

Neutrino Sources

International Neutrino Summer School 2026

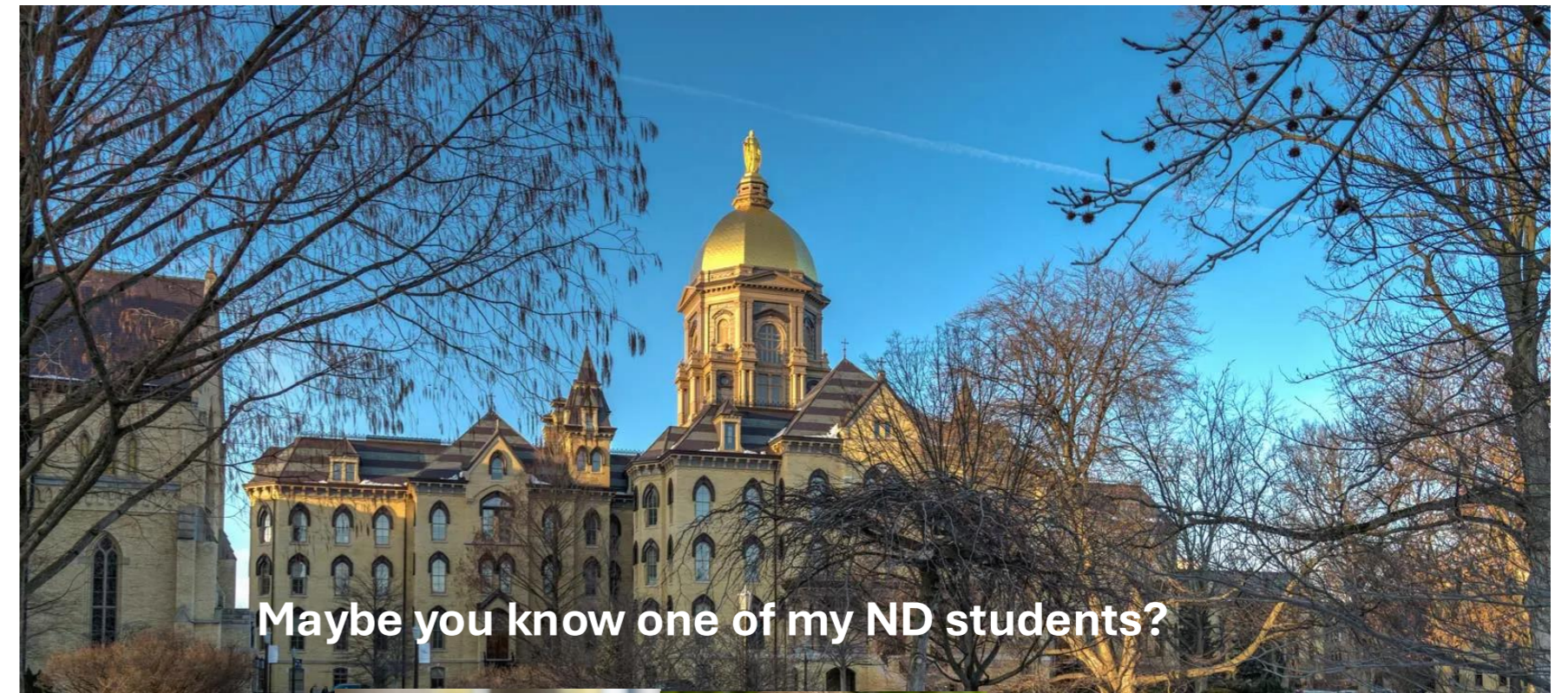
Laura Fields, University of Notre Dame



Source of this craziness: Google Gemini

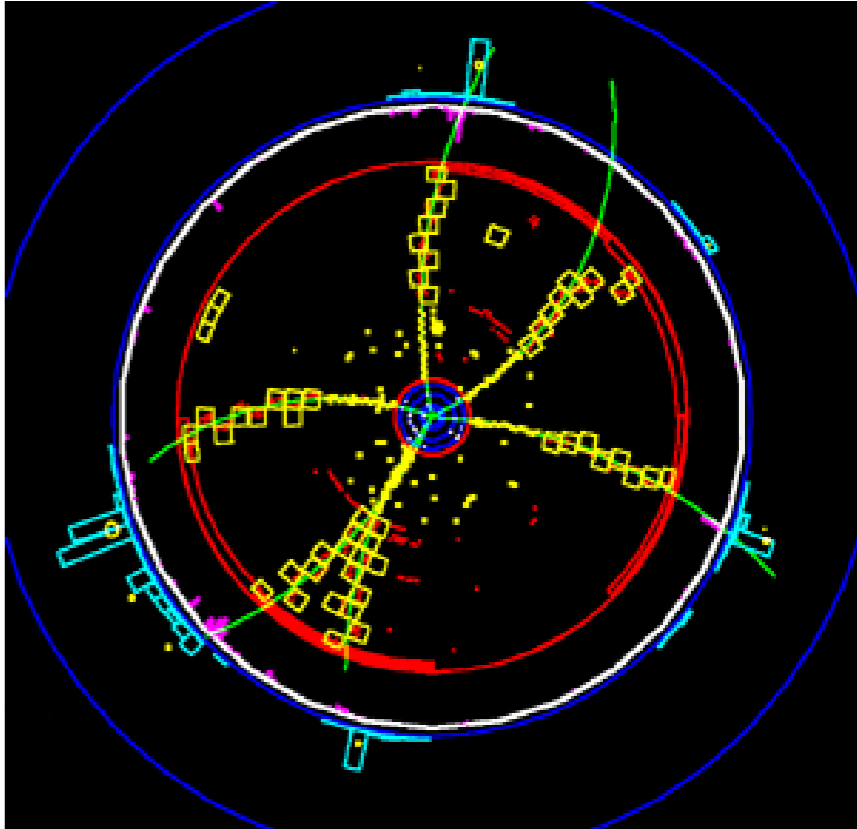
About Me

- I'll start off by telling you a tiny bit **about me and why I care about neutrino sources**
- I'm from **the University of Notre Dame**
- I work a lot on **neutrino beam-related topics**, on Fermilab neutrino experiments like DUNE and MINERvA, and hadron-production experiments like EMPHATIC and NA61/SHINE

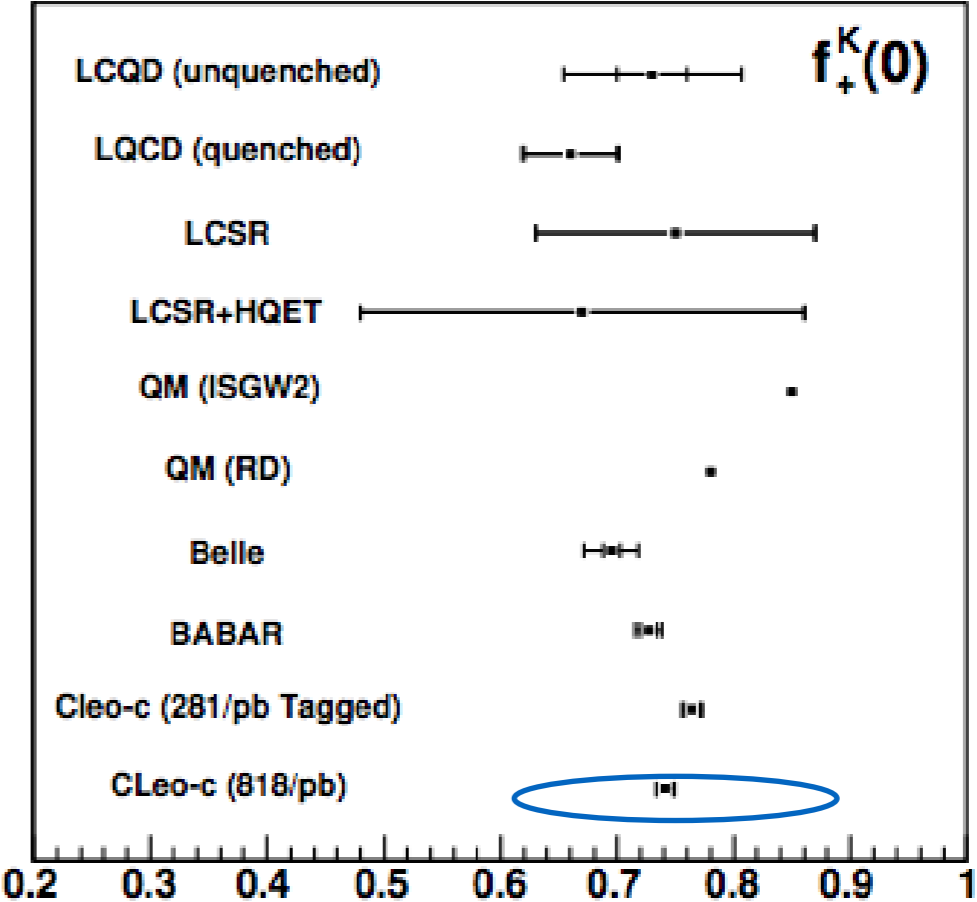


How I Got Here

- As a PhD student, I was not a neutrino physicist – I worked on a collider experiment called CLEO; my PhD advisor (Ritchie Patterson) is known for making very **high precision measurements**
- That definitely appealed to me, and we went on to make some very precise measurements to **test Lattice QCD**

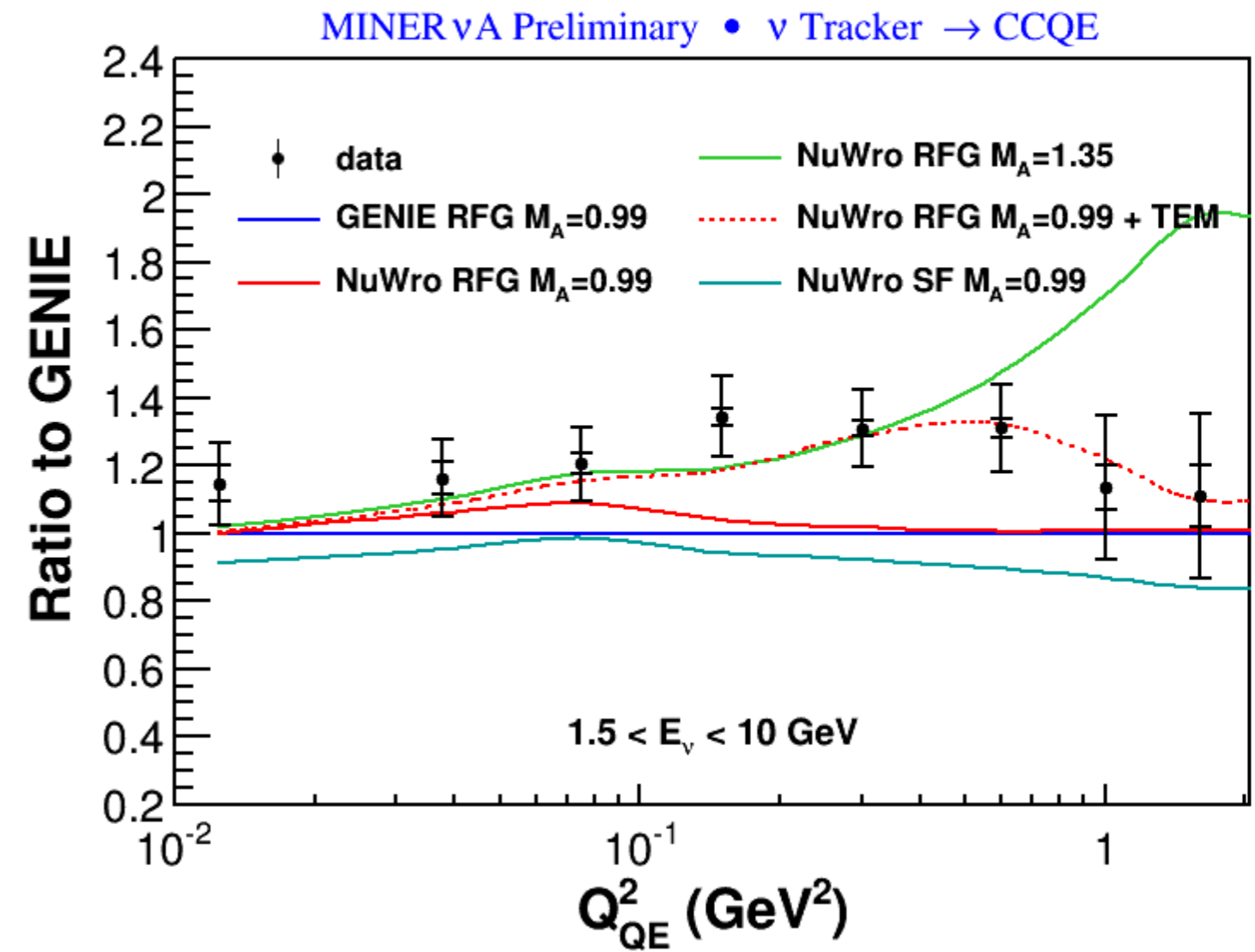


One of my thesis measurements
— 2% uncertainty!

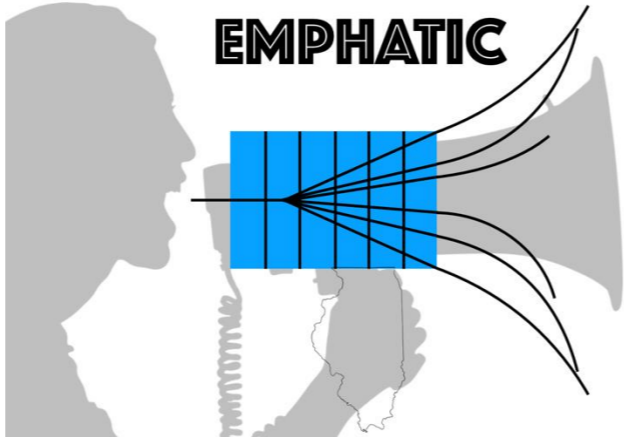
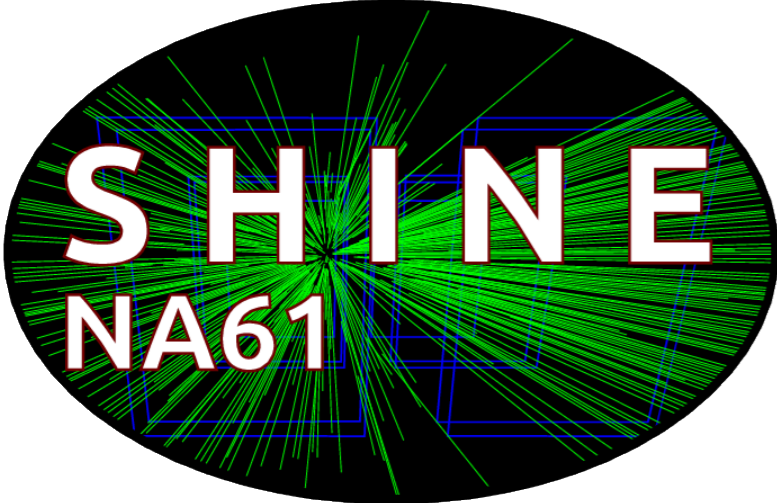


How I Got Here

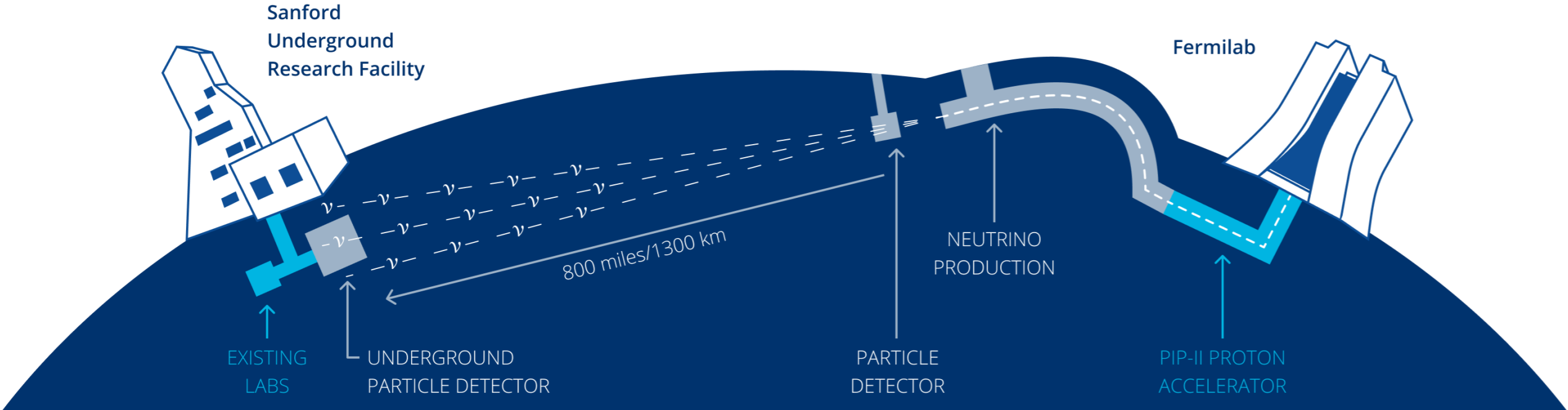
- As a postdoc, I switched to neutrino physics, working on the MINERvA experiment with Northwestern, working at Fermilab
- My first MINERvA measurements had 10-20% uncertainties — much larger than my thesis measurement (and those were really precise by neutrino standards!)



How I Got Here

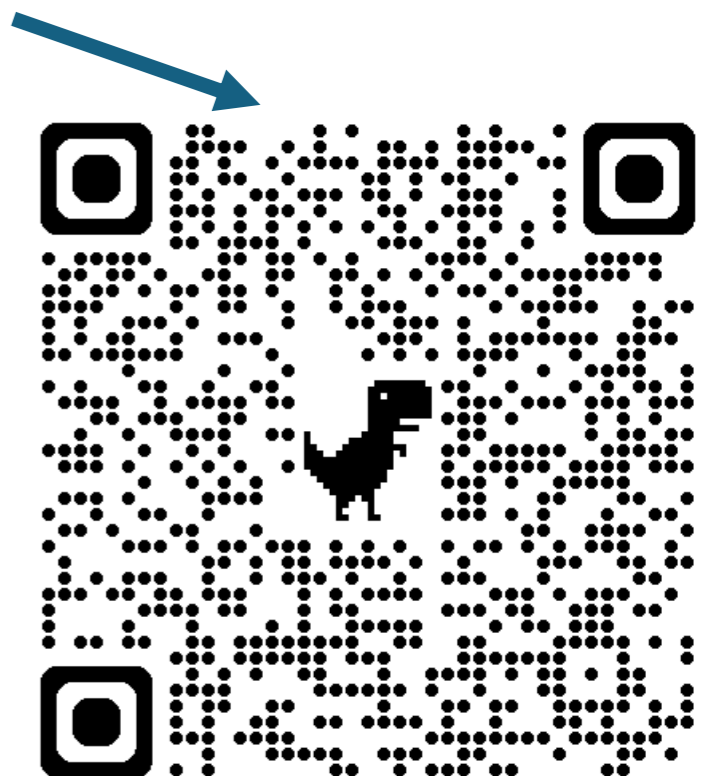


- I learned that the difficulty with precision neutrino physics has many culprits, but it starts with our sources
- So I've spent much of the rest of my career working on making better and better understood neutrino beams




Some Logistics

- 90 minutes is a long time
 - We will take a short break about halfway through
 - Get up and move around – it helps you learn better!
- Please ask questions!
 - I talk fast, and you asking questions helps me slow down
 - If you can't tolerate asking questions in class, ask them here



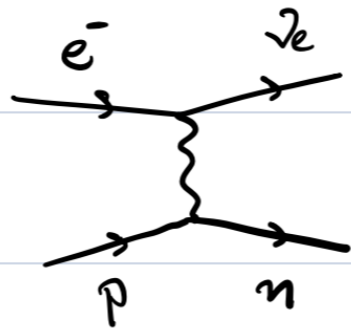
Neutrino Sources at Past INSS

16th International Neutrino Summer School 2025 at Fermilab NPC

Coffee break	
atrium	10:30 - 11:00
Neutrino sources	Pedro Accioly Nogueira Machado 
One West, Fermi National Accelerator Laboratory	11:00 - 12:00
Lunch	



What is the problem? Weak Interactions



$$\sigma \sim \frac{G_F^2 s}{4\pi} \sim 2 G_F^2 E_e m_p / 4\pi$$

$$1 \text{ GeV } \bar{e}: \sigma \sim 2 \times (10^{-5} \text{ GeV}^{-2})^2 (1 \text{ GeV})(1 \text{ GeV}) / 4\pi$$

$$\sim 2 \times 10^{-11} \text{ GeV}^{-2} (\hbar c)^2 \quad (2 \times 10^{-14} \text{ GeV cm})^2$$

$$\sim 8 \times 10^{-39} \text{ m}^2 \sim 10^{-38} \text{ m}^2$$

Neutrino Sources at Past INSS

15th International Neutrino Summer School 2024

Jun 3 – 14, 2024
Bologna, Italy
Europe/Rome timezone



Neutrino Beams & Fluxes

Sudeshna Ganguly
15th International Neutrino Summer School 2024

14th International Neutrino Summer School 2023

Aug 7 – 18, 2023
Fermi National Accelerator Laboratory
US/Central timezone

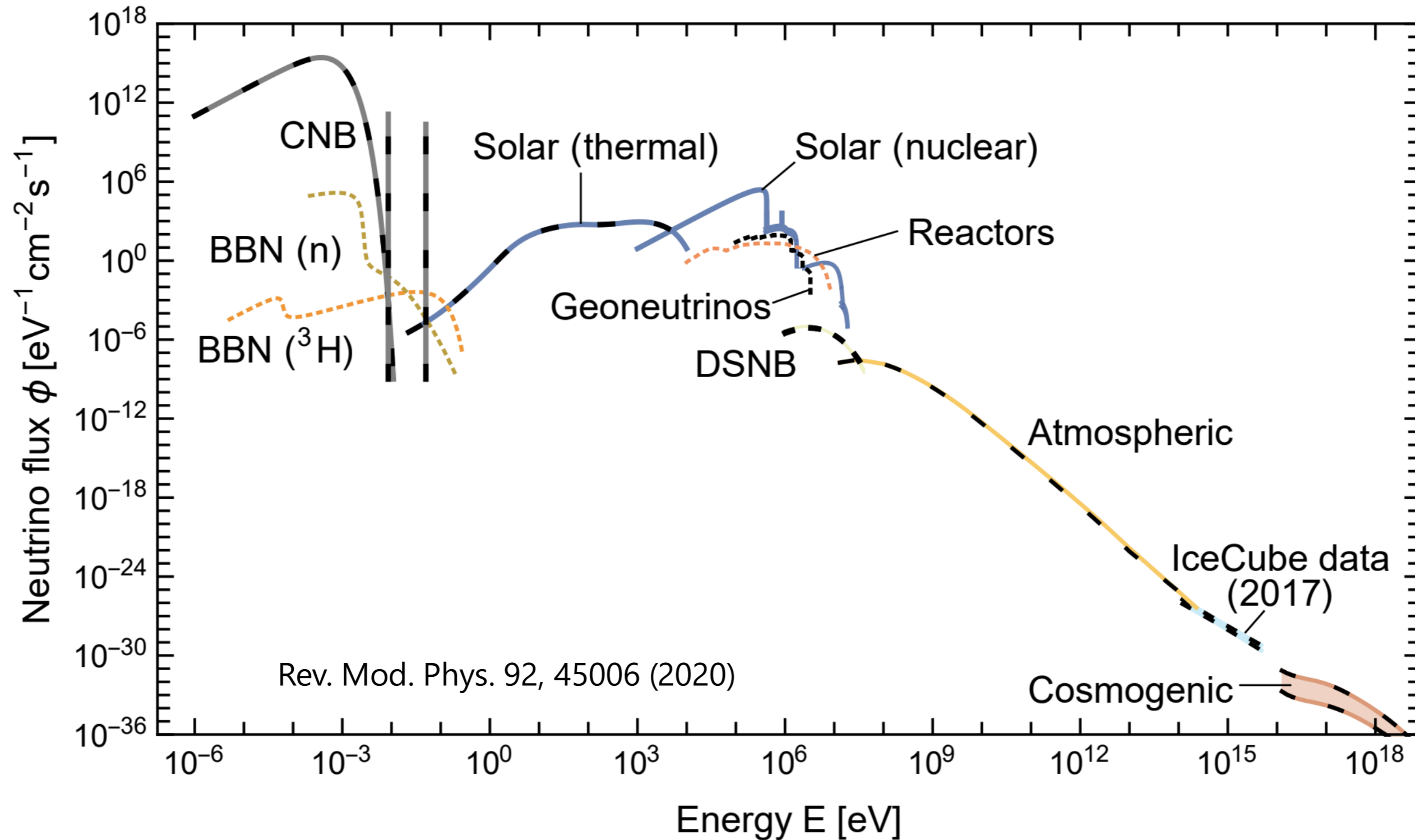
Neutrino Beams and Fluxes



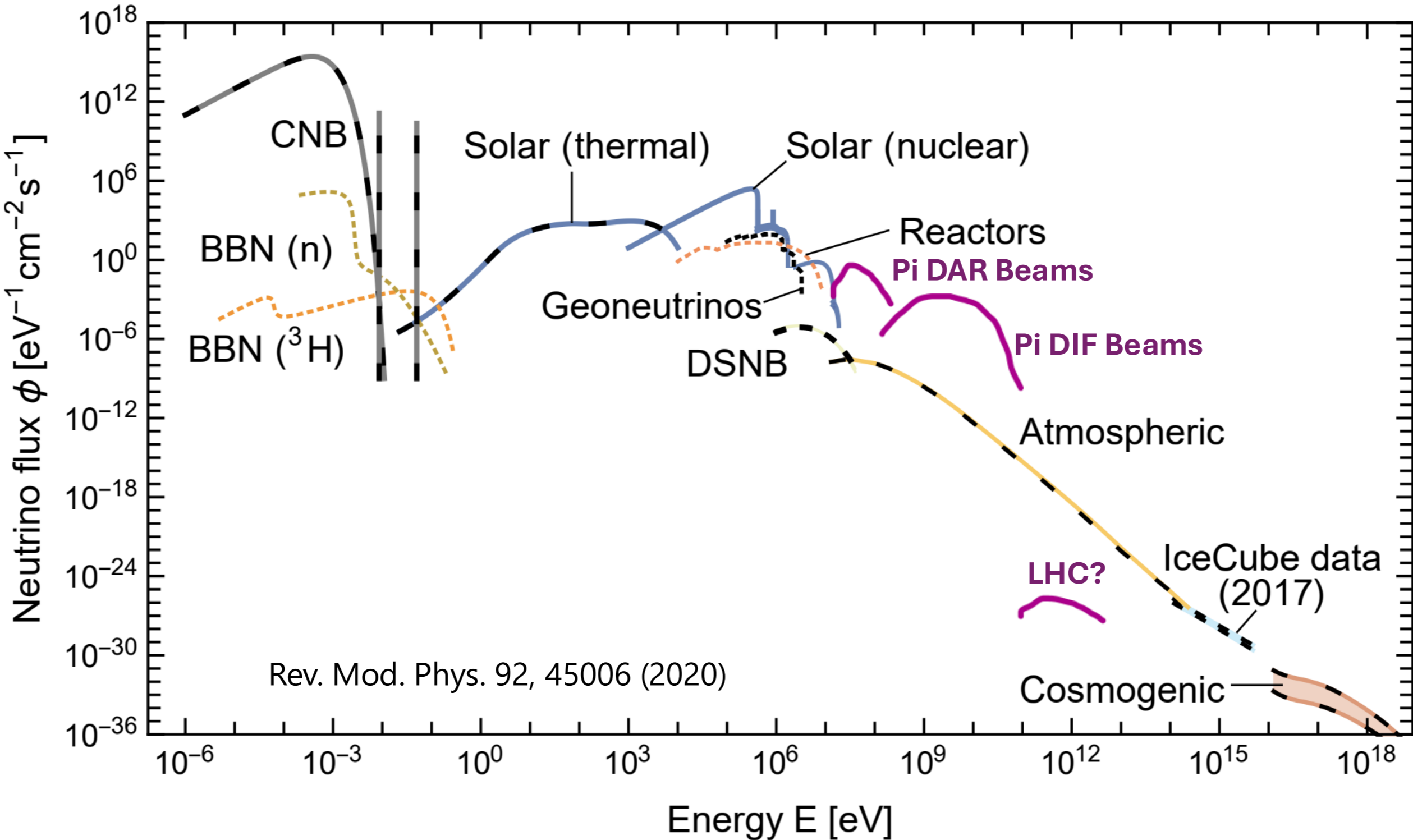
Thanks to Sudeshna and Josh, for kindly letting me steal beam-related content from their talks.

Tell Me About the Sources You Use

My Job Today and Tomorrow

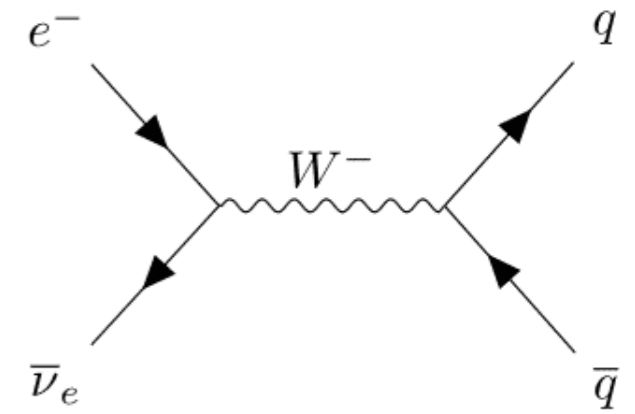
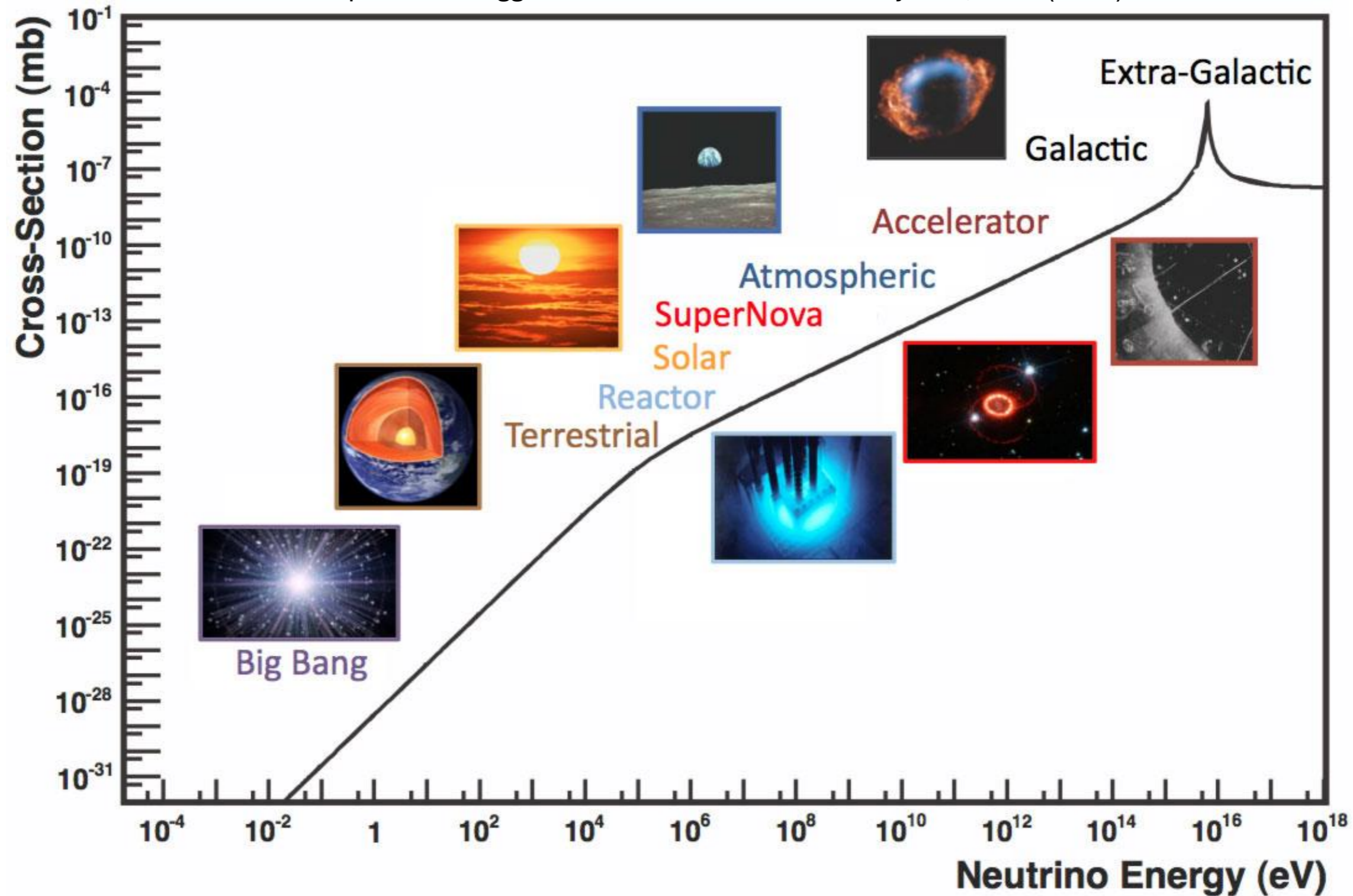


My Job Today and Tomorrow



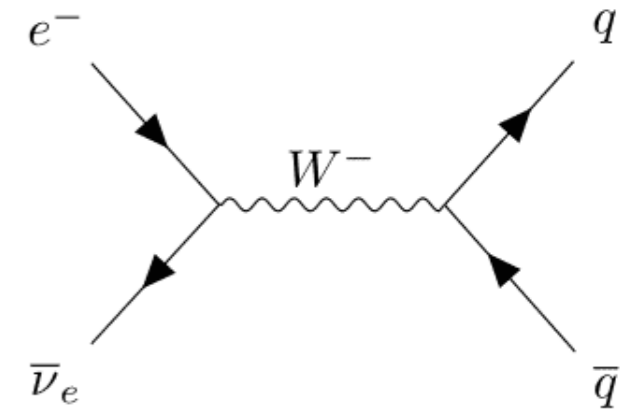
Another View

Joseph A. Formaggio and G. P. Zeller Rev. Mod. Phys. 84, 1307 (2012)



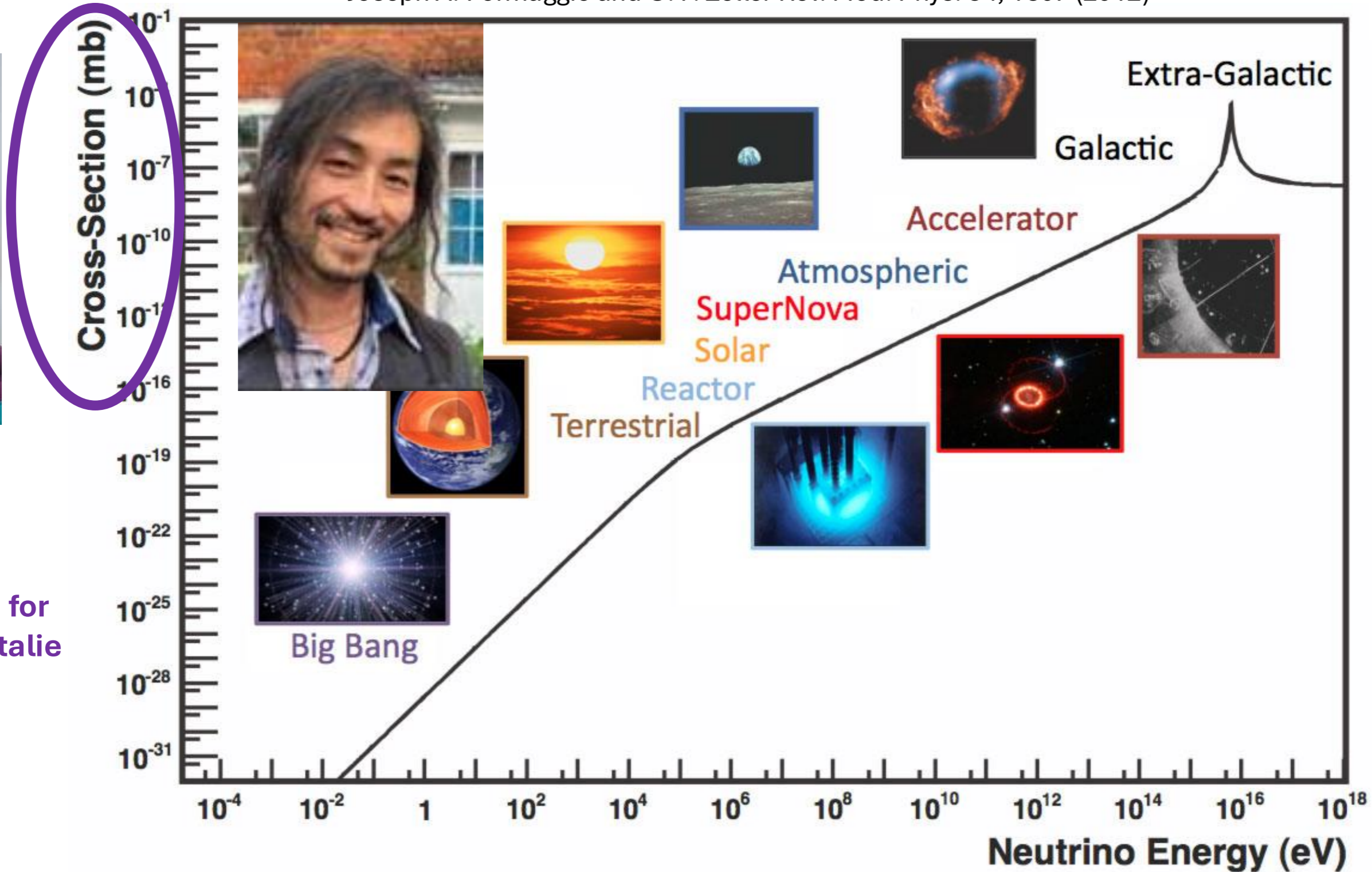
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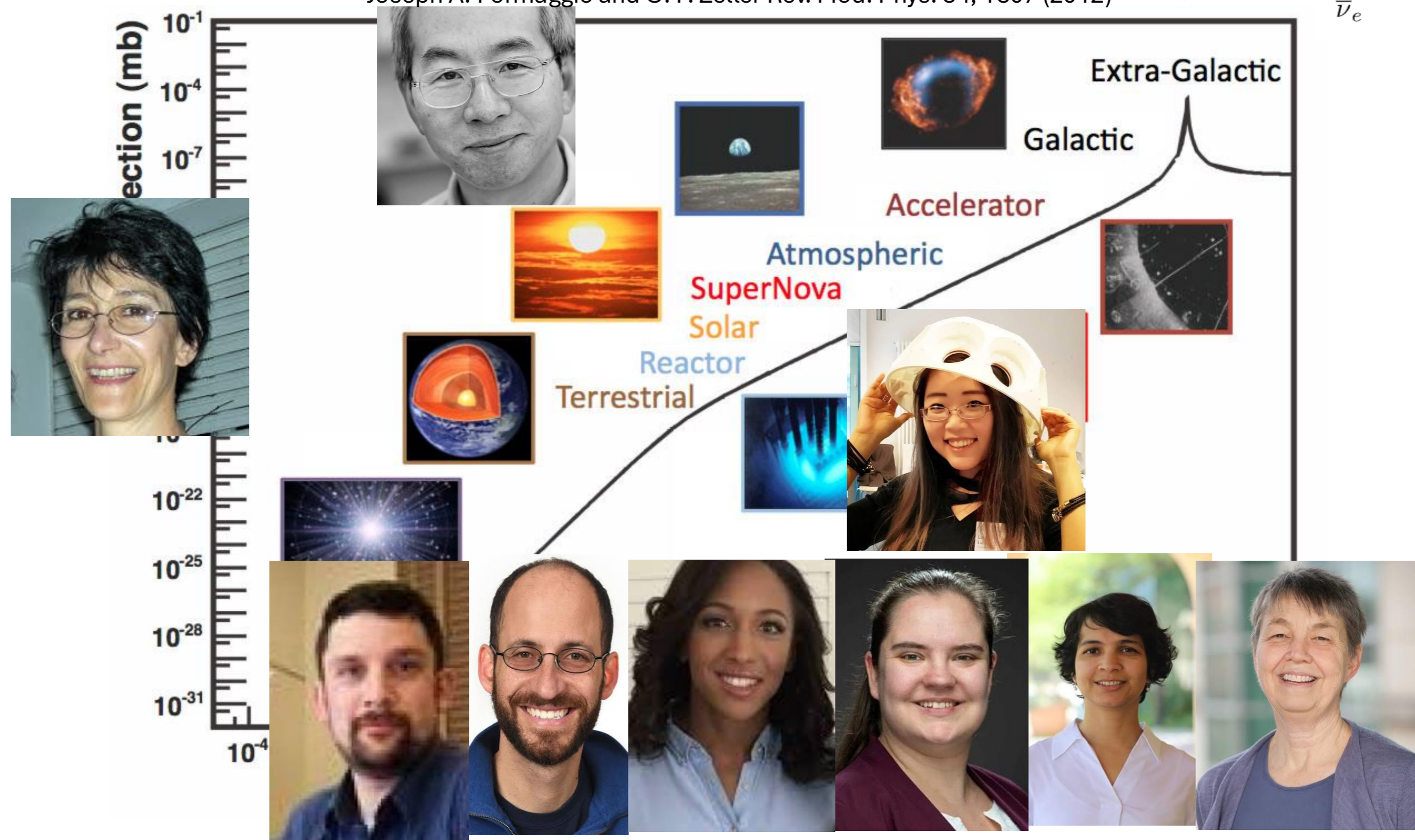
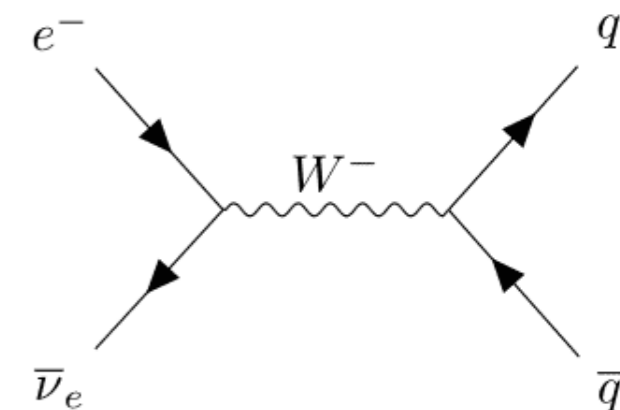
Not really my purview,

But stay tuned for Teppei and Natalie



Actually Stay Tuned for a Lot More

Joseph A. Formaggio and G. P. Zeller Rev. Mod. Phys. 84, 1307 (2012)



Order of Operations

- Some preliminaries
 - Weak Interactions
 - Neutrino flux predictions
- Natural Sources
 - Solar
 - Astrophysical
 - Big Bang
 - Atmospheric
 - Terrestrial
- Artificial Sources
 - Reactors
 - Pion decay in flight
 - Pion decay at rest
 - Radioactive Isotope Sources
 - LHC Neutrinos
 - Potential Future Sources

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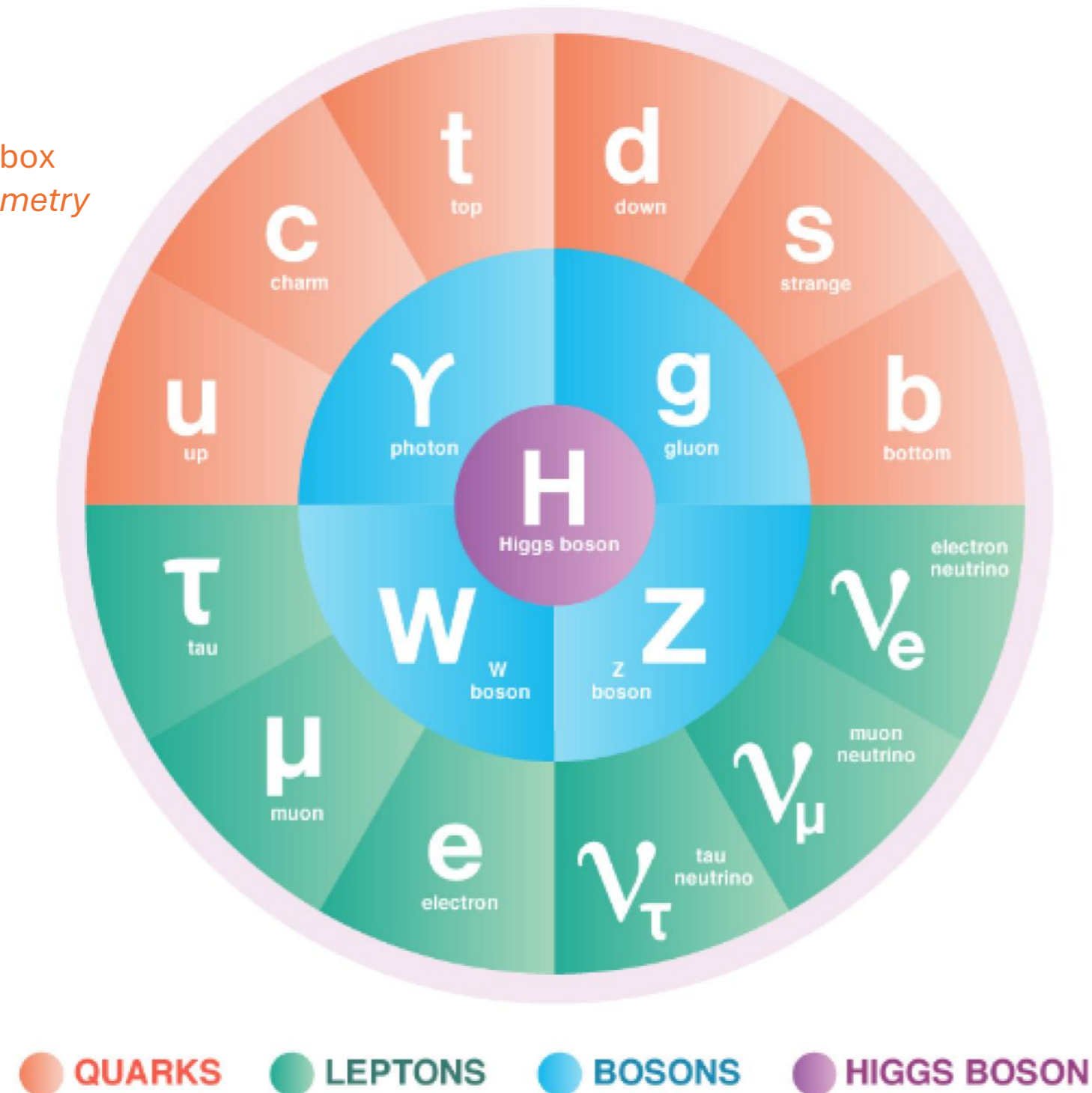
~Today



~Tomorrow

Source Basics: Weak Interactions

Figure by Sandbox
Studio for *Symmetry*
magazine



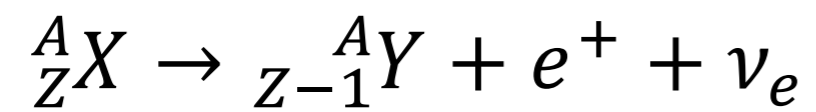
- Neutrinos only interact with other particles via the weak force
- Anytime a neutrino is made, there will be a weak interaction, mediated by the W or Z boson

Source Basics: Weak Interactions

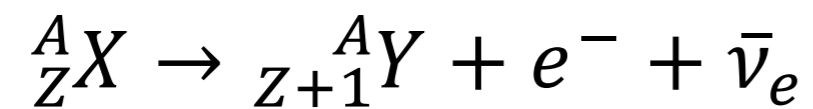
Requires unstable nucleus

- Beta decay:

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



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



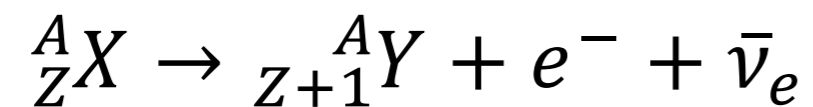
Source Basics: Weak Interactions

- Beta decay:

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



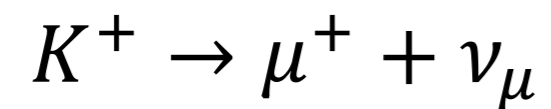
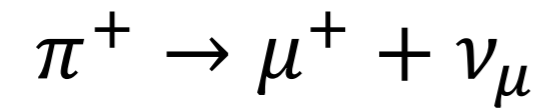
- $\beta^- : n \rightarrow p + e^- + \bar{\nu}_e$



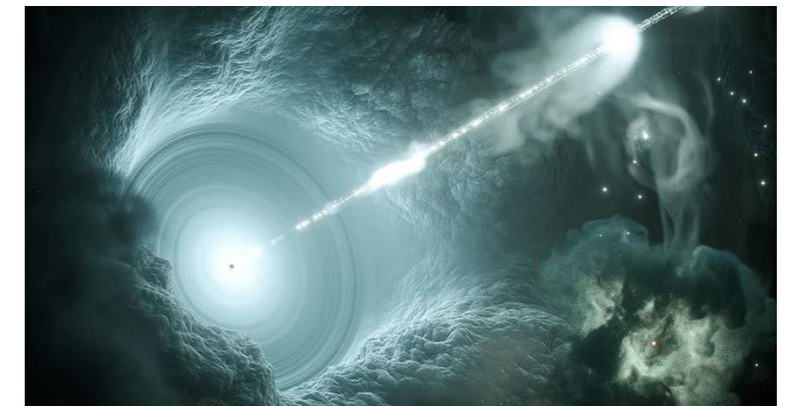
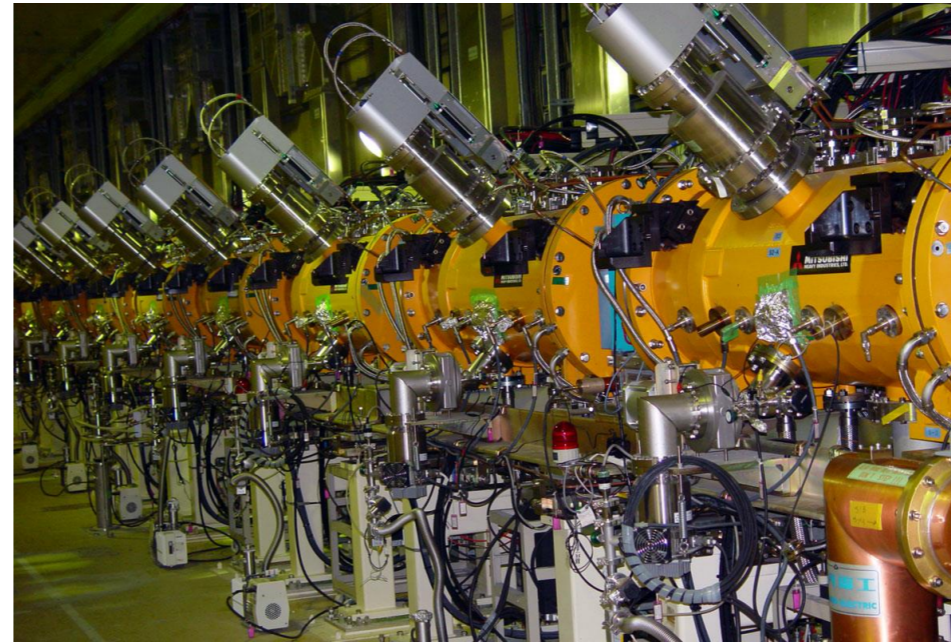
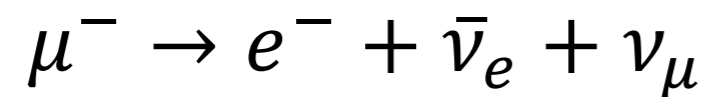
- Electron capture: $p + e^- \rightarrow n + \nu_e$
- URCA process: Beta decay + Electron capture cycle

Source Basics: Weak Interactions

- Hadron decay



- Muon decay

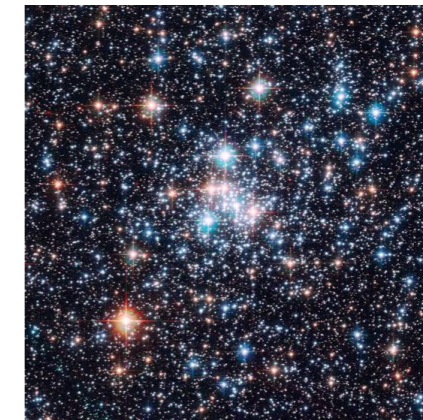


These are the most common channels. Neutrinos are also produced via other decays, e.g. other charged kaon channels, neutral kaon, charm meson, and tau decay

(And corresponding charge conjugate decays)

Source Basics: Weak Interactions

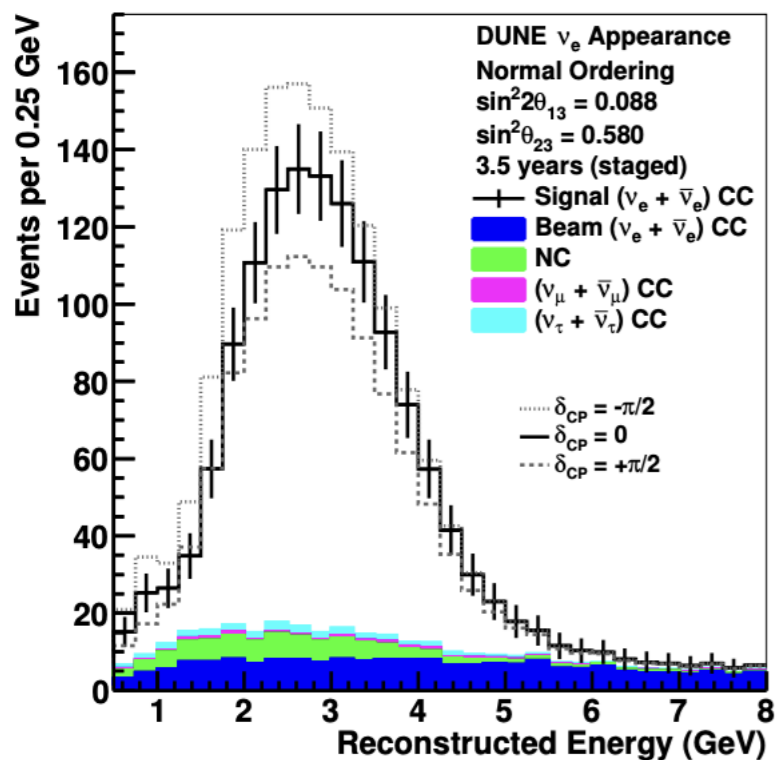
- Processes that make neutrinos
 - "Thermal production":
 - Electron/positron annihilation
$$e^+ + e^- \rightarrow \nu + \bar{\nu}$$
 - Bremsstrahlung
 - e. g. $N + N \rightarrow N + N + \nu + \bar{\nu}$
 - Photoneutrino process
$$\gamma + e^- \rightarrow e^- + \nu + \bar{\nu}$$
 - Plasmon decay
$$\gamma^* \rightarrow \nu + \bar{\nu}$$



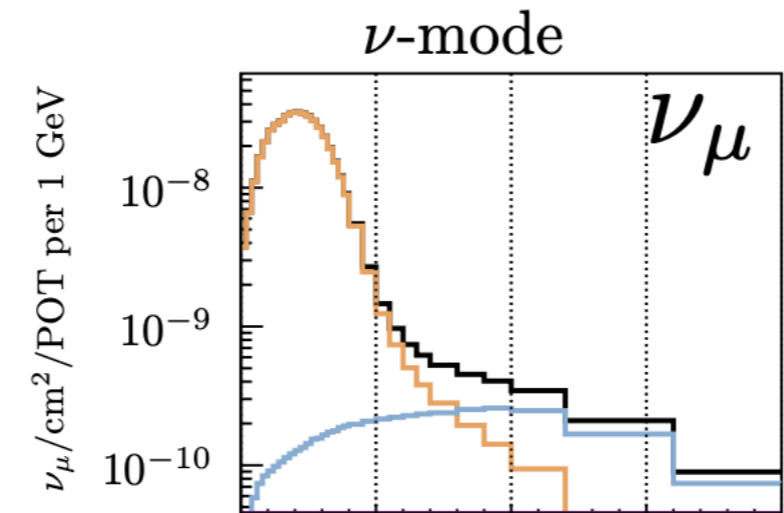
Thermal production happens in hot, dense environments where particles are in thermal equilibrium with their environment and create neutrinos through collisions

Flux Predictions and Uncertainties

- In order to transform between what we see in our detectors and fundamental knowledge of the universe, we almost always need a simulation:



+

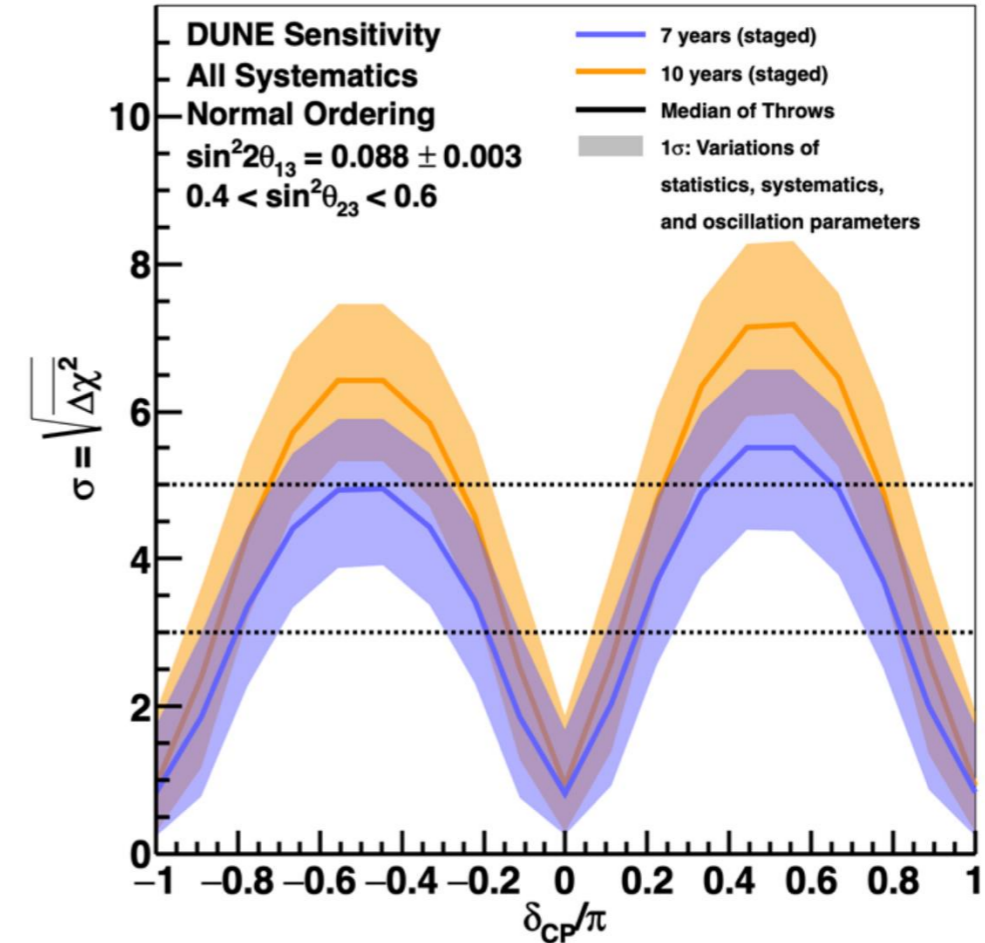


+

Lots of other stuff

=

DUNE TDR

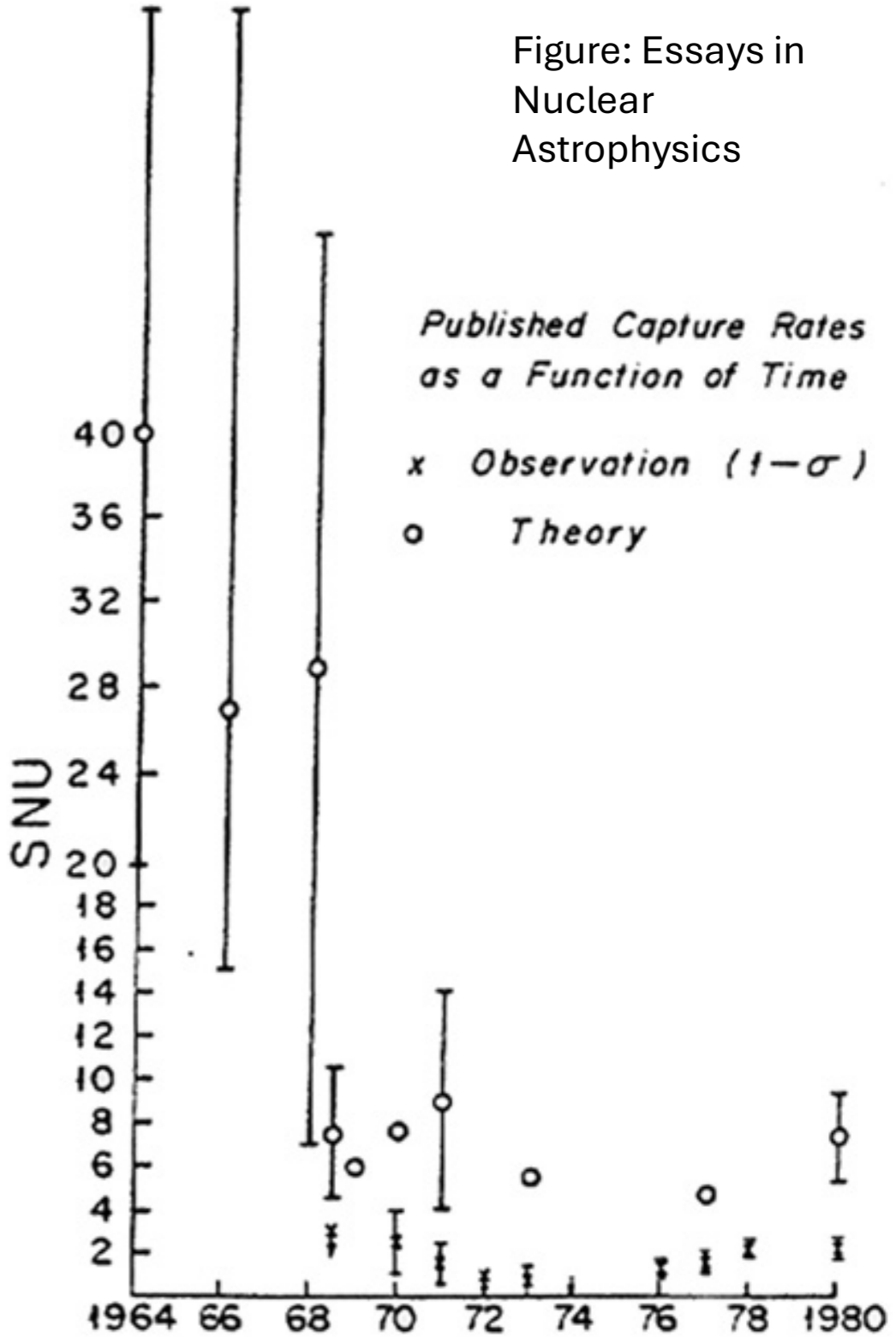


Flux Predictions and Uncertainties

- The **Ray Davis Experiment** studied solar neutrinos in the homestake mine in South Dakota in the 1960's.
- Was the first of many to observe **fewer solar neutrinos than expected** — “the solar neutrino problem”
- This was **Beyond the Standard Model Physics!!!!** But it took decades to figure that out in part because the solar neutrino flux was not well understood
- When you guys discover BSM, let's make sure that you can celebrate immediately



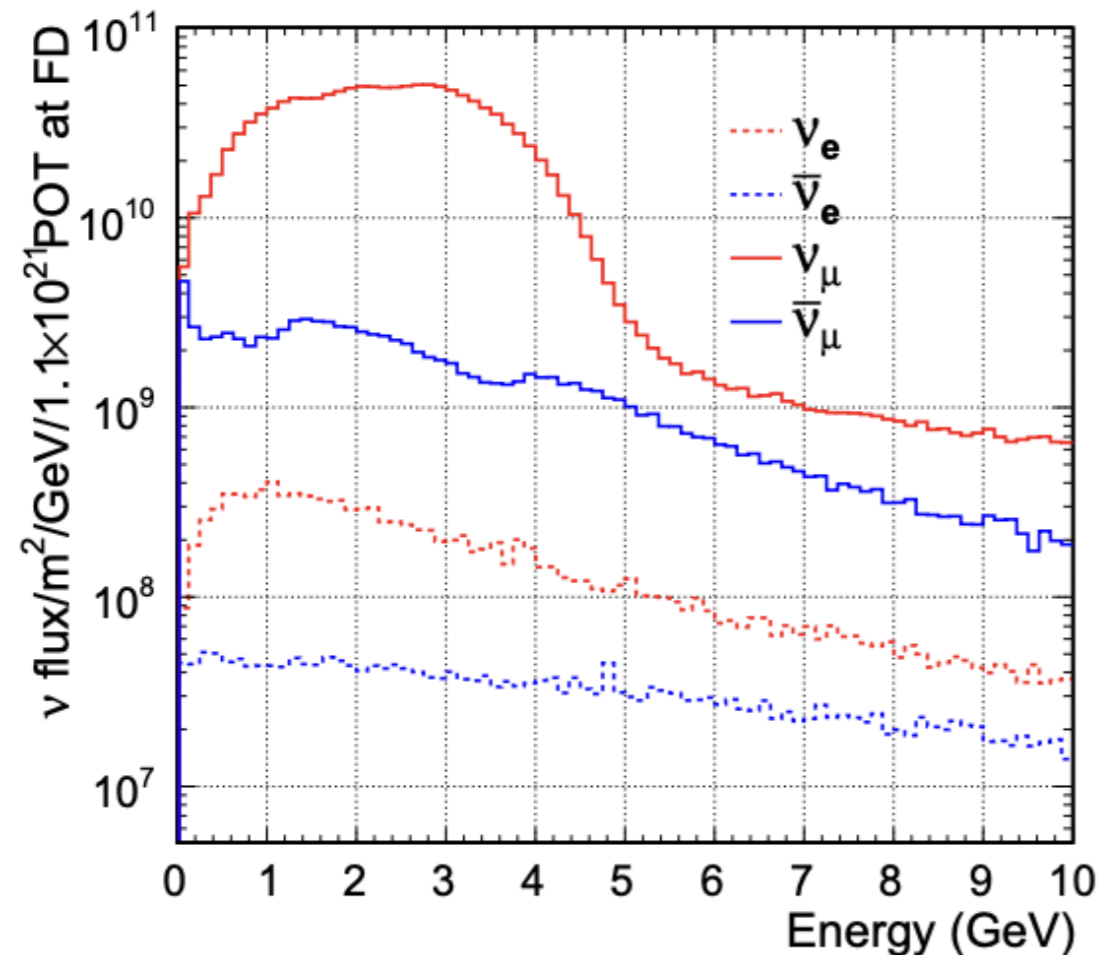
A big tank of dry cleaning fluid



Flux Predictions and Uncertainties

- Quantifying the flux of your source is often a HUGE challenge related to neutrino sources.
- What do we need exactly?

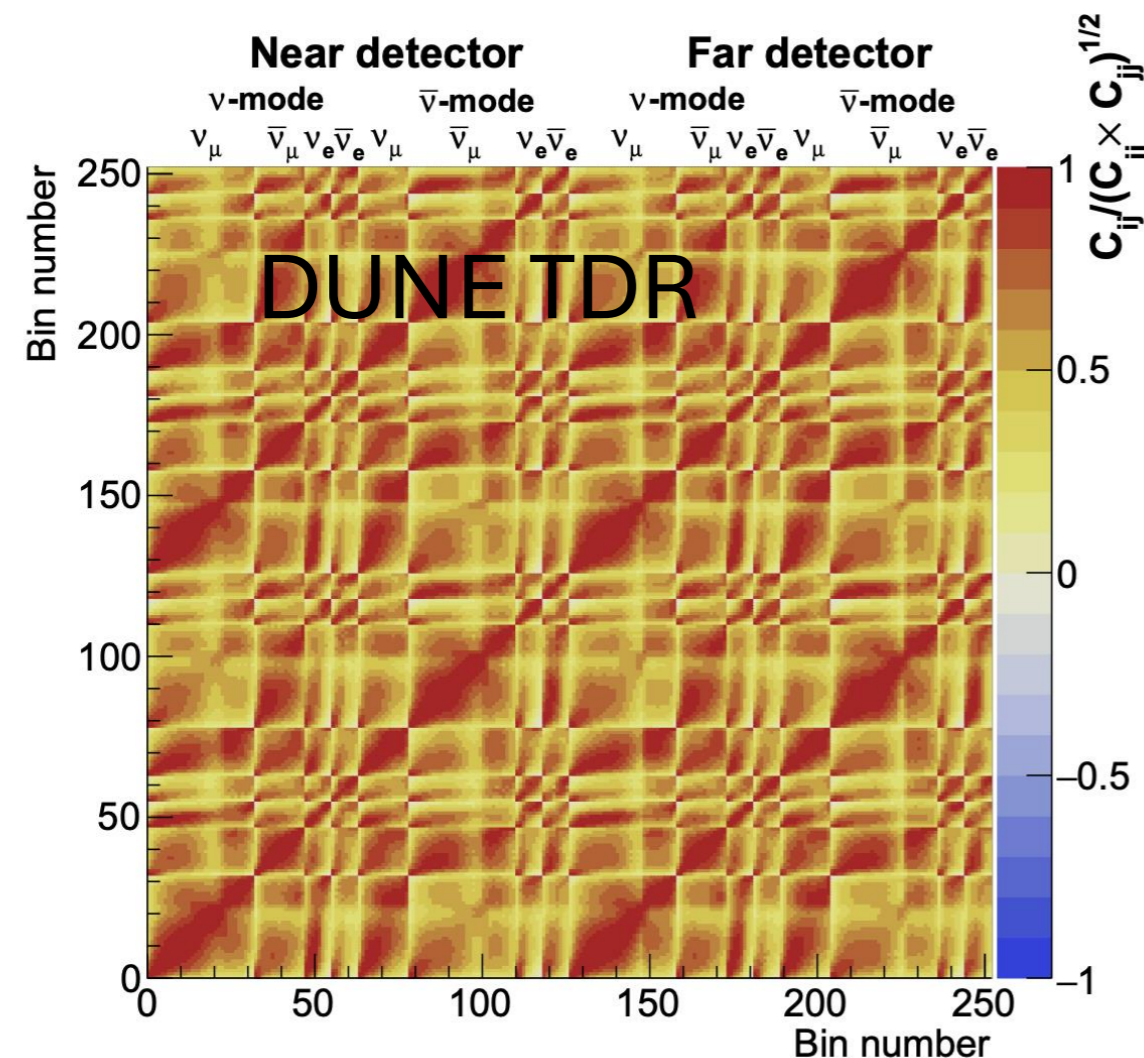
DUNE TDR



- The rate at which your source produces neutrinos
- Their flavor
- Their energy and angular spectrum
- Uncertainties on all of this
- Correlations of those uncertainties

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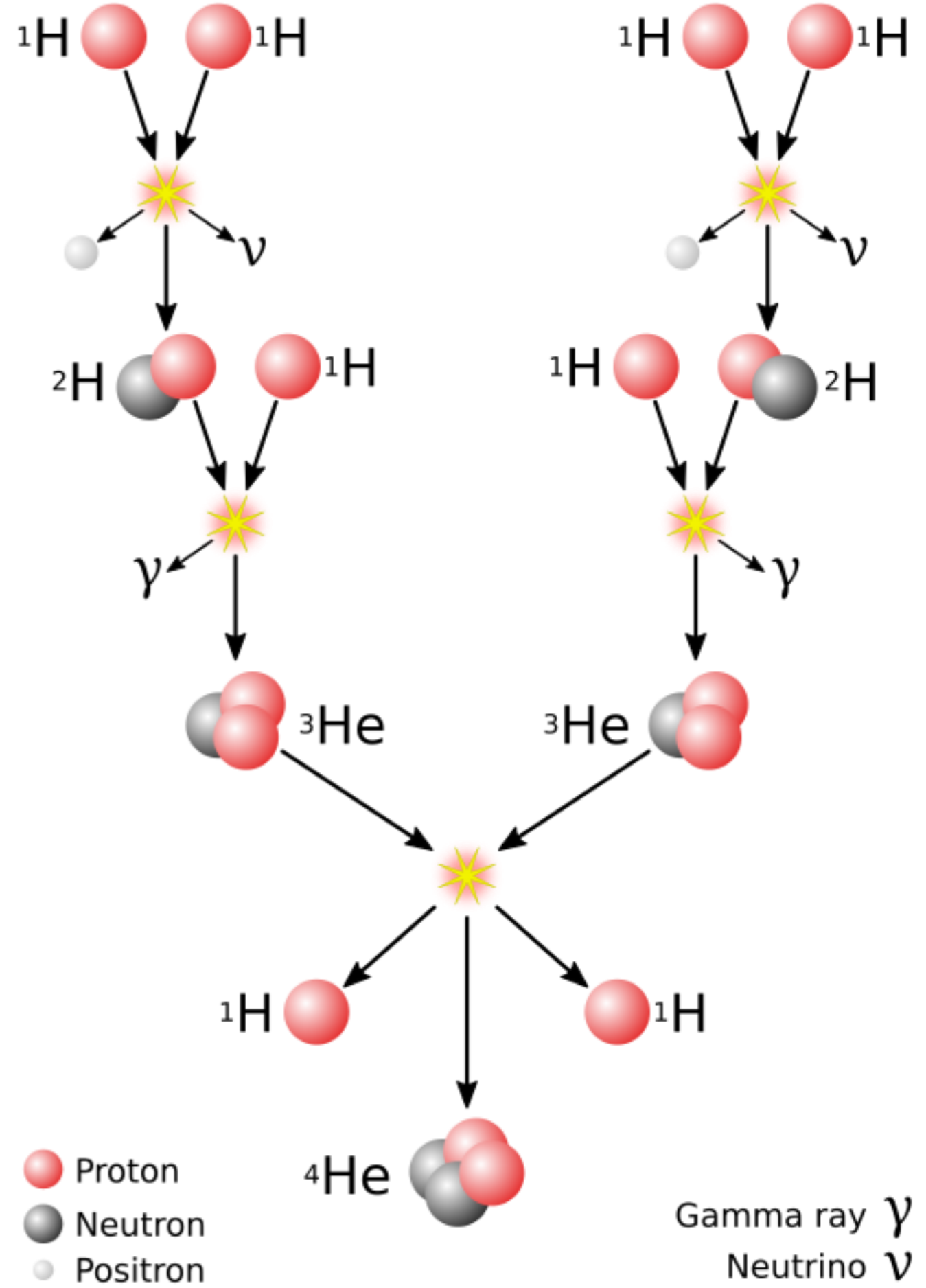
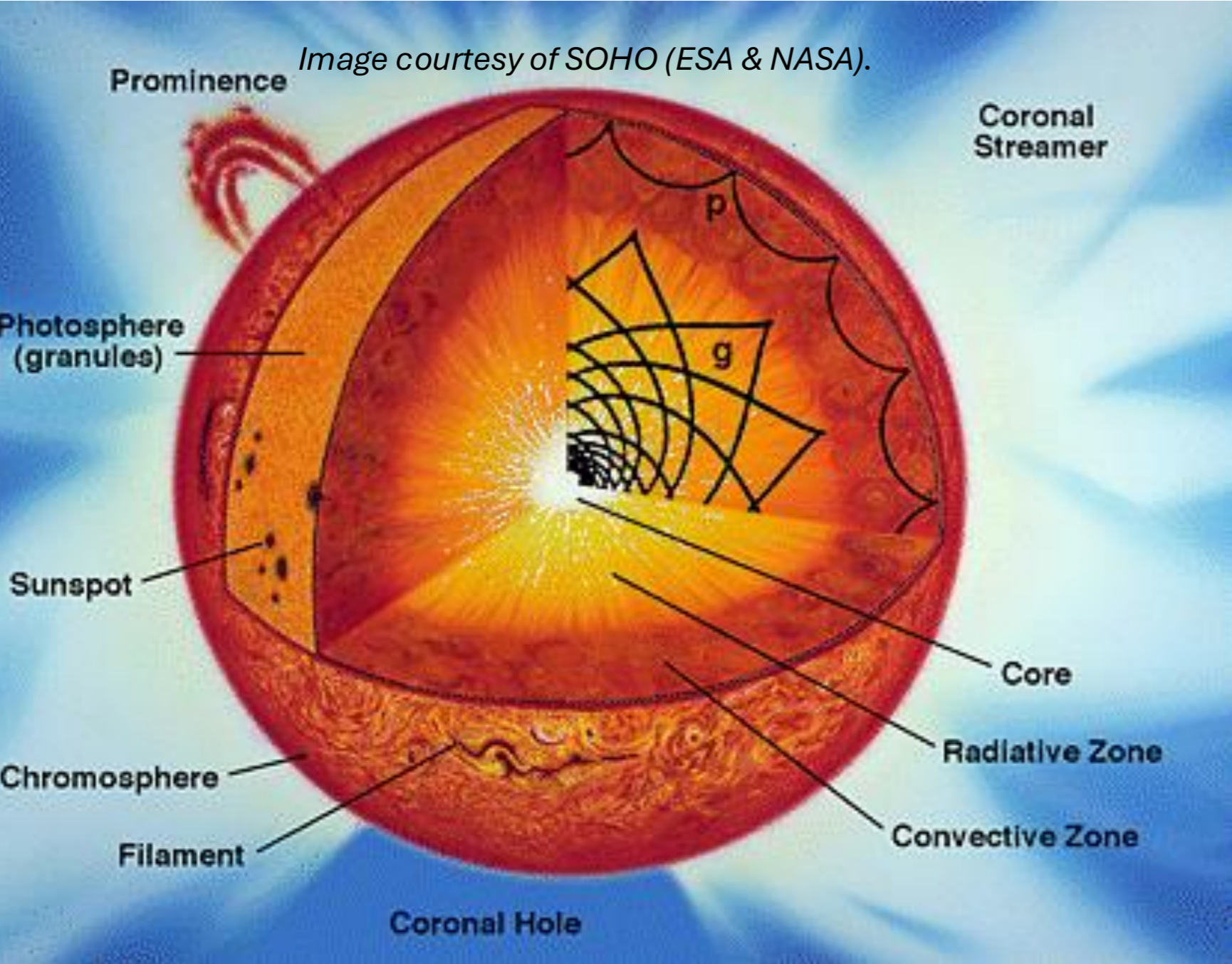
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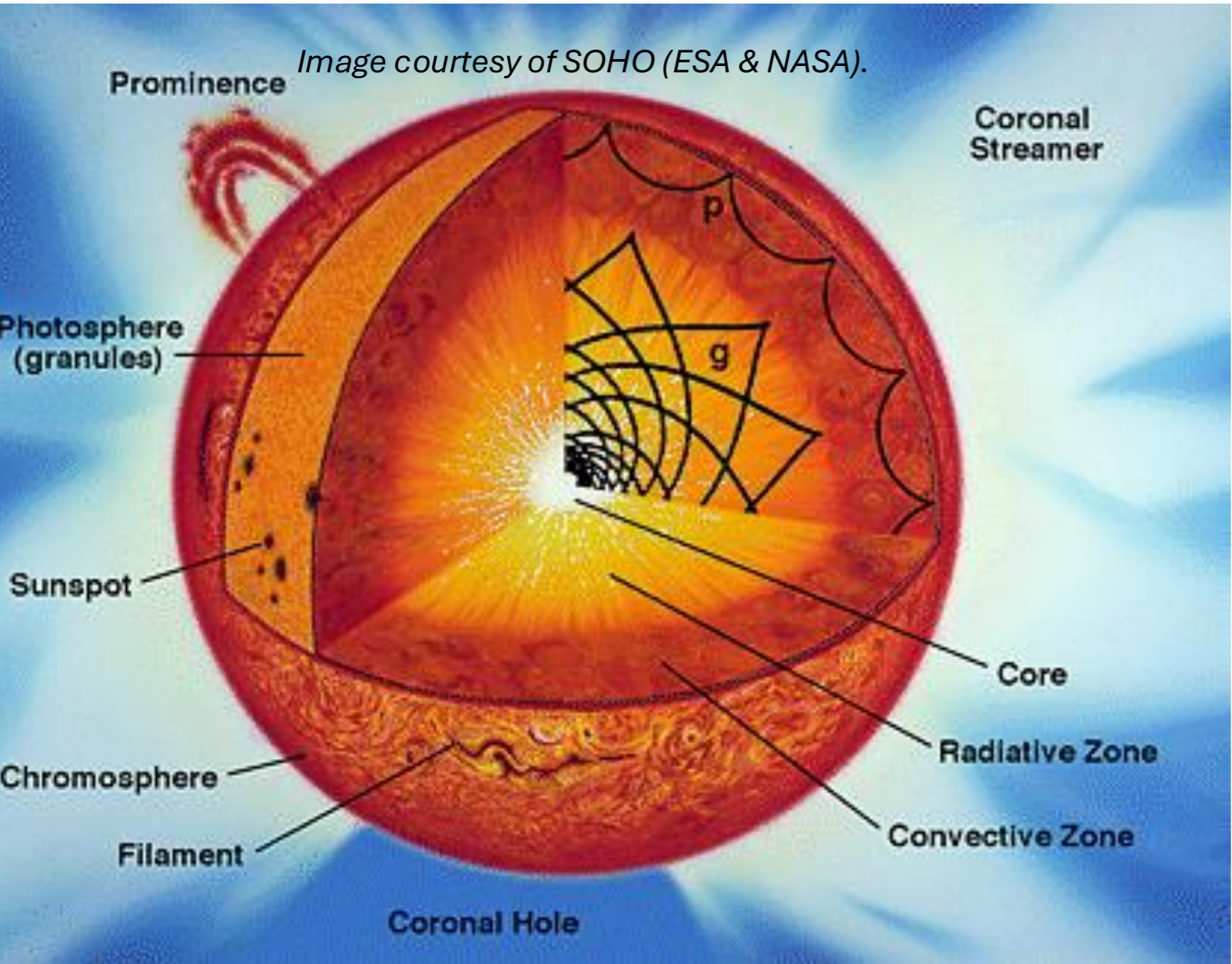
Solar Neutrinos



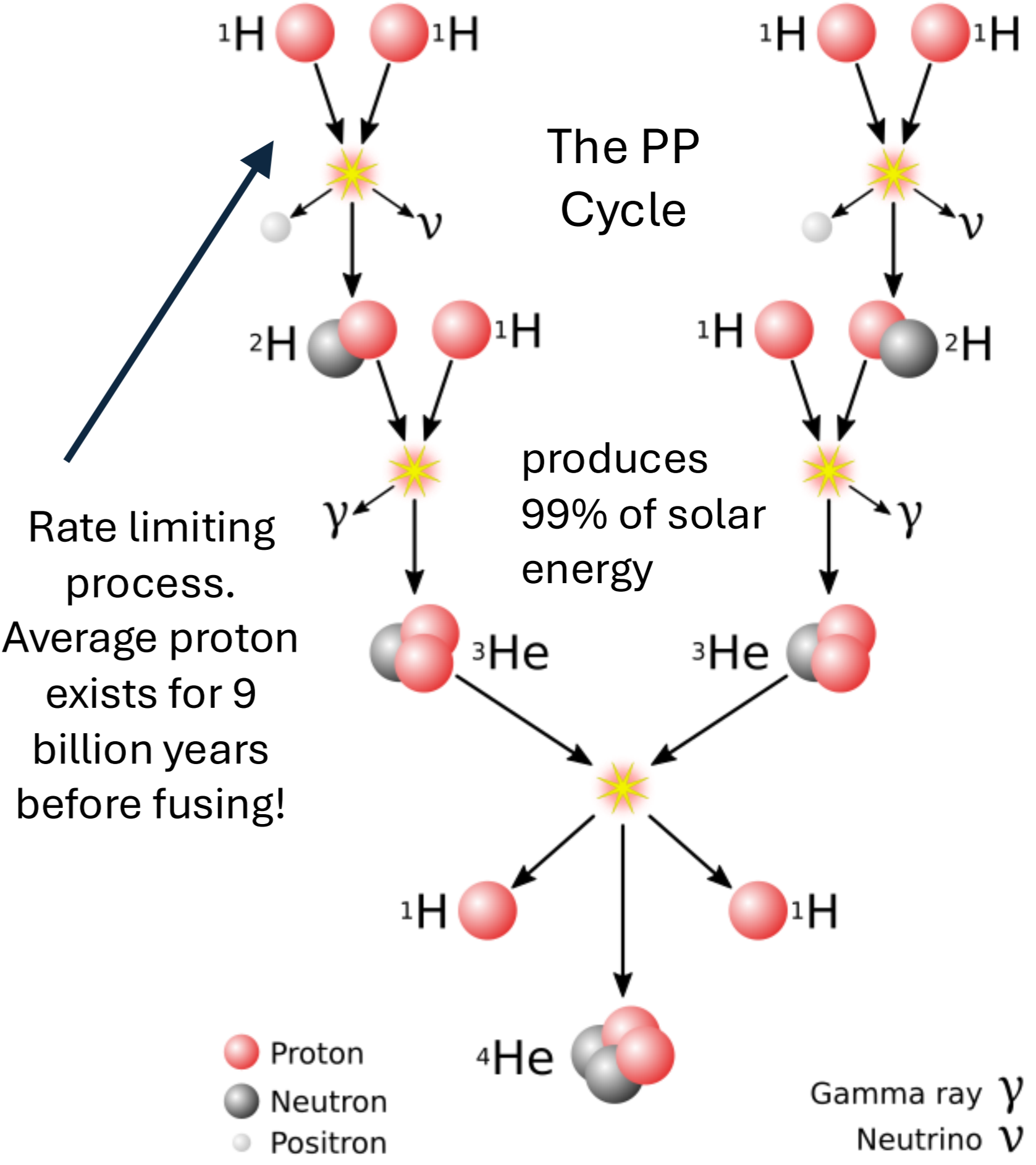
Solar Neutrinos



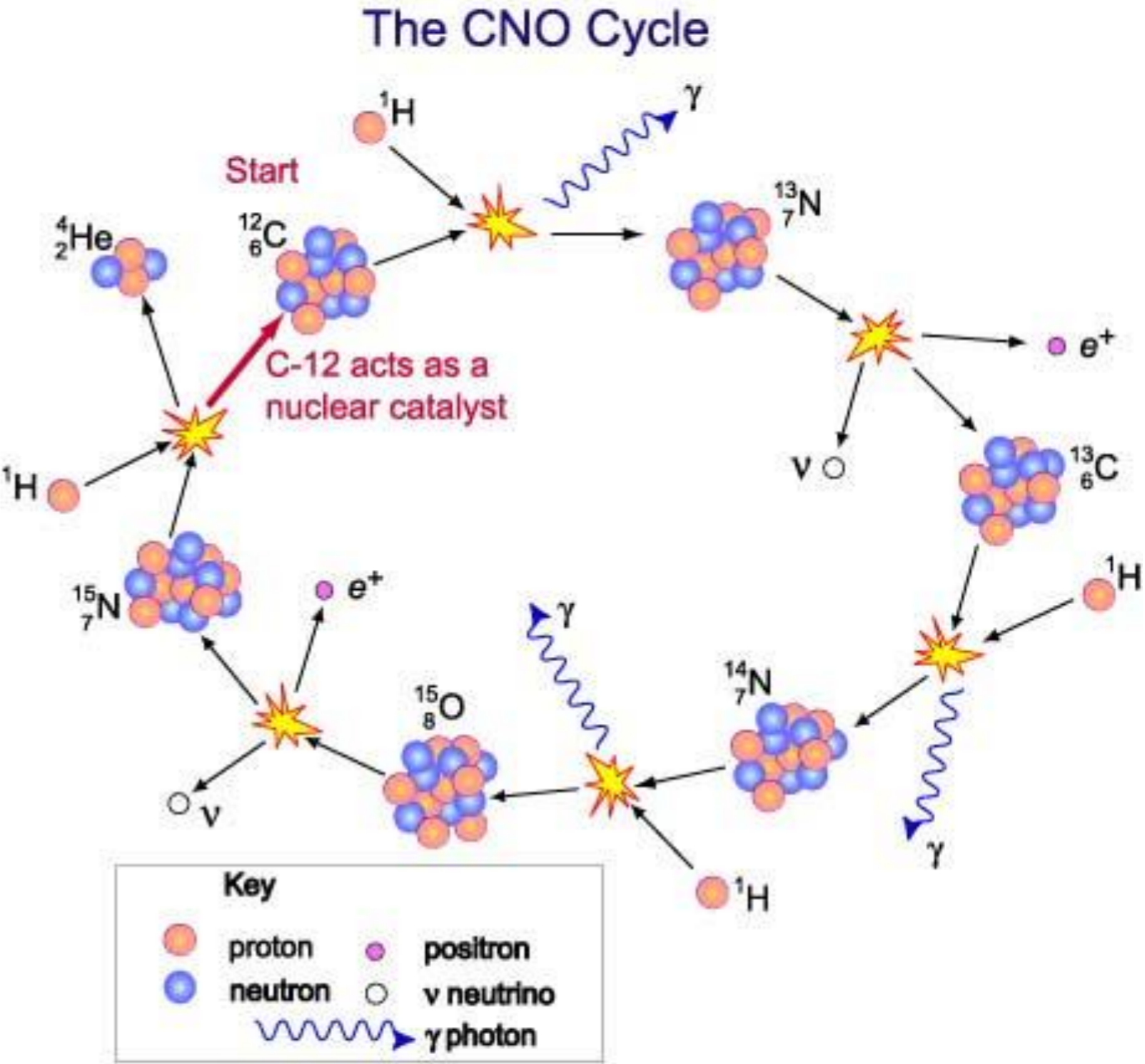
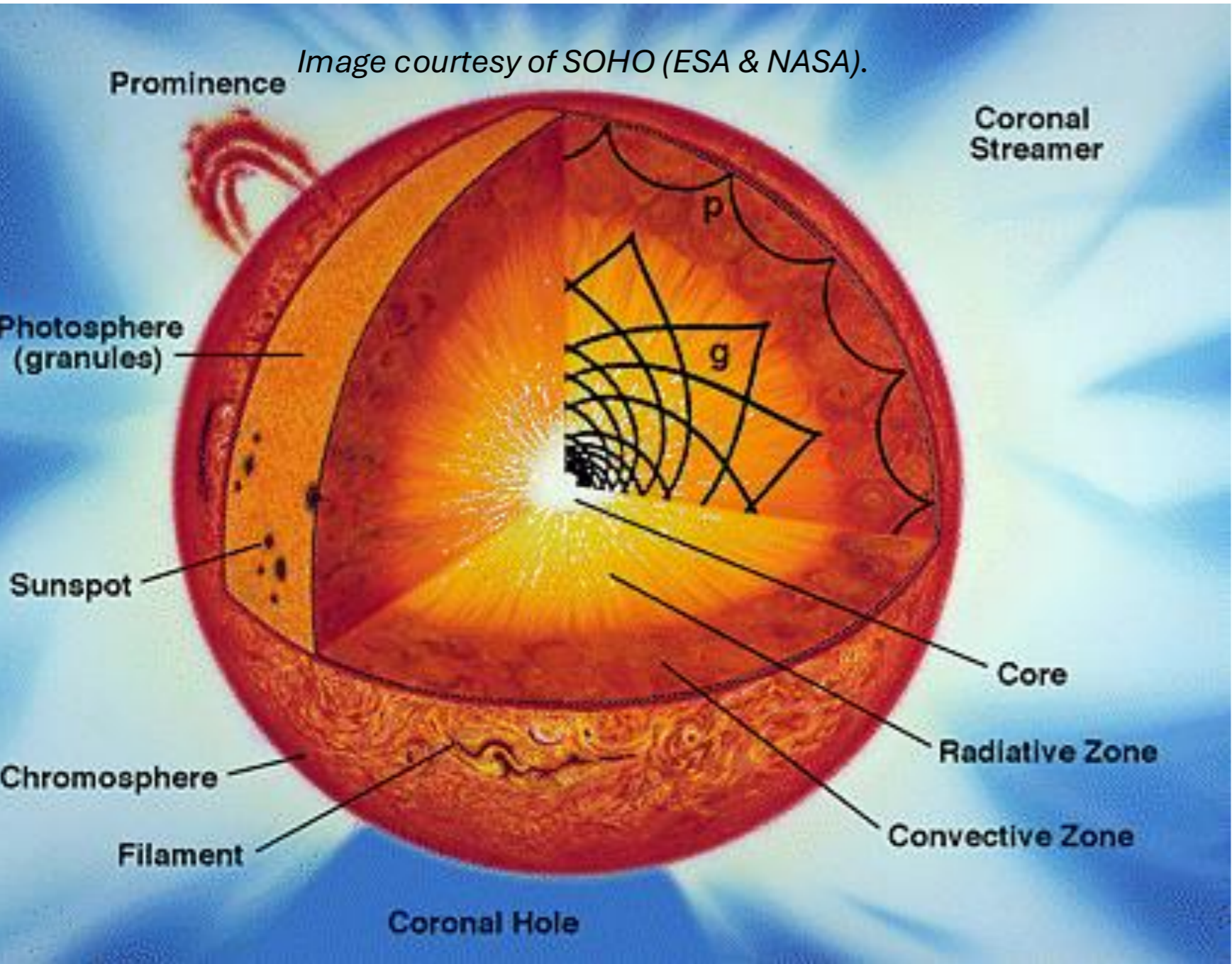
Solar Neutrinos



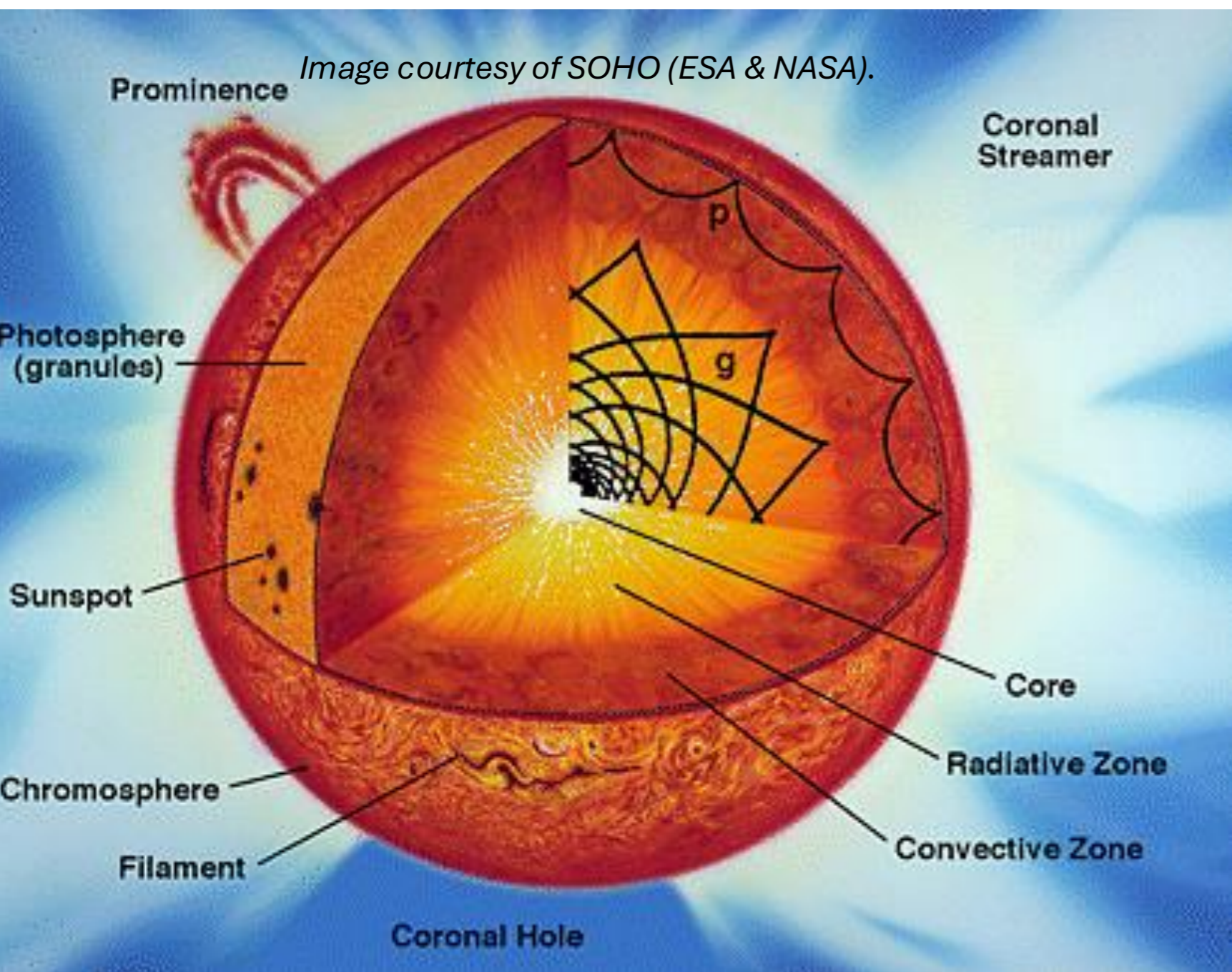
Initial process also produces most of the solar neutrinos



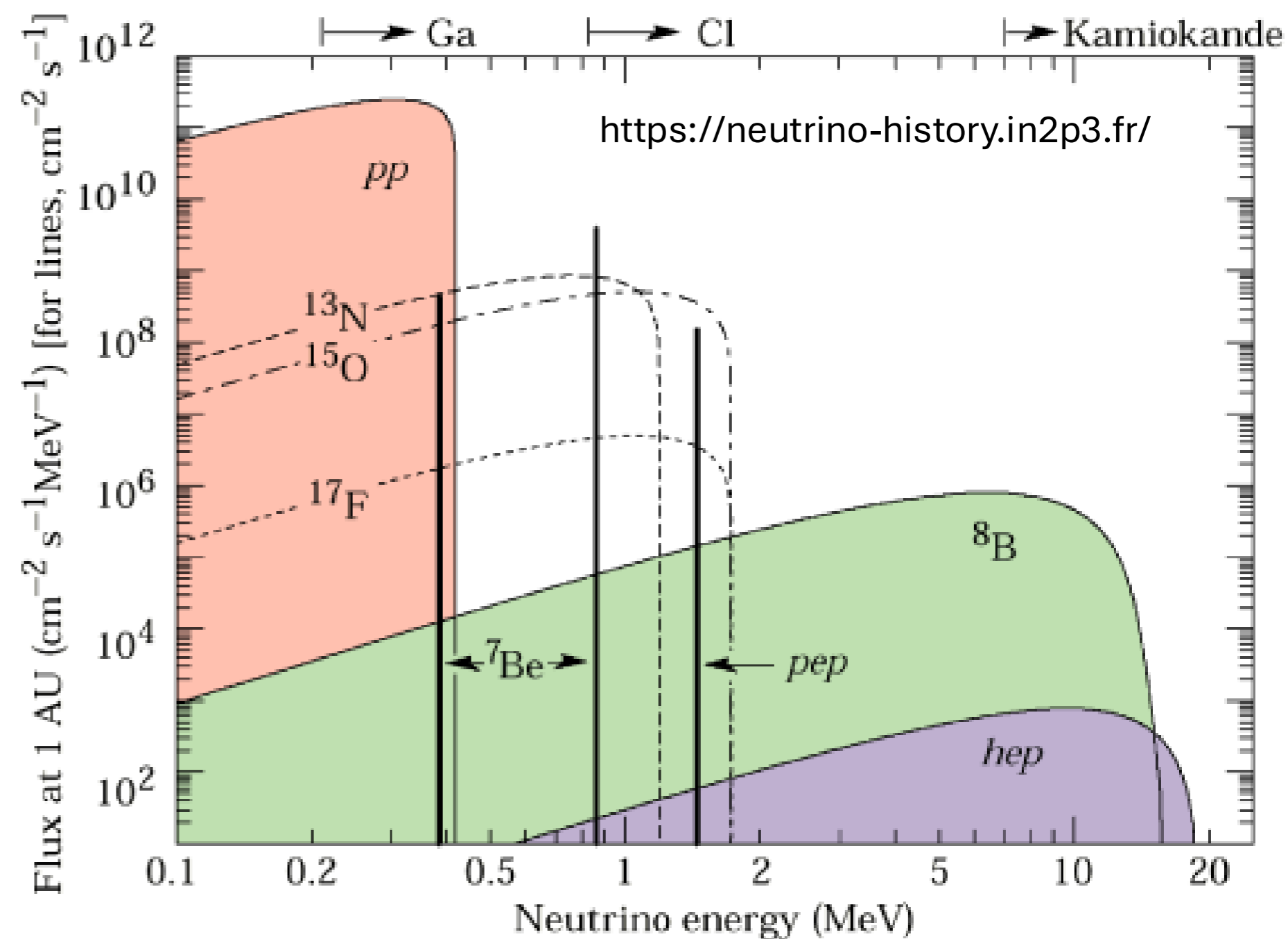
Solar Neutrinos



Solar Neutrinos

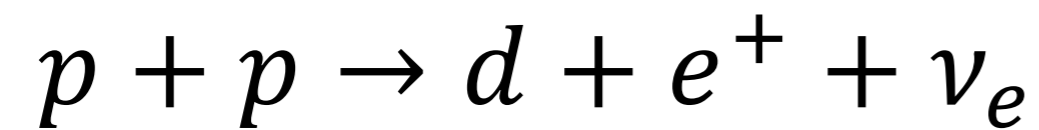


Neutrinos produced inside the sun are electron neutrinos (almost no antineutrinos), although they may oscillate to other flavors before they are detected on earth

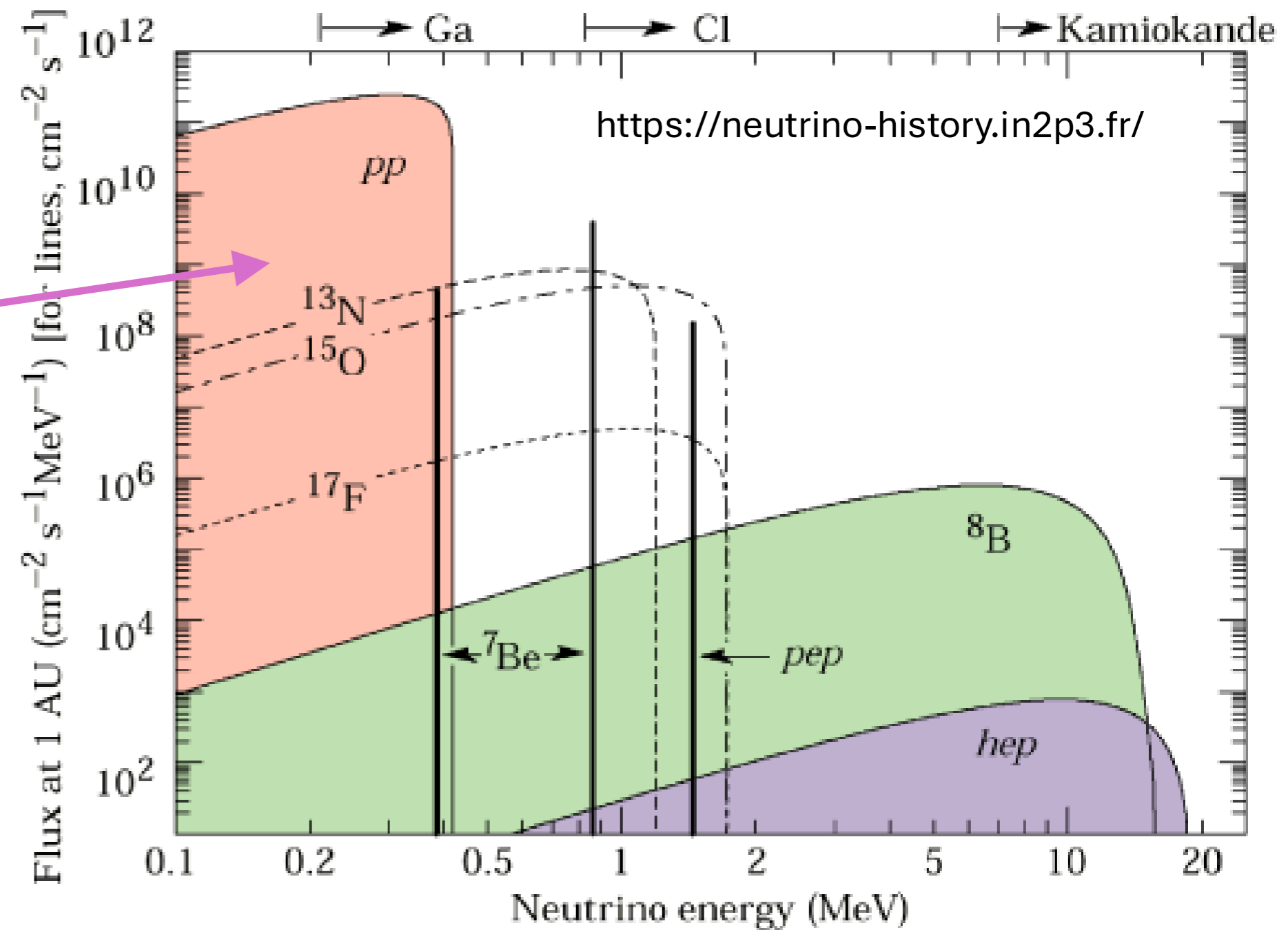


Bahcall, J. N., et al. "Solar Neutrino Spectrum from the Standard Solar Model."

Solar Neutrinos

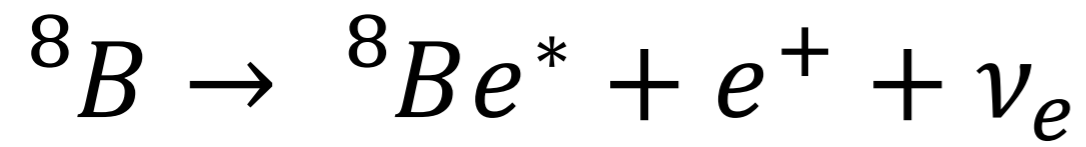


- 91% of solar neutrinos are produced through this process
- But challenging to observe due to very low energy (<0.42 MeV)
- But they have been observed by Borexino, Gallex/GNO, and SAGE

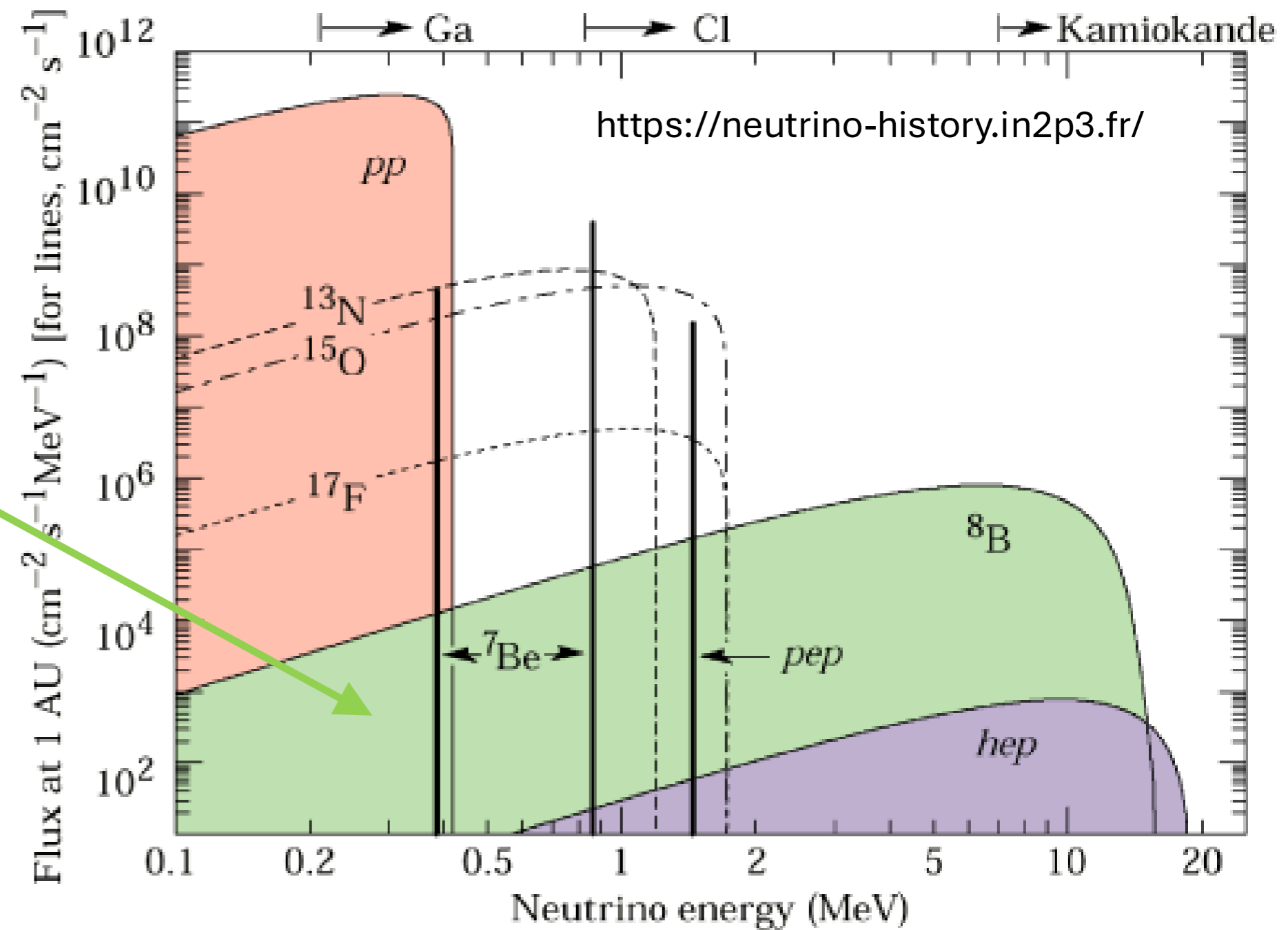


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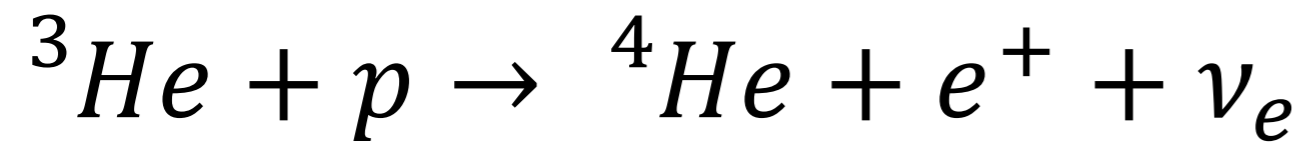


- Part of a non-dominant branch of the pp cycle
- Kinematic endpoints of 1.2-1.7 MeV; ~0.1% of flux, but dominates above 2 GeV
- Primary flux seen by Cherenkov detectors such as Super-K and SNO

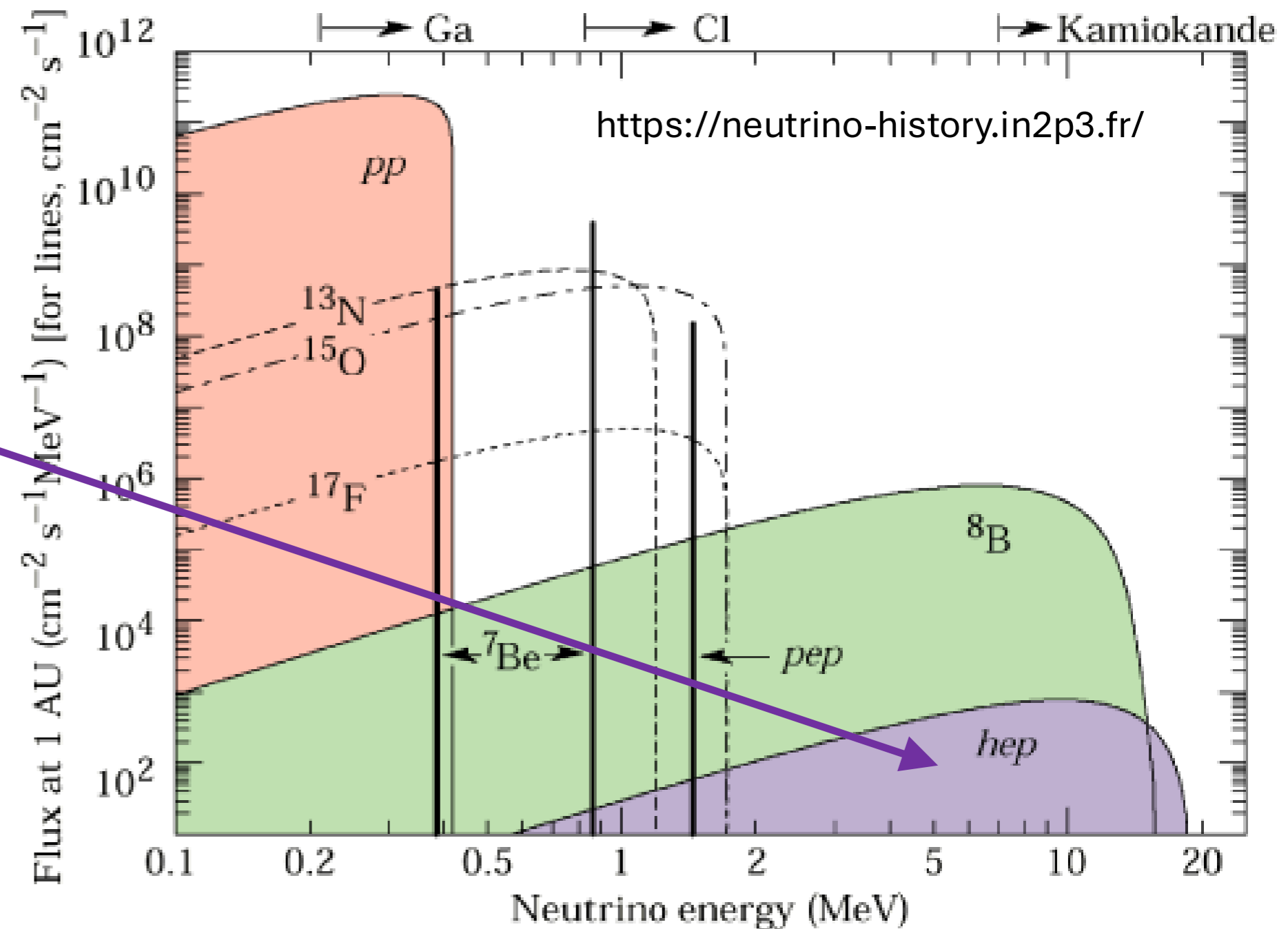


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Solar Neutrinos

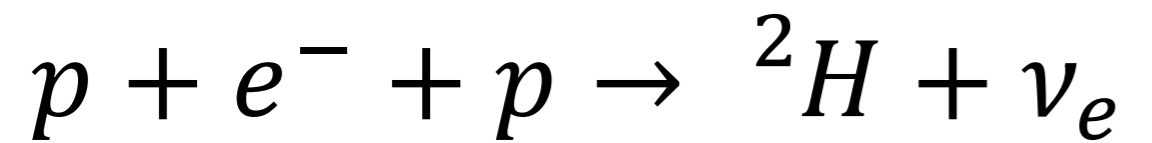
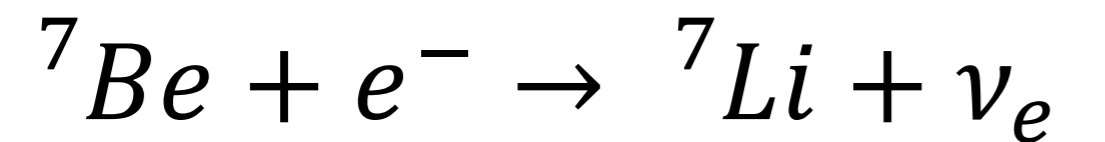
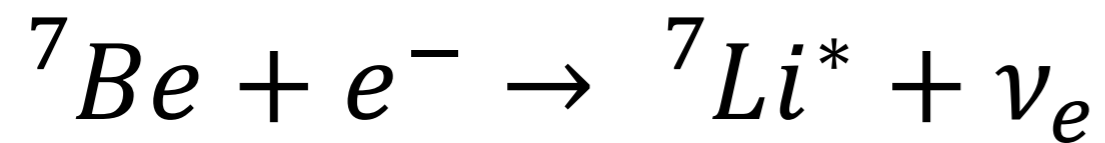


- Part of the pp cycle
- Highest energy solar neutrinos, but very rare (0.00001% of flux), up to 18.8 MeV
- Has never been definitively observed, but HyperKamiokande, JUNO, and DUNE will try

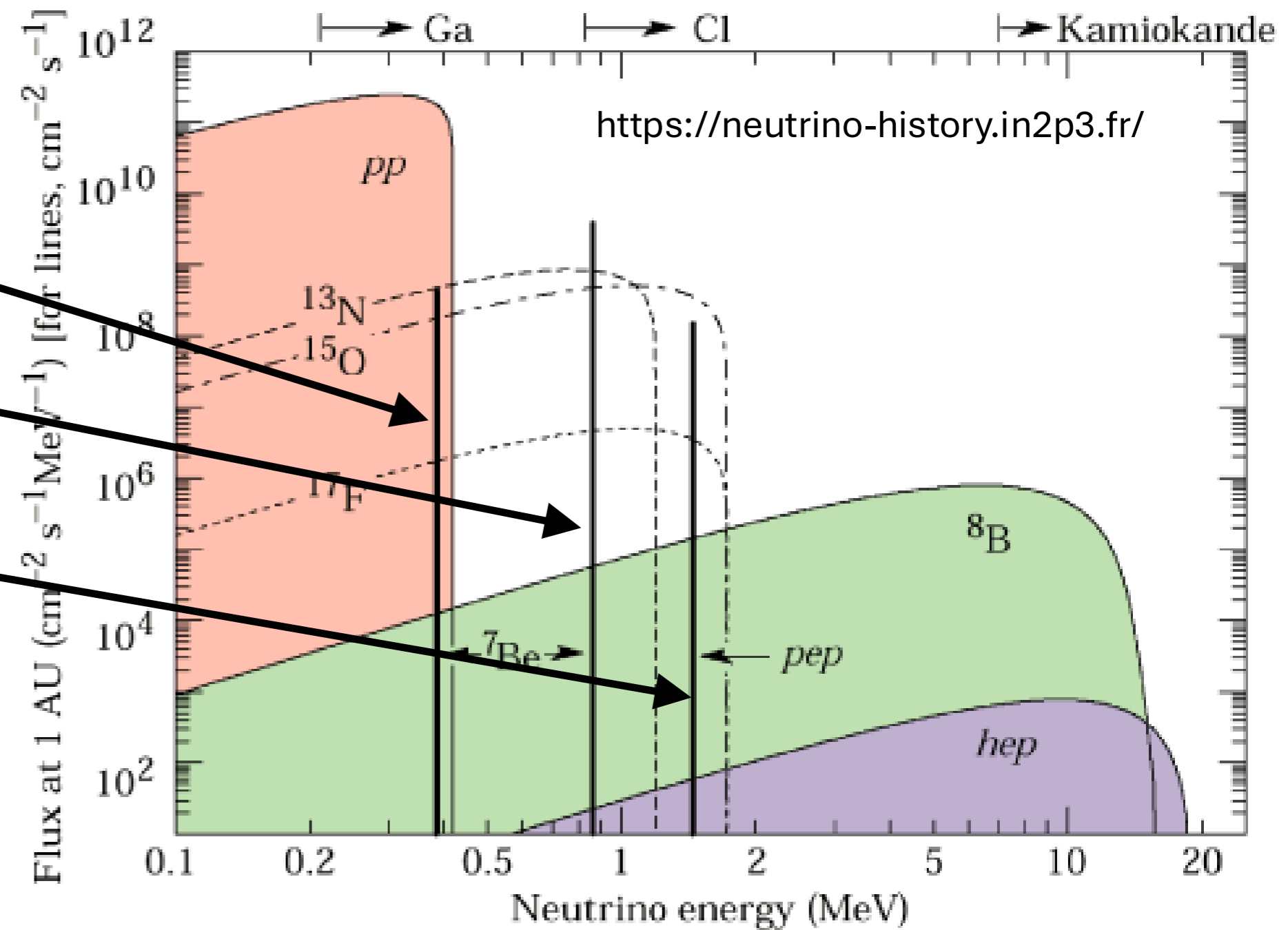


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Solar Neutrinos

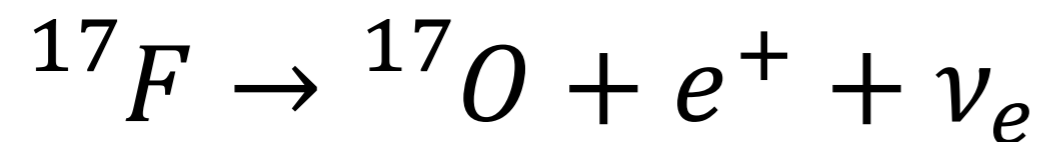
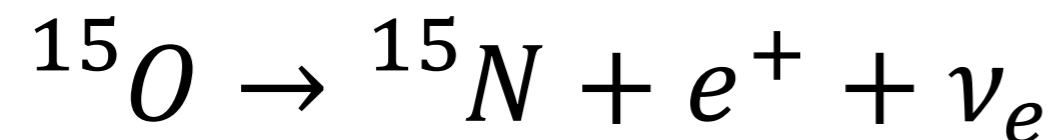
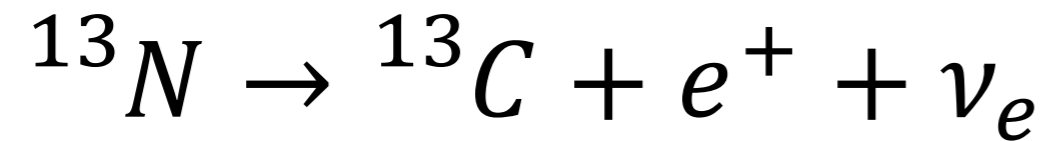


- PP-cycle monoenergetic fluxes at 0.384, 0.862, and 1.442 MeV
- All three have been measured by Borexino
- Higher energy unobserved lines exist due to CNO & ${}^8\text{Be}$ Electron Capture

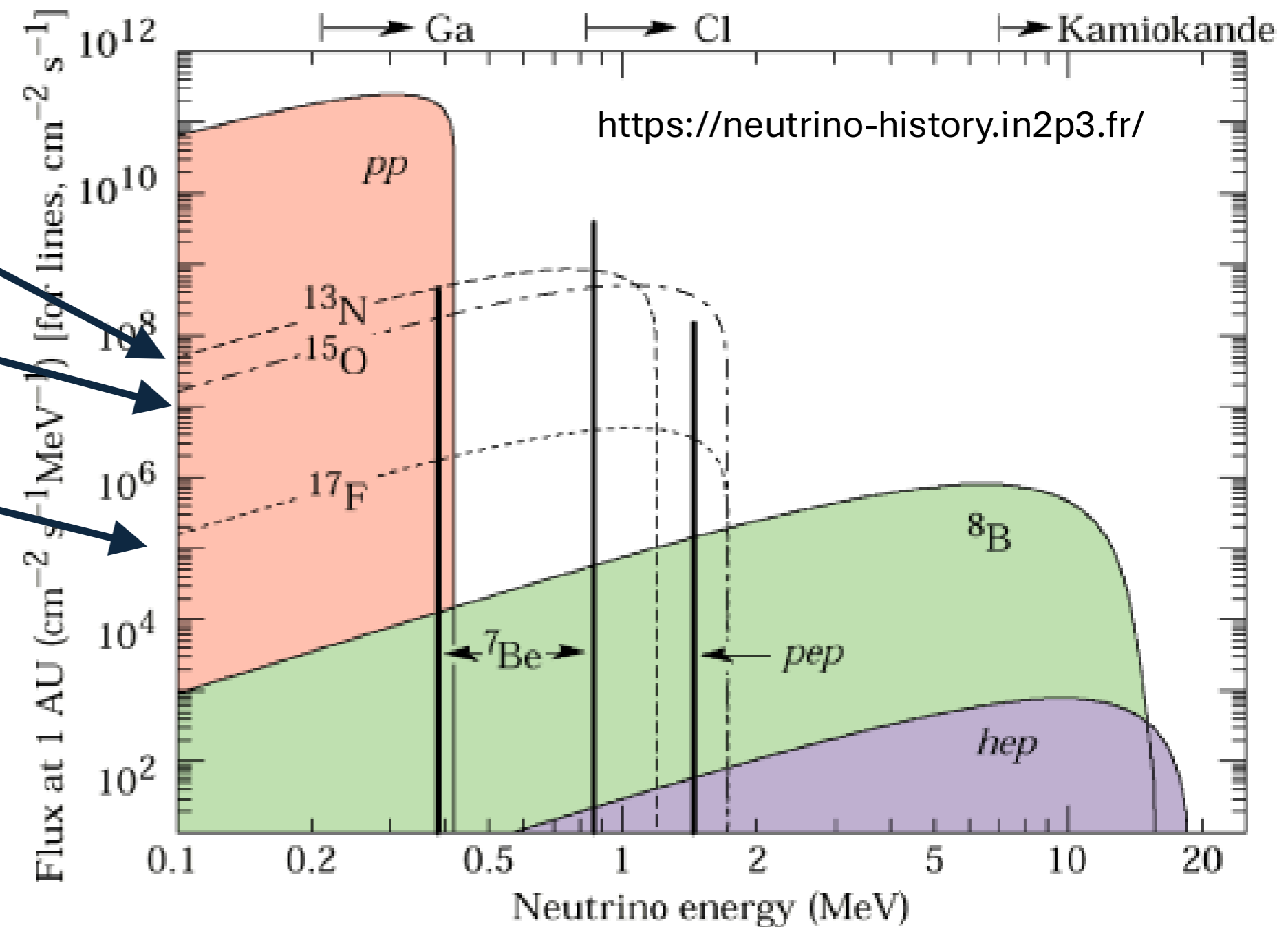


Bahcall, J. N., et al. "Solar Neutrino Spectrum from the Standard Solar Model."

Solar Neutrinos



- Part of the CNO cycle that converts hydrogen to helium within the sun
- Kinematic endpoints of 1.2-1.7 MeV; ~1% of solar neutrino flux
- Challenging due to high backgrounds; First observed in 2020 by Borexino

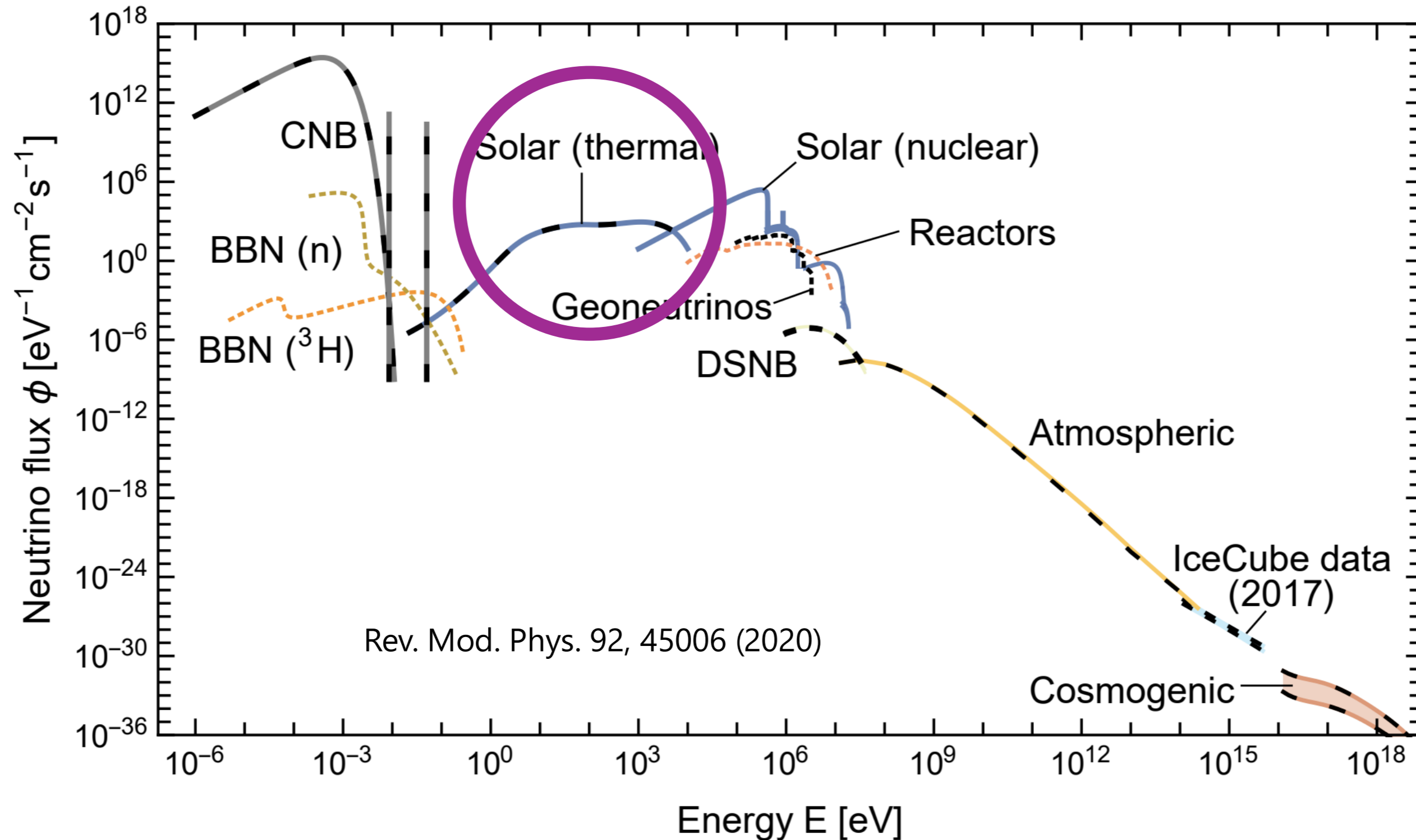


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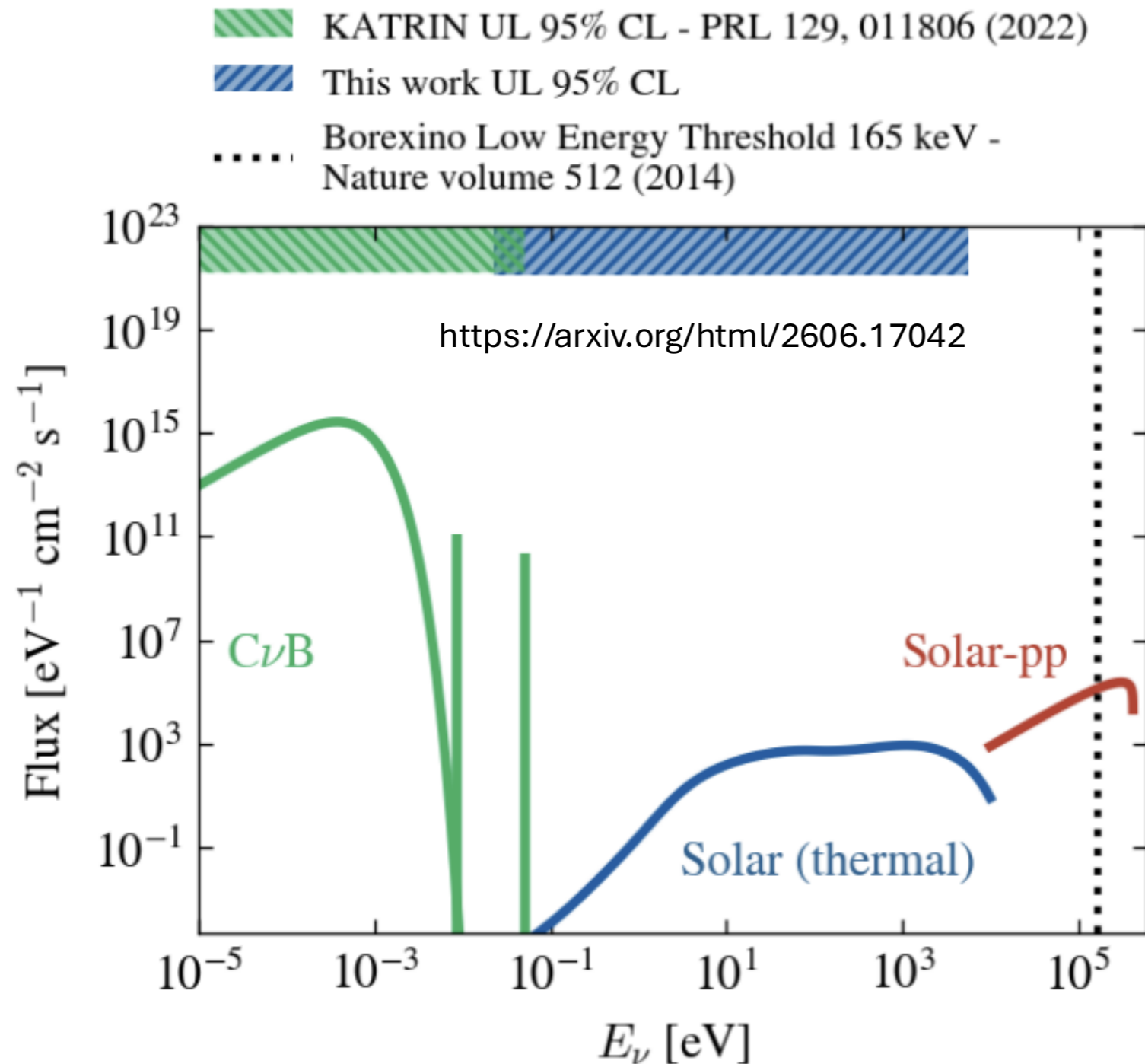
Solar Flux Uncertainties

- Some sources of uncertainty in our models of neutrino flux
 - Astrophysical S-Factor
 - Parameterizes extrapolation from higher energy lab cross section measurements to solar energies
 - Solar Core Temperature (T_C)
 - Some fluxes depend on T_C^{24} !
 - Solar metallicity
 - Modern models disagree with old models, but old models agreed better with helioseismology models
- Total flux uncertainties range from 1-40%

Thermal Solar Neutrinos

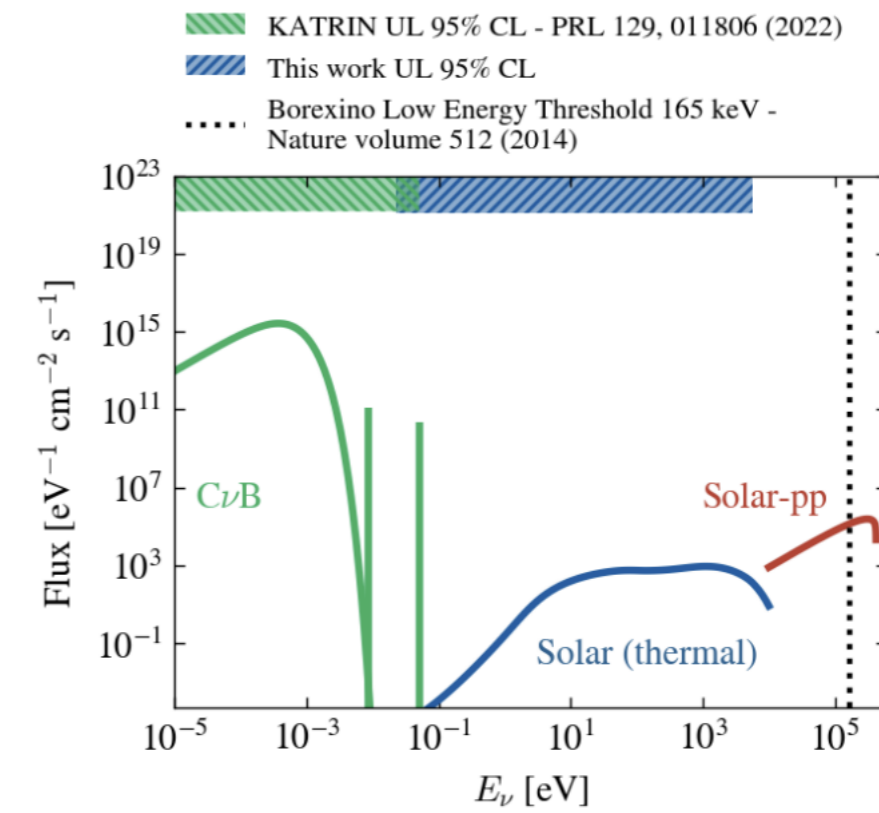
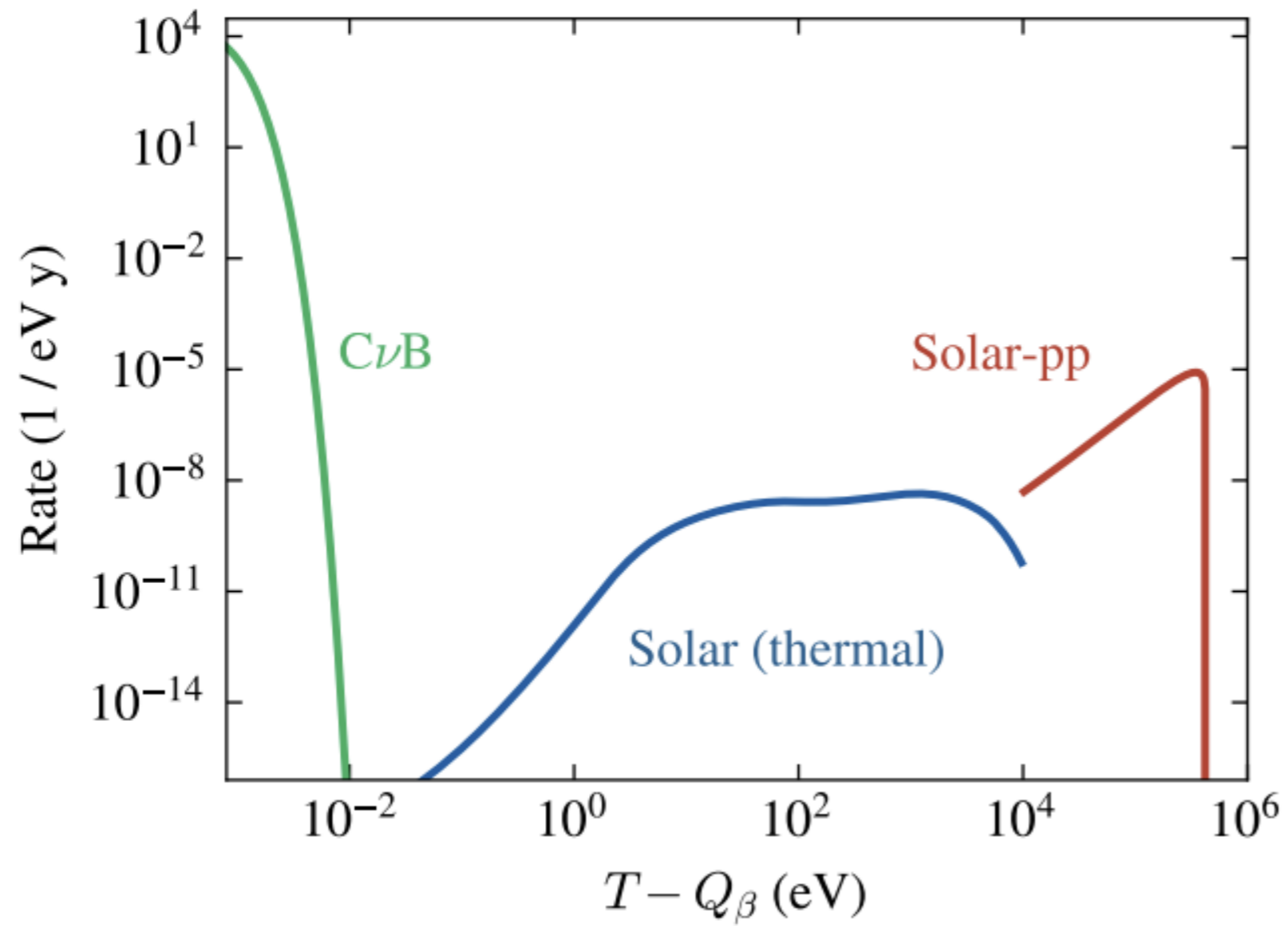


Thermal Solar Neutrinos



- The low energy of thermal solar neutrinos makes detection challenging, and humans have not yet detected these neutrinos
- A paper with the first experimental limit (using public KATRIN data appeared on the arXiv this month!
- One of the authors of that paper (Brooke Russell) is another lecturer at this school!

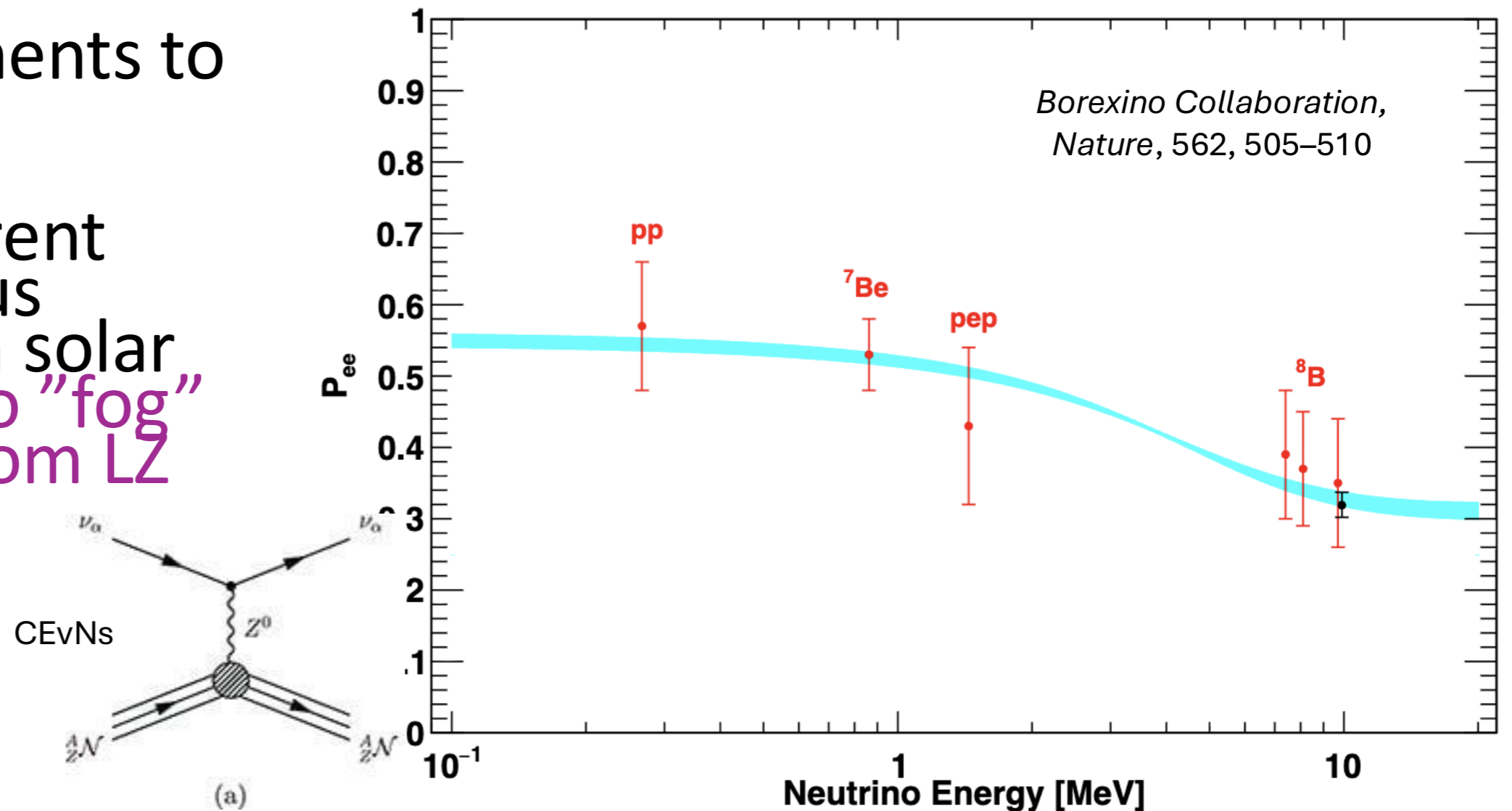
Thermal Solar Neutrinos



What to Look Forward To – Solar Neutrinos

- Definitive measurement of hep neutrinos
- Precise measurements of “upturn” region
- Precise CNO measurements to inform solar metallicity tensions
- Measurement of Coherent Elastic Neutrino-Nucleus Scattering (CEvNS) with solar neutrinos (The neutrino “fog” or “floor”) Evidence from LZ presented last week at NEUTRINO 2026!!!

The predicted “upturn” in electron neutrino survival probability around a few GeV is due to the transition from vacuum to matter-dominated oscillations, but experimental measurements are lacking here



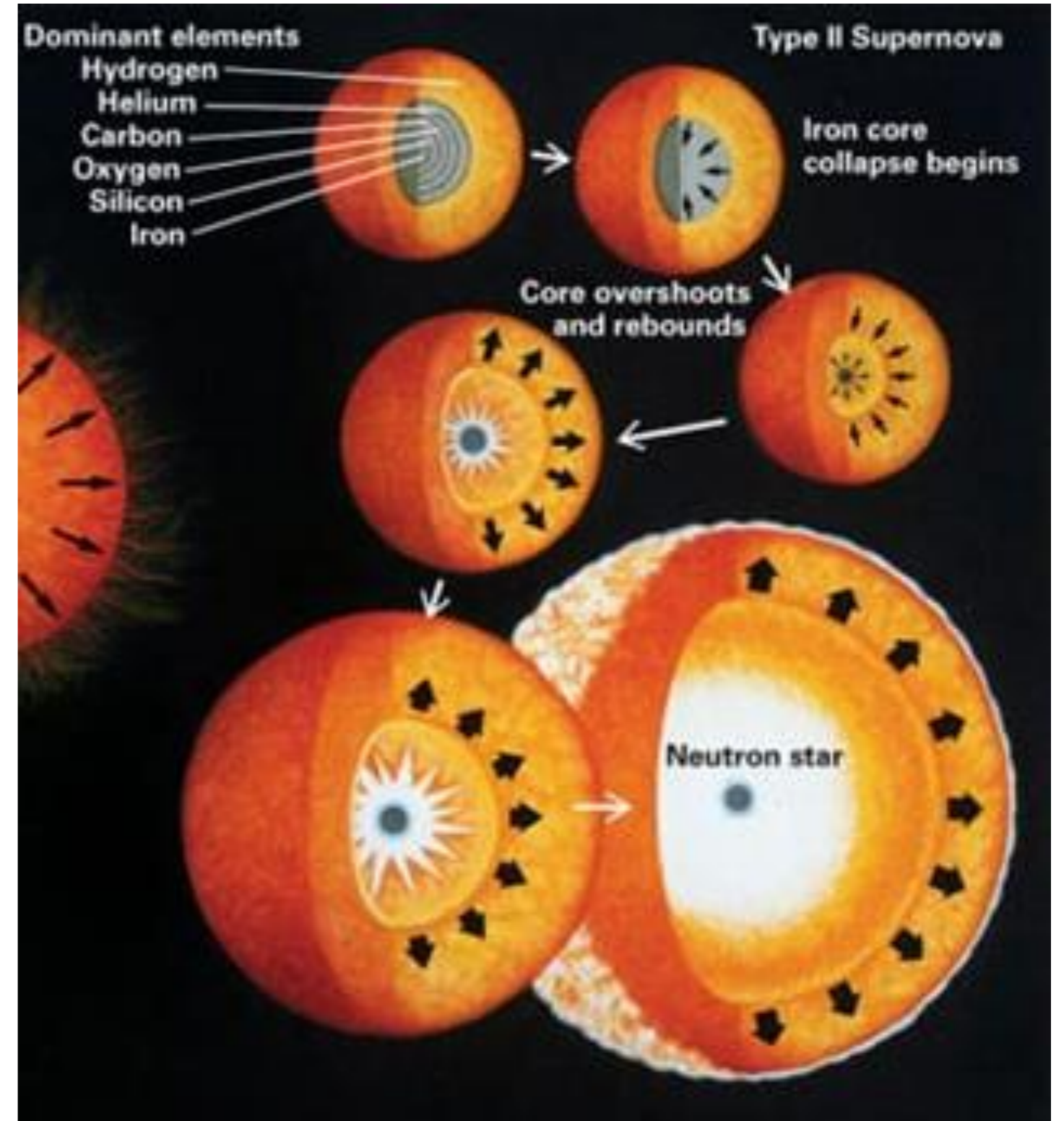
A visualization of the cosmic web, showing a complex network of filaments and nodes of matter. The filaments are colored in shades of green, blue, and orange, with a central blue region. The background is dark with scattered white stars.

Supernova Neutrinos



Core Collapse Supernovae

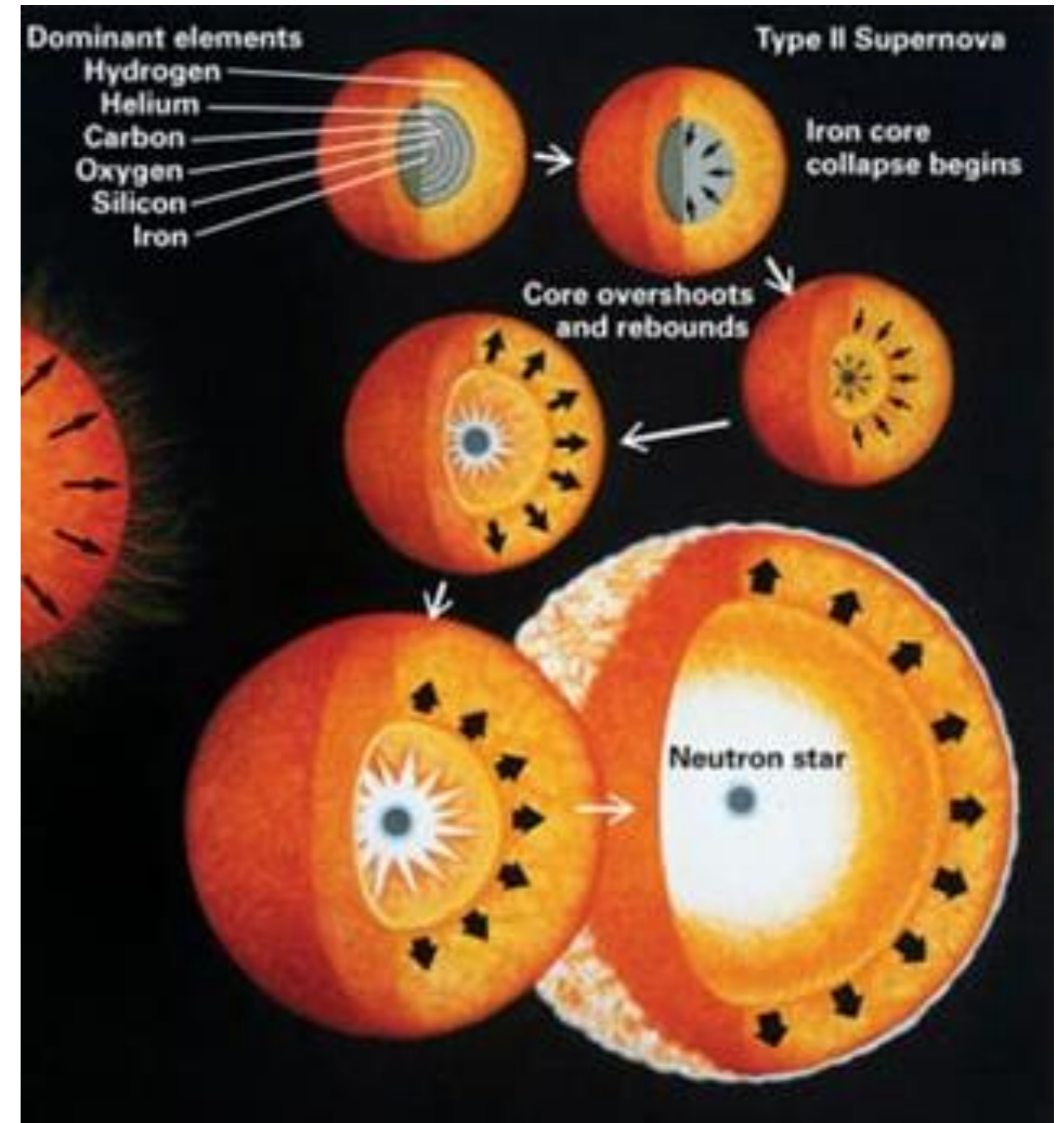
Brooks/Cole - Thomson Learning / Standard Educational Resource



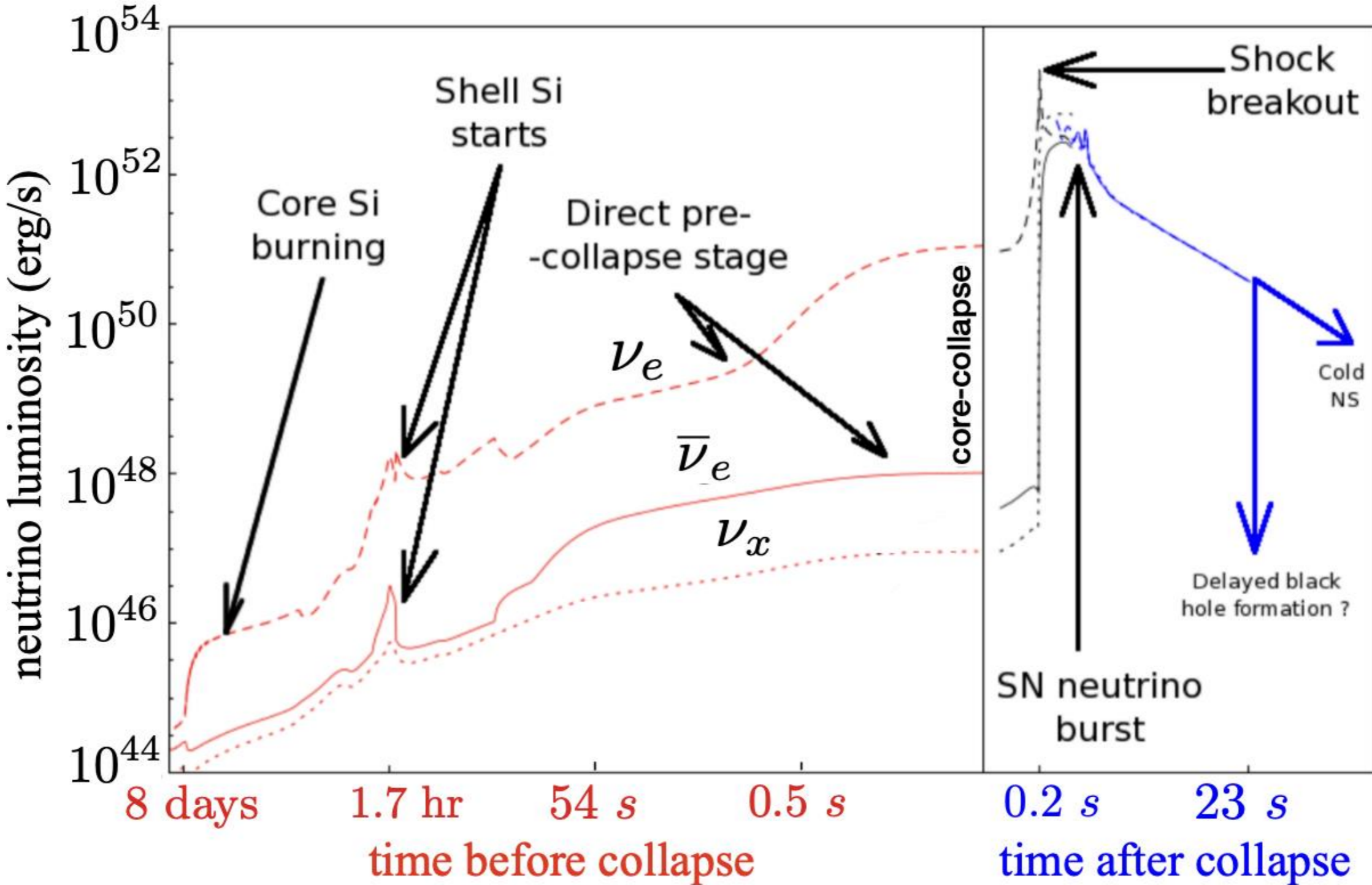
Core Collapse Supernovae

Brooks/Cole - Thomson Learning / Standard Educational Resource

- Core-collapse supernovae are prolific sources of neutrinos
- 99% of the energy of the supernova is released as neutrinos
- 10^{44} J of energy
- Roughly equal to the energy output of our sun over its entire 10 billion year life, released in a fraction of a second



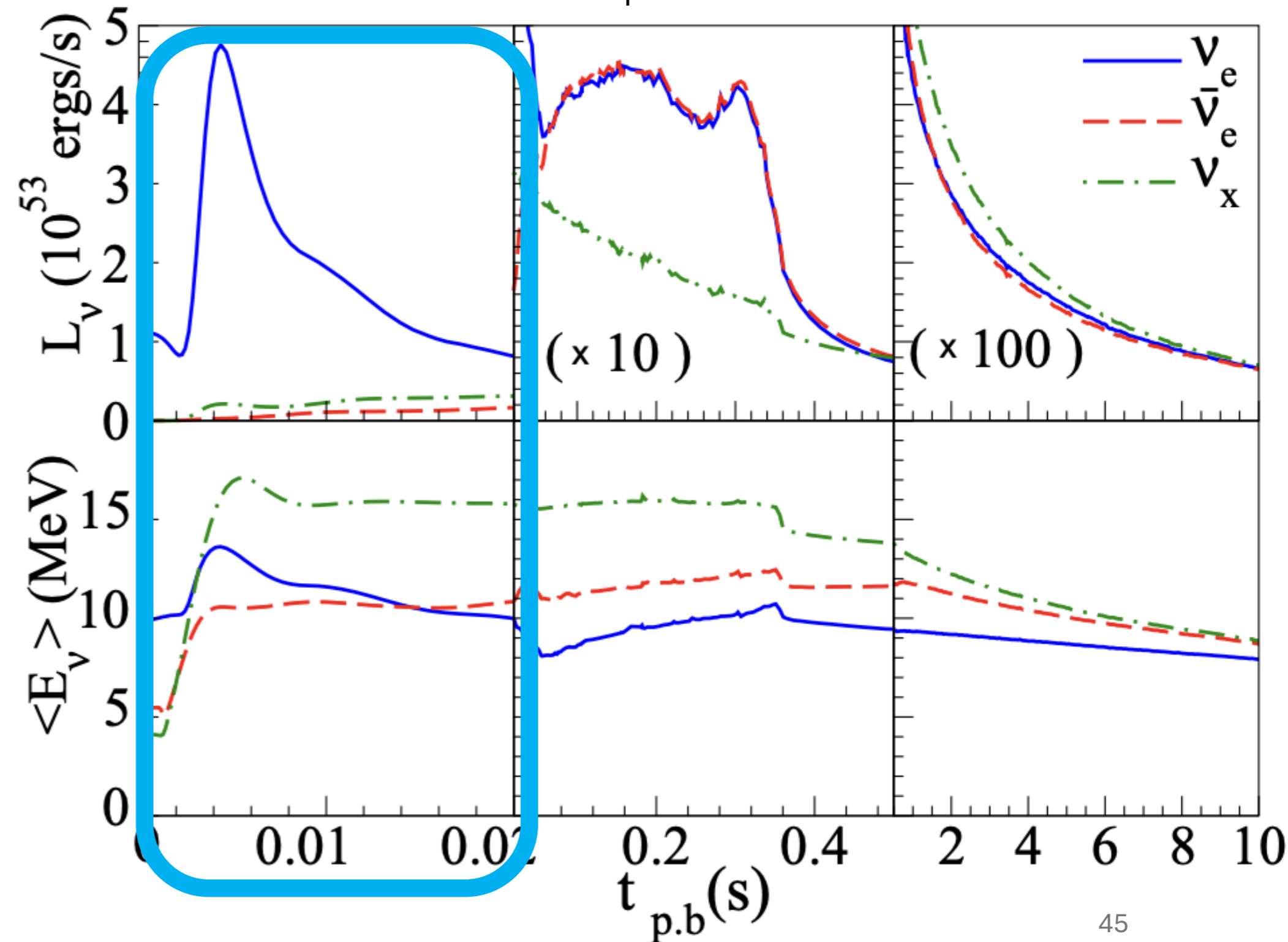
Core Collapse Supernovae



Core Collapse Supernovae

Phys. Rev. D 89, 013011 (2014); 18 Solar Mass Supernova

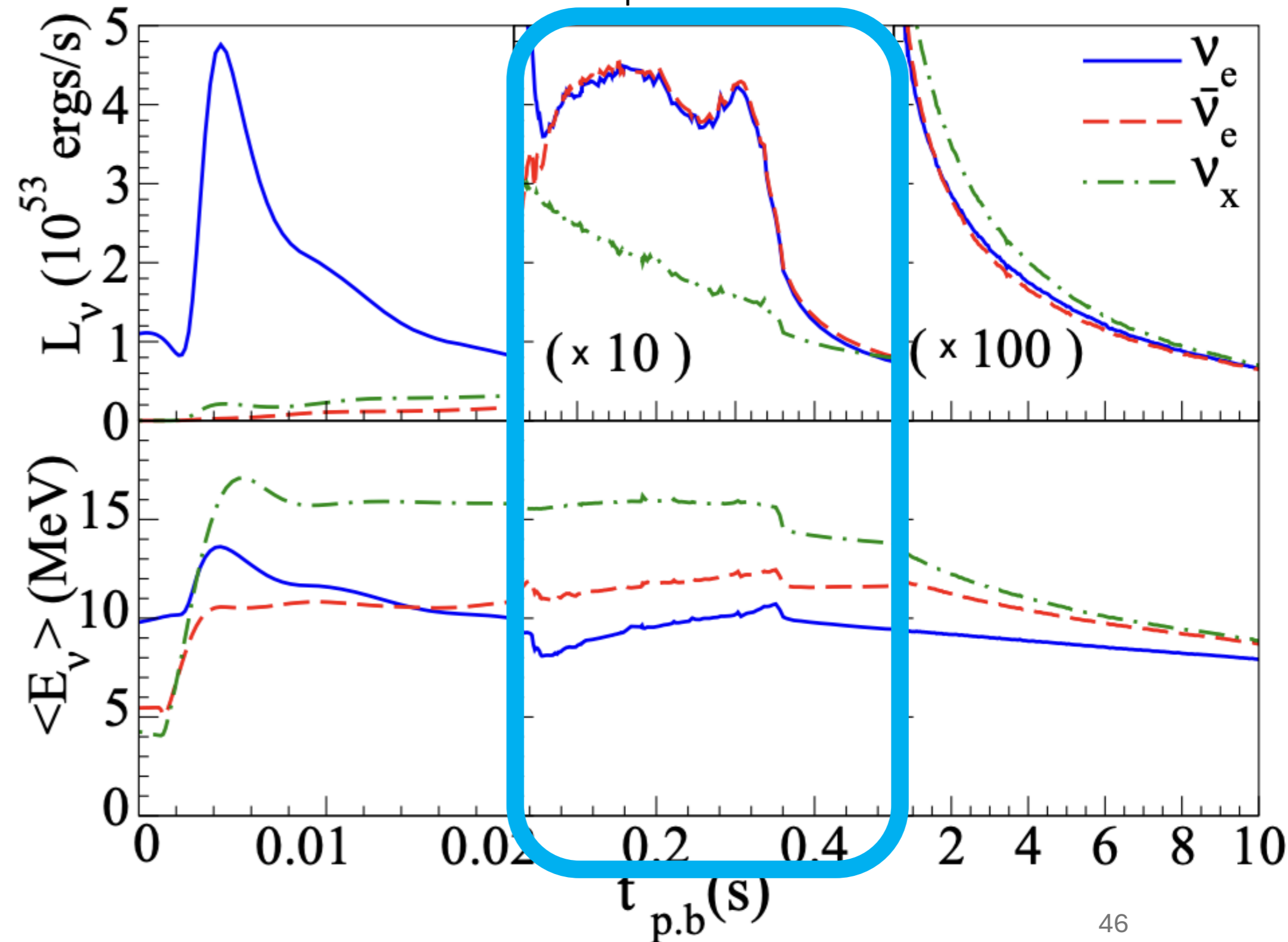
- Neutronization phase occurs immediately after collapse
- Electrons and protons combine to produce neutrons and electron neutrinos



Core Collapse Supernovae

Phys. Rev. D 89, 013011 (2014); 18 Solar Mass Supernova

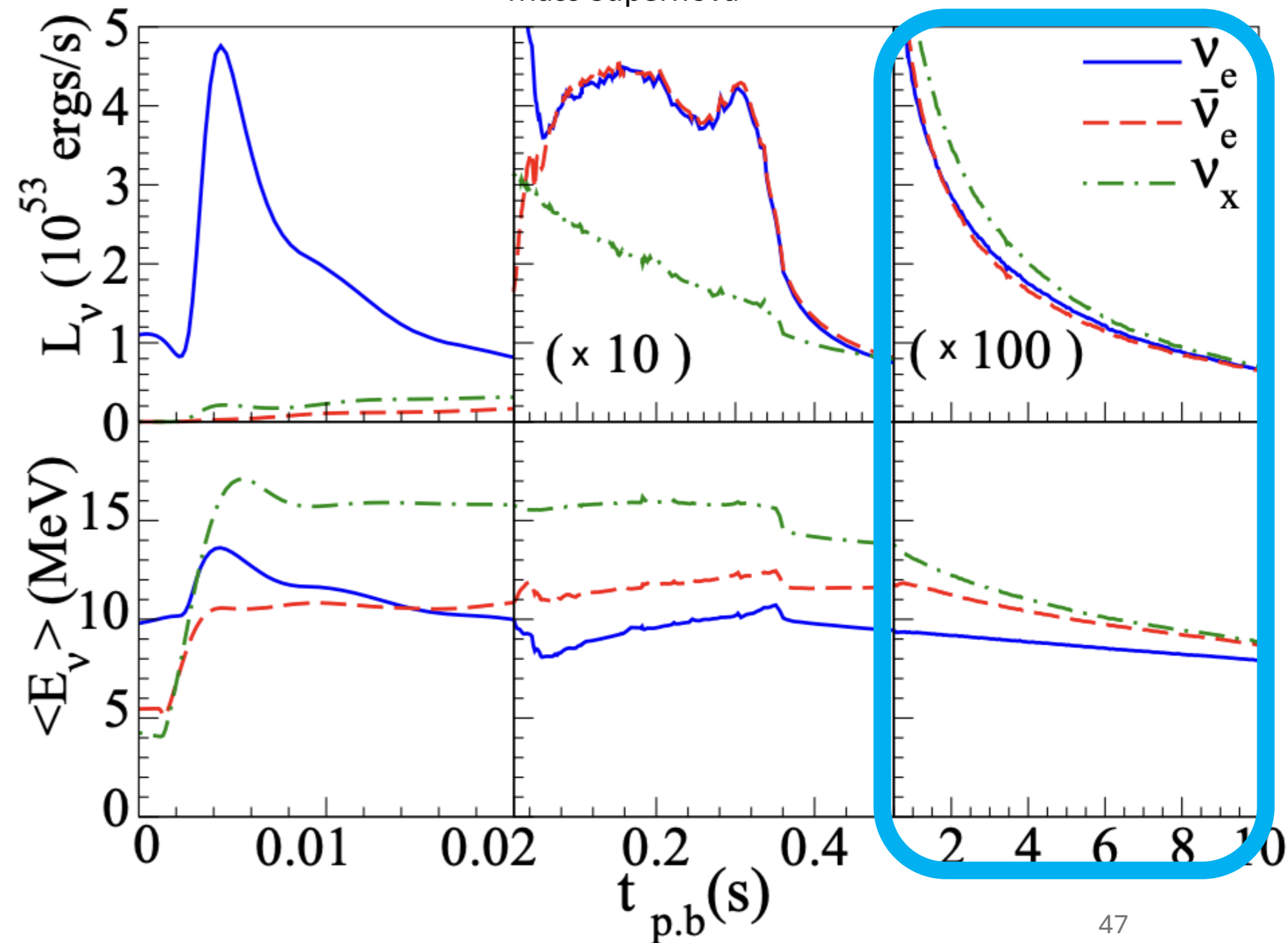
- After the initial collapse and shockwave, mass falls into the proto-neutron star in an “accretion phase”
- All neutrino flavors are released here, but many electron neutrinos and antineutrinos



Core Collapse Supernovae

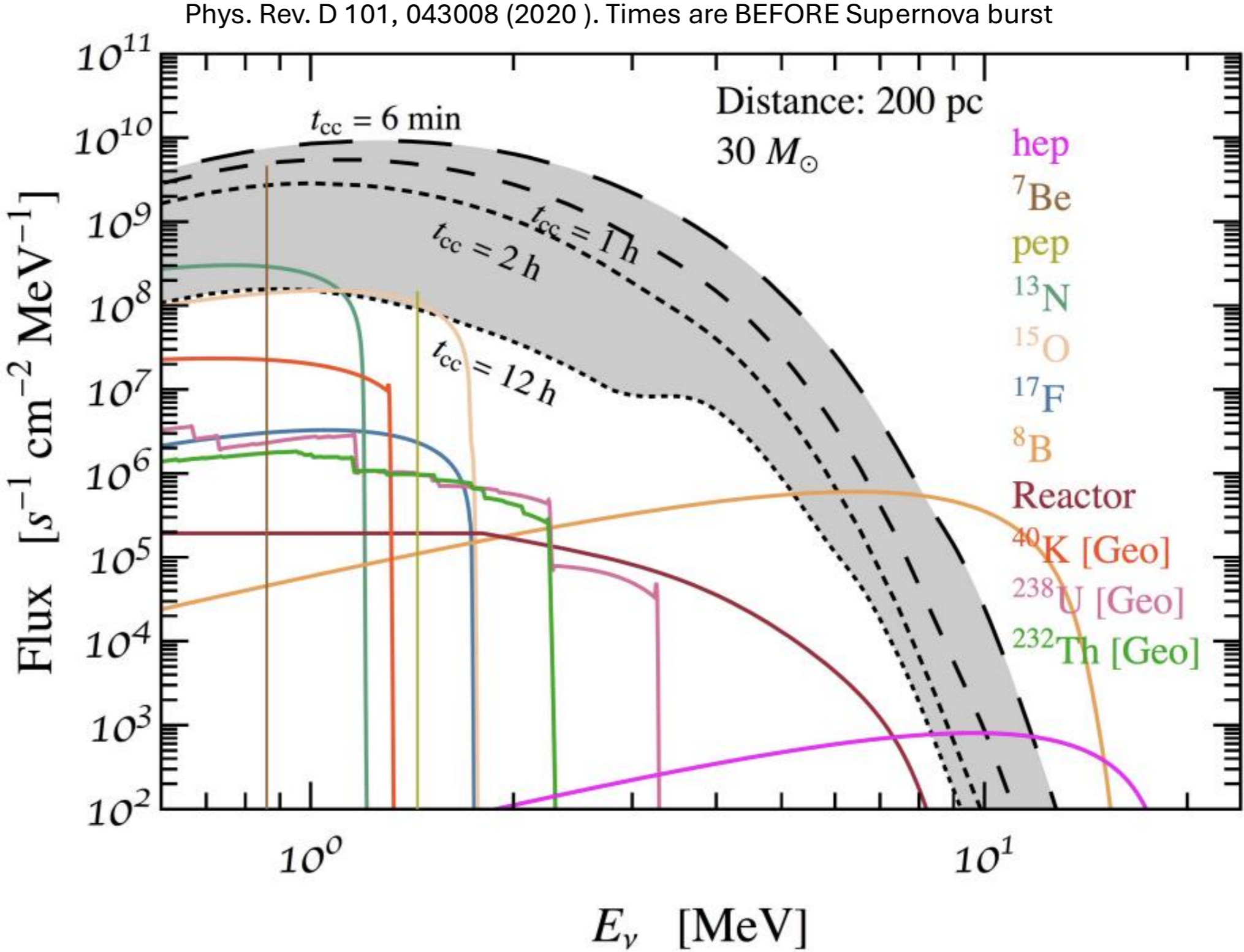
Phys. Rev. D 89, 013011 (2014); 18 Solar
Mass Supernova

- During the cooling phase, the hot and dense neutron star generates all six neutrino flavors thermally



Core Collapse Supernovae

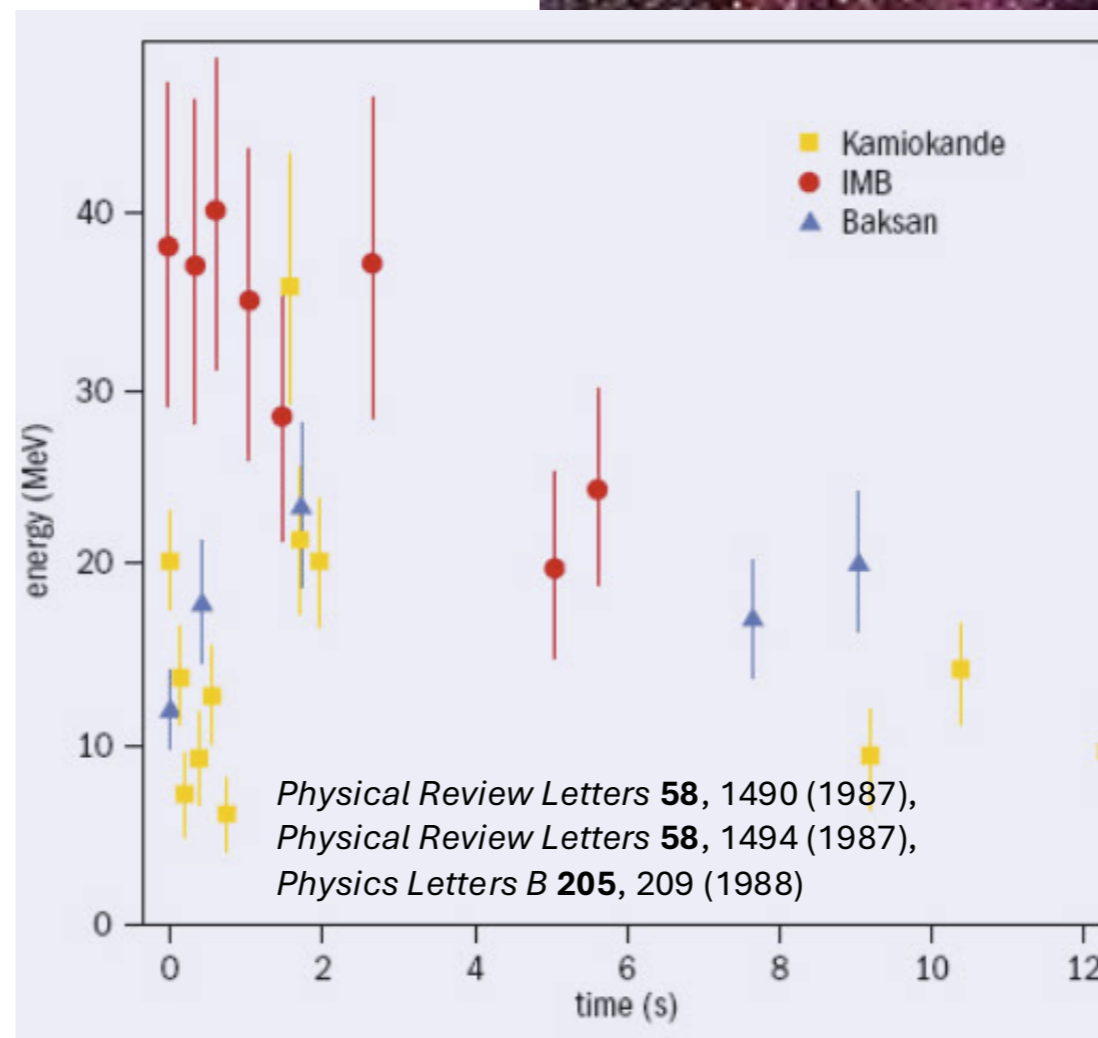
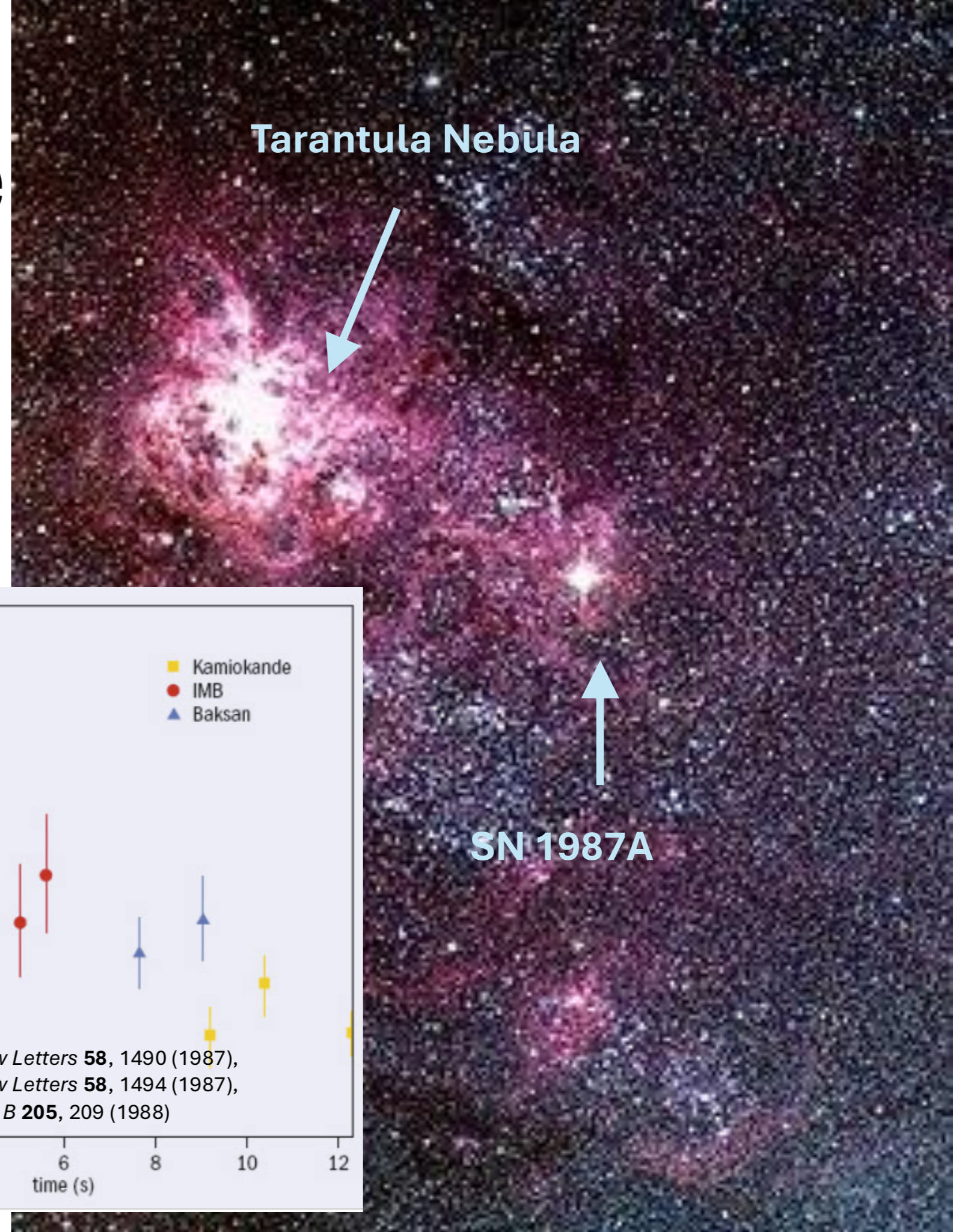
The Supernova Neutrino Early Warning System works by looking for anomalous neutrino production before the core collapse



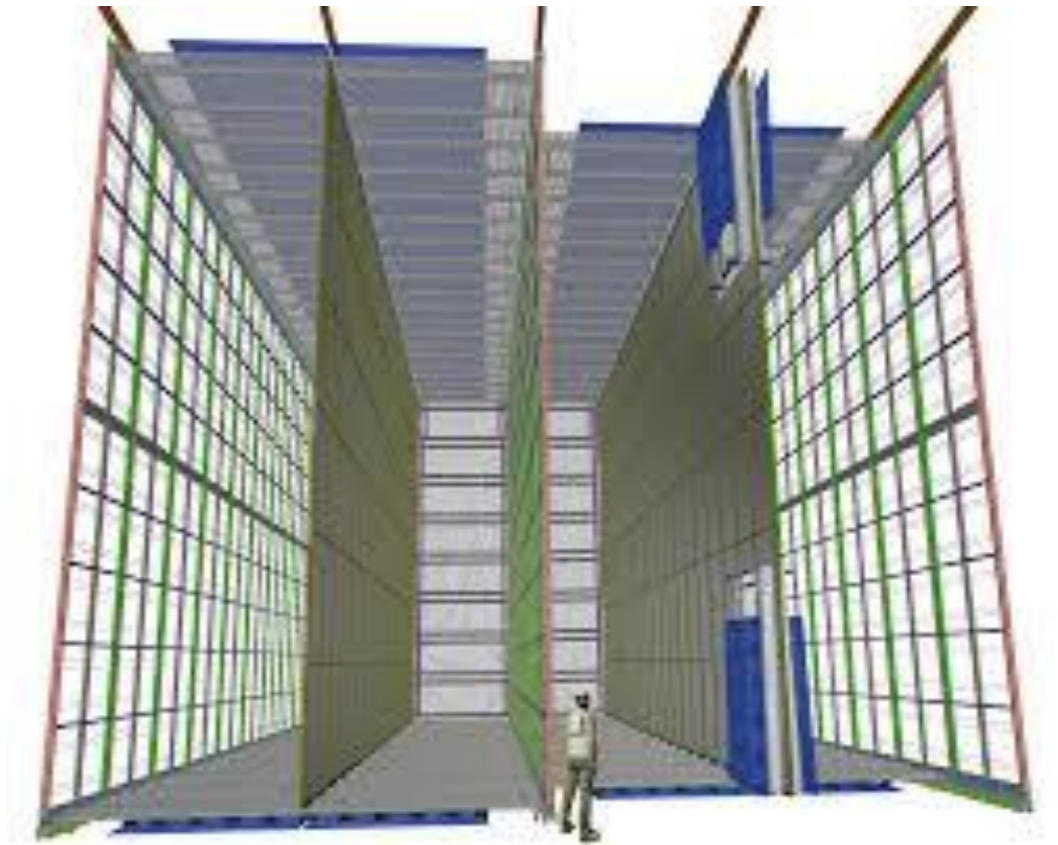
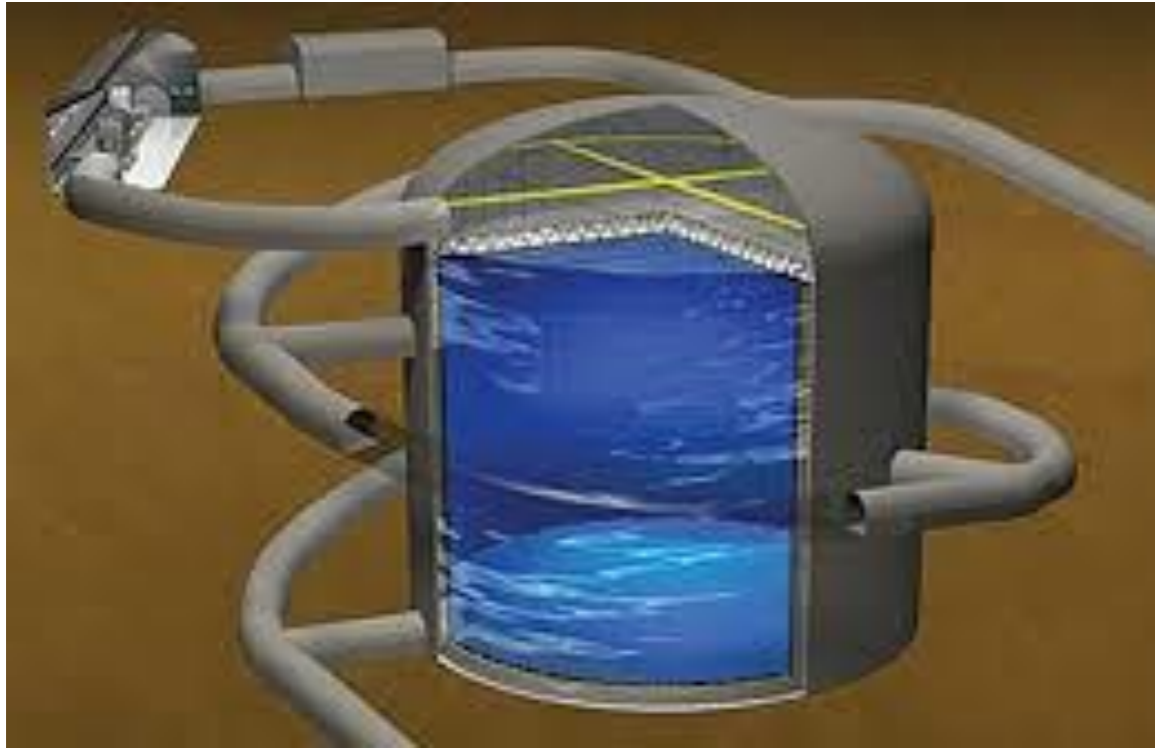
Core Collapse Supernovae

Humans have seen neutrinos from supernovae exactly 1 time, SN 1987A

25 neutrinos were observed at Kamiokande-II, IMB (Irvine-Michigan-Brookhaven), and Baksan, all 2-3 hours before light was observed



Core Collapse Supernovae



Giant detectors are coming online and waiting for the next galactic supernova. They are predicted to happen 2-3 times per century.

Also possible to see supernovae in nearby galaxies (1987A!)

What we will learn about from the next one:

- Supernova dynamics and neutron star or black hole formation
- Neutrino mass ordering
- Potential Beyond-The-Standard model neutrino behavior

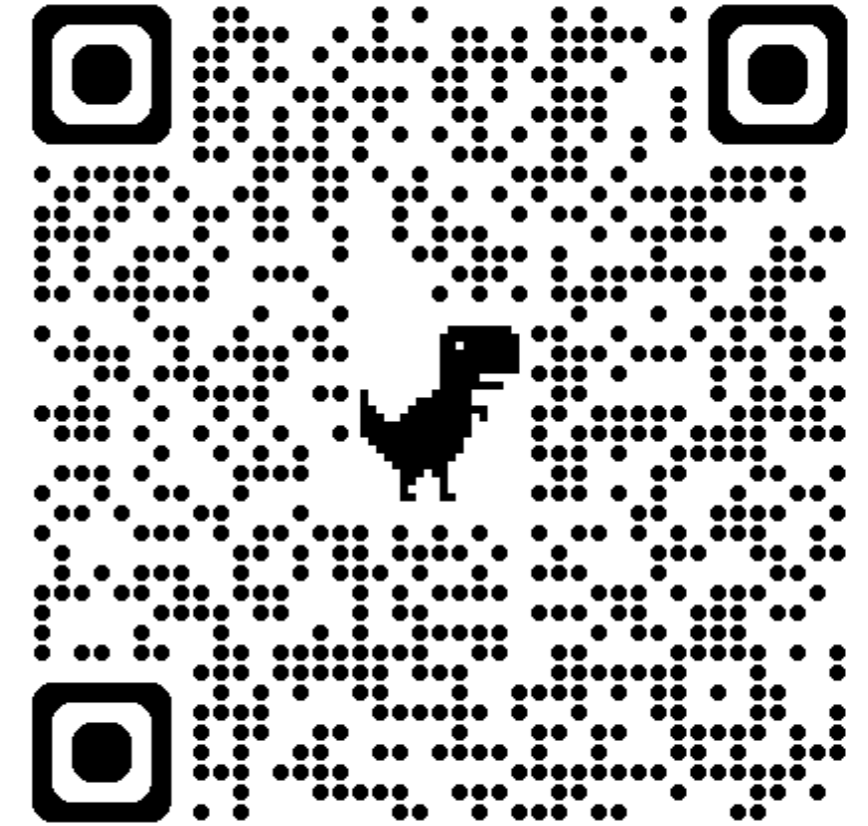
	ν_e	$\bar{\nu}_e$	ν_x
DUNE	89%	4%	7%
SK ¹	10%	87%	3%
JUNO ²	1%	72%	27%

¹Super-Kamiokande, *Astropart. Phys.* **81** 39-48 (2016)

²Lu, Li, and Zhou, *Phys Rev. D* **94** 023006 (2016)

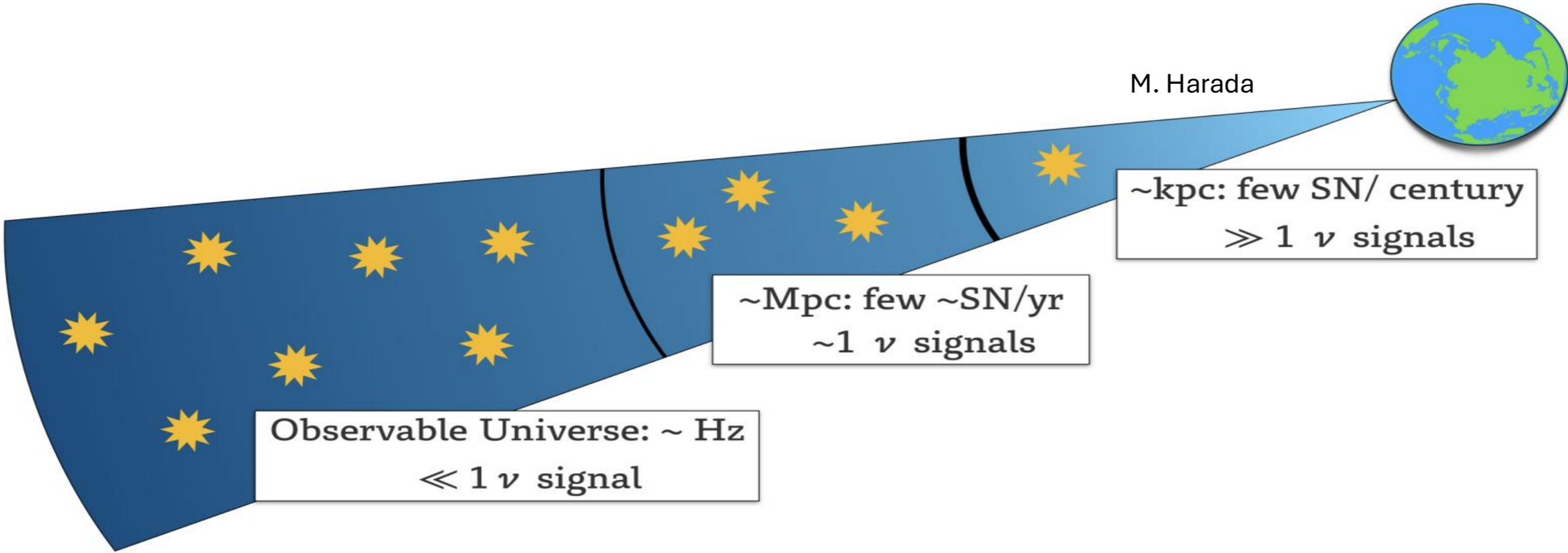
Break Time

- Let's take a short break
- Homework for break:
 - Get up and move around
 - Talk to someone you haven't talked to before
 - Ask any questions you have about the material so far here:
 - <https://forms.gle/QdCCeejHyc2dNNmZ6>

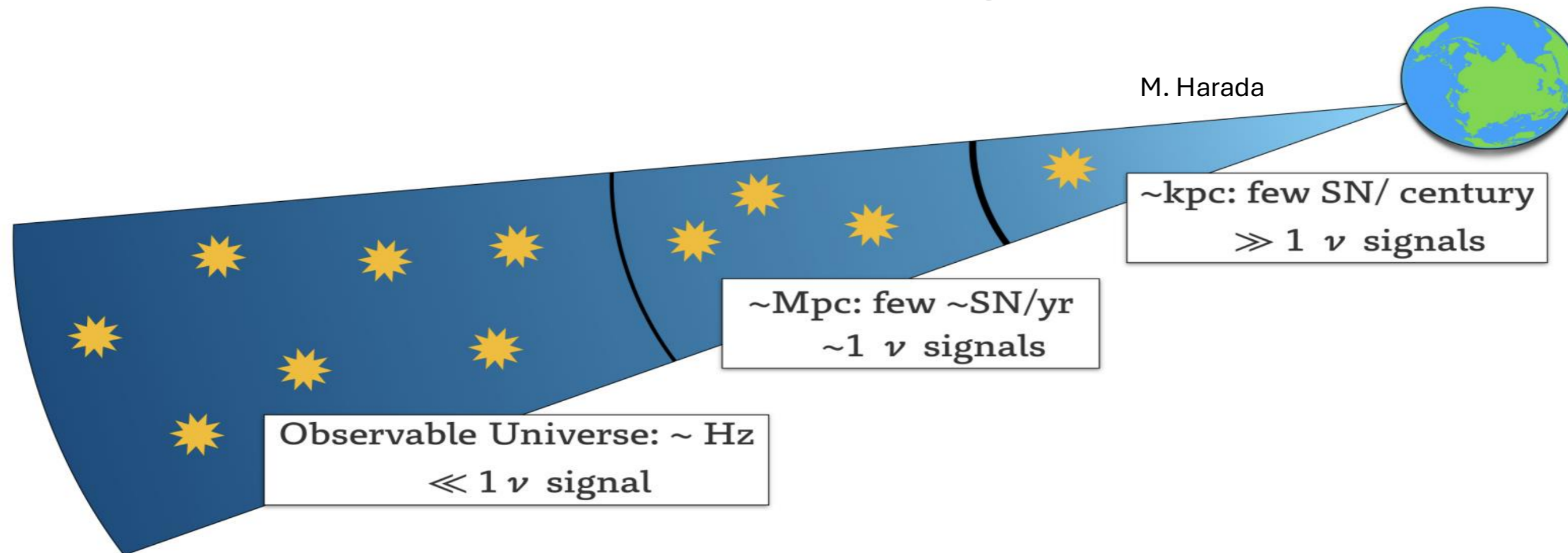




Diffuse Supernova Background



Diffuse Supernova Background



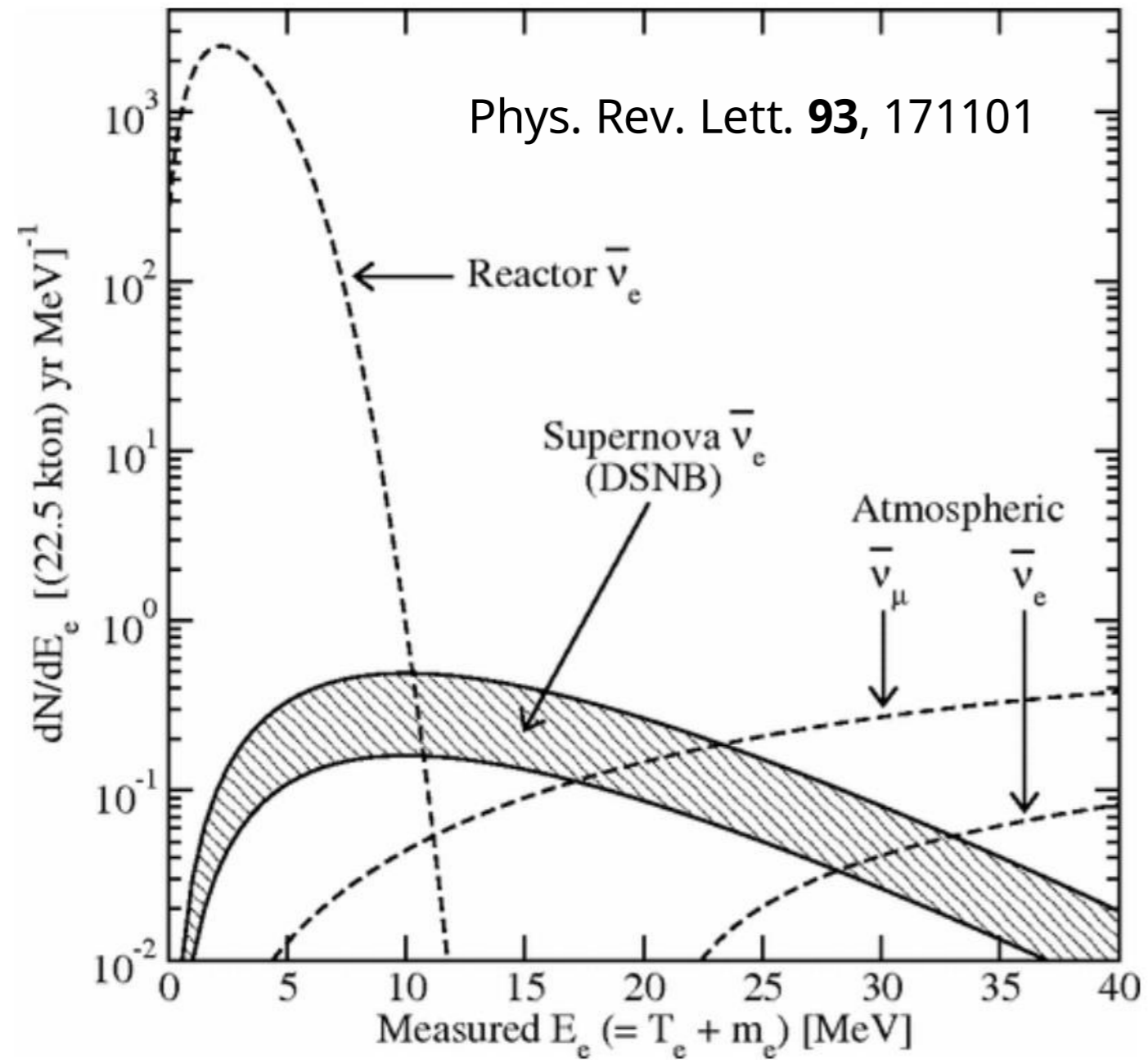
To see a Supernova directly, we need it to happen relatively close, which is rare

But far-flung supernovae happen all the time!

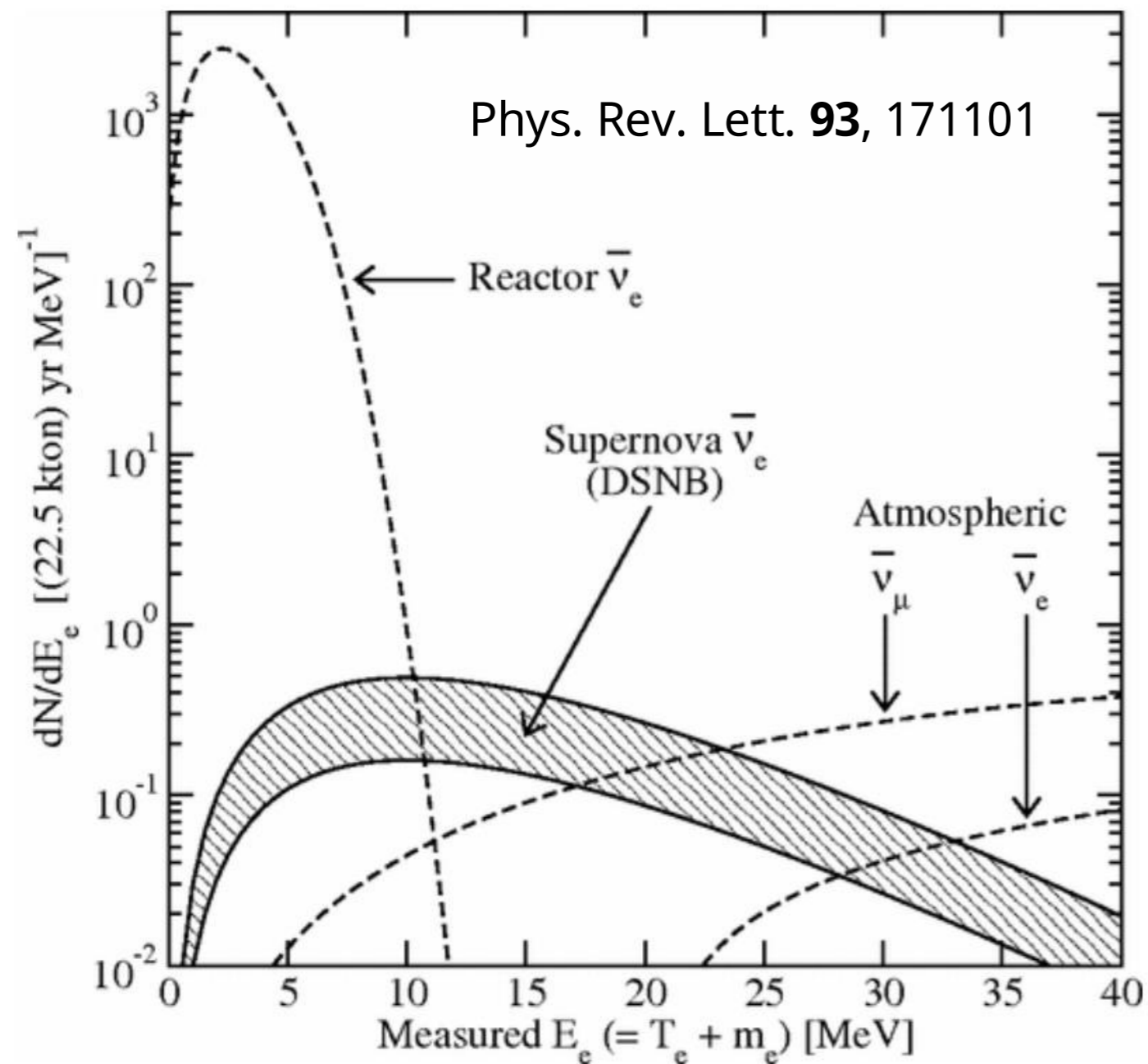
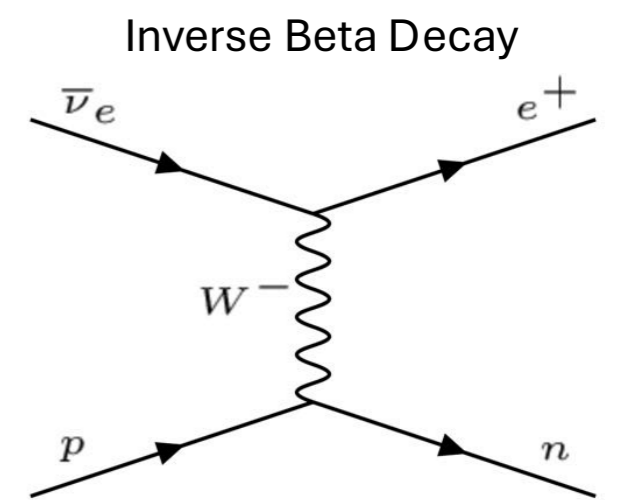
This creates an isotropic “diffuse supernova neutrino background”



Diffuse Supernova Background



Diffuse Supernova Background



Humans have not yet observed the DSNB

It is swamped by reactor neutrinos at low energy

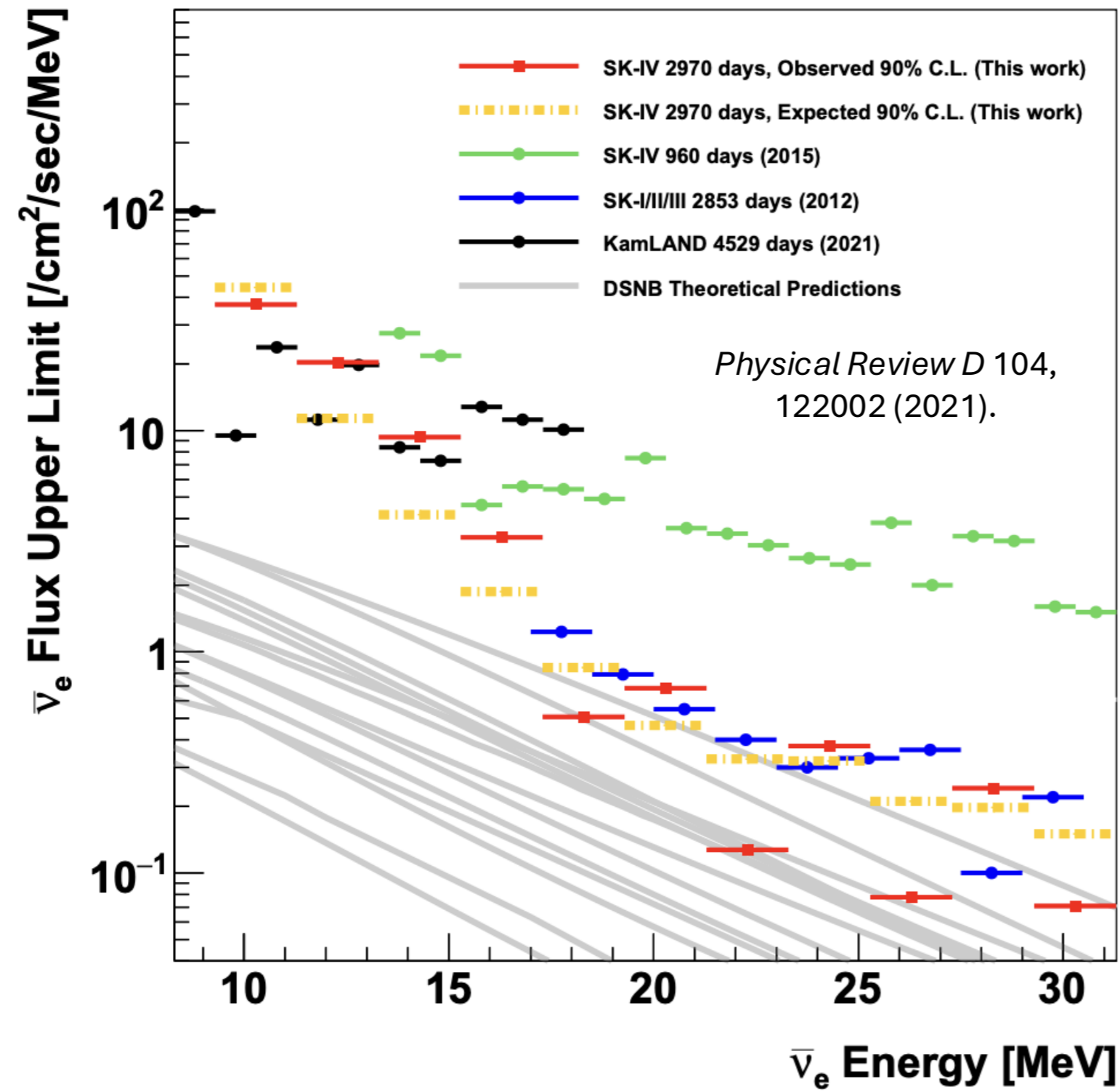
And atmospheric neutrinos at high energy

The best hope of seeing them is in the narrow energy range between the two

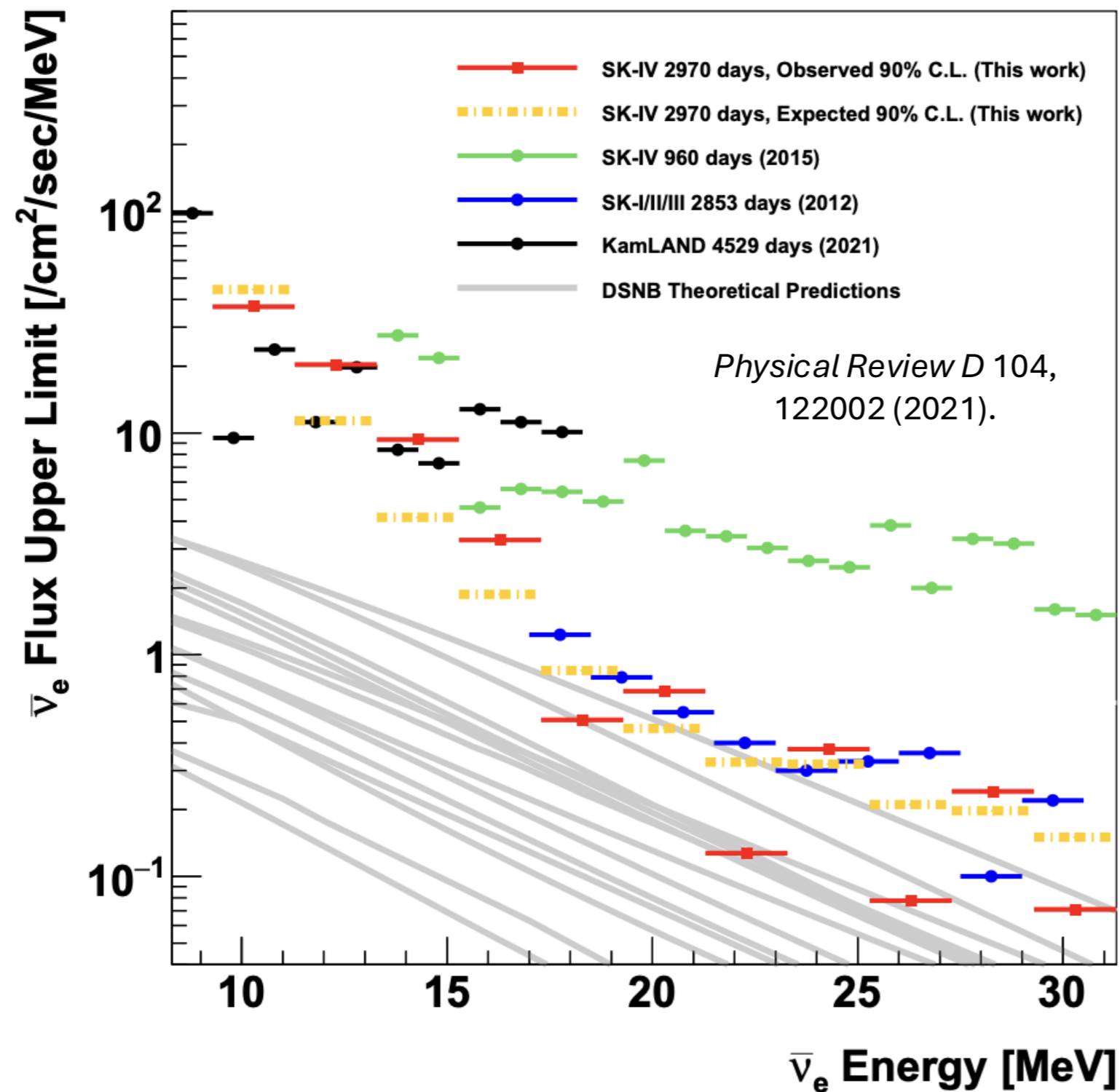
DSNB is both neutrinos and antineutrinos, but antineutrinos are much easier to search for, via inverse beta decay



Diffuse Supernova Background



Diffuse Supernova Background



DSNB predicted fluxes have big uncertainties

But SuperK is starting to reach sensitivity to models with higher flux predictions

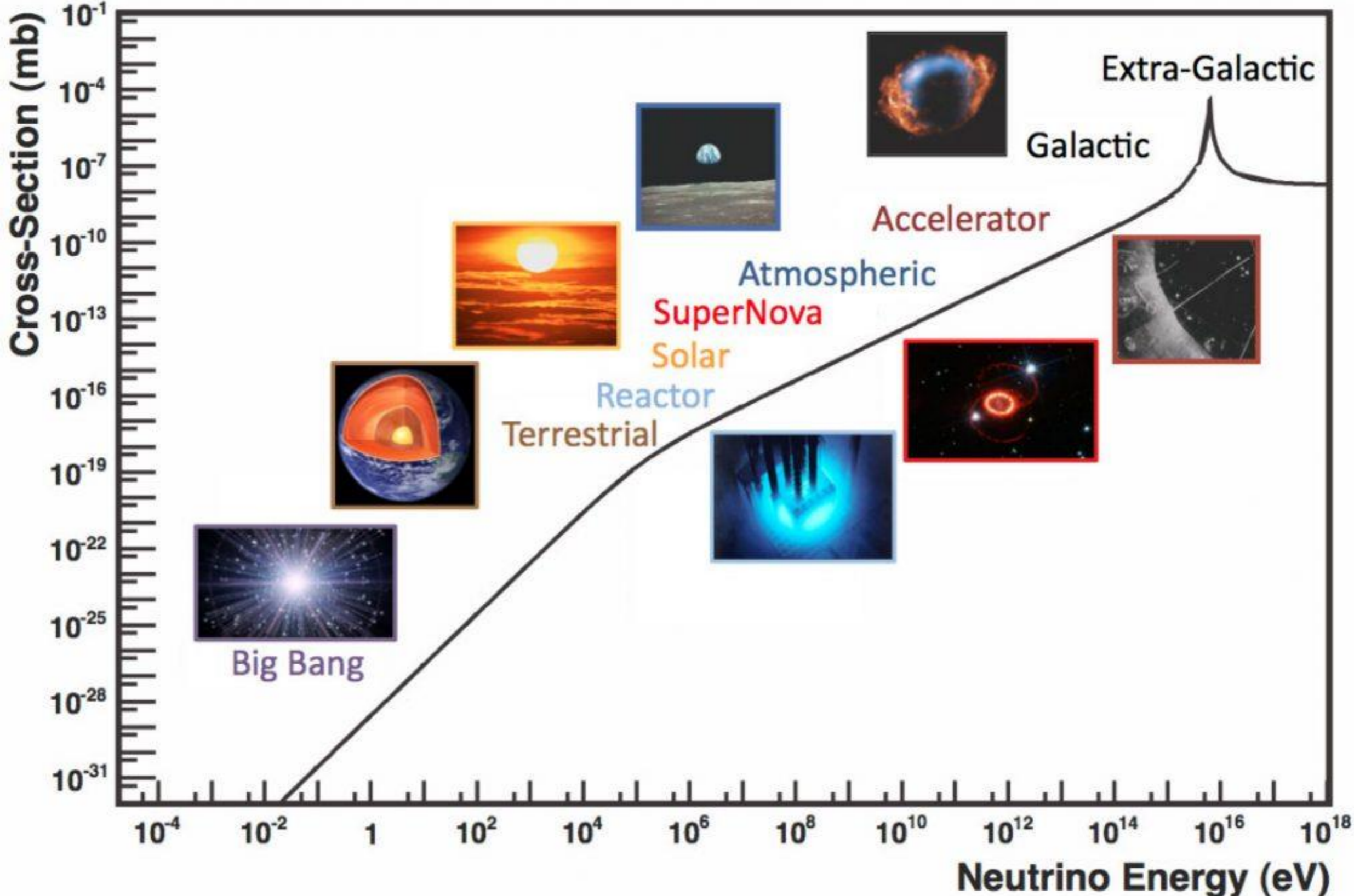
HyperK, JUNO, and DUNE will go further

High Energy Astrophysical Neutrinos



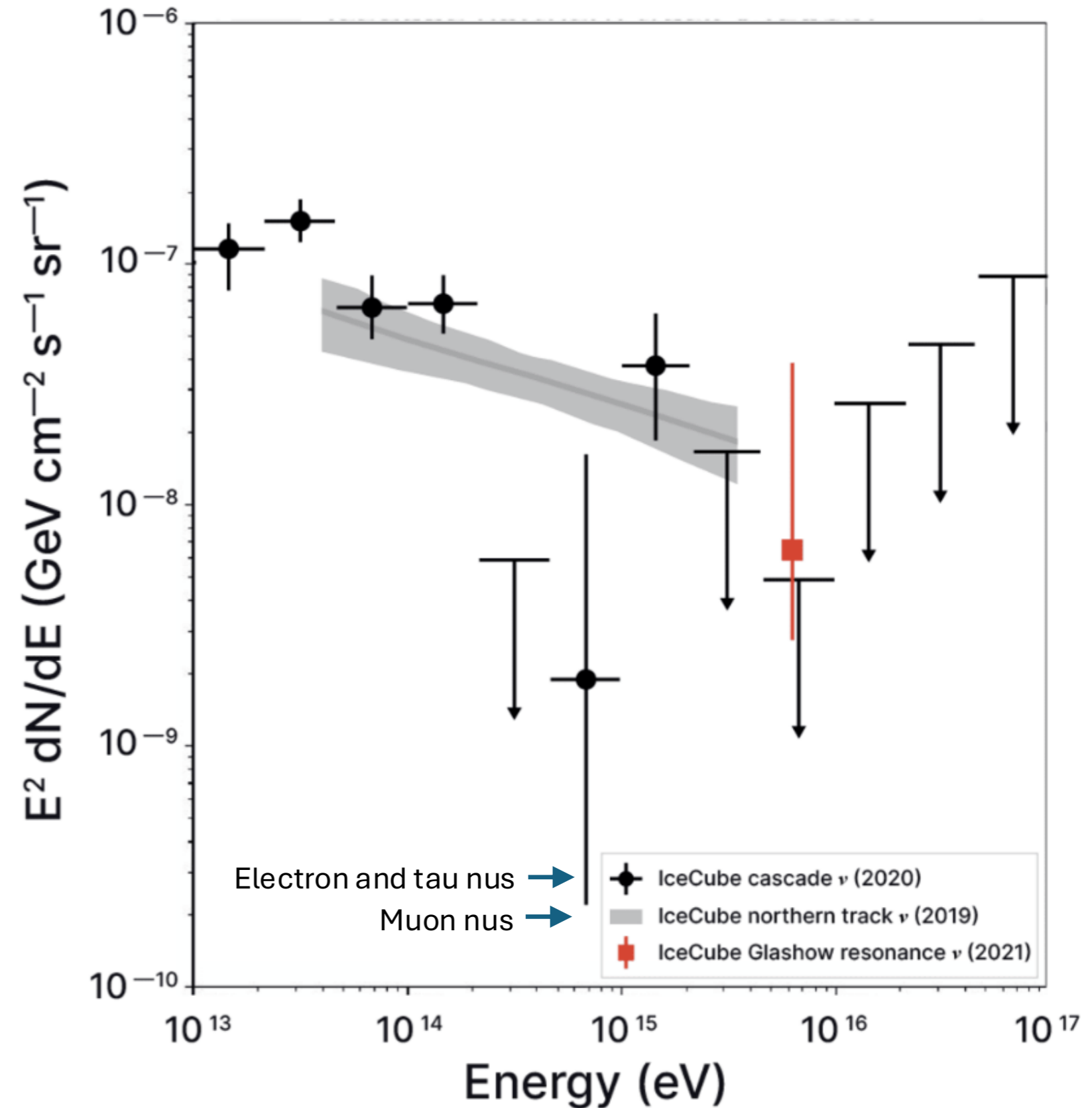
High Energy Neutrinos

Rev. Mod. Phys. 84, 1307 (2012)



High Energy Neutrinos

The High Energy Astrophysical flux between 10^{13} and 10^{16} eV has been measured by IceCube



High Energy Neutrinos

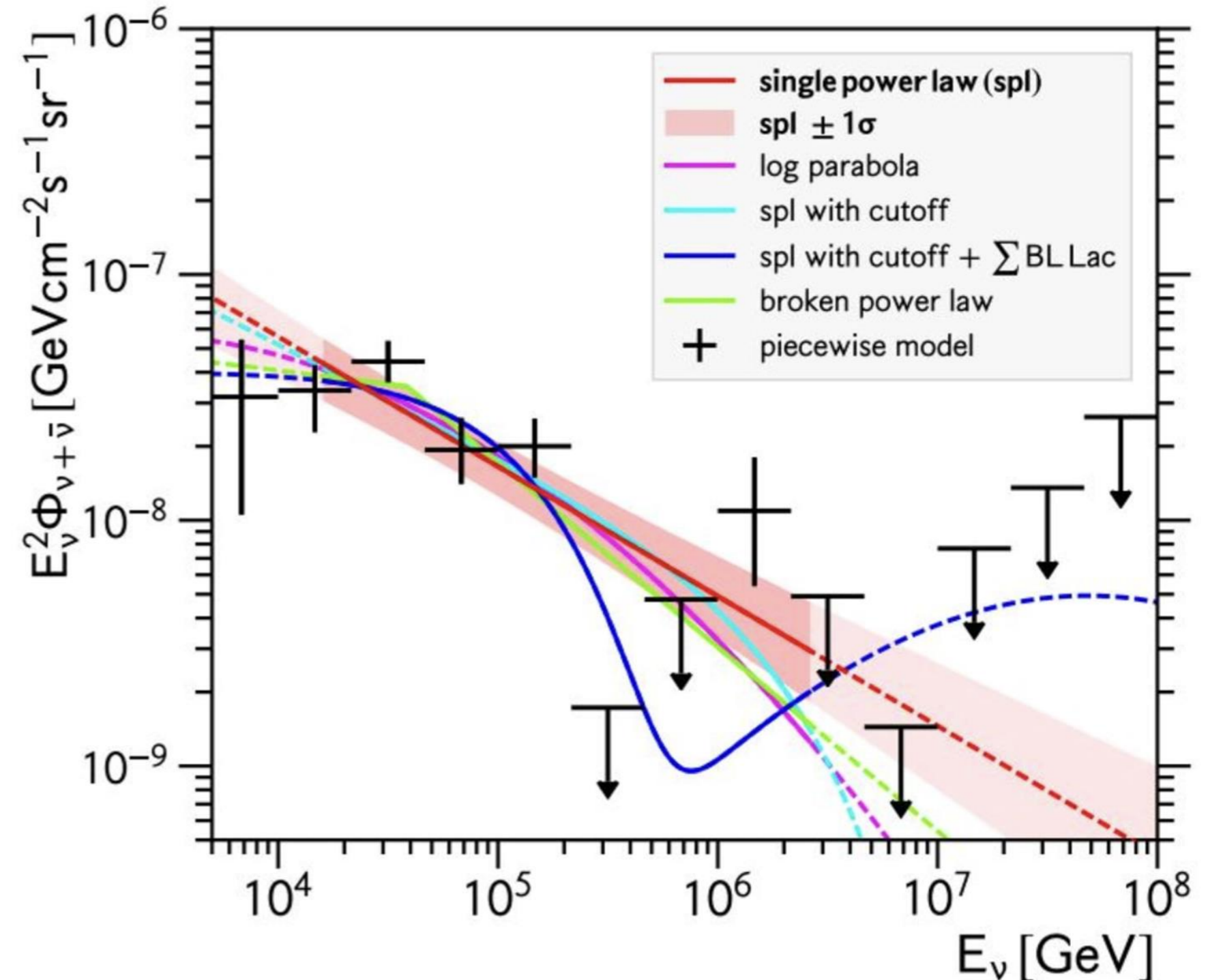
<https://icecube.wisc.edu/science/research/#neutrinoastronomy>

The flux is typically modeled as **a power law**

Other models exist, but data cannot yet discriminate between these

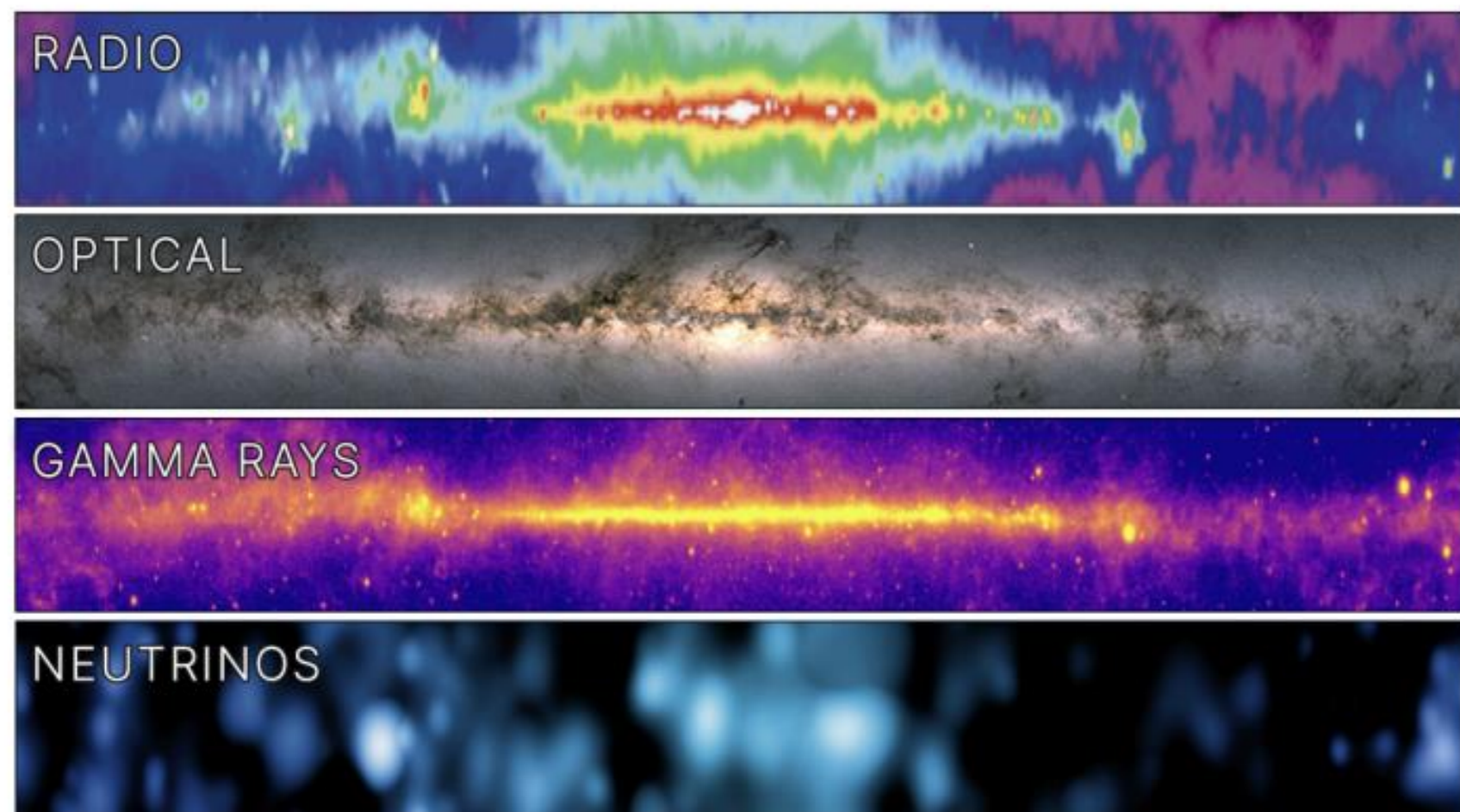
Flux is roughly **equal parts electron, muon, and tau neutrinos at Earth** (although it was preferentially muon and electron before oscillations)

Combination of **neutrinos and antineutrinos**, but the ratio is not well known



High Energy Neutrino Sources: Milky Way

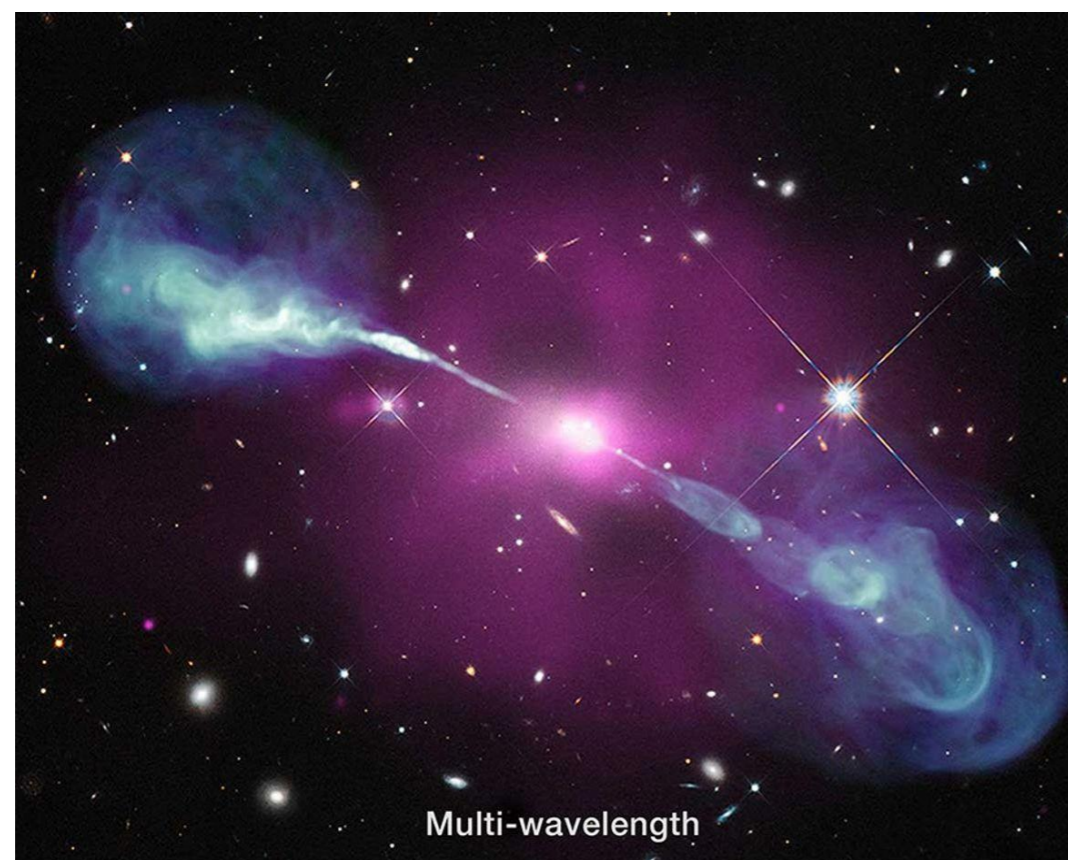
The Milky Way Imaged Four Different Ways



IceCube has mapped neutrinos from the plane of the Milky Way

These neutrinos are thought to originate from pions created by high energy cosmic ray collisions with interstellar medium of the Milky Way

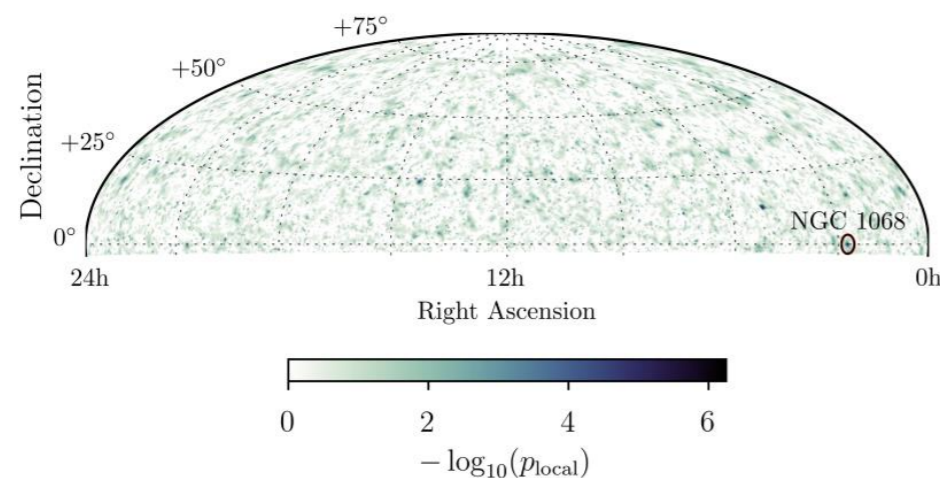
High Energy Neutrino Sources: AGN



Active galactic nuclei (AGN) are bright regions of galaxies thought to be due to accretion of matter by supermassive blackholes at their center

IceCube has published evidence for neutrino emission from AGN

IceCube ApJL 1000 L26 (2026)

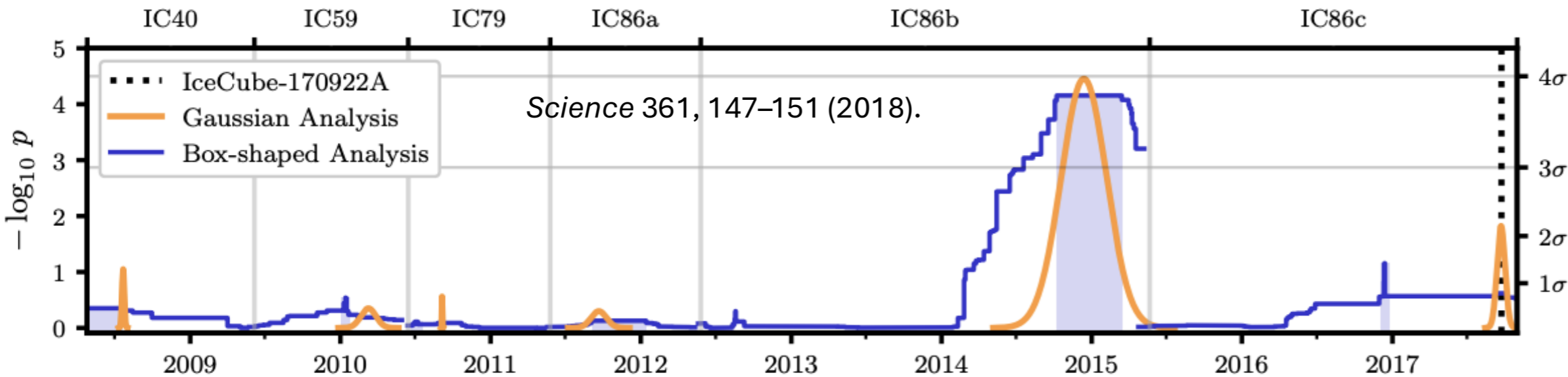


High Energy Neutrino Sources: Blazars



Blazars are active galactic nuclei with relativistic jets pointed toward earth

IceCube first discovered blazar TXS 0506+056 in 2017 – the first discovery of an astrophysical neutrino source other than SN1987a and the Sun

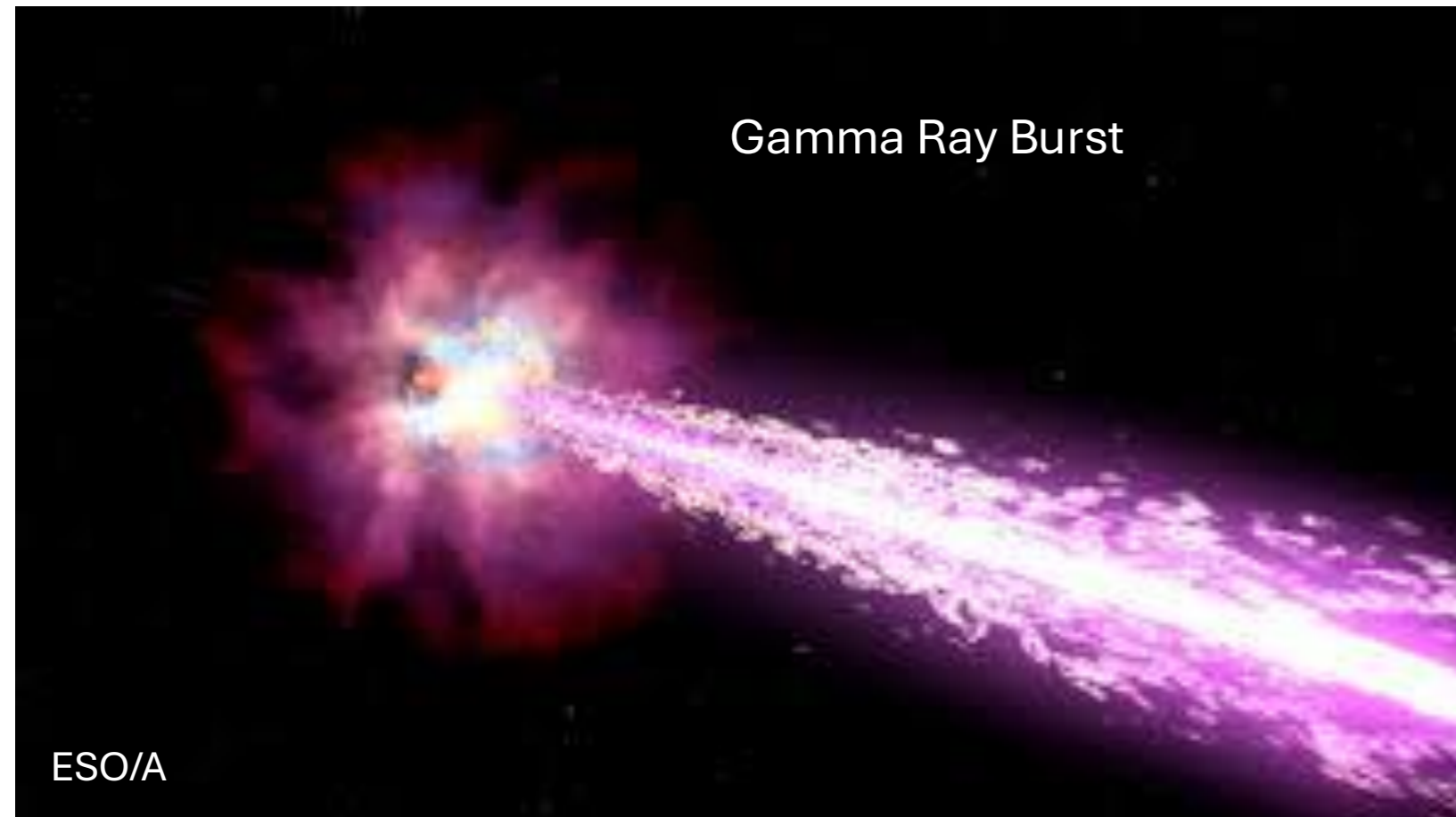


High Energy Neutrinos

Other high energy neutrino sources contribute to a diffuse high-energy neutrino flux

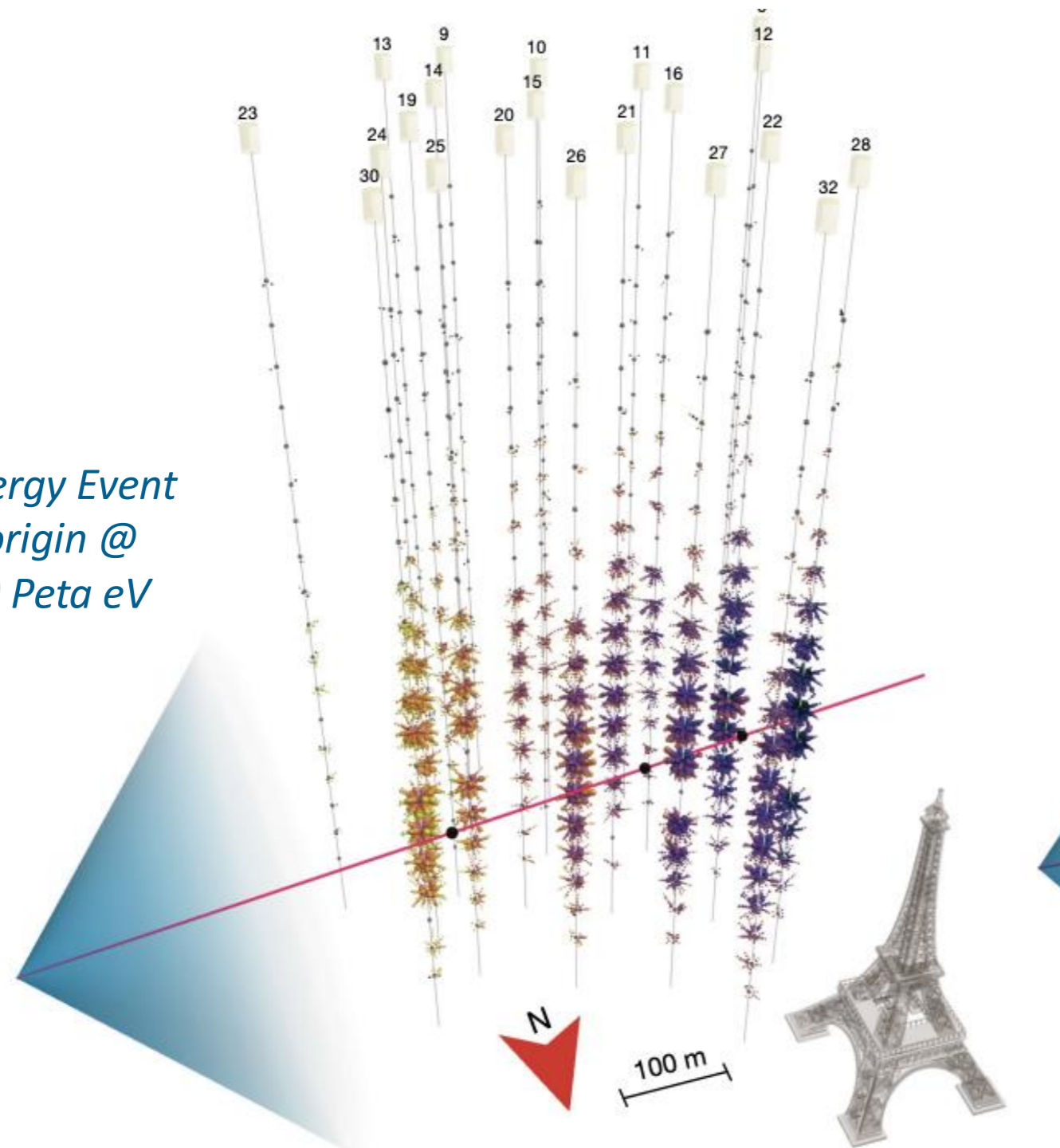
Potential sources include:

- Gamma ray bursts: the most violent events in the universe, caused by collapse of massive stars or binary neutron star collisions
- Starburst galaxies: galaxies with exceptionally high rates of star formation
- Tidal disruption events: when a star wanders too close to a black hole and is ripped apart



High Energy Neutrinos

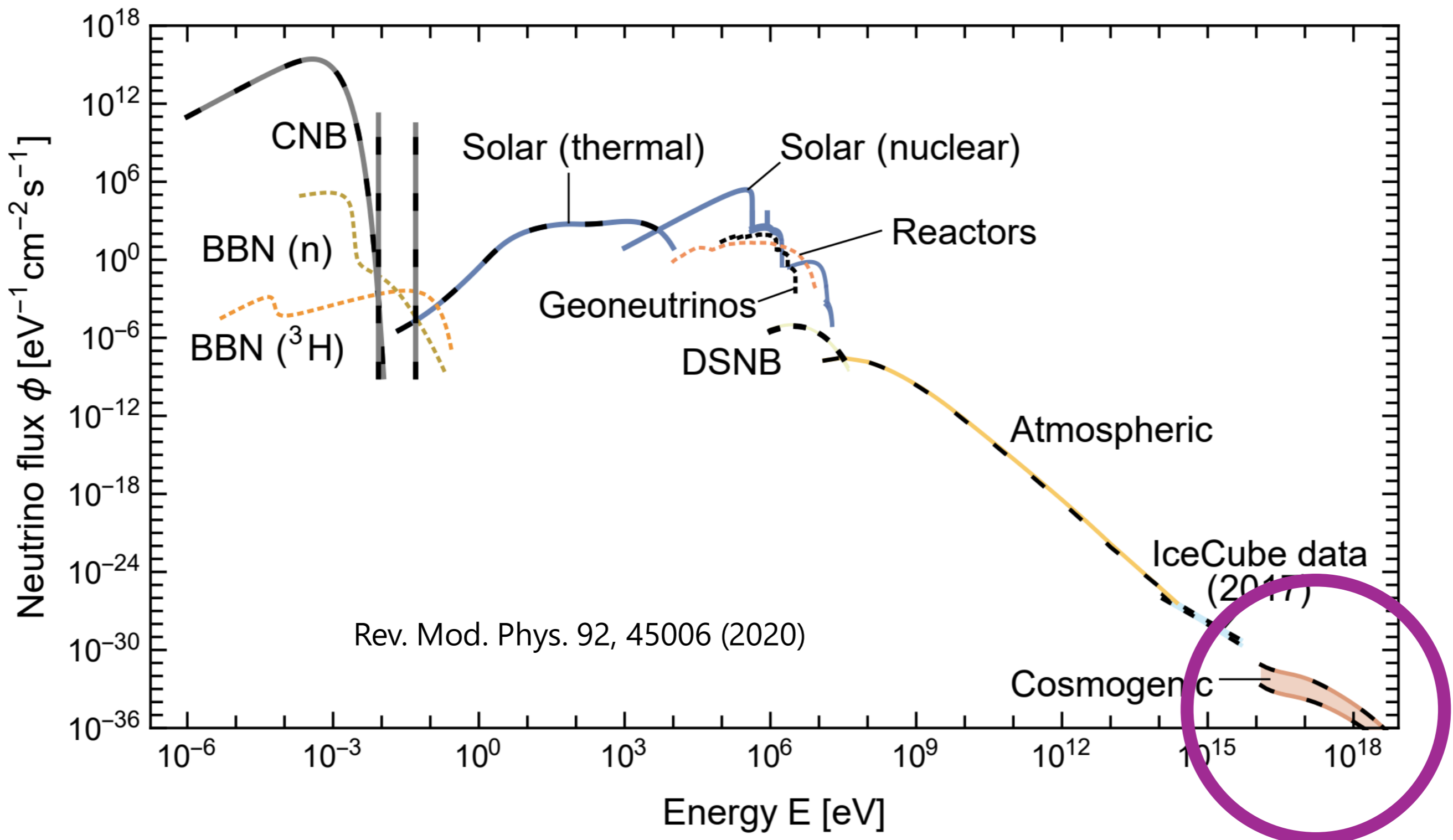
*Very High Energy Event
of unknown origin @
KM3NET: 120 Peta eV*



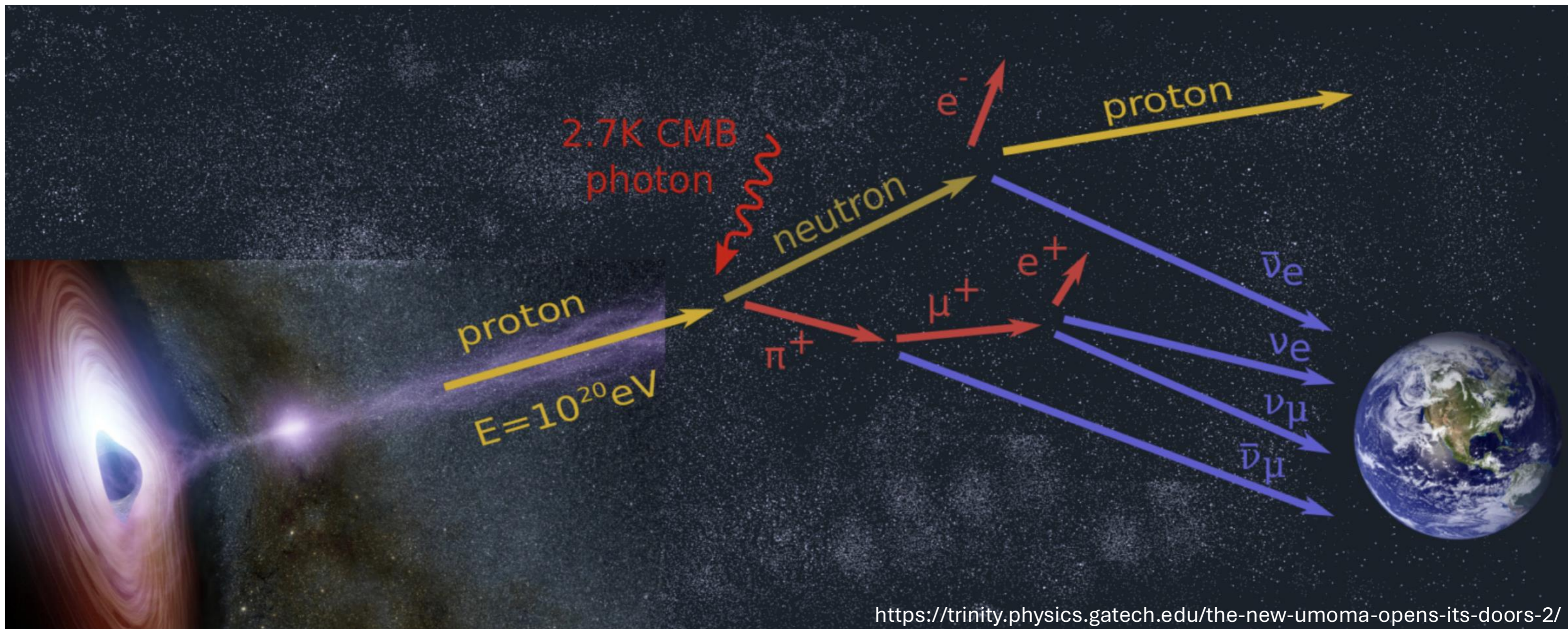
KM3 Net has seen a single very high energy neutrino event – $120 \text{ PeV} = 10^{18} \text{ eV}$

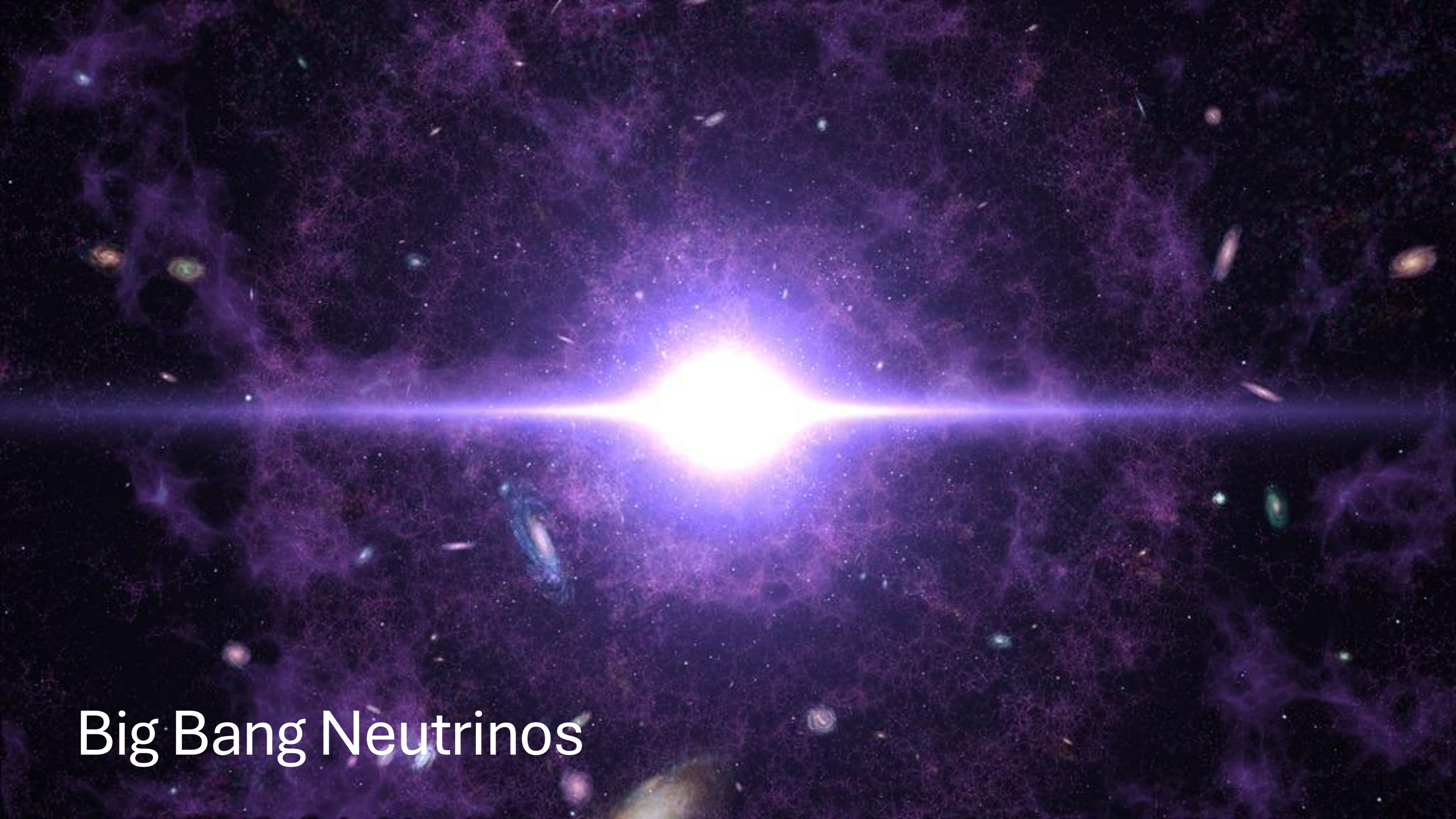
Could be the first observed
“Cosmogenic” neutrino

High Energy Neutrinos

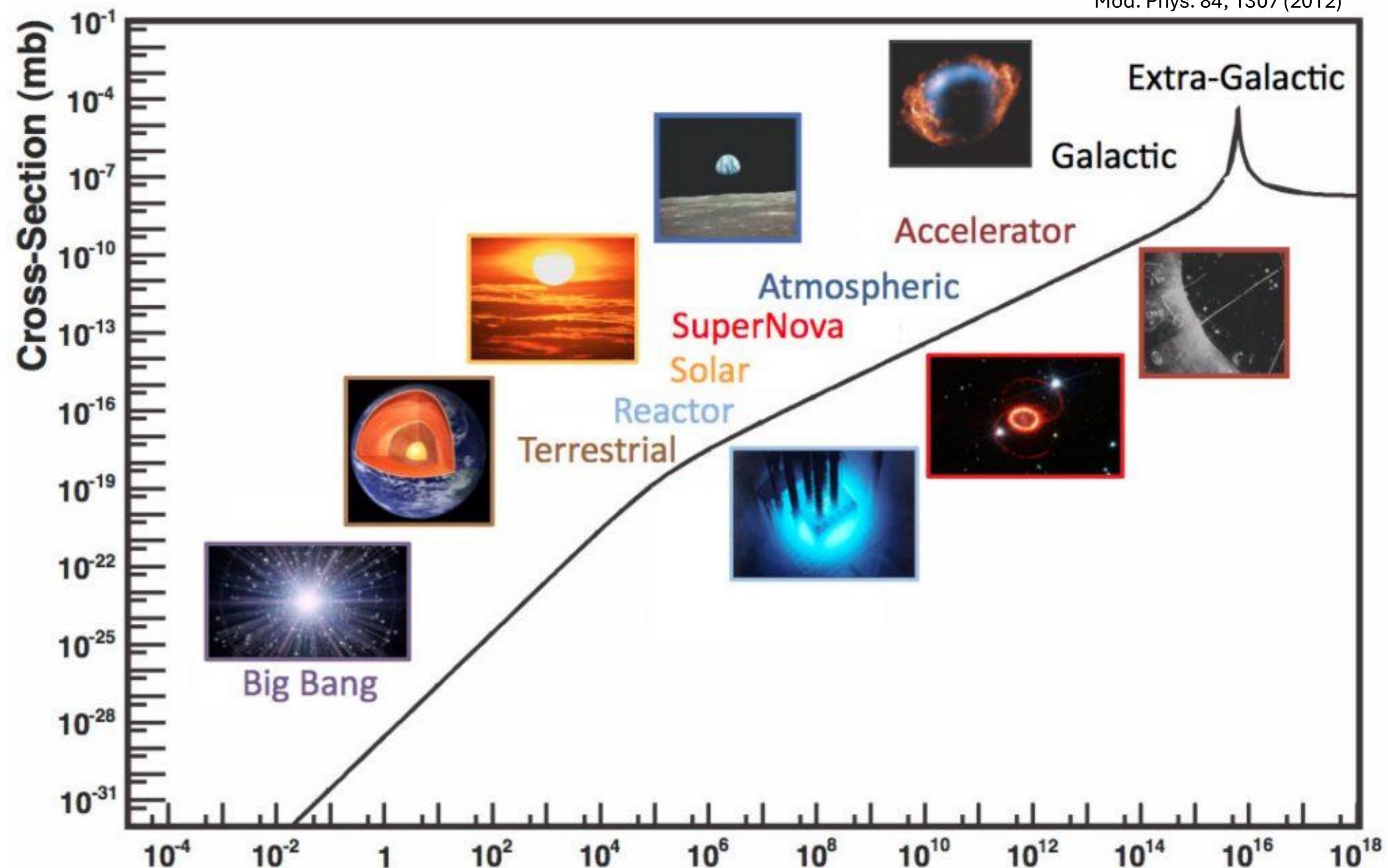


Cosmogenic Neutrinos

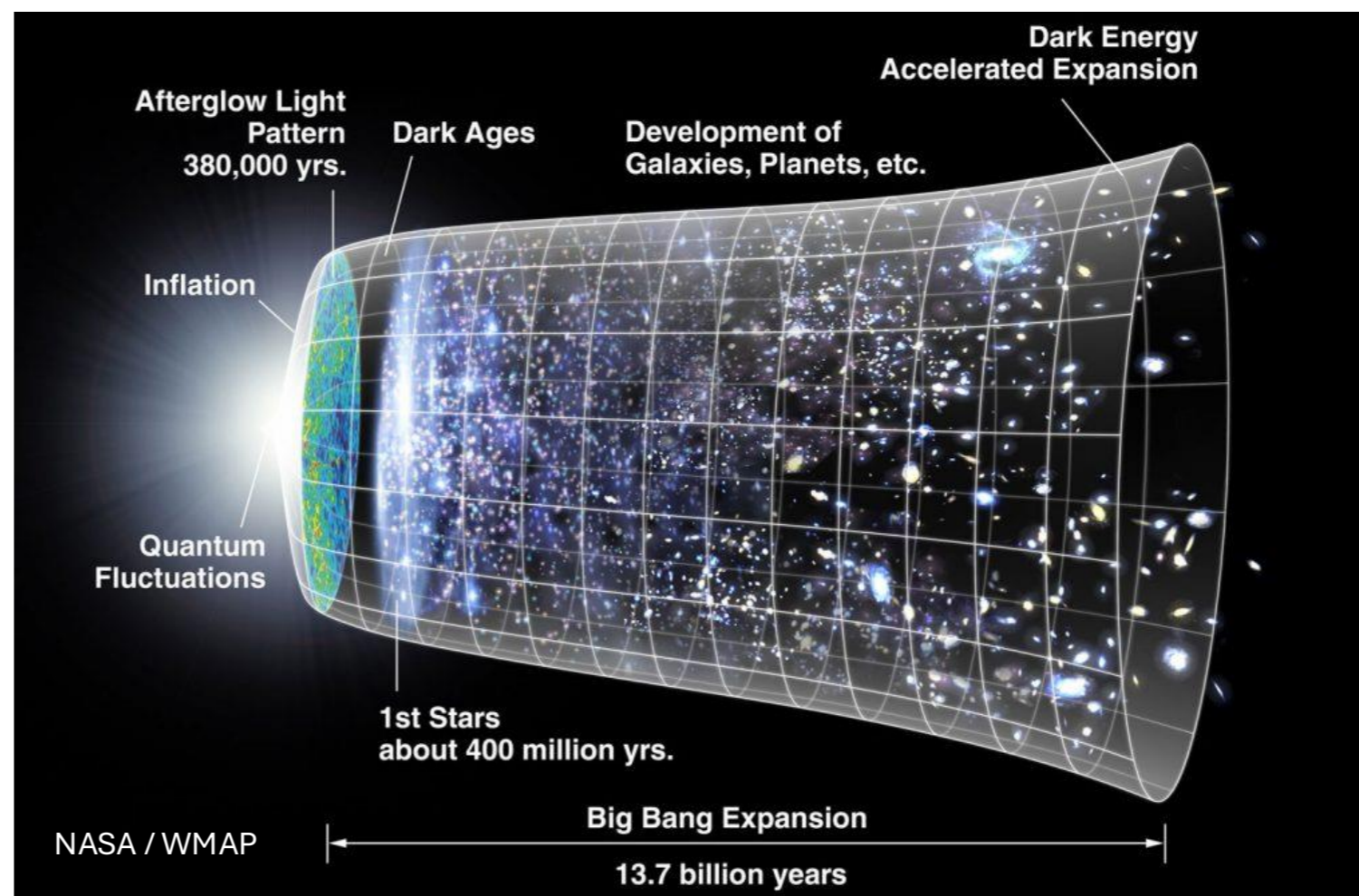
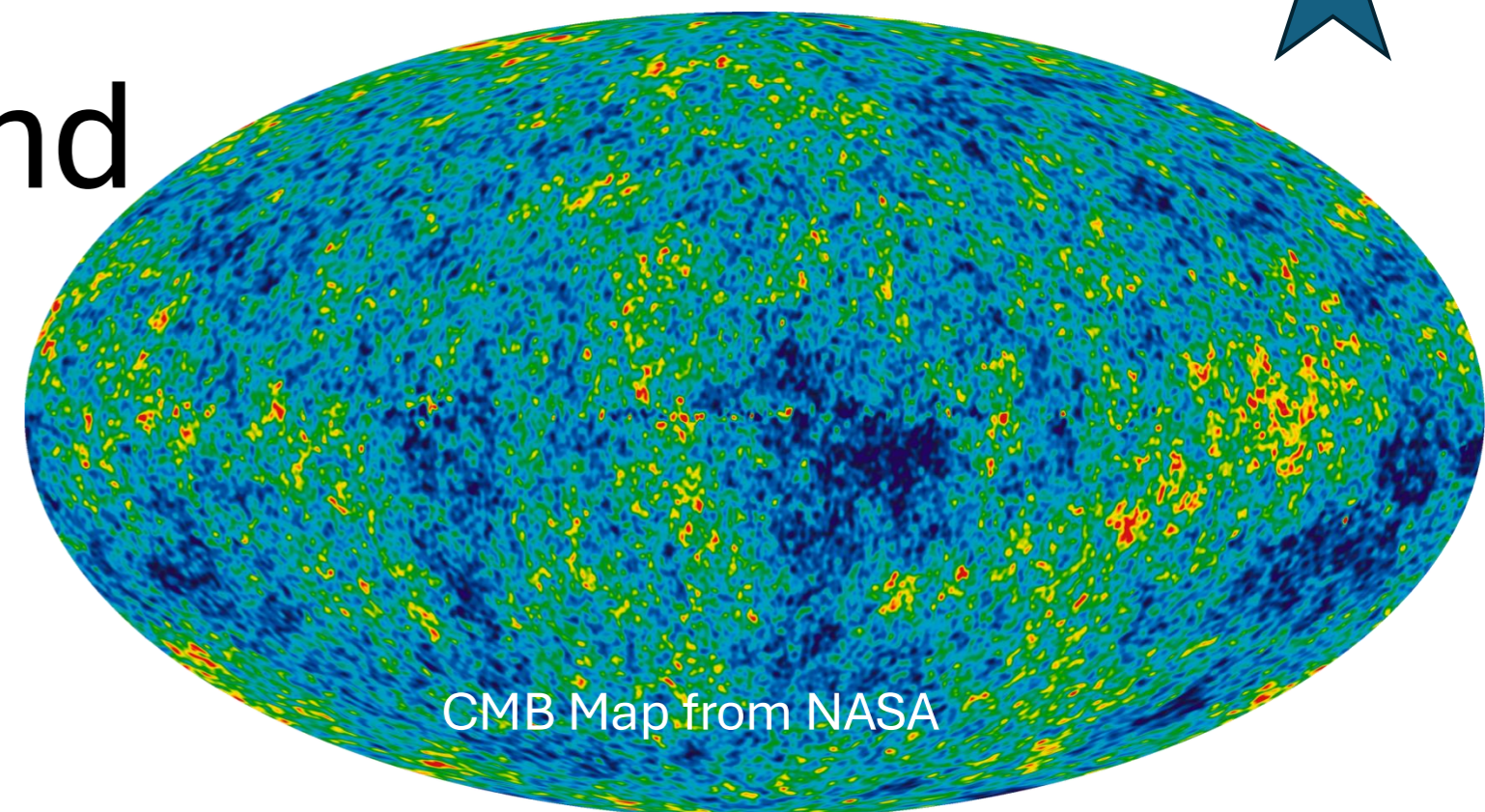




Big Bang Neutrinos



Cosmic Neutrino Background

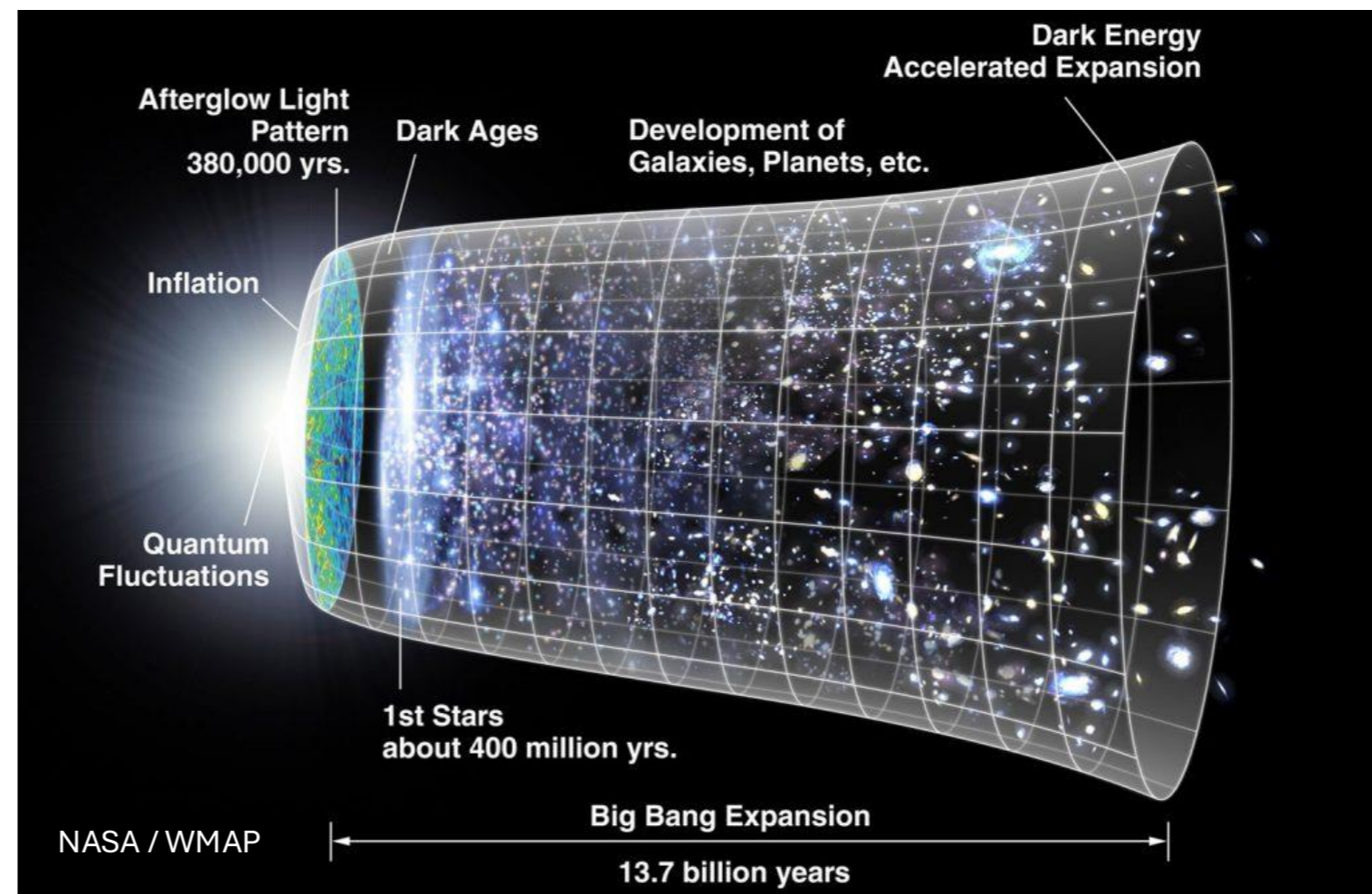
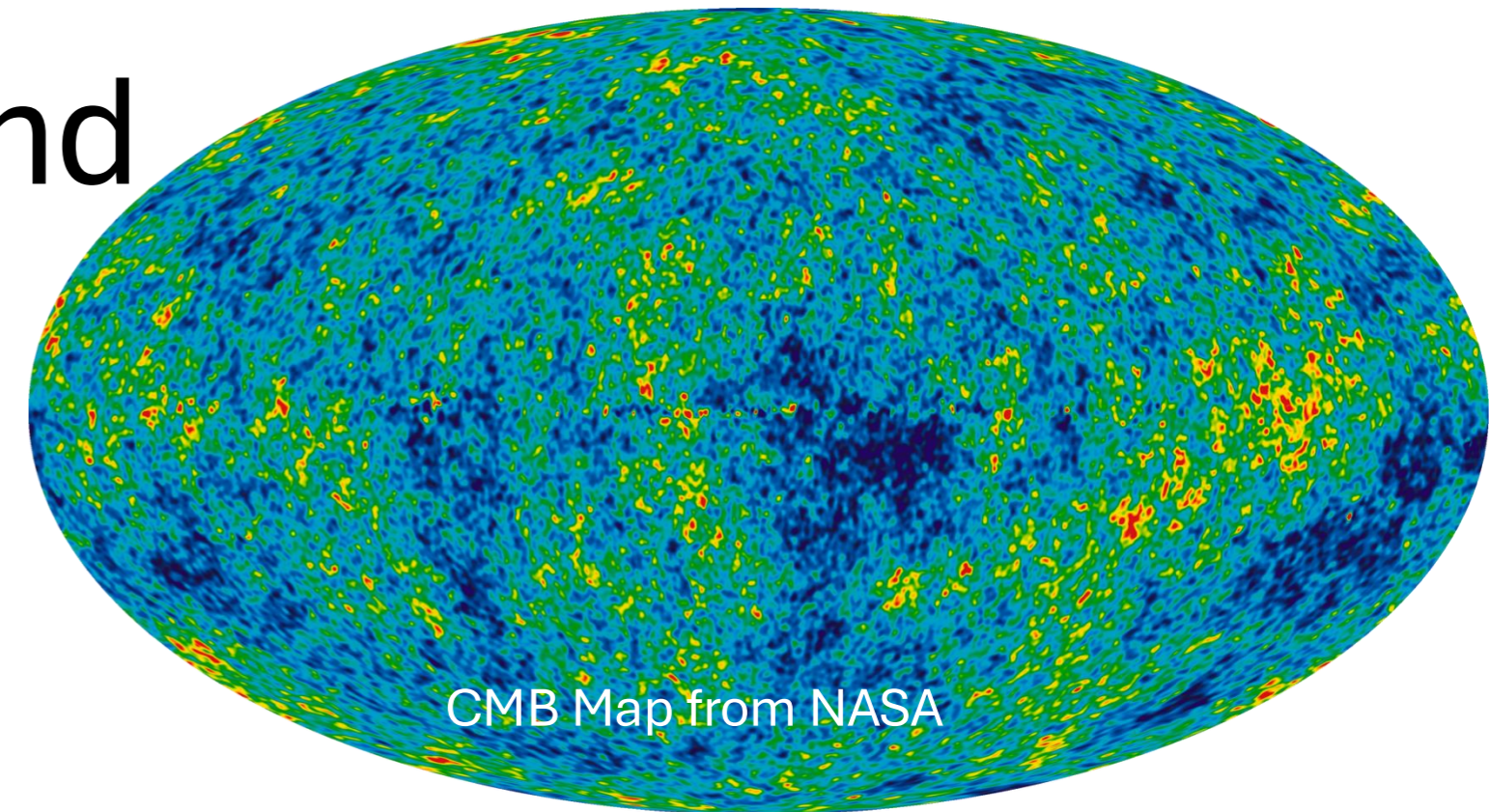


Cosmic Neutrino Background

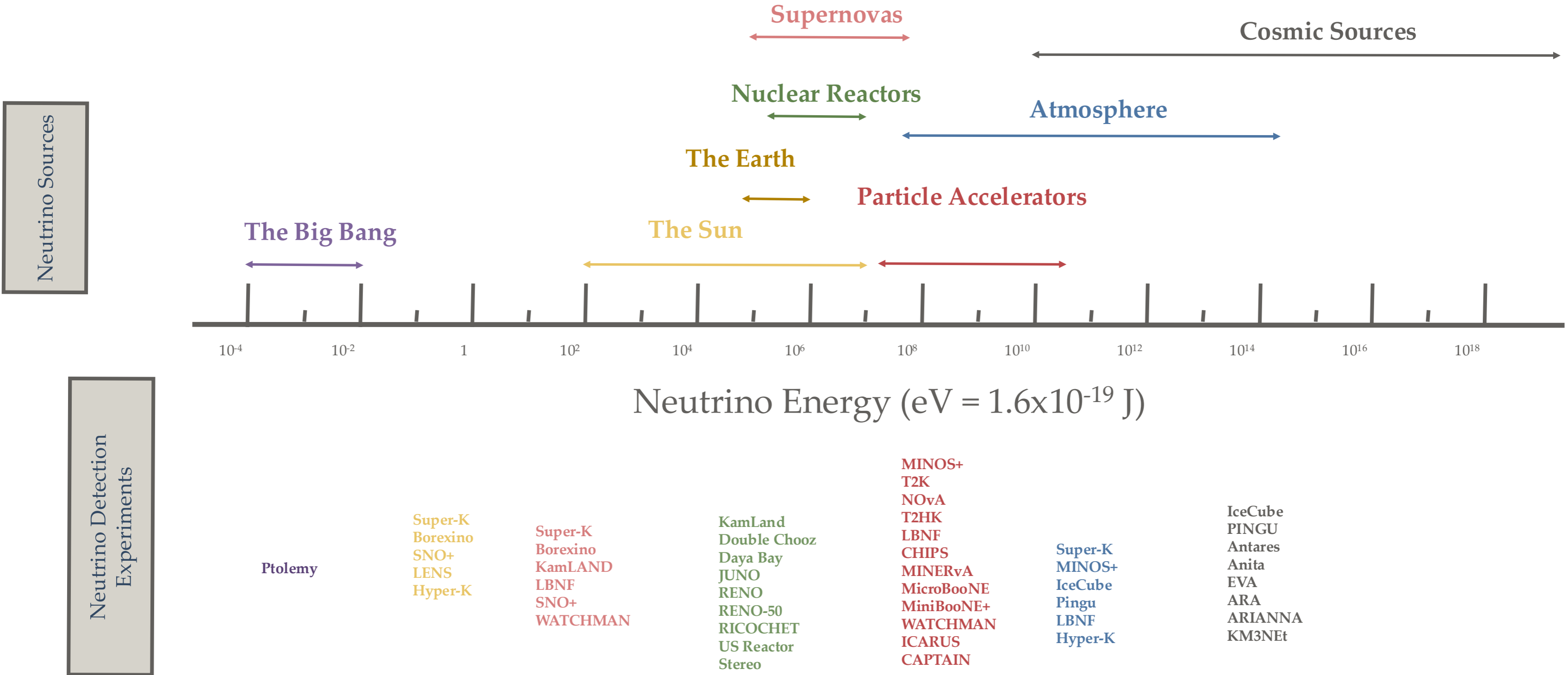
According to our standard model of cosmology, neutrinos were created during the big bang and decoupled from other particles about ~ 1 second after the big bang

In contrast, photons decoupled 380,000 years after the big bang!

In principle, observing the cosmic neutrino background would give us a view of the universe when it was 1 second old!



Cosmic Neutrino Background



Although these CNB neutrinos were around 1 MeV at freeze out, they have been redshifted to $\sim 10^{-4}$ eV today, meaning they are going to be very, very, very, very hard to see

Cosmic Neutrino Background

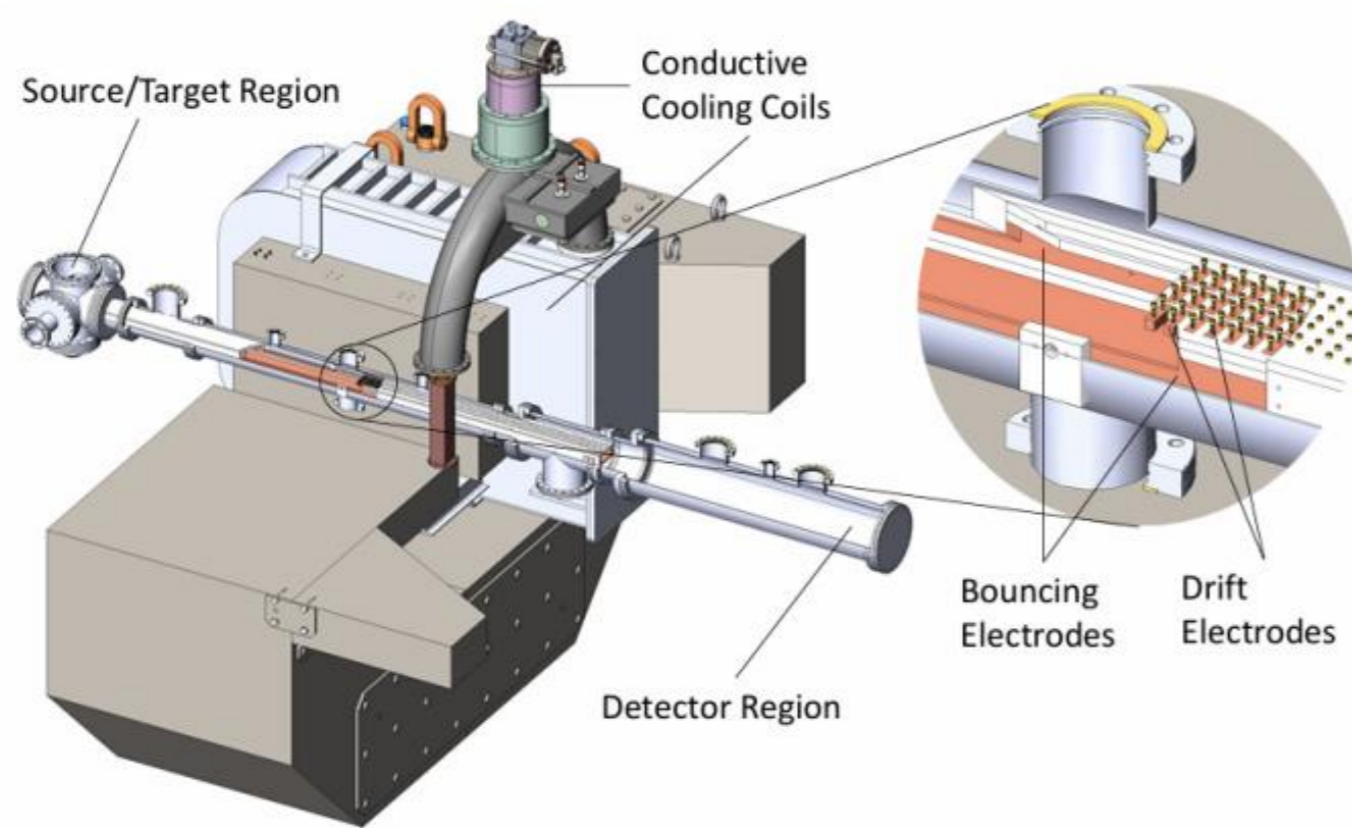
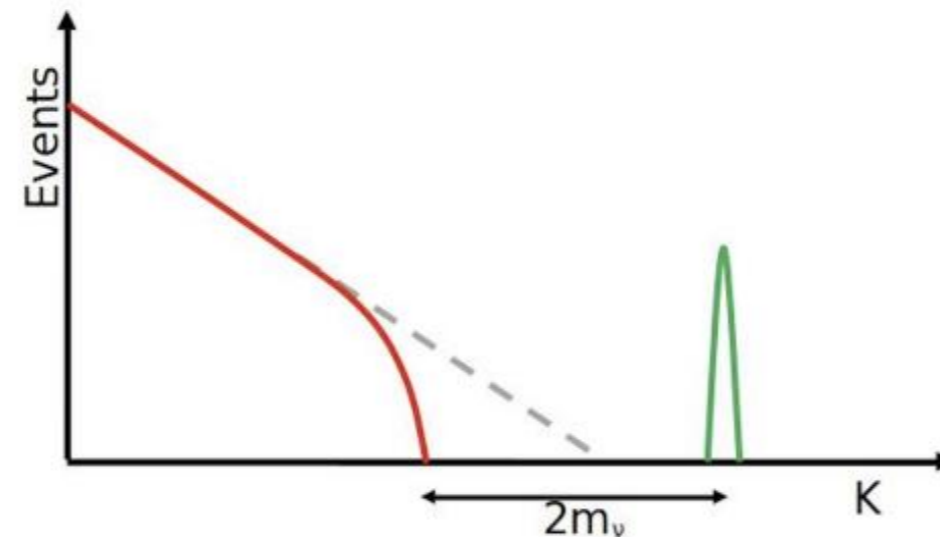
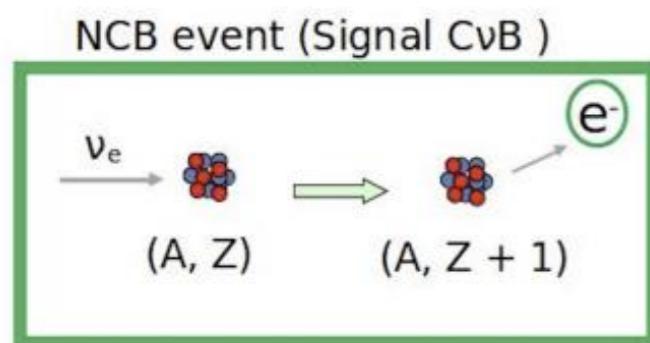


Figure 10: 3D model of PTOLEMY demonstrator.

arXiv:1902.05508

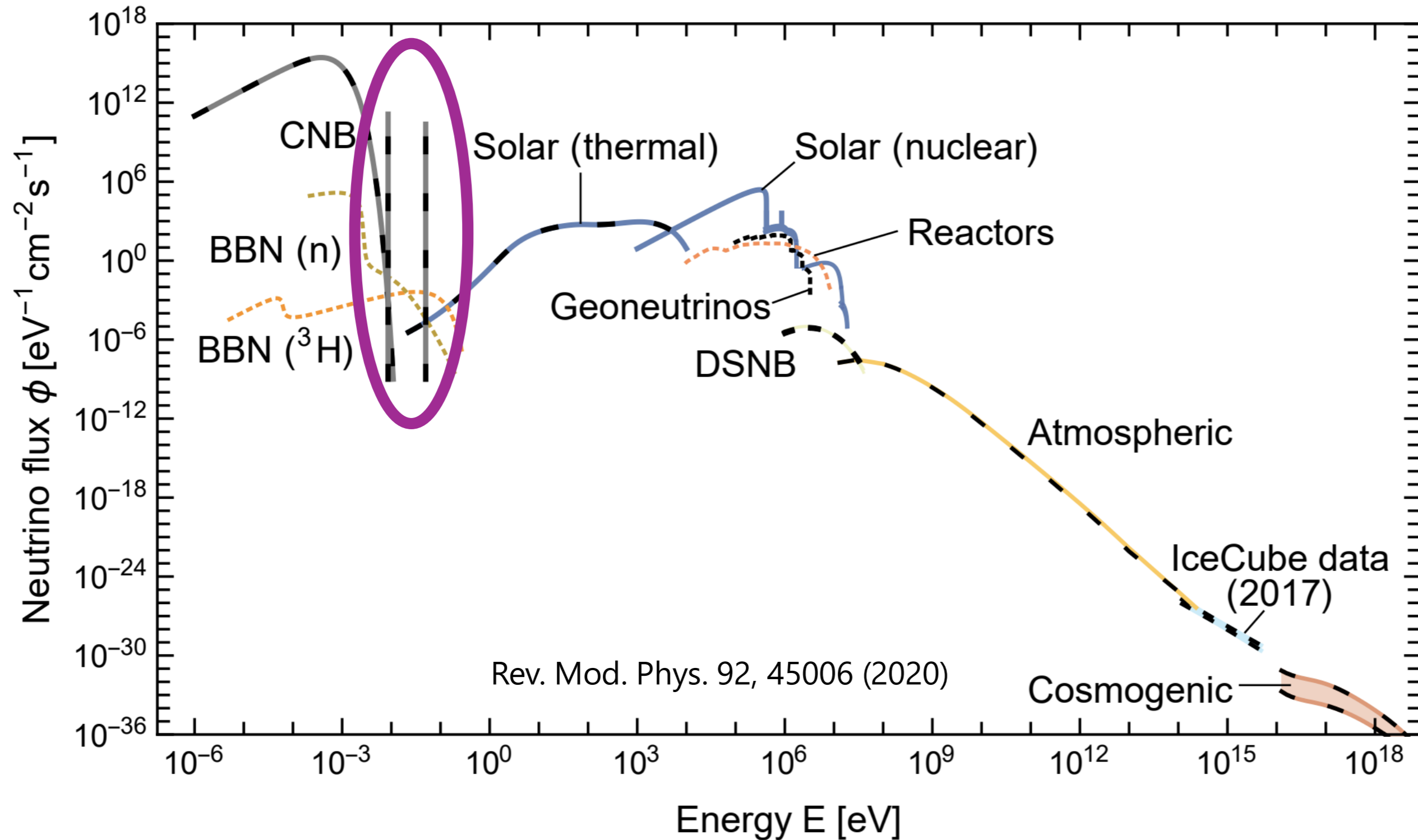


An experiment called Ptolemy is looking for CNB neutrinos by looking for inverse beta decay on tritium

Signal is an electron with higher energy than electrons from tritium beta decay

Unlike with free protons, there is no neutrino energy threshold for inverse beta decay on tritium

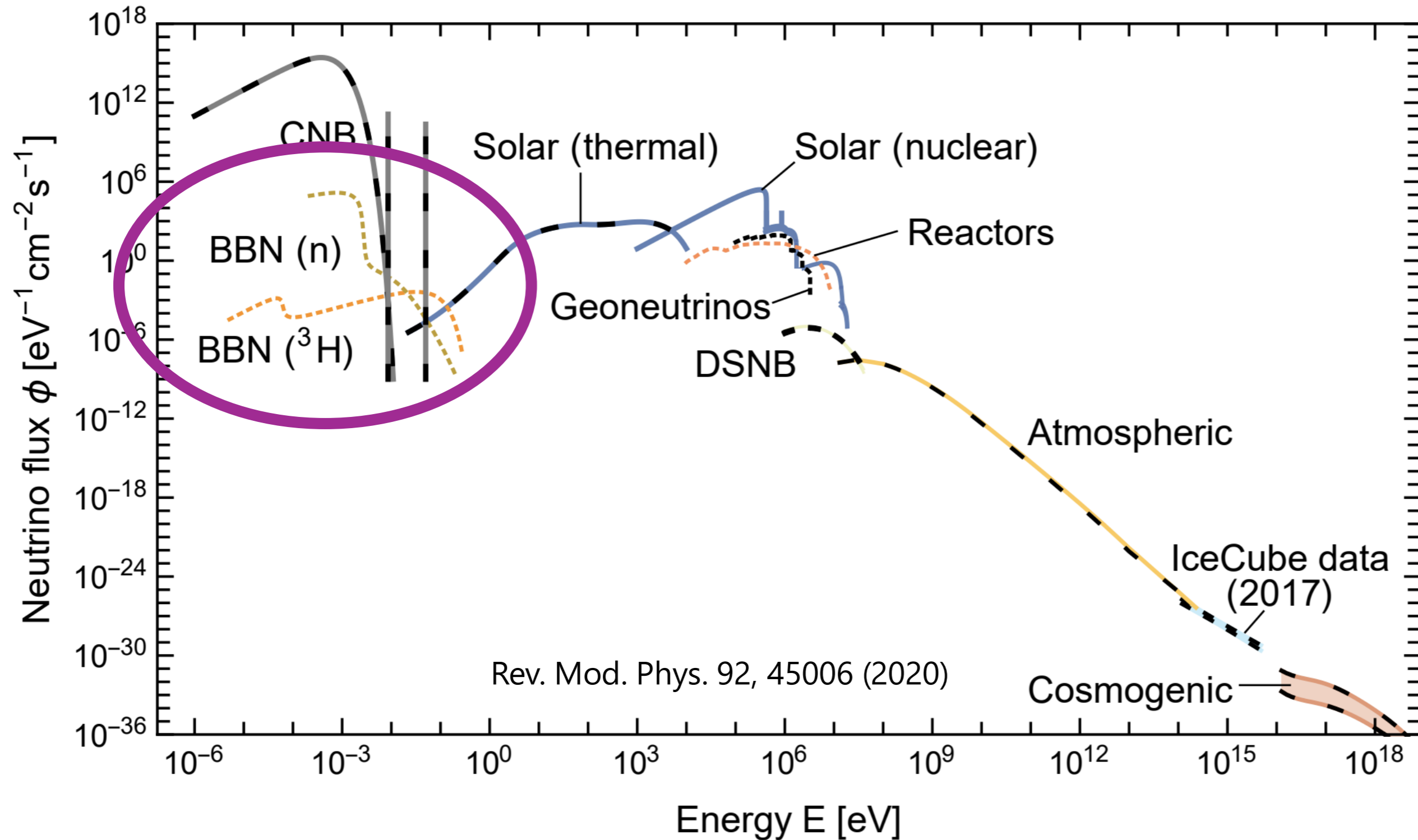
CNB Flux Structure



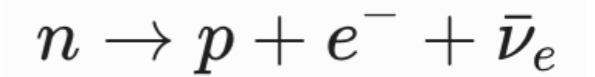
The predicted CNB flux has a funny structure, with two vertical lines around 8.6 and 50 MeV

These are the two higher neutrino mass states (ν_2 and ν_3). Because their mass is higher than that mean CNB energy, their mass dominates their energy and they are not relativistic.

More Big Bang Neutrinos



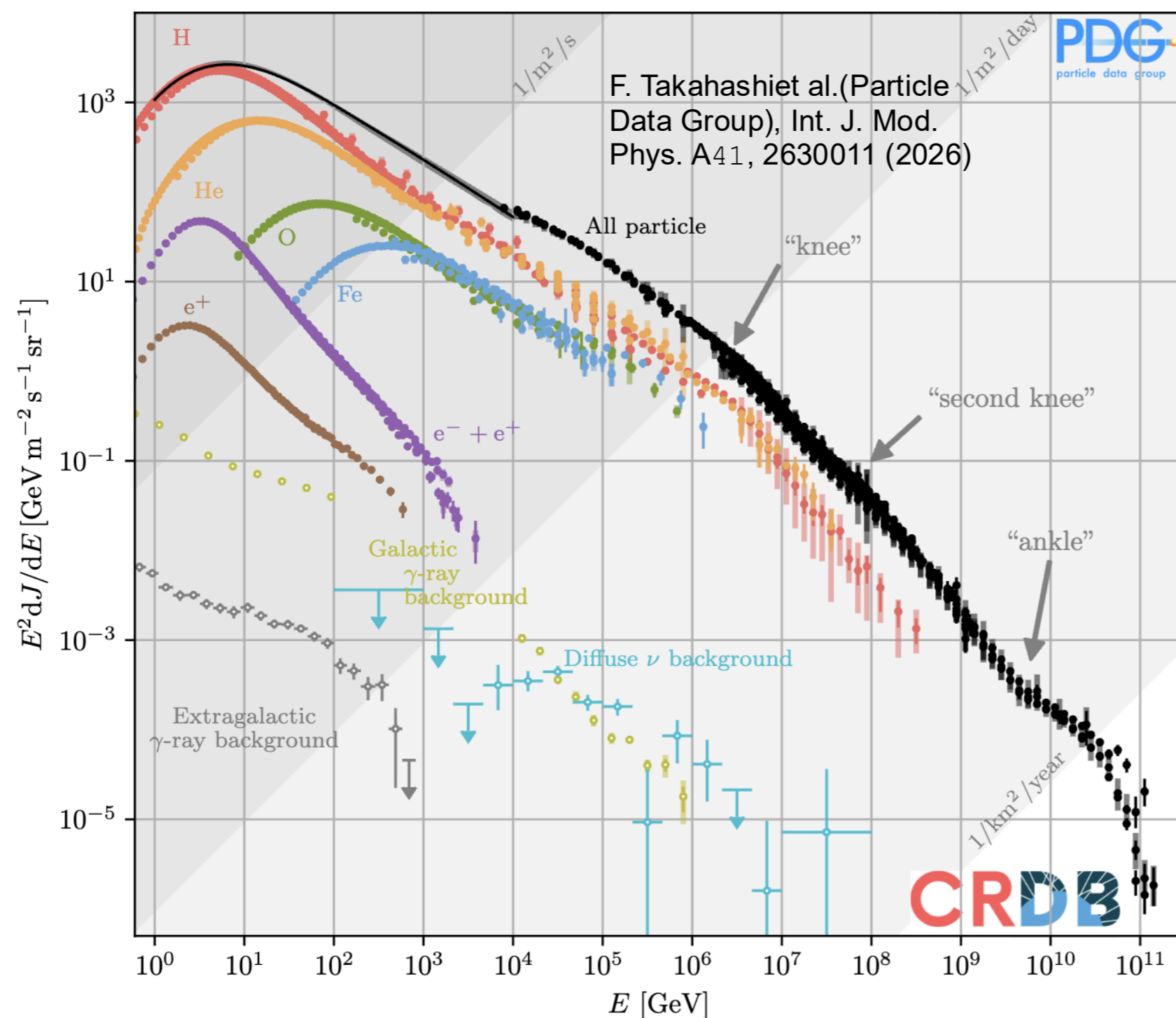
After big bang neutrinos decoupled, additional neutrinos were produced during big bang nucleosynthesis



Atmospheric Neutrinos

A view of Earth from space, showing the curvature of the planet, the blue atmosphere, and white clouds. The sun is visible on the left, creating a bright glow and lens flare. The title 'Atmospheric Neutrinos' is overlaid in white text in the upper center.

Atmospheric Neutrinos

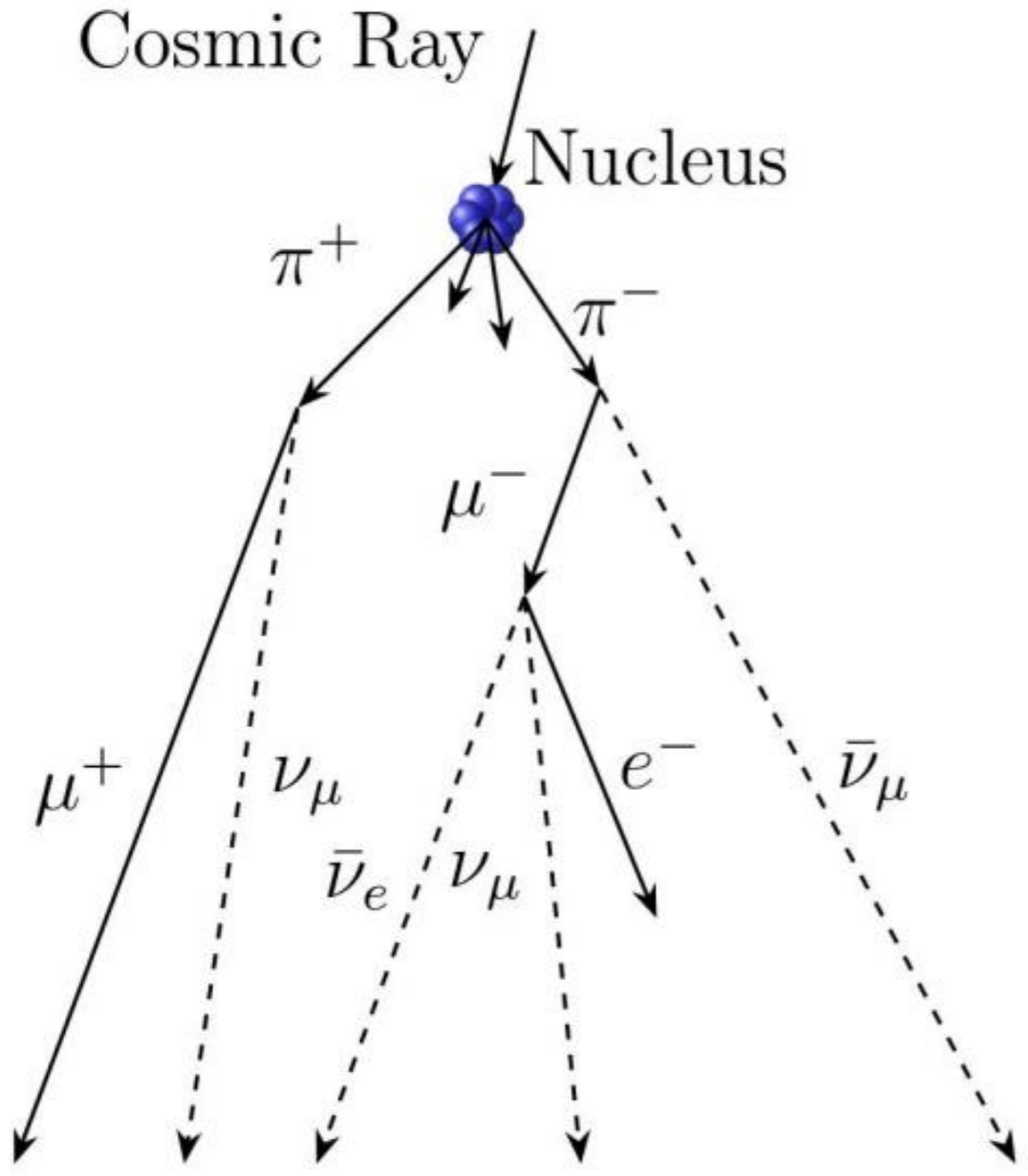


Atmospheric neutrinos are created by cosmic rays striking the Earth's atmosphere

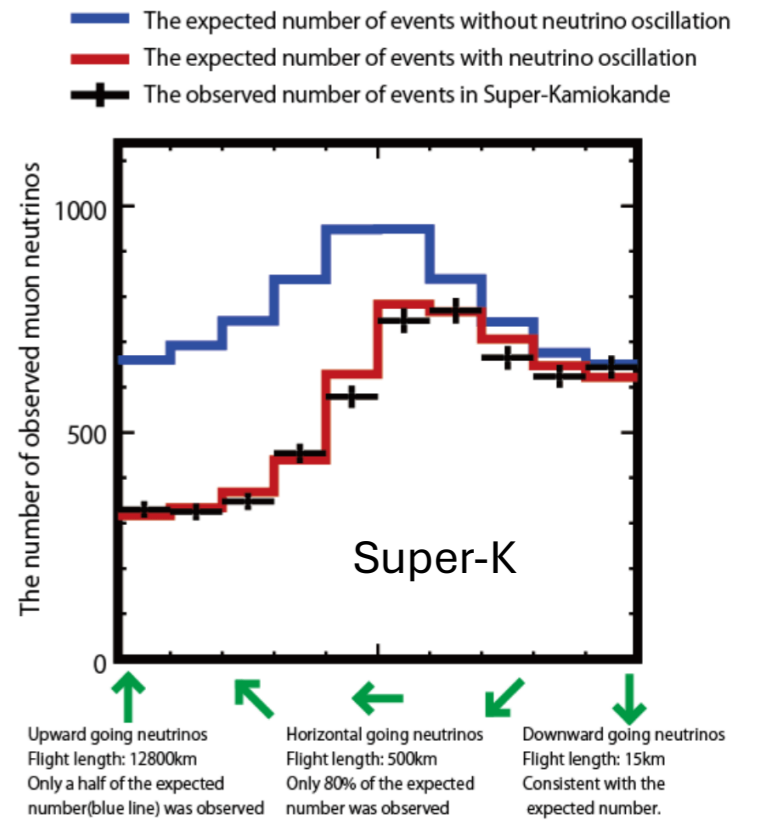
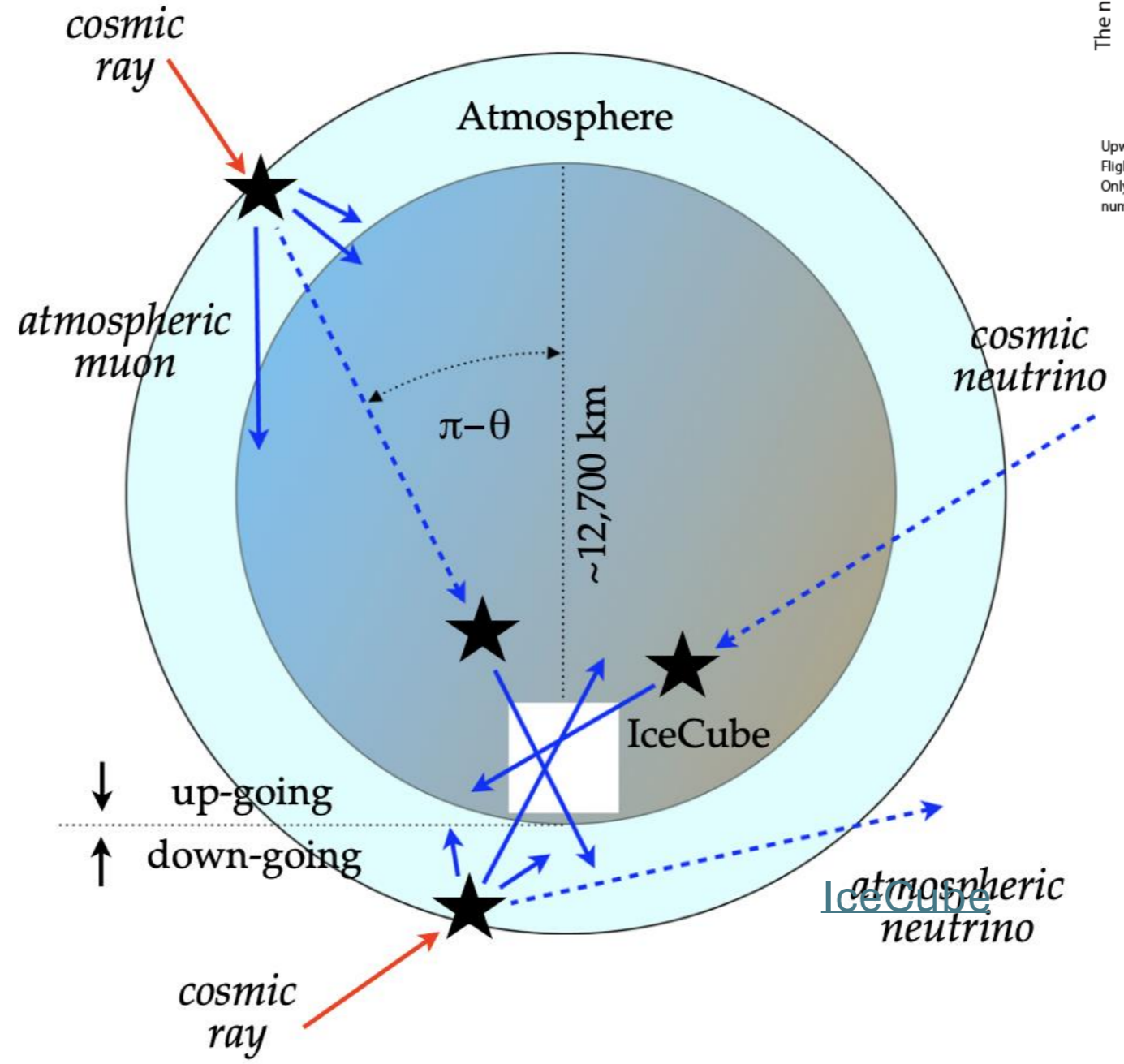
Cosmic rays are made up of many different nuclei and particles

But primarily protons and other nuclei

Atmospheric Neutrinos

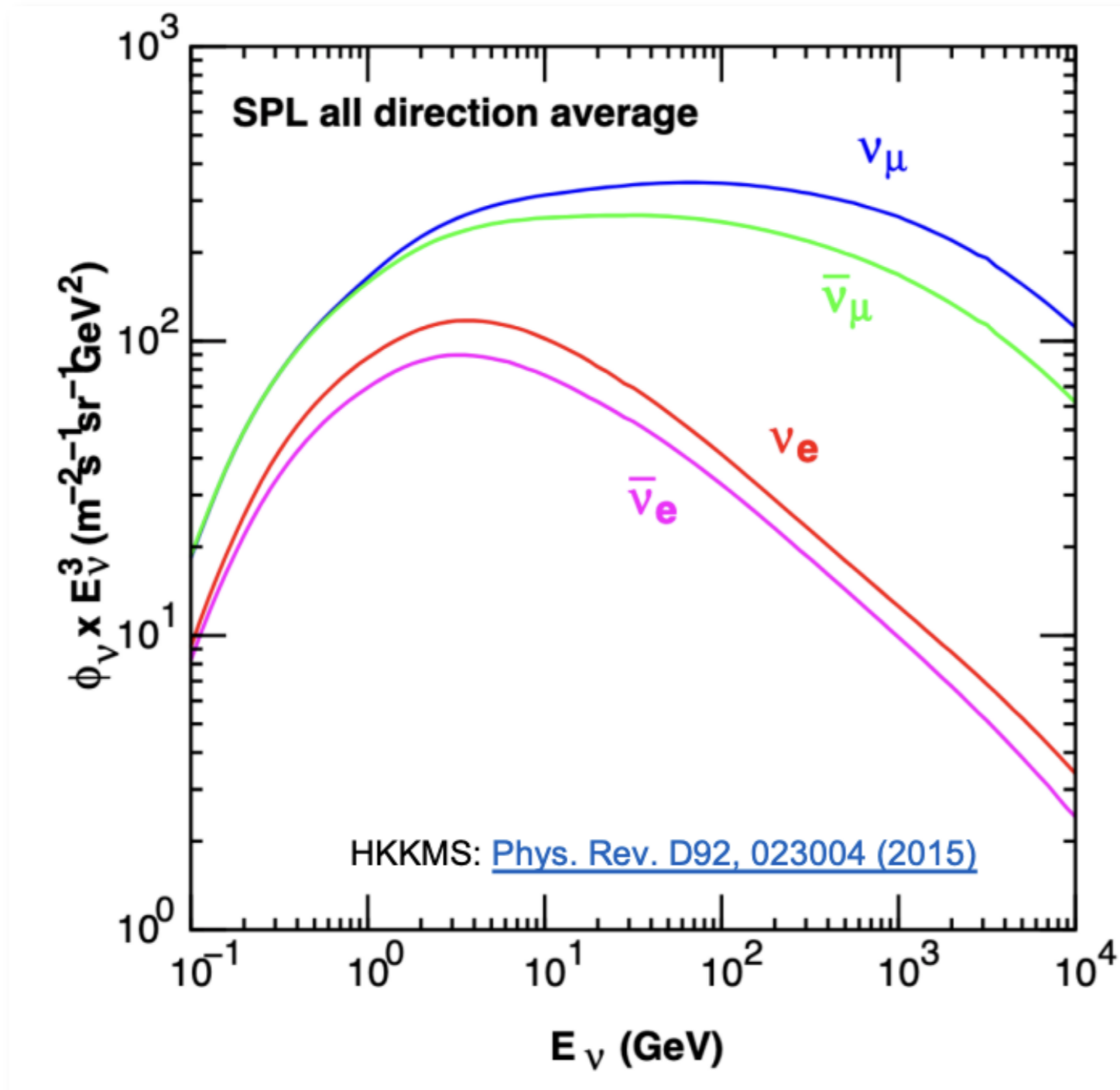


Marcelo Ismerio Oliveira [NuFlux](#)



<https://www-sk.icrr.u-tokyo.ac.jp/en/sk/neutrino/kajita/vibration/>

Atmospheric Neutrinos



Atmospheric neutrinos offer one of the broadest energy ranges of all of the sources we'll be talking about this week

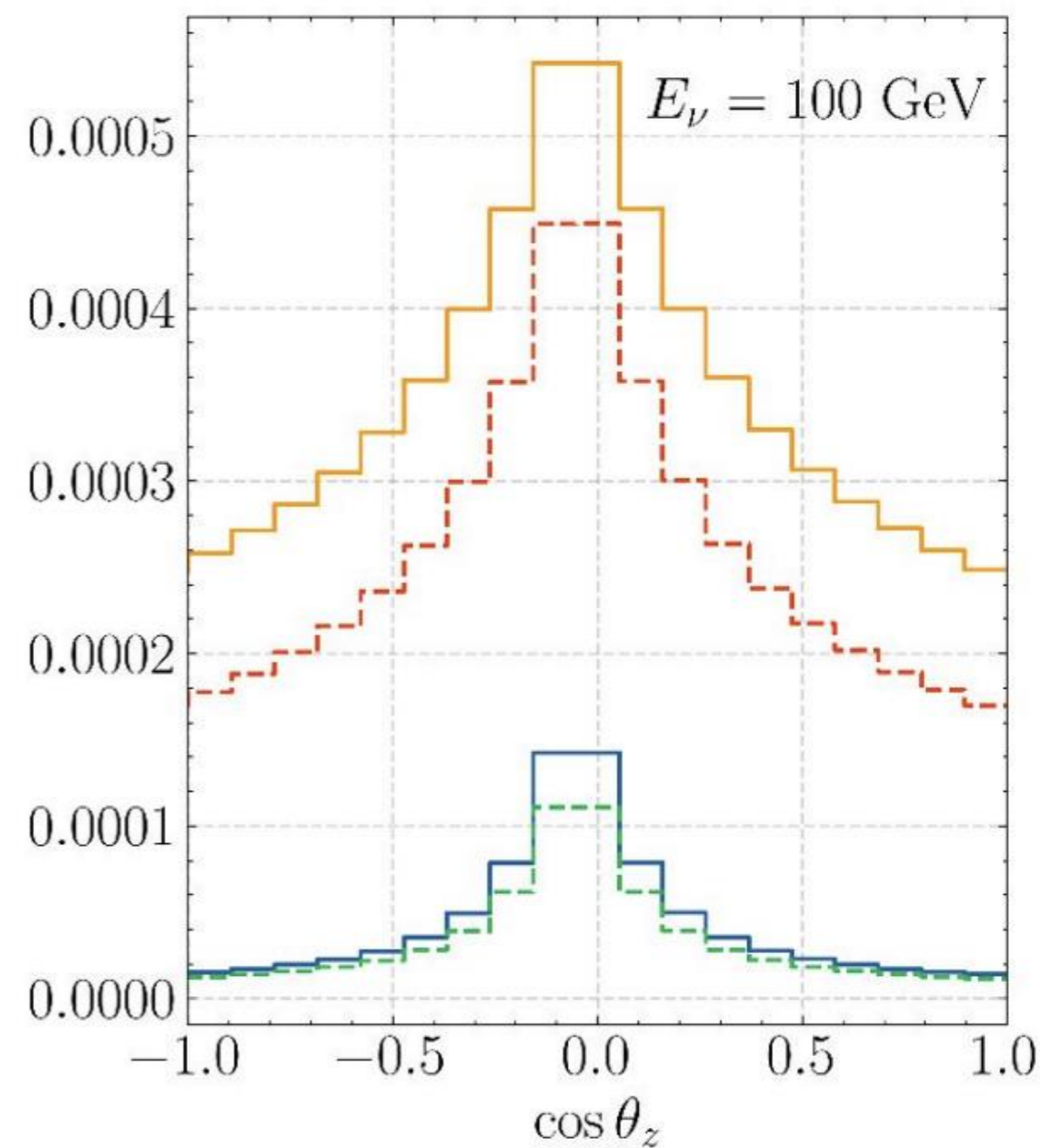
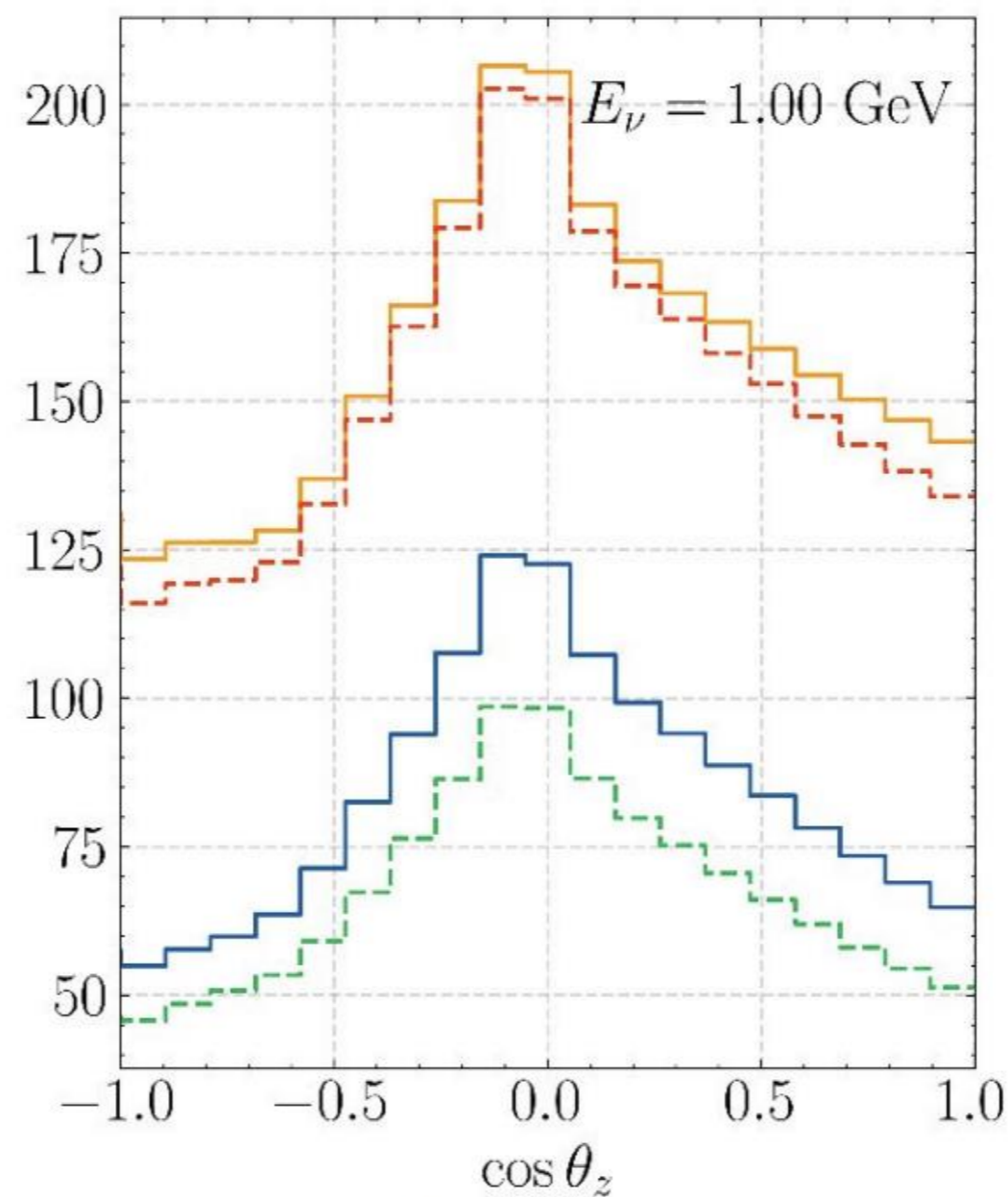
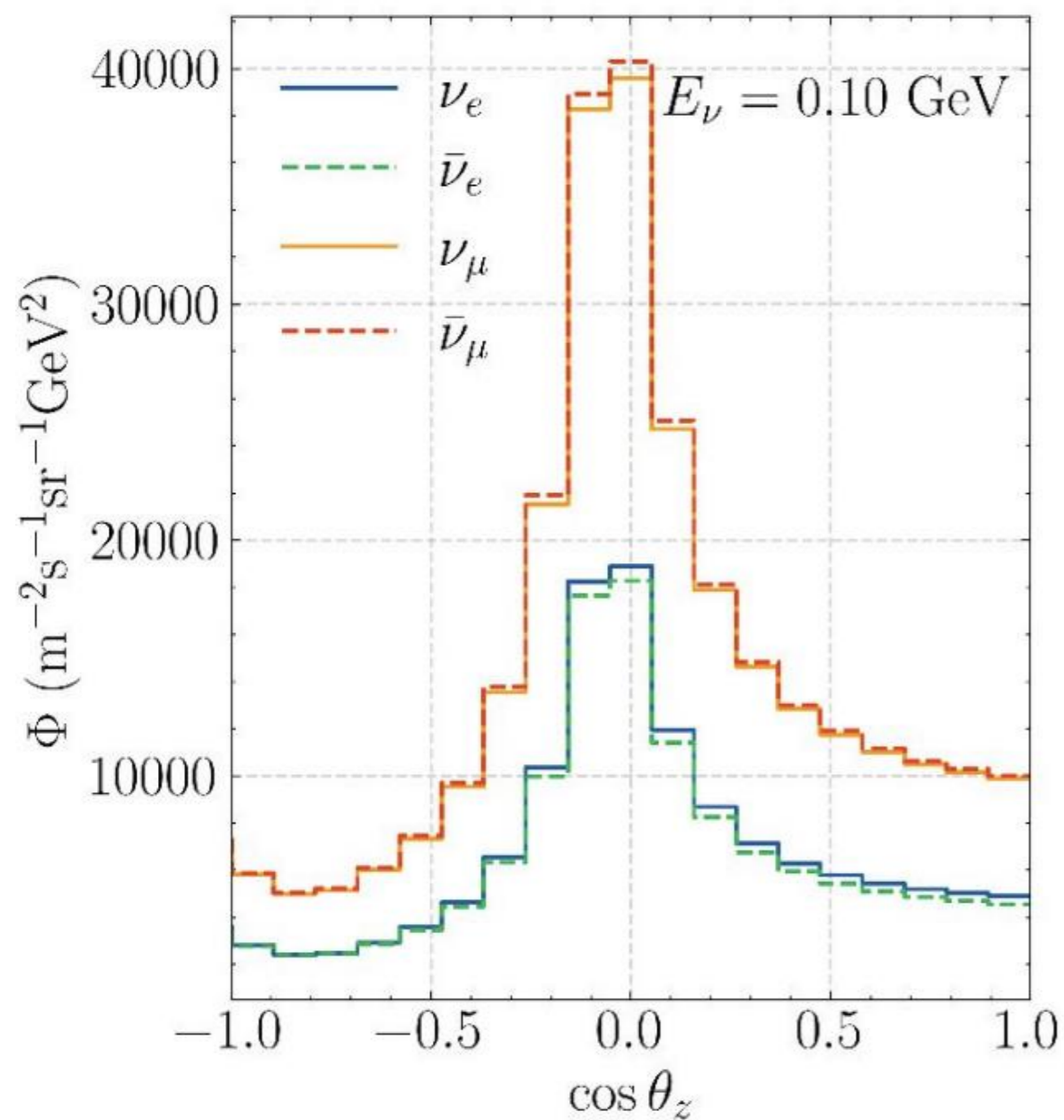
Primarily made of muon neutrinos, muon antineutrinos, with smaller electron (anti) neutrino component

Also a small tau component from charm decay (not shown)

Atmospheric Neutrinos

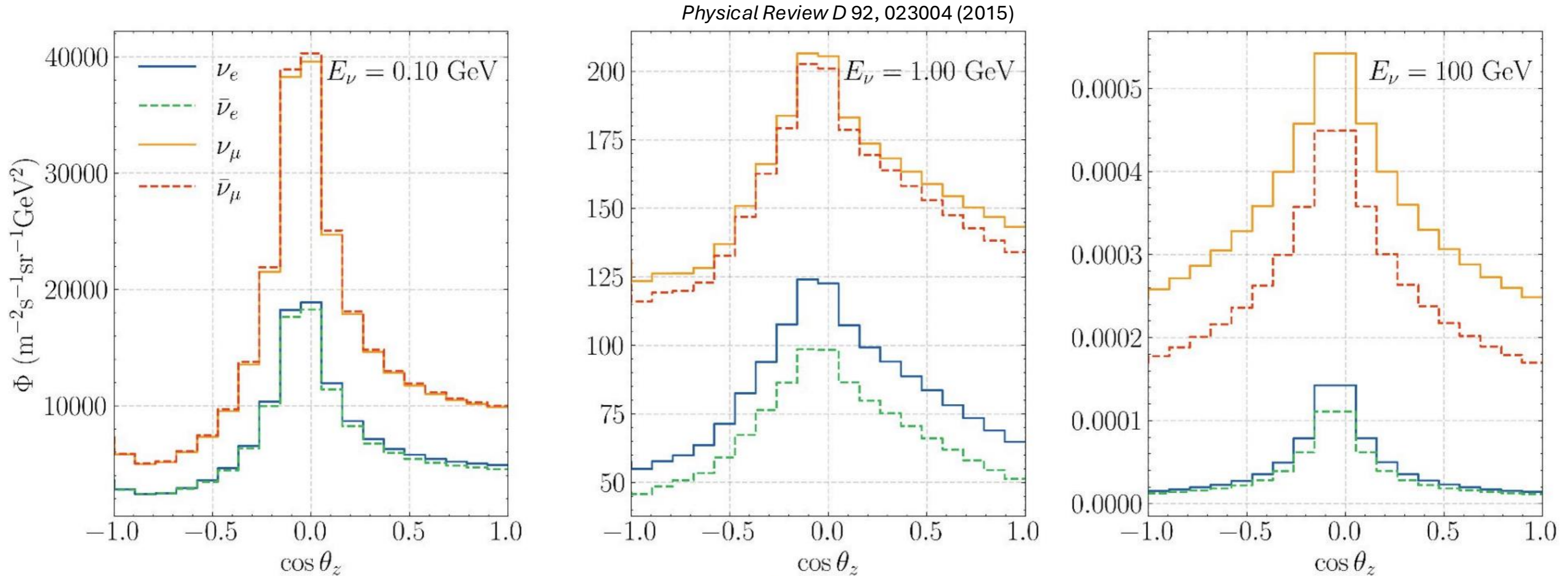


Physical Review D 92, 023004 (2015)



Flux predictions for the Honda model (HKKM 2015).

Atmospheric Neutrinos – Angular Dependence



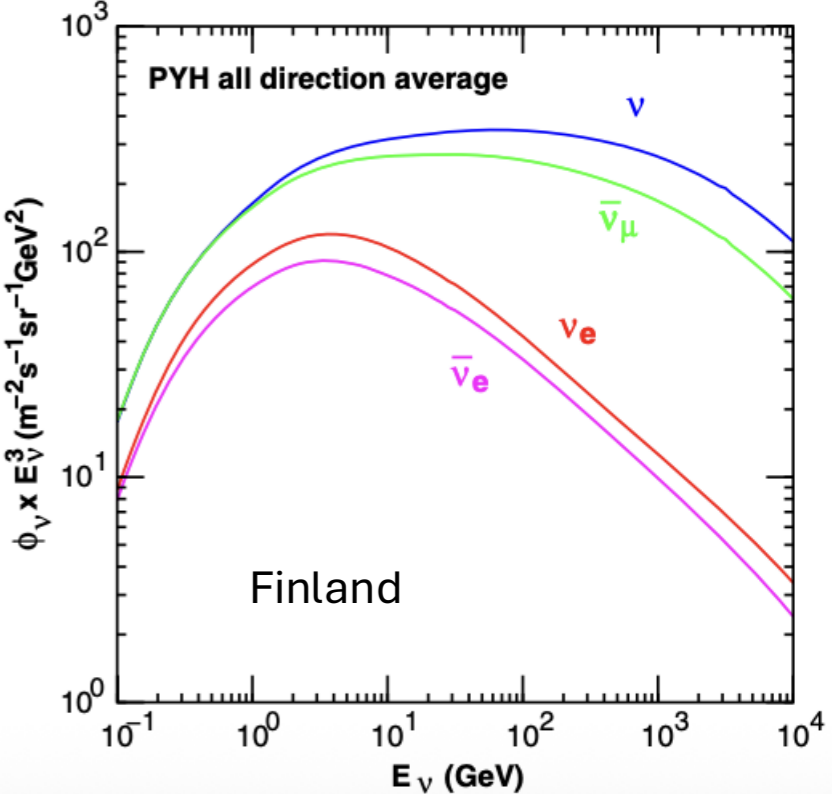
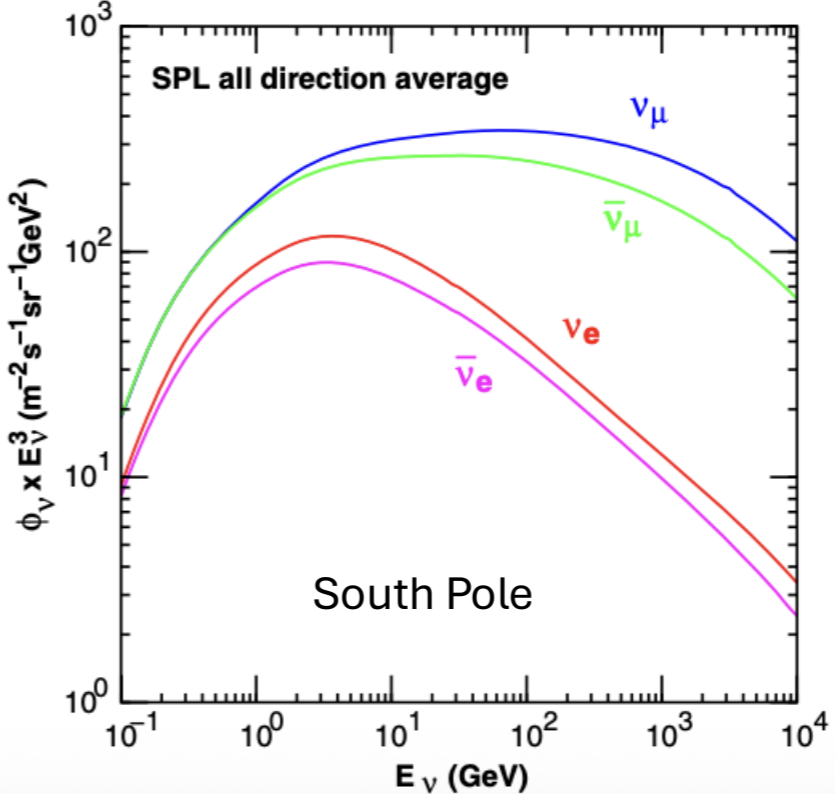
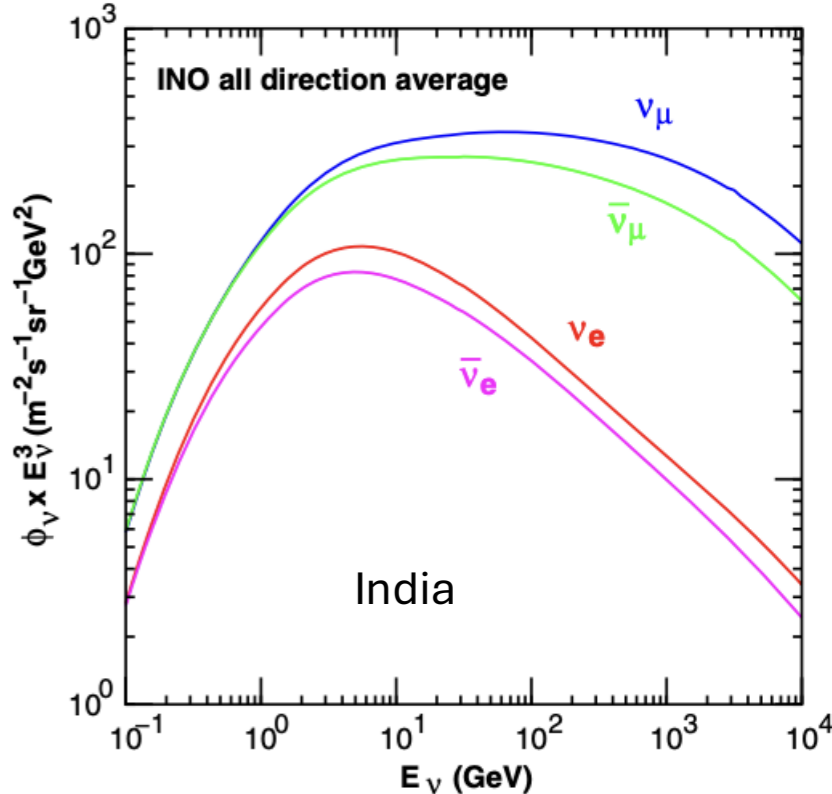
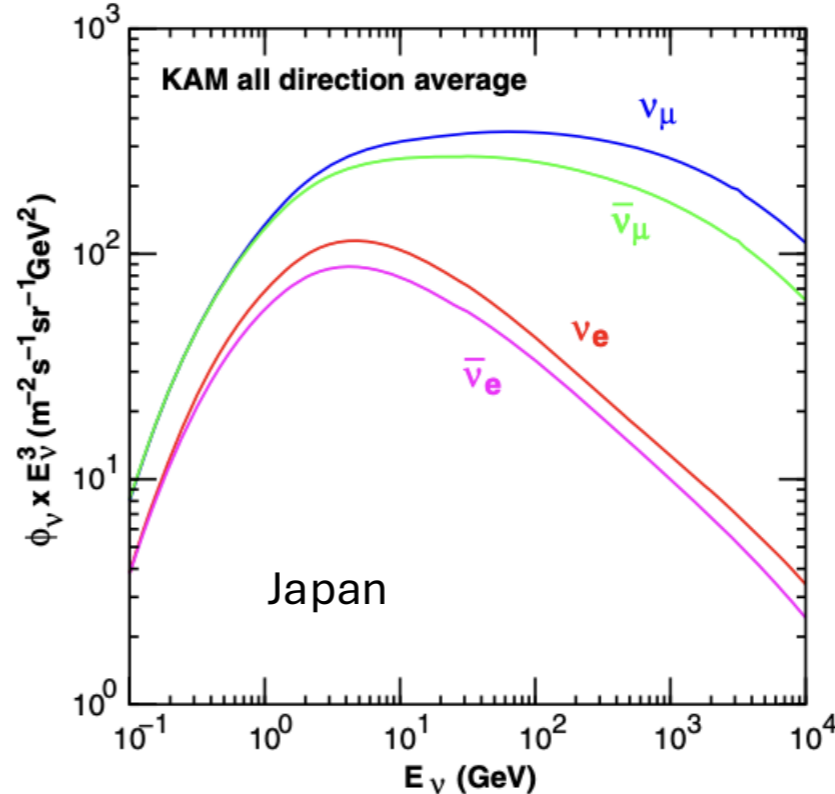
Flux predictions for the Honda model (HKKM 2015).

- Peak at $\theta_z = 0$: hadrons traveling horizontally through atmosphere have more time to decay
- Asymmetry between upward/downward going flux at low energy due to Earth's mag field
- Reduced electron neutrino flux at high energy due to strong time dilation -> less muon decay

Atmospheric Neutrinos

Atmospheric fluxes must be calculated for an individual detector location

But variations are modest



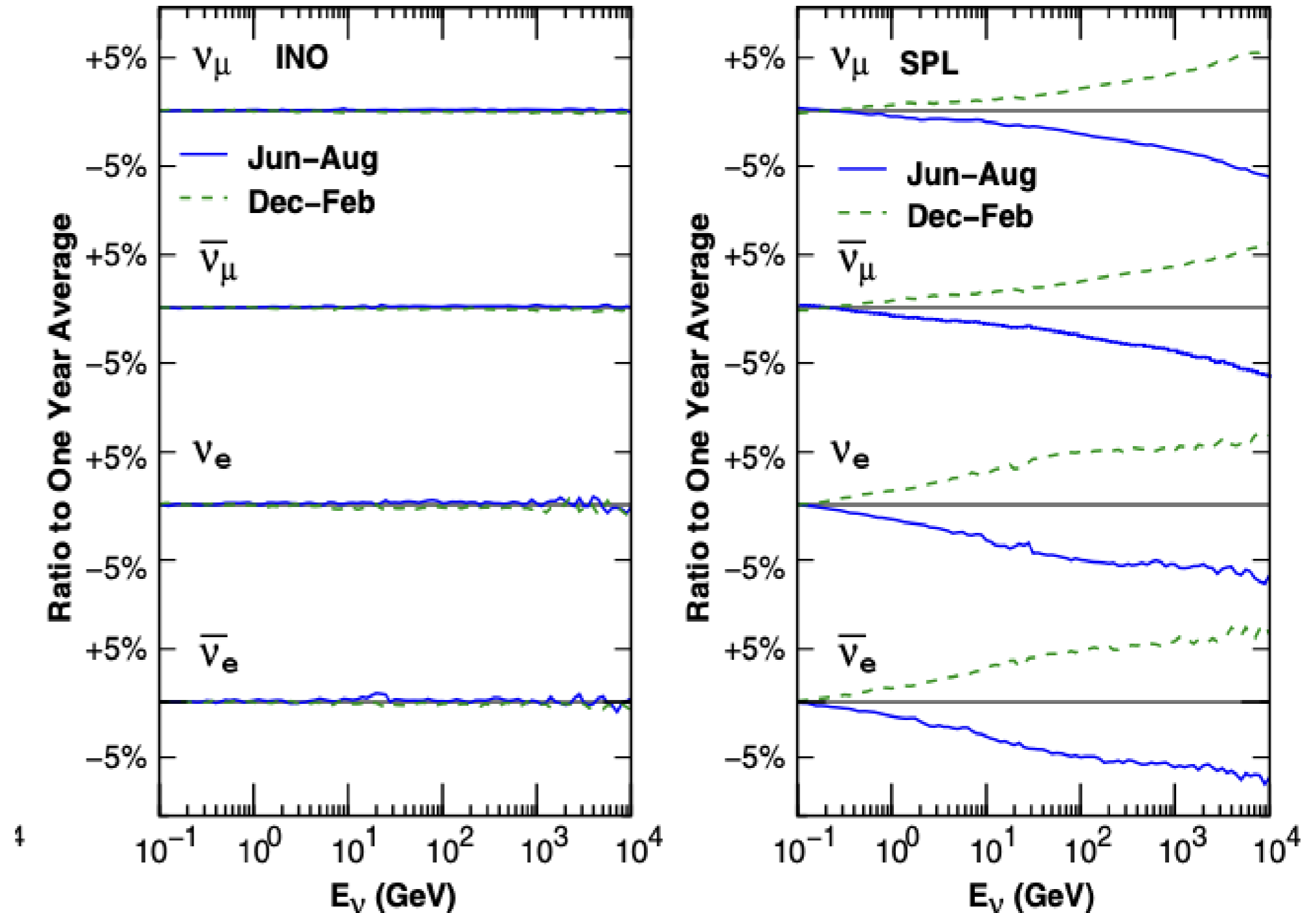
These are fluxes averaged over a year

Atmospheric Neutrinos

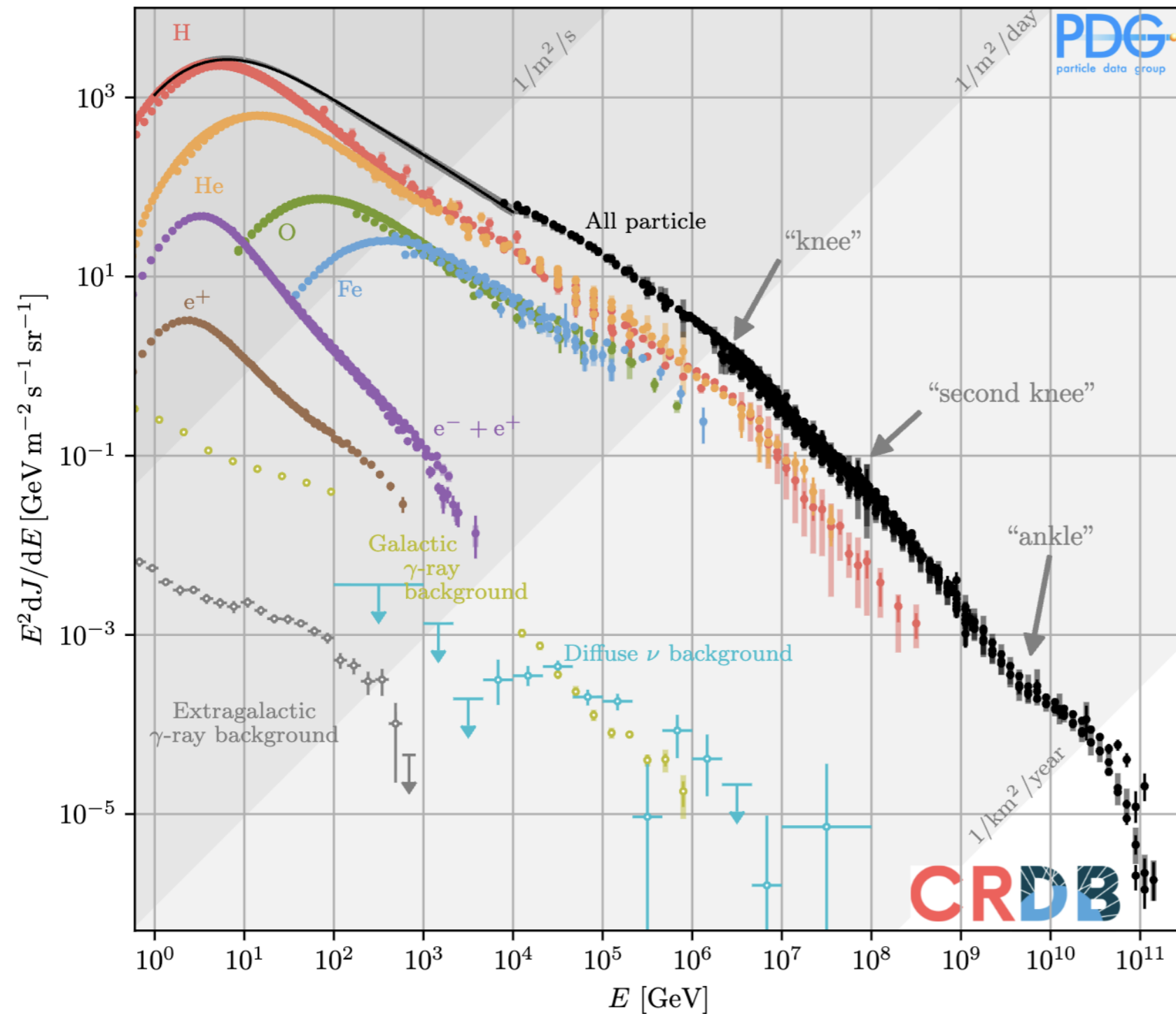
PHYSICAL REVIEW D 92, 023004 (2015)

Variations throughout the year are dependent on location.

The earth's poles see much larger variations in temperature and therefore atmospheric density than the equator.



Atmospheric Neutrinos



Uncertainties in
cosmic ray flux:

Normalization

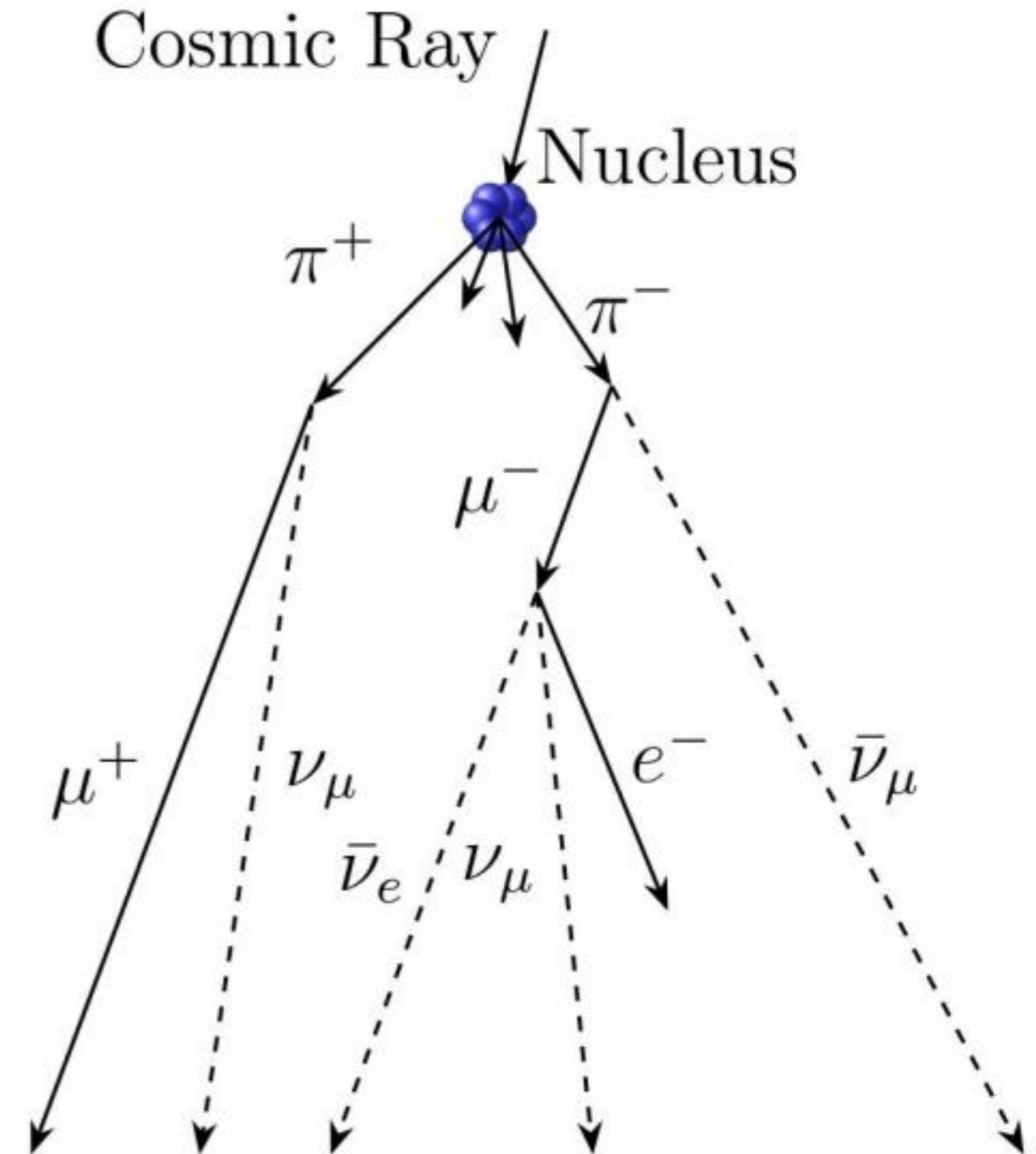
Energy spectrum

Composition

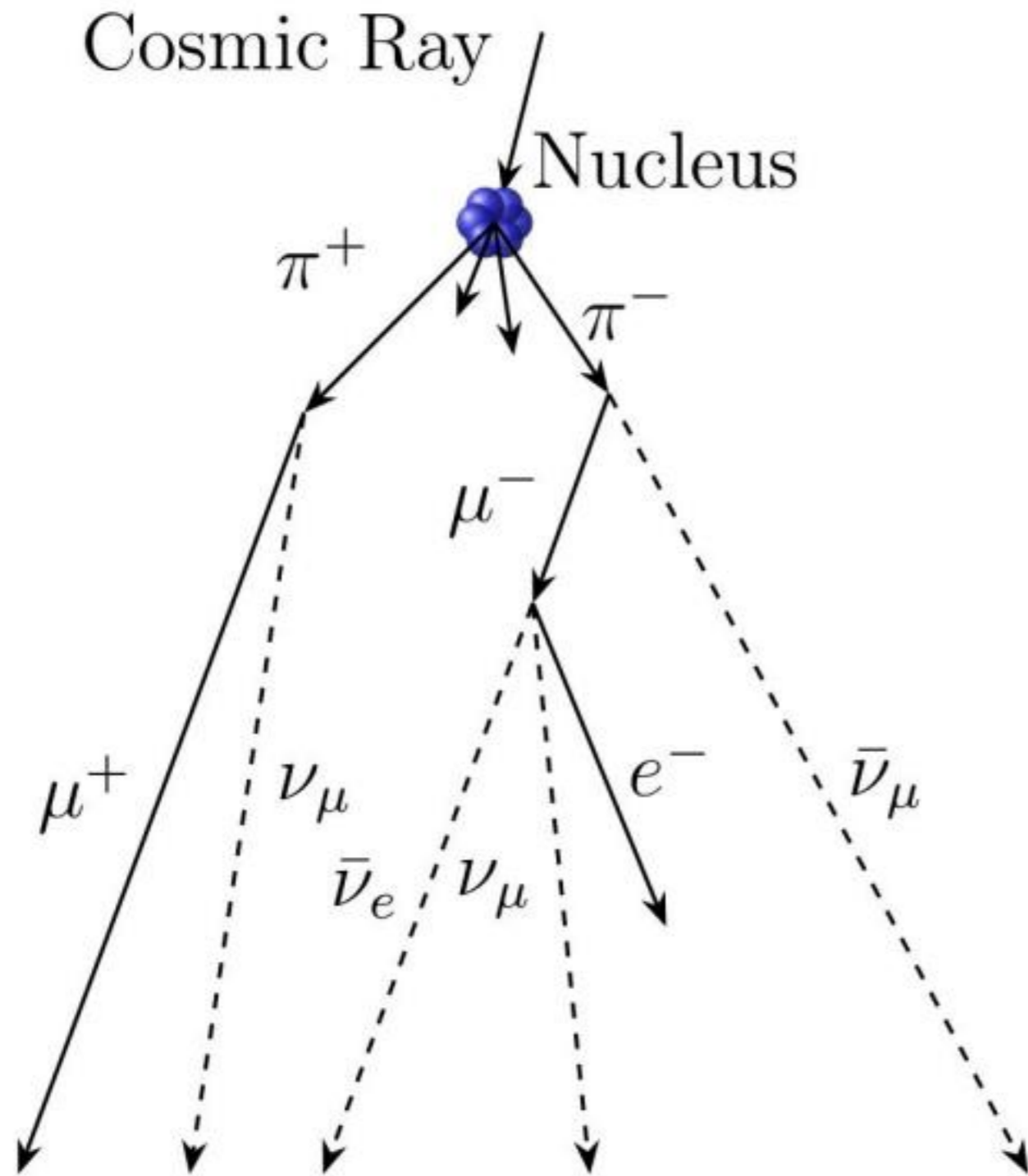
Solar modulation
(wind + magnetic
field affects flux up
to ~ 10 GeV)

Atmospheric Neutrinos

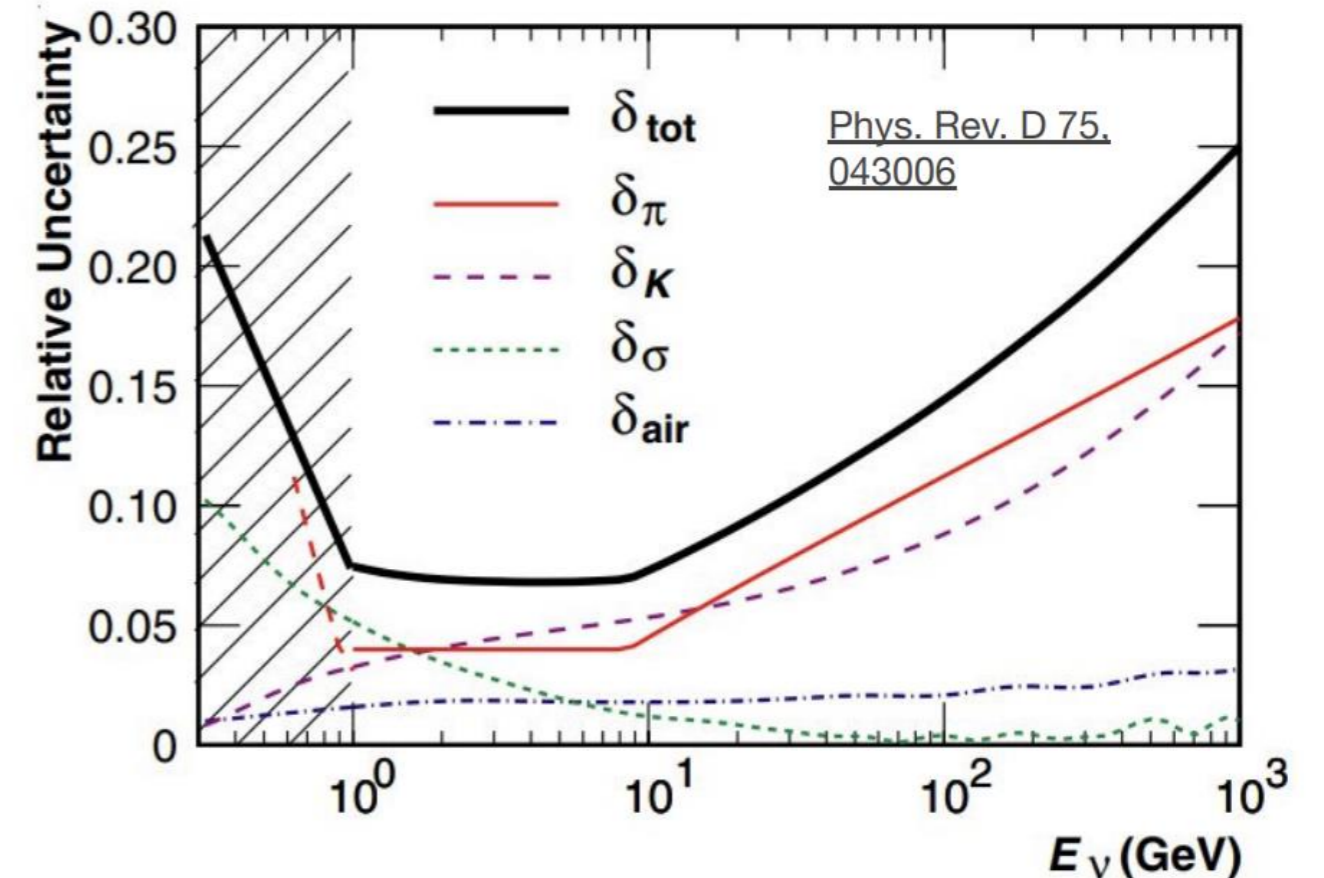
- CR/Air interaction model uncertainties:
- Hadron–air cross section
- pi/k production yields
- Atmospheric density profile
- Geomagnetic field



Atmospheric Neutrinos



- CR/Air interaction model uncertainties:
 - Hadron–air cross section
 - pi/k production yields
 - Atmospheric density profile
 - Geomagnetic field



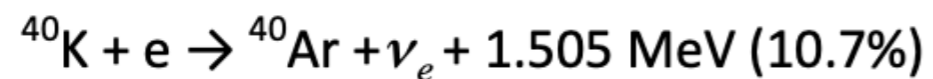
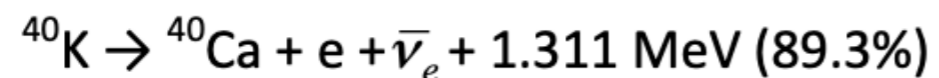
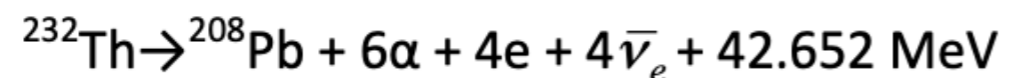
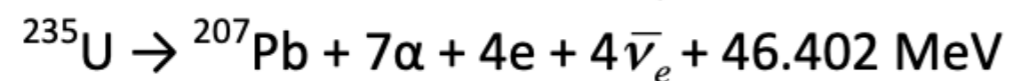
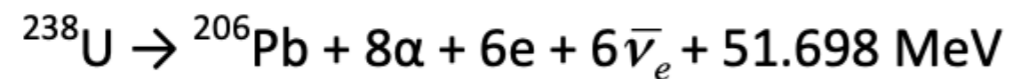
Relative uncertainty breakdown for the Honda flux model.

A satellite image of Earth showing the African continent and surrounding oceans. The text "Geo-Neutrinos" is overlaid in white. The image shows the African continent in the center, with the Atlantic Ocean to the west and the Indian Ocean to the east. The text "Geo-Neutrinos" is centered over the African continent.

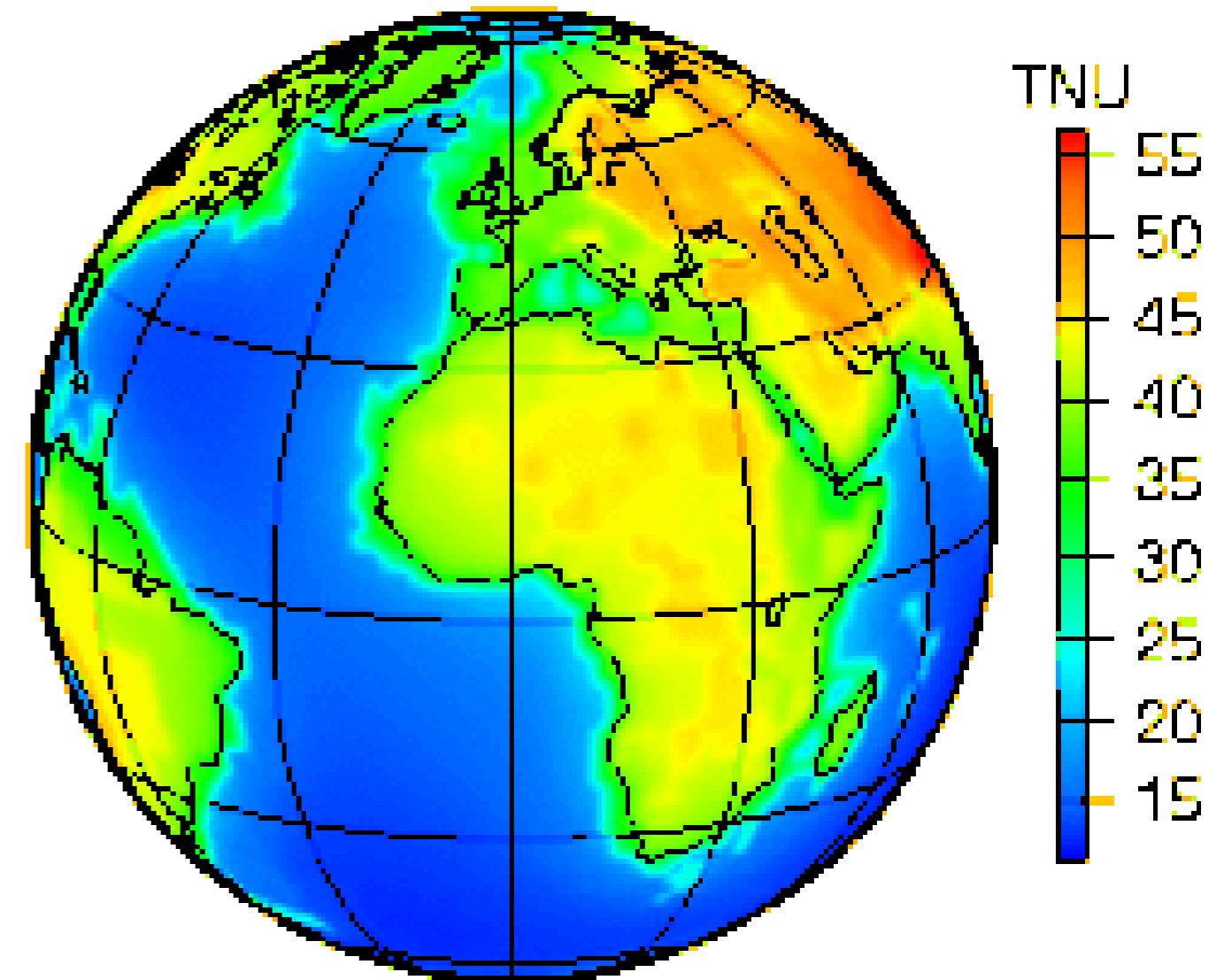
Geo-Neutrinos

Geo-Neutrinos

- Geoneutrinos are generated in radioactive decay chains inside the earth

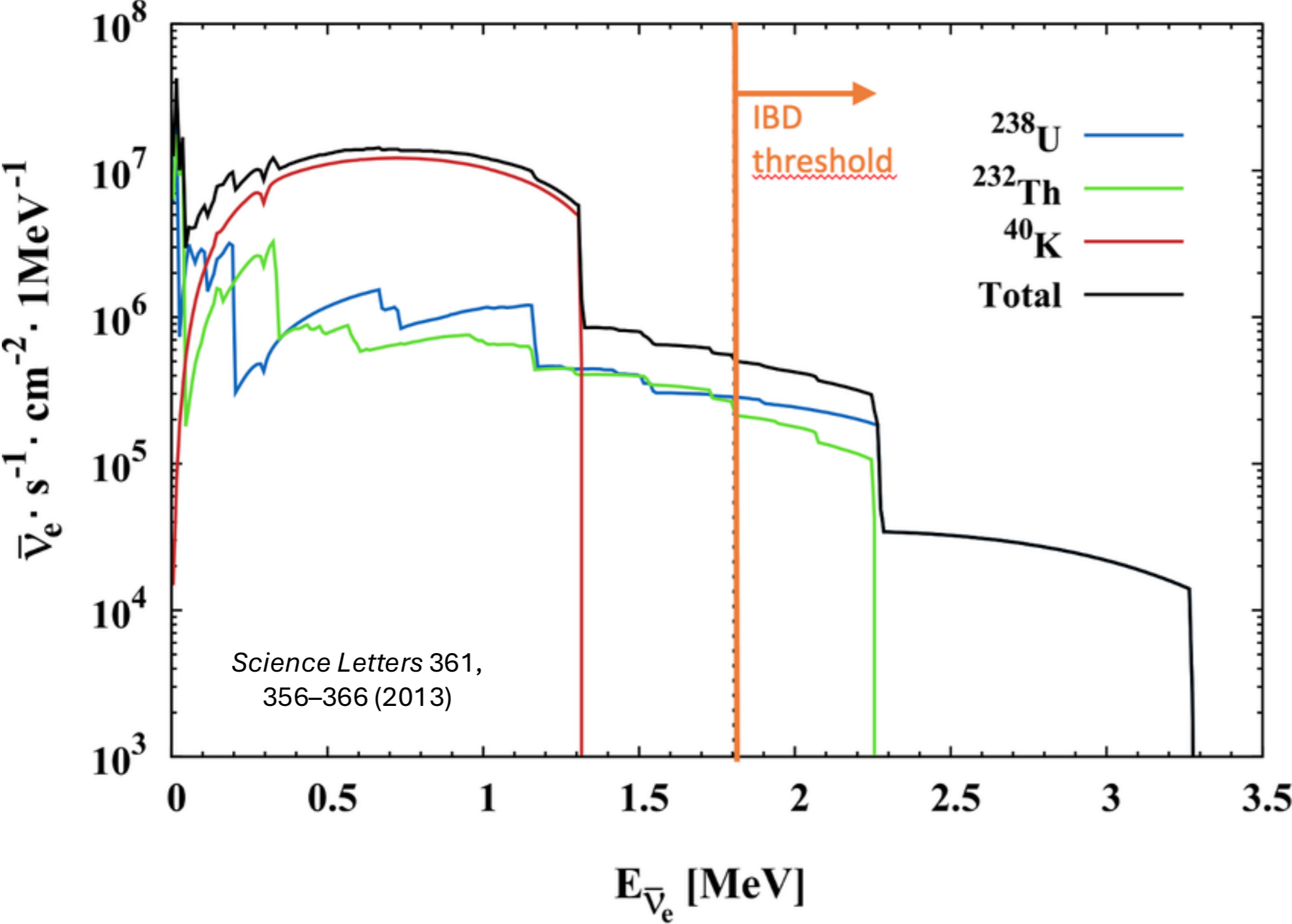


- Within those chains, the geoneutrinos are created through beta decay processes
- Continental crust is enriched with these elements, so high geoneutrino flux correlates with continents



Wikimedia

Geo-Neutrinos



- Geoneutrinos are primarily electron antineutrinos

Geo-Neutrinos

- Geoneutrinos have been observed by KamLAND, Borexino, and SNO+
- Provided constraints on what fraction of the Earth's total heat output is due to radioactive decay vs primordial heat from the formation of Earth (answer: a little less than half radioactive)
- What to look forward to: Massive statistics from JUNO, underwater detection, direction detection, low energy detection (not with IBD)

