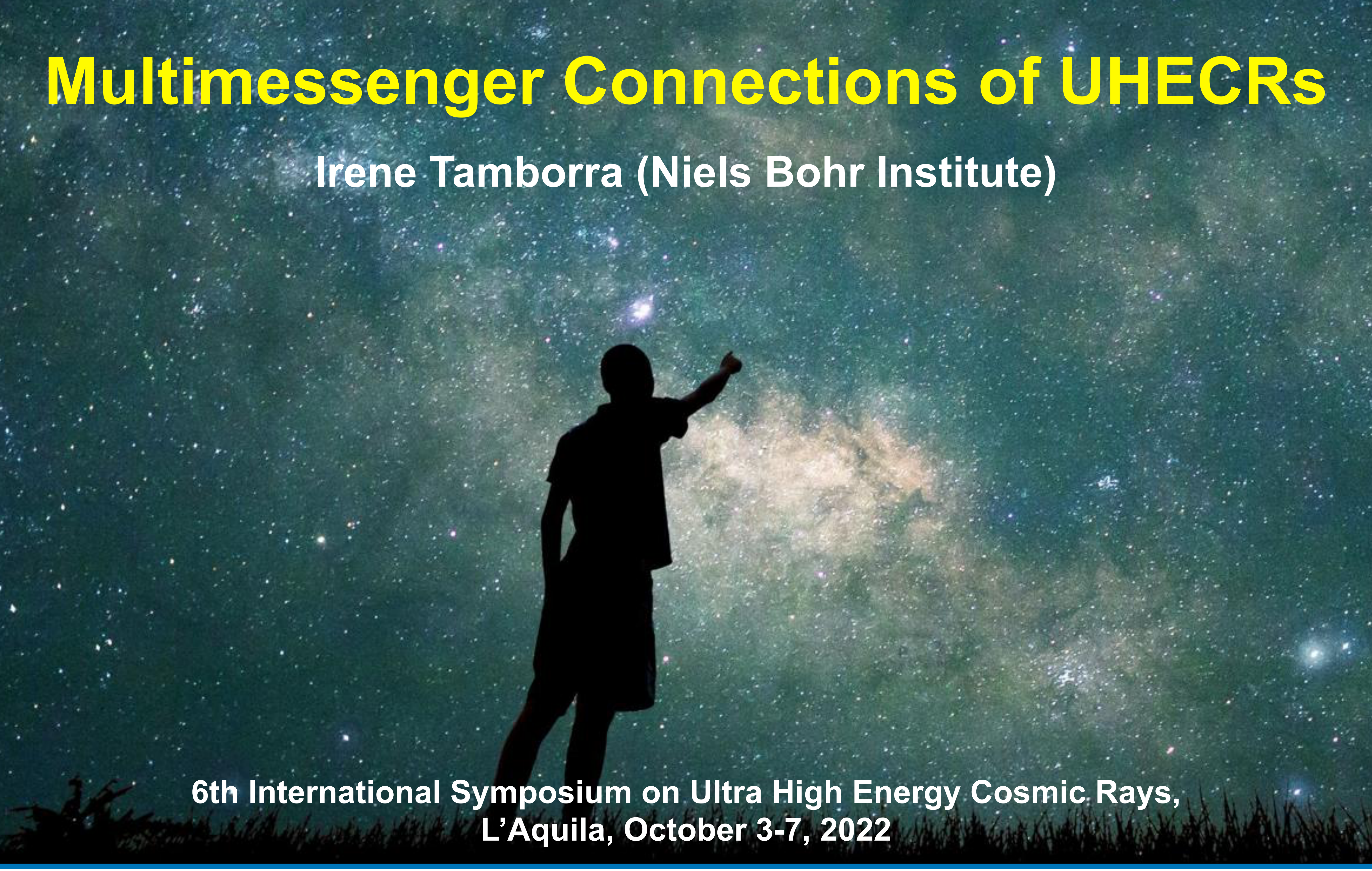
Multimessenger Connections of UHECRs

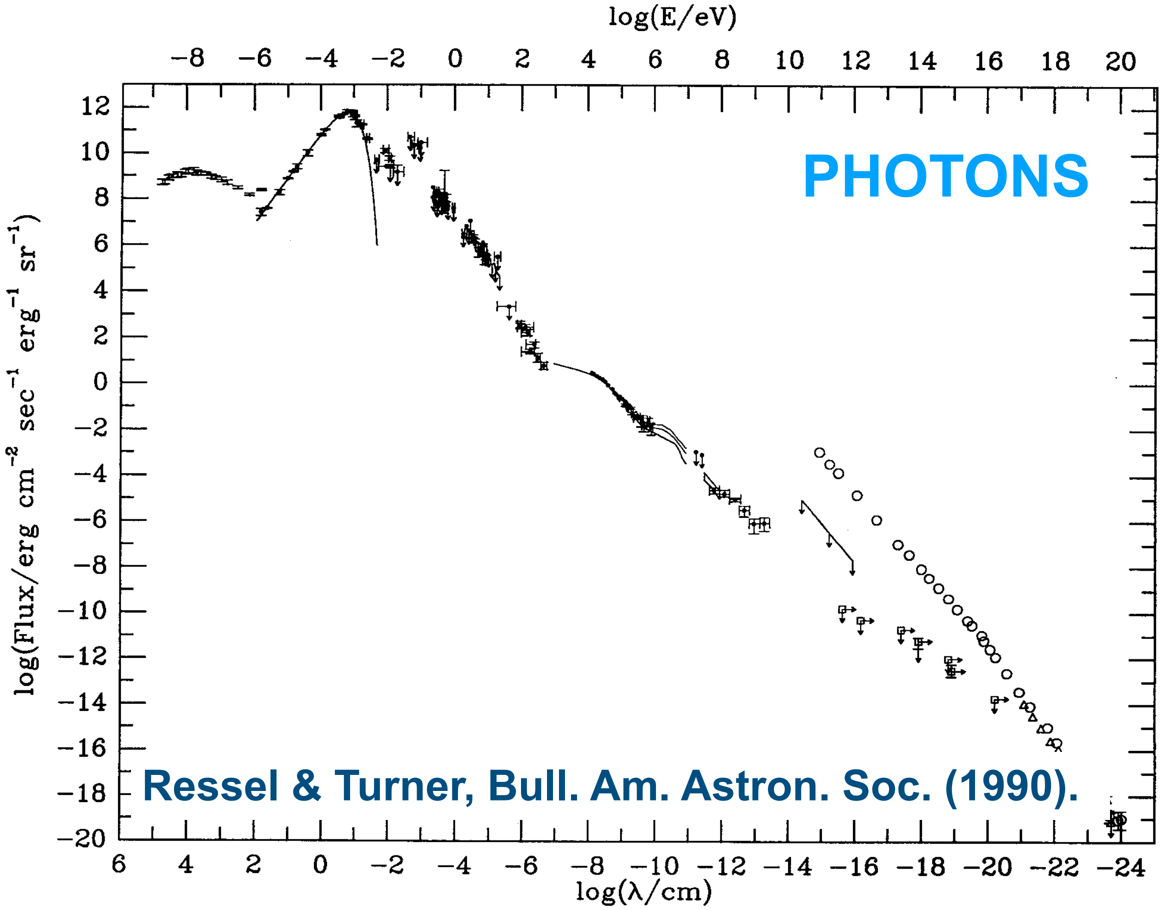
Irene Tamborra (Niels Bohr Institute)

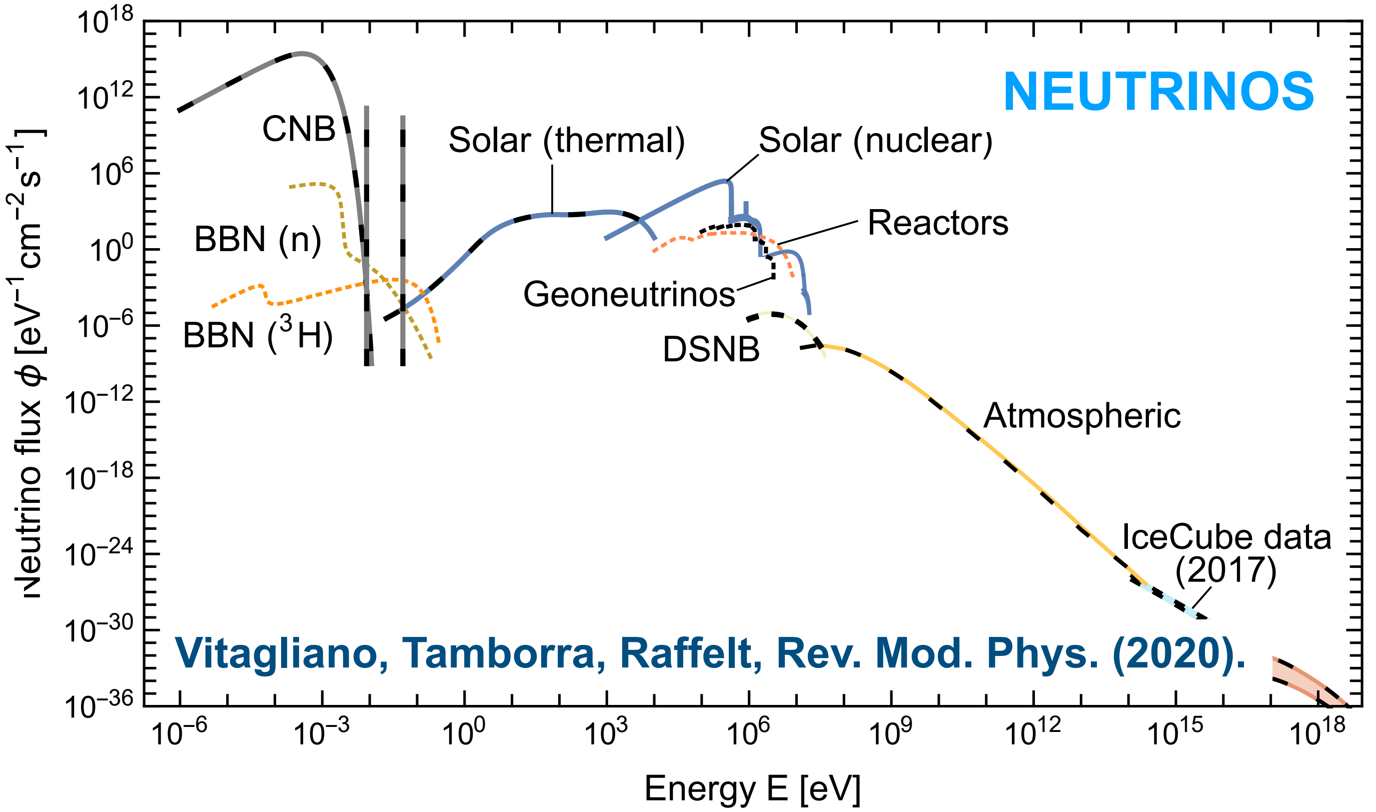


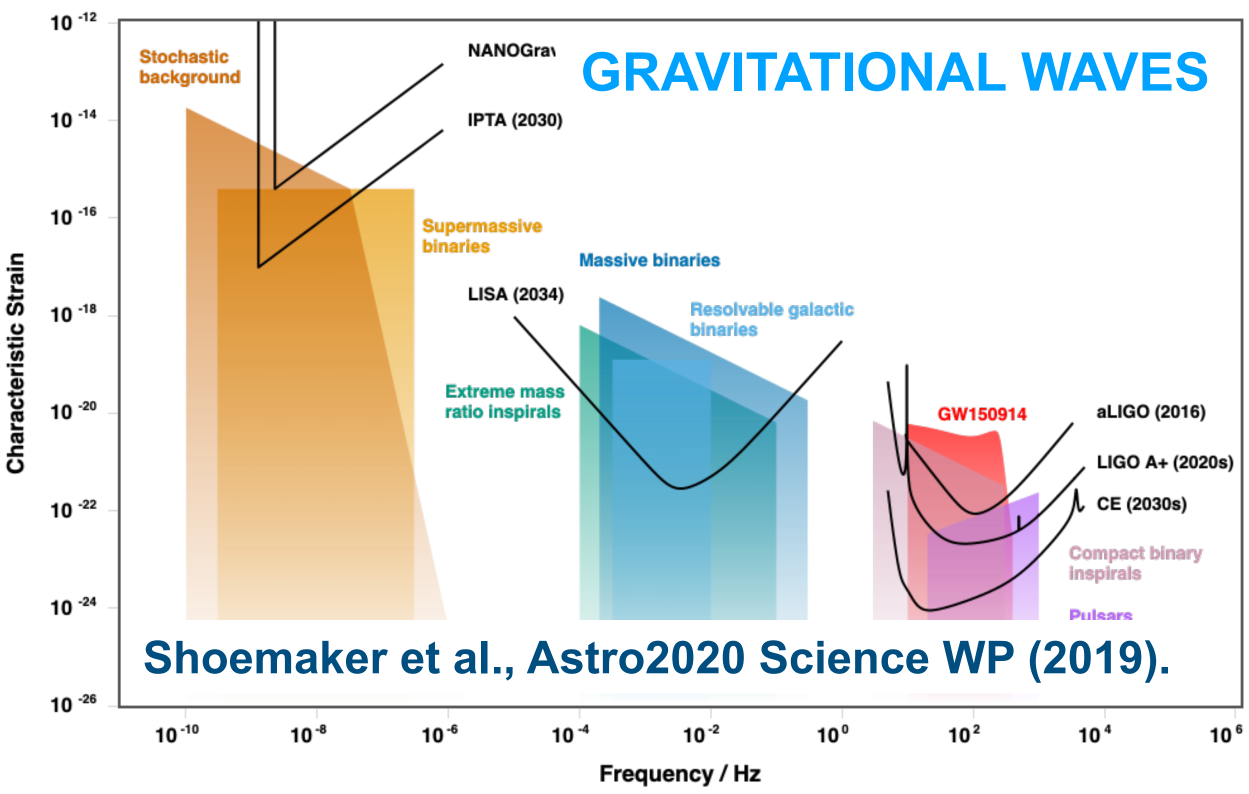
6th International Symposium on Ultra High Energy Cosmic Rays,
L’Aquila, October 3-7, 2022

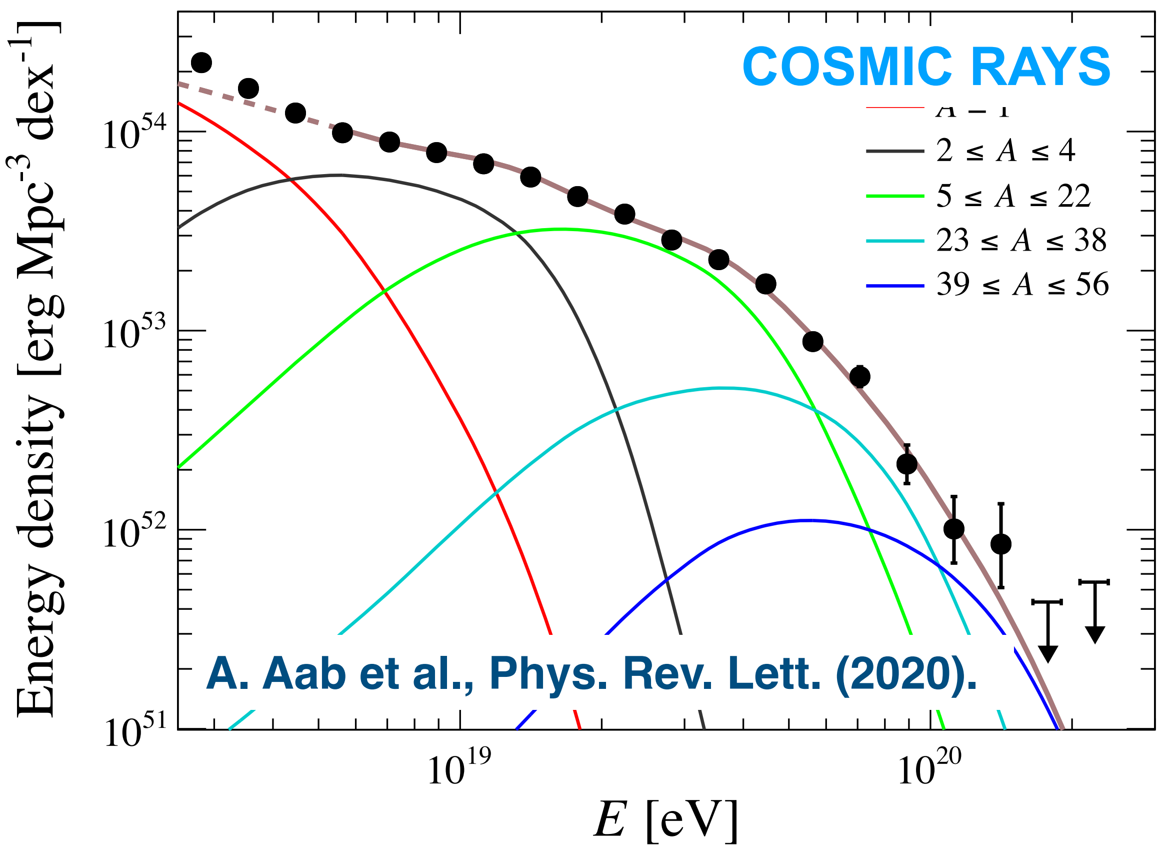
VILLUM FONDEN
Sapere Aude
CARLSBERG FOUNDATION
SFB 1258 Neutrinos Dark Matter Messengers

Cosmic Messengers

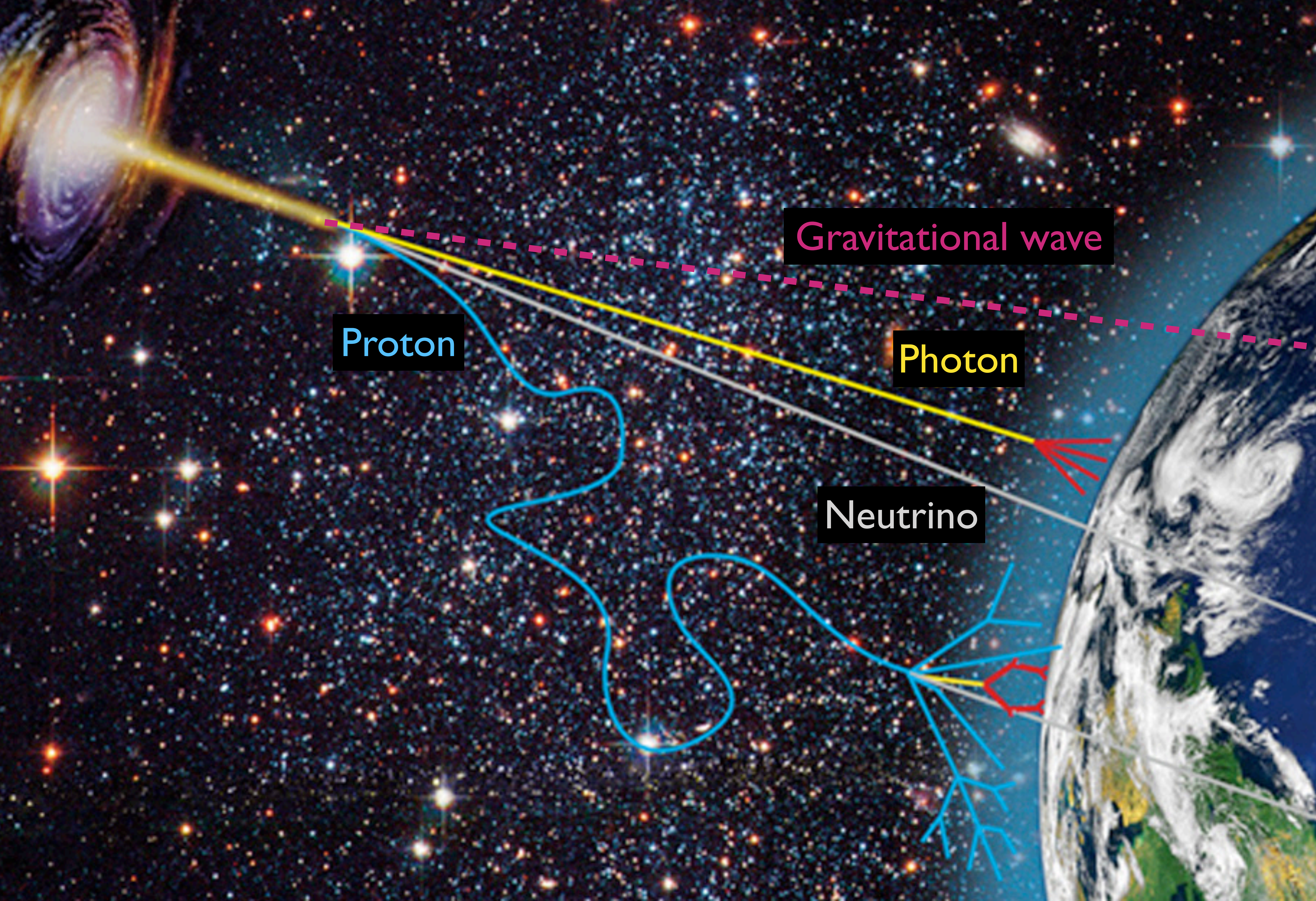








Cosmic Messengers

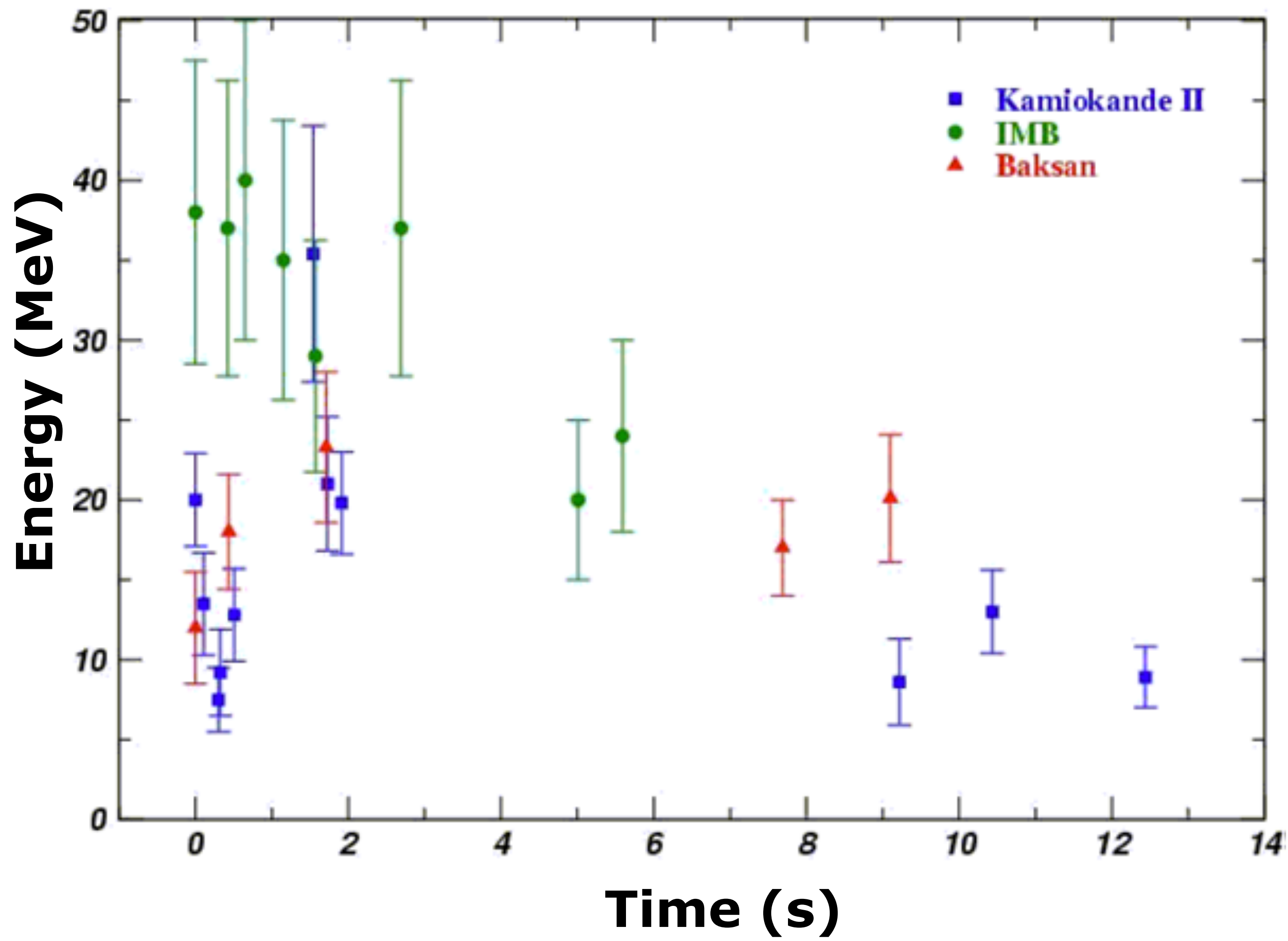


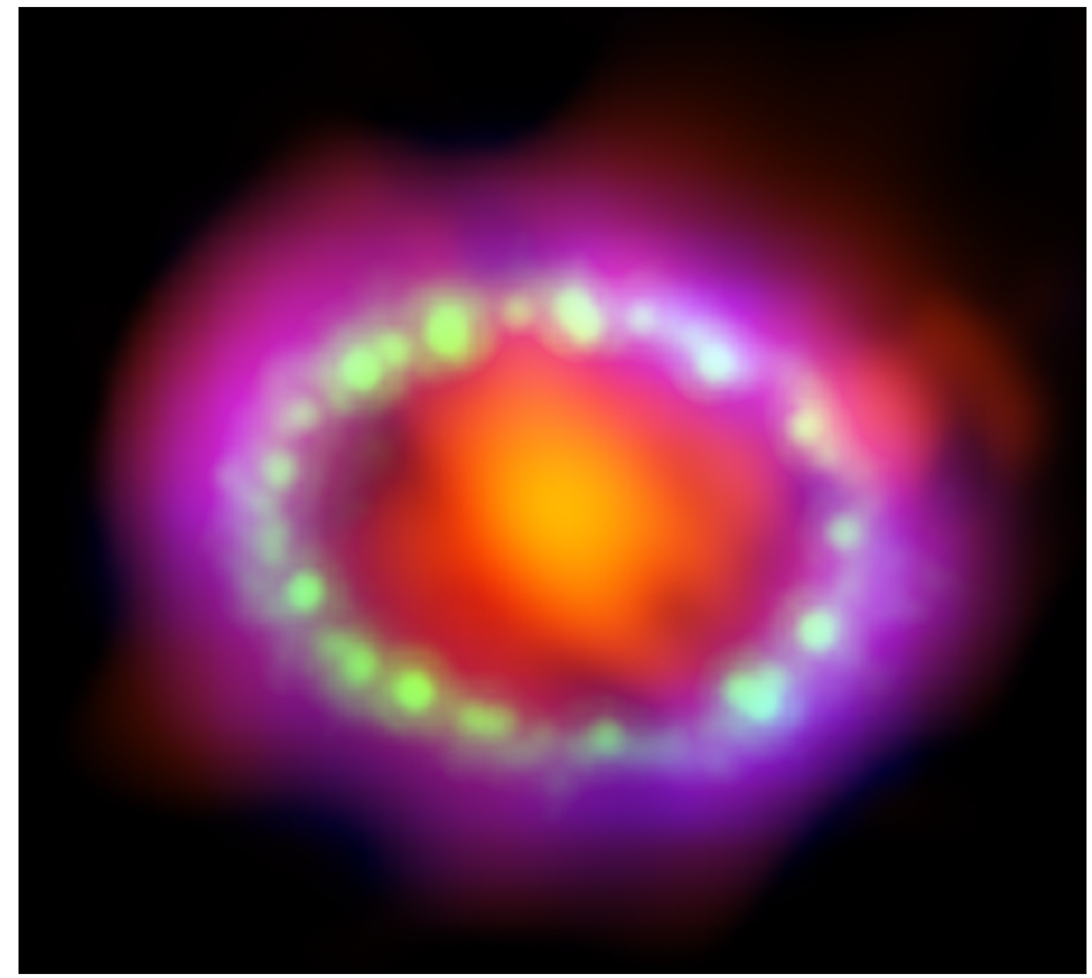
Outline

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

Multi-Messenger Sources as of 2022: No. 1

Supernova 1987A





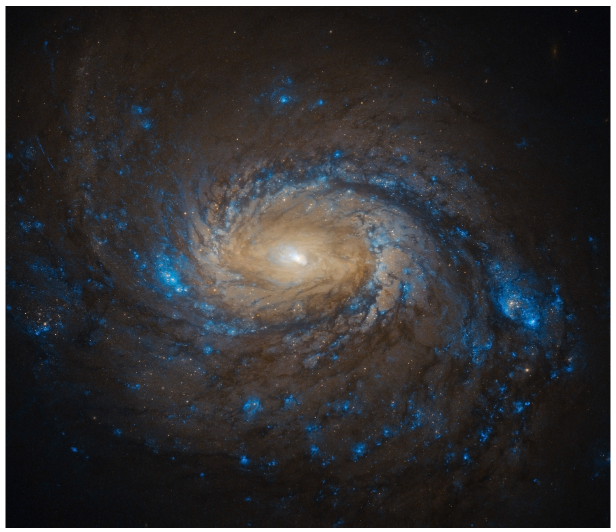
Multi-messenger observations. ⇨ **Test of core-collapse physics**.

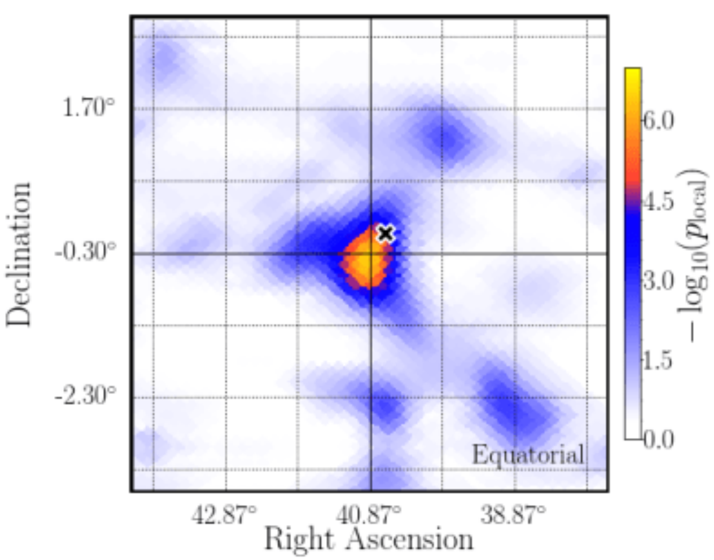
Image credits: NASA, CERNCOURIER.

Multi-Messenger Sources as of 2022: No. 2

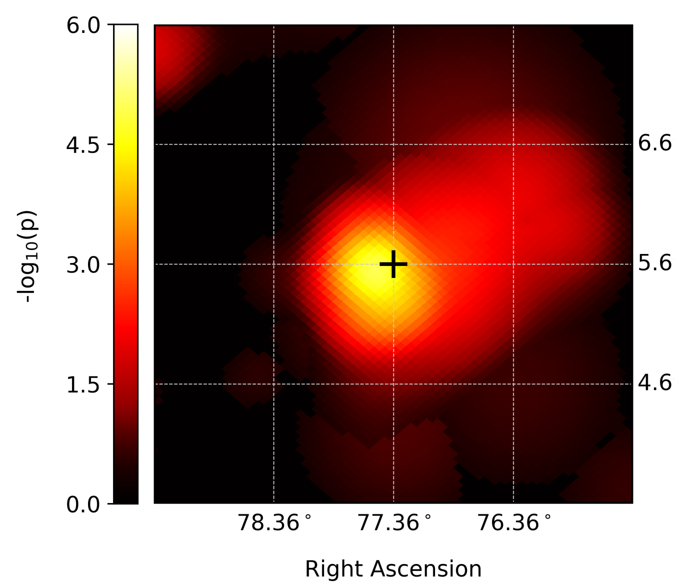
Cosmic Accelerators

Starburst Galaxies

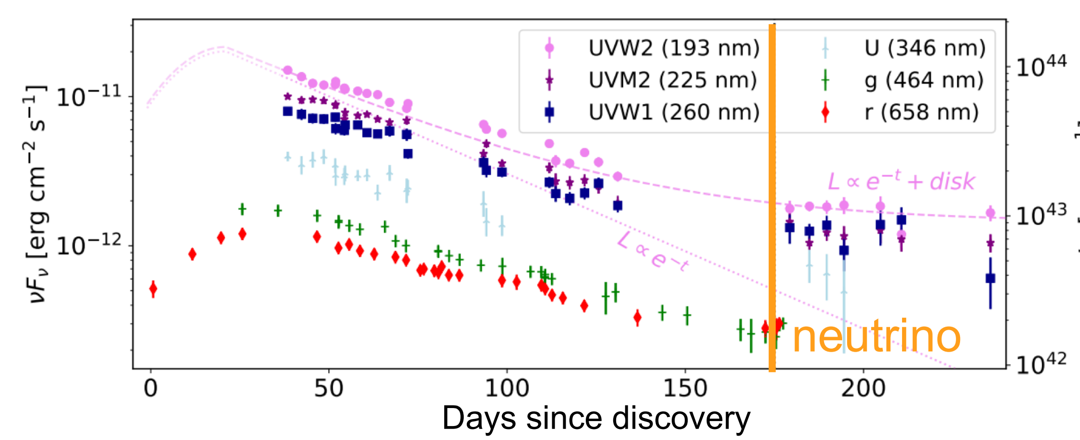




Blazars



Tidal Disruption Events

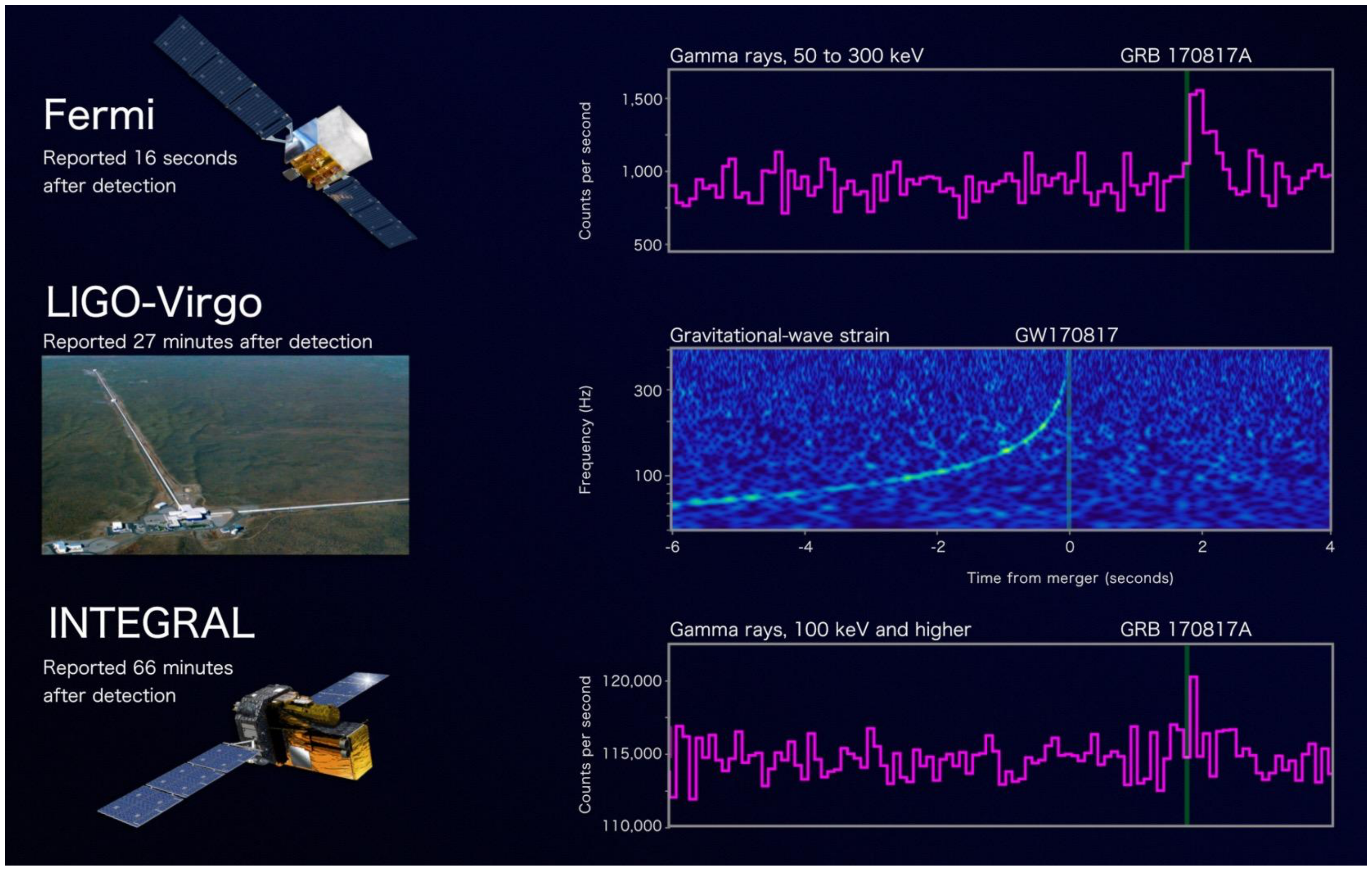


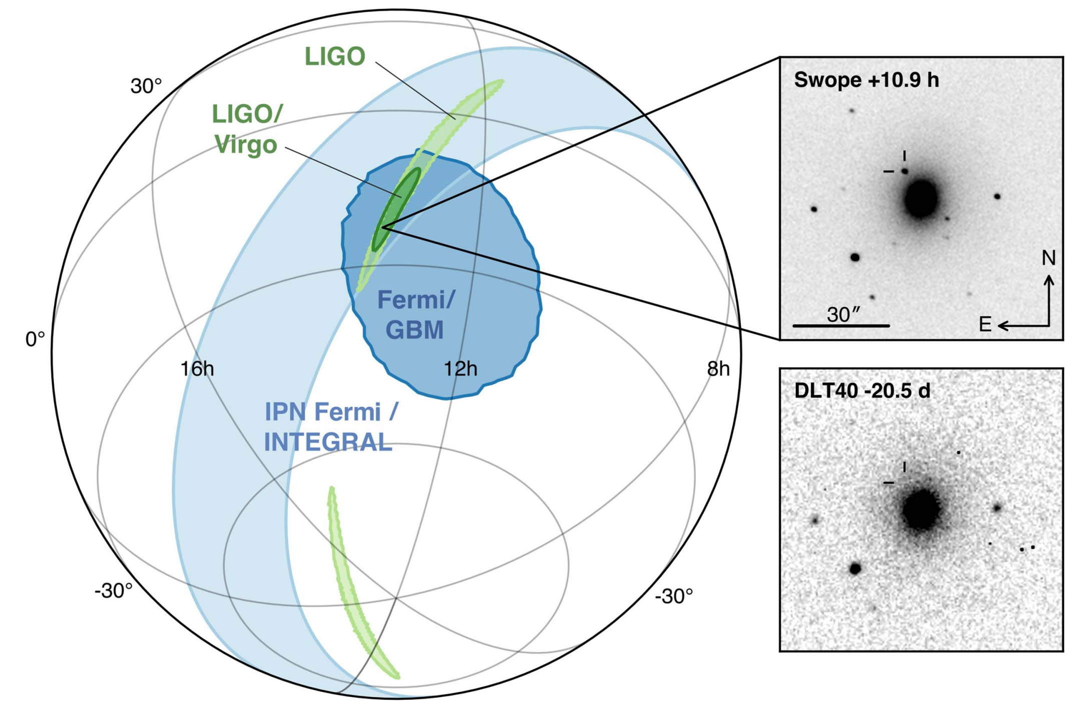
Several likely point source associations ⇨ **Test particle acceleration theory.**
Need for improved source modeling.

Image credits: IceCube Collaboration.

Multi-Messenger Sources as of 2022: No. 3

GW170817 & GRB 170817A





First joint detection of GWs and EM radiation. ⇨ **Test merger/GRB/kilonova physics. Hints on origin of heavy elements.**

Figure credits: Abbott et al., ApJ (2017), ESA.

Core-Collapse Supernovae

Figure credits: Royal Society

The Next Local Supernova (SN 2XXXA)

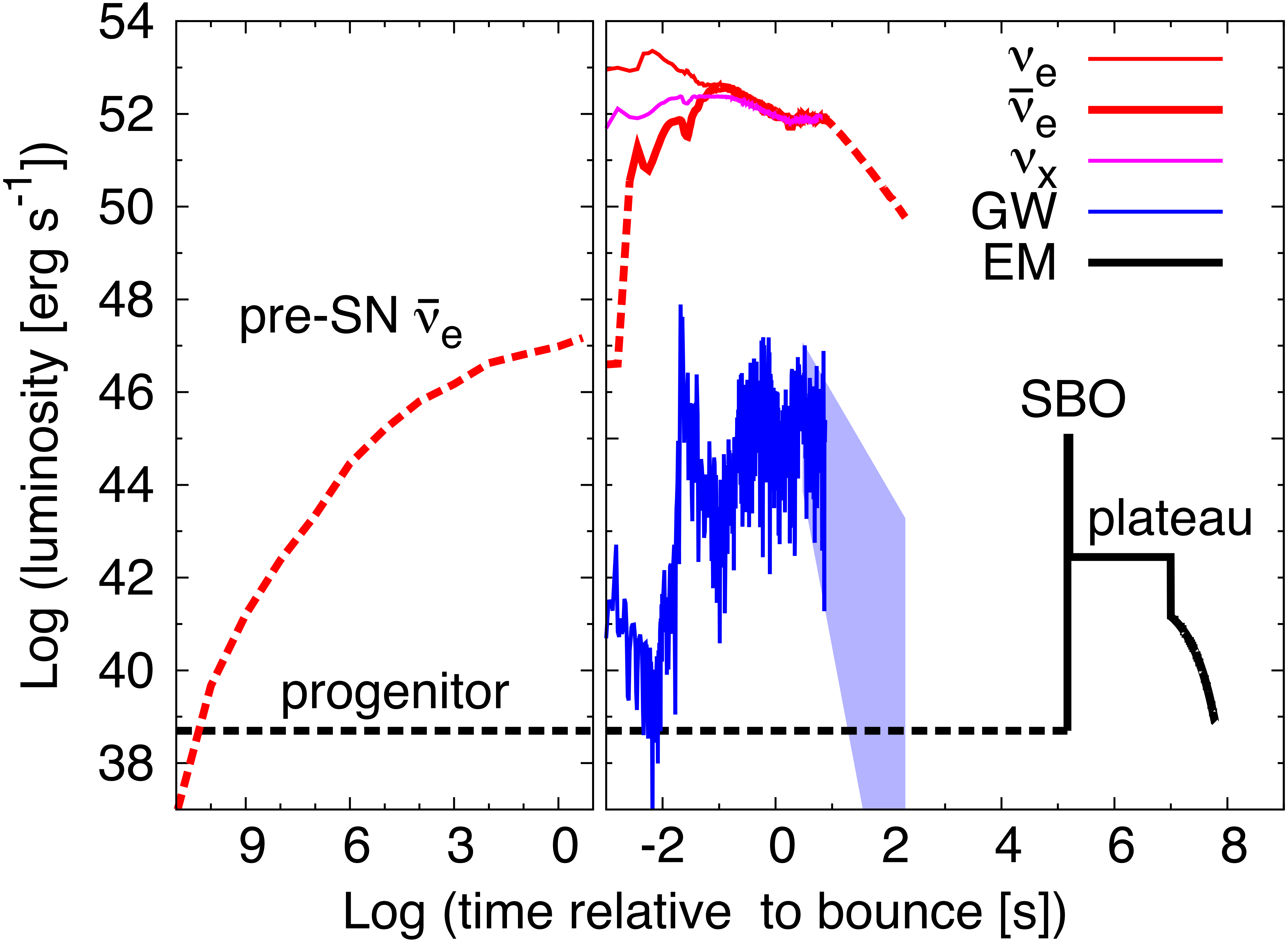
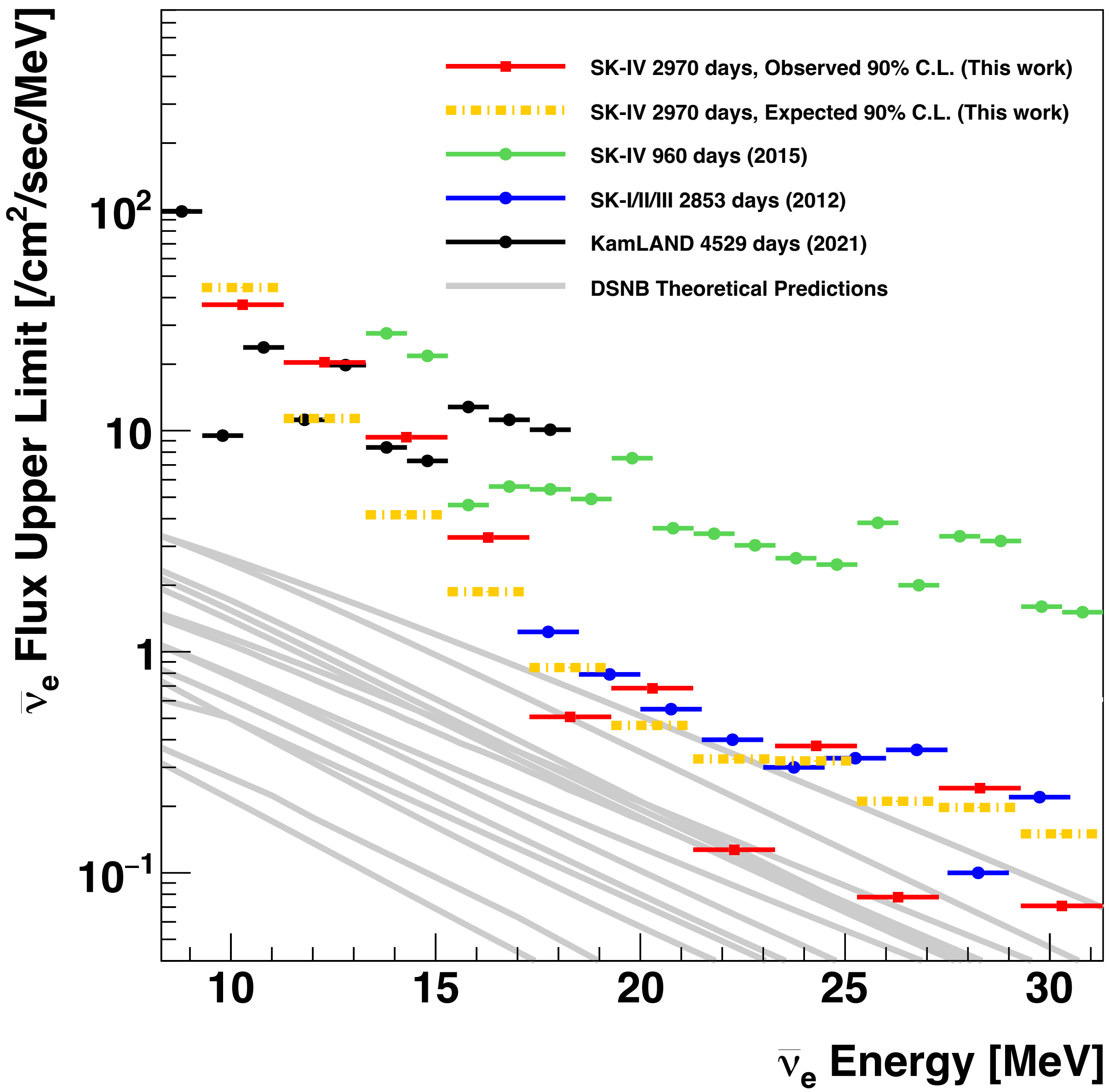


Figure from Nakamura et al., MNRAS (2016).

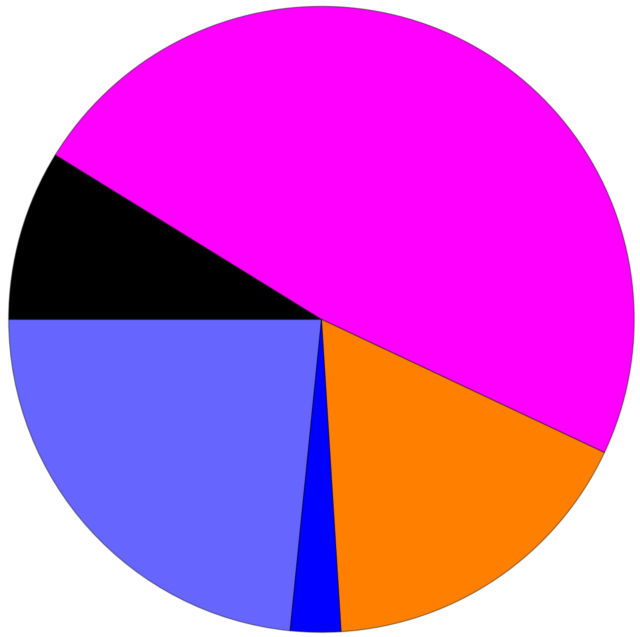
Diffuse Supernova Neutrino Background

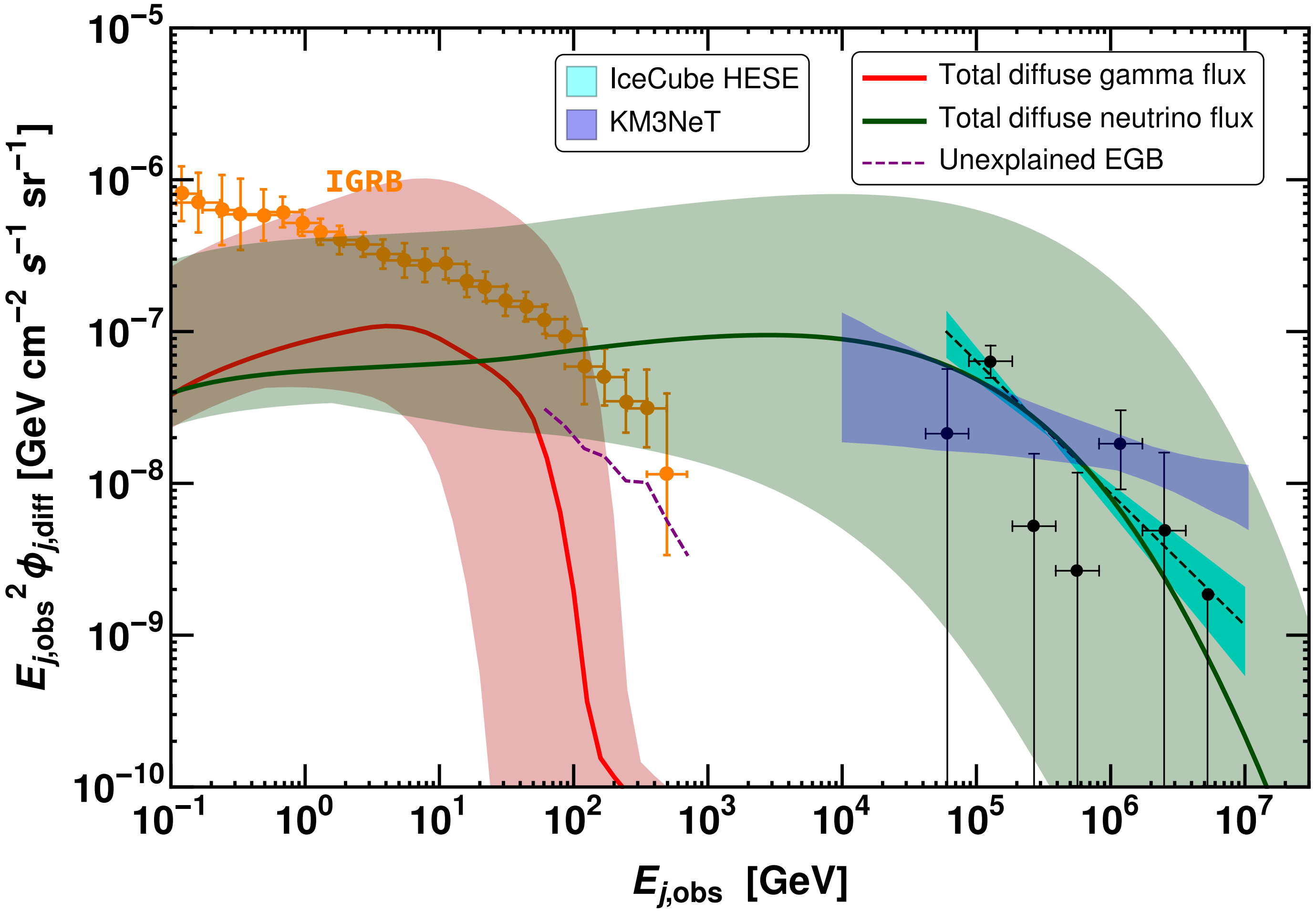


- Independent insight on supernova population.
- Modeling uncertainties are to be reduced.
- Detection expected to happen soon!

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., MNRAS (2022, in press).

High Energy Emission from Supernovae





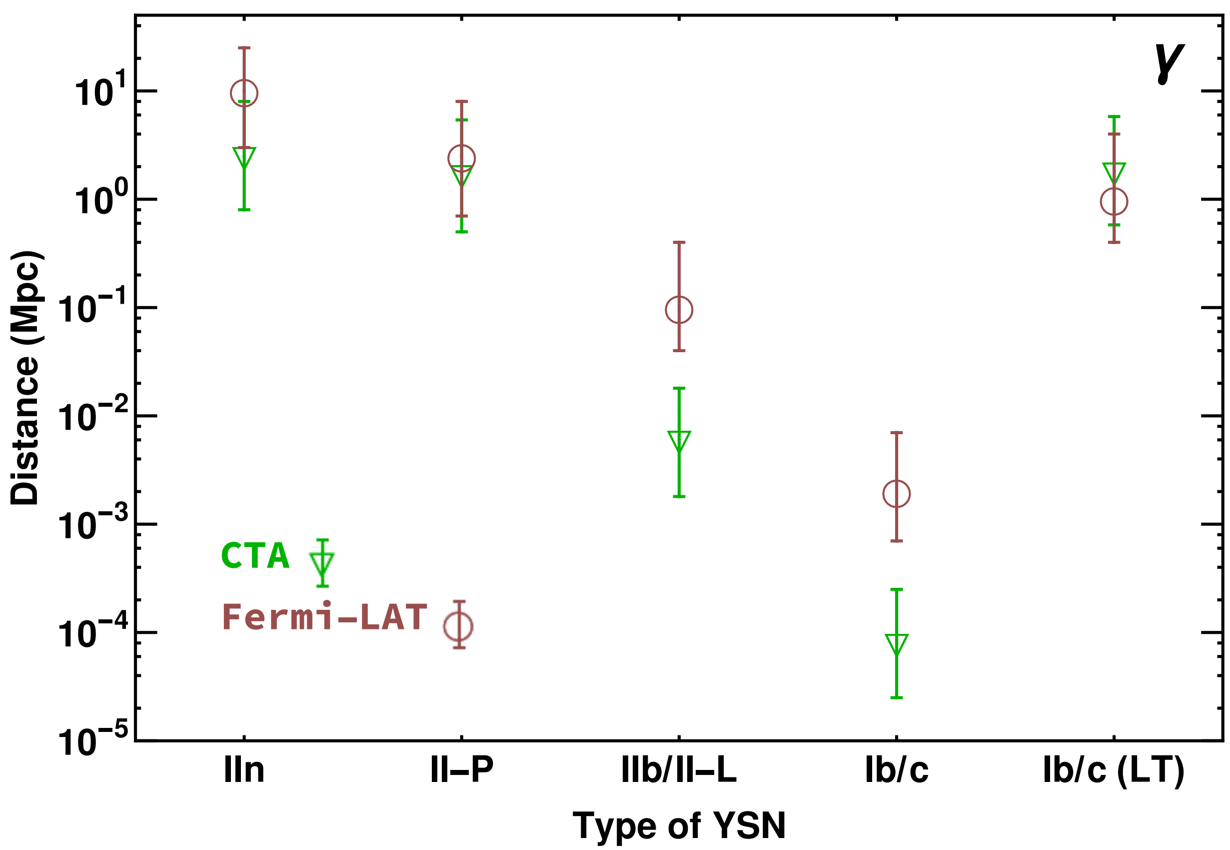
Supernovae may be sources of high-energy neutrinos and gamma-rays.

They 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?).

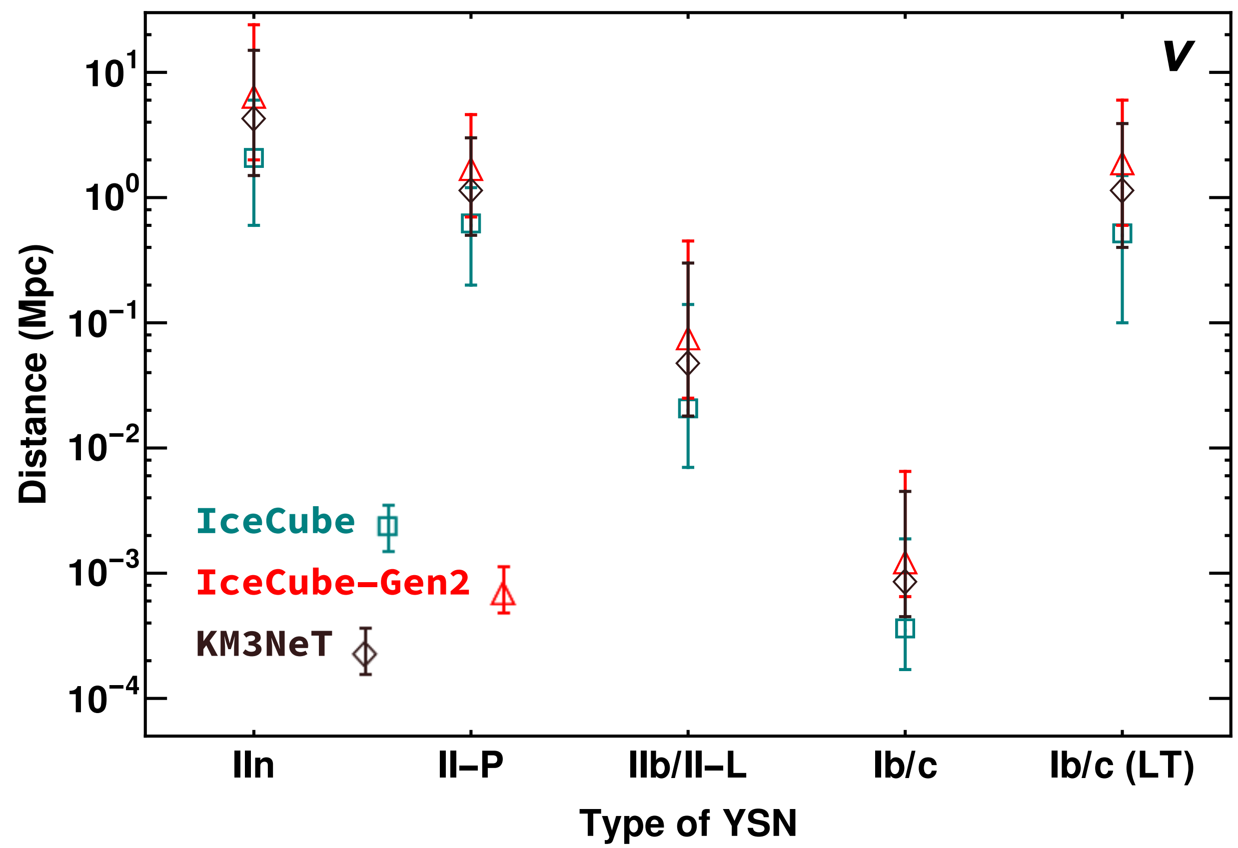
Sarmah, Chackraborty, Tamborra, Auchettl, JCAP (2022). Pitik, Tamborra, Angus, Auchettl, ApJ (2022). Brose, Sushch, Mackey, arXiv: 2208.04185.

High Energy Emission from Supernovae

Gamma-rays



Neutrinos



SNe of Type IIn and II-P could be detectable in gamma-rays and neutrinos locally.

Sarmah, Chackaborty, Tamborra, Auchettl, JCAP (2022). Pitik, Tamborra, Angus, Auchettl, ApJ (2022). Kheirandish & Murase, arXiv: 2204.08518. Christofari et al., MNRAS (2022).

Compact Binary Mergers

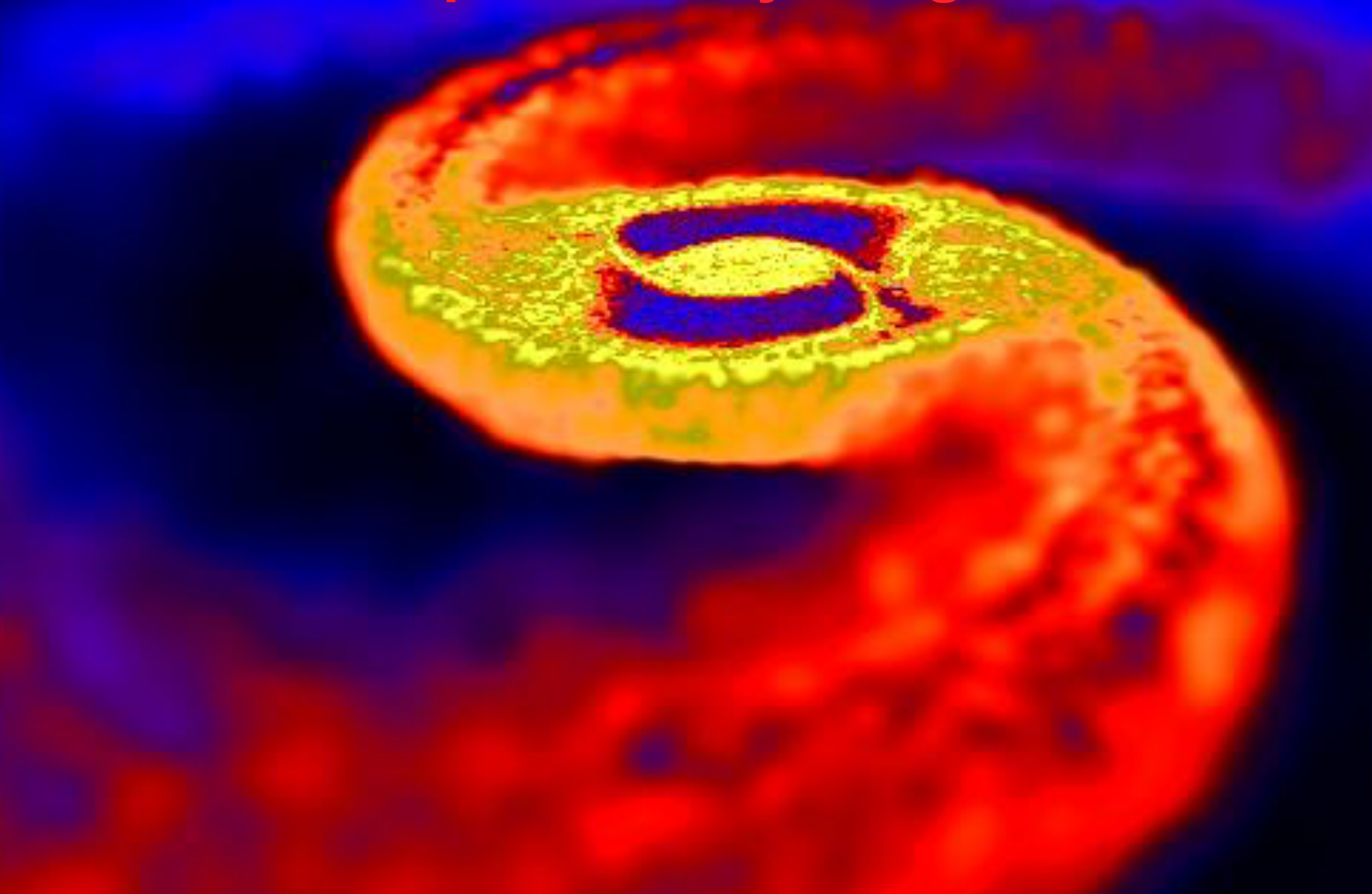


Figure credit: Price & Rosswog, Science (2006).

The Next Binary Merger (GW XXXX22)

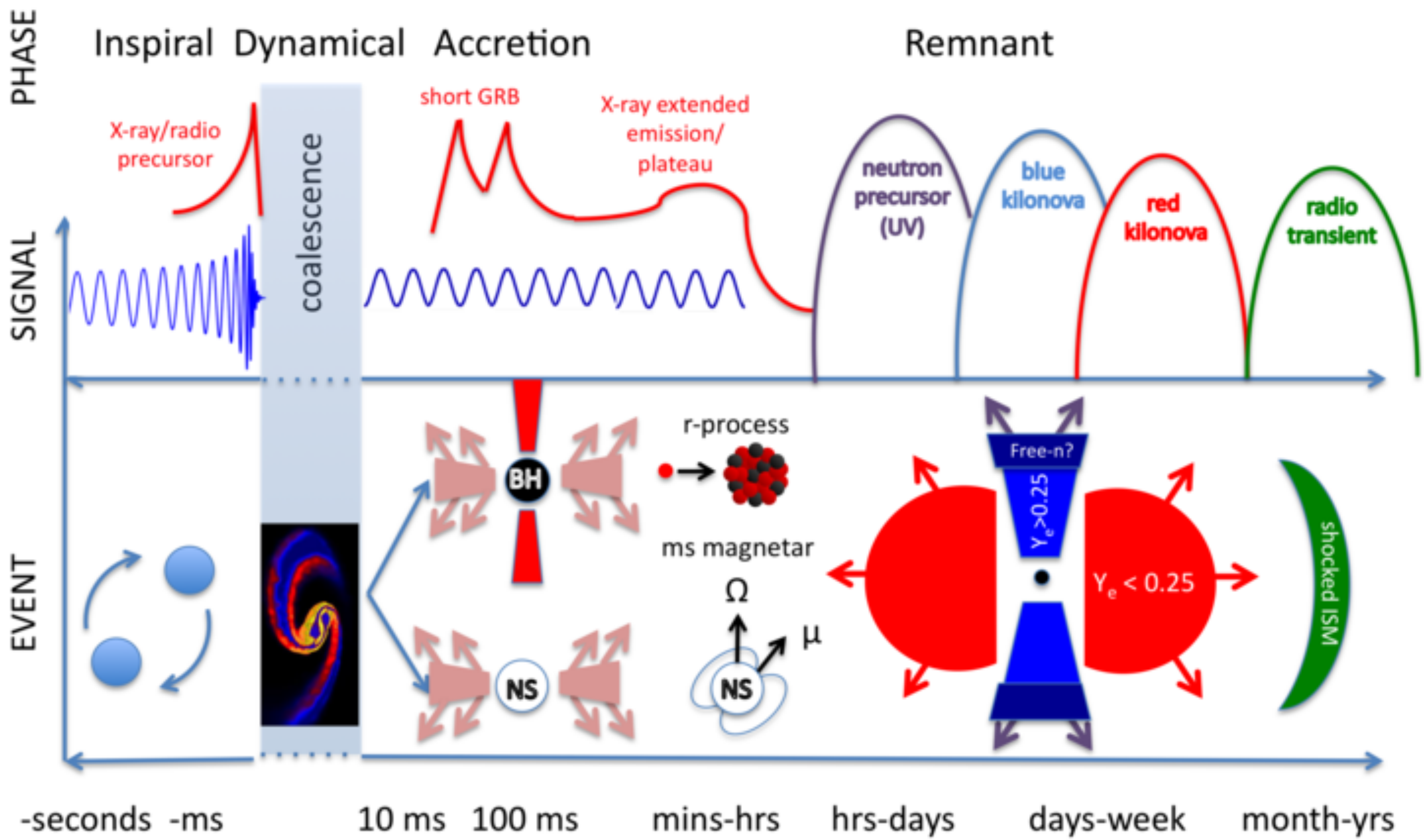
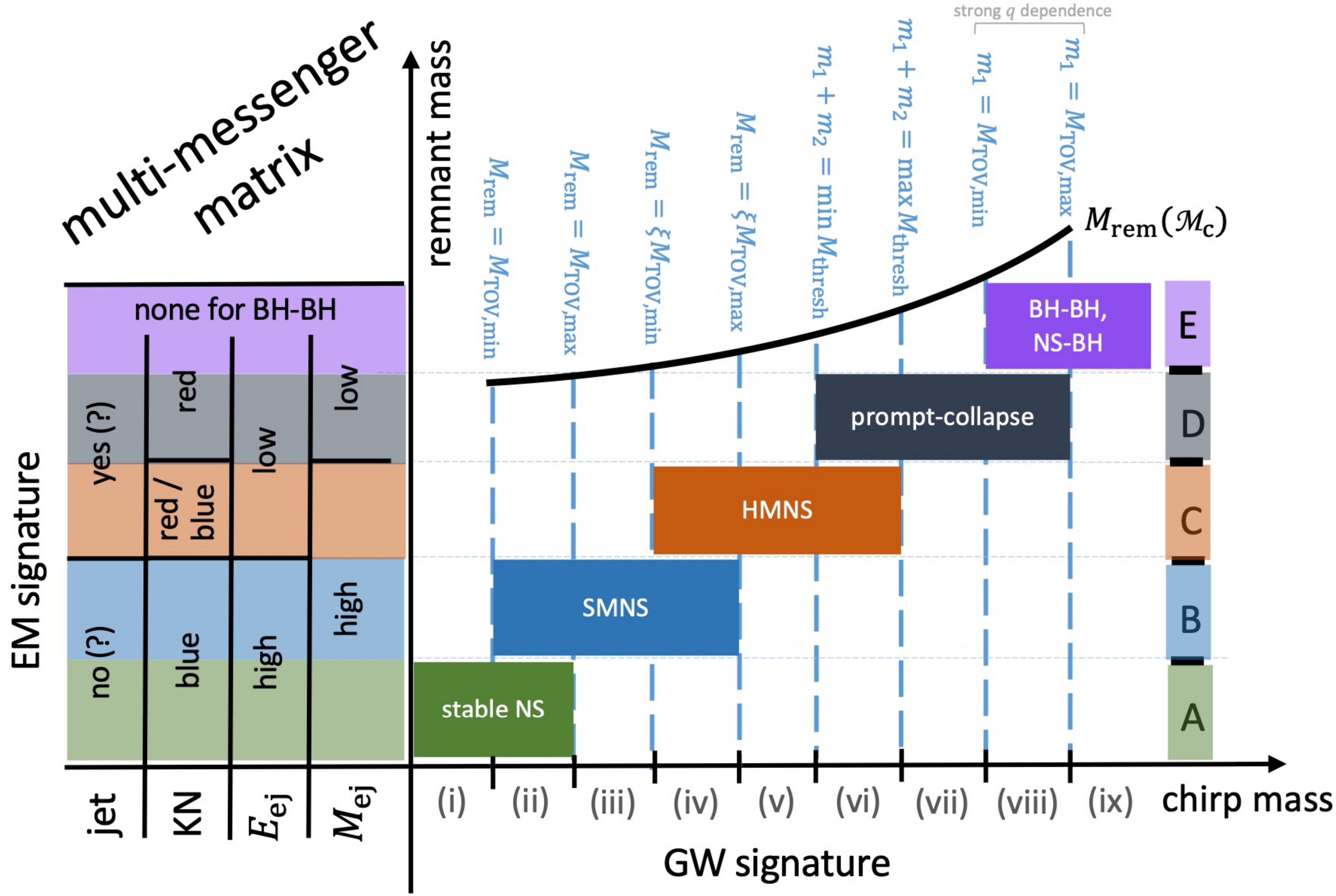


Figure credit: R. Fernandez & B. Metzger, Ann. Rev. Nucl. Part. Sci. (2016).

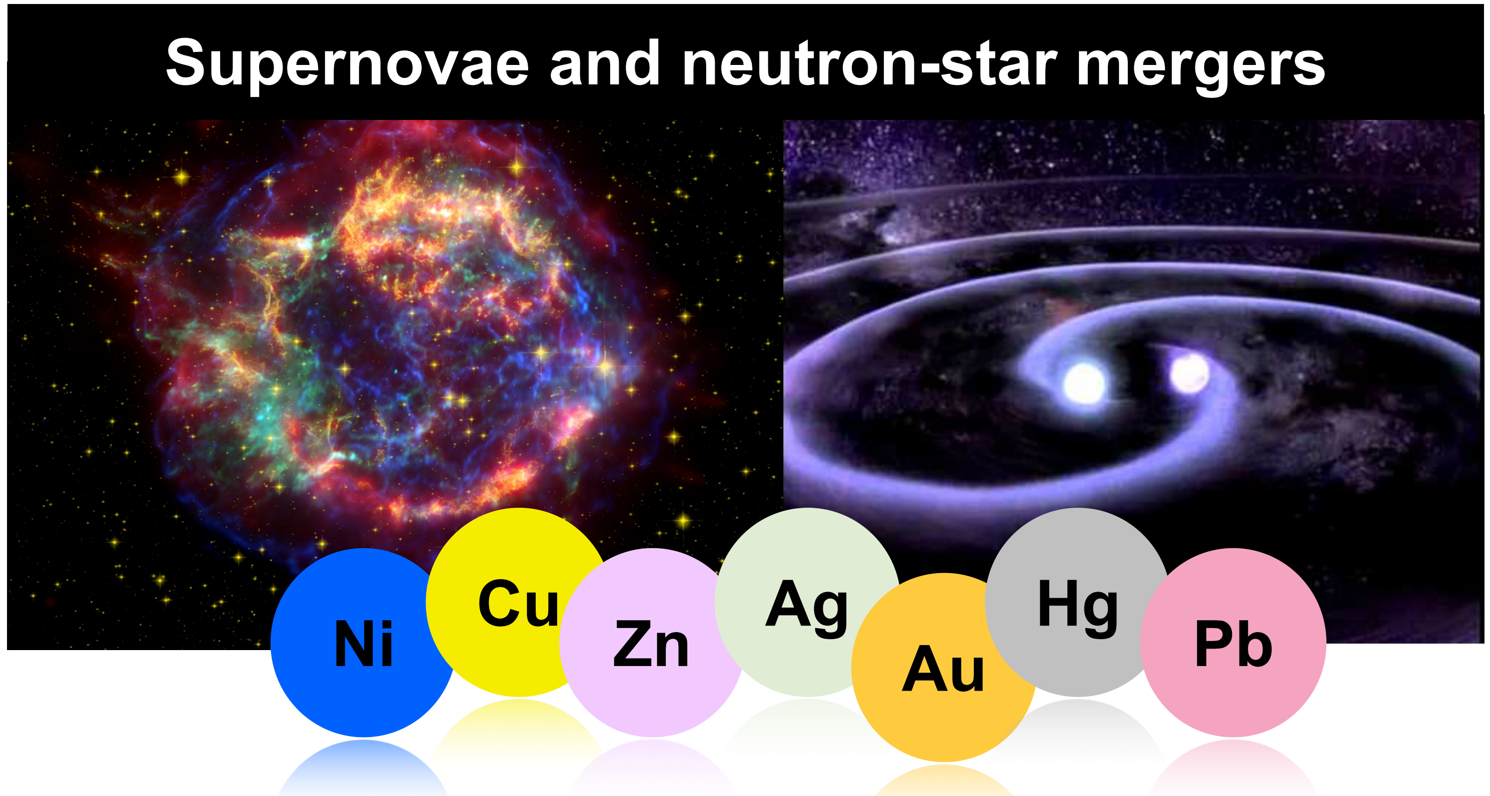
Multi-Messenger Opportunities



Using EM observations to ascertain the outcome 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

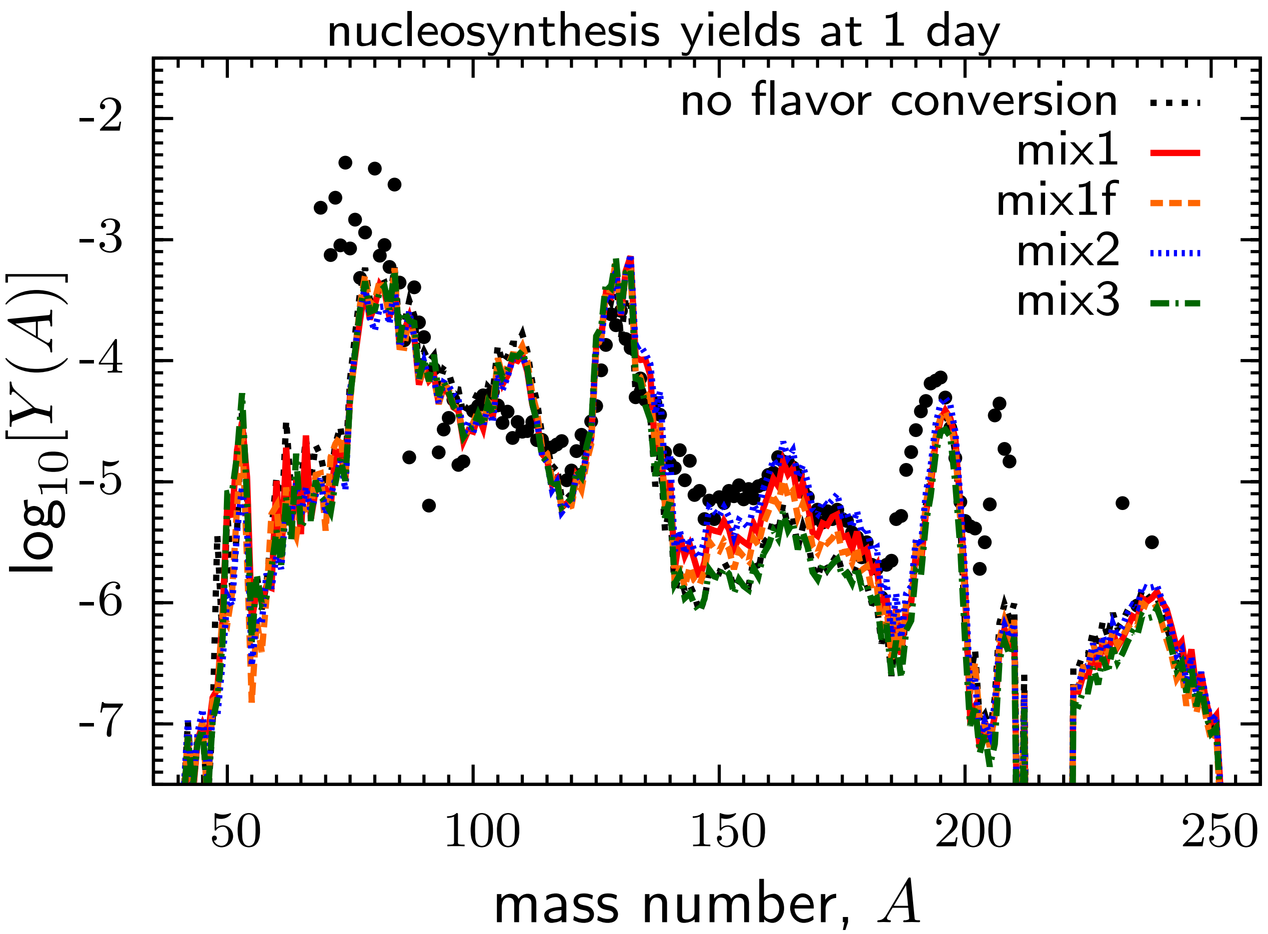


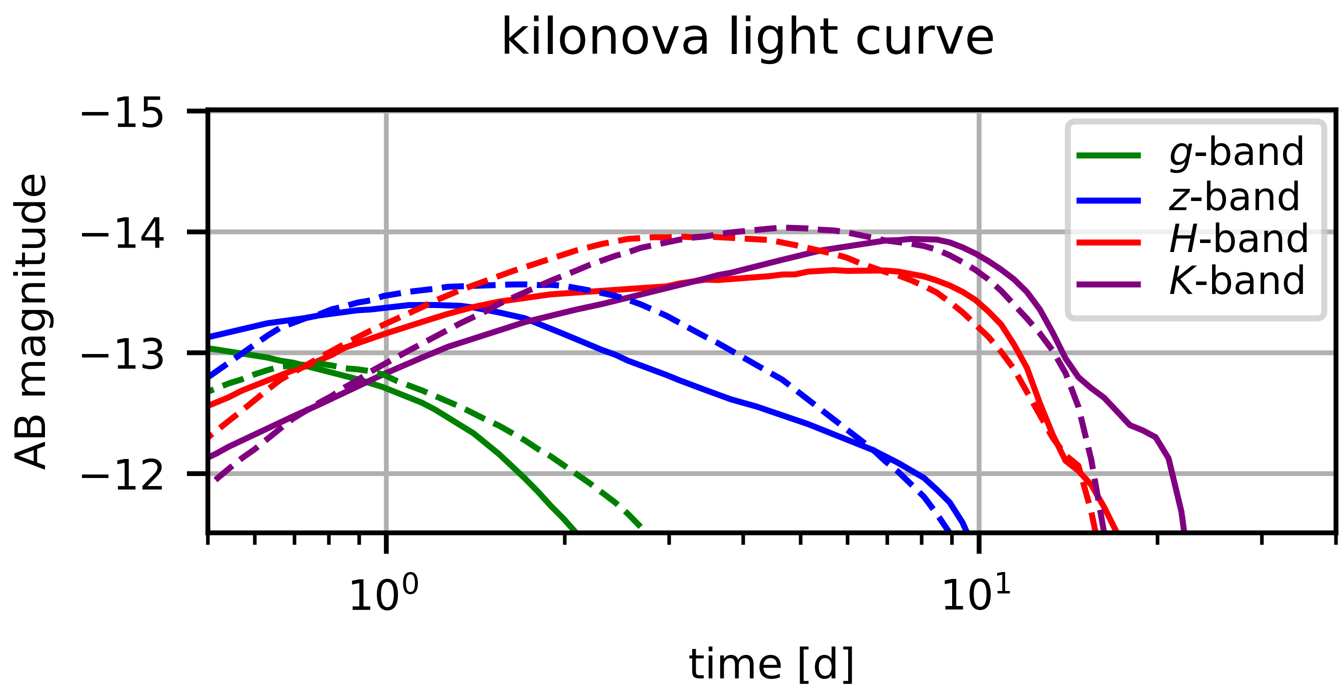
Synthesis of heavy elements depends on neutrino flavor.

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

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

Nucleosynthesis of the Heavy Elements

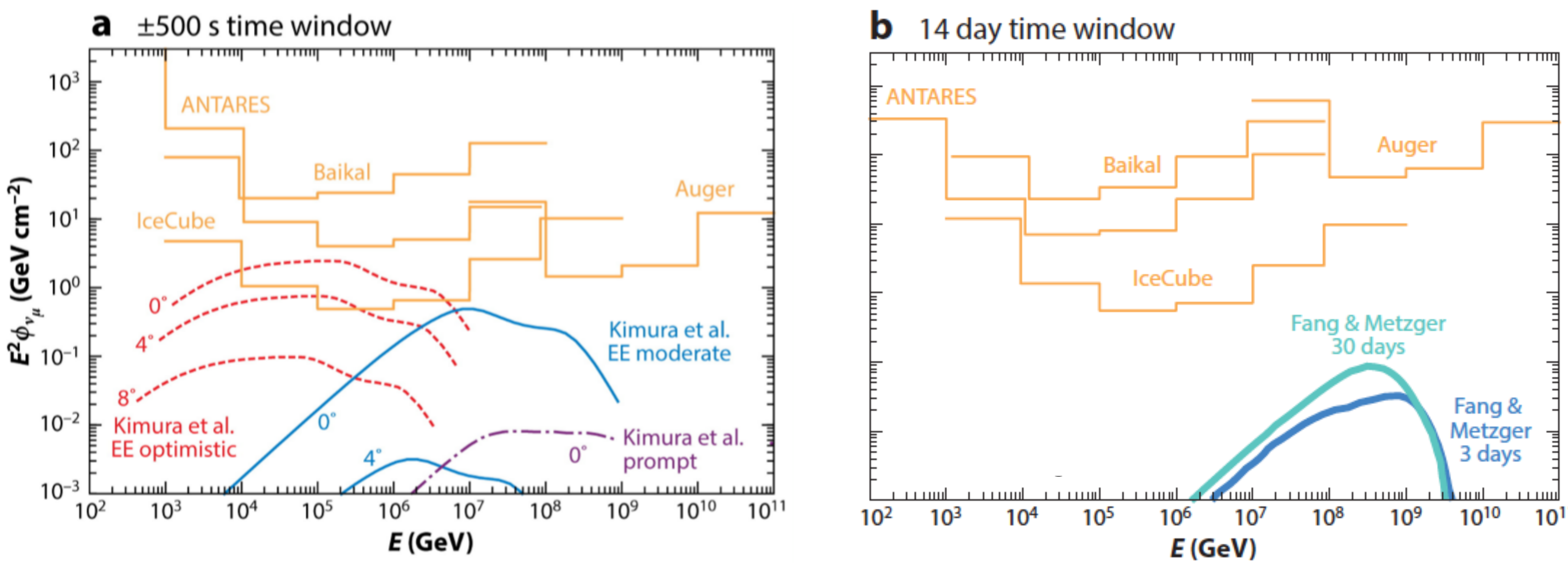




- Flavor conversion enhances synthesis nuclei with A>130 by a factor 2-3.
- More work needed to grasp how neutrinos affect electromagnetic emission.

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.

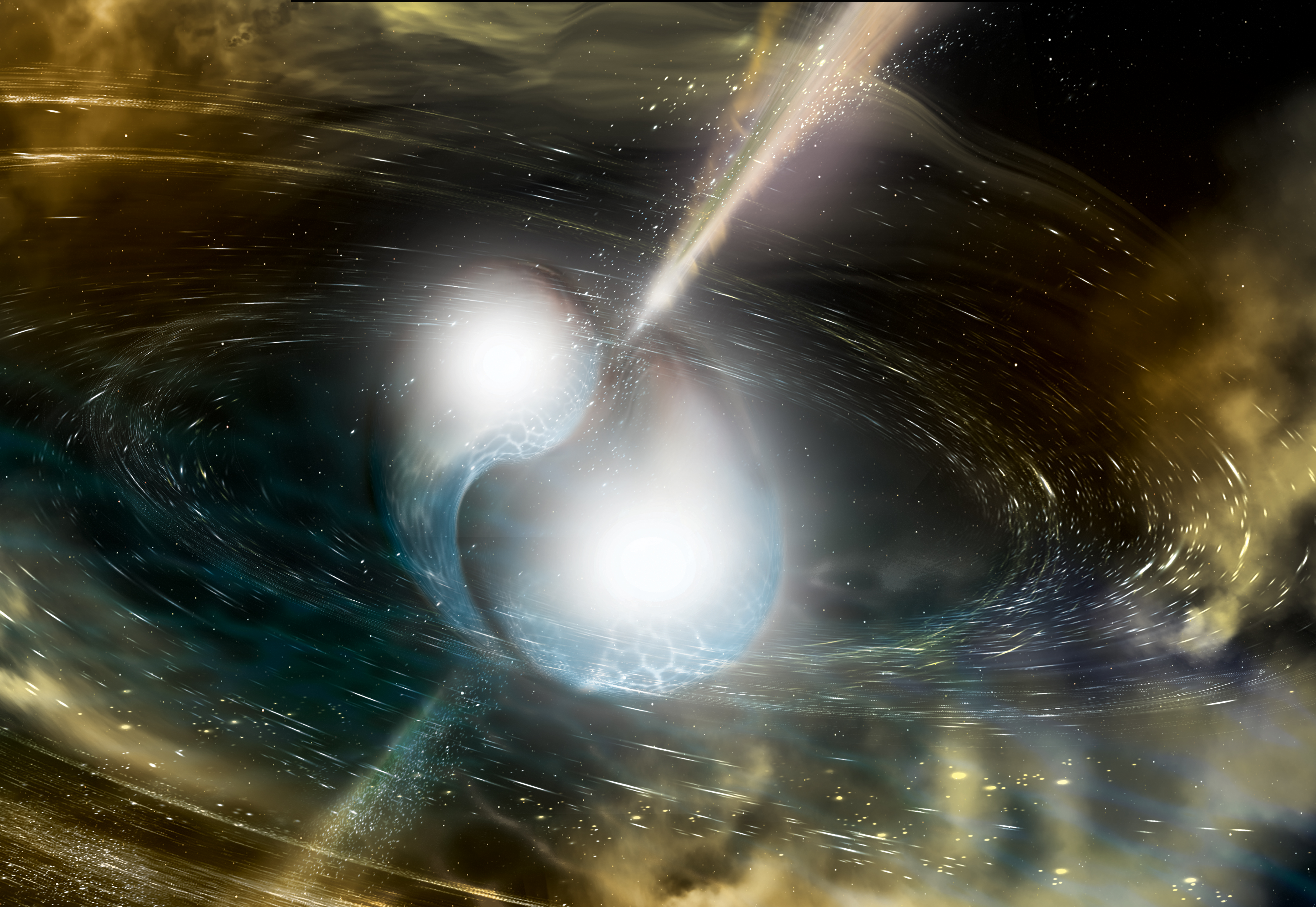
High Energy Neutrinos from GRB 170817A?



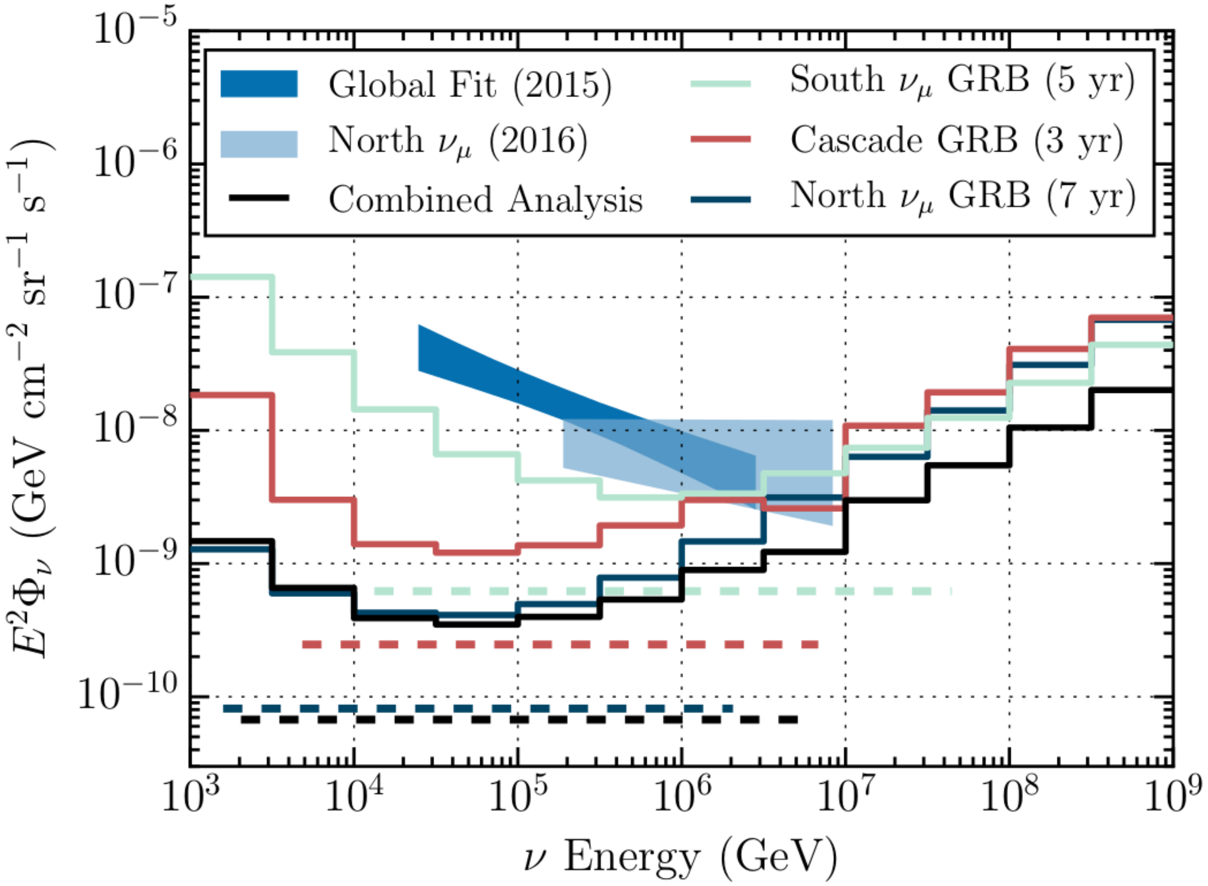
- No neutrinos detected from prompt short GRB phase.
- Neutrinos from long-lived ms magnetar following the merger.
- Neutrinos from internal shock propagating in kilonova ejecta.
- Favorable detection opportunities with multi-messenger triggers.

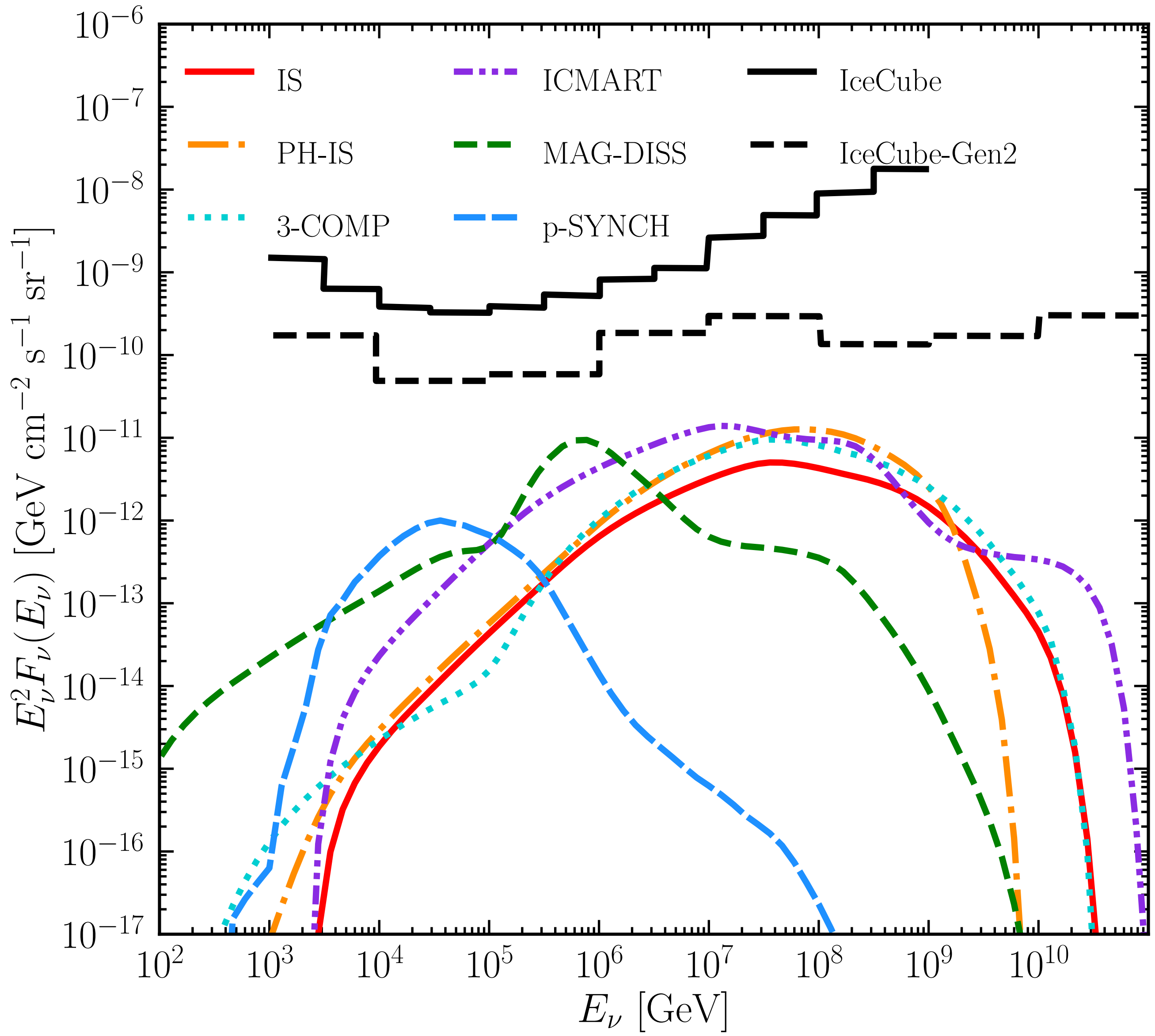
Figure credit: Christian Spiering. Murase& Bartos, Ann. Rev. (2019). Fang & Metzger, ApJ (2017). Kimura et al., PRD (2018). Biehl et al., MNRAS (2018). Kyutoku, Kashiyama, PRD (2018). Tamborra, Ando, JCAP (2015). Gottlieb, Globus, ApJL (2021).

Other Cosmic Accelerators



Long Duration Gamma-Ray Bursts

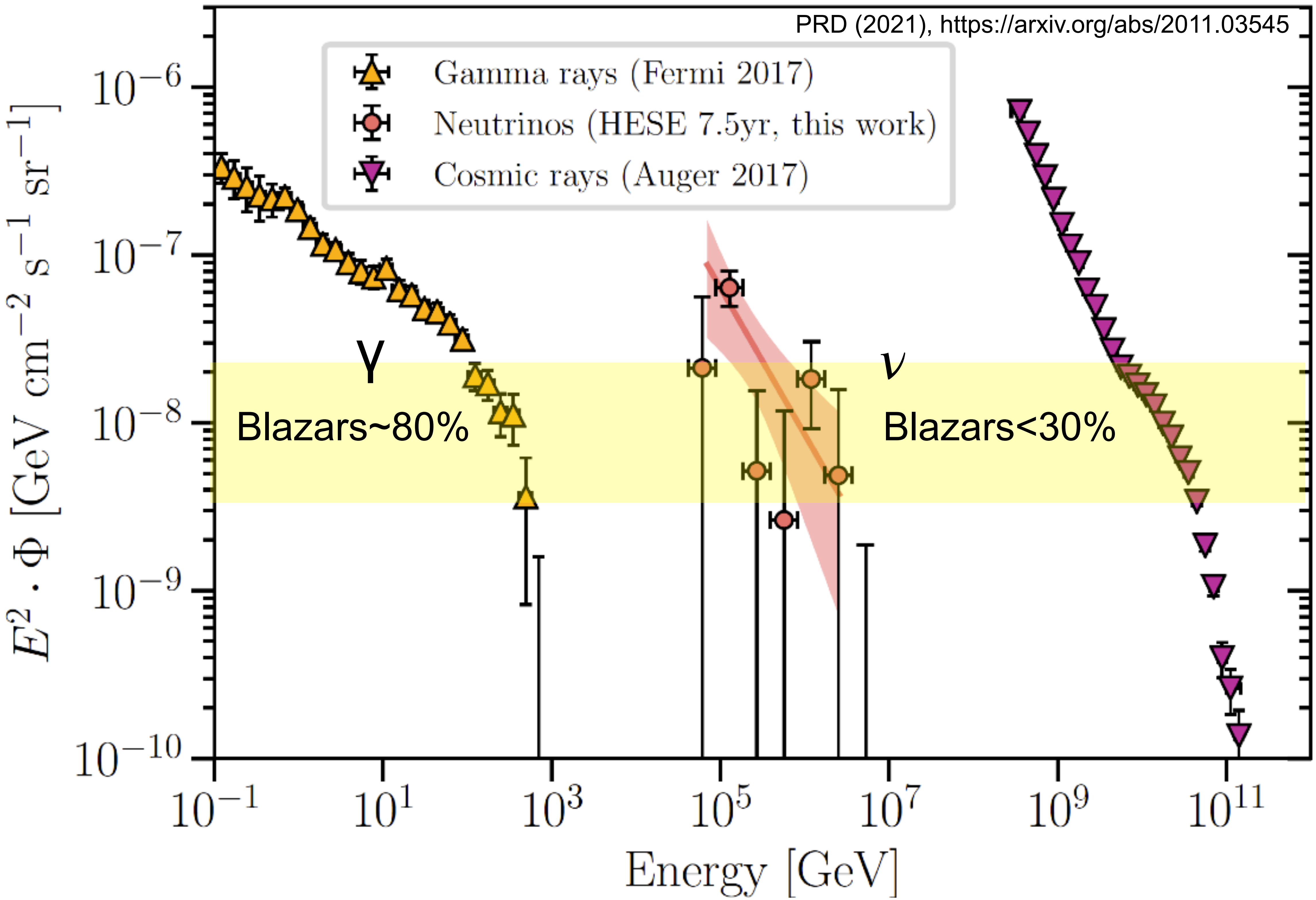




- No successful detection of high energy neutrinos from long GRBs (<1% to diffuse emission).
- Neutrino emission strongly depends on GRB emission mechanism.
- Neutrino emission from low-power GRBs can be copious.

ANTARES Coll., MNRAS (2020). IceCube Coll., ApJ (2017). Pitik, Tamborra, Petropoulou, JCAP (2021). Rudolph et al., MNRAS (2022), ApJ (2020). Heinze et al., MNRAS (2020).

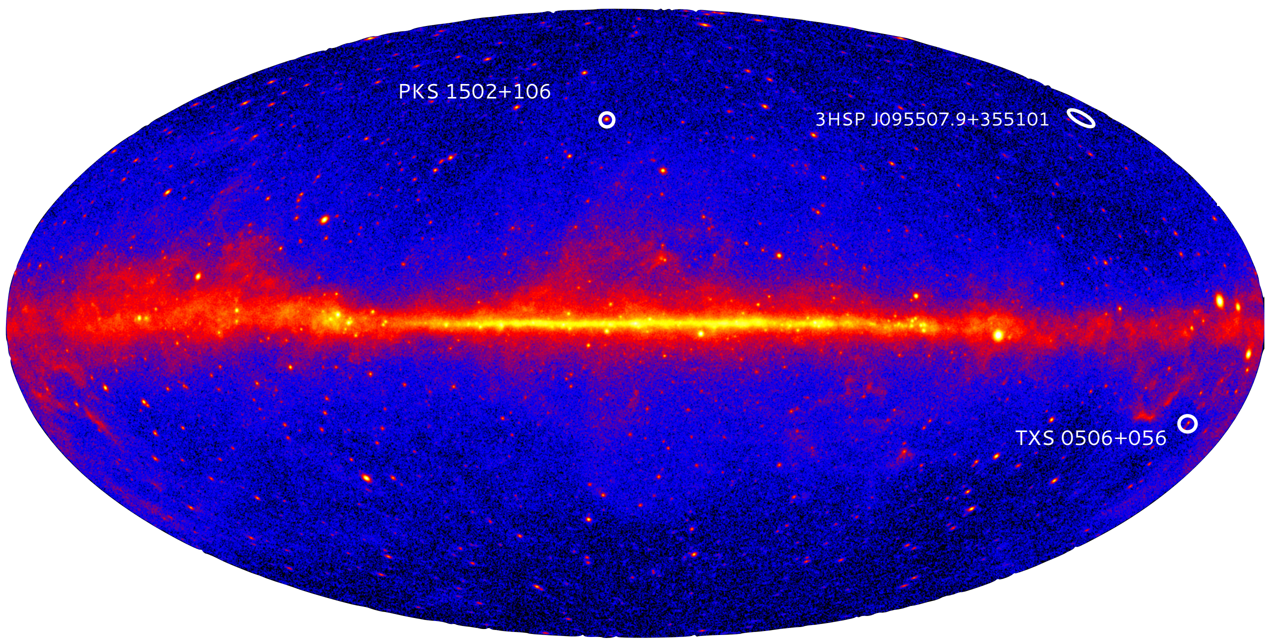
Do We See a Connection Among All Messengers?

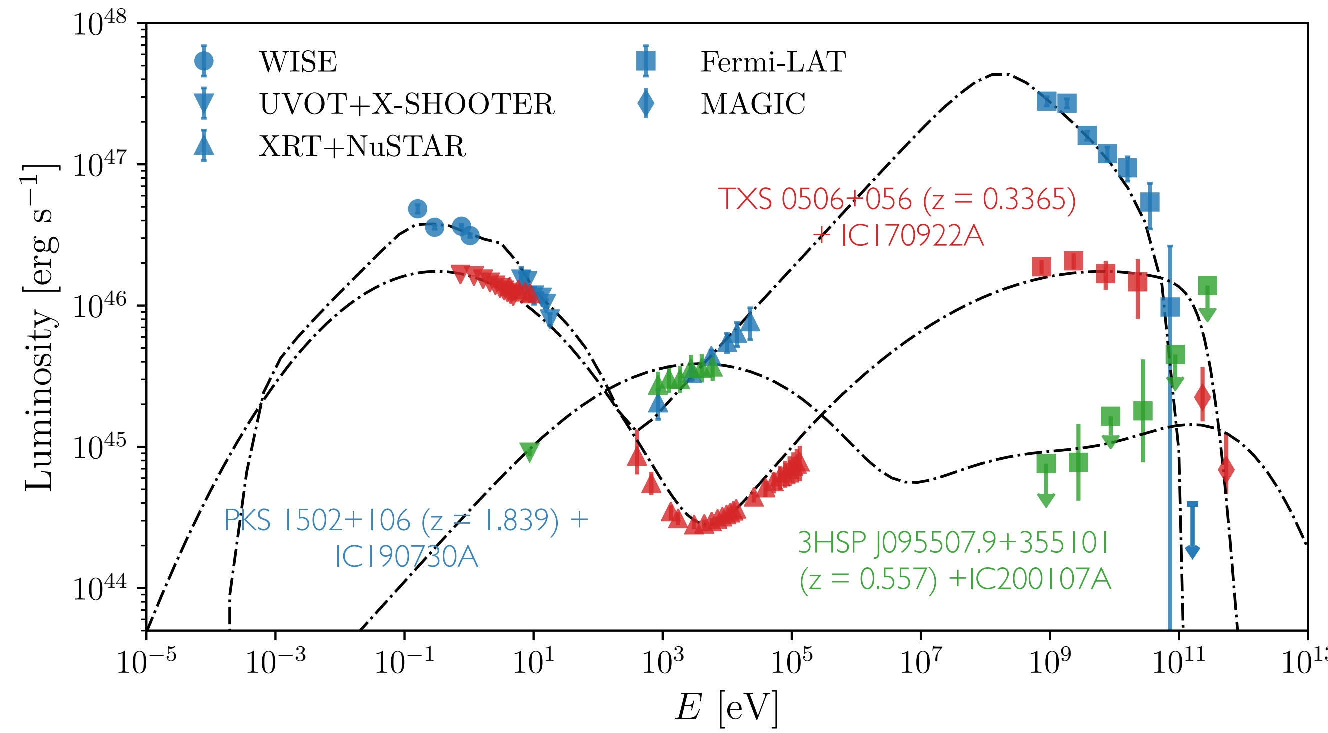


Marek Kowalski, ICRC 2021, PoS 022.

Blazars

Several IceCube neutrino events may be in coincidence with blazars.



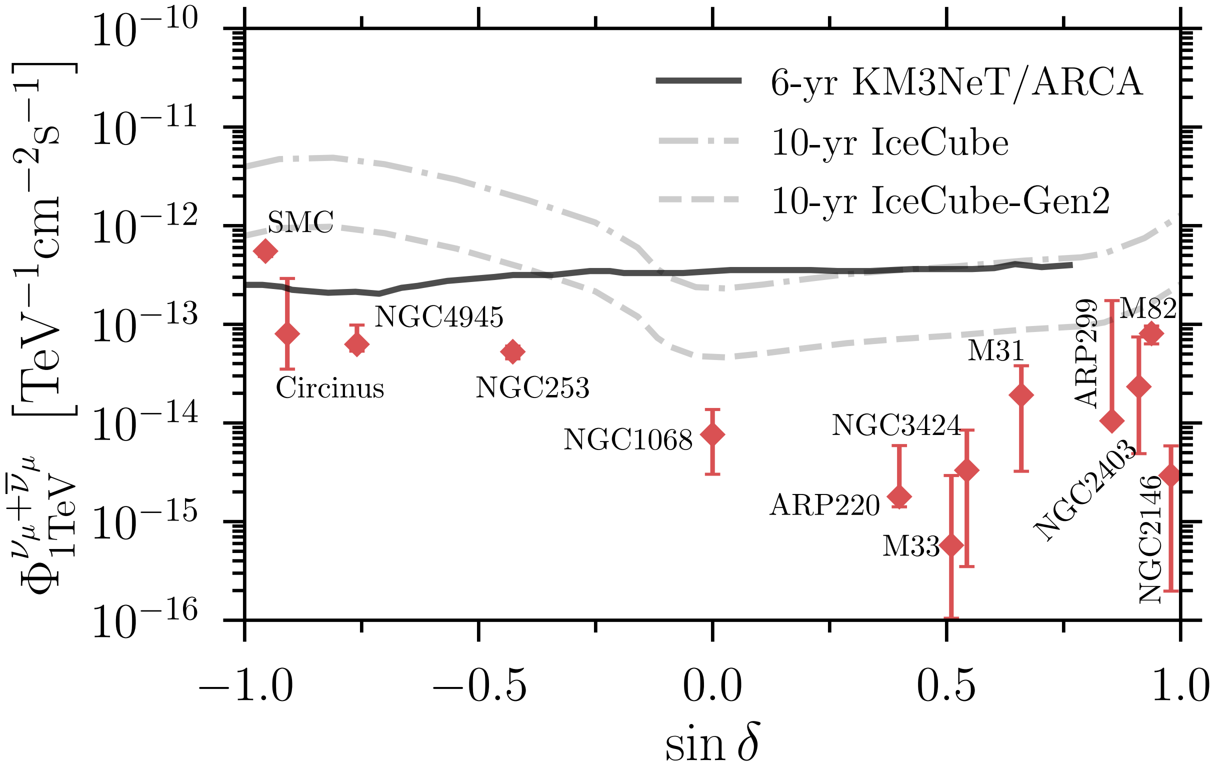


- Models statistically consistent with the detection of neutrinos but require extreme parameters, atypical of the blazar population.
- Need to move beyond one-zone model as well as investigate time variability.
- Multi-wavelength long-term evolution needs to be explored.
- Emerging trend of possible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

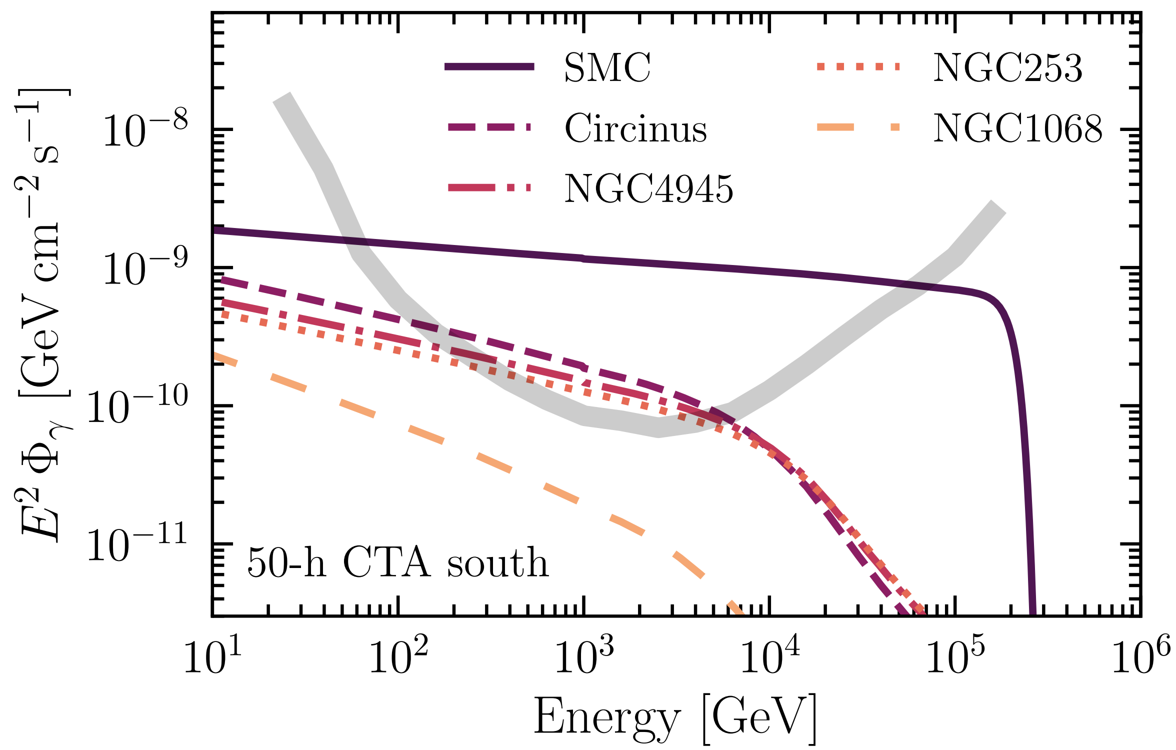
Figure credit: F. Oikonomou.

Starburst Galaxies

Neutrinos



Gamma-rays



Joint detection of neutrinos and gamma-rays will be a smoking gun signature of hadronic interactions (optimistic detection prospects).

Ambrosone et al. ApJL (2021), MNRAS (2022). Condorelli et al., arXiv: 2209.08593. Tamborra, Ando, Murase, JCAP (2014). Bechtol et al., ApJ (2017). Peretti et al., MNRAS (2022), MNRAS (2020).

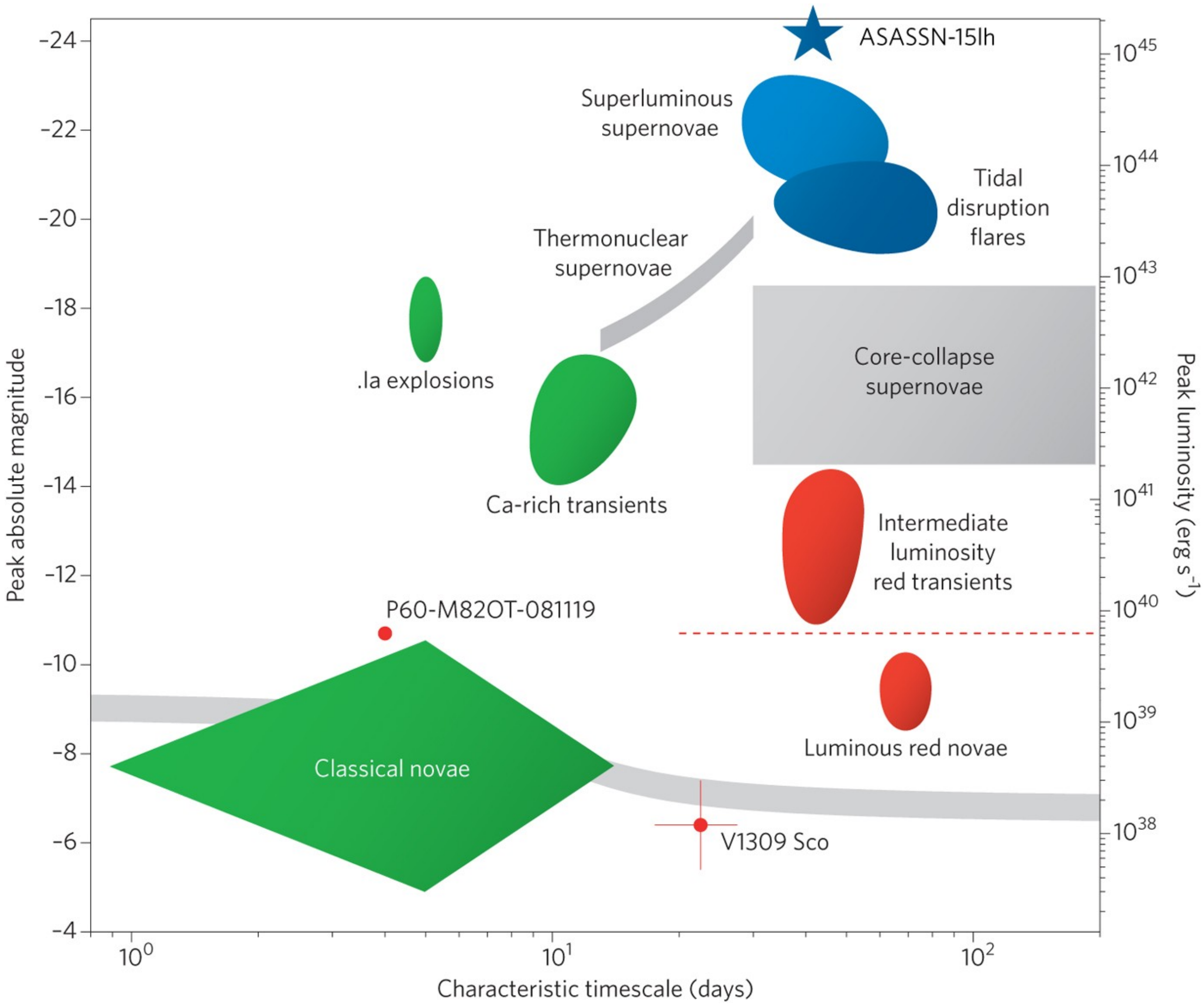
Tidal Disruption Events

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, (**maybe SLSN**)
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.

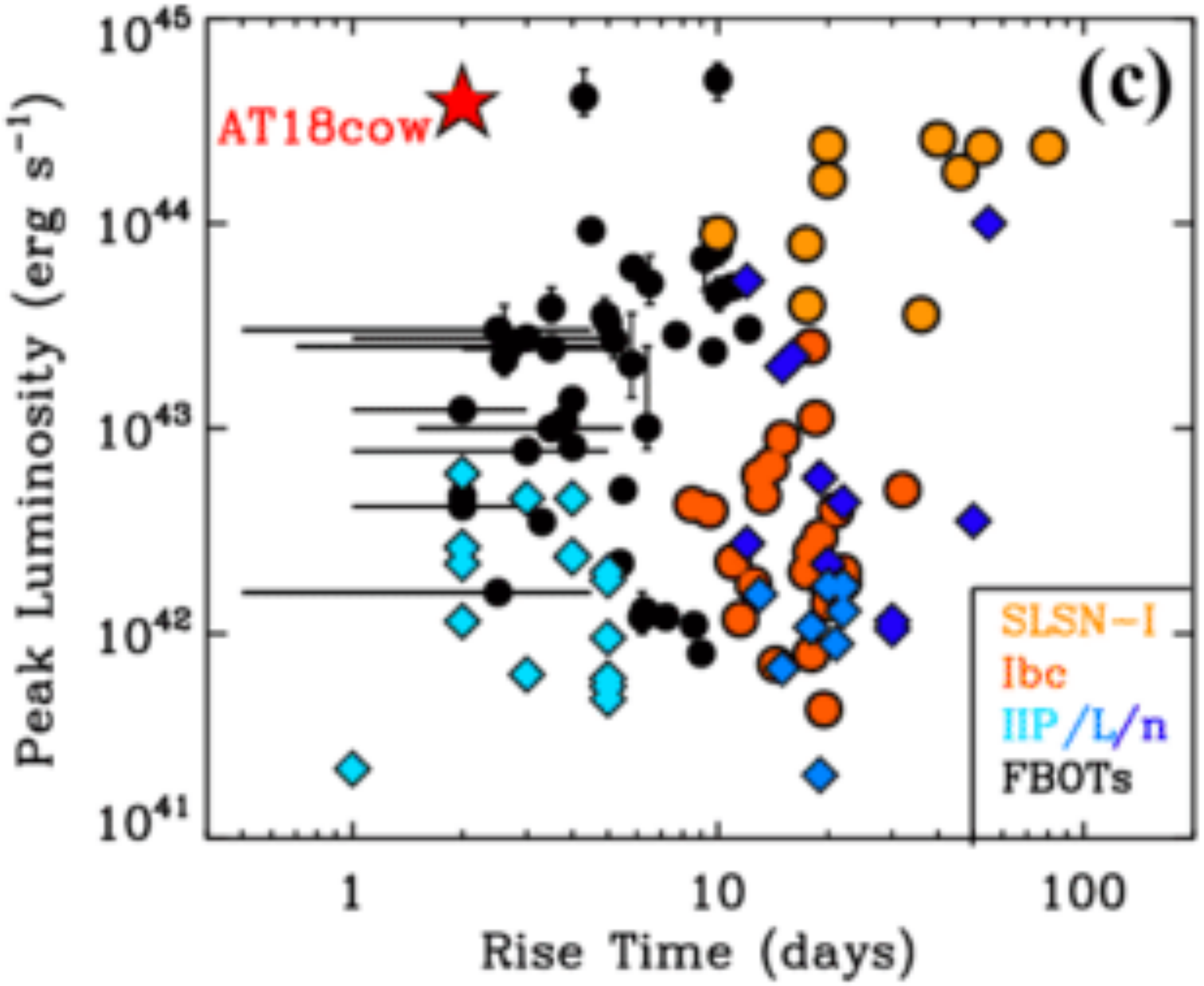
Stein et al., Nature Astronomy (2021). K. Hayasaki, Nat. Astr. (2021). Winter & Lunardini, Nat. Astr. (2021). Liu et al., PRD (2020). Murase et al., ApJ (2020). van Velzen et al., arXiv: 2111.09391. Liao et al., ApJL (2022). Reusch et al., PRL (2022). Pitik, Tamborra, Angus, Auchettl, ApJ (2022).

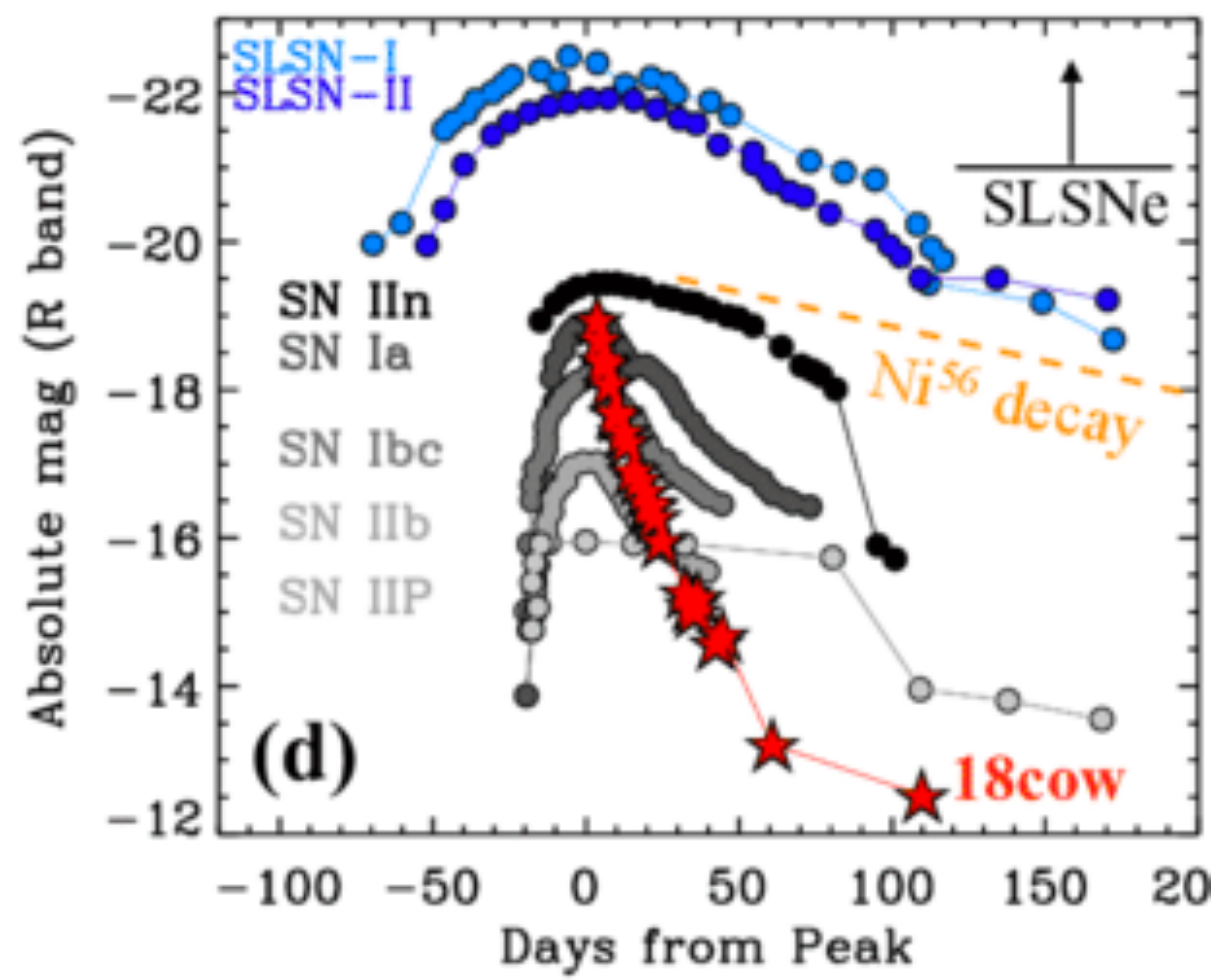
New Species in the Transient Zoo?



S. Bradley Cenko, Nature Astronomy (2017).

Fast Blue Optical Transients



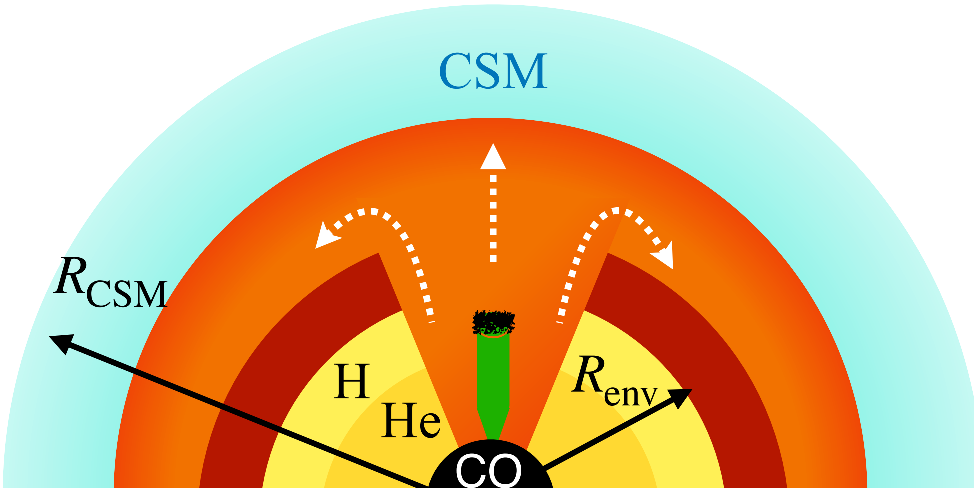


- Extremely fast rise time.
- Powered by a compact object launching an asymmetric outflow responsible for multi-wavelength EM emission.

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

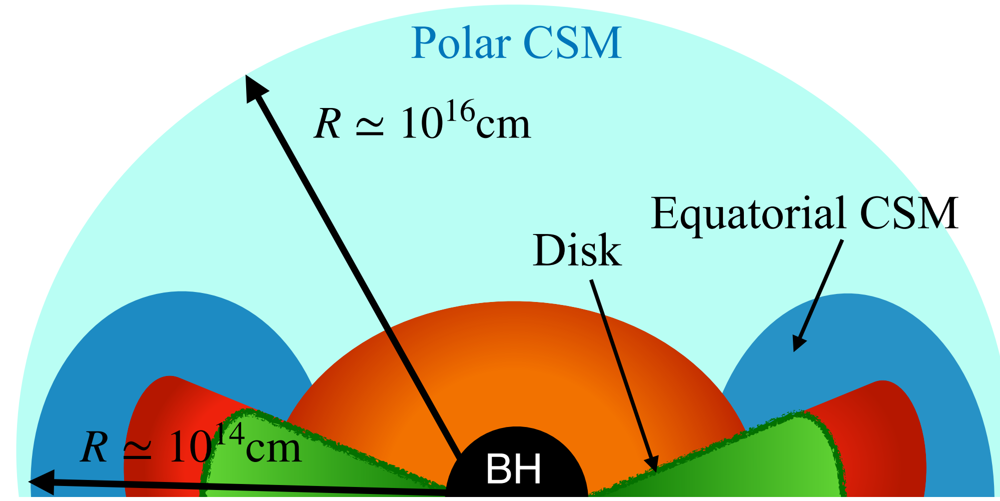
Fast Blue Optical Transients

Cocoon model

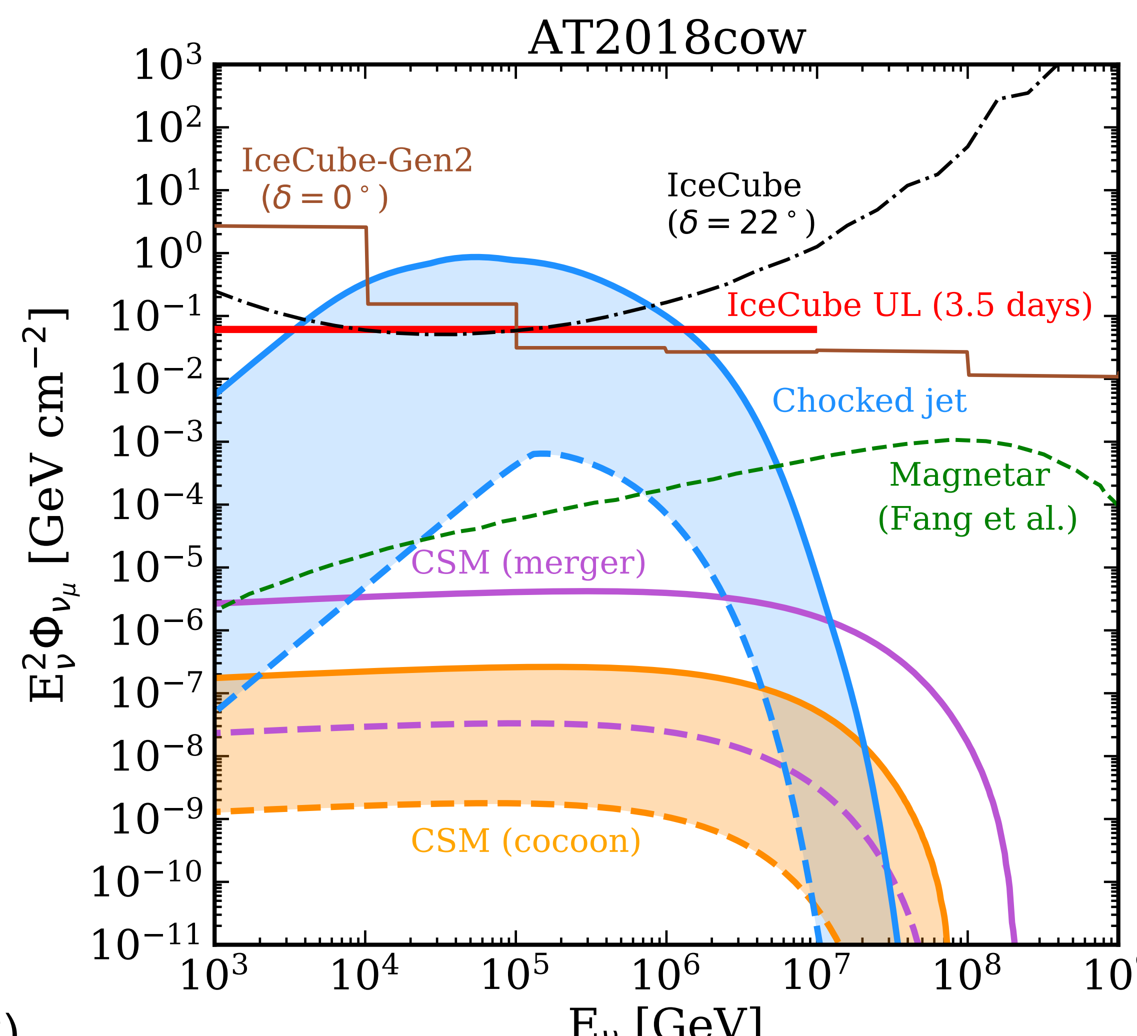


Collapse of a massive star, possibly not completely H-stripped, which launches a jet. The latter is choked in the envelope.

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 test particle acceleration.

- Microphysics modeling is still preliminary.

- Exciting growing number of likely multi-messenger detections.

Thank you!