The Niels Bohr International Academy

DARK

Multi-Messenger Supernova Detection

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SN neutrinos at the crossroads: astrophysics, oscillations, and detection

Trento, May 13, 2019

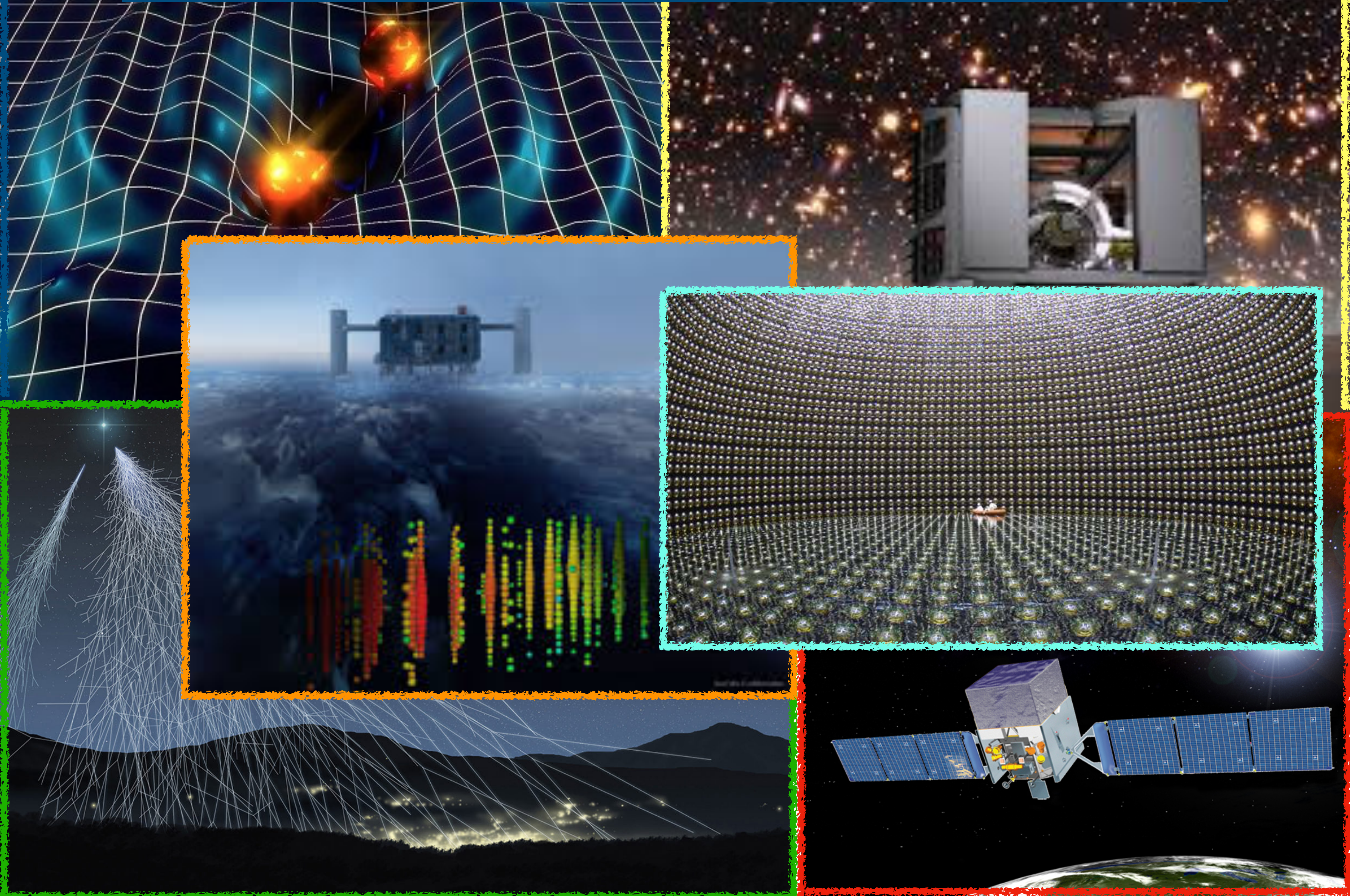
VILLUM FONDEN

Sapere Aude

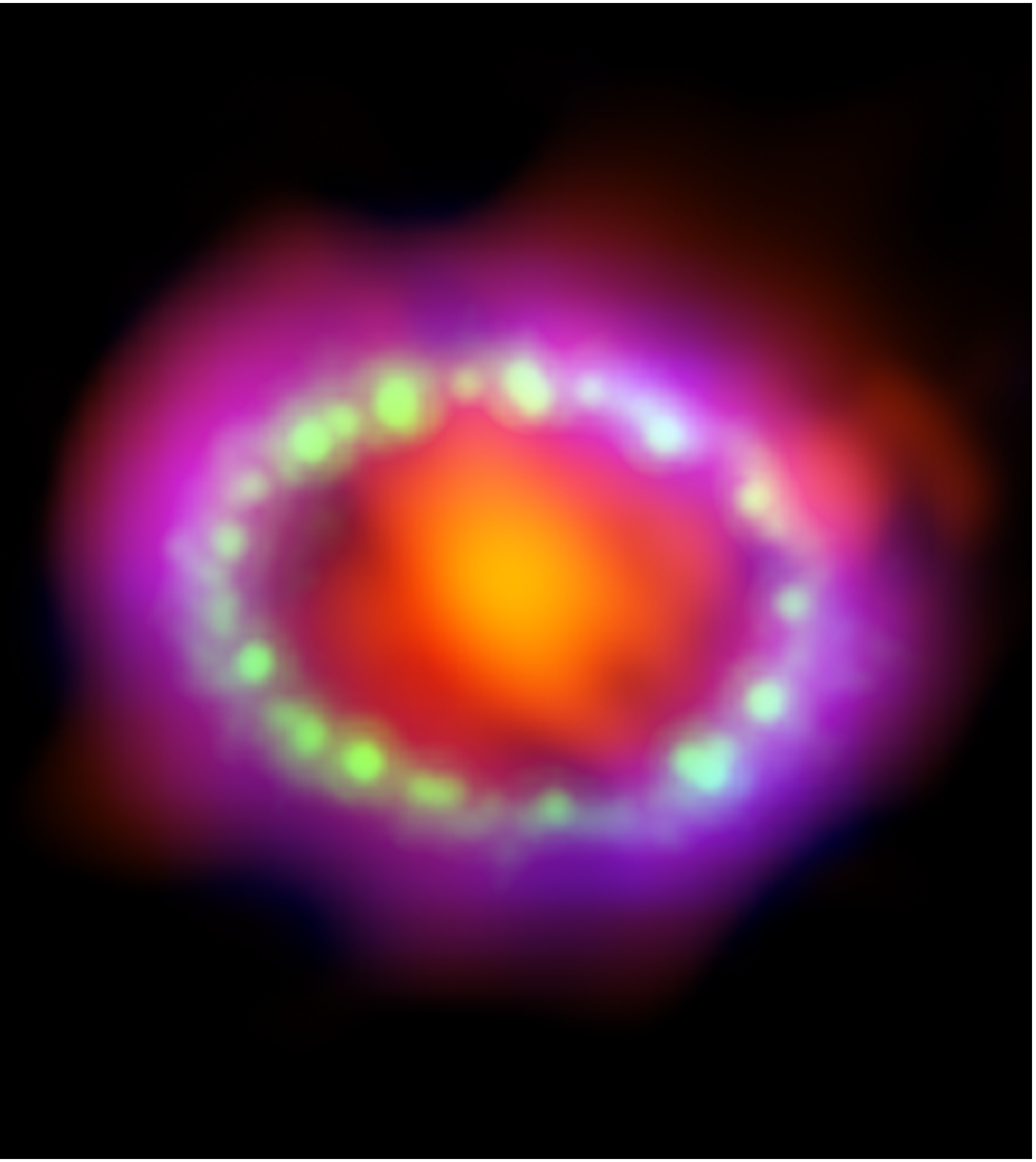
CARLSBERG FOUNDATION

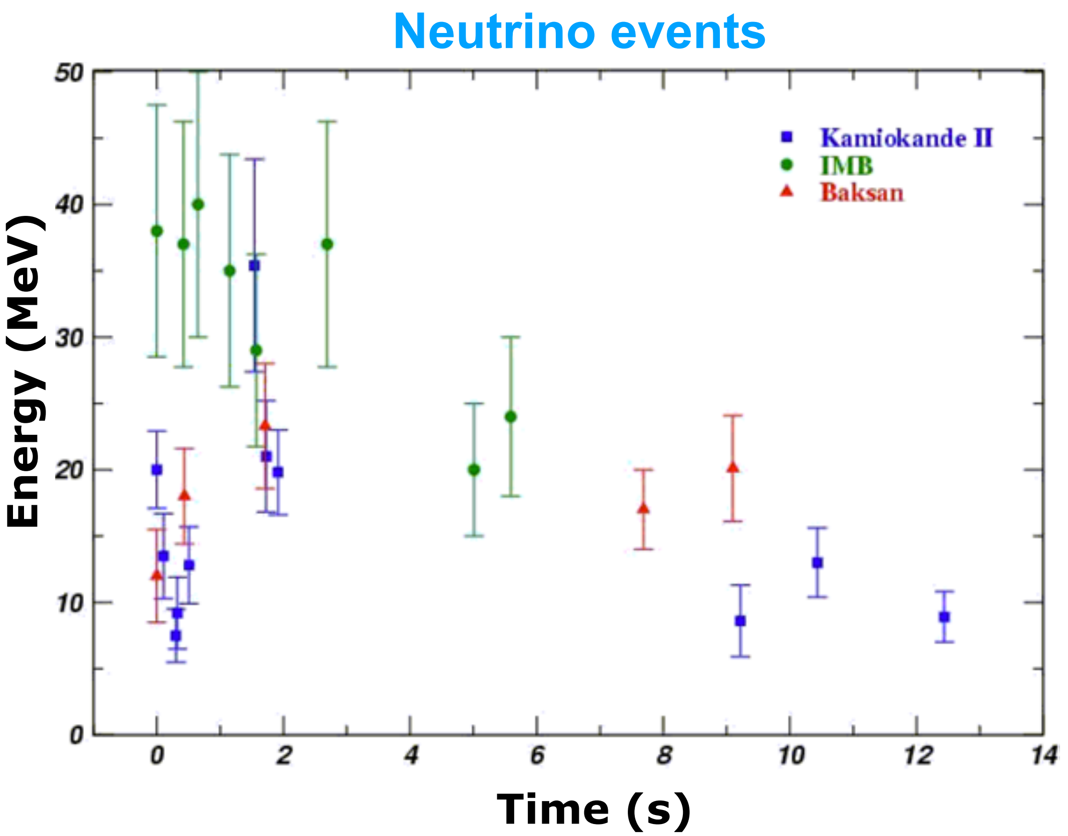
SFB 1258 Neutrinos Dark Matter Messengers

Messengers of the Universe



SN 1987a





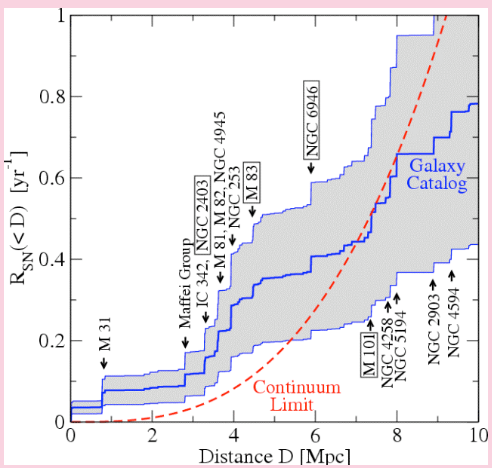
The only supernova explored via electromagnetic multi-wavelength observations and neutrinos.

Image credits: NASA, ESA.

Detection Frontiers

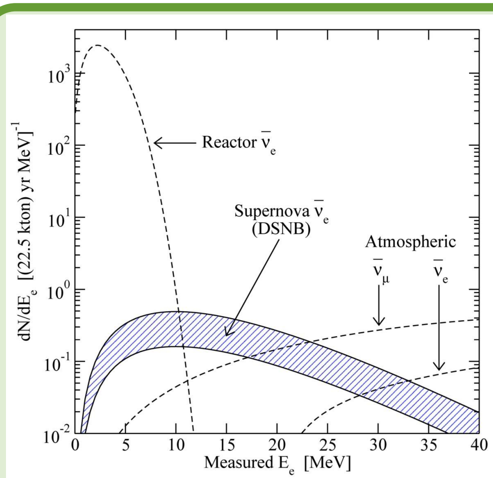
Supernova in our Galaxy (one burst per 40 years).

Excellent sensitivity to details.



Supernova in nearby Galaxies (one burst per year).

Sensitivity to general properties.



Diffuse Supernova Background
(one supernova per second).

Average supernova emission. Guaranteed signal.

The Next Nearby Supernova (SN 2XXXa)

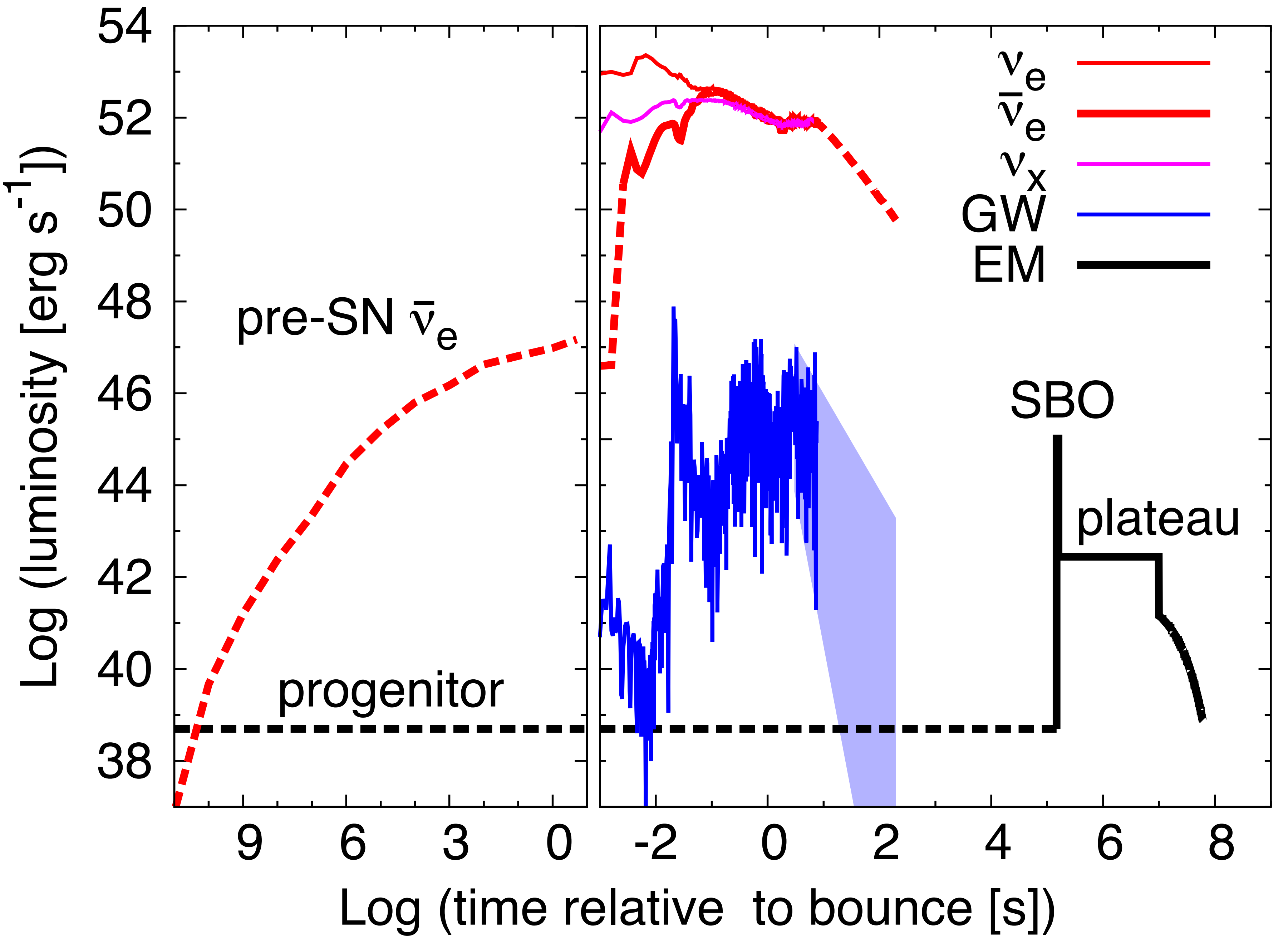


Figure from Nakamura et al., MNRAS (2016).

Supernova Hunting

SuperNova Early Warning System (SNEWS)

SNEWS

- Super-Kamiokande
- Kamland
- HALO
- Borexino
- LVD
- IceCube
- Daya Bay

→ Concidence Sever (@ BNL)

→ E-mail alert
ATel alerts, LIGO, GCN

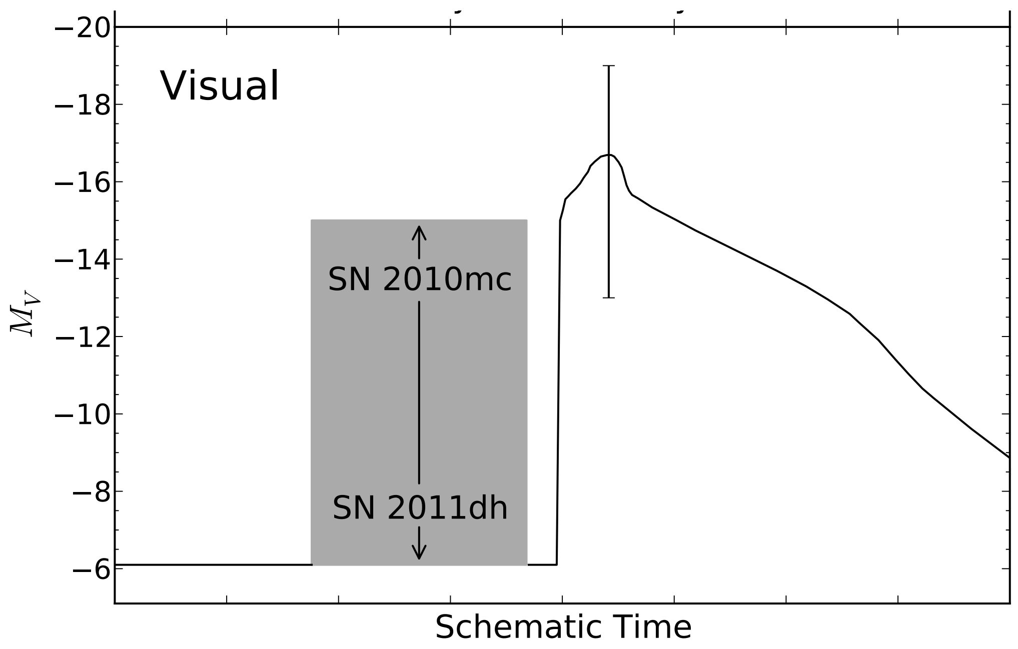
SNEWS 2.0

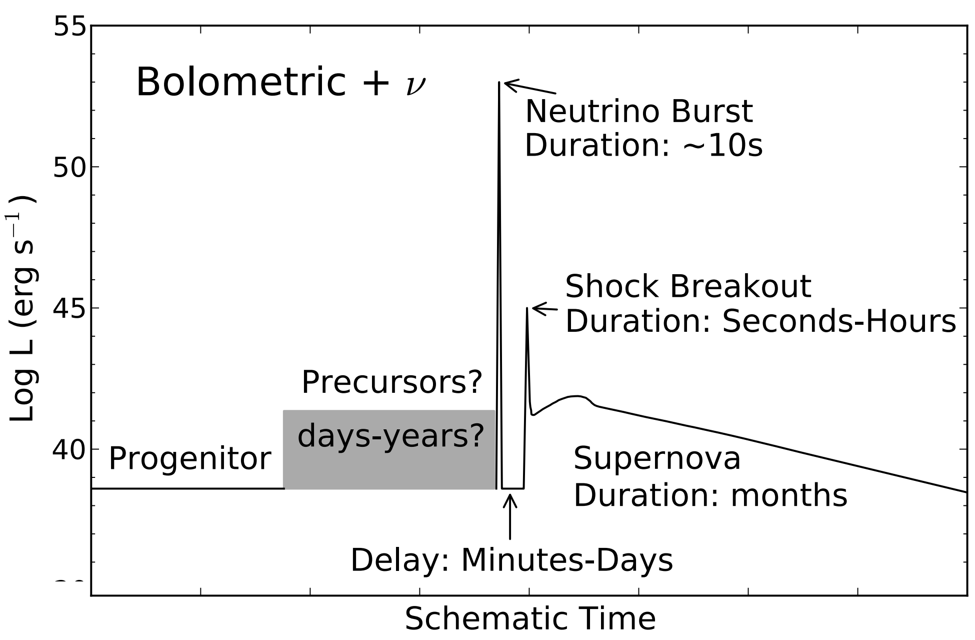
http://snews.bnl.gov.

Supernova Hunting

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

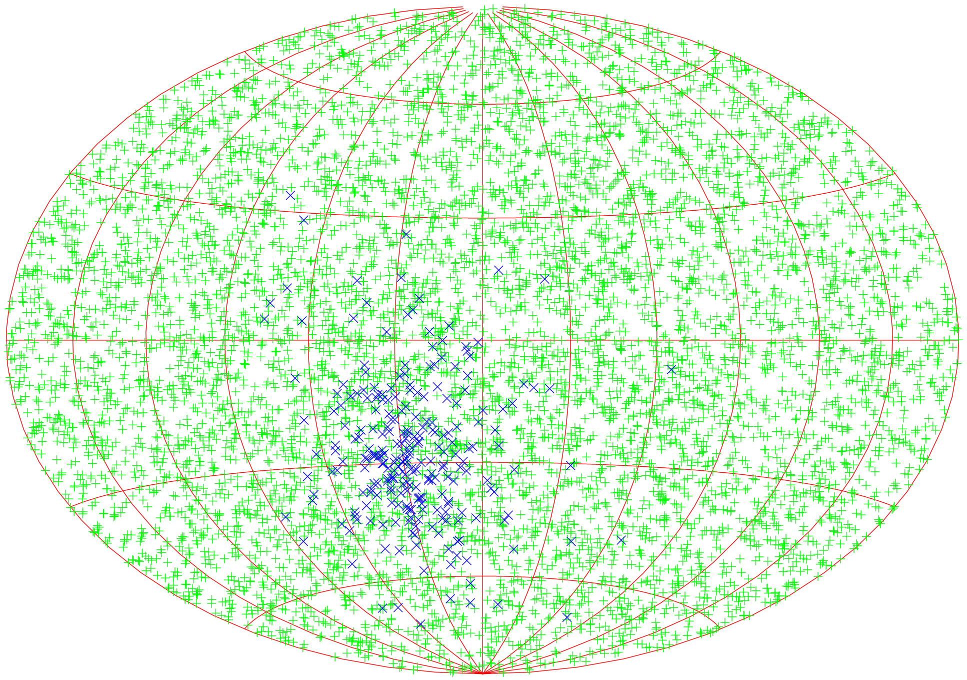
Electromagnetic trigger:
- High-cadence EM surveys (ZTF, ASAS-SN, etc.) could guarantee early coverage.
- Neutrino trigger would provide independent check.





Adams et al., ApJ (2013).

Supernova Pointing



$$\nu + e^- \to \nu + e^-$$

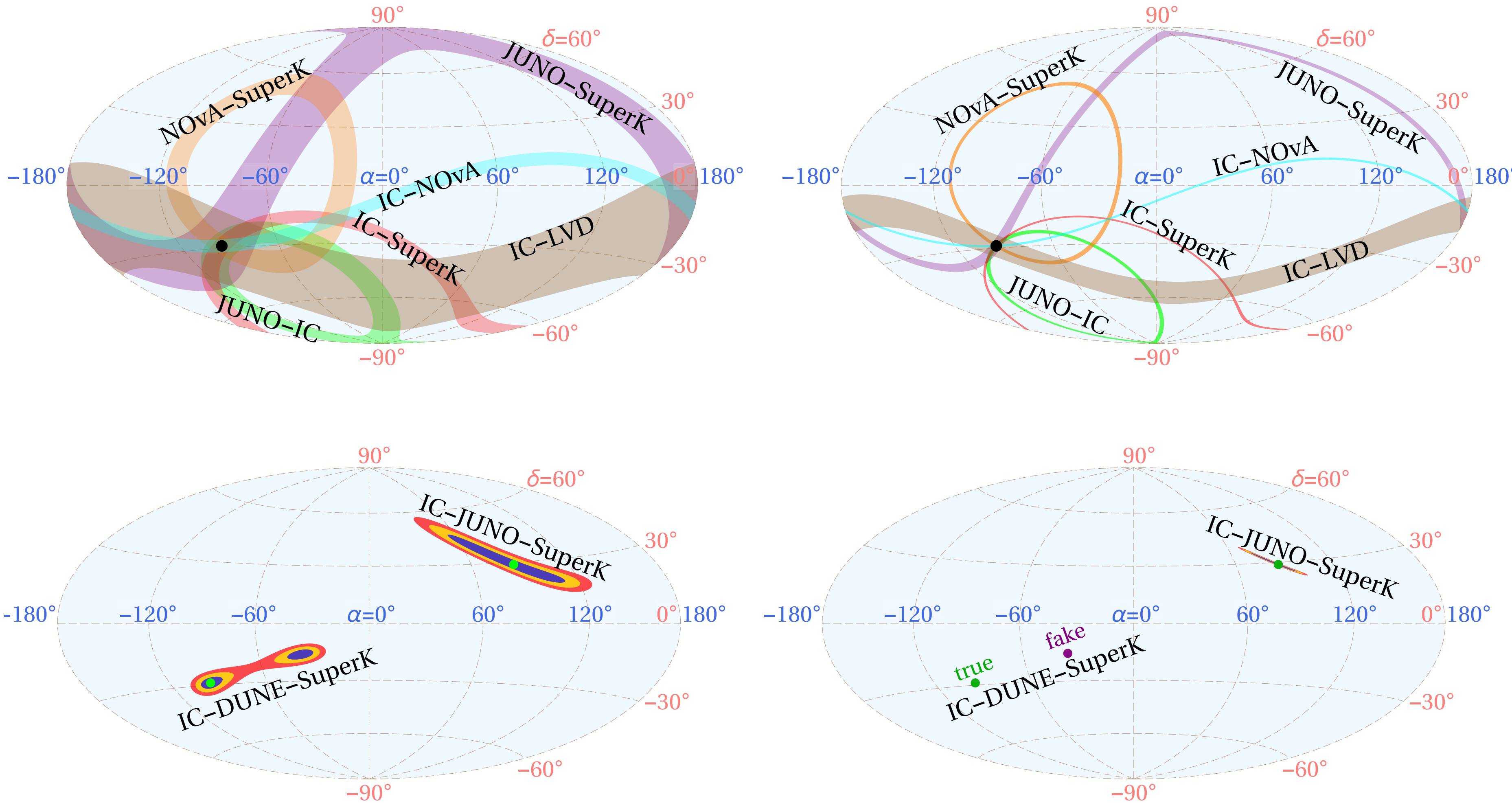
	Super-K	Hyper-K
water	6 deg	1.4 deg
water+Gd	3 deg	0.6 deg

- SN location with neutrinos 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).

Supernova Triangulation

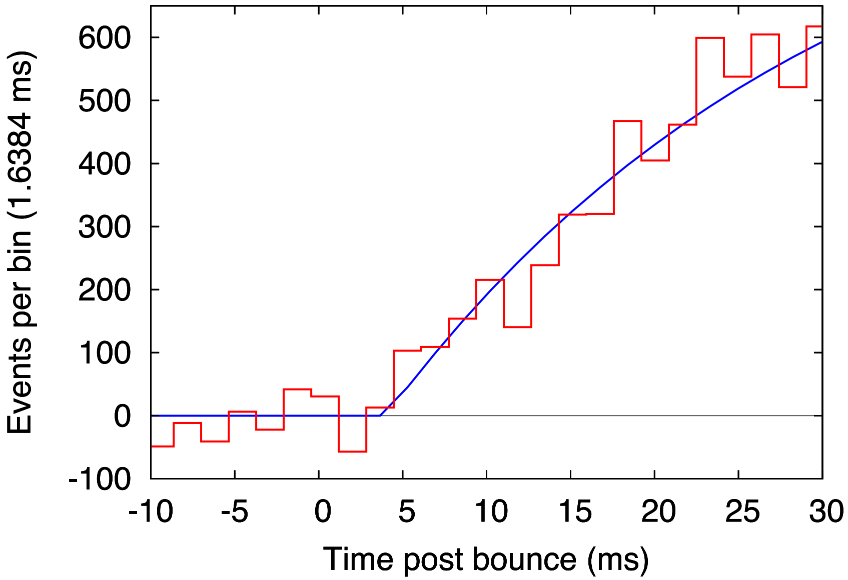
Core-collapse supernova | **Failed supernova**



Triangulation may reach precision of few degrees for CC-SN and sub-degree for failed SN.

Brdar, Lindner, Xu, JCAP (2018). Muehlbeier et al., PRD (2013).

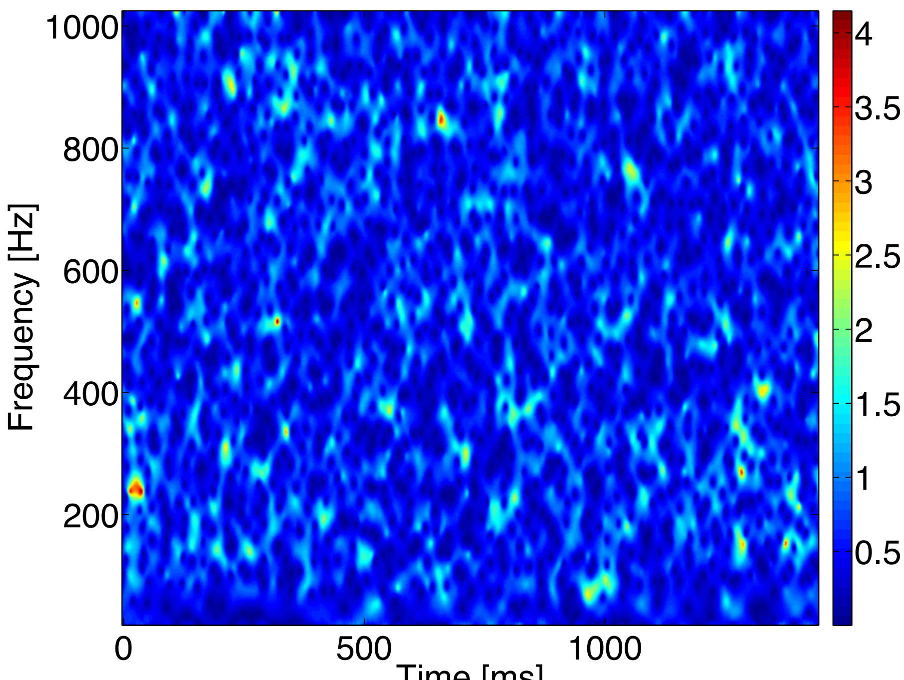
Neutrino Timing



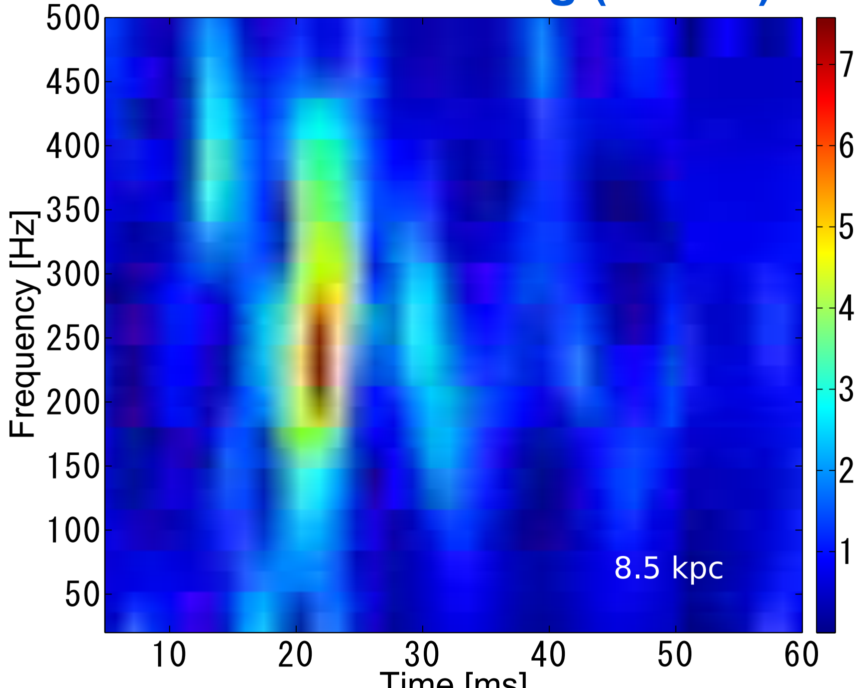
Probe core bounce time with neutrinos.

Timing for gravitational wave detection.

Without neutrino timing (S/N~3.5)



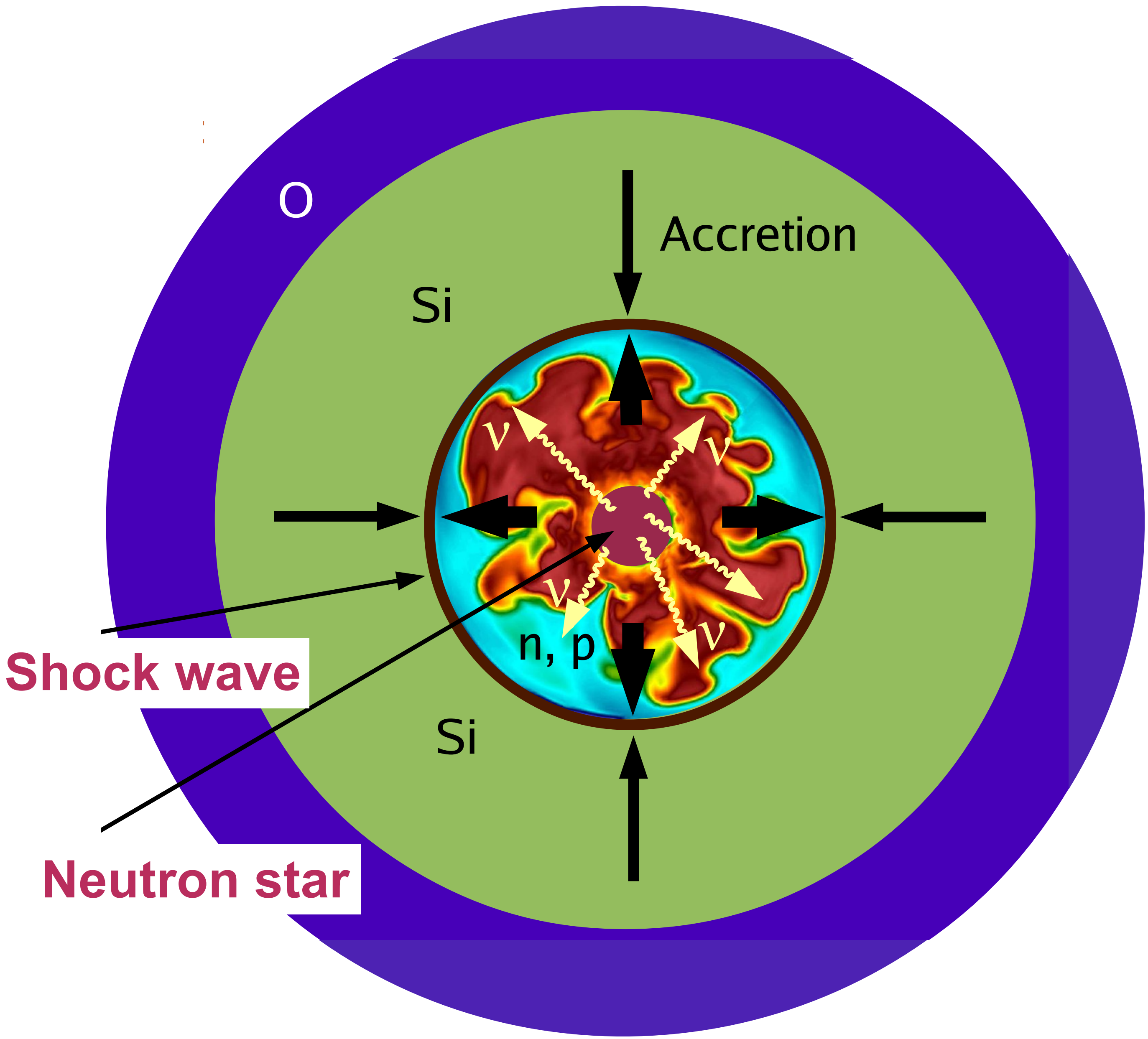
With neutrino timing (S/N ~7)



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

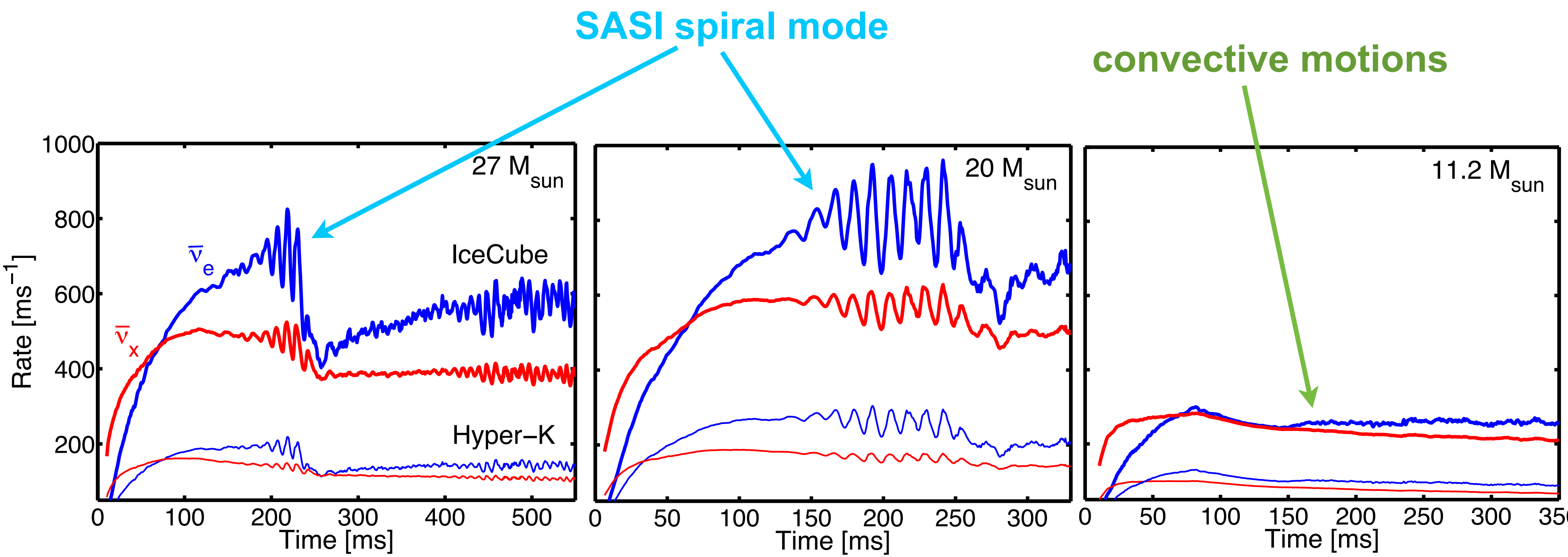
Supernova Explosion Mechanism

Shock wave forms within the iron core. It dissipates energy dissociating the iron layer.
Neutrinos provide energy to the stalled shock wave to start re-expansion.



Recent reviews: Janka (2017). Mirizzi, Tamborra et al. (2016).

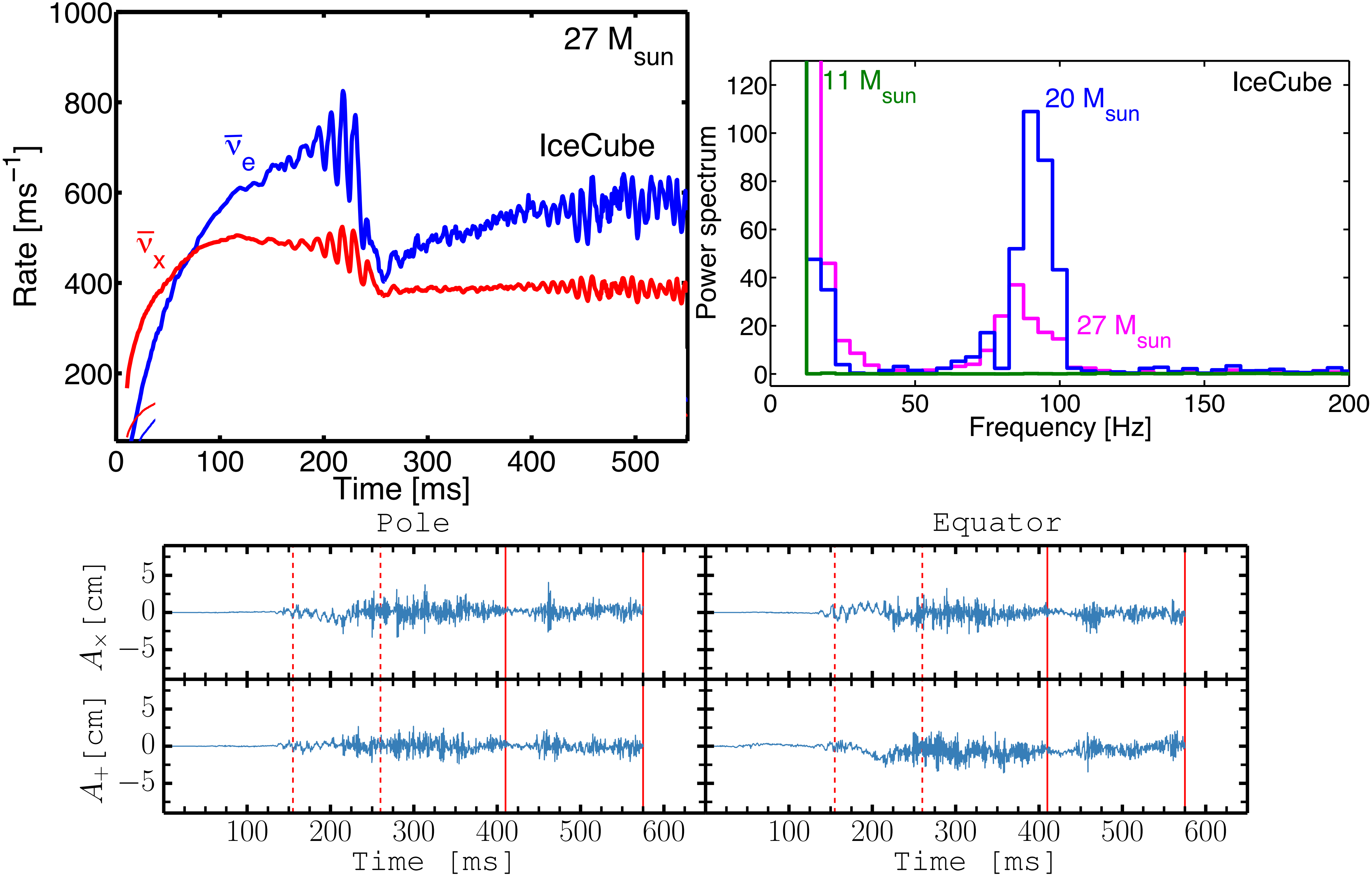
Imprints of Hydrodynamical Instabilities



- Neutrinos (and gravitational waves) carry signatures of hydrodynamical instabilities.
- Outcome depending on progenitor mass.
- Only SN models with high mass exhibit SASI.

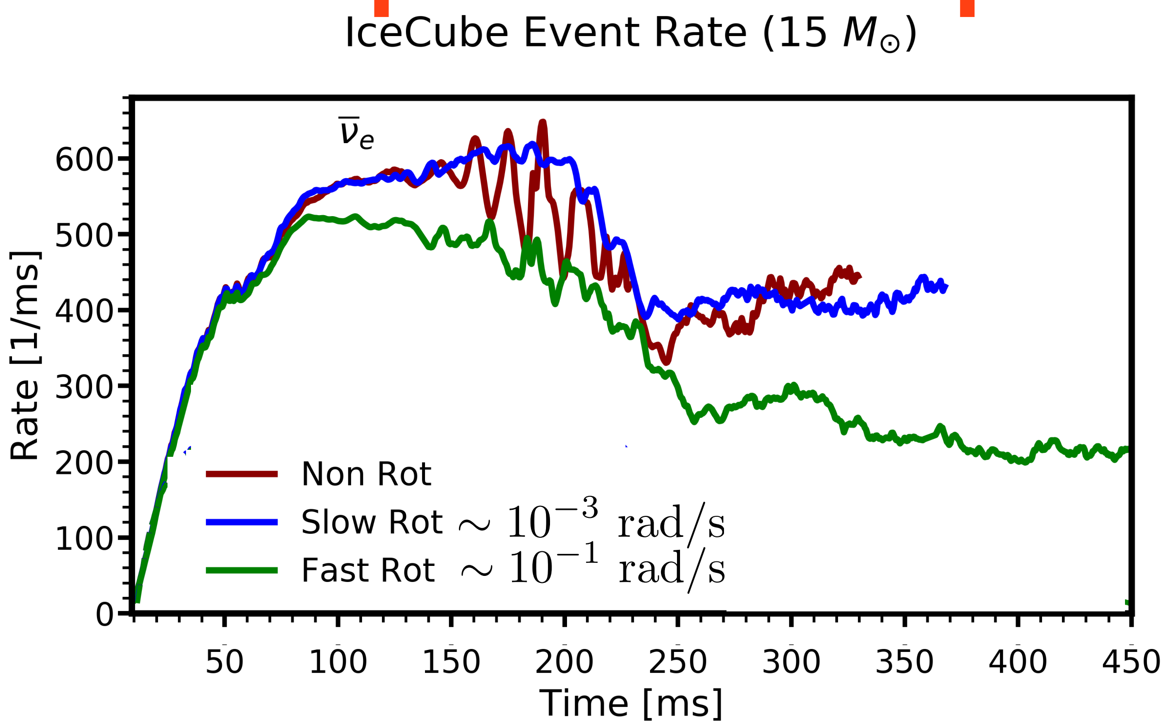
Tamborra et al., PRL (2013). Tamborra et al., PRD (2014). Bethe, Rev. Mod. Phys. (1990). Blondin et al., ApJ (2003). Blondin & Mezzacappa, Nature (2007).

Imprints of Hydrodynamical Instabilities

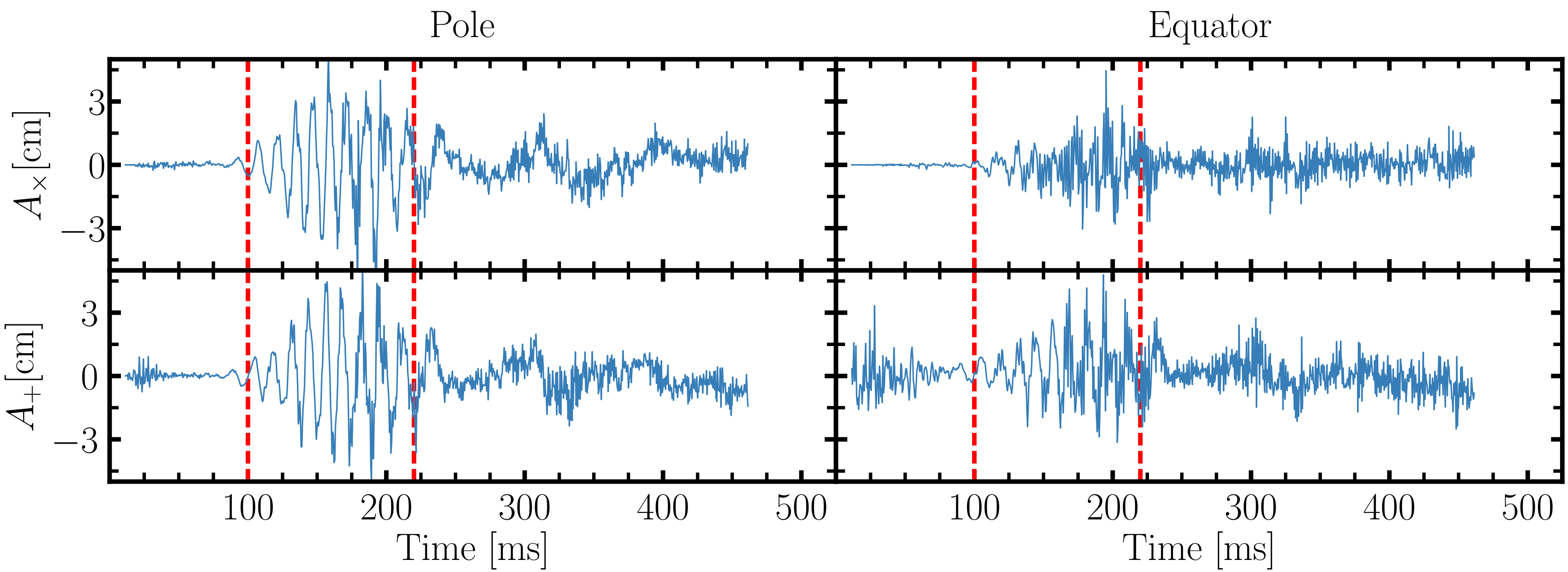


Tamborra et al., PRL (2013), PRD (2014). Andresen et al., MNRAS (2017). Kuroda et al., ApJ (2017). Mueller & Janka, ApJ (2014). Foglizzo et al., ApJ (2007).

Imprints of Supernova Rotation

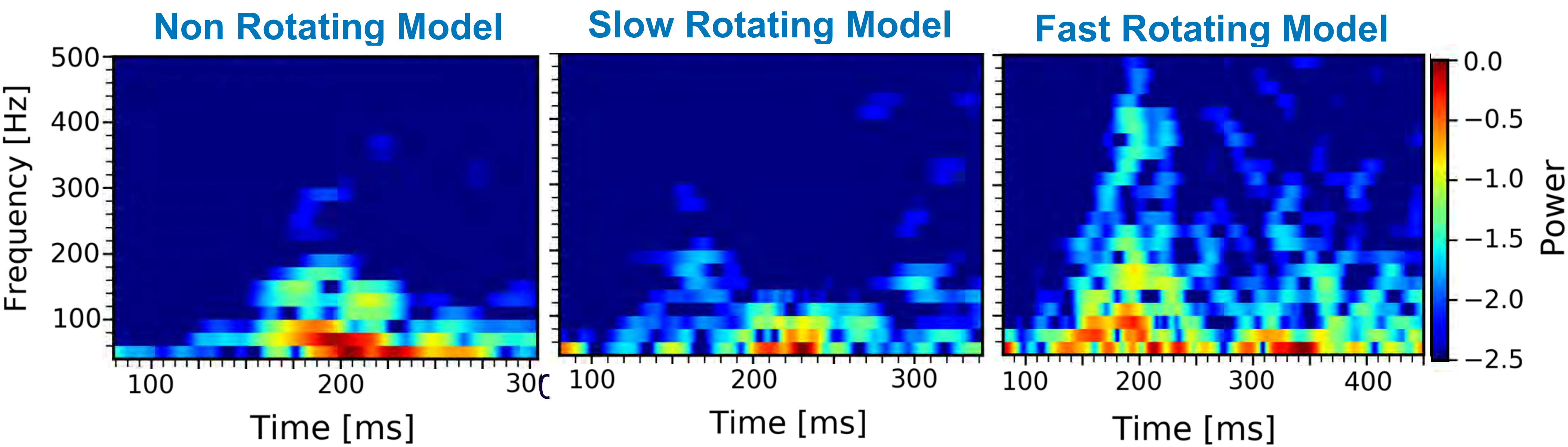


Rotation smears SASI modulations in neutrino signal.



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

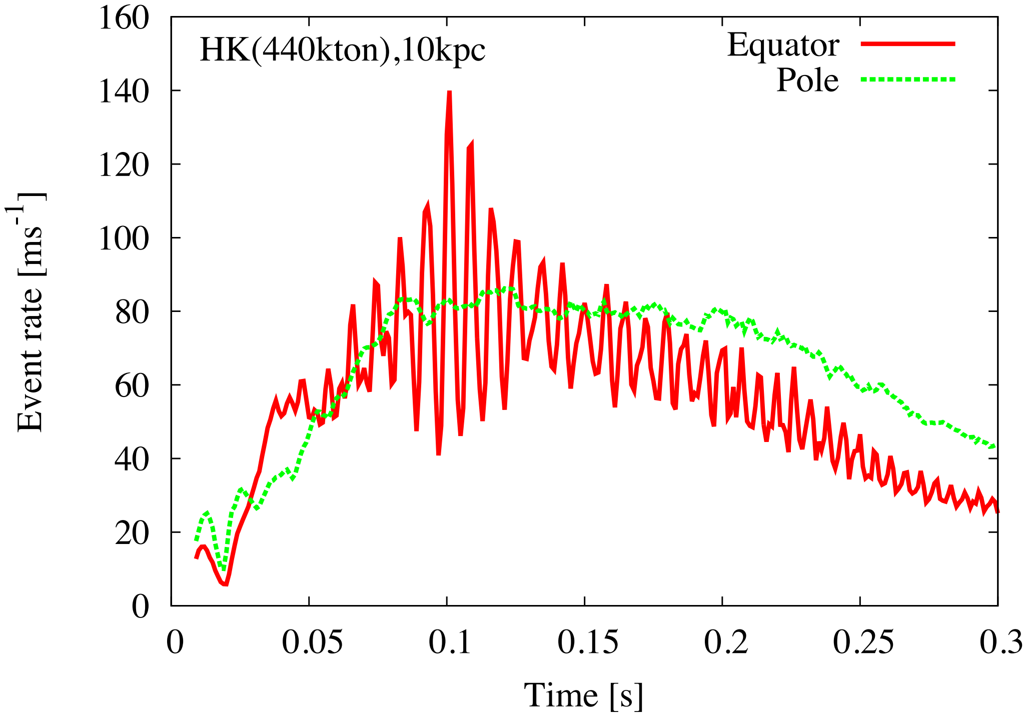
Imprints of Supernova Rotation

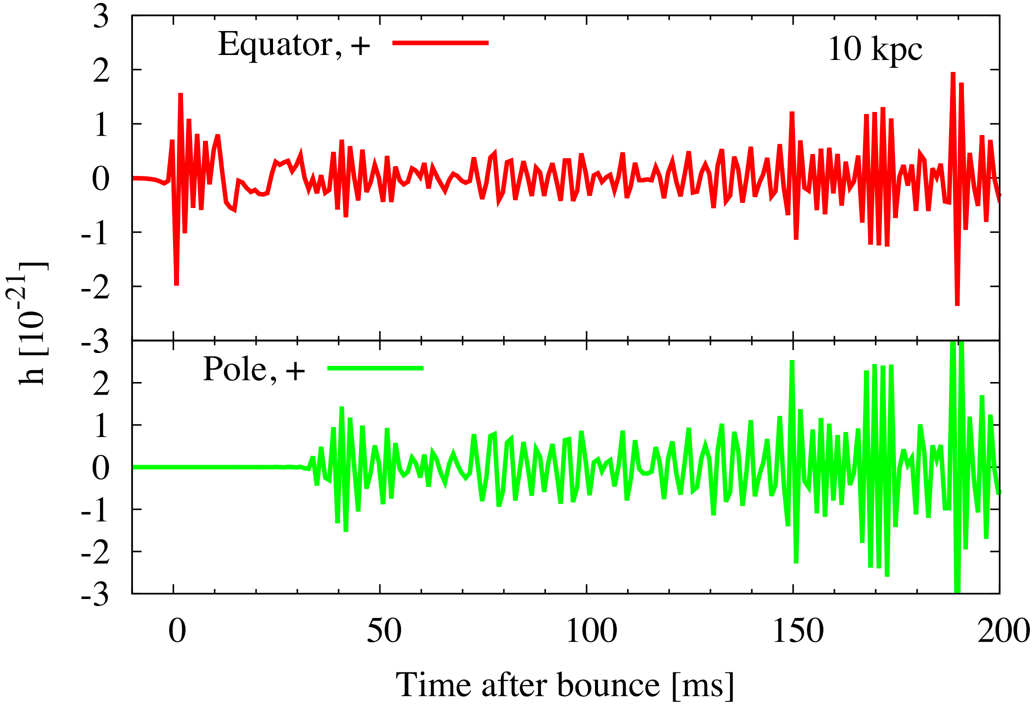


High frequency modulations appear in the spectrogram as rotational speed increases.

Walk, Tamborra, Janka, Summa, PRD (2018). Walk, Tamborra, Janka, Summa, arXiv: 1901.06235.

Imprints of Rapid Supernova Rotation

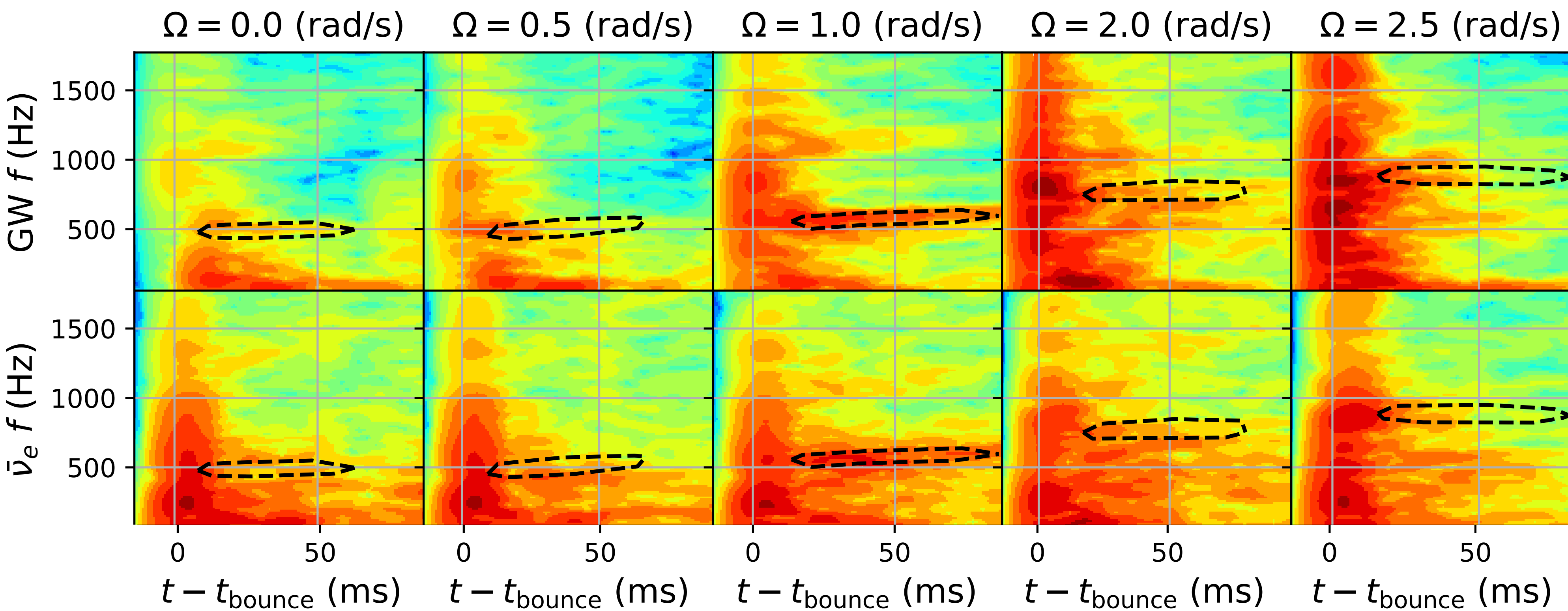




Anisotropic emission of neutrinos and gravitational waves due to rapid rotation ($\sim 2\ \mathrm{rad/s}$).

Takiwaki & Kotake, MNRAS Lett. (2018).

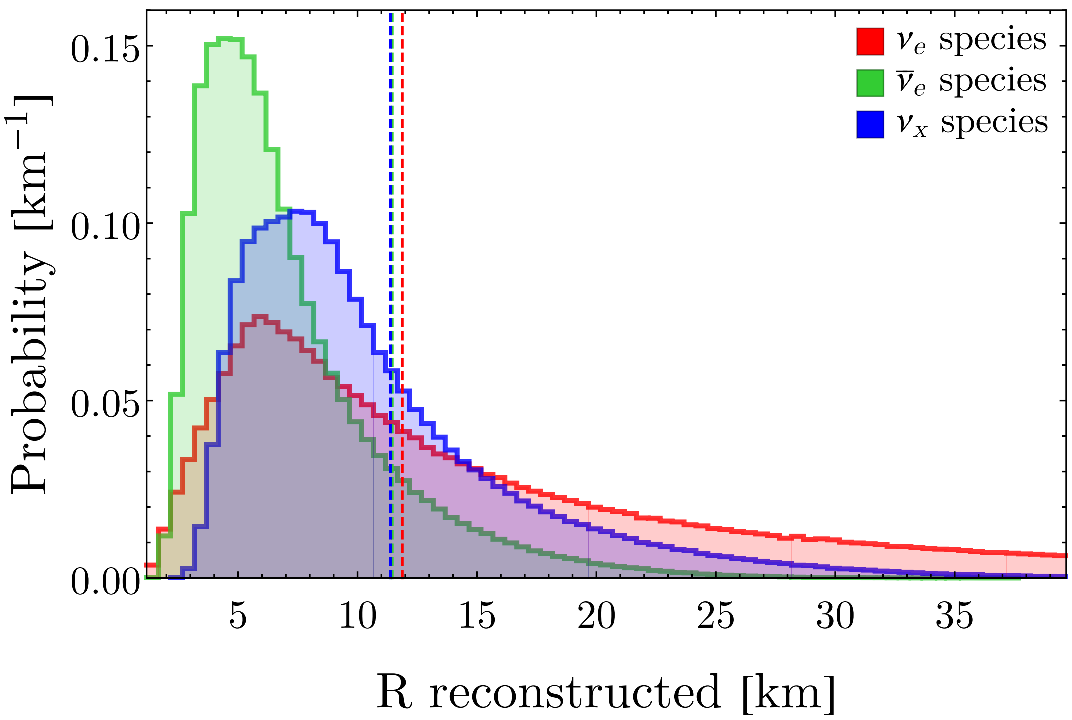
Supernova Astroseismology



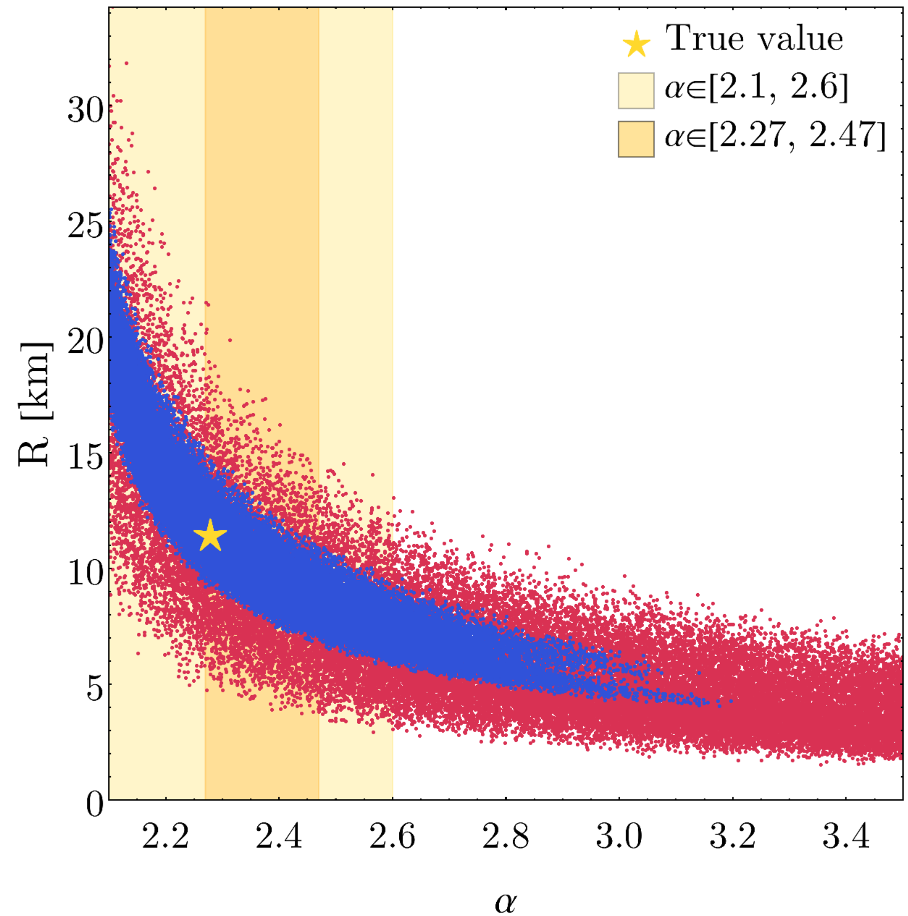
Astroseismology of rotating supernovae is possible through neutrinos and gravitational waves.

Westernacher-Schneider, O'Connor et al., in preparation.
Torres-Forne et al., MNRAS (2017, 2018). Morozova et al., ApJ (2018). Andrersson et al., MNRAS (1998).

Neutron Star Properties



(a) Default case



(a) $\overline{\nu}_e$ species

Late time neutrino signal can determine neutron star radius with 50-10% precision.

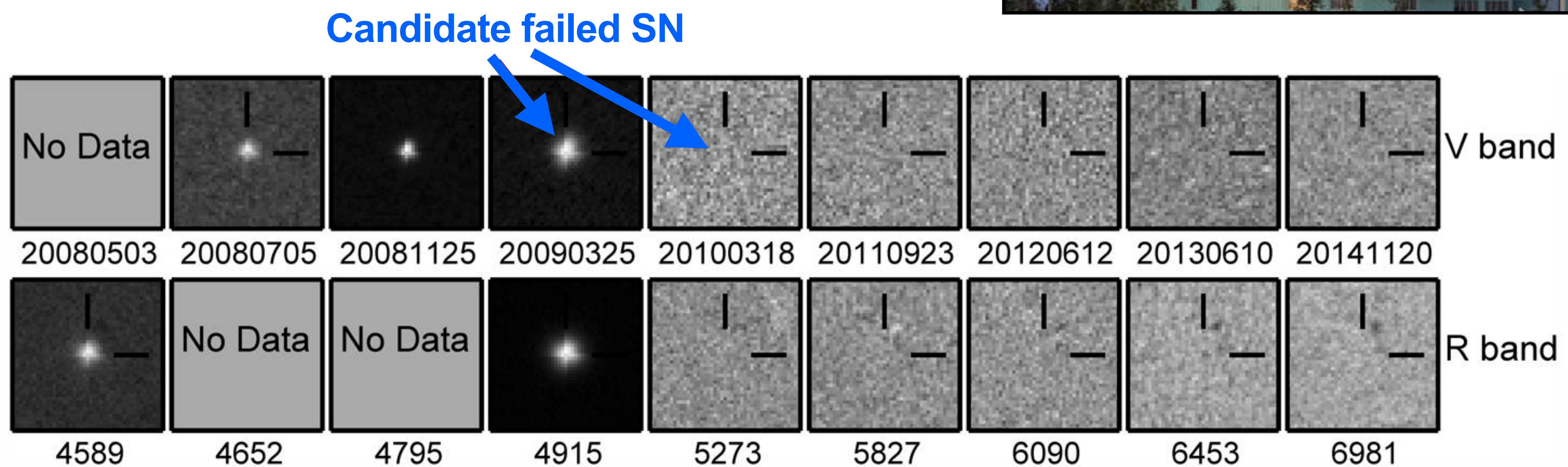
Complementary information with respect to EM and gravitational wave determination (few %).

Gallo Rosso et al., JCAP (2018).
Lattimer & Steiner, ApJ (2014). Gendreau & Arzoumanian, Nature (2017). Lattimer & Prakash, Phys. Rep. (2007). LIGO and Virgo, PRL (2018).

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**.

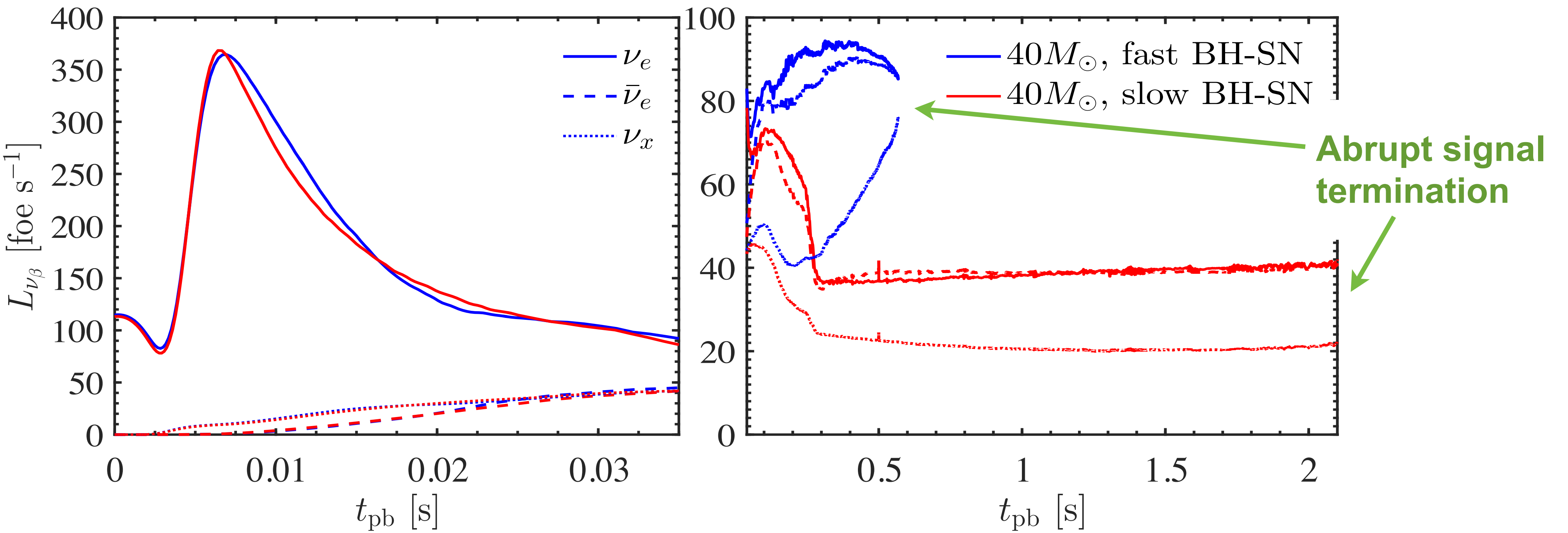


Failed core-collapse fraction: 4-43% (90% CL)

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

Signatures of Black-Hole Formation

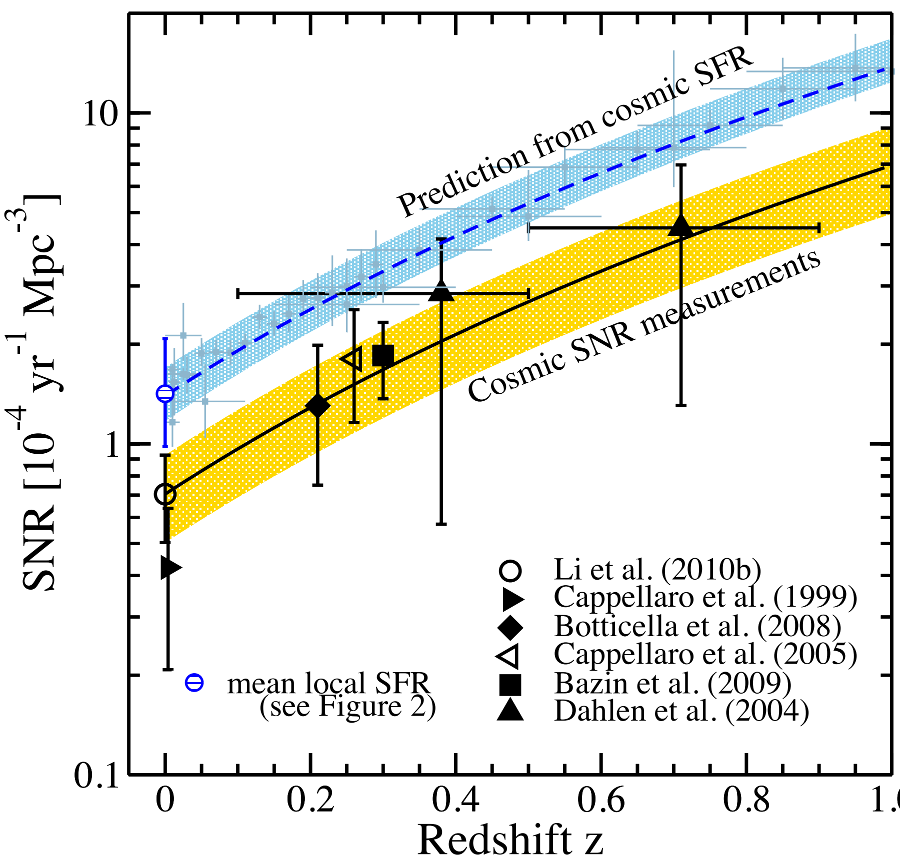
Failed supernova (40 M_{sun})

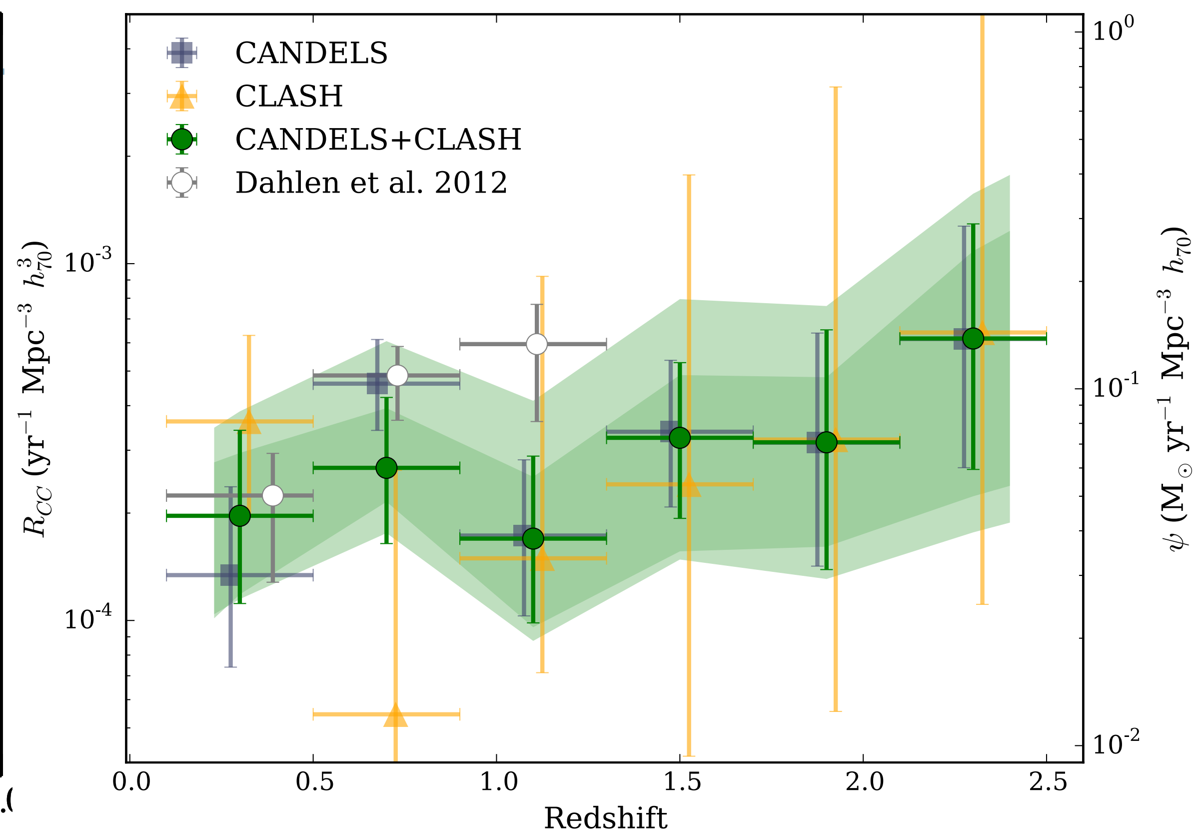


- Failed supernovae up to 20-40% of total (low-mass progenitors can also lead to failed SN).
- Neutrinos may be the only probes revealing black-hole formation.

Sukhbold et al., ApJ (2016). Ertl et al., ApJ (2016). Horiuchi et al., MNRSL (2014). O'Connor & Ott, ApJ (2011). O'Connor, ApJ (2015). Kuroda et al., MNRAS (2018).

Supernova Rate

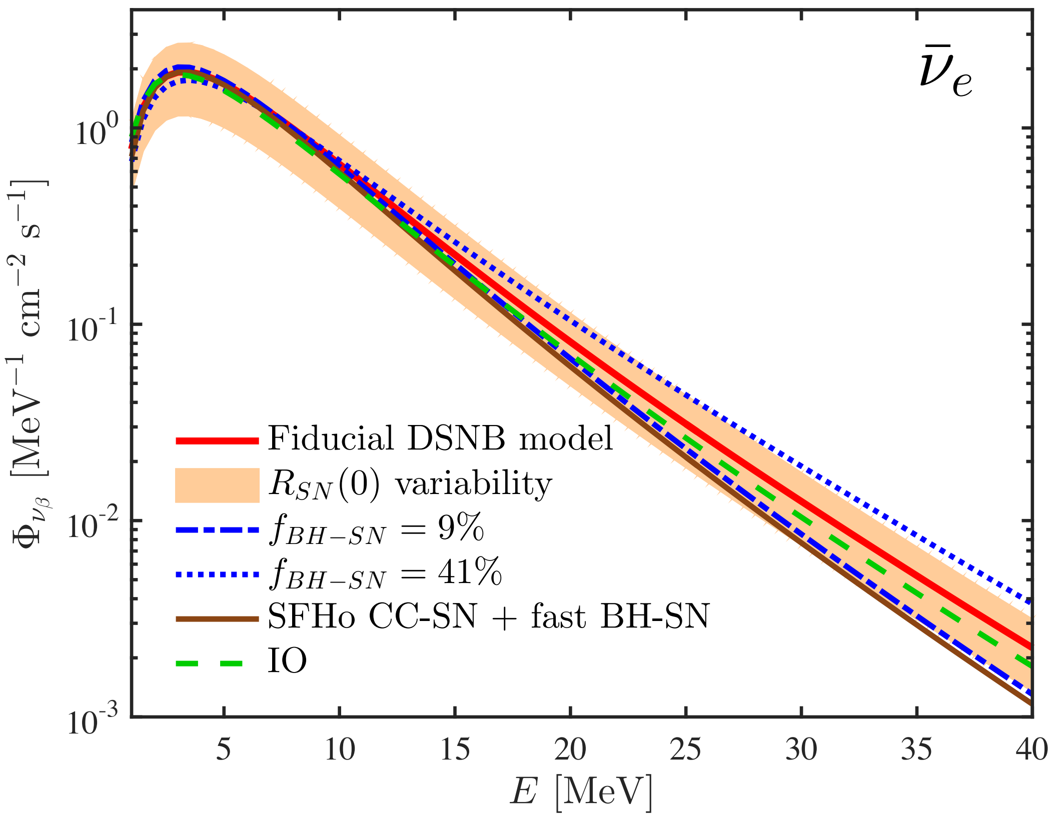


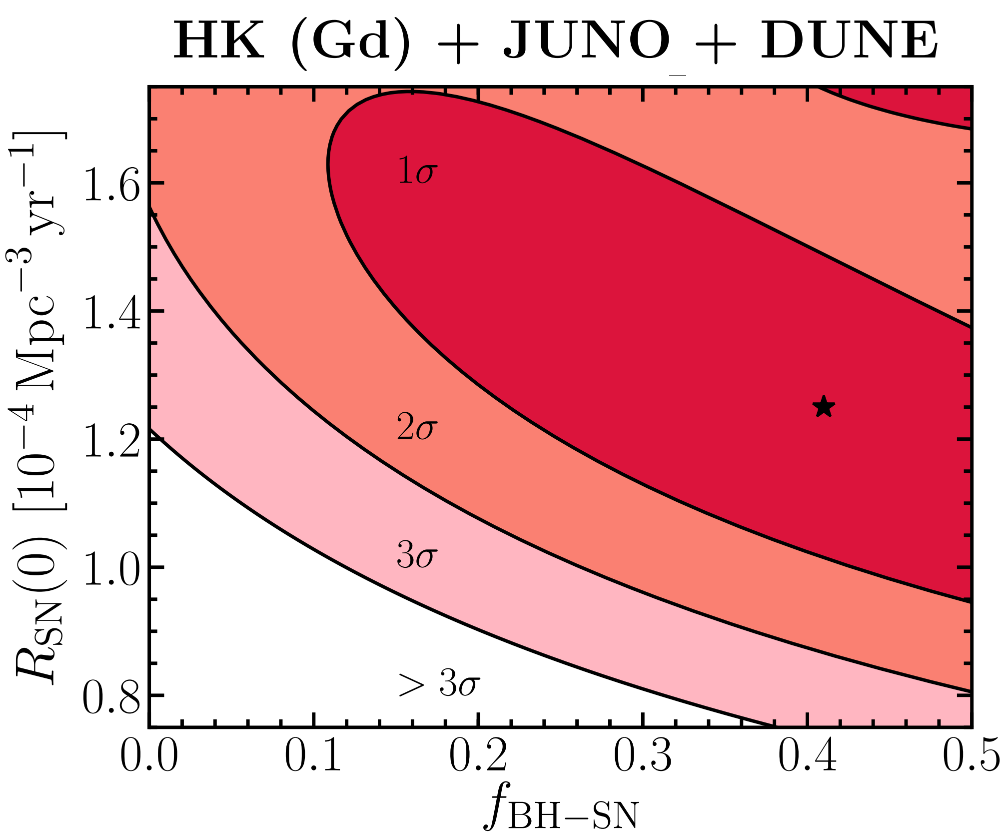


Existing measurements of the supernovae rate plagued by normalization errors.

Horiuchi et al., ApJ (2011); Botticella et al., A&A (2012). Strolger et al., ApJ (2015).

Characterizing the Supernova Population

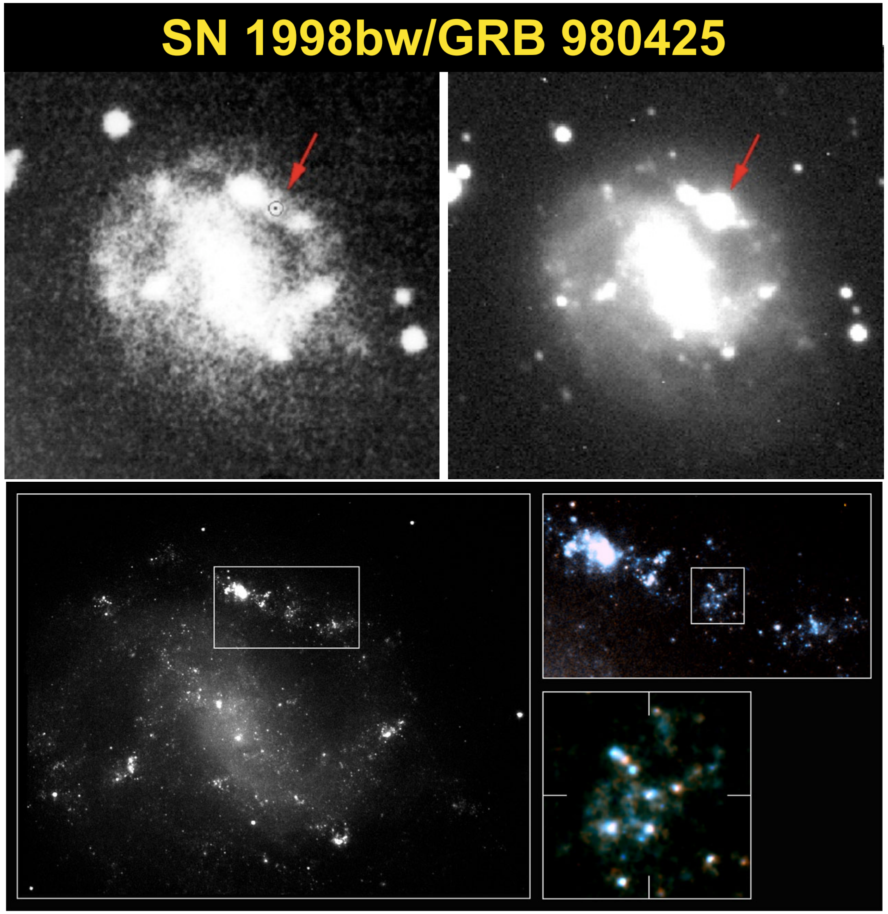


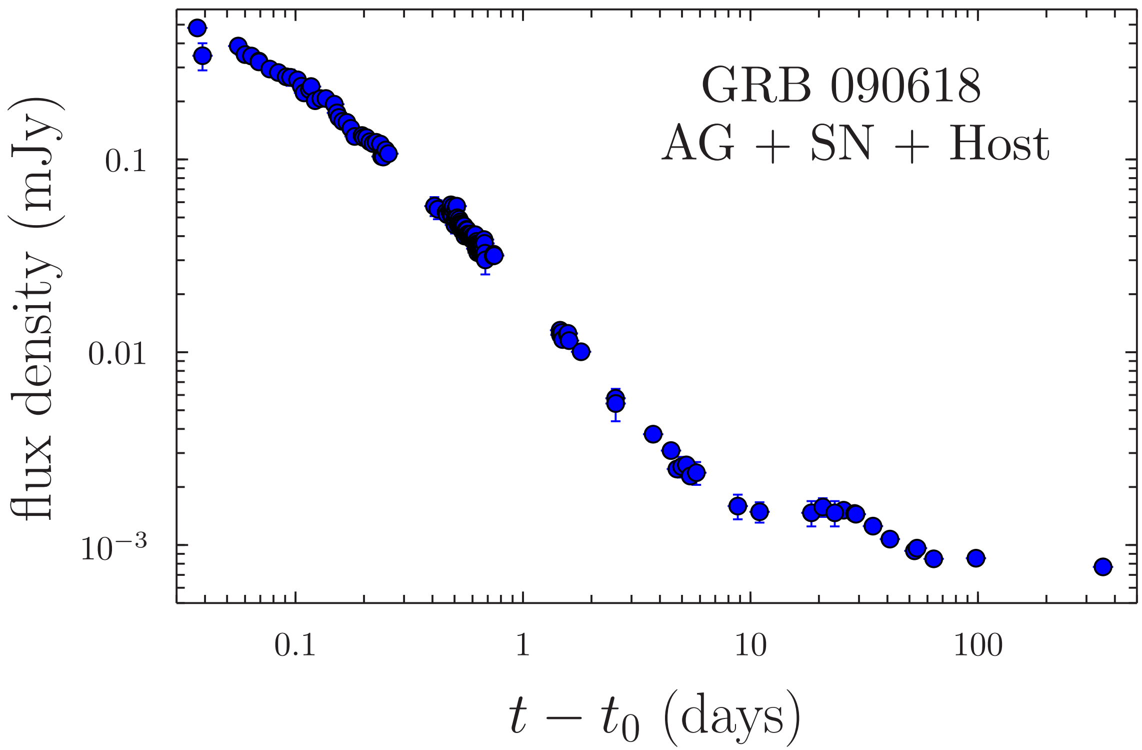


- DSNB detection may happen soon with, e.g., upcoming JUNO and Gd-Super-K project .
- Independent test of the local supernova rate (~30% precision).
- Constraints on fraction of failed supernovae.

Moller, Suliga, Tamborra, Denton, JCAP (2018). Nakazato et al., ApJ (2015). Horiouchi et al., MNRAS (2018). Priya and Lunardini, JCAP (2017). Beacom, ARNPS (2010).

Supernova-GRB Connection



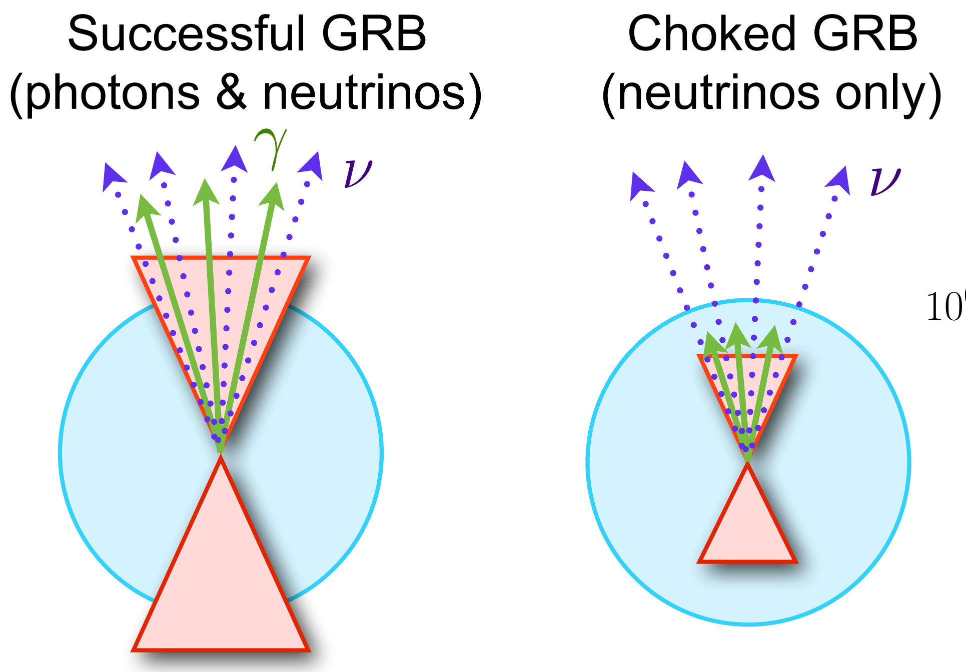


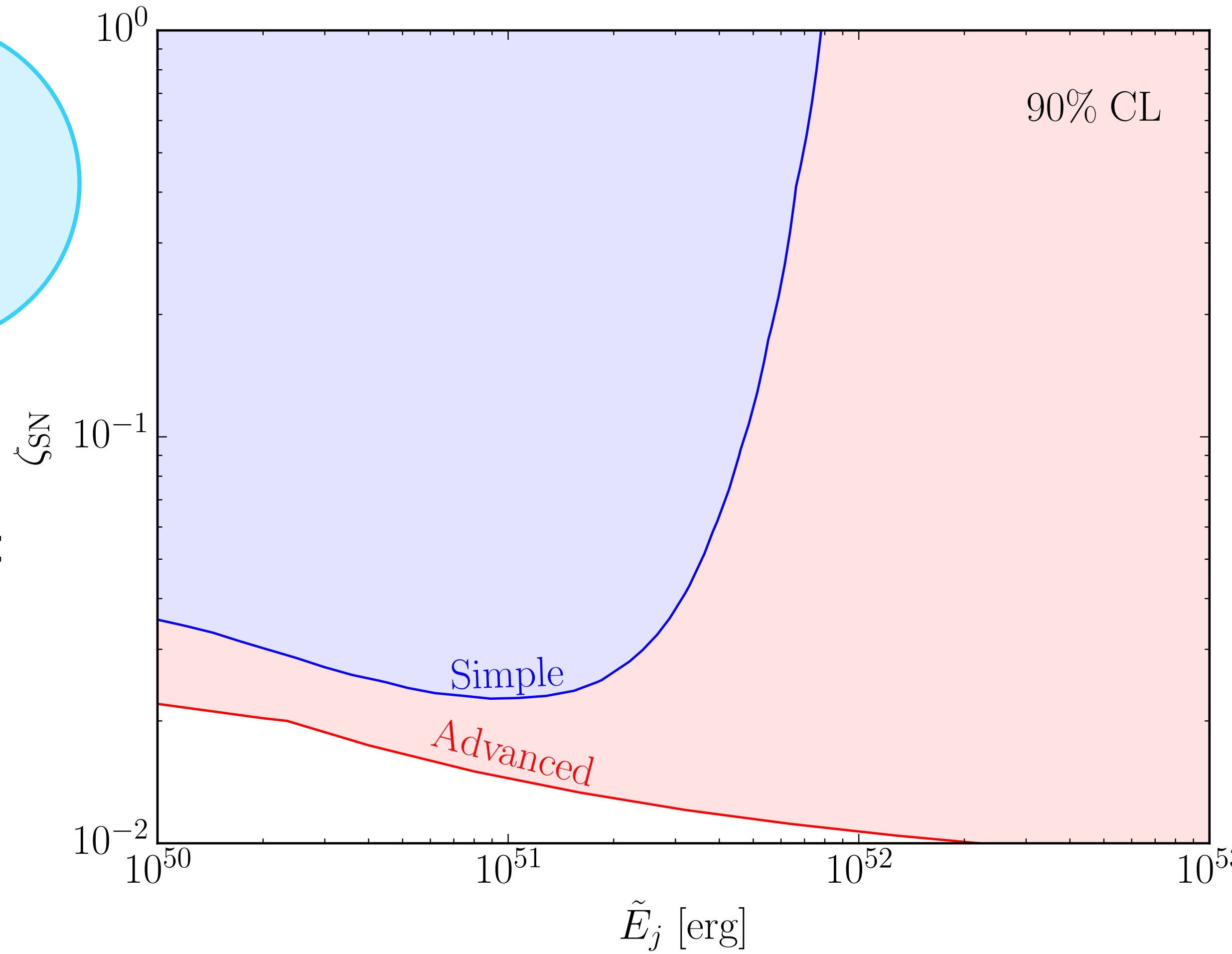
Limitations:

- 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).

Exploring the Supernova-GRB Connection



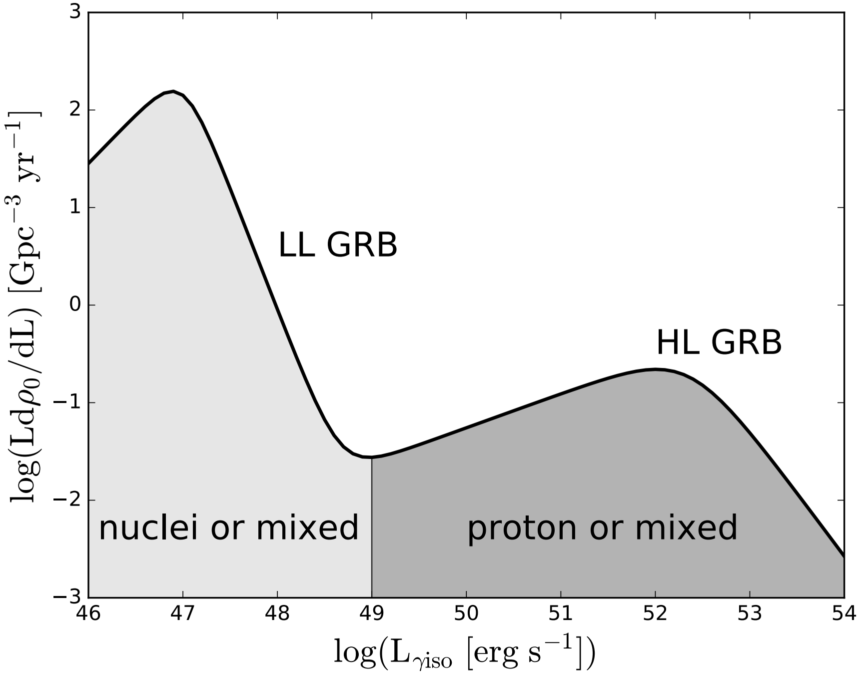


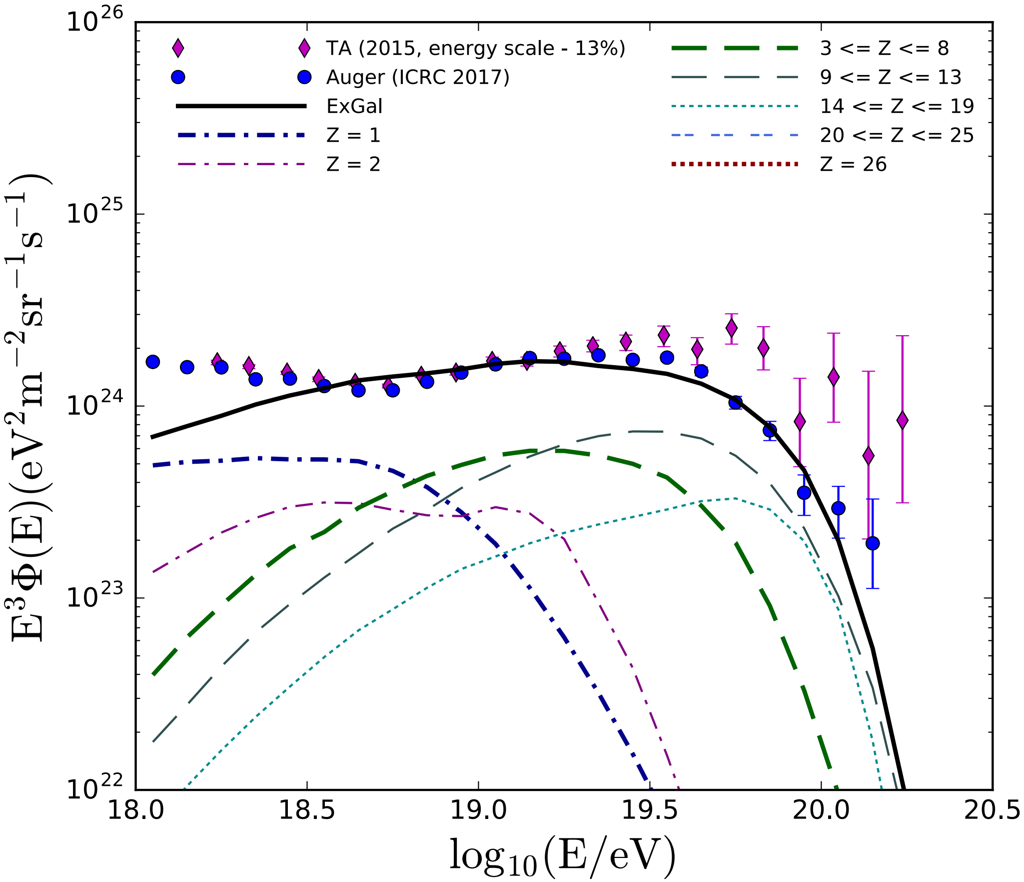
IceCube data can already constrain:

- 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).

Supernova Aftermath





- Supernova nucleosynthesis affects nuclear composition of jets and multi-messenger signals.
- UHE cosmic rays may come from low-luminosity GRBs and engine-driven supernovae.
- Ultra high energy neutrinos likely detectable by next generation experiments.

Zhang et al., PRD (2018). Murase & Zhang, arXiv: 1812.10289. Horiouchi et al., ApJ (2018). Moller, Denton, Tamborra, arXiv: 1809.04866. Tamborra & Ando, JCAP (2015).

Conclusions

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

NBIA-LANL Neutrino Quantum Kinetics in Dense Environments

26-30 August 2019
Niels Bohr Institute
Europe/Copenhagen timezone

Contact

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The workshop is jointly organized by Niels Bohr International Academy and Los Alamos National Laboratory.

Organizers
Mark Paris (Los Alamos National Laboratory)
Shanshank Shalgar (NBIA & DARK, Niels Bohr Institute)
Irene Tamborra (NBIA & DARK, Niels Bohr Institute)

Starts 26 Aug 2019, 10:00
Ends 30 Aug 2019, 17:00
Europe/Copenhagen

Niels Bohr Institute
Auditorium A
Blegdamsvej 17, 2100 København

Thank you!