25th CAN Symposium
26 March 2021

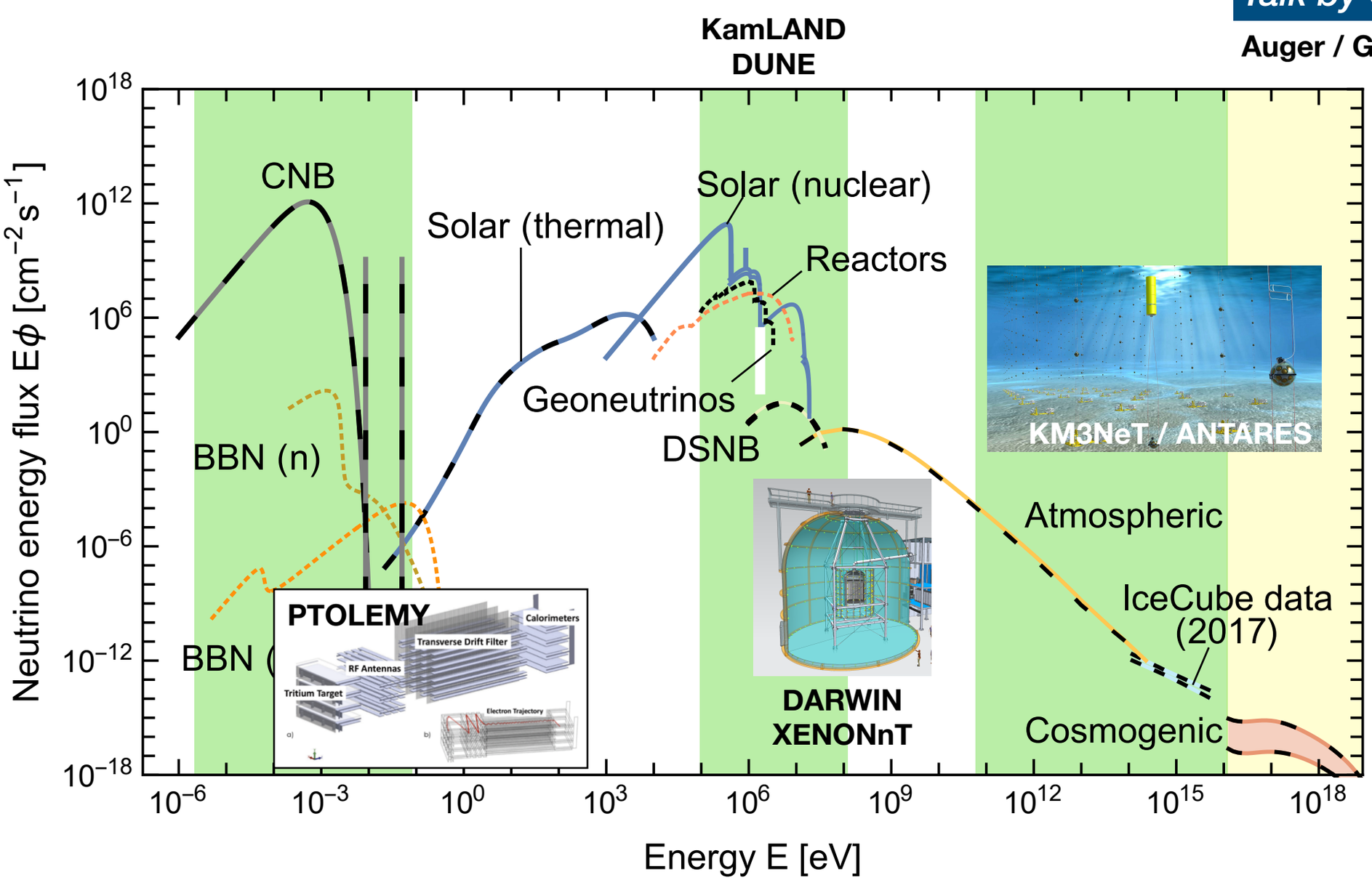
Cosmic Neutrinos: From meV to PeV

Shin'ichiro Ando
University of Amsterdam

GRAPPA
GRavitation AstroParticle Physics Amsterdam

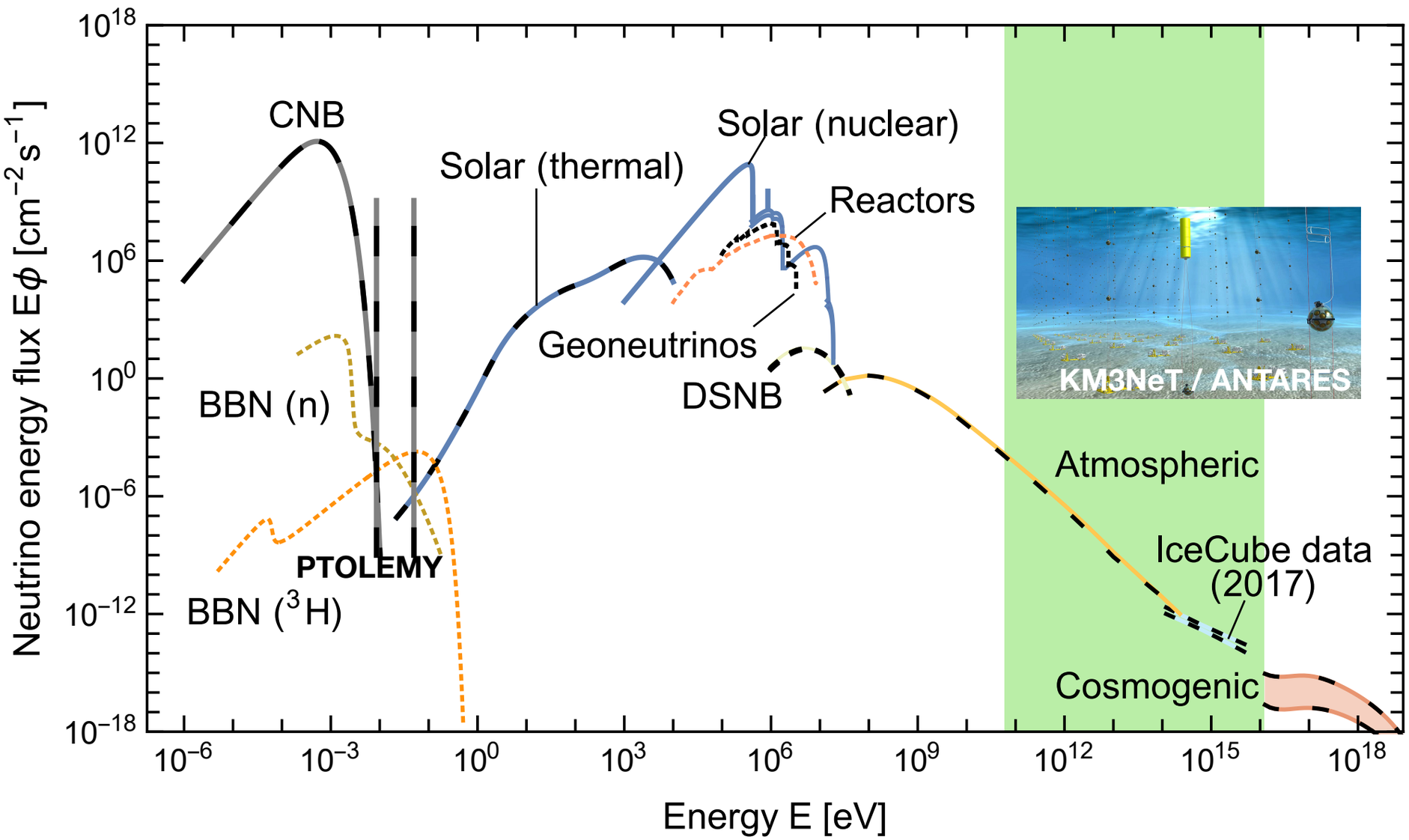
“Grand unified” neutrino spectrum

Talk by C. Galea



Vitagliano, Tamborra, Raffelt, *Rev. Mod. Phys.* **92**, 045006 (2020)

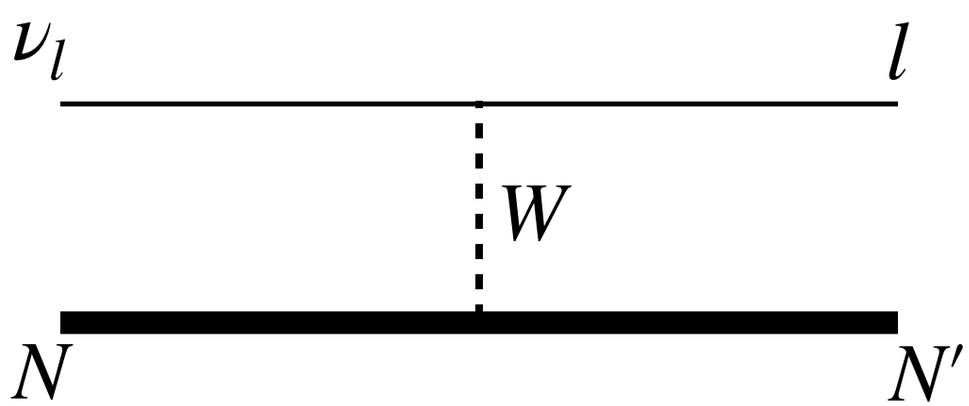
“Grand unified” neutrino spectrum



Vitagliano, Tamborra, Raffelt, *Rev. Mod. Phys.* **92**, 045006 (2020)

High-energy neutrinos: Detection

- Neutrinos interact with target nucleons (protons in water), and produce charged leptons



Lepton	Identification
Electron	EM cascades
Muon	Tracks
Tau	Hadronic cascades

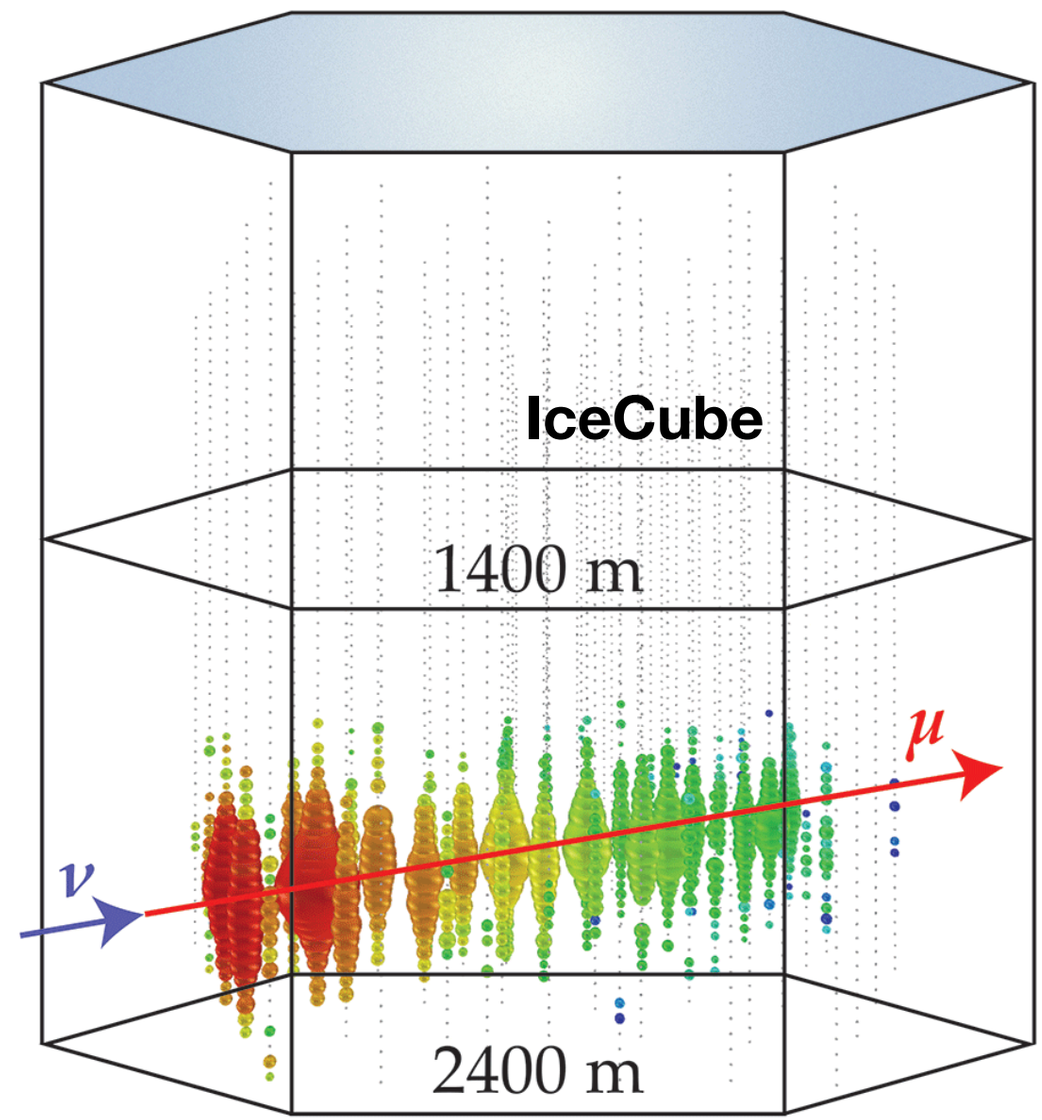
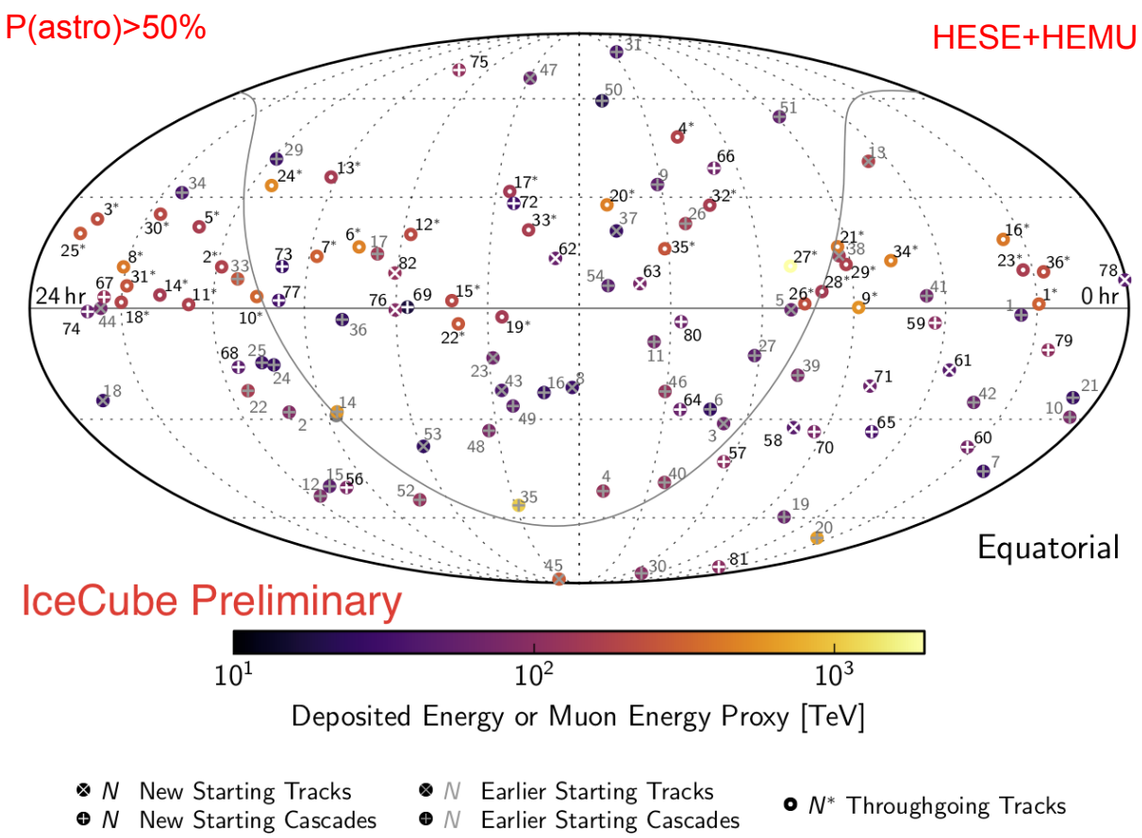
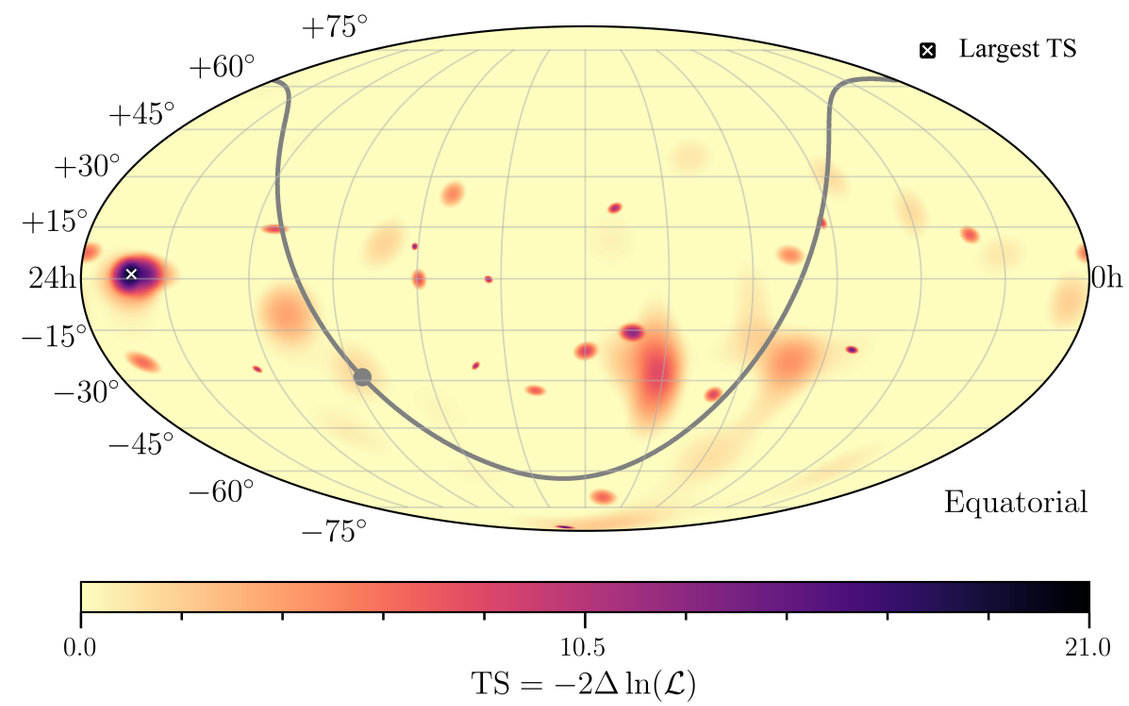


Image: *physics.aps.org*

High-energy neutrinos: Highlights

IceCube, arXiv:2011.03545 [astro-ph.HE]



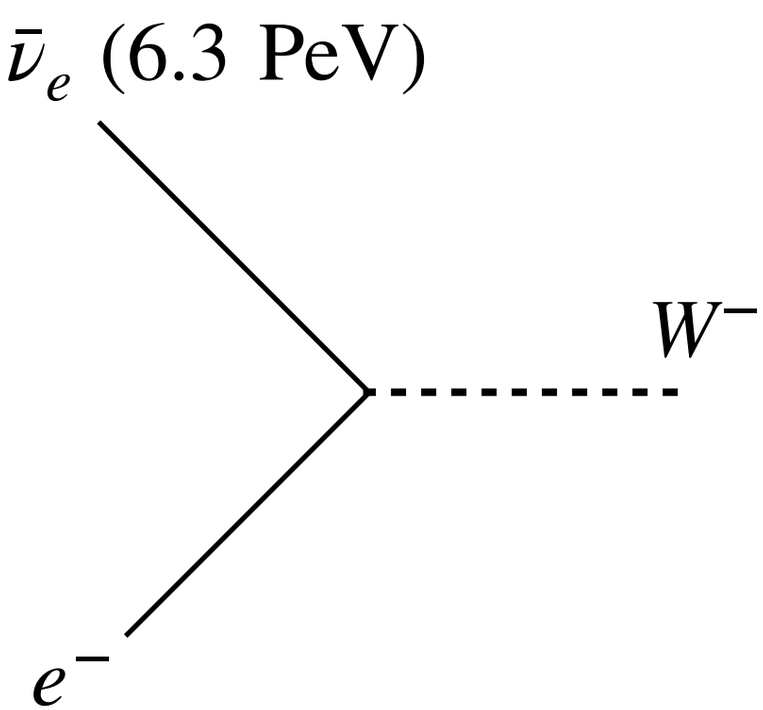


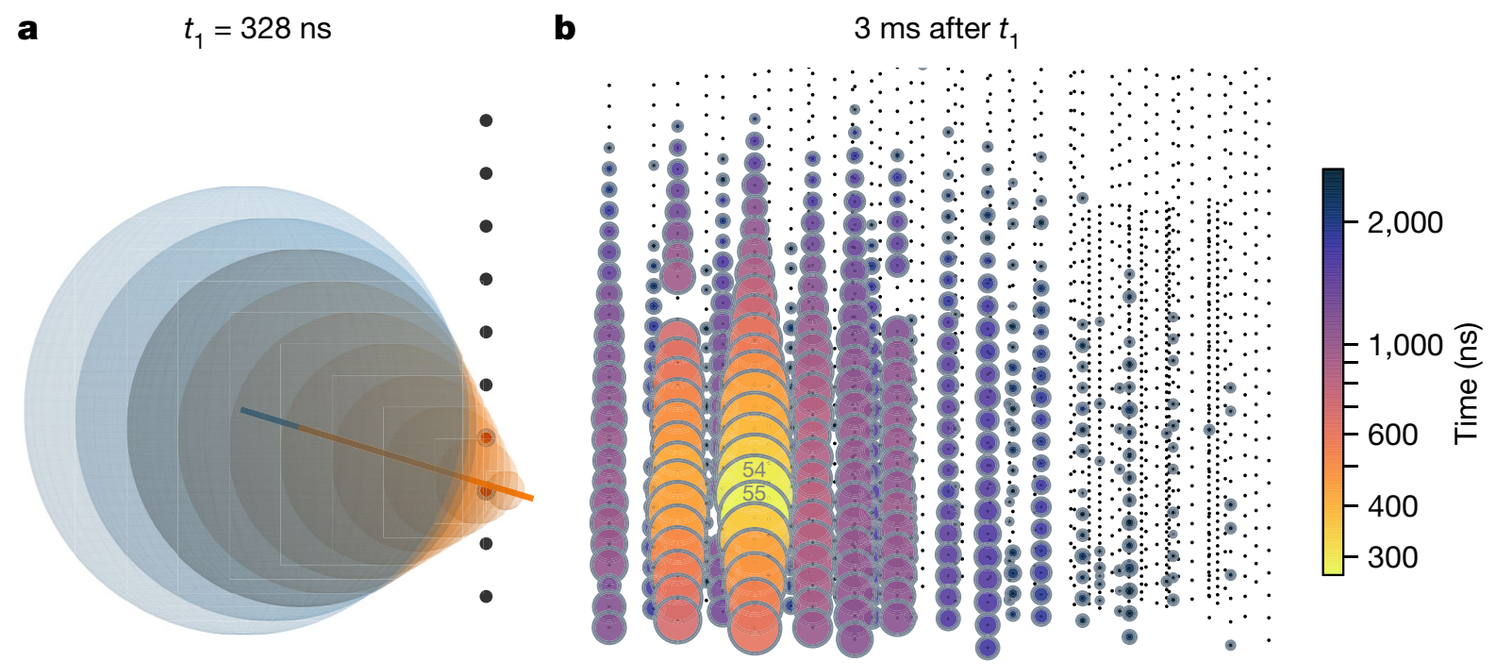
- Detected: Starting events and up-going muon events
- Their distribution is consistent with isotropy
- **No source has been identified yet** (largest TS corresponds to p = 0.092)

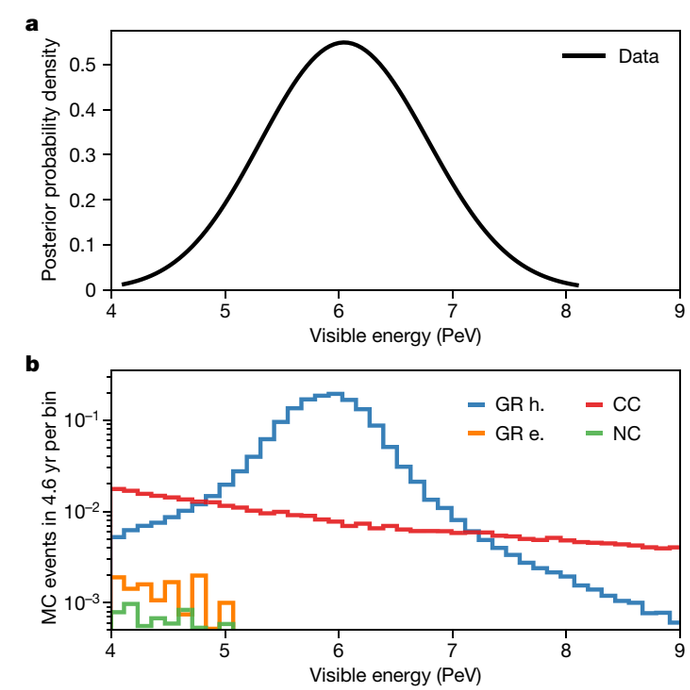
High-energy neutrinos: Highlights

First possible Glashow resonance event (6.3 PeV)

IceCube, *Nature* **591**, 220 (2021)





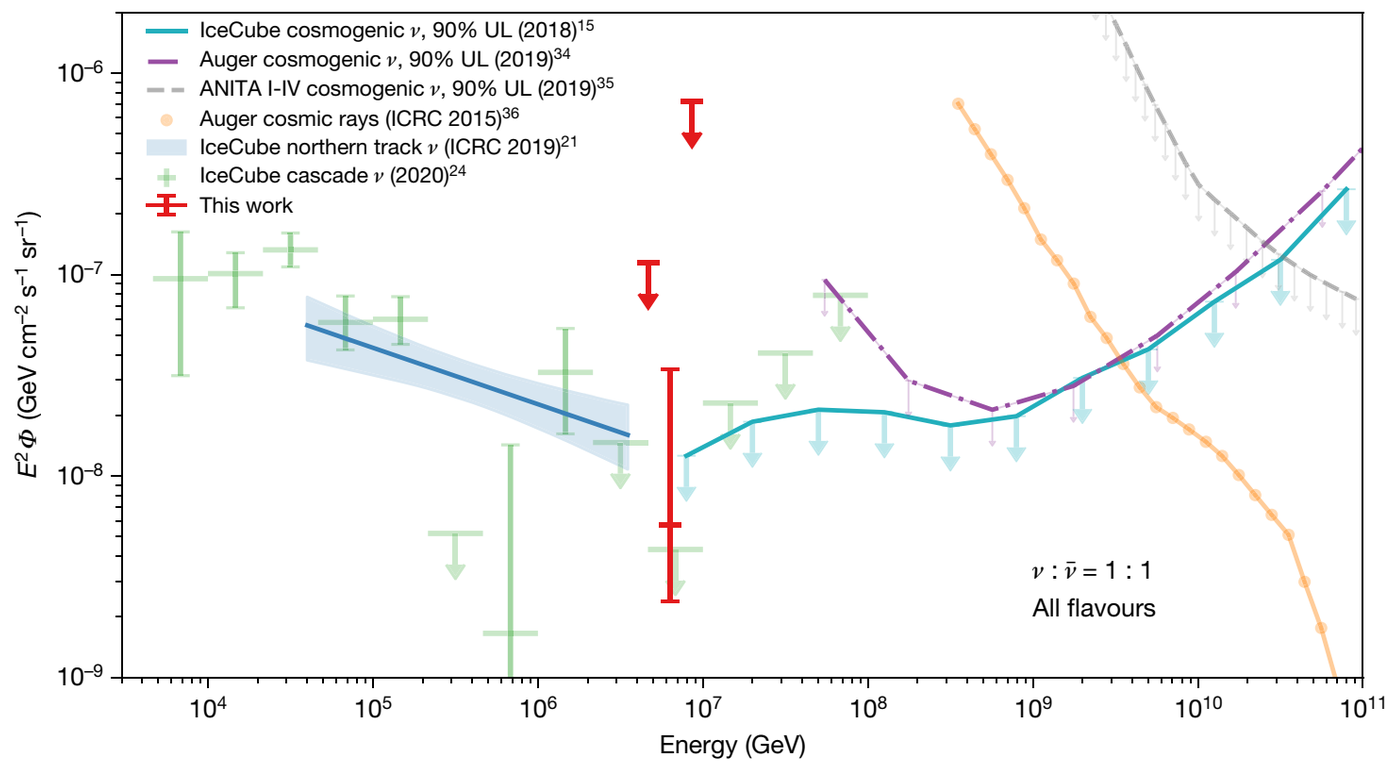


- One event identified with deposited energy: 6.05 ± 0.72 PeV (background is rejected at $> 5\sigma$)
- 1.55 Glashow resonance event expected (assuming $\bar{\nu} : \nu = 1 : 1$ ratio expected for pp interactions)
- Reject CC interaction at 2.3σ

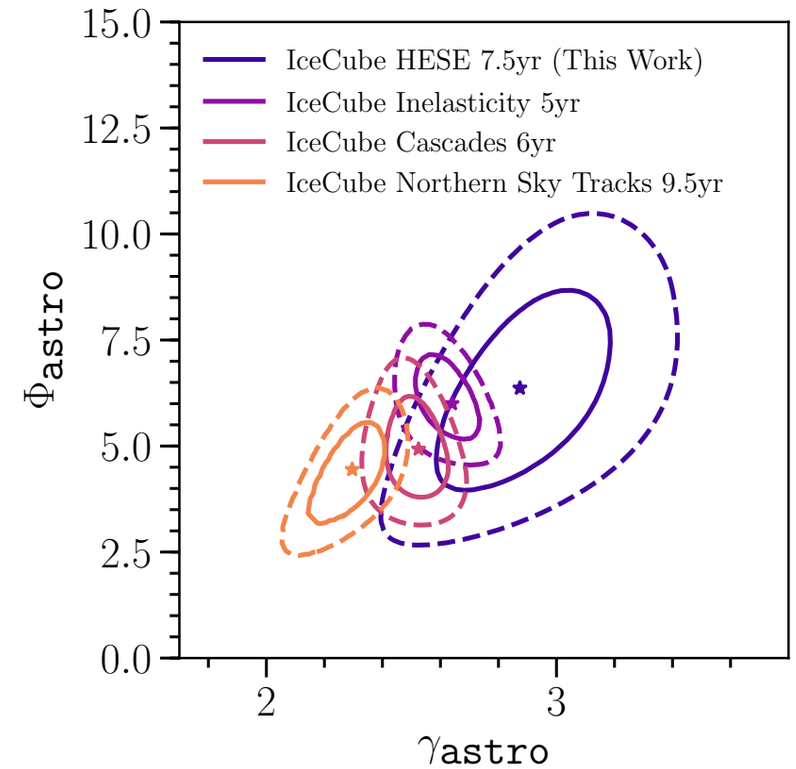
High-energy neutrinos: Highlights

Energy spectrum and flavor ratio

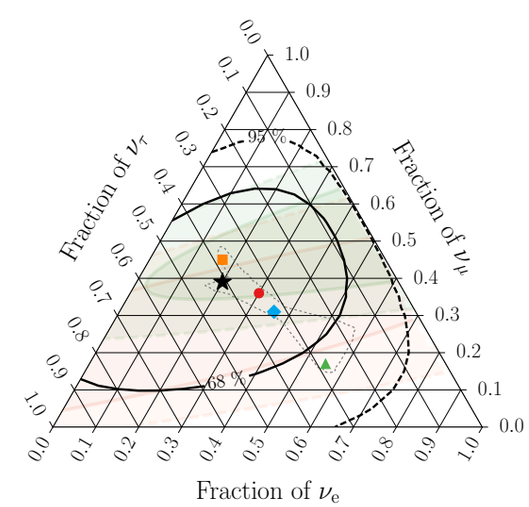
IceCube, *Nature* **591**, 220 (2021)



IceCube, arXiv:2011.03545 [astro-ph.HE]



- Single power-law fits to different data sets imply tension in spectral index
- First ν_τ-like events reported in 2020
- Flavor ratio is consistent with 1:1:1 expected from flavor mixing and standard astrophysics



IceCube, arXiv:2011.03561 [hep-ex]

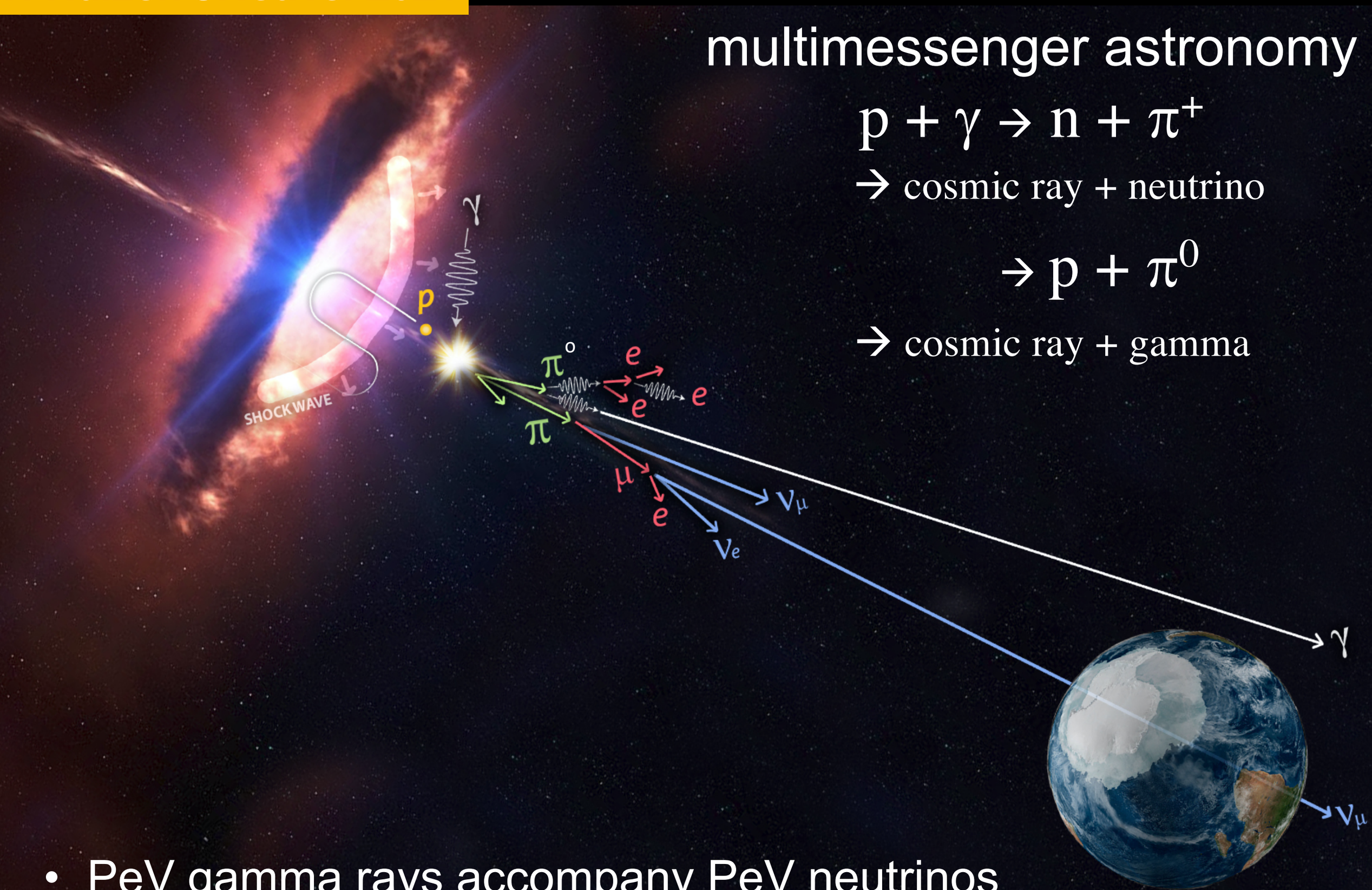
multimessenger astronomy

$$p + \gamma \rightarrow n + \pi^+$$

→ cosmic ray + neutrino

$$\rightarrow p + \pi^0$$

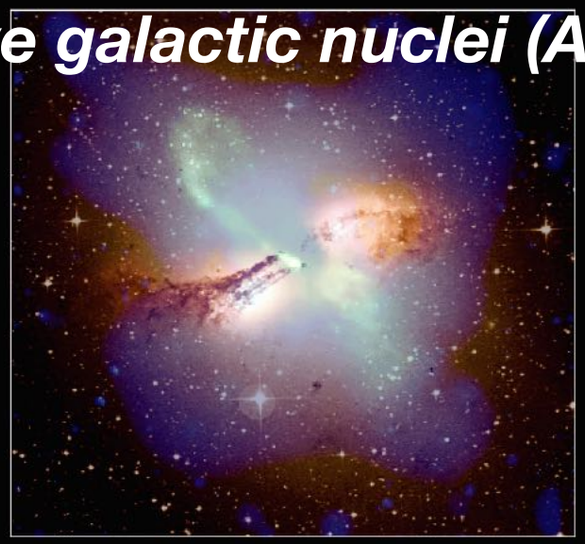
→ cosmic ray + gamma

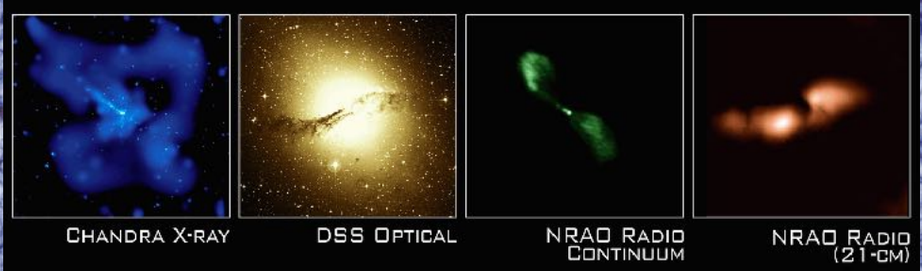


- PeV gamma rays accompany PeV neutrinos
- PeV gamma rays are absorbed by CMB photons

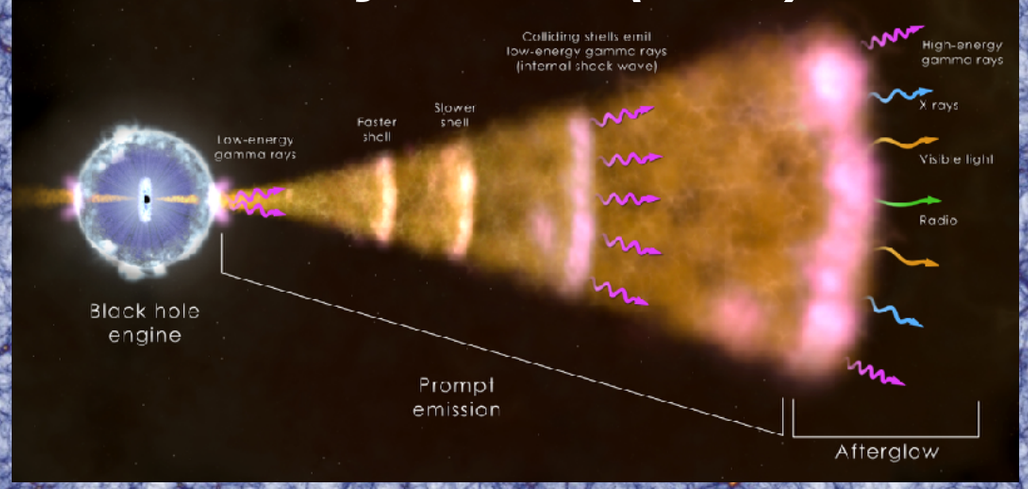
Possible astrophysical explanations

Active galactic nuclei (AGN)





Gamma-ray bursts (GRB)



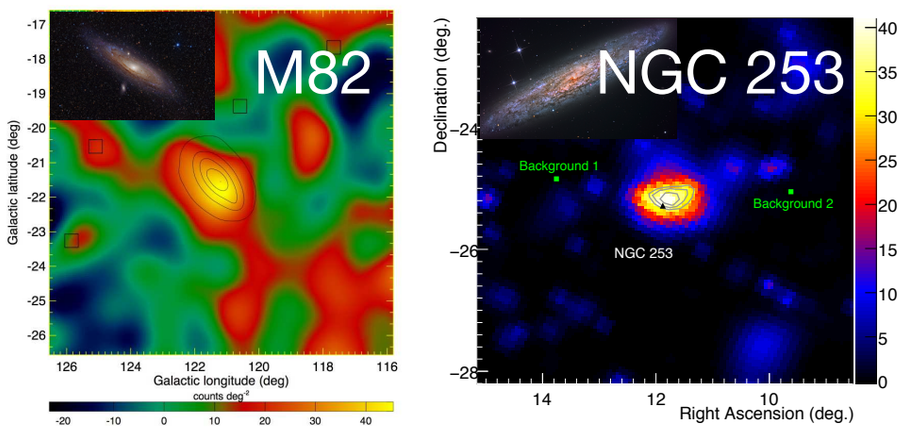
Galaxy clusters

Star-forming galaxies (SFG)
Starburst galaxies (SB)

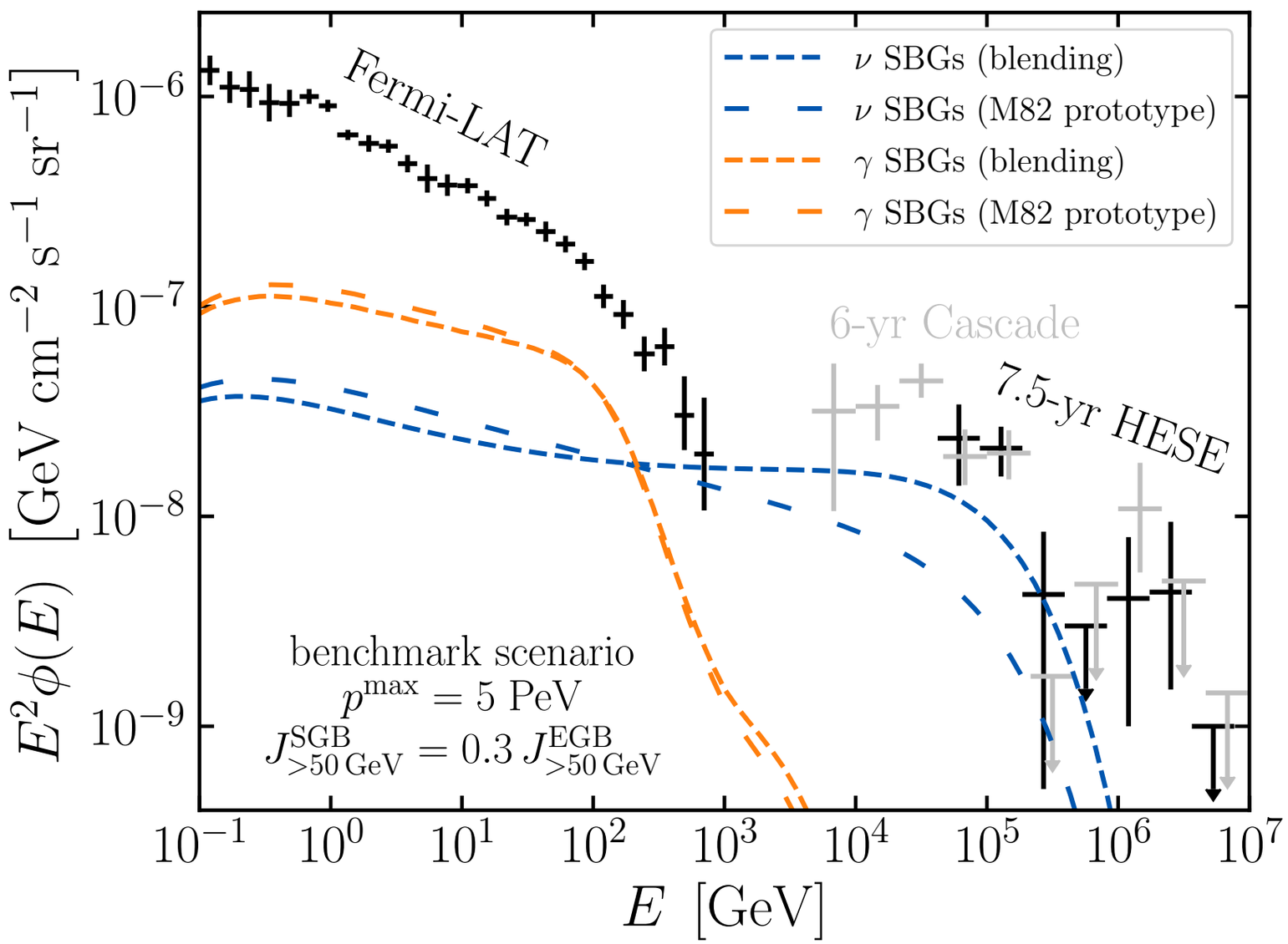
Tidal disruption events

Unknown sources?
Particle dark matter?

Starburst galaxies: pp source

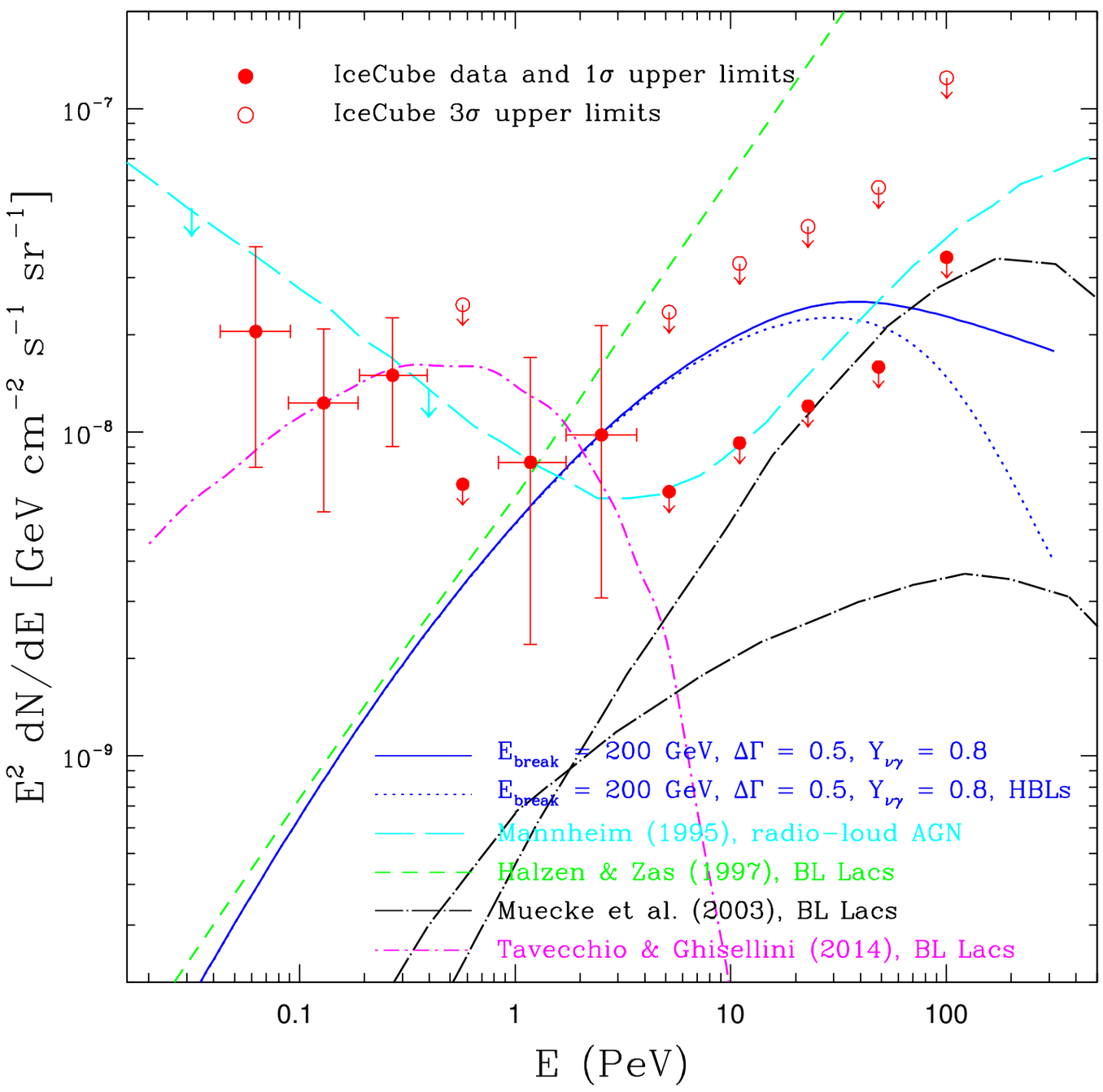


Ambrosone, Chianese et al. arXiv:2011.02483 [astro-ph.HE]



- Starbursts are bright in gammas (M82 and NGC 253 at ~3 Mpc)
- Gamma-ray spectrum roughly follows $E^{-2.3}$
- Modeling the gamma-ray and neutrino luminosity functions following Tamborra, Ando, Murase (2014) with
  - IR luminosity function (Herschel)
  - IR-gamma correlation (Fermi)

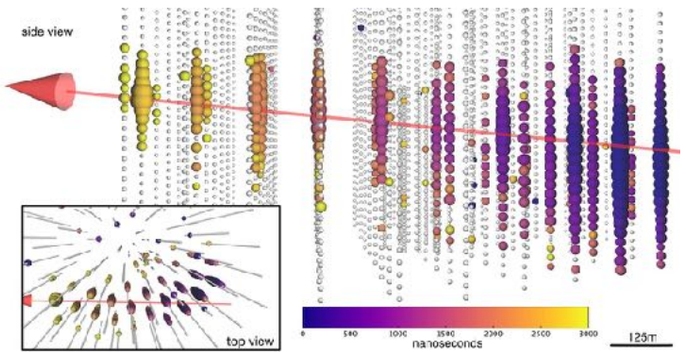
Blazars: pγ source

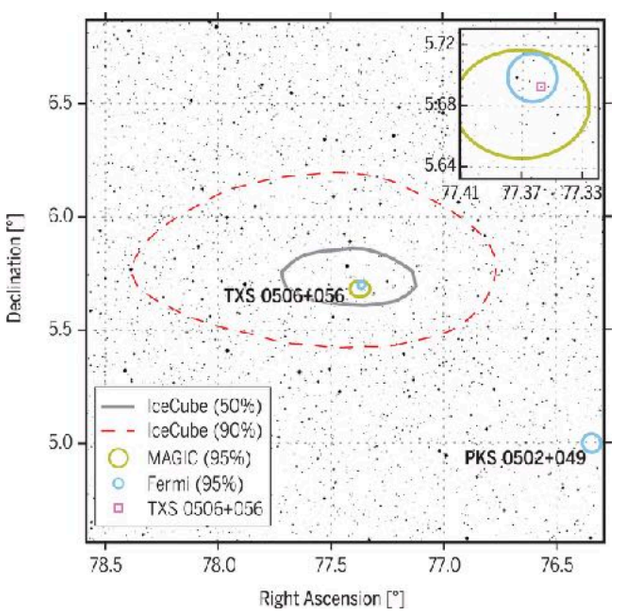


Padvani et al., *Mon. Not. R. Astron. Soc.* **452**, 1877 (2015)

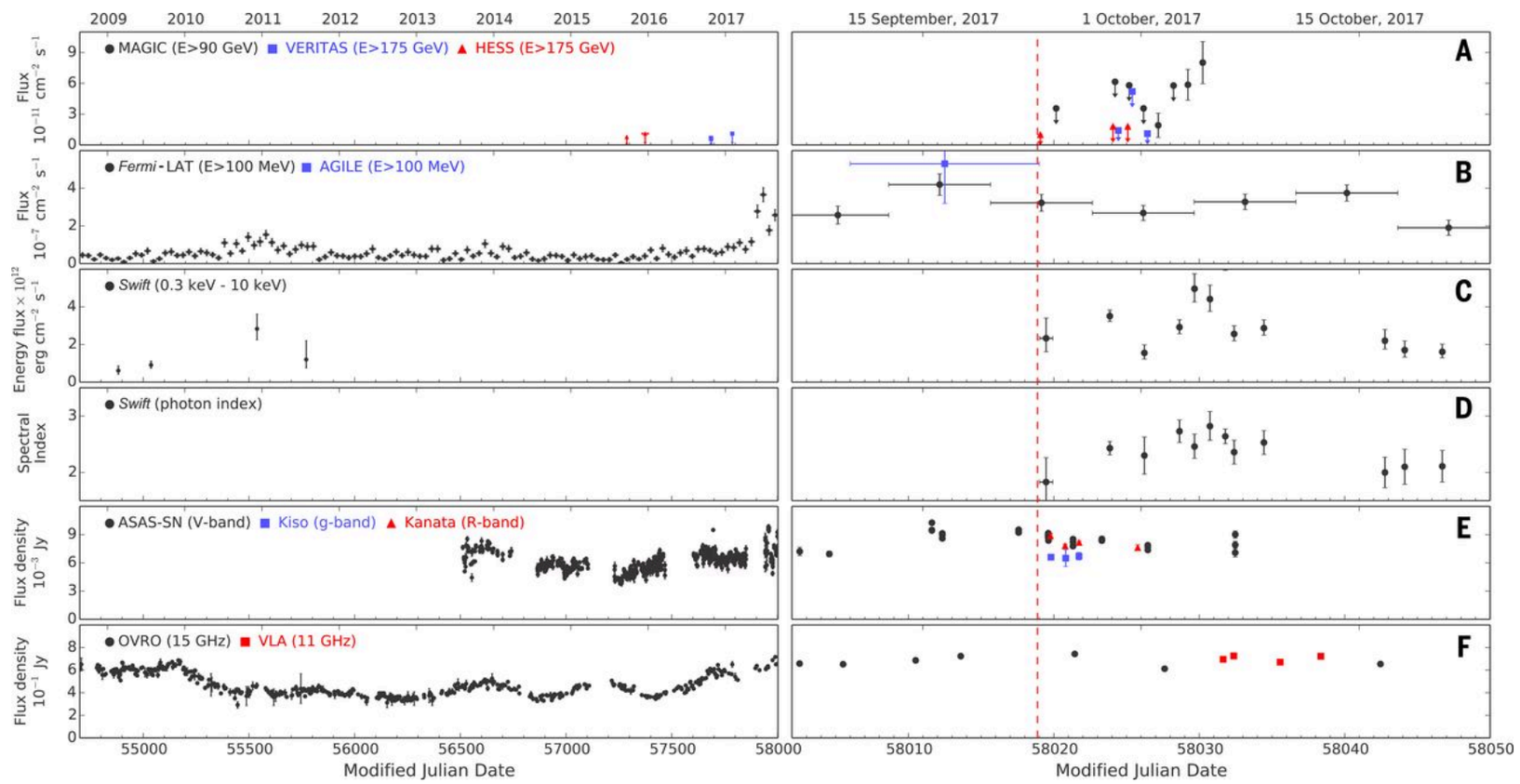
- The cosmic ray protons accelerated in jets interact with surrounding photons
- The neutrino spectrum depends on that of seed photons
- Consequences are in general much more model dependent

Neutrinos from TXS 0506+056?

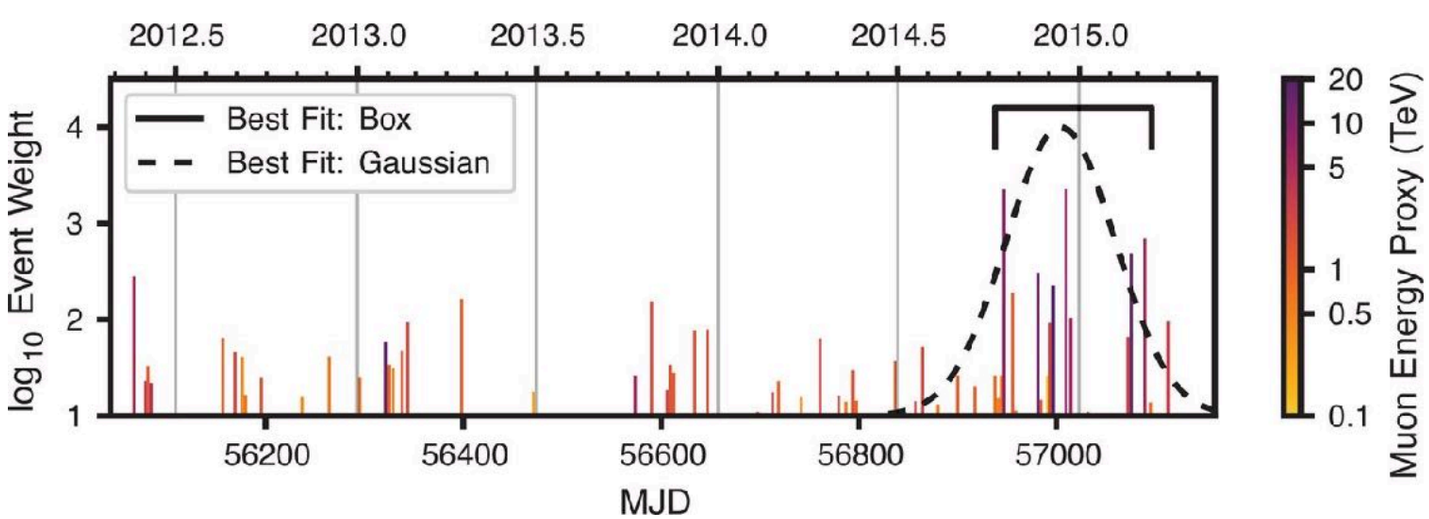




A neutrino event (IceCube-170922A) at ~290 TeV coincident with blazar gamma-ray flare **(3σ)**



Science **361**, eaat1378 (2018)



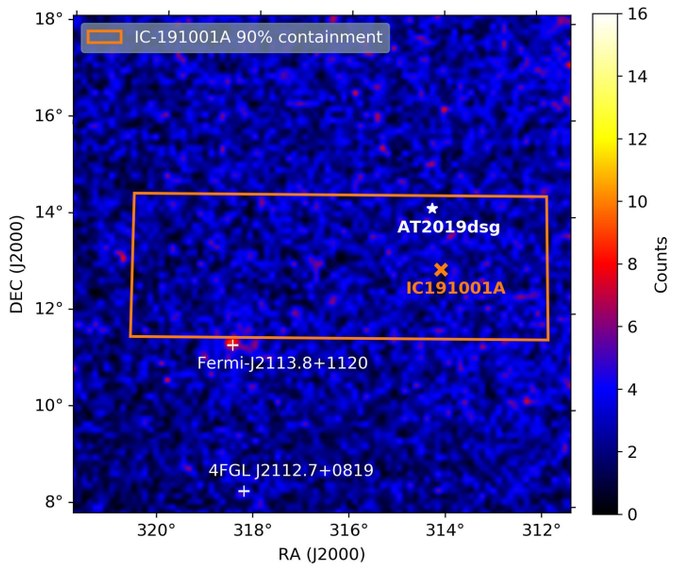
13±5 neutrinos above backgrounds in 2014-2015 (3.5σ)

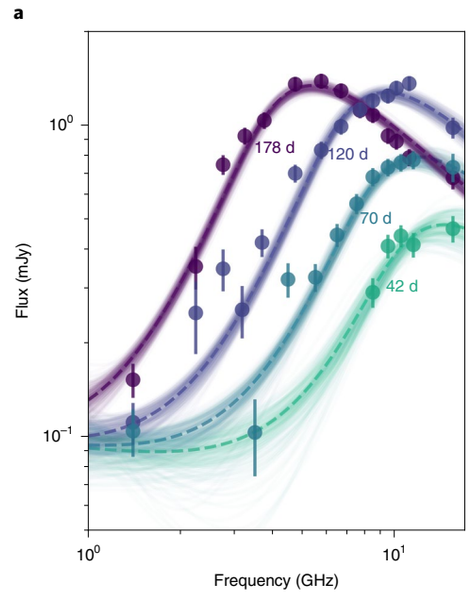
But no gamma-ray counterpart

Science **361**, 147 (2018)

Neutrinos from TDE AT2019dsg?

Stein et al. *Nature Astron.* (2021)



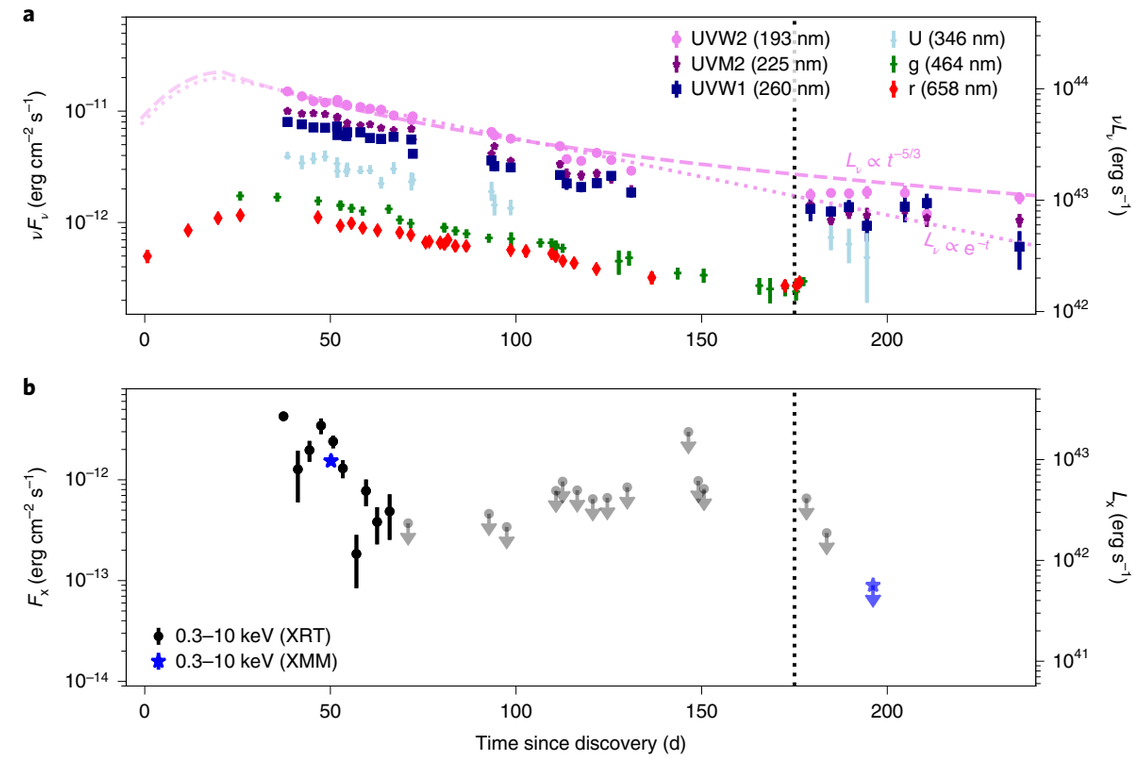


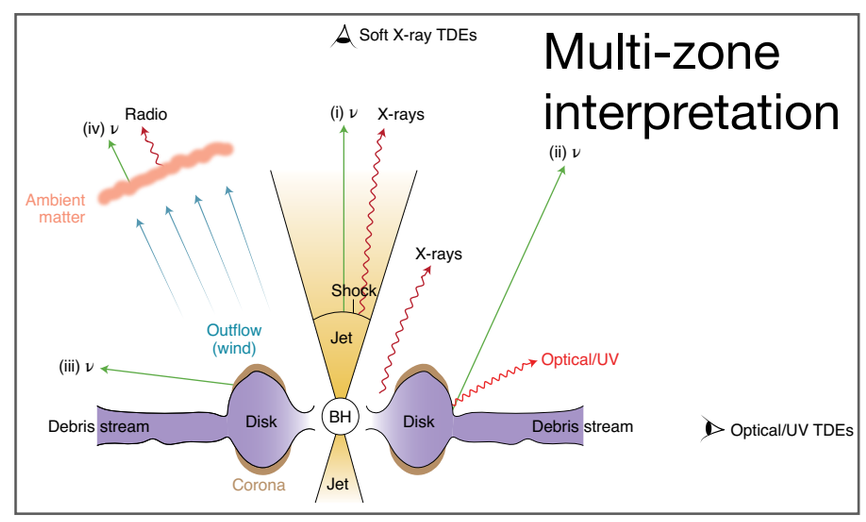
- **~0.2 PeV neutrino IC19001A (59% probability of being astrophysical)** was detected on 1 October 2019
- Followup observation by ZTF revealed TDE, AT2019dsg
- **Chance probability of 0.5%** (but 0.2% of TDE at least as bright as this one)

Talk by S. van Velzen

AT2019dsg

Discovered	9 April 2019
Distance	D_L = 230 Mpc (z = 0.051)



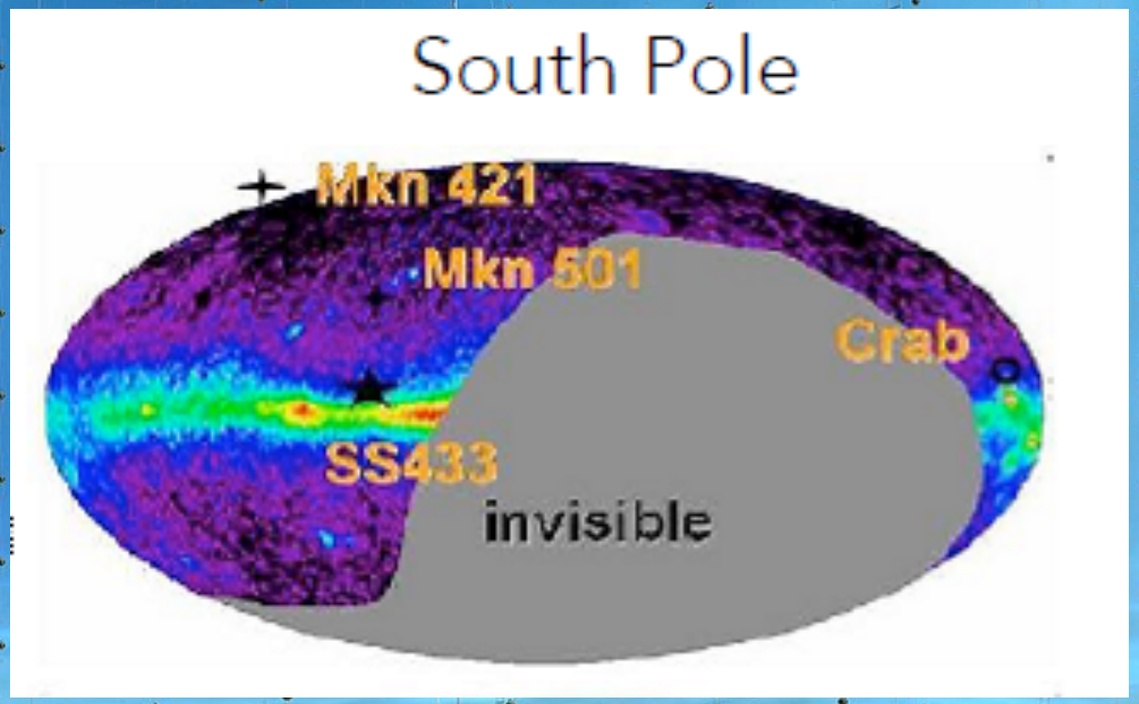


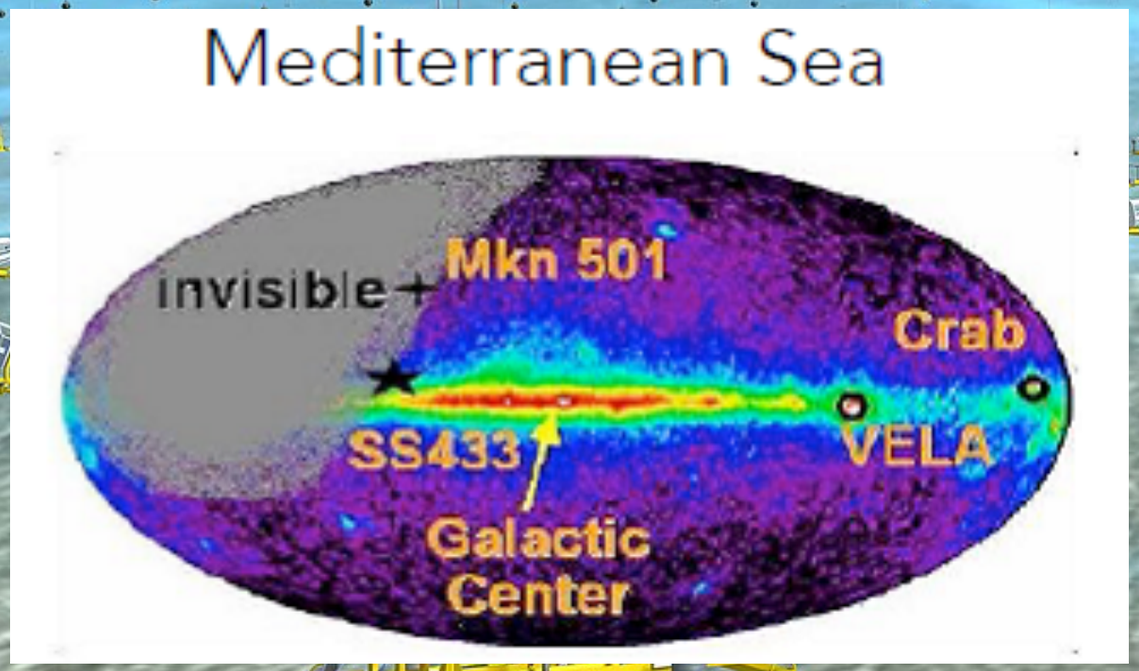
Hayasaki, *Nature Astron.* (2021)

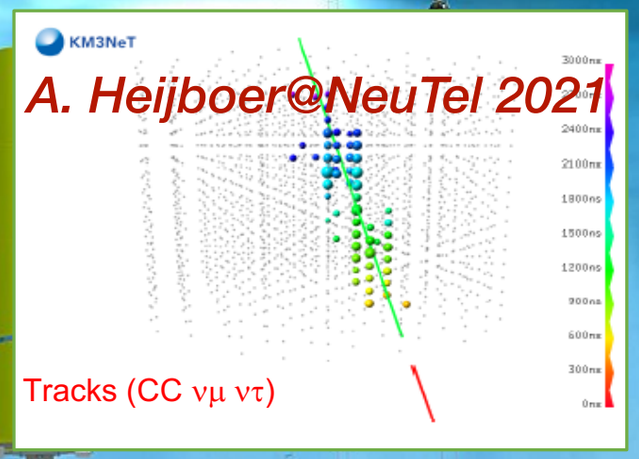
KM3NeT

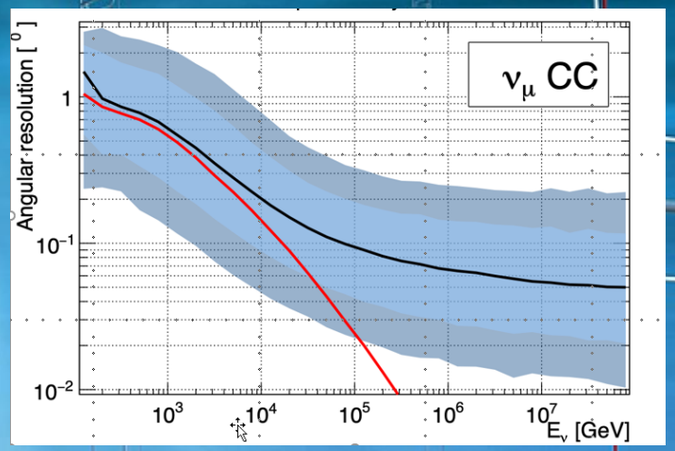
Talk by V. Pestel

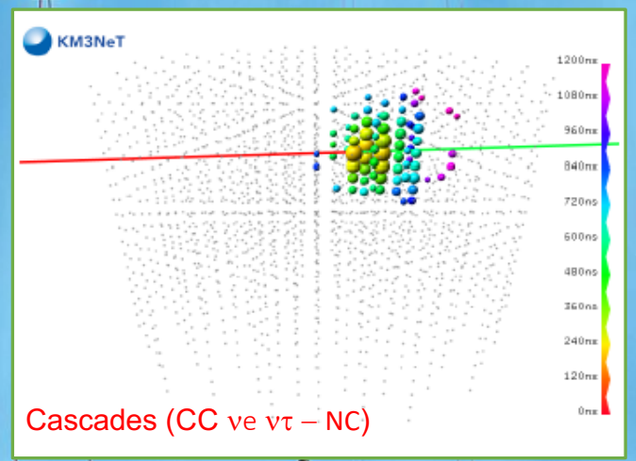
A. Heijboer@NeuTel 2021

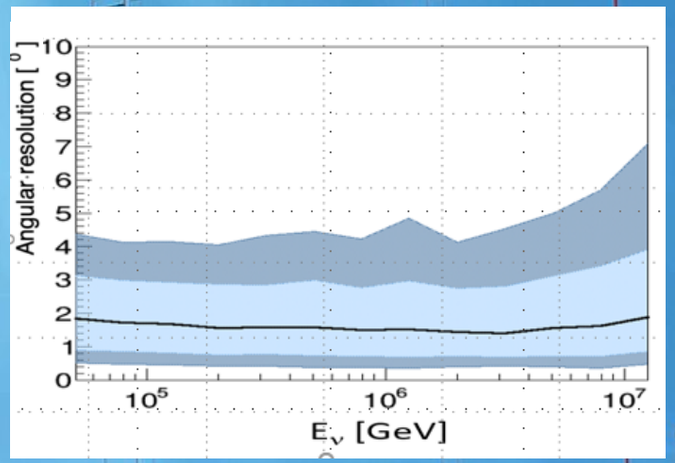








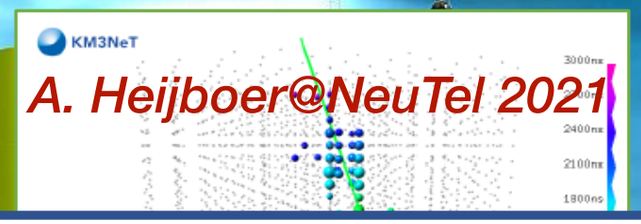


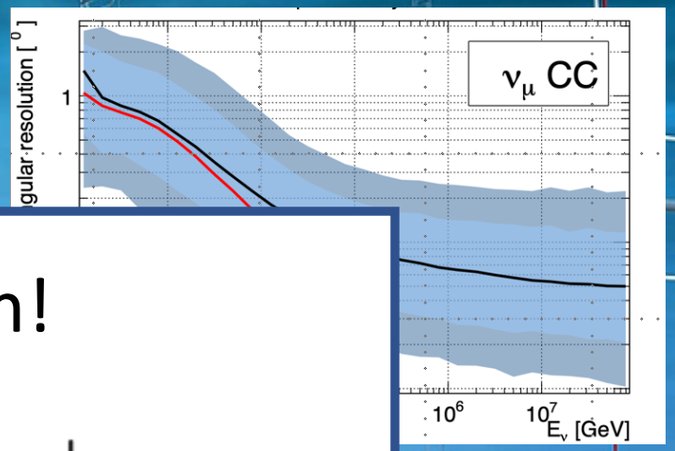


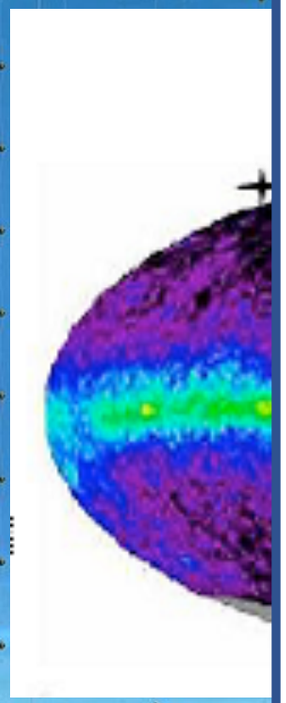
- **ARCA** for astrophysics; **ORCA** for particle physics
- Good coverage of the Galactic plane/center
- Better angular resolution than IceCube

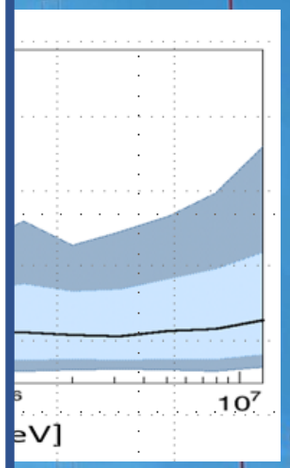
KM3NeT

Talk by V. P





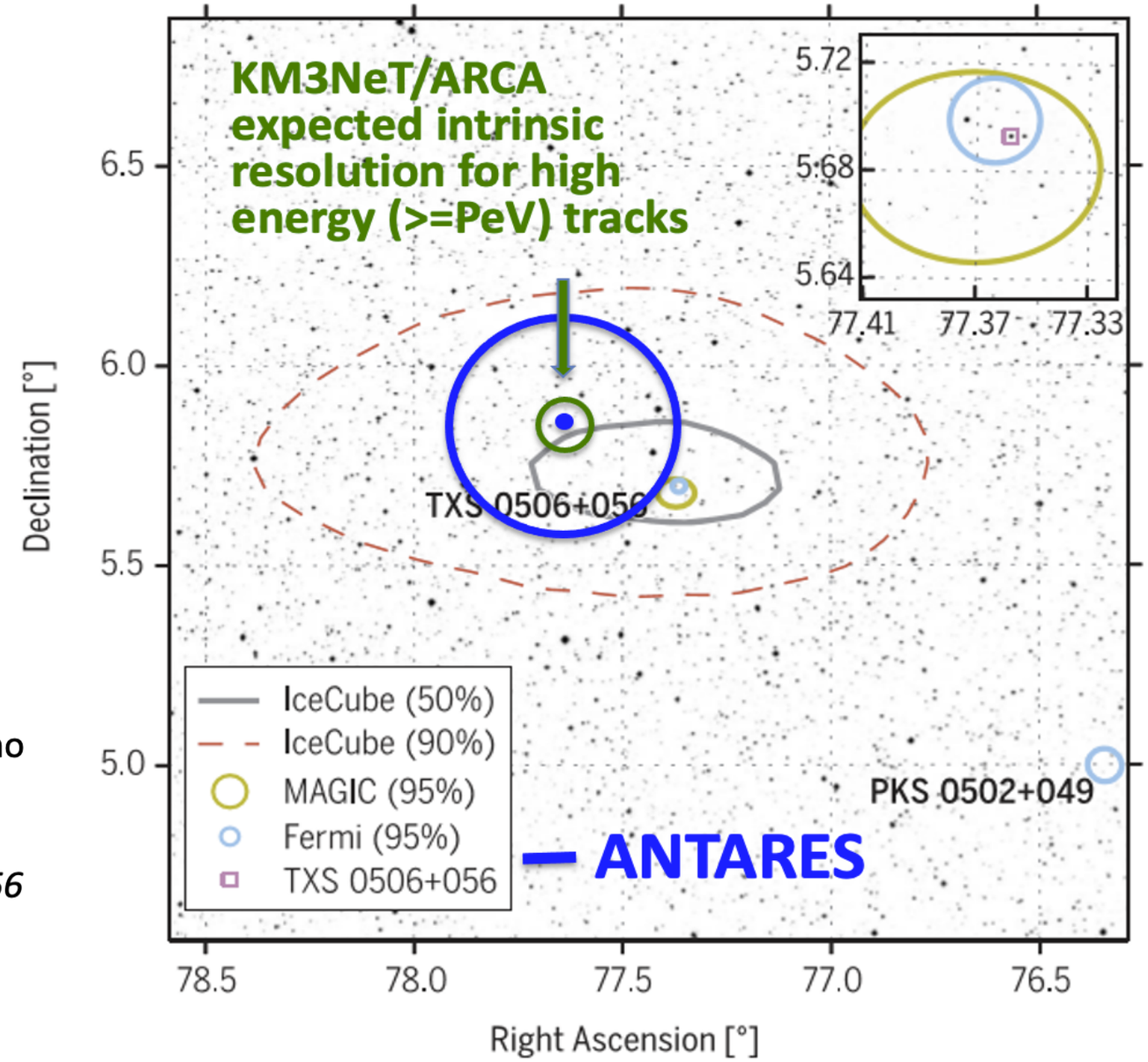




The promise of KM3NeT/ARCA: Resolution!

Optical Skymap around first identified cosmic high energy neutrino source (IceCube)

Blazar TXS 0506+056



A. Heijboer@NeuTel 2021

Science 13 Jul 2018: Vol. 361, Issue 6398, 1378

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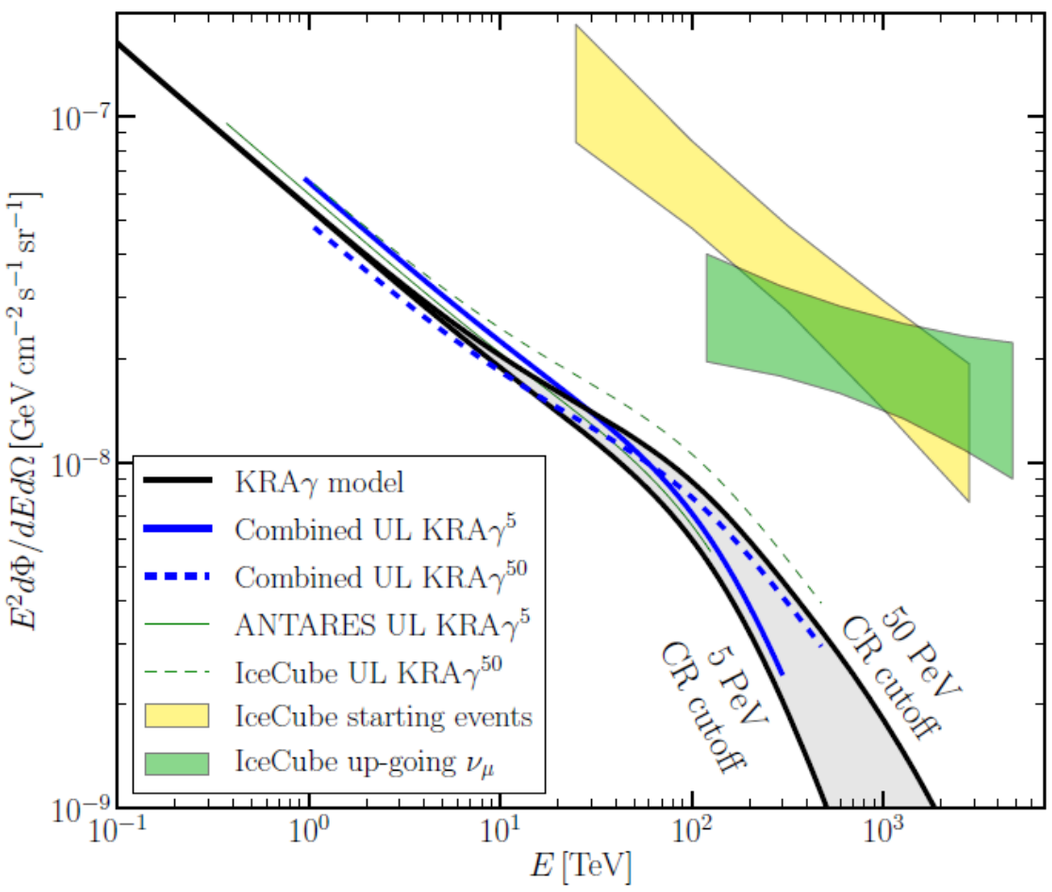
ANTARES

A. Kouchner@NeuTel 2021

Combined U.L. at 90% CL (blue line) on the 3-flavor neutrino flux of the KRAγ model (5-50 PeV cutoff)

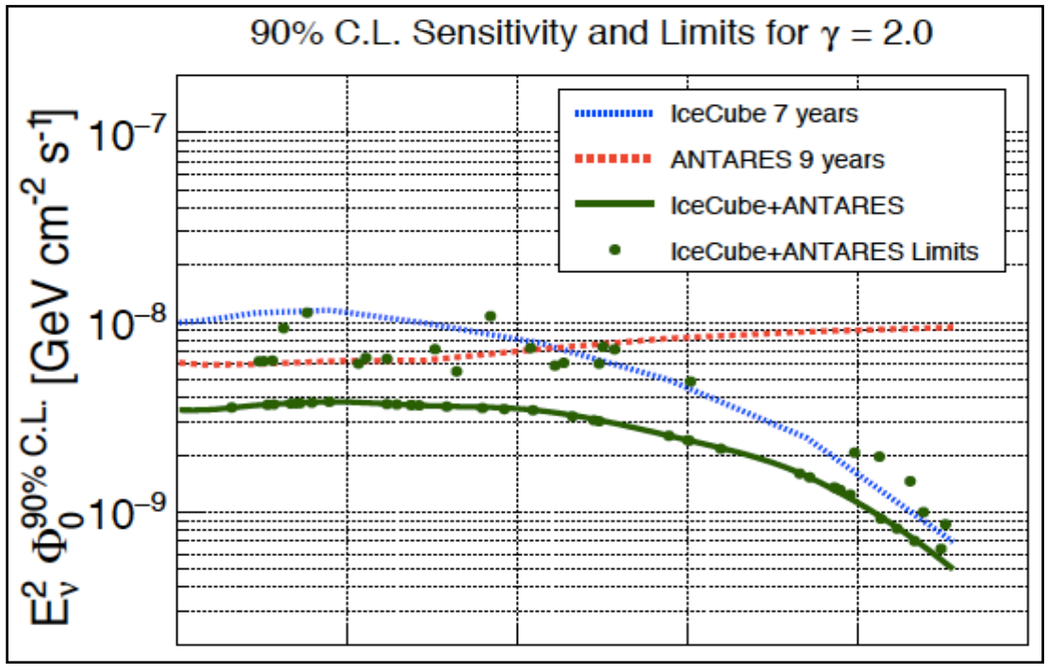


Result: total flux contribution of **diffuse Galactic neutrino** emission <9% *of the total diffuse IC astrophysical signal* (E_ν> 30 TeV)

Updates ongoing…

📖 Phys. Rev. D 96, 062001 (2017)

Combined point-source search



Other interesting physics results

- Diffuse flux results compatible with IceCube
- Followup of TXS 0506+056, TDE AT2019dsg, GW sources, and upper limits on neutrino counterpart
- Indirect dark matter searches

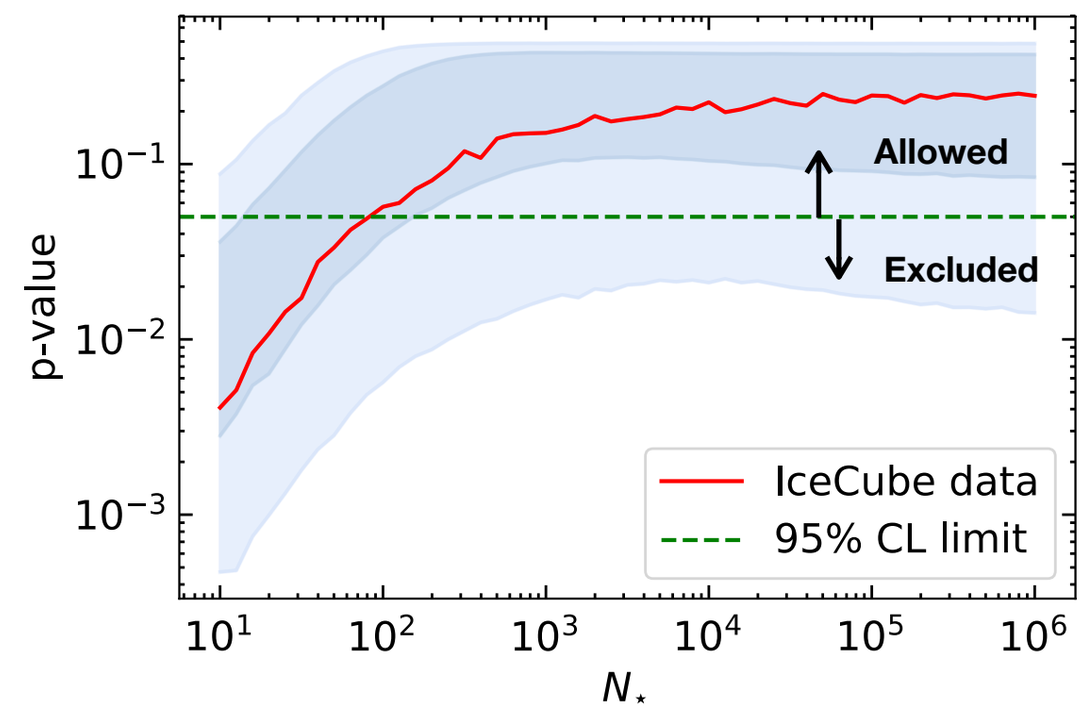
Statistical analysis: Anisotropies

- So far spatial distribution of neutrino events is consistent with isotropy / diffuse
- Any models that yield strong anisotropies are already disfavored
  - **Small-scale power** (very bright point sources)
  - **Large-scale power** (Galactic sources; dark matter decay / annihilation)
- Cross correlations with, e.g., catalogs of galaxies

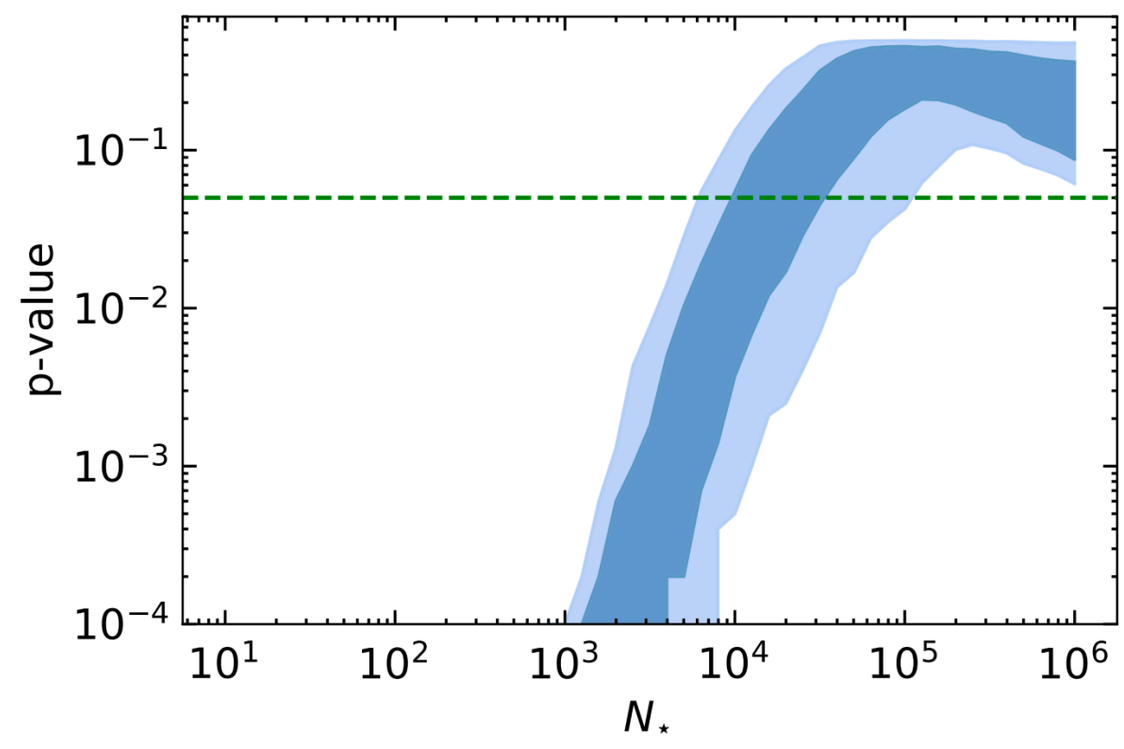
e.g., Ando, Tamborra, Zandanel (2015); Mertsch et al. (2017); Fang et al. (2020)

Source	N^*
Blazars	600
Radio galaxies	10^5
Starbursts	10^7

Dekker, Ando, *JCAP* **1902**, 002 (2019)

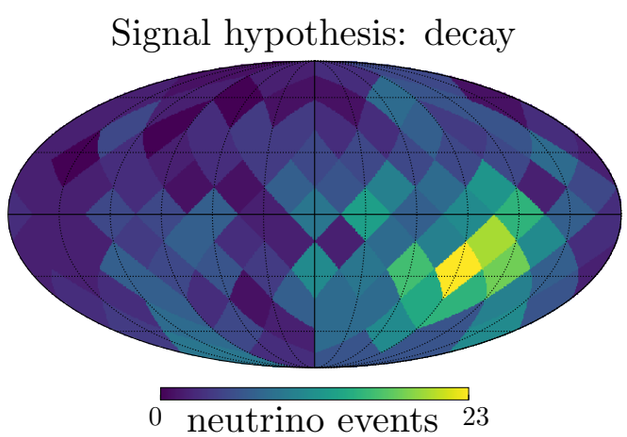


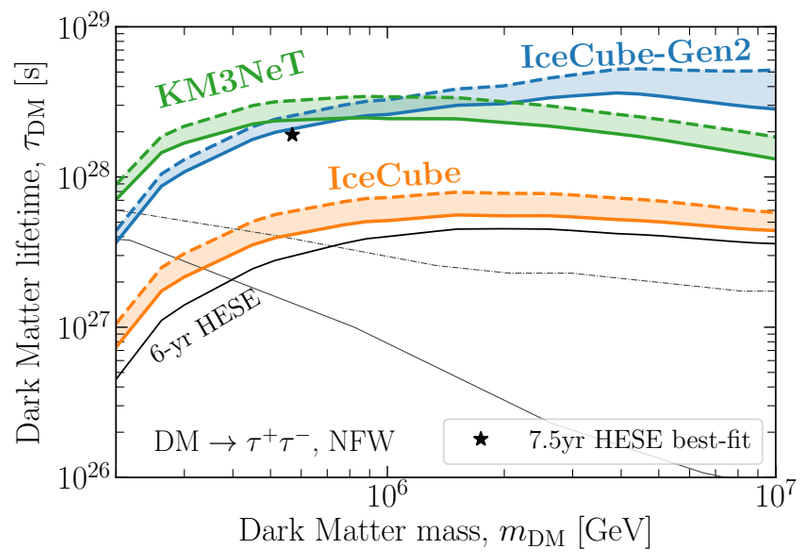
KM3NeT



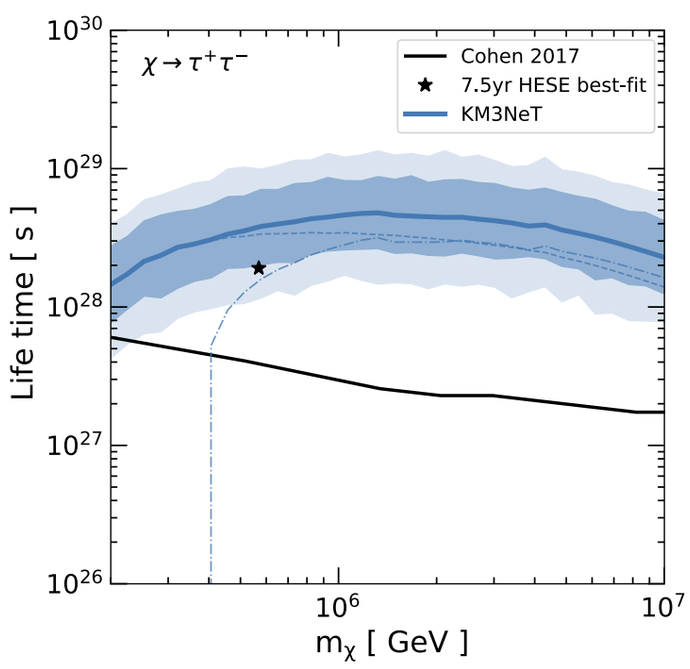
Anisotropy constraints on dark matter

Dekker, Chianese, Ando, *JCAP* **09**, 007 (2020)



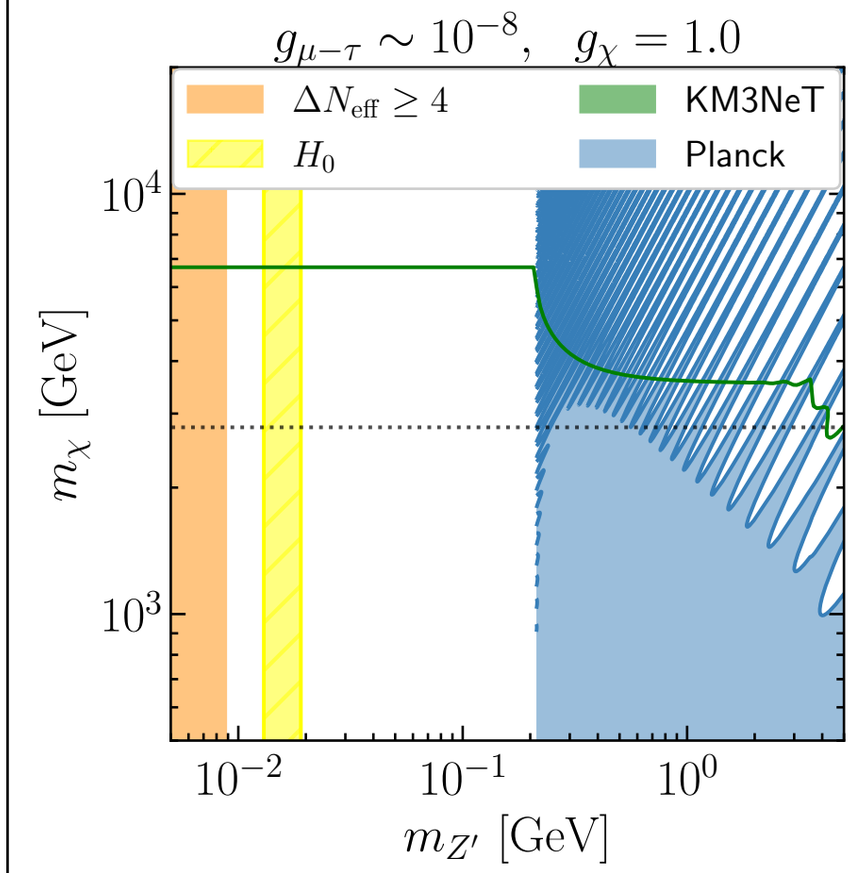


Ng, Dekker, Ando et al., arXiv:2007.03692 [astro-ph.HE]



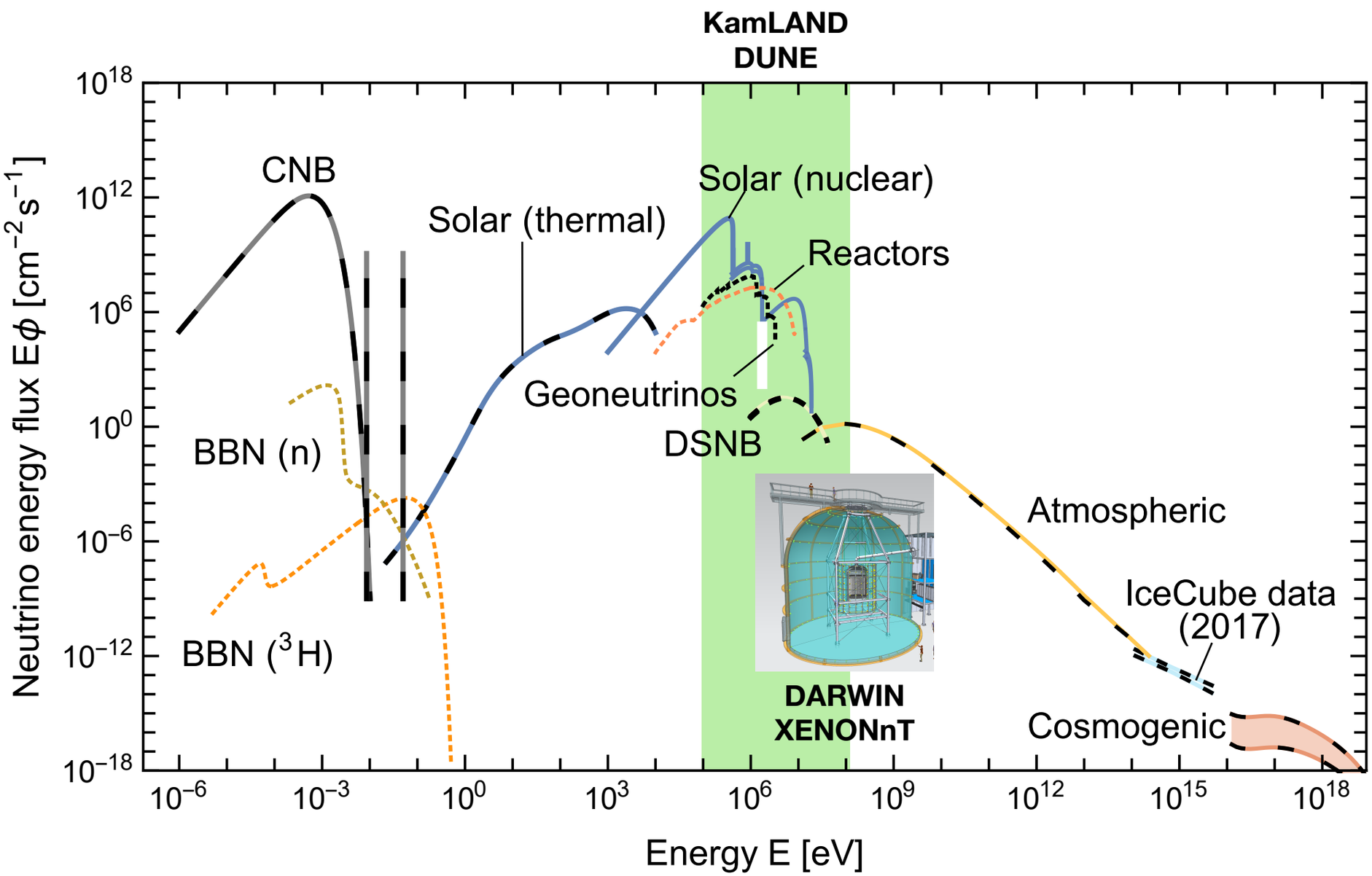
Undergraduate workshop in theoretical physics 2020

Talk by S. Basegmez du Pree



Basegmez du Pree et al.
arXiv:2103.01237 [hep-ph]

“Grand unified” neutrino spectrum

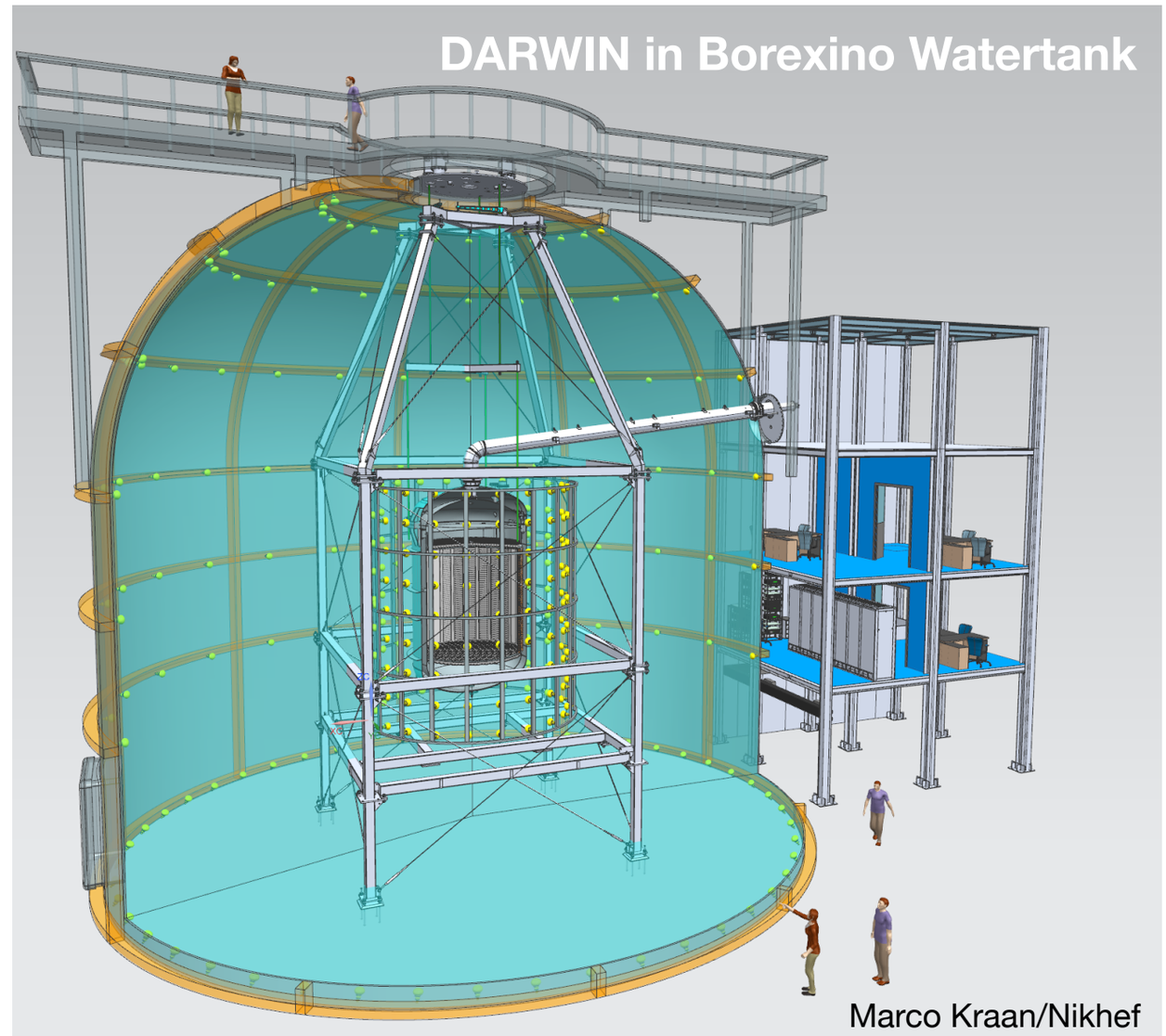


Vitagliano, Tamborra, Raffelt, *Rev. Mod. Phys.* **92**, 045006 (2020)

Based on slides by Patrick Decowski

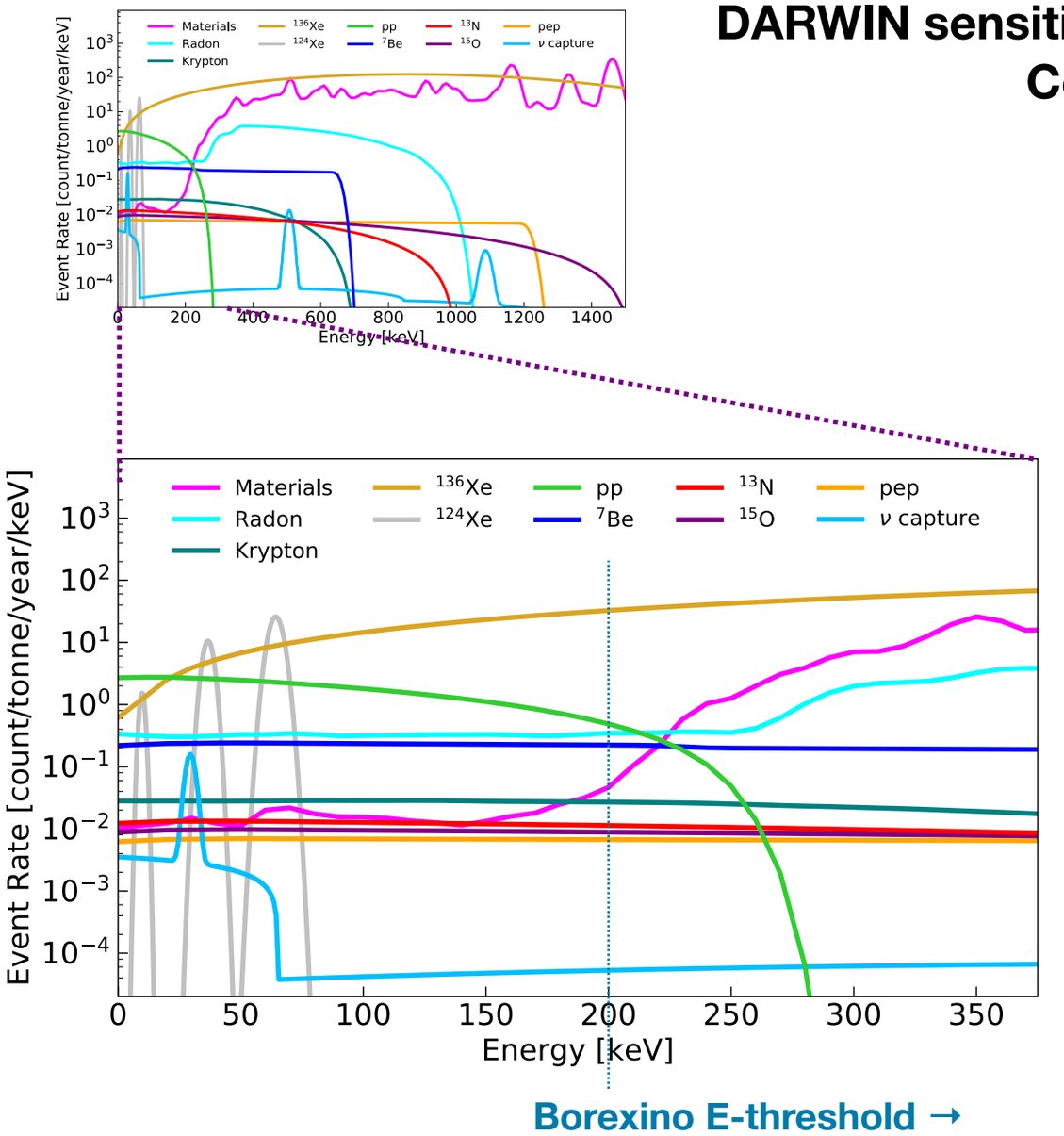
DARWIN

- DARWIN is a 40t liquid xenon TPC
  - ~5x bigger than XENONnT
  - Much lower radioactive backgrounds
- Ultimate DM detector
- Also rich neutrino program!

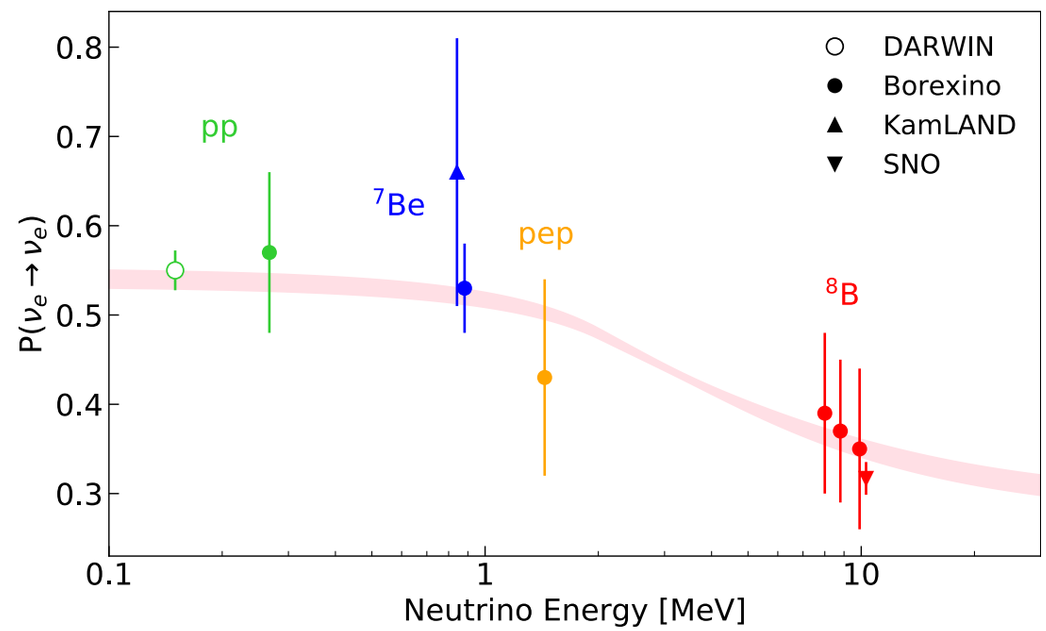


Based on slides by Patrick Decowski

Low-energy solar neutrinos



DARWIN sensitive to: Elastic scattering of solar ν on Xe electrons
Coherent Neutrino-Nucleus Scattering



DARWIN, arXiv:2006.03114

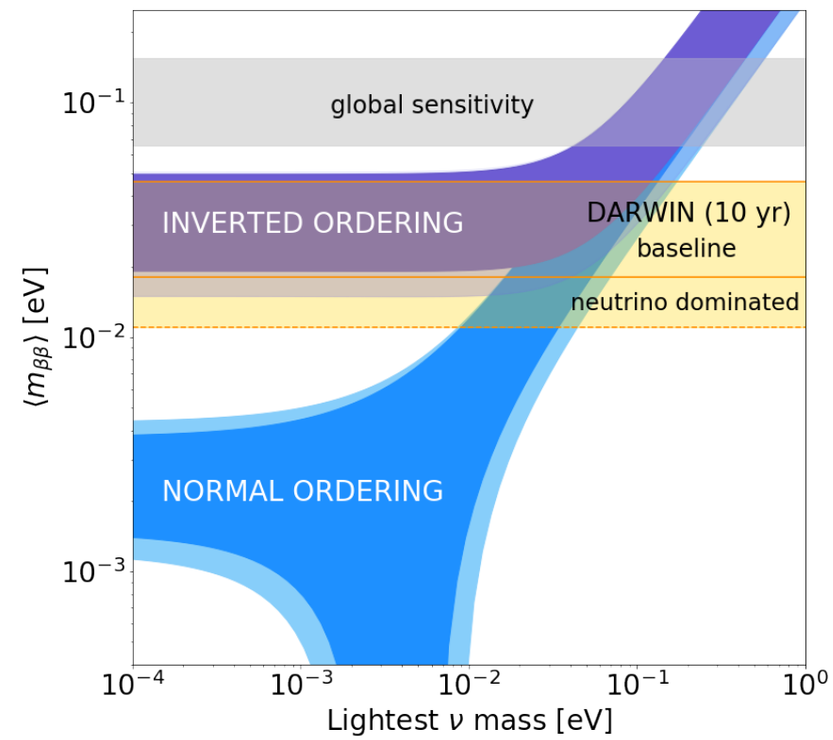
- 1% measurement of solar pp-neutrinos
- Map out the vacuum to matter oscillation transition
- Detailed measurement of other ν components allows to determine metallicity of the Sun
- Non-standard neutrino interactions

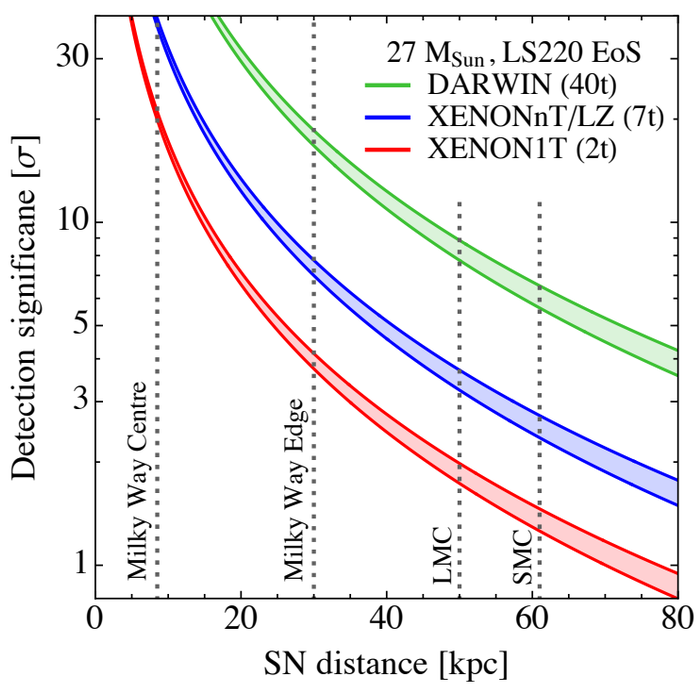
Based on slides by Patrick Decowski

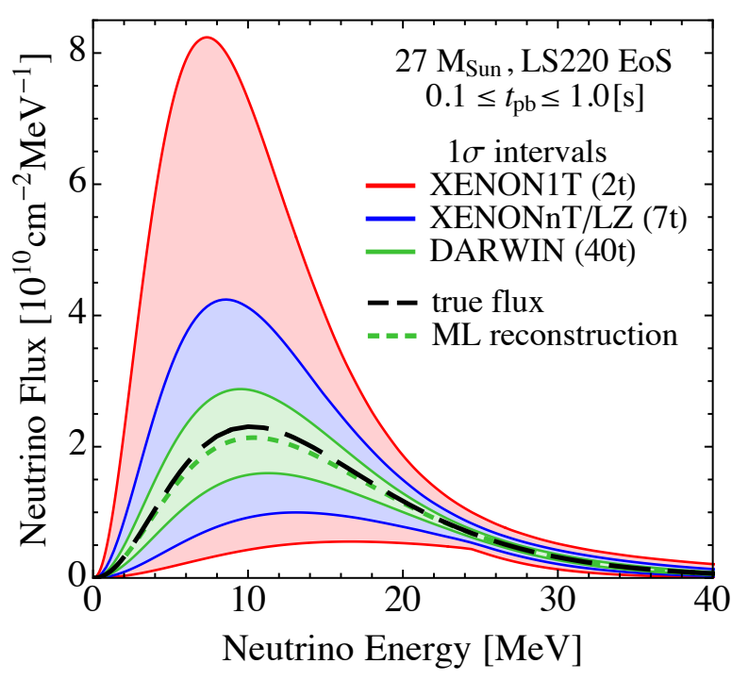
Other neutrino physics

- Extremely low backgrounds, excellent energy resolution
  - World competitive 0ν2β sensitivity, covering most of the inverted mass ordering
- Enhanced neutrino magnetic moment
- Galactic supernova
  - sensitive to all active neutrino species from core-collapse supernovae

DARWIN, *EPJC* **80**, 808 (2020)



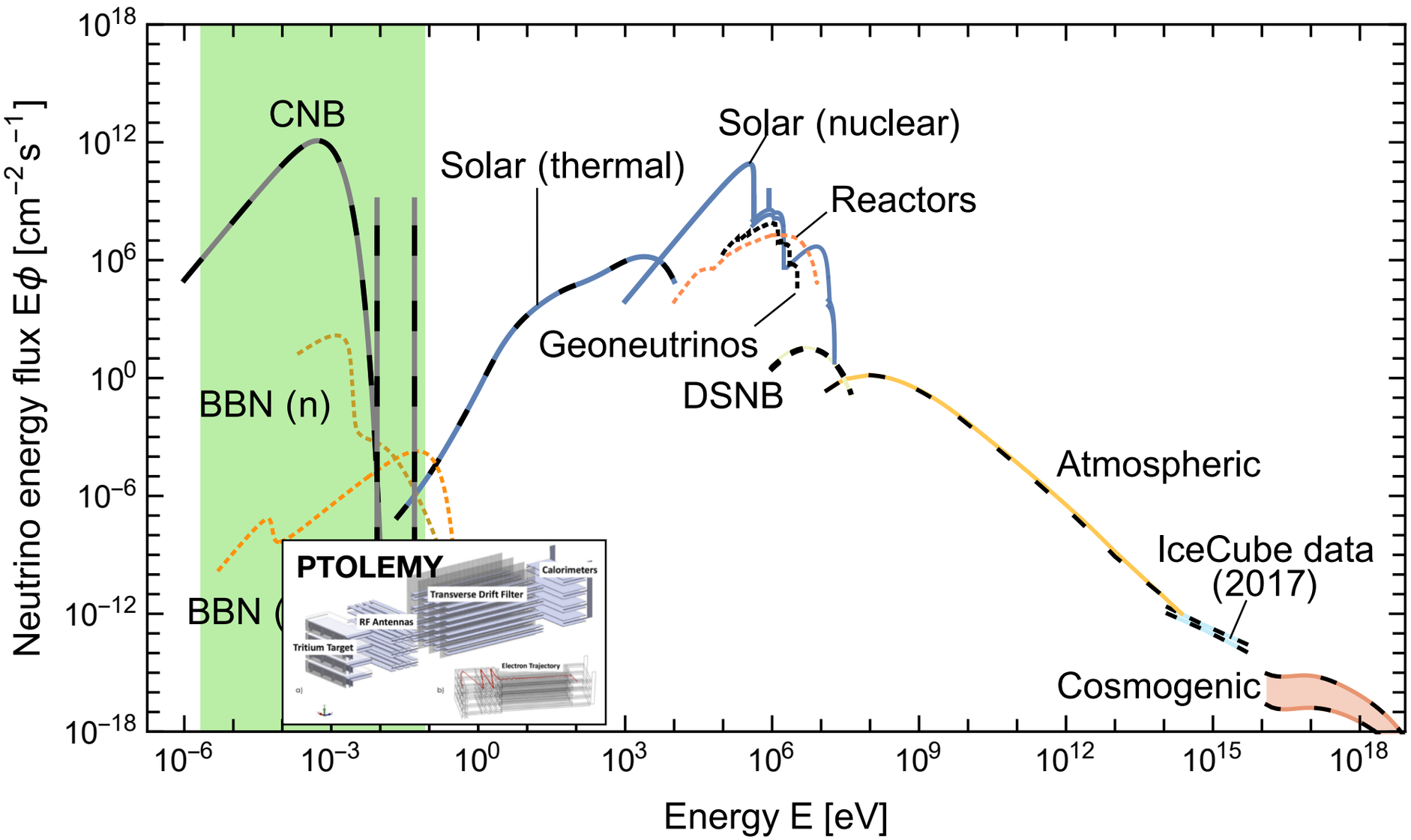




Hundreds of events will allow detailed ν measurements

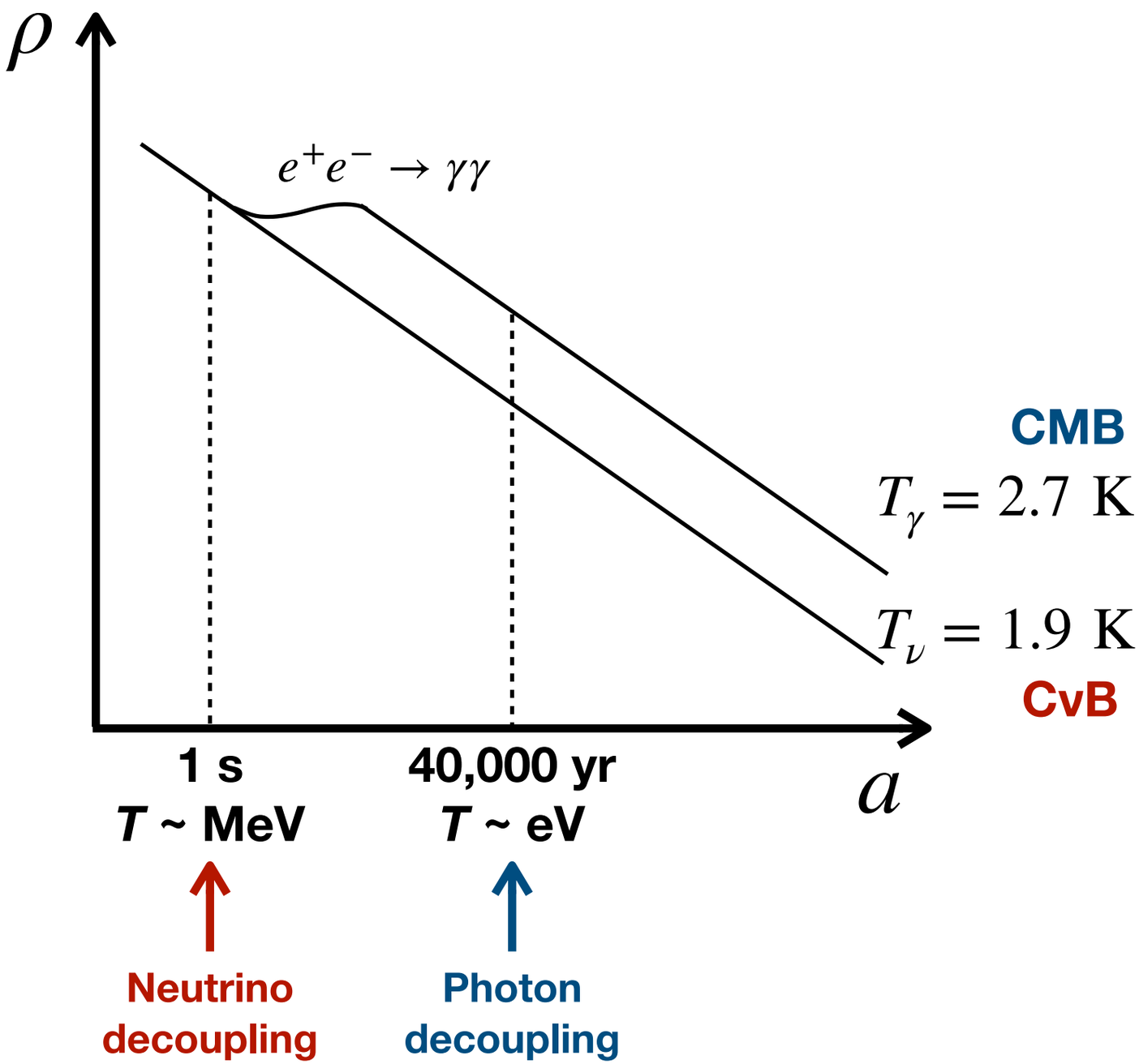
R. Lang et al, *Phys. Rev. D* **94**, 103009 (2016)

“Grand unified” neutrino spectrum



Vitagliano, Tamborra, Raffelt, *Rev. Mod. Phys.* **92**, 045006 (2020)

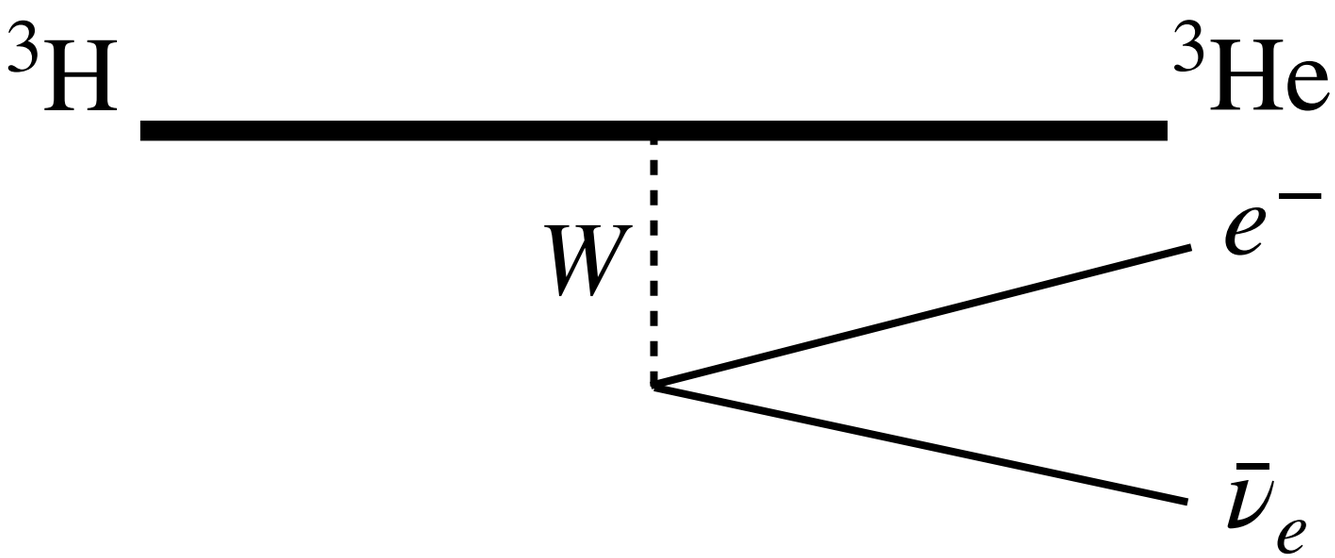
Cosmic neutrino background: Relic of the hot Big Bang



- Relic neutrino temperature is precisely calculated as $T_\nu = (4/11)^{1/3} T_{\rm CMB} = 1.95$ K
- Their momentum follows $$f(p) = \frac{1}{1 + \exp(p/T_\nu)}$$
- Number density: $n_{\nu+\bar{\nu}} \approx 110\ {\rm cm}^{-3}$ per flavor

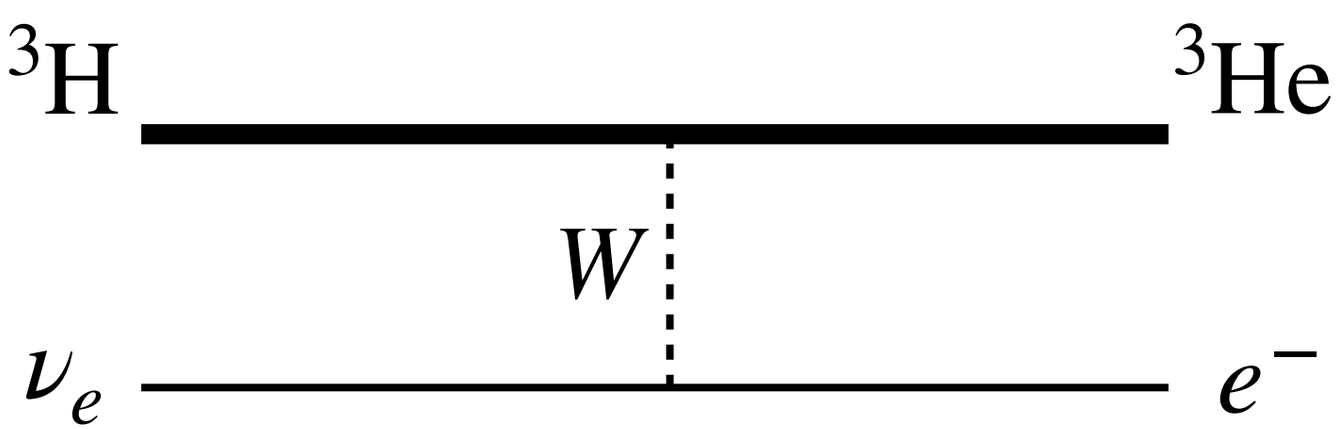
Detection of CNB

Tritium beta decay



Neutrino mass measurement:
Sensitive down to ~0.2 eV

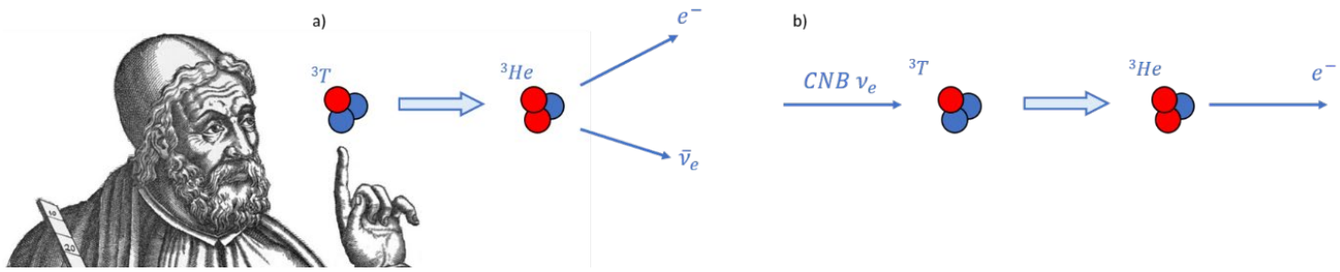
Tritium beta decay induced by CNB



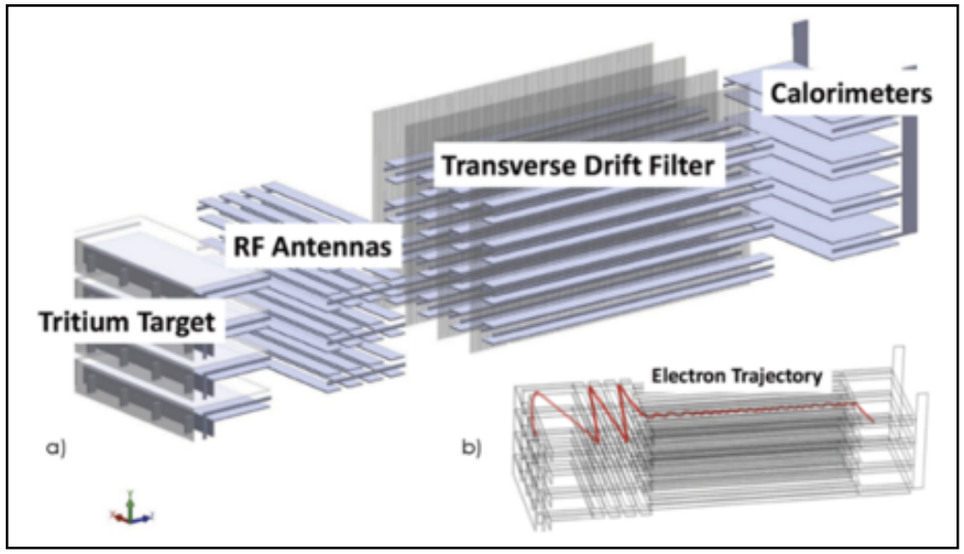
Weinberg, *Phys. Rev.* **128**, 1457 (1962)

- “Same” Feynman diagram
- No threshold: neutrinos with very small energy can be detected!

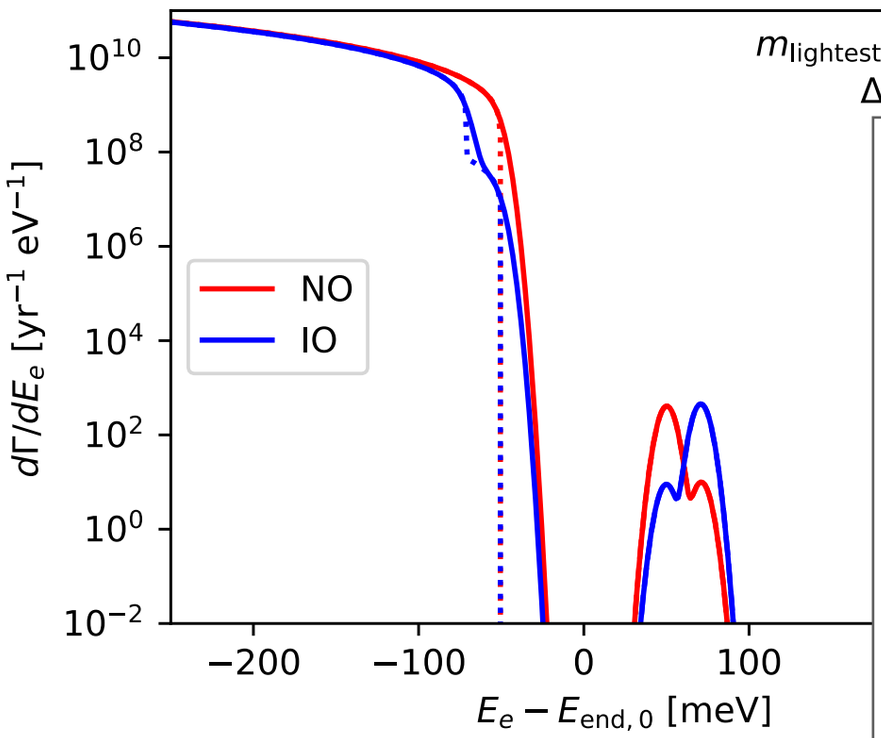
Detection of CNB: PTOLEMY

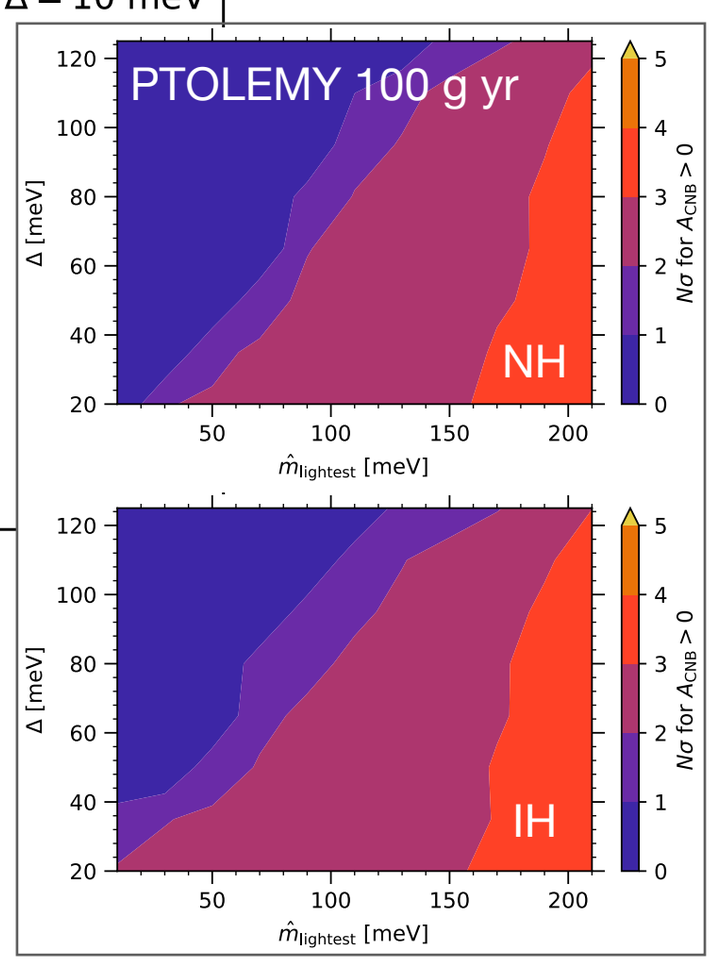


Pon**T**ecorvo **O**bservatory for **L**ight, **E**arly-universe, **M**assive-neutrino **Y**ield

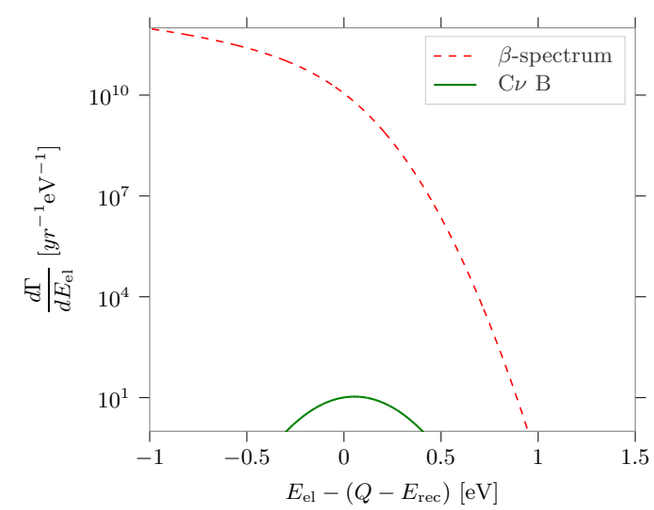


PTOLEMY, *JCAP* **07**, 047 (2019)



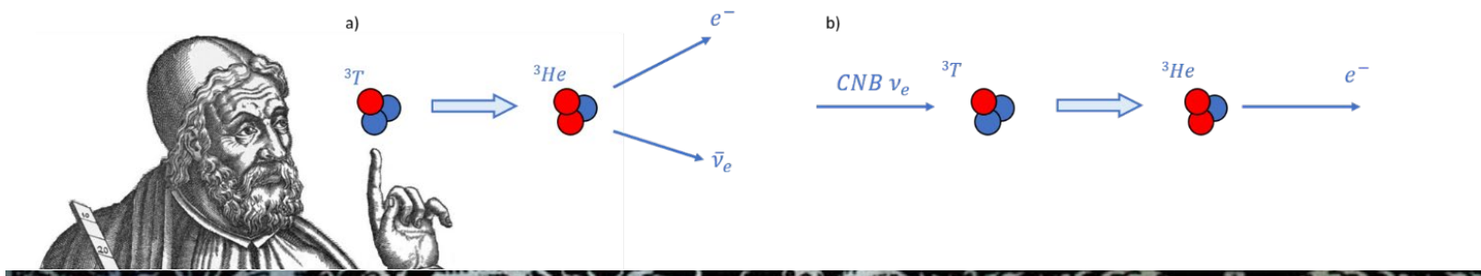


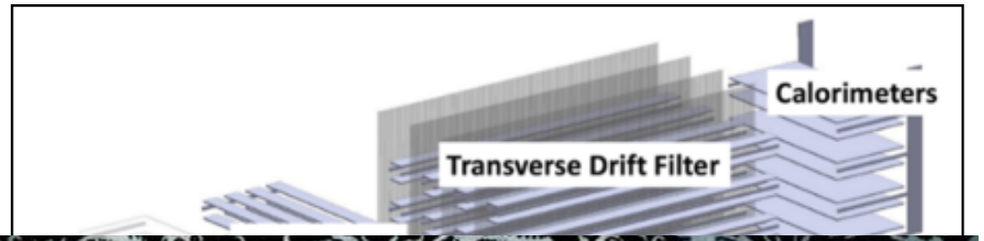
- Very fine energy resolution needed -> molecular tritium (like KATRIN) doesn't work -> graphene target
- Uncertainty principle might be the bottleneck



Cheipesh et al., arXiv:2101.10069 [hep-ph]

Detection of CNB: PTOLEMY

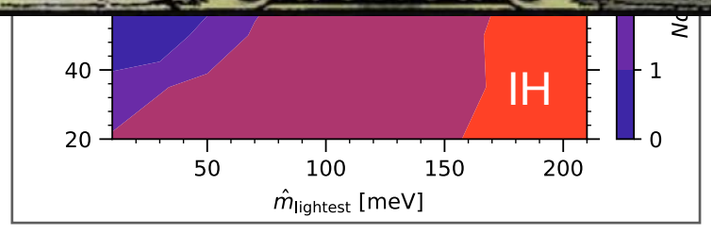


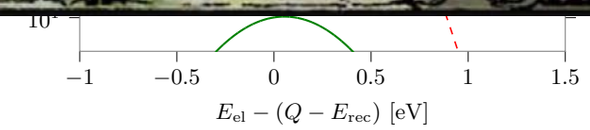


NWA-ORC Project

"One second after the big bang"

Ando, Colijn (PI), de Groot, Lock, van Rossum, Zeitler



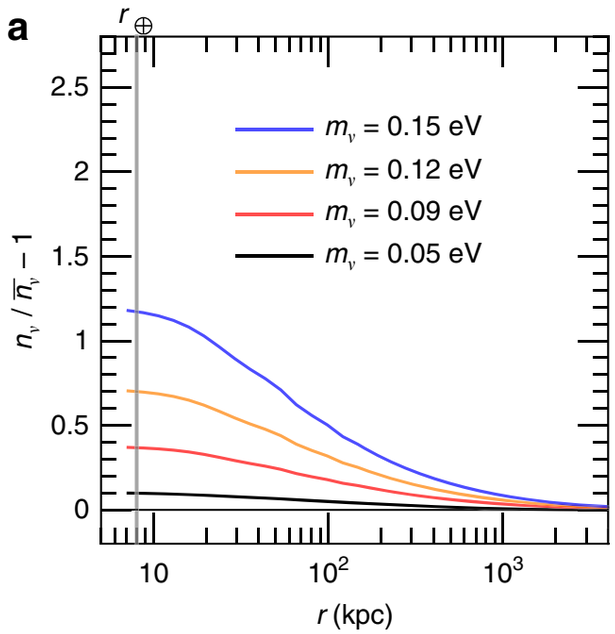


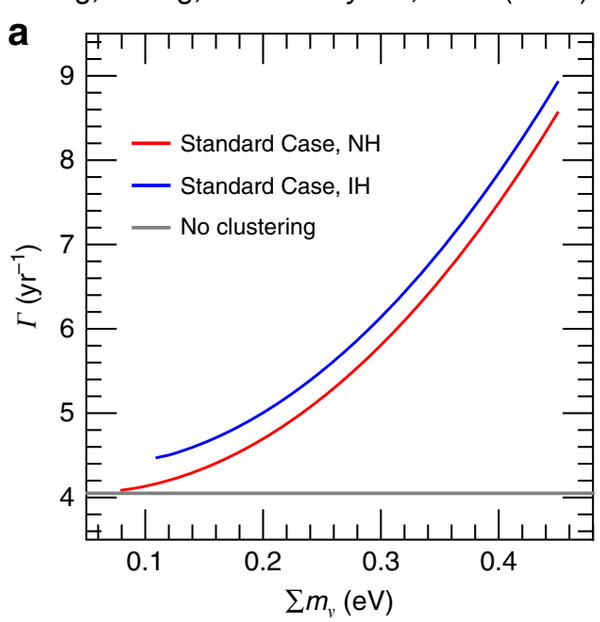
Cheipesh et al., arXiv:2101.10069 [hep-ph]

Various possibilities

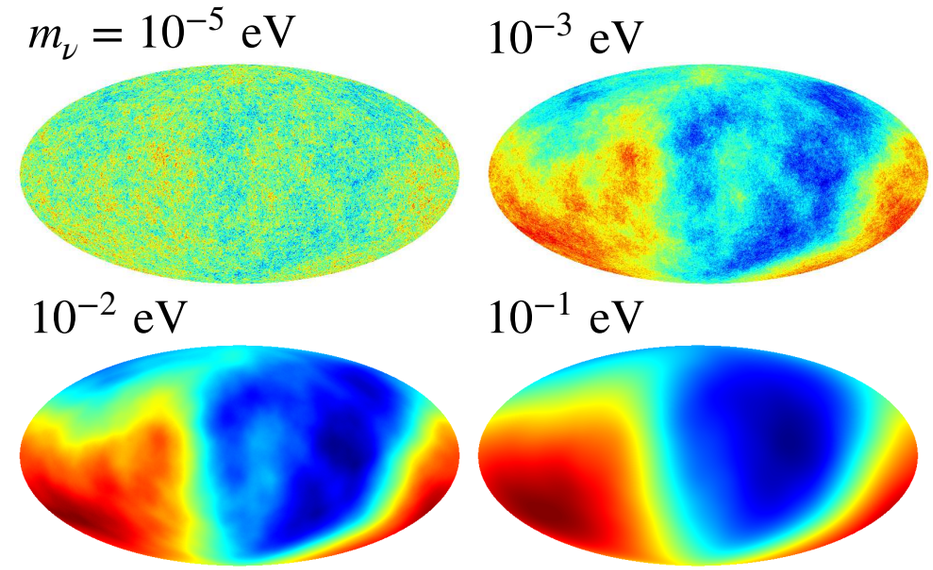
Inhomogeneity

Zhang, Zhang, *Nature Phys.* **9**, 1833 (2018)



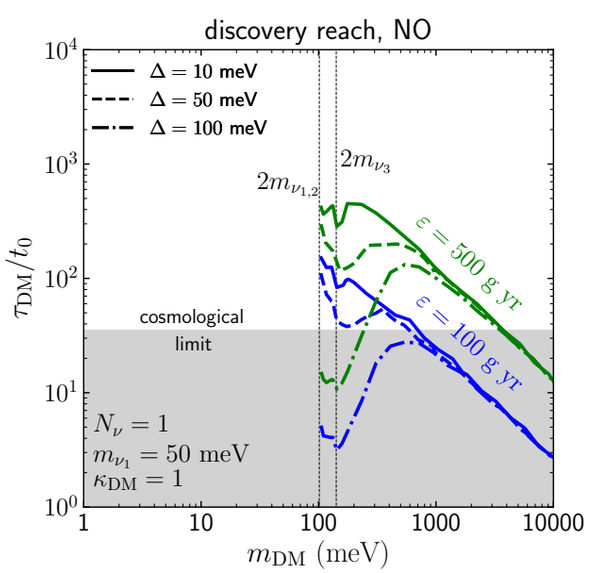


Anisotropy



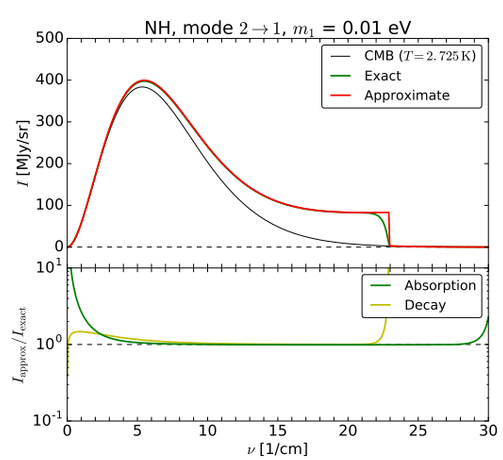
PTOLEMY, arXiv:1808.01892 [physics.ins-det]

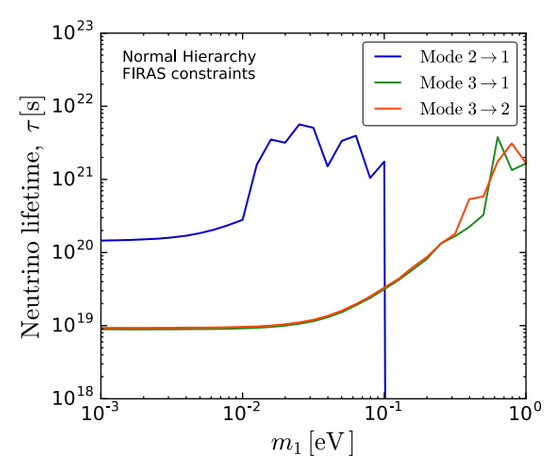
sub-eV dark matter



Bondarenko et al., 2012.09704 [astro-ph.CO]

Radiative decay





Aalberts et al., *Phys. Rev. D* **98**, 023001 (2018)

Undergraduate workshop in theoretical physics 2018

Conclusions

TeV-PeV

- IceCube detected TeV-PeV neutrinos (including a Glashow resonance candidate), but **no source has been identified**
- Interesting coincident with blazar flares and tidal disruption event
- **KM3NeT (ANTARES)** is complementary in terms of **sky coverage** and **better angular resolution**

MeV

- Unique neutrino physics with **DARWIN**: **pp solar neutrinos** at 0.1-0.2 MeV and hundreds of neutrino events from **Galactic supernova**

meV

- **PTOLEMY** aims at detecting the cosmic neutrino background, relic of **1 second after the Big Bang**
- Lots of space for exploration even for theorists!