Neutrinos

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Kopenhagen
erdam
Berlin
Bochum
Deutschland
jien
Prag
Tschechien
München
Wien
Zürich
Österreich
Schweiz


Kopenhagen
Berlin
erdam
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jien
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Österreich
Schweiz


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erdam
Berlin
Bochum
Deutschland
gien
Prag
Tschechien
München
Wien
Zürich
Österreich
Schweiz

Which neutrino sources do you know?

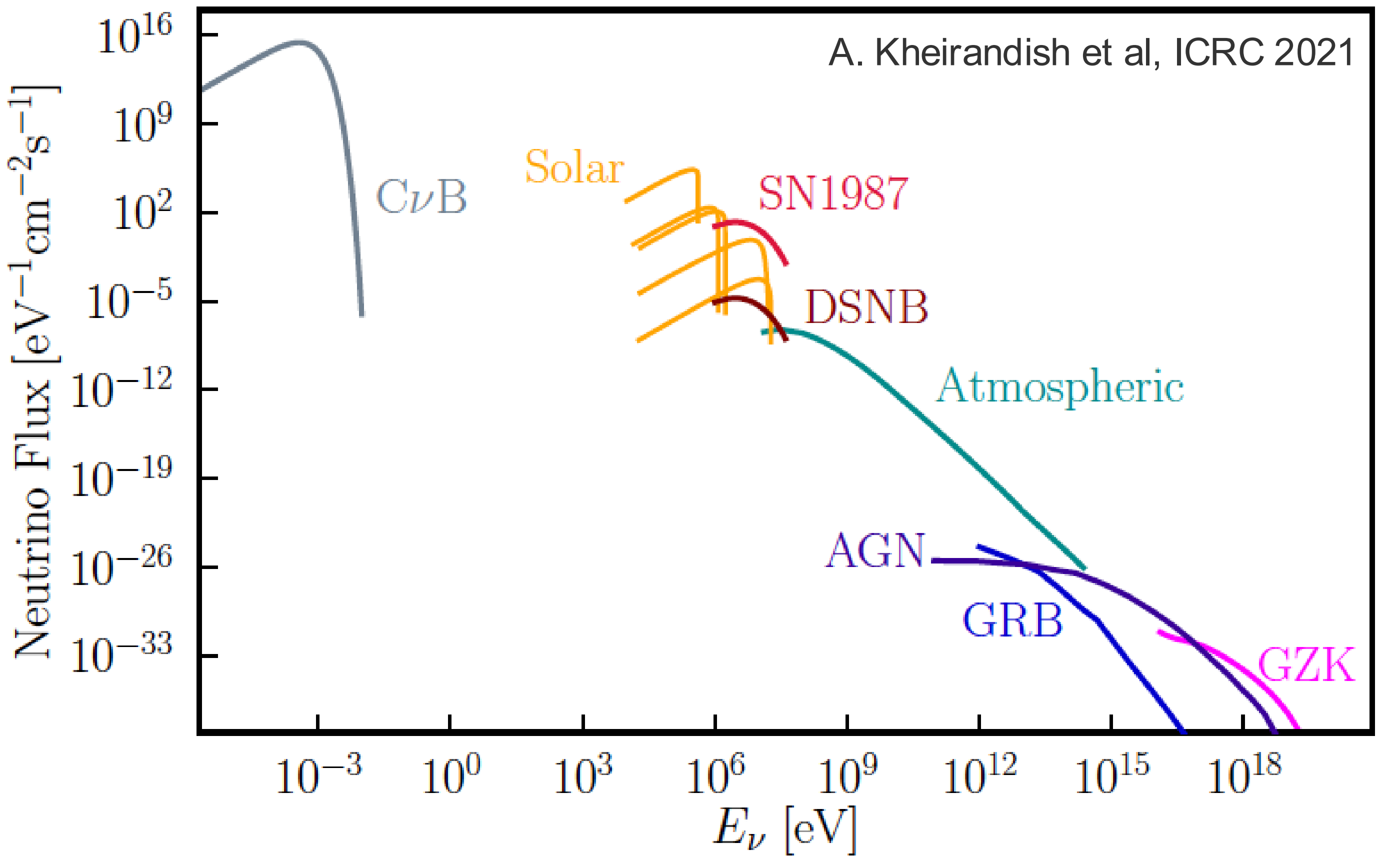
Content of the 3 lectures

- Low-energy (MeV) neutrinos
  - Sun
  - Supernovae
- High-energy (TeV-PeV) neutrinos
  - Astrophysics
  - Particle physics
- Even higher energies?

Learning Objectives

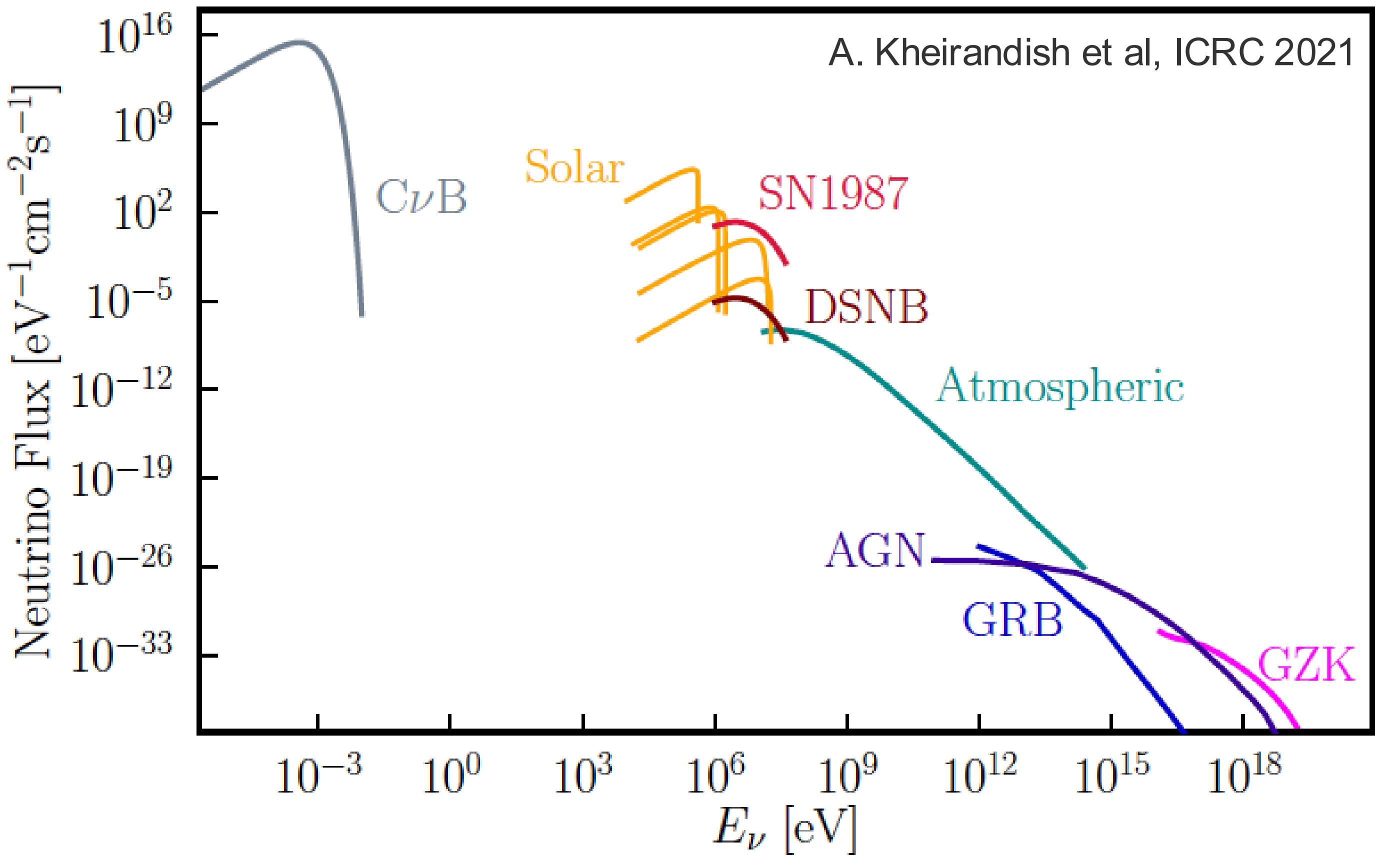
- What have we learned from MeV solar and supernova neutrinos?
- Are we ready for the next Galactic supernova?!

- How can we detect high-energy astrophysical neutrinos?
- What is the background in the search for high-energy cosmic neutrinos and how can we disentangle it from the signal?
- What have we learned so far from high-energy neutrino detections?
- How can we improve in the future?



A. Kheirandish et al, ICRC 2021
Neutrino Flux [eV^{-1}cm^{-2}s^{-1}]
10^{16}
10^{9}
10^{2}
10^{-5}
10^{-12}
10^{-19}
10^{-26}
10^{-33}
CνB
Solar
SN1987
DSNB
Atmospheric
AGN
GRB
GZK
10^{-3}
10^{0}
10^{3}
10^{6}
10^{9}
10^{12}
10^{15}
10^{18}
E_ν [eV]

RUB



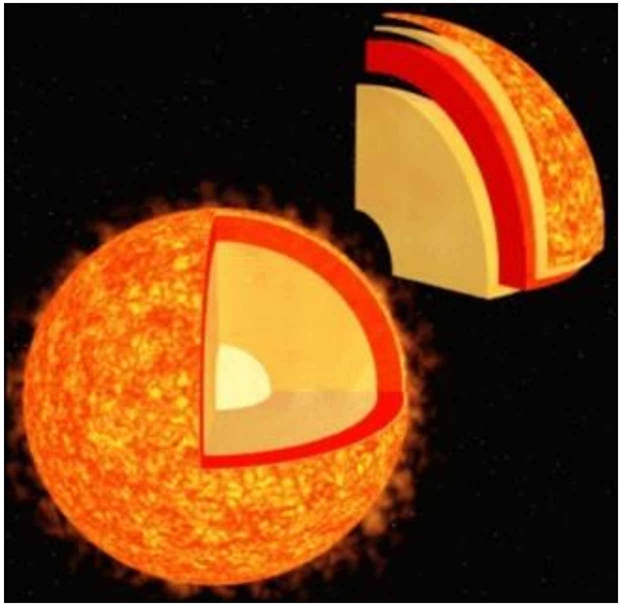
Ideas: neutrino capture on unstable nucleus (e.g. tritium)

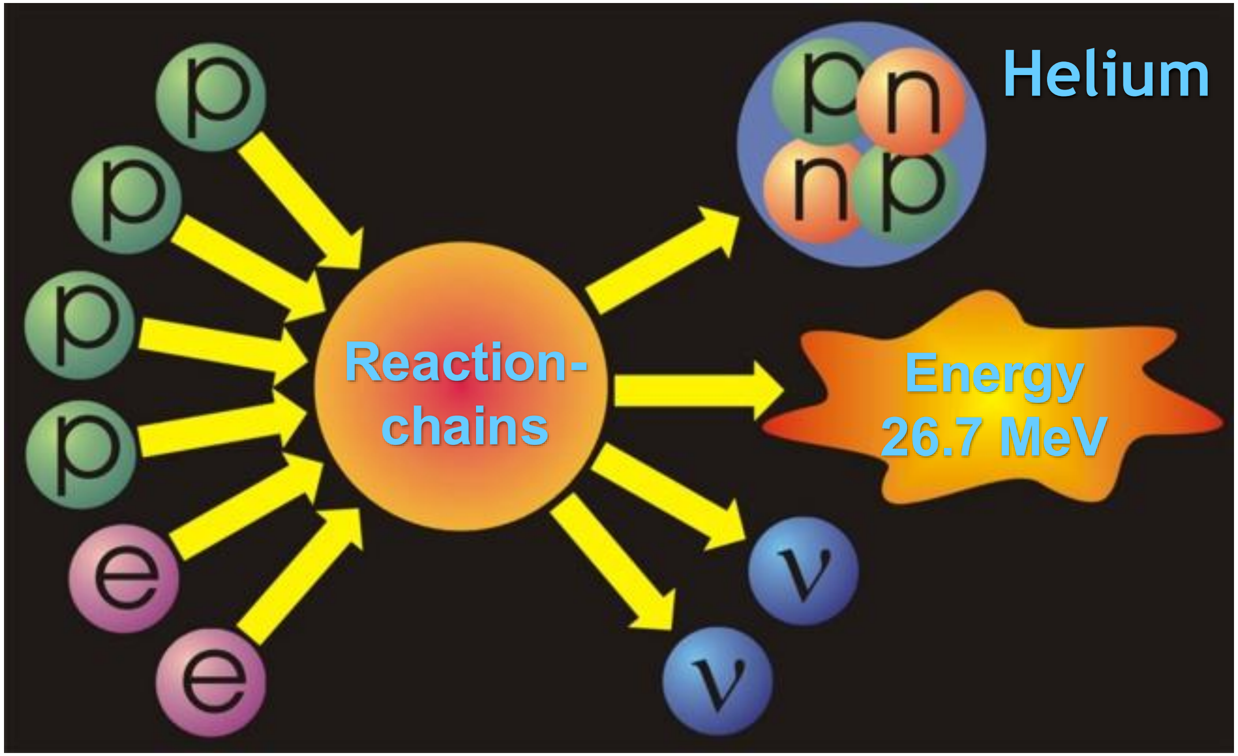
Neutrino capture on stable nucleus (Chlorine, Gallium)

Water / ice Cherenkov detectors

Radio arrays, cosmic-ray detectors

Solar Neutrinos





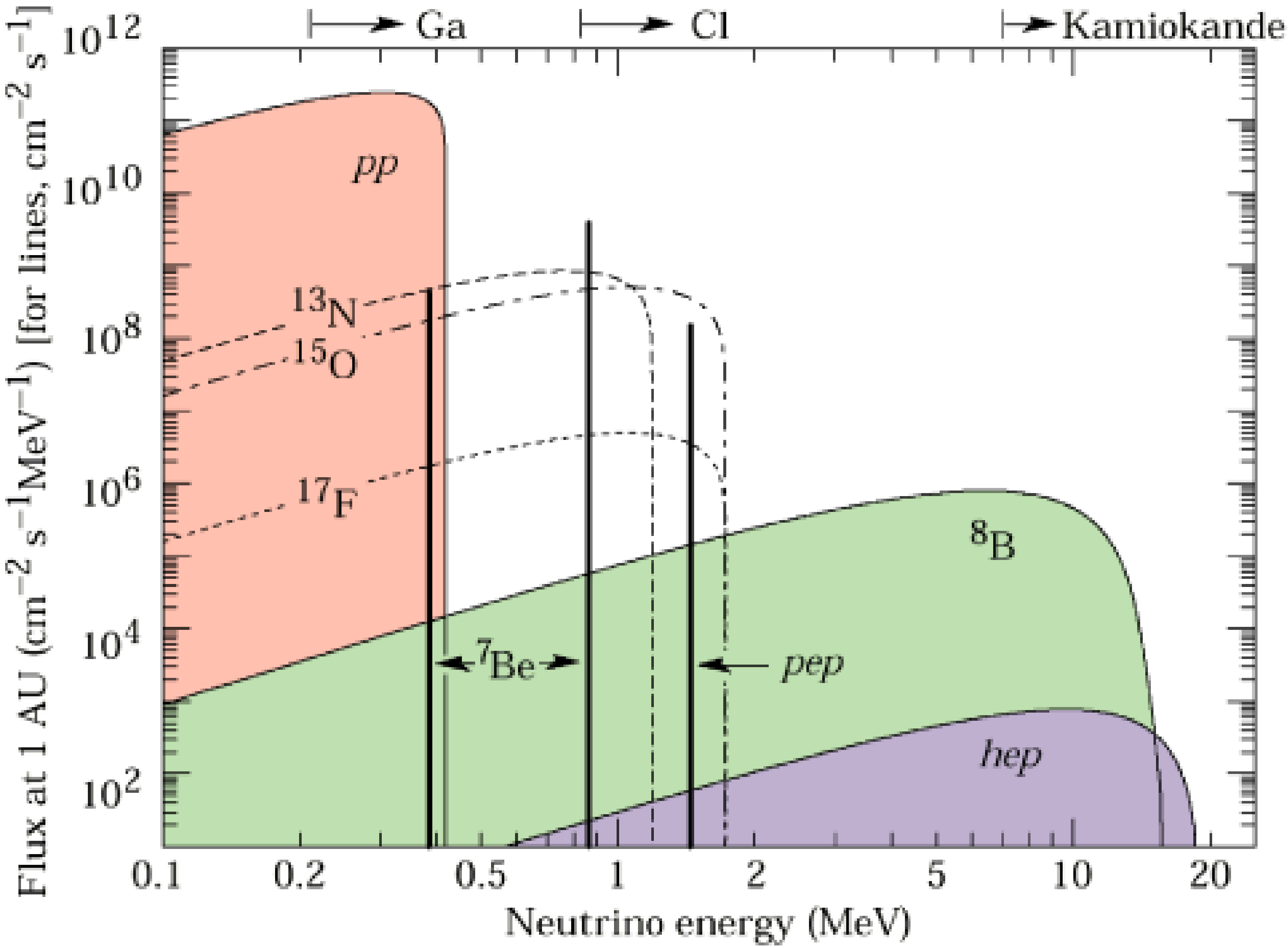
1967

Solar radiation:

- 98% light
- 2% **electron-neutrinos**

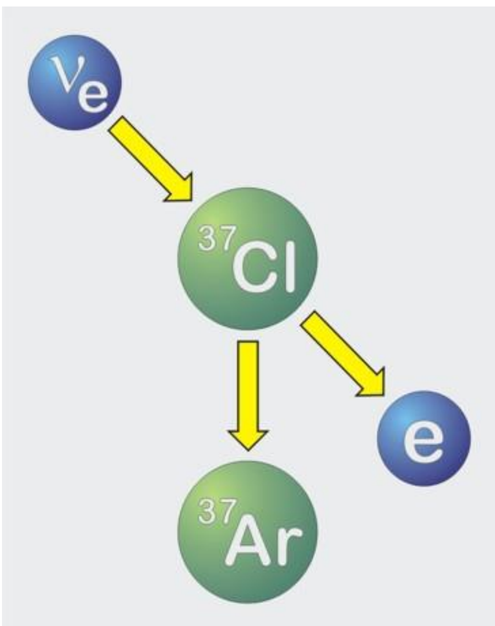
→ at Earth: 66 billion neutrinos / cm^2 / s

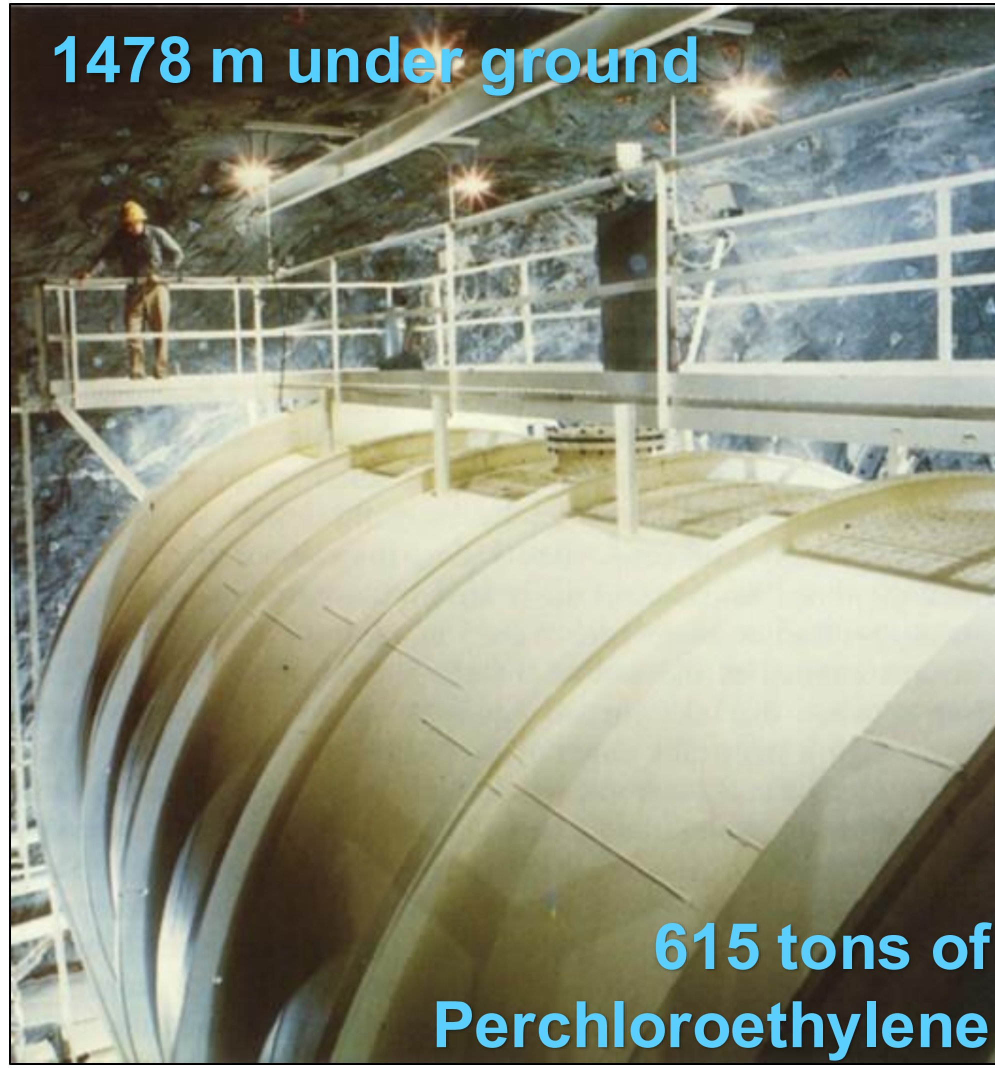
Solar Neutrino Spectrum



The Homestake Experiment

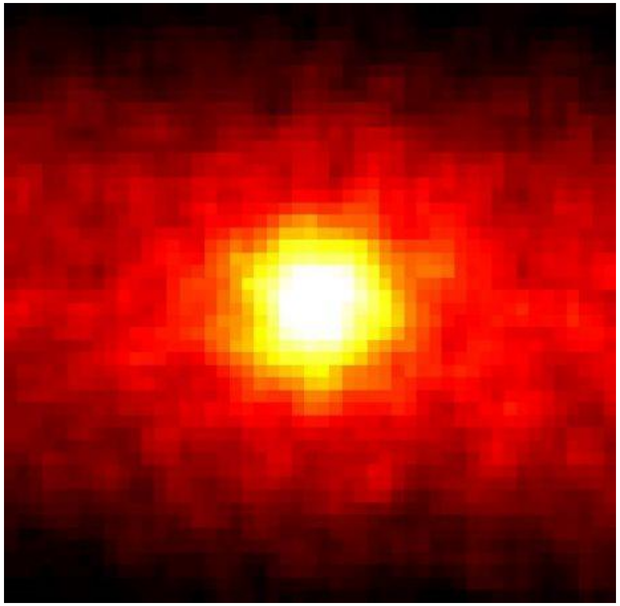
$$\nu_e + {}^{37}\mathrm{Cl} \longrightarrow {}^{37}\mathrm{Ar} + e^-$$





Solar Neutrinos

Astronomy Picture of the Day
June 5, 1998



The Sun in Neutrinos seen
by Super-Kamiokande

Combining neutrinos and electromagnetic information led to:

- **The solar neutrino problem**

Solar Neutrinos

Astronomy Picture of the Day
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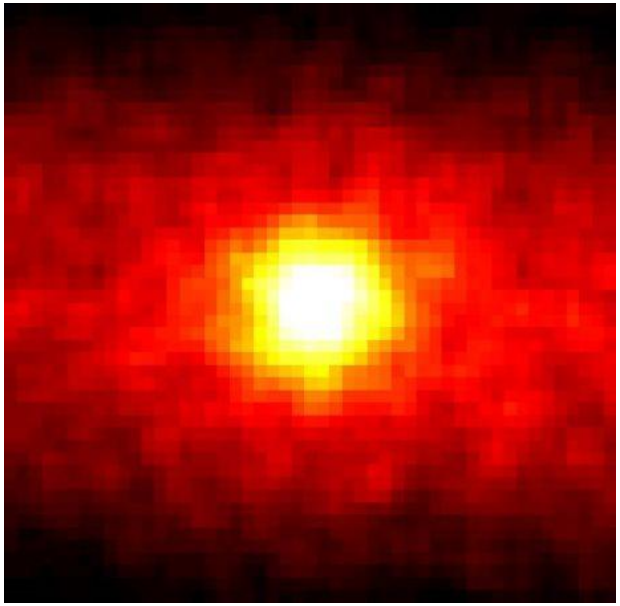
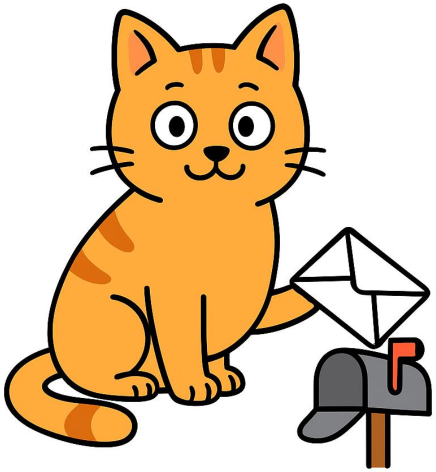


The Sun in Neutrinos seen
by Super-Kamiokande

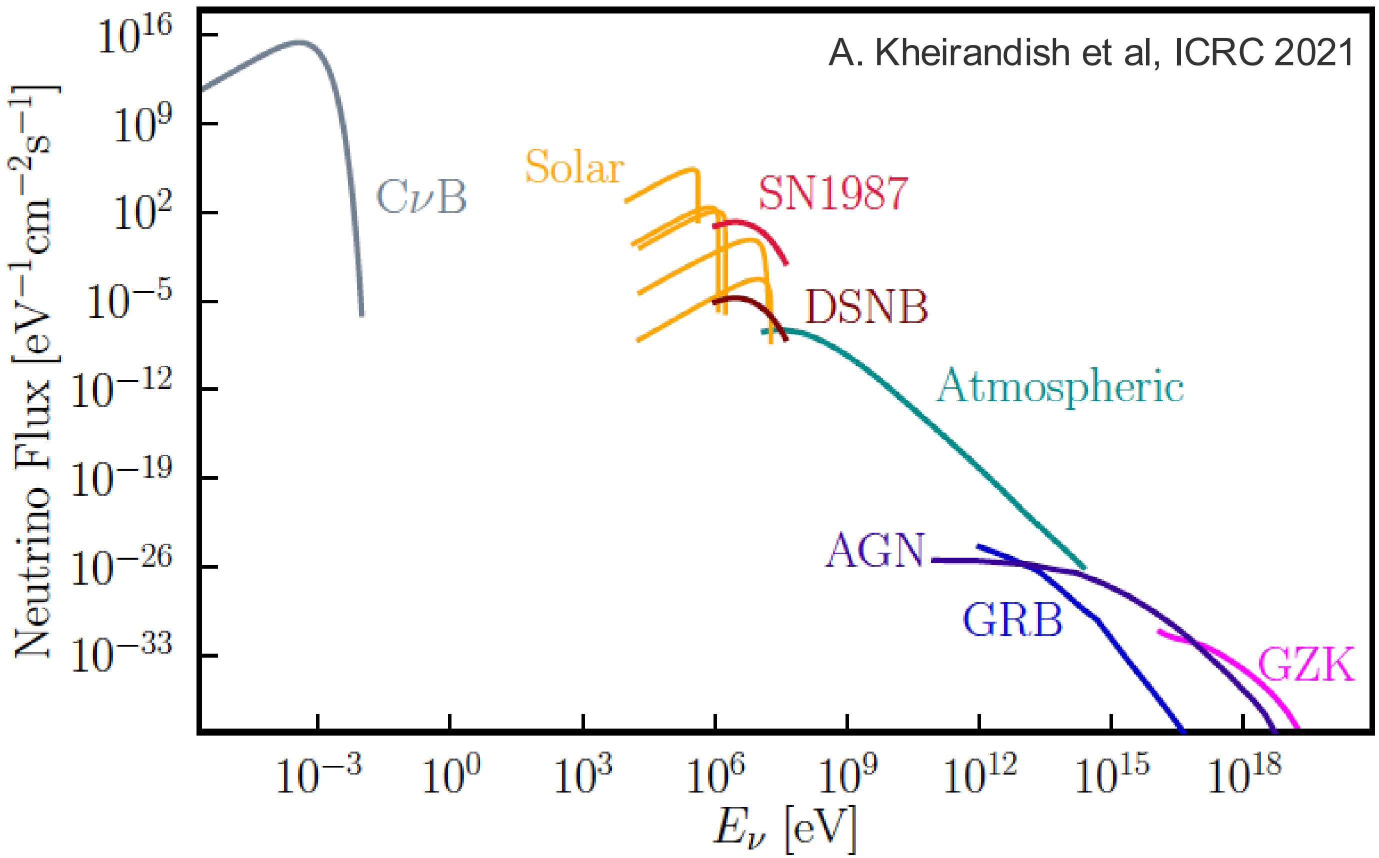
Combining neutrinos and electromagnetic information led to:

- Confirmation of model of fusion
- New understanding of the standard model of particle physics
  → neutrinos oscillate → have mass!



Take home message

Too few electron neutrinos have been detected from the sun, but the number matches expectations if all flavors are considered.
This is explained by neutrino oscillation, which only works when neutrinos have mass.



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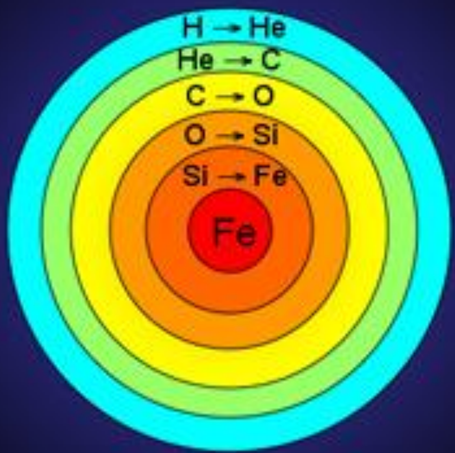
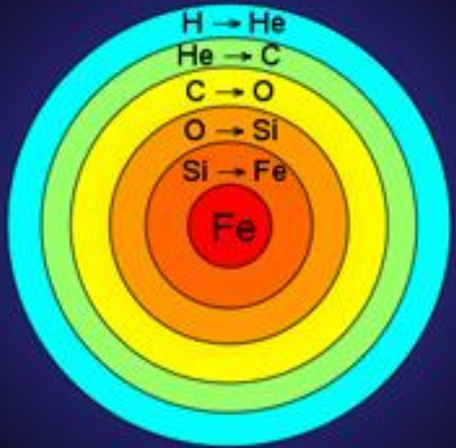
Supernova Neutrinos



For a 25 solar mass star:

Stage	Duration
H → He	7×10^6 years
He → C	7×10^5 years
C → O	600 years
O → Si	6 months
Si → Fe	1 day
Core Collapse	1/4 second

Supernova Neutrinos



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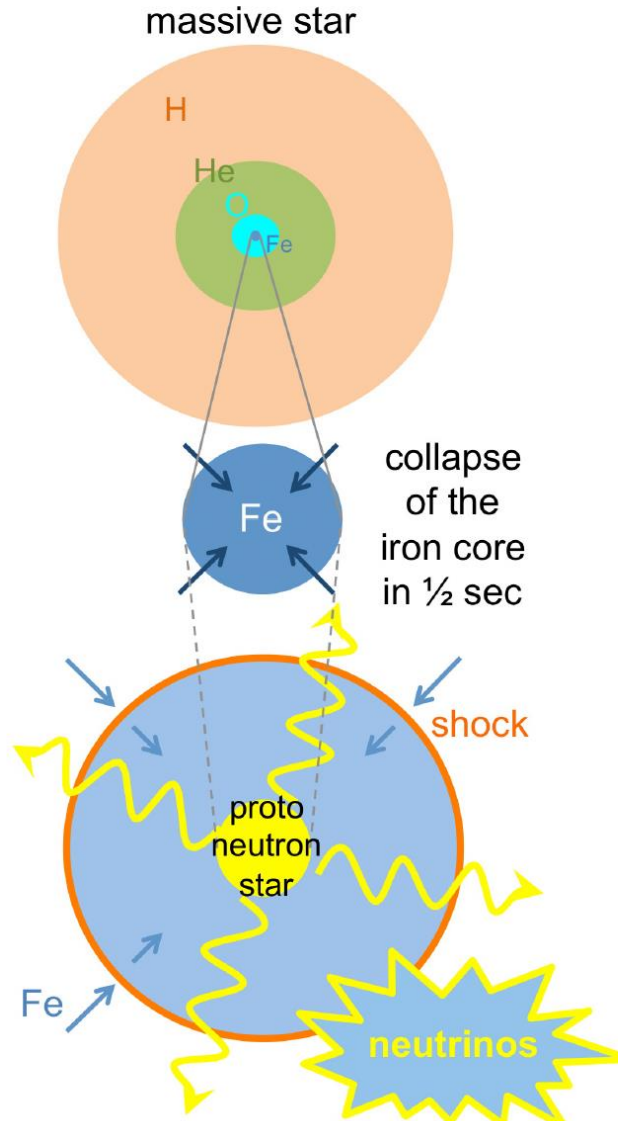
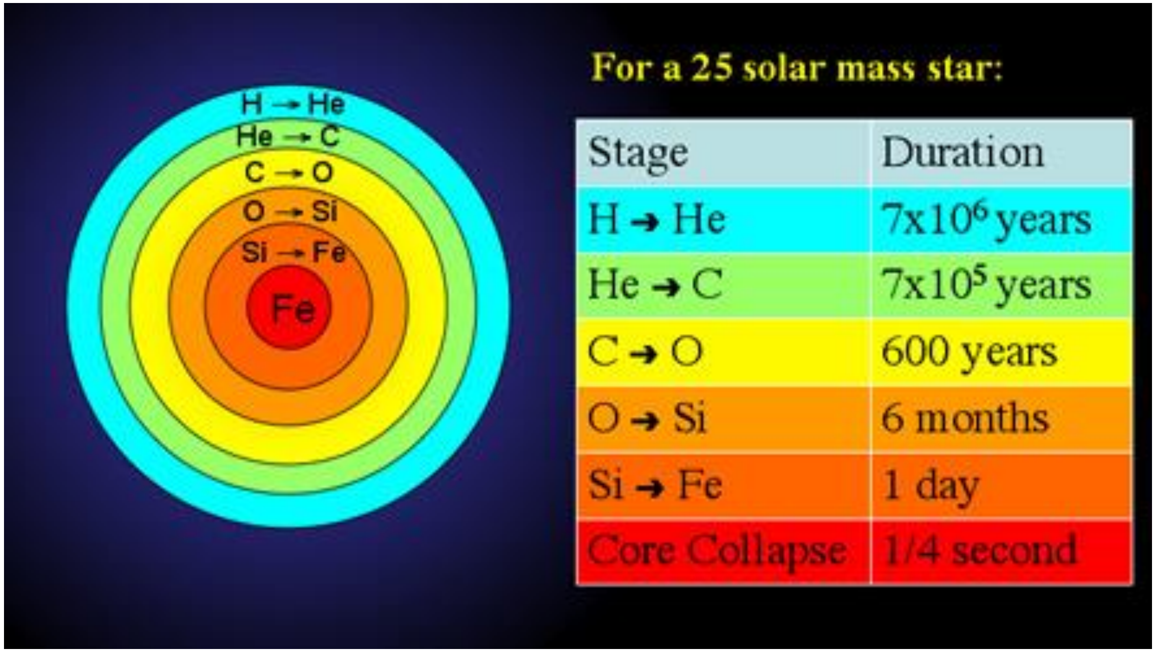


Supernova Neutrinos



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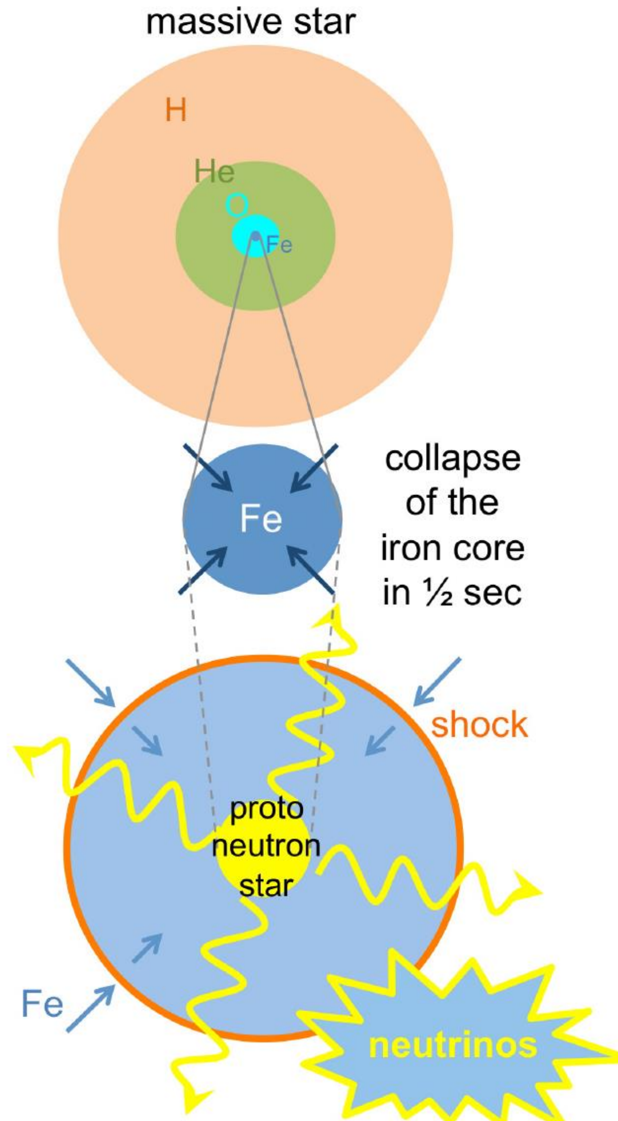
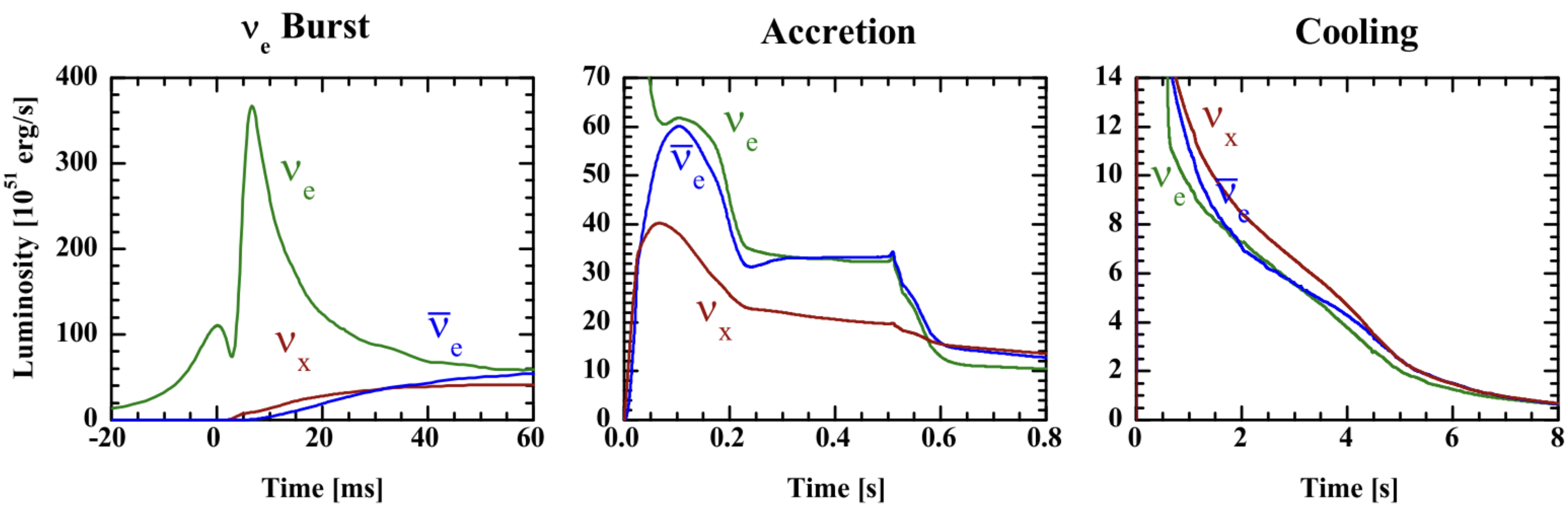


Neutronization burst: $e^- + p \rightarrow n + \nu_e$
Thermal neutrinos of all flavors

- $\sim 10^{58}$ neutrinos in ~10s
- 99% of gravitational energy
- typical energy: 10-20 MeV

Expected neutrino signal



Initial neutronization burst

$$e^- + p \to n + \nu_e$$

Material falls onto the proto-neutron star, e^- and e^+ in hot plasma

$$e^- + p \to n + \nu_e$$

$$e^+ + n \to p + \bar{\nu}_e$$

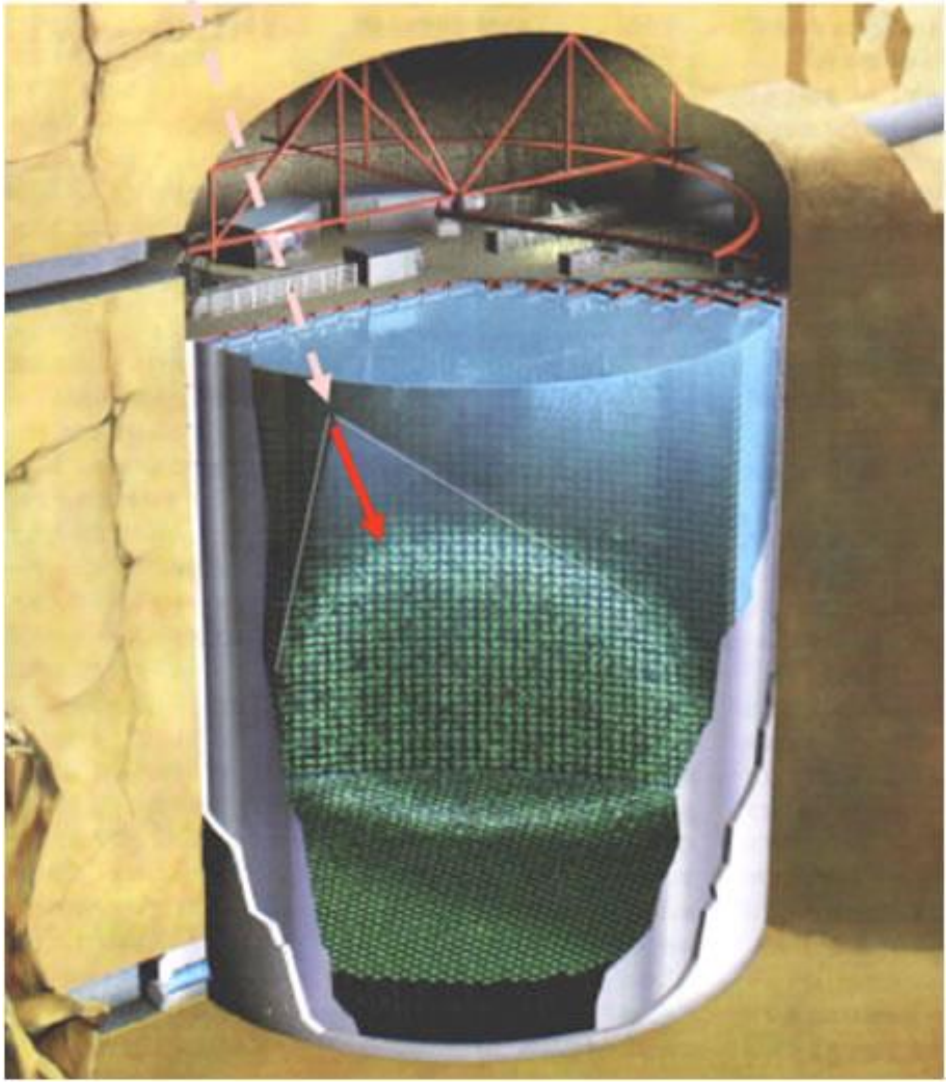
proto-neutron star loses trapped thermal energy mainly by neutrino emission of all flavors

$$e^+ e^- \to \nu\bar{\nu}$$

1D spherically symmetric supernova simulation (M=27 M), Garching group.

(Super) Kamiokande

Volume: 3kT (50kT)



Detection channels:

Inverse beta decay:

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

Elastic scattering:

$$\nu_e + e^- \rightarrow \nu_e + e^-$$

Charged current absorption on oxygen:

$$\nu_e + ^{16}O \rightarrow e^- + ^{16}F$$

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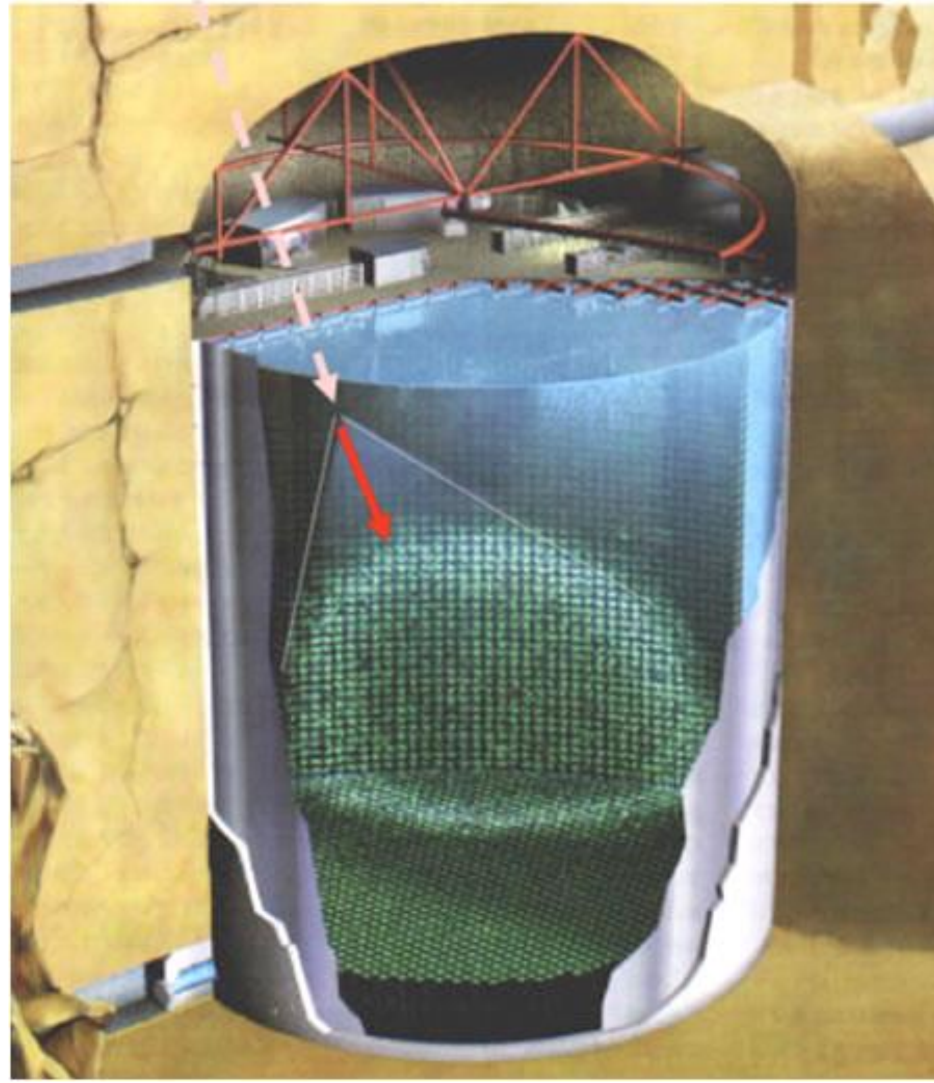


Detection channels:

Inverse beta decay:

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

Most efficient

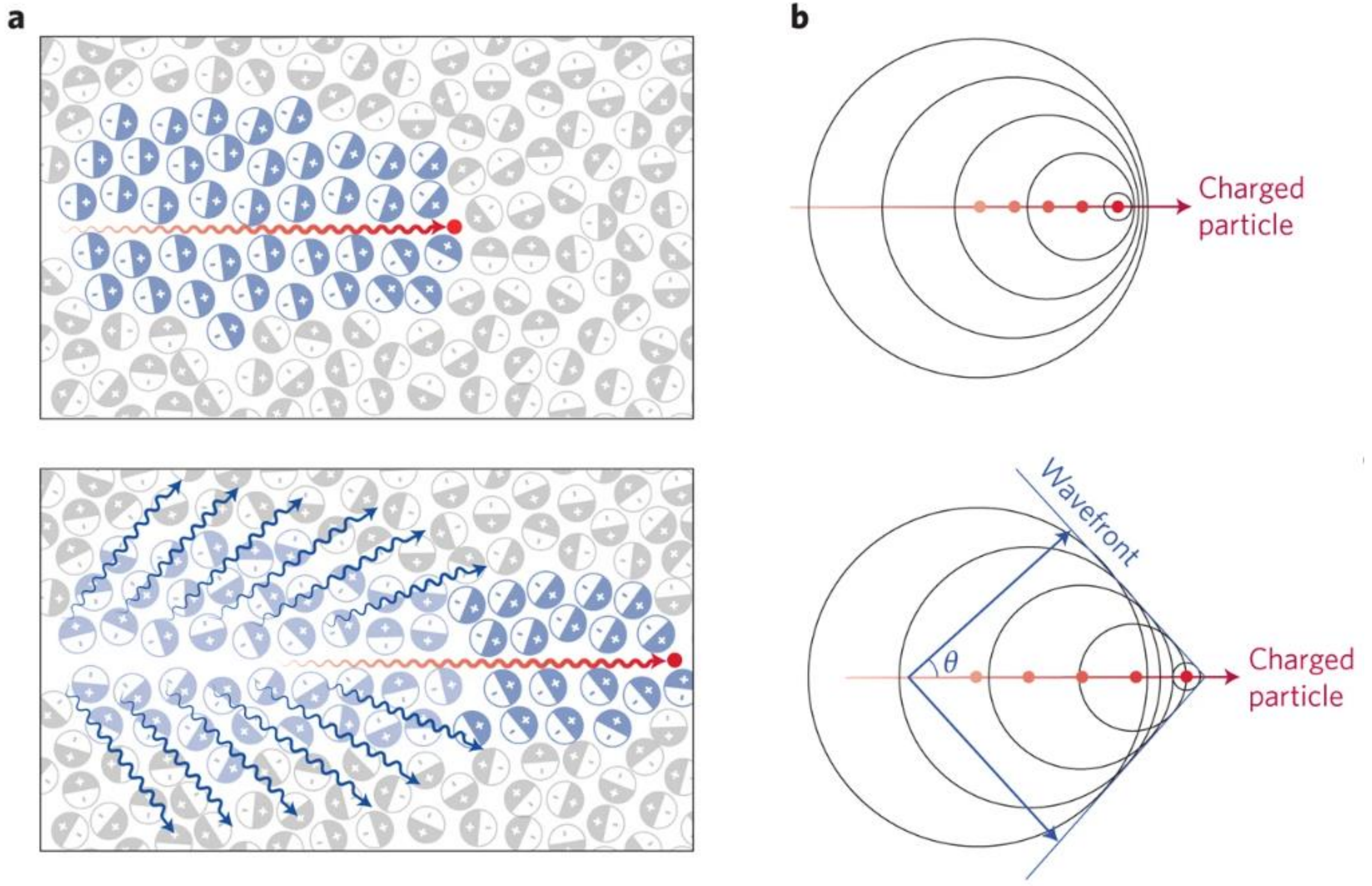
Elastic scattering:

$$\nu_e + e^- \rightarrow \nu_e + e^-$$

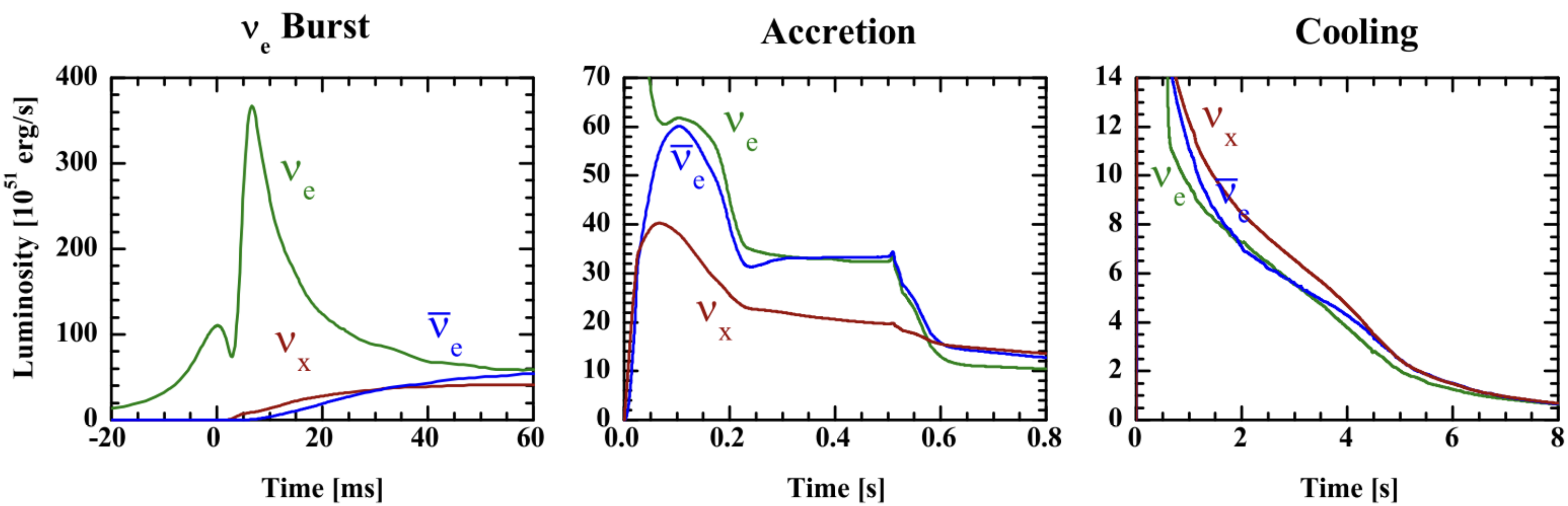
Charged current absorption on oxygen:

$$\nu_e + {}^{16}O \rightarrow e^- + {}^{16}F$$

Different detection technique: Cherenkov Effect



Expected neutrino signal



Initial neutronization burst

$$e^- + p \rightarrow n + \nu_e$$

Material falls onto the proto-neutron star, e^- and e^+ in hot plasma

$$e^- + p \rightarrow n + \nu_e$$

$$e^+ + n \rightarrow p + \bar{\nu}_e$$

proto-neutron star loses trapped thermal energy mainly by neutrino emission of all flavors

$$e^+ e^- \rightarrow \nu\bar{\nu}$$

Expected signal in Super-K dominated by **anti-electron neutrinos**

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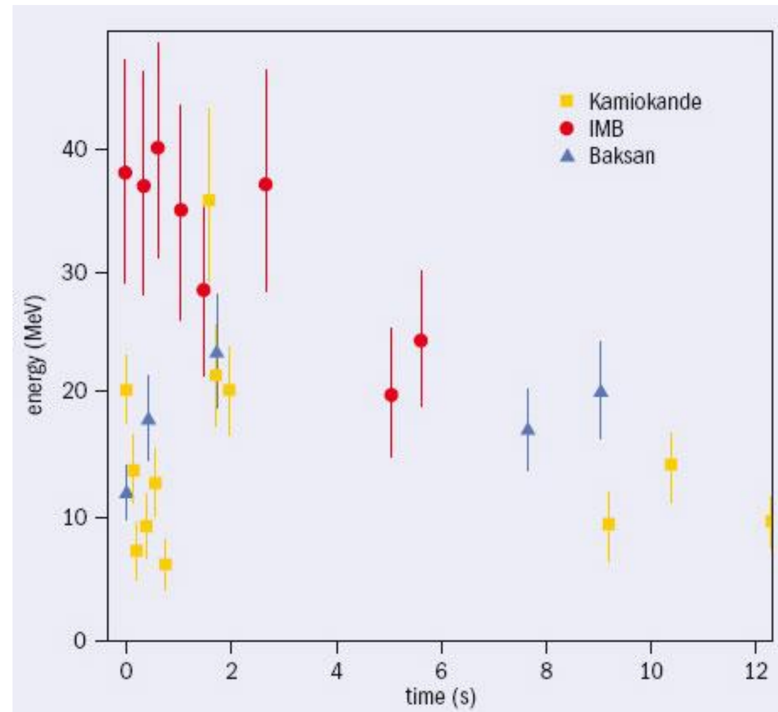
1D spherically symmetric supernova simulation (M=27 M), Garching group.

First and only Supernova neutrino detection

Optical detection of SN1987A in LMC

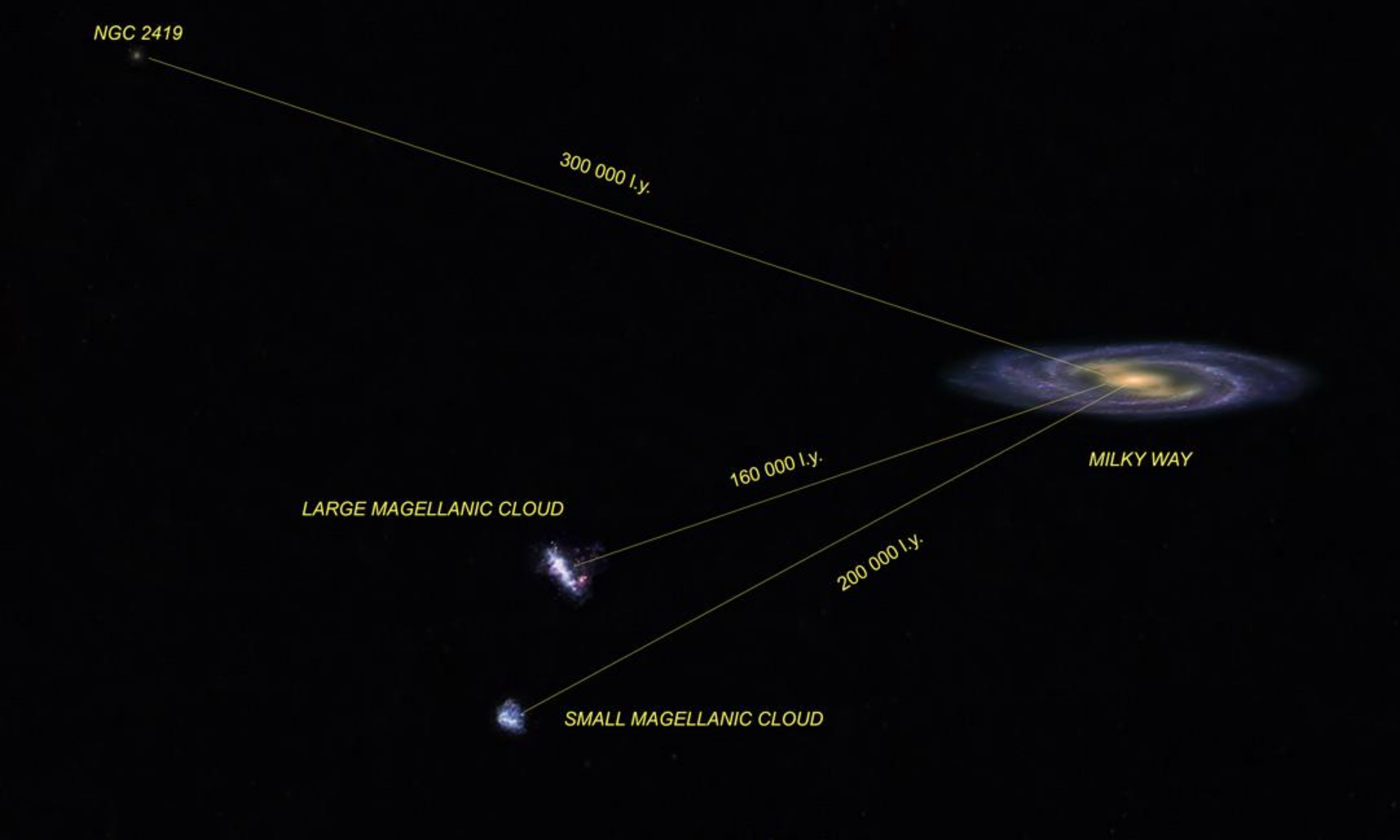
MeV neutrino burst



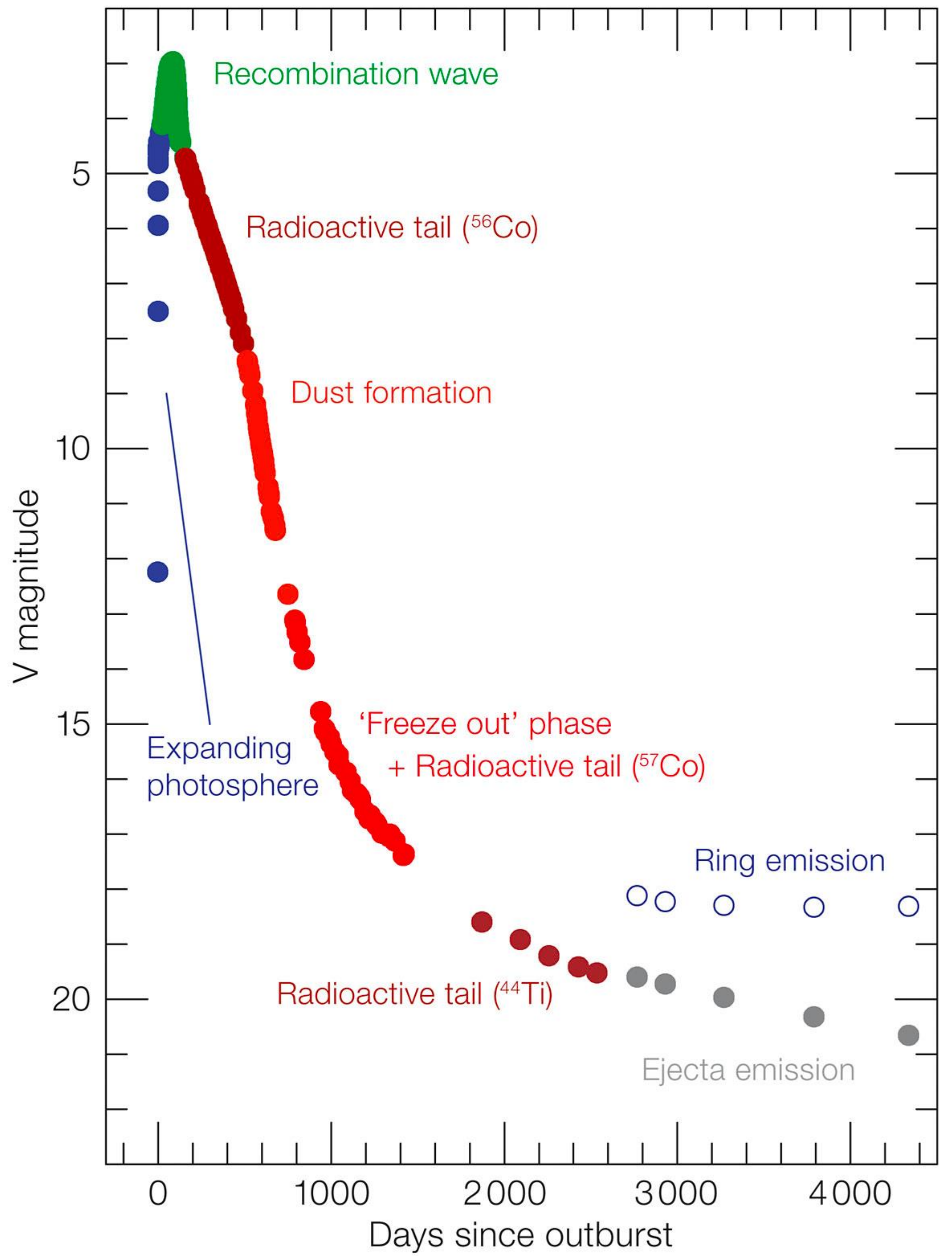
Neutrinos arrived 2-3h earlier

Location of Magellanic Clouds

Distance: 50kpc = 160000 Ly



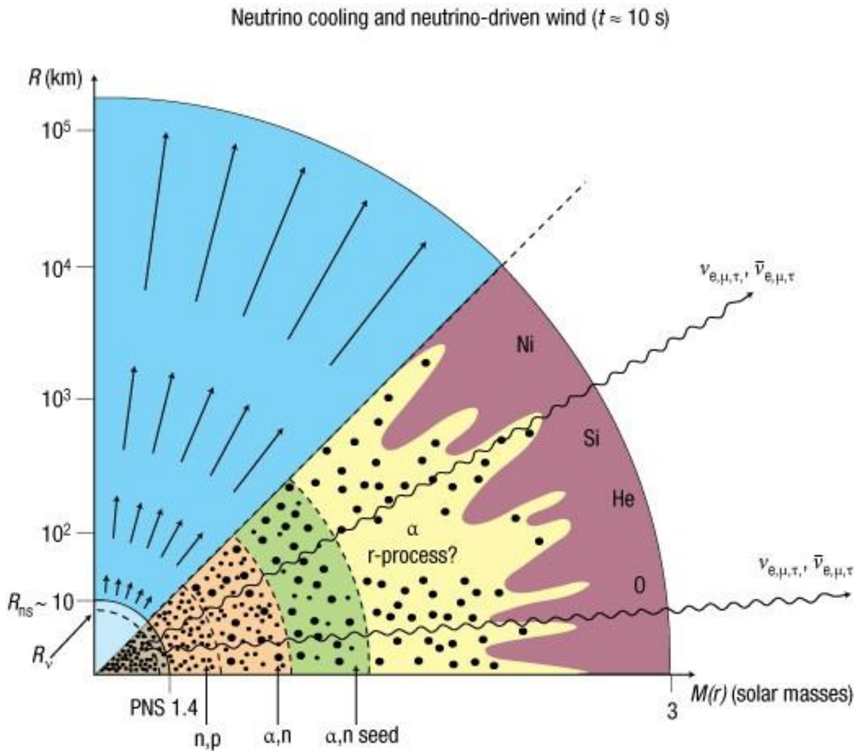
SN1987A light curve



Credit: ESO

First (and only) detection of a Supernova

First direct confirmation of our basic picture of a stellar collapse



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Woosely & Janka,
Nature Physics 2005

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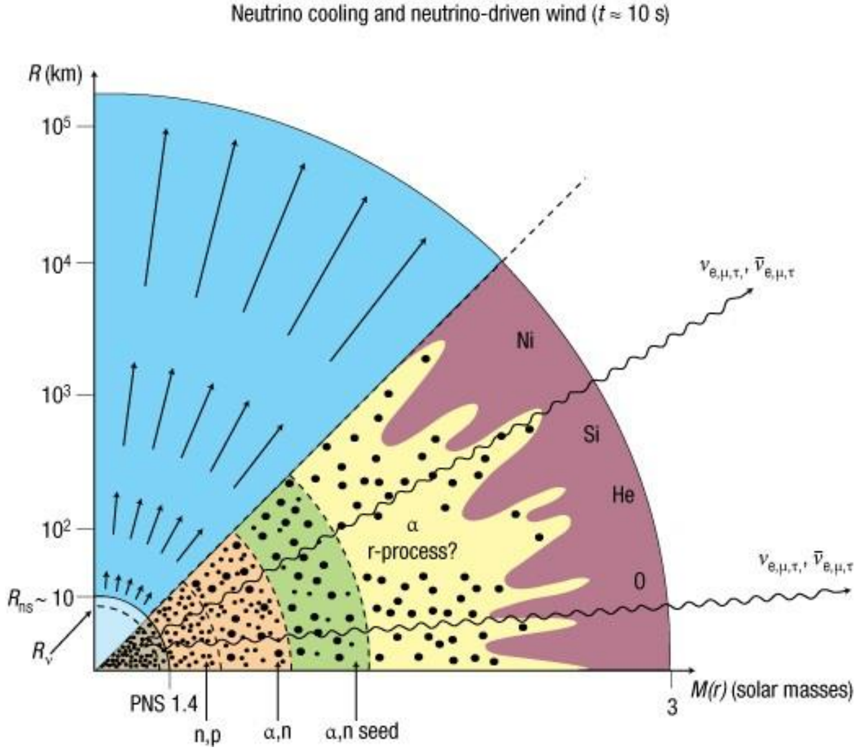
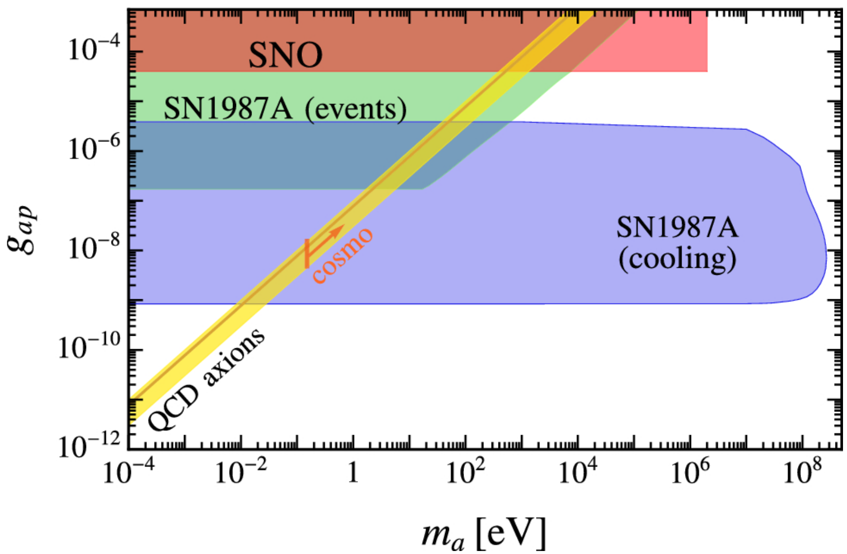


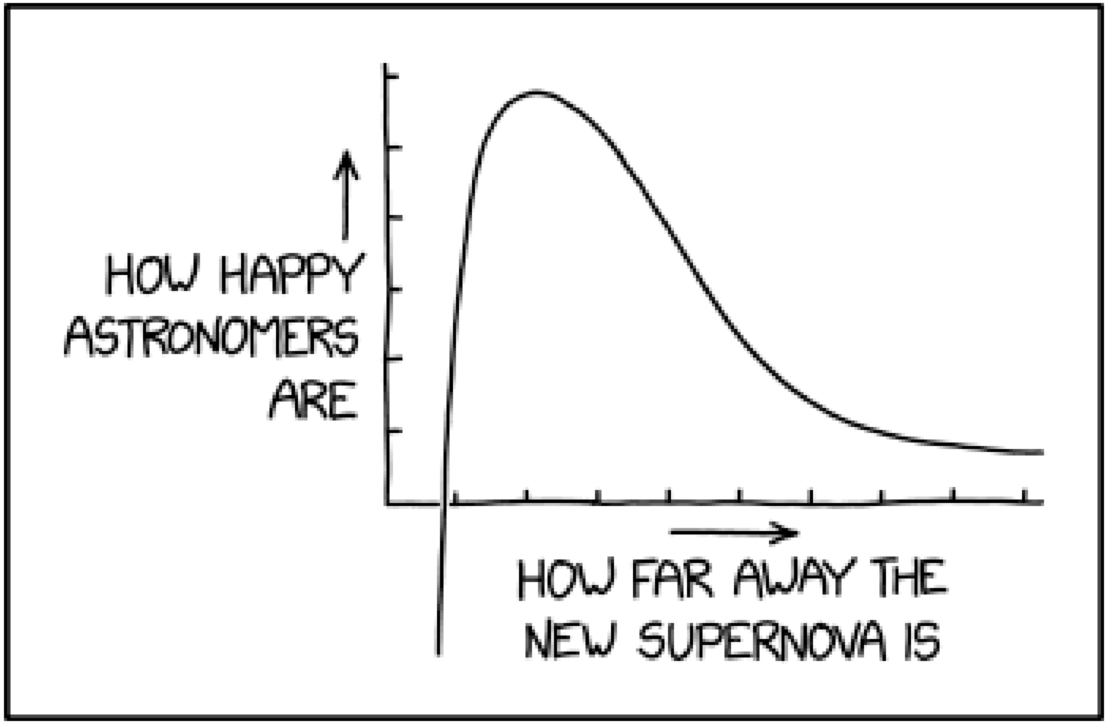
Woosely & Janka, Nature Physics 2005

Constraints on exotic physics (e.g. axions)



Lella et al. PRD 109 (2024)

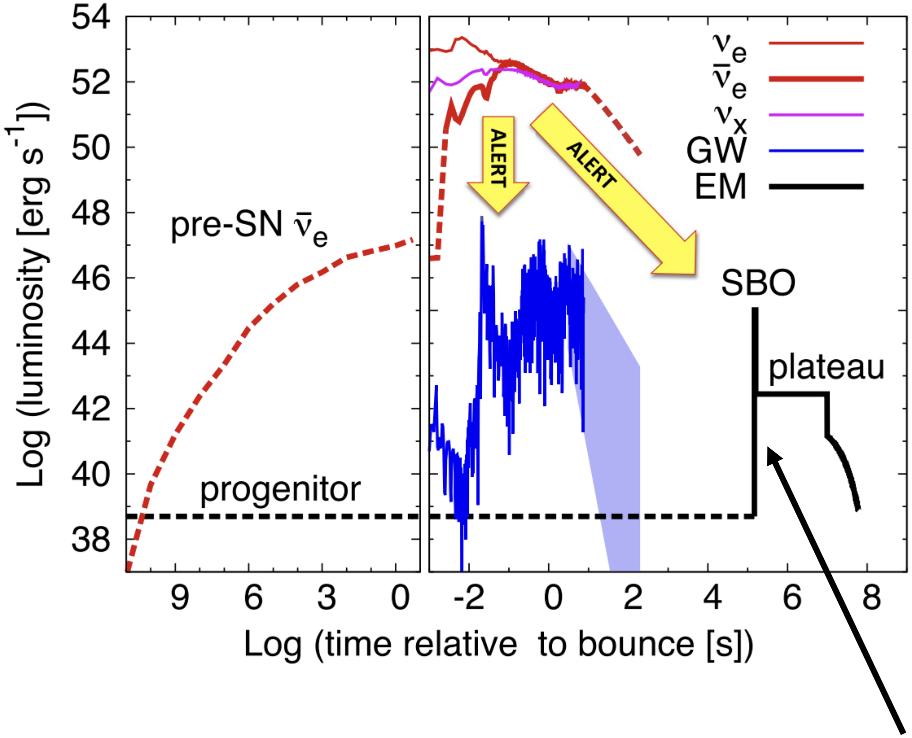
Are we ready for the next Galactic Supernova?!



https://xkcd.com/2878/

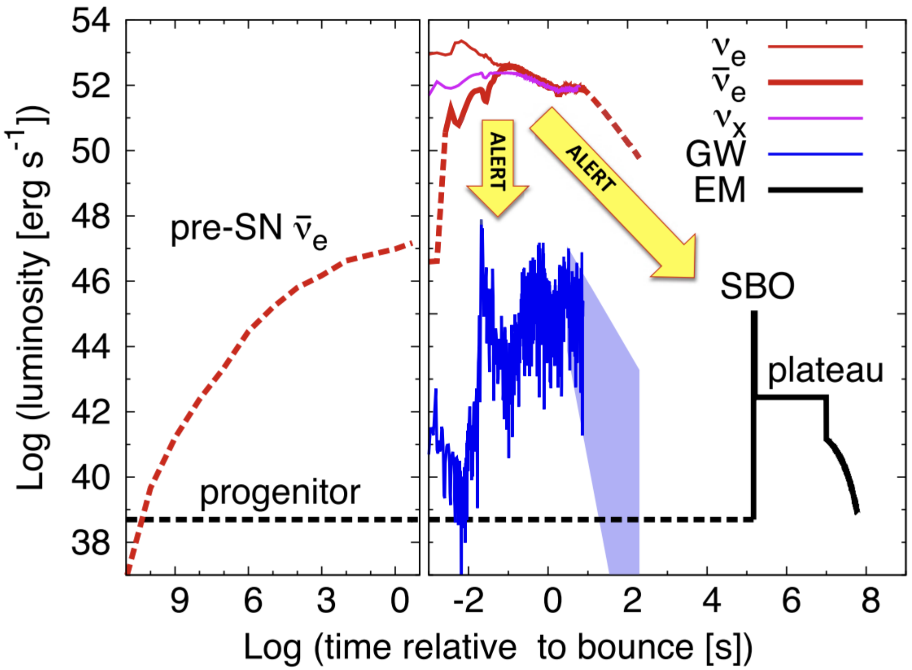
Supernova early warning system

SNEWS
SUPERNOVA EARLY WARNING SYSTEM



Shock breakout in X-ray
and UV emission

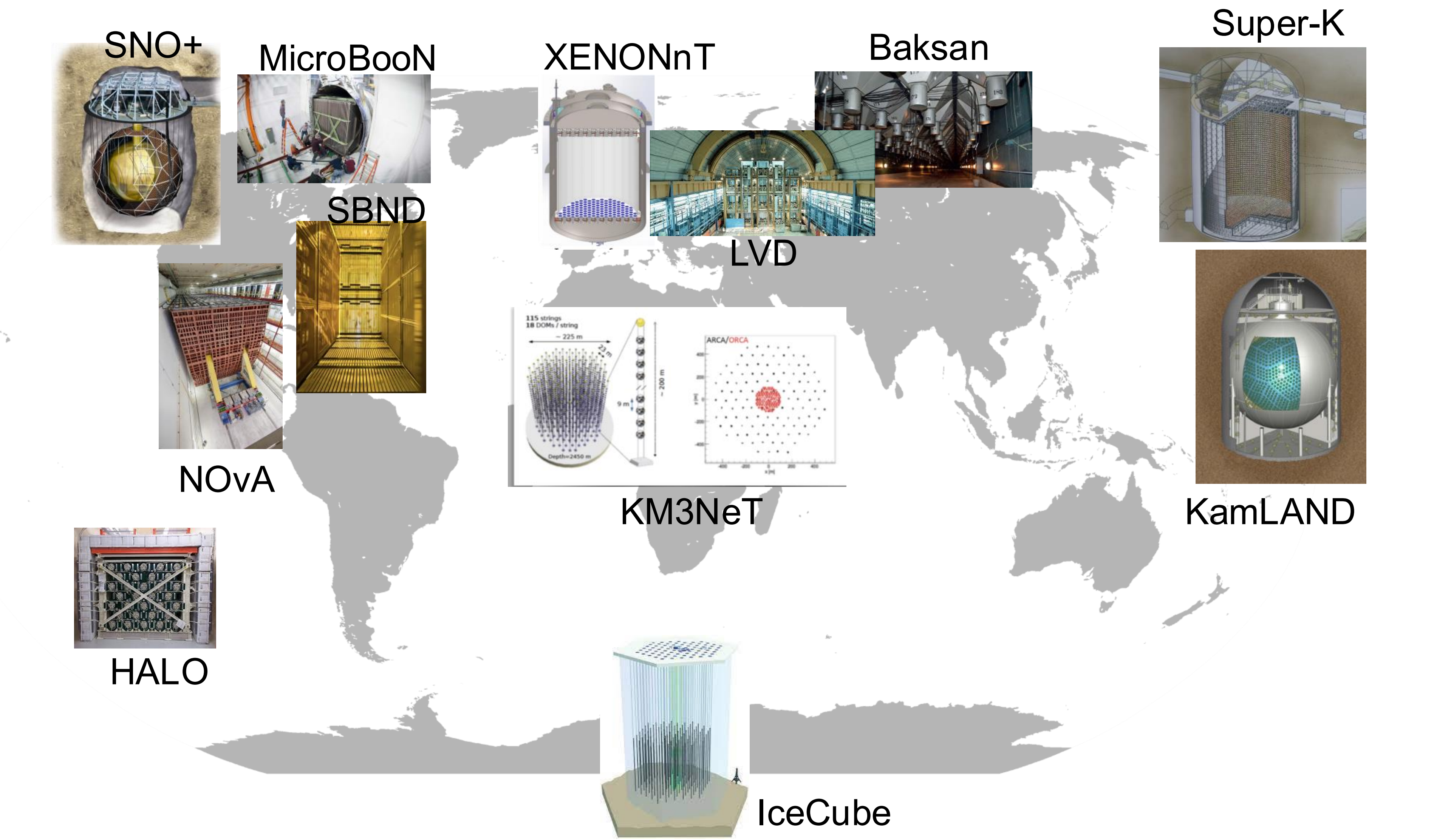
Supernova early warning system



MeV neutrino burst as trigger for electromagnetic supernovae observations

Al Kharusi et al New J. Phys. **23** 2021

Detectors participating in SNEWS



https://snews2.org/

Supernova early warning system

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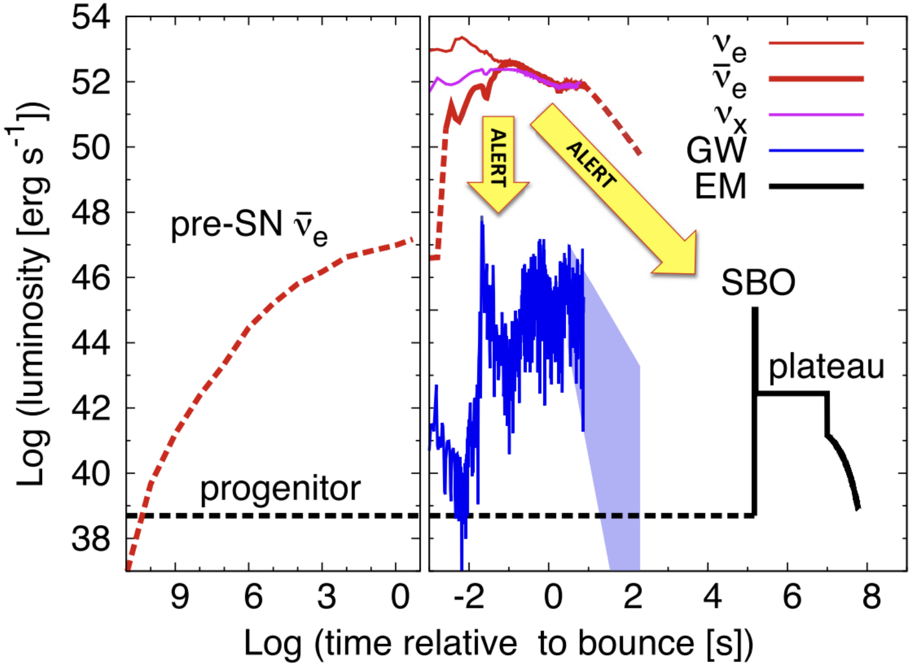

MeV neutrino burst as trigger for electromagnetic supernovae observations

SNEWS 2.0:

- new infrastructure
- public sub-threshold alerts
- pointing using inter-experiment triangulation
- searches for pre-supernova neutrinos

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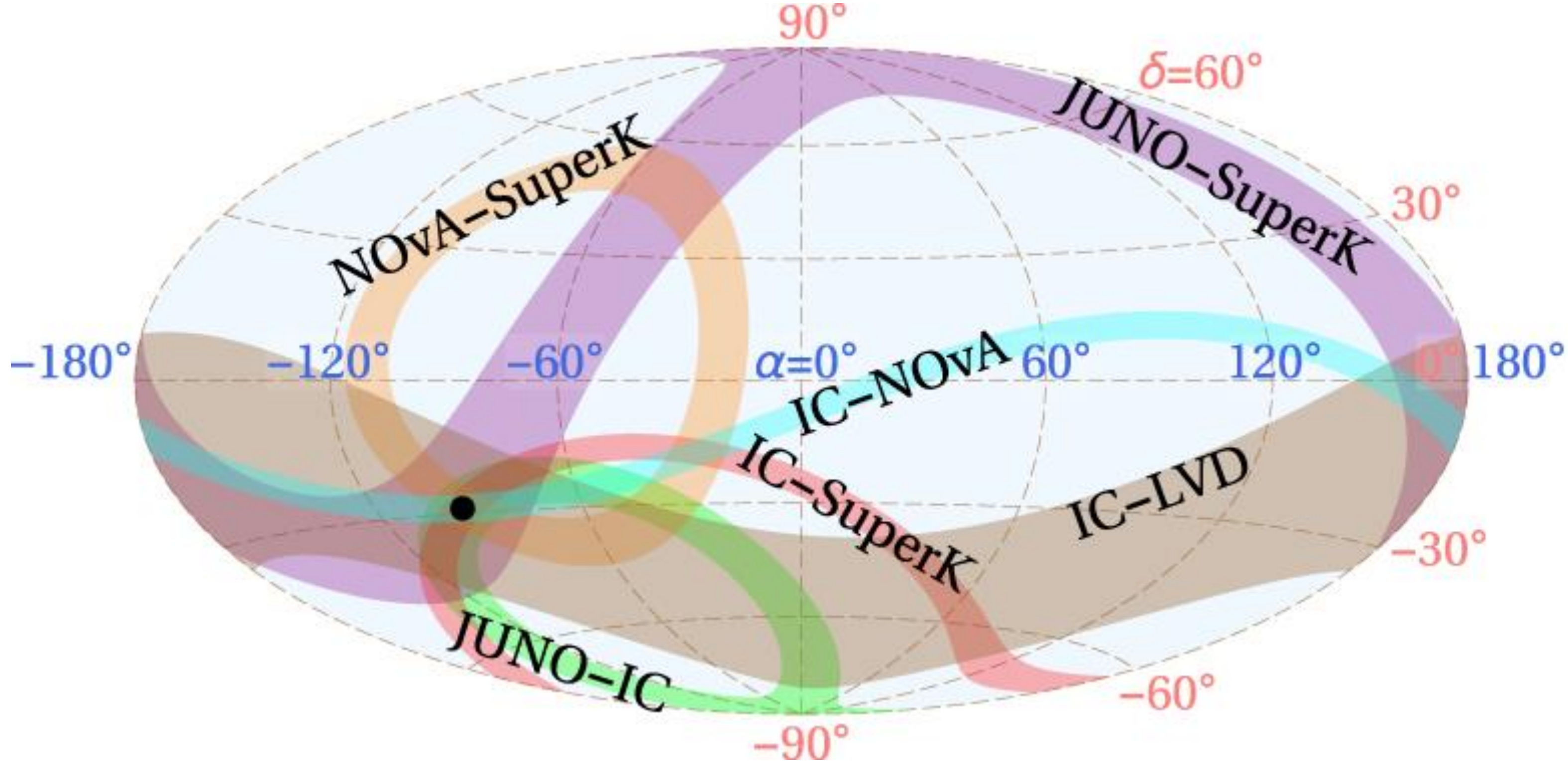
Al Kharusi et al New J. Phys. **23** 2021

Supernova localization



Coordinated follow-up observations with wide-field-of-view instruments are necessary

Al Kharusi et al New J. Phys. **23** 2021

Catching the next Galactic Neutrino Supernova

- Unprecedented insights into the explosion mechanism
- Information about surrounding material
- Spatially resolved imaging of early phases of explosion

Kistler et al., ApJ 778 (2013)

Catching the next Galactic Neutrino Supernova

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- Information about surrounding material
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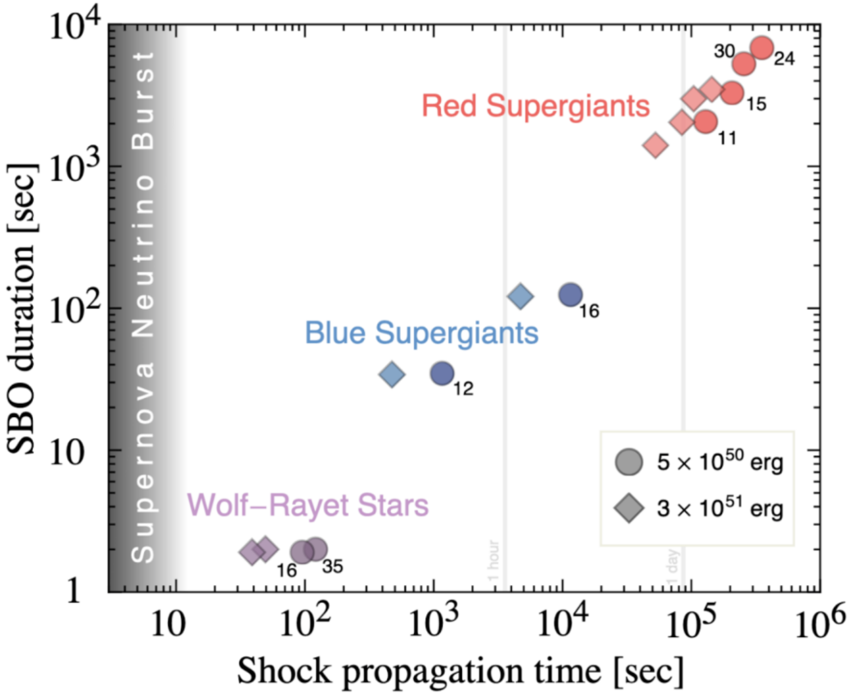
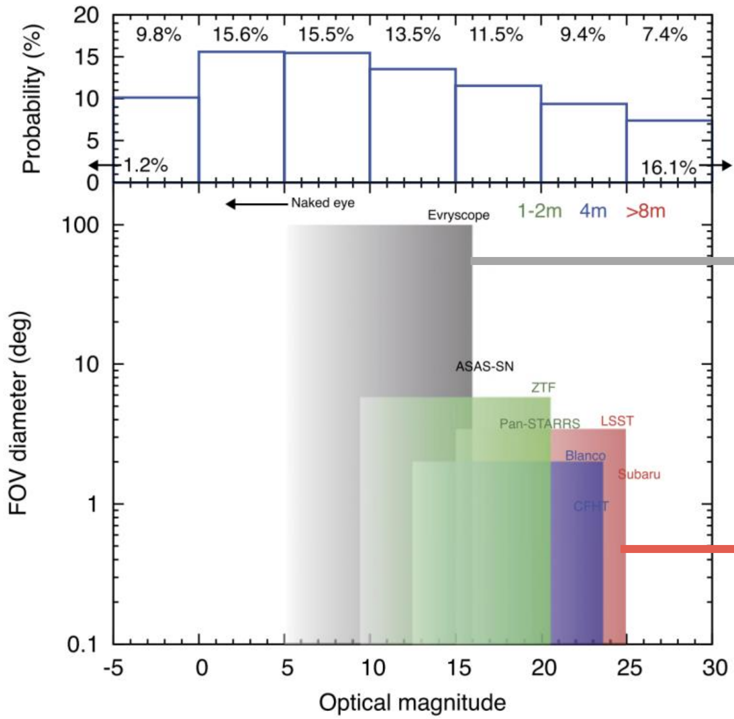
Delay between neutrino burst and optical signal: 2 min to 2 days



Kistler et al., ApJ 778 (2013)

Catching the next Galactic Neutrino Supernova

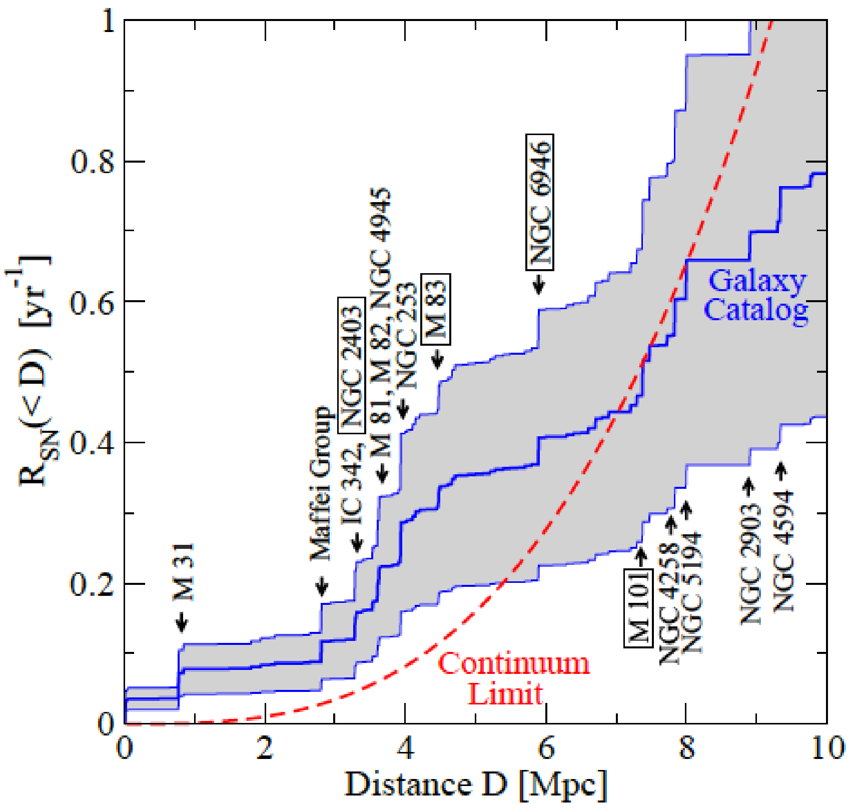
Detectability of shock breakout



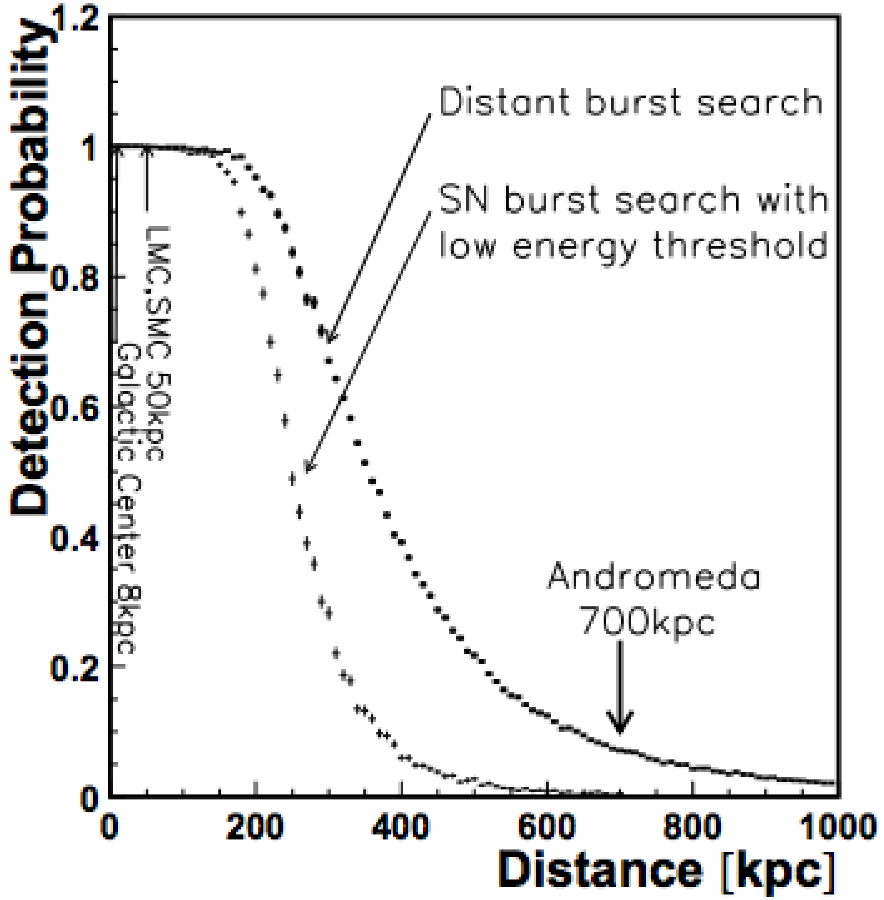
Optical counterpart can appear within minutes of neutrino alert → take full advantage of once-in-a-lifetime event

Al Kharusi et al New J. Phys. **23** 2021

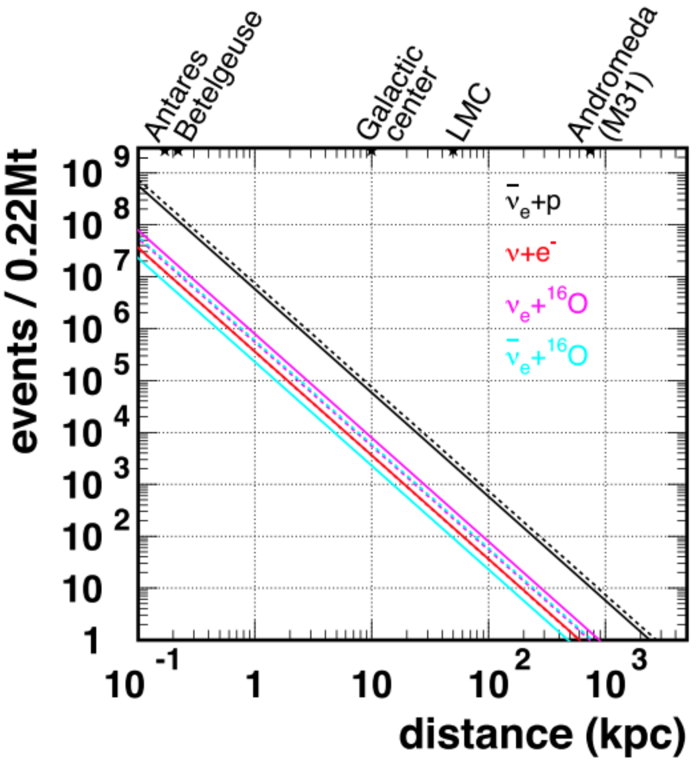
Sensitivity to Supernovae today

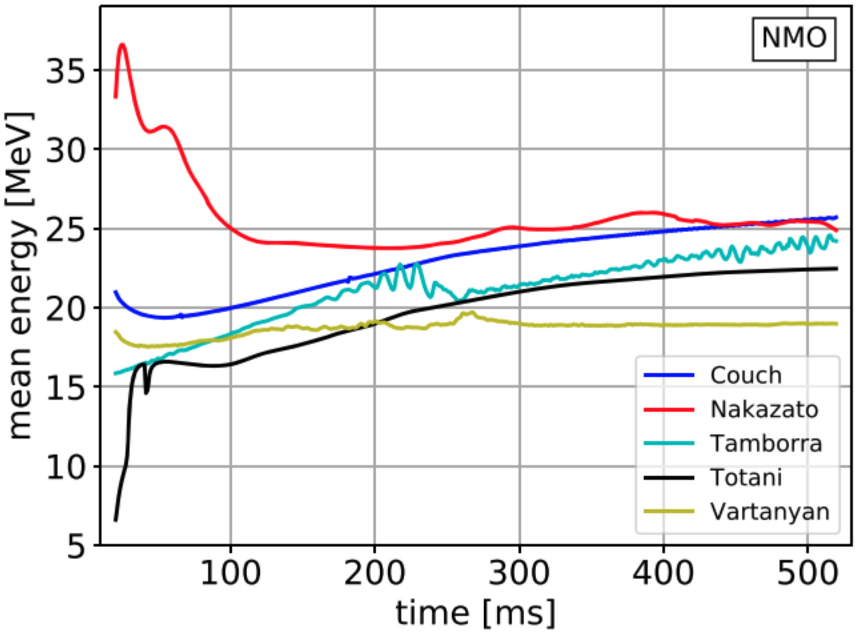


Super-Kamiokande

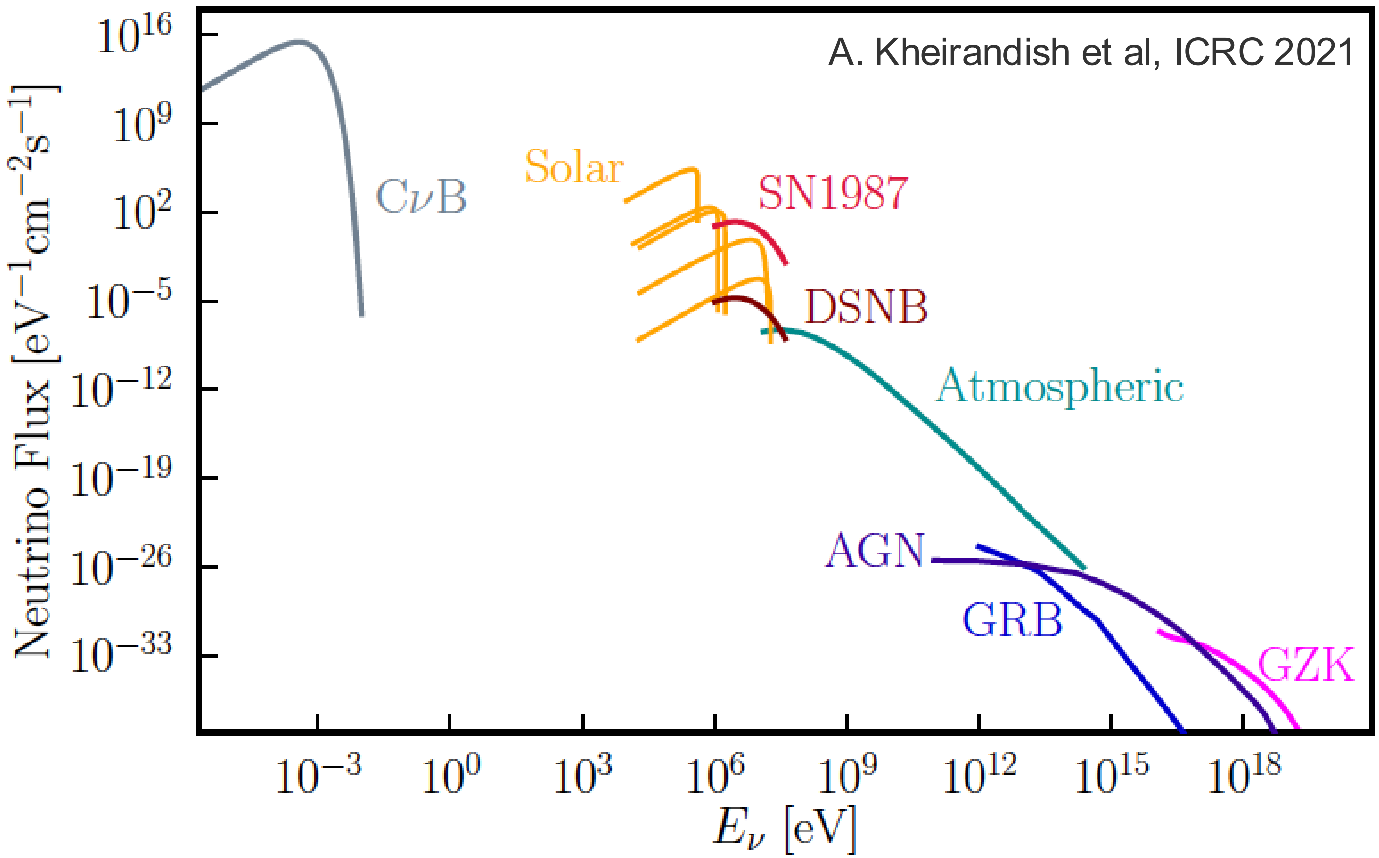


In the future: Hyper-Kamiokande (~2030)





Distinguish different supernova models



Ideas: neutrino capture on unstable nucleus (e.g. tritium)

Neutrino capture on stable nucleus (Chlorine, Gallium)

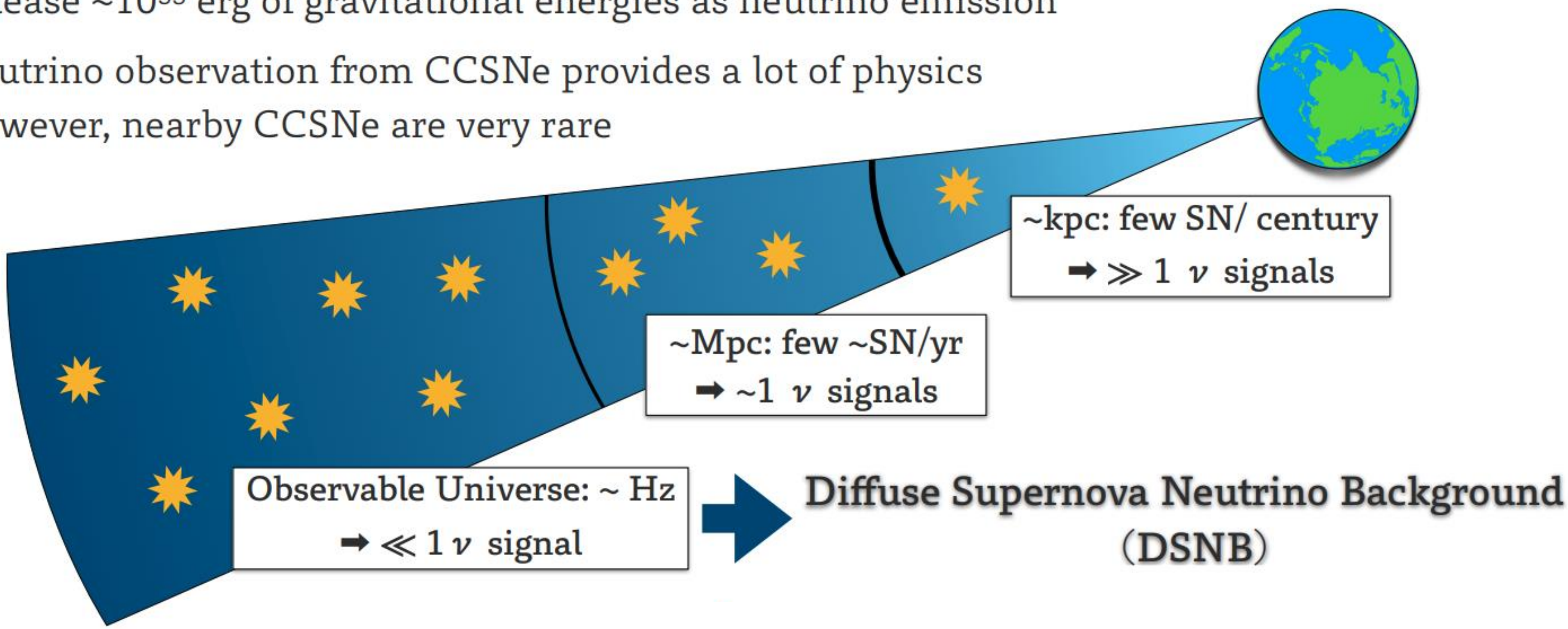
Water / ice Cherenkov detectors

Radio arrays, cosmic-ray detectors

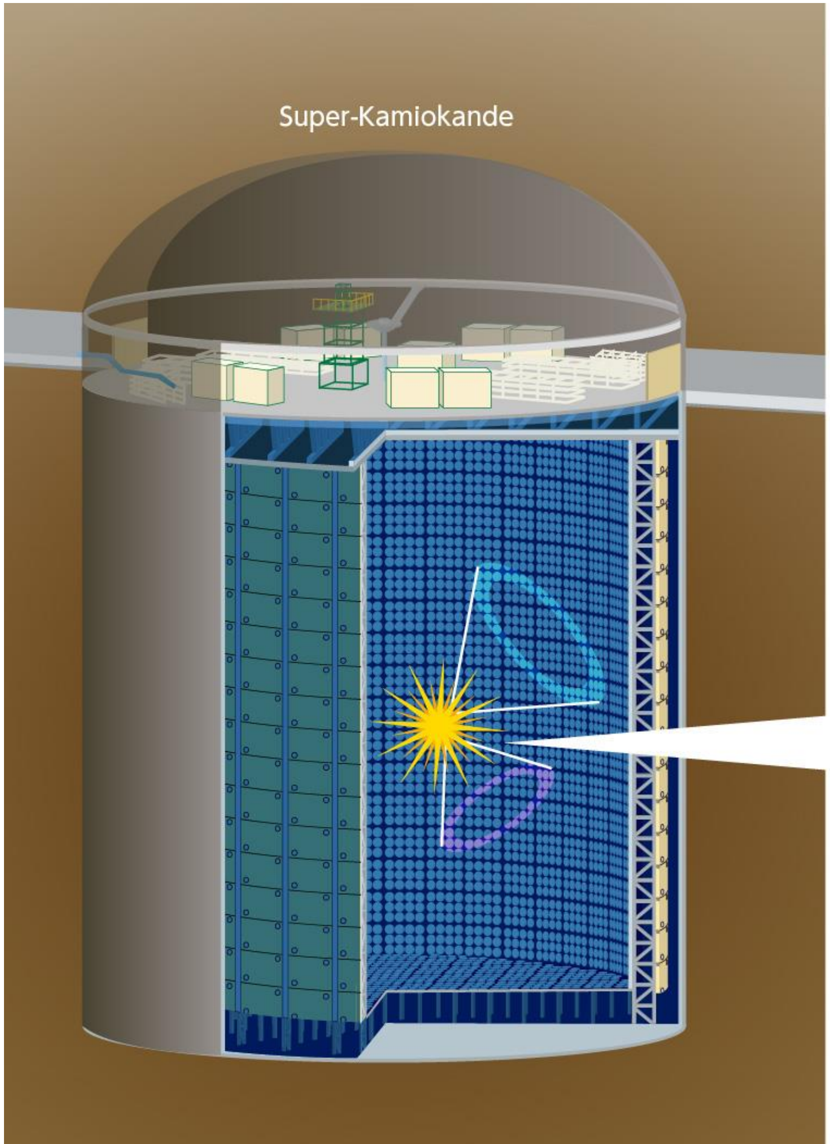
Diffuse Supernova Background (DSNB)

Core-Collapse Supernova (CCSN)

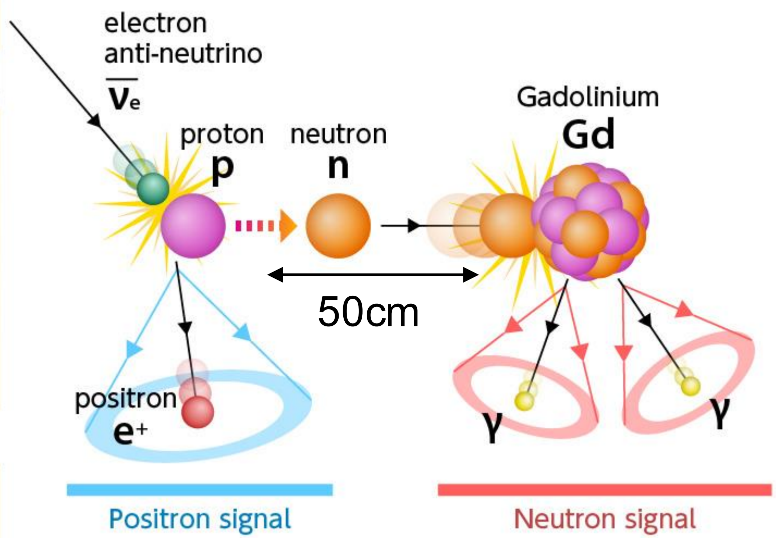
- Release ~10^{53} erg of gravitational energies as neutrino emission
- Neutrino observation from CCSNe provides a lot of physics
  However, nearby CCSNe are very rare



Super Kamiokande with Gadolinium



Gadolinium: highest affinity for capturing neutrons among all elements in nature.



0.1% concentration of Gd: 90% of neutrons will be captures
→ highly efficient background suppression

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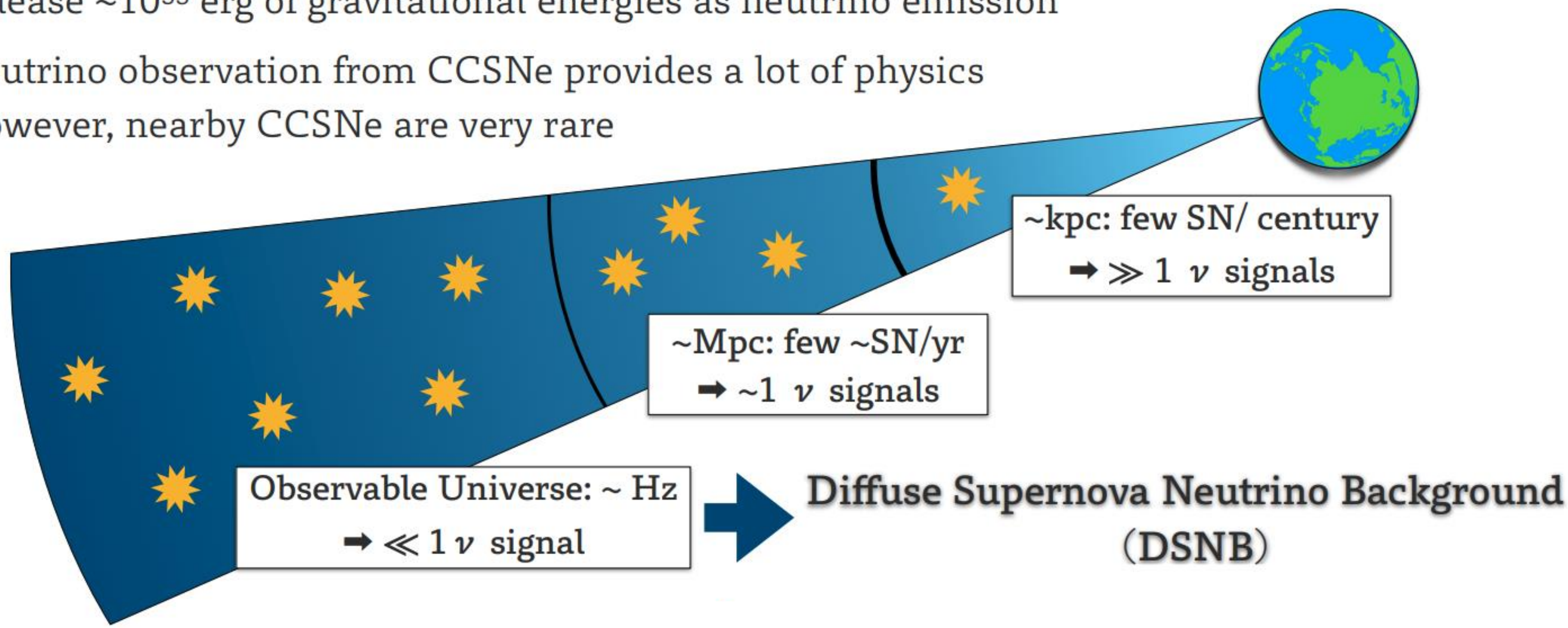
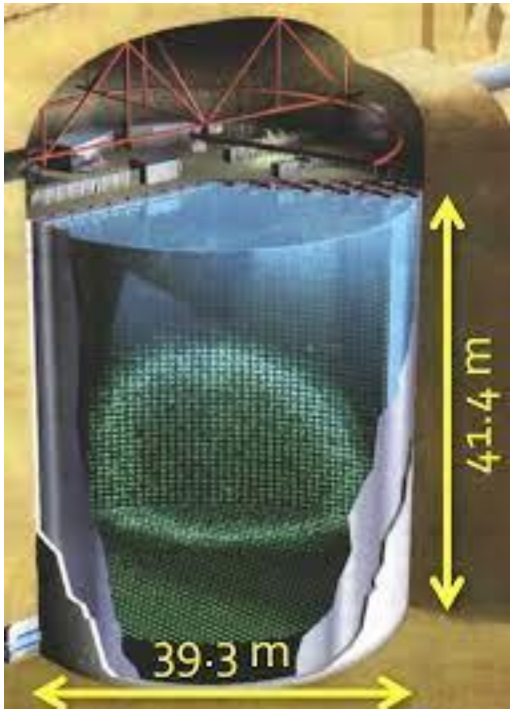


- Also, the latest update of DSNB search in SK-Gd using additional more condensed Gd-water data are exhibited
  ➡ There is no significant DSNB signal, however, some excess appears to be visible in the signal region, which is 2.3 σ tension from non-DSNB hypothesis
- Looking forward to discovery of DSNB in the next decade !!

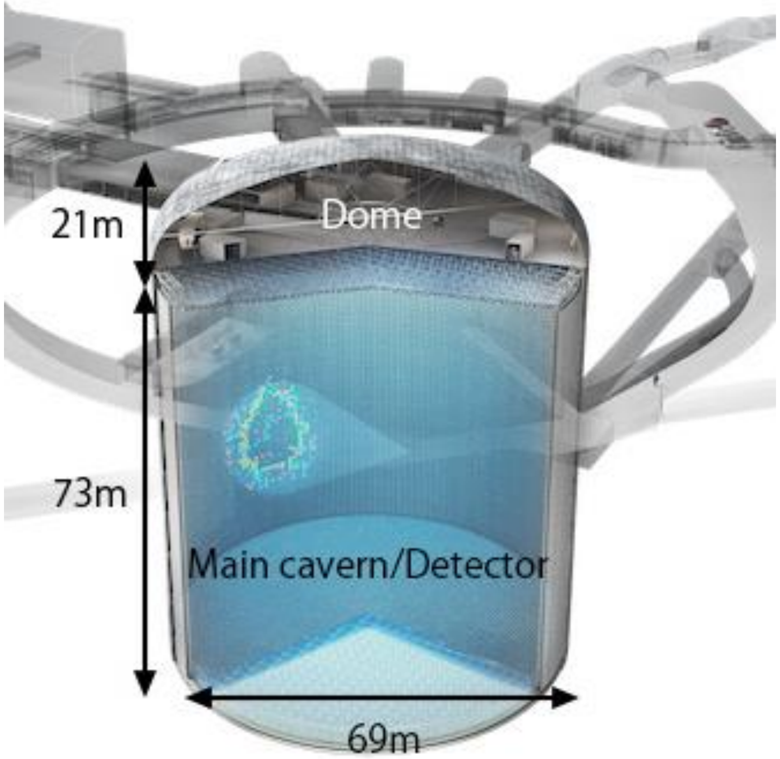
Next Generation Detector: Hyper Kamiokande

Super Kamiokande



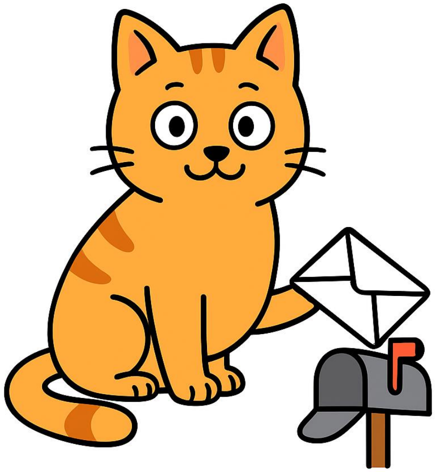
Volume: 50kT

Hyper Kamiokande



Volume: 260kT

Data taking start in 2027

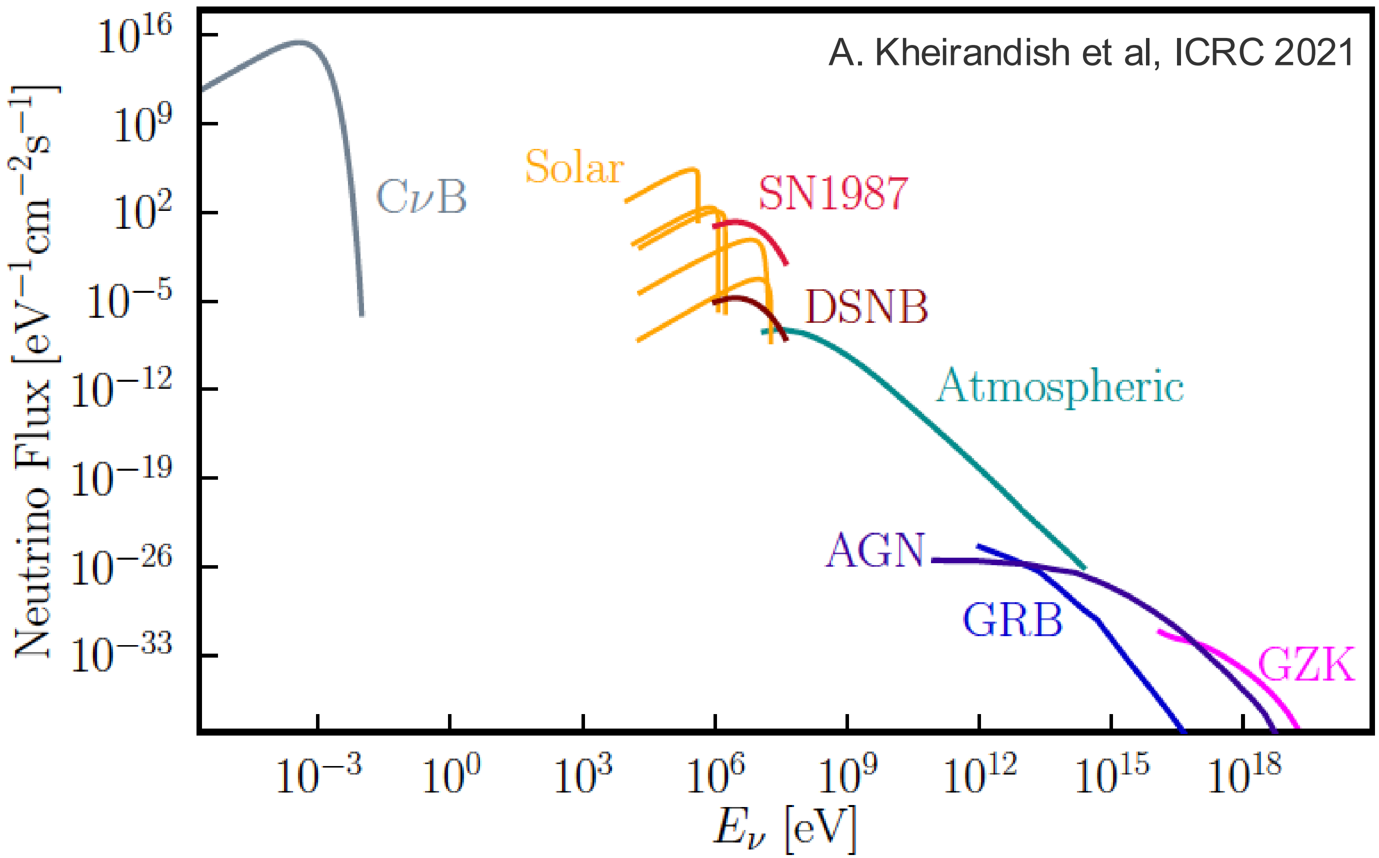


Take home message

A short burst of ~10MeV neutrinos is expected from a core-collapse supernova and can be detected for Galactic source, expected only 1-3 times per 100 years. SNEWS connects many instruments and will send an alert to trigger observations.

Questions?!

https://forms.gle/uHCYKcGDBP2bGRsC6



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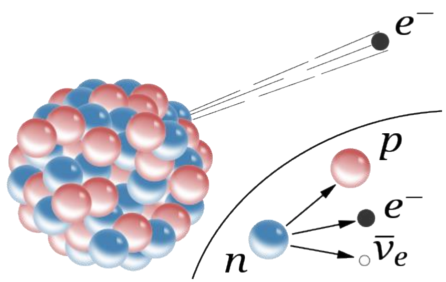
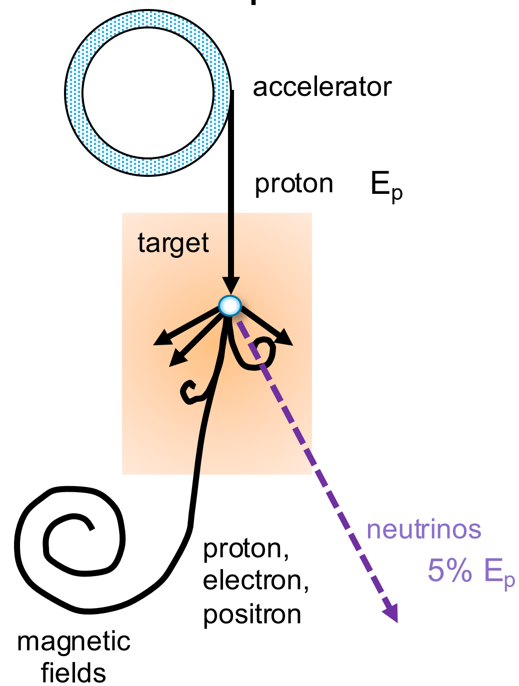
How are high-energy neutrinos produced?

MeV neutrinos from nuclear processes, (inverse) beta decay



TeV-PeV neutrinos from cosmic-ray "beam dumps"



Two ingredients:

- Proton acceleration
- Target for interaction

Neutrino Production Processes

Cosmic ray

pp

$p\gamma$ $\rightarrow$

target

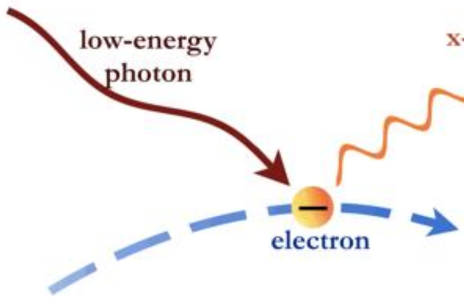
$$\left\{\begin{array}{l} \ldots + \pi^{+} \rightarrow \mu^{+} + \nu_{\mu} \rightarrow e^{+} + \nu_{e} + \bar{\nu}_{\mu} + \nu_{\mu} \\ \ldots + \pi^{-} \rightarrow \mu^{-} + \bar{\nu}_{\mu} \rightarrow e^{-} + \bar{\nu}_{e} + \nu_{\mu} + \bar{\nu}_{\mu} \\ \ldots + \pi^{0} \rightarrow \gamma\gamma \end{array}\right.$$

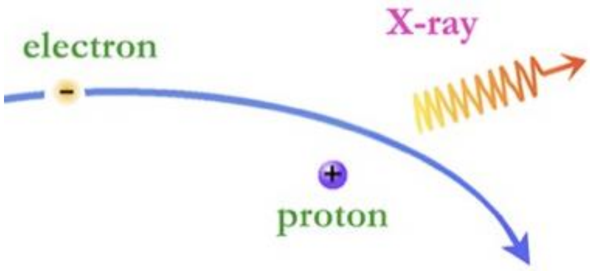
Neutrino Production Processes

Cosmic ray pp, $p\gamma$ target $\rightarrow$

$$\begin{cases} \ldots + \pi^{+} \rightarrow \mu^{+} + \nu_{\mu} \rightarrow e^{+} + \nu_{e} + \bar{\nu}_{\mu} + \nu_{\mu} \\ \ldots + \pi^{-} \rightarrow \mu^{-} + \bar{\nu}_{\mu} \rightarrow e^{-} + \bar{\nu}_{e} + \nu_{\mu} + \bar{\nu}_{\mu} \\ \ldots + \pi^{0} \rightarrow \gamma\gamma \end{cases}$$

Gamma-rays are not exclusively produced in hadronic processes





Neutrino Production Processes

Cosmic ray

pp

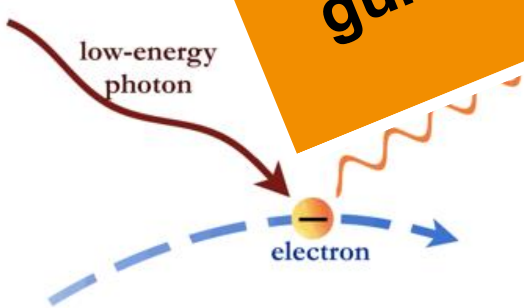
$p\gamma$

target

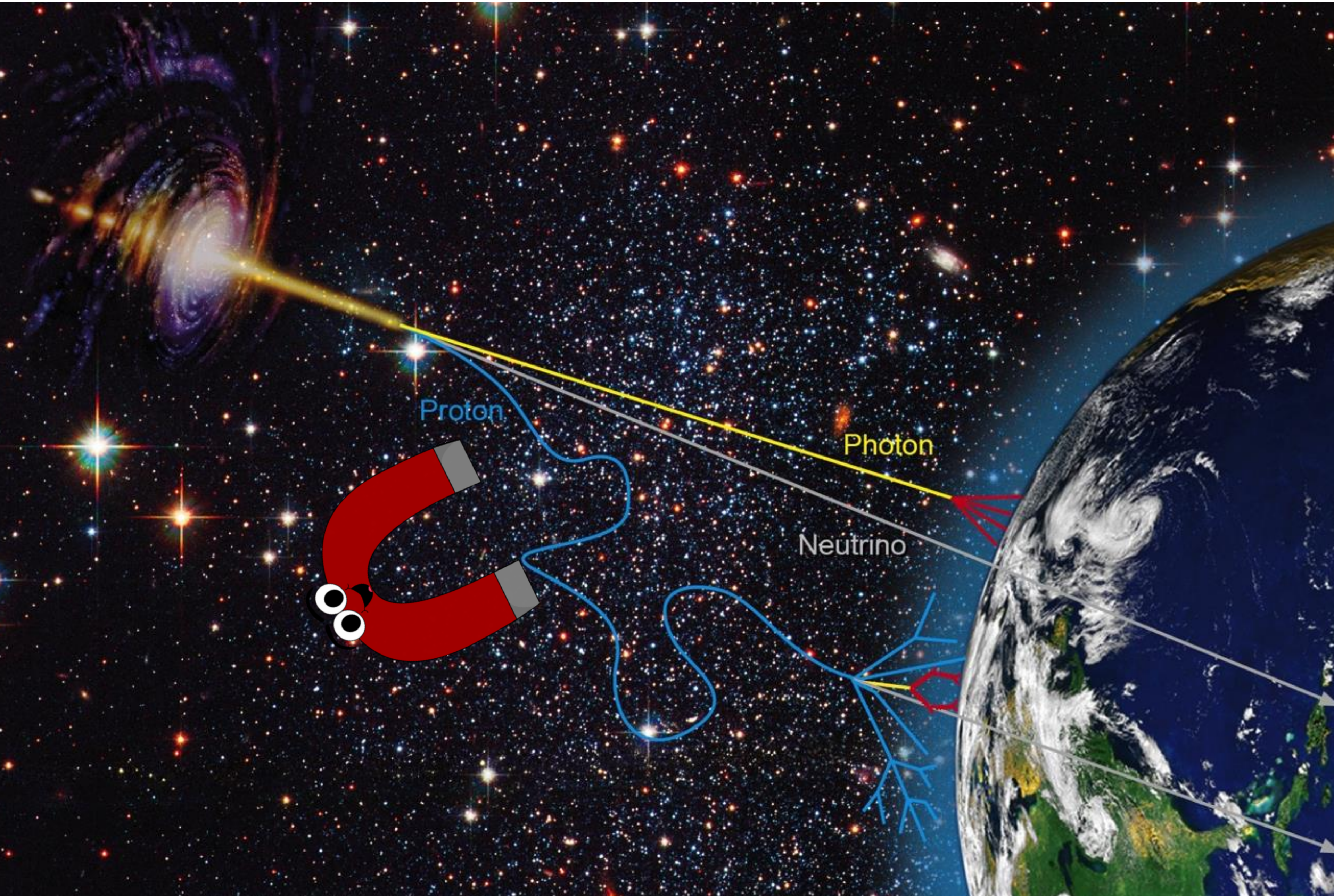
$$\rightarrow \begin{cases} \ldots + \pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_e + \bar{\nu}_\mu + \nu_\mu \\ \ldots + \pi^- \rightarrow \mu^- + \bar{\nu}_\mu \rightarrow e^- \ldots \nu_\mu + \bar{\nu}_\mu \\ \ldots + \pi^0 \rightarrow \gamma\gamma \end{cases}$$

Neutrinos are the smoking gun signature for hadronic acceleration

Gamm… …uced in hadronic processes



What are the Cosmic-Ray Sources?



High-energy Neutrino Detectors

- Huge volumes necessary: ~1km^3 → need to use natural medium
- Transparent medium (Cherenkov emission of secondary charged particles)

Waxman-Bahcall Bound

- Protons are accelerated in the sources with an energy spectrum proportional to $dN_{CR}/dE_{CR} \propto E^{-2}$
- Energy production rate in CRs between 10^{19}eV and 10^{21}eV is 5×10^{44} erg $\mathrm{Mpc}^{-3}\,\mathrm{yr}^{-1}$
- All protons undergo photohadronic interactions ($p\gamma$), producing neutrons, gamma rays and neutrinos

$$p\gamma \rightarrow \Delta^+ \begin{cases} n + \pi^+ \\ p + \pi^0 \end{cases}$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_e + \nu_\mu + \bar{\nu}_\mu$$

$$\pi^0 \rightarrow \gamma\gamma$$

Waxman & Bahcall, PRD59:023002,1999

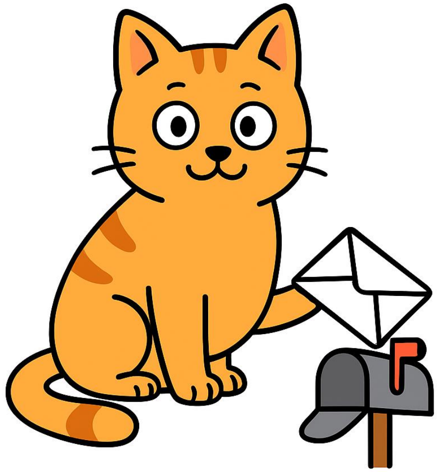
Waxman-Bahcall Bound

- Protons are accelerated in the sources with an energy spectrum proportional to $dN_{CR}/dE_{CR} \propto E^{-2}$
- Energy production rate in CRs between 10^{19}eV and 10^{21}eV is 5×10^{44} erg Mpc^{-3} yr^{-1}
- All protons undergo photohadronic interactions (pγ), producing neutrons, gamma rays and neutrinos
- The sources are optically thin to neutrons, which leave the sources and subsequently decay into protons, accounting for the UHECR flux observed at the Earth
- Energy flux of neutrinos cannot be greater than that of CR

$$E^2\Phi < 3 \times 10^{-8}\,\mathrm{GeV\,s^{-1}\,sr^{-1}\,cm^{-2}}$$

1km^3 volume needed to probe this flux

Waxman & Bahcall, PRD59:023002,1999



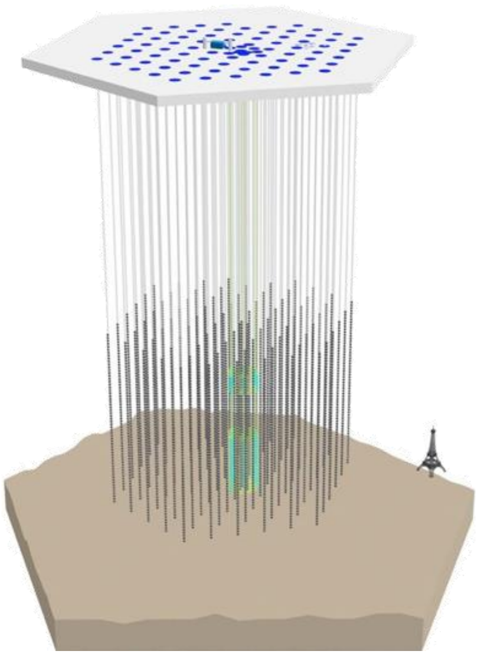
Take home message

Cubic-kilometer sized neutrino detectors are needed to detect cosmic neutrinos.

Those could reveal the sources of cosmic rays and deliver information from dense environments

High-energy Neutrino Detectors

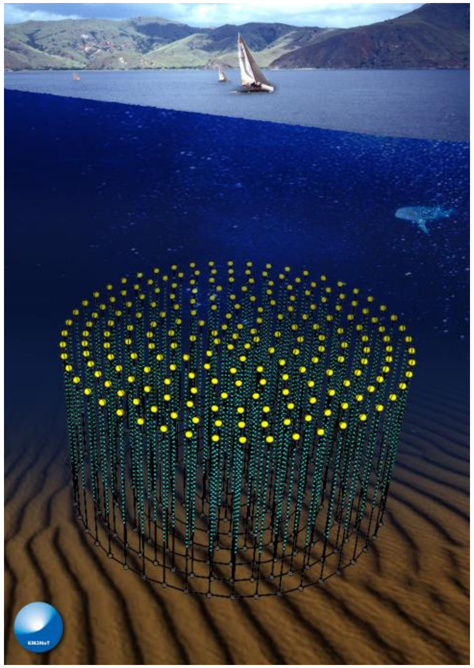
IceCube (1 km^3)



IceCube-Gen2
(8km^3) planned

M.G. Aartsen *et al* 2017 *JINST* **12** P03012
M.G. Aartsen *et al* J.Phys.G 48 (2021) 6, 060501

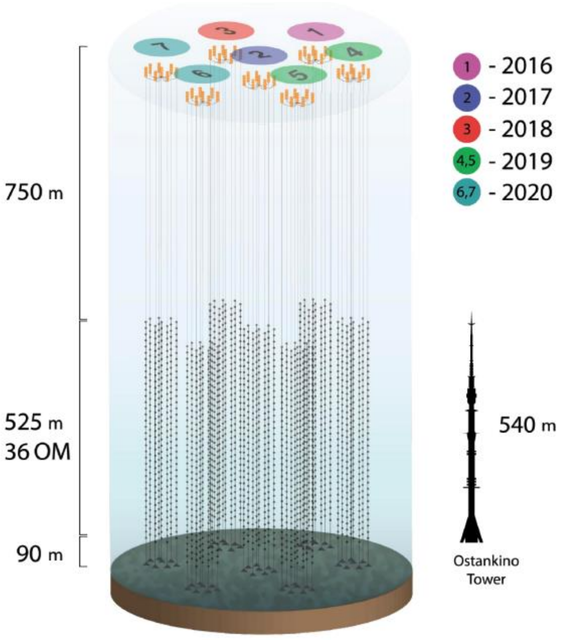
KM3NeT (2 x 0.5 km^3)
Under construction
Predecessor ANTARES decommissioned after 14y



Two sites: ARCA for HE and ORCA for LE, roughly ~20% complete

S. Adrián-Martínez et al. arXiv:1601.07459

Baikal-GVD (1 km^3)
Under construction



2022: 10 clusters
2026: 18 clusters

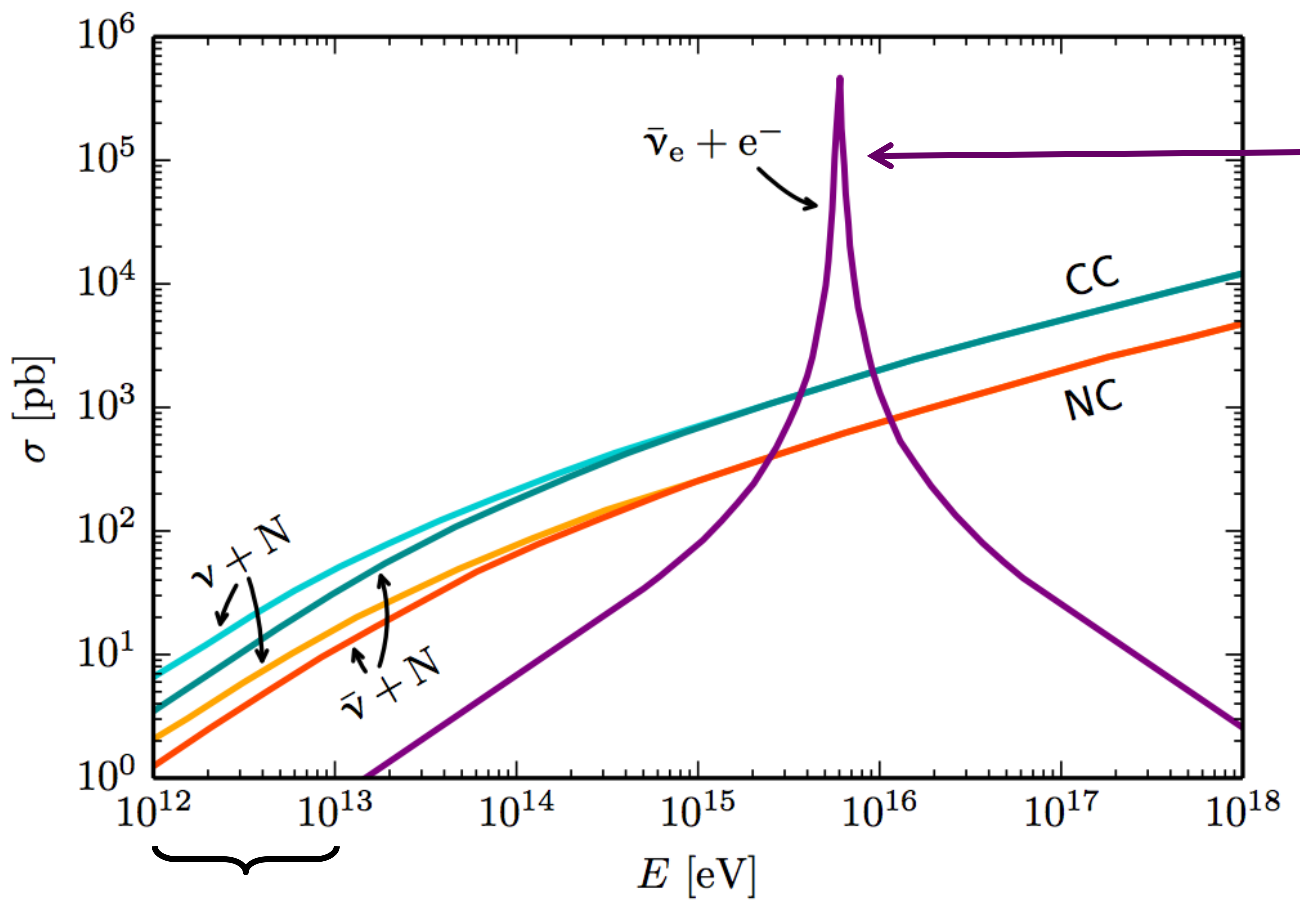
A.D. Avrorin et al. arXiv:2011.09209

Differences between ice and water detectors

Property	Lake Baikal	Mediterranean (ANTARES)	Antarctic Ice
Absorption length (m)	22	60	100
Effective Scattering (m)	480	265	25
Depth	1370	2475	2450
Noise	Quiet	^{40}K, bioluminescence	Quiet
Retrieve/redeploy	Yes	Yes	No

Long scattering length in Mediterranean implies better angular resolution; long absorption length for IceCube allows sparser instrumentation. Smaller depth implies larger atmospheric muon background.

Neutrino Cross-Sections

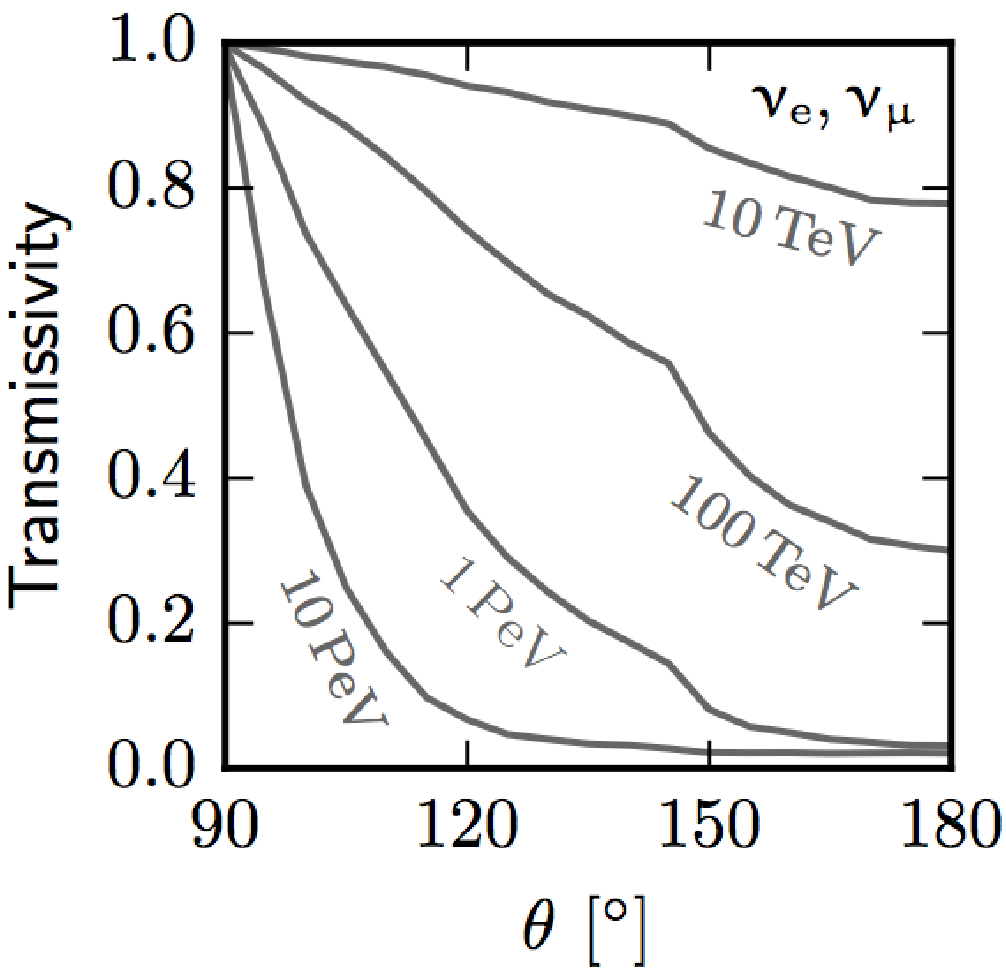


Linear with E, Smaller for anti-neutrinos due to helicity

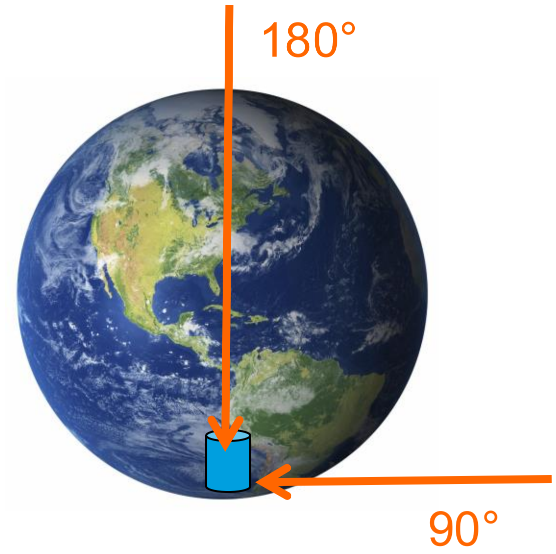
damped by the W-boson propagator

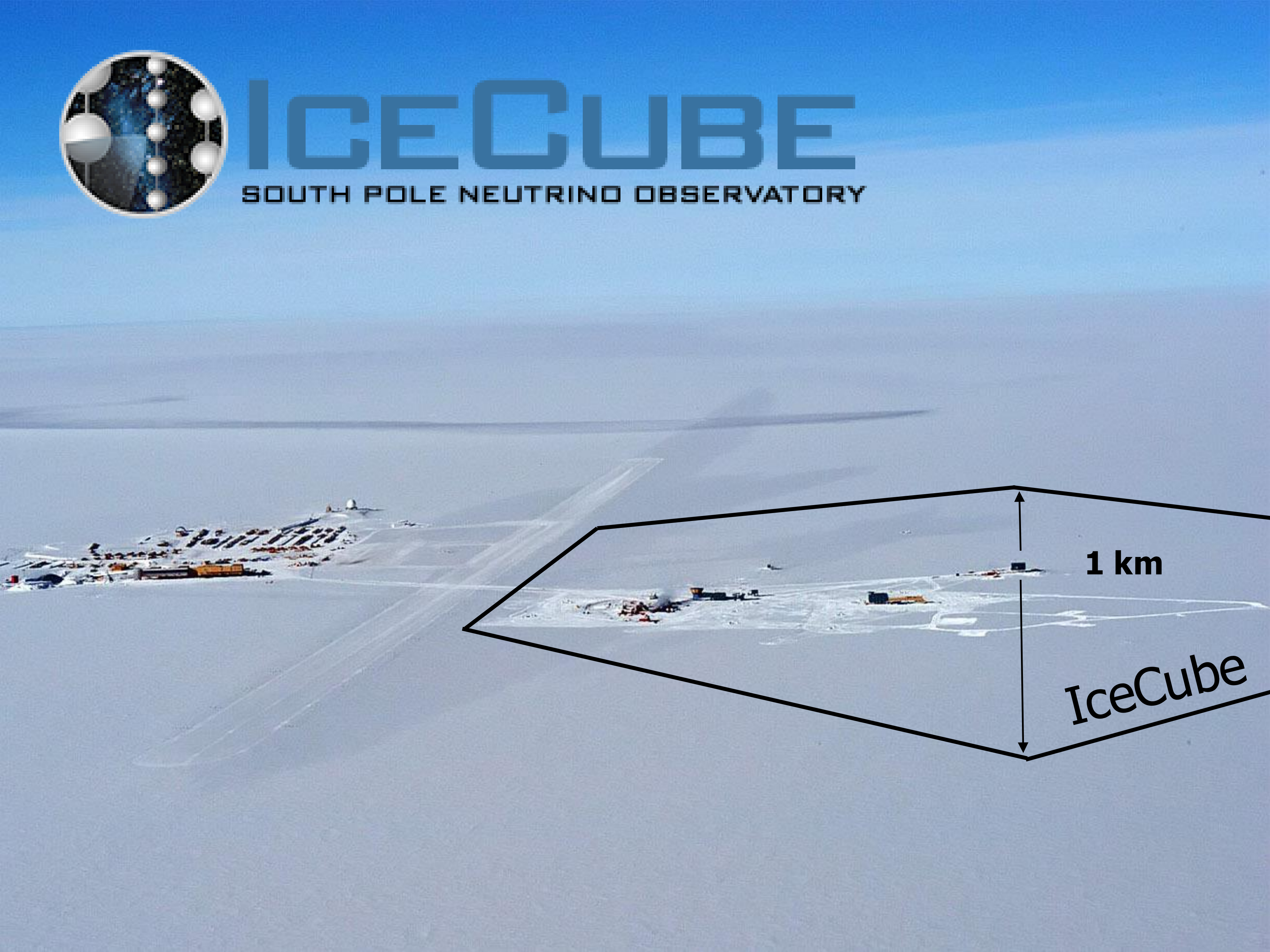
Glashow resonance: resonance when the center-of-mass energy of the system reaches the mass of the mediating boson. For electrons at rest and the mass of the $W^{\pm}$ boson (80 GeV), the Glashow resonance occurs at a neutrino energy of 6.3×10^{15} eV

Absorption of High-Energy Neutrinos in the Earth



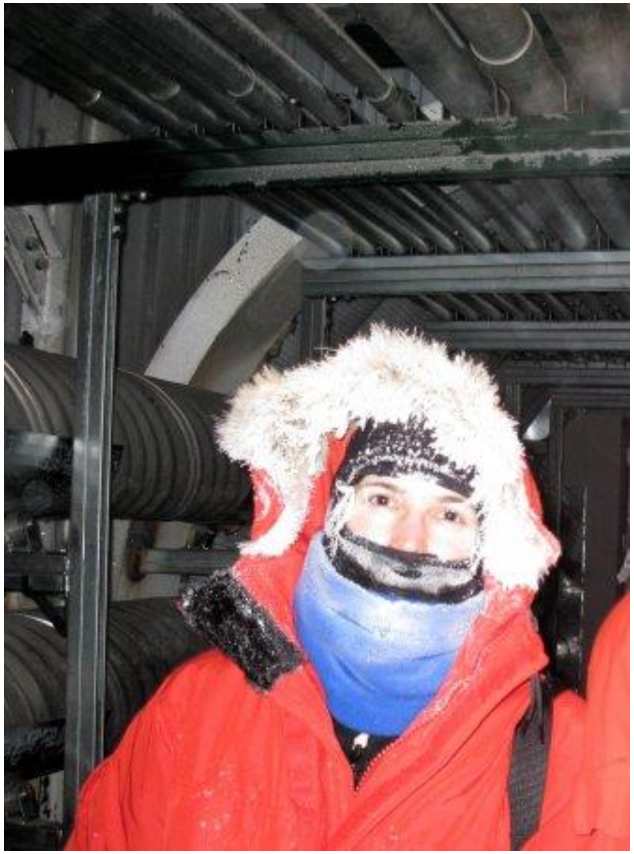
For high-energies Earth becomes opaque to neutrinos

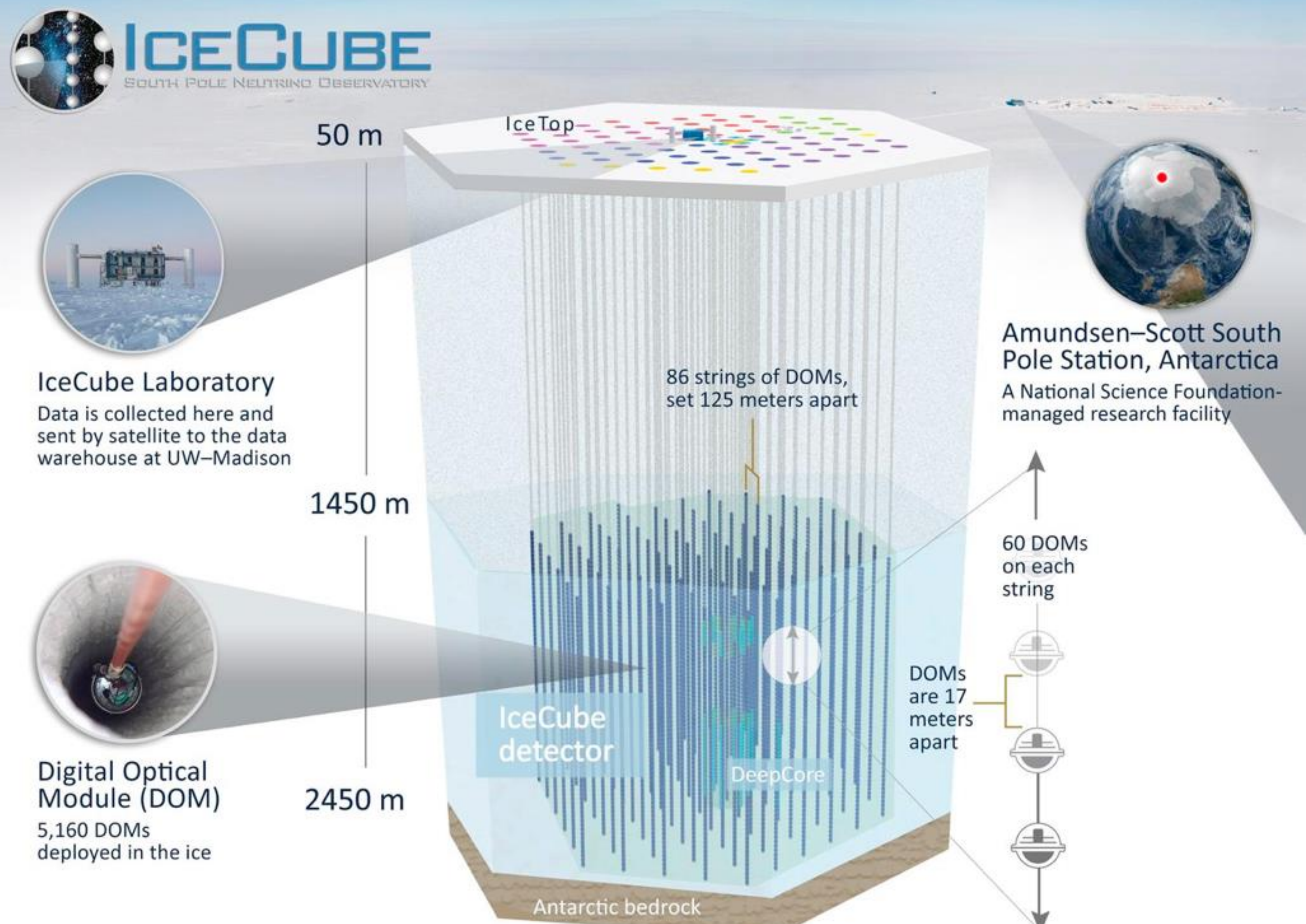



IceCube
SOUTH POLE NEUTRINO OBSERVATORY
1 km
IceCube

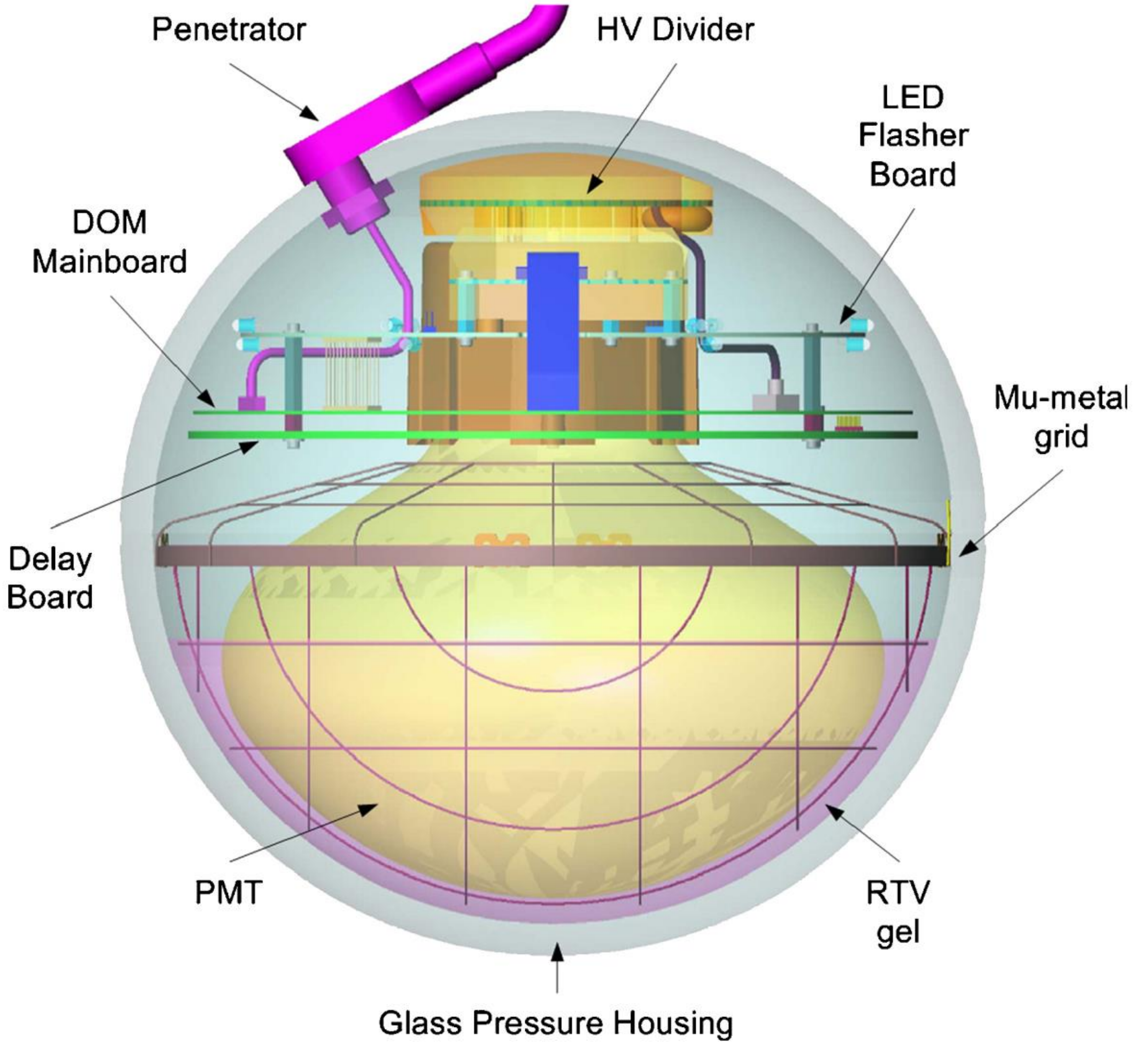
The South Pole

Elevation: 2,835 m
Average temperate: -28°C (summer), -60°C (winter)





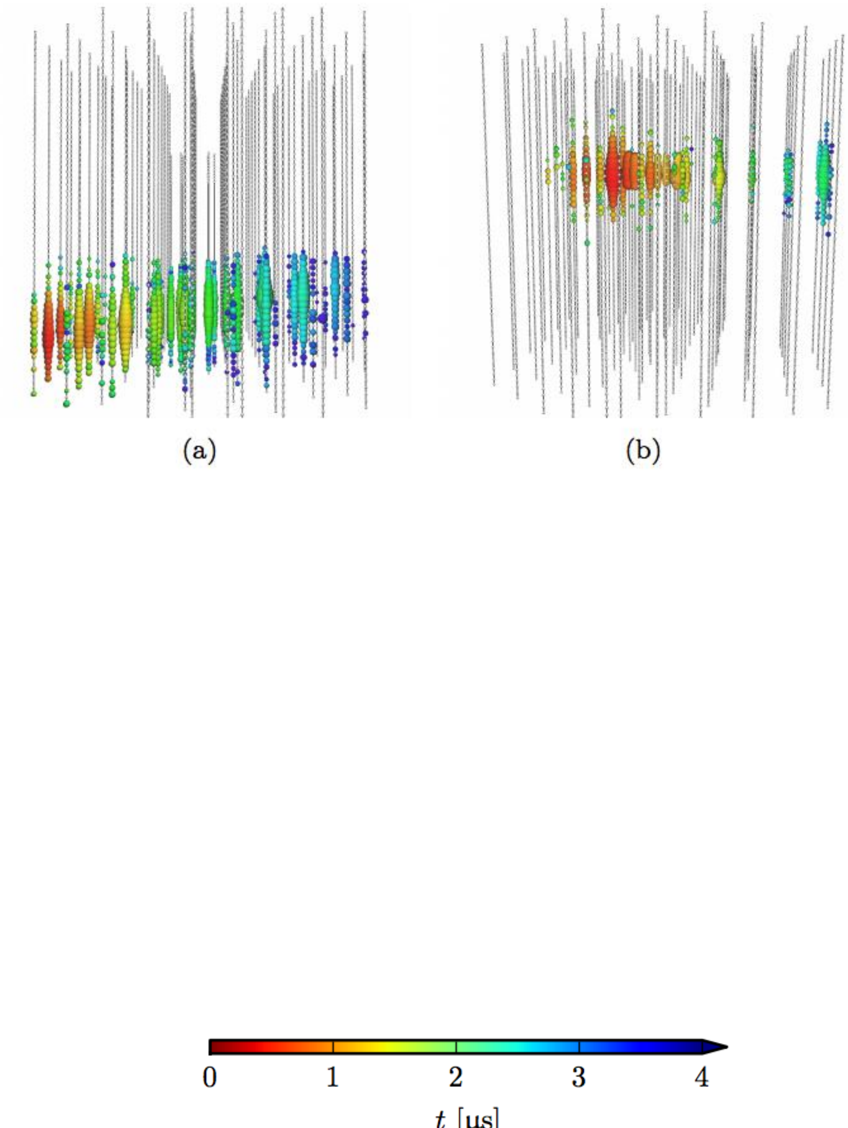
IceCube Coll., JINST 12 P03012 (2017)



5160 DOMs deployed
Failure rate: <0.3%

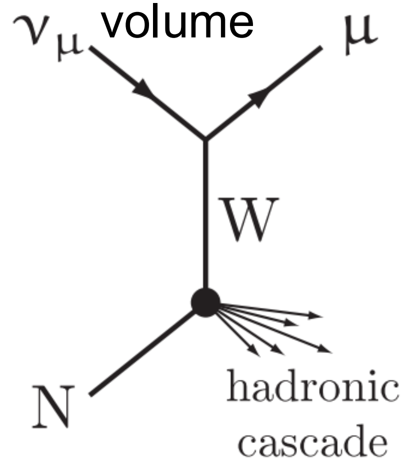
IceCube Coll., JINST 12 P03012 (2017)

Event Signatures

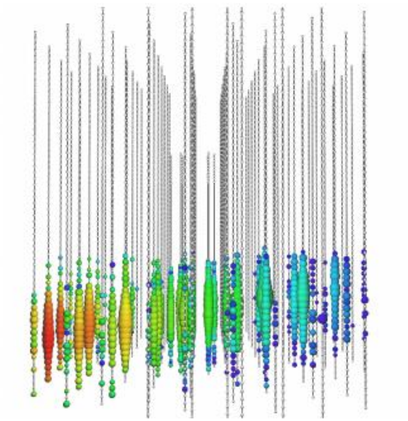


a) **through-going muon track E ~ 140 TeV**
b) **Starting muon track E ~ 70 TeV**

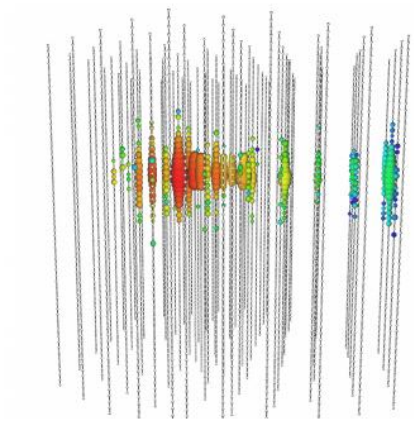
Charged current interaction of muon neutrino outside / inside the detector volume



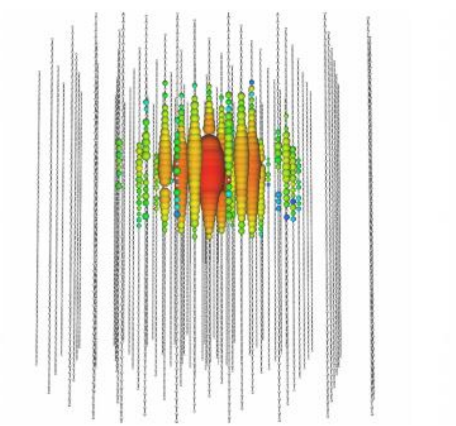
Event Signatures



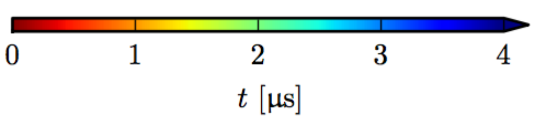
(a)



(b)

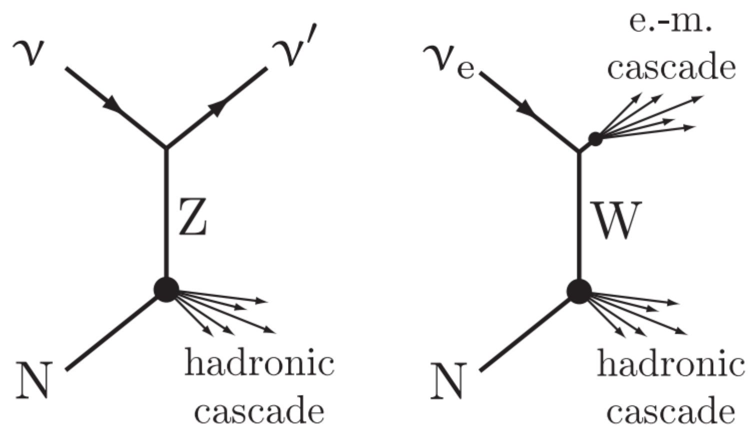


(c)



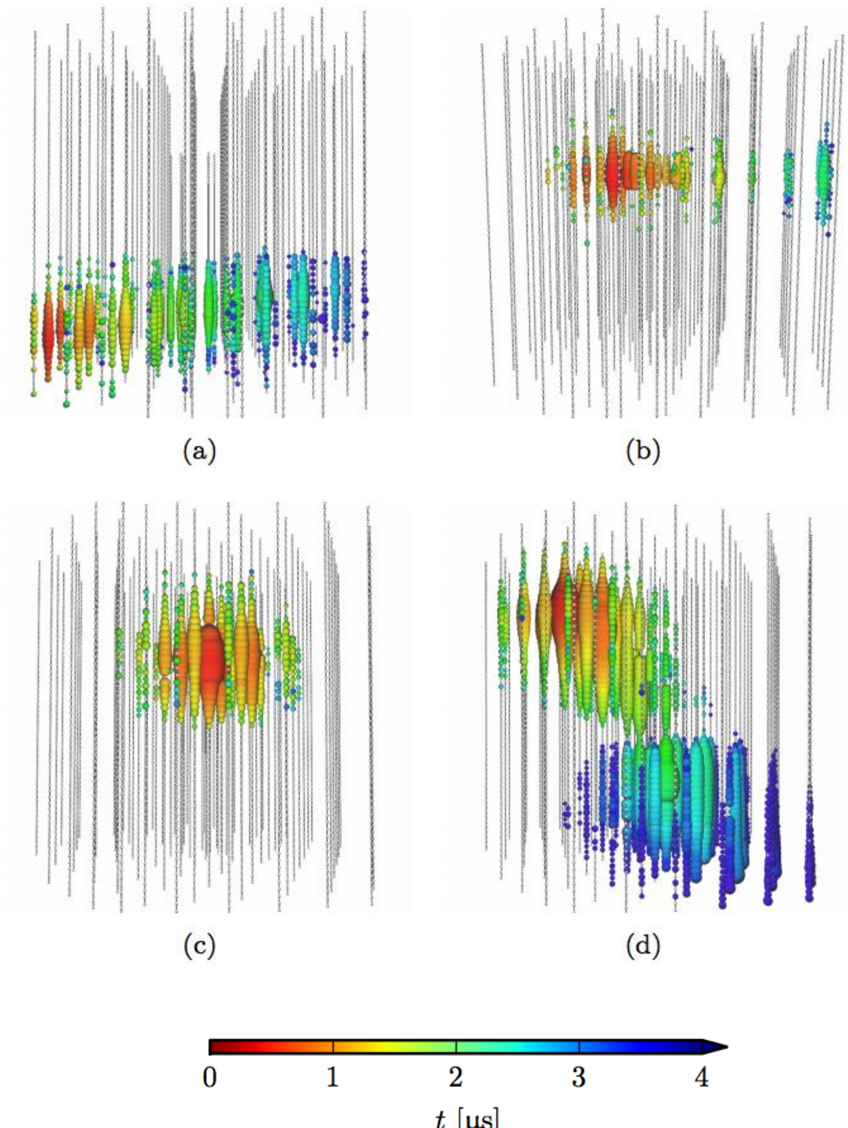
a) through-going muon track E ~ 140 TeV
b) Starting muon track E ~ 70 TeV
c) Shower event E ~ 1 PeV

Neutral current or electron neutrino charged current interaction



Cannot distinguish between showers (size few meters)

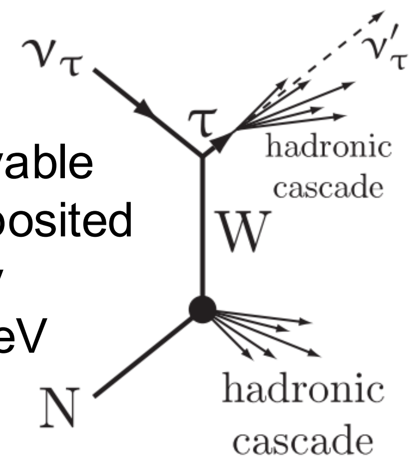
Event Signatures



a) through-going muon track E ~ 140 TeV
b) Starting muon track E ~ 70 TeV
c) Shower event E ~ 1 PeV
d) “double bang” event E ~ 200 PeV

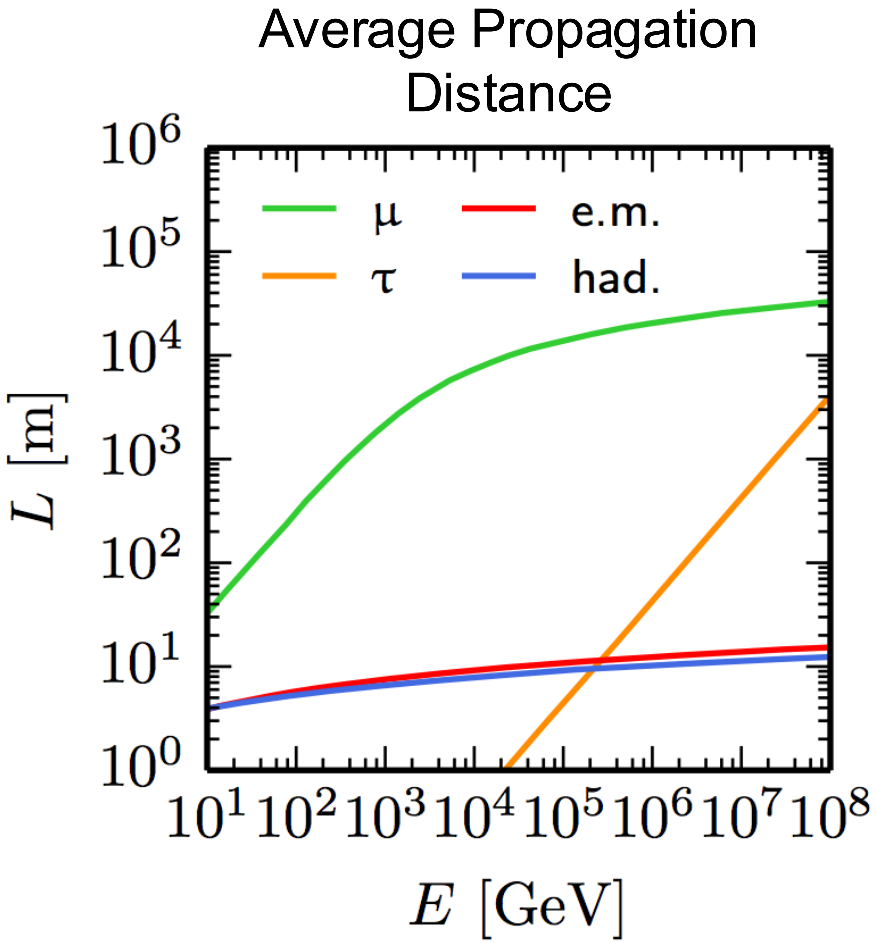
Tau neutrino charged current interaction

Resolvable for deposited energy >100TeV



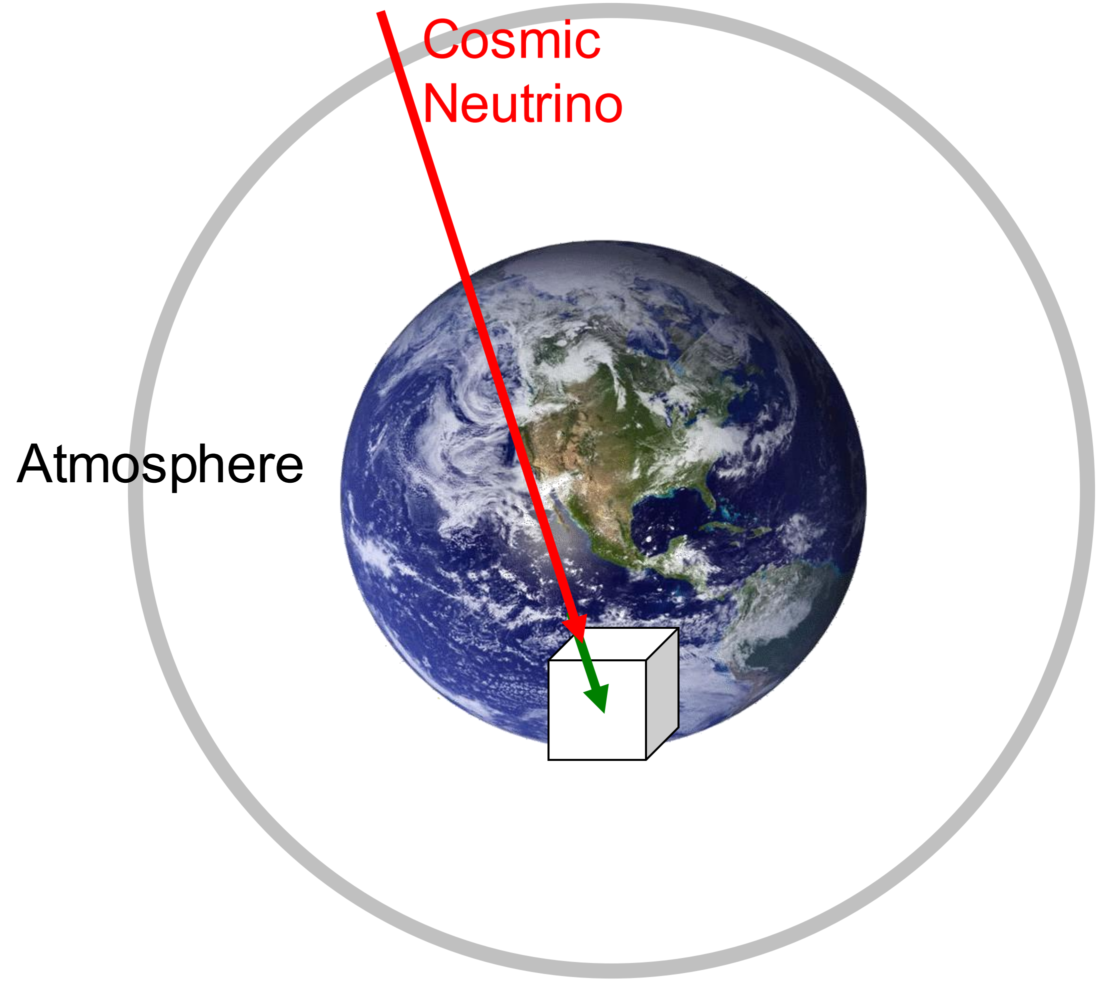
Only for very large energies the two showers can be separated (otherwise signature c)

Secondary Particle Interactions in Ice

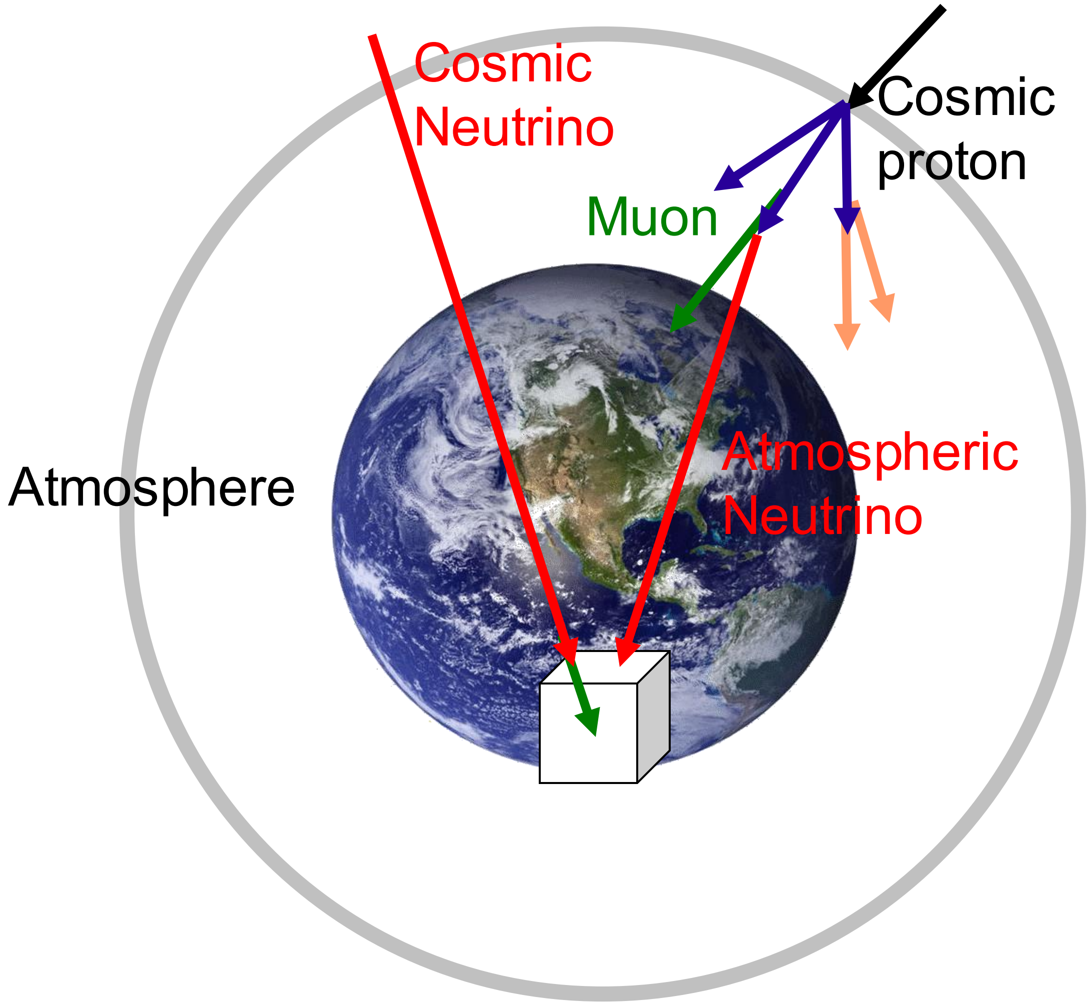


In the TeV range muons travel 1-10km, while showers have a small extension of few meters. Tau needs to reach >100TeV energies to reach detectable length of >10 meters.

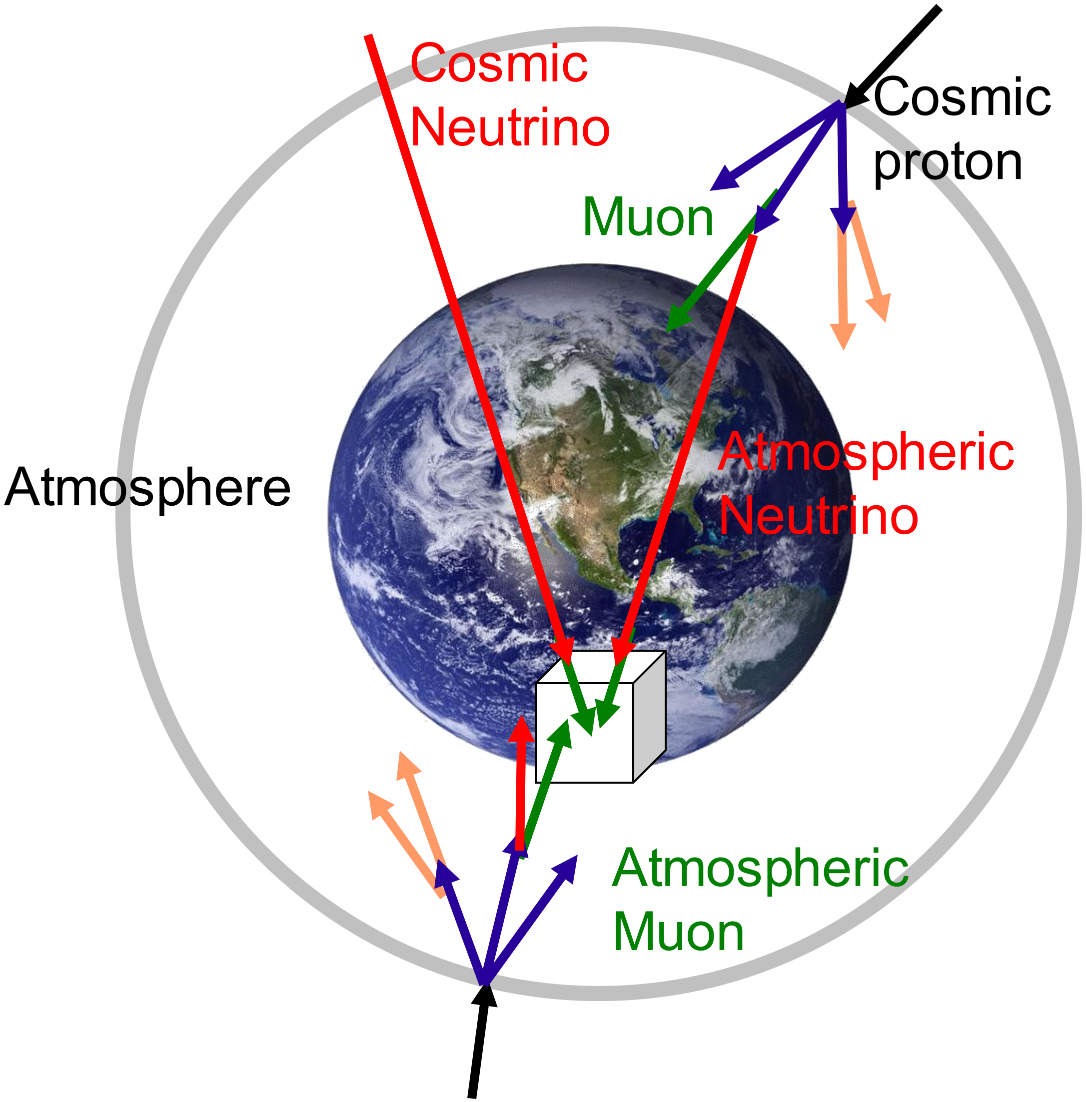
Background in Search for Cosmic Neutrinos



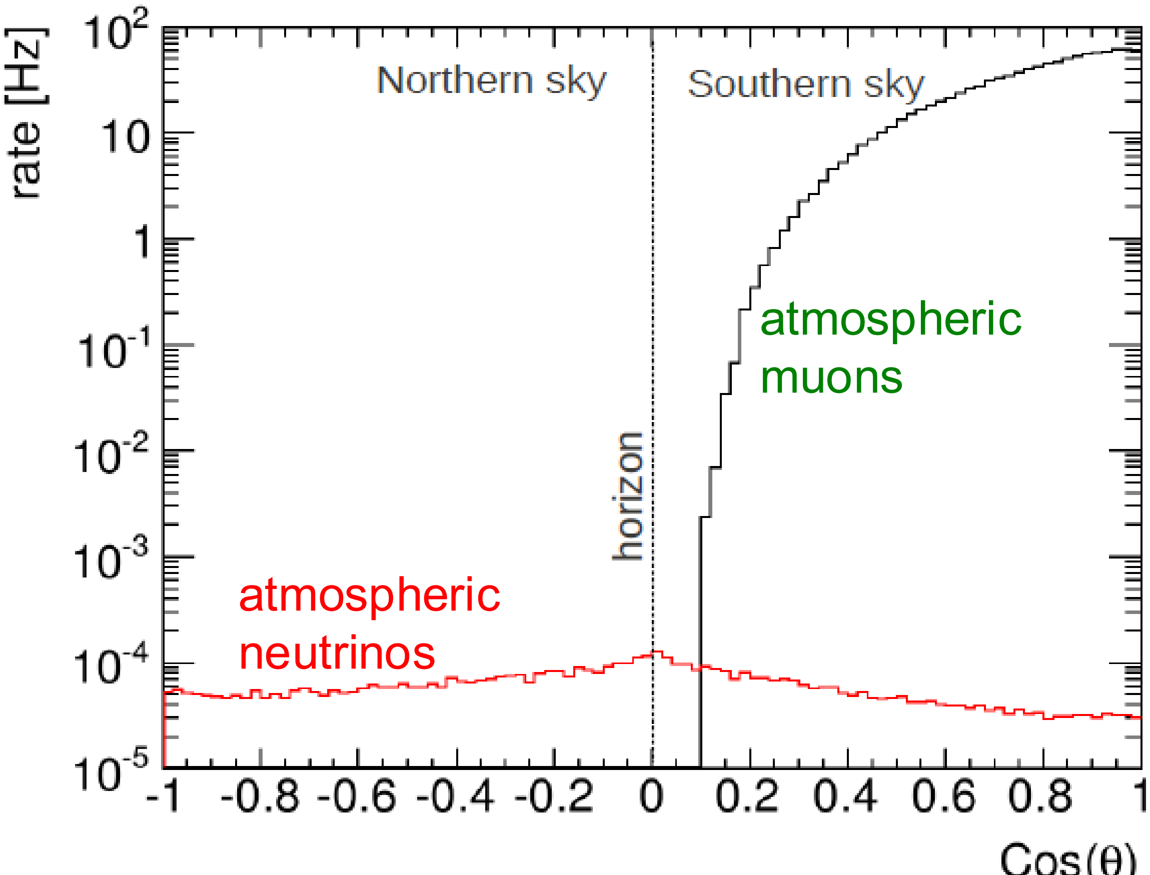
Background in Search for Cosmic Neutrinos

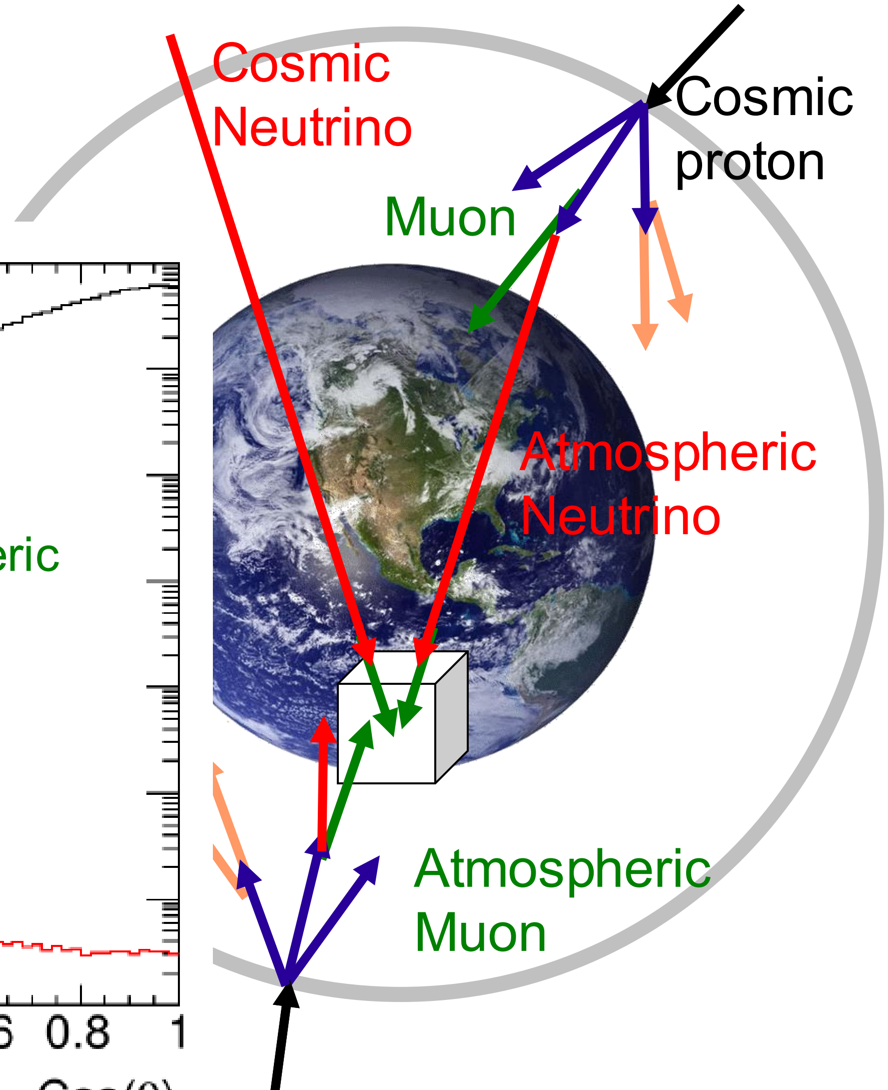


Background in Search for Cosmic Neutrinos



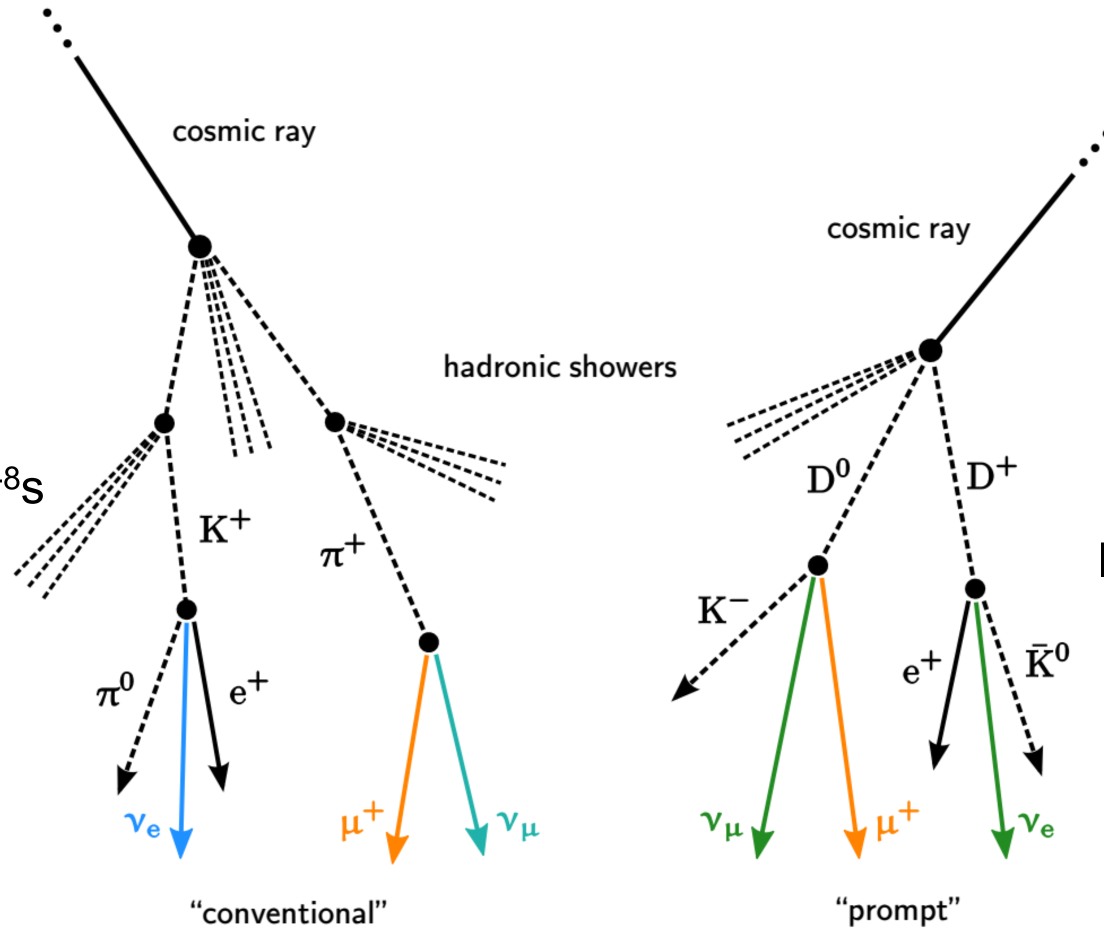
Background in Search for Cosmic Neutrinos





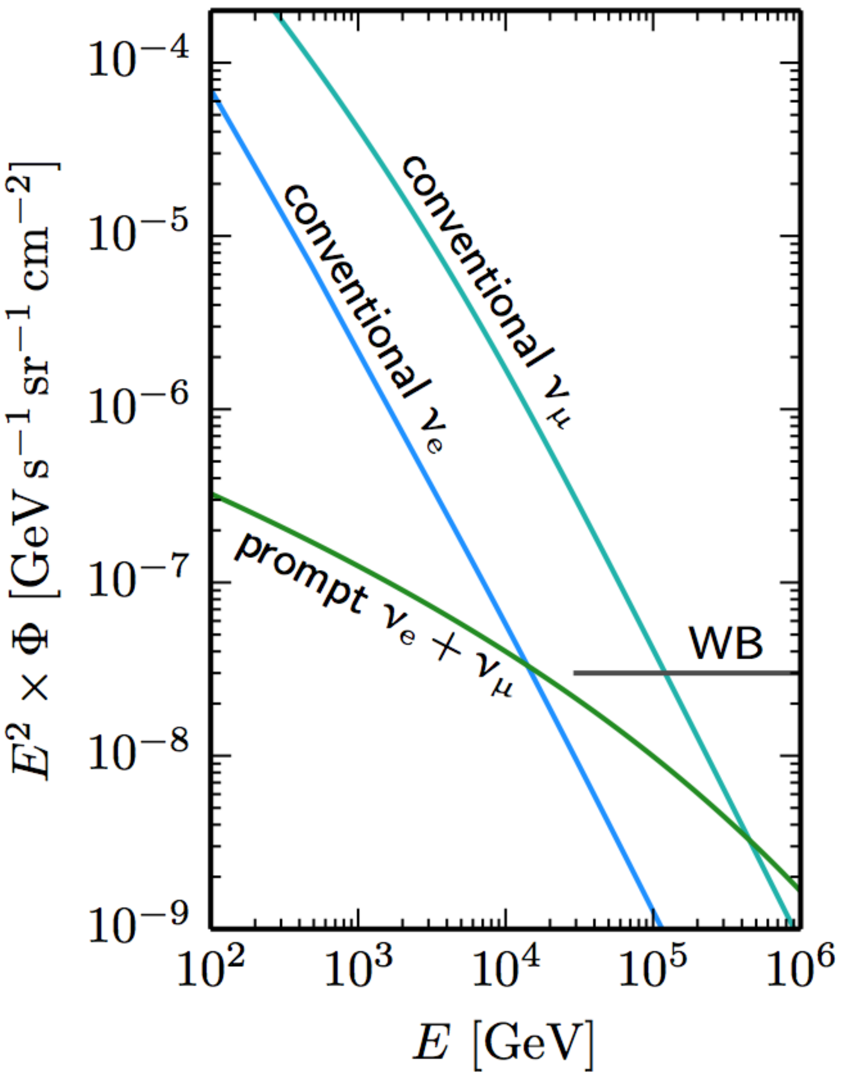
Atmospheric Neutrinos - Production

Kaon/pion
lifetime ~ 10^{-8}s



charm
component
lifetime ~ 10^{-12}s

Atmospheric Neutrinos - Spectrum



Kaons and pions (conventional)

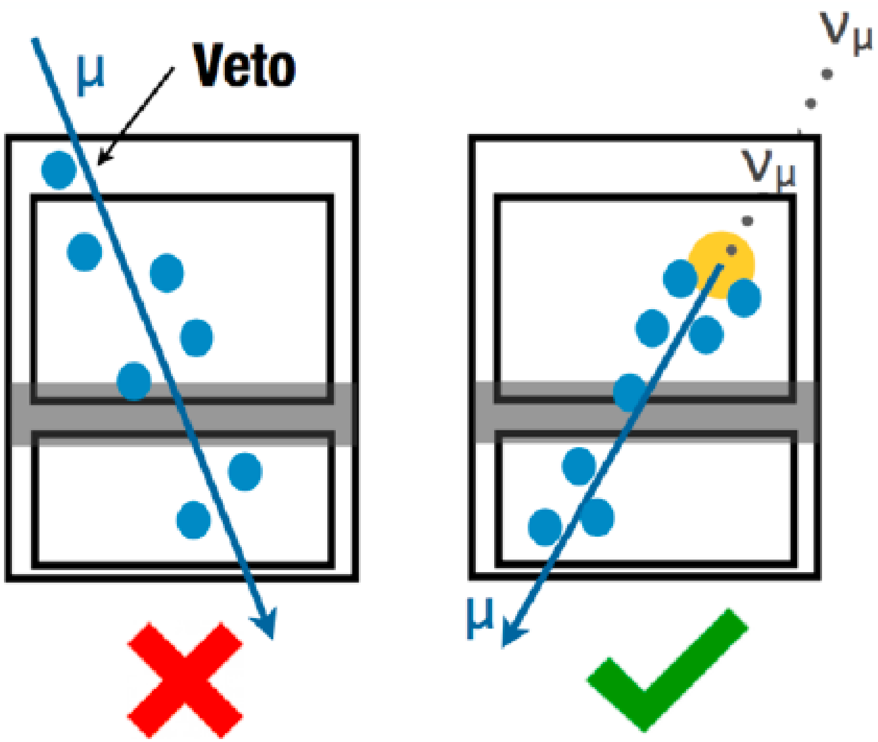
- predominantly decay into muon neutrinos rather than electron neutrinos
- are more likely to interact in the atmosphere rather than to decay into neutrinos if the atmosphere is denser

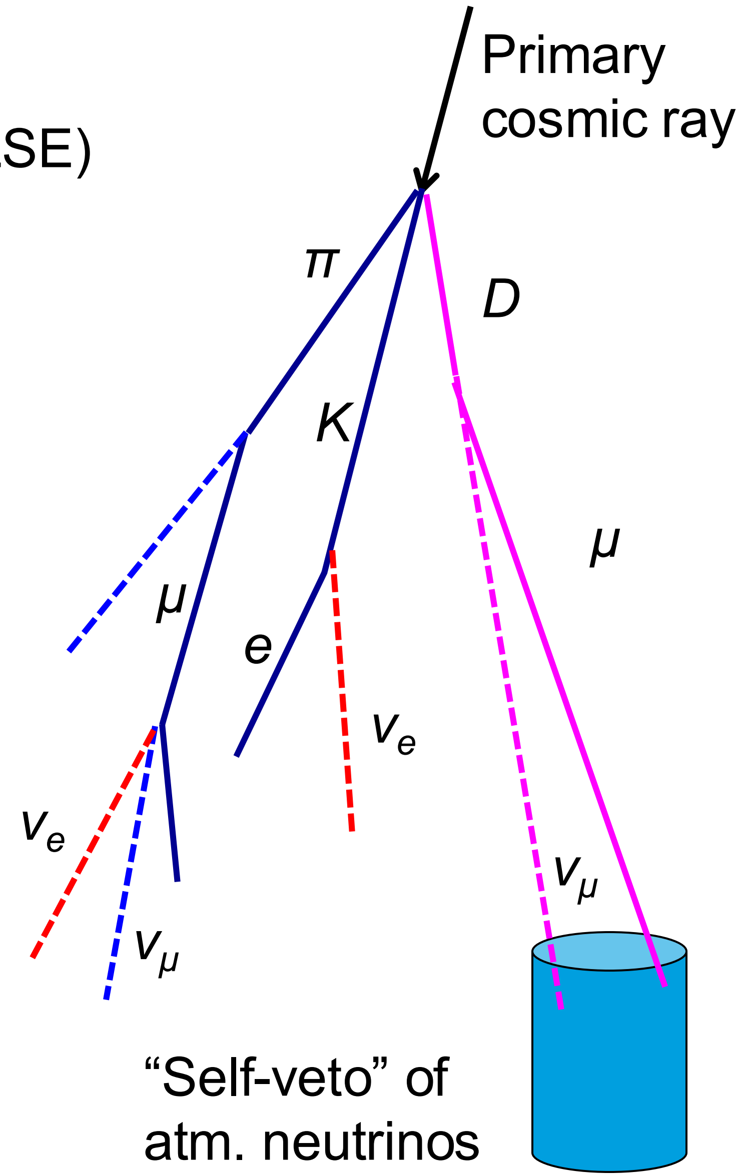
Charm (prompt)

- Decay before interacting

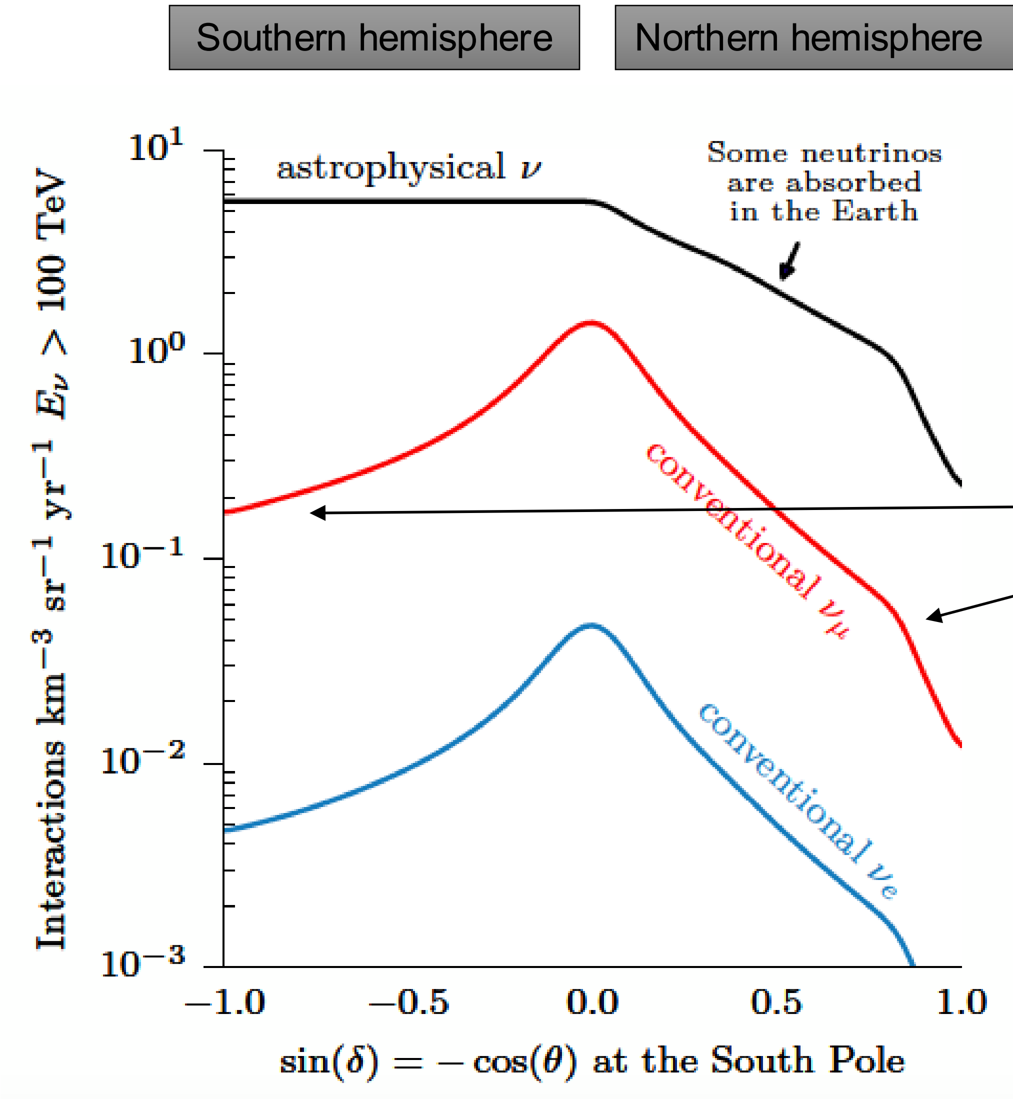
Vetoing Atmospheric Muons and Neutrinos

Selection of high-energy starting events (HESE)





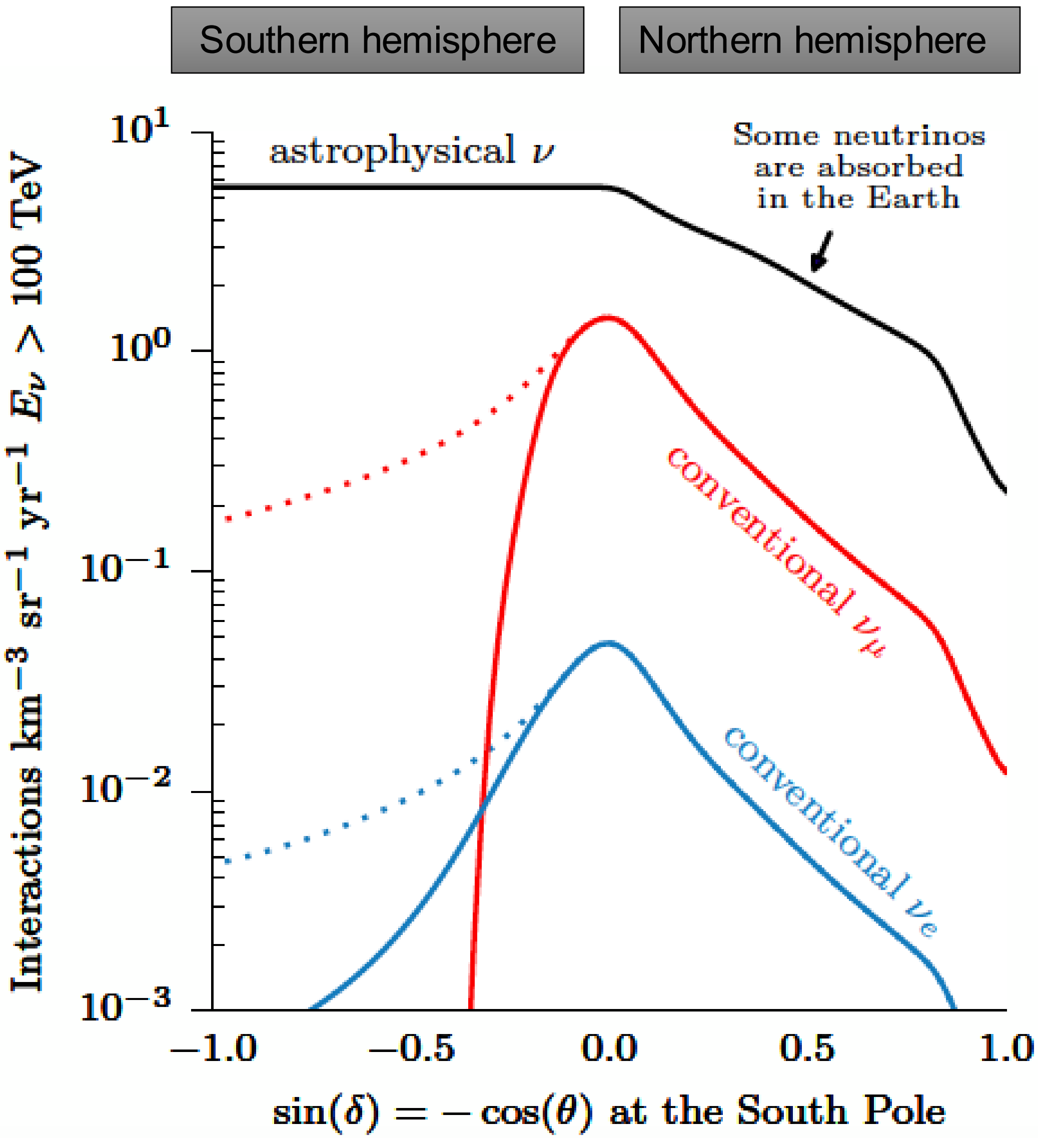
Zenith Distribution



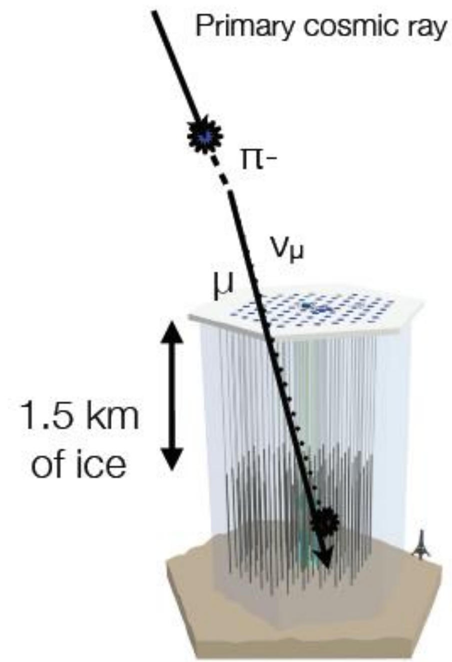
from vertical directions denser parts of the atmosphere are reached more quickly, leading to a suppression of the neutrino flux

Schönert, Gaisser, Resconi, Schulz, Phys. Rev. D, 79:043009 (2009)
Gaisser, Jero, Karle, van Santen, Phys. Rev. D, 90:023009 (2014)

Zenith Distribution



active muon veto removes down-going atmospheric neutrinos



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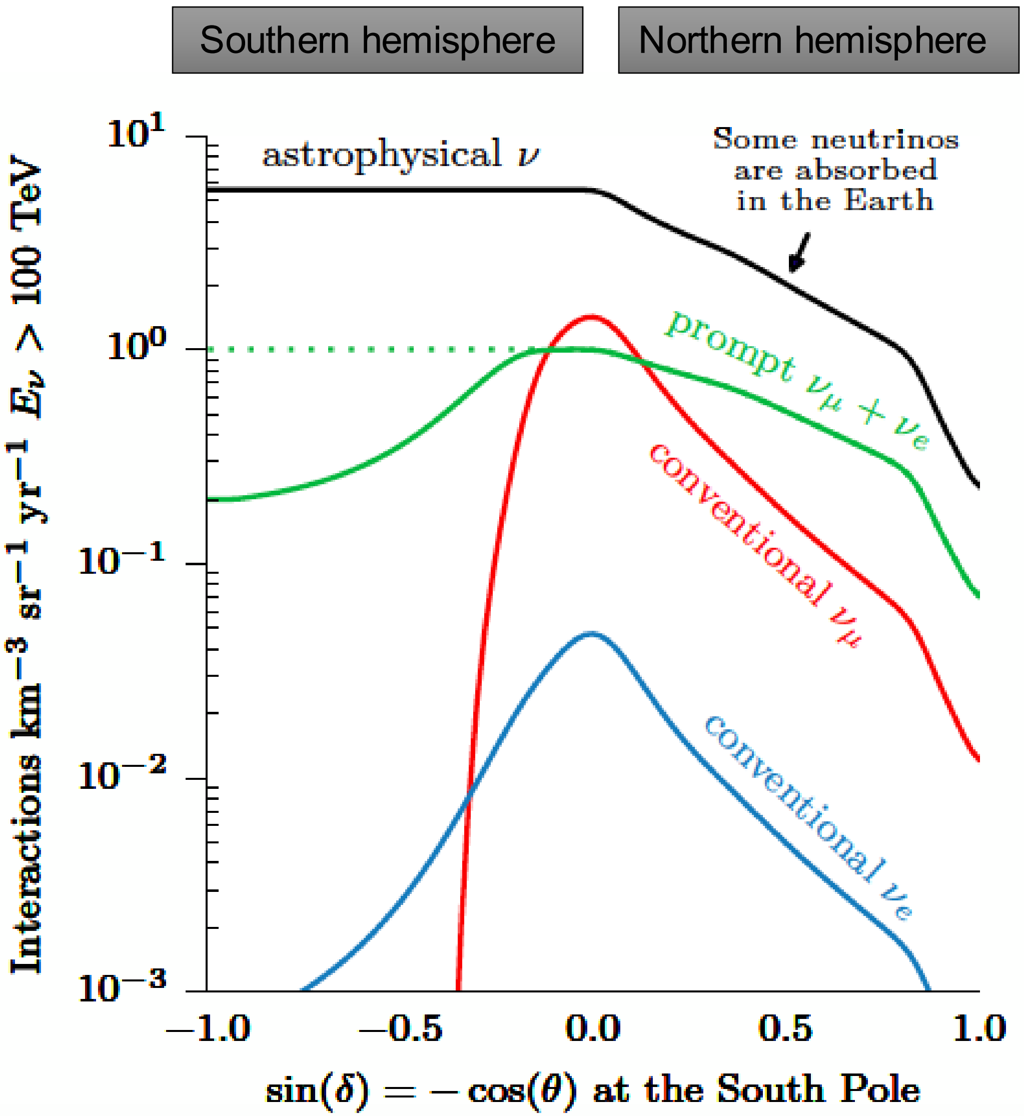
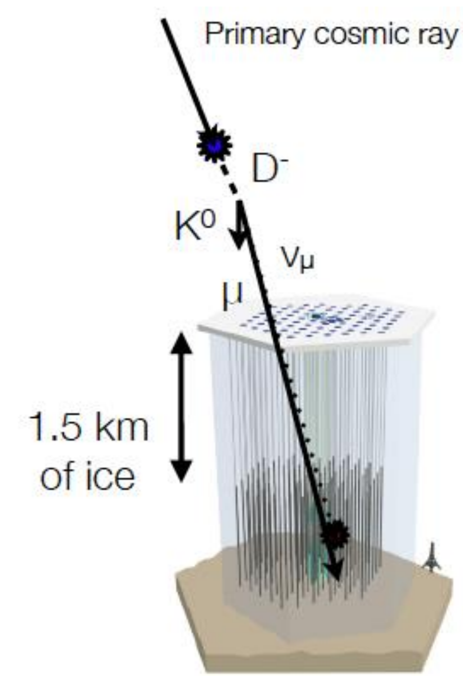


Prompt atmospheric neutrinos are vetoed too



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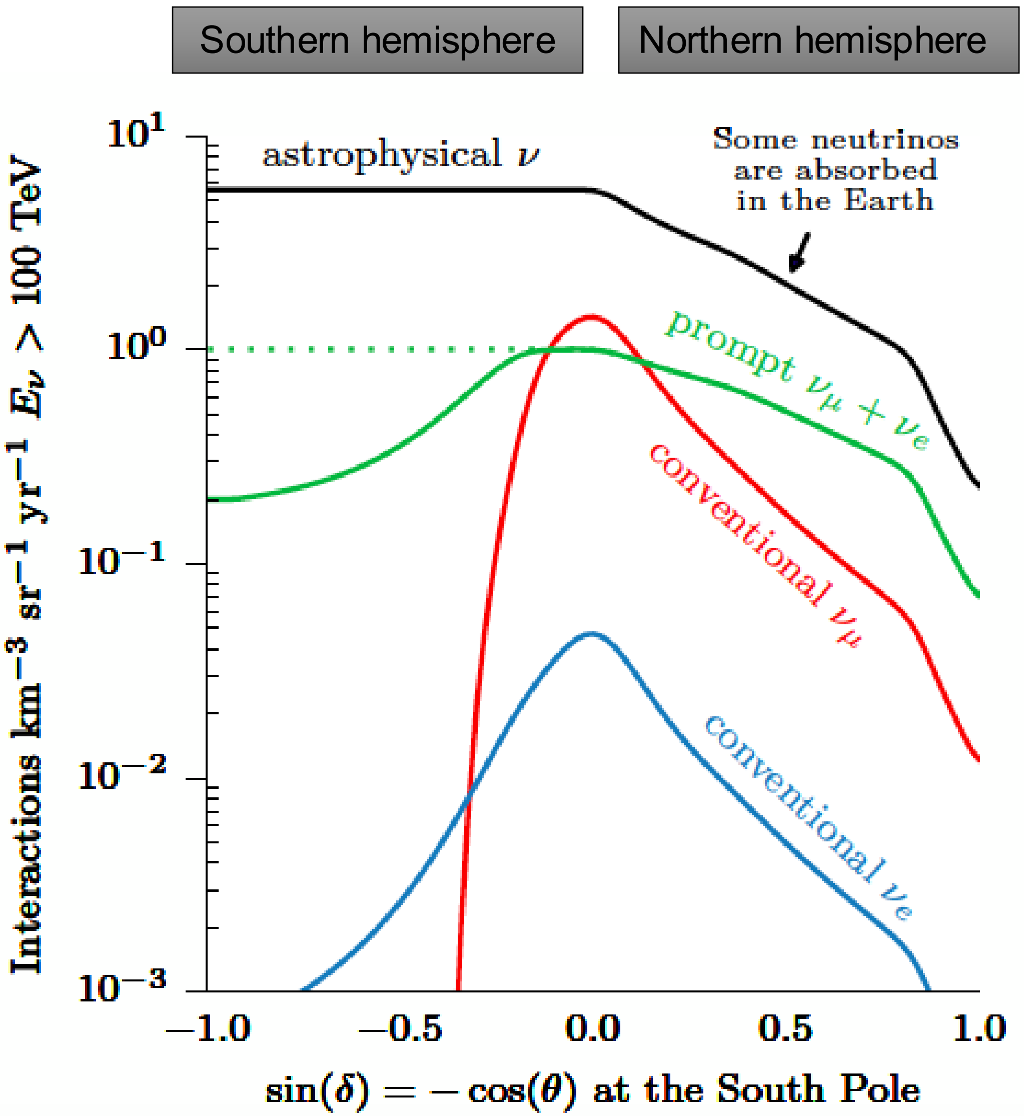
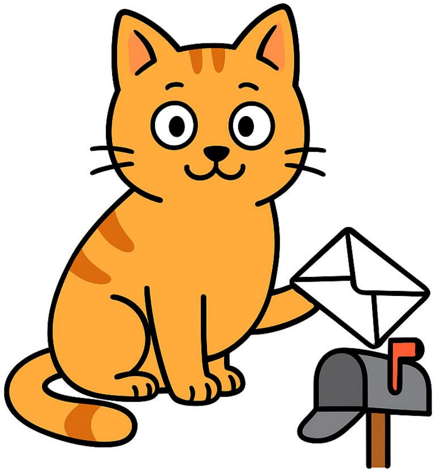


The zenith distributions of high-energy astrophysical and atmospheric neutrinos are fundamentally different.

Schönert, Gaisser, Resconi, Schulz, Phys. Rev. D, 79:043009 (2009)
Gaisser, Jero, Karle, van Santen, Phys. Rev. D, 90:023009 (2014)



Take home message

Water or ice Cherenkov detectors can reach km^3 size.
Atmosperic muons and neutrinos are a background for the search of cosmic neutrinos
→ using outer detector layers as veto can reduce this background

RUB

https://forms.gle/dr1h4NkN1zip3z3XA

Results from water / ice Cherenkov Telescopes

- Astronomy
  - Diffuse Flux
  - Milky Way
  - Source Candidates
- Neutrino as a particle
  - Neutrino Oscillations
  - Neutrino Cross Section
- New physics
  - Sterile Neutrinos
  - Dark Matter

Results from water / ice Cherenkov Telescopes

- Astronomy
  - **Diffuse Flux**
  - Milky Way
  - Source Candidates
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  - Neutrino Oscillations
  - Neutrino Cross Section
- New physics
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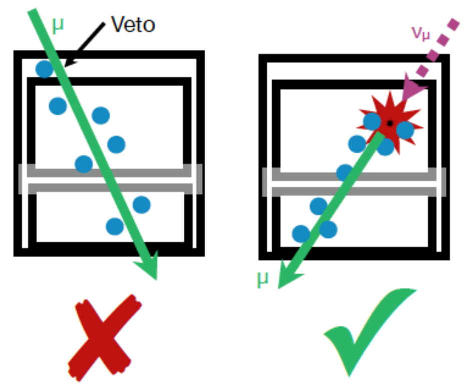
  - Dark Matter

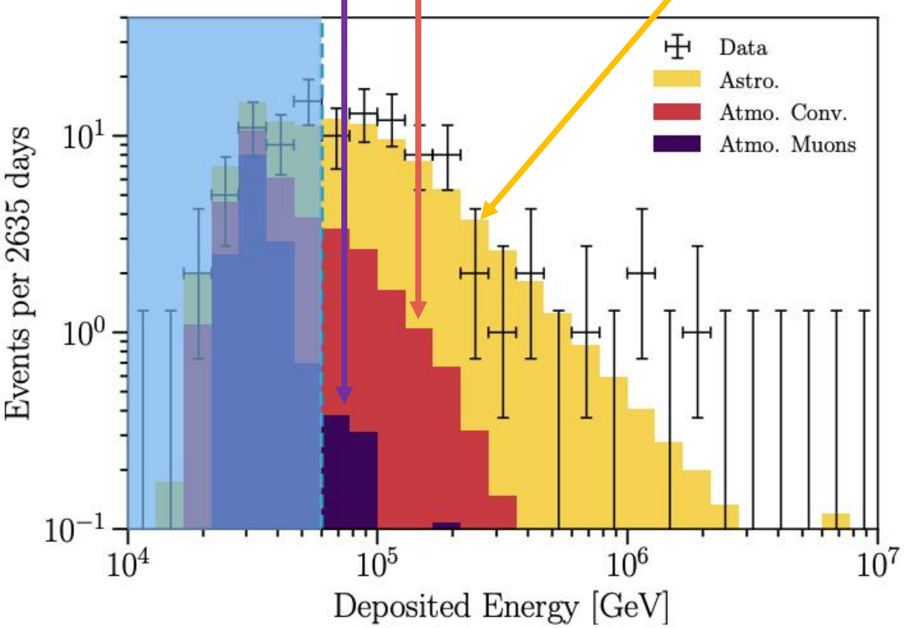
Discovery of High-Energy Astrophysical Neutrinos

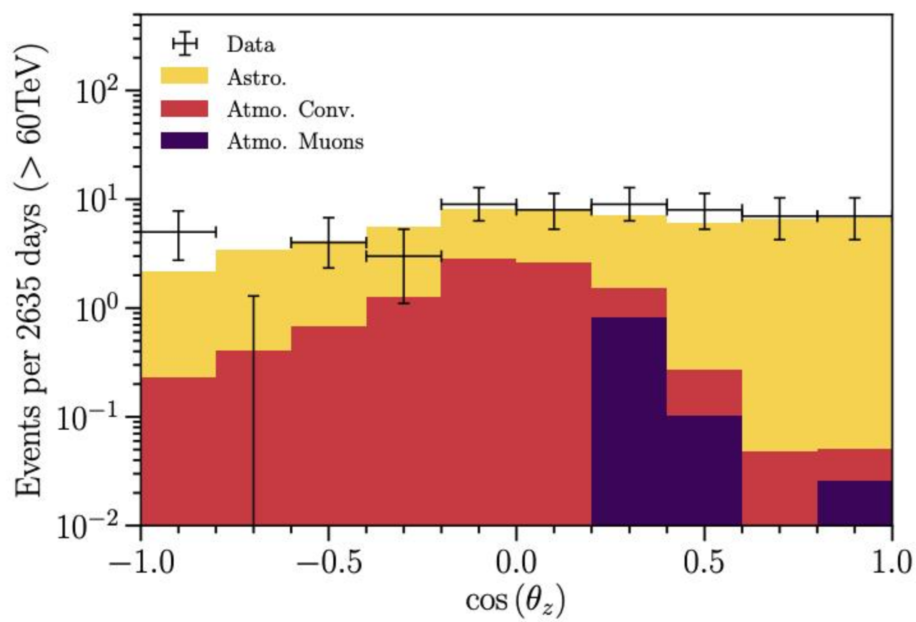


Atmospheric muons

Atmospheric neutrinos

Excess → Signal!

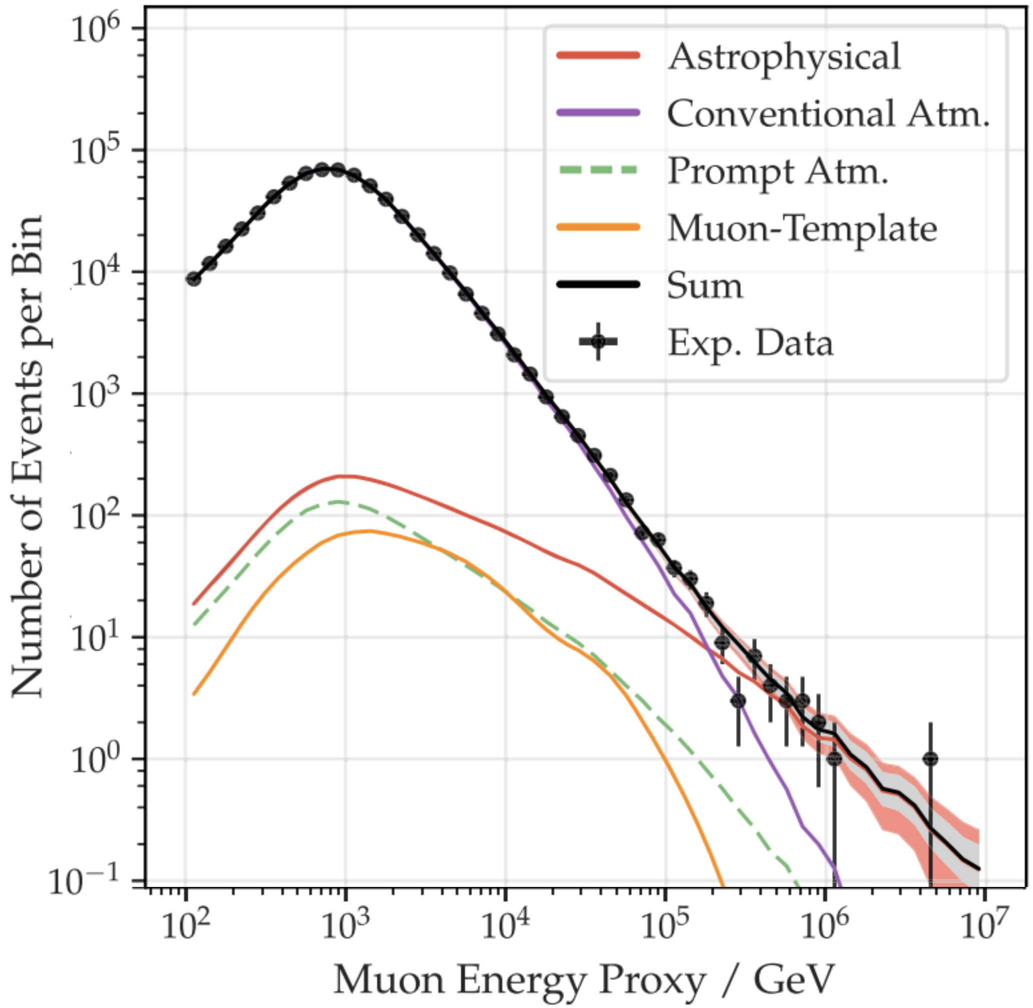


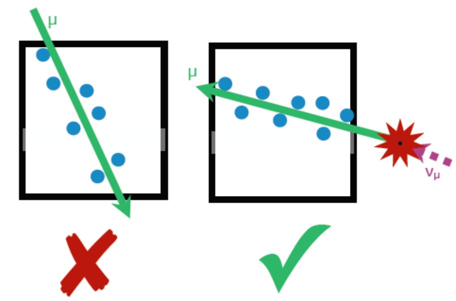


Northern sky Southern sky

IceCube Coll., Science 342, 2013, PRL 113, 101101 (2014)

Diffuse flux seen in different channels



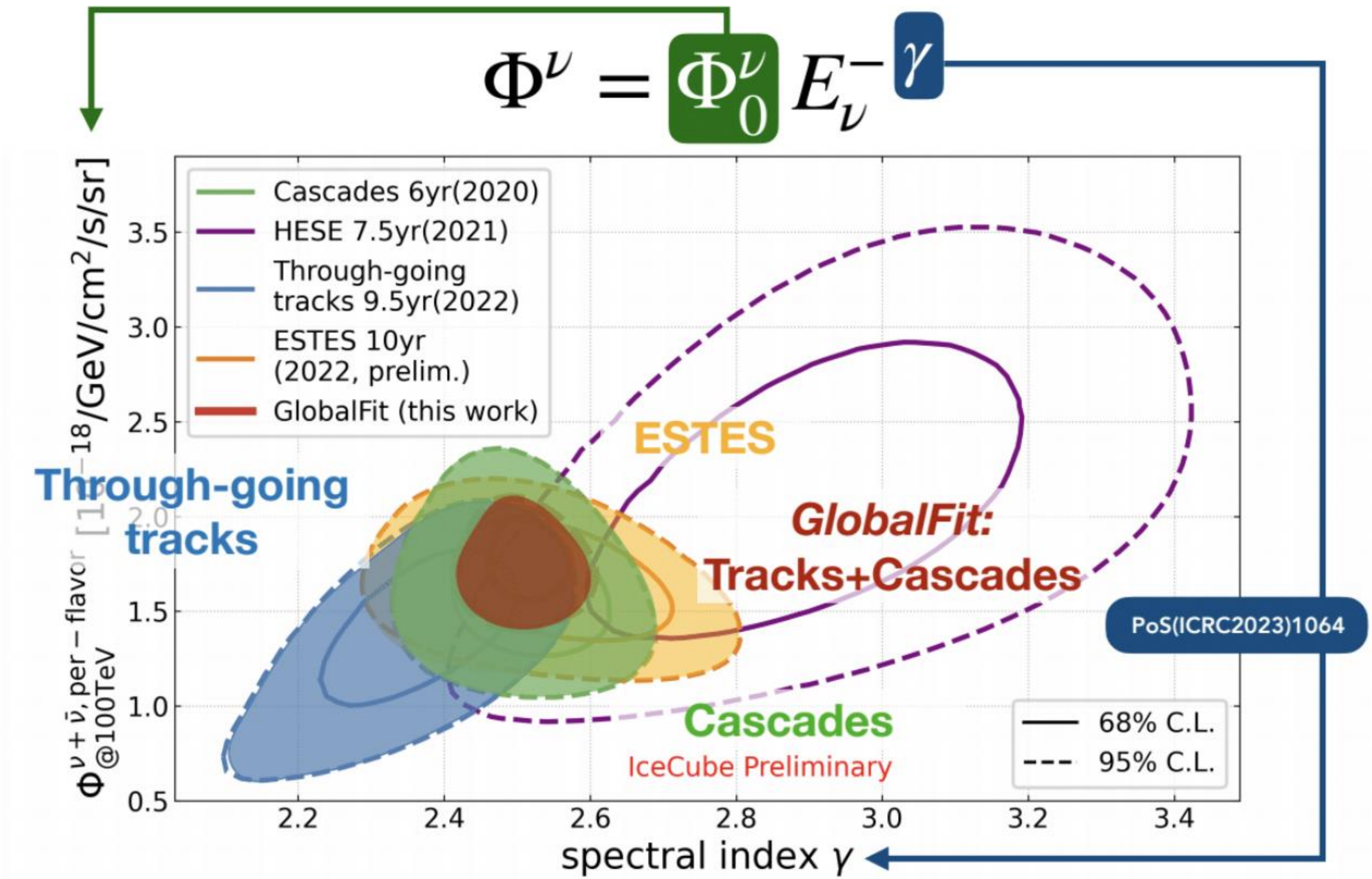


- Selected horizontal and up-going muon tracks
- Sensitive to astrophysical neutrinos above ~100 TeV

R. Abbasi *et al* 2022 *ApJ* **928** 50

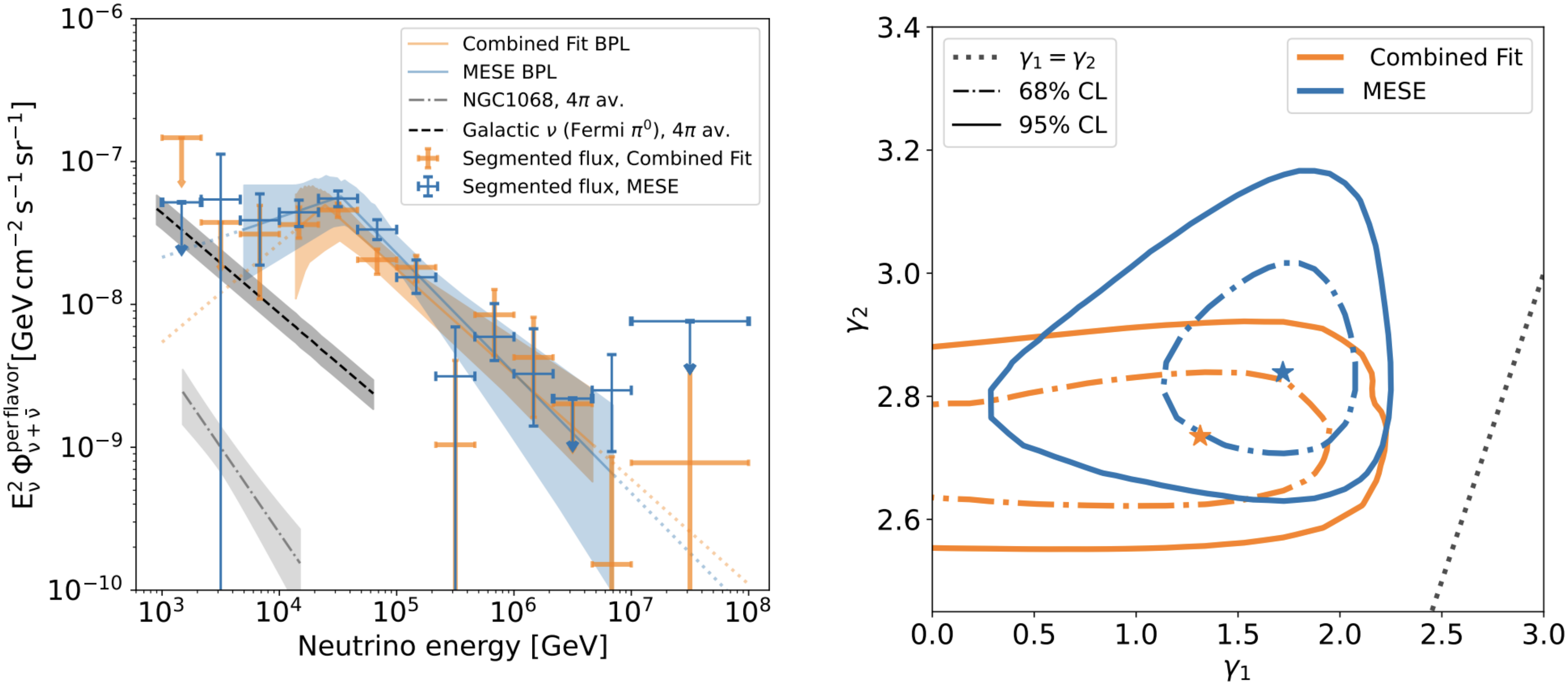
Spectrum of diffuse flux

$$\Phi^{\nu} = \Phi_0^{\nu} E_{\nu}^{-\gamma}$$



RUB

Spectrum of diffuse flux: not a power law?



IceCube arXiv:2507.22233

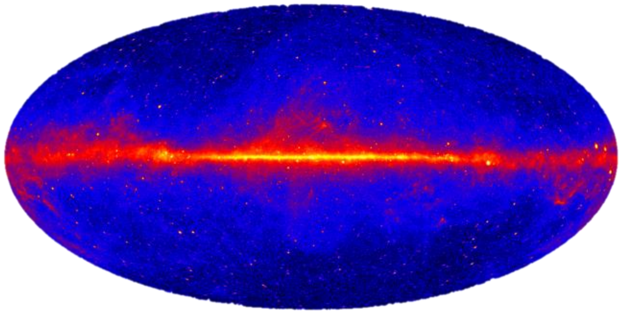
What is the origin of the diffuse flux?

Results from water / ice Cherenkov Telescopes

- Astronomy
  - Diffuse Flux
  - **Milky Way**
  - Source Candidates
- Neutrino as a particle
  - Neutrino Oscillations
  - Neutrino Cross Section
- New physics
  - Sterile Neutrinos
  - Dark Matter

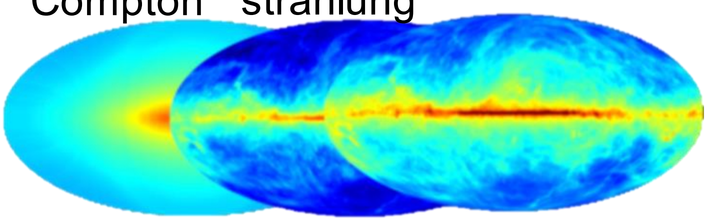
Galactic Contribution

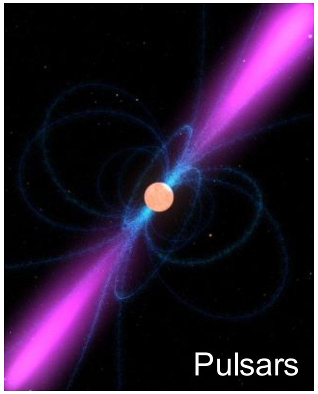
GeV gamma-ray sky by Fermi-LAT

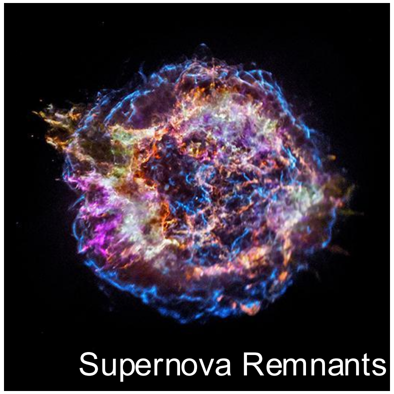


Cosmic rays propagate through the Galaxy and interact with photons and gas

Inverse Compton | Brems-strahlung | π^0 decay







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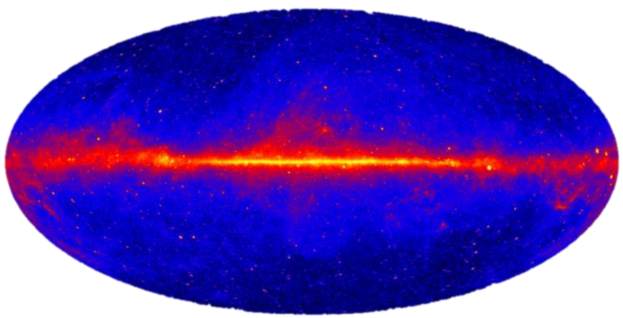
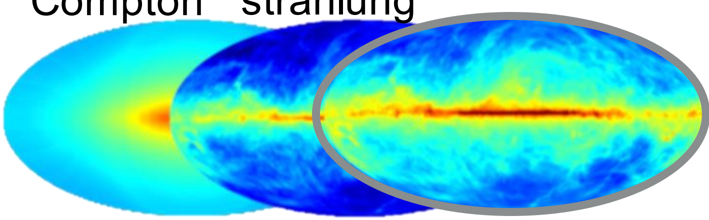
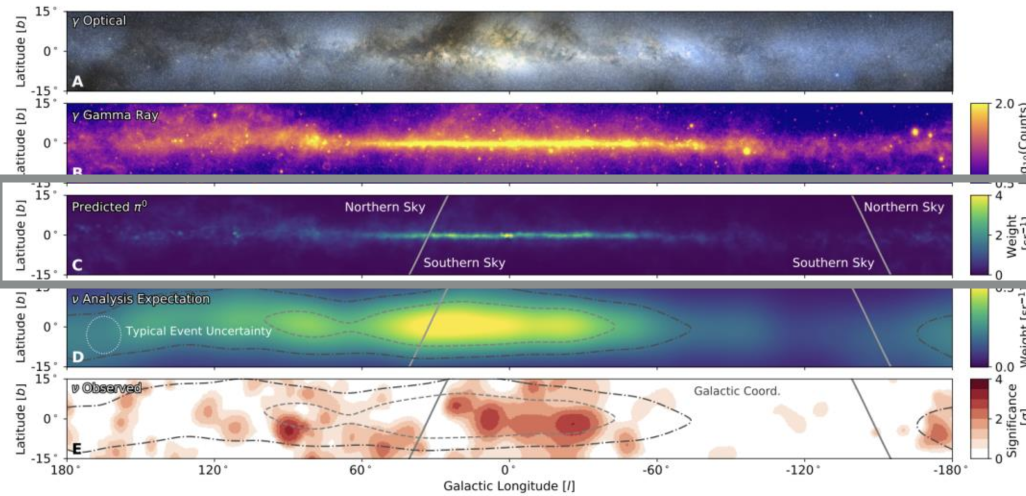


Inverse Compton

Brems-strahlung

π^0 **decay**

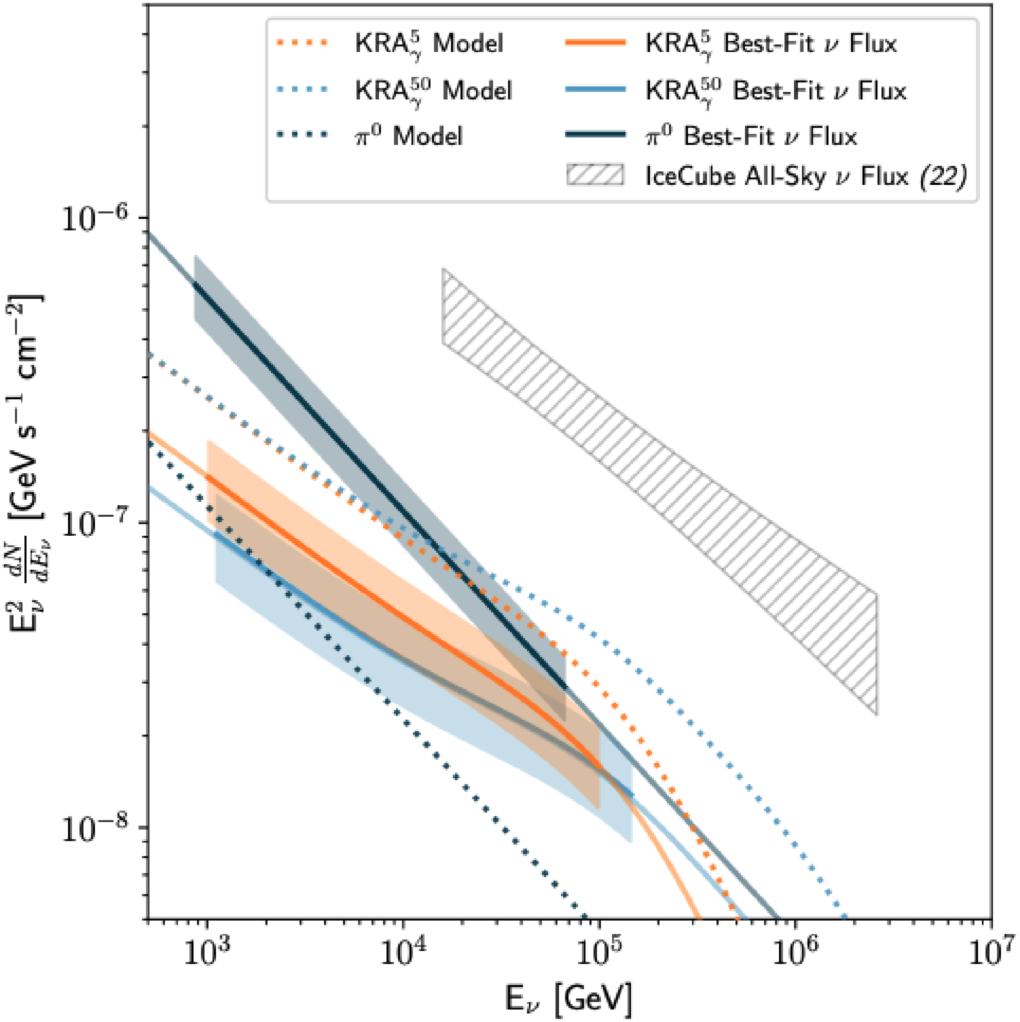




First detection of galactic plane neutrino flux thanks to gamma-ray template fit

IceCube Science 380 (2023)

Galactic Neutrinos



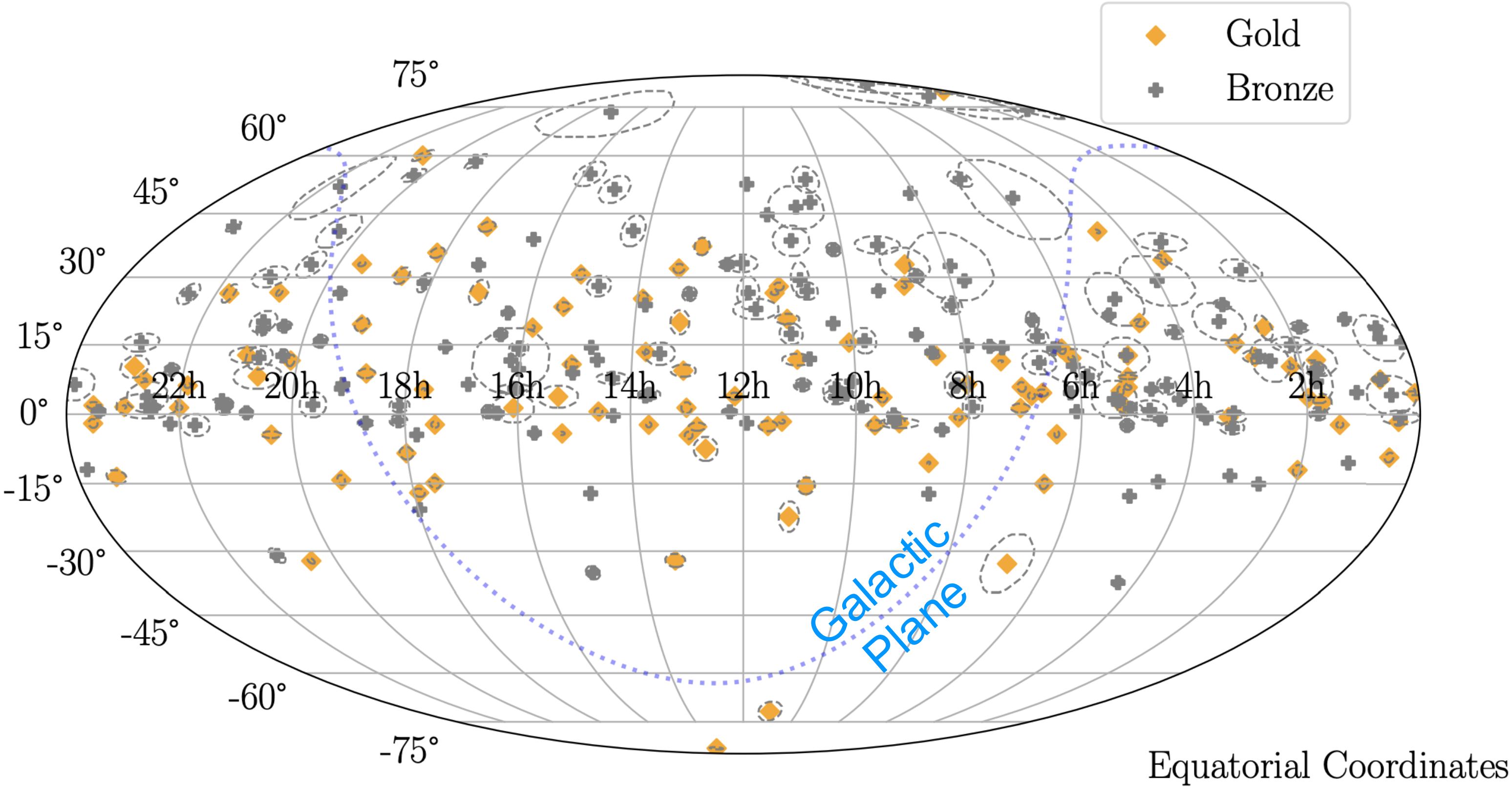
Galactic neutrinos make up ~10% of diffuse neutrinos

Results from water / ice Cherenkov Telescopes

- Astronomy
  - Diffuse Flux
  - Milky Way
  - **Source Candidates**
- Neutrino as a particle
  - Neutrino Oscillations
  - Neutrino Cross Section
- New physics
  - Sterile Neutrinos
  - Dark Matter

Neutrino Sky Map

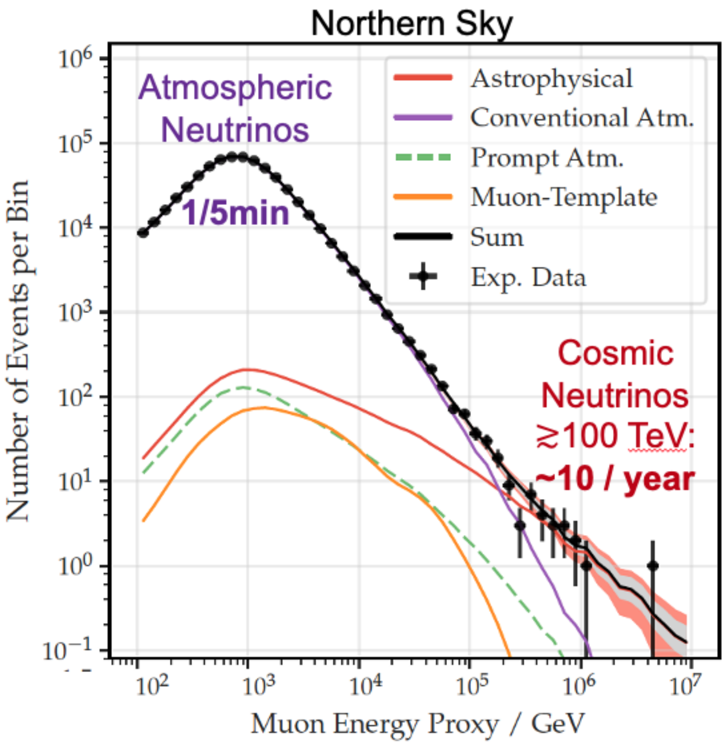
IceCube neutrinos with high (>30%) probability to be of cosmic origin



Neutrinos alone do not reveal the sources (yet)

IceCube ApJS 269 (2023)

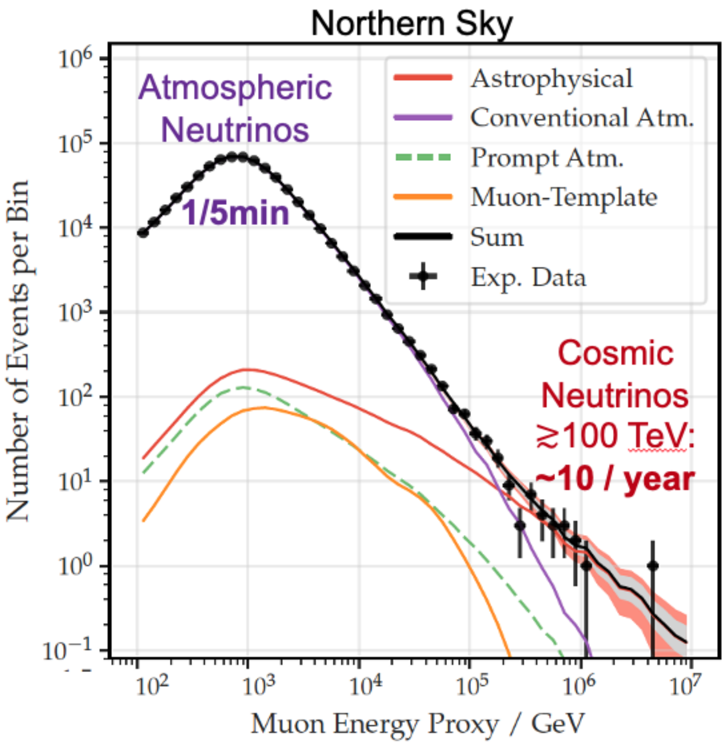
Search for Extragalactic Sources: Strategies



1. Look for hotspots in the neutrino sky → identify source candidates
2. Start from EM source catalog → look for neutrinos from source population
3. Focus on high-energy neutrinos with high signal probability → look for EM counterparts

IceCube Coll. ApJ 928 (2022) 50

Search for Extragalactic Sources: Strategies



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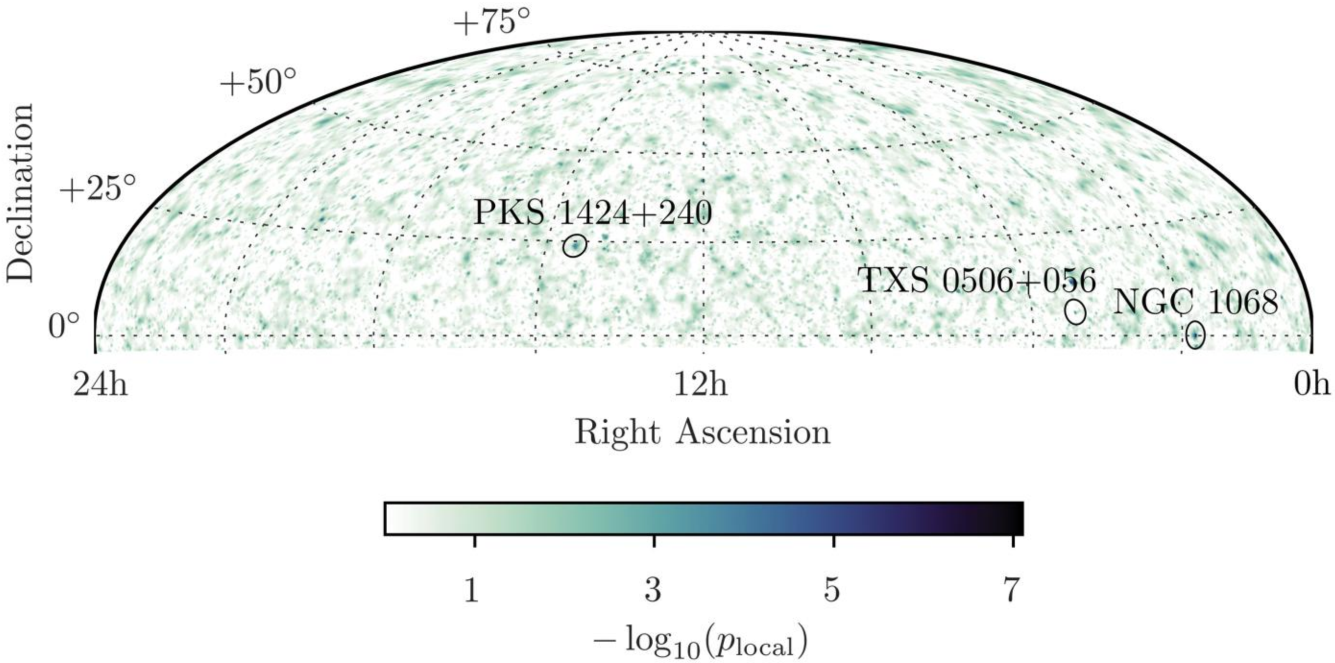
IceCube Coll. ApJ 928 (2022) 50

Search for hotspots in the neutrino sky



IceCube Science 378 (2022)

Maximum Likelihood Technique

Signal probability

$$\mathcal{L}(n_S, \gamma) = \prod_i \left(\frac{n_S}{N} \mathcal{S}\left(\left| \mathbf{x}_S - \mathbf{x}_i \right|, E_i; \gamma \right) + \left(1 - \frac{n_S}{N}\right) \mathcal{B}\left(\sin \delta_i, E_i\right) \right)$$

Neutrino event *i*

background probability

Test Statistic:

$$\mathcal{TS} = 2 \log \left(\mathcal{L}(\hat{n}_S, \hat{\gamma}) / \mathcal{L}(n_S = 0) \right)$$

Maximum Likelihood Technique

$$\mathcal{S} = \frac{1}{2\pi\sigma_i^2} e^{-\frac{|\mathbf{x}_S - \mathbf{x}_i|^2}{2\sigma_i^2}} \times \mathcal{E}_S\left(E_i, \sin\delta_i; \gamma\right)$$

Signal probability

$$\mathcal{L}\left(n_S, \gamma\right) = \prod_i \left(\frac{n_S}{N} \mathcal{S}\left(\left|\mathbf{x}_S - \mathbf{x}_i\right|, E_i; \gamma\right) + \left(1 - \frac{n_S}{N}\right) \mathcal{B}\left(\sin\delta_i, E_i\right)\right)$$

x_s: source position
x_i: neutrino direction
δ_i: neutrino declination
σ_i: neutrino declination
E_i: neutrino energy
γ: spectral index

Maximum Likelihood Technique

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Spectral index (**free parameter in fit**)

Signal probability

$$\mathcal{L}(n_S, \gamma) = \prod_i \left(\frac{n_S}{N} \mathcal{S}\left(|\mathbf{x}_S - \mathbf{x}_i|, E_i; \gamma\right) + \left(1 - \frac{n_S}{N}\right) \mathcal{B}\left(\sin\delta_i, E_i\right) \right)$$

number of events from source (**free parameter in fit)**

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background probability

$$\mathcal{B} = \frac{\mathcal{P}_{\mathcal{B}}\left(\sin\delta_i\right)}{2\pi} \times \mathcal{E}_{\mathcal{B}}\left(E_i, \sin\delta_i\right)$$

x_s: source position
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γ: spectral index

Maximum Likelihood Technique

$$\mathcal{S} = \frac{1}{2\pi\sigma_i^2} \mathrm{e}^{-\frac{|\mathbf{x}_S - \mathbf{x}_i|^2}{2\sigma_i^2}} \times \mathcal{E}_S\left(E_i, \sin\delta_i; \gamma\right)$$

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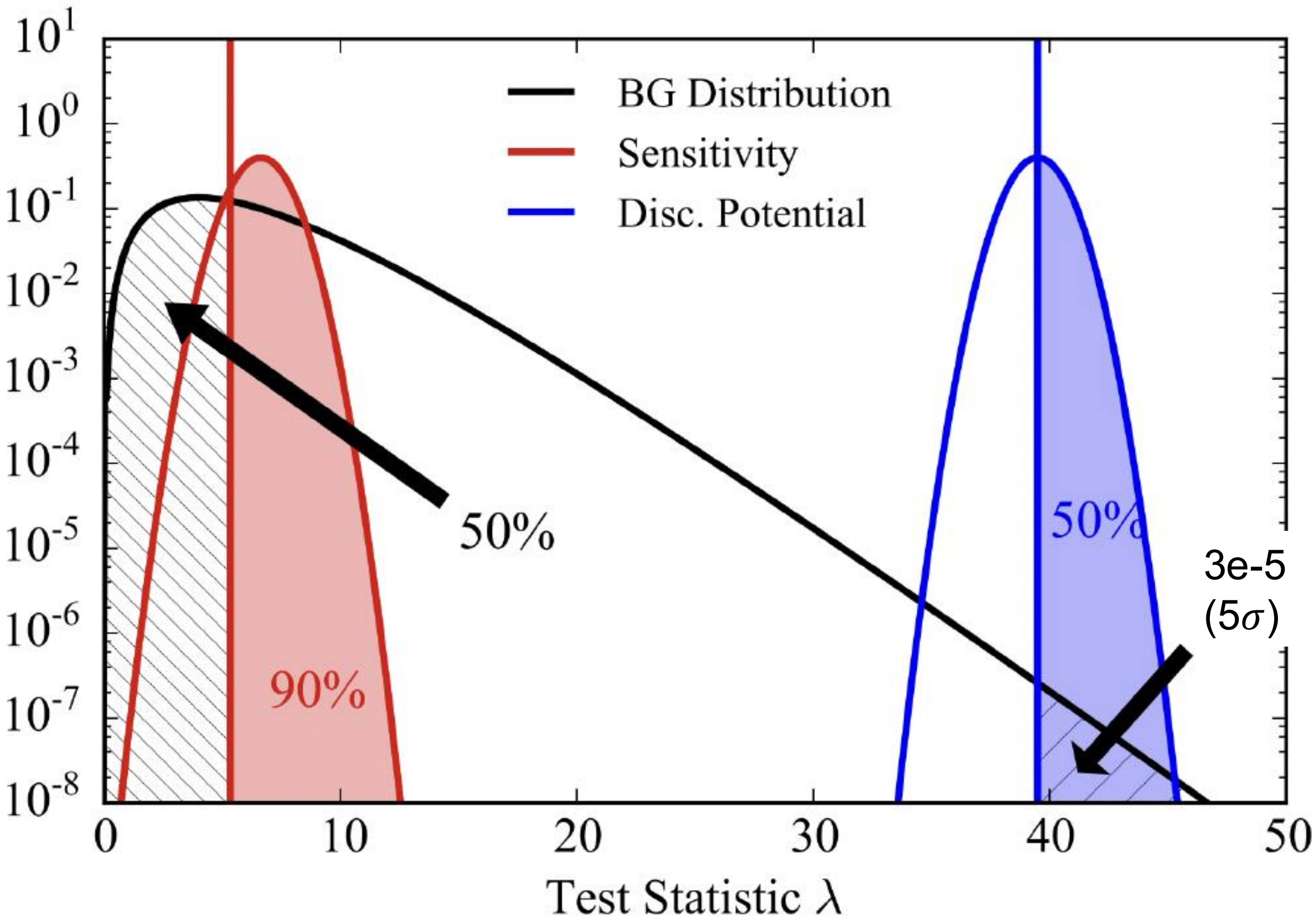
RUB

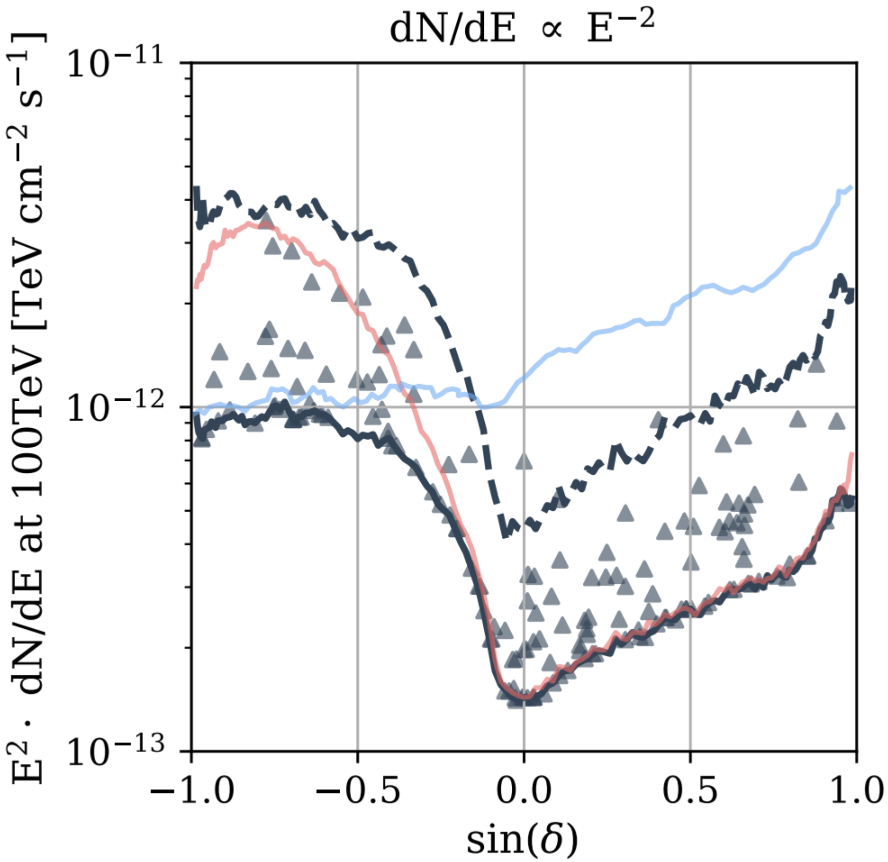
Definition of Sensitivity



RUB

Point Source Sensitivity

Signal trials: determine how much signal needs to be injected to end have 90% of the signal trials yield a TS greater than the median TS derived from background trials



IceCube arXiv:2507.07275

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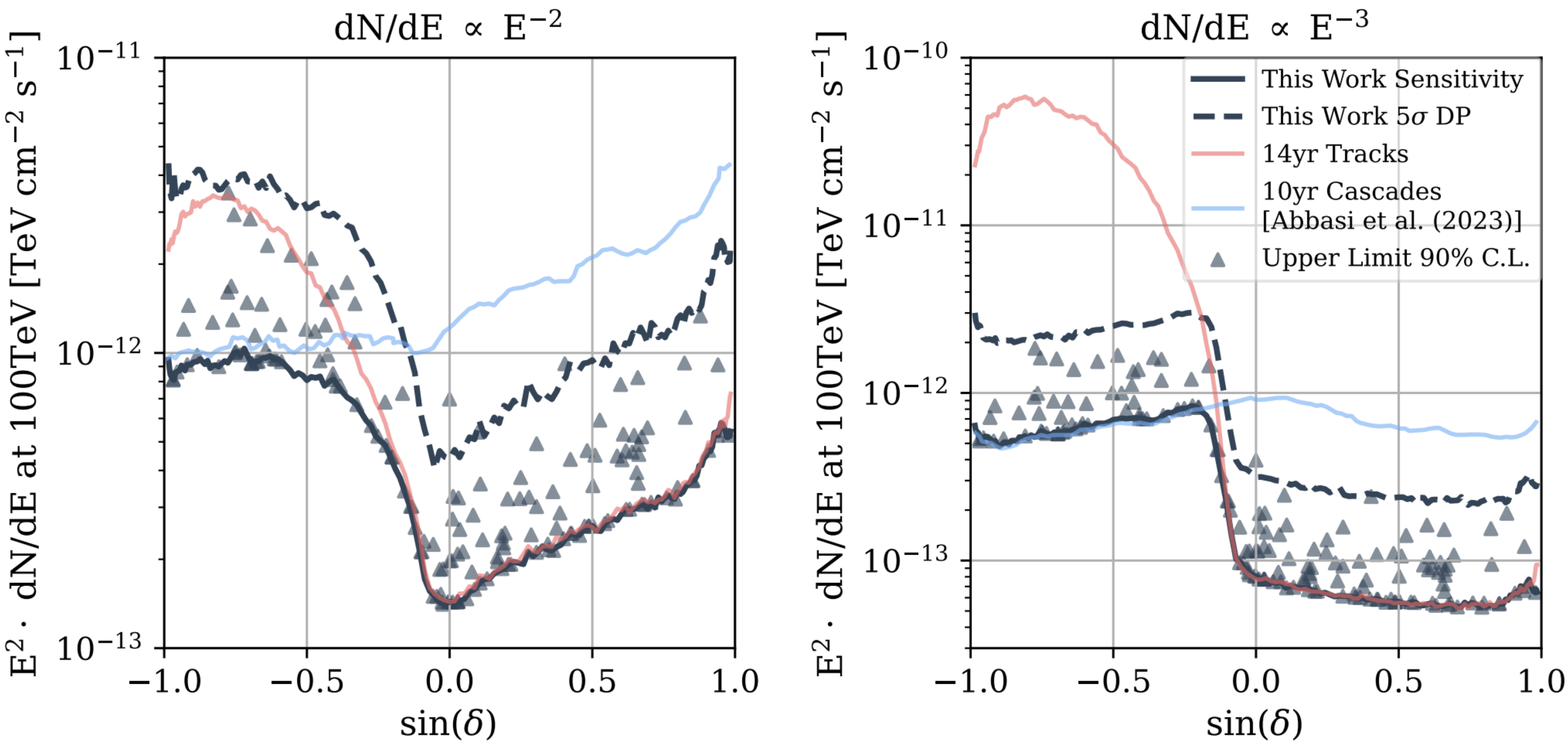
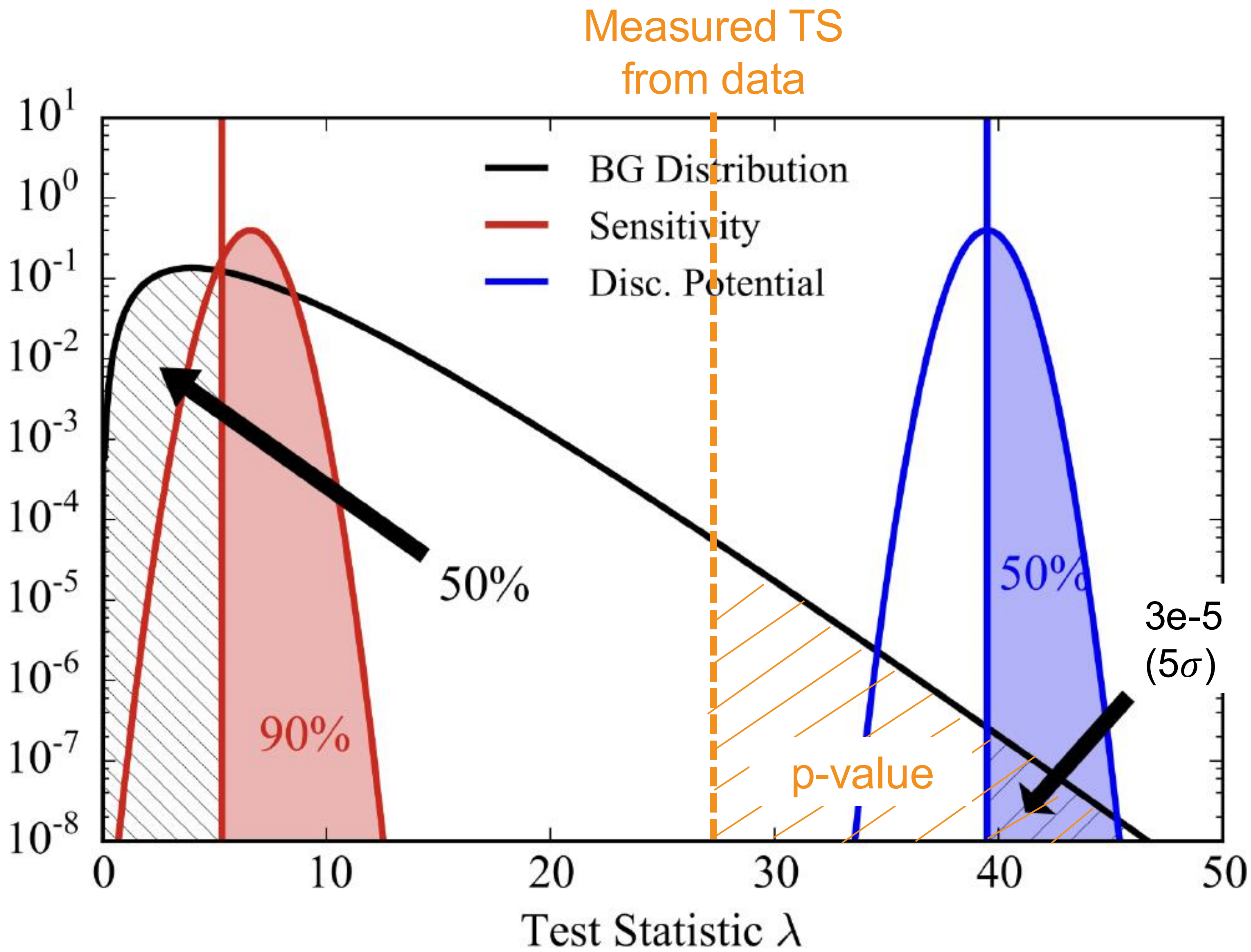
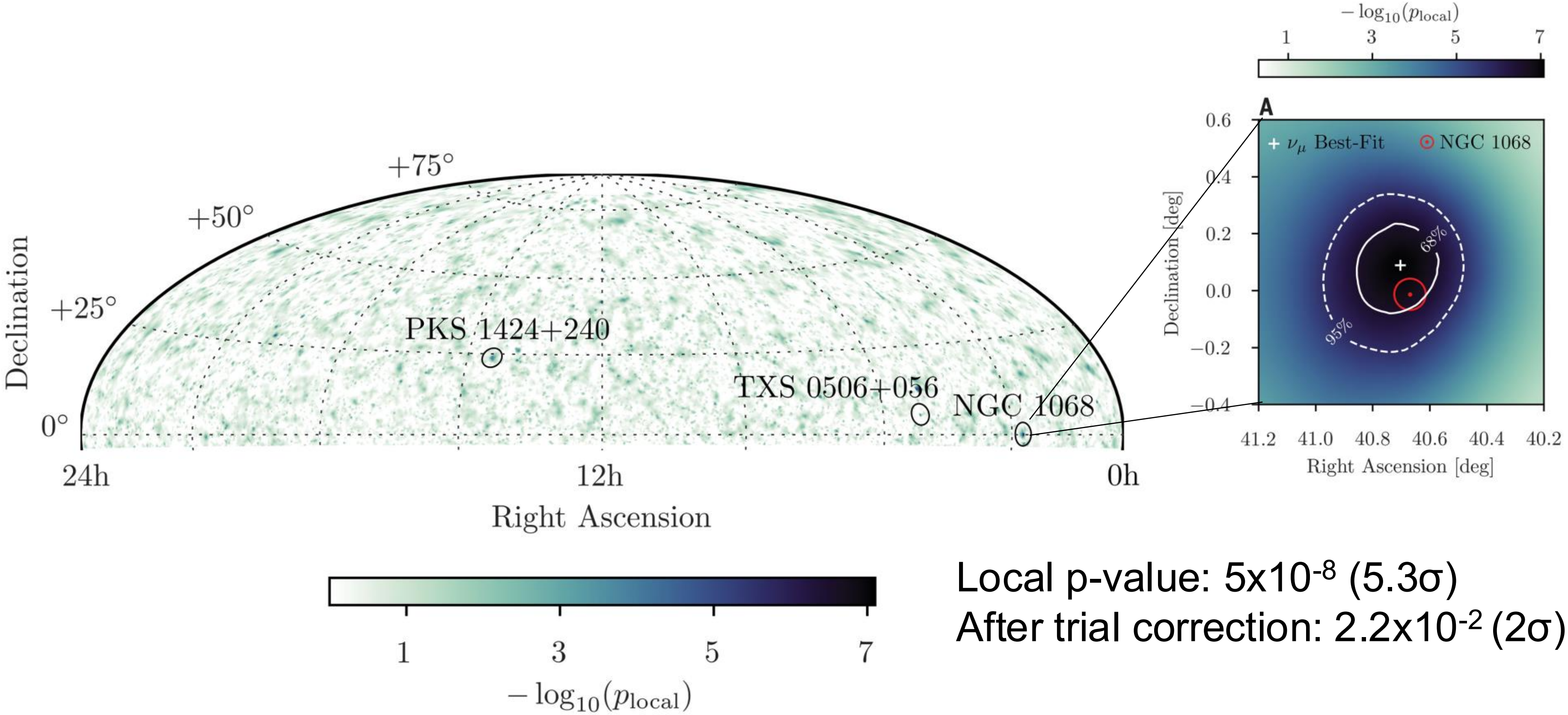


IceCube arXiv:2507.07275

Definition of p-value



Search for hotspots in the neutrino sky

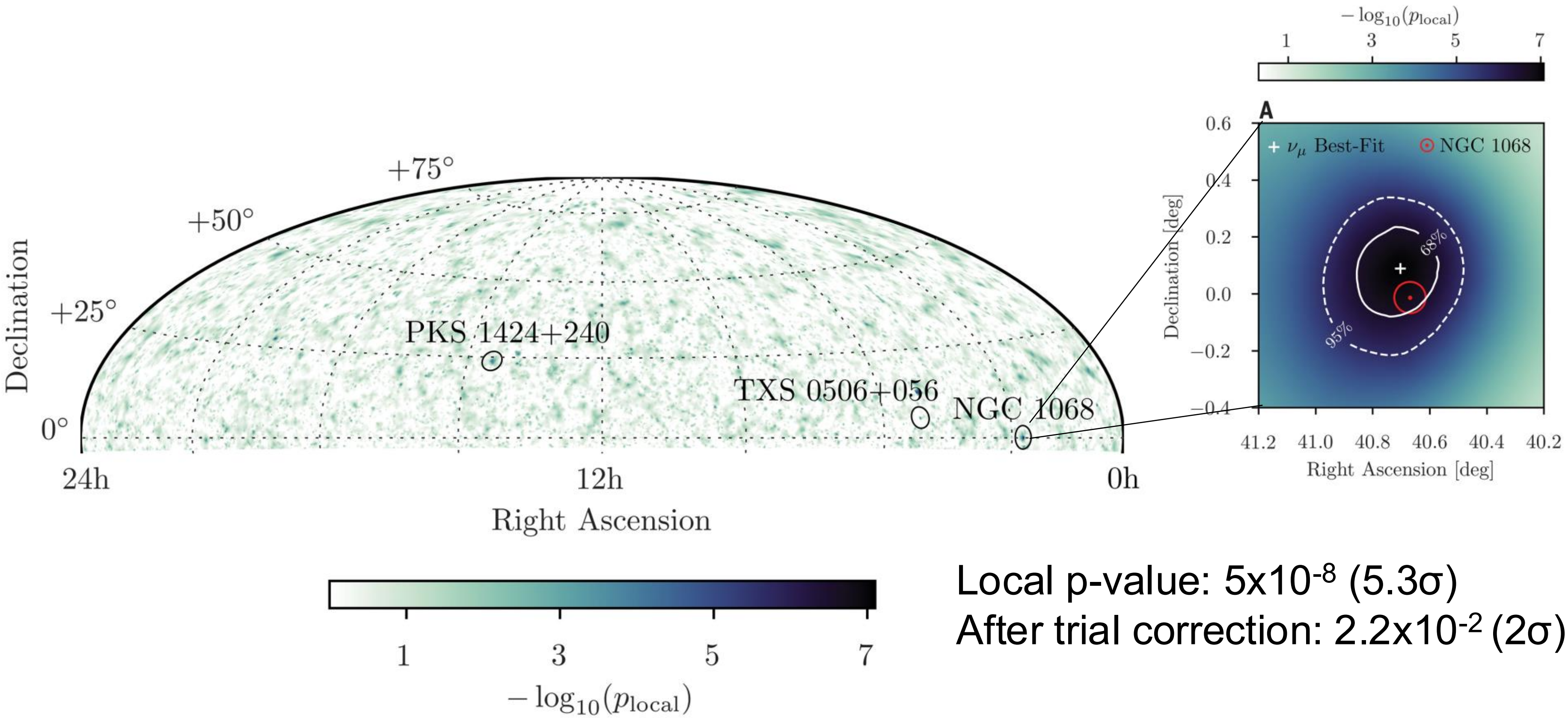


Local p-value: 5×10^{-8} (5.3σ)
After trial correction: 2.2×10^{-2} (2σ)

The post-trial probability is estimated by comparing the p-value of the hottest spot in the data with a distribution of hottest spots in a large number of background trials.

IceCube Science 378 (2022)

Search for hotspots in the neutrino sky



Local p-value: 5×10^{-8} (5.3σ)
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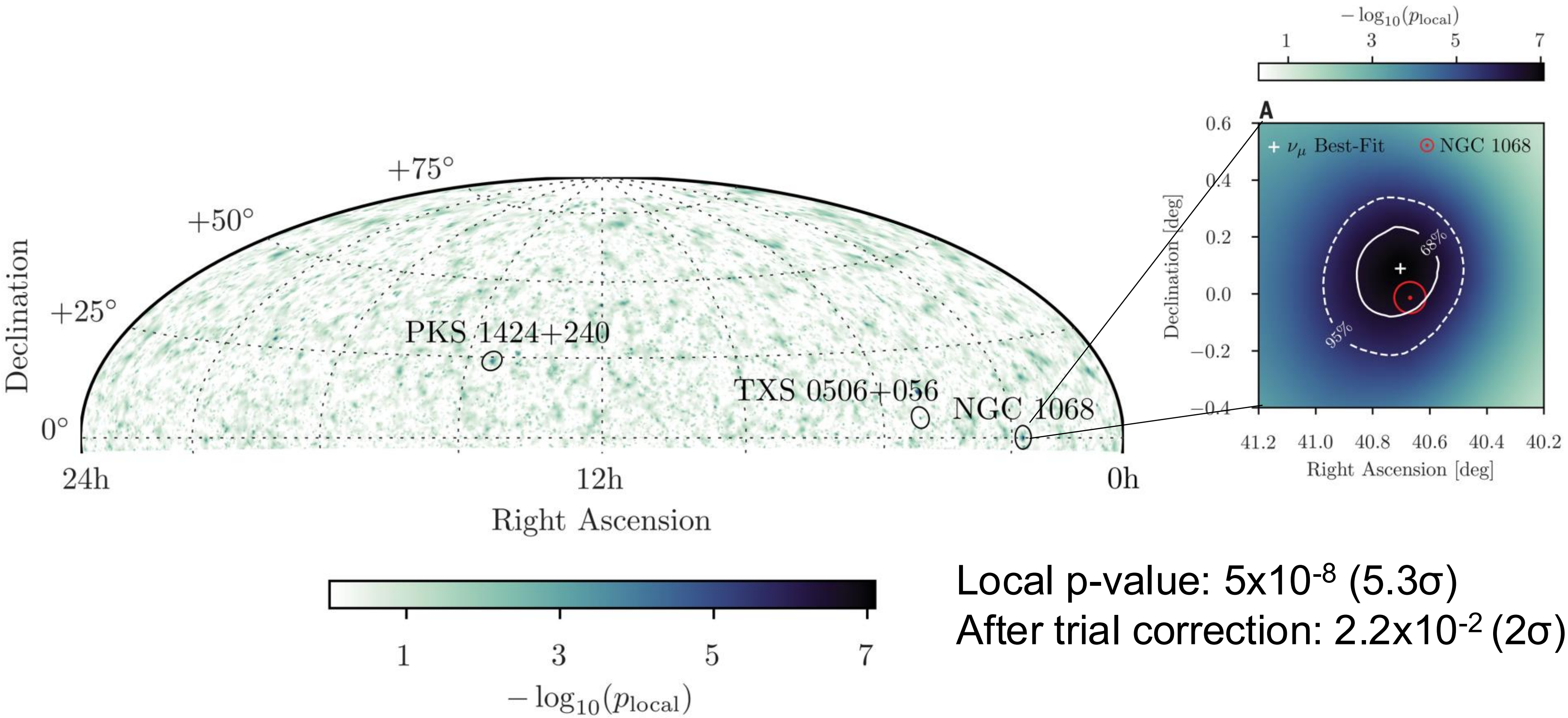
Challenge: Atmospheric background, large trial factor

IceCube Science 378 (2022)

Search for hotspots in the neutrino sky



Local p-value: 5×10^{-8} (5.3σ)
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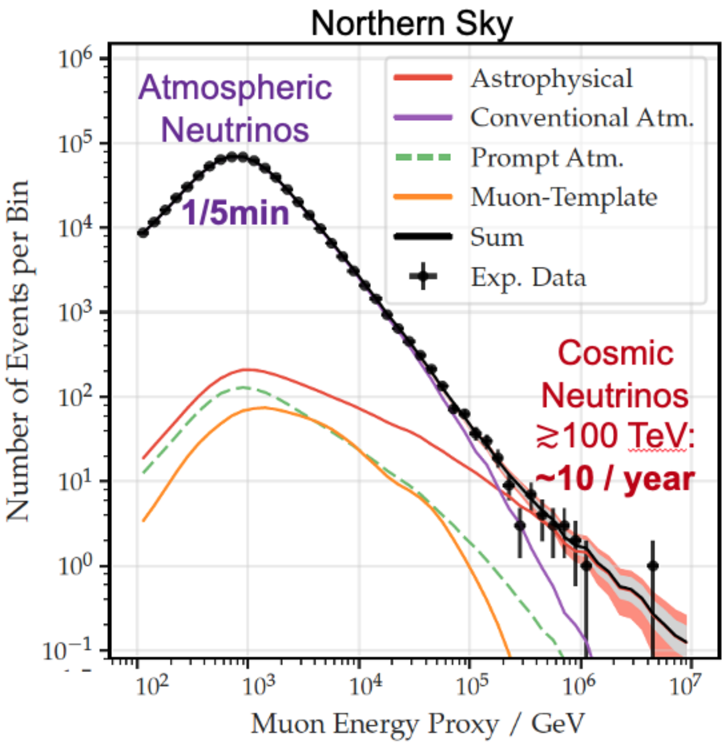
Solution: Use predefined source lists to reduce trials

IceCube Science 378 (2022)

Search for Extragalactic Sources: Strategies



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IceCube Coll. ApJ 928 (2022) 50

Predefined source list

110 sources based on gamma-ray properties and weighted with neutrino search sensitivity

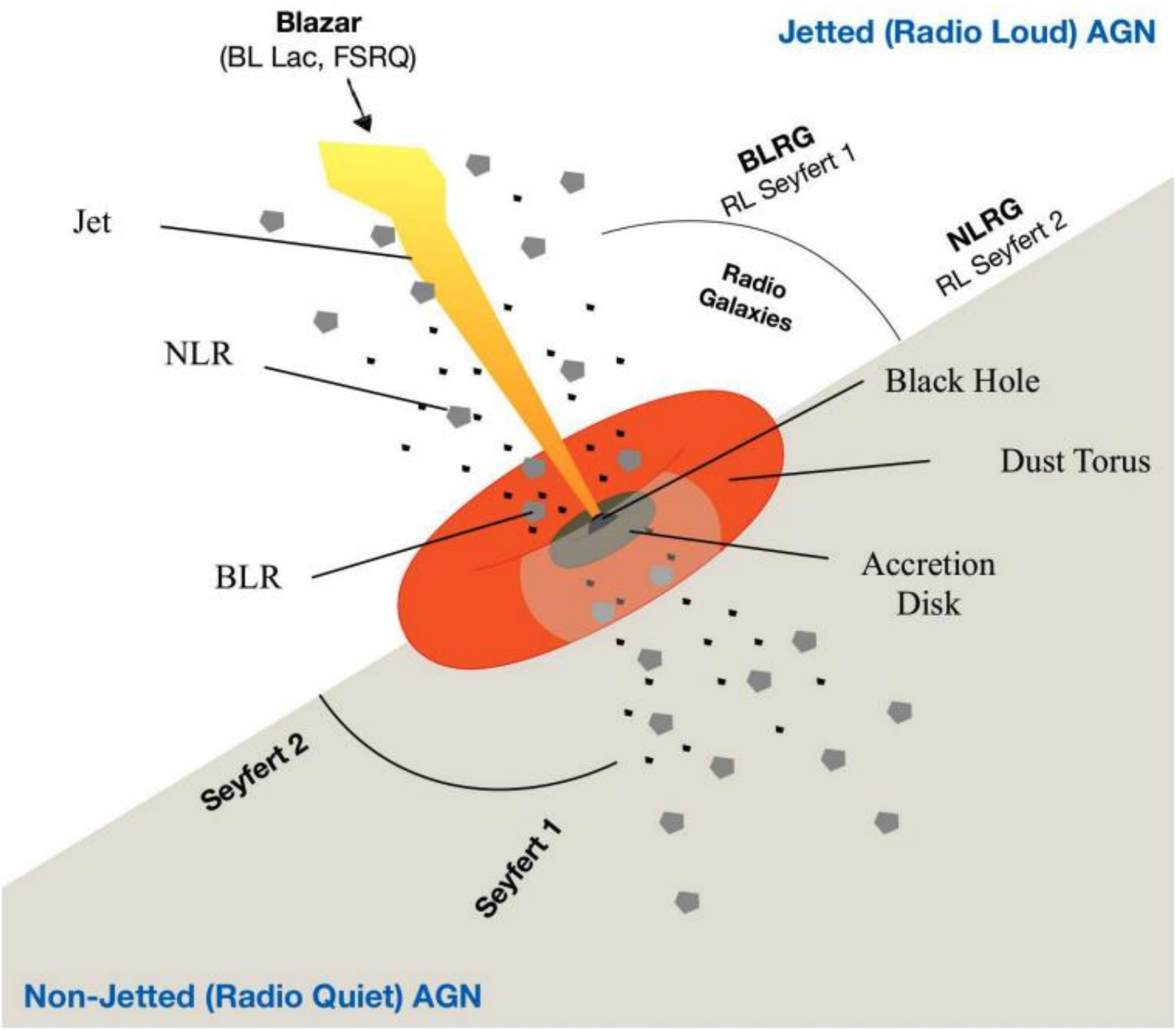
Why 110 sources: 5 σ p-value before trials would remain above 4 σ after trials

Extragal. Sources:

1. 4FGL sources weighted according to the integral gamma-ray flux > 1 GeV divided by the sensitivity neutrino flux for this analysis at the respective source declination
2. 5% highest-weighted BL Lacs and flat spectrum radio quasars (FSRQs) are each selected
3. minimum weighted integral flux from the combined selection of BL Lac and FSRQs is used as a flux threshold to include unidentified blazars and AGN
4. Starburst galaxies in 4FGL (8 sources) are included in addition

→ **87 extragalactic gamma-ray sources**

Unified AGN Model



Predefined source list

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Why 110 sources: 5 σ p-value before trials would remain above 4 σ after trials

Galactic Sources:

1. VHE gamma-ray sources from TeVCat and gammaCat
2. Convert gamma-ray spectra to equivalent neutrino fluxes, assuming a purely hadronic origin: $E_\gamma = 2E_\nu$
3. Keep sources with predicted energy fluxes > 50% of neutrino sensitivity (assuming E^{-2} spectrum)

→ **12 Galactic gamma-ray sources**

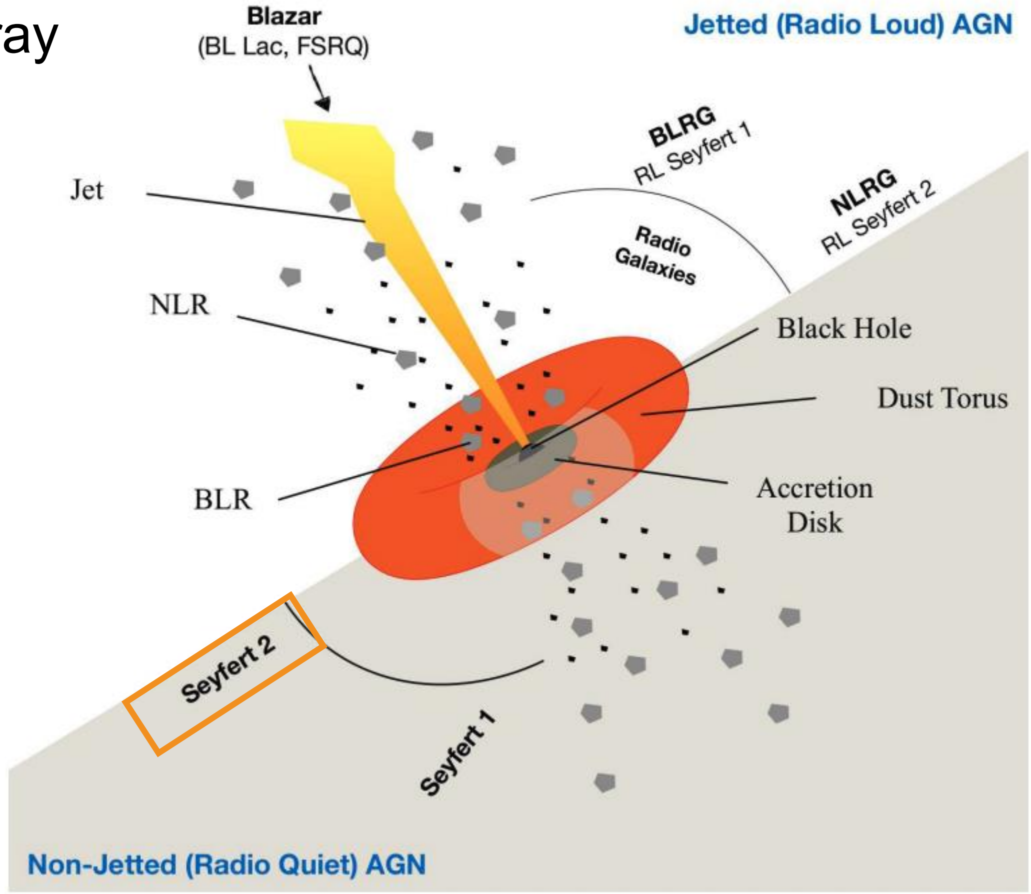
Predefined source list: Results

110 sources based on gamma-ray properties and weighted with neutrino search sensitivity

Most significant candidate:

NGC 1068 (M77), 4.2σ

- Nearby (M=14Mpc) Seyfert 2 galaxy
- AGN and star-forming activity



Combining gamma-ray source list with neutrino data allowed neutrino source detection

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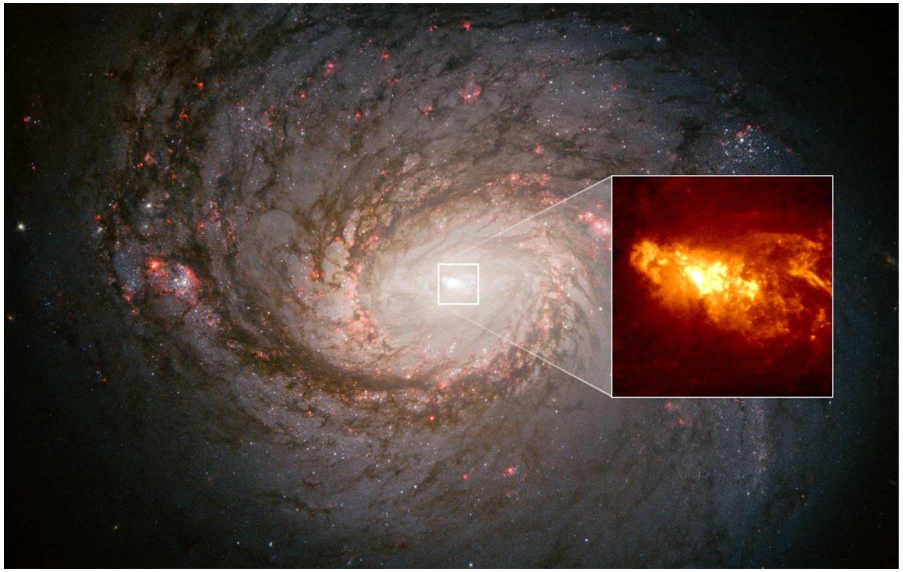
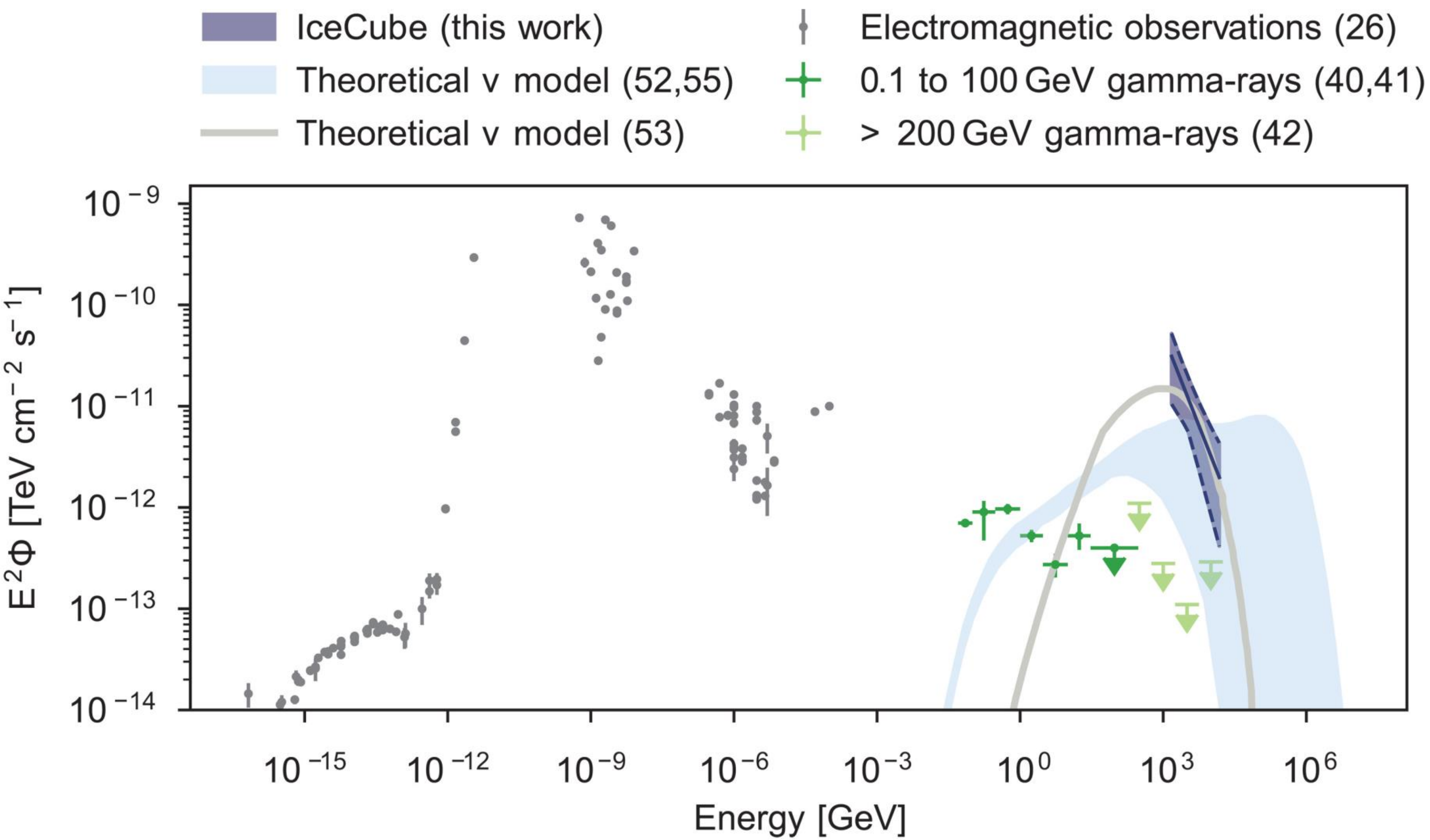


Combining gamma-ray source list with neutrino data allowed neutrino source detection

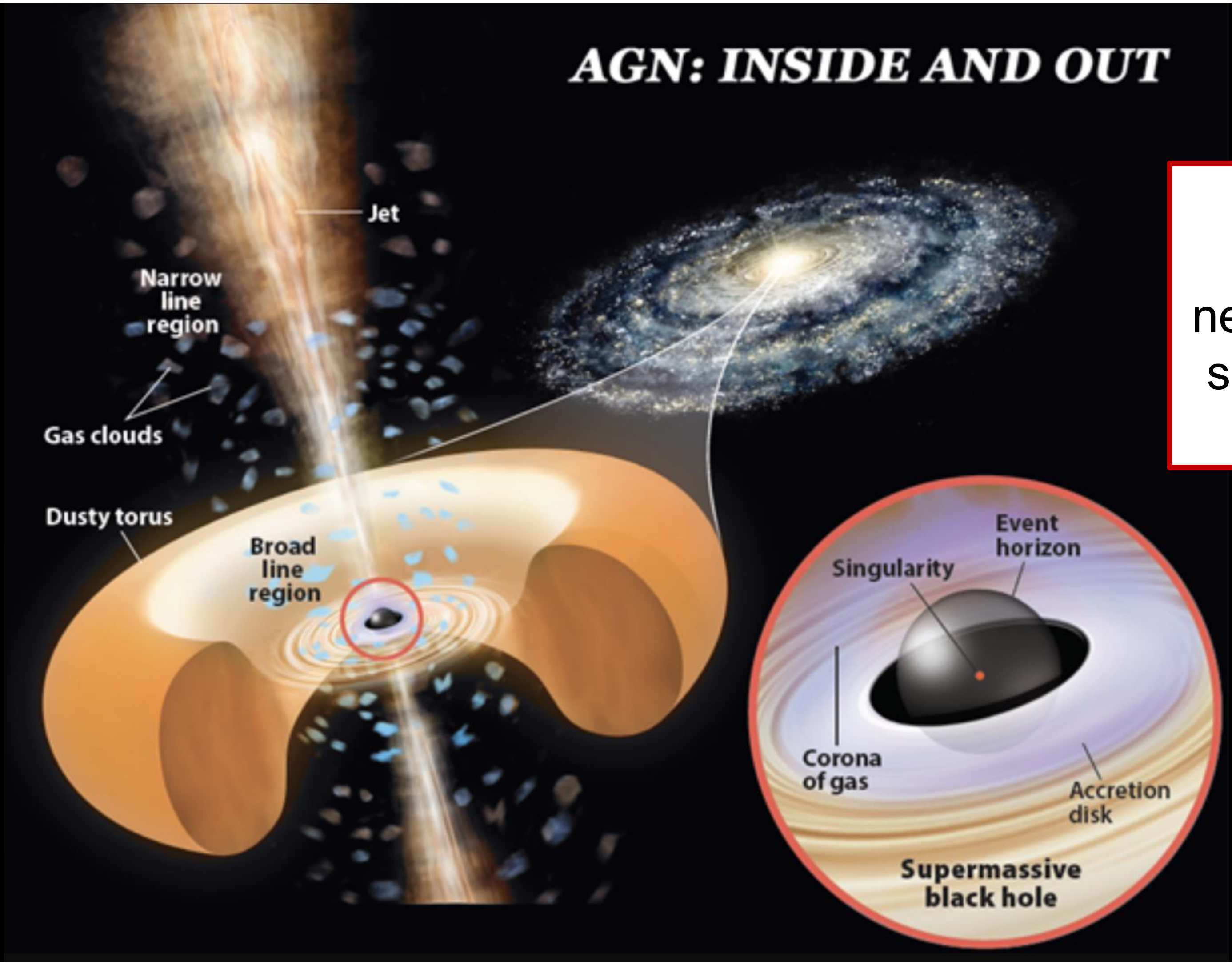
IceCube Science 378 (2022)

Complete Multi-wavelength data of NGC 1068



Gamma rays need to be absorbed

IceCube Science 378 (2022)

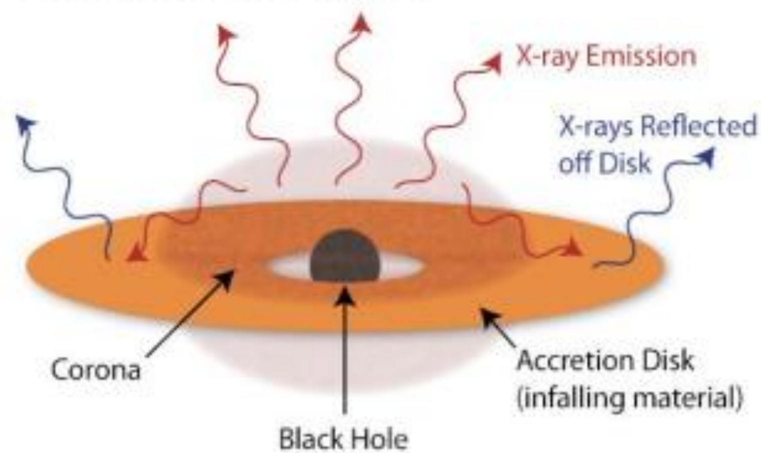


Lack of gamma rays places neutrino production site in the heart of the galaxy

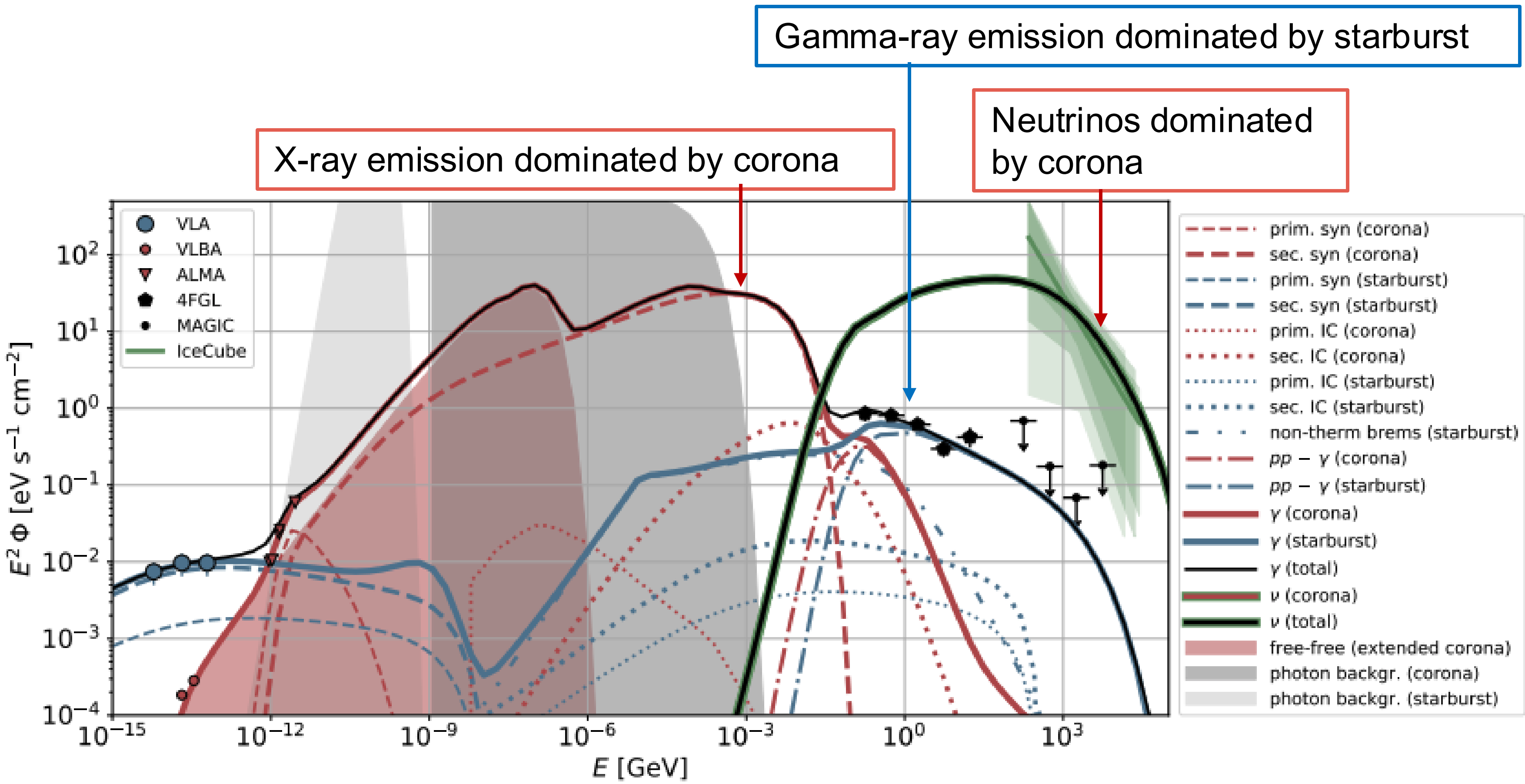
What is the corona?

- region of very **hot plasma (10^8–10^9 K)** close to accretion disk (few **gravitational radii)**
- Accretion disk emits thermal **optical/UV photons**.
- In the corona: low-energy photons undergo **inverse Compton scattering** with energetic electrons → **X-rays**
- X-ray emission is observe in AGN spectra (**power-law component**)
- X-ray flux changes on timescales of hours to days → consistent with a **very compact region**

credit: D. Wilkins



Detailed Modeling of Starburst-AGN Composite

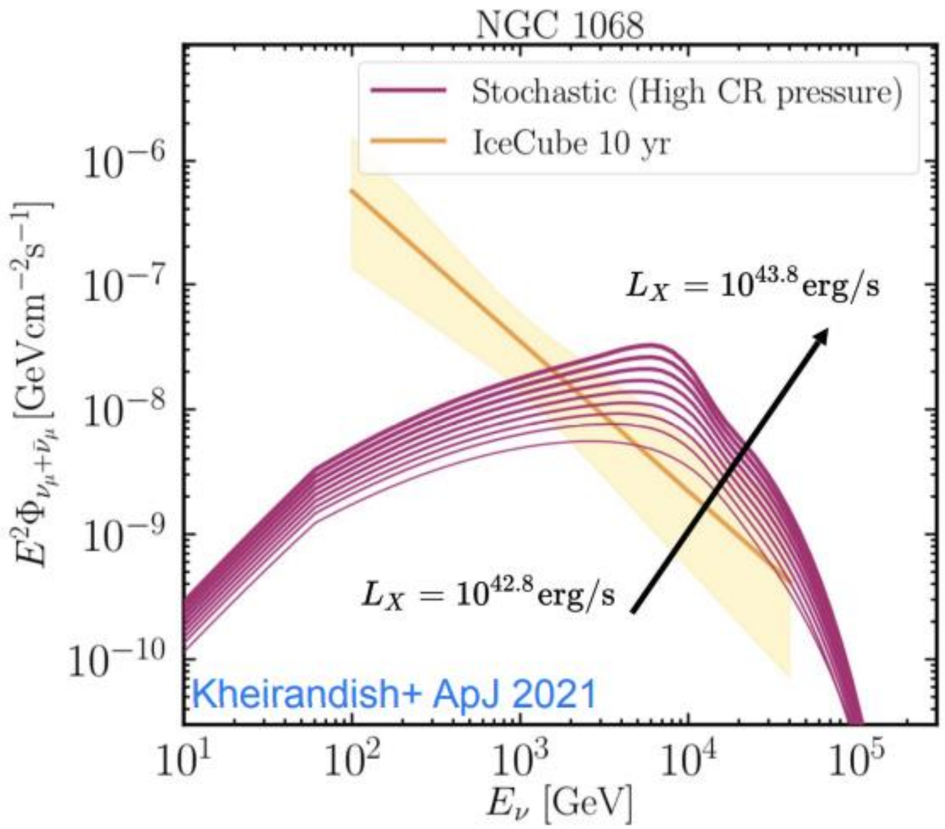


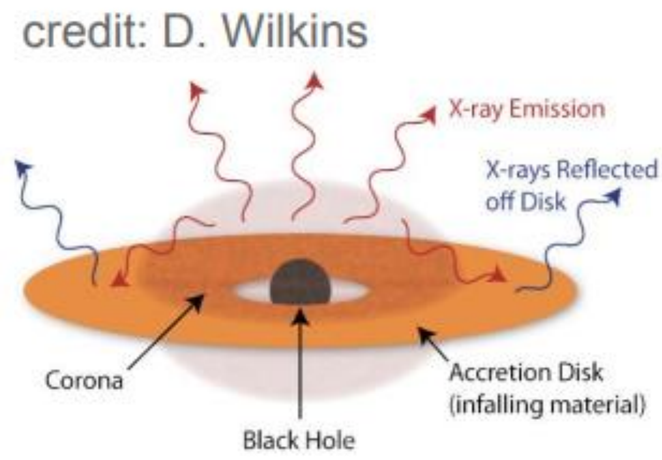
Eichmann ApJ 939 (2022) 43

RUB

More Seyferts?

Assumption: Neutrino flux scales with intrinsic X-ray flux (2–10 keV)





IceCube arXiv:2406.07601

Stacking Search

- Use catalog of sources (here: Seyferts)
- Assume neutrino spectral shape (often power-law, here: disk corona model prediction)
- Assume weighting scheme between neutrino sources (here: neutrino flux follows X-ray flux)

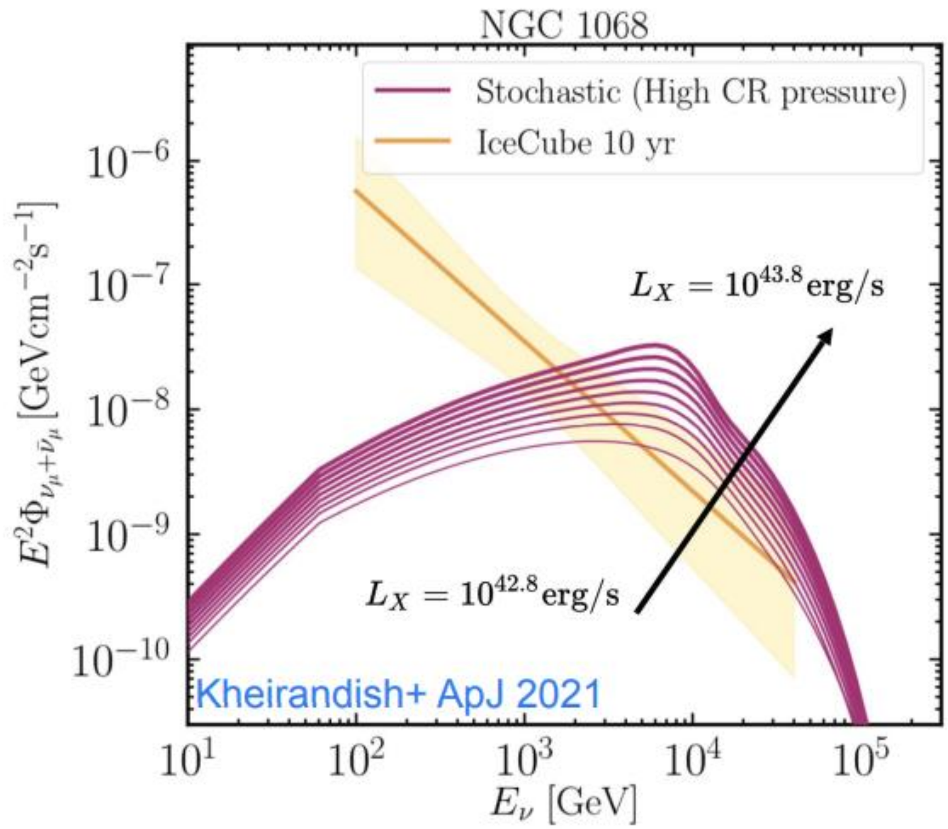
→ only one fit parameter for entire population: overall normalization

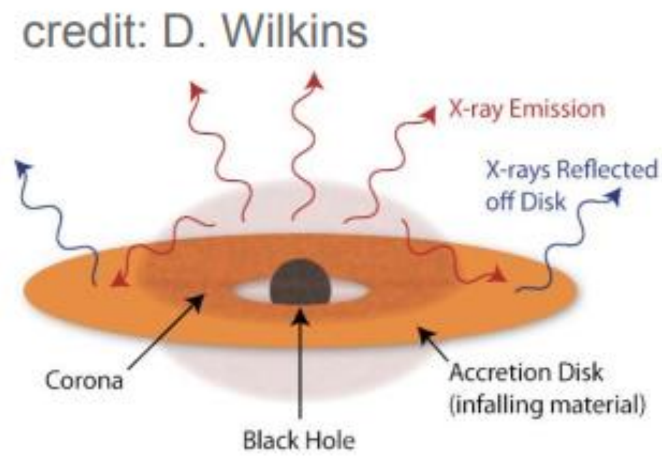
Potential problem: if assumption (weighting) does not hold, sensitivity is reduced

Alternative: fit each individually and combine results with binomial test

More Seyferts: Stacking results

Assumption: Neutrino production in disk corona, intrinsic X-ray flux (2–10 keV) as proxy for neutrino emission



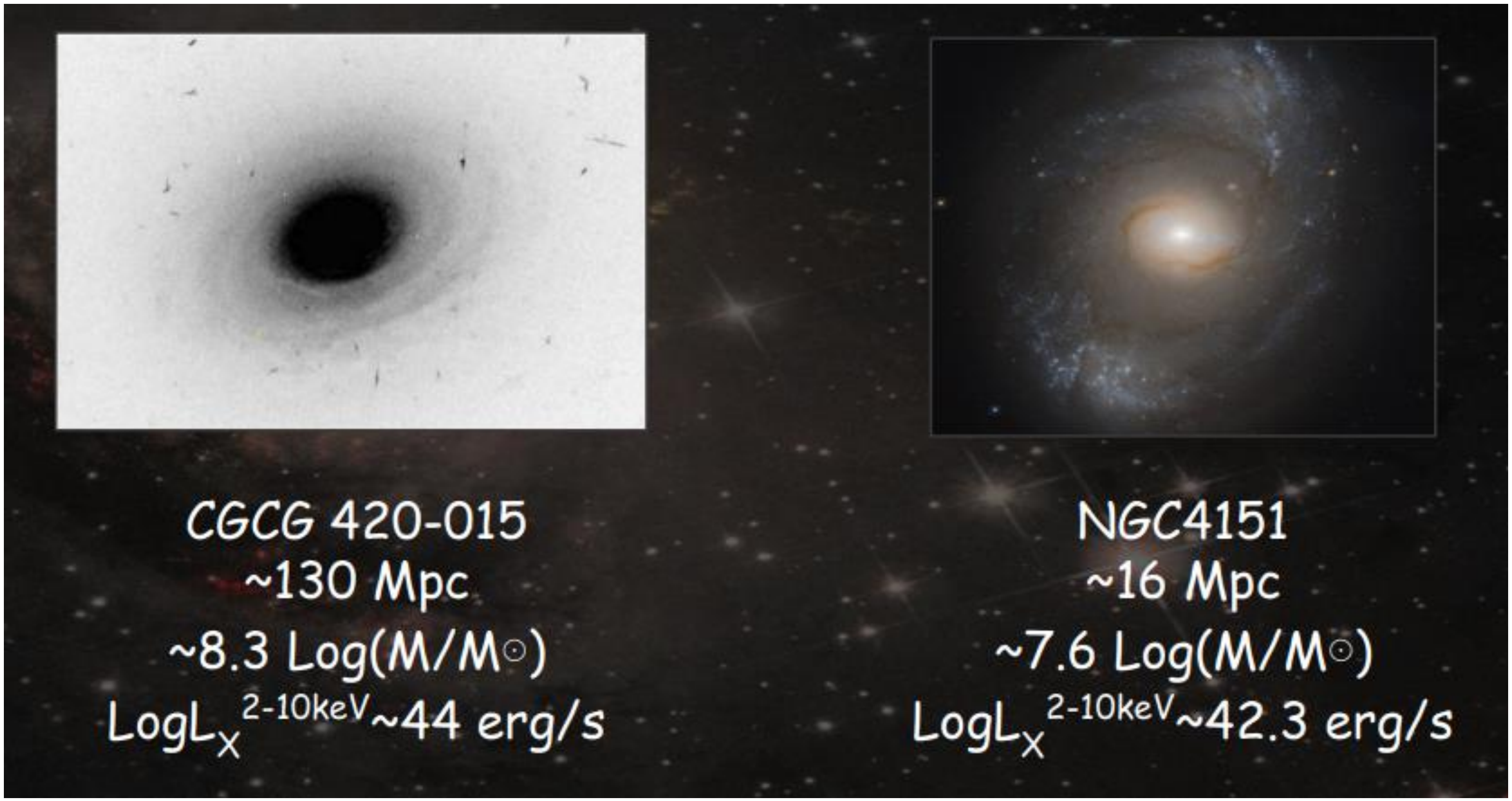


No significant emission is found in the stacking search excluding NGC 1068.

IceCube arXiv:2406.07601

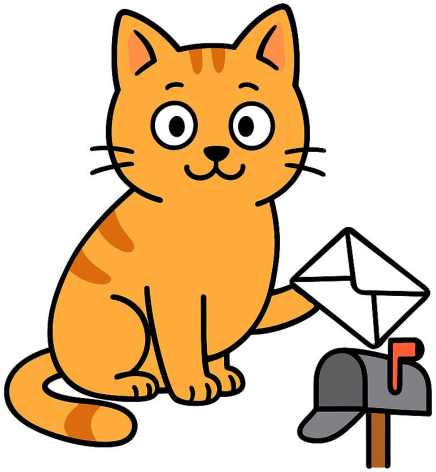
More Seyferts: Individual sources

No assumption about neutrino emission model



Two more source candidates at 2.5σ and 2.1σ level

IceCube *ApJ.* 988 (2025) , see also Neronov et al. PRL 132 (2024)

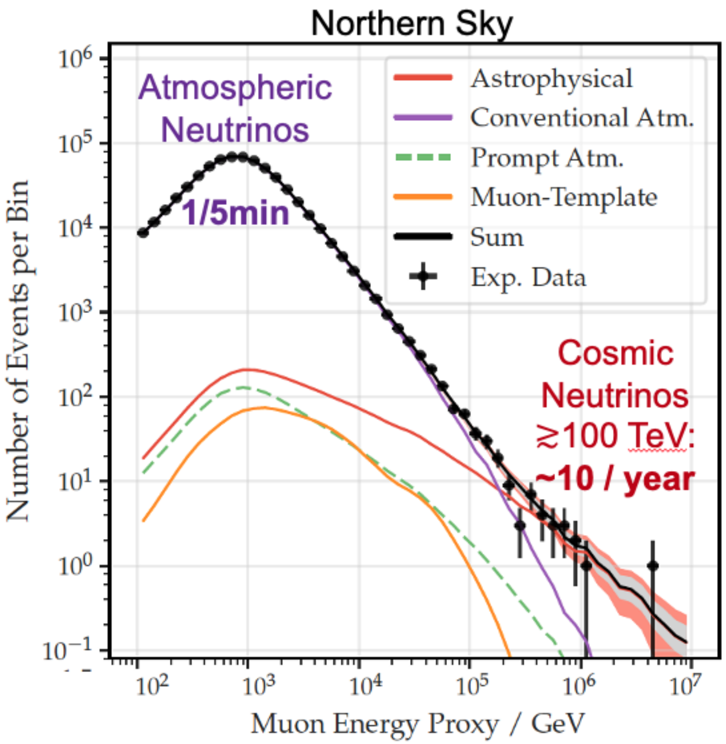


Take home message

Seyferts are currently the most promising neutrino source class.

However, it seems we do not fully understand their emission processes.

Search for Extragalactic Sources: Strategies



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IceCube Coll. ApJ 928 (2022) 50

Neutrinos as Triggers

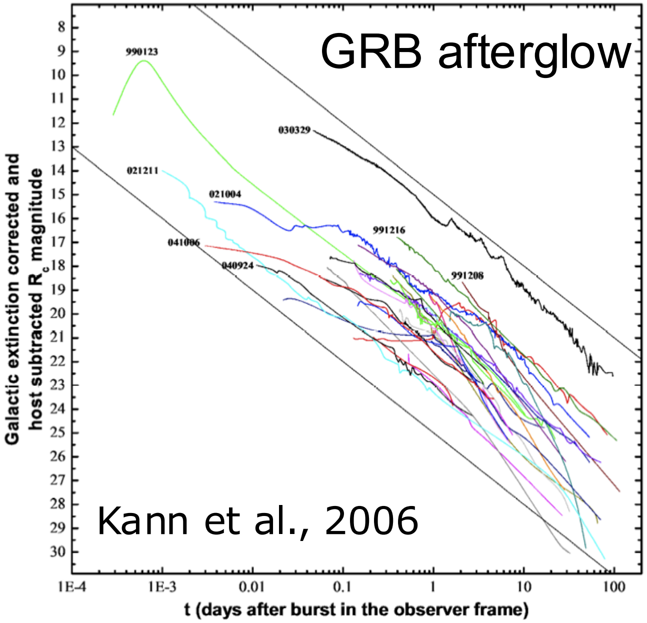
Public alerts since April 2016

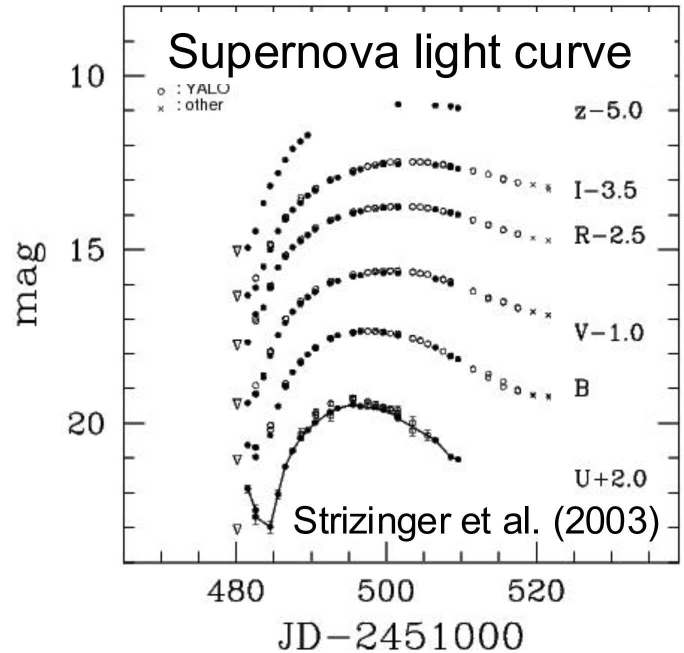
- Single high-energy muon track events (> ~100TeV)
- “Gold” alert stream: 10 / yr, ~5 / yr of cosmic origin
- Median latency: 30 sec

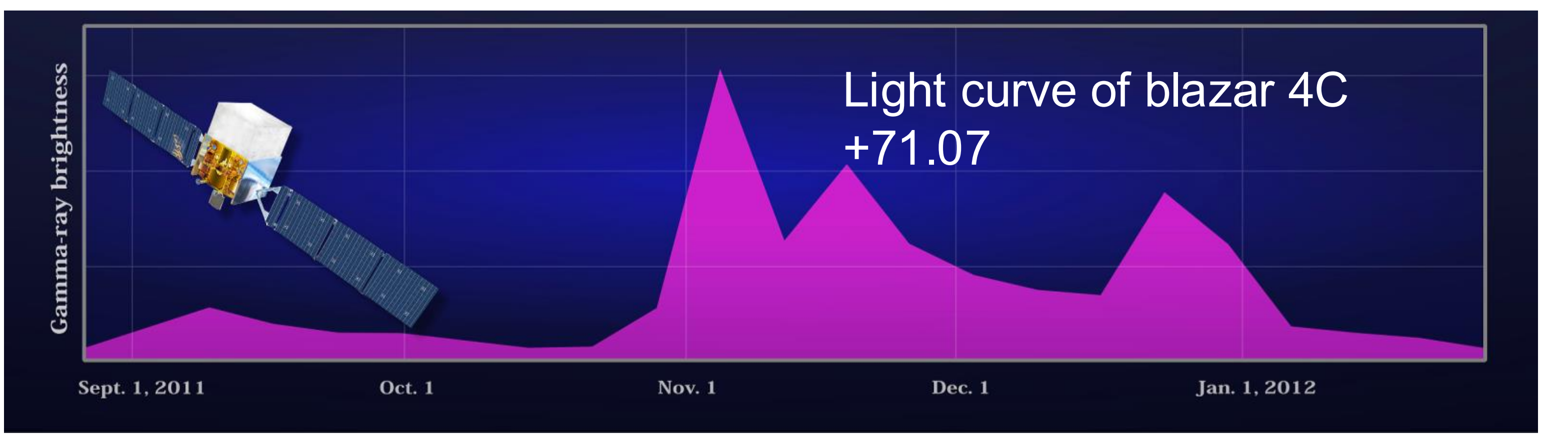
Goal: Find electromagnetic counterpart

Astropart. Phys., 92, 30 (2017)

Expected EM Counterparts

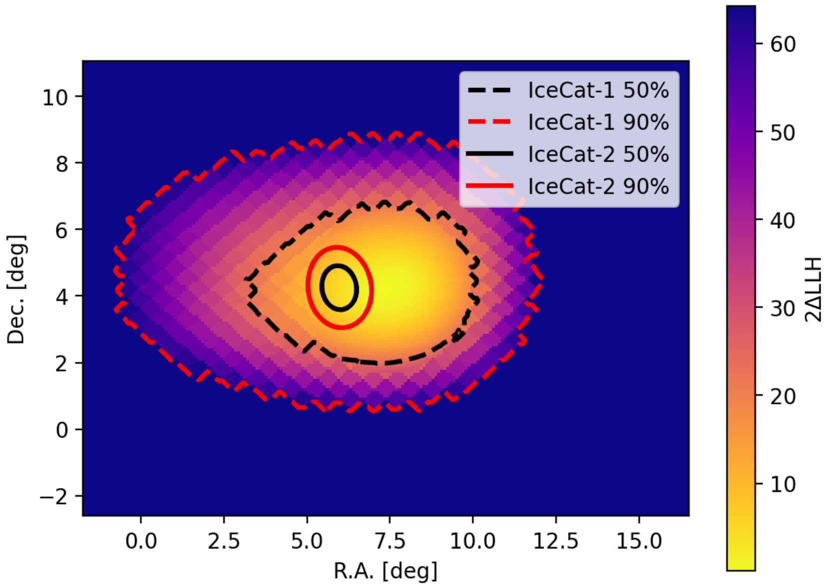


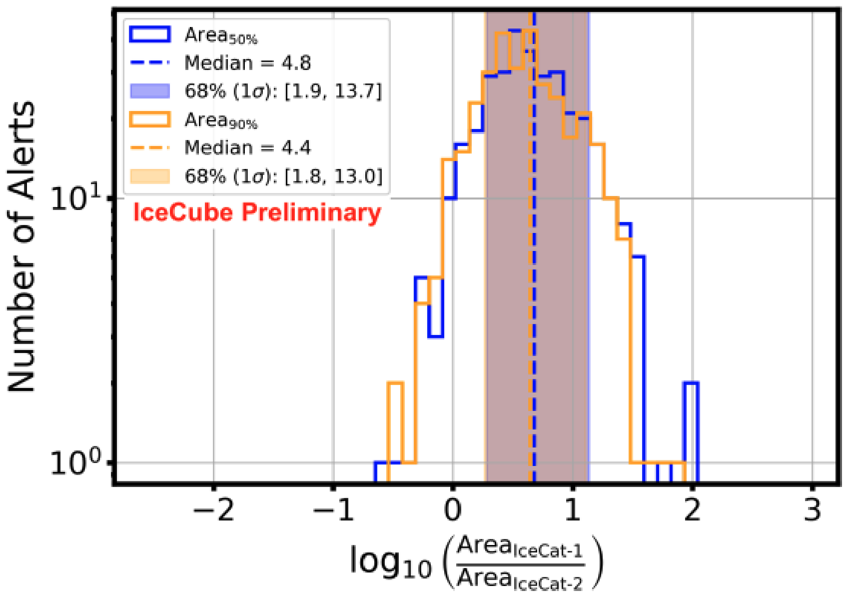




RUB

IceCat-2



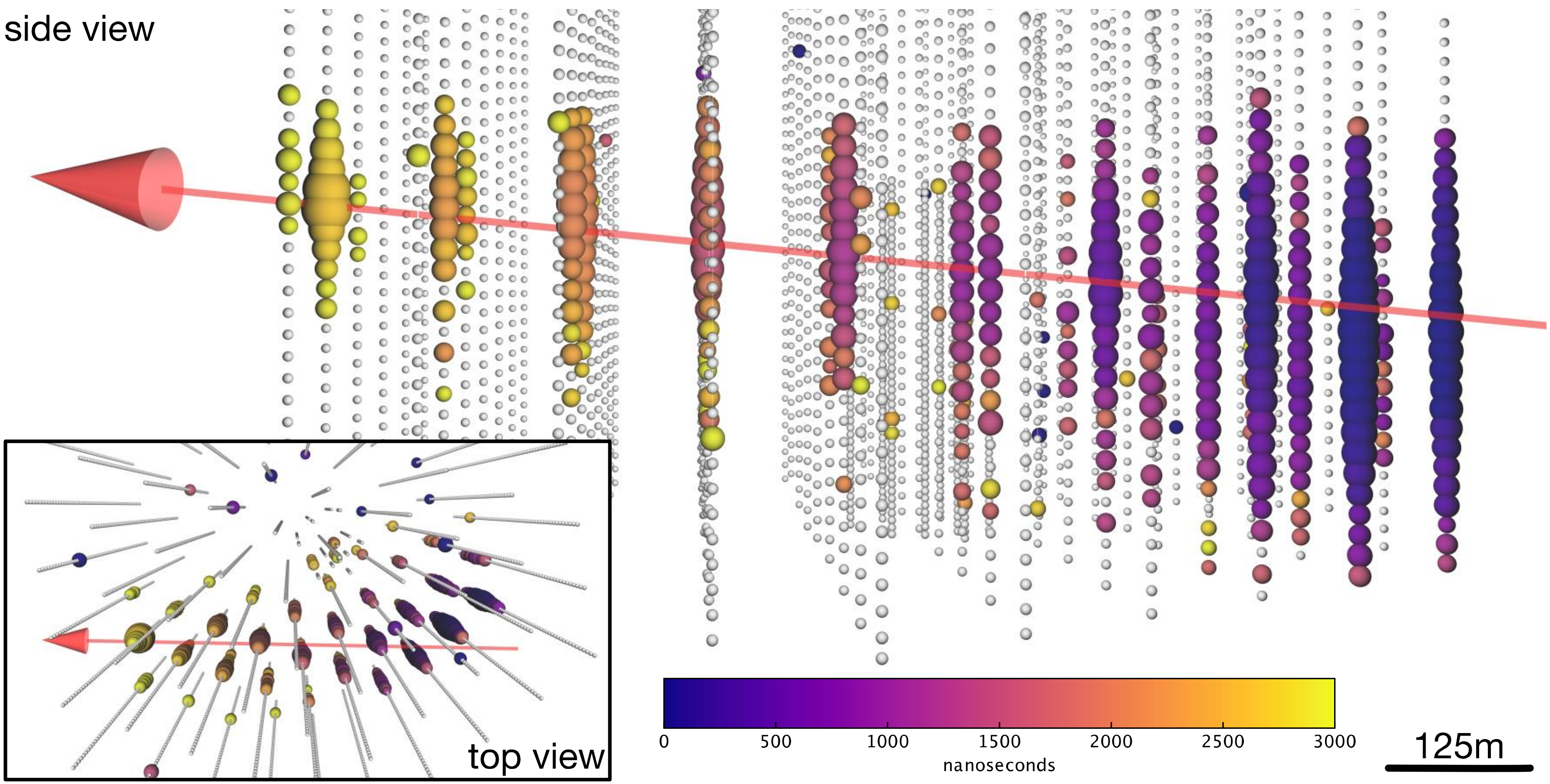


Improvement in 90% uncertainty area of factor 4.4

Archival alert catalog (IceCat-2) under development

A. Zegarelli for IceCube, ICRC 2025, arXiv:2507.06176

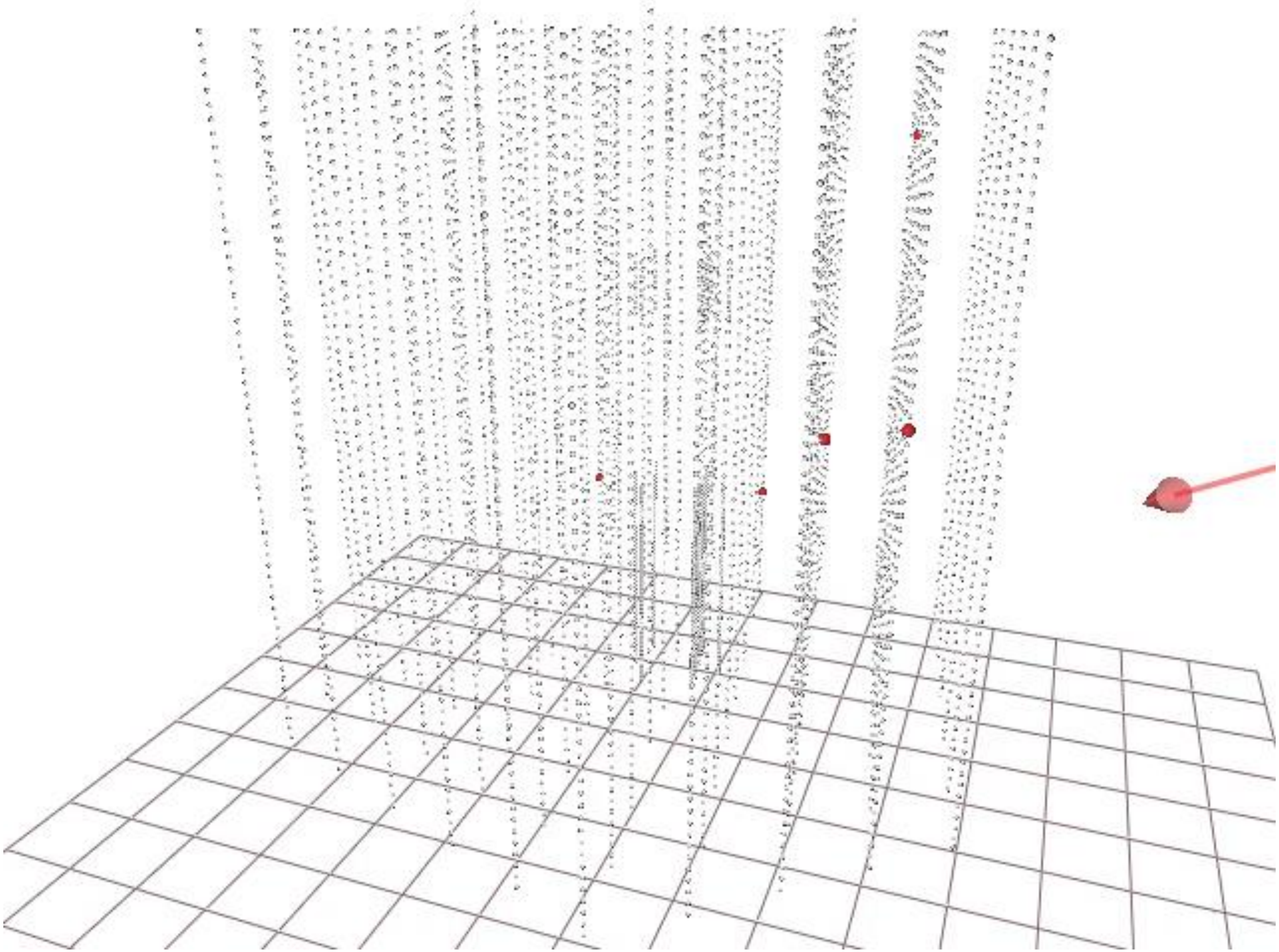
First example: IC-170922A – a 290 TeV Neutrino



Signalness: 56.5%

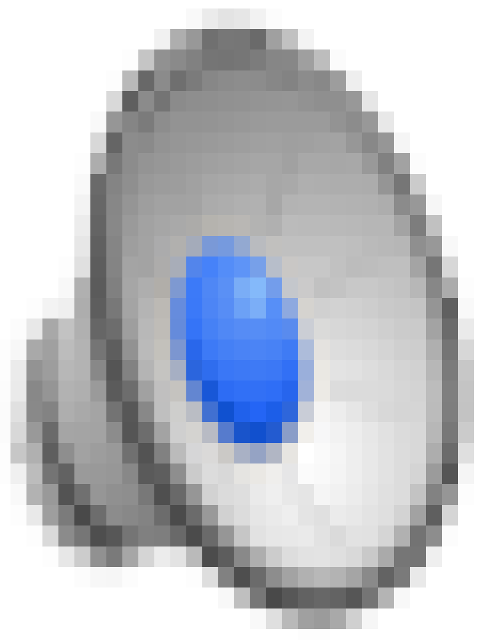
IceCube, Fermi-LAT, MAGIC, AGILE, ASAS-SN, HAWC, H.E.S.S, INTEGRAL, Kapteyn, Kanata, Kiso, Liverpool, Subaru, Swift, VERITAS, VLA, Science 2018

IC-170922A – a 290 TeV Neutrino



IceCube, Fermi-LAT, MAGIC, AGILE, ASAS-SN, HAWC, H.E.S.S, INTEGRAL, Kapteyn, Kanata, Kiso, Liverpool, Subaru, Swift, VERITAS, VLA, Science 2018

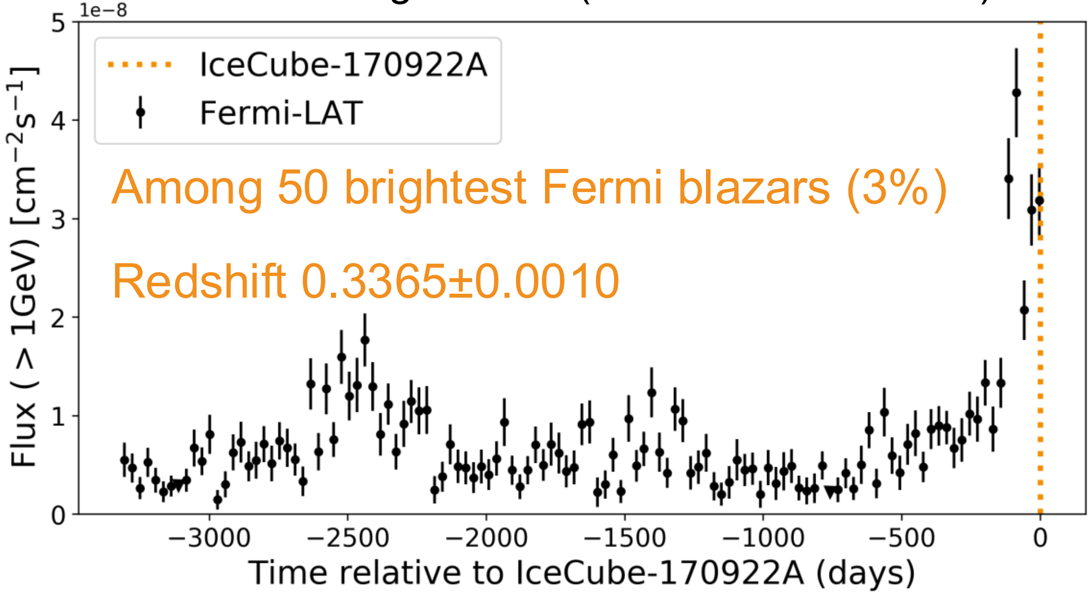
Fermi-LAT finds Flaring Source

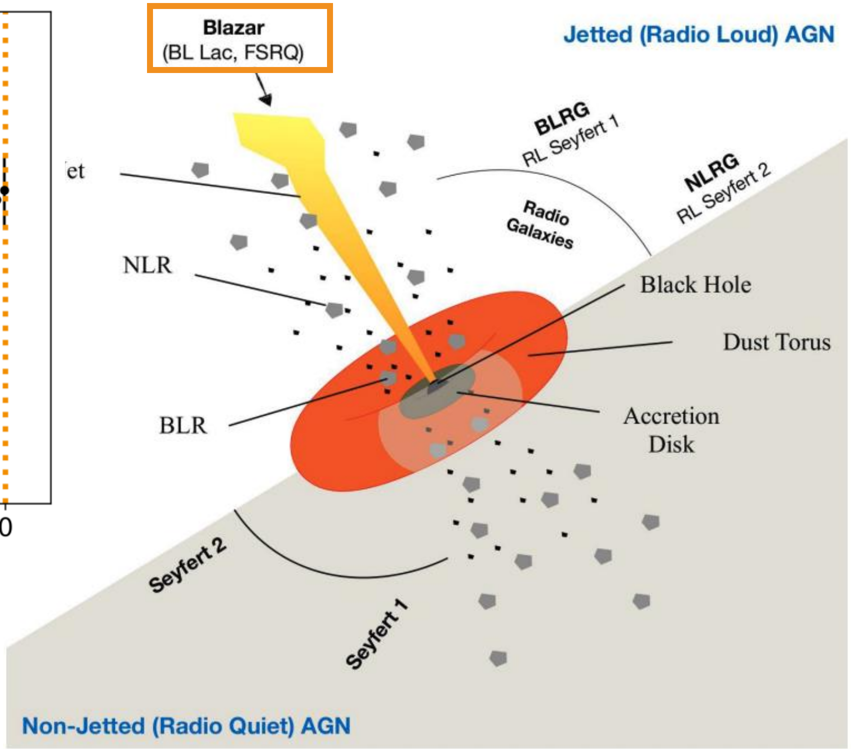


Fermi-LAT Coll., ApJ 846, 2017, Video credits: Matteo Giomi, Fermi-LAT Collaboration

Fermi-LAT finds Flaring Blazar, TXS 0506+056

Fermi-LAT light curve (100 MeV – 300 GeV)





RUB

Fermi-LAT finds Flaring Blazar, TXS 0506+056

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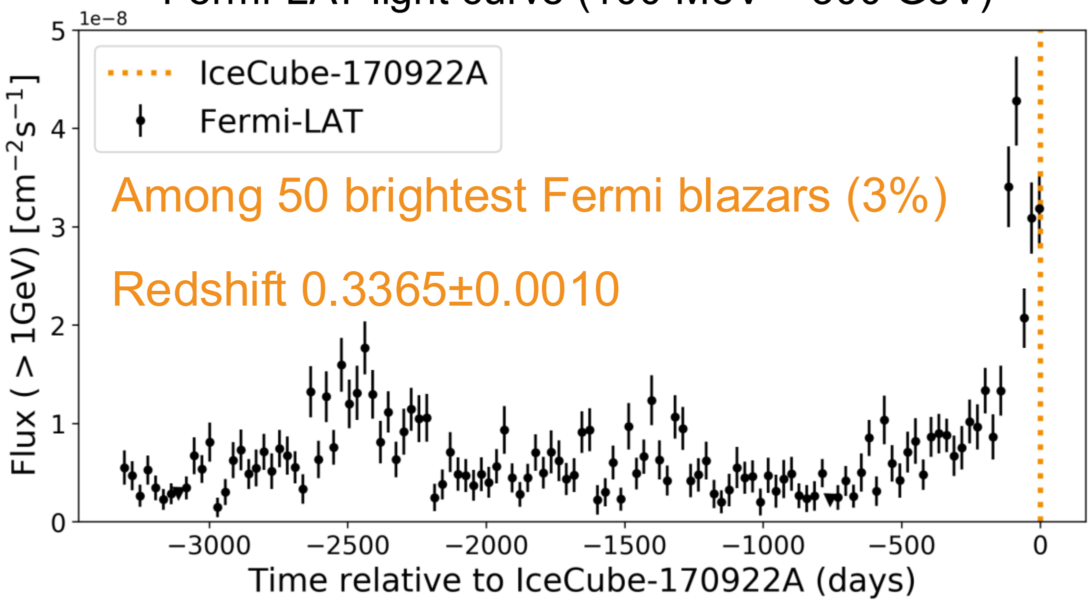
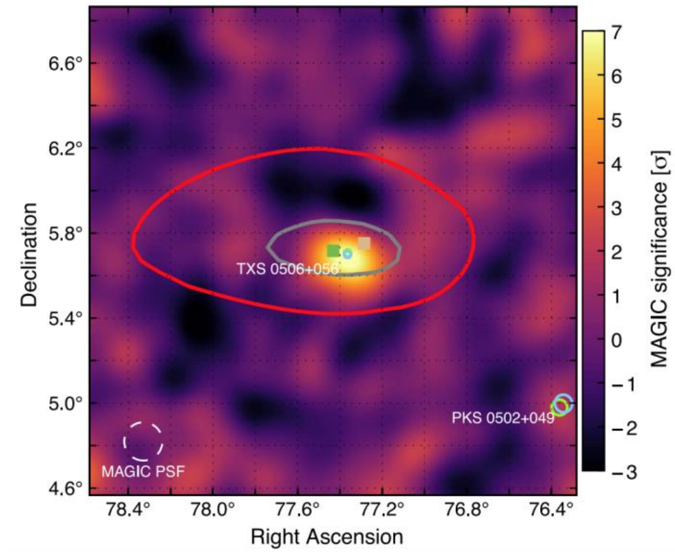


MAGIC Significance map:
TeV gamma rays



RUB

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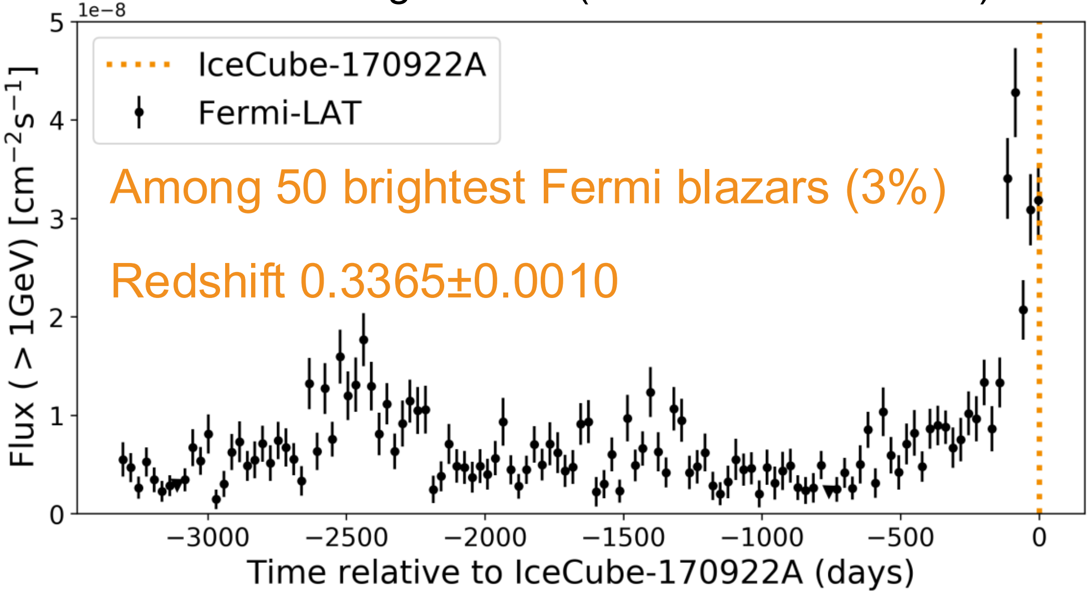

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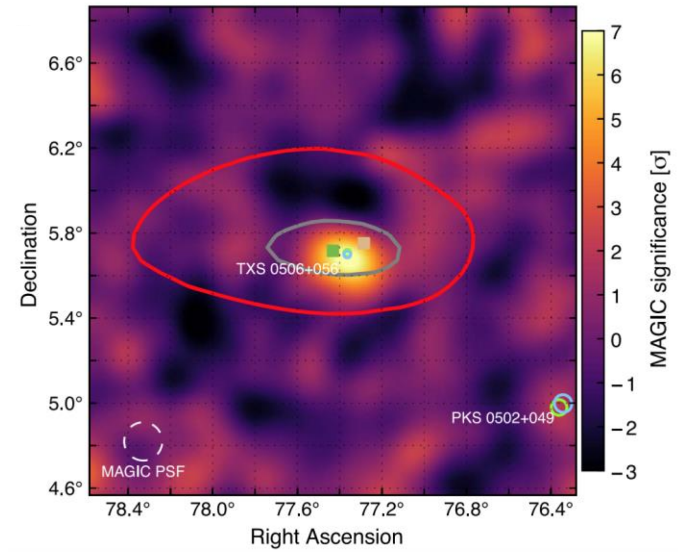
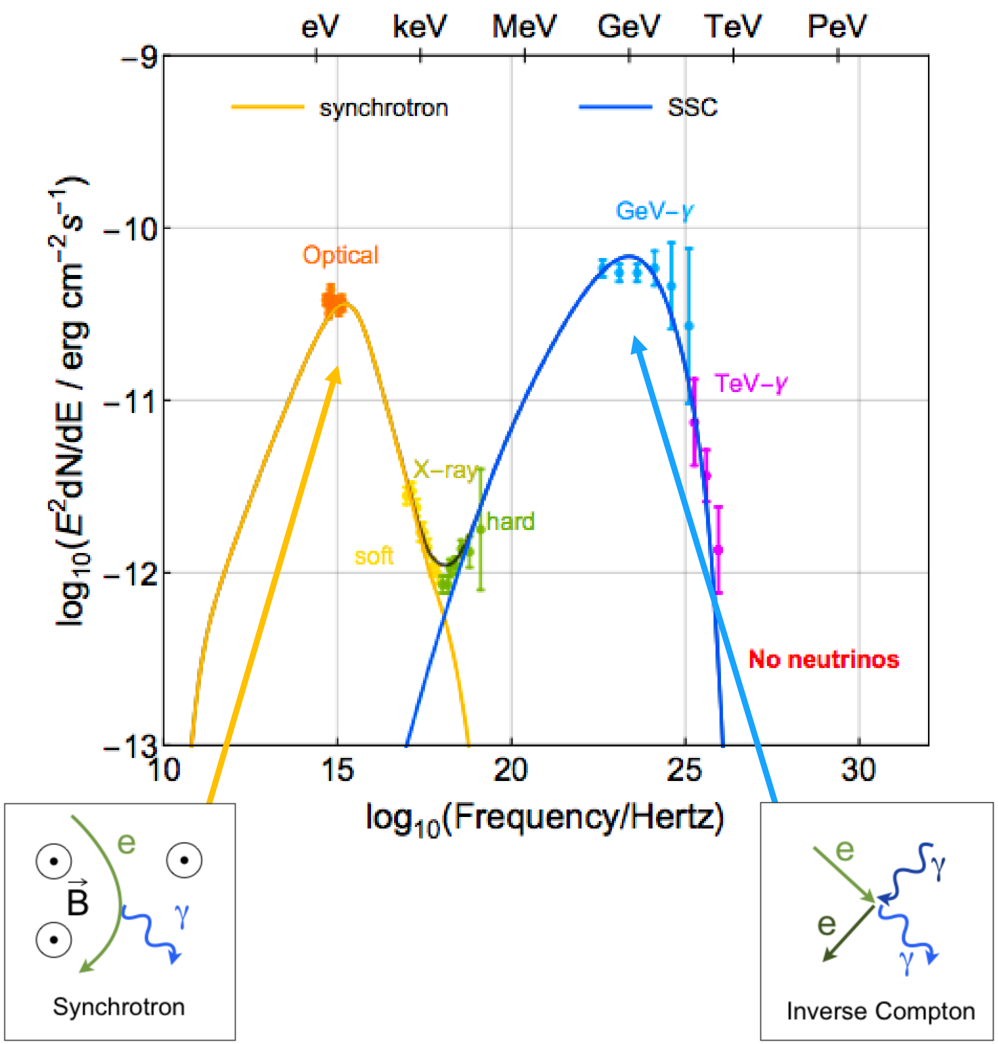


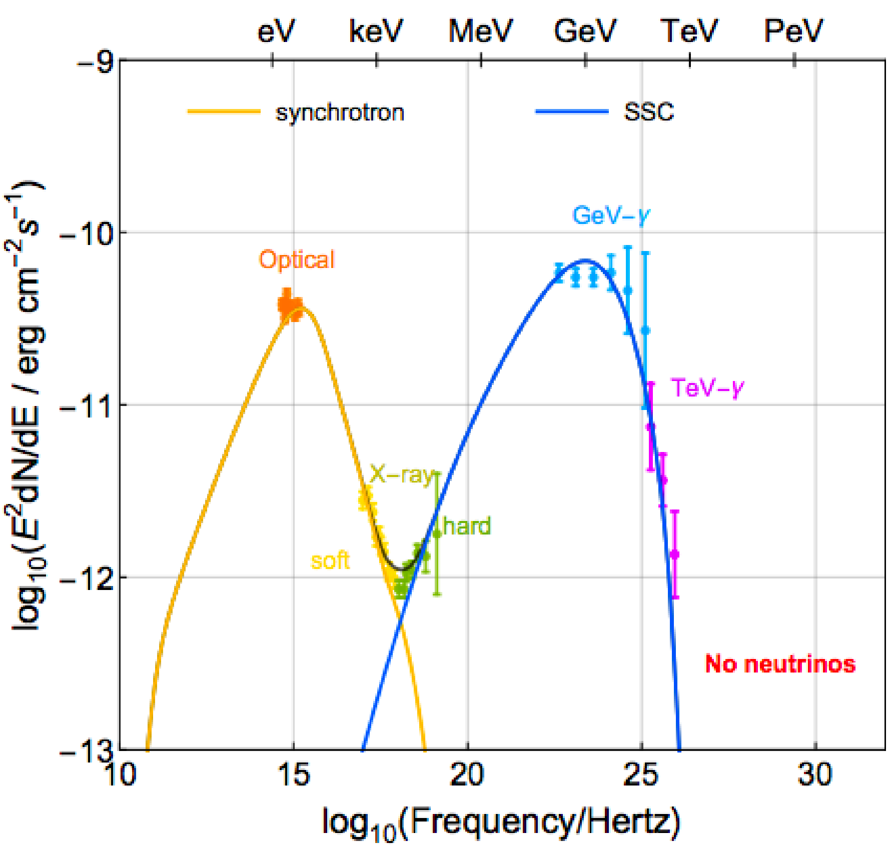
3 sigma significance including trials
> 6 PeV protons accelerated in the source

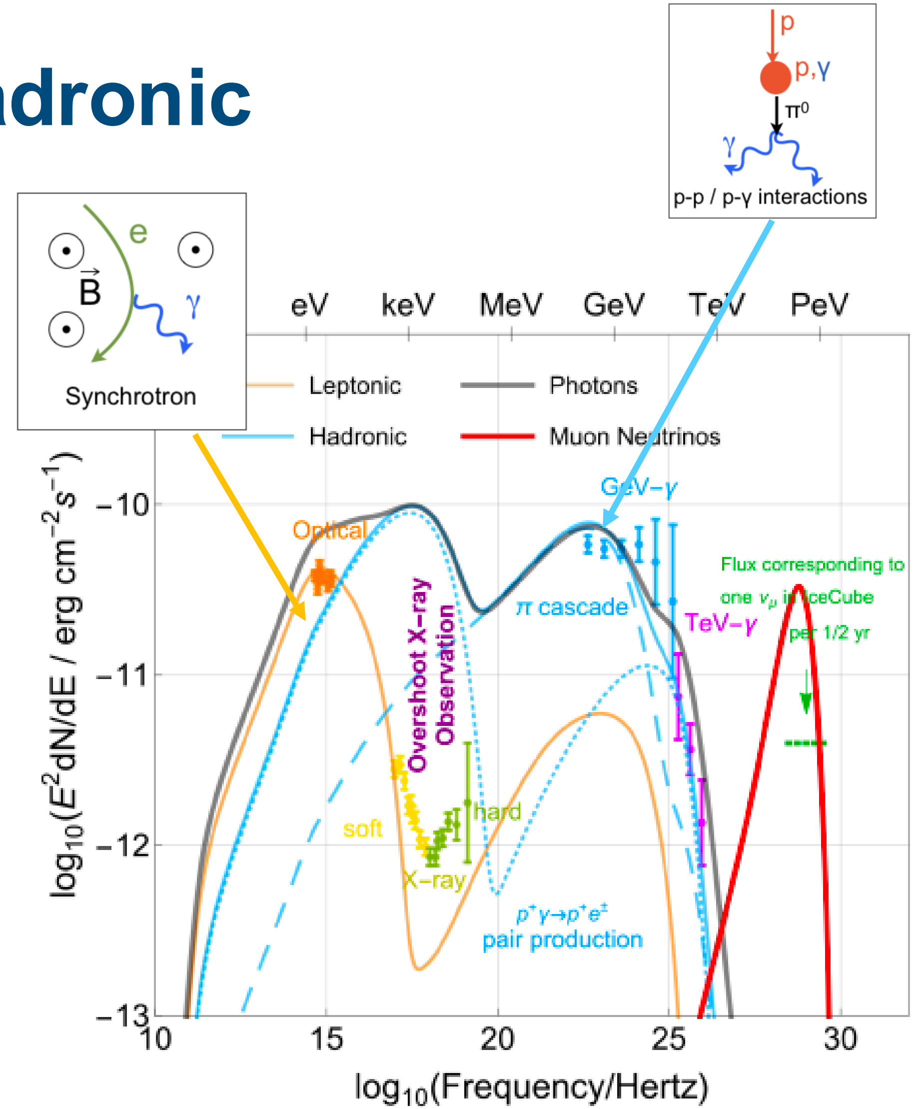
Modeling – leptonic



Gao et al., Nature Astronomy 2018,
Keivani et al., ApJ, 2018, MAGIC Coll., ApJ, 2018, Cerruti et al. MNRAS 2018, …

Modeling – leptonic, hadronic

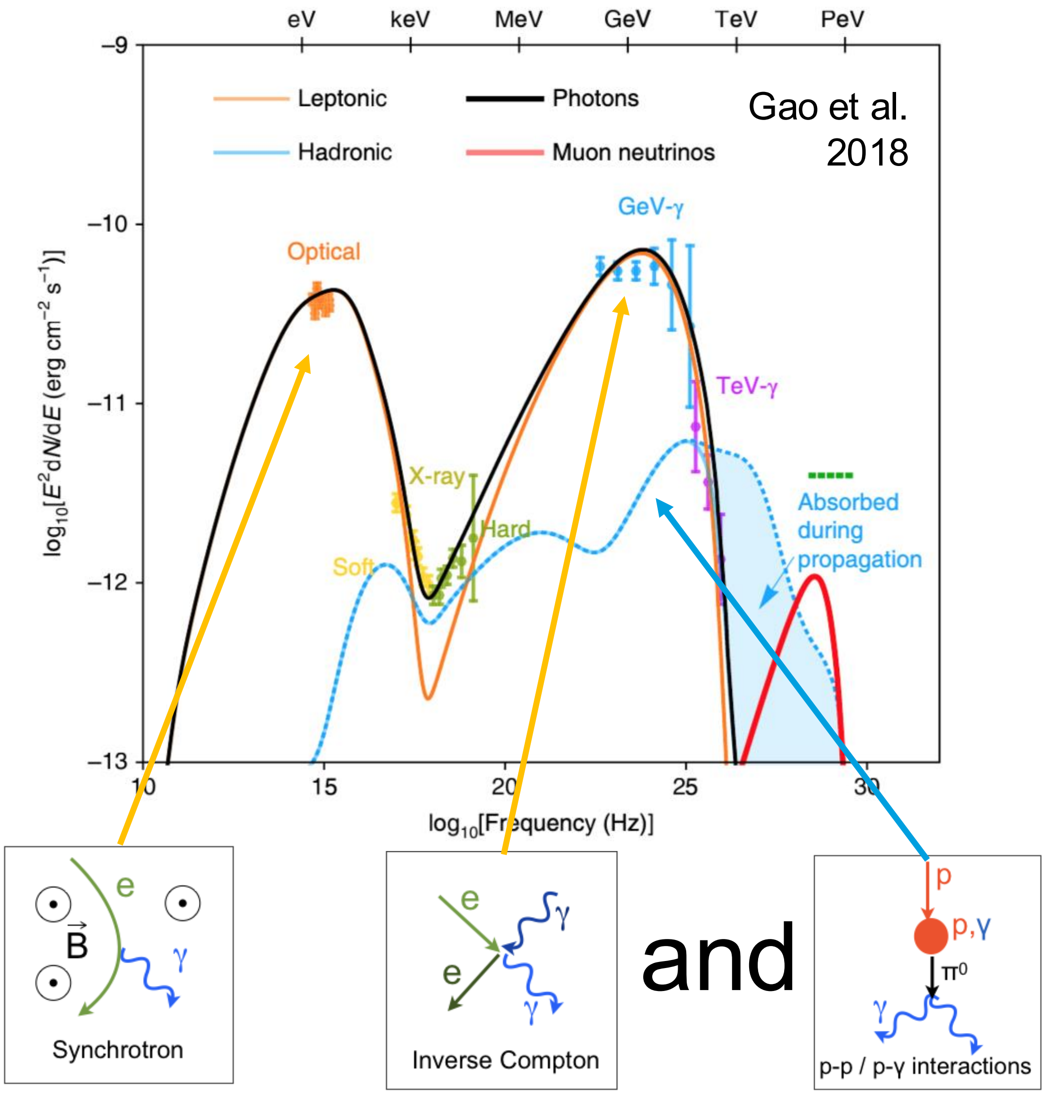




Simple one-zone hadronic models violate X-ray constraints
→ More complex models needed

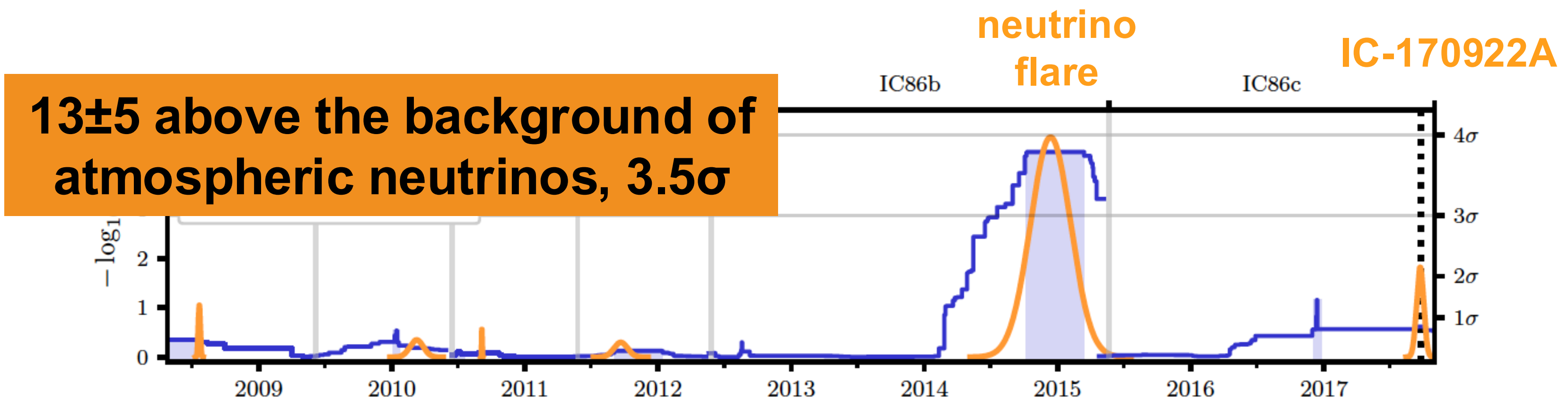
Gao et al., Nature Astronomy 2018,
Keivani et al., ApJ, 2018, MAGIC Coll., ApJ, 2018, Cerruti et al. MNRAS 2018, …

Modeling – lepto-hadronic



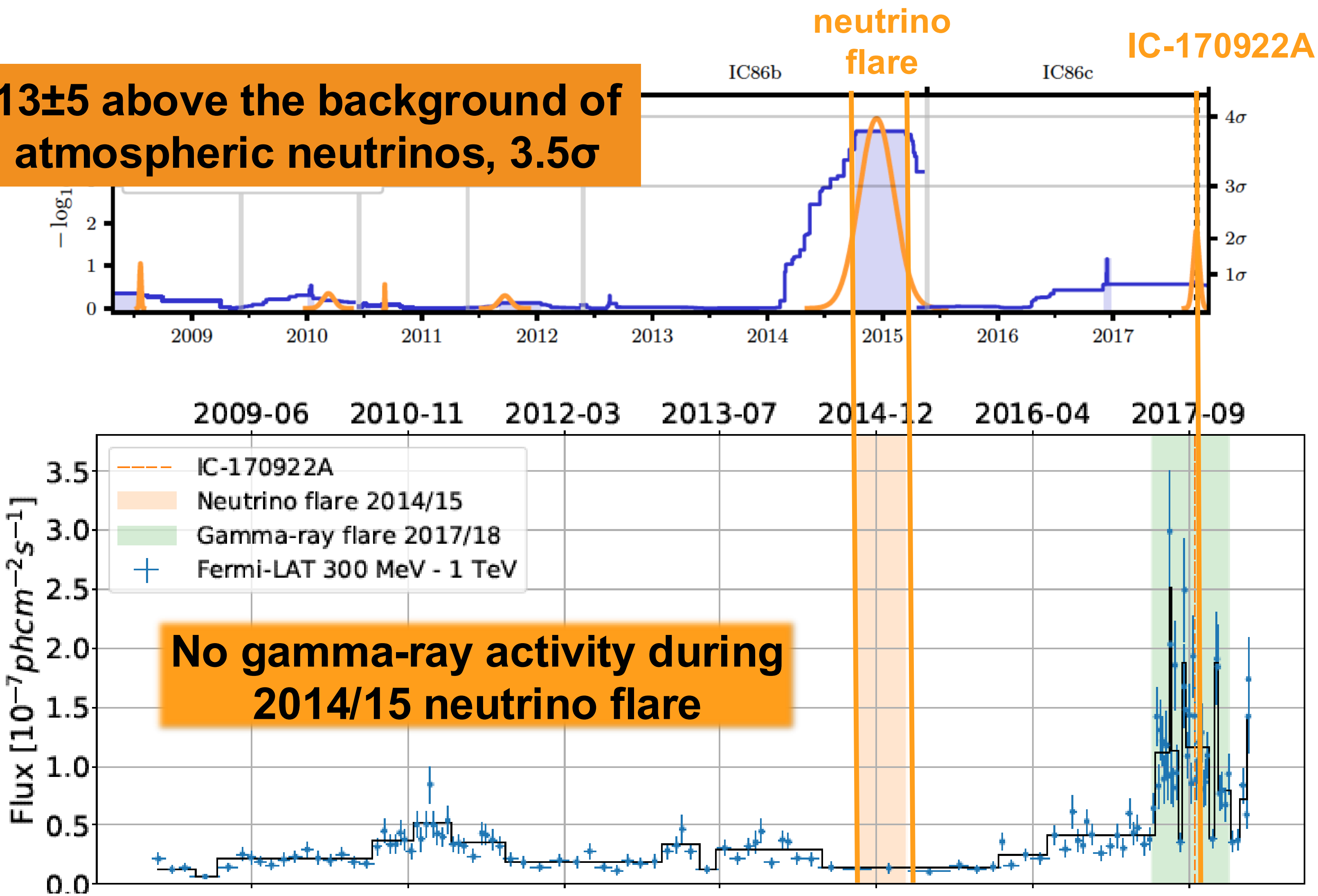
Gao et al., Nature Astronomy 2018,
Keivani et al., ApJ, 2018, MAGIC Coll., ApJ, 2018, Cerruti et al. MNRAS 2018, …

Are there more Neutrinos from this Source?



IceCube, Science 361, 2018

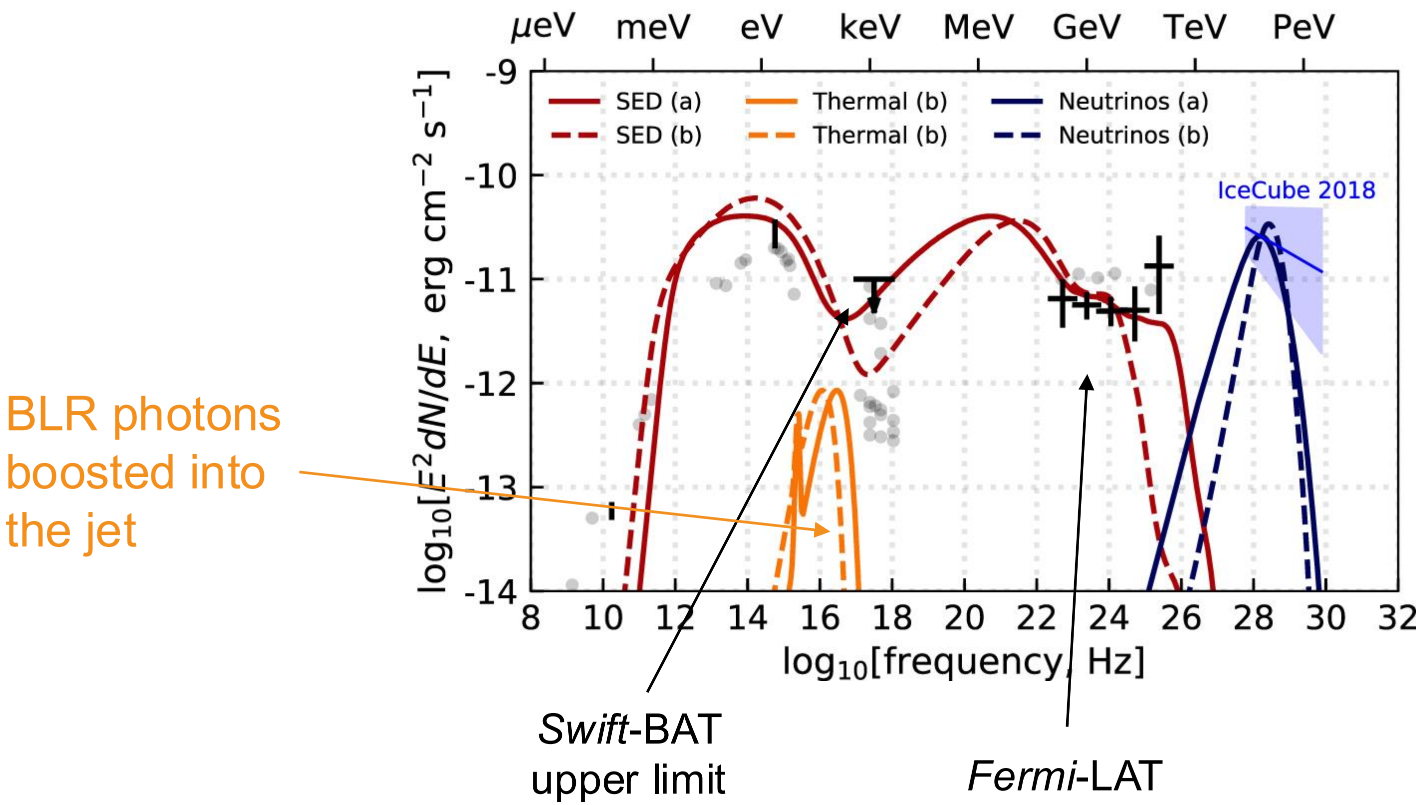
Is there also a Gamma-ray Flare?



IceCube, Science 361, 2018, Garrappa et al. ApJ 880 2019, Padovani et al. MNRAS 480 2019

Modeling of 2014/15 neutrino flare

neutrino luminosity is ~4 times higher than gamma-ray luminosity
→ **challenge for models**



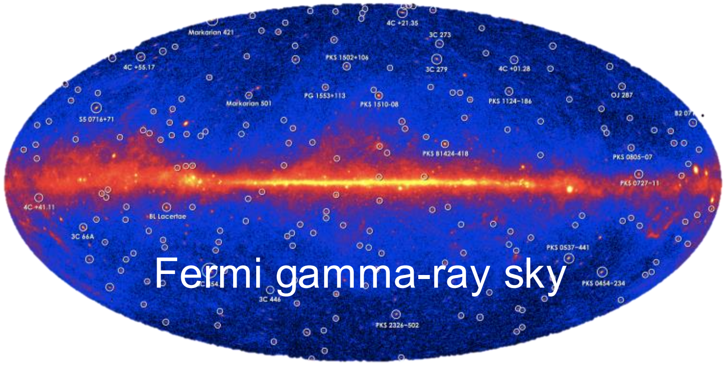
see e.g. Rodrigues et al. ApJL 874 2019, A. Reimer et al. ApJ 881 2019, F. Halzen et al. ApJL 874 2019

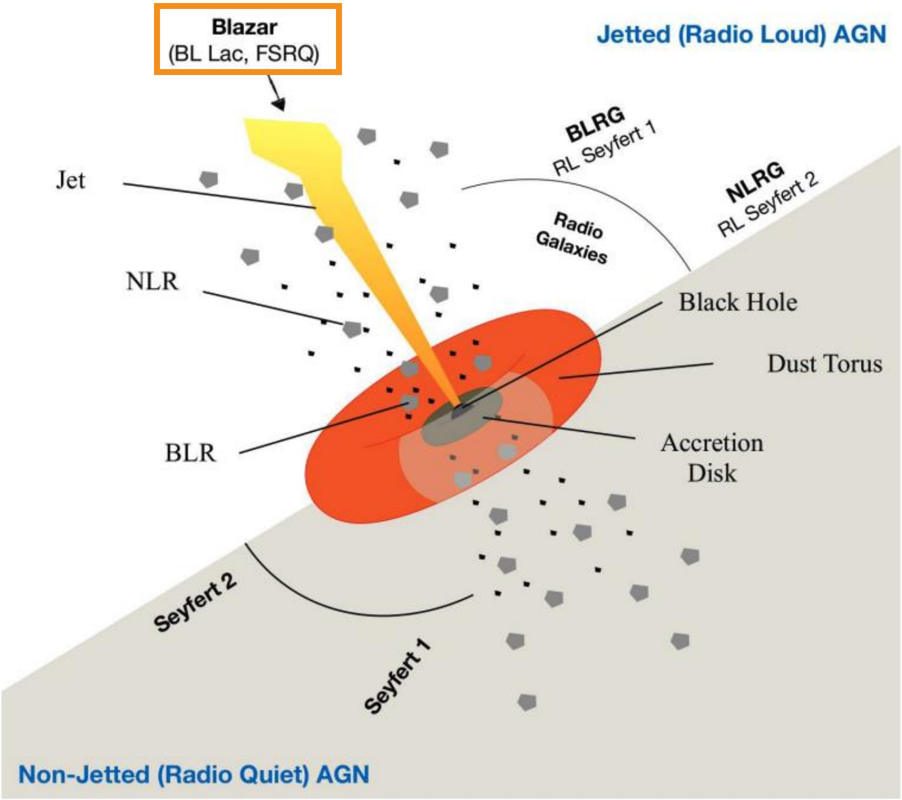
RUB

Do gamma-ray blazars produce all diffuse neutrinos?

Fermi Blazars

Gamma rays tell us **where** to look for neutrinos





Fermi Blazars

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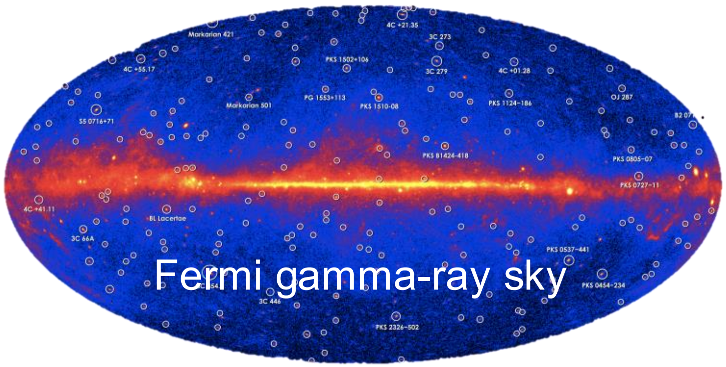
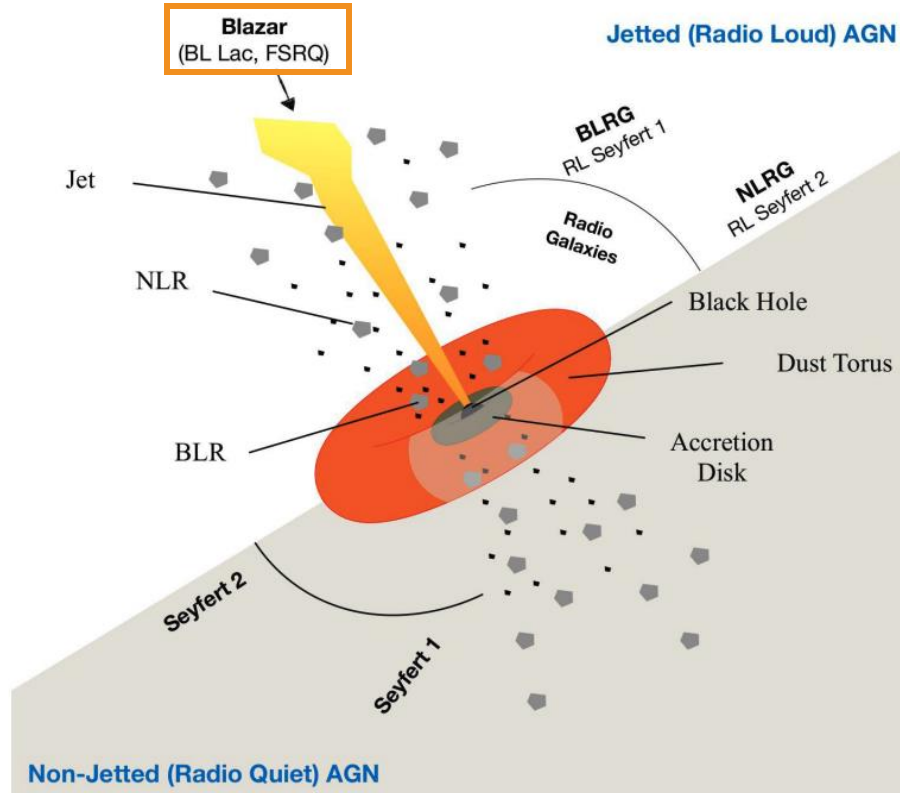




Correlation study of 12 years of IceCube data and 2089 ***Fermi*-LAT blazars**

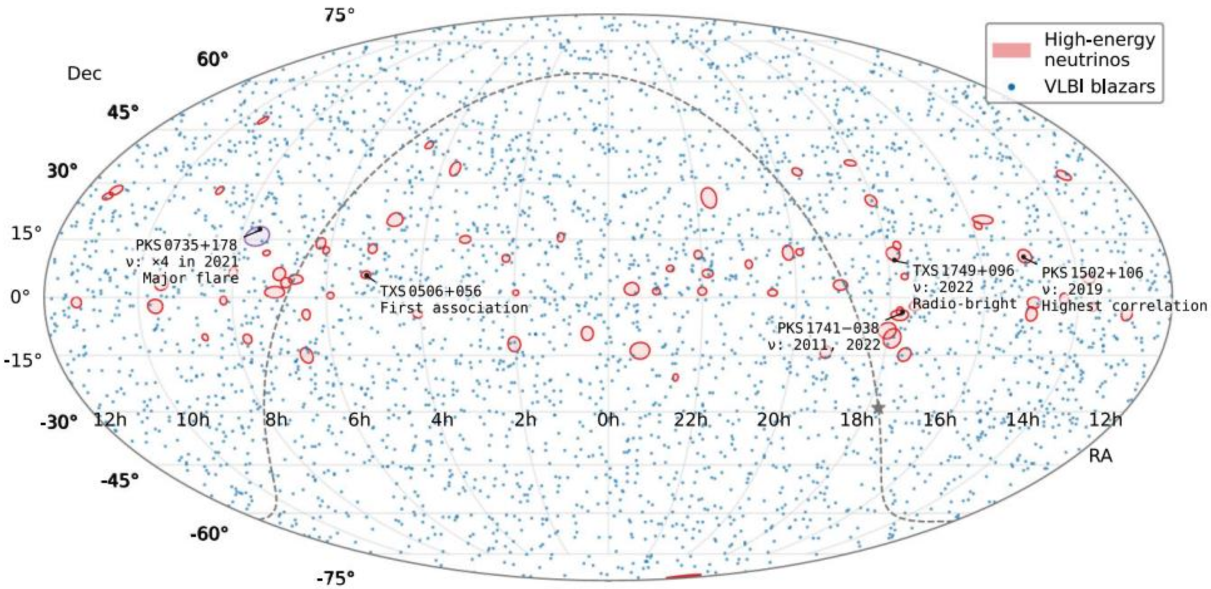
***Fermi*-LAT blazars** can only be responsible for a **small fraction** of the observed ν's.

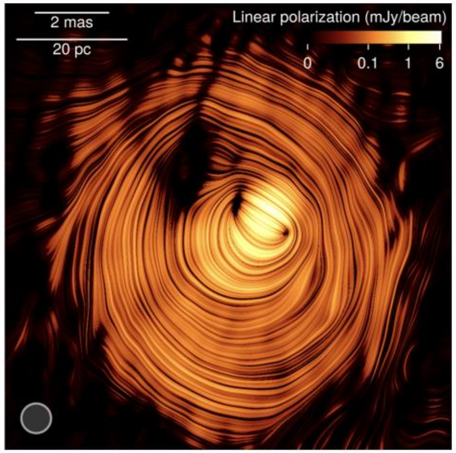
IceCube Coll. ApJ 954 (2023) 1, 75

Other wavelength as tracer for neutrinos from blazars?

Radio Core Brightness as Tracer

Correlation with VLBI-flux-density limited sample of blazars





Correlation of radio-bright blazars with IceCube neutrino alerts at chance coincidence of $3{\cdot}10^{-4}$

Plavin et al., ApJ 894 (2020), MNRAS 523 (2023), Kovalev et al. arXiv:2504.09287

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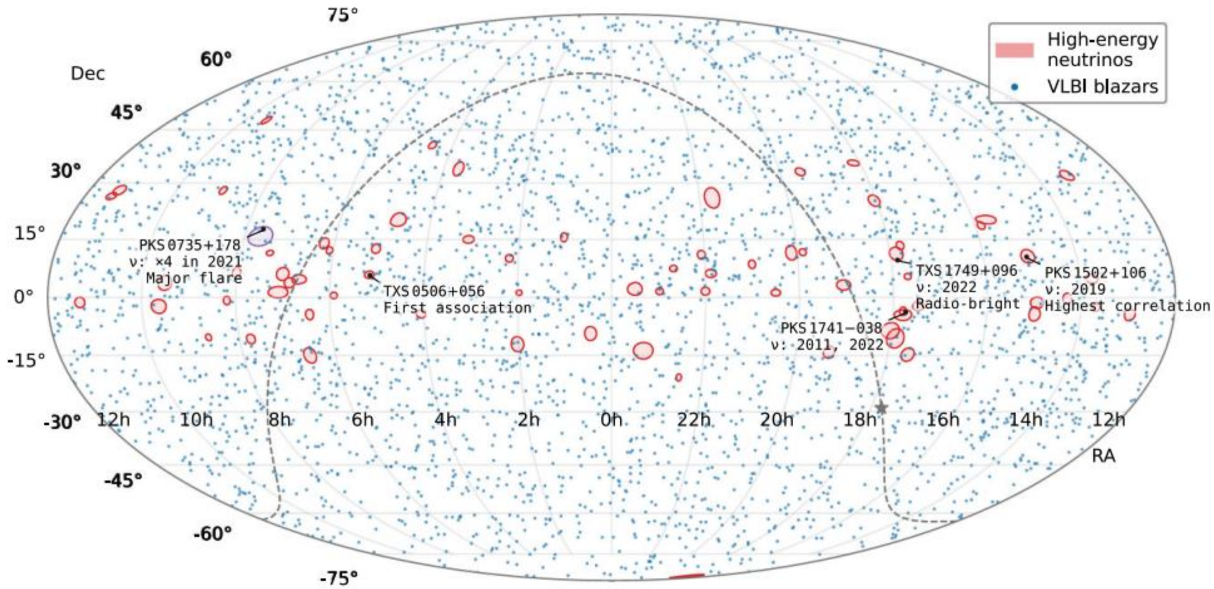
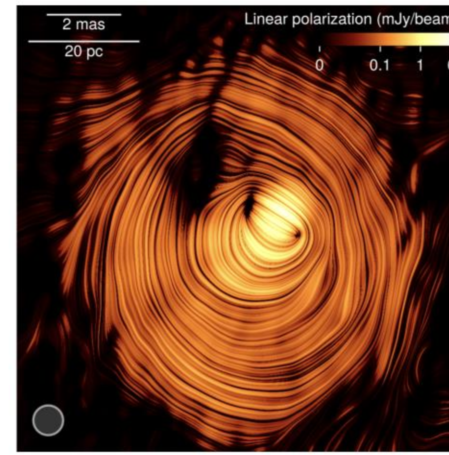
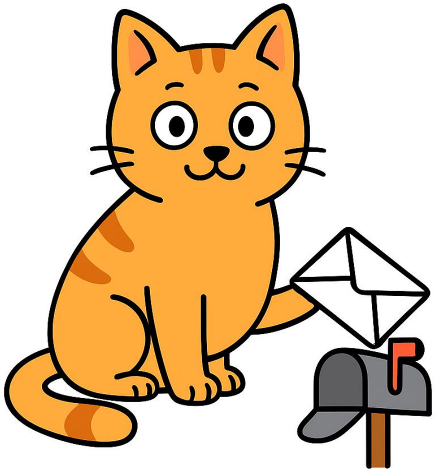




Correlation of radio-bright blazars with IceCube neutrino alerts at chance coincidence of $3{\cdot}10^{-4}$

Correlation not confirmed by slightly different anlyses
Zhou et al. 2021 PRD 103 (2021), IceCube ApJ 954 (2023)

Plavin et al., ApJ 894 (2020), MNRAS 523 (2023), Kovalev et al. arXiv:2504.09287

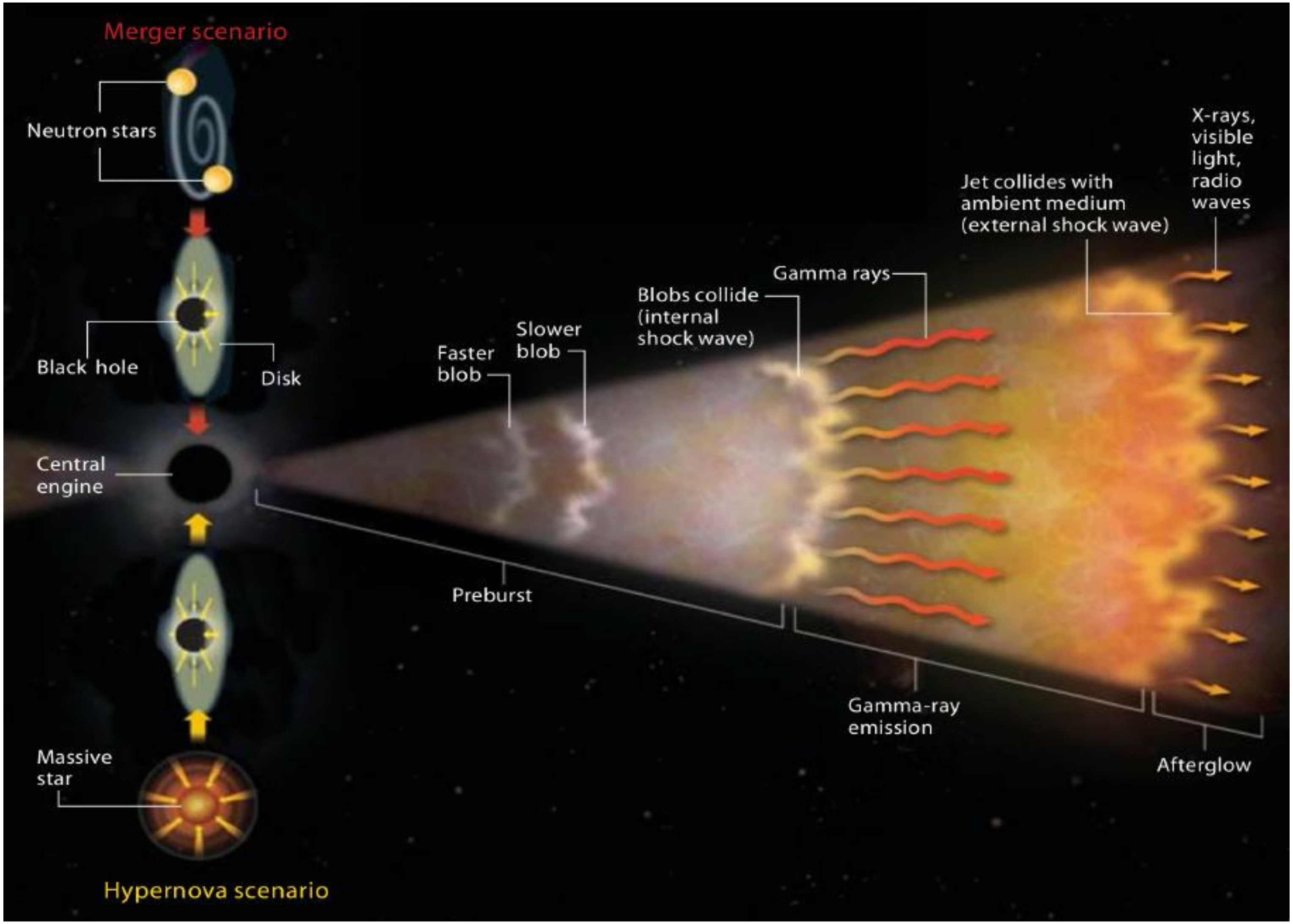


Take home message

Gamma-ray emission in blazars could not be established as a univeral tracer for neutrino emission, but blazars are not ruled out as neutrino sources.

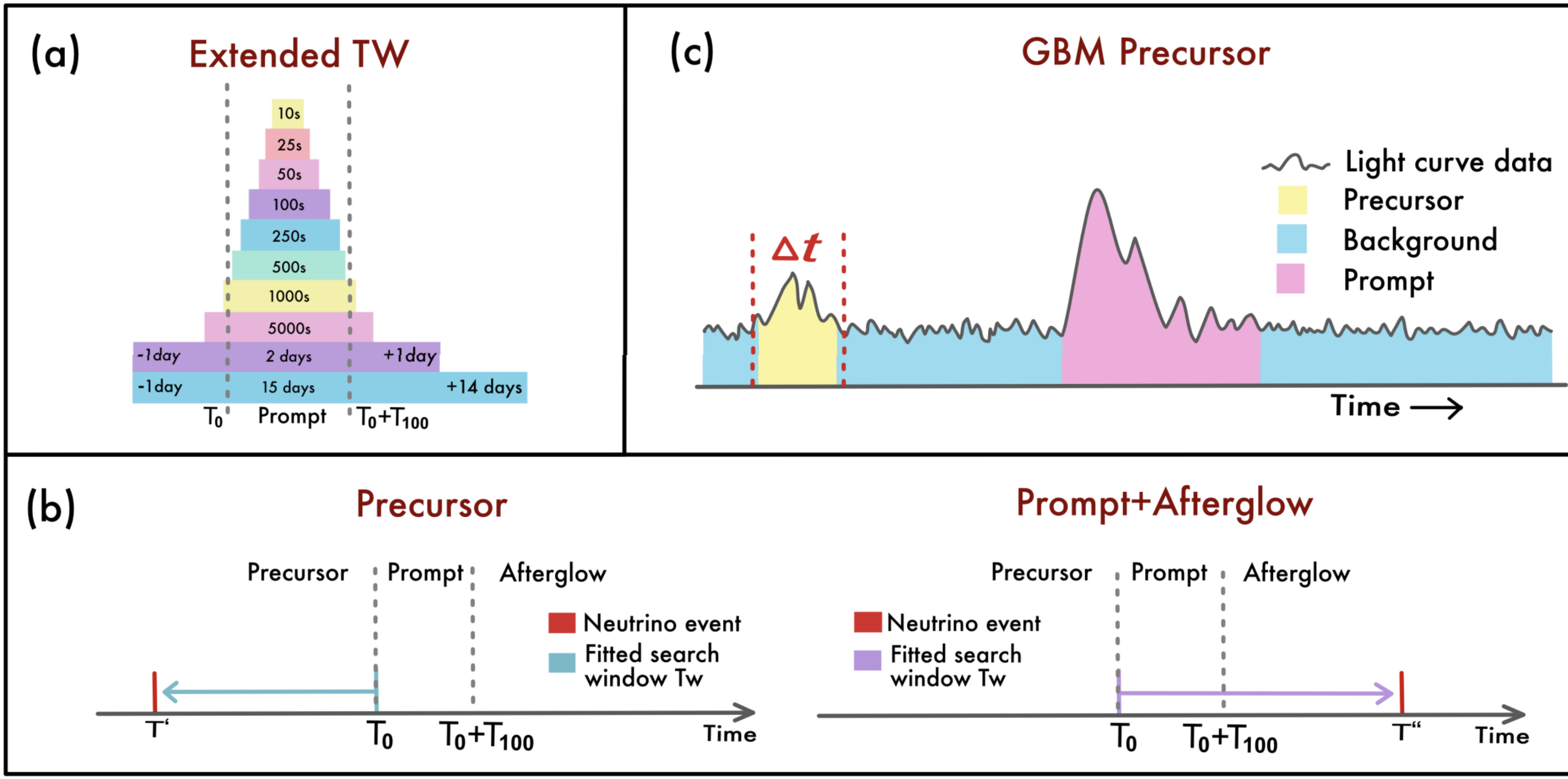
Stellar collapse as neutrino sources?

Gamma-ray Bursts



No excess found → Prompt neutrinos contribute <1% to diffuse neutrino flux

Gamma-ray Bursts: Neutrino Searches



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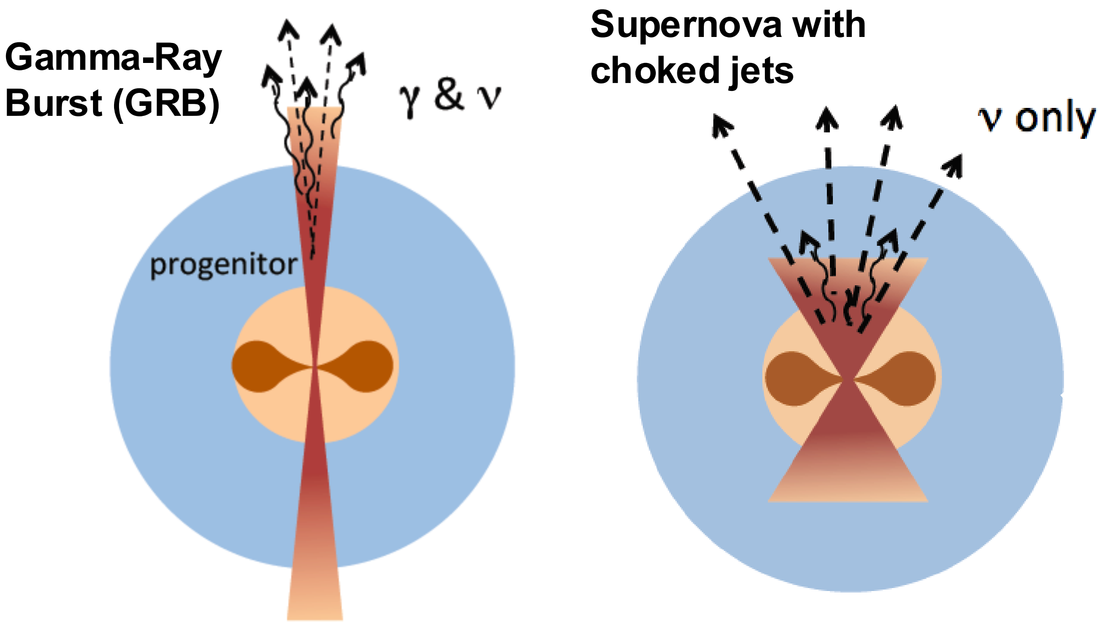
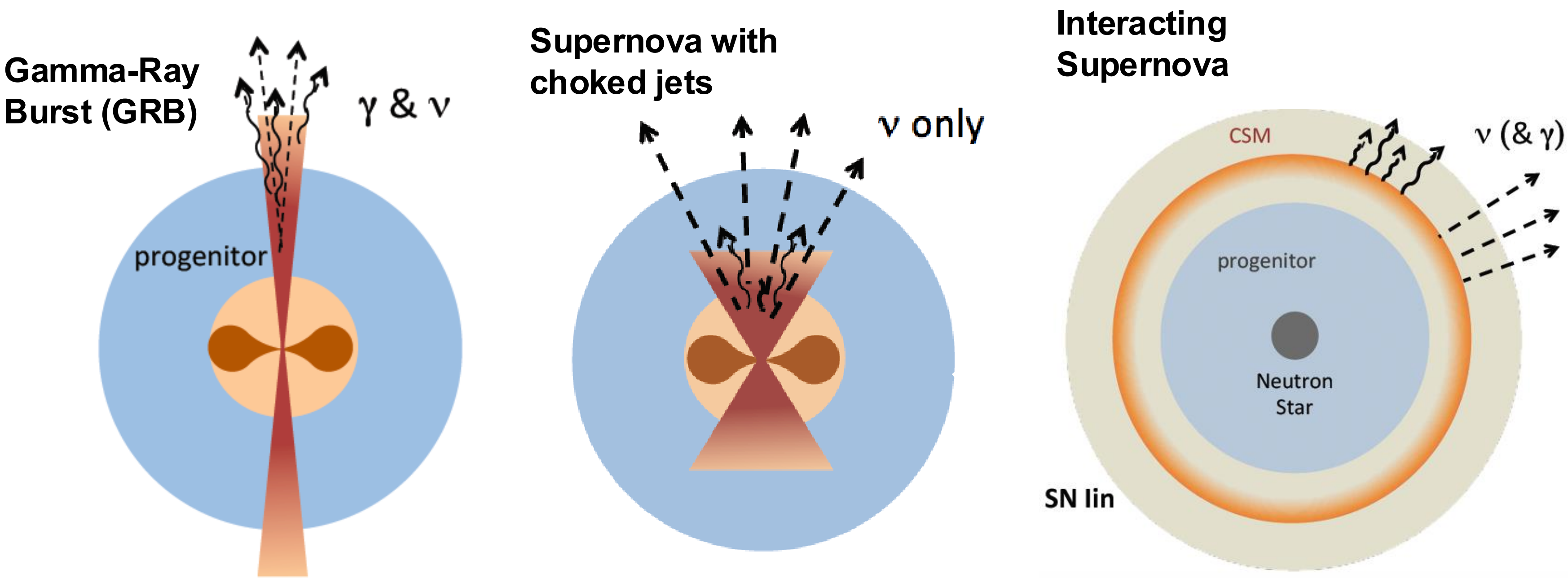
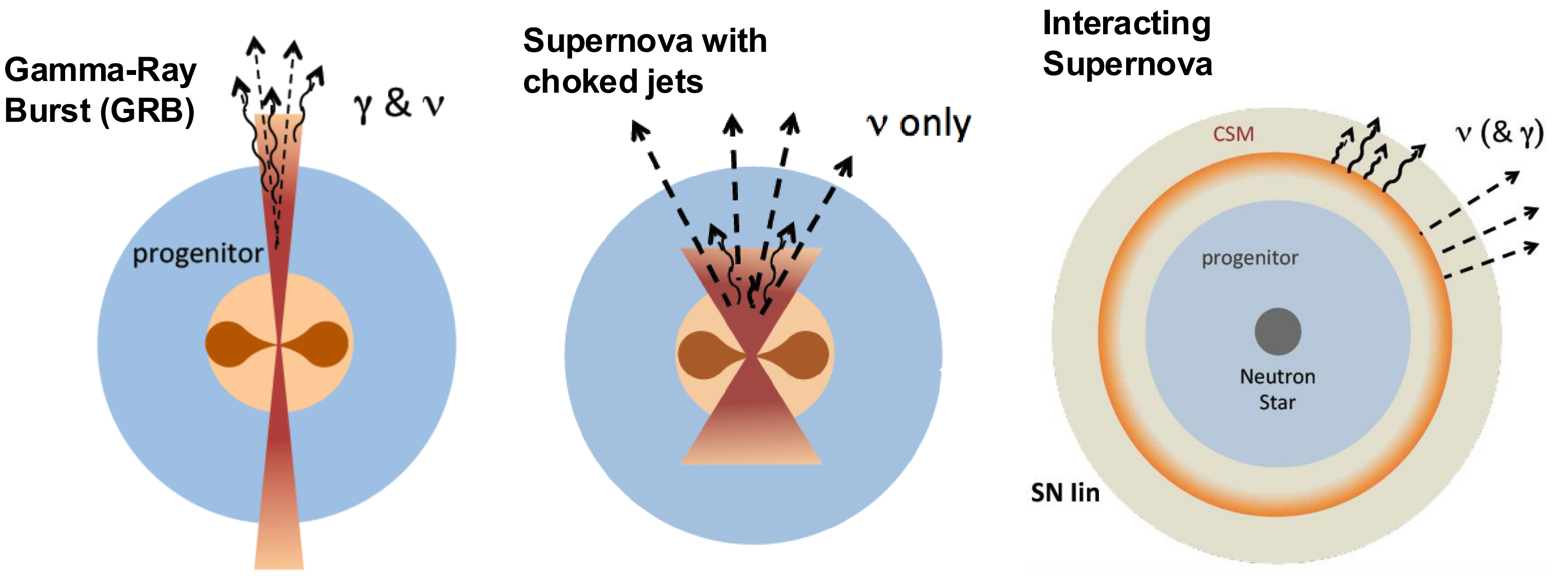
Alternatives to GRBs



Alternatives to GRBs



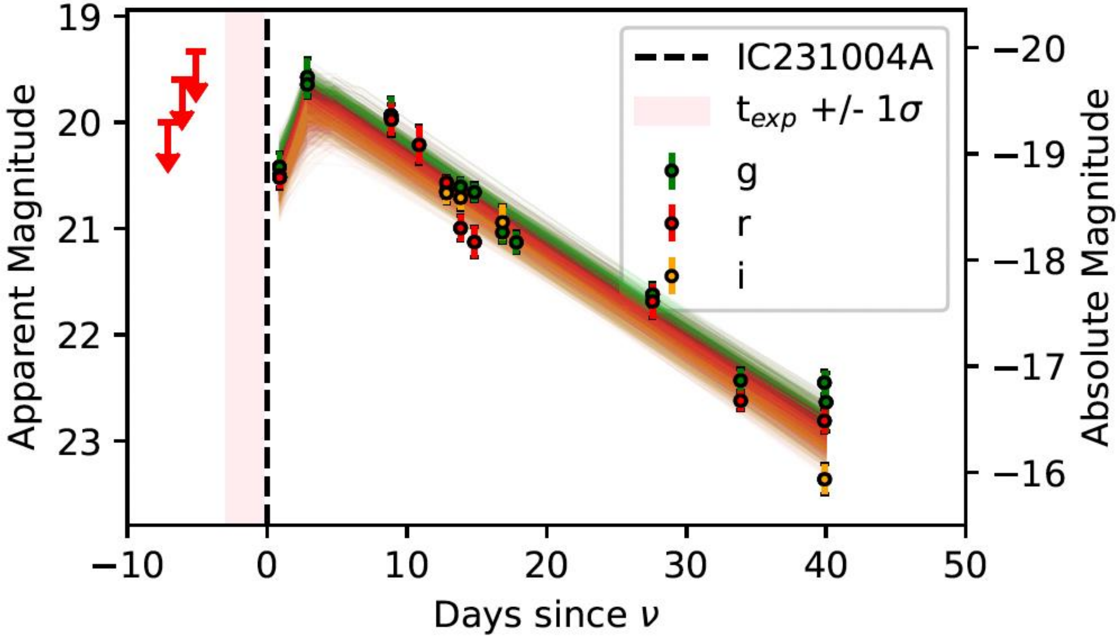
Alternatives to GRBs



“hidden“ sources, best discovered in the optical

Optical Counterpart to a high-energy neutrino: SN2023uqf

IC-231004A
440 TeV Neutrino
84% signalness
3σ association
Distance: 700 Mpc



Stein et al. arXiv:2508.08355

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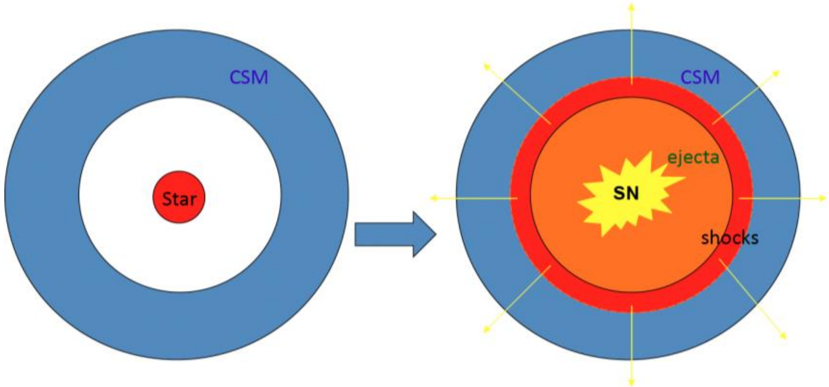
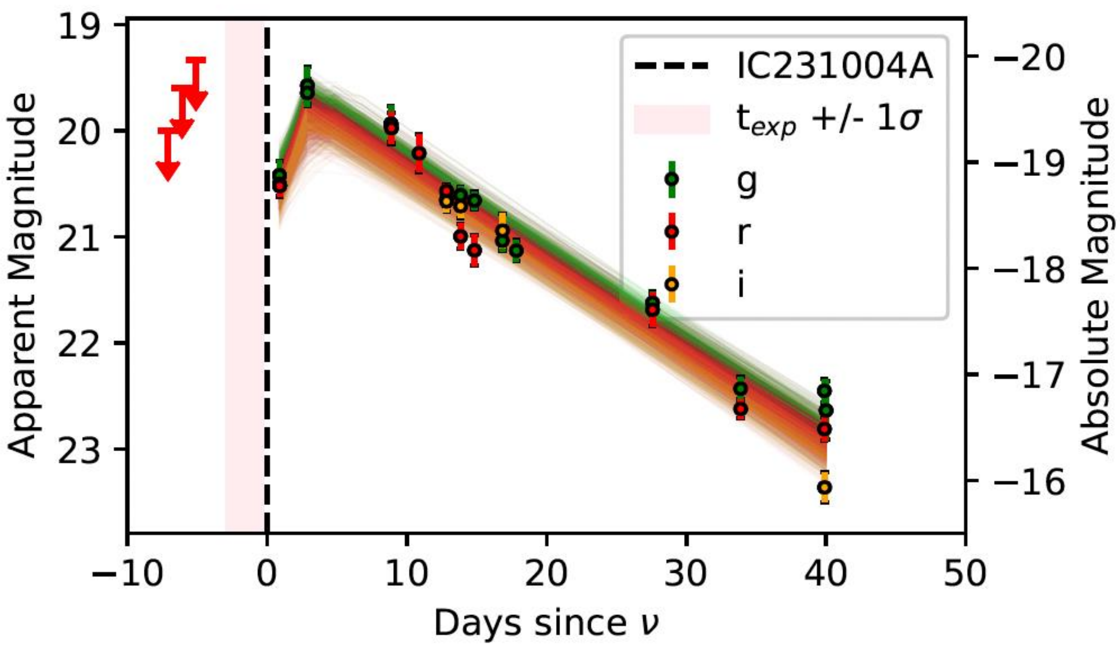


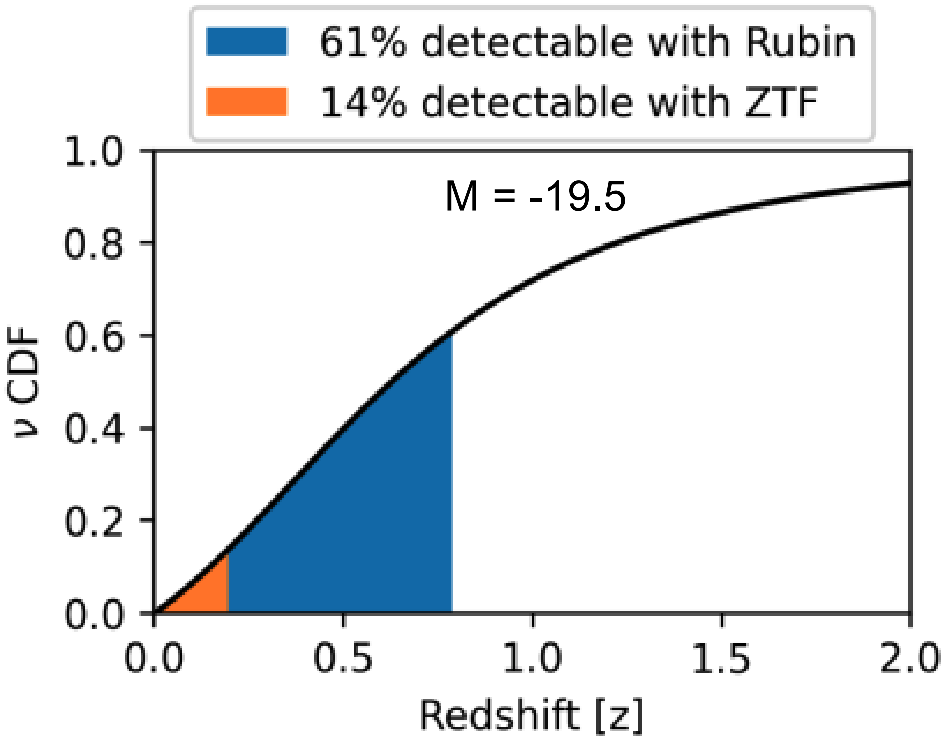
Murase MNRAS 440 (2013)



Evidence for hadronic acceleration in core-collapse supernova explosions

Stein et al. arXiv:2508.08355

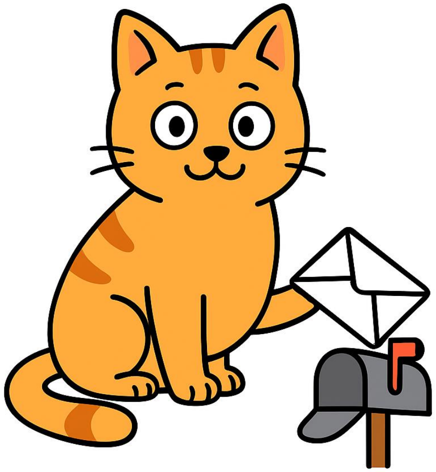
Improved follow-up



First light: July 2025, Alert stream 4-7 months later
Rubin ToO report: 2-12 triggers/year

RUB

https://arxiv.org/pdf/2411.04793

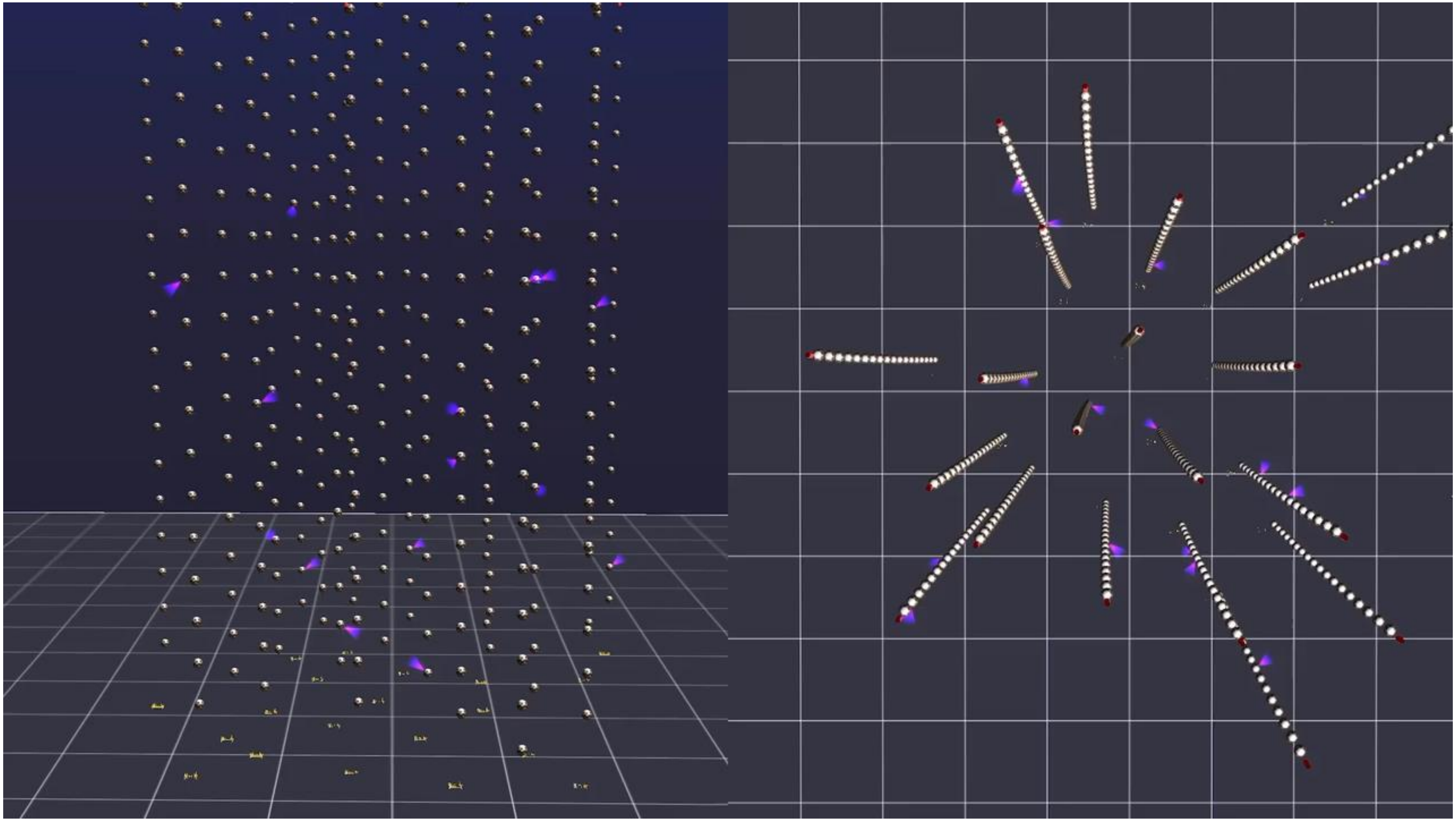


Take home message

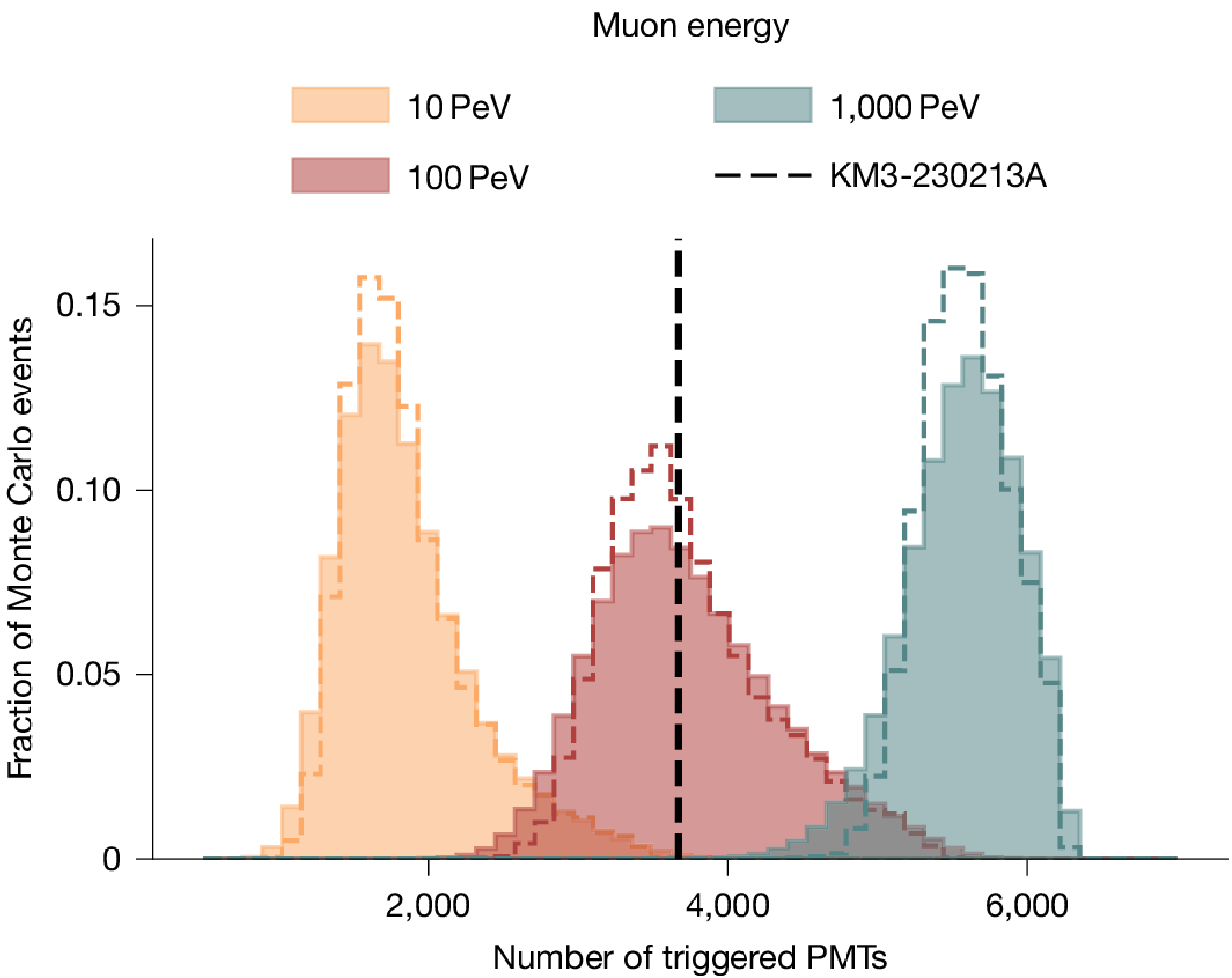
While GRBs are disfavored, choked-jet or interacting Supernovae are promising source classes, which we‘ll be able to probe with up-coming instruments

The highest energy neutrino event ever detected

220 PeV Event from KM3NeT

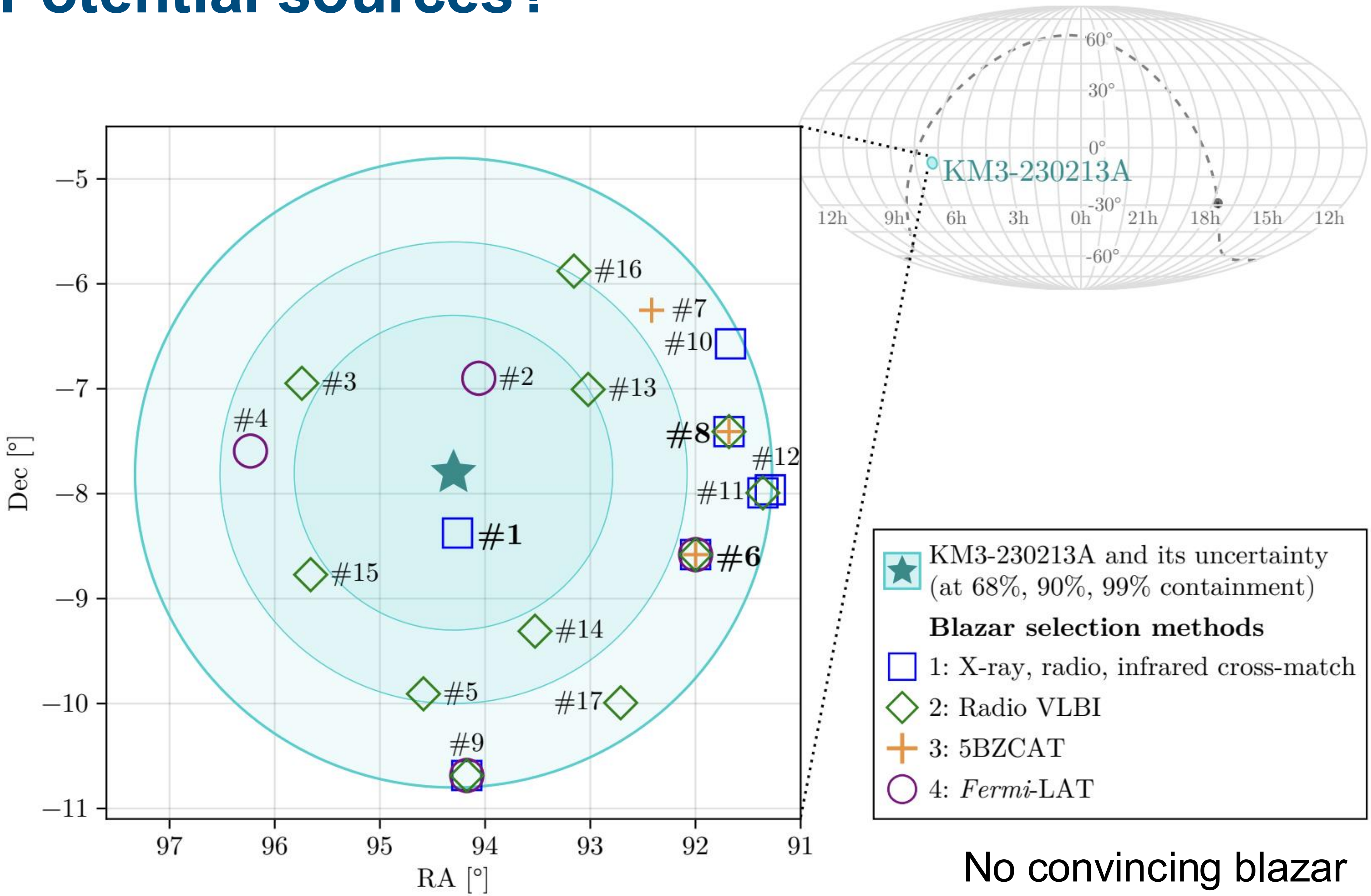


KM3NeT Nature 638 (2025)



KM3NeT Nature 638 (2025)

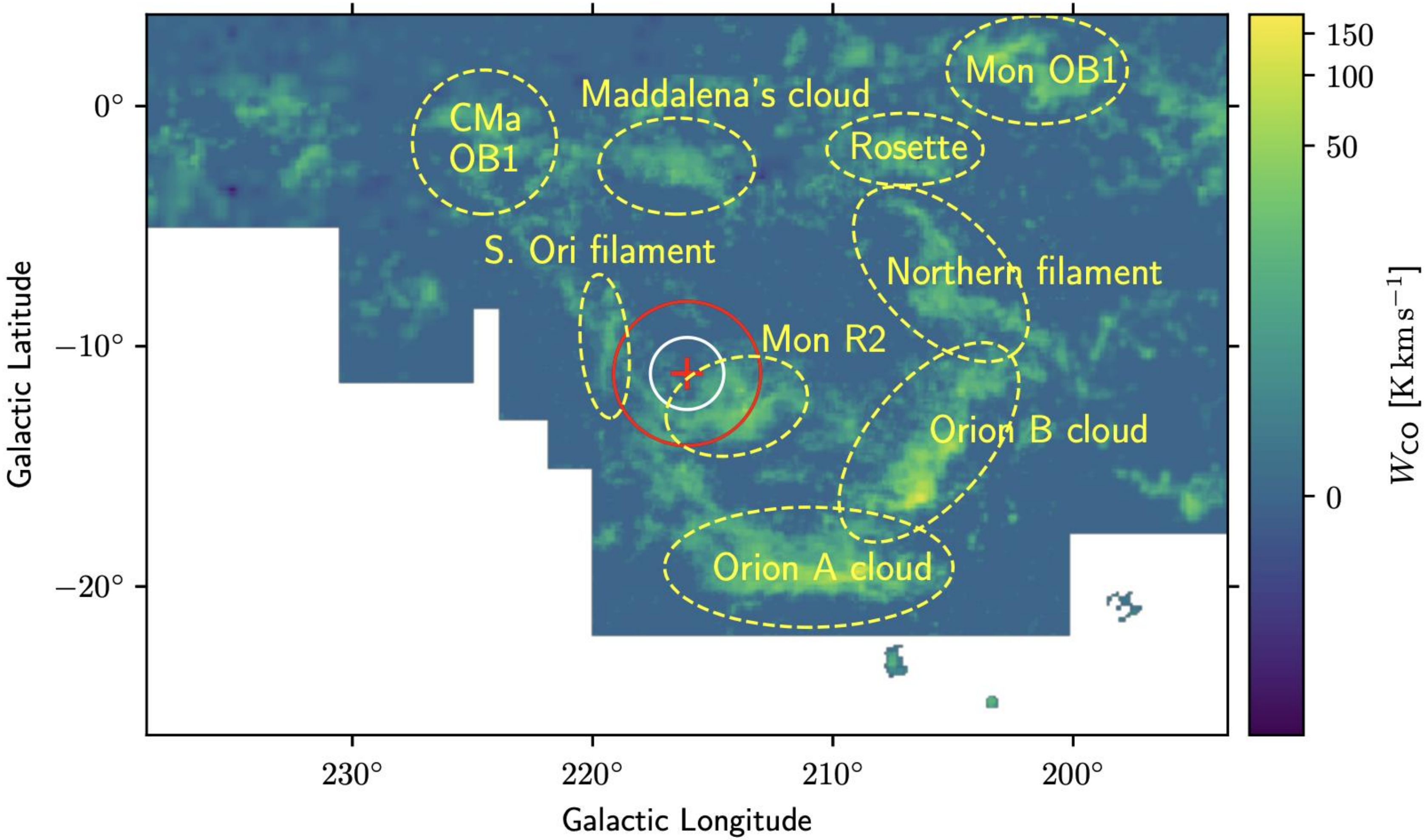
Potential sources?



No convincing blazar counterpart found

KM3NeT et al. arXiv, 2502.08484

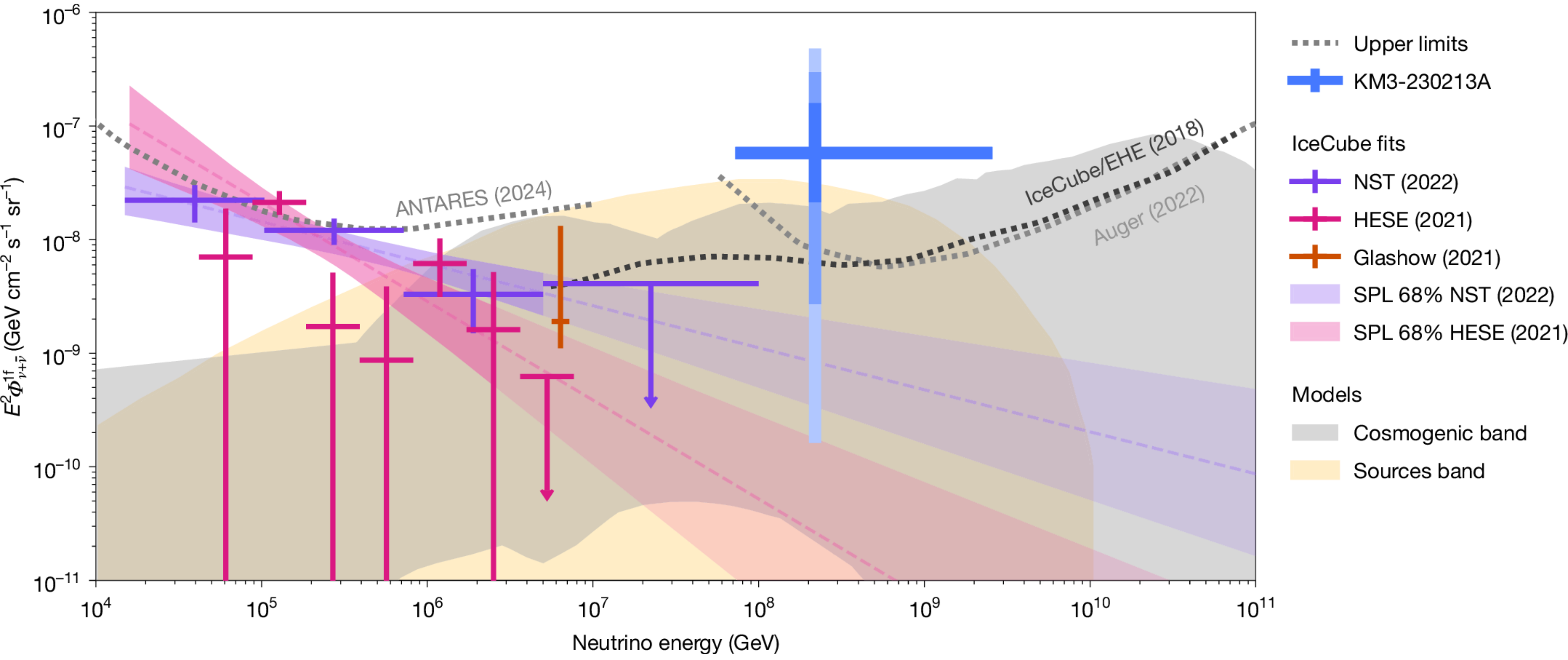
Potential sources?



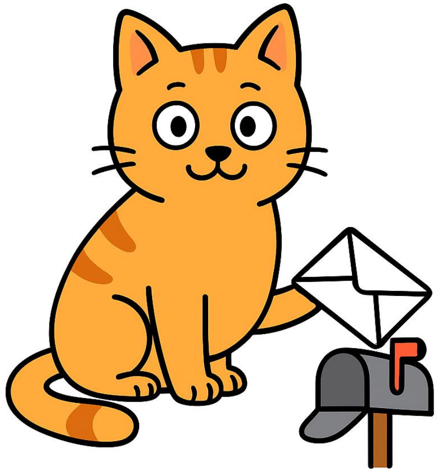
Galactic origin unlikely

KM3NeT, arXiv:2502.08387

Tension with IceCube and Auger upper limits?



RUB



Take home message

KM3NeT detected the highest energy neutrino event with ~220PeV.
This is in mild tension with IceCube upper limits.
It‘s origin is unknown.

Results from water / ice Cherenkov Telescopes

- **Astronomy Summary**
  - Diffuse Flux
    - First detected in 2013, now deviation from simple power law
  - Milky Way: ~10% of diffuse flux
  - Source Candidates
    - Neutrino map alone does not reveal sources
    - Using electromagnetic information
      - Seyfert galaxy NGC 1068 at 4 sigma in 10 year data + other potential Seyfert candidates
      - Blazar TXS 0506+056 at 3 sigma through realtime observations
      - Interacting Supernova SN2023uqf ?

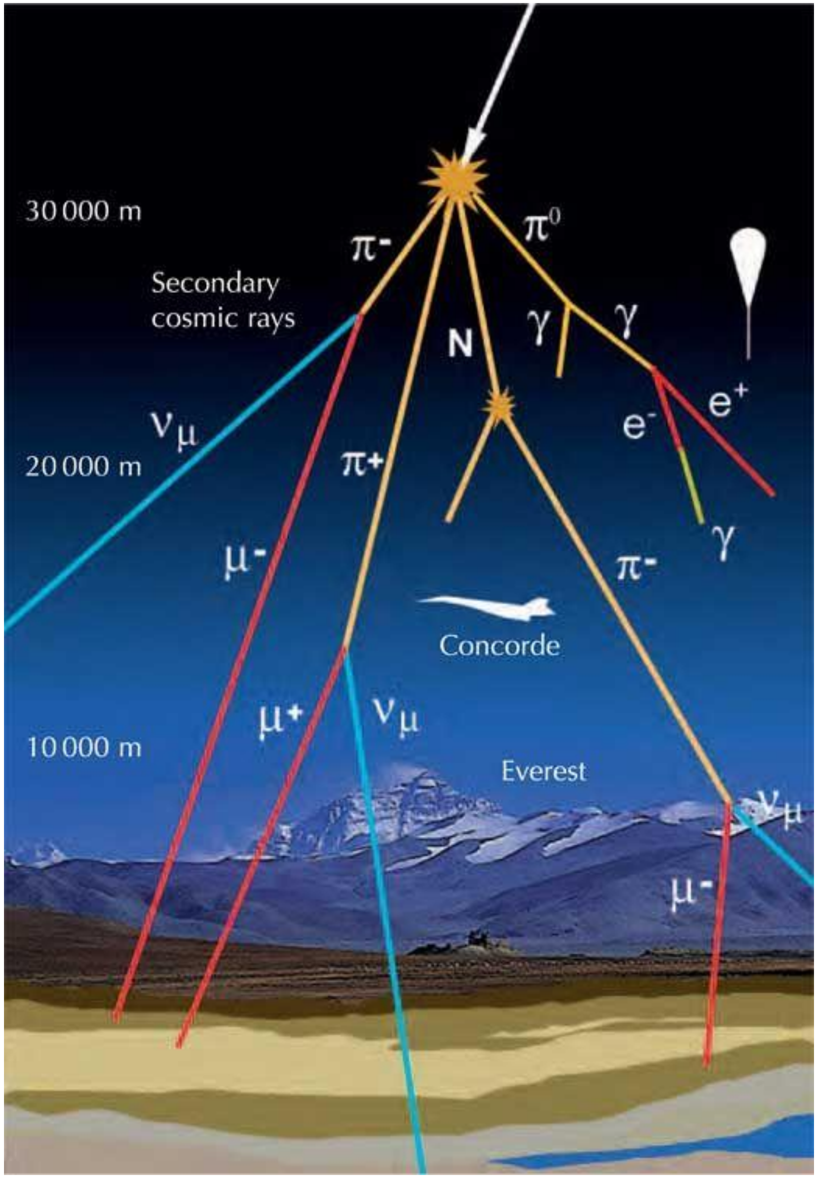
Astro Quiz

https://forms.gle/UHKjRUvZPEJZqJqy5

Results from water / ice Cherenkov Telescopes

- Astronomy
  - Diffuse Flux
  - Milky Way
  - Source Candidates
- **Neutrino as a particle**
  - Neutrino Oscillations
  - Neutrino Cross Section
- New physics
  - Sterile Neutrinos
  - Dark Matter

Atmospheric Neutrinos



What is neutrino oscillation?

- Three neutrino flavor states: one per lepton flavor
- Mixing between these flavor states and the neutrino mass states
  - Characterised by the PMNS matrix

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

- A neutrino produced as a given flavor is thus a superposition of all three mass states

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- The wavefunction of each mass state evolves with a different frequency (defined by its mass) as they propagate
- The superposition of the flavor states therefore changes over time → time-dependent flavour composition

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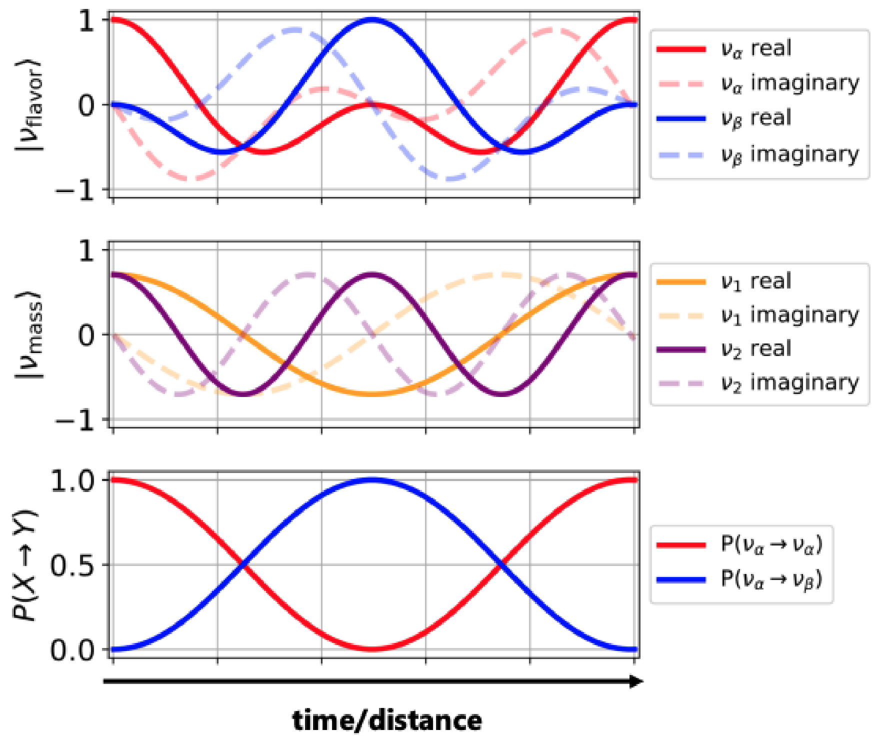
- The wavefunction of each mass state evolves with a different frequency (defined by its mass) as they propagate
- The superposition of the flavor states therefore changes over time → time-dependent flavour composition
- A neutrino produced as one flavor can therefore be detected later as another → this is neutrino oscillations

A simple example (credit: T. Stuttard)

Visualise the superposition effects and resulting oscillations using simplified model…

- 2 neutrino states (flavour = ν_α, ν_β, mass = ν_1, ν_2) → flavor states are 50:50 mix of mass states ($\theta = 45°$)
- $m_2 = \sqrt{2}\, m_1$



$$|\nu_j(L)\rangle = \exp\left\{-i\frac{m_j^2 L}{2E}\right\}|\nu_j(0)\rangle$$

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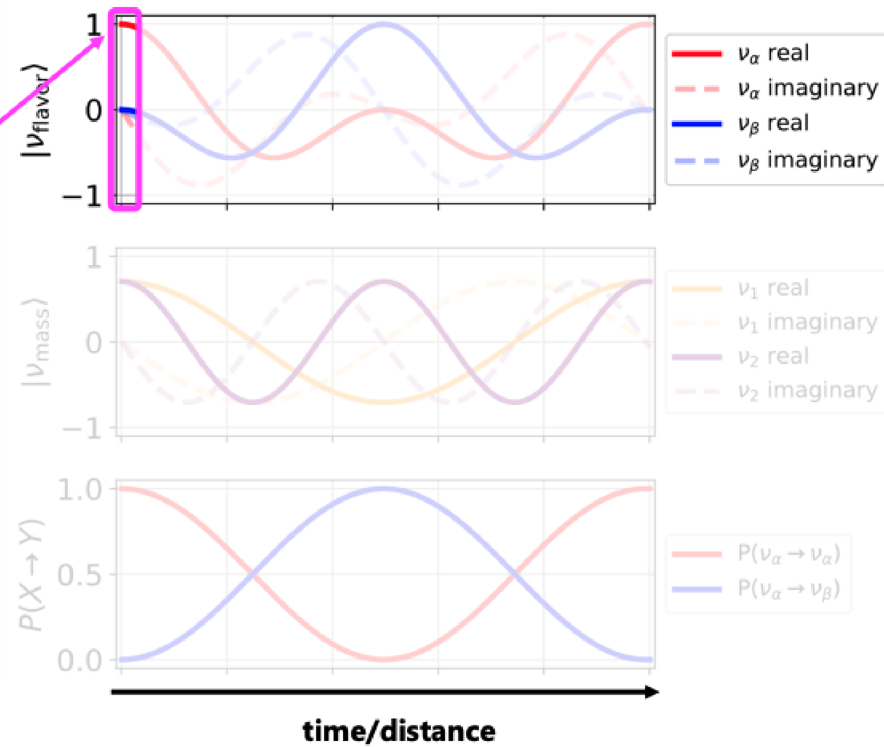
1) Neutrino produced in pure (single) flavor state

In this case ν_α



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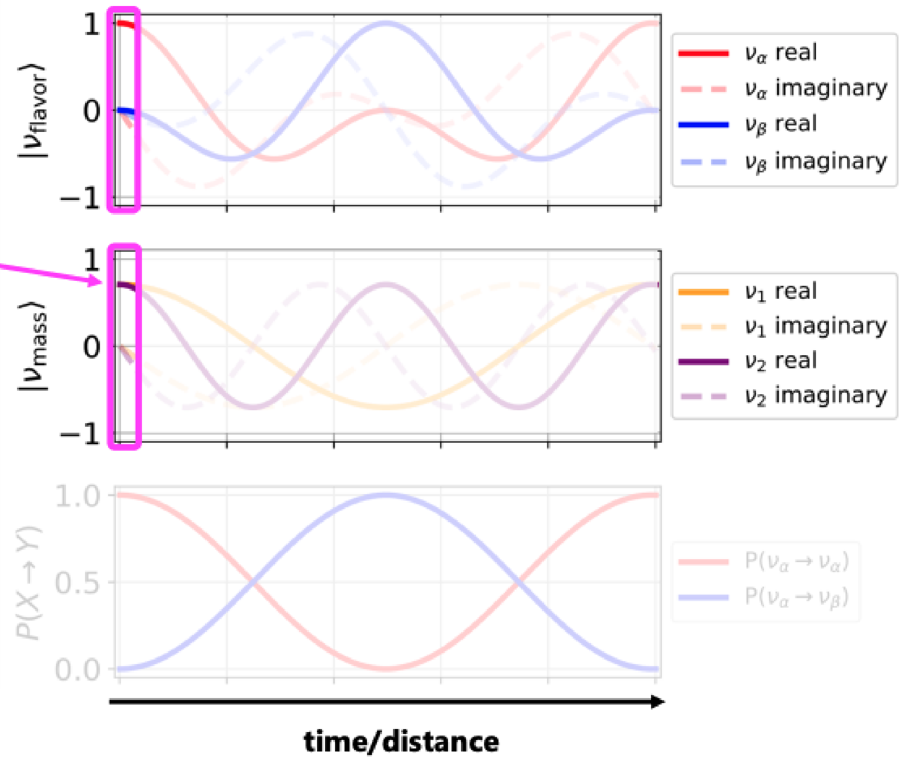
2) This means the neutrino is initially an equal mix of the two mass states

Because of 50:50 mixing in this example



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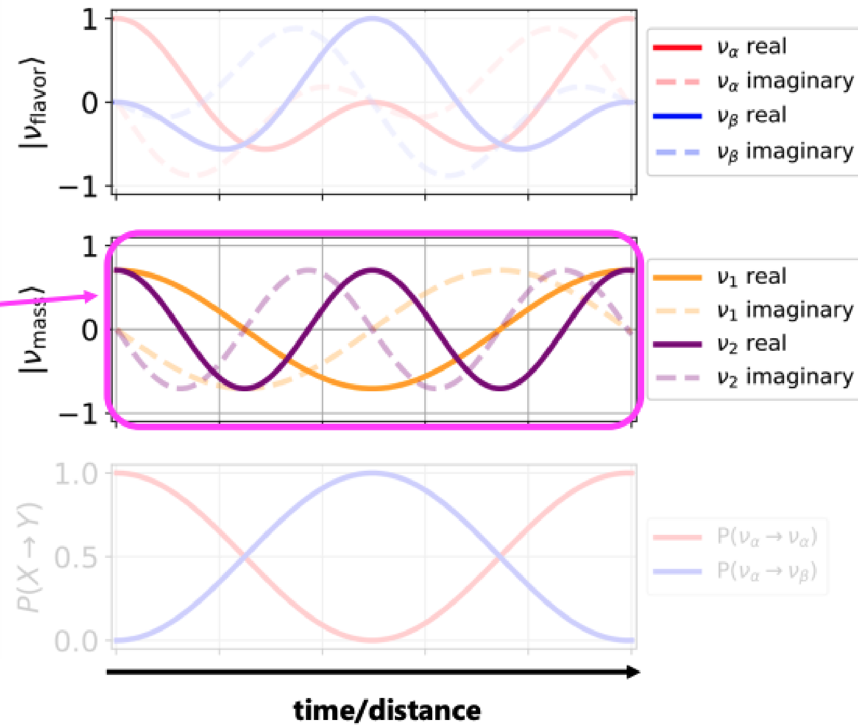
3) The wavefunctions of the mass states evolve over time

The frequency of this evolution depends on the mass

The frequency of ν_2 is 2x ν_1 in this example



$$|\nu_j(L)\rangle = \exp\left\{-i\frac{m_j^2 L}{2E}\right\}|\nu_j(0)\rangle$$

Mass state evolution

(Plane wave)

RUB

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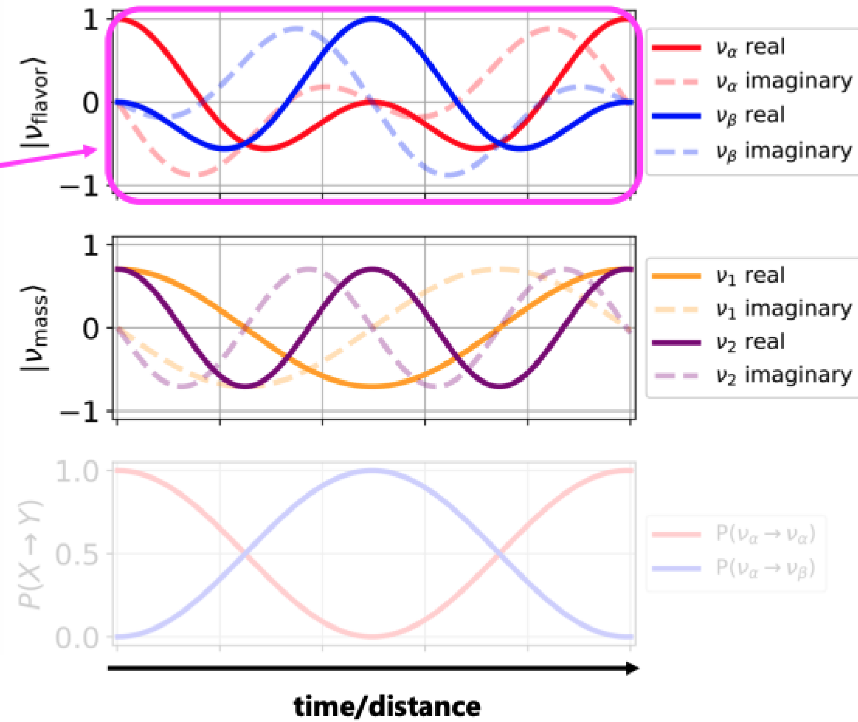
- $m_2 = \sqrt{2}\, m_1$

4) The evolution of the mass states modified the flavor state superposition over time



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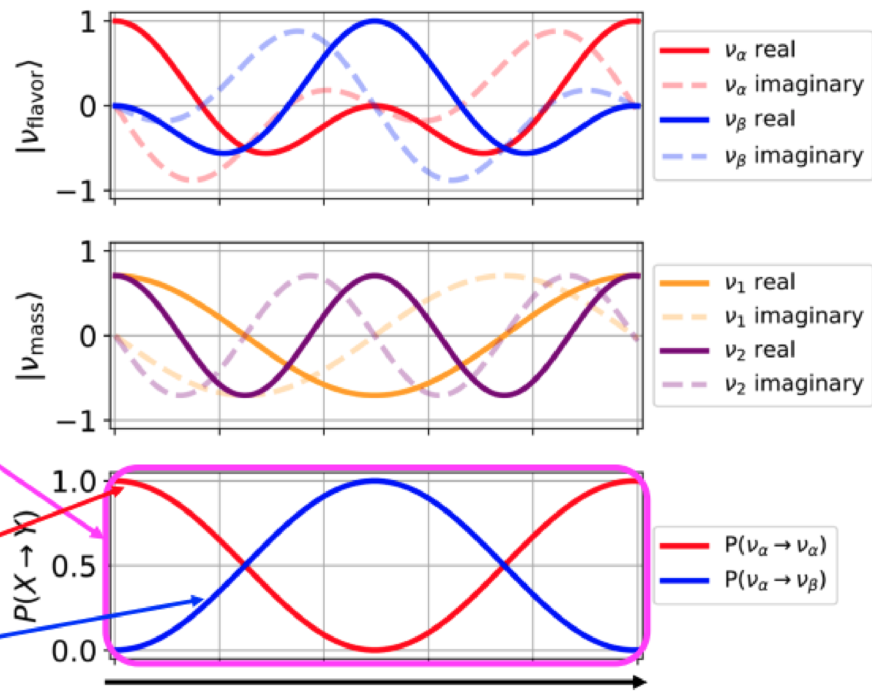
- 2 neutrino states (flavour = ν_α, ν_β, mass = ν_1, ν_2) → flavor states are 50:50 mix of mass states ($\theta = 45°$)
- $m_2 = \sqrt{2}\, m_1$

5) The probability to be detected as a given flavor thus changes over time

Initially the probability to detect as the production flavor is 100%

Probability to detect as another flavor (*oscillate*) rises and falls over time



$$|\nu_j(L)\rangle = \exp\left\{-i\frac{m_j^2 L}{2E}\right\}|\nu_j(0)\rangle$$

Mass state evolution

(Plane wave)

Neutrino Oscillations

- Neutrino mixing characterised by the (complex) PMNS matrix

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

- If unitary, can be parameterised as 3 mixing angles and a CP-violating phase

$$\theta_{12},\ \theta_{13},\ \theta_{23},\ \delta_{CP}$$

- Oscillation frequency depends on the mass-difference between mass states

$$\Delta m^2_{21},\ \Delta m^2_{31}$$

→ 6 oscillation parameters to measure in experiments

How can we access those parameters?

- Probability of oscillating between flavors (for simplified 2-flavour case)

$$P_{\alpha\beta} = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

Mixing defines oscillation amplitude

Frequency also depends on L/E ratio for a given neutrino

Mass-difference defines frequency

How can we access those parameters?

- Probability of oscillating between flavors (for simplified 2-flavour case)

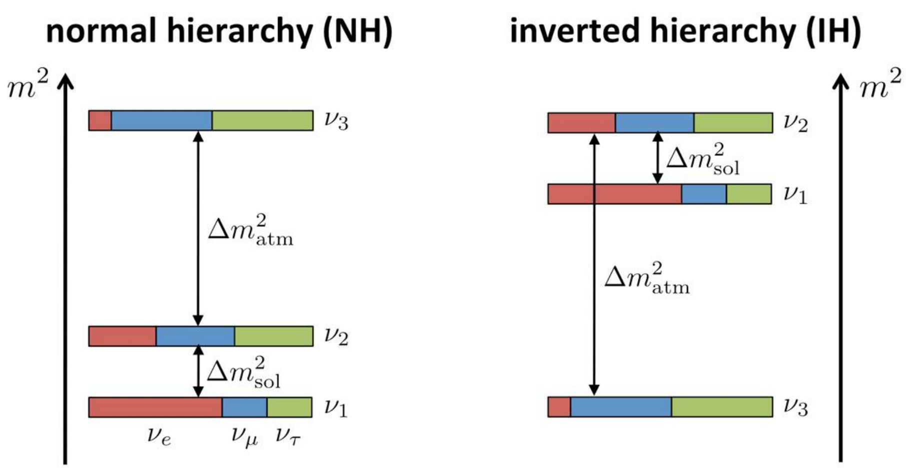
$$P_{\alpha\beta} = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

Mixing defines oscillation amplitude

Frequency also depends on L/E ratio for a given neutrino

Mass-difference defines frequency

- Insensitive to the sign of Δm^2 → neutrino mass ordering problem



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Mixing defines oscillation amplitude

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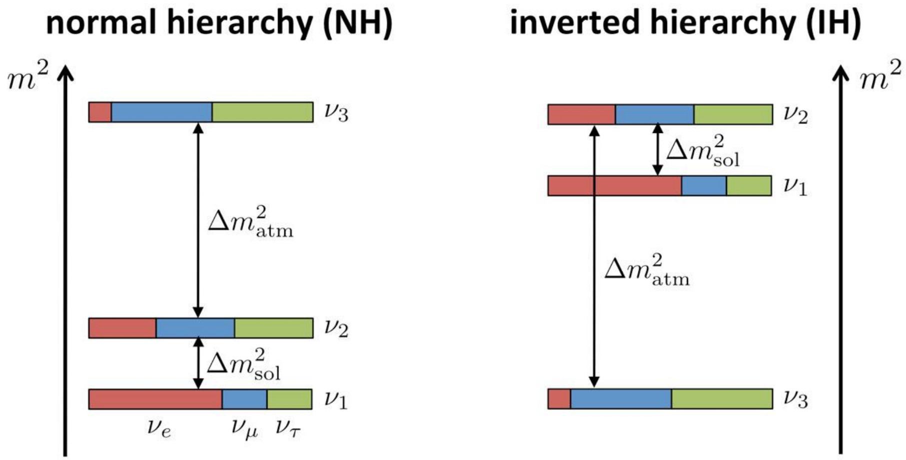
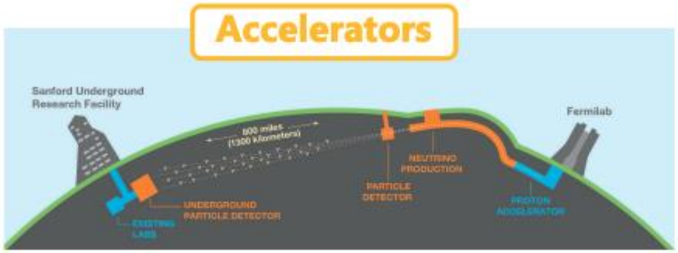
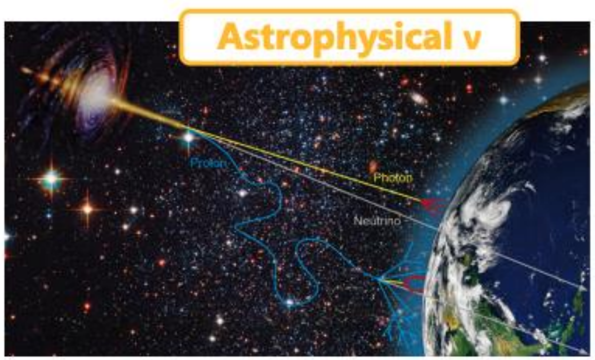


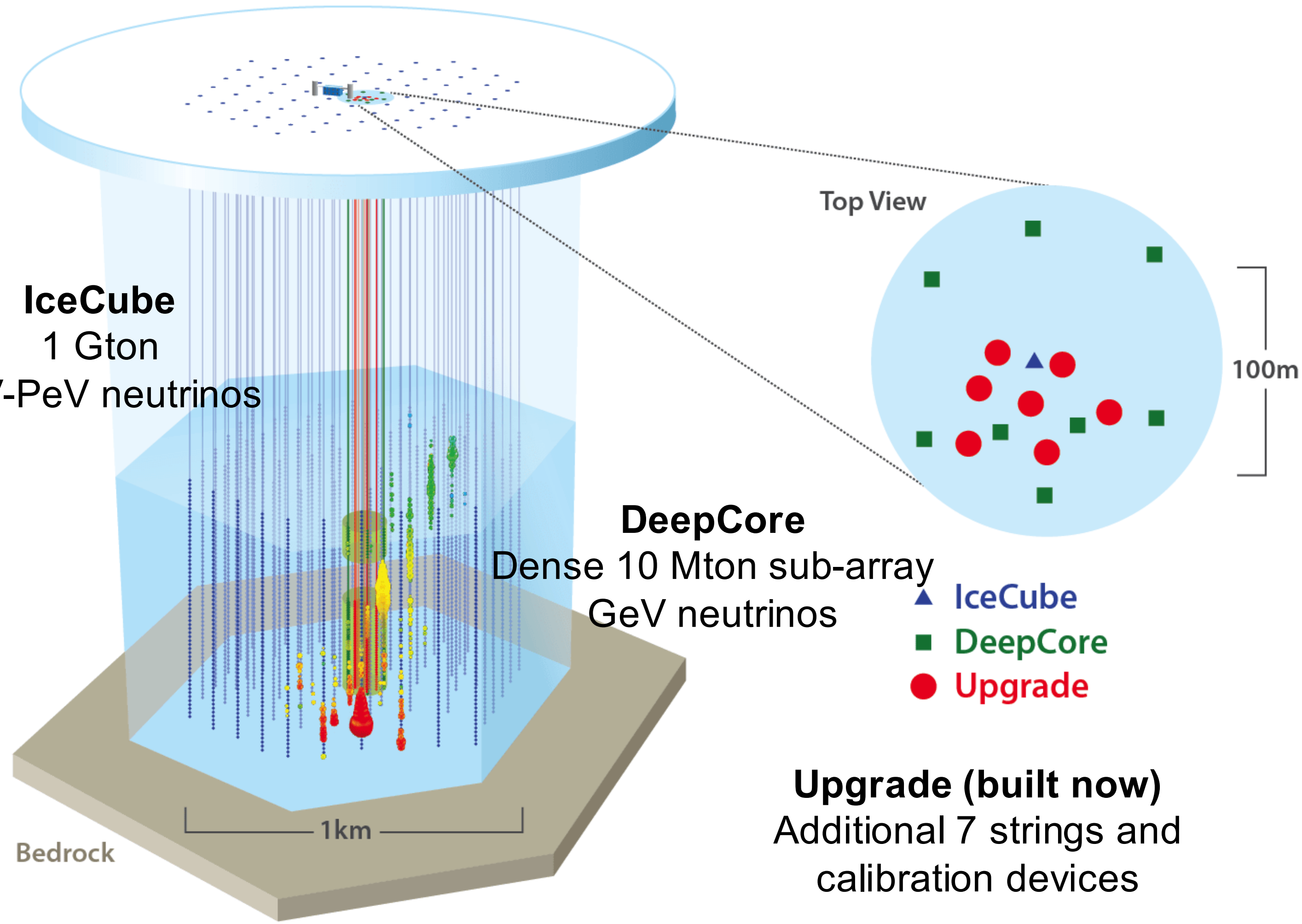
Modified oscillation effects for neutrinos passing through matter

Experiments





IceCube DeepCore



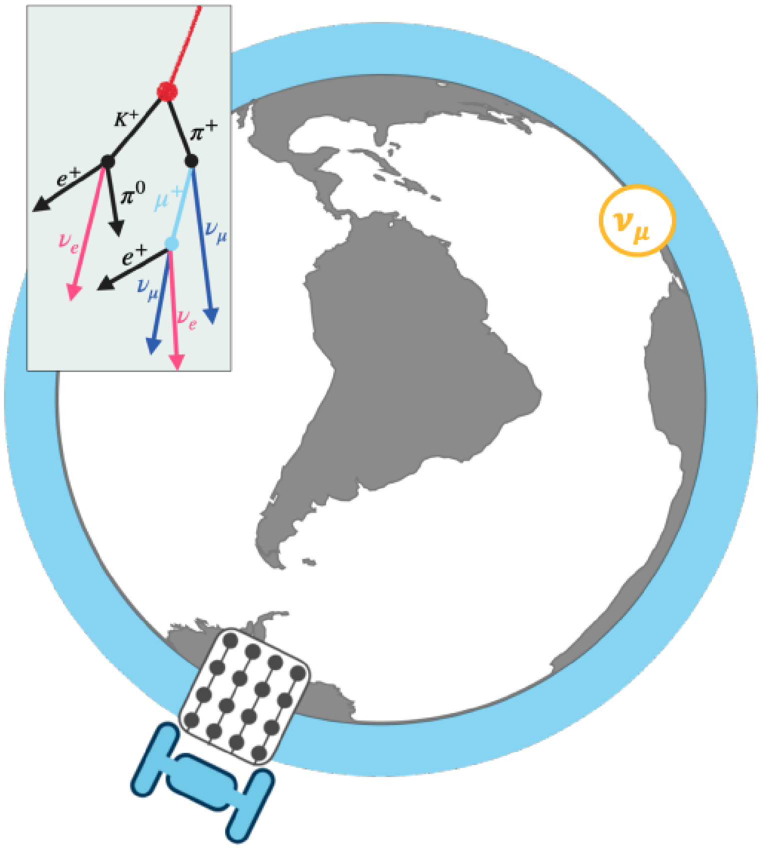
IceCube
1 Gton
TeV-PeV neutrinos

DeepCore
Dense 10 Mton sub-array
GeV neutrinos

Upgrade (built now)
Additional 7 strings and
calibration devices

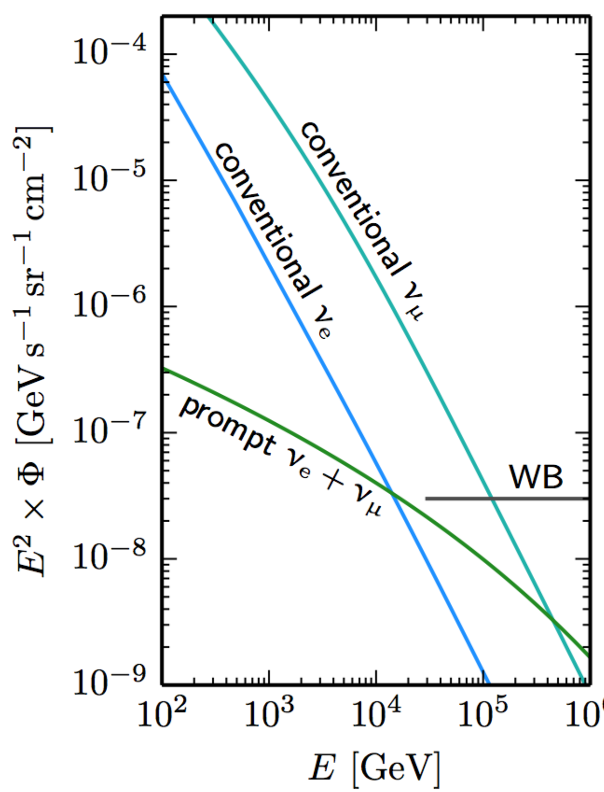
https://icecube-gen2.wisc.edu/science/publications/tdr/

Atmospheric Neutrinos: Background to one, signal to another



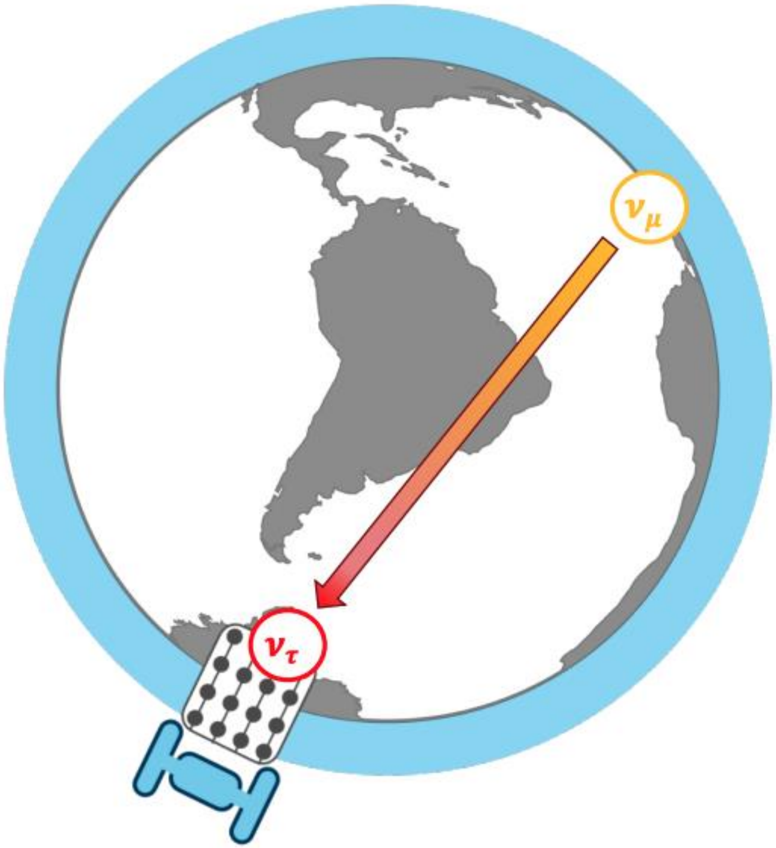
(1) Cosmic rays interact in the atmosphere and produce air showers

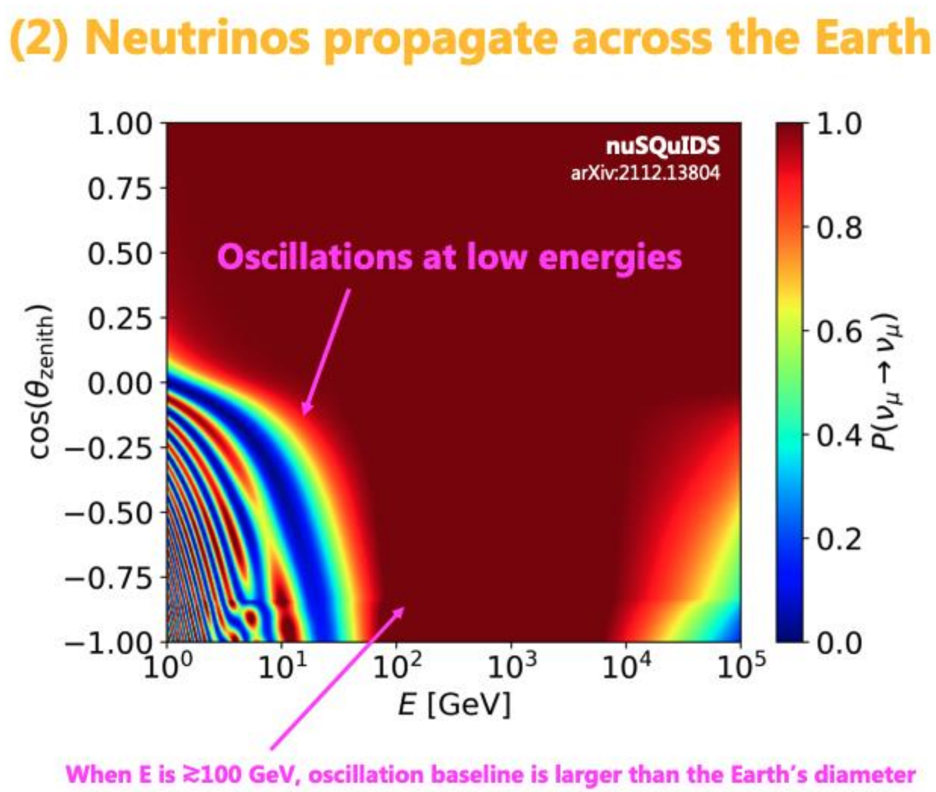
→ Large flux of high energy neutrinos



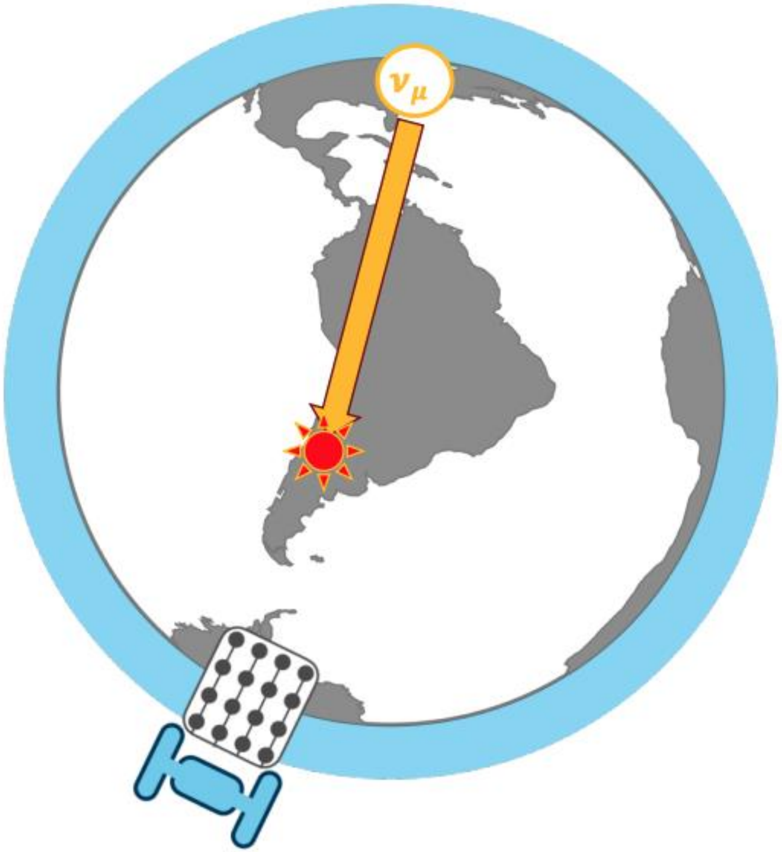
RUB

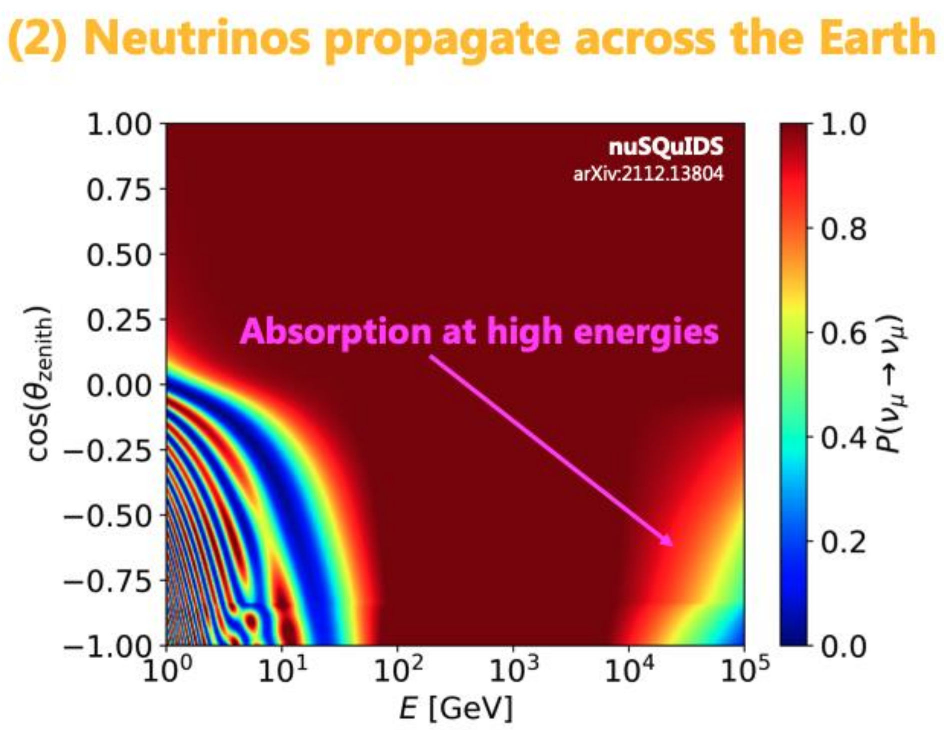
Atmospheric Neutrinos - Oscillations



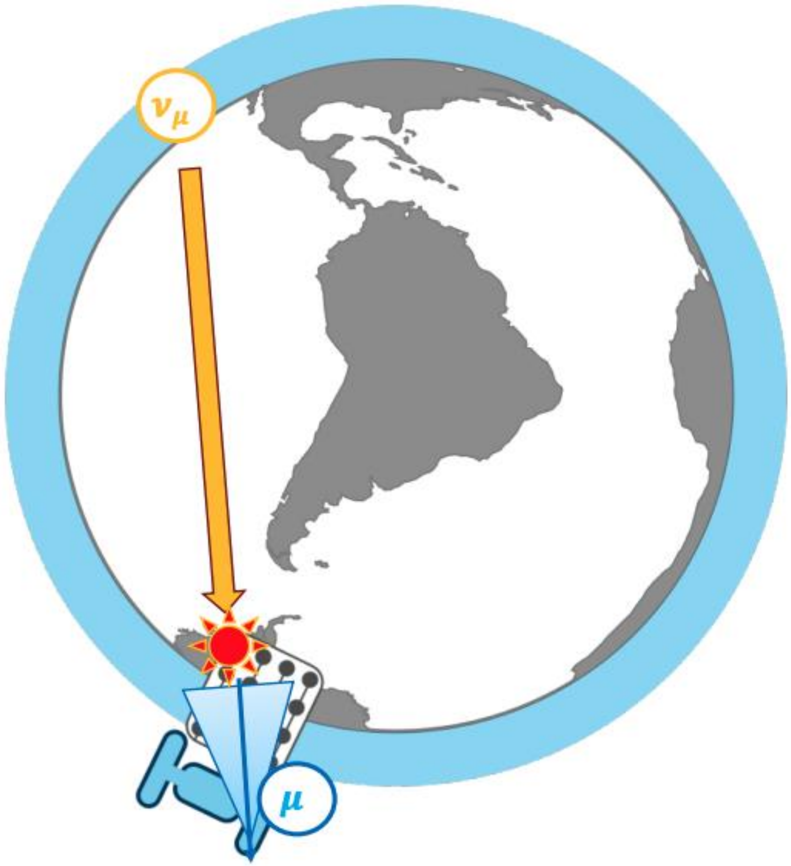


Atmospheric Neutrinos - Oscillations





Atmospheric Neutrinos - Oscillations

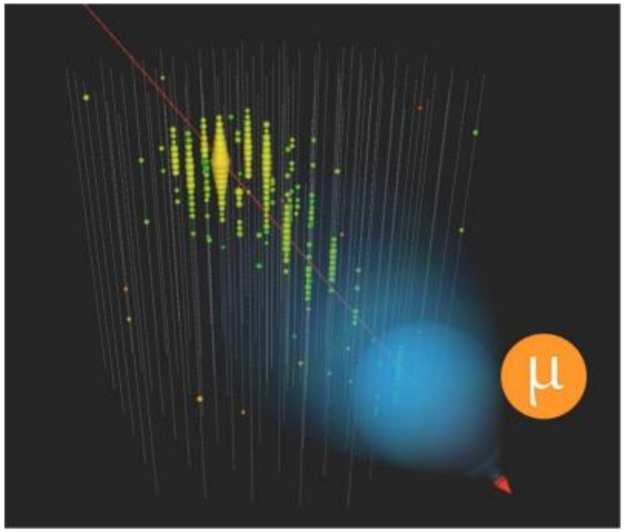


(3) Detection via Cherenkov emission from products of $\nu - N$ interactions

Predominantly Deep Inelastic Scattering (DIS)

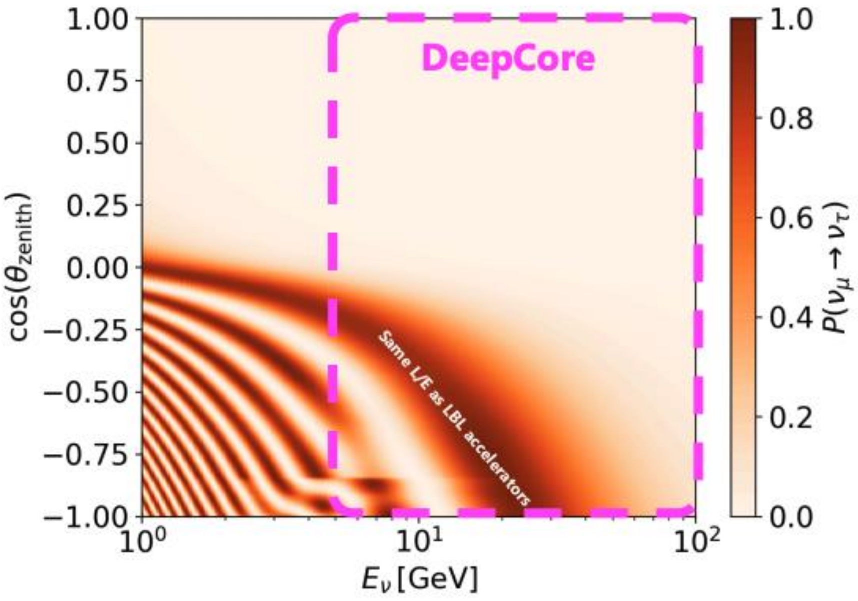
"Tracks" from secondary μ

"Cascades" from secondary e, τ and hadrons



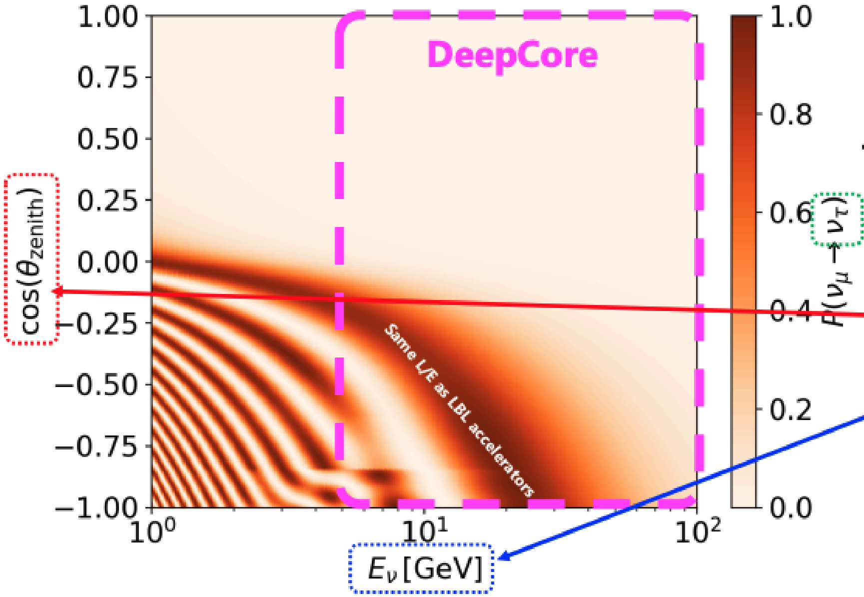
Measuring Neutrino Oscillations

- The DeepCore sub-array of IceCube can measure atmospheric neutrino oscillations in the 5 – 100 GeV energy range
  - Earth-crossing $\boldsymbol{\nu_\mu}$ **near maximally oscillate to** $\boldsymbol{\nu_\tau}$ → measures θ_{23} and Δm_{32}^2



$$P_{\alpha\beta} = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

Measuring Neutrino Oscillations



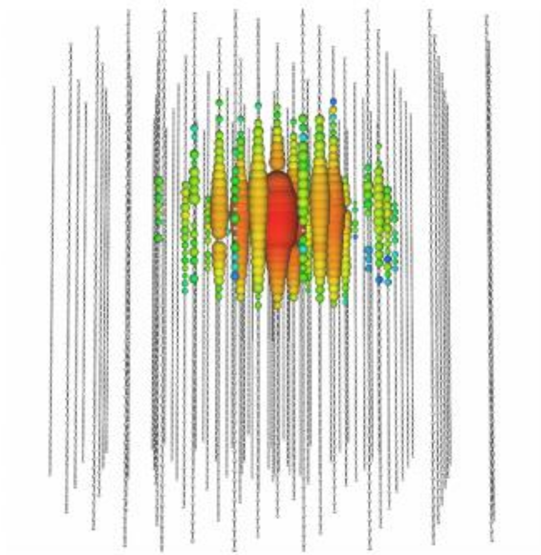
To measure these effects, for each neutrino must reconstruct:

- **Flavor** – also known as Particle ID (PID)
- **Baseline** - determined from arrival (zenith) angle
- **Energy**

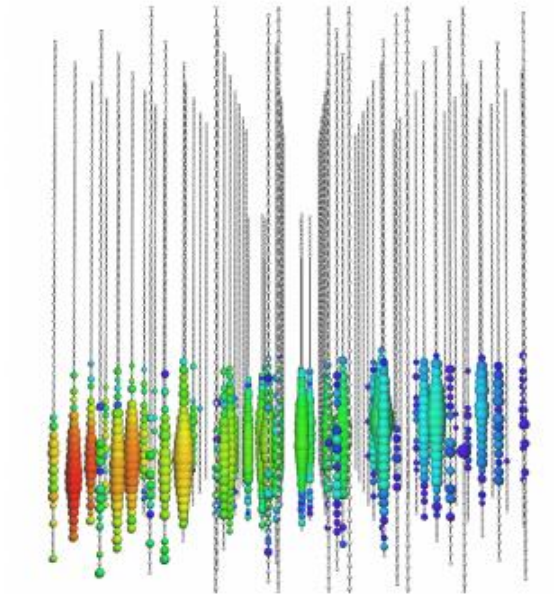
$$P_{\alpha\beta} = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

Measuring Neutrino Oscillations

- Two event topologies at high energies



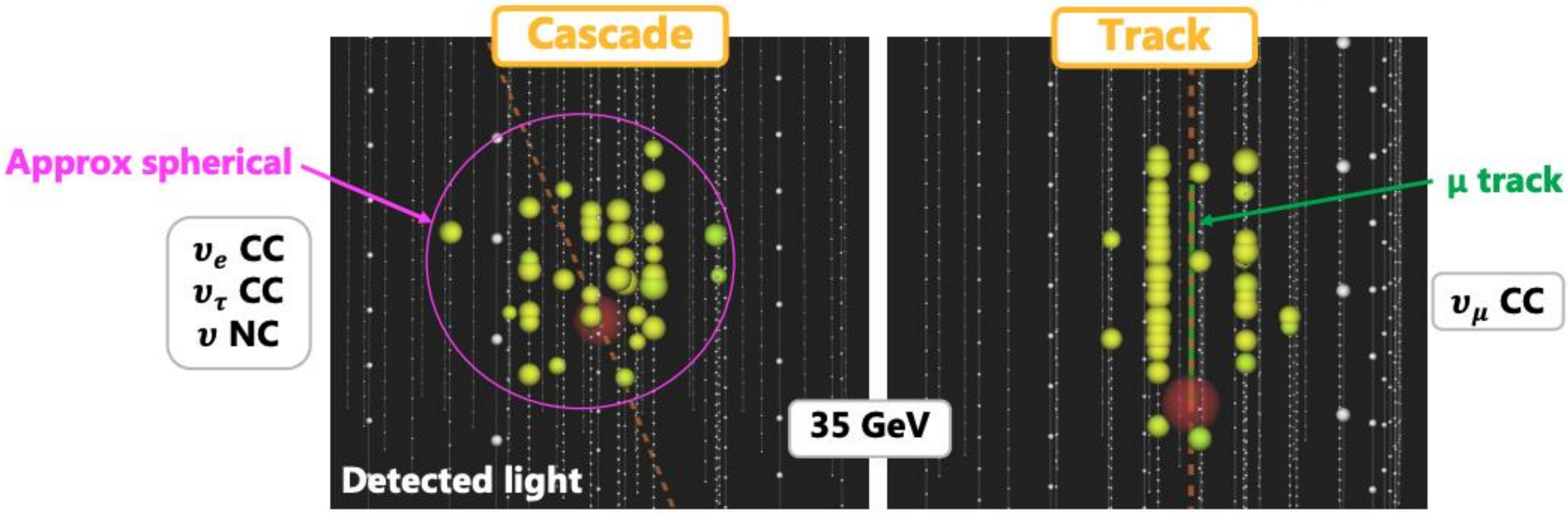
Cascade
E ~ 1 PeV



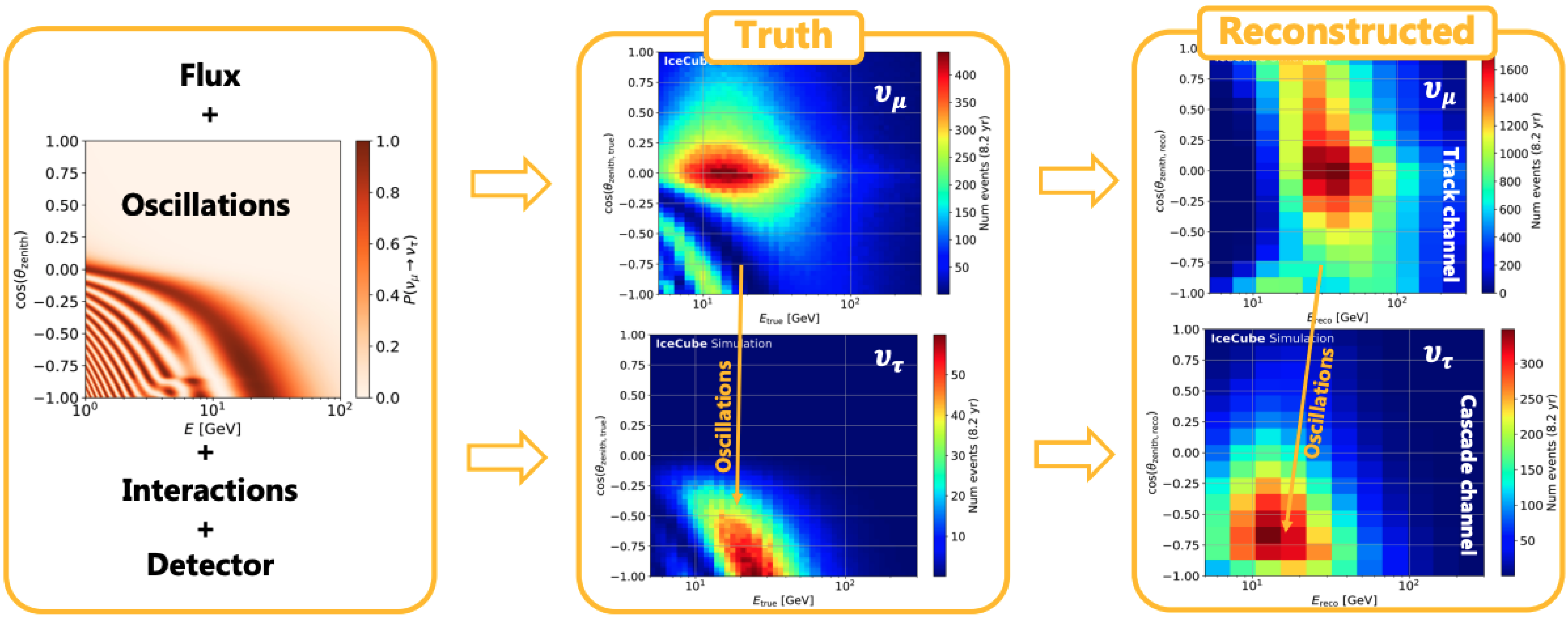
Muon track
E ~ 140 TeV

Measuring Neutrino Oscillations

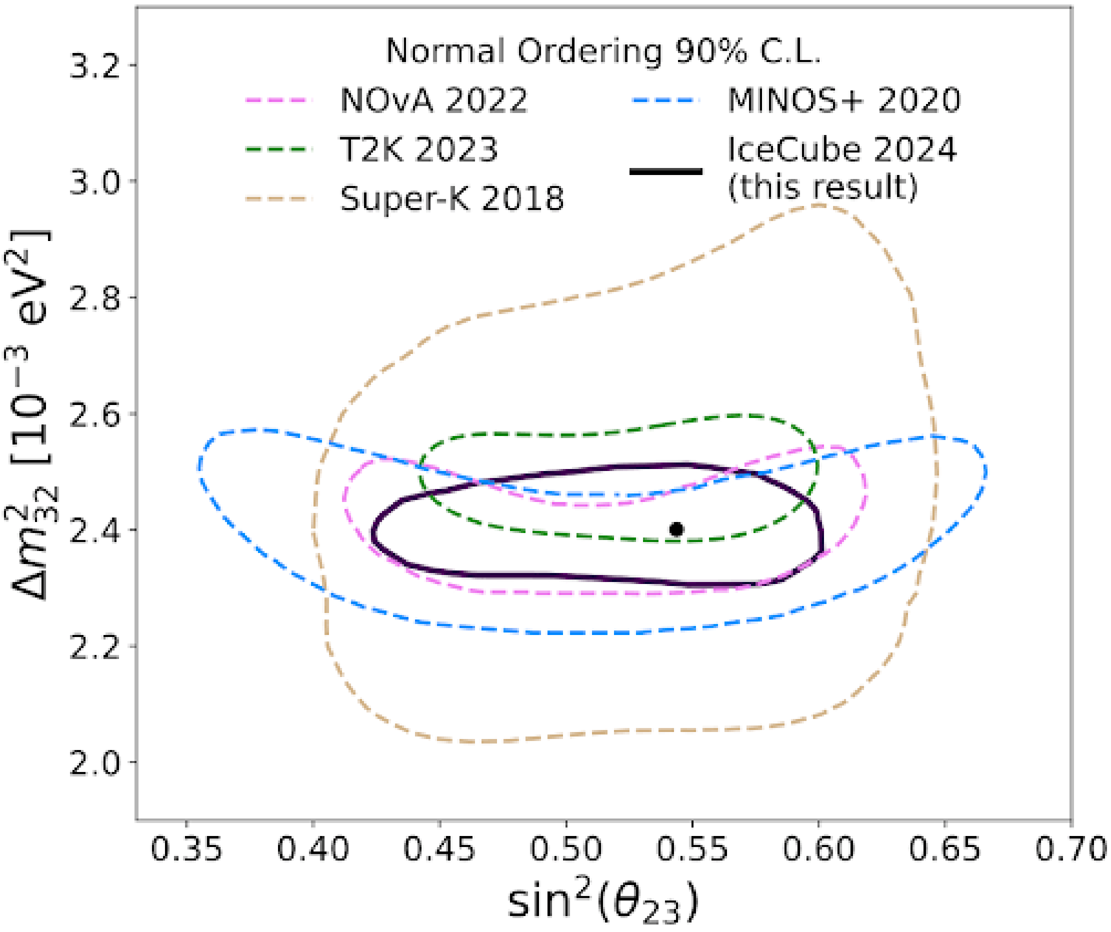
- Two event topologies at oscillation energies:



Measuring Neutrino Oscillations



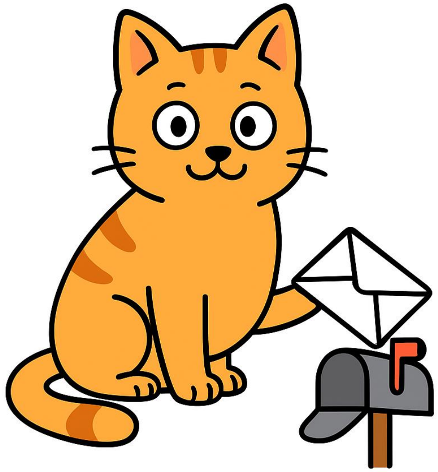
Neutrino Oscillations: Results



DeepCore data taken between 2012-2021

150,000 candidate neutrino events between 5 GeV and 100 GeV

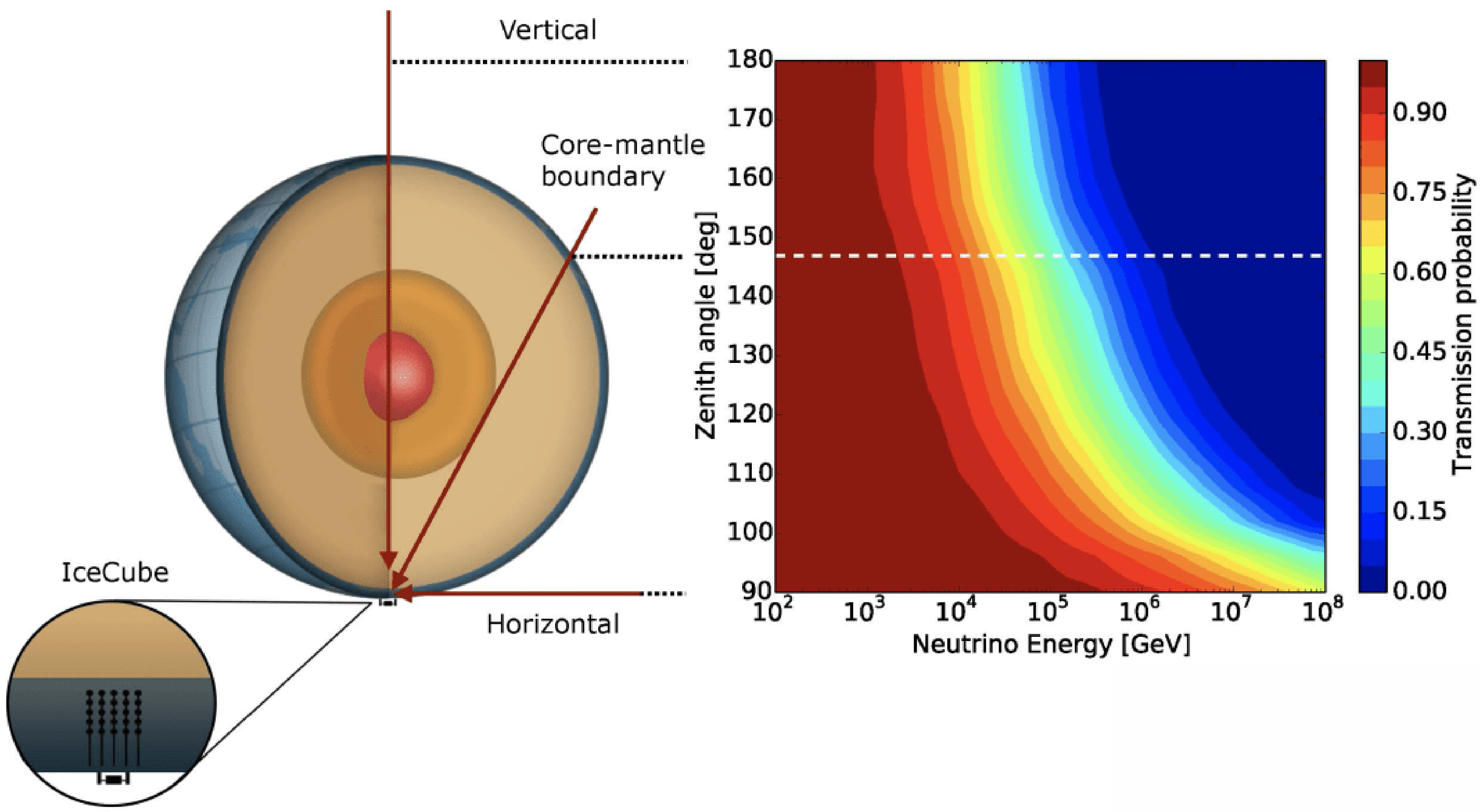
IceCube, PRL 134 (2025) 9, 091801



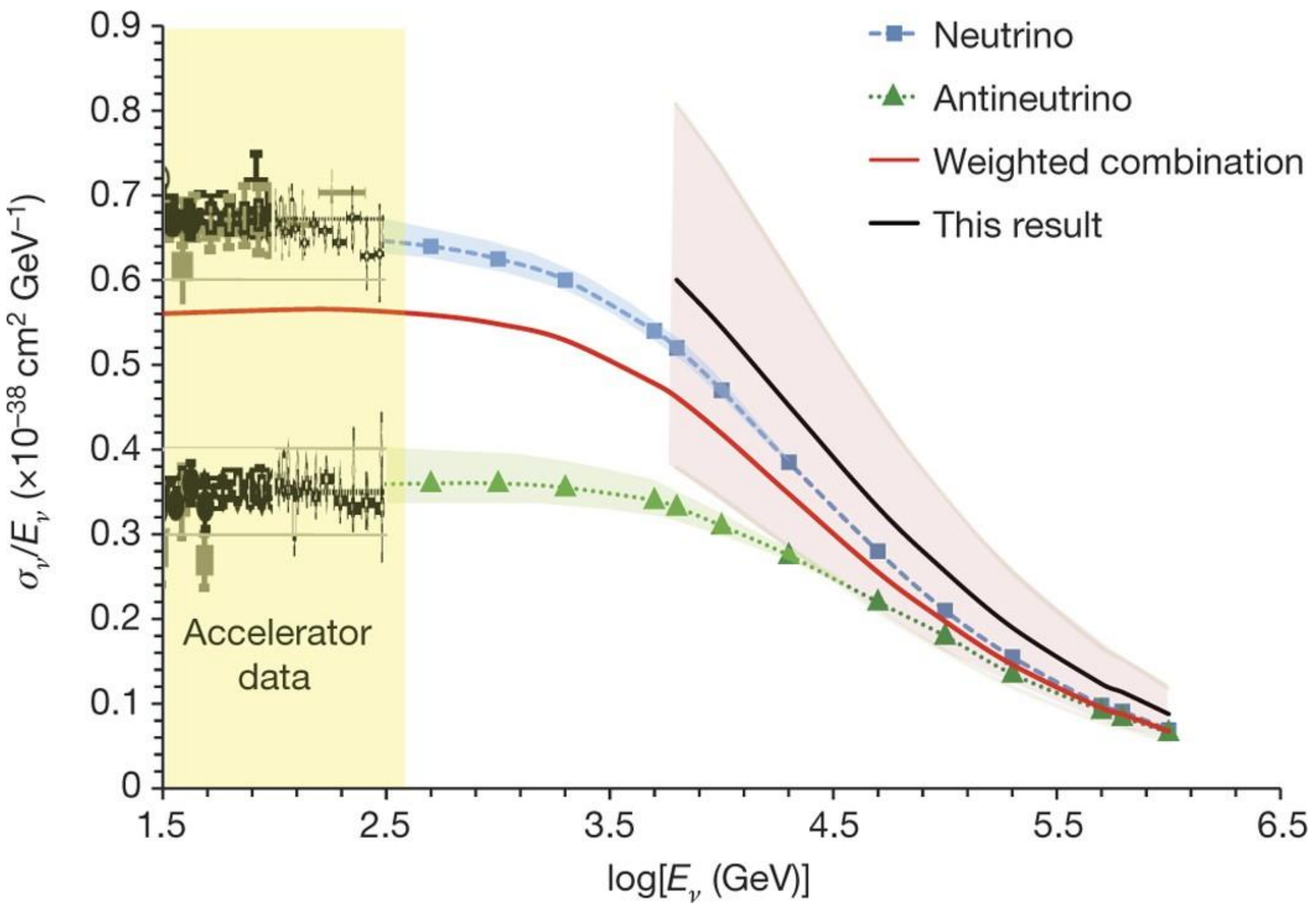
Take home message

Neutrino telescopes can do competitive measurements of neutrino oscillation parameters. The *O*(10GeV) range is crucial.

Neutrino Cross Section Measurement

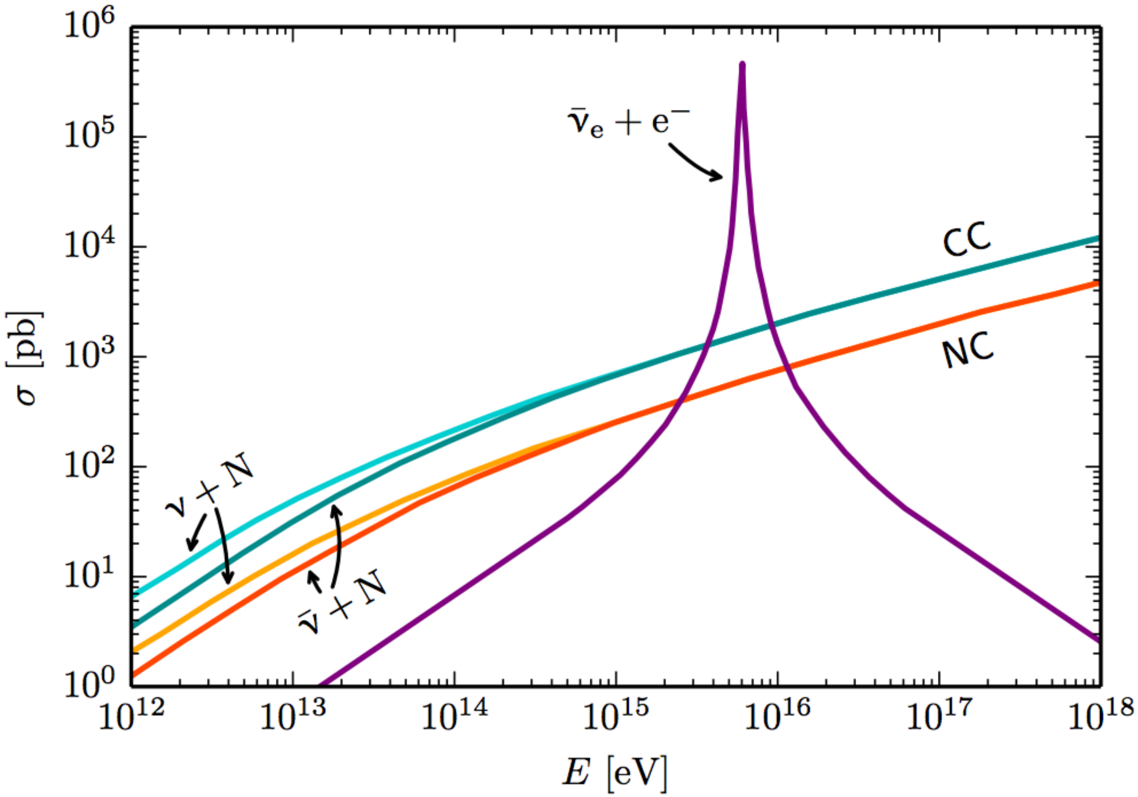


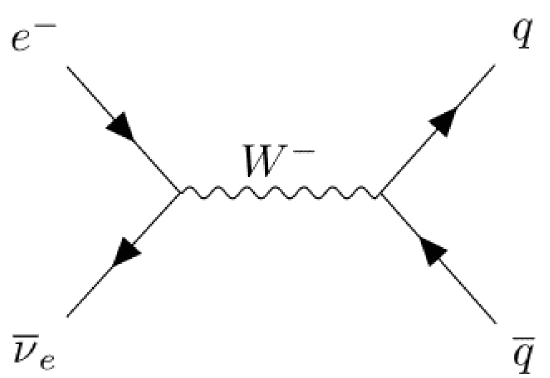
Neutrino Cross Section Measurement



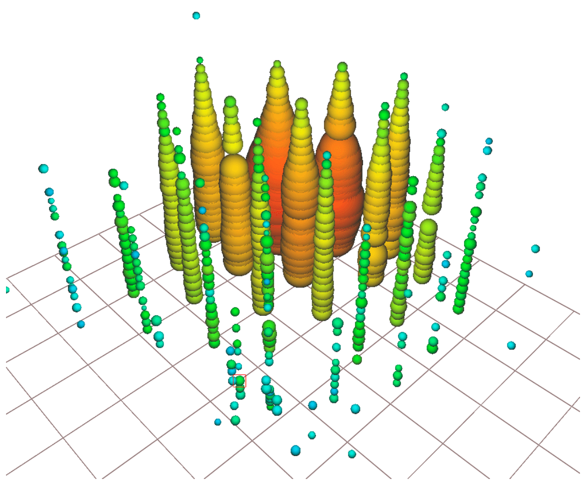
Glashow Resonance

Glashow resonance: resonant formation of a W^- boson during the interaction of a high-energy electron antineutrino with an electron, peaking at an antineutrino energy of 6.3 PeV in the rest frame of the electron.





Glashow Resonance



E = 6.05 ± 0.72 PeV

- astrophysical neutrino at the 5σ level
- consistent with the hadronic decay of a W^{-} boson produced on the Glashow resonance
- probability that the event is produced off-resonance by deep inelastic scattering is 0.01

- Confirms standard model
- Measurement of the diffuse flux
- Opens a way to distinguish ν_e and $\bar{\nu}_e$

→ identify hadronuclear or photohadronic interactions, with or without strong magnetic fields

IceCube, Nature 591, 220–224 (2021)

Neutrino Production Processes

$$pp \rightarrow \begin{cases} p + n + \pi^{+} \\ p + p + \pi^{+} + \pi^{-} \\ p + p + \pi^{0} \end{cases}$$

$$p\gamma \rightarrow \Delta^{+} \begin{cases} n + \pi^{+} \\ p + \pi^{0} \end{cases}$$

RUB

Neutrino Production Processes

$$pp \rightarrow \begin{cases} p + n + \pi^+ \\ p + p + \pi^+ + \pi^- \\ p + p + \pi^0 \end{cases}$$

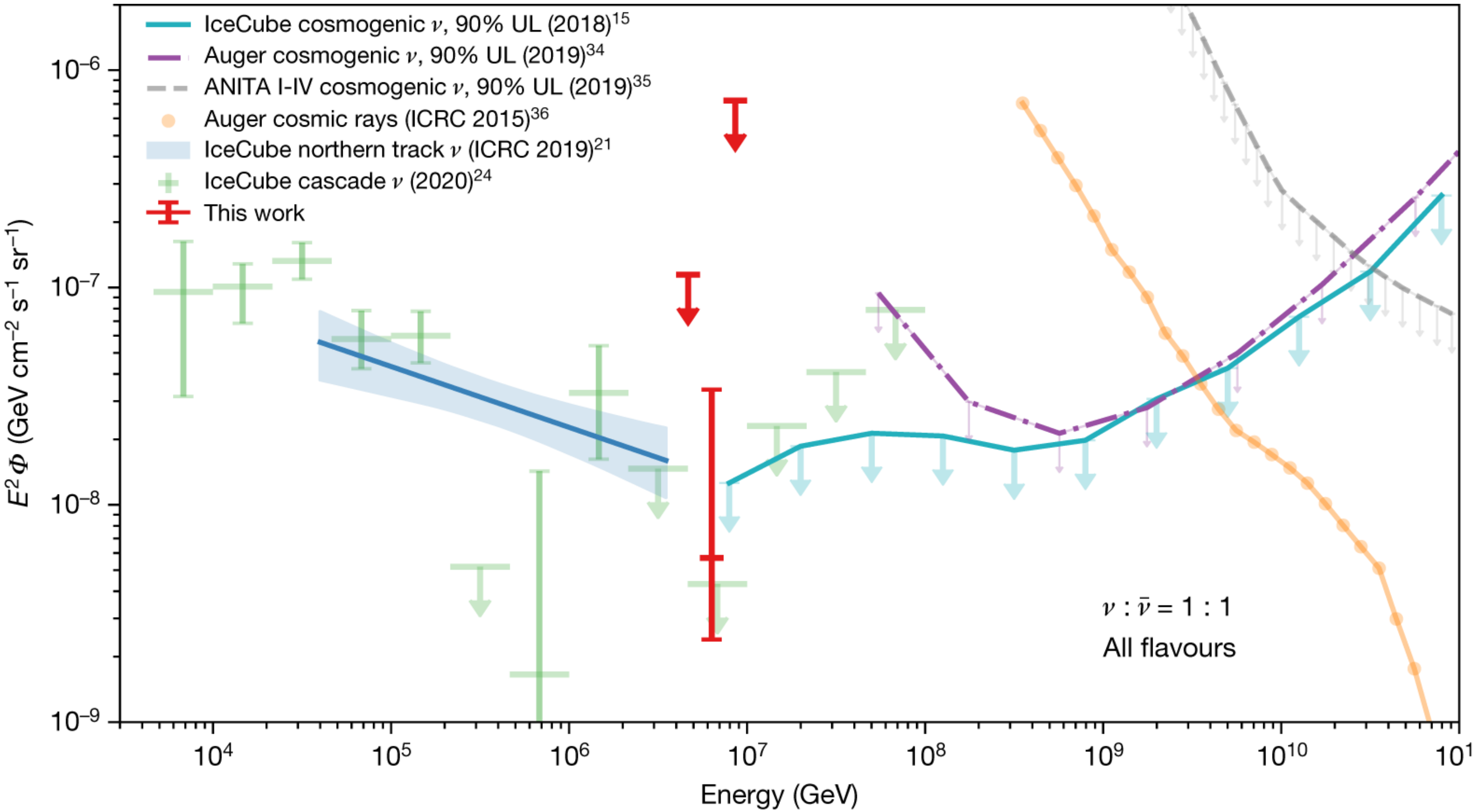
$$p\gamma \rightarrow \Delta^+ \begin{cases} n + \pi^+ \\ p + \pi^0 \end{cases}$$

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu \rightarrow e^- + \bar{\nu}_e + \nu_\mu + \bar{\nu}_\mu$$

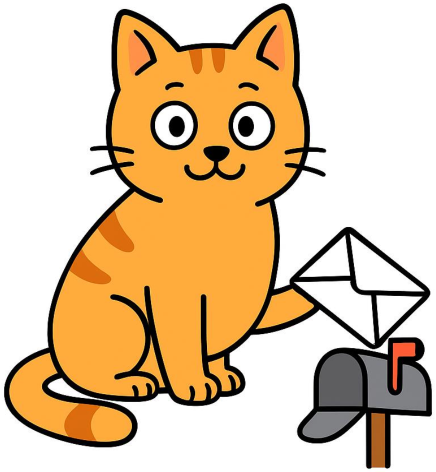
- Only π^- decays produce $\bar{\nu}_e$, those are common in pp, but not in $p\gamma$
- In strong magnetic fields, muons cool before they decay

RUB

Glashow Resonance



IceCube, Nature 591, 220–224 (2021)

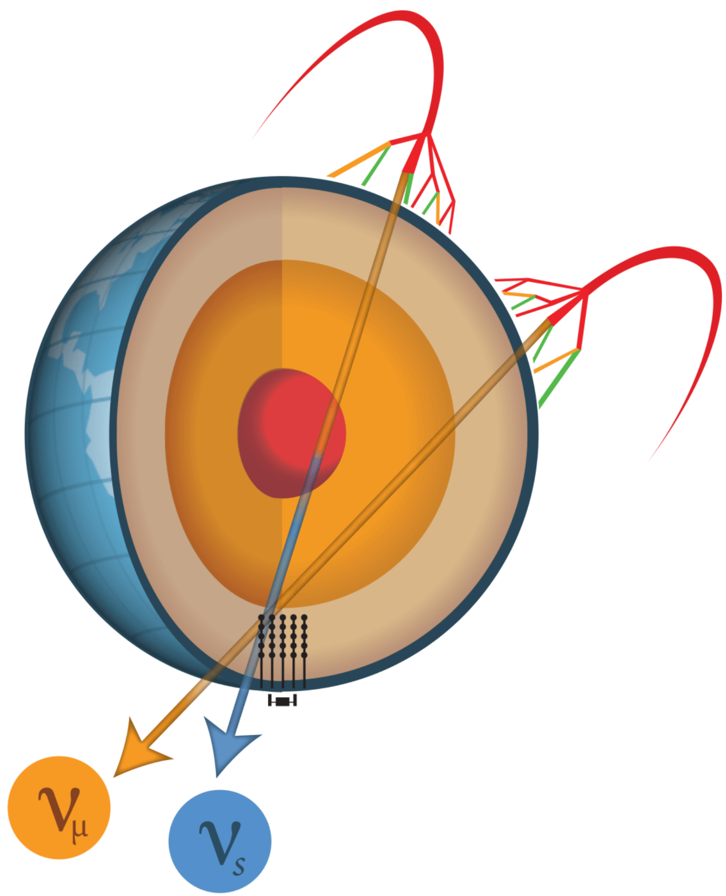


Take home message

Earth absorption can be used to measure the neutrino cross section.

One event consistent with the Glashow resonance was found.

Exotic Physics – Sterile Neutrinos



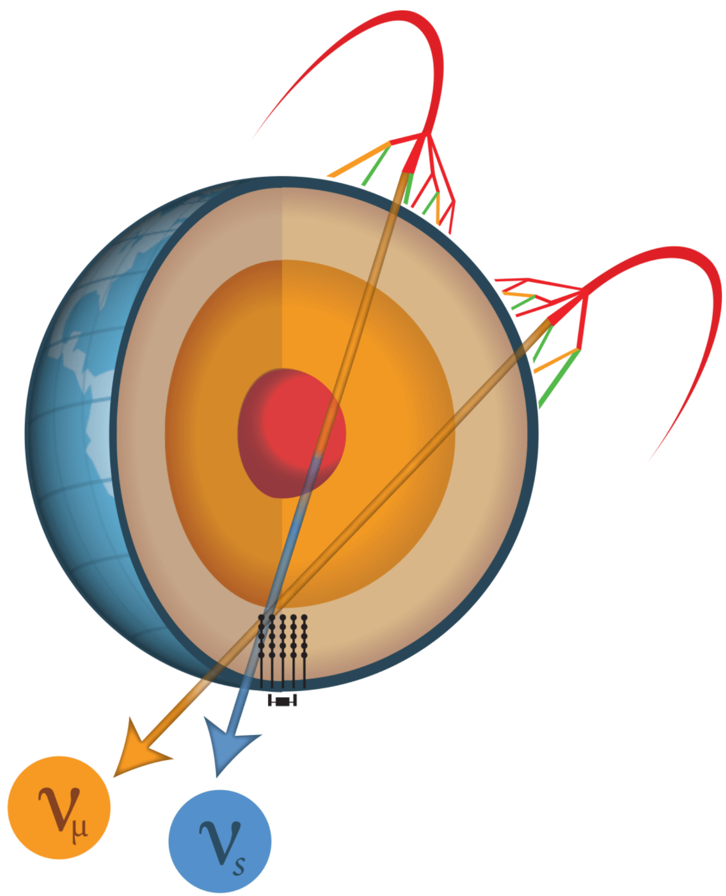
Sterile neutrino: A forth neutrino, that does not interact weakly, but can mix with other neutrinos

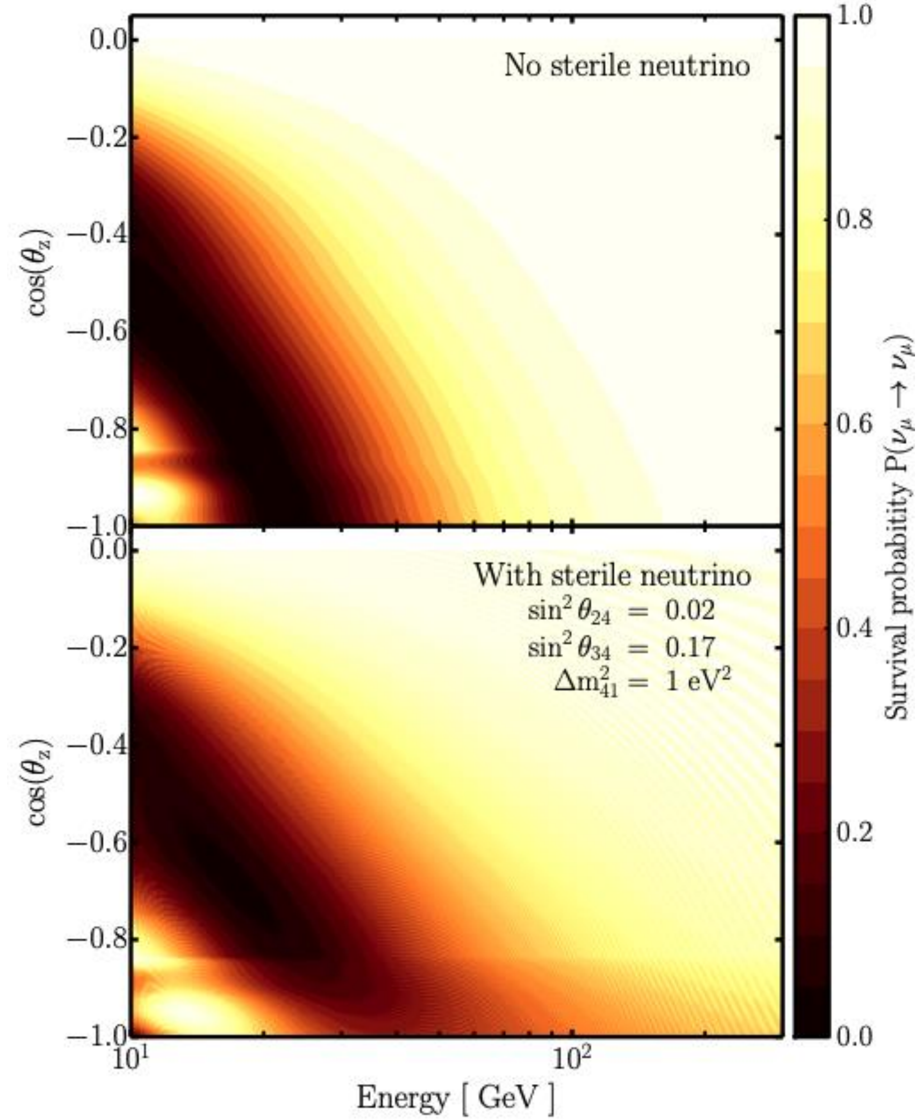
Motivation:

- Dark matter candidate
- Anomalies seen by reactor and accelerator neutrino experiments
- In the see-saw mechanism, heavy sterile neutrinos explain small neutrino mass

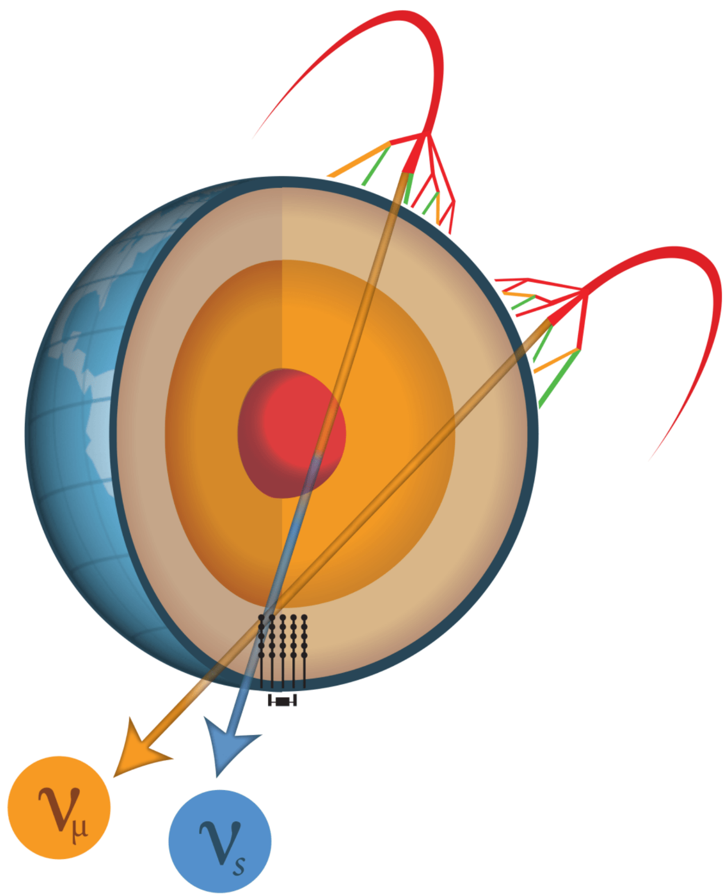
Search: Look for modifications in oscillation pattern

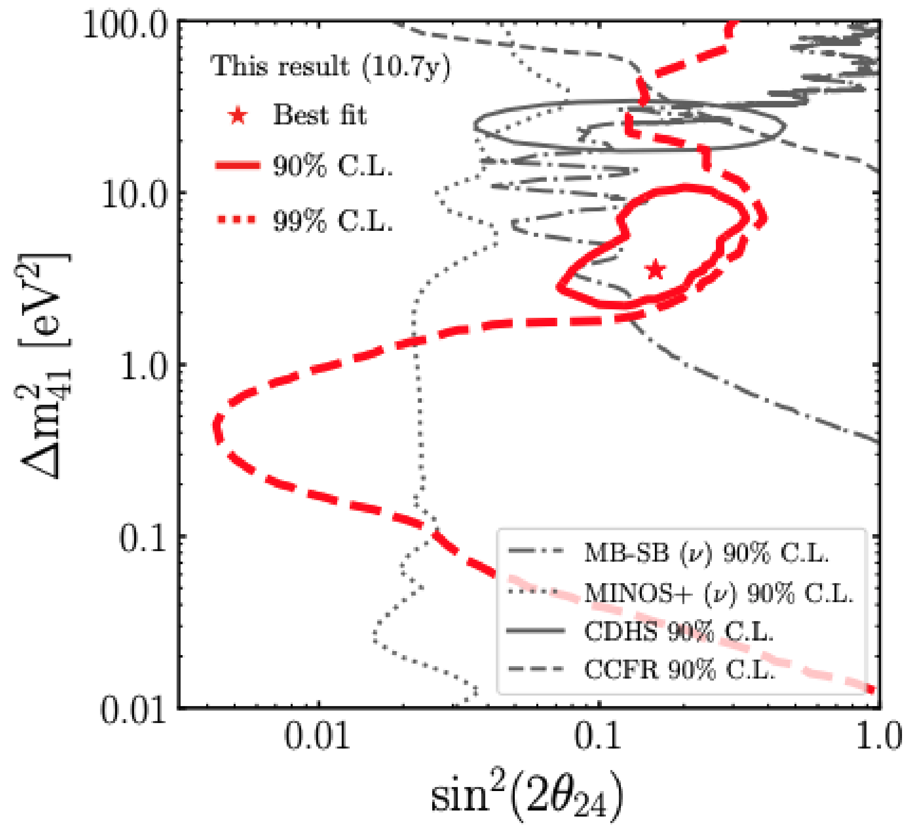
Exotic Physics – Sterile Neutrinos





Exotic Physics – Sterile Neutrinos



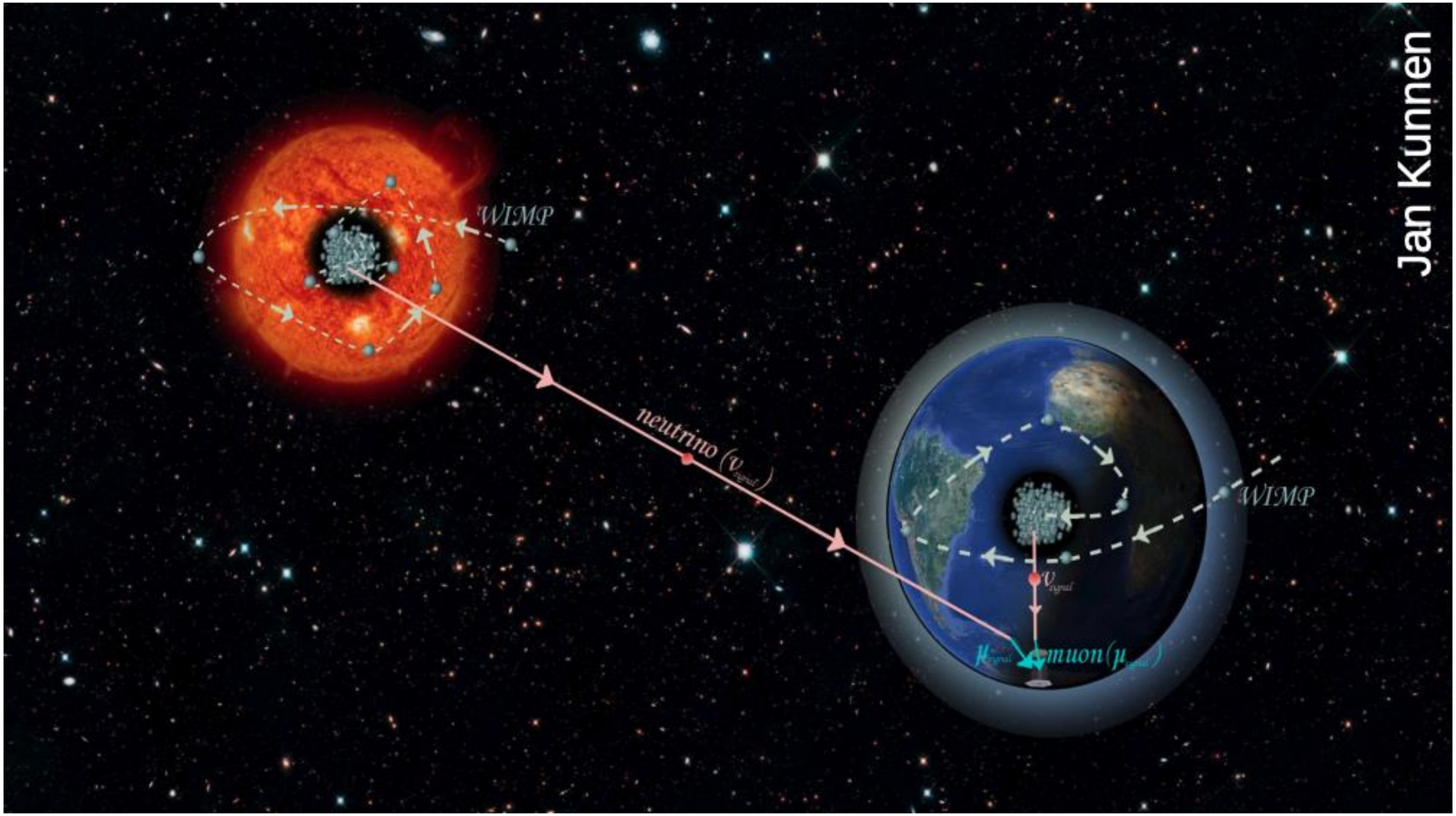


Results: no significant excess found
→ anomalies largely excluded

IceCube PRD 110, 092009 (2024)

Exotic Physics – Searches for WIMP Dark Matter

WIMP dark matter particles can be captured by celestial bodies like the Sun or Earth



Exotic Physics – Searches for WIMP Dark Matter

WIMP dark matter particles can be captured by celestial bodies like the Sun or Earth → enhanced self-annihilation into Standard Model particles including neutrinos

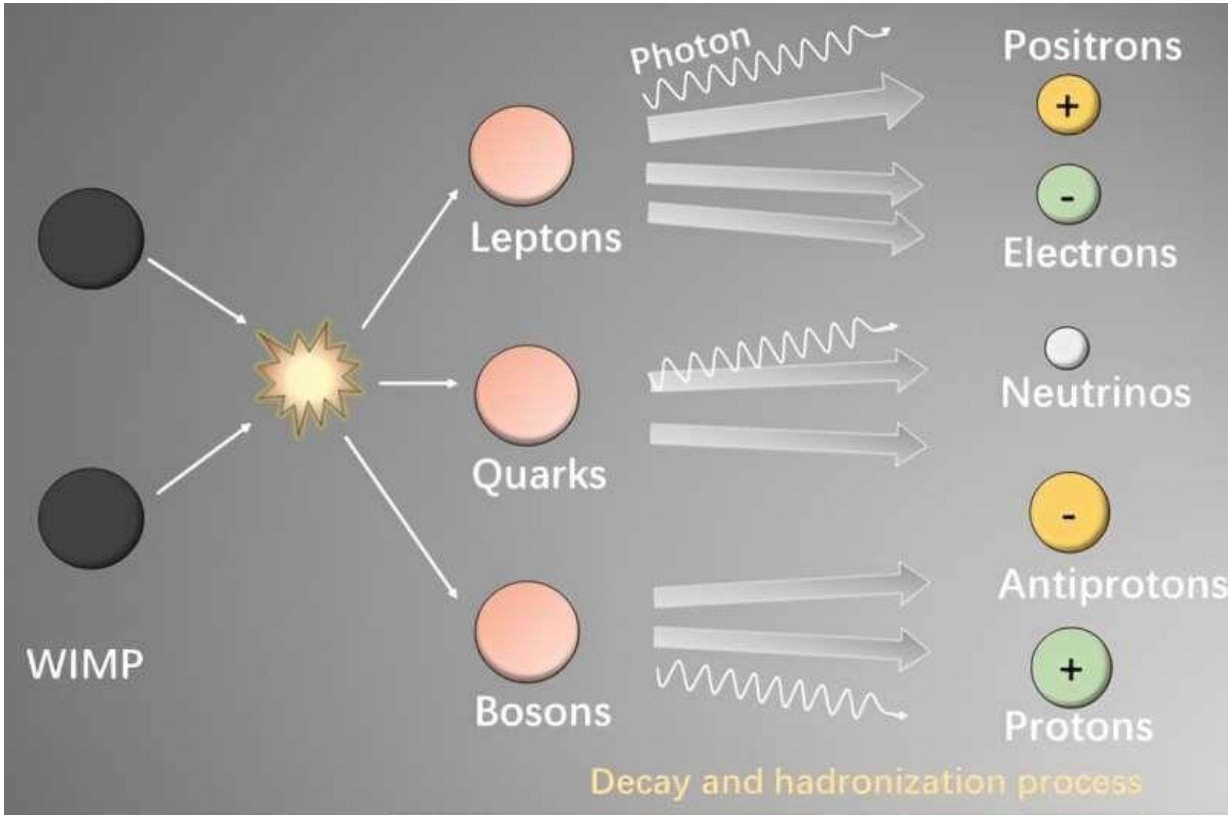
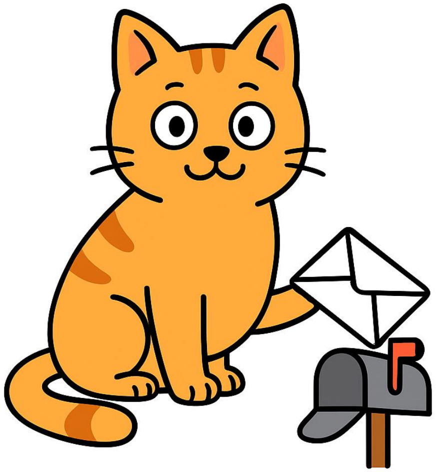


Image Credit: Gao Linqing and Lin Sujie

RUB



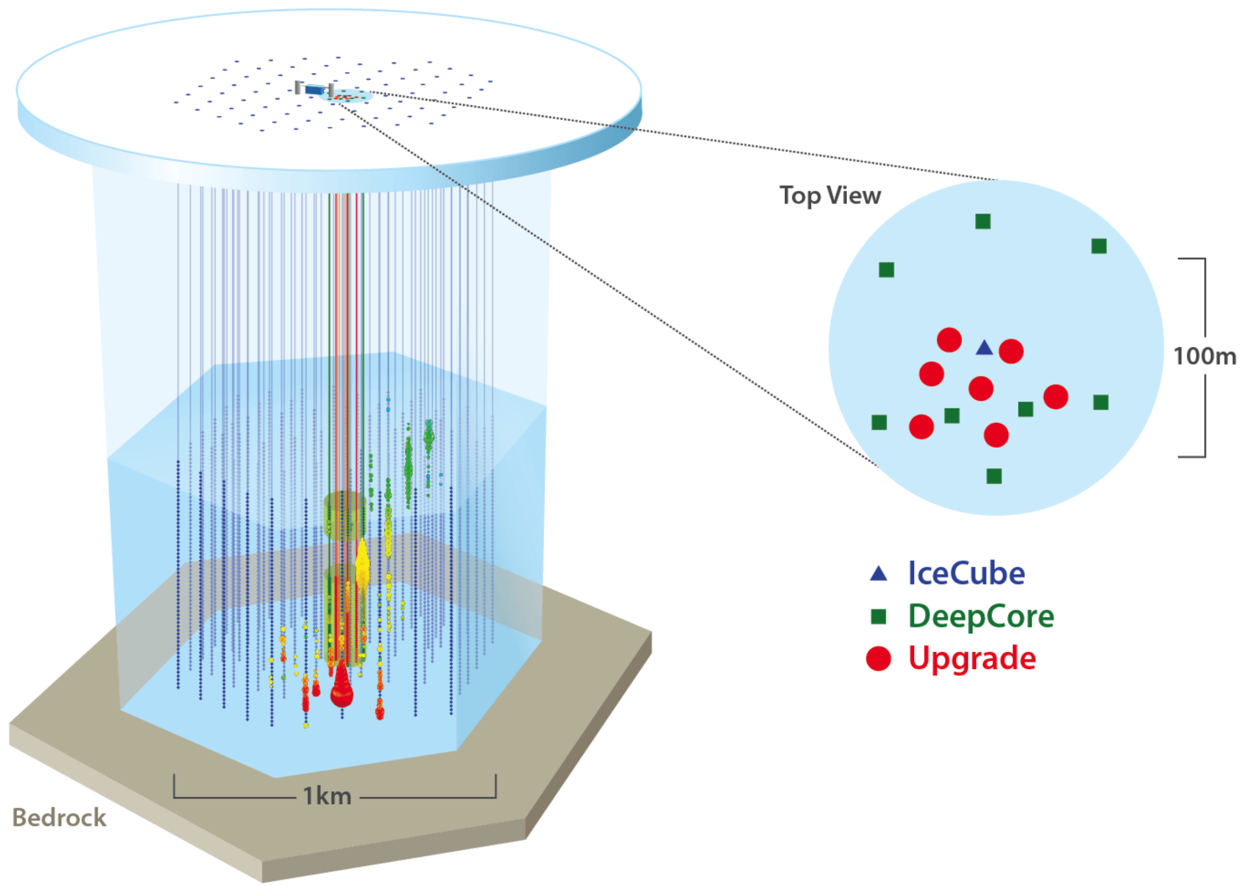
Take home message

Deviations from the expected neutrino oscillation pattern could be caused by sterile neutrinos.
WIMPs can accumulate in the Earth and Sun and produce an excess of neutrino when annihilating.

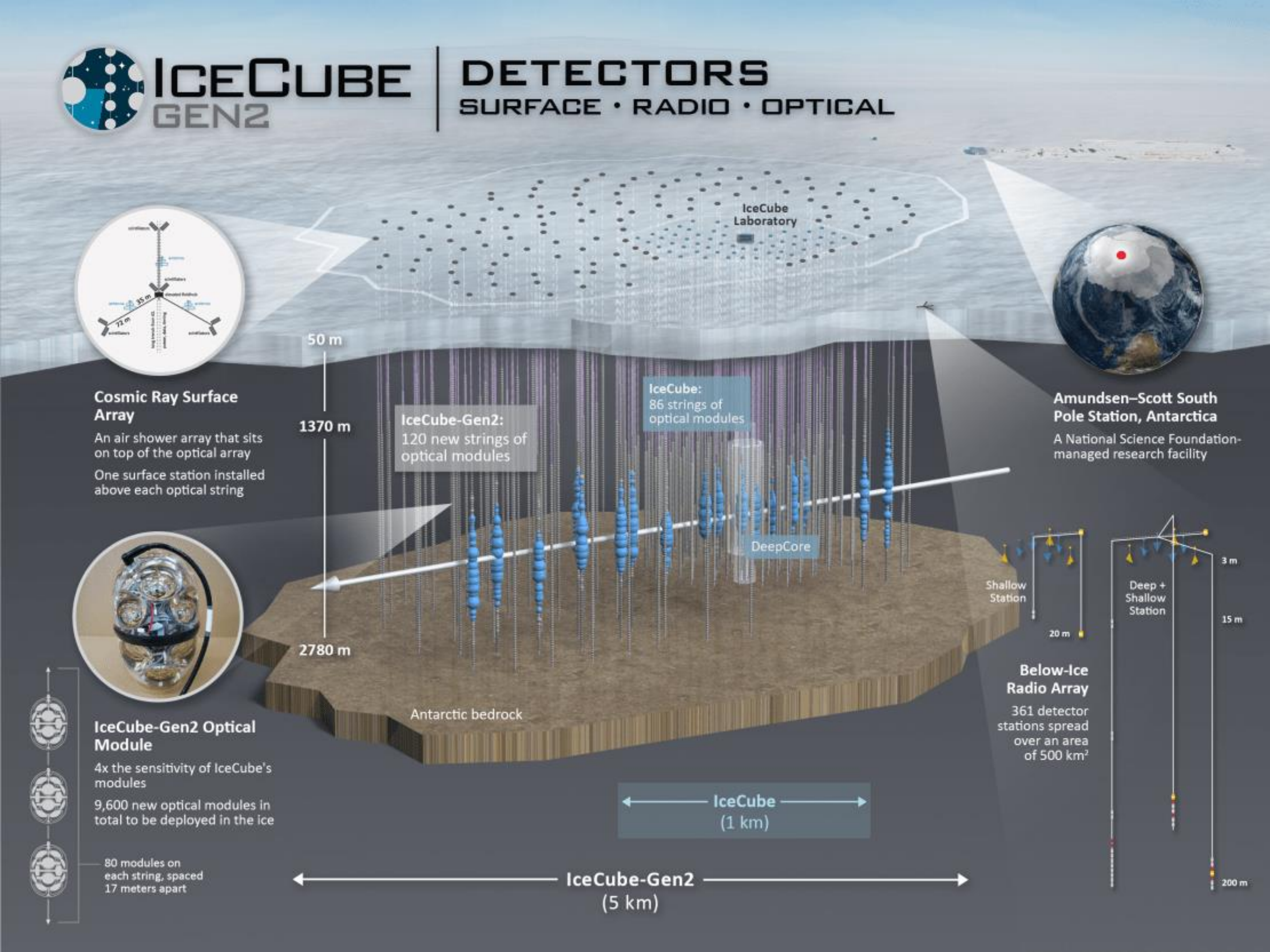
Future Detectors

IceCube-Upgrade: Low-energy Extension and Calibration

- First step towards IceCube-Gen2 (8 km³)
- 7 new strings in the center of IceCube
- **New calibration devices**
- Science focus: Neutrino properties



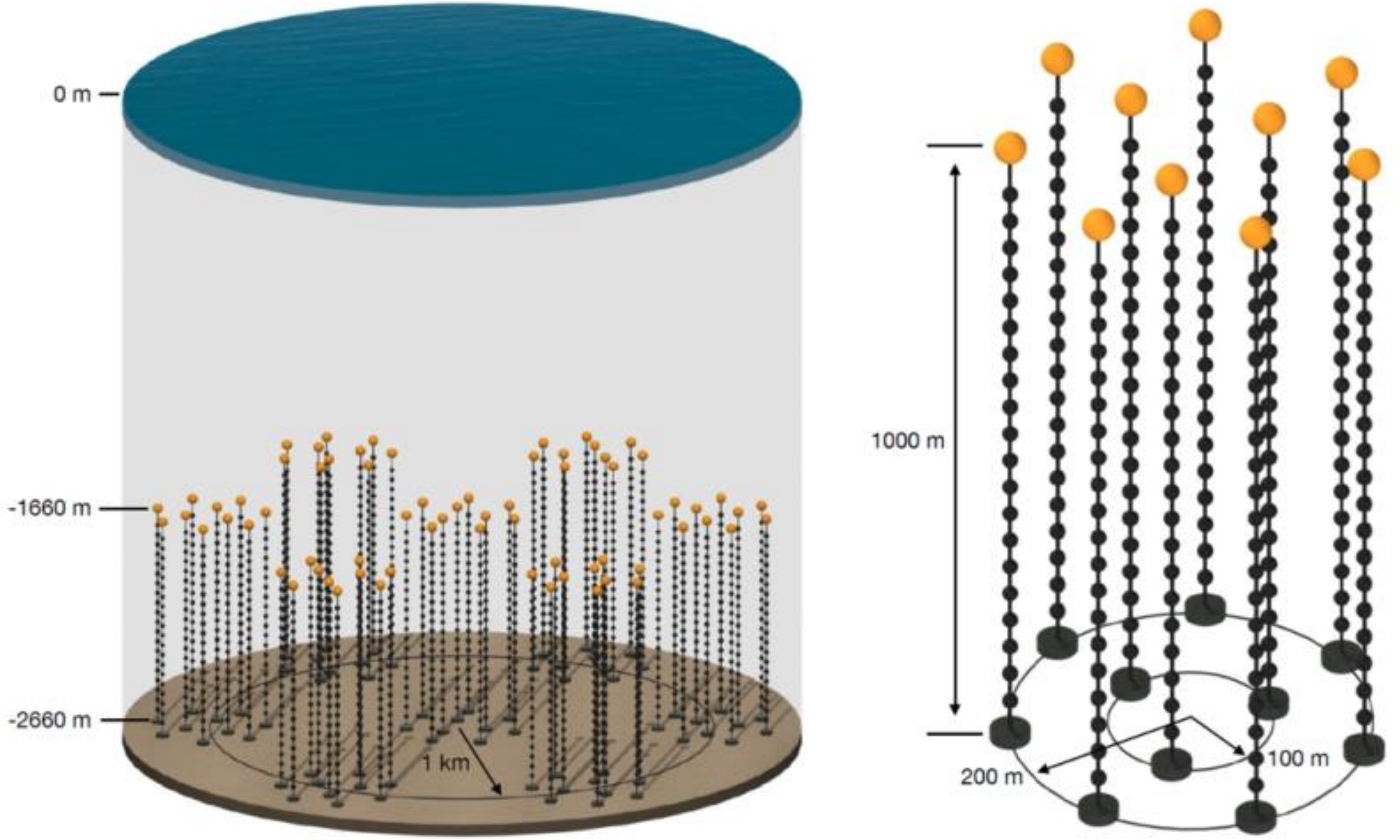
https://icecube-gen2.wisc.edu/science/publications/tdr/



ICECUBE GEN2
DETECTORS
SURFACE • RADIO • OPTICAL
IceCube Laboratory
50 m
1370 m
2780 m
Cosmic Ray Surface Array
An air shower array that sits on top of the optical array
One surface station installed above each optical string
IceCube-Gen2: 120 new strings of optical modules
IceCube: 86 strings of optical modules
DeepCore
Amundsen–Scott South Pole Station, Antarctica
A National Science Foundation-managed research facility
Shallow Station
Deep + Shallow Station
3 m
15 m
20 m
200 m
Below-Ice Radio Array
361 detector stations spread over an area of 500 km²
Antarctic bedrock
IceCube-Gen2 Optical Module
4x the sensitivity of IceCube's modules
9,600 new optical modules in total to be deployed in the ice
80 modules on each string, spaced 17 meters apart
IceCube (1 km)
IceCube-Gen2 (5 km)

High-energy Neutrino Detectors

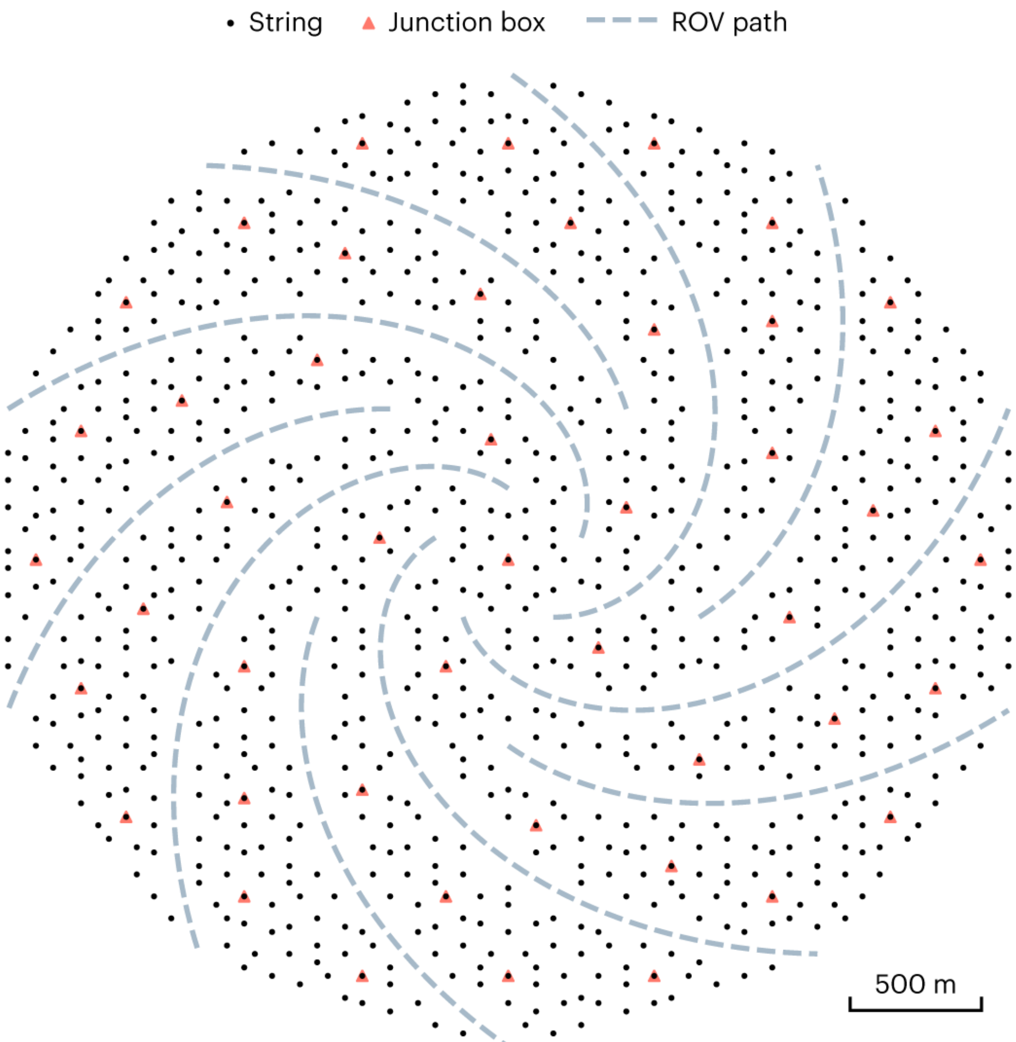
P-ONE



planned deployment of 10 strings explorer in 2025-2026
70 strings between 2028-2030

M. Agostini et al. Nature Astronomy 4 (2020)

High-energy Neutrino Detectors



Tropical Deep-sea Neutrino Telescope (TRIDENT), South Chinese Sea

depth of ~3.5 km

Volume: 7.5 km^3

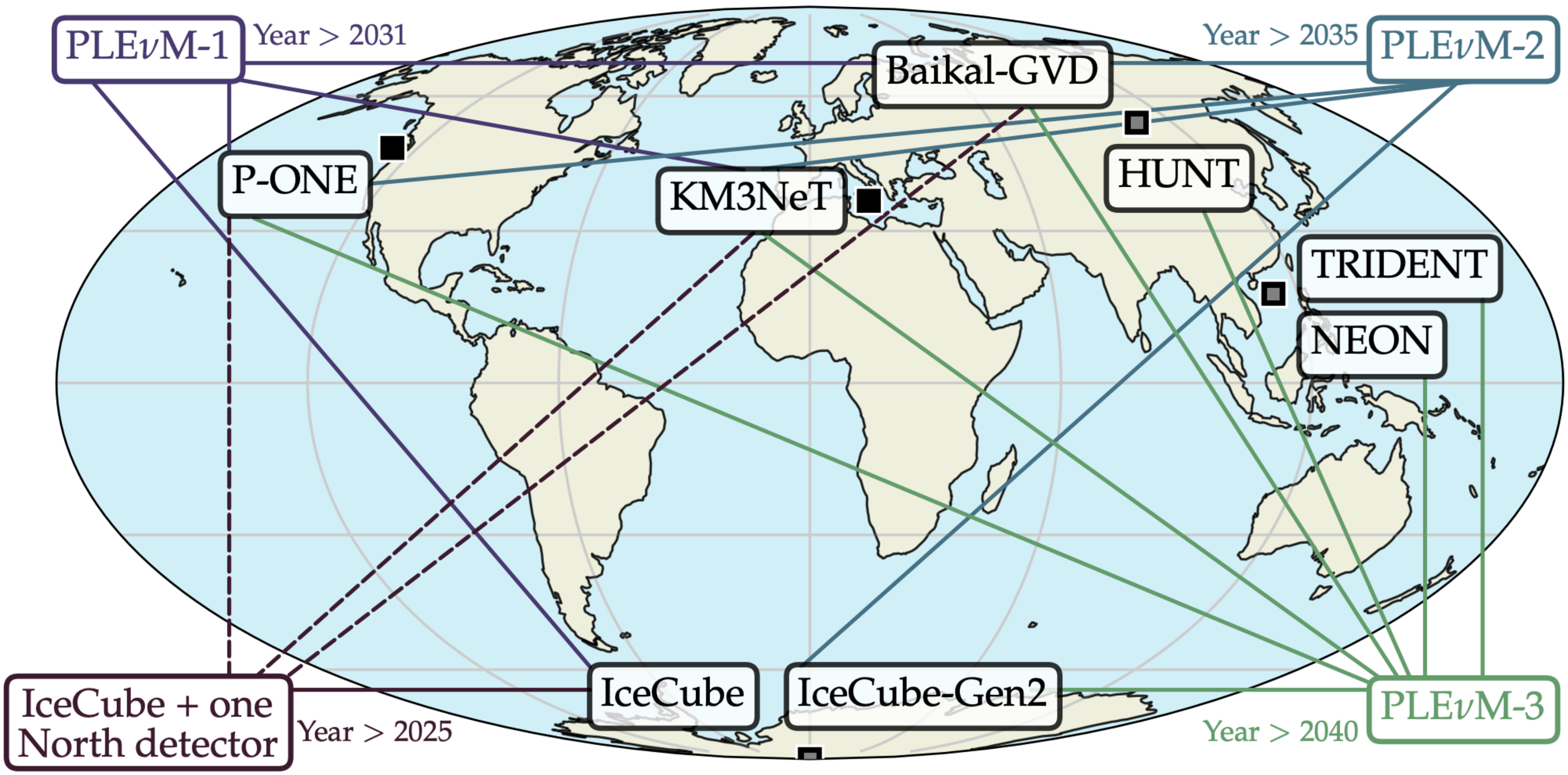
2021: water quality measurements

Full deployment in 2030

Ye et al. Nature Astronomy 7 (2023)

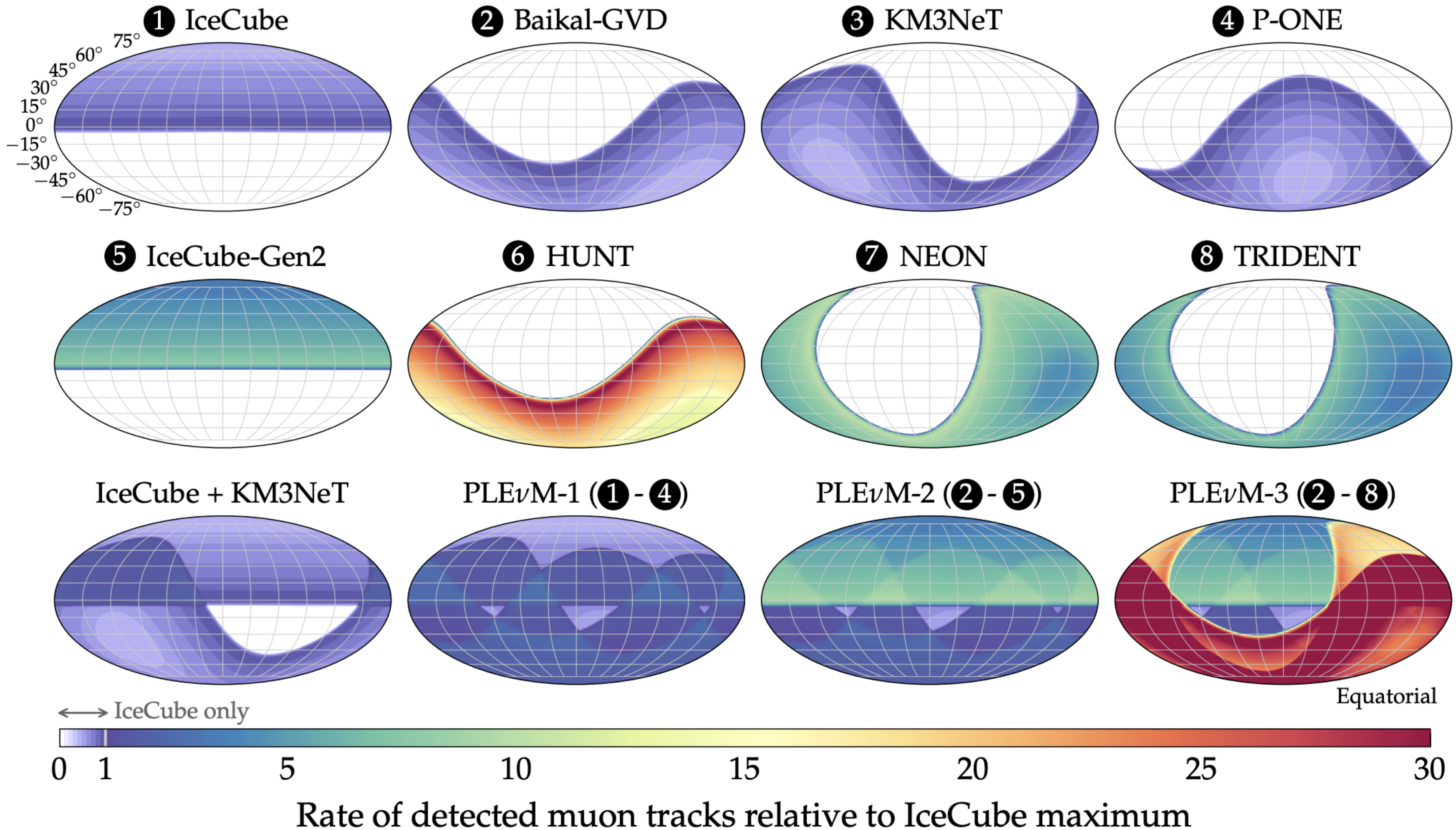
Planetary Neutrino Monitoring network (PLEnuM)

Idea: combined analysis of global data will expedite source discovery

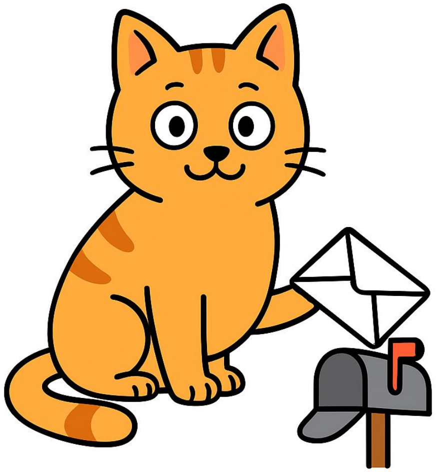


L. Schumacher et al. arXiv:2503.07549

Planetary Neutrino Monitoring network (PLEnuM)

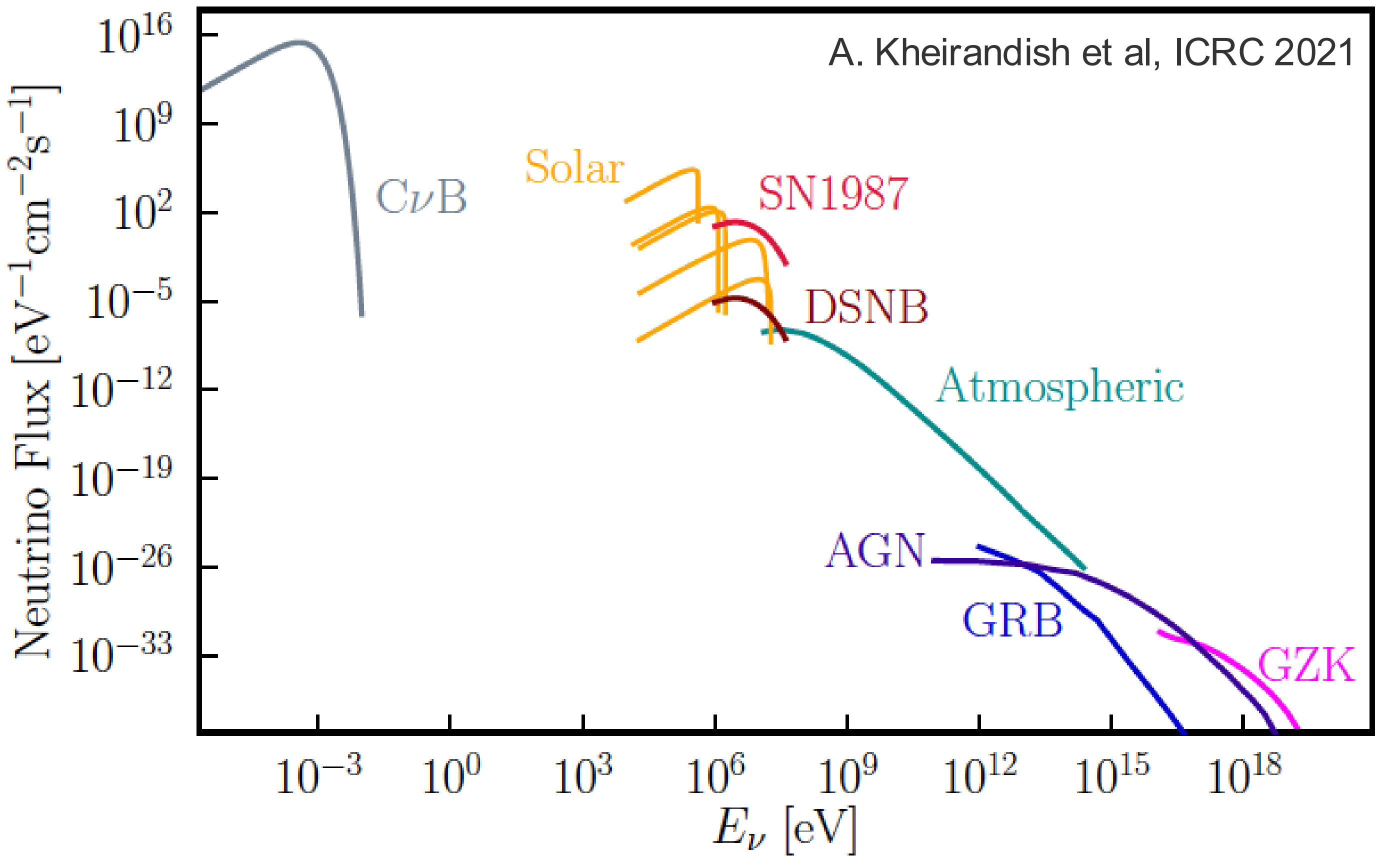


L. Schumacher et al. arXiv:2503.07549



Take home message

New high-energy neutrino telescopes are currently under construction / planned. Combining their data increases the sky coverage and sensitivity.



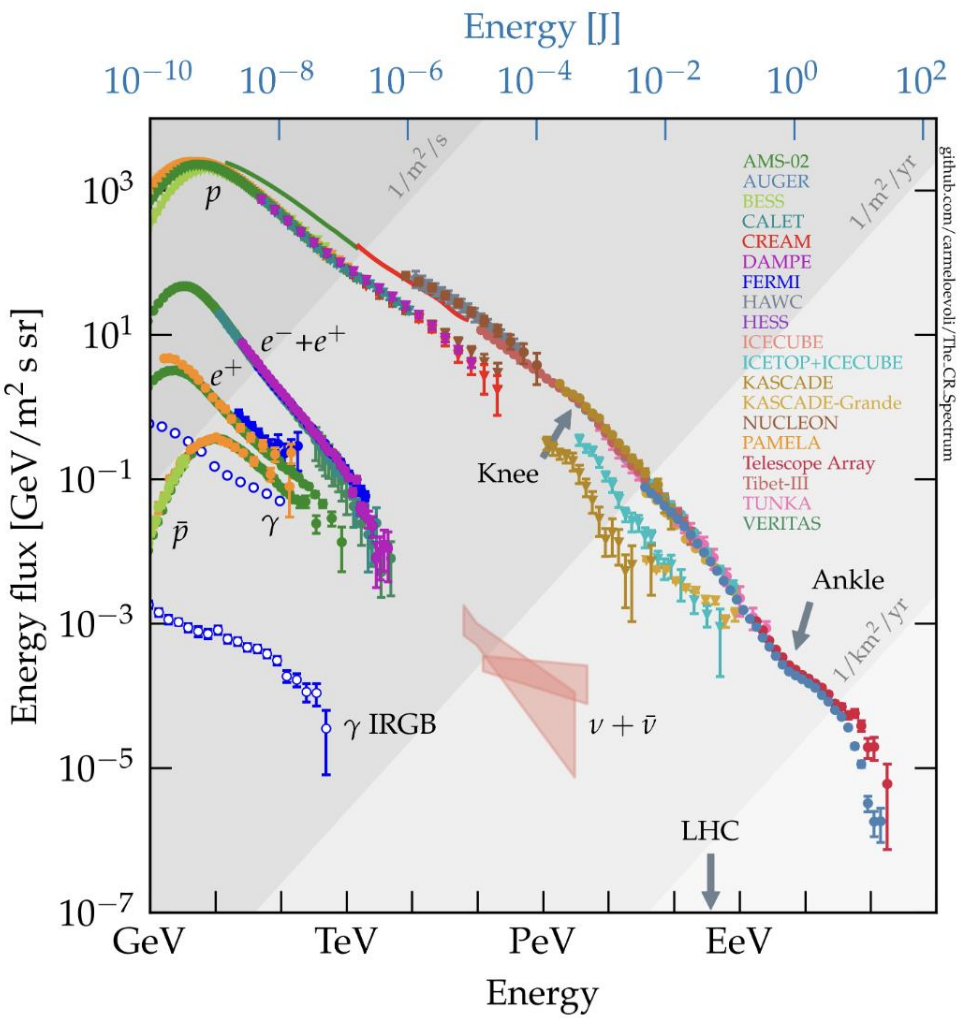
Ideas: neutrino capture on unstable nucleus (e.g. tritium)

Neutrino capture on stable nucleus (Chlorine, Gallium)

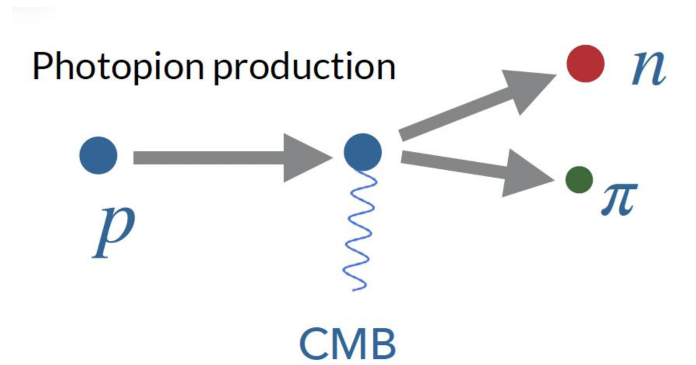
Water / ice Cherenkov detectors

Radio arrays, cosmic-ray detectors

Cosmogenic Neutrinos



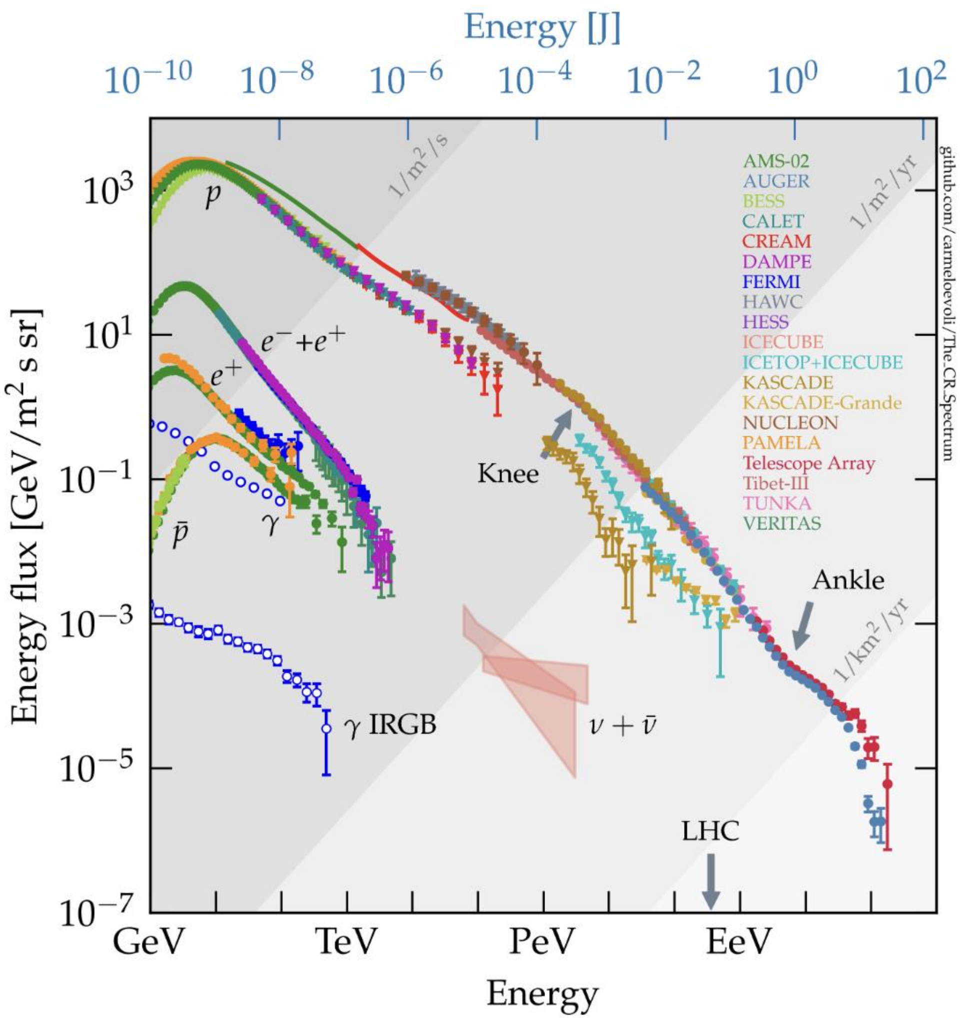
For Protons:



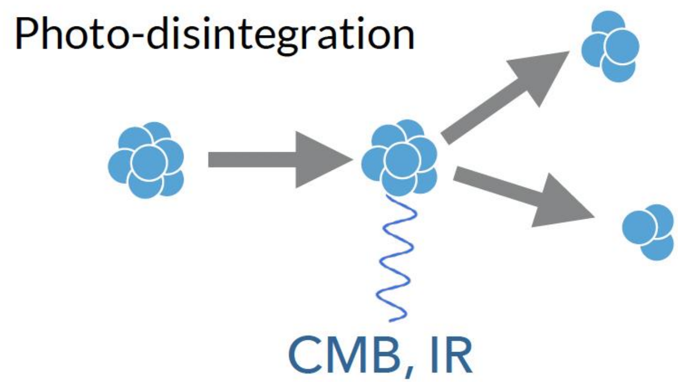
$$p + \gamma_{CMB} \rightarrow \Delta^+ \rightarrow \begin{cases} p + \pi^0 \\ n + \pi^+ \end{cases}$$

Energy Threshold: $5 \cdot 10^{19} eV$

Cosmogenic Neutrinos

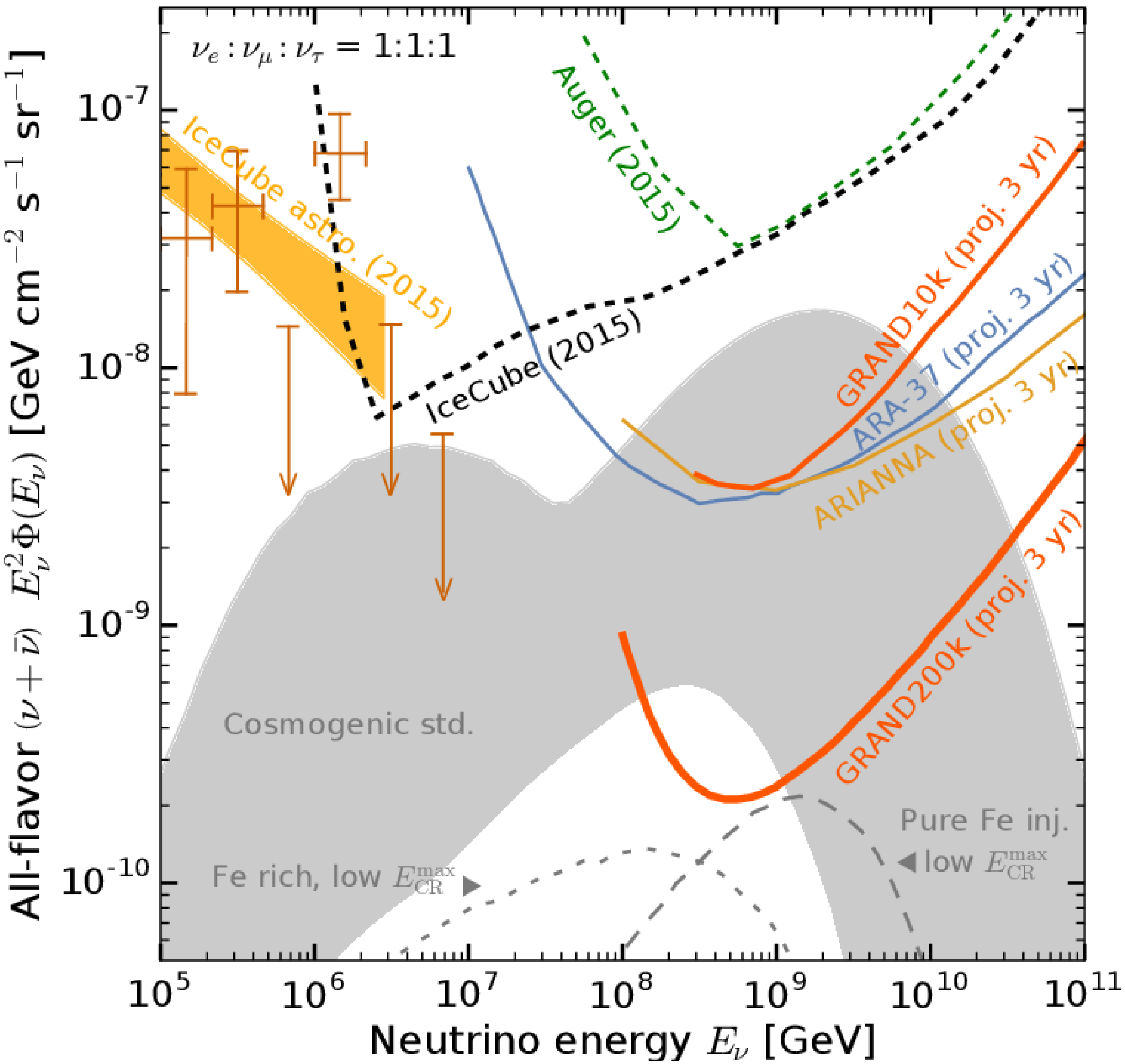


For heavier elements:

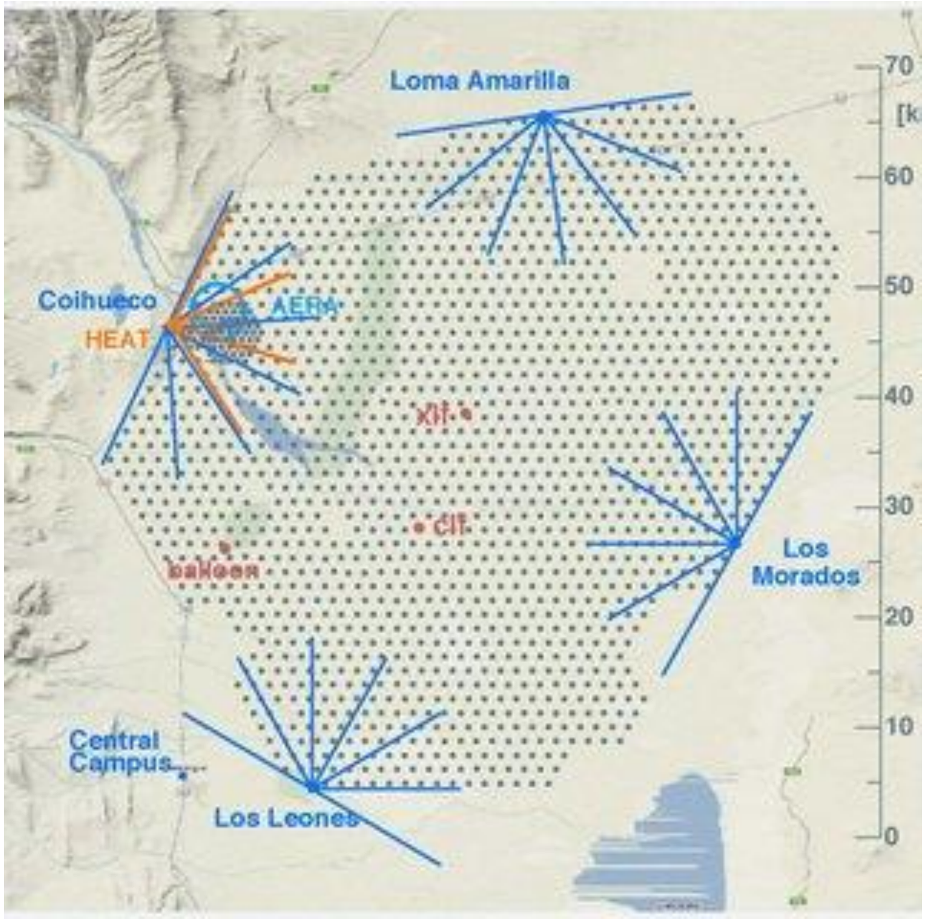


→ Neutrinos can help to infer the composition

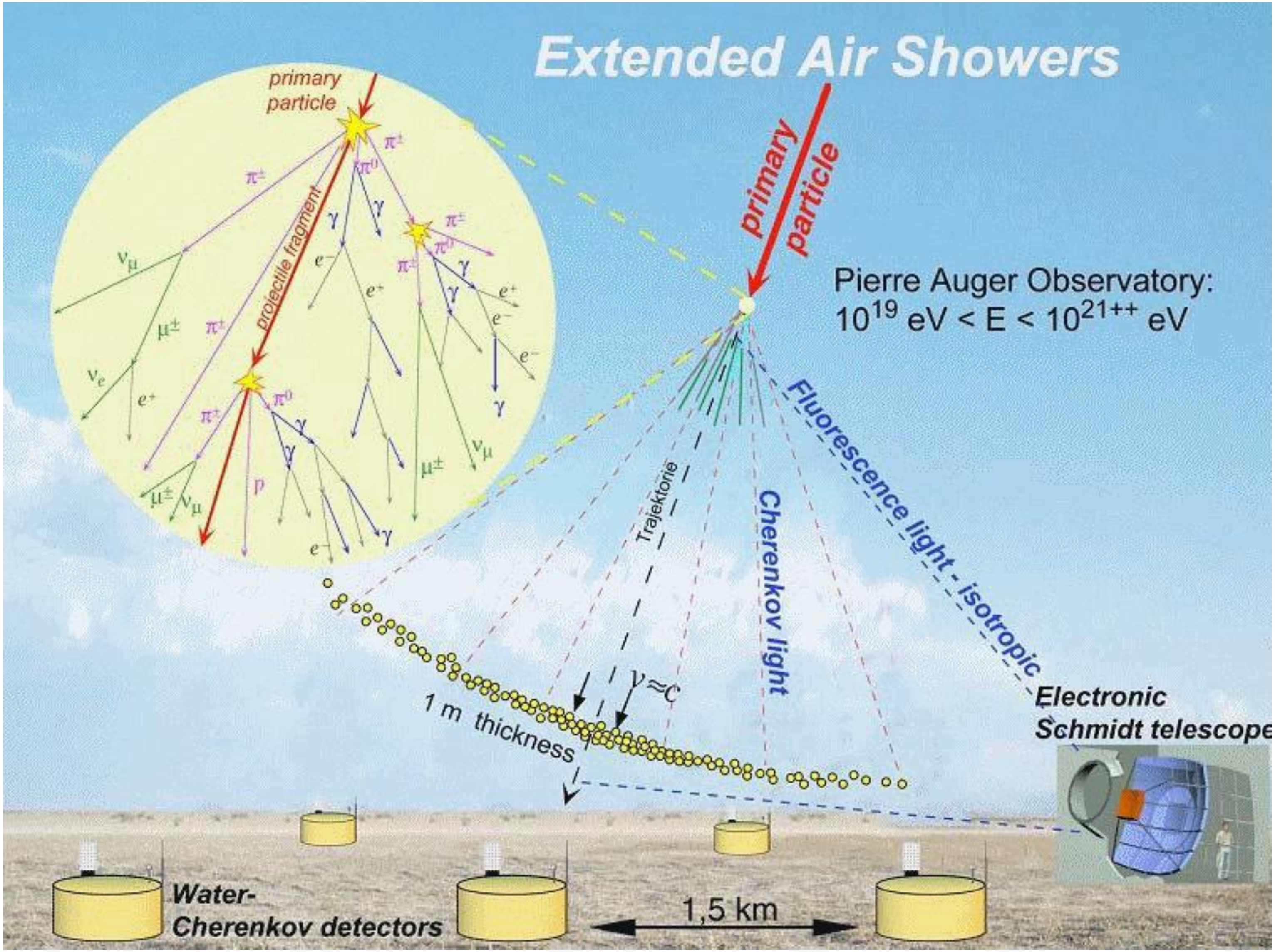
Cosmogenic Neutrinos



Neutrinos with the Pierre Auger Observatory

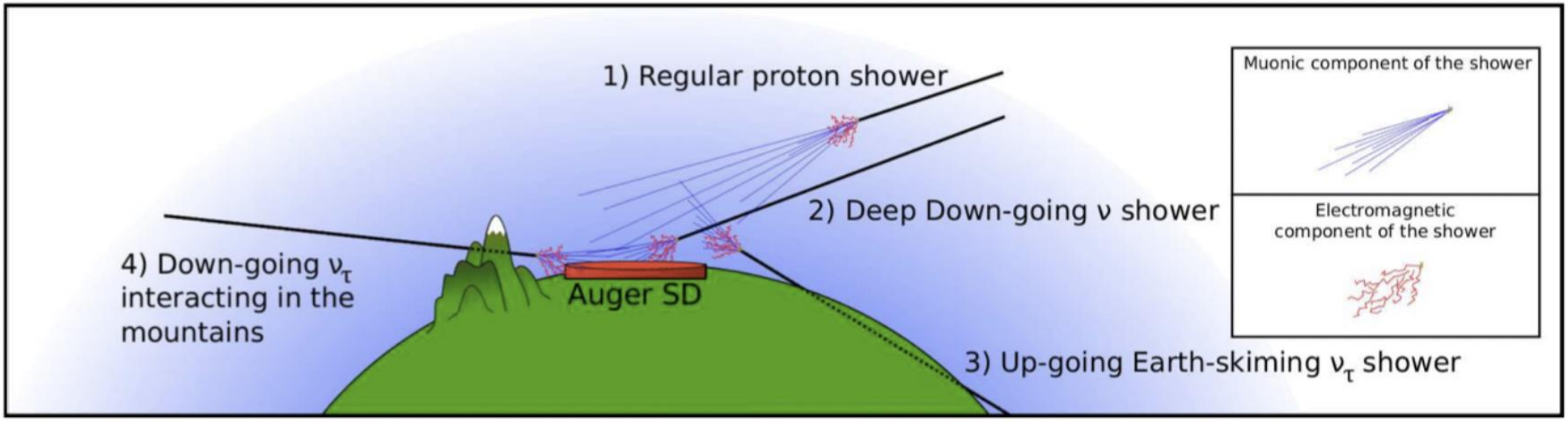


Neutrinos with the Pierre Auger Observatory

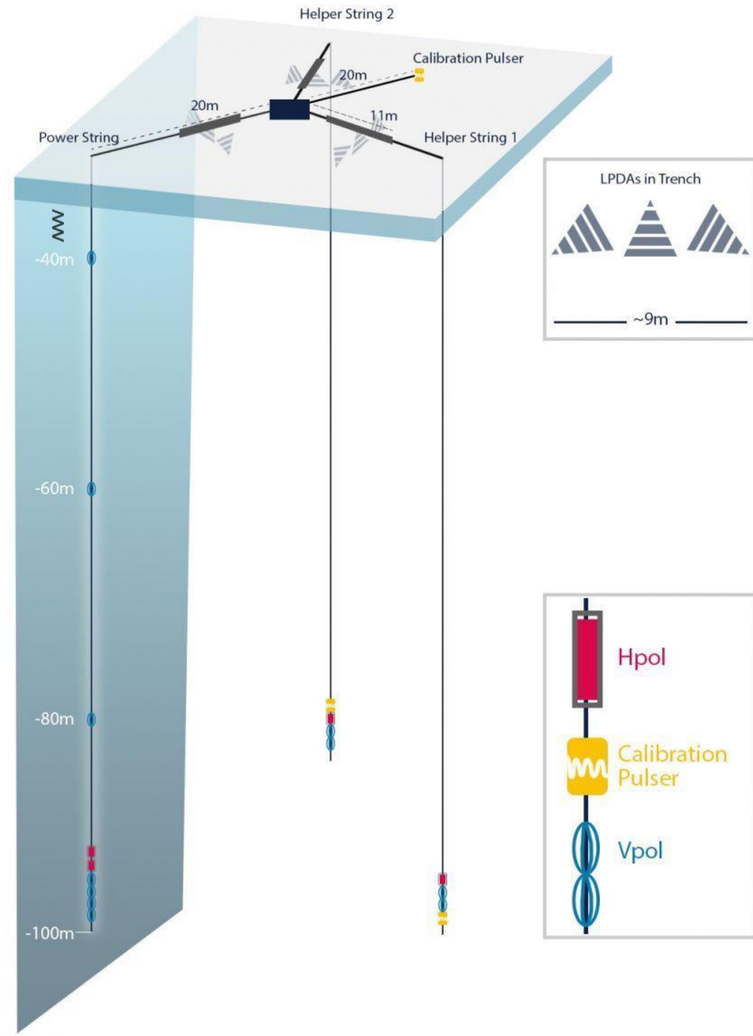


RUB

Neutrinos with the Pierre Auger Observatory



RNO-G

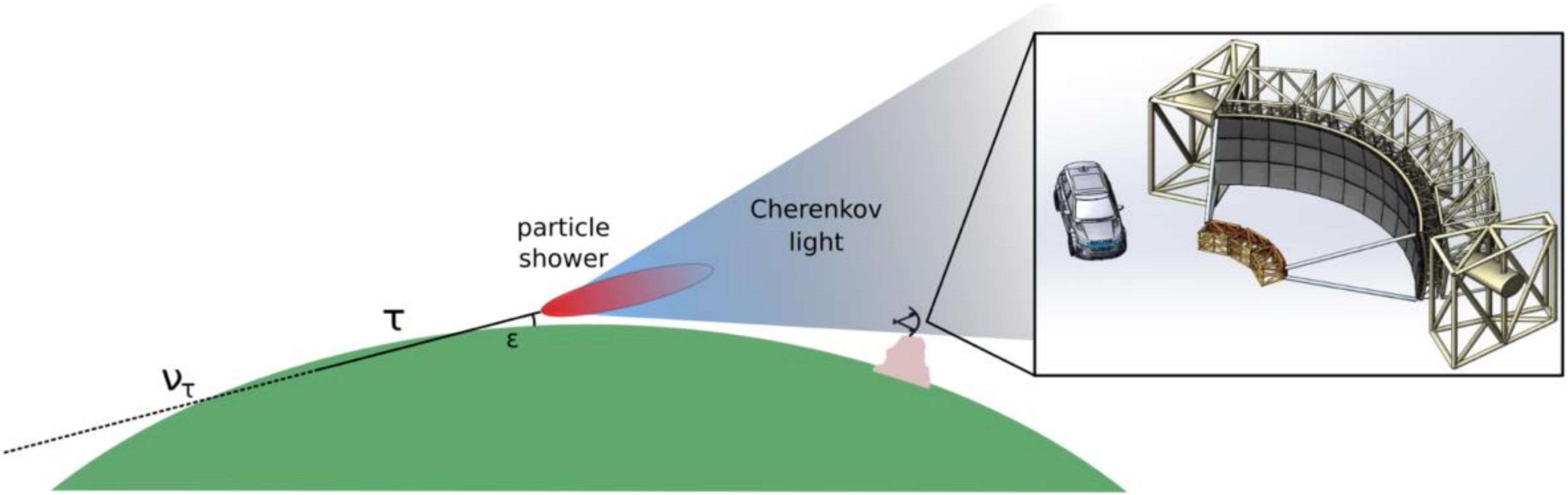


Askaryan effect:

- Negative charge accumulation in the shower front gives rise to a changing current, which gives rise to radio emission
- Emission is coherent at frequencies corresponding to the size of the shower

Trinity

One of 18 planned Trinity telescopes

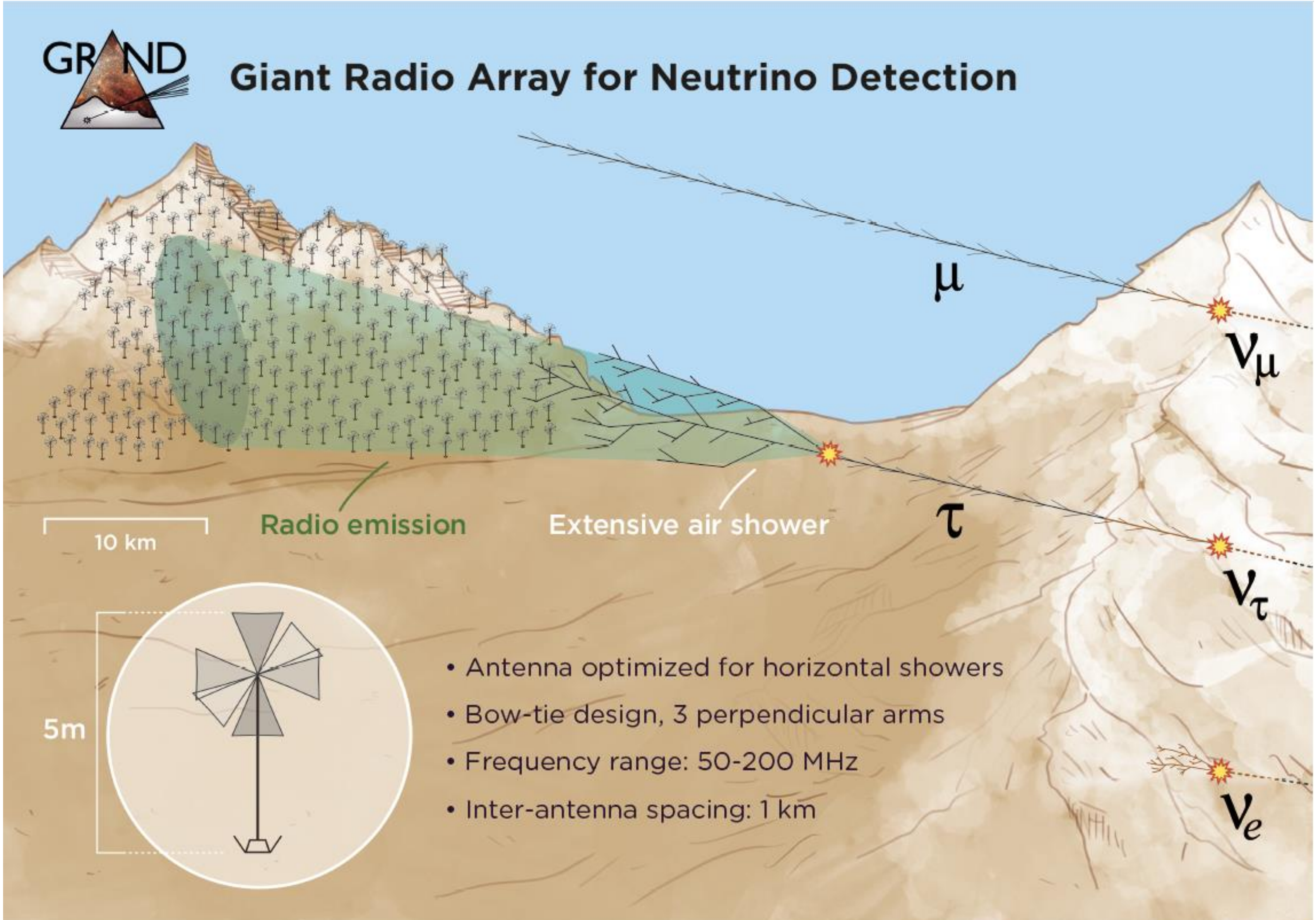


Trinity demonstrator

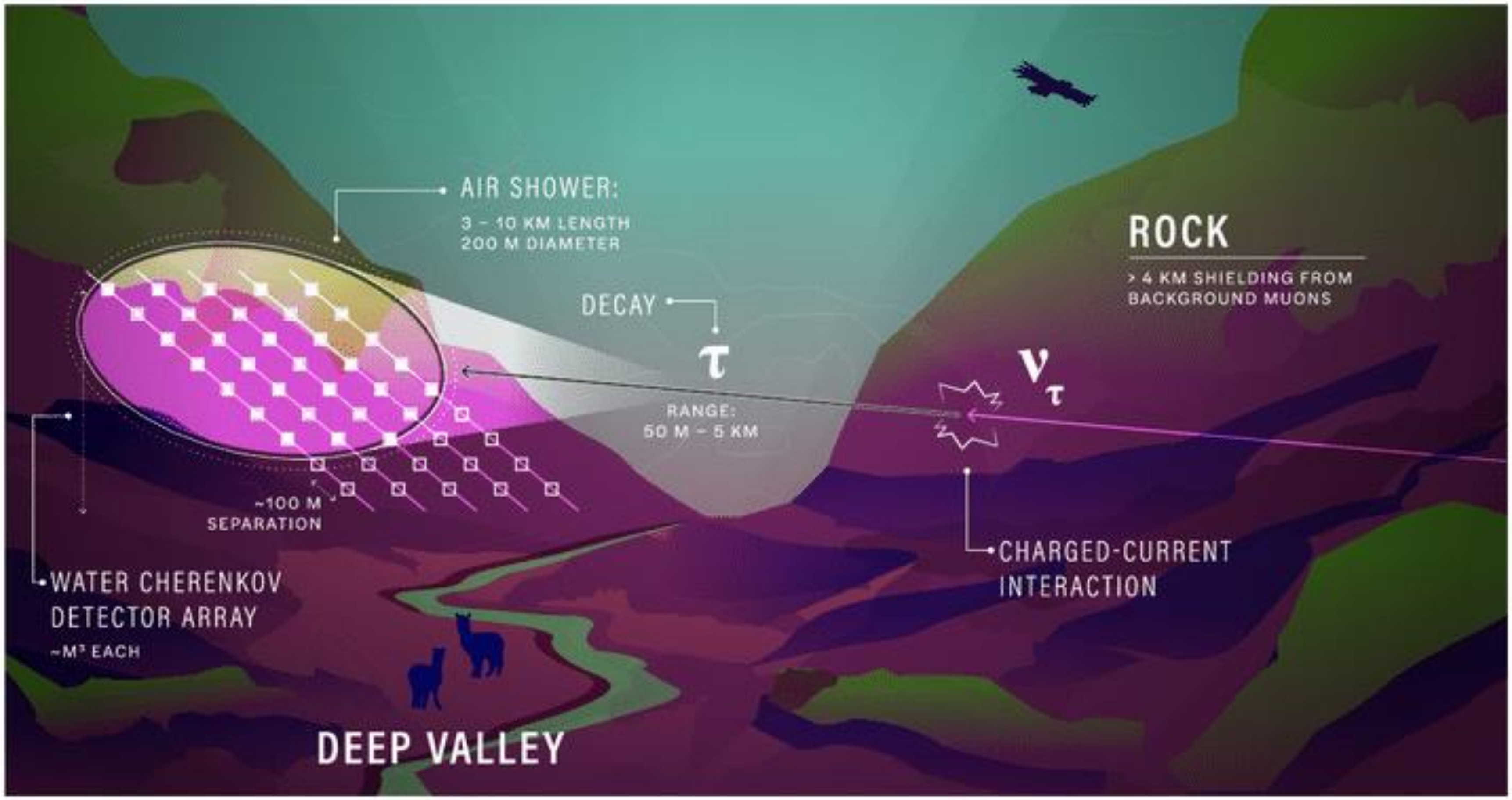
Deployed: Oct 2023

Frisco Peak, UT

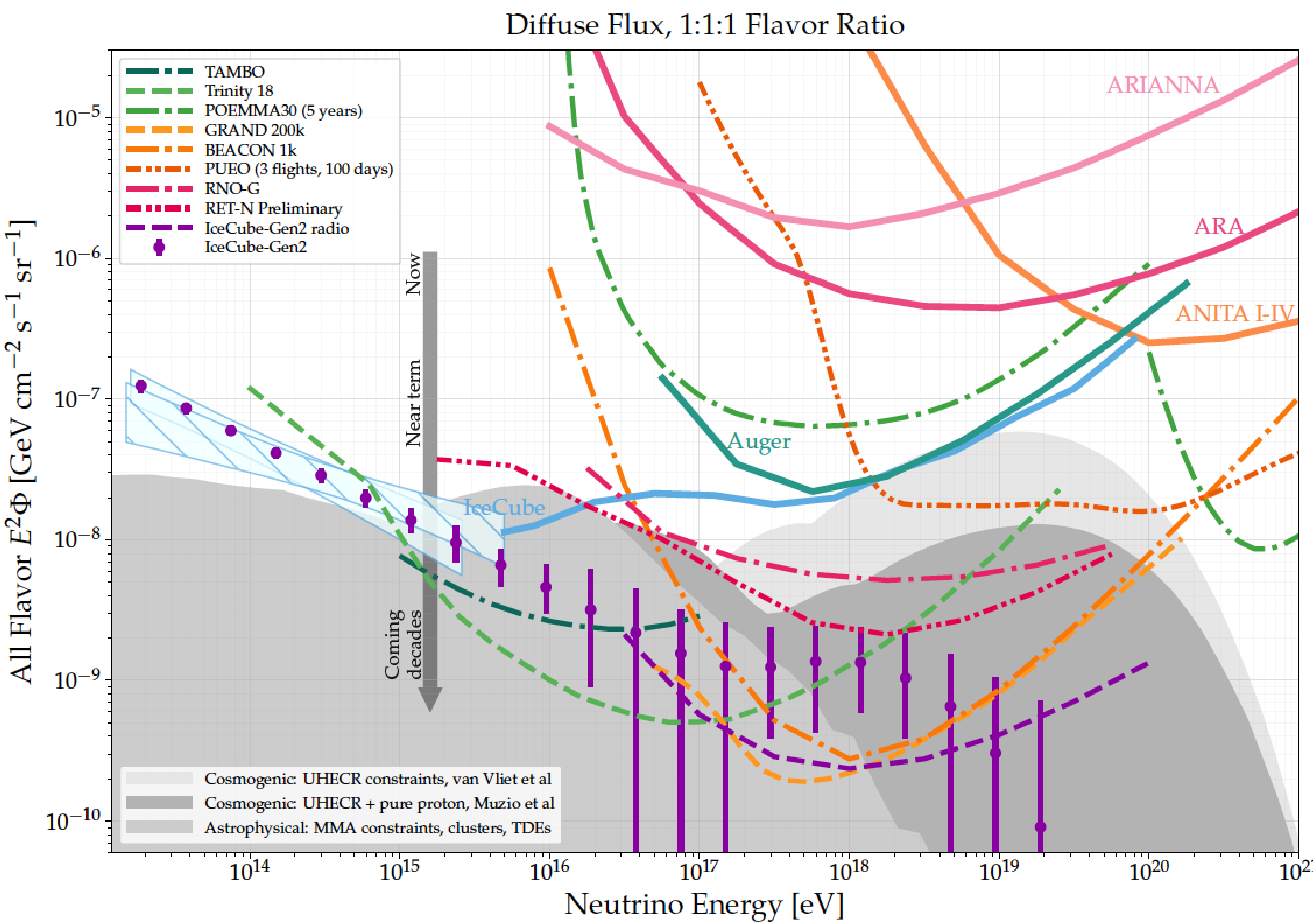
GRAND


GRAND
Giant Radio Array for Neutrino Detection
μ
ν_μ
τ
ν_τ
ν_e
10 km
Radio emission
Extensive air shower
5m
• Antenna optimized for horizontal showers
• Bow-tie design, 3 perpendicular arms
• Frequency range: 50-200 MHz
• Inter-antenna spacing: 1 km

TAMBO

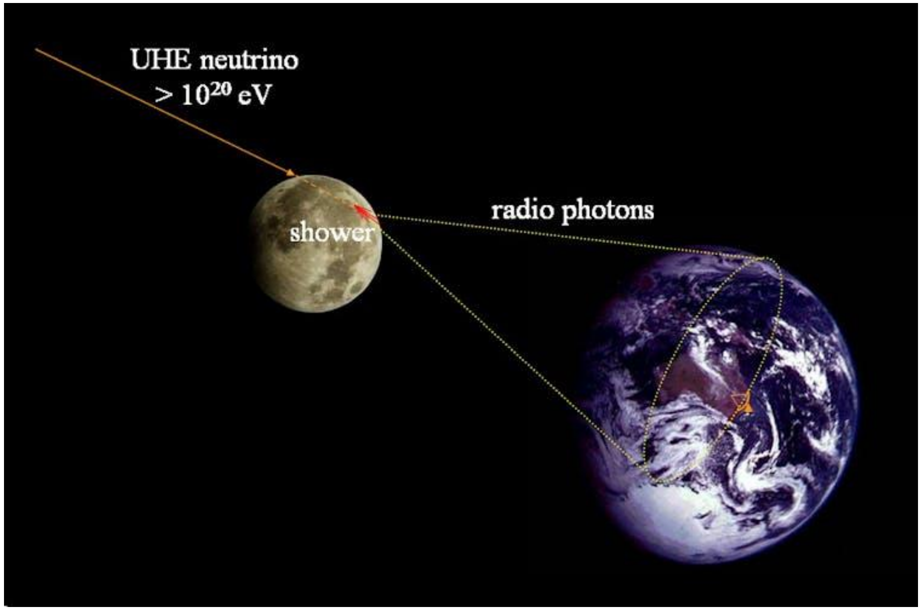


TAU AIR-SHOWER MOUNTAIN-BASED OBSERVATORY (TAMBO) · COLCA VALLEY, PERU



Ackermann et al., JHEAp 36 (2022) 55-110

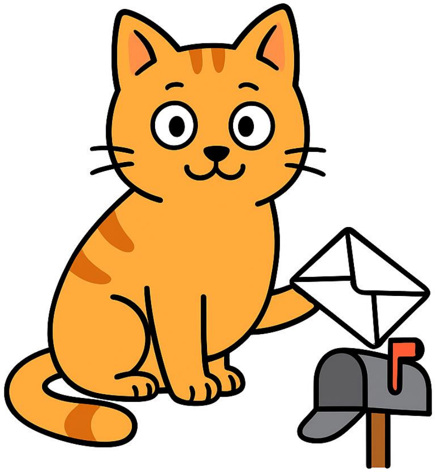
Other detector Concepts



O. Scholten 2011

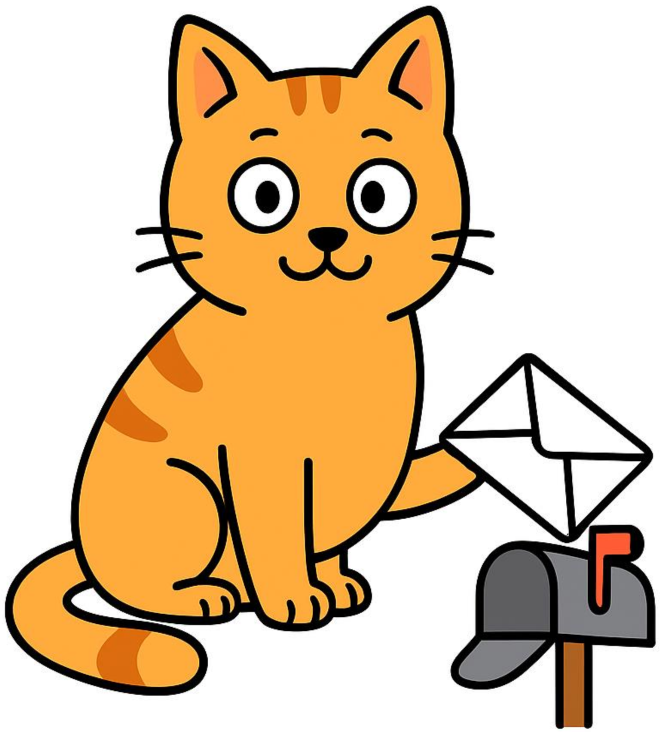
trees are efficient broadband antennas

S. Prohira 2024, arXiv:2401.14454



Take home message

Cosmogenic neutrinos are produced in interactions of UHECR during propagation.
New detector technologies target this energy range.



Take home message

Neutrinos are awesome!

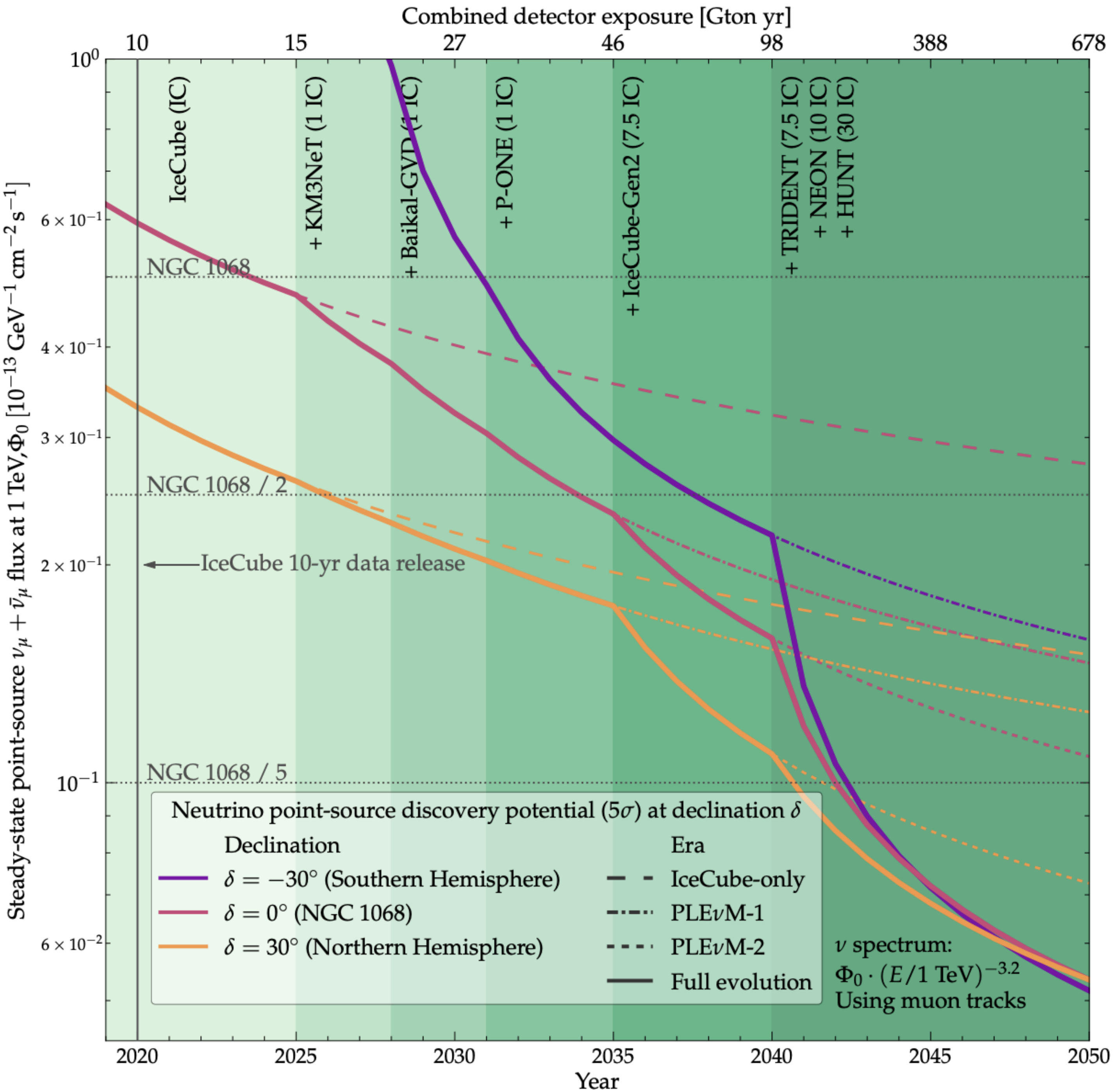
Backup

Tree antennas

Two ways to connect tree antennas to electronics

- drive a nail into the tree and run a wire from this nail, separate lead is connected to a grounding rod, these are connected to the readout electronics.
- toroidal coil wrapped around the tree 1-2 m above grade, inductively coupling the tree to the readout electronics.

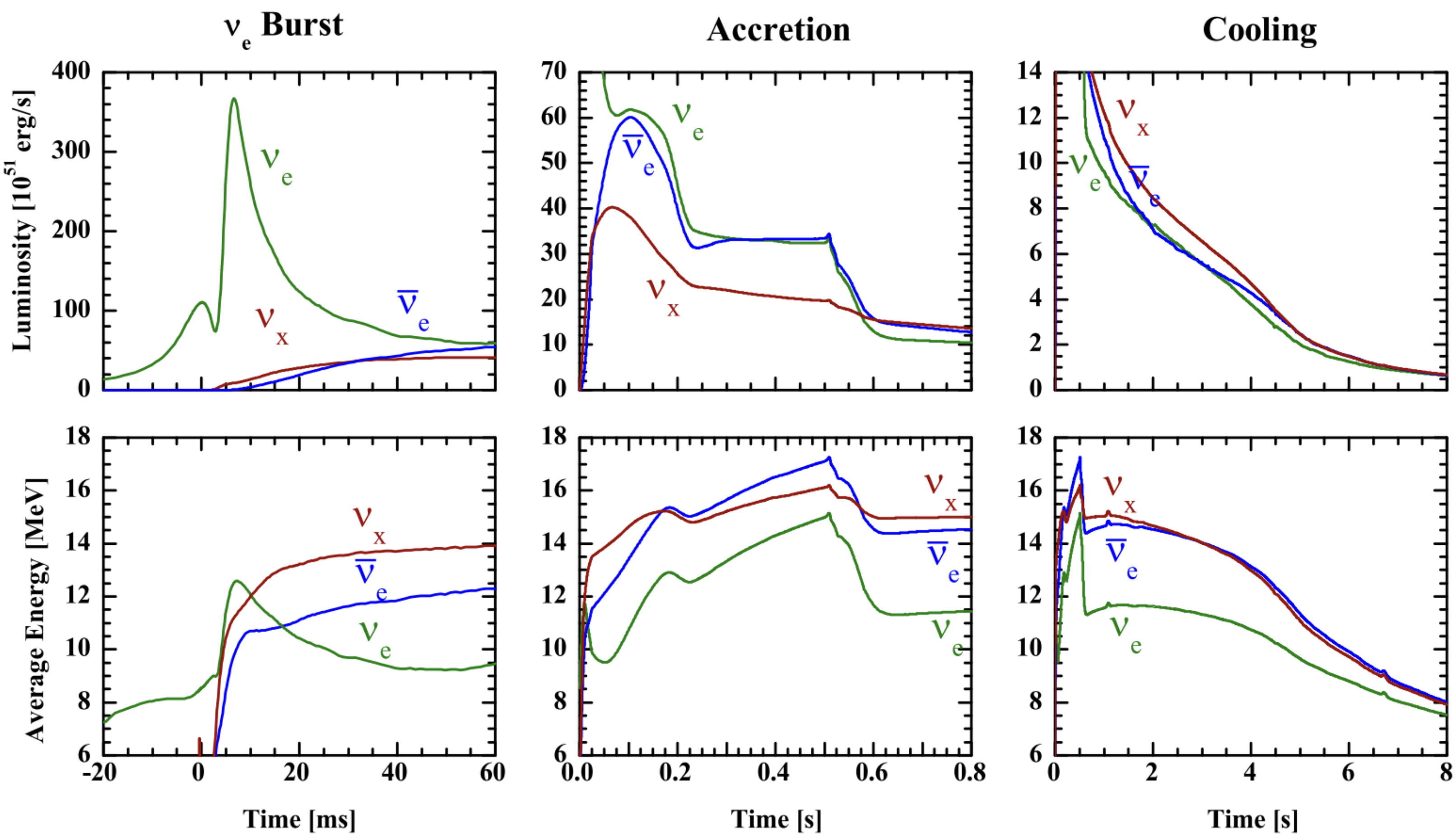
Both systems demonstrated improvements over manufactured monopole or dipole antennas of the same length and configuration (when insulated from the tree) or the toroidal coil in free space



Combined detector exposure [Gton yr]
10
15
27
46
98
388
678
IceCube (IC)
+ KM3NeT (1 IC)
+ Baikal-GVD (1 IC)
+ P-ONE (1 IC)
+ IceCube-Gen2 (7.5 IC)
+ TRIDENT (7.5 IC)
+ NEON (10 IC)
+ HUNT (30 IC)
NGC 1068
NGC 1068 / 2
NGC 1068 / 5
IceCube 10-yr data release
Steady-state point-source $\nu_\mu + \bar{\nu}_\mu$ flux at 1 TeV, Φ_0 [10^{-13} GeV^{-1} cm^{-2} s^{-1}]
10^0
6×10^{-1}
4×10^{-1}
3×10^{-1}
2×10^{-1}
10^{-1}
6×10^{-2}
Neutrino point-source discovery potential (5σ) at declination δ
Declination
$\delta = -30°$ (Southern Hemisphere)
$\delta = 0°$ (NGC 1068)
$\delta = 30°$ (Northern Hemisphere)
Era
IceCube-only
PLEνM-1
PLEνM-2
Full evolution
ν spectrum:
$\Phi_0 \cdot (E/1\ \text{TeV})^{-3.2}$
Using muon tracks
2020
2025
2030
2035
2040
2045
2050
Year

RUB

Expected neutrino signal

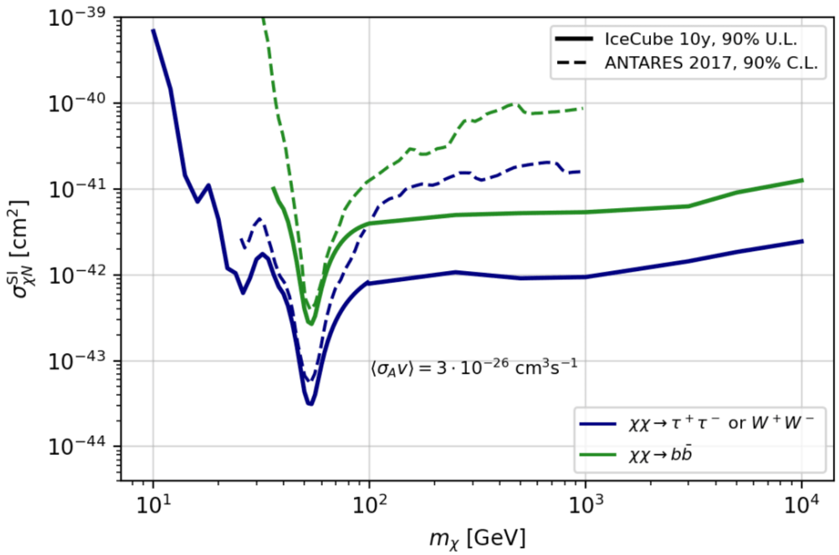


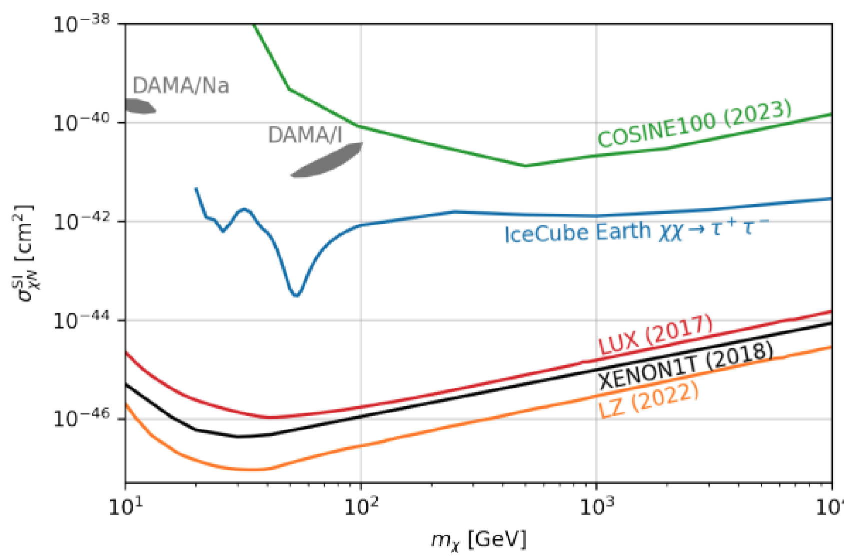
1D spherically symmetric supernova simulation (M=27 M), Garching group.

Exotic Physics – Searches for WIMP Dark Matter

WIMP dark matter particles can be captured by celestial bodies like the Sun or Earth → enhanced self-annihilation into Standard Model particles including neutrinos

Search for WIMP decay to neutrinos from the **Earth center**





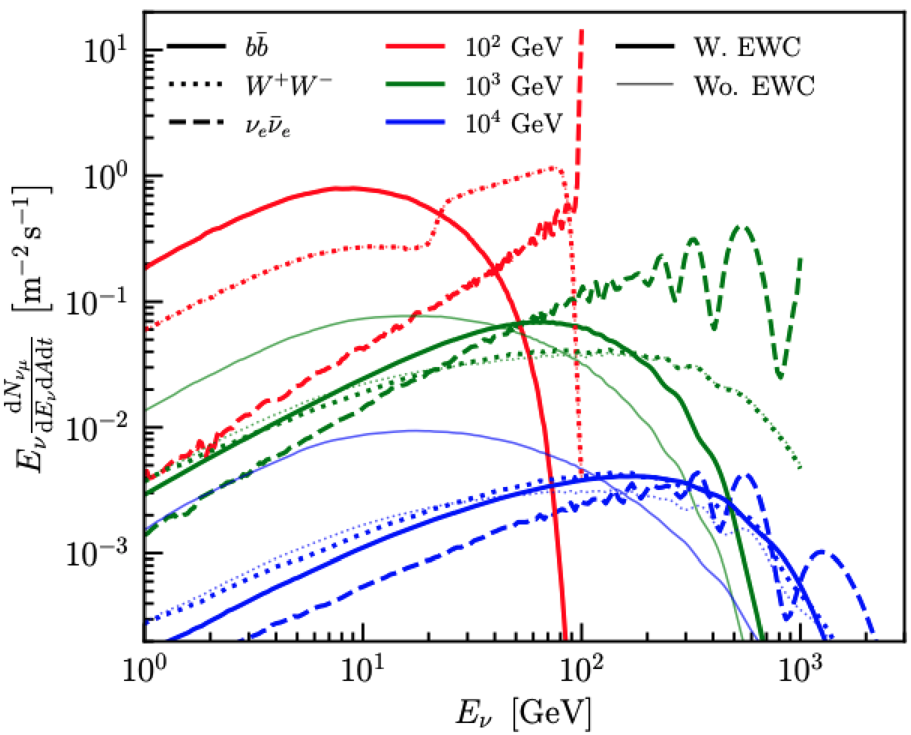
RUB

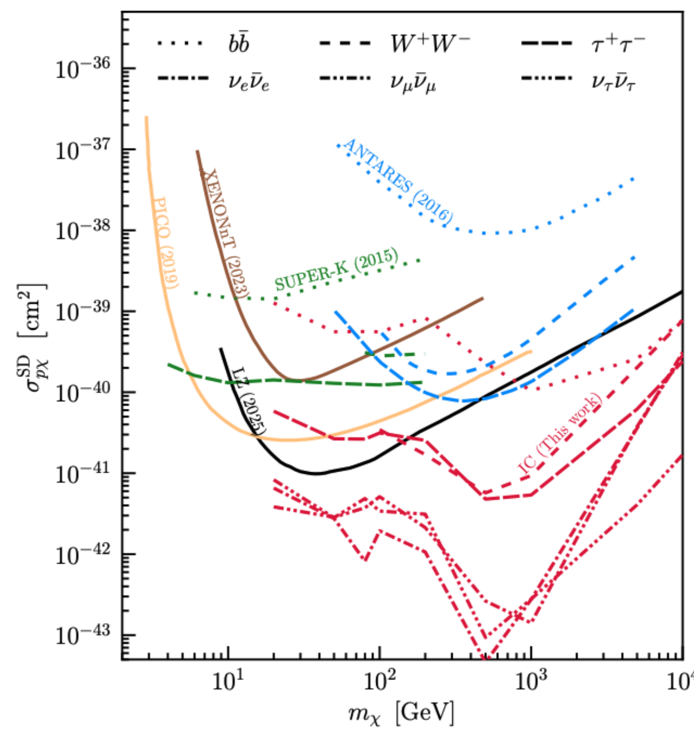
IceCube Eur.Phys.J.C 85 (2025) 5, 490

Exotic Physics – Searches for WIMP Dark Matter

WIMP dark matter particles can be captured by celestial bodies like the Sun or Earth → enhanced self-annihilation into Standard Model particles including neutrinos

Search for WIMP decay to neutrinos from the **Sun**





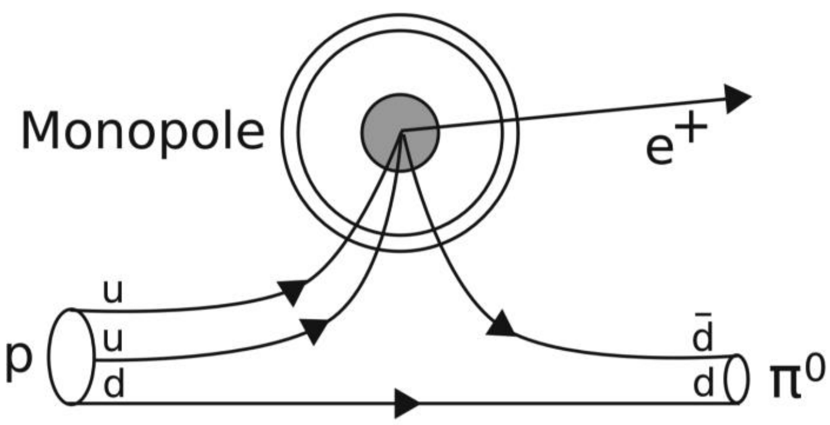
IceCube Collaboration arXiv:2507.08457

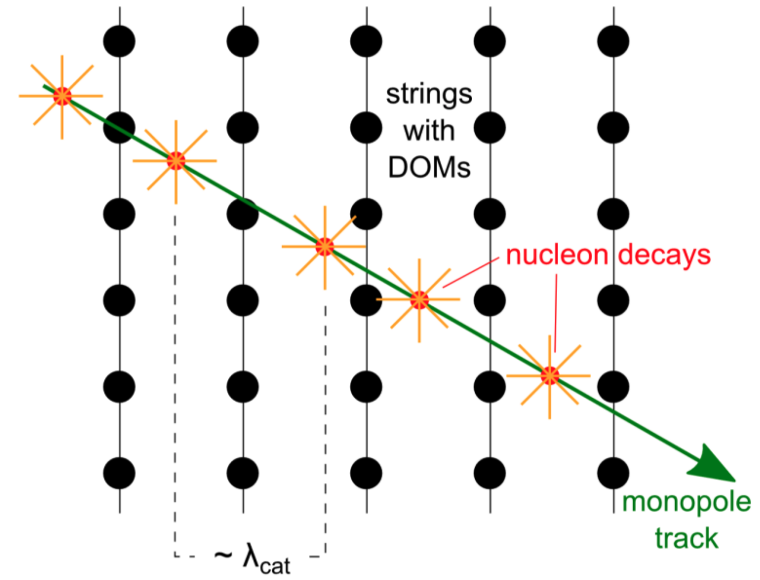
Exotic Physics – Searches for Magnetic Monopols

Interaction of monopols with surrounding medium depends on velocity β

- Cherenkov light (at relativistic speeds)
- Luminescences light (ionisation of media)
- Heavy monopols (sub-relativistic speeds) can produce light via nucleon decays

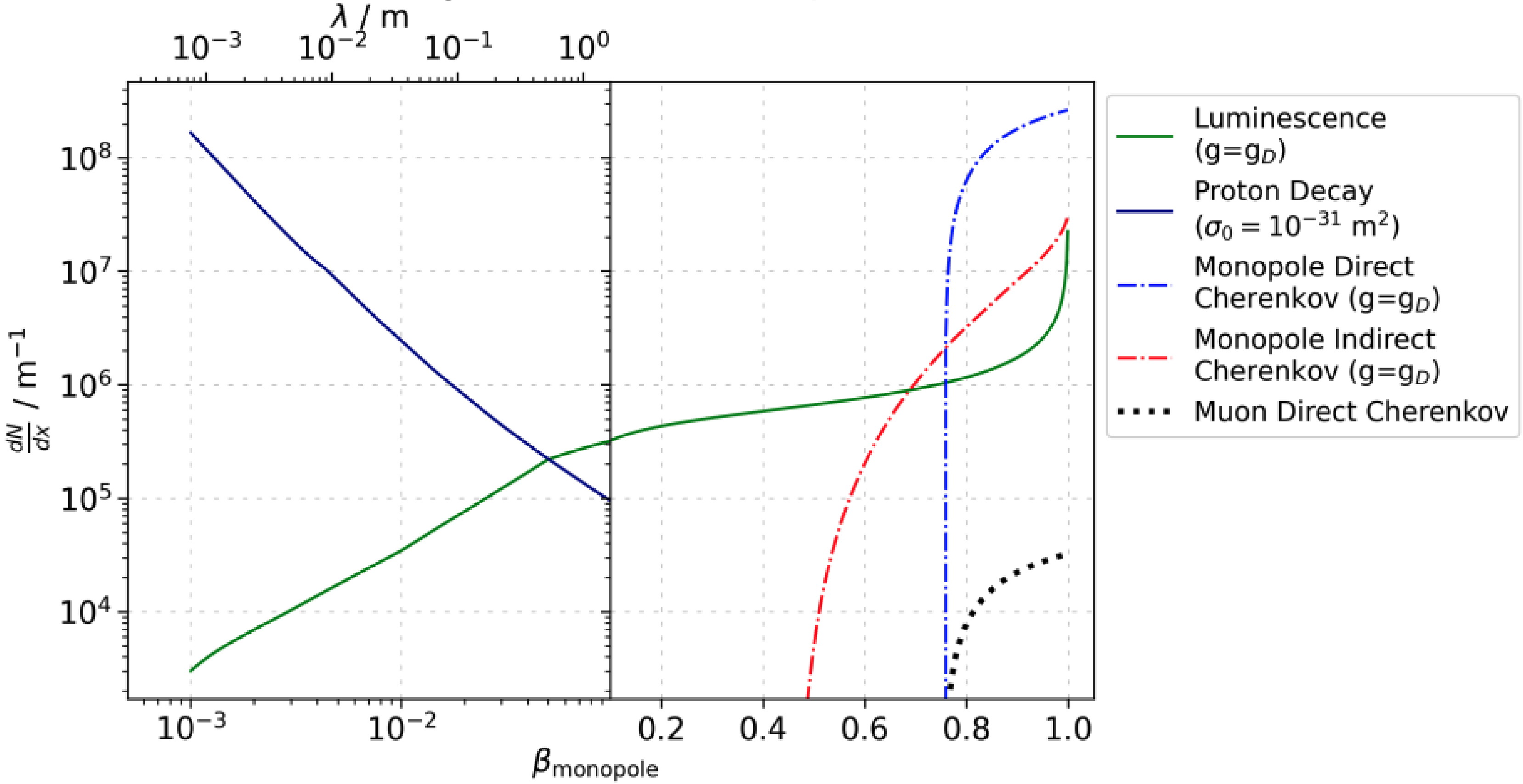
Rubakov-Callan effect allows catalyzation of nucleon decays by heavy MMs ($M \gtrsim 10^{13}$GeV)



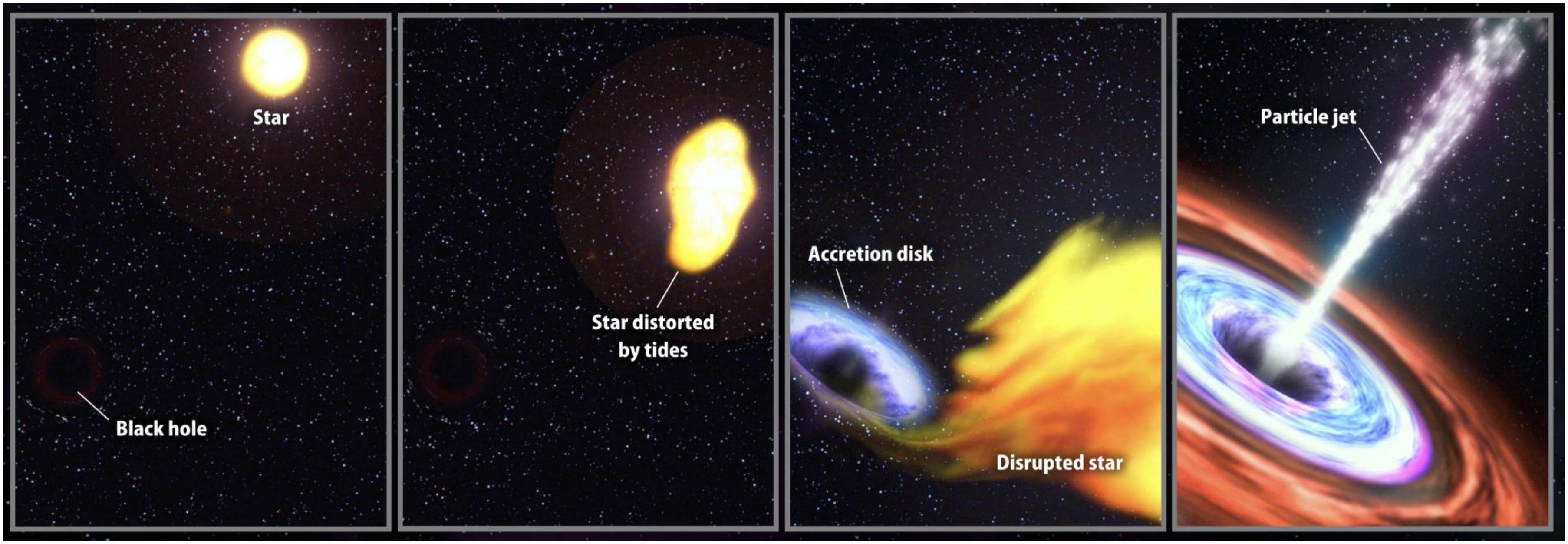


Exotic Physics – Searches for Magnetic Monopols

Interaction of MMs with surrounding medium depends on velocity β

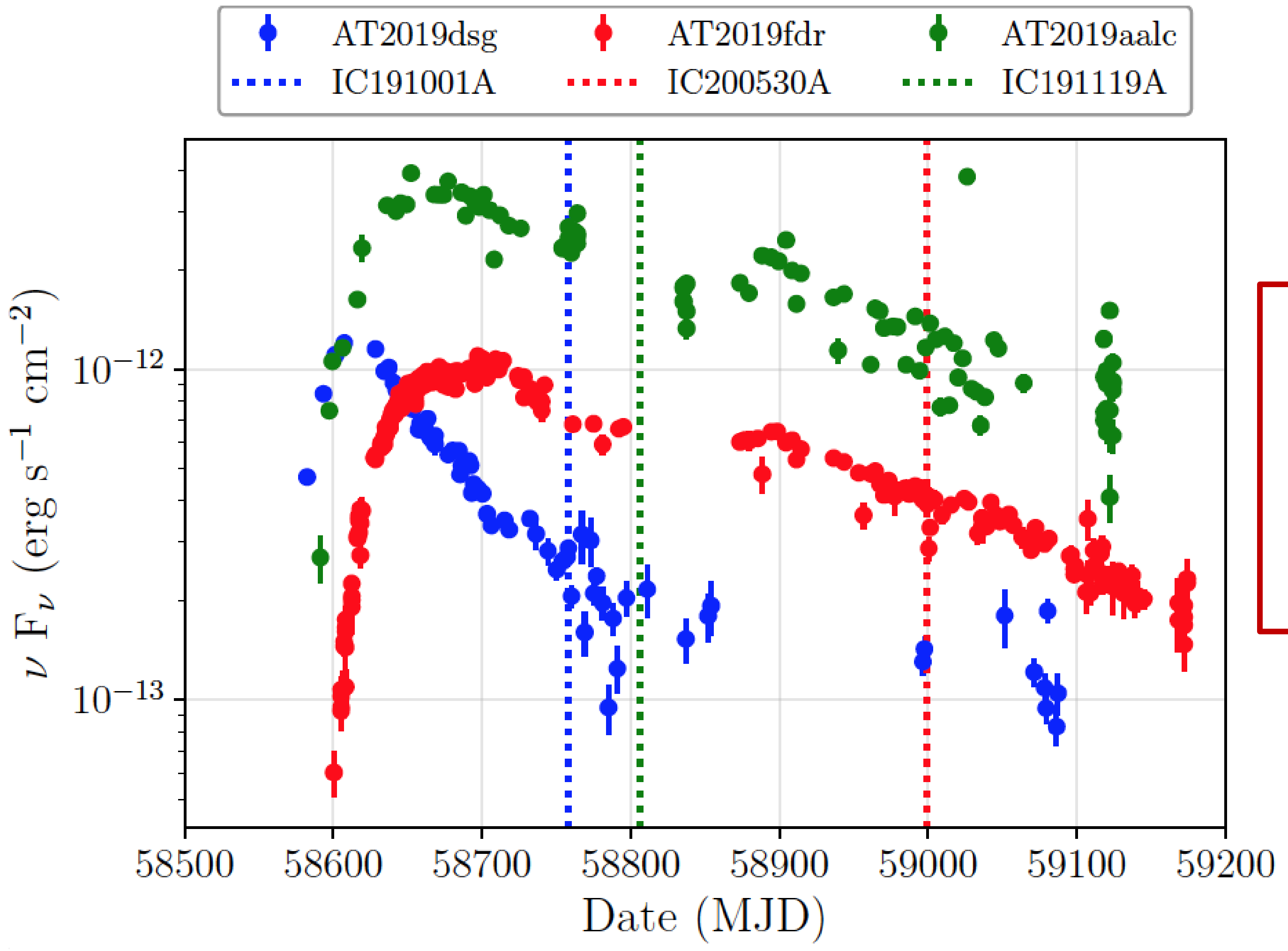


What about quiet black holes? Tidal Disruption Events



~50 TDEs identified, 4 jetted TDEs bright in optical

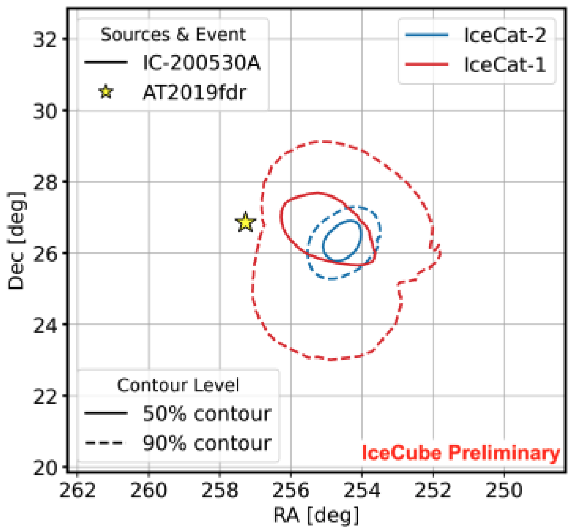
Tidal Disruption Events as Neutrino Candidates



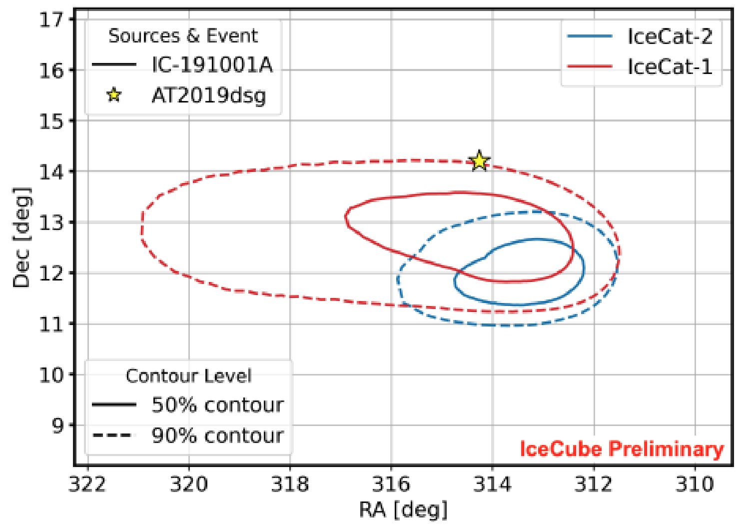
First hint of neutrino production in TDEs
→ **Very efficient neutrino production in TDEs compared to AGN?**

R. Stein et al., Nature Astronomy 2021, S. Reusch et al. PRL 2022, S. Van Velzen et al. MNRAS 529 (2024)

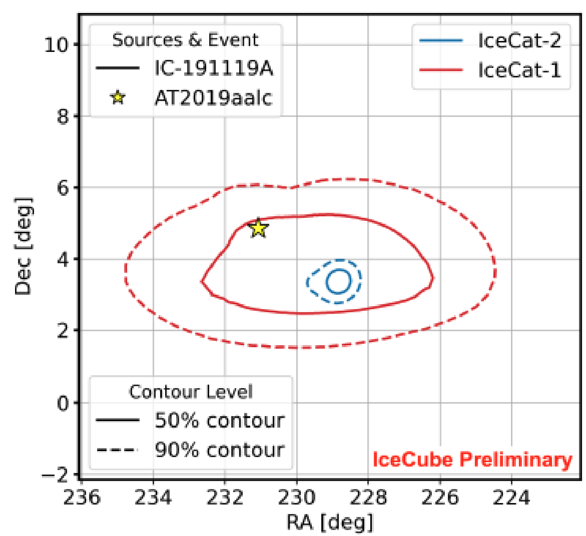
Neutrino TDEs disfavored with IceCat-2



(a) AT2019fdr



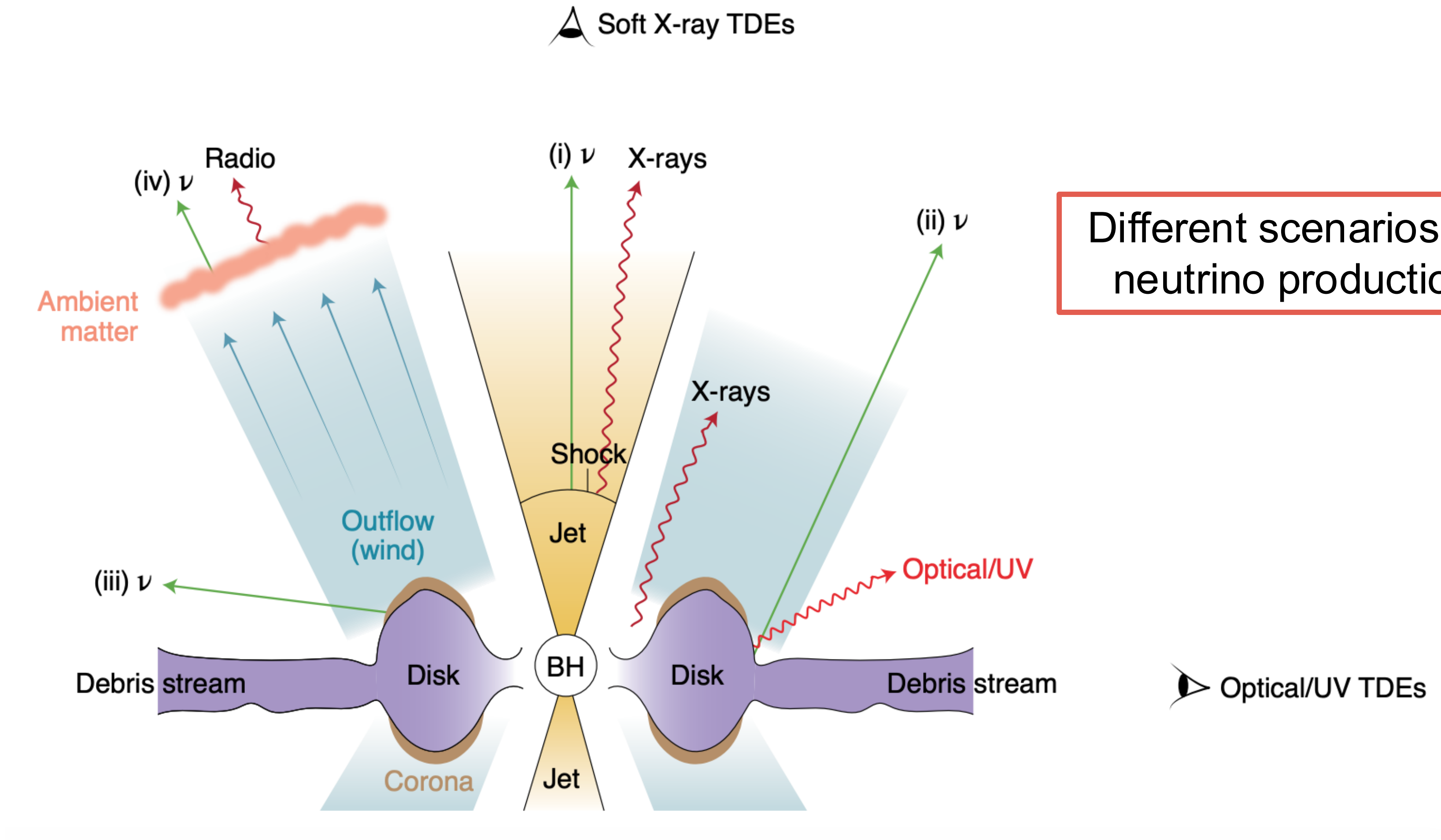
(b) AT2019dsg



(c) AT2019aalc

A. Zegarelli for IceCube, ICRC 2025, arXiv:2507.06176

Neutrino Production in TDEs



Different scenarios for neutrino production

Hayasaki, Nature Astronomy 2021, Winter & Lunardini, Nature Astronomy 2021, Liu et al. PRD, 102 (2020) Murase et al. ApJ 902 (2020)