Astrophysical Neutrinos

elusive and powerful probes of the Universe

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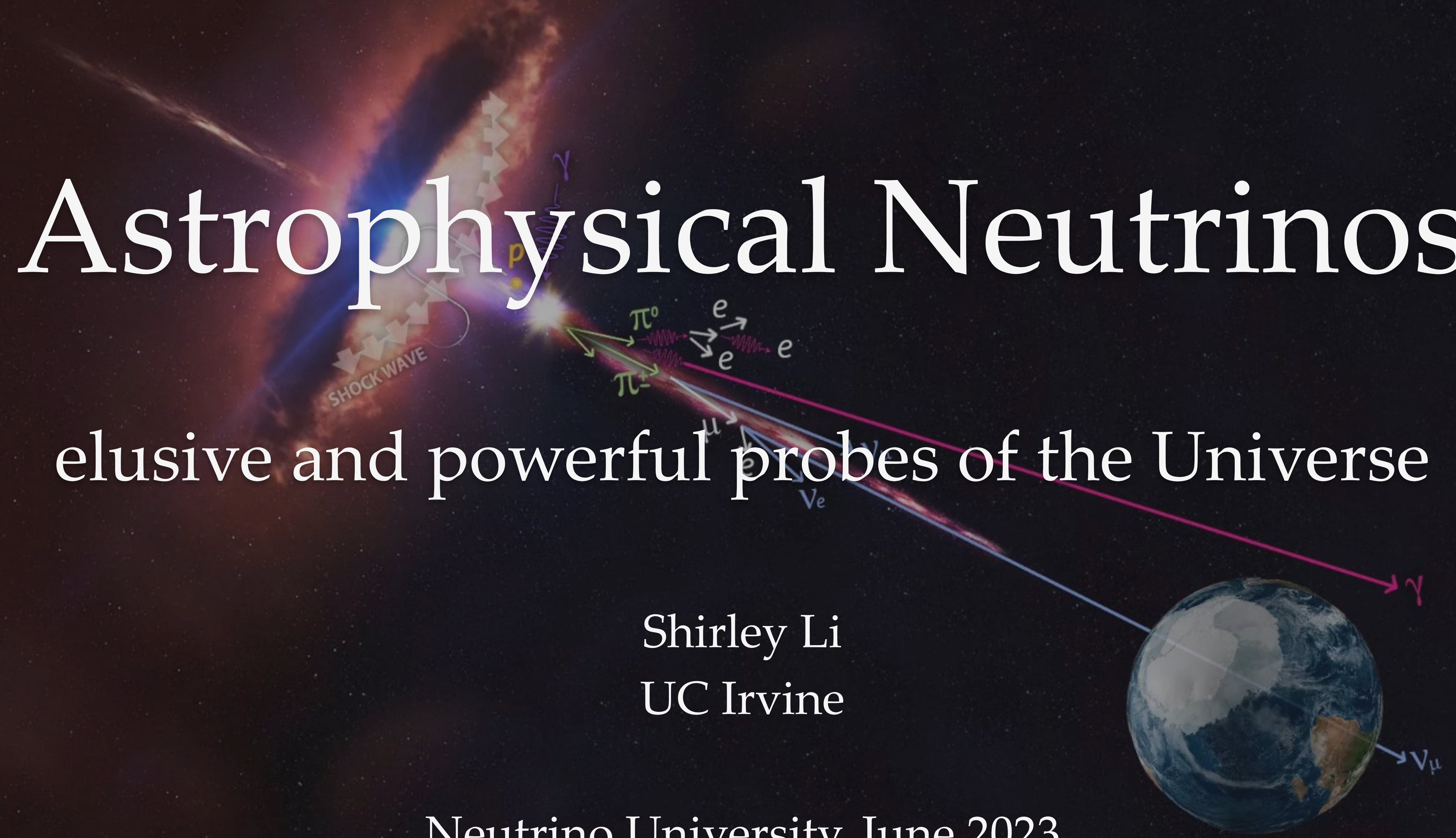
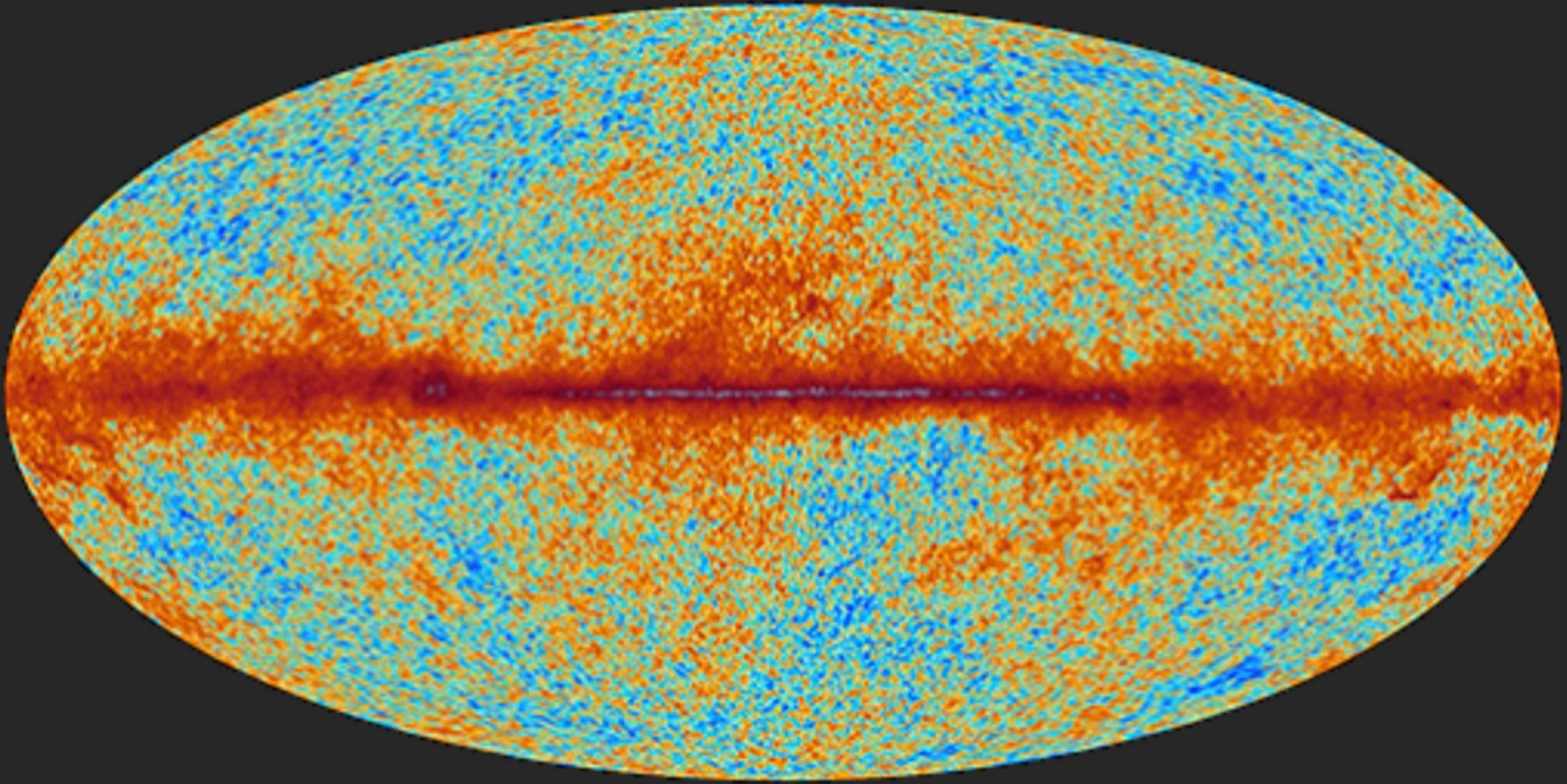
UC Irvine

Neutrino University, June 2023

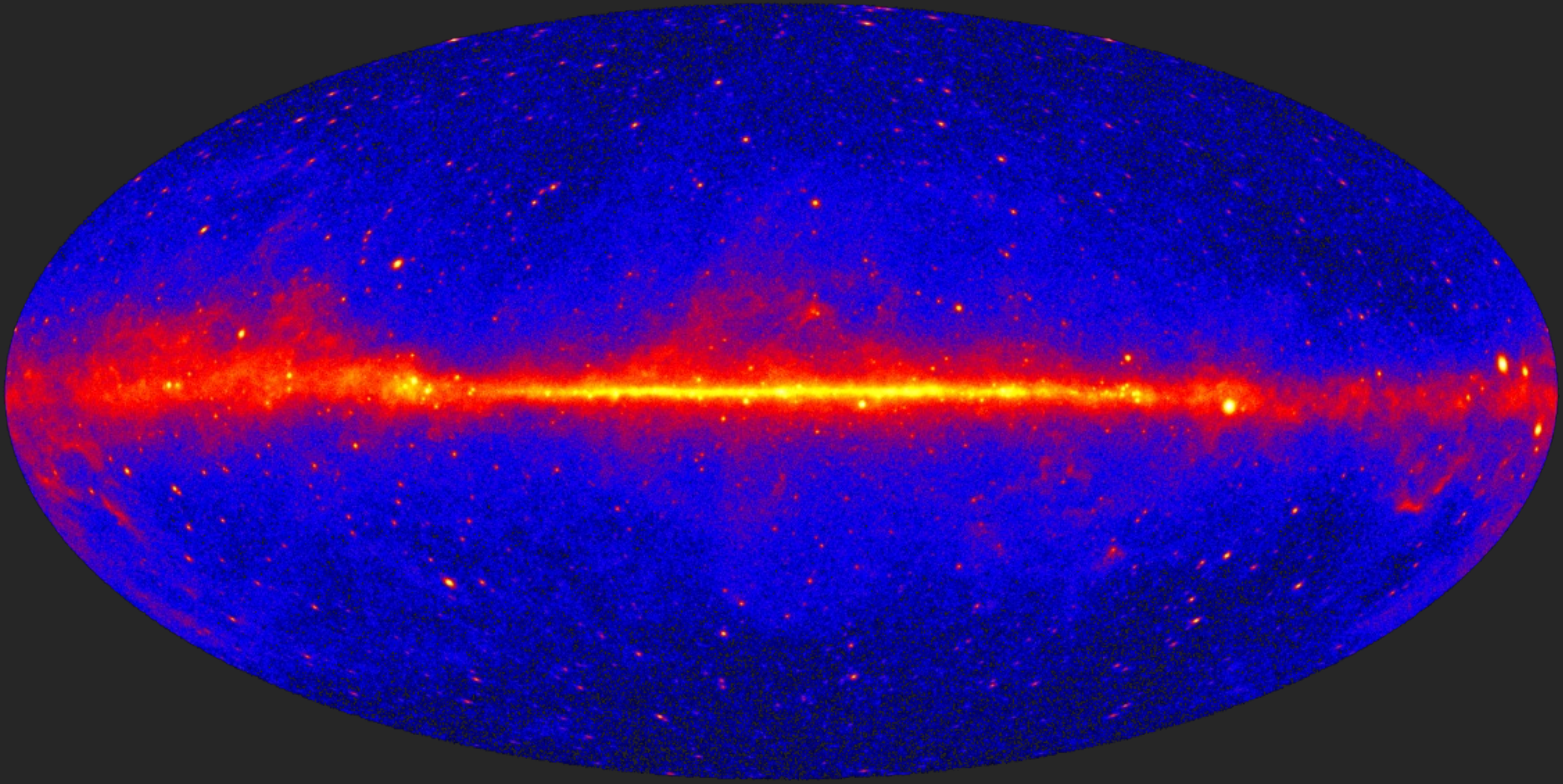


The Optical Sky

The Microwave Sky

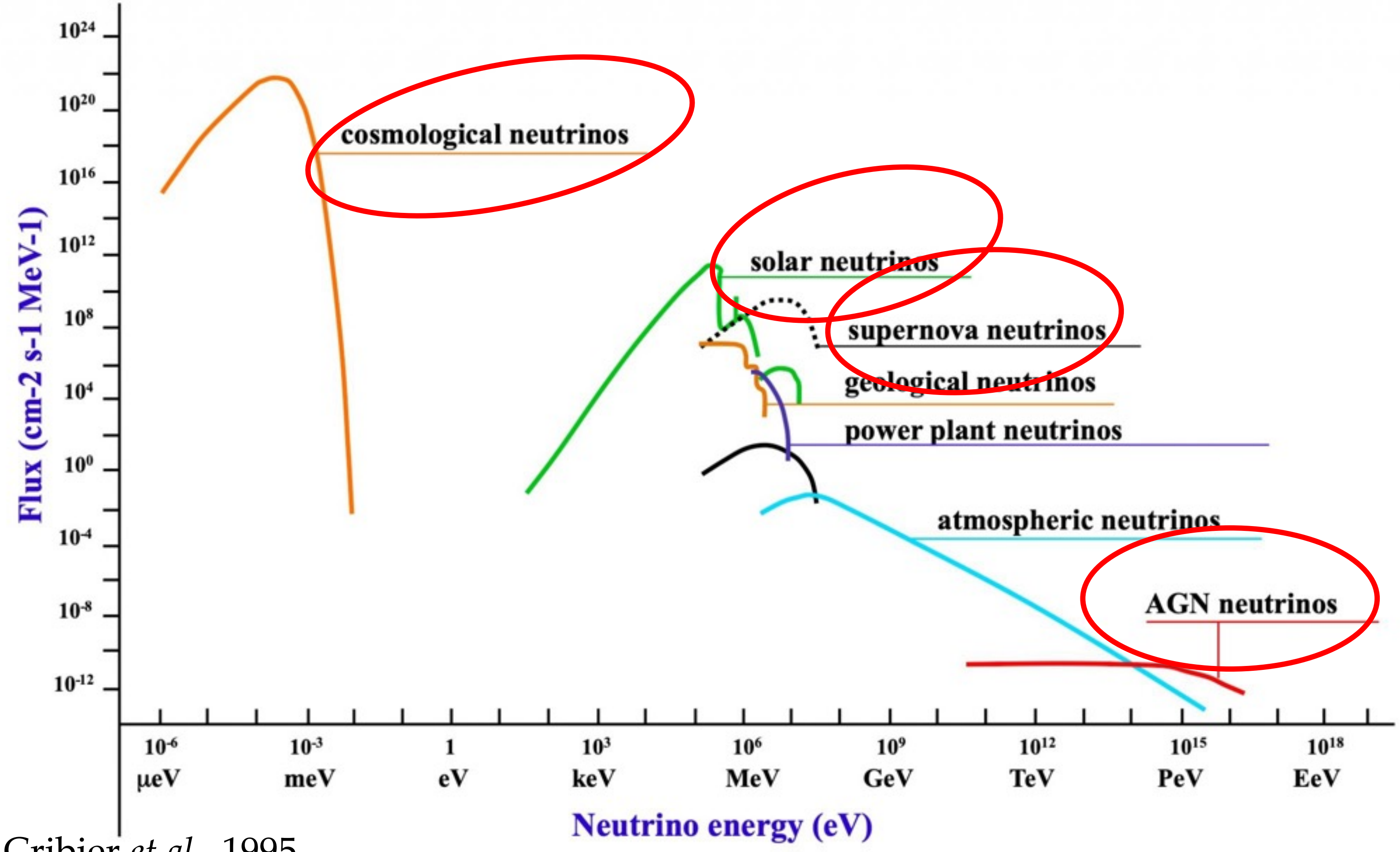


The Gamma Ray Sky



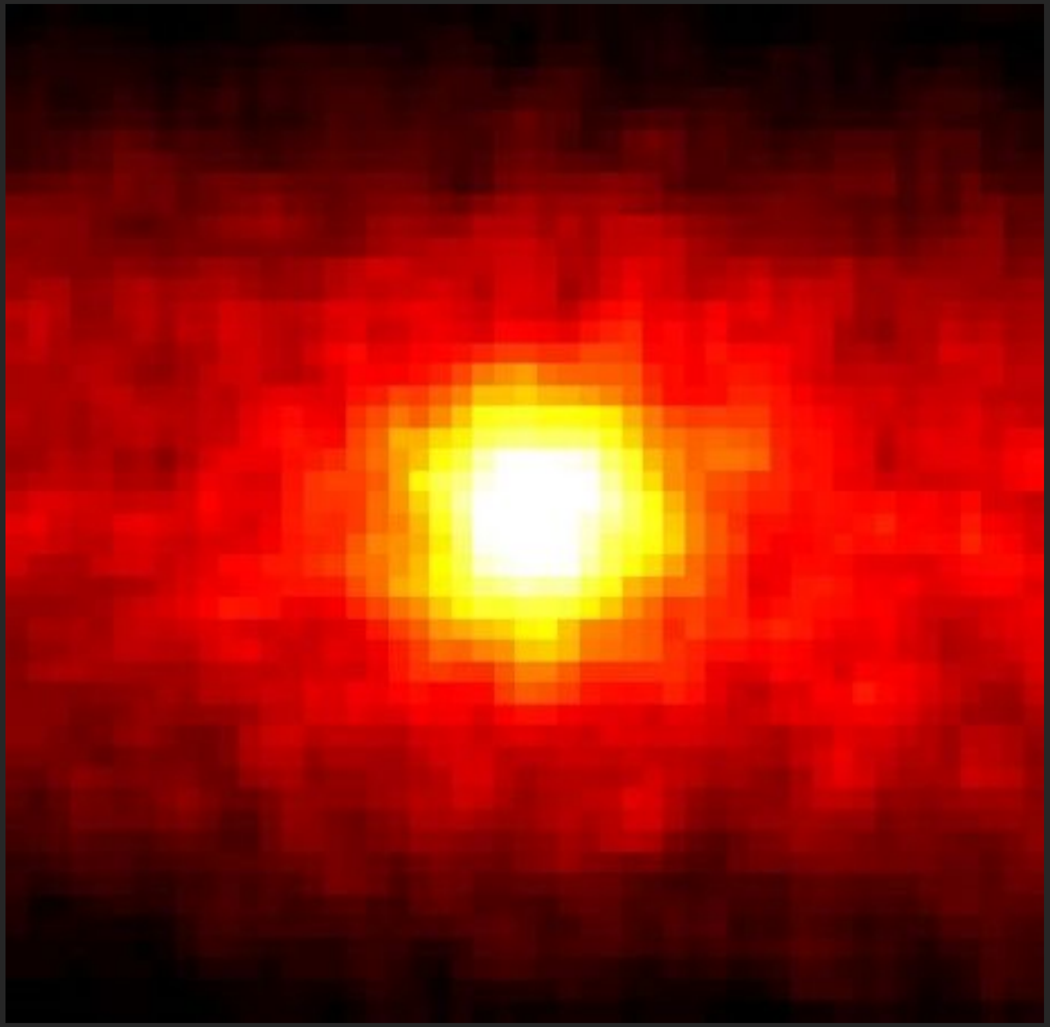
The Neutrino Sky?

The Neutrino Sky



Cribier *et al.*, 1995

Neutrinos from Hot, Dense Environments



For example…

the core of the Sun:

temperature: 27 million degrees F

density: 160 g/cm^3

$p + p \rightarrow 2\text{He} + e^{+} + \nu_e$

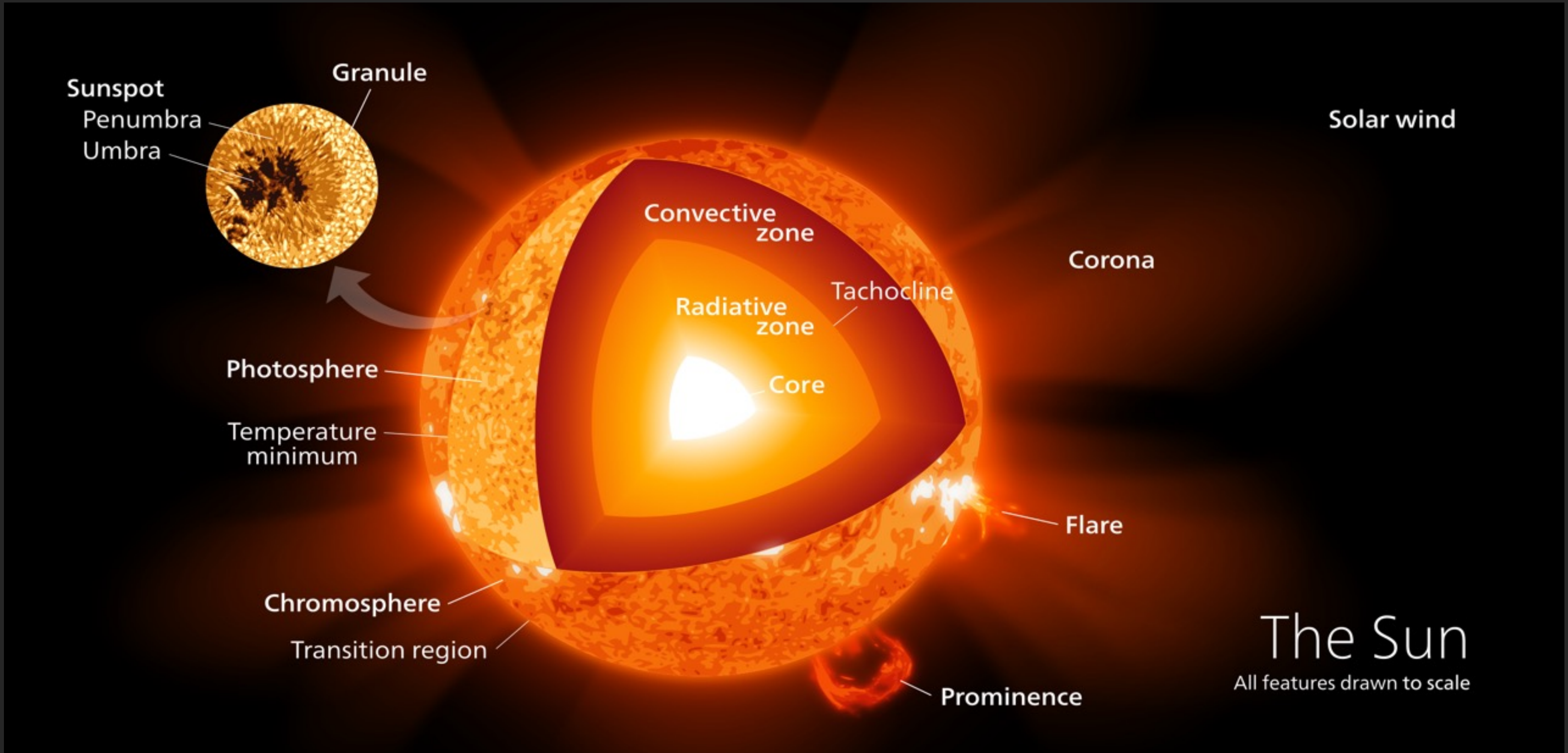
$e^{+} + e^{-} \rightarrow \nu + \bar{\nu}$

$\pi \rightarrow \mu + \nu_\mu$

…

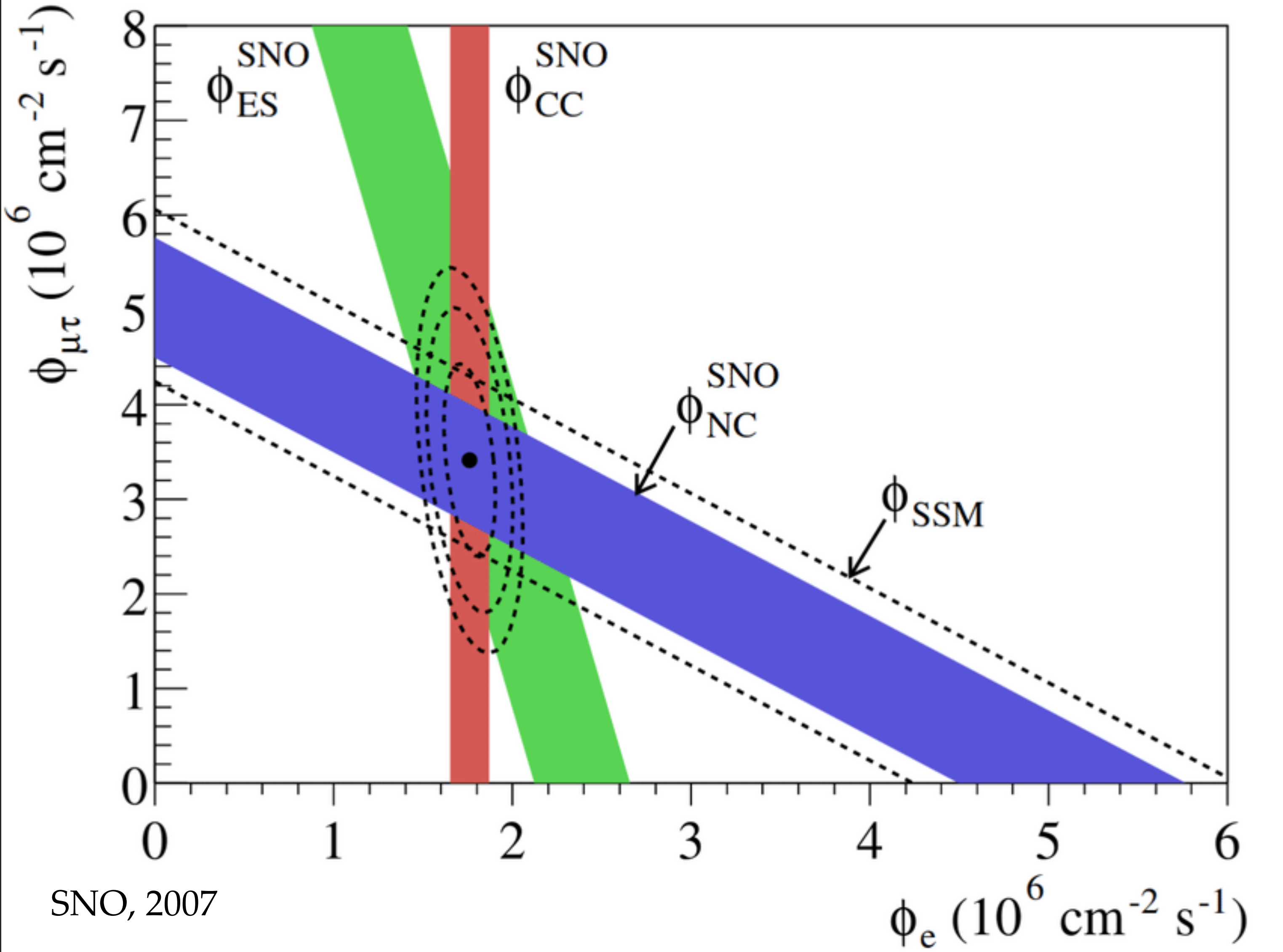
Many particles are produced, neutrinos escape more easily

Solve Mysteries in Astro- and Particle Physics



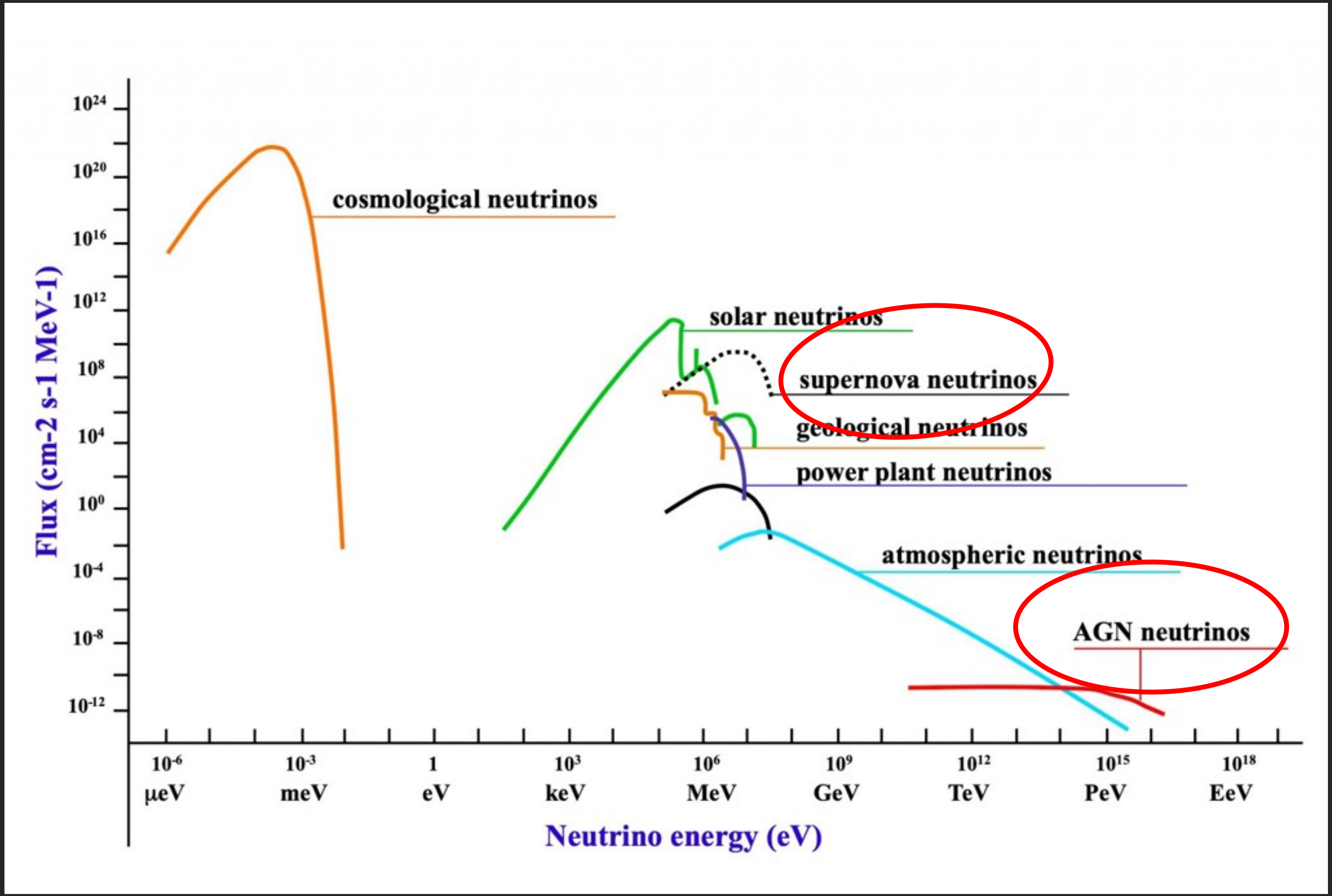
Solar neutrinos may help solve solar metallicity problem

Solve Mysteries in Astro- and Particle Physics



Solar neutrinos were one piece to discover neutrino oscillation, which proves that neutrinos have masses

This Talk:

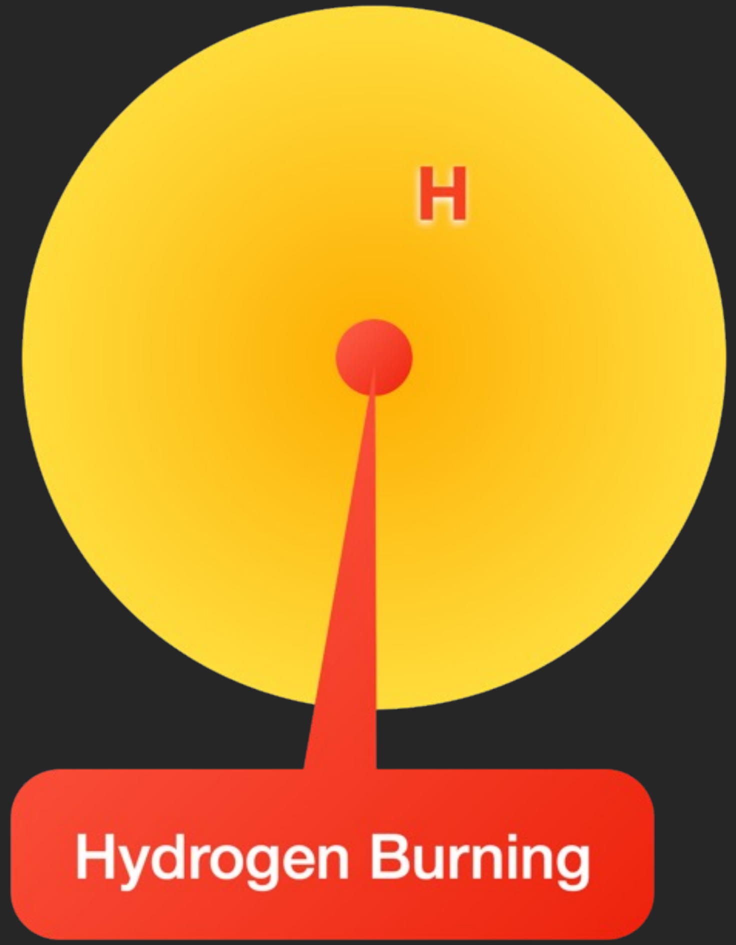


cosmological neutrinos
solar neutrinos
supernova neutrinos
geological neutrinos
power plant neutrinos
atmospheric neutrinos
AGN neutrinos
Flux (cm-2 s-1 MeV-1)
10^{24}
10^{20}
10^{16}
10^{12}
10^{8}
10^{4}
10^{0}
10^{-4}
10^{-8}
10^{-12}
10^{-6} μeV
10^{-3} meV
1 eV
10^{3} keV
10^{6} MeV
10^{9} GeV
10^{12} TeV
10^{15} PeV
10^{18} EeV
Neutrino energy (eV)

Supernova neutrinos

Core-collapse Supernovae

The death of Massive Stars ($> 8\ M_\odot$)



Figures remade from Raffelt's talk

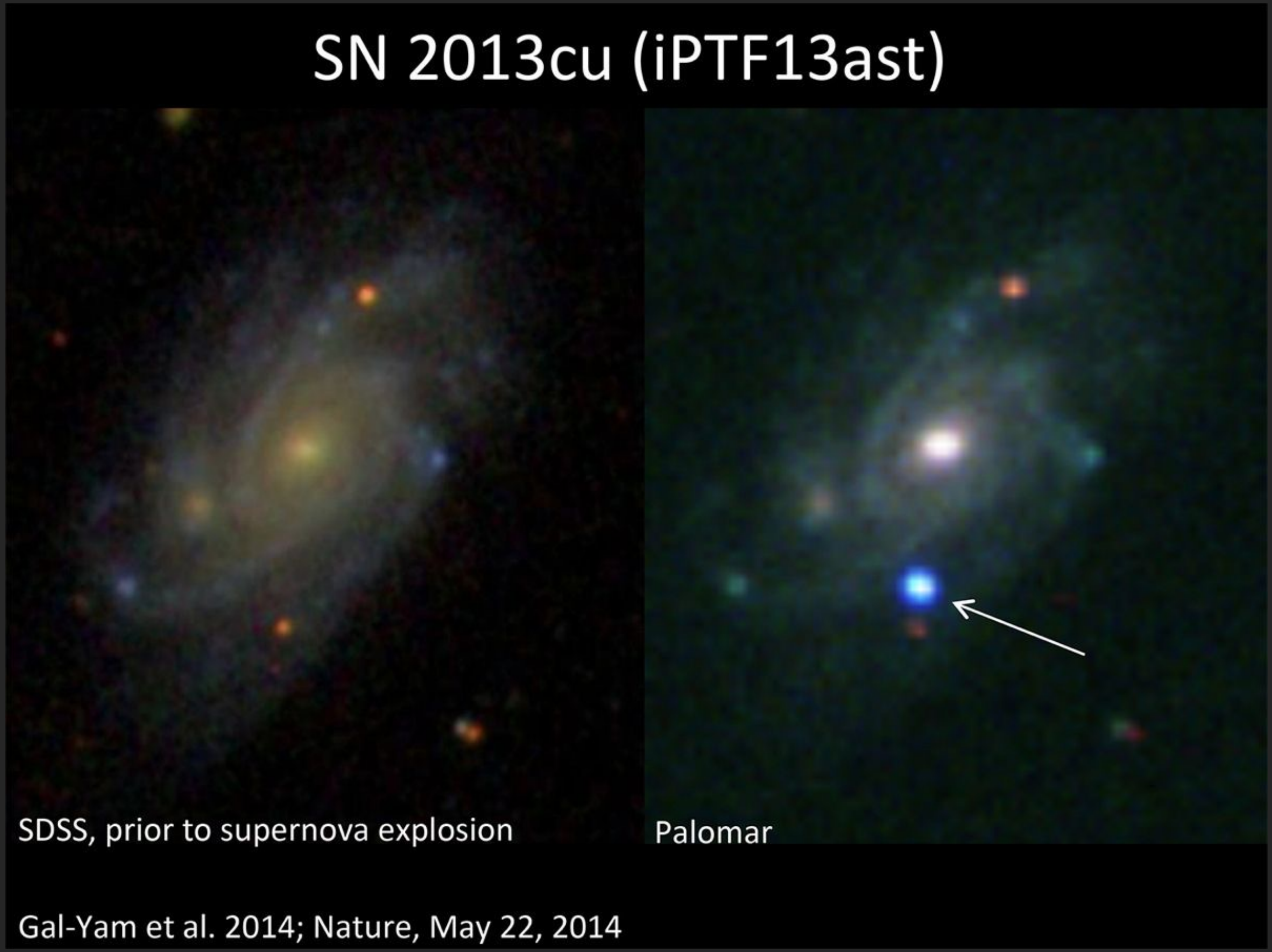
Core-collapse Supernovae

The death of Massive Stars ($> 8\, M_{\odot}$)

[Simulation link]

Figures remade from Raffelt's talk

Huge Amount of Energy and Neutrinos



Among the most energetic events in the Universe

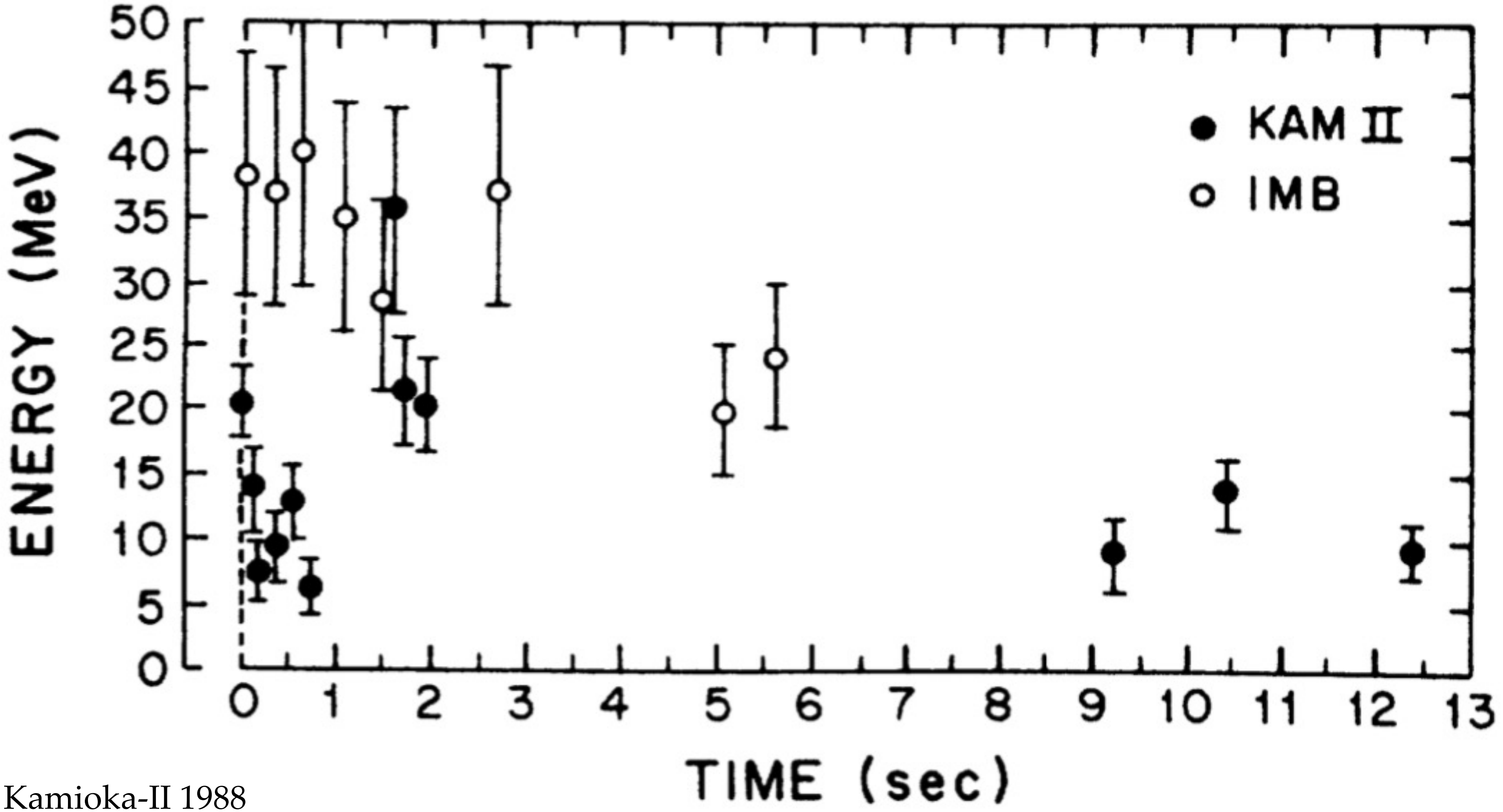
Optically, they can outshine the entire host galaxy for weeks

Release 10^46 J of energy >> Sun traveling at the speed of light

Mostly in neutrinos

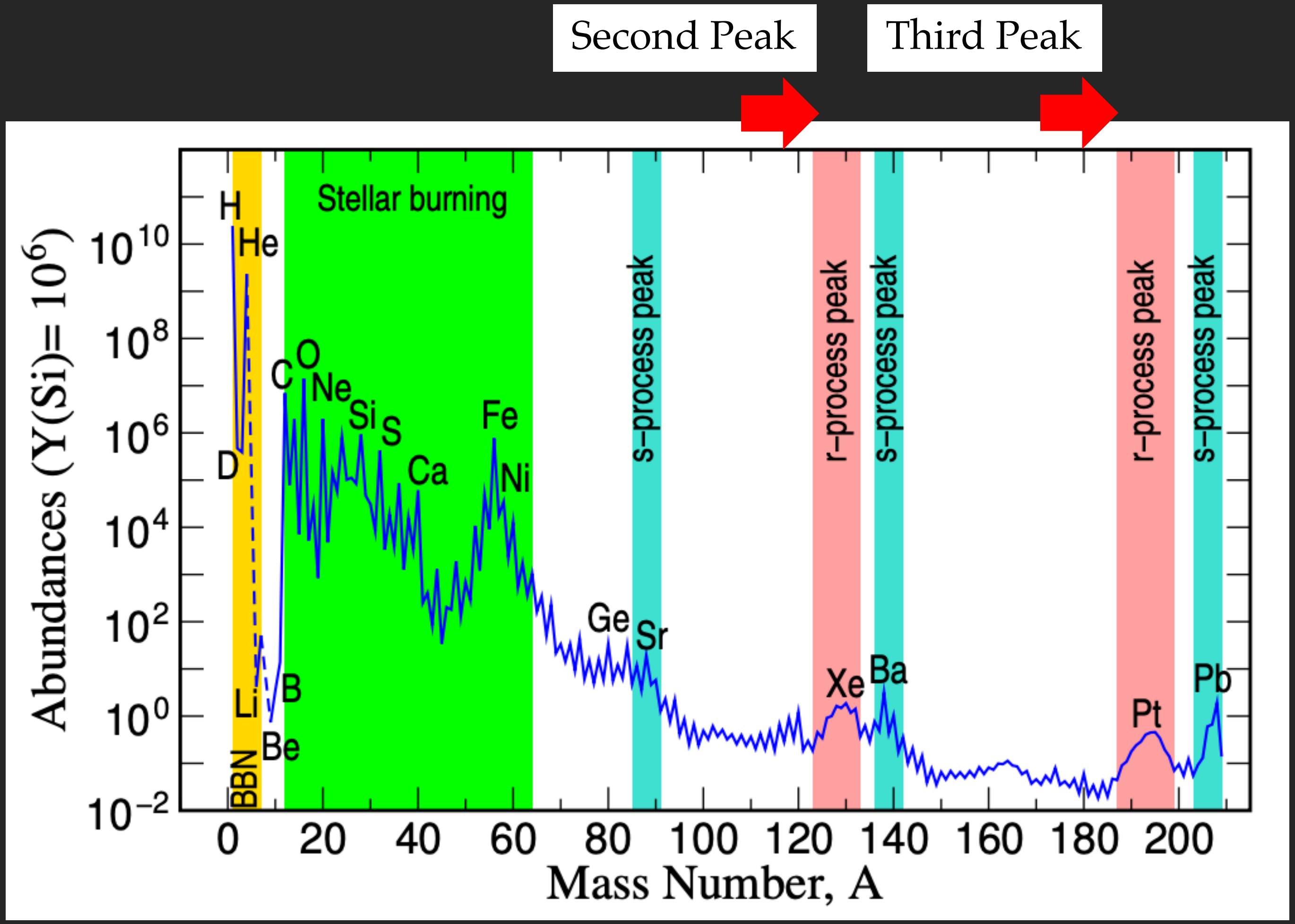
We can detect the neutrinos if it's nearby!

It Happened Once! Supernova 1987A

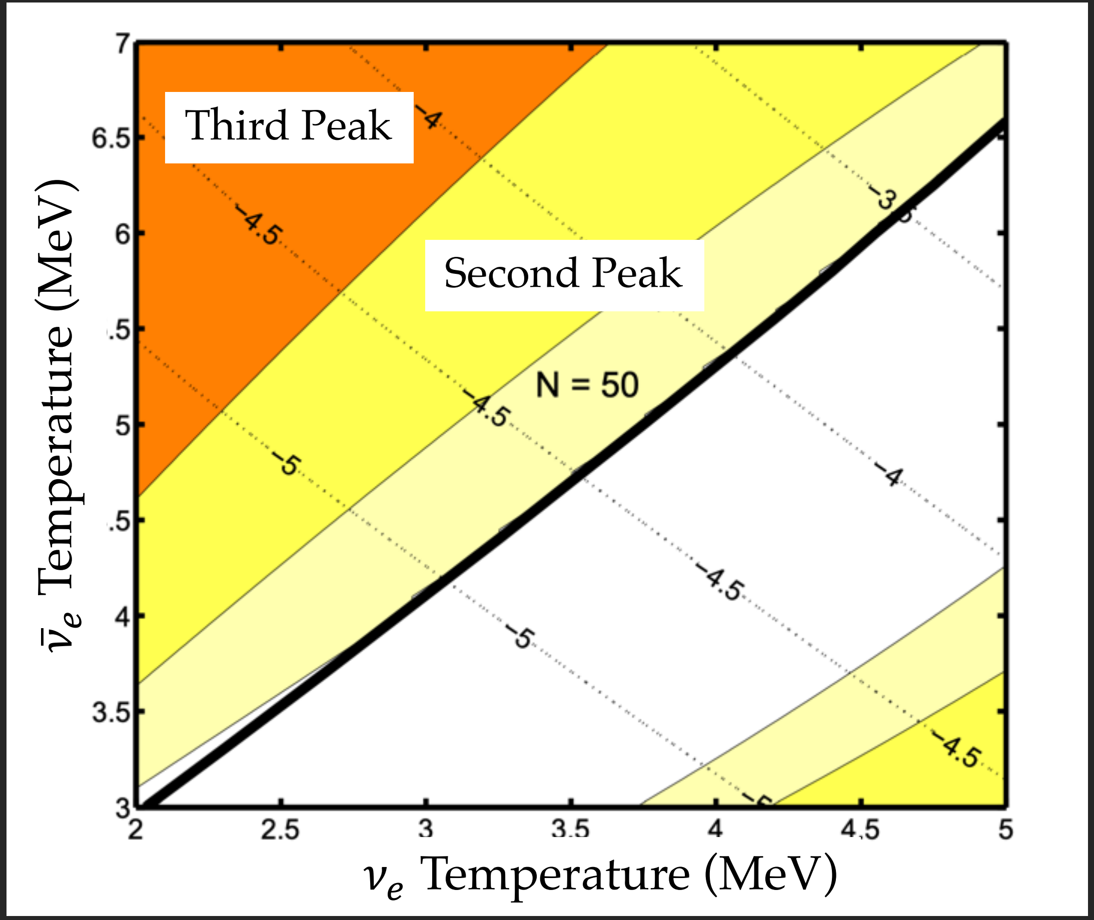


Kamioka-II 1988

Provide Information on Nucleosynthesis



Cowan et al., 2019



Roberts et al., 2011

Provide Information on the Remnant

What is the fate of SN 1987A? We still don't know!

Literature Limits on SN 1987A

Frequency (Hz)	Flux Density (erg s^{-1} cm^{-2} Hz^{-1})	Epoch ([YYYY–]YYYY)	Instr.[a]	Resolution[b]	Conf. Level[c]	References
$(0.076–8.642) \times 10^{9}$	$(5.1–0.17) \times 10^{-23}$	2013–2014	MWA, ATCA	U	···	Callingham et al. (2016)
1.7×10^{9}	0.3×10^{-26}	2008	VLBI	R	3-σ	Ng et al. (2011)
9×10^{9}	0.3×10^{-26}	1996[d]	ATCA	S	3-σ	Ng et al. (2008)
36.2×10^{9}	$0.3 \pm 0.2 \times 10^{-26}$	2008	ATCA	S	E	Potter et al. (2009)
44×10^{9}	2.2×10^{-26}	2011	ATCA	S	E	Zanardo et al. (2013)
94×10^{9}	1×10^{-26}	2011	ATCA	S	2-σ	Lakićević et al. (2012b)
$(0.6–4.3) \times 10^{12}$	$(50–150) \times 10^{-26}$	2012	SPIRE, PACS	U	···	Matsuura et al. (2015)
$(12–83) \times 10^{12}$	$(1.0–76) \times 10^{-26}$	2003–2015	MIPS, IRAC	U	···	Arendt et al. (2016)
26×10^{12}	0.34×10^{-26}	2005	T-ReCS	R	3-σ	Bouchet et al. (2006)
29×10^{12}	0.32×10^{-26}	2003	T-ReCS	R	E[e]	Bouchet et al. (2004)
$(0.5–1.5) \times 10^{19}$	$(1.9–0.6) \times 10^{-31}$	2010–2011	IBIS	U	···	Grebenev et al. (2012)
$(2.4–24.2) \times 10^{23}$	$(2.2–0.22) \times 10^{-36}$	2008–2014	LAT	U	···	Ackermann et al. (2016)
$(2.4–24.2) \times 10^{26}$	$(2.8–0.04) \times 10^{-40}$	2003–2012	HESS	U	···	H.E.S.S. Collaboration et al. (2015)

Alp *et al.*, 2018

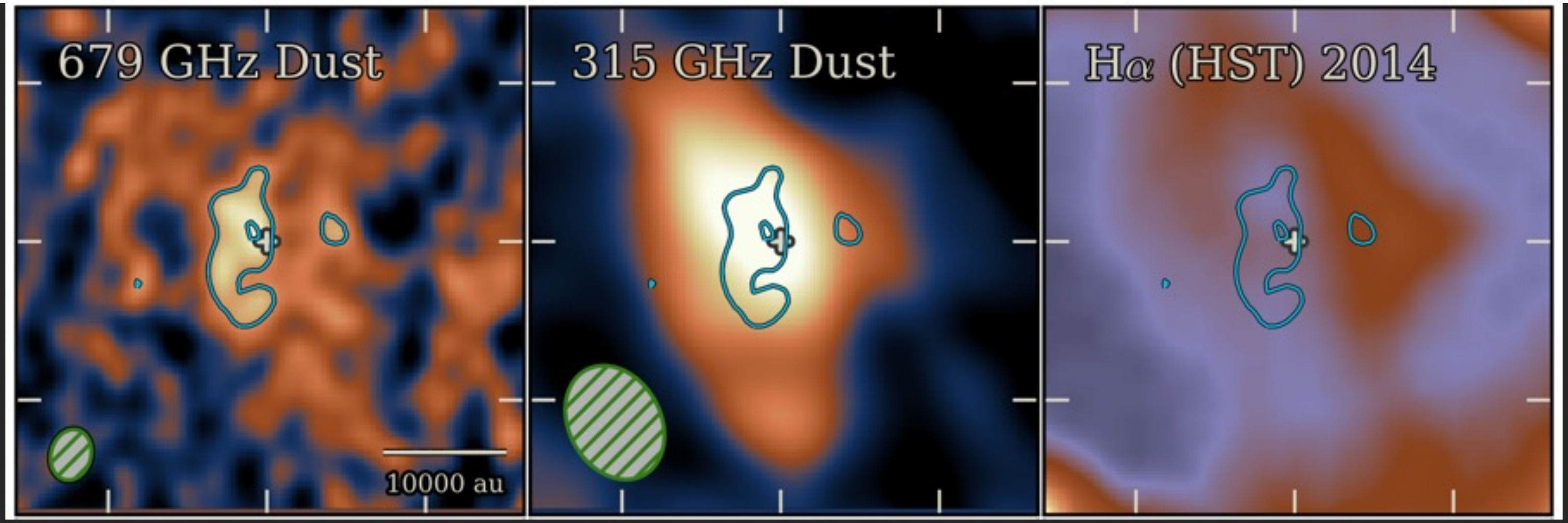
Provide Information on the Remnant

What is the fate of SN 1987A? We still don't know!

High angular resolution ALMA images of dust and molecules in the SN 1987A ejecta

PHIL CIGAN,[1] MIKAKO MATSUURA,[1] HALEY L. GOMEZ,[1] REMY INDEBETOUW,[2] FRAN ABELLÁN,[3] MICHAEL GABLER,[4] ANITA RICHARDS,[5] DENNIS ALP,[6] TIM DAVIS,[1] HANS-THOMAS JANKA,[4] JASON SPYROMILIO,[7] M. J. BARLOW,[8] DAVID BURROWS,[9] ELI DWEK,[10] CLAES FRANSSON,[11] BRYAN GAENSLER,[12] JOSEFIN LARSSON,[6] P. BOUCHET,[13, 14] PETER LUNDQVIST,[11] J. M. MARCAIDE,[3] C.-Y. NG,[15] SANGWOOK PARK,[16] PAT ROCHE,[17] JACCO TH. VAN LOON,[18] J. C. WHEELER,[19] AND GIOVANNA ZANARDO[20]

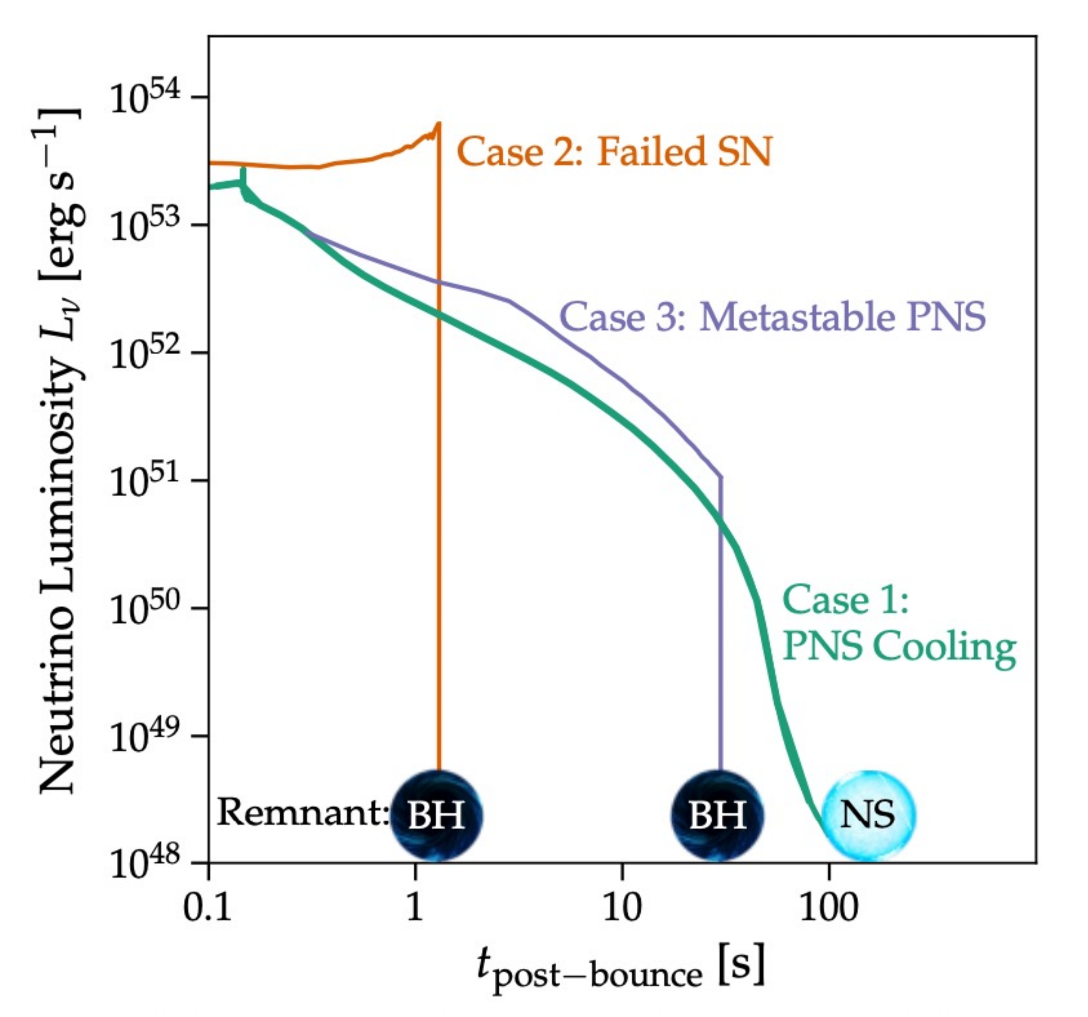
images. That dust peak, combined with CO and SiO line spectra, suggests that the dust and gas could be at higher temperatures than the surrounding material, though higher density cannot be totally excluded. One of the possibilities is that a compact source provides additional heat at that location. Fits to the far-infrared–



Cigan *et al.*, 2019

Provide Information on the Remnant

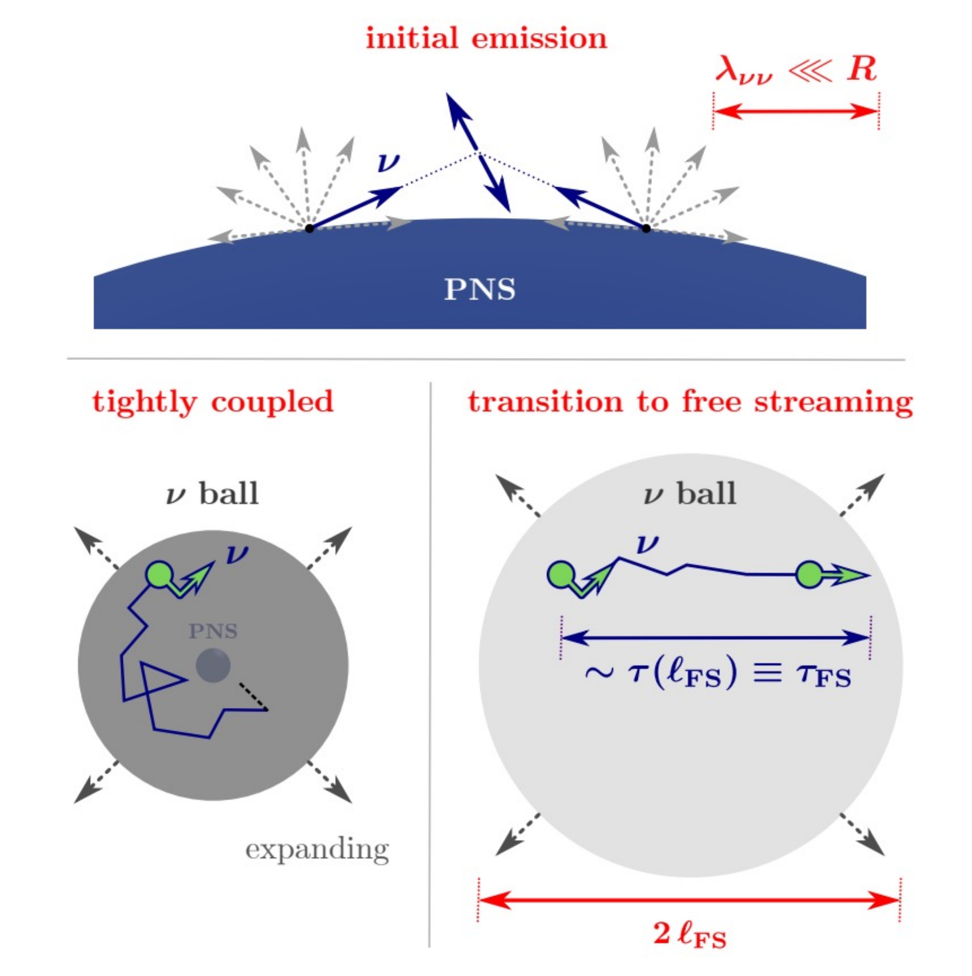
We can directly measure remnant formation using neutrinos!

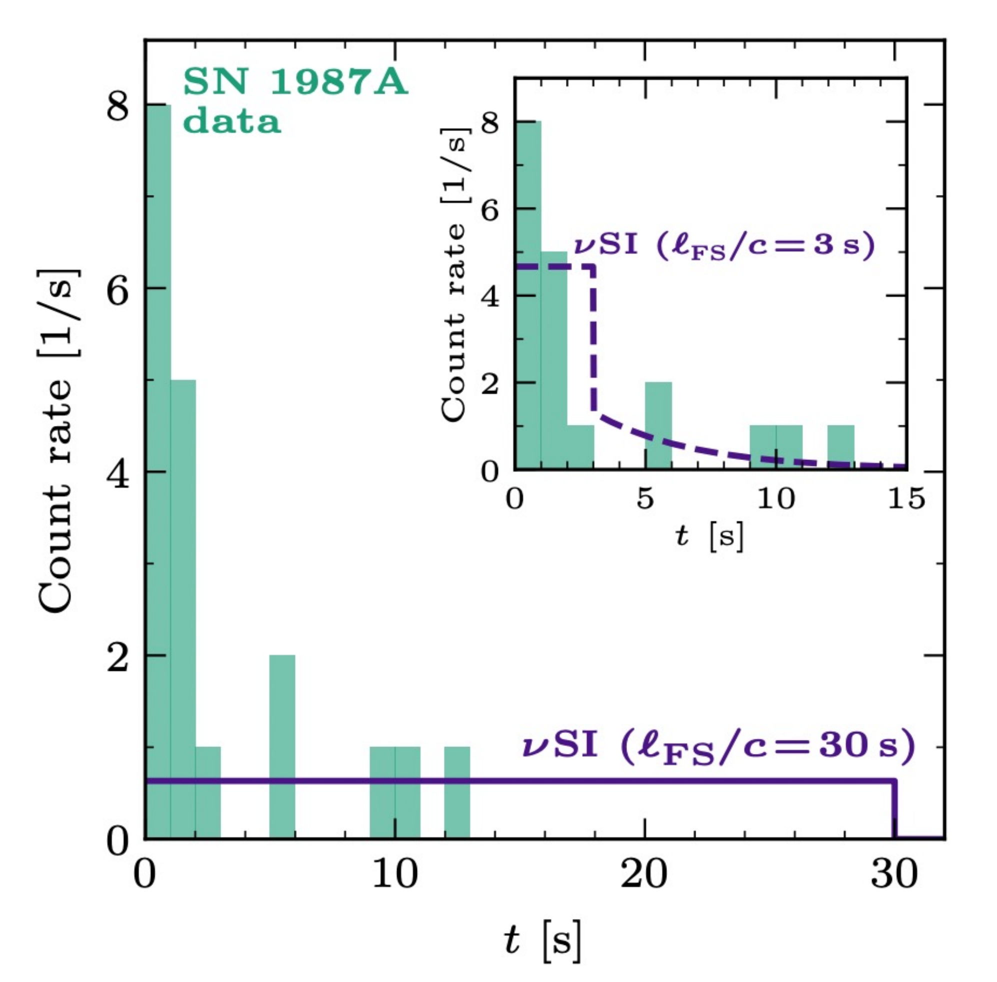


Li *et al.*, 2020

Provide Information on ν Properties

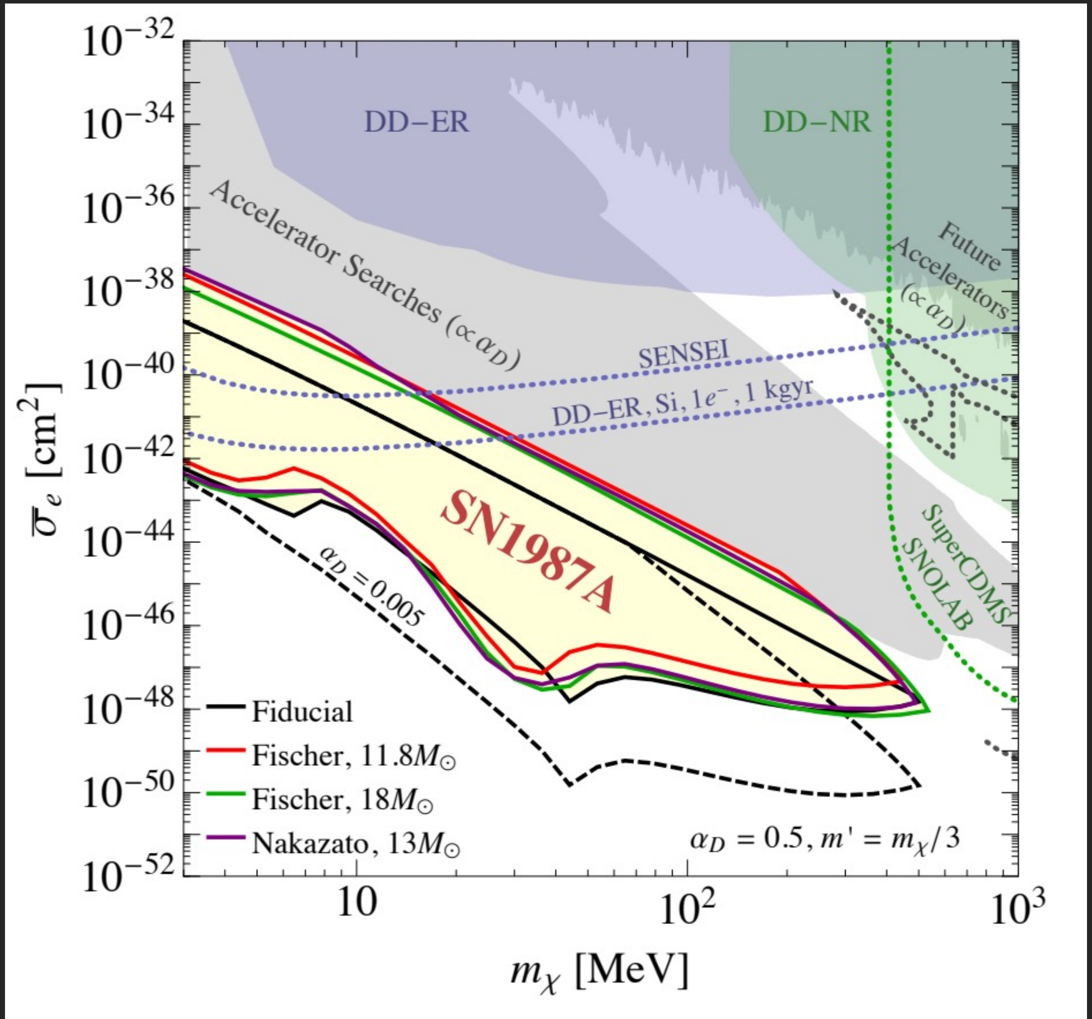
Neutrino-neutrino collider



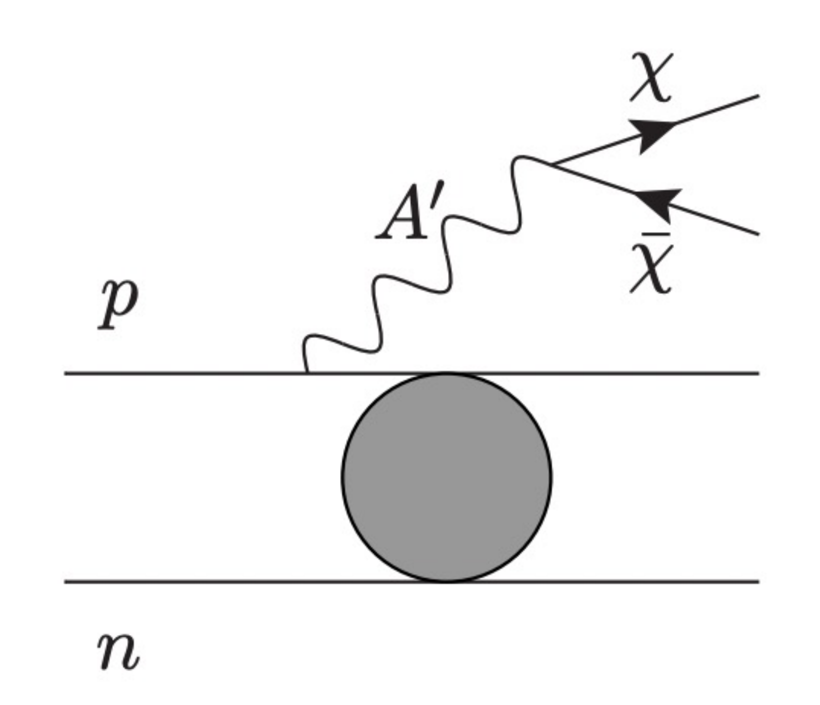


Chang *et al.*, 2022

Provide Information on BSM



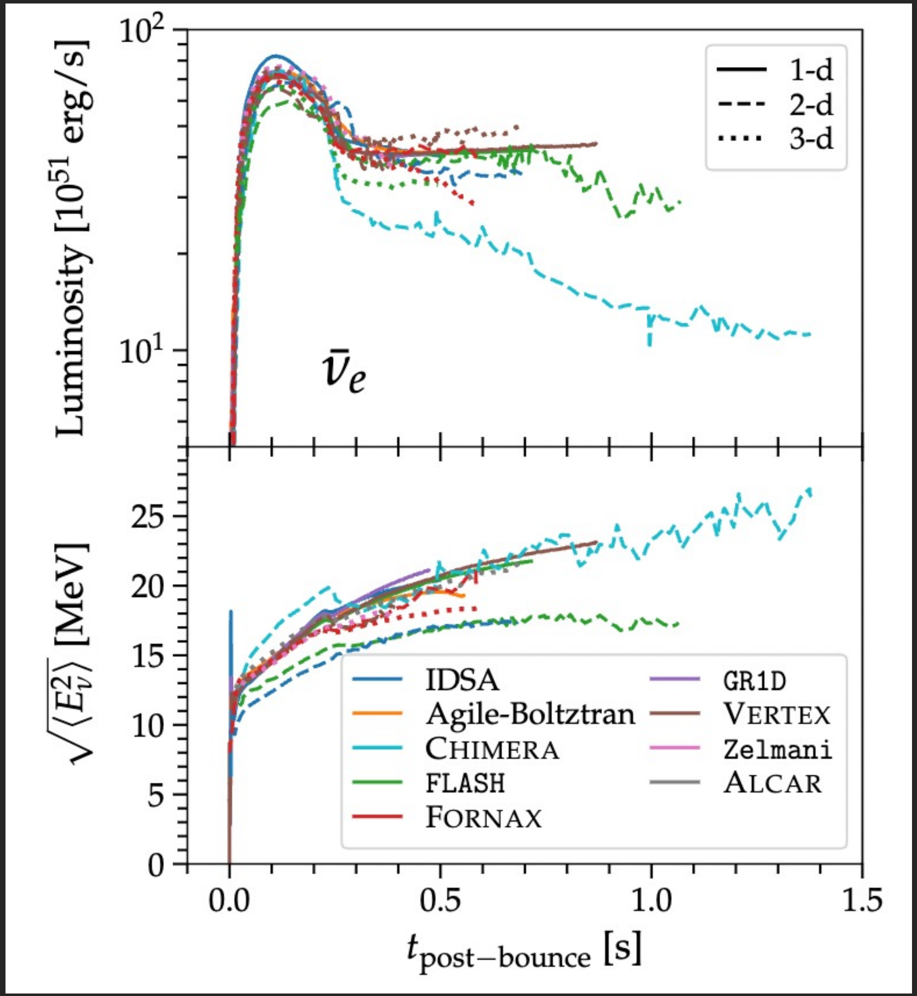
Could produce light dark matter, milli-charged particles, axions, …



Chang *et al.*, 2018

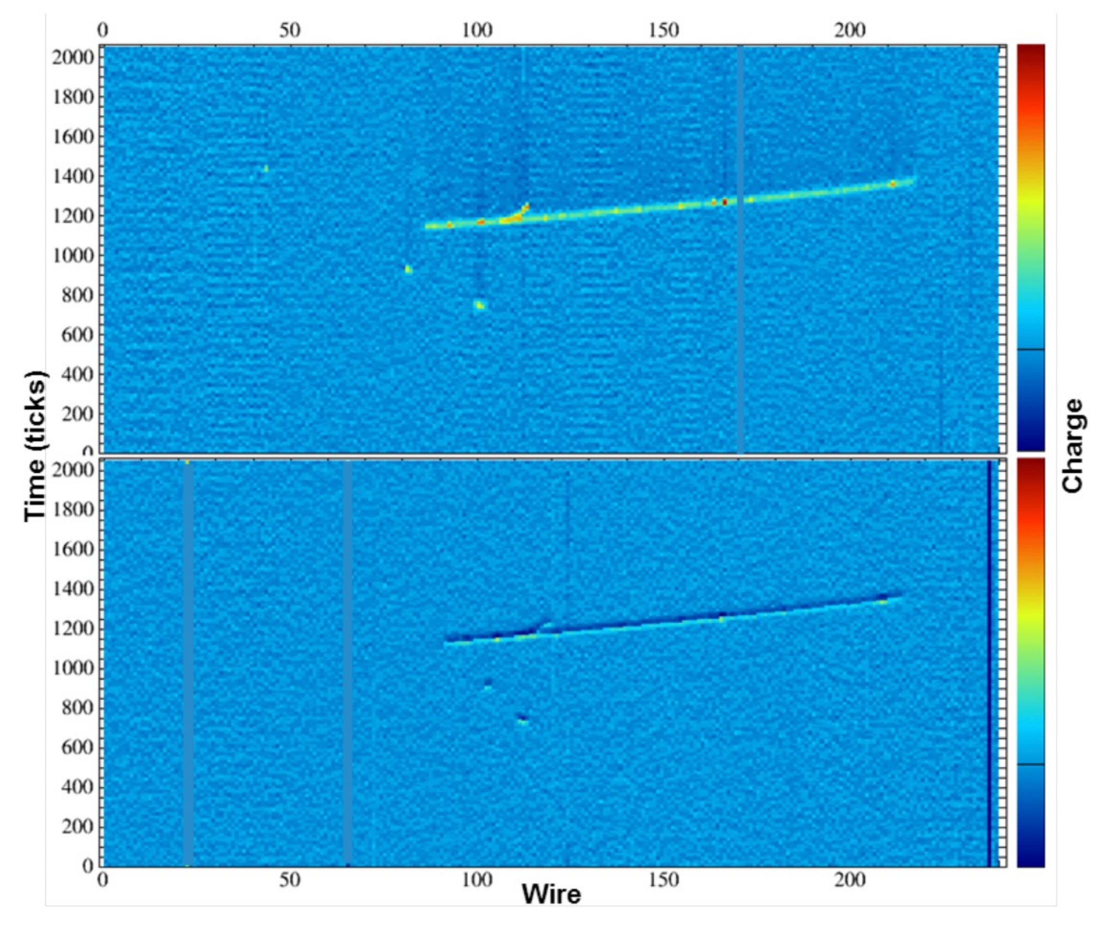
Ongoing Efforts

Examples…

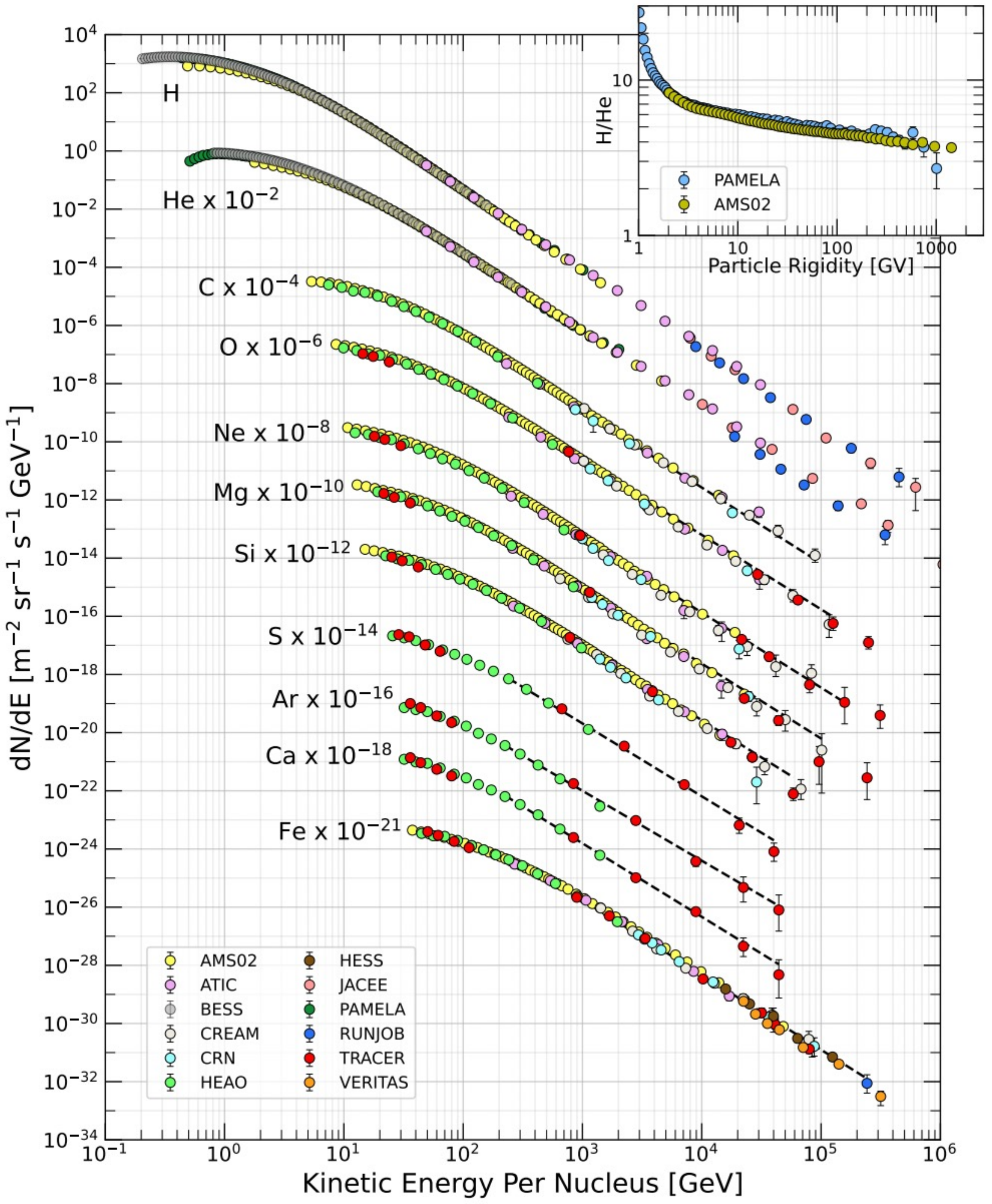


Li *et al.*, 2023

ArgoNeuT, 2018



High-energy astrophysical neutrinos

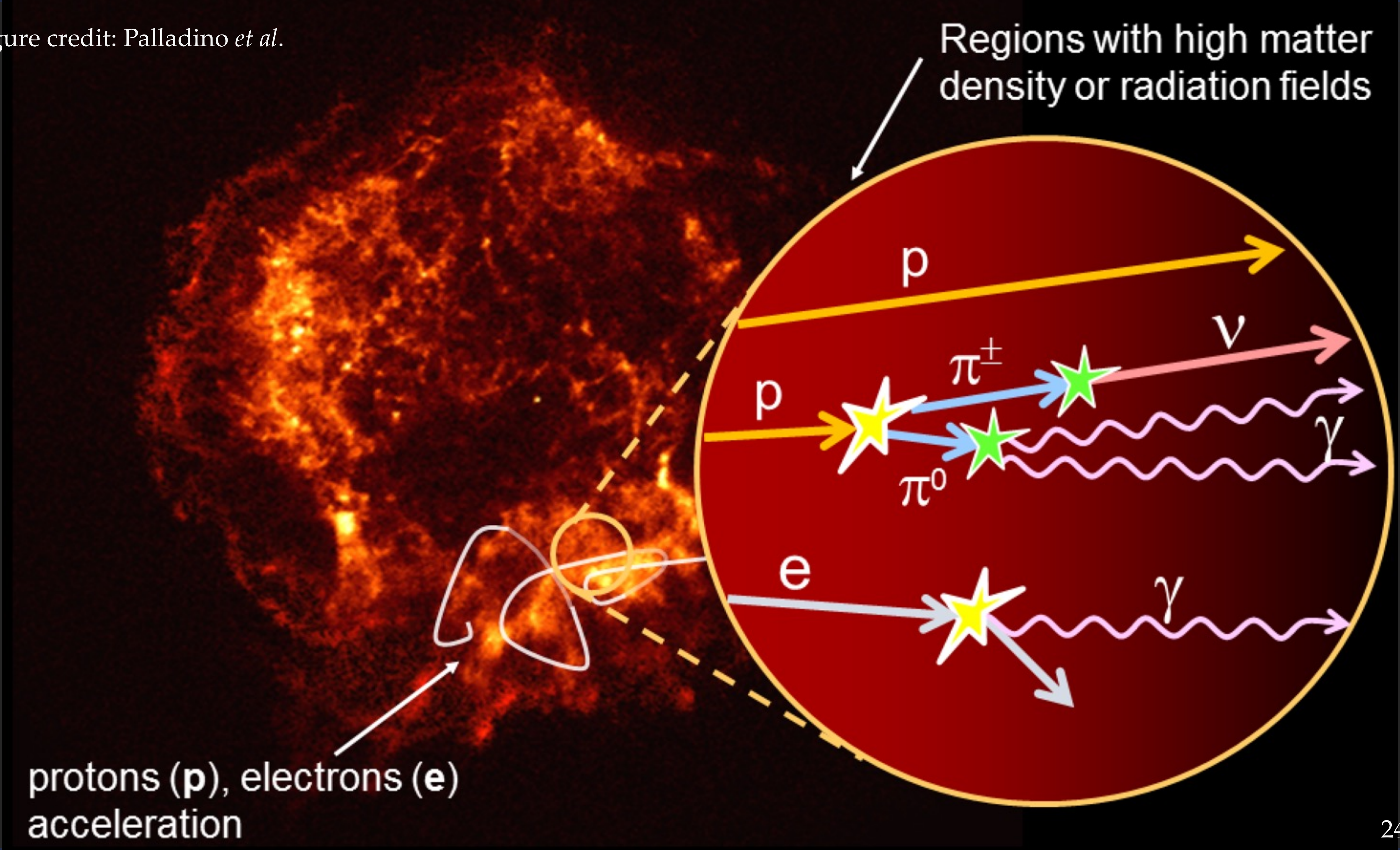


Cosmic Rays

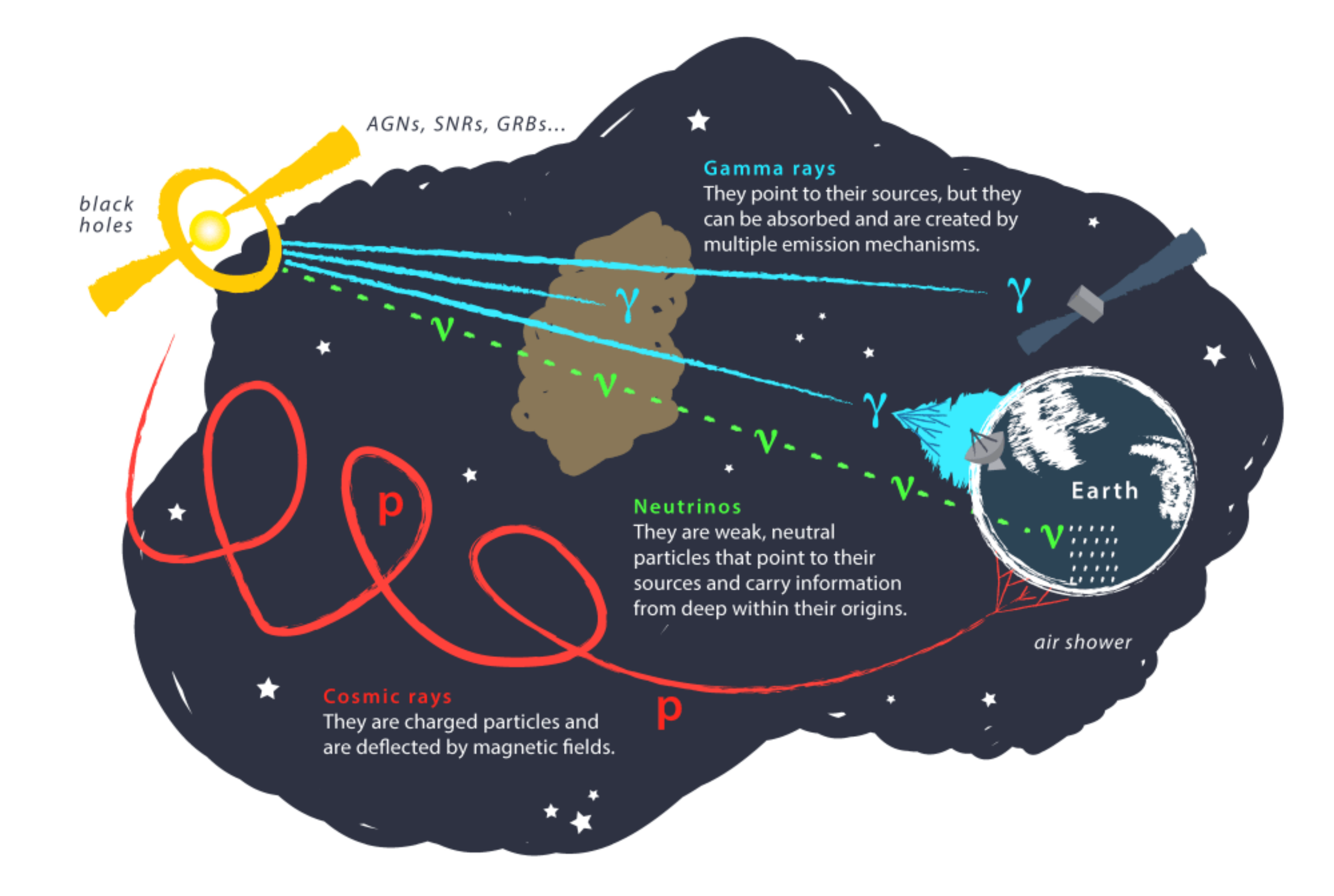
A one-hundred-year puzzle
– where are they from?

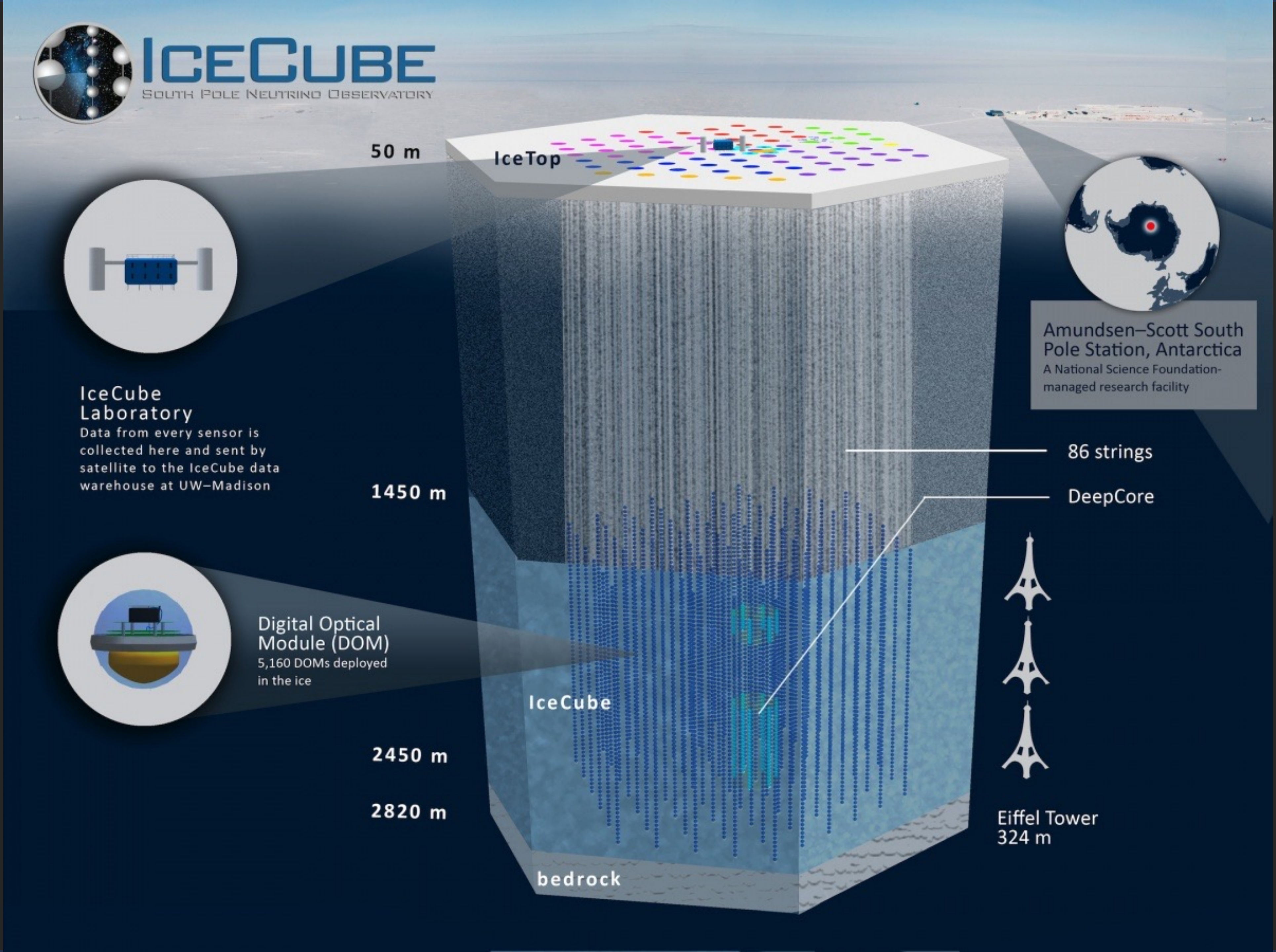
PDG, 2022

Figure credit: Palladino *et al*.

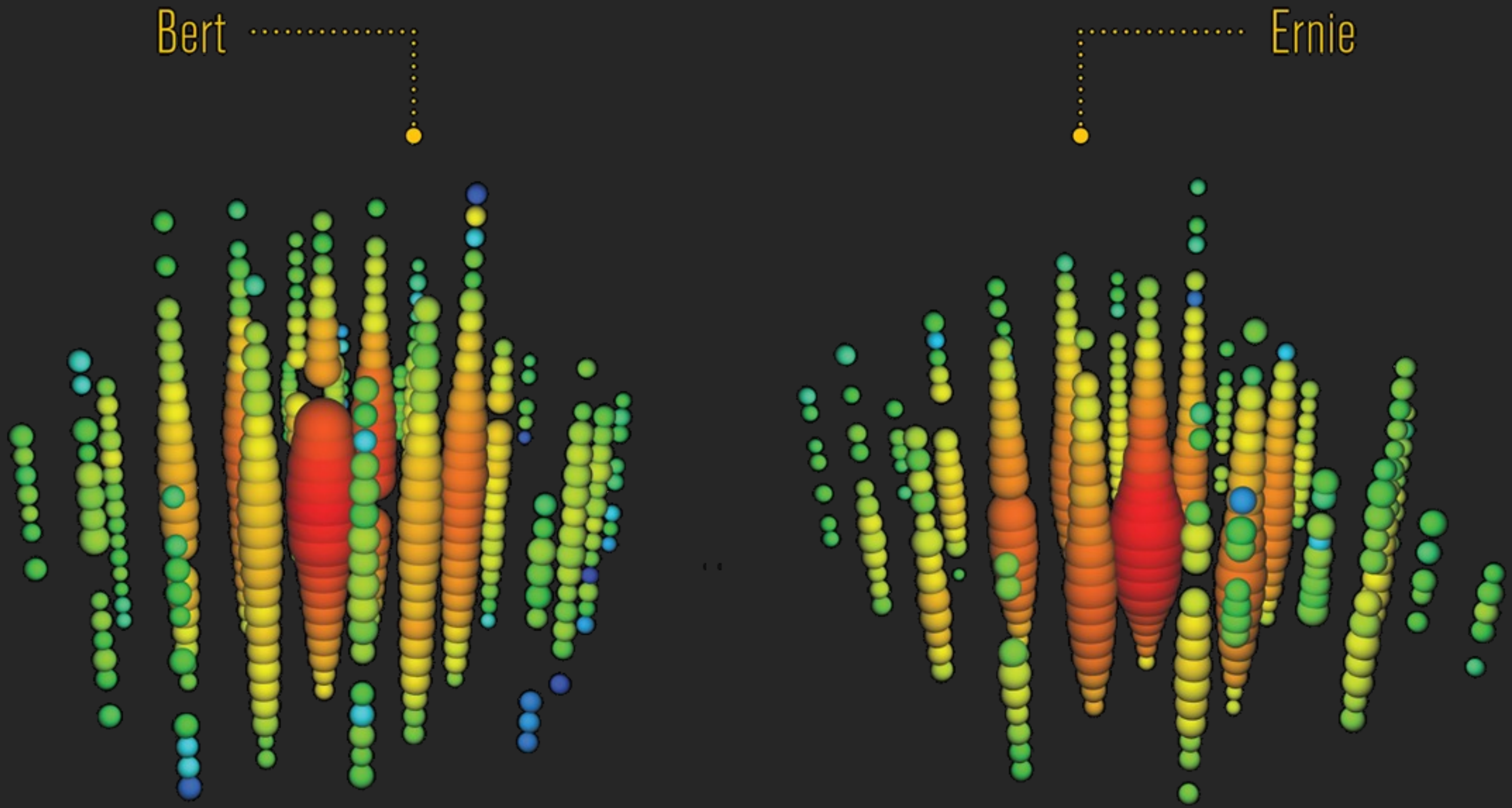


Neutrinos as Cosmic Messengers

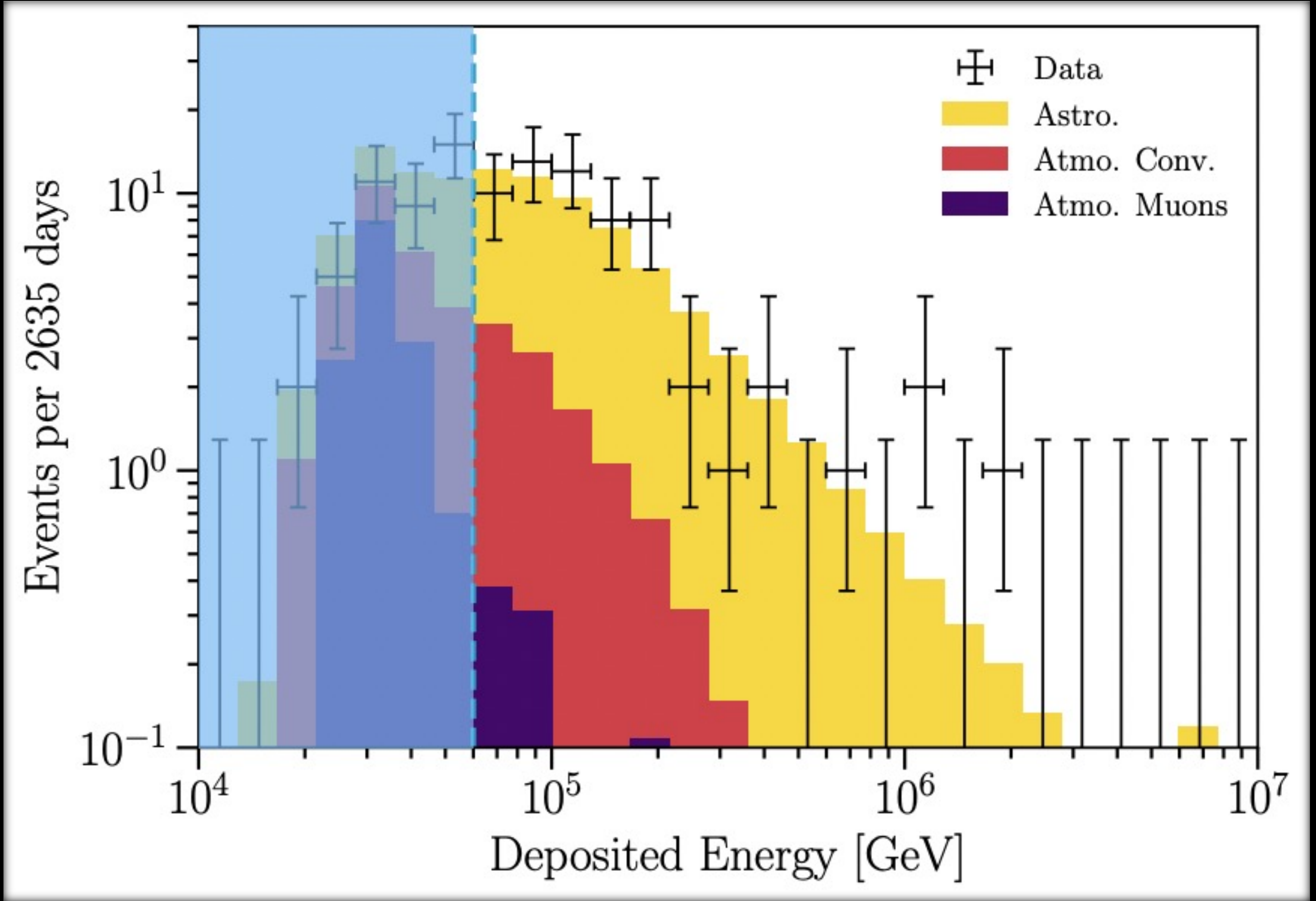



ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY
50 m
IceTop
IceCube
Laboratory
Data from every sensor is
collected here and sent by
satellite to the IceCube data
warehouse at UW–Madison
1450 m
Digital Optical
Module (DOM)
5,160 DOMs deployed
in the ice
IceCube
2450 m
2820 m
bedrock
Amundsen–Scott South
Pole Station, Antarctica
A National Science Foundation-
managed research facility
86 strings
DeepCore
Eiffel Tower
324 m

IceCube Has Detected Astro ν



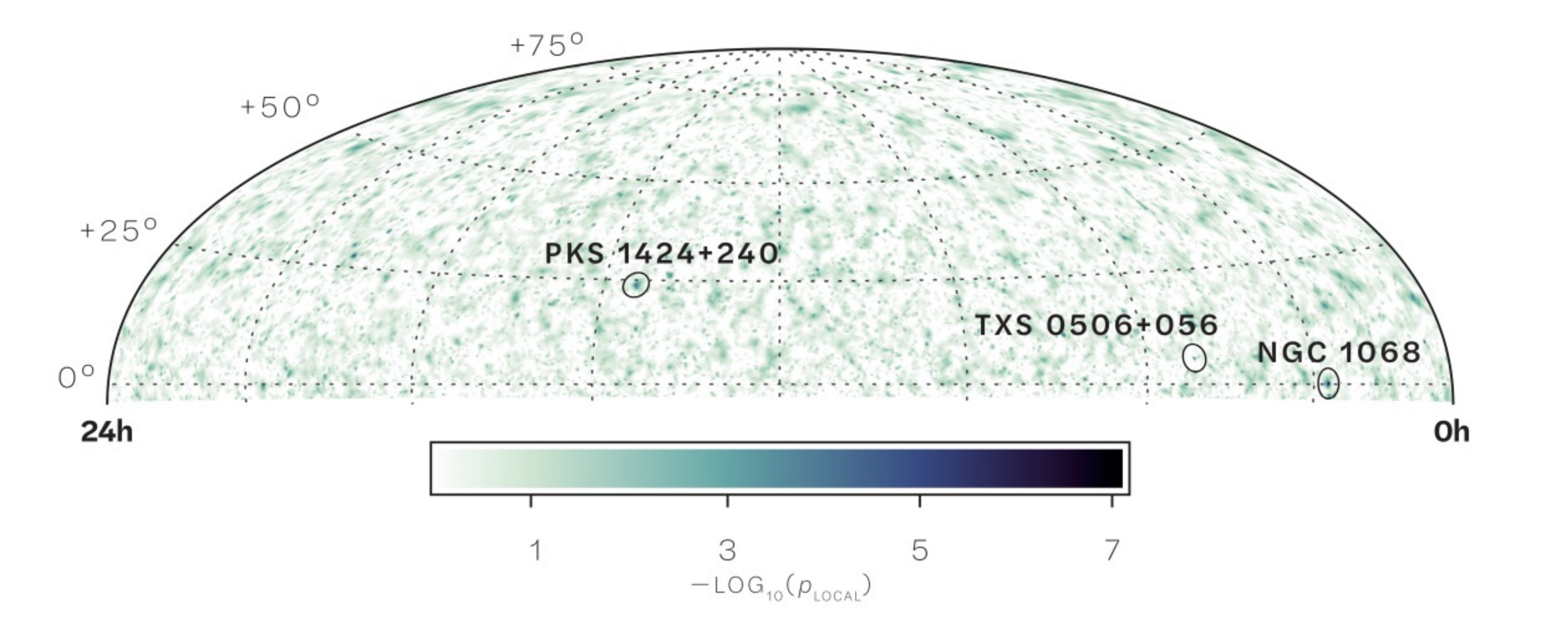
But… Diffuse Flux…



All sky, uniform in direction fluxes

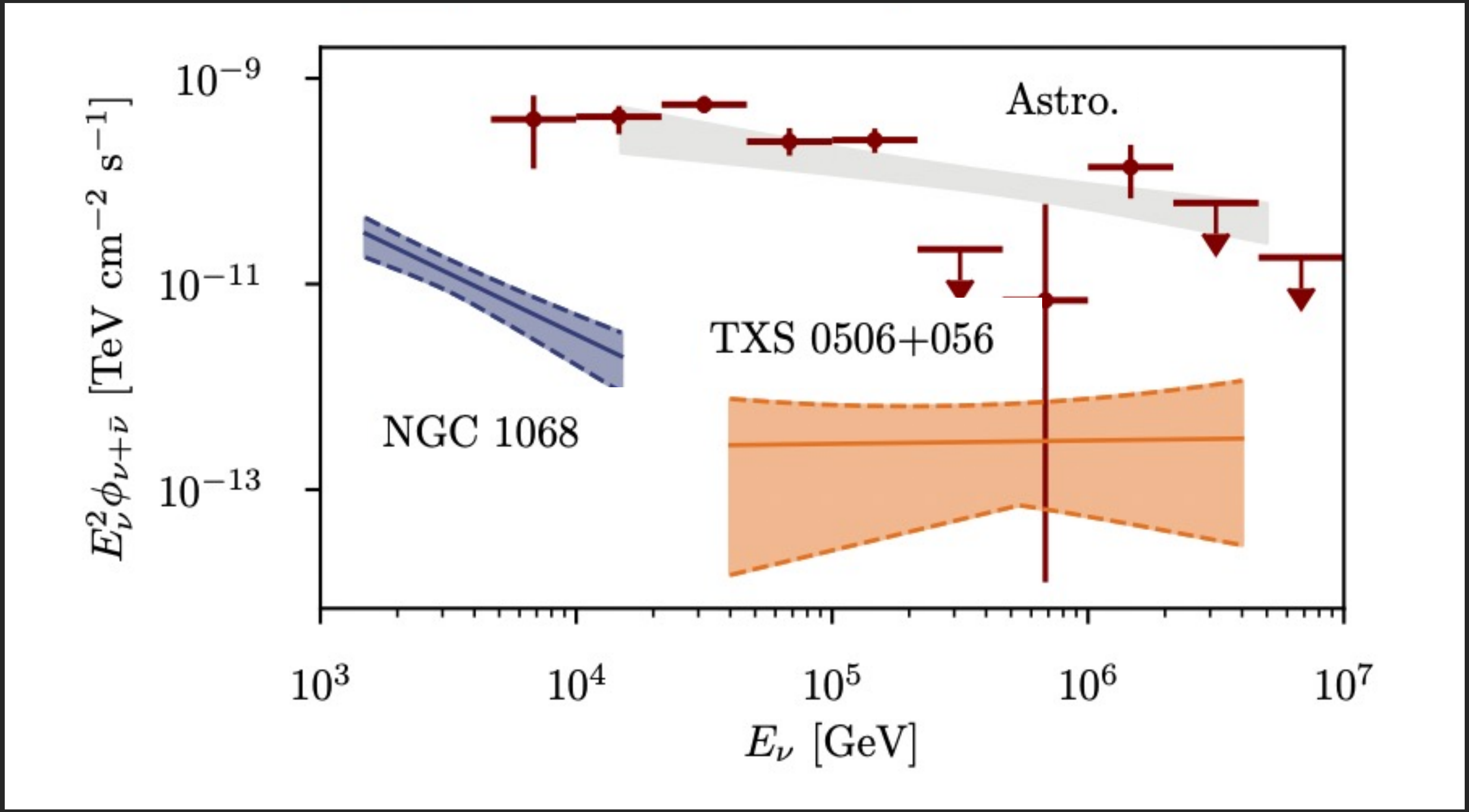
Pointing does NOT obviously help to find the sources

Promising Sources



IceCube, 2022

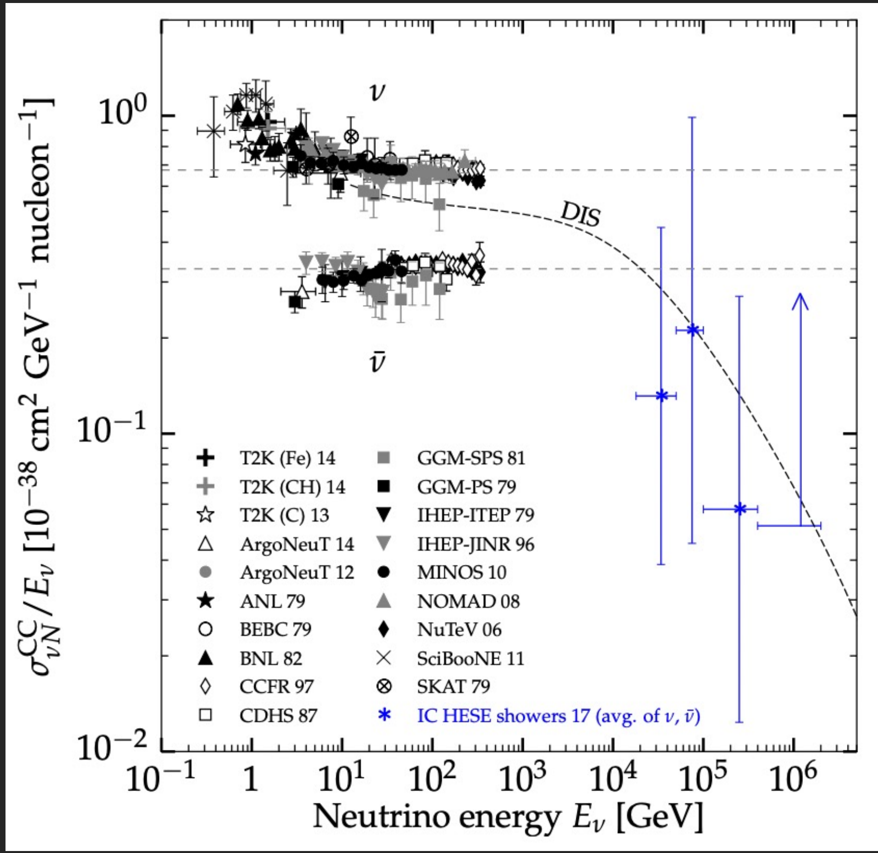
Promising Sources



IceCube, 2022

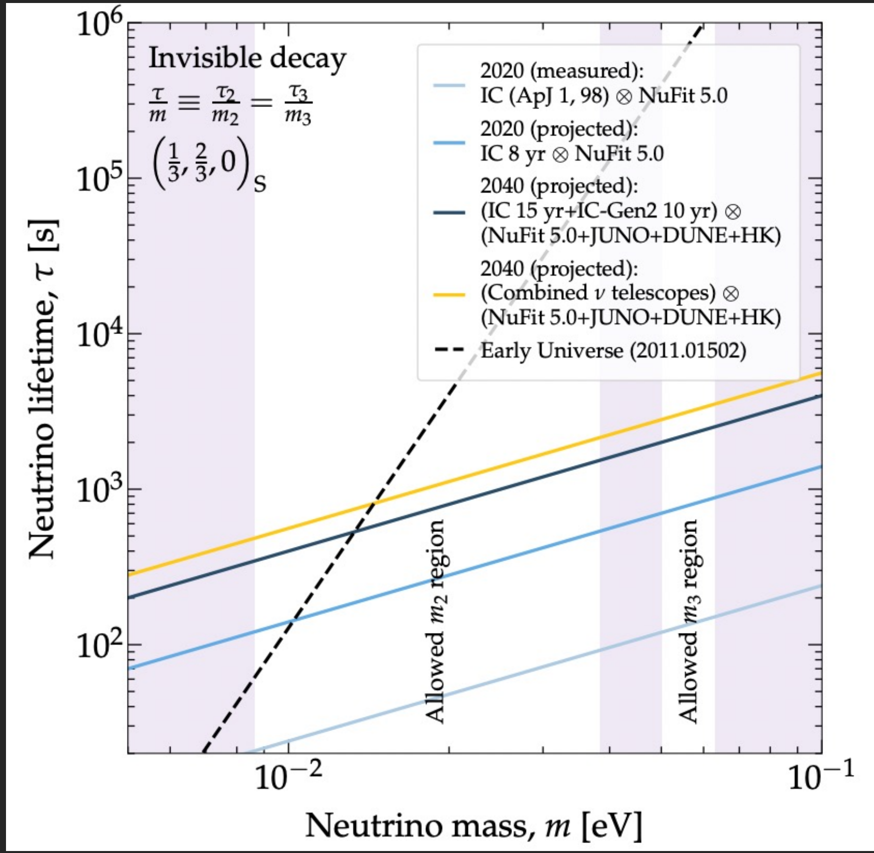
Provide Information on Particle Properties

Neutrino-matter interaction



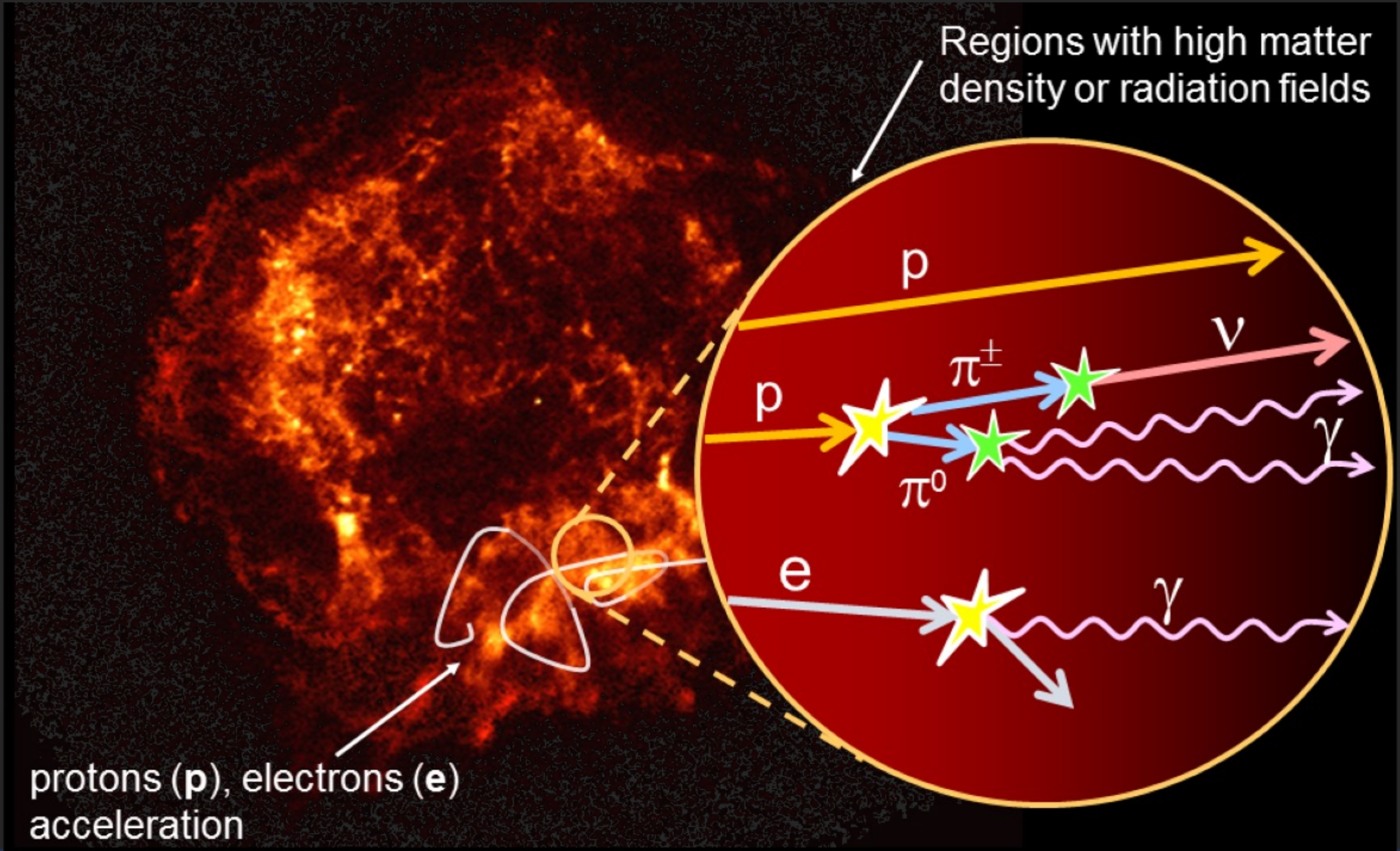
Bustamante *et al.*, 2017

Neutrino decay

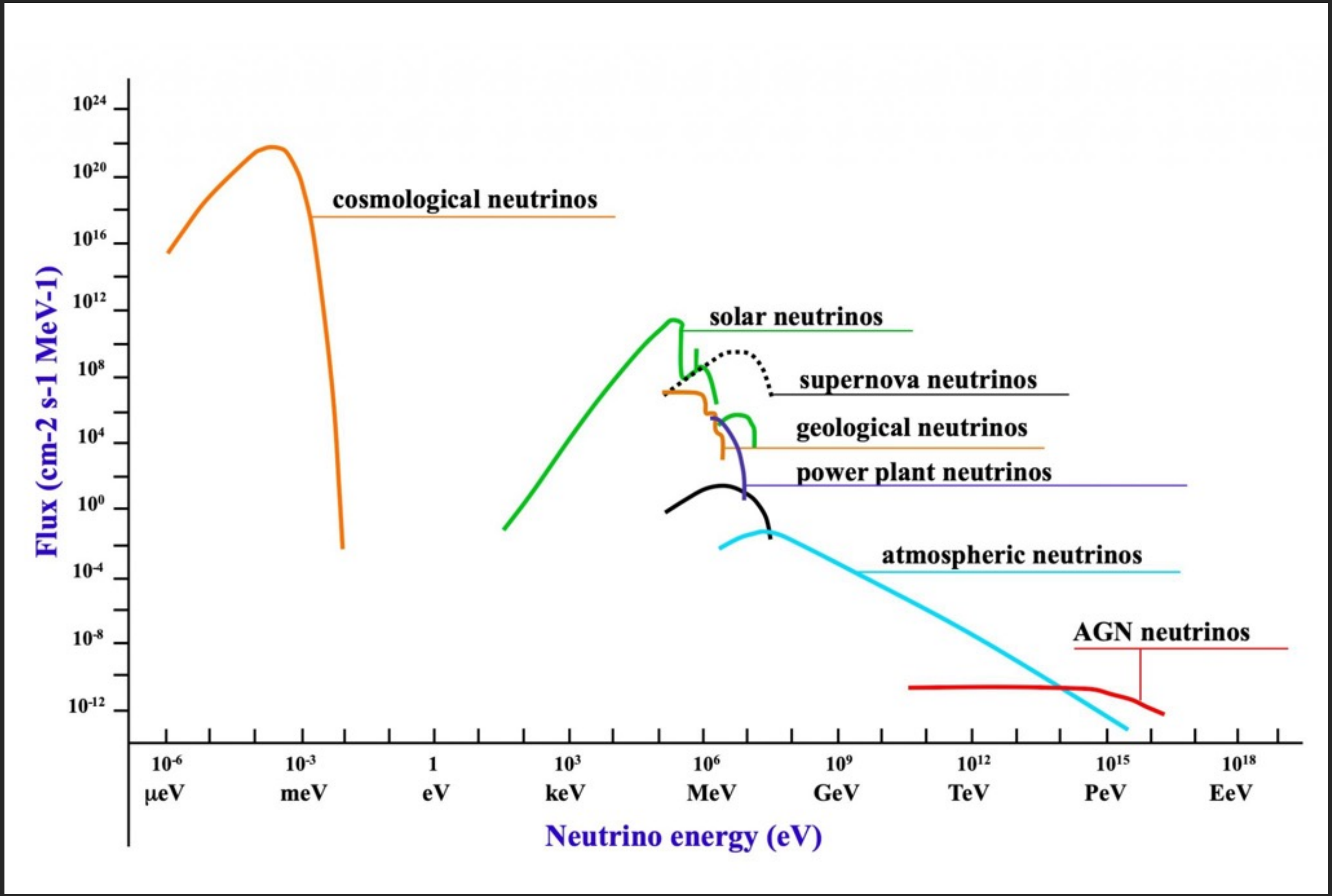


Song *et al.*, 2020

Conclusions



Conclusions



Conclusions