The Niels Bohr International Academy

DARK

Supernova Neutrinos

Irene Tamborra (Niels Bohr Institute)

International Neutrino Summer School, August 2-13, 2021

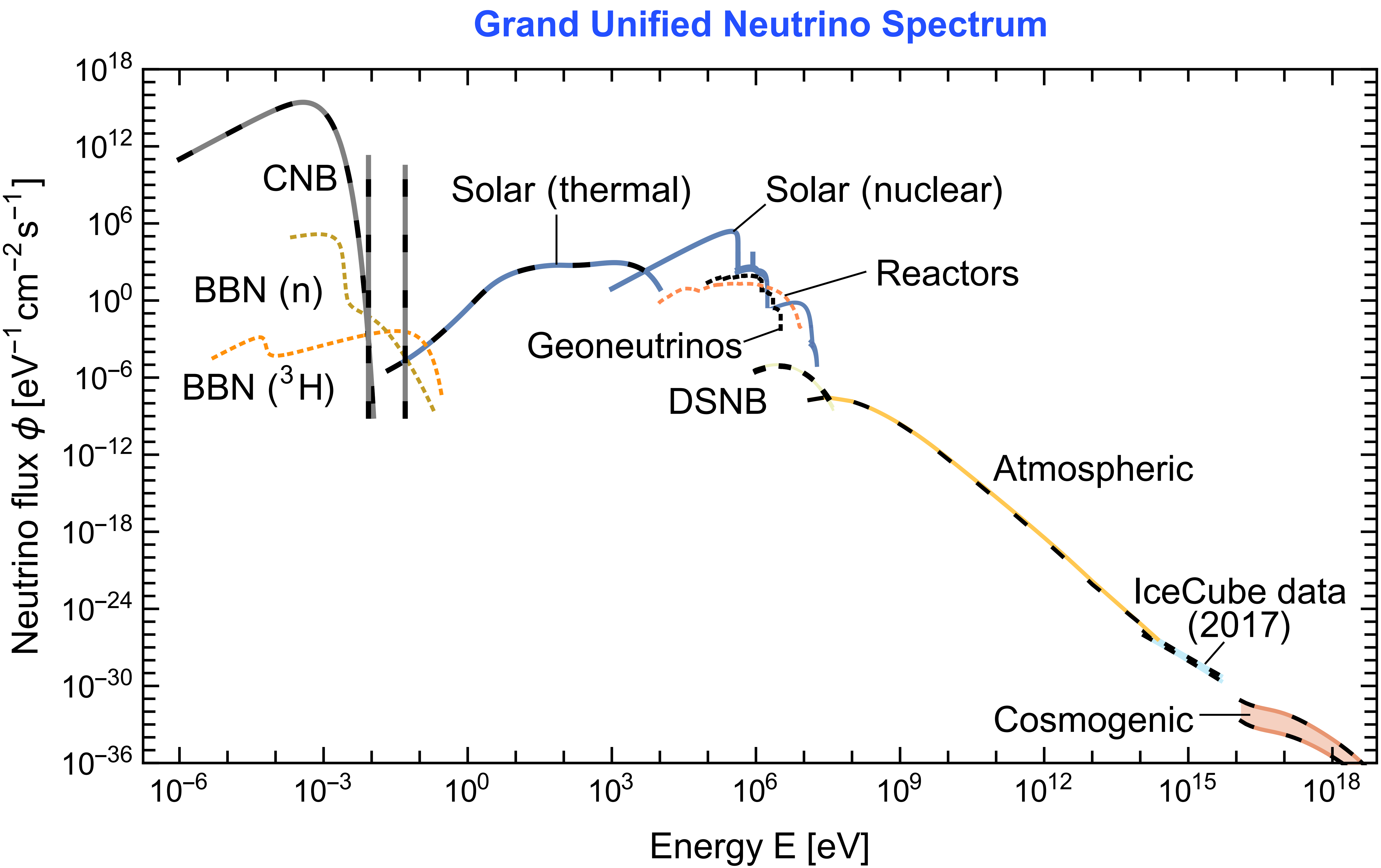
VILLUM FONDEN

Sapere Aude

CARLSBERG FOUNDATION

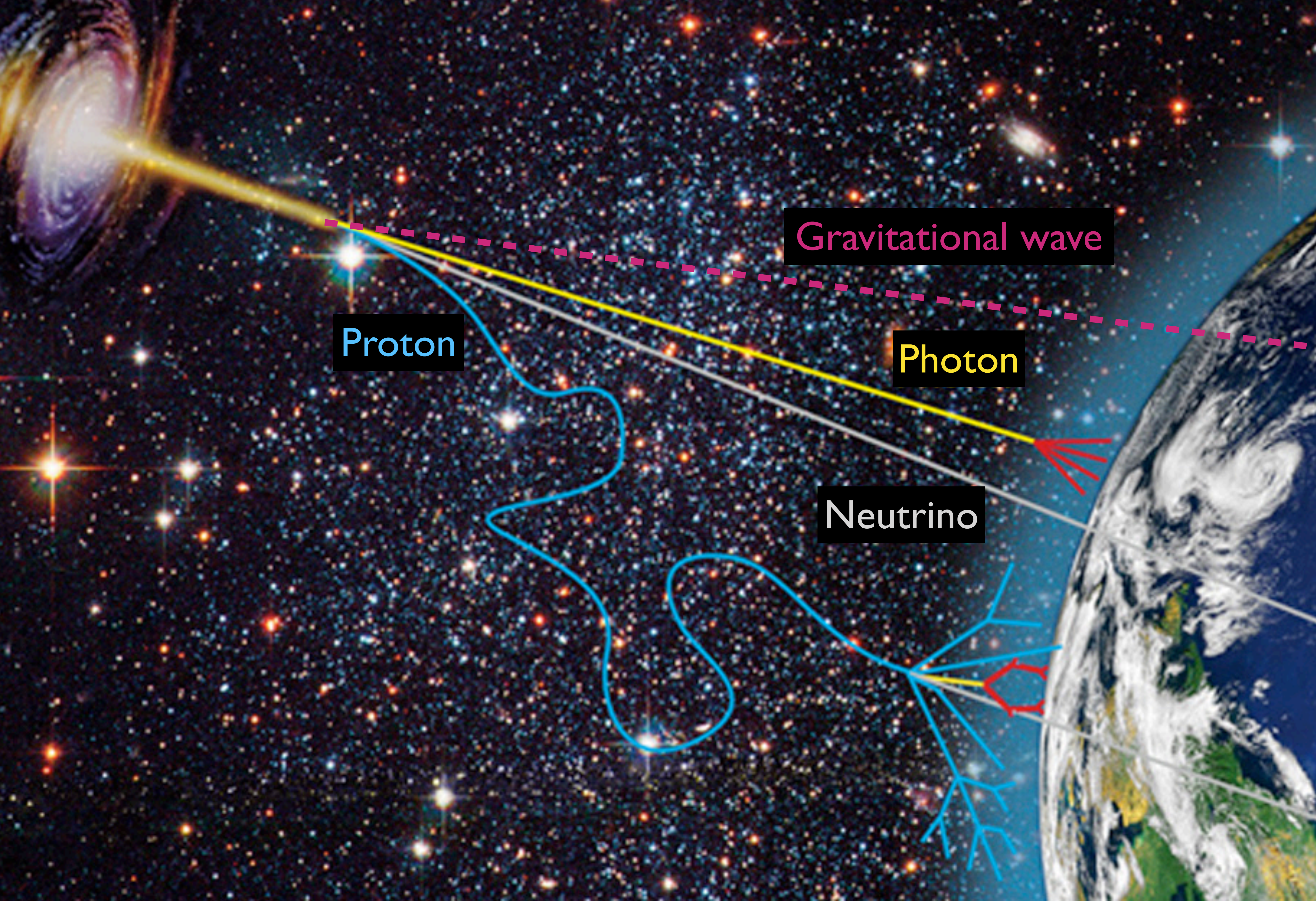
SFB 1258 Neutrinos Dark Matter Messengers

The Cosmos in Neutrinos



Vitagliano, Tamborra, Raffelt, Rev. Mod. Phys. (2020).

Ideal Messengers



Neutrino Mixing

Neutrinos **oscillate** into each other by flavor mixing, because of their tiny non-vanishing mass.

Flavor states

ν_e

ν_μ

ν_τ

= **Linear combination**

Mass states

ν_1

ν_2

ν_3

Flavor Oscillations

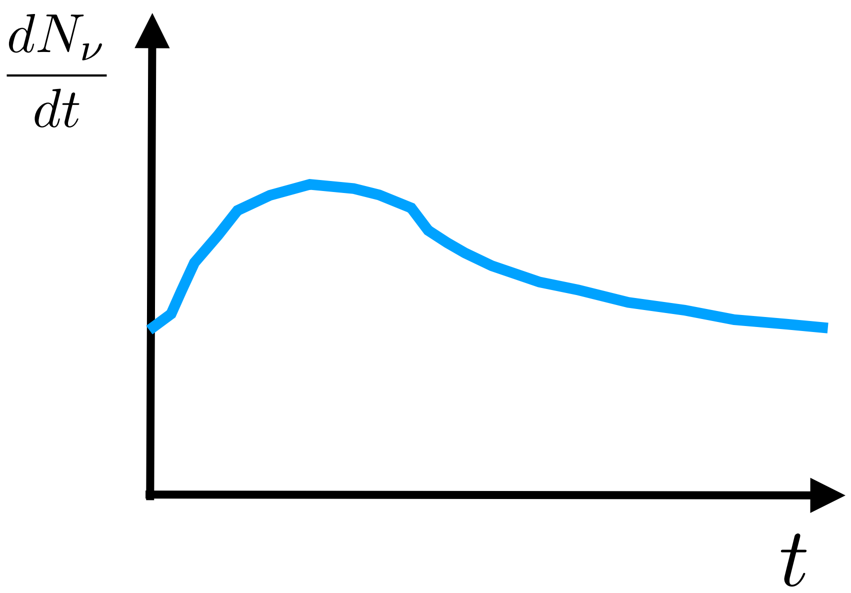
- Neutrino flavor ratio provides information about **neutrino properties**.
- Flavor conversions are affected by background fermion distribution.
- In turn, flavor conversions can affect source dynamics.
  ⇨ Study of flavor evolution allows to learn about **source properties**.

Powerful Probes in Astrophysics

Energy distribution

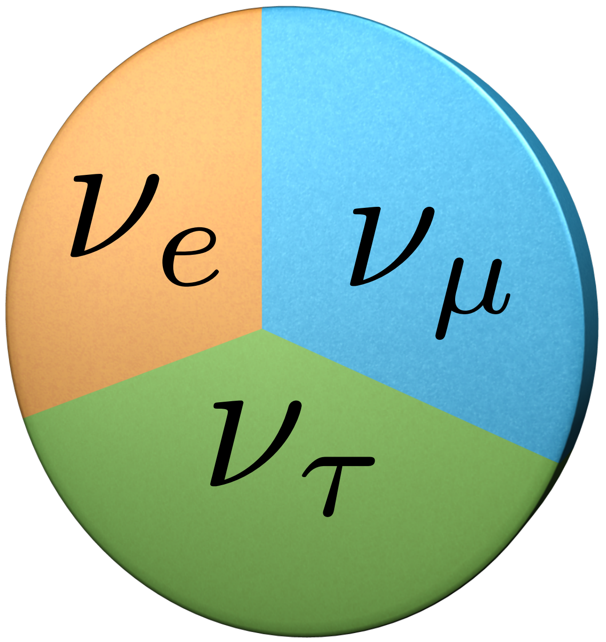
Similar to photons

Neutrino curve



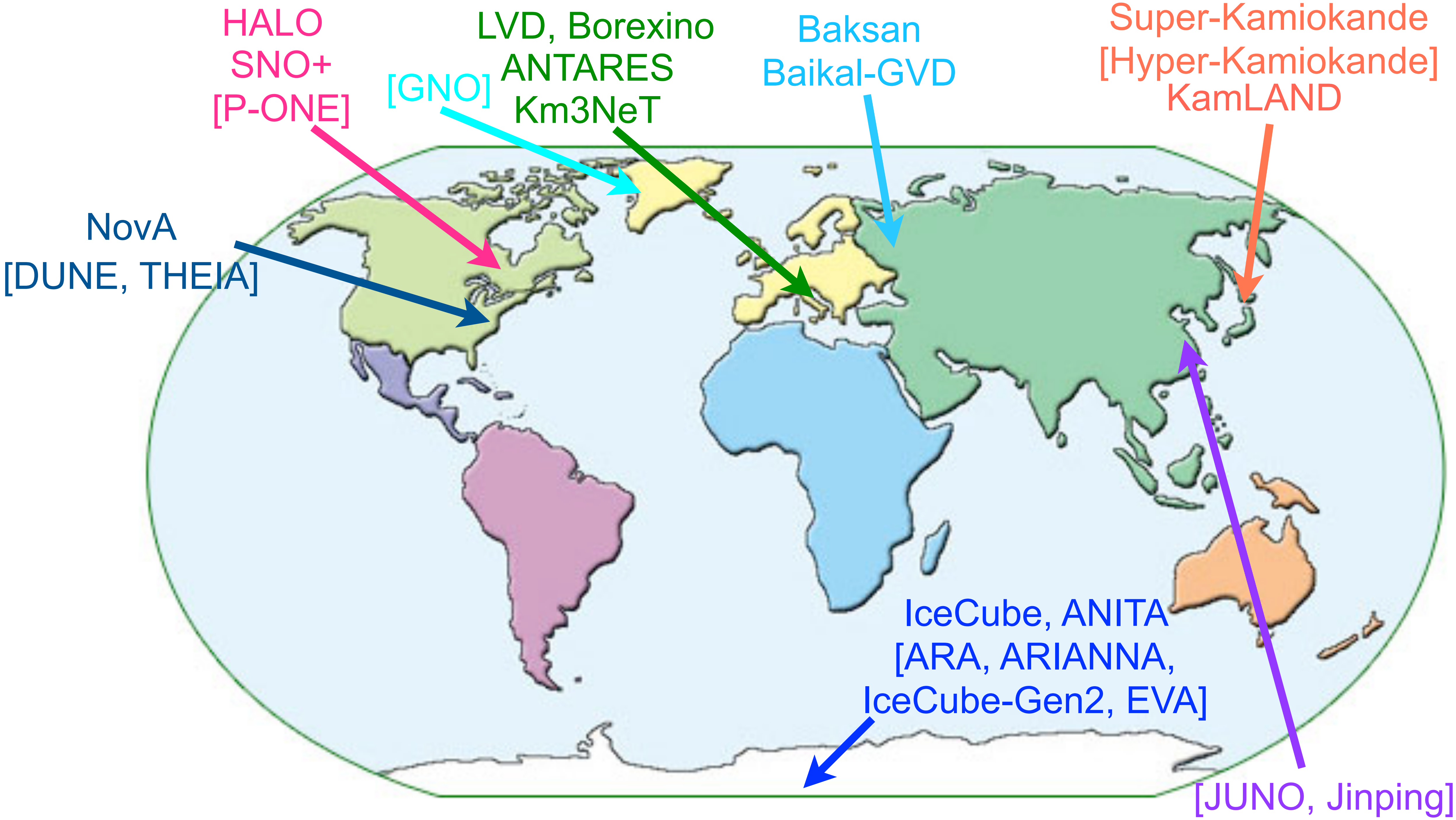
Similar to photons

Flavor ratio



Neutrinos only!

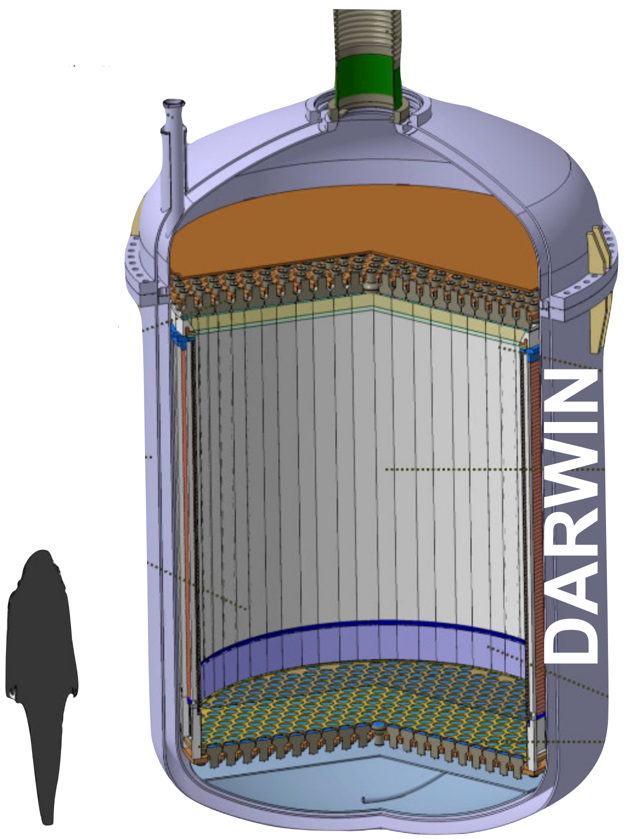
Neutrino "Telescopes"



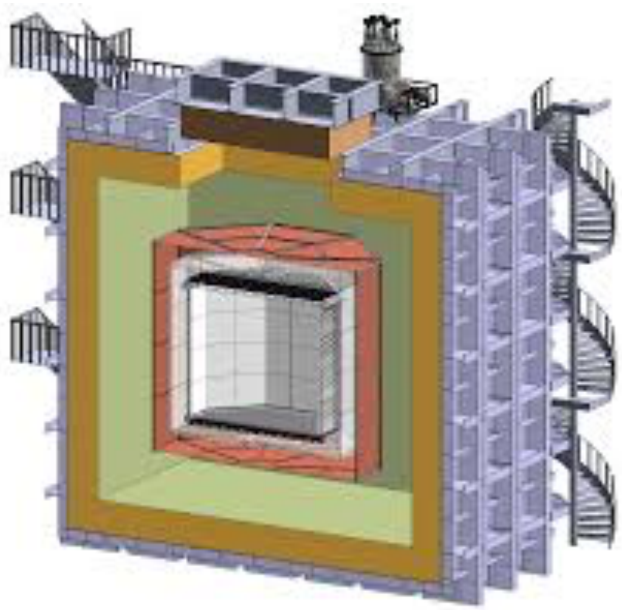
Fundamental to combine astrophysical signals from detectors employing different technologies (e.g., Cherenkov and liquid scintillator detectors).

Neutrino “Telescopes”

Neutrino Telescopes Based on Coherent Scattering



DarkSide-20k & ARGO



RES-NOVA

- Flavor insensitive (complementary to other neutrino telescopes).
- Compact size and excellent time resolution.

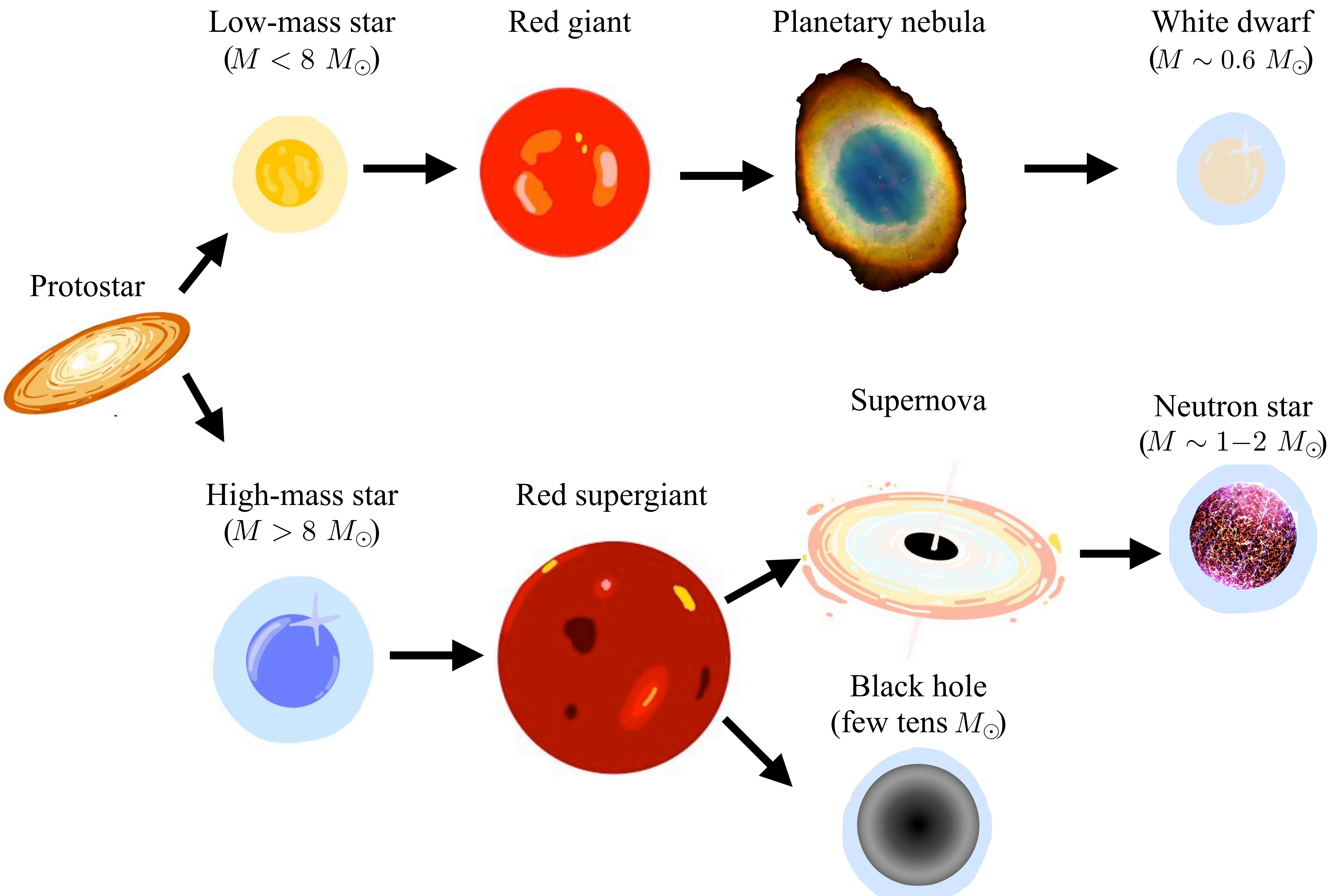
Pattavina, Ferreiro Iachellini, Tamborra, PRD (2020). Lang, McCabe, Reichard, Selvi, Tamborra, PRD (2016). Horowitz et al. PRD (2003). Drukier and Stodolsky, PRD (1984). Agnes et al., arXiv: 2011.07819.

Lecture 1:
Neutrinos as Astrophysical Probes

Intended Learning Objectives

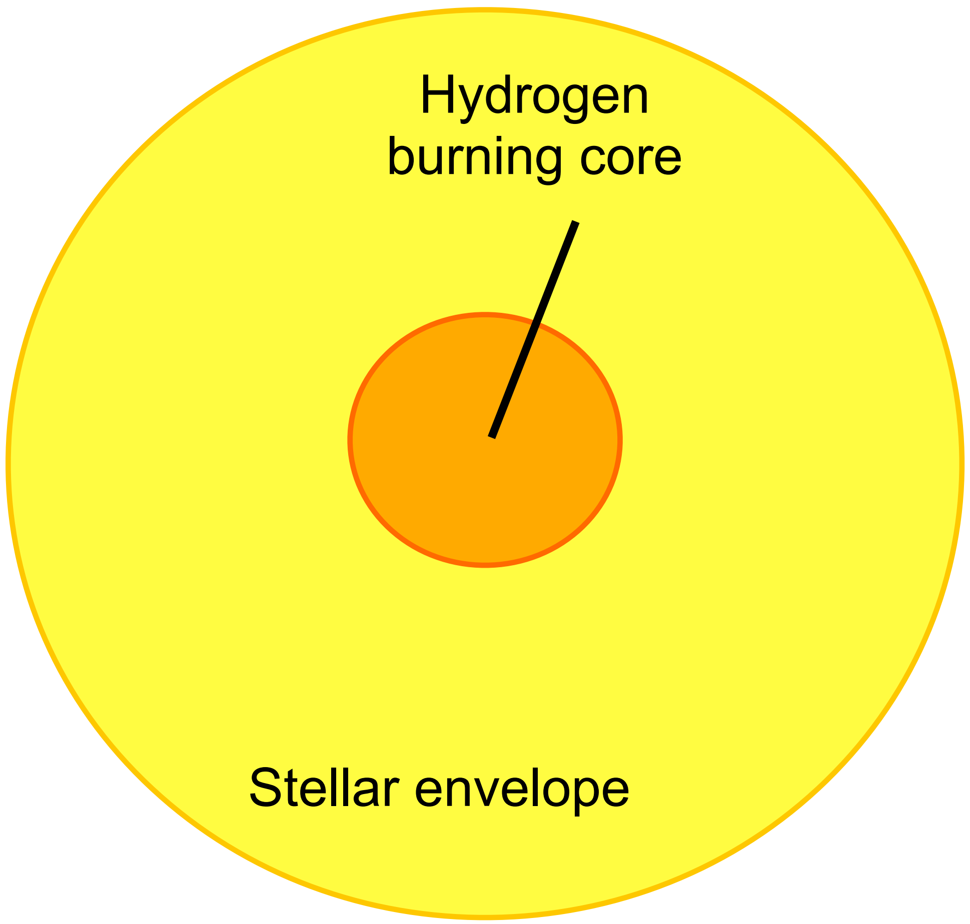
- Supernova physics
- Neutrinos as messengers of the supernova physics

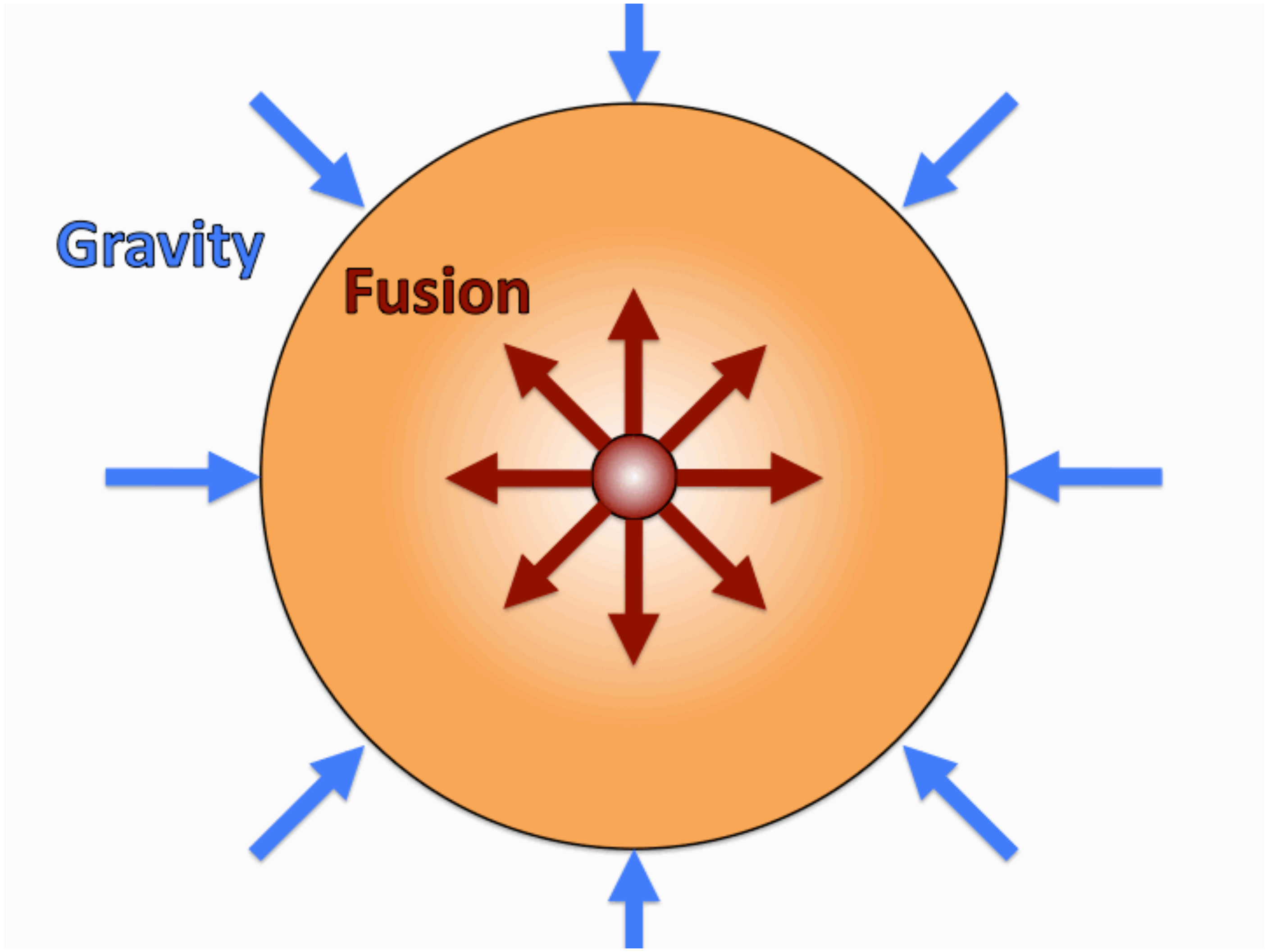
Lifecycle of a Star



Lifecycle of a Sun-like Star

A young star fuses hydrogen into helium (keeps burning until it runs out of hydrogen).



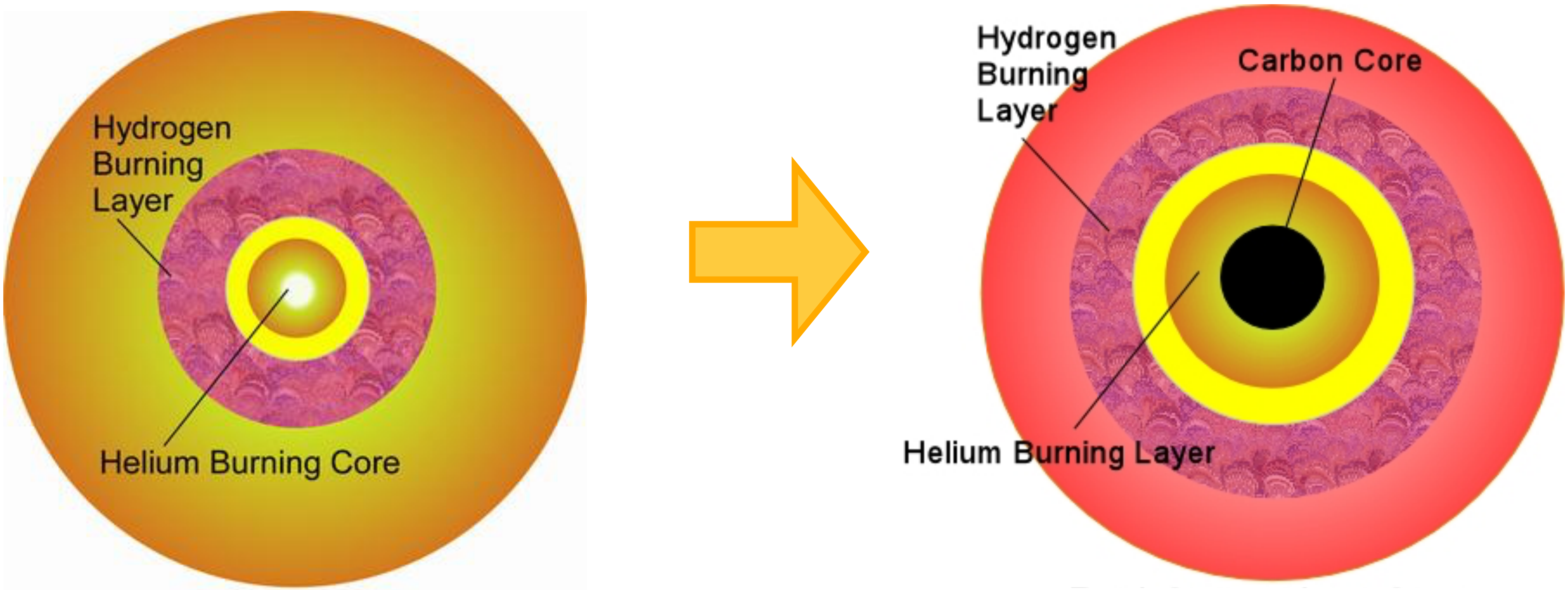


Pressure (from energy produced in the core from nuclear fusion)
= Gravity

Hydrostatic equilibrium

Lifecycle of a Massive Star

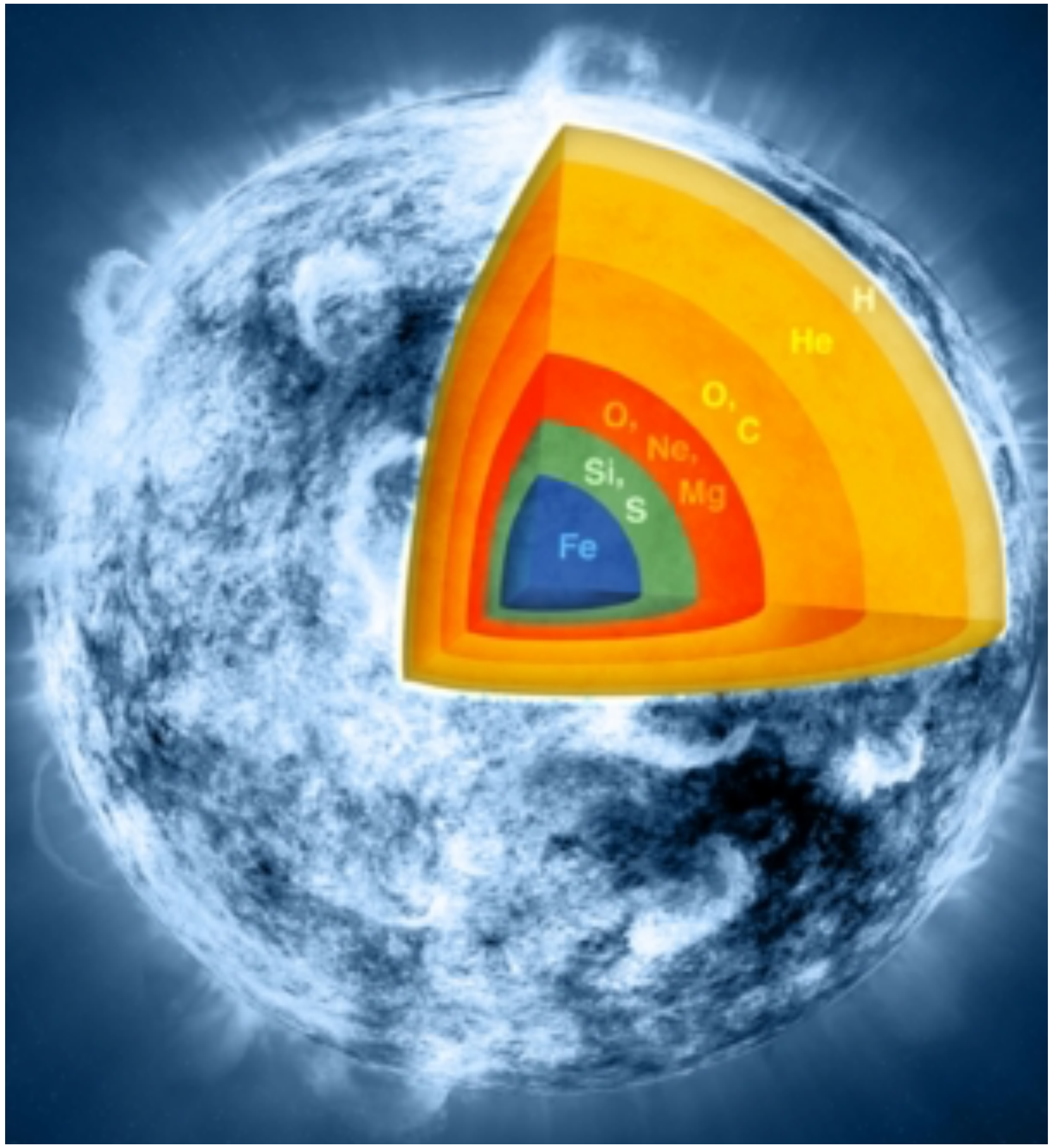
When the star exhausts hydrogen, the core drops its pressure. Gravity compresses the core and the latter heats up. Helium burning starts. It continues for all elements up to Iron.



- Red supergiant phase.
- Blue supergiant phase. Helium core contracts and ignites helium burning in the core. The envelope becomes hot and appears blue.
- Red supergiant phase. Carbon-oxygen core forms. Envelope expands and cools, appears red. Carbon-oxygen core contracts heating up. Carbon burning.

Lifecycle of a Massive Star

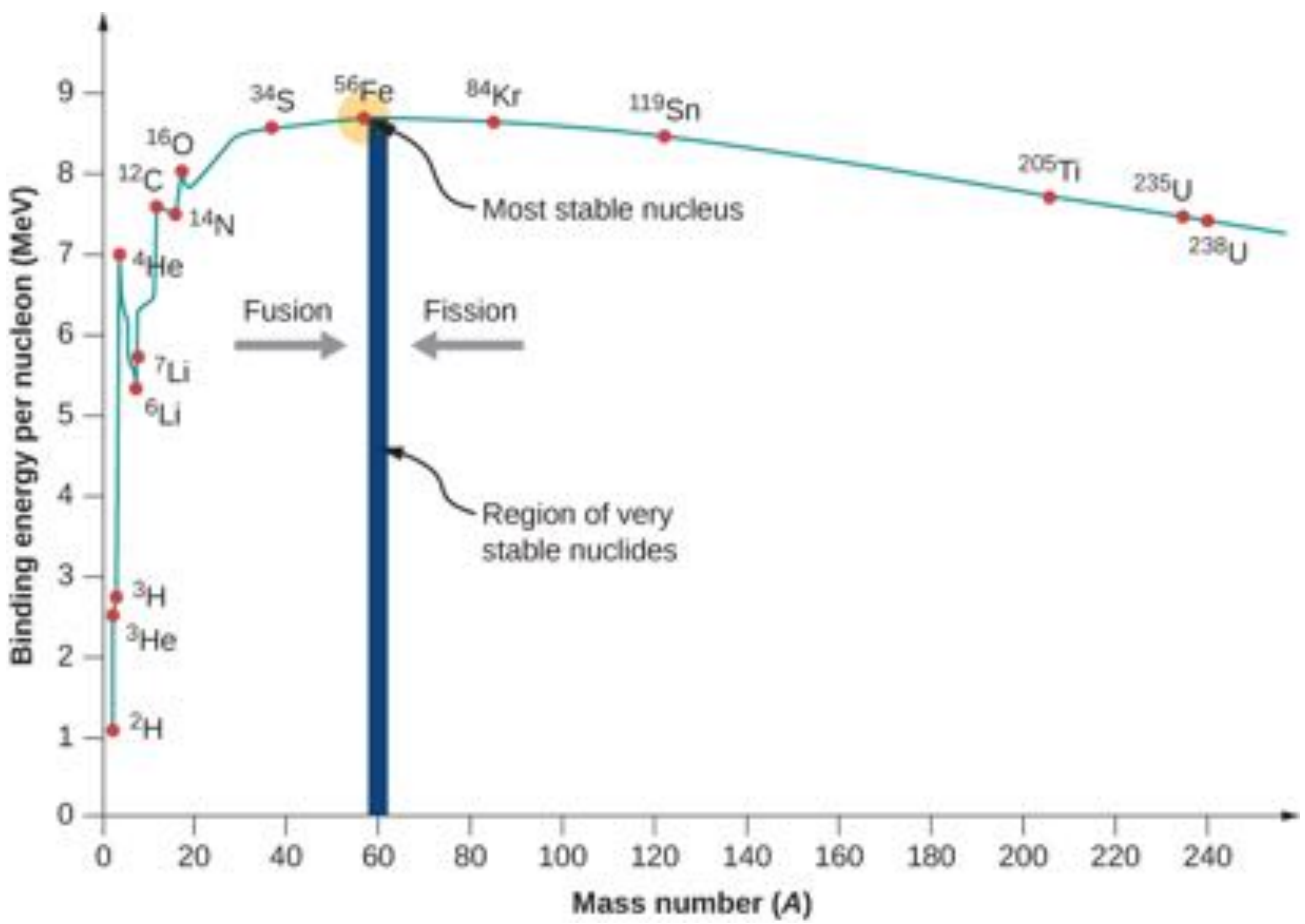
When iron is formed, no more temperature raising occurs, no more counter pressure. Core collapses by gravitation and an explosion occurs. **Core-collapse supernova**.

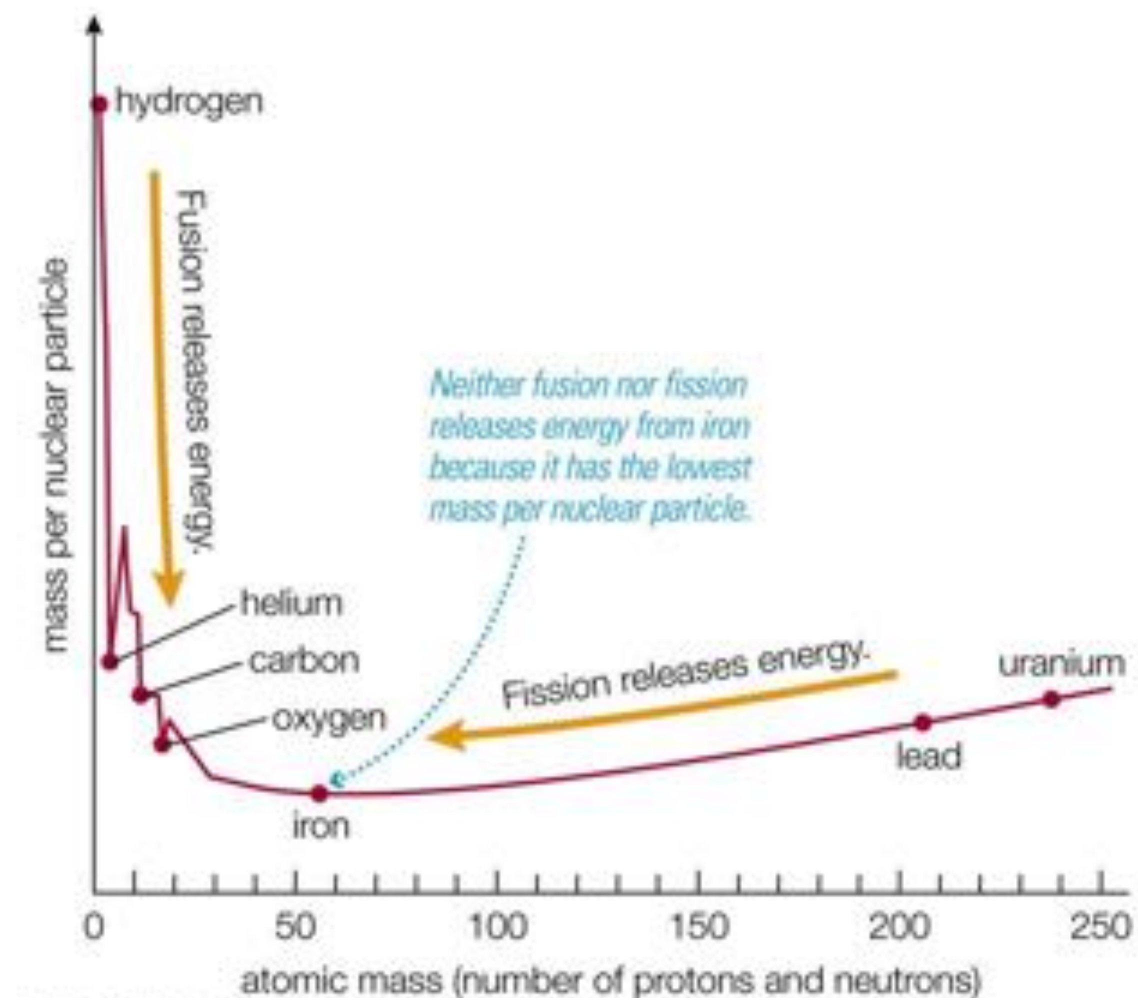


What prevents stellar burning to proceed indefinitely?

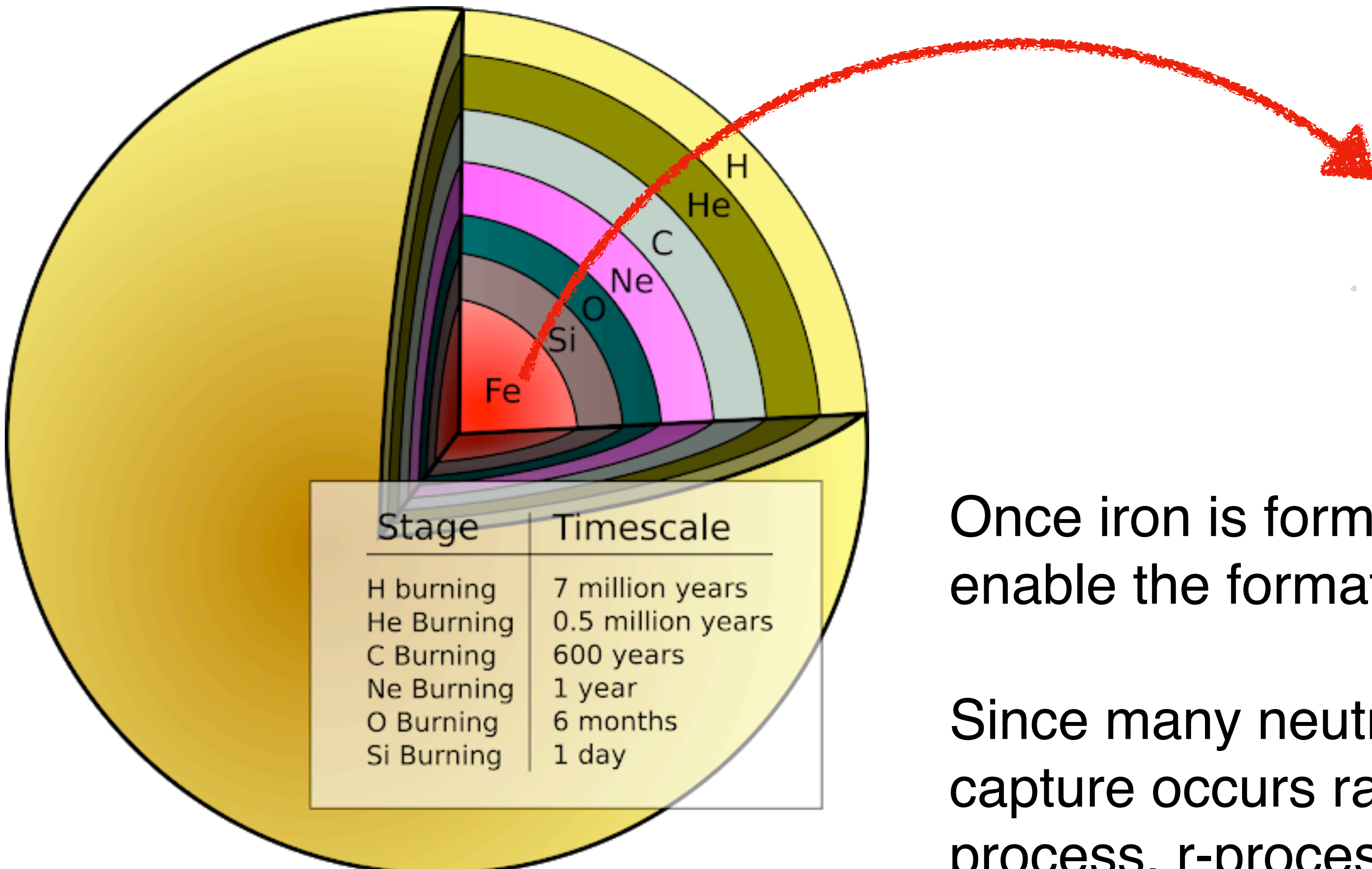
Why Does Stellar Fusion Stop at Fe?

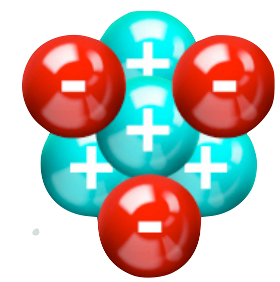
Iron does not release energy since it has the highest binding energy.





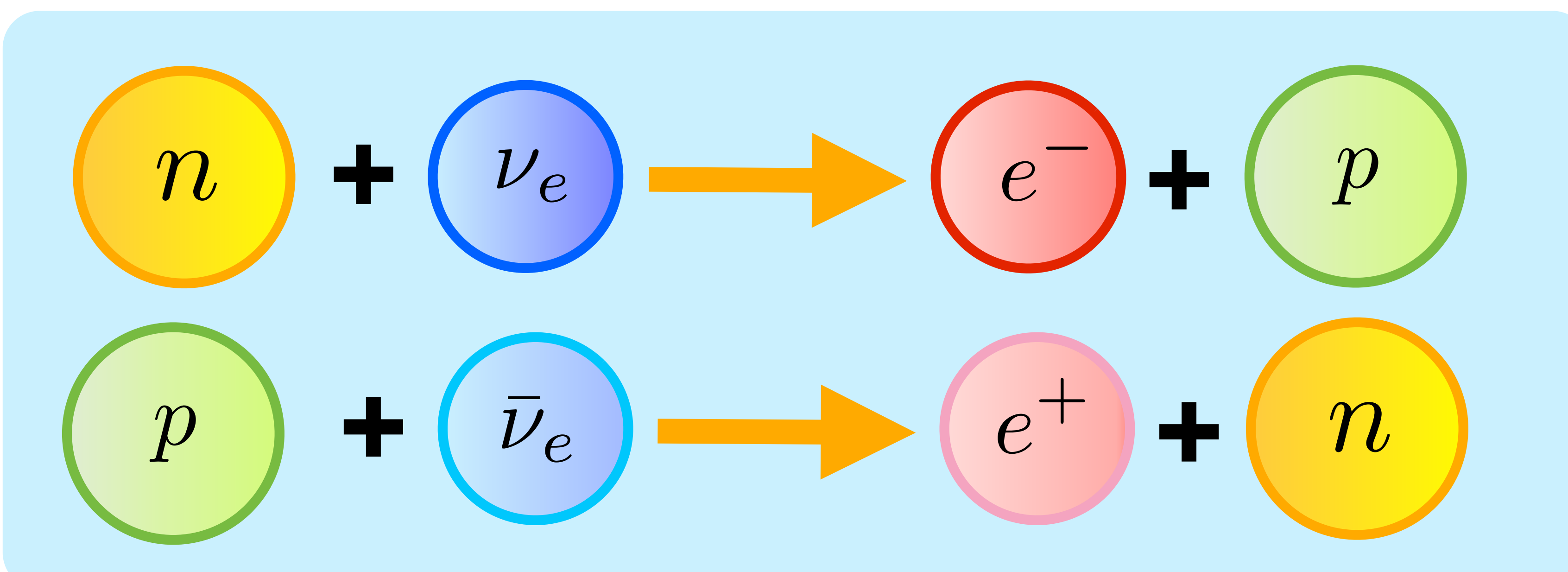
How Are Elements> Fe Produced in SNe?



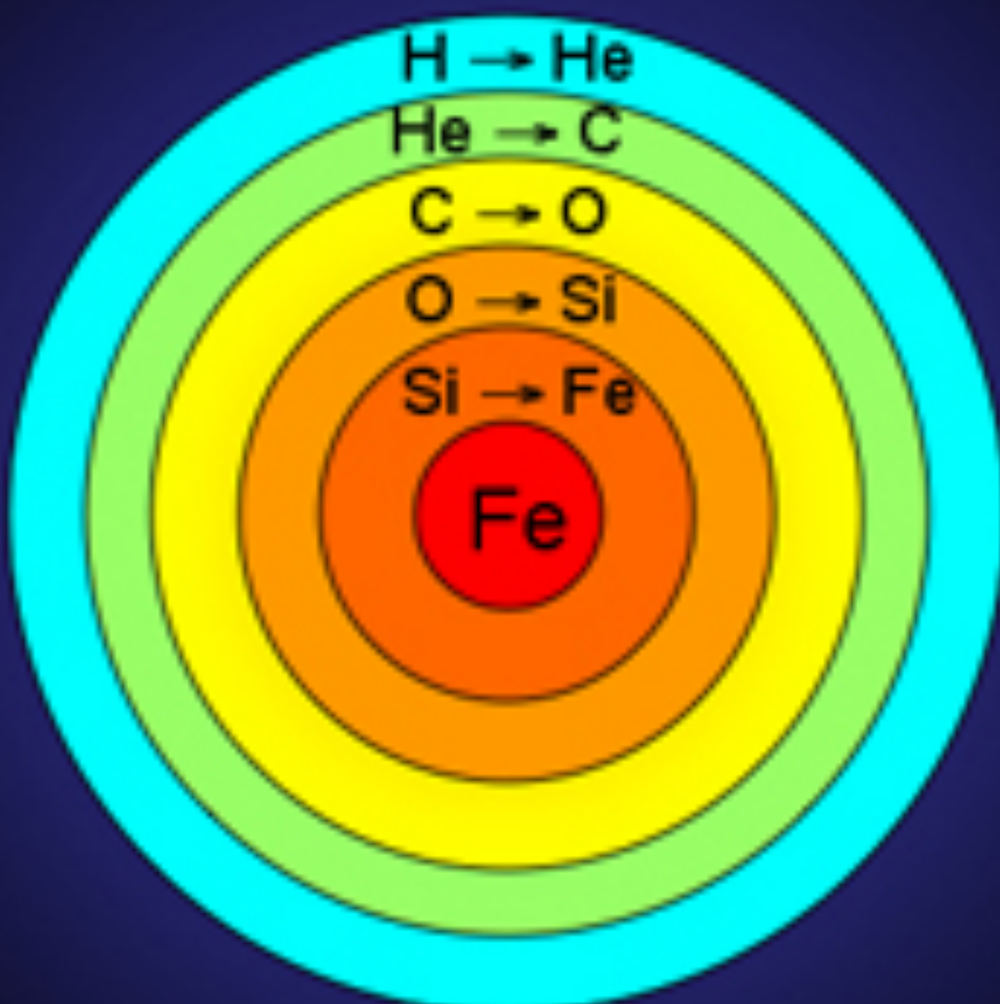


Once iron is formed, multiple neutron captures enable the formation of heavier elements.

Since many neutrons are available, neutron capture occurs rapidly (rapid neutron capture process, r-process).



Stellar Final Stages



For a 25 solar mass star:

Stage	Duration
H → He	7×10^6 years
He → C	7×10^5 years
C → O	600 years
O → Si	6 months
Si → Fe	1 day
Core Collapse	1/4 second

Core Collapse Supernova

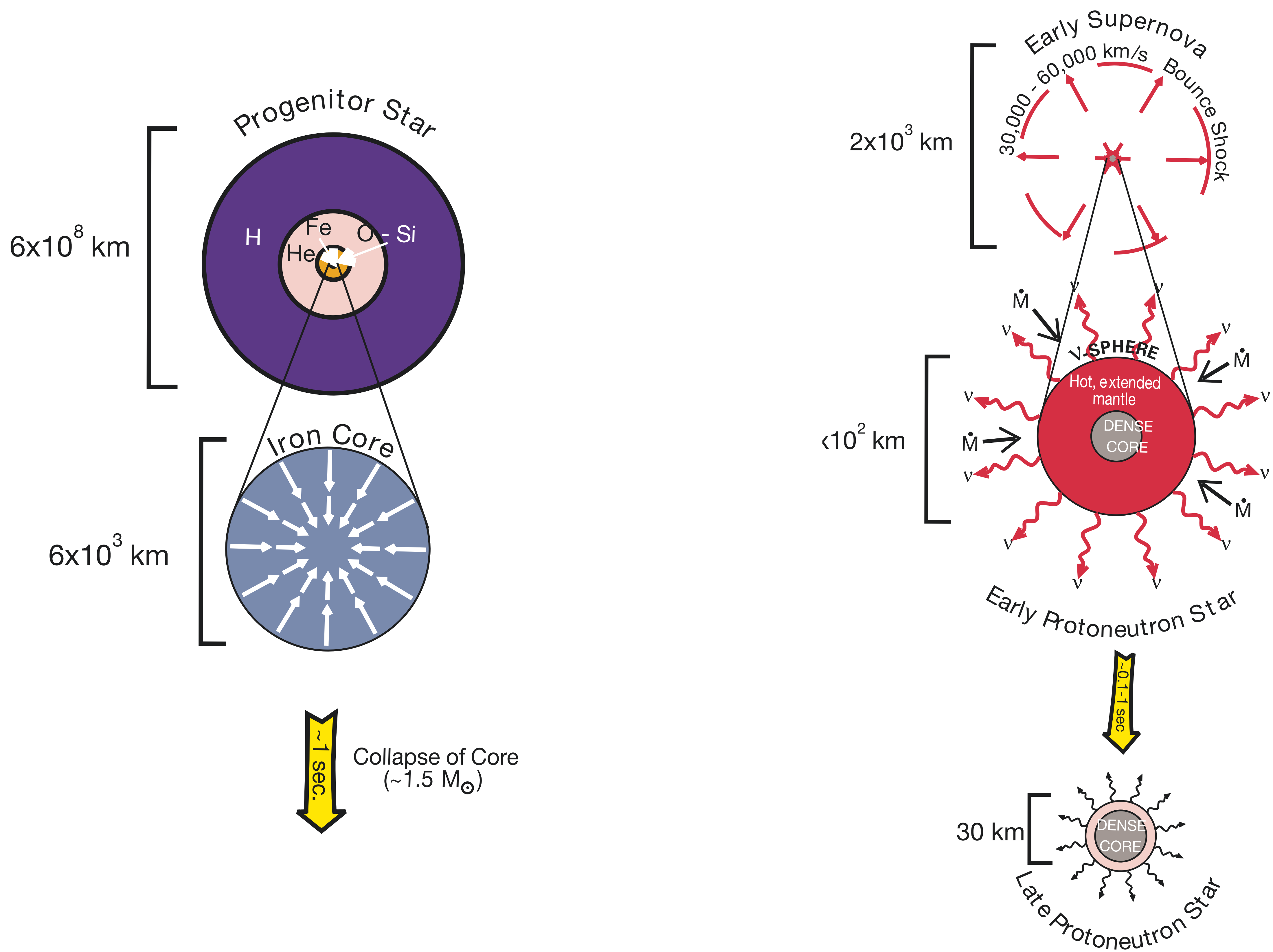


Figure credit: A. Burrows, Nature (2000).

Core Collapse Supernova

- The star blows away its outer layers during the supernova explosion.
- The central core will collapse in a compact object of a few solar masses (**neutron star**).
- Pressure is so high that electrons and protons combine to form stable neutrons.

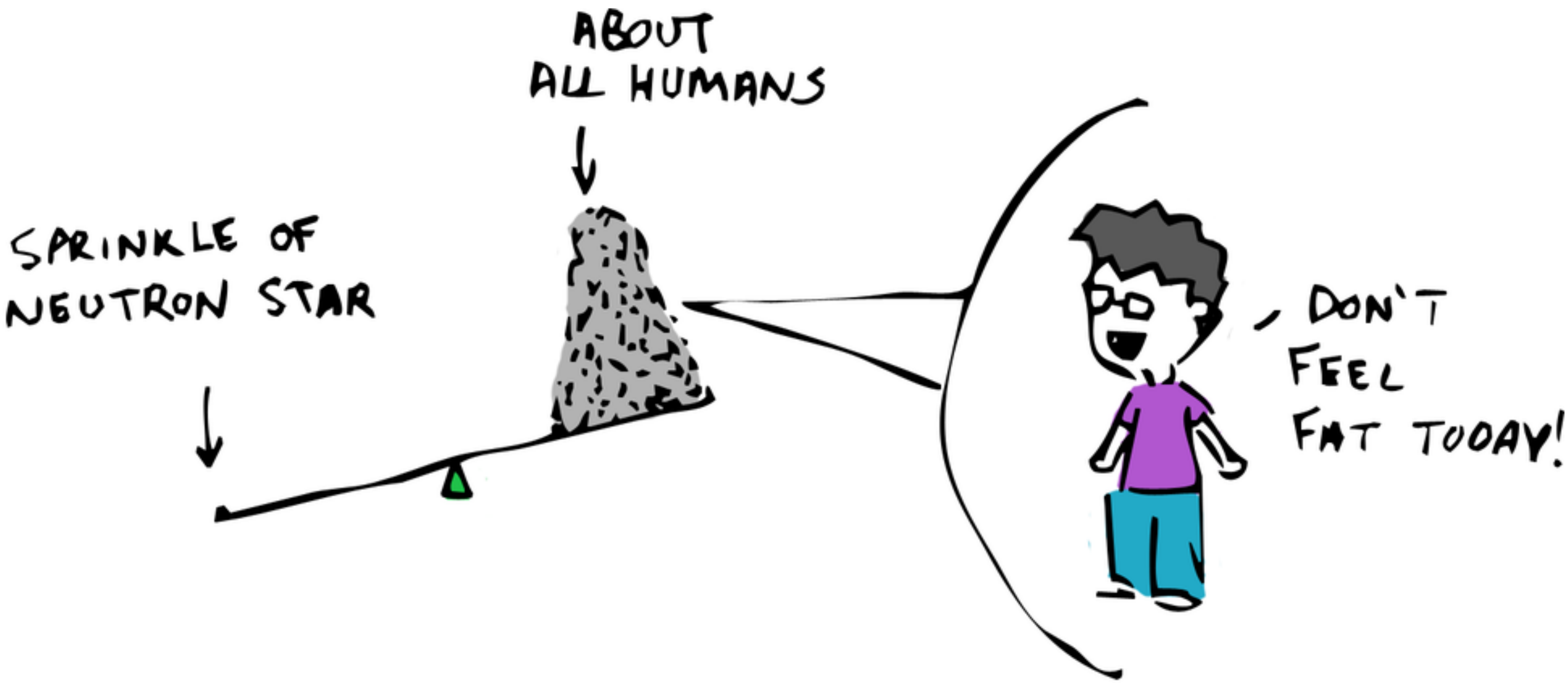


Figure credit: quora.com.

Numbers

Nucleon mean kinetic energy $\langle E_k \rangle \simeq \frac{1}{2}\frac{G_N M_{ns} m_N}{R_{ns}} \simeq 25\ \mathrm{MeV}$

with $M_{ns} \simeq 1.4\ M_{\odot}$ and $R_{ns} \simeq 15\ \mathrm{km}.$

Energy equipartition
$$T_\nu \simeq \frac{2}{3}\langle E_k \rangle$$

Gravitational energy released during neutron star collapse (Gauss theorem)

$$E_g \approx \frac{3}{5}\frac{G_N M_{ns}^2}{R_{ns}} = 1.7 \times 10^{59}\ \mathrm{MeV}$$

1% of E_g goes into kinetic explosion energy. Therefore, the expected number of neutrinos is

$$E_g/\tilde{T}_\nu \sim 10^{58}$$

Gravitational binding energy $\simeq 3 \times 10^{53}\ \mathrm{erg} \simeq 17\%\ M_{\mathrm{sun}} c^2$

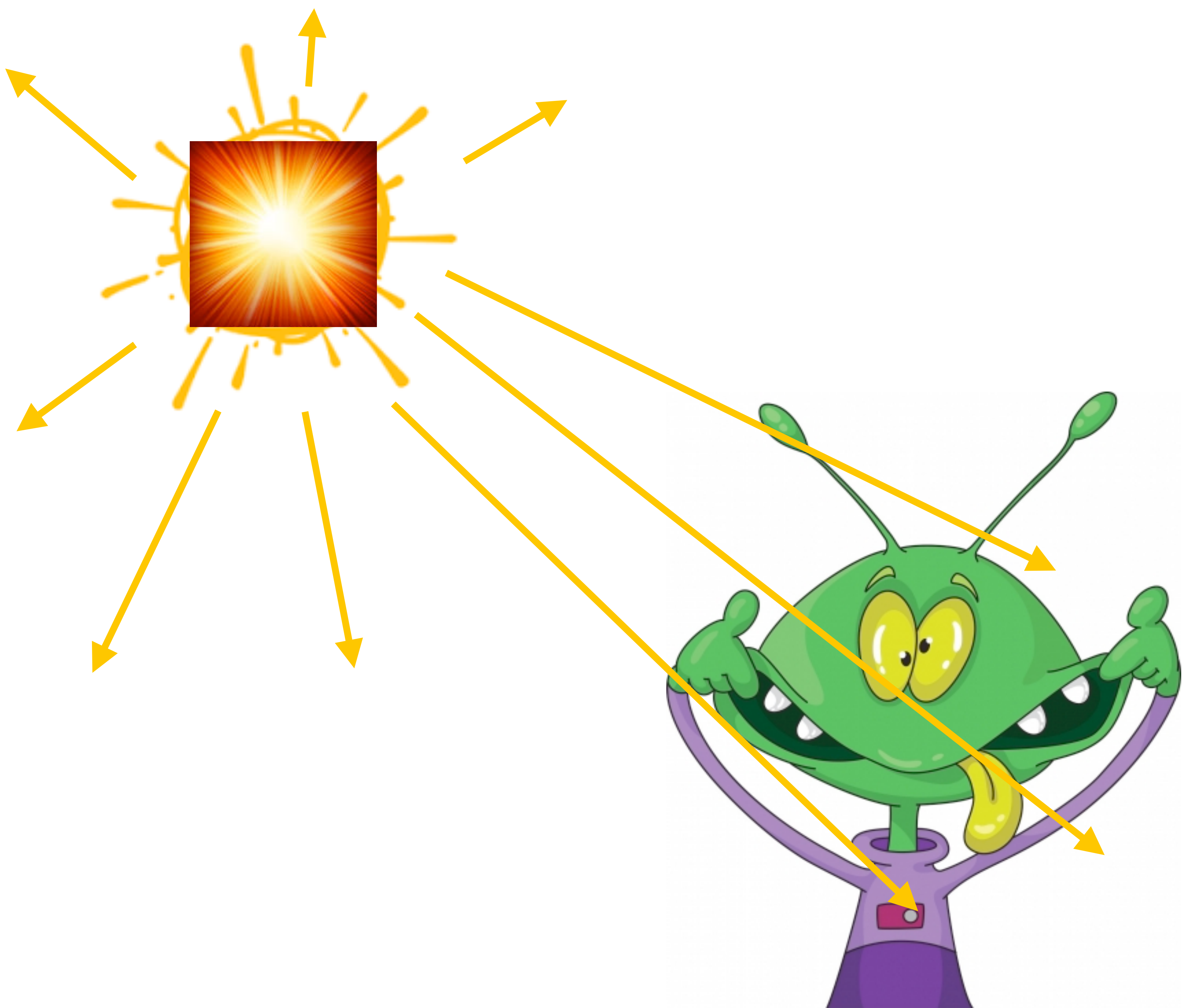
kinetic explosion energy

99% neutrinos

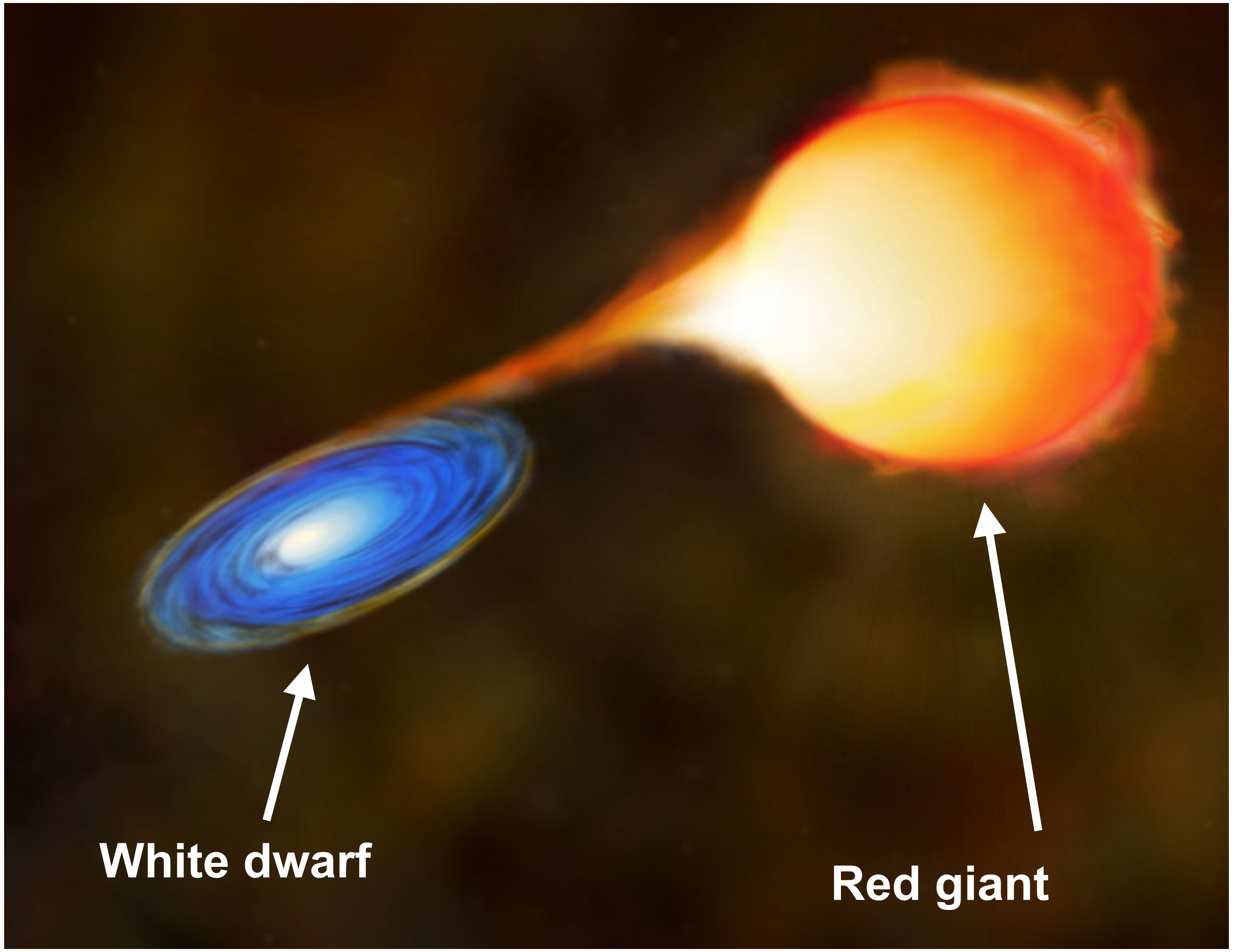
photons

$$L_\nu \simeq \frac{3 \times 10^{53}\ \mathrm{erg}}{3\ \mathrm{s}} \simeq 3 \times 10^{19} L_{\mathrm{sun}}$$

If the Sun were a supernova, aliens on Mars would be incinerated by neutrino radiation!



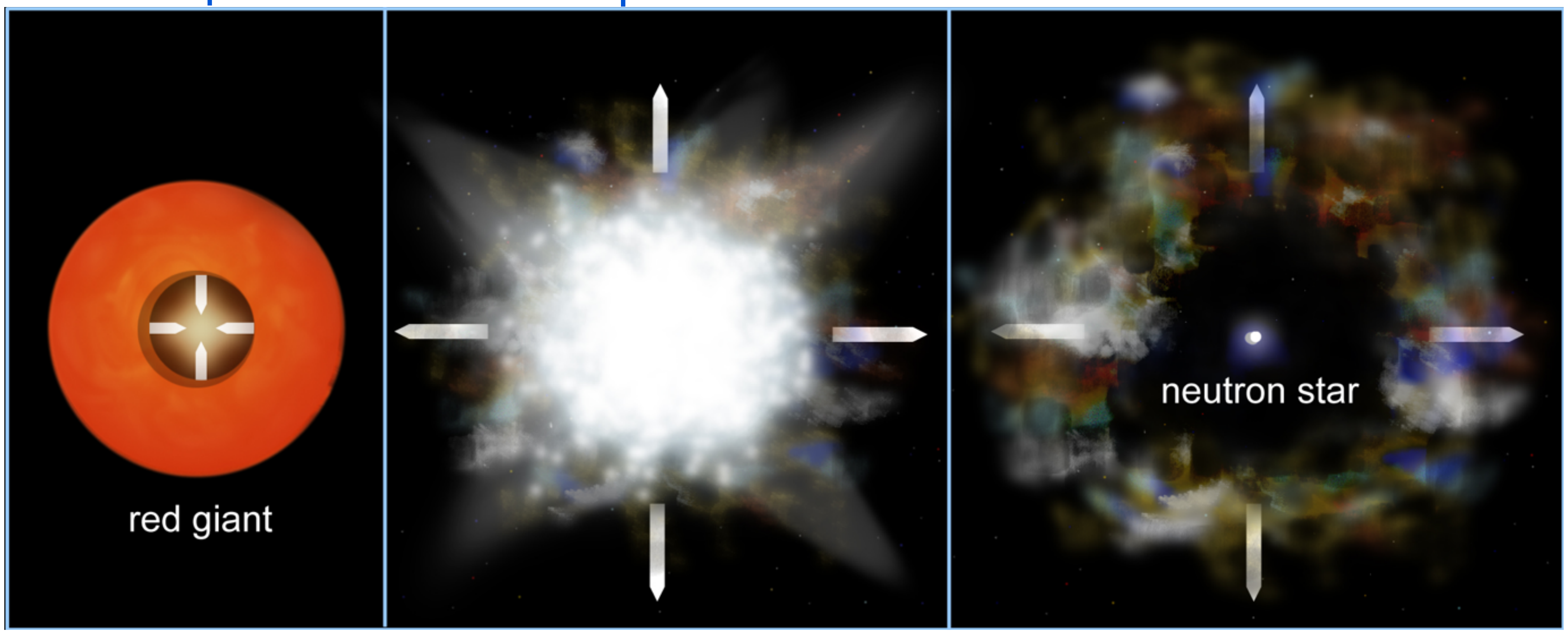
Alternative Path to Explosion



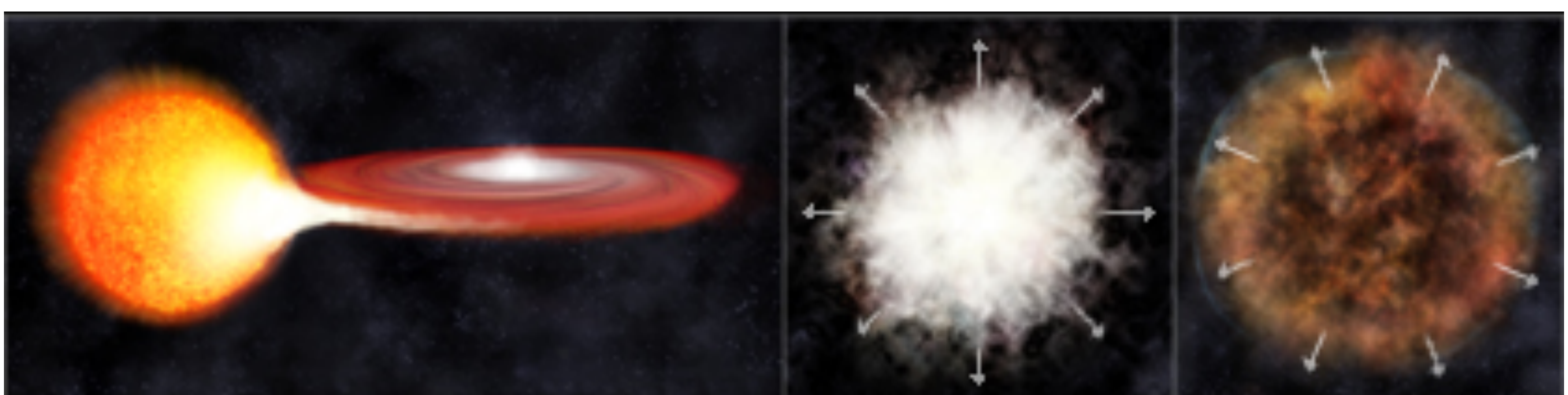
- Many stars live in binary systems.
- A white dwarf may accumulate material from a companion star (often a red giant).
- **Thermo-nuclear supernova explosion**.

Supernova Types

Core-collapse or type II supernova



Thermonuclear or type I supernova



Supernova Classification

Comparable energy release in photons: **3×10^{51} ergs**.

Spectral Type	**Type I**	**Core Collapse**
Physical Mechanism	Nuclear explosion of low-mass star	Core collapse of massive star
Compact remnant	None	Neutron star (black hole)
Local rate [Mpc^-3 yr^-1]	~ 0.00002	~ 0.0002
Neutrinos	Almost none	A lot

SN 1987A

SN 1987A occurred in the Large Magellanic Cloud (50 kpc).

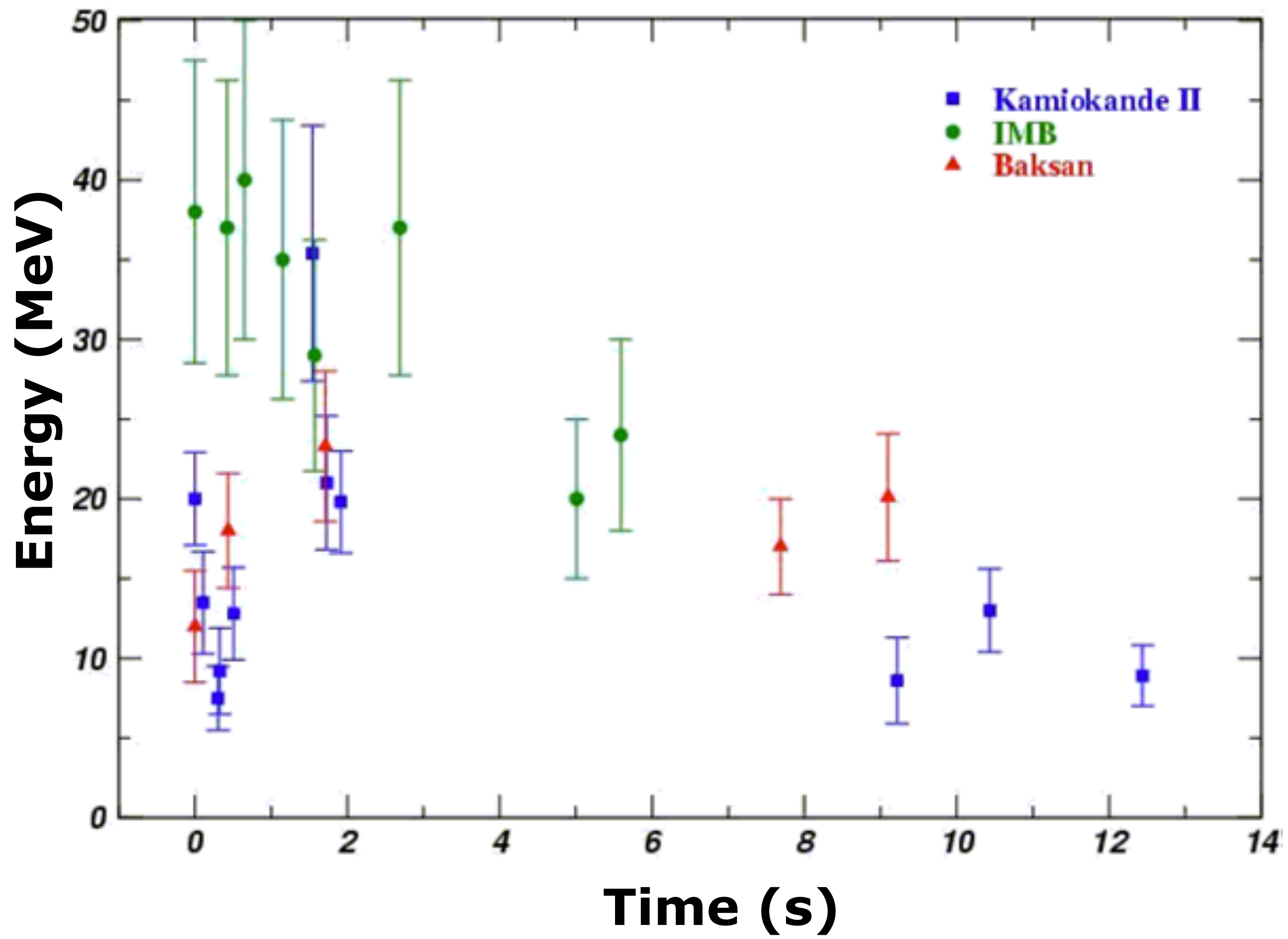
Sanduleak -69° 202

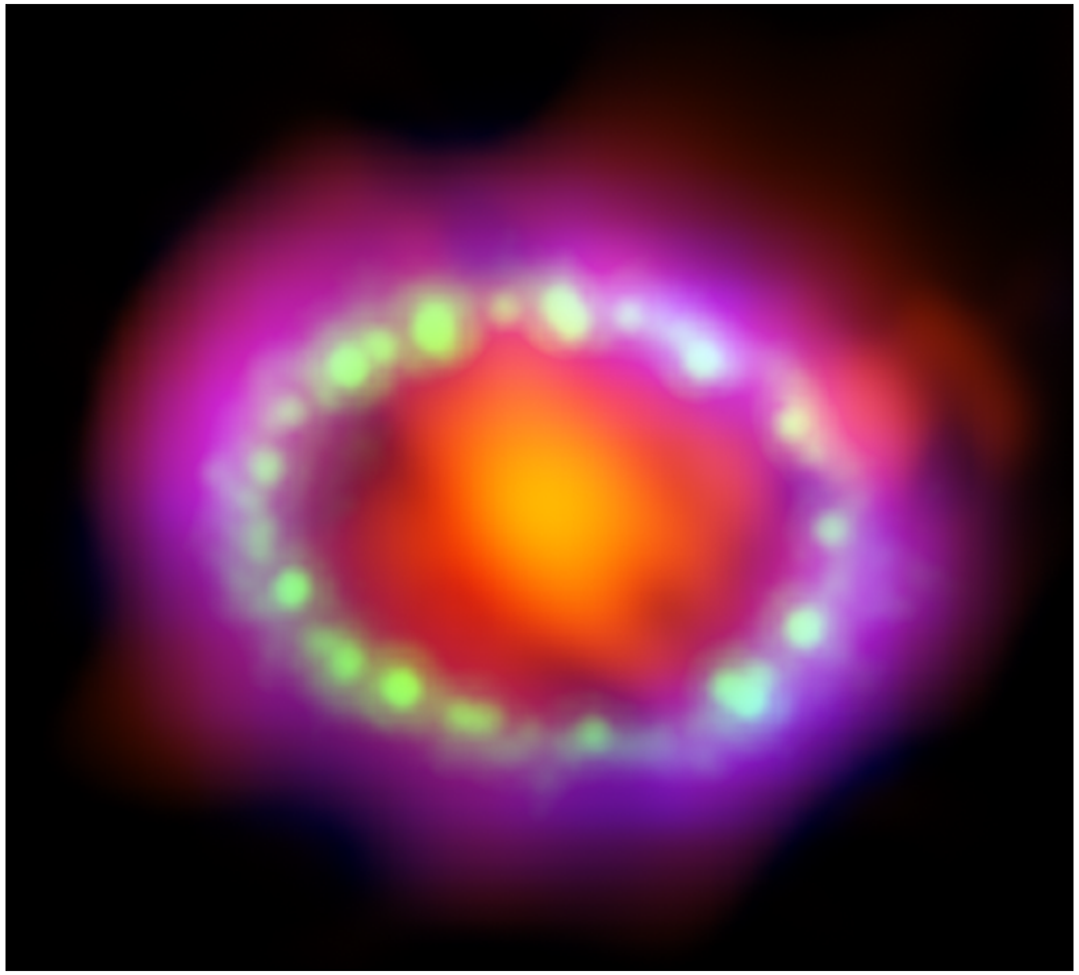
SN 1987A (Feb. 23, 1987)

First and only supernova observed in neutrinos.
First verification of stellar evolution mechanism.

SN 1987A

Few detectors were able to detect SN 1987A neutrinos.





Feb. 24, 1987: “Did you hear what happened today? 10^{58} neutrinos! All in one go!”

From L. Pontecorvo’s memories (F. Close).

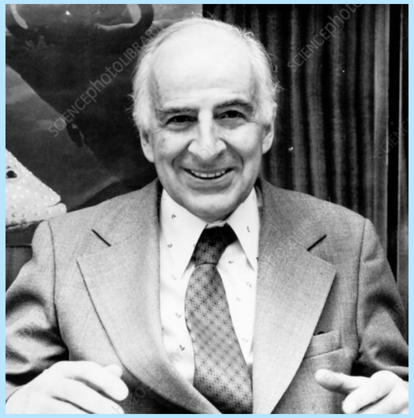


Image credits: NASA, CERNCOURIER.

Historical Supernovae

Table 1 Supernovae that have exploded in our Galaxy and the Large Magellanic Cloud within the last millennium

Supernova	Year (AD)	Distance (kpc)	Peak visual magnitude
SN1006	1006	2.0	–9.0
Crab	1054	2.2	–4.0
SN1181	1181	8.0	?
RX J0852-4642	~1300	~0.2	?
Tycho	1572	7.0	–4.0
Kepler	1604	10.0	–3.0
Cas A	~1680	3.4	~6.0?
SN1987A	1987	50 ± 5	3.0

These 'historical' supernovae are only a fraction of the total, because the majority were shrouded from view by the dust that pervades the Milky Way. Thus, it is estimated that this historical cohort represents only about 20% of the galactic supernovae that exploded since AD1000. Included are SN1987A, which exploded not in the Milky Way but in the Large Magellanic Cloud (one of its nearby satellite galaxies), RX J0852-4642 (ref. 77, ref. 11), a supernova remnant whose recent (~AD1300) and very nearby birth went unrecorded, perhaps because it resides in the Southern Hemisphere (but in fact for reasons that are as yet unknown), and Cas A, a supernova remnant that was born in historical times, but whose fiery birth was accompanied by a muted visual display that may have been recorded only in the ambiguous notes of the seventeenth-century astronomer John Flamsteed (ref. 78). The distances and peak visual magnitudes quoted are guesses at best, except for SN1987A. Astronomical magnitudes are logarithmic and are given by the formula $M_V = -2.5\log_{10}(\text{brightness}) + \text{constant}$. Hence, every factor of ten increase in brightness represents a decrease in magnitude by 2.5. For comparison, the Moon is near –12 magnitudes, Venus at peak is –4.4 magnitudes, and good eyes can see down to about +6 magnitudes.

A. Burrows, Nature (2000).

The Next Supernova (SN 2XXXA)

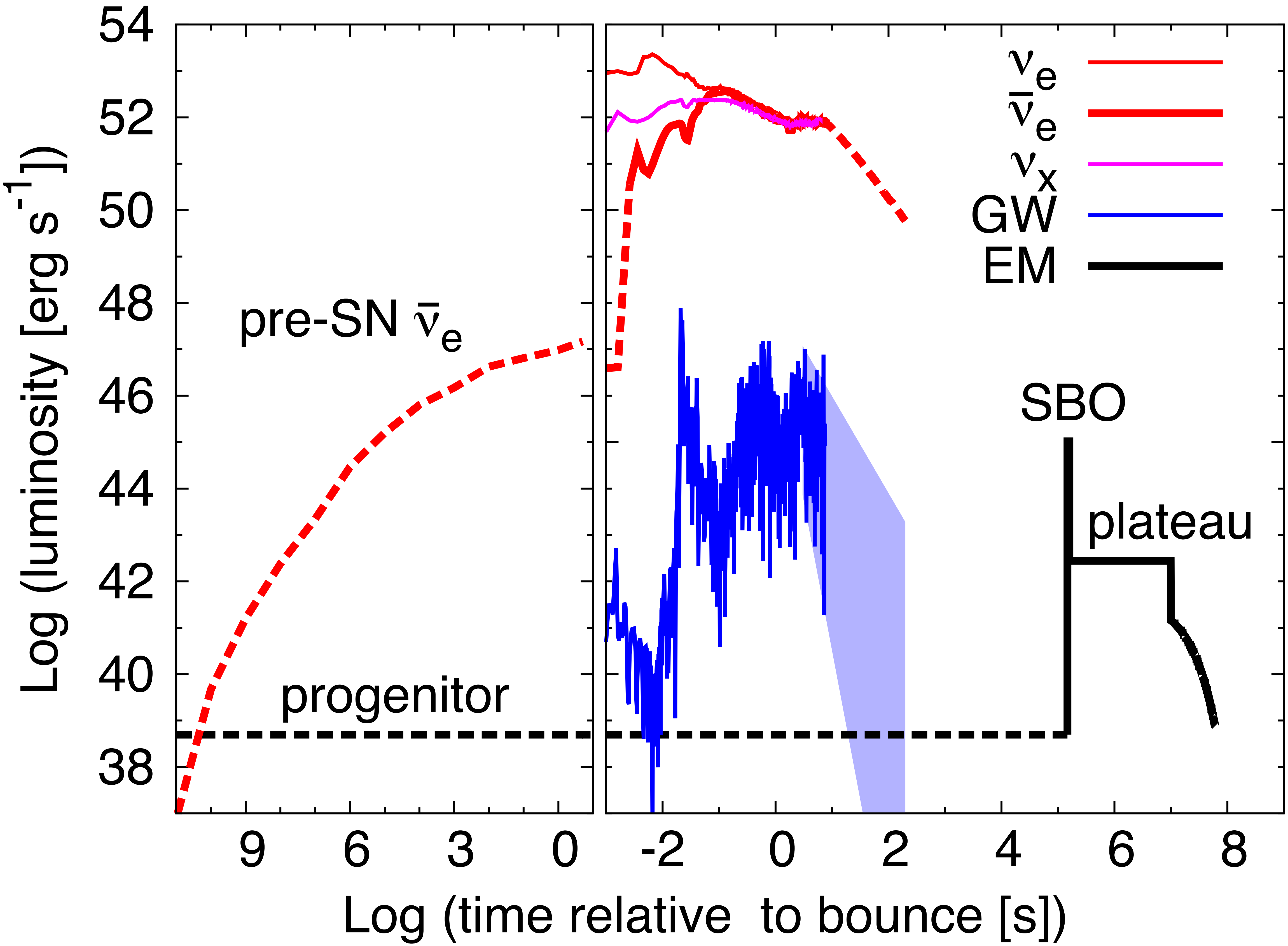
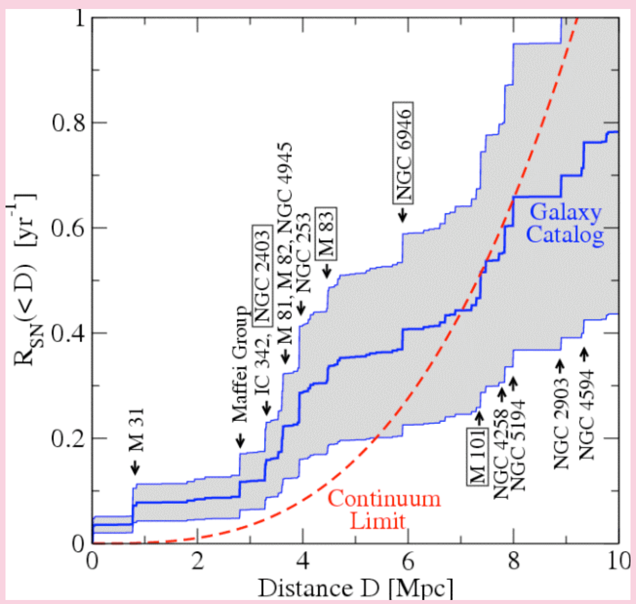


Figure from Nakamura et al., MNRAS (2016).

Detection Frontiers

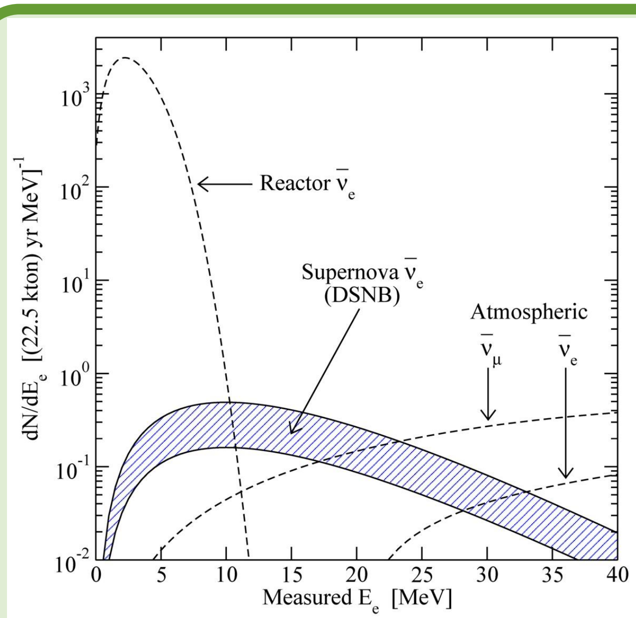
Supernova in our Galaxy (one burst per 40 years).

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.

Why Neutrinos from Core-Collapse Supernovae?

- Neutrino luminosity is 100 times its optical luminosity.

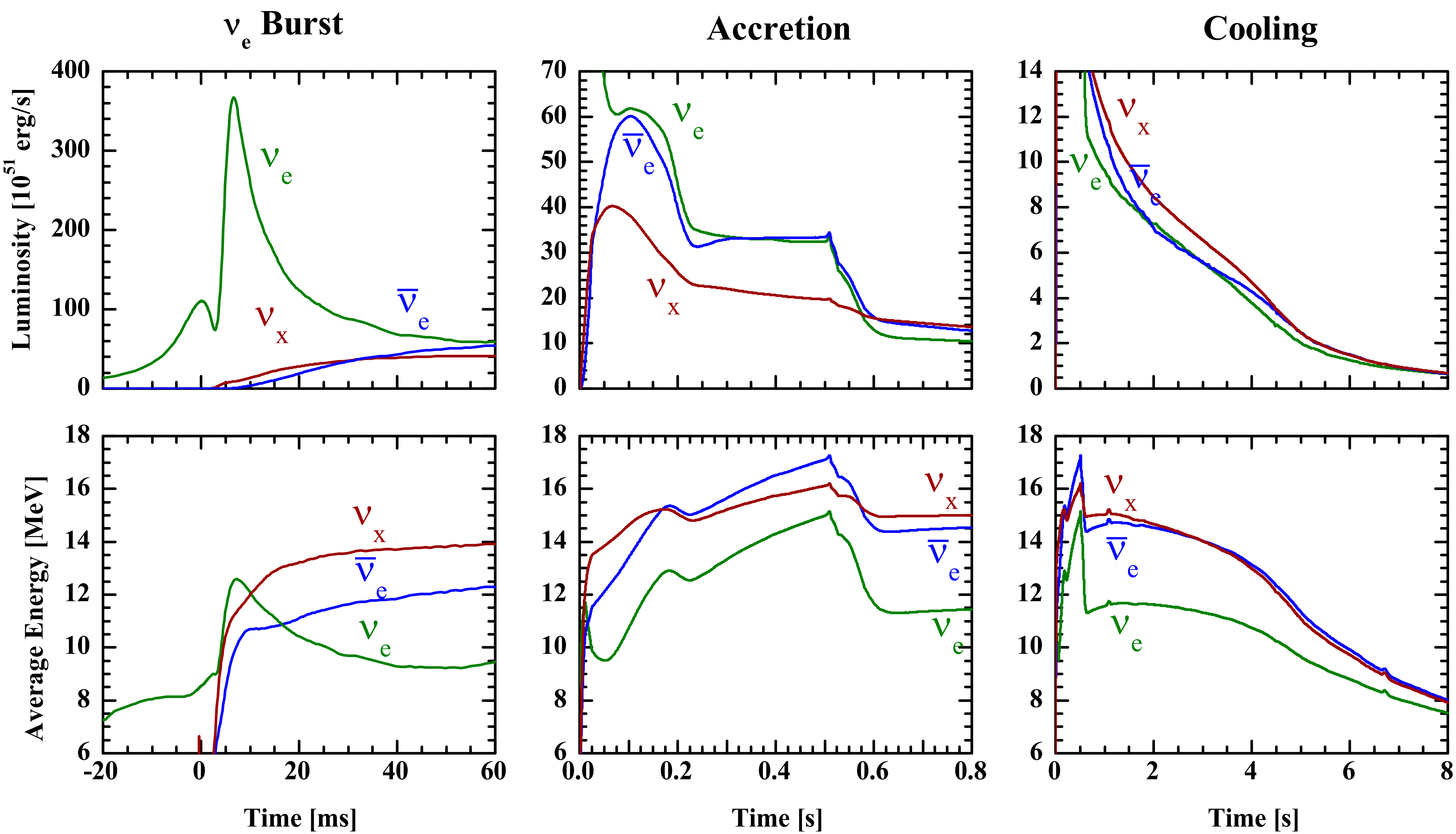
- Neutrino signal emerges from the core promptly.
  Photons may take hours to days to emerge from the stellar envelope.

- Supernovae would not explode without neutrinos.
  Elements could not be formed.

- Neutrinos provide information inaccessible to other kinds of astronomy.

- An optical supernova display may be never seen for a given core collapse.

Neutrino Signal



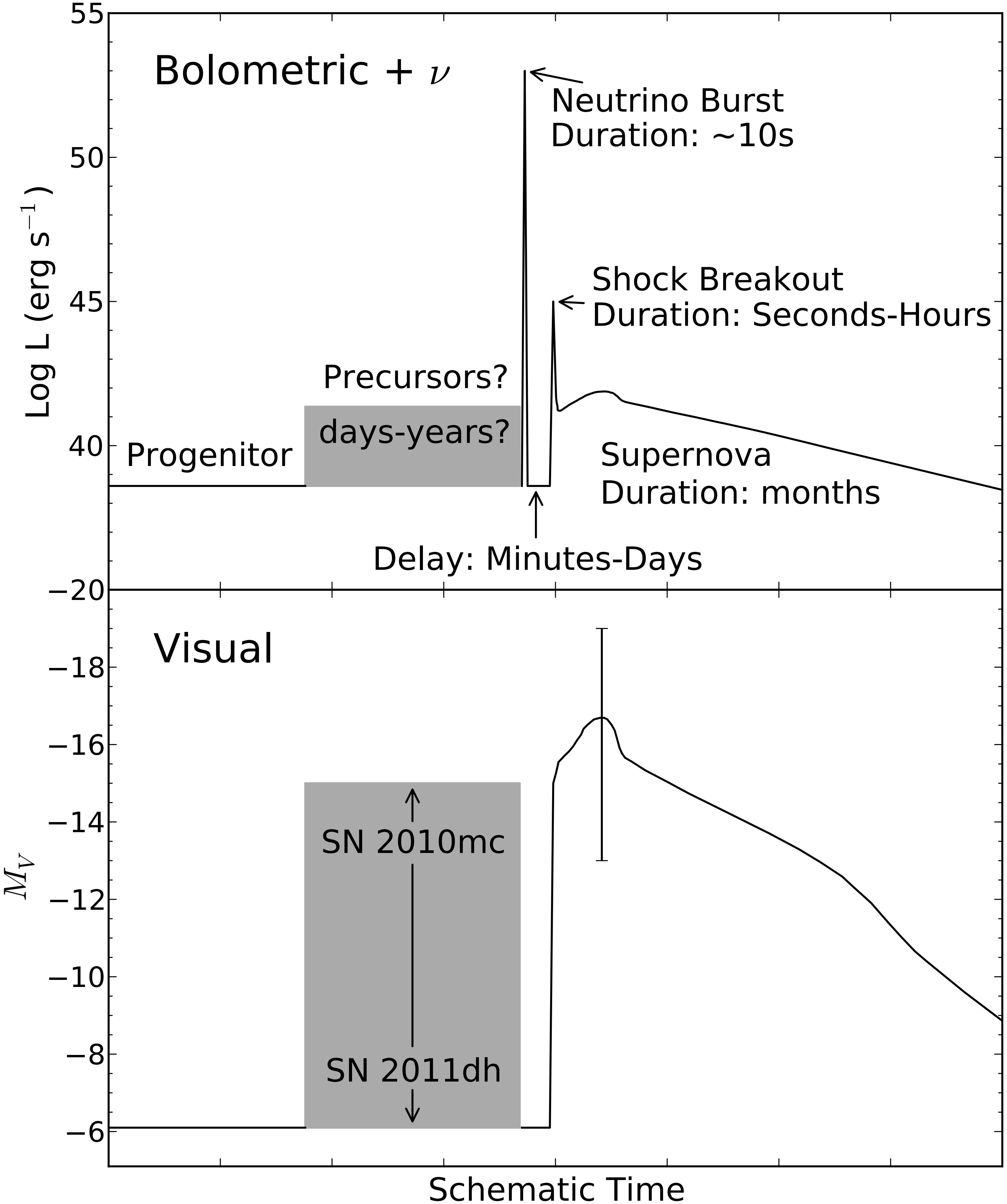
Large ν_e luminosity peak

Large fluxes.
Large $\overset{(-)}{\nu}_e - \overset{(-)}{\nu}_x$ flux difference.

Smaller fluxes.
Small $\overset{(-)}{\nu}_e - \overset{(-)}{\nu}_x$ flux difference.

Figure: 1D spherically symmetric SN simulation (M=27 M_{sun}), Garching group.

Neutrinos & EM Radiation



Neutrinos could allow early EM detection of SN signal.

Image credit: Adams et al., ApJ (2013).

Supernova Warning System

SuperNova Early Warning System (SNEWS 2.0)

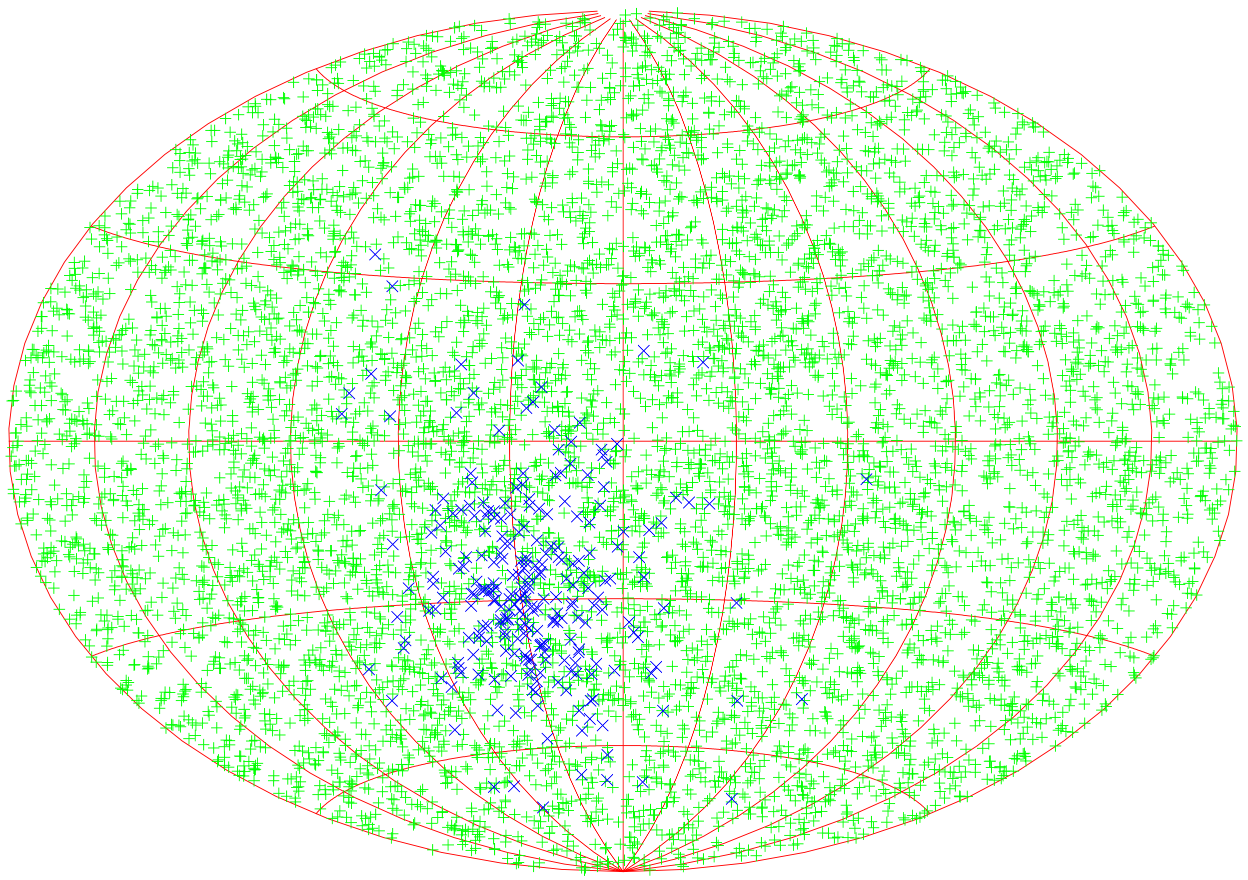
Concidence Sever (@ BNL)

E-mail alert
ATel alerts, LIGO, GCN

Shock breakout arrives mins to hours after neutrino signal.

Al Kharusi et al., arXiv: 2011.00035. SNEWS: http://snews.bnl.gov

Neutrinos Tell Us Where To Look



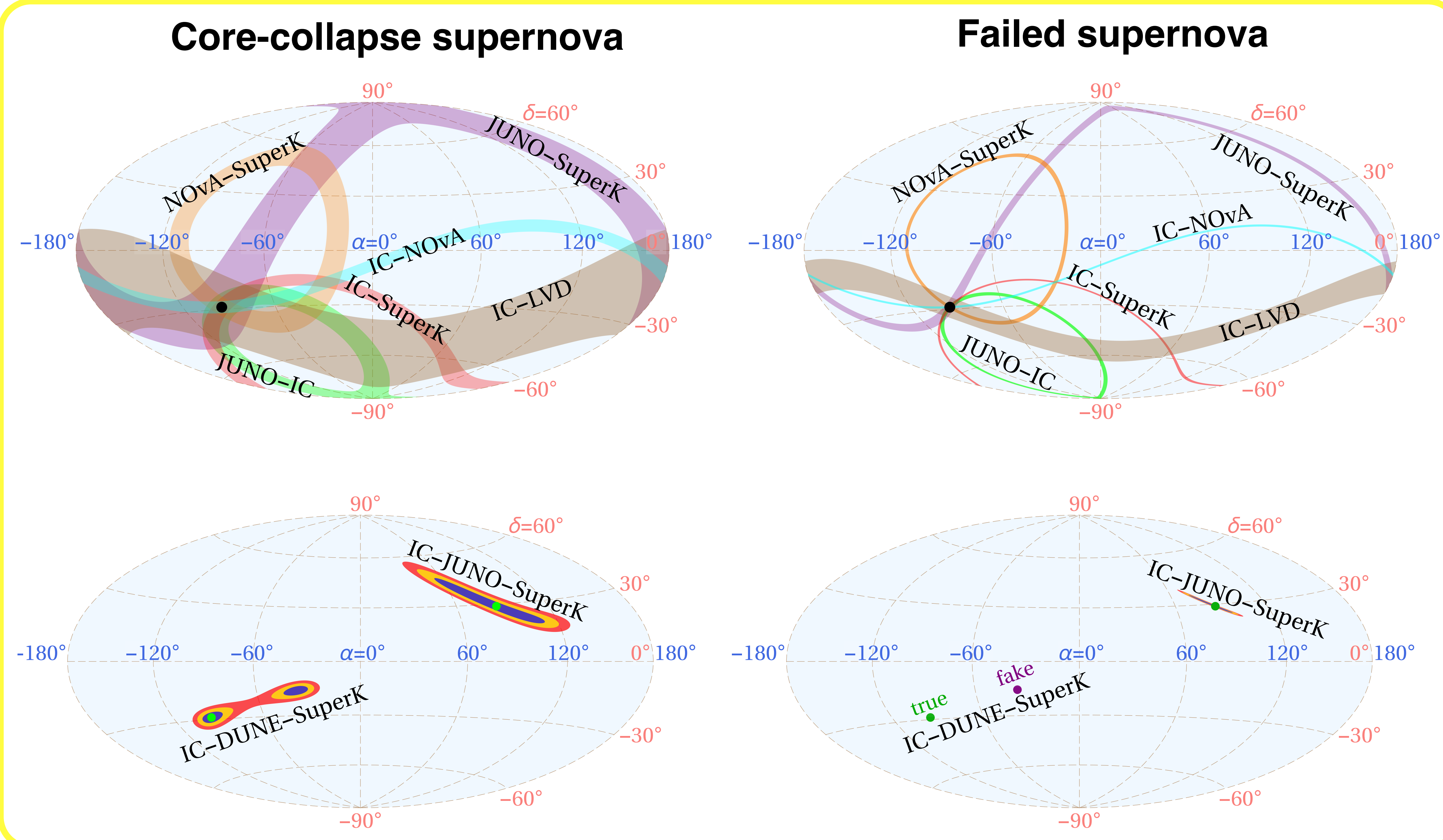
$$\nu + e^- \to \nu + e^-$$

	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, PRD (1999). Tomas et al., PRD (2003). Fisher et al., JCAP (2015).

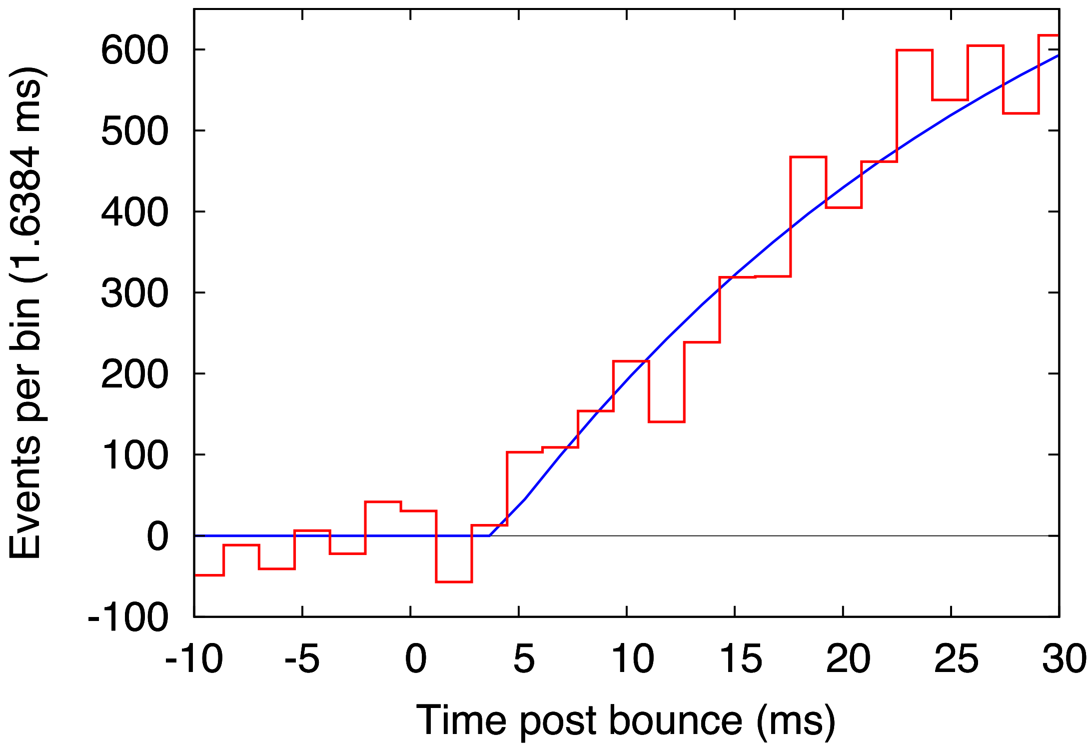
Triangulation with Neutrinos



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

Brdar, Lindner, Xu, JCAP (2018). Linzer and Scholberg, PRD (2019). Muehlbeier et al., PRD (2013).

Neutrino Timing for Gravitational Waves

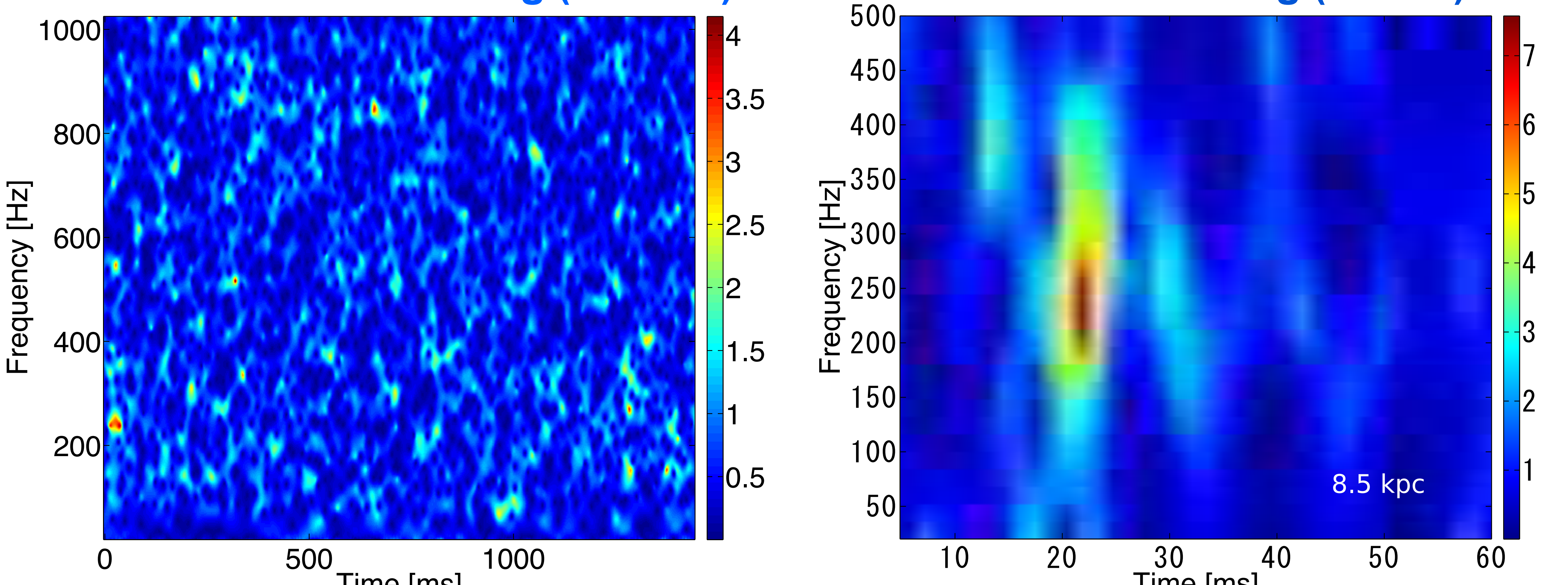


Probe core bounce time with neutrinos.

Help timing for gravitational wave detection.

Without neutrino timing (S/N~3.5)

With neutrino timing (S/N ~7)



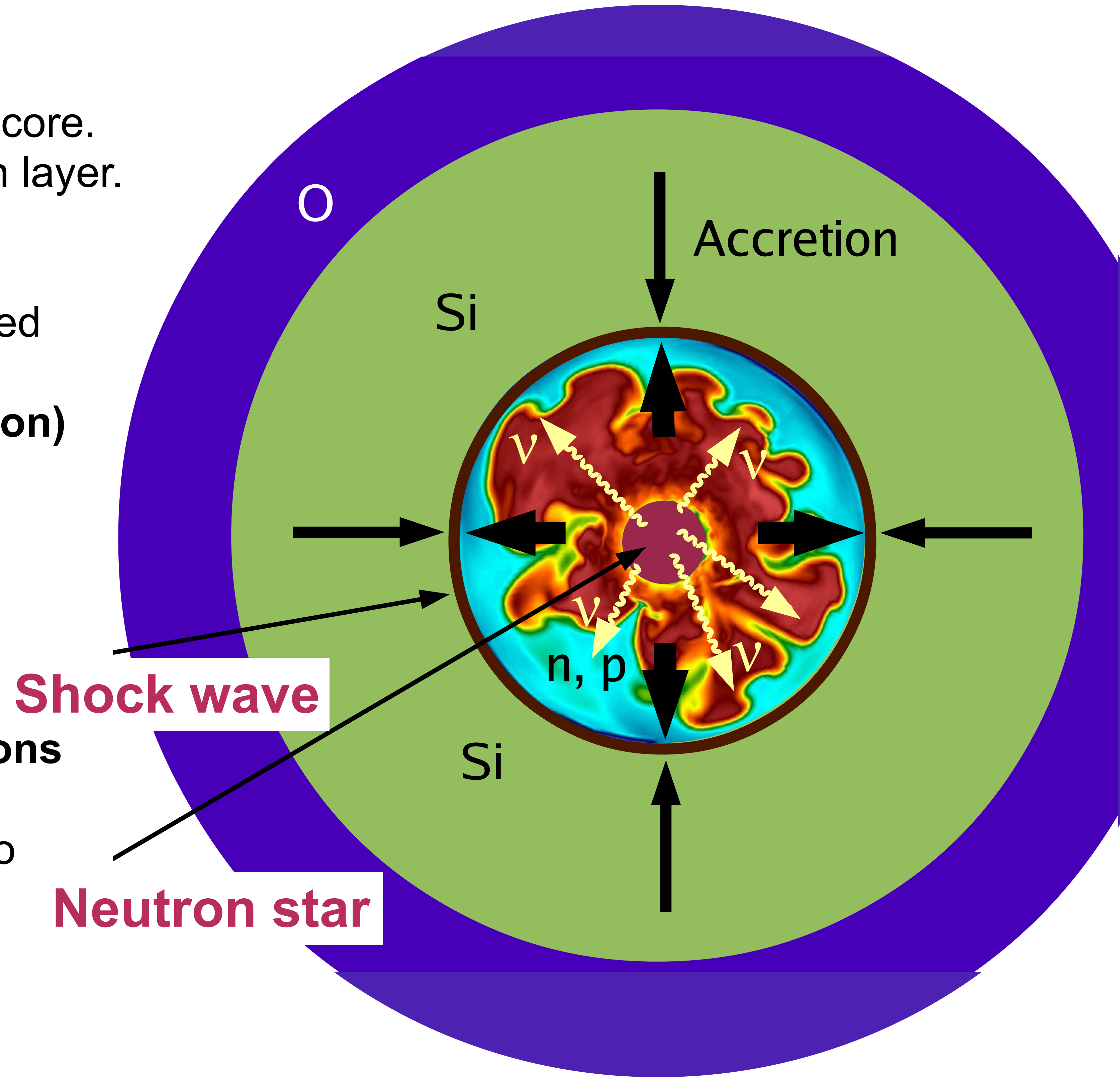
Pagliaroli et al., PRL (2009), Halzen & Raffelt PRD (2009). Nakamura et al., MNRAS (2016).

Supernova Explosion Mechanism

★ Shock wave forms within the iron core.
It dissipates energy dissociating iron layer.

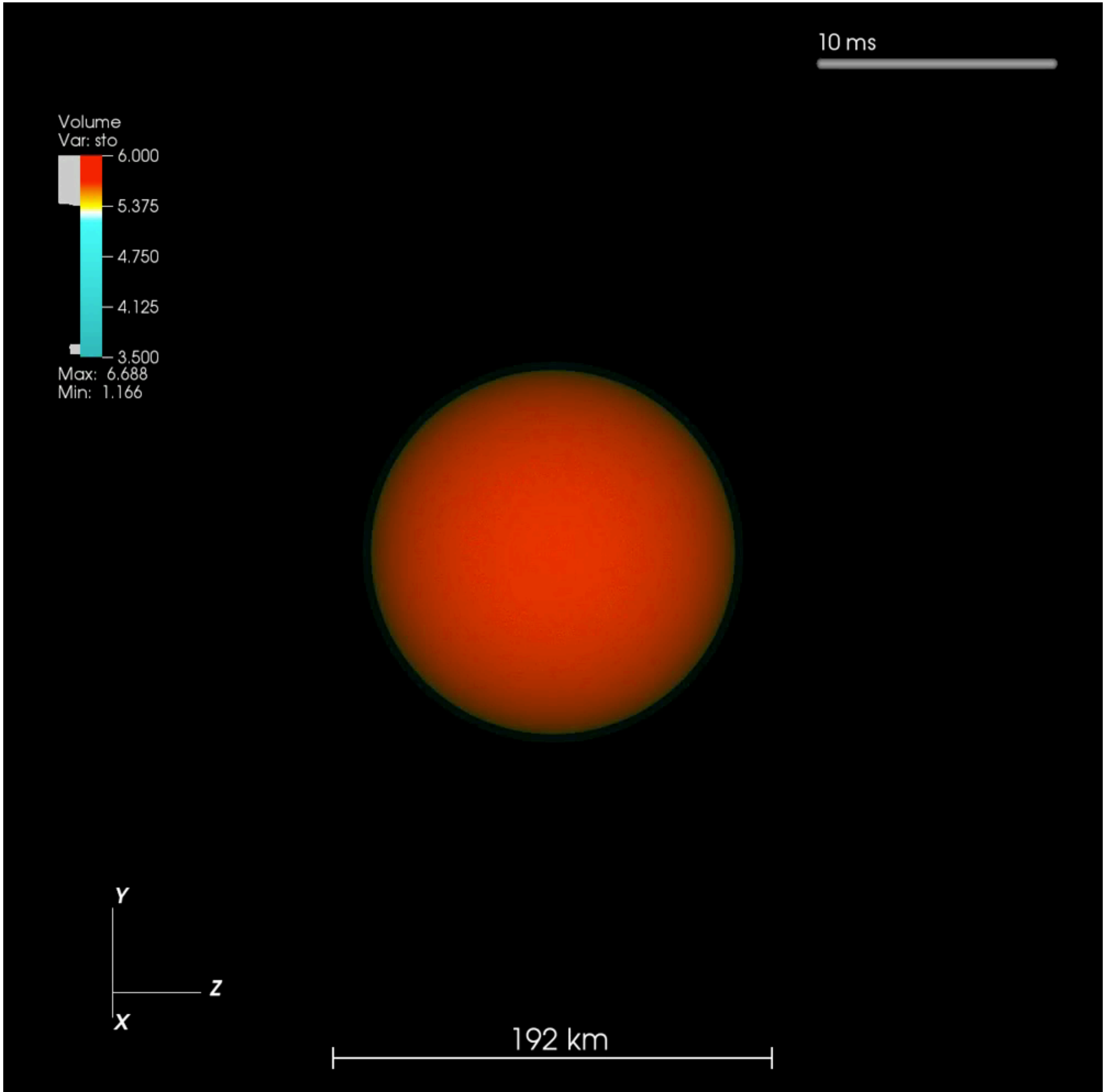
★ **Neutrinos** provide energy to stalled shock wave to start re-expansion.
(Delayed Neutrino-Driven Explosion)

★ **Convection** and **shock oscillations** (standing accretion shock instability, **SASI**) enhance efficiency of neutrino heating and revive the shock.



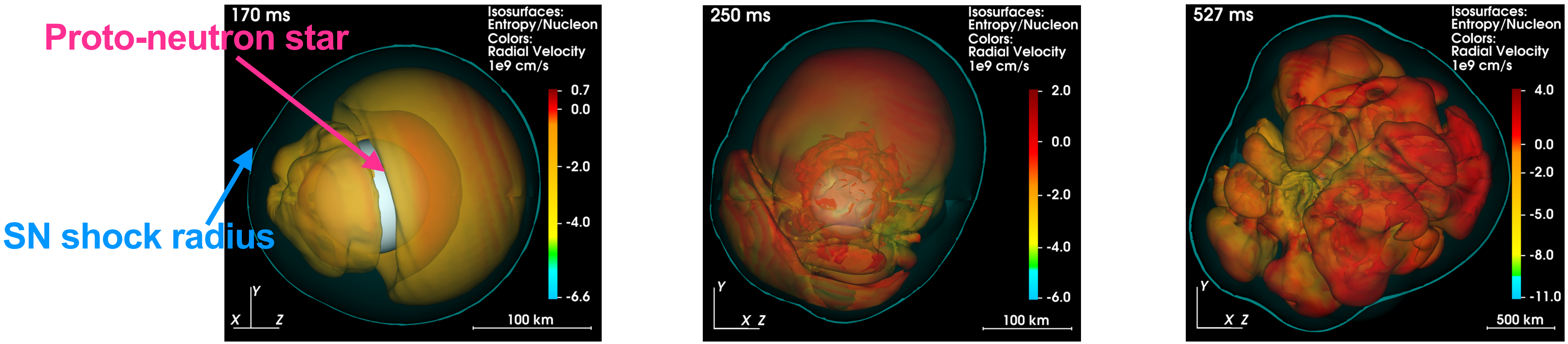
Recent reviews: Janka (2017). Mirizzi, Tamborra et al. (2016).

20 M_{sun} Supernova Simulation



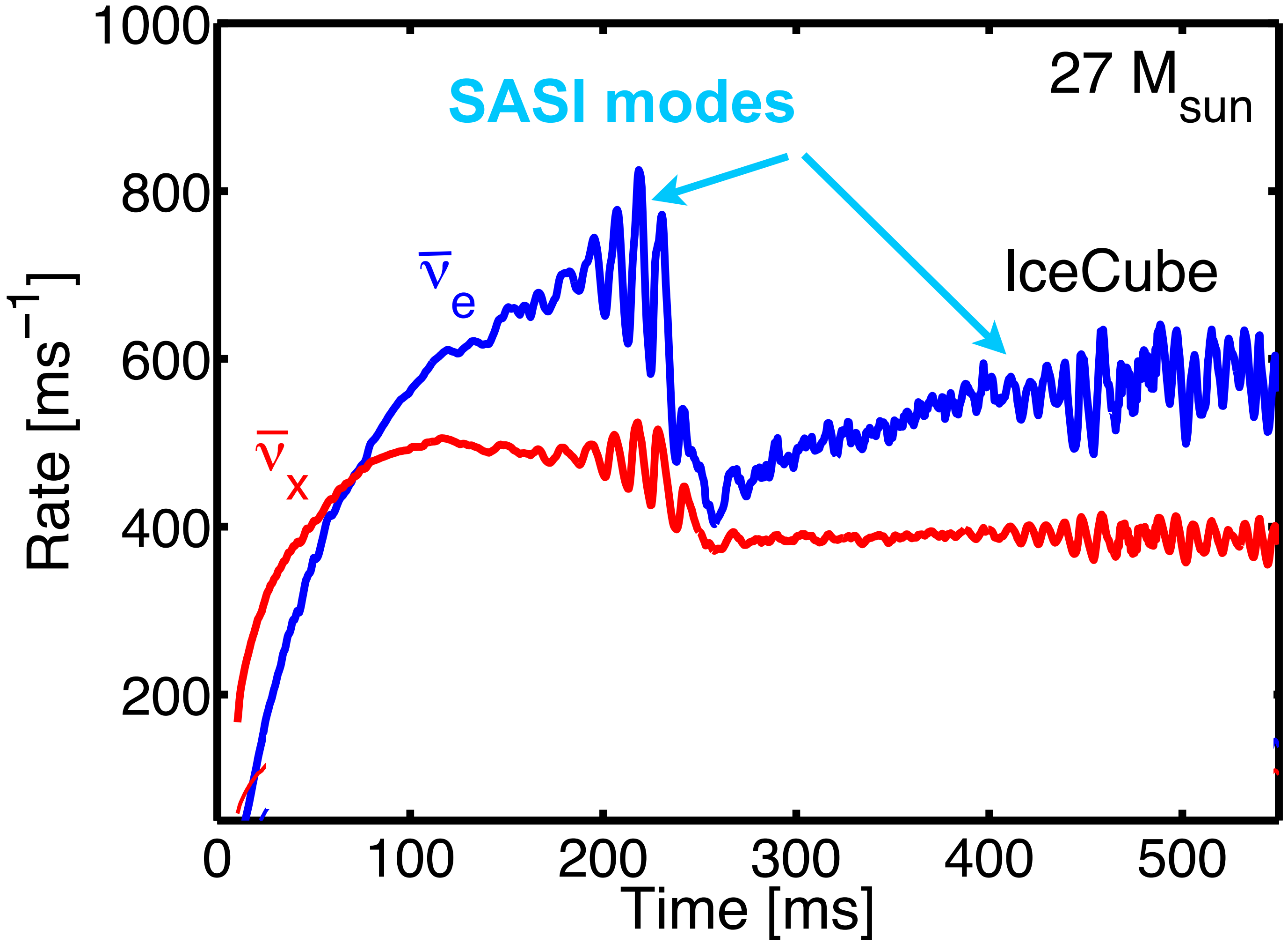
Supernova Simulations

t=170 ms t=250 ms t=520 ms

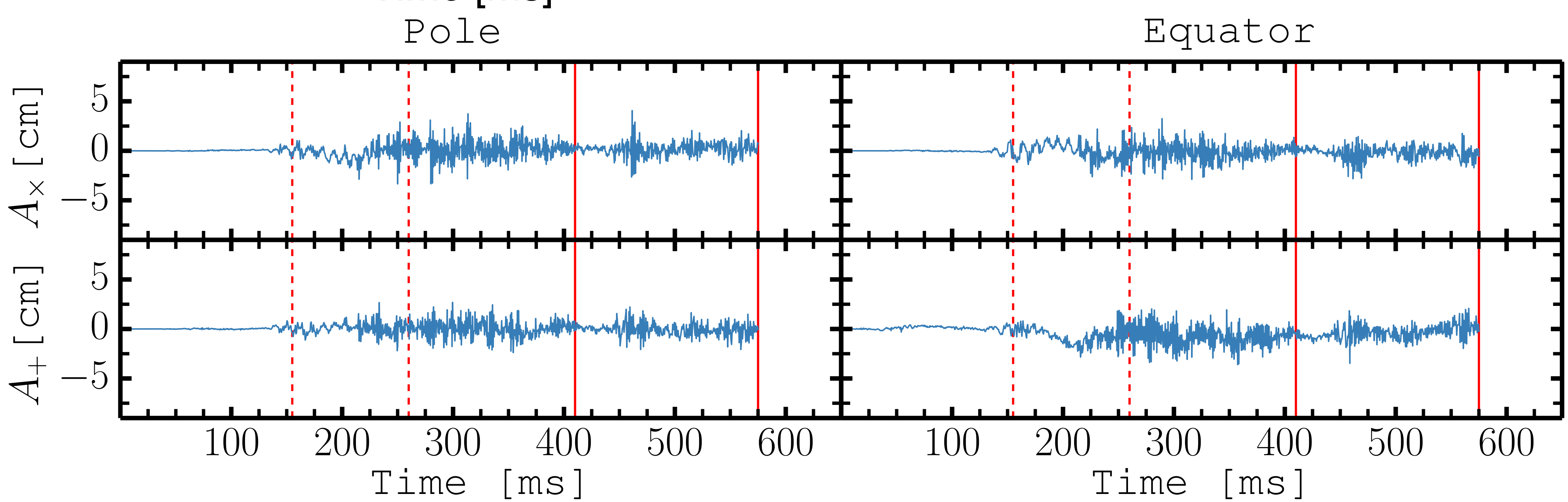


- SN simulations: Benchmark models to test neutrino-driven mechanism.
- Long-term 3D SN simulations not yet available. 3D modeling yet to be refined.

Standing Accretion Shock Instability

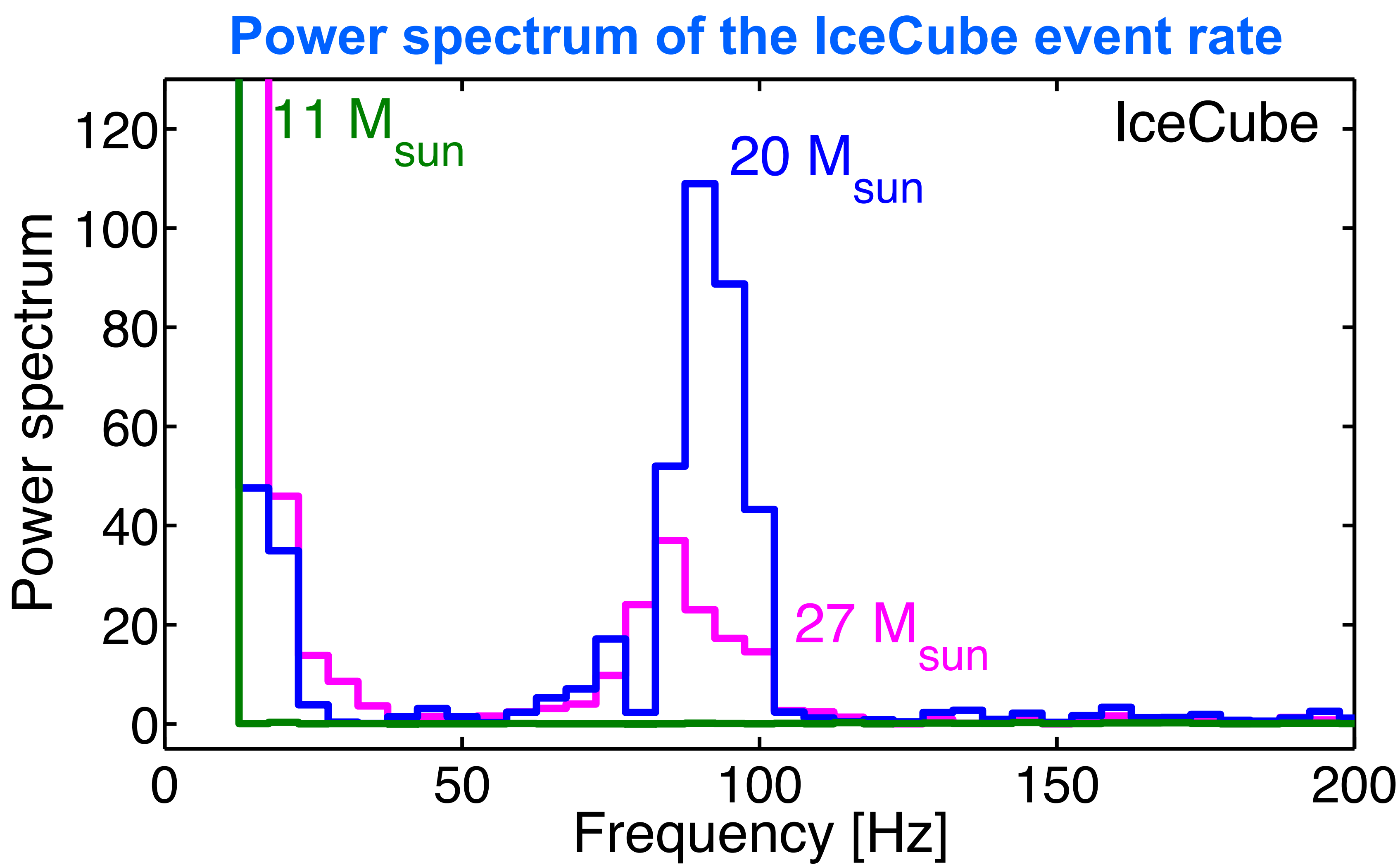


SASI imprints visible in neutrinos and gravitational waves.



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

Standing Accretion Shock Instability

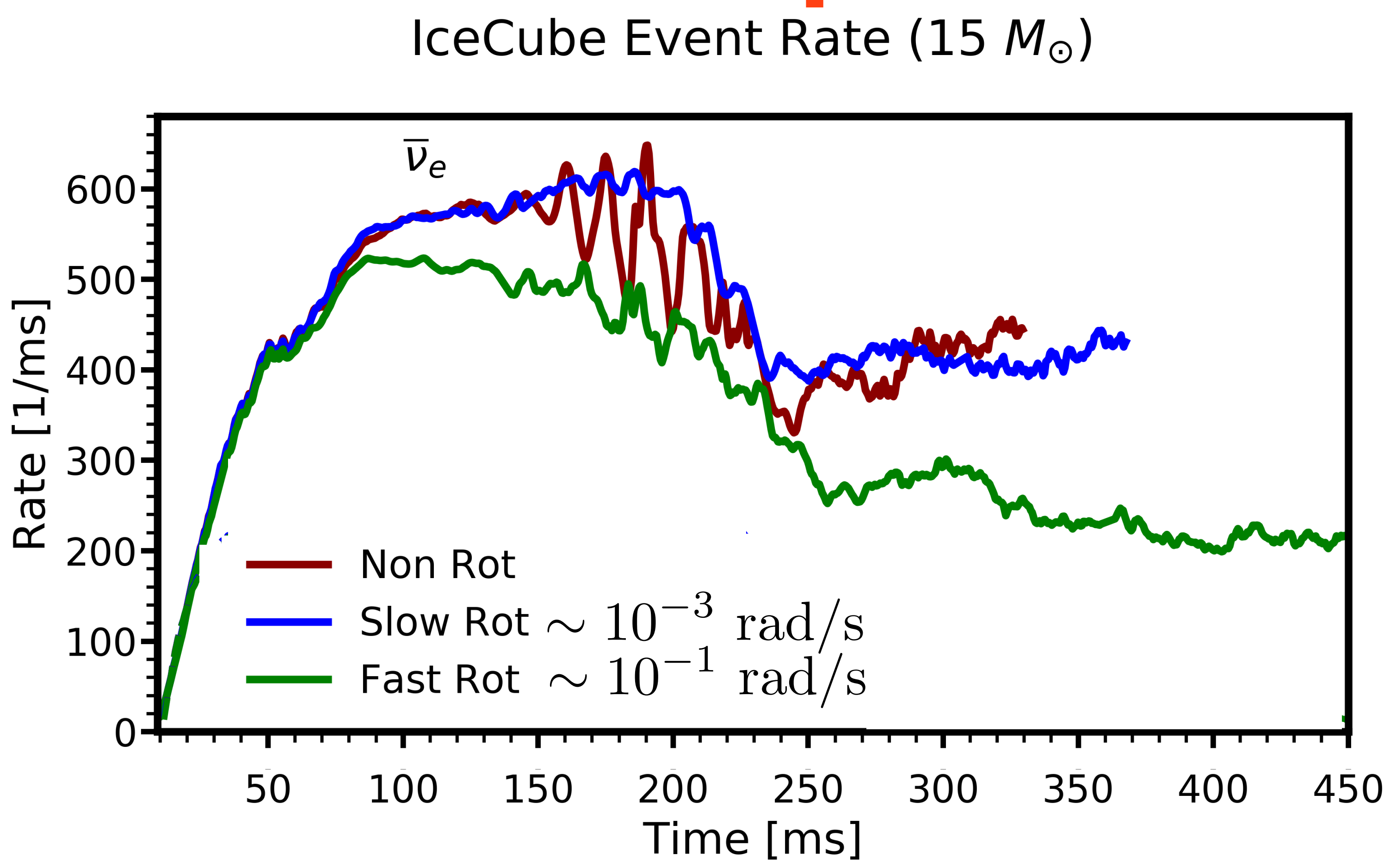


A peak appears in the power spectrum at the SASI frequency.

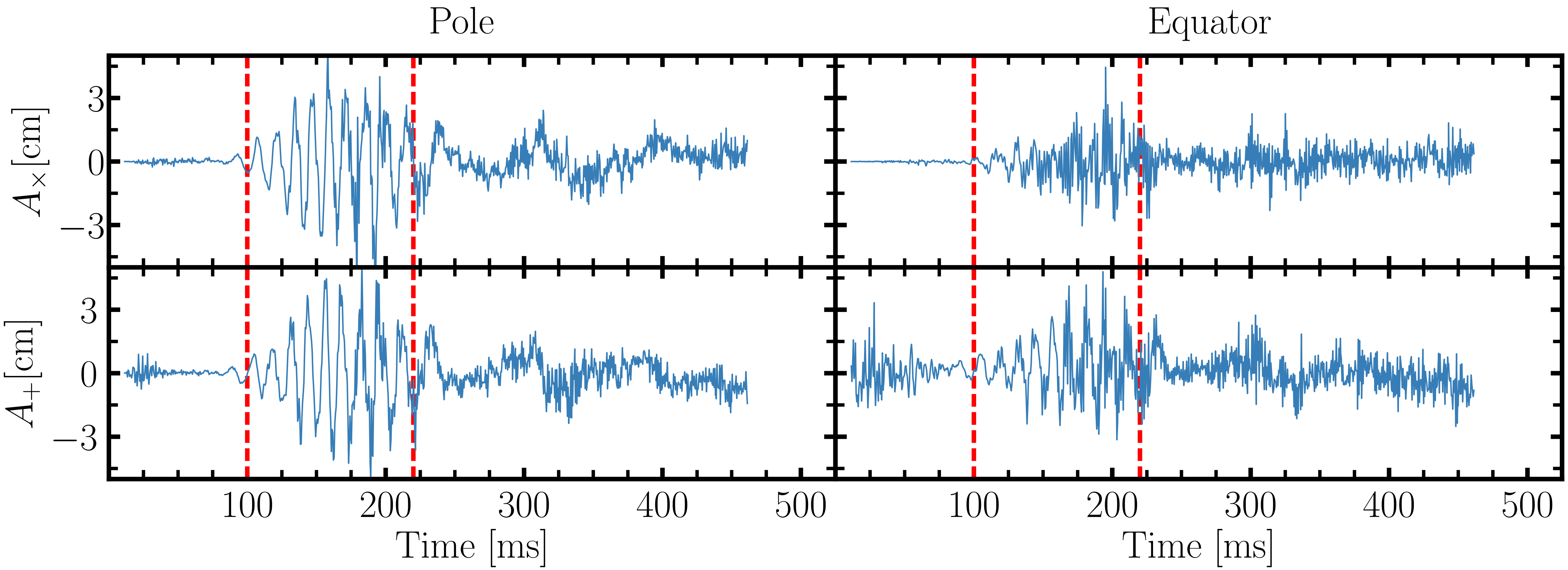
$$T_{\mathrm{SASI}} = 19\,\mathrm{ms}\left(\frac{r_{\mathrm{sh}}}{100\,\mathrm{km}}\right)^{3/2}\ln\left(\frac{r_{\mathrm{sh}}}{r_{\mathrm{PNS}}}\right).$$

Tamborra et al., PRL (2013). Mueller & Janka, ApJ (2014). Foglizzo et al., ApJ (2007).

Supernova Rotation



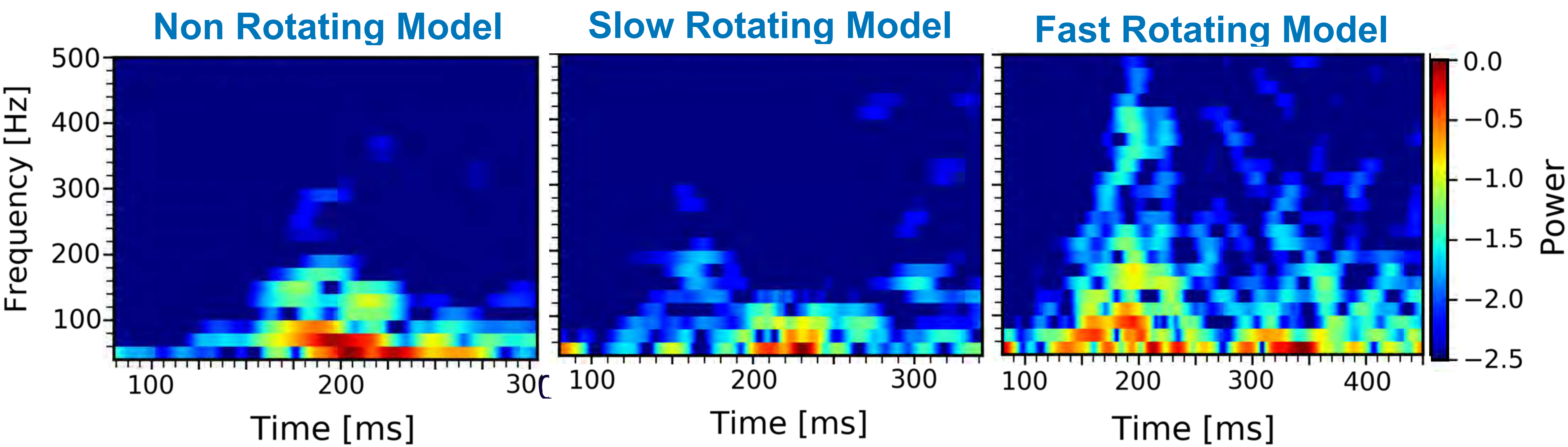
Rotation smears SASI modulations in neutrino signal.



Walk, Tamborra et al., PRD (2018). Walk, Tamborra et al., PRD (2019). Andresen et al., MNRAS (2019).

Supernova Rotation

Spectrogram of the IceCube event rate



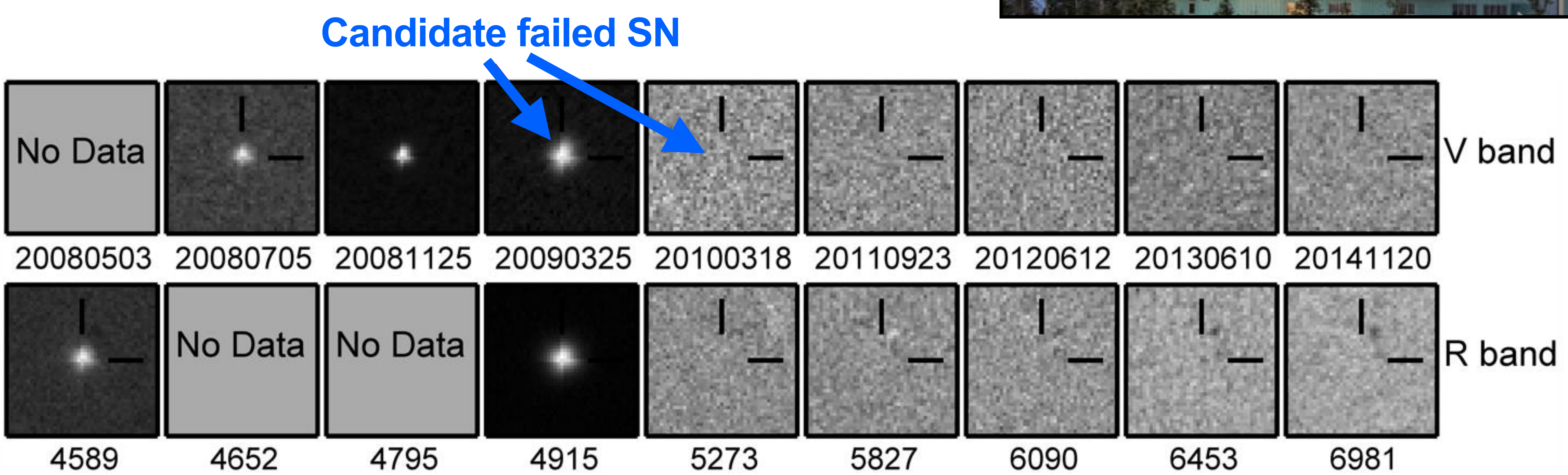
High frequency modulations appear as the rotational speed increases.

Walk, Tamborra, Janka, Summa, PRD (2018). Walk, Tamborra, Janka, Summa, PRD (2019).

A Survey About Nothing

- Search for disappearance of red supergiants (27 galaxies within 10 Mpc with Large Binocular Telescope).

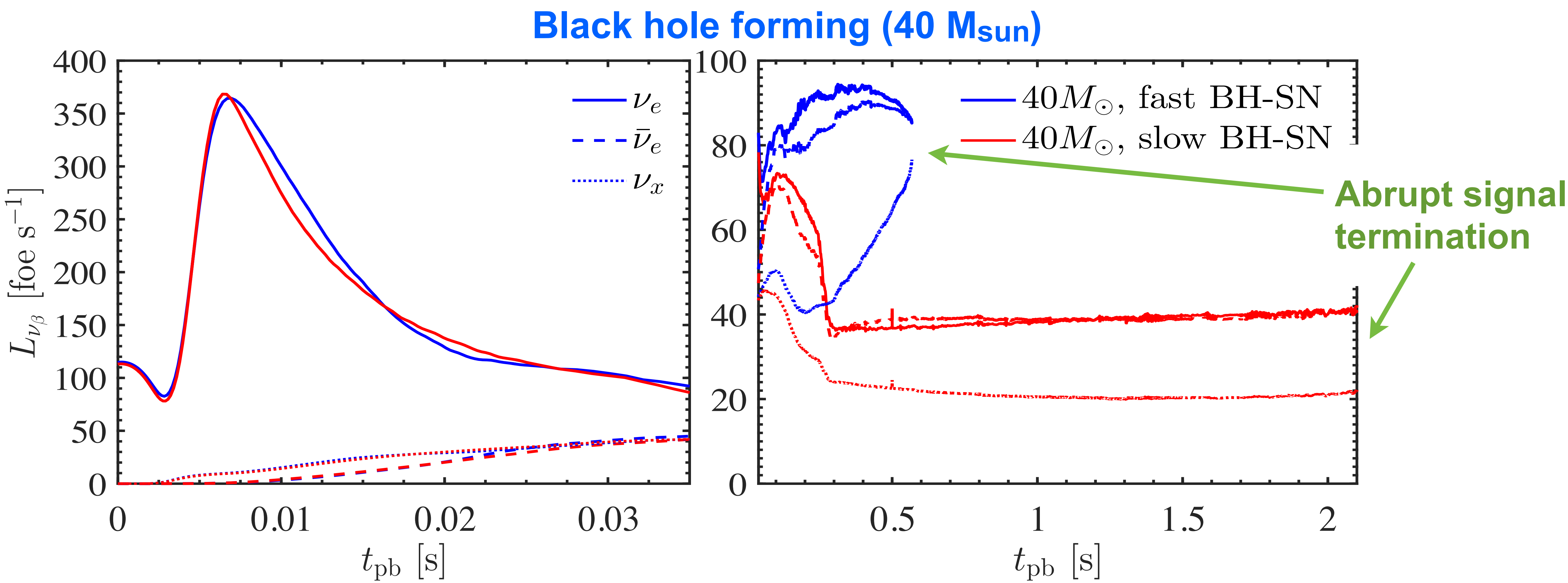
- First 7 years of survey:
6 successful core-collapse, **1 candidate failed supernova**.



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).

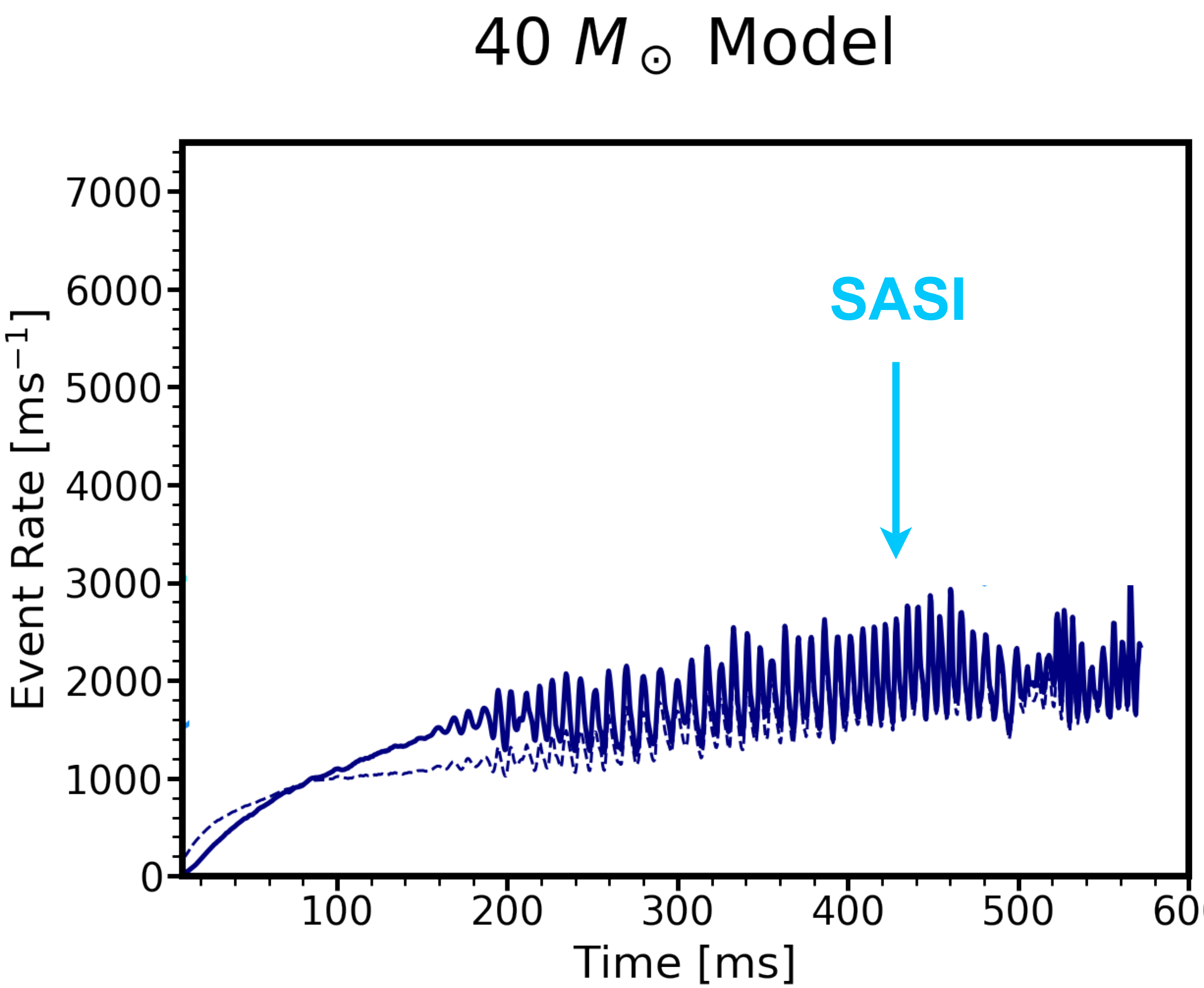
Black Hole Formation



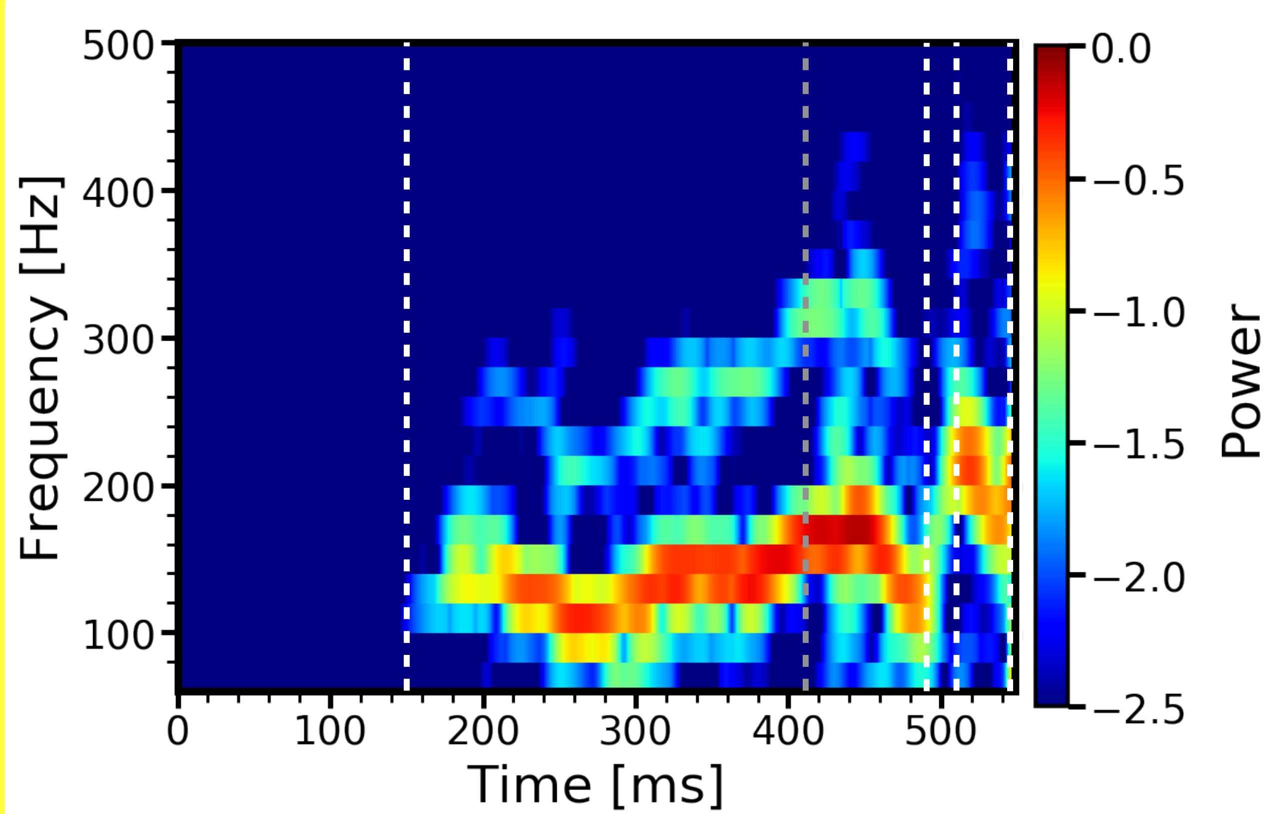
- Black hole forming collapses up to 20-40% of total.
- Neutrinos may be the only probes revealing the black hole formation.

Figure credit: Mirizzi, Tamborra et al. (2016).

Black Hole Formation



Neutrinos (and gravitational waves) probe black hole formation.

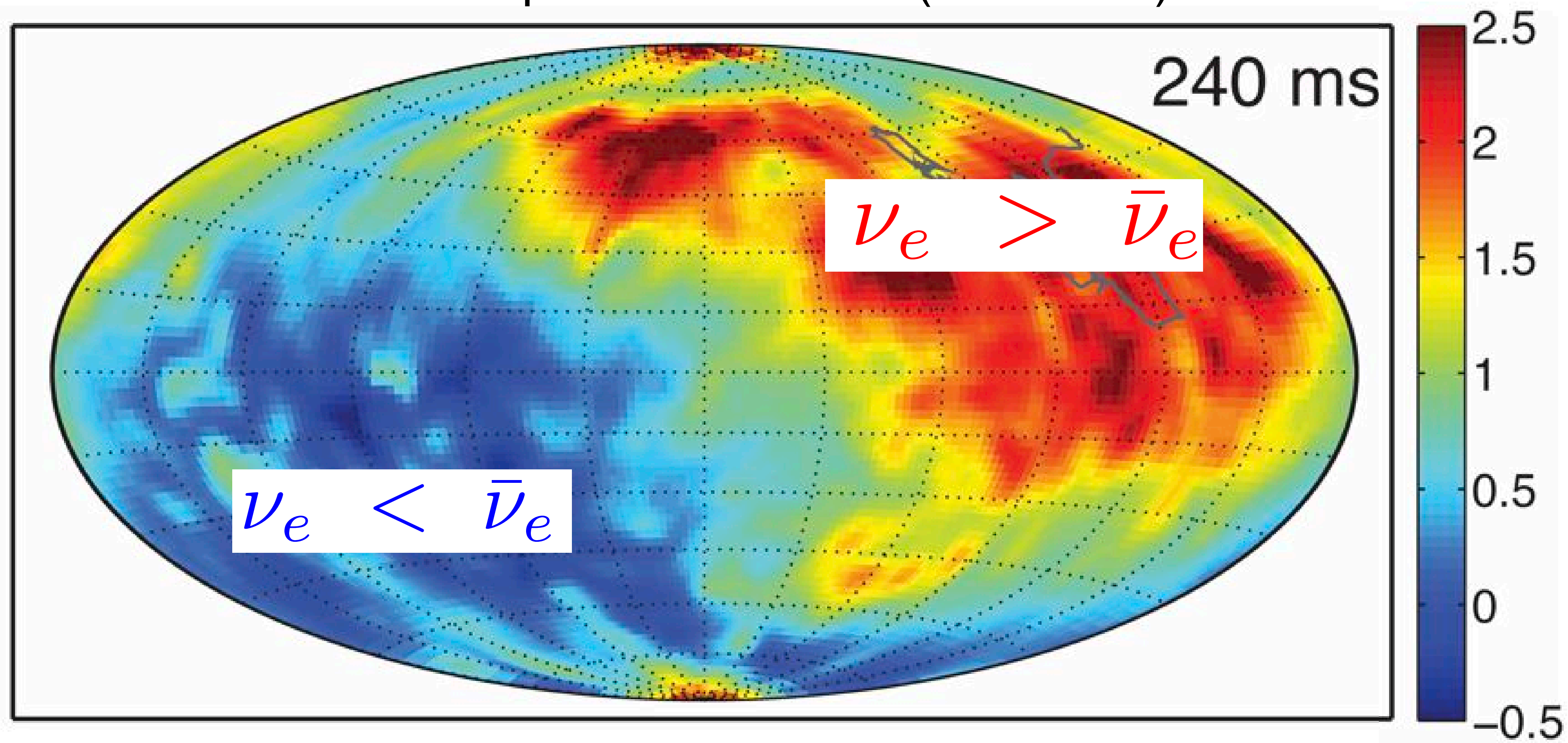


SASI frequency evolution = Shock radius evolution

Walk, Tamborra, Janka, Summa, Kresse, PRD (2020).

LESA: Neutrino-Driven Instability

Neutrino lepton-number flux (11.2 M_{sun})

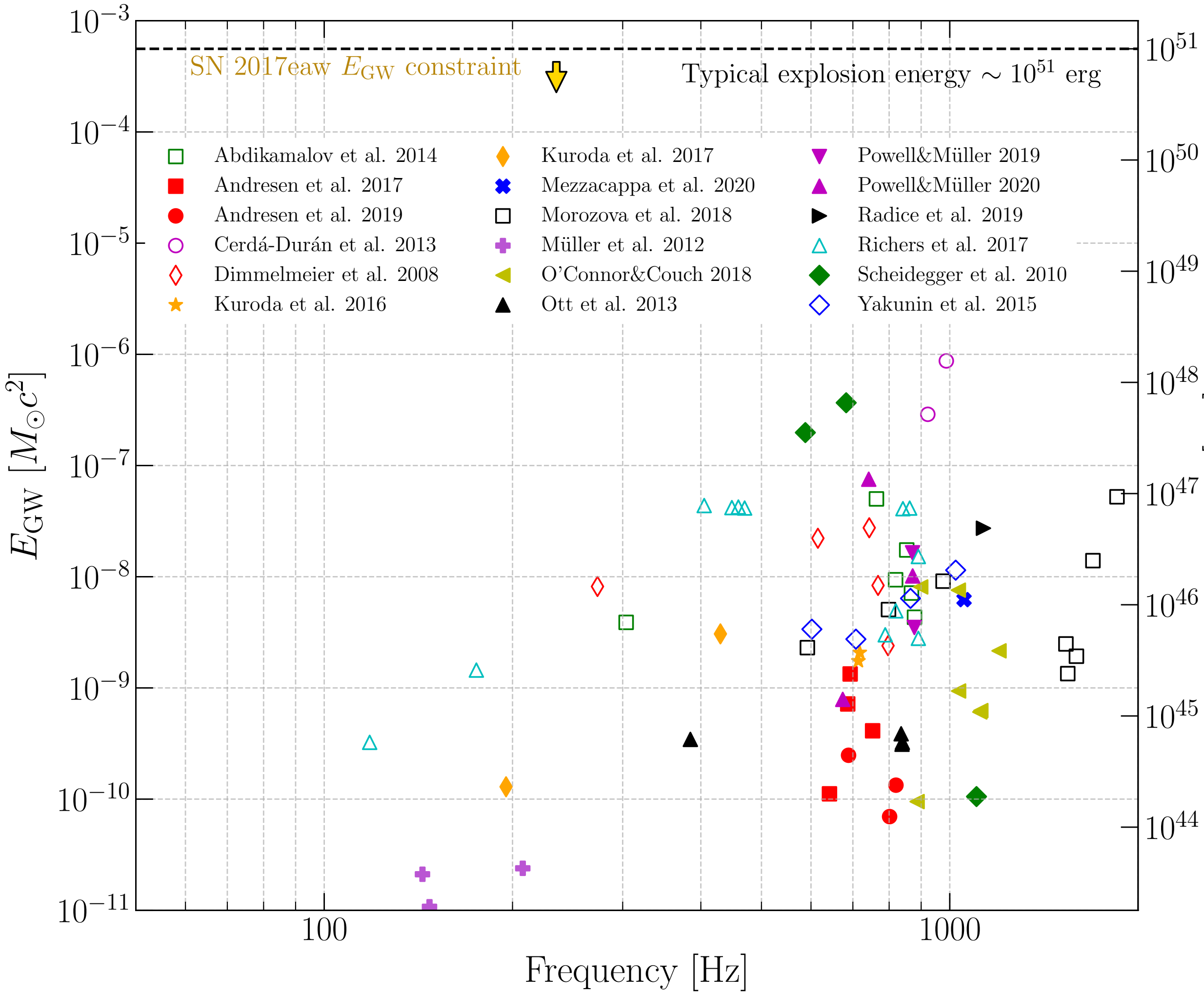


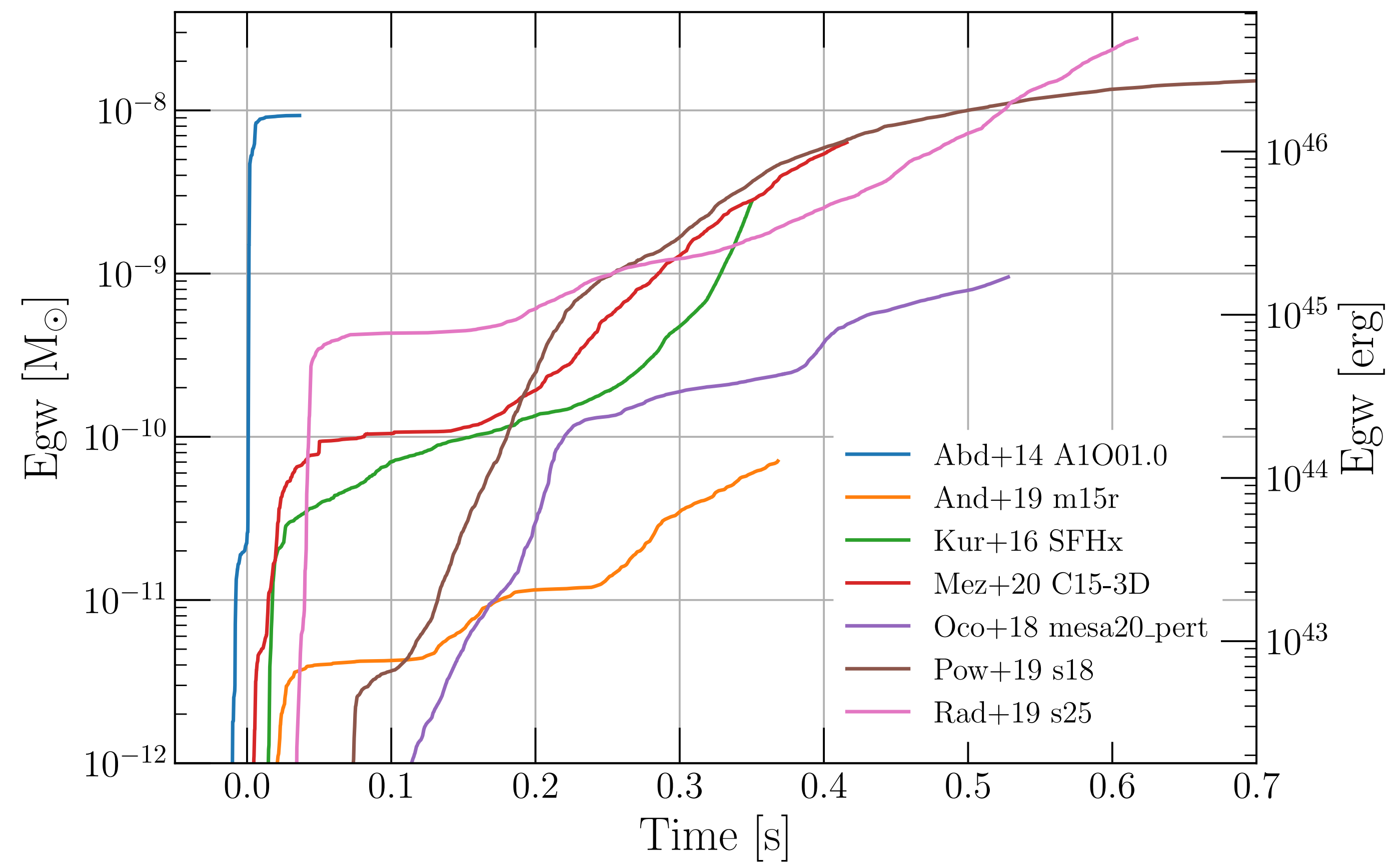
Lepton-number emission asymmetry (**LESA**). Possible major implications for

- Neutron star kicks.
- Direction dependent supernova nucleosynthesis.
- Viewing angle dependent neutrino energy distributions.
- Direction dependent neutrino flavor conversion physics.

Tamborra et al., ApJ (2014). Janka et al., ARNPS (2016). Glas et al., ApJ (2019), Vartanyan et al., MNRAS (2019), O'Connor & Couch, ApJ (2018). Powell & Mueller, MNRAS (2019). …

Gravitational Waves



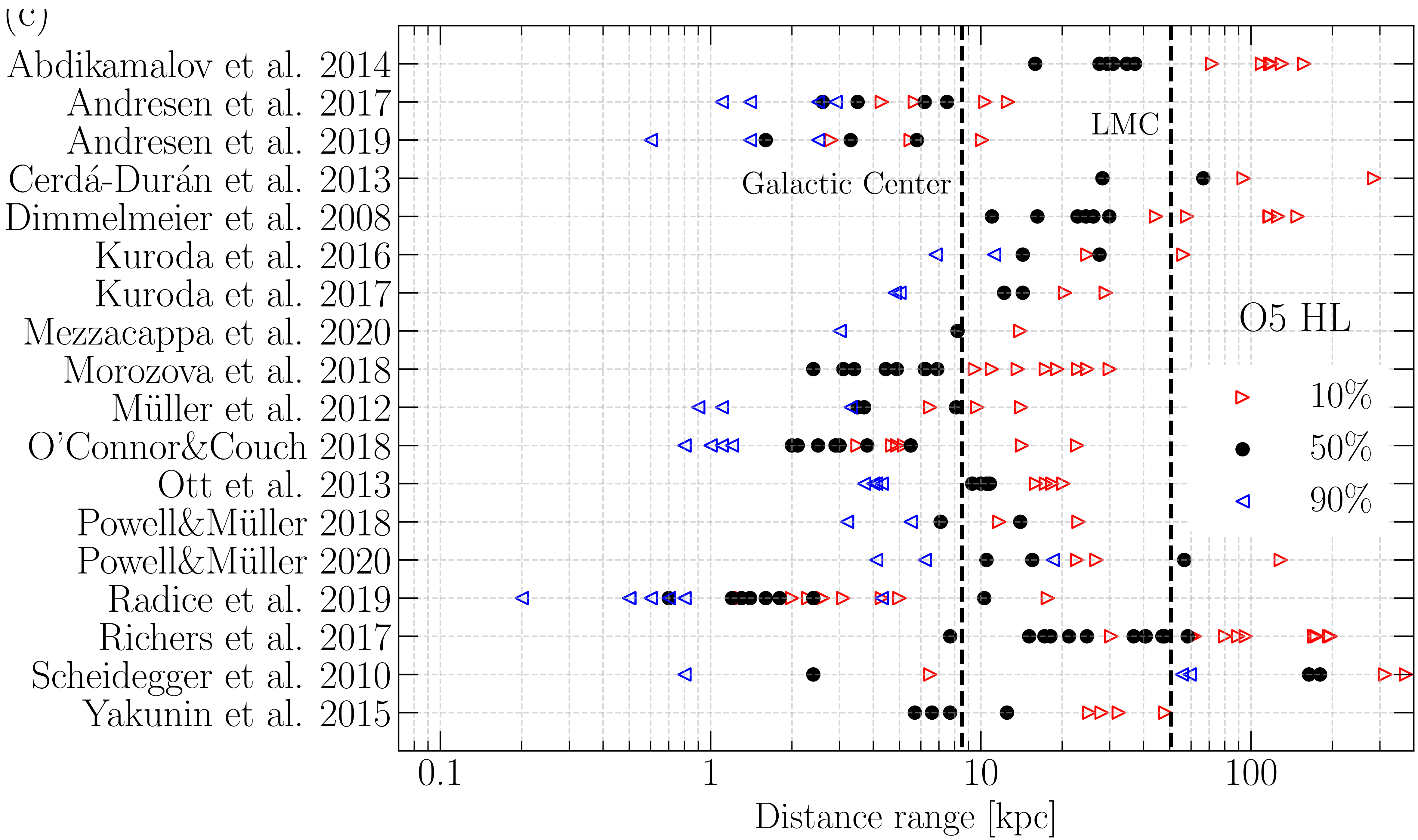


The peak frequencies lay between 300 Hz and 1000 Hz, corresponding to the proto-neutron star oscillations. The typical energy is smaller than 0.01% of a typical SN explosion energy.

For neutrino-driven explosions, most of the energy is emitted after around 100 ms.

Szczepanczyk et al., arXiv: 2104.06462.

Gravitational Waves



Distances at 10%, 50% and 90% detection efficiencies for 3D supernova models. The predicted detection ranges for O5 are typically between 1 kpc and 100 kpc. This range contains the distances to the Galactic center and the Large Magellanic Cloud (LMC) that hosted SN 1987A.

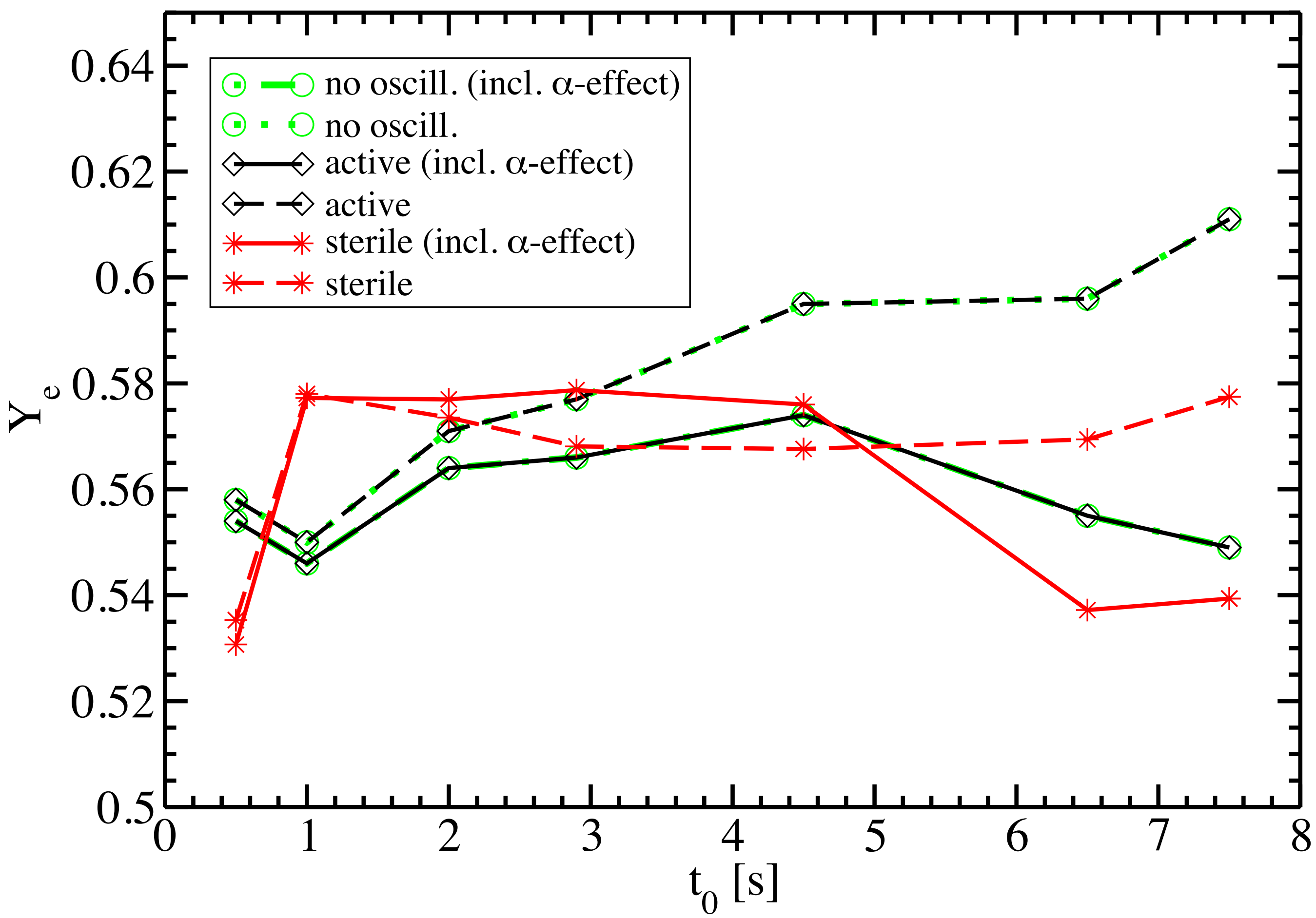
Szczepanczyk et al., arXiv: 2104.06462.

Neutrinos Affect Element Production

Location of r-process nucleosynthesis (origin elements with A >100) unknown.

Flavor oscillations affect element production mainly via

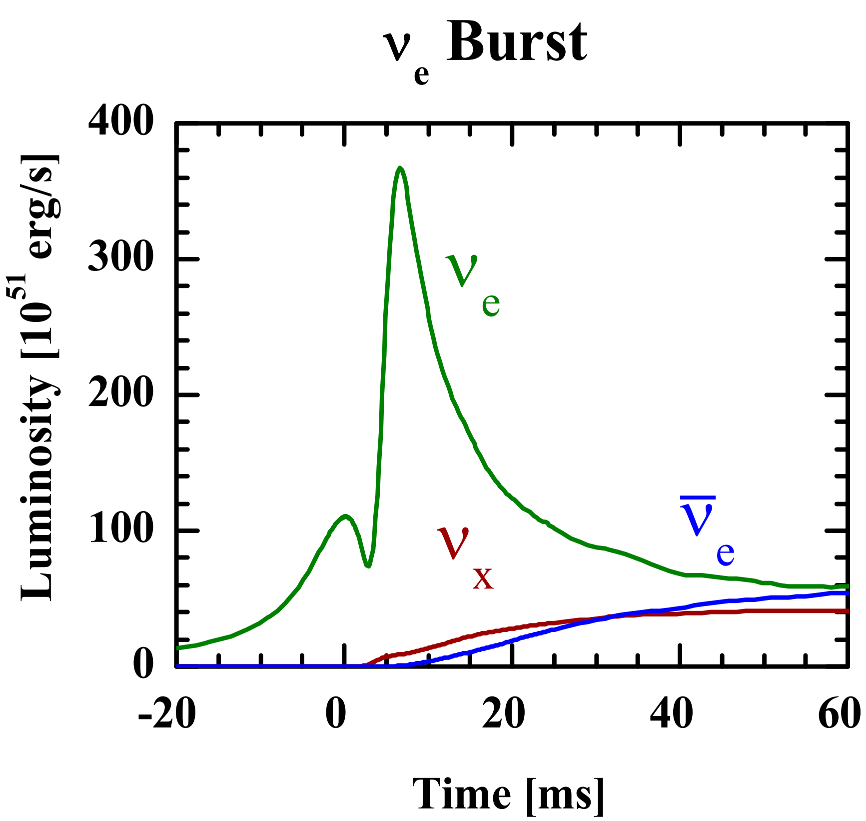
$$\nu_e + n \rightleftharpoons p + e^-$$
$$\overline{\nu}_e + p \rightleftharpoons n + e^+$$

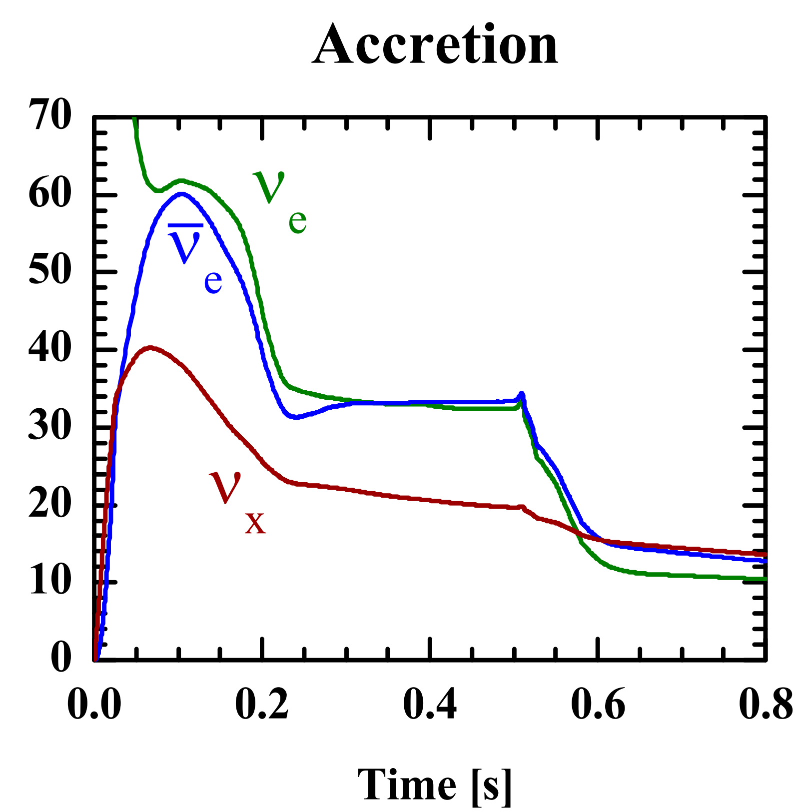


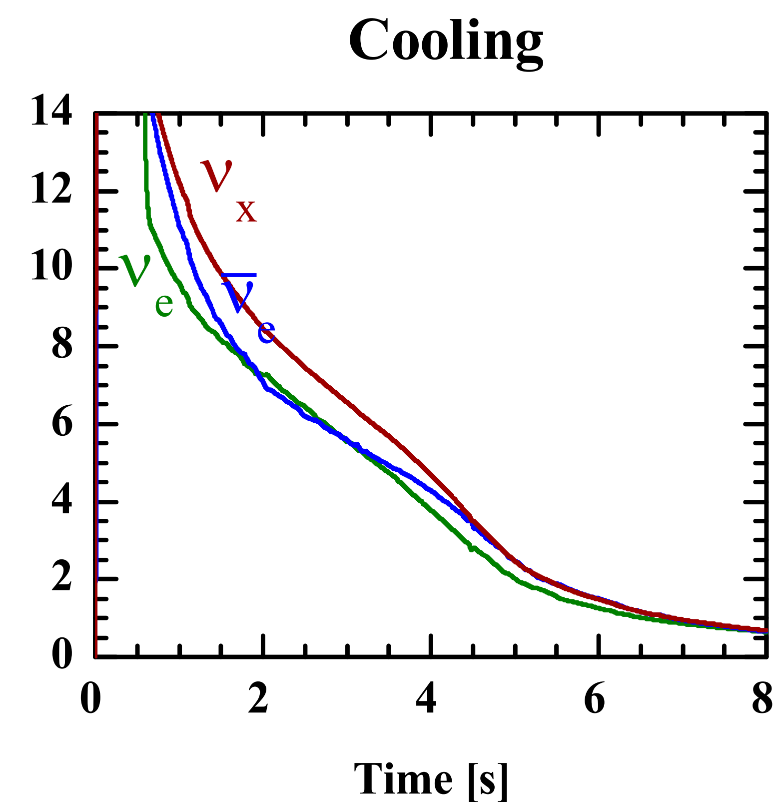
Recent work suggests unlikely r-process conditions in SNe, but further work needed.

Xiong et al., arXiv: 2006.11414. Pllumbi, Tamborra et al., ApJ (2015). Wu et al., PRD (2015). Tamborra et al., JCAP (2013). Duan et al., J. Phys. G (2011).

Synopsis







Signal independent on SN mass and EoS.

- SN distance.
- (Test oscillation physics.)

Signal has strong variations (mass, EoS, 3D effects).

- Core collapse astrophysics.
- (Test oscillation physics.)

EoS and mass dependence.

- Test nuclear physics.
- Nucleosynthesis.

Summary

- Neutrinos play a fundamental role in the supernova explosion mechanism.
- Neutrinos are important to test the explosion mechanism.
- Neutrinos can potentially provide information on the supernova properties and trigger multi-messenger detection.

Recent review papers:

➡ A. Mirizzi et al., https://arxiv.org/abs/1508.00785
➡ Vitagliano, Tamborra, Raffelt, https://arxiv.org/abs/1910.11878 (Sections VIII & IX)
➡ B. Mueller, https://arxiv.org/abs/1904.11067
➡ H.-T. Janka, https://arxiv.org/abs/1702.08825
➡ A. Burrows, https://arxiv.org/abs/1210.4921
➡ Tamborra & Shalgar, https://arxiv.org/abs/2011.01948
➡ K. Scholberg, https://arxiv.org/abs/1707.06384
➡ J. Beacom, https://arxiv.org/abs/1004.3311