Advances in Multimessenger Astrophysics

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VILLUM FONDEN

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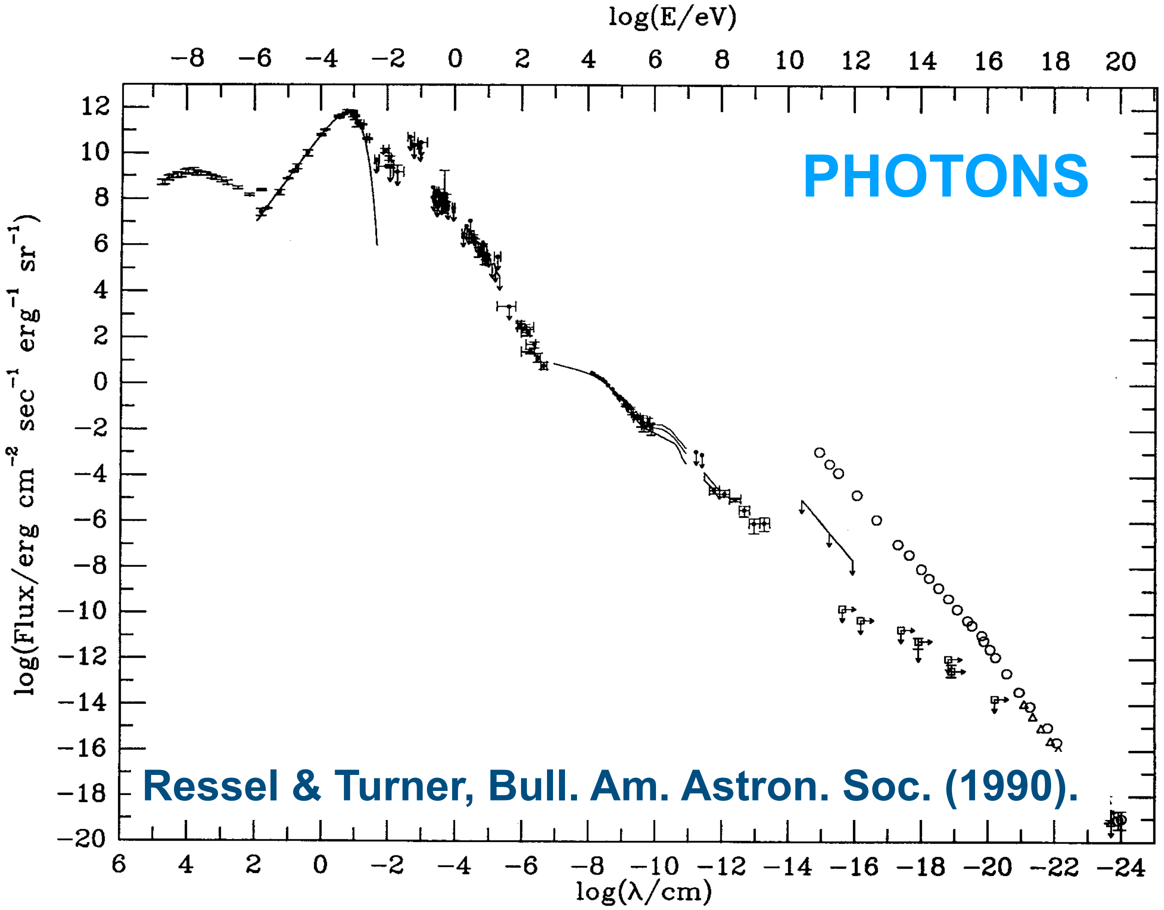
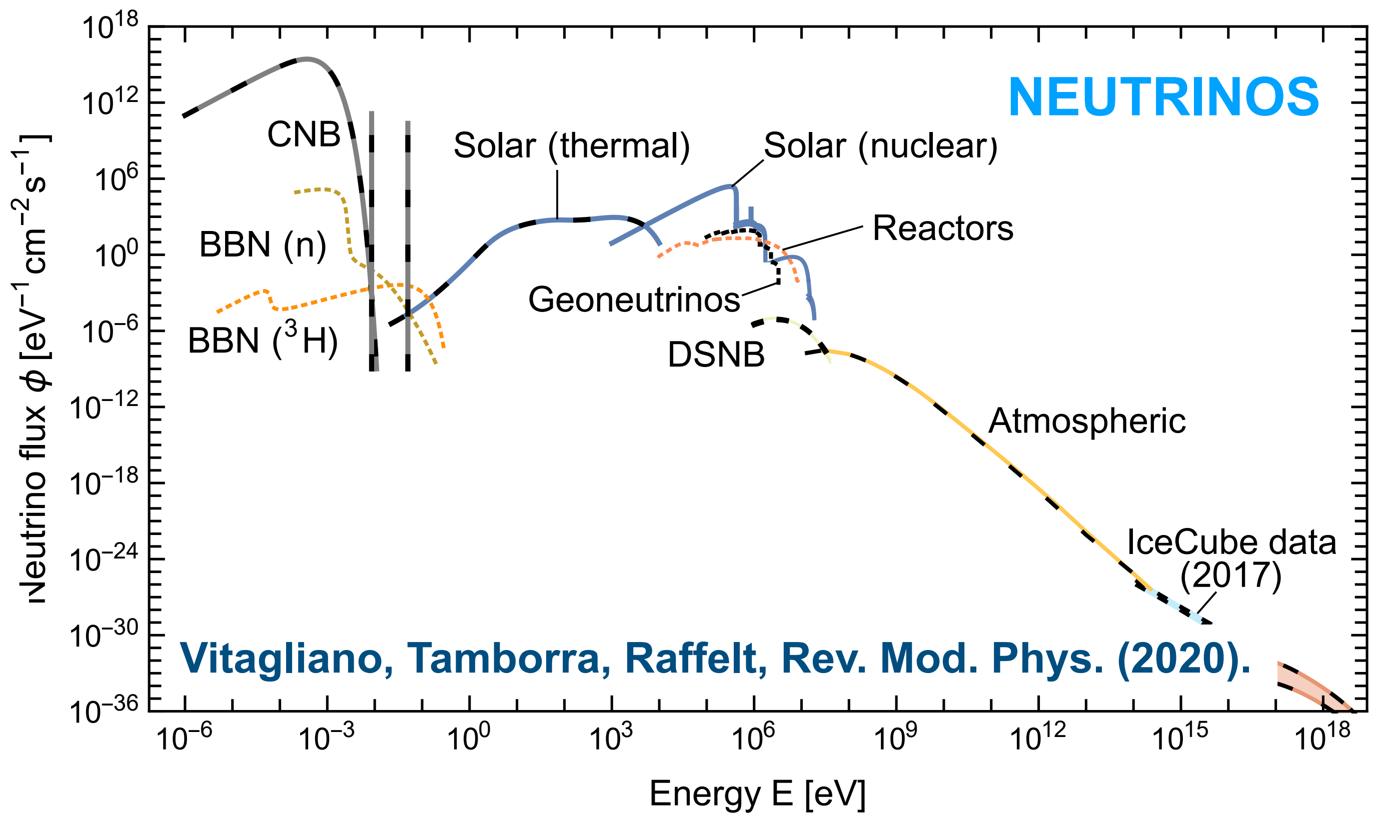
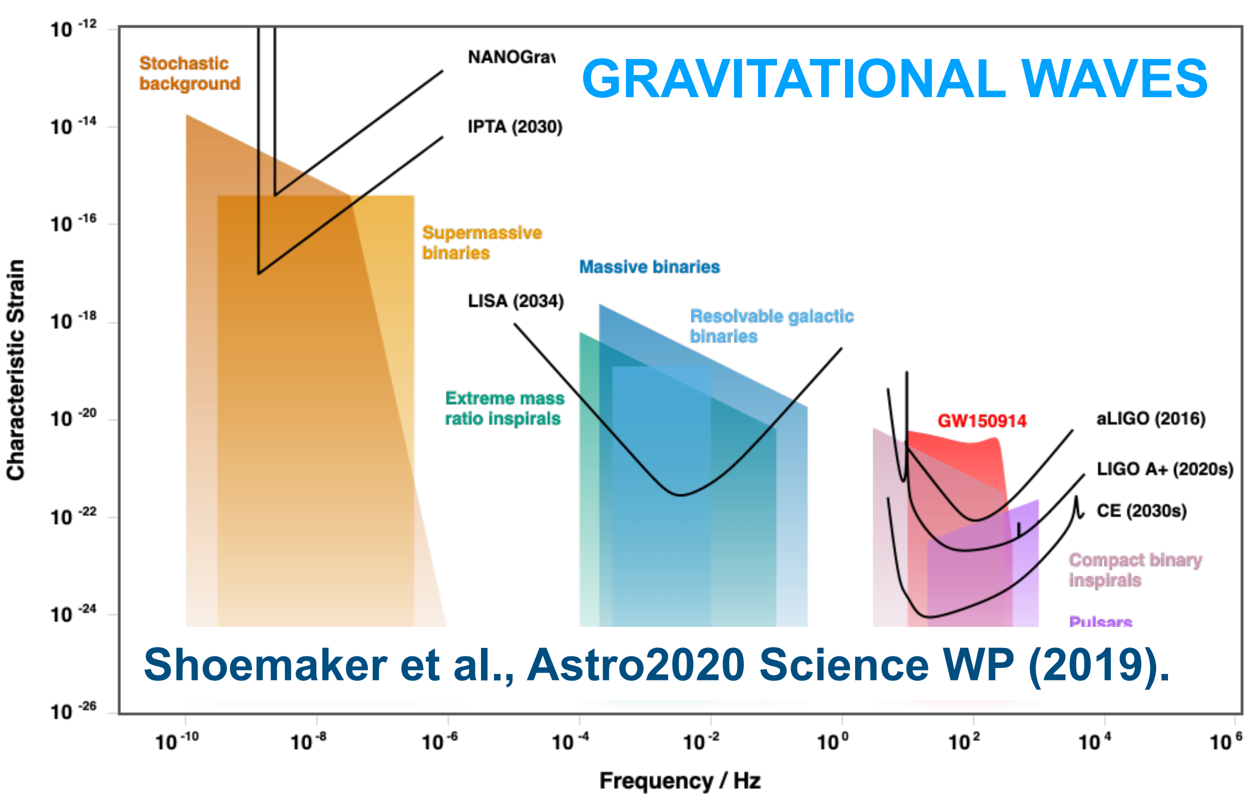
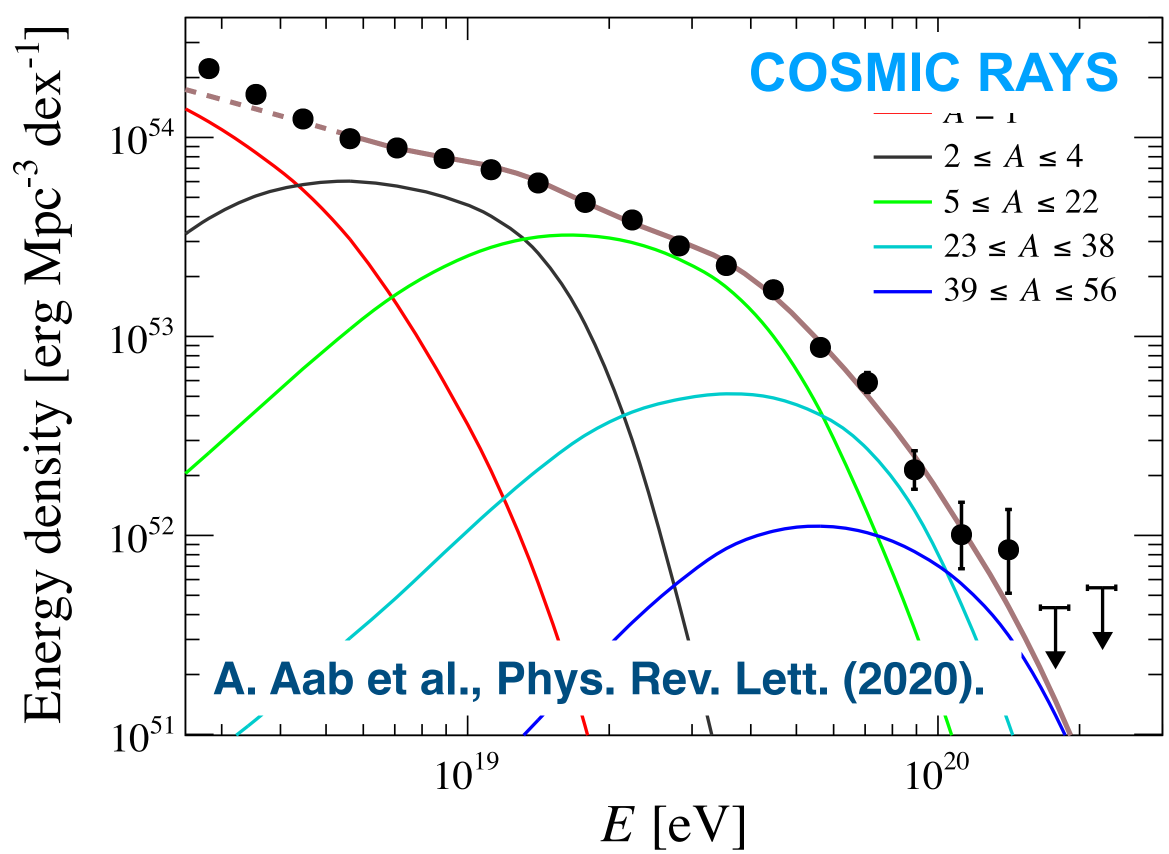
SFB 1258 Neutrinos Dark Matter Messengers

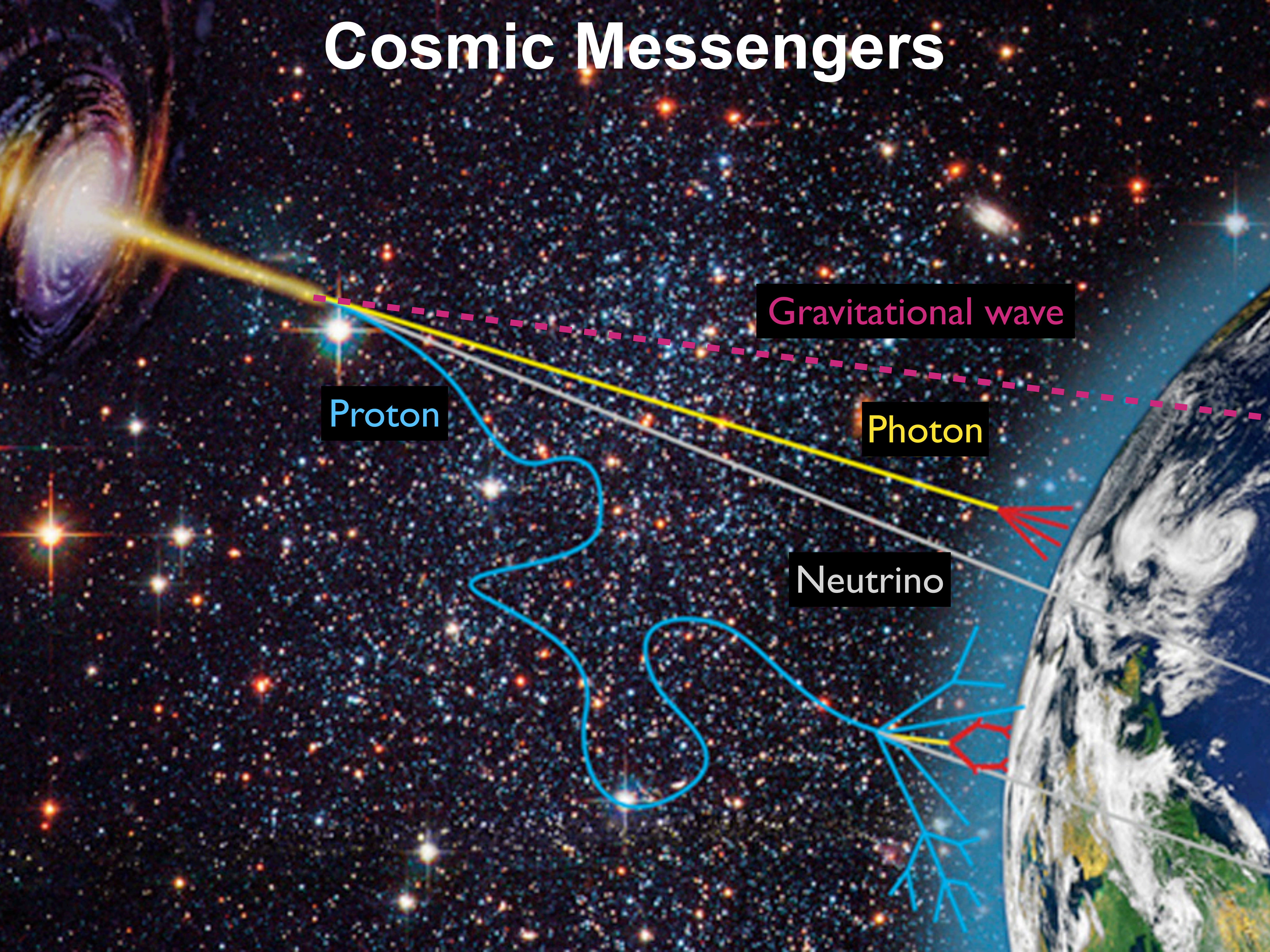
Cosmic Messengers









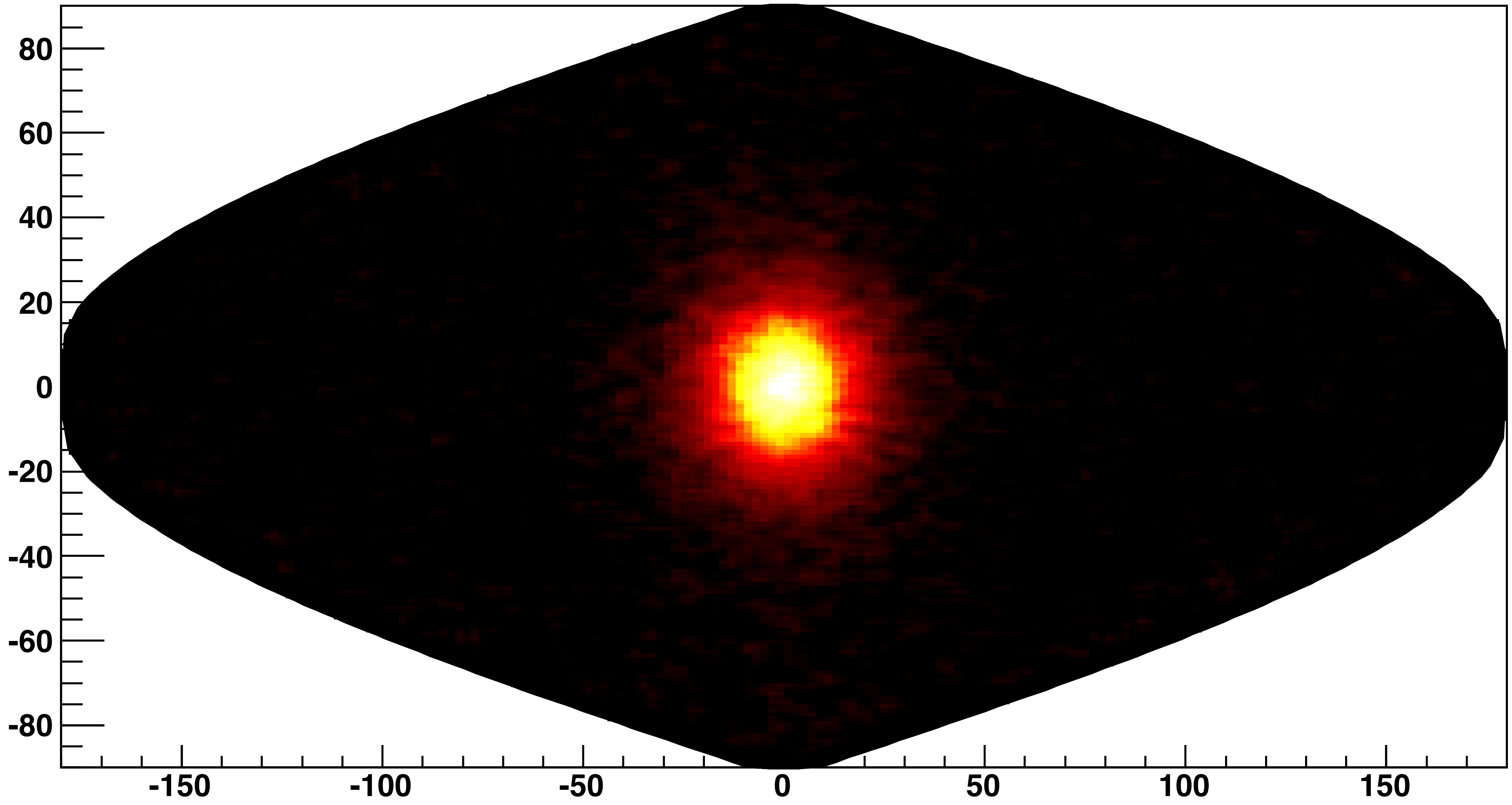

Cosmic Messengers
Gravitational wave
Proton
Photon
Neutrino

Outline

- Overview on current status
- Core-collapse supernovae and compact binary mergers
- Cosmic accelerators
- Outlook

Multi-Messenger Sources as of 2022: No. 1

The Sun

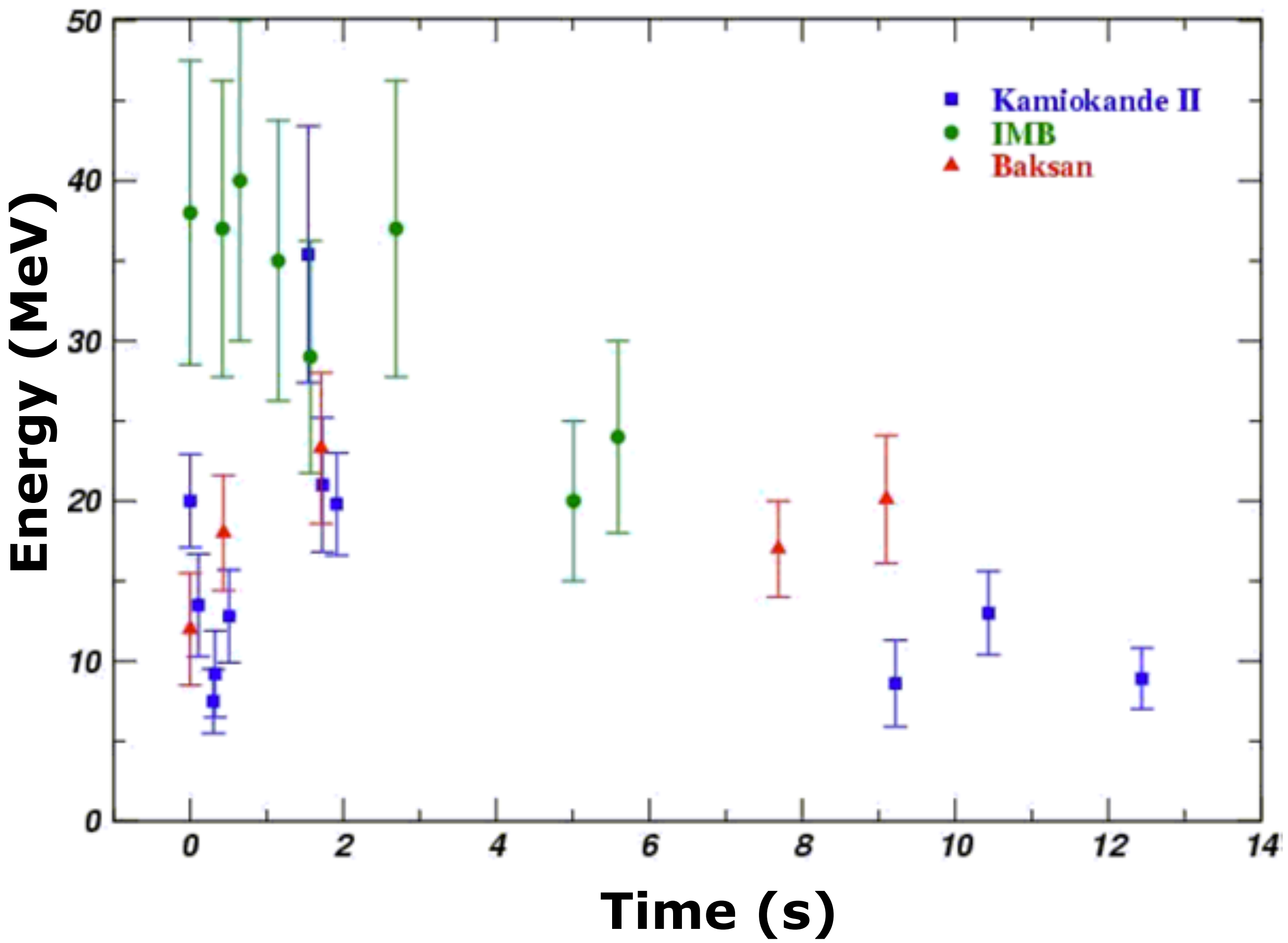


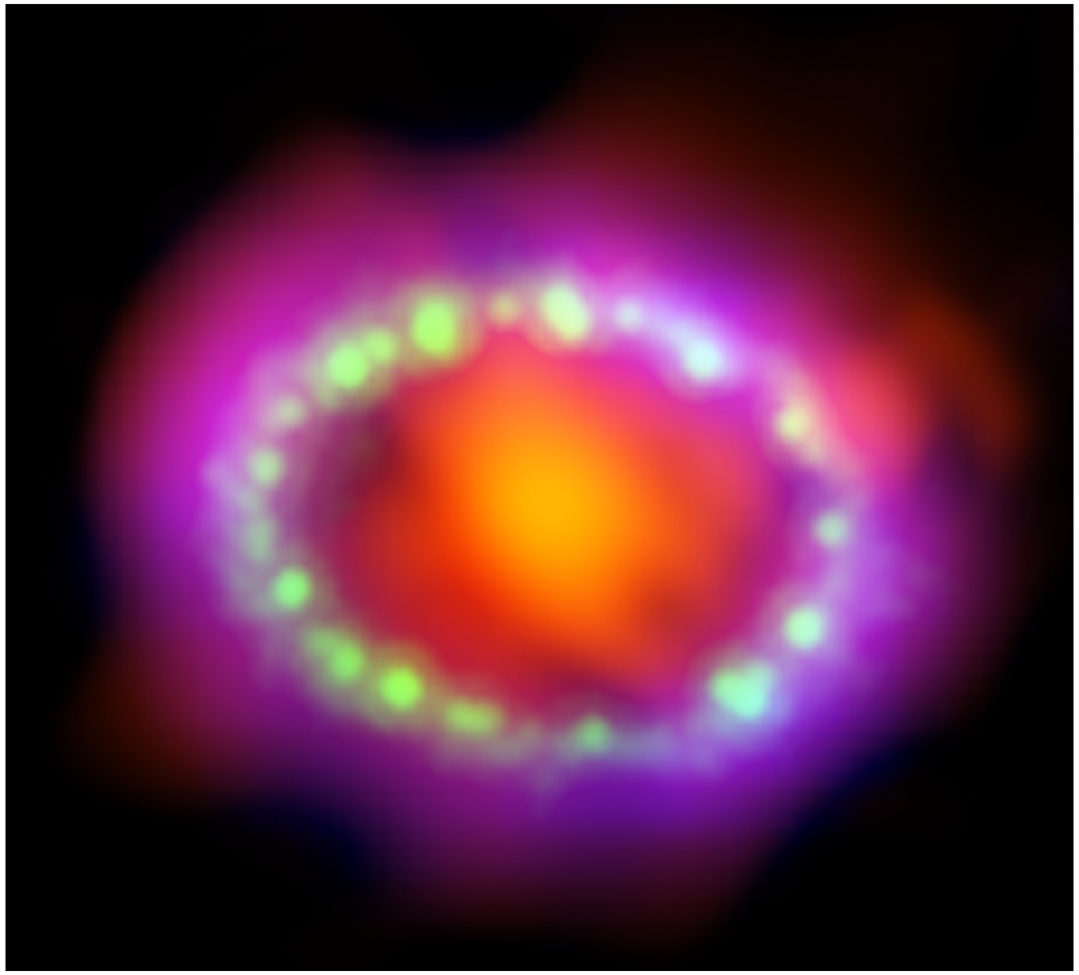
Multi-messenger observations. ⇨ **Discovery of neutrino oscillations.**
Test of Standard Solar Model.
Constraints on New Physics scenarios.

Image credits: Super-Kamiokande Collaboration.

Multi-Messenger Sources as of 2022: No. 2

Supernova 1987A





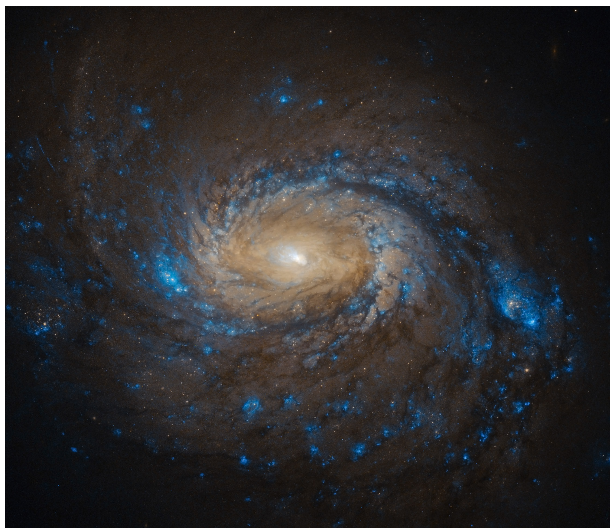
Multi-messenger observations. ⇨ **Test of core-collapse physics. Constraints on New Physics scenarios.**

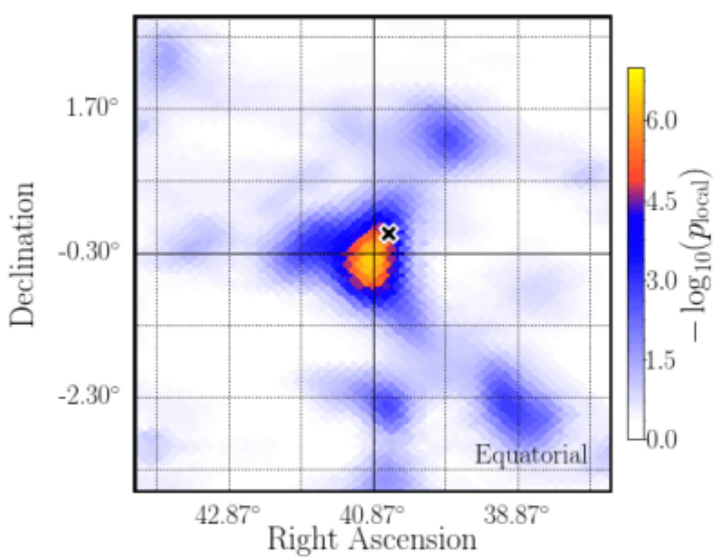
Image credits: NASA, CERNCOURIER.

Multi-Messenger Sources as of 2022: No. 3

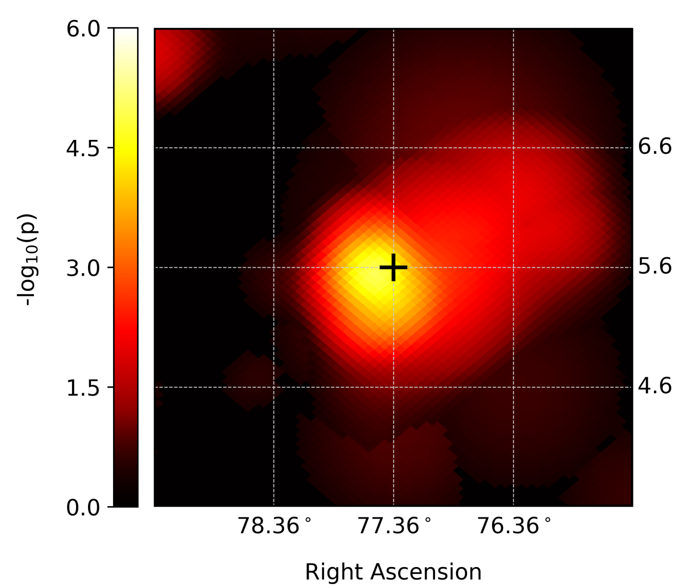
Cosmic Accelerators

Starburst Galaxies

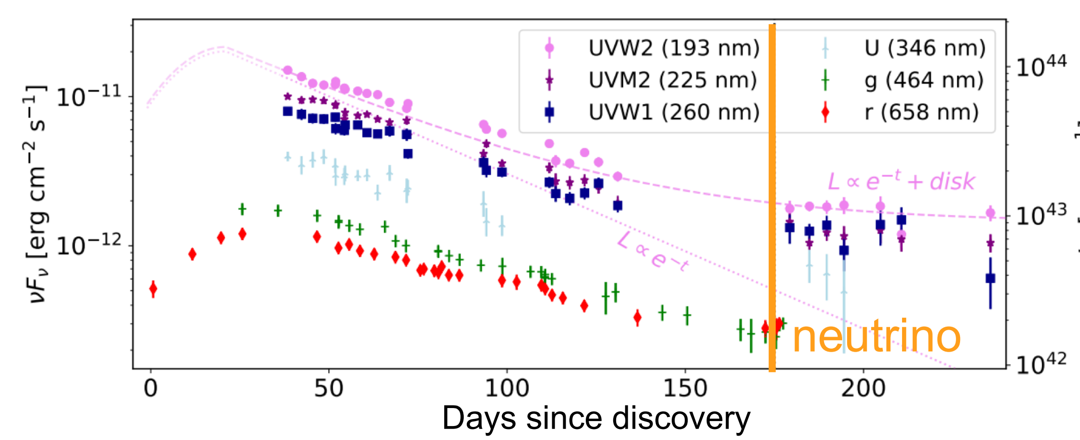




Blazars



Tidal Disruption Events



Several likely point source associations ⇨ **Test particle acceleration theory. Need for improved source modeling.**

Image credits: IceCube Collaboration.

Core-Collapse Supernovae

Figure credits: Royal Society

The Next Local Supernova (SN 2XXXA)

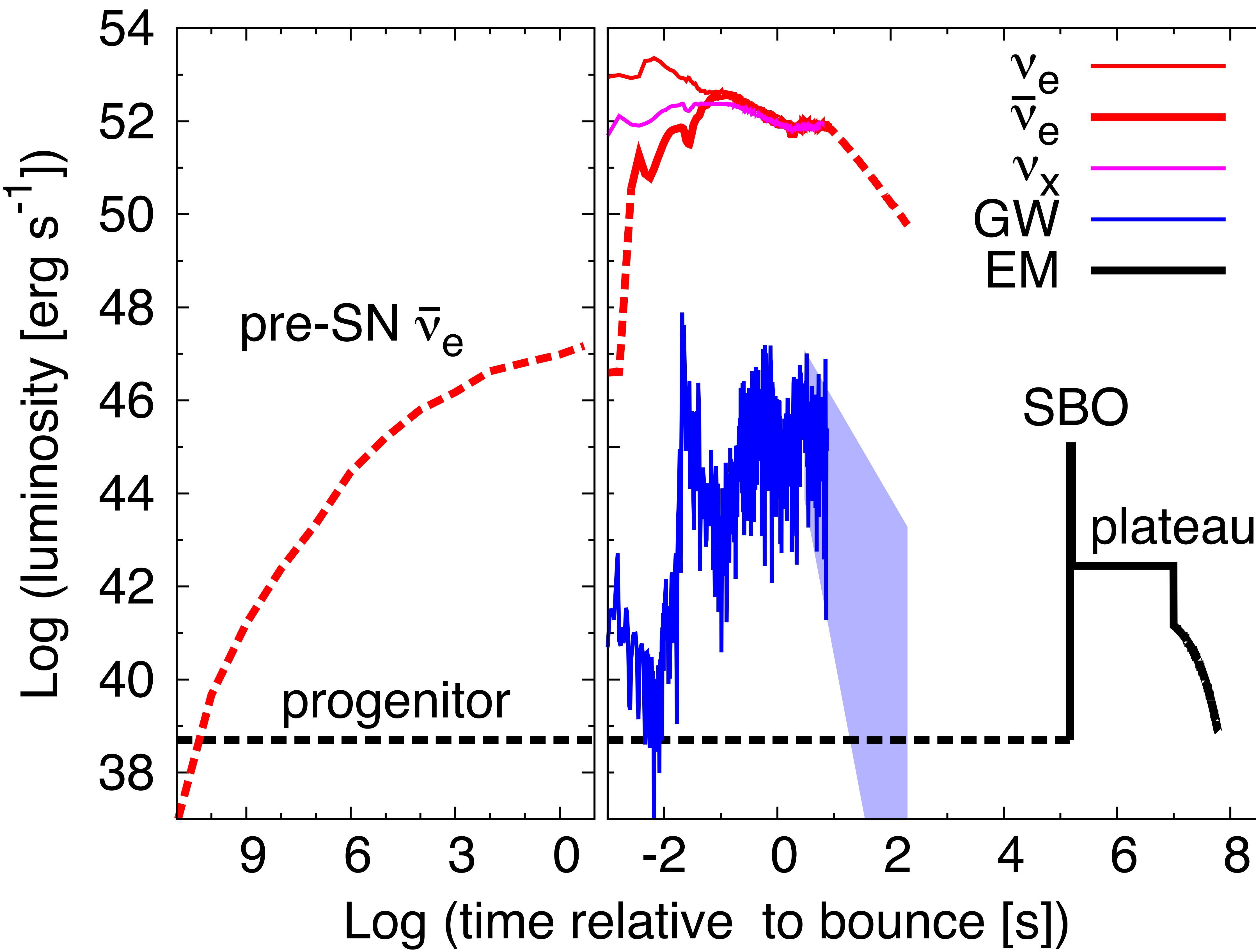
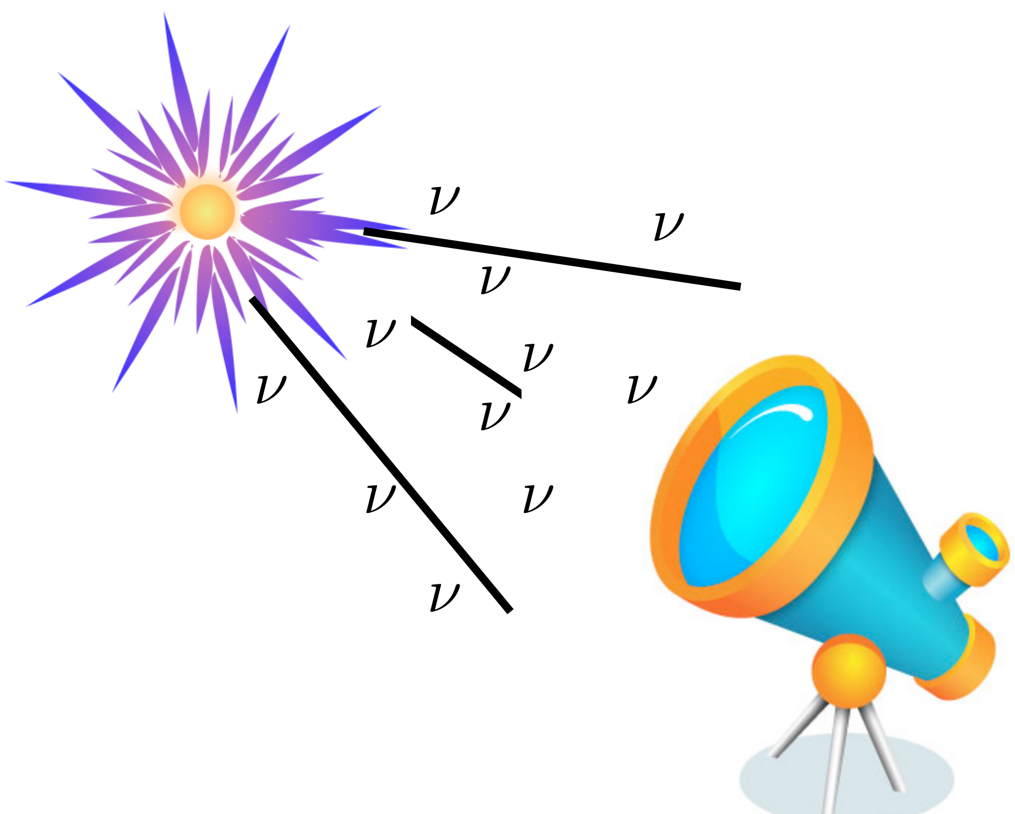


Figure from Nakamura et al., MNRAS (2016).

Neutrino Alert & Timing

SuperNova Early Warning System (SNEWS 2.0).

Network to alert astronomers of a burst.

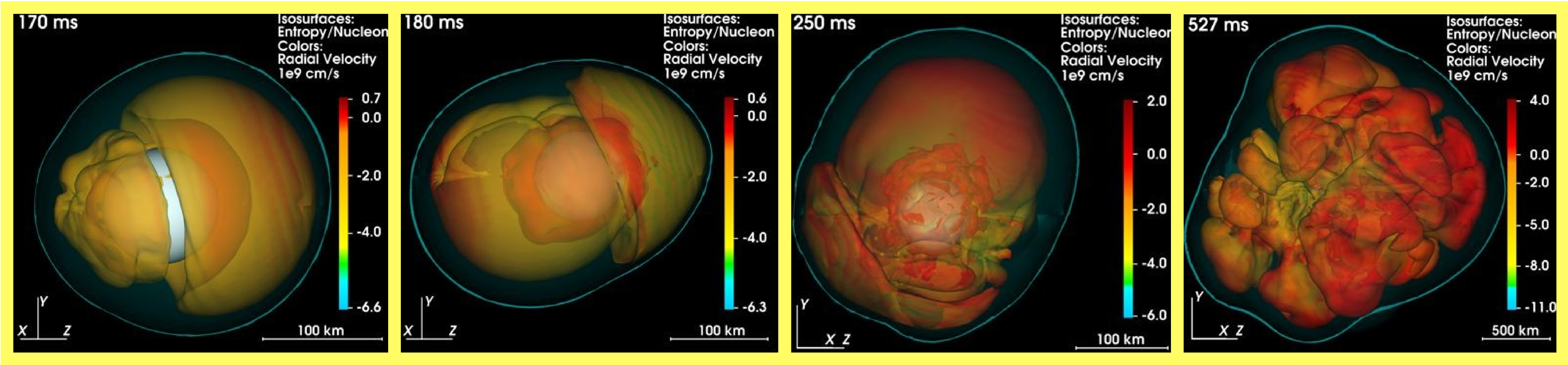


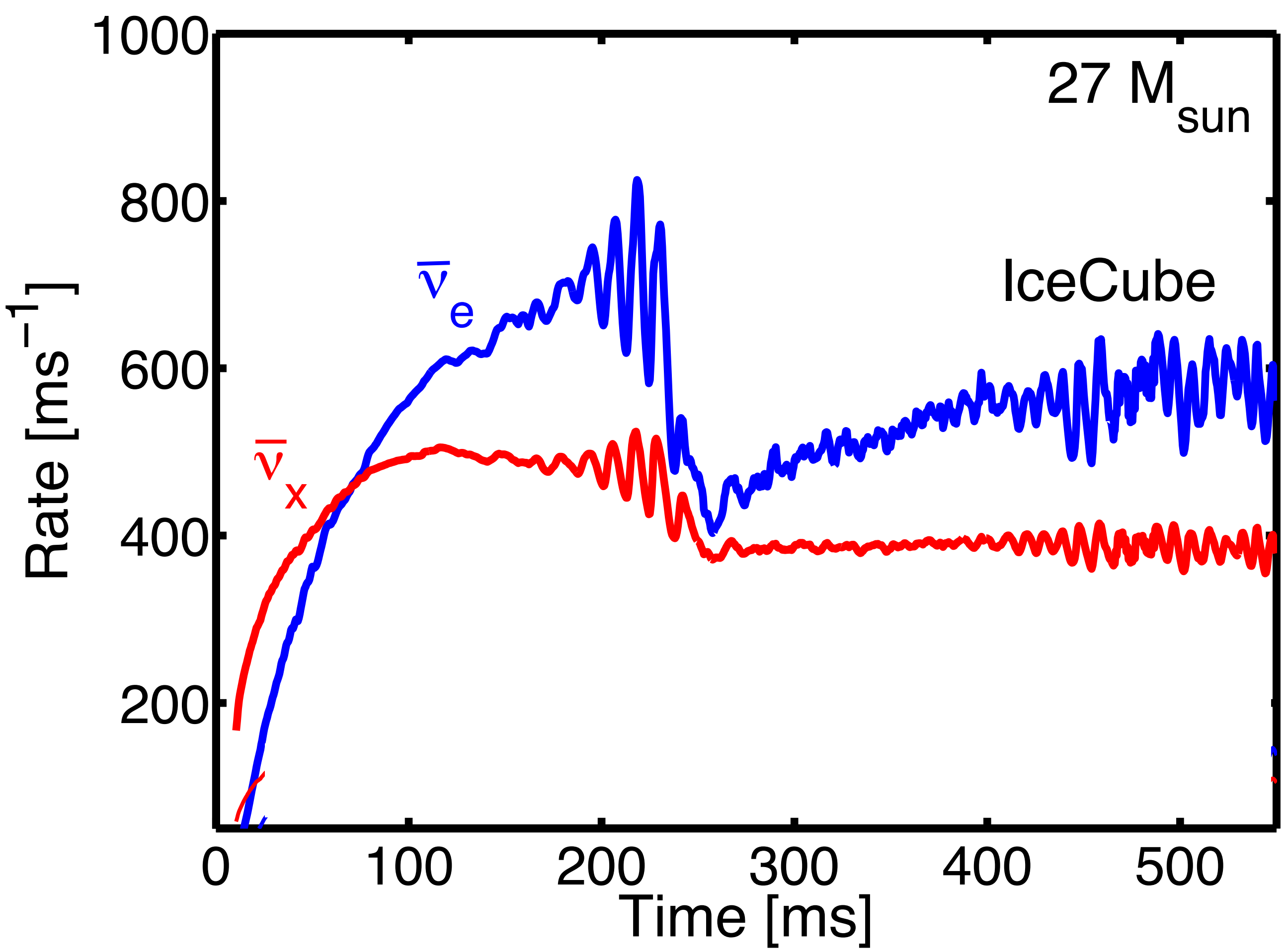
Determination of **supernova direction** with neutrinos [crucial for electromagnetically dim supernovae].

Determination of **core bounce time** with neutrinos [timing for gravitational wave detection].

SNEWS 2.0, New J. Phys. (2021). Sarfati, Hansen, Tamborra, PRD (2022). Tomas et al. (2003). Fisher et al. (2015). Linzer & Scholberg, PRD (2019). Brdar, Lindner, Xu, JCAP (2018). Muehlbeier et al., PRD (2013). Halzen & Raffelt PRD (2009).

Supernova Mechanism



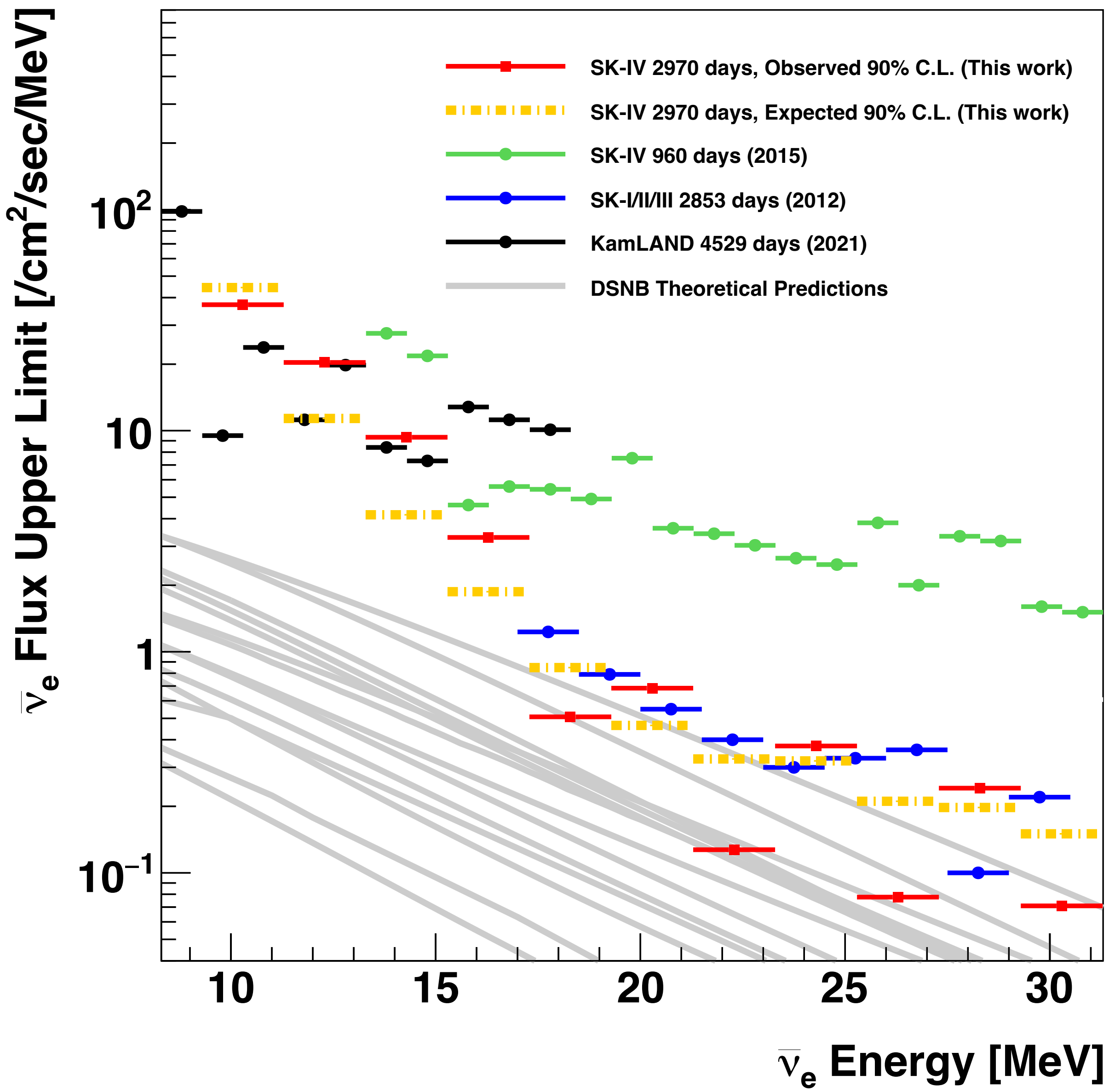


Neutrinos and gravitational waves

- Carry imprints of pre-explosion physics.
- Probe black hole formation.

Tamborra et al., PRL (2013), PRD (2014). Kuroda et al., ApJ (2017). Walk, Tamborra et al., PRD (2018, 2019, 2020). Andresen et al., MNRAS (2017,2019). Takiwaiki et al., MNRAS (2021) Lin et al., PRD (2020). Mezzacappa et al., arXiv: 2208.10643.

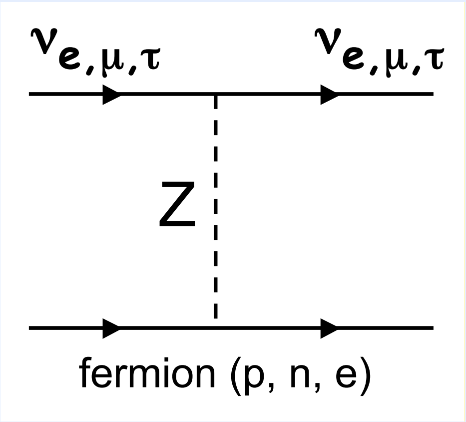
Diffuse Supernova Neutrino Background

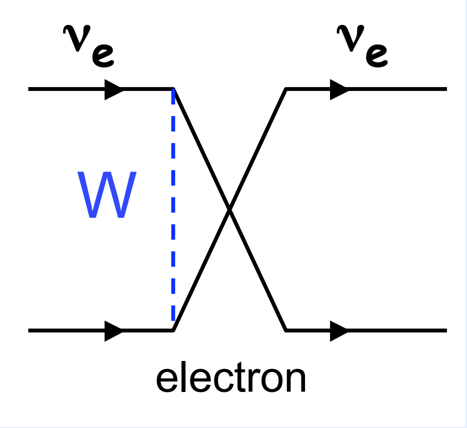


- Independent test of local supernova rate and fraction of black hole forming collapses.
- Modeling uncertainties are to be reduced.
- Detection expected to happen soon!

Figure from Abe et al., PRD (2021). Moller, Suliga, Tamborra, Denton, JCAP (2018). Kresse, Ertl, Janka, ApJ (2021). Lunardini & Tamborra, JCAP (2012). Horiuchi et al., PRD (2021). Ziegler et al., arXiv: 2205.07845.

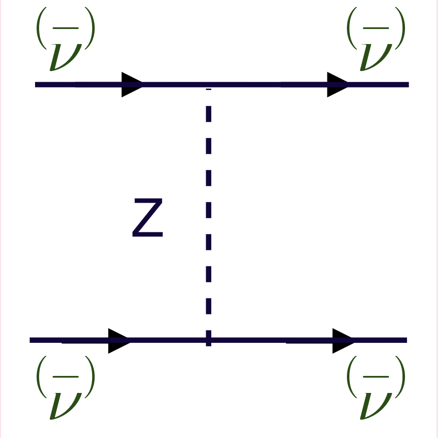
Neutrino Interactions





Neutrinos interact with background matter.

Linear phenomenon.

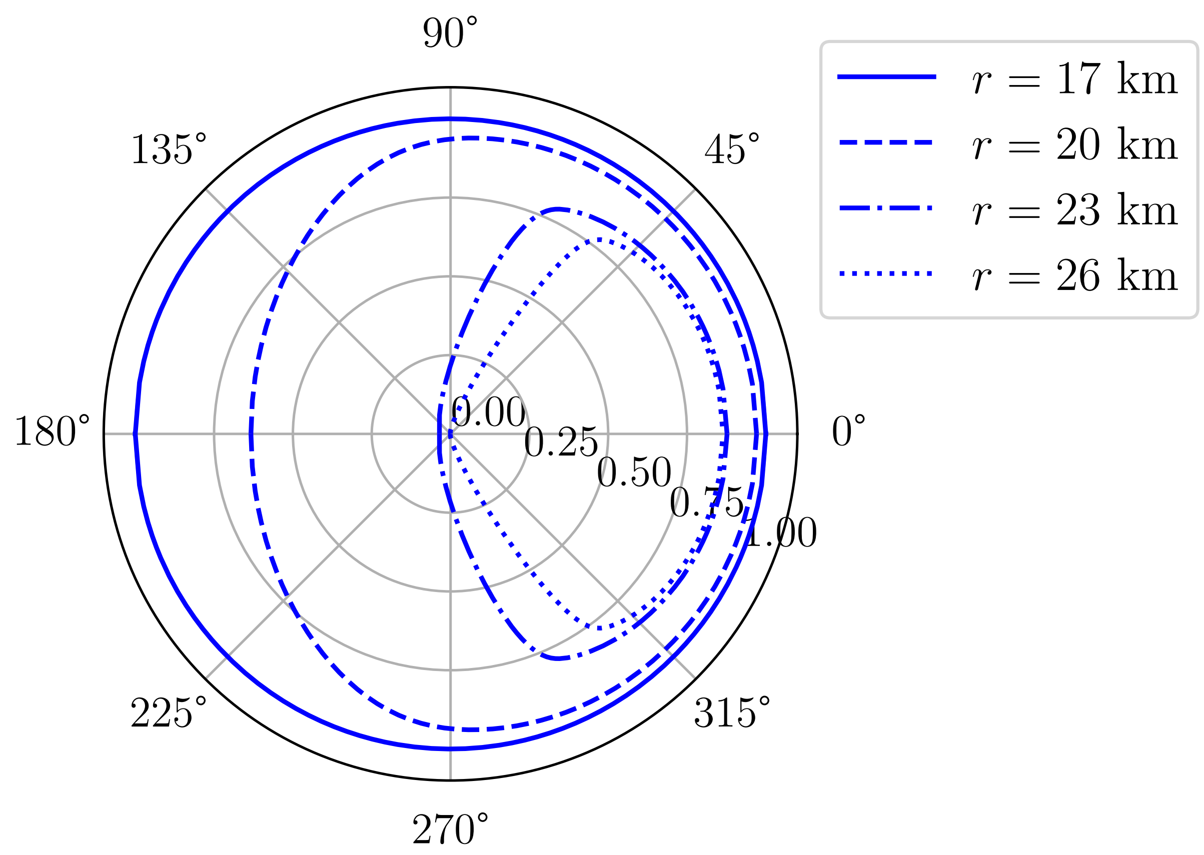


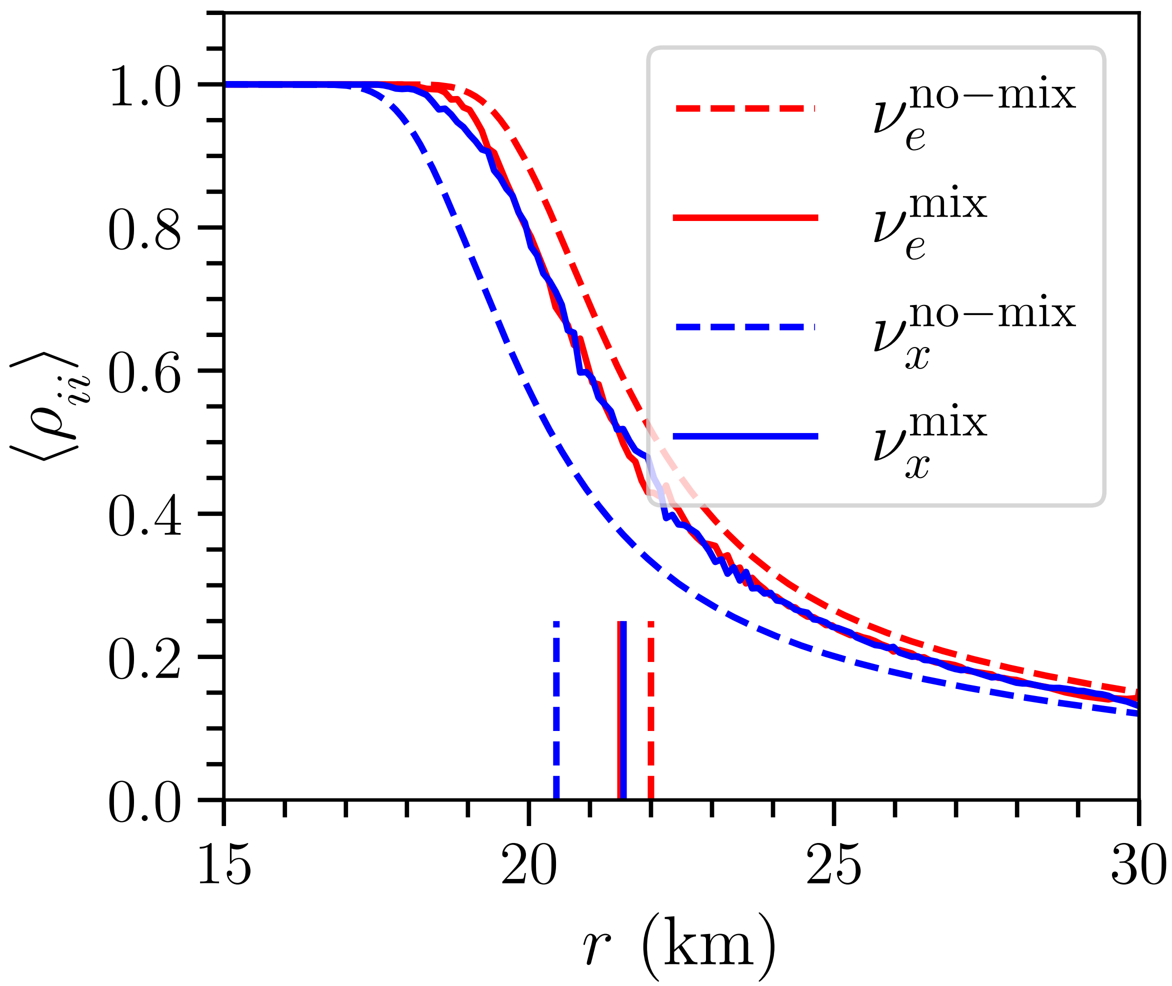
Neutrinos interact among themselves.

Non-linear phenomenon, trajectory is crucial!

Recent reviews: Tamborra & Shalgar, Ann. Rev. Nucl. Part. Sci. (2021). Richers & Sen, arXiv: 2207.03561.

Flavor Conversion in the Supernova Core

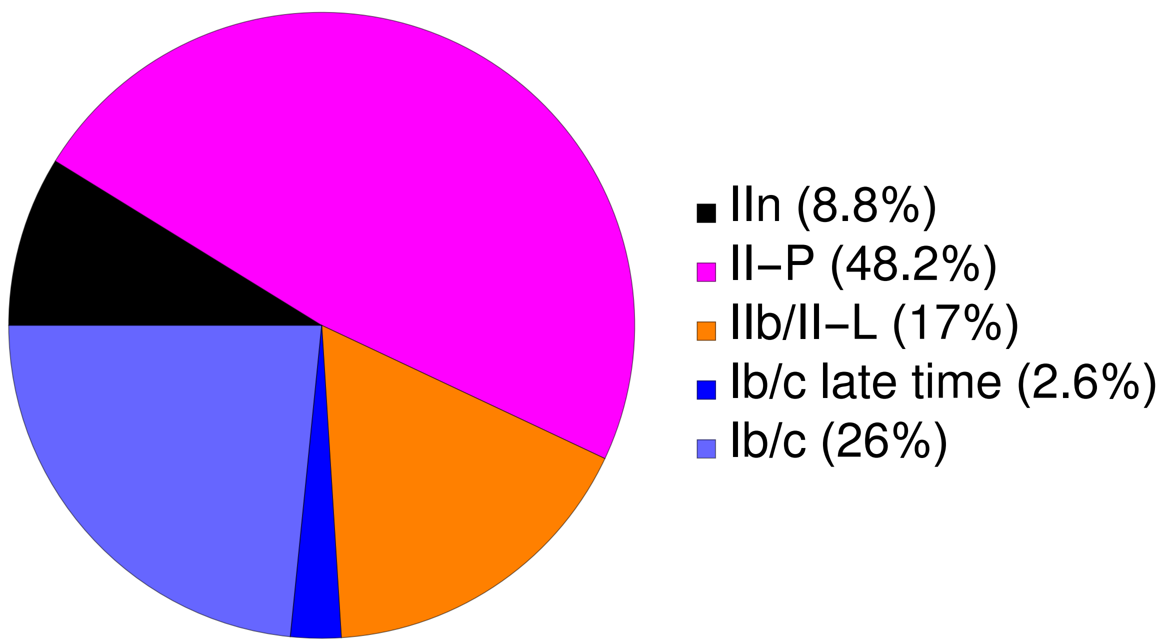


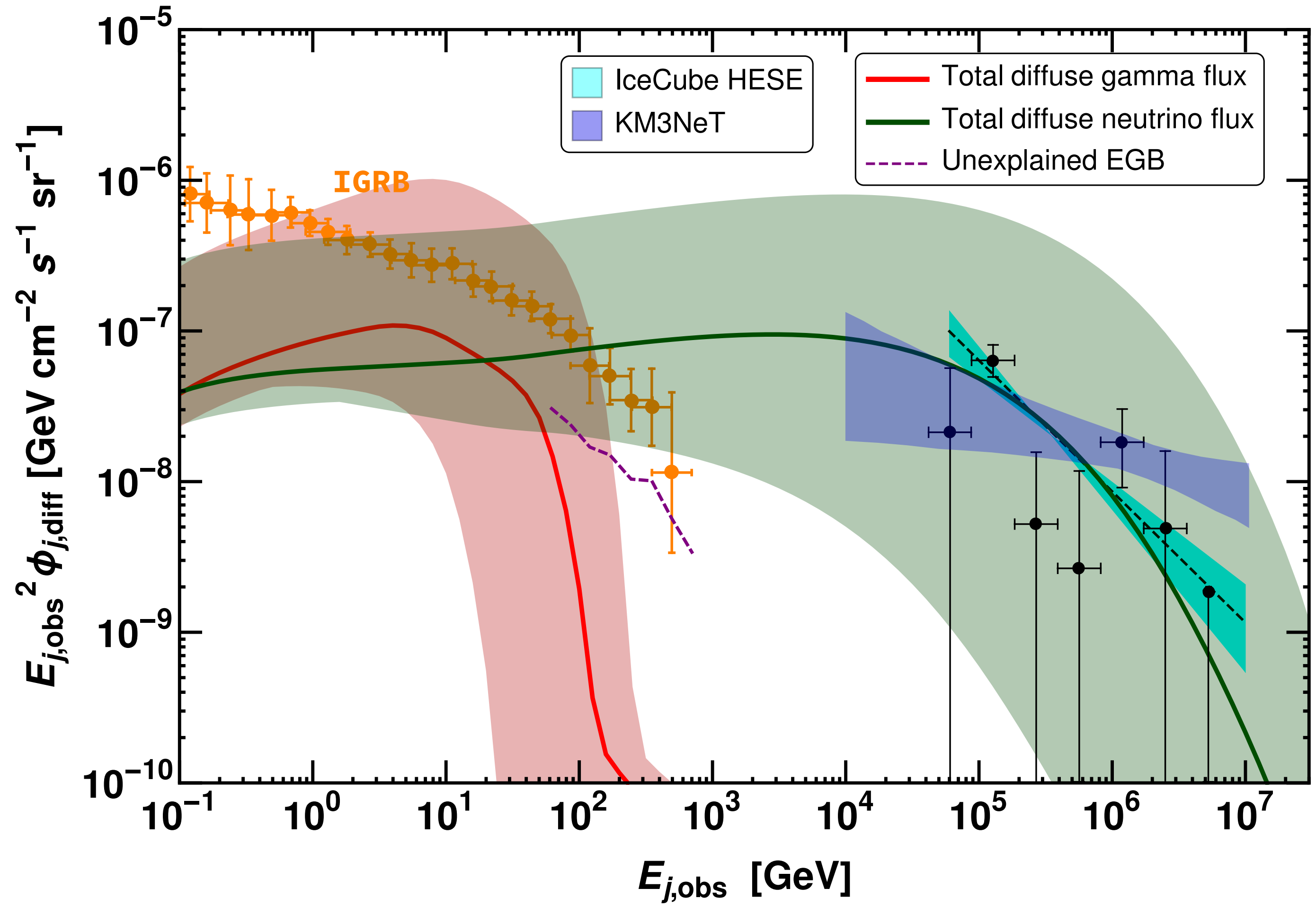


- Neutrino conversion is strongly affected by collisions and advection.
- Neutrino decoupling from matter is affected by flavor conversion.
- Implications on multi-messenger observations yet to be determined.

Shalgar & Tamborra, arXiv: 2206.00676, arXiv: 2207.04058. Padilla-Gay, Tamborra, Raffelt, PRL (2022). Shalgar, Padilla-Gay, Tamborra, JCAP (2020). Shalgar, Tamborra, PRD (2020, 2021). Richers, Willcox, Ford, PRD (2021). Wu et al., PRD (2021). …

High Energy Emission from Supernovae





Supernovae may explain the low-energy excess observed in the diffuse background of high-energy neutrinos, without overshooting the gamma-ray diffuse background (no need to invoke hidden cosmic ray accelerators?).

Sarmah, Chackraborty, Tamborra, Auchettl, JCAP (2022). Brose, Sushch, Mackey, arXiv: 2208.04185.
Murase, Guetta, Ahlers, PRL (2016). Murase, Ioka, PRL (2013). Tamborra, Ando, PRD (2014).

Compact Binary Mergers

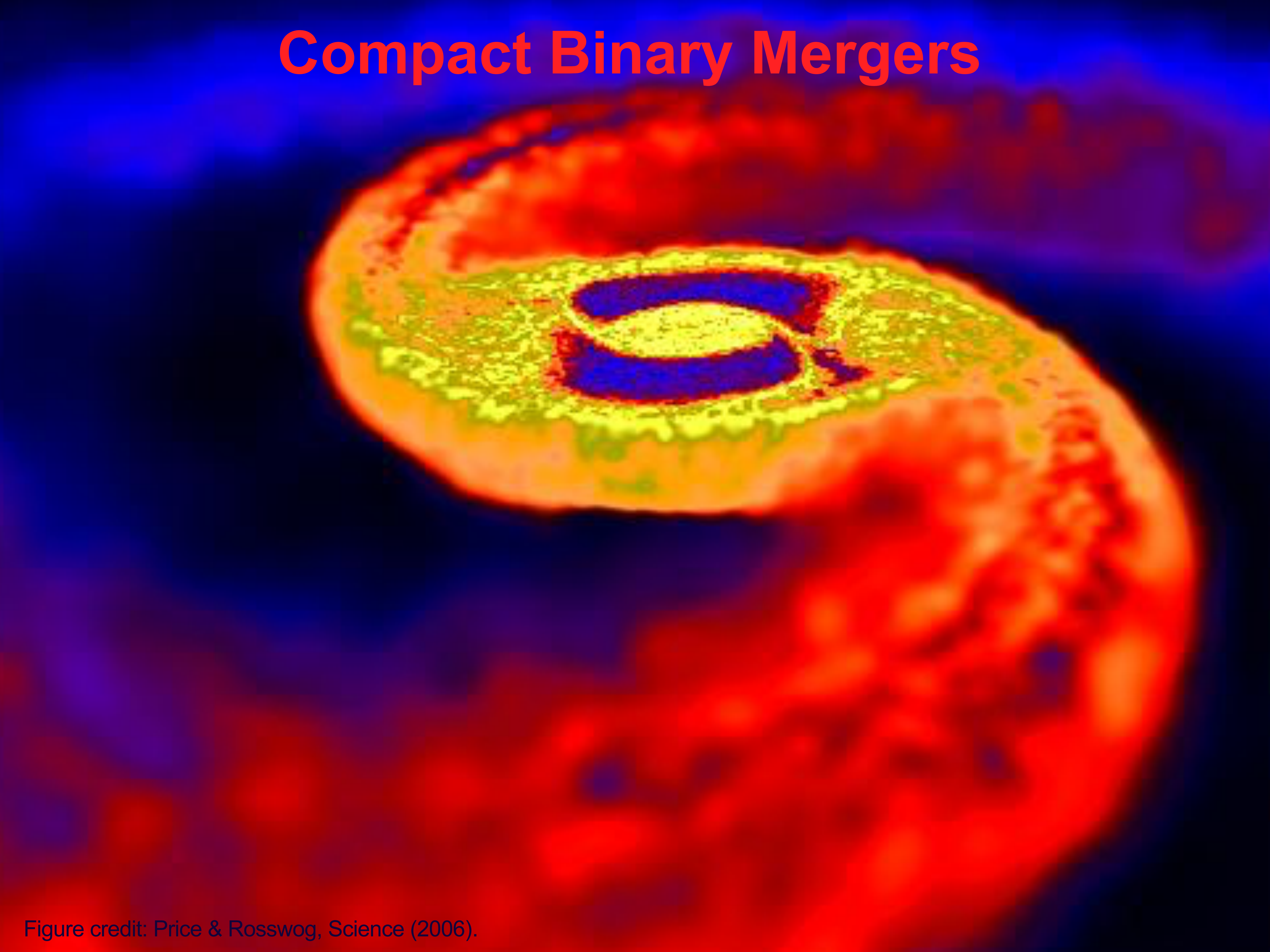


Figure credit: Price & Rosswog, Science (2006).

The Next Binary Merger (GW XXXX22)

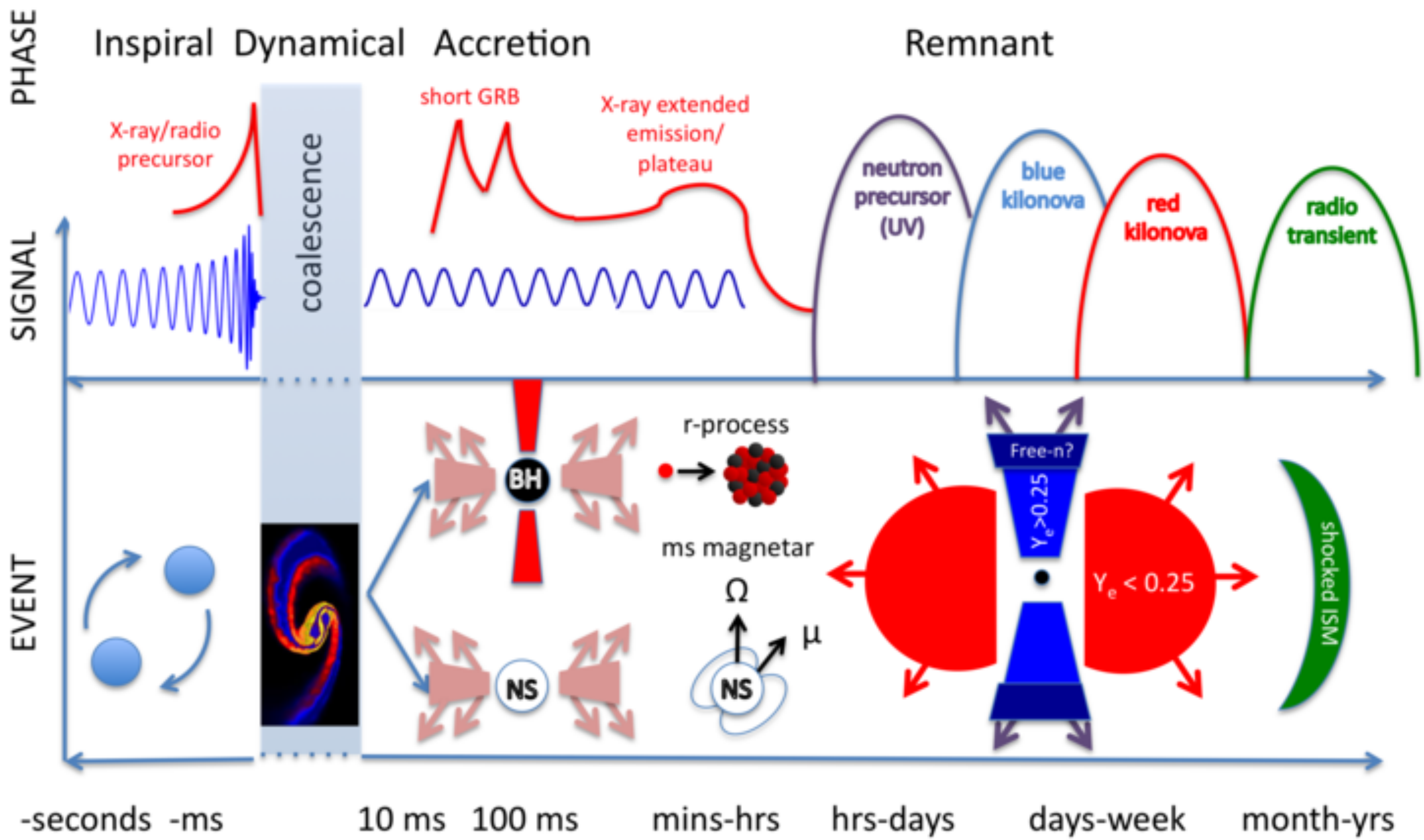
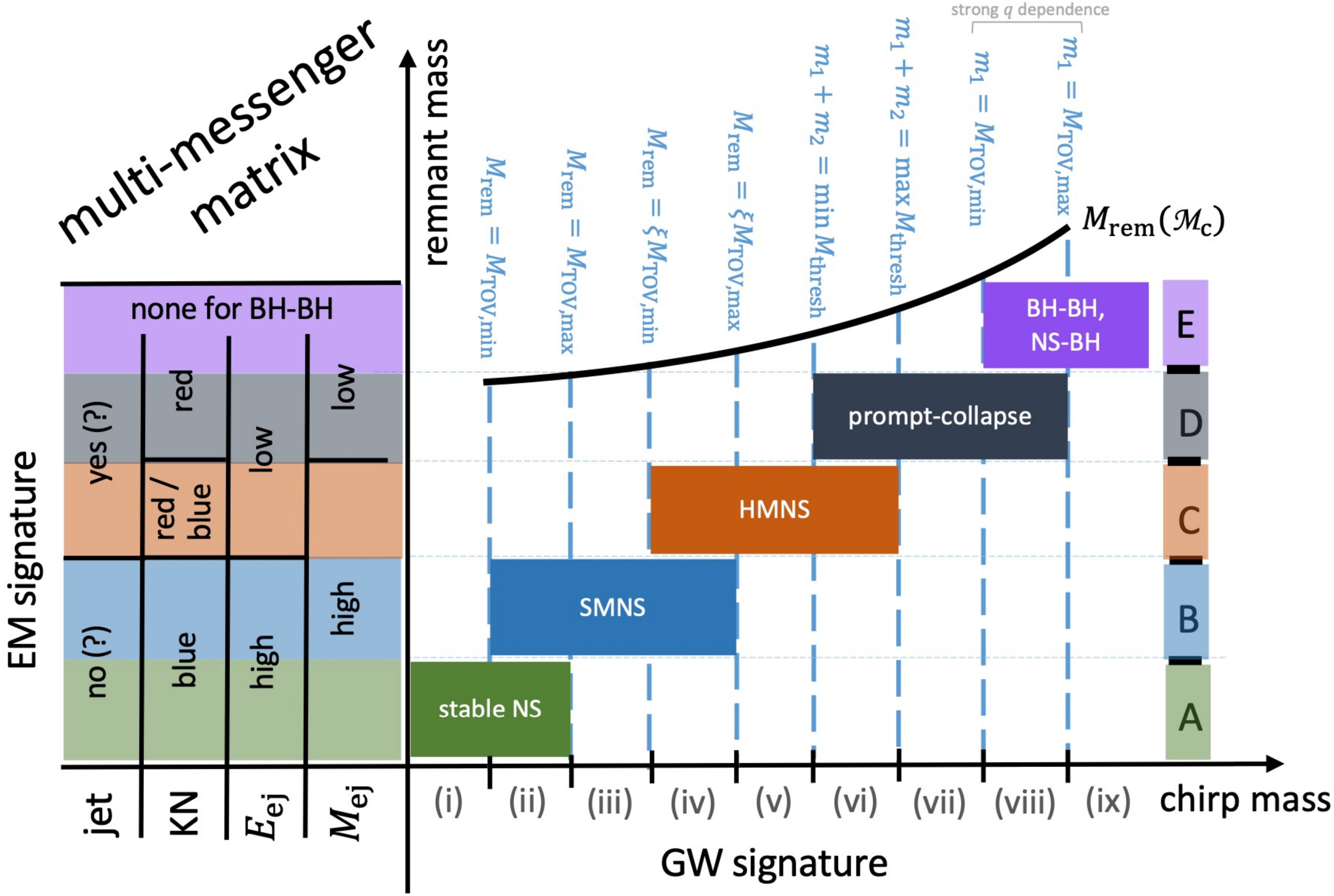


Figure credit: R. Fernandez & B. Metzger, Ann. Rev. Nucl. Part. Sci. (2016).

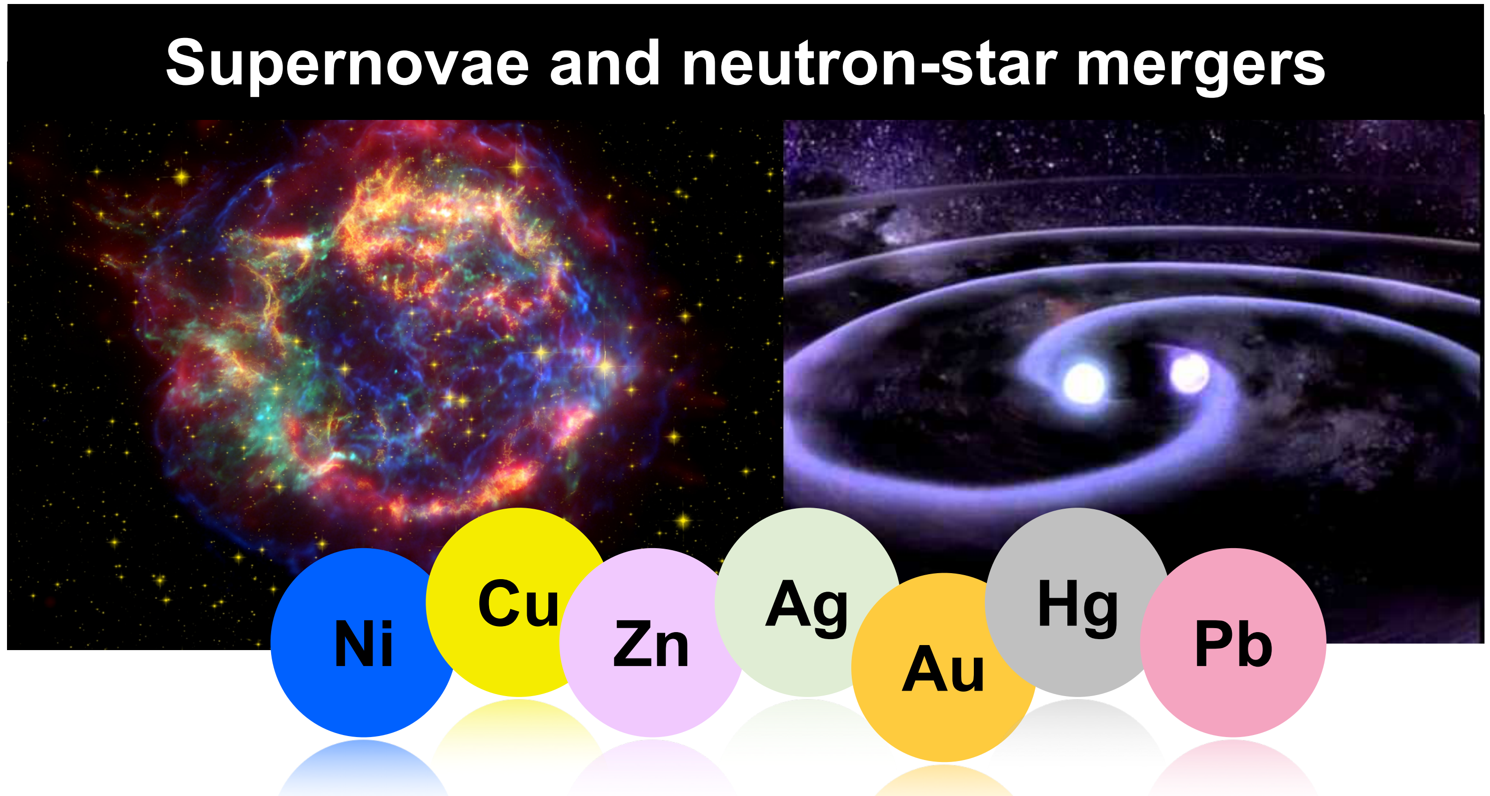
Multi-Messenger Opportunities



Using EM observations to ascertain the outcomes of future compact mergers detected in GWs, we could assess the diversity of their r-process contributions and probe nuclear EoS.

Margalit & Metzger, ApJL (2019). Bauswein et al., ApJL (2017).

Nucleosynthesis of the Heavy Elements

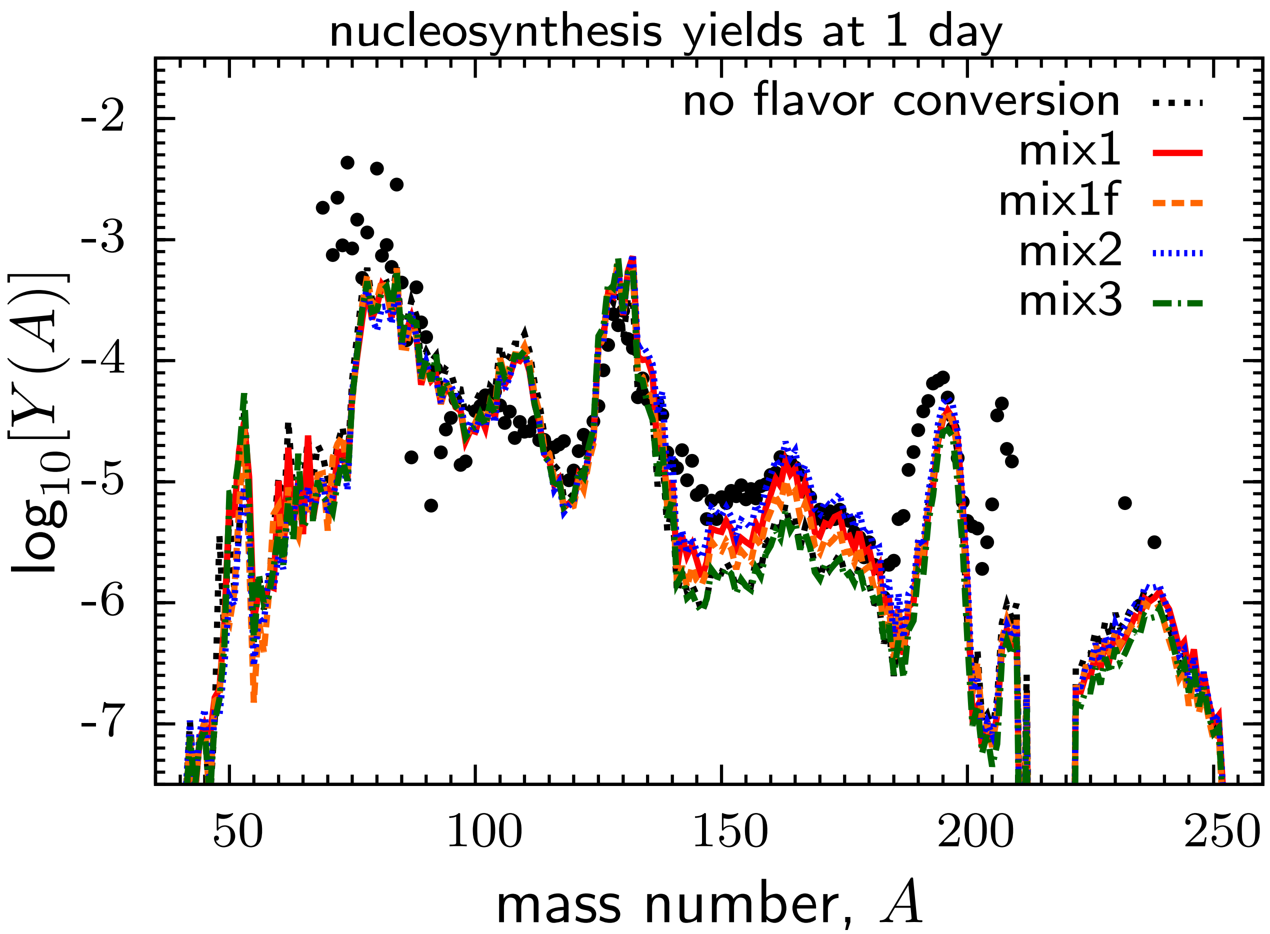


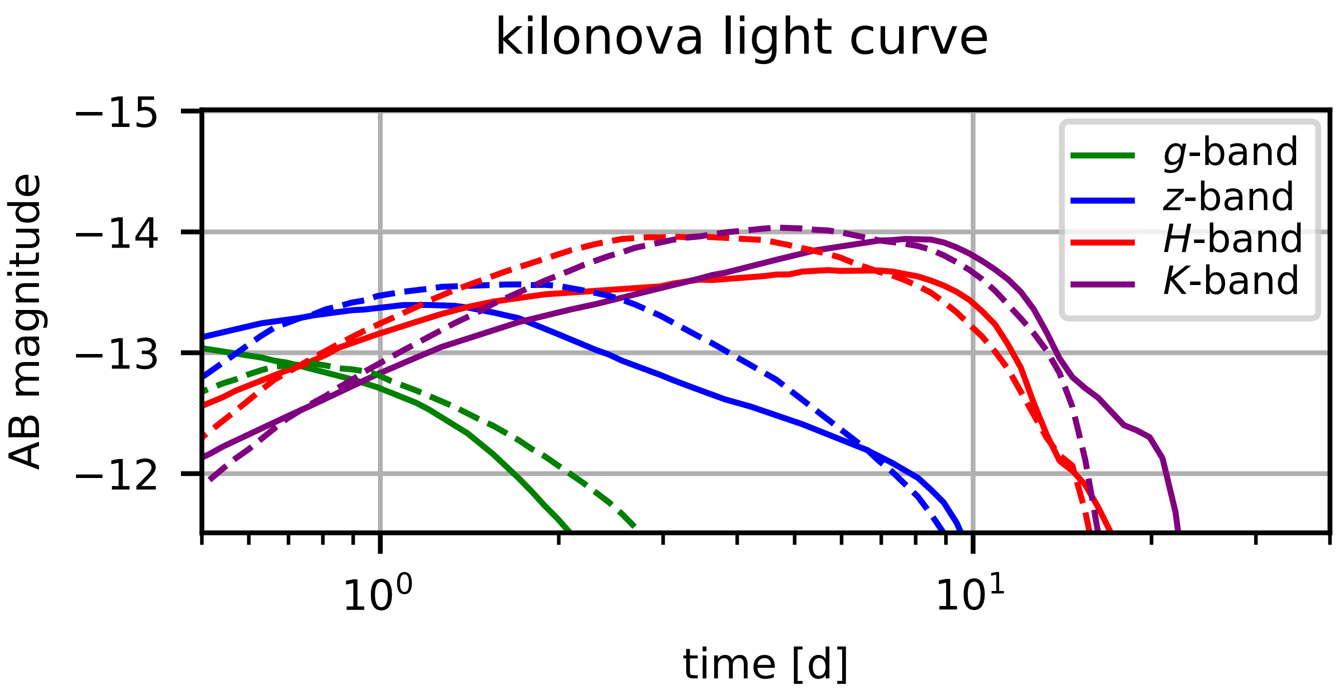
Synthesis of heavy elements depends on neutrino flavor.

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

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

Nucleosynthesis of the Heavy Elements

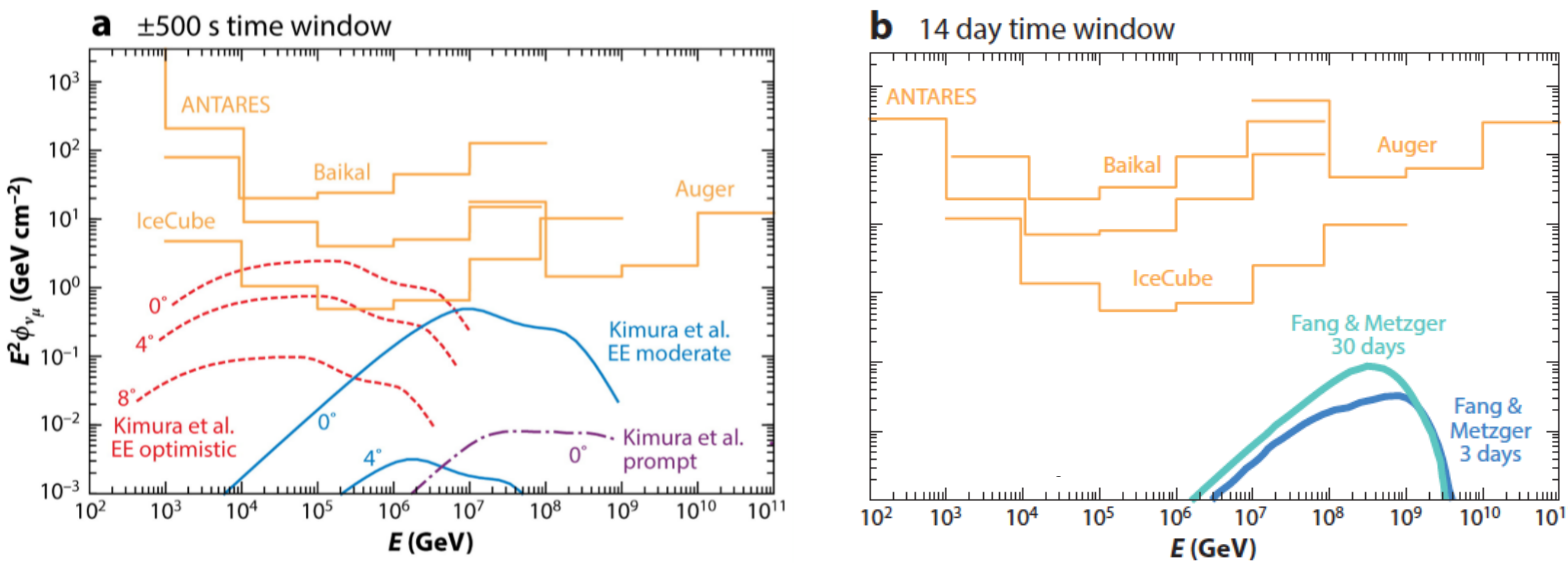




- Flavor conversion enhances synthesis nuclei with A>130 by a factor 2-3.
- More work needed to grasp how neutrinos affect electromagnetic emission.

Just, Abbar, Wu, Tamborra, Janka, Capozzi, PRD (2022). Wu, Tamborra, Just, Janka, PRD (2017). Wu & Tamborra, PRD (2017). Padilla-Gay, Shalgar, Tamborra, JCAP (2021). George, Wu, Tamborra, Ardevol-Pulpillo, Janka, PRD (2020). Li & Siegel, PRL (2021). Fernandez, Richers, Mulyk, Fahlman, arXiv: 2207.10680.

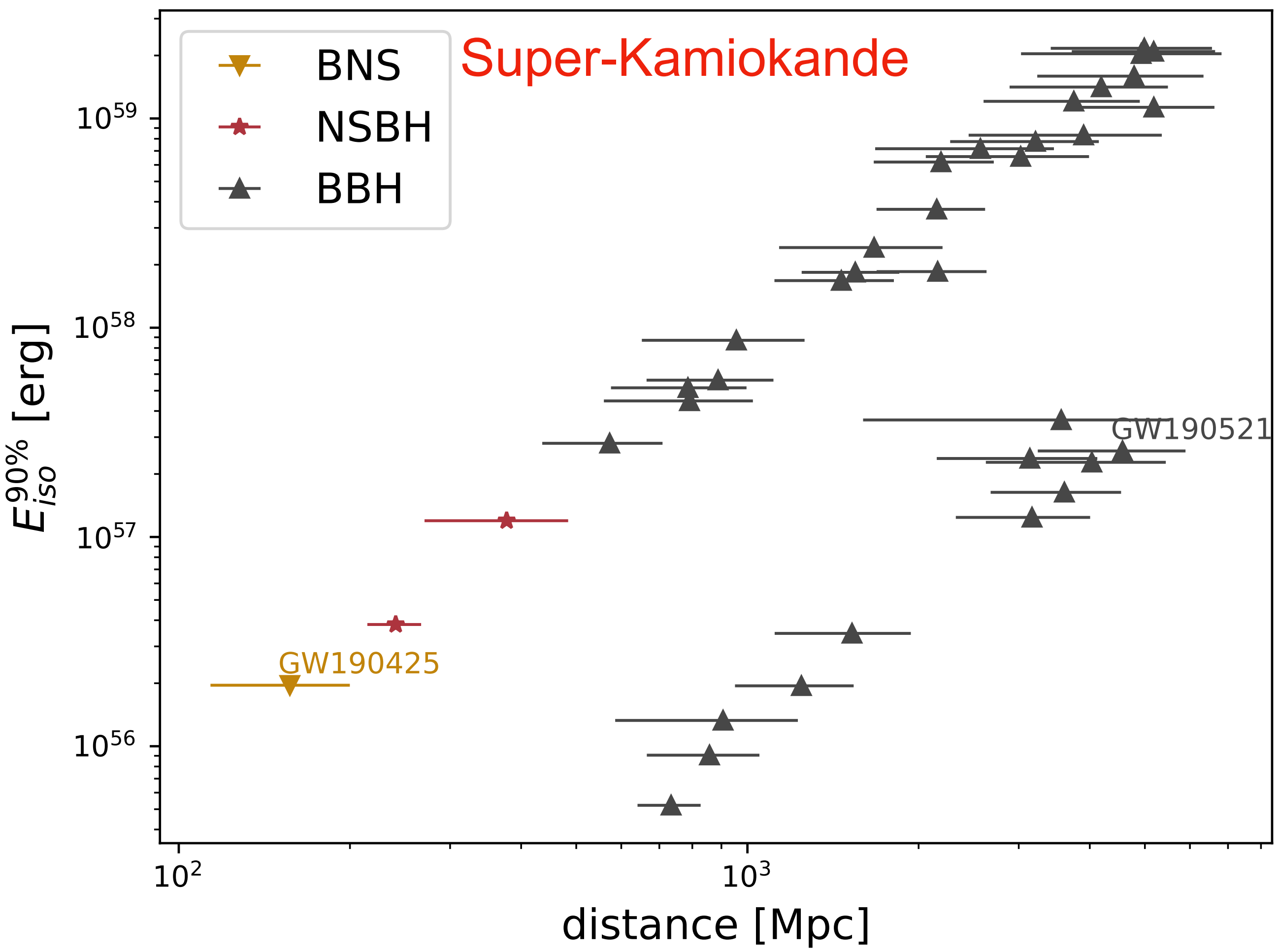
High Energy Neutrinos from GRB 170817A?

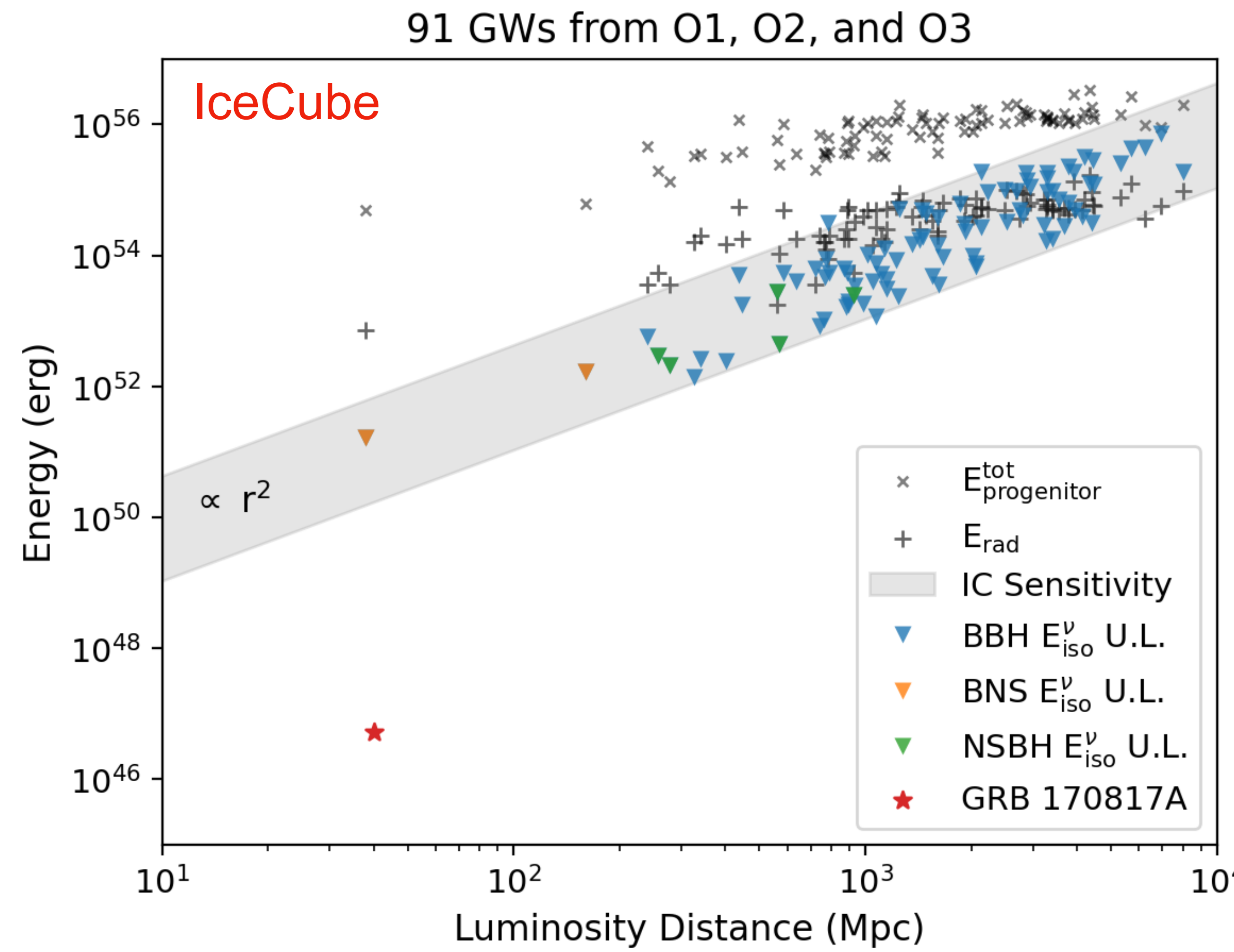


- No neutrinos detected from prompt short GRB phase.
- Neutrinos from long-lived ms magnetar following the merger.
- Neutrinos from internal shock propagating in kilonova ejecta.
- Favorable detection opportunities with multi-messenger triggers.

Figure credit: Christian Spiering. Murase& Bartos, Ann. Rev. (2019). Fang & Metzger, ApJ (2017). Kimura et al., PRD (2018). Biehl et al., MNRAS (2018). Kyutoku, Kashiyama, PRD (2018). Tamborra, Ando, JCAP (2015). Gottlieb, Globus, ApJL (2021).

Neutrinos from Gravitational Wave Sources

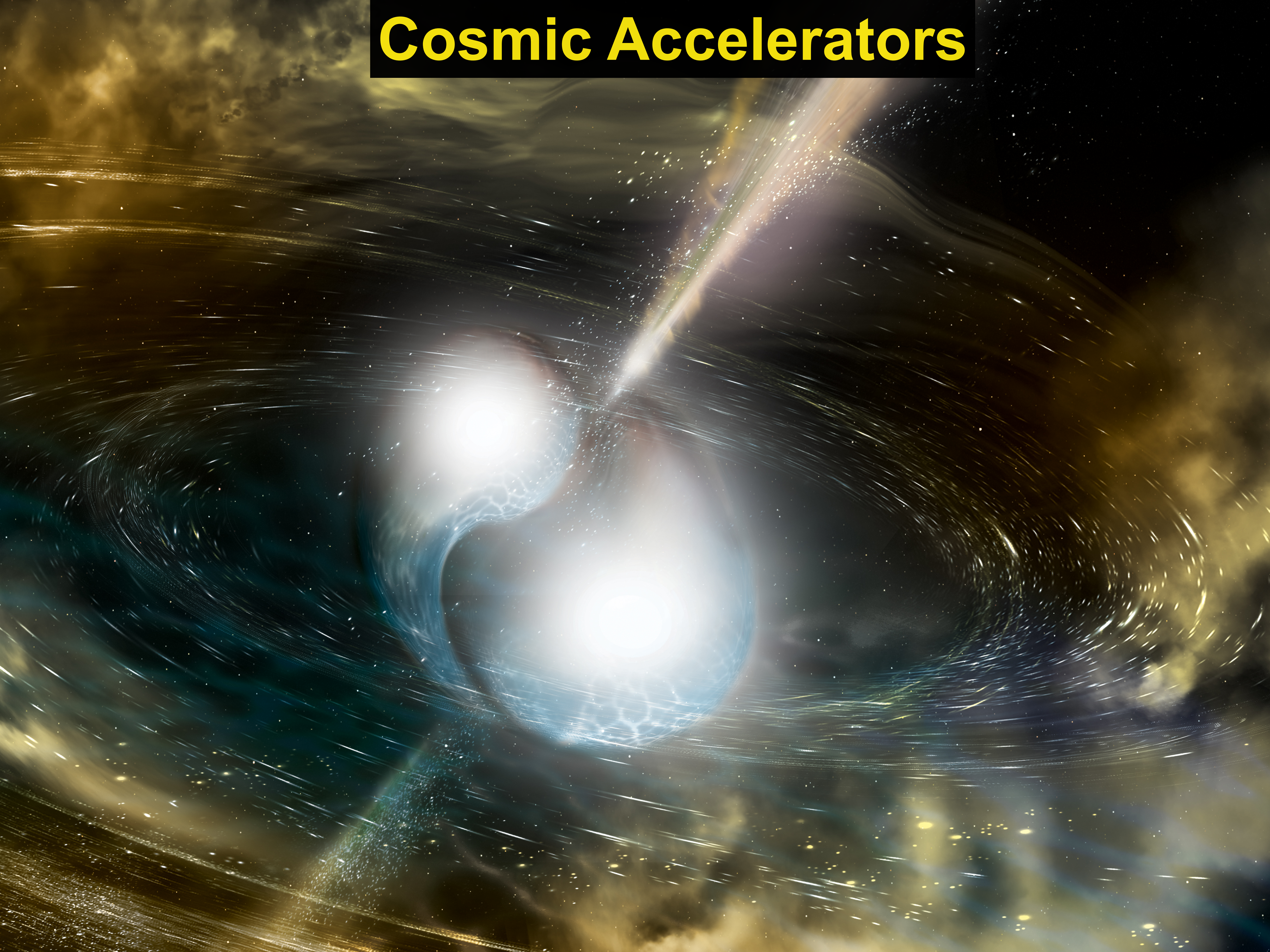




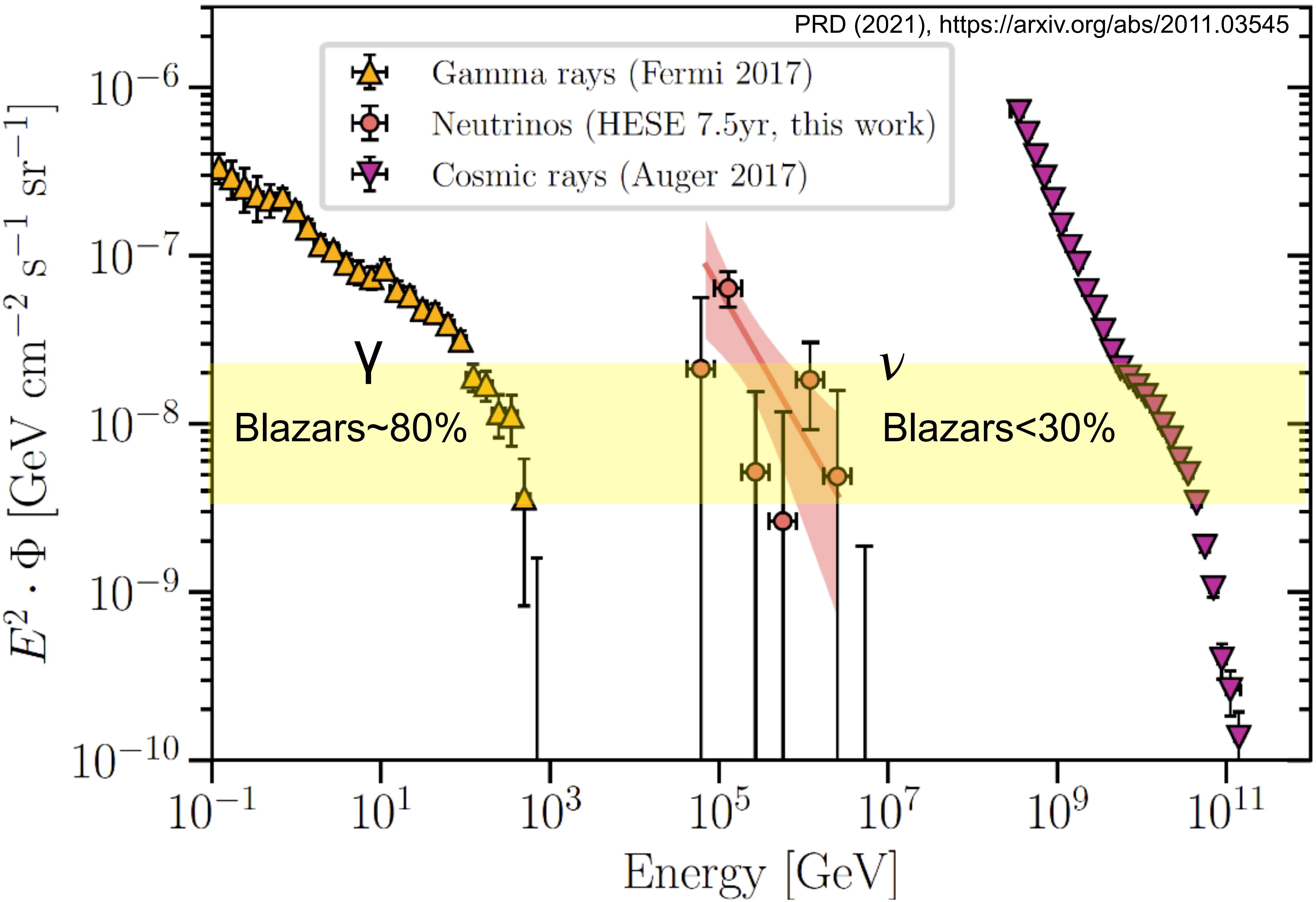
No neutrino counterpart found, upper limits in agreement with theoretical expectations.

Abe et al., ApJ (2021). Doga Veske, ICRC 2021, PoS 950. Abbassi et al., arXiv: 2208.09532.

Cosmic Accelerators



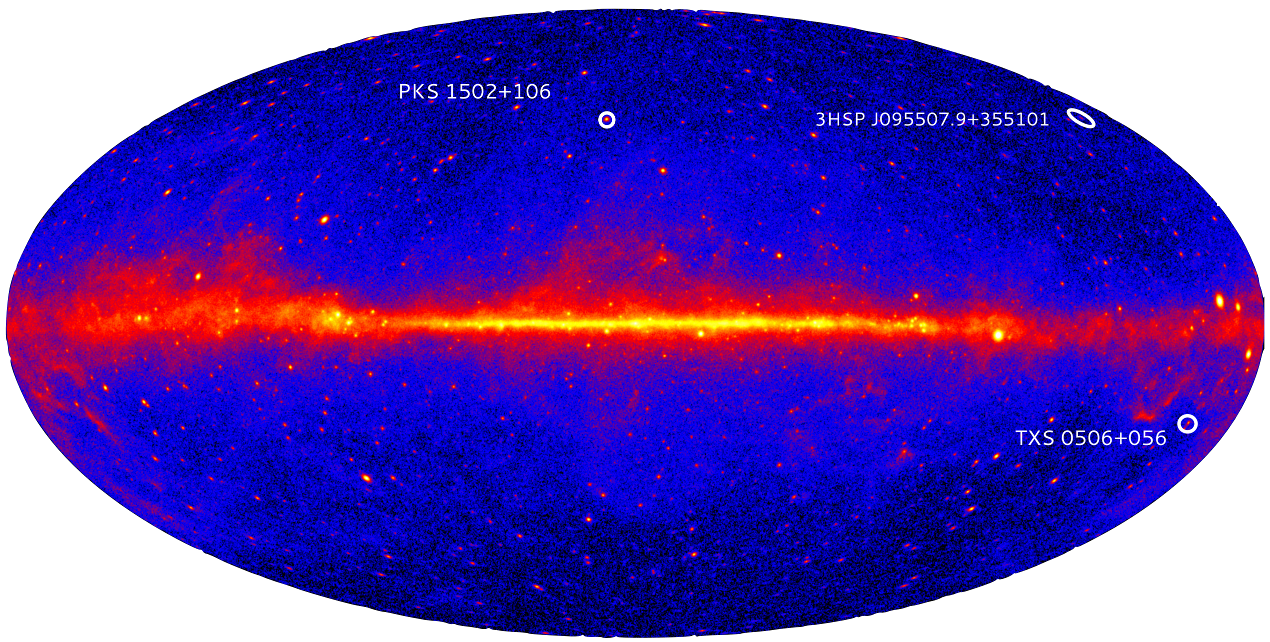
Do We See a Connection Among All Messengers?

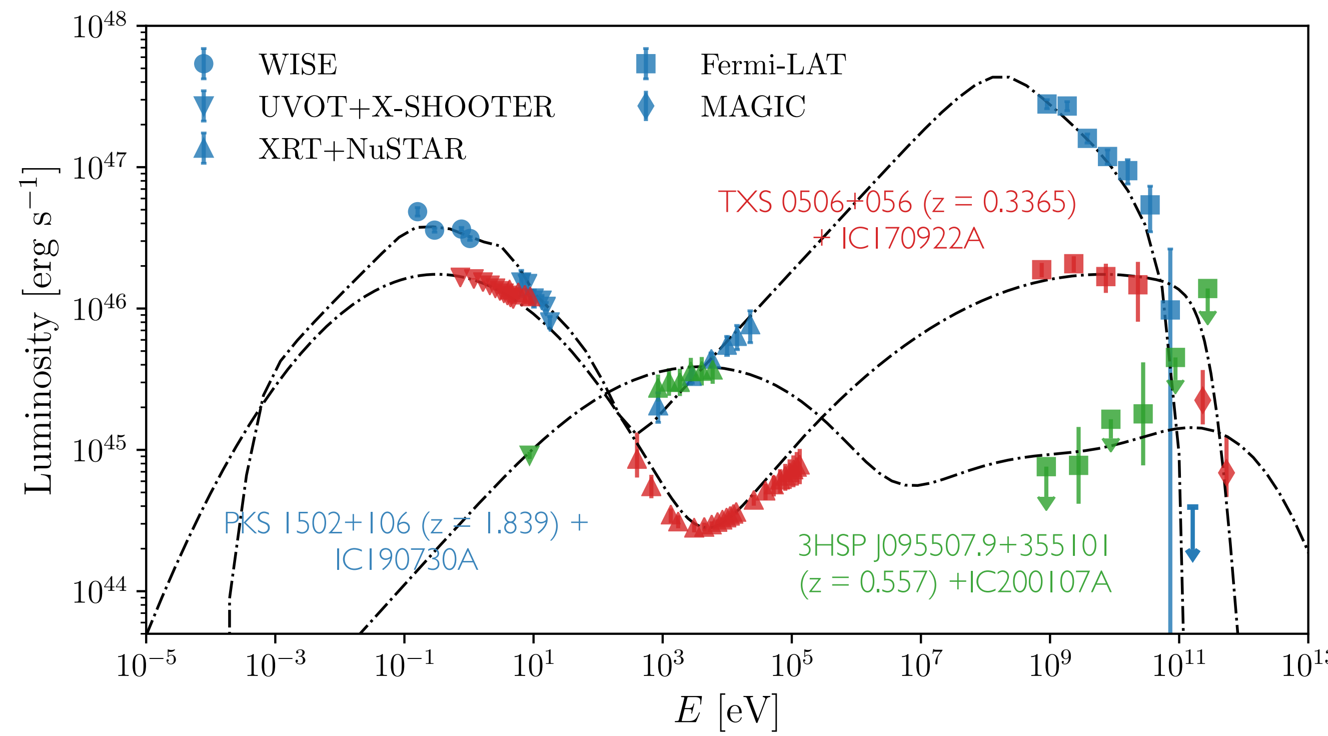


Marek Kowalski, ICRC 2021, PoS 022.

High-Energy Neutrinos from Blazars?

Several IceCube neutrino events may be in coincidence with blazars.





- Models statistically consistent with the detection of neutrinos but require extreme parameters, atypical of the blazar population.
- Need to move beyond one-zone model as well as investigate time variability.
- Multi-wavelength long-term evolution needs to be explored.
- Emerging trend of possible correlation between neutrino and radio/X-ray data to be understood.

Figure credit: F. Oikonomou.

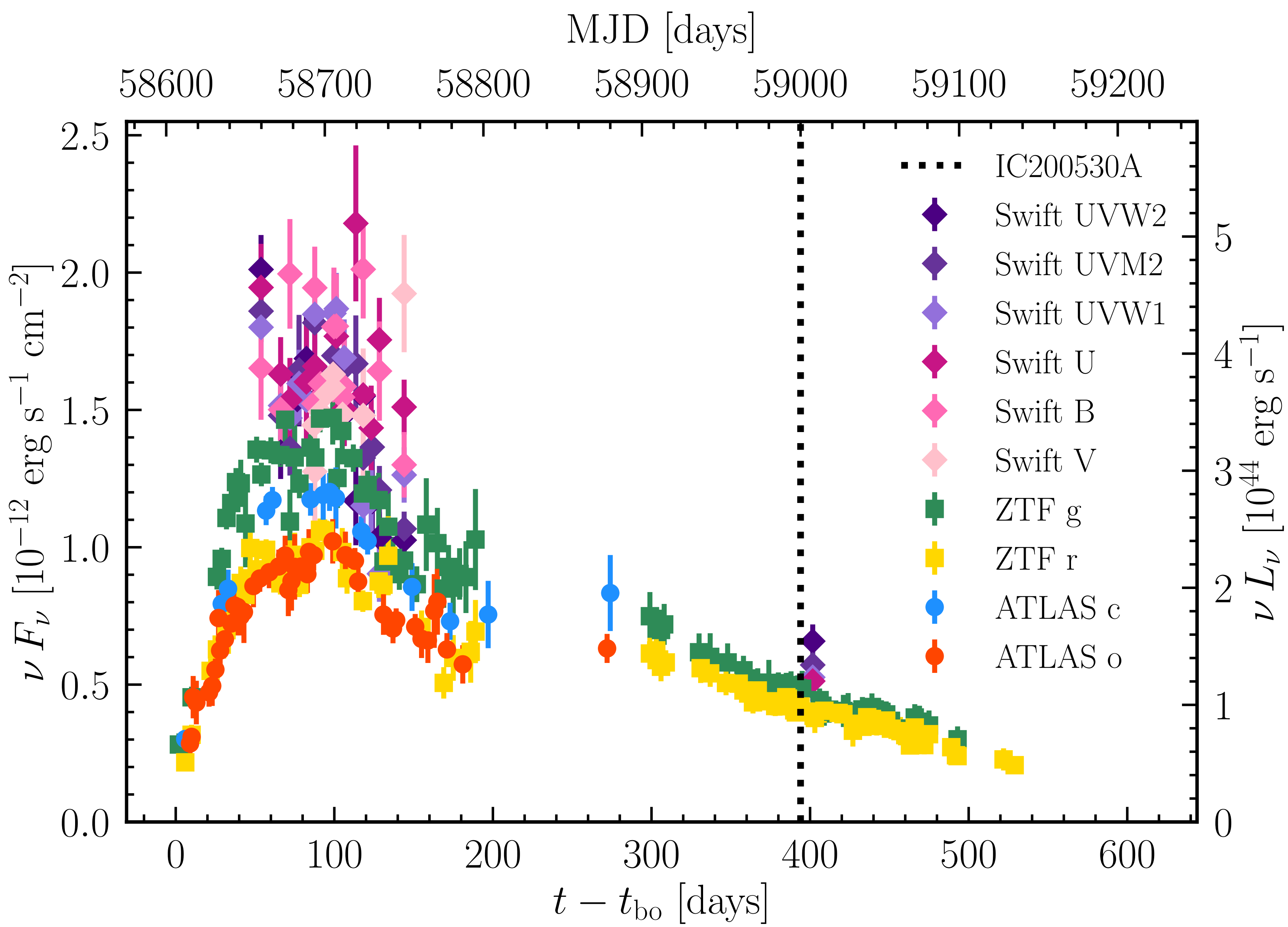
High-Energy Neutrinos from Tidal Disruptions?

Name	Neutrino energy (PeV)	Neutrino arrival time (day)	Distance (Mpc)	Core
AT2019dsg	0.2	150	220	Non-AGN
AT2019fdr	0.08	300	1360	LL-AGN
AT2019aalc	0.15	150	160	LL-AGN

- Copious UV and optical emission, weak in X-rays and radio, very large bolometric flux.
- No signature of relativistic jet.
- Neutrinos detected >O(100) days after discovery.
- Theoretical scenarios under debate.

Stein et al., Nature Astronomy (2021). K. Hayasaki, Nat. Astr. (2021). Winter & Lunardini, Nat. Astr. (2021). Liu et al., PRD (2020). Murase et al., ApJ (2020). van Velzen et al., arXiv: 2111.09391. Liao et al., ApJL (2022). Reusch et al., PRL (2022).

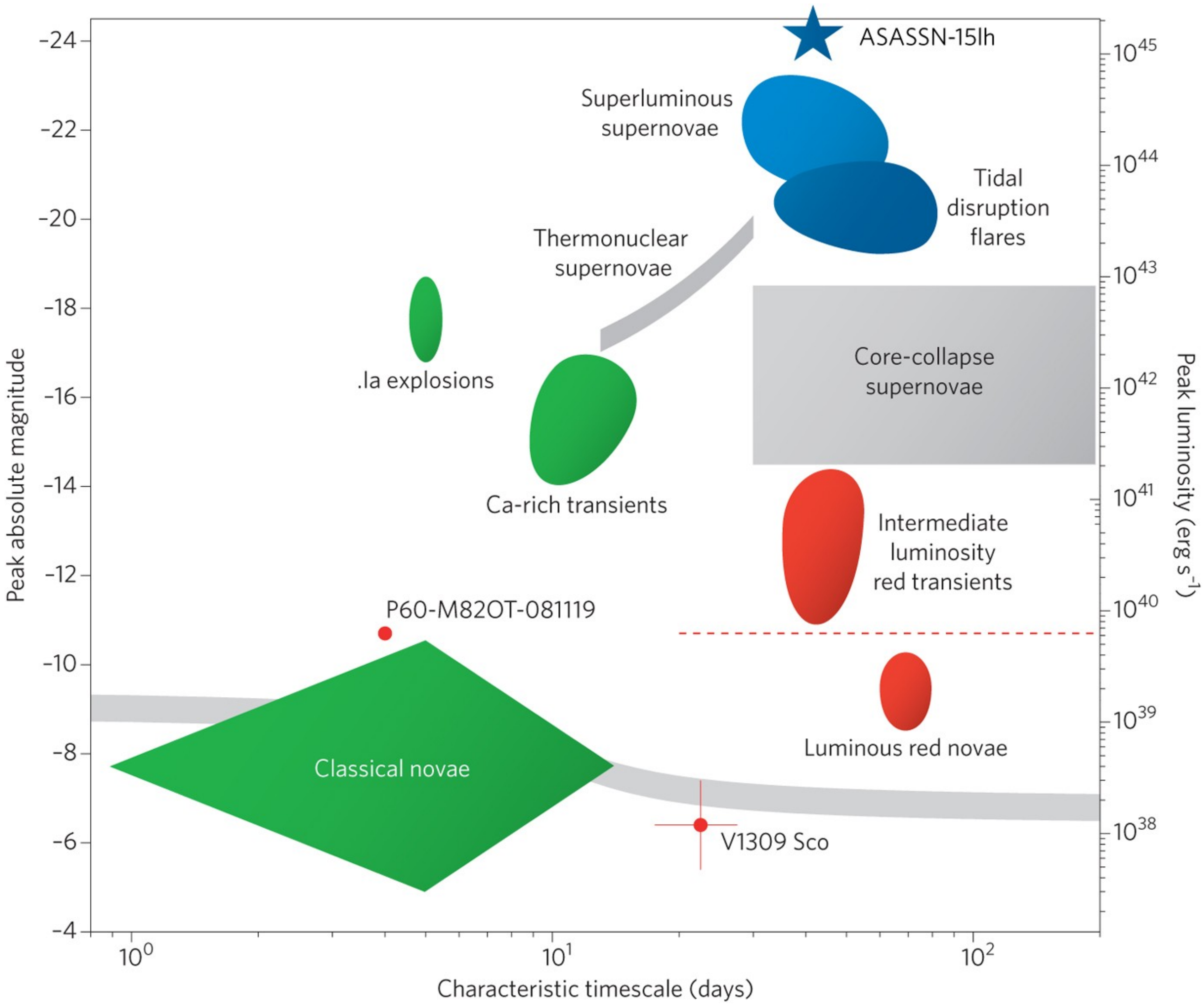
Source Misidentification?



- AT 2019fdr: coincident with neutrino event IC200530A (80 TeV).
- Is AT2019fdr a TDE in a narrow-line Seyfert Galaxy or a superluminous supernova?
- Hydrogen-rich superluminous supernova scenario compatible with IC200530A.
- Rebrigthening recently observed. Challenging to explain by invoking TDE origin.

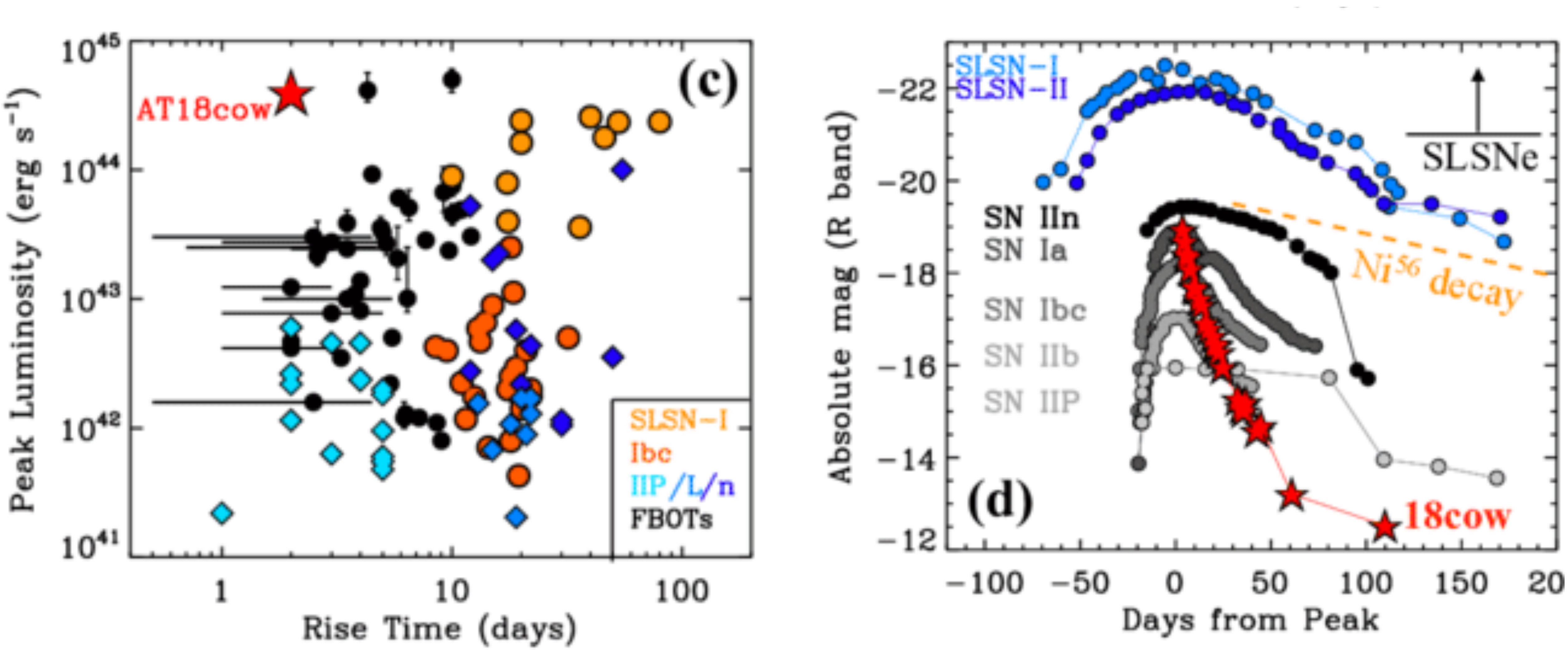
Pitik, Tamborra, Angus, Auchettl, ApJ (2022).

New Species in the Transient Zoo?



S. Bradley Cenko, Nature Astronomy (2017).

Fast Blue Optical Transients

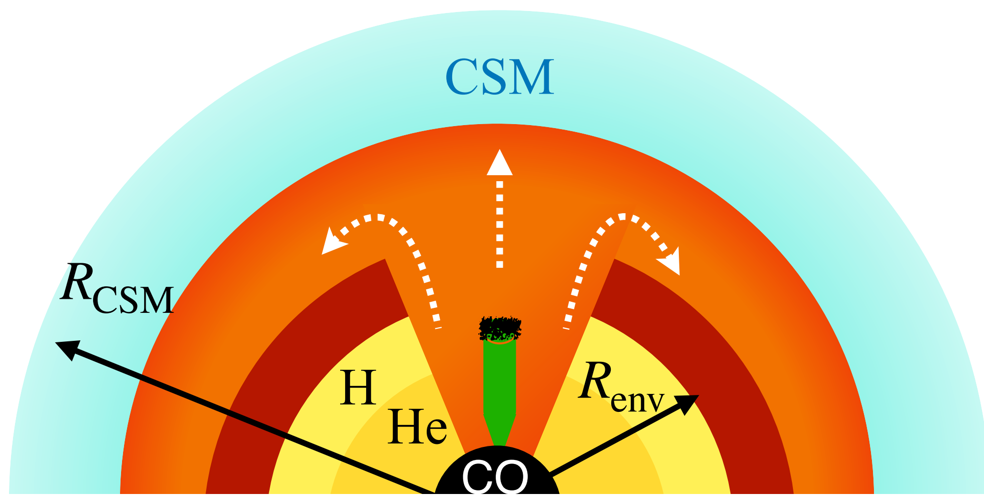


- Extremely fast rise time.
- Powered by a compact object launching an asymmetric outflow responsible for multi-wavelength EM emission.

Perley et al., MNRAS (2019). Drout et al., ApJ (2014). Coppejans et al., ApJL (2020). Ho et al., arXiv: 2105.08811.

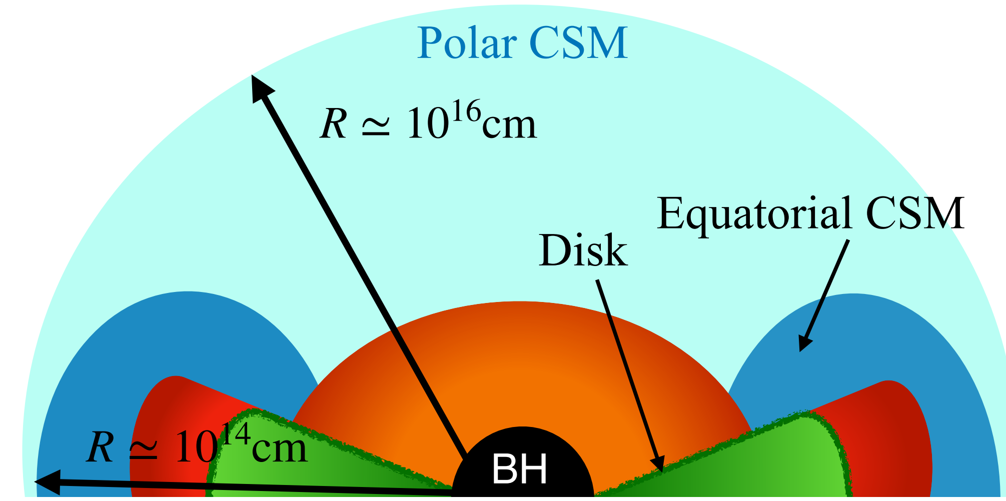
Fast Blue Optical Transients

Cocoon model



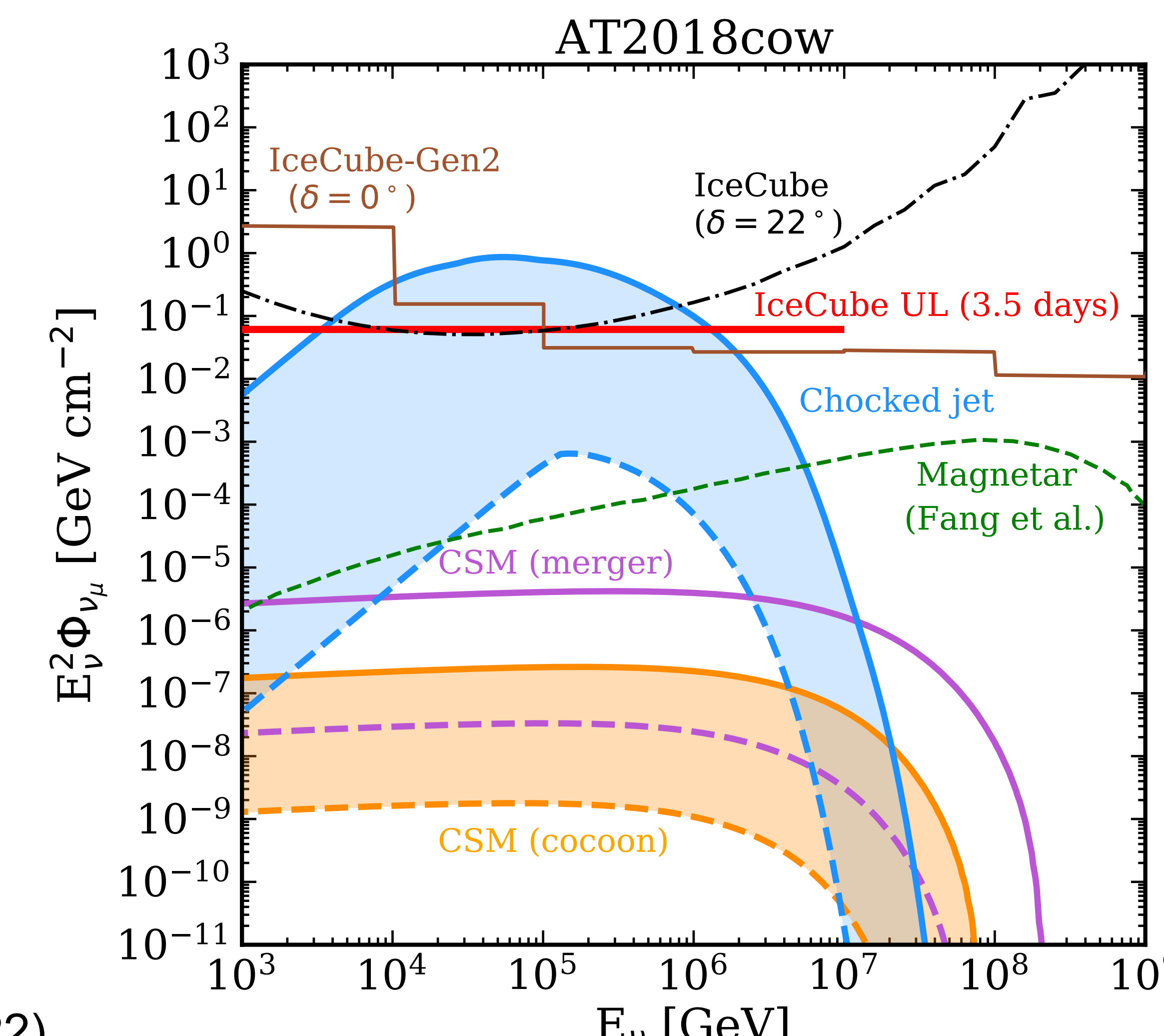
Collapse of a massive star, possibly not completely H-stripped, which launches a jet. The latter is choked in the envelope.

Merger model



Delayed Wolf-Rayet star–black hole merger. Formation of an asymmetric CSM.

Neutrinos can shed light on the engine of FBOTs.



Guarini, Tamborra, Margutti, ApJ (2022).
Gottlieb, Tchekhovskoy, Margutti, MNRAS (2022). Metzger, ApJ (2022).

Conclusions

- Multi-messenger observations carry imprints of the source engine and are crucial to understand the origin of the heavy elements.

- Microphysics modeling is still preliminary.

- Sources of high energy neutrinos unknown.
  Growing number of likely multi-messenger associations.

Thank you!