The Niels Bohr International Academy

DARK

Multi-Messenger Fingerprints of Nearby Objects

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XVIII International Workshop on Neutrino Telescopes
Venice, March 18, 2019

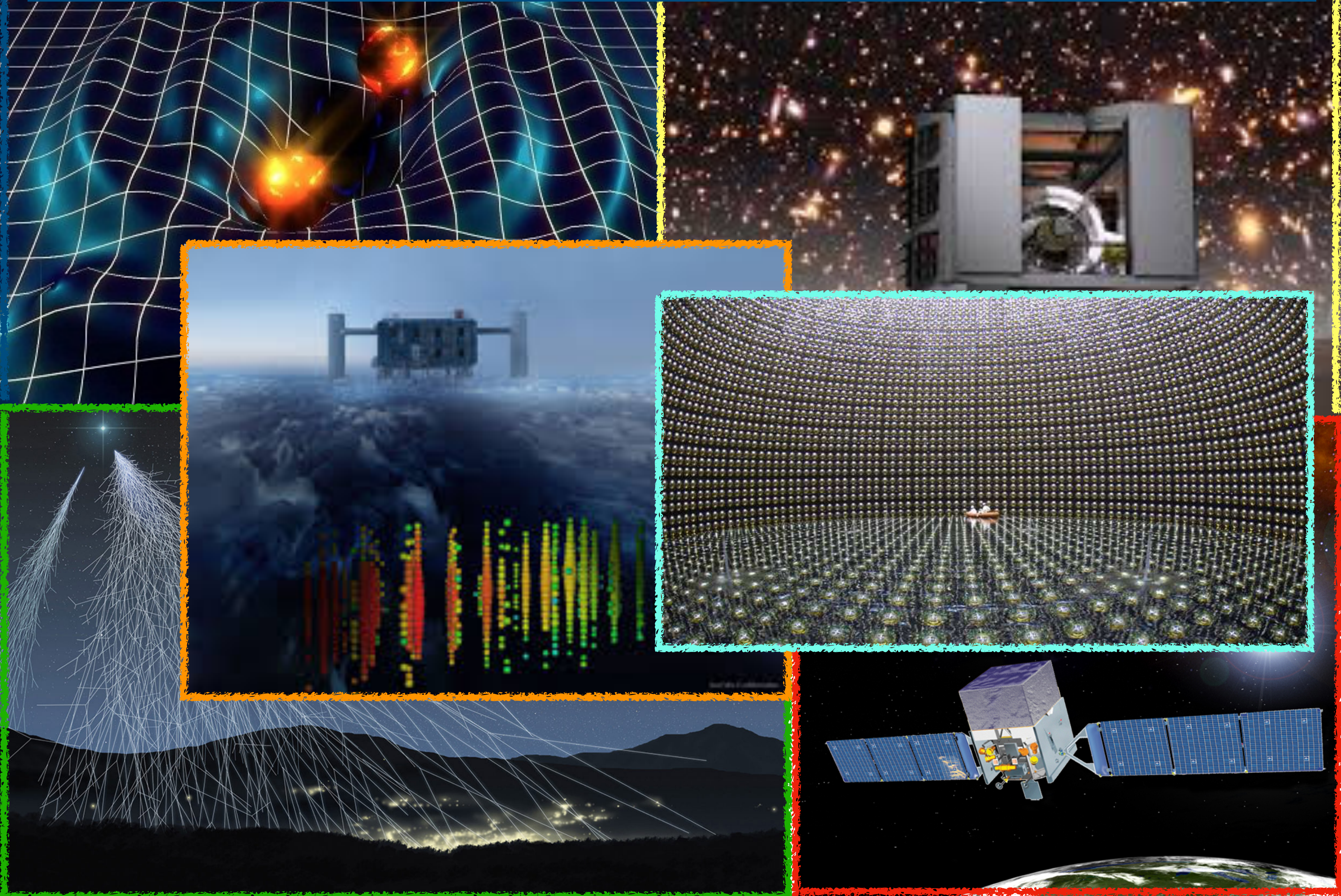
VILLUM FONDEN

SFB 1258 Neutrinos Dark Matter Messengers

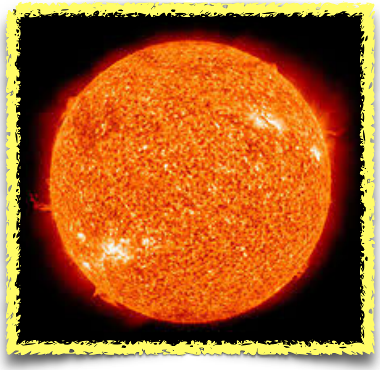
CARLSBERG FOUNDATION

Sapere Aude

Deciphering the Nearby Universe

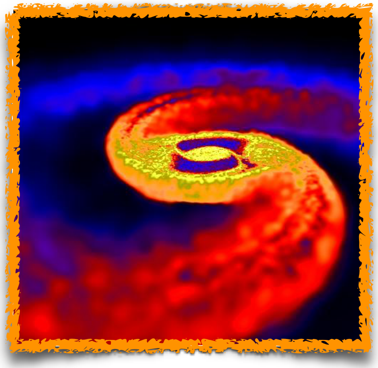


Nearby Objects

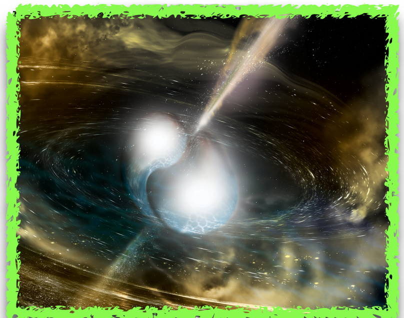


Sun

Supernovae



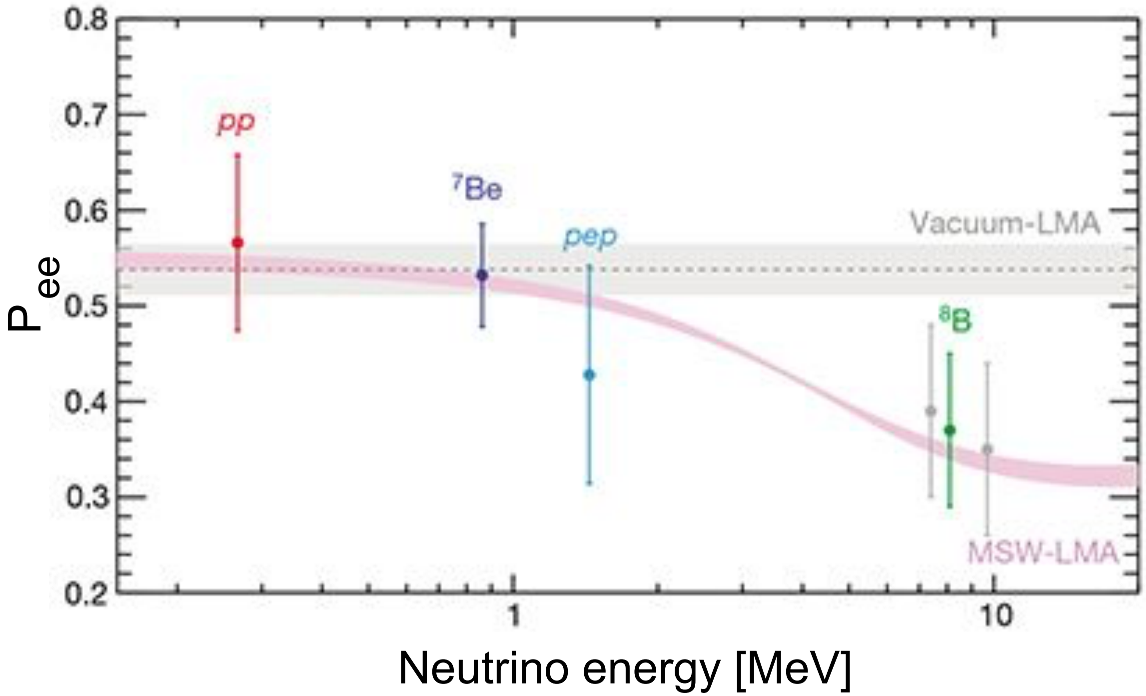
Compact binary mergers



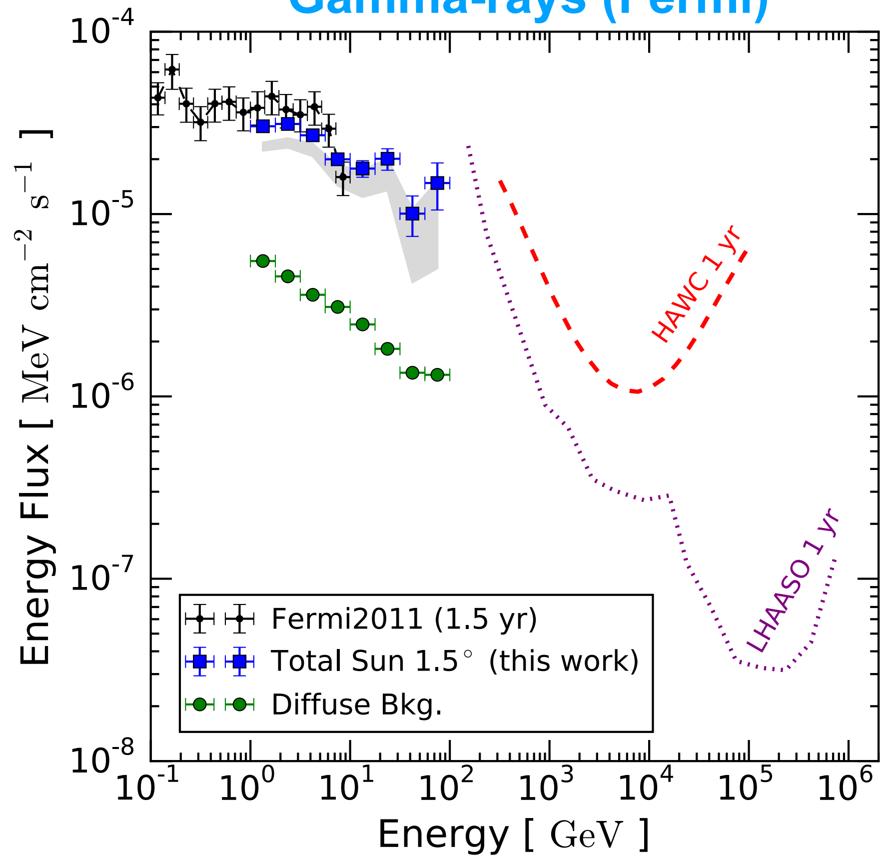
Jetted transients

The Nearest Object: Our Sun

Neutrino survival probability (Borexino)



Gamma-rays (Fermi)

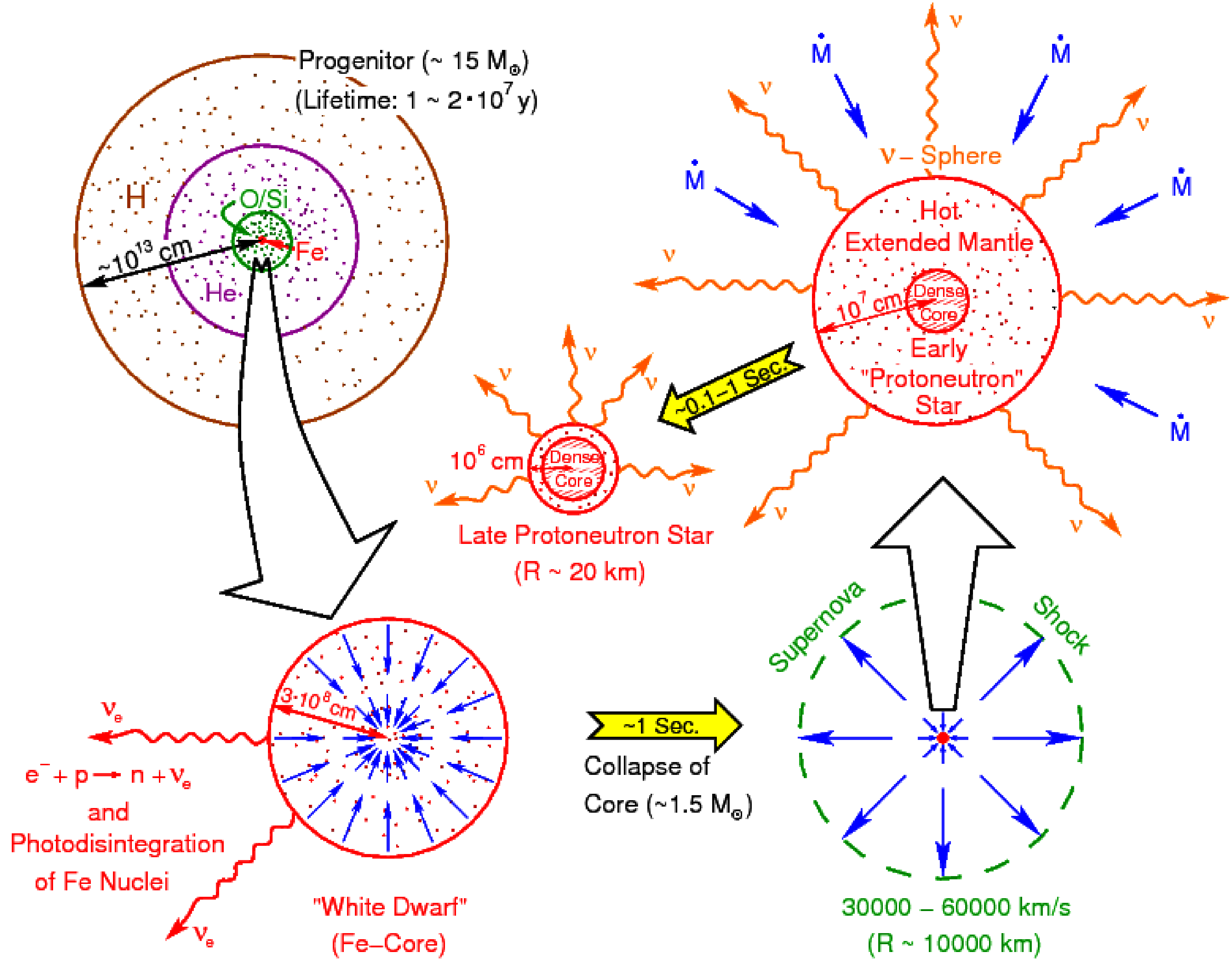


- Optical emission and neutrinos: the Sun is main-sequence star powered by nuclear fusion.
- Neutrinos: test of stellar structure and oscillation physics.
- Gamma-rays: probes of solar atmospheric magnetic fields and cosmic-ray physics. Gamma-ray emission poorly understood (flux ten times brighter than predicted).

See talk by Vissani

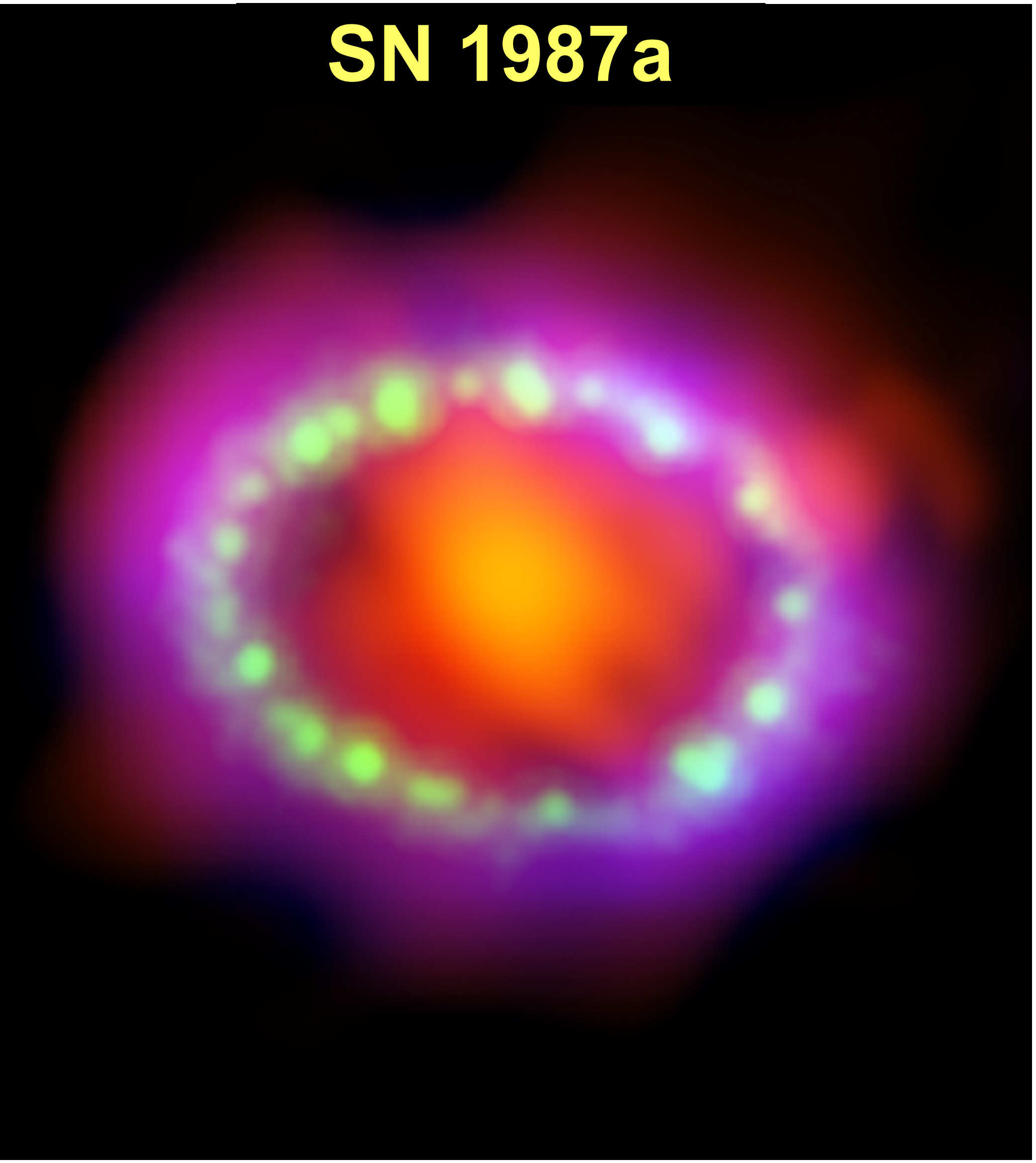
Image credits: Borexino Collaboration, Nature (2018). Ng et al., PRD (2016). Fermi-LAT, ApJ (2011).

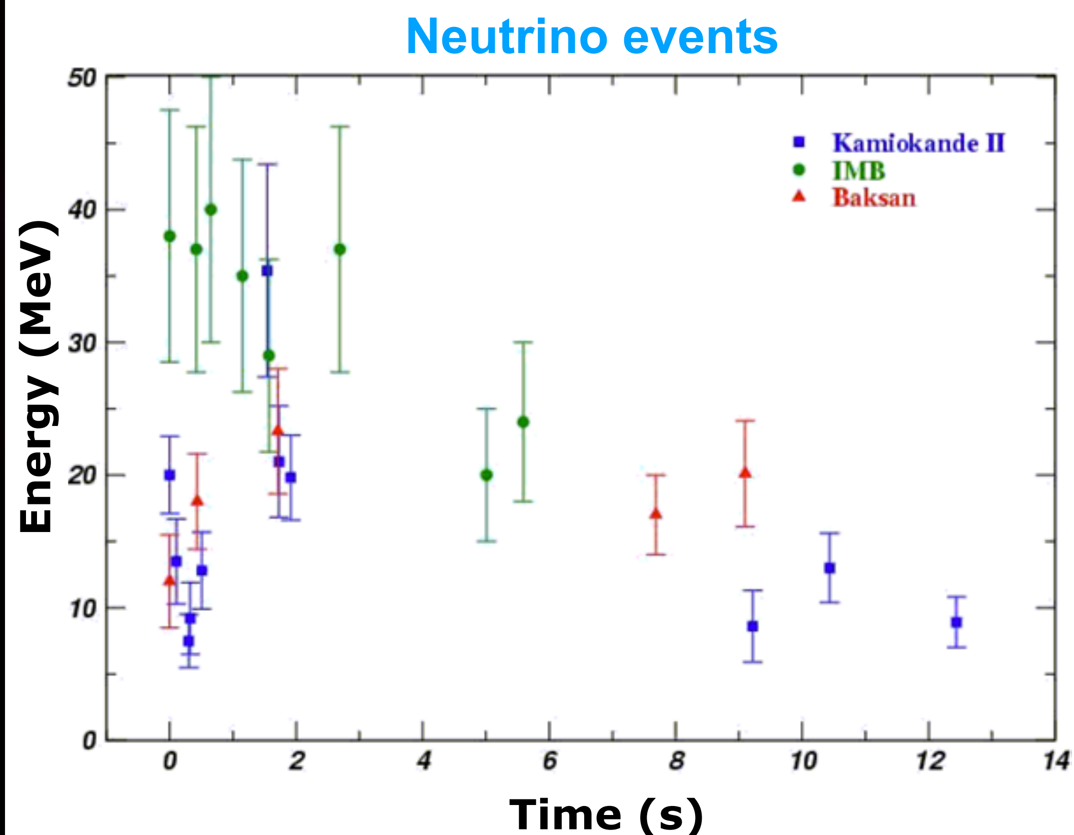
Core-Collapse Supernovae



Adapted from A. Burrows (1990).

The Local Supernova





The only supernova explored via electromagnetic multi-wavelength observations and neutrinos.

Image credits: NASA, ESA.

The Next Local Supernova (SN 2XXXa)

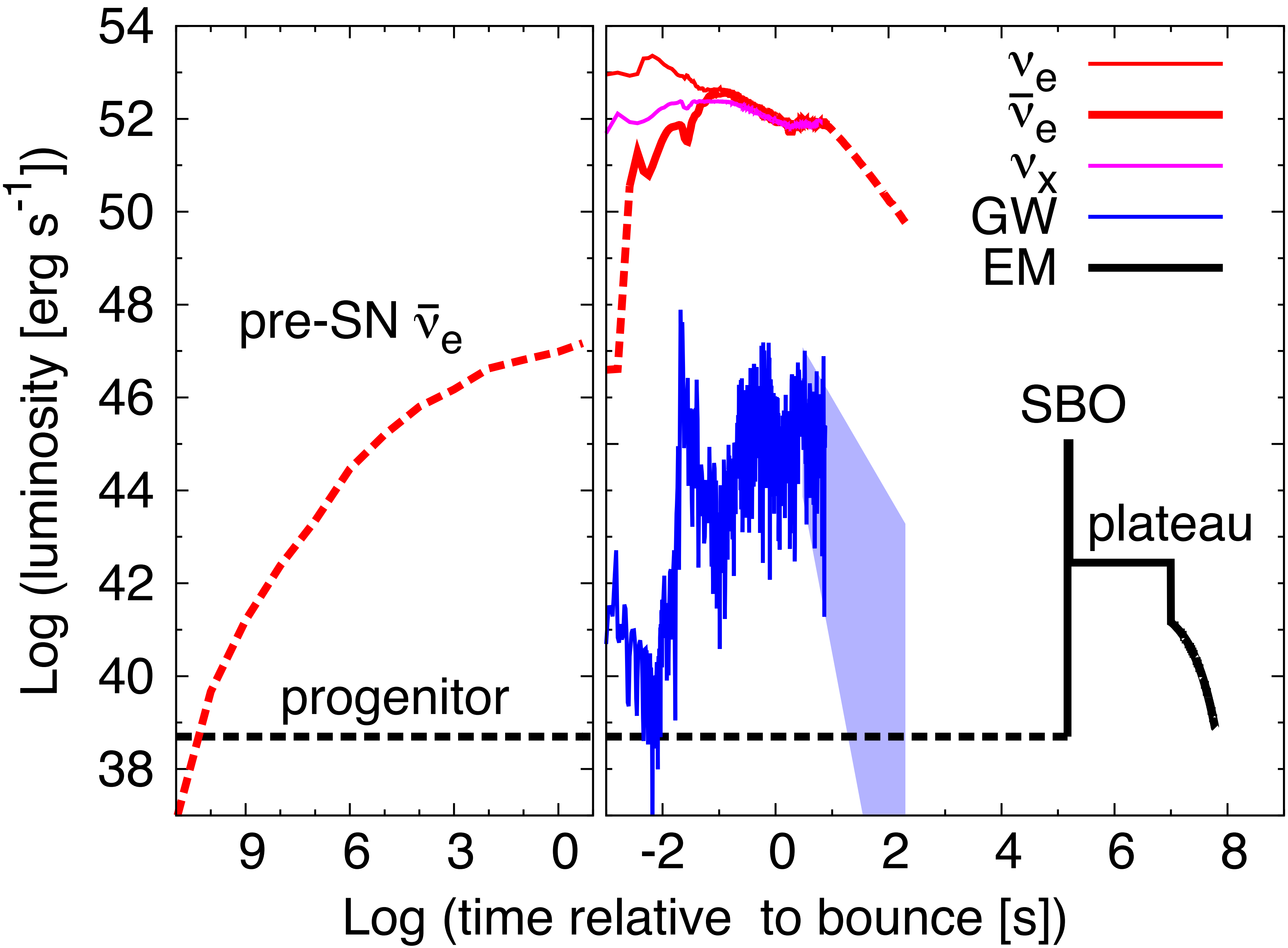


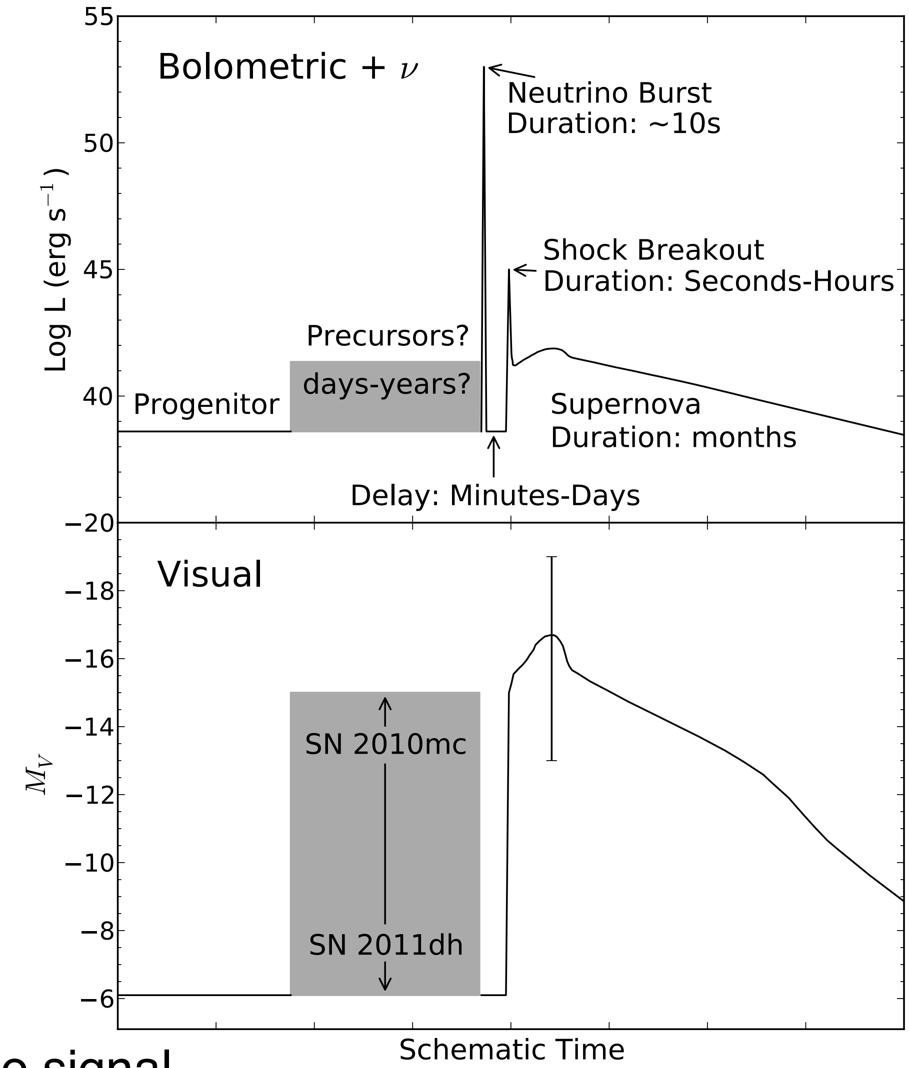
Figure from Nakamura et al., MNRAS (2016).

Supernova Hunting

SuperNova Early Warning System (SNEWS)

Concidence Sever

E-mail alert
ATel alerts, LIGO, GCN



- Shock break out arrives mins to hours after neutrino signal.

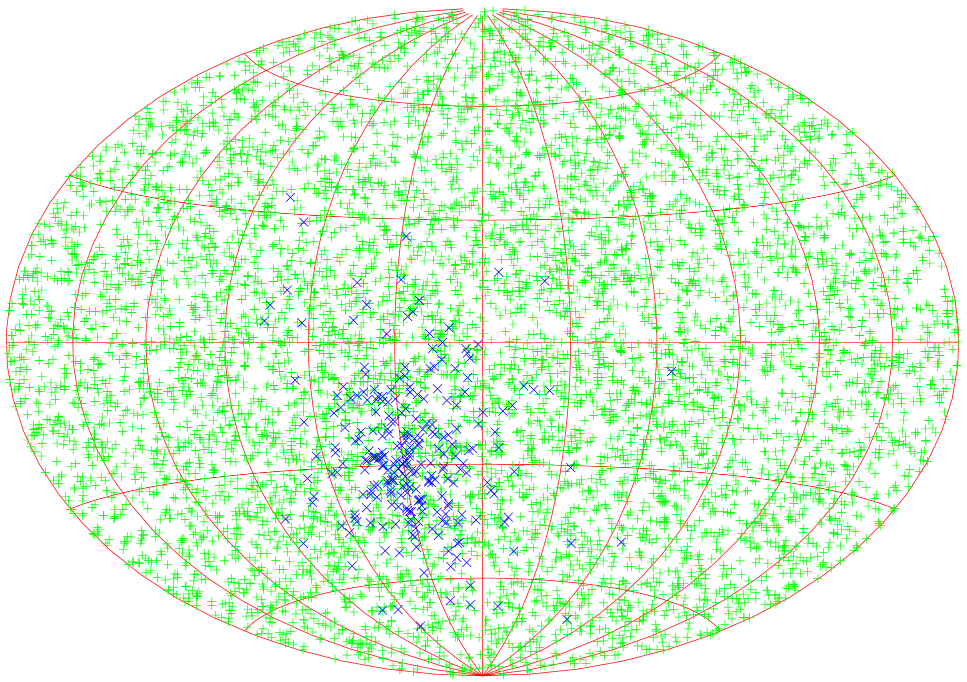
Individual detectors, e.g.:

- Super-K could release alert within 1 hour of neutrino burst (time, pointing).
- Super-K-Gd project may potentially release alert within 1 sec.

See talk by Gil Botella

http://snews.bnl.gov. Adams et al., ApJ (2013).

Supernova Hunting



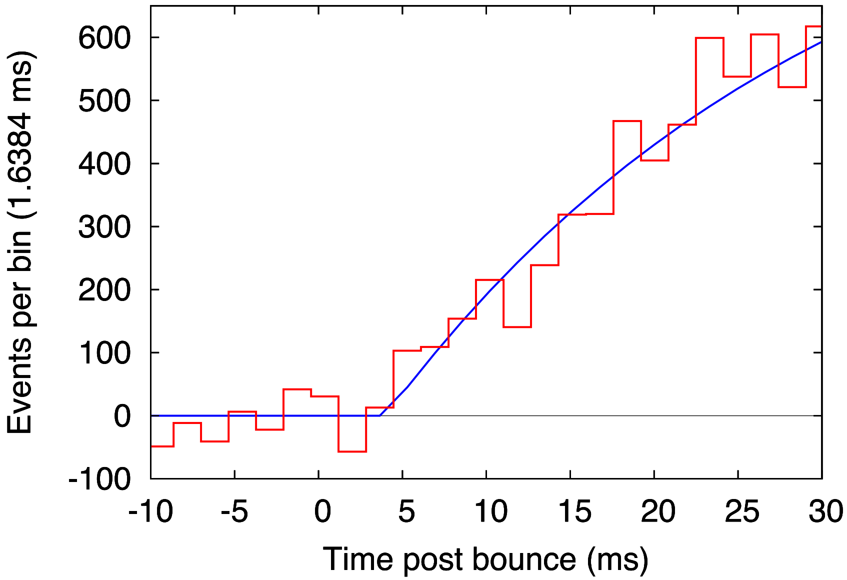
$$\nu + e^- \rightarrow \nu + e^-$$

	Super-K	Hyper-K
water	6 deg	1.4 deg
water+Gd	3 deg	0.6 deg

- SN location with neutrinos (pointing and triangulation) crucial for vanishing or weak SNe.
- Fundamental for multi-messenger searches.
- Angular uncertainty comparable to e.g., ZTF, LSST potential.

Beacom & Vogel (1999). Tomas et al. (2003). Fisher et al. (2015). Muehlbeier et al. (2013). Brdar, Lindner, Xu (2018).

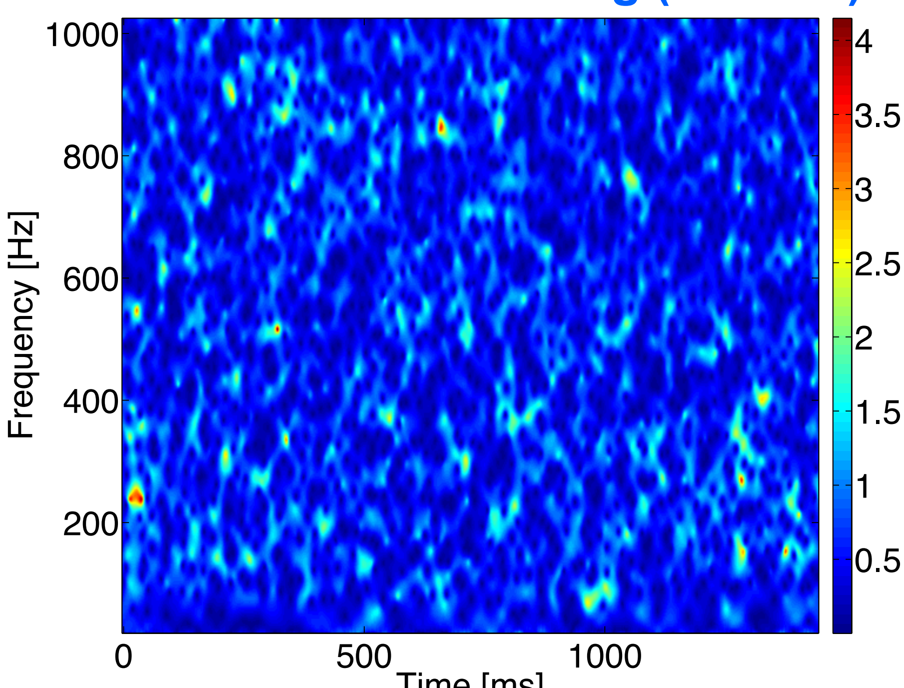
Neutrino Timing for Gravitational Waves



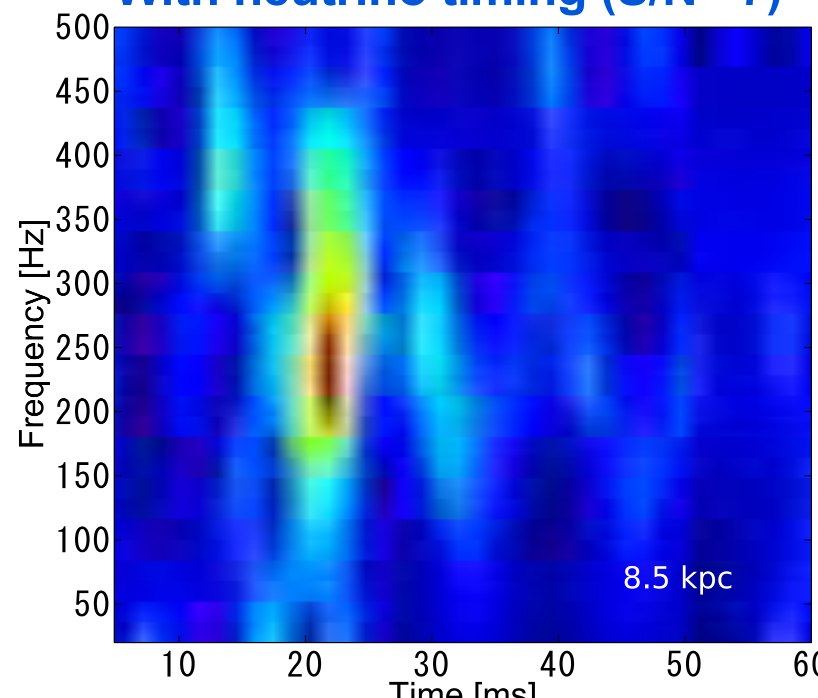
Probe core bounce time with neutrinos.

Help timing for gravitational wave detection.

Without neutrino timing (S/N~3.5)

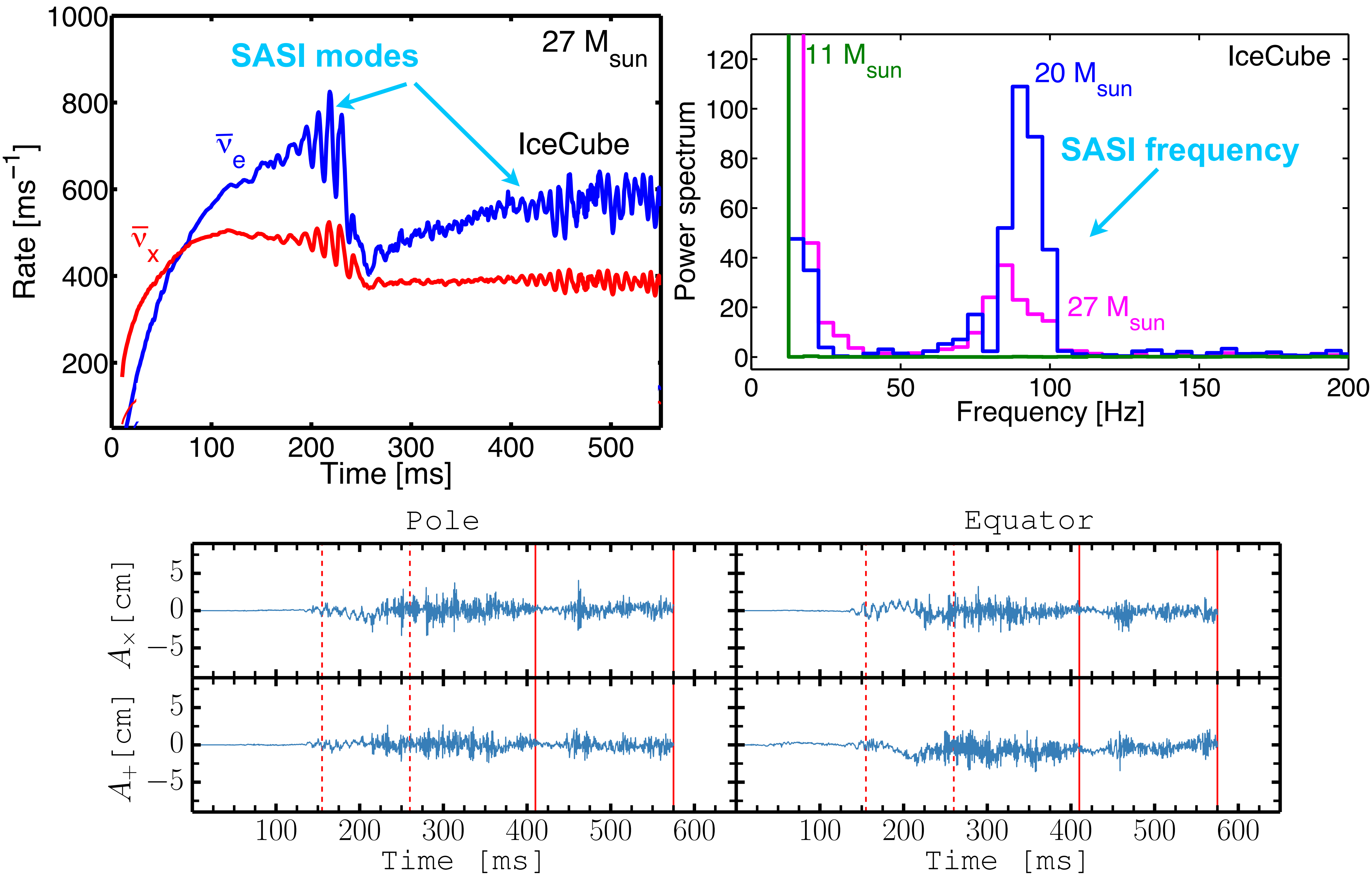


With neutrino timing (S/N ~7)



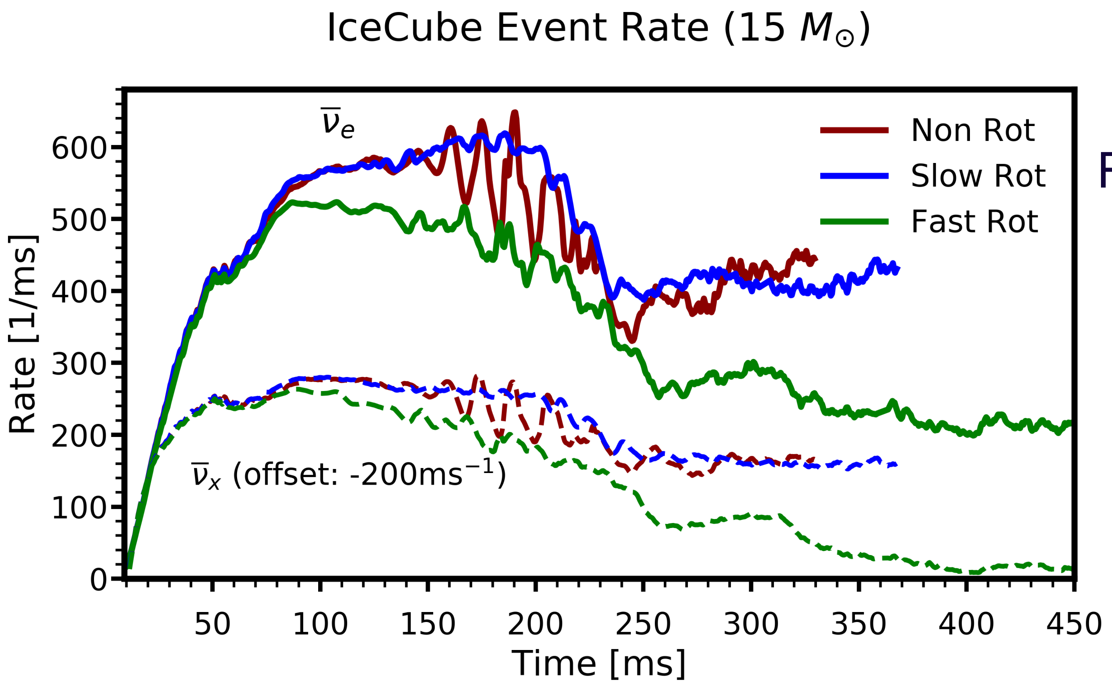
Pagliaroli et al., PRL (2009), Halzen & Raffelt PRD (2009). Nakamura et al., MNRAS (2016).

Fingerprints of the Explosion Mechanism



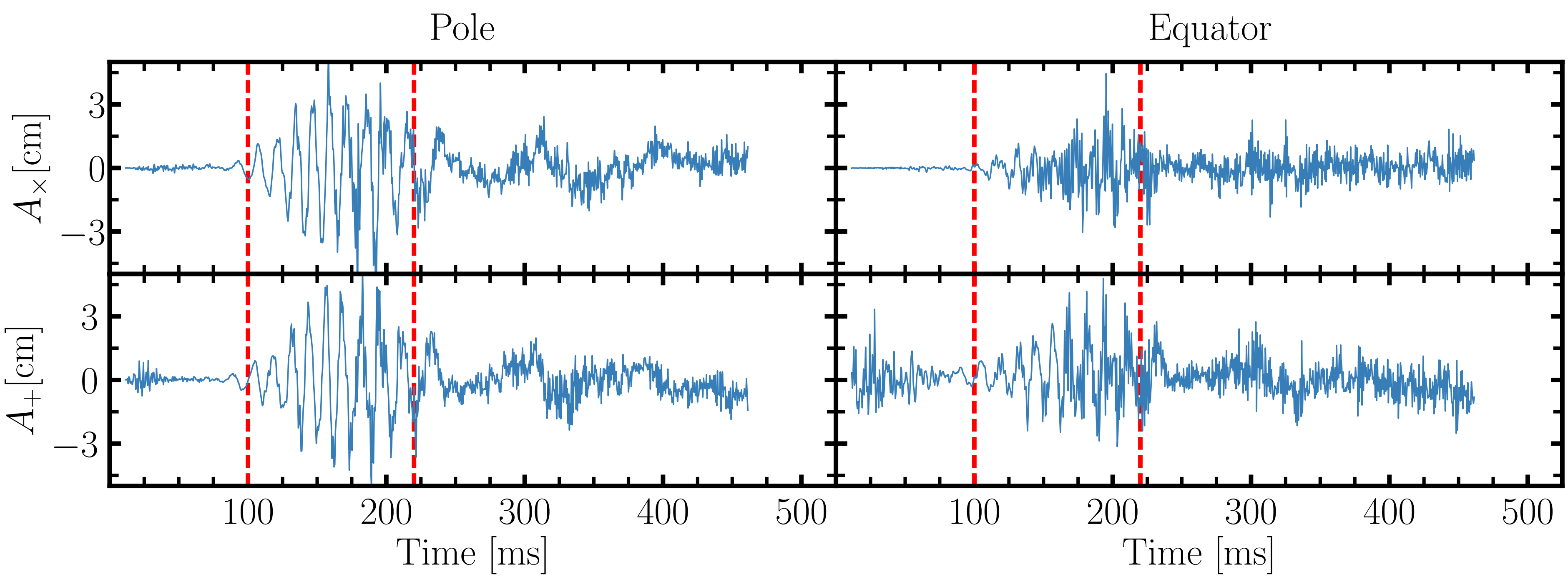
Tamborra et al., PRL (2013), PRD (2014). Andresen et al., MNRAS (2017). Kuroda et al., ApJ (2017).

Fingerprints of Supernova Rotation



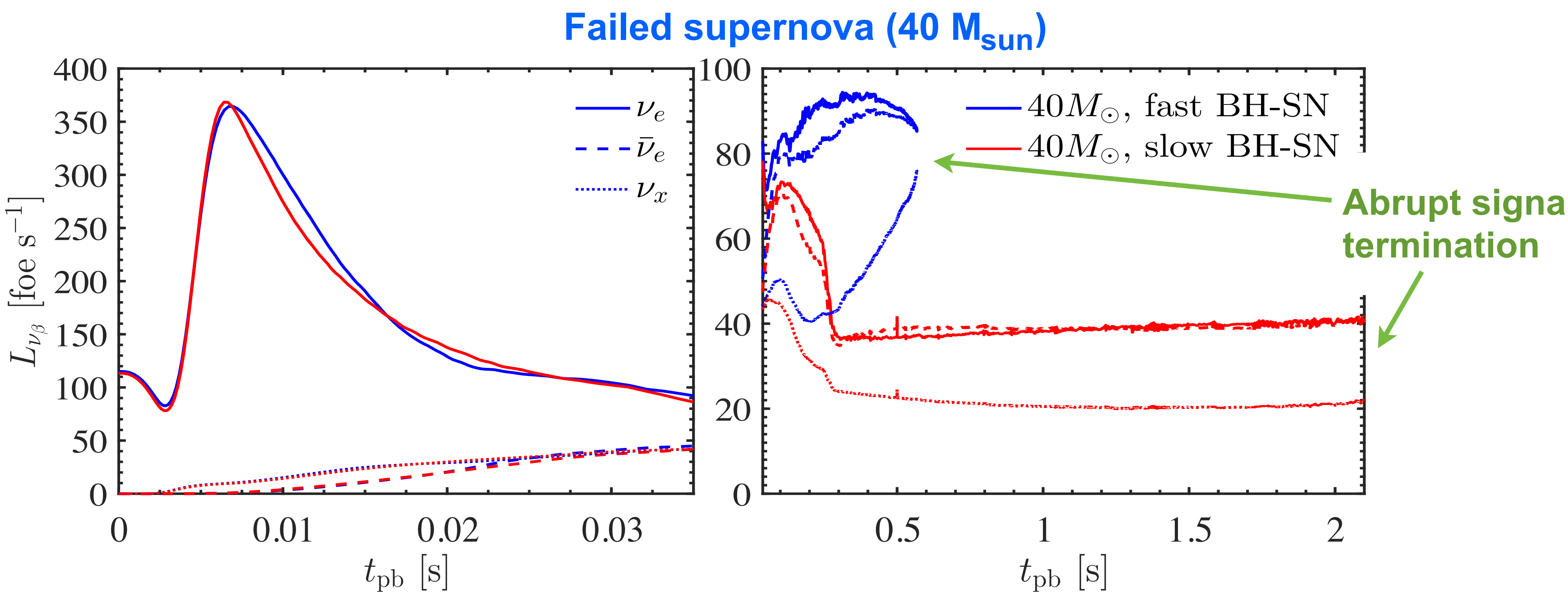
Rotation induces high-frequency modulations.

Neutrinos as supernova gyroscopes.



Walk, Tamborra et al., PRD (2018). Walk, Tamborra et al., arXiv: 1901.06235. Andresen et al., arXiv: 1810.07638.

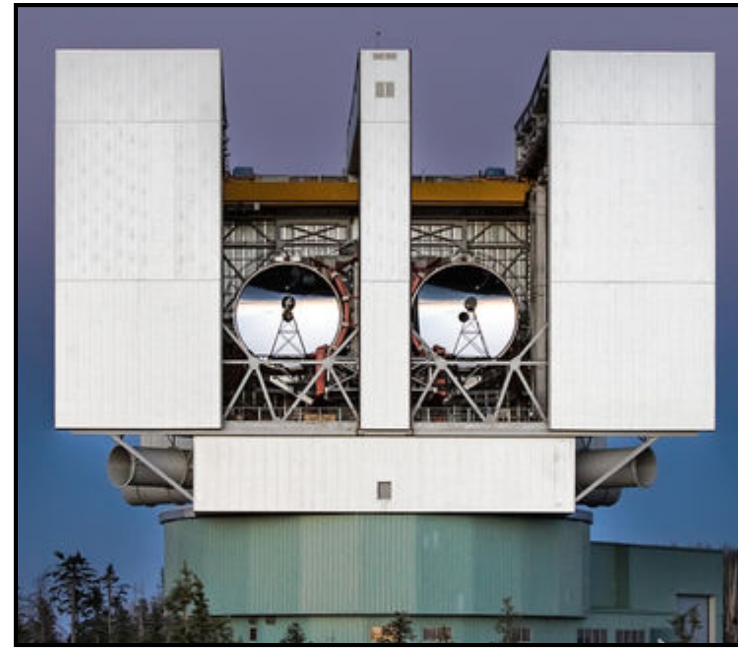
Fingerprints of Black Hole Formation



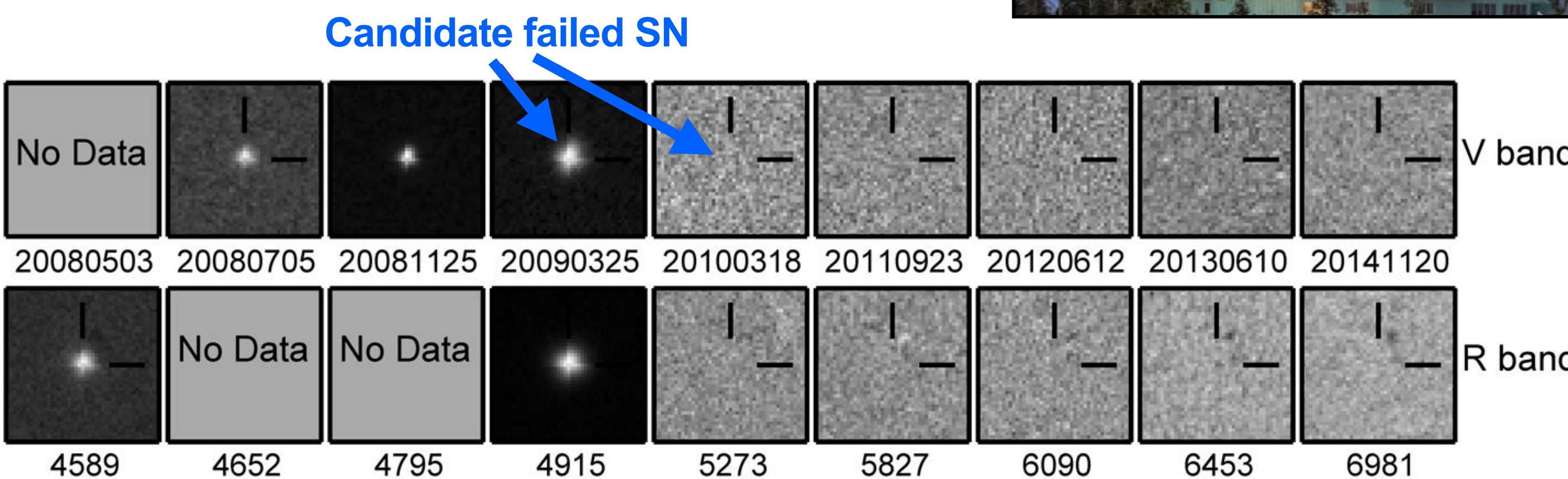
- Failed supernovae up to 20-40% of total (low-mass progenitors can also lead to failed SN).
- Neutrinos may be the only probes revealing the black-hole formation.

Sukhbold et al., ApJ (2016). Ertl et al., ApJ (2016). Horiuchi et al., MNRSL (2014). O'Connor & Ott, ApJ (2011). O'Connor, ApJ (2015).

A Survey About Nothing



- Search for disappearance of red supergiants (27 galaxies within 10 Mpc with Large Binocular Telescope).
- First 7 years of survey: 6 successful core-collapse, **1 candidate failed supernova**.

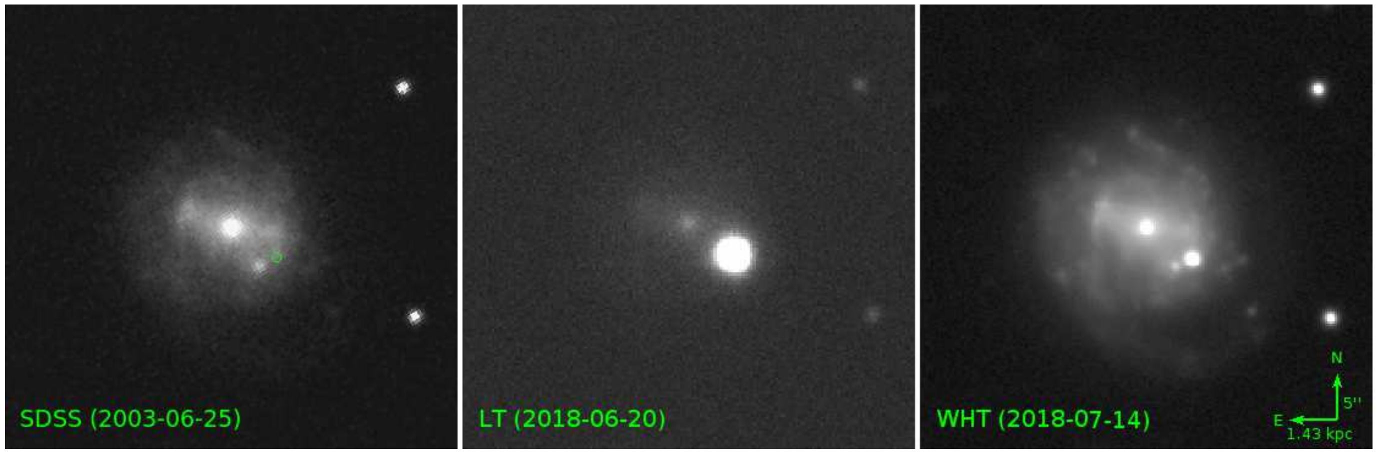


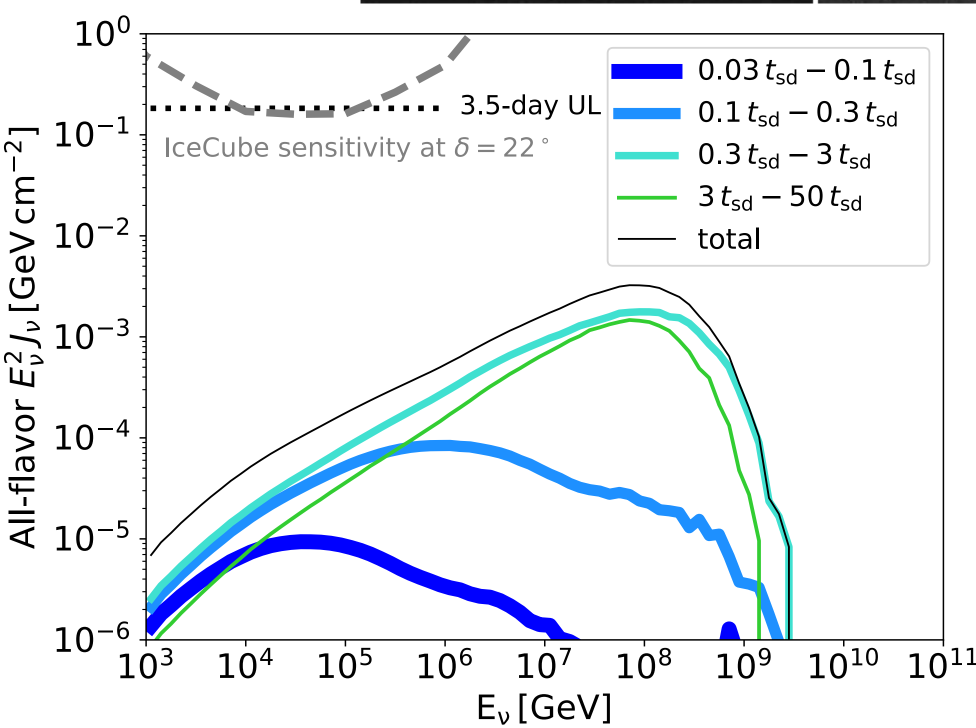
Failed core-collapse fraction: 4-43% (90% CL)

Adams et al., MNRAS (2017), MNRAS (2017). Gerke, Kochanek & Stanek, MNRAS (2015). Kochanek et al., ApJ (2008).

A Fast High-Luminosity Transient (AT2018cow)

- Super-luminous transient with low ejecta mass. Extensive multi-wavelength analysis.
- First direct evidence for a central engine (time-variable X-ray emission).
- Fortuitous coincidence of neutrino events.





AT2018cow-like transients are good targets for multi-messenger observatories.

Perley et al., MNRAS (2019). Margutti et al., ApJ (2019). Fang et al., arXiv: 1812.11673.

Gamma-Ray Bursts

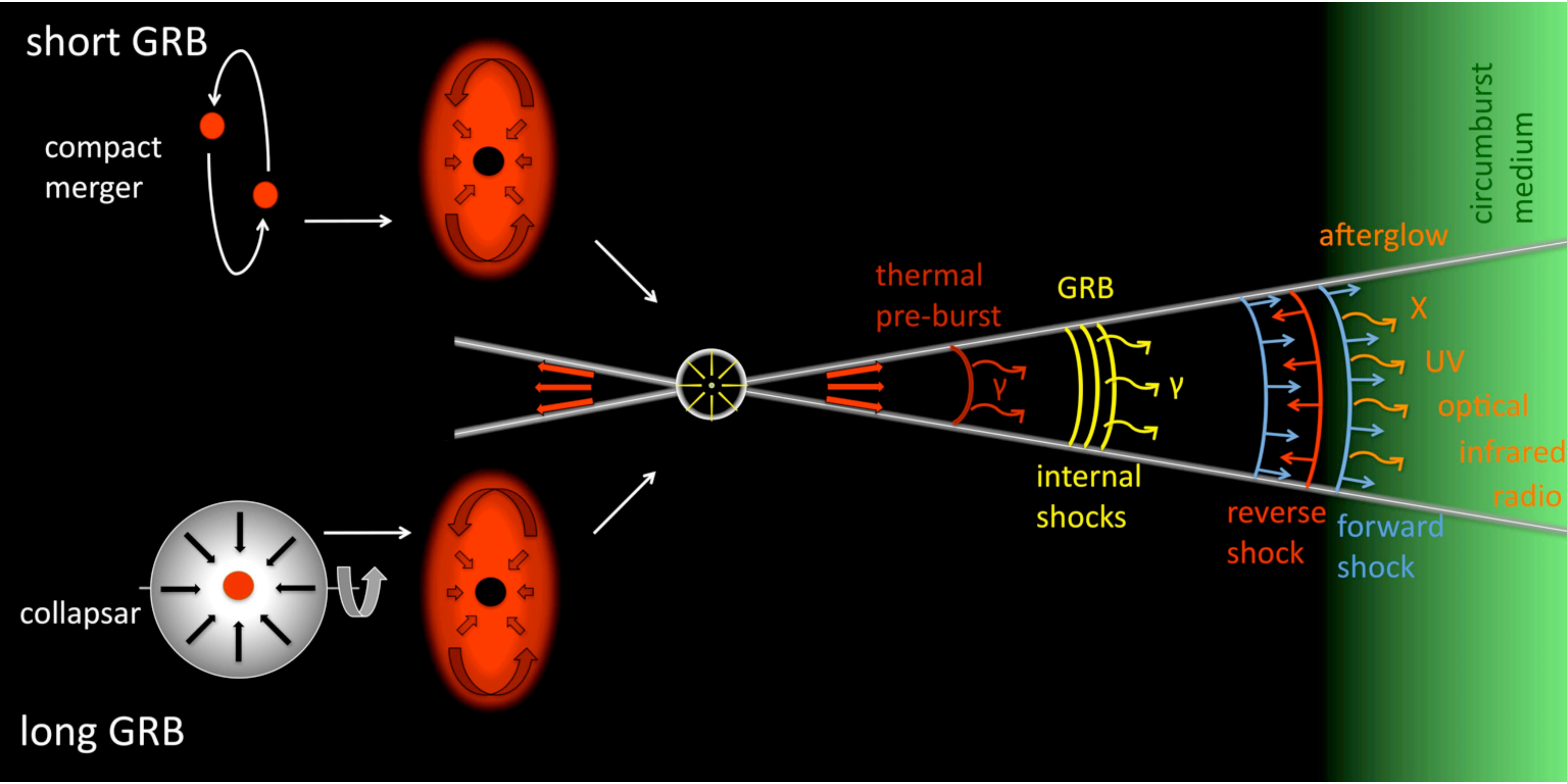
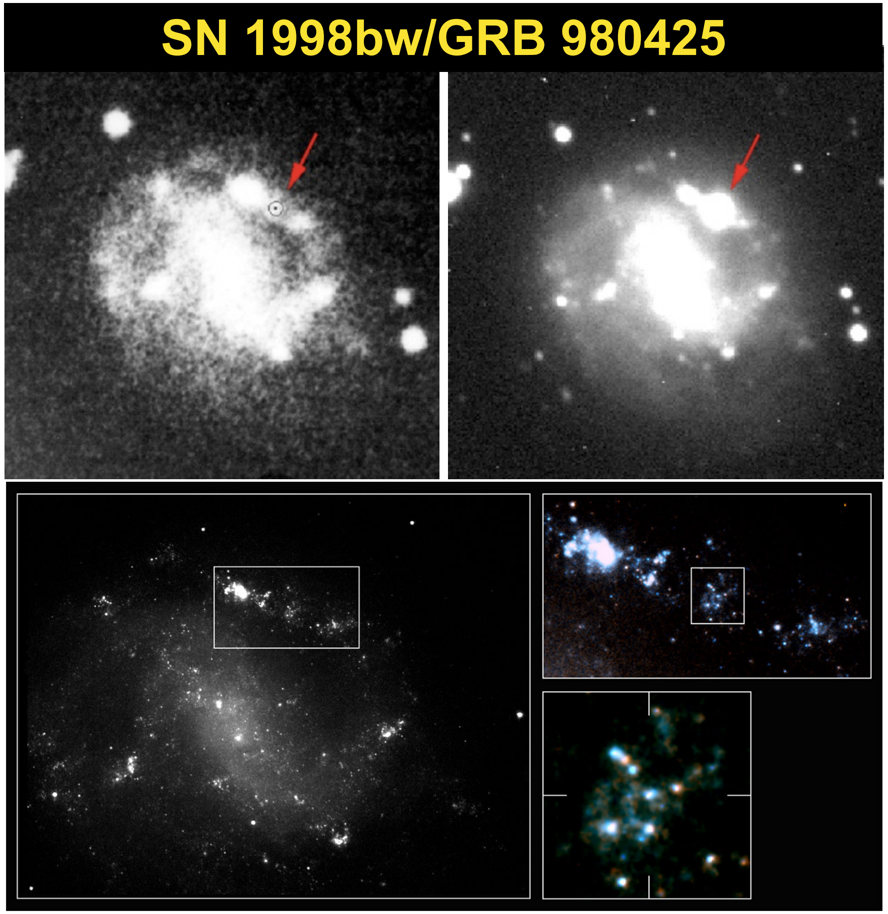
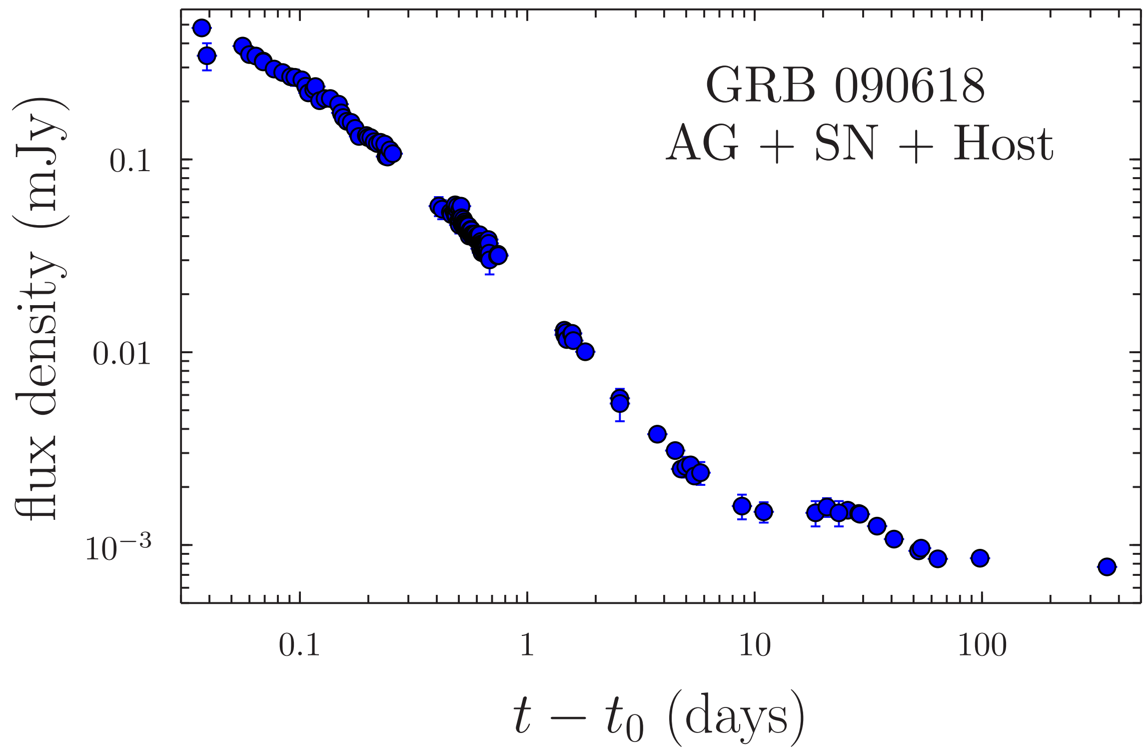


Image credit: Gomboc, Contemp. Phys. (2012).

Supernova-GRB Connection



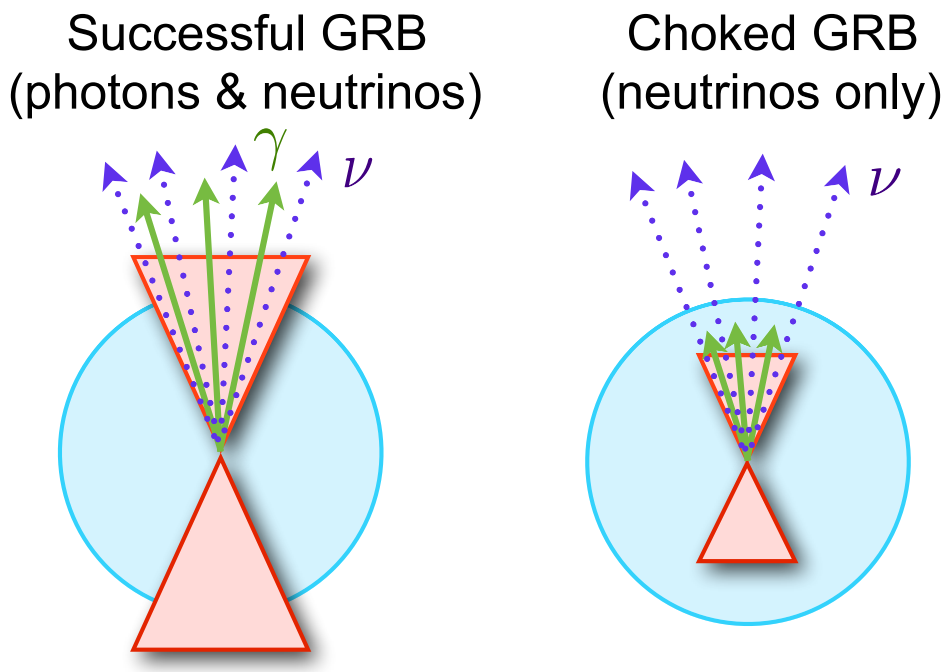


Limitations:

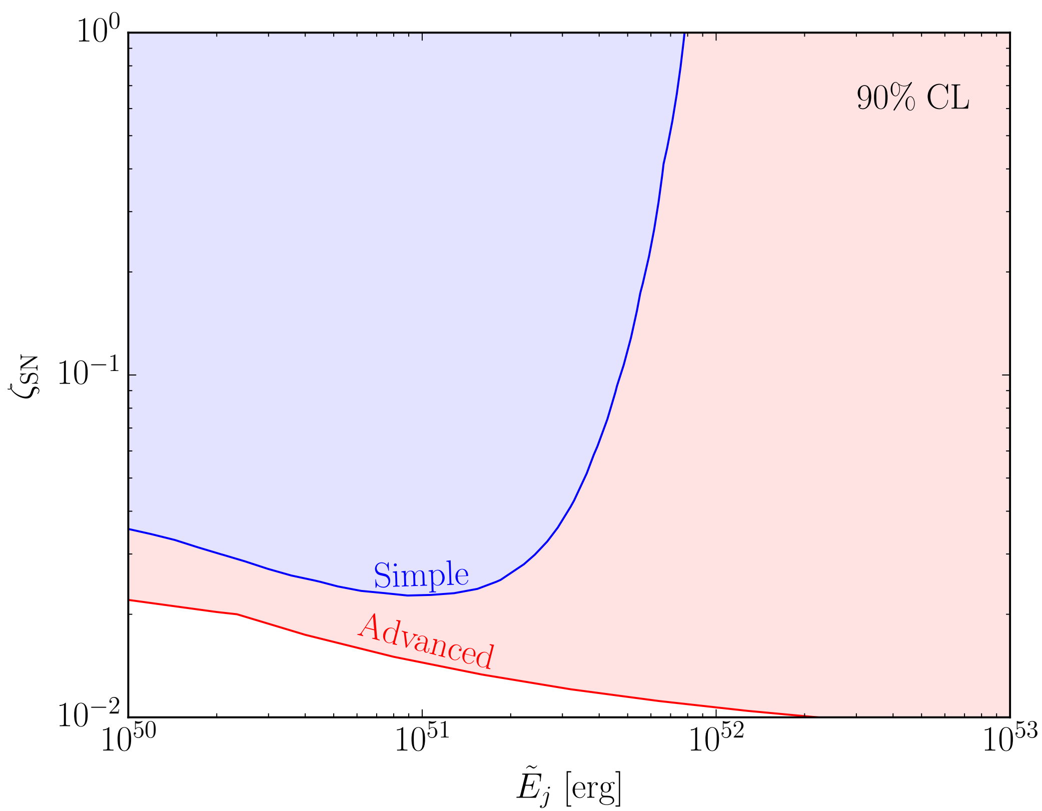
- Follow-up of SN-GRB biased towards low-z events.
- Several SN-GRB are low-luminosity GRBs that may not represent the GRB population.
- Systematic surveys begin to allow statistical studies (e.g. GTC GRB-SN program).

Figures taken from Bloom & Hjorth (2011) and Cano et al. (2017).

Supernova-GRB Connection



Neutrinos may be the only particles successfully escaping the stellar envelope.



IceCube data can already constrain:

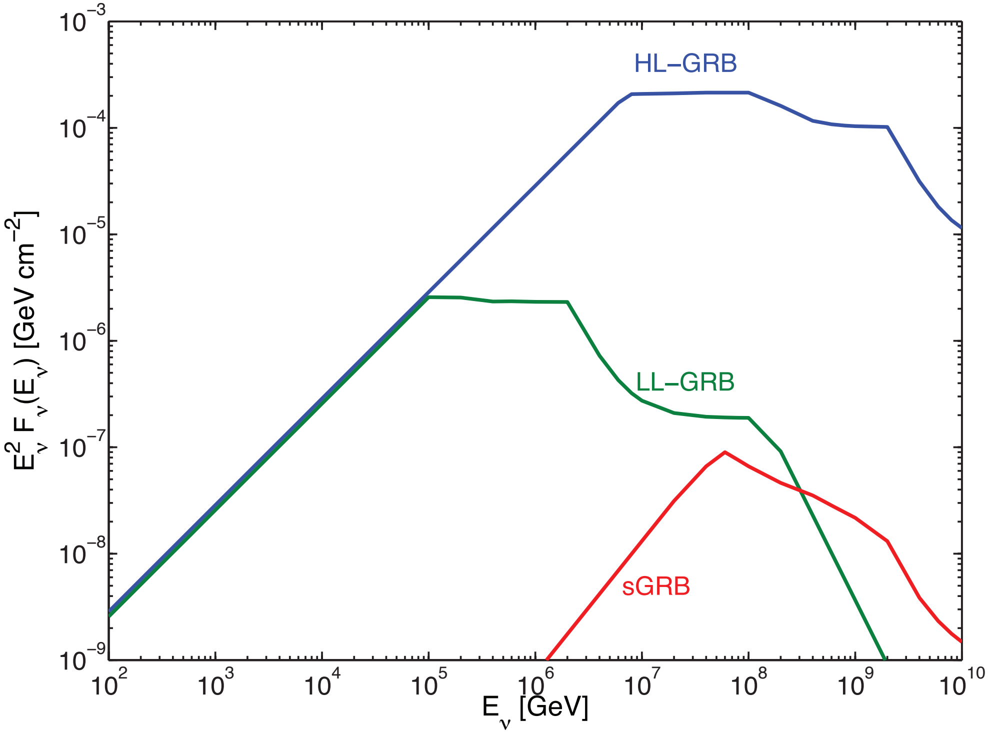
- The fraction of SNe harboring jets
- The fraction of choked jets (compatible with EM observations).

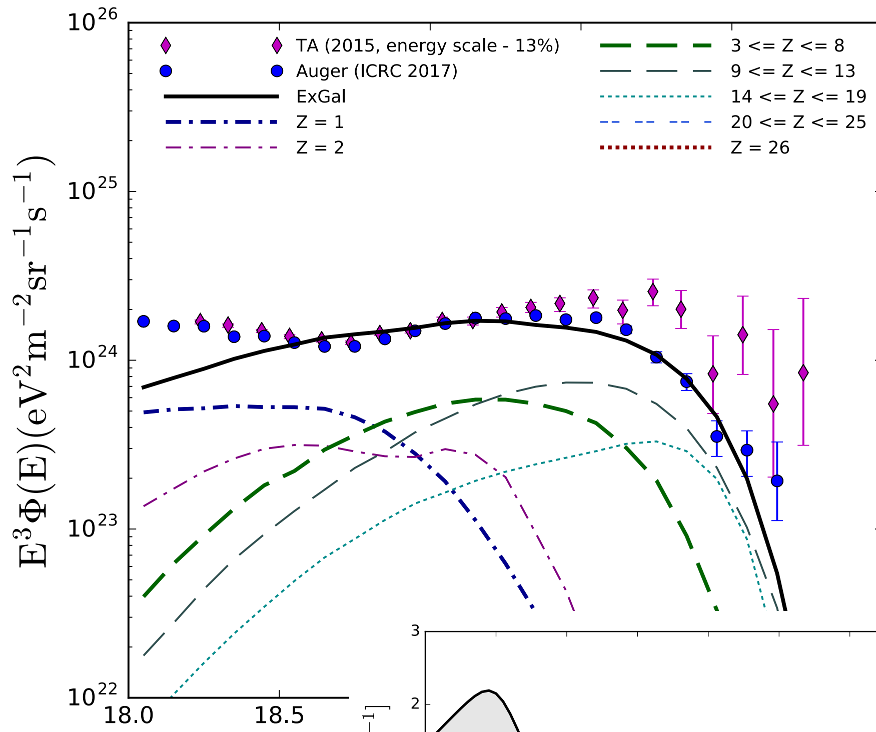
Denton & Tamborra, ApJ (2018). Denton & Tamborra, JCAP (2018). Esmaili & Murase, JCAP (2018).
Tamborra & Ando, PRD (2016). Senno et al., PRD (2015). Meszaros & Waxman, PRL (2001). Levan et al., ApJ (2014).

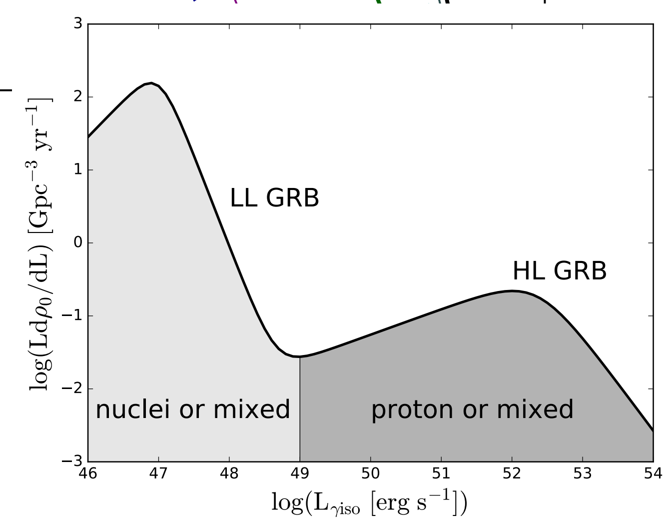
Messengers from Gamma-Ray Bursts

UHE cosmic rays from LL-GRBs?

Neutrino fluence







- GRBs are systematically observed with photons.
- Neutrinos not yet detected (over ~1200 GRBs).
  No tension with theoretical models.
- UHE cosmic rays may come from low-luminosity GRBs.

Tamborra & Ando, JCAP (2015). Zhang et al., PRD (2018). IceCube Coll., ApJ (2017). Liu&Wang (2013), Razzaque & Yang (2015). Denton & Tamborra, JCAP (2018).

Compact Binary Mergers

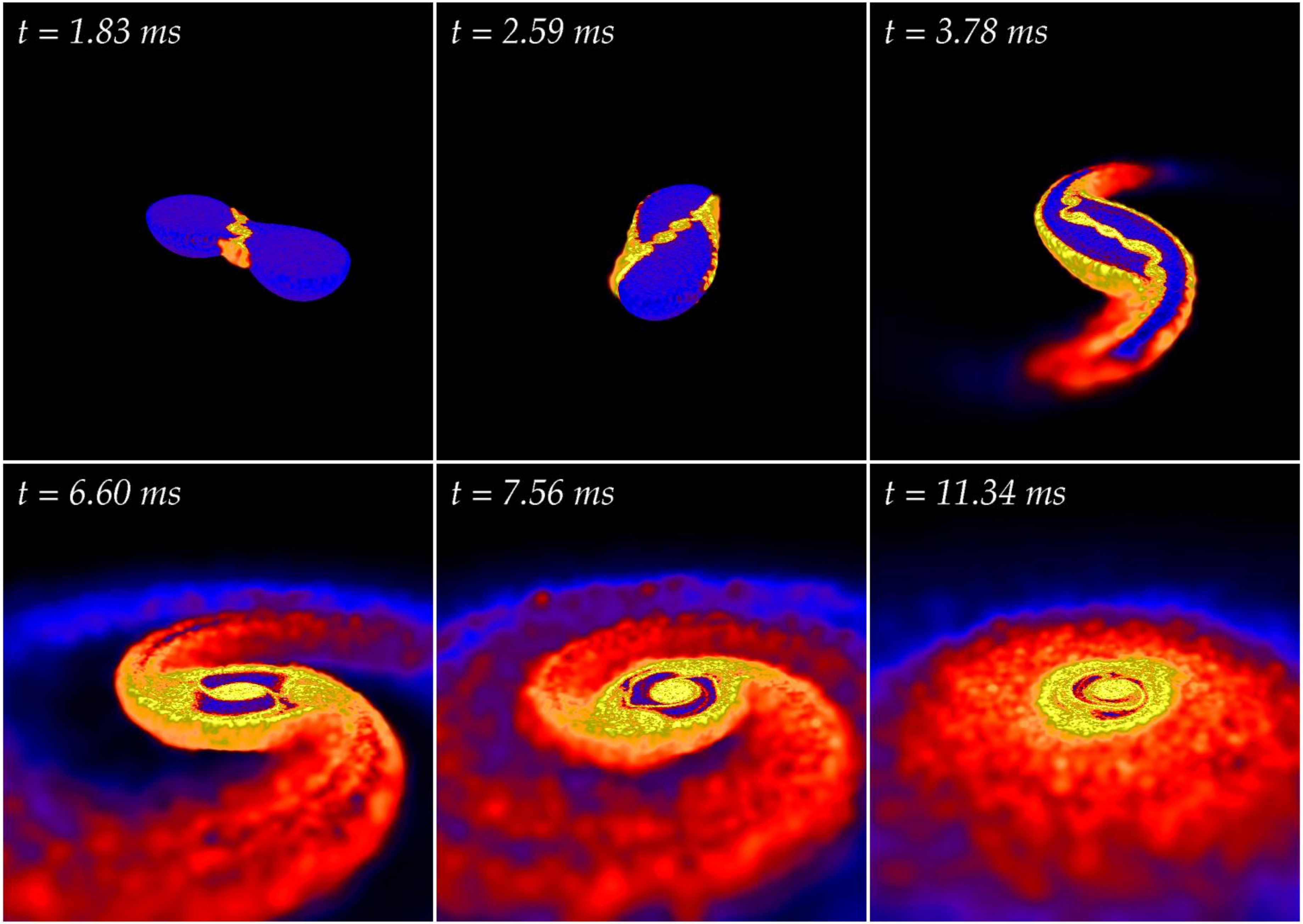
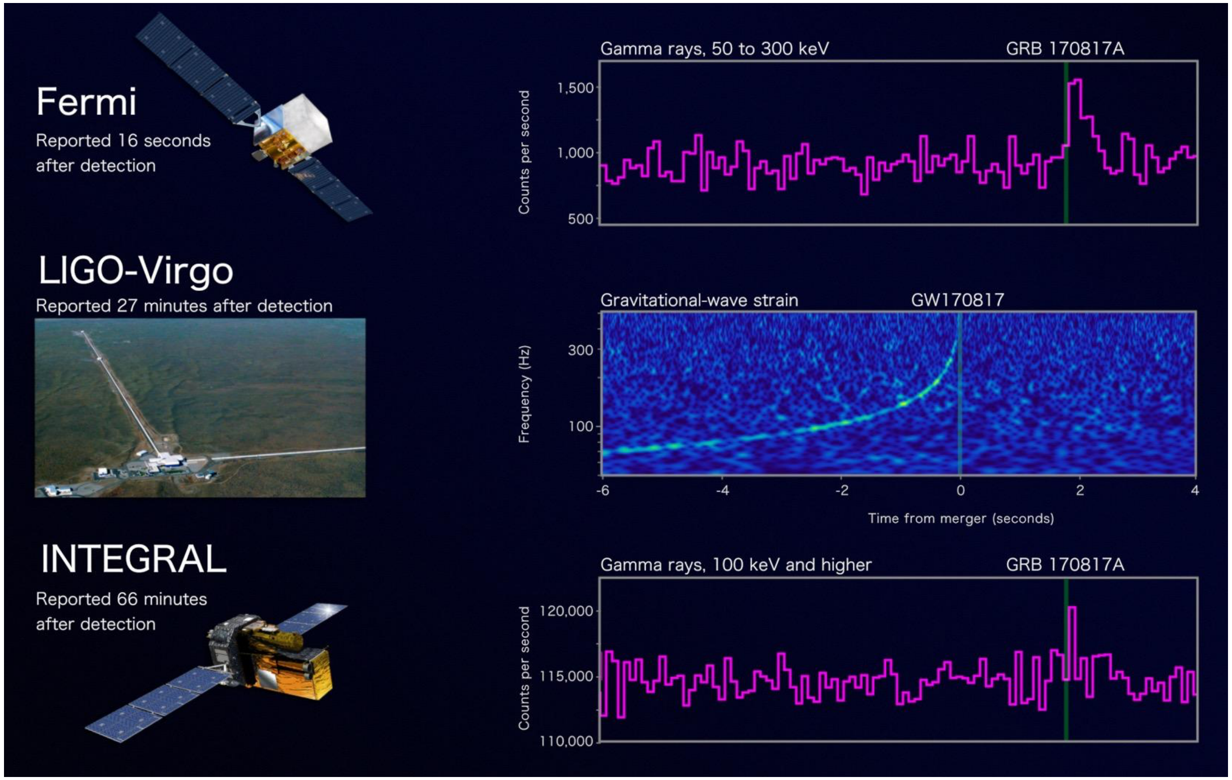
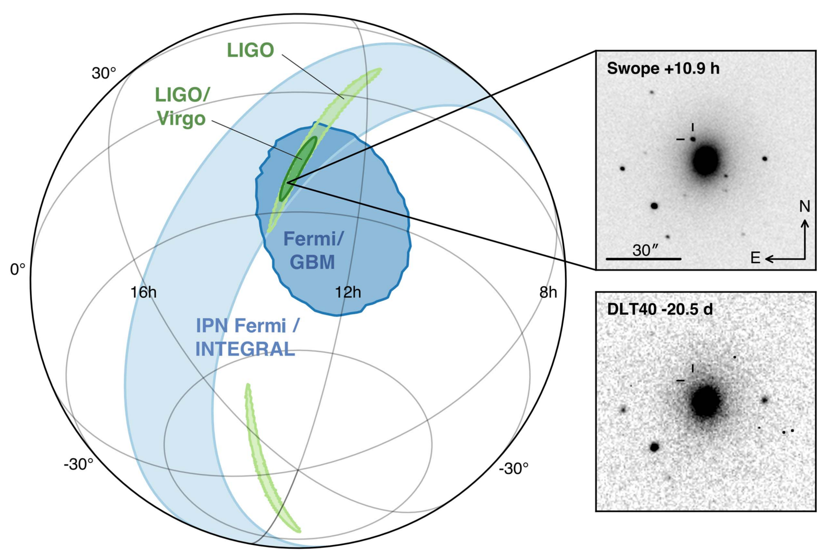


Figure credit: Price & Rosswog, Science (2006).

Multi-Messenger Fingerprints of Mergers



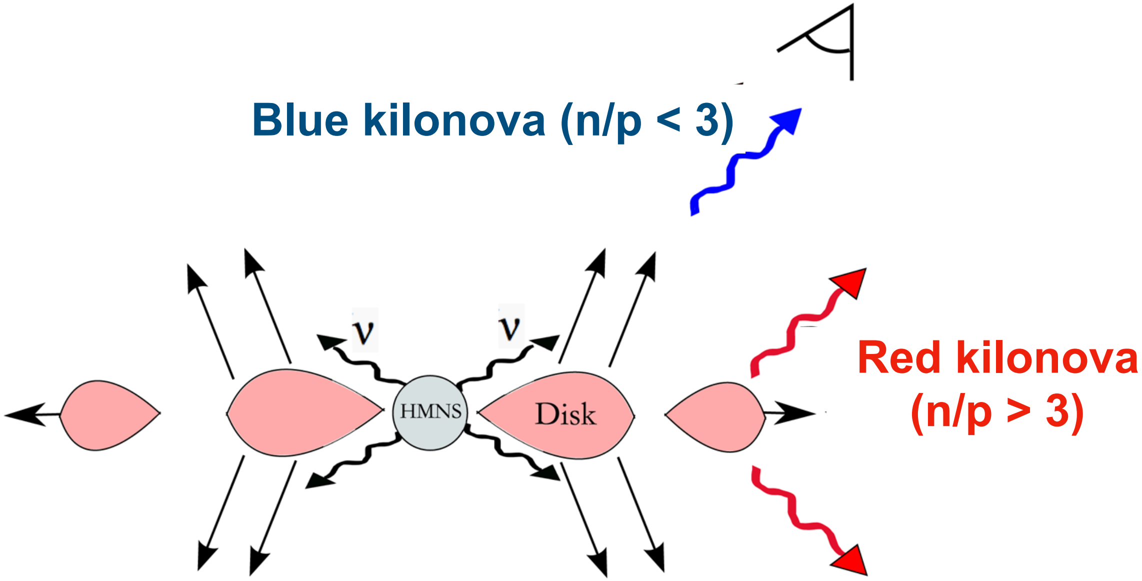


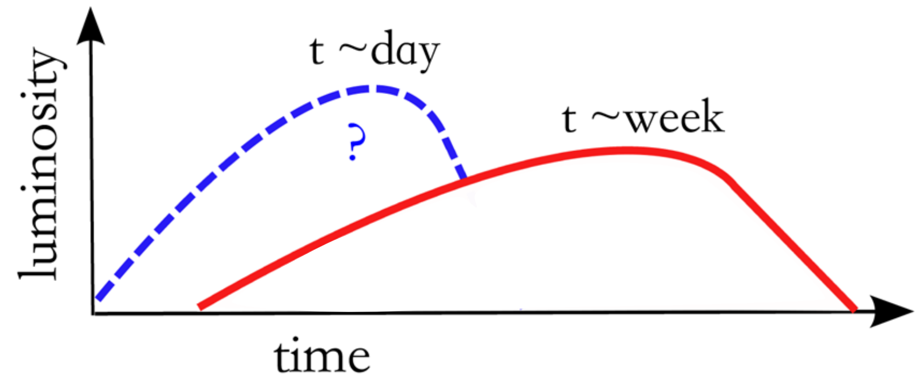
First joint detection of gravitational and electromagnetic radiation (GW170817 & GRB170817A).

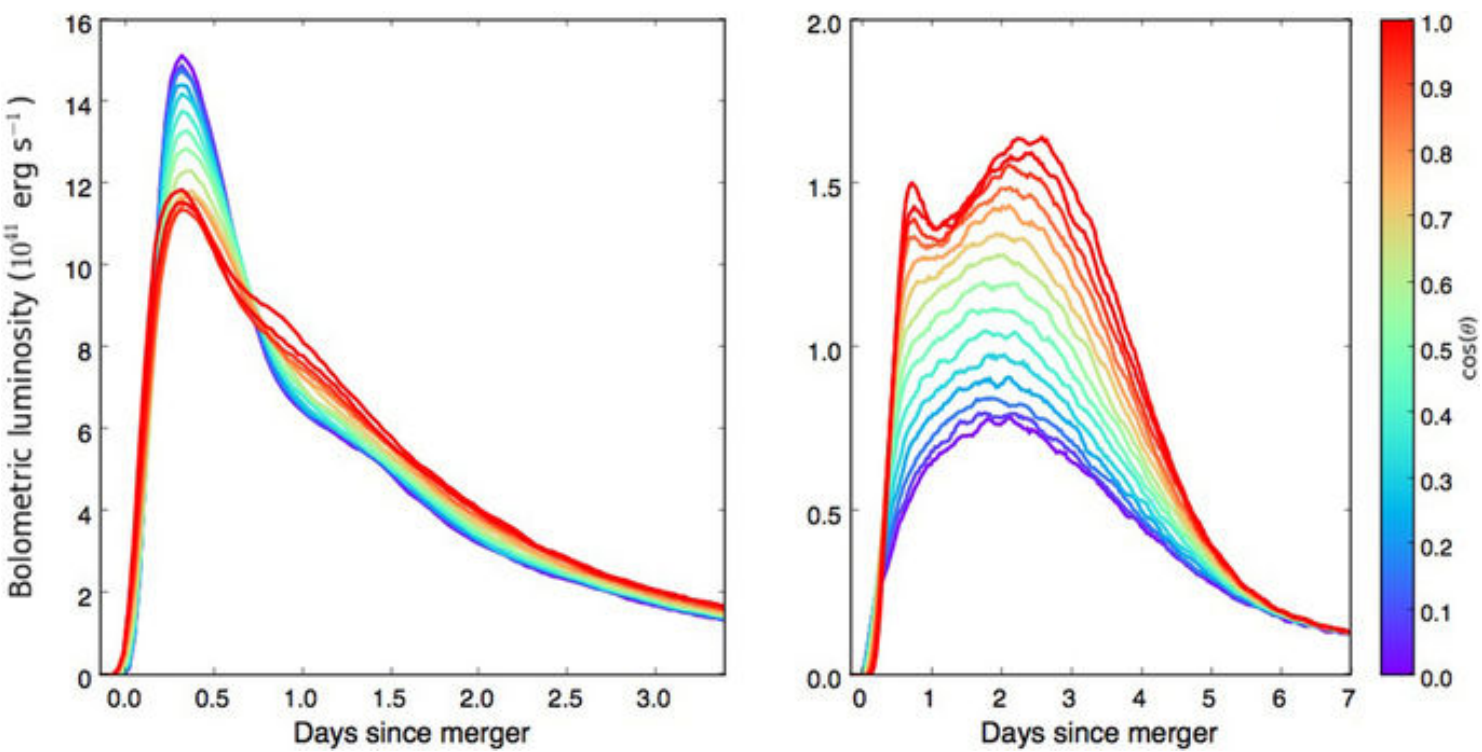
See talk by Mapelli

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

Red and Blue Kilonova Components

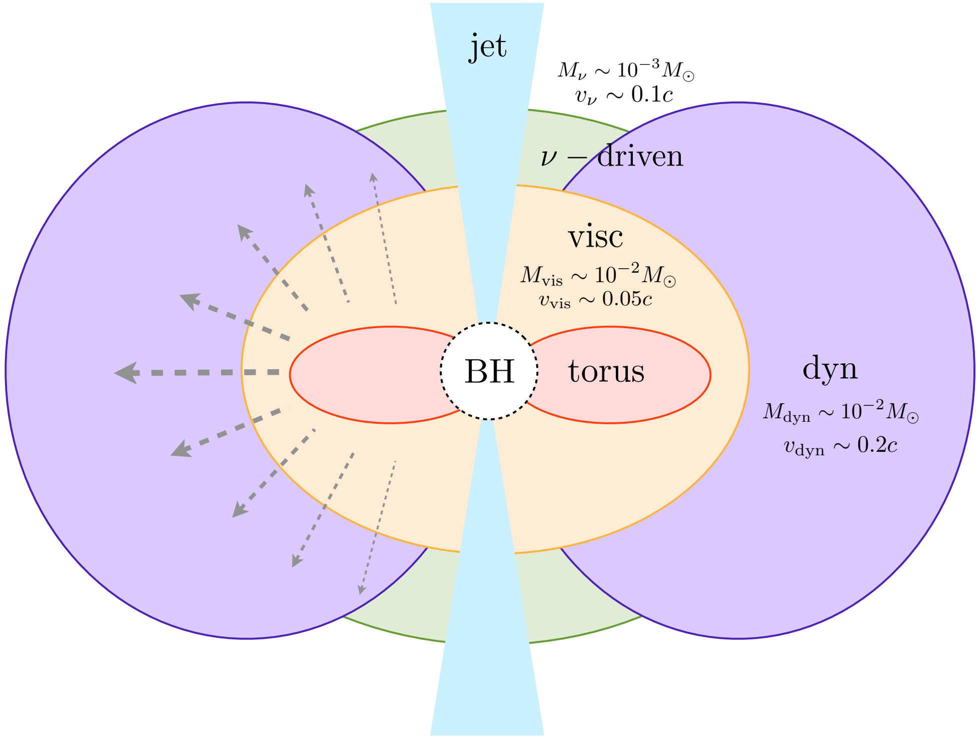


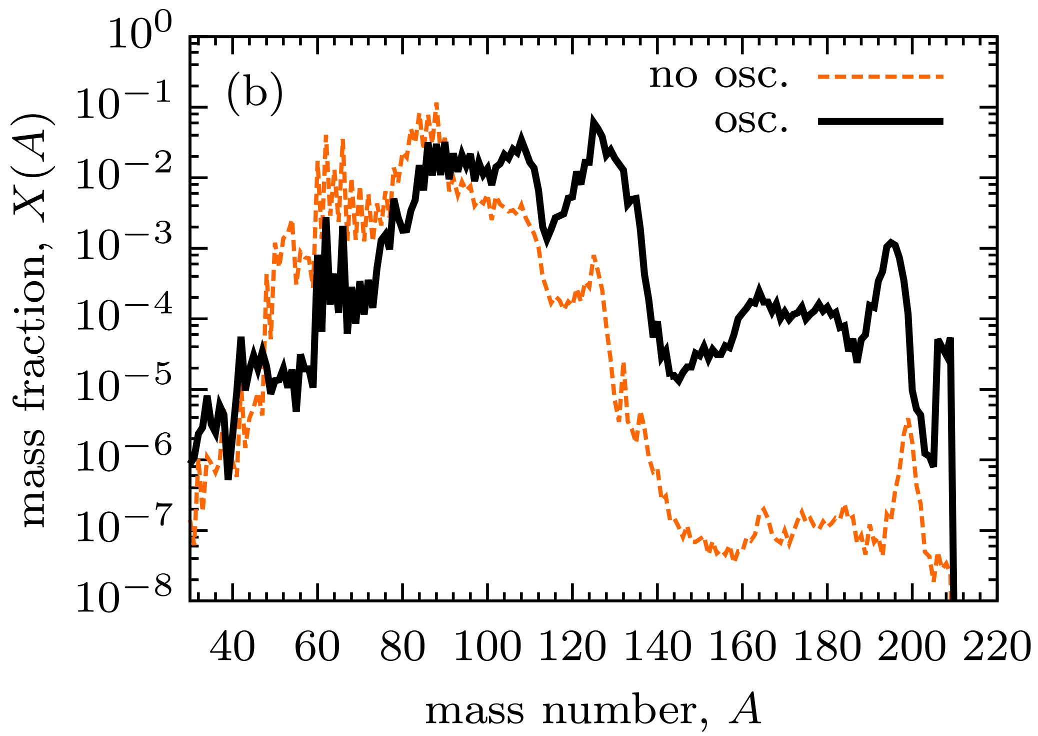




Figures taken from: Metzger & Fernandez, MNRAS (2014); Kasen et al., Nature 2017.

What About Neutrinos?

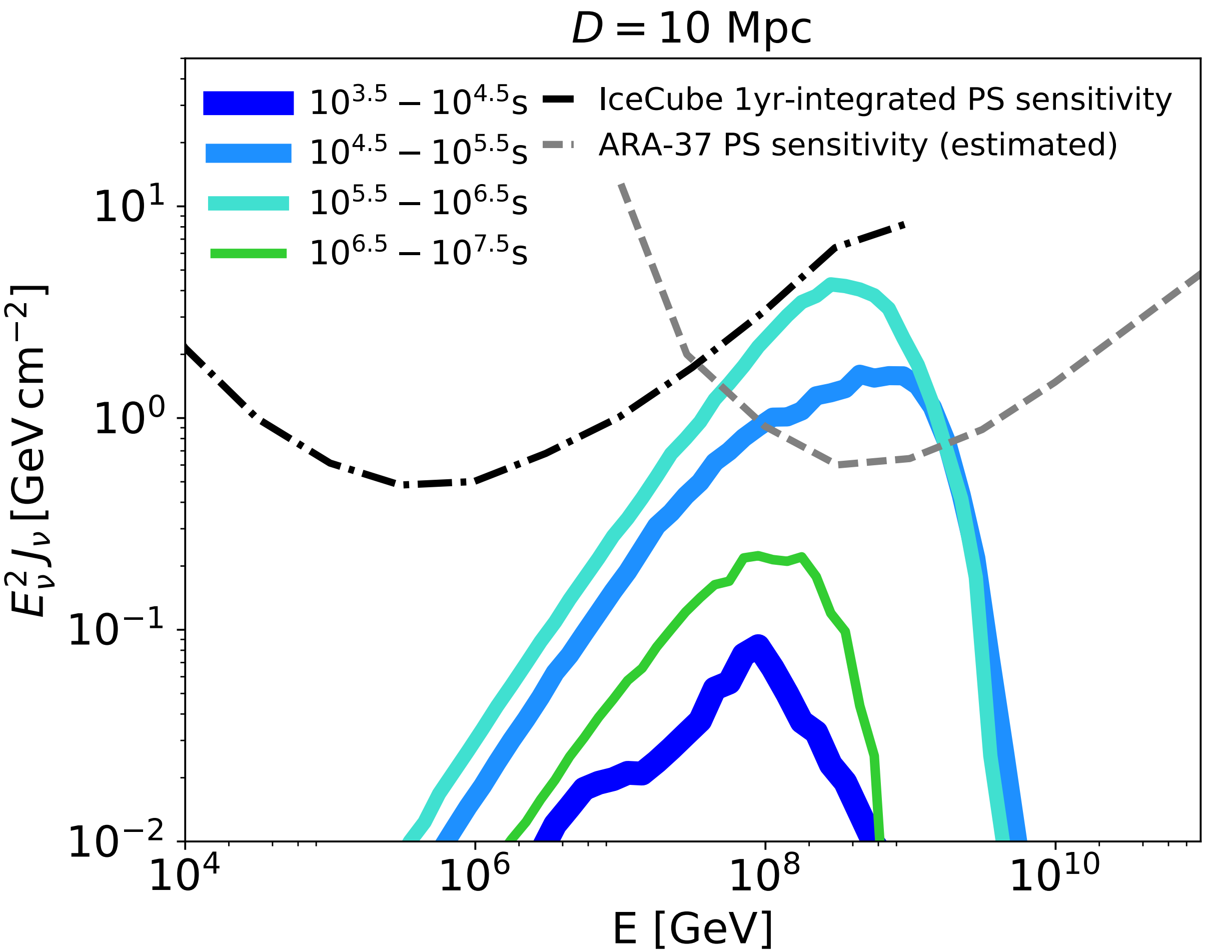




- Poor detection chances of MeV neutrinos from compact binary mergers.
- Neutrino may play an "indirect" major role in element production around the polar region.
- Possible implications for blue kilonova component.

Wu, Tamborra, Just, Janka, PRD (2017). Wu & Tamborra, PRD (2017). Kyutoku & Kashiyama, PRD (2018).

Neutrinos from GRB 170817A



- Poor detection chances from prompt GRB phase.
- Copious neutrino production from long-lived ms magnetar following the merger.
- Extended emission leads to efficient neutrino production.
- Favorable detection opportunities with multi-messenger triggers.

Biehl, Heinze, Winter, MNRAS (2018). Tamborra & Ando, JCAP (2015). Fang & Metzger, ApJ (2017). Kimura et al., ApJ (2017).

Conclusions

- Multi-messenger observations of nearby objects are now possible.
- Multi-messenger methods are powerful to unravel the source properties.
- Neutrinos are unique probes of the source physics.
- Excellent opportunities for exploring nearby objects with next generation facilities.

Thank you for your attention!