# IceCube Physics Results

## *Studying Neutrinos from the South Pole*

**Brian Clark (MSU)**
*for the IceCube Collaboration*

Particle Physics & Cosmology 2022
St. Louis / June 9, 2022



MICHIGAN STATE
UNIVERSITY

IC: Martin Wolf, IceCube/NSF

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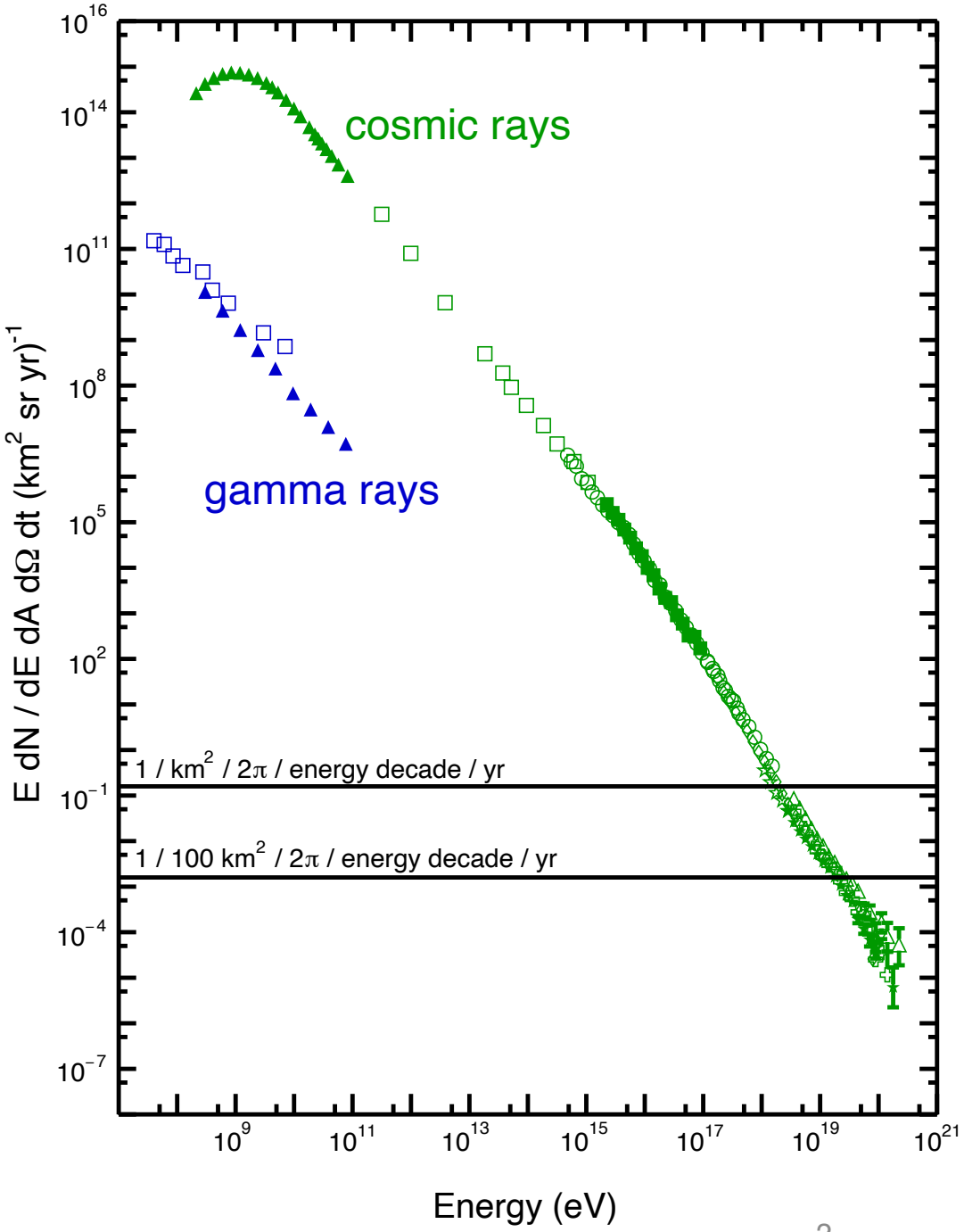

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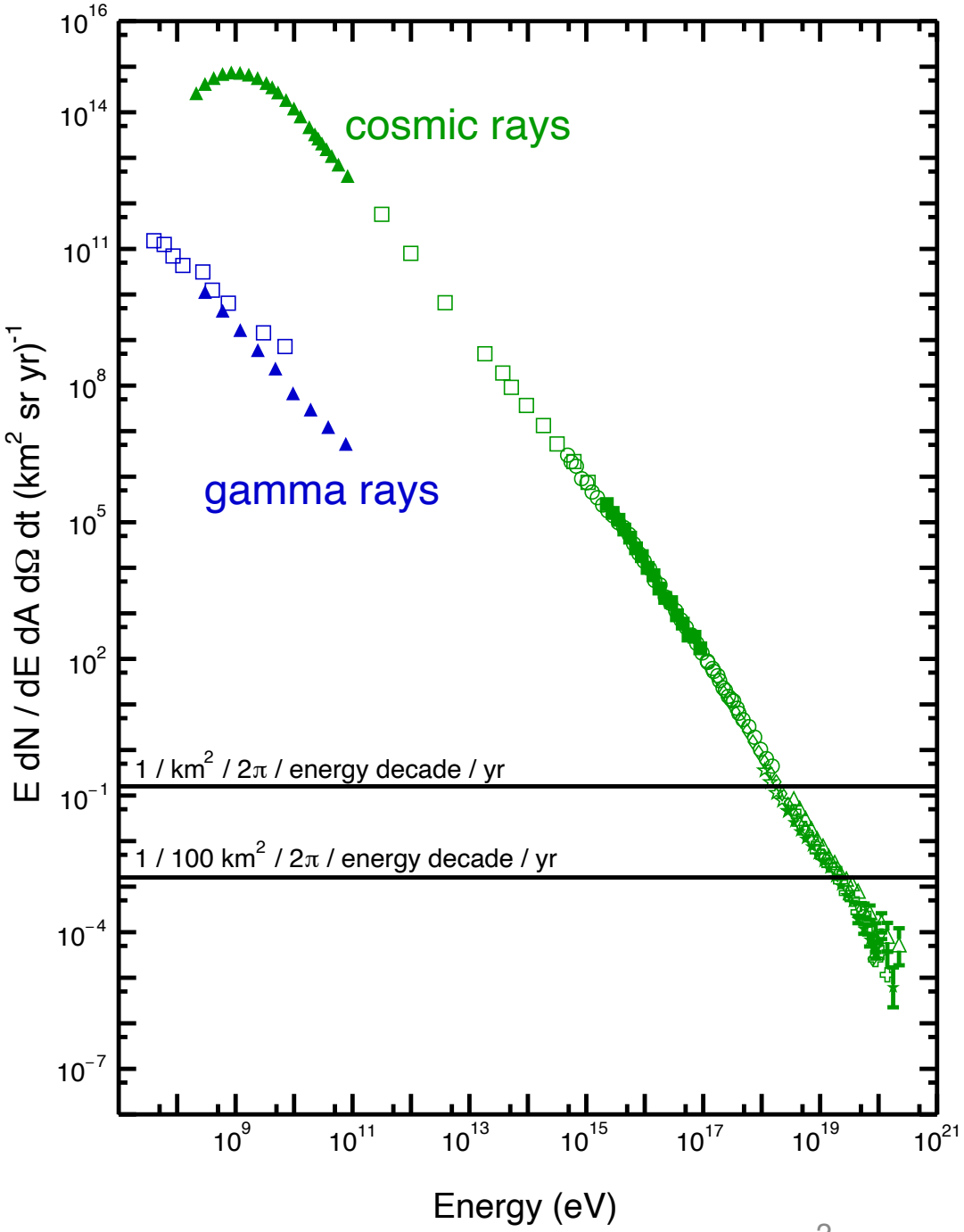

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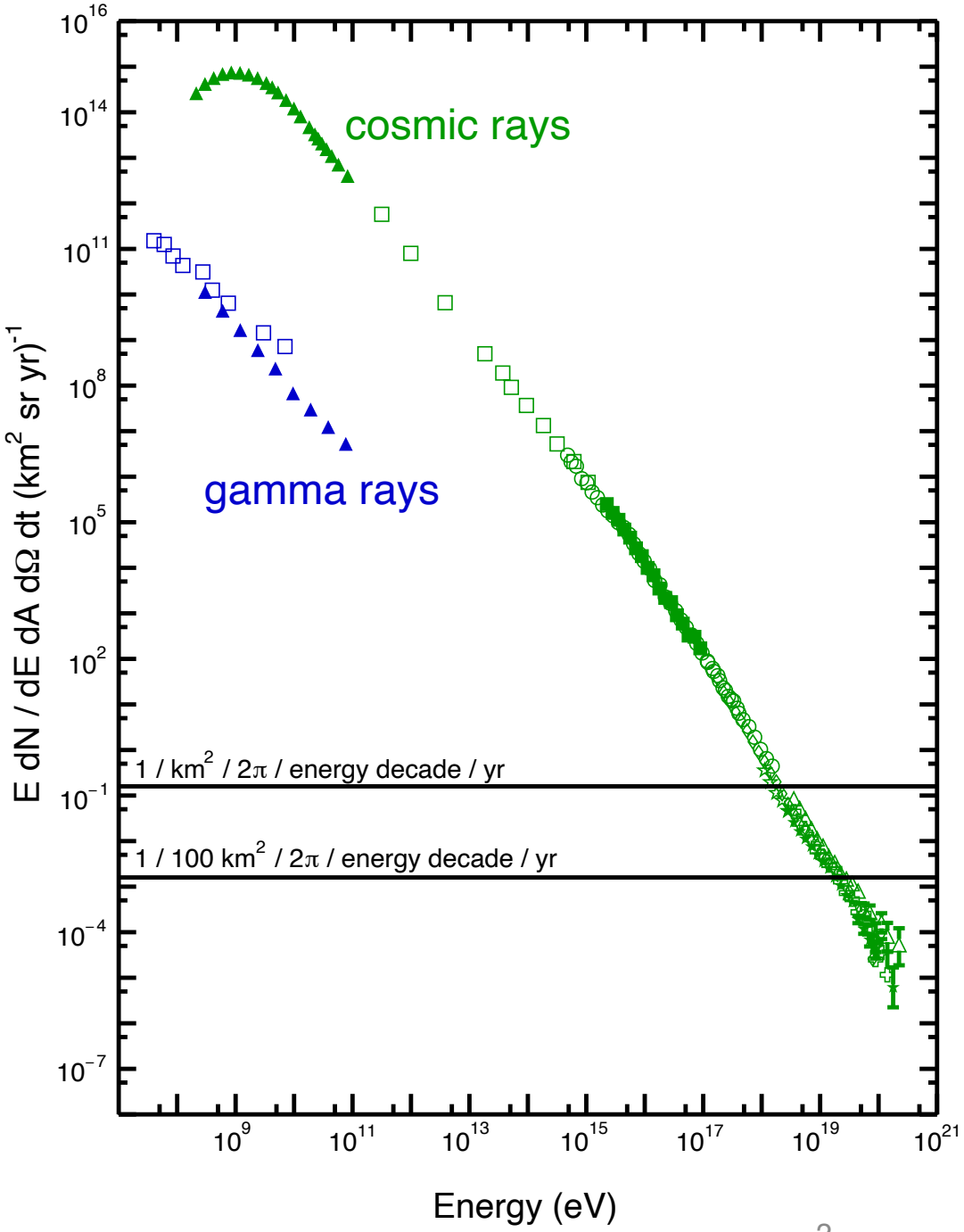

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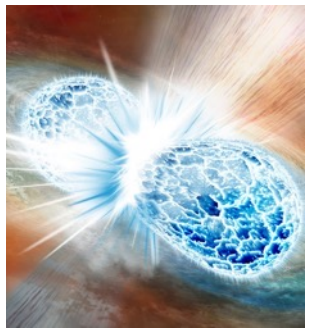
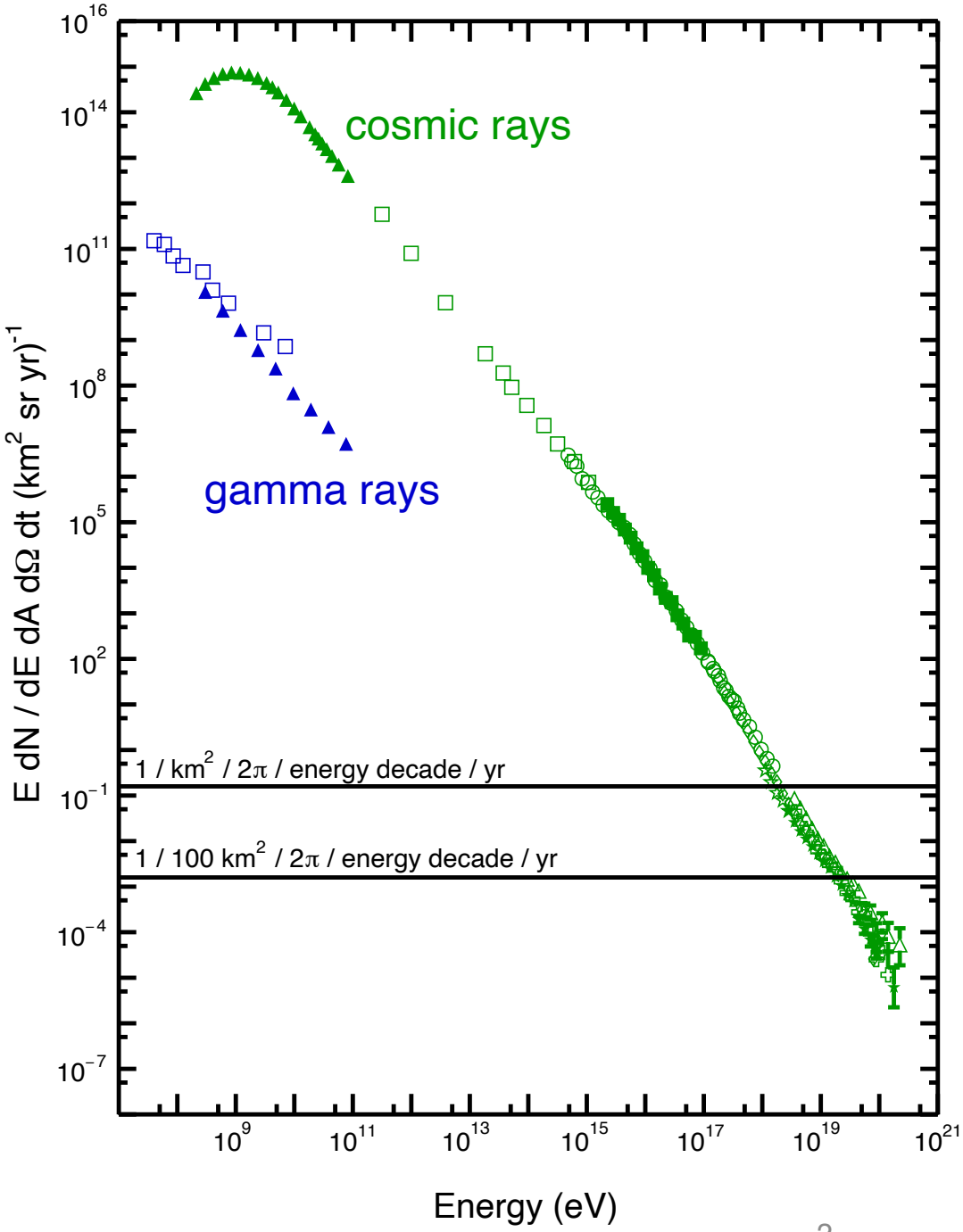


Mergers?



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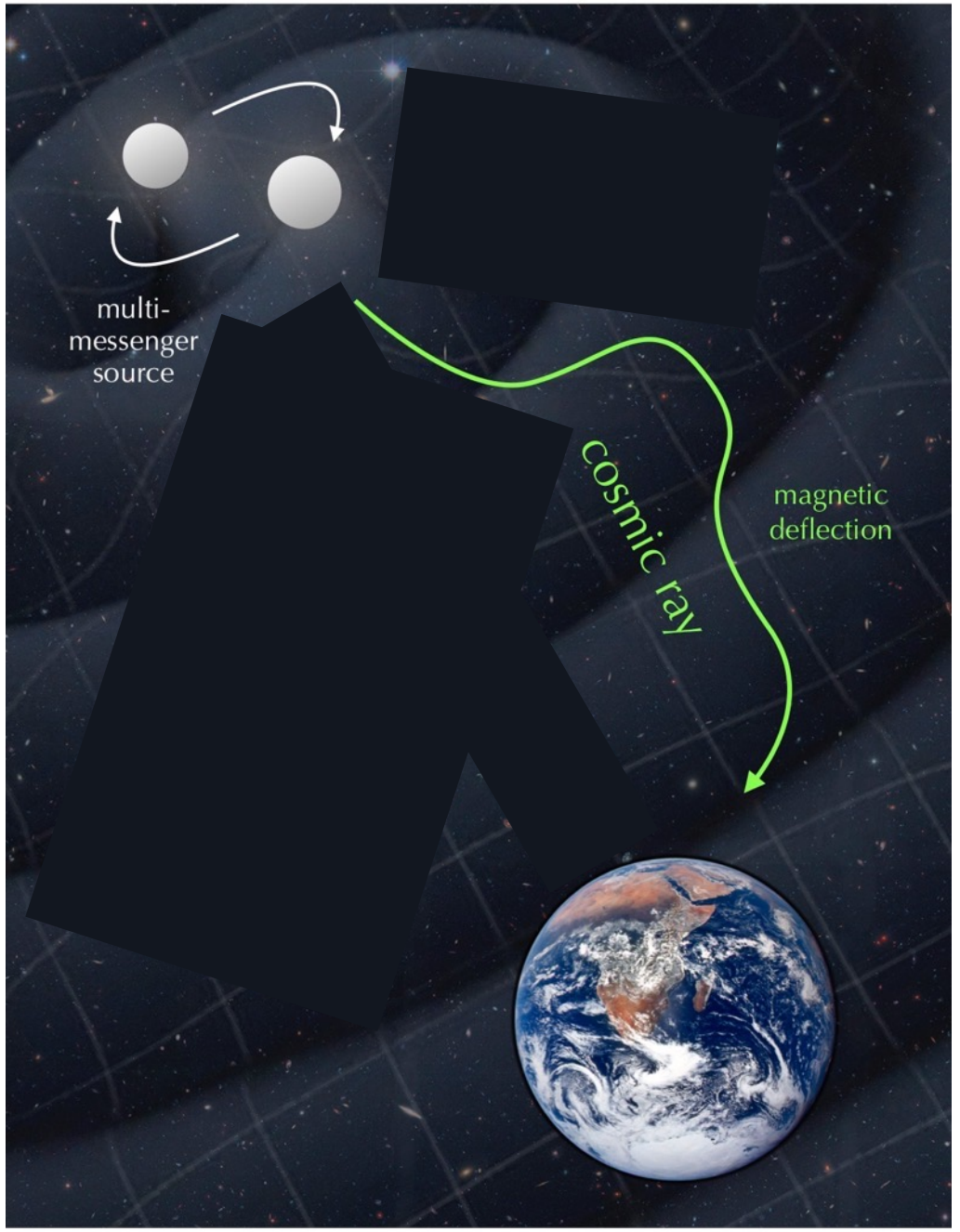

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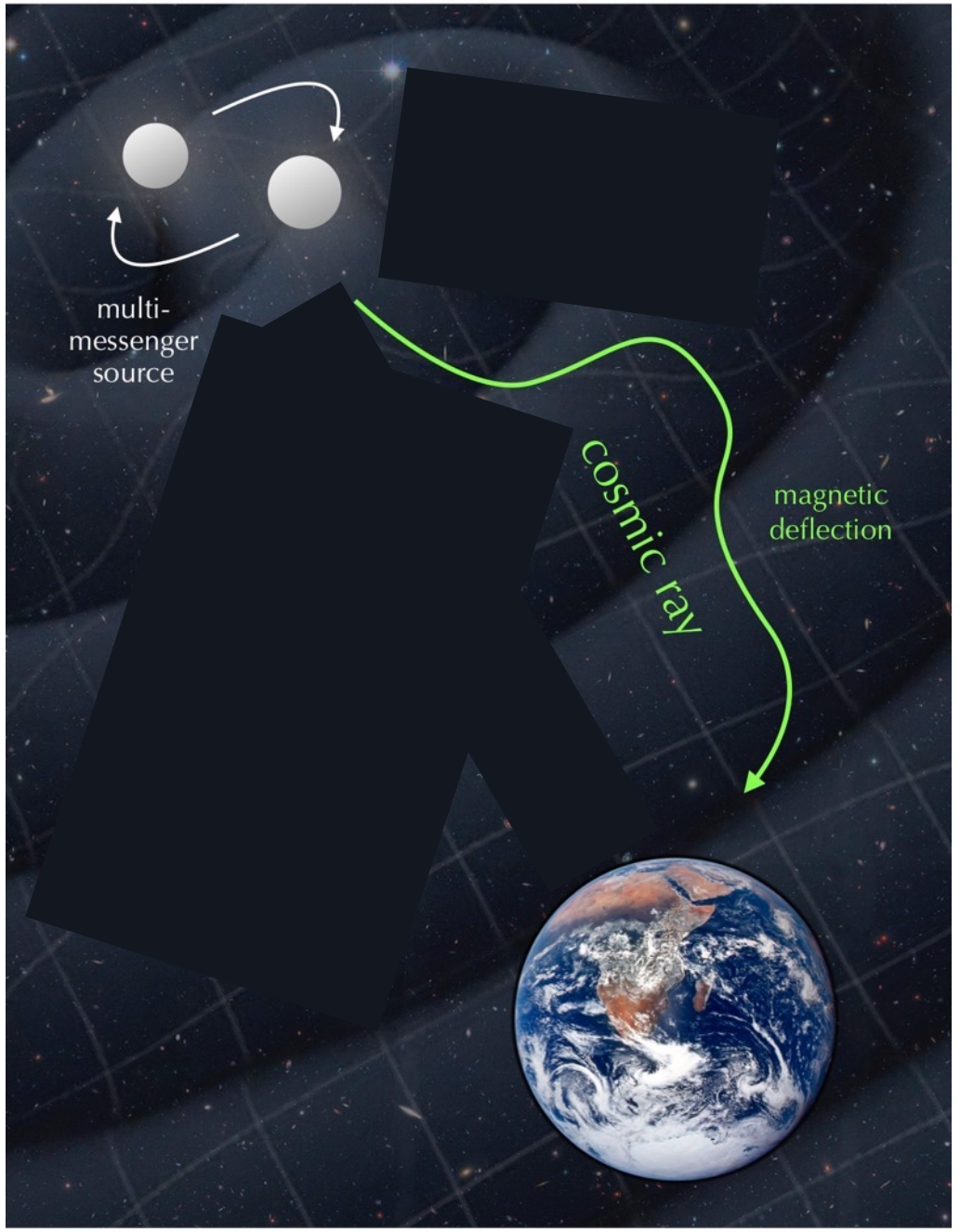

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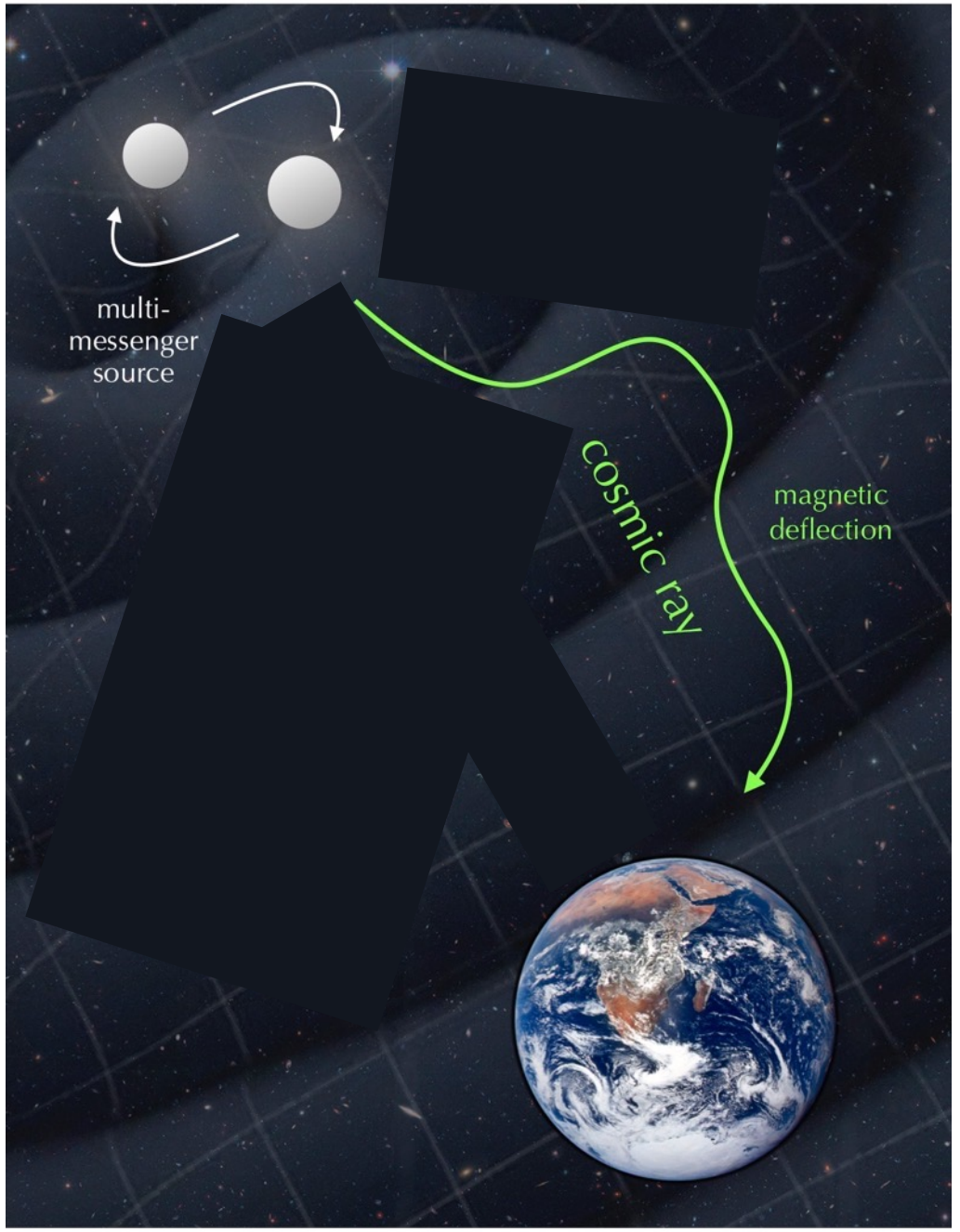

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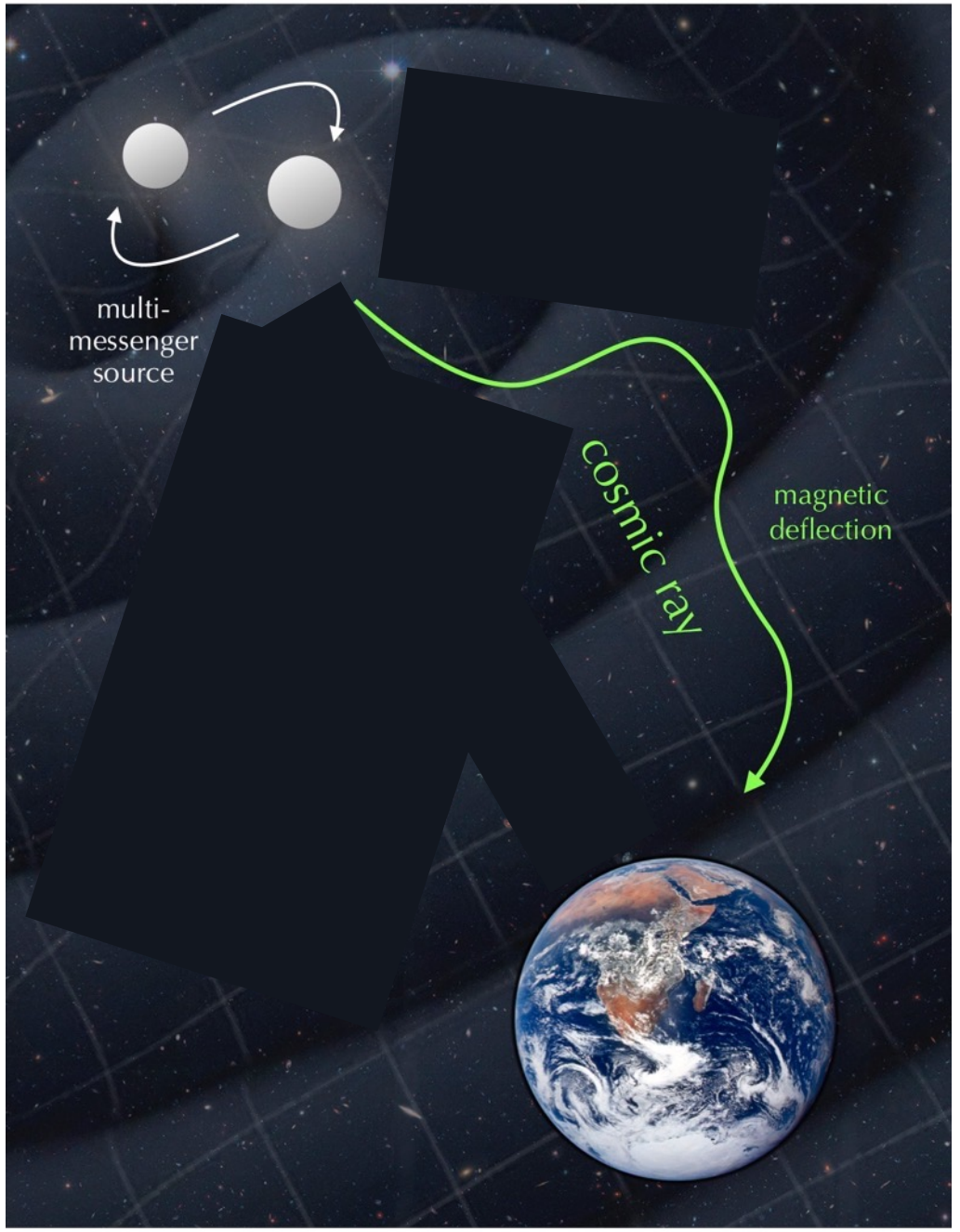

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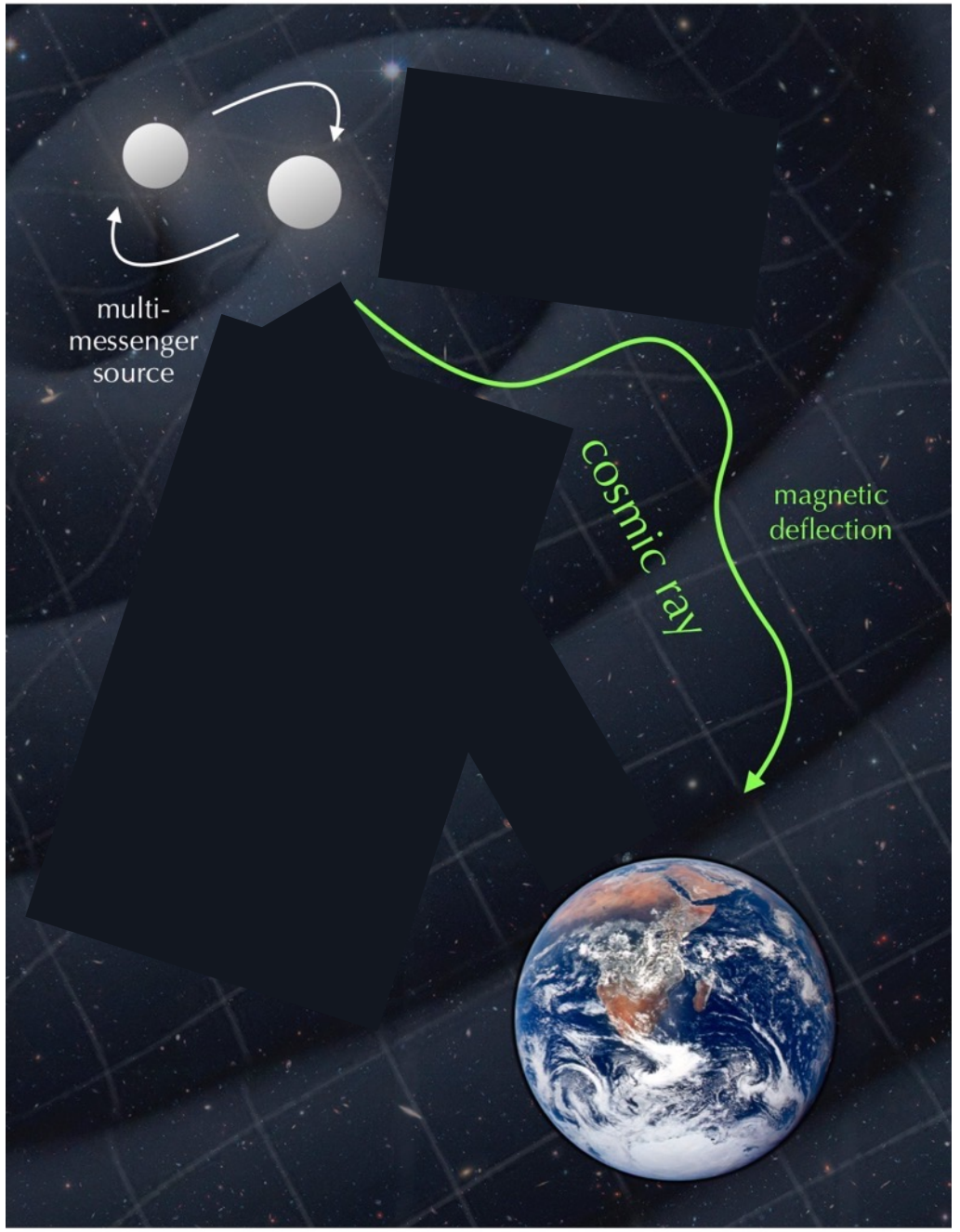

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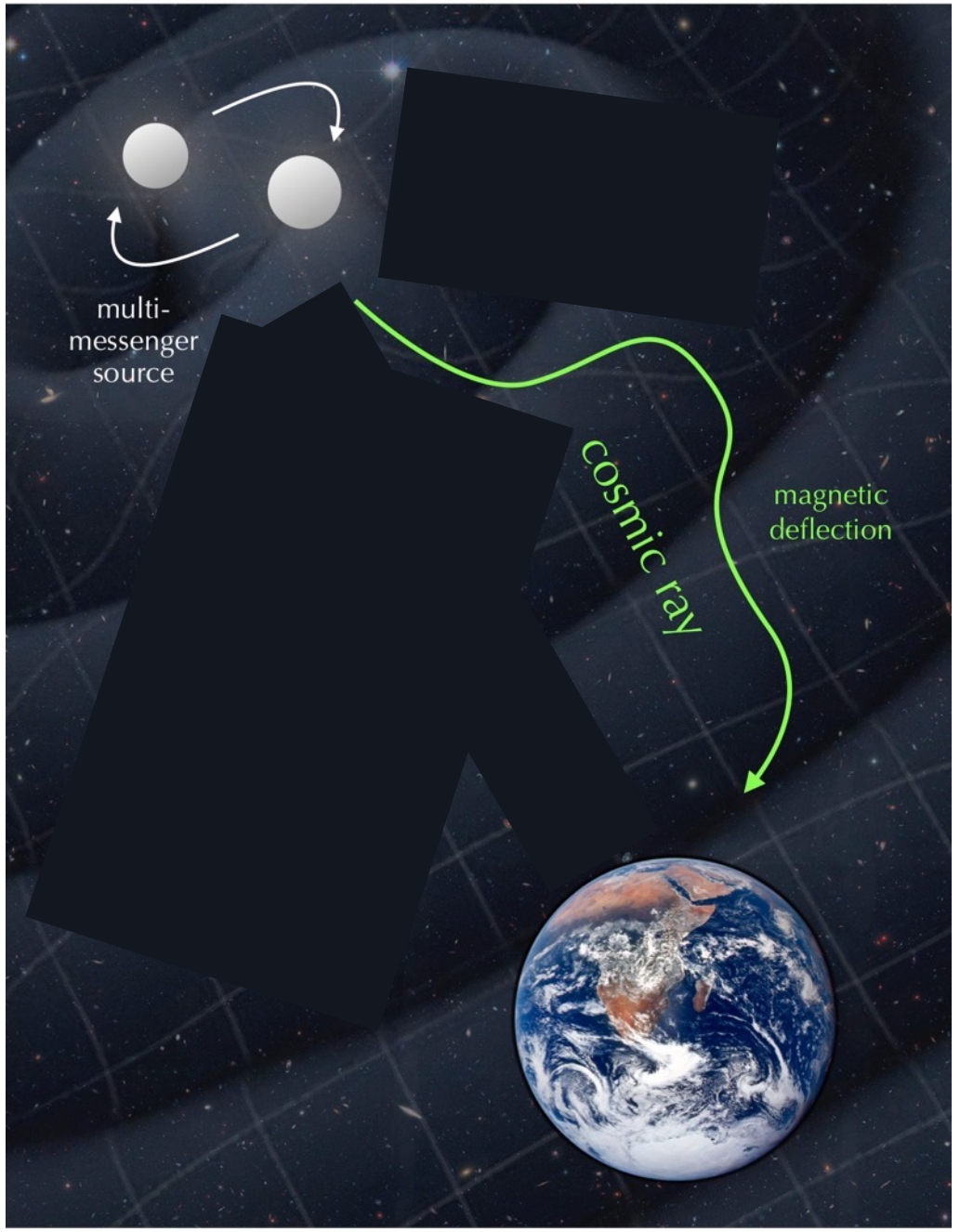

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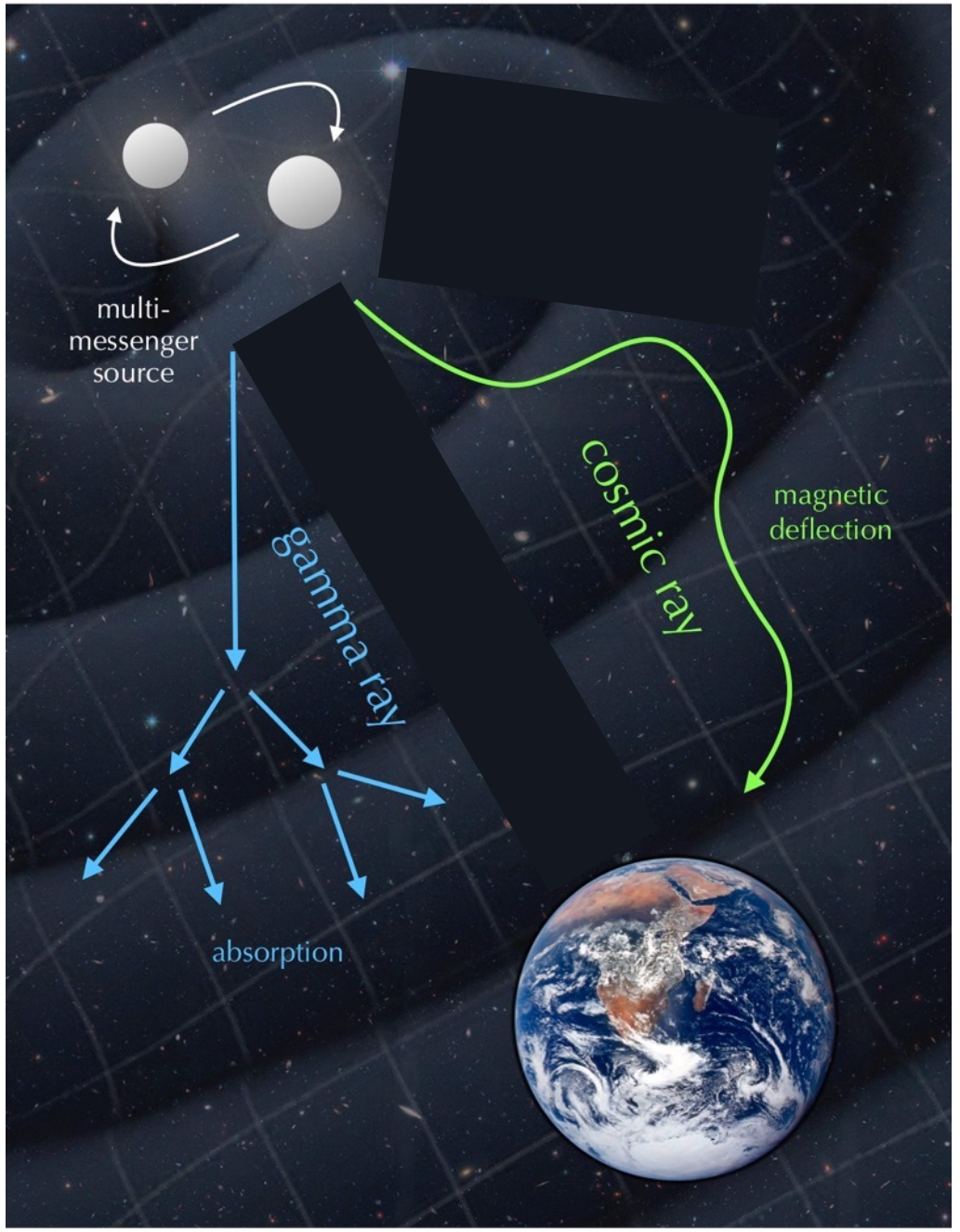

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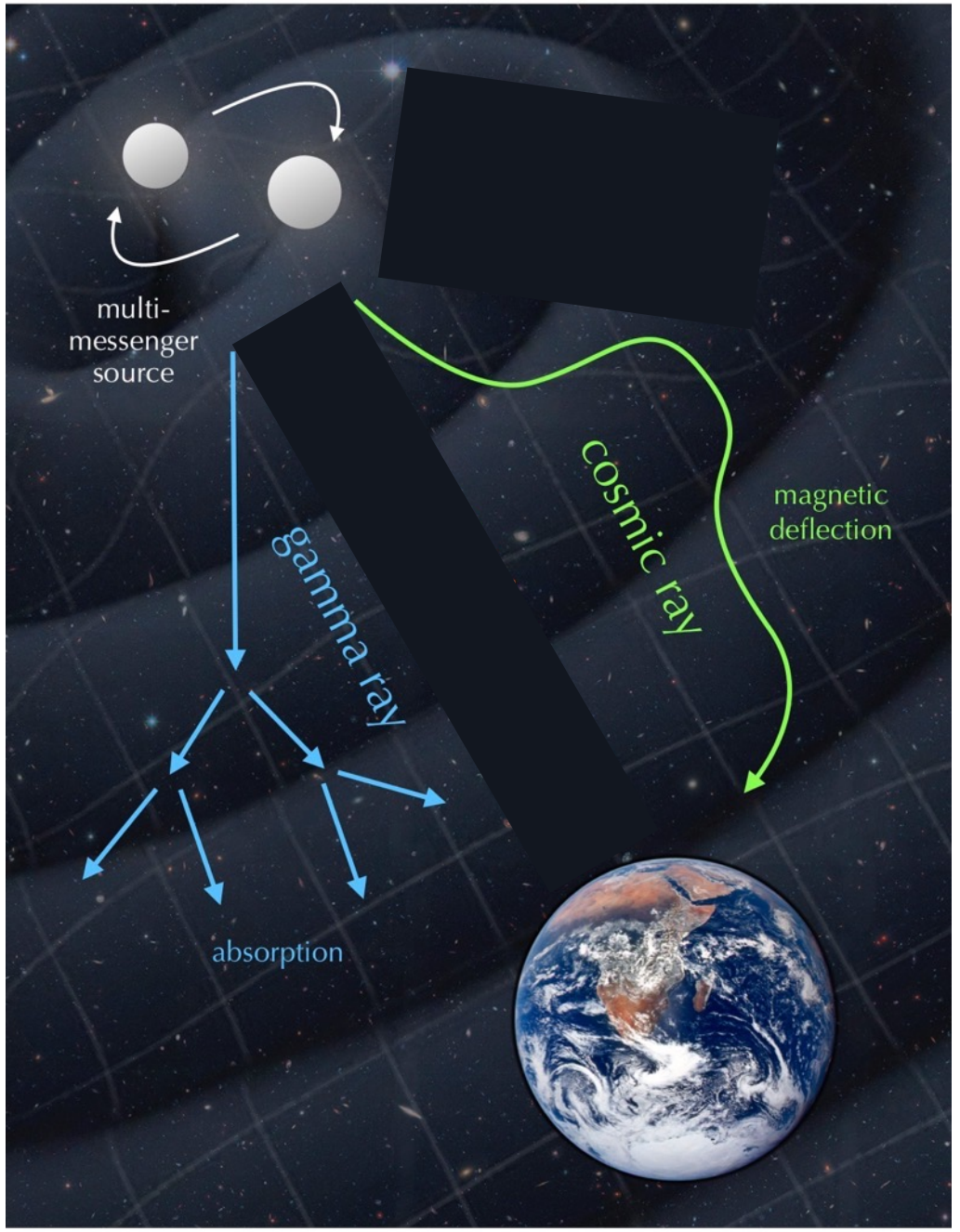

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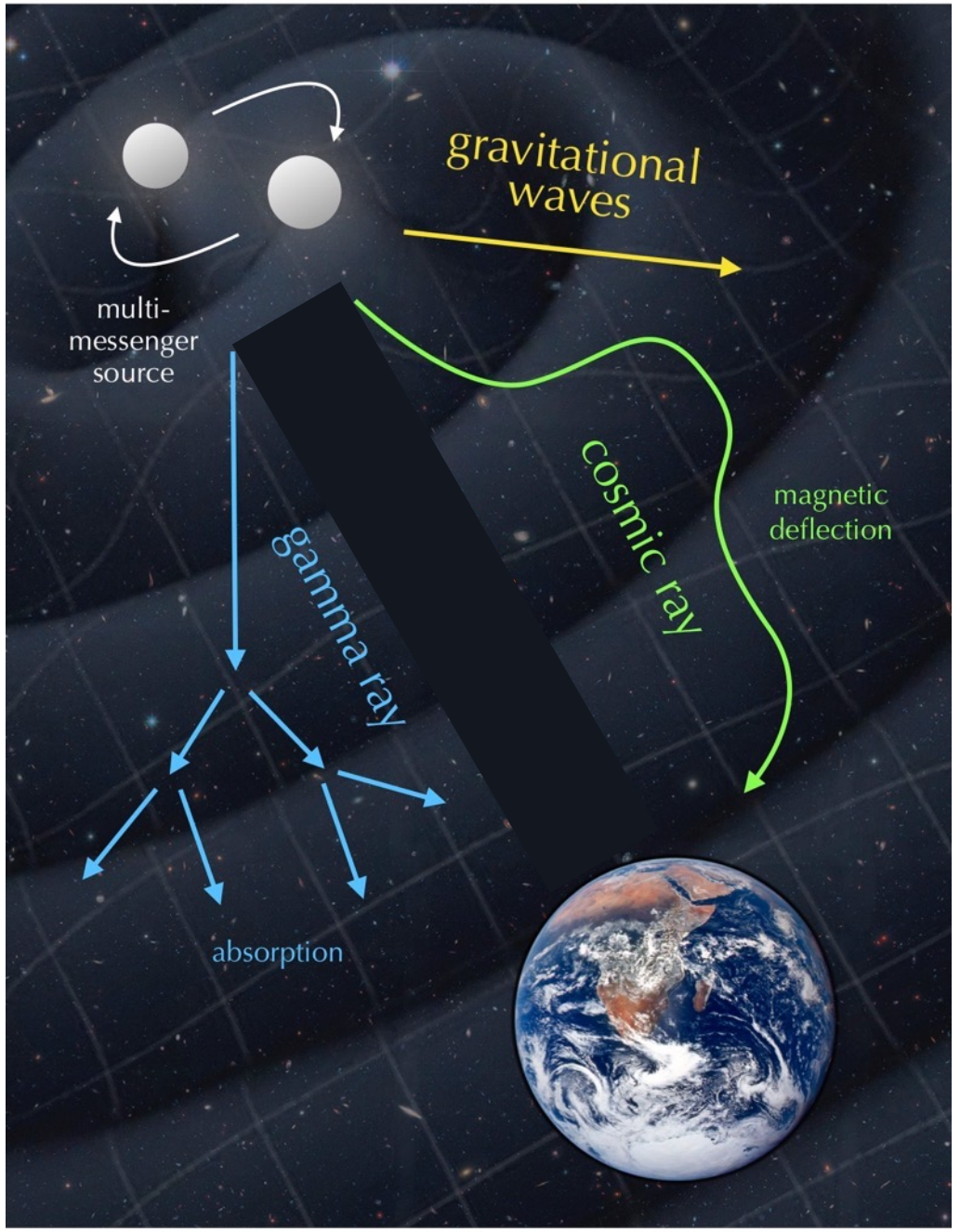

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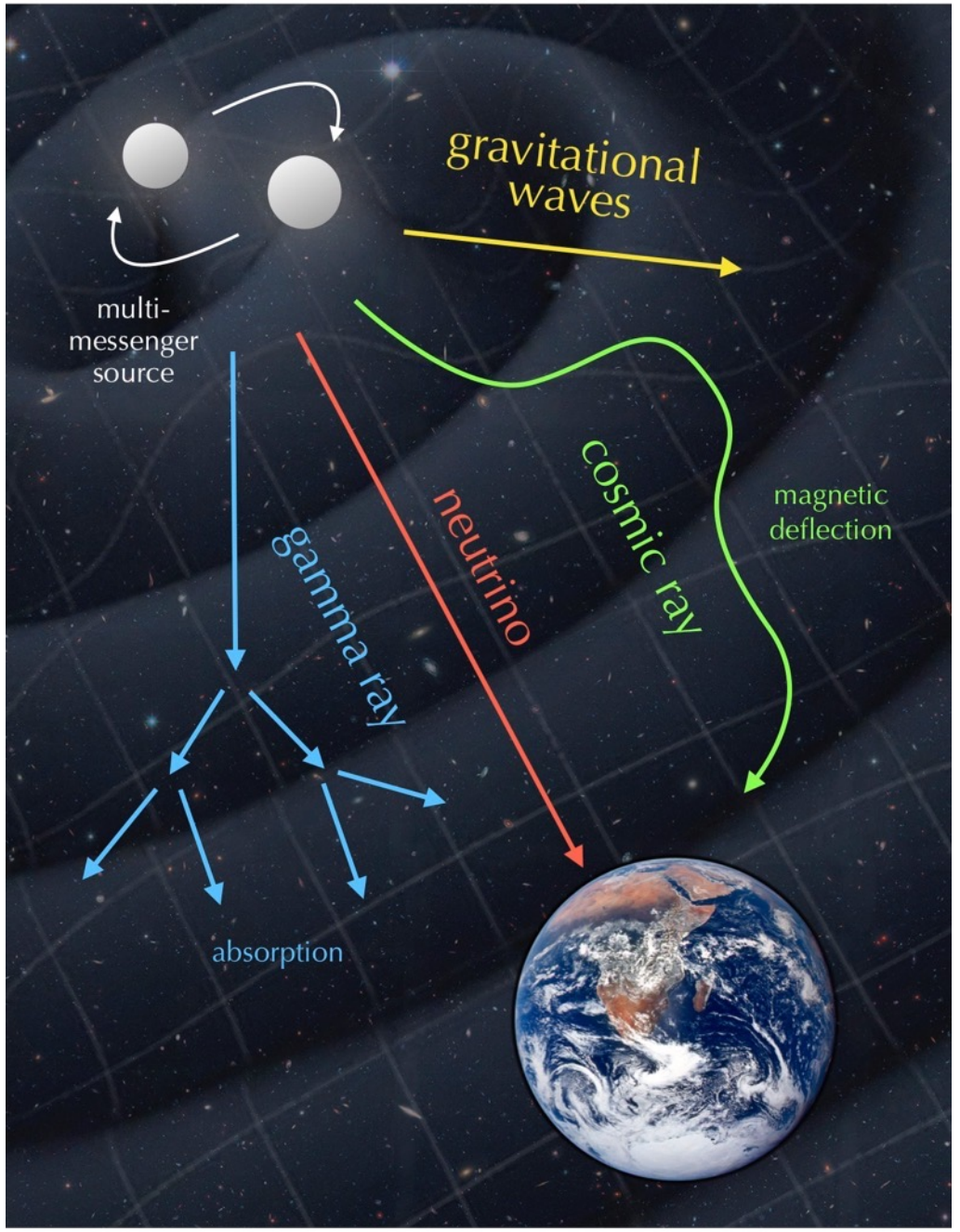

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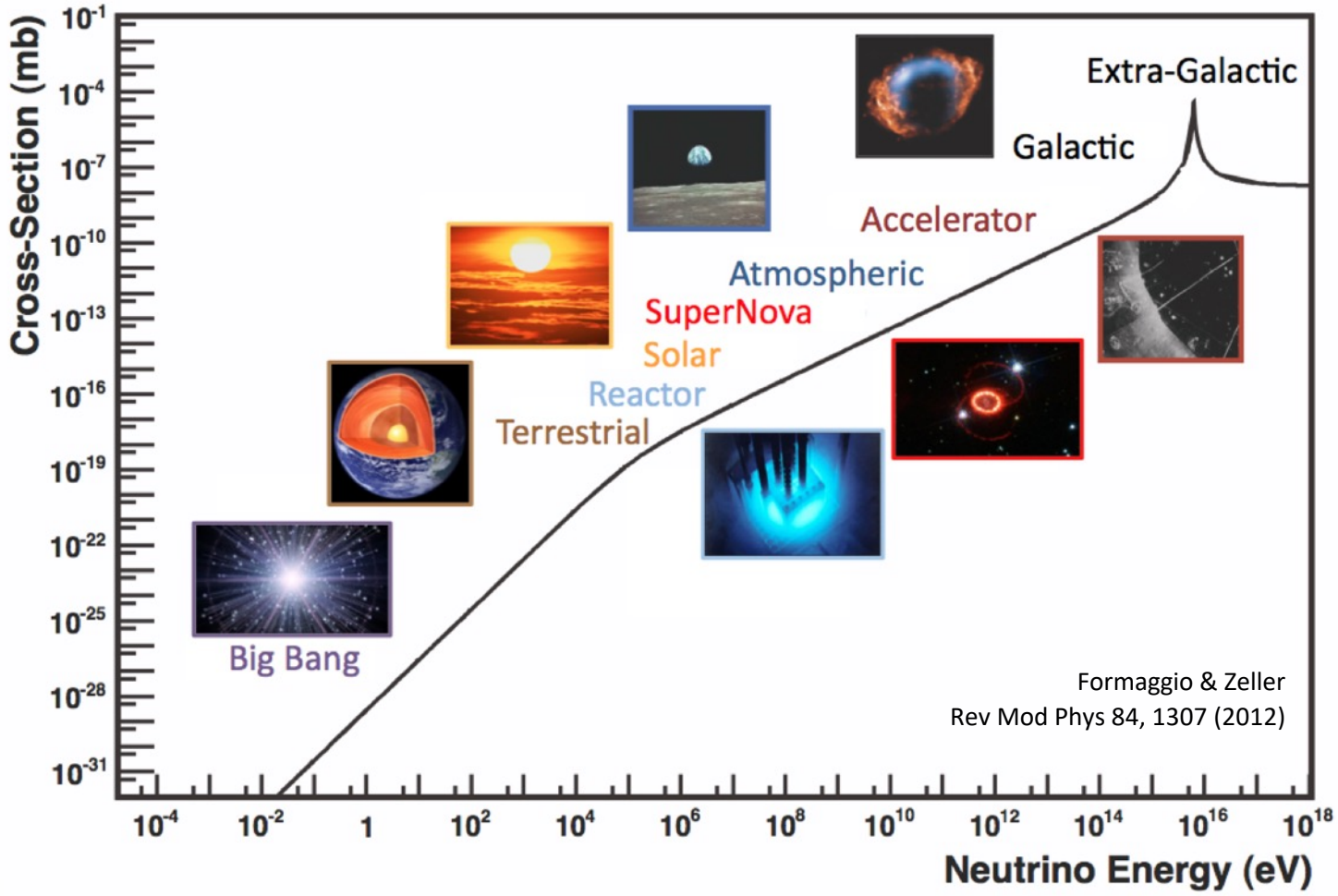


Formaggio & Zeller
Rev Mod Phys 84, 1307 (2012)

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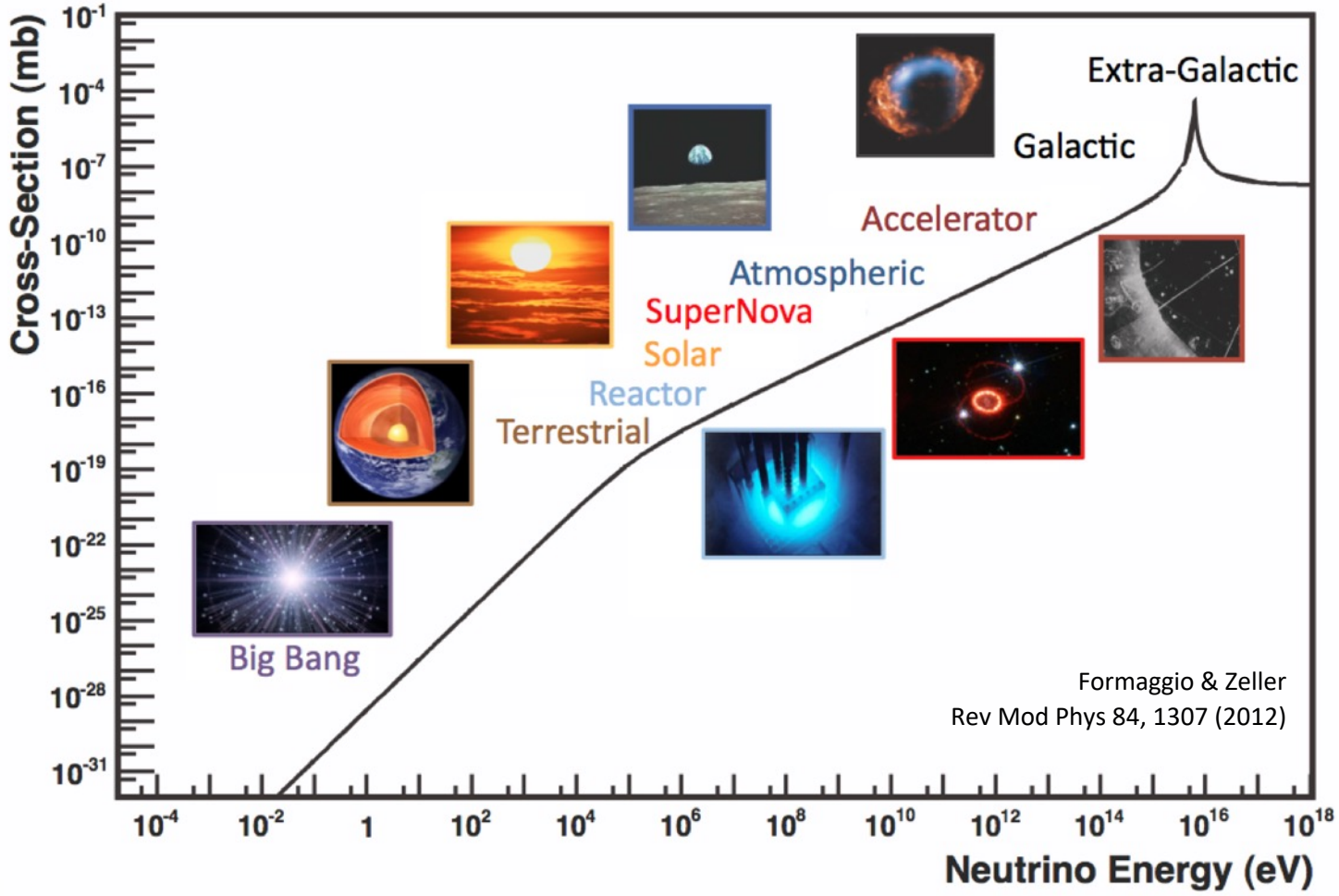


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Earth starts absorbing neutrinos above ~40 TeV.

Mean free path @ 1 EeV is ~40 km (in rock)

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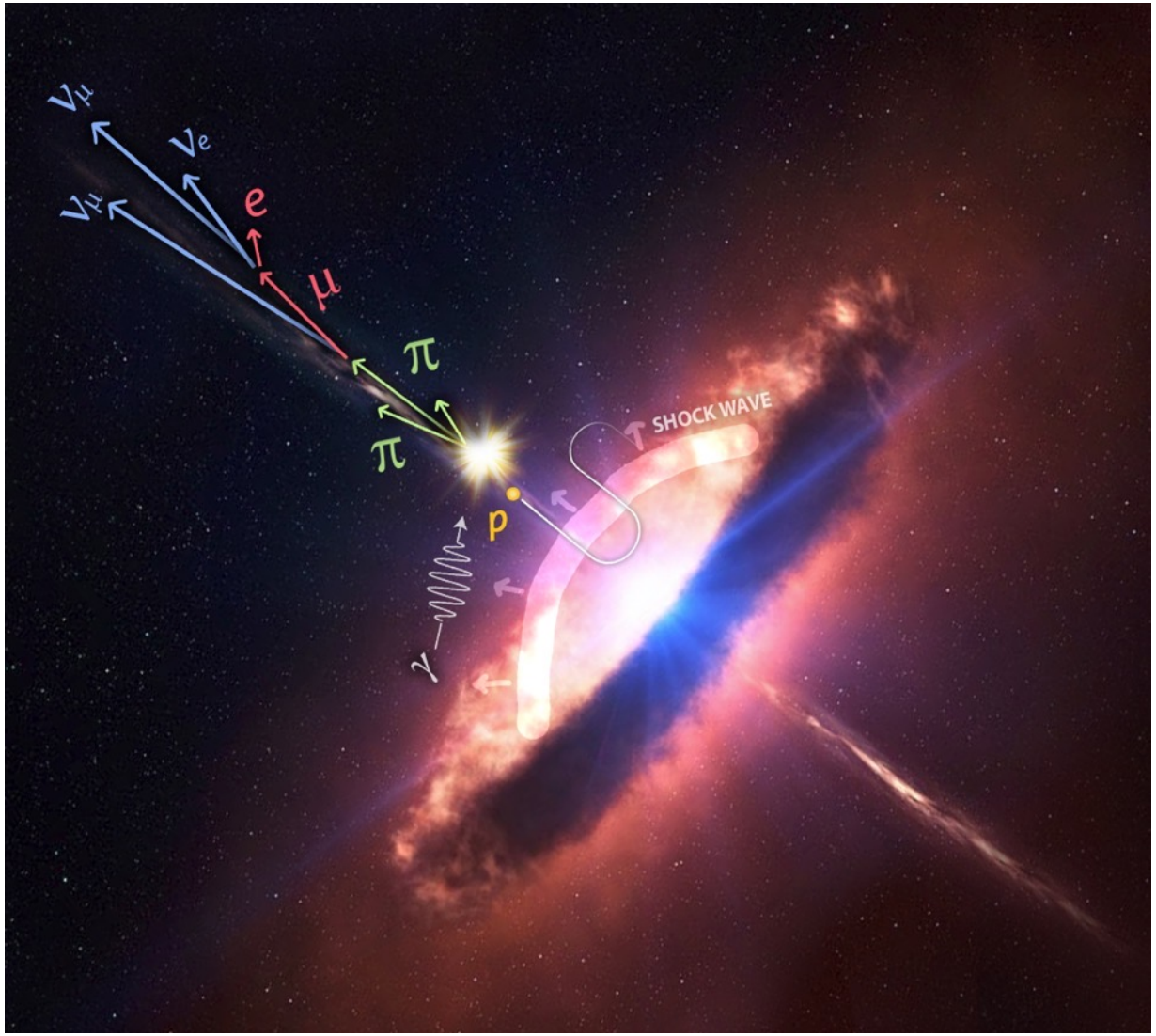

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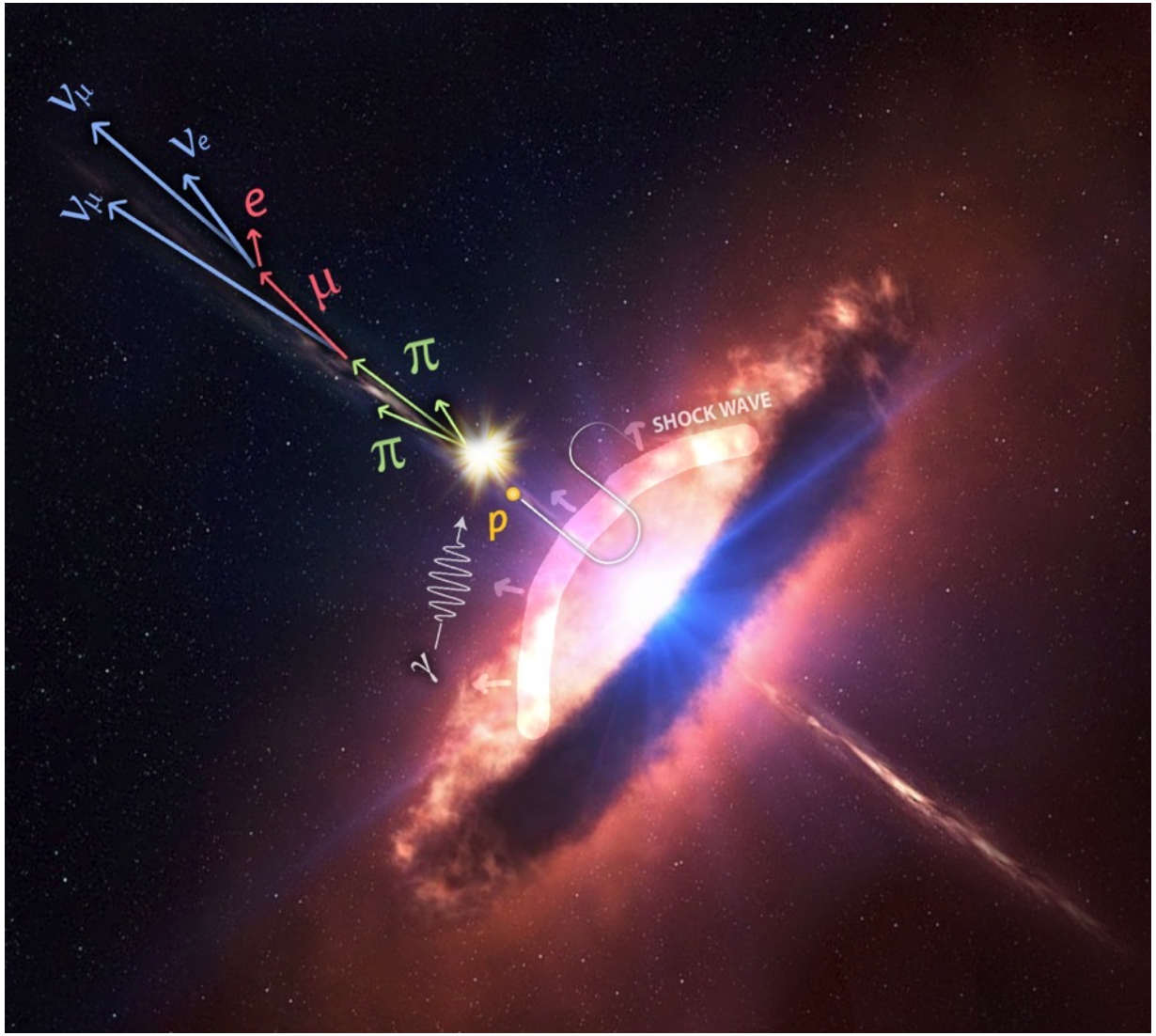

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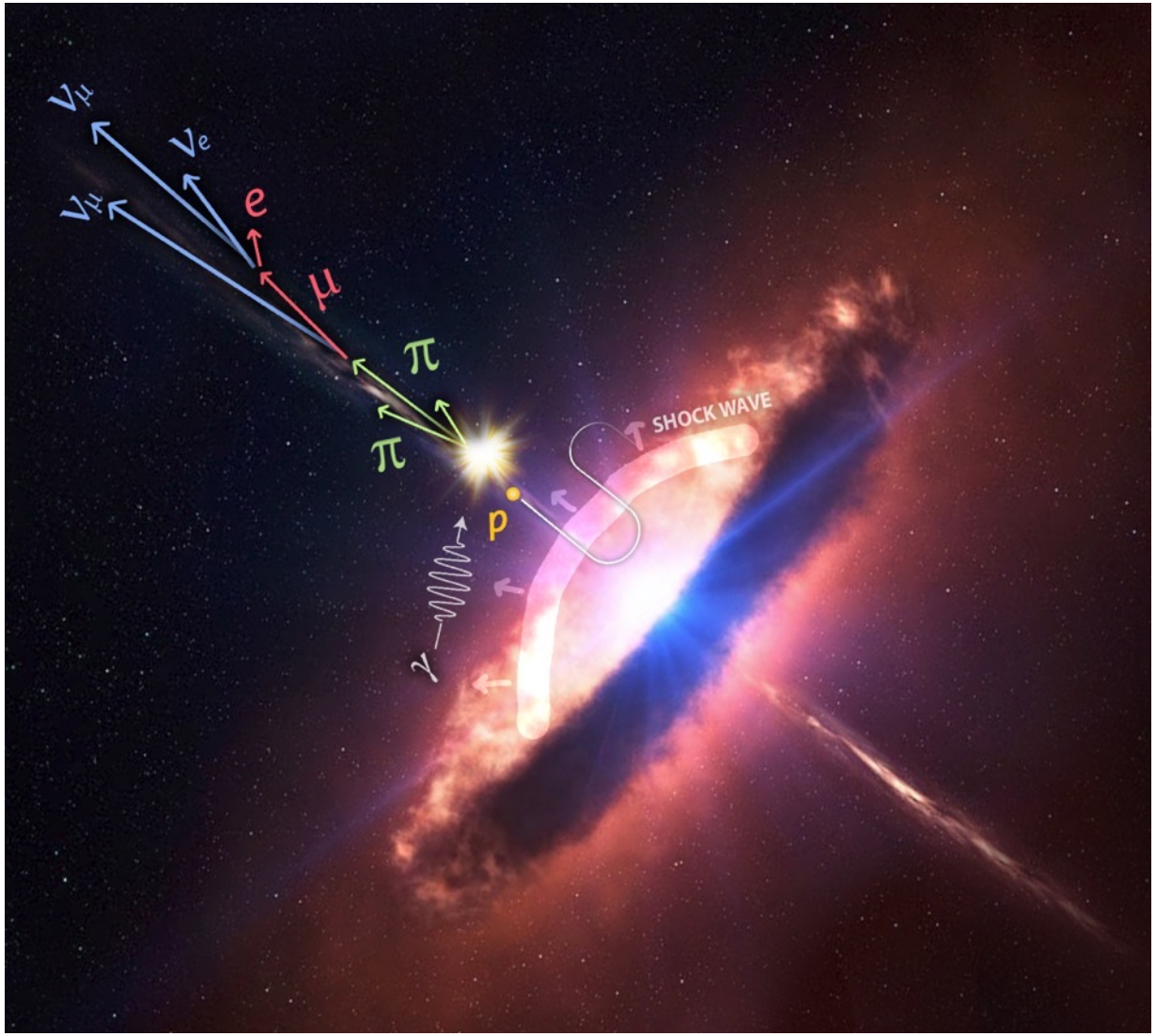

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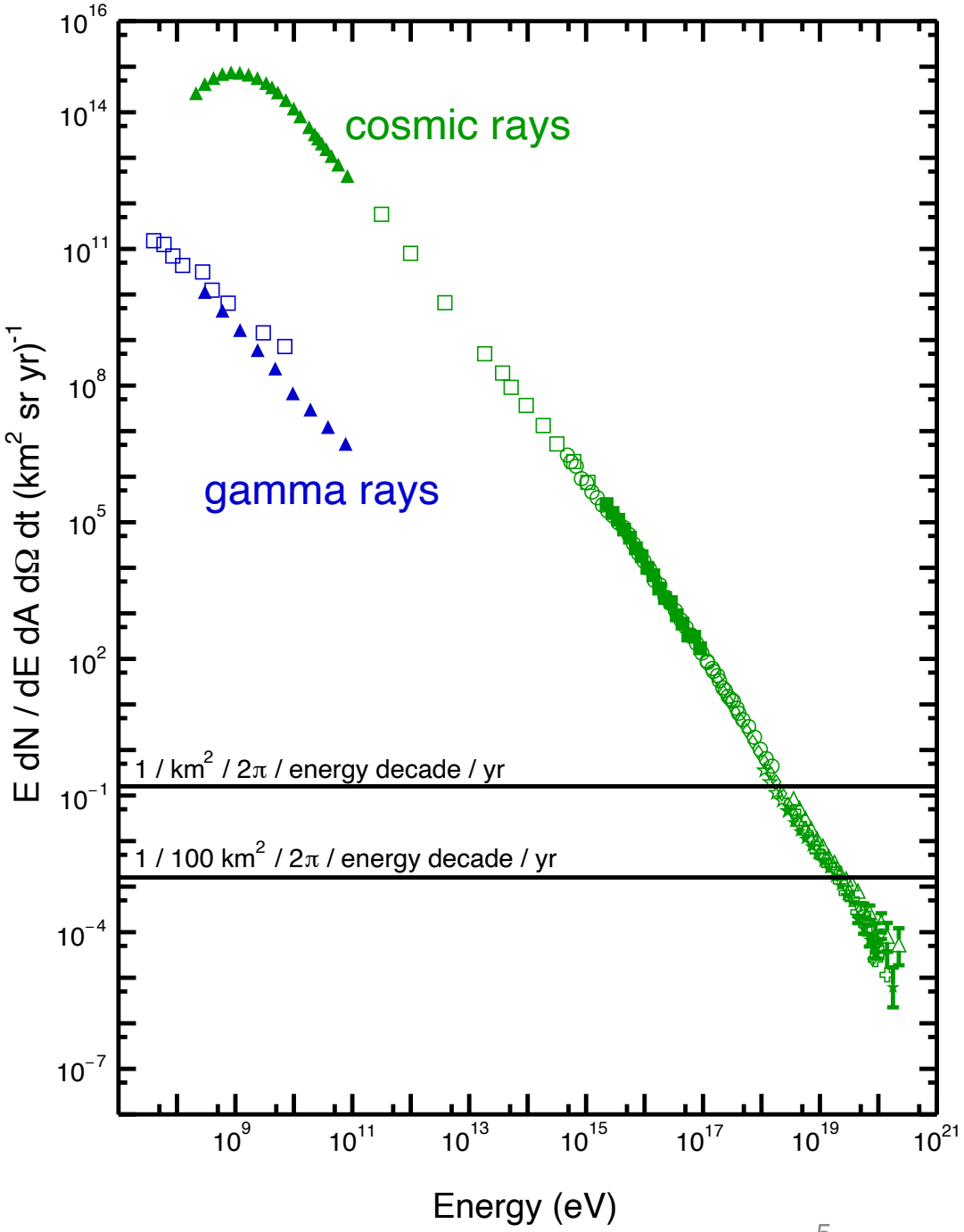

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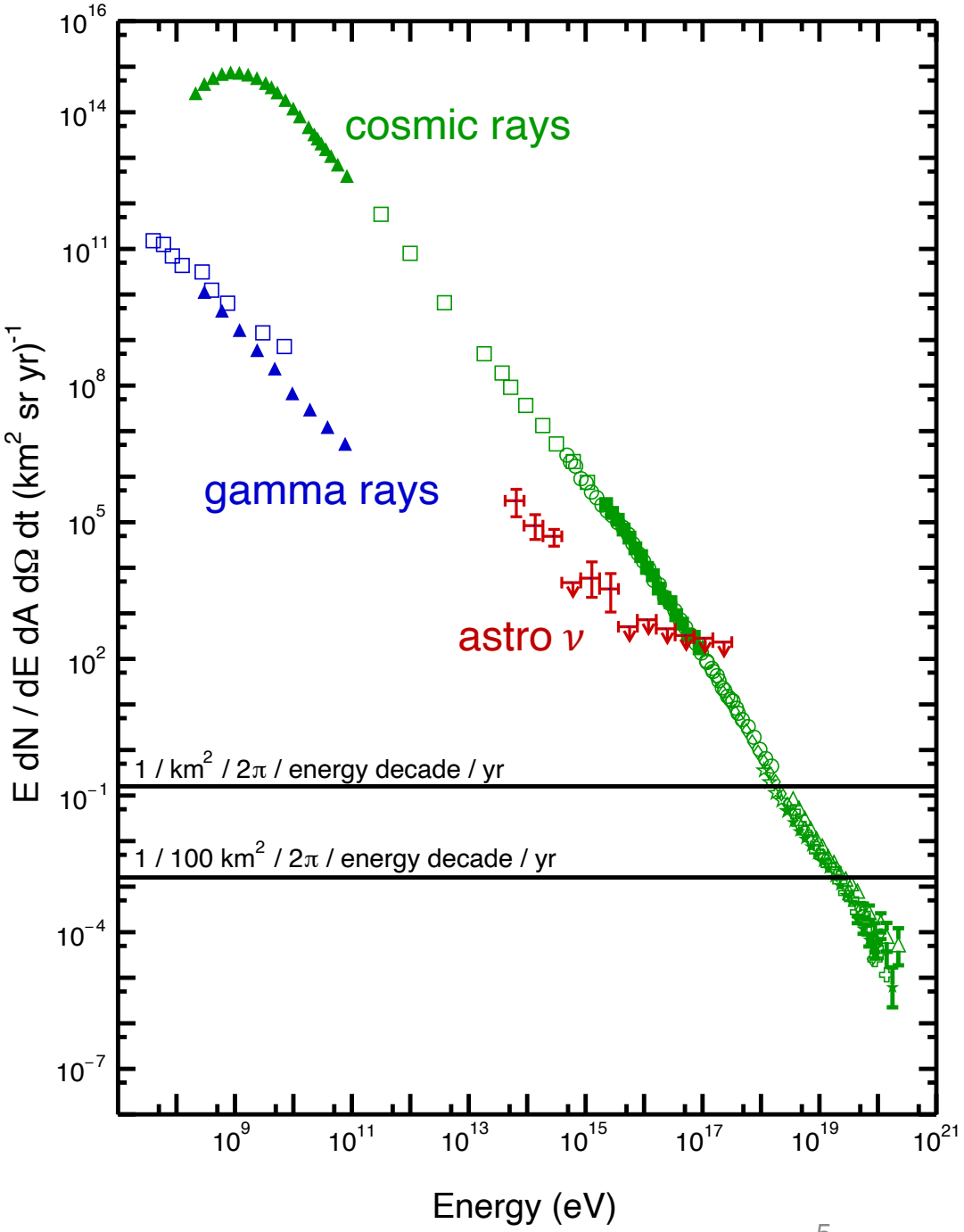

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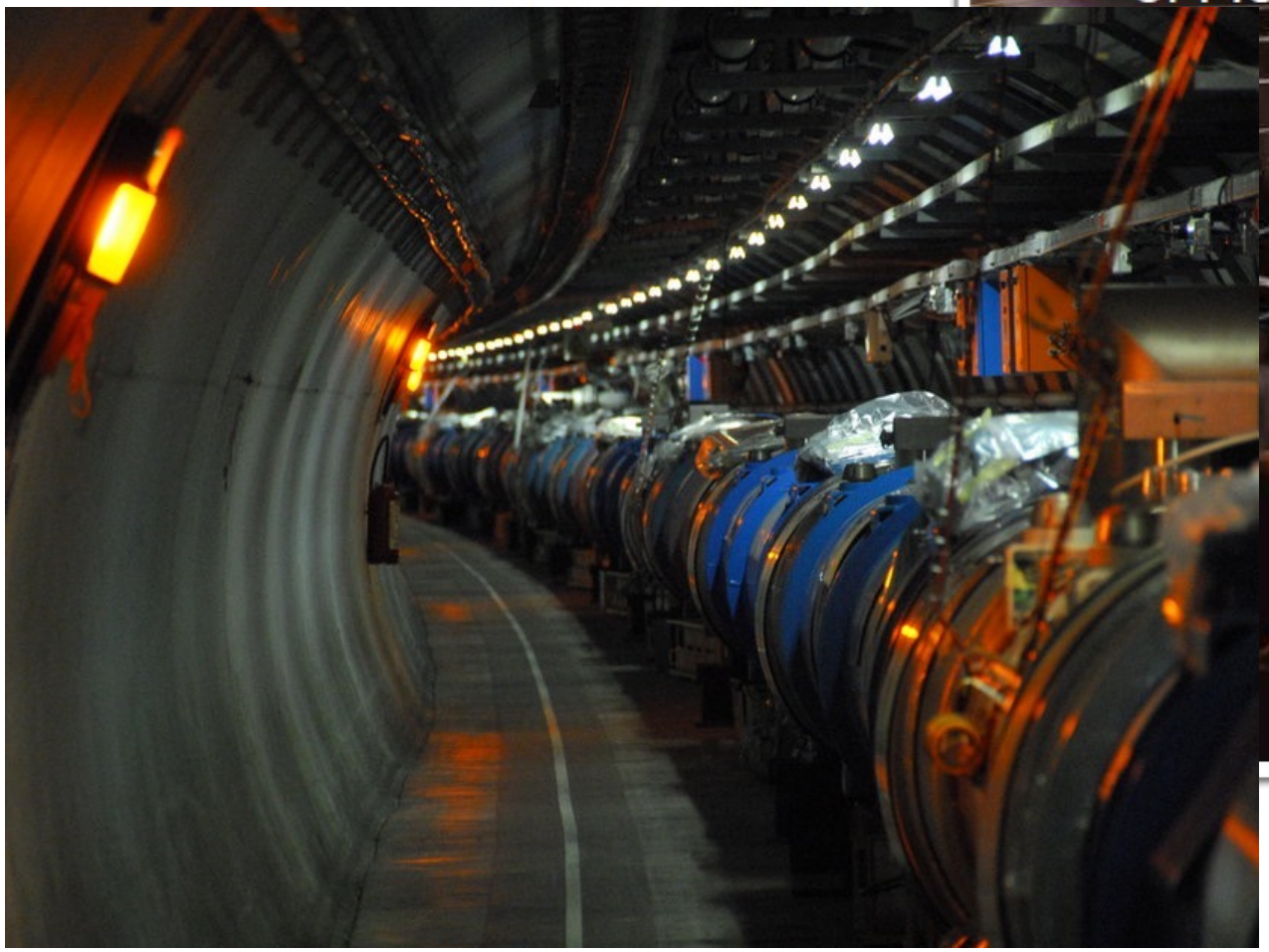

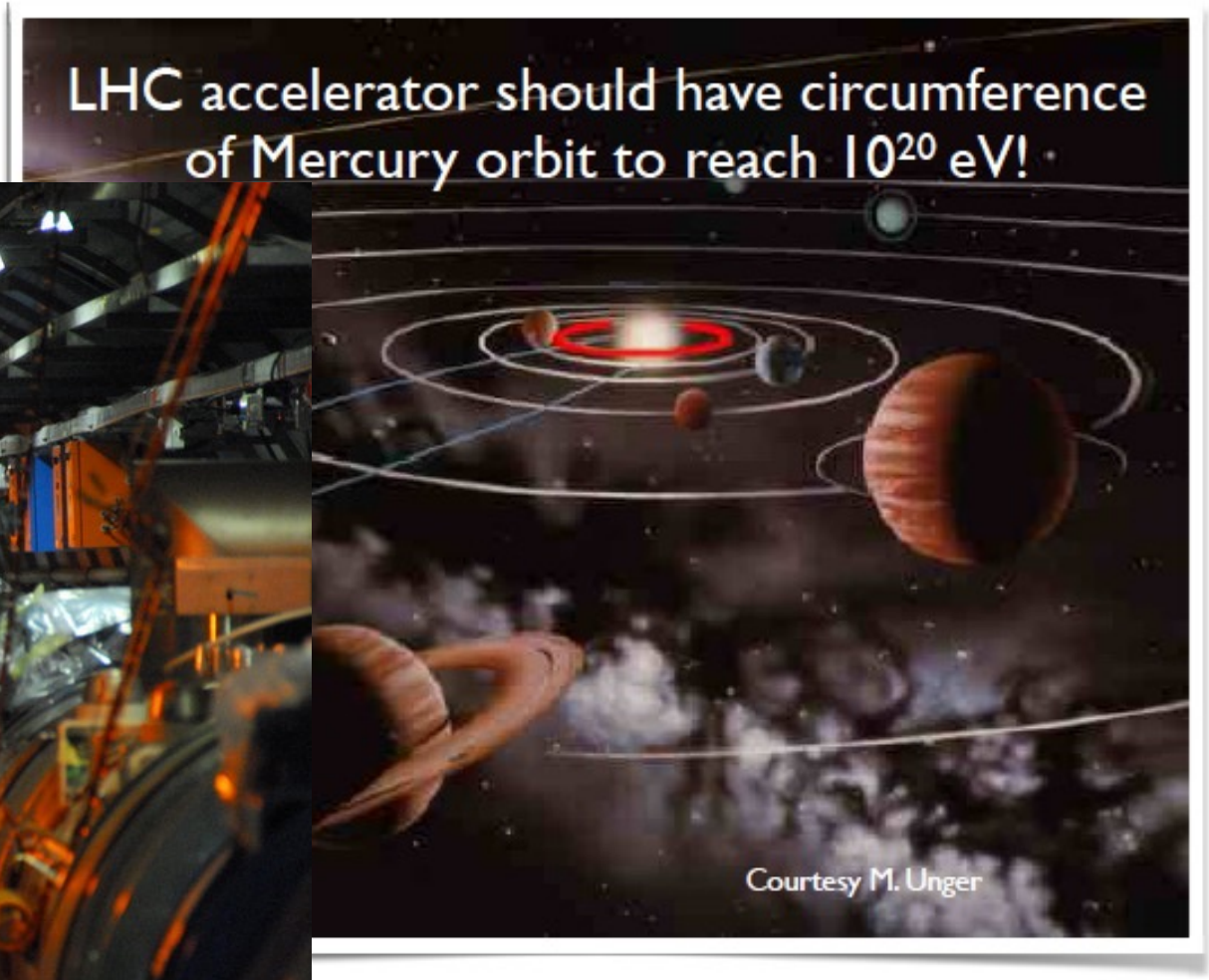


Courtesy of Francis Halzen

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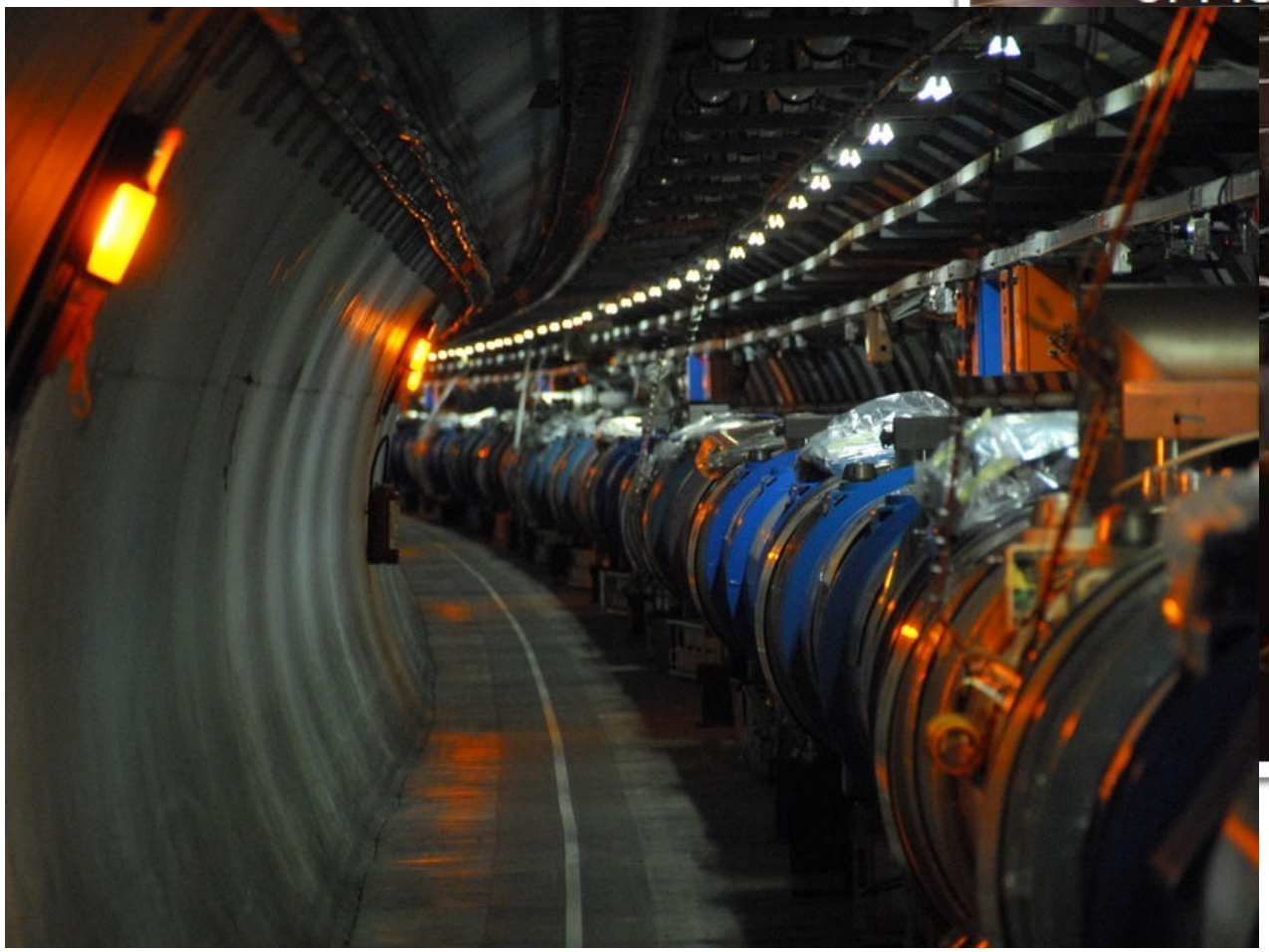
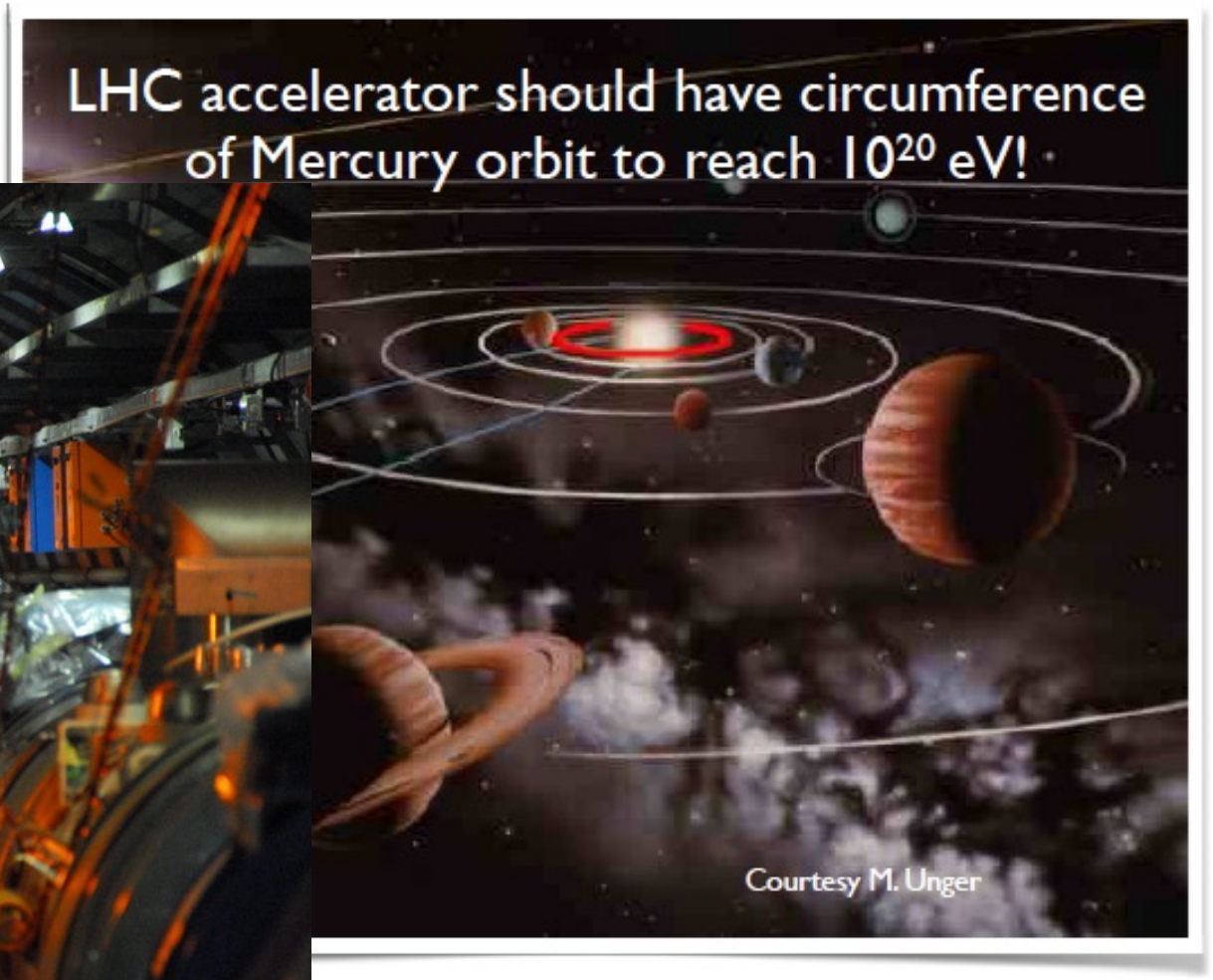
Probe cross-sections at energies above accelerators



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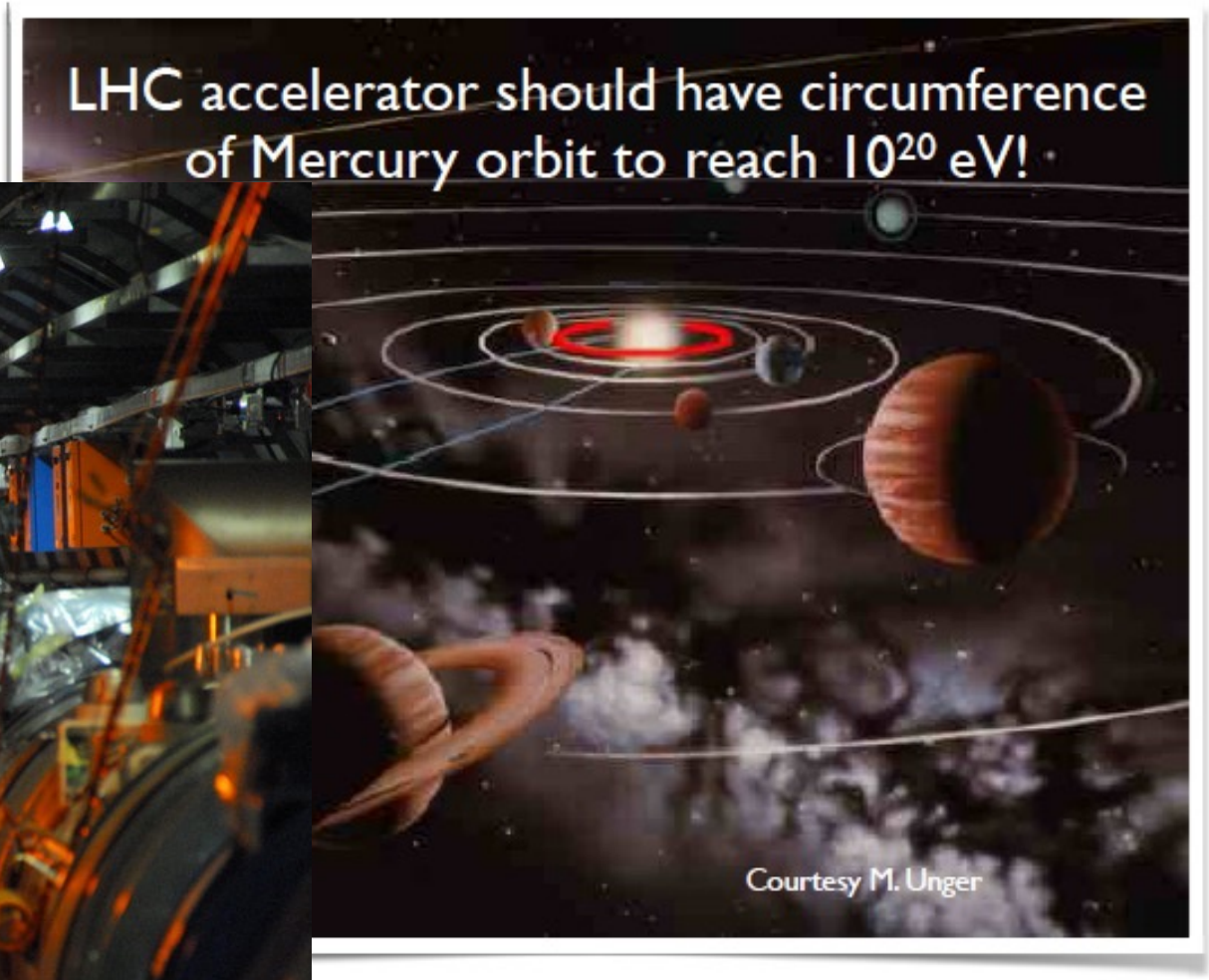


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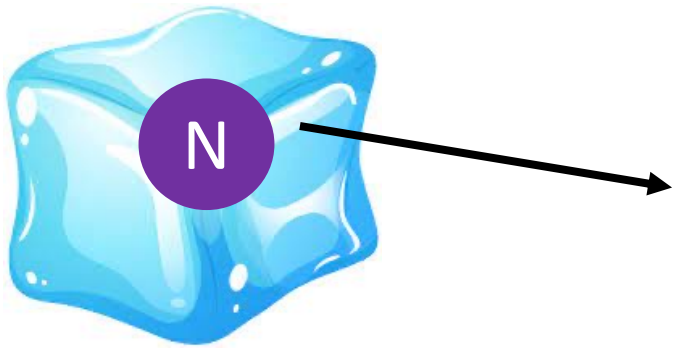

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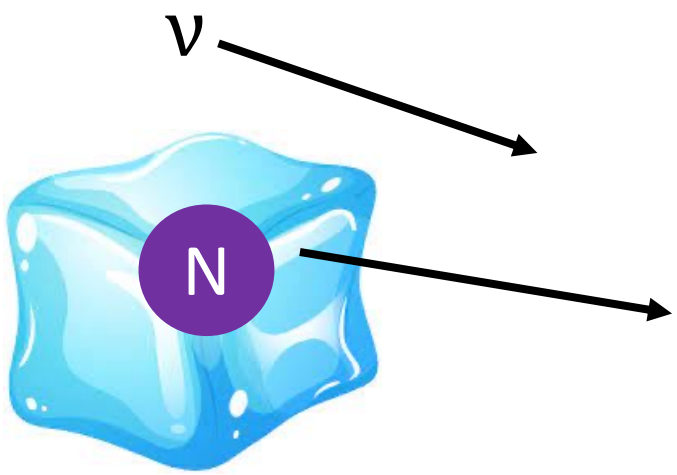

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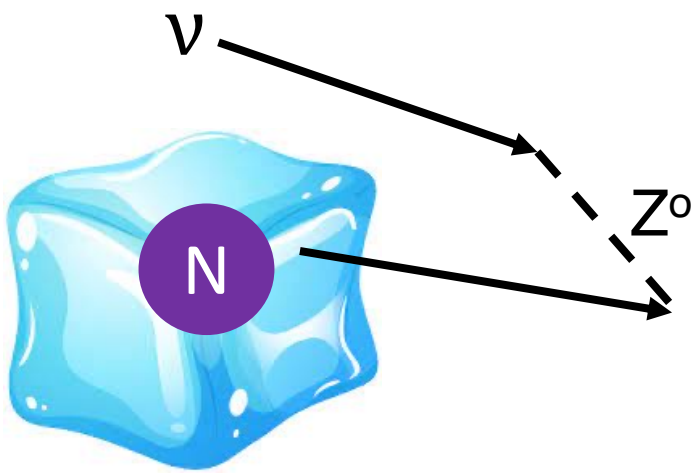

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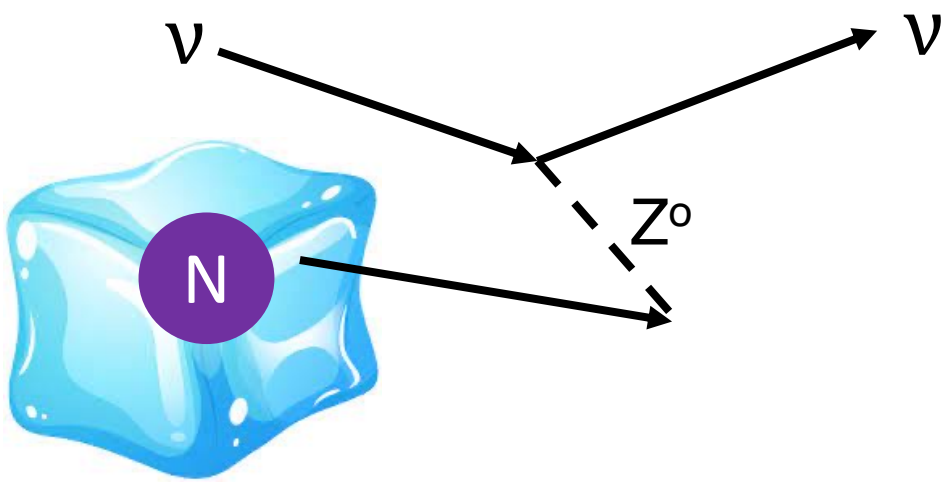

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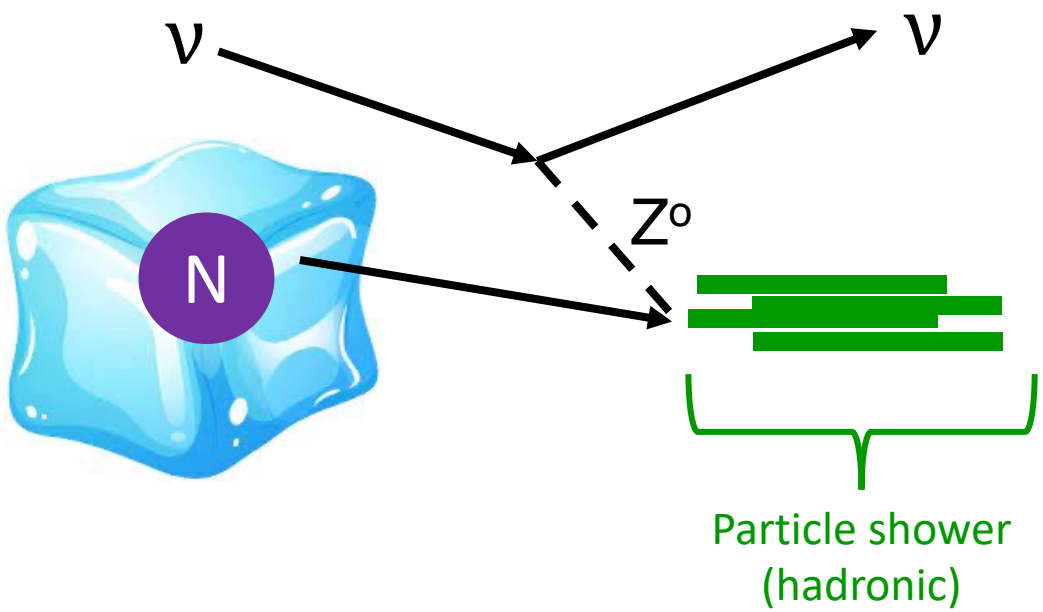

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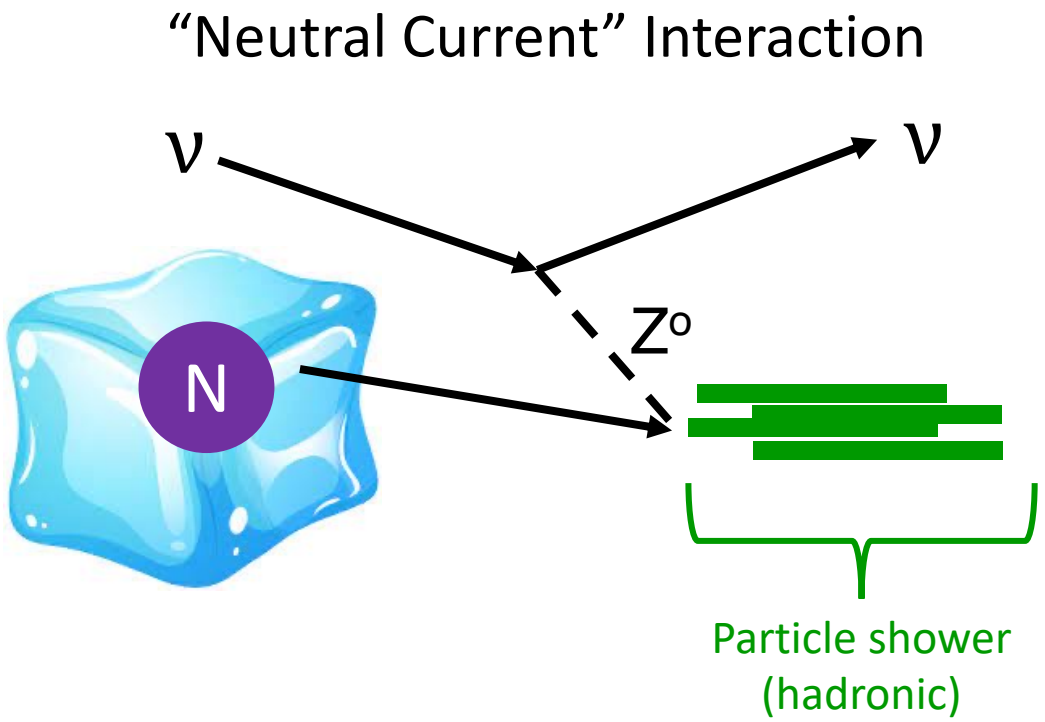

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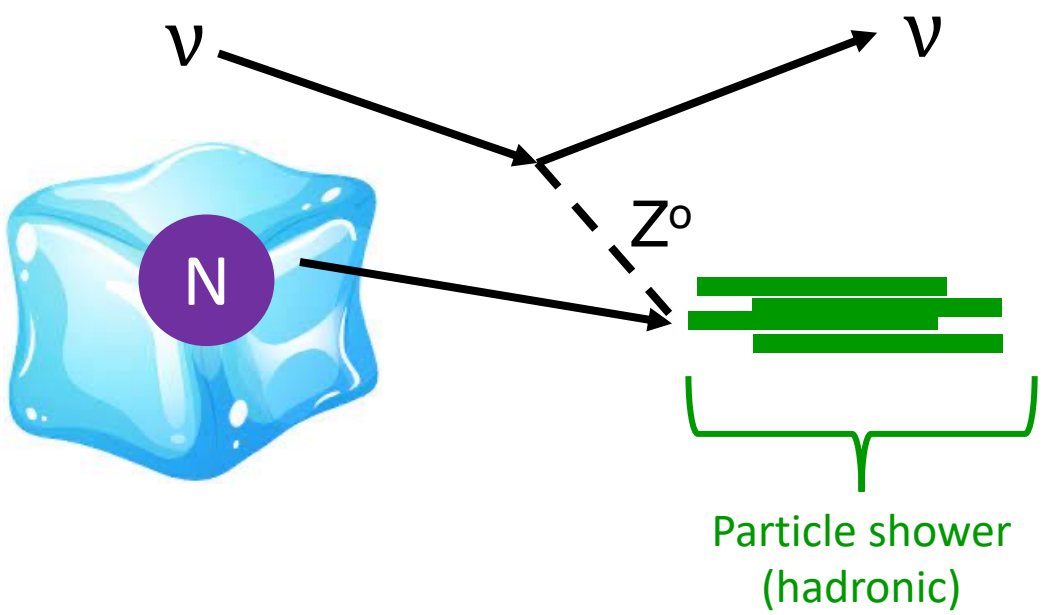


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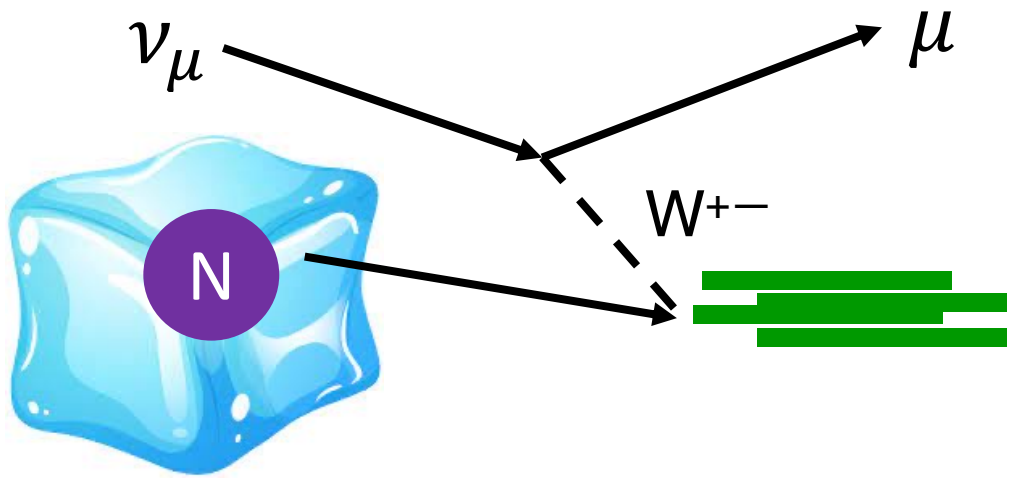

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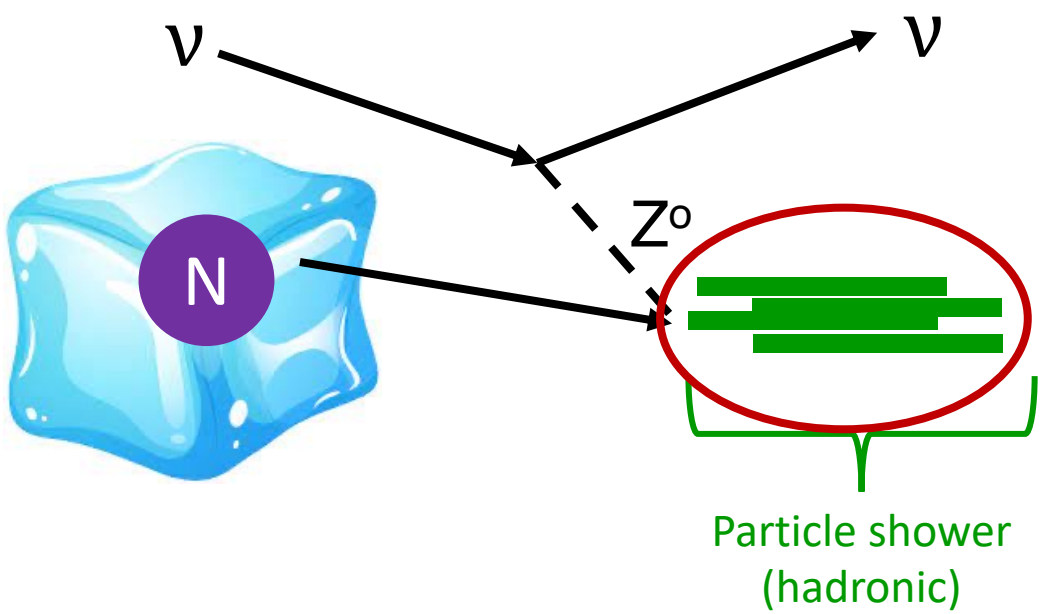


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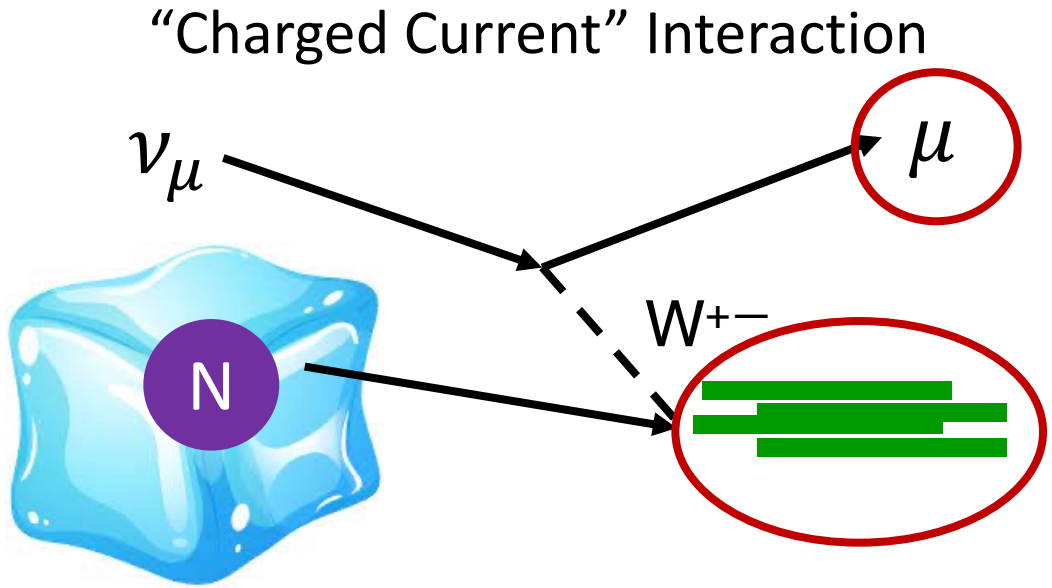


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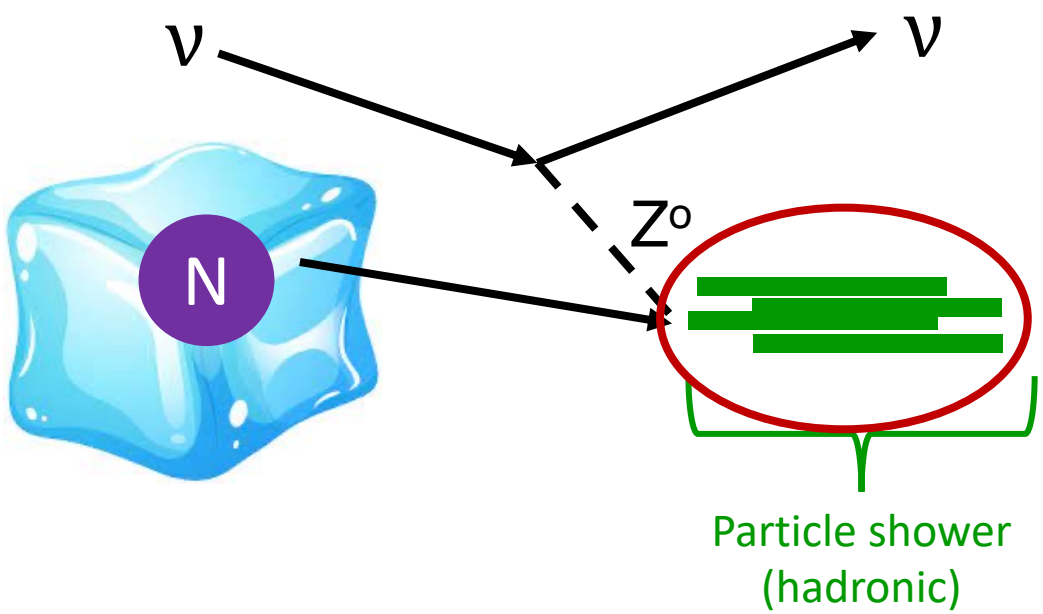


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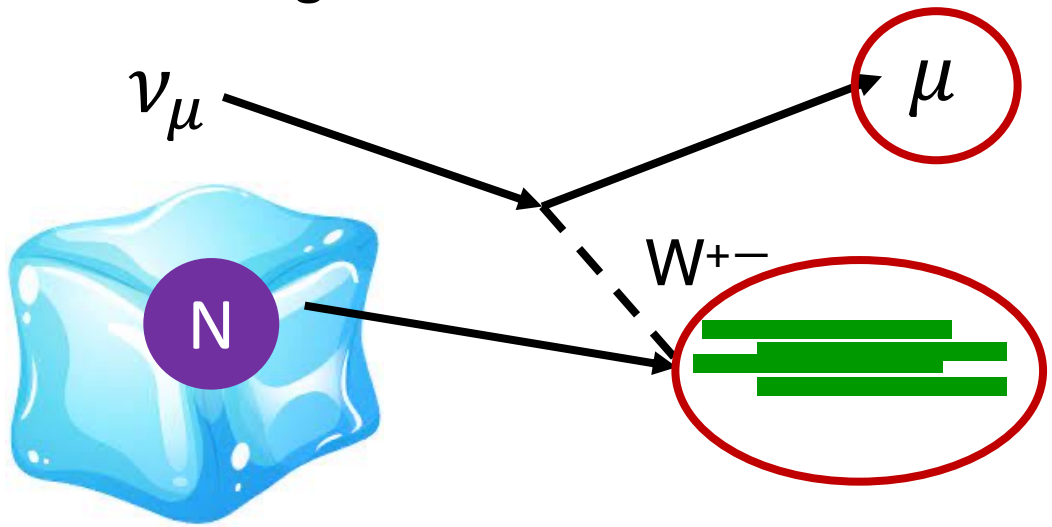


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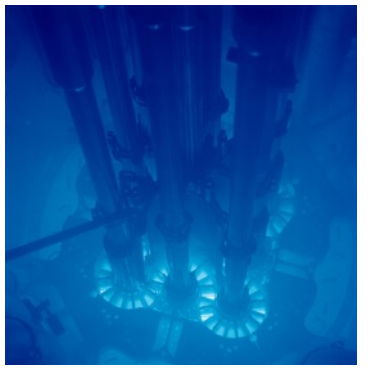

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Antarctica

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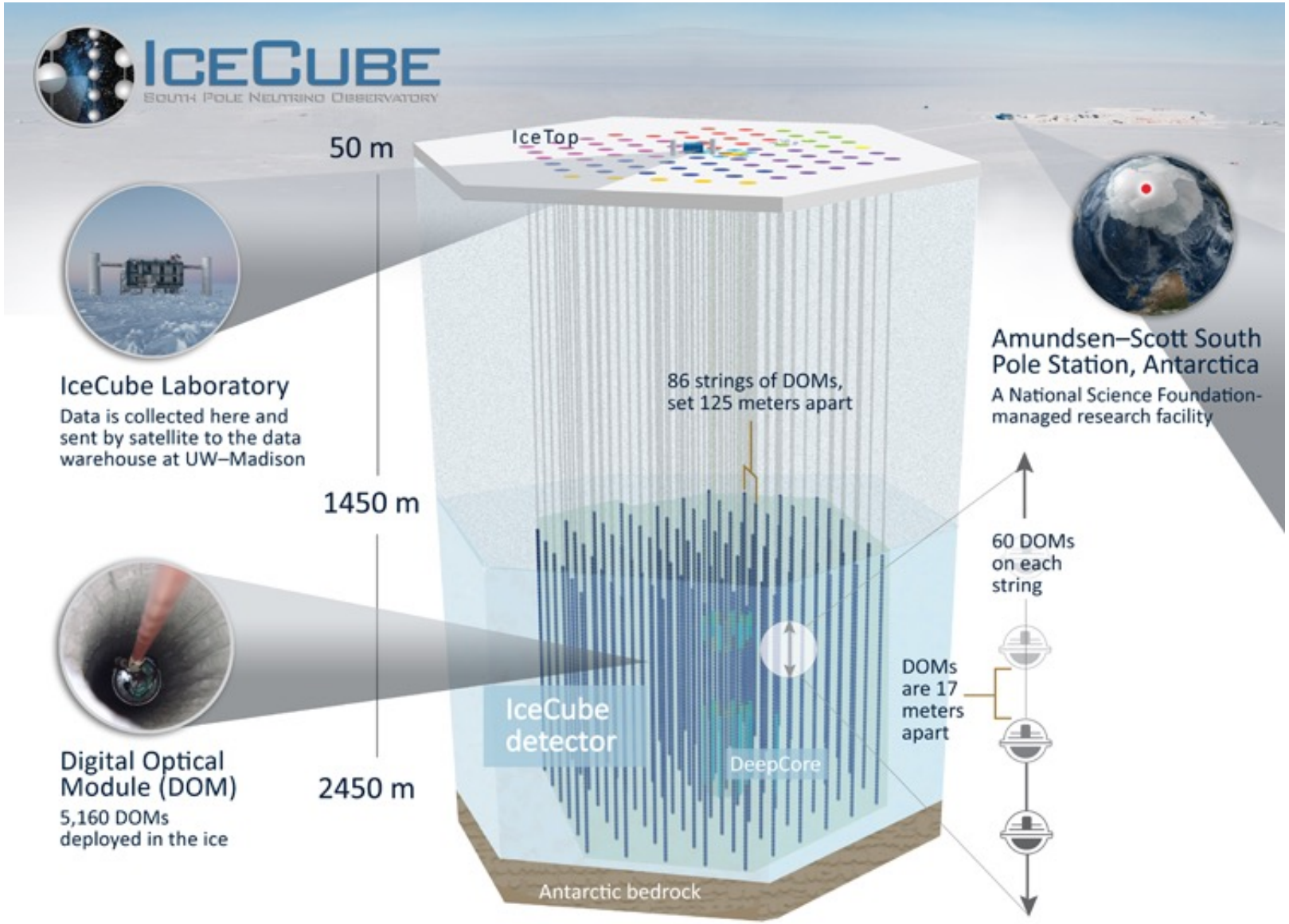
5160 photomultiplier tubes buried 2.5km in the ice near South Pole



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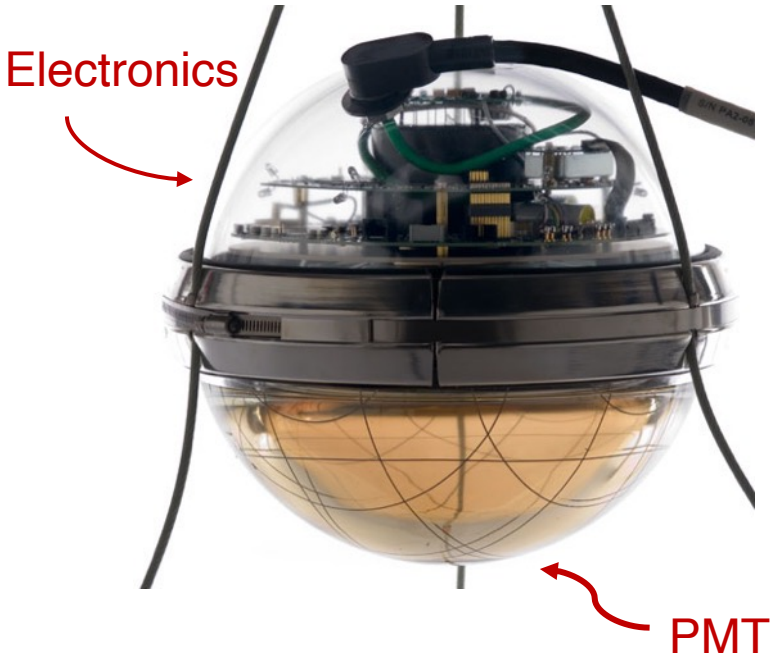


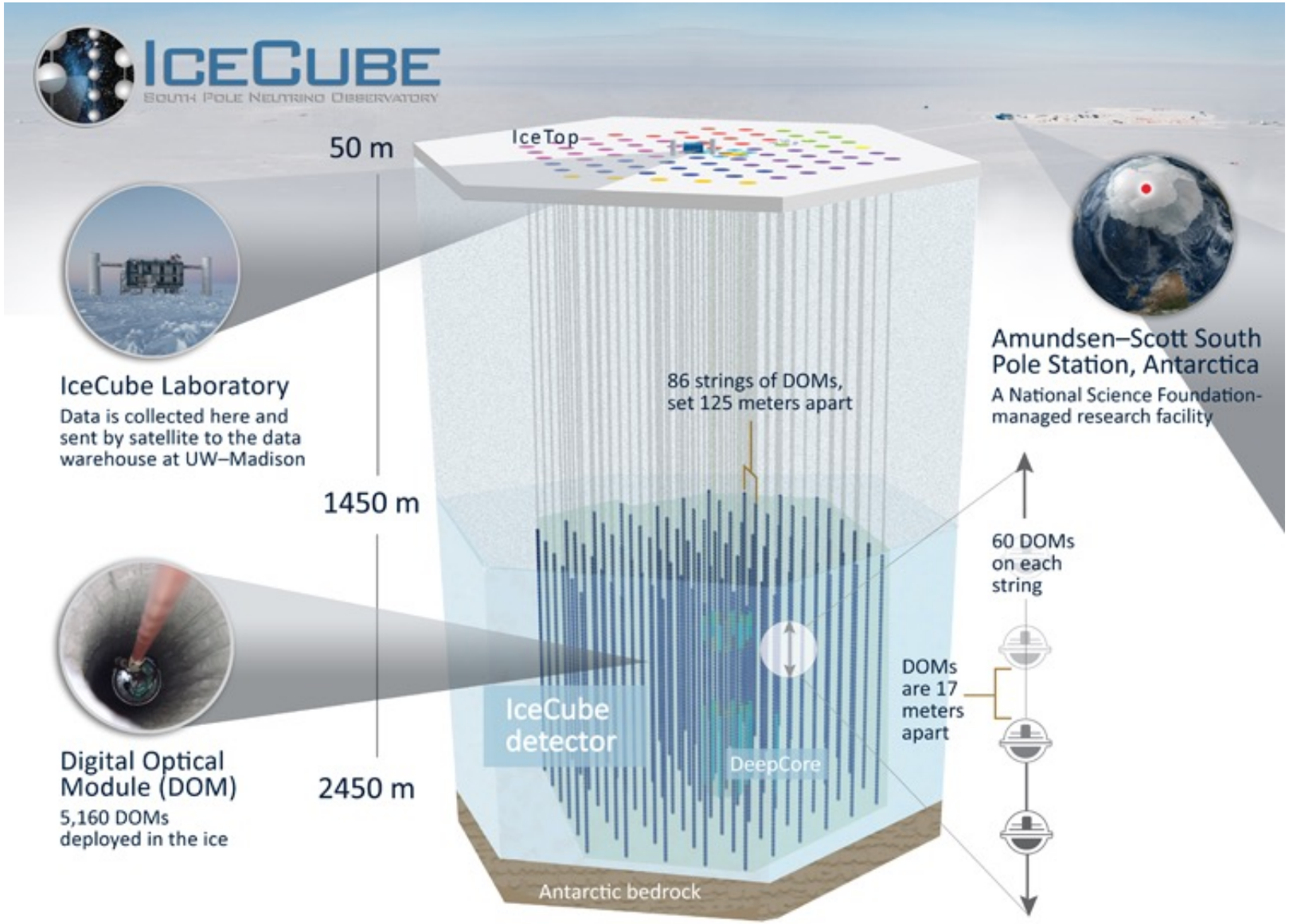

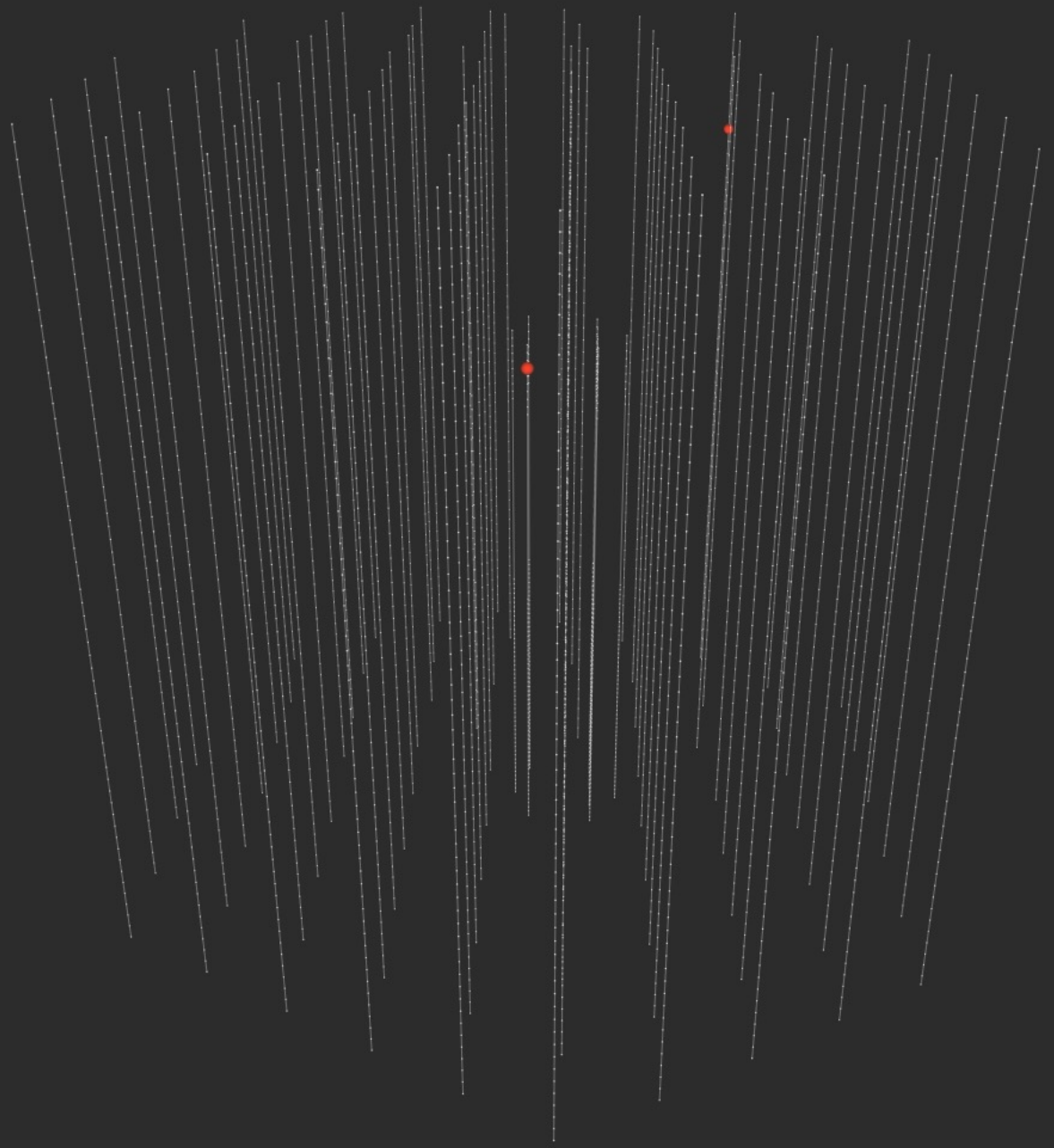

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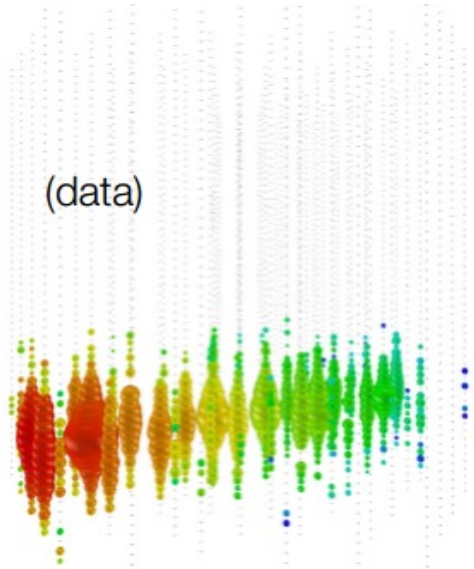

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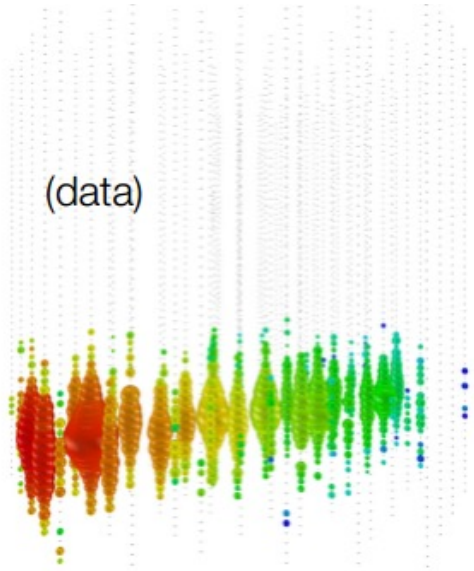


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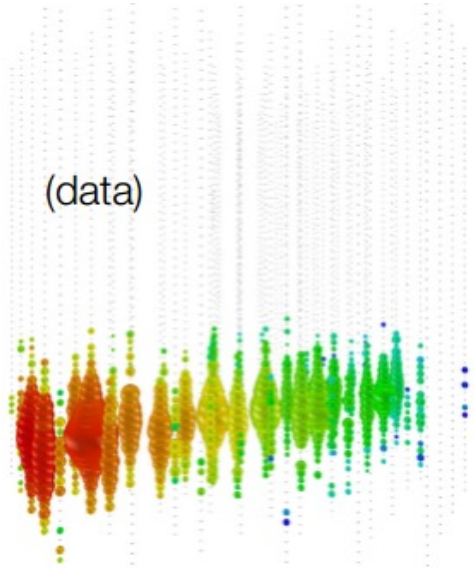


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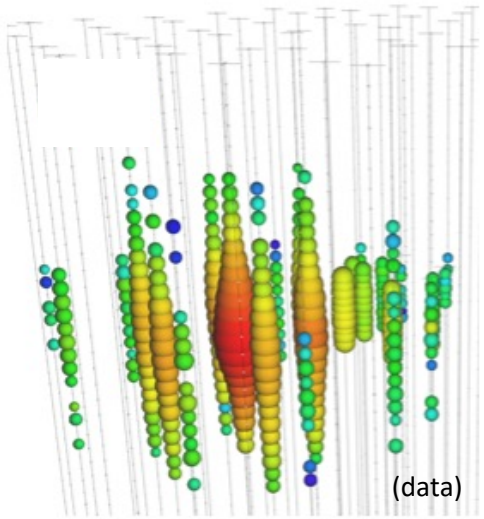
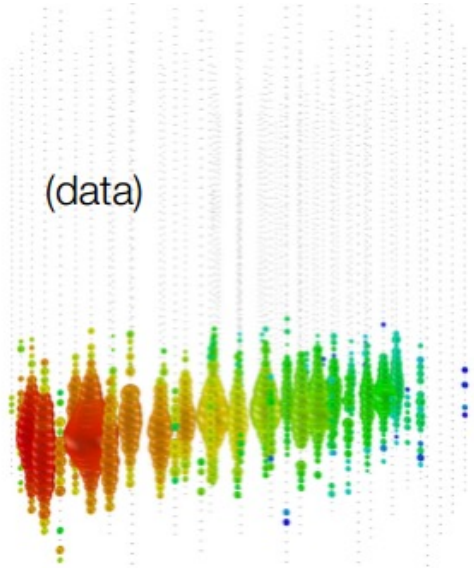
Cascades



# Detection Channels

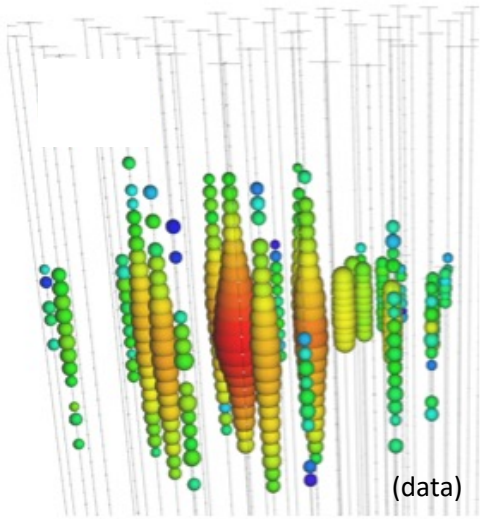
Tracks




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

(Mostly)

Cascades




$\nu_{e/\tau} + N \rightarrow e/\tau + X$

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

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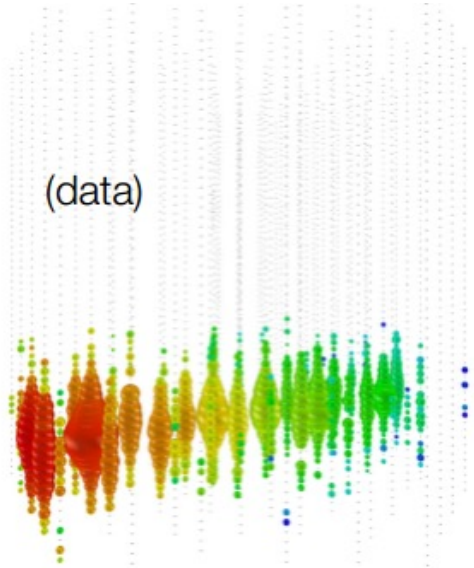
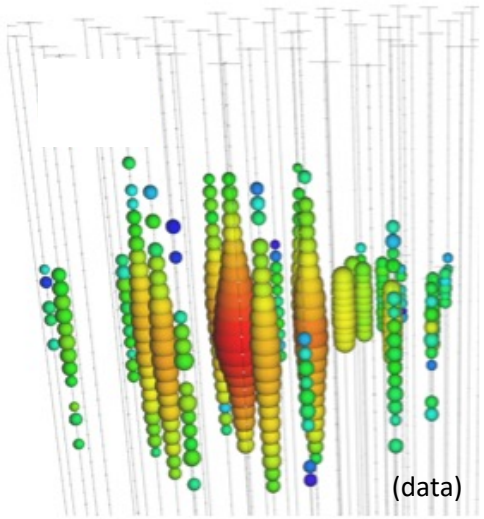
Tracks




$$\nu_\mu + N \rightarrow \mu + X$$
(Mostly)

Angular Resolution ~0.5°
Energy resolution: ~2x

Cascades

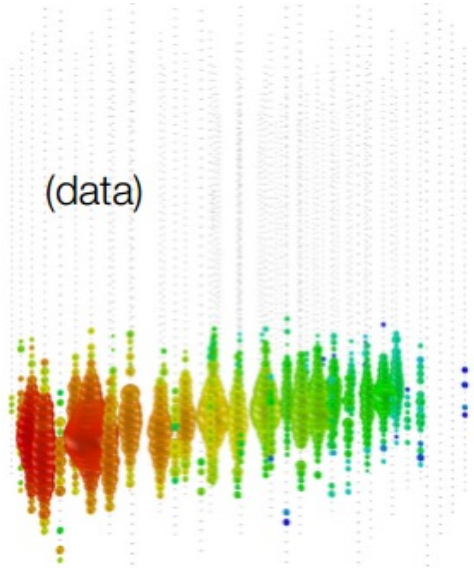



$$\nu_{e/\tau} + N \rightarrow e/\tau + X$$
$$\nu_x + N \rightarrow \nu_x + X$$

Angular Resolution ~8°
Energy resolution: ~10%

# Detection Channels

Tracks

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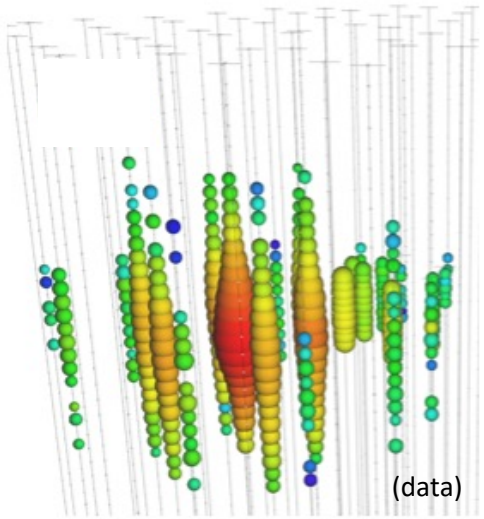


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Angular Resolution ~8°
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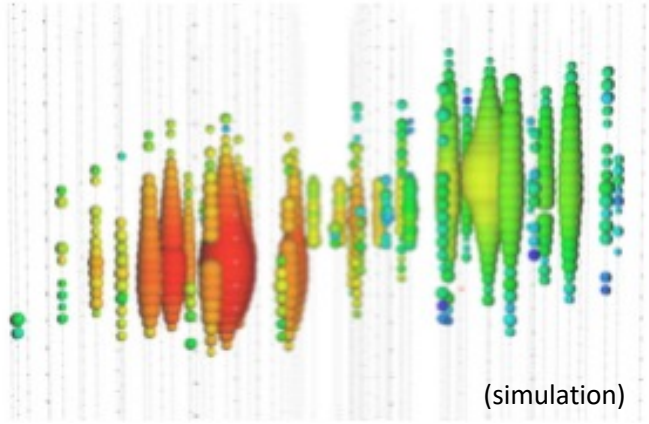
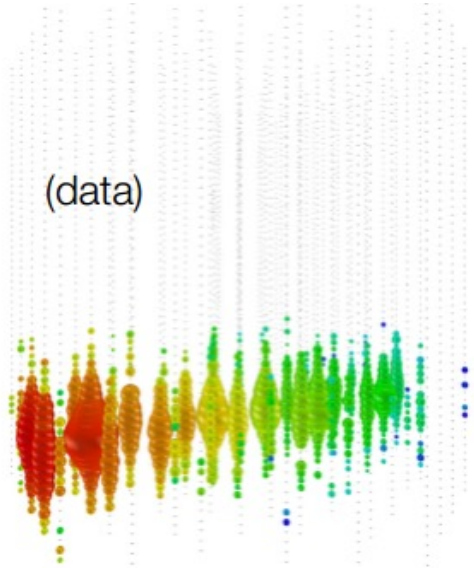
Double cascades



# Detection Channels

## Tracks

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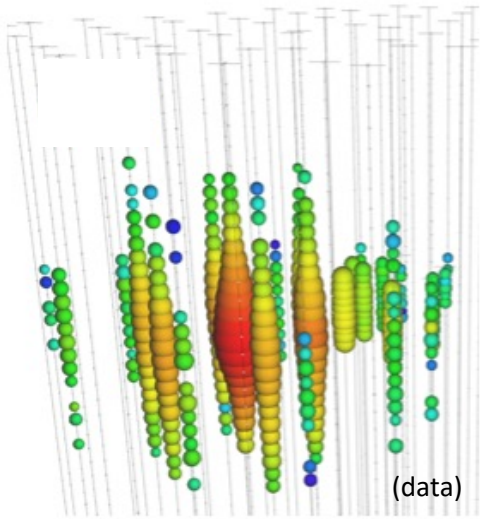


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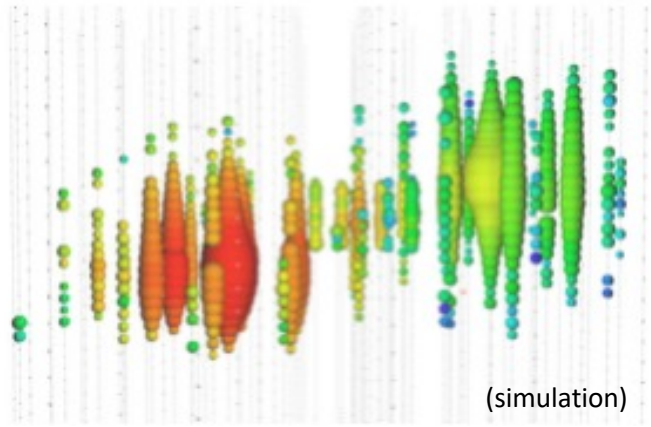
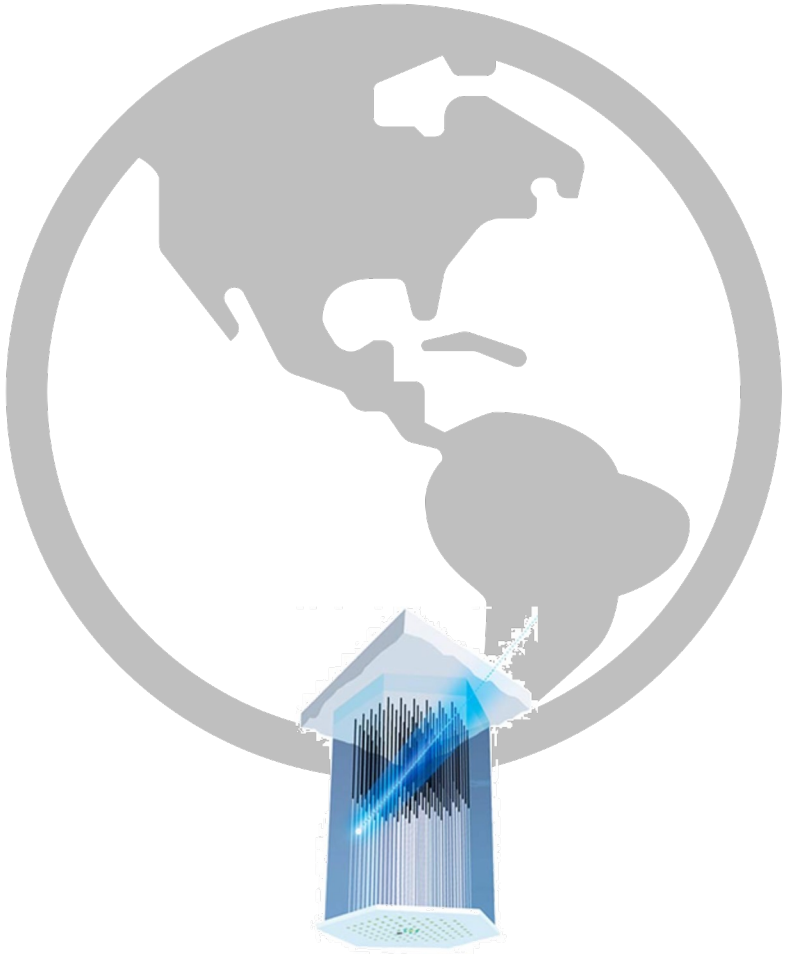


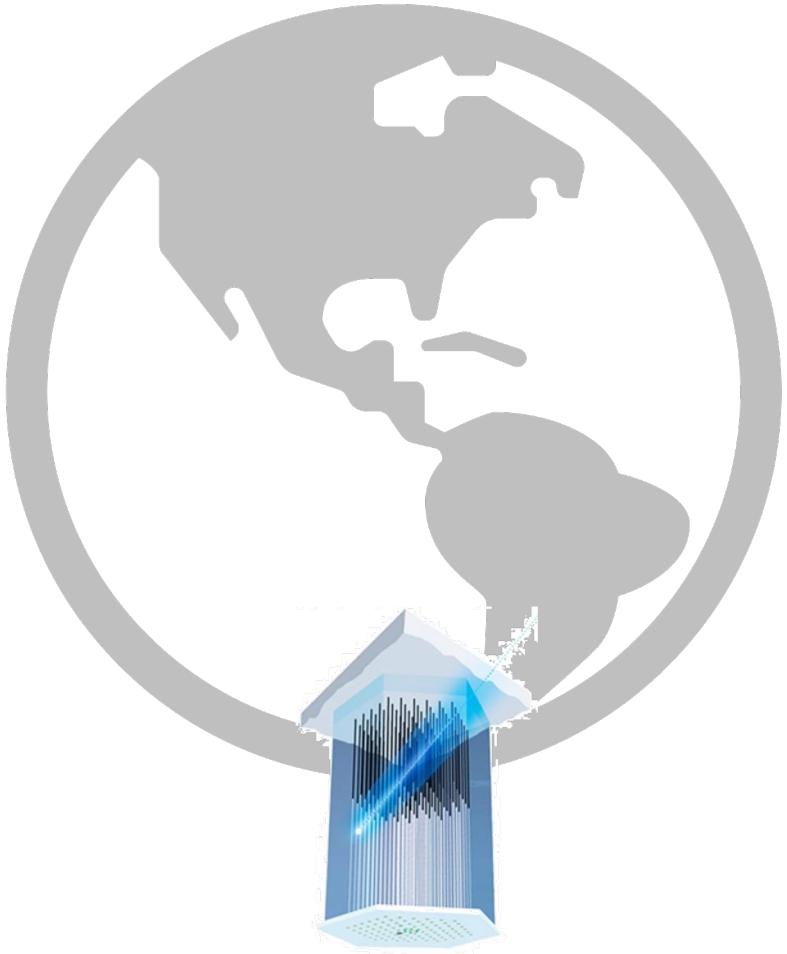

$\nu_\tau + N \rightarrow \tau + X$

$\tau$ decay length is 50m/PeV

Unobserved,
but searches ongoing!



**Astrophysics:**
astrophysical neutrinos arriving isotropically



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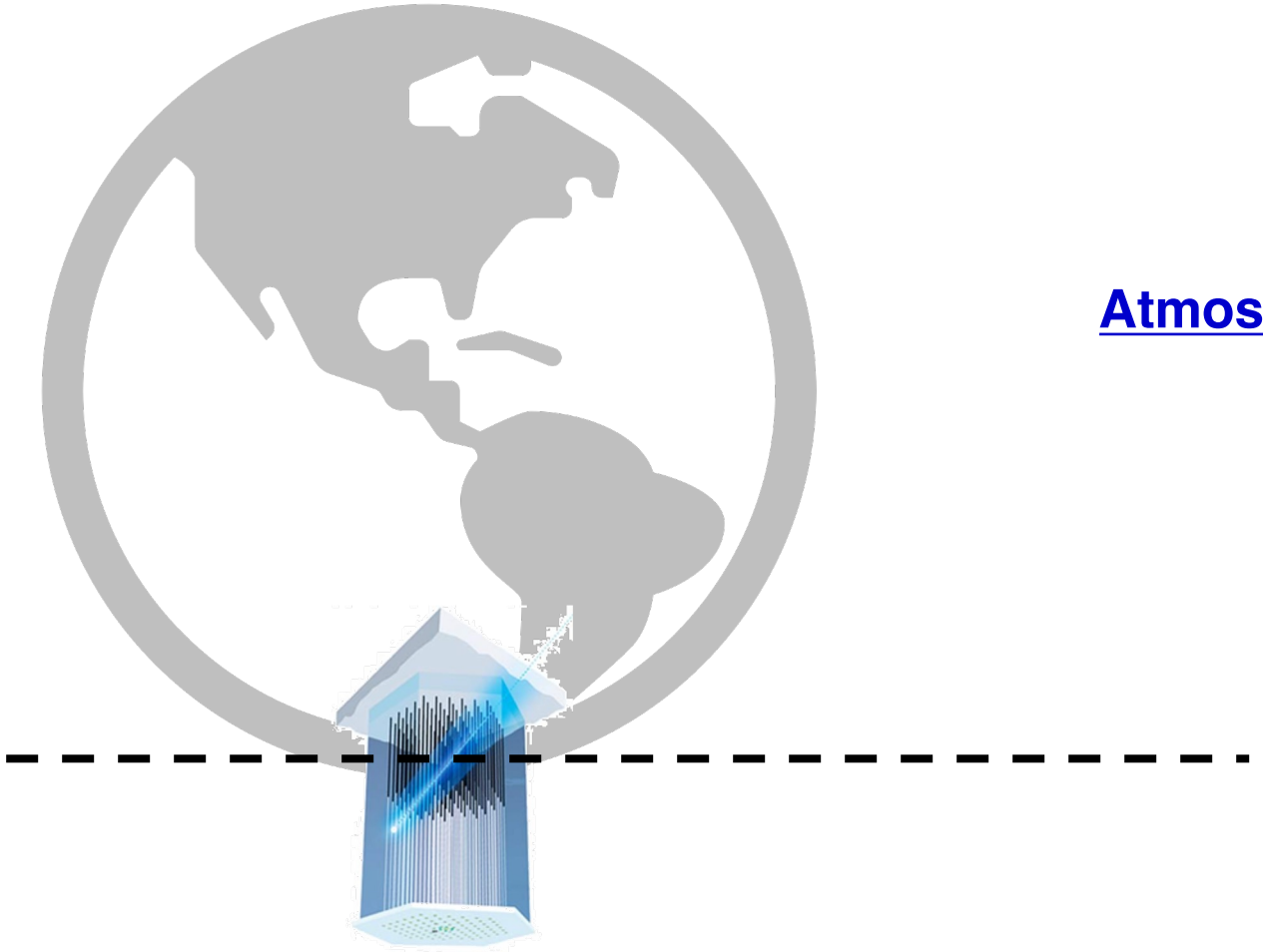

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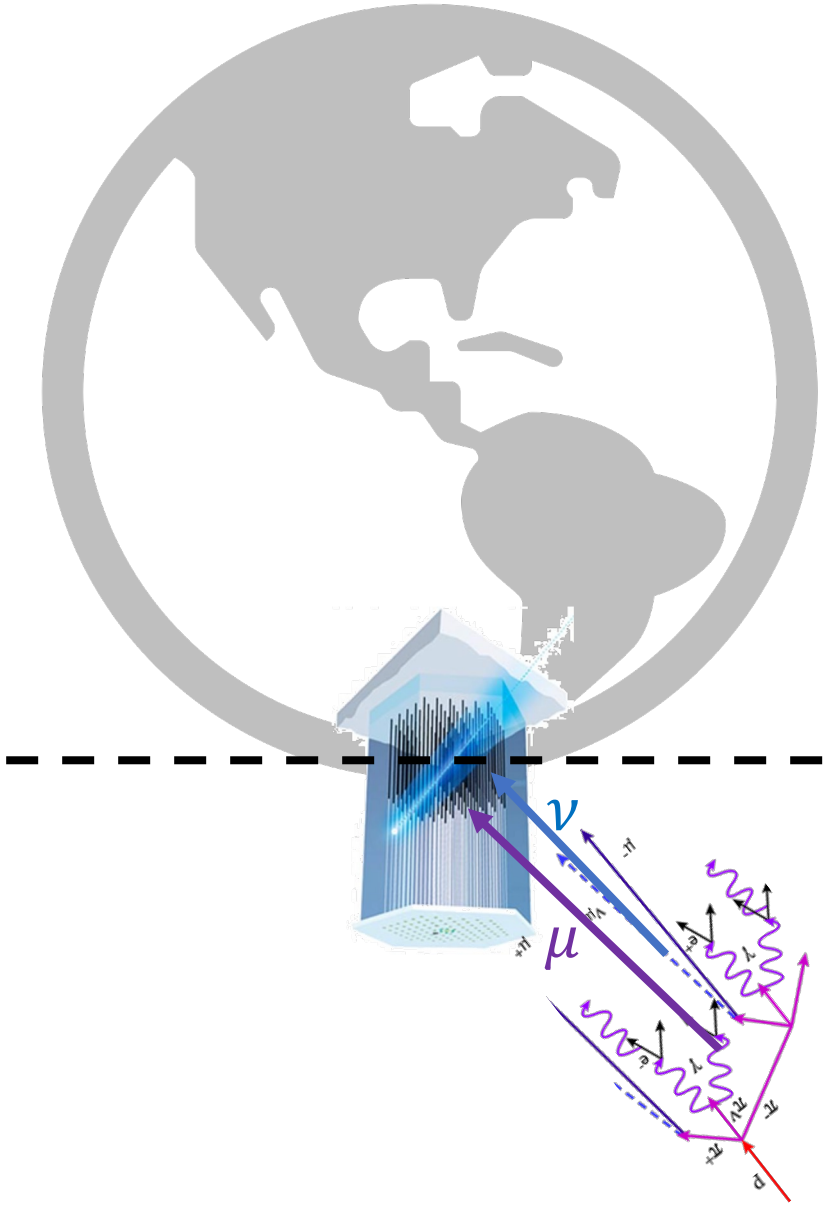
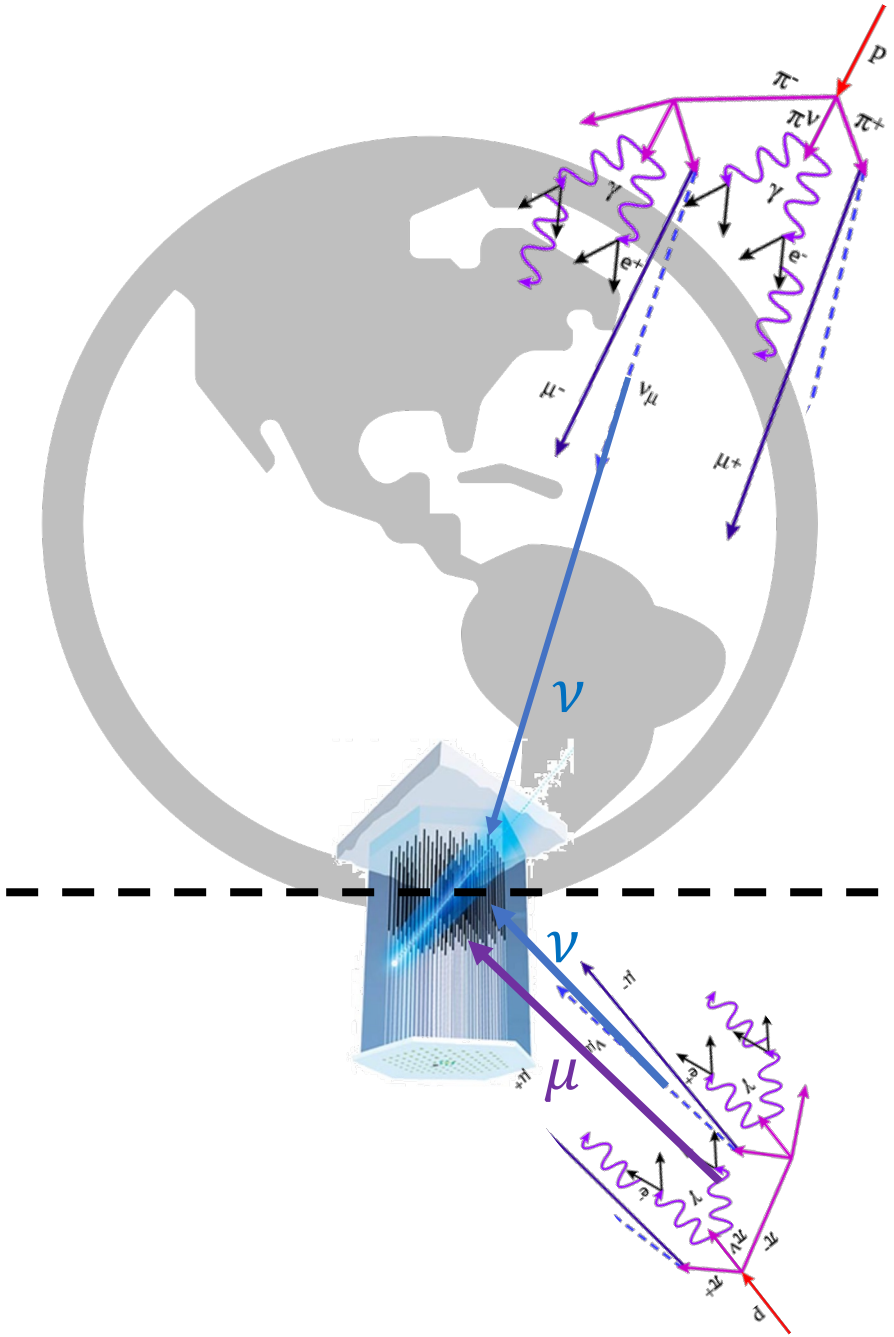



**Atmospherics**

**Southern Sky**

Atmospheric Muons
+
Atmospheric Neutrinos

**Astrophysics:**
astrophysical neutrinos arriving isotropically

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**Northern Sky**

Atmospheric Neutrinos
(Earth absorbs atm muons)

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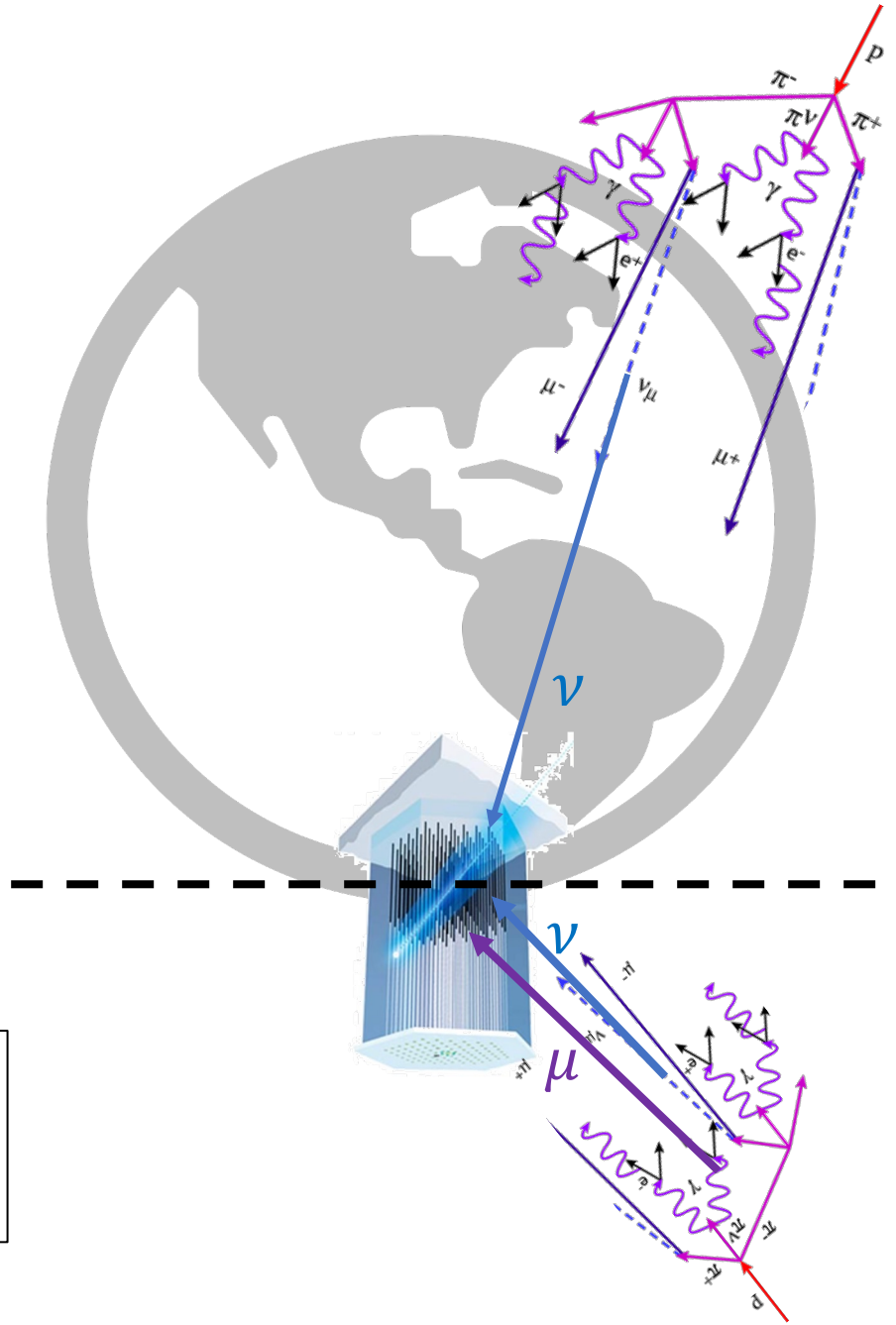



**Atmospherics**

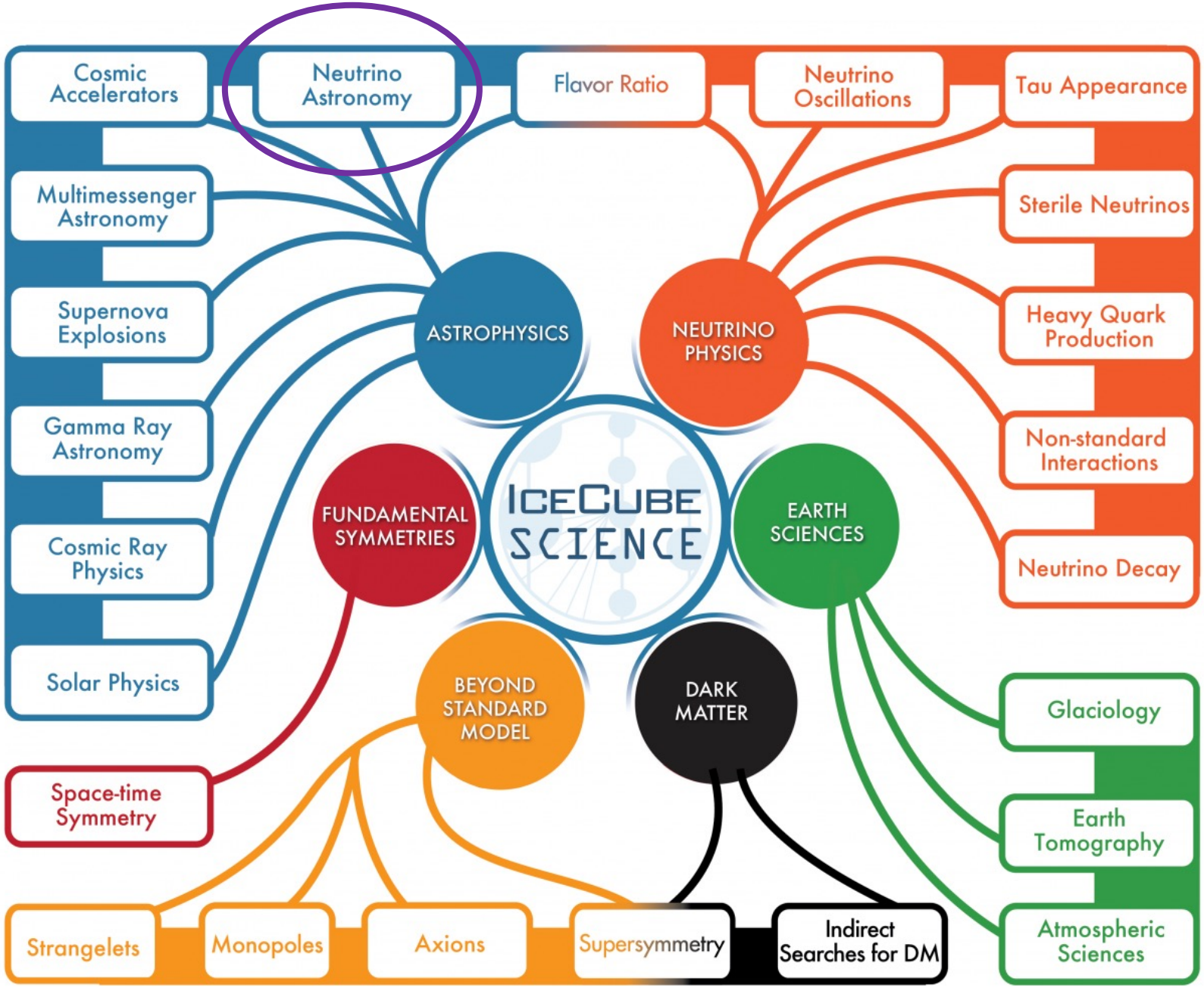
**Northern Sky**

Atmospheric Neutrinos
(Earth absorbs atm muons)

**Southern Sky**

Atmospheric Muons
+
Atmospheric Neutrinos

Atmospheric $\mu$: 2 khz
Atmospheric $\nu$: 5 mHz
Astrophysical $\nu$: ~1 μHz


ICECUBE SCIENCE
ASTROPHYSICS
NEUTRINO PHYSICS
FUNDAMENTAL SYMMETRIES
EARTH SCIENCES
BEYOND STANDARD MODEL
DARK MATTER
Cosmic Accelerators
Neutrino Astronomy
Multimessenger Astronomy
Supernova Explosions
Gamma Ray Astronomy
Cosmic Ray Physics
Solar Physics
Flavor Ratio
Neutrino Oscillations
Tau Appearance
Sterile Neutrinos
Heavy Quark Production
Non-standard Interactions
Neutrino Decay
Space-time Symmetry
Glaciology
Earth Tomography
Atmospheric Sciences
Strangelets
Monopoles
Axions
Supersymmetry
Indirect Searches for DM

# Astrophysical Neutrino Searches

For astrophysical neutrino searches, atmospherics are a background

Two search strategies:

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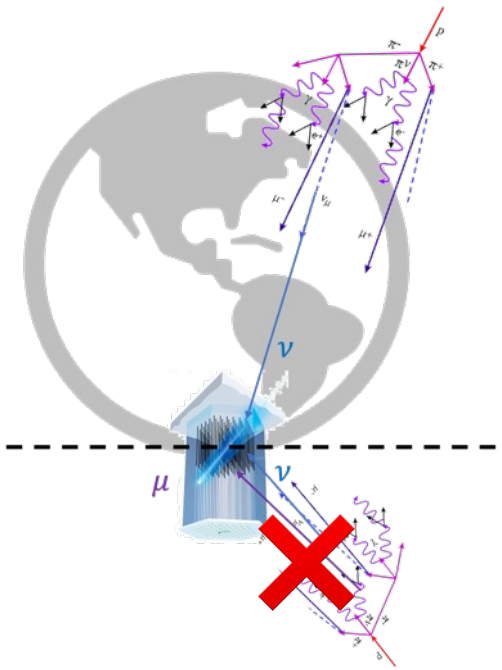

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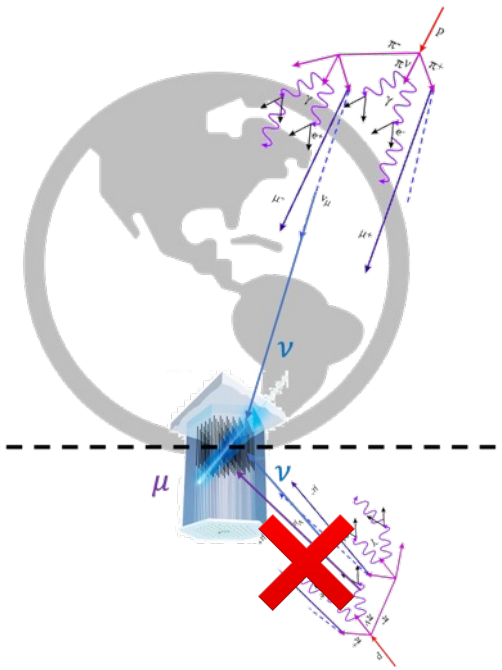


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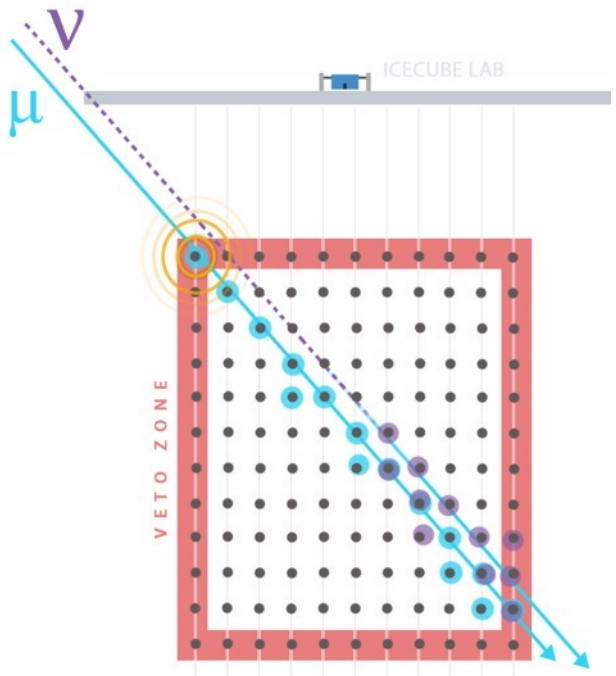

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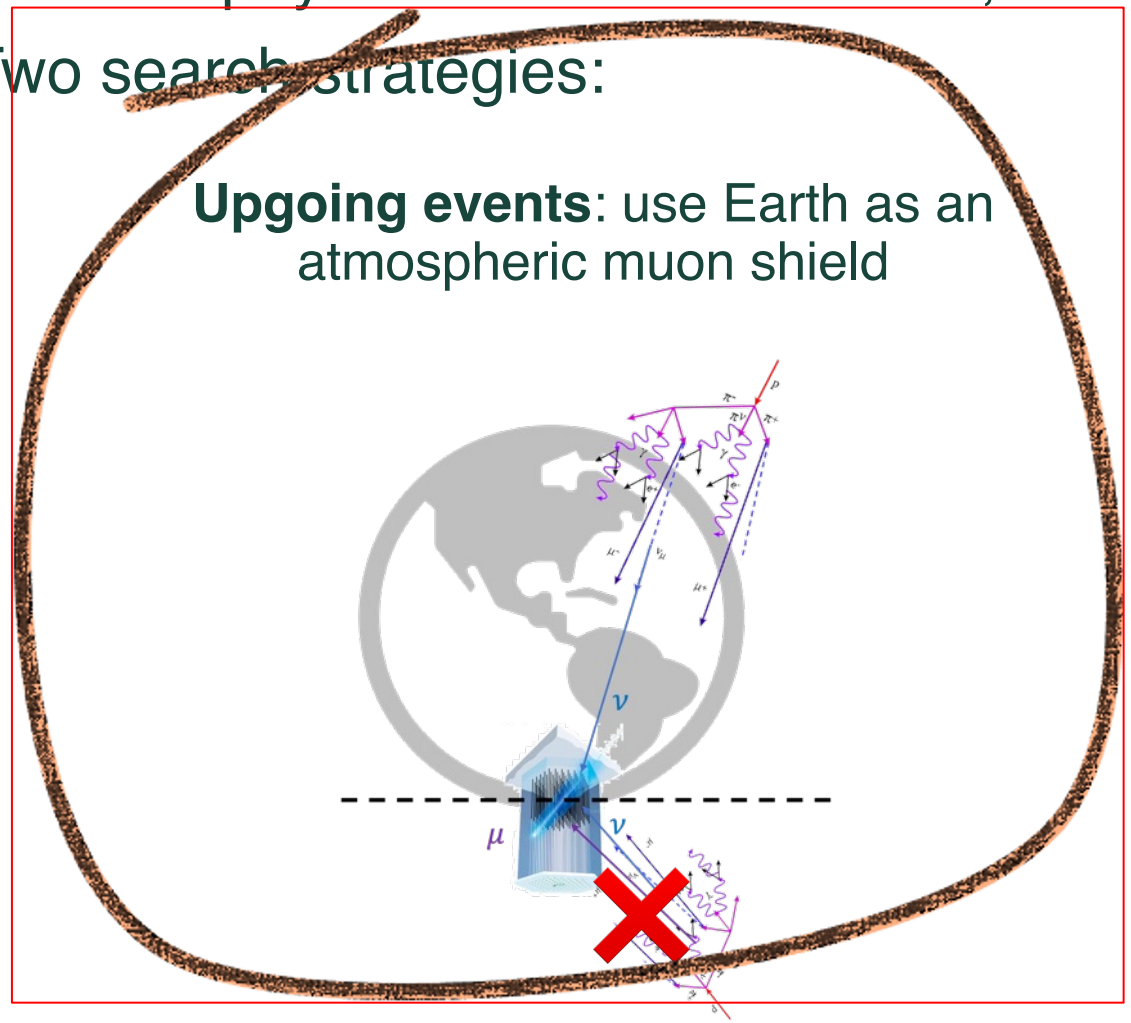


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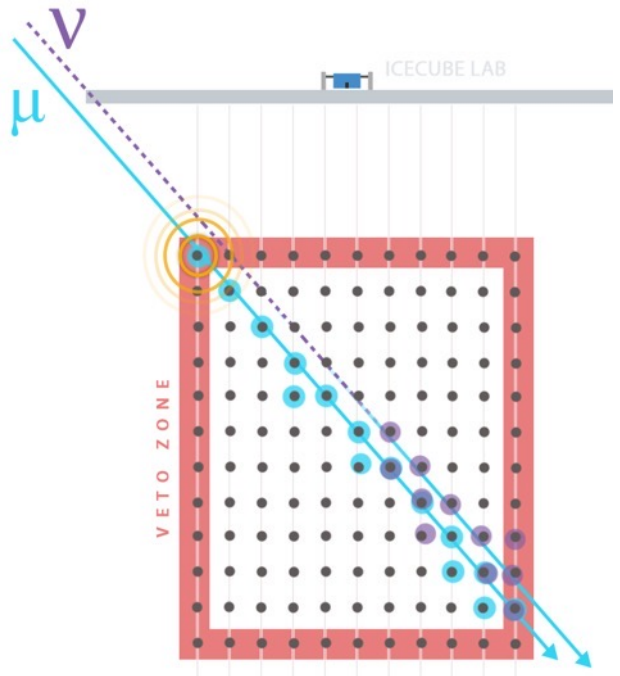

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Selection of 650k upgoing and horizontal muon neutrinos

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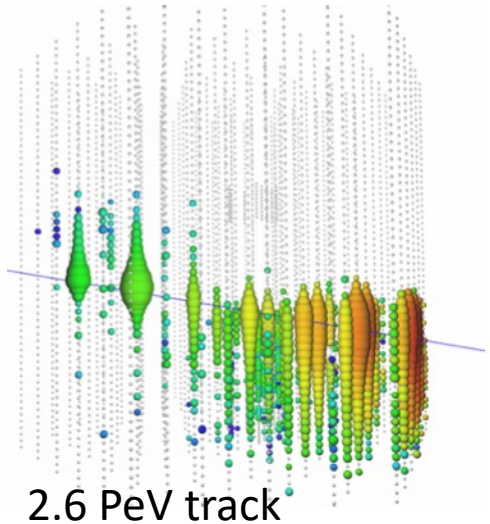

2.6 PeV track

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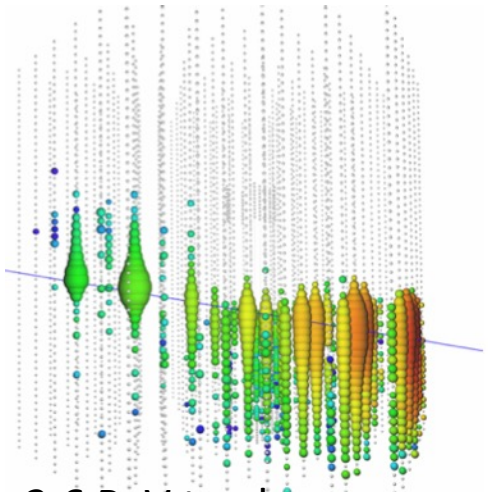

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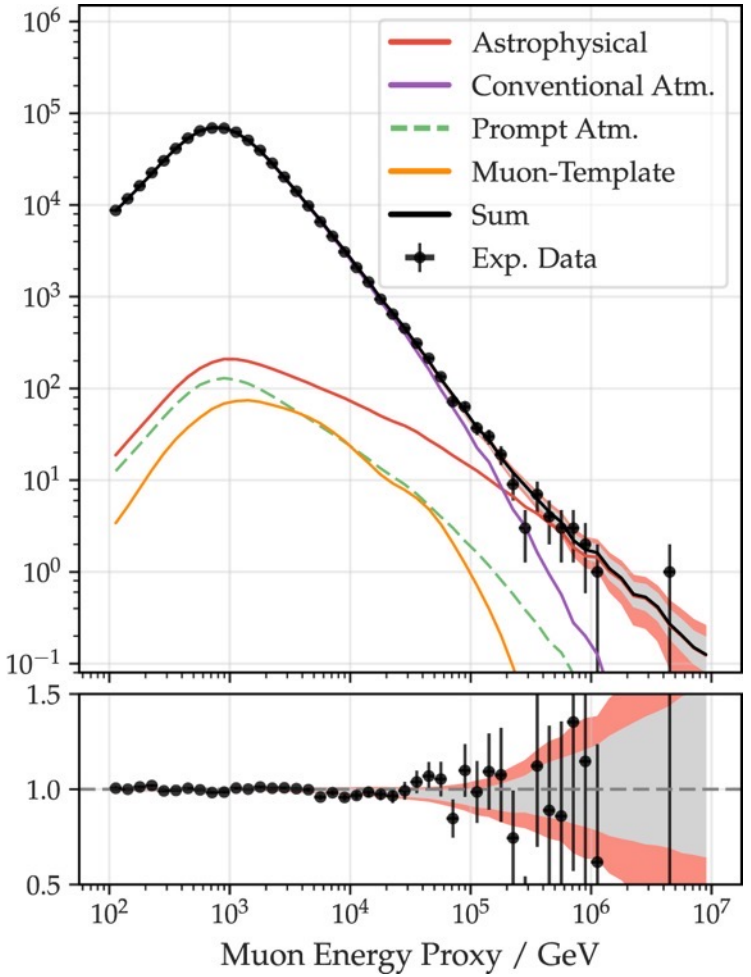
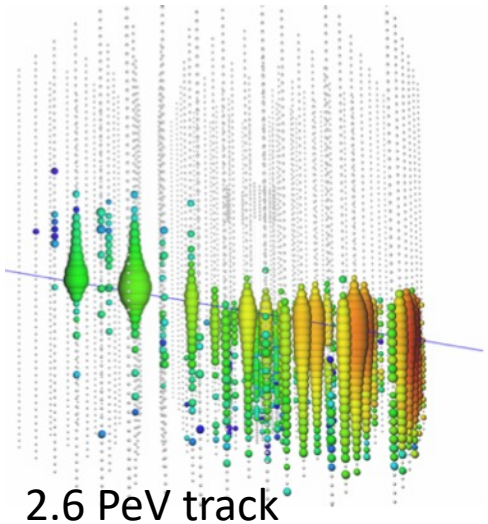


# Upgoing Track Selection

Selection of 650k upgoing and horizontal muon neutrinos

Updated w/

- 50% more data (6 → 9.5 yrs)
- Improved calibration & systematics treatment



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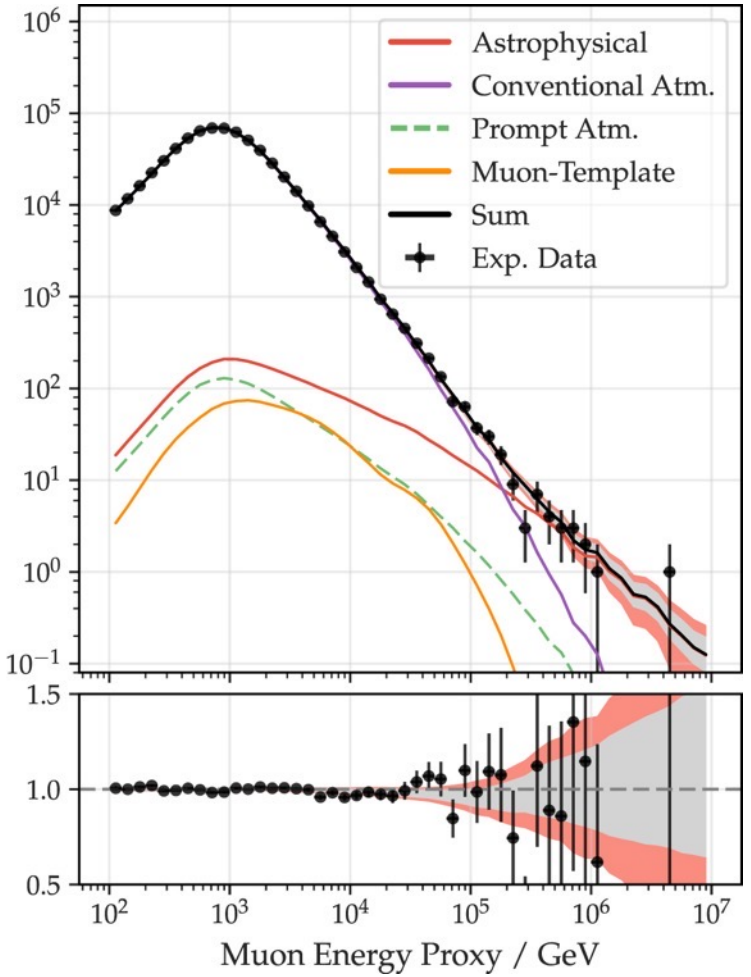

# Upgoing Track Selection

Selection of 650k upgoing and horizontal muon neu*t2.37±0.09*

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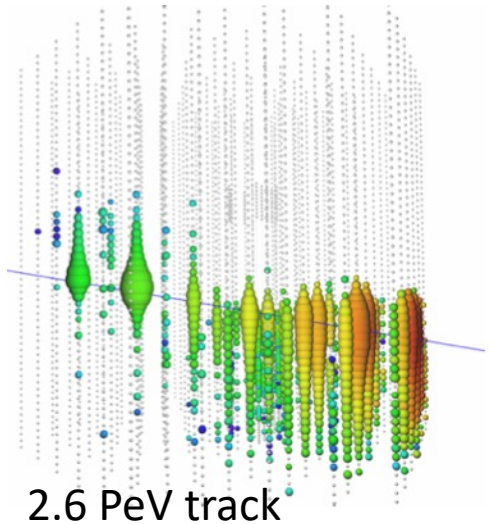
Data consistent with single power law, fits w/ $\gamma = 2.37 \pm 0.09$



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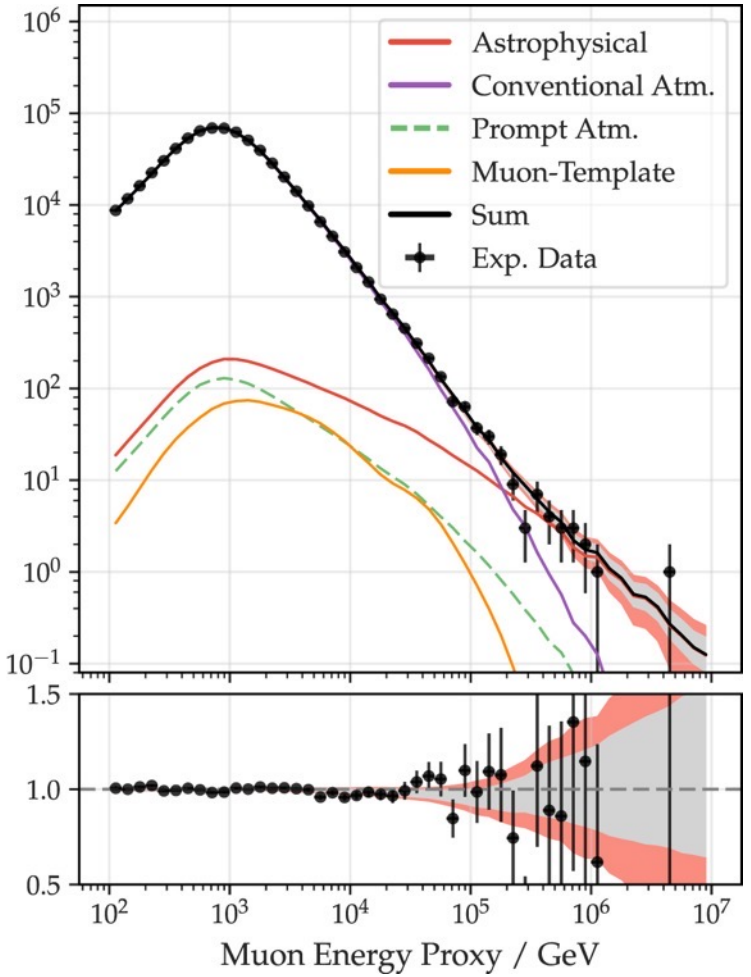


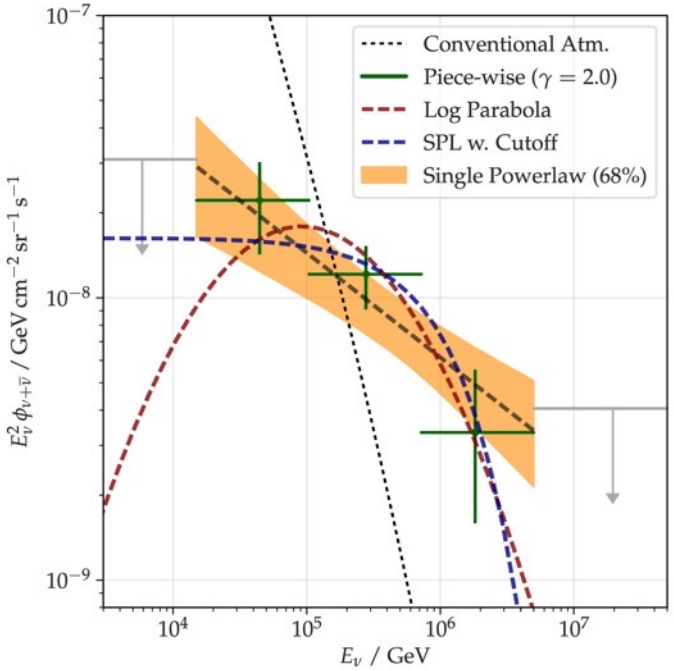


ApJ 928 50, 2022
(arxiv 2111.10299)

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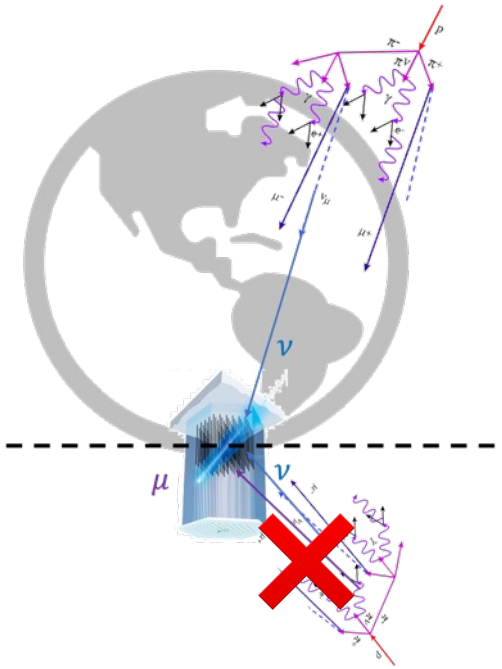


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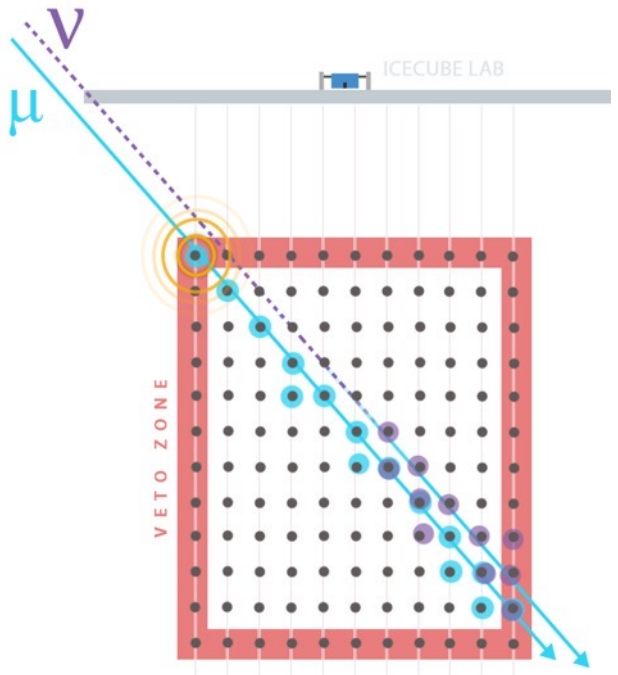

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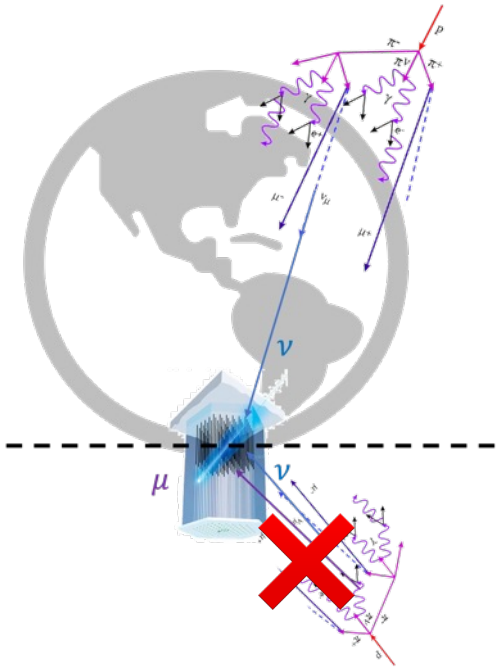


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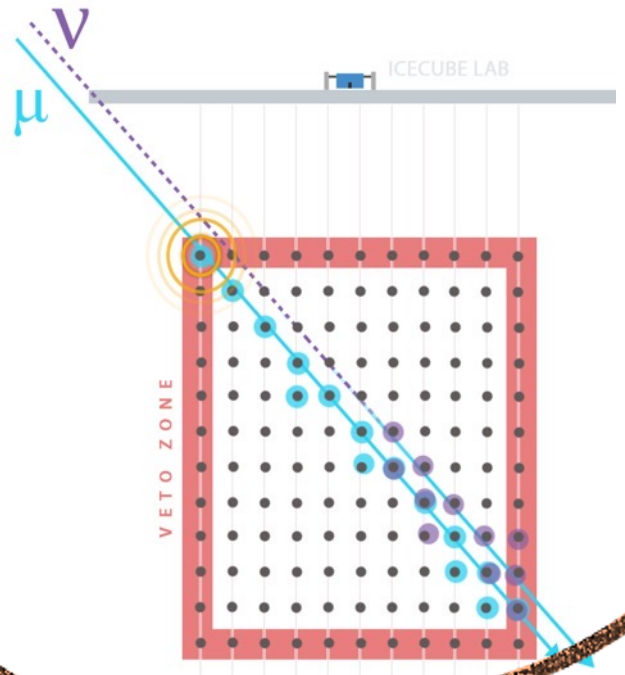

# Cascade Selection

## High Energy Starting Events

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Selection of 60 *starting* events
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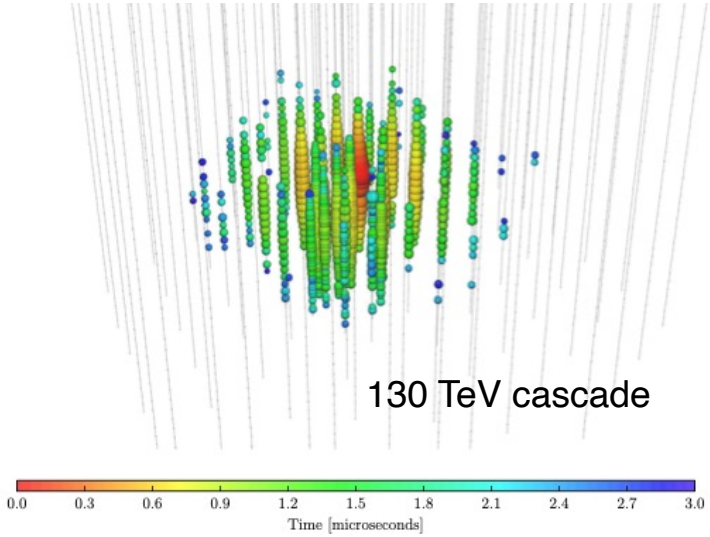

PRD 104, 022002 (2021)
(arxiv 2011.03545)

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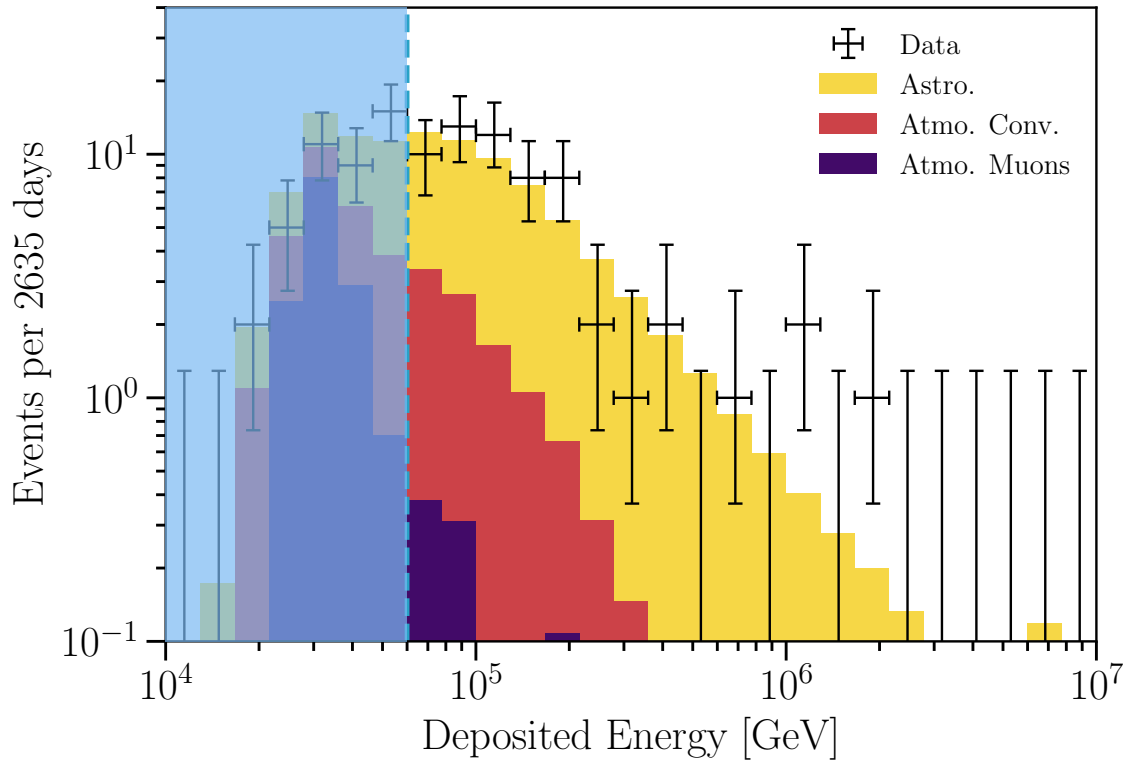
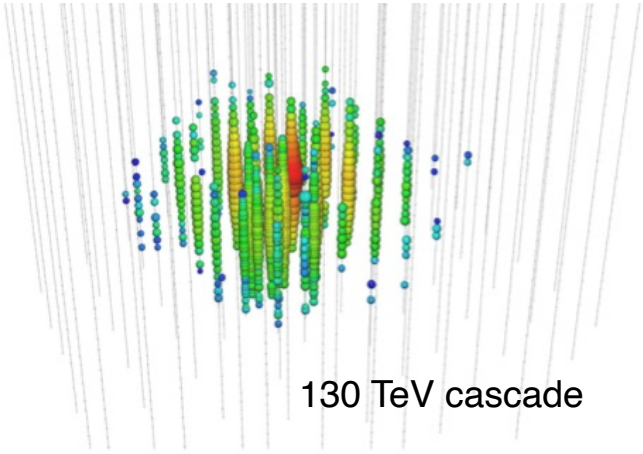
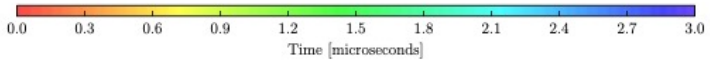


130 TeV cascade



PRD 104, 022002 (2021)
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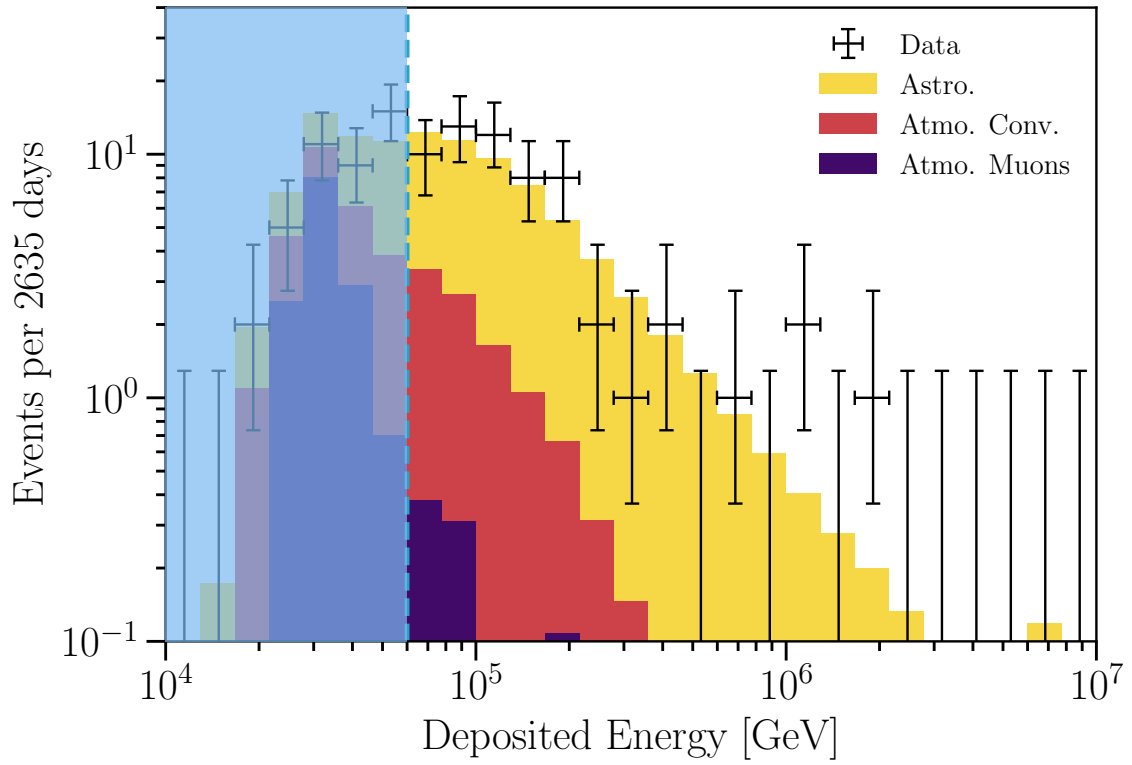
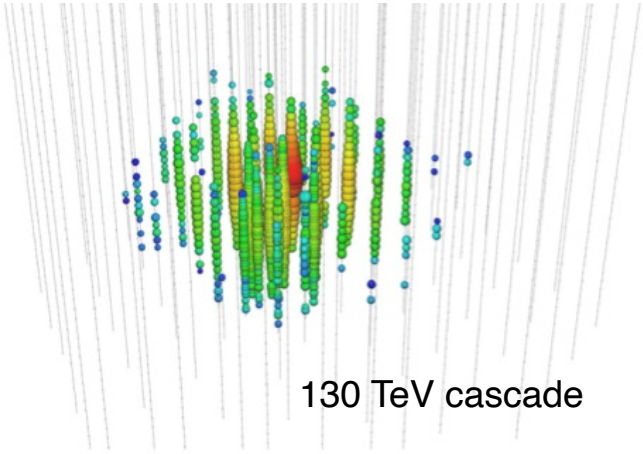
# Cascade Selection

## High Energy Starting Events

Selection of 60 *starting* events above 60 TeV

>2x as much data (3→7.5 yrs), updated detector & ice models, and systematics treatment



PRD 104, 022002 (2021)
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# Cascade Selection

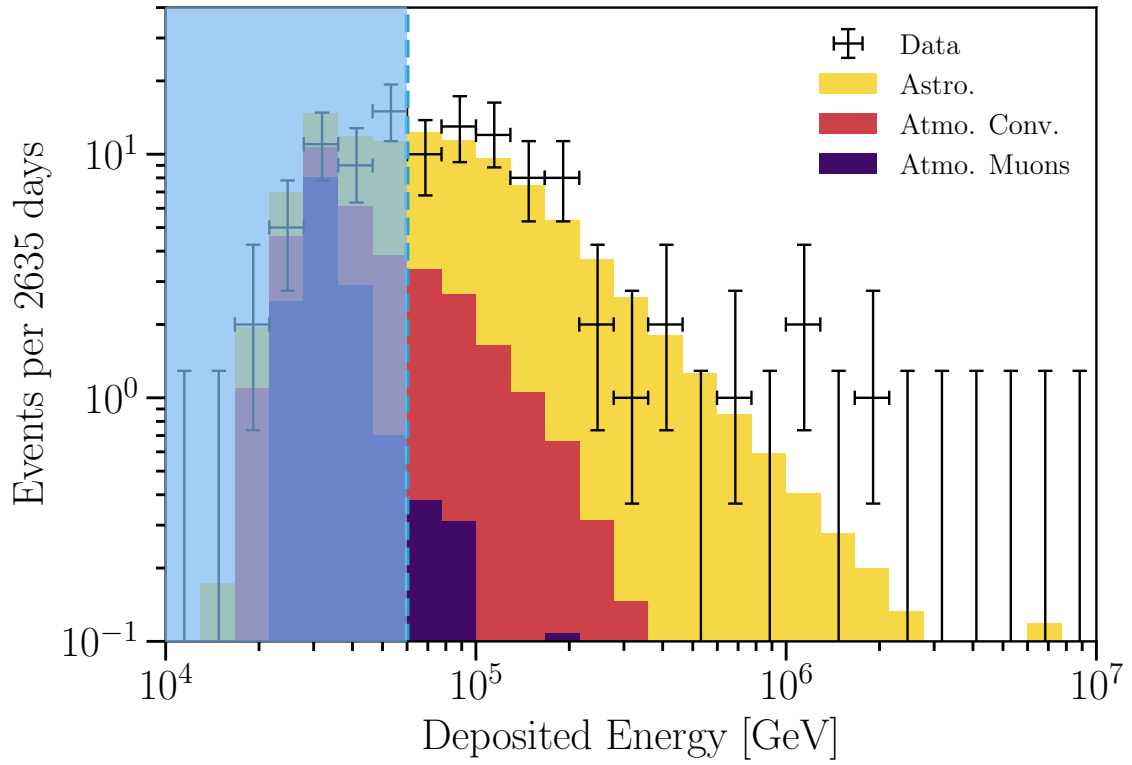
## High Energy Starting Events

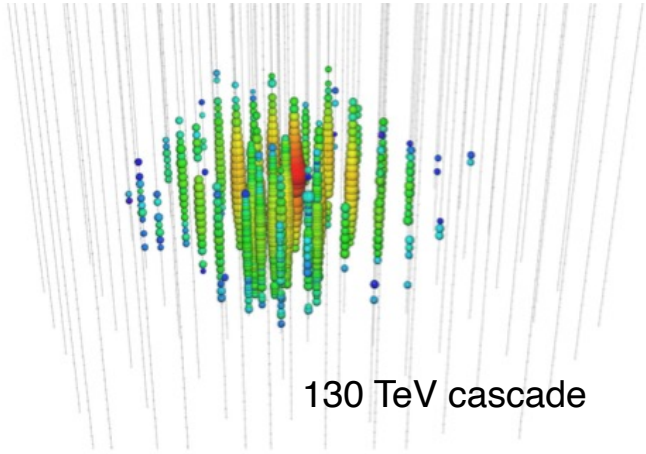
Selection of 60 *starting* events above 60 TeV

>2x as mu*c2.87±0.2*

→7.5 yrs), updated detector & ice models, and systematics treatment

Data still consistent with single power law, fits w/ $\gamma = 2.87 \pm 0.2$



# Astrophysical Neutrinos

## The Landscape Today

# Astrophysical Neutrinos

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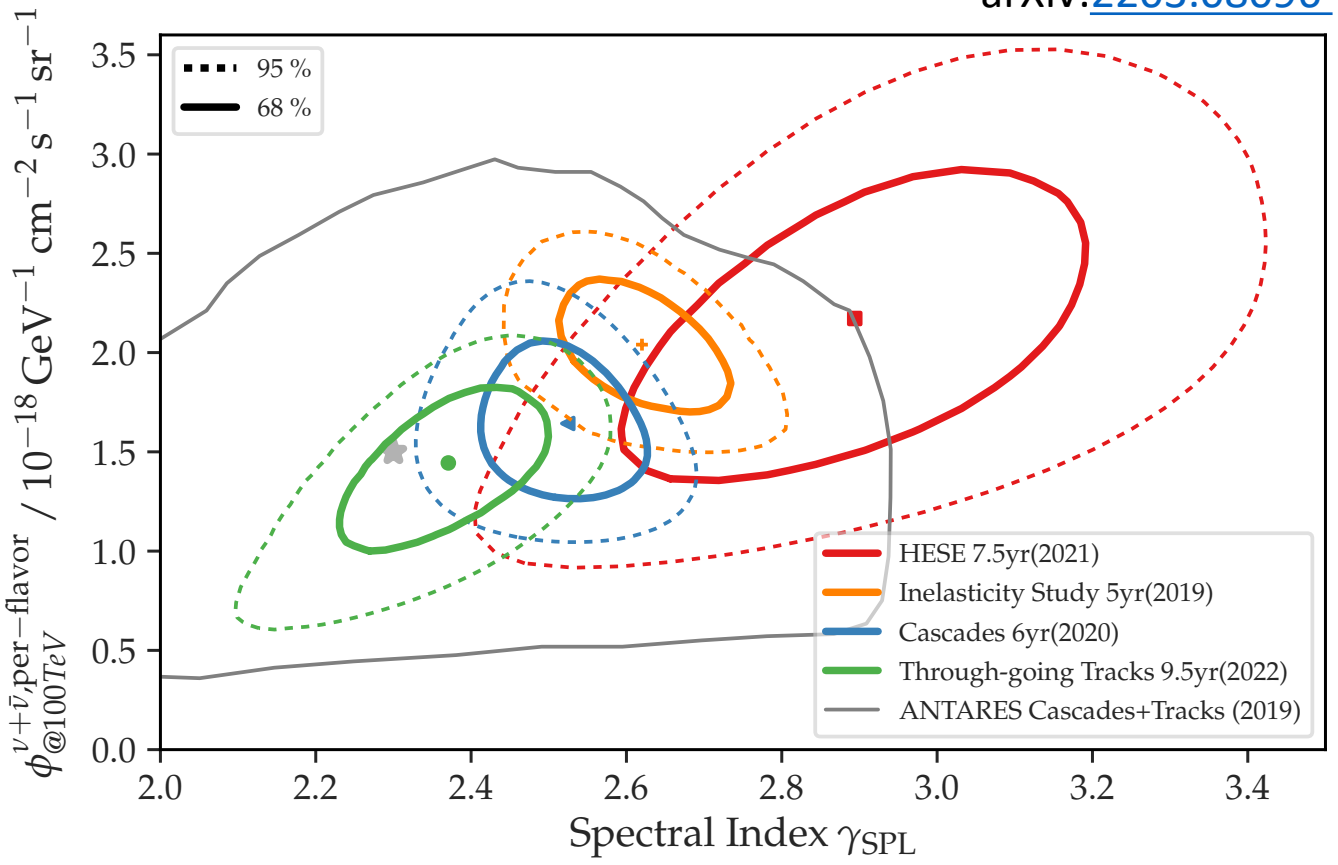
arXiv:2203.08096



# Astrophysical Neutrinos

## The Landscape Today

Several complementary measurements

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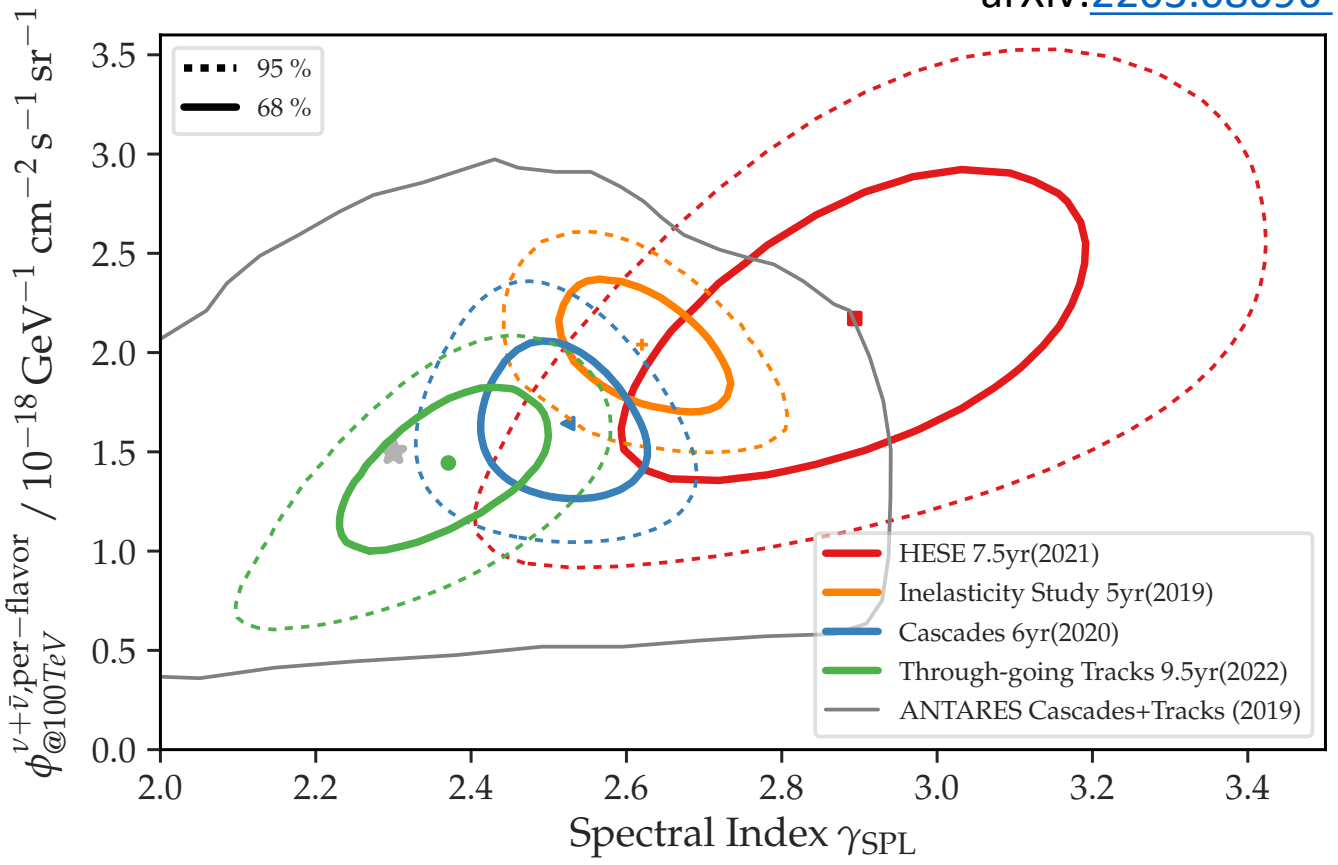


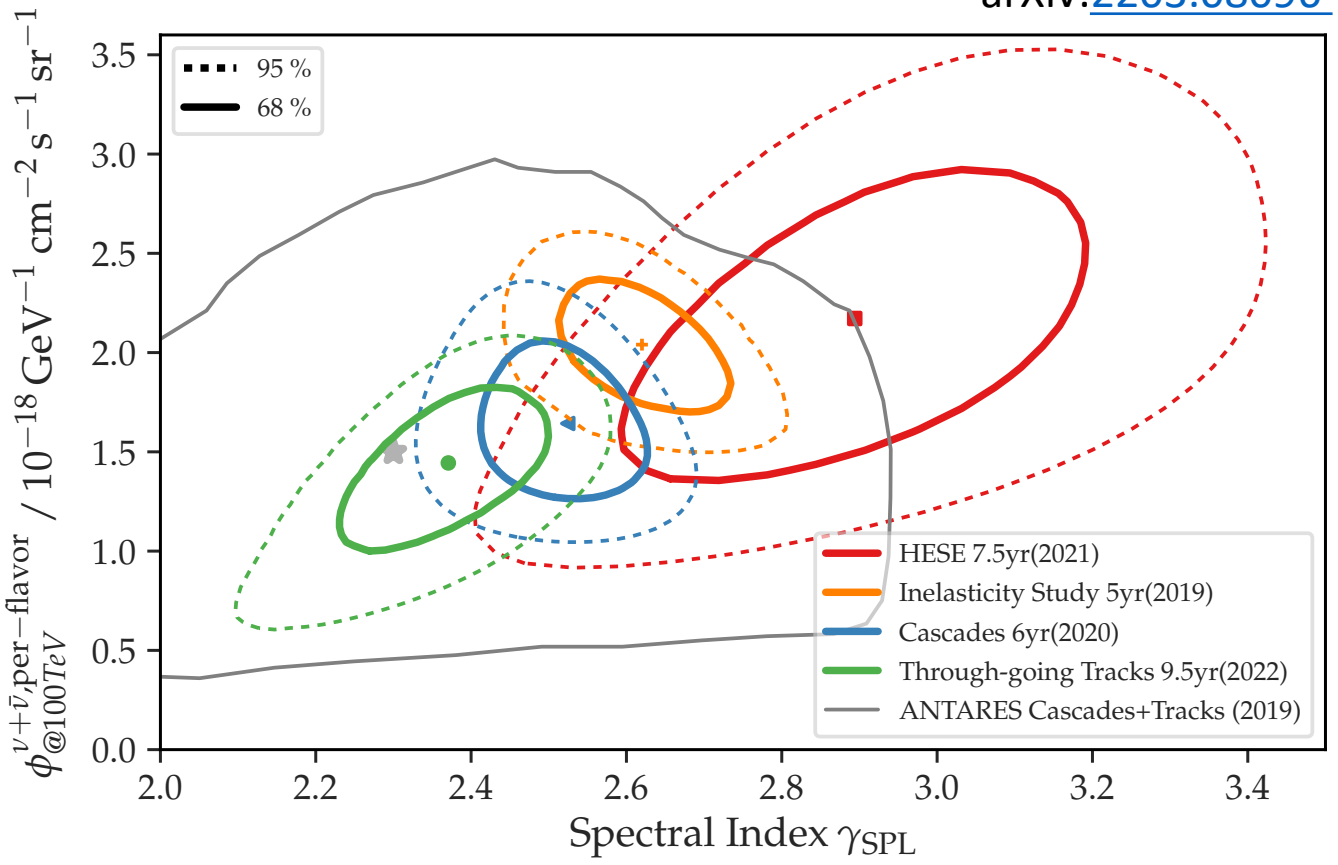
# Astrophysical Neutrinos

## The Landscape Today

Several complementary measurements

- All consistent with SPL hypothesis

arXiv:2203.08096



# Astrophysical Neutrinos

## The Landscape Today

Several complementary measurements

- All consistent with SPL hypothesis
- Consistent w/ each other @ 2σ

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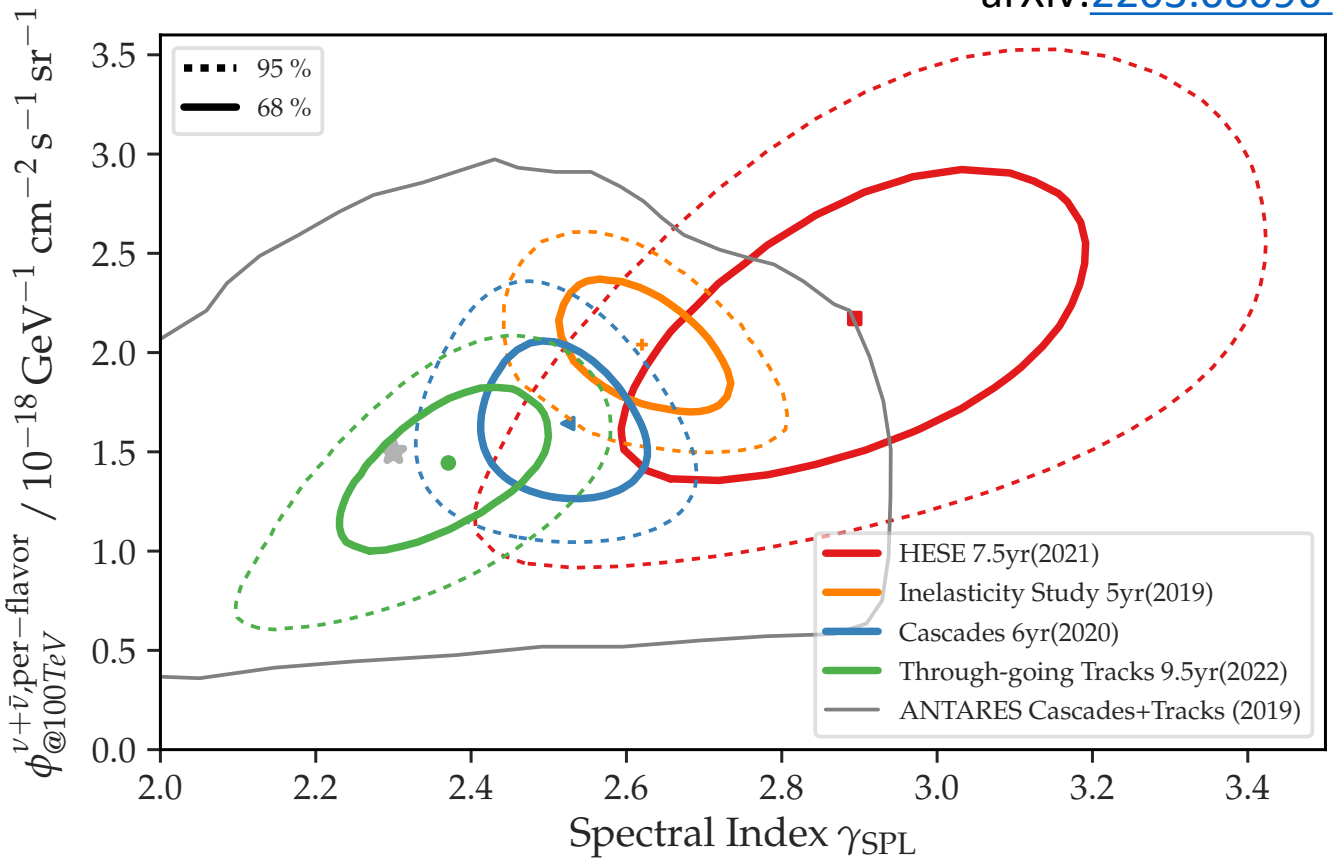


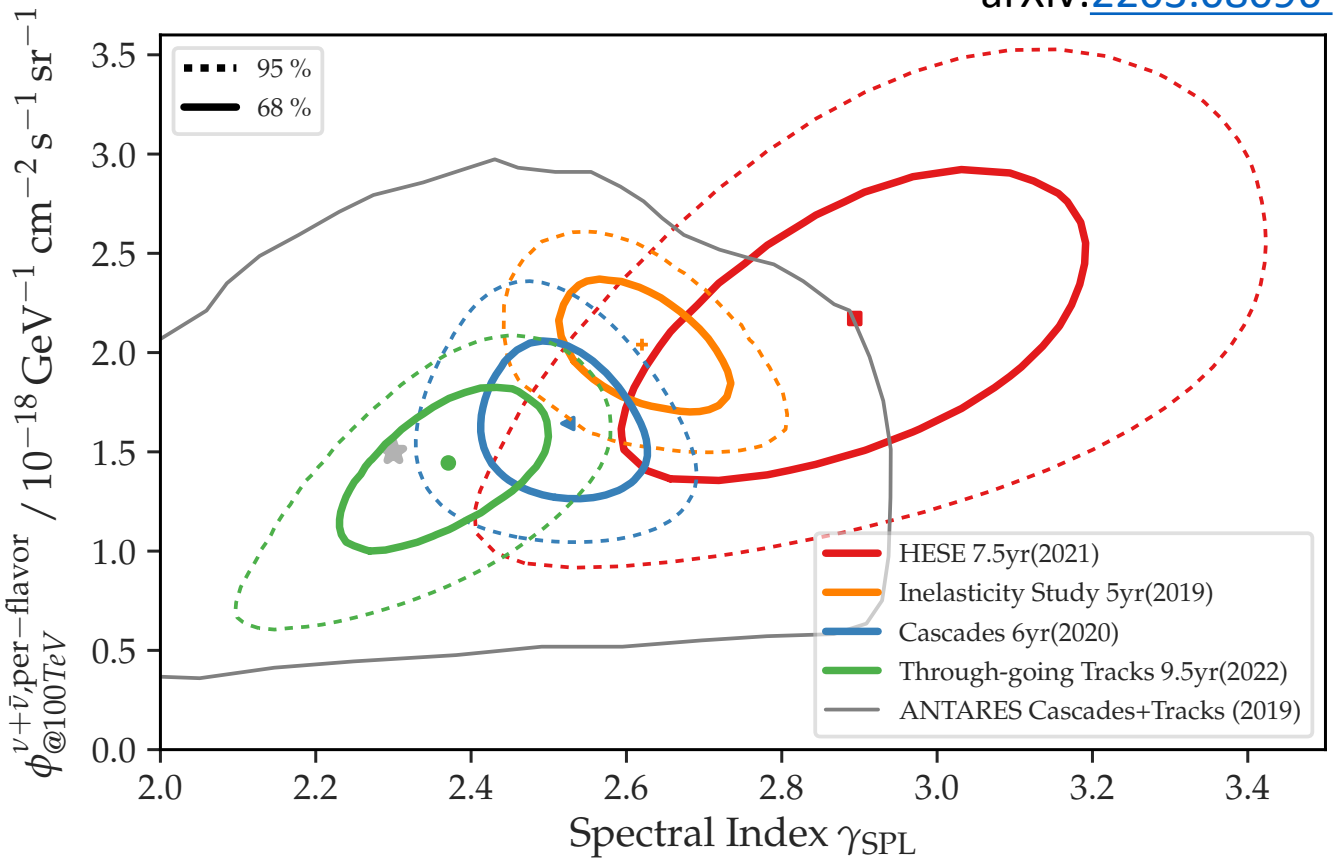
# Astrophysical Neutrinos

## The Landscape Today

Several complementary measurements

- All consistent with SPL hypothesis
- Consistent w/ each other @ 2σ
- But different, and challenging, systematics

arXiv:2203.08096



# Astrophysical Neutrinos

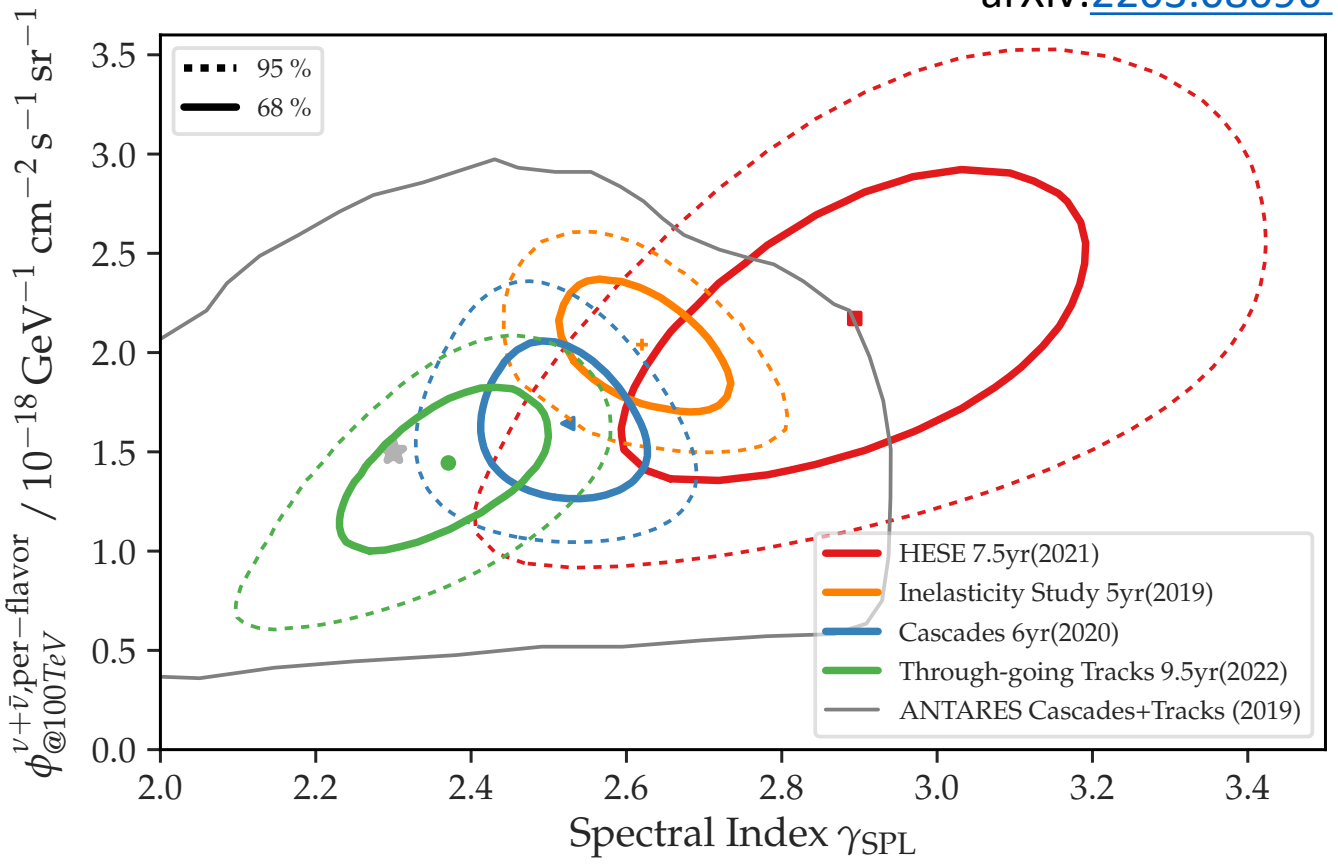
## The Landscape Today

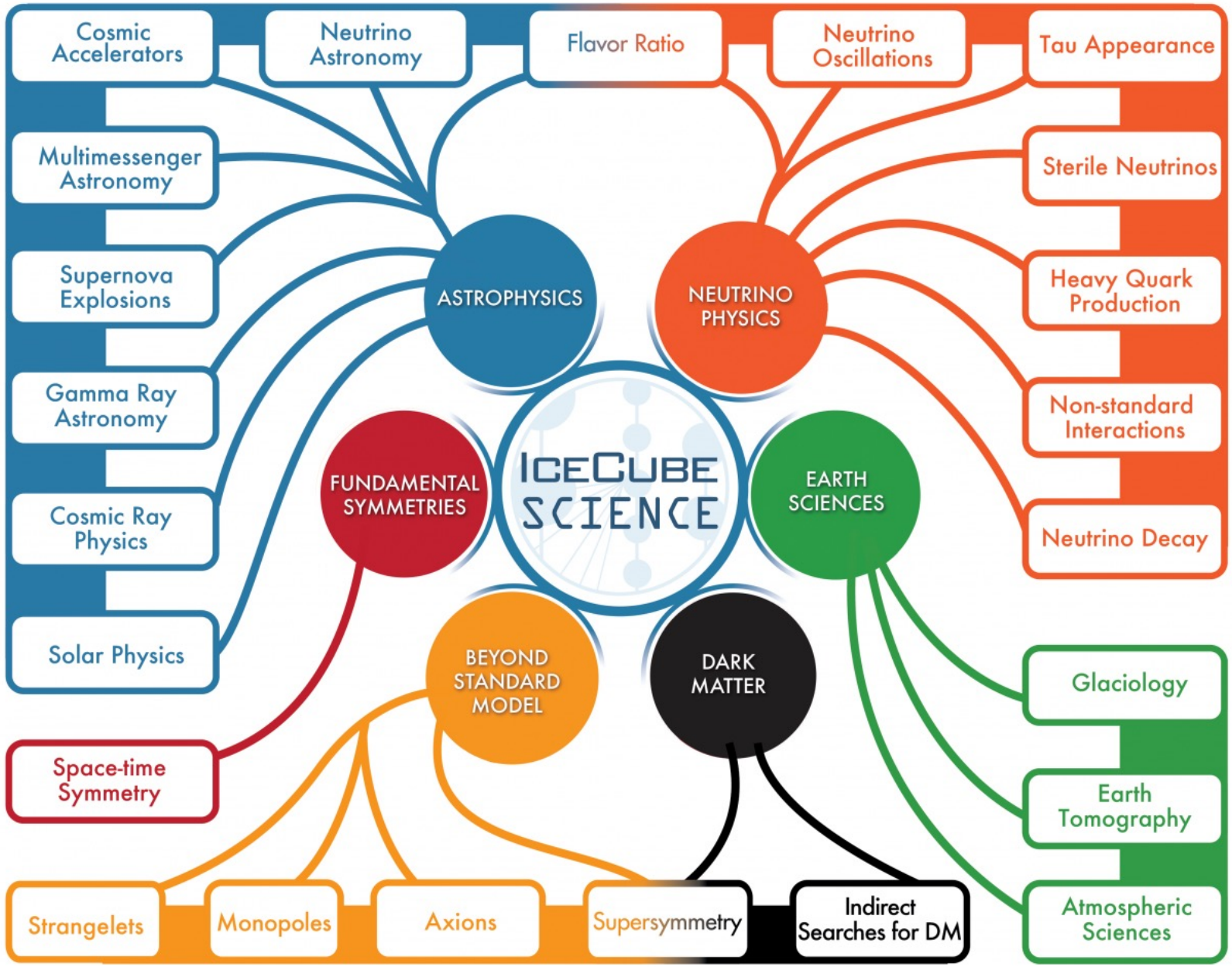
Several complementary measurements

- All consistent with SPL hypothesis
- Consistent w/ each other @ 2σ
- But different, and challenging, systematics

Global fit efforts are planned!

arXiv:2203.08096

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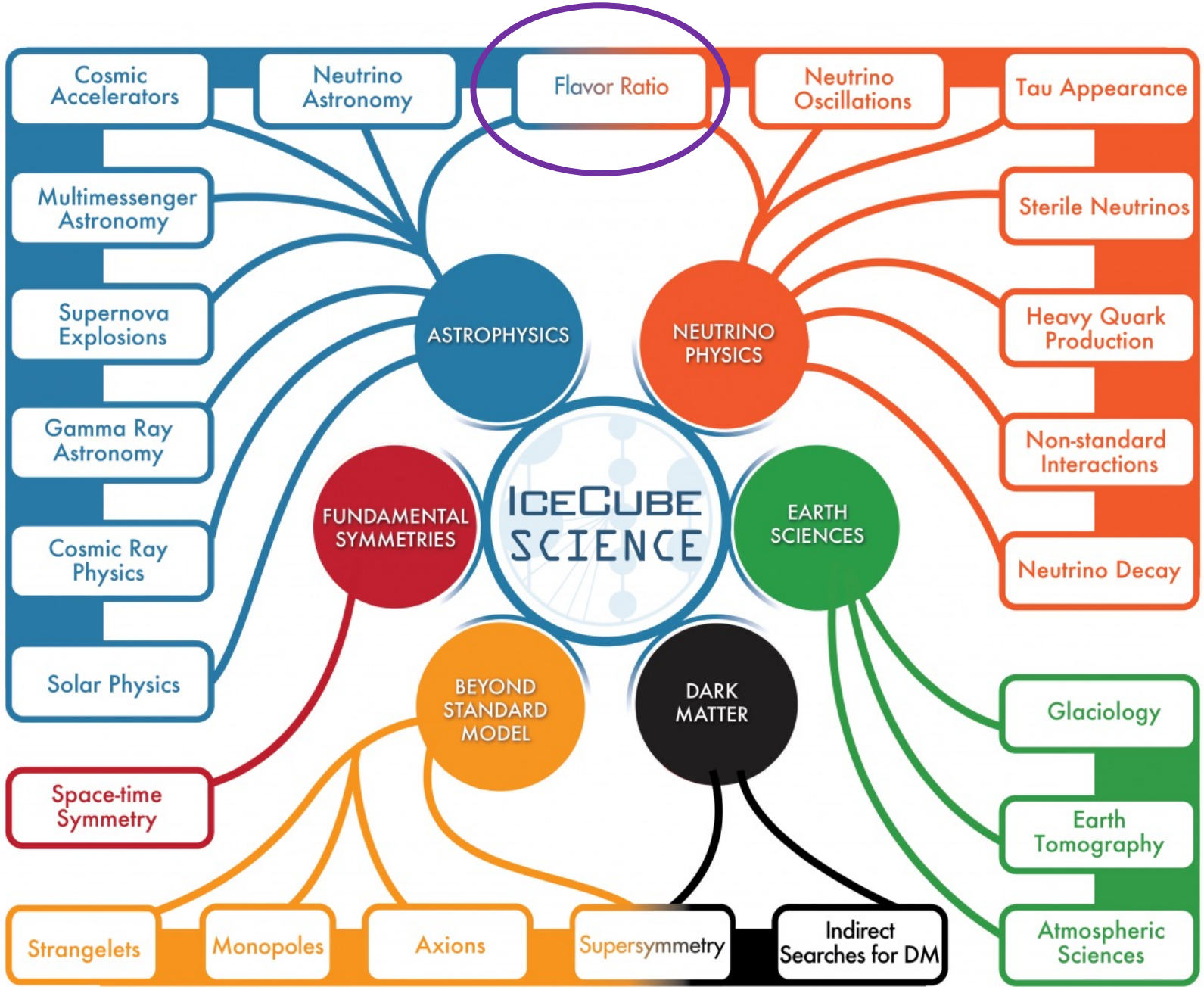
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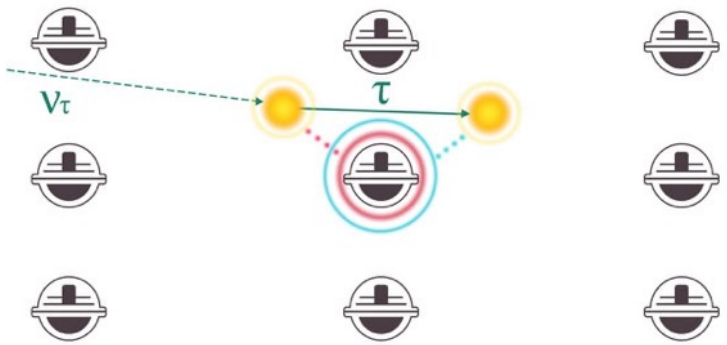

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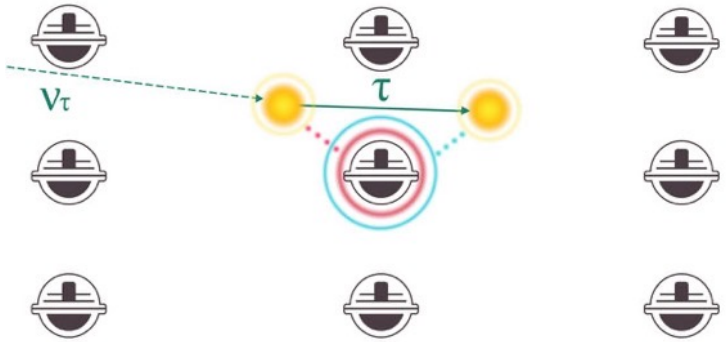


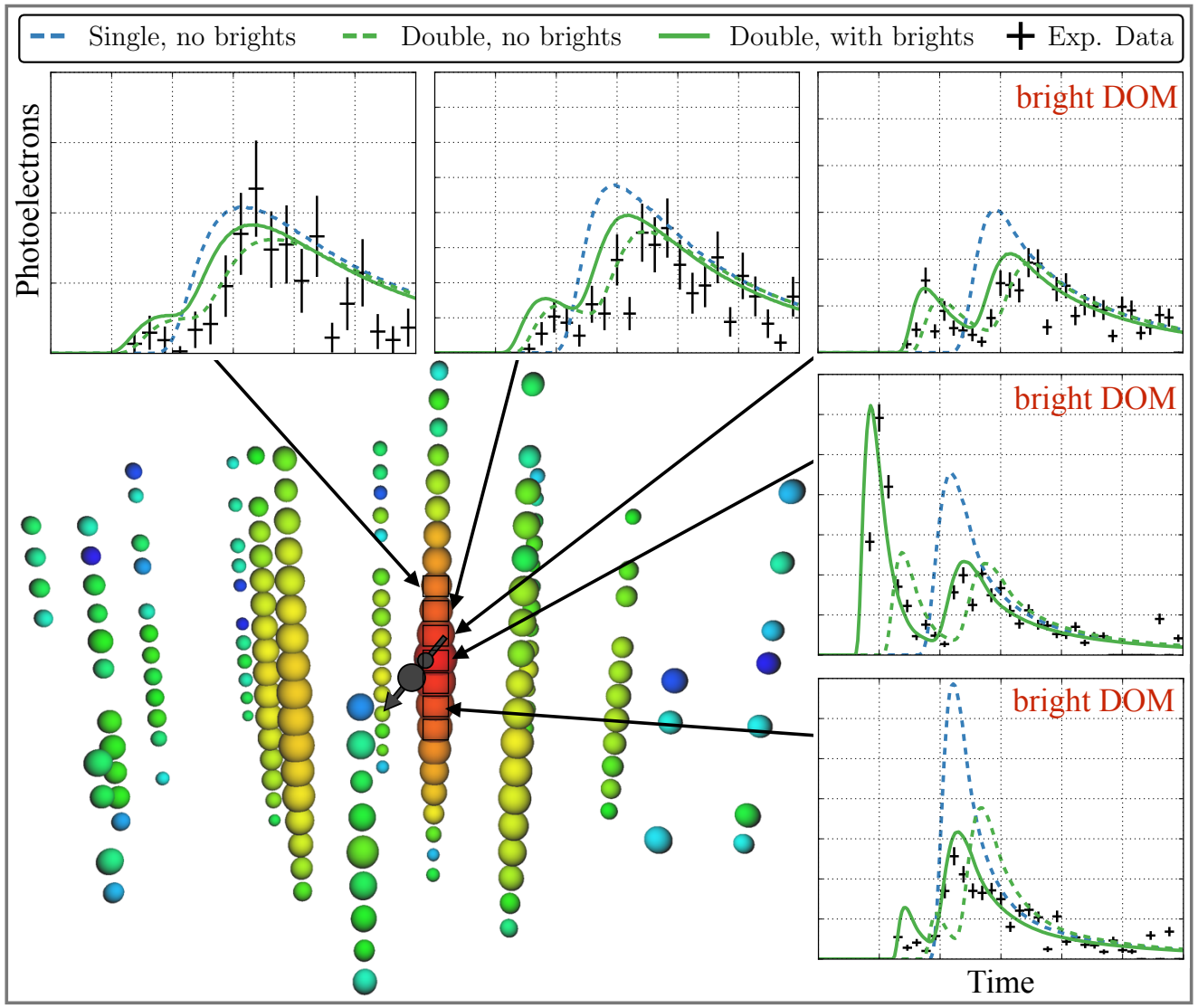


arxiv 2011.03561
(Submitted to EPJC)

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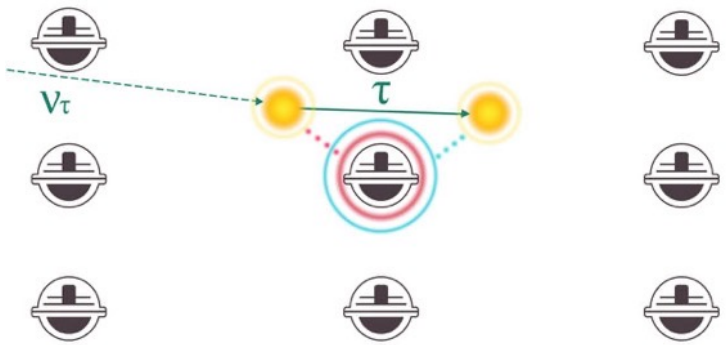

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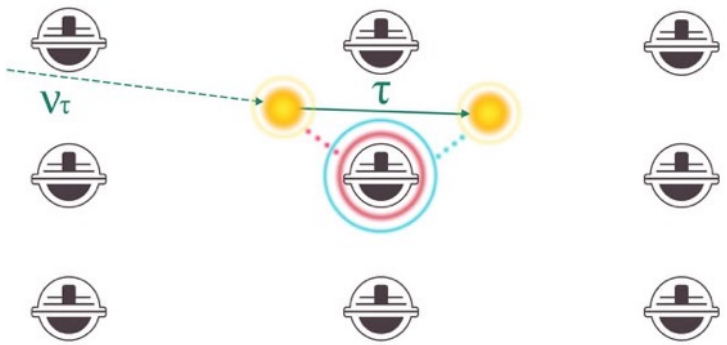


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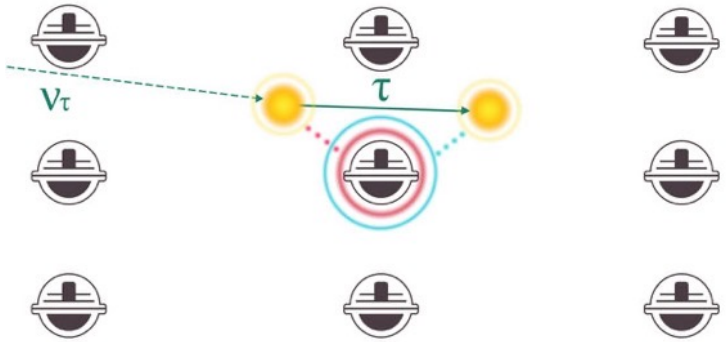


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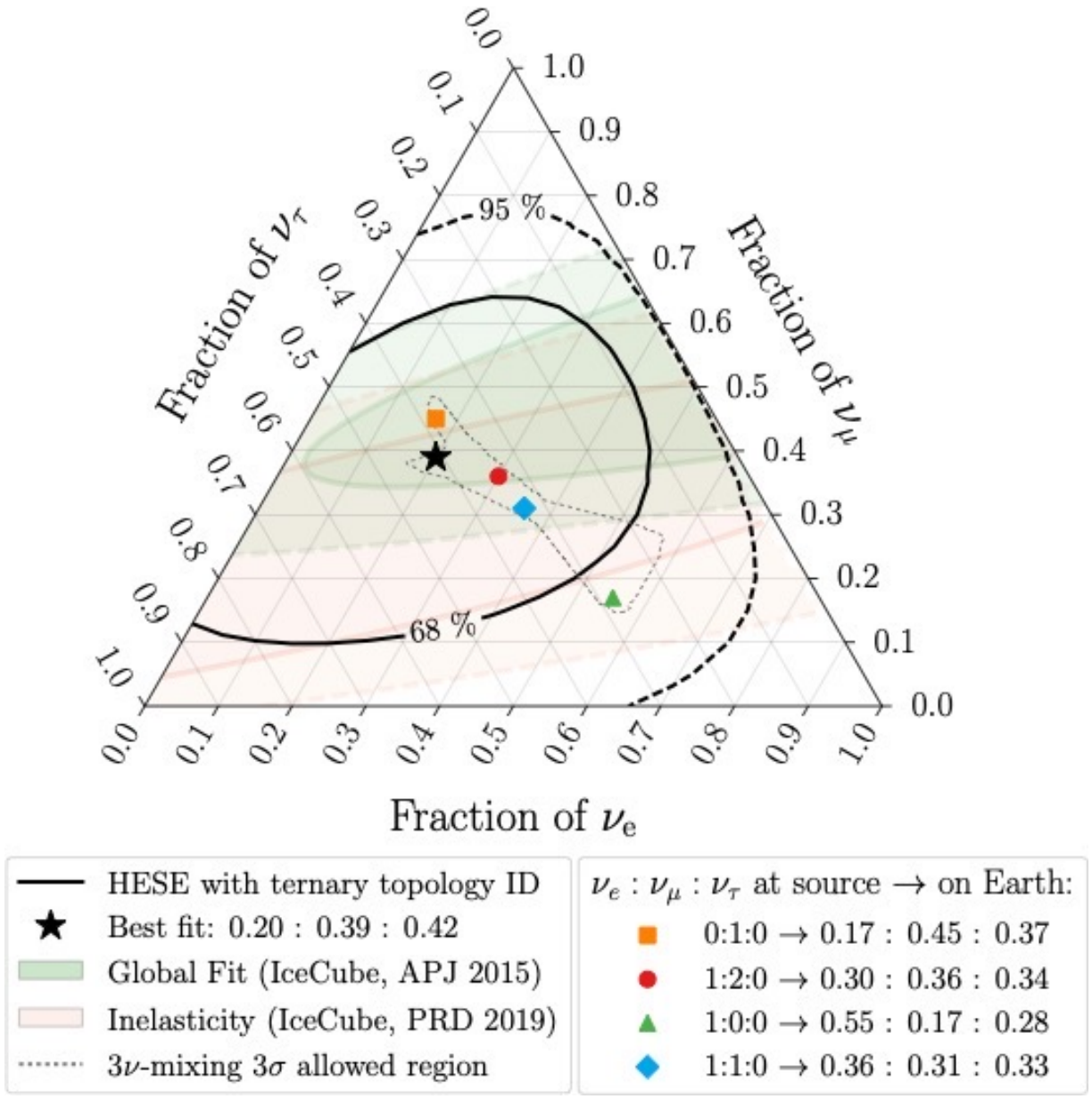


Best-fit has all flavor components >0.

# Glashow Resonance

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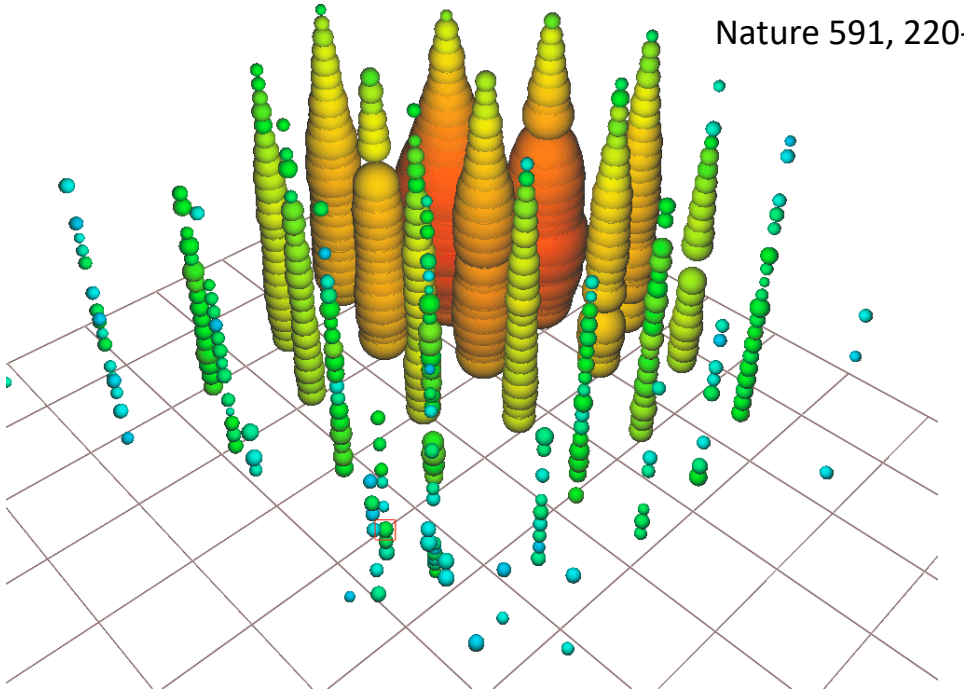

Nature 591, 220-224 (2021)

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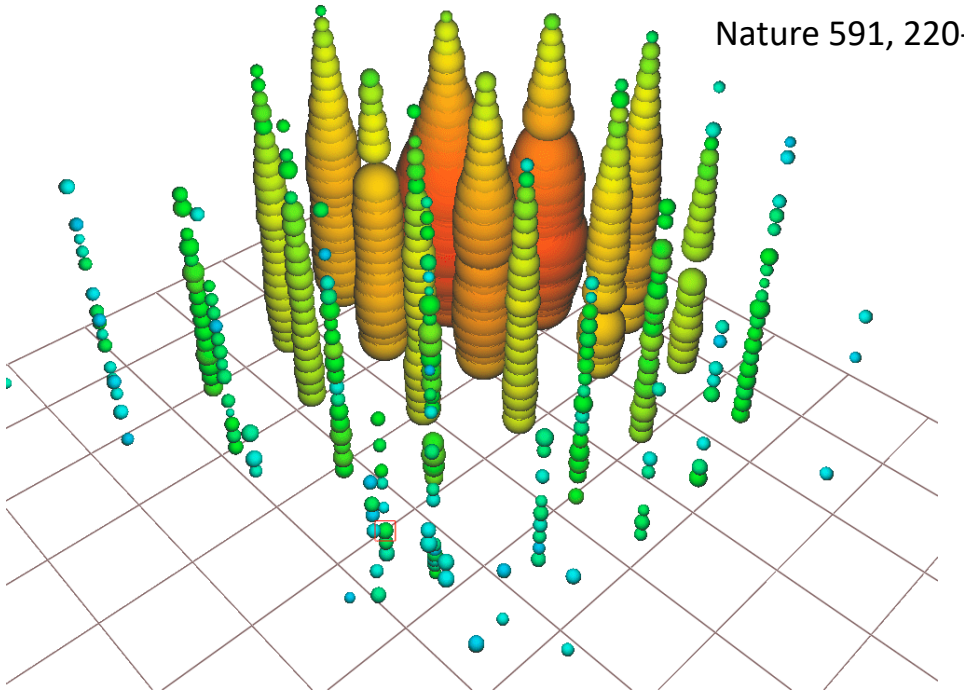

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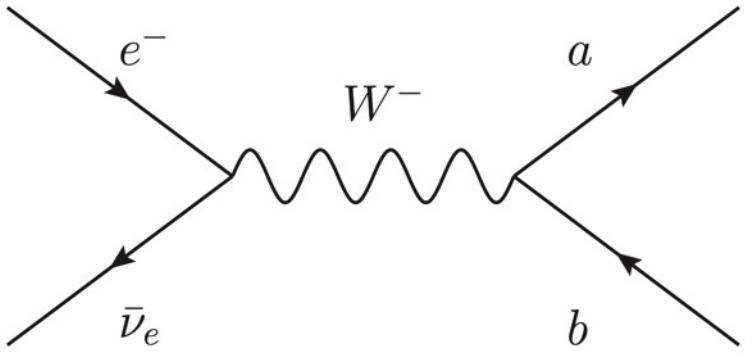

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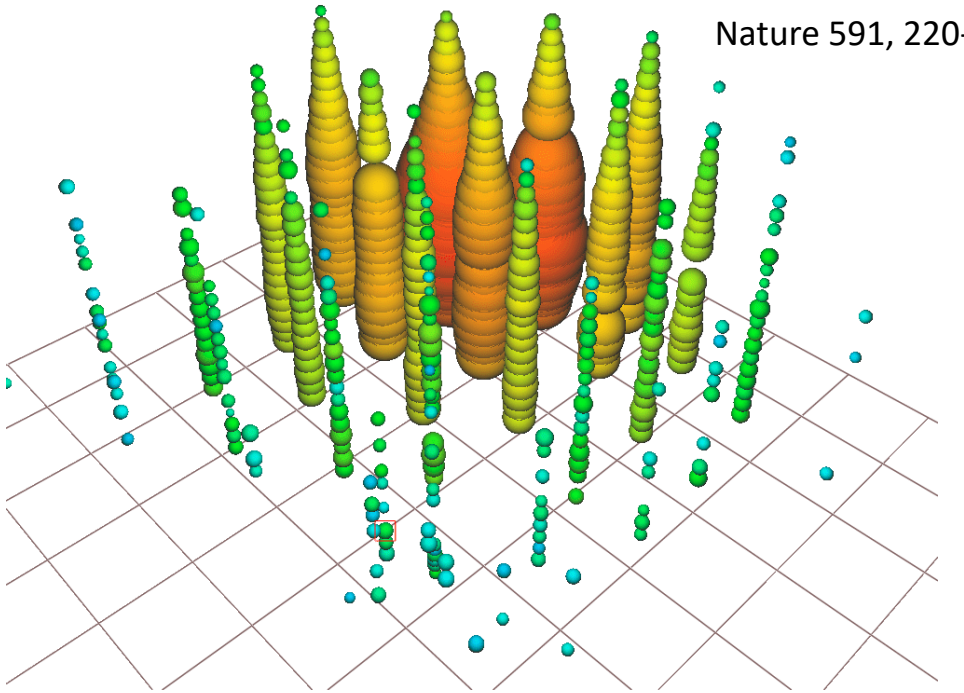
First observation of this interaction, and a confirmed astrophysical $\nu\, e$

$\nu\, e \quad e\, e\, e\, \nu\, e$



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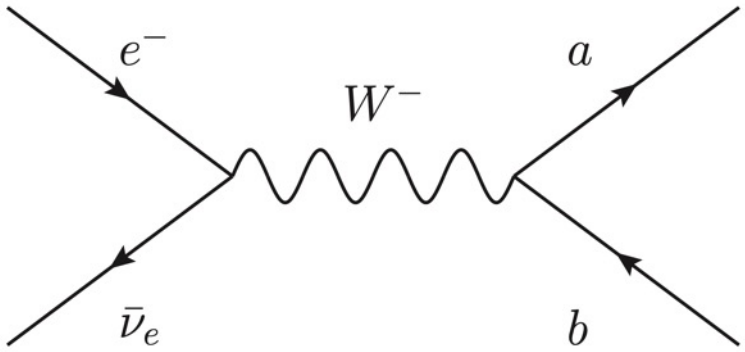

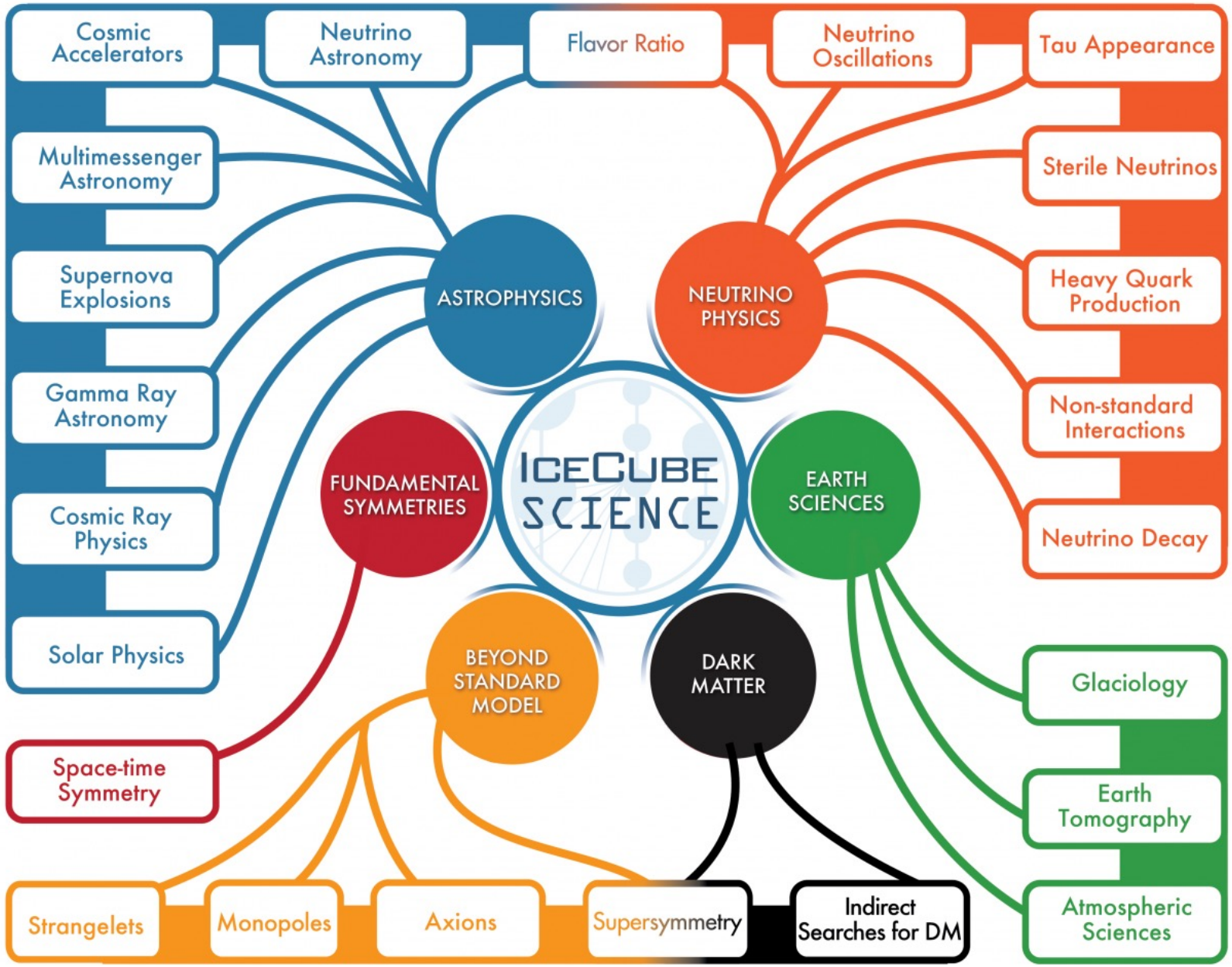
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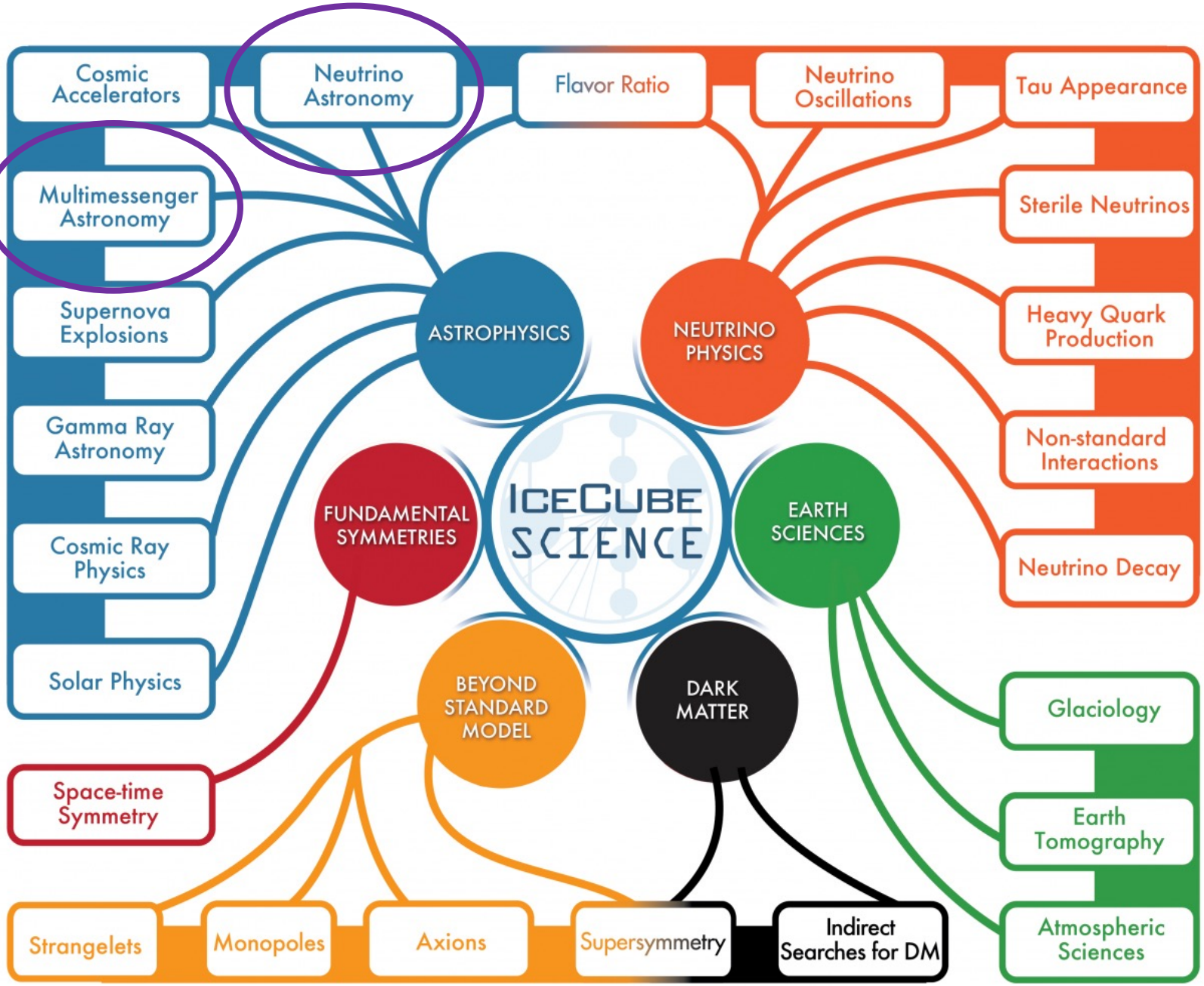
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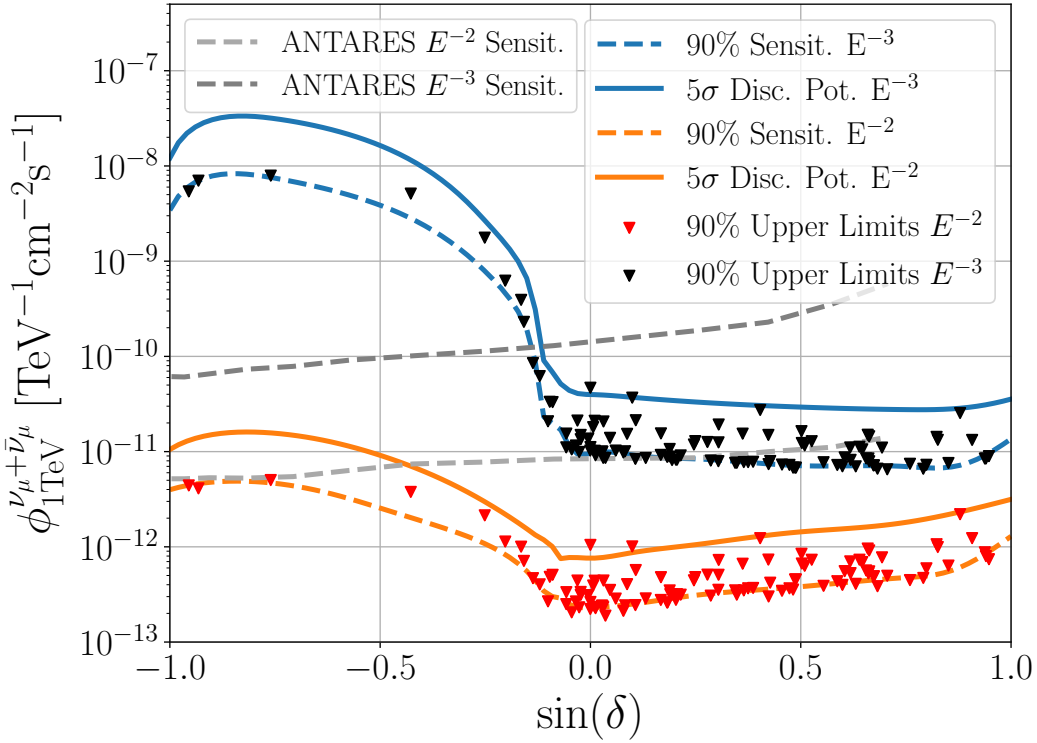


PRL 124, 051103 (2020)
(arxiv 1910.08488)

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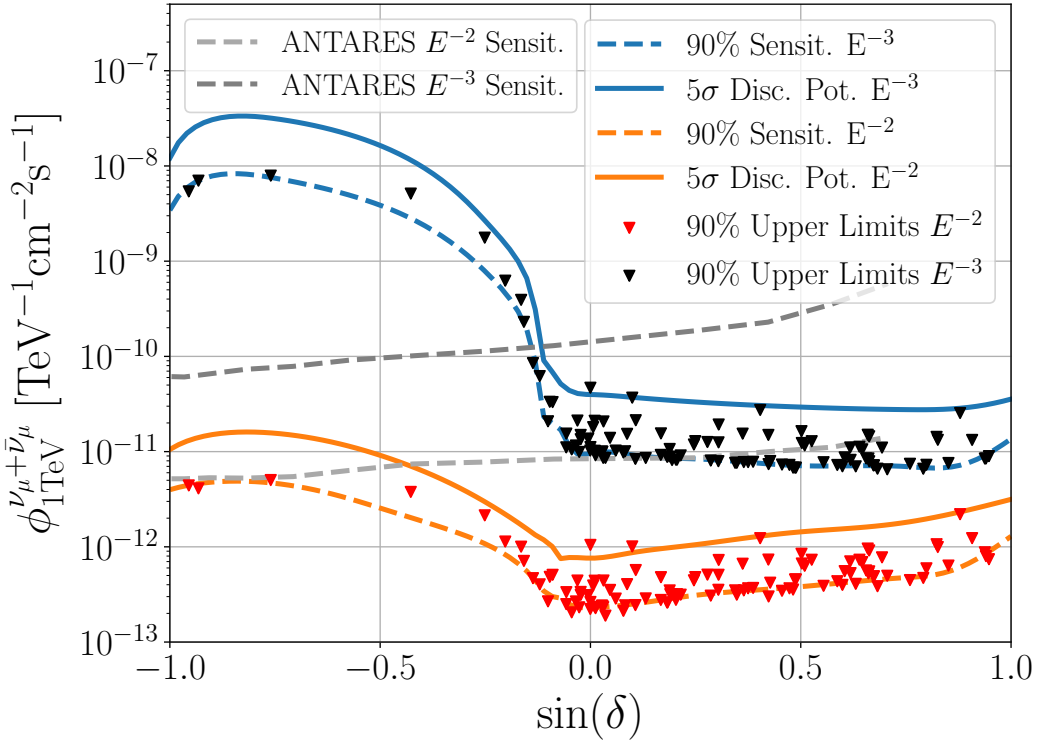


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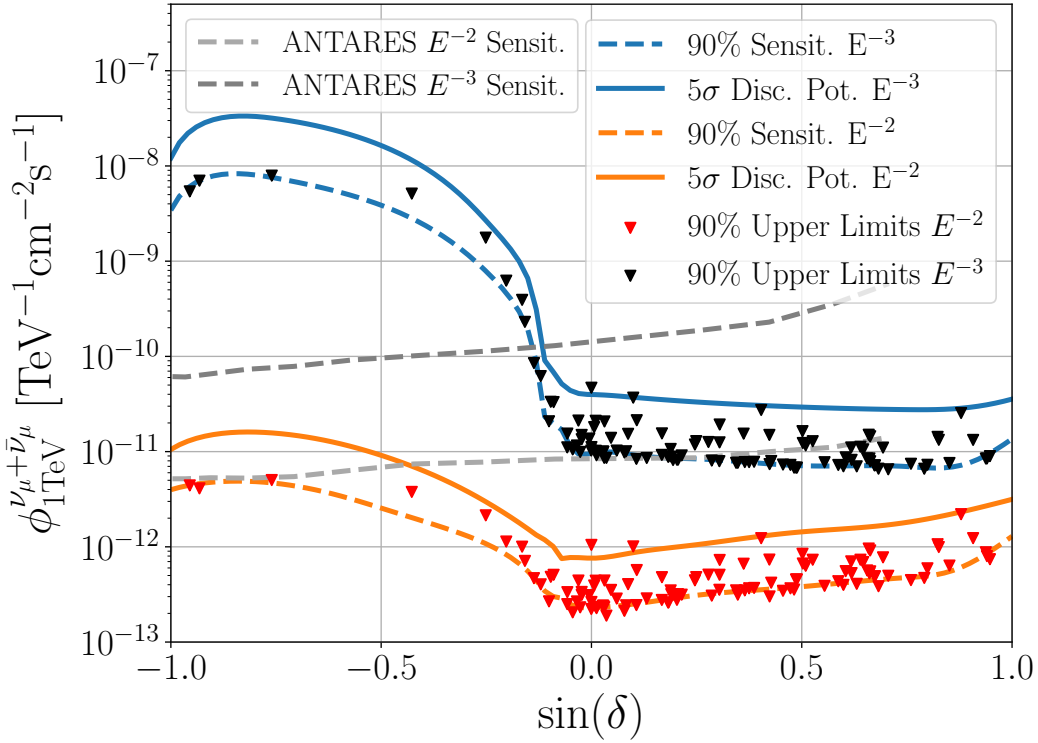


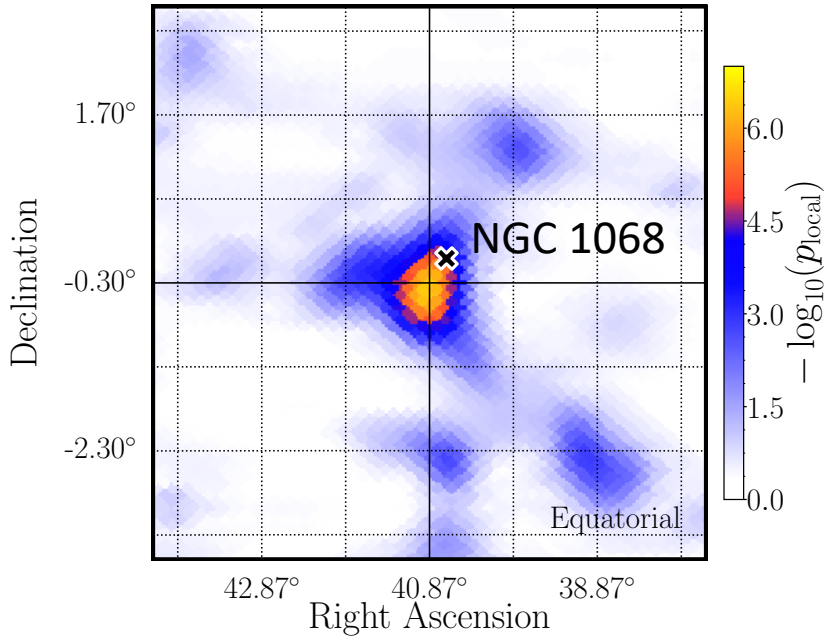


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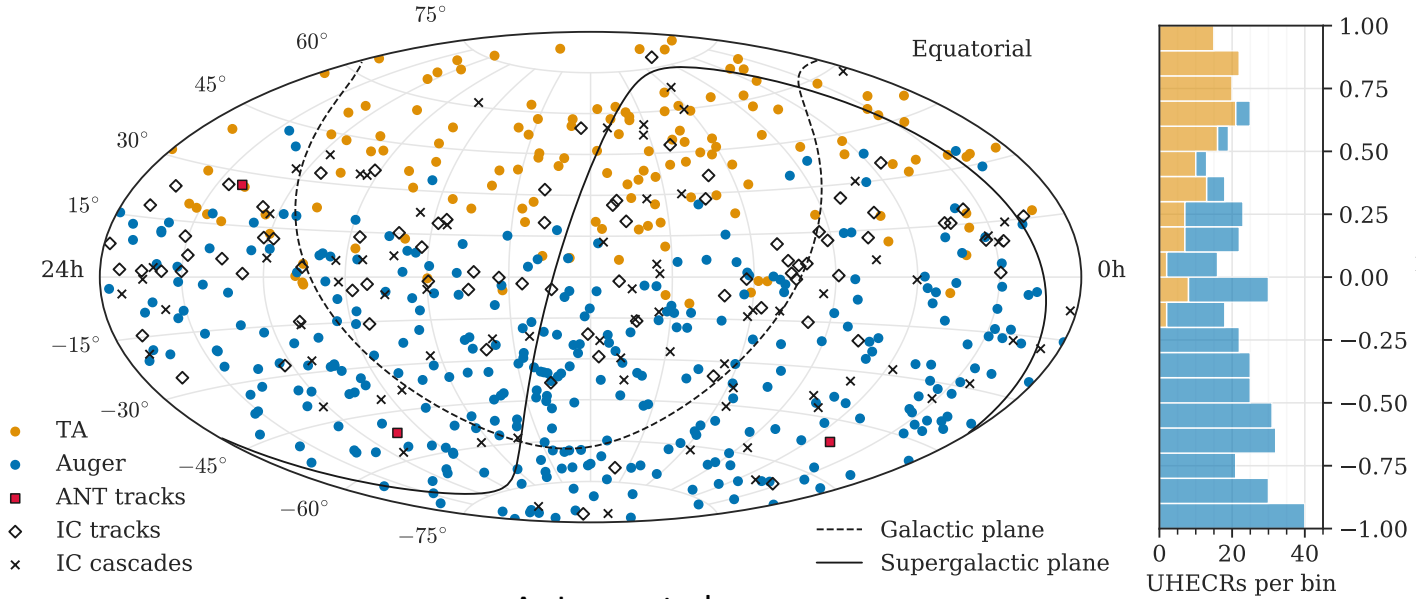
Cosmic rays:

Neutrinos:




ApJ accepted
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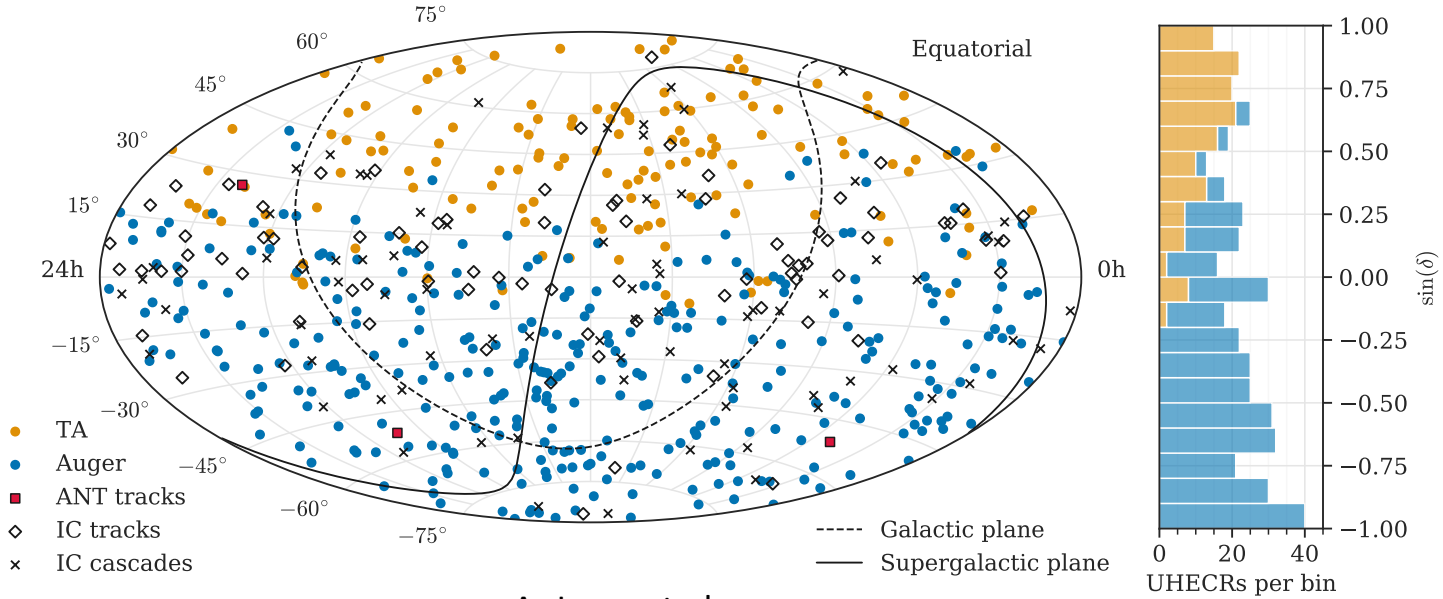


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Neutrinos:

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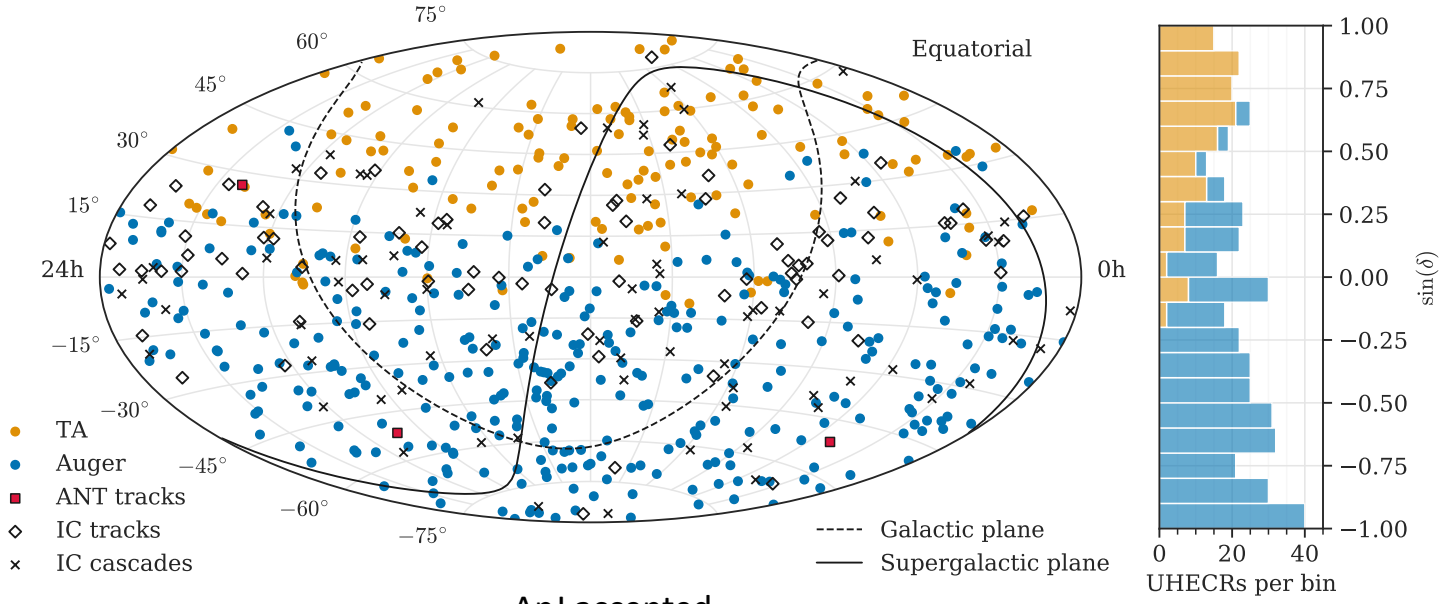
No significant correlations found

Not necessarily unexpected!

Good CR accelerators may be optically thin and therefore poor neutrino beam dumps

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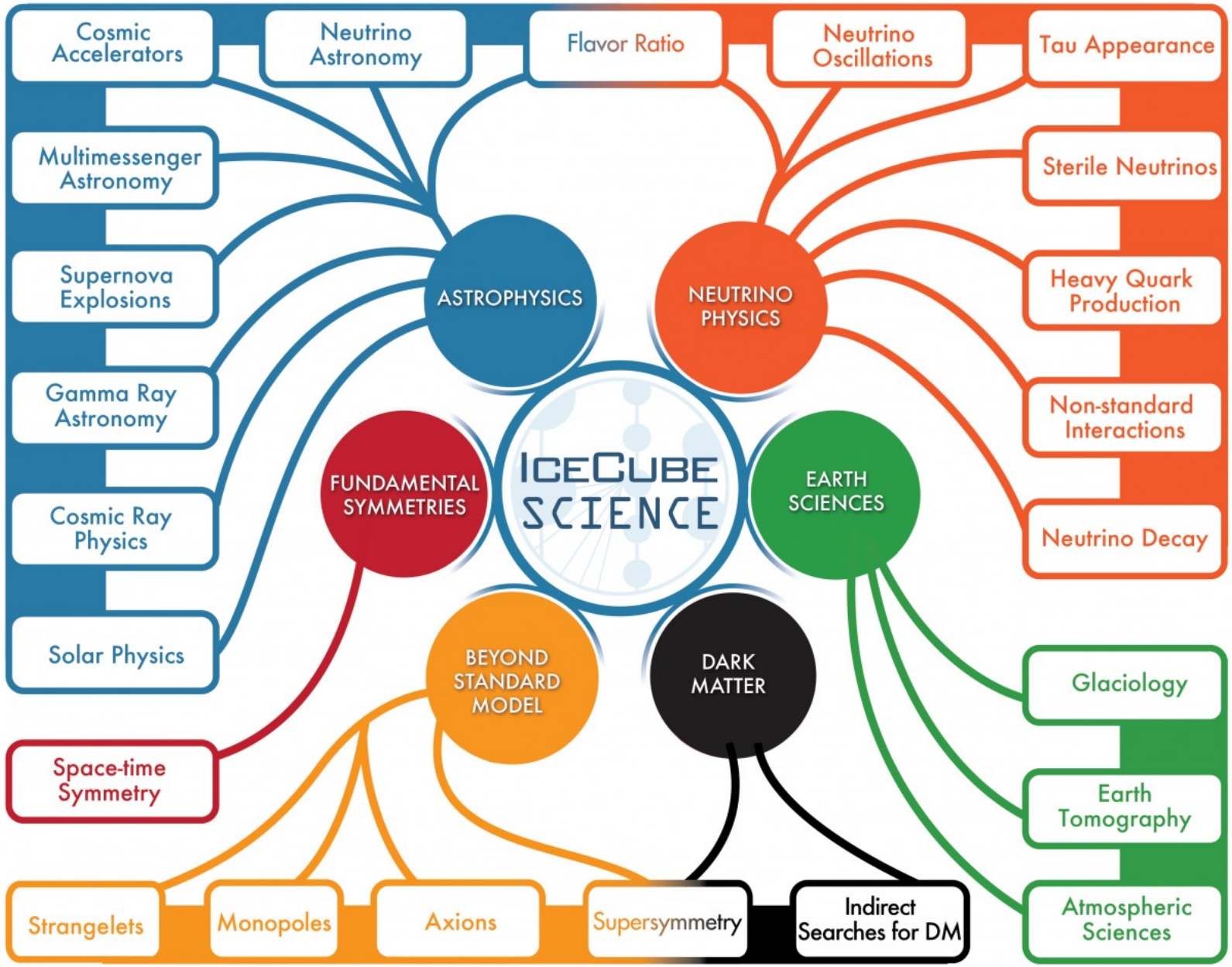
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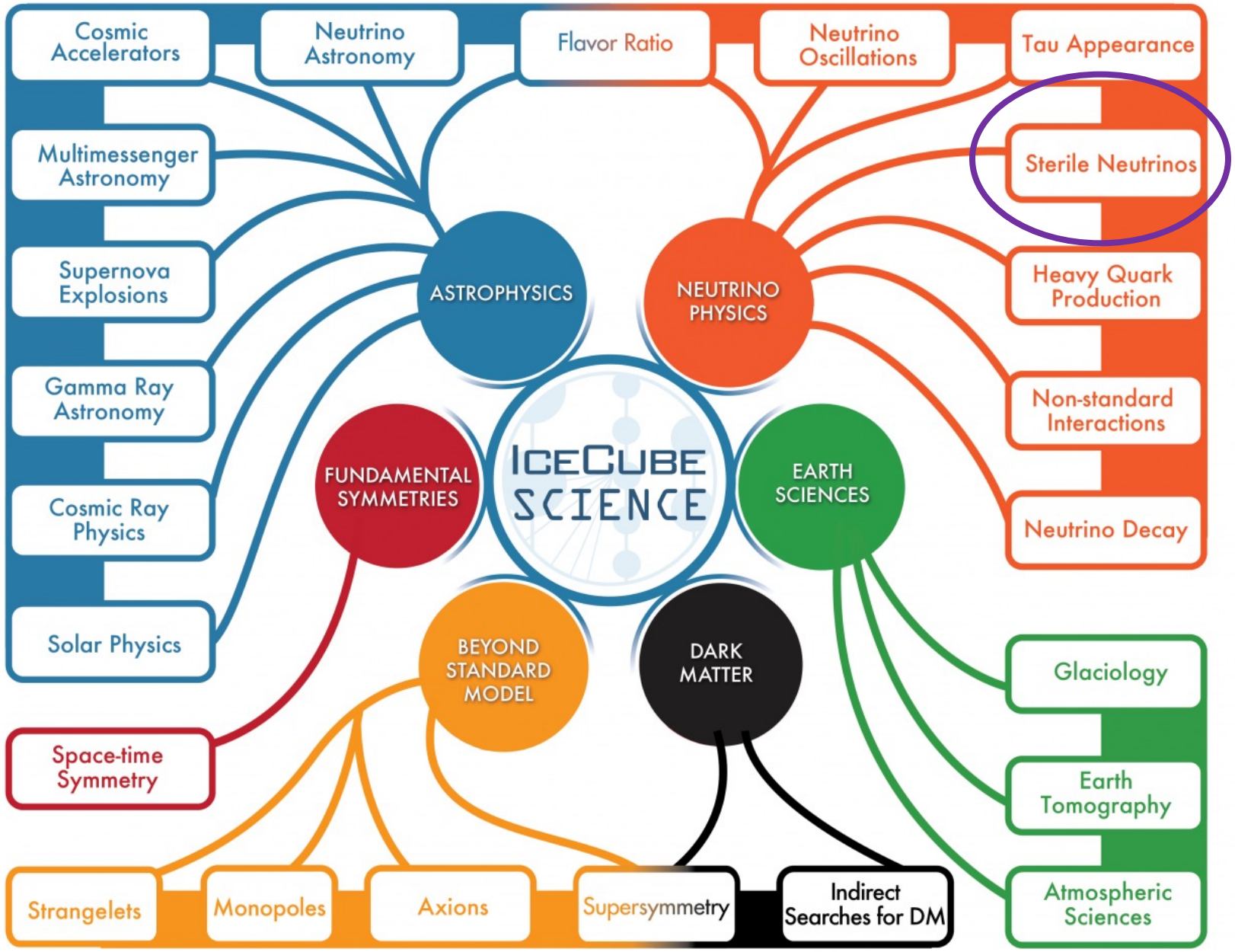
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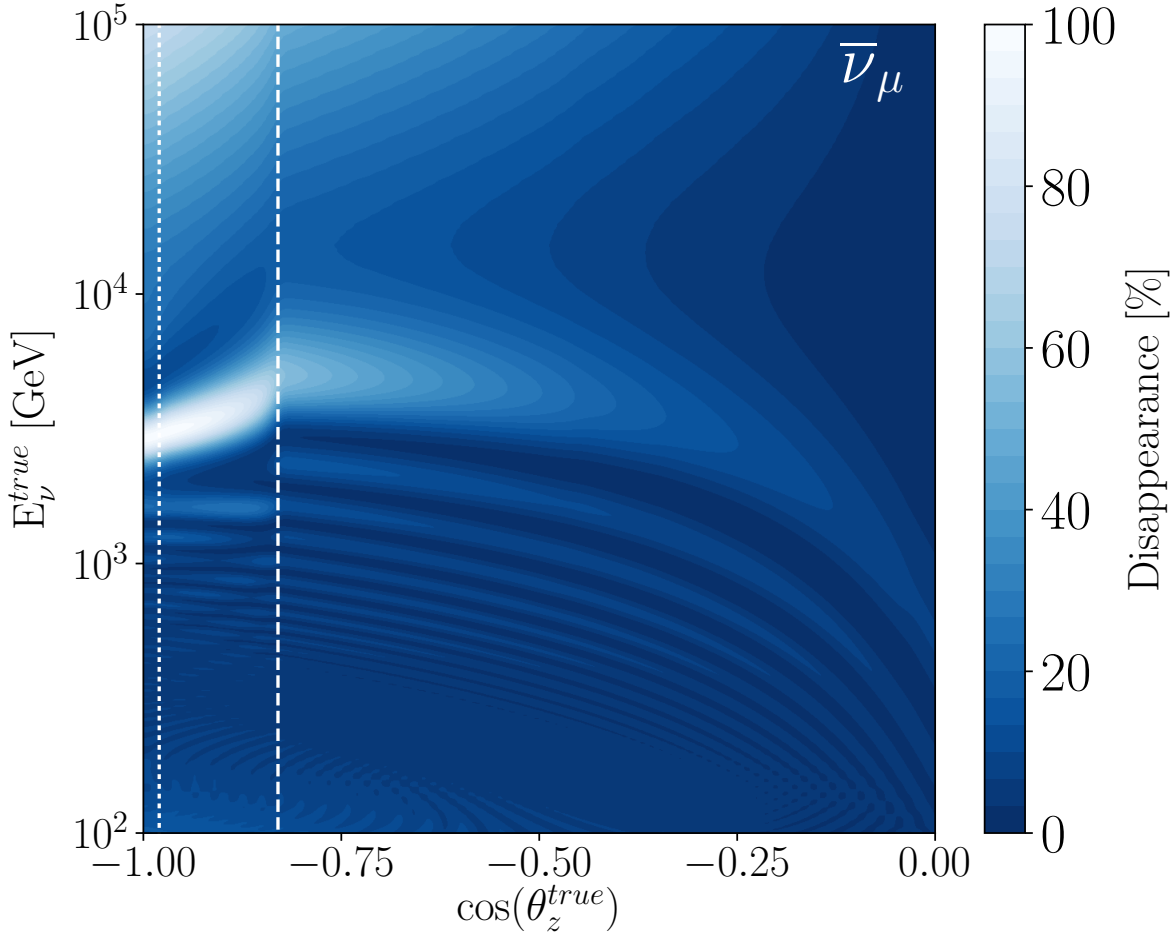


PRL 125, 141801 (2020)
(arxiv 2005.12942)

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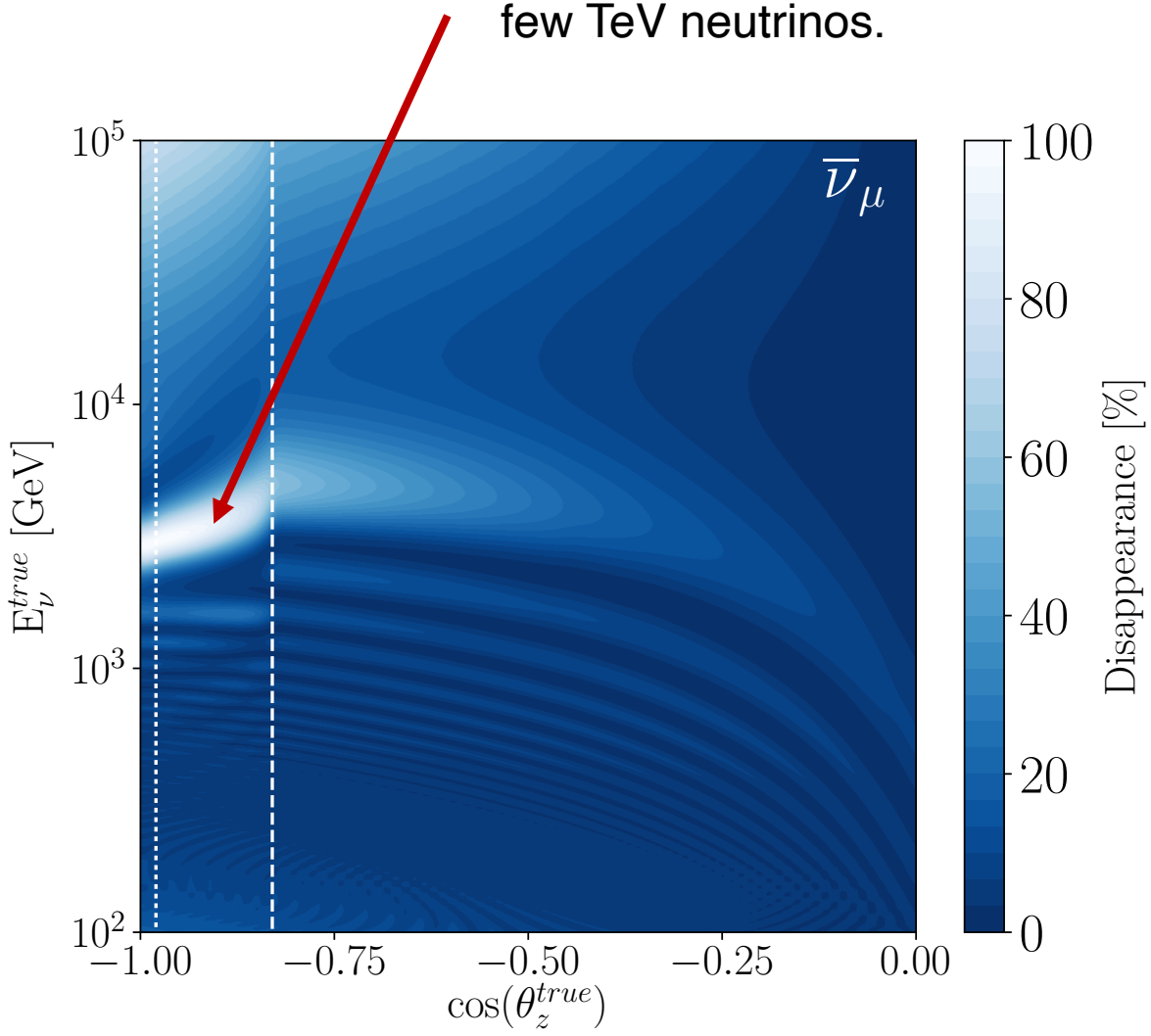
A sterile neutrino leads to a matter-enhanced resonance, and near total disappearance of Earth-traversing few TeV neutrinos.

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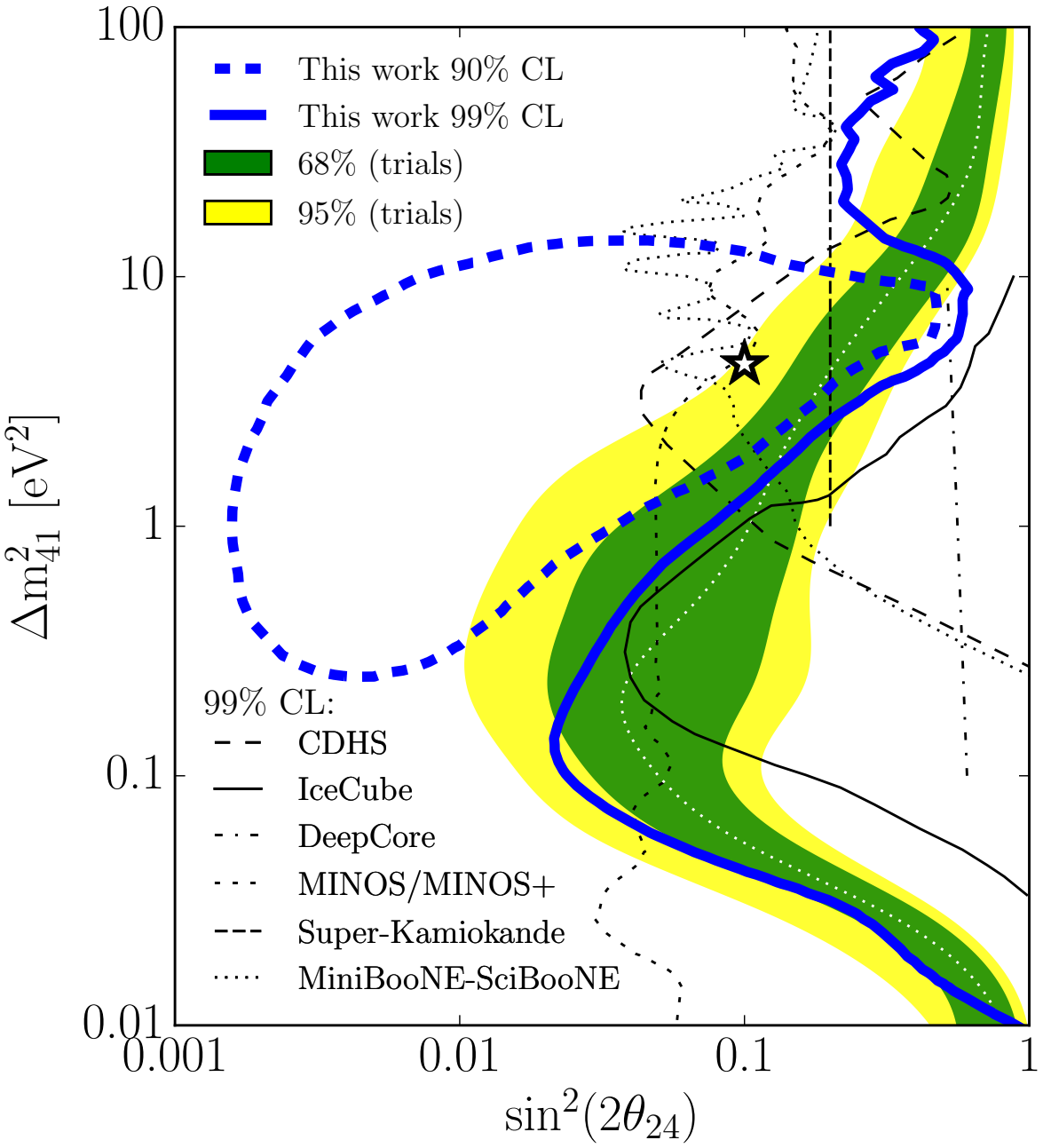
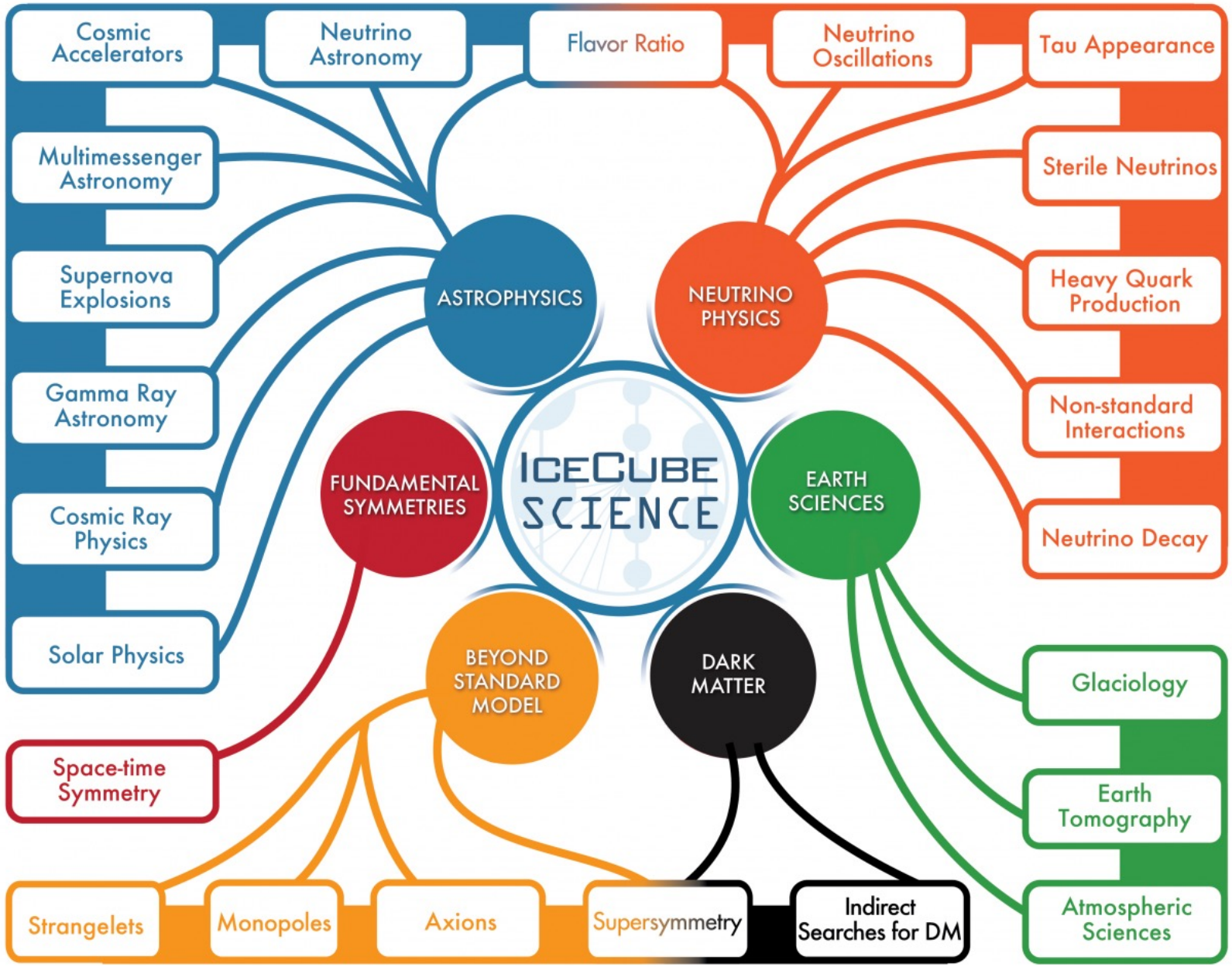
Result consistent with no-sterile hypothesis w/ p-value = 8%; 90% contour closes

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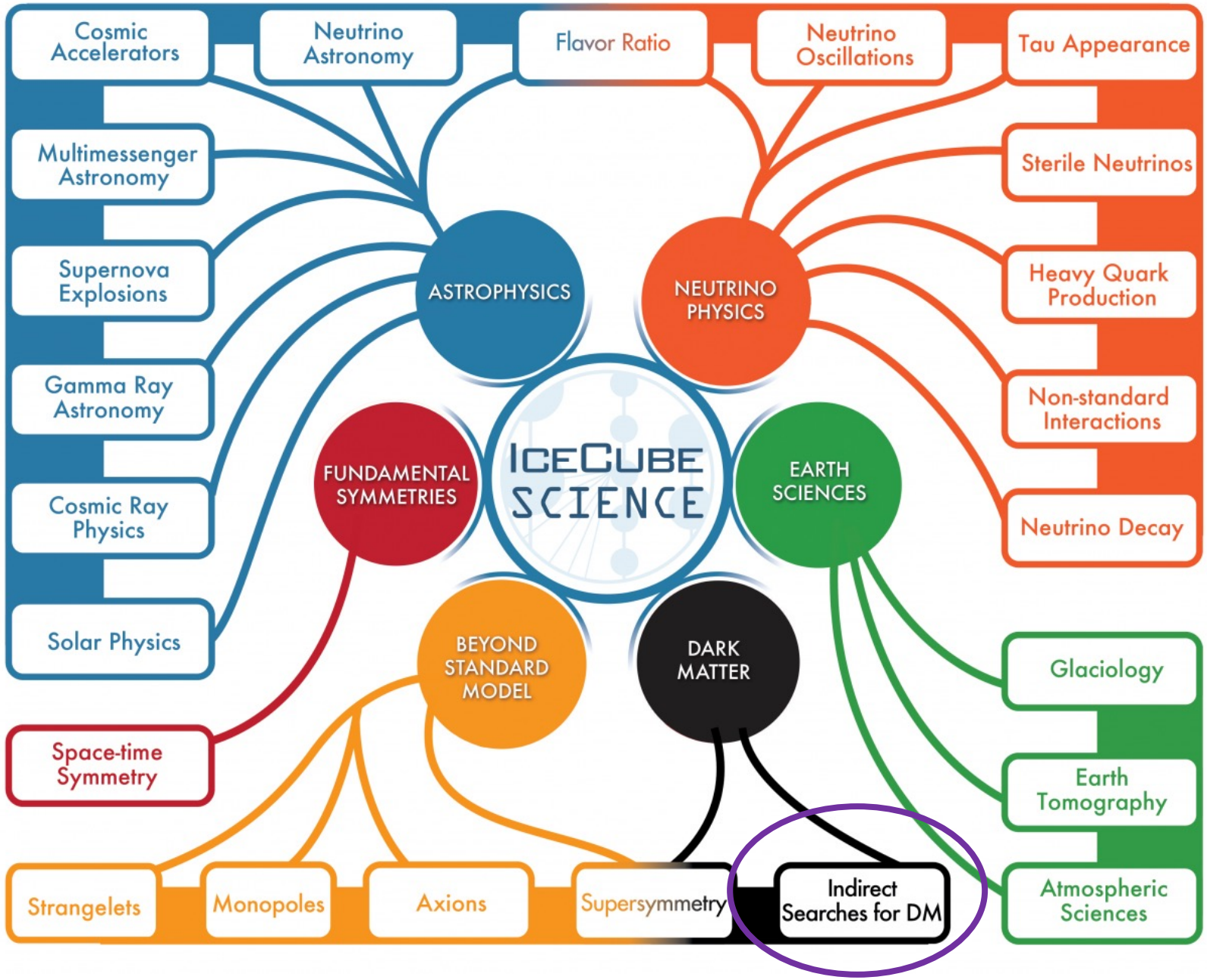
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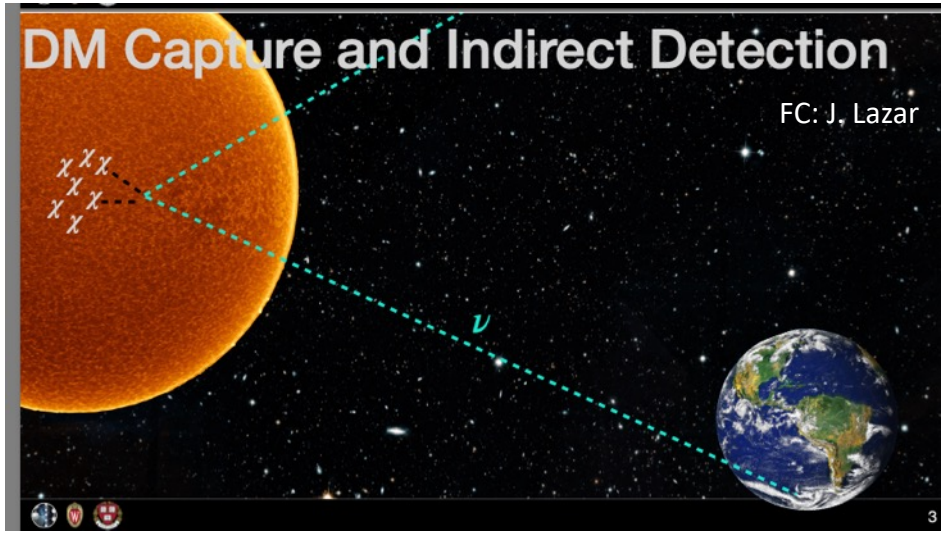

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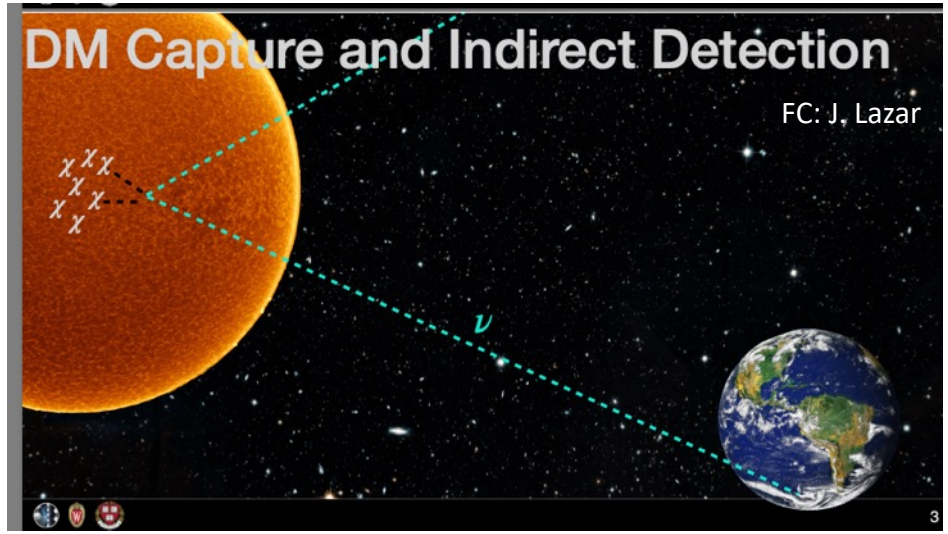

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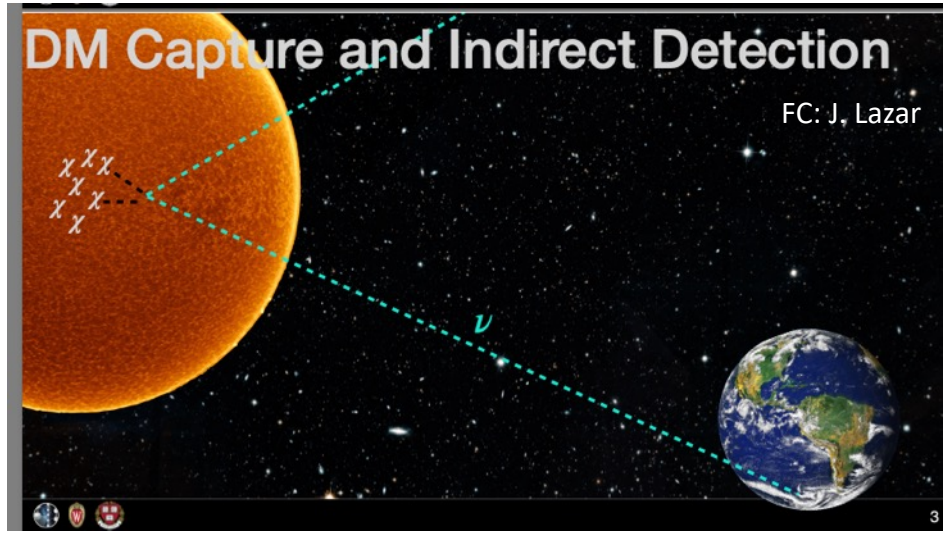

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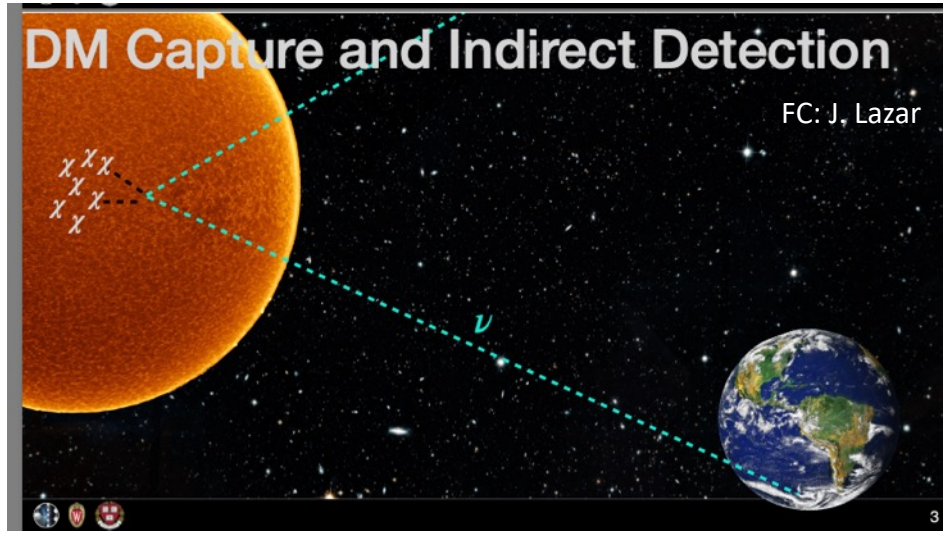
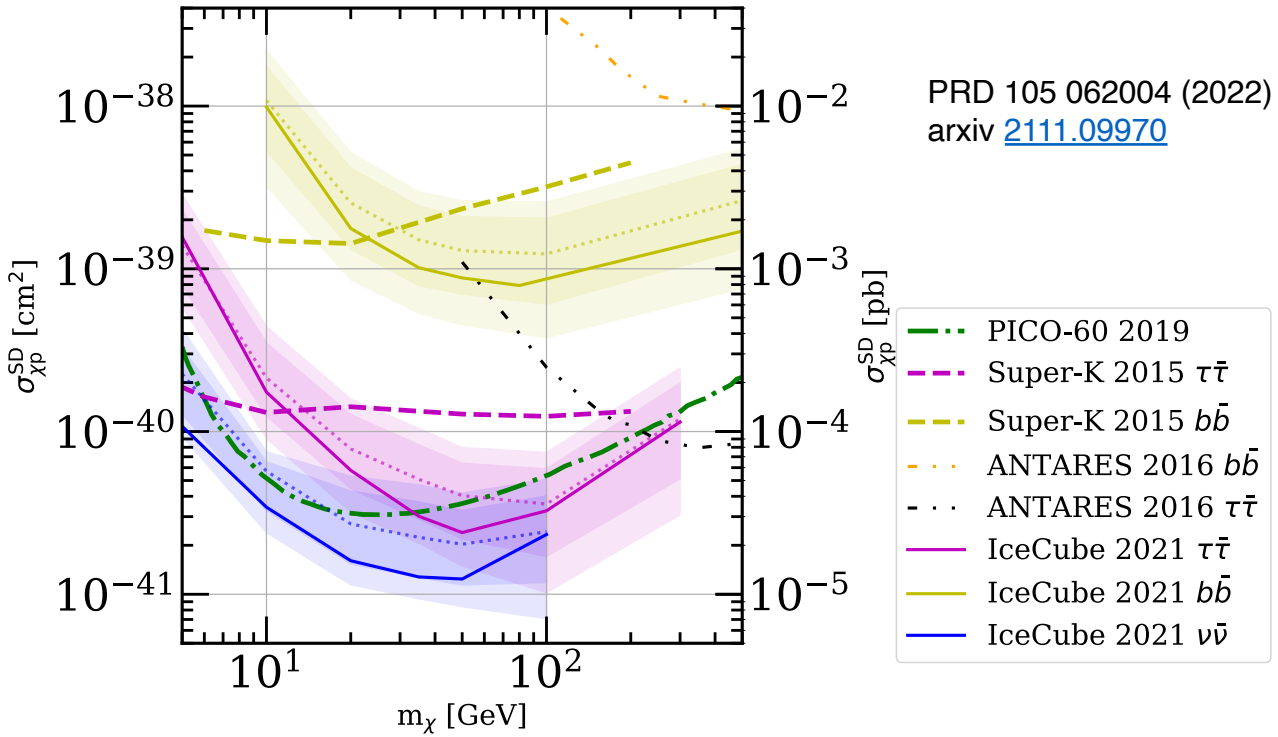
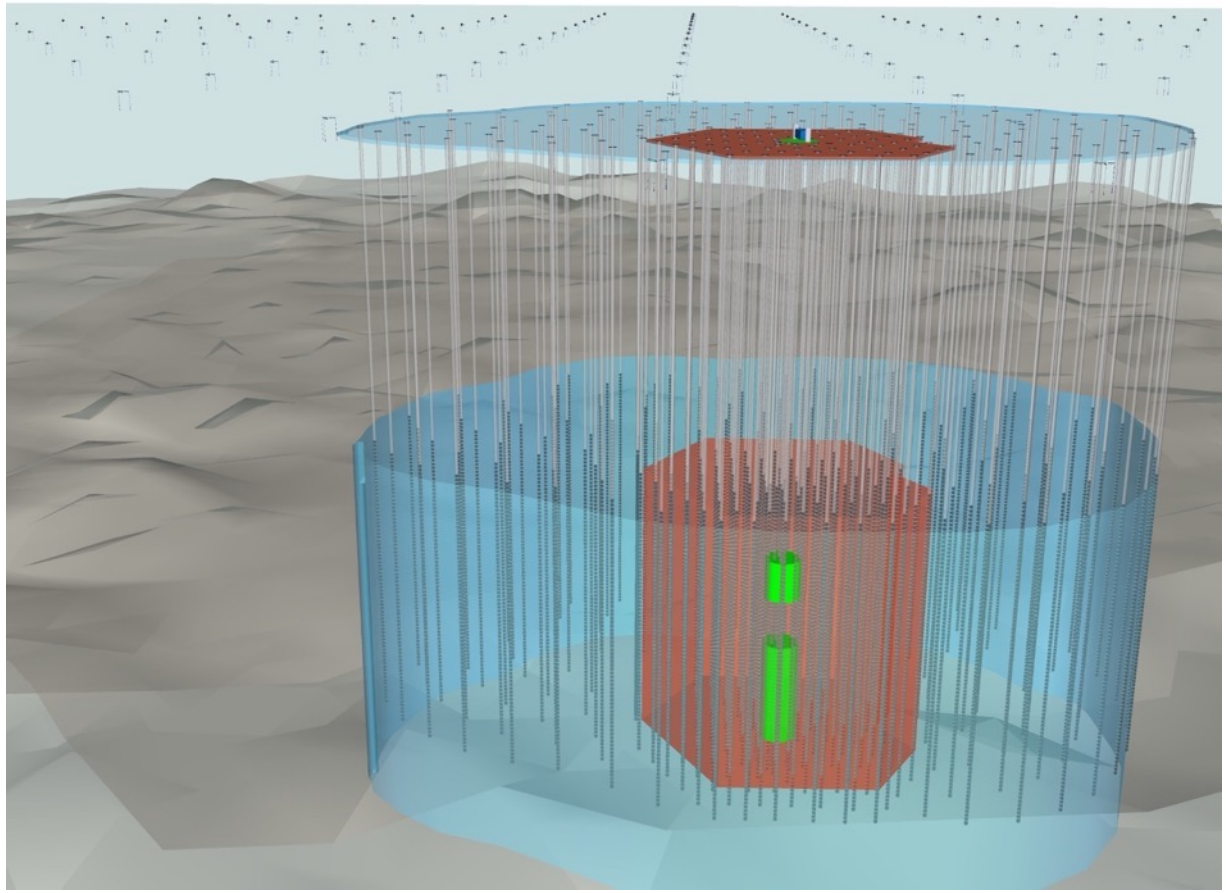



PRD 105 062004 (2022)
arxiv 2111.09970

# The Future: IceCube-Gen2

Four new elements



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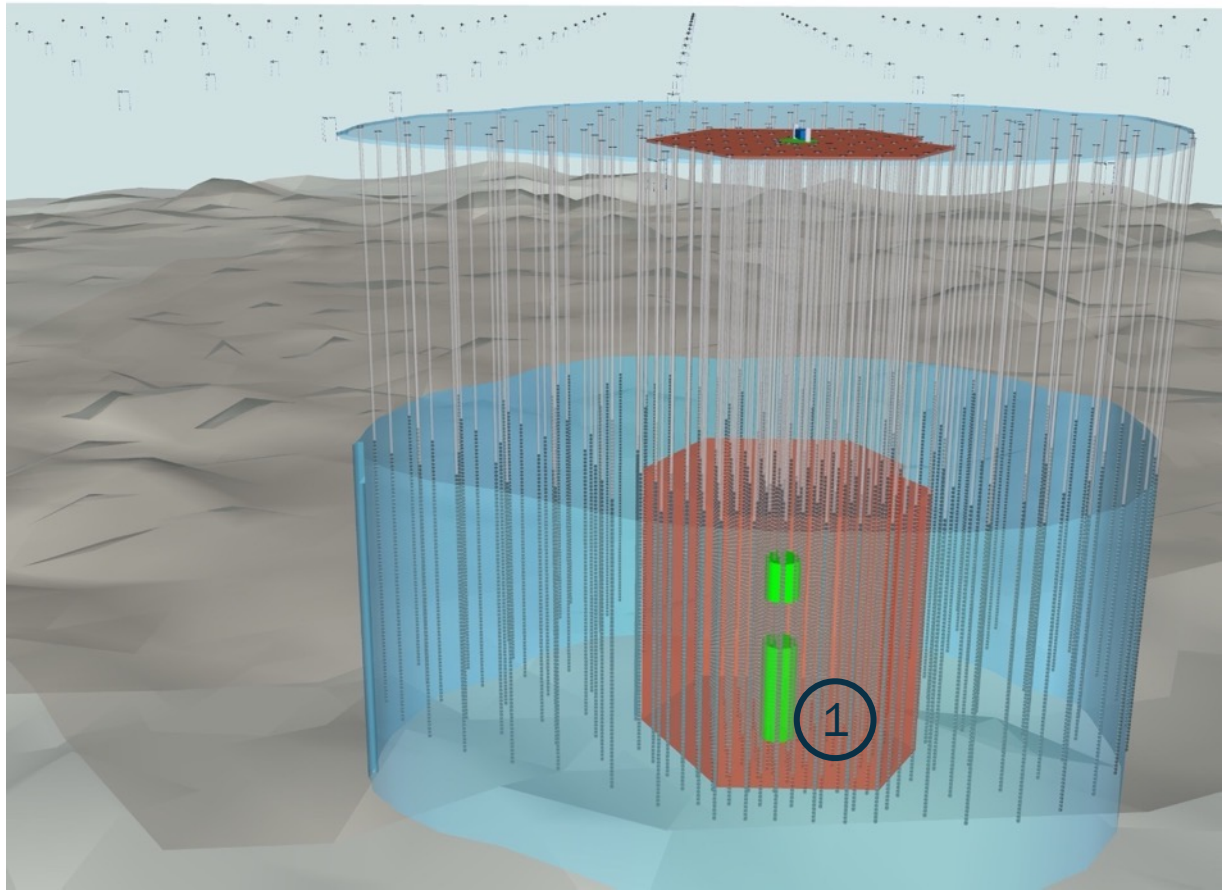
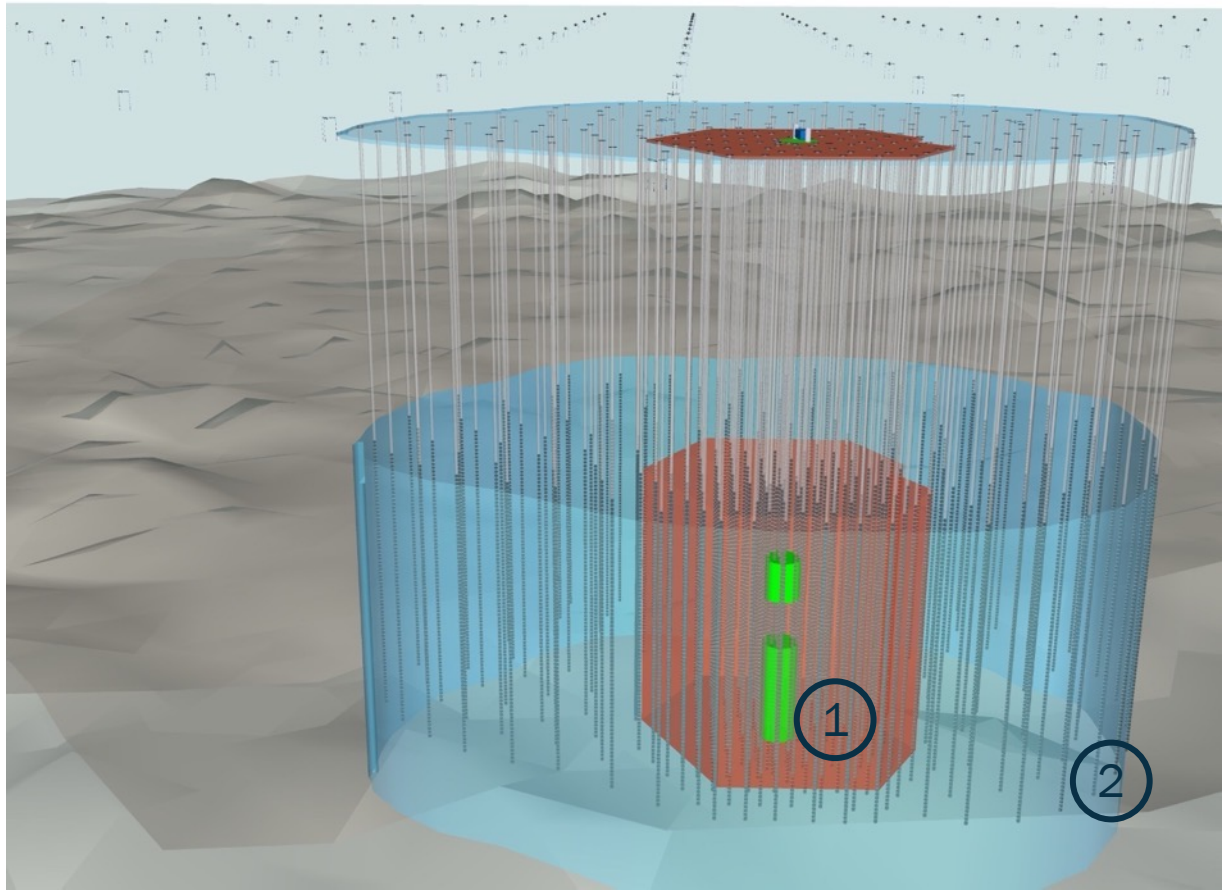


# The Future: IceCube-Gen2

Four new elements

1. IceCube Upgrade
2. Enlarged deep optical array



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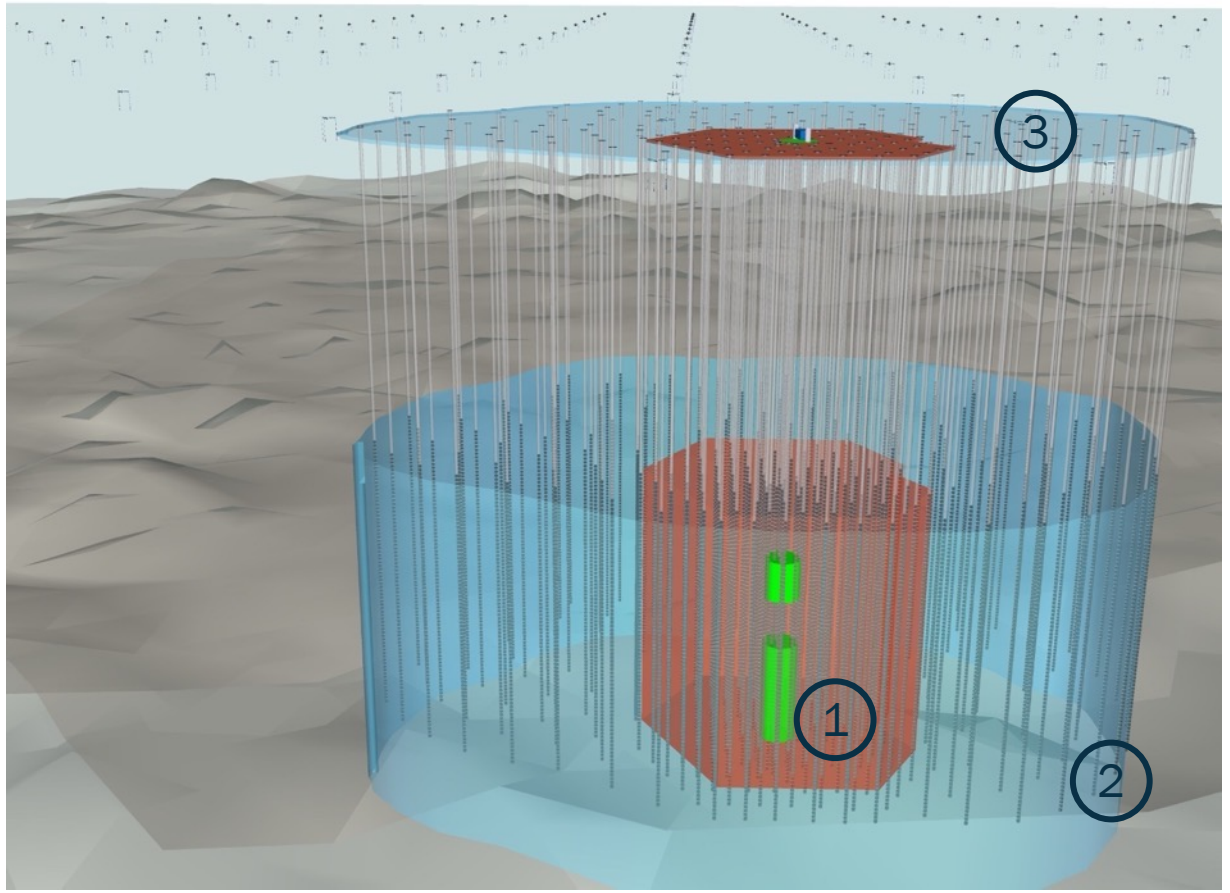
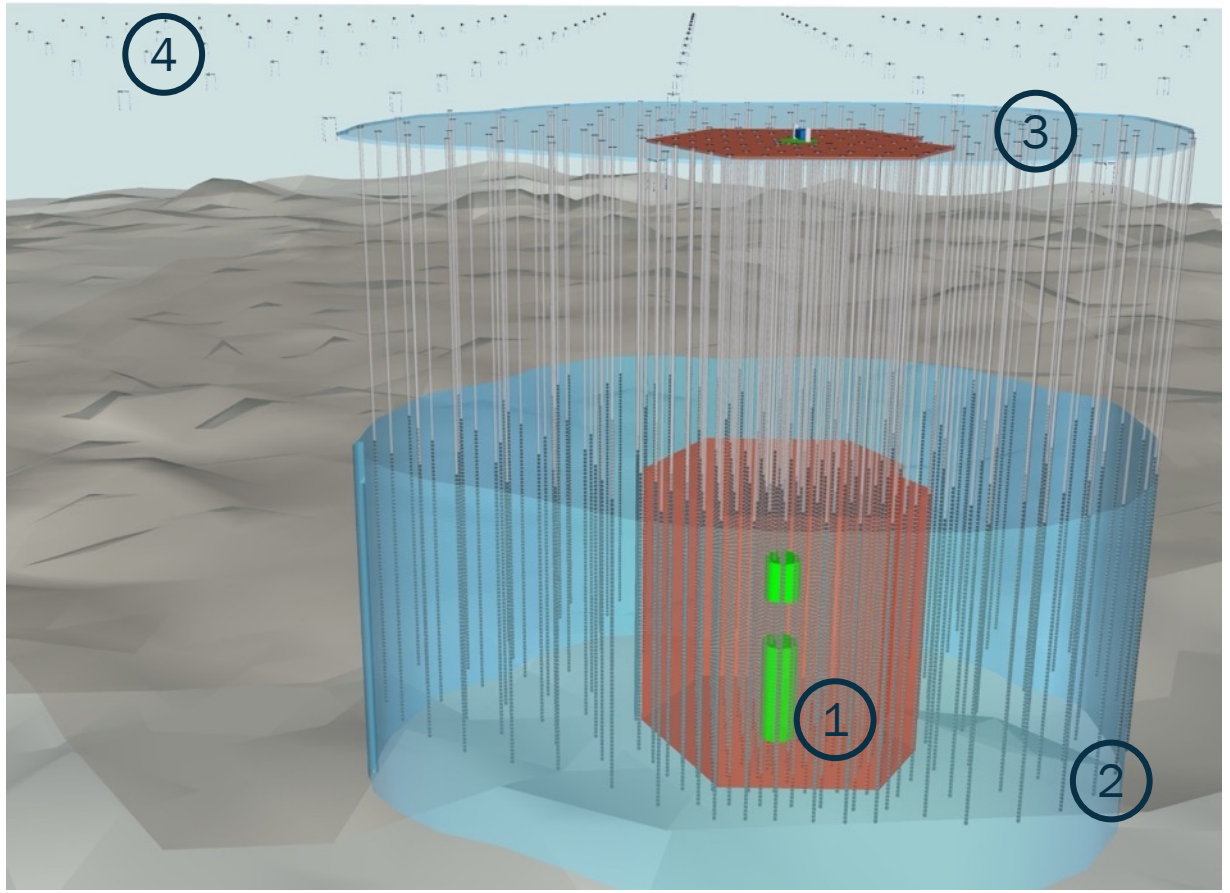
3. Surface array extension



# The Future: IceCube-Gen2

Four new elements

1. IceCube Upgrade
2. Enlarged deep optical array
3. Surface array extension
4. Shallow radio array

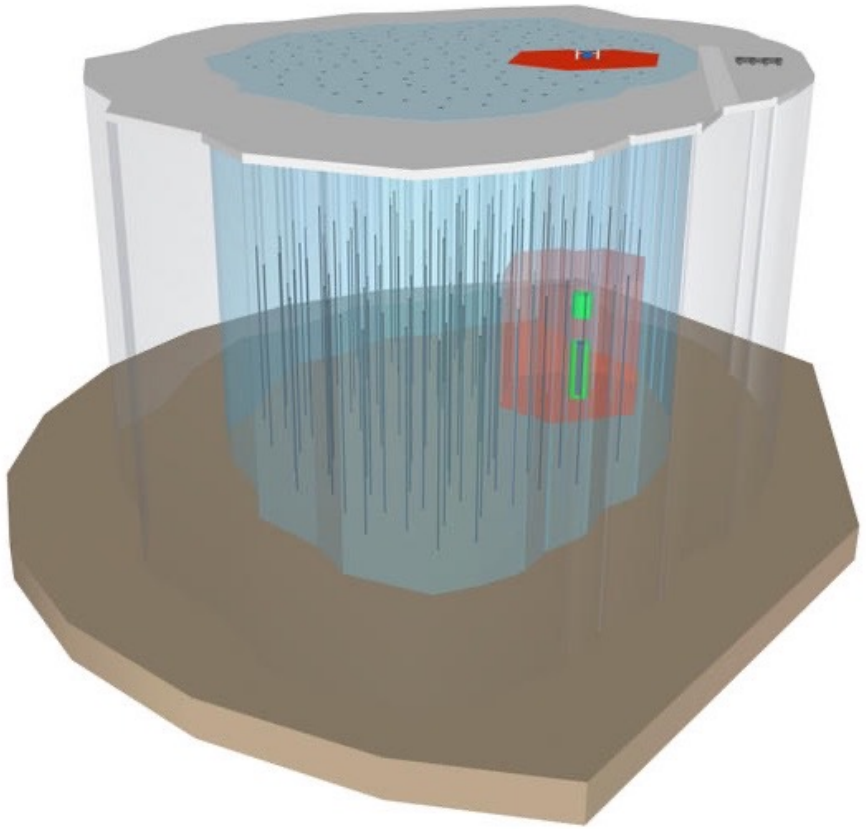


# IceCube-Gen2 Optical

~10x the contained volume of IceCube

5x the effective area

2x the angular resolution (on tracks)



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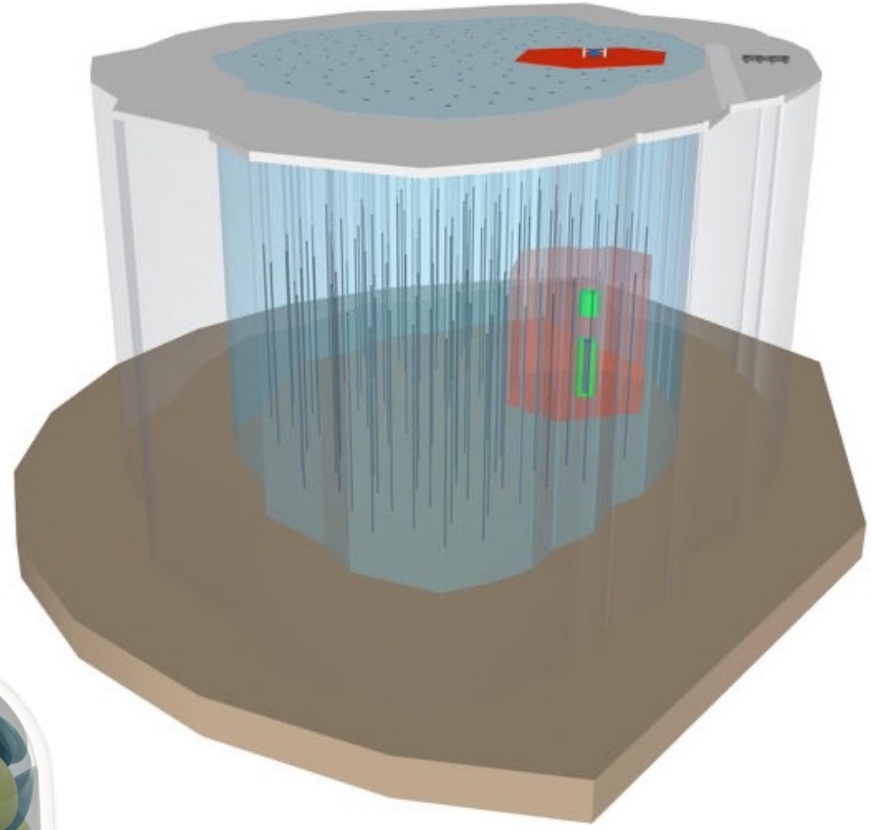
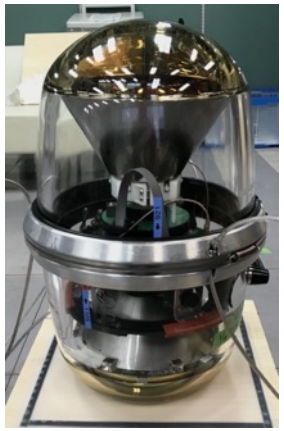


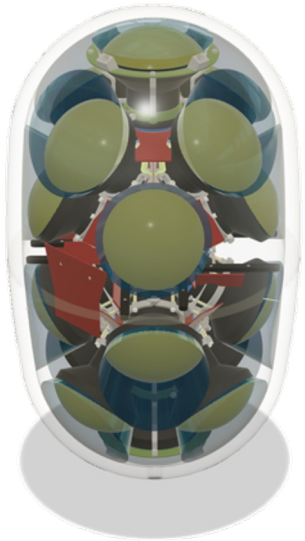


D-Egg

+

mDOM

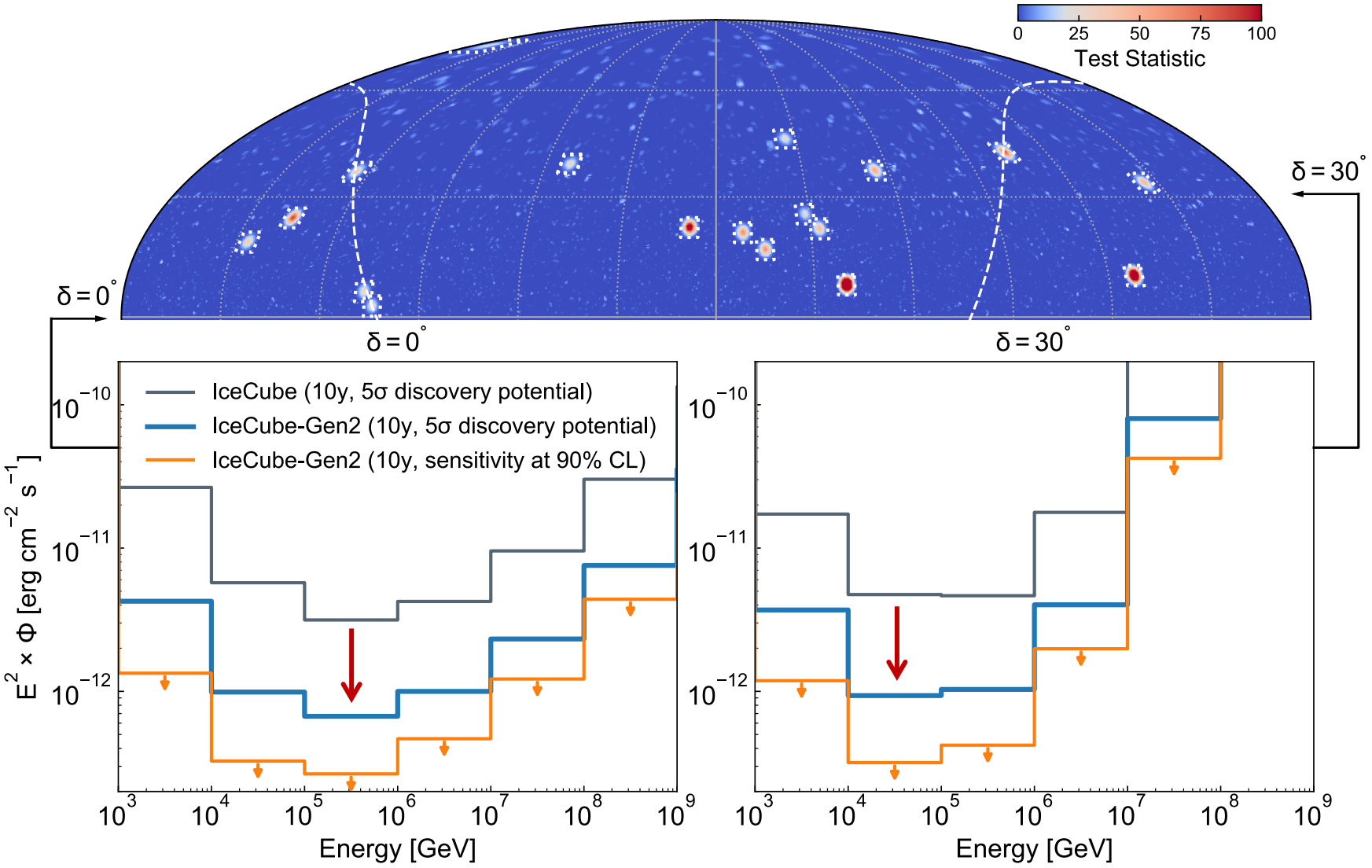
=



Gen2 DOM

Features new pixelated module, based on development work in the IceCube Upgrade

# Sensitive to sources 5x fainter than IceCube



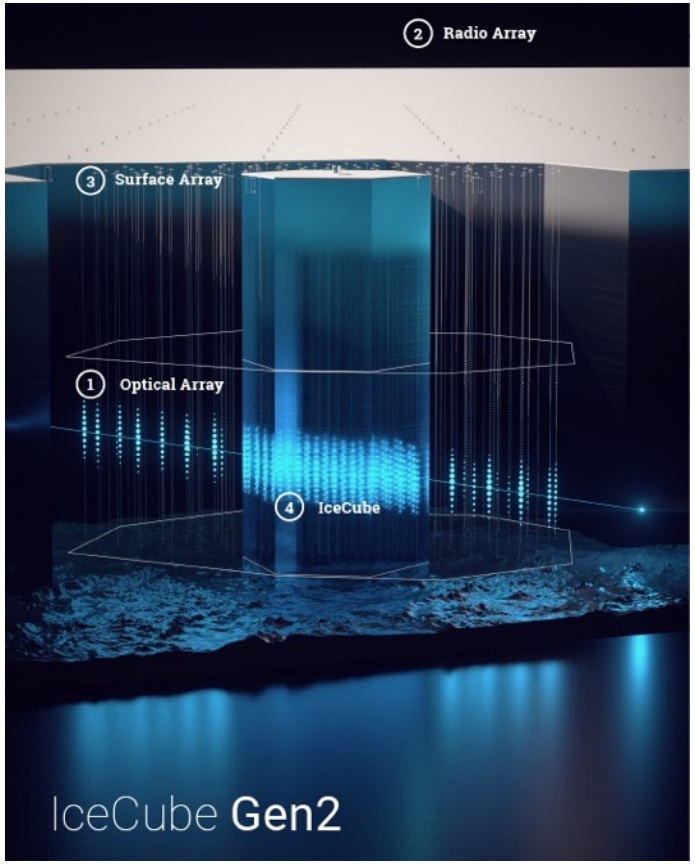
# Conclusions

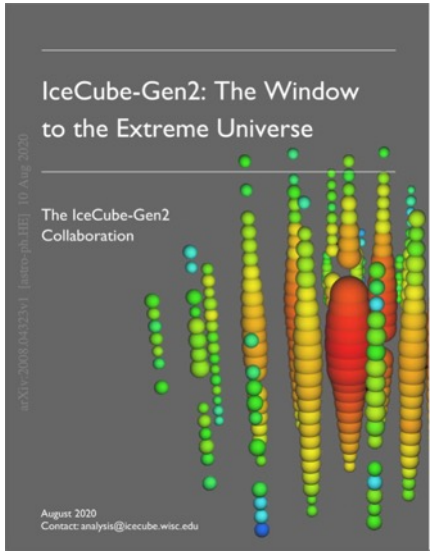
Neutrinos are unique messengers to the cosmos

Very exciting first decade w/ IceCube

- Discovery of high-energy neutrinos & identification of first potential sources
- Powerful probes of particle & neutrino physics
- World-leading sensitivity to BSM physics

Future is bright!




The presenter acknowledges support from the NSF through award 1903885.

J. Phys. G. 48 (2021) 6, 060501
arXiv 2008.04323

# Thank You!

*Questions?*

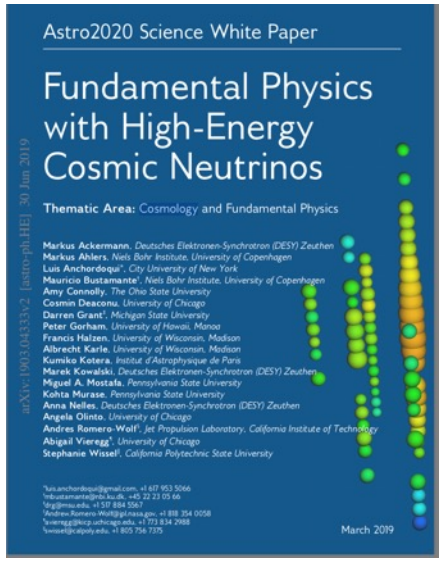
***”Where the telescope ends, the microscope begins. Which of the two has the grander view?”***

**—Victor Hugo**

# Backup

# Particle Physics

# Particle Physics




Astro 2020 White Paper
“Fundamental physics with High-Energy Cosmic Neutrinc
Ackerman et al. 1903.04333

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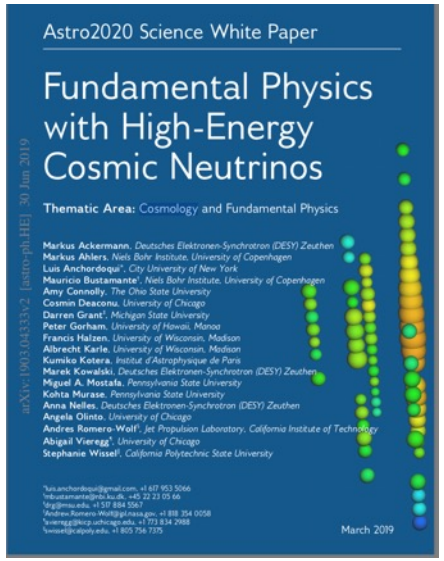


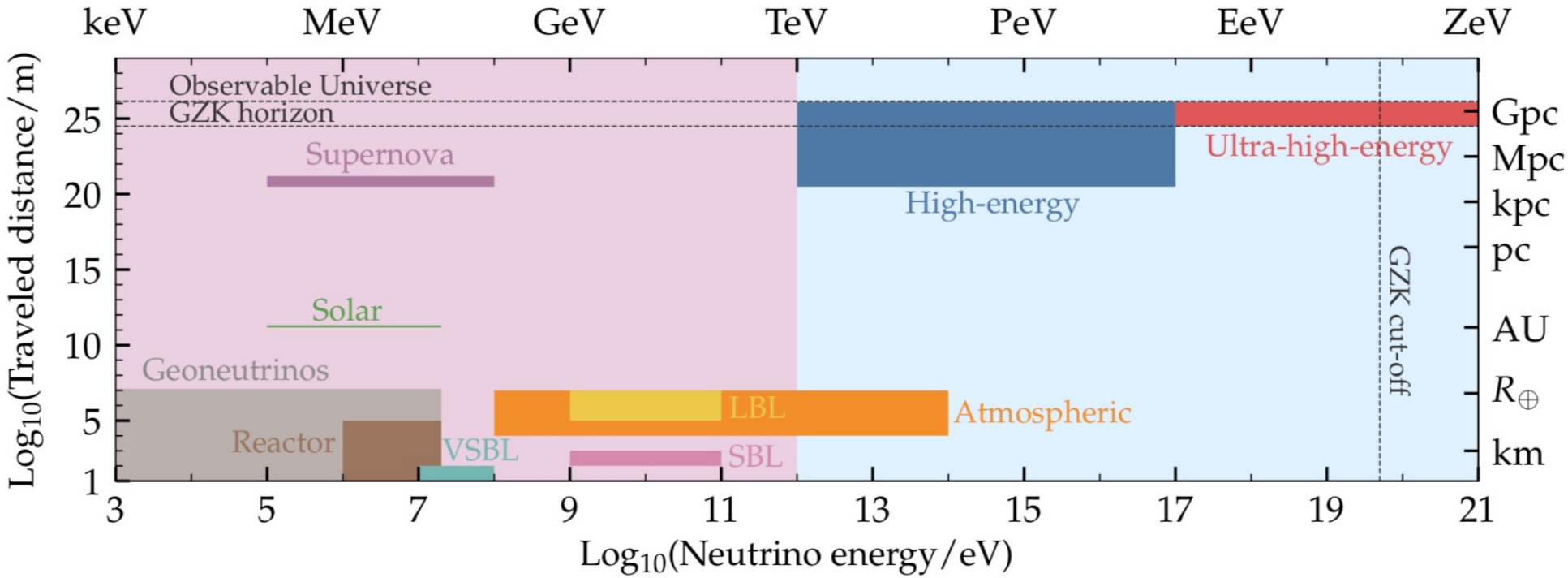


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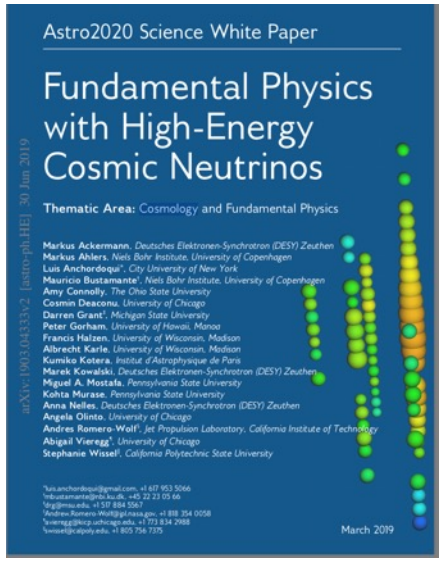


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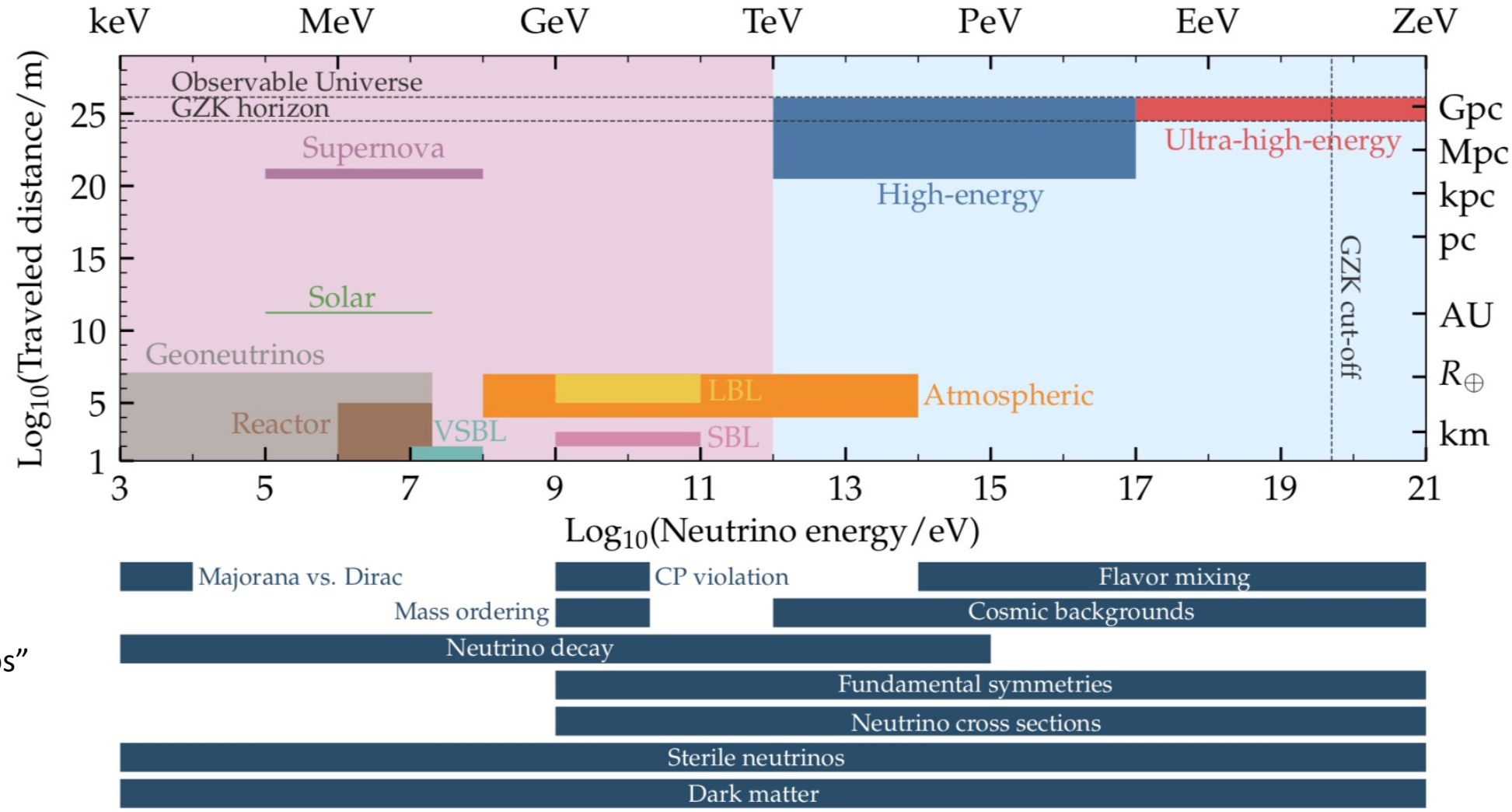
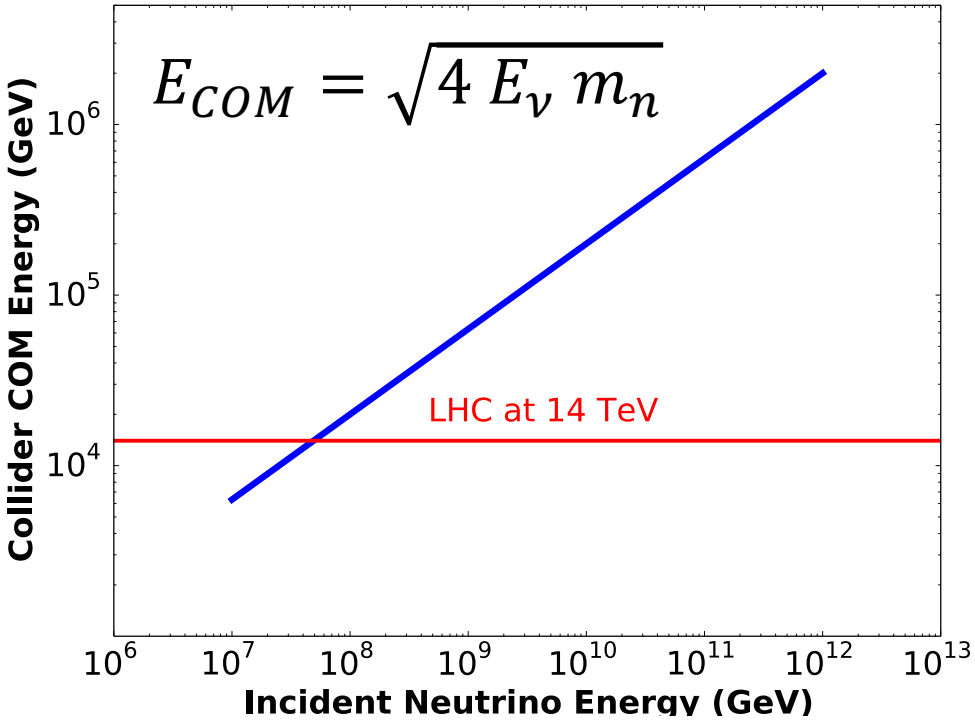
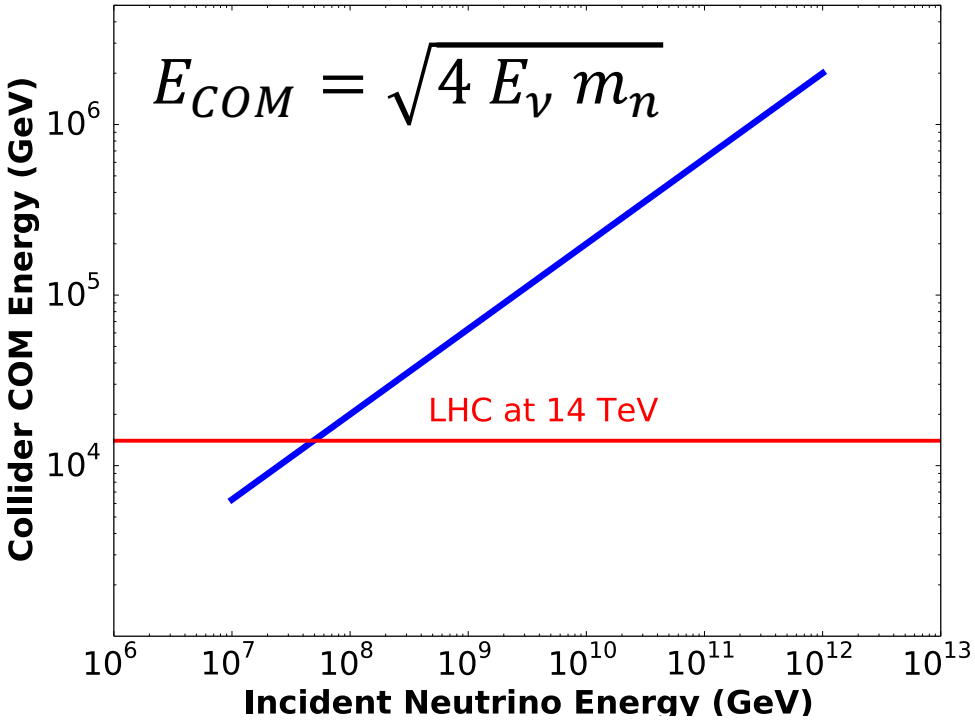


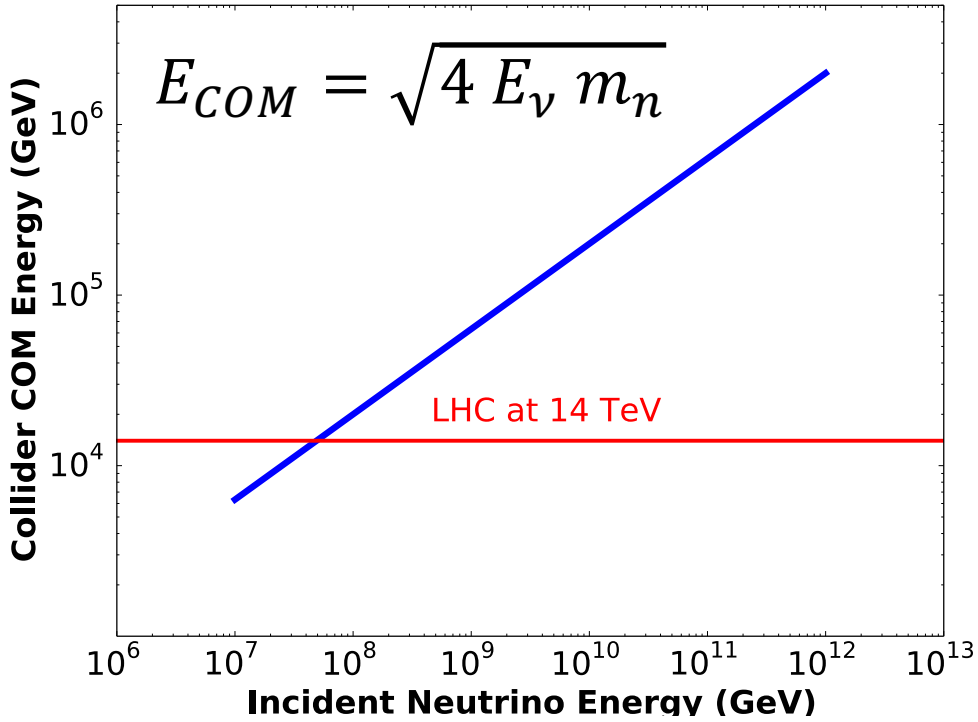

$E_{COM} = \sqrt{4\,E_\nu\,m_n}$
LHC at 14 TeV
Collider COM Energy (GeV)
$10^6$
$10^5$
$10^4$
$10^6$ $10^7$ $10^8$ $10^9$ $10^{10}$ $10^{11}$ $10^{12}$ $10^{13}$
Incident Neutrino Energy (GeV)

# Particle Physics



# Particle Physics

Probe cross-sections at energies above accelerators



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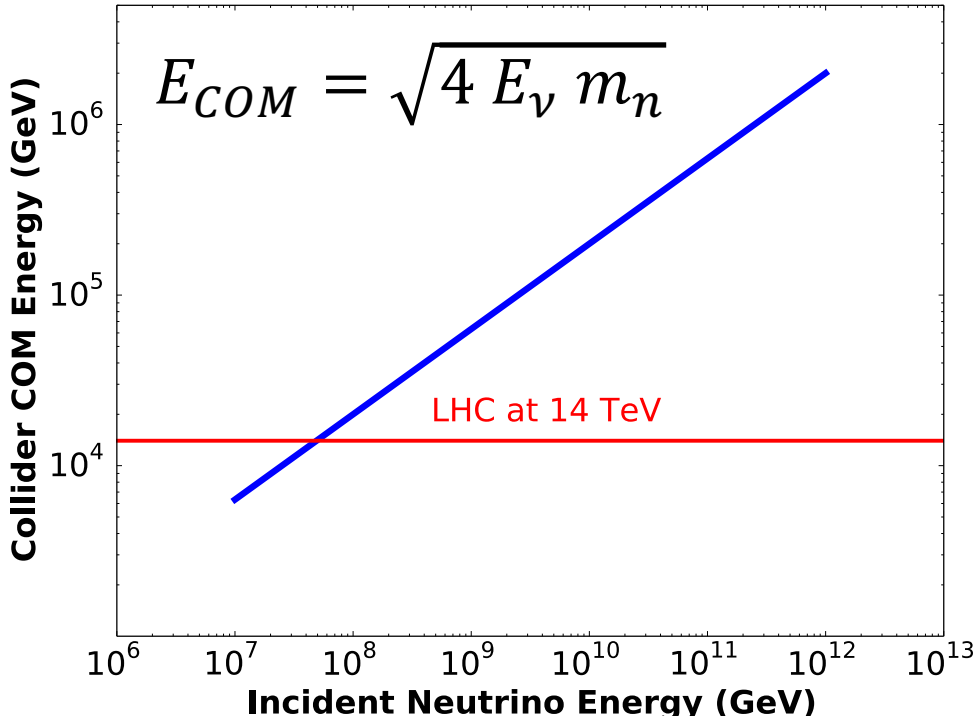
Probe cross-sections at energies above accelerators

Ex: An EeV ($10^{18}$ eV ) neutrino interacting in ice has COM energy of ~60 TeV (note: LHC  14 TeV)



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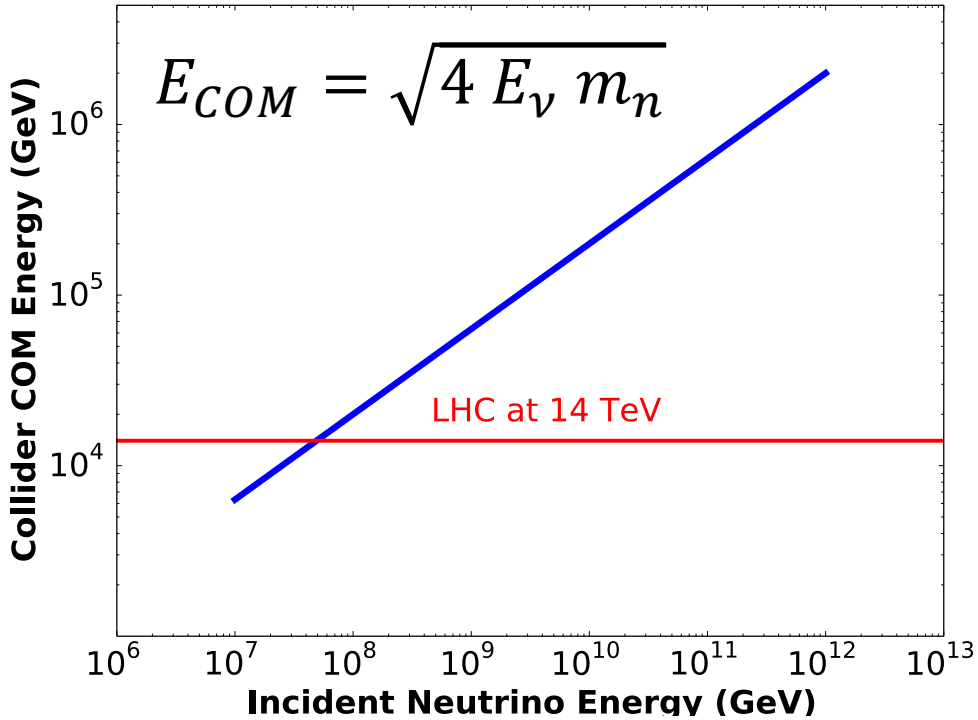
These are the highest energy leptons ever observed!



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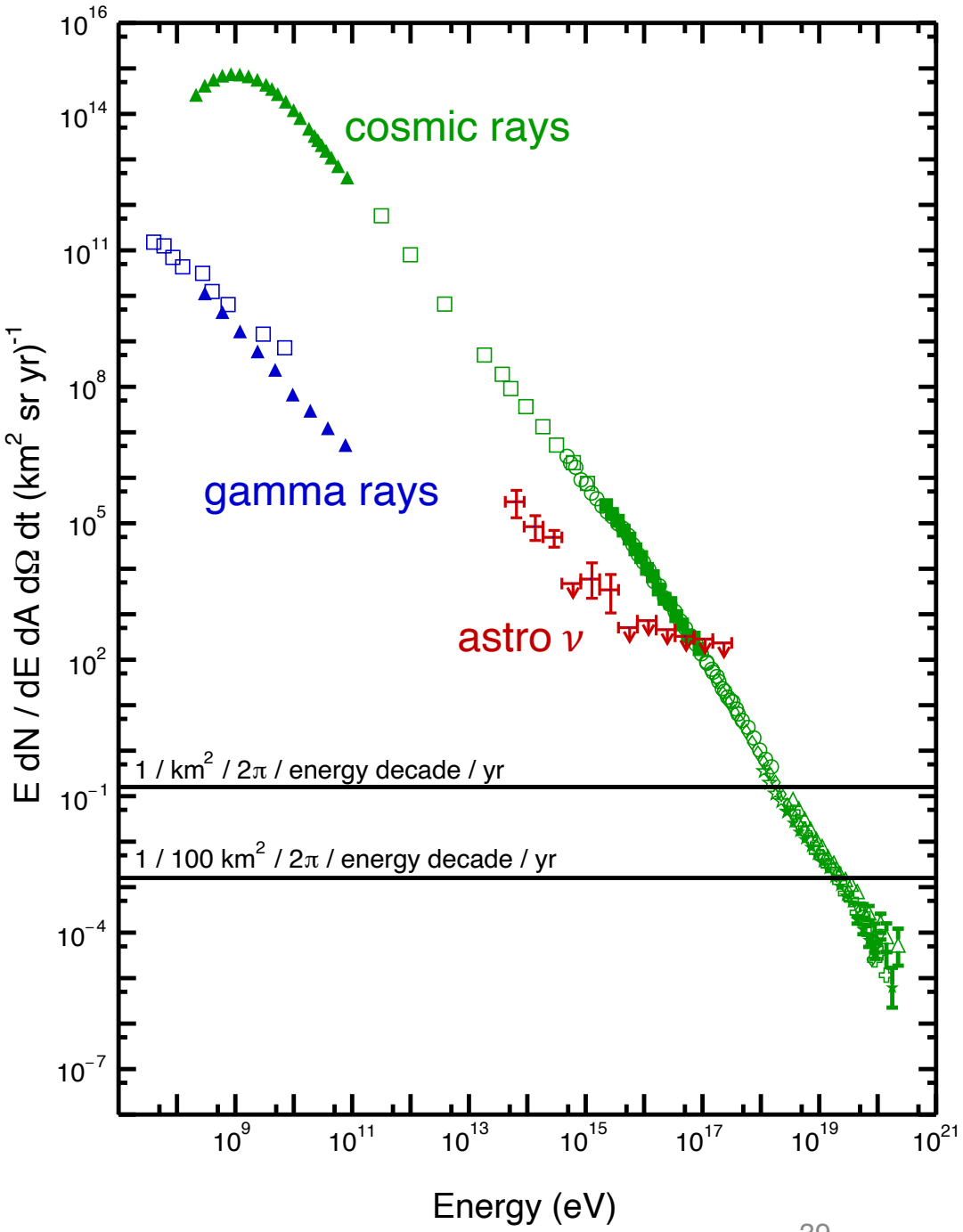

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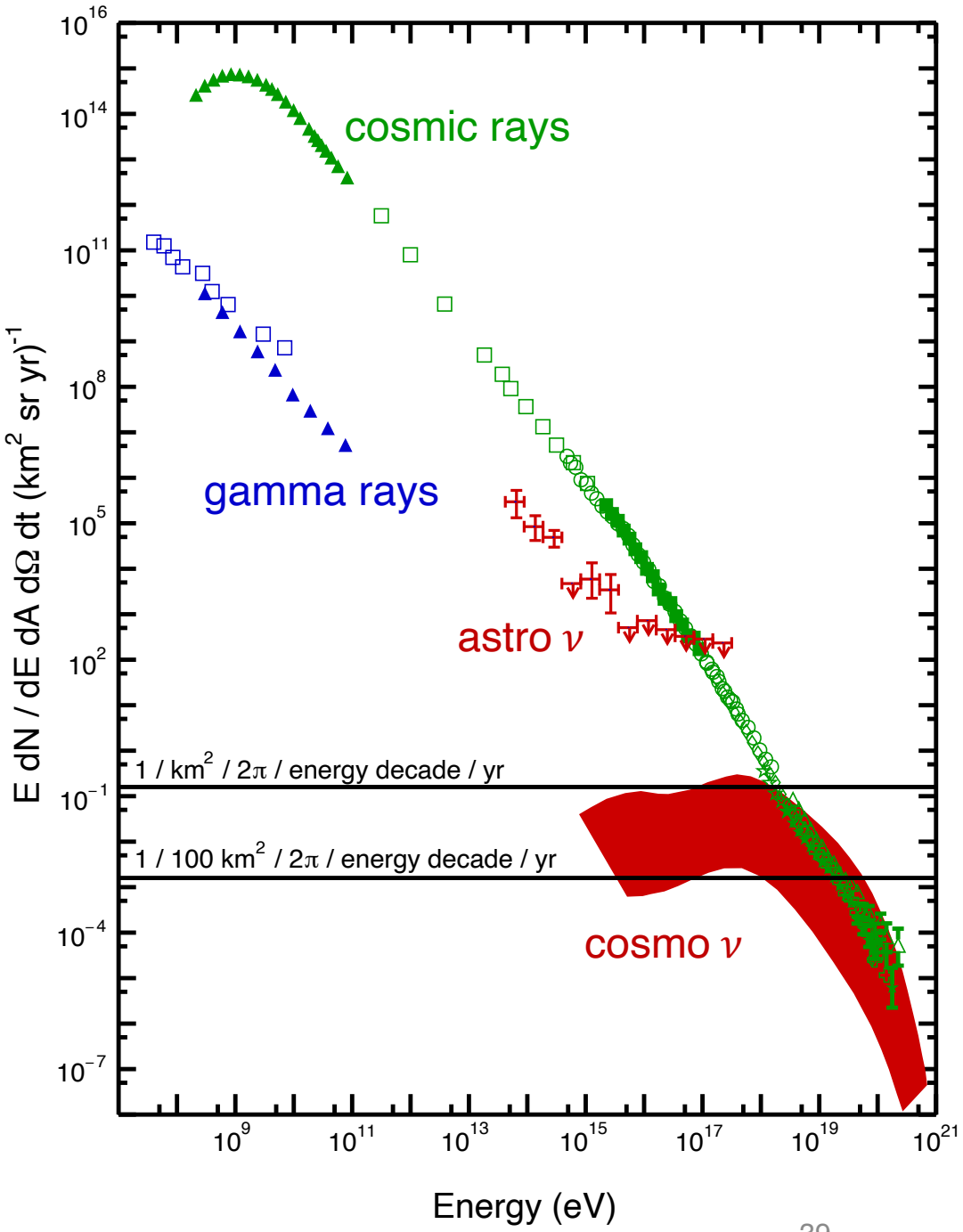

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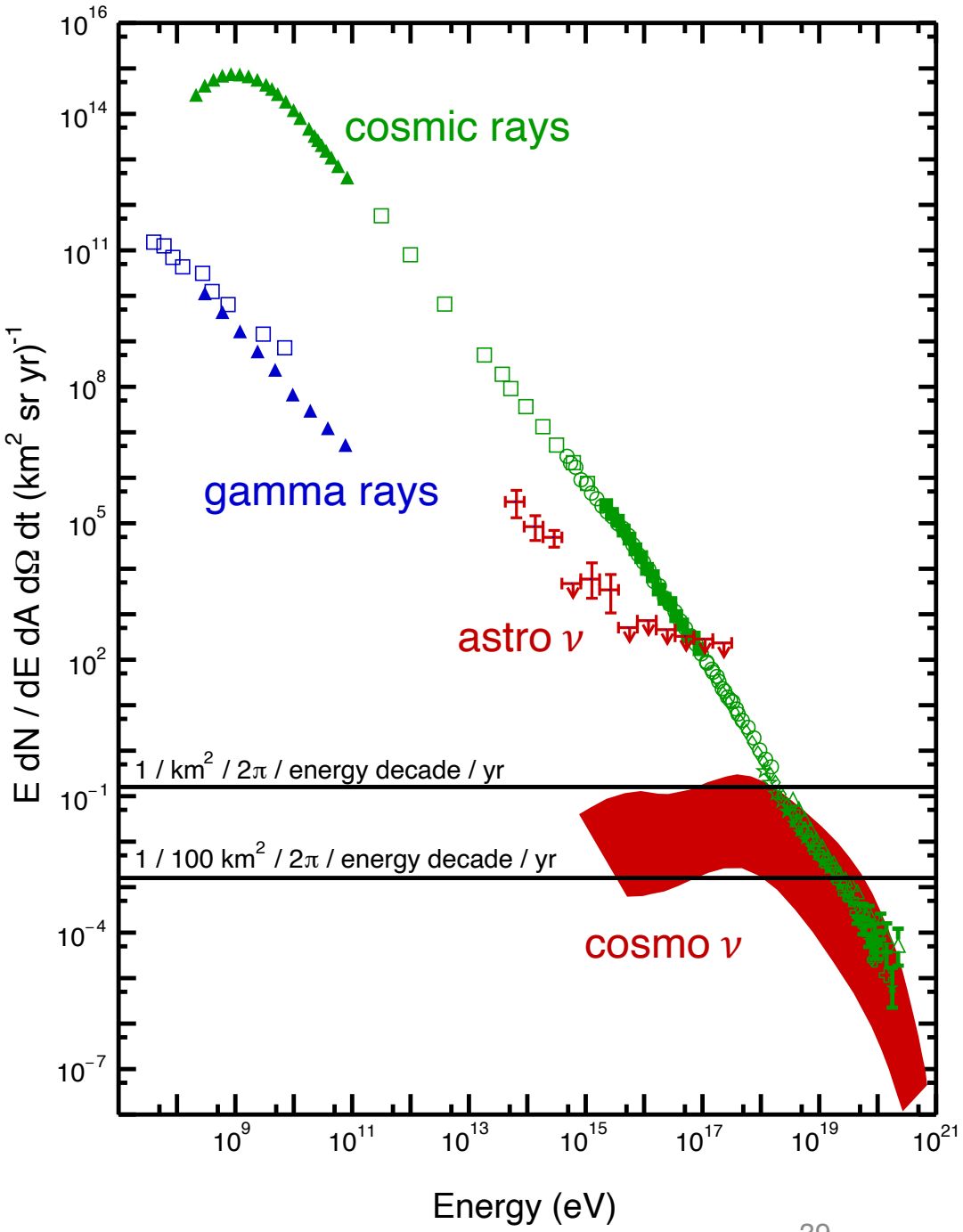

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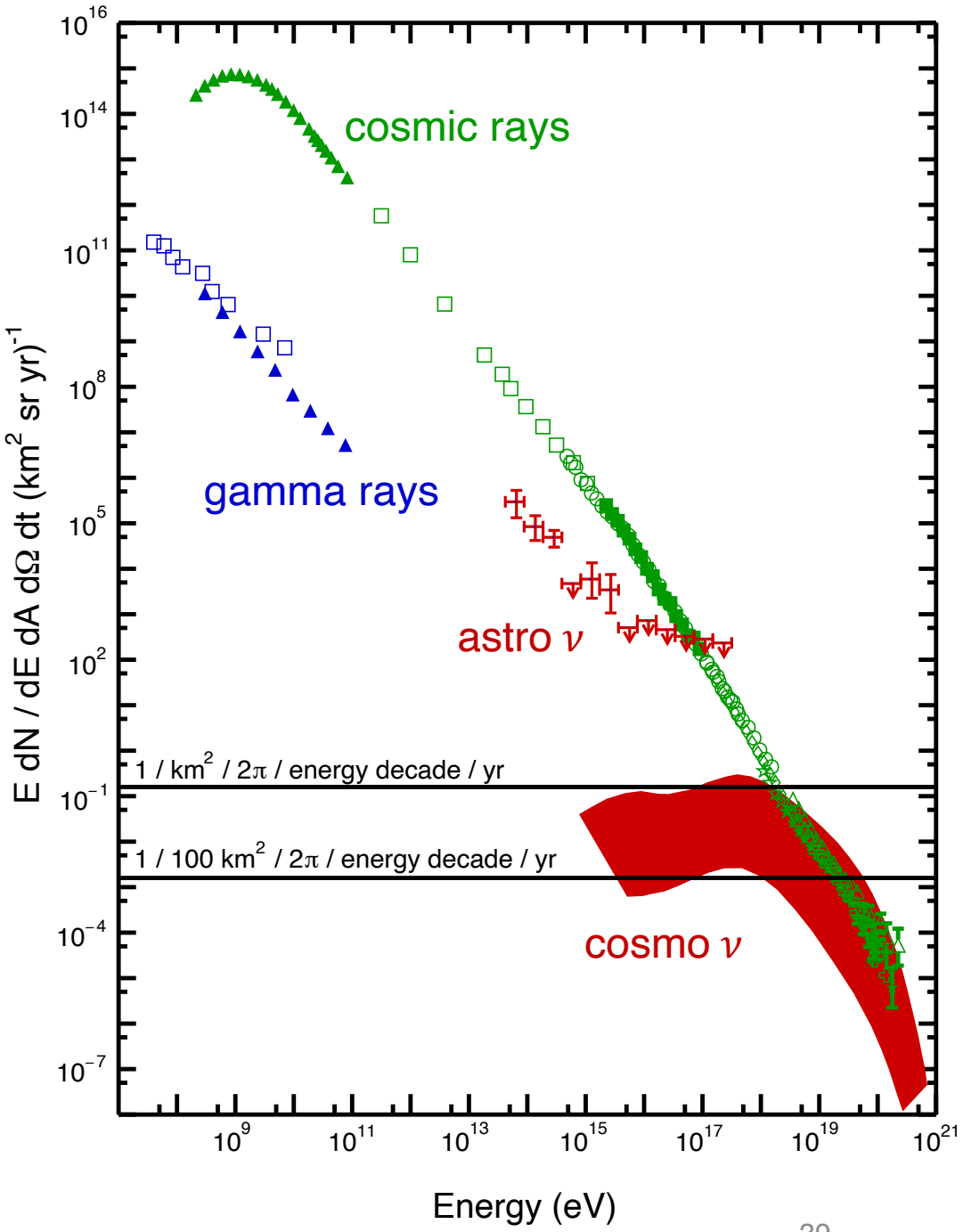

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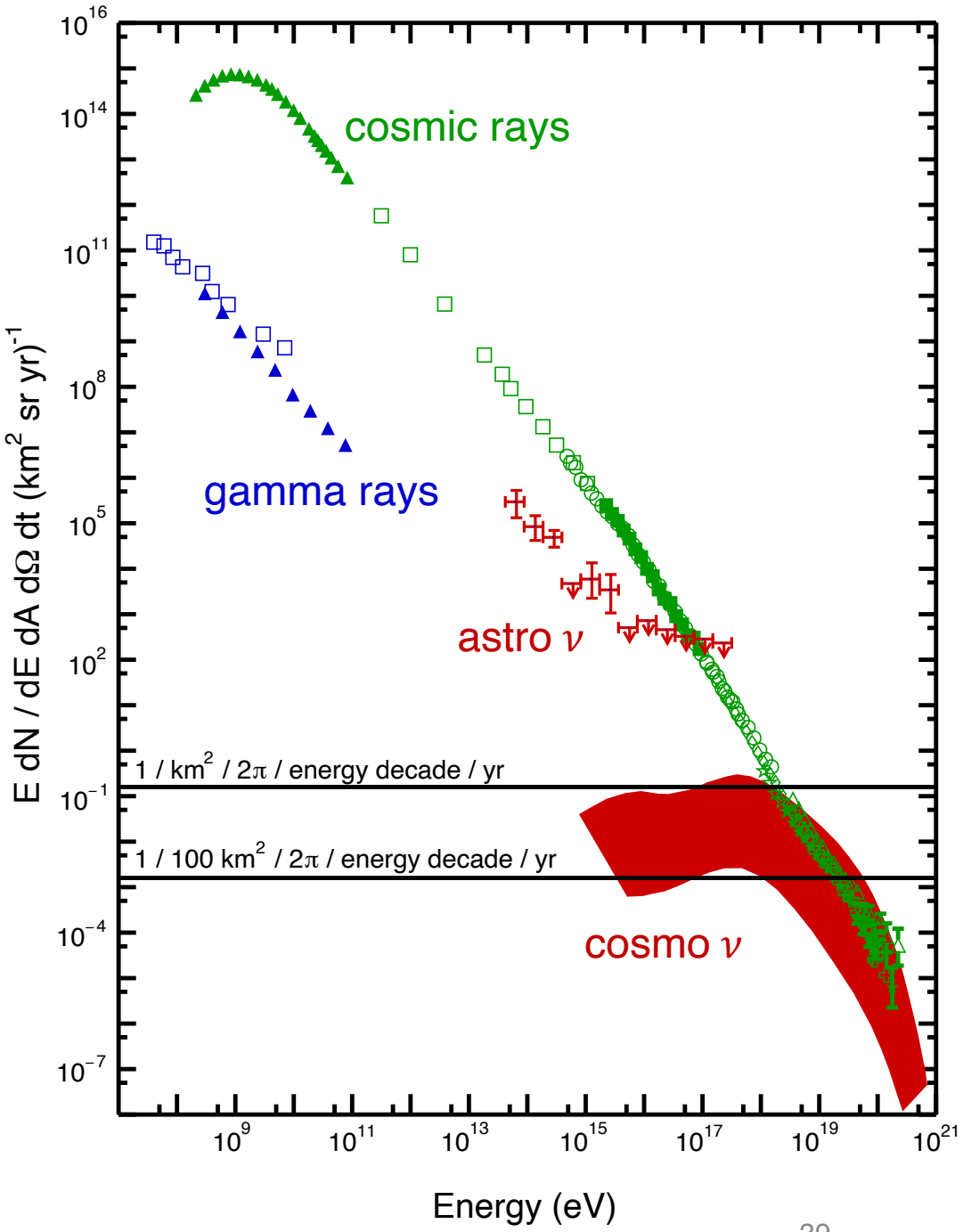

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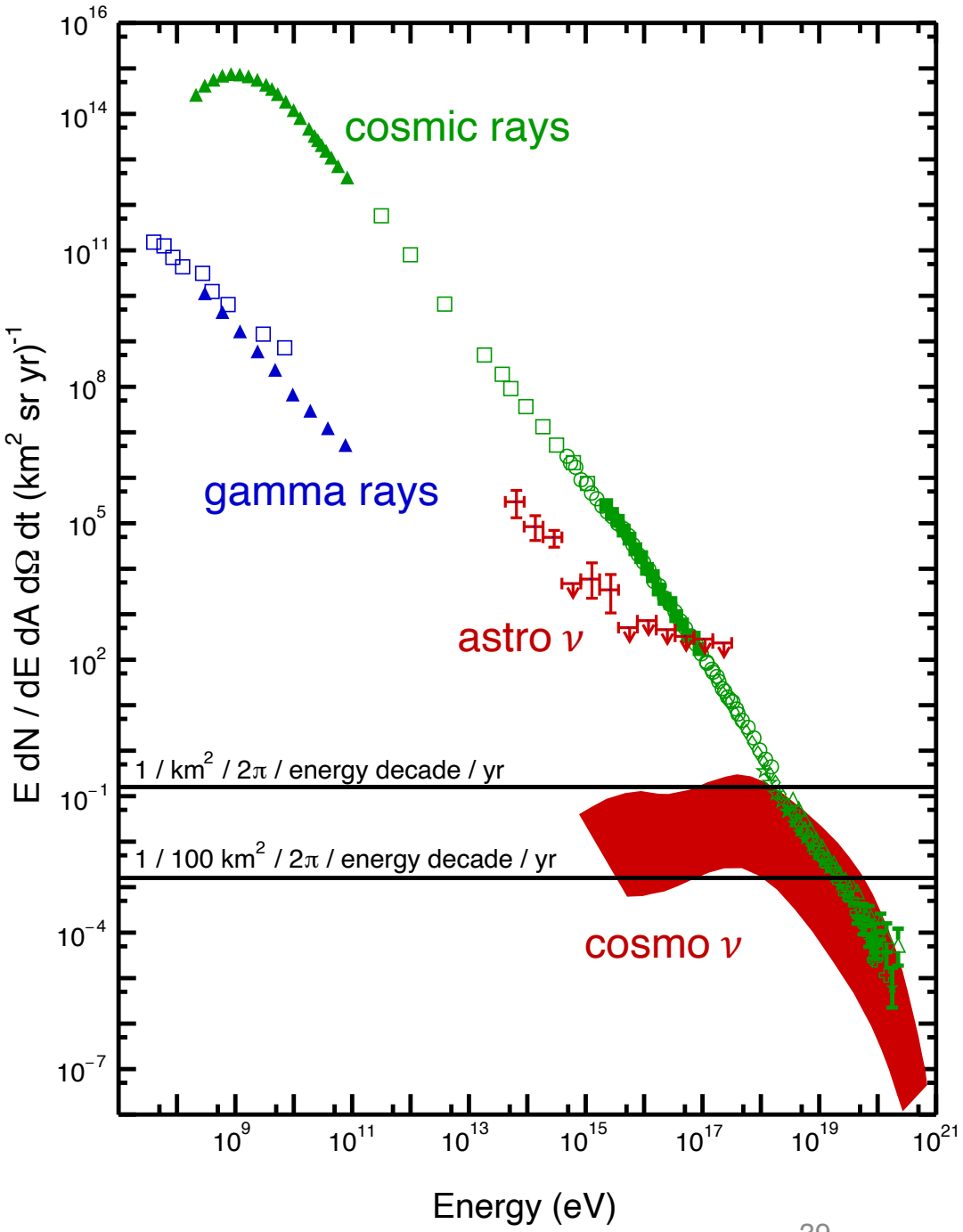
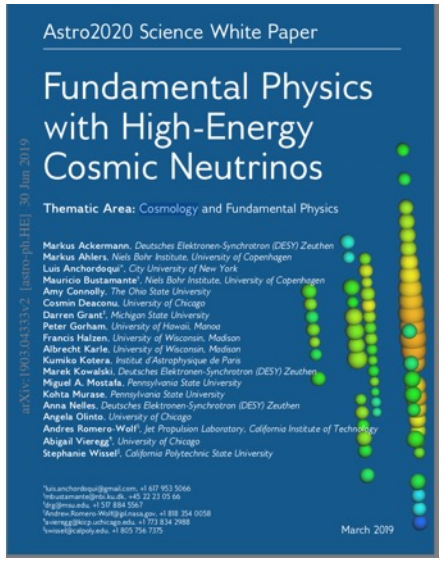
Undetected. But! Shape encodes important astrophysics:

- Maximum accelerating energy
- Source redshift evolution
- Cosmic ray composition



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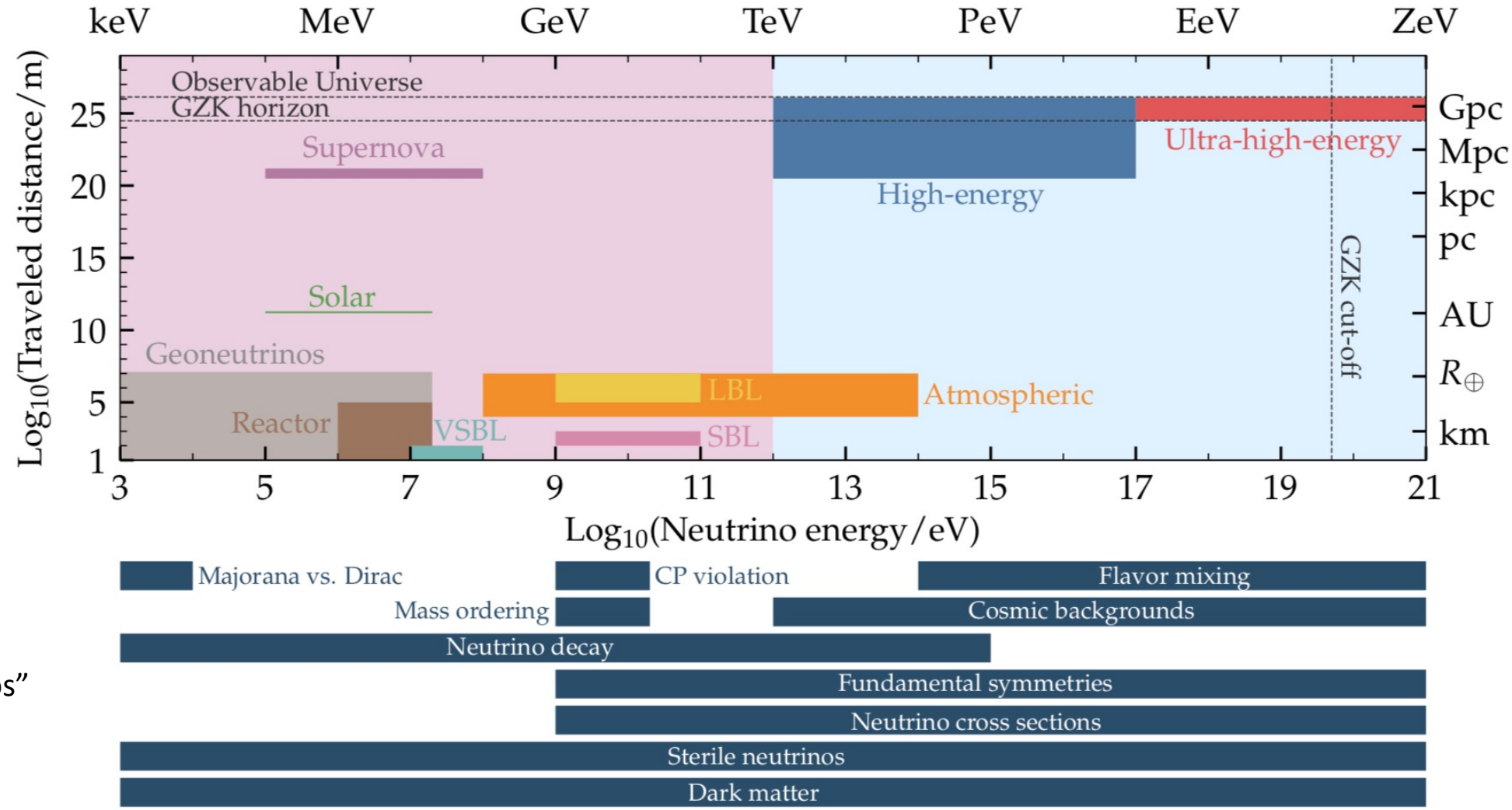


# Old Idea

M.A. Markov & I. M. Zheleznykh

In the papers by Zheleznykh and myself (1958, 1960) possibilities of experiments with cosmic ray neutrinos are analyzed. We have considered those neutrinos produced in the earth's atmosphere from pion decay. From the known $\mu$ spectrum the neutrino energy spectrum is reconstructed. We propose setting up apparatus in an underground lake or deep in the ocean in order to separate charged particle directions by Čerenkov radiation. We consider $\mu$ mesons

# Optical Cherenkov Effect

## “Photonic Sonic Boom”

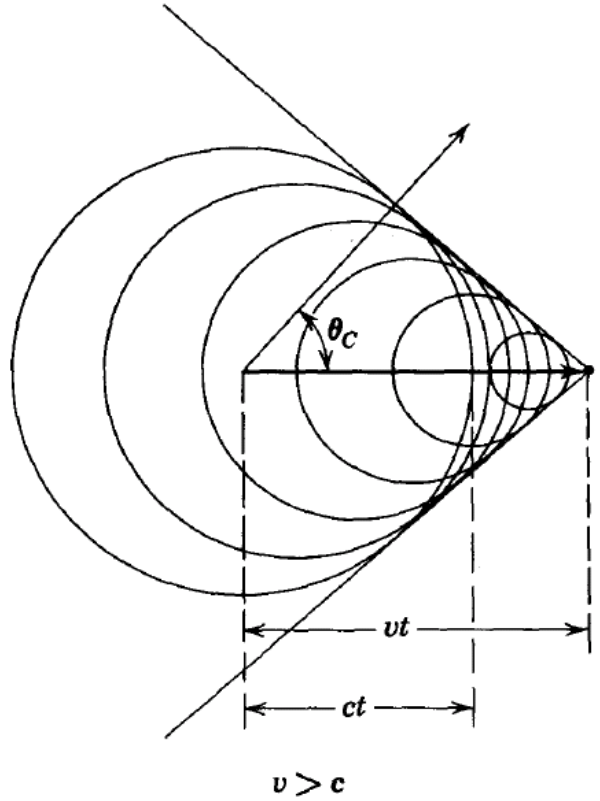
# Optical Cherenkov Effect

## “Photonic Sonic Boom”

A particle *outruns* its own electric field

# Optical Cherenkov Effect

## "Photonic Sonic Boom"

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# Optical Cherenkov Effect

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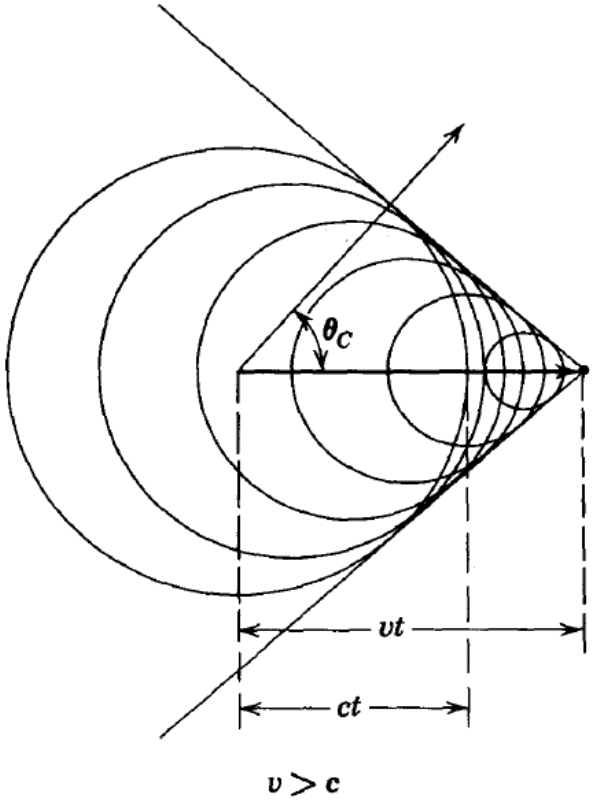



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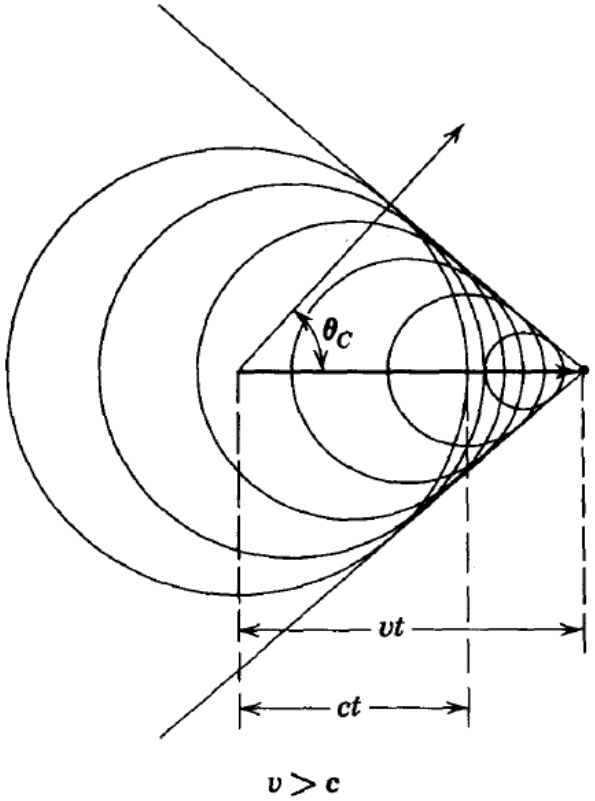


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Emitted at a characteristic angle ($\theta_C$), and has a distinctive blue and UV glow

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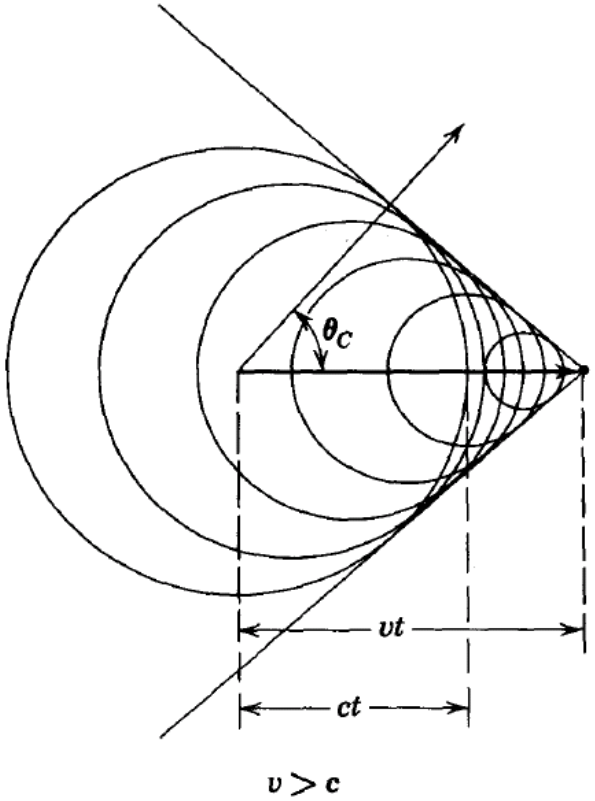


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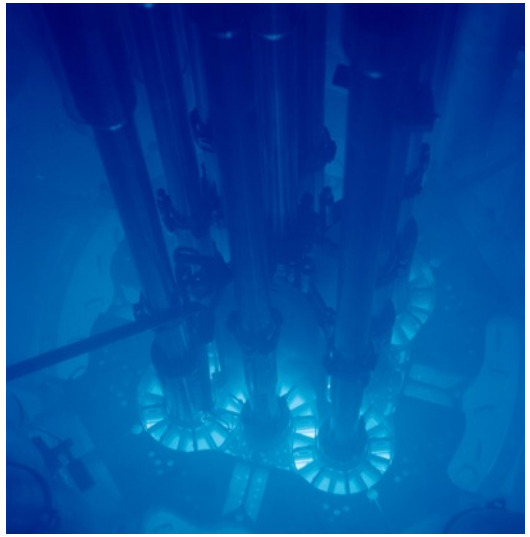
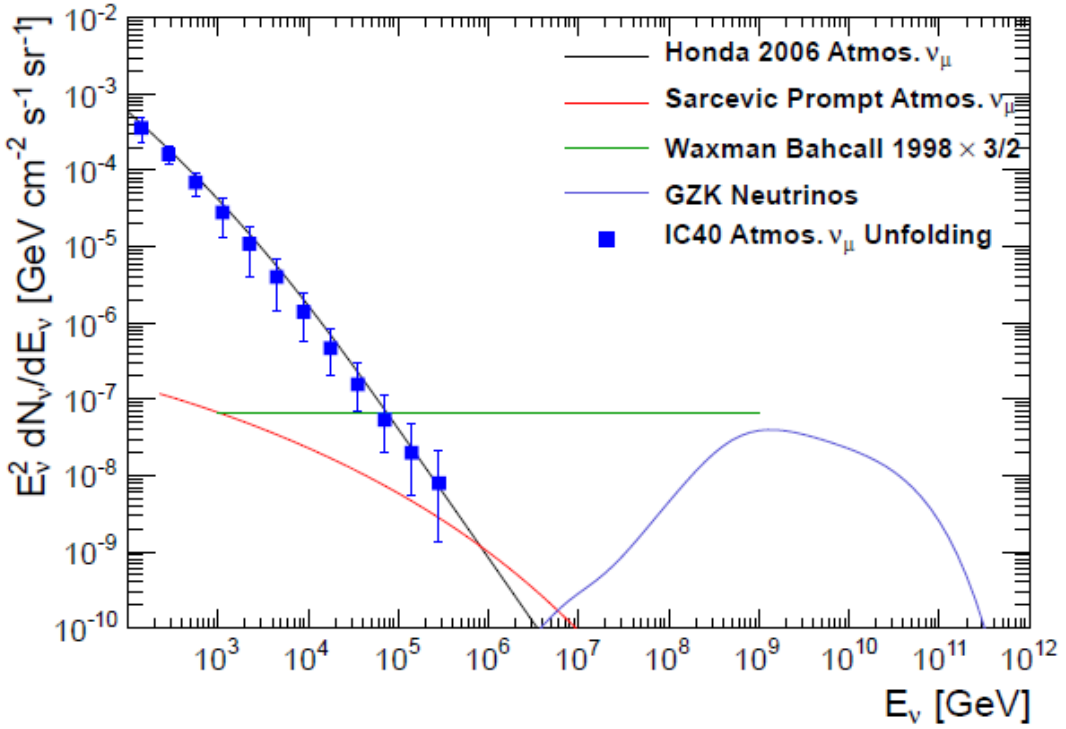


# Atmospheric Neutrinos




- $\pi/K$ Atmospheric Neutrinos (dominant $< 100$ TeV)
- Charm Atmospheric Neutrinos ("prompt", $\sim 100$ TeV)
- Astrophysical Neutrinos (maybe dominant $> 100$ TeV)
- Cosmogenic Neutrinos ($> 10^6$ TeV)

N. Whitehorn. UW Madison

IceCube Collaboration meeting in Brussels, May 19 2022

# THE ICECUBE COLLABORATION

**AUSTRALIA**
University of Adelaide

**BELGIUM**
UCLouvain
Université libre de Bruxelles
Universiteit Gent
Vrije Universiteit Brussel

**CANADA**
SNOLAB
University of Alberta–Edmonton

**DENMARK**
University of Copenhagen

**GERMANY**
Deutsches Elektronen-Synchrotron
ECAP, Universität Erlangen-Nürnberg
Humboldt–Universität zu Berlin
Karlsruhe Institute of Technology
Ruhr-Universität Bochum
RWTH Aachen University
Technische Universität Dortmund
Technische Universität München
Universität Mainz
Universität Wuppertal
Westfälische Wilhelms-Universität Münster

**ITALY**
University of Padova

**JAPAN**
Chiba University

**NEW ZEALAND**
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Michigan State University
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Pennsylvania State University
South Dakota School of Mines and Technology
Southern University and A&M College
Stony Brook University
University of Alabama
University of Alaska Anchorage
University of California, Berkeley
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University of Delaware
University of Kansas
University of Maryland
University of Rochester
University of Texas at Arlington
University of Utah
University of Wisconsin–Madison
University of Wisconsin–River Falls
Yale University


FUNDING AGENCIES

Fonds de la Recherche Scientifique (FRS-FNRS)
Fonds Wetenschappelijk Onderzoek-Vlaanderen (FWO-Vlaanderen)
Federal Ministry of Education and Research (BMBF)
German Research Foundation (DFG)
Deutsches Elektronen-Synchrotron (DESY)
Japan Society for the Promotion of Science (JSPS)
Knut and Alice Wallenberg Foundation
Swedish Polar Research Secretariat
The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)


IceCube
South Pole Neutrino Observatory

icecube.wisc.edu

# Astronνmy

## First Neutrino Source (2017)

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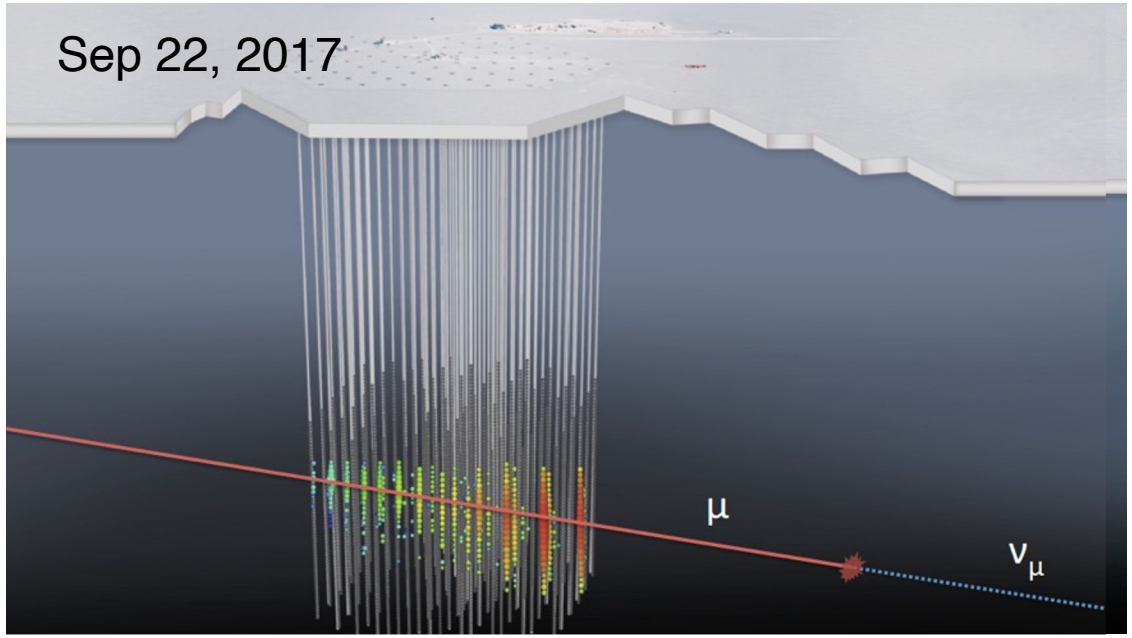

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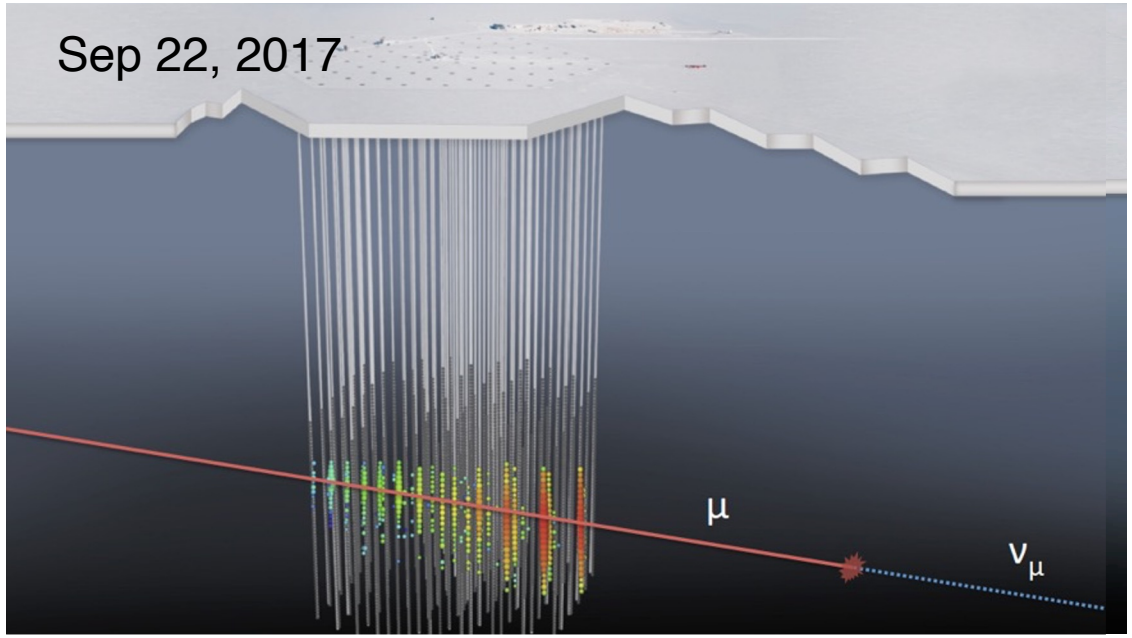
## First Neutrino Source (2017)

290 TeV neutrino observed in coincidence with flaring blazar (~3$\sigma$)



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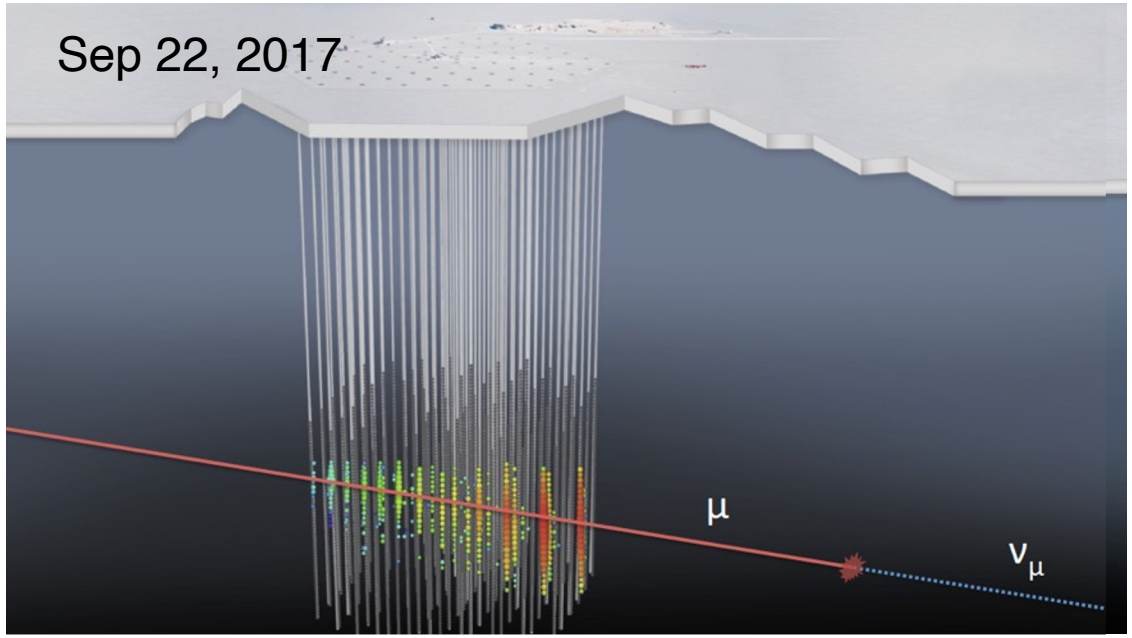
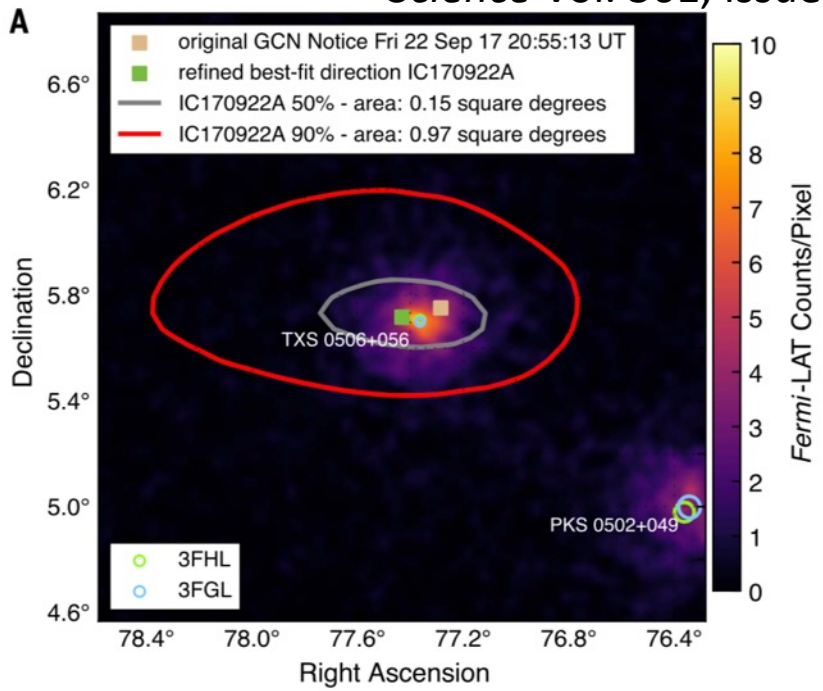



*Science* Vol. 361, Issue 6398



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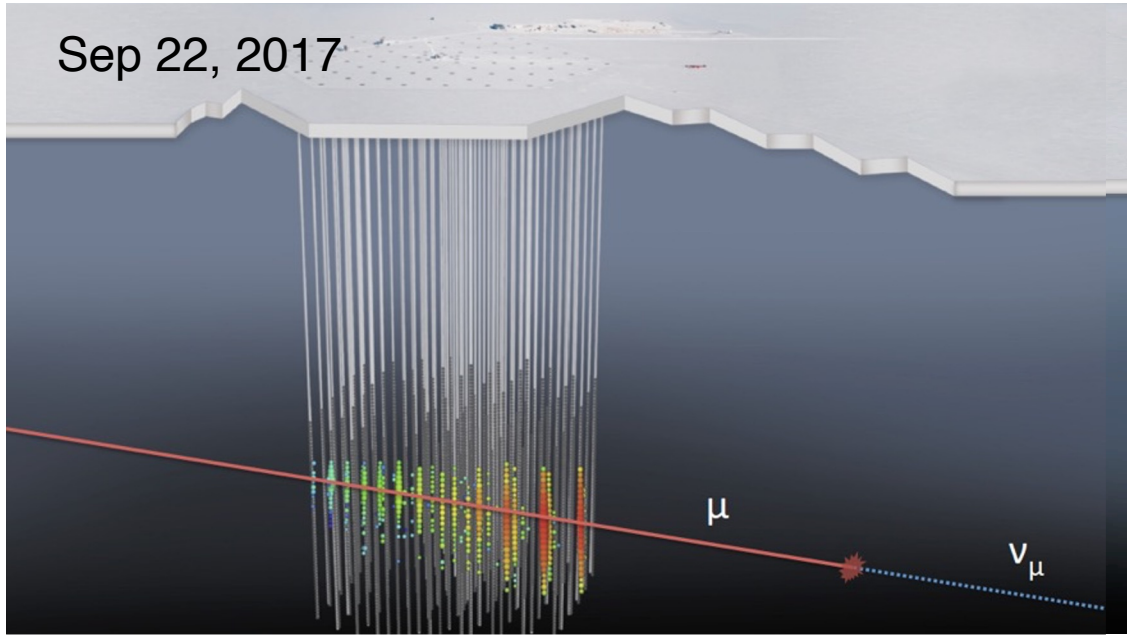
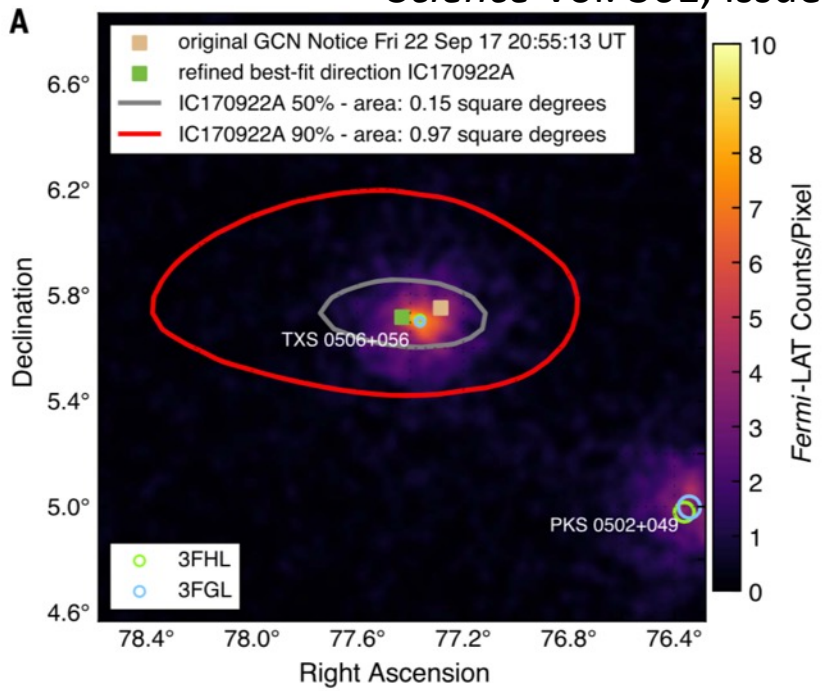
290 TeV neutrino observed in coincidence with flaring blazar (~3$\sigma$)

Archival search reveals additional 3.5$\sigma$ excess




*Science* Vol. 361, Issue 6398

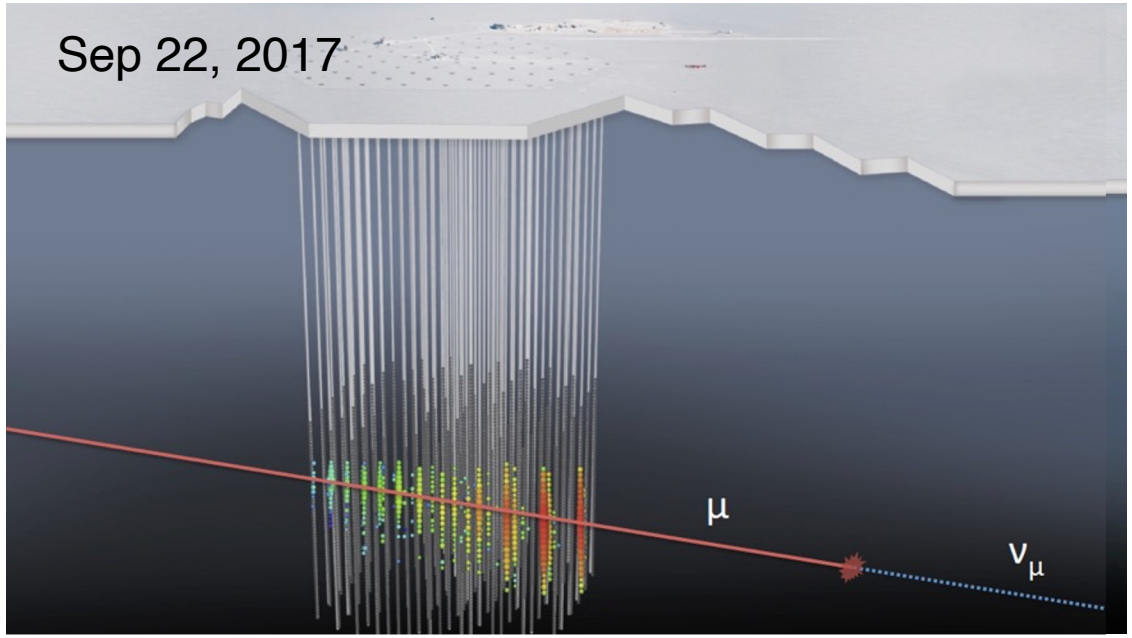


# Astronνmy

## First Neutrino Source (2017)

290 TeV neutrino observed in coincidence with flaring blazar (~3$\sigma$)

Archival search reveals additional 3.5$\sigma$ excess

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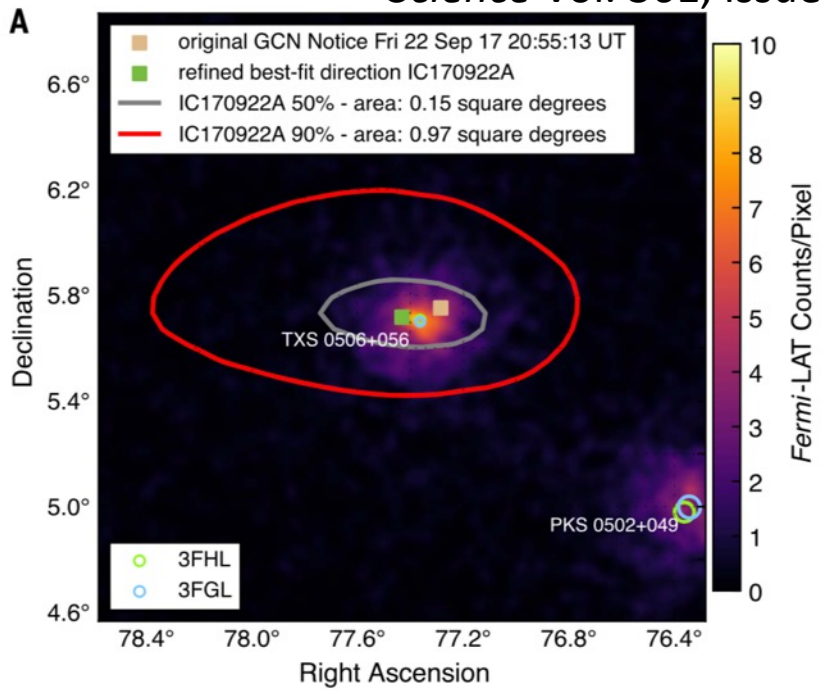
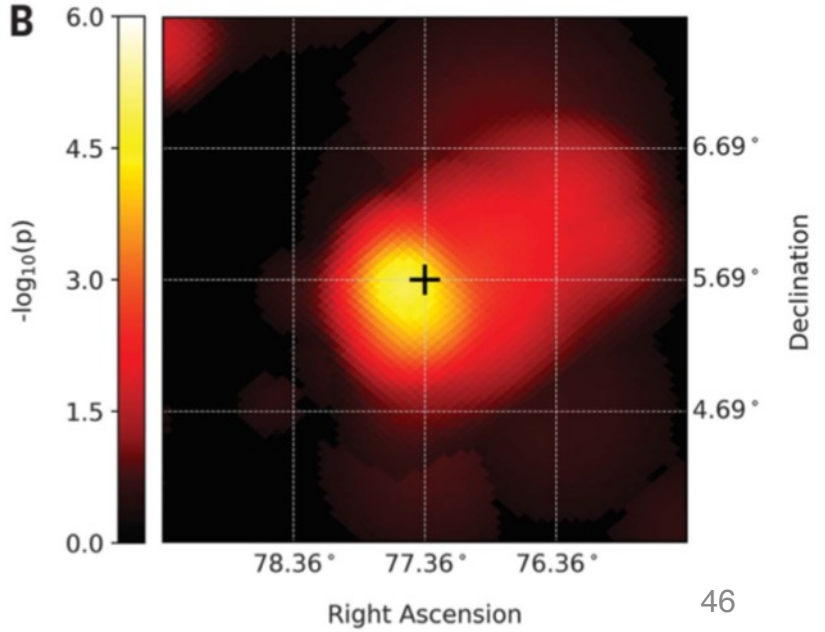


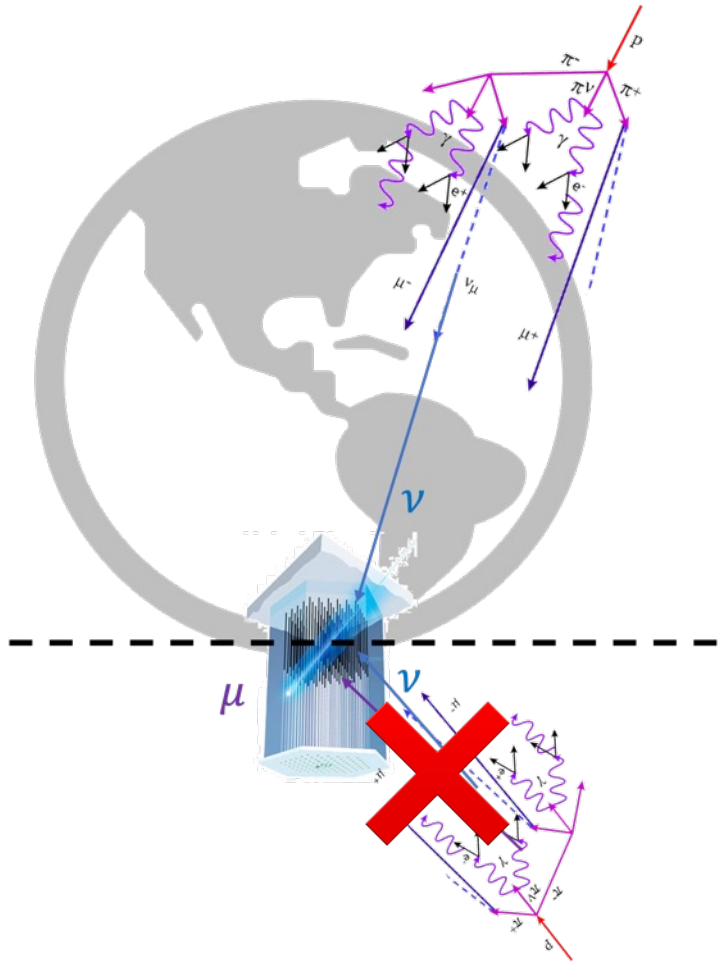



# Astrophysical Neutrino Searches

For astrophysical neutrino searches, atmospherics are a background

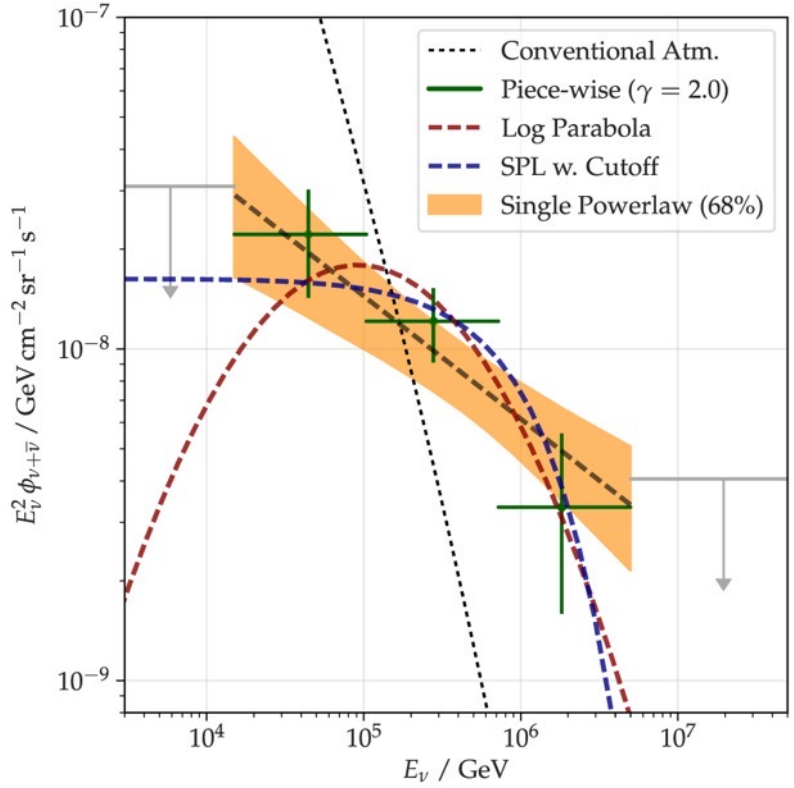
One strategy: look for **upgoing** events

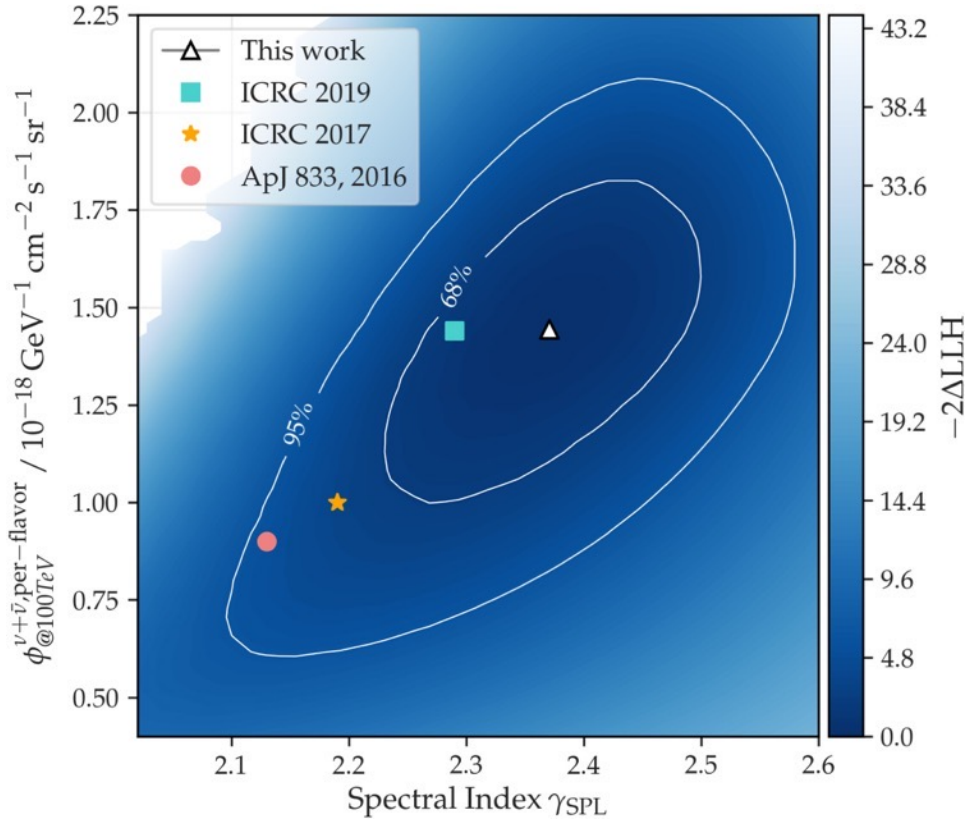
Uses the Earth as a shield to atmospheric muons



# Upgoing Track Selection

$$= 2.37 \pm 0.09$$

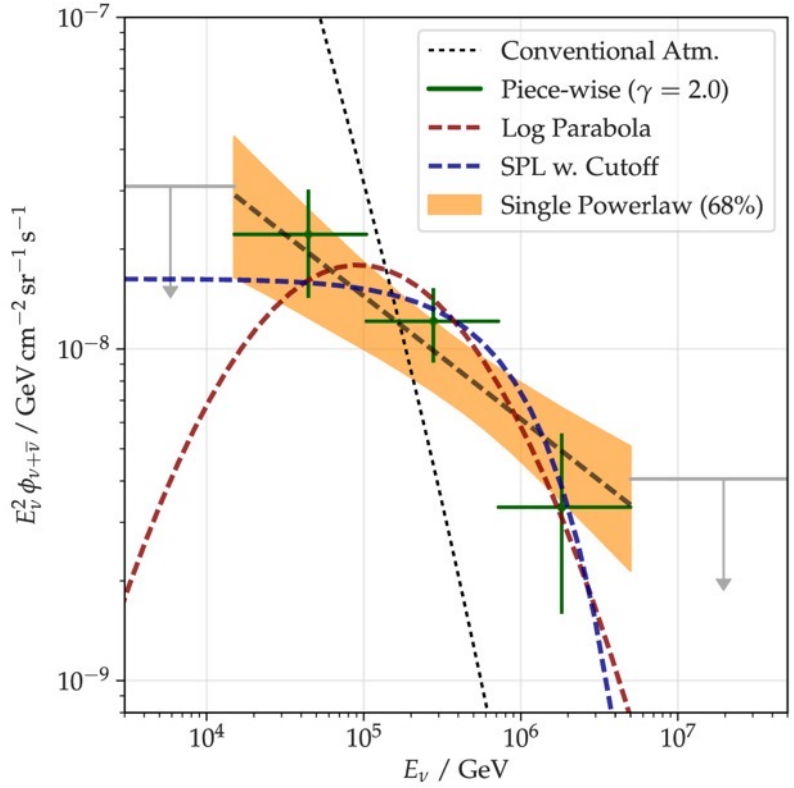


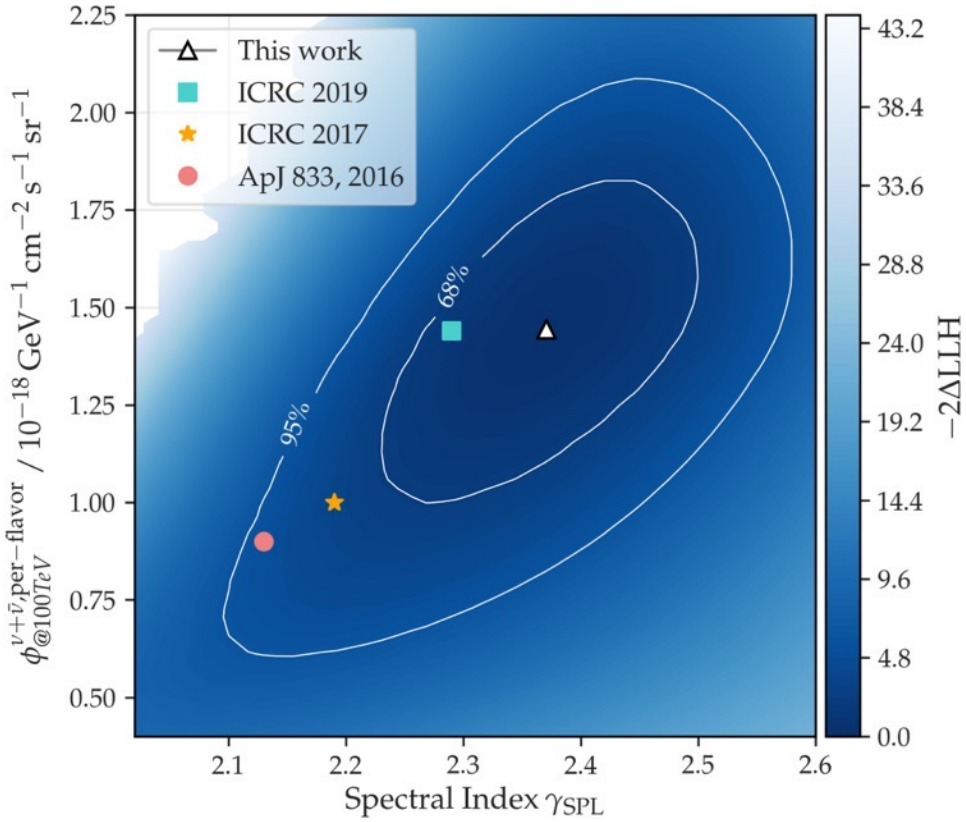

ApJ 928 50, 2022
(arxiv 2111.10299)

# Upgoing Track Selection

$= 2.37 \pm 0.09$




Softer, but still consistent with, previous results

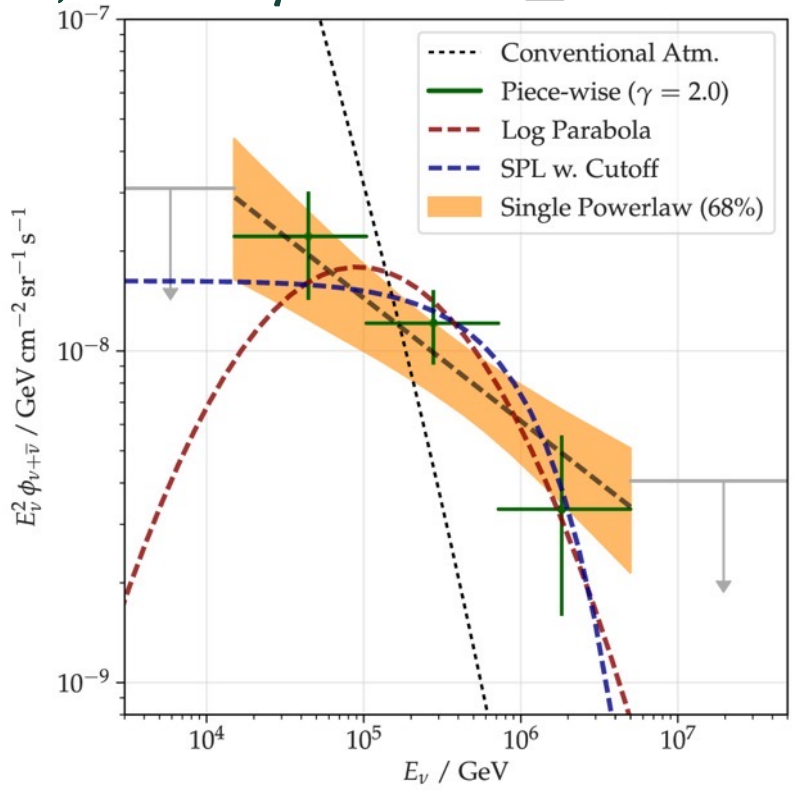



ApJ 928 50, 2022
(arxiv 2111.10299)

# Upgoing Track Selection

*2.37±0.09*

*Data* still consistent with single power law, fits w/ $\gamma = 2.37 \pm 0.09$

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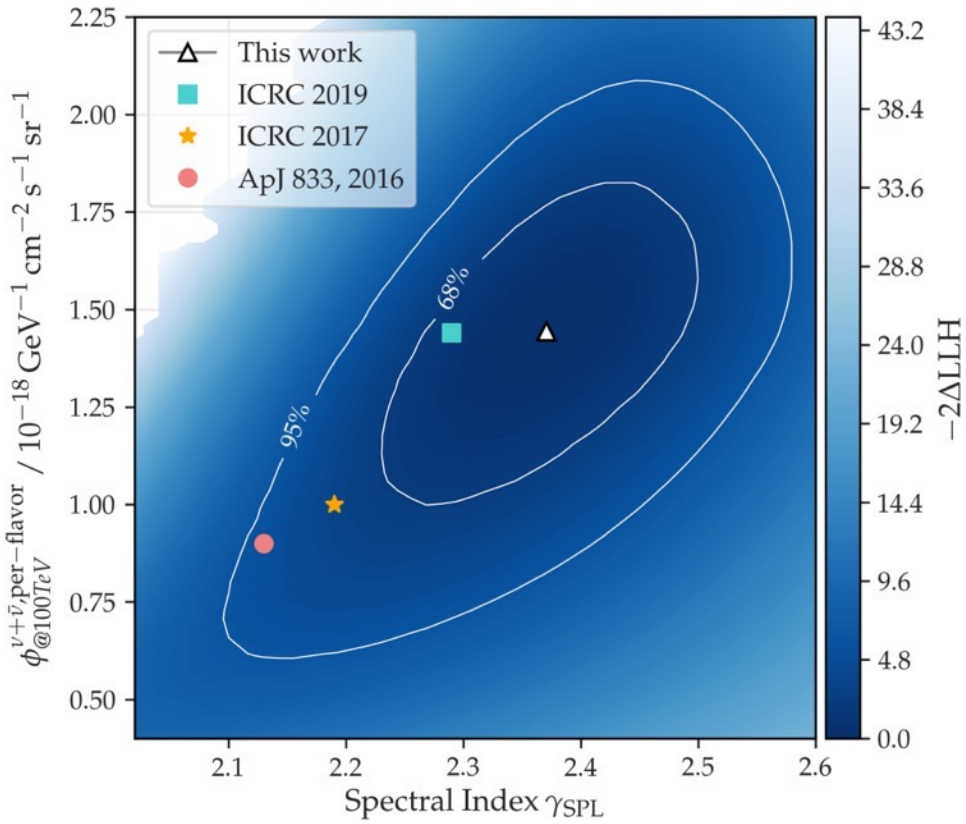


ApJ 928 50, 2022
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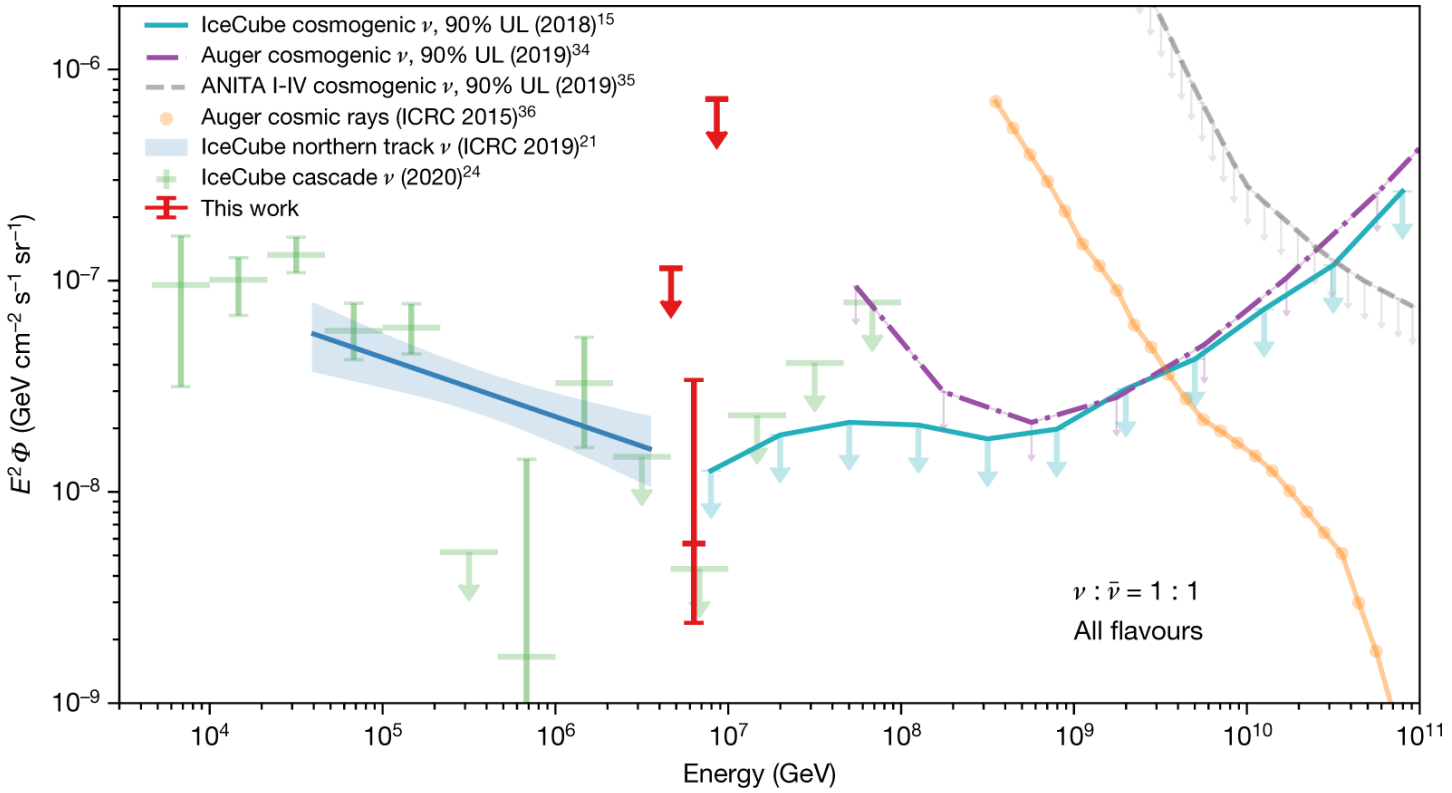
# Glashow

# Glashow


IceCube cosmogenic ν, 90% UL (2018)[15]
Auger cosmogenic ν, 90% UL (2019)[34]
ANITA I-IV cosmogenic ν, 90% UL (2019)[35]
Auger cosmic rays (ICRC 2015)[36]
IceCube northern track ν (ICRC 2019)[21]
IceCube cascade ν (2020)[24]
This work
$E^2\Phi$ (GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$)
$10^{-6}$
$10^{-7}$
$10^{-8}$
$10^{-9}$
$10^4$
$10^5$
$10^6$
$10^7$
$10^8$
$10^9$
$10^{10}$
$10^{11}$
Energy (GeV)
$\nu : \bar{\nu} = 1 : 1$
All flavours

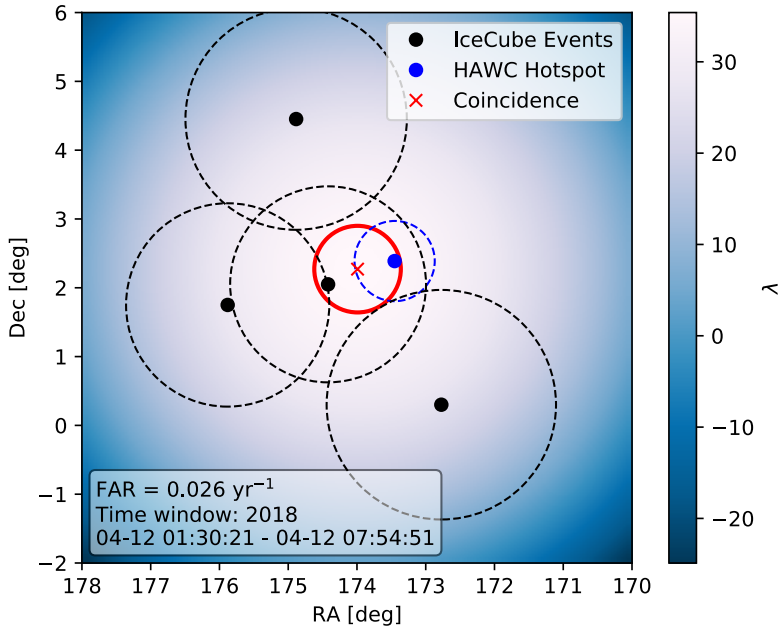
# Searching for Sources

## Correlations with Photon Catalogs

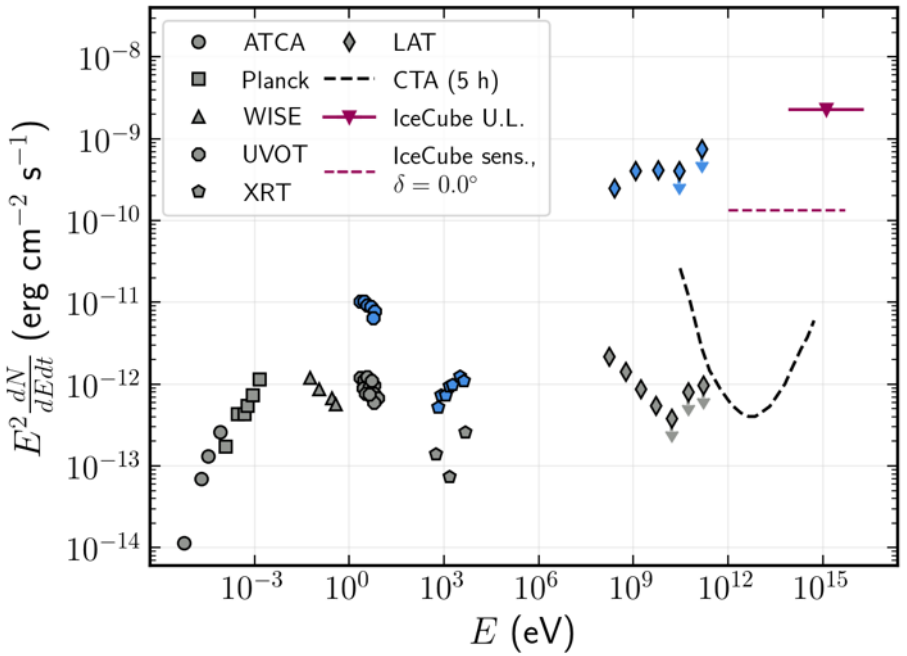
IceCube follows-up other messengers

Through AMON, sub-threshold searches ongoing between HAWC and IceCube

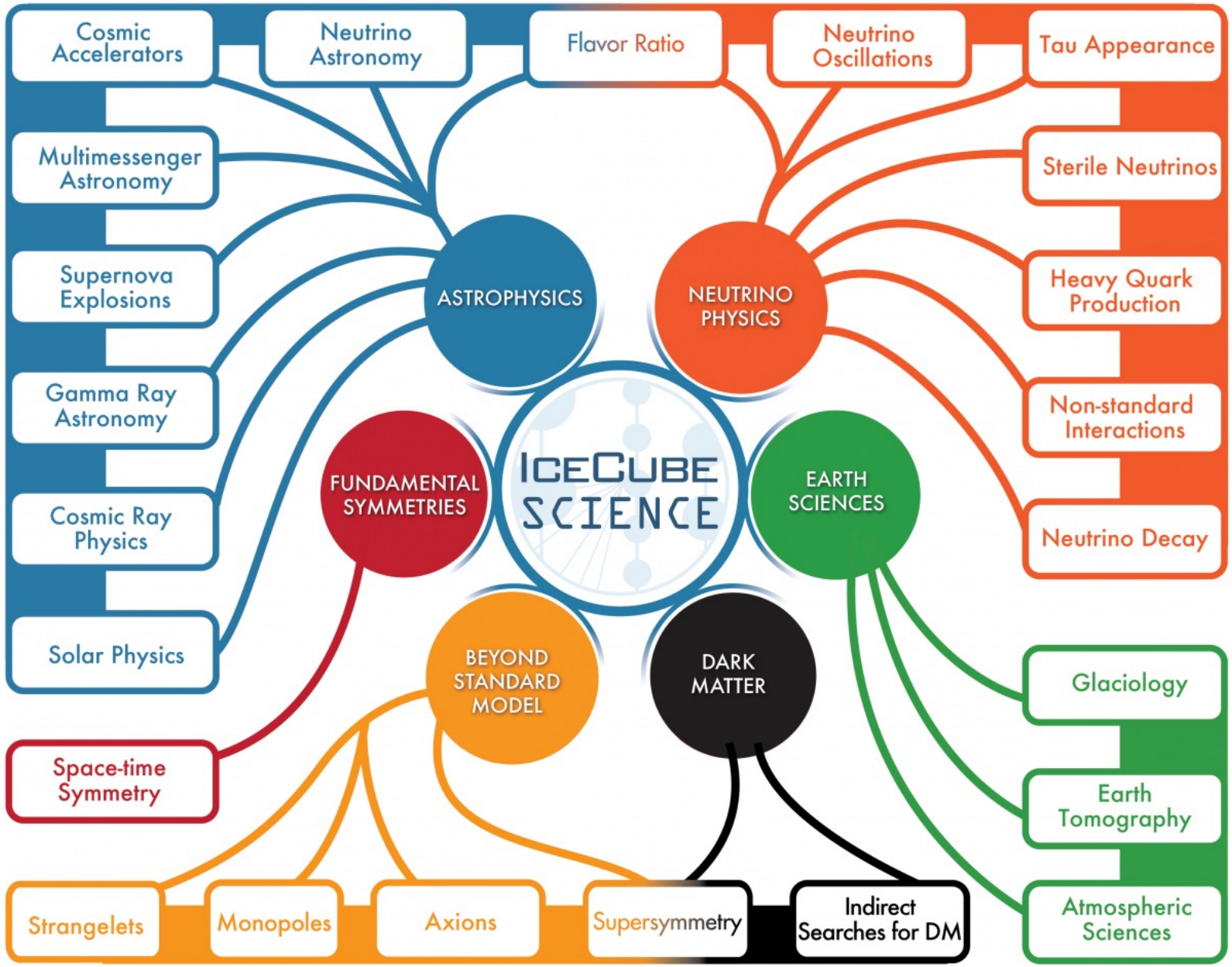
Generic fast-response analysis tool for responding to the community




A HAWC-IceCube coincidence; post-trials p-value ~7%.
ApJ 906 (2021) 63
arxiv 2008.10616




IceCube follow up of FSRQ PKS 0346-27, observed in an enhanced flux state. p-value ~14.5%.
ApJ 910 (2021) 4
arxiv 2012.04577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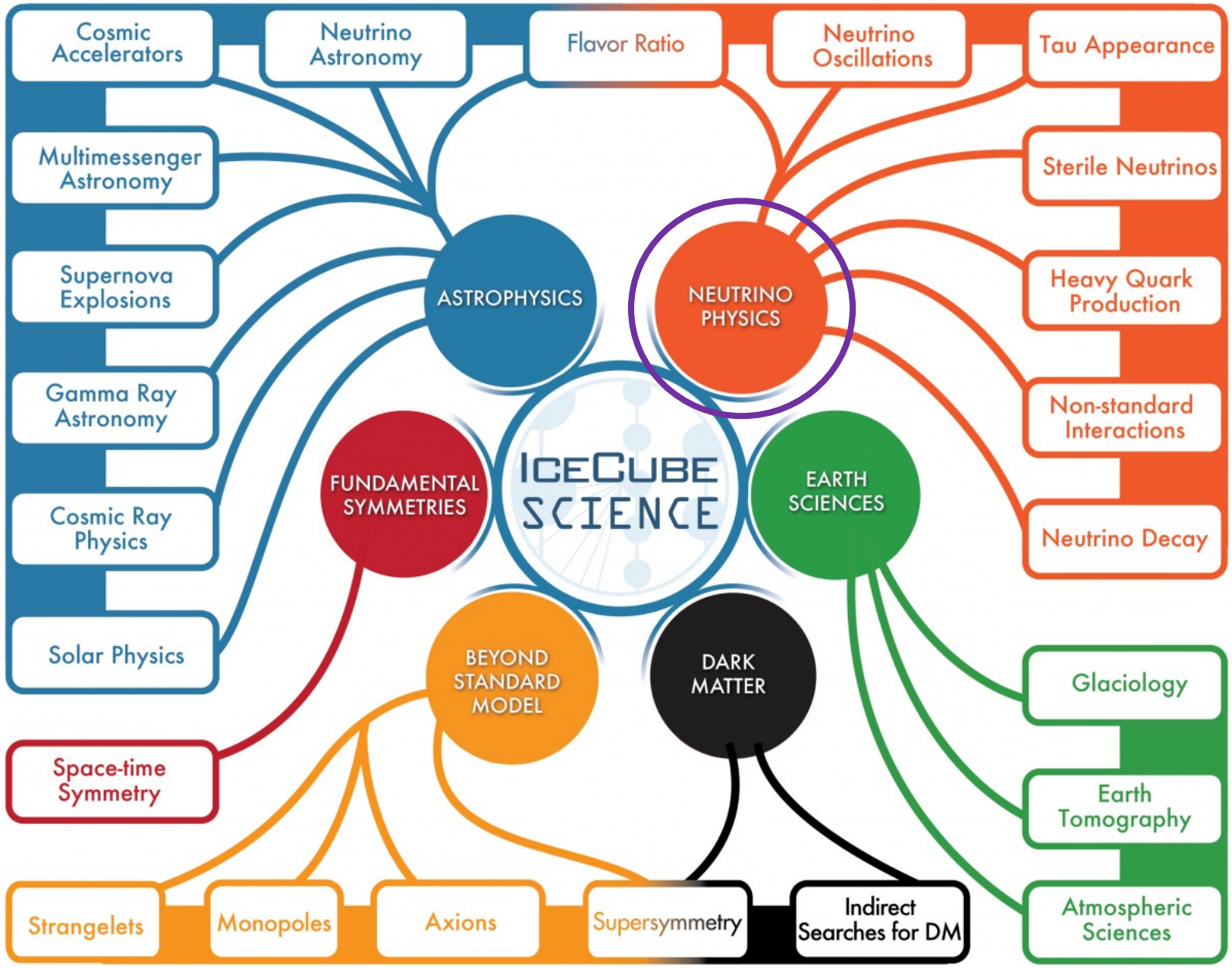
Strangelets
Monopoles
Axions
Supersymmetry
Indirect Searches for DM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# Cross Section

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The Earth attenuates upgoing neutrinos

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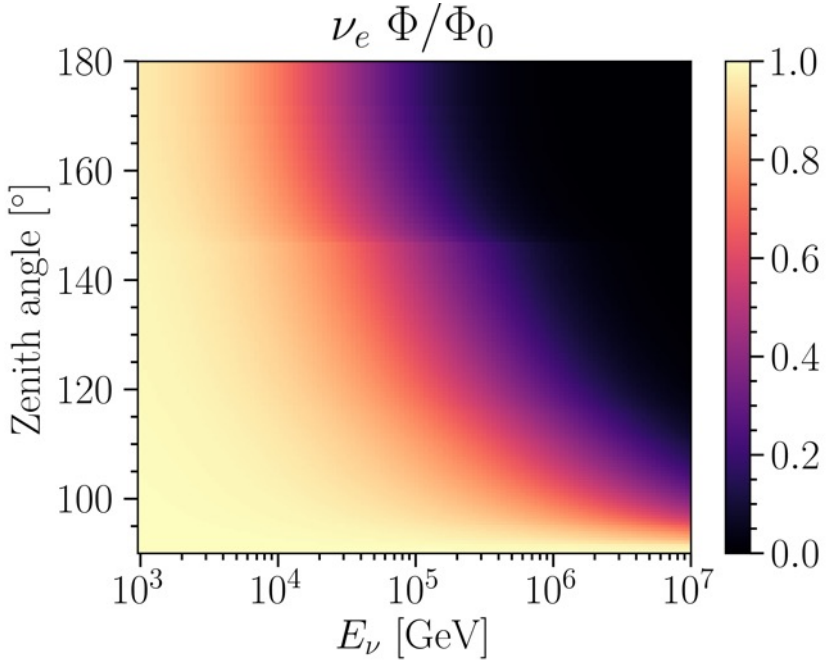
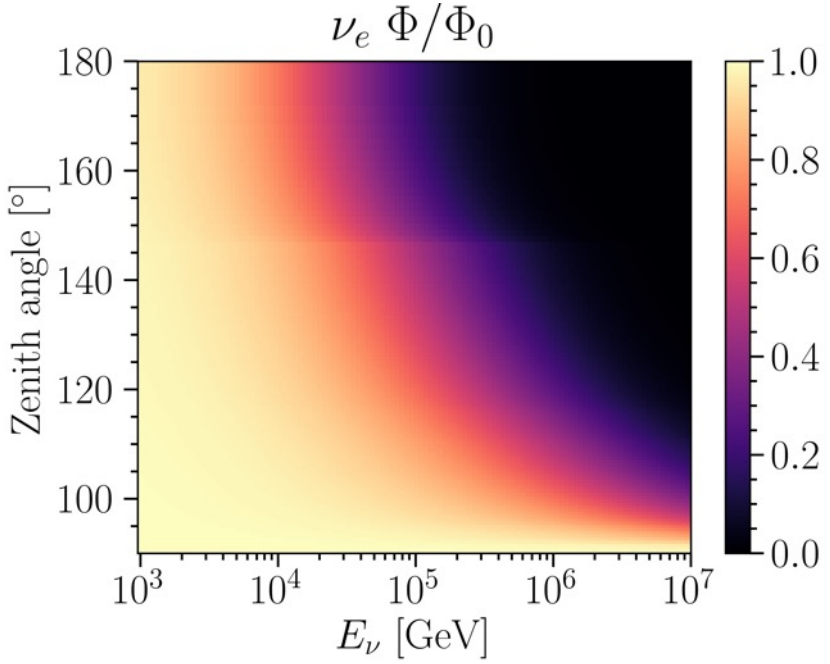



PRD 104, 022001 (2021)
(arxiv 2011.03560 )

# Cross Section

The Earth attenuates upgoing neutrinos

Can use this to measure the neutrino cross-section—done most recently with the HESE dataset

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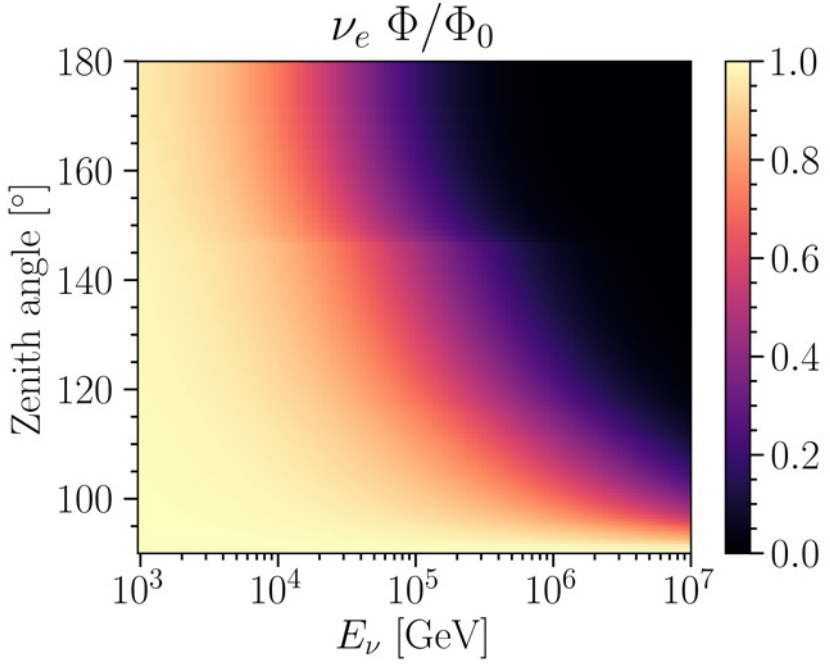


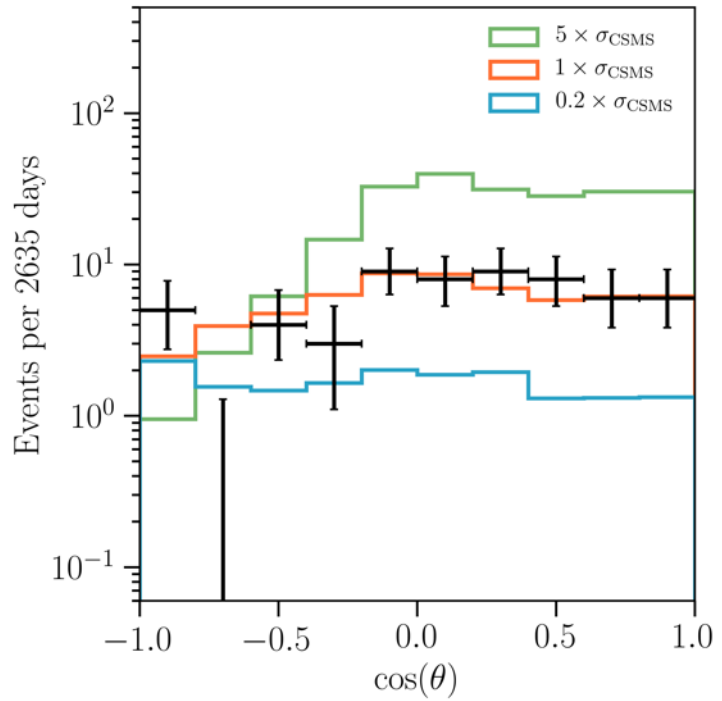


PRD 104, 022001 (2021)
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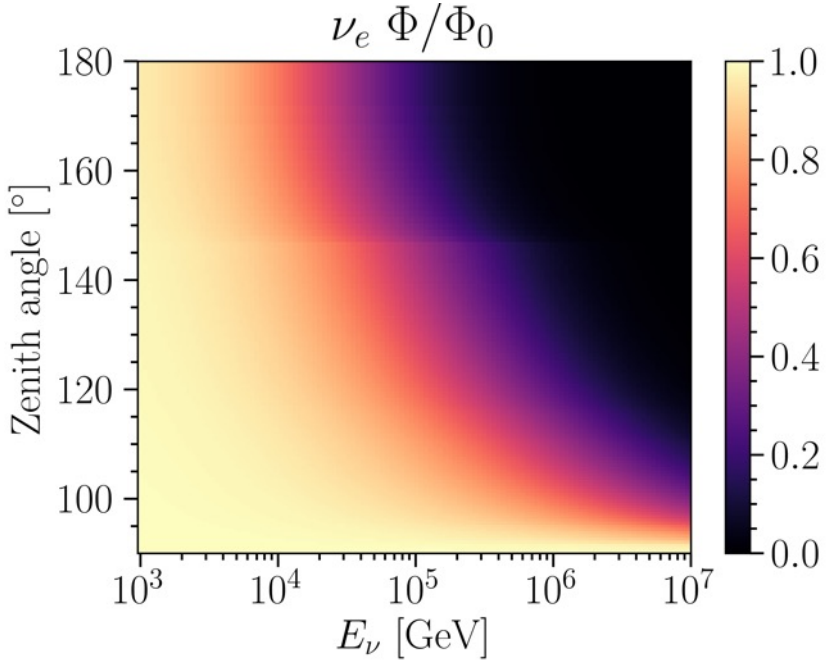
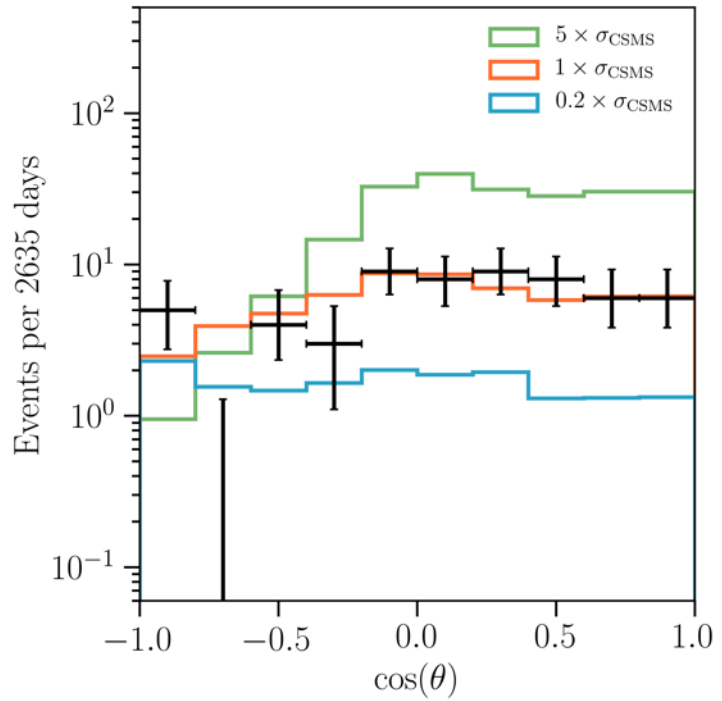
Results consistent with CSMS




PRD 104, 022001 (2021)
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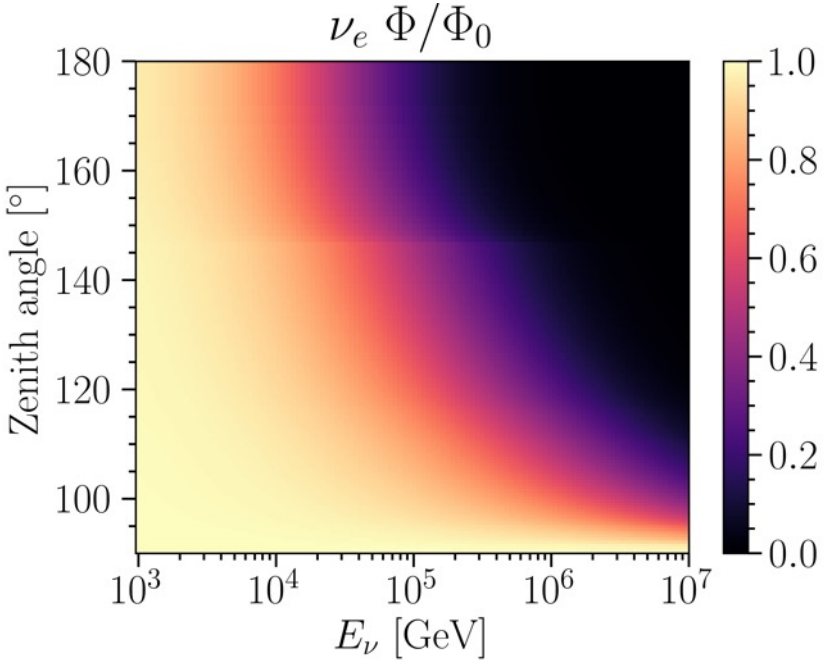


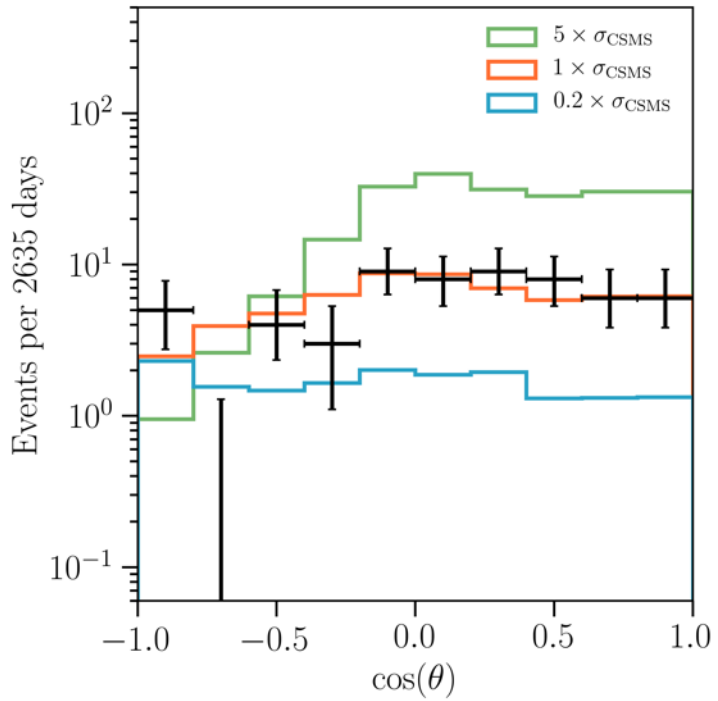


PRD 104, 022001 (2021)
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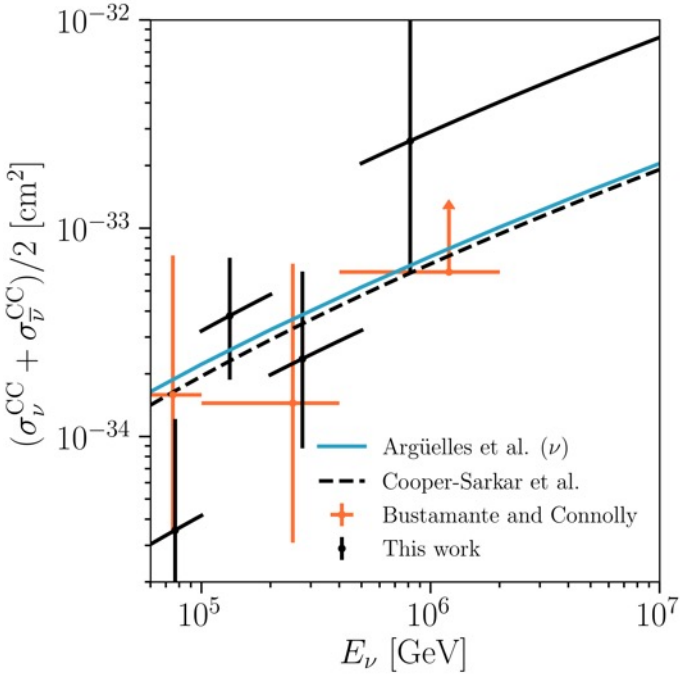
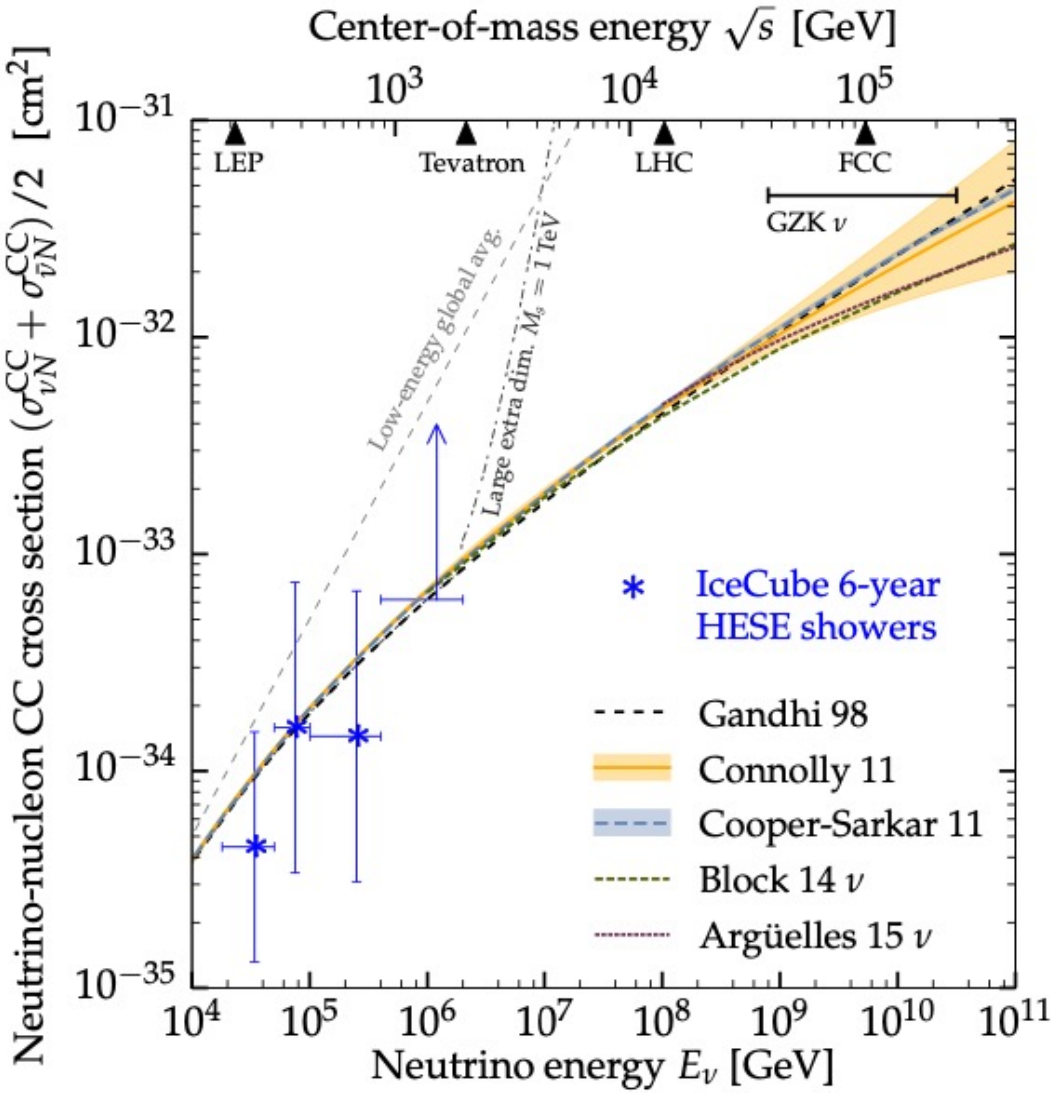
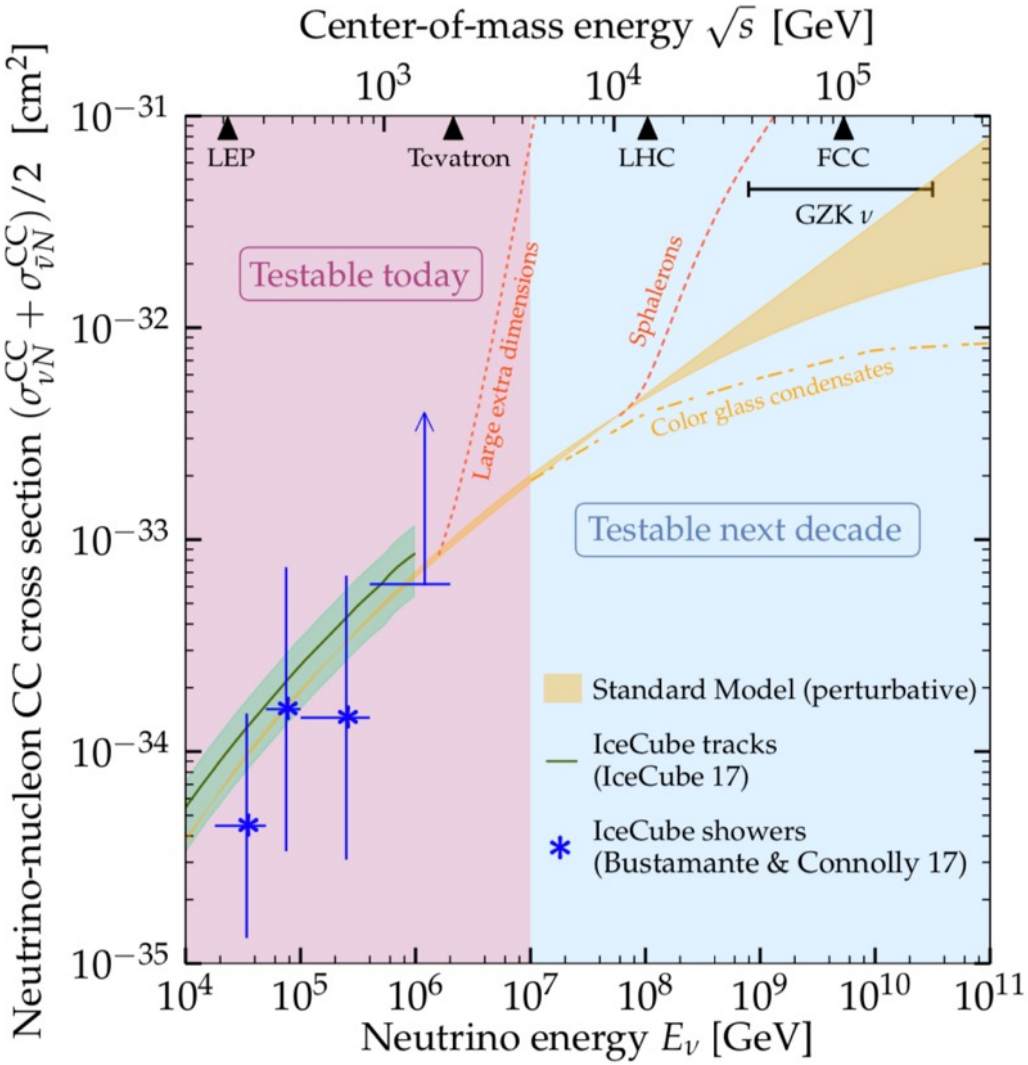


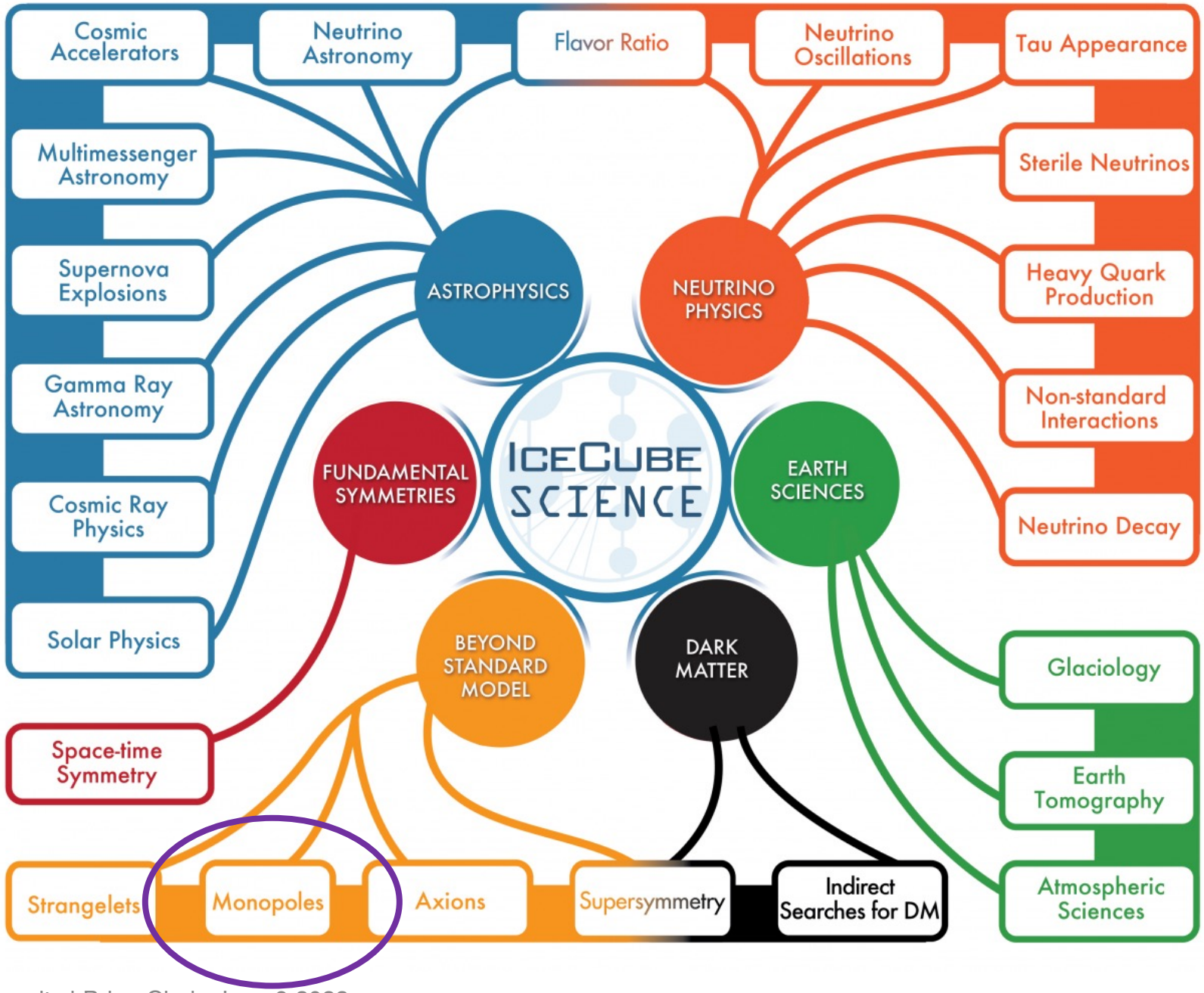
# Cross Section

Measurements of the cross-section probe various BSM scenarios (e.g. sphalerons, LEDM, etc.)




Bustamante and Connolly, PRL 122, 041101 (2019)


Center-of-mass energy $\sqrt{s}$ [GeV]
$10^3$
$10^4$
$10^5$
LEP
Tevatron
LHC
FCC
GZK $\nu$
Testable today
Large extra dimensions
Sphalerons
Color glass condensates
Testable next decade
Standard Model (perturbative)
IceCube tracks
(IceCube 17)
IceCube showers
(Bustamante & Connolly 17)
Neutrino-nucleon CC cross section $(\sigma^{CC}_{\nu N} + \sigma^{CC}_{\bar{\nu} N})/2$ [cm$^2$]
$10^{-31}$
$10^{-32}$
$10^{-33}$
$10^{-34}$
$10^{-35}$
$10^4$ $10^5$ $10^6$ $10^7$ $10^8$ $10^9$ $10^{10}$ $10^{11}$
Neutrino energy $E_\nu$ [GeV]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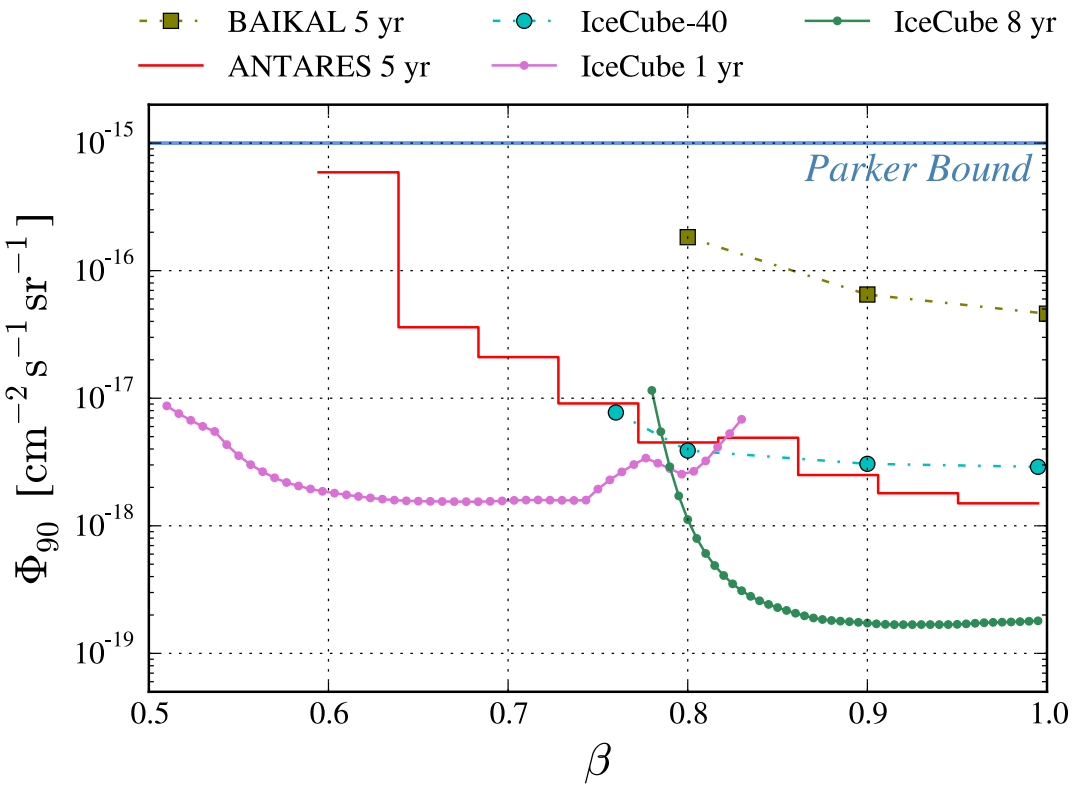
# Monopoles

Use IceCube as a gigaton detector for novel BSM particles like monopoles

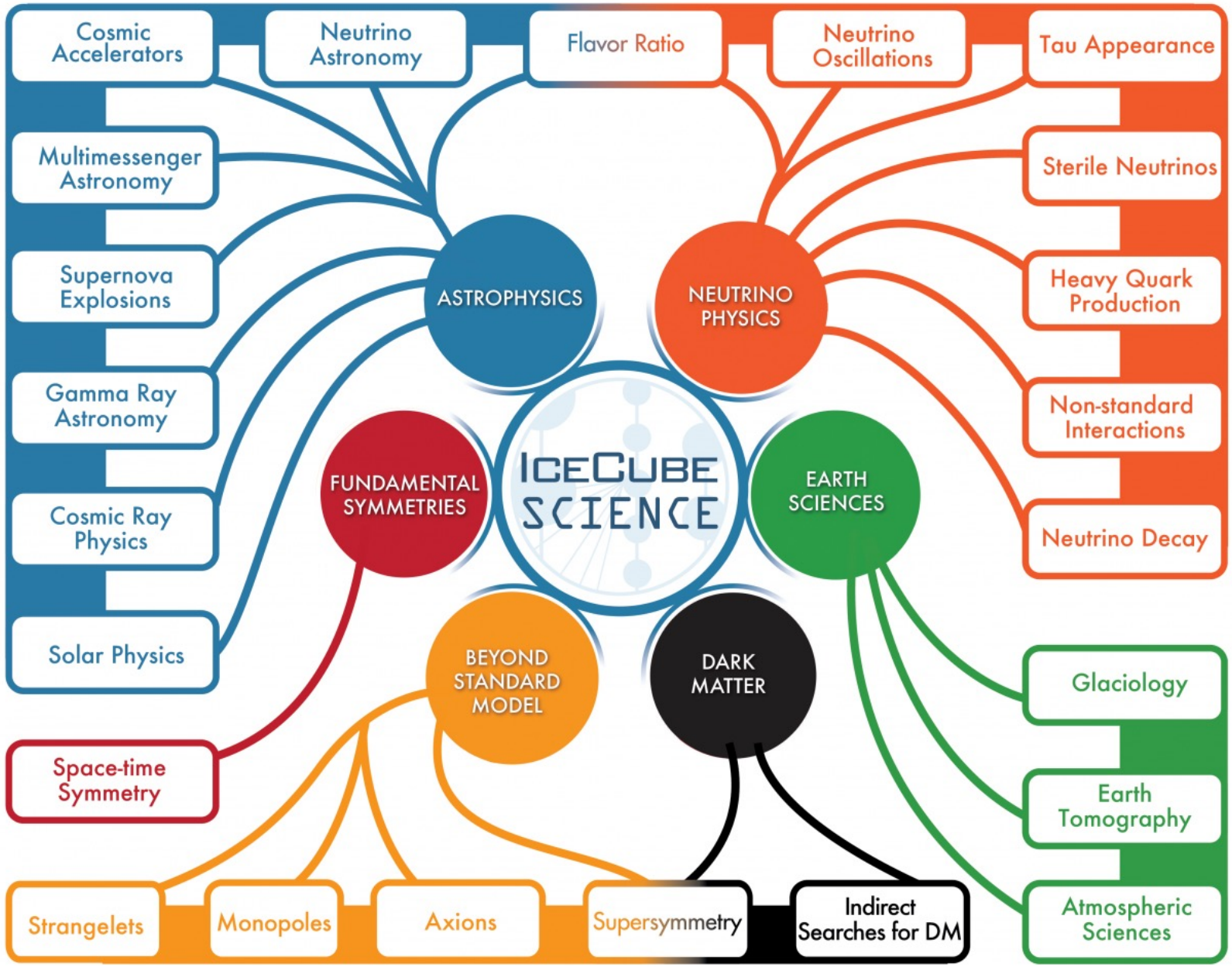
Latest search looks for relativistic ($\beta > 0.75$) monopoles -- appears as "slow" track with a smooth light deposition pattern

No passing events on background of ~0.3, set strict upper limit




PRL 128 051101 (2022)
arxiv 2109.13719

| Analysis level | $n_{obs}$ | $n_{sg}$ | $n_{bg}$ |
|---|---|---|---|
| Online filter | $1.63 \times 10^8$ | 178 | 371 |
| Step I: | | | |
| Initial off-line cuts | $3.16 \times 10^4$ | 89.9 | 57.2 |
| Track quality cut | $8.46 \times 10^3$ | 64.1 | 20.4 |
| Down-going cut | 3 | 35.5 | 10.1 |
| IceTop surface veto | 3 | 35.5 | $10.0^{+10.3}_{-5.1}$ |
| Step II | 0 | 33.2 | $0.27^{+0.27}_{-0.14}$ |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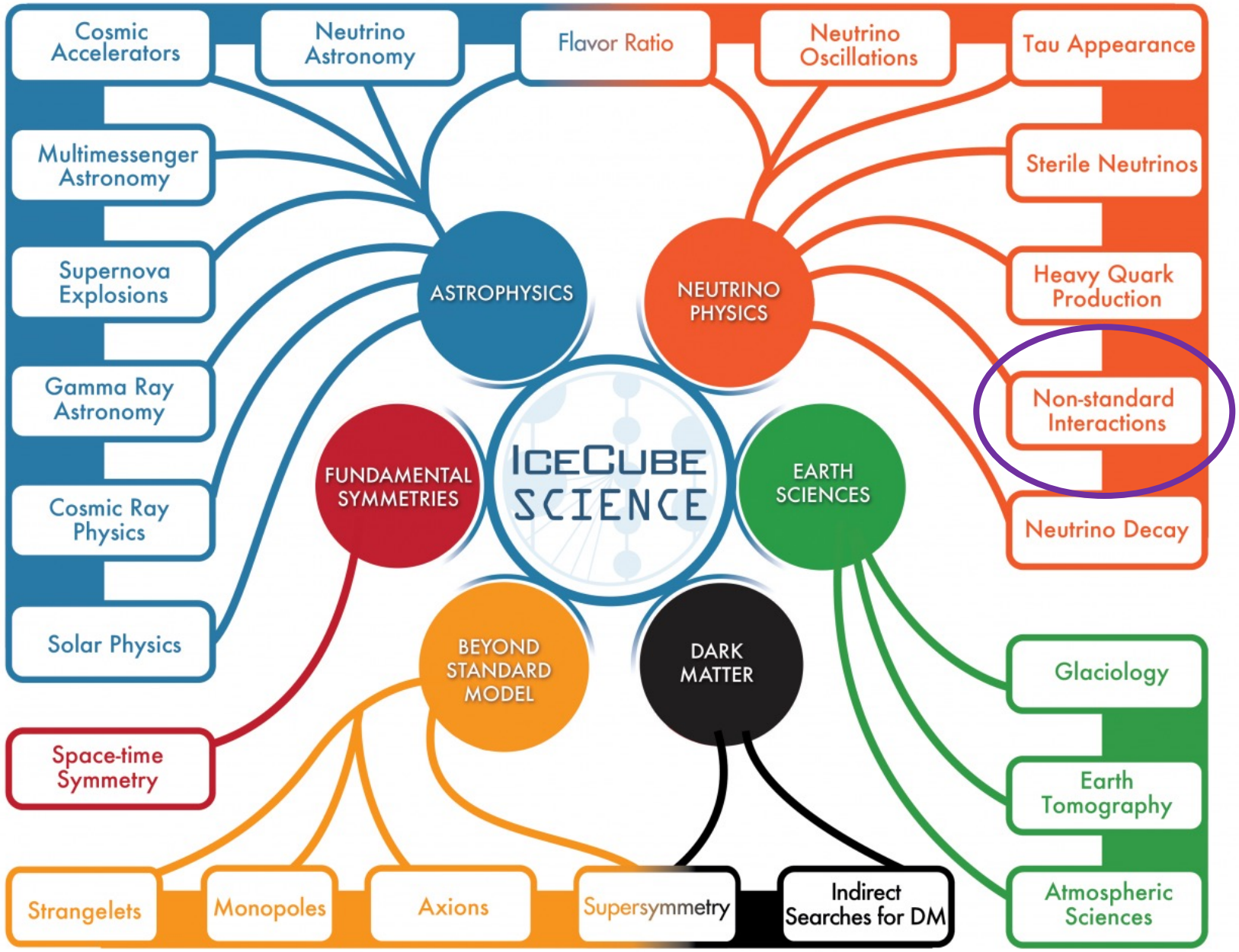
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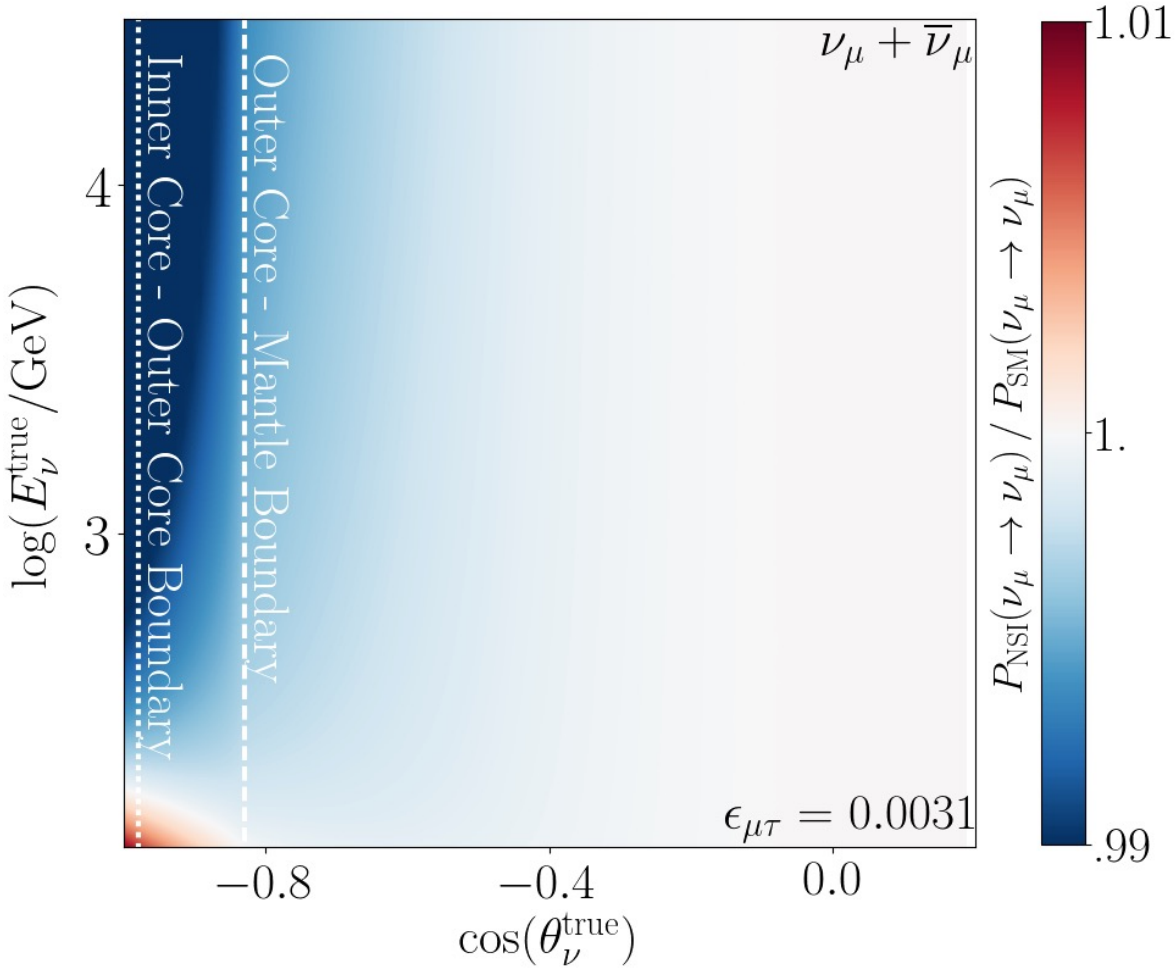
# Non-Standard Interactions

$$P(\nu_\mu \to \nu_\tau) = \left| \sin 2\theta_{23} \frac{\Delta m^2_{31}}{2E_\nu} + 2\epsilon_{\mu\tau} V_d \right|^2 \left( \frac{L}{2} \right)^2$$

$$+\overline{\nu_\mu}$$



# Non-Standard Interactions

Neutrino oscillations are affected by matter in the Earth

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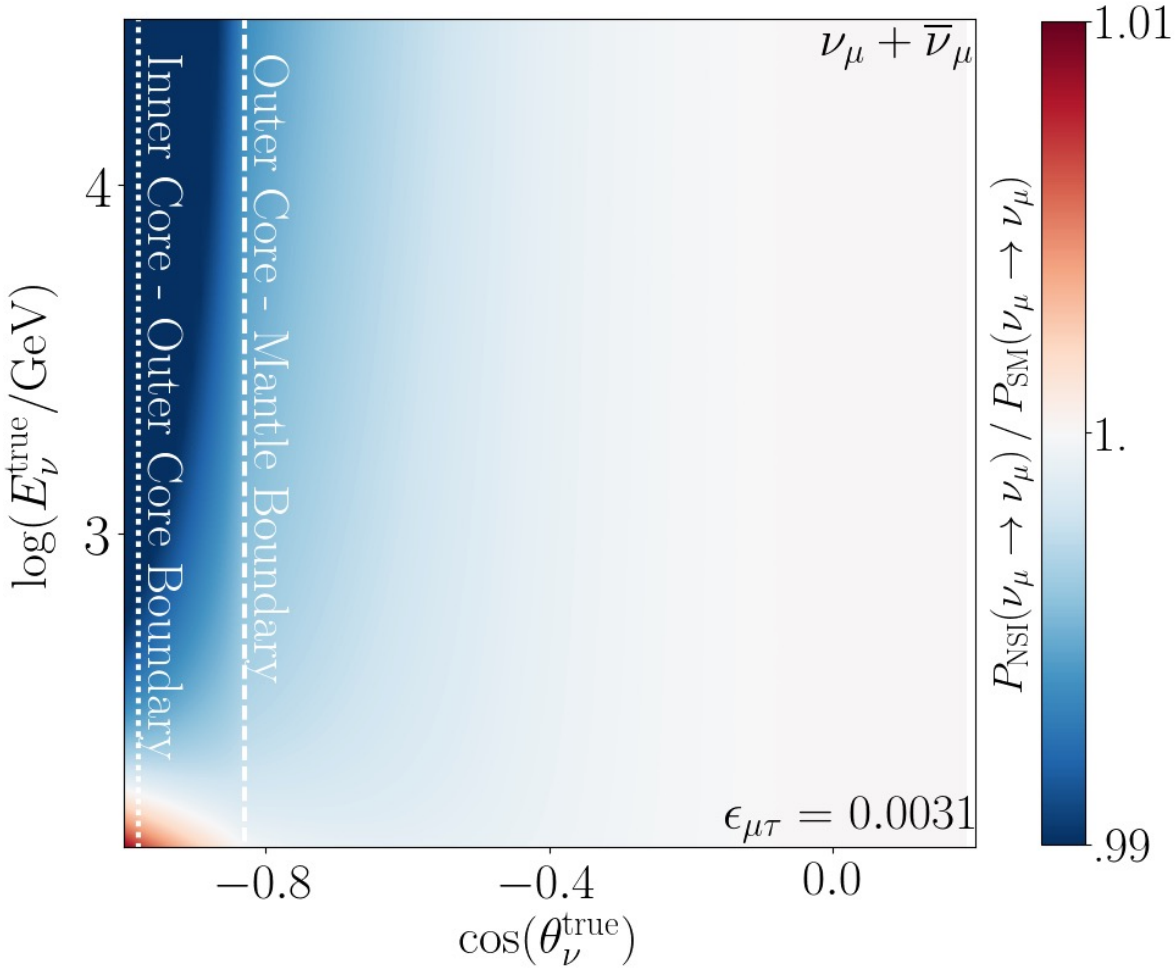

# Non-Standard Interactions

Neutrino oscillations are affected by matter in the Earth

NSI leads to %-scale deviations from SM expectations, parameterized by $\epsilon_{\mu\tau}$

$\mu\tau$ $\tau$ $\mu\tau$

$$P(\nu_\mu \to \nu_\tau) = \left| \sin 2\theta_{23} \frac{\Delta m^2_{31}}{2E_\nu} + 2\epsilon_{\mu\tau} V_d \right|^2 \left( \frac{L}{2} \right)^2$$

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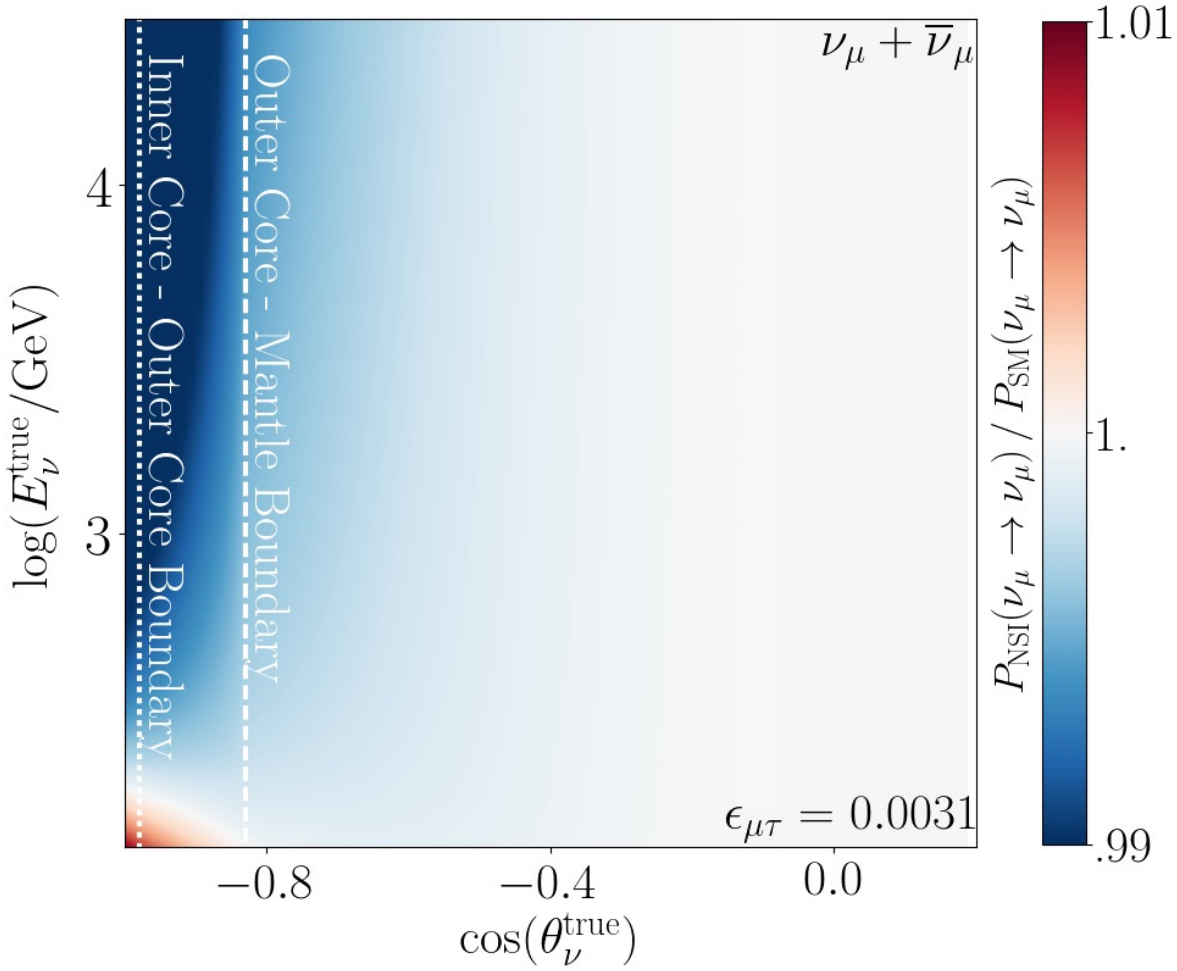

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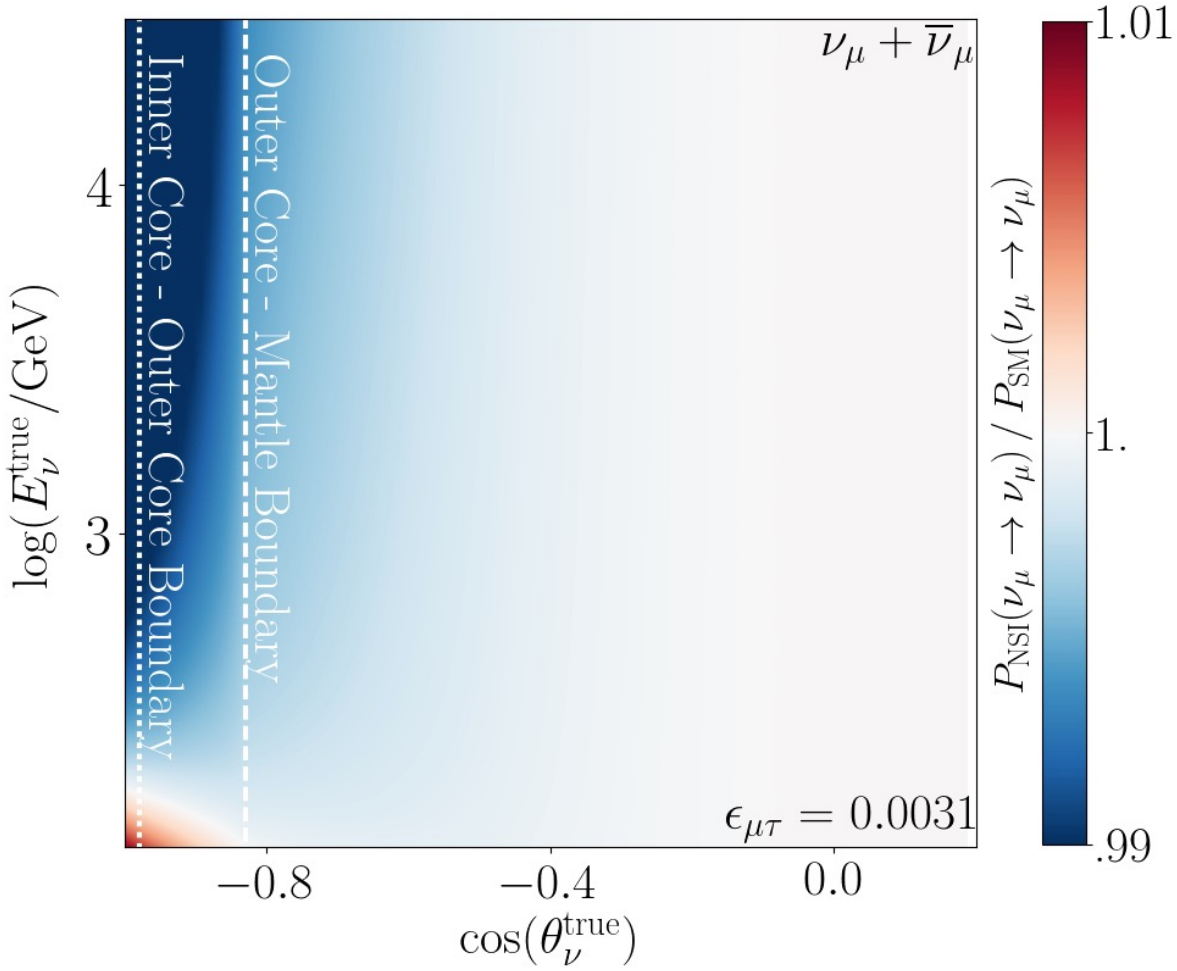
$+\overline{\nu_\mu}$



# Non-Standard Interactions

$\nu\ \mu \quad \nu\ \mu\ \nu\nu\ \nu\ \mu\ \mu\mu\ \nu\ \mu \quad \nu\ \mu$

Neutrino oscillations are affected by matter in the Earth

NSI leads to %-scale deviations from SM expectations, parameterized by $\epsilon\ \mu\tau$

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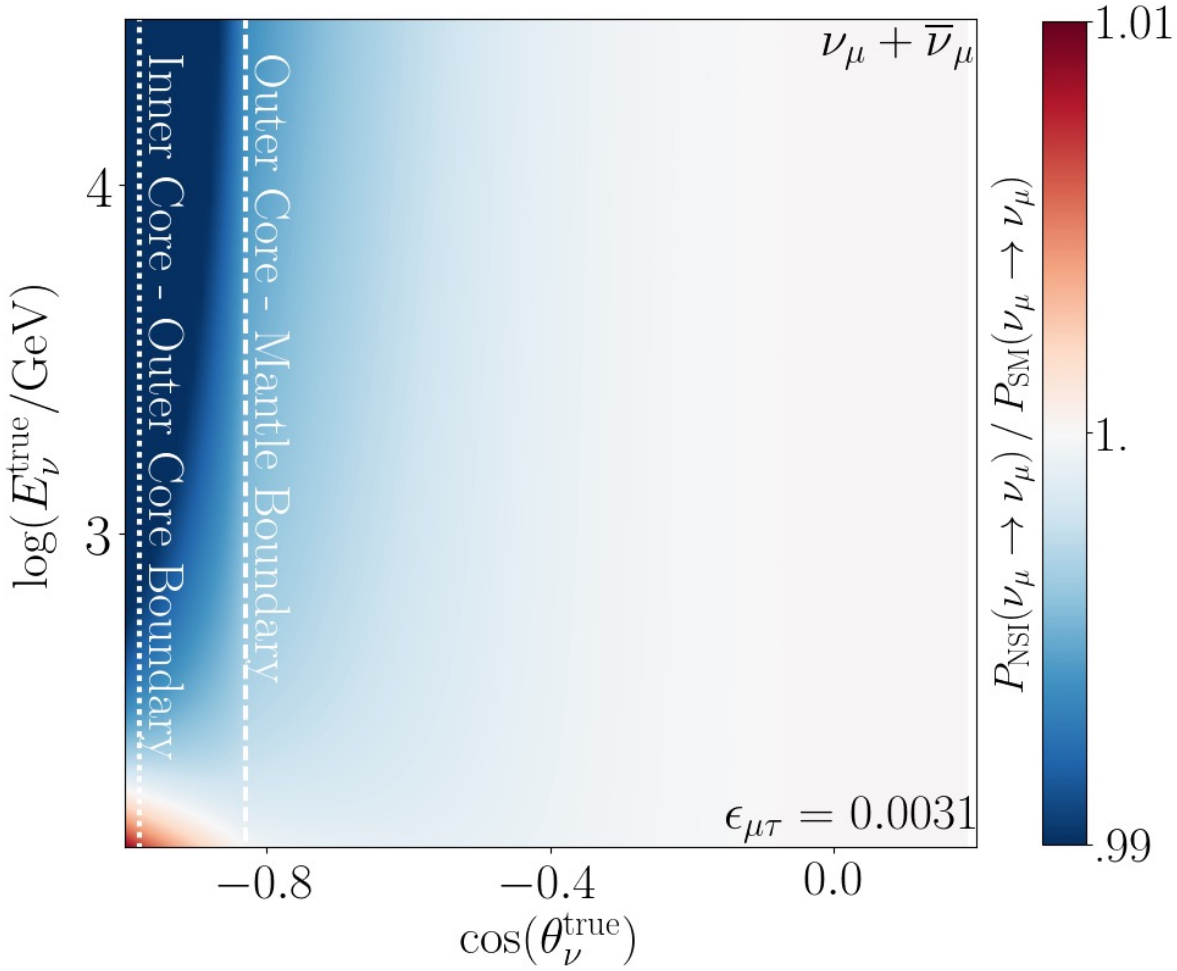
Search for this using TeV $\nu\ \mu + \ \mu\ \mu\ \mu\ + \overline{\nu_\mu}$

$+\overline{\nu_\mu}$



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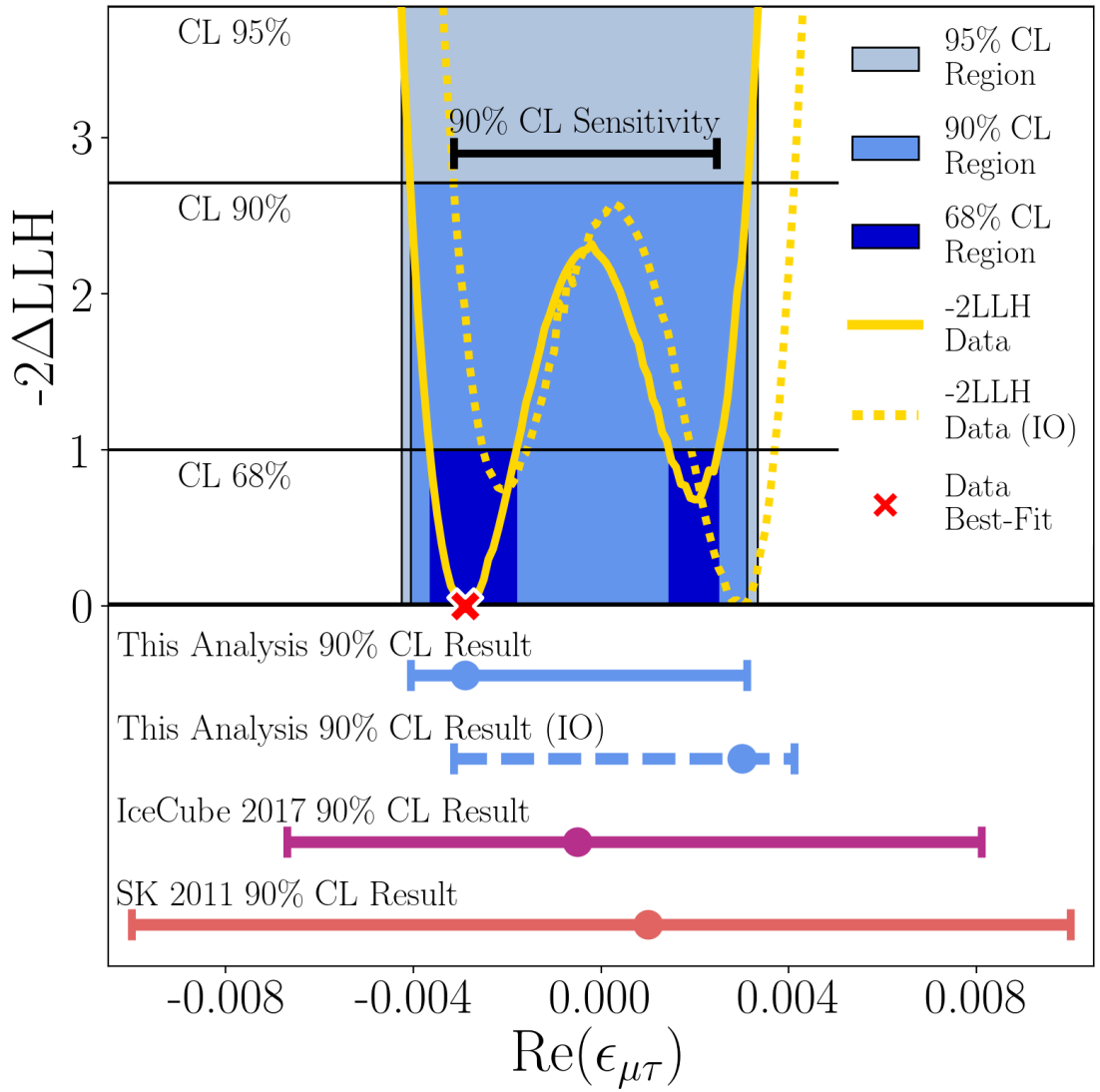
NSI leads to %-scale deviations from SM expectations, parameterized by $\epsilon_{\mu\tau}$

$$P(\nu_\mu \to \nu_\tau) = \left| \sin 2\theta_{23} \frac{\Delta m^2_{31}}{2E_\nu} + 2\epsilon_{\mu\tau} V_d \right|^2 \left( \frac{L}{2} \right)^2$$

Search for this using TeV $\nu_\mu + \overline{\nu_\mu}$

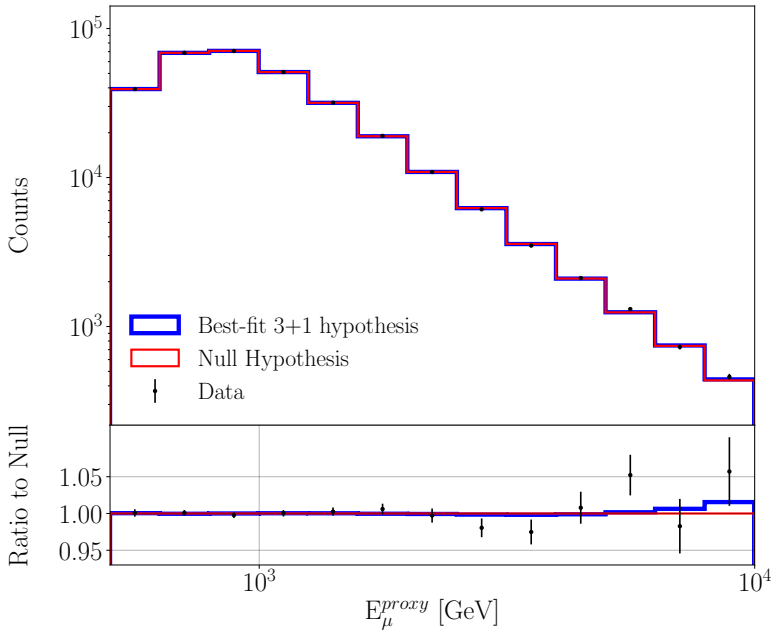
Set world's strongest constraint!



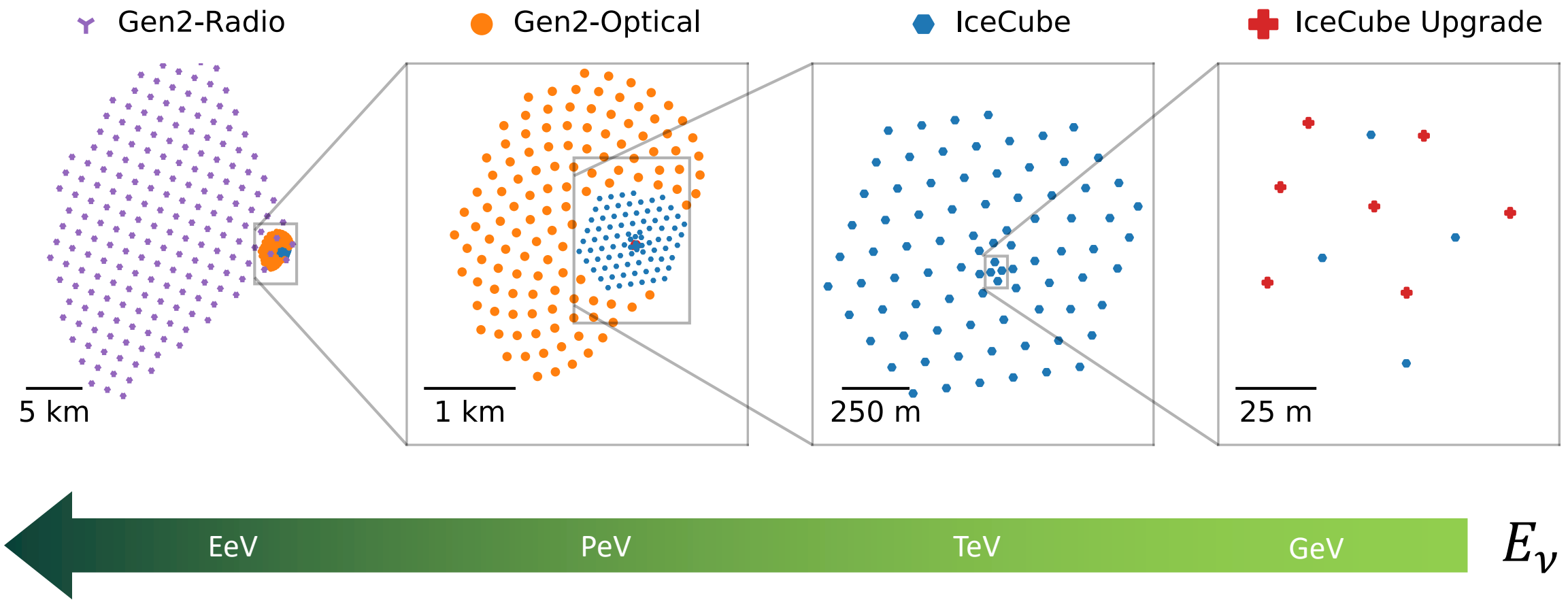
# Steriles

# Steriles

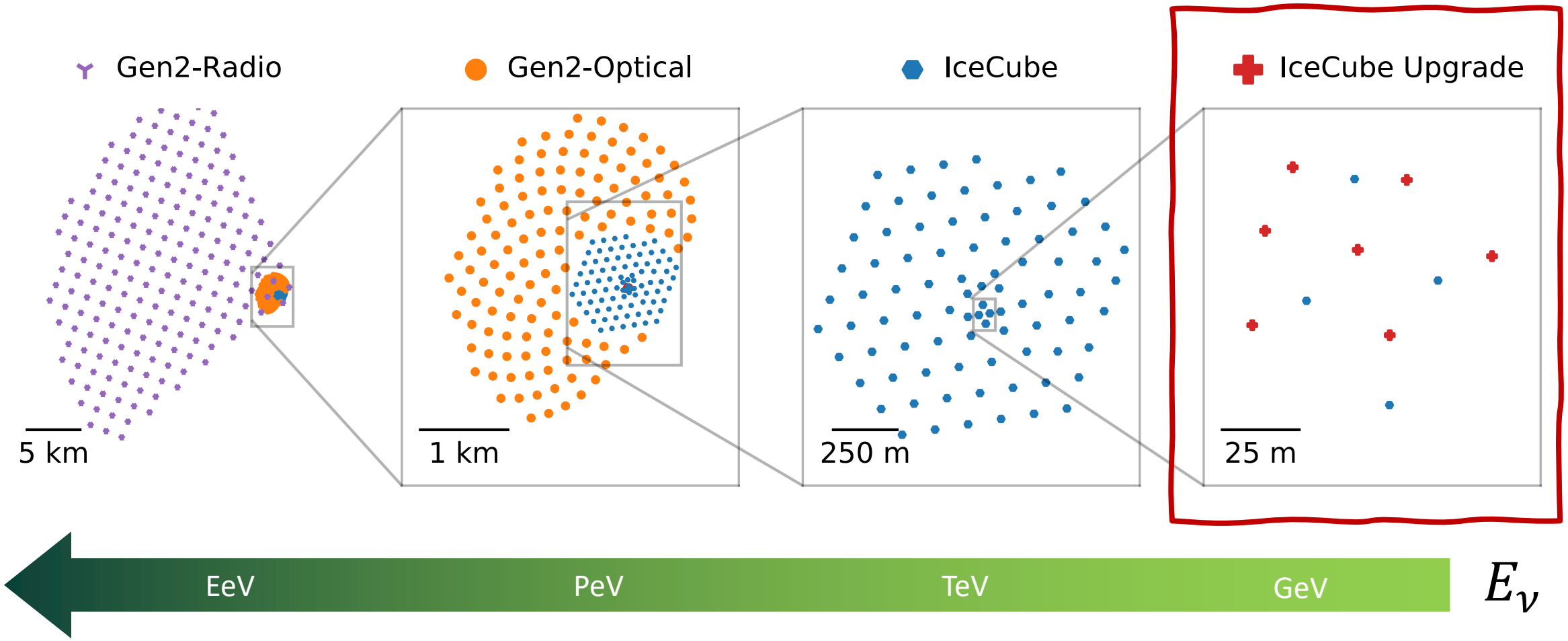
PRL 125 141801 (2020)
arxiv 2005.12942



# The IceCube-Gen2 Facility

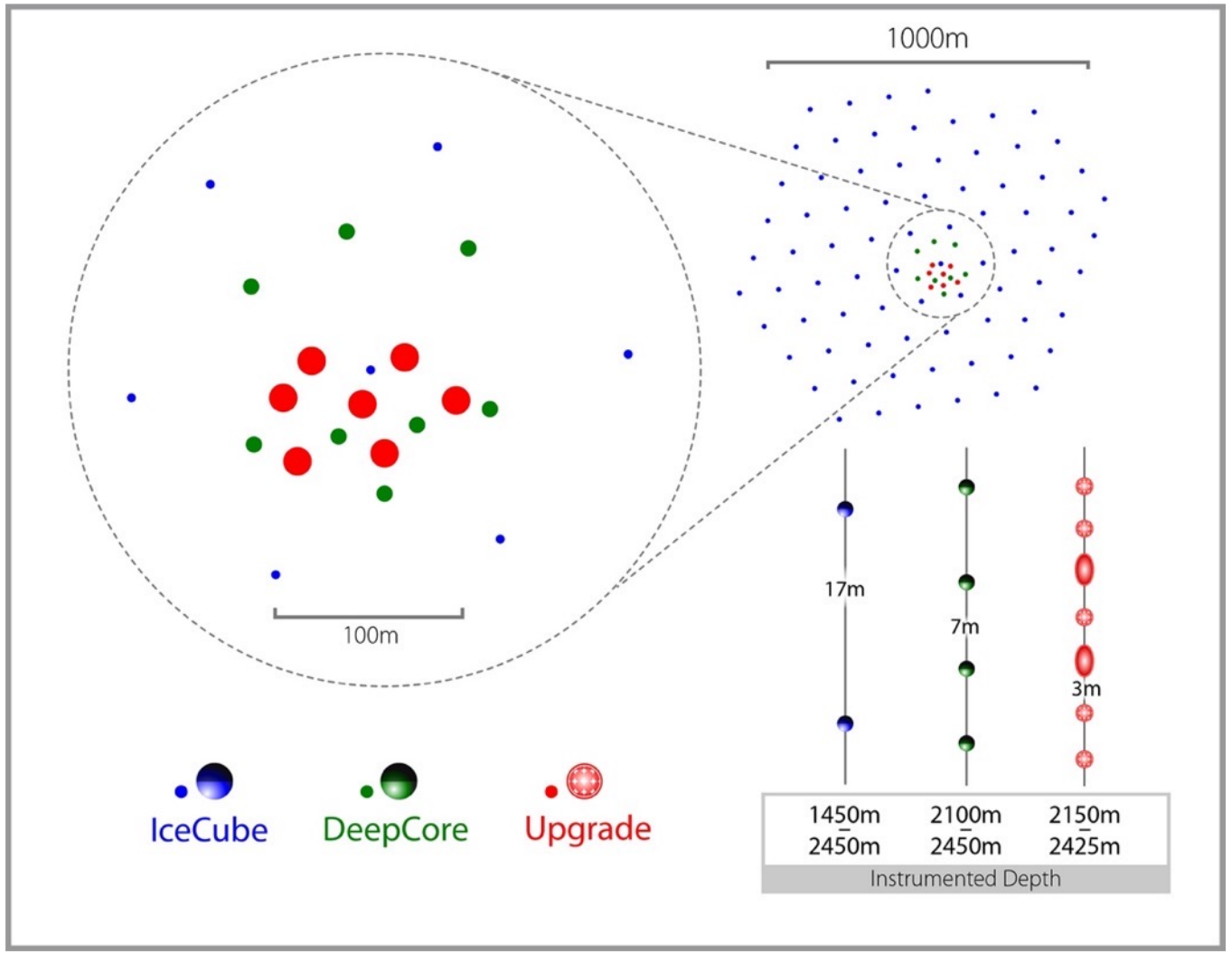


# The IceCube-Gen2 Facility

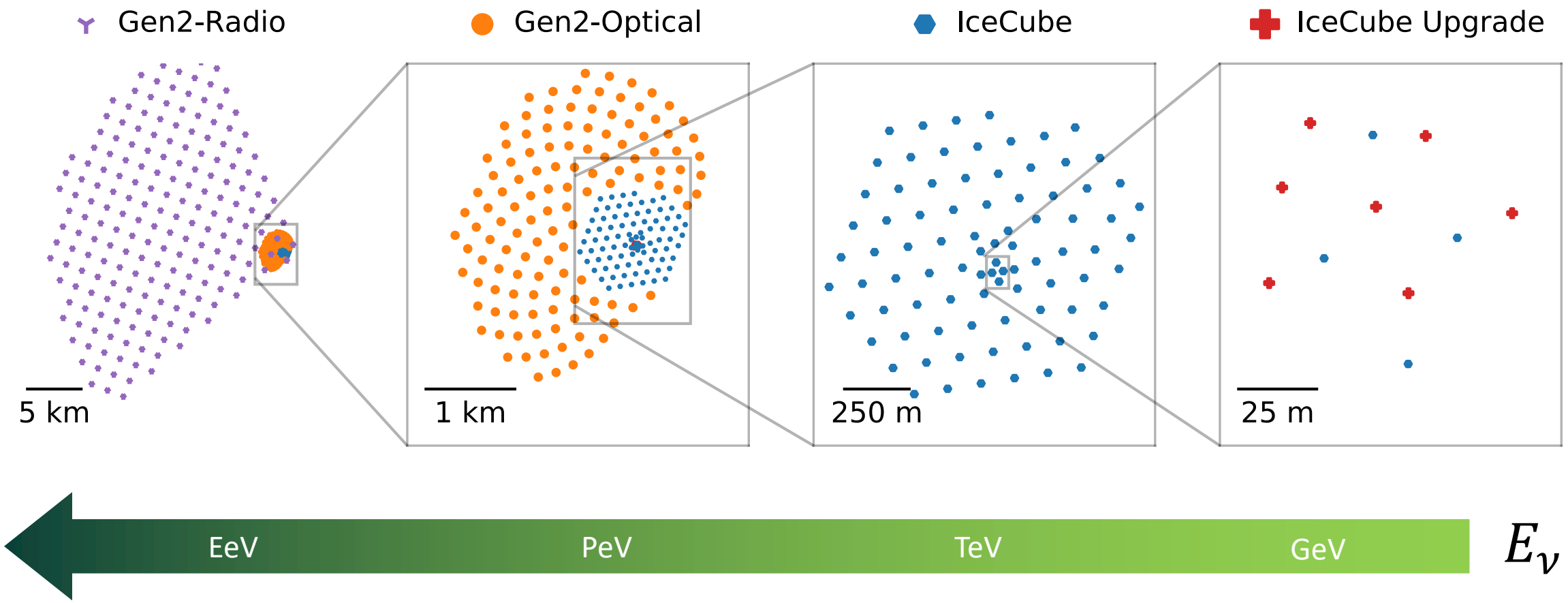


# IceCube Upgrade

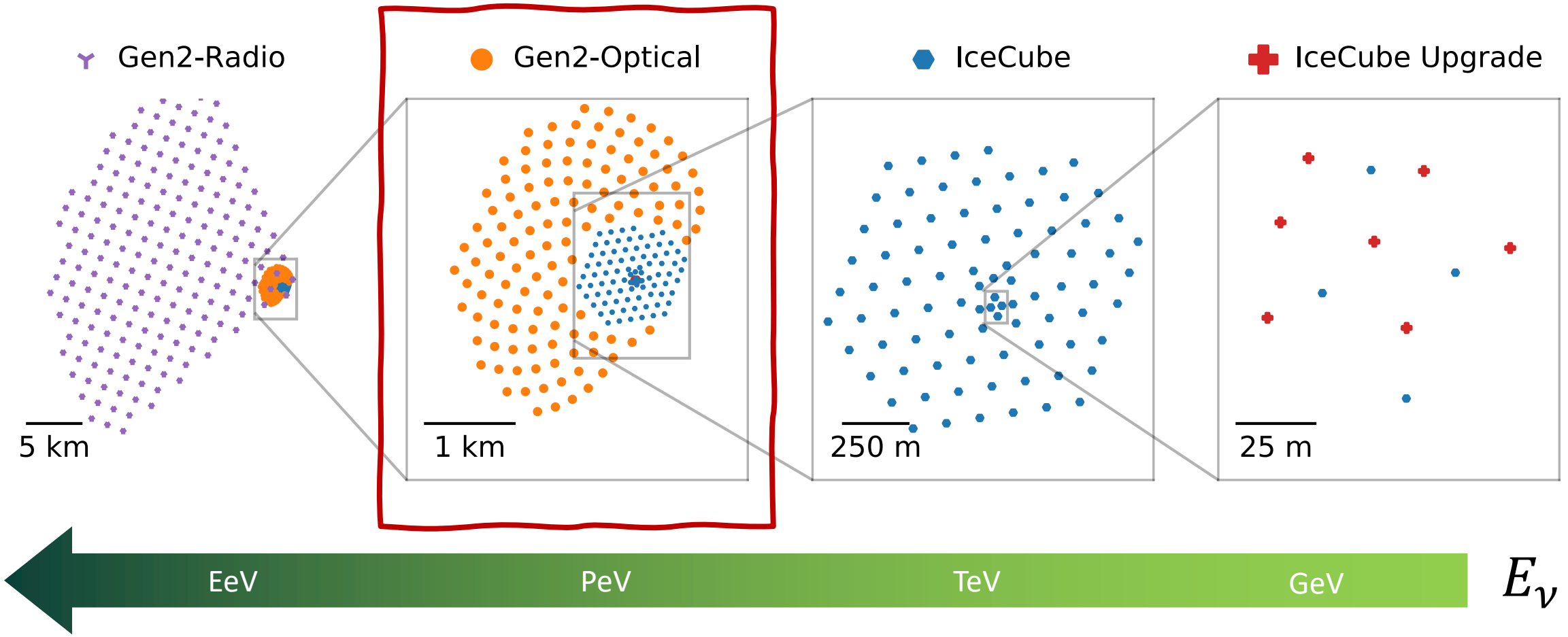
- 7 new strings, ~100 sensors/string
- 5 year construction project underway
- Key goals: ice calibration, sensitivity to GeV neutrinos
- R&D platform: pixelated detectors, wavelength shifting sensors



# The IceCube-Gen2 Facility

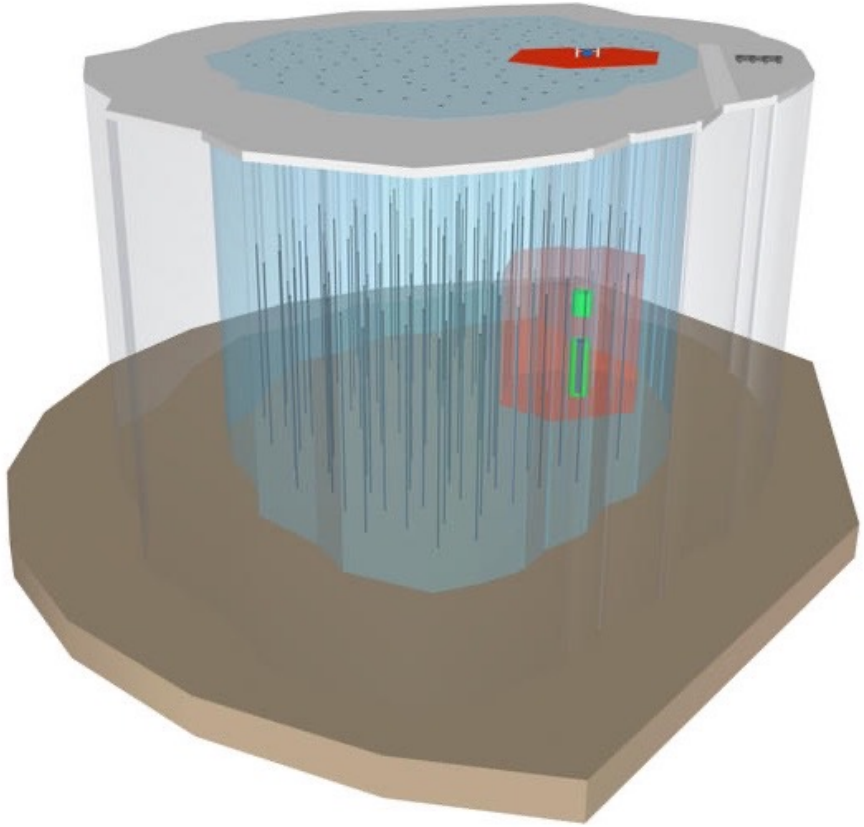


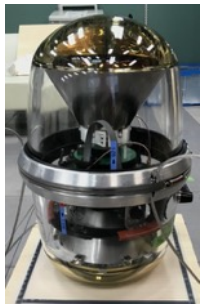
# The IceCube-Gen2 Facility



# IceCube-Gen2 Optical

- Enlarged, 8 $km^3$ optical array in "Sunflower" layout
  - 122 strings, 240m lateral spacing
  - 80 Oms/string, 17m vertical spacing
- ~10x the contained volume
- 5x the effective area
- 2x the angular resolution



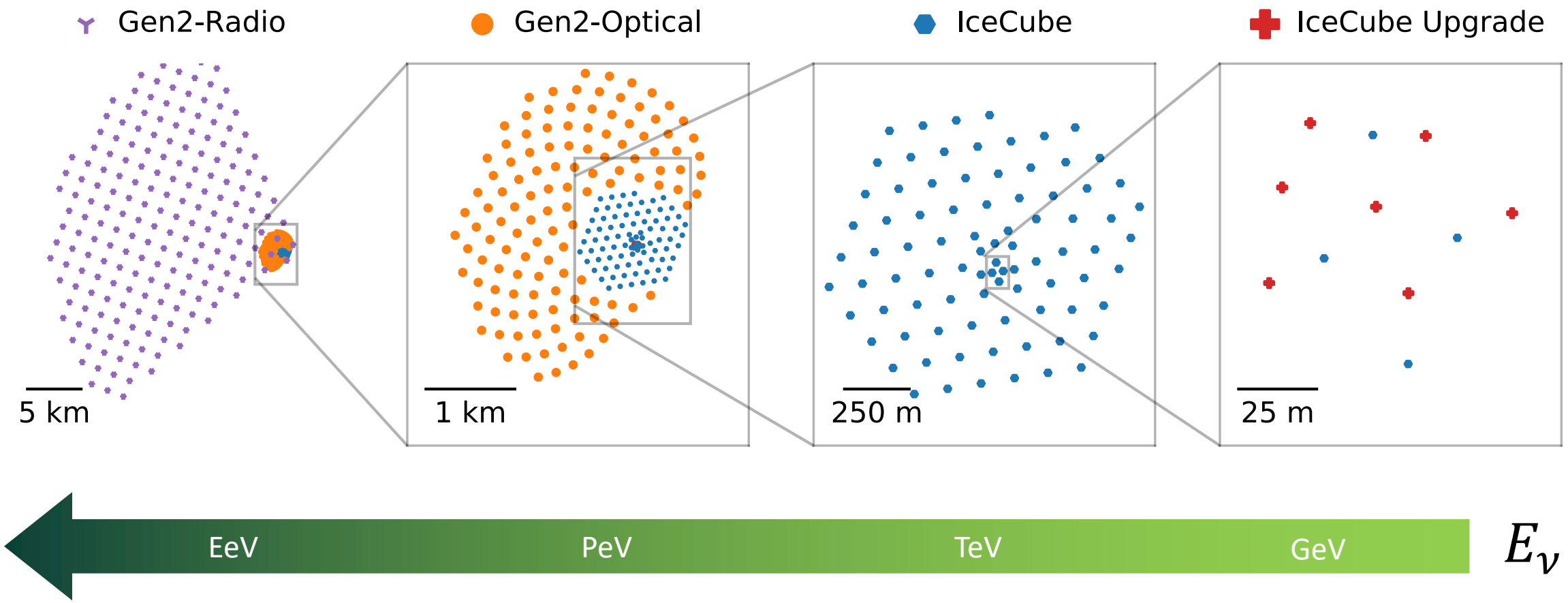


D-Egg

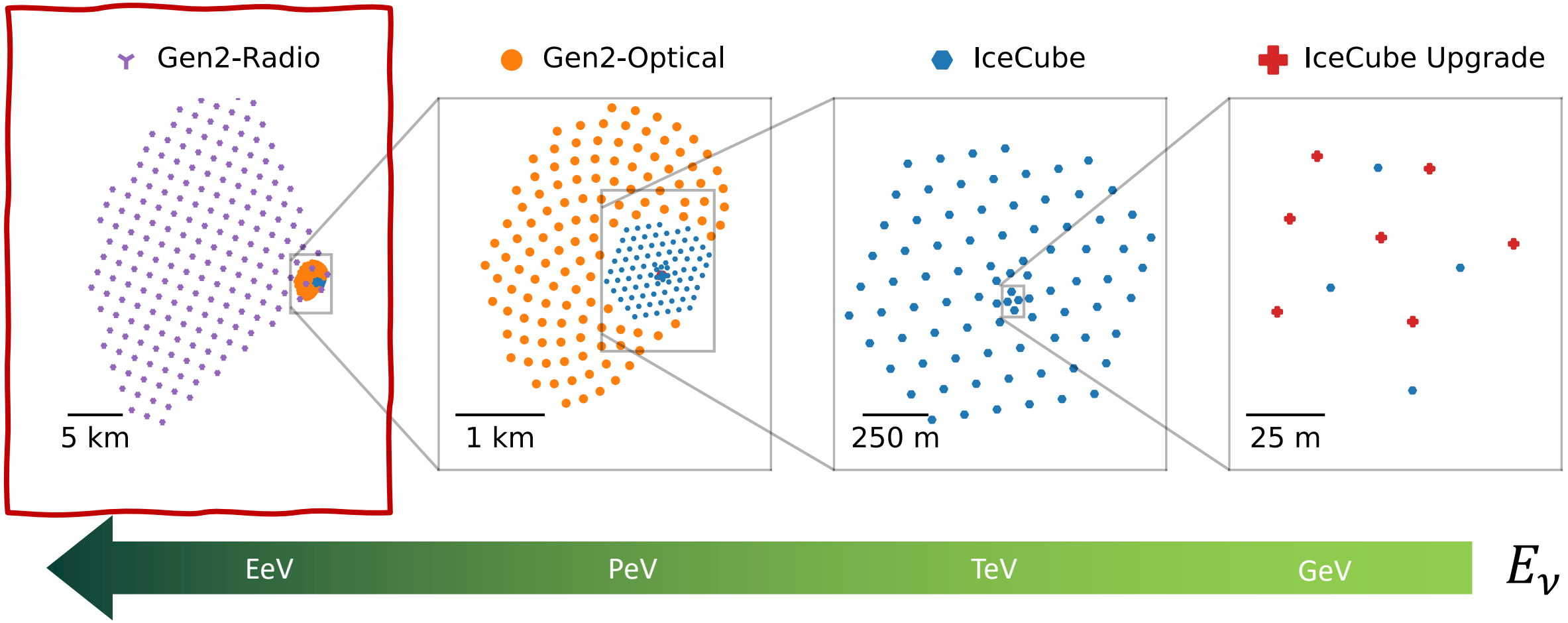
mDOM

Features new pixelated optical modules

# The IceCube-Gen2 Facility



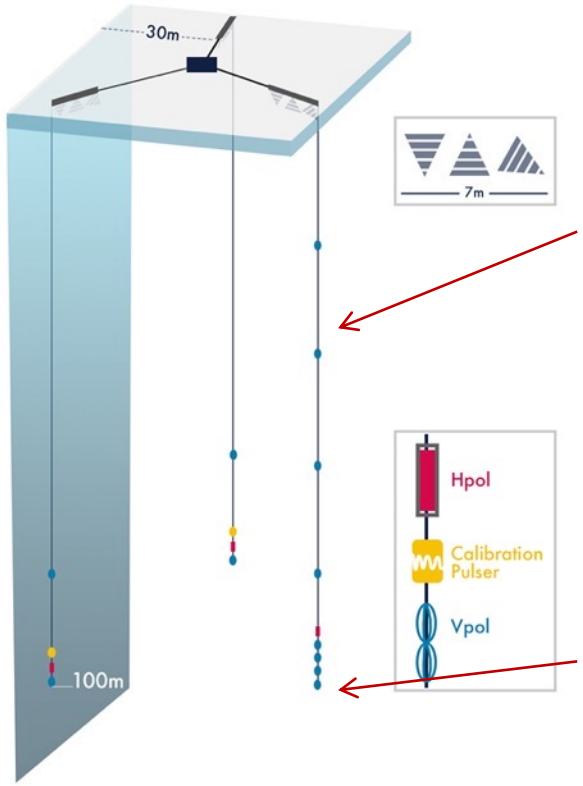
# The IceCube-Gen2 Facility



# IceCube-Gen2 Radio

500 km$^2$ radio array

Probes even pessimistic cosmogenic models




Auxiliary antennas for reconstruction

Phased-array for low threshold triggering