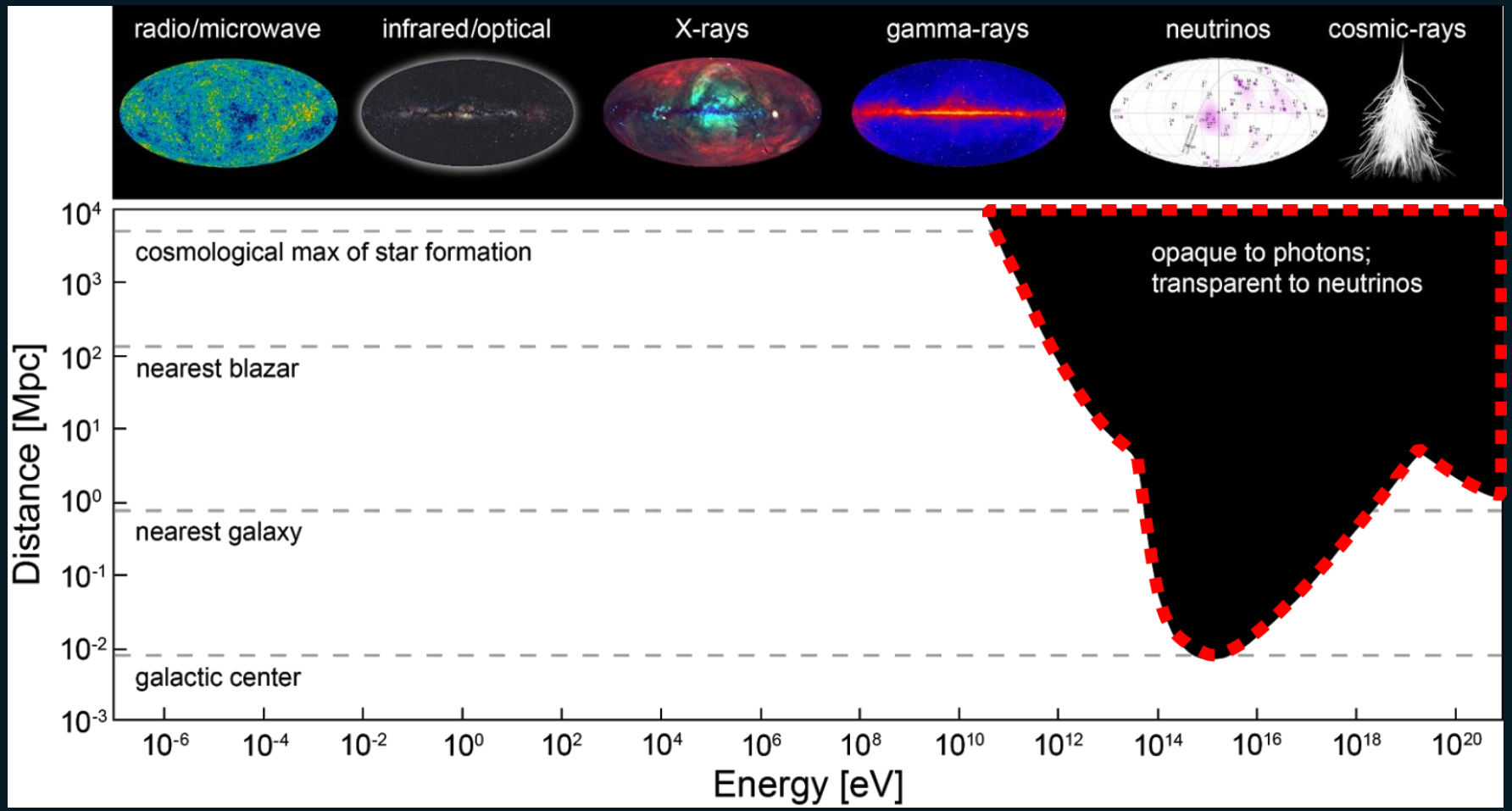
Search for New Physics via Astrophysical neutrino flavour in IceCube

Kareem RHAM Farrag, SEPNet Student Conference

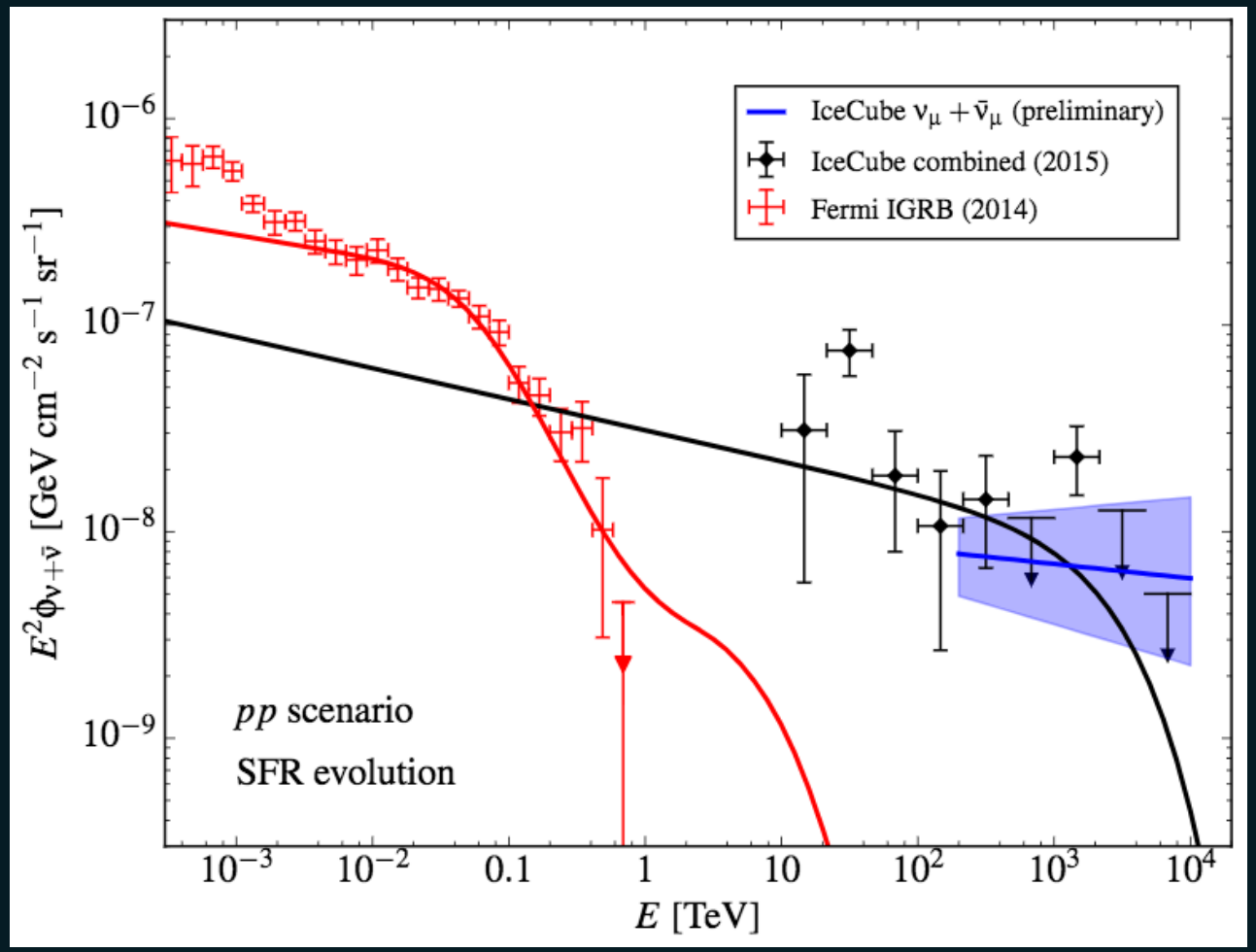
4 April 2019

#PostHiggs #Savethepenguins!

Neutrinos can probe the opaque universe



IceCube Collaboration, 2015



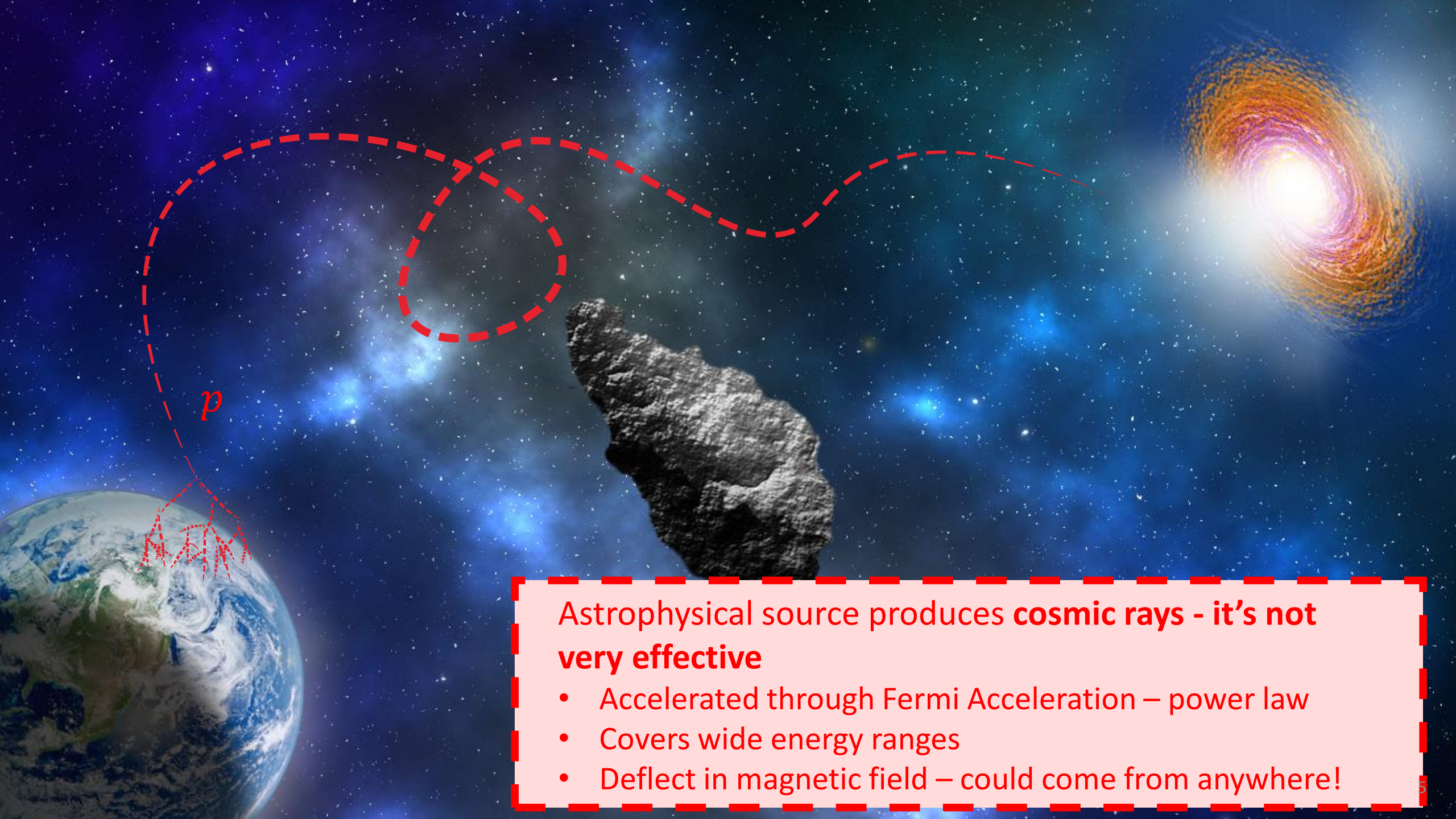
Fluxes of high energy neutrino appear to complete cascade gamma spectrum from Fermi

Consistent with UHECR production mechanisms

Assumed flux (1:1:1) Earth. The flavour composition is then derived varying the normalizations of all three flavours independently

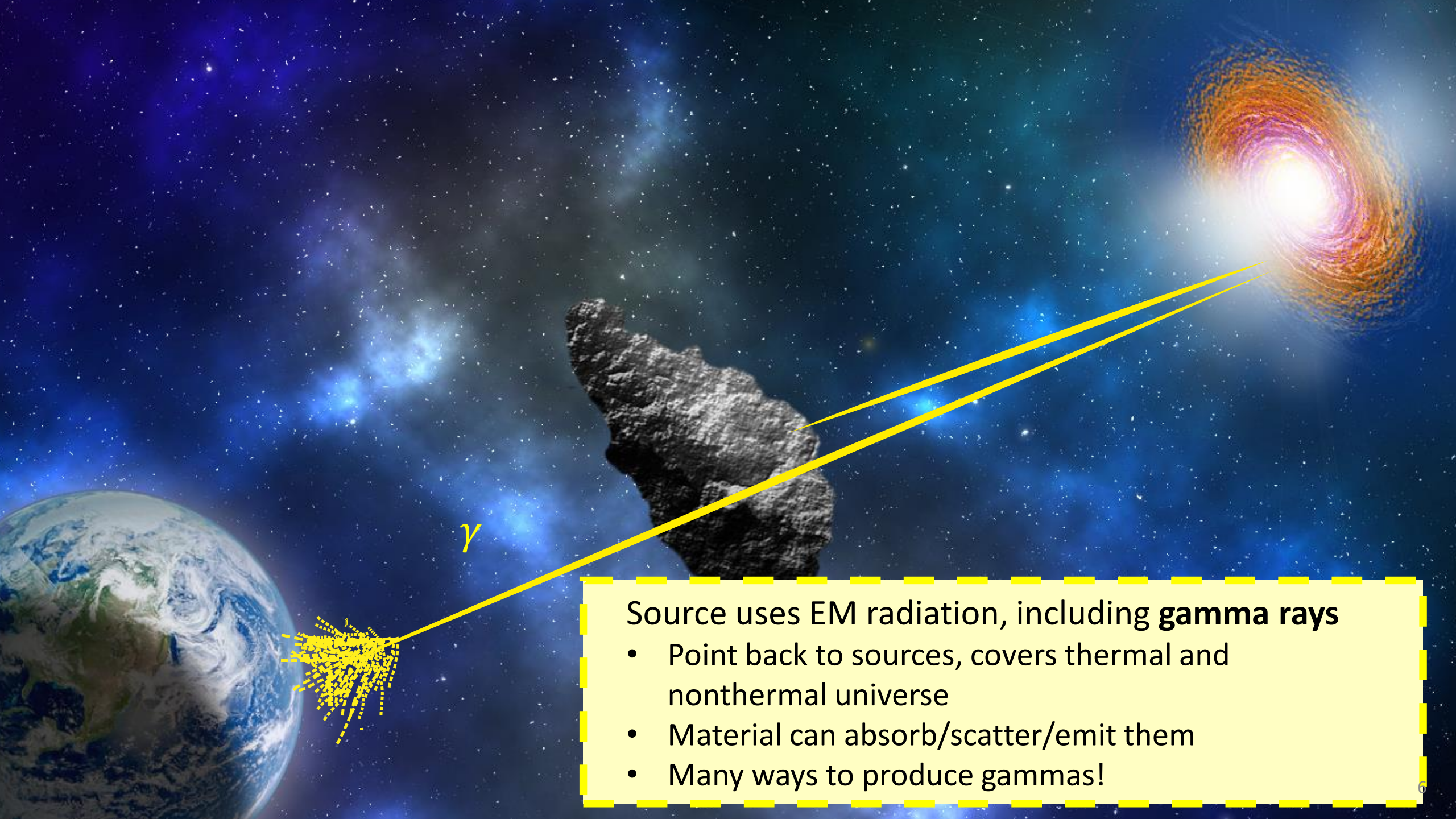
Assumes neutrino energy spectrum is identical (spectral index -2)

Markus Ahlers and Francis Halzen 2015 **Rep. Prog. Phys.** 78 126901



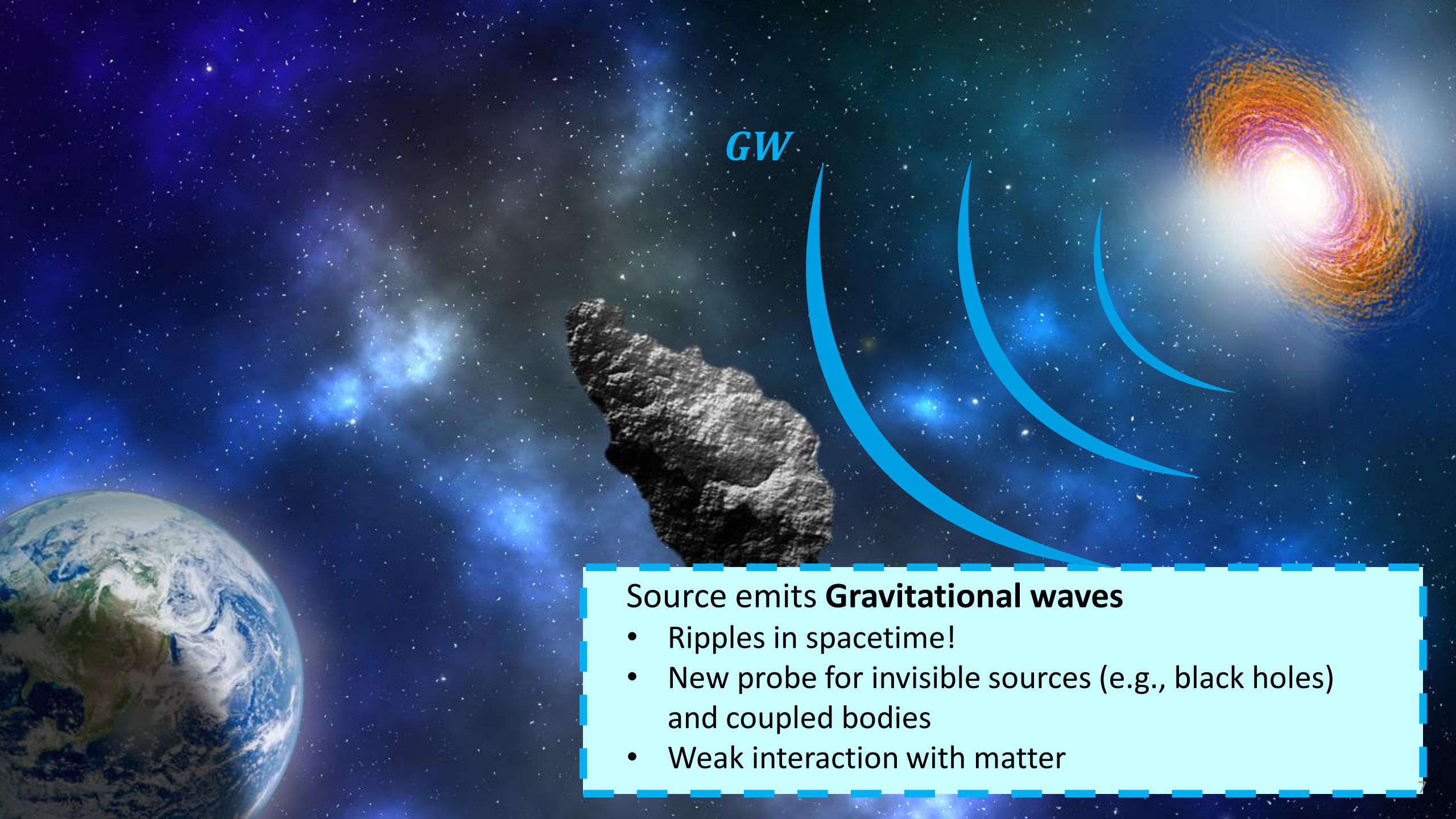
Astrophysical source produces **cosmic rays - it's not very effective**

- Accelerated through Fermi Acceleration – power law
- Covers wide energy ranges
- Deflect in magnetic field – could come from anywhere!



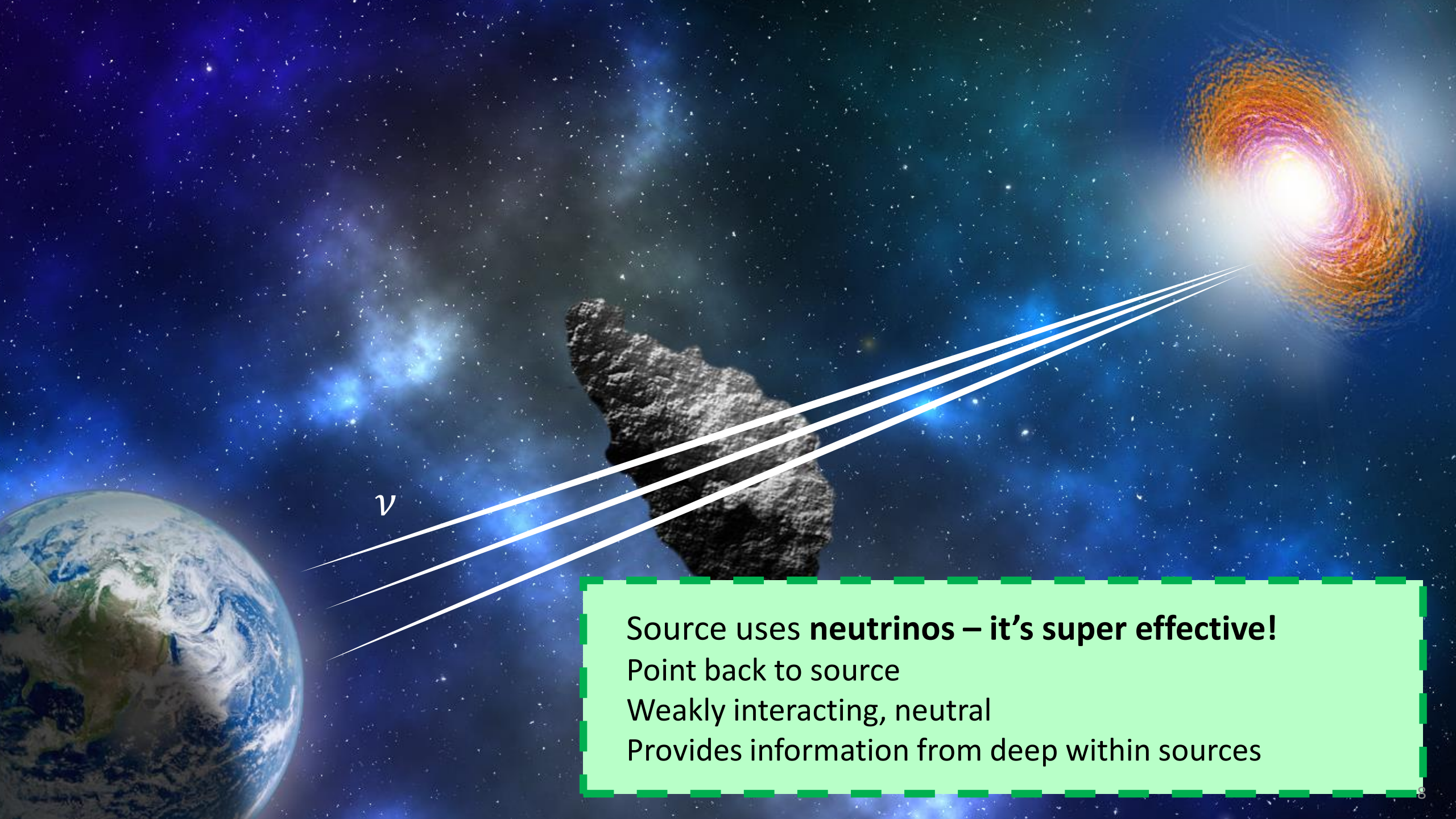
Source uses EM radiation, including **gamma rays**

- Point back to sources, covers thermal and nonthermal universe
- Material can absorb/scatter/emit them
- Many ways to produce gammas!



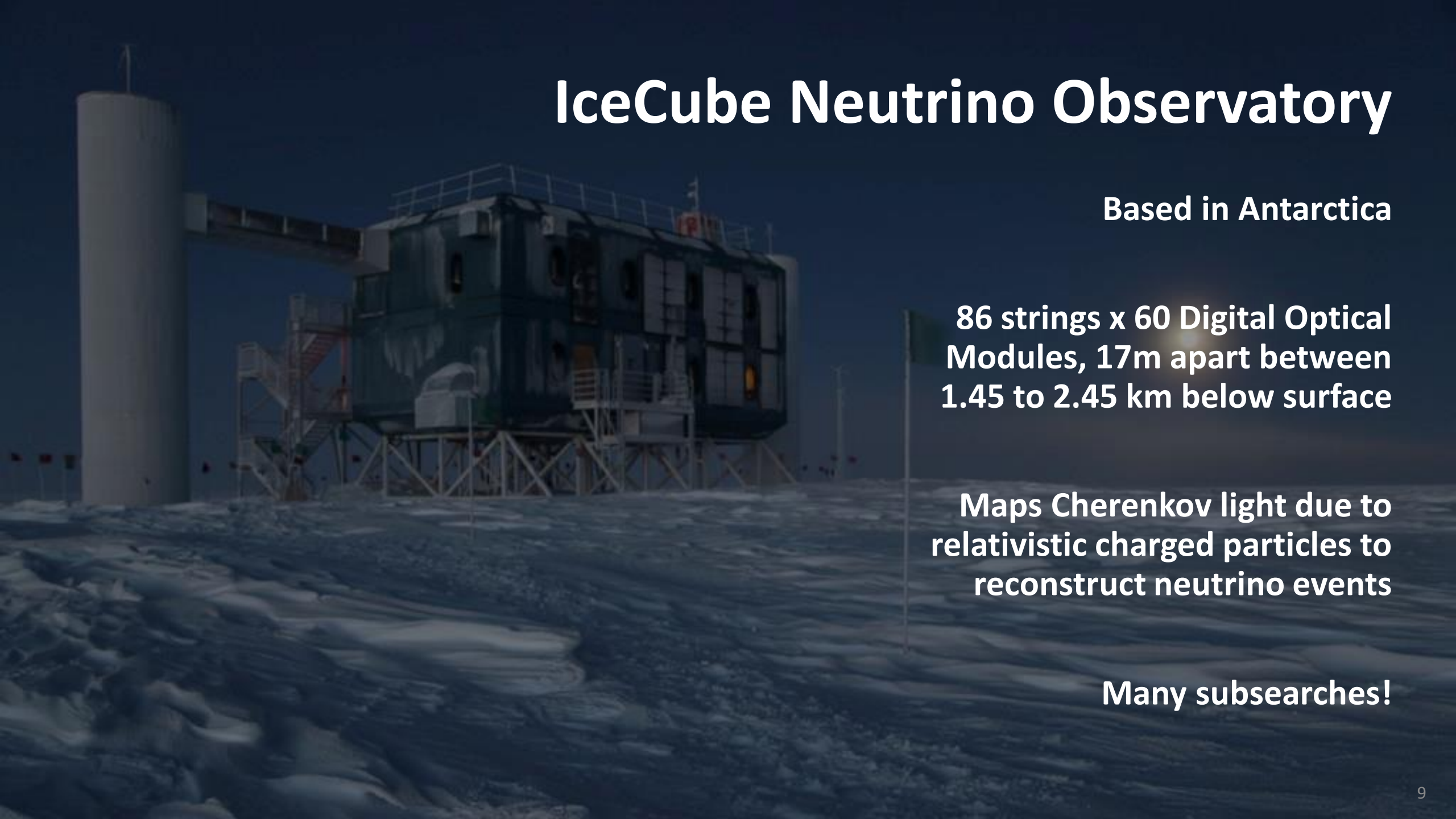
Source emits **Gravitational waves**

- Ripples in spacetime!
- New probe for invisible sources (e.g., black holes) and coupled bodies
- Weak interaction with matter



Source uses **neutrinos – it's super effective!**
Point back to source
Weakly interacting, neutral
Provides information from deep within sources

IceCube Neutrino Observatory



Based in Antarctica

86 strings x 60 Digital Optical Modules, 17m apart between 1.45 to 2.45 km below surface

Maps Cherenkov light due to relativistic charged particles to reconstruct neutrino events

Many subsearches!

IceCube reconstructs for neutrinos

IceCube reconstructs for neutrinos

ENERGY

Info about production region

ANGULAR DISTRIBUTION

Tells us where sources are

FLAVOUR COMPOSITION

Tells us about production mechanism

IceCube reconstructs for neutrinos

Question:

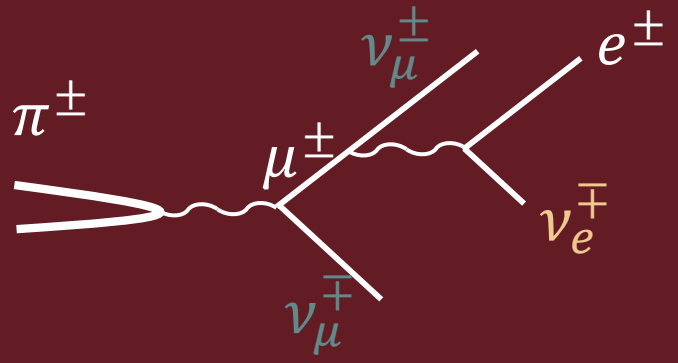
How can we use neutrino flavor ratio to probe New Physics?

FLAVOUR COMPOSITION

Tells us about production mechanism

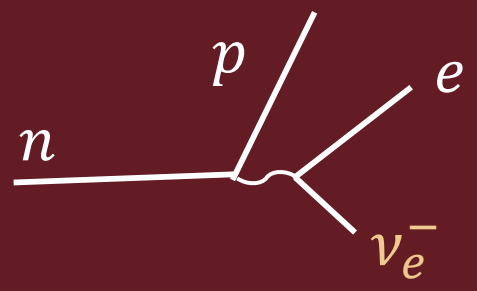
Neutrino Mixing and flavour

There are standard astrophysical production mechanisms for the ratio of different (anti) neutrino flavours



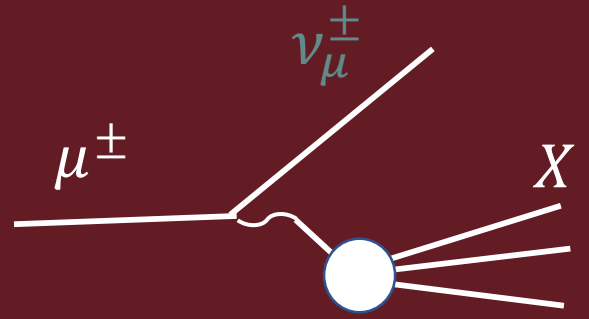
PION PRODUCTION

(1 : 2 : 0)



NEUTRON DECAY

(1 : 0 : 0)



MUON ENERGY LOSS

(0 : 1 : 0)

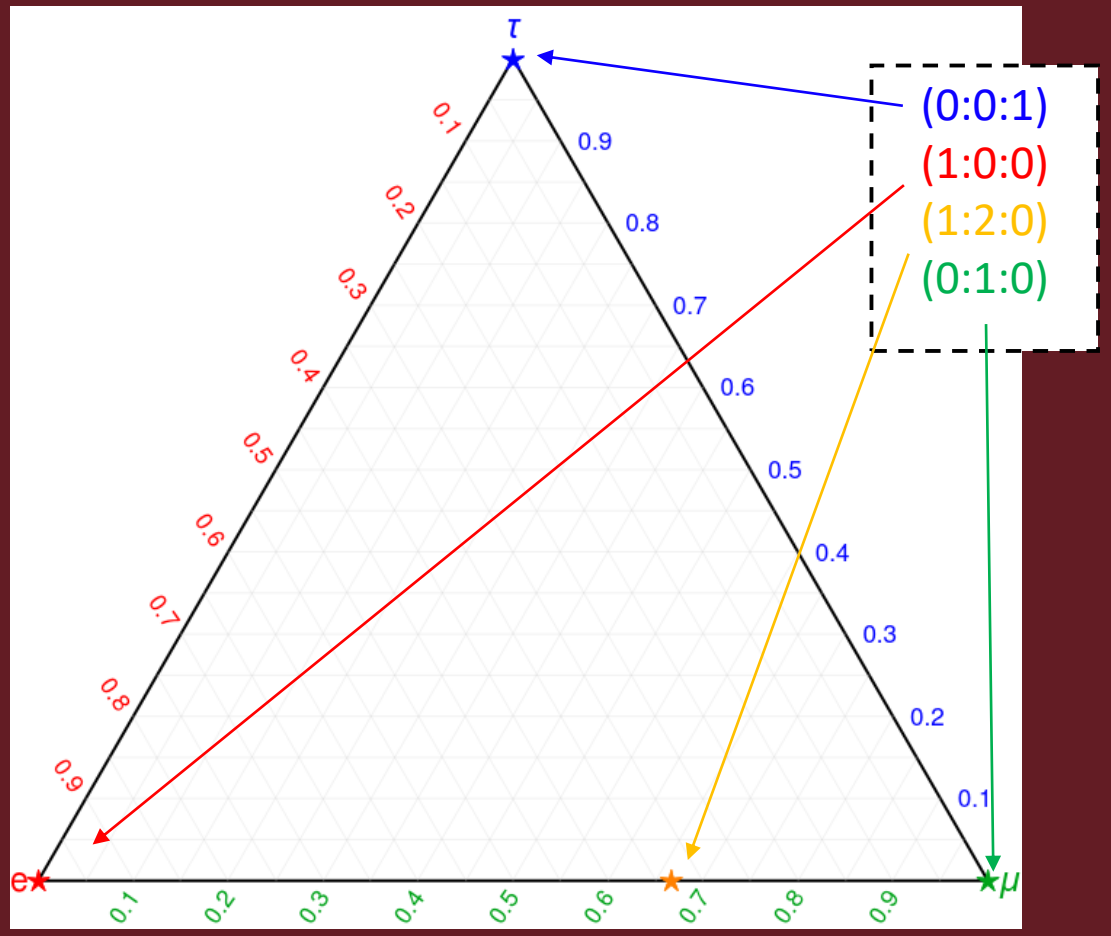
Neutrino Mixing in diffuse neutrinos

Astrophysical neutrinos mix

oscillations die out

$$P_{\alpha\beta} = \sum_i |U_{\alpha i}|^2 |U_{\beta i}|^2$$

Nature will give us a single point on this plot!



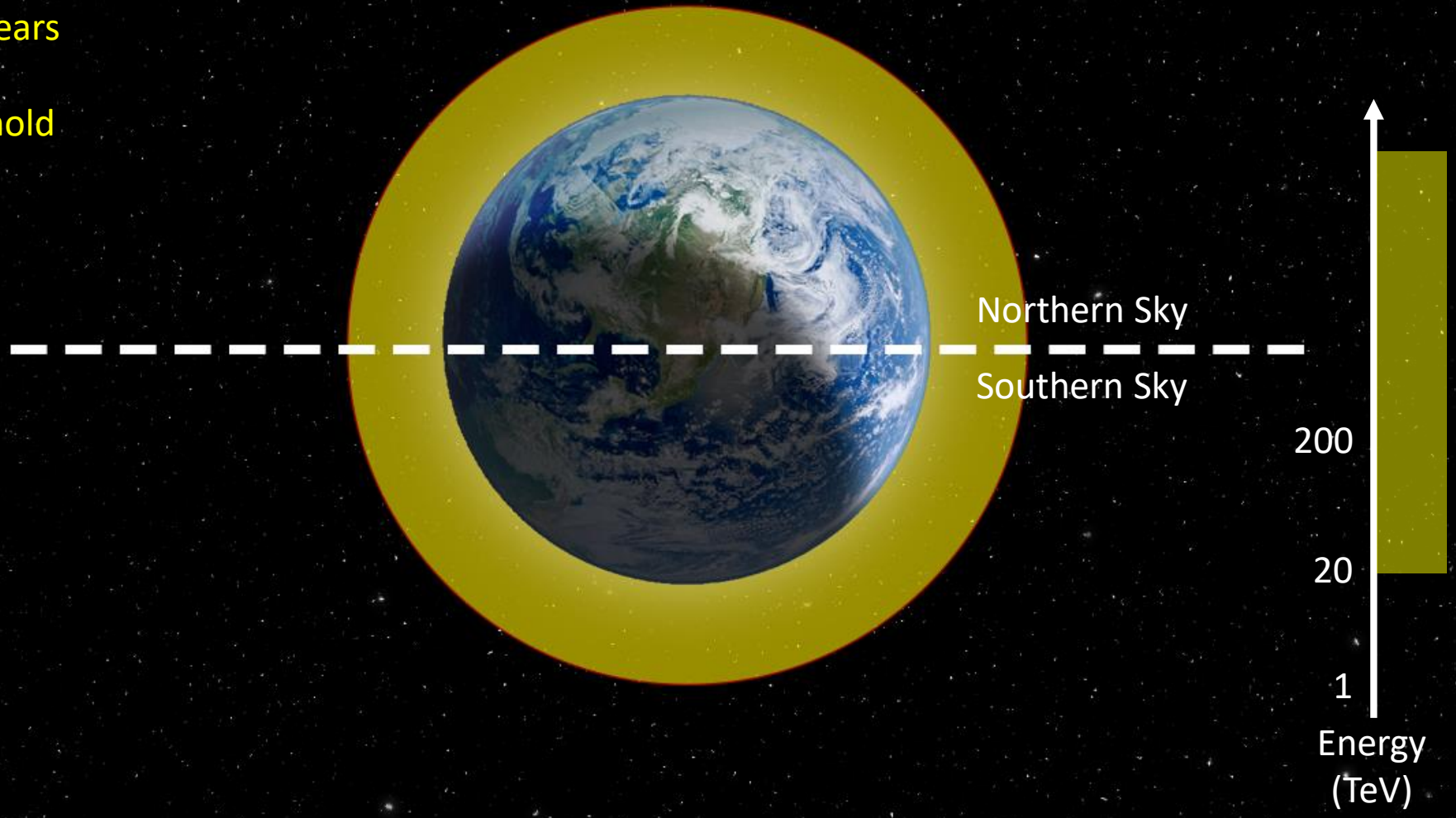
Results from HESE 7.5 year data

#PostHiggs #Savethepenguins!

Some Icecube Event Sets

HESE – High Energy Starting Events

- 103 Events in 7.5 Years
- Full Sky
- High Energy Threshold



M. Chianese, (2018)

Some Icecube Event Sets

HESE – High Energy Starting Events
- 103 Events in 7.5 Years
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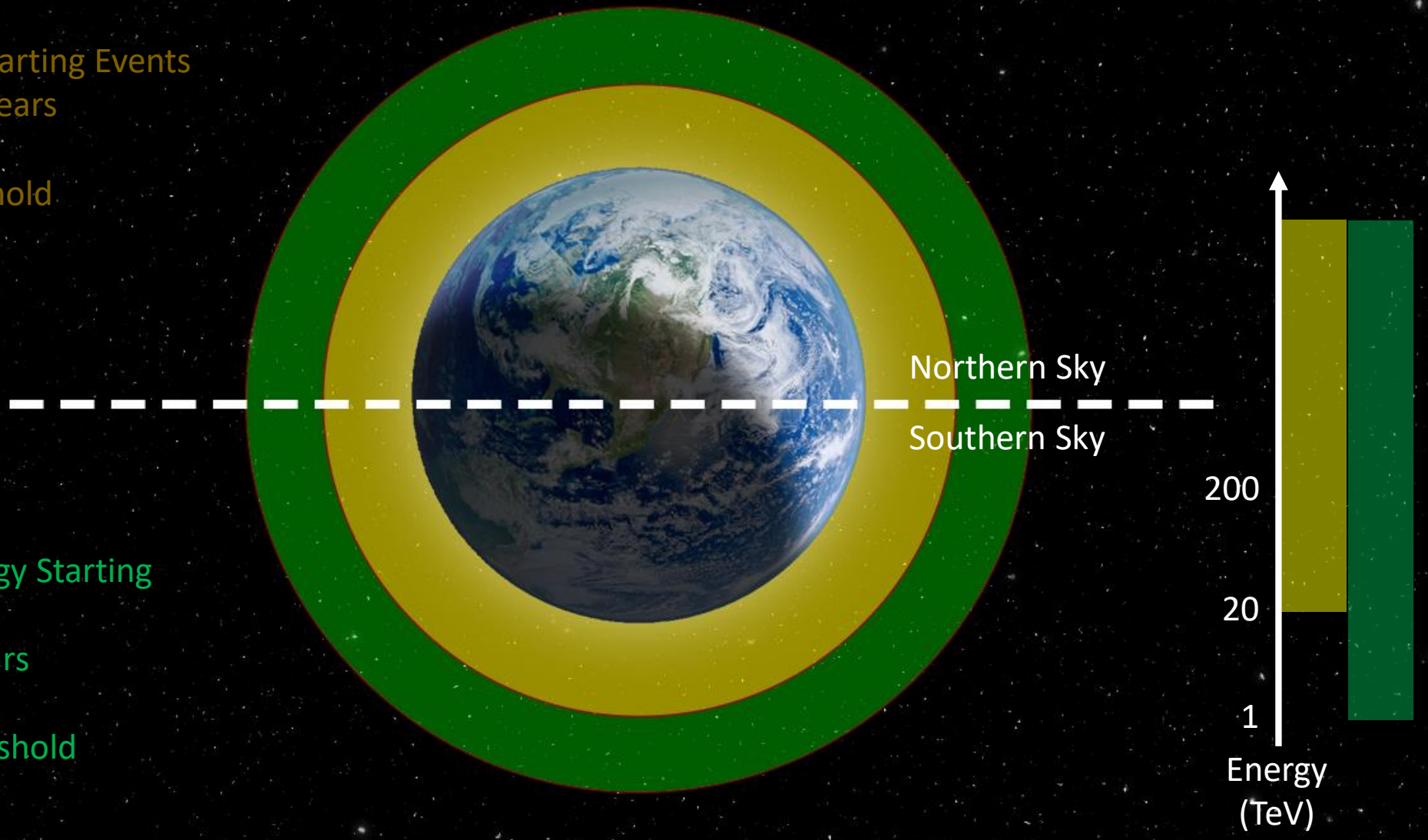
- High Energy Threshold

MESE – Medium Energy Starting Events
- 388 Events in 6 Years
- Full Sky
- Lower Energy Threshold



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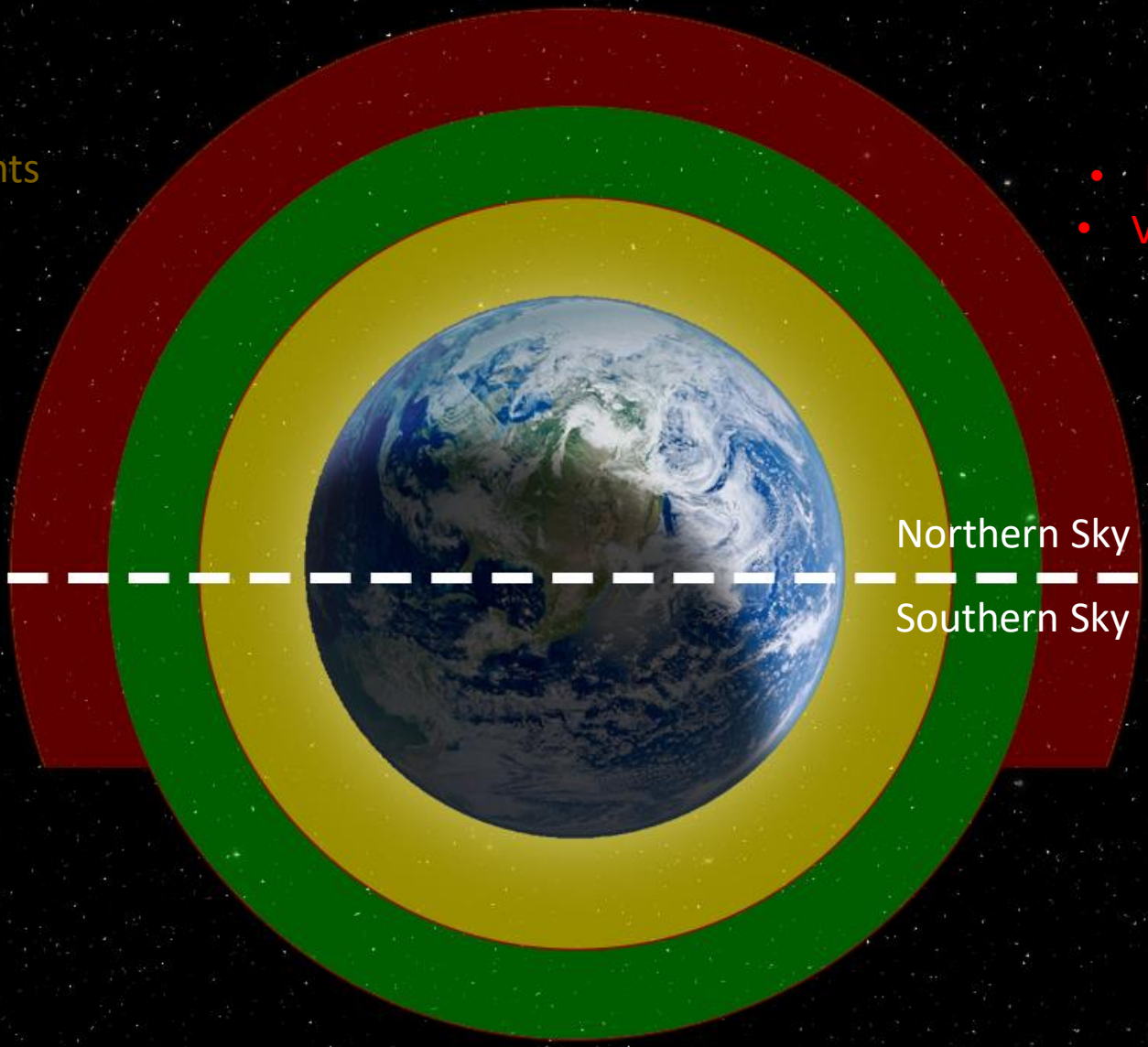
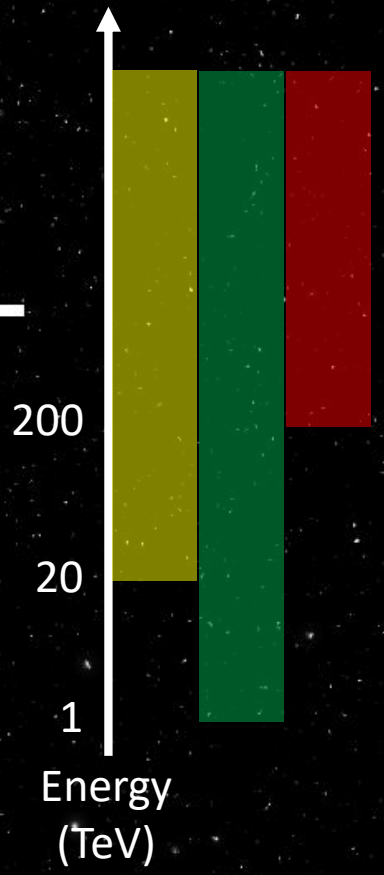


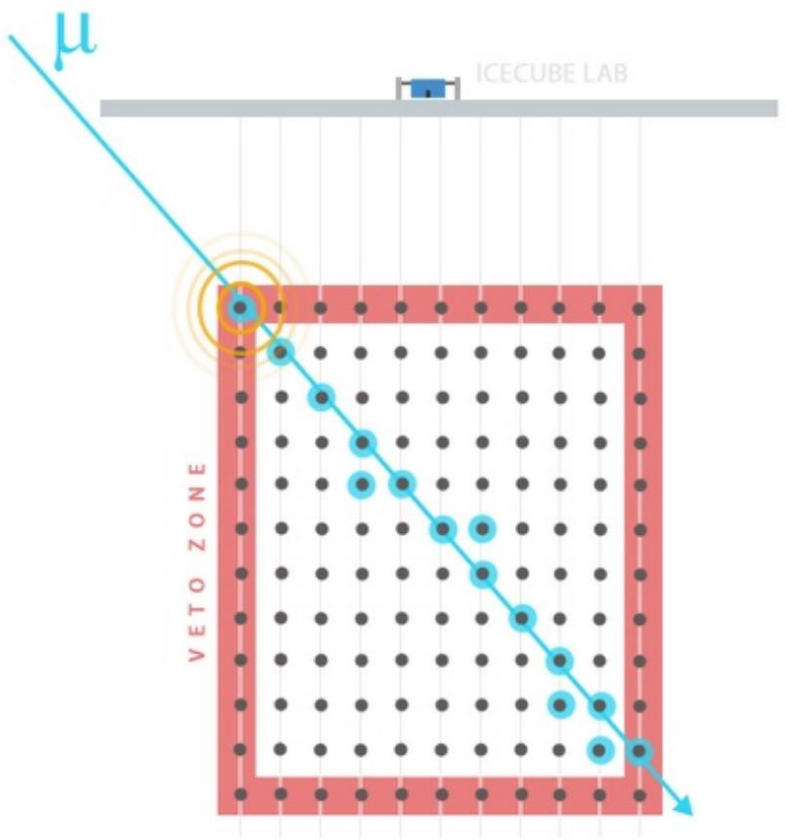
Upgoing ν_μ
- O(10) Events in 8 Years
- Mainly north sky (upgoing)
- Very High Energy Threshold



M. Chianese, (2018)

HESE

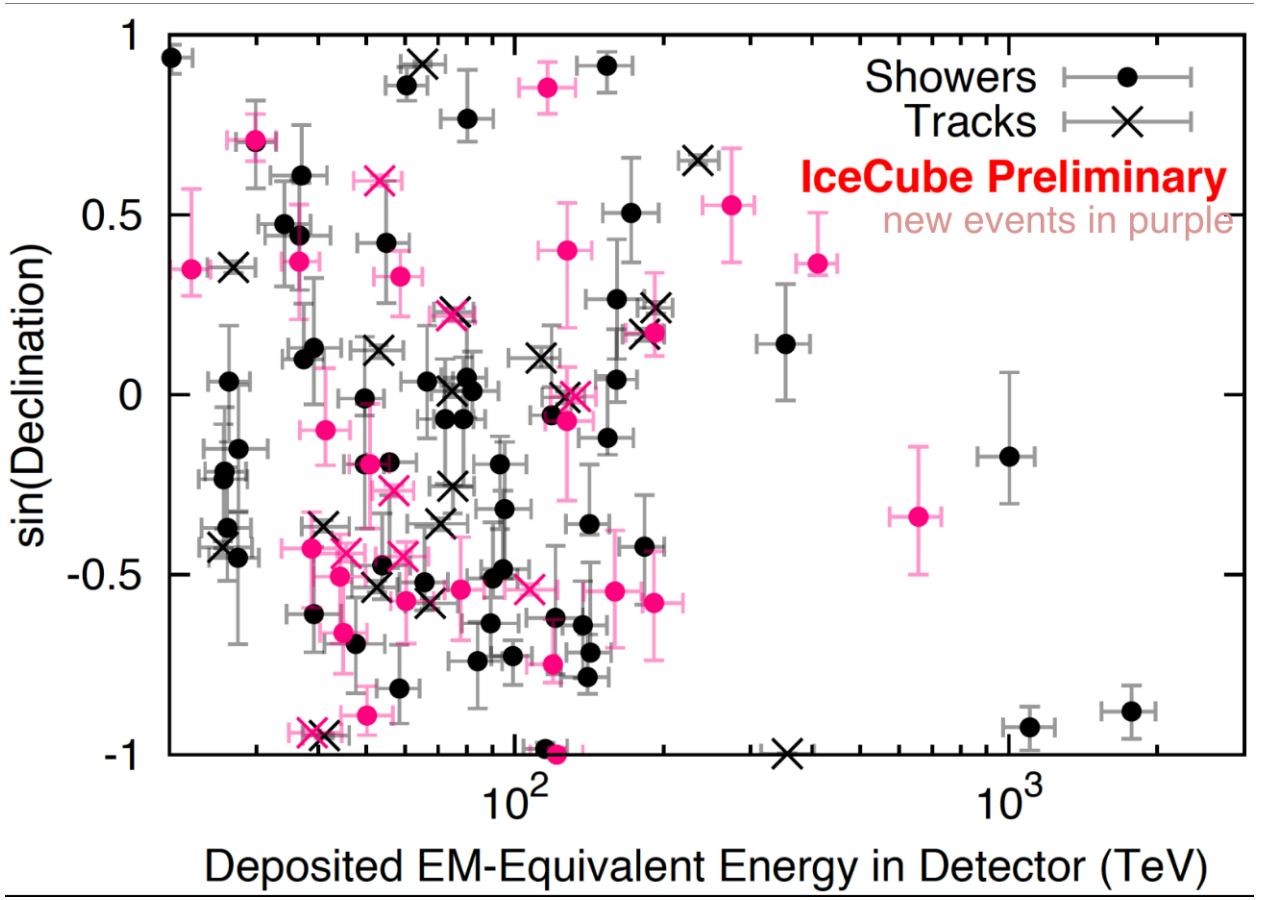
- Contained Search at High energies
- Cut total charge deposited > 6000 photoelectrons
- Most sensitive above 60 TeV
- Outer layer acts as veto for atmospheric muon starting and indirect veto of atmospheric neutrino background, which travel from **outside inner detector region**



The IceCube collaboration (2017)

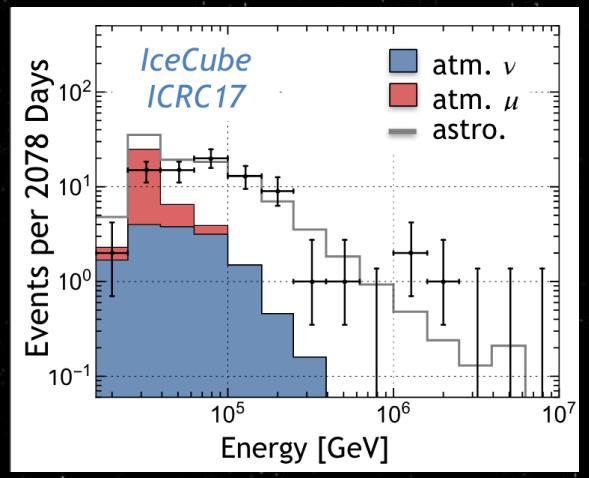
HESE 7.5 Data

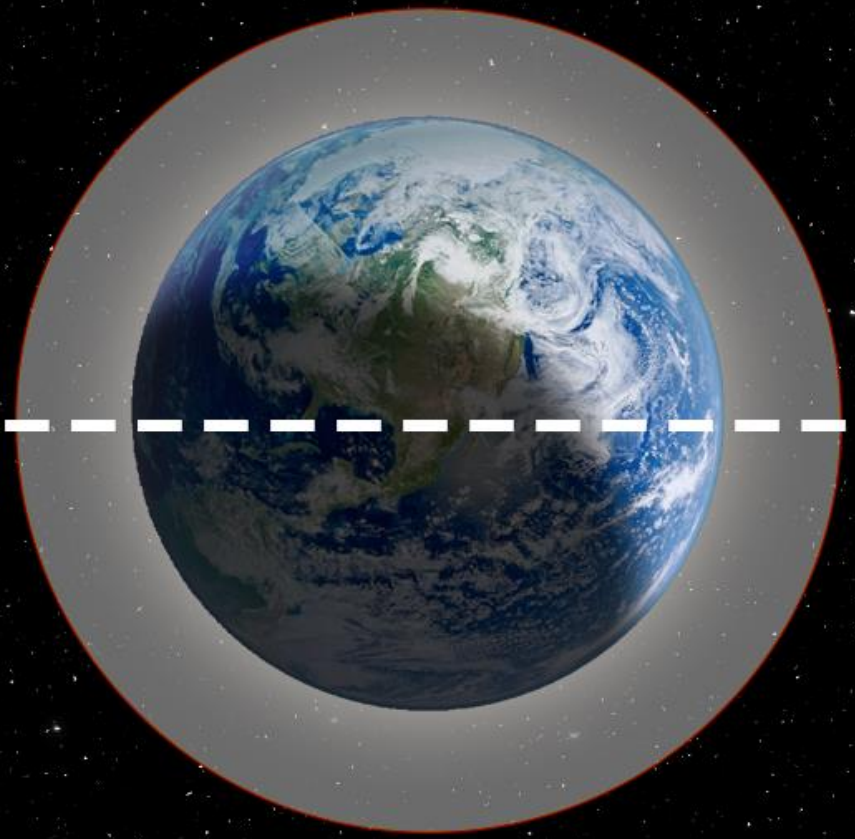
- 103 events in 7.5 Years
- 60 Events > 60 TeV deposited energy
- >75% Astrophysical purity
- Improved calibration and reconstruction
- Spectral index fit largely unchanged
- $\gamma = 2.87 \pm 0.3$
- Work ongoing



The IceCube collaboration (2017)

Backgrounds and Systematics





Northern Sky

Southern Sky

Atmospheric Background

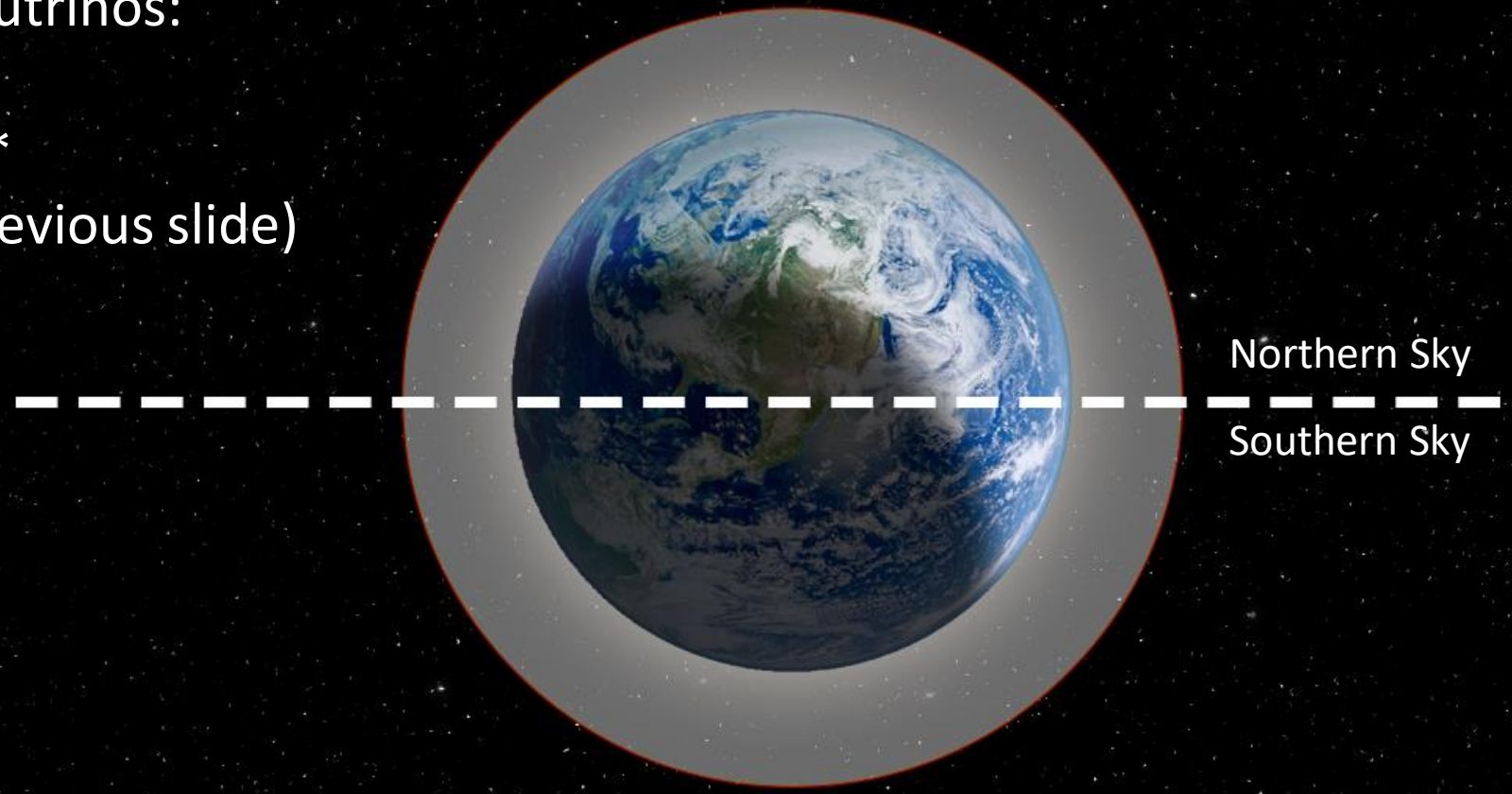
- Penetrating Muons
- Conventional Neutrinos (from π, K decays)
- Prompt Neutrinos (from c-meson decays)

M. Chianese, (2018), The IceCube collaboration (2018)

Backgrounds and Systematics

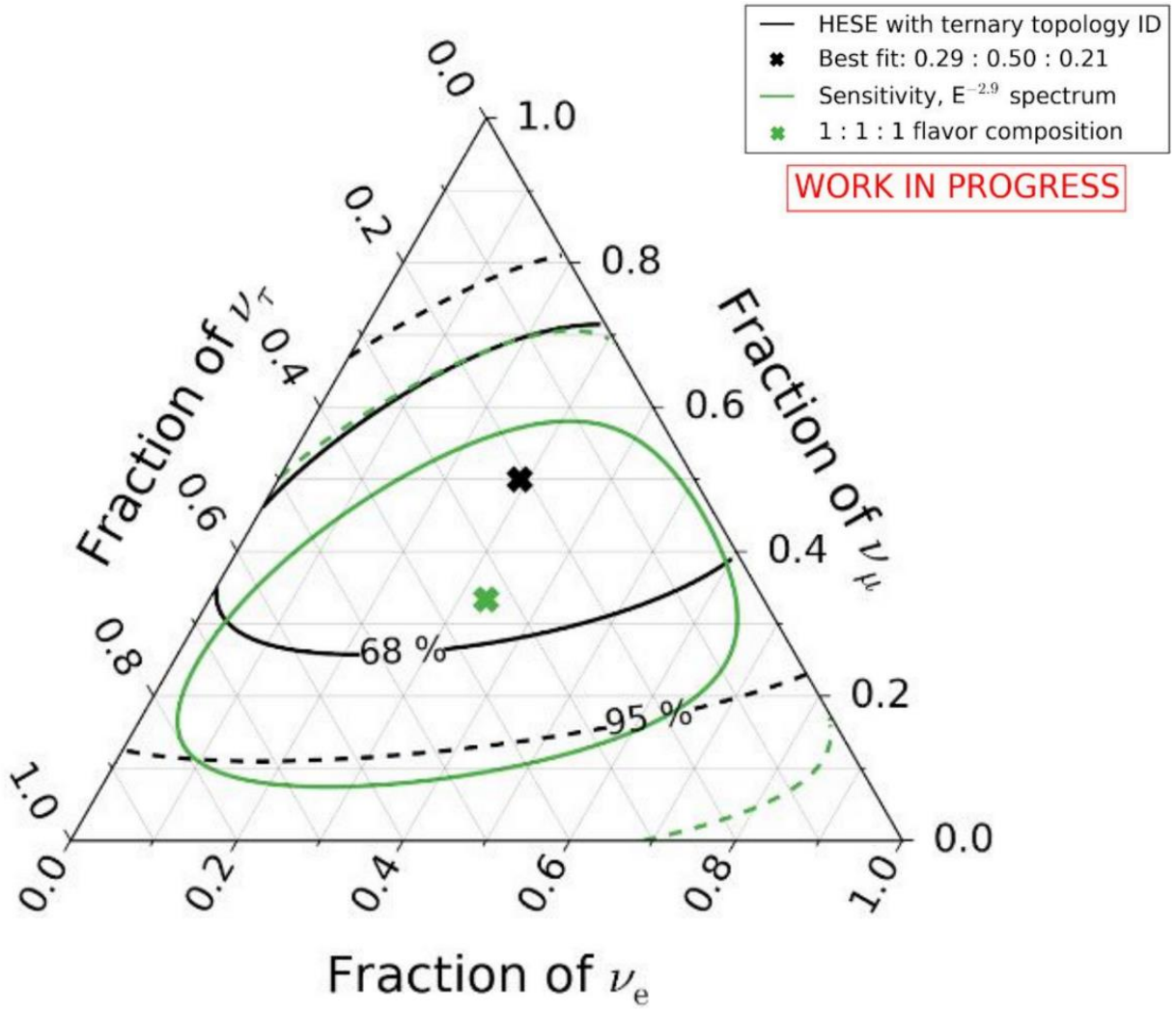
Most relevant systematics to astrophysical neutrinos:

Passing fraction*
Backgrounds (previous slide)
Ice Model



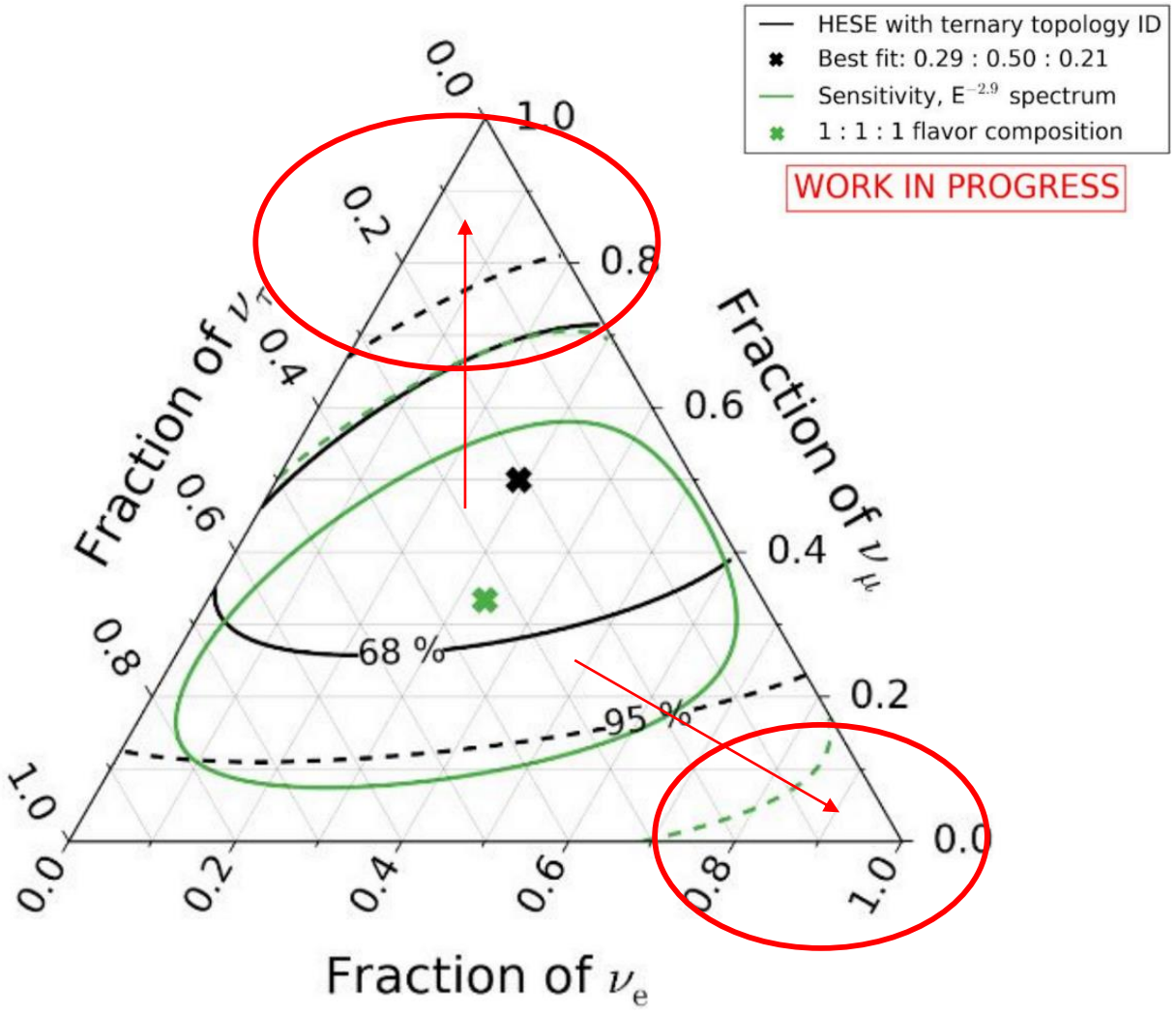
M. Chianese, (2018), The IceCube collaboration (2017)

Standard Model Analysis



Standard Model consistent with (1:1:1) neutrino flux admixture

Standard Model Analysis + **New Physics**



Standard Model consistent with (1:1:1) neutrino flux admixture

New physics can drive us outside the (1:1:1) bubble (SME Formalism)

If we attain an anomalous flavor ratio, then we discover new physics!

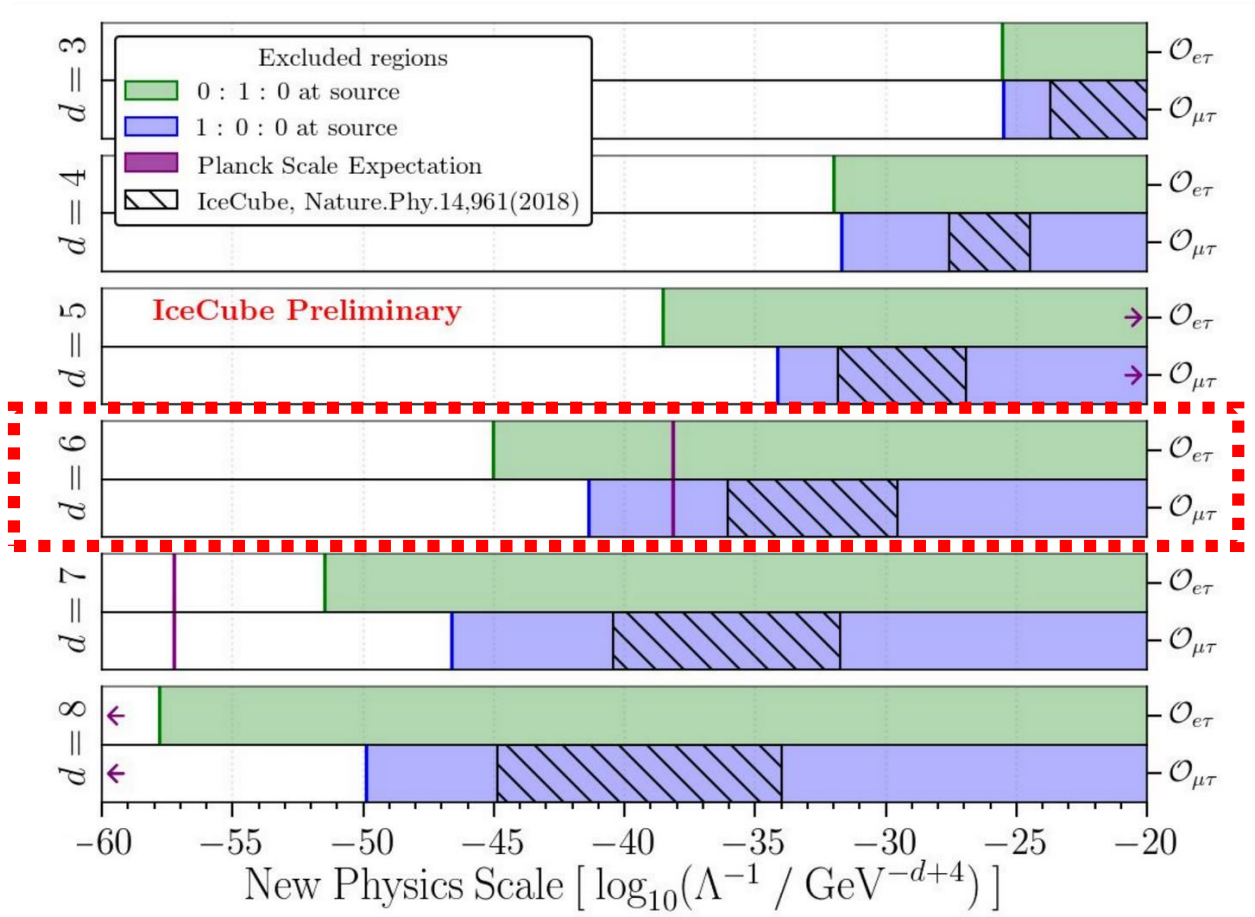
This did not happen with Lorentz Violation (yet…)

IceCube places limits on the scale of new physics scenarios in an effective framework

CPT-odd (dimension-3)
$<2.0 \times 10^{-24}$ GeV

CPT-even (dimension-4)
$<2.8 \times 10^{-28}$ GeV

Some of strongest limits!



IceCube Collaboration, *Nature Physics* **Volume 14**, 961–966 (2018)

Summary

- Neutrino Flavour can describe production mechanisms
- In the presence of new physics, we may see anomalous flavour composition in the diffuse neutrino flux
- We didn’t find Lorentz Violation, but set competitive limits

#PostHiggs #Savethepenguins!

Backups

Analysis Summary - LV

- Use SME Formalism, parameterizing new physics in an effective Hamiltonian

$$H_d = \frac{1}{2E}\, U\, M^2\, U^\dagger + \sum_{d>3} \left(\frac{E^{d-3}}{\Lambda_d} \right) \tilde{U}_d\, O_d\, \tilde{U}_d^\dagger$$

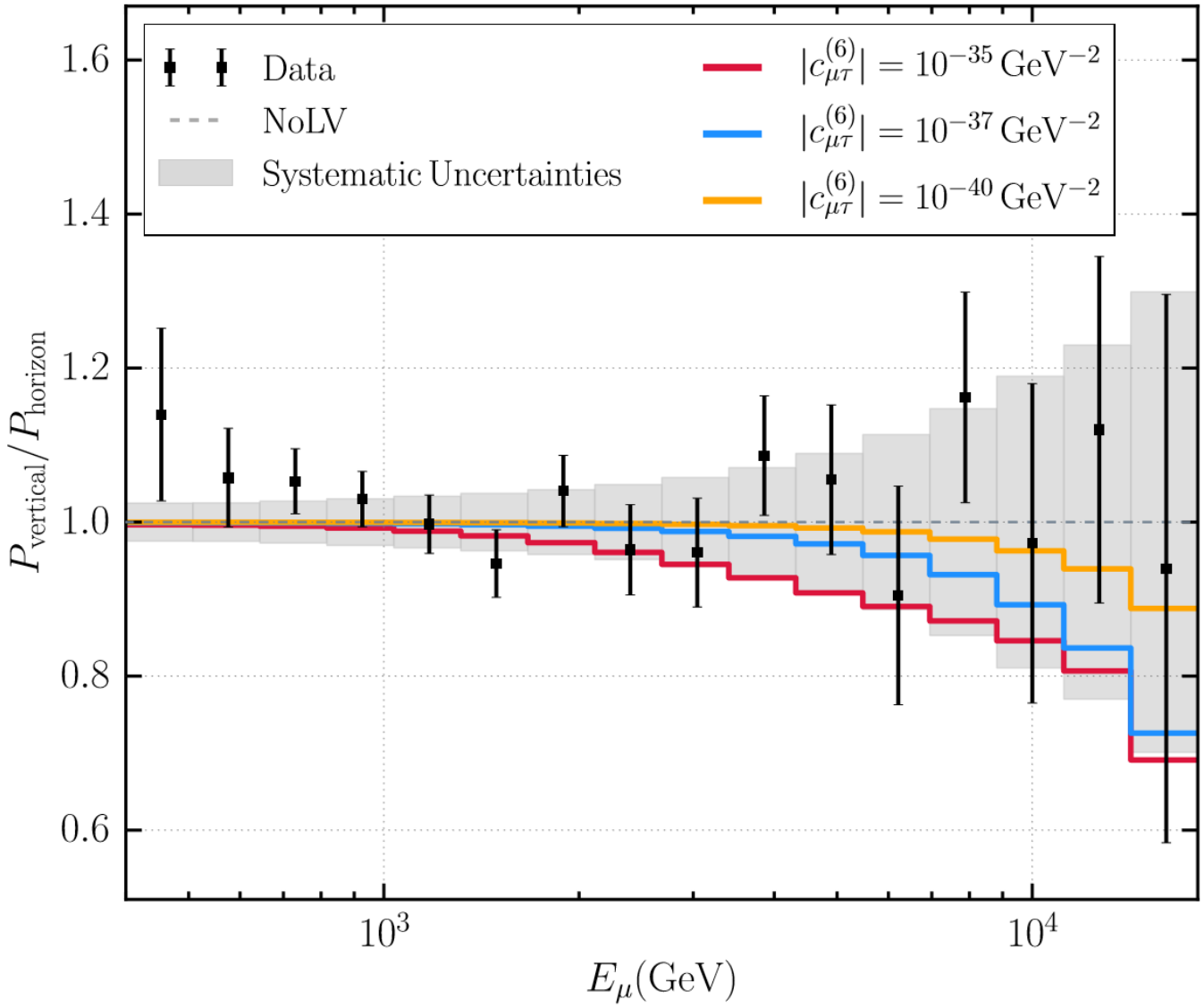
- 20 Bins from 60 TeV – 10 PeV for HESE 7.5 year
- Zenith -1 < cos <1 in 10 bins
- Anarchic Sampling for prior elements
- Bayesian Monte Carlo Markov chain to retrieve posteriors
- Wilk's theorem for best fit

IceCube Collaboration, *Nature Physics* **Volume 14**, 961–966 (2018)

Analysis Summary - LV

Earth acts as as interferometer with different baselines

Transition probabilities consistent up to O(10 TeV)

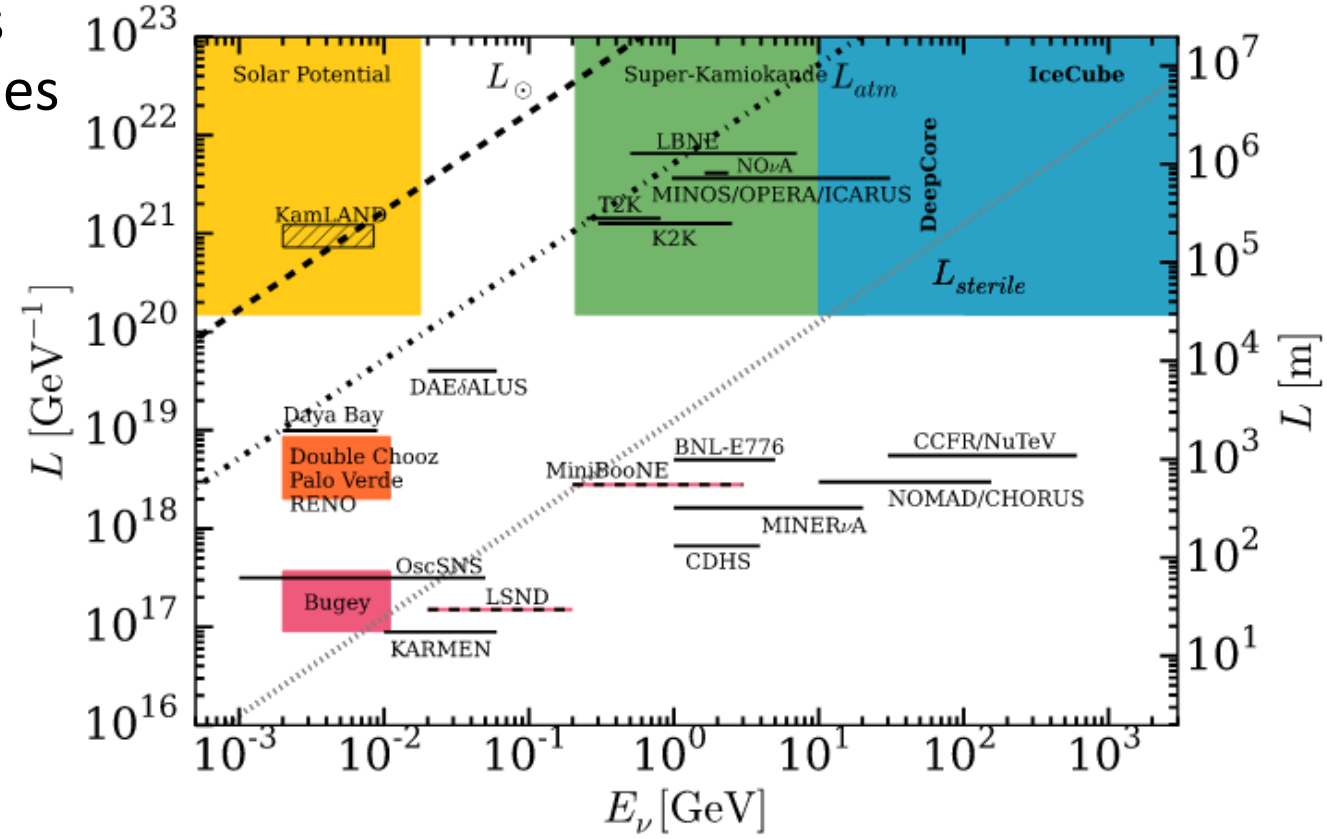


IceCube Collaboration, Phys. Rev. D, 10.1038 (2017)

IceCube is a great detector…

- The neutrino experimental landscape is rich and diverse in baselines and energies
- But…

Astrophysical neutrinos lie elsewhere on this plot…



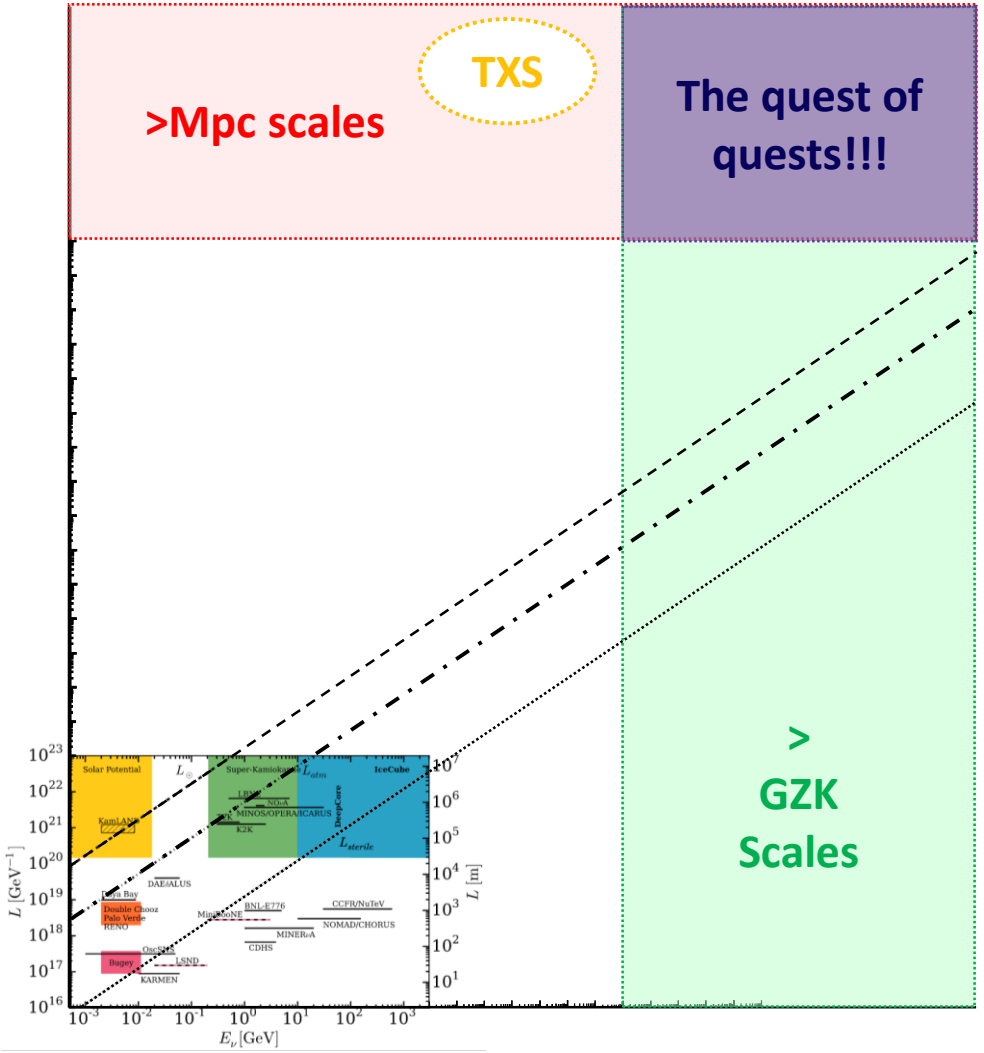
Kostelecký, Mewes Phys. Rev. D 69, 016005 (2004)

…to probe astrophysical scales!

- The neutrino experimental landscape is rich and diverse in baselines and energies
- But…

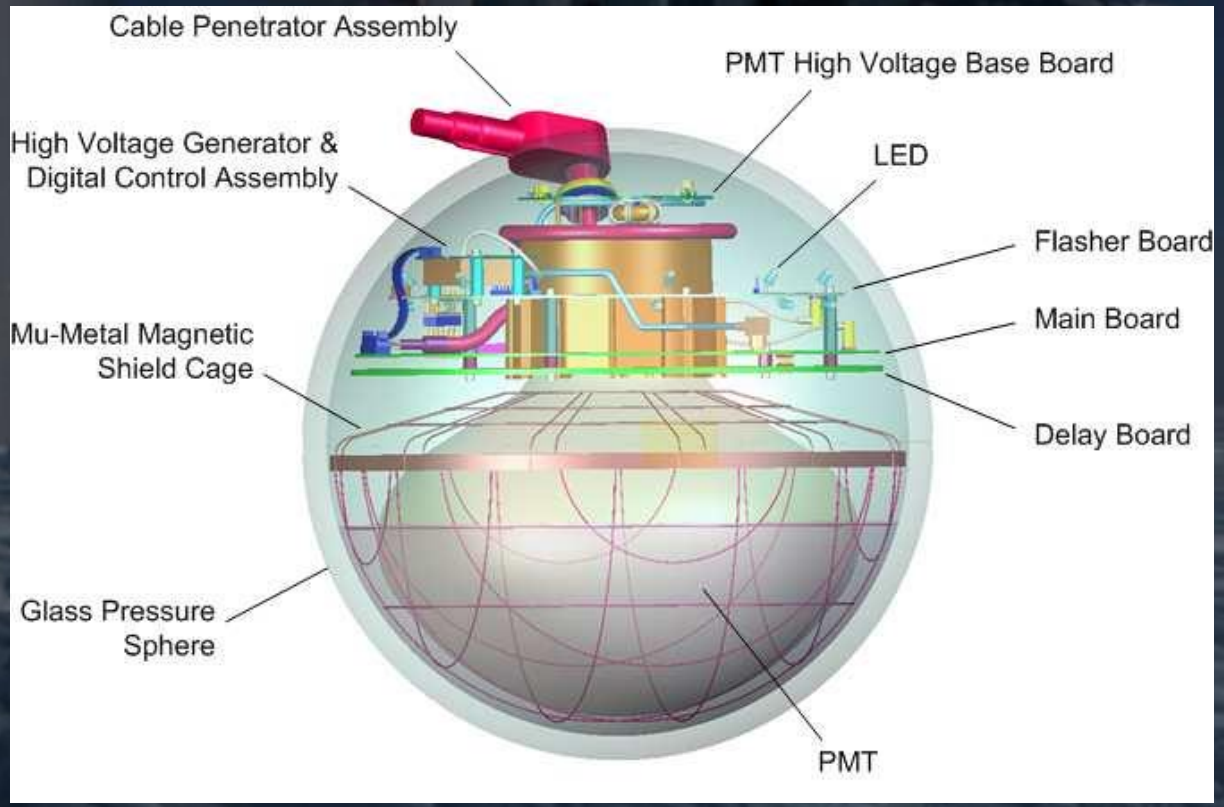
  Astrophysical neutrinos lie elsewhere on this plot, and Icecube has observed some!

- Much of the astrophysical landscape is left that we should probe!



Kostelecký, Mewes Phys. Rev. D 69, 016005 (2004)

Digital Optical Module



Autonomous light detecting unit

Detects light (350-650nm)

PMT Quantum efficiency 25-45% @ 1.5 kV

Gain ~ O(10^7)

Digitizes waveforms (plot of voltage wrt time)

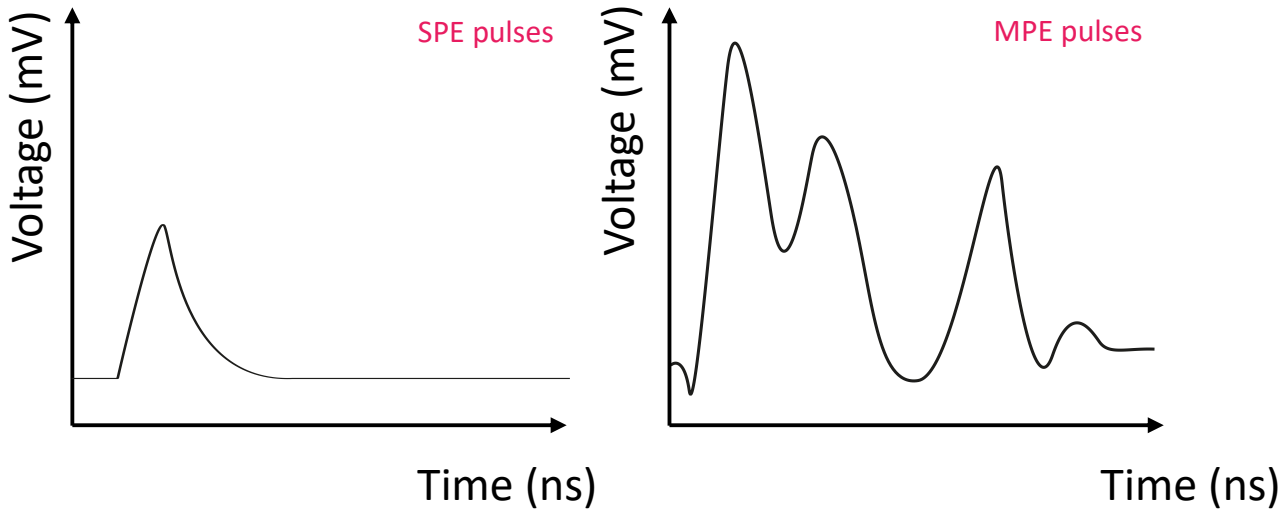
ATWD, 3 channels, 300 Megasamples/sec, pulse window 427ns (short waveforms)

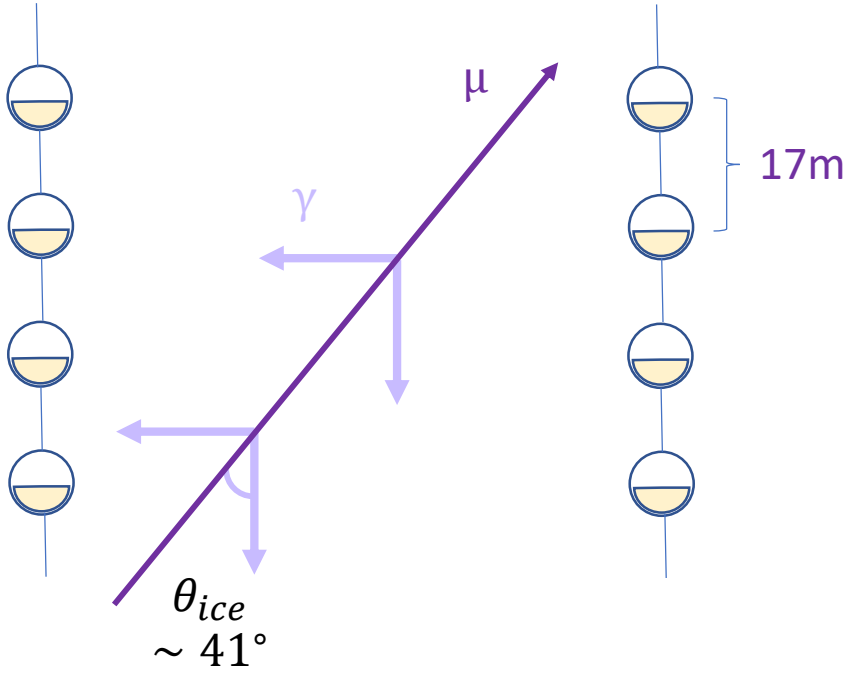
FADC, 1 channel, 40 Megasamples/sec, pulse window 6.4 μs (long waveforms)

Calibration done on board using flasher to 1 photoelectron

Waveform pulses

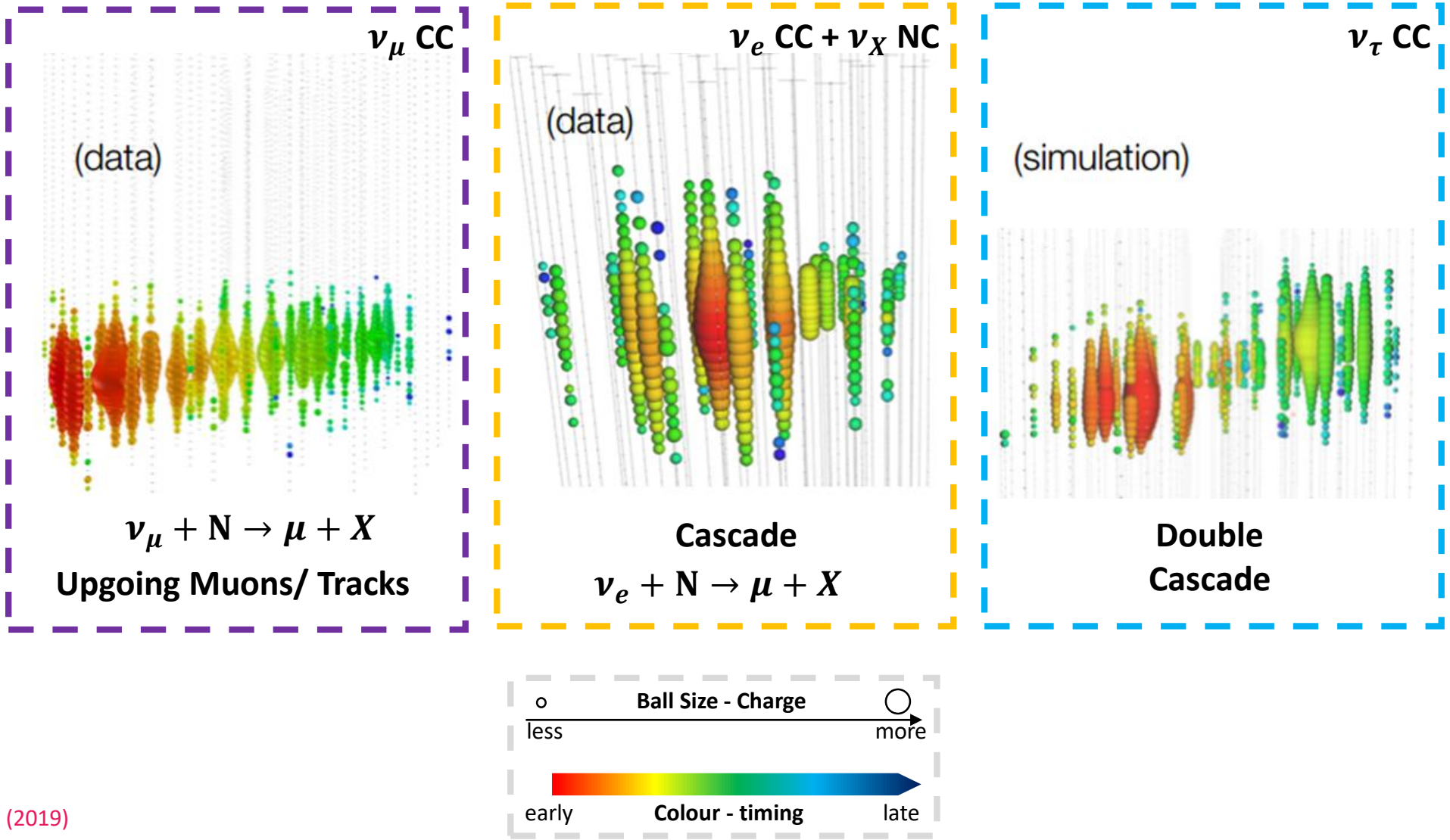
- Light is collected in the array of DOMs
- By stamping the photon arrival times and how many there are, give us information about direction and energies of leptons, and hence allows us to reconstruct properties of incoming neutrinos
- Waveform readouts paired with timestamp





Event topologies infer flavours

- There are three topologies we look for



Icecube Collaboration, (2019)

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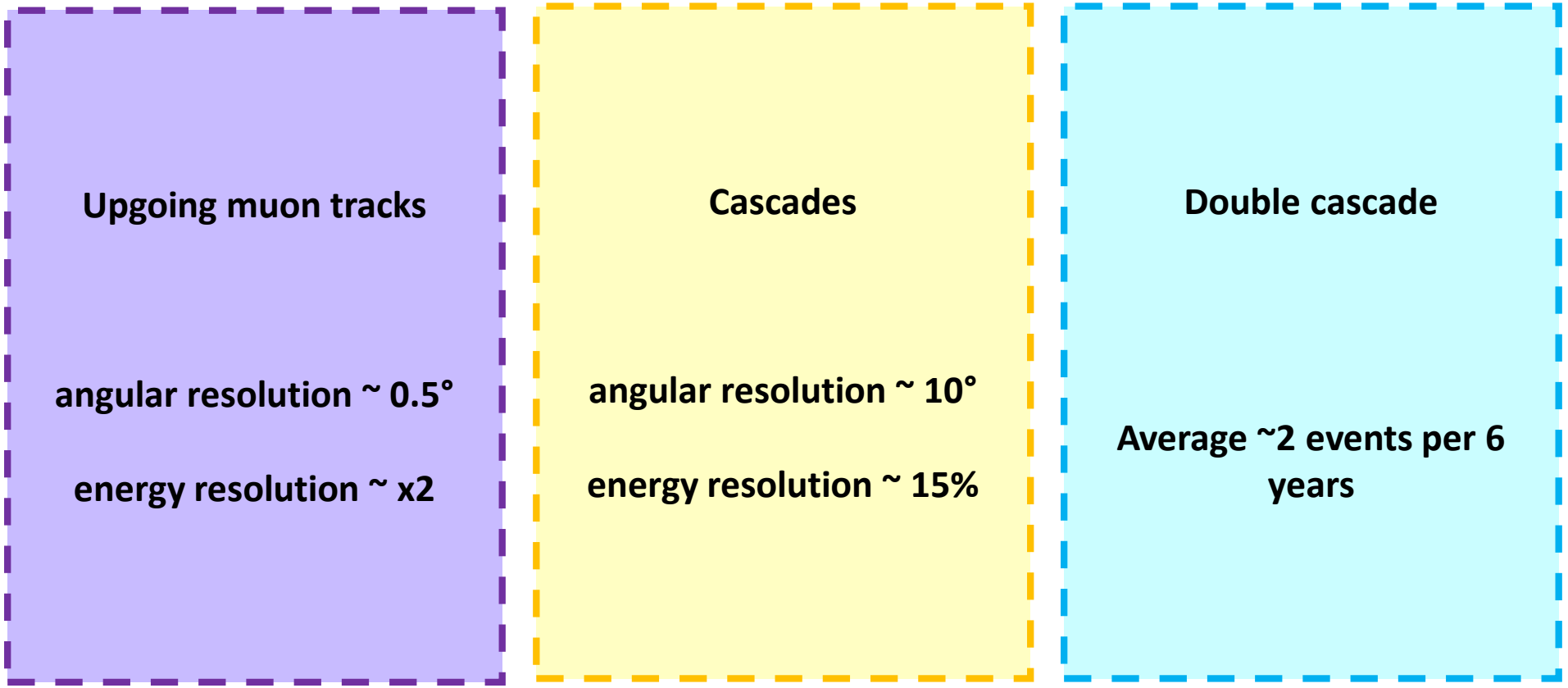

Icecube Collaboration, (2019)

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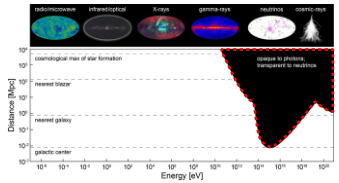
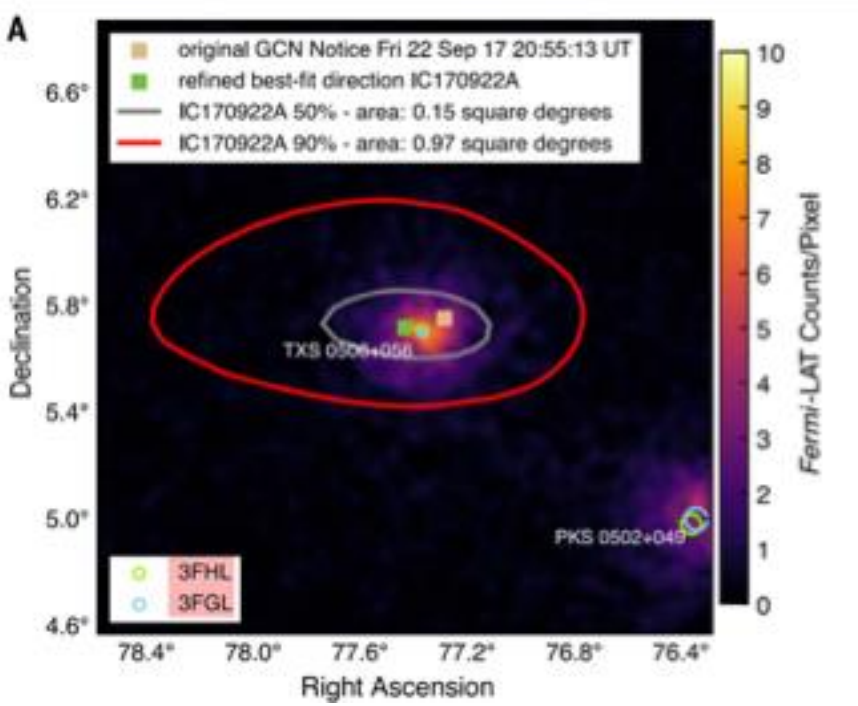


		The Opaque universe			
Energy	**~ MeV**	**GeV-TeV**	**TeV-PeV**	**PeV-EeV**	**> EeV**
Physics	Supernovae	DM, Oscillations, Atmospheric ν	Point sources, GRB, diffuse	GZK Neutrinos, Cosmic Rays	?
Event Signatures/ Topologies	PMT counts go up on average	Tracks, Contained Events	Tracks, Cascade	Tracks, Cascade, Double Cascade, Lollipop	*Sonic the Hedgehog??*

The IceCube Collaboration, **IOPScience** (2015)

TXS 0506 +056

- Blazar:
  - Active galactic nucleus with relativistic jets
  - One jet points at Earth
- TXS
  - $z = 0.3365 \pm 0.0010$
  - 13 Candidate events found
  - Only candidate sources other than Sun and SN1987A



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

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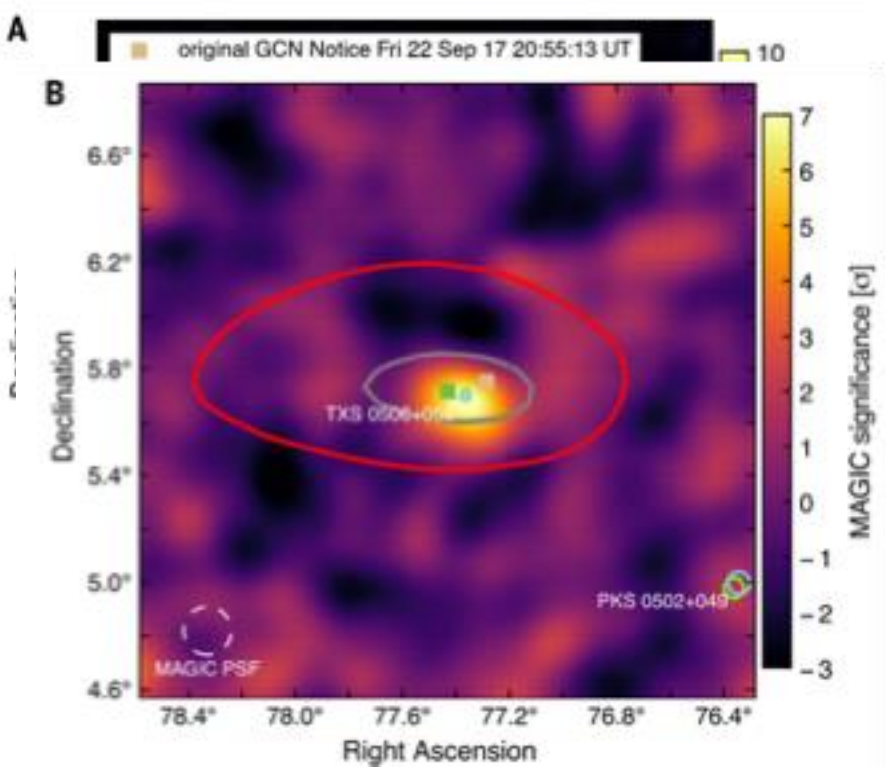
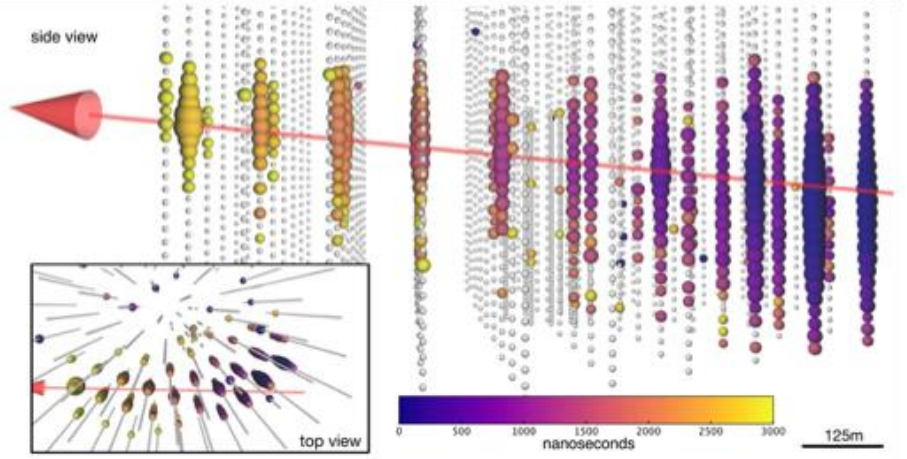
  - One jet points at Earth
- TXS
  - $z = 0.3365 \pm 0.0010$
  - 13 Candidate events found
  - Only candidate sources other than Sun and SN1987
- Significant excess seen by Fermi and MAGIC telescopes shortly after IC alert (3σ)
- Independent flare seen 2014-15 (3.5σ)



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

IC – 170922A

- Upgoing muon track (5.7° below horizon) observed on September 22, 2017
- 311 TeV best fit (assuming E^{-2} spectrum)
- We are awaiting more data!



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

Analysis Summary

- Systematics (6 nuisance parameters)
  - Flux normalisations
    - Conventional (40%)
    - Prompt (free)
    - Astrophysical (free)
  - Flux components
    - Primary Cosmic Ray Index (2%)
    - Astrophysical Neutrinos Index (25%)
    - π/K ratio for conventional flux (10%)

Systematics - Passing Fraction

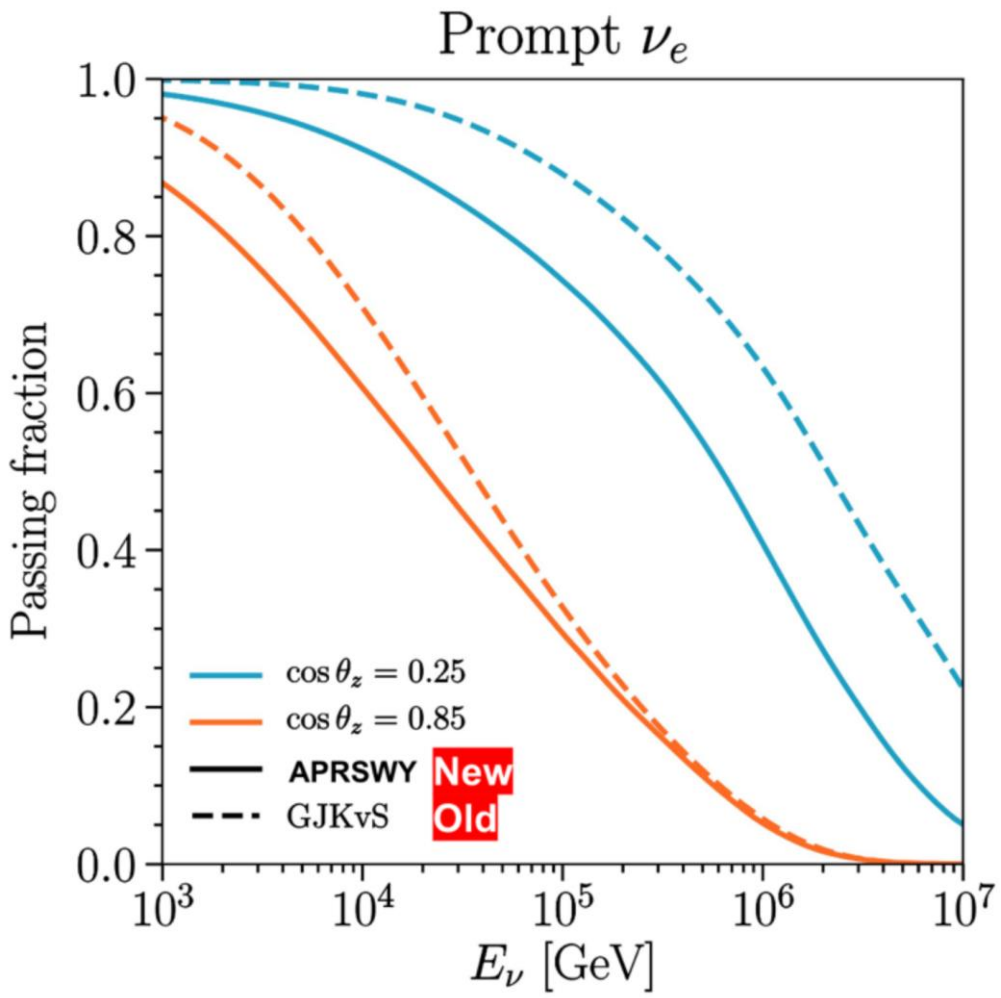
- Passing Fraction :=

Cosmic Ray Flux

× Shower Development

× Muon energy loss

× Detector Response



Schönert, Gaisser, Resconi, Schulz, Phys. Rev. D 79; 043009 (2009) Gaisser, Jero, Karle, van Santen Phys. Rev. D 90; 023009(2014) Argüelles, Palomares-Ruiz, AS, Wille, Yuan JCAP 1807 (2018) no.07, 047