Neutrinos

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RUB


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


Kopenhagen
erdam
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Schweiz


Kopenhagen
Berlin
Bochum
Deutschland
Prag
Tschechien
München
Wien
Zürich
Österreich
Schweiz

Which neutrino sources do you know?

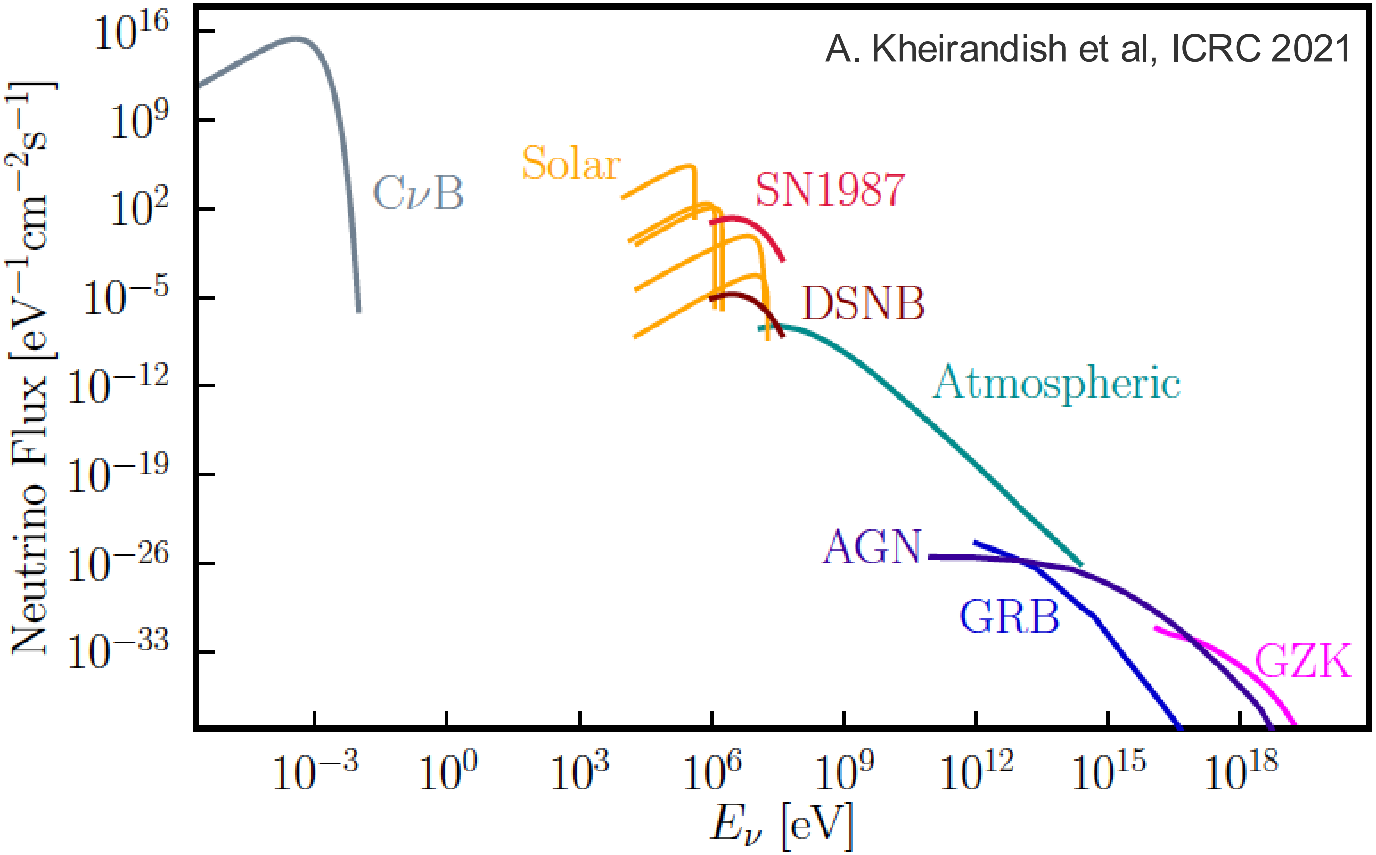
Content of the 3 lectures

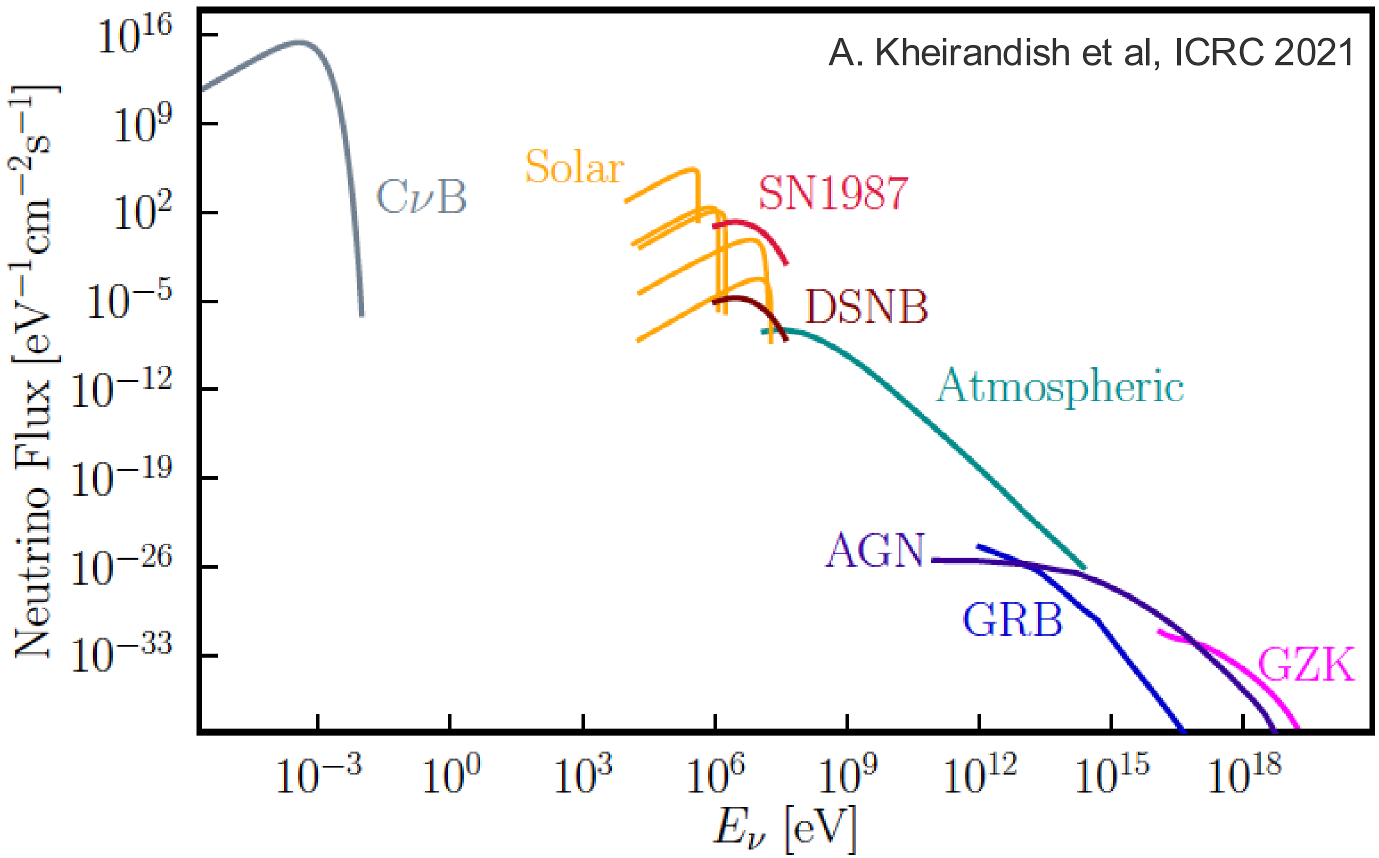
- Low-energy (MeV) neutrinos
  - Sun
  - Supernovae
- High-energy (TeV-PeV) neutrinos
  - Astrophysics
  - Particle physics
- Even higher energies?

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



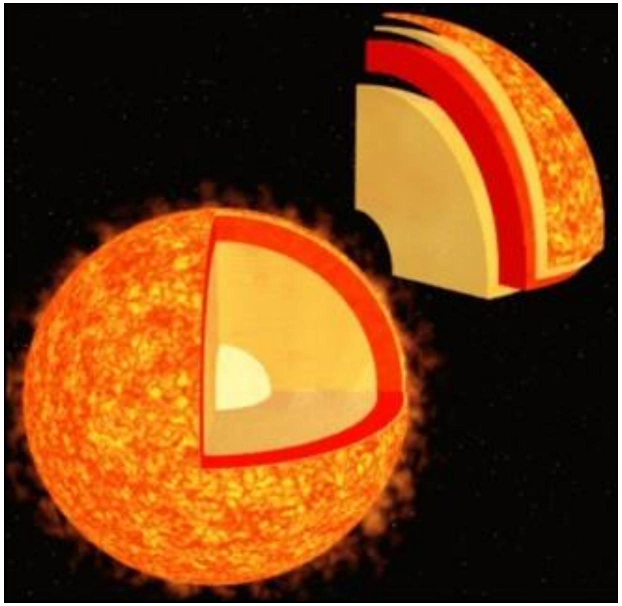
Ideas: neutrino capture on unstable nucleus (e.g. tritium)

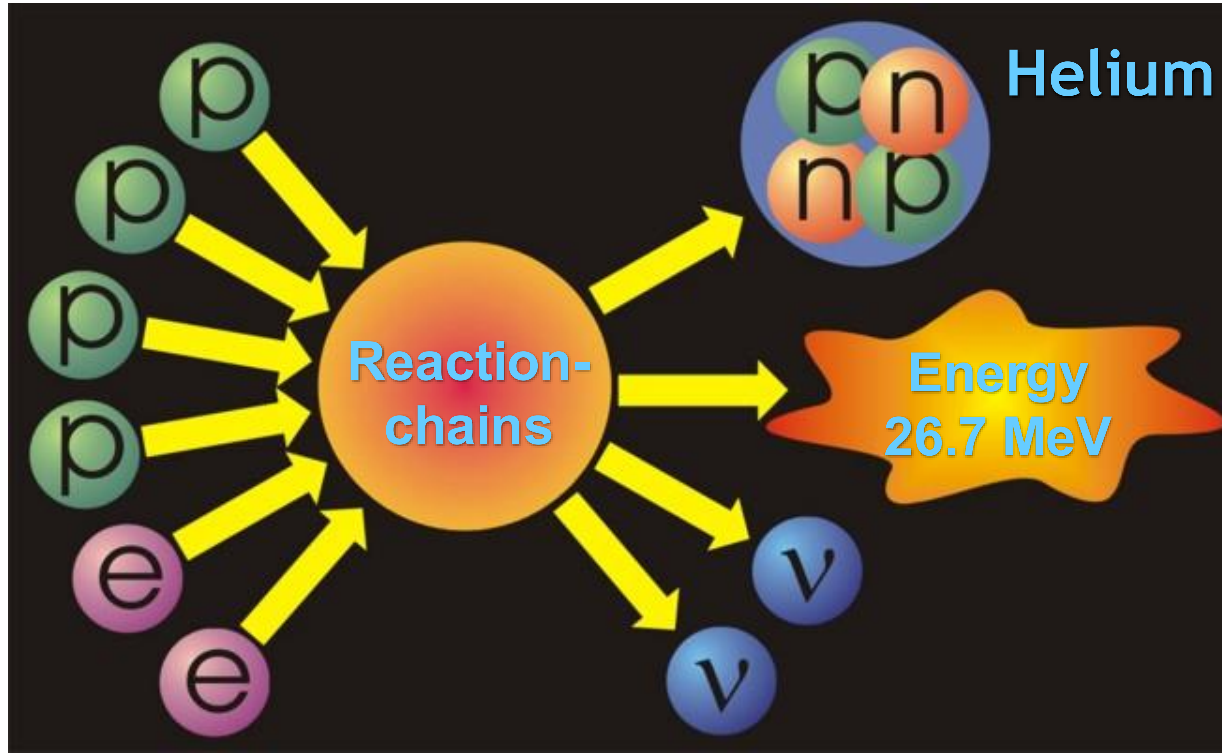
Neutrino capture on stable nucleus (Chlorine, Gallium)

Water / ice Cherenkov detectors

Radio arrays, cosmic-ray detectors

Solar Neutrinos





1967

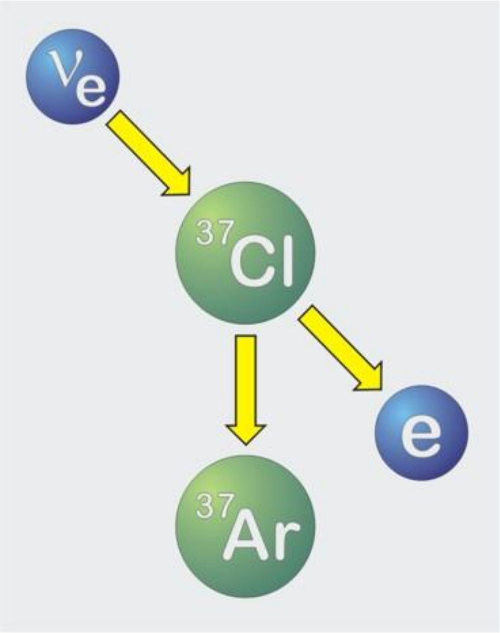
Solar radiation:

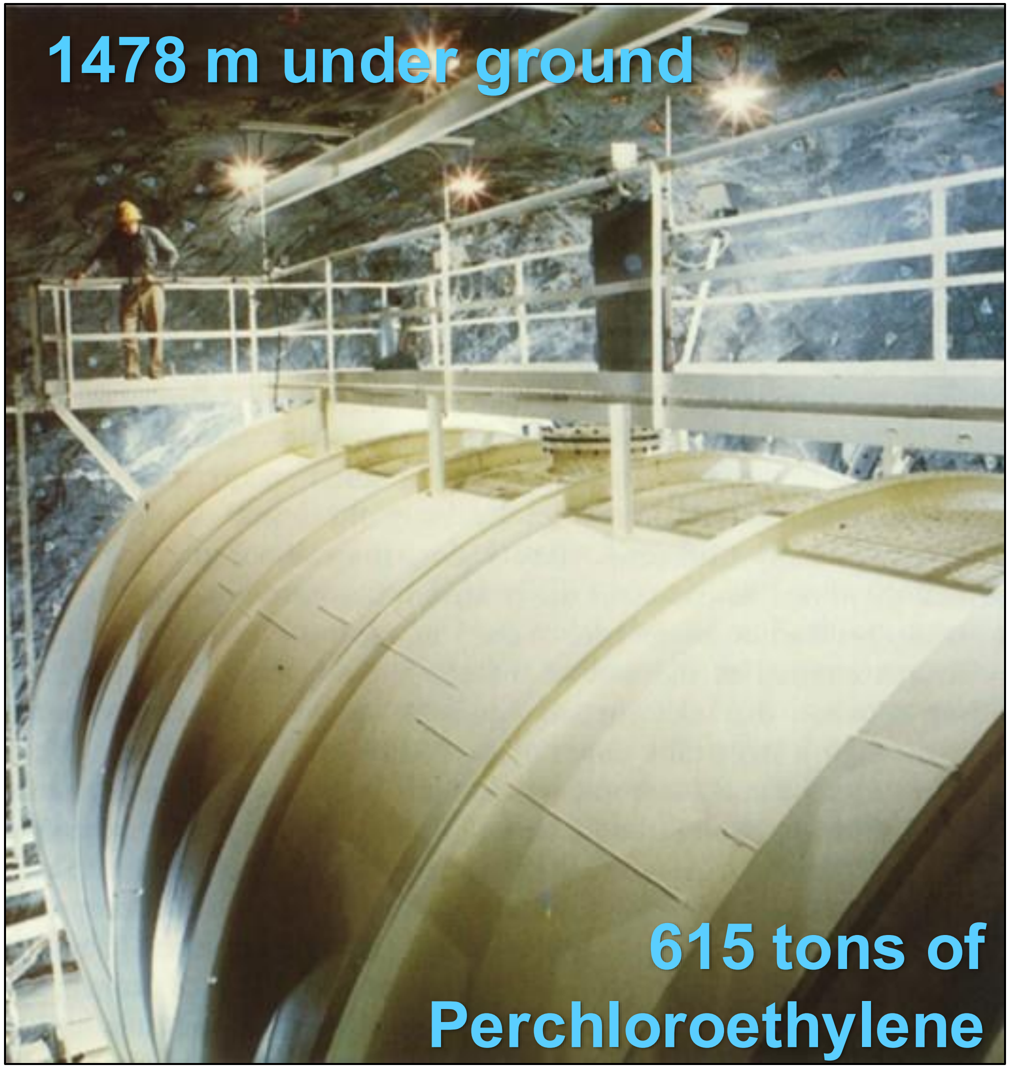
- 98% light
- 2% **electron-neutrinos**

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

The Homestake Experiment

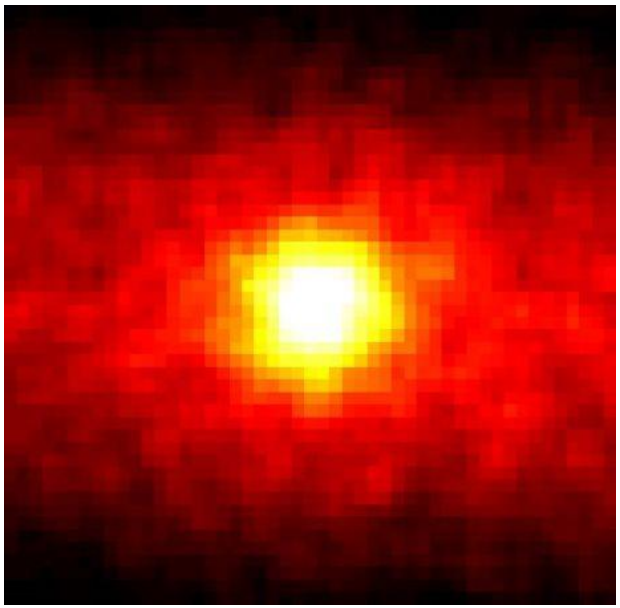
$$\nu_e + {}^{37}\mathrm{Cl} \longrightarrow {}^{37}\mathrm{Ar} + e^-$$





Solar Neutrinos

Astronomy Picture of the Day
June 5, 1998



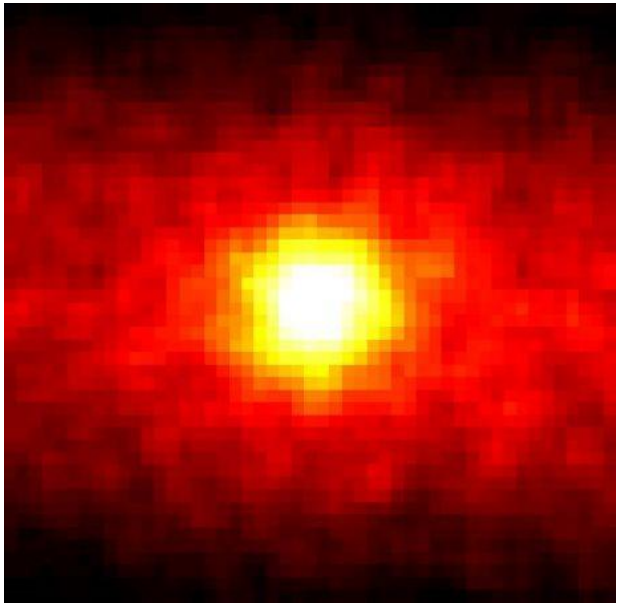
The Sun in Neutrinos seen
by Super-Kamiokande

Combining neutrinos and electromagnetic information led to:

- **The solar neutrino problem**

Solar Neutrinos

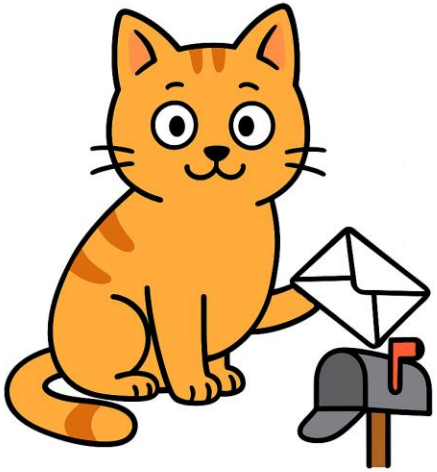
Astronomy Picture of the Day
June 5, 1998



The Sun in Neutrinos seen
by Super-Kamiokande

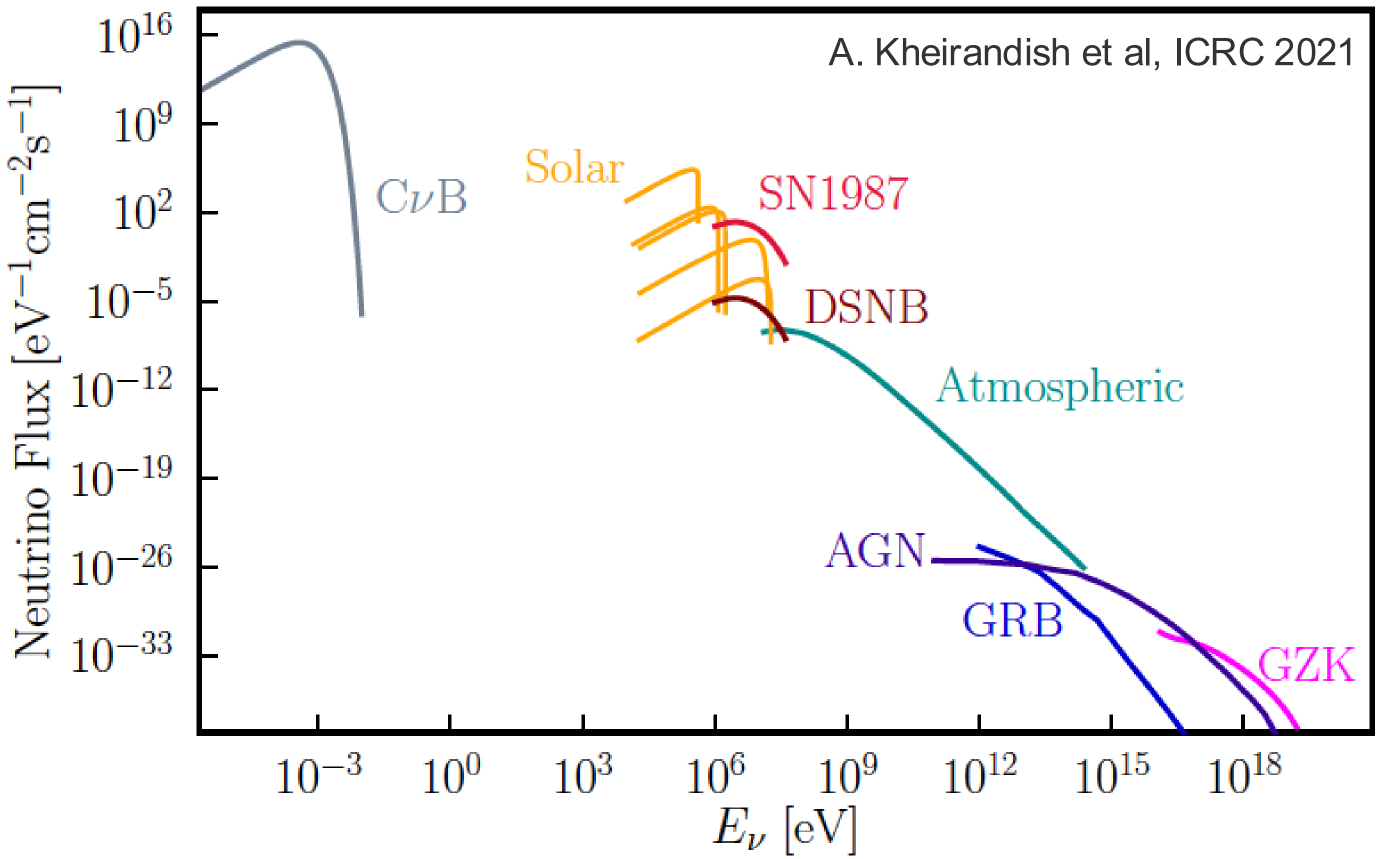
Combining neutrinos and electromagnetic information led to:

- 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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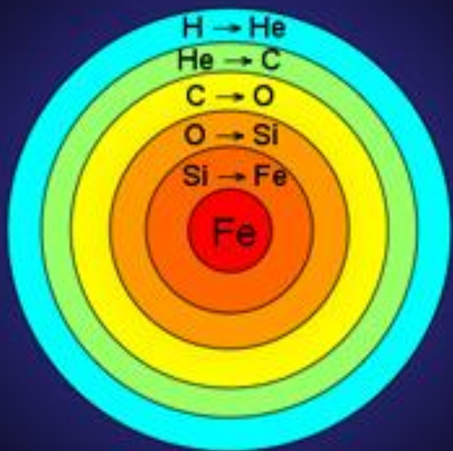
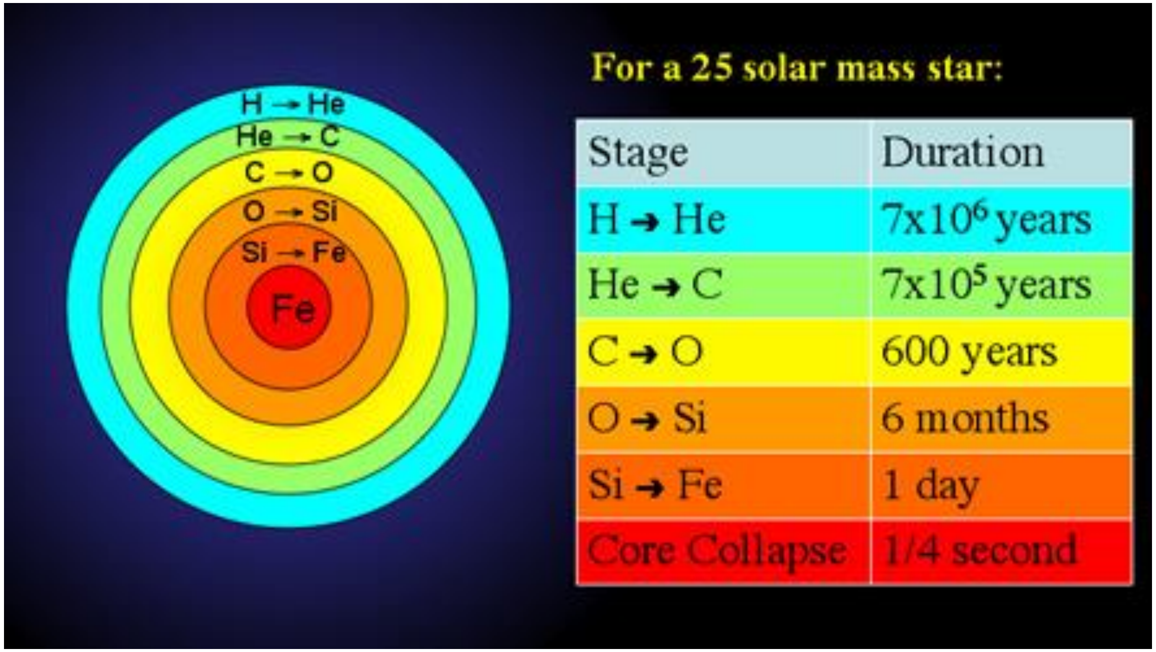
Supernova Neutrinos



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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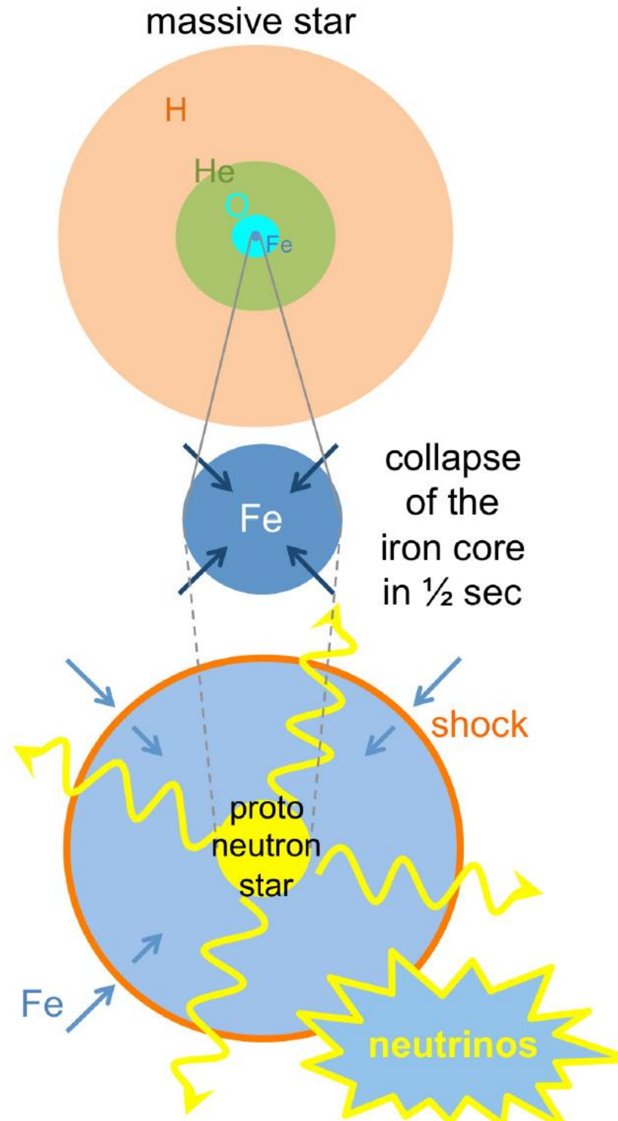
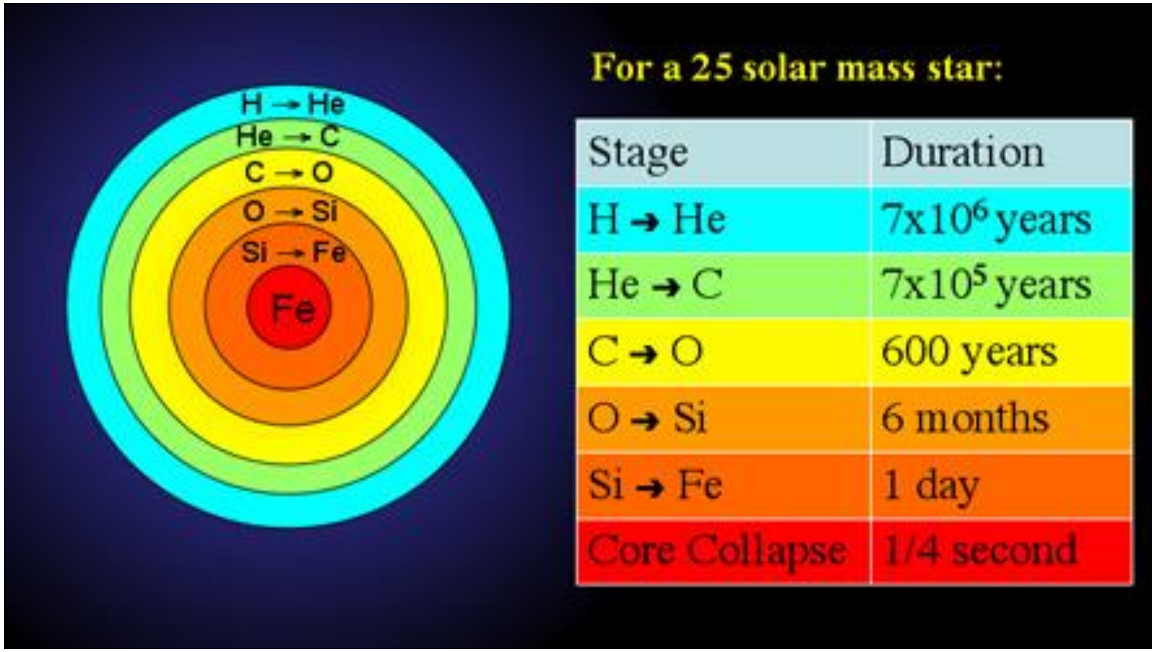


Supernova Neutrinos



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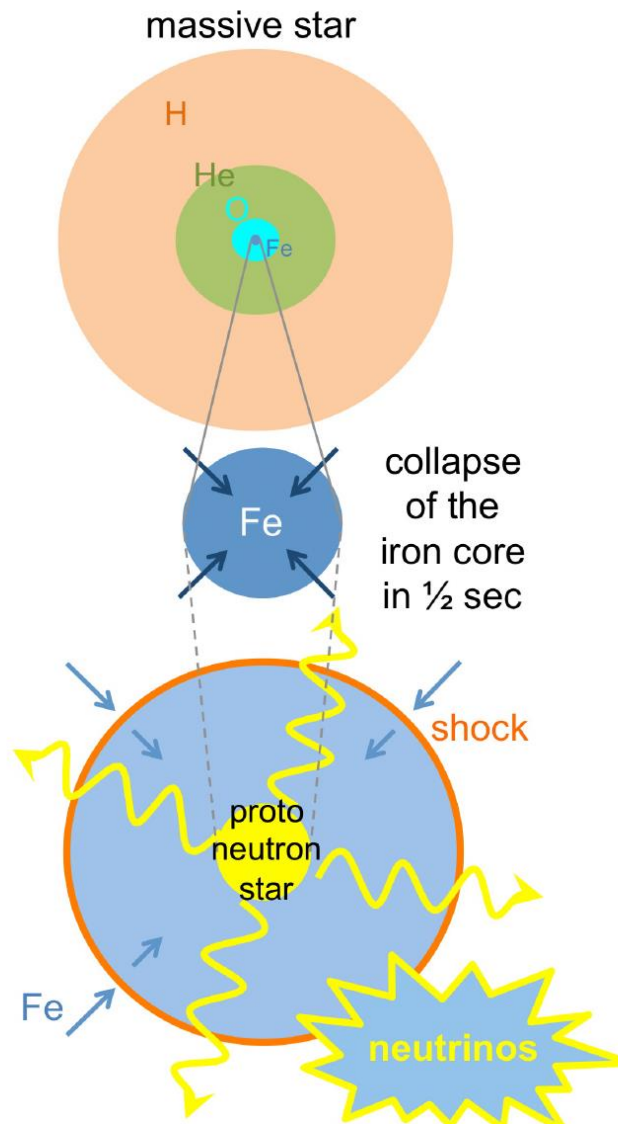

Neutronization burst: $e^- + p \rightarrow n + \nu_e$
Thermal neutrinos of all flavors

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

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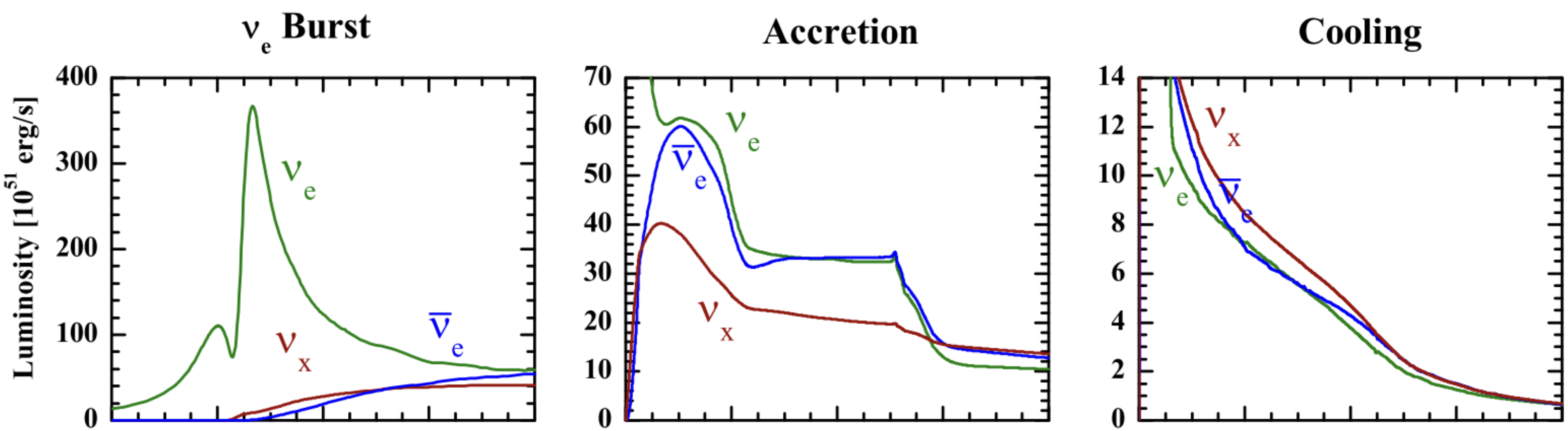
Expected neutrino signal



Initial neutronization burst

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

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

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

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

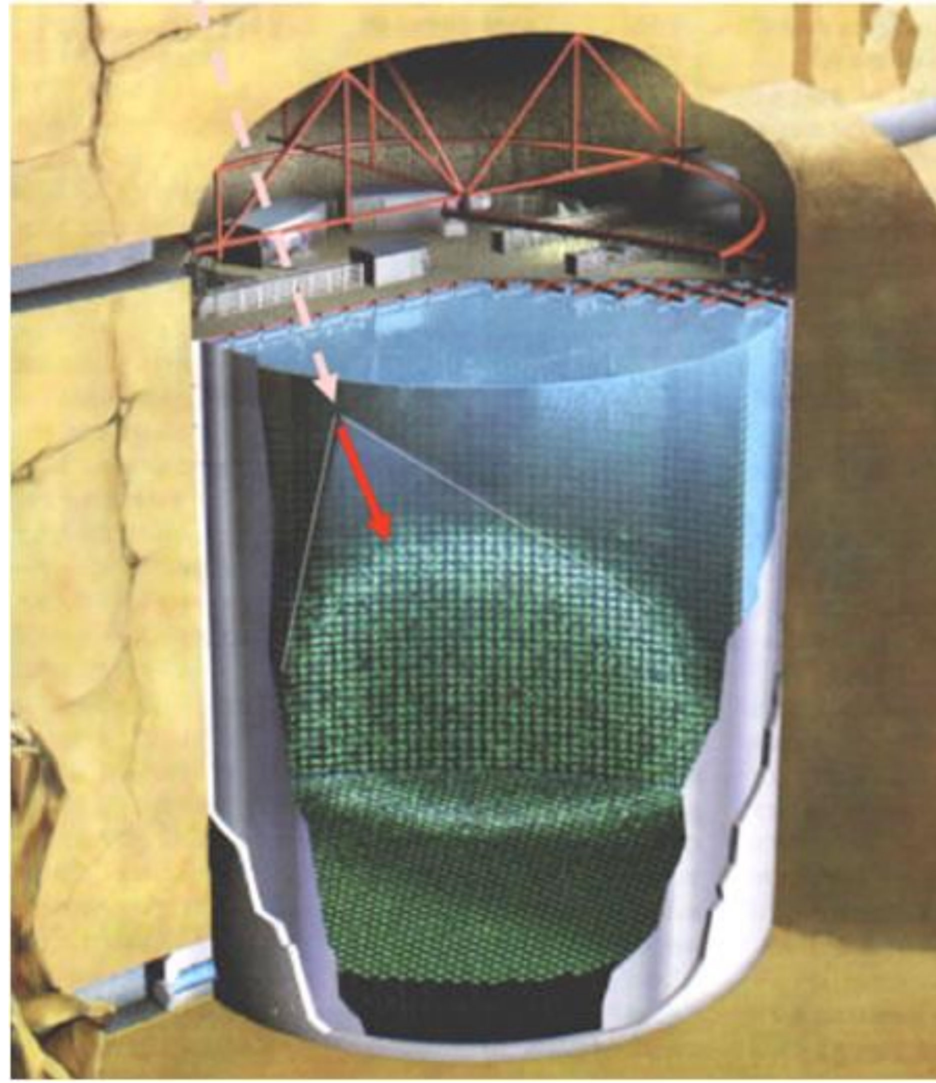
proto-neutron star loses trapped thermal energy mainly by neutrino emission of all flavors

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

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:

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

(Super) Kamiokande

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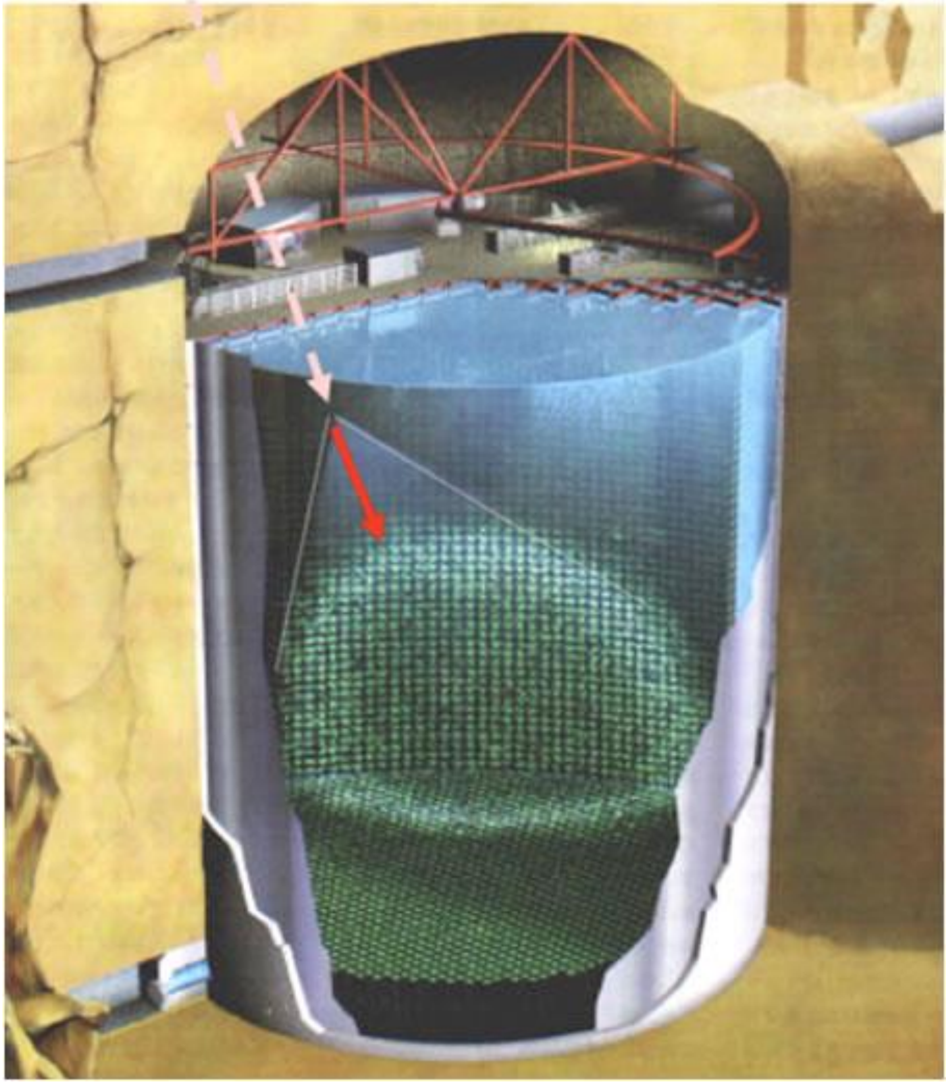


Detection channels:

Inverse beta decay:

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

Most efficient

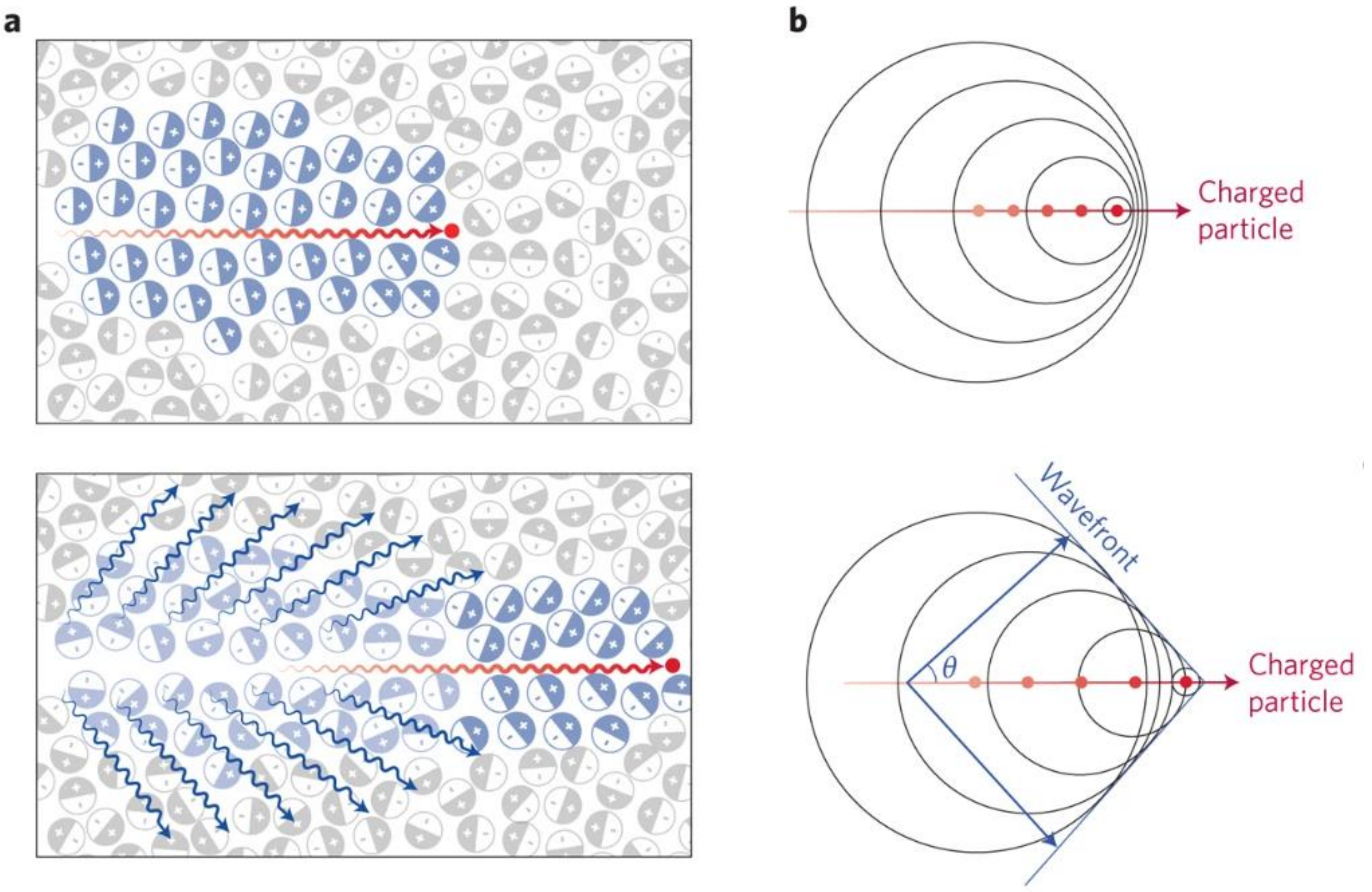
Elastic scattering:

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

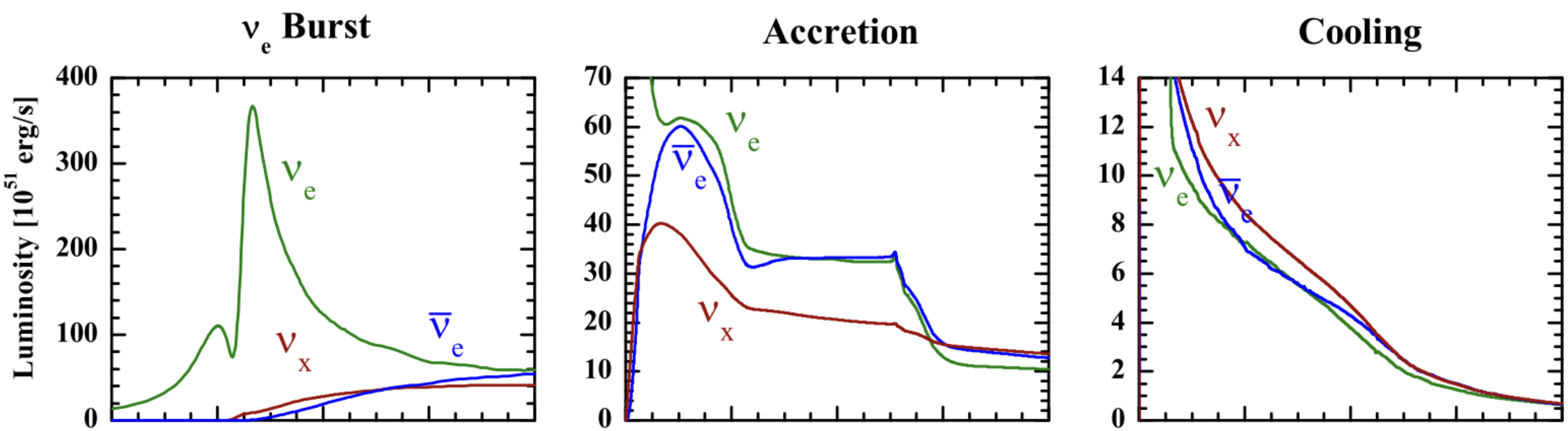
Charged current absorption on oxygen:

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

Different detection technique: Cherenkov Effect



Expected neutrino signal



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

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

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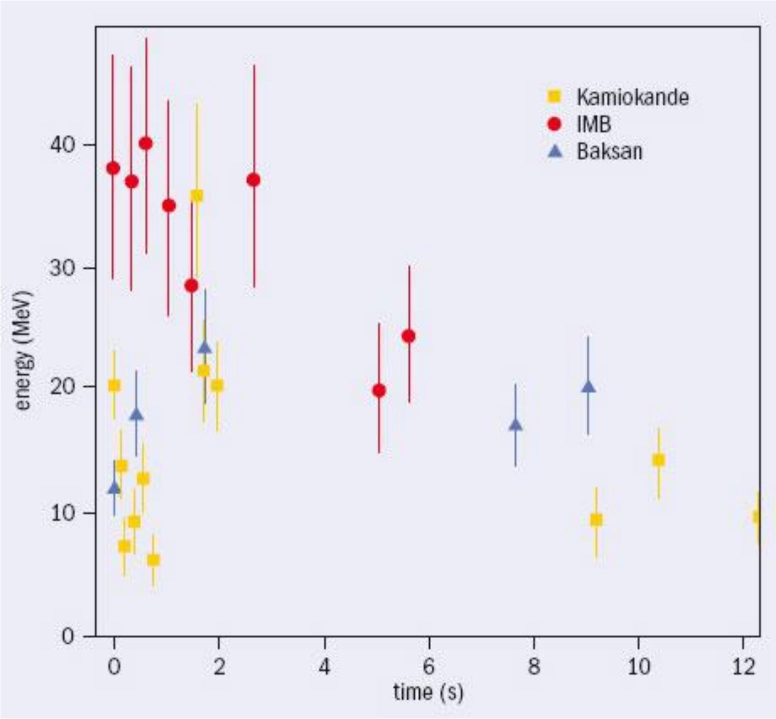
1D spherically symmetric supernova simulation (M=27 M), Garching group.

First and only Supernova neutrino detection

Optical detection of SN1987A in LMC

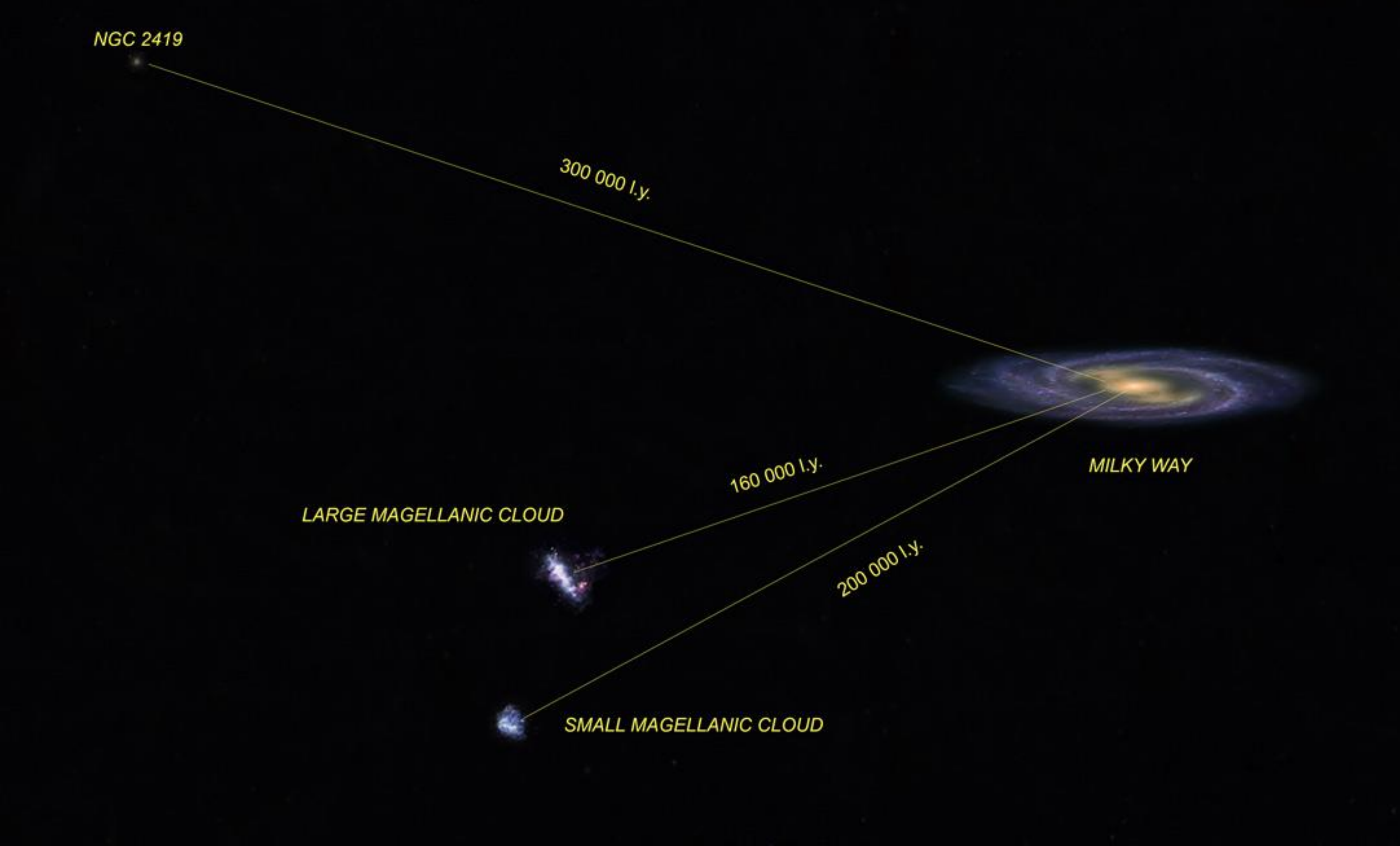
MeV neutrino burst



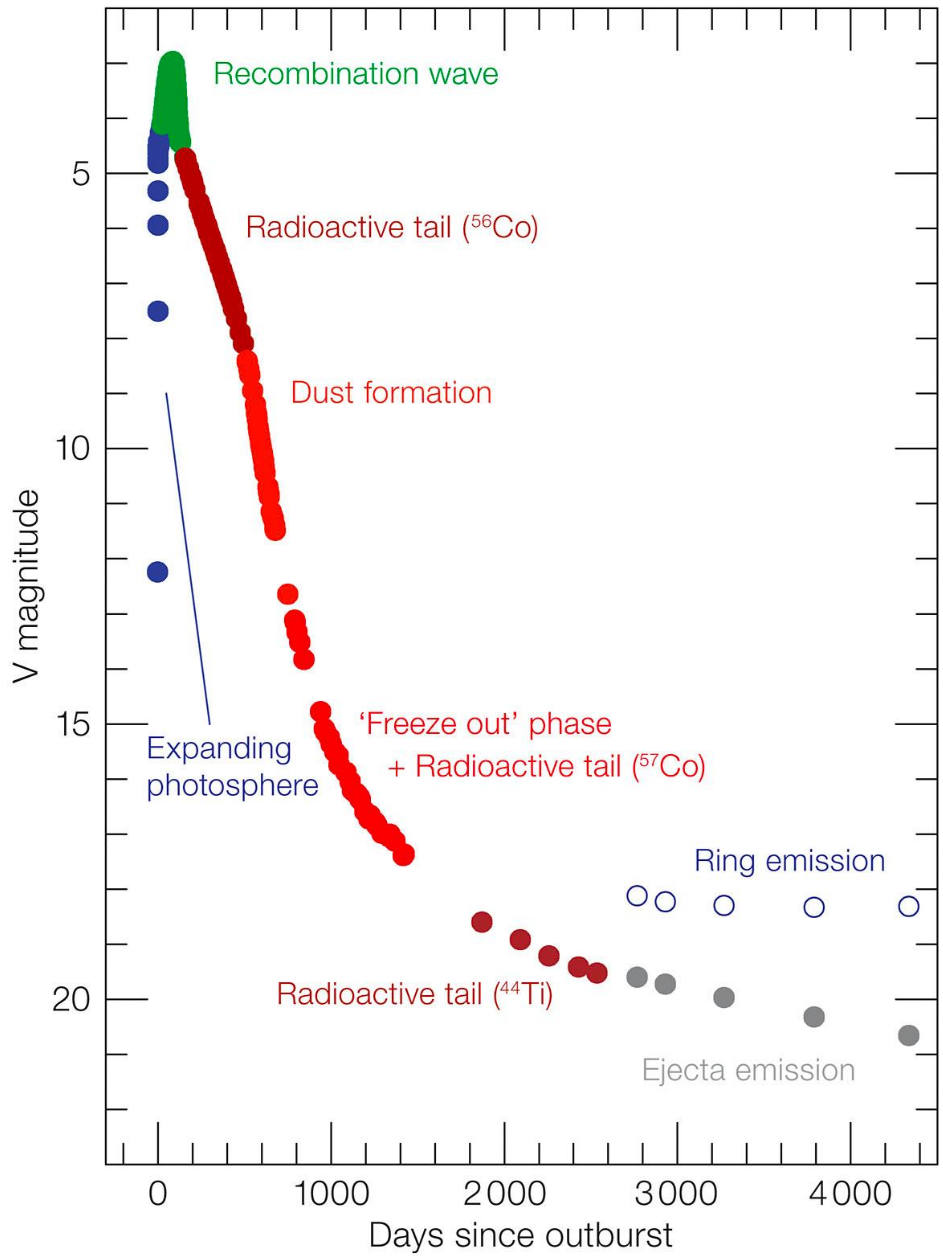
Neutrinos arrived 2-3h earlier

Location of Magellanic Clouds

Distance: 50kpc = 160000 Ly



SN1987A light curve



Credit: ESO

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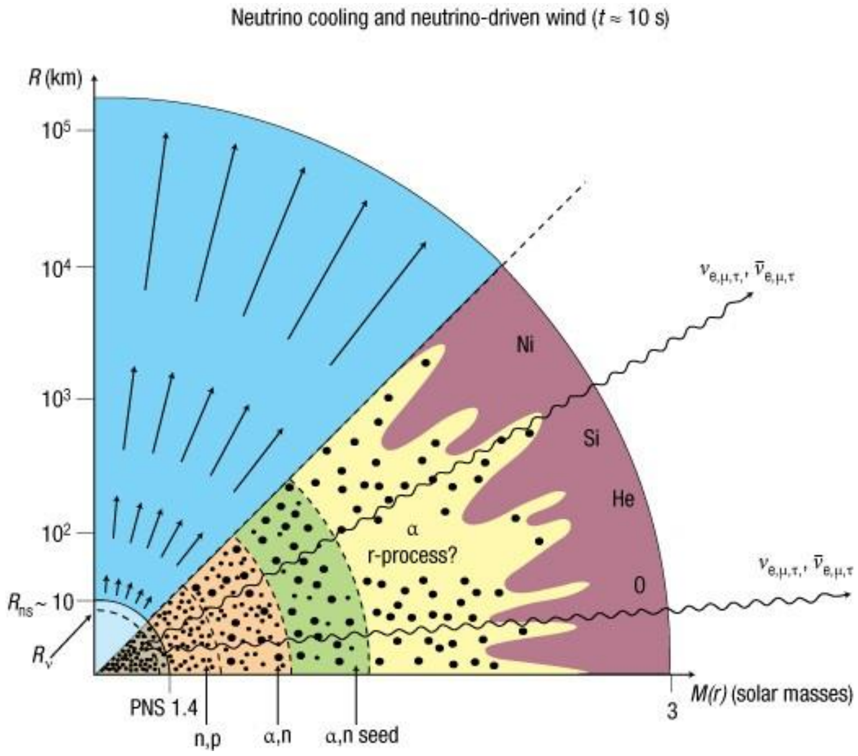
First (and only) detection of a Supernova

First direct confirmation of our
basic picture of a stellar collapse



27

Woosely & Janka,
Nature Physics 2005

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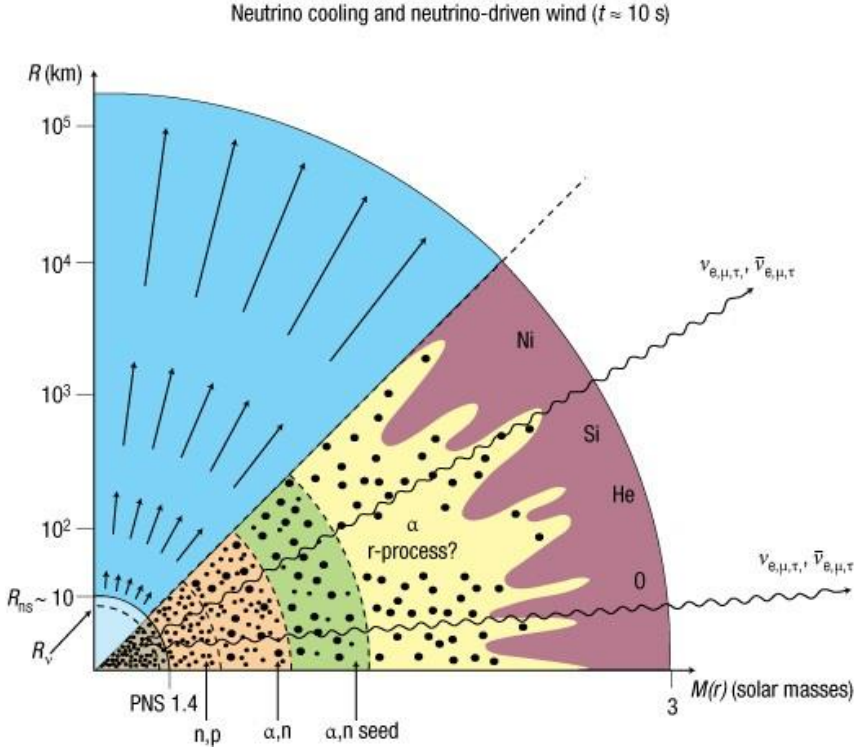
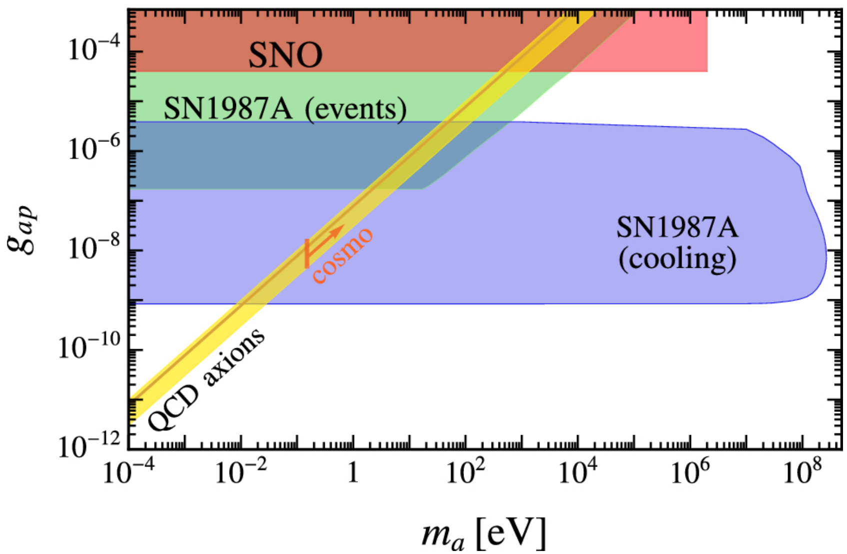
First (and only) detection of a Supernova

First direct confirmation of our basic picture of a stellar collapse

Constraints on exotic physics (e.g. axions)

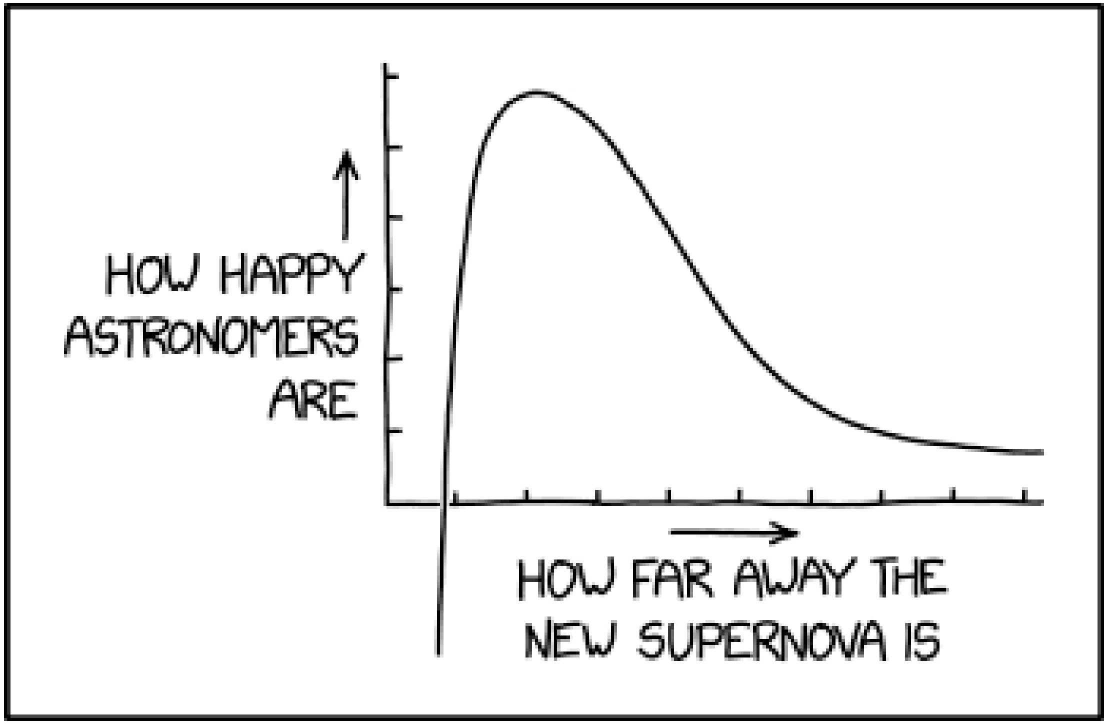




Lella et al. PRD 109 (2024)

Woosely & Janka, Nature Physics 2005

Are we ready for the next Galactic Supernova?!



https://xkcd.com/2878/

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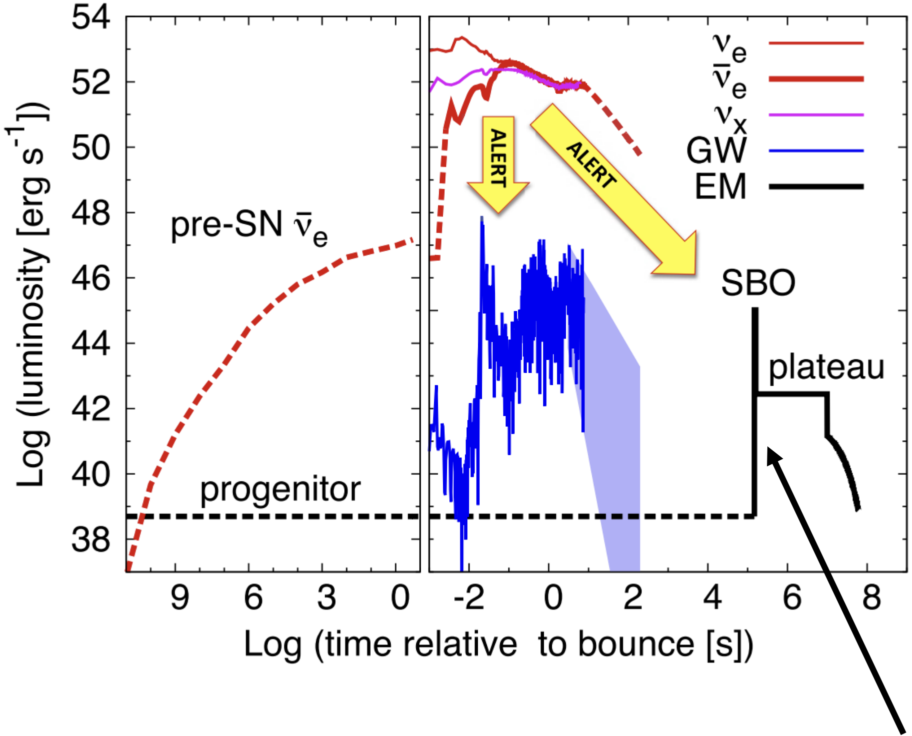
Supernova early warning system

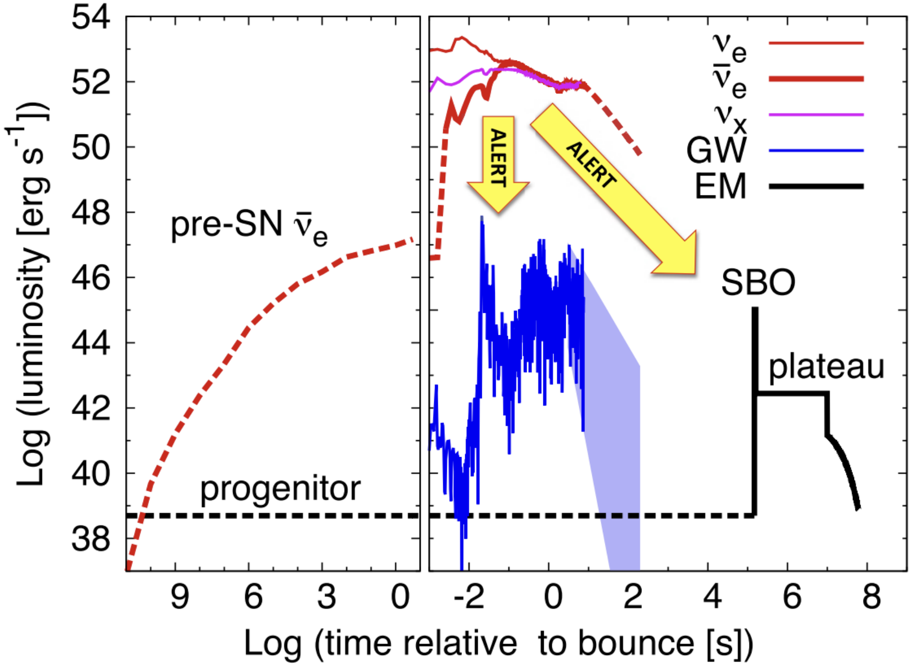
SNEWS
SUPERNOVA EARLY WARNING SYSTEM



Shock breakout in X-ray
and UV emission

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

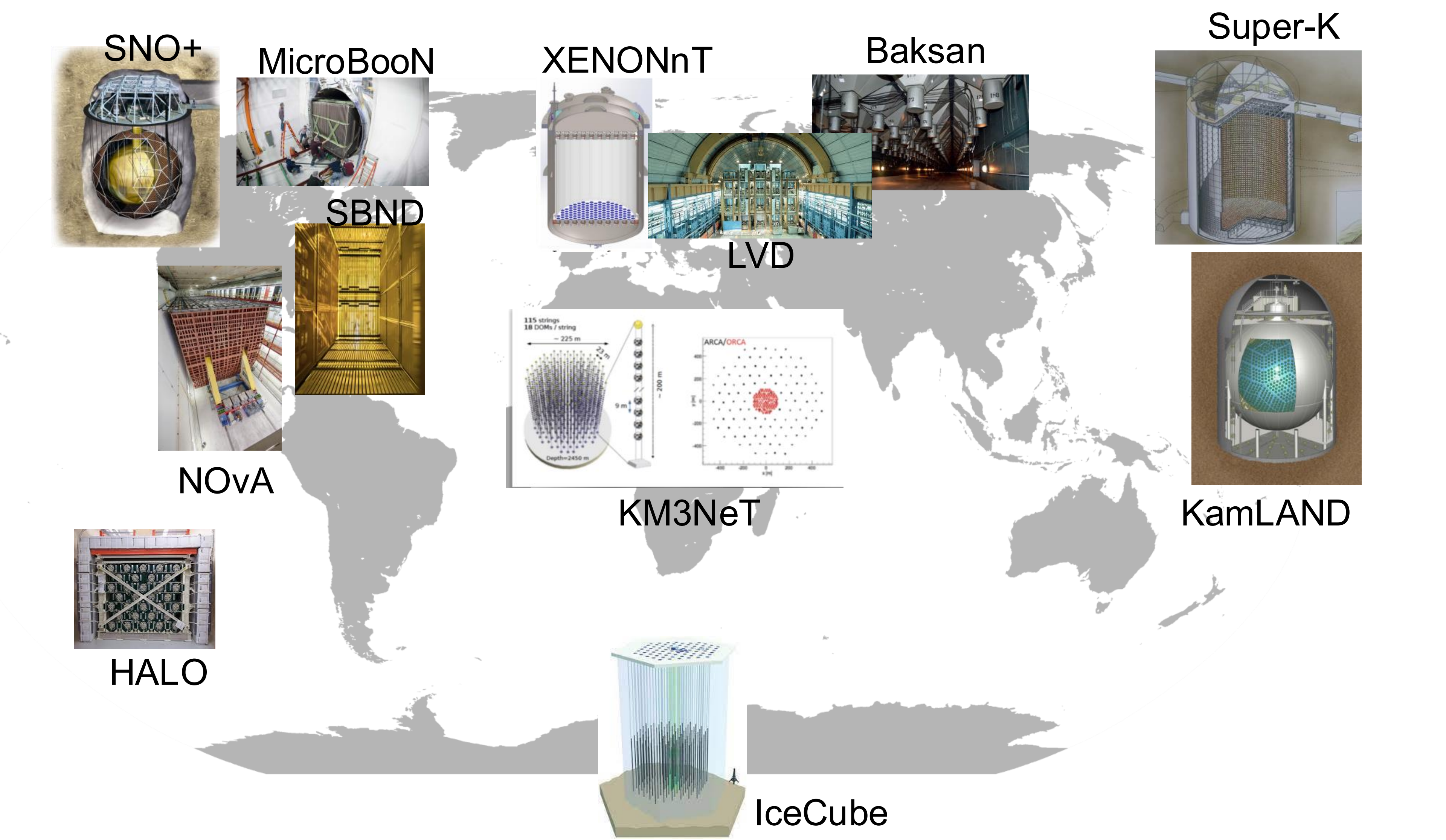
Supernova early warning system



MeV neutrino burst as trigger for electromagnetic supernovae observations

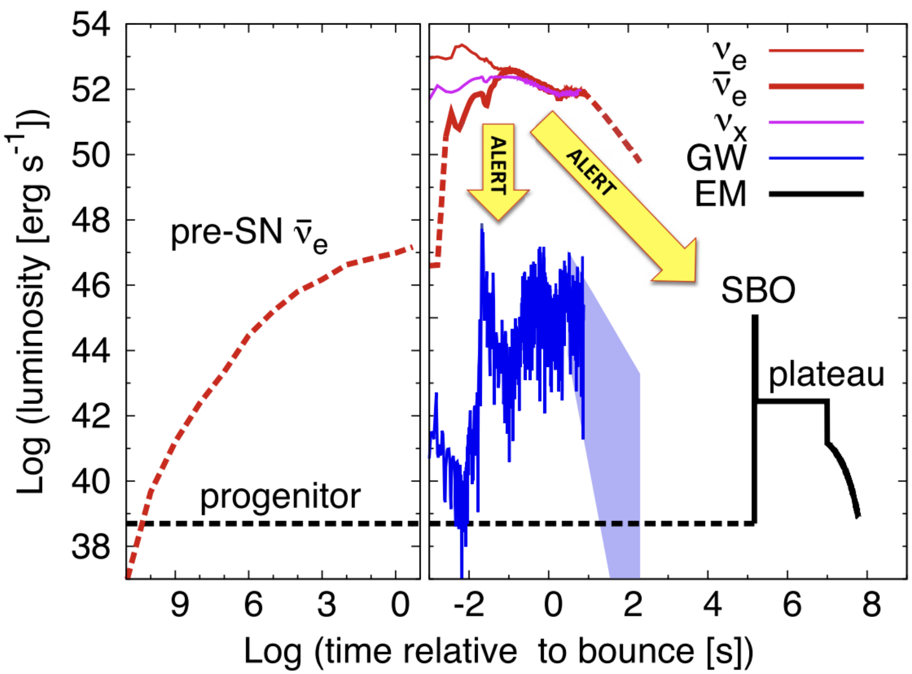
Al Kharusi et al New J. Phys. **23** 2021

Detectors participating in SNEWS



https://snews2.org/

Supernova early warning system



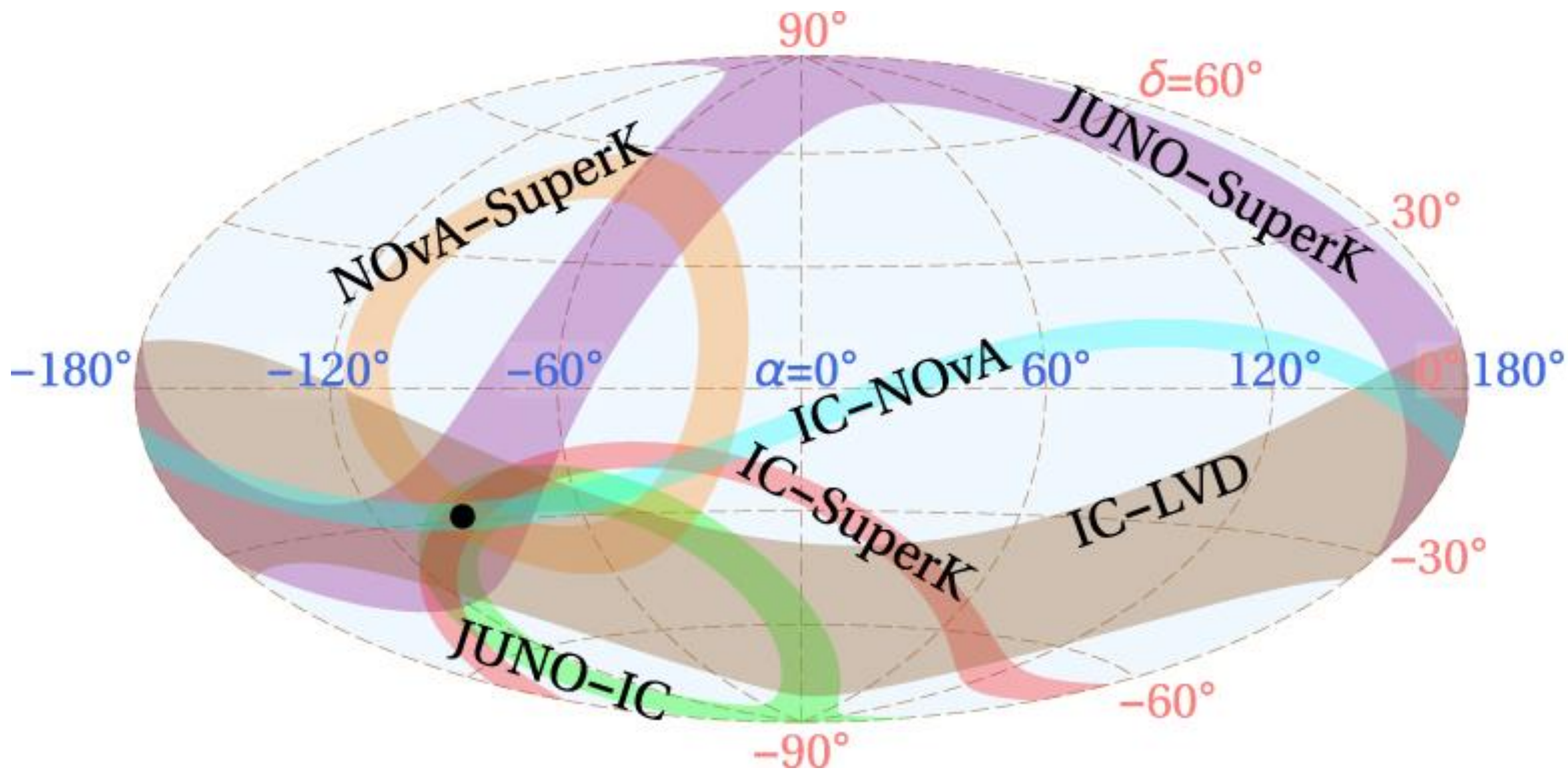
MeV neutrino burst as trigger for electromagnetic supernovae observations

SNEWS 2.0:

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

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

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Kistler et al., ApJ 778 (2013)

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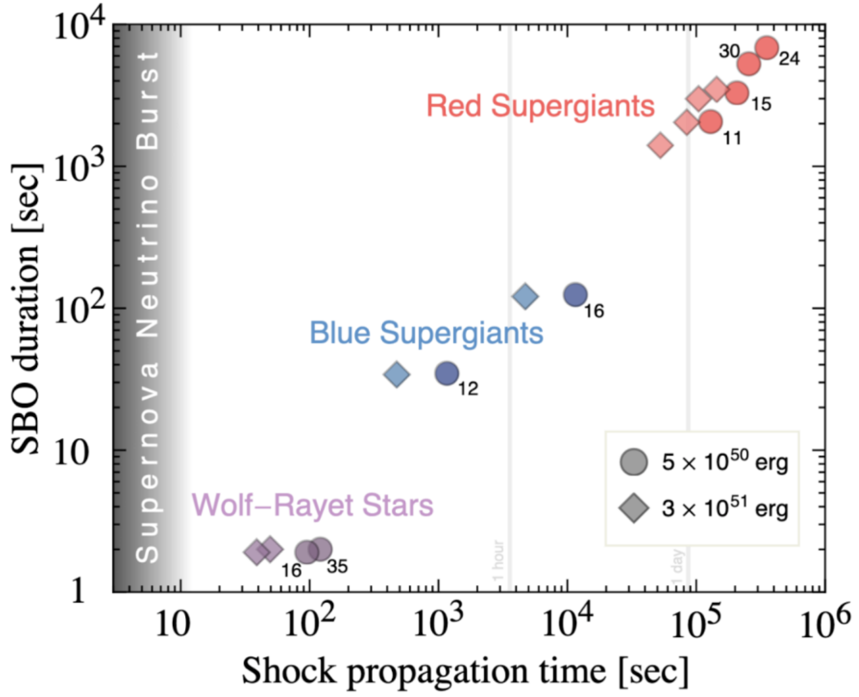
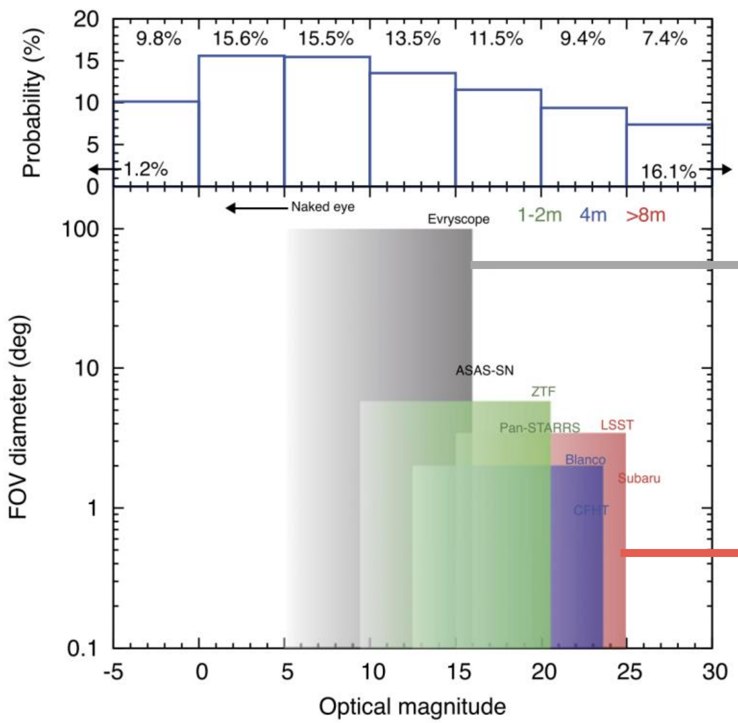
Delay between neutrino burst and optical signal: 2 min to 2 days



Kistler et al., ApJ 778 (2013)

Catching the next Galactic Neutrino Supernova

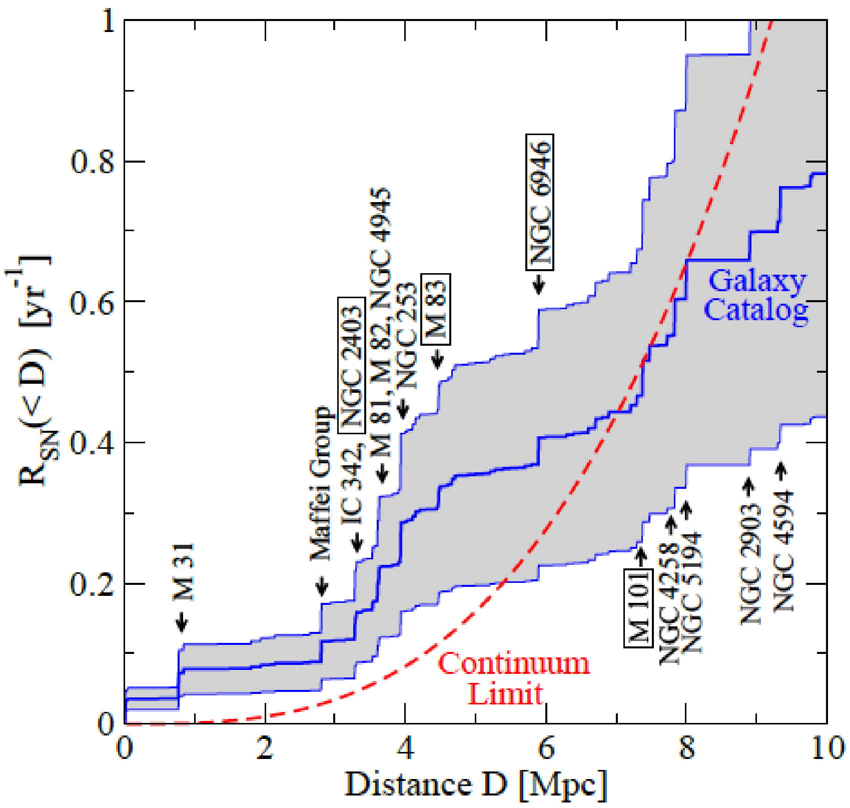
Detectability of shock breakout



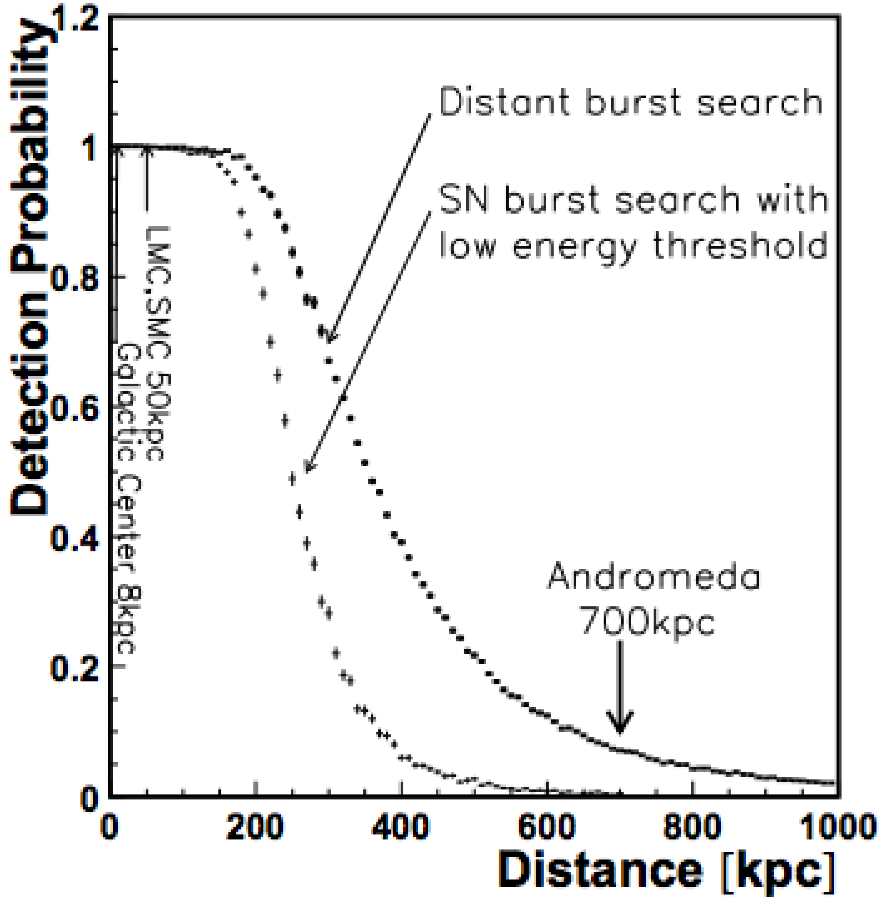
Optical counterpart can appear within minutes of neutrino alert → take full advantage of once-in-a-lifetime event

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

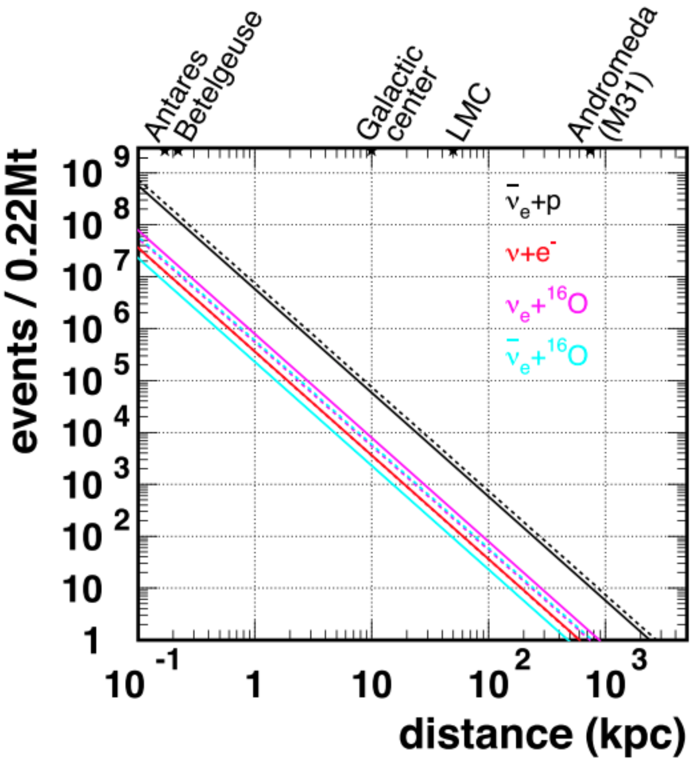
Sensitivity to Supernovae today

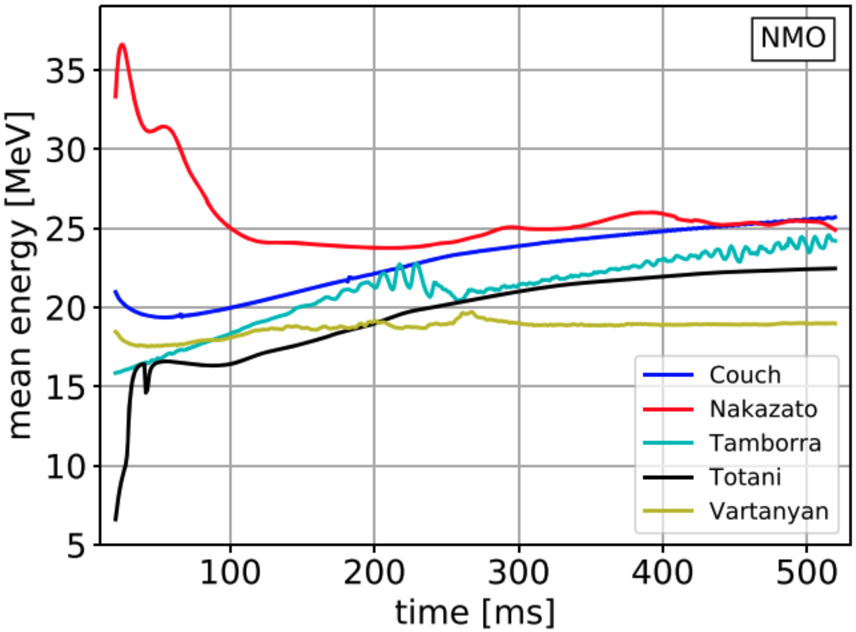


Super-Kamiokande

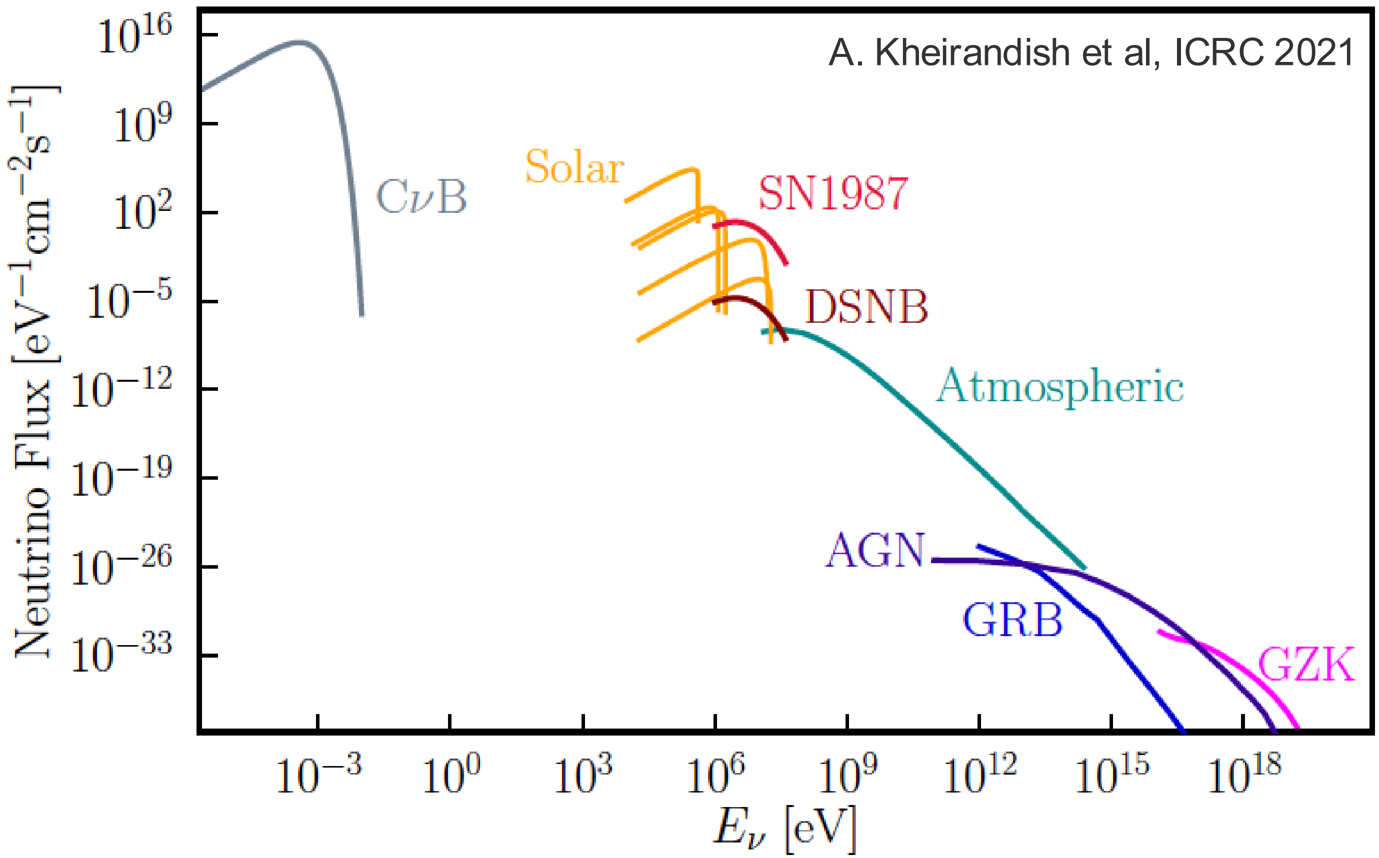


In the future: Hyper-Kamiokande (~2030)





Distinguish different supernova models



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Neutrino capture on stable nucleus (Chlorine, Gallium)

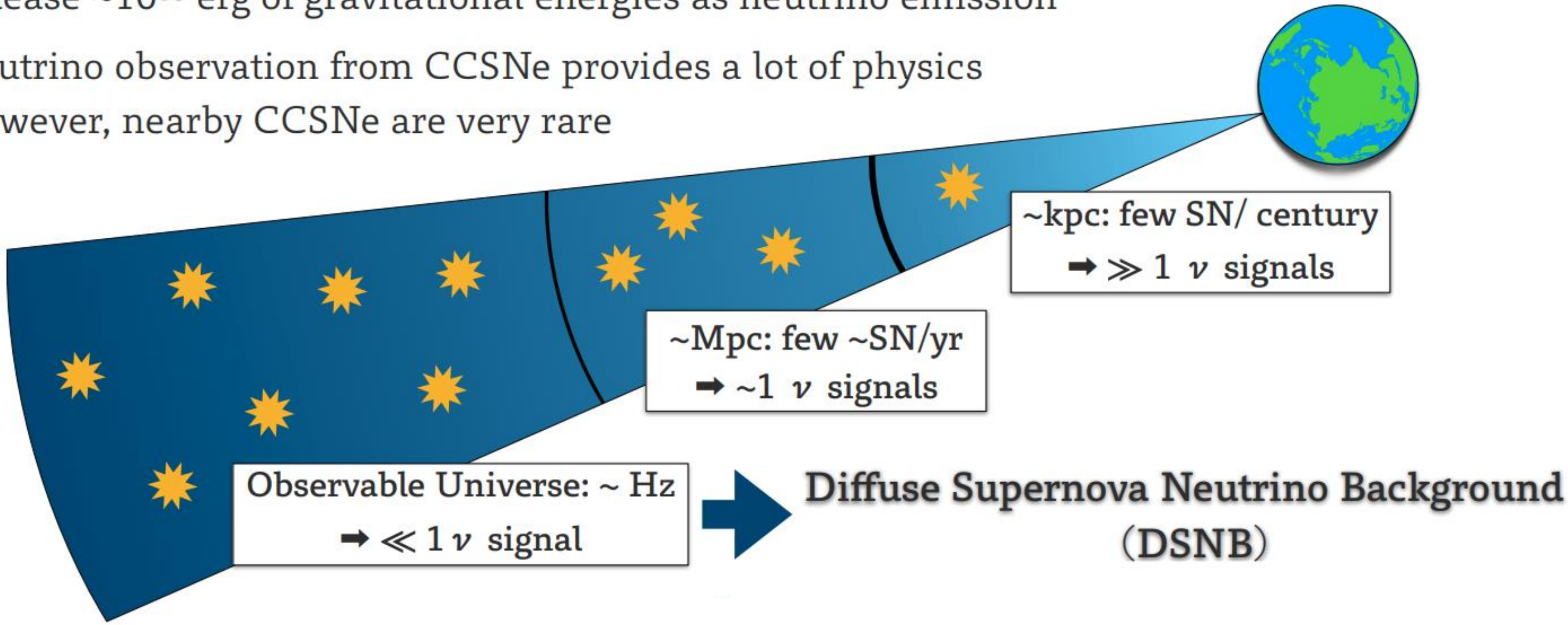
Water / ice Cherenkov detectors

Radio arrays, cosmic-ray detectors

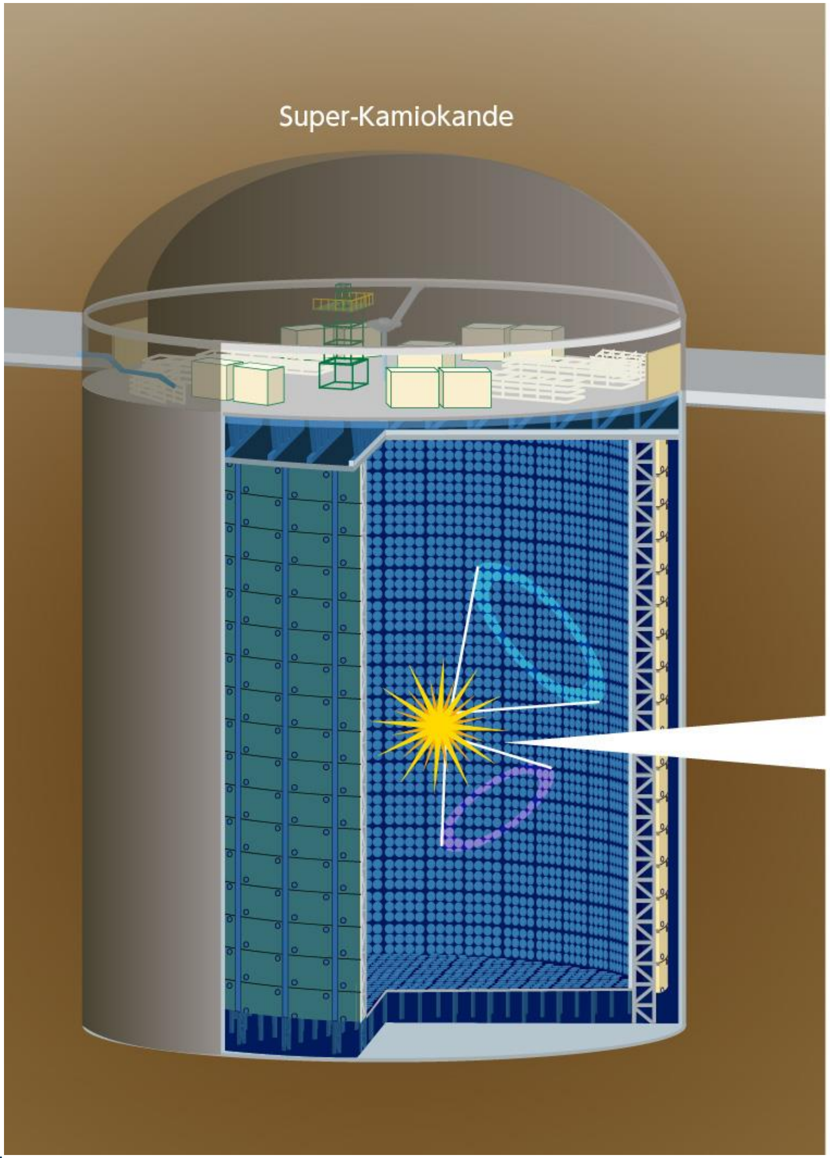
Diffuse Supernova Background (DSNB)

Core-Collapse Supernova (CCSN)

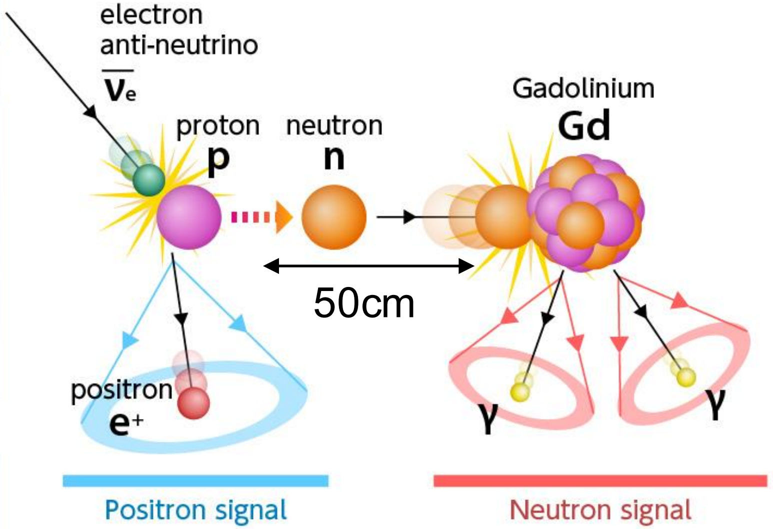
- Release ~10^{53} erg of gravitational energies as neutrino emission
- Neutrino observation from CCSNe provides a lot of physics
  However, nearby CCSNe are very rare



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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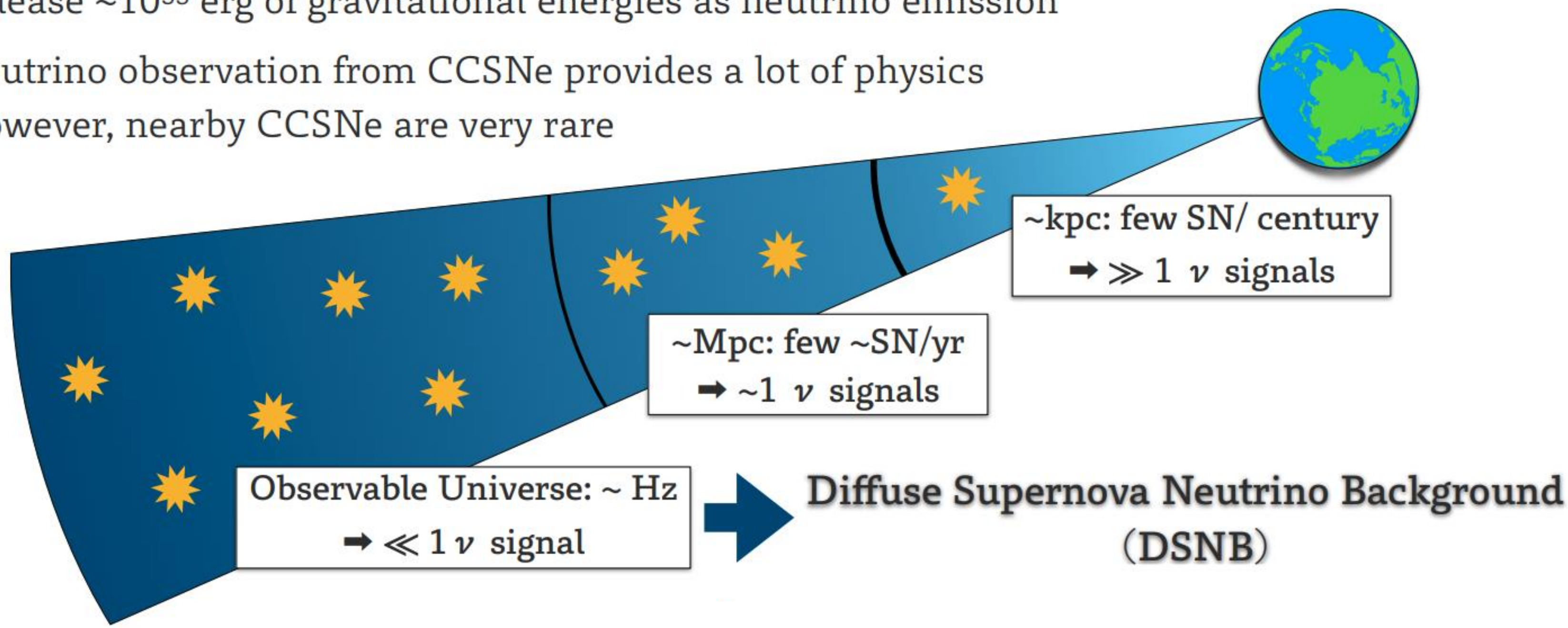
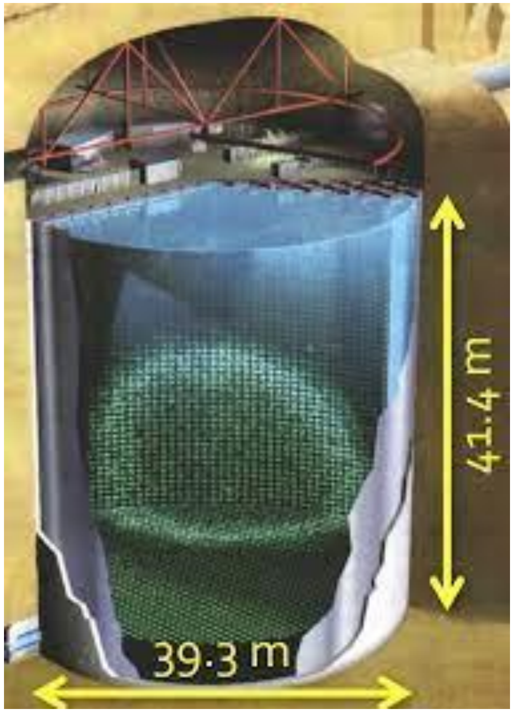


- Also, the latest update of DSNB search in SK-Gd using additional more condensed Gd-water data are exhibited
  ➡ There is no significant DSNB signal, however, some excess appears to be visible in the signal region, which is 2.3 σ tension from non-DSNB hypothesis
- Looking forward to discovery of DSNB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

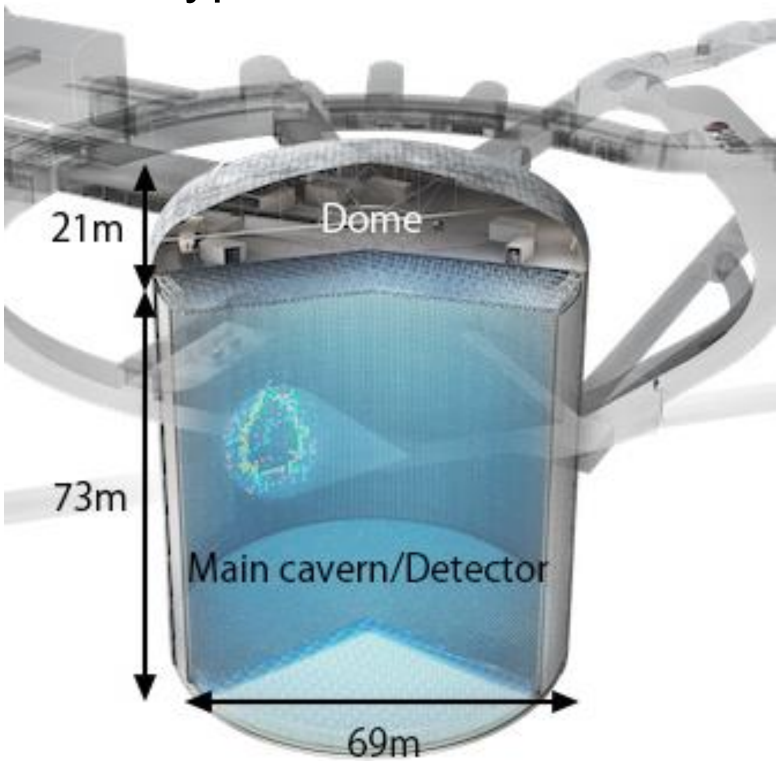
Next Generation Detector: Hyper Kamiokande

Super Kamiokande



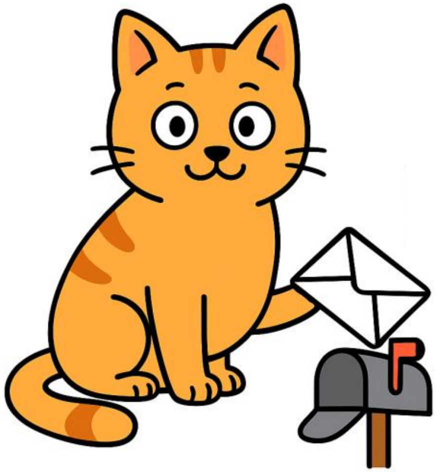
Volume: 50kT

Hyper Kamiokande



Volume: 260kT

Data taking start in 2027

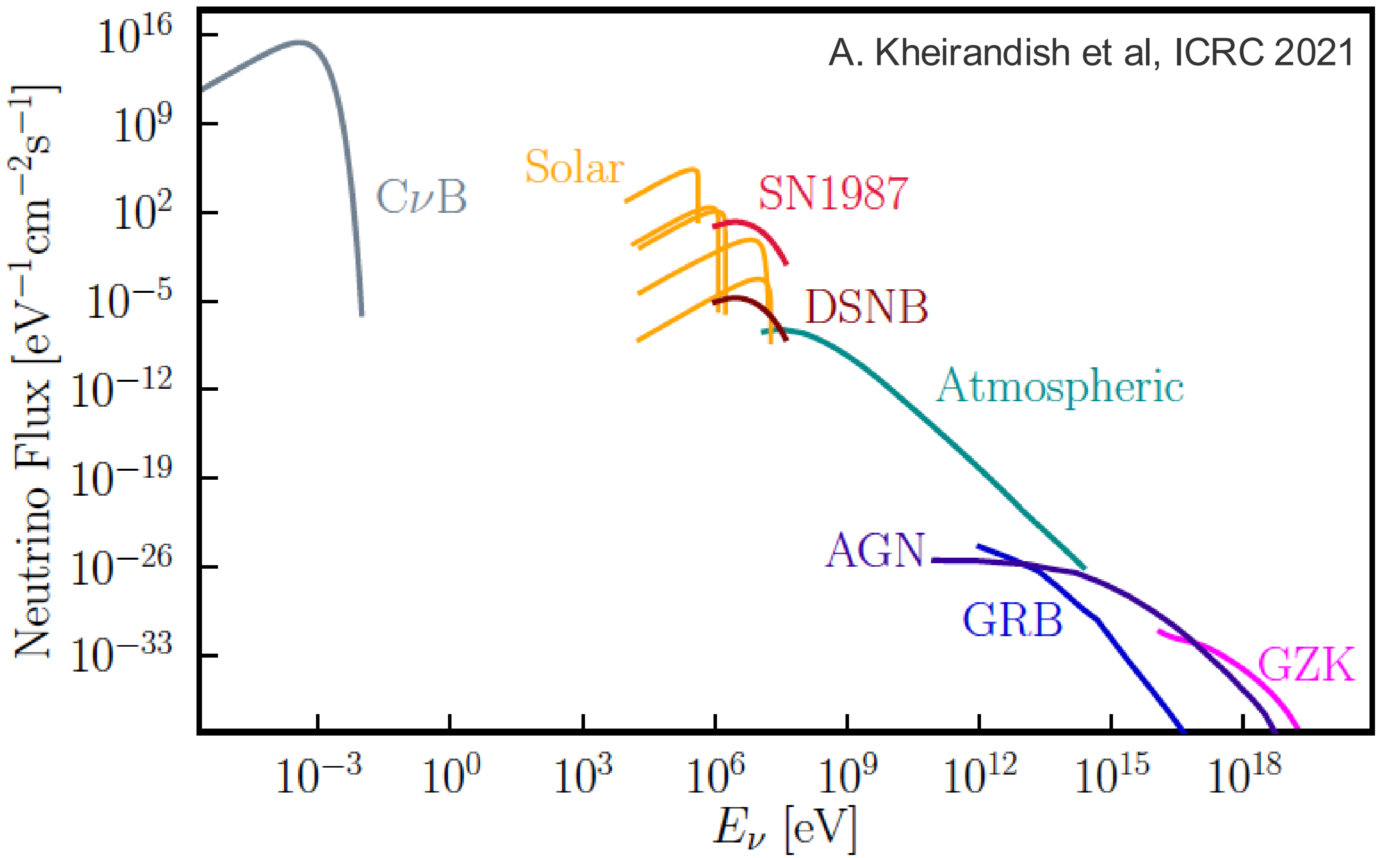


Take home message

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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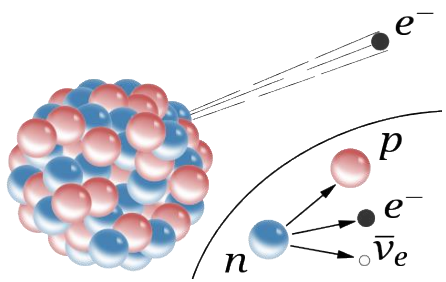
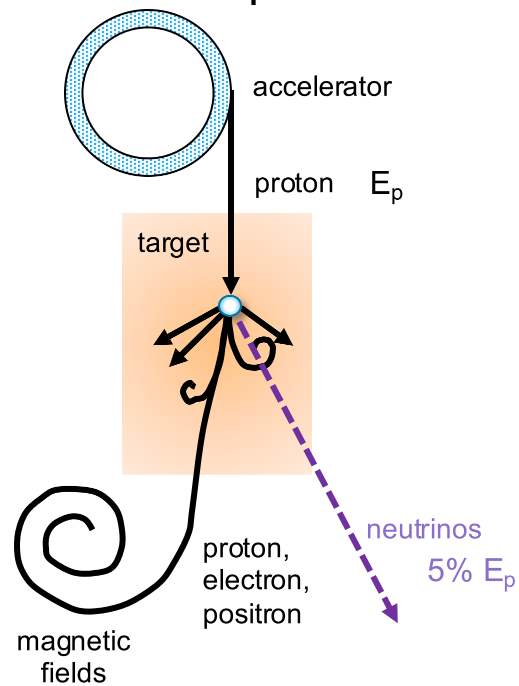
How are high-energy neutrinos produced?

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

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

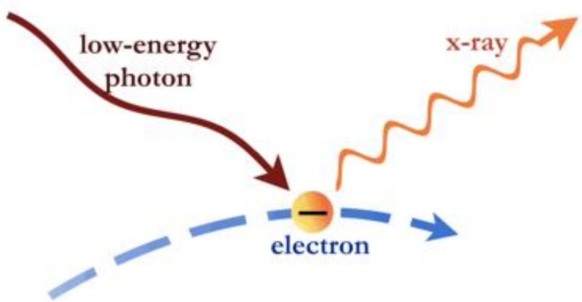
Neutrino Production Processes

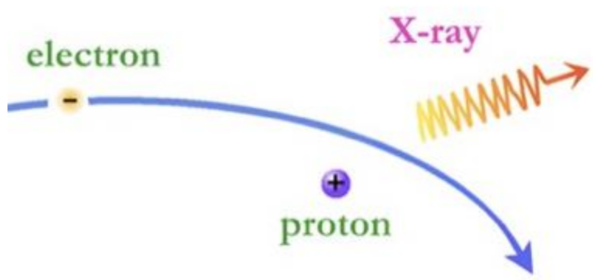
Cosmic ray

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

target

Gamma-rays are not exclusively produced in hadronic processes





Neutrino Production Processes

Cosmic ray

pp

$p\gamma$

target

$\rightarrow$

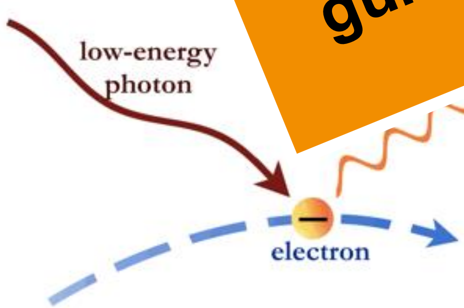
$$\ldots + \pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_e + \bar{\nu}_\mu + \nu_\mu$$

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

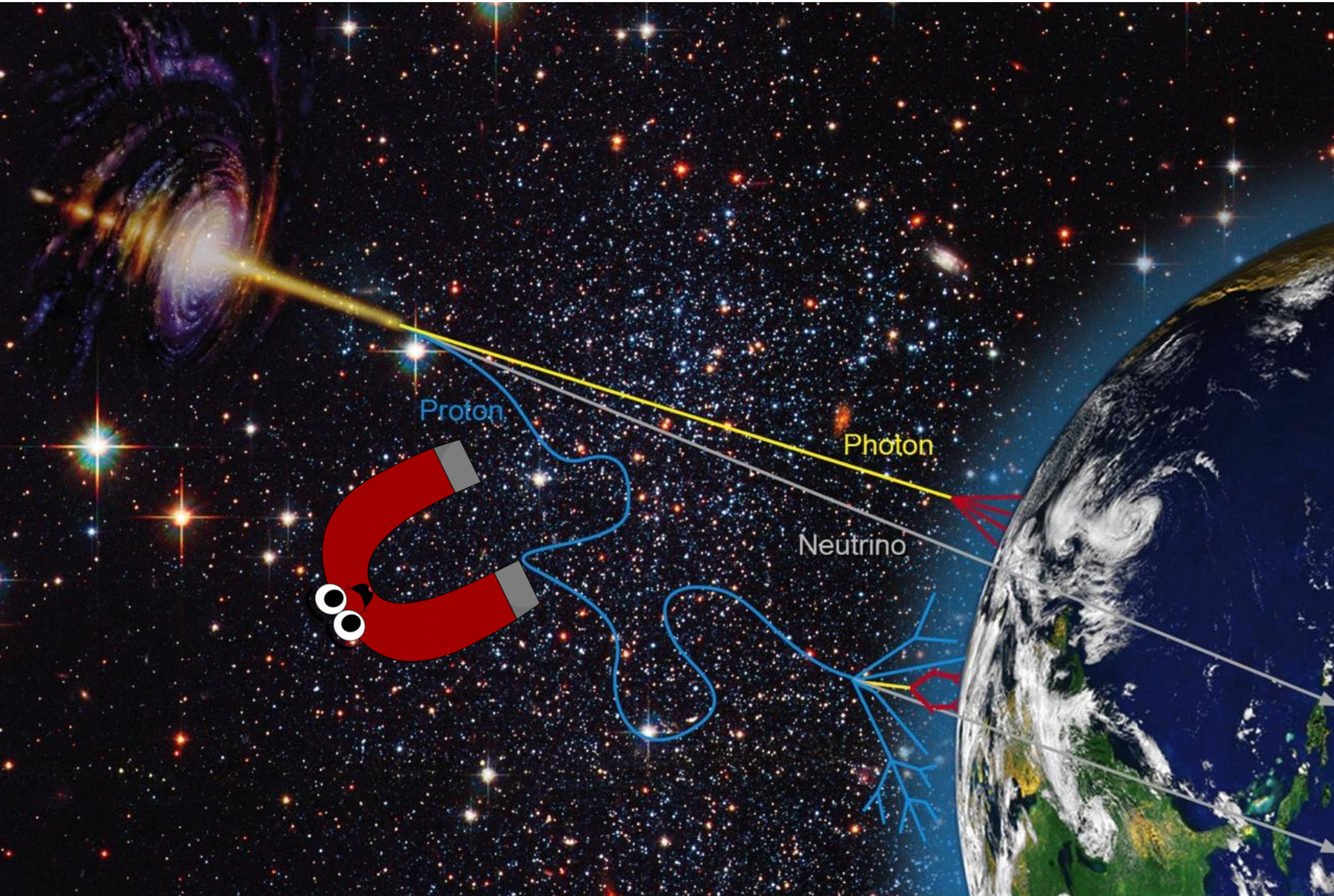
$$\ldots + \pi^0 \rightarrow \gamma\gamma$$

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 Mpc^{-3} 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

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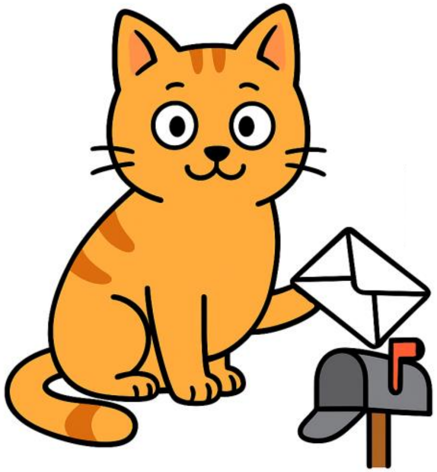
- All protons undergo photohadronic interactions (pγ), producing neutrons, gamma rays and neutrinos
- The sources are optically thin to neutrons, which leave the sources and subsequently decay into protons, accounting for the UHECR flux observed at the Earth
- Energy flux of neutrinos cannot be greater 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



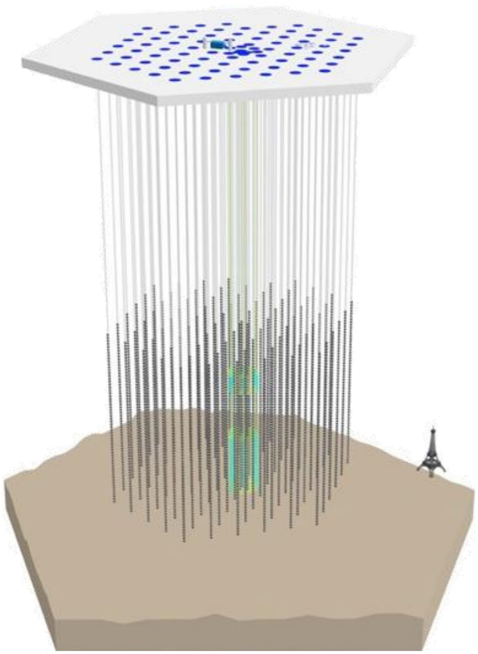
Take home message

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

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

High-energy Neutrino Detectors

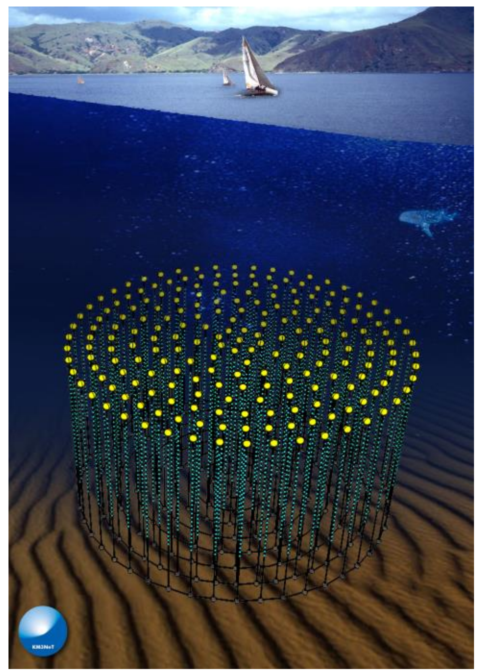
IceCube (1 km^3)



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

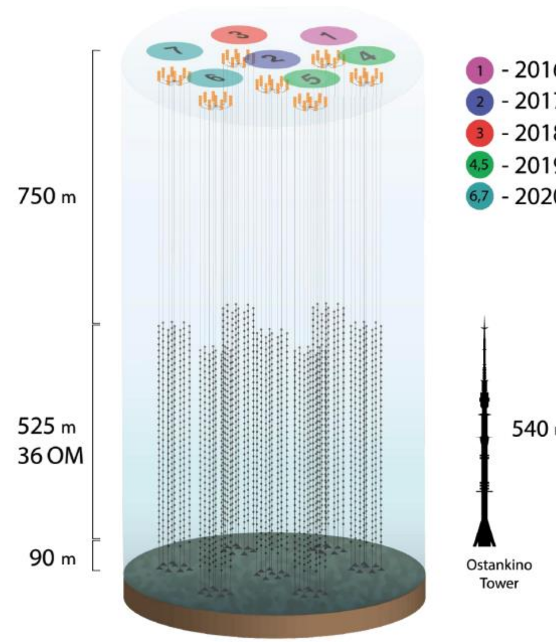
KM3NeT (2 x 0.5 km^3)
Under construction
Predecessor ANTARES decommissioned after 14y



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

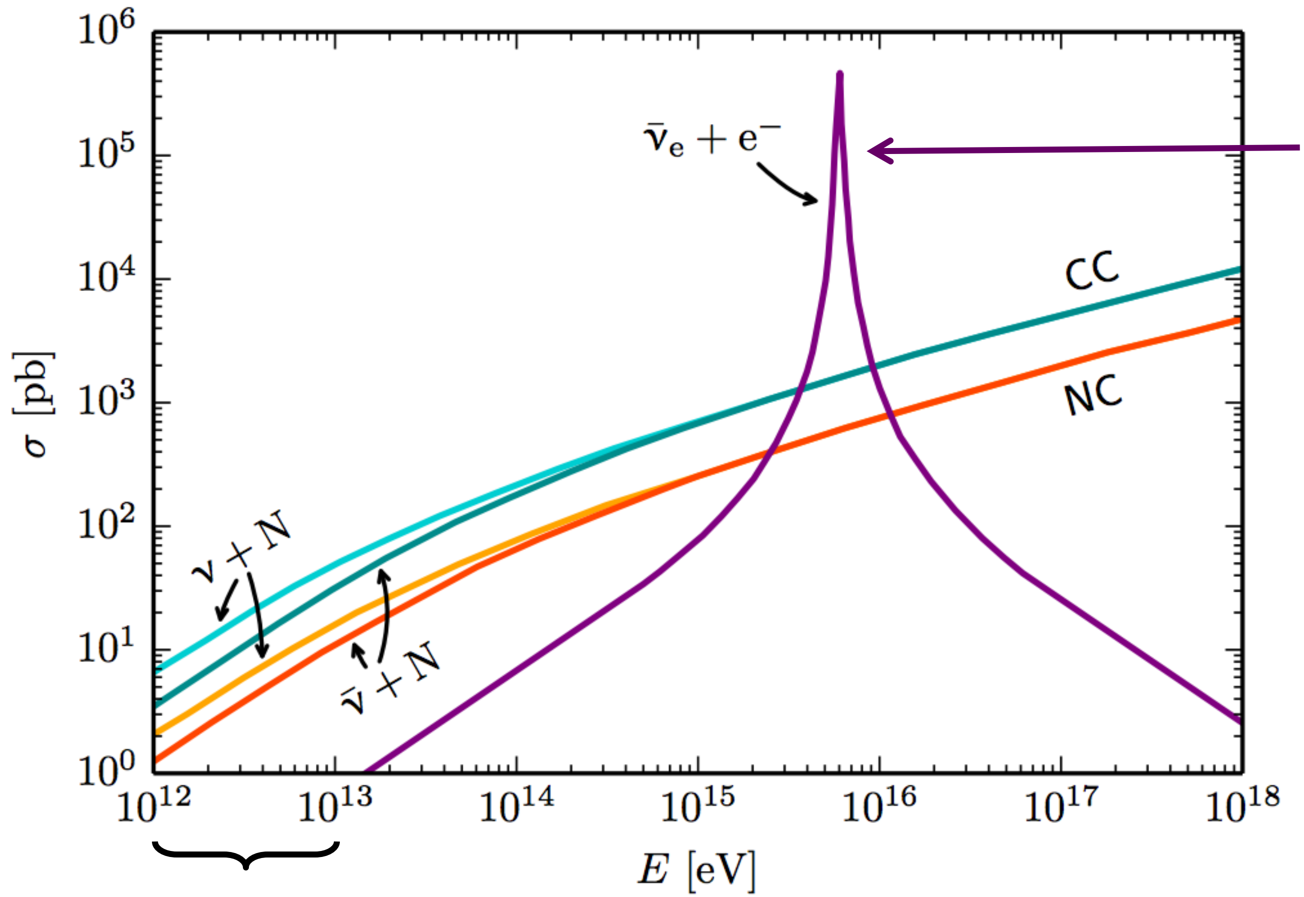
A.D. Avrorin et al. arXiv:2011.09209

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

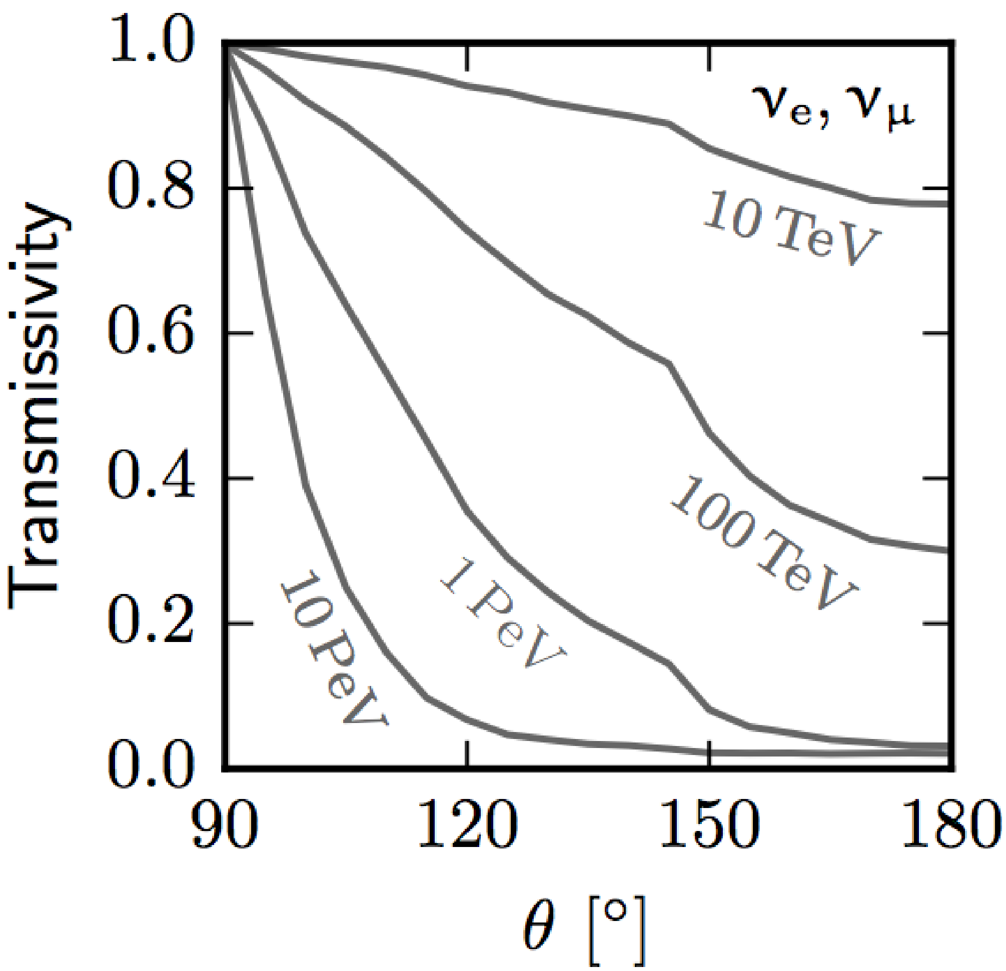


Linear with E, Smaller for anti-neutrinos due to helicity

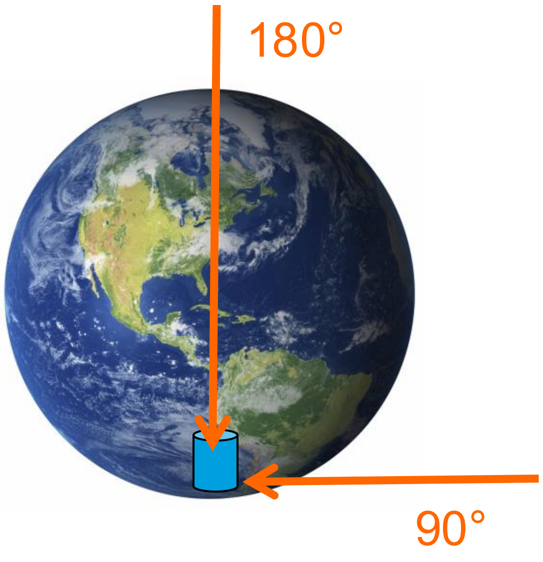
damped by the W-boson propagator

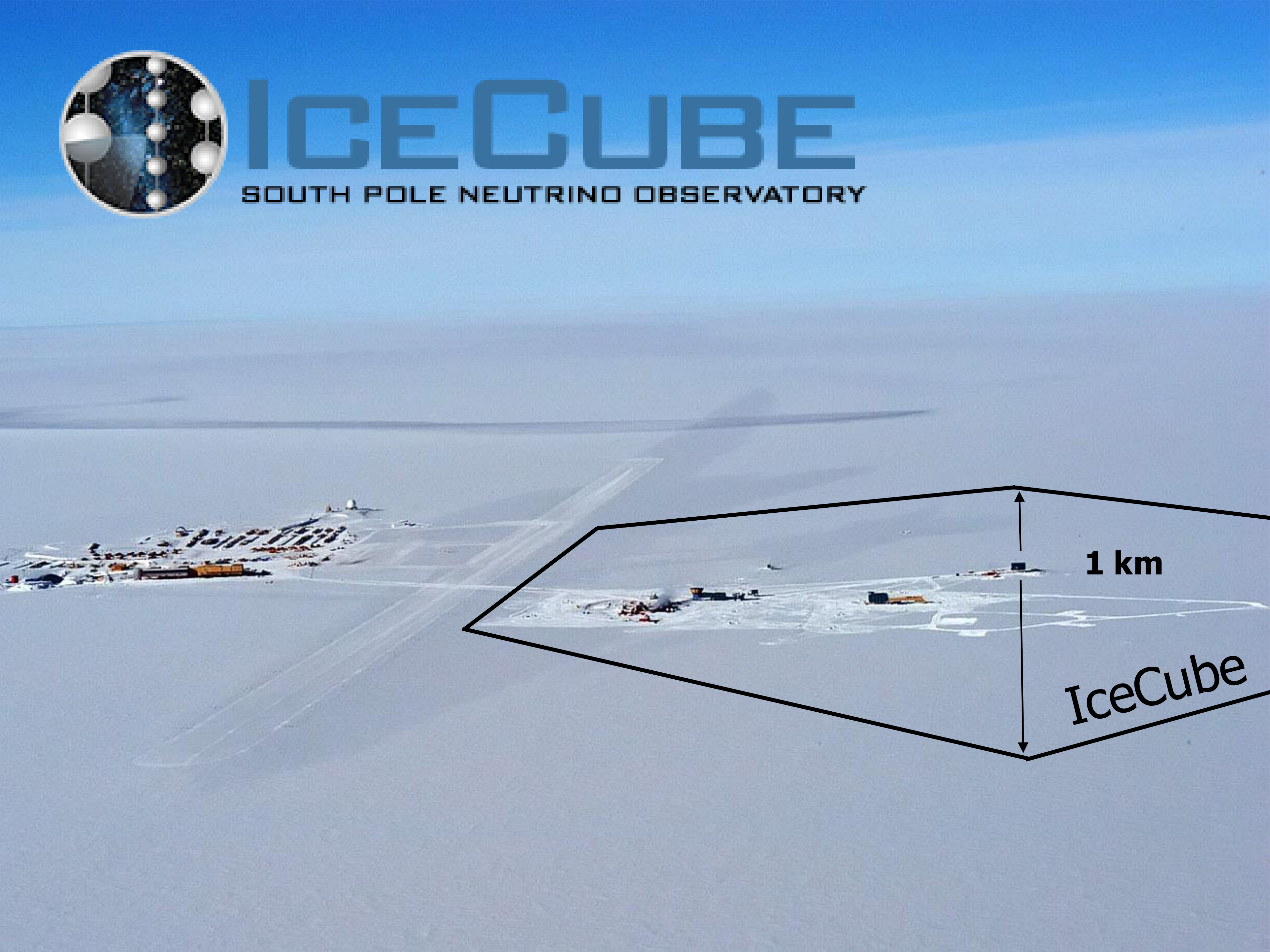
Glashow resonance: resonance when the center-of-mass energy of the system reaches the mass of the mediating boson. For electrons at rest and the mass of the $W^{\pm}$ boson (80 GeV), the Glashow resonance occurs at a neutrino energy of 6.3×10^{15} eV

Absorption of High-Energy Neutrinos in the Earth



For high-energies Earth becomes opaque to neutrinos

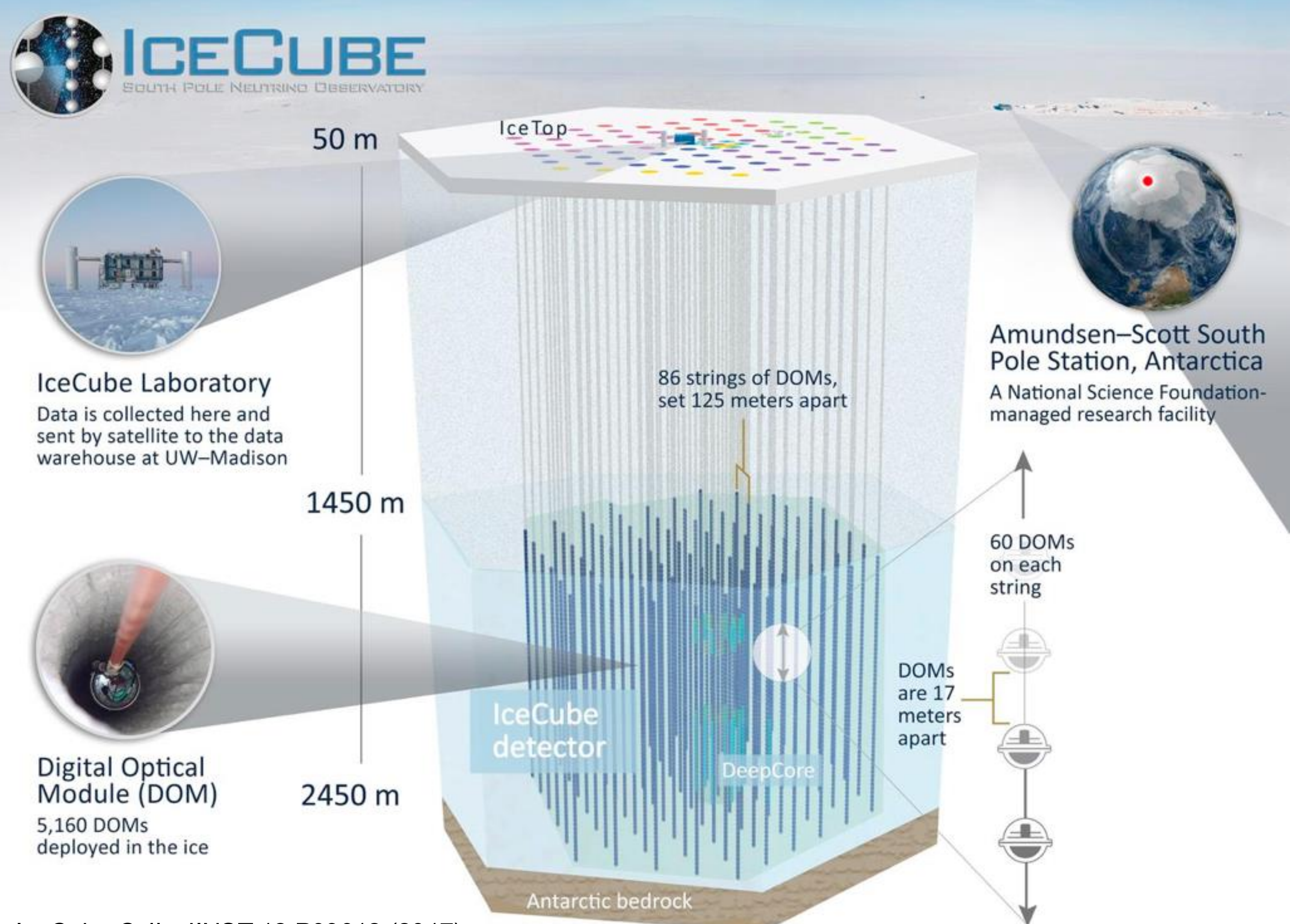



IceCube
SOUTH POLE NEUTRINO OBSERVATORY
1 km
IceCube

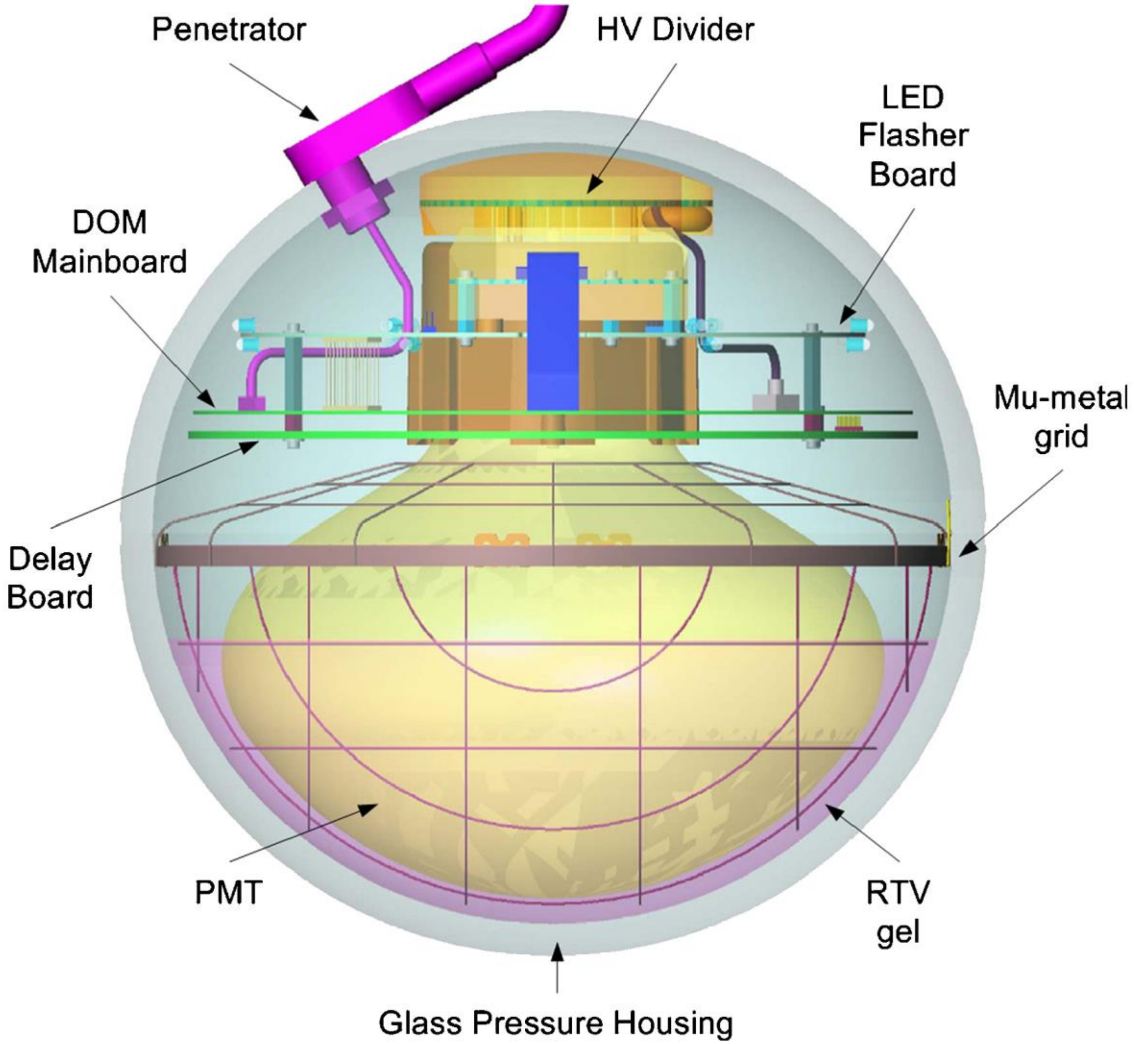
The South Pole

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

RUB



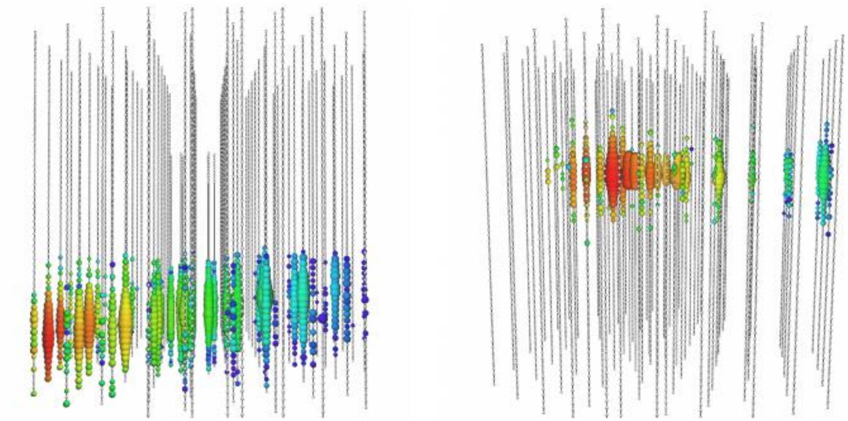
IceCube Coll., JINST 12 P03012 (2017)



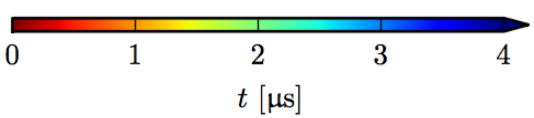
5160 DOMs deployed
Failure rate: <0.3%

IceCube Coll., JINST 12 P03012 (2017)

Event Signatures

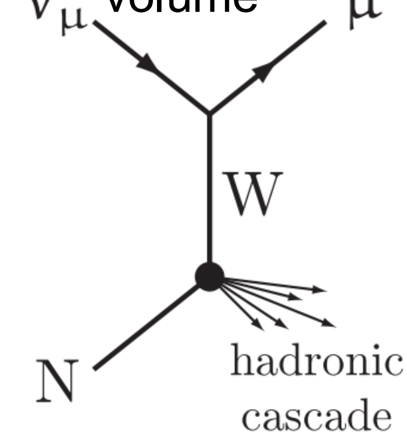


(a) (b)

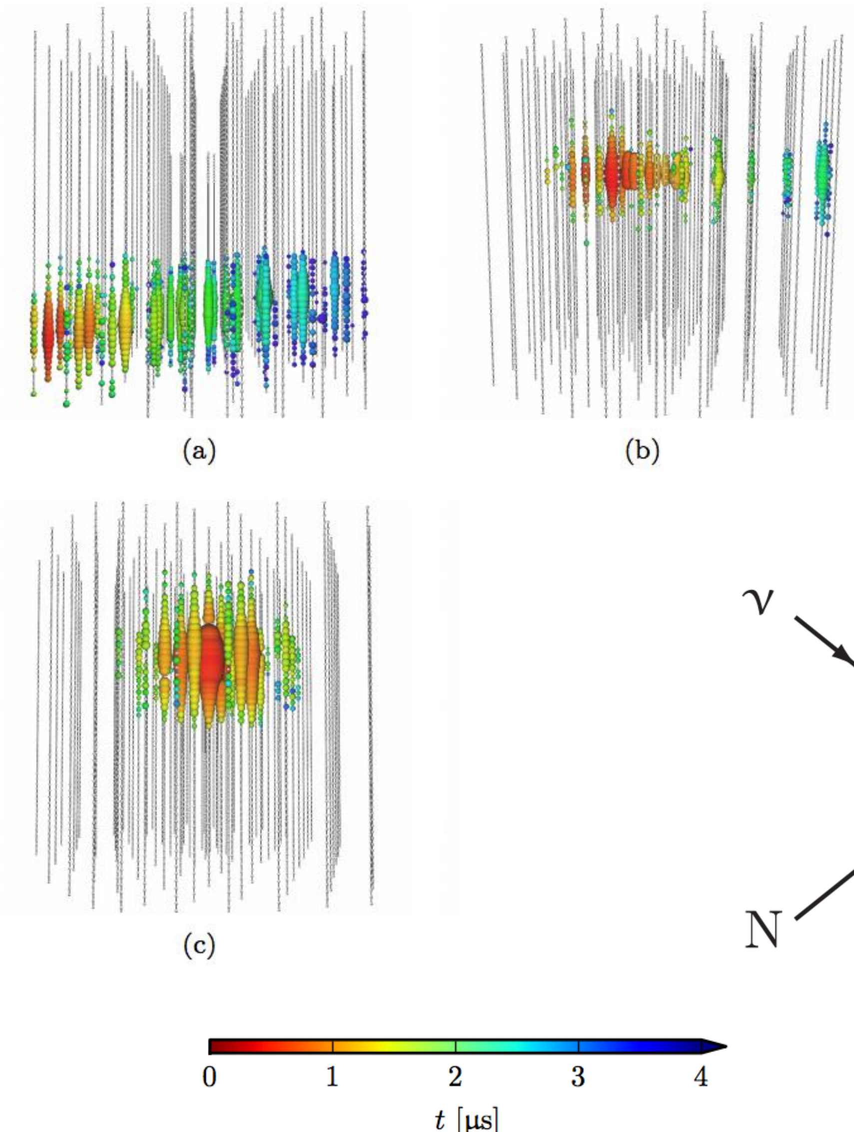


a) **through-going muon track E ~ 140 TeV**
b) **Starting muon track E ~ 70 TeV**

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

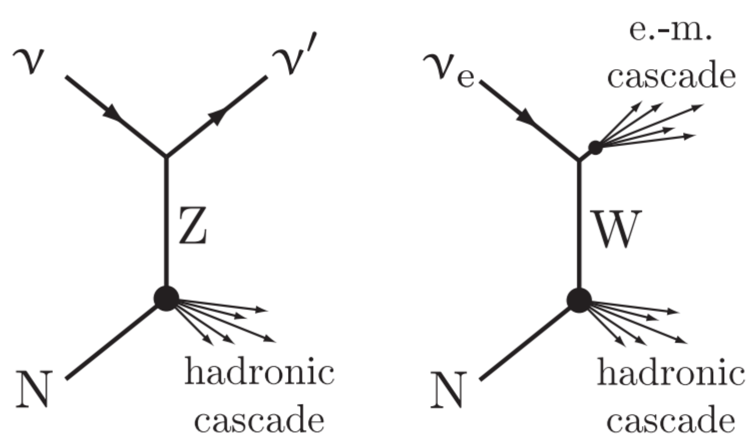


Event Signatures



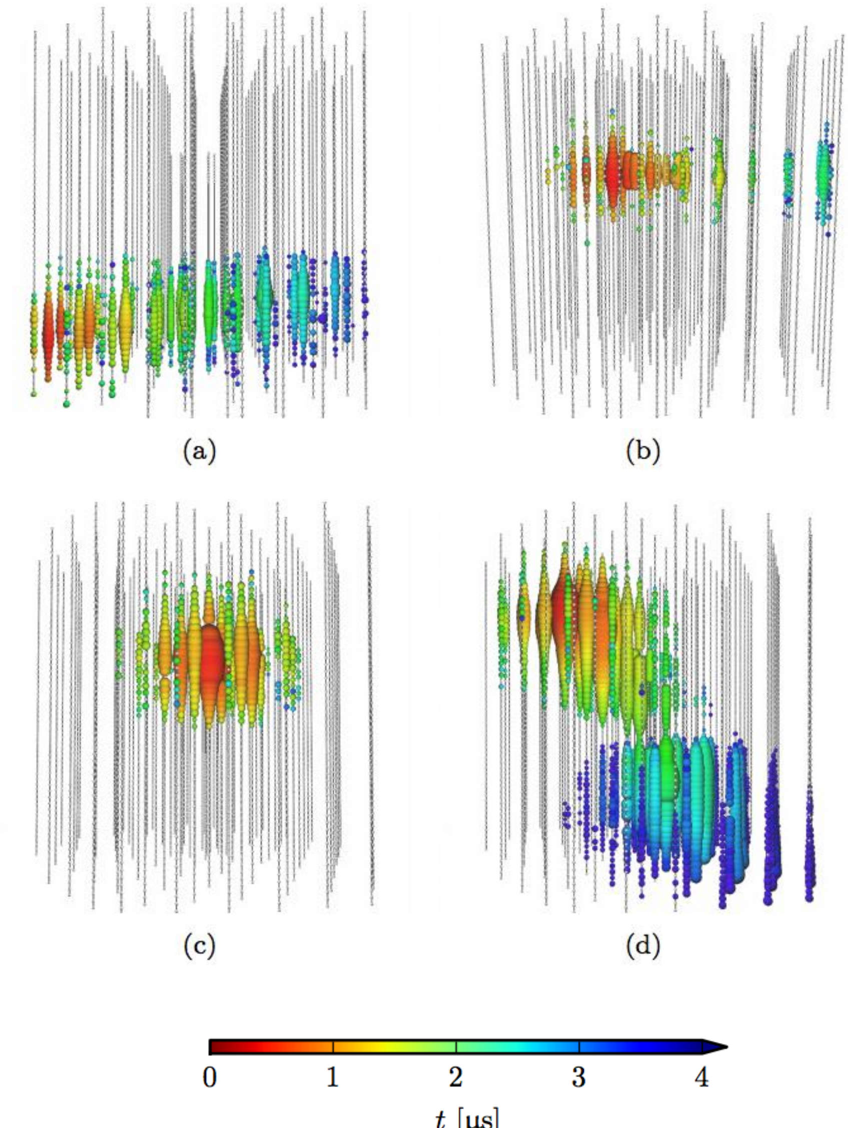
a) through-going muon track E ~ 140 TeV
b) Starting muon track E ~ 70 TeV
c) Shower event E ~ 1 PeV

Neutral current or electron neutrino charged current interaction



Cannot distinguish between showers (size few meters)

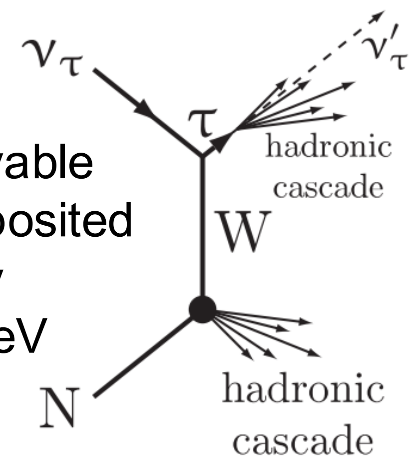
Event Signatures



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

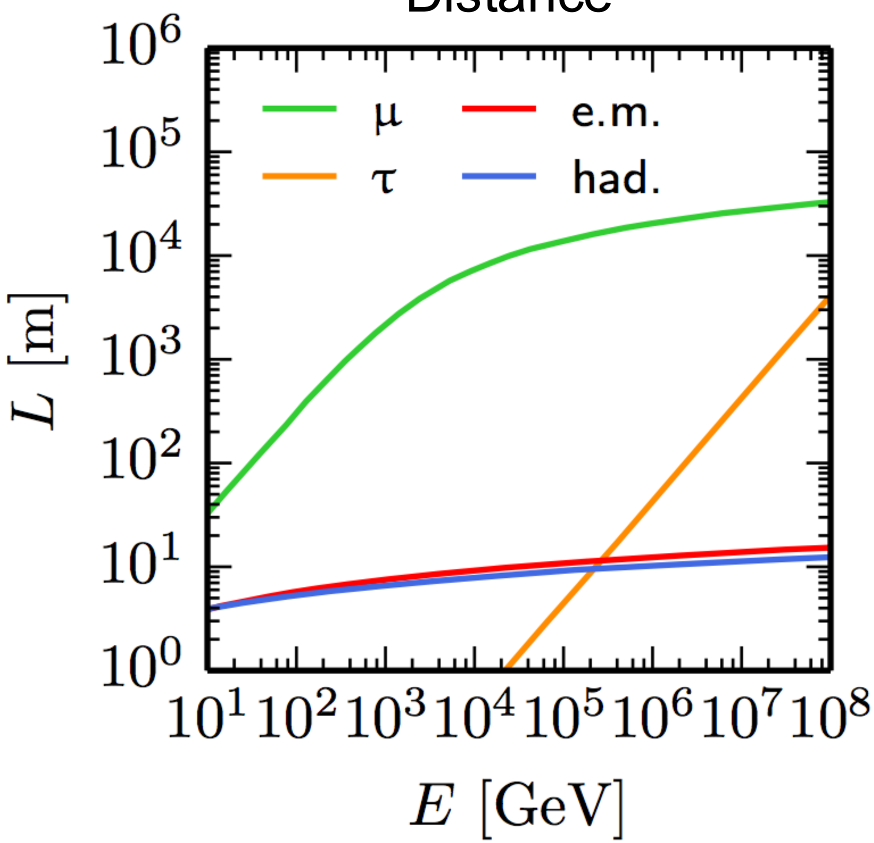
Resolvable for deposited energy >100TeV



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

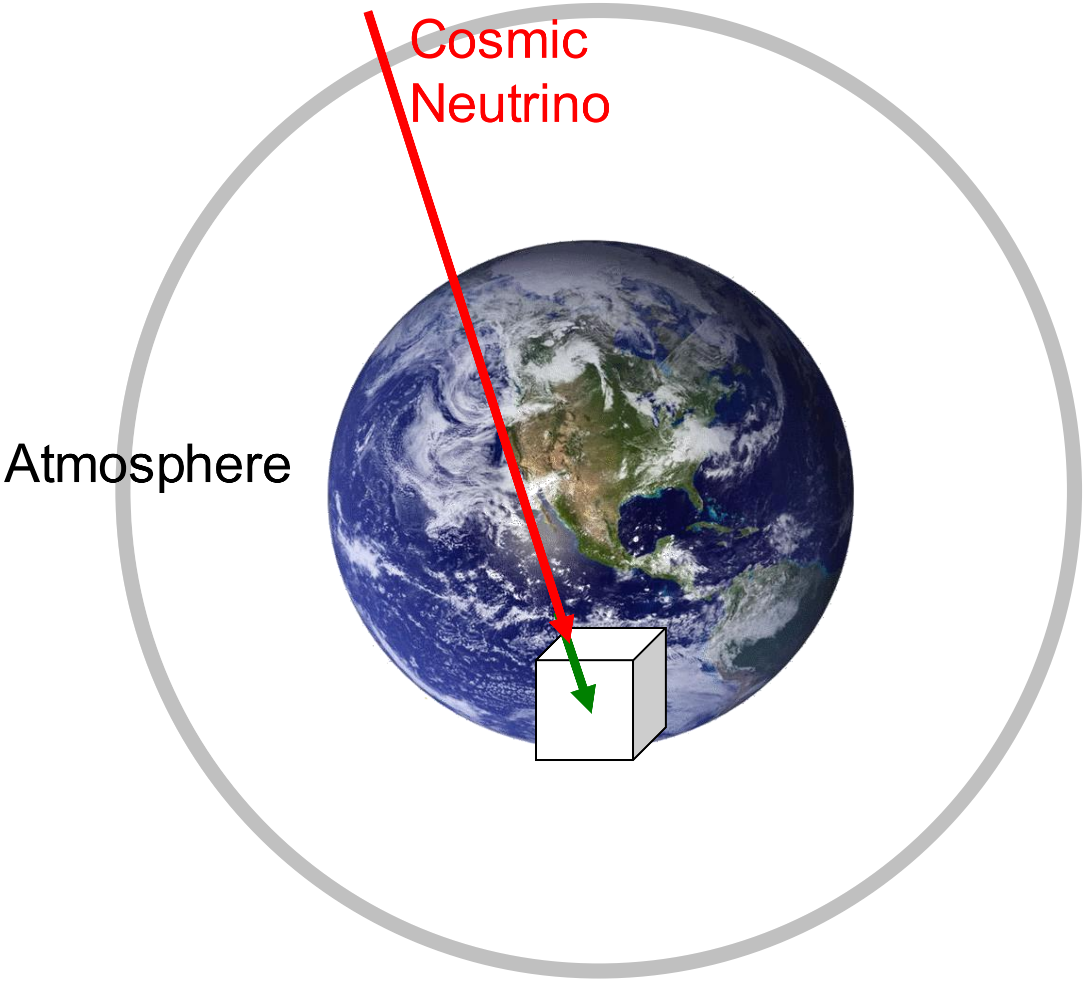
Secondary Particle Interactions in Ice

Average Propagation Distance

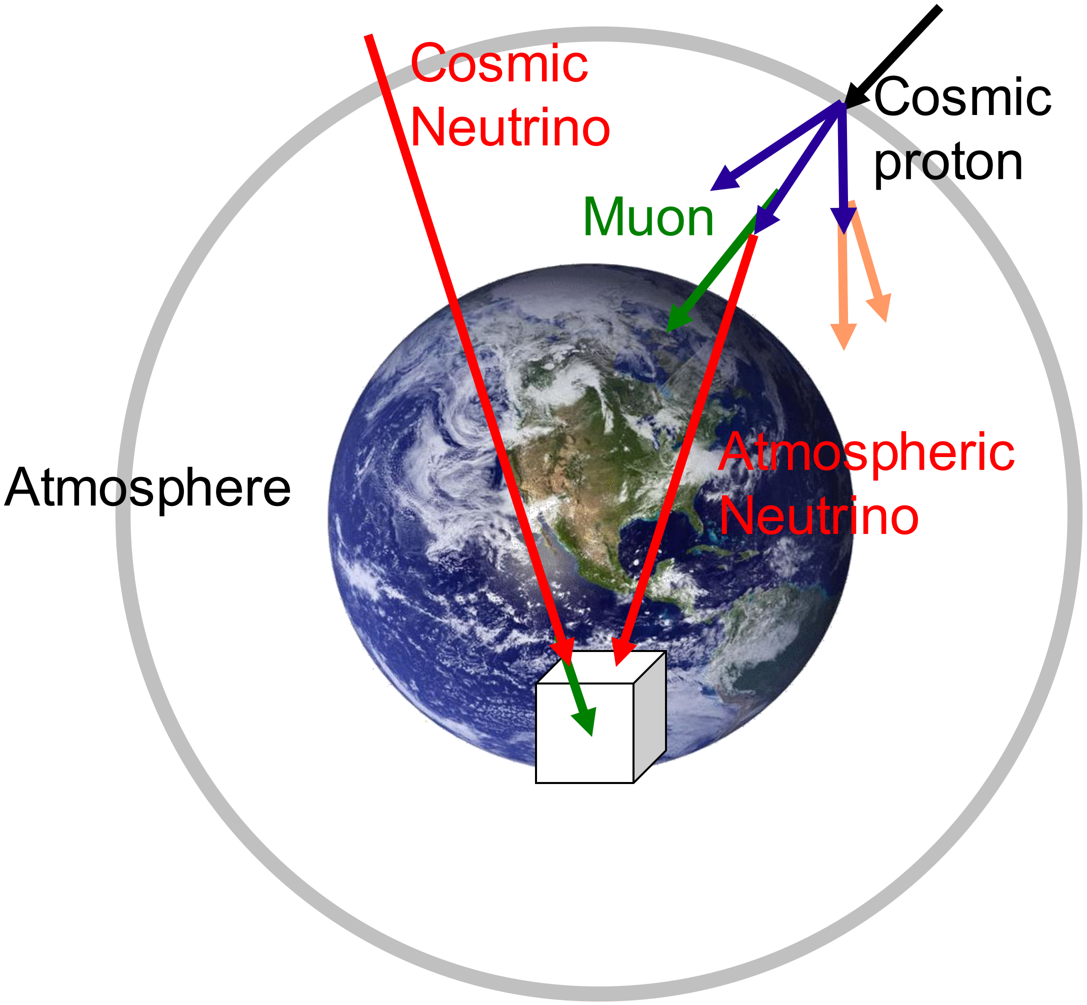


In the TeV range muons travel 1-10km, while showers have a small extension of few meters. Tau needs to reach >100TeV energies to reach detectable length of >10 meters.

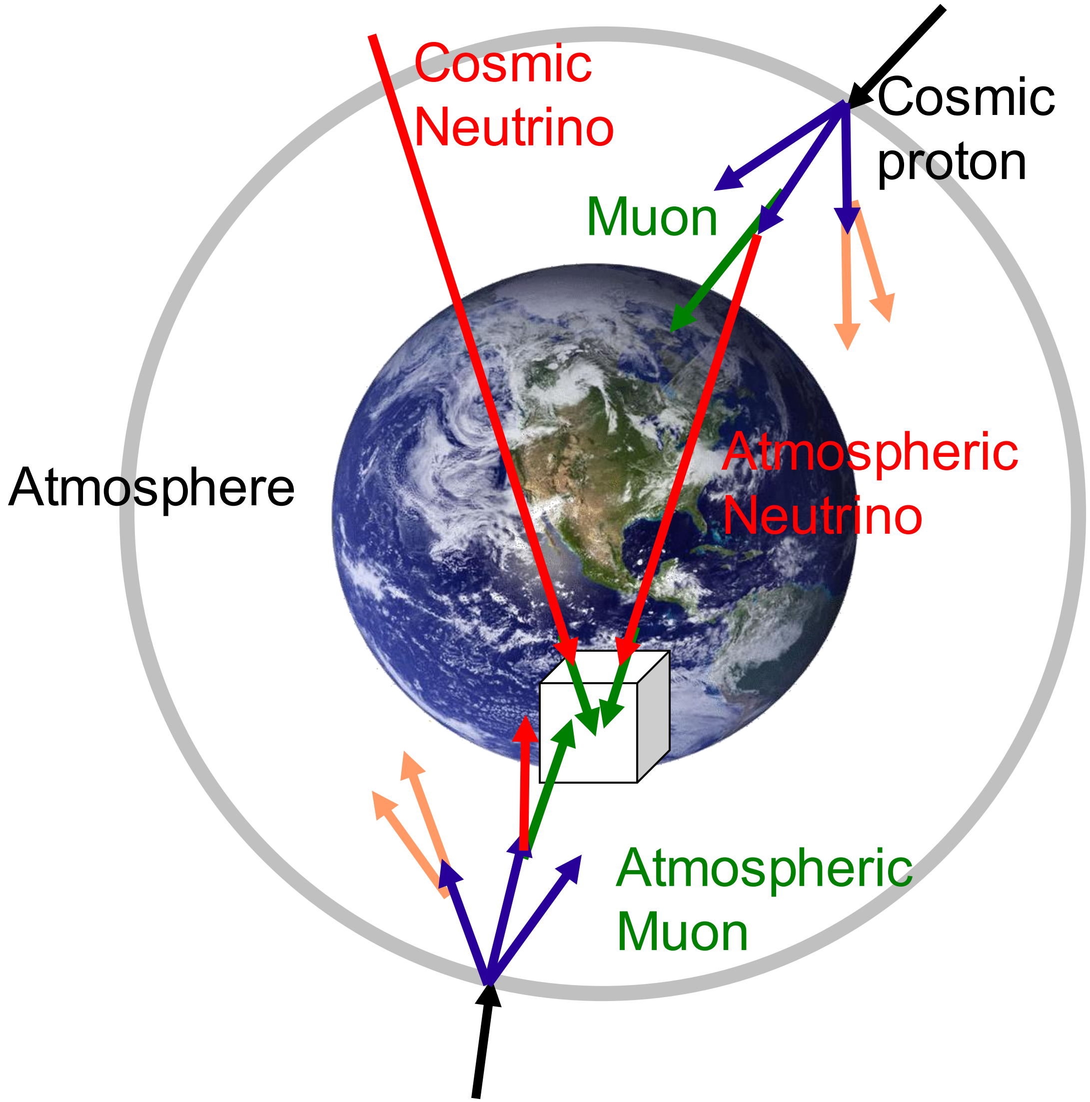
Background in Search for Cosmic Neutrinos



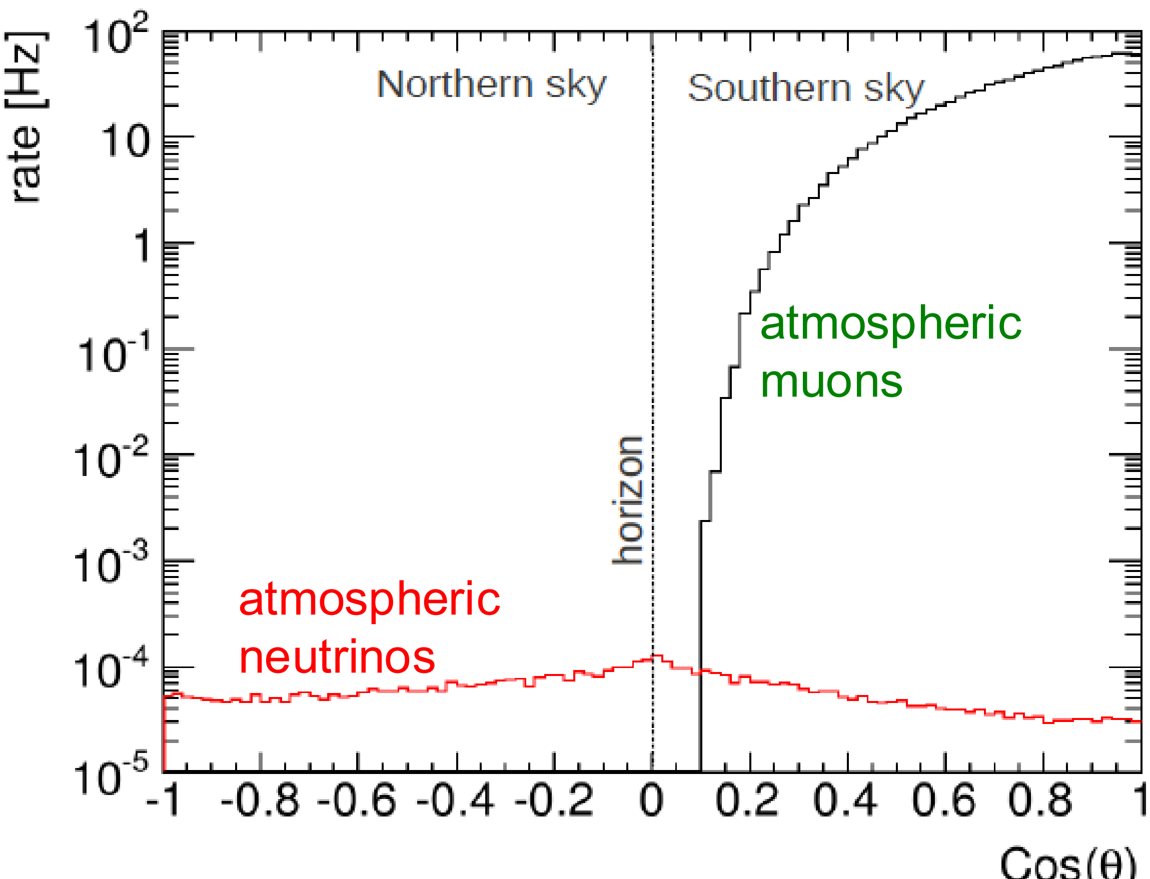
Background in Search for Cosmic Neutrinos

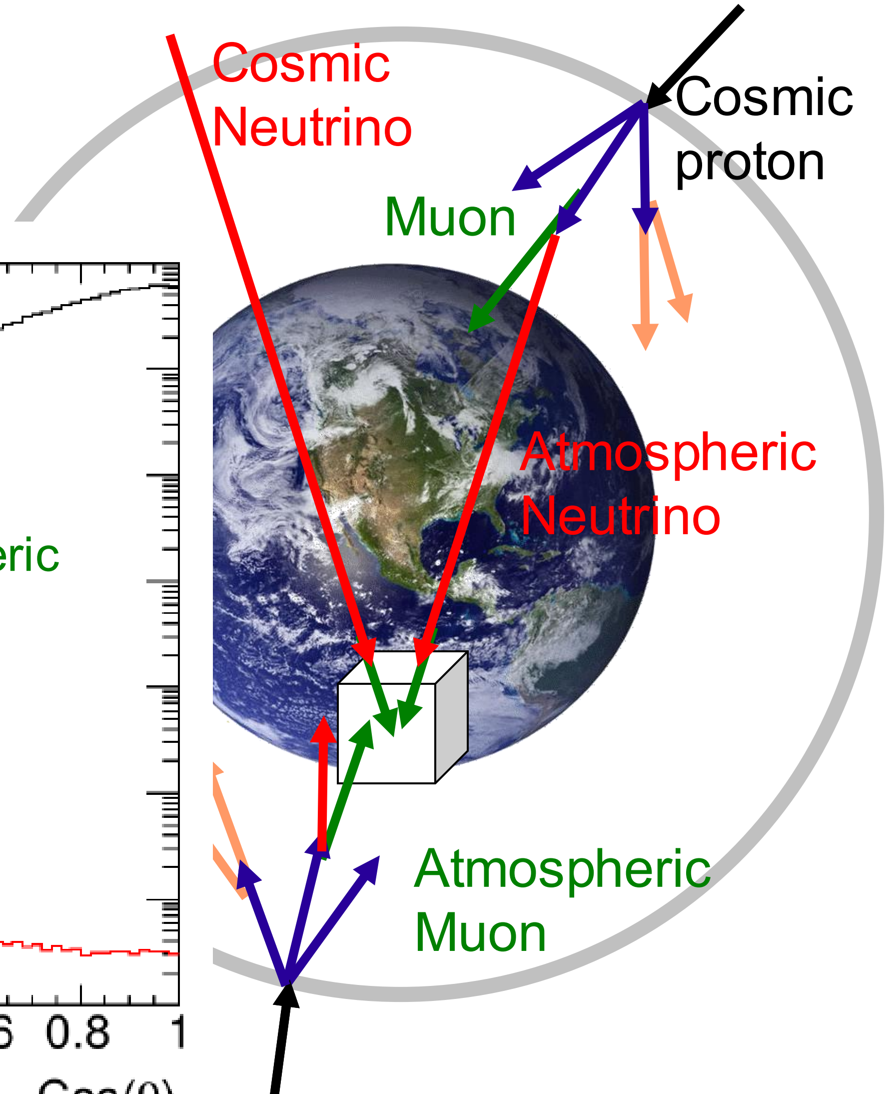


Background in Search for Cosmic Neutrinos



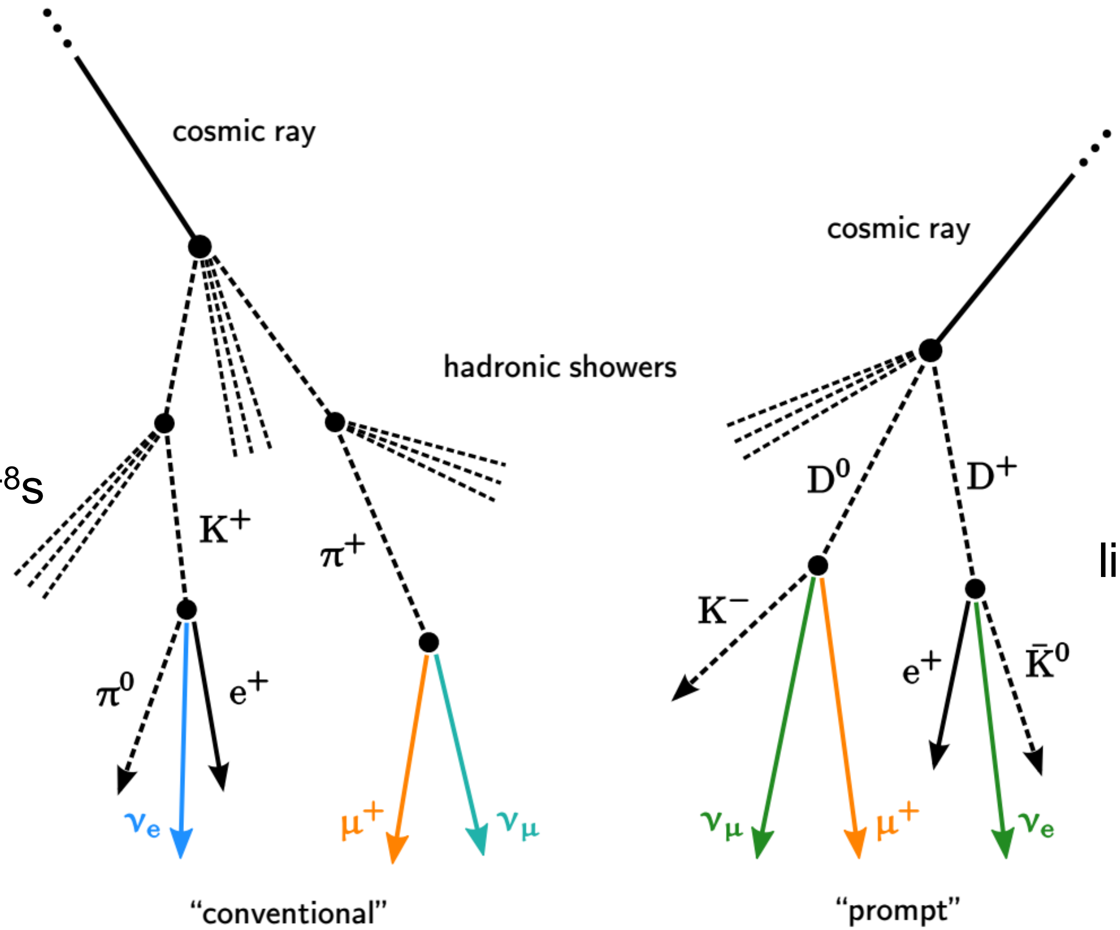
Background in Search for Cosmic Neutrinos





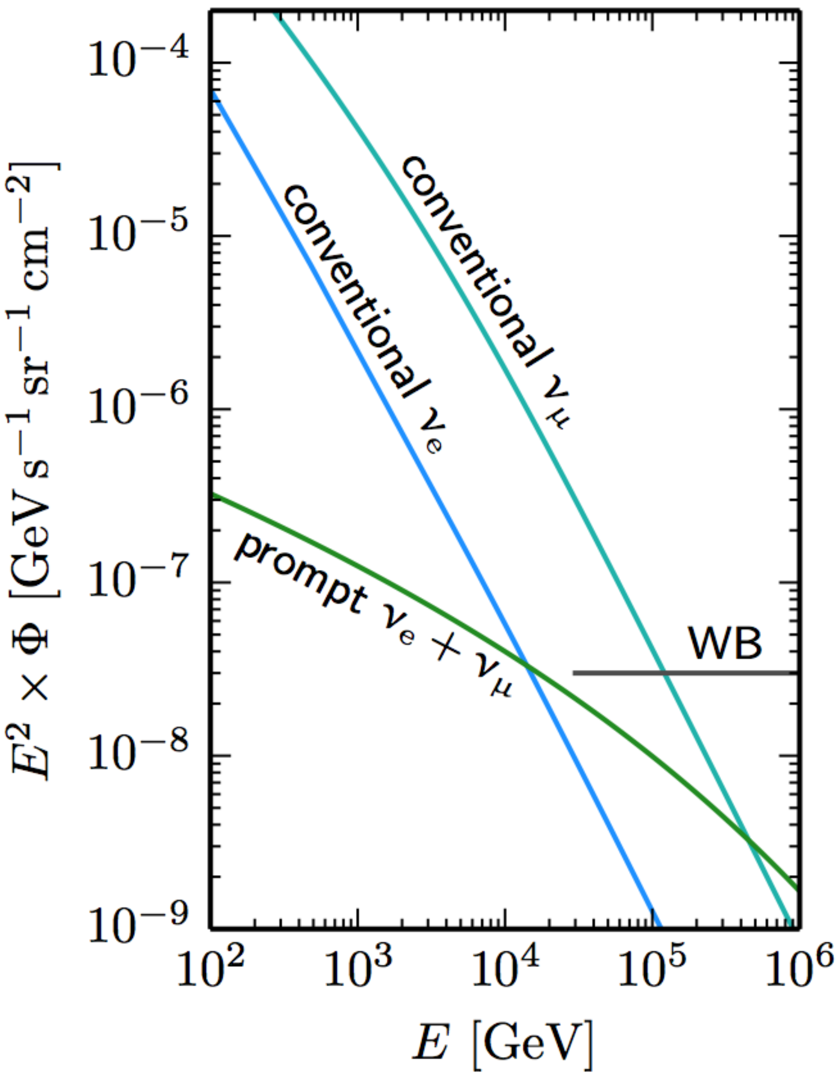
Atmospheric Neutrinos - Production

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



charm
component
lifetime ~ 10^{-12}s

Atmospheric Neutrinos - Spectrum



Kaons and pions (conventional)

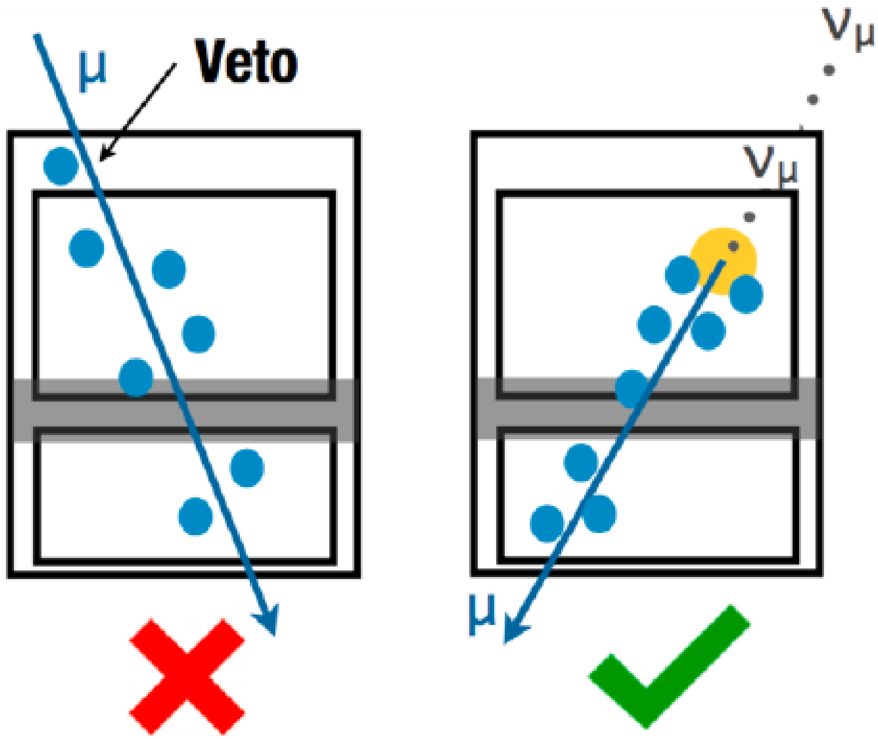
- predominantly decay into muon neutrinos rather than electron neutrinos
- are more likely to interact in the atmosphere rather than to decay into neutrinos if the atmosphere is denser

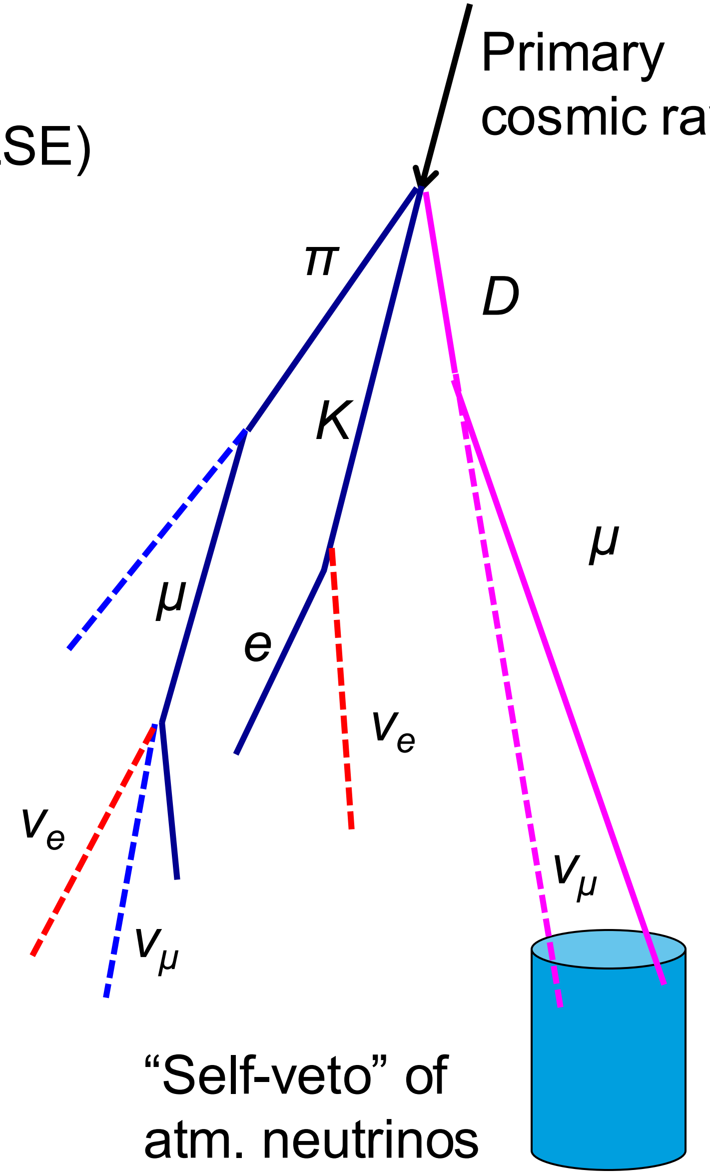
Charm (prompt)

- Decay before interacting

Vetoing Atmospheric Muons and Neutrinos

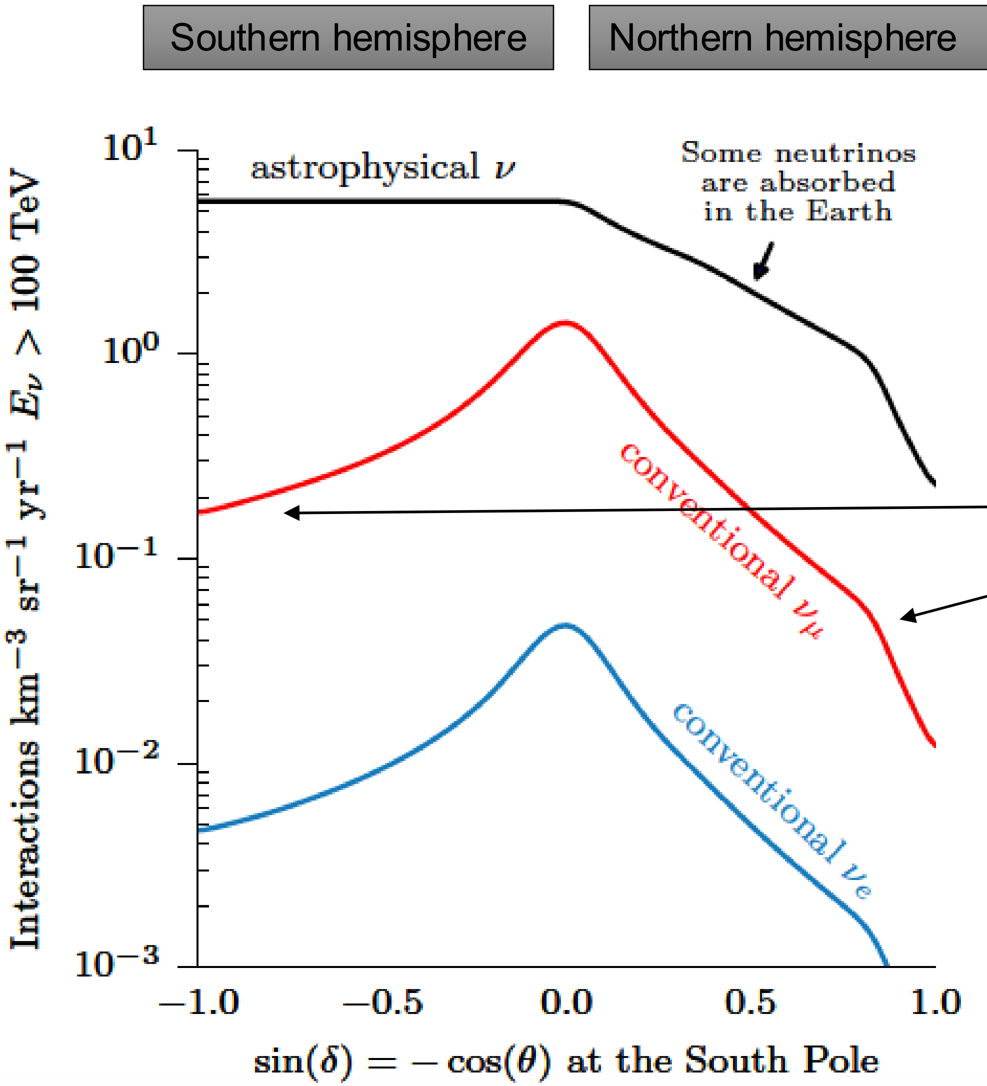
Selection of high-energy starting events (HESE)





"Self-veto" of atm. neutrinos

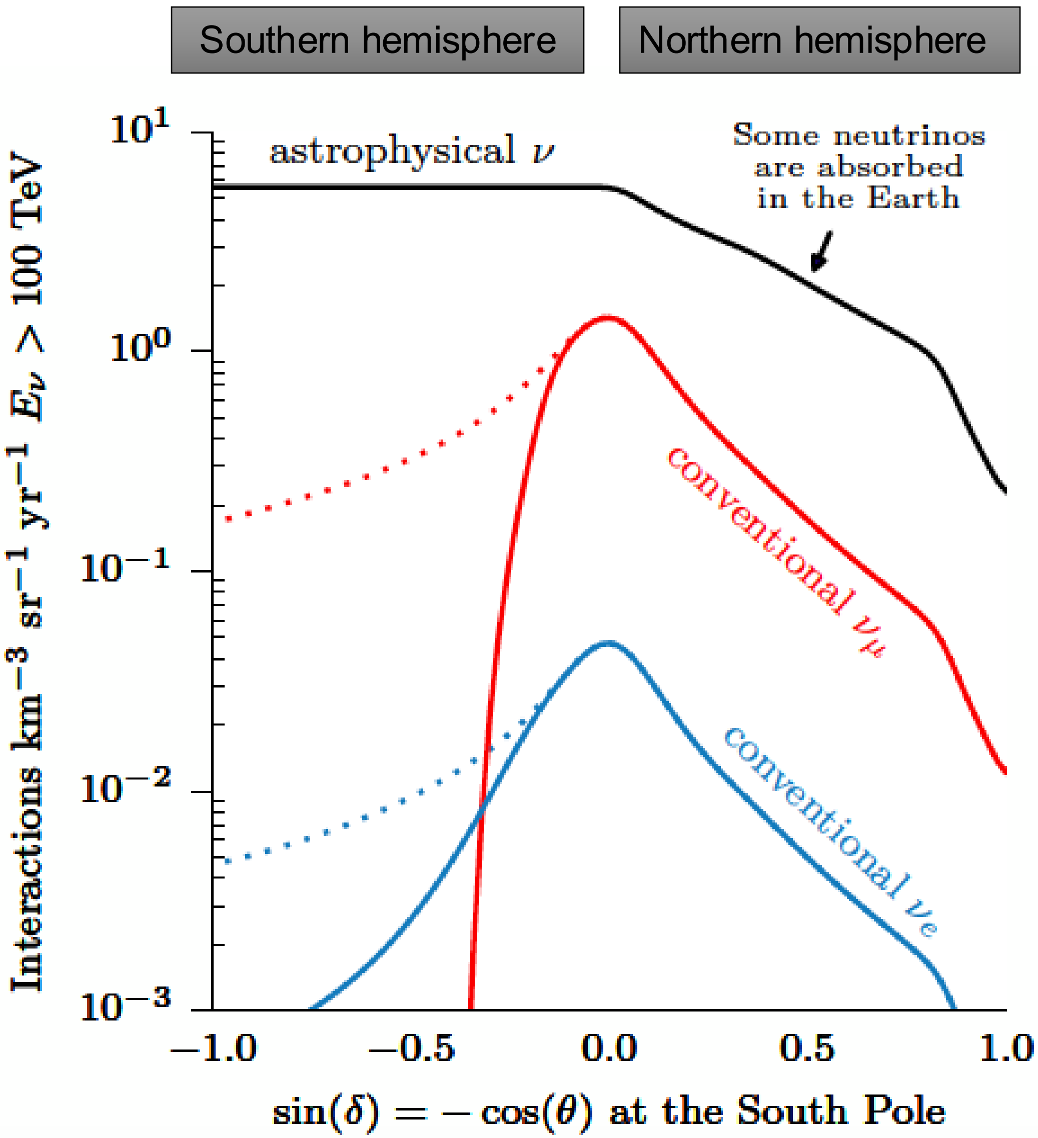
Zenith Distribution



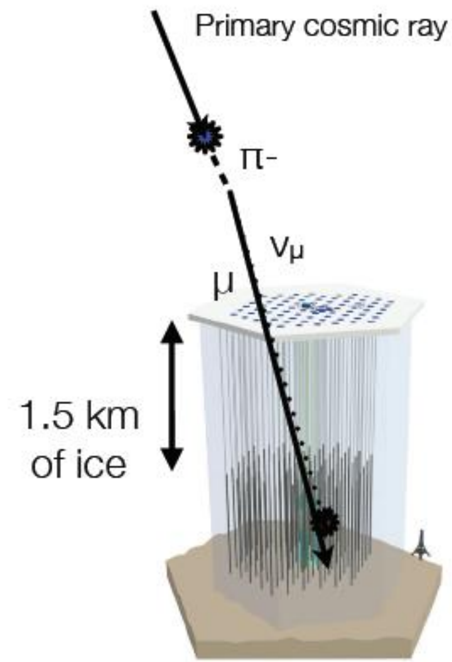
from vertical directions denser parts of the atmosphere are reached more quickly, leading to a suppression of the neutrino flux

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

Zenith Distribution



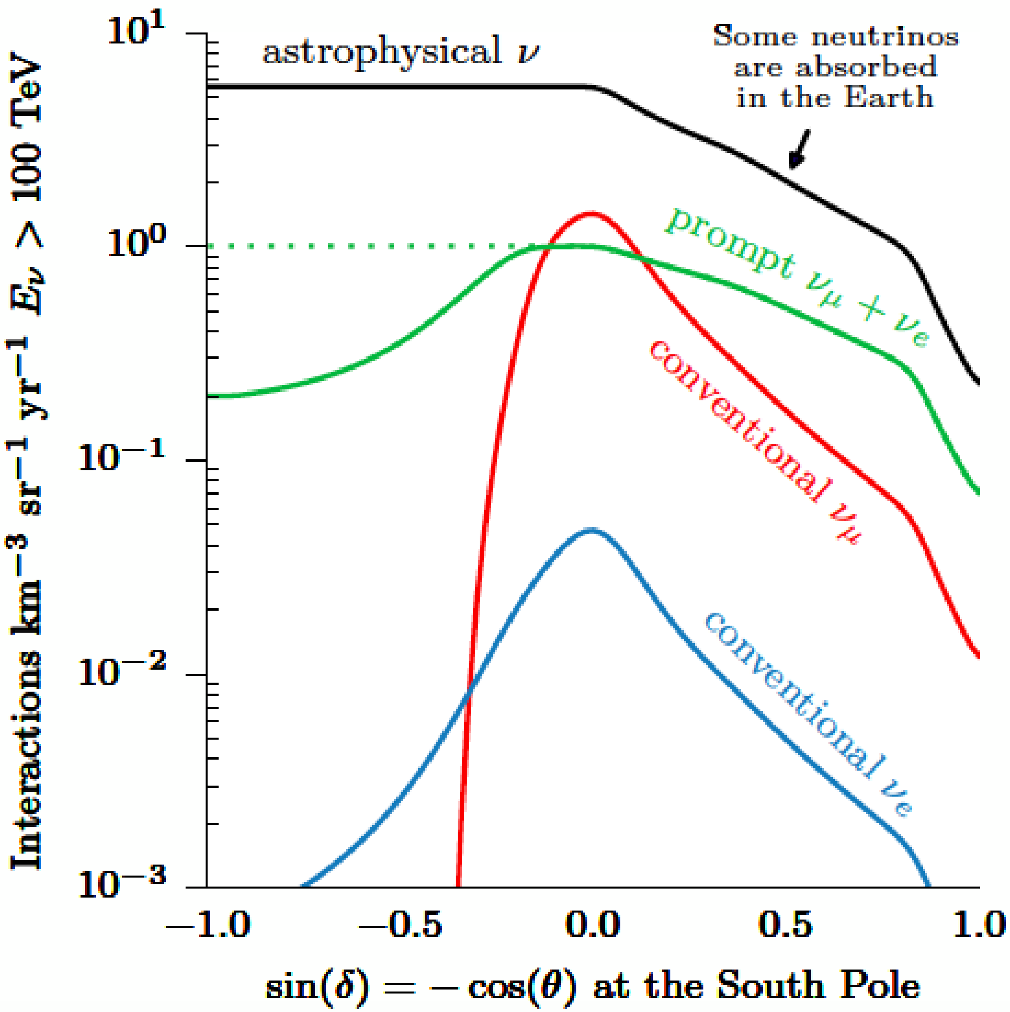
active muon veto removes down-going atmospheric neutrinos



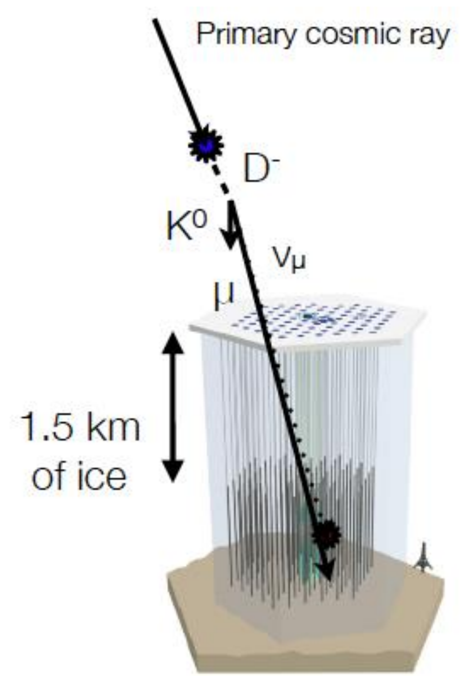
Schönert, Gaisser, Resconi, Schulz, Phys. Rev. D, 79:043009 (2009)
Gaisser, Jero, Karle, van Santen, Phys. Rev. D, 90:023009 (2014)

Zenith Distribution

Southern hemisphere | Northern hemisphere

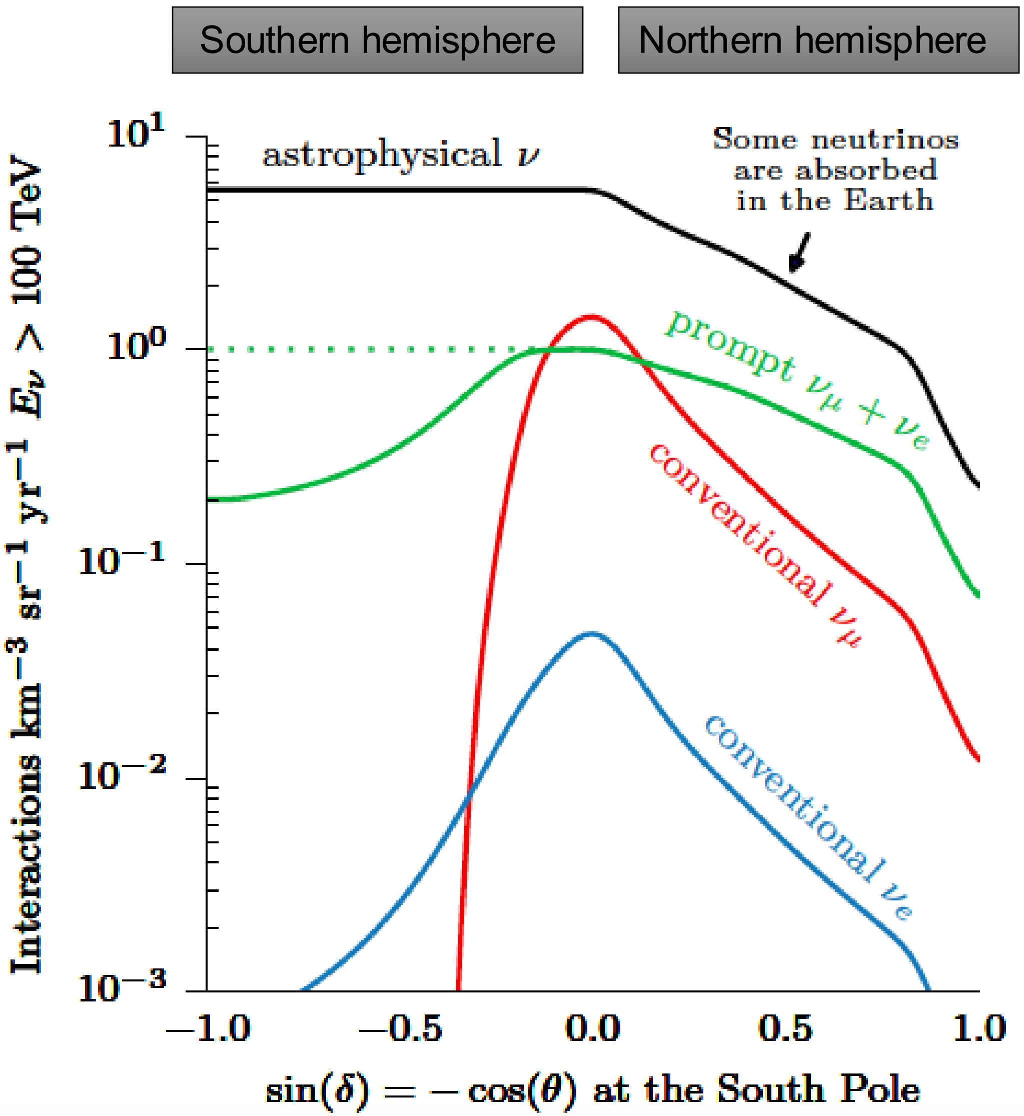


Prompt atmospheric neutrinos are vetoed too



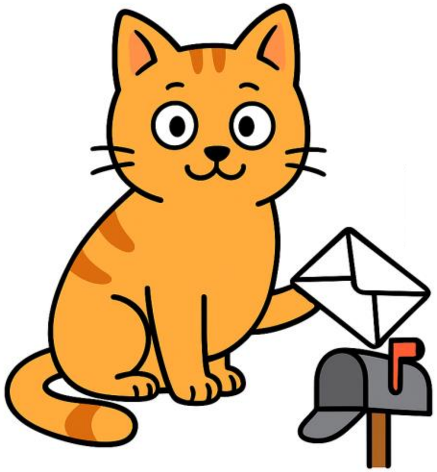
Schönert, Gaisser, Resconi, Schulz, Phys. Rev. D, 79:043009 (2009)
Gaisser, Jero, Karle, van Santen, Phys. Rev. D, 90:023009 (2014)

Zenith Distribution



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

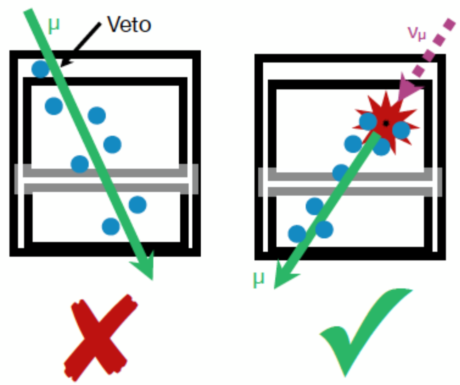
Results from water / ice Cherenkov Telescopes

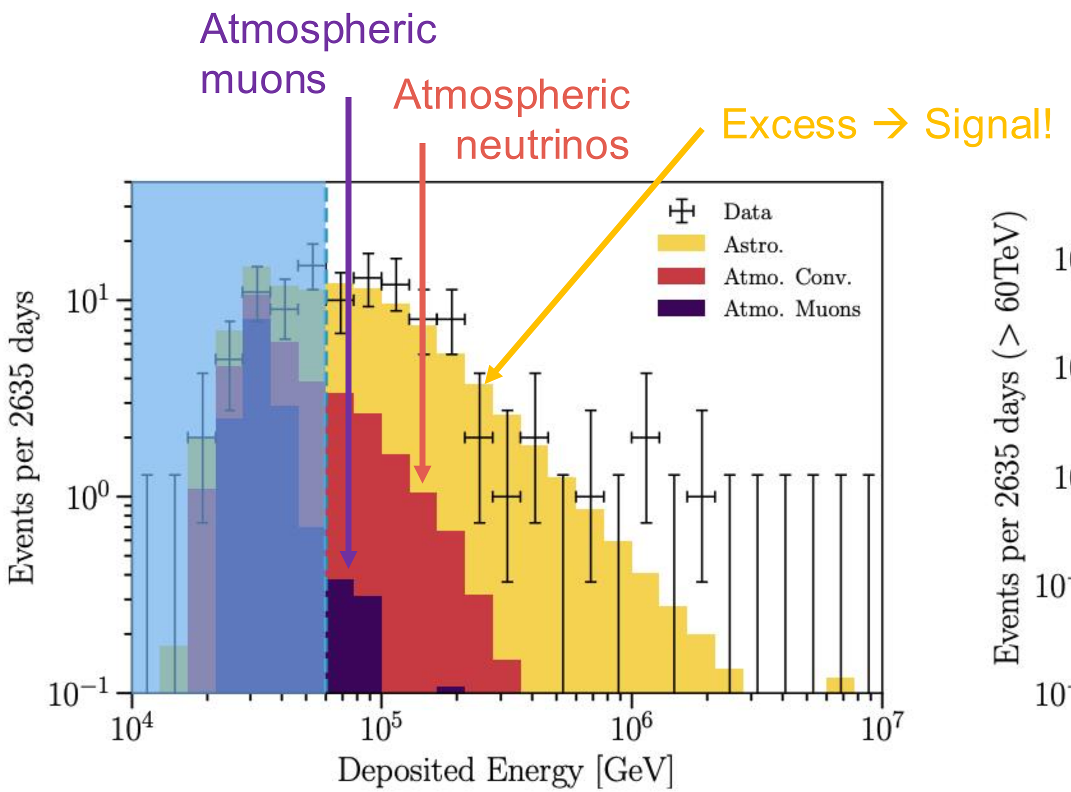
- Astronomy
  - Diffuse Flux
  - Milky Way
  - Source Candidates
- Neutrino as a particle
  - Neutrino Oscillations
  - Neutrino Cross Section
- New physics
  - Sterile Neutrinos
  - Dark Matter

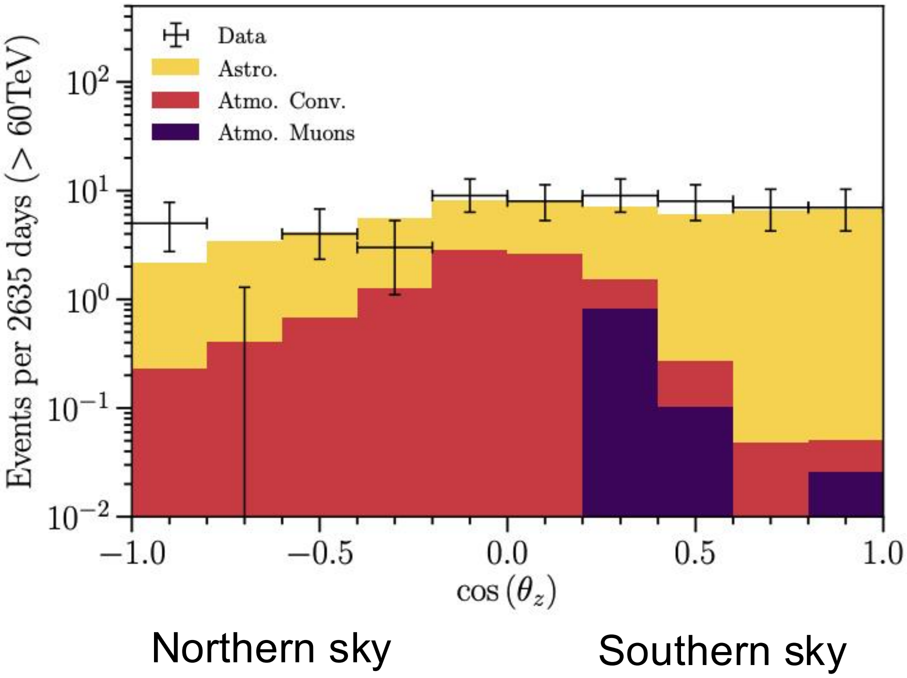
Results from water / ice Cherenkov Telescopes

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

Discovery of High-Energy Astrophysical Neutrinos

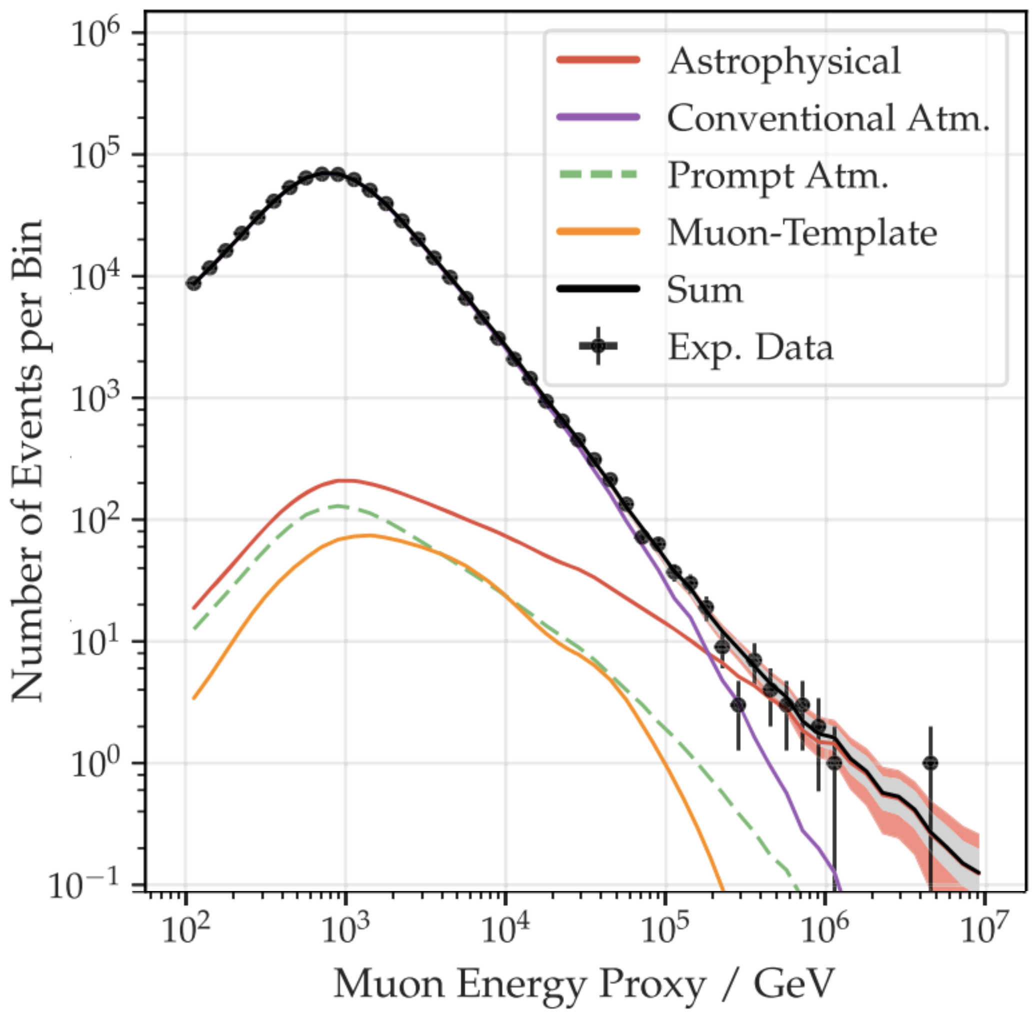


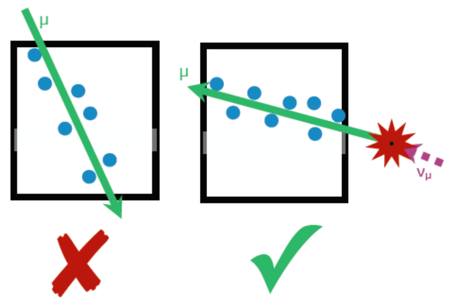




IceCube Coll., Science 342, 2013, PRL 113, 101101 (2014)

Diffuse flux seen in different channels



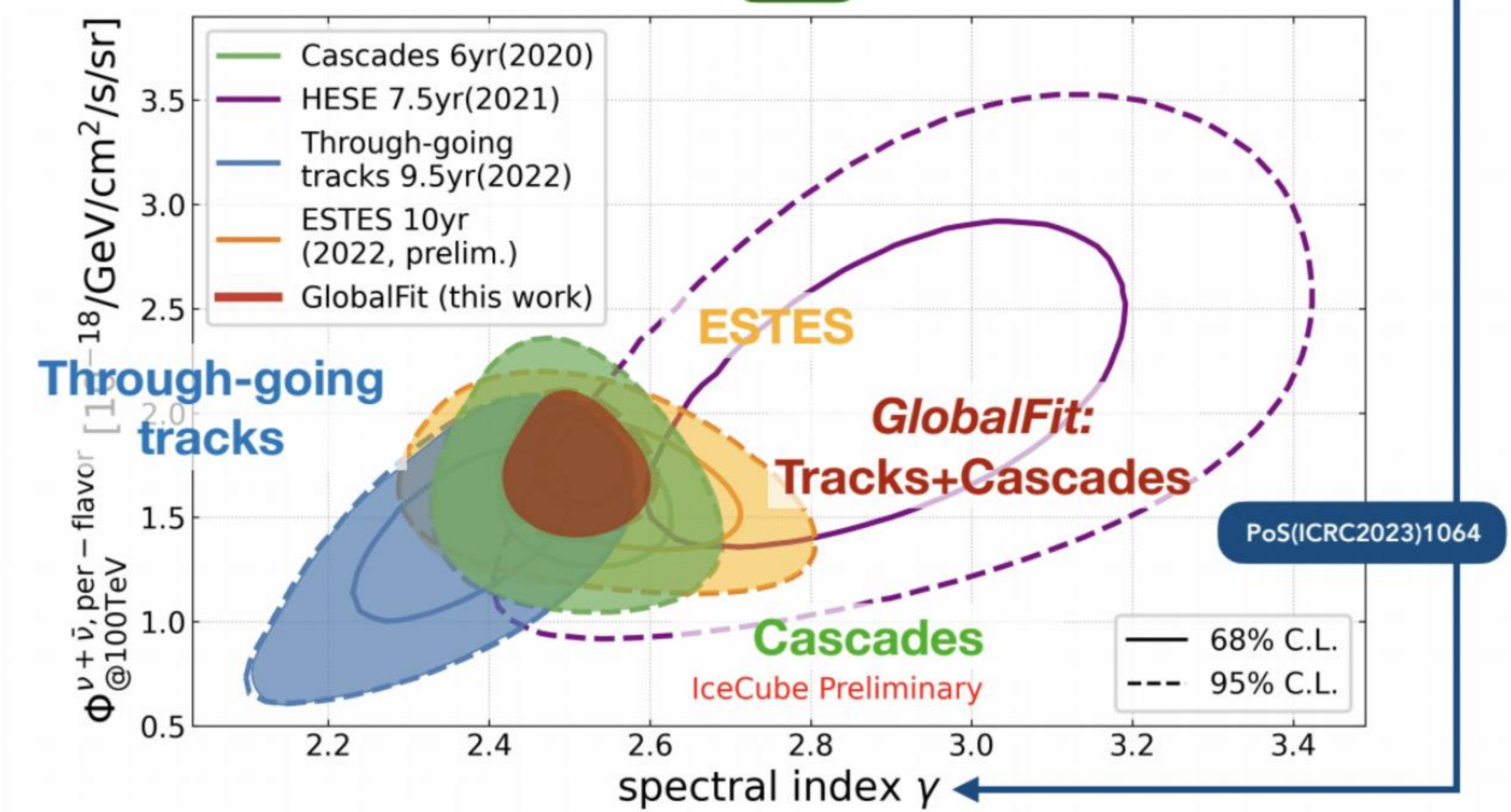


- Selected horizontal and up-going muon tracks
- Sensitive to astrophysical neutrinos above ~100 TeV

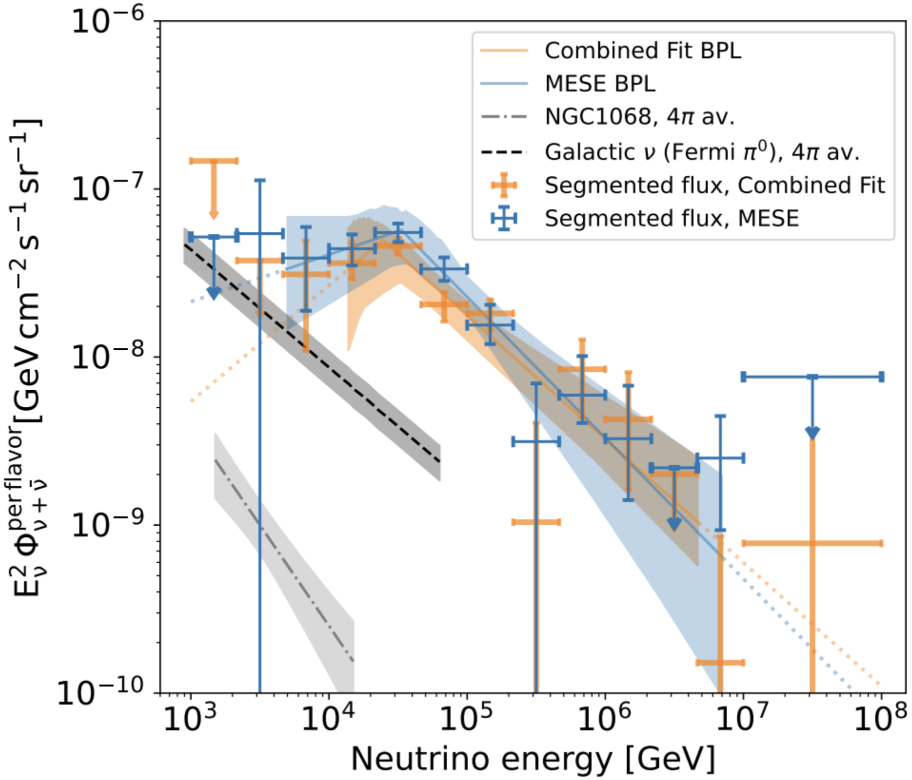
R. Abbasi *et al* 2022 *ApJ* **928** 50

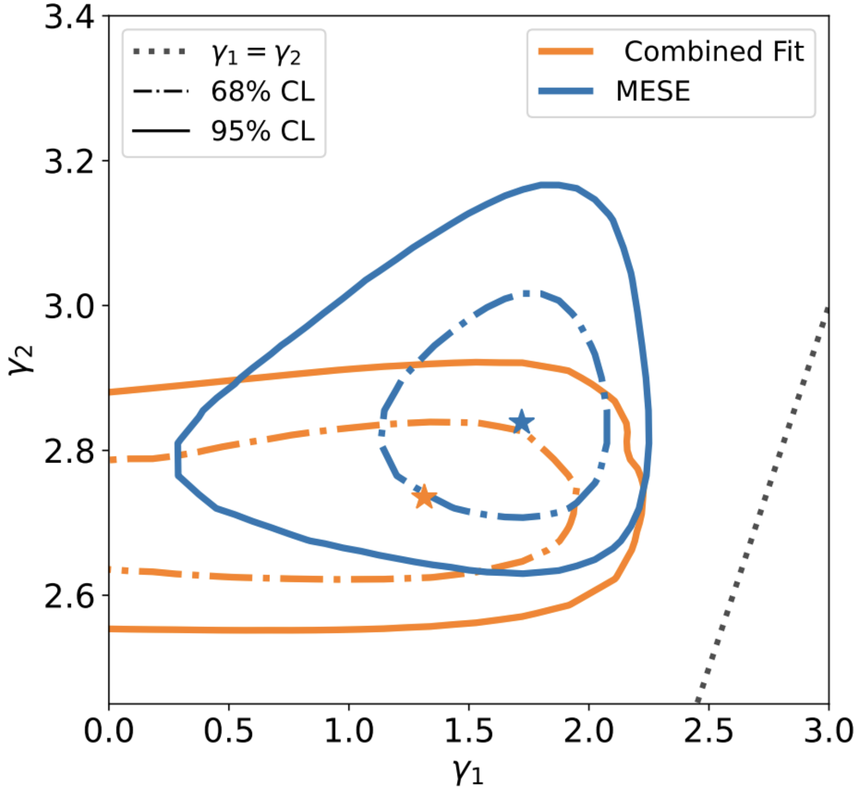
Spectrum of diffuse flux

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



Spectrum of diffuse flux: not a power law?





IceCube arXiv:2507.22233

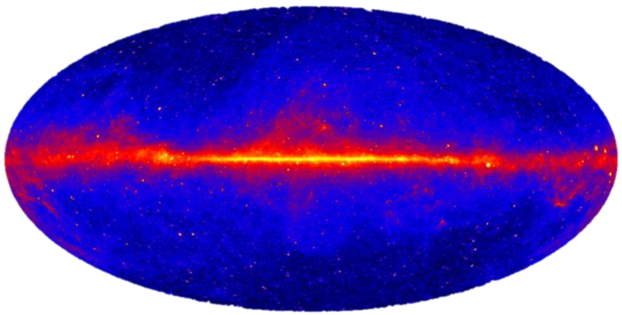
What is the origin of the diffuse flux?

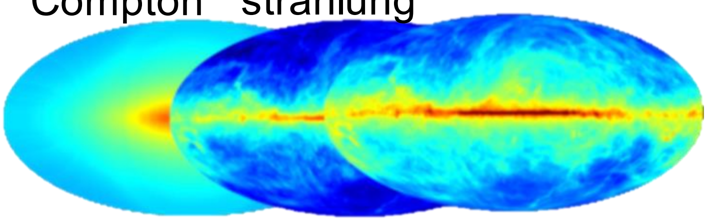
Results from water / ice Cherenkov Telescopes

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

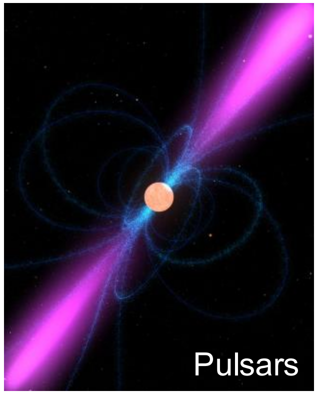
Galactic Contribution

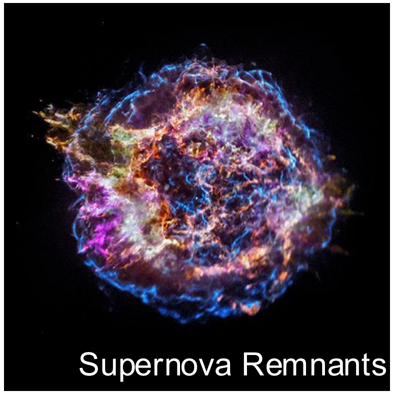
GeV gamma-ray sky by Fermi-LAT





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

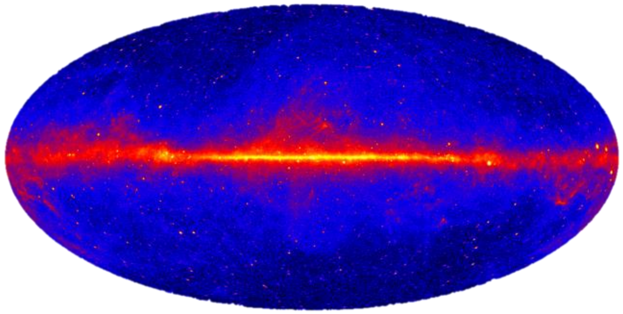


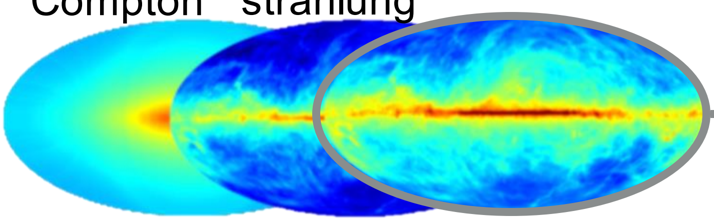


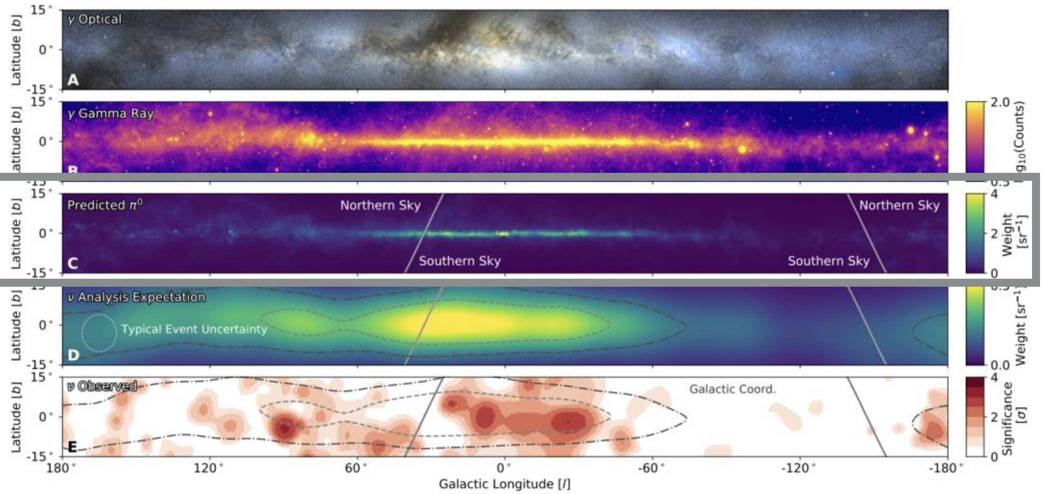
RUB

Galactic Contribution

GeV gamma-ray sky by Fermi-LAT



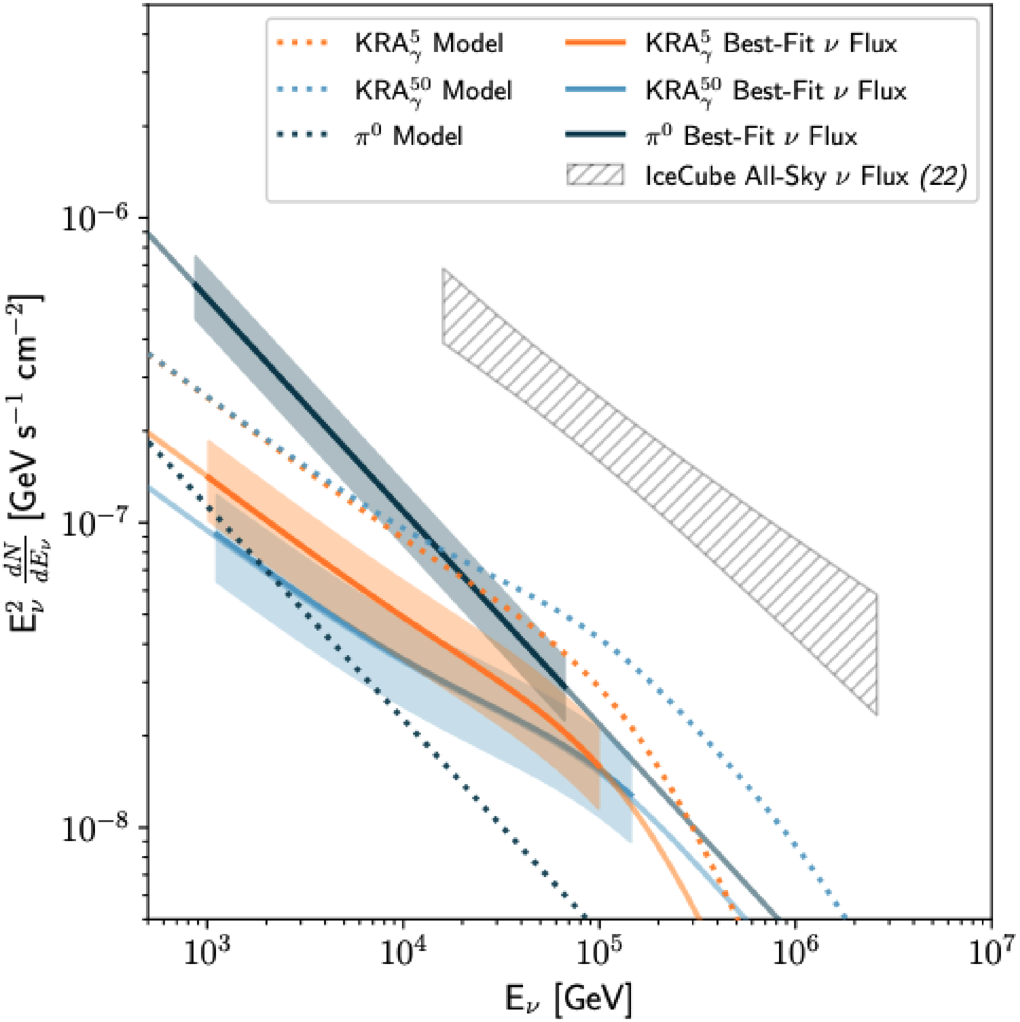




First detection of galactic plane neutrino flux thanks to gamma-ray template fit

IceCube Science 380 (2023)

Galactic Neutrinos



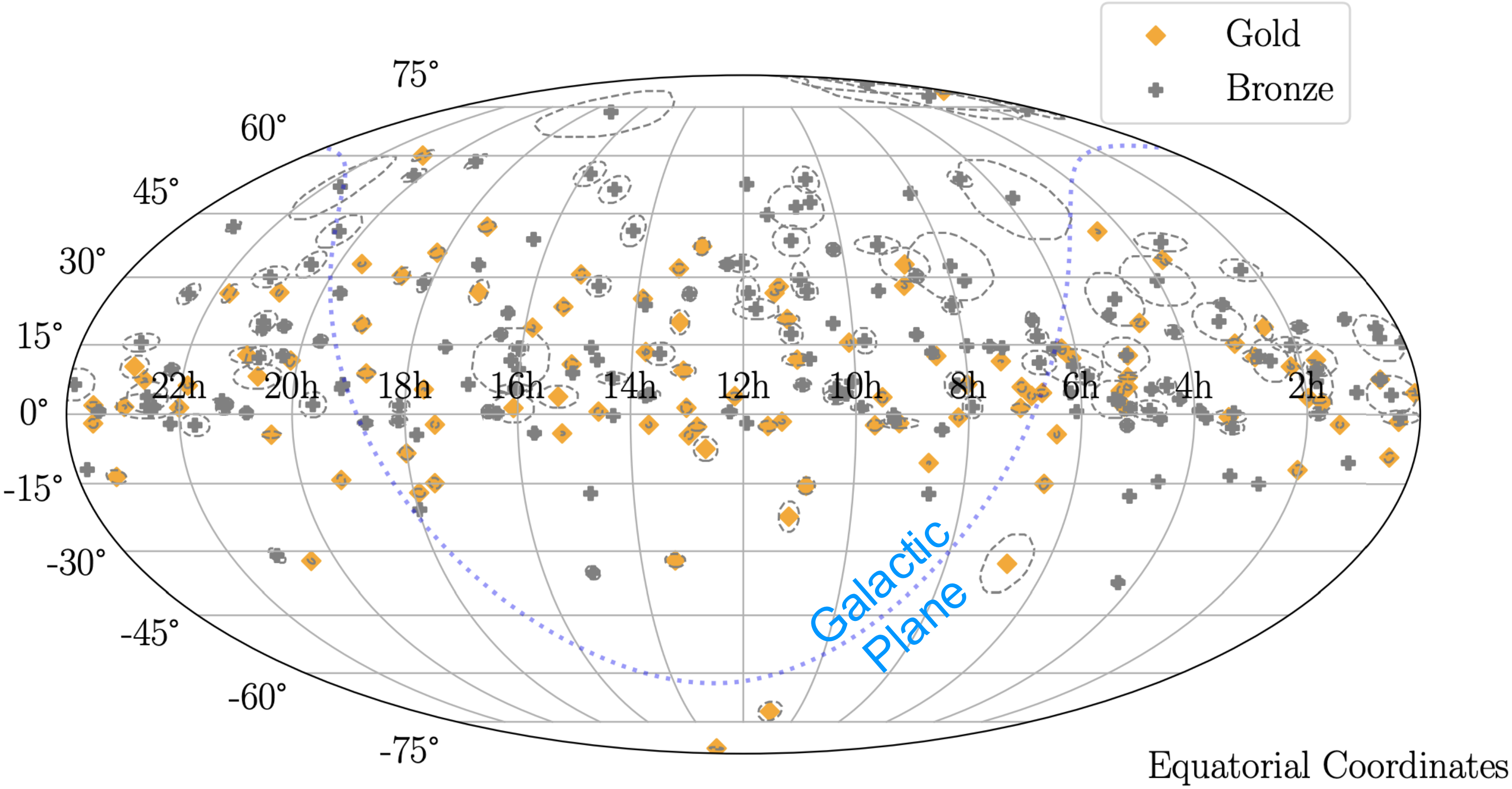
Galactic neutrinos make up ~10% of diffuse neutrinos

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

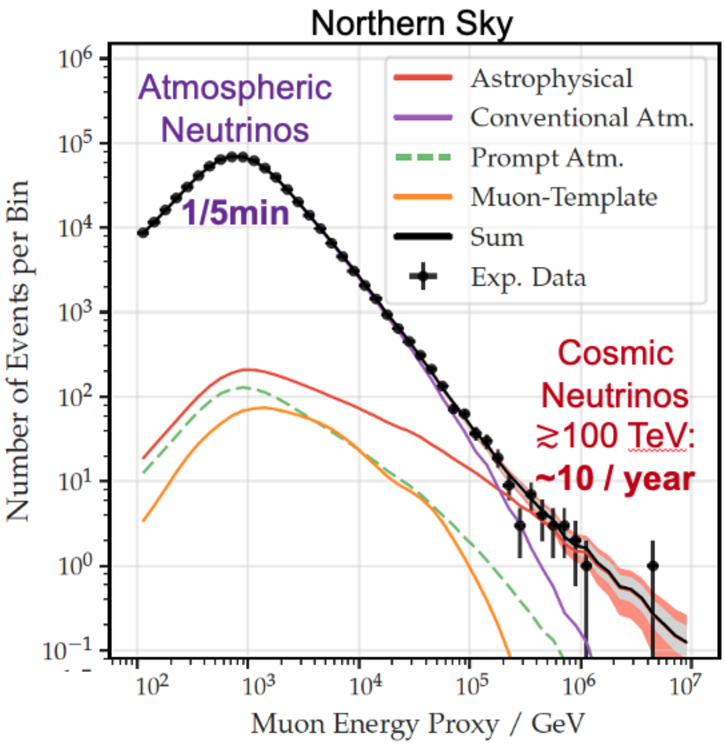
IceCube neutrinos with high (>30%) probability to be of cosmic origin



Neutrinos alone do not reveal the sources (yet)

IceCube ApJS 269 (2023)

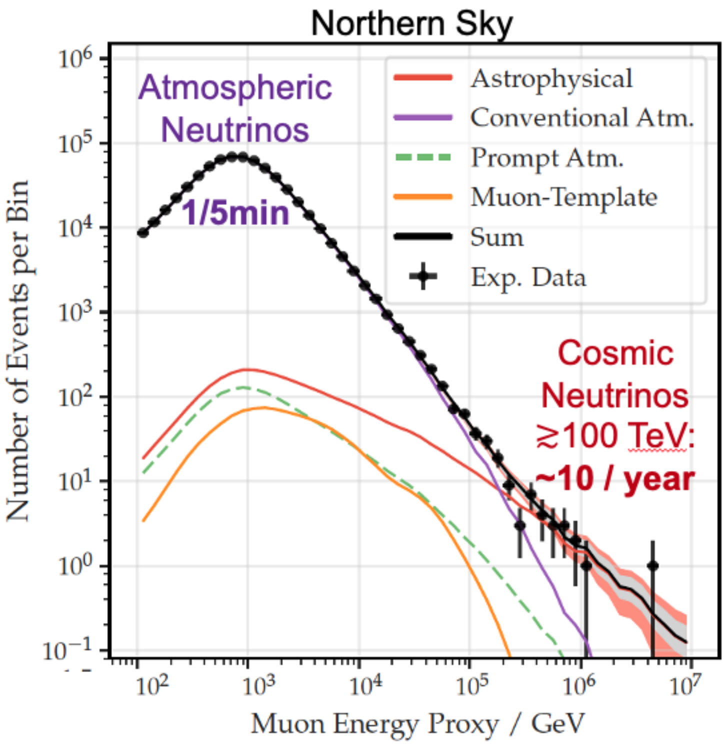
Search for Extragalactic Sources: Strategies



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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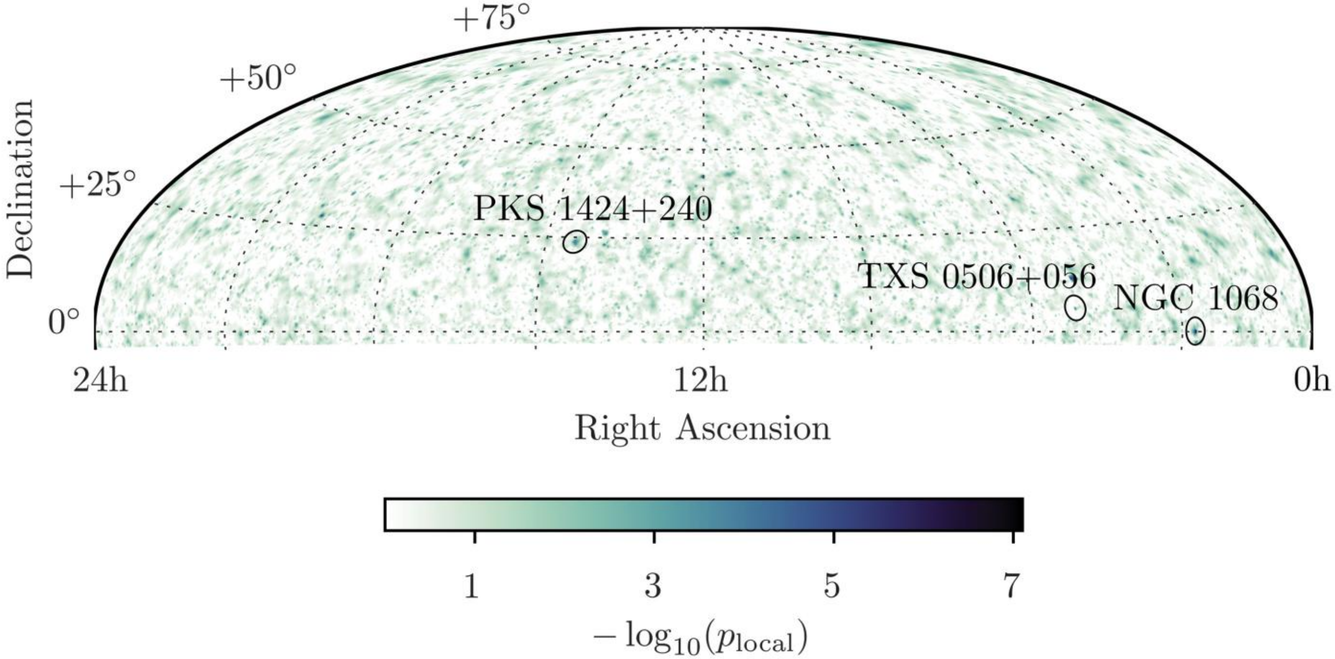
IceCube Coll. ApJ 928 (2022) 50

Search for hotspots in the neutrino sky



IceCube Science 378 (2022)

Maximum Likelihood Technique

Signal probability

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

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

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

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

RUB

Maximum Likelihood Technique

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

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

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

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Maximum Likelihood Technique

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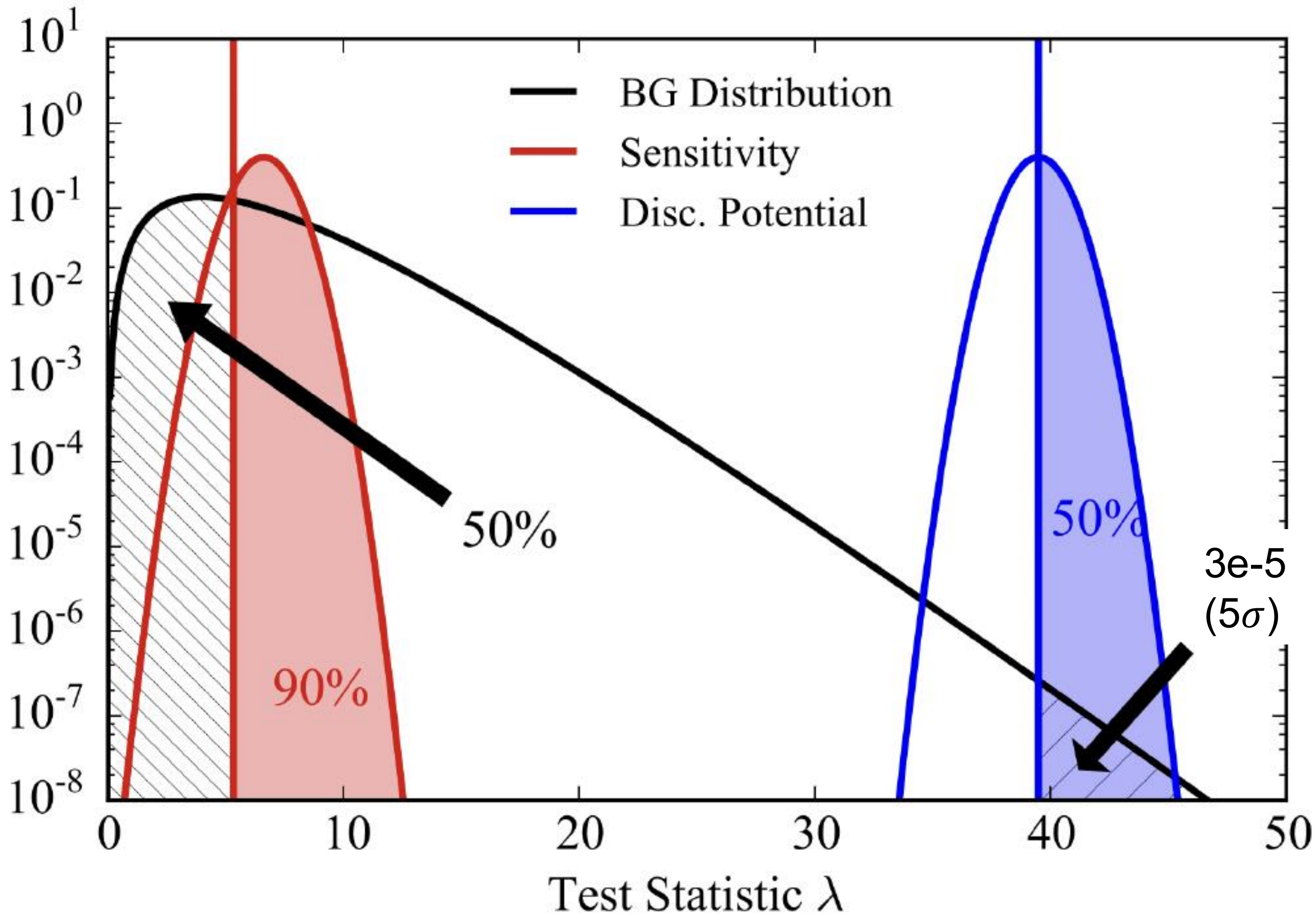
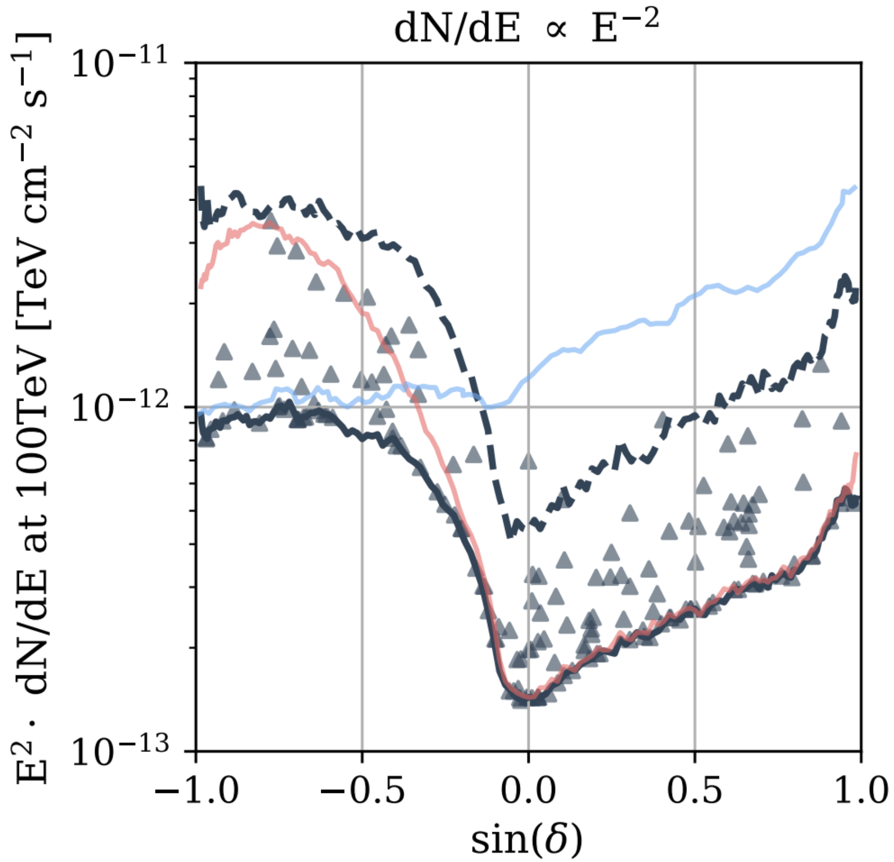
Definition of Sensitivity



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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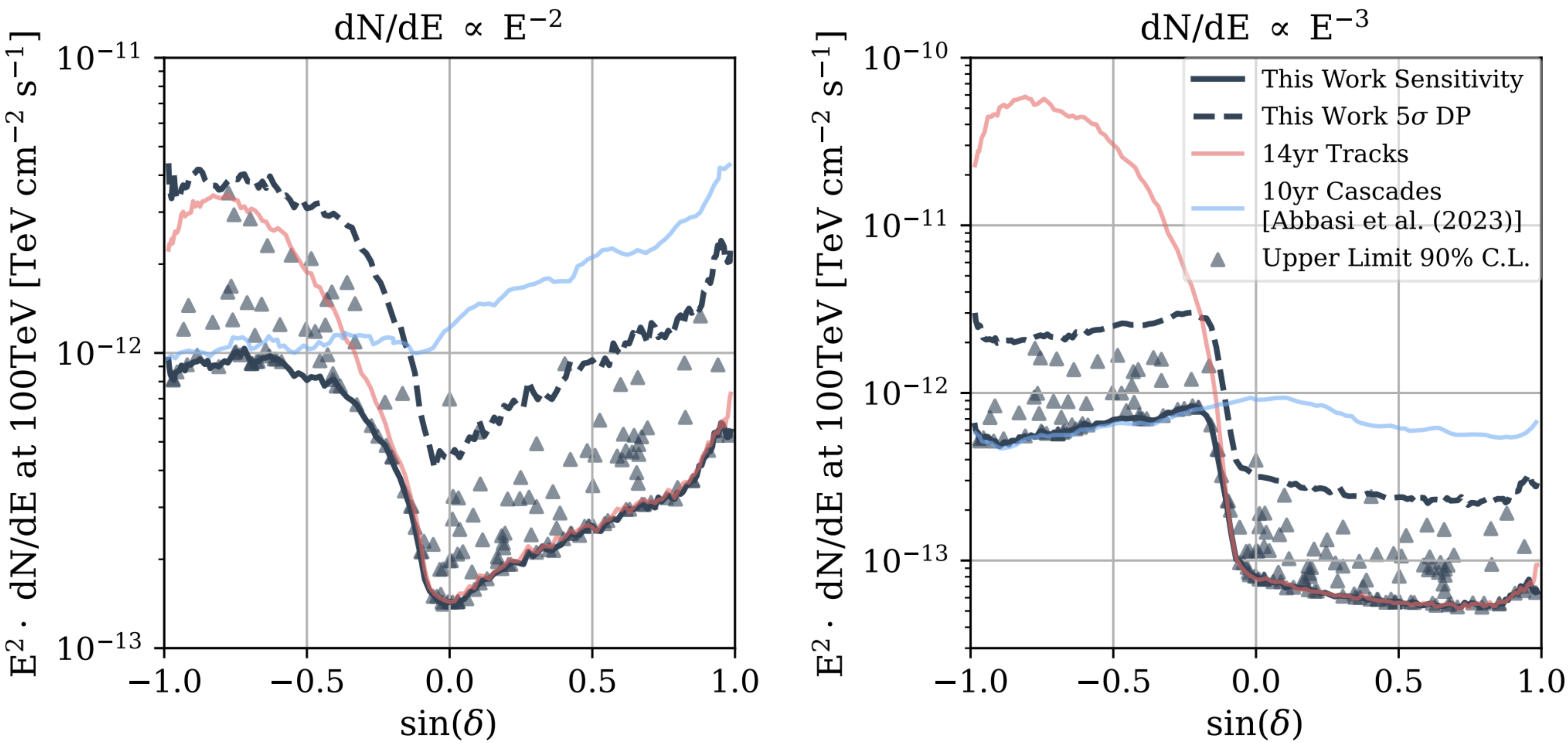
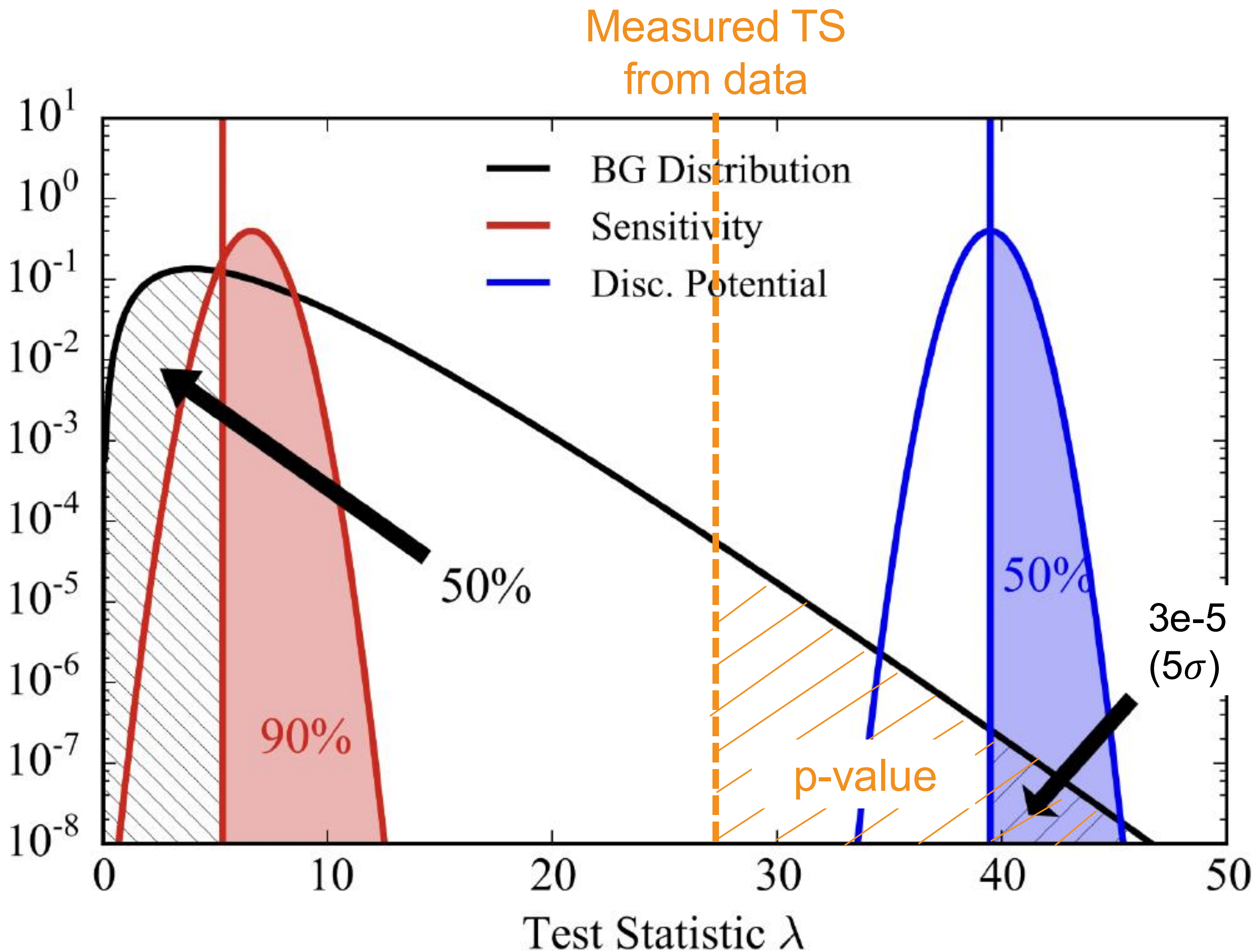


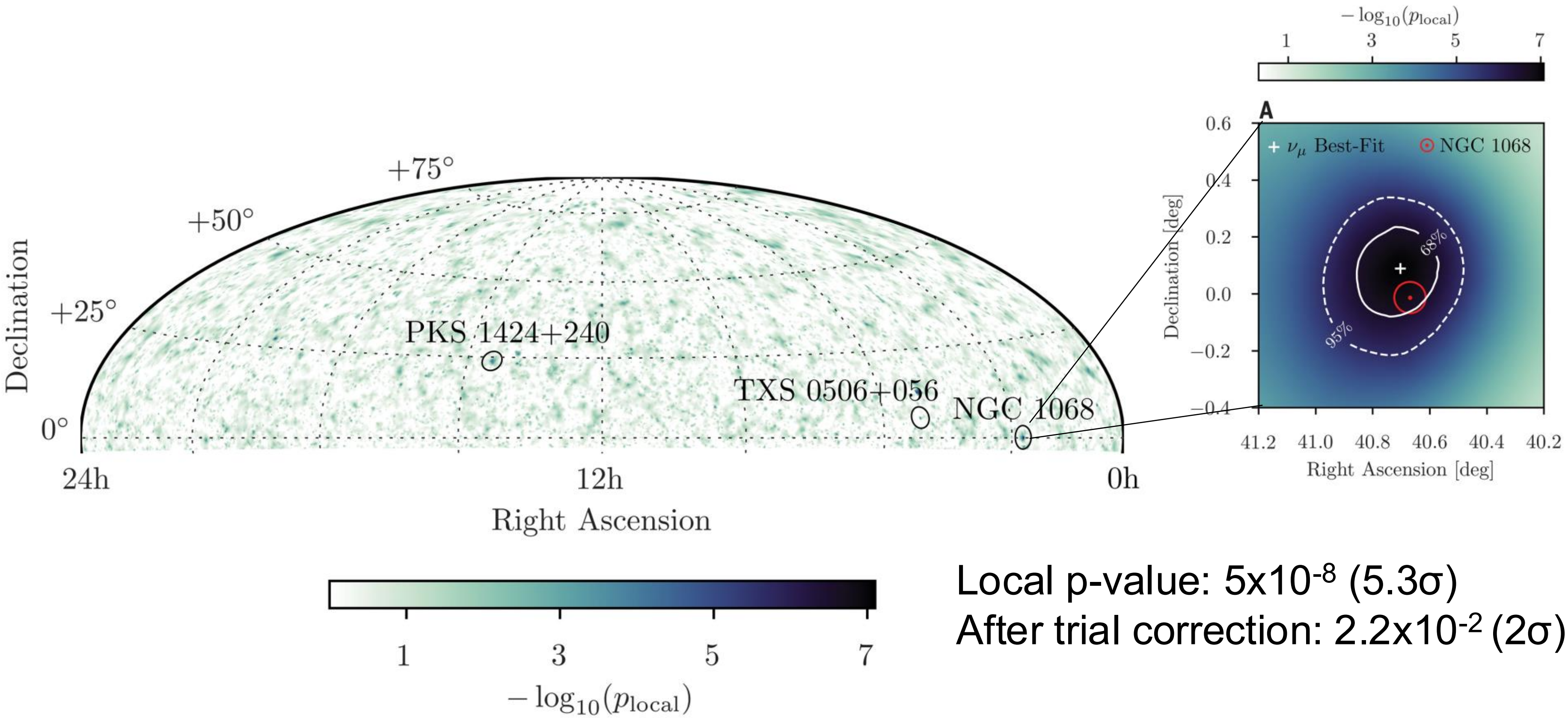
IceCube arXiv:2507.07275

Definition of p-value



RUB

Search for hotspots in the neutrino sky

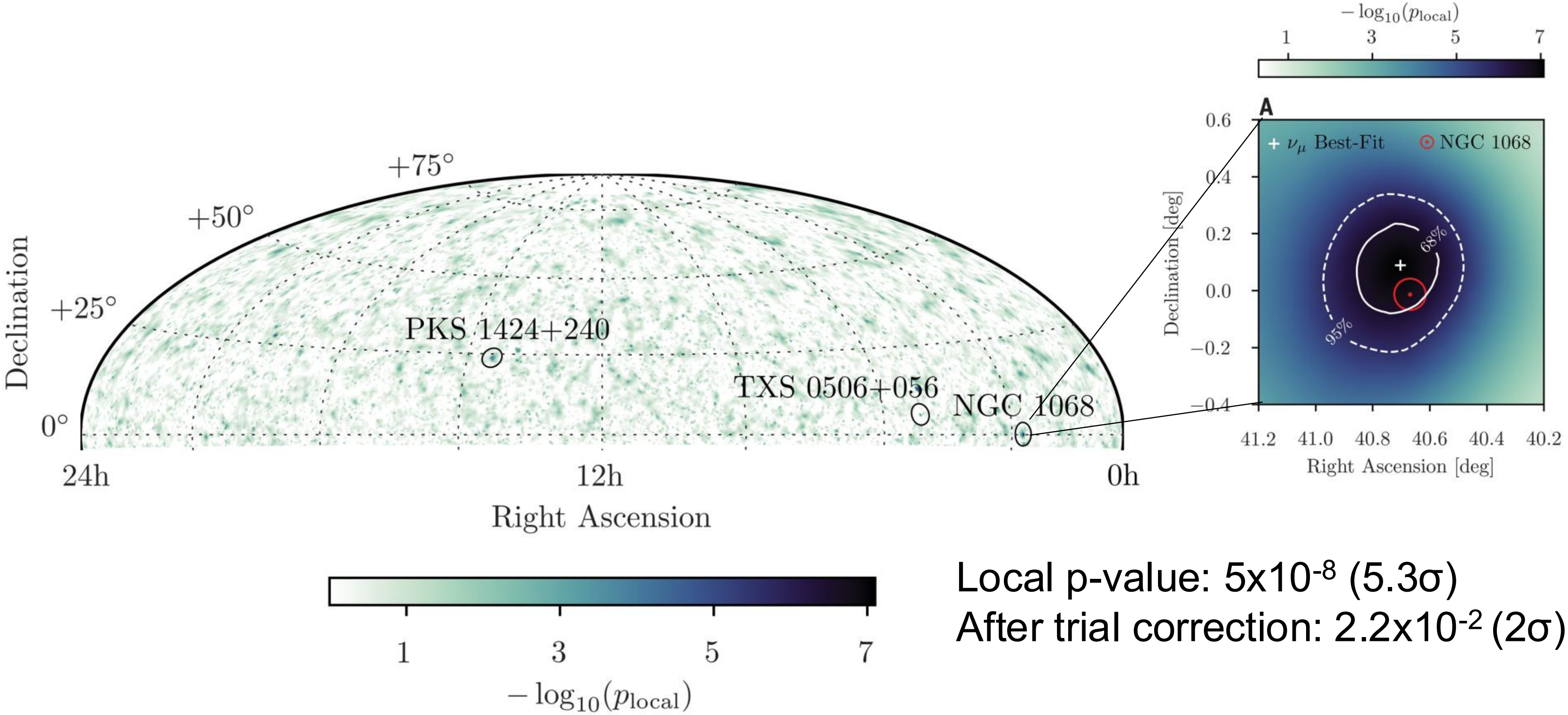


Local p-value: $5\text{x}10^{-8}$ (5.3σ)
After trial correction: $2.2\text{x}10^{-2}$ (2σ)

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

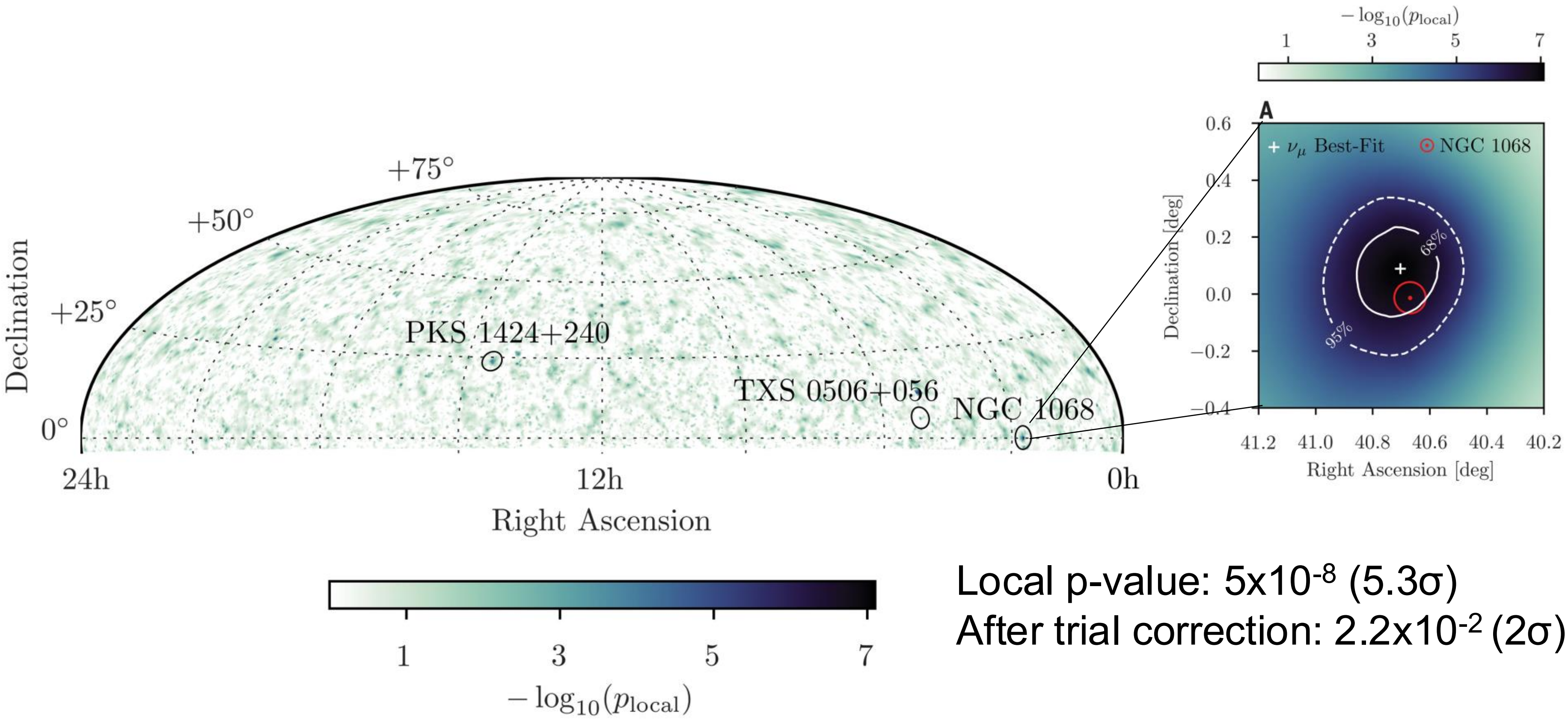


Local p-value: 5×10^{-8} (5.3σ)
After trial correction: 2.2×10^{-2} (2σ)

Challenge: Atmospheric background, large trial factor

IceCube Science 378 (2022)

Search for hotspots in the neutrino sky



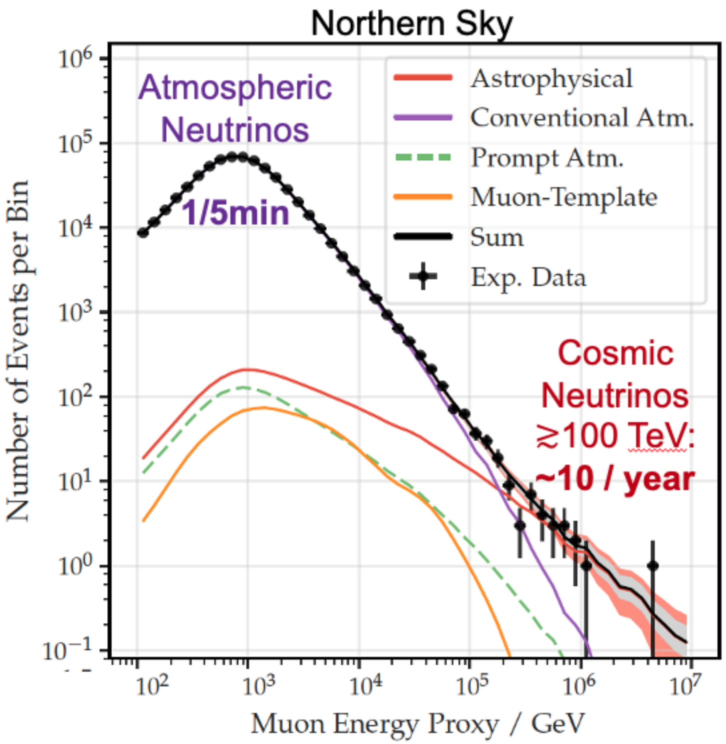
Local p-value: $5\mathrm{x}10^{-8}$ (5.3σ)

After trial correction: $2.2\mathrm{x}10^{-2}$ (2σ)

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

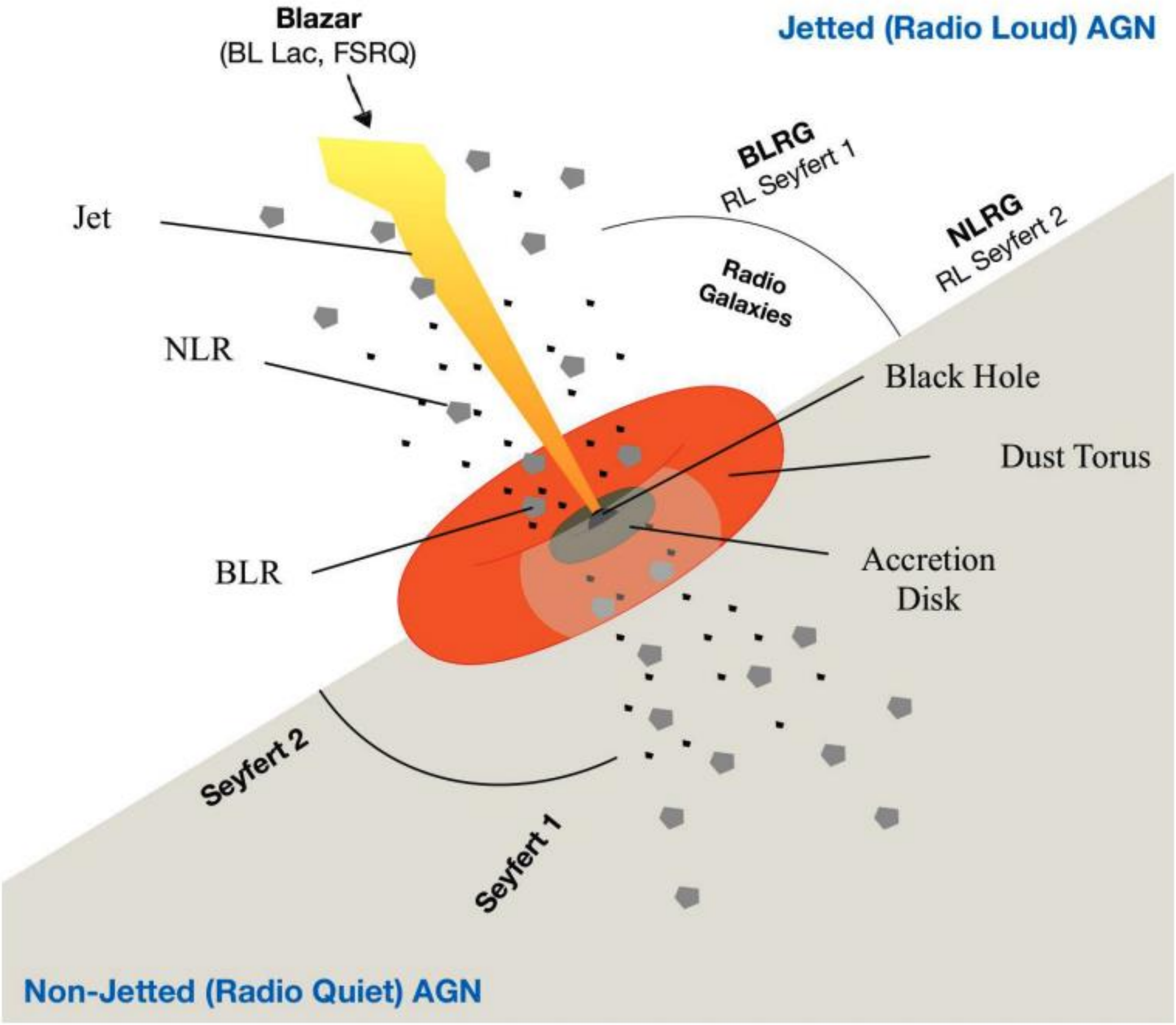
Why 110 sources: 5 σ p-value before trials would remain above 4 σ after trials

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

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

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**

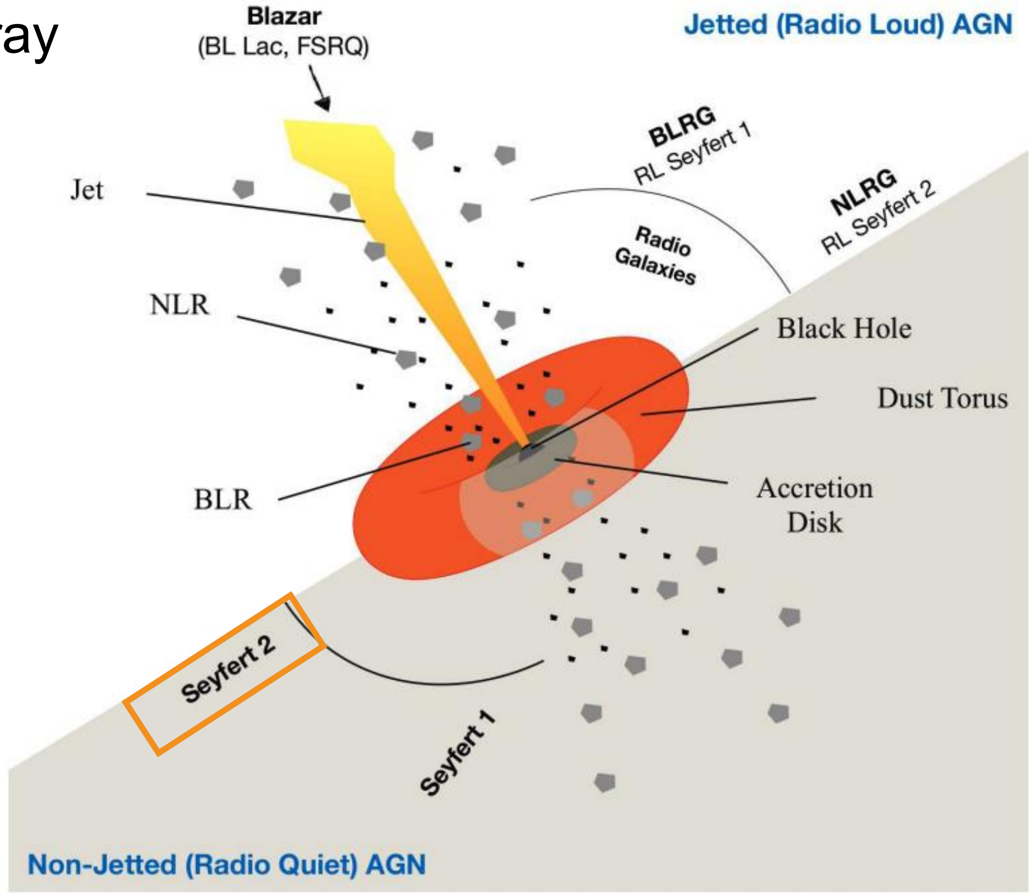
Predefined source list: Results

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

IceCube Science 378 (2022)

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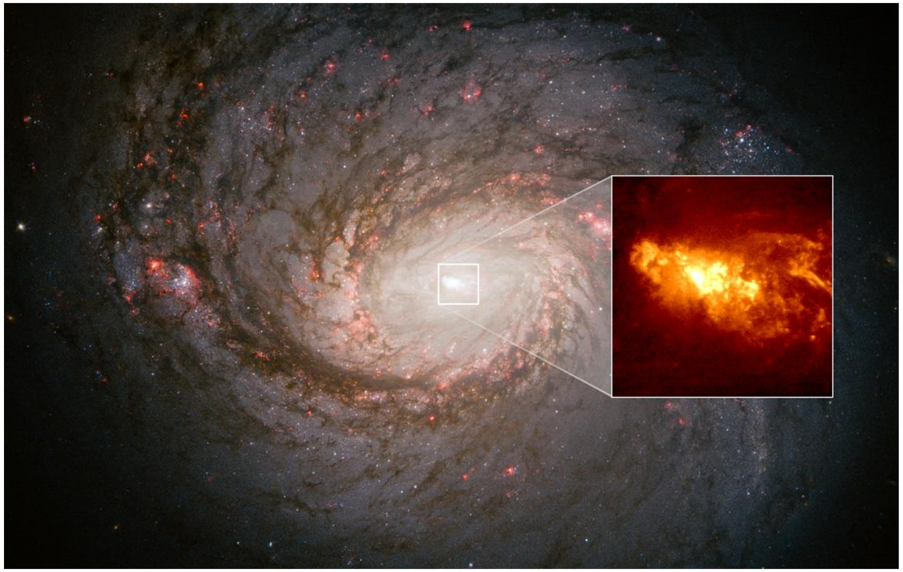

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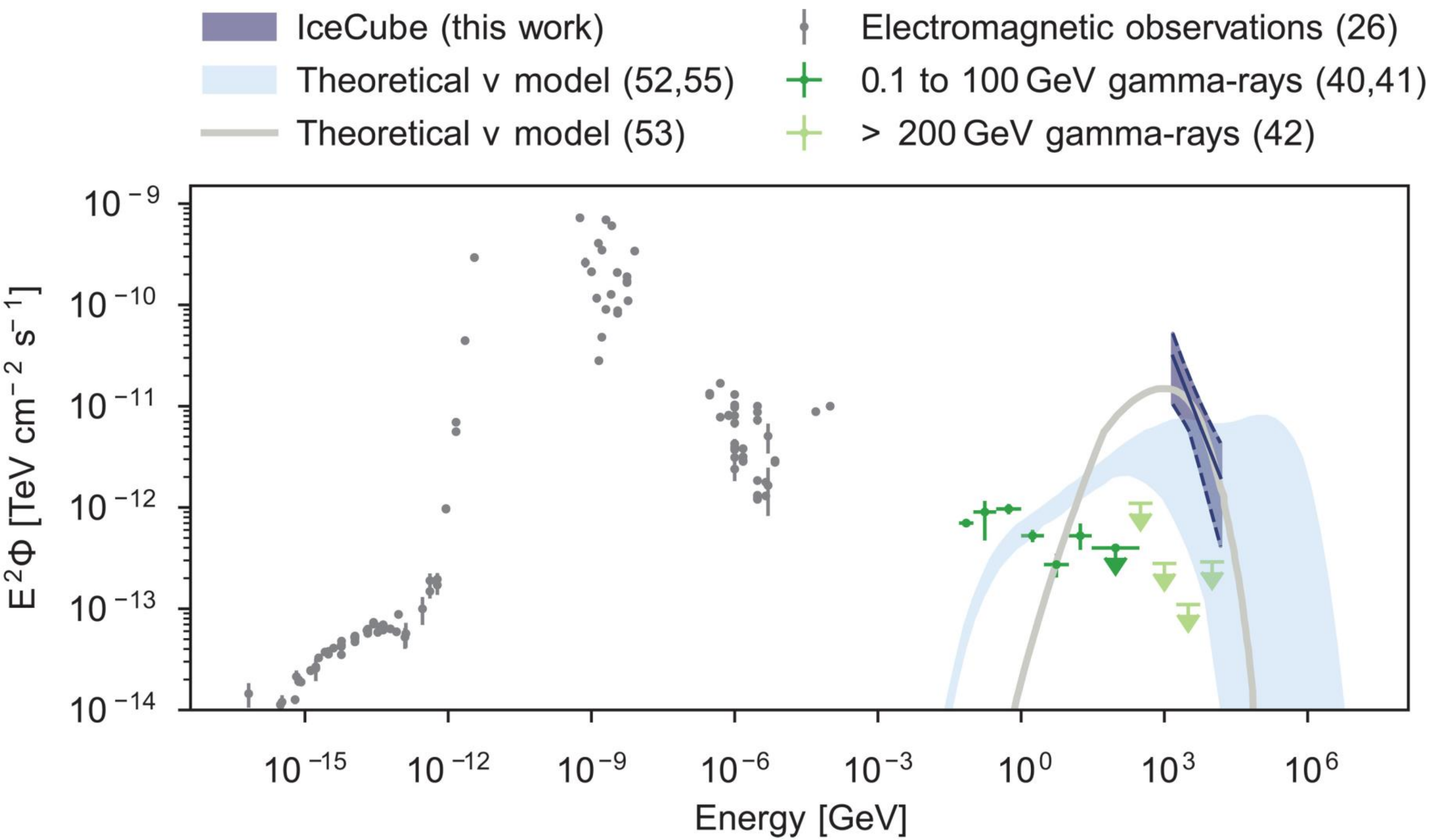
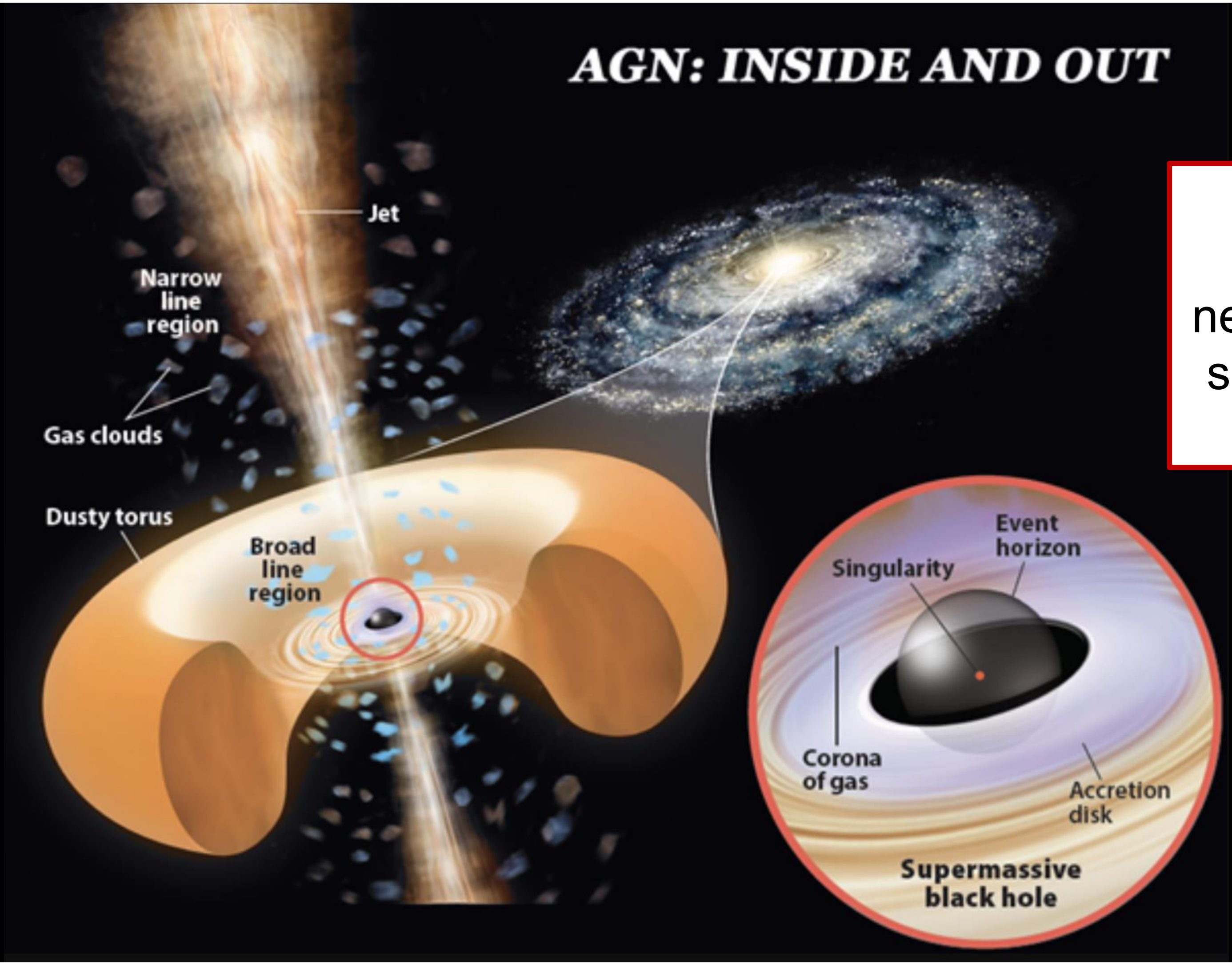
IceCube Science 378 (2022)

Complete Multi-wavelength data of NGC 1068



Gamma rays need to be absorbed

IceCube Science 378 (2022)

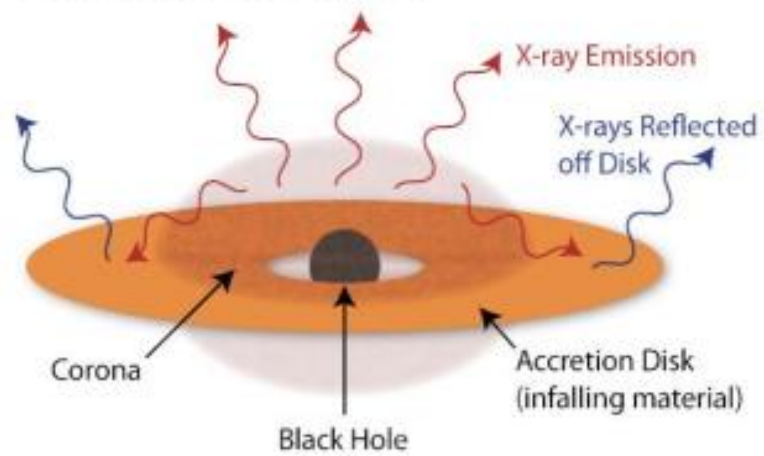


Lack of gamma rays places neutrino production site in the heart of the galaxy

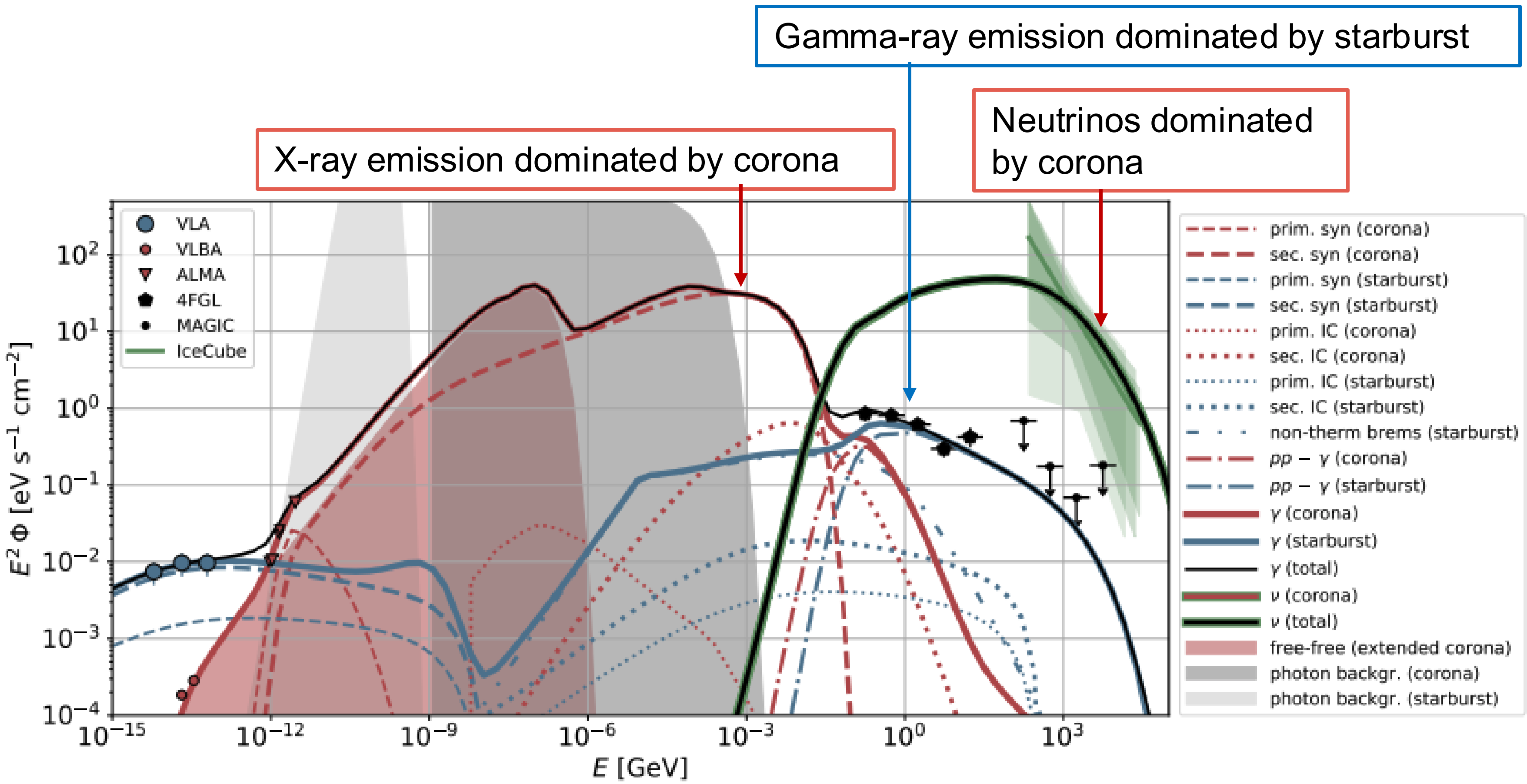
What is the corona?

- 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



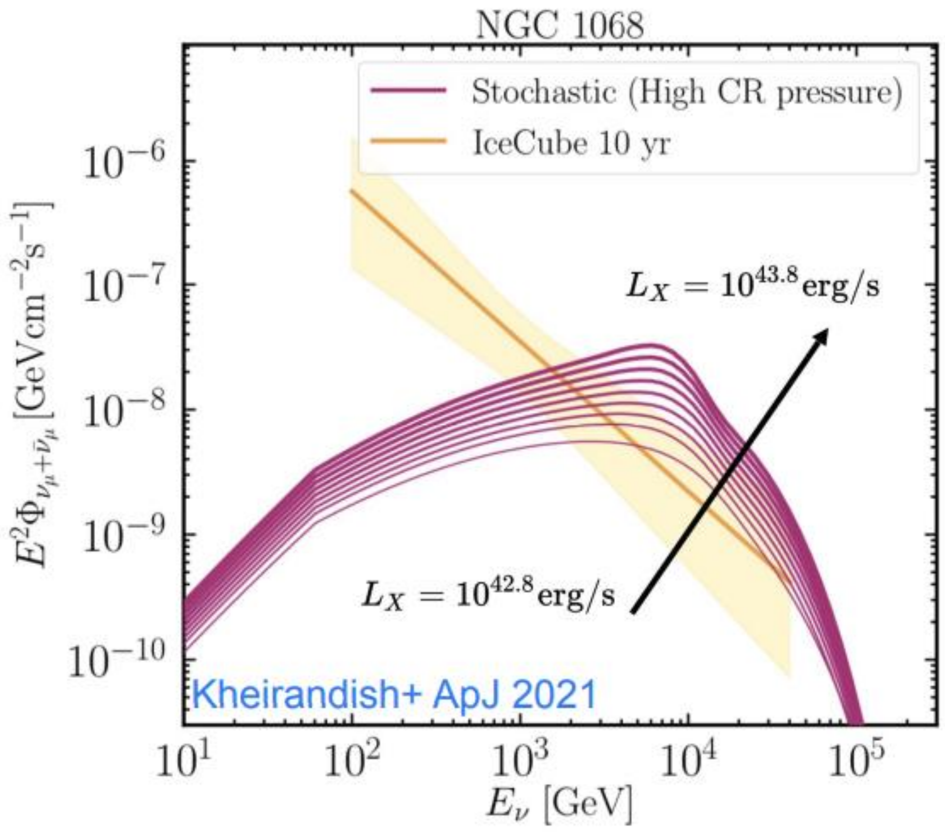
Detailed Modeling of Starburst-AGN Composite

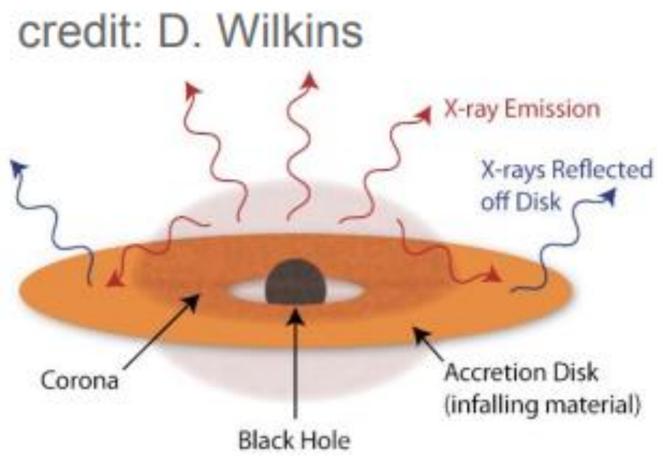


Eichmann ApJ 939 (2022) 43

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)

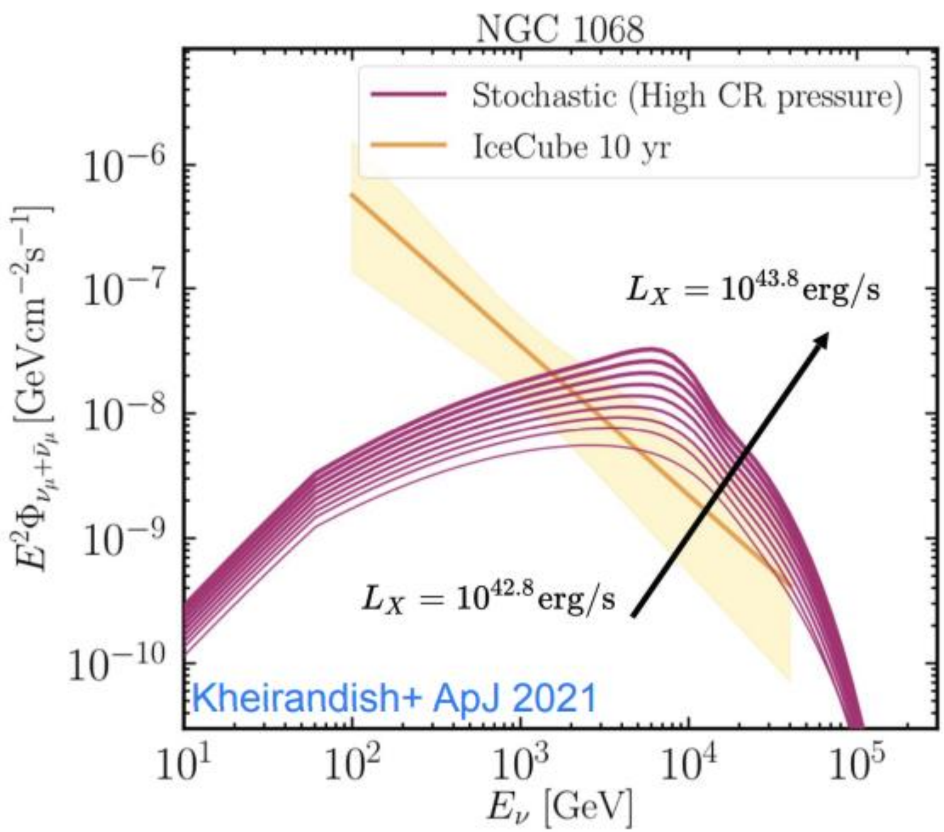
→ only one fit parameter for entire population: overall normalization

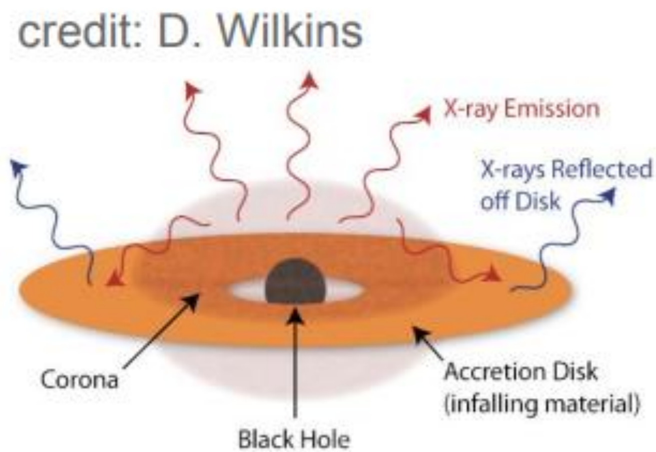
Potential problem: if assumption (weighting) does not hold, sensitivity is reduced

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



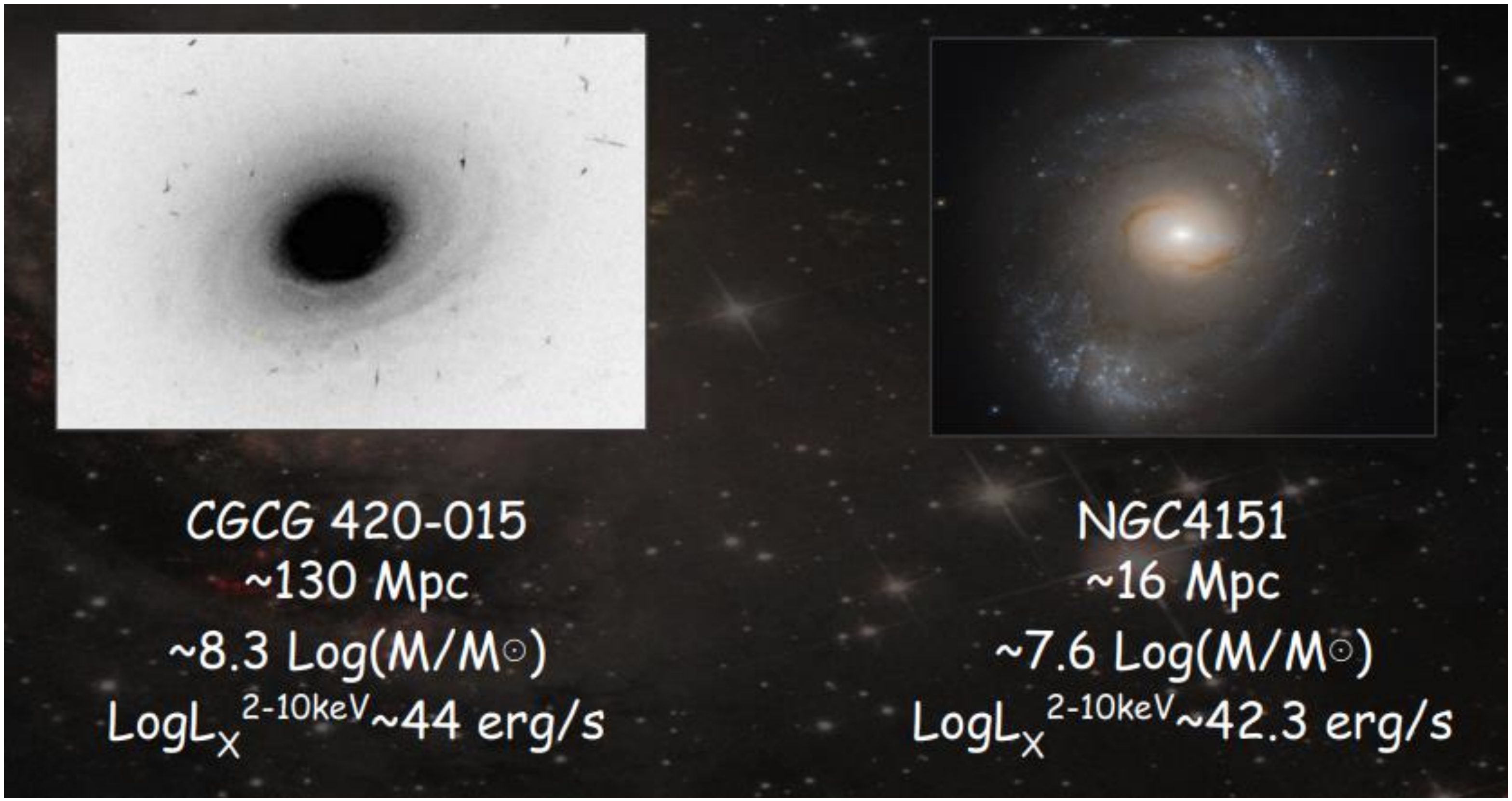


No significant emission is found in the stacking search excluding NGC 1068.

IceCube arXiv:2406.07601

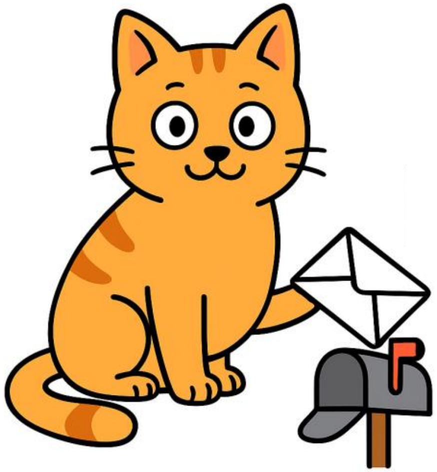
More Seyferts: Individual sources

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)

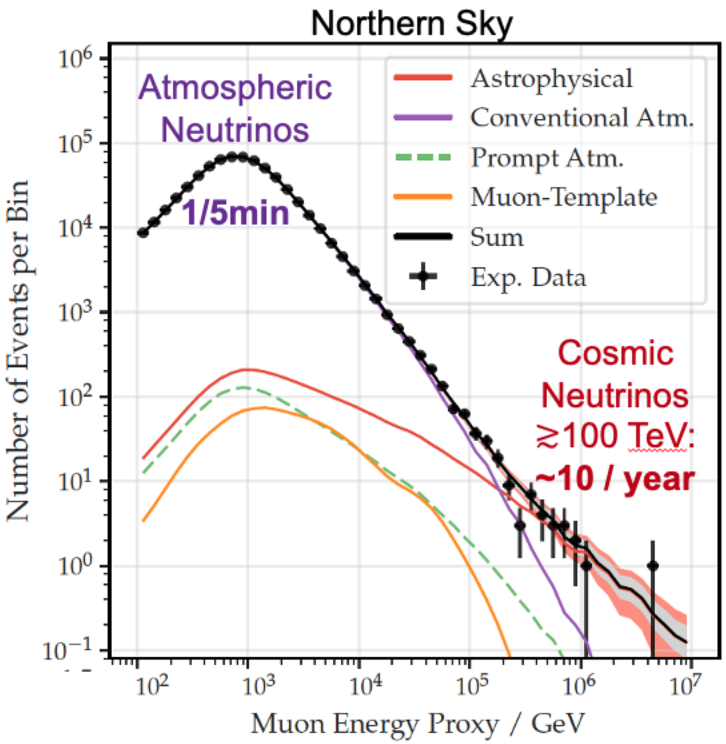


Take home message

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

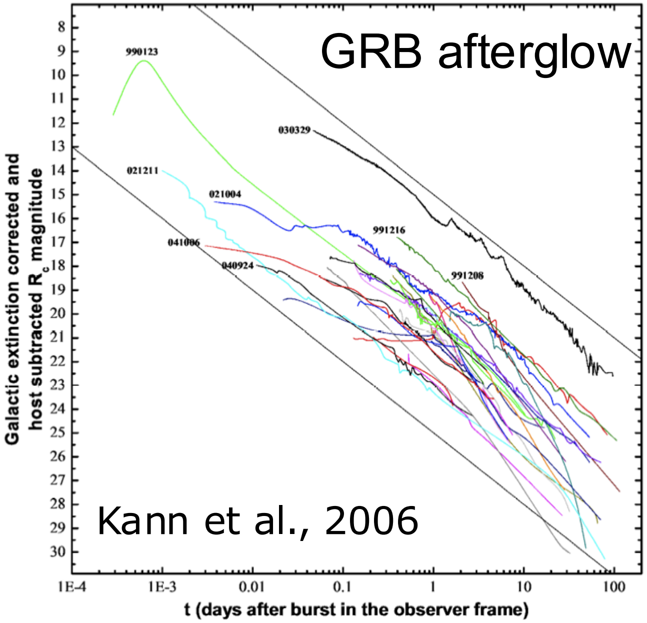
Public alerts since April 2016

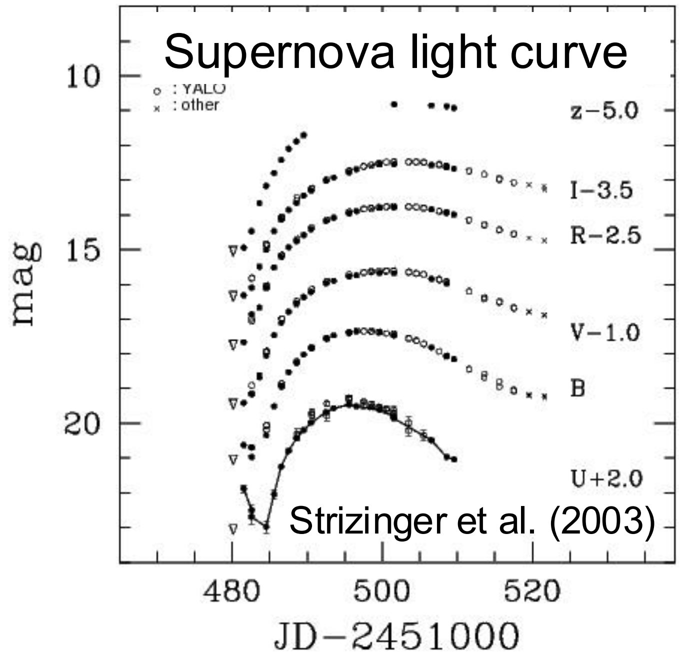
- Single high-energy muon track events (> ~100TeV)
- “Gold” alert stream: 10 / yr, ~5 / yr of cosmic origin
- Median latency: 30 sec

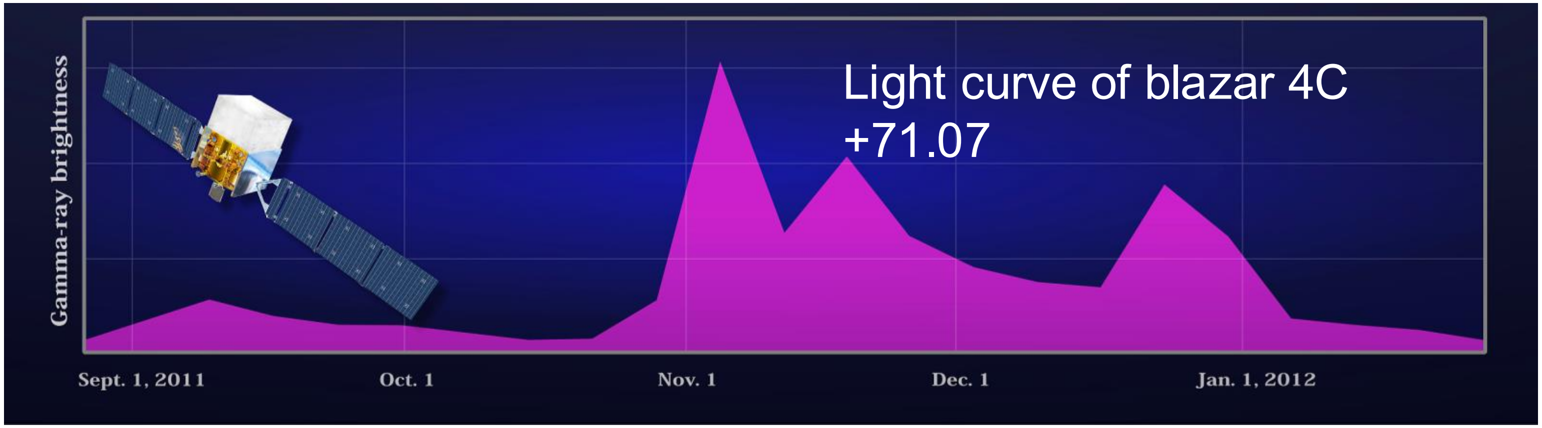
Goal: Find electromagnetic counterpart

Astropart. Phys., 92, 30 (2017)

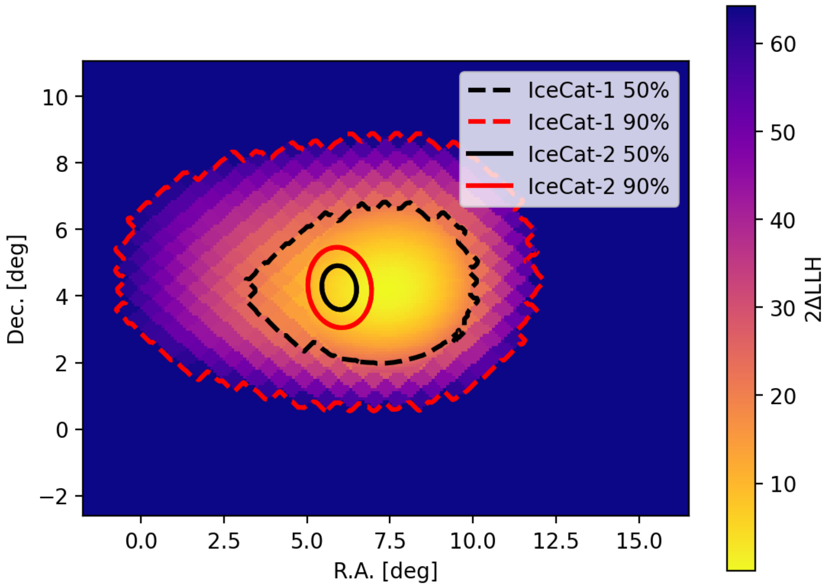
Expected EM Counterparts

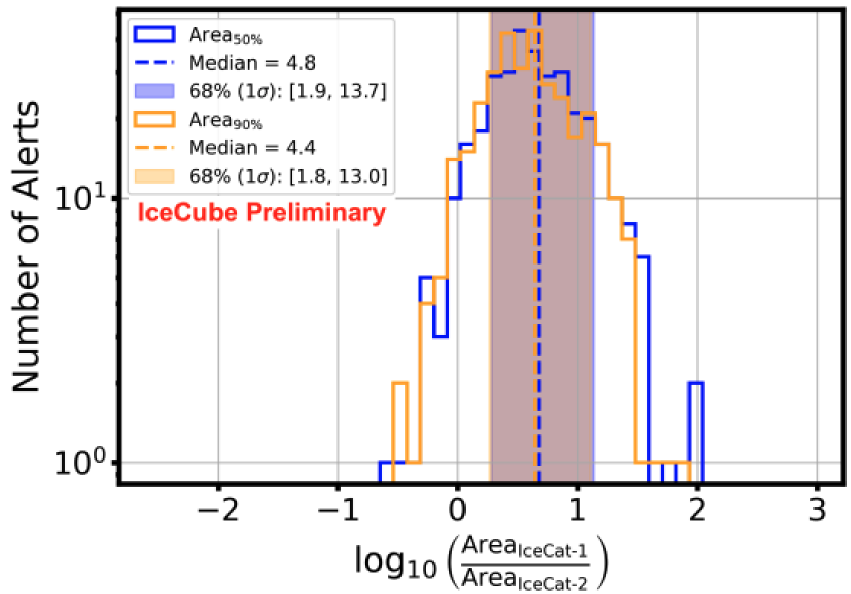






IceCat-2

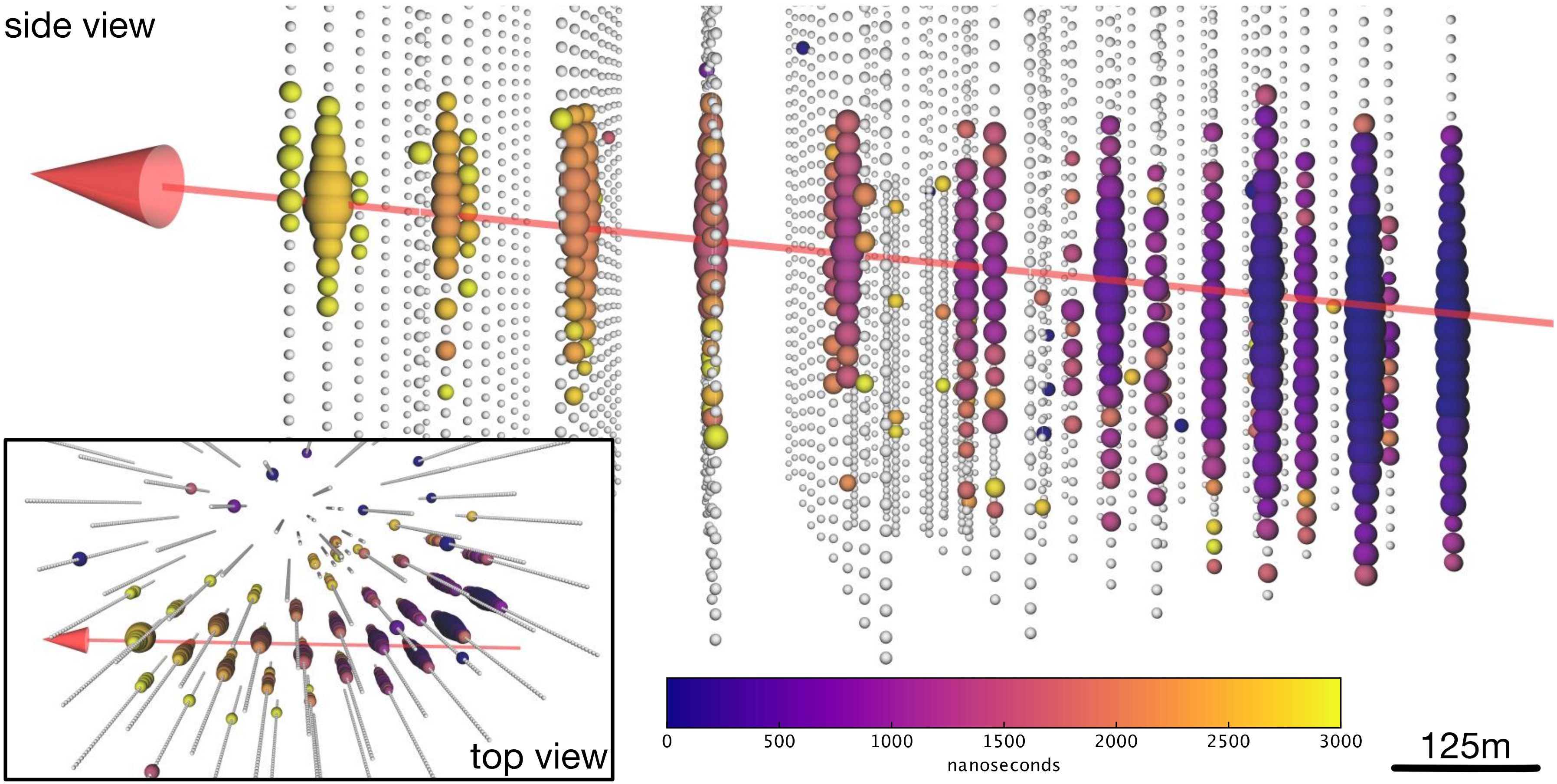




Improvement in 90% uncertainty area of factor 4.4

Archival alert catalog (IceCat-2) under development

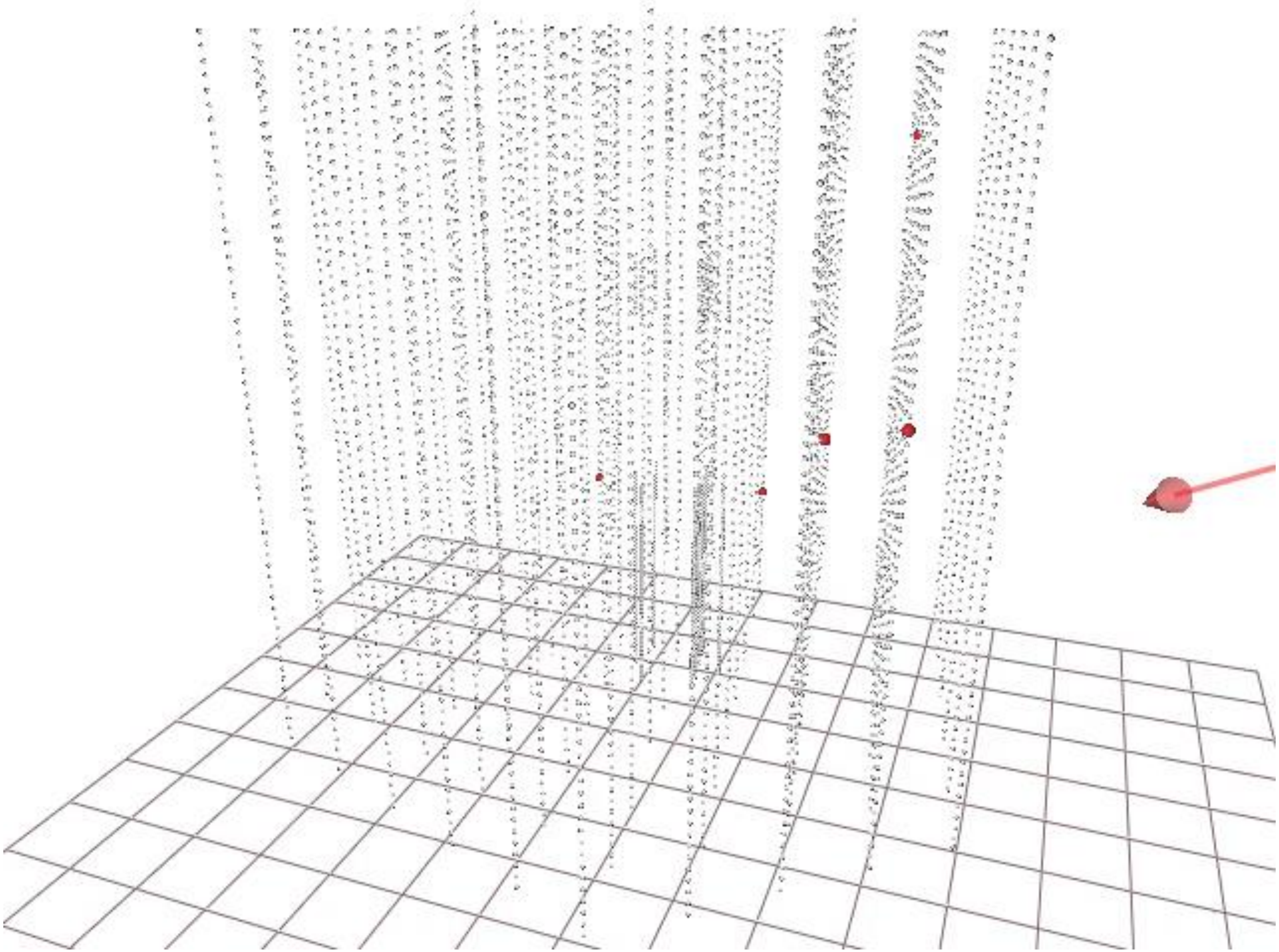
First example: IC-170922A – a 290 TeV Neutrino



Signalness: 56.5%

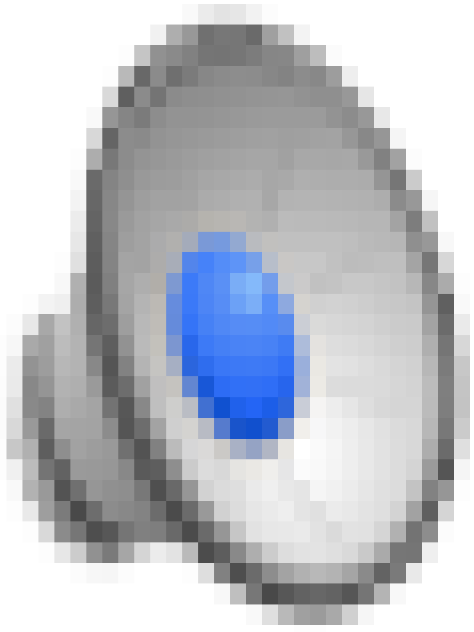
IceCube, Fermi-LAT, MAGIC, AGILE, ASAS-SN, HAWC, H.E.S.S, INTEGRAL, Kapteyn, Kanata, Kiso, Liverpool, Subaru, Swift, VERITAS, VLA, Science 2018

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

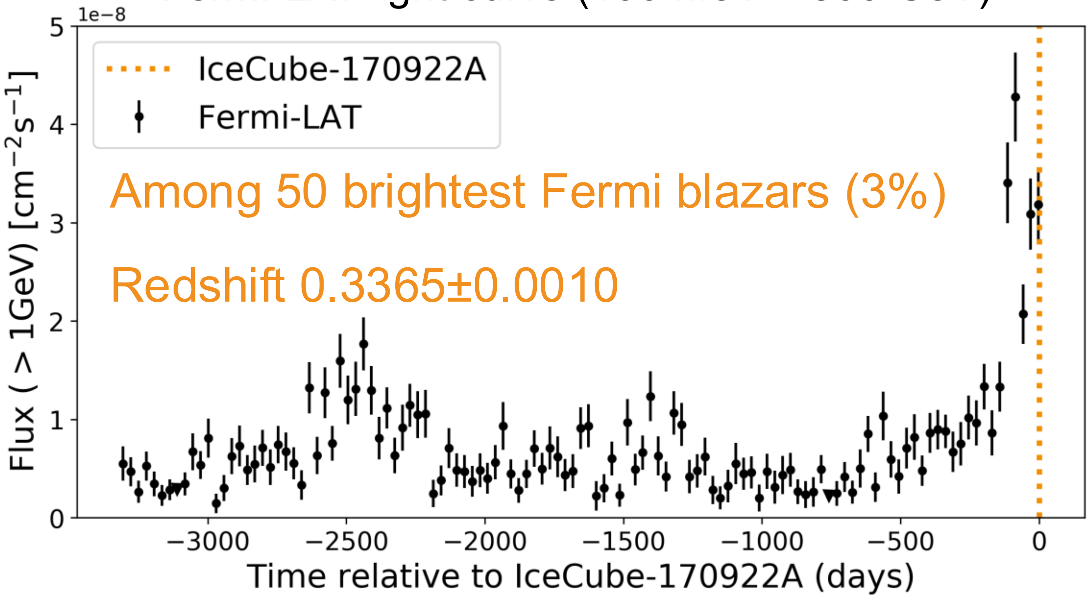
Fermi-LAT finds Flaring Source

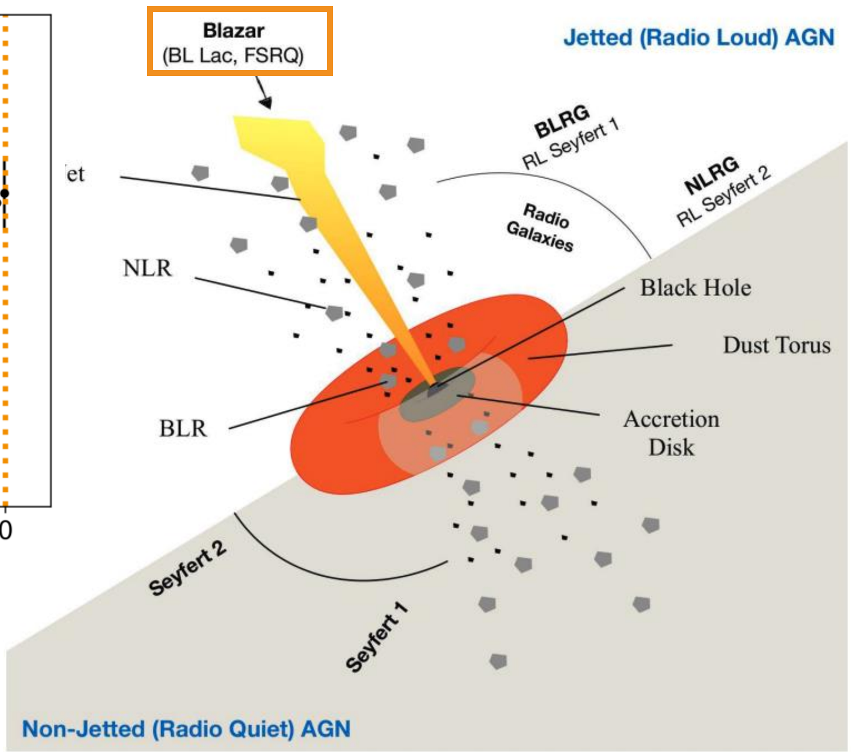


Fermi-LAT Coll., ApJ 846, 2017, Video credits: Matteo Giomi, Fermi-LAT Collaboration

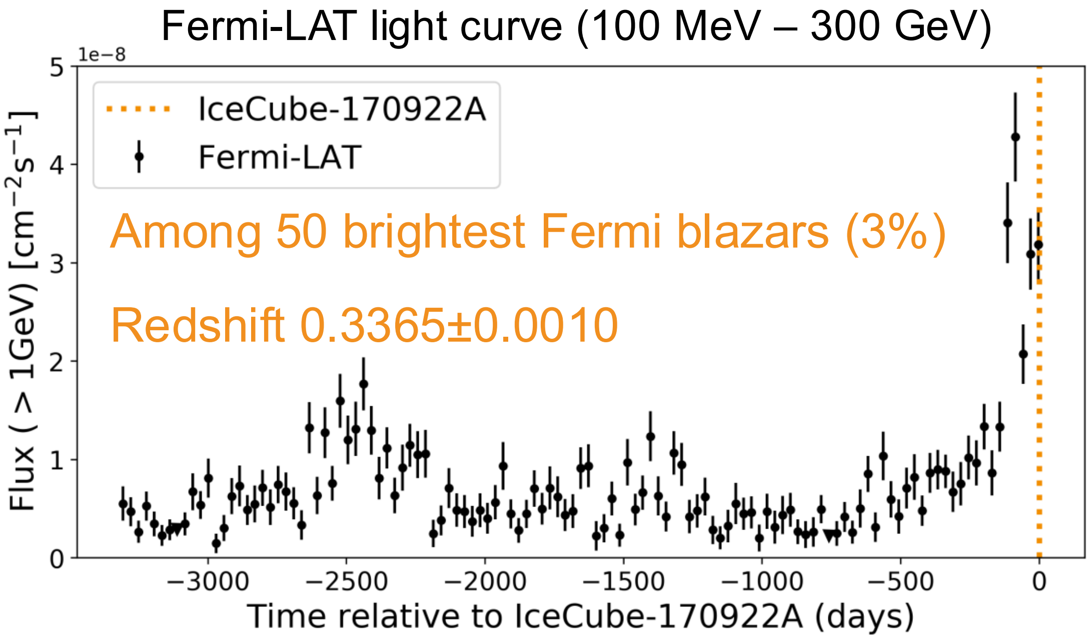
Fermi-LAT finds Flaring Blazar, TXS 0506+056

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

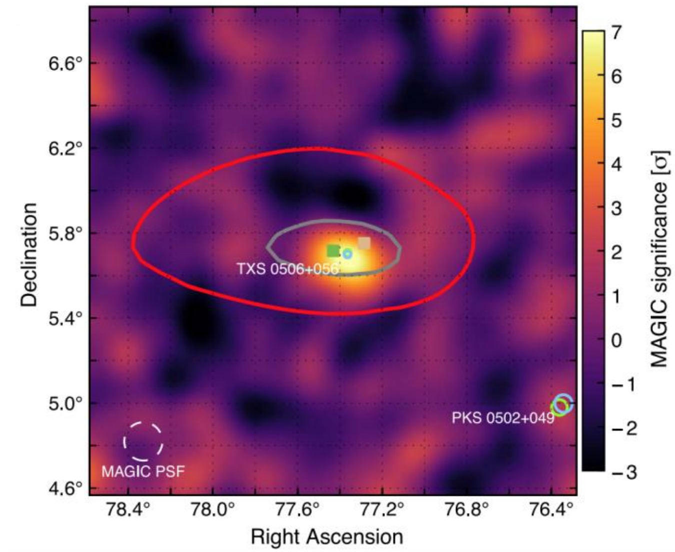




Fermi-LAT finds Flaring Blazar, TXS 0506+056

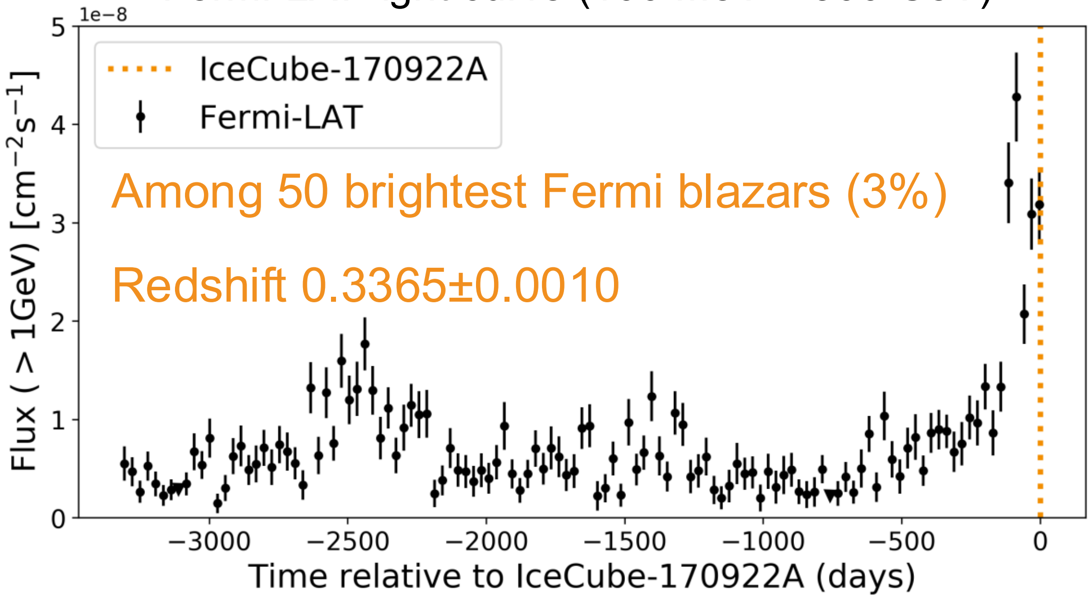


MAGIC Significance map:
TeV gamma rays

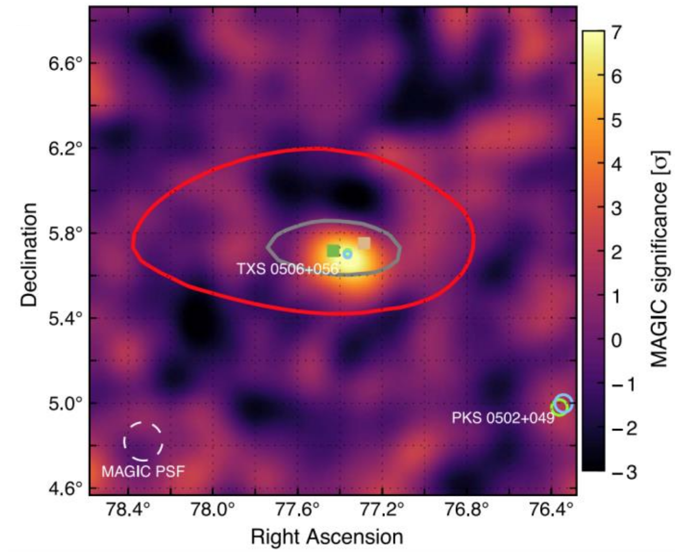


Fermi-LAT finds Flaring Blazar, TXS 0506+056

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

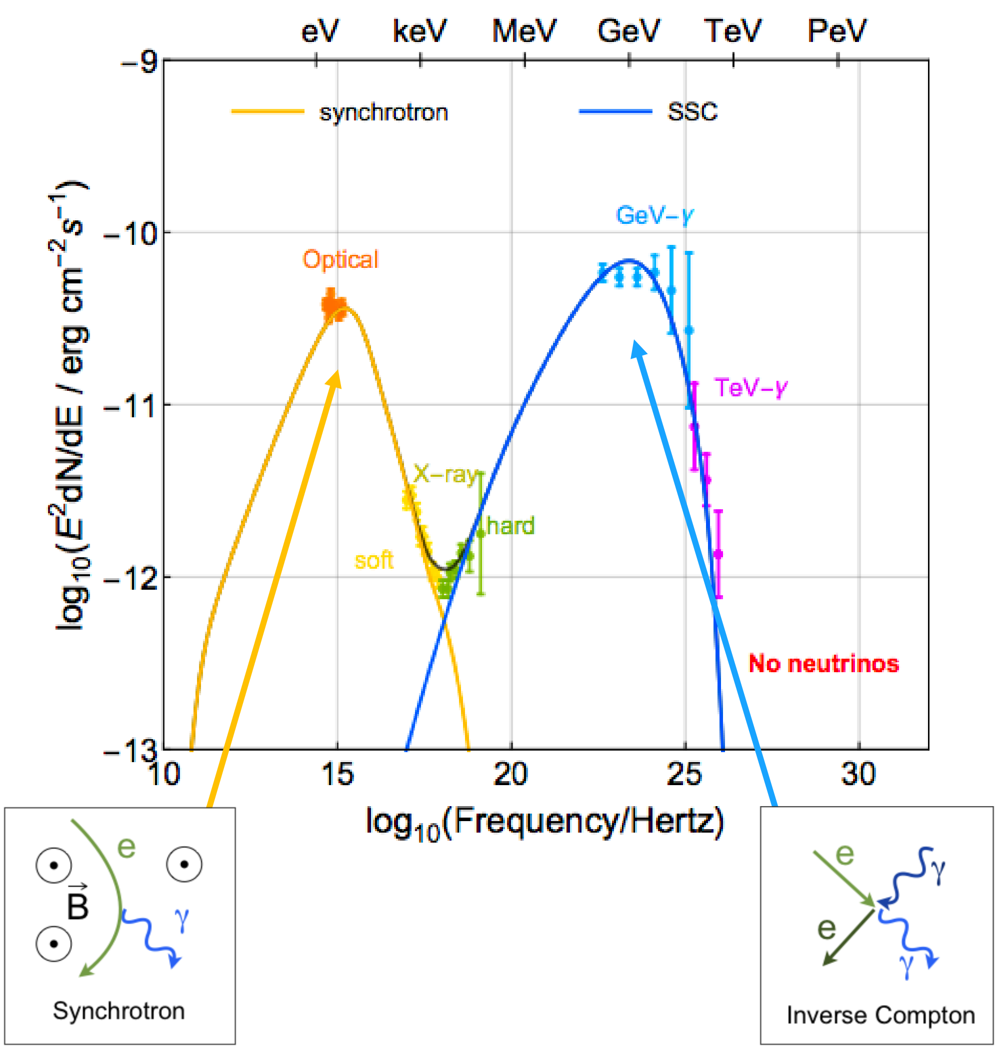


MAGIC Significance map:
TeV gamma rays



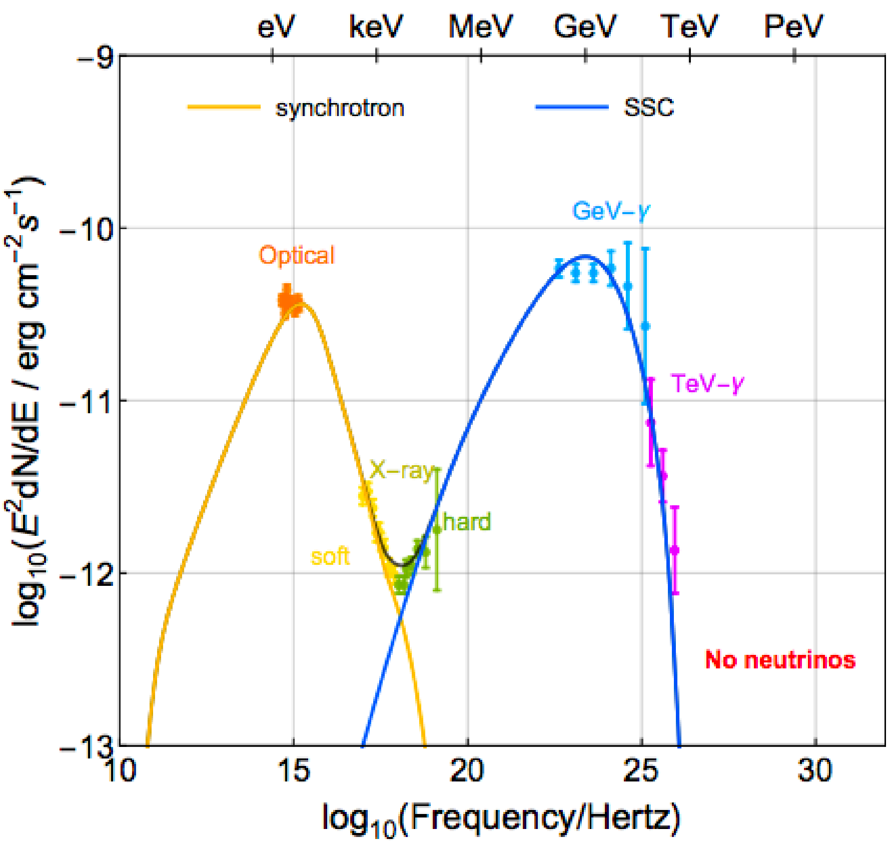
3 sigma significance including trials
> 6 PeV protons accelerated in the source

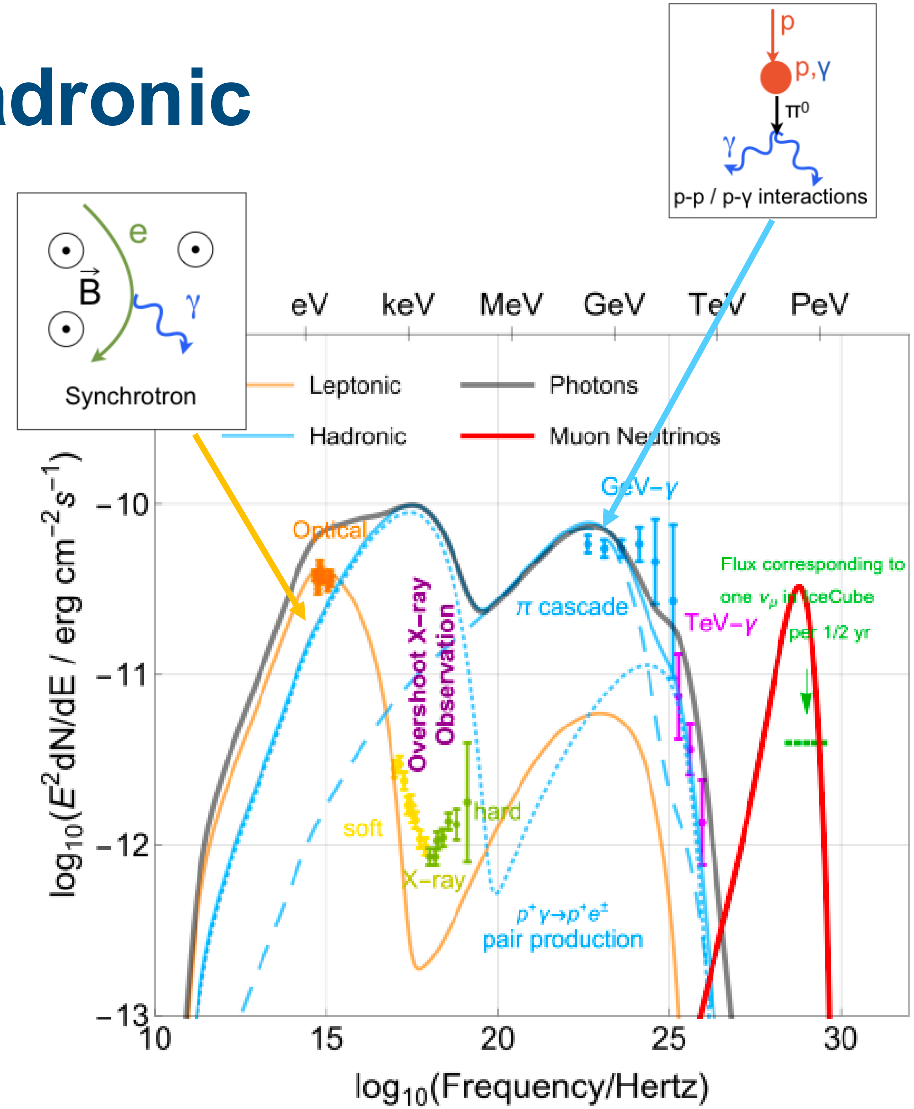
Modeling – leptonic



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

Modeling – leptonic, hadronic

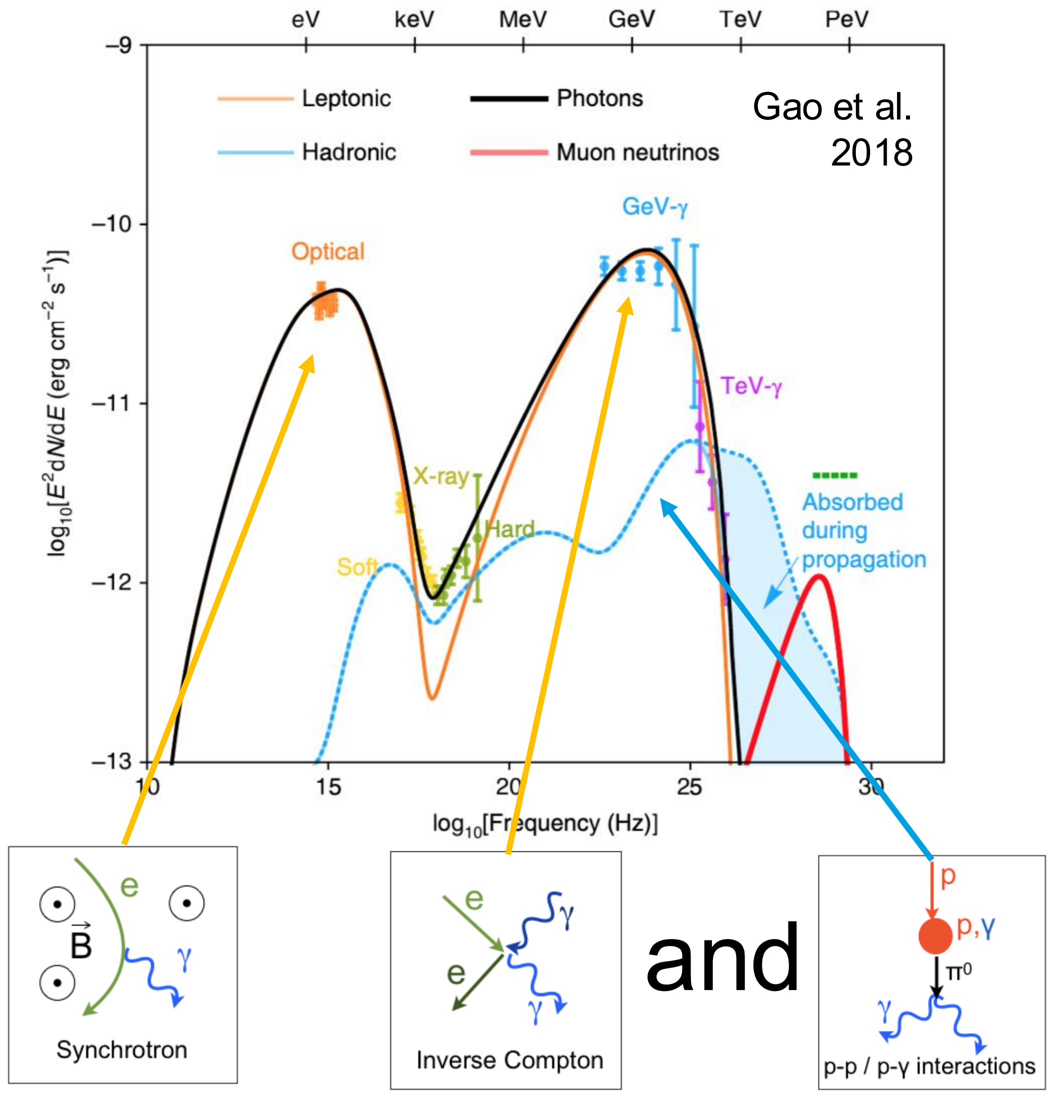




Simple one-zone hadronic models violate X-ray constraints
→ More complex models needed

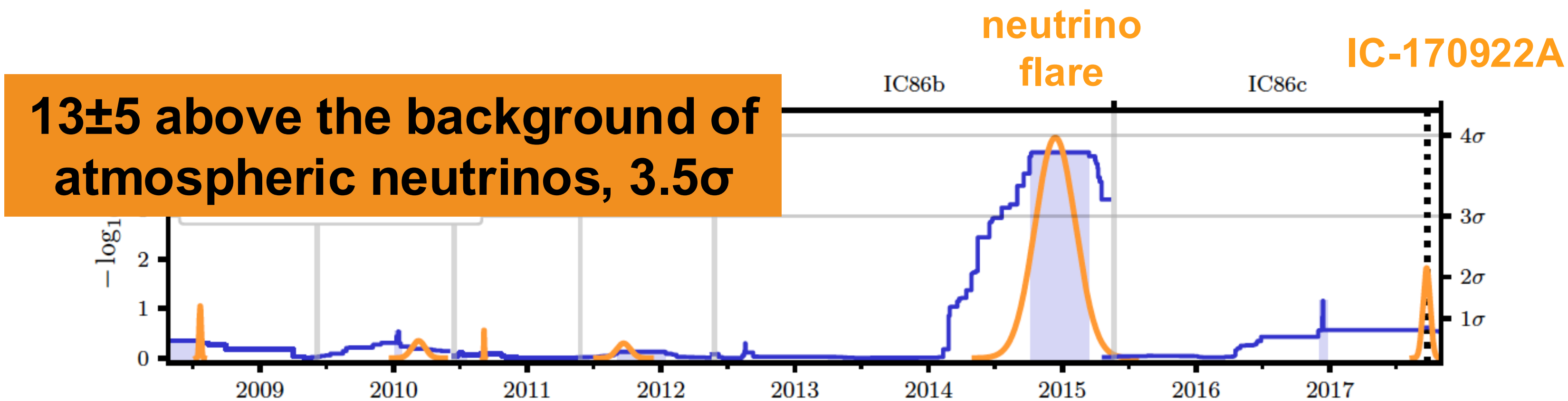
Gao et al., Nature Astronomy 2018,
Keivani et al., ApJ, 2018, MAGIC Coll., ApJ, 2018, Cerruti et al. MNRAS 2018, …

Modeling – lepto-hadronic



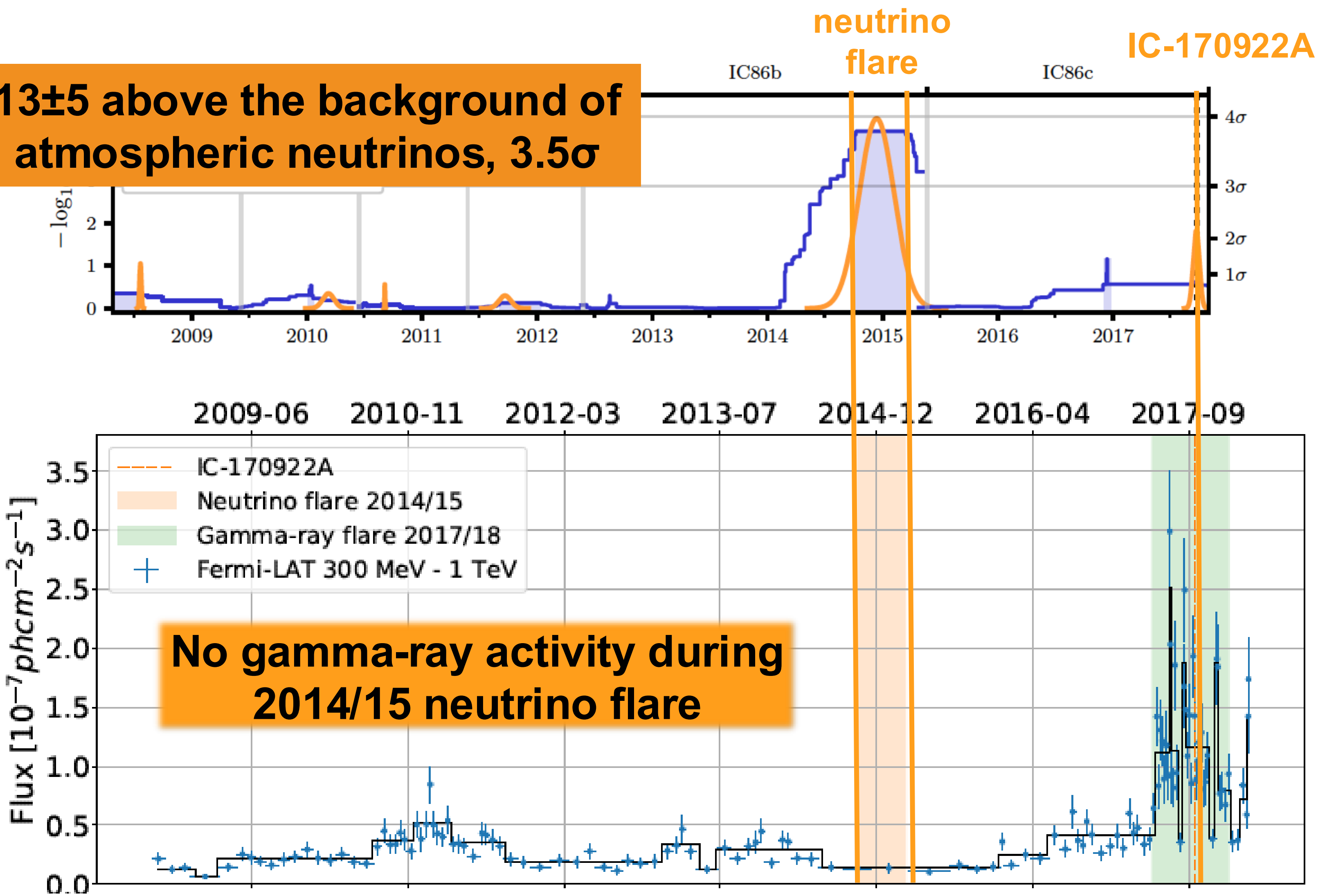
Gao et al., Nature Astronomy 2018,
Keivani et al., ApJ, 2018, MAGIC Coll., ApJ, 2018, Cerruti et al. MNRAS 2018, …

Are there more Neutrinos from this Source?



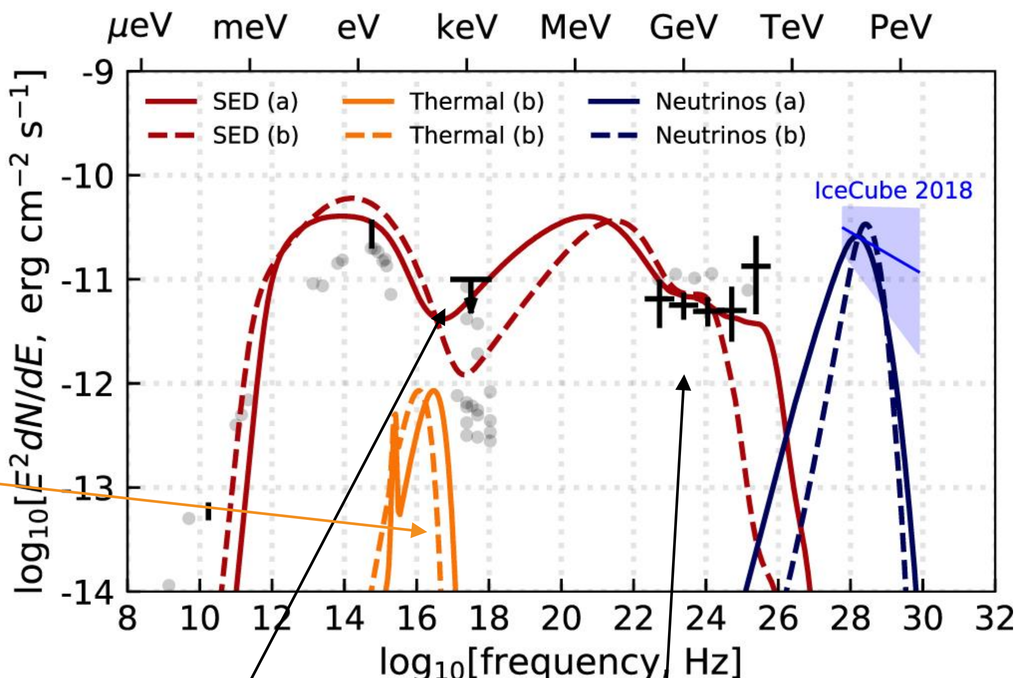
IceCube, Science 361, 2018

Is there also a Gamma-ray Flare?



Modeling of 2014/15 neutrino flare

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



BLR photons boosted into the jet

Swift-BAT upper limit

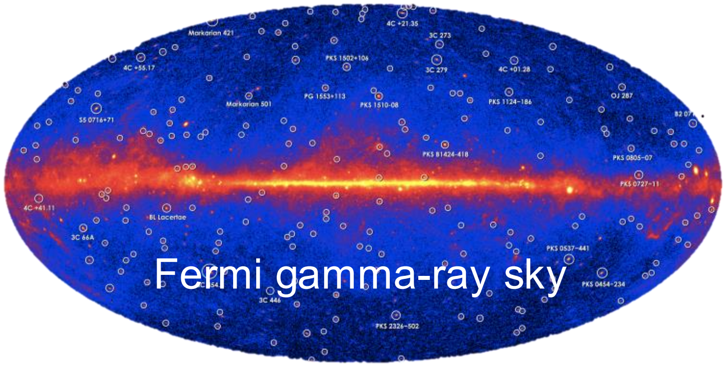
Fermi-LAT

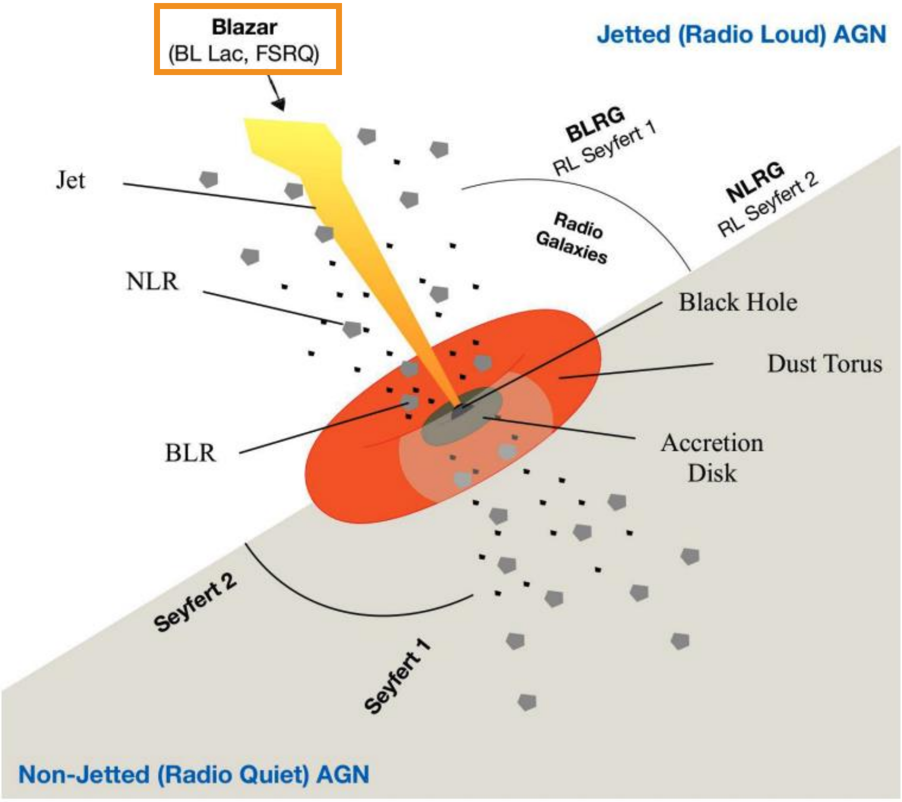
see e.g. Rodrigues et al. ApJL 874 2019, A. Reimer et al. ApJ 881 2019, F. Halzen et al. ApJL 874 2019

Do gamma-ray blazars produce all diffuse neutrinos?

Fermi Blazars

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

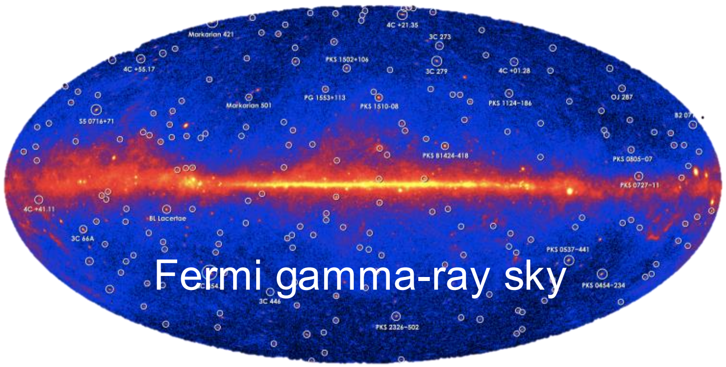




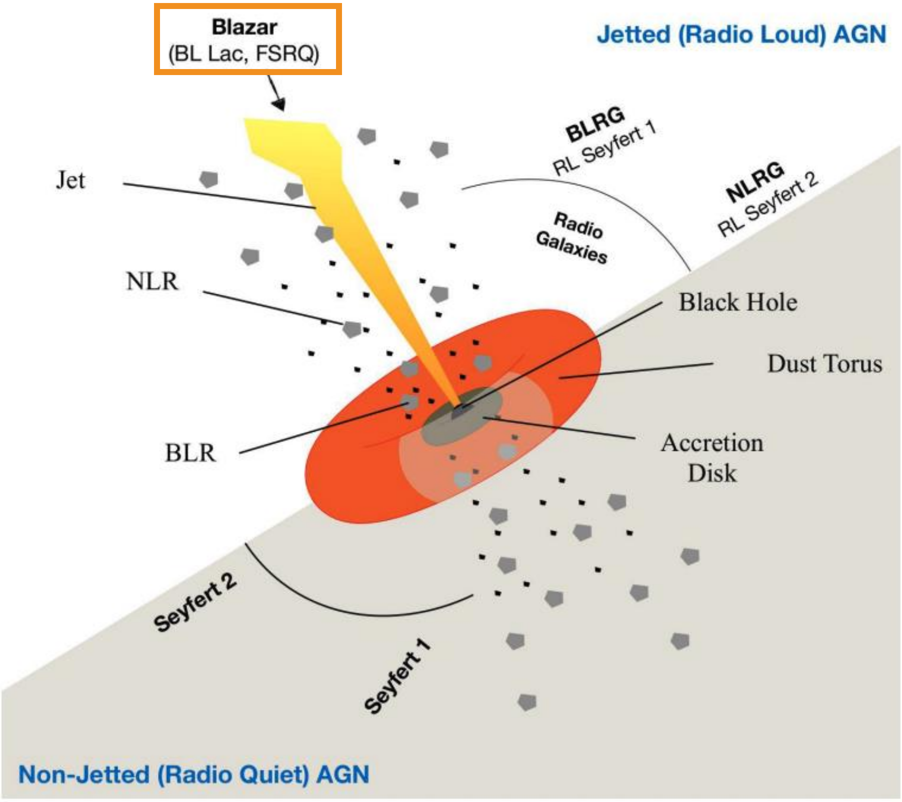
RUB

Fermi Blazars

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



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.

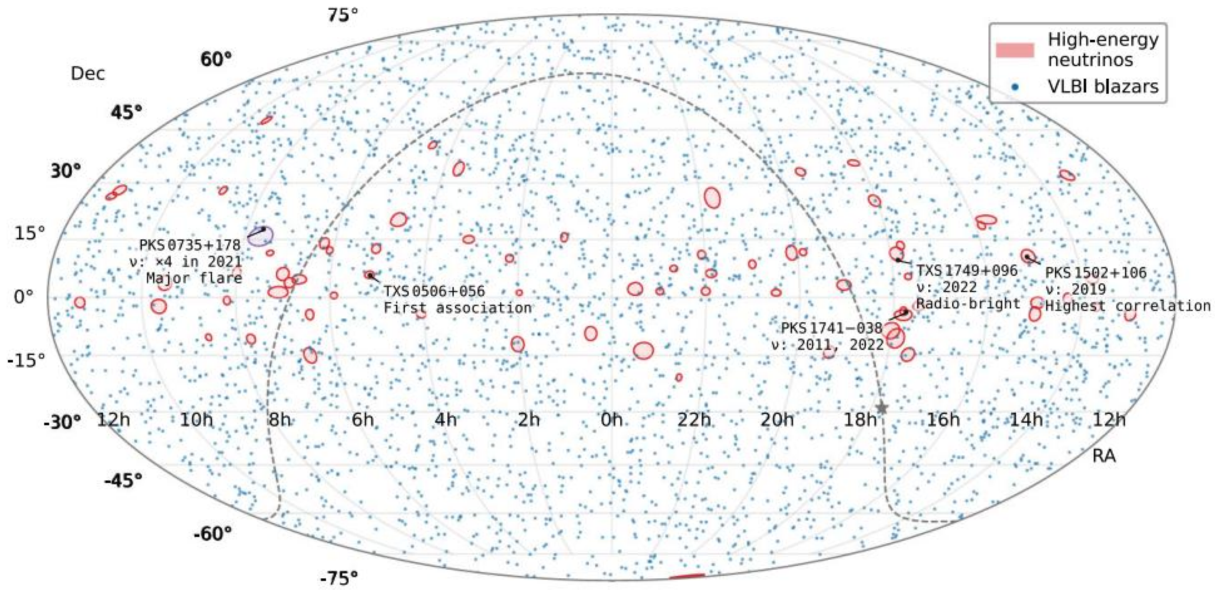
IceCube Coll. ApJ 954 (2023) 1, 75

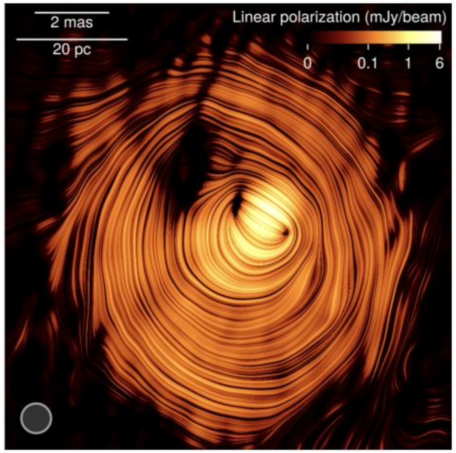
Other wavelength as tracer for neutrinos from blazars?

RUB

Radio Core Brightness as Tracer

Correlation with VLBI-flux-density limited sample of blazars



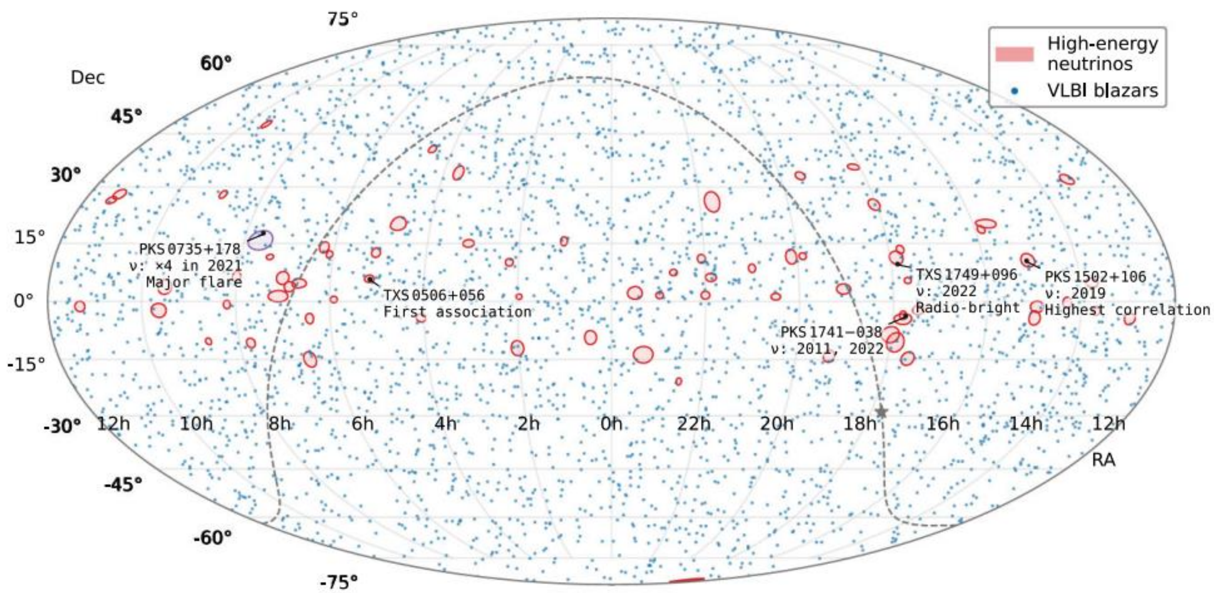


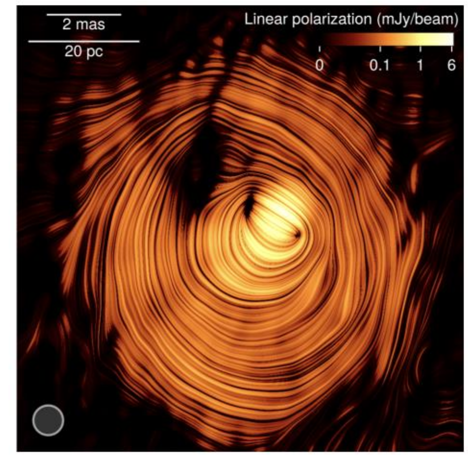
Correlation of radio-bright blazars with IceCube neutrino alerts at chance coincidence of $3 \cdot 10^{-4}$

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

Radio Core Brightness as Tracer

Correlation with VLBI-flux-density limited sample of blazars

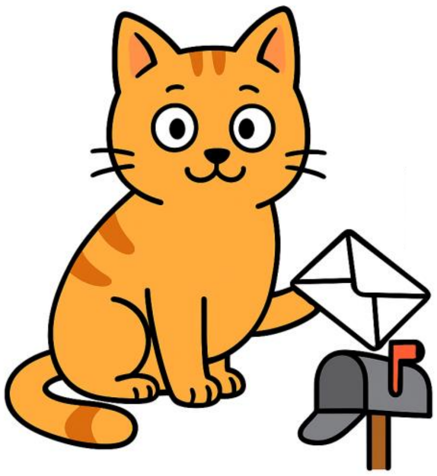




Correlation of radio-bright blazars with IceCube neutrino alerts at chance coincidence of $3{\cdot}10^{-4}$

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

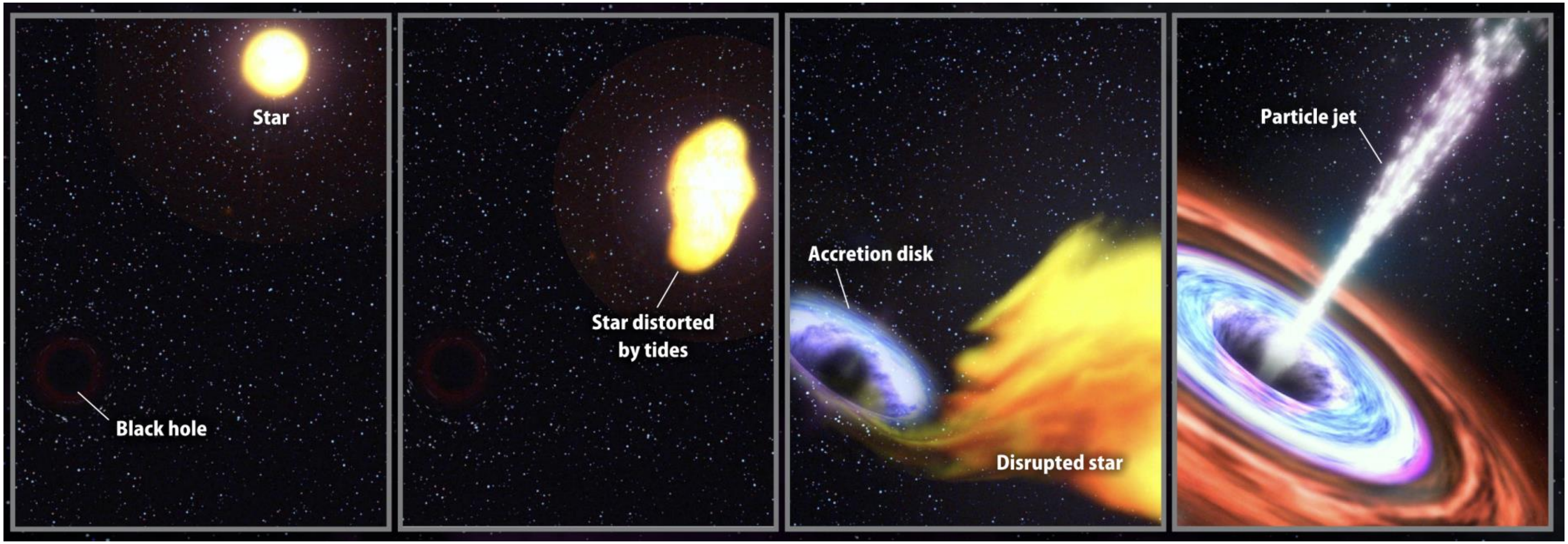


Take home message

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.

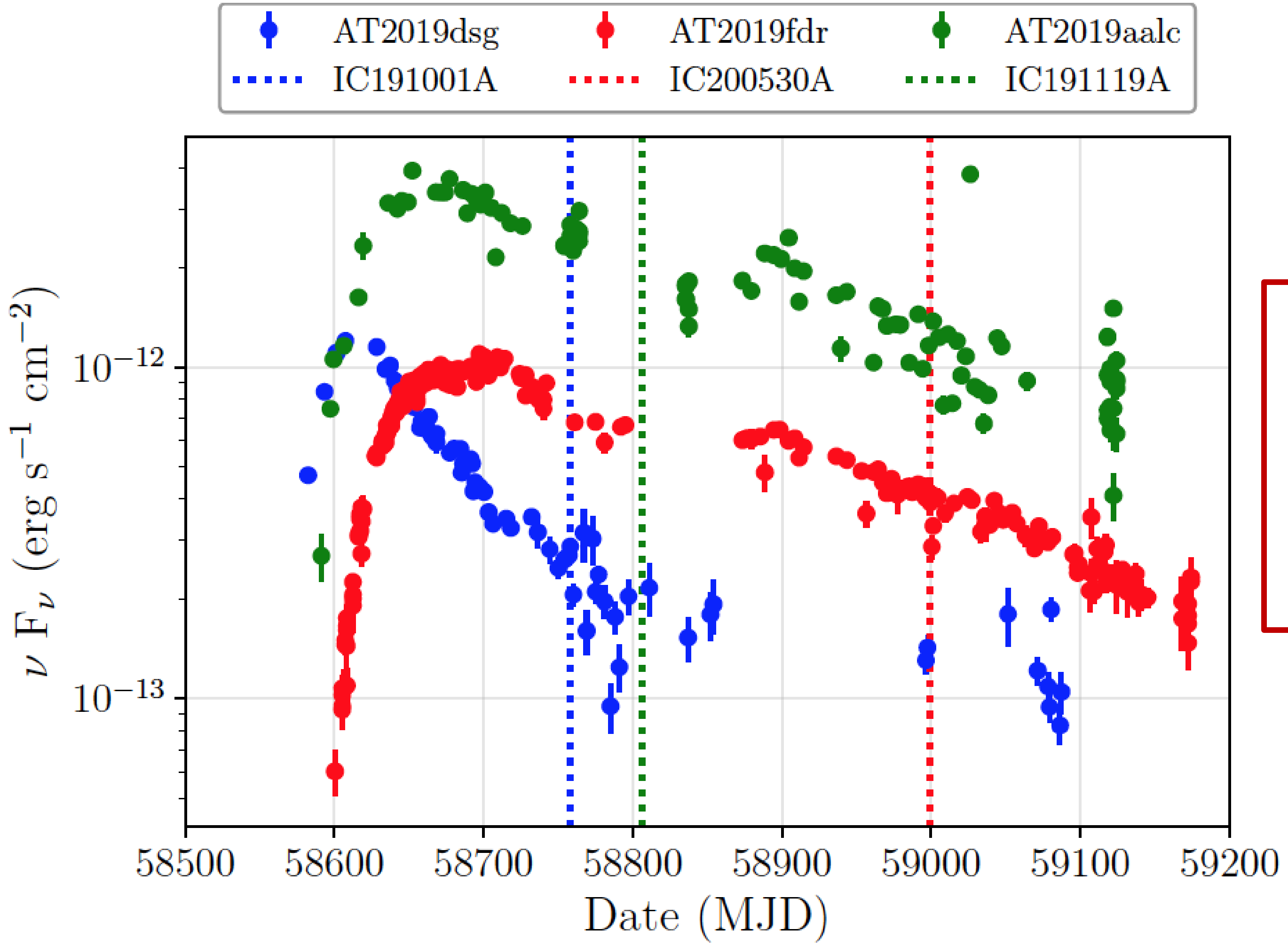
Other Sources?

What about quiet black holes? Tidal Disruption Events



~50 TDEs identified, 4 jetted TDEs
bright in optical

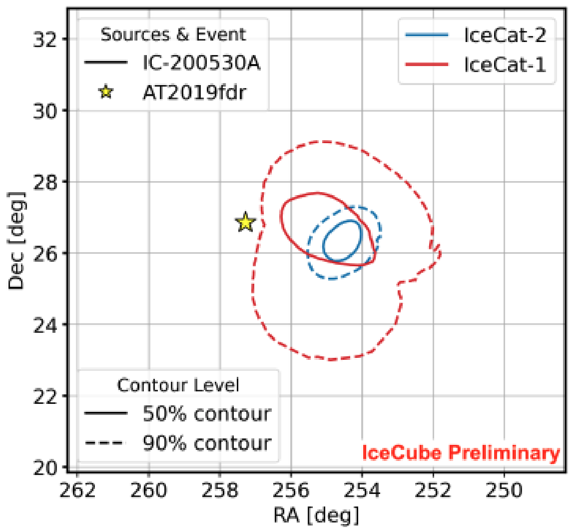
Tidal Disruption Events as Neutrino Candidates



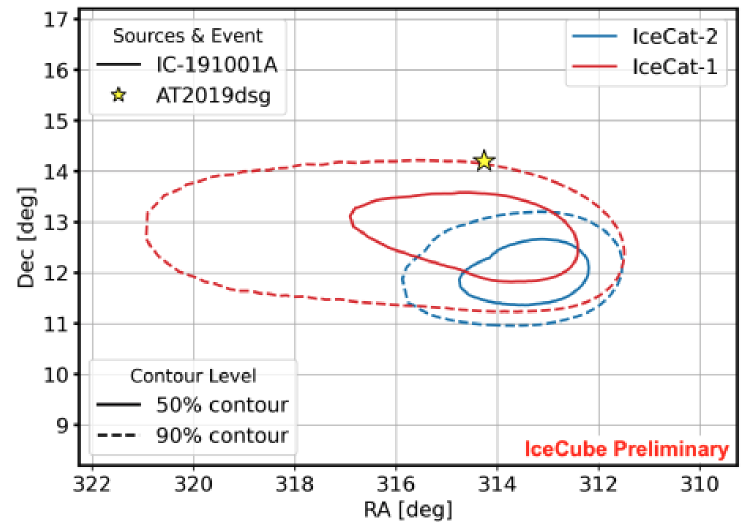
First hint of neutrino production in TDEs
→ **Very efficient neutrino production in TDEs compared to AGN?**

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

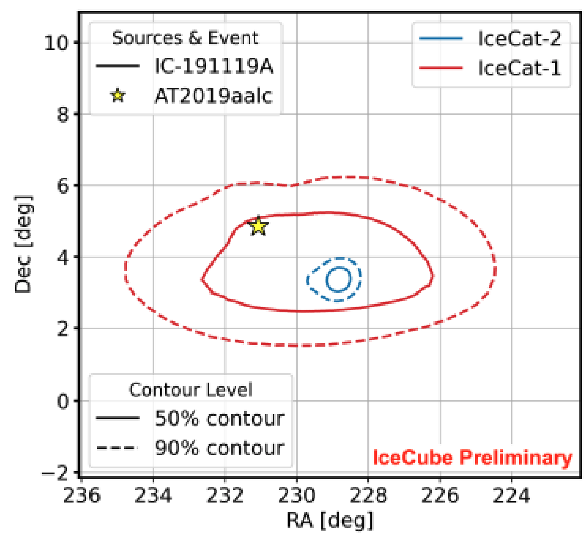
Neutrino TDEs disfavored with IceCat-2



(a) AT2019fdr



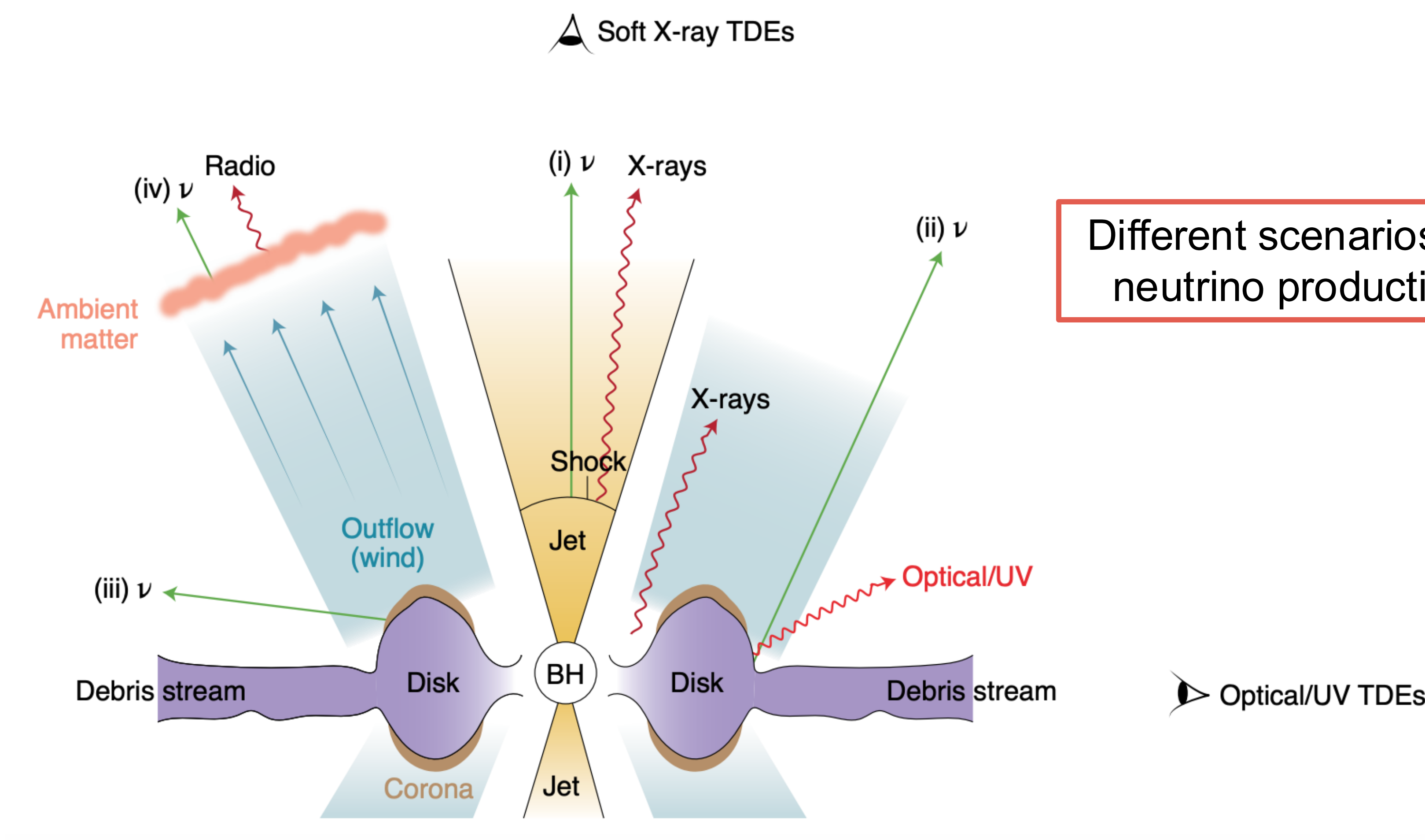
(b) AT2019dsg



(c) AT2019aalc

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

Neutrino Production in TDEs

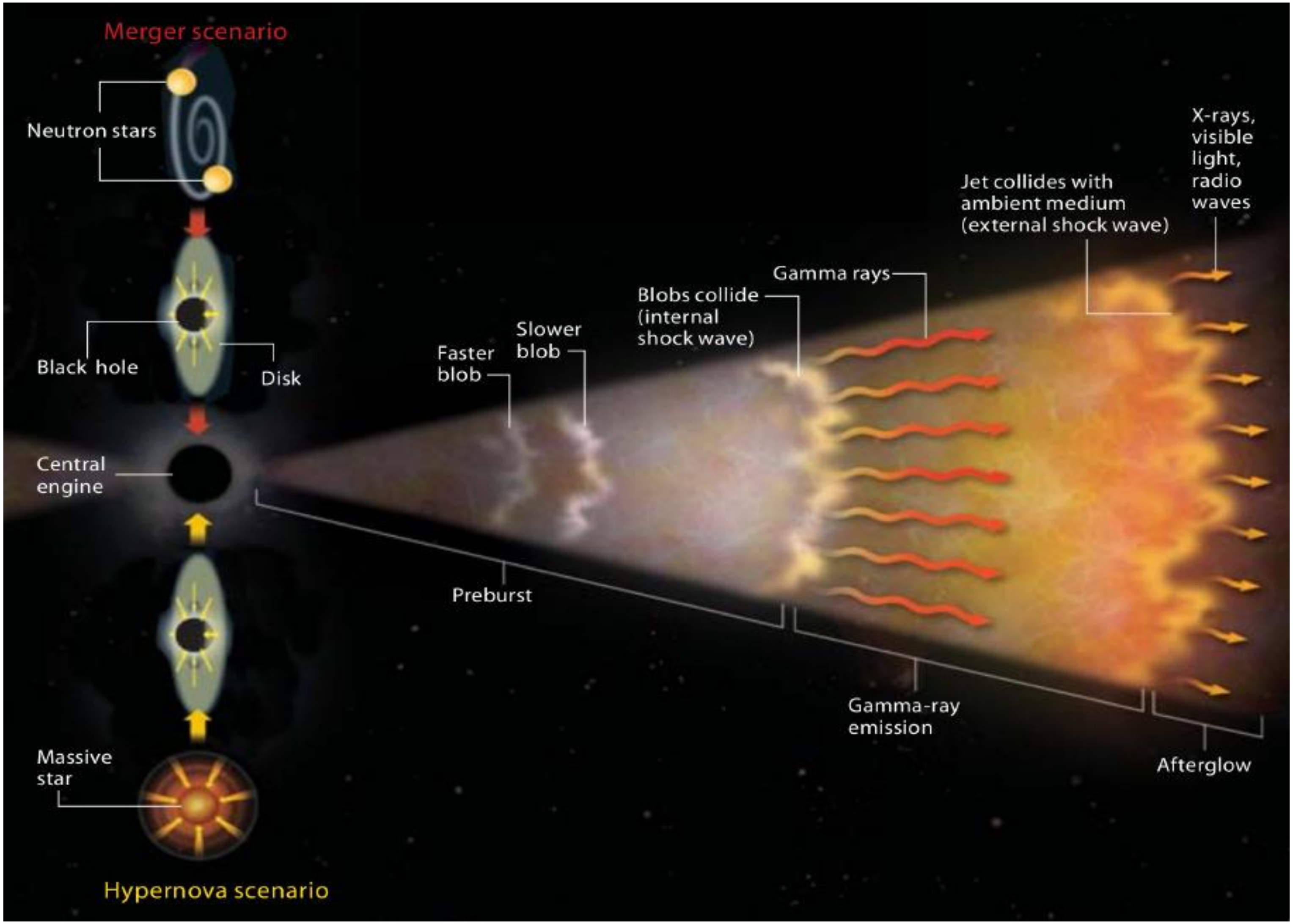


Different scenarios for neutrino production

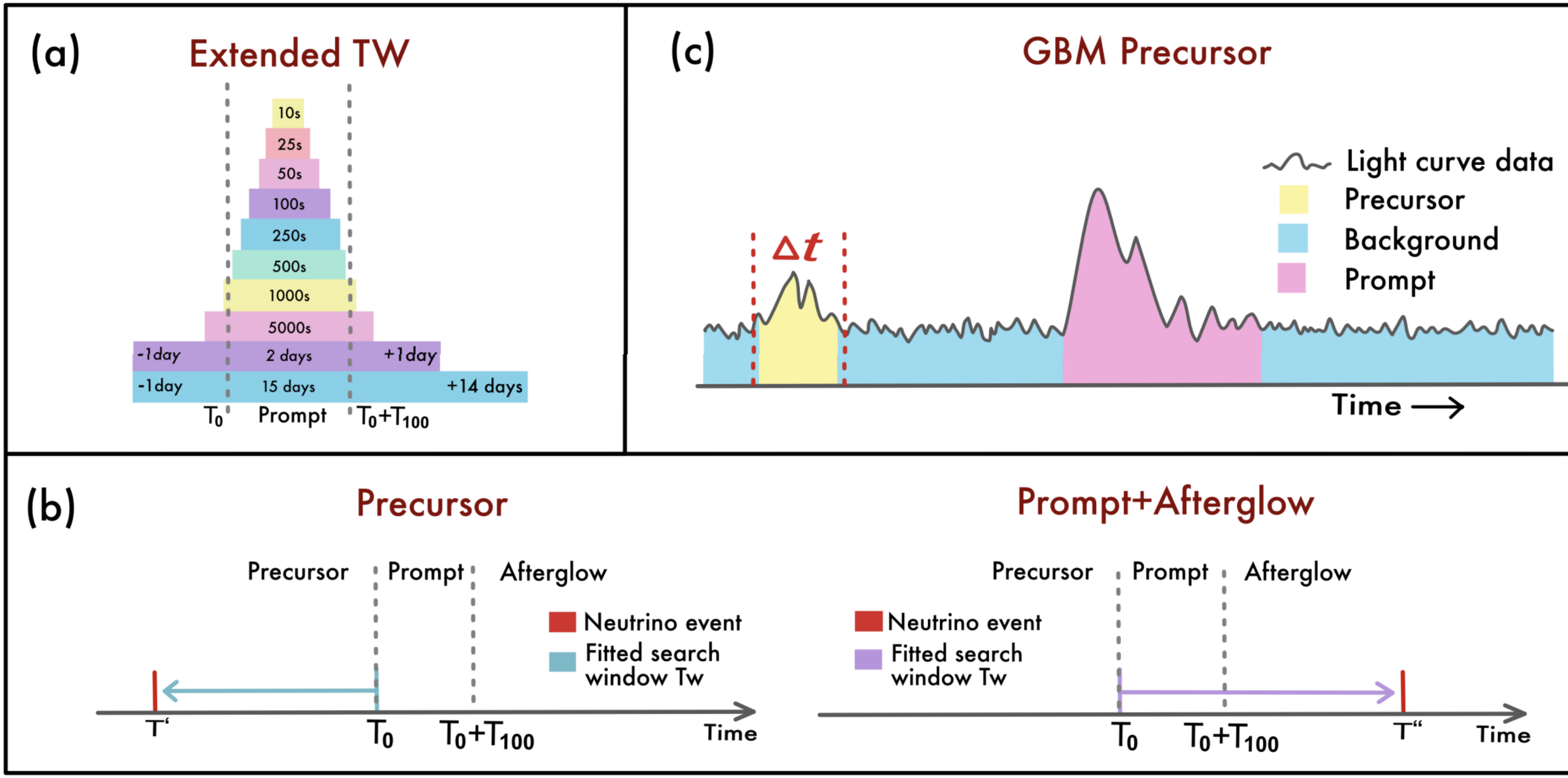
Hayasaki, Nature Astronomy 2021, Winter & Lunardini, Nature Astronomy 2021, Liu et al. PRD, 102 (2020) Murase et al. ApJ 902 (2020)

Stellar collapse as neutrino sources?

Gamma-ray Bursts

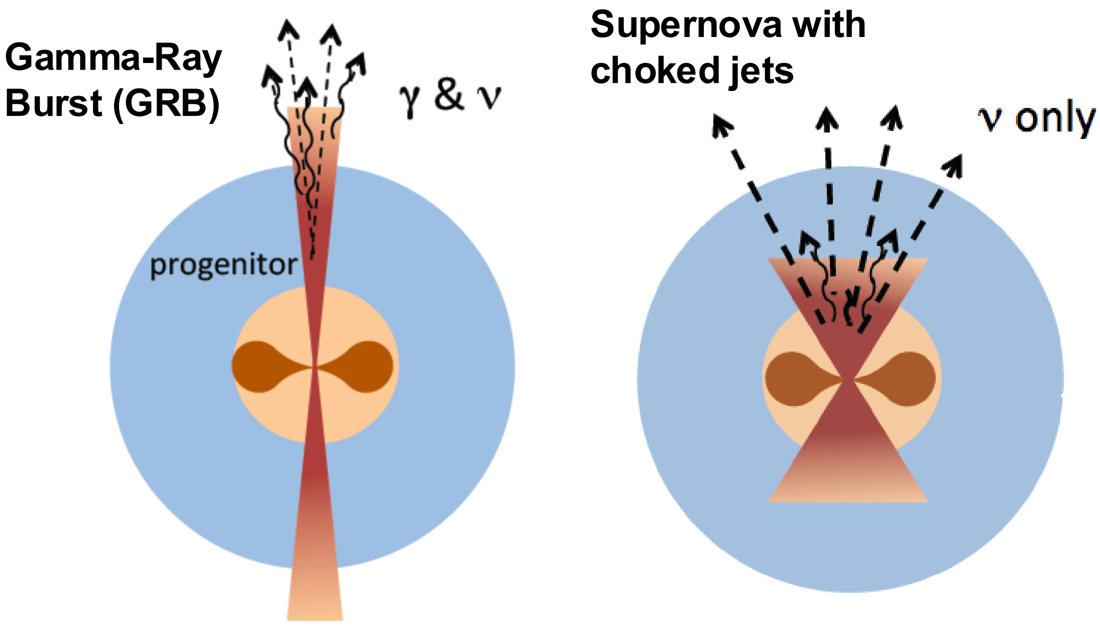


Gamma-ray Bursts: Neutrino Searches

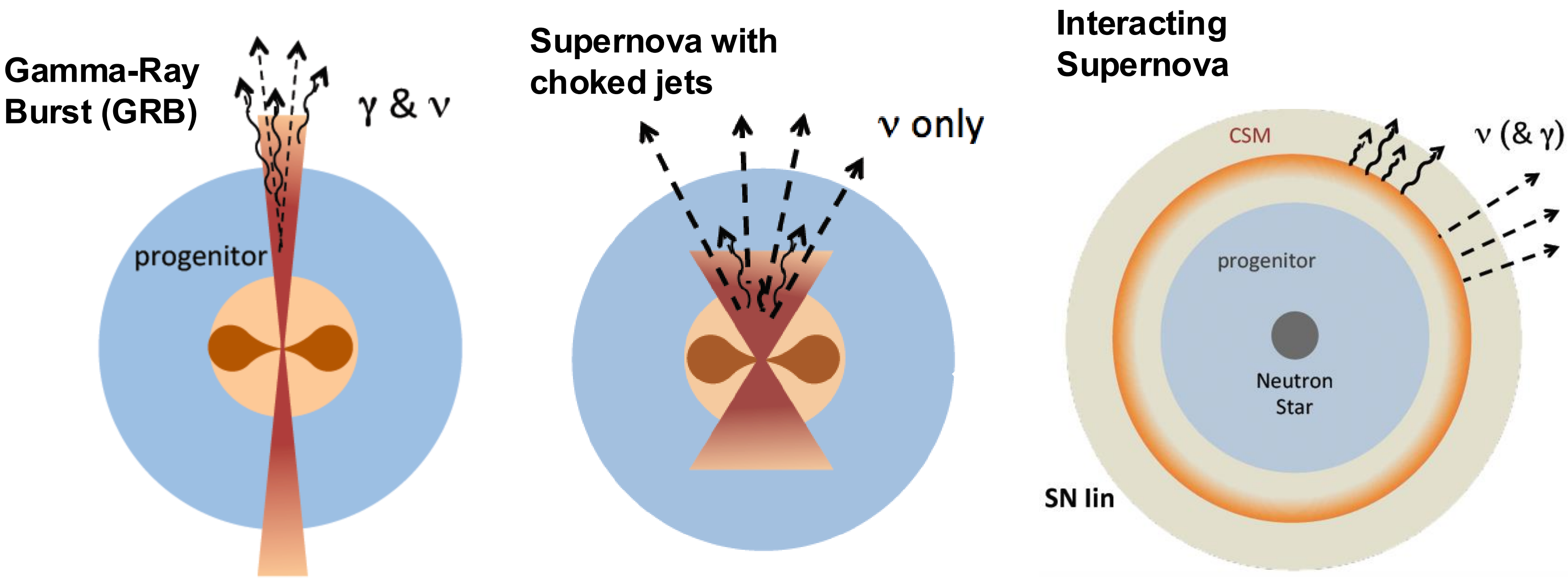


No excess found → Prompt neutrinos contribute <1% to diffuse neutrino flux

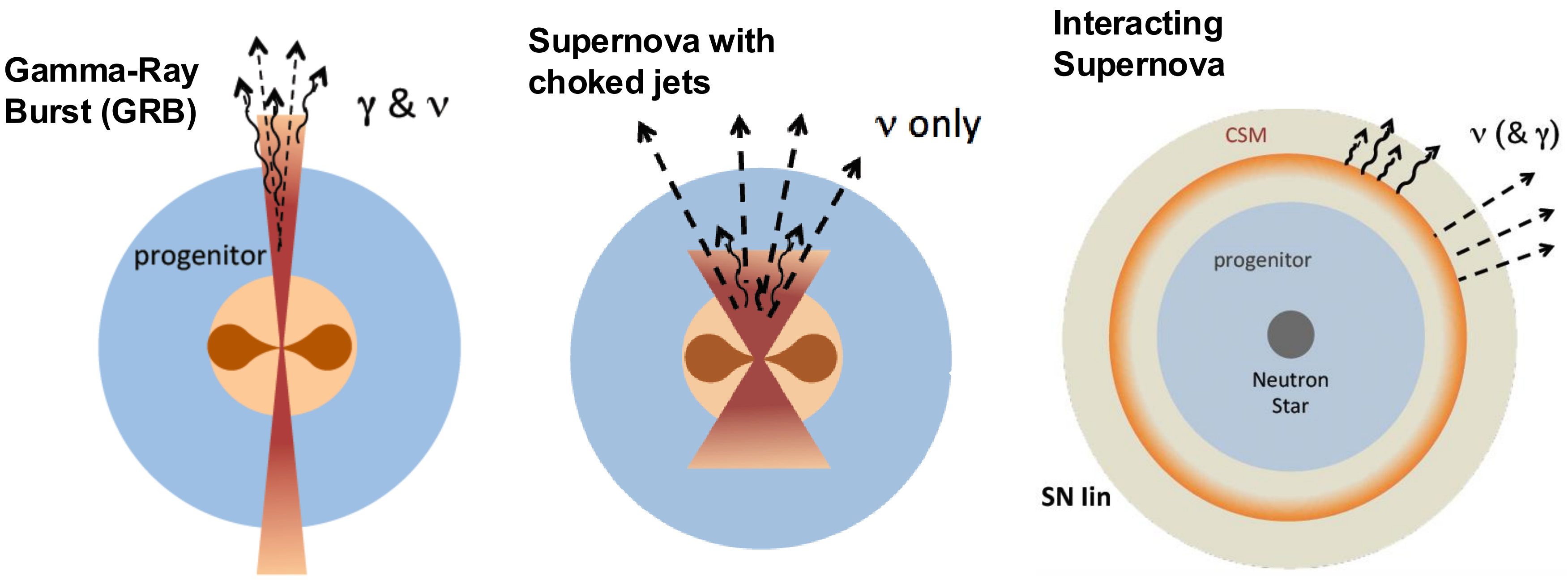
Alternatives to GRBs



Alternatives to GRBs



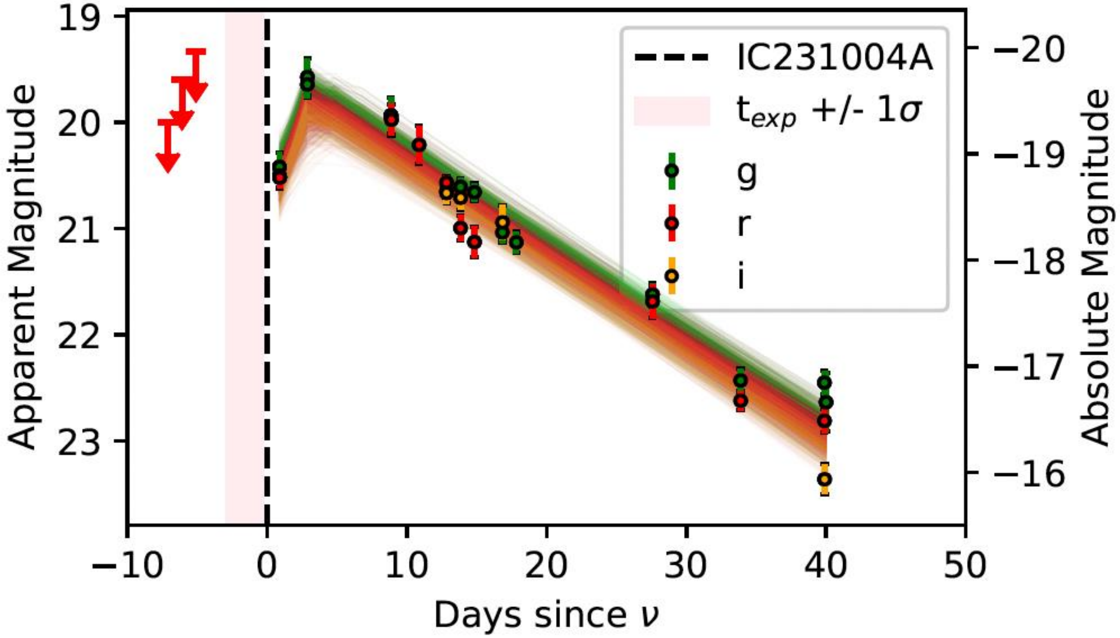
Alternatives to GRBs



"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. submitted

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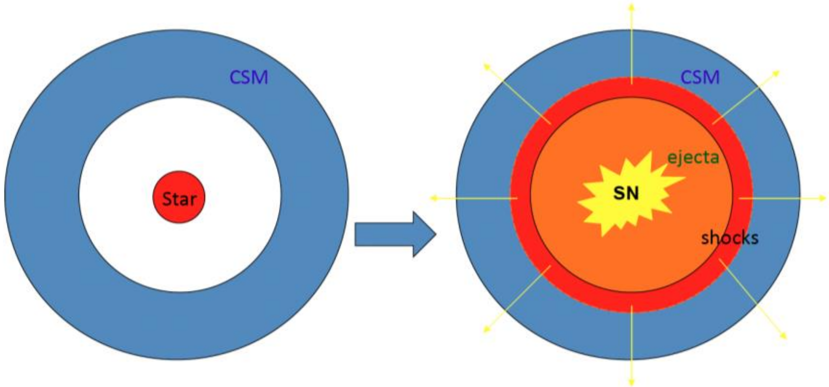
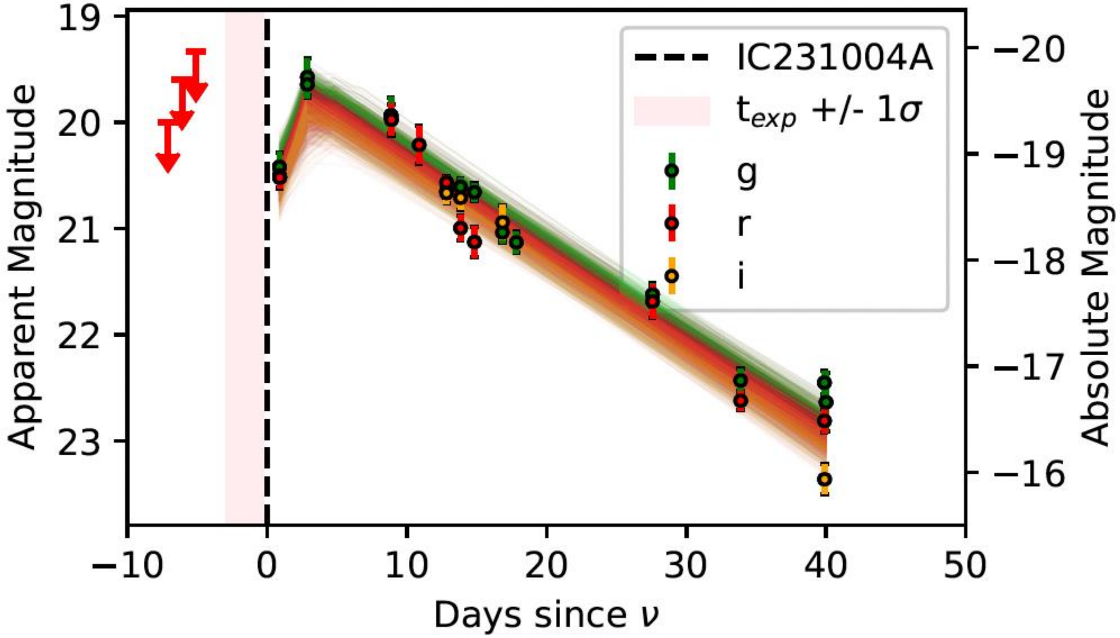


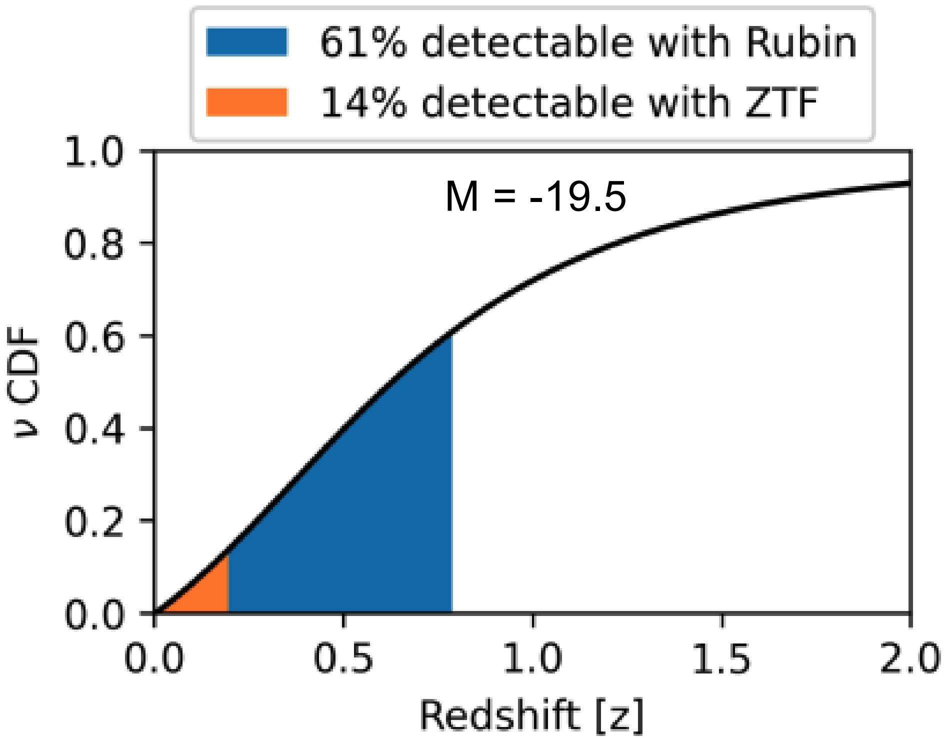
Murase MNRAS 440 (2013)



Evidence for hadronic acceleration in core-collapse supernova explosions

Stein et al. submitted

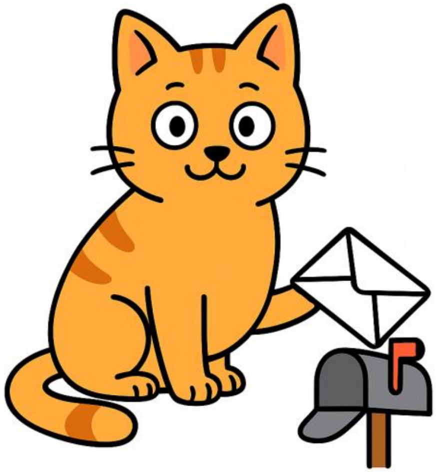
Improved follow-up



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

RUB

https://arxiv.org/pdf/2411.04793



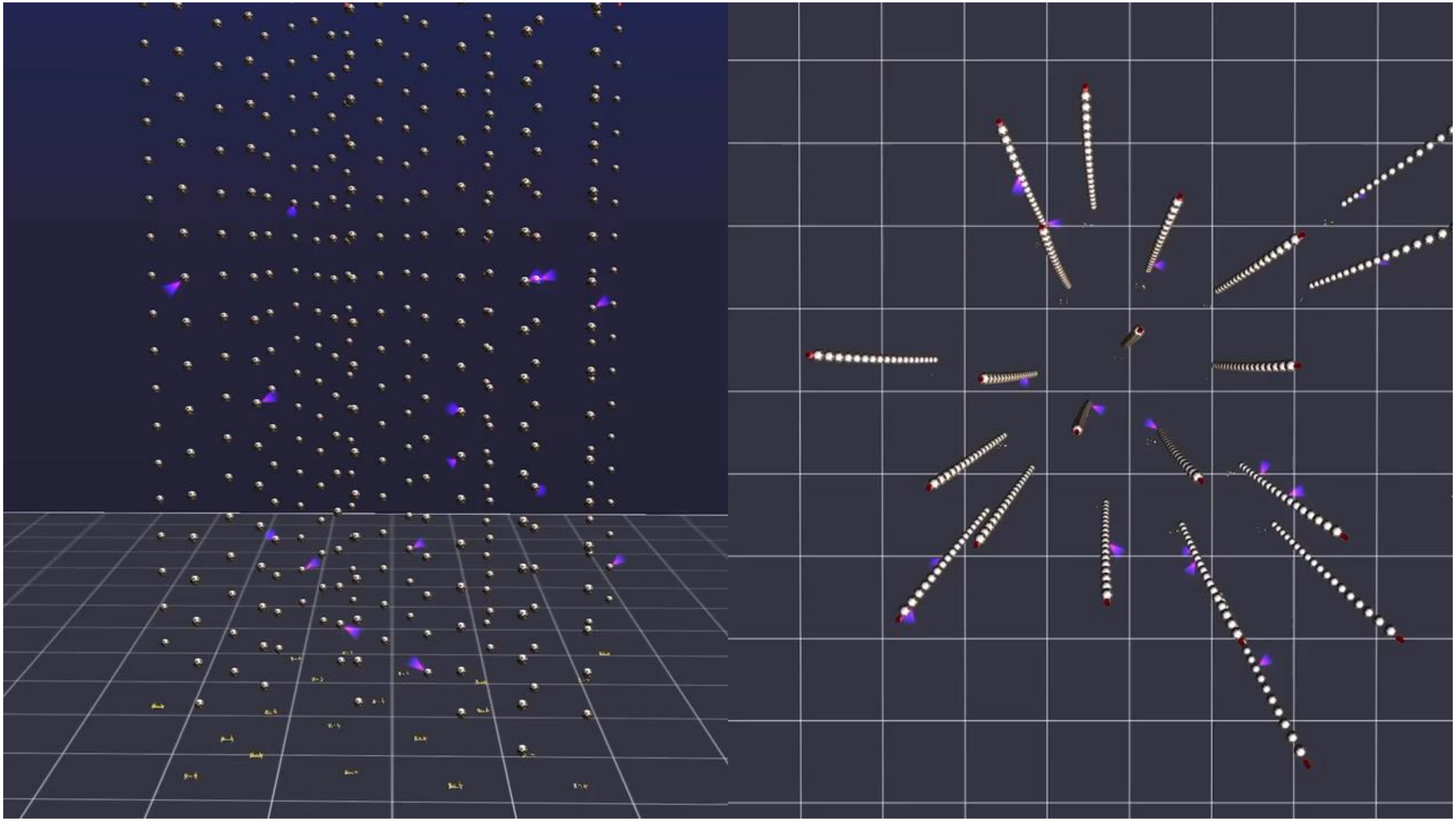
Take home message

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

RUB

The highest energy neutrino event ever detected

220 PeV Event from KM3NeT

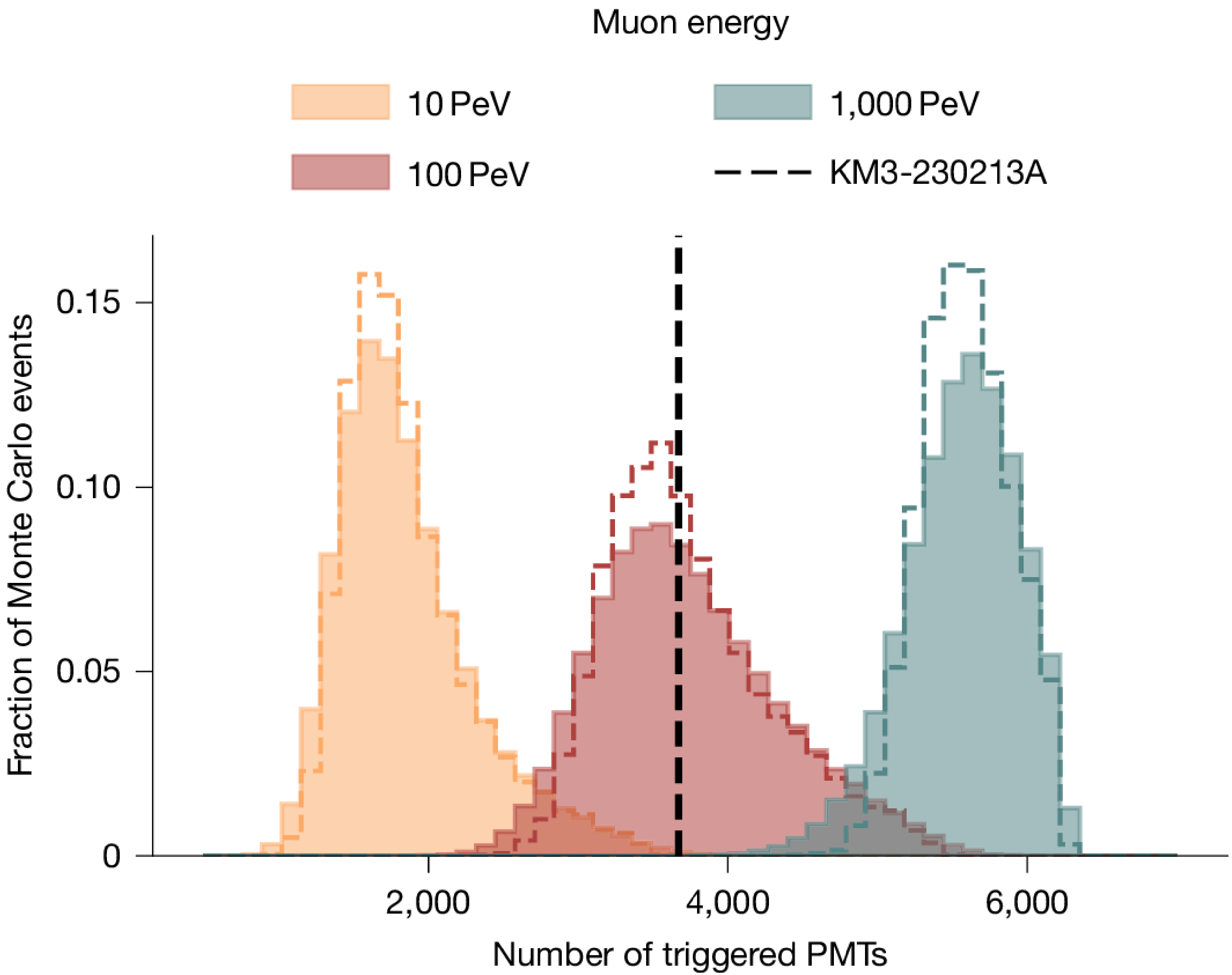


KM3NeT Nature 638 (2025)

220 PeV Event from KM3NeT

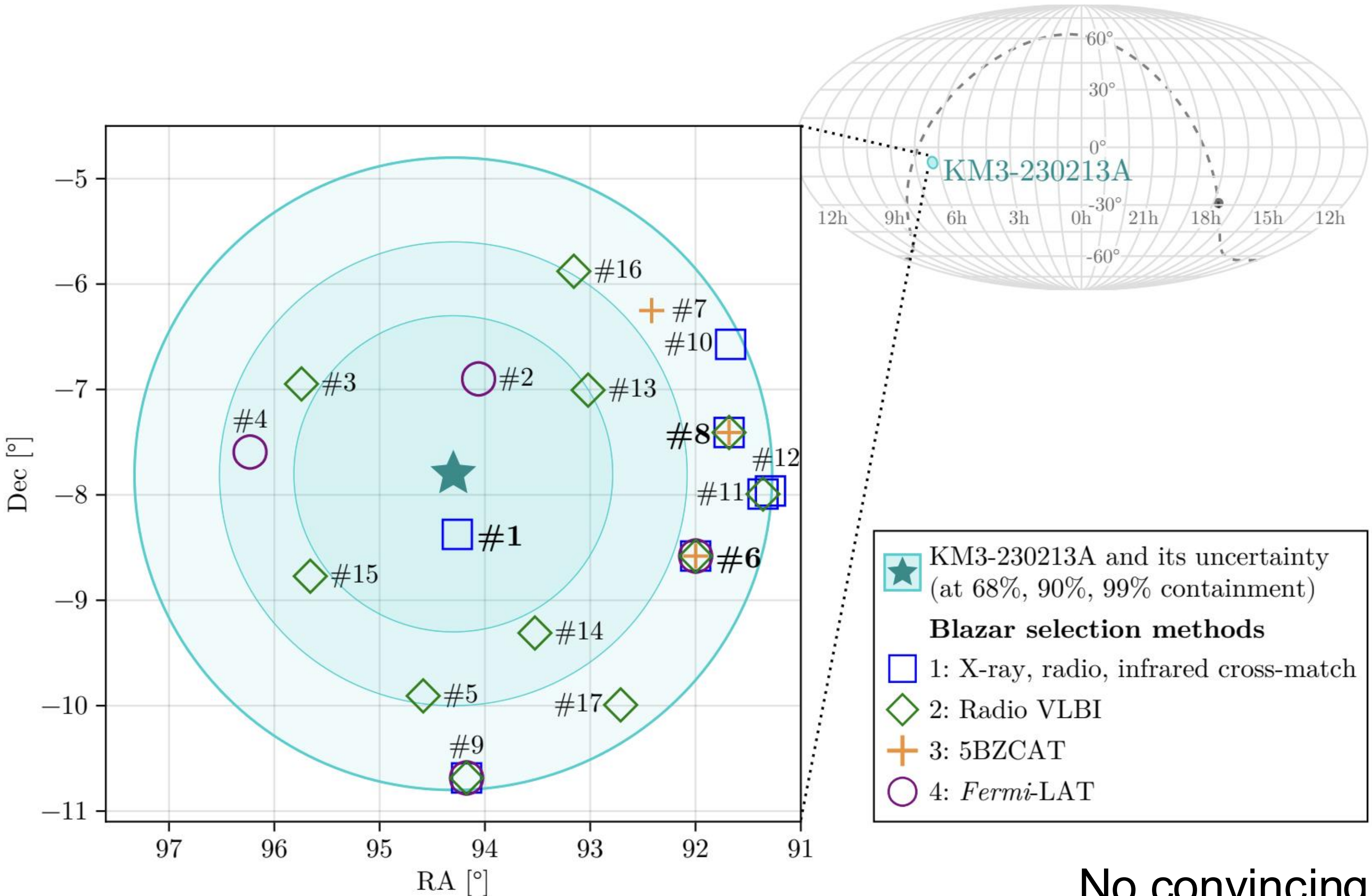
- Huge amount of light seen in the ARCA detector
- Horizontal event (1deg above horizon) as expected since Earth opaque to neutrinos as PeV scale
- 3672 PMTs (35%) were triggered
- Muon simulation indicate that 100 PeV muons are needed to reproduce this signature

KM3NeT Nature 638 (2025)



KM3NeT Nature 638 (2025)

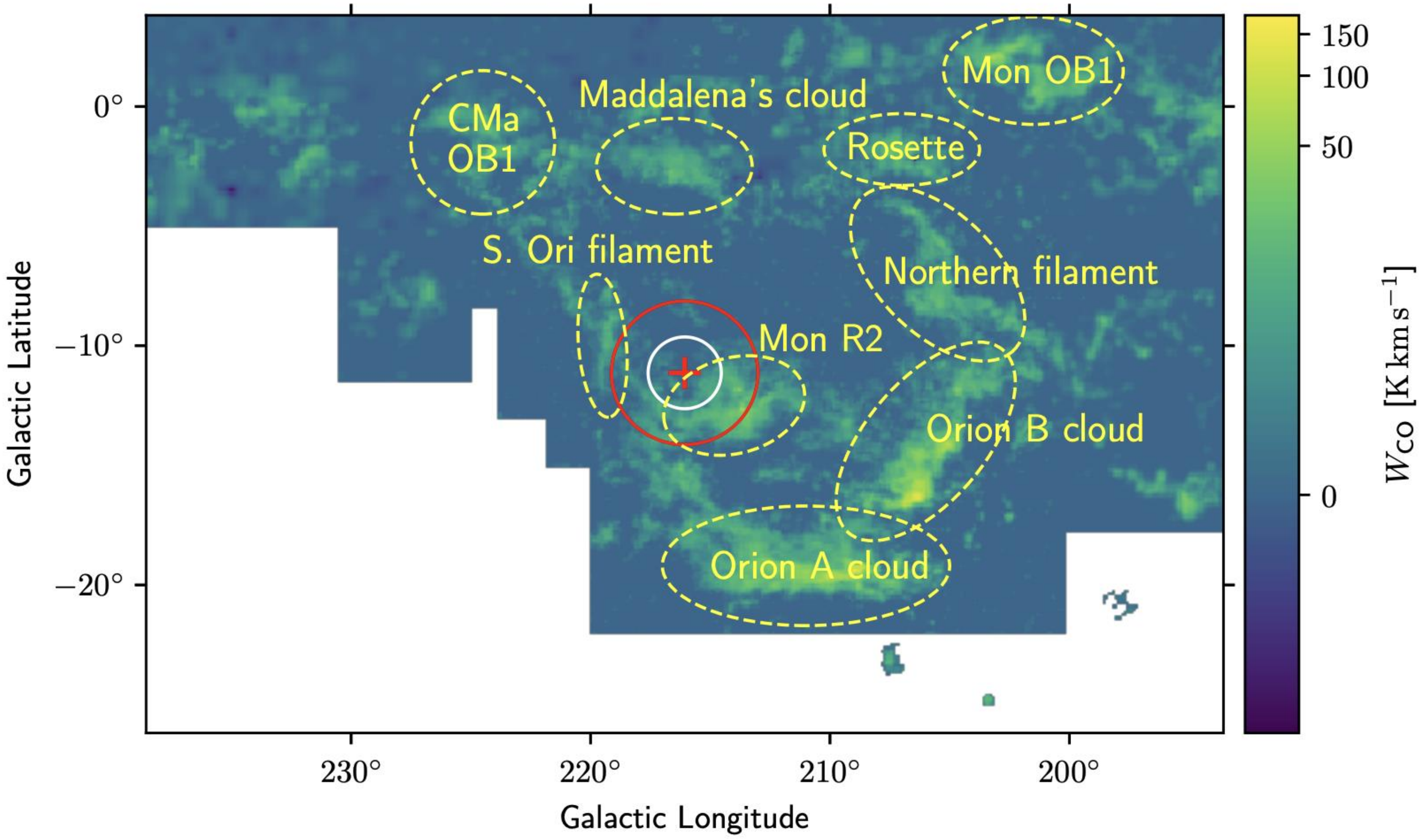
Potential sources?



No convincing blazar counterpart found

KM3NeT et al. arXiv, 2502.08484

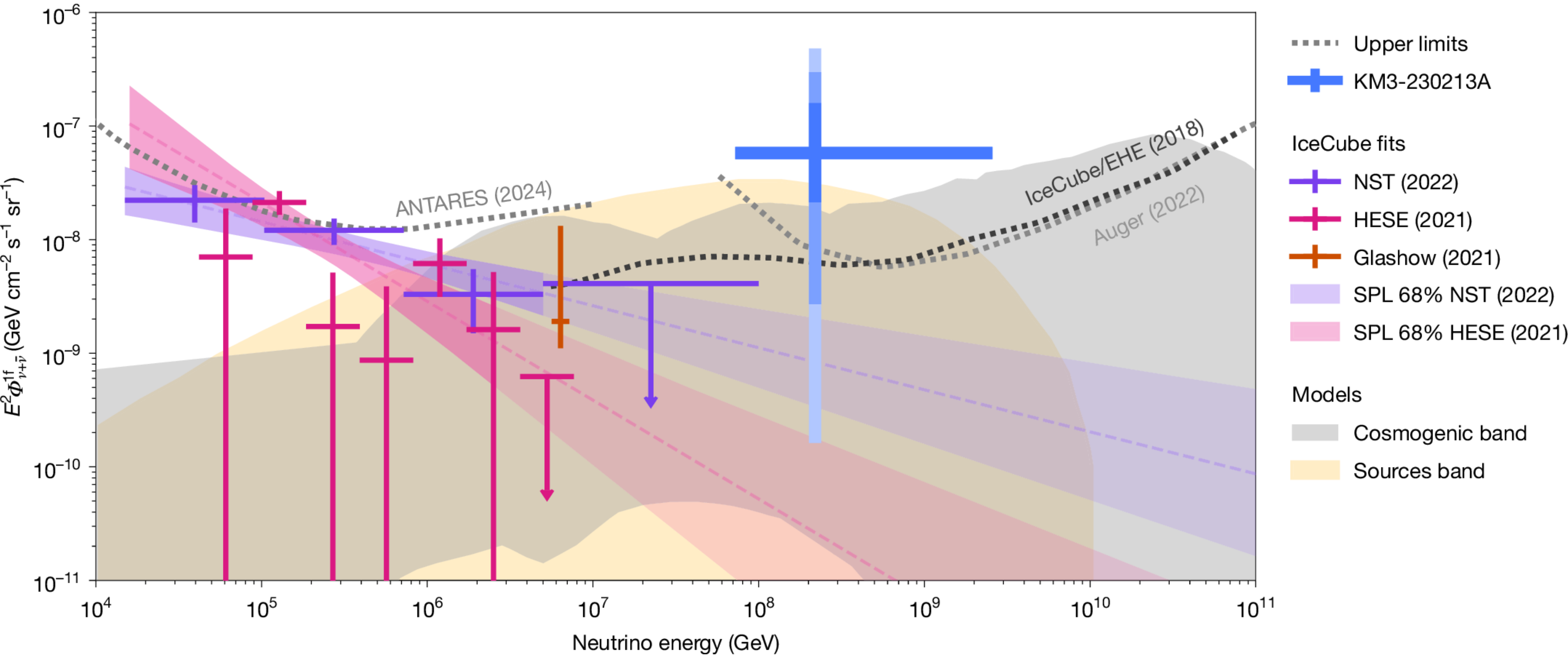
Potential sources?

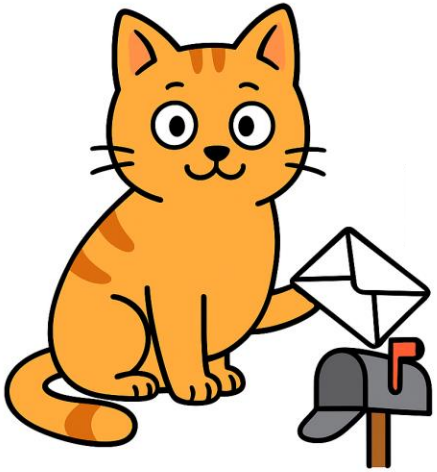


Galactic origin unlikely

KM3NeT, arXiv:2502.08387

Tension with IceCube and Auger upper limits?





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 ?

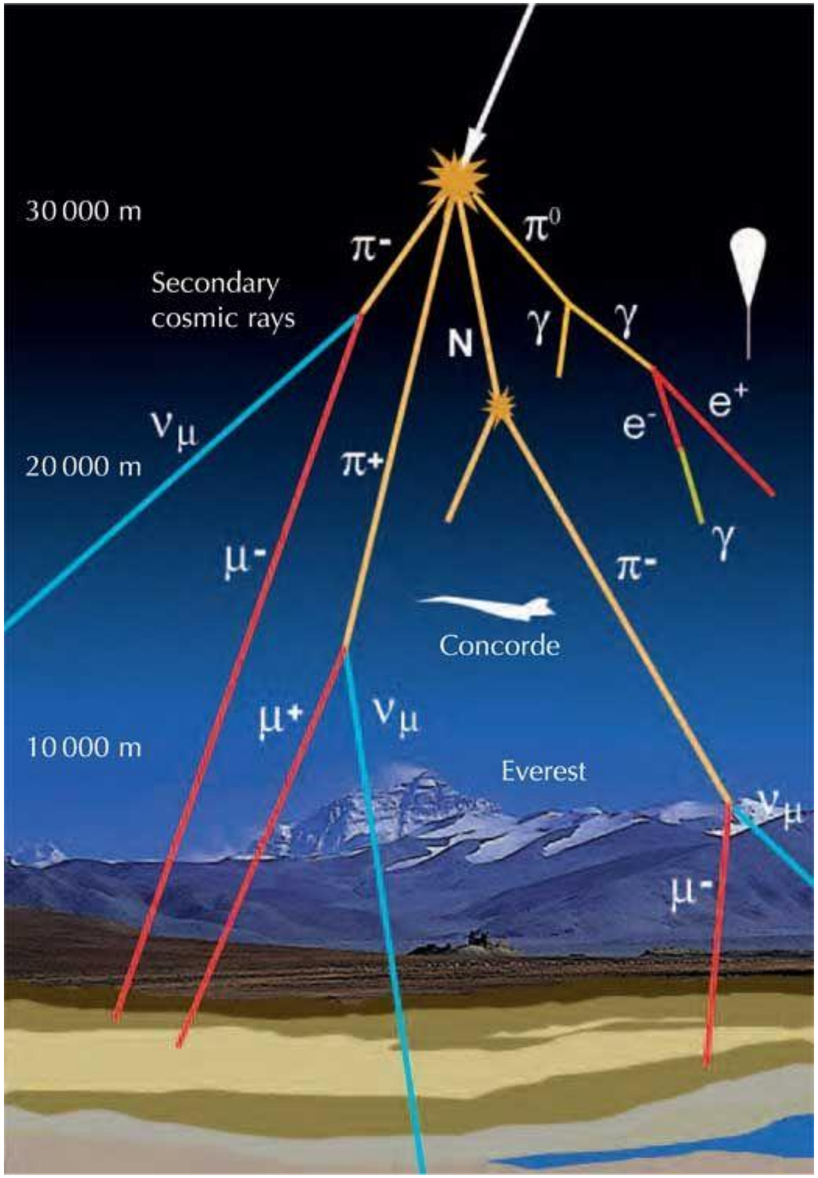
Astro Quiz

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

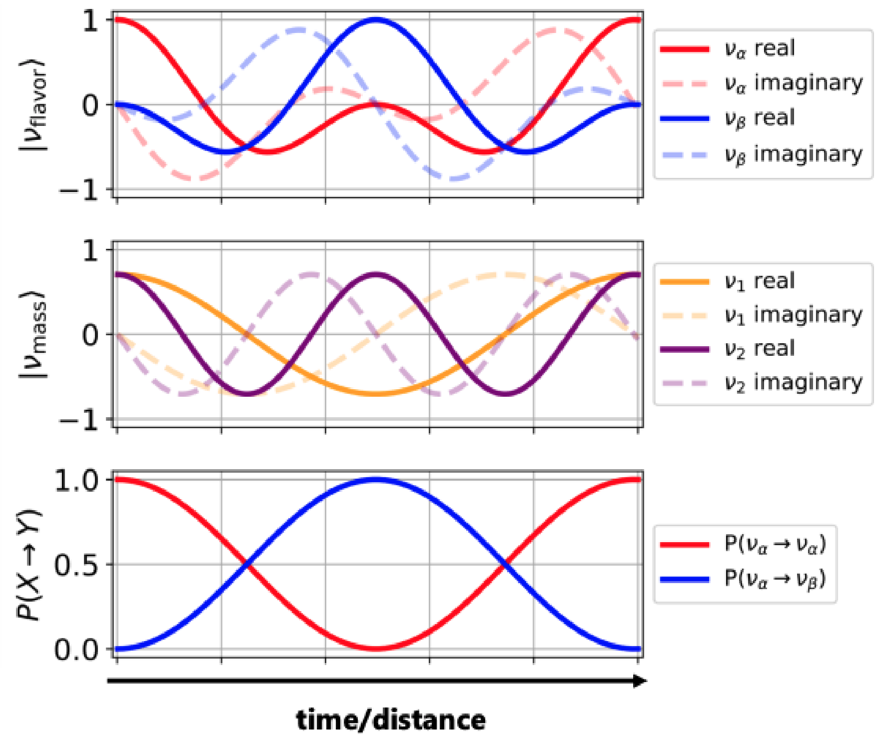
$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

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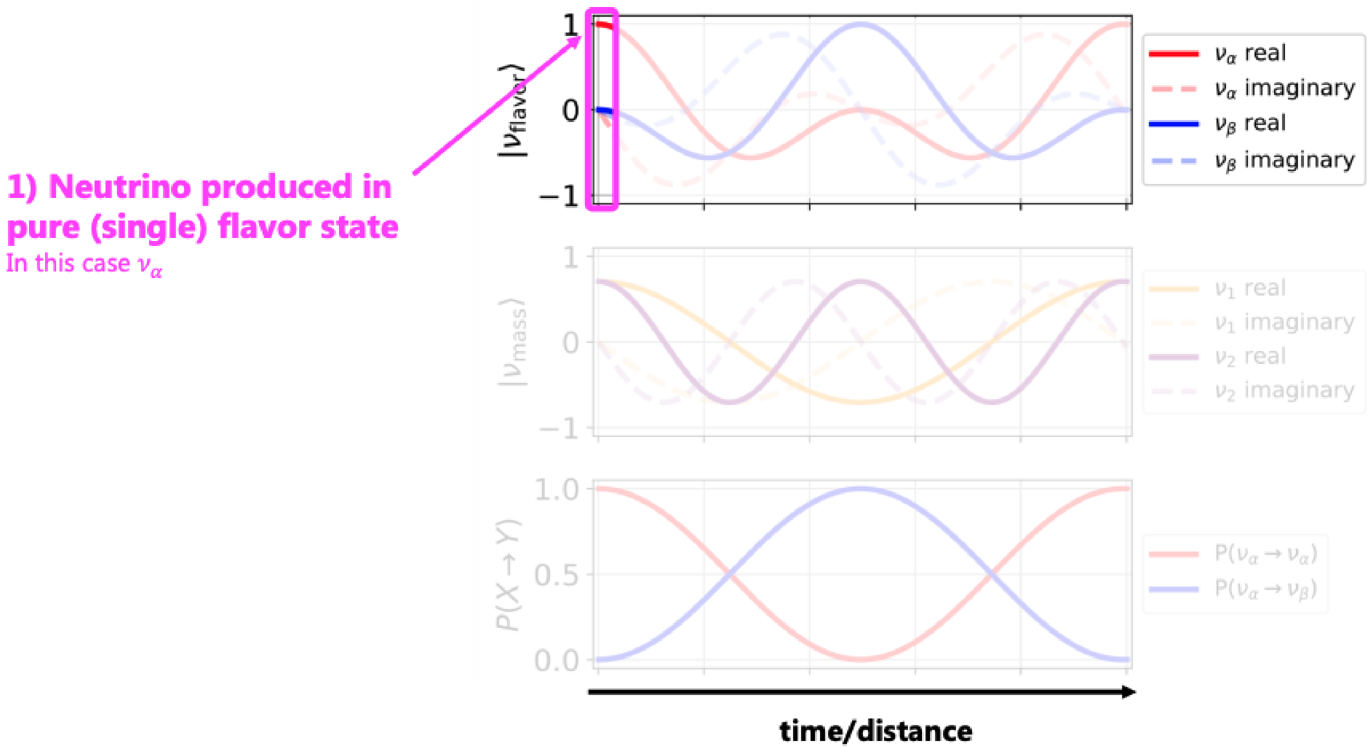

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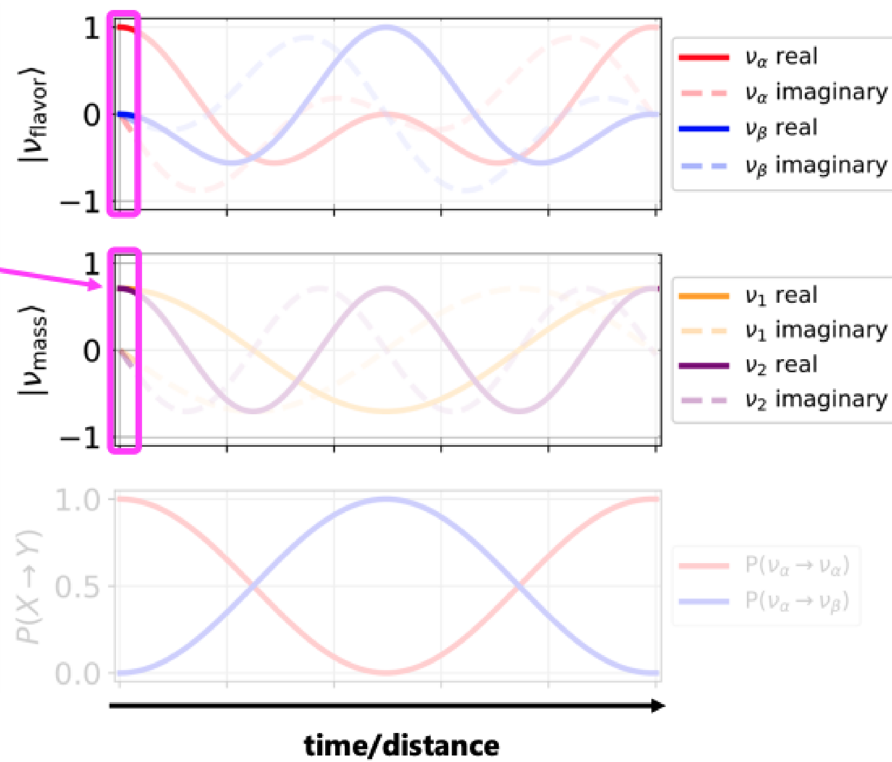
- 2 neutrino states (flavour = ν_α, ν_β, mass = ν_1, ν_2) → flavor states are 50:50 mix of mass states ($\theta = 45°$)
- $m_2 = \sqrt{2}\, m_1$

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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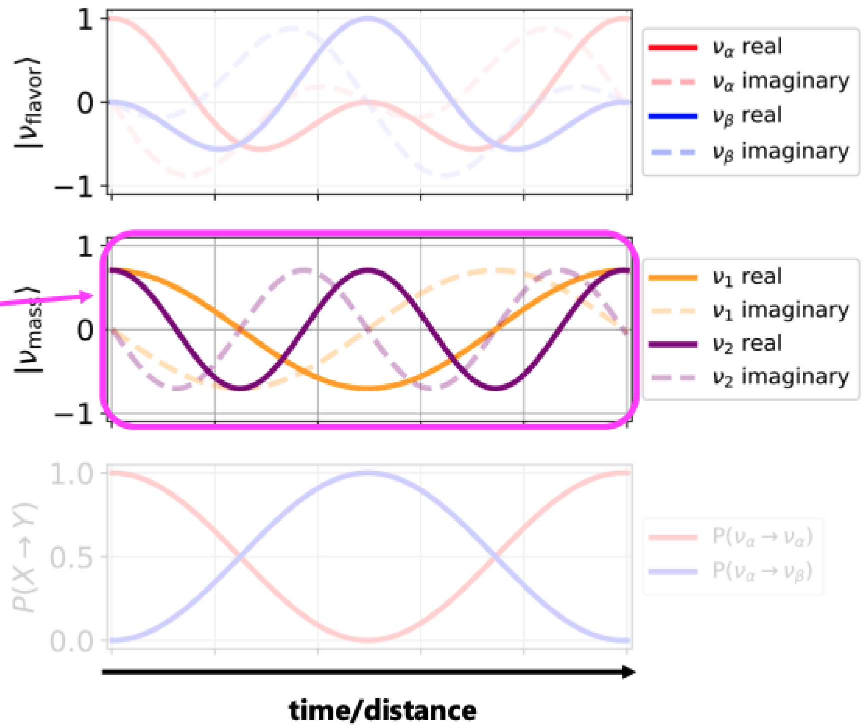
Visualise the superposition effects and resulting oscillations using simplified model…

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

3) The wavefunctions of the mass states evolve over time

The frequency of this evolution depends on the mass state 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

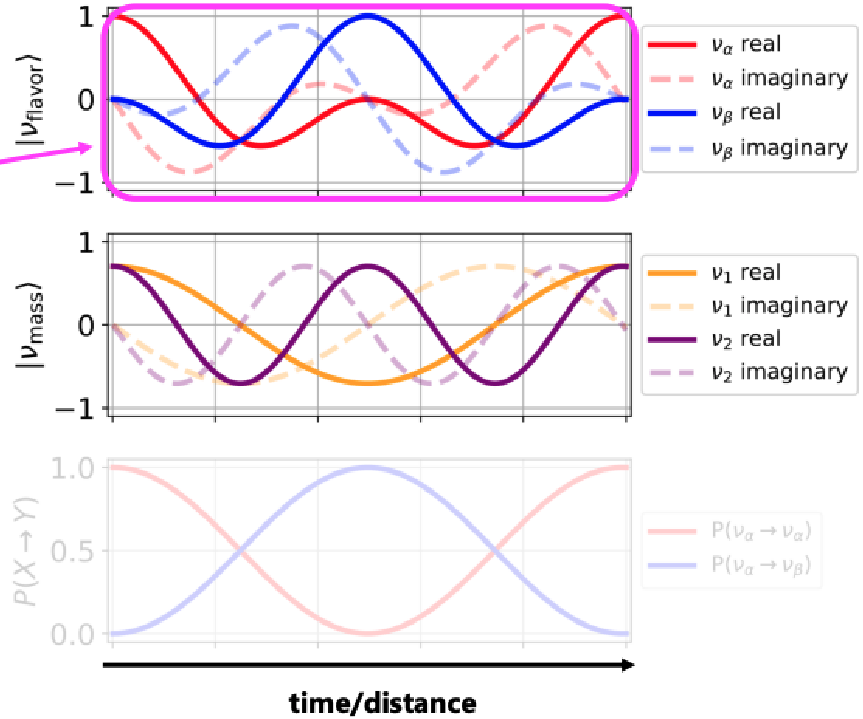
(Plane wave)

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 ($\theta = 45°$)
- $m_2 = \sqrt{2}\, m_1$

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



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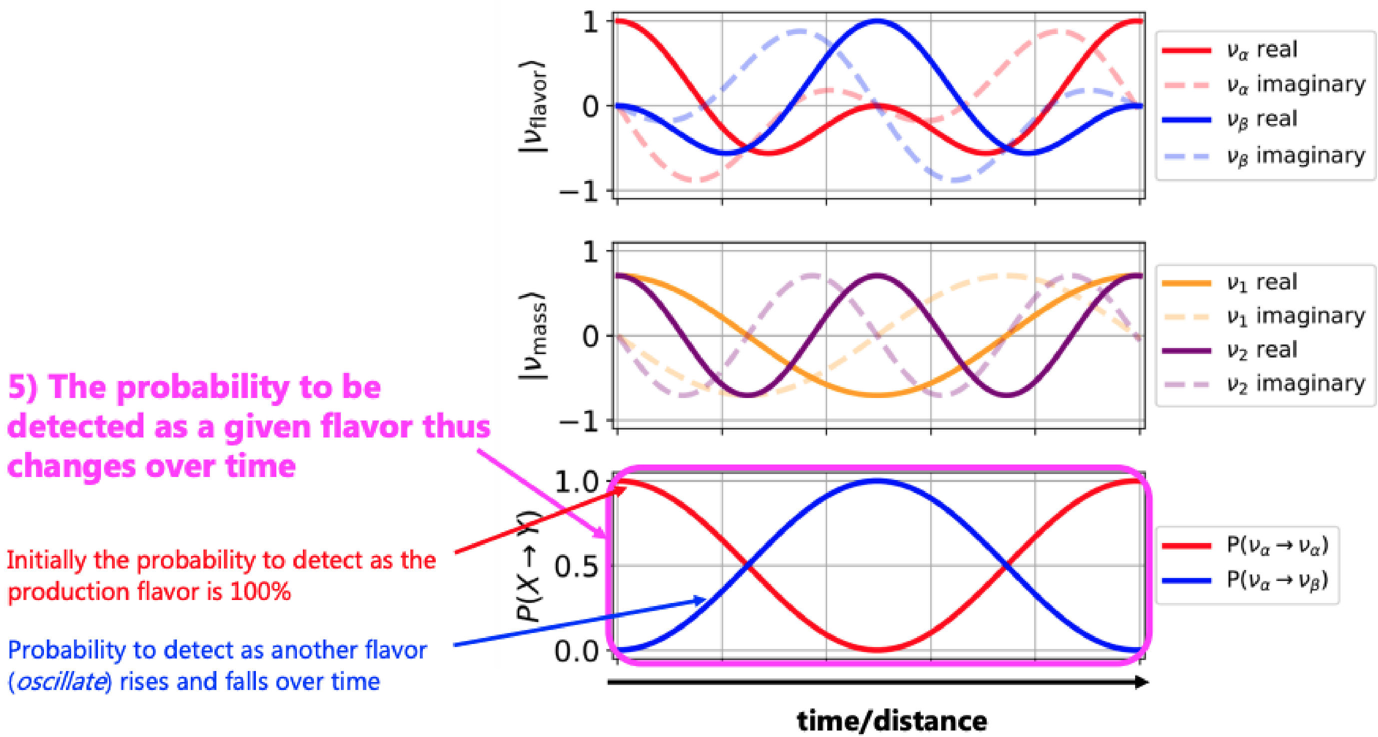


$$|\nu_j(L)\rangle = \exp\left\{-i\frac{m_j^2 L}{2E}\right\}|\nu_j(0)\rangle$$

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)

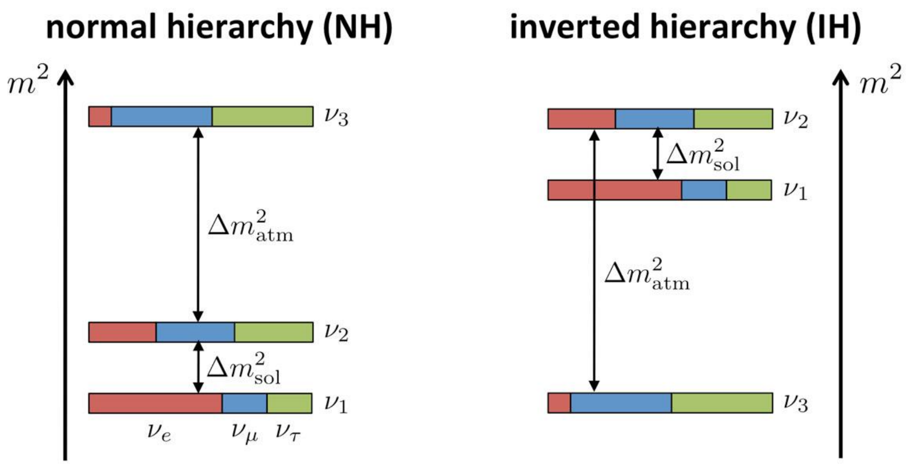
$$P_{\alpha\beta} = \sin^2(2\theta)\,\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

Mixing defines oscillation amplitude

Mass-difference defines frequency

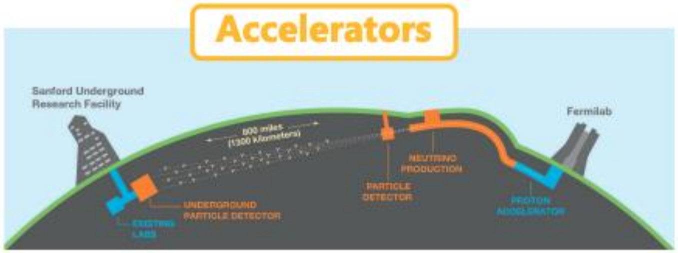
Frequency also depends on L/E ratio for a given neutrino

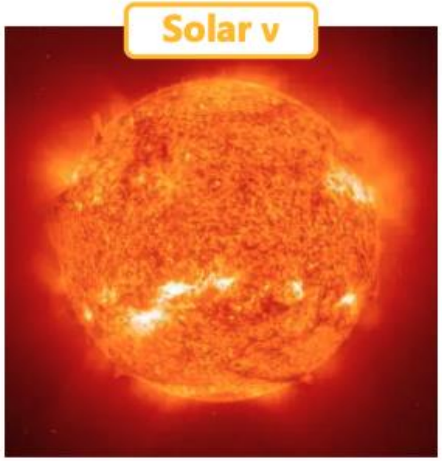
- Insensitive to the sign of Δm^2 → neutrino mass ordering problem

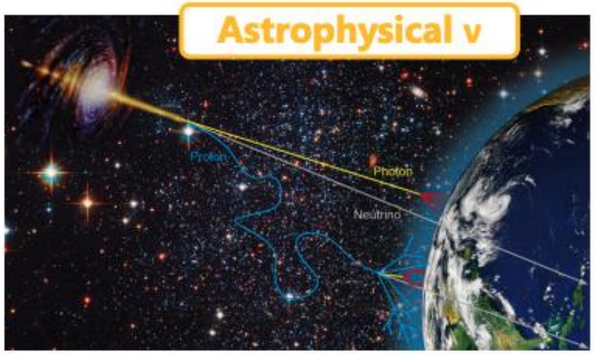


Modified oscillation effects for neutrinos passing through matter

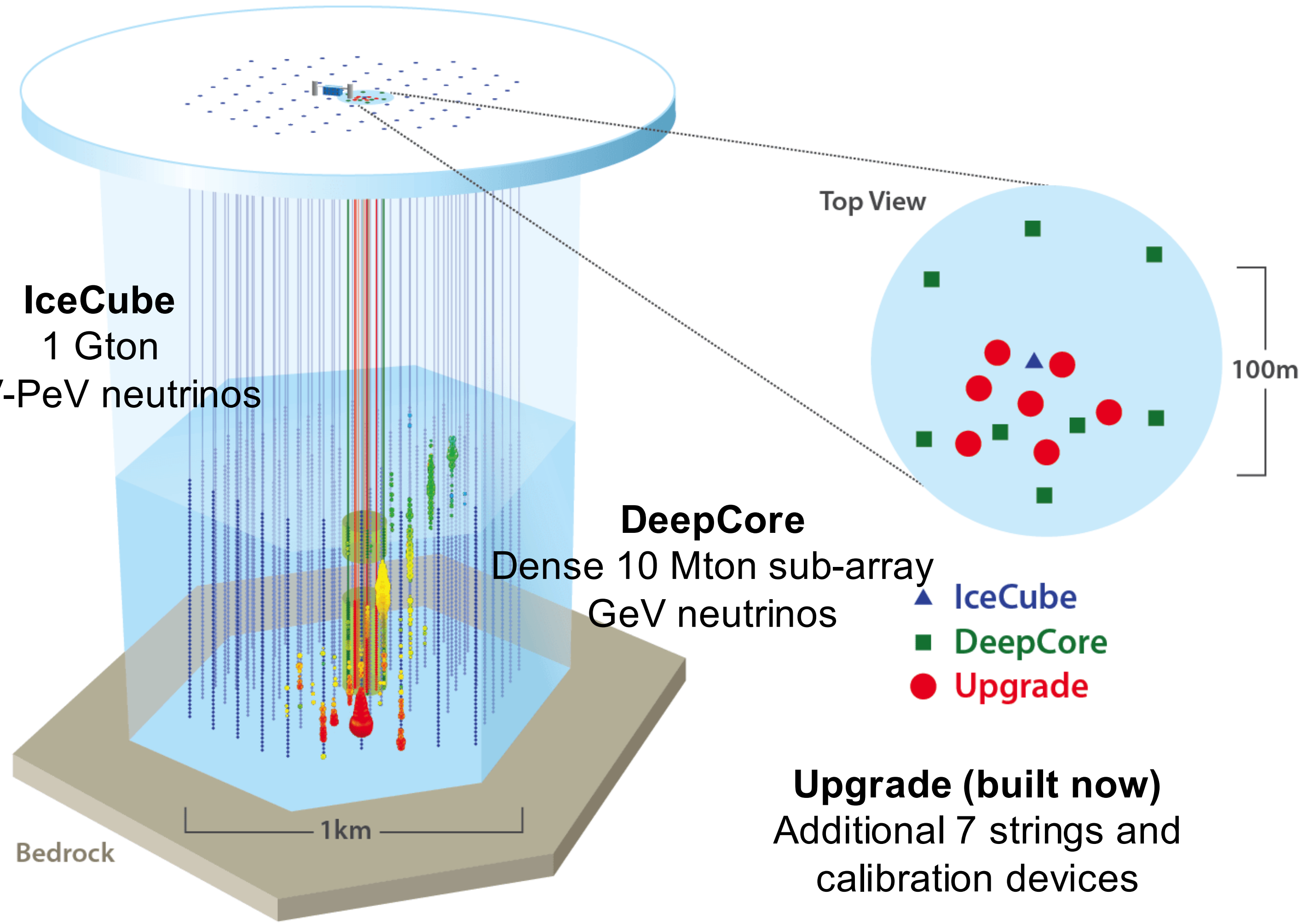
Experiments







IceCube DeepCore



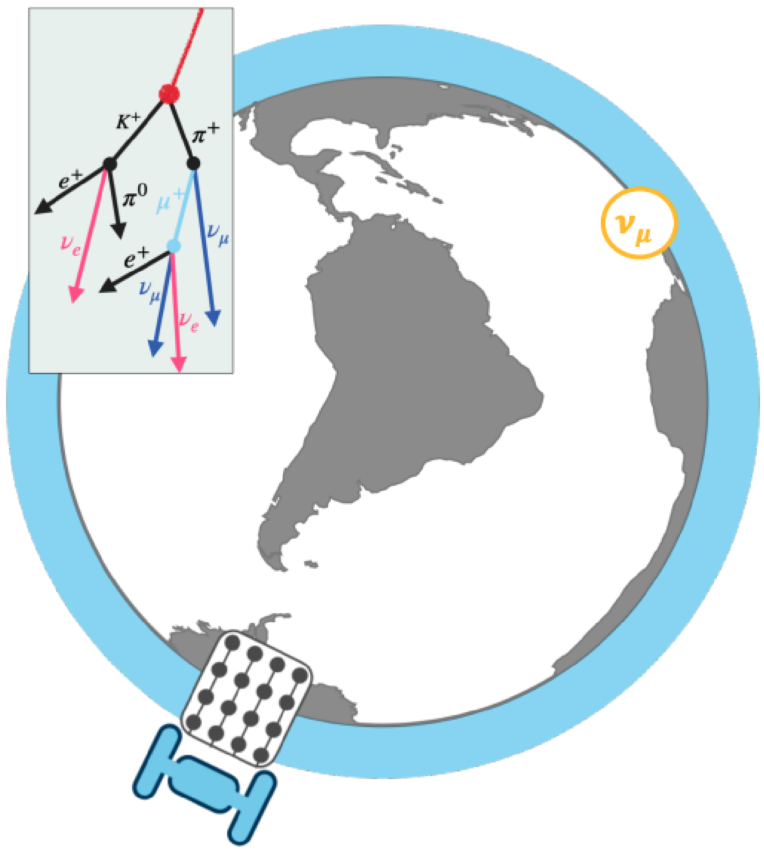
IceCube
1 Gton
TeV-PeV neutrinos

DeepCore
Dense 10 Mton sub-array
GeV neutrinos

Upgrade (built now)
Additional 7 strings and
calibration devices

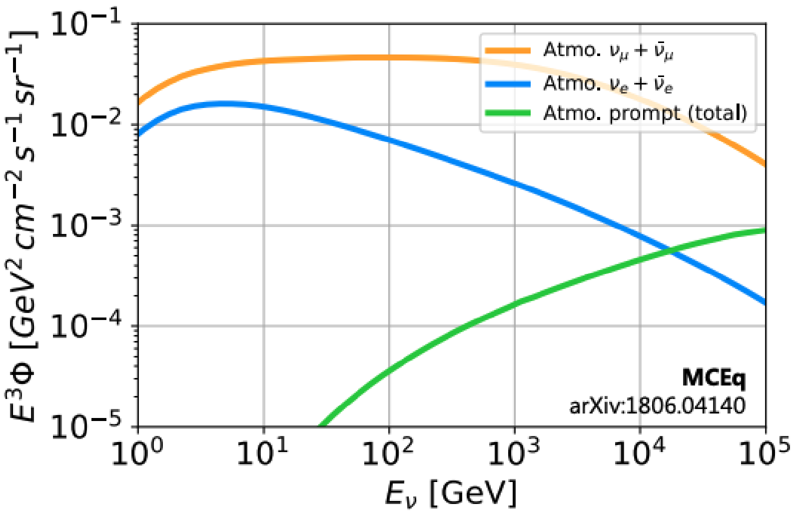
https://icecube-gen2.wisc.edu/science/publications/tdr/

Atmospheric Neutrinos: Background to one, signal to another

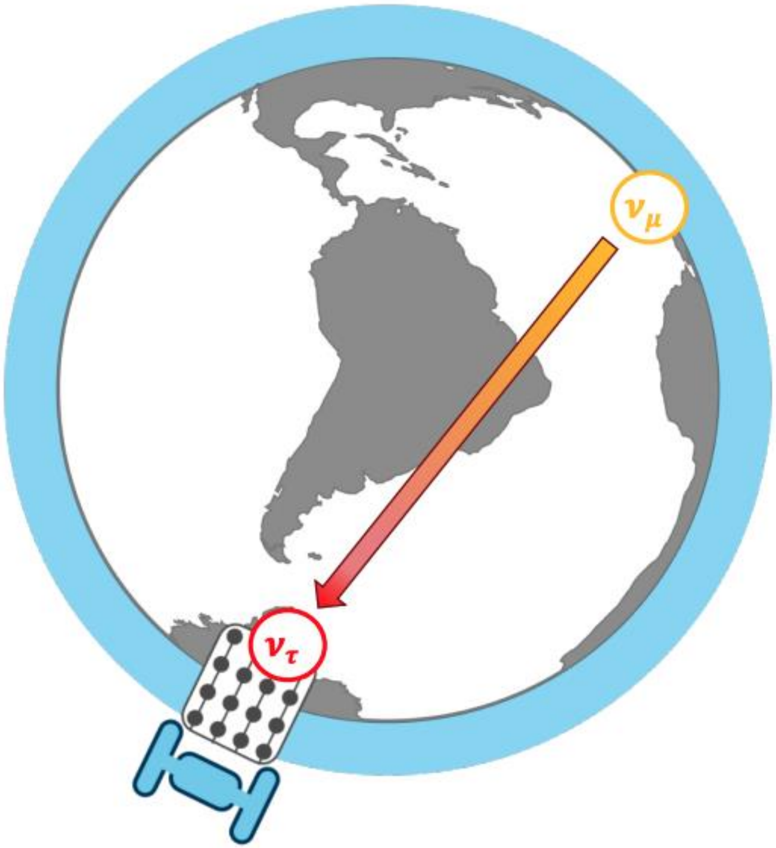


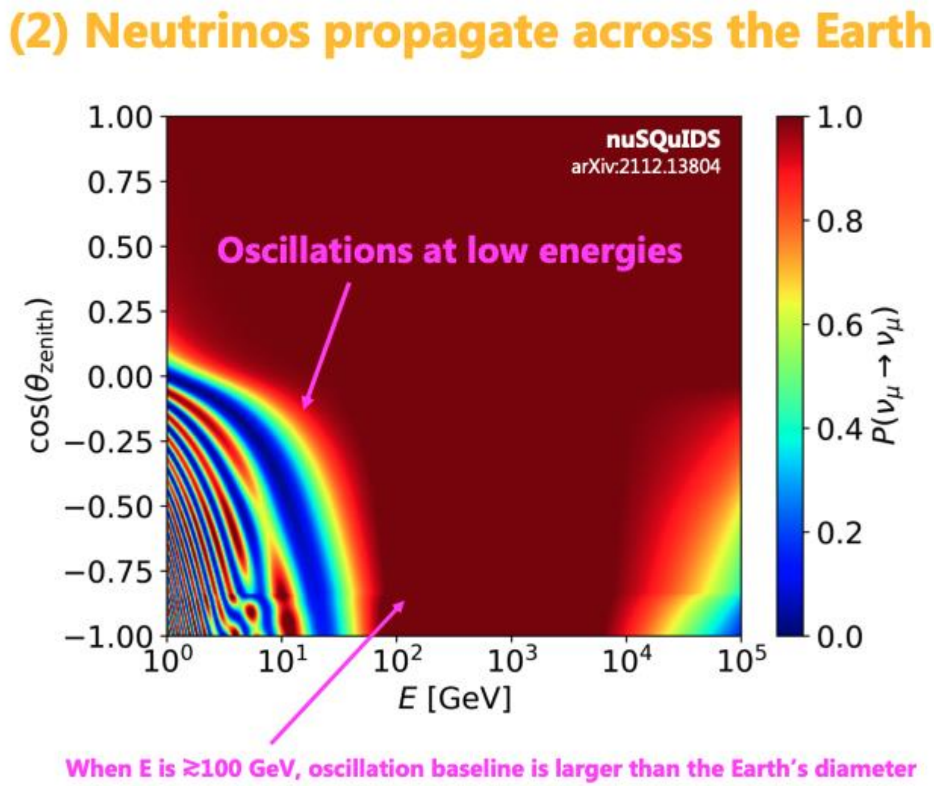
(1) Cosmic rays interact in the atmosphere and produce air showers

→ Large flux of high energy neutrinos

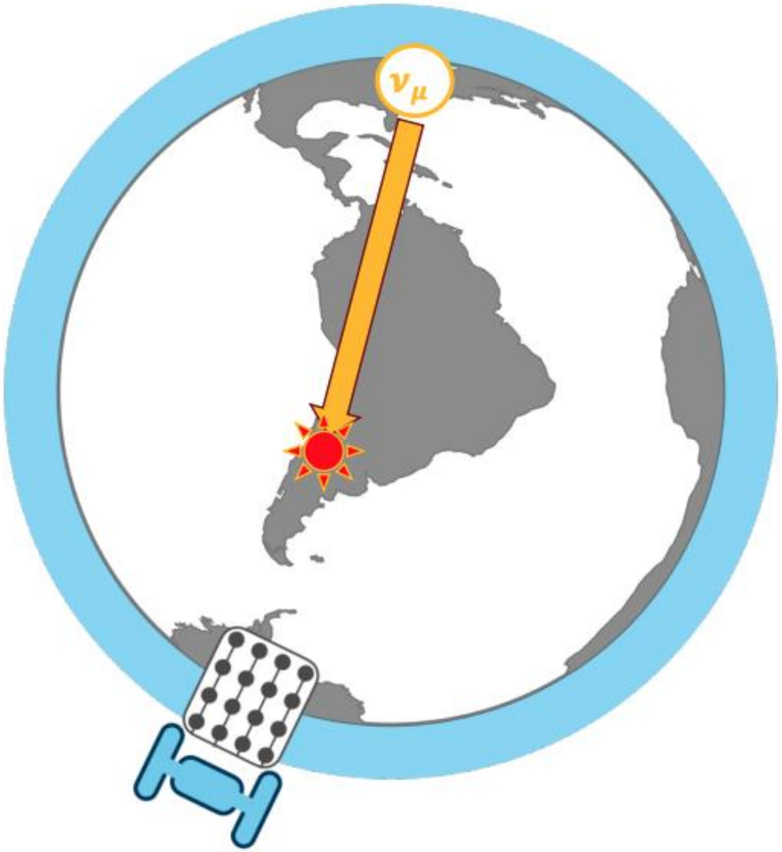


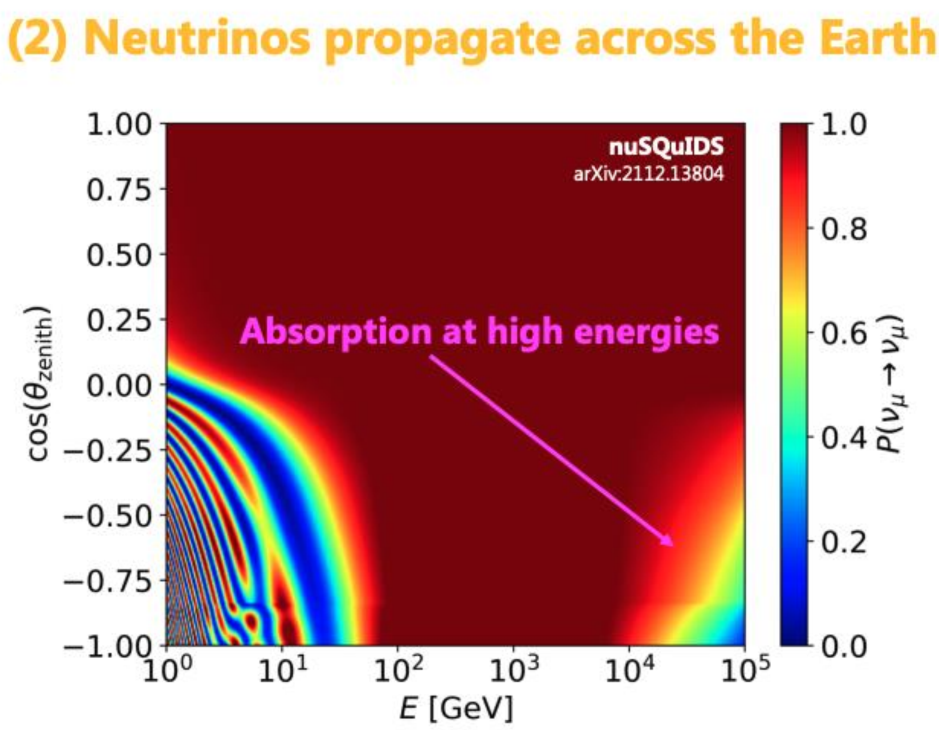
Atmospheric Neutrinos - Oscillations



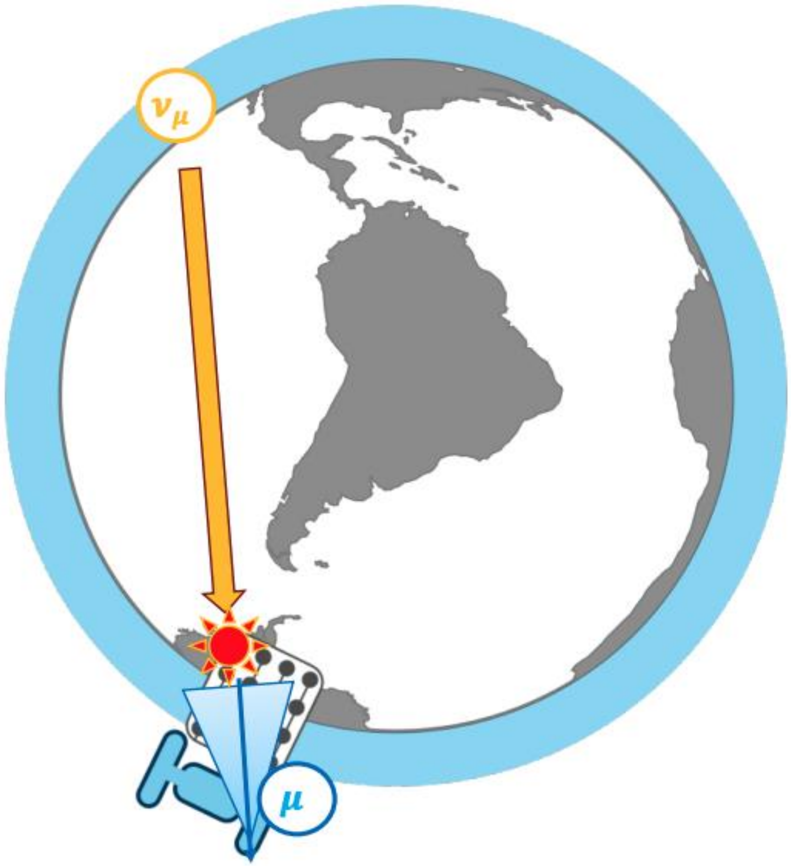


Atmospheric Neutrinos - Oscillations





Atmospheric Neutrinos - Oscillations

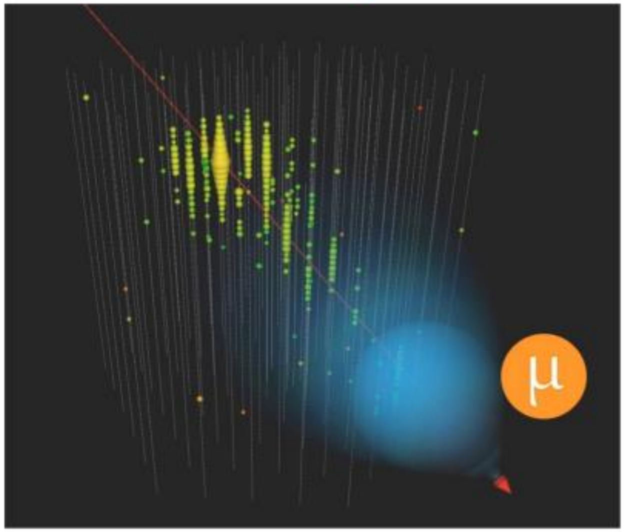


(3) Detection via Cherenkov emission from products of $\nu - N$ interactions

Predominantly Deep Inelastic Scattering (DIS)

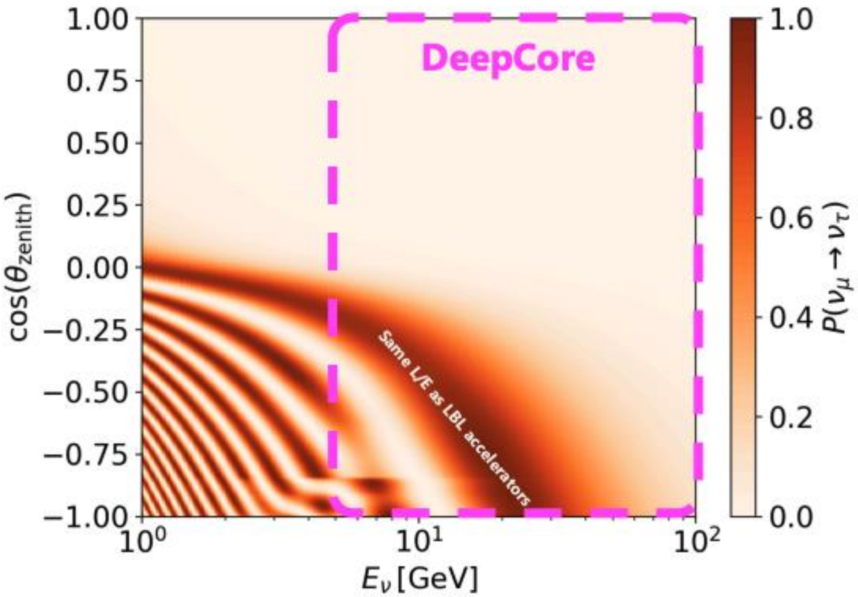
"Tracks" from secondary μ

"Cascades" from secondary e, τ and hadrons



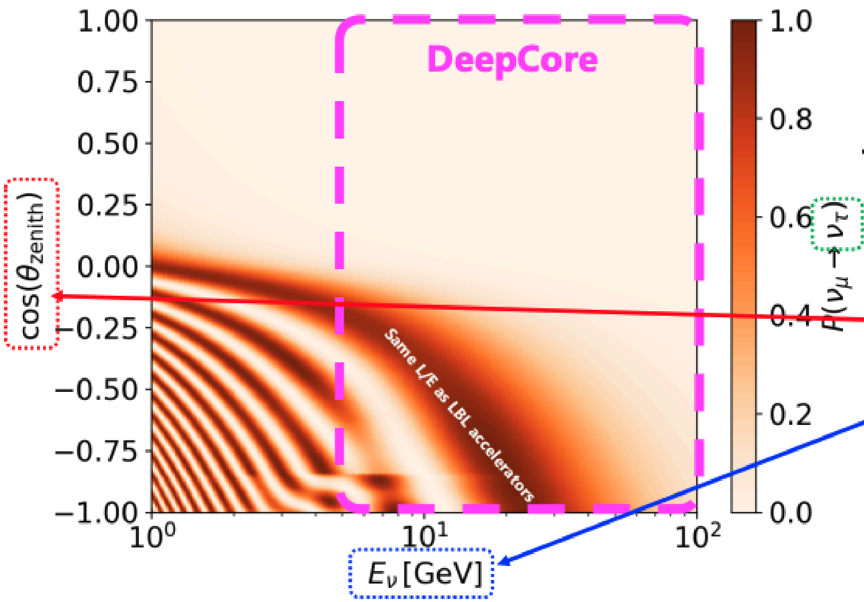
Measuring Neutrino Oscillations

- 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^2_{32}



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

Measuring Neutrino Oscillations



To measure these effects, for each neutrino must reconstruct:

Flavor – also known as Particle ID (PID)

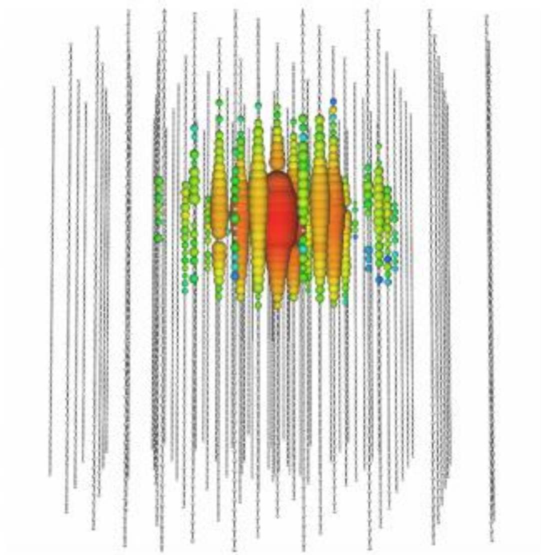
Baseline - determined from arrival (zenith) angle

Energy

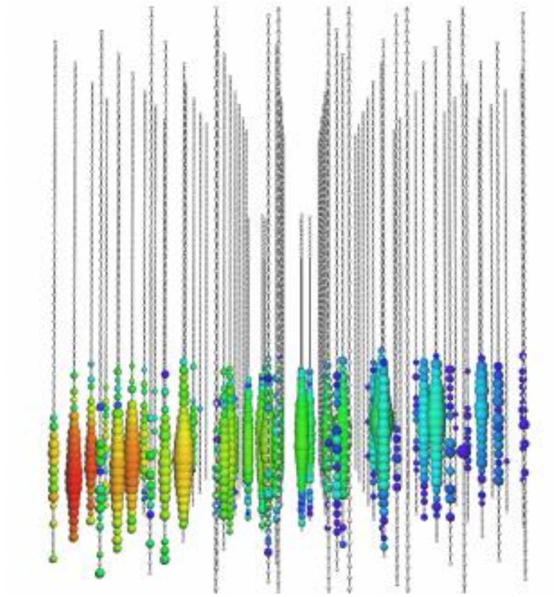
$$P_{\alpha\beta} = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

Measuring Neutrino Oscillations

- Two event topologies at high energies



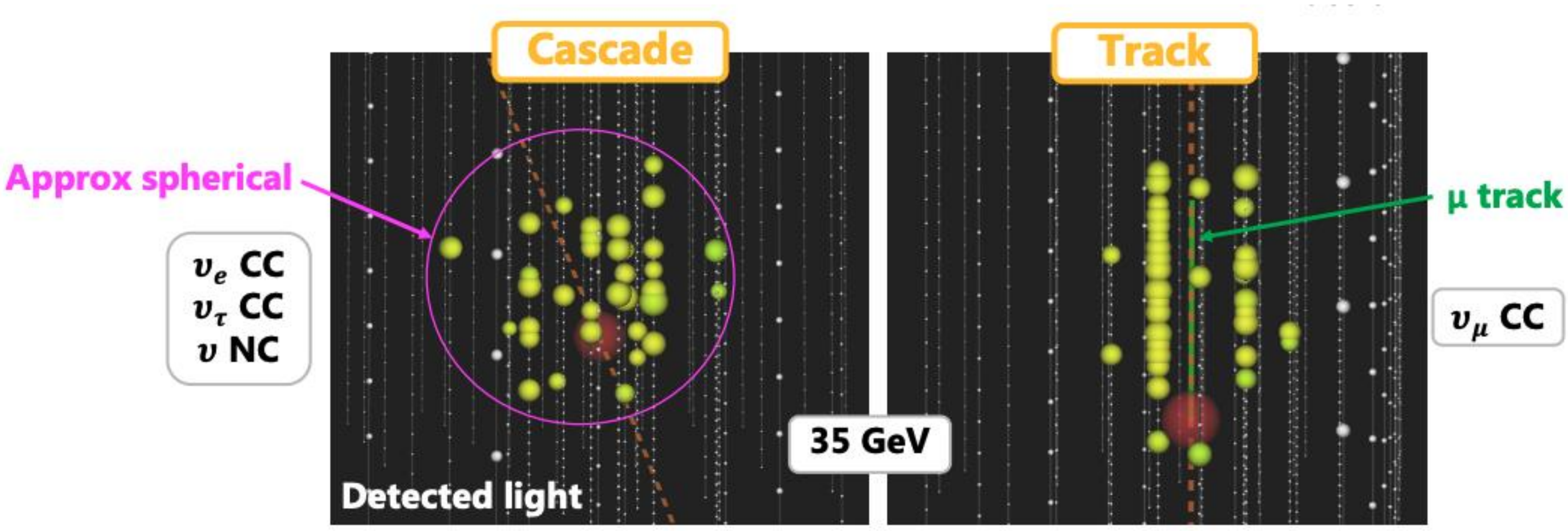
Cascade
E ~ 1 PeV



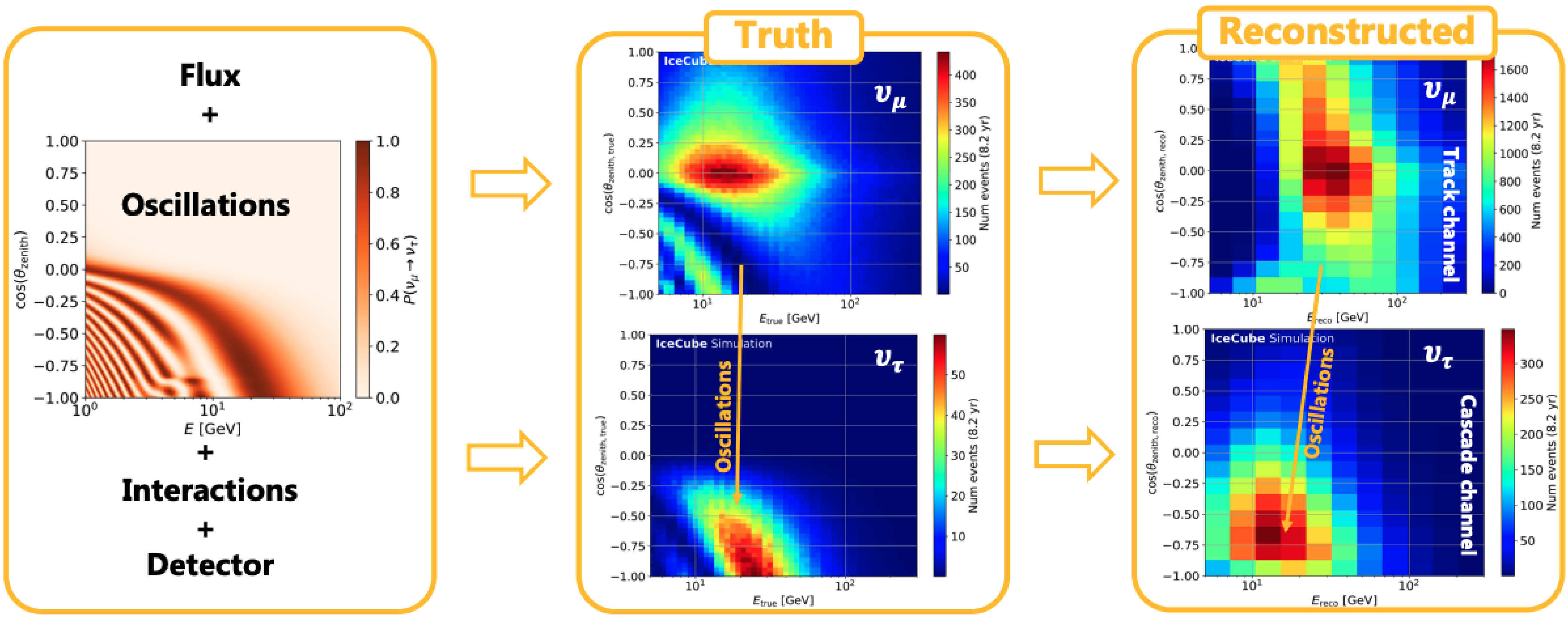
Muon track
E ~ 140 TeV

Measuring Neutrino Oscillations

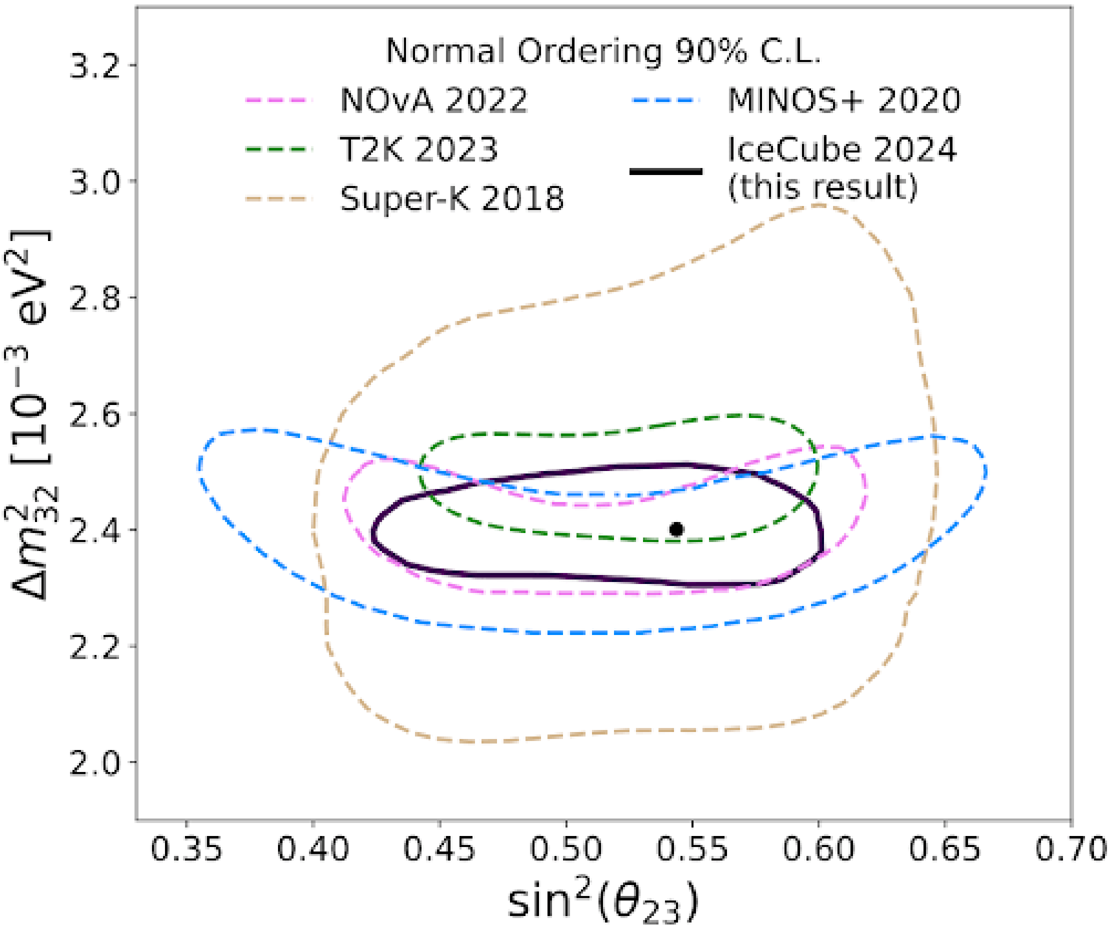
- Two event topologies at oscillation energies:



Measuring Neutrino Oscillations



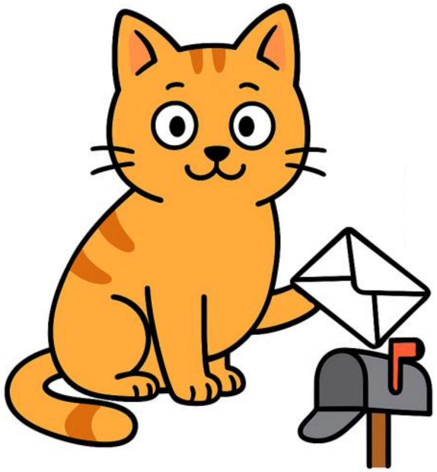
Neutrino Oscillations: Results



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.