NEWS FROM NEUTRINO TELESCOPES

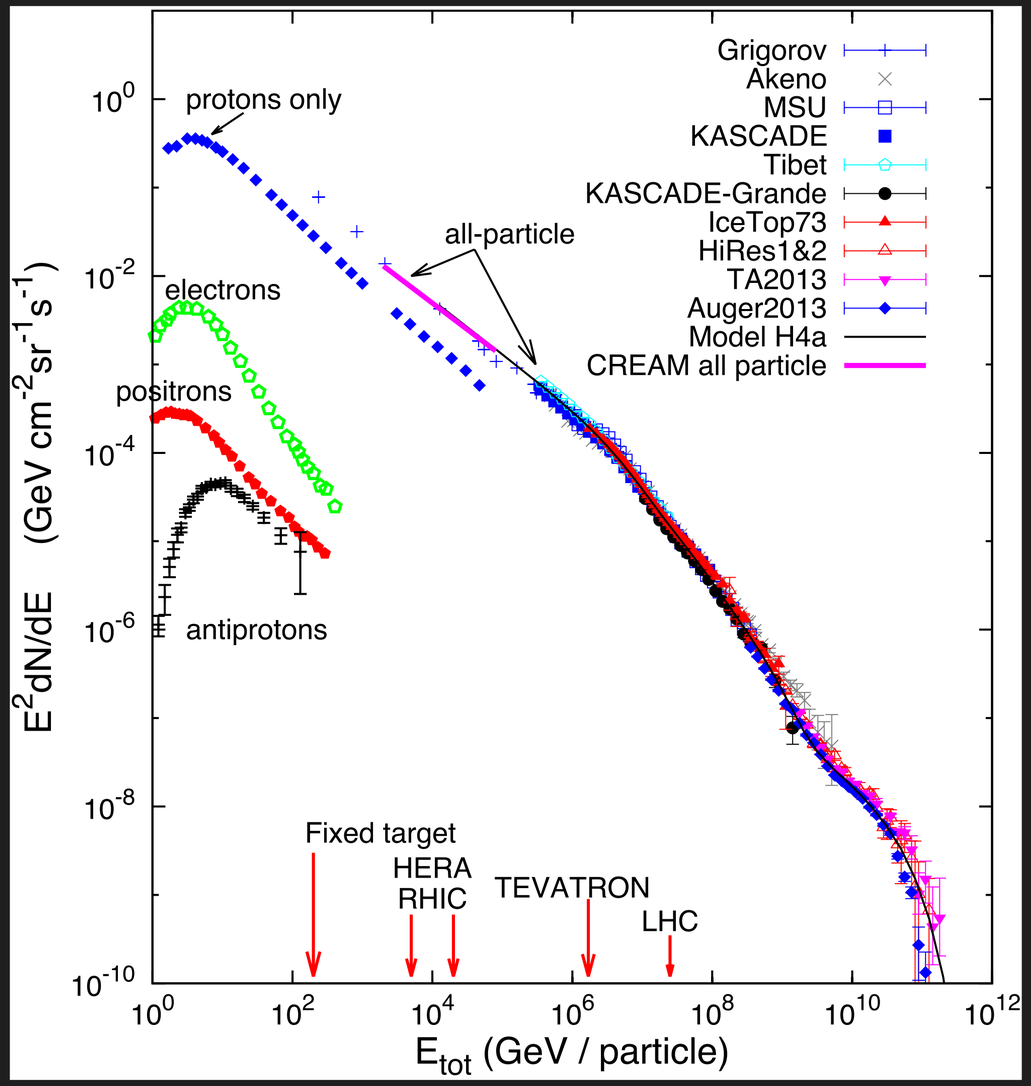
Claudio Kopper

ECAP ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

FAU Friedrich-Alexander-Universität Erlangen-Nürnberg

COSMIC RAYS

where (and how) are they accelerated?



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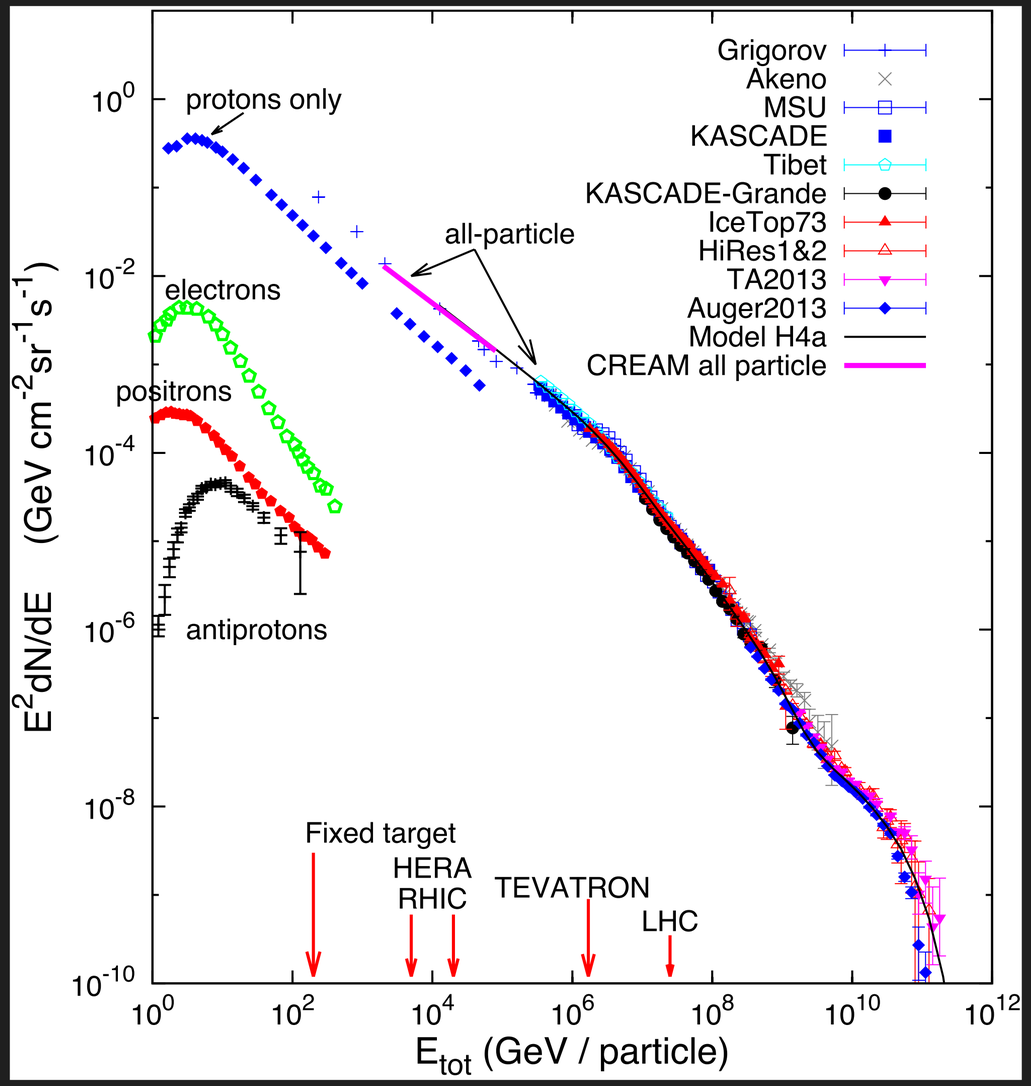
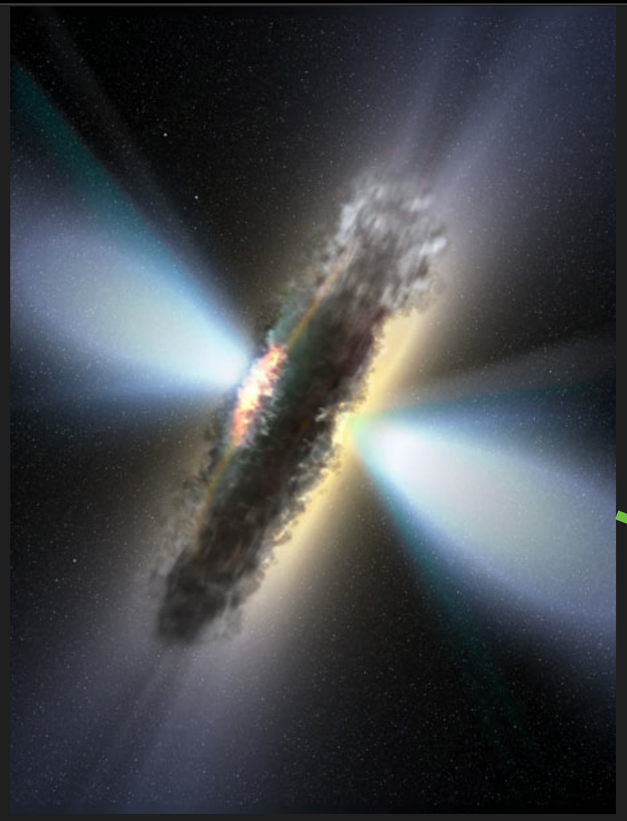


We know their energy spectrum over 11 orders of magnitude

Their sources (especially at the highest energies) are still mostly unknown

MULTI-MESSENGER ASTROPHYSICS WITH NEUTRINOS



- **Nuclei** can be deflected by magnetic fields

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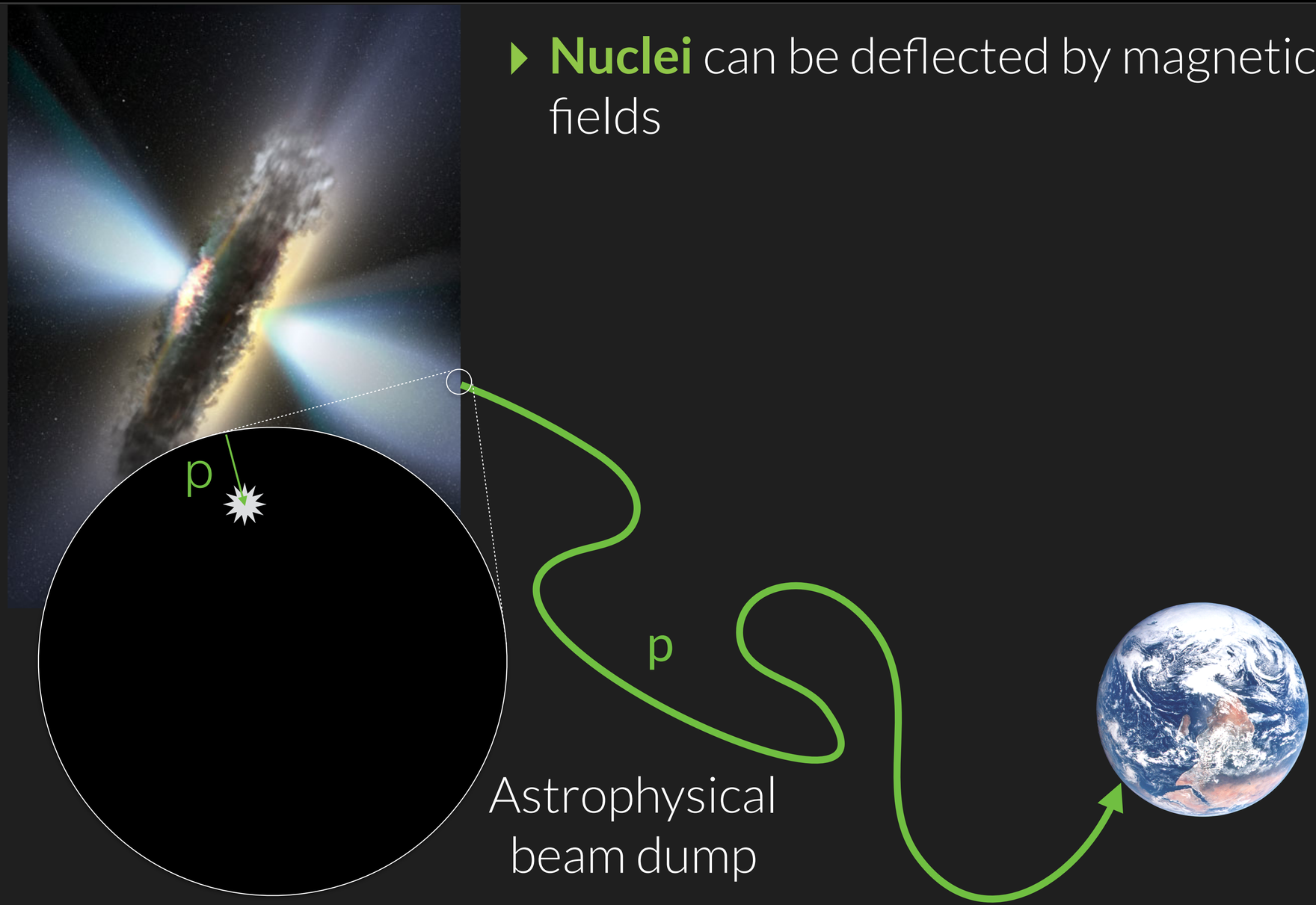

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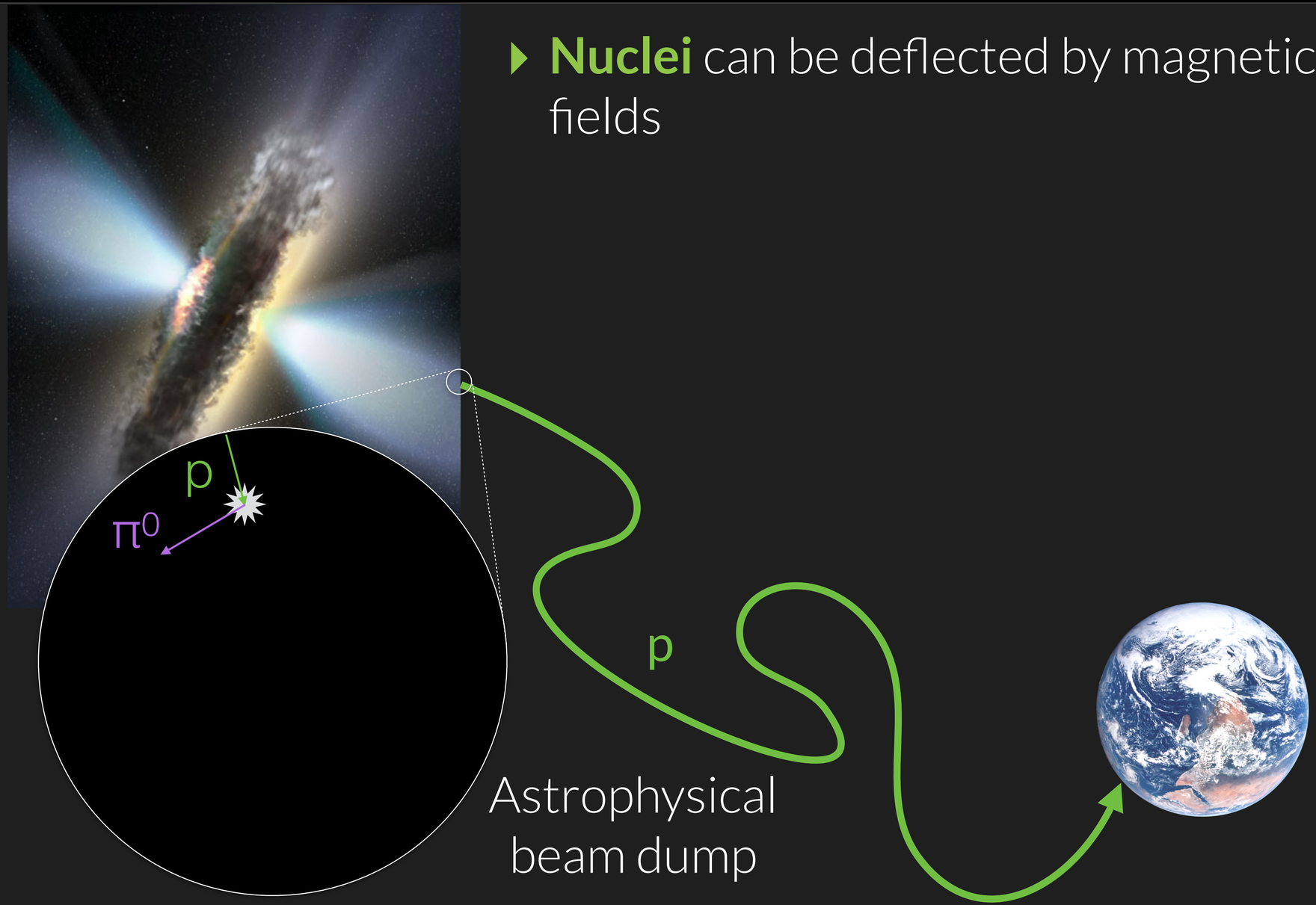

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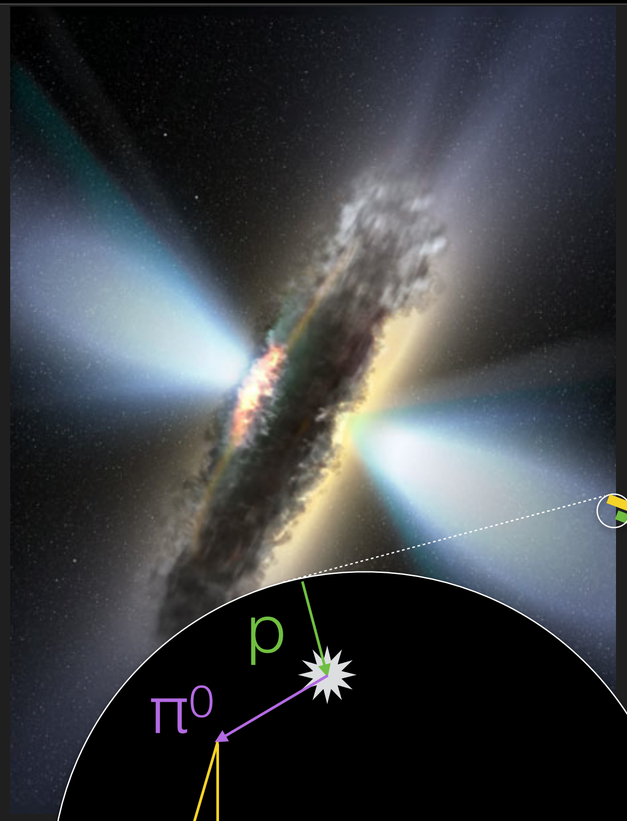
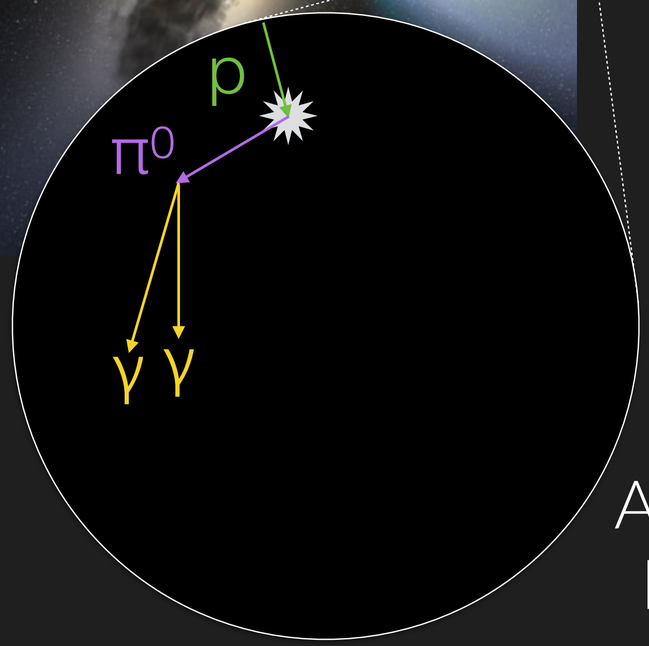
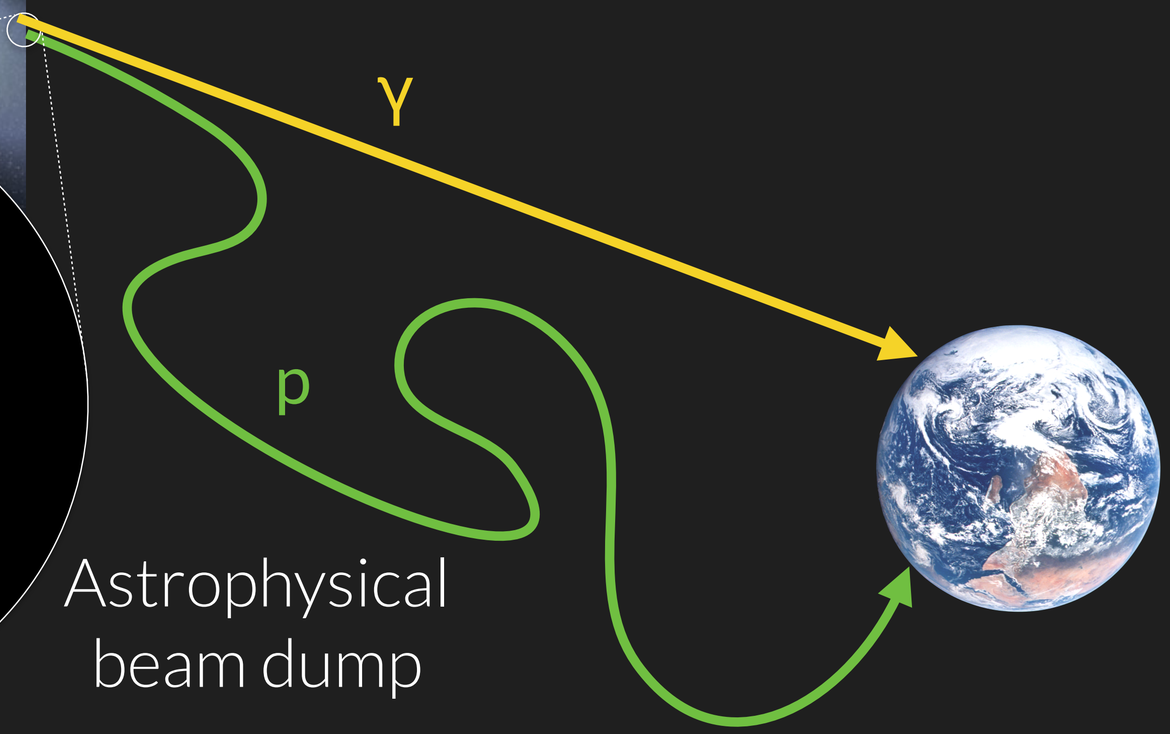


- **Nuclei** can be deflected by magnetic fields
- **Gamma rays** can be absorbed





Astrophysical beam dump

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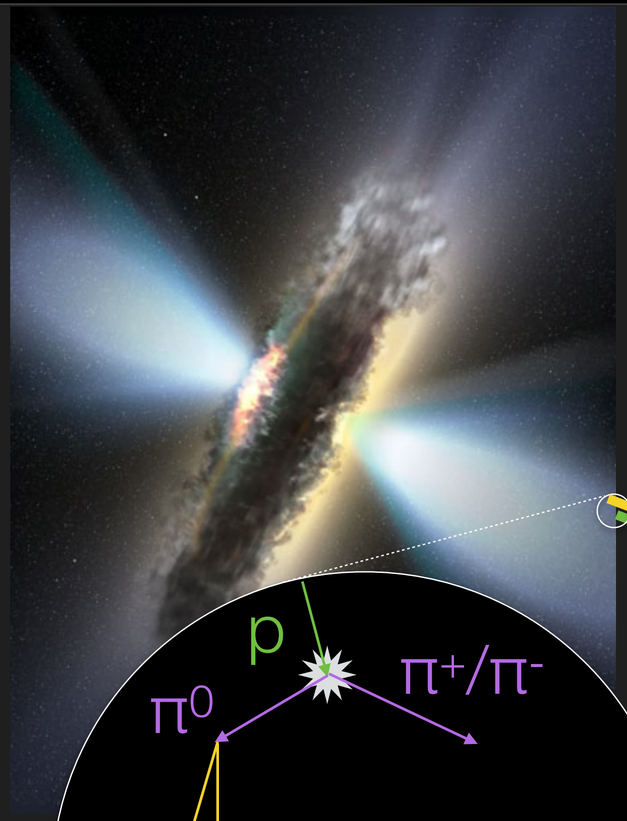

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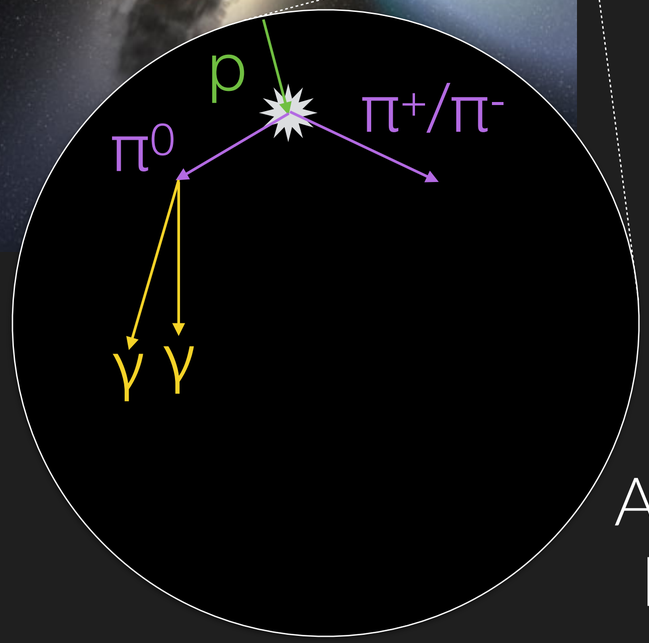

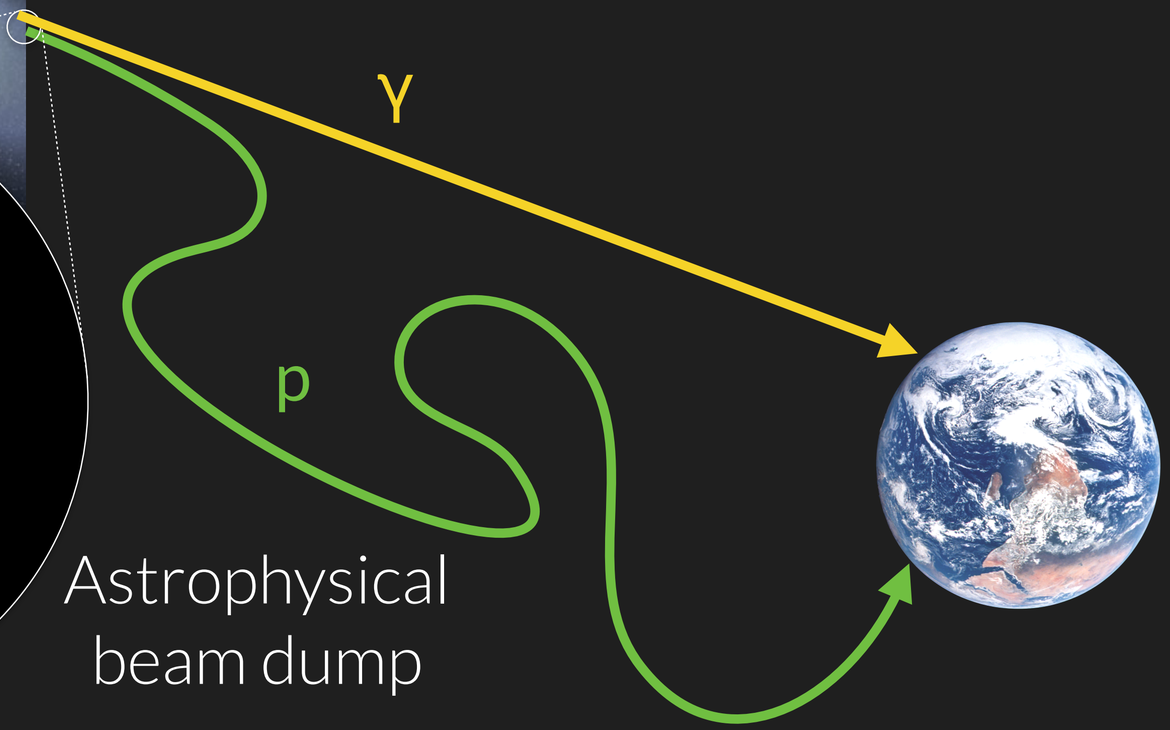

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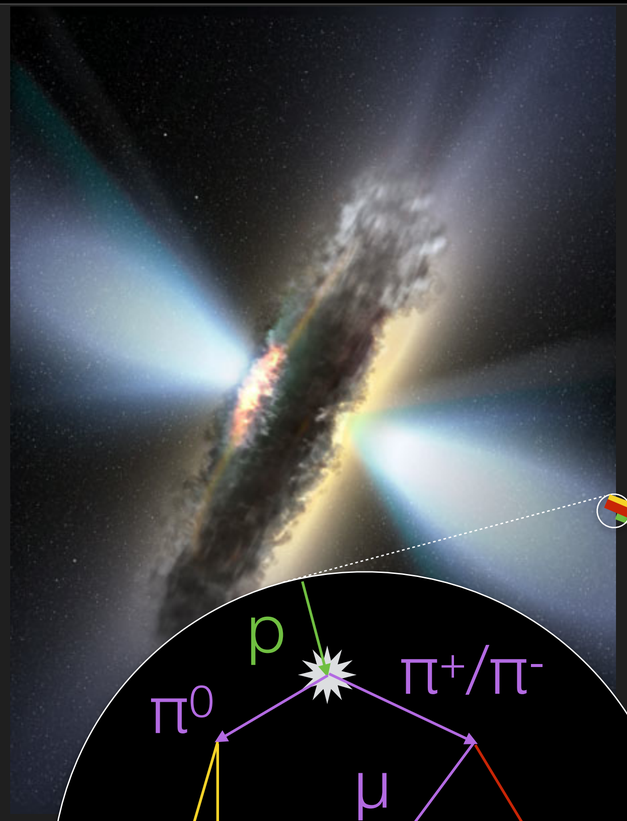
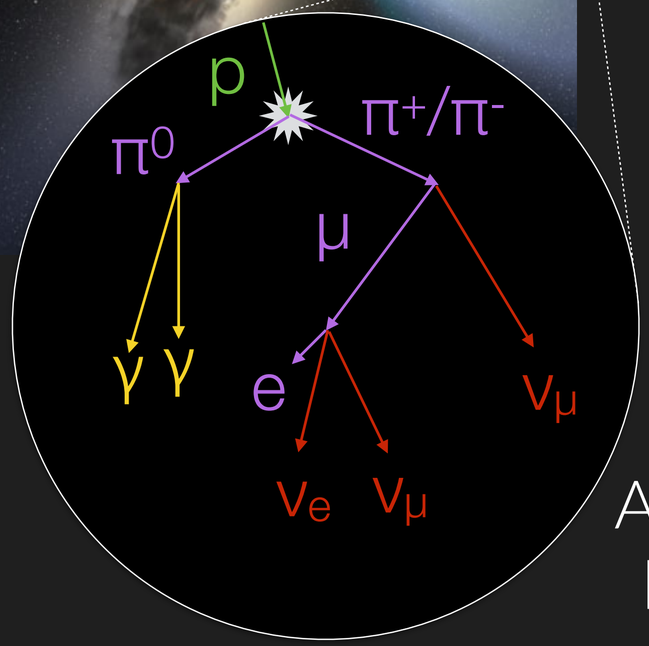
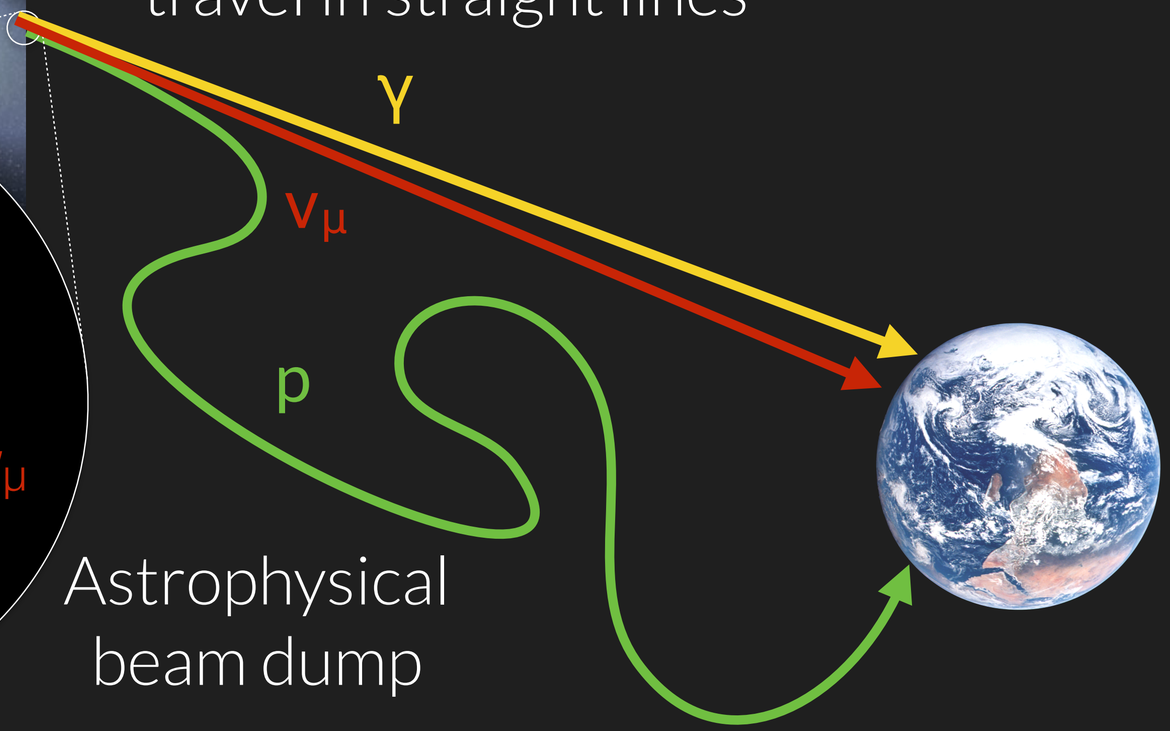


- **Nuclei** can be deflected by magnetic fields
- **Gamma rays** can be absorbed
- **Neutrinos** are difficult to stop and travel in straight lines

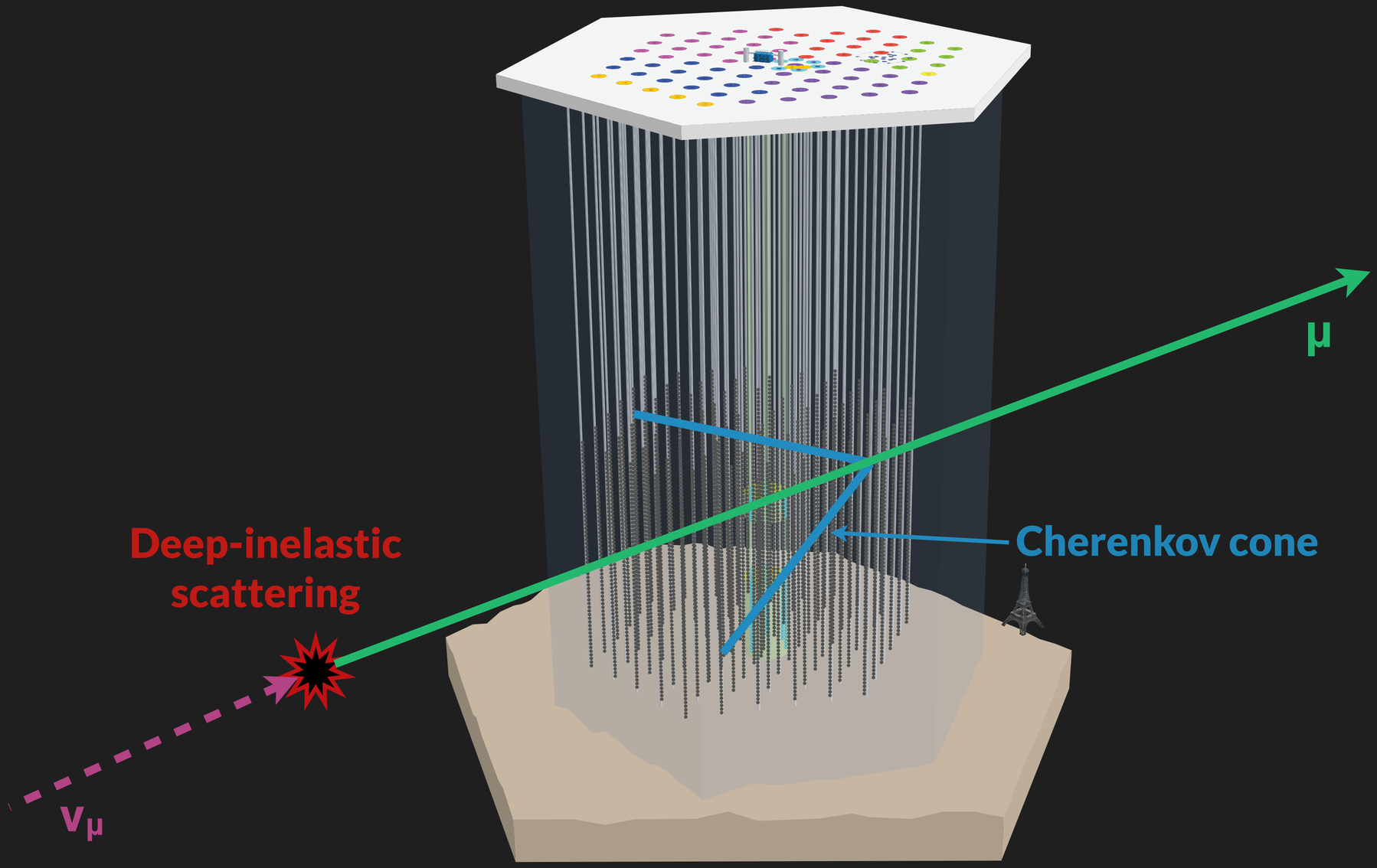




Astrophysical beam dump

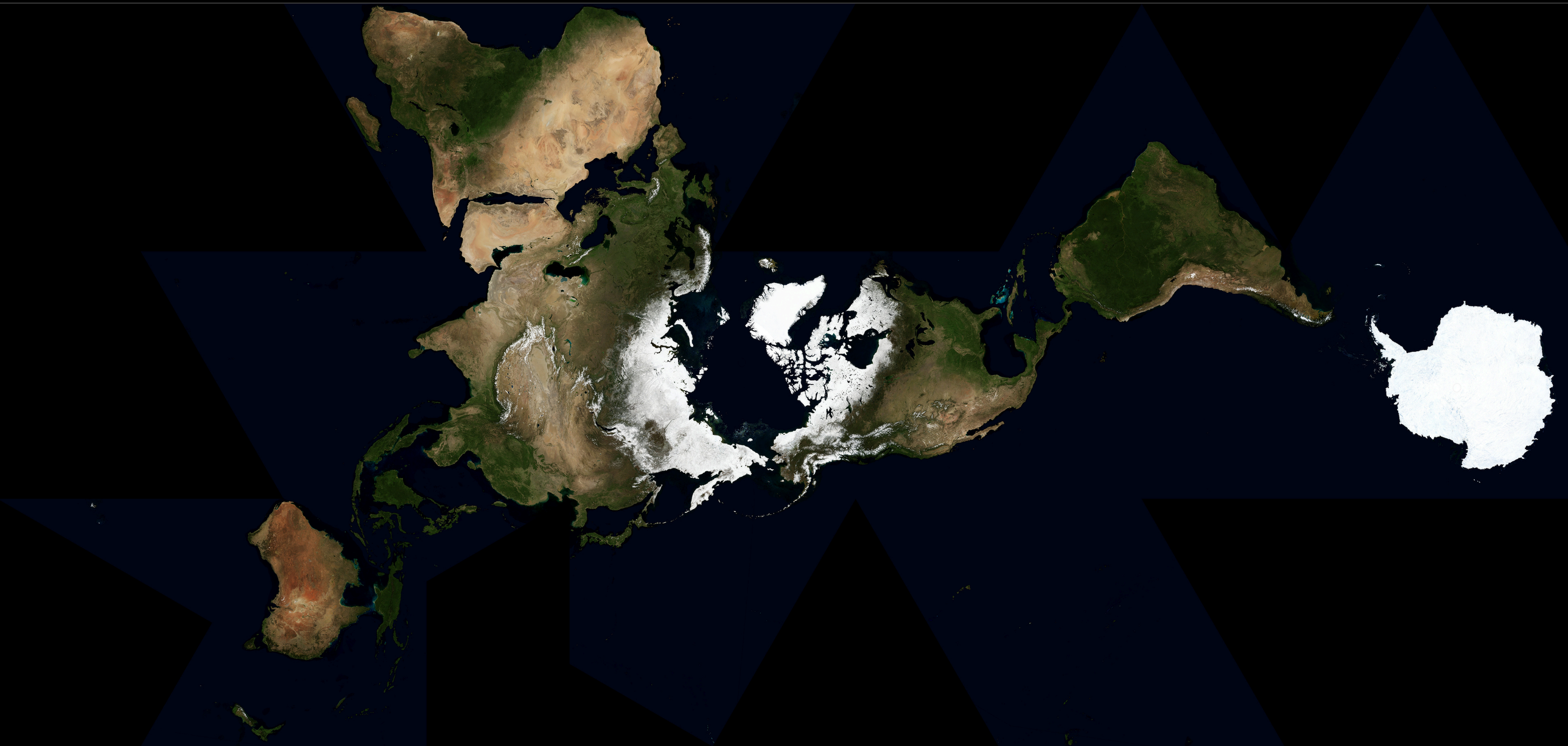
DETECTING NEUTRINOS

Neutrinos are detected by looking for Cherenkov radiation from secondary particles (muons, particle showers)



HIGH-ENERGY NEUTRINO TELESCOPE SITES

deep natural sites with water/ice (deep sea, lakes, glaciers) for optical cherenkov - ice for radio



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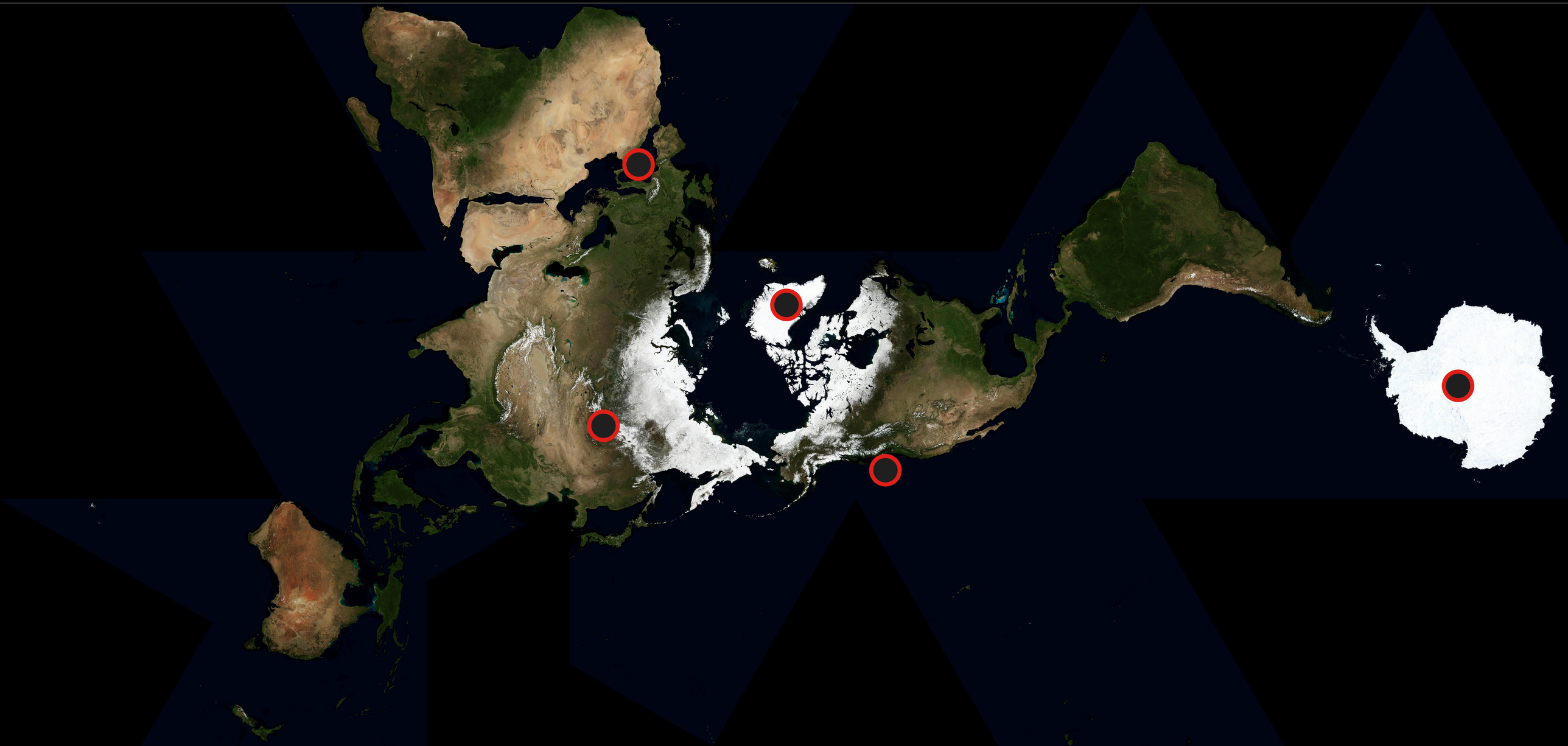

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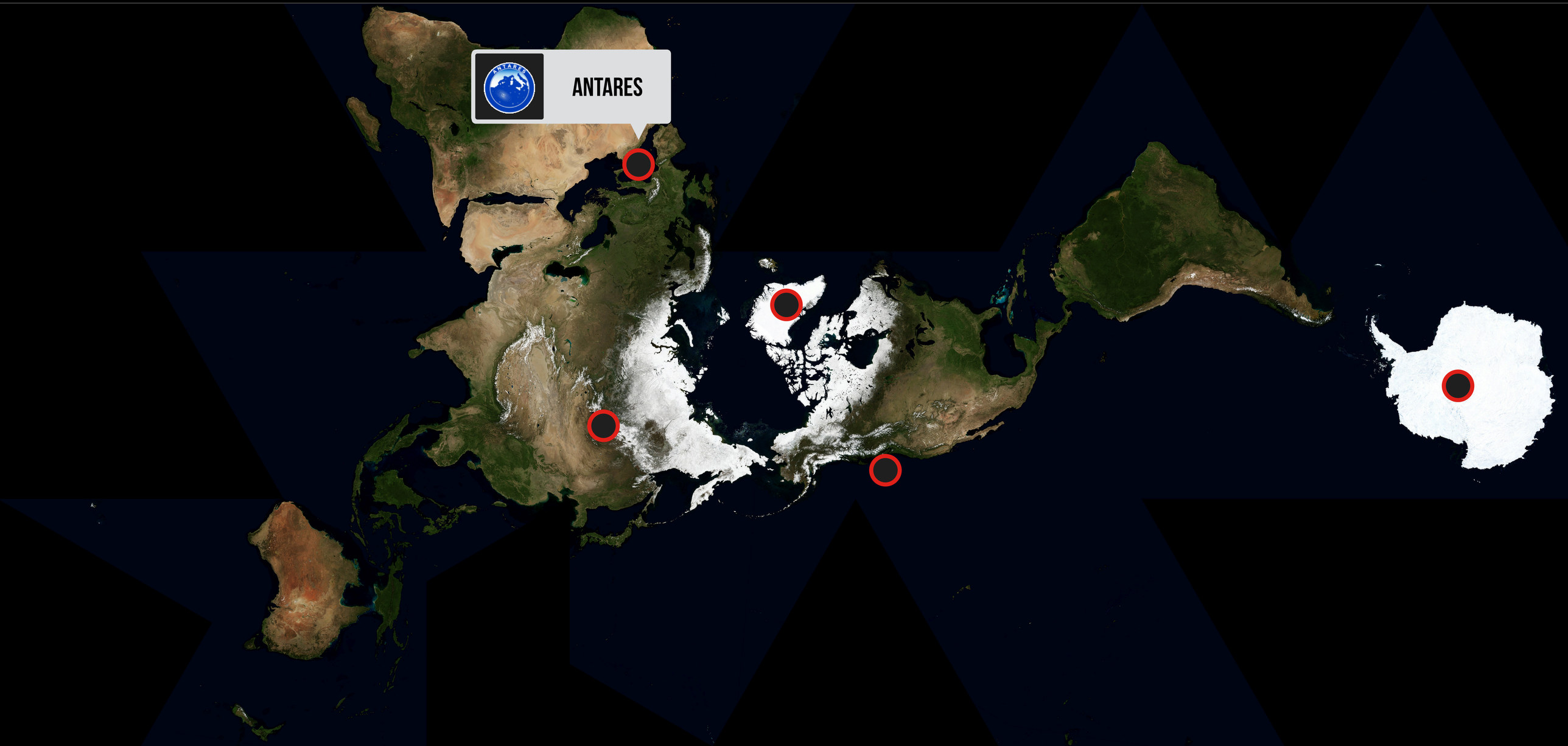

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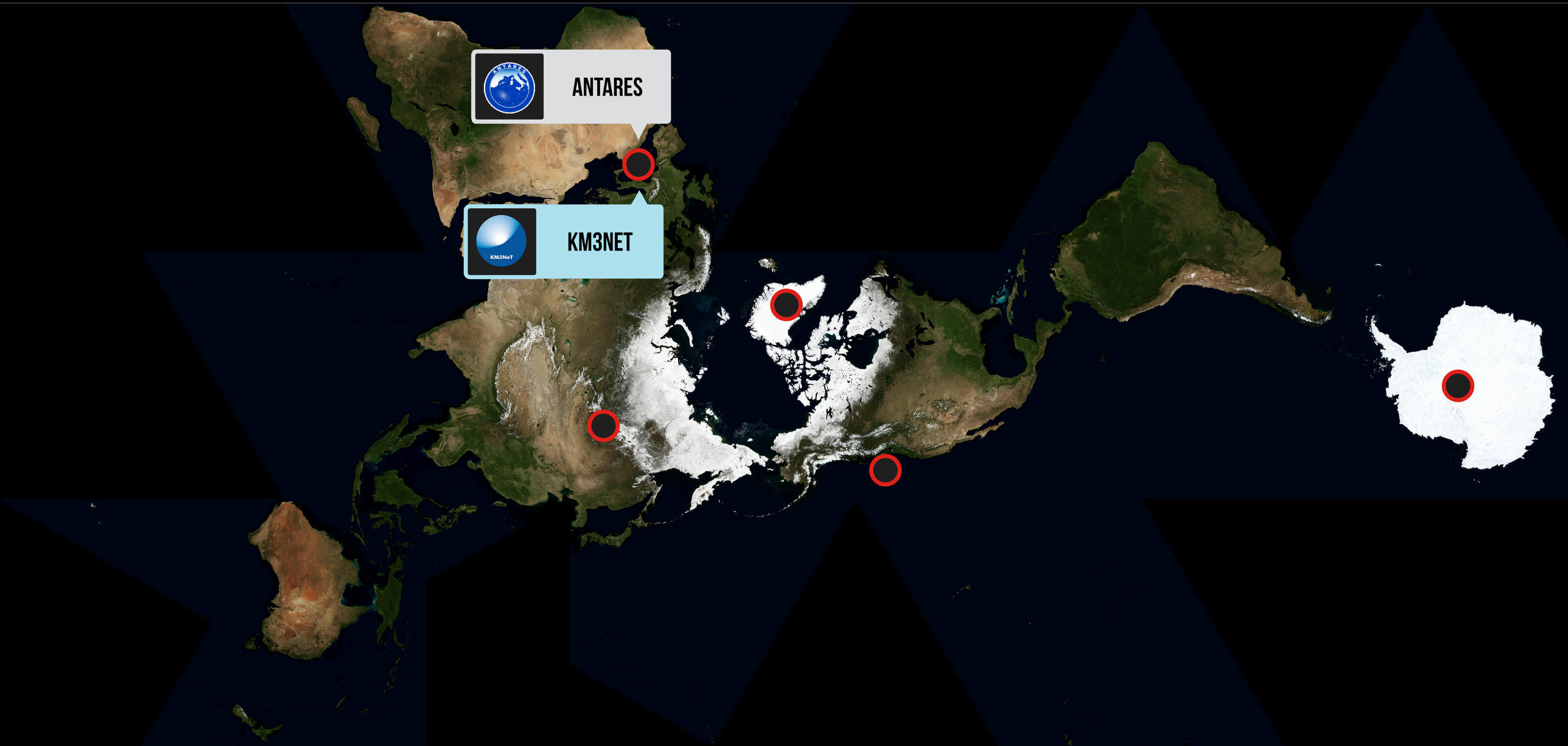

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deep natural sites with water/ice (deep sea, lakes, glaciers) for optical cherenkov - ice for radio

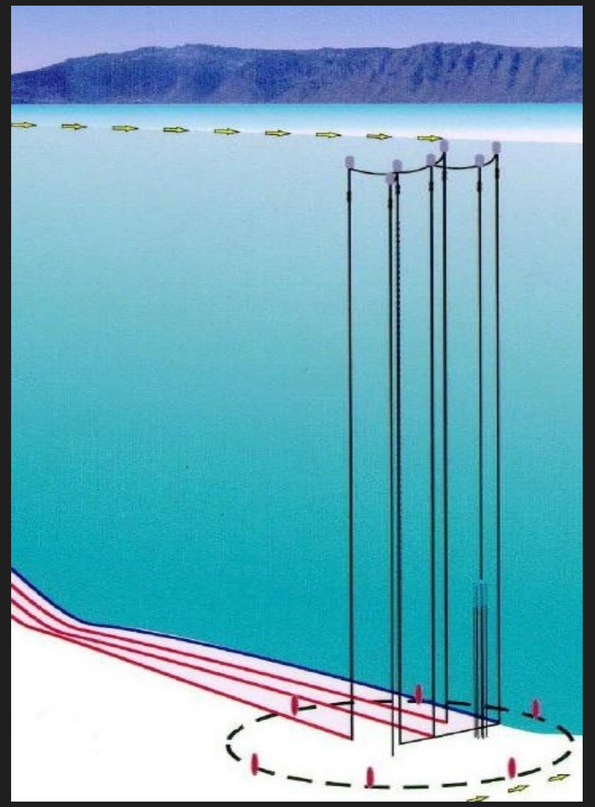
Lake Baikal

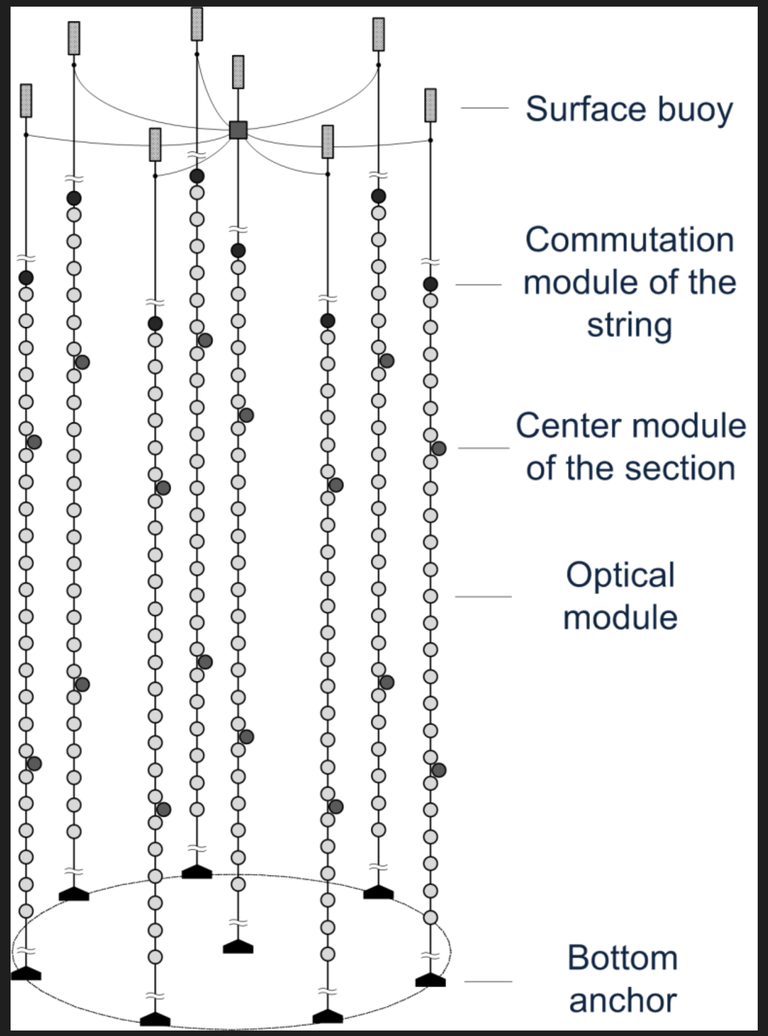
BAIKAL / BAIKAL-GVD

Neutrino telescope deployed in Lake Baikal

8 clusters of a gigaton detector deployed as of 2021

Plan: 14 such arrays, 112 strings

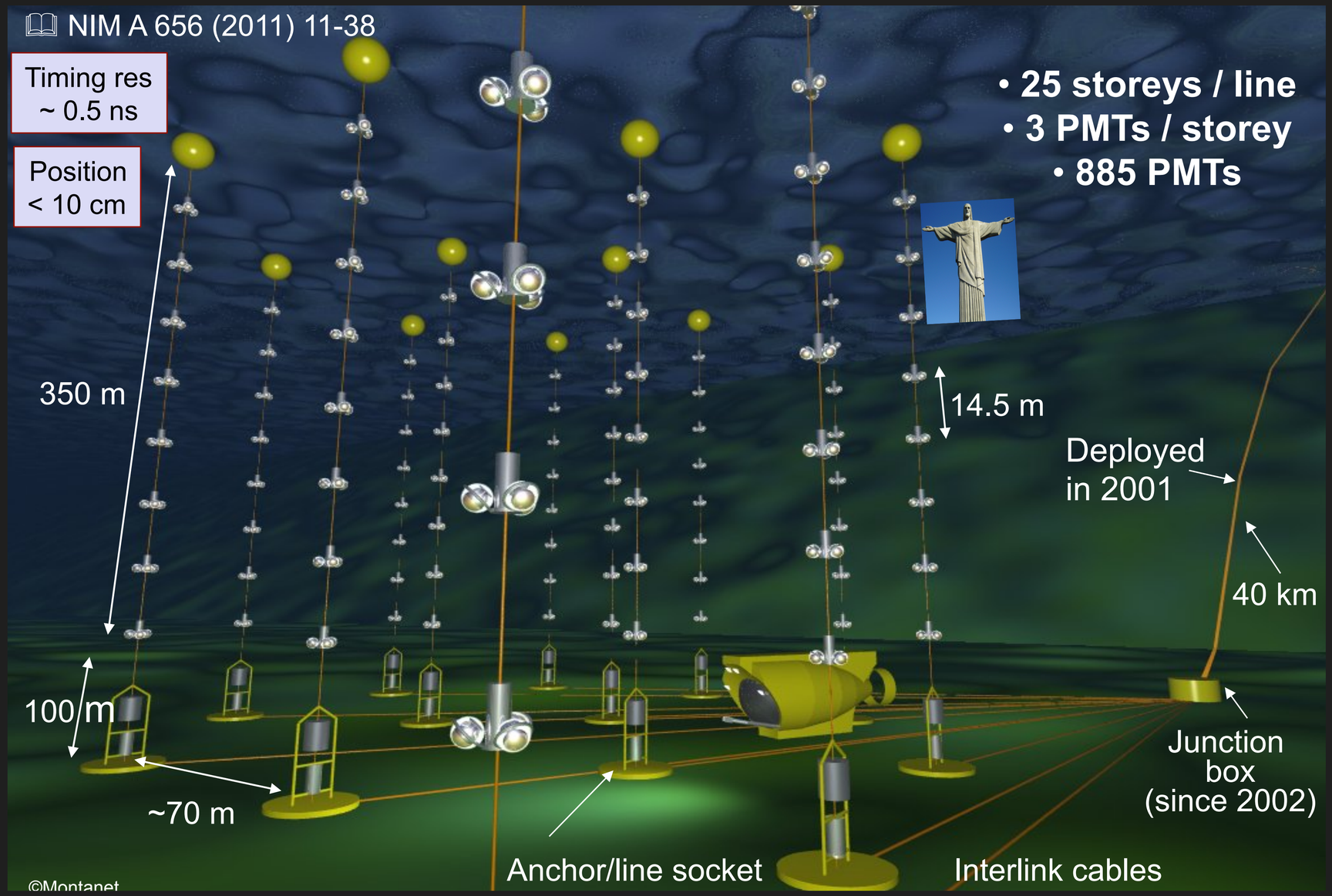


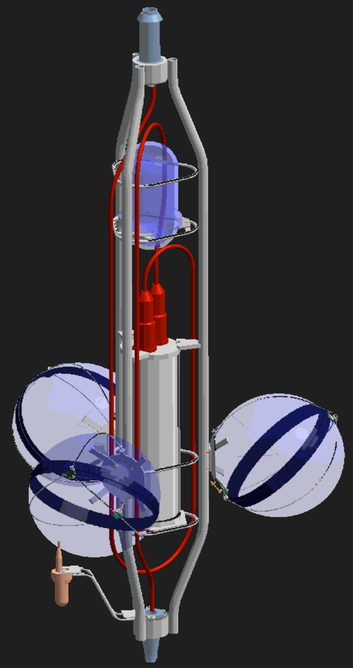



Mediterranean Sea

THE ANTARES NEUTRINO TELESCOPE

In the Mediterranean Sea near Toulon, France





“storey” with 3 OMs

THE KM3NET NEUTRINO TELESCOPE

In the Mediterranean Sea - Two Sites!

Cities and Sites of KM3NeT

~250 people
42+8 Institutes
15+5 Countries

Australia
Sydney

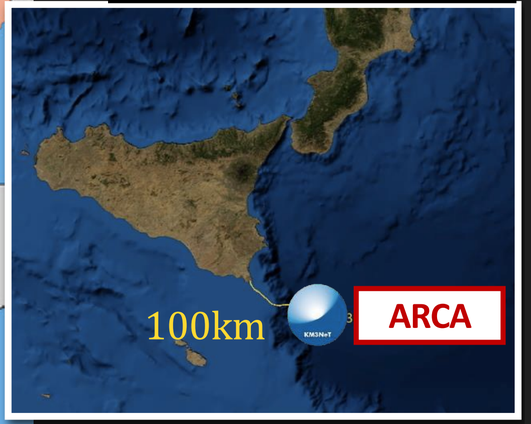
Johannesburg
Potchefstroom
South Africa

Israel
Ari'el

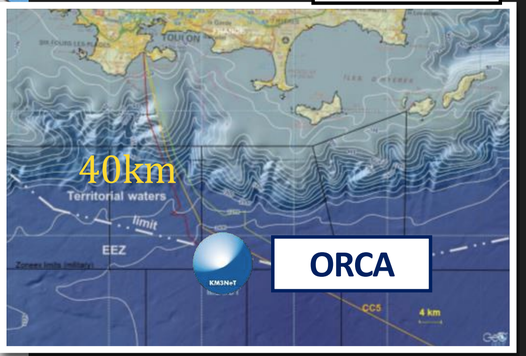
China
Guangzhou

Amsterdam
Delft
Leiden
Texel
Hull
Münster
Louvain
Paris
Caen
Nantes
Strasbourg
Bamberg
Würzburg
Erlangen
Tübingen
Prague
Warsaw
Bratislava
Bucharest
Tbilisi
Montpellier
Marseille
Toulon
Genova
Bologna
Rome
Caserta
Bari
Naples
Salerno
Vilanova i la Geltrú
Valencia
Gandia
Granada
Catania
Athens
Nicosia
Constantine
Rabat
Oujda
Ben Guerir
Marrakesh
Sharjah
Abu Dhabi

Portopalo di Capo Passero



Toulon

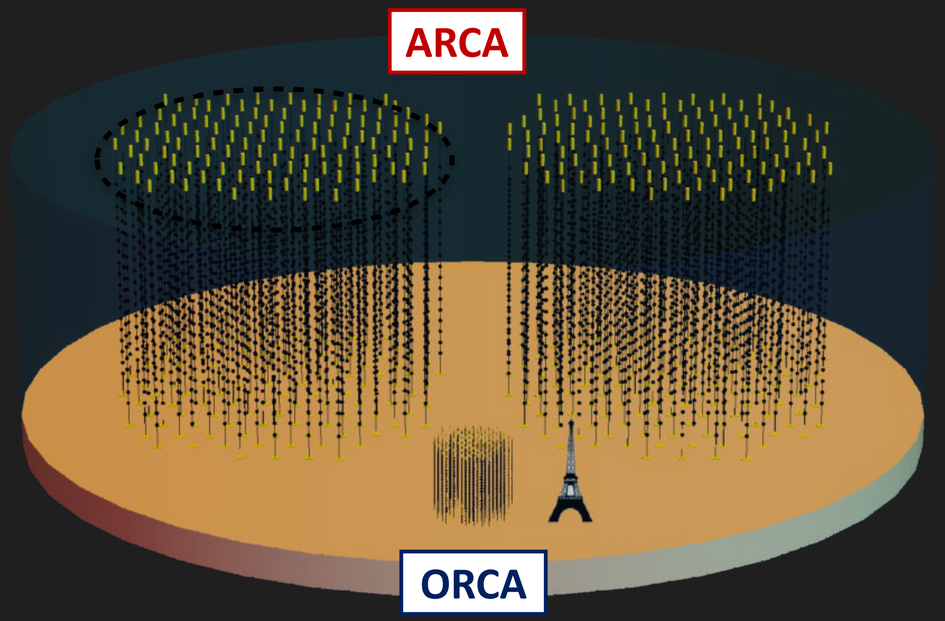


THE KM3NET NEUTRINO TELESCOPE

In the Mediterranean Sea - Two Sites!

Digital **O**ptical **M**odule

31×3" PMTs

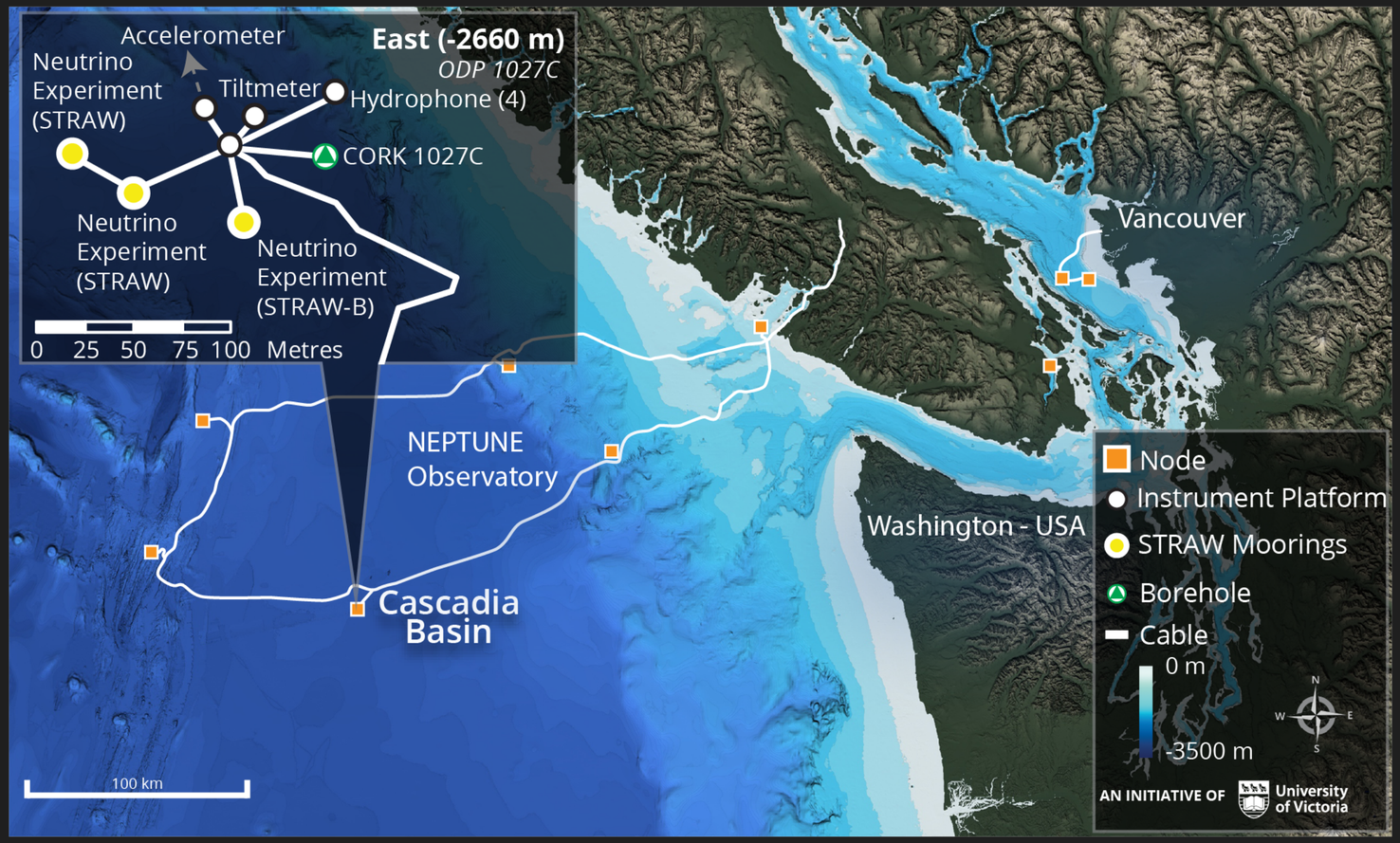


1 Building Block (BB) = 115 Detection Units (DU)

	ARCA	ORCA
Location	Italy (Sicily)	France (Toulon)
Depth	3450 m	2450 m
Distance from shore	100 km	40 km
Number of DUs	115 x 2 (2 BB)	115 (1 BB)
DU horizontal spacing	90 m	20 m
DOM vertical spacing	36 m	9 m
#DOMs/DU	18	18
#PMTs/DOM	31	31
Instrumented volume	~ 1 Gton	~ 7 Mton
	> 1km^3 neutrino telescope	
Deployed DUs	21	18

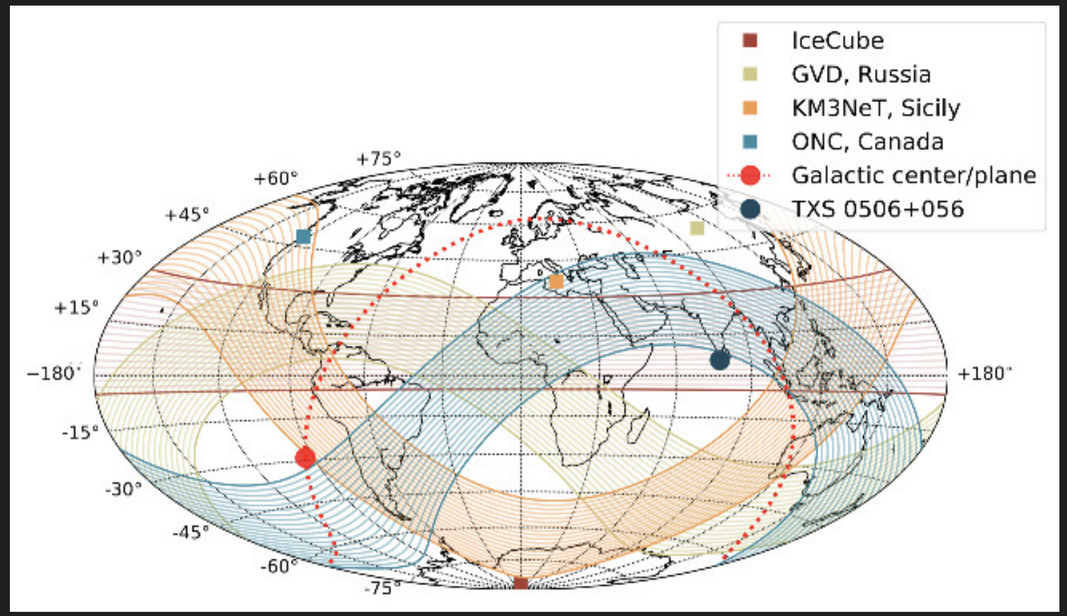
P-ONE

An idea for a project off the Canadian Pacific Coast



First test strings have been taking data for a while

Plan to deploy P-ONE-1 soon



NEUTRINOS VIA RADIO IN GREENLAND: RNO-G

Radio Neutrinos - See Sjoerd's talk on Monday (and the end of this presentation)

First test strings have been taking data for a while

Plan to deploy P-ONE-1 soon

Summit Station

DESY-Zeuthen

FAU-Erlangen

Radboud University

Université Libre de Bruxelles

Vrije Universiteit Brussels

University of Nebraska-Lincoln

University of Kansas

University of Wisconsin-Madison

University of Chicago

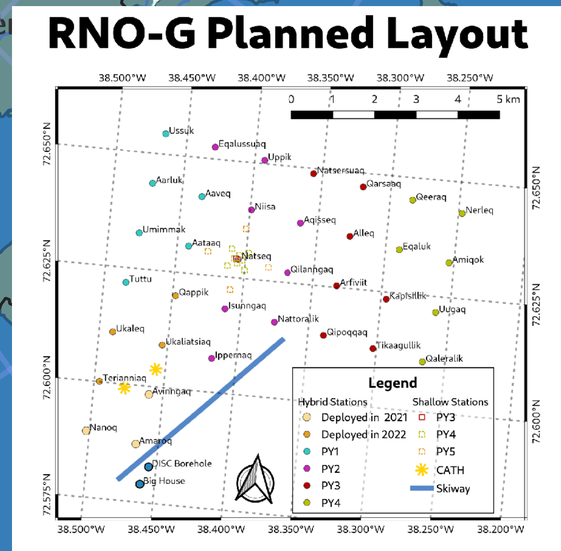
The Ohio State University

Pennsylvania State University

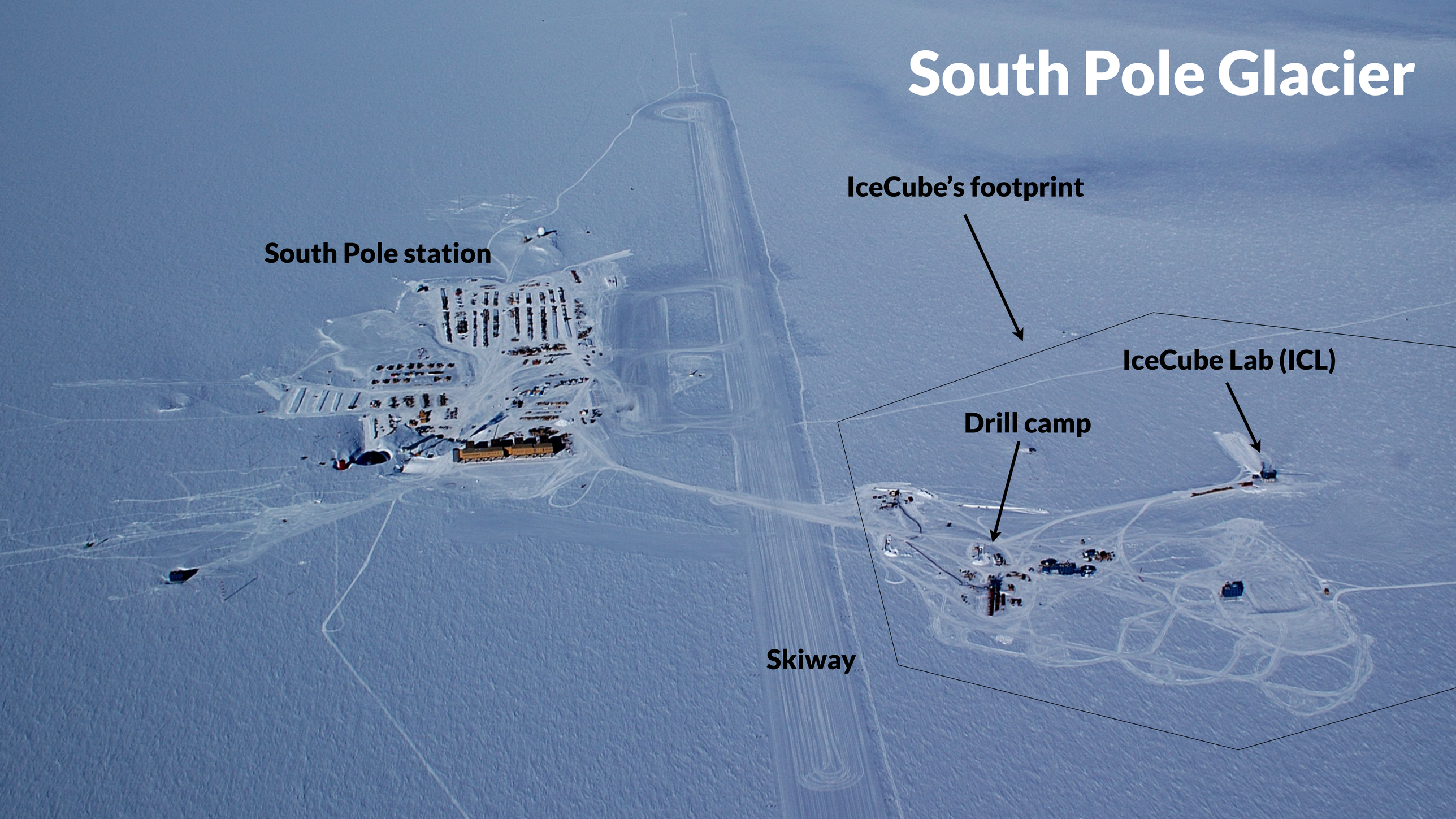
University of Delaware

University of Maryland

ersity of Alabama



South Pole Glacier



THE ICECUBE NEUTRINO OBSERVATORY

Deployed in the deep glacial ice at the South Pole

5160 PMTs

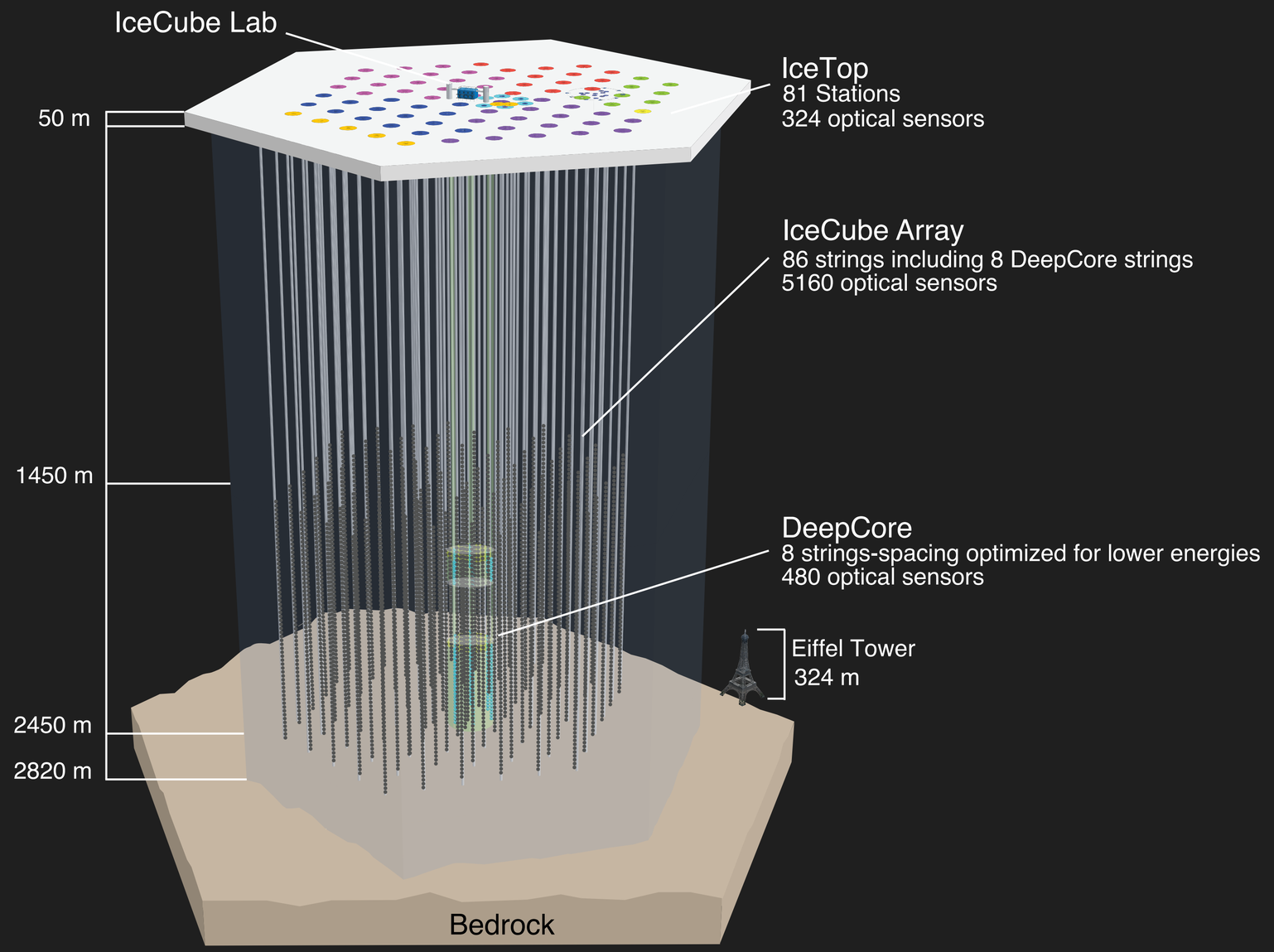
1 km³ volume

86 strings

17 m vertical spacing

125 m string spacing

Completed **2010**



PHYSICS REACH OF ICECUBE, KM3NET & CO.

Astrophysical Neutrinos

Understand Cosmic Ray Source Populations

Indirect Dark Matter Searches

Lorentz Invariance Violation

Direct Observation of ν_τ

Atmospheric Neutrinos

Measurement of Atmospheric Neutrino Spectrum (100k events/year)

Measurement of θ_{23}

Cross-sections at ultra-high energies

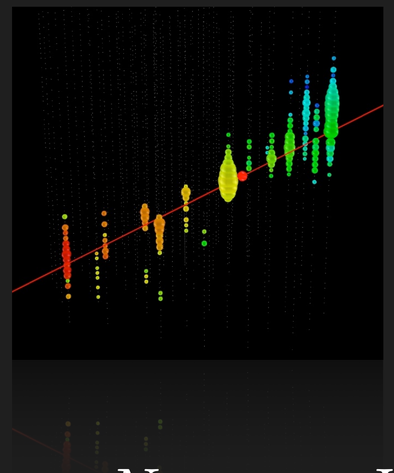
Cosmic Ray Measurements

NEUTRINO EVENT SIGNATURES

Signatures of signal events

time

CC Muon Neutrino

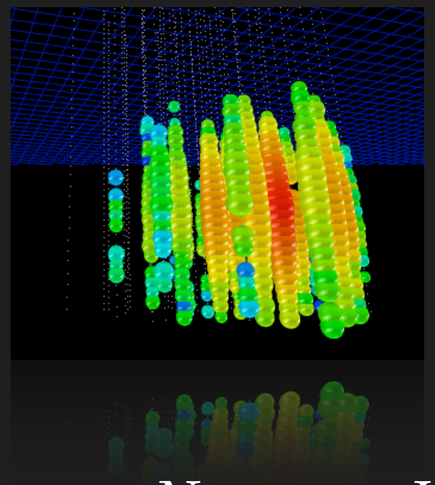


$$\nu_\mu + N \rightarrow \mu + X$$

track (data)

factor of ≈ 2 energy resolution
< 1° angular resolution at high energies

Neutral Current / Electron Neutrino



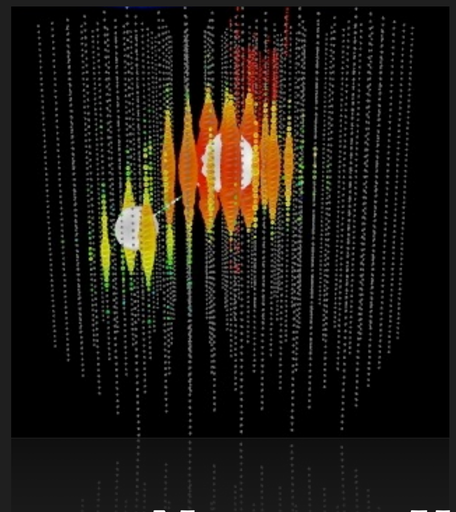
$$\nu_e + N \rightarrow e + X$$

$$\nu_x + N \rightarrow \nu_x + X$$

cascade (data)

≈ ±15% deposited energy resolution
≈ 10° angular resolution (in IceCube)
(at energies ≳ 100 TeV)

CC Tau Neutrino



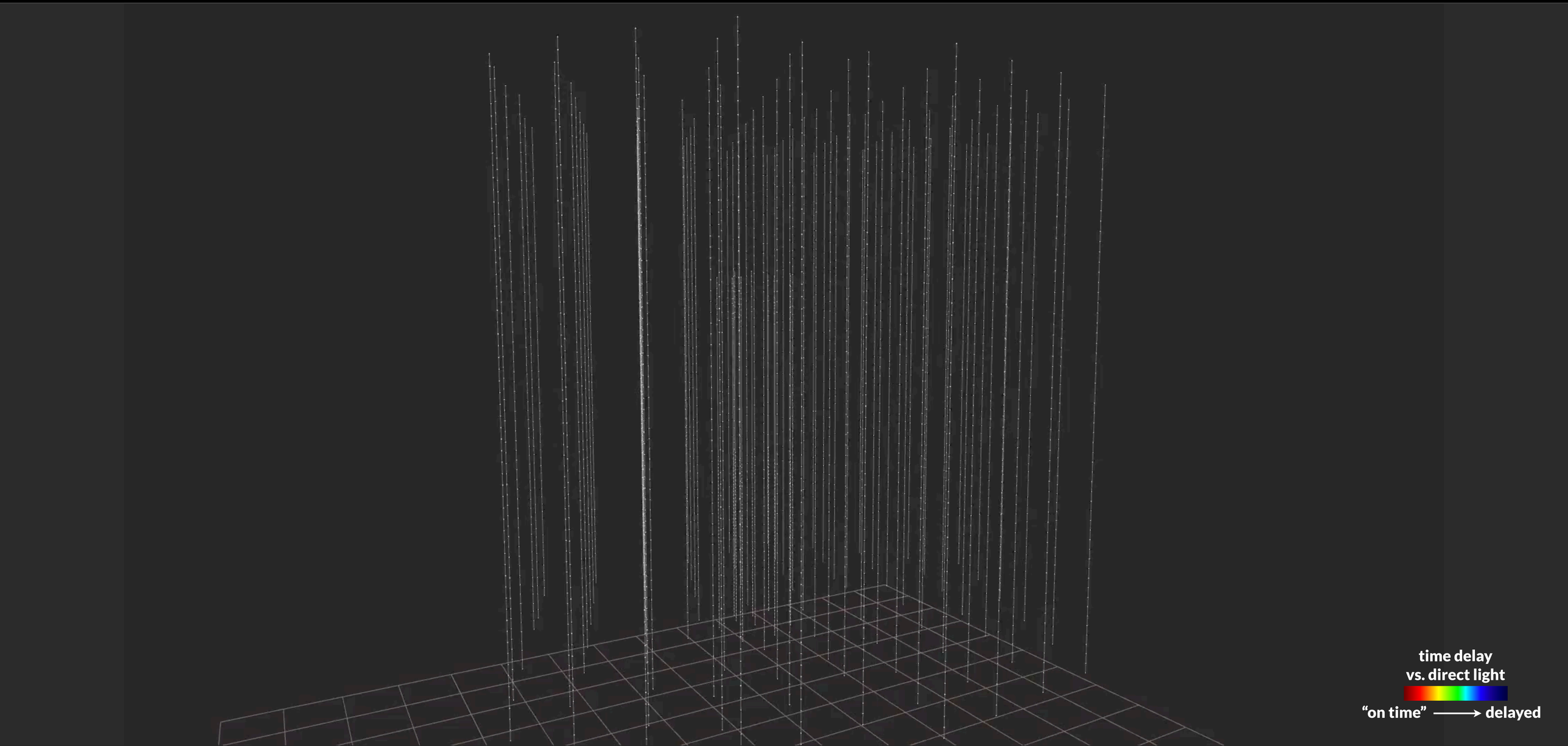
$$\nu_\tau + N \rightarrow \tau + X$$

“double-bang” (≳10PeV) and other signatures such as tracks and cascades

(τ decay length is 50 m/PeV)

DETECTION PRINCIPLE (MUON IN ICE)

Neutrinos are detected by looking for Cherenkov radiation from secondary particles



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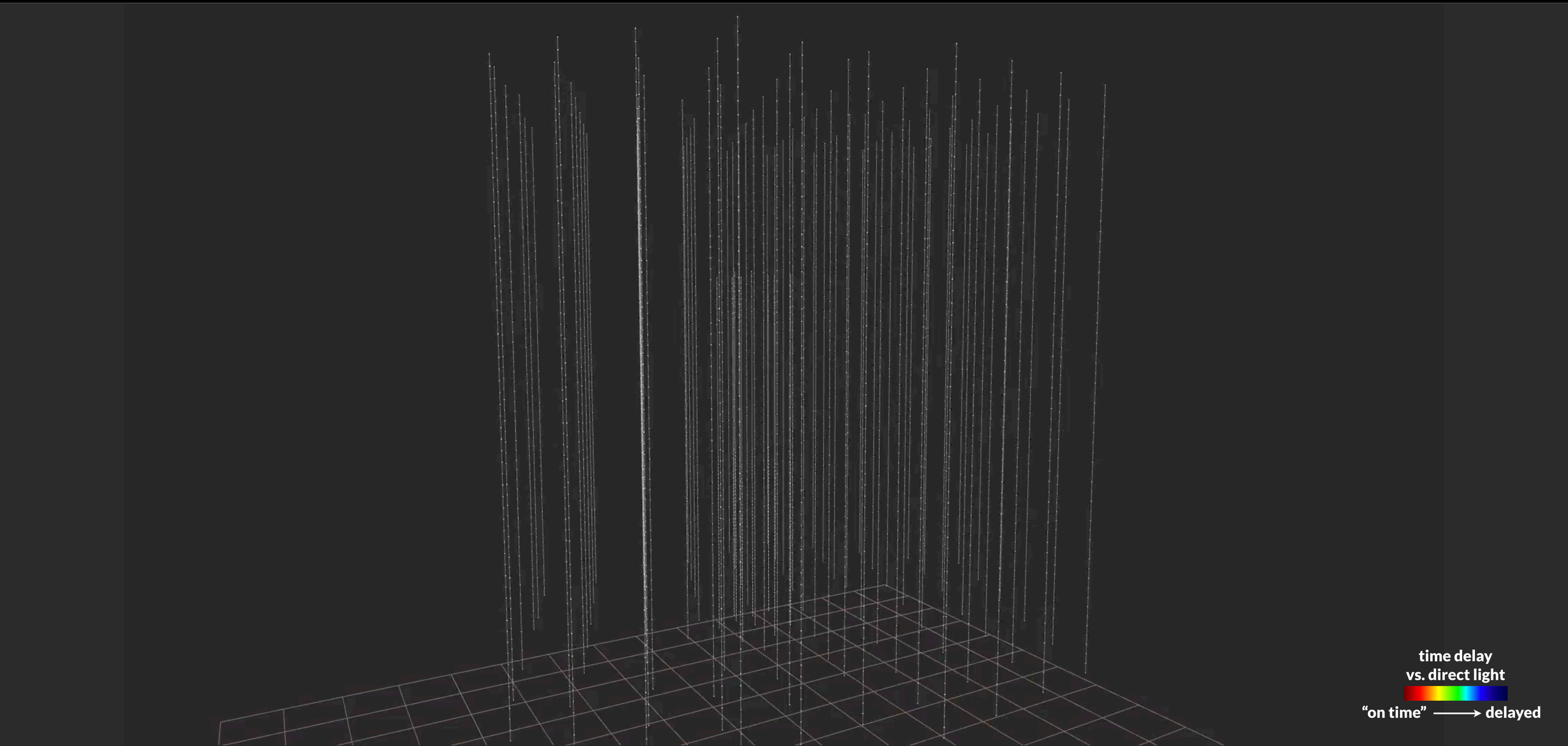

DETECTION PRINCIPLE (CASCADE IN ICE)

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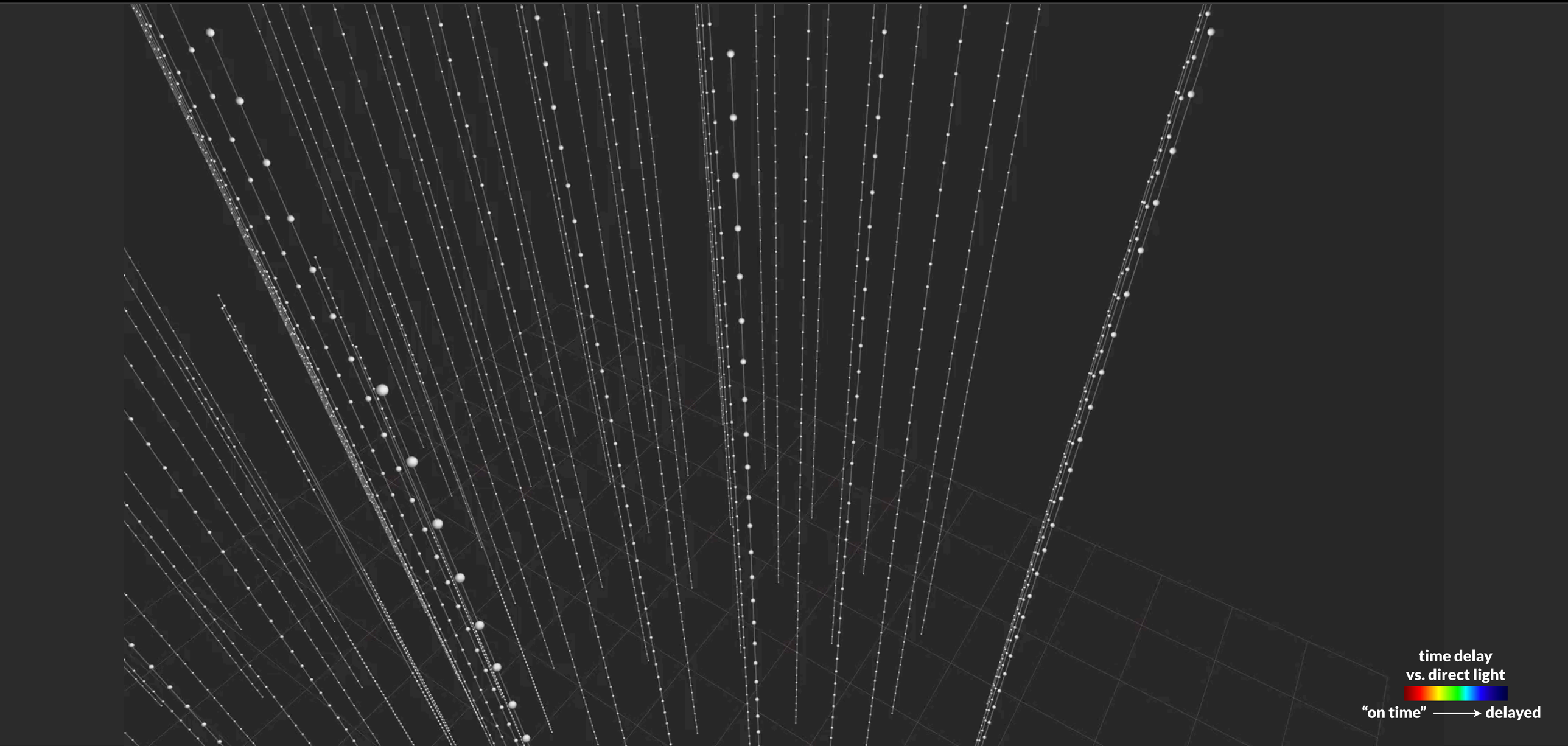

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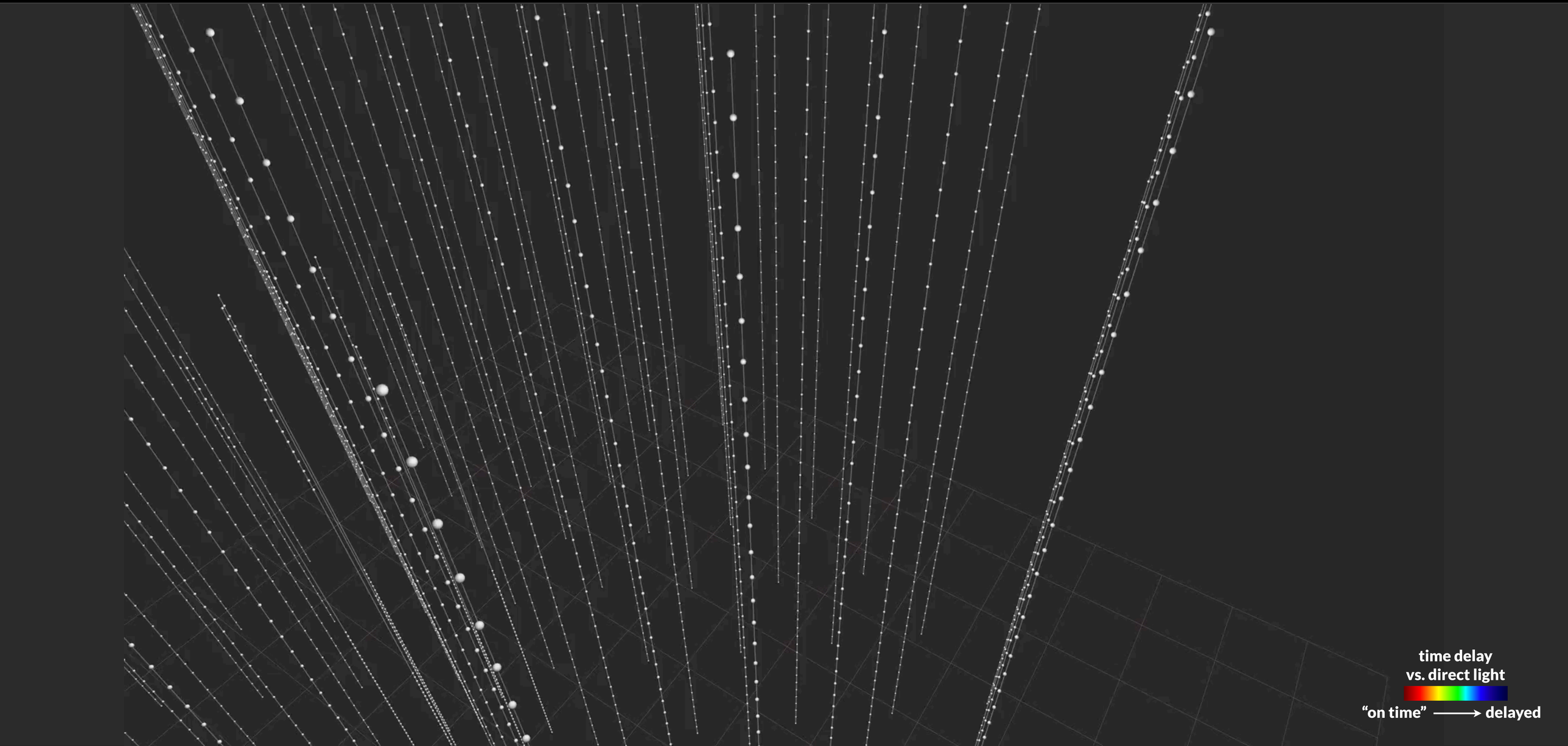
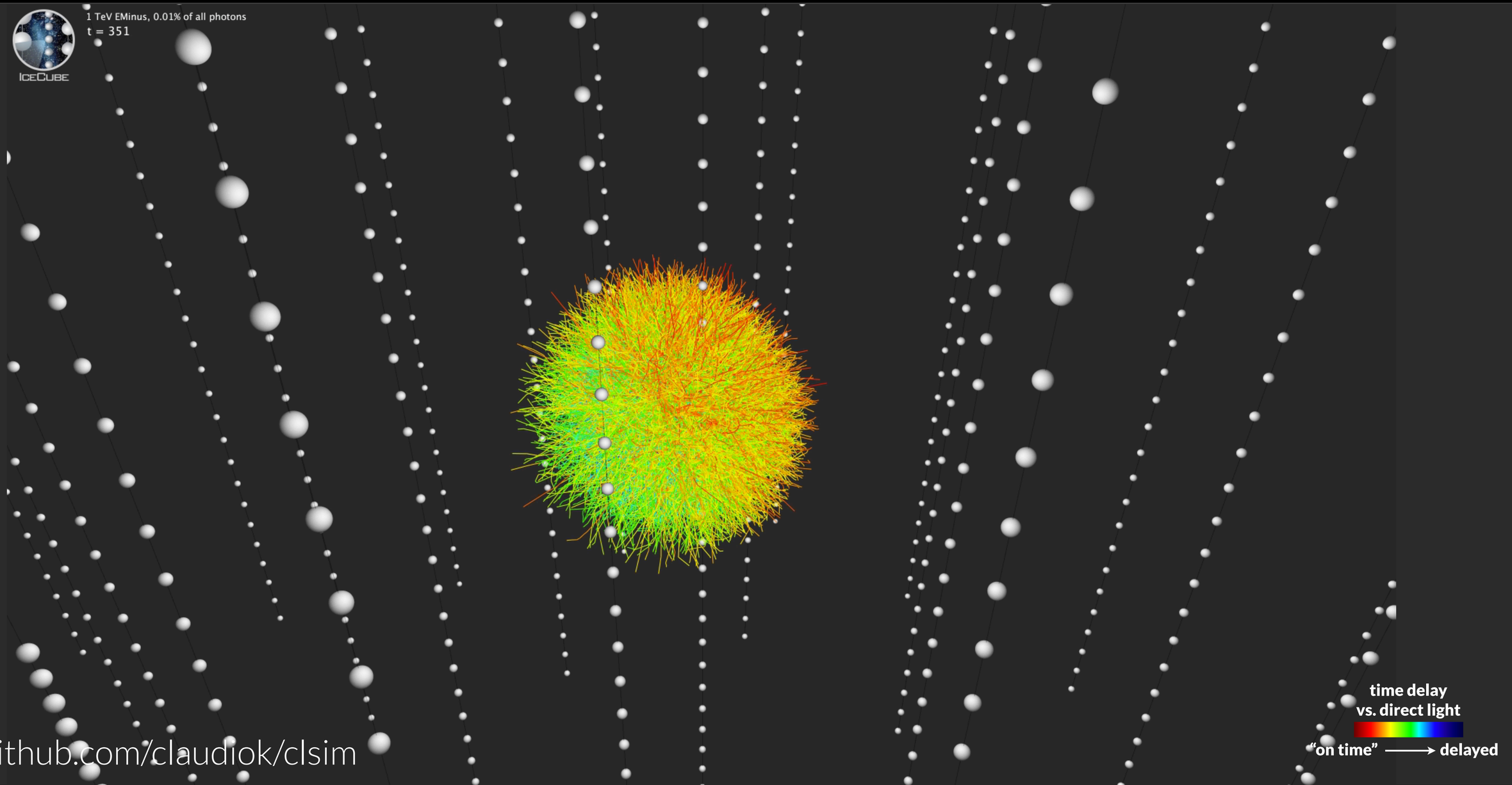


DETECTION PRINCIPLE (CASCADE IN ICE)

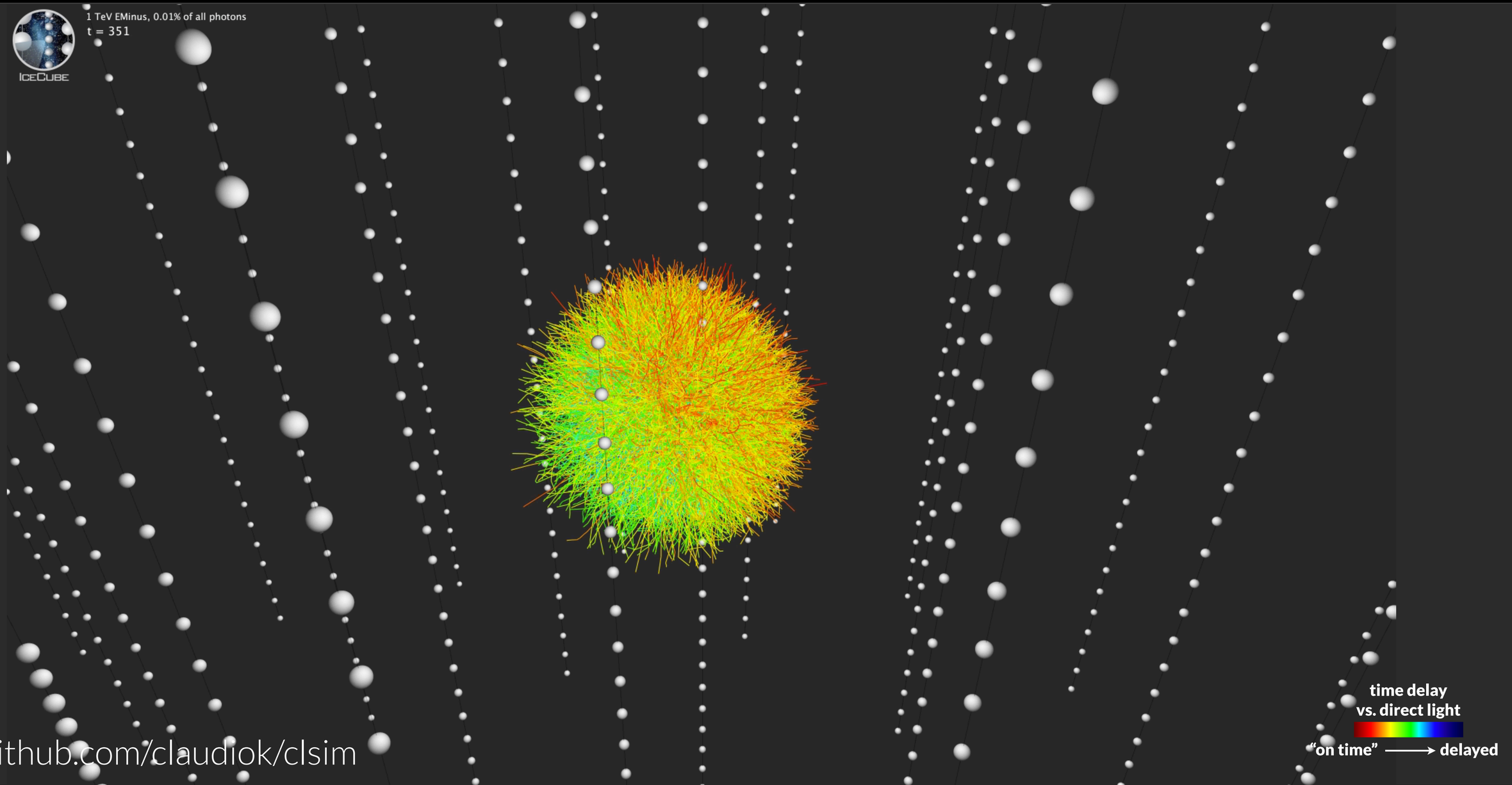
Another Shower



http://github.com/claudiok/clsim

DETECTION PRINCIPLE (CASCADE IN ICE)

Another Shower



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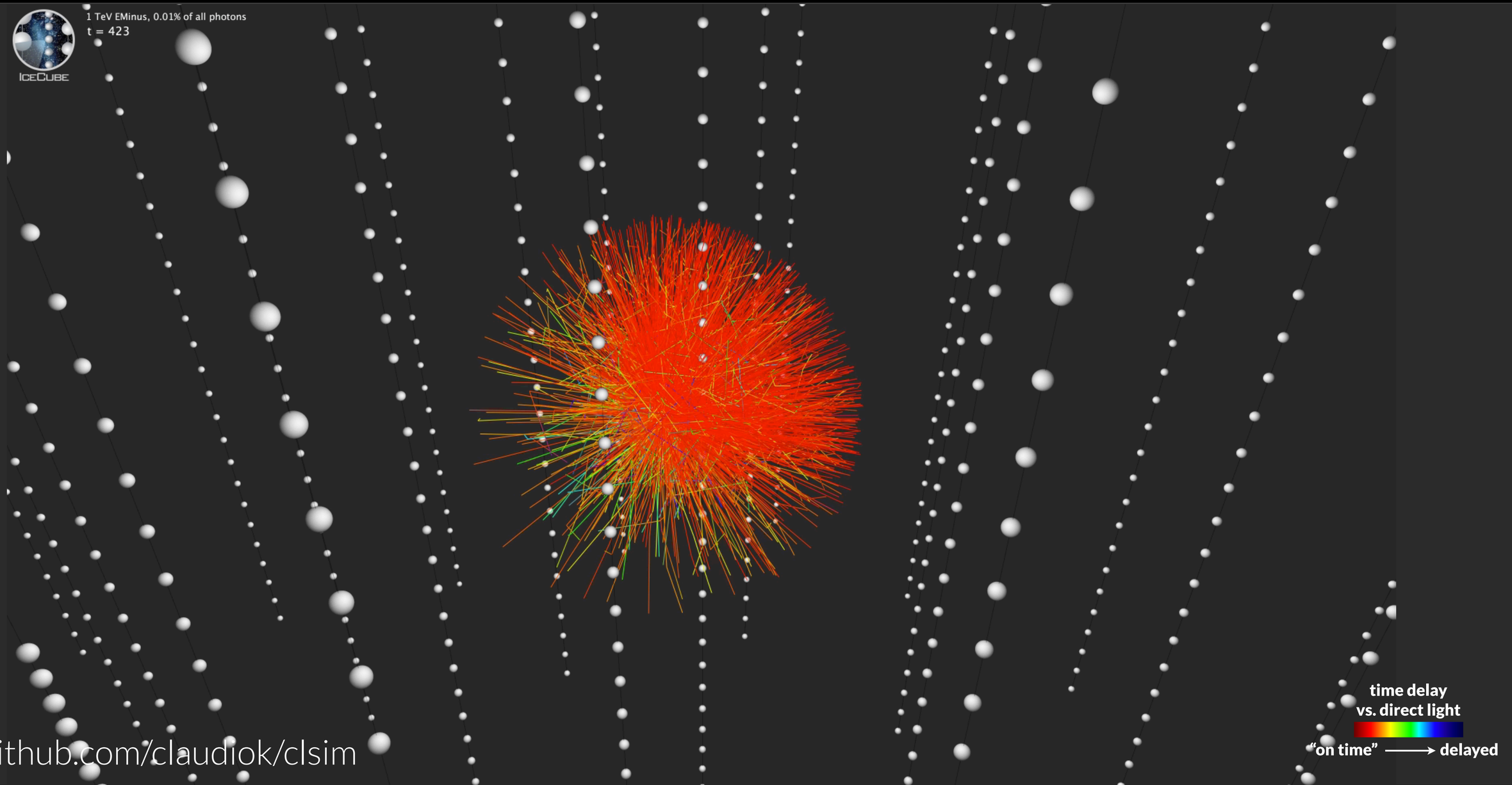
DETECTION PRINCIPLE (CASCADE IN WATER)

This is how it would look in sea water (KM3NeT/ANTARES)



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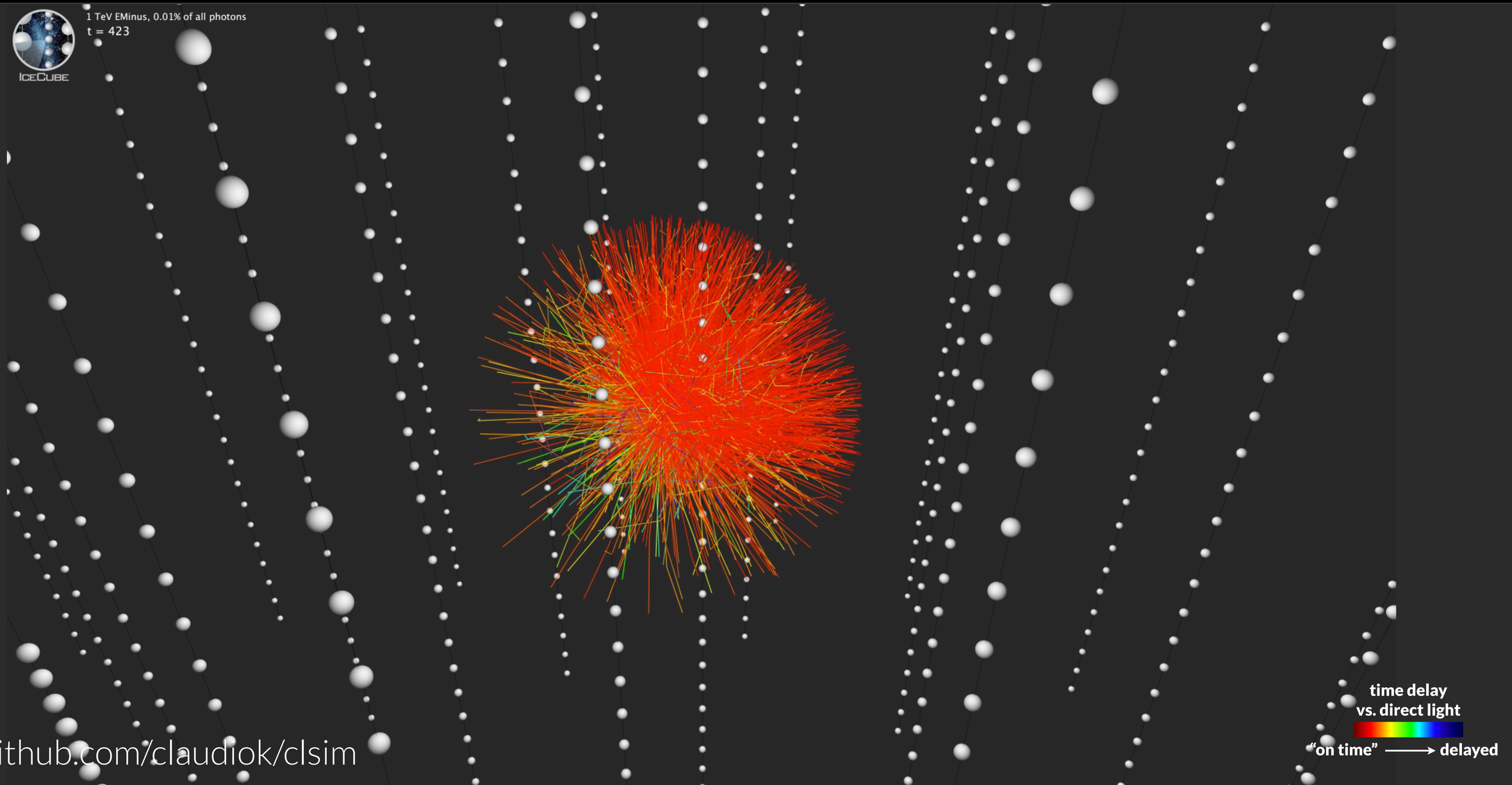

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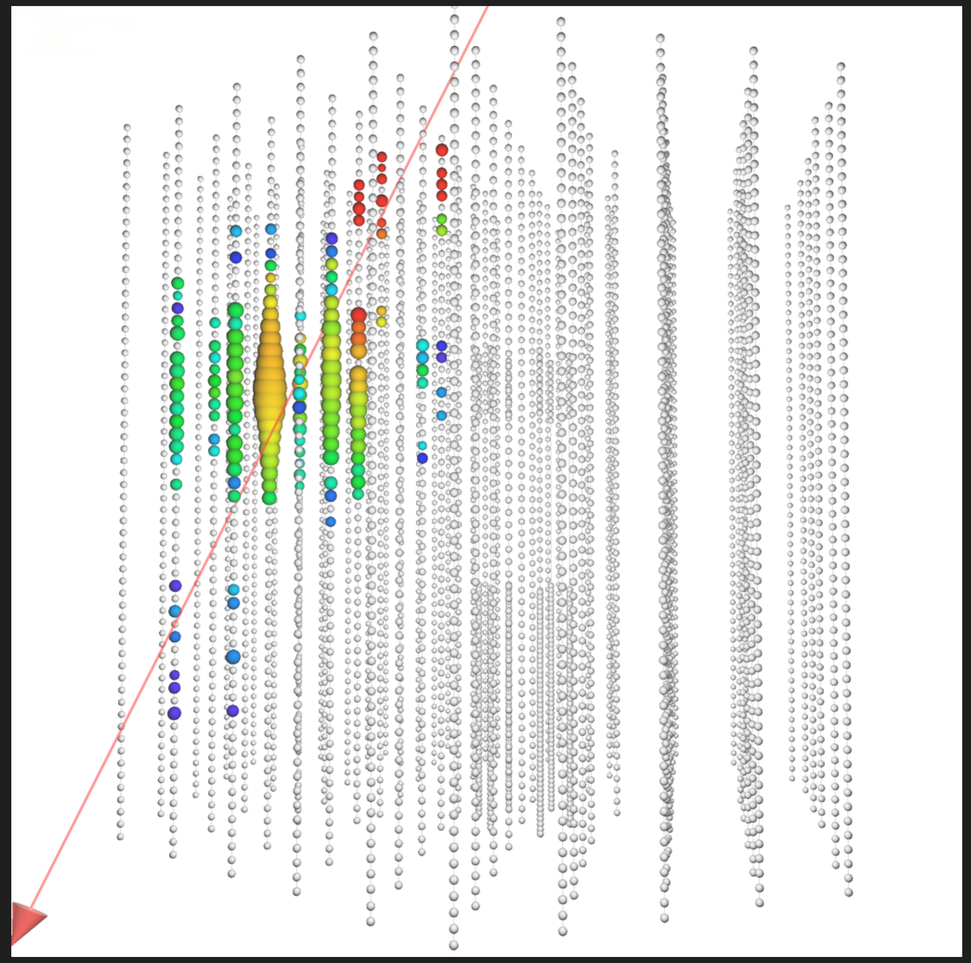
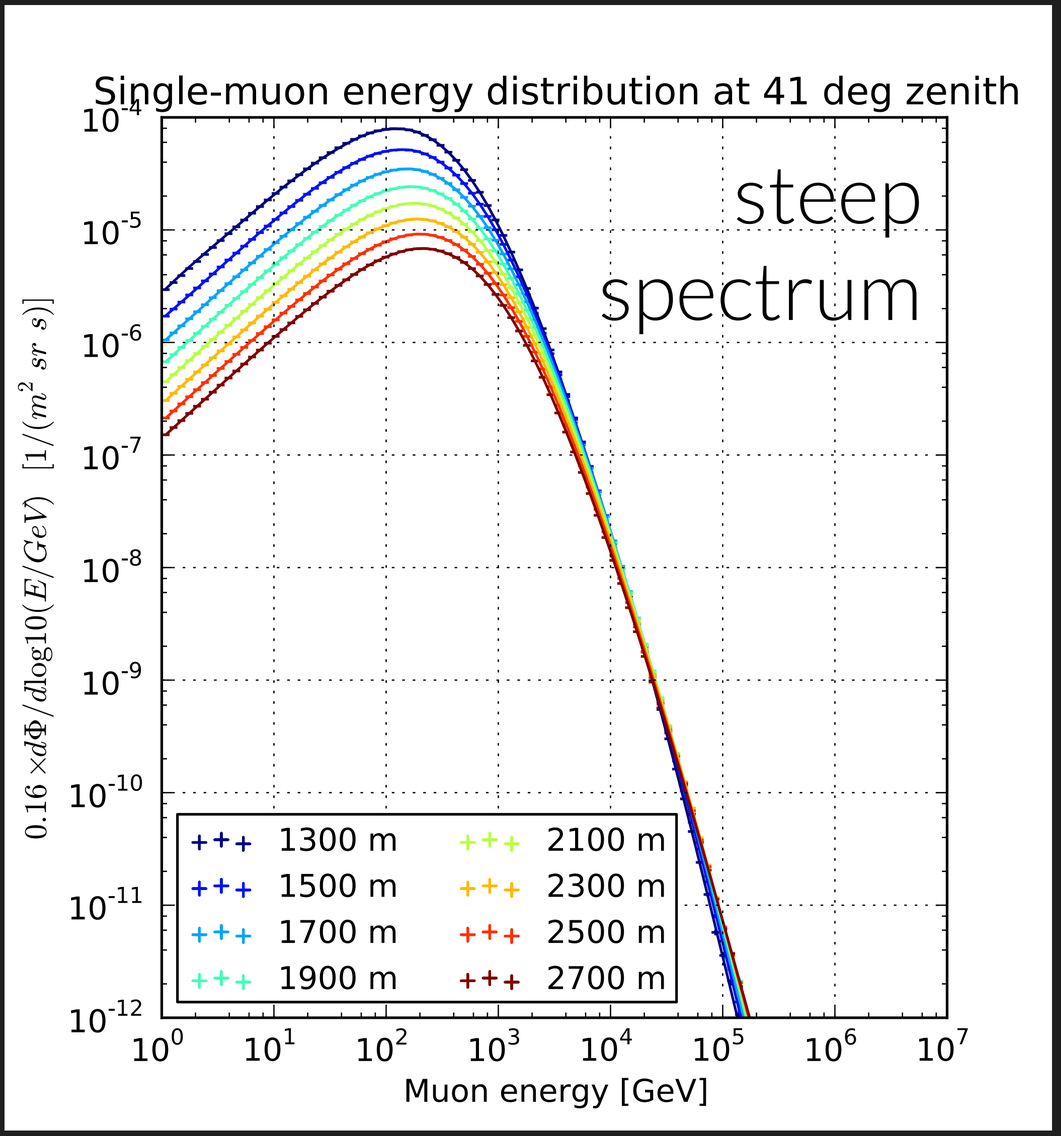
BACKGROUND: PENETRATING MUONS

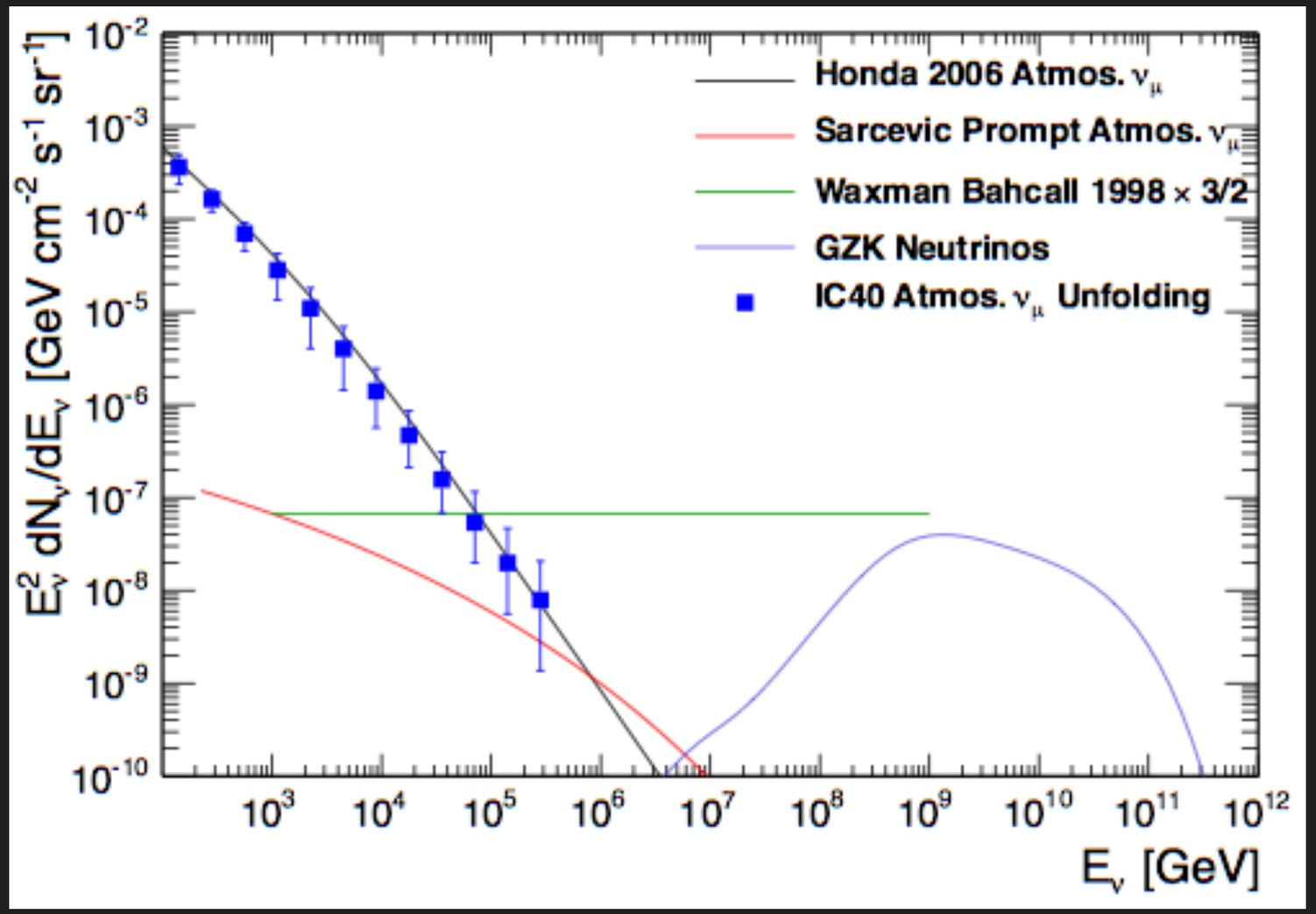


100 TeV single muon



NEUTRINOS ABOVE 1 TEV

sketch of the different expected neutrino flux components



(not a real measurement - just for illustration)

NEUTRINOS ABOVE 1 TEV

sketch of the different expected neutrino flux components

ATMOSPHERIC NEUTRINOS (π/K)

dominant < 100 TeV

ATMOSPHERIC NEUTRINOS (CHARM)

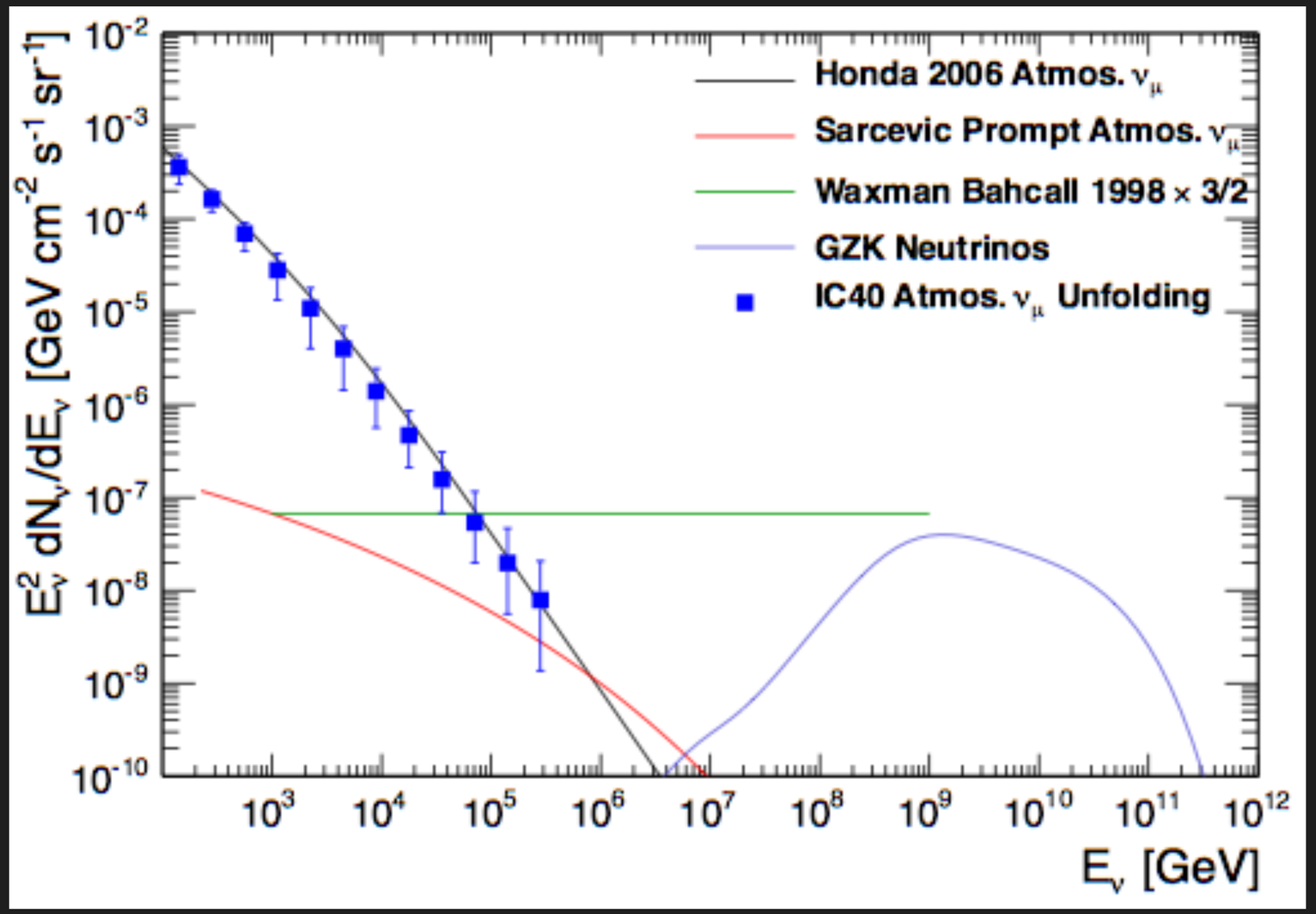
“prompt” ~ 100 TeV

ASTROPHYSICAL NEUTRINOS

maybe dominant > 100 TeV

COSMOGENIC NEUTRINOS

>10^6 TeV



(not a real measurement - just for illustration)

ISOLATING NEUTRINO EVENTS

two strategies

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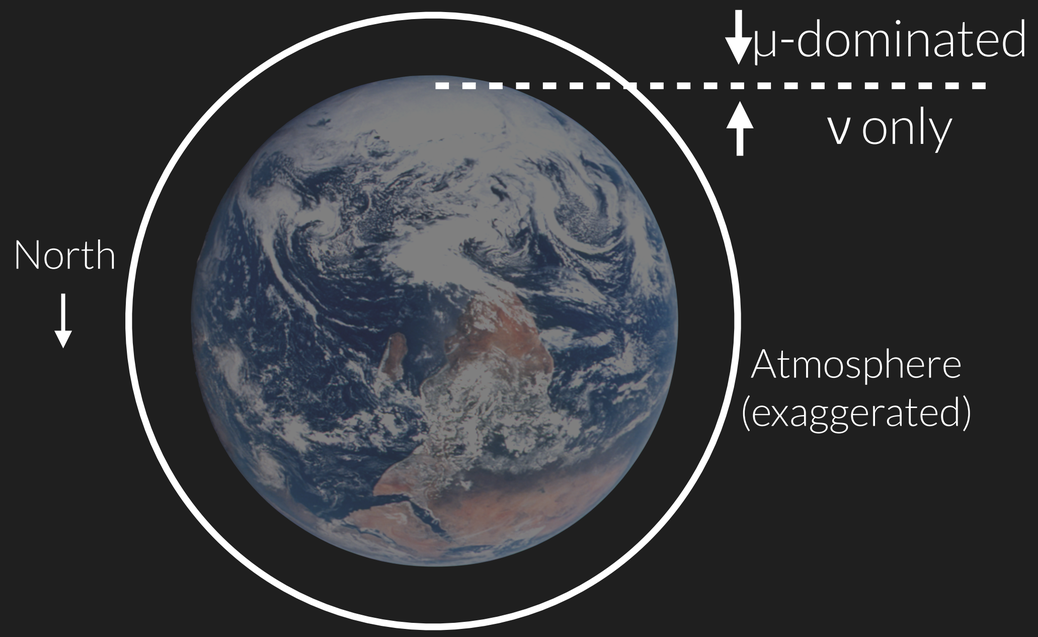
two strategies

Up-going tracks



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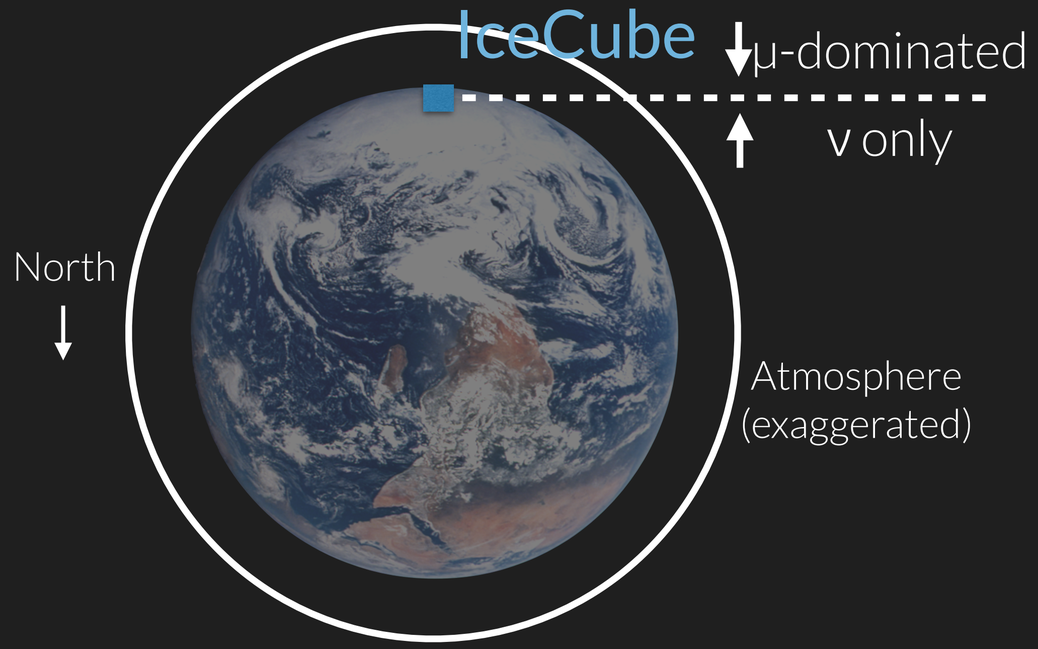

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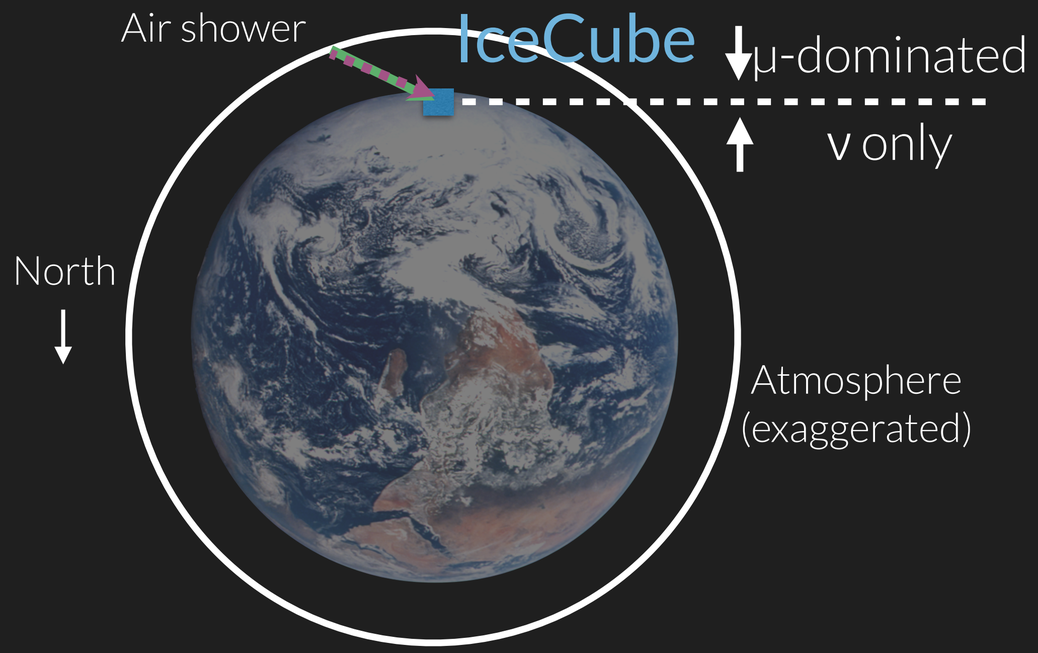

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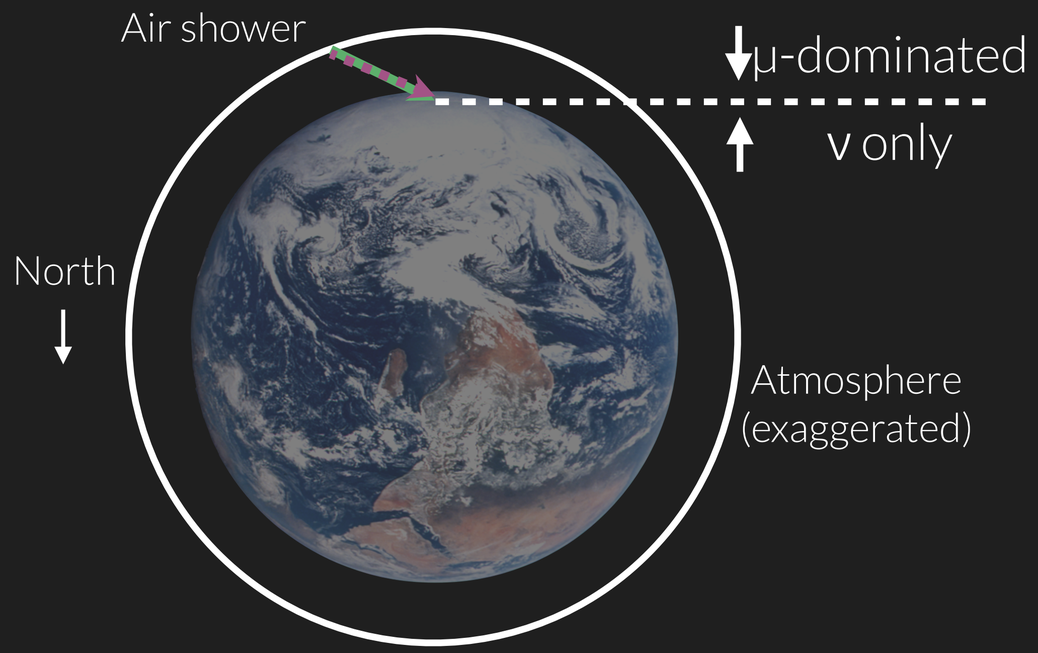

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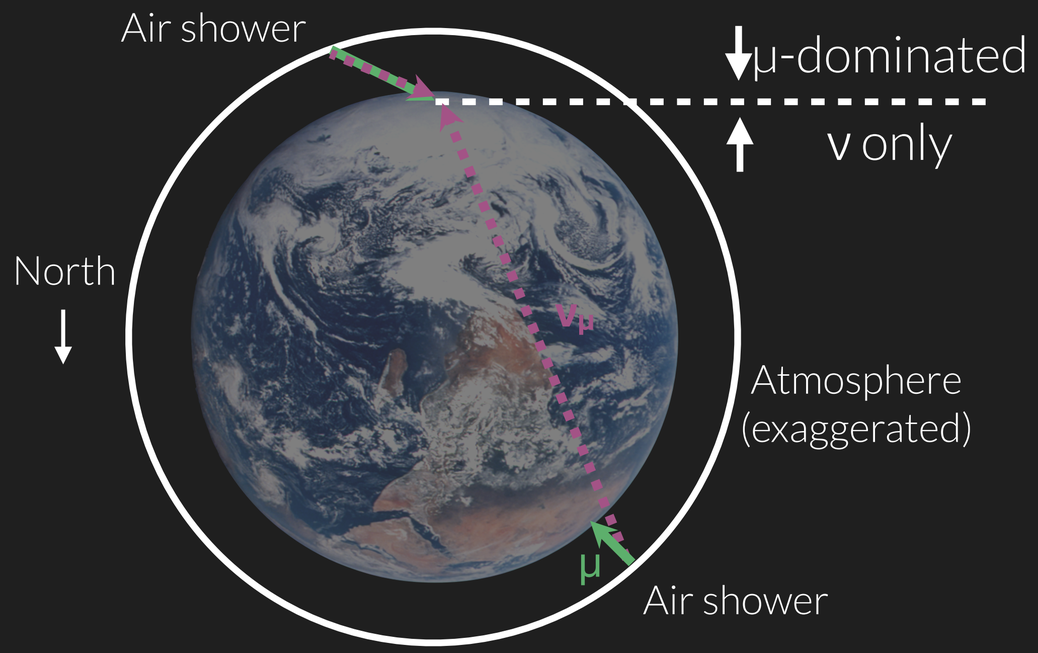

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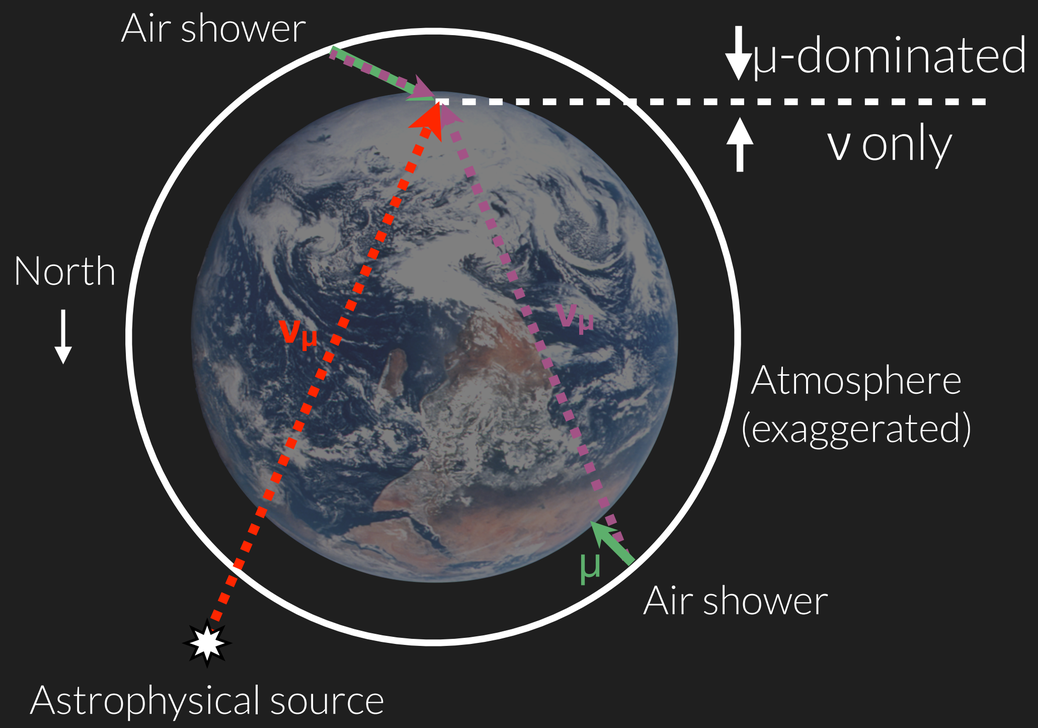

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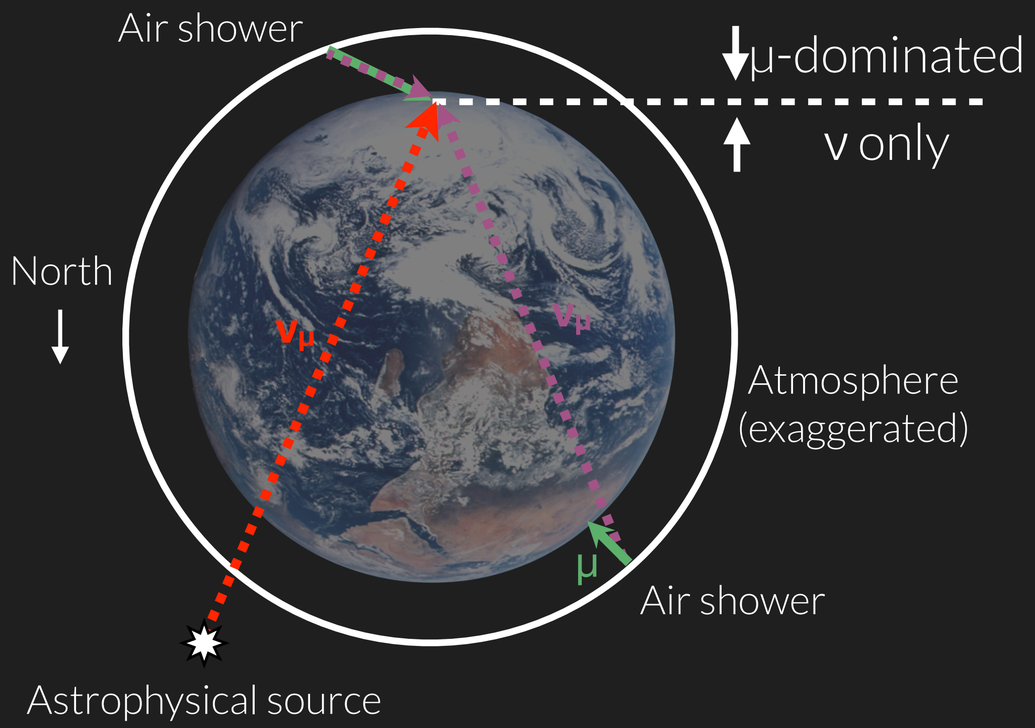

Earth stops penetrating muons

Effective volume larger than detector

Sensitive to ν_μ only

Sensitive to “half” the sky

ISOLATING NEUTRINO EVENTS

two strategies

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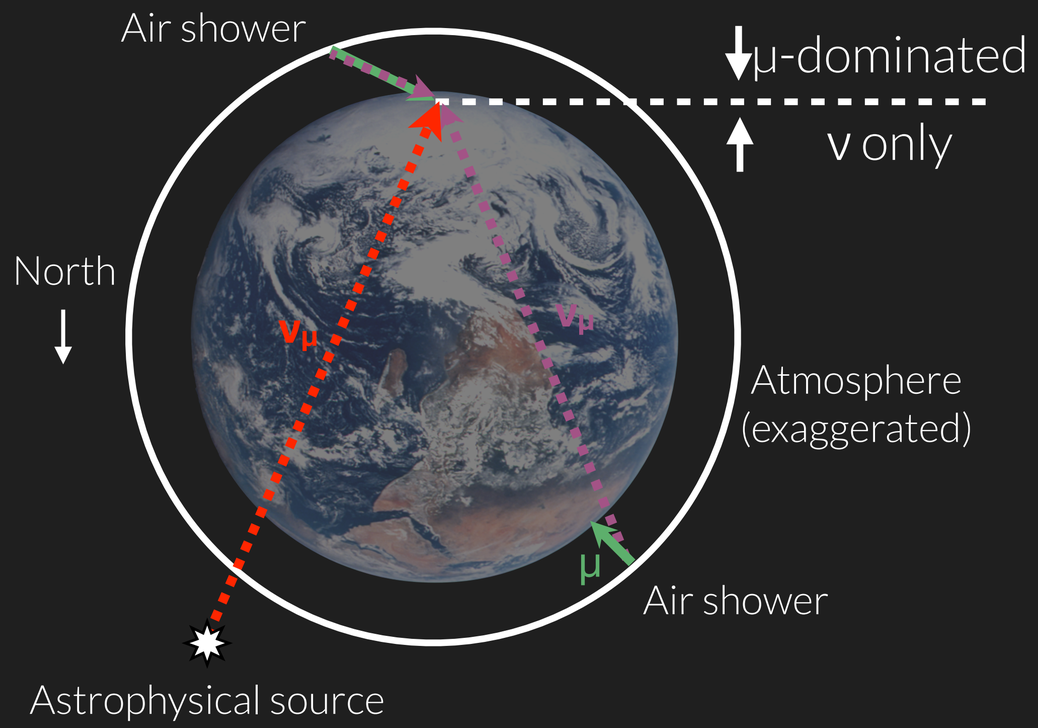

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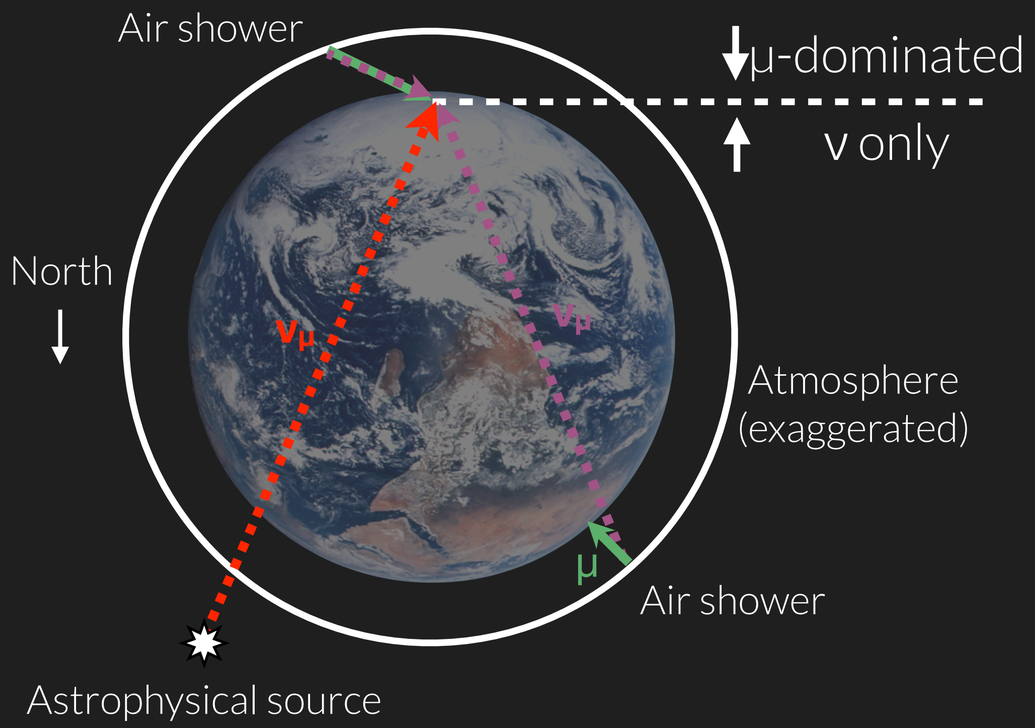

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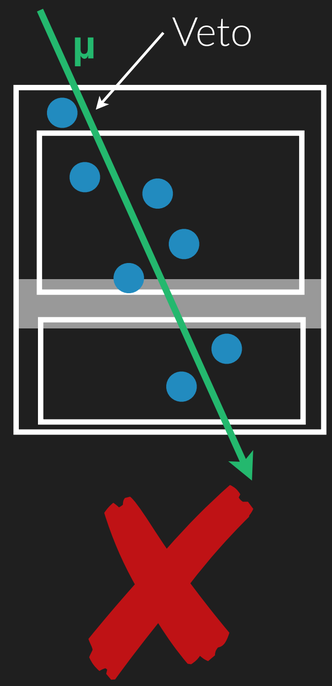

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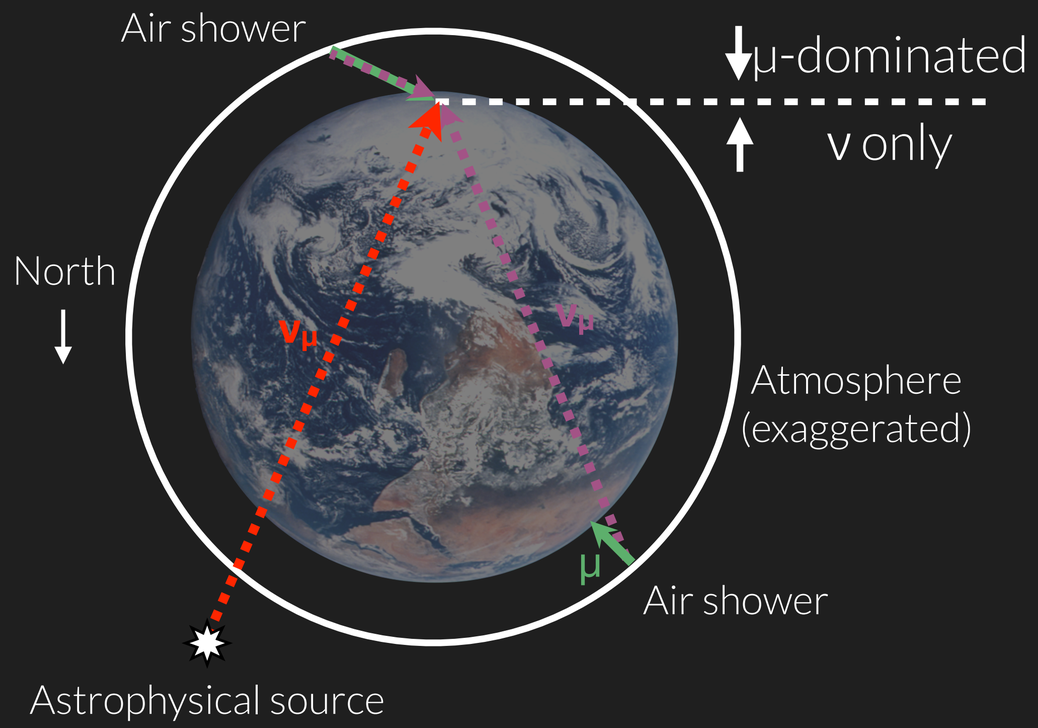

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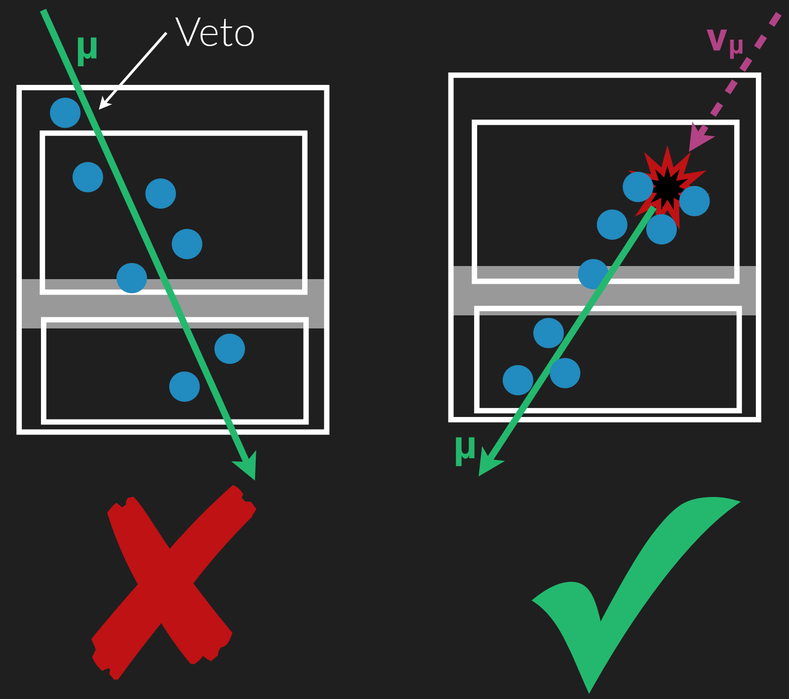

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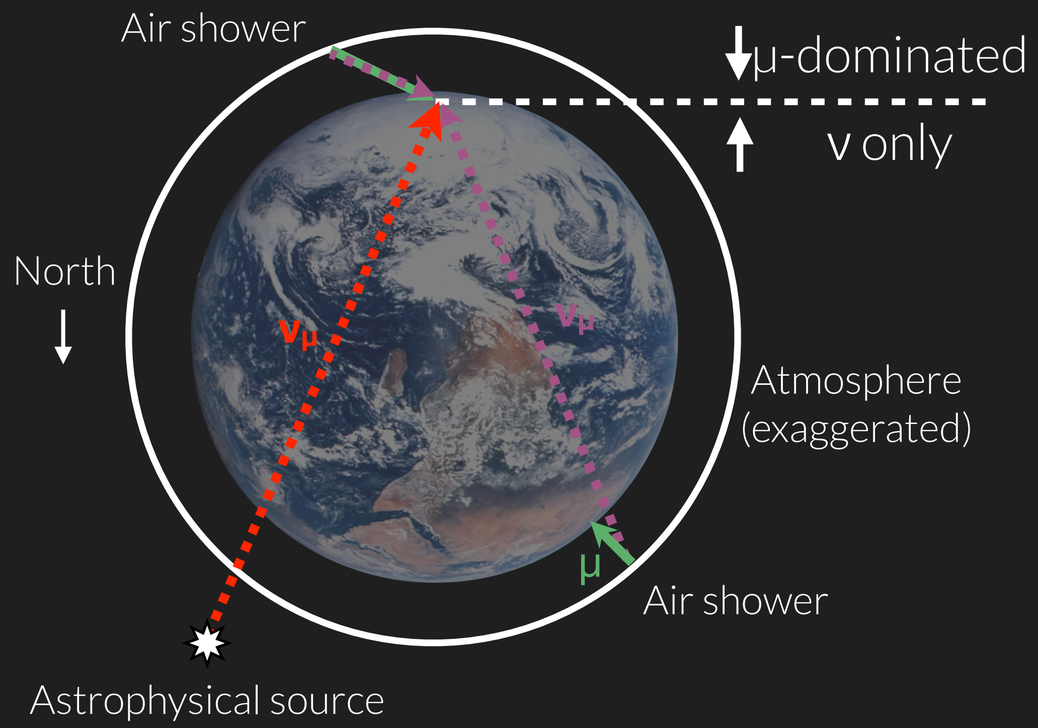
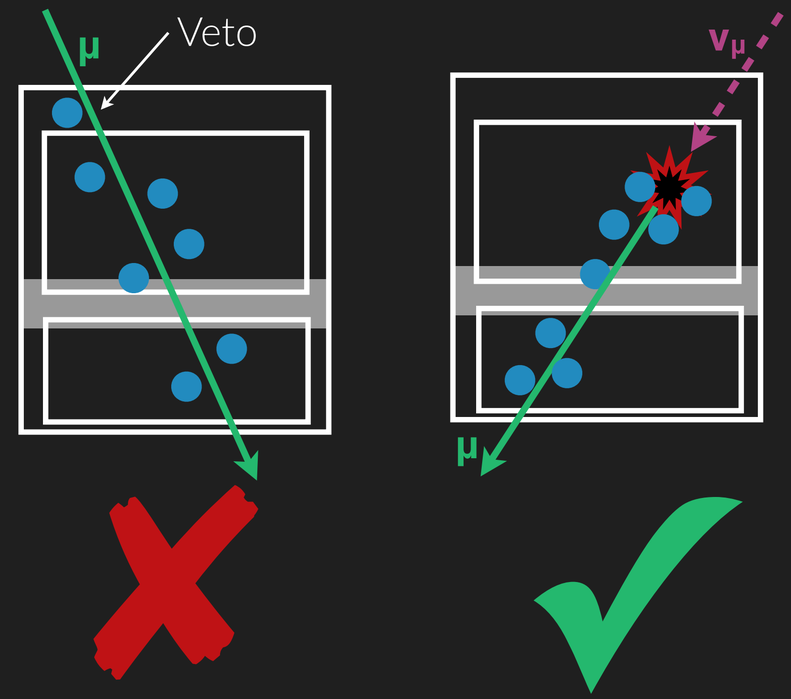


Earth stops penetrating muons
Effective volume larger than detector
Sensitive to ν_μ only
Sensitive to "half" the sky

Active veto



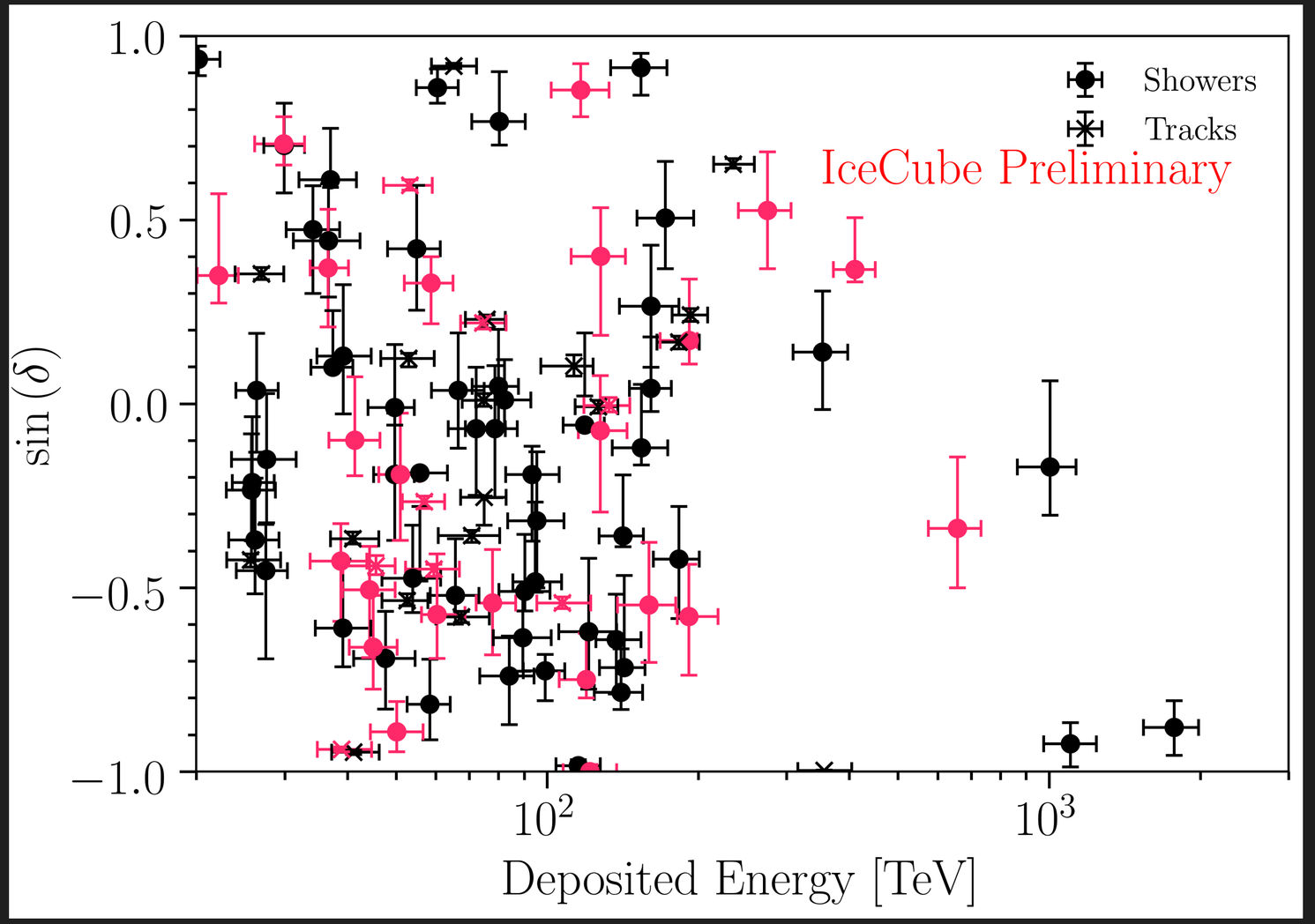
Veto detects penetrating muons
Effective volume smaller than detector
Sensitive to all flavors
Sensitive to the entire sky

HOW IT STARTED

High-Energy Starting Events

Now 7.5 years of data

started with only 37 events on a background of 15 events…



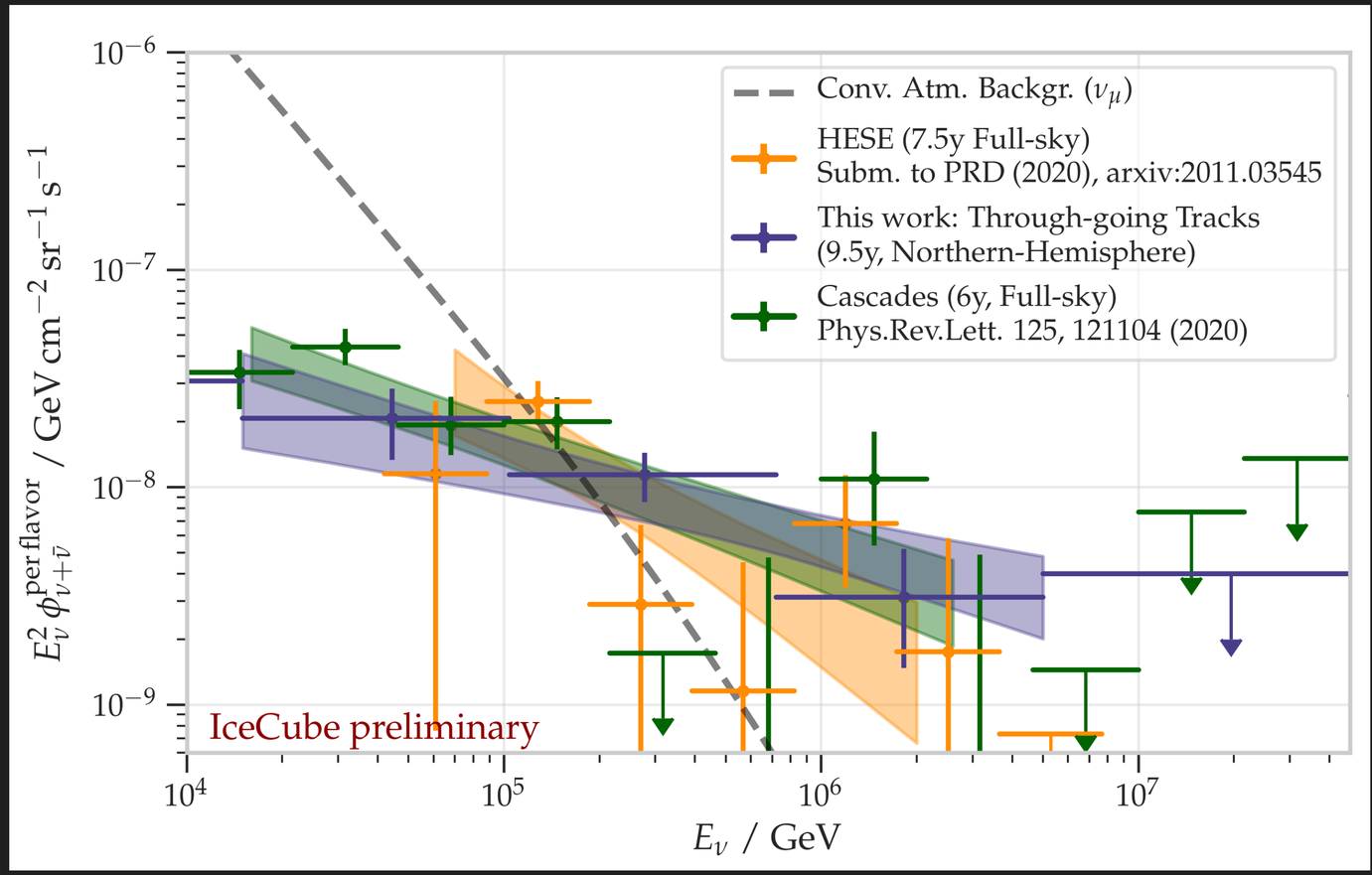
ENERGY SPECTRUM NOW

Measured in various channels

Polar-law spectrum

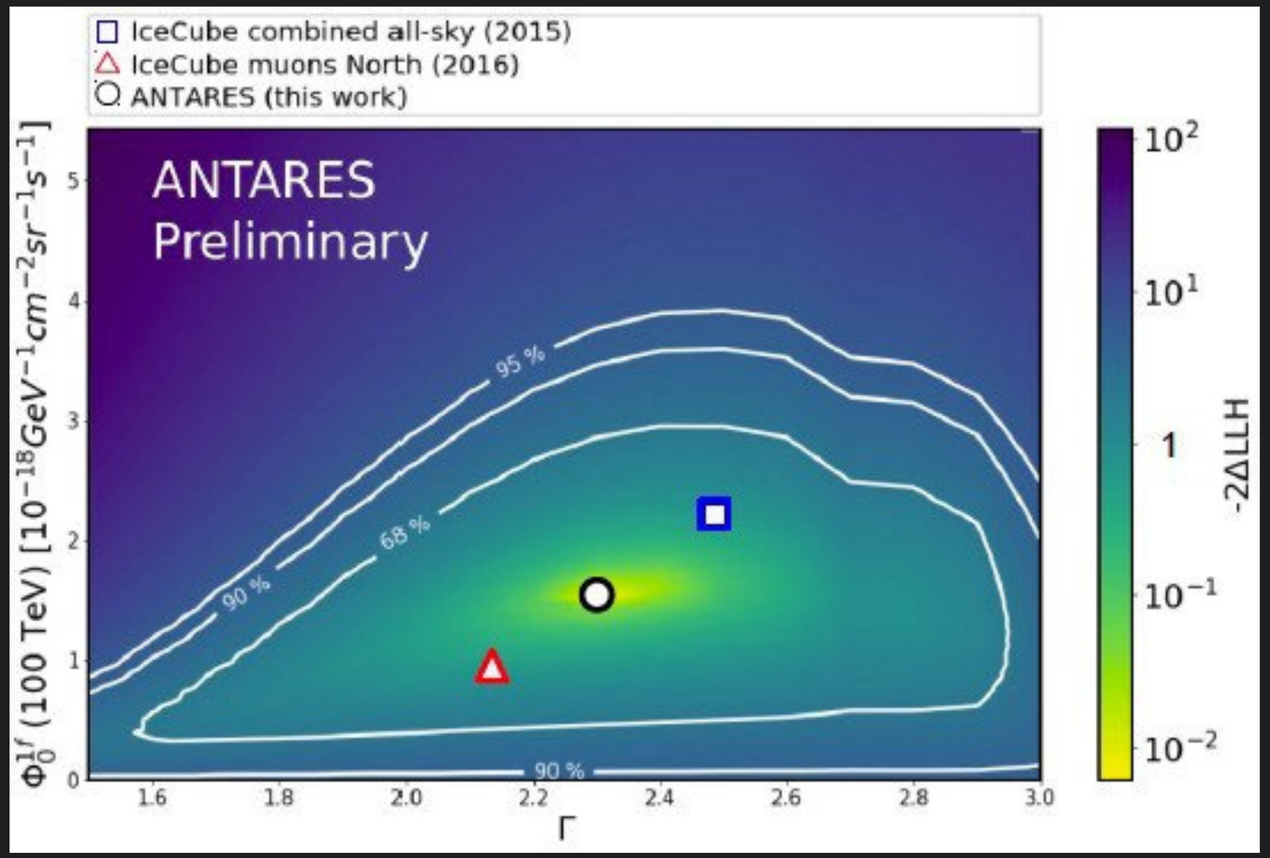
As bright as it could possibly be, similar to (or brighter than!) gamma rays

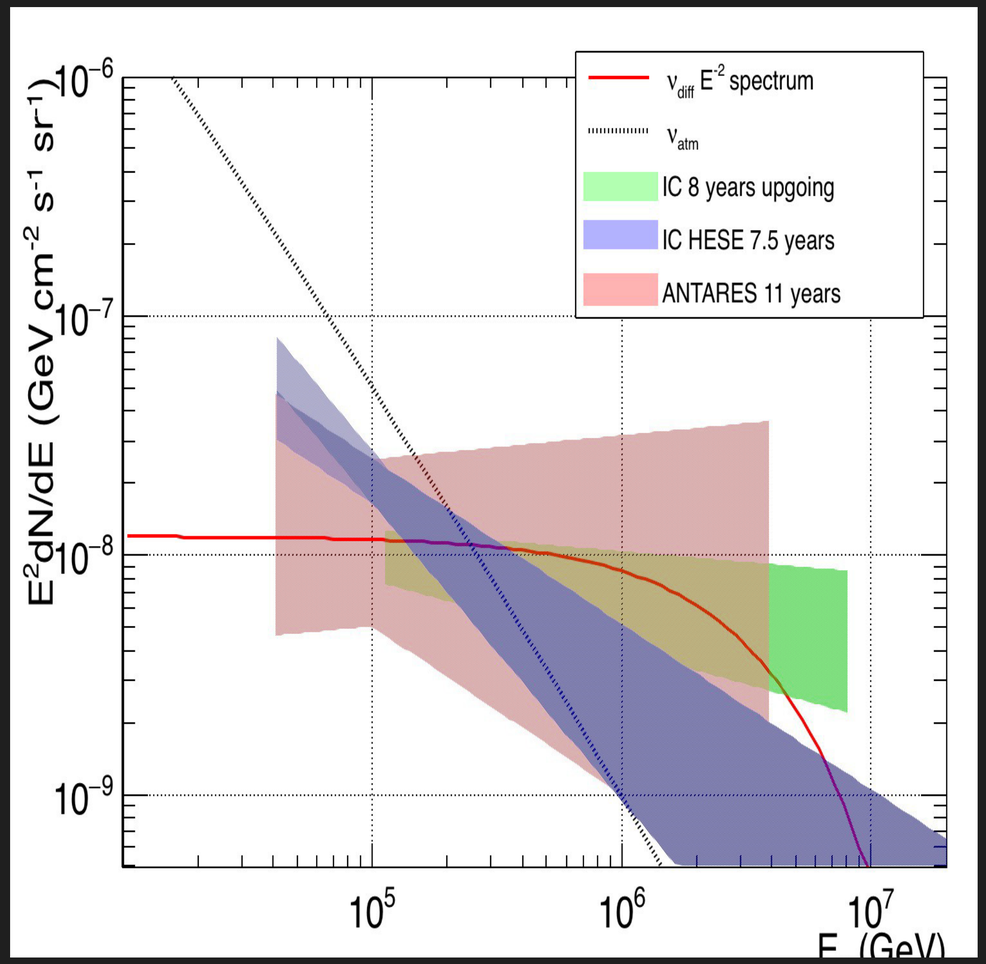
Thousands of astrophysical neutrinos per year



AS SEEN BY ANTARES

Results not really constraining... but fully compatible with IceCube





$\Phi_{100TeV} = 1.5 \pm 1.0 \times 10^{-18}$ GeV^{-1} cm^{-2} s^{-1} sr^{-1} $\quad \gamma = 2.3 \pm 0.4$

HIGH-ENERGY EVENTS AS PUBLIC ALERTS

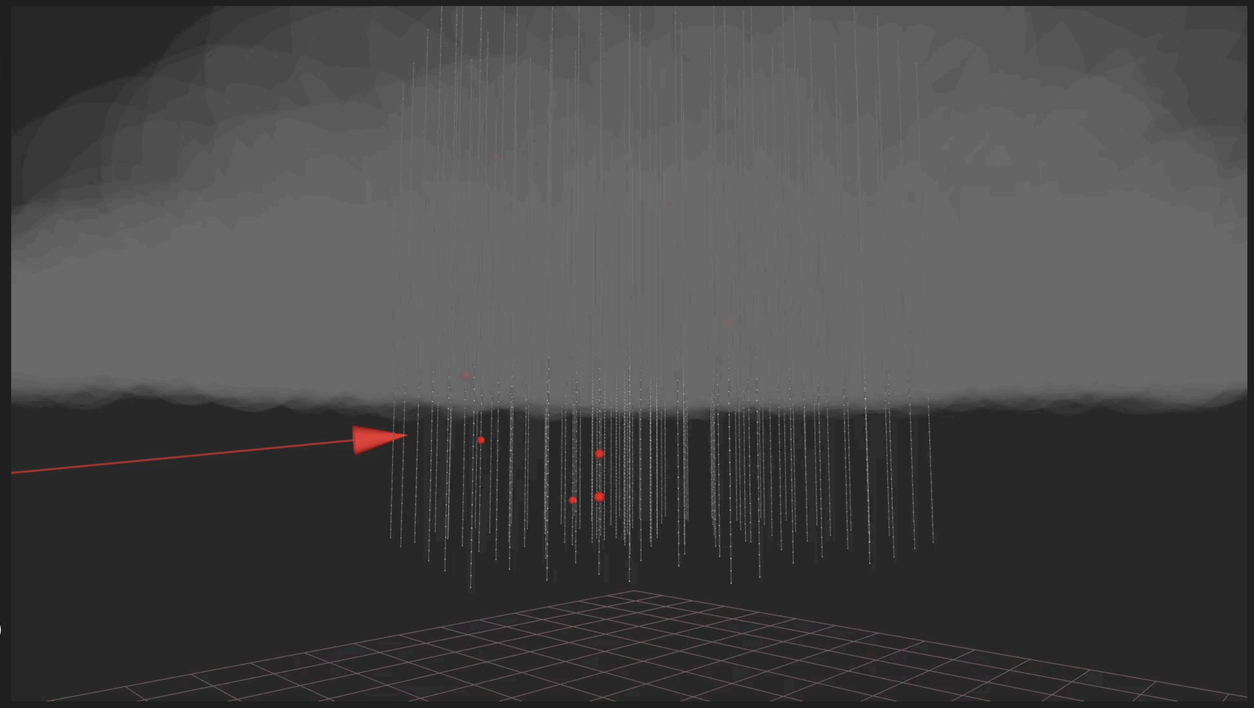
We send our high-energy events in real-time as public GCN alerts!

```
TITLE:            GCN/AMON NOTICE
NOTICE_DATE:      Fri 22 Sep 17 20:55:13 UT
NOTICE_TYPE:      AMON ICECUBE EHE
RUN_NUM:          130033
EVENT_NUM:        50579430
SRC_RA:            77.2853d {+05h 09m 08s} (J2000),
                   77.5221d {+05h 10m 05s} (current),
                   76.6176d {+05h 06m 28s} (1950)
SRC_DEC:           +5.7517d {+05d 45' 06"} (J2000),
                   +5.7732d {+05d 46' 24"} (current),
                   +5.6888d {+05d 41' 20"} (1950)
SRC_ERROR:        14.99 [arcmin radius, stat+sys, 50% containment]
DISCOVERY_DATE:   18018 TJD;   265 DOY;   17/09/22 (yy/mm/dd)
DISCOVERY_TIME:   75270 SOD {20:54:30.43} UT
REVISION:         0
N_EVENTS:         1 [number of neutrinos]
STREAM:           2
DELTA_T:          0.0000 [sec]
SIGMA_T:          0.0000e+00 [dn]
ENERGY :          1.1998e+02 [TeV]
SIGNALNESS:       5.6507e-01 [dn]
CHARGE:           5784.9552 [pe]
SUN_POSTN:        180.03d {+12h 00m 08s}   -0.01d {-00d 00' 53"}
SUN_DIST:         102.45 [deg]   Sun_angle= 6.8 [hr] (West of Sun)
MOON_POSTN:       211.24d {+14h 04m 58s}   -7.56d {-07d 33' 33"}
```

Example:

IC170922A sent on Sep 22, 2017

We automatically send **rough reconstructions first** and then **update them.**



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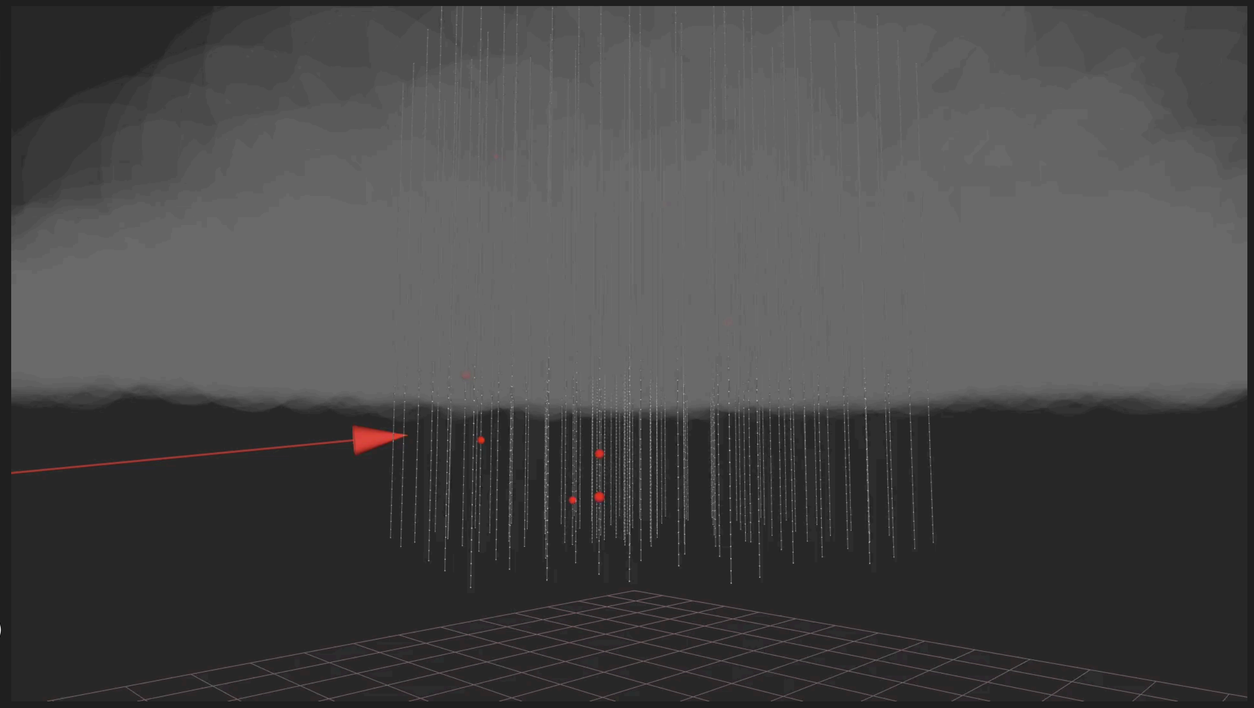

MANY FOLLOW-UPS: TXS 0506+056

This is where things became very interesting…

TITLE: GCN CIRCULAR
NUMBER: 21916
SUBJECT: IceCube-170922A - IceCube observation of a high-energy neutrino candidate event
[…]

Claudio Kopper (University of Alberta) and Erik Blaufuss (University of Maryland) report on behalf of the IceCube Collaboration […].

On 22 Sep, 2017 IceCube detected a track-like, very-high-energy event with a high probability of being of astrophysical origin. The event was identified by the Extremely High Energy (EHE) track event selection. The IceCube detector was in a normal operating state.[…]

After the initial automated alert […], more sophisticated reconstruction algorithms have been applied offline, with the direction refined to:

Date: 22 Sep, 2017
Time: 20:54:30.43 UTC
RA: 77.43 deg (-0.80 deg/+1.30 deg 90% PSF containment) J2000
Dec: 5.72 deg (-0.40 deg/+0.70 deg 90% PSF containment) J2000

We encourage follow-up by ground and space-based instruments to help identify a possible astrophysical source for the candidate neutrino.

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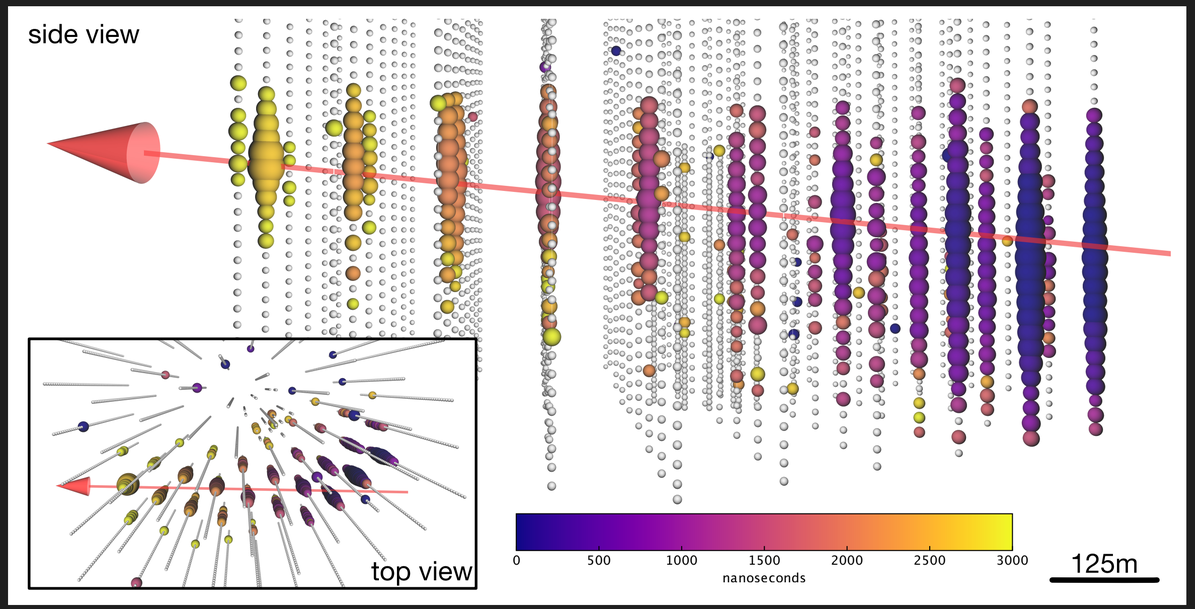

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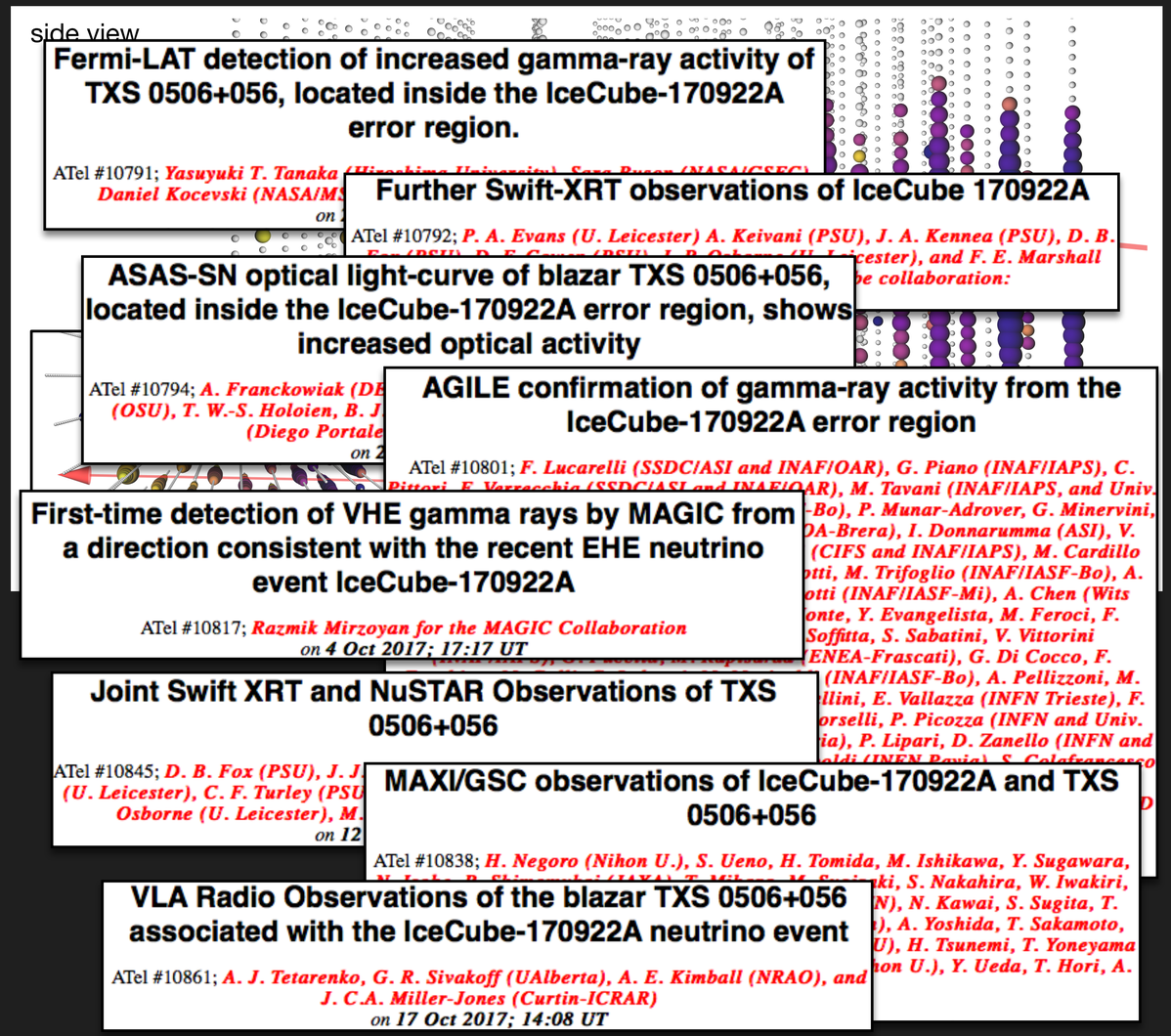


ICECUBE-170922A AND TXS 0506+056

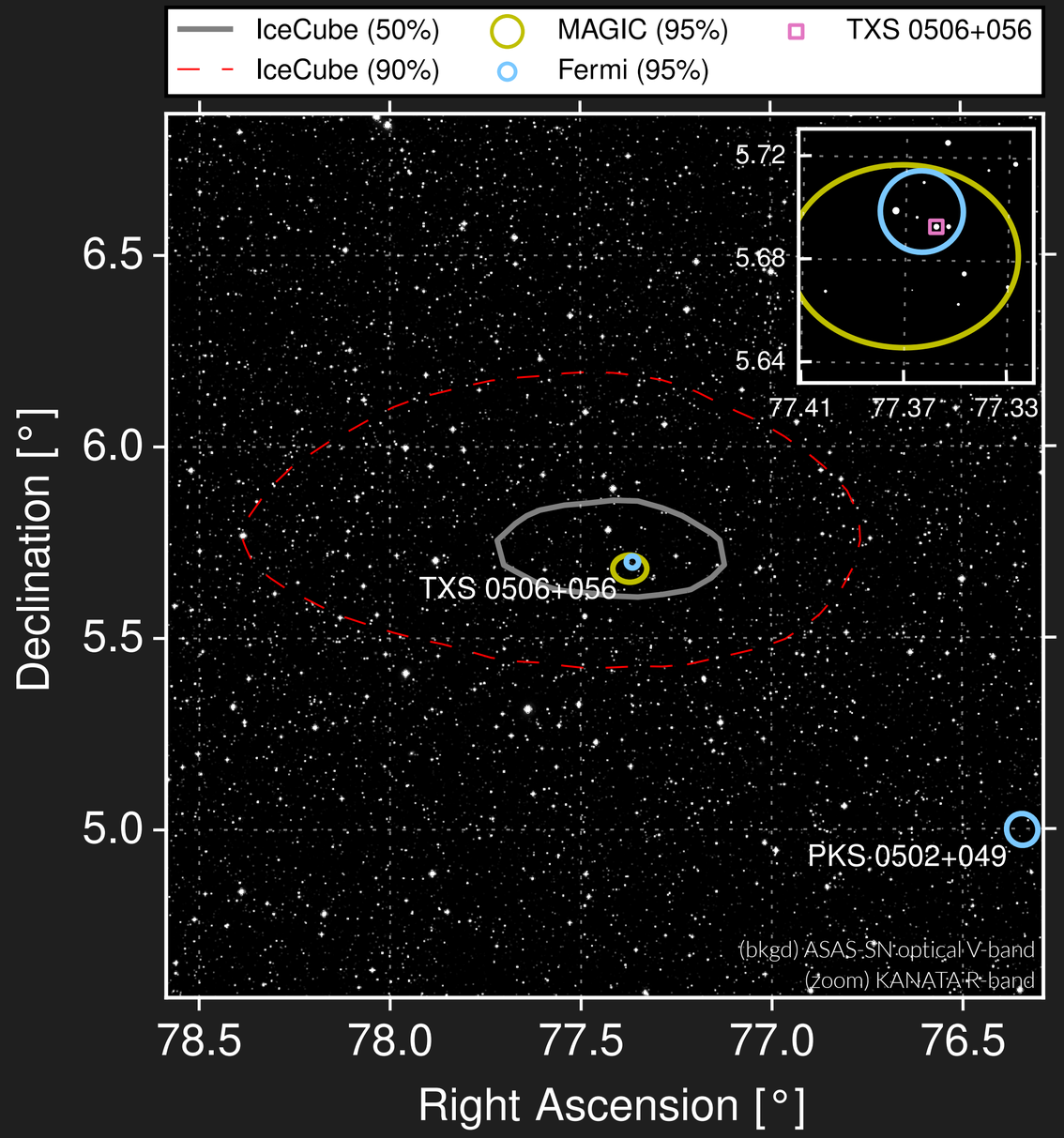
(Science 361 (2018) 6398, eaat1378)

TXS 0506+056 redshift of z = 0.3365
(S. Paiano et al. ApJL 854, L32 (2018).)

Time-averaged luminosity an order of magnitude higher than Mkn 421, Mkn 501, or 1ES 1959+605

Time-integrated neutrino spectrum is approximately $E^{-2.1}$

Chance probability of a Fermi-IceCube coincident observation: **3σ** level
(Significance determined using all known Fermi-LAT blazars and the historical data sample from IceCube.)



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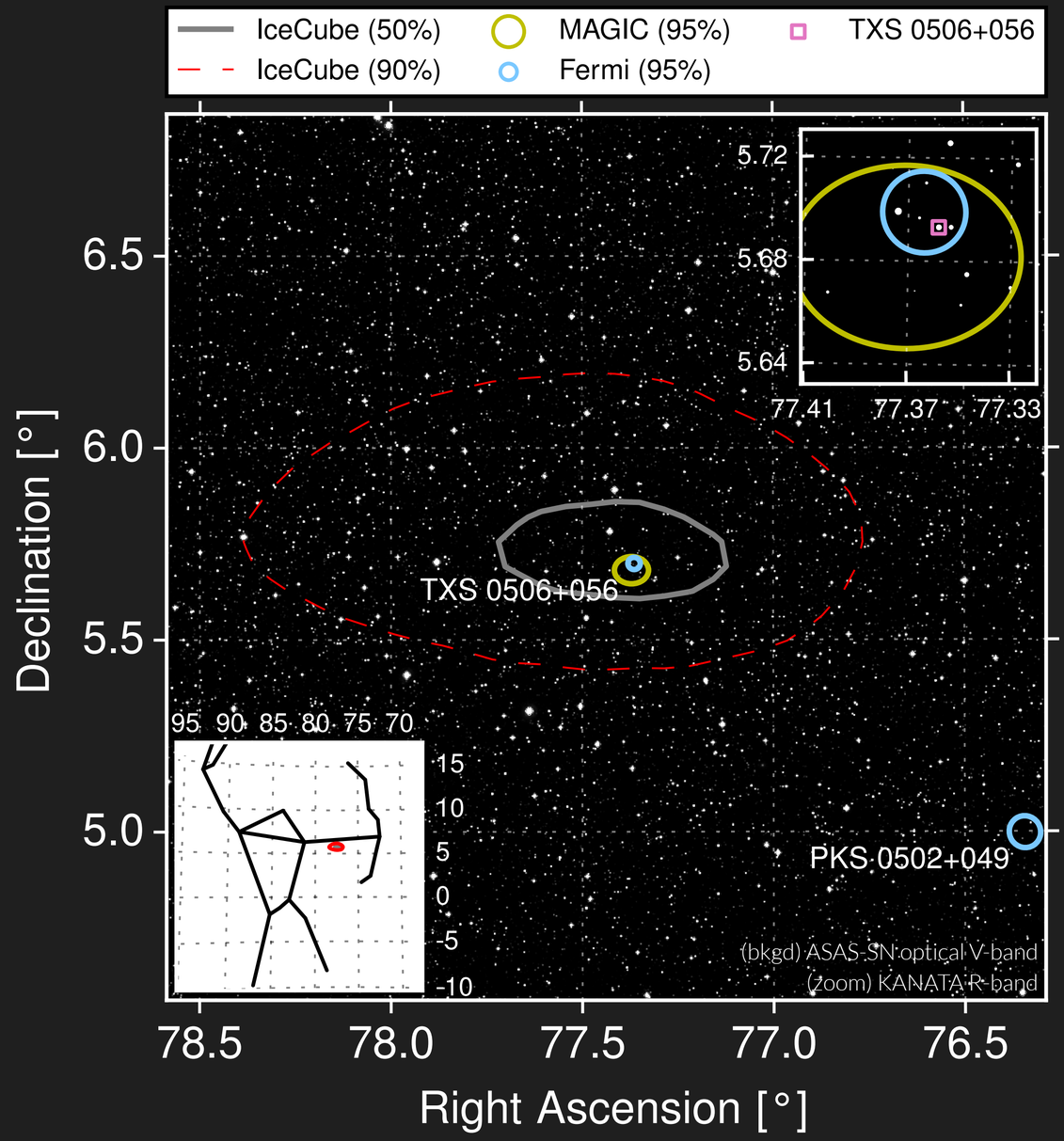


ICECUBE-170922A AND TXS 0506+056

IceCube archival search

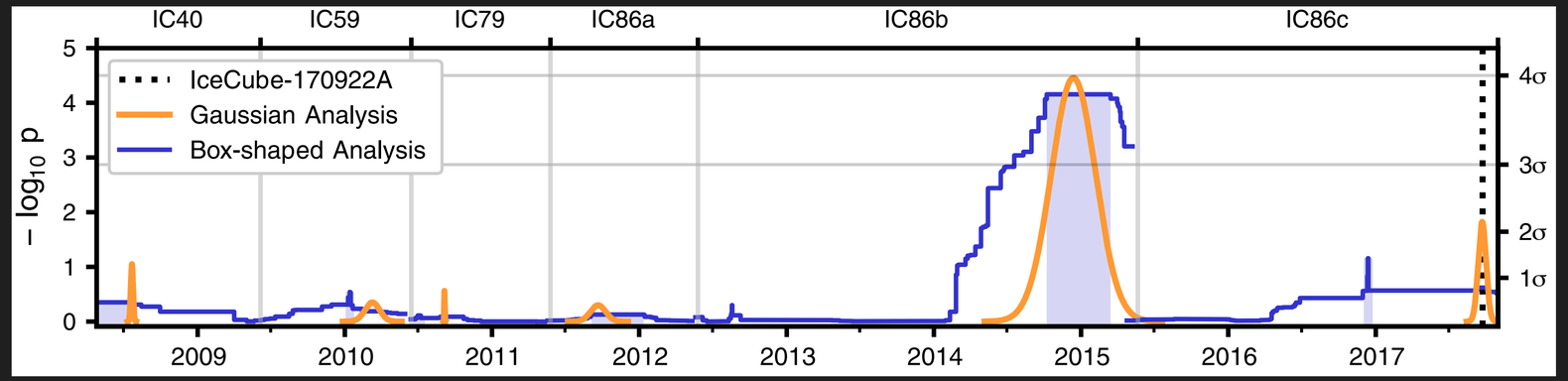
(Science 361 (2018) 6398, 147-151)

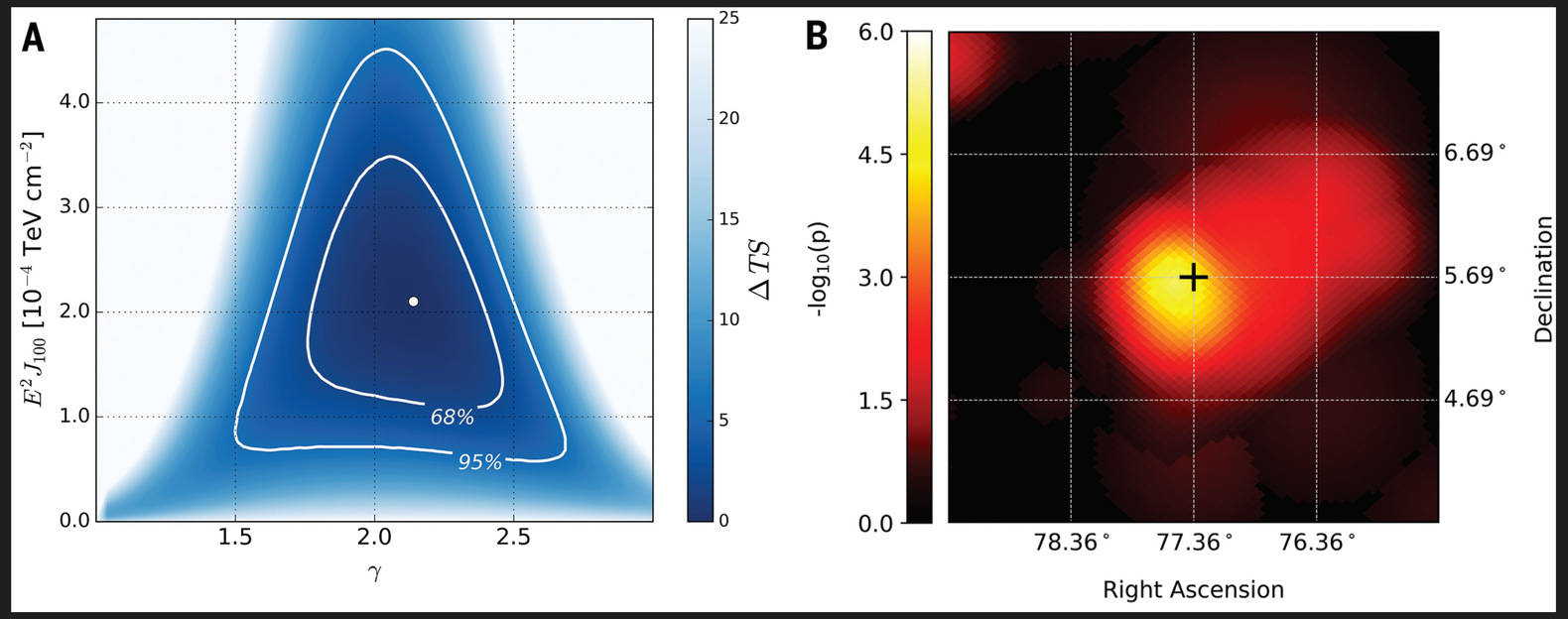
IceCube evaluated 9.5 years of archival data in the direction of TXS 0506+056

13+5 events excess compared to background expectations (Sept 2014—March 2015)

Inconsistent with bkg-only hypothesis at the **3.5σ** level

(In addition and independently of the previous 3σ when looking in this specific direction)





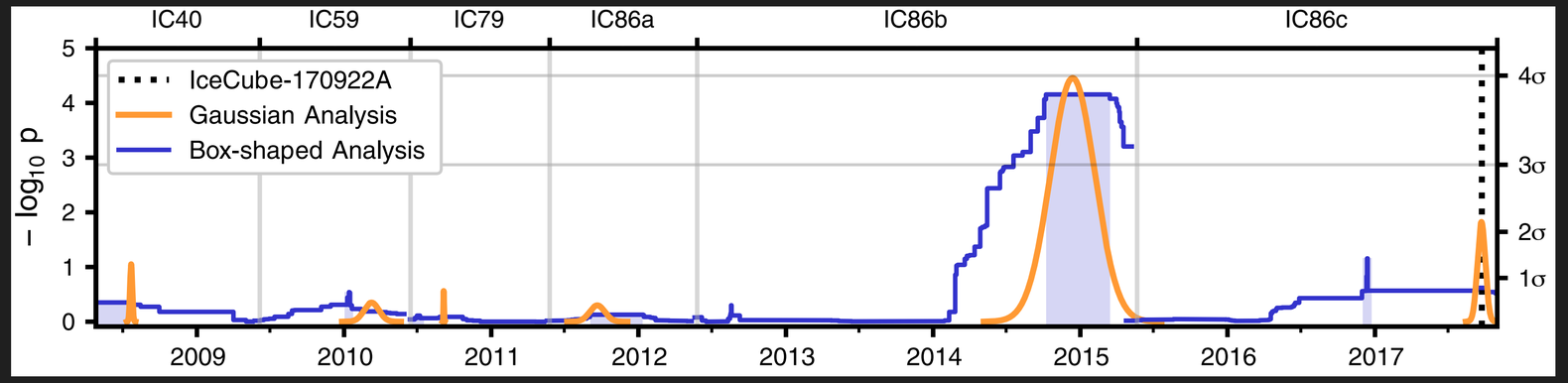
TXS 0506+056 - TIME-DEPENDENCE

No obvious correlation with a γ flare – source quiescent then

2014 excess much larger than 2017

Emission seems quite bursty

No real clue what was special in 2014



WHY IS THIS OUR FIRST SOURCE?

Not an especially notable/famous source – there are many nearer/brighter blazars

Extremely far away (4.5 billion light years)

At every other band/messenger, bright nearby sources dominate – why not here

WHAT WE KNOW FROM THIS RESULT

What we do know

Independent 3.0σ and 3.5σ evidence for neutrino emission

Two different measurements seem to be telling us different stories about emission

2014 flare at least an order of magnitude brighter than 2017 one

What we don’t know

Why **this** source?

Why is the 2014 emission so much brighter?

What is the emission mechanism?

SO WHAT ARE THE SOURCES?

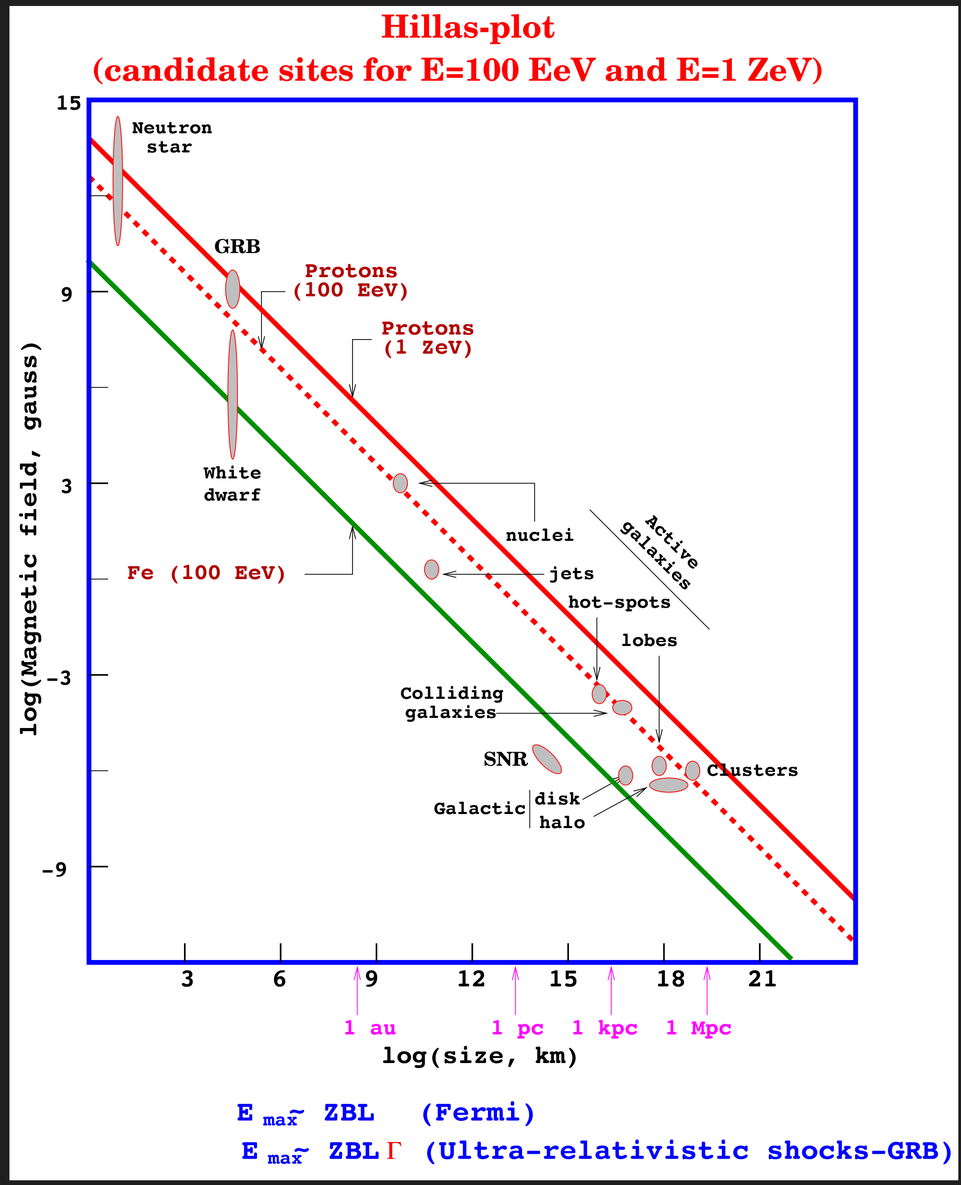
Things we have ruled out (making "standard" assumptions) - or where we have more information

THE POSSIBILITIES

diffuse flux/cosmic rays

Limited number of possibilities to accelerate the highest energy cosmic rays

Need to contain newborn cosmic rays during acceleration



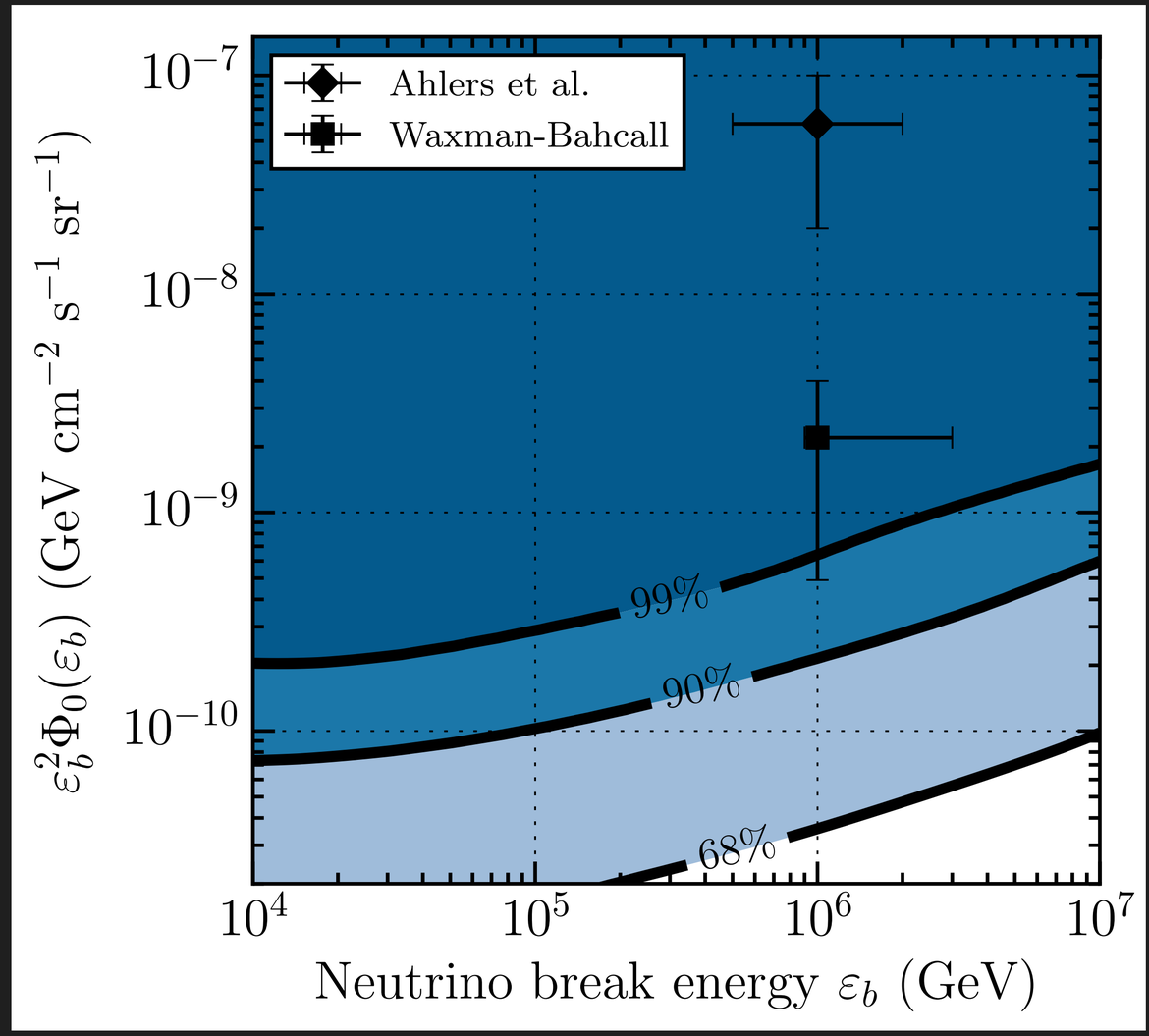
GAMMA-RAY BURSTS?

the biggest explosions in the universe

About one GRB daily

Energy density in photons about right

Ruled out by ~ two orders of magnitude
—unless many are hidden



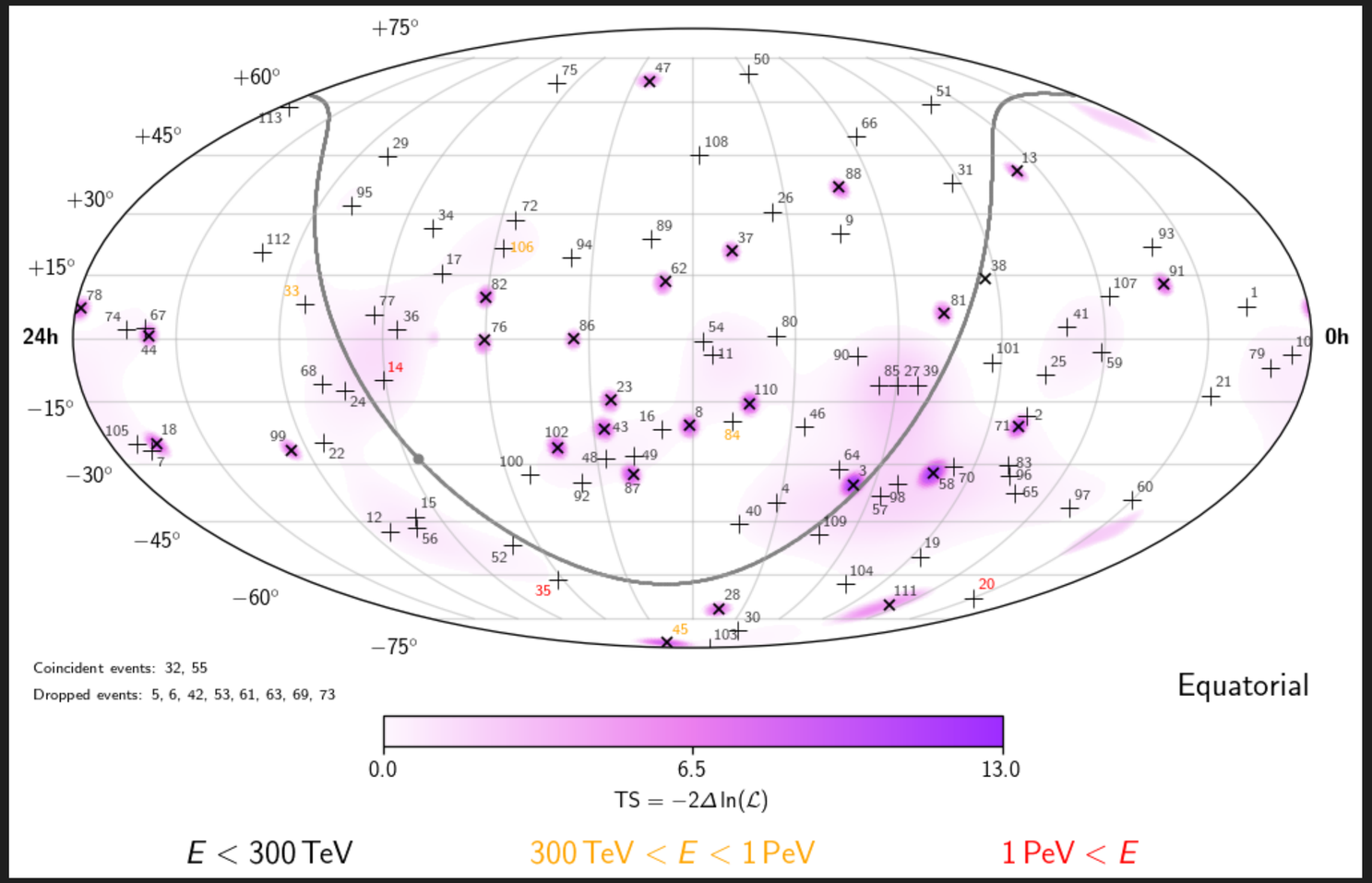
arXiv:1702.06868

GALACTIC SOURCES?

At basically all (EM) wavelengths, the galaxy is the brightest thing

No obvious correlation to the galactic plane published at this point

But there **should** be a component at some level, so stay tuned…



DARK MATTER DECAYS?

PeV dark matter one of several exotic possibilities

Largely consistent with the data

Some enhancement expected at galactic center?

Not clear how to prove/disprove this

BLAZARS?

published limits in arXiv:1611.03874

Dominant contribution to Fermi-LAT diffuse gamma background

Hints of neutrinos from other AGN (NGC 1068)

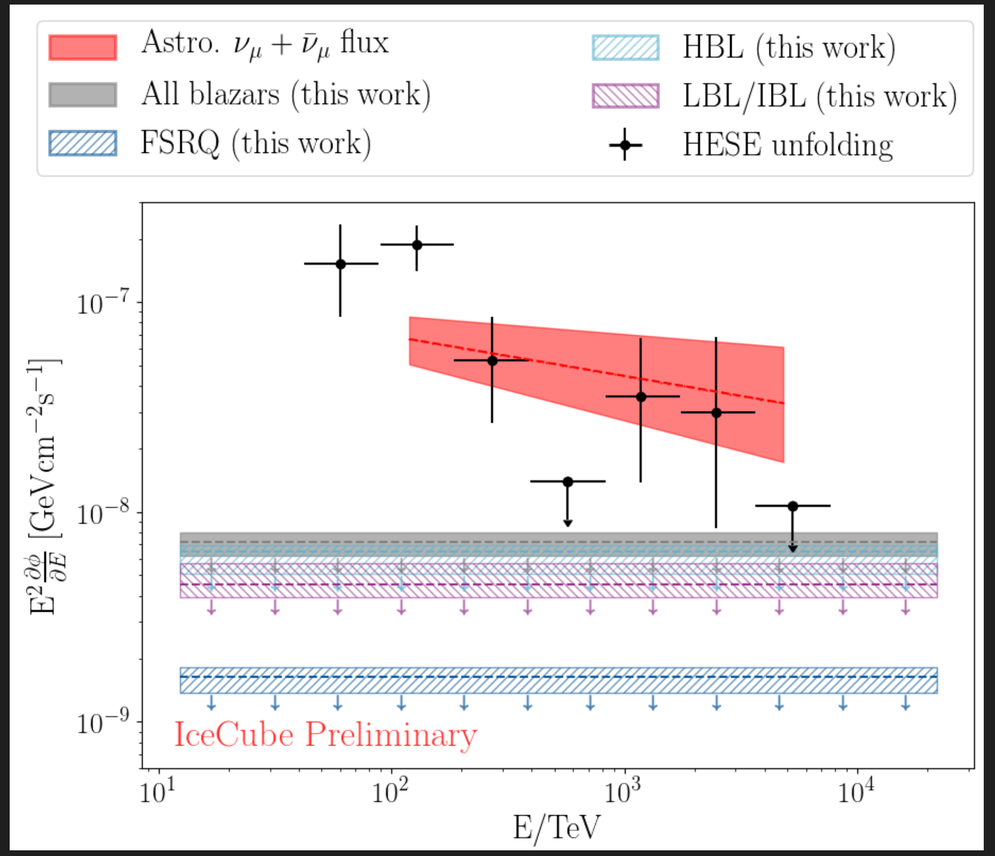
Blazars are the largest piece of this

Neutrinos proportional to gamma emission

Ruled out by ~ one order of magnitude

Not blazars—at least not in any simple model

No association with blazars in 100 other alerts



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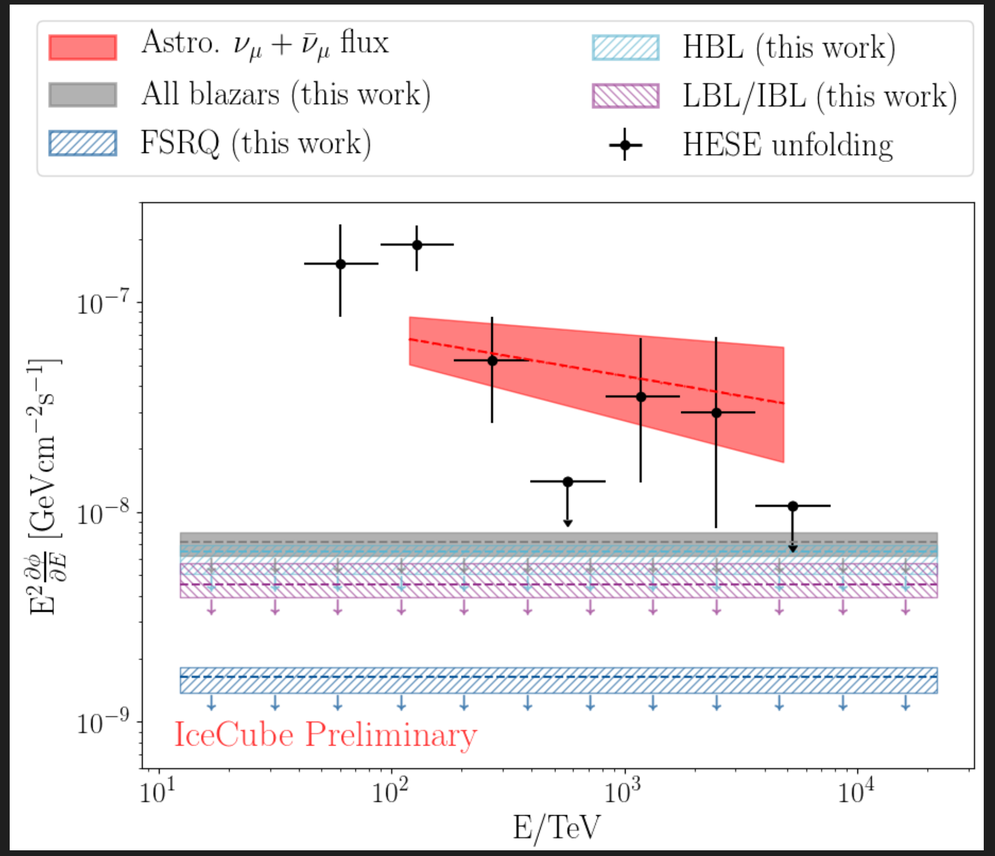

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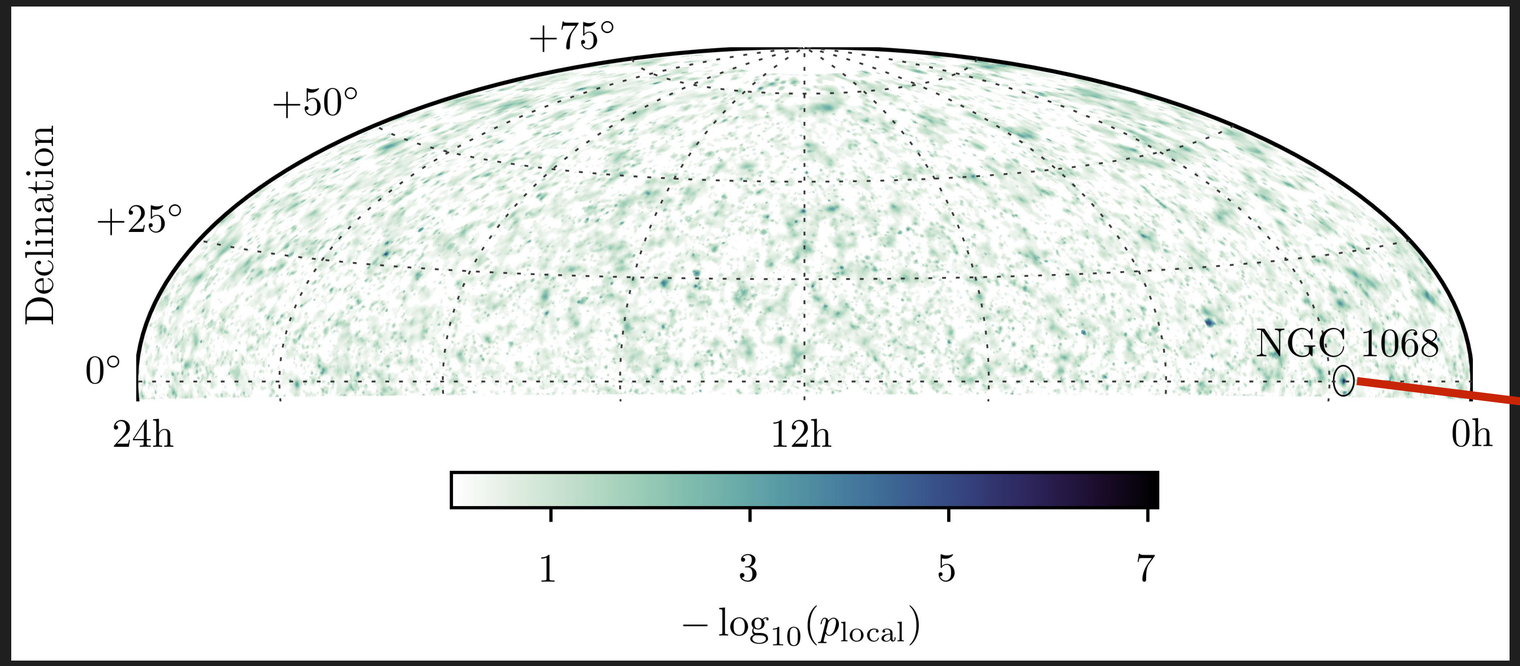
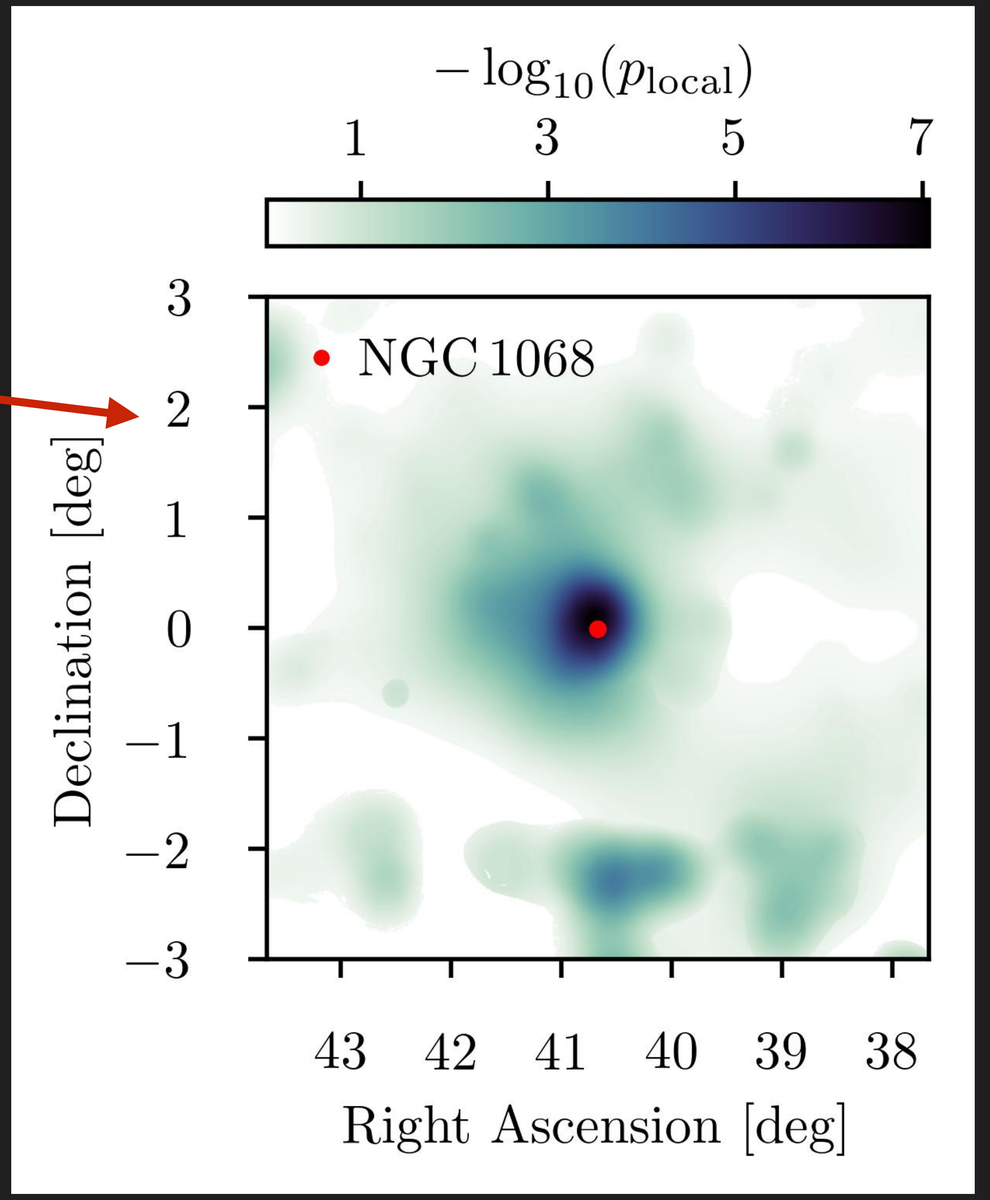
NGC 1068

Updated point source analysis with improved systematics treatment & additional data



Updated point source analysis

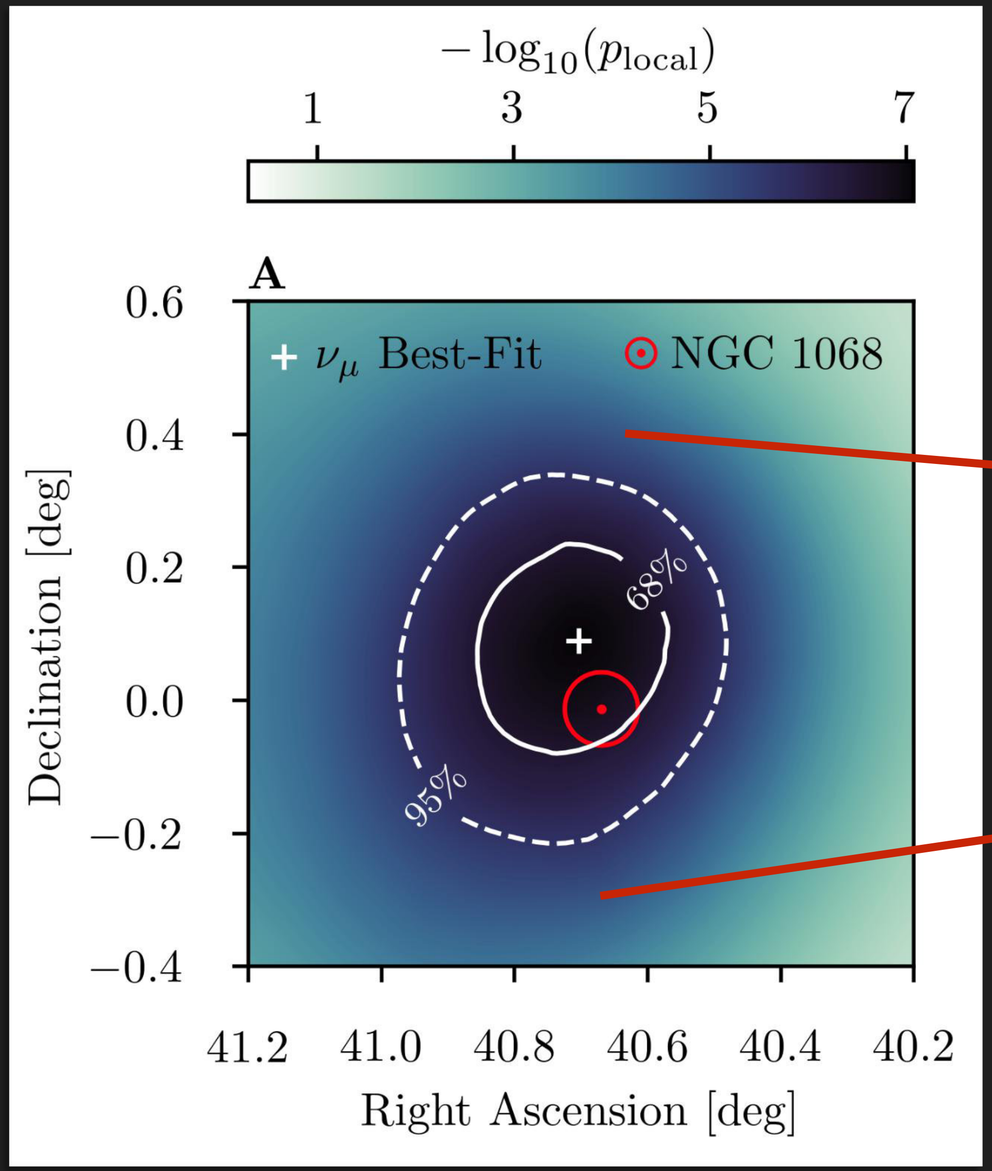
Improved systematics treatment,
especially better-matched directional distributions
between MC and data

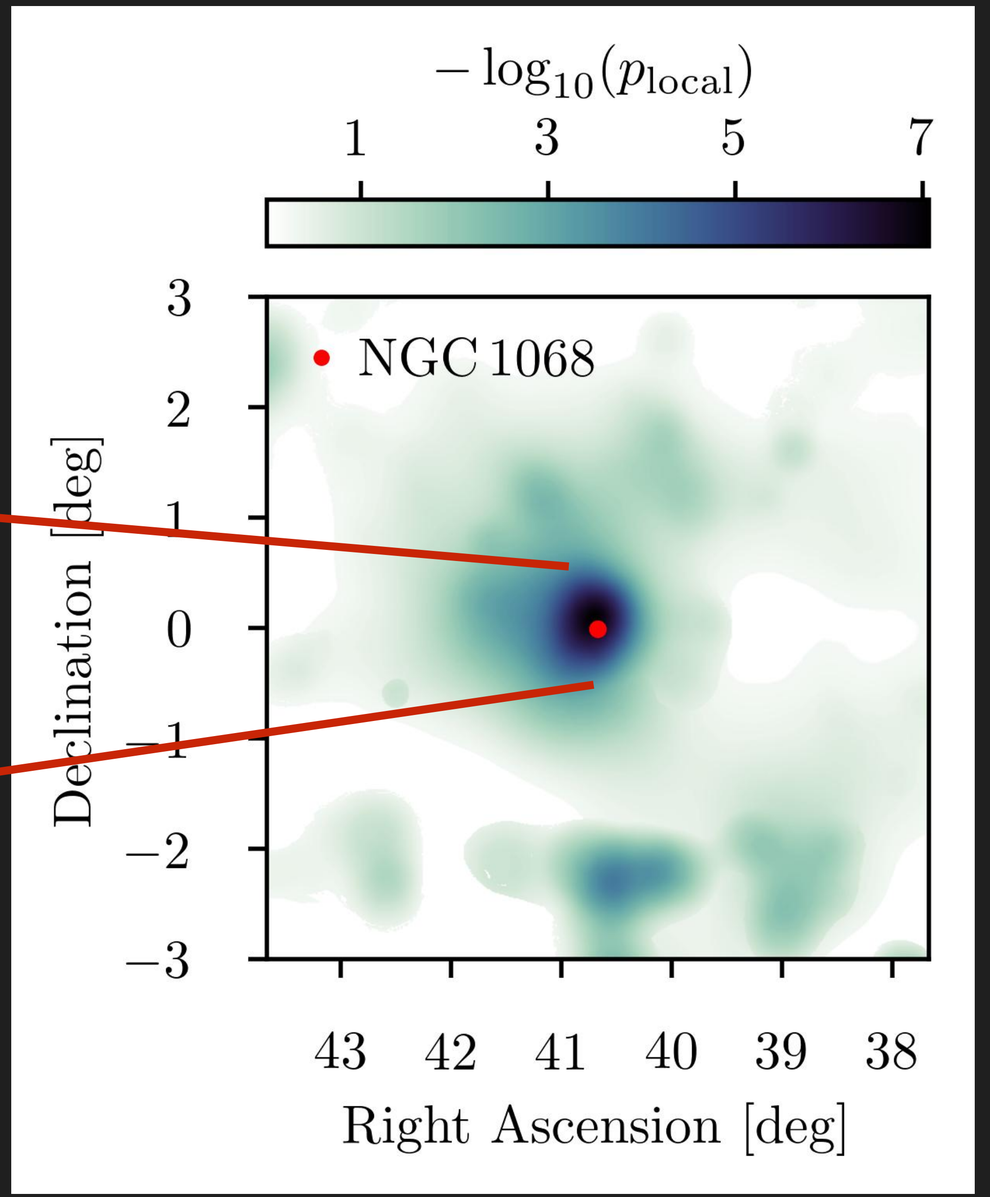


Science, Vol 378, Issue 6619, pp. 538-543

NGC 1068

Updated point source analysis with improved systematics treatment & additional data





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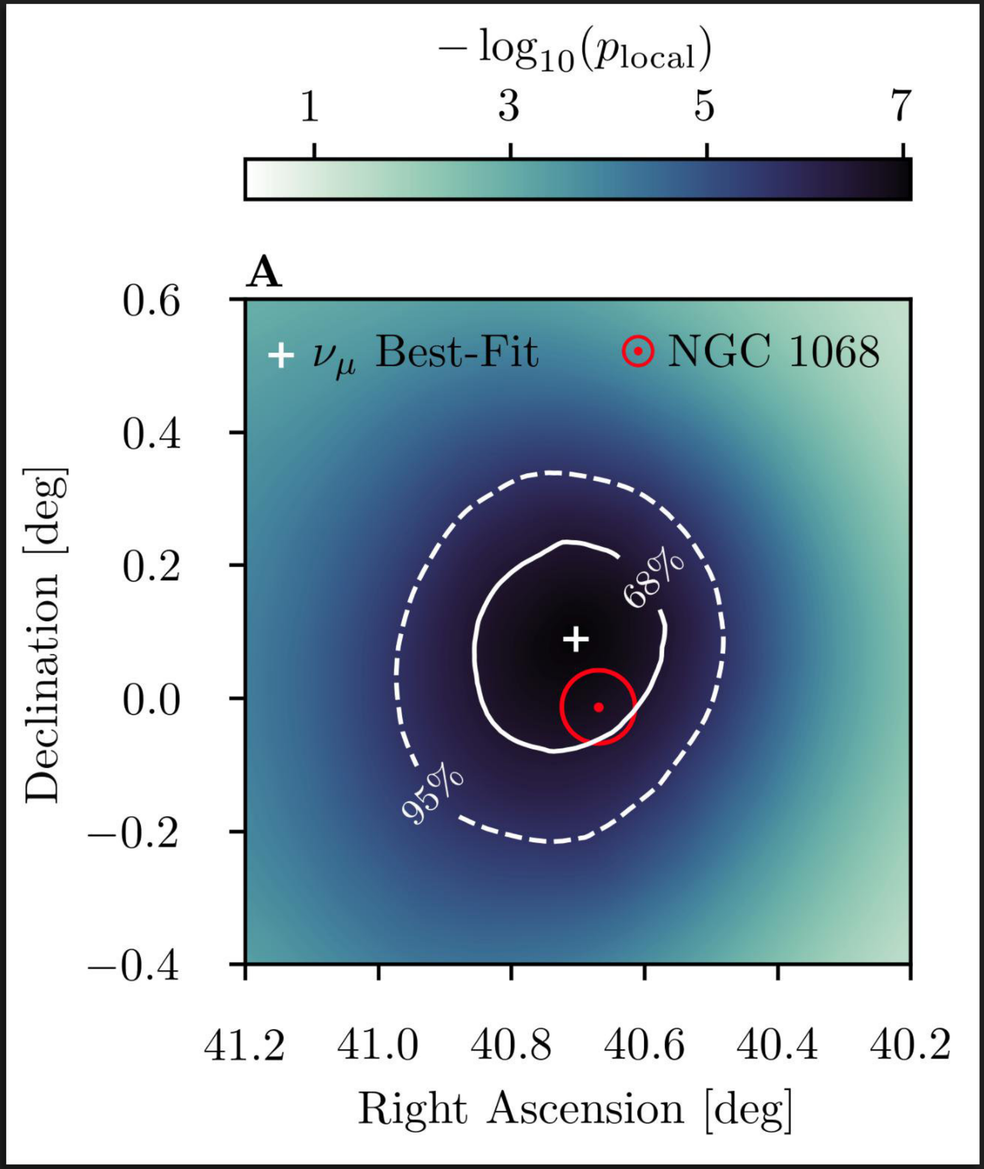

Location of **NGC 1068** is consistent with location of strongest clustering of neutrinos!

NGC 1068 was part of a pre-defined catalog search in this analysis

Trials-correcting the significance and accounting for the catalog size (110 sources):

4.2σ (global significance)

Evidence for neutrino emission from NGC 1068

NGC 1068

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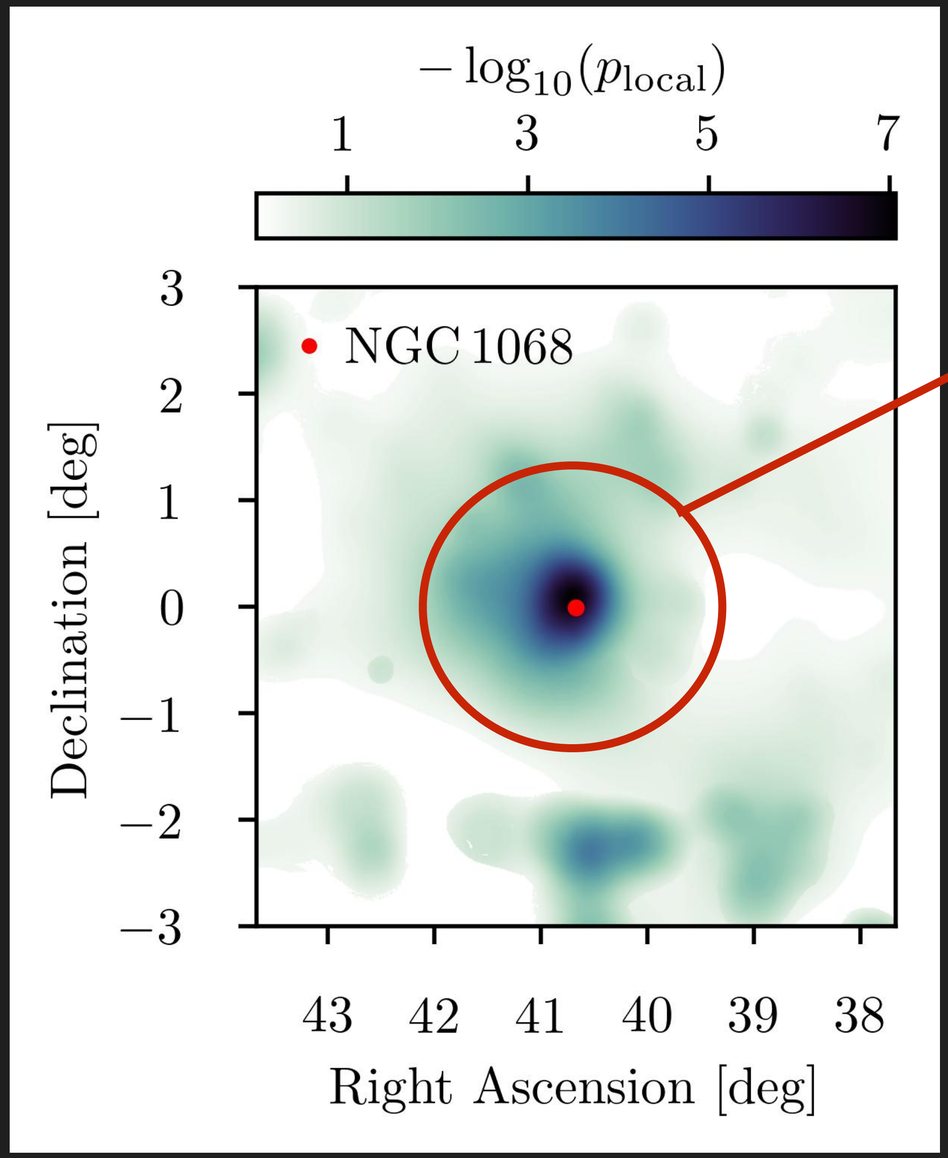
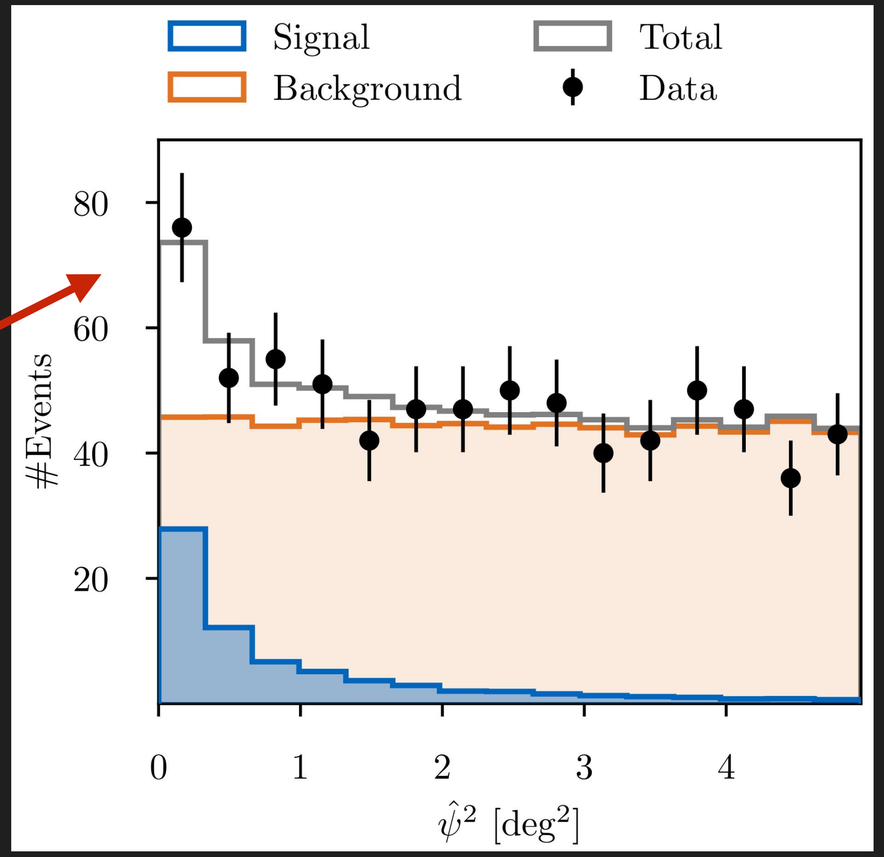




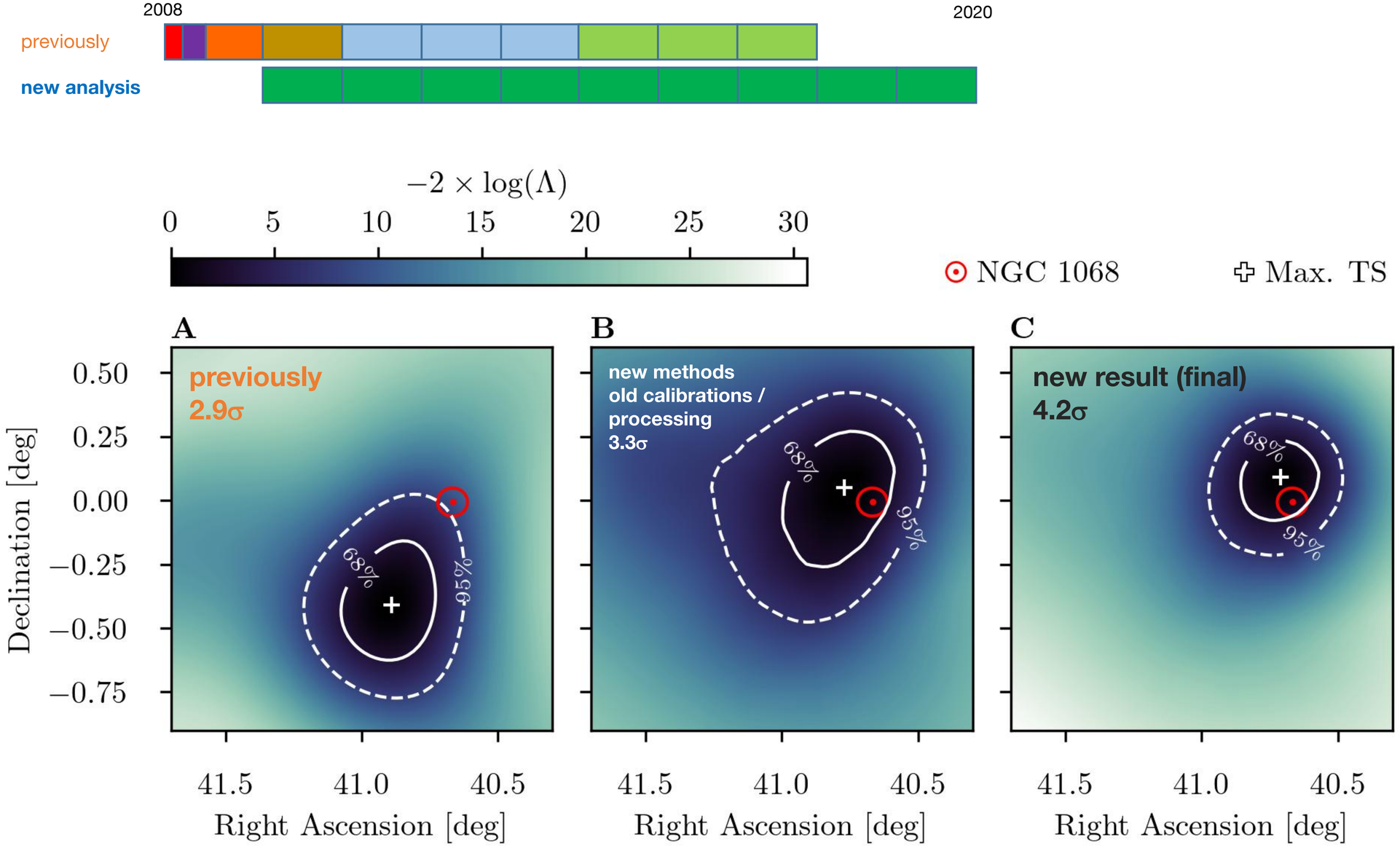
Measured astrophysical neutrino events: 79^{+22}_{-20}

Measured spectral index: 3.2±0.2

(data matches model description)

Slide courtesy of Hans Niederhausen

large contribution from other improvements in data quality (updated calibrations, uniform processing)



(new processing + old methods: 3.8σ)

NGC 1068

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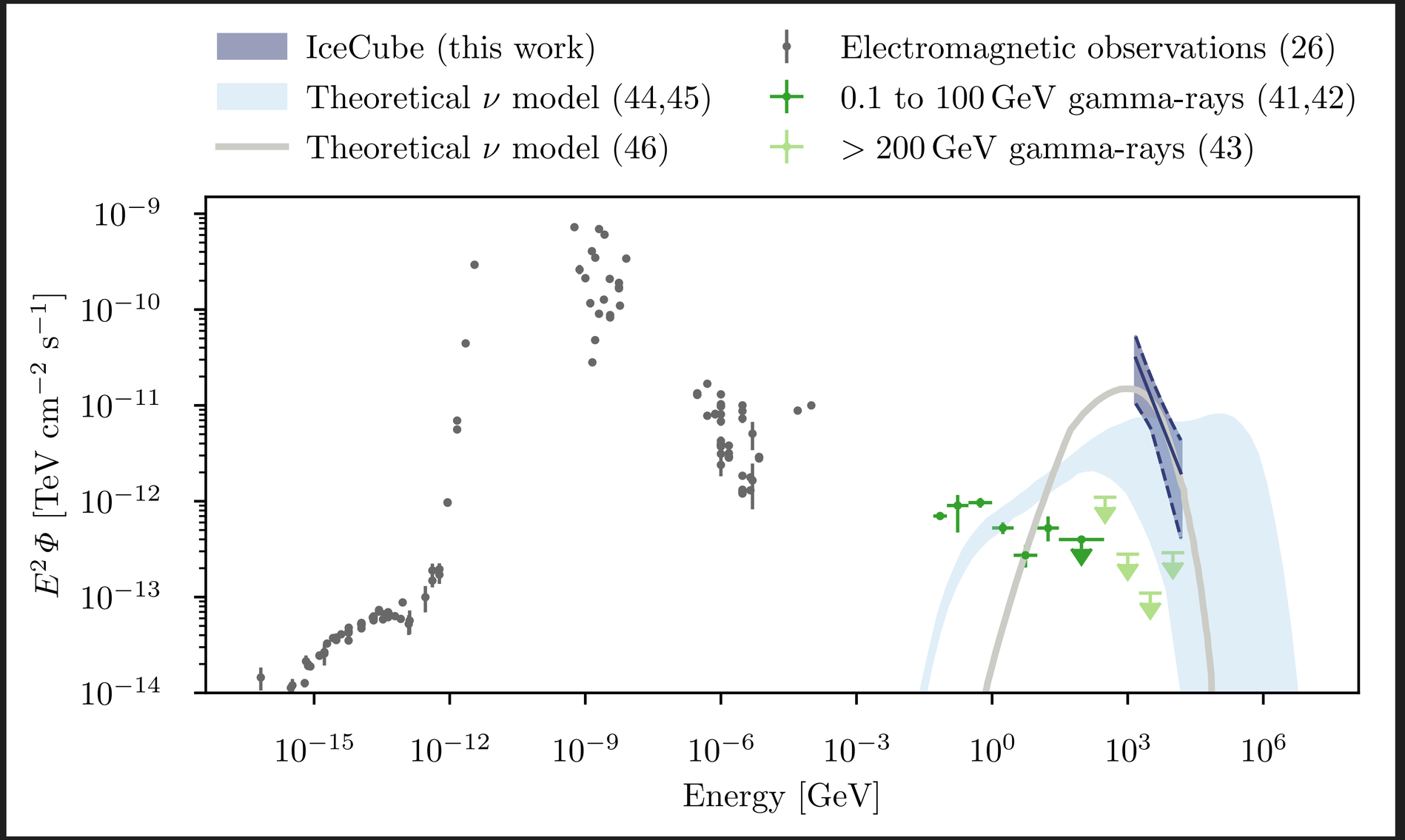
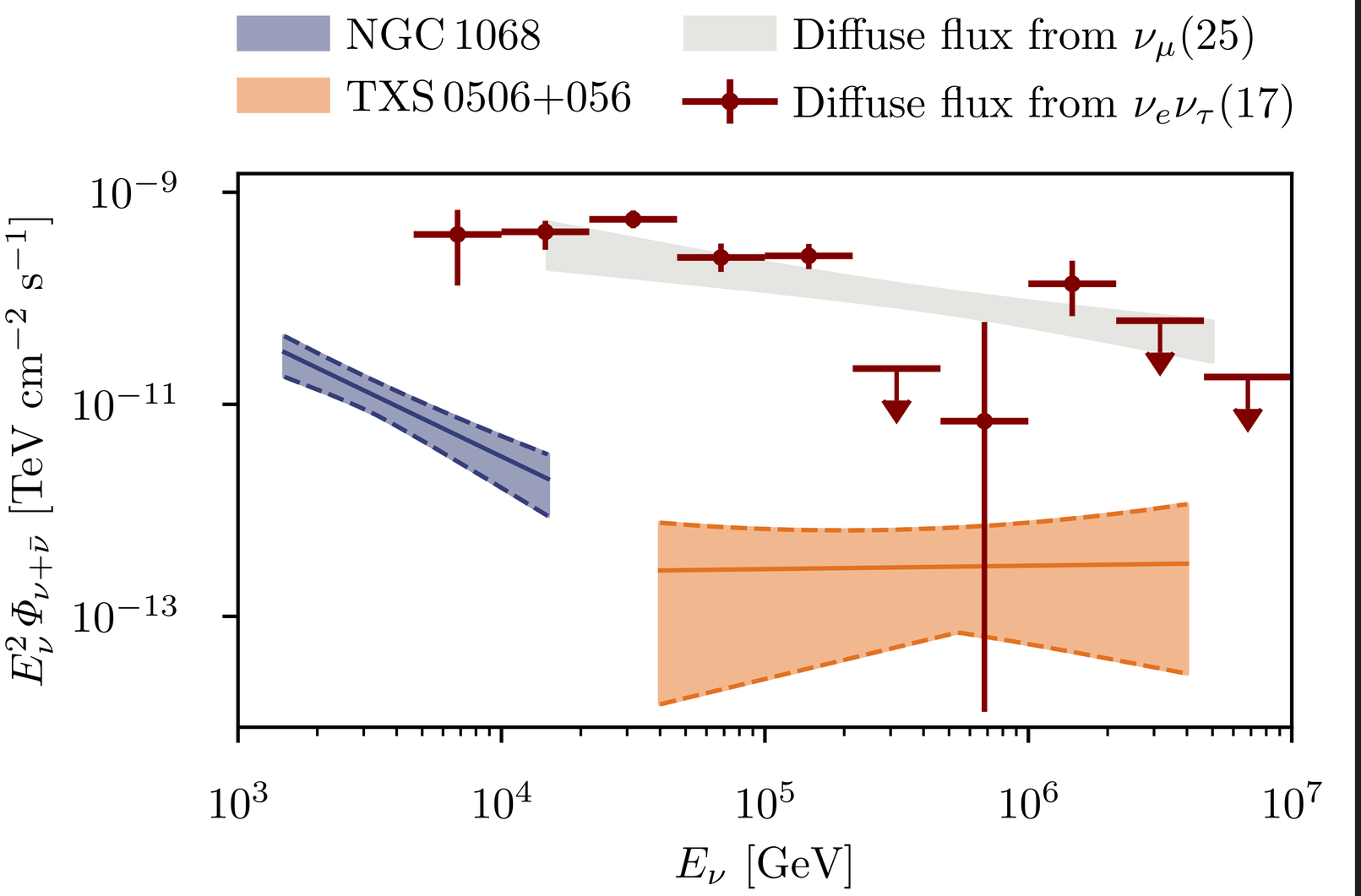


NGC 1068

point source fluxes vs. diffuse neutrino flux



TXS 0506+056 and NGC 1068 are measured in very different energy ranges.

Both correspond to O(1%) of the diffuse flux in their respective energy ranges.

TXS 0506+056 is ~100x farther away than NGC 1068, suggesting multiple populations.

SO WHAT?

Objects like TXS 0506+056 and NGC 1068 in terms of gamma emission cannot make all the neutrinos

Something beyond the galaxy

AGN seem to be emerging as a source class - however, potentially multiple populations

No significant clustering – distant/common sources?

Something interesting going on:
the neutrino sky does not look like the photon (or GW) sky

HOW CAN WE ESCAPE THESE CONSTRAINTS?

In general: anything that de-correlates the gamma and neutrino sky / pushes sources far away

Sources extremely common?

Gives high degree of isotropy

... why is the brightest one 1.5 Gpc away?

Sources extremely strongly evolved?

Gives high degree of isotropy

... why?

Optically thick?

Kills mandatory gamma-ray emission

... where is the energy going?

Exotics: is the neutrino background primordial?

Genuine diffuse origin

... requires new physics

WHAT DO WE DO TO GET OUT OF THIS?

Additional measurements!

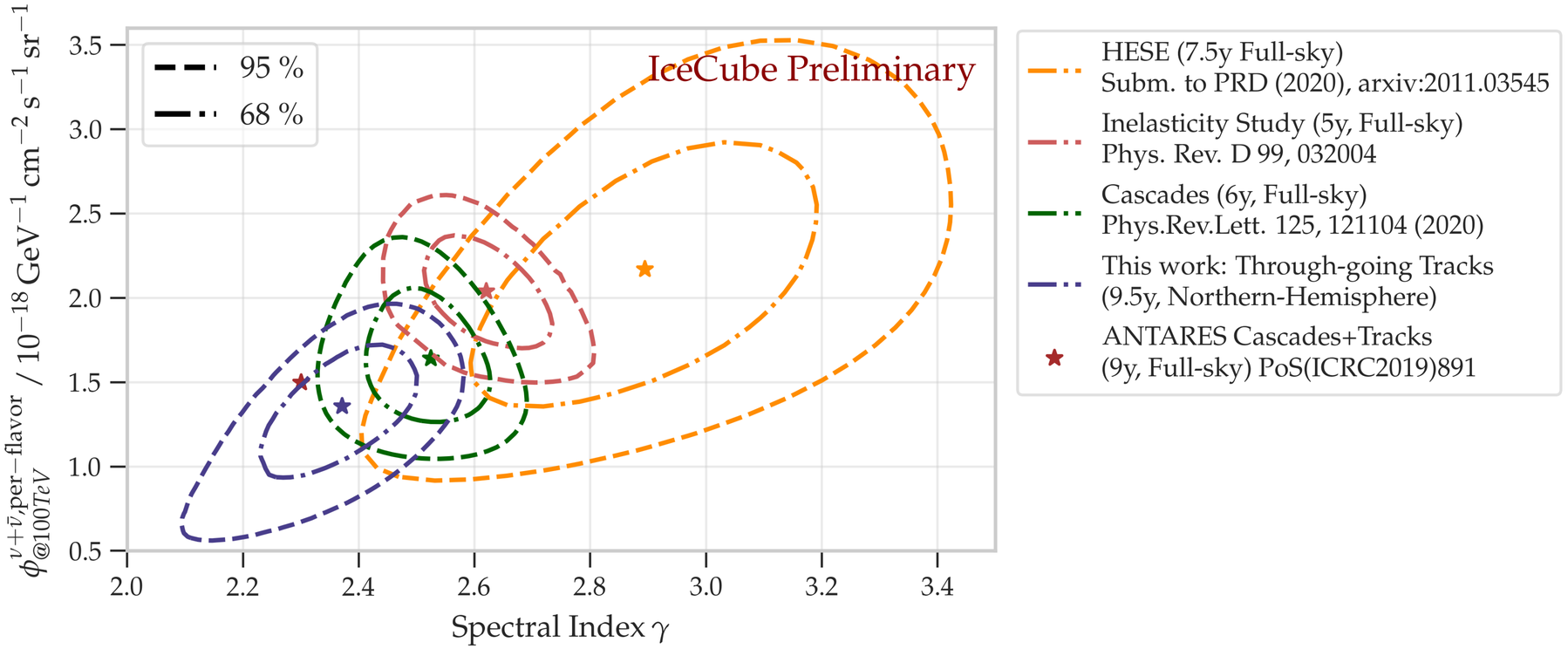
Spectrum and flavor: Tells us something about the production environment

Better resolution: 20000+ astrophysical neutrinos in sample

New detectors, **better events**

NEW INFORMATION: SPECTRUM

new information



Some minor tension between analyses

Hints of structure?

Not clear yet

NEW INFORMATION: FLAVOR

Flavor ratio at Earth contains information about source ratio after oscillations en route to Earth

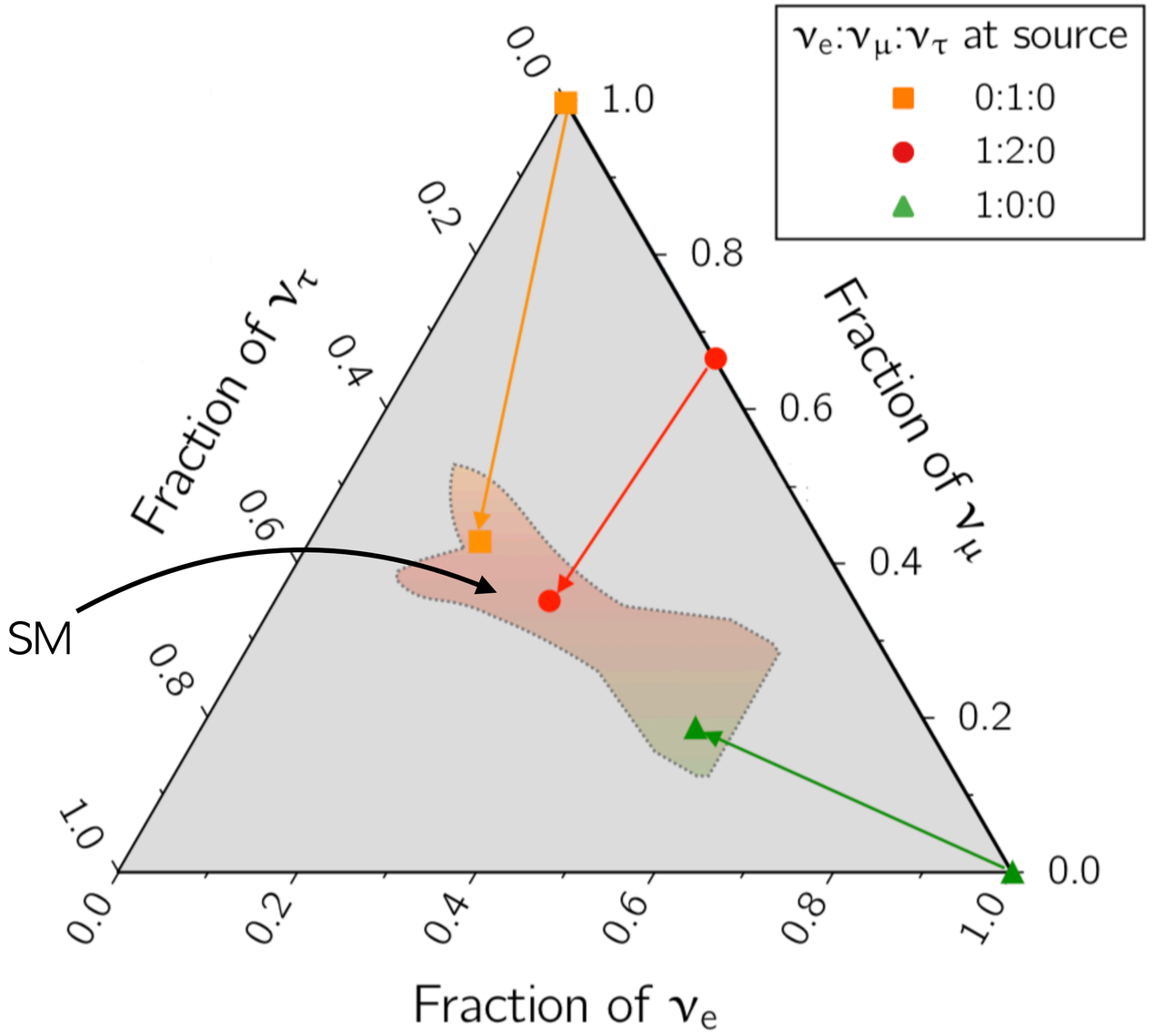
Tells us about:

Neutrino production mechanism

Possible non-standard behavior

(Almost zero sensitivity to neutrinos vs. anti-neutrinos)

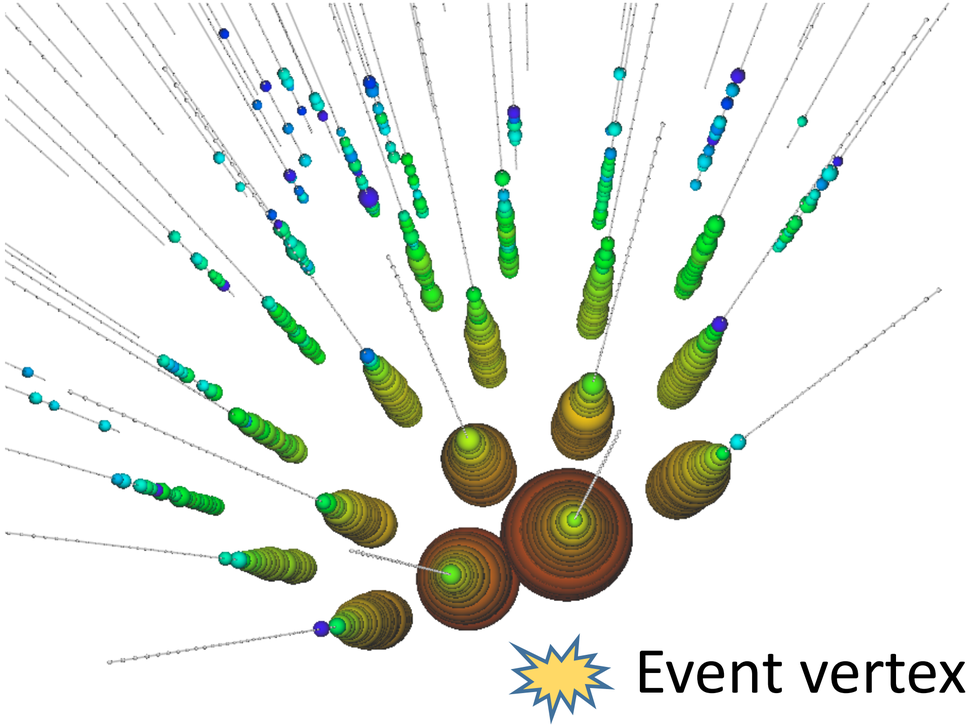
	at source			at Earth		
	ν_e	ν_μ	ν_τ	ν_e	ν_μ	ν_τ
pion decay	1	2	0	0.33	0.33	0.33
muon-damped	0	1	0	0.20	0.39	0.39
neutron decay	1	0	0	0.56	0.22	0.22

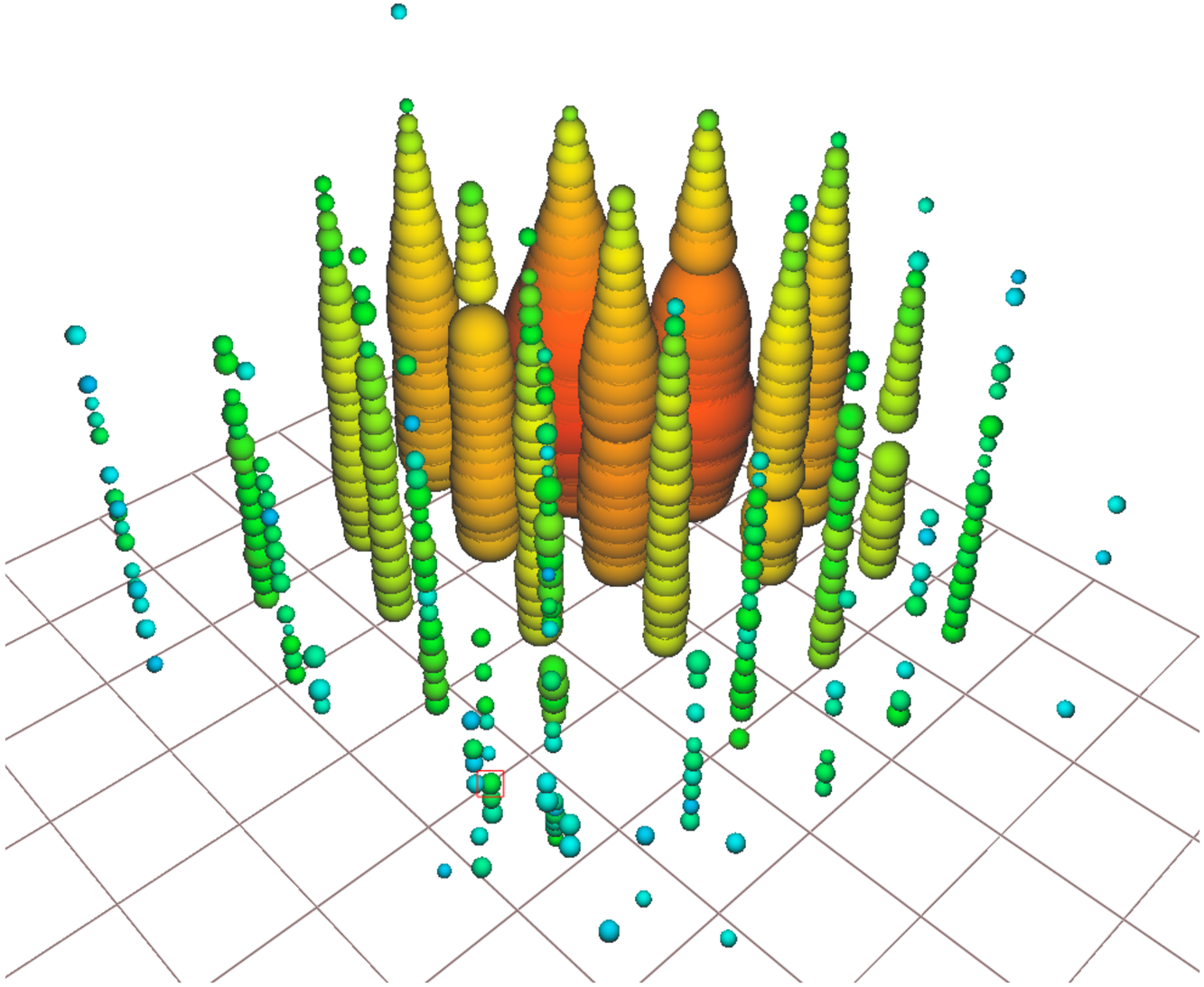


NEW INFORMATION: ANTI-NEUTRINOS

from an extremely high-energy event

Found with the "PEPE" high-energy selection
Best-fit vertex outside of the detector
Reconstructed energy ~6PeV
Has early hits





NEW INFORMATION: ANTI-NEUTRINOS

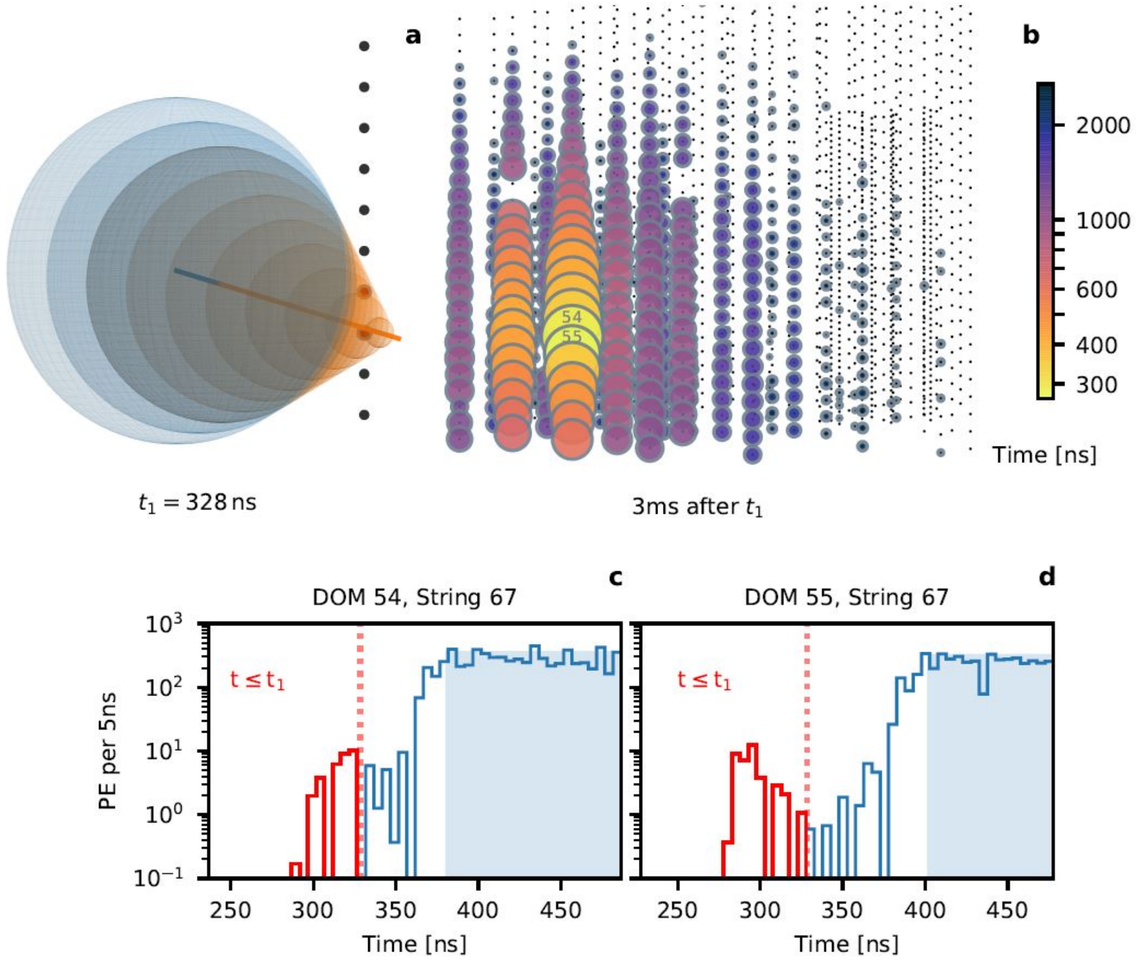
from an extremely high-energy event

Limited sensitivity to $\bar{\nu}$, through $\bar{\nu}_e + e \rightarrow W^-$

Resonant at 6.3 PeV

Now know the background includes some $\bar{\nu}$

Techniques will improve flavor measurements



NEW INFORMATION: BETTER POINTING

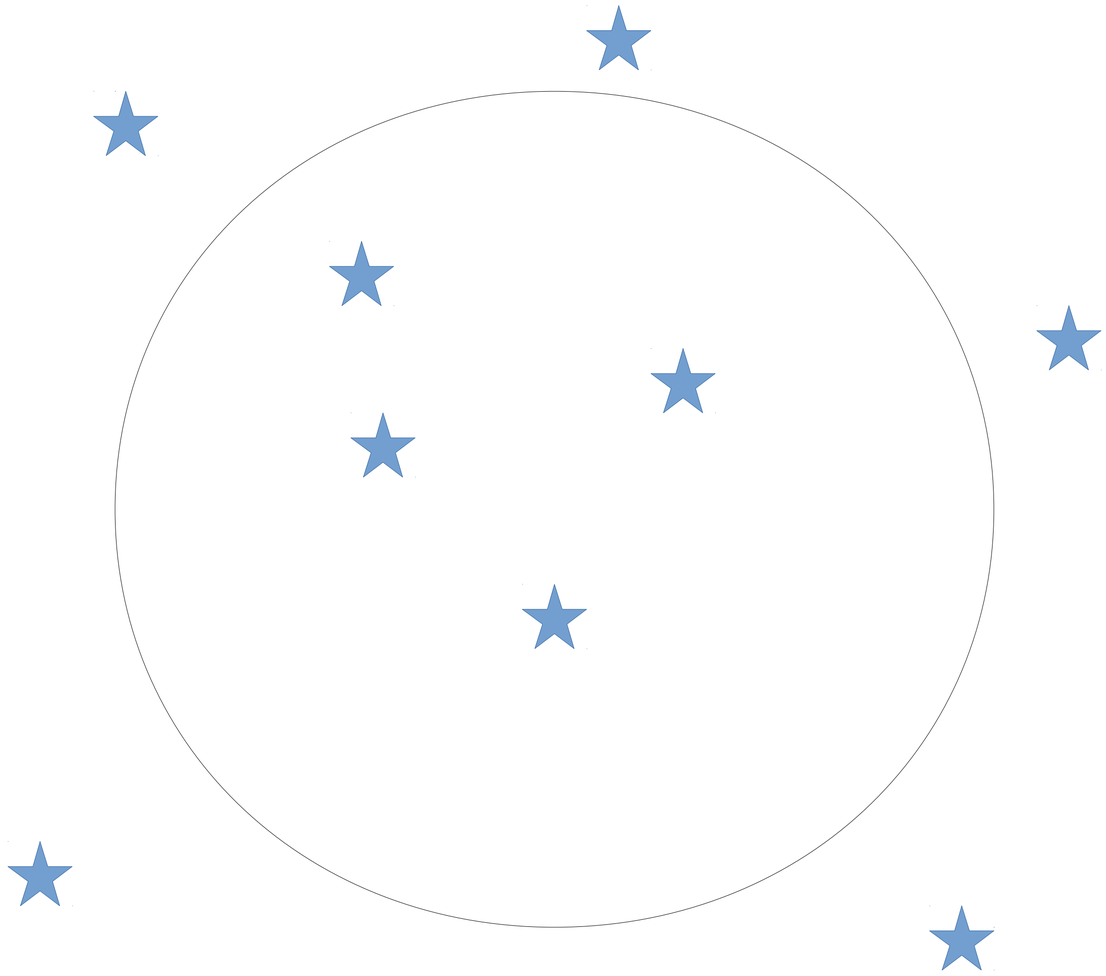
from an extremely high-energy event

Point source sensitivity linear in resolution

Beginning to understand the detector in detail
(e.g. improvements in PS analysis led to NGC 1068 evidence!)

Marginal (~ 20%) improvements could move TXS up to 5σ

Bigger ones help a lot:
factor of 5 goes from 1 to 12 sources

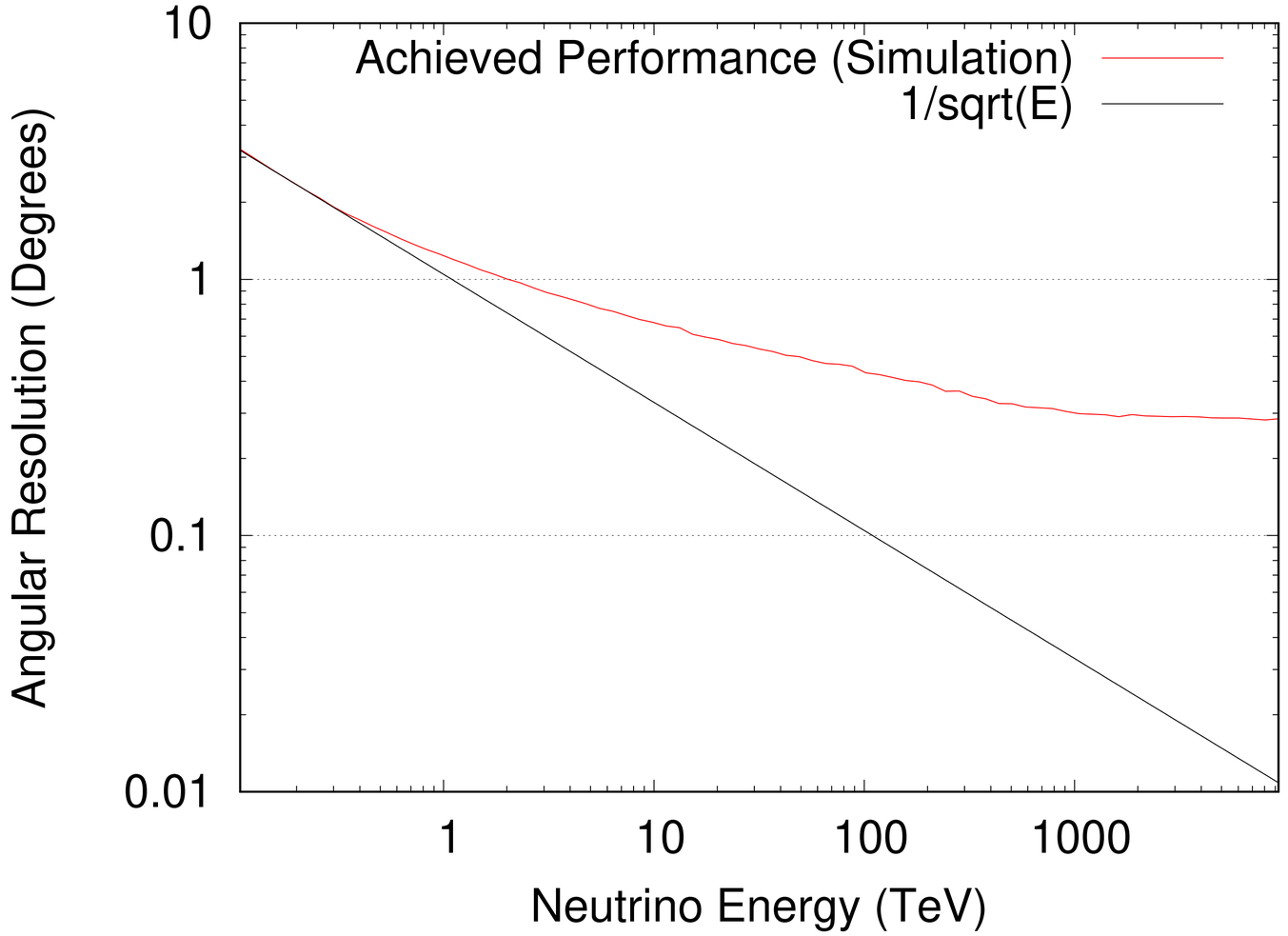


PATH TO BETTER ANGULAR RESOLUTION

Key task is understanding muon energy loss

Large (up to 5x) improvements possible!

Very small fractions of this get us more sources



WE'RE GONNA NEED A BIGGER DETECTOR!

New detectors, detector designs, and improvements to calibration

ICECUBE UPGRADE

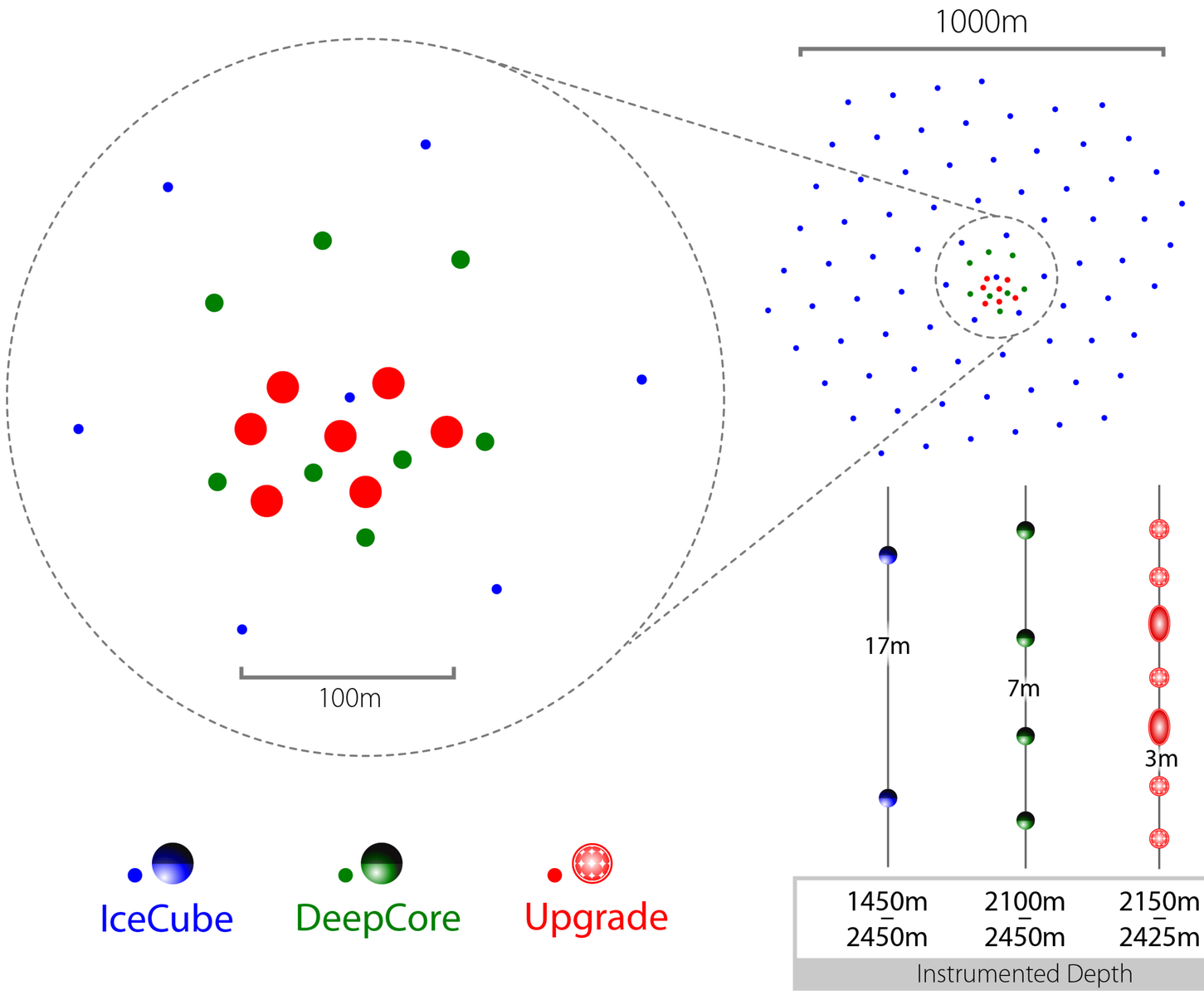
Science goals:

ν_μ disappearance

ν_τ appearance

precise calibration of IceCube **optical properties** and **DOM response**

Funded, deploying 2023 (possible COVID delays)



INSTRUMENTATION

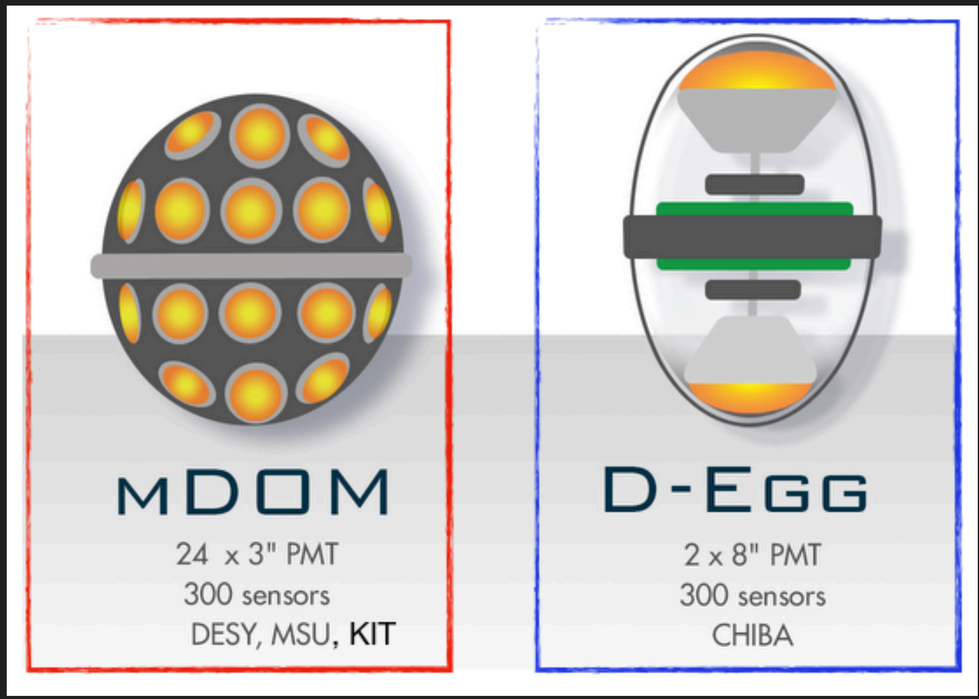
New optical sensor modules

Many new devices currently developed and tested:

Larger PMT effective coverage

Pixelated effective area

Prototype devices for IceCube-Gen2 (e.g. WOM)



ICECUBE UPGRADE

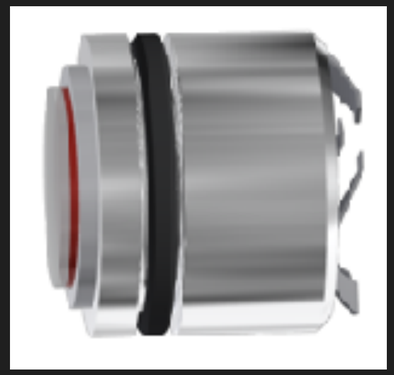
enhancing IceCube high-energy science through better calibration

Integrated devices

LED flashers

Acoustic sensors

Optical cameras



piezo module

POCAM

Stand-alone light sources

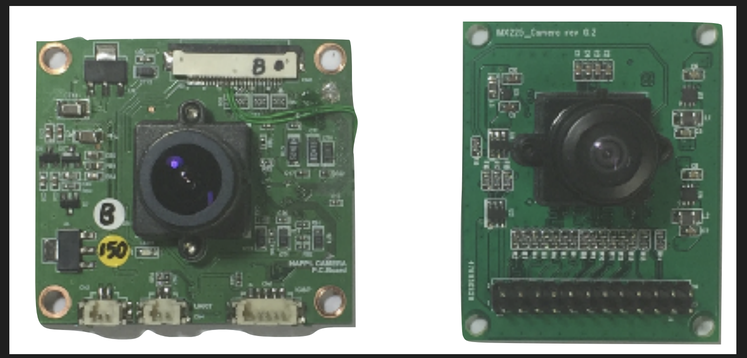
Precision Optical Calibration Module (POCAM)

“Movable” sub-ns pulsed LEDs

Reduce primary systematic uncertainties

Better calibration of new and existing sensors

Improved knowledge of glacial ice



CCD / CMOS

ICECUBE-GEN2

A wide band neutrino observatory (MeV - EeV) using several detection technologies - optical, radio, and surface veto

IceCube has provided an amazing sample of events, but is still limited by the small number of events

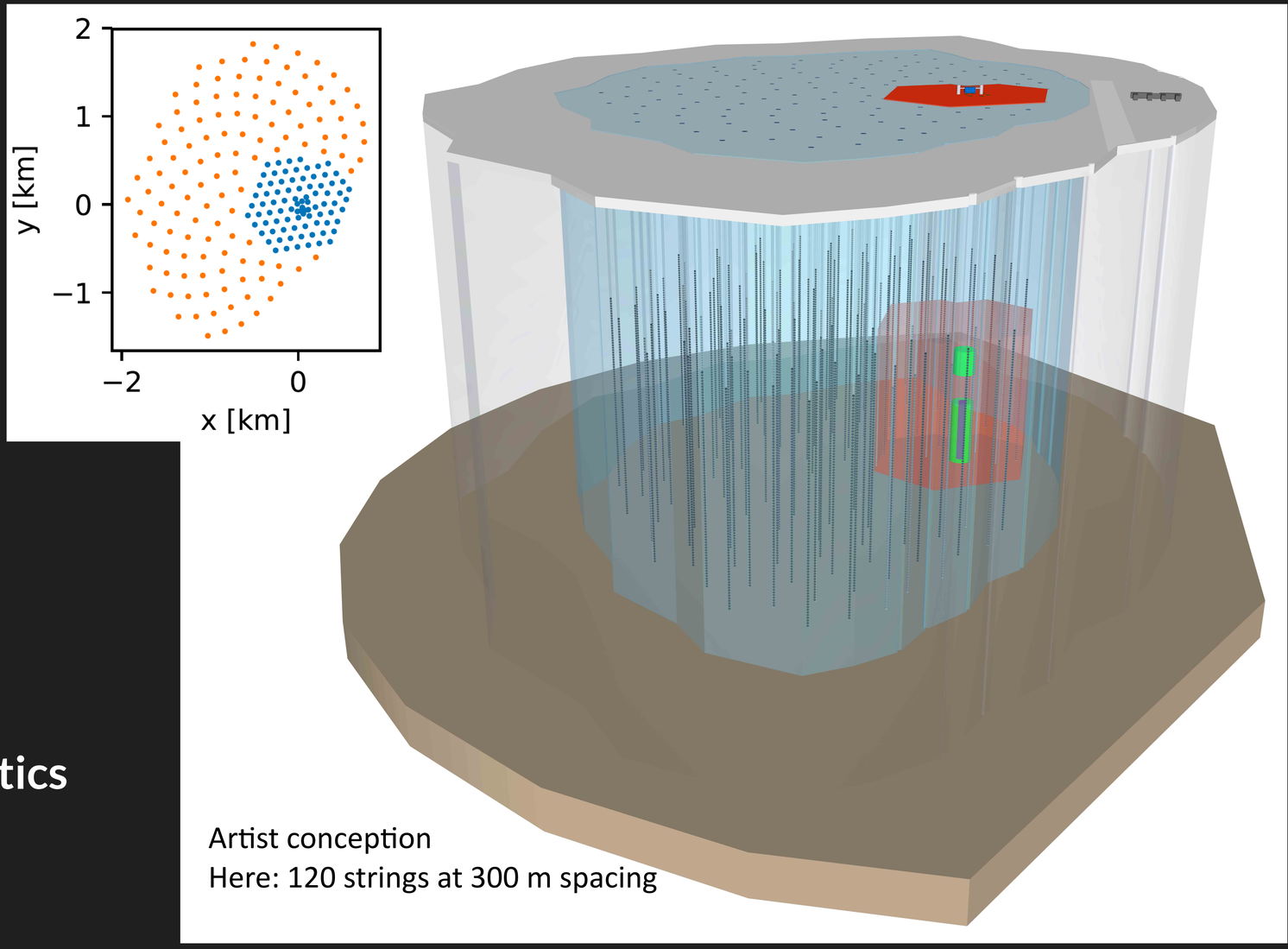
few 10's of astrophysical neutrinos per year

The IceCube-Gen2 High-Energy Array will instrument up to an order of magnitude larger volume

Includes in-ice array, surface array, and radio (>10PeV, cosmogenic)

Much higher event rates and better systematics

Compounds with analysis improvements



Artist conception
Here: 120 strings at 300 m spacing

RADIO DETECTION

Builds on heritage from RICE, ARA (deep antennas), ARIANNA (near surface antennas), and ANITA

Discover ultra high energy neutrinos, or place limits on the diffuse flux that constrain production models.

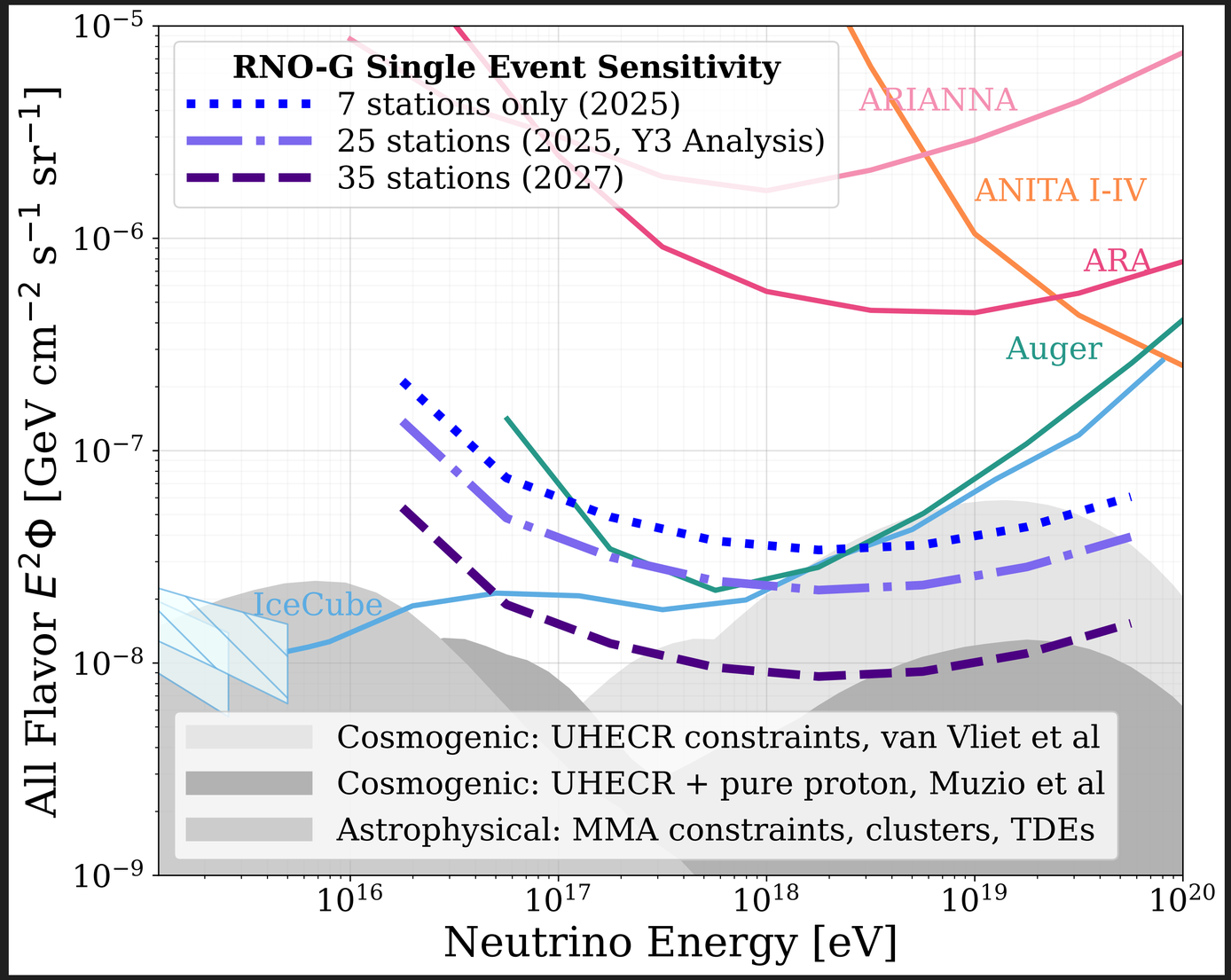
All Flavor Sensitivity at the heart of the cosmogenic neutrino flux

Point source & transient neutrino searches and followup

Pave the way for a larger radio array planned for IceCube-Gen2

40 km² instrument currently being built at Summit Station in **Greenland**

7 stations currently operating
Science operations in 2028



borrowed from Stephanie Wissel, APS April Meeting, April 2023

RADIO DETECTION

Builds on heritage from RICE, ARA (deep antennas), ARIANNA (near surface antennas), and ANITA

RNO-G Station Concept

- 24 channels (15 deep / 9 shallow)
- 2 deep / 1 surface calibration pulsers
- Solar power / LTE & LoraWan comms

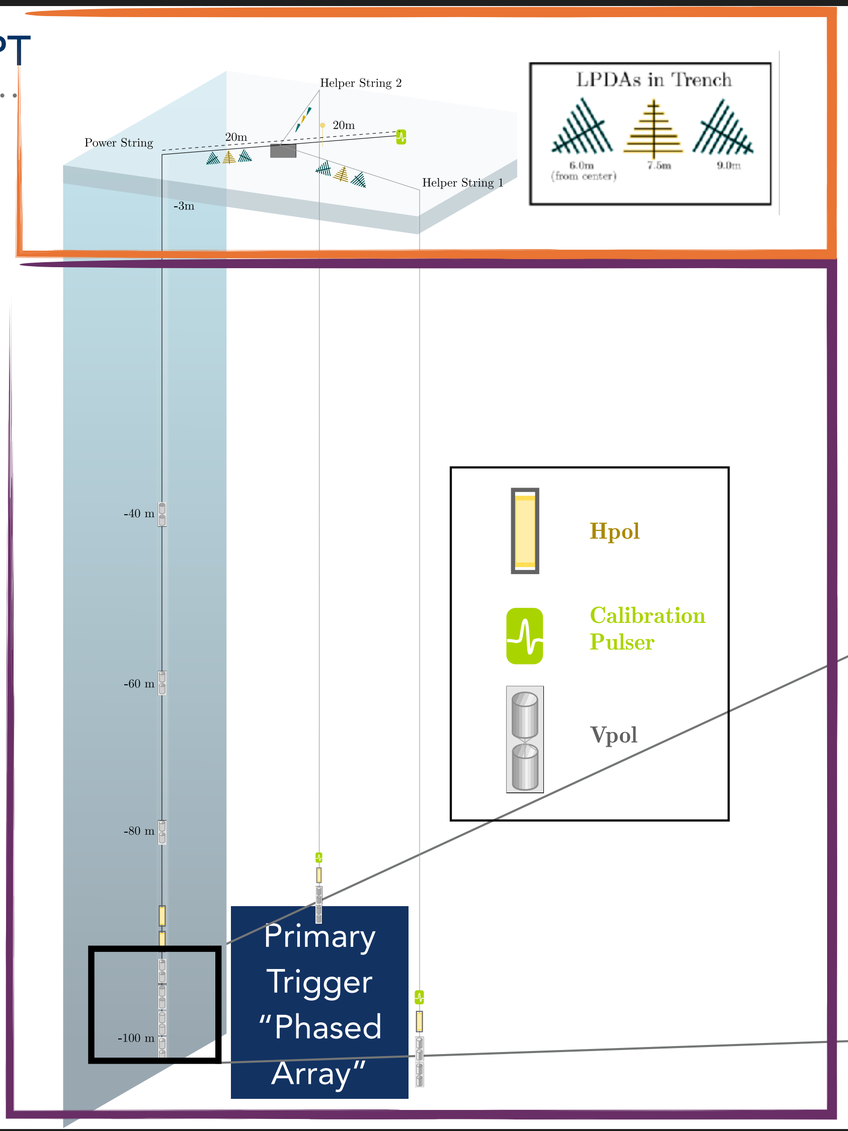
Deep component:

Effective Volume

Low Threshold trigger with compact phased array

⟶ expect SNR~2×thermal noise

Outrigger antennas enable reconstruction



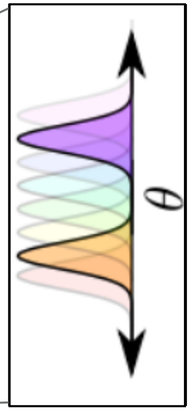
Shallow component:

Cosmic rays

Veto

Additional channels for reconstruction

Independent trigger



Multiple beams formed with phasing

Directional followup by tuning beams

6

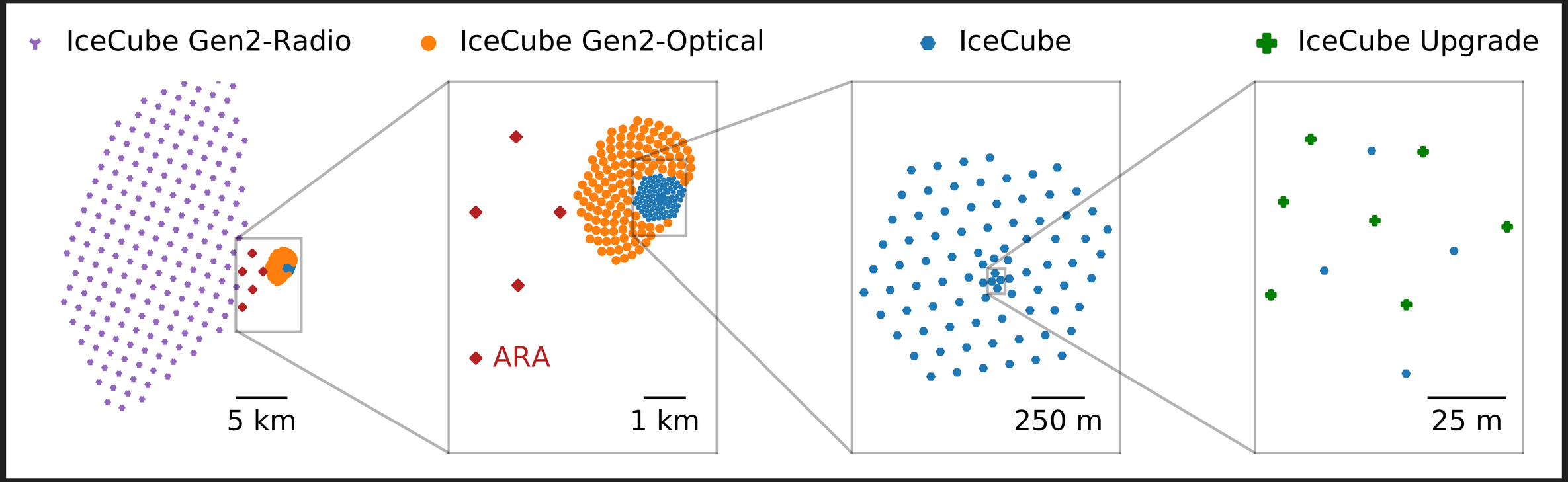
borrowed from Stephanie Wissel, APS April Meeting, April 2023

GEN2 RADIO

Gen2 radio **goal**: improve the sensitivity by 100x in the EeV range

…by expanding footprint by hundreds of km^2

…by using radio (1 km attenuation length)



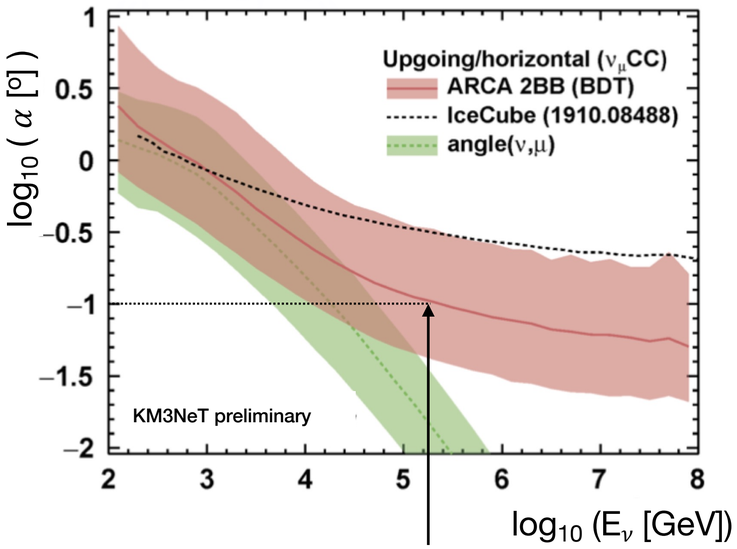
borrowed from Stephanie Wissel, APS April Meeting, April 2023

ARCA - THE HIGH-ENERGY PART OF KM3NET

(I am omitting the amazing science ORCA is doing here...)

"tracks"

PoS(ICRC2021) 1077

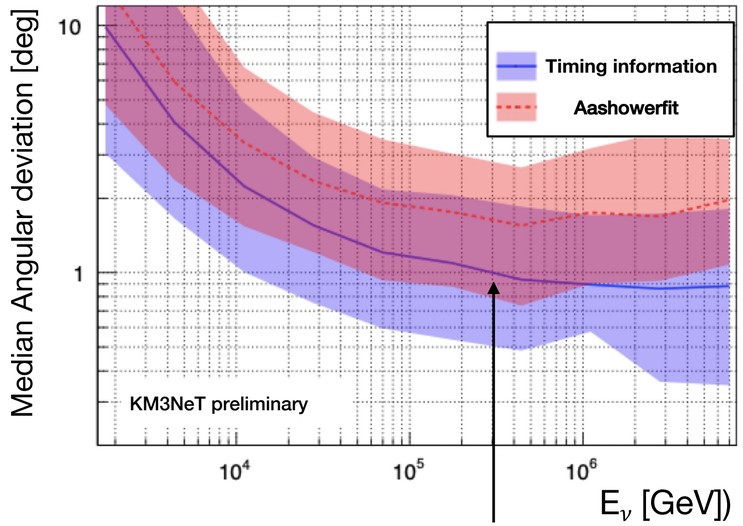


Better than 0.1° at 100 TeV

Energy Resolution ~ 0.27 in $\log_{10}(E_{reco}/E_\mu)$
($10\ TeV < E_\mu < 10\ PeV$)

"showers"

PoS(ICRC2021) 1089



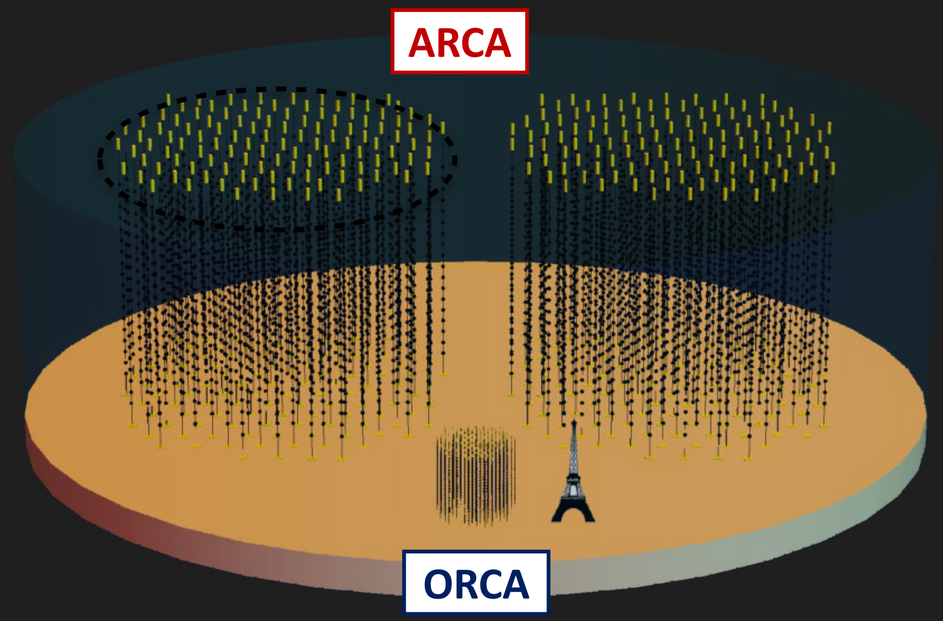
Better than 1° at 30 TeV

Energy Resolution < 5%

Showers (ν_x NC + ν_e CC): contained events
Deposited energy strongly correlated with primary E_ν
Effective area smaller compared to "tracks"

Digital Optical Module

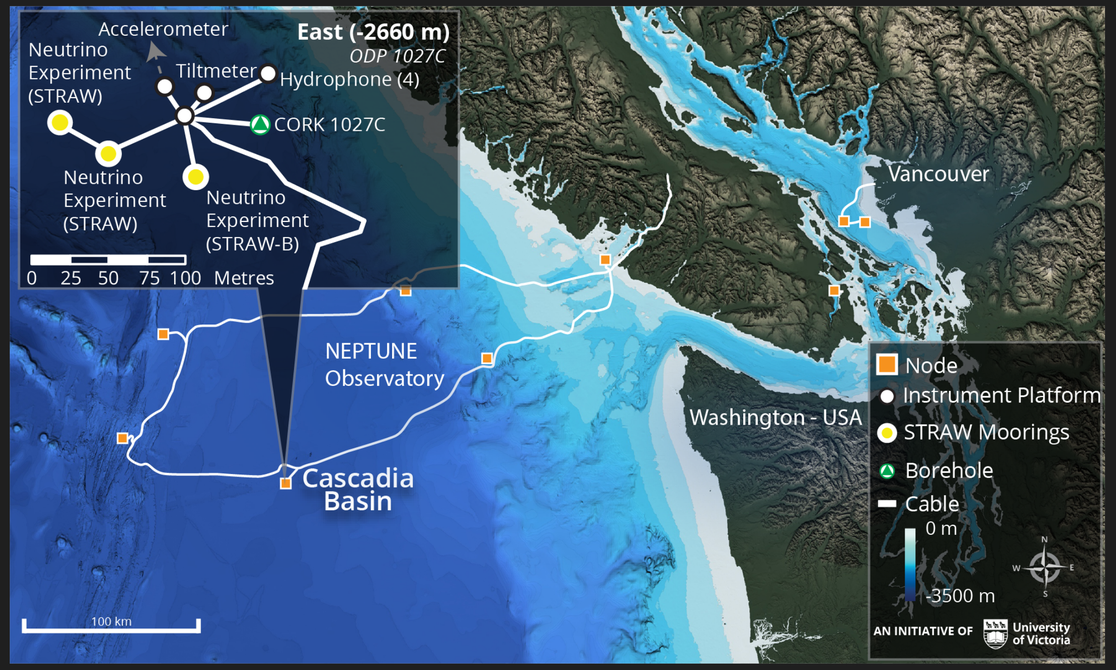
31×3" PMTs



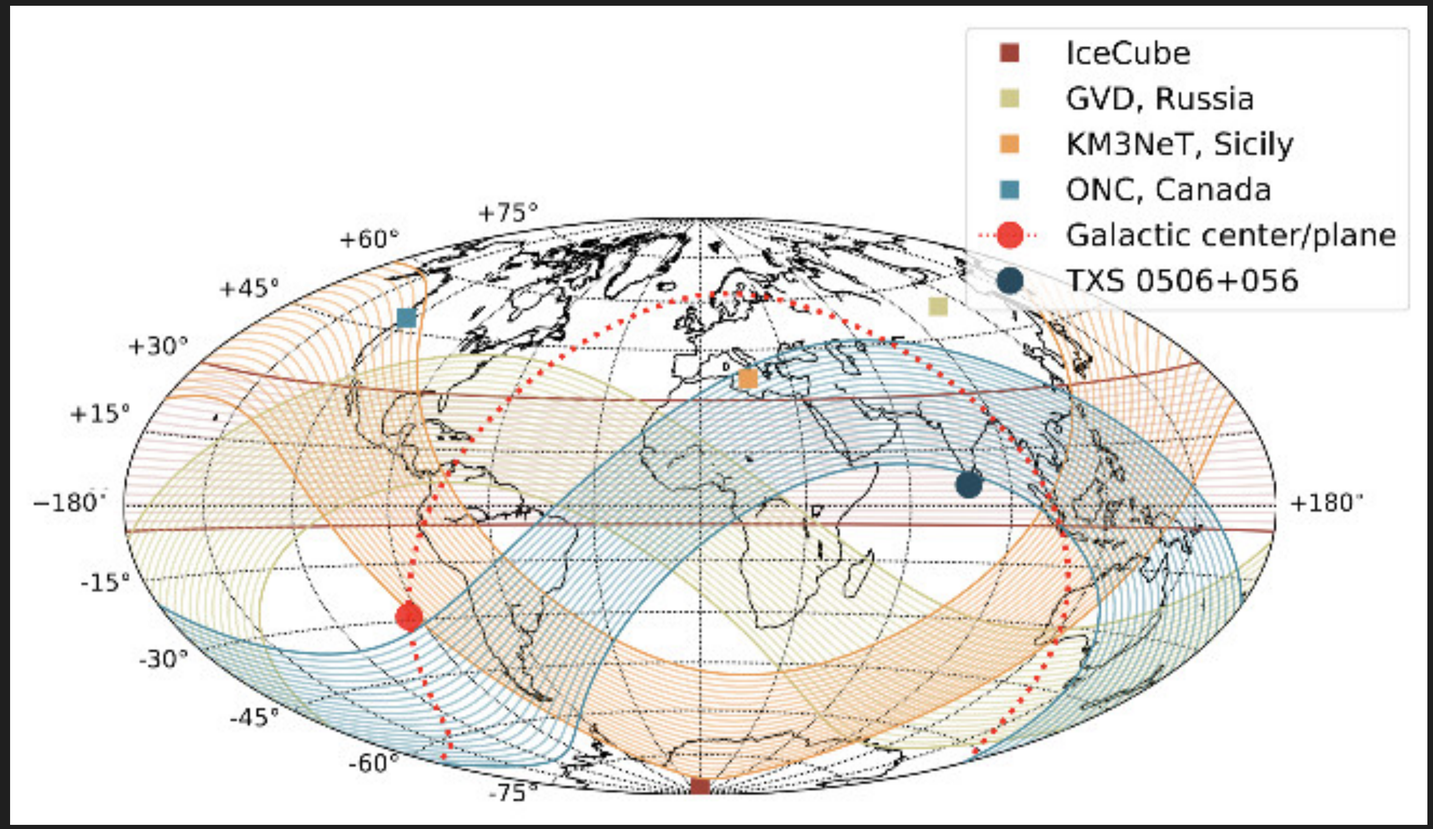
1 Building Block (BB) = 115 Detection Units (DU)

P-ONE

Pacific Ocean Neutrino Experiment (P-ONE)



With P-ONE we will have the ability to monitor the complete neutrino sky for transients!



THE BEGINNING

I could only cover a very small subset of topics...

Large diffuse neutrino background detected extending up to 10 PeV

Two sources (maybe more...)!

Emission mechanism seems to be complicated, sources not as expected

However, more sources likely just below threshold

New detectors and upgrades are coming online

We have ambitious plans for the future!

THANK YOU!

most photographs/timelapse: M. Wolf/NSF
https://www.flickr.com/photos/135762220@N06/

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https://www.flickr.com/photos/135762220@N06/

THANK YOU!