The Niels Bohr International Academy

DARK

Neutrino Astrophysics I

Irene Tamborra (Niels Bohr Institute)

14th International Neutrino Summer School, August 7-18, 2023

VILLUM FONDEN

Sapere Aude

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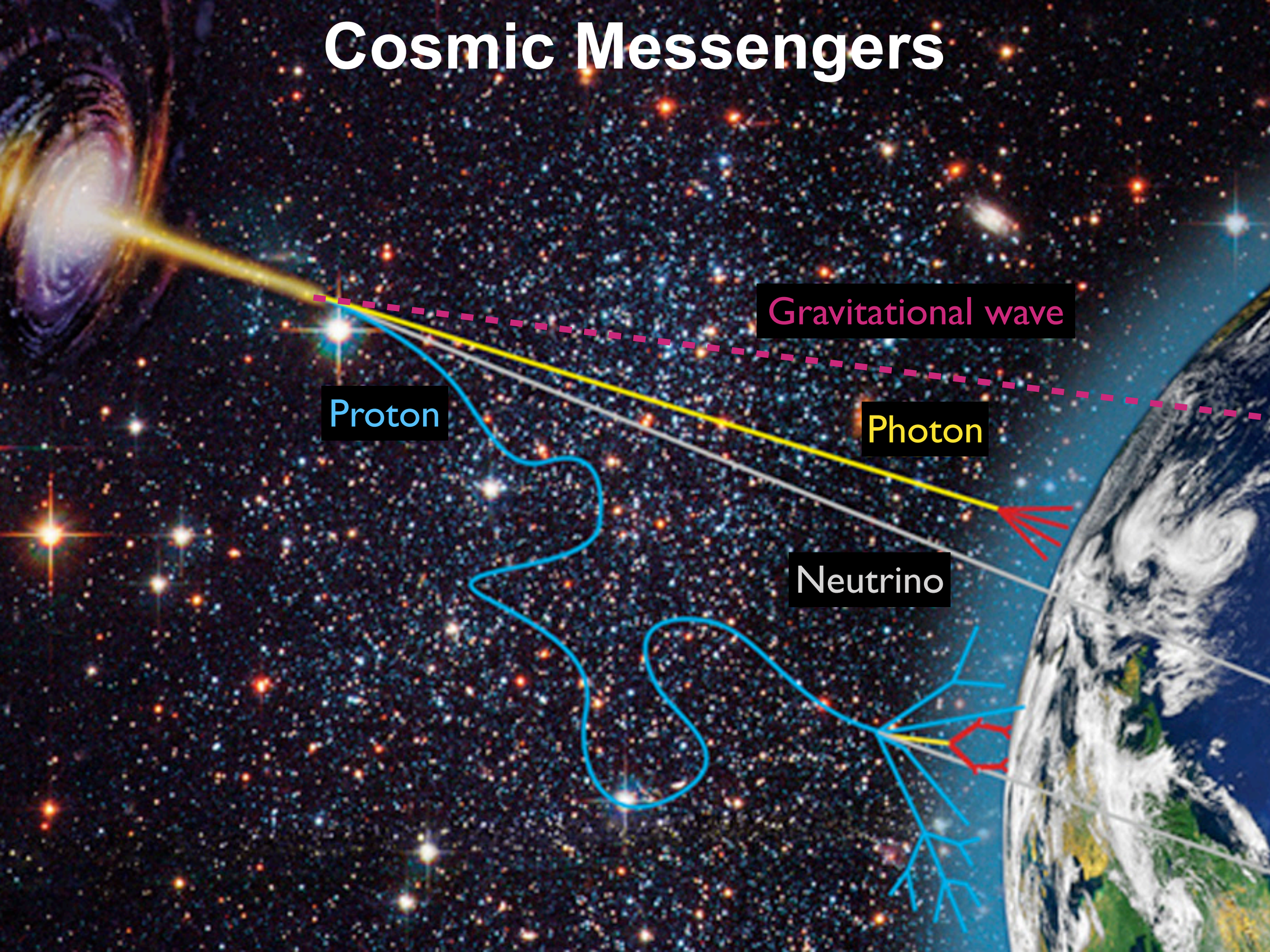
SFB 1258 Neutrinos Dark Matter Messengers

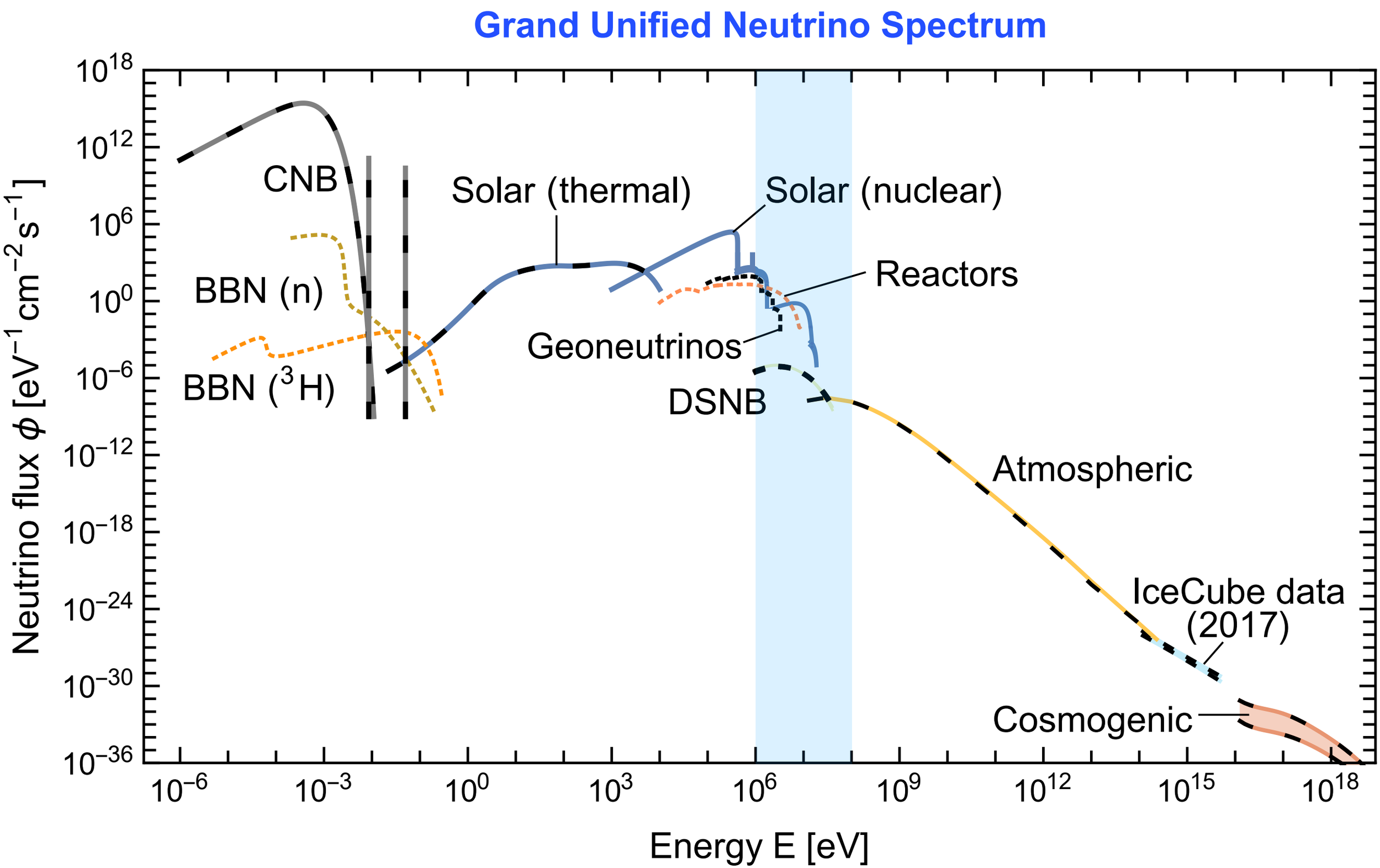
Cosmic Messengers



Lecture 1:
Core-Collapse Supernovae and Compact Binary Mergers
Intended Learning Objectives

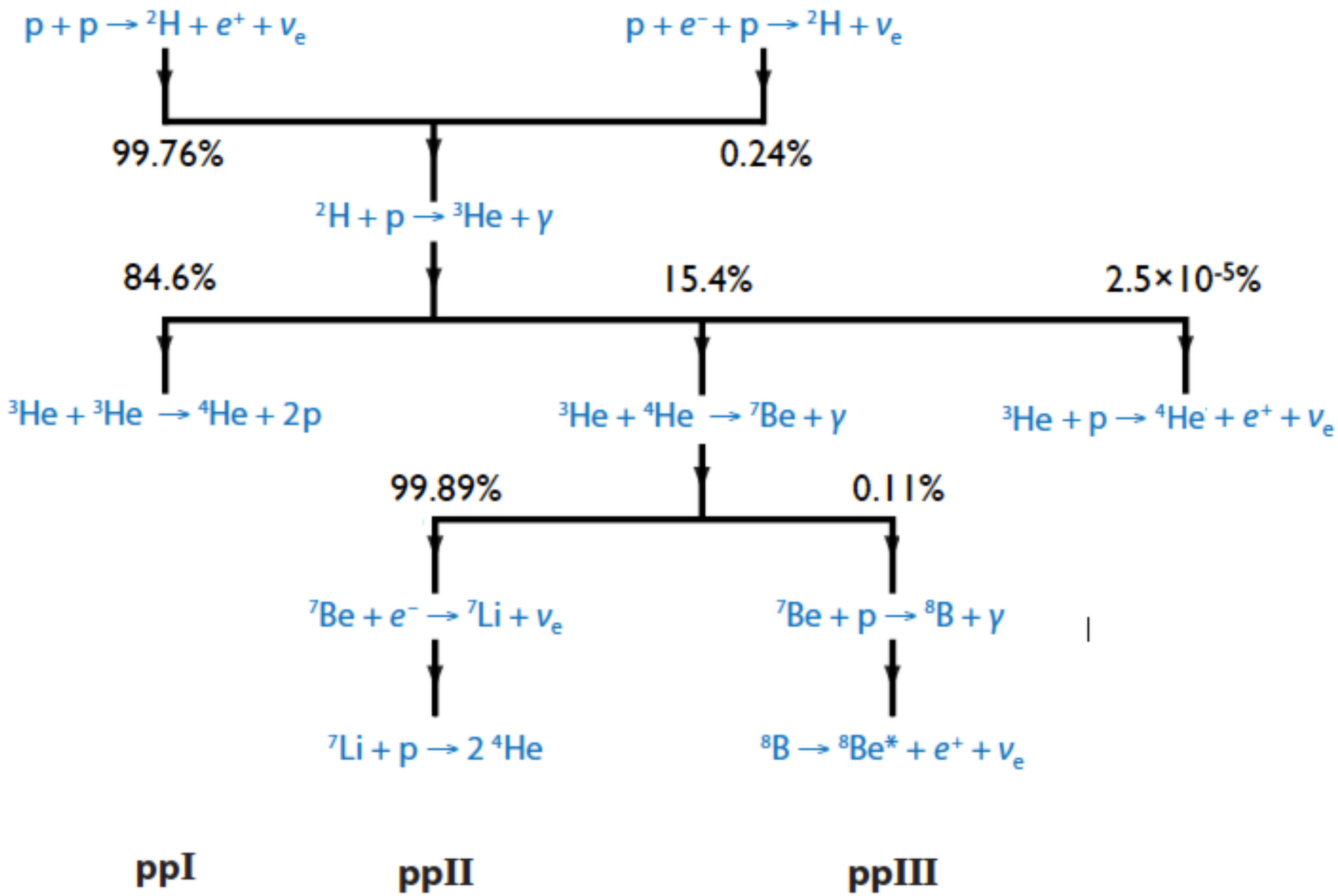
- Core-collapse supernovae
- Supernova mechanism and energetics
- Neutrino flavor conversion
- Diffuse supernova neutrino background
- Neutron star mergers
- Neutrinos and nucleosynthesis

This Lecture



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

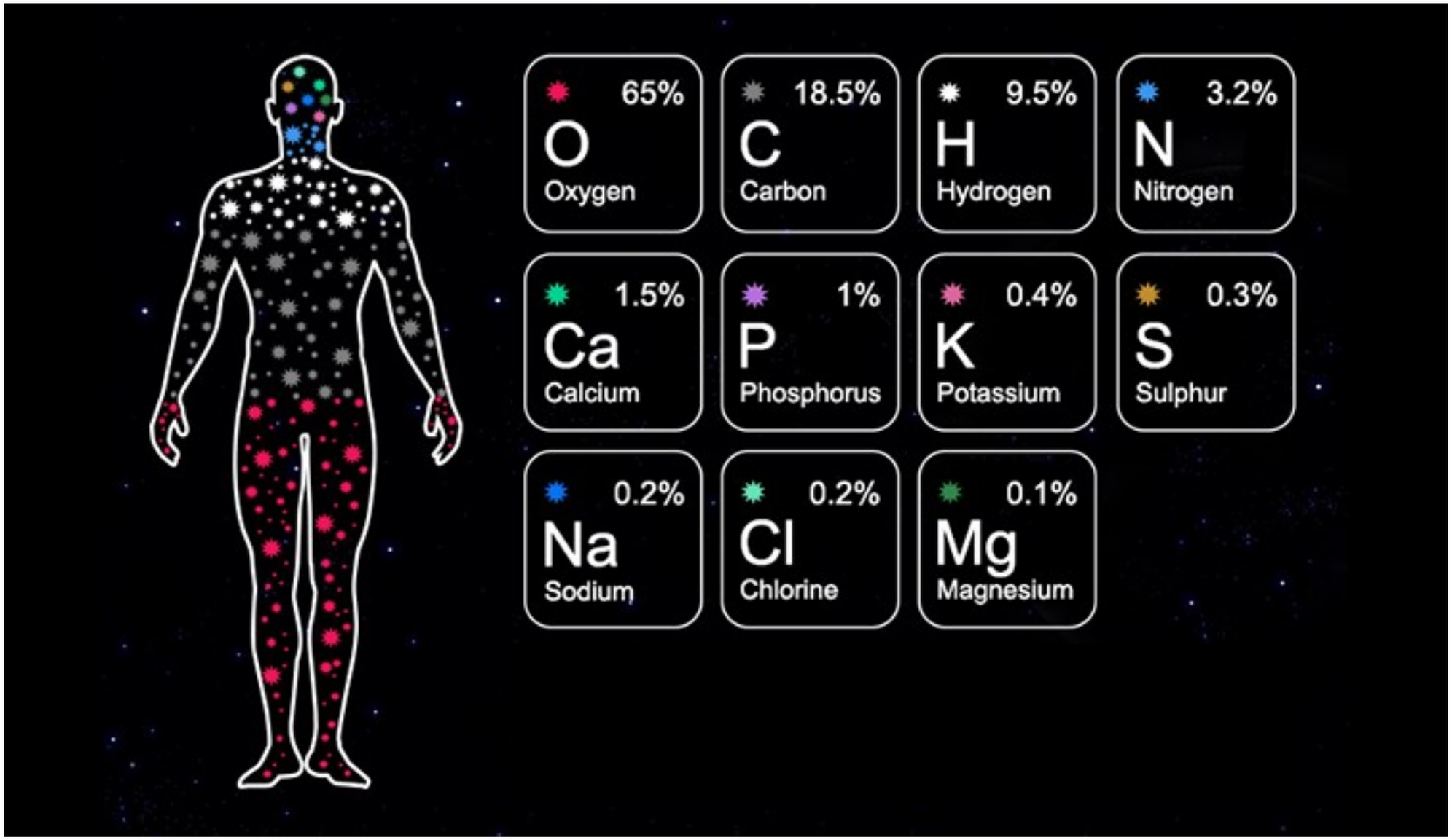
Solar Neutrinos



Solar neutrinos ⇨ **Test Standard Solar Model.**
Discovery of neutrino oscillations.

Core Collapse Supernovae

Why Do We Care?



- Elements essential to our life.
- Laboratory to investigate extreme physics.

Figure credits: Natural History Museum, London

Lifecycle of a Star

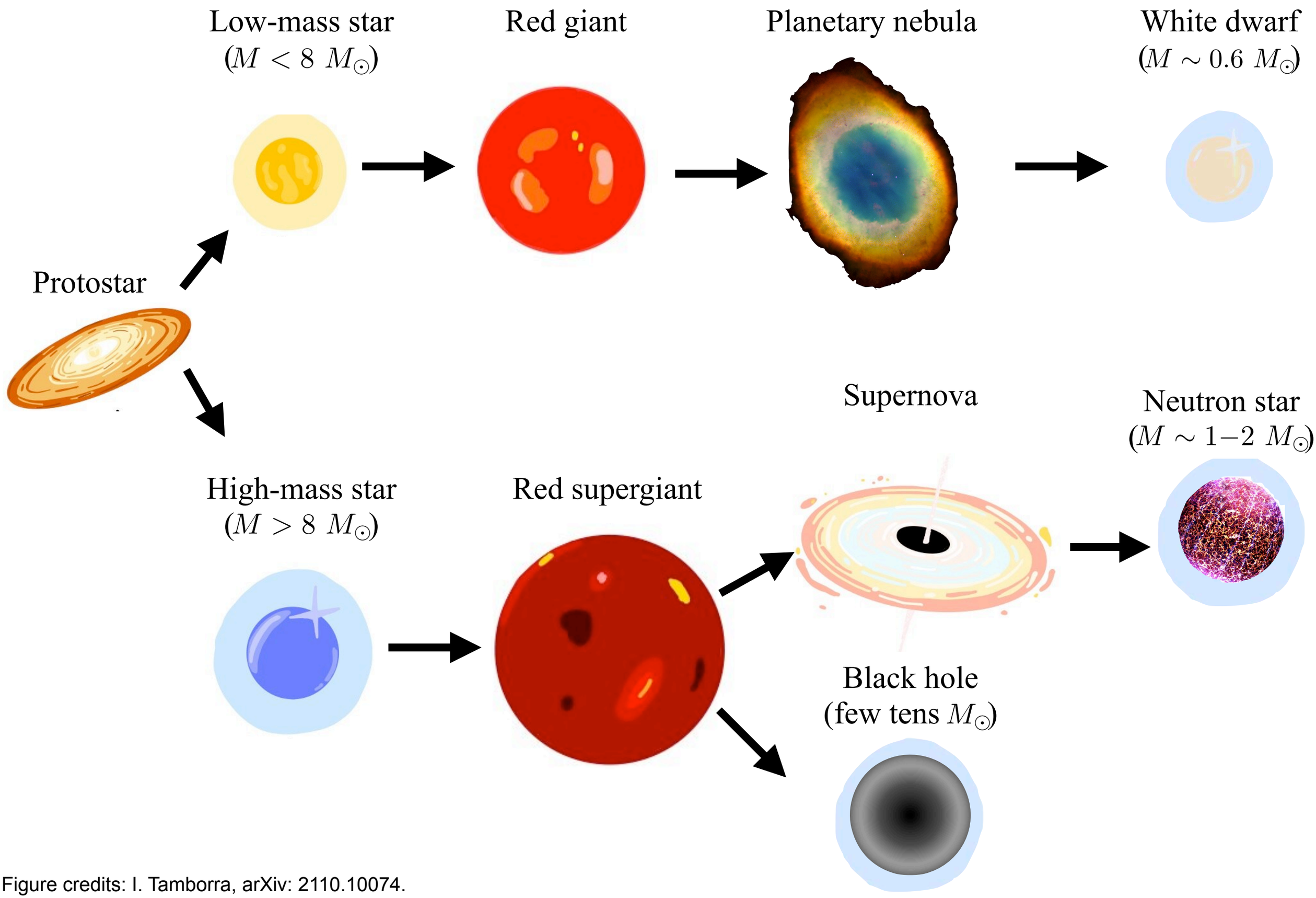
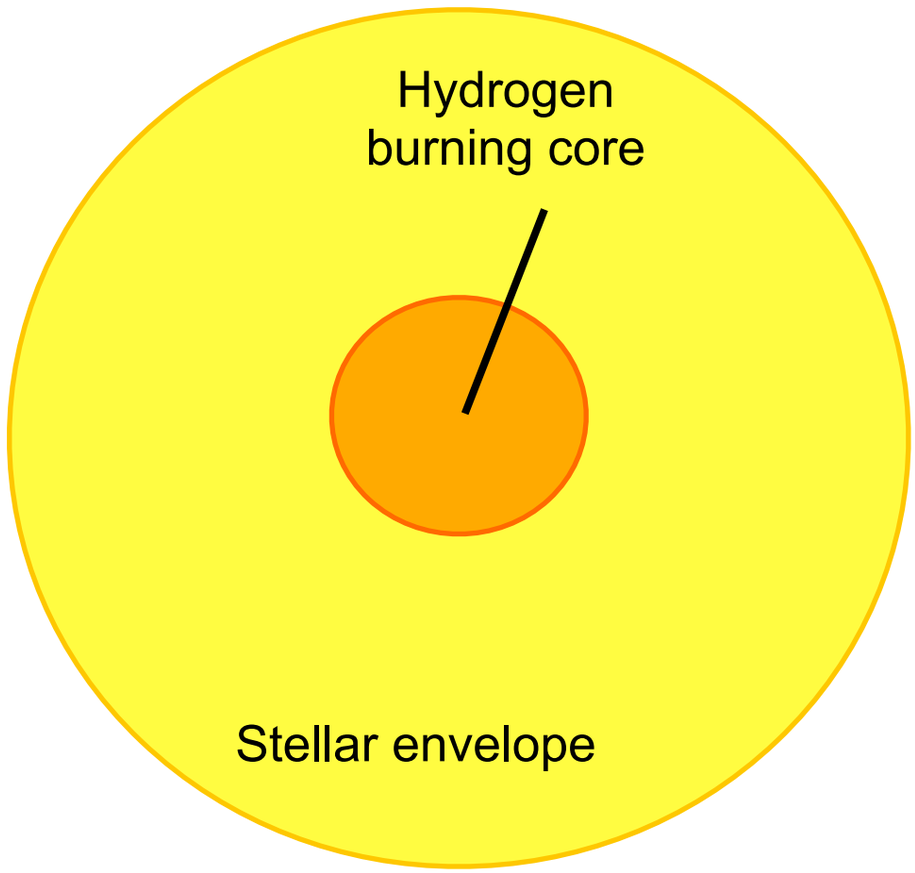
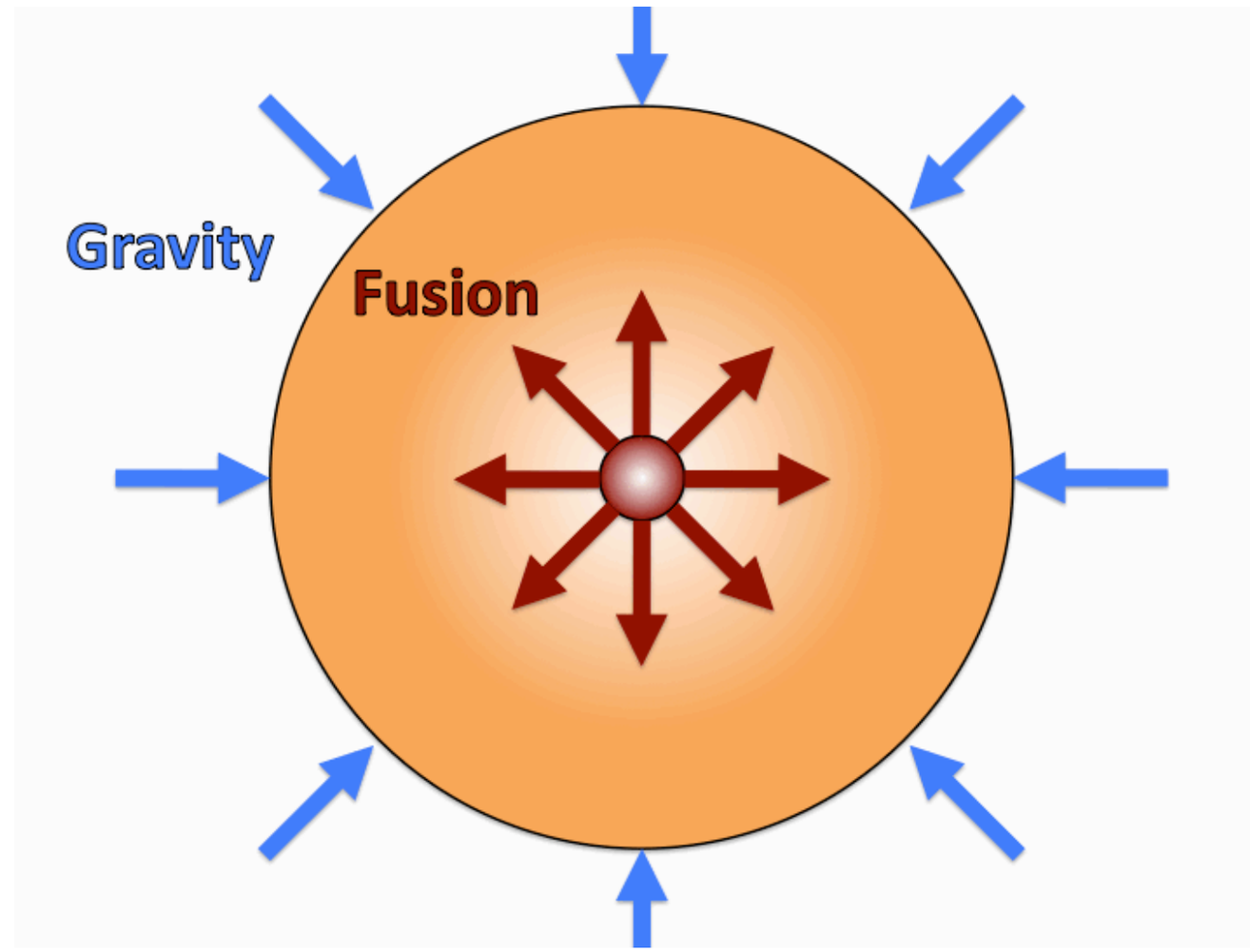


Figure credits: I. Tamborra, arXiv: 2110.10074.

Lifecycle of a Massive Star

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



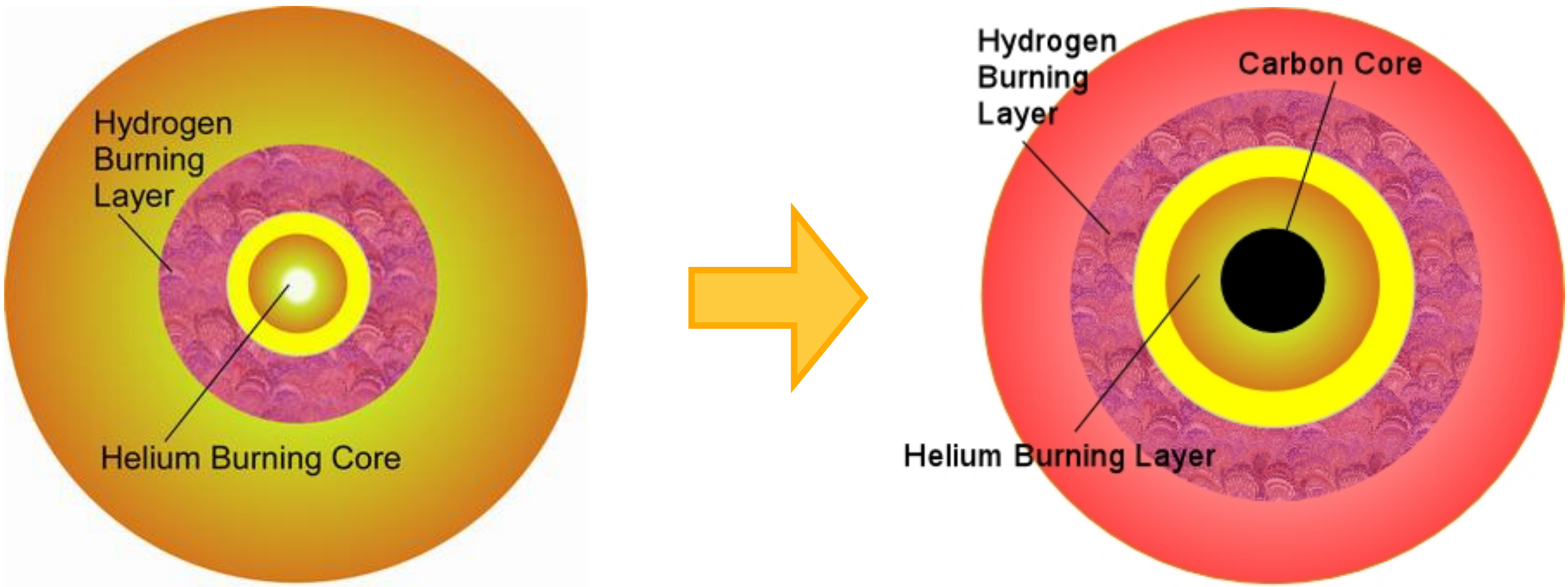


Pressure (from energy produced in the core from nuclear fusion)
= Gravity

Hydrostatic equilibrium

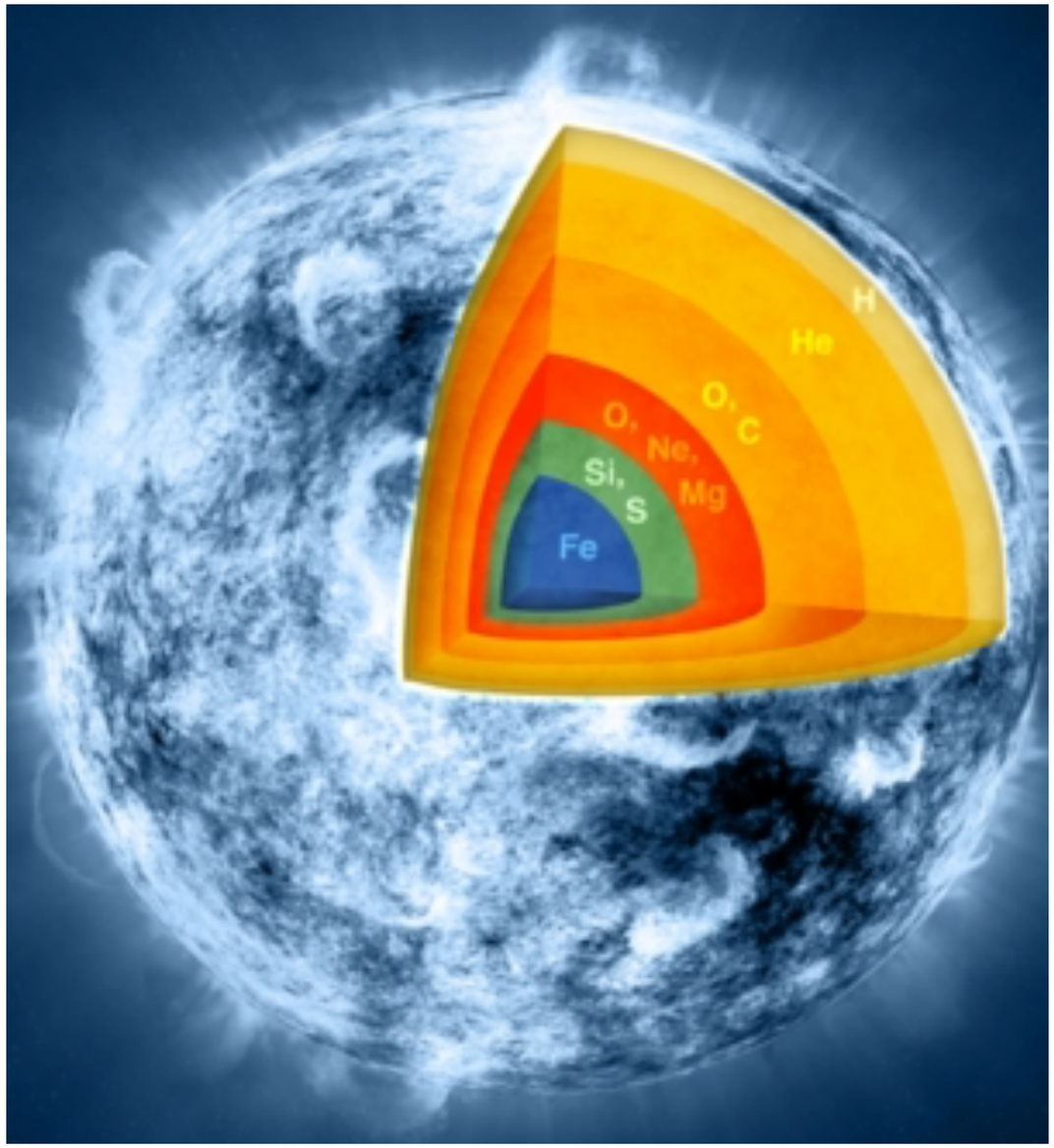
Lifecycle of a Massive Star

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.



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

Timescales

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

Figure credits: https://astronomy.swin.edu.au/cosmos/c/core-collapse

Final Stages of Stellar Collapse

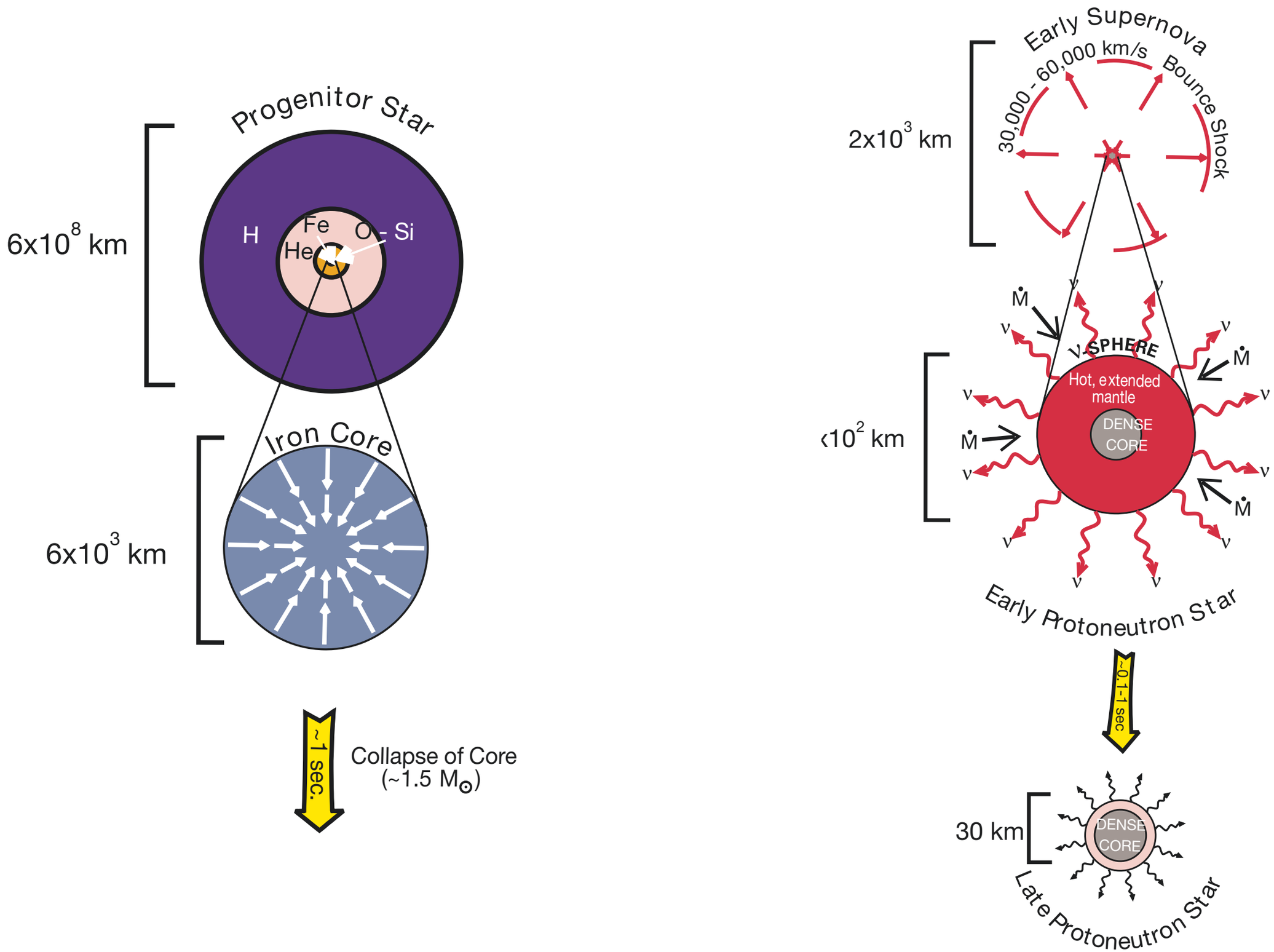


Figure credit: A. Burrows, Nature (2000).

Energetics

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

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

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

Gravitational energy released during neutron star collapse (Gauss theorem)

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

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

$$E_g / T_\nu \sim 10^{58}$$

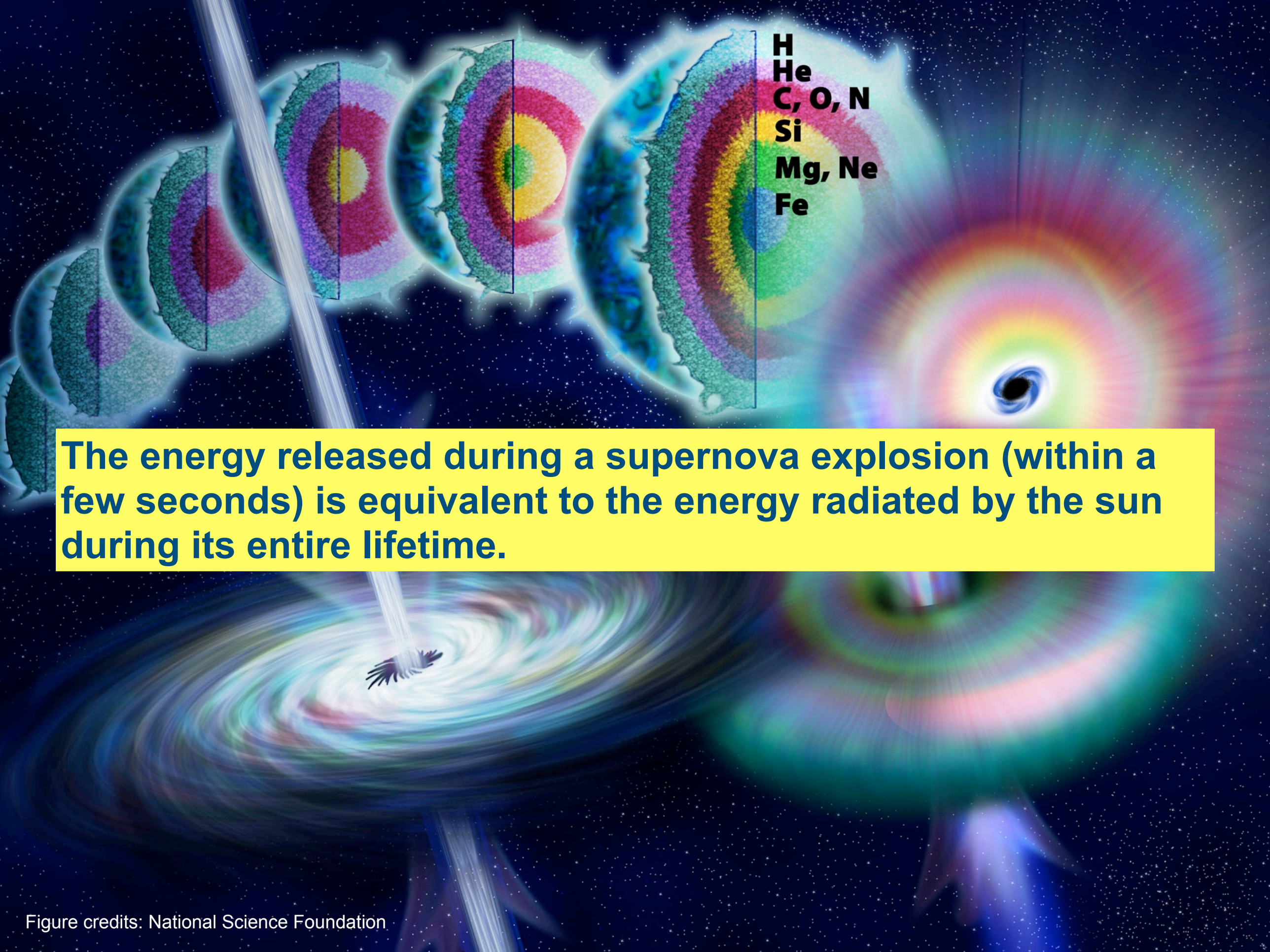
Gravitational binding energy $\simeq 3 \times 10^{53} \text{ erg} \simeq 17\%\ M_{\text{sun}} c^2$

kinetic explosion energy

99% neutrinos

photons

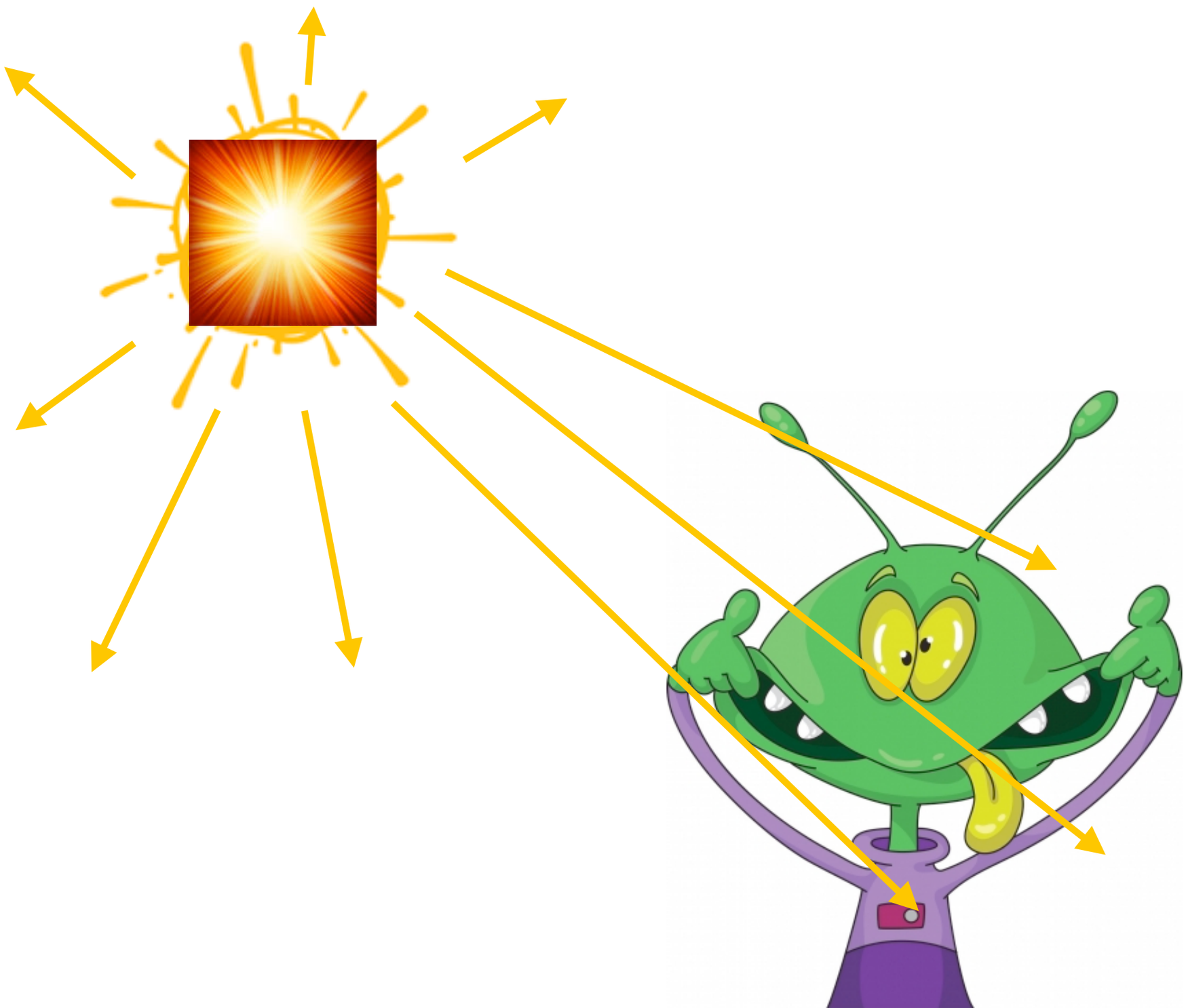
$$L_\nu \simeq \frac{3 \times 10^{53} \text{ erg}}{3 \text{ s}} \simeq 3 \times 10^{19} L_{\text{sun}}$$



The energy released during a supernova explosion (within a few seconds) is equivalent to the energy radiated by the sun during its entire lifetime.

Figure credits: National Science Foundation

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



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.

Figure credit: Anglo-Australian Observatory.

SN 1987A

A few detectors were able to detect SN 1987A neutrinos.

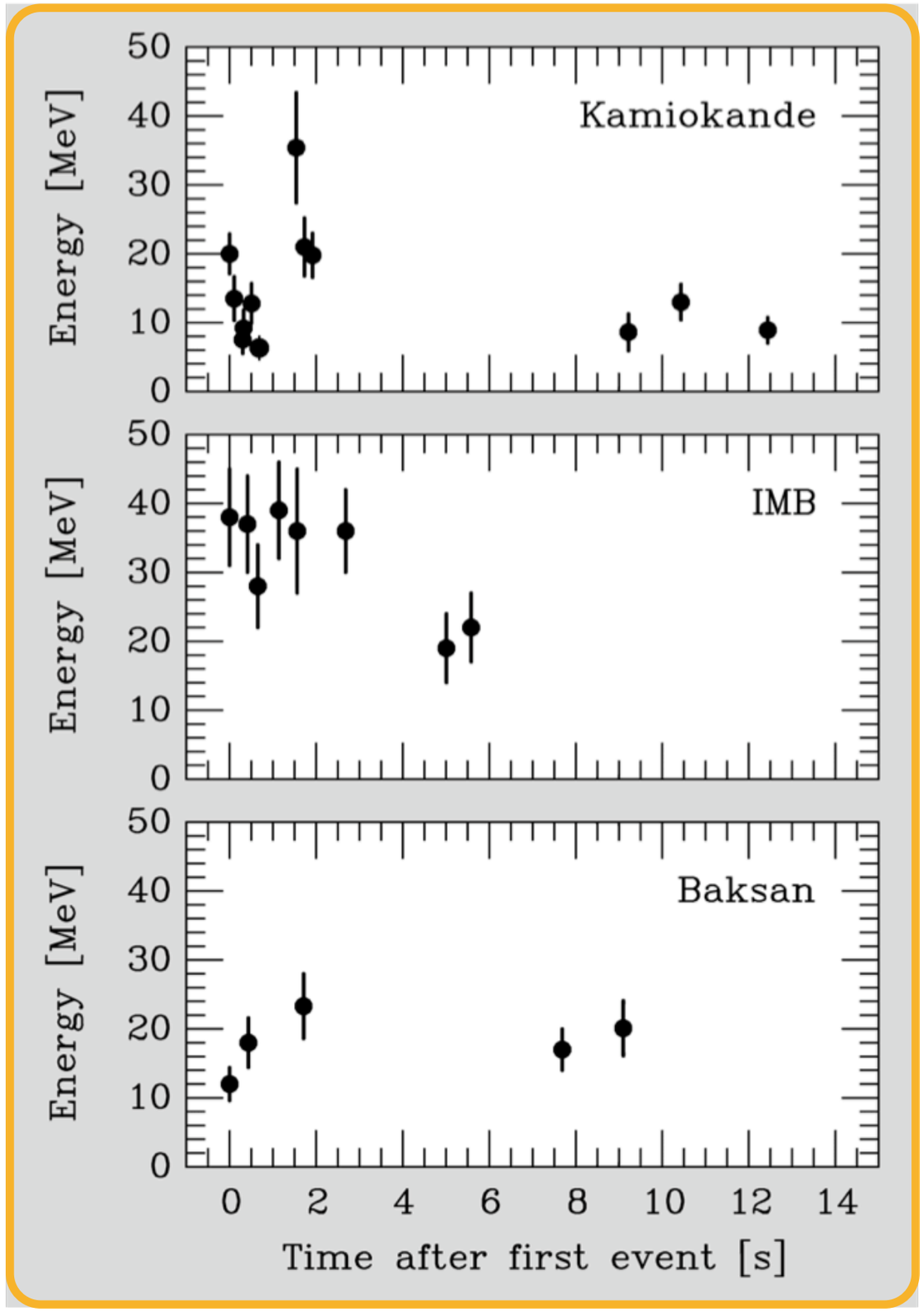


Figure credit: G. Raffelt.

The Next Supernova (SN 2XXXA)

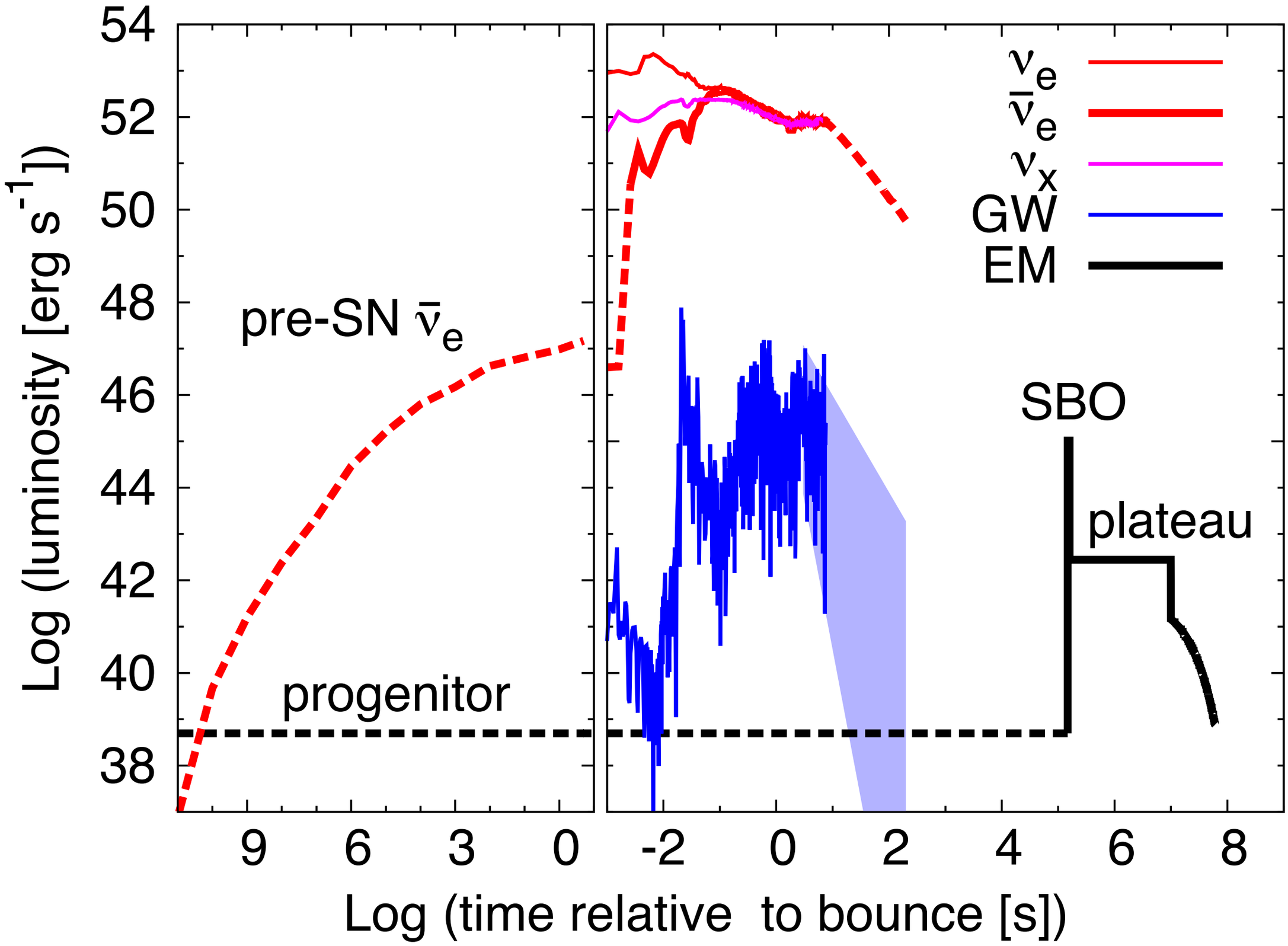
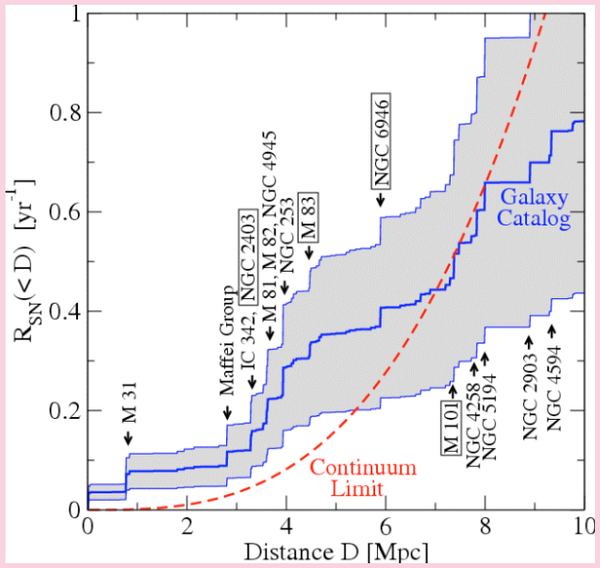


Figure from Nakamura et al., MNRAS (2016).

Detection Frontiers

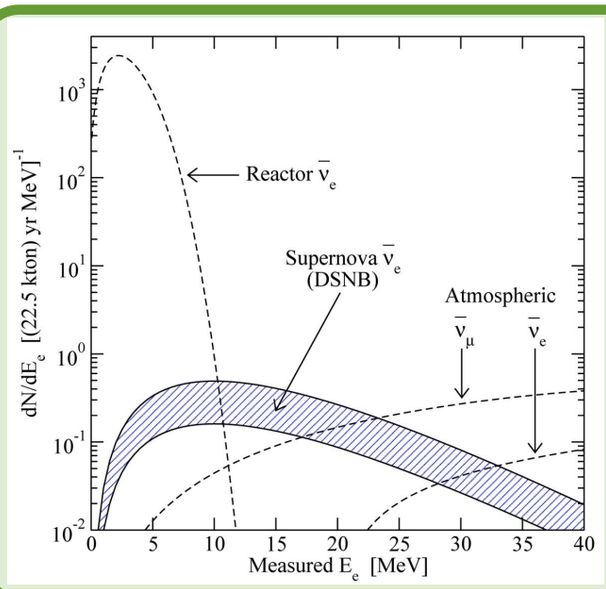
Supernova in our Galaxy (one burst per 40 years).

Excellent sensitivity to details.



Supernova in nearby Galaxies (one burst per year).

Sensitivity to general properties.



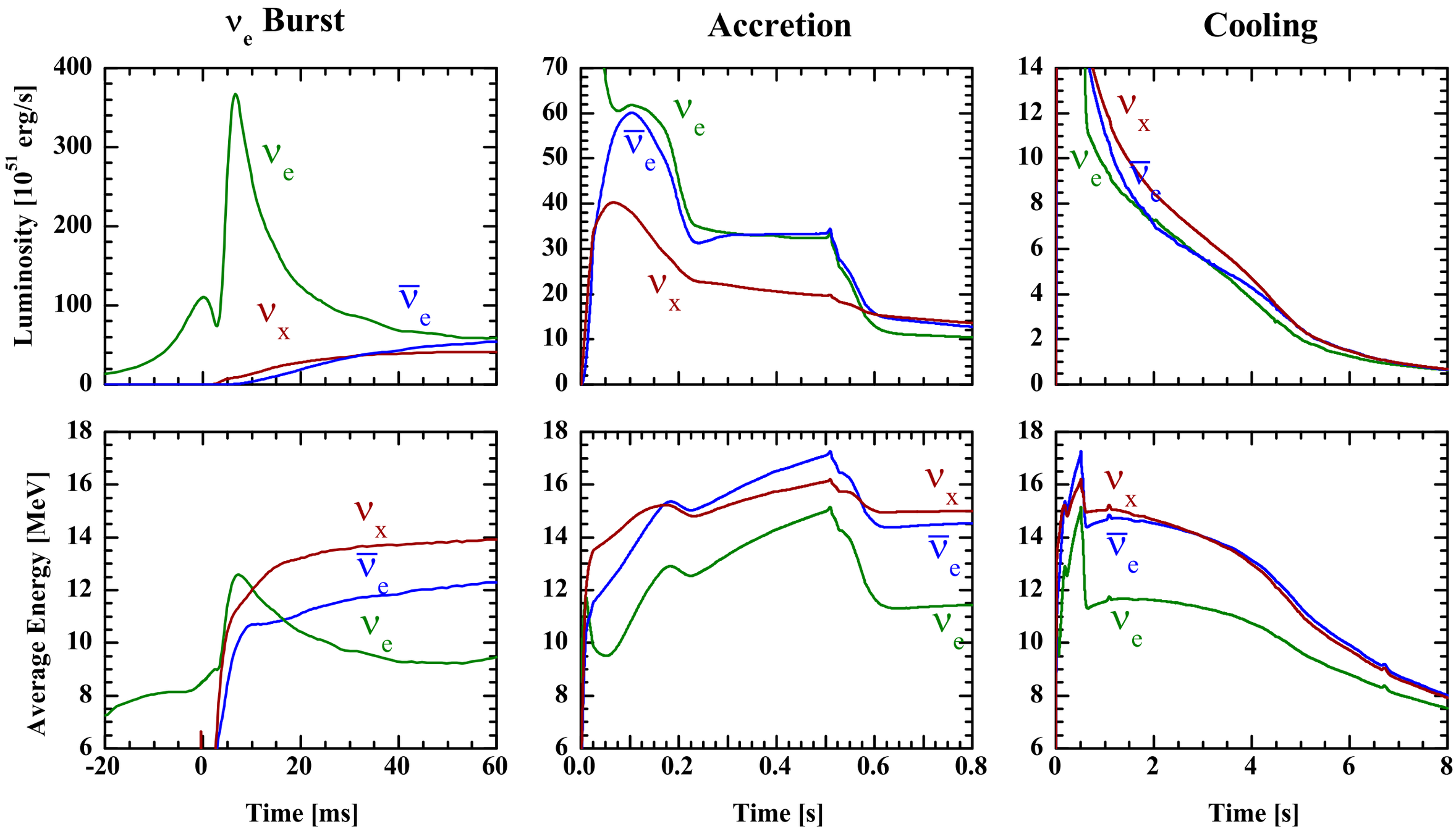
Diffuse Supernova Background
(one supernova per second).

Average supernova emission. Guaranteed signal.

Why Neutrinos from Core-Collapse Supernovae?

- Neutrino luminosity is 100 times the 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.
- 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 $\bar{\nu}_e - \bar{\nu}_x$ flux difference.

Smaller fluxes.
Small $\bar{\nu}_e - \bar{\nu}_x$ flux difference.

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

Neutrinos & Electromagnetic Radiation

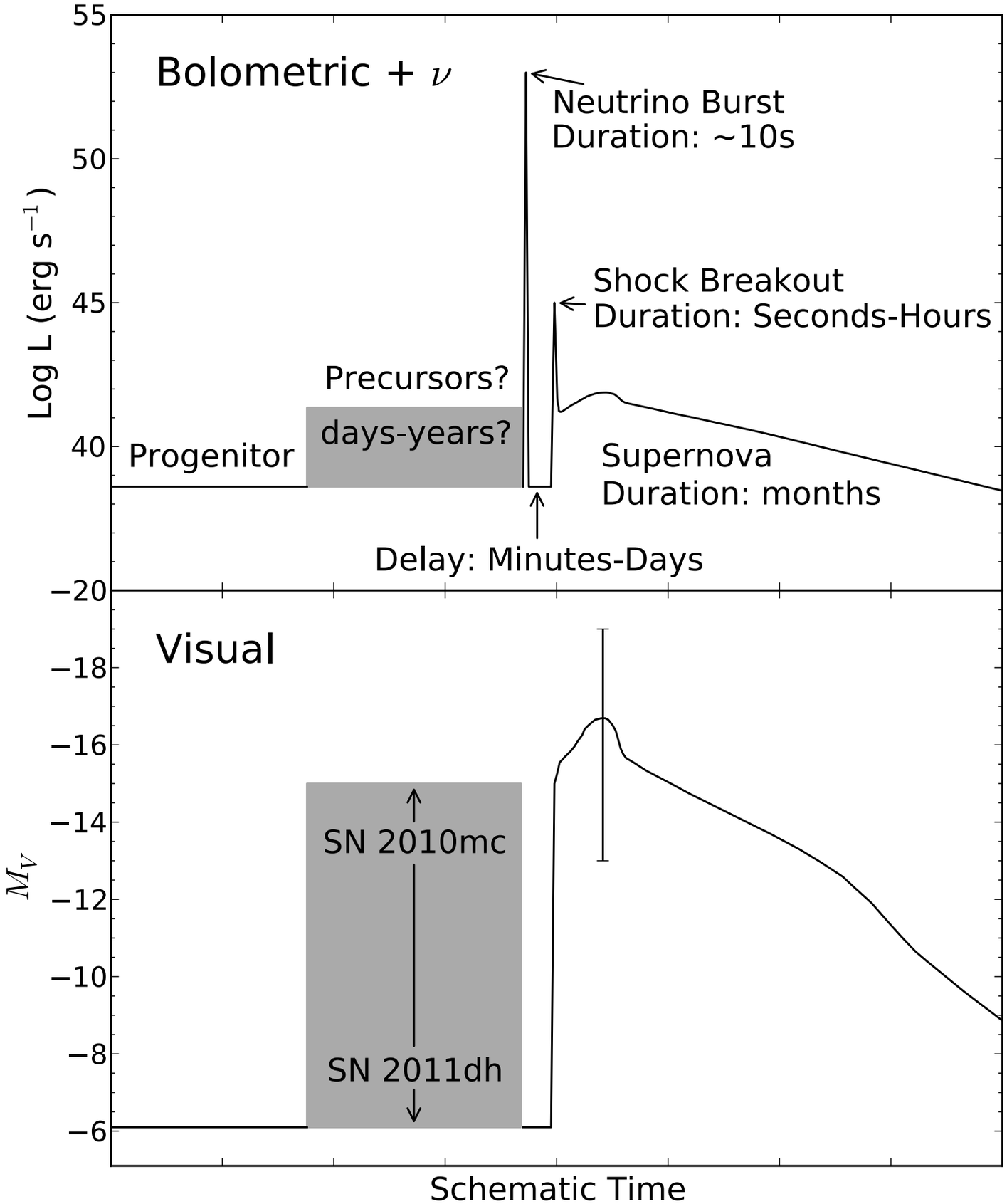


Image credit: Adams et al., ApJ (2013).

Neutrinos could allow early EM detection of SN signal.

Supernova Early 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.

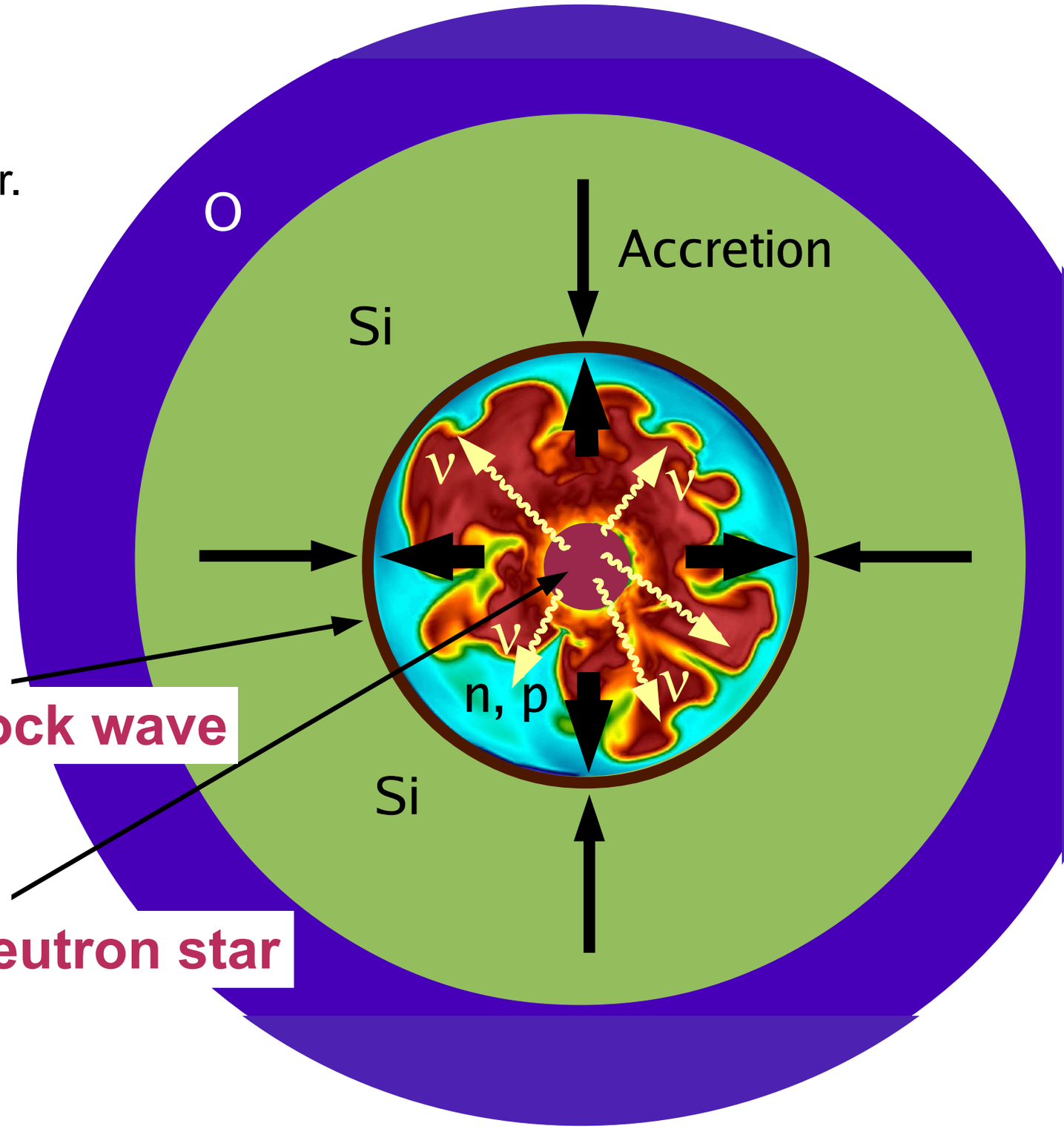
Al Kharusi et al., New J.Phys. (2021). SNEWS: http://snews.bnl.gov

Supernova Explosion Mechanism

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

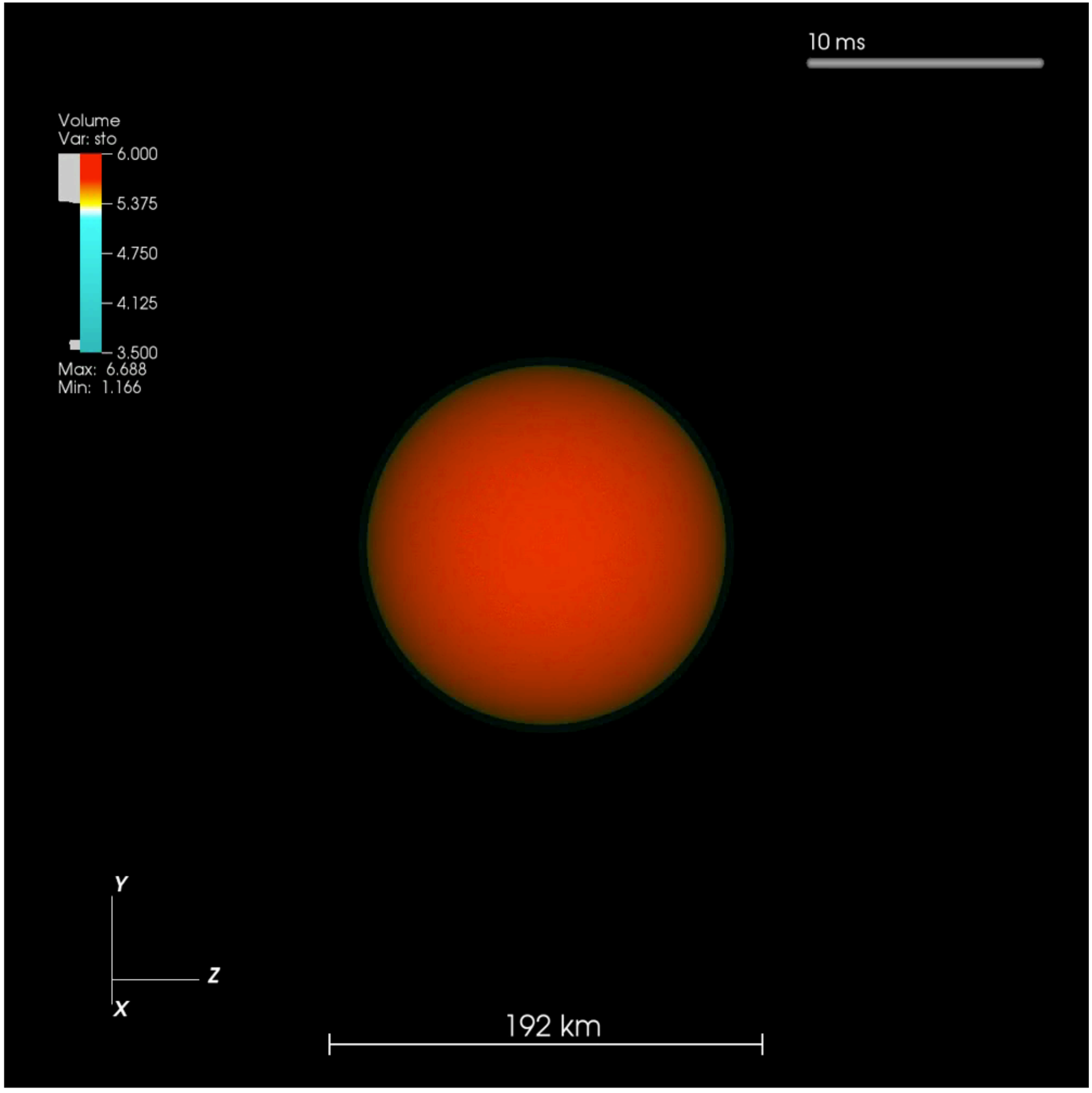
★ **Neutrinos** provide energy to stalled shock wave to start re-expansion.
(Delayed Neutrino-Driven Explosion)

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

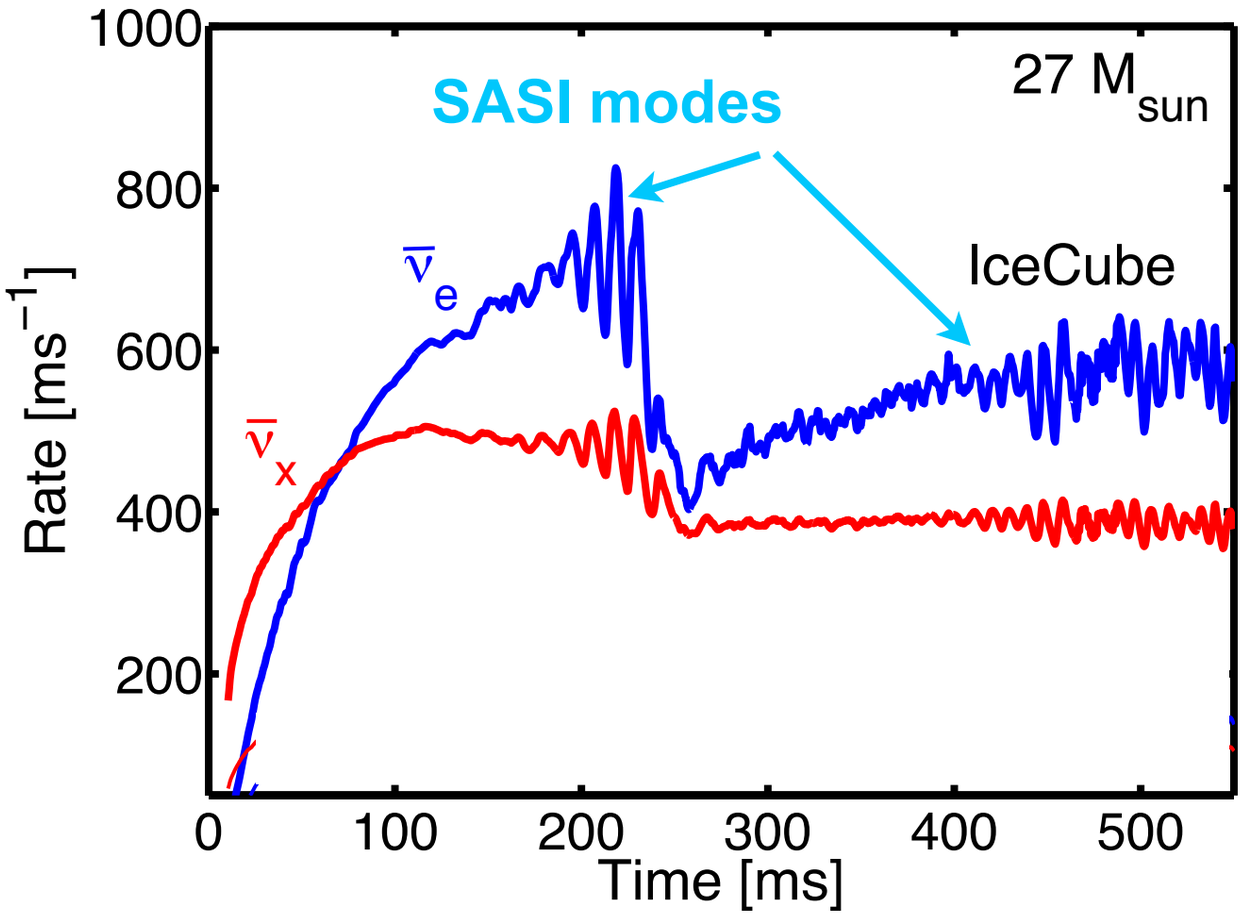


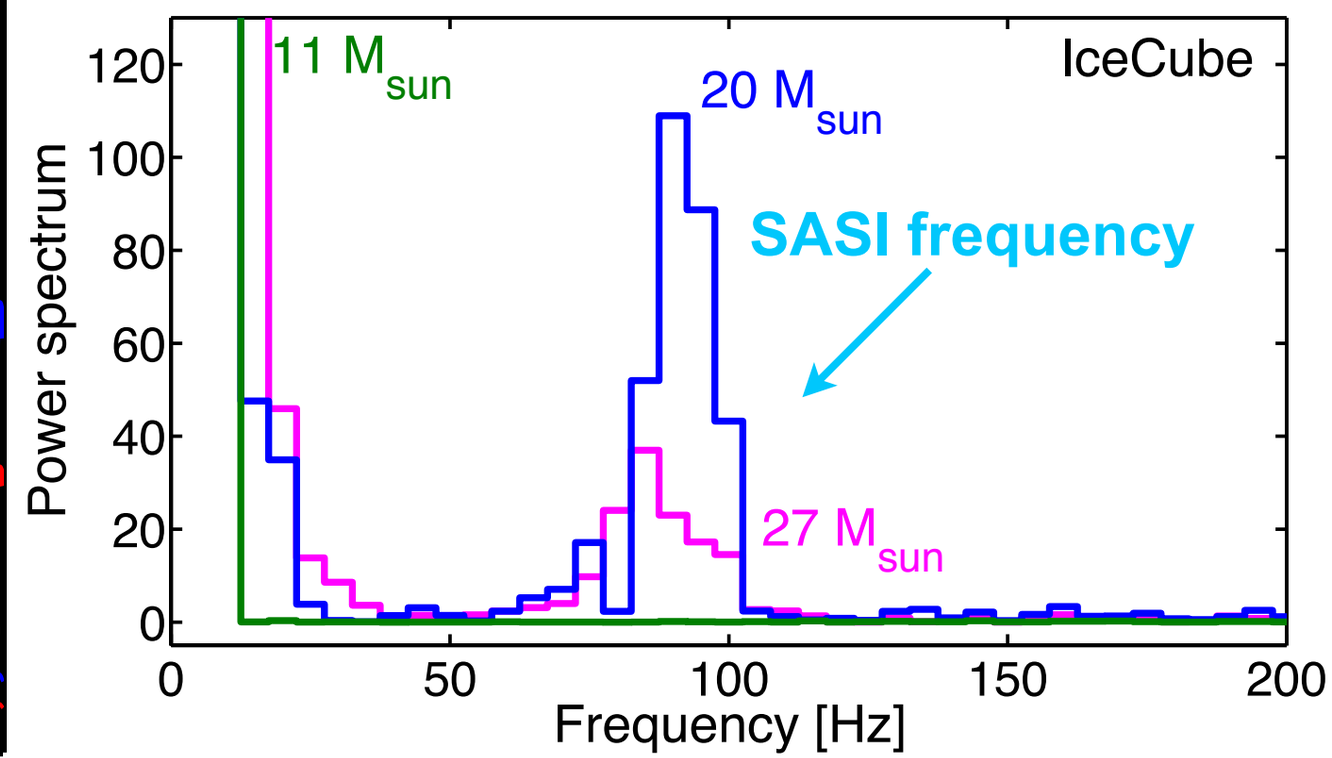
Recent reviews: Janka (2017). Mirizzi, Tamborra et al. (2016).

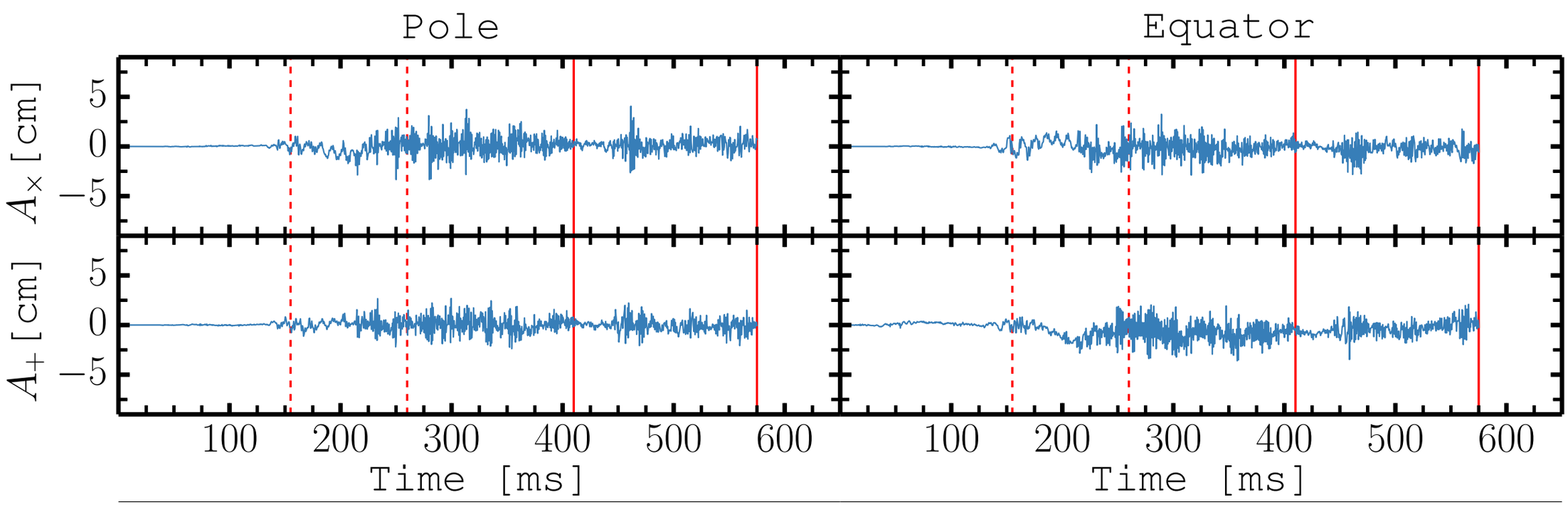
20 M_{sun} Supernova Simulation, Garching group



Fingerprints of the Explosion Mechanism

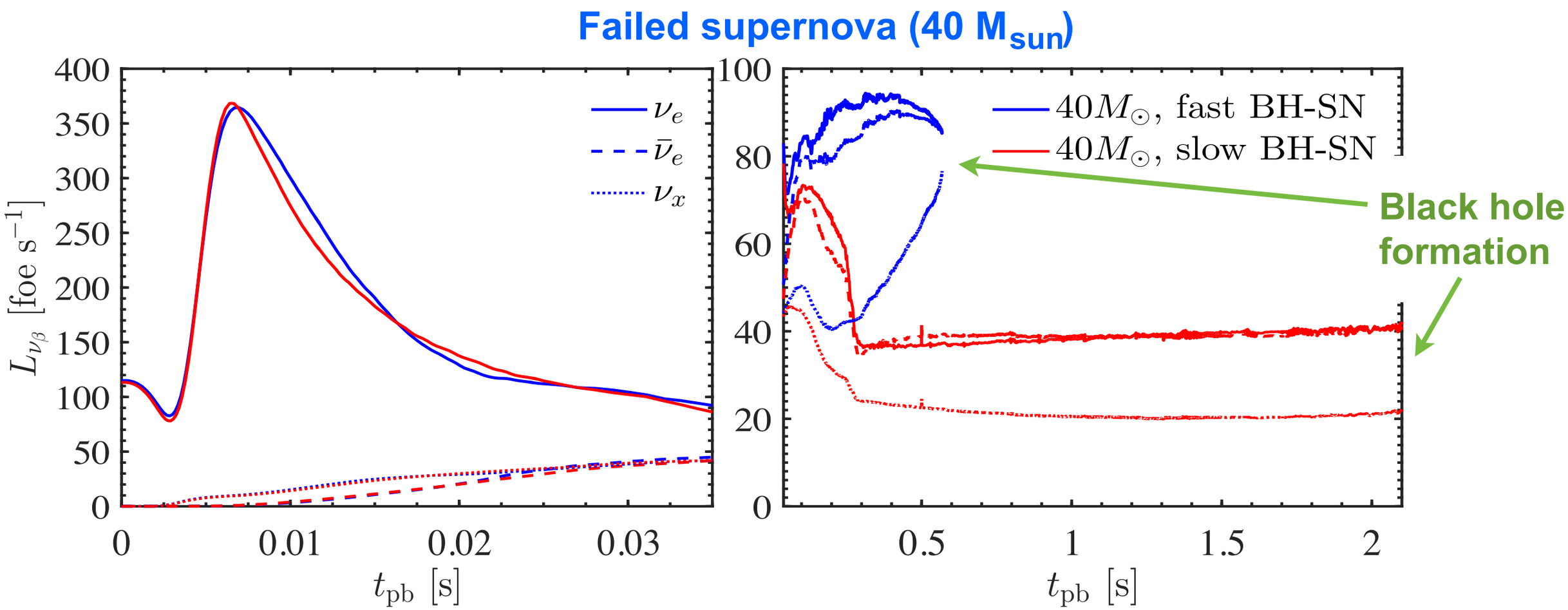






Tamborra et al., PRL (2013), PRD (2014). Andresen et al., MNRAS (2017). Kuroda et al., ApJ (2017).

Black Hole Formation



- Black hole forming collapses up to 20-40% of total (low-mass progenitors can also lead to black hole formation).

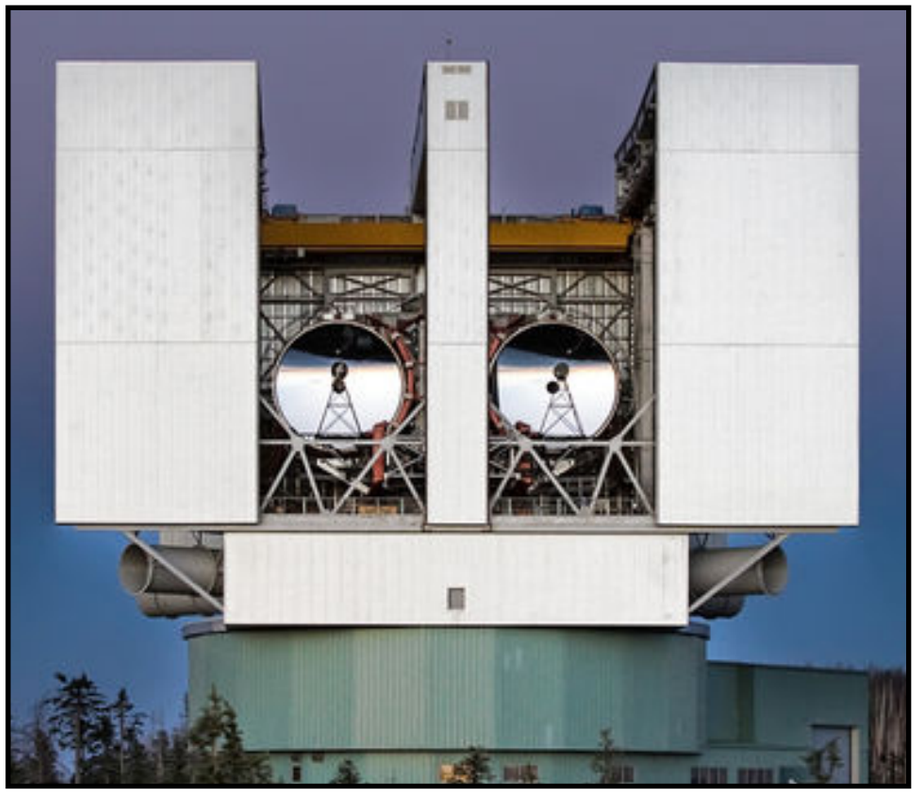
- Neutrinos (and gravitational waves) may be the only probes revealing the black hole formation.

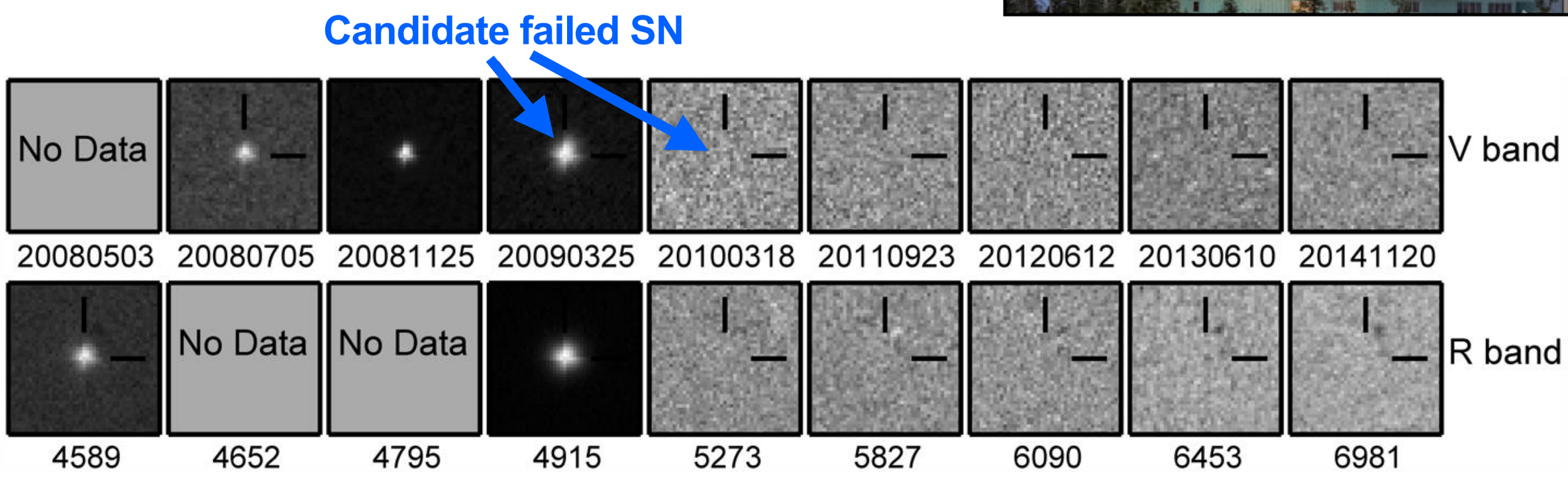
Figure credit: Mirizzi, Tamborra et al. (2016).

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**.

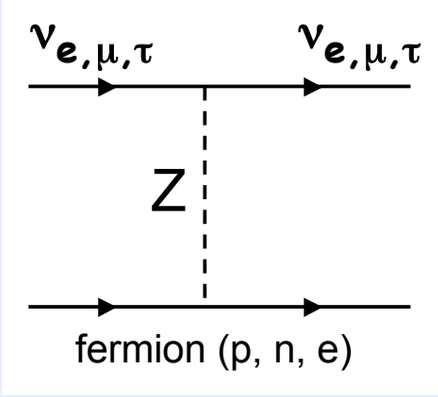


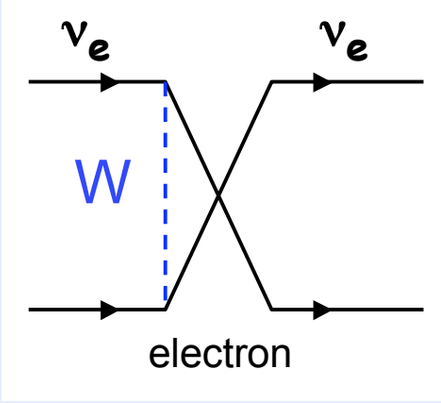


Failed core-collapse fraction: 4-43% (90% CL)

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

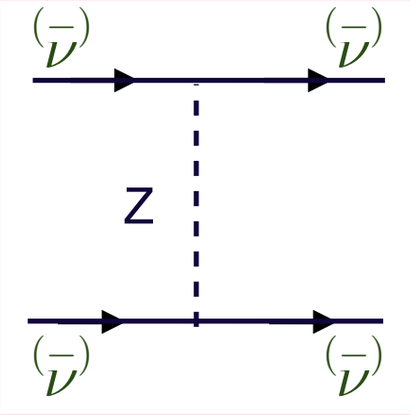
Neutrino Flavor Conversion in Dense Media





Neutrinos interact with background matter.

Linear phenomenon.



Neutrinos interact among themselves.

Non-linear phenomenon, trajectory is crucial!

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

Neutrino Quantum Kinetics

Full neutrino transport + flavor oscillations = **7D problem!**

Density Matrix

$$\left(\partial_t + \vec{v}\cdot\vec{\nabla}_x + \vec{F}\cdot\vec{\nabla}_p\right)\rho(t,\vec{x},\vec{p}) = -i\,[H(t,\vec{x},\vec{p}),\rho(t,\vec{x},\vec{p})] + \mathcal{C}[\rho(t,\vec{x},\vec{p})]$$

External forces

Collision term

Vacuum term

Matter term
[MSW resonant conversion]

$\nu-\nu$ **interaction term**
[neutrino self-interactions]

Challenging problem:

- Stiff equations of motion, involving non-linear term (nu-nu interactions).
- Quantities changing on very different time scales involved.

Equations of Motion, an Example

If we assume to have a stationary, spherically symmetric supernova, then

$$i\,\dot{\varrho}_{E,\vartheta} = [\mathsf{H}_{E,\vartheta}, \varrho_{E,\vartheta}] \qquad \text{and} \qquad i\,\dot{\bar{\varrho}}_{E,\vartheta} = [\bar{\mathsf{H}}_{E,\vartheta}, \bar{\varrho}_{E,\vartheta}]$$

with the Hamiltonian defined as

$$\mathsf{H}_{E,\vartheta} = \frac{\mathsf{U}\mathsf{M}^2\mathsf{U}^\dagger}{2E} + \sqrt{2}G_{\mathrm{F}}\,\mathsf{N}_l + 2\pi\sqrt{2}G_{\mathrm{F}}\int dE'\int d\cos\vartheta'\;\left(\varrho_{E',\vartheta'} - \bar{\varrho}_{E',\vartheta'}\right)\left(1-\cos\vartheta\cos\vartheta'\right)$$

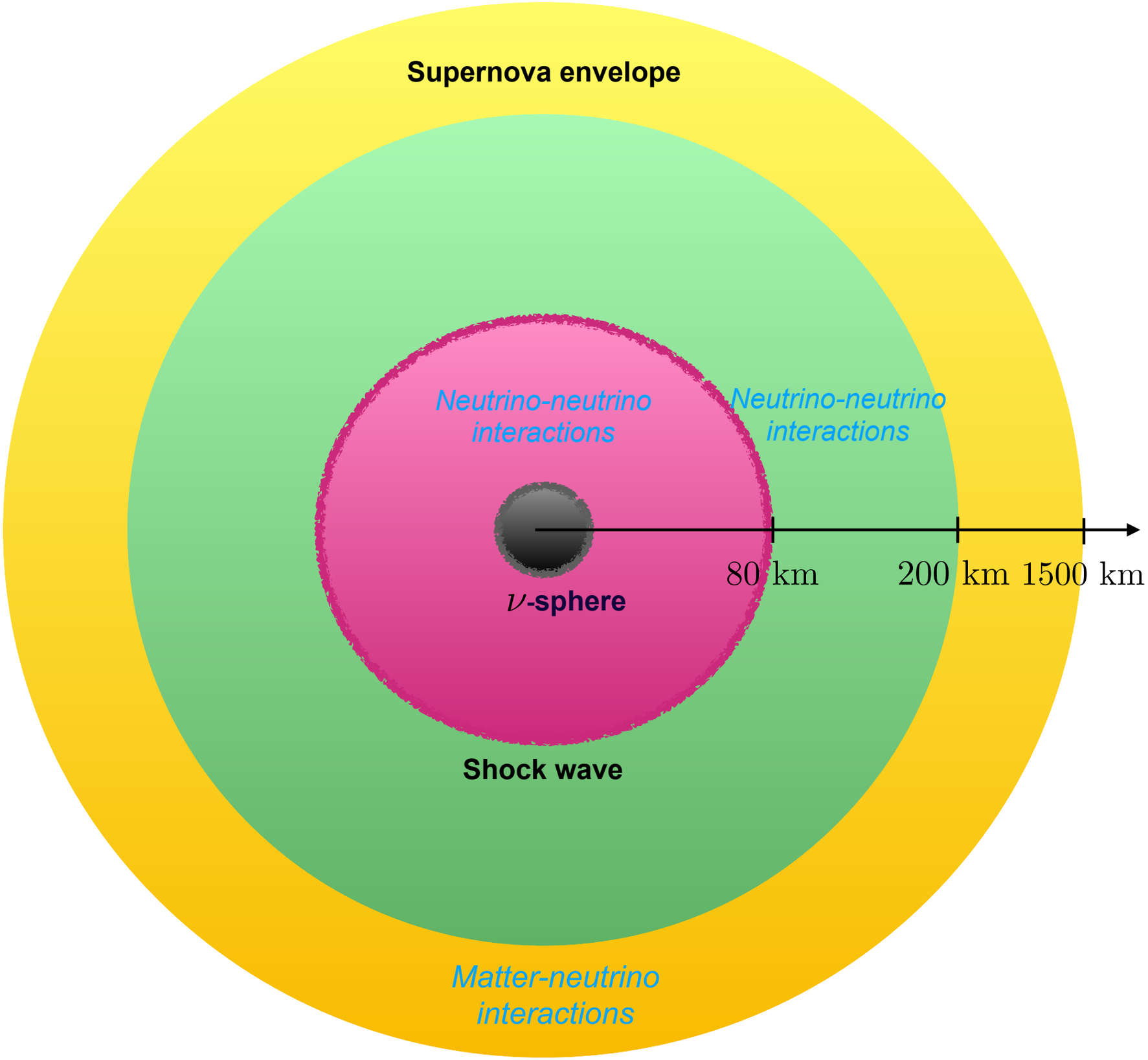
vacuum term

matter term
[MSW resonant conversion]

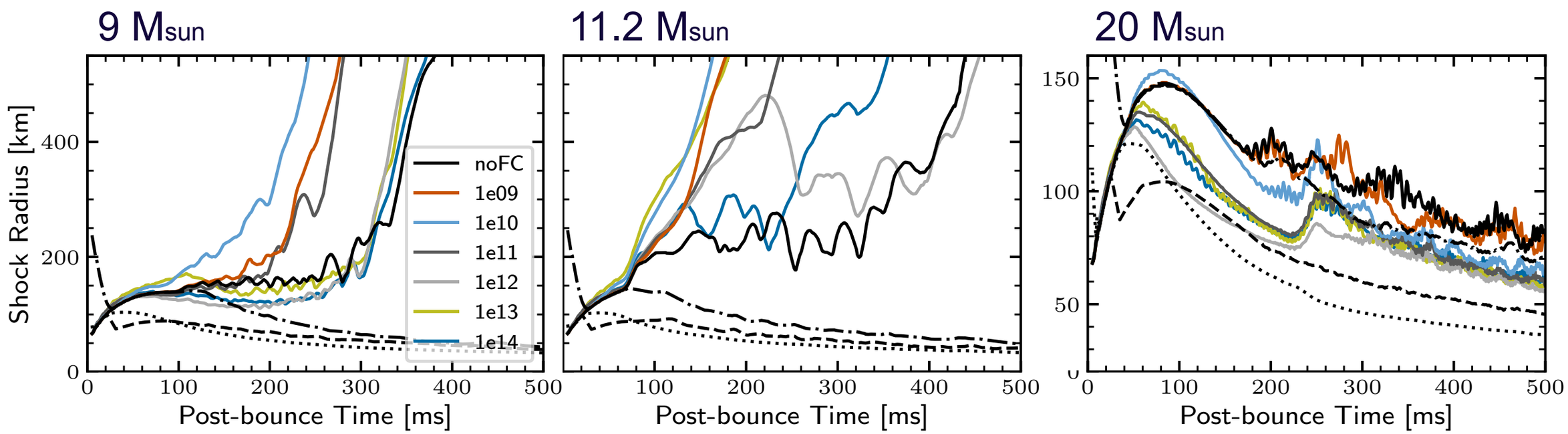
$\nu - \nu$ **interaction term**
[neutrino self-interactions]

The Hamiltonian for antineutrinos has the vacuum term with opposite sign.

Does Flavor Conversion Affect Supernova Mechanism?



Does Flavor Conversion Affect Supernova Mechanism?

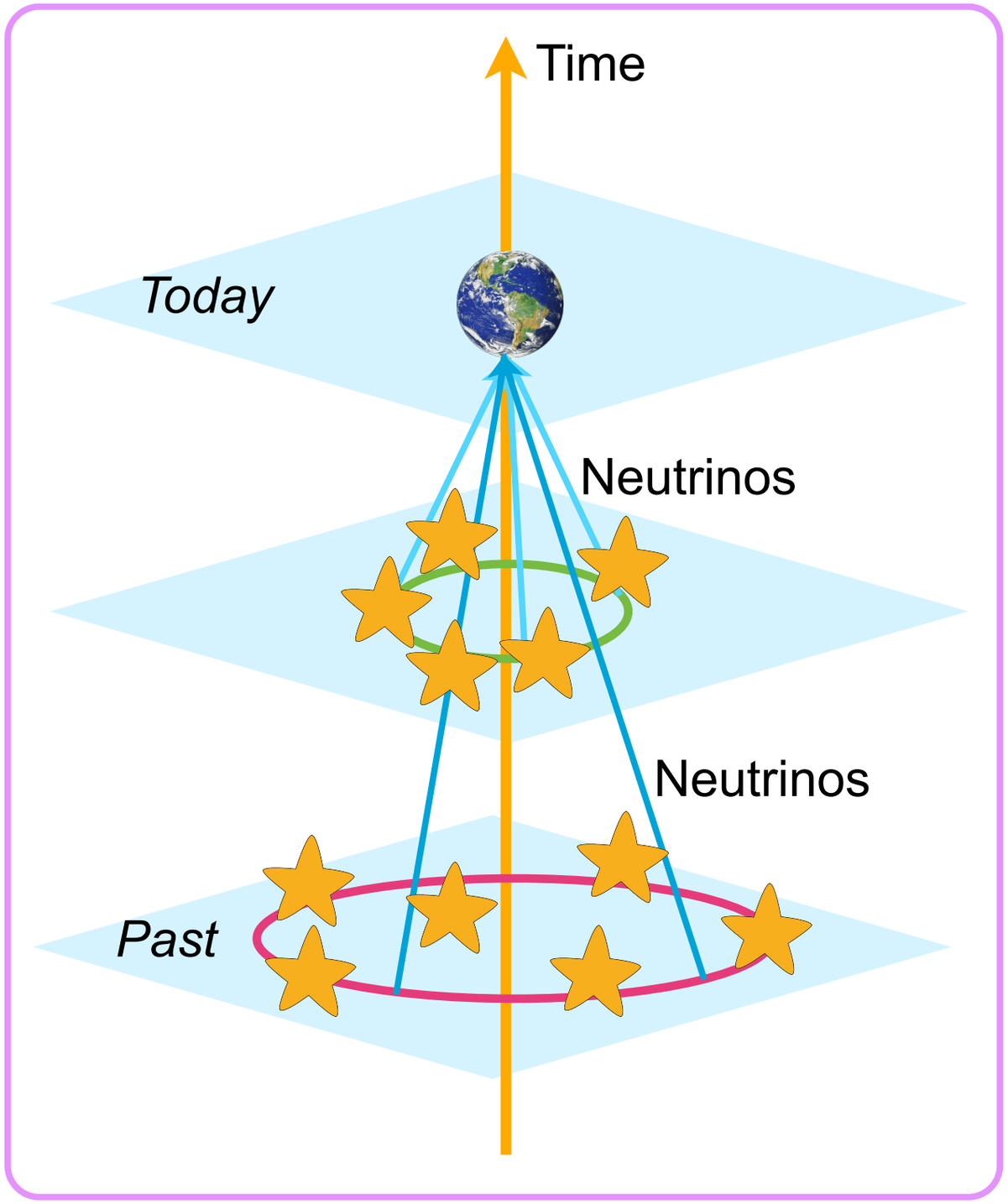


- Parametric implementation of flavor conversion in hydrodynamical simulations highlights non-trivial feedback on SN physics.
- Flavor conversion aids the explosion for low mass progenitors (9-12 Msun) and hinders explosion of higher-mass models (20 Msun).

Ehring, Abbar, Janka, Raffelt, Tamborra, PRL (2023). Ehring, Abbar, Janka, Raffelt, Tamborra, PRD (2023).
Nagakura, PRL (2023).

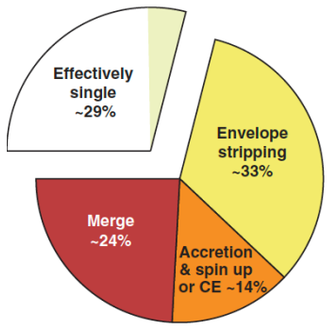
Diffuse Supernova Neutrino Background

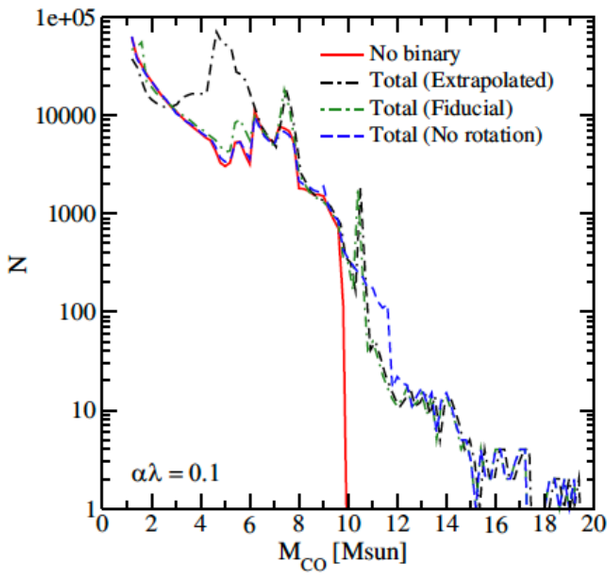
On average 1 SN/s somewhere in the universe → Diffuse neutrino background (**DSNB**).



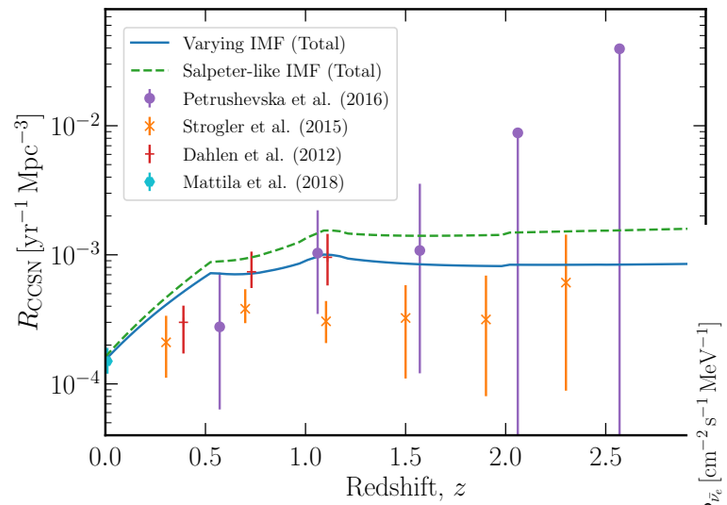
DSNB Modeling: What's Missing?

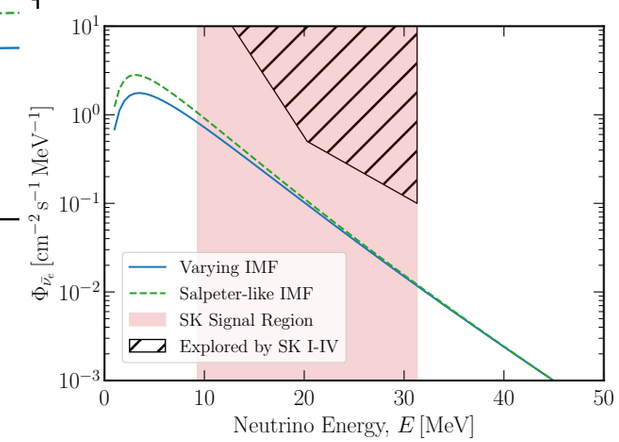
Affected by binary interactions (mass transfer and mergers)



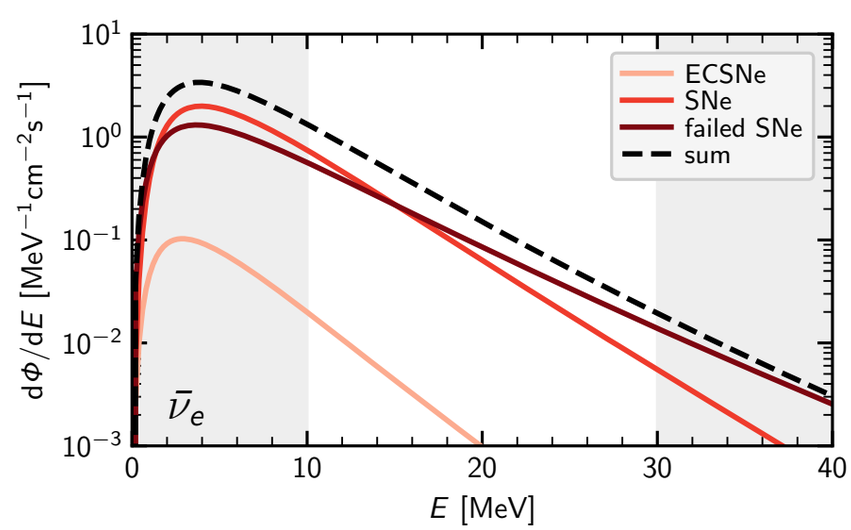


Affected by uncertainties on stellar evolution, stellar initial mass function





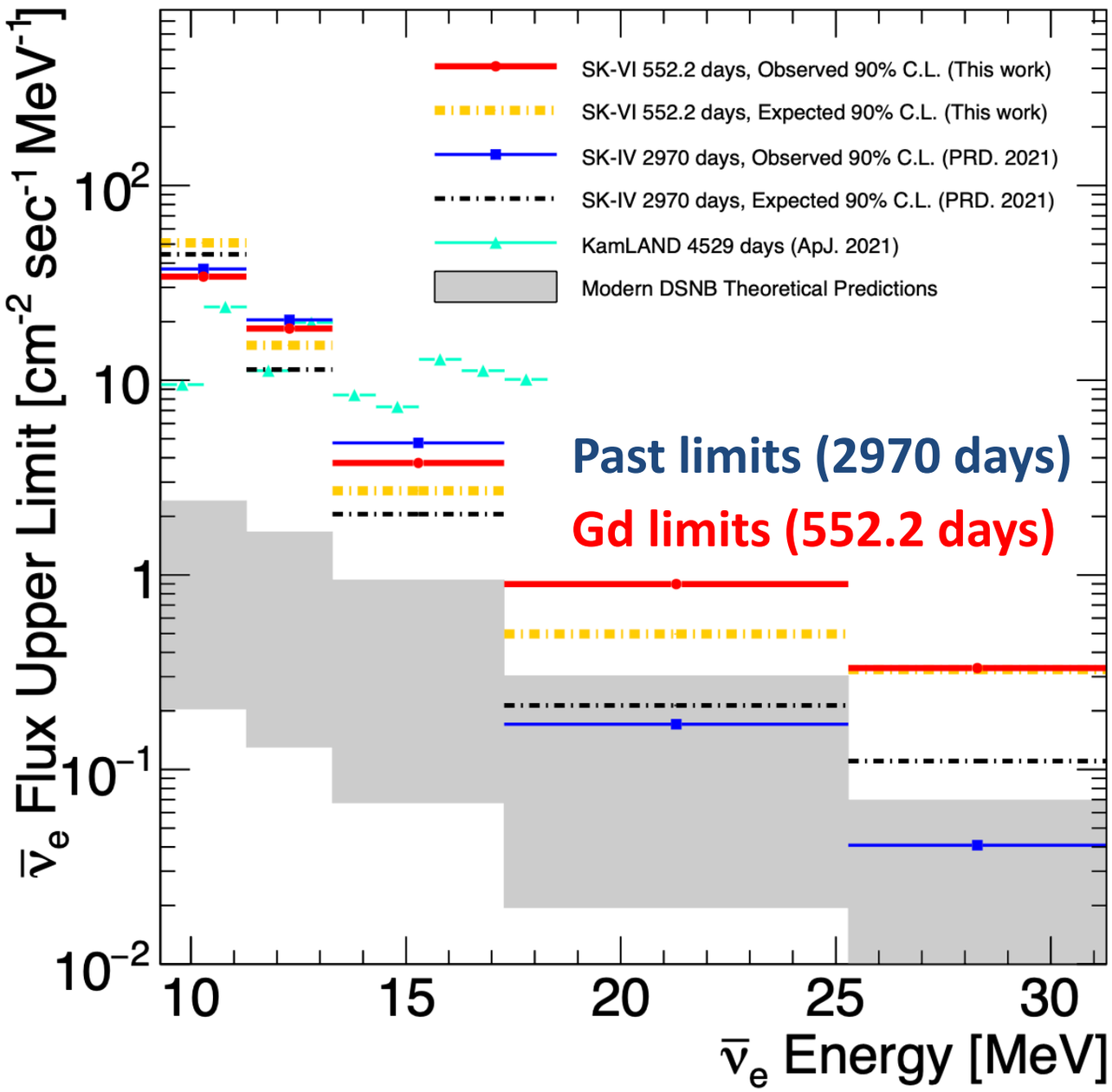
Affected by fraction of black hole forming collapses



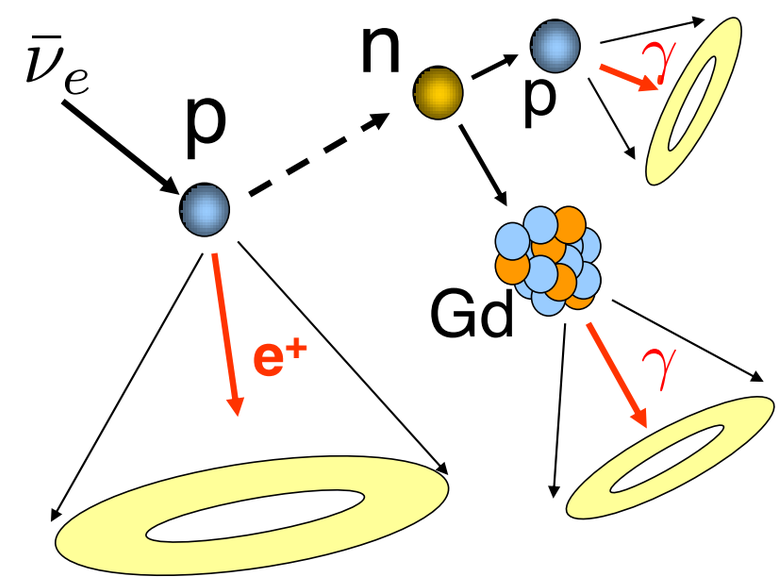
Moller, Suliga, Tamborra et al., JCAP (2018). Kresse, Ertl, Janka, ApJ (2020). Horiuchi et al., PRD (2021). Ashida, Nakazato, Tsujimoto, arXiv: 2305.13543. Ziegler et al., MNRAS (2022).

DSNB with Super-Kamiokande-Gd

The DSNB has not been observed yet. Most stringent limits from Super-Kamiokande (SK):



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



Positron and gamma ray vertices are within ~50cm.

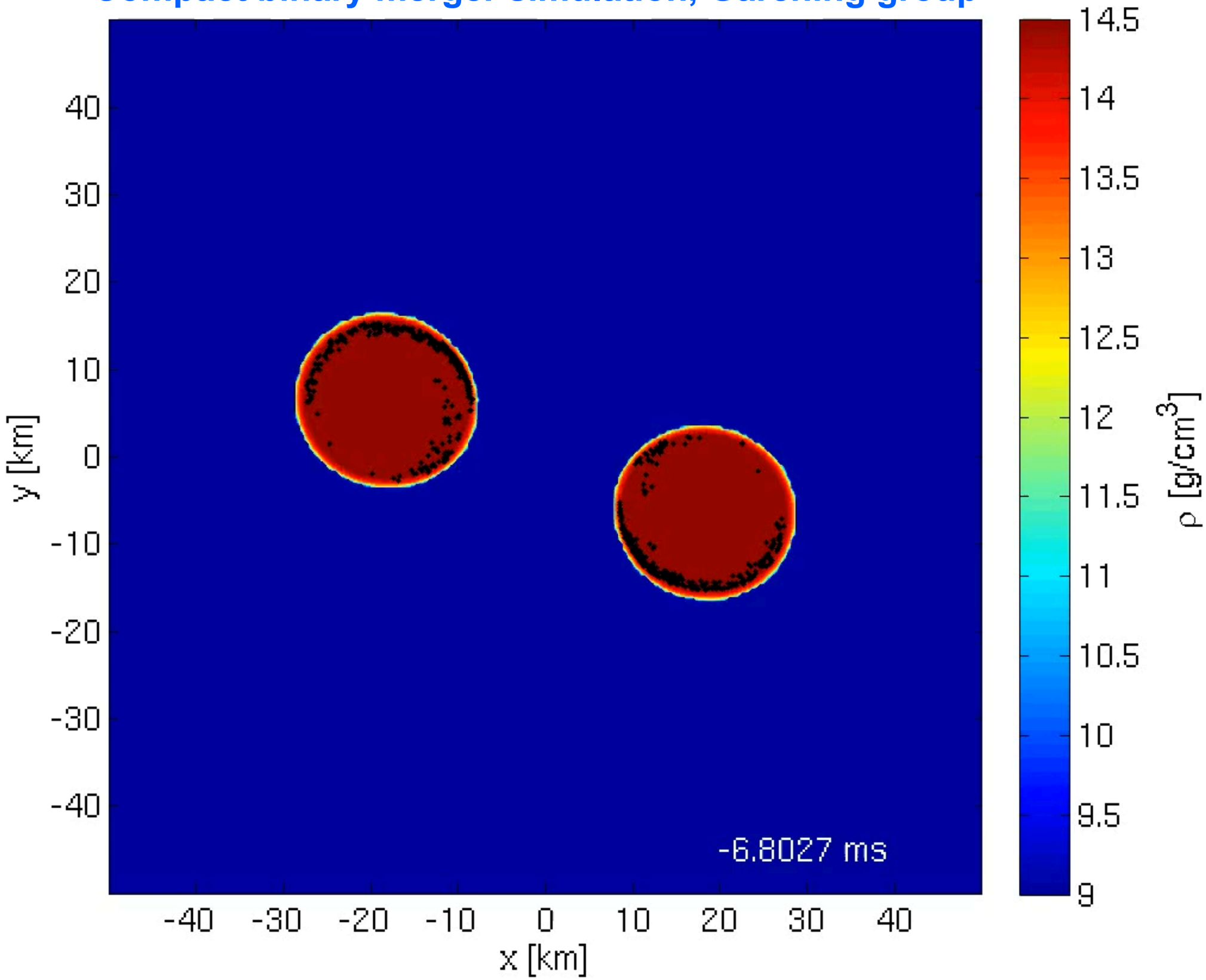
SuperK-Gd results with 0.01% Gd already comparable to ~10 years of pre-Gd results.

Figure from Harada et al., ApJ Lett. (2023).

Neutron Star Mergers

Compact Binary Mergers

Compact binary merger simulation, Garching group



Compact Binary Mergers

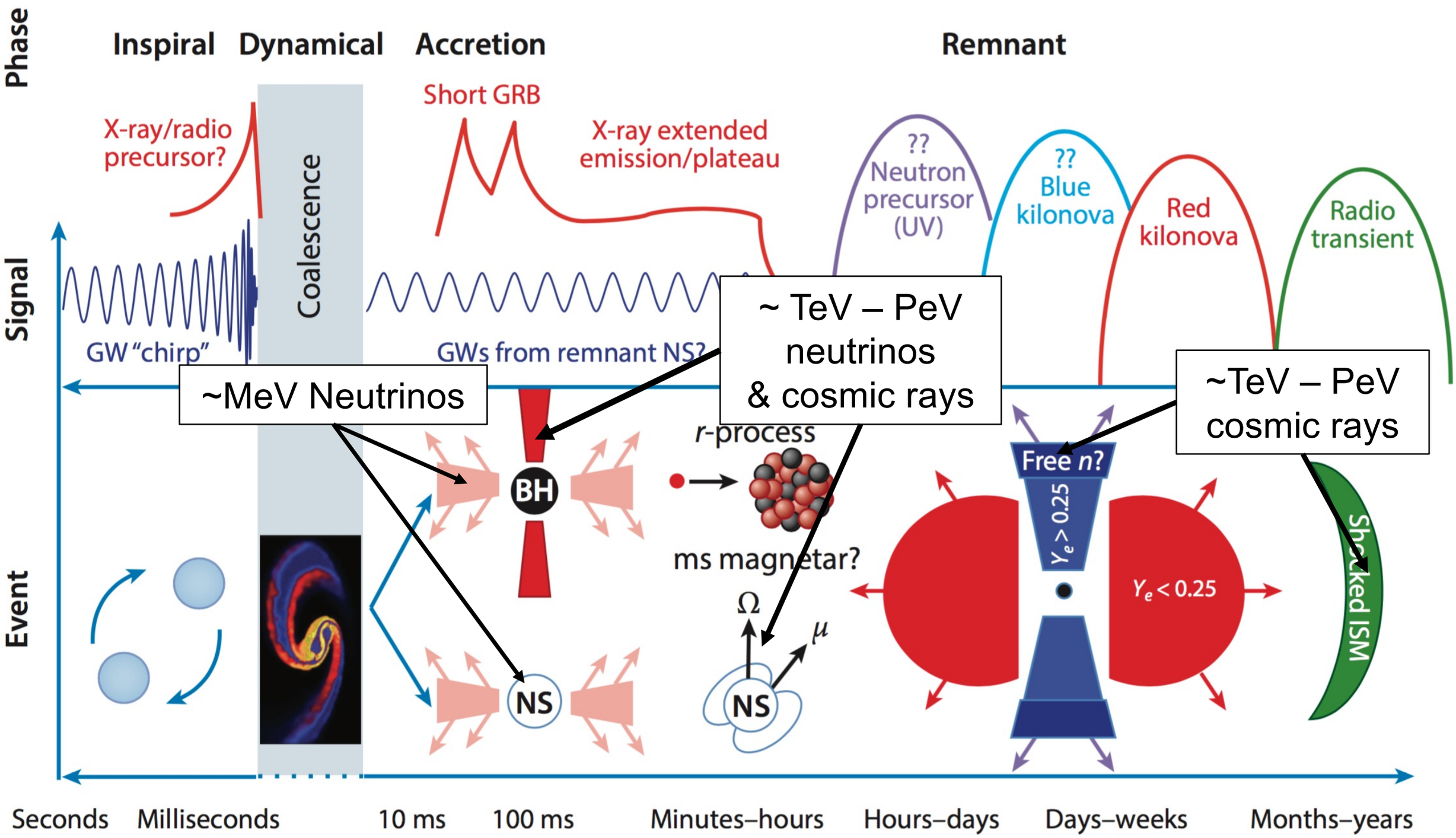


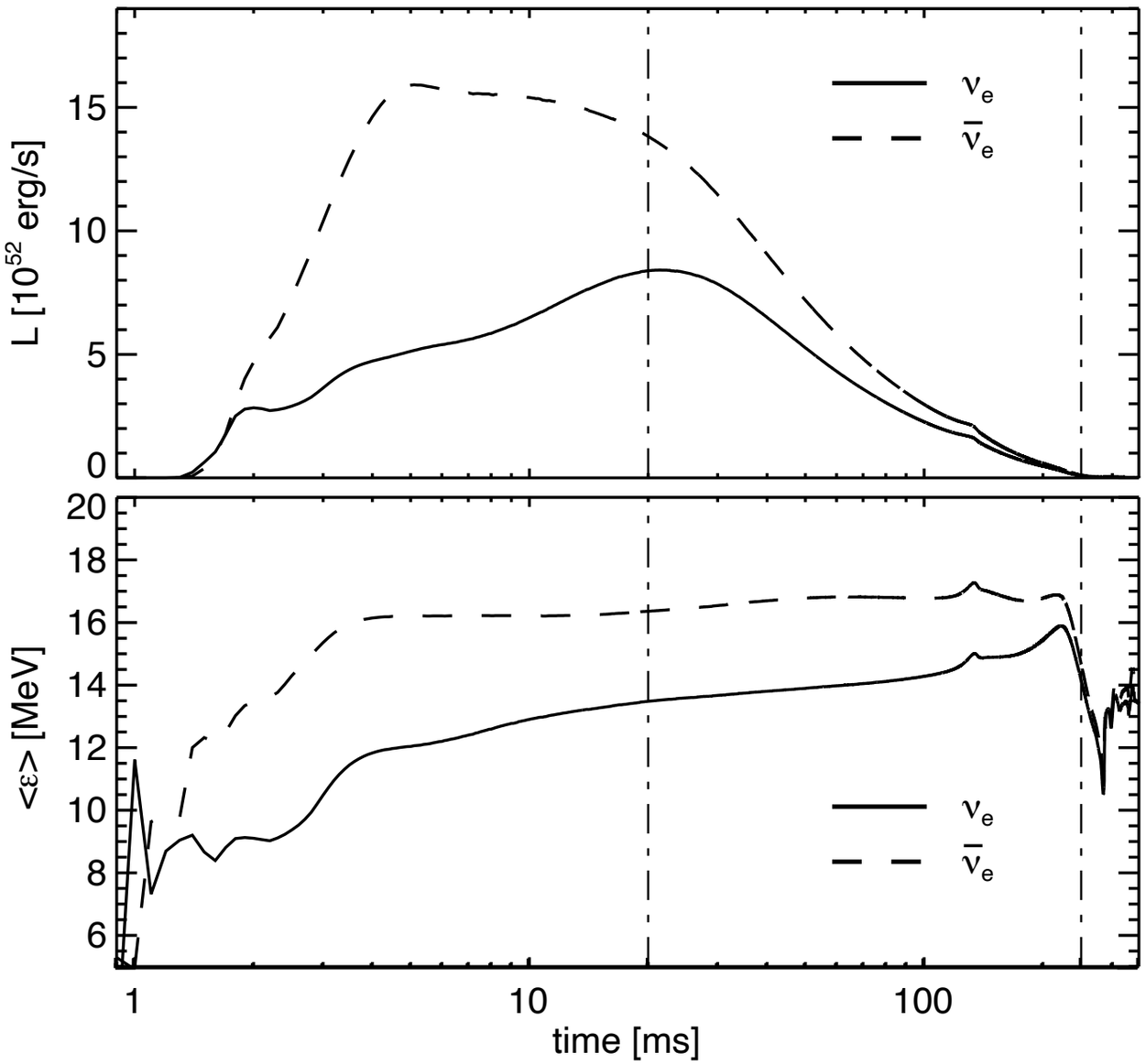
Figure credit: B. Metzger.

Compact Mergers vs. Supernovae

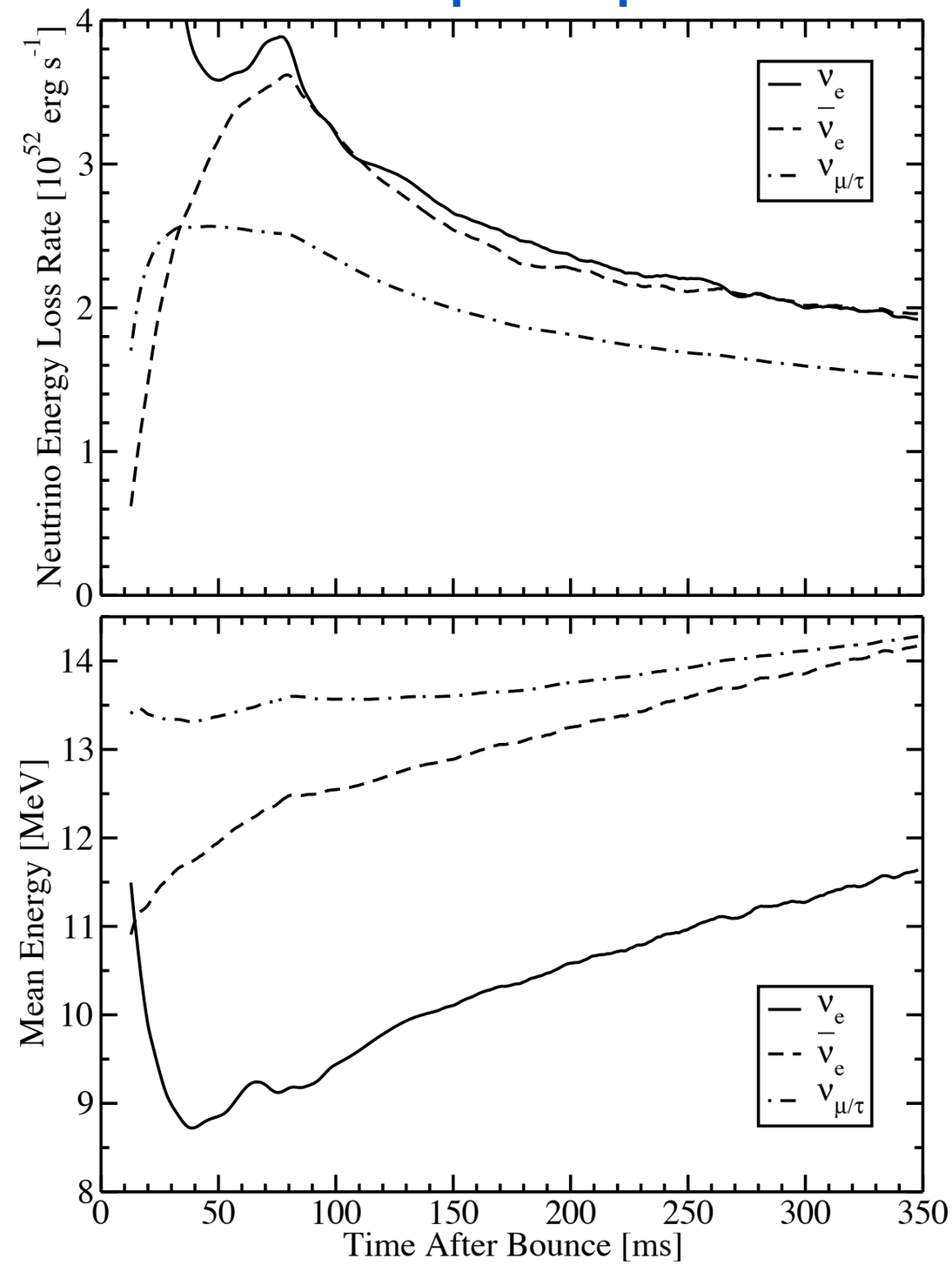
Event Type	Mergers	Core-Collapse SN
Physical Mechanism	Merging of two neutron stars	Core collapse of massive star
Neutrino Properties	Comparable (>SN)	Comparable
Neutrinos Features	Antineutrino rich	Neutrino rich
Detectability	Nucleosynthesis imprints	Galactic source

Neutrino Emission Properties

Neutron star merger remnant



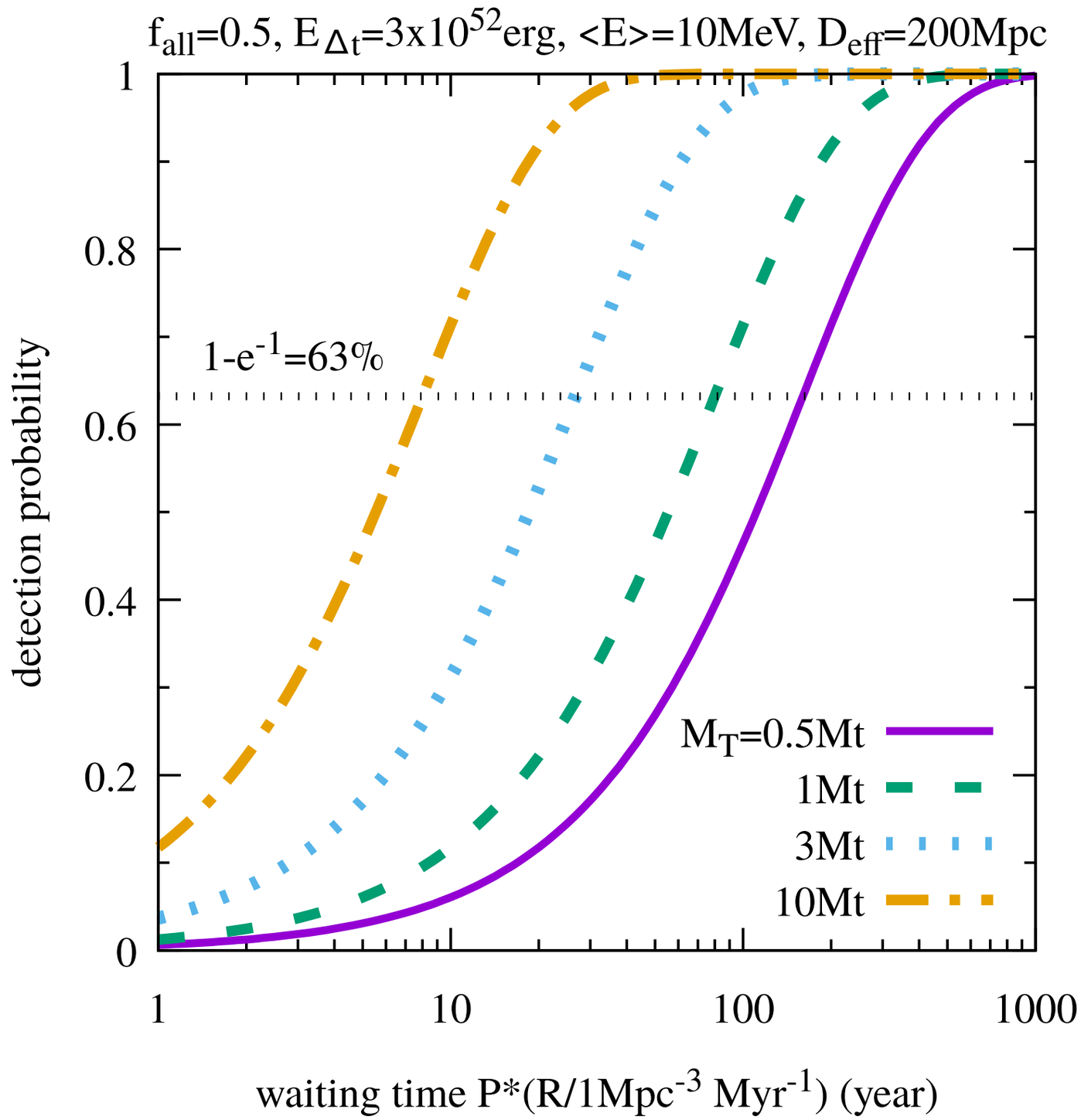
Core-collapse supernova



Mergers exhibit excess of antineutrinos over neutrinos (conversely to supernovae).

Figures from Wu, Tamborra et al., PRD (2017), Tamborra et al., PRD (2014).

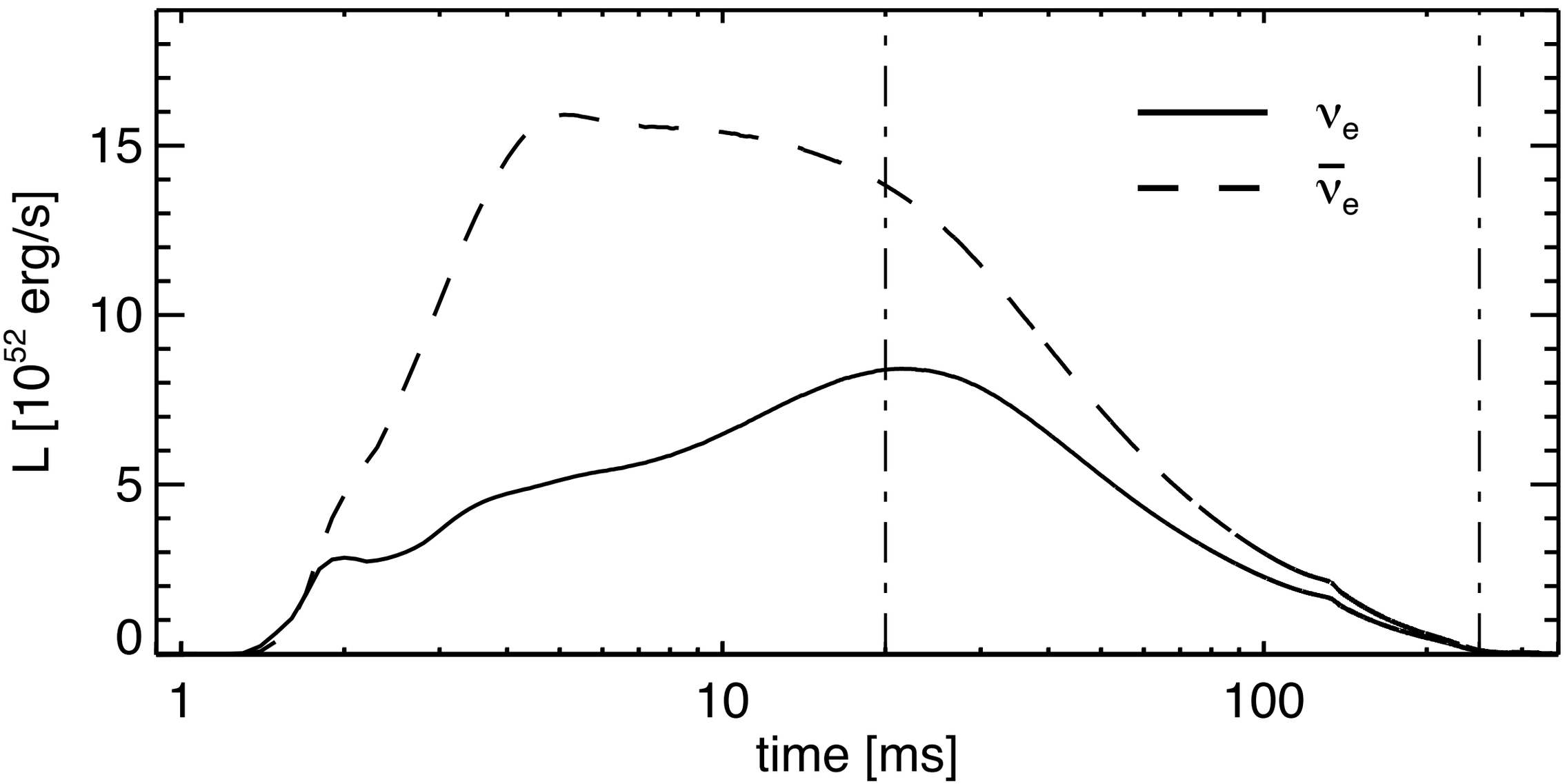
Detection Prospects



Neutrino signal from mergers is more luminous and shorter than SN neutrino signal.
Poor detection chances due to compact merger distribution (1 event/80Mt years in Hyper-K).

Figure credit: Kyutoku & Kashiyama, PRD (2018).

Matter-Neutrino Resonance

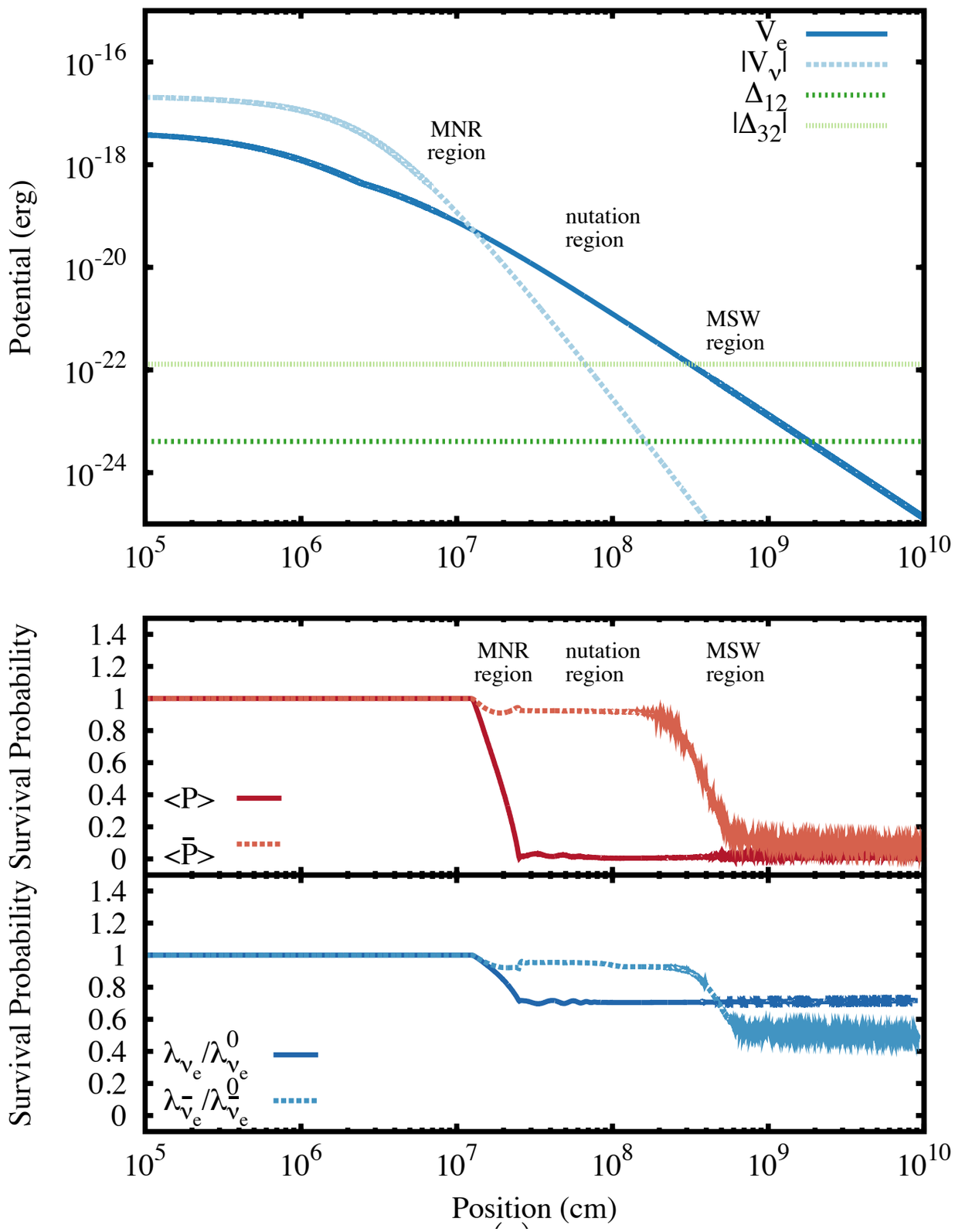


$F_{\bar{\nu}} > F_{\nu}$

New flavor conversion effects, not present in SNe.

Figure from Wu, Tamborra et al., PRD (2017).

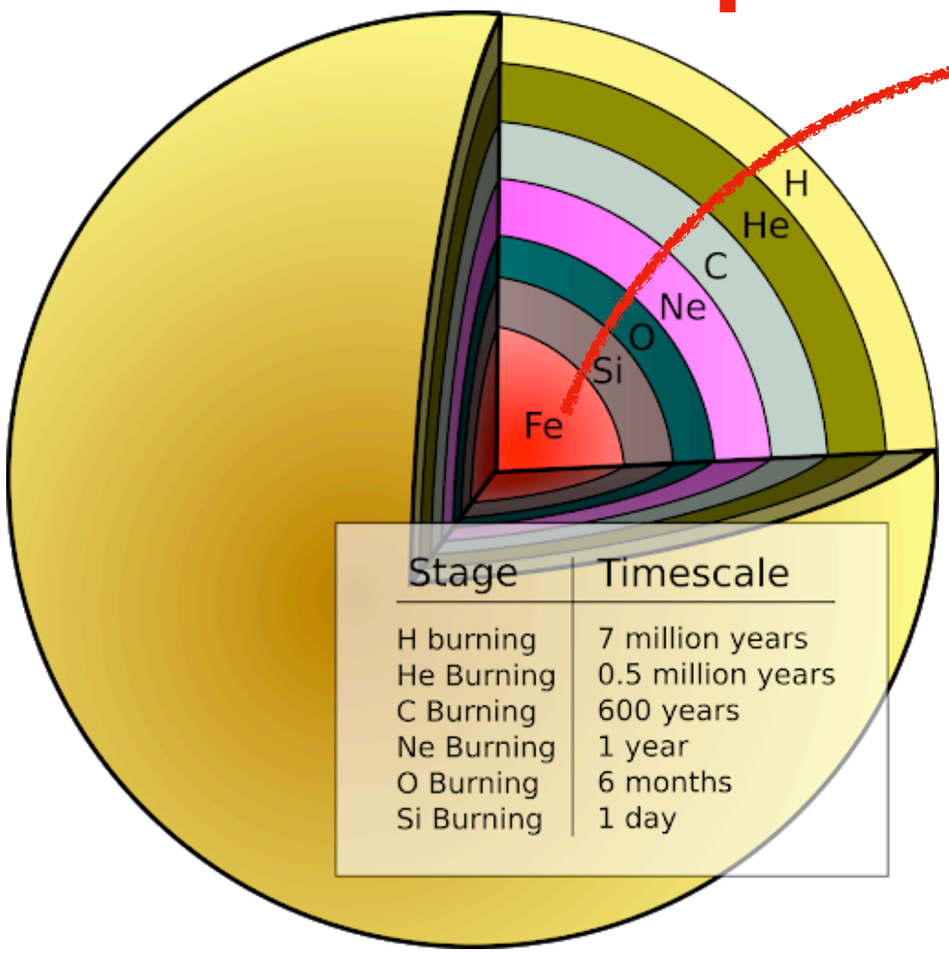
Matter-Neutrino Resonance



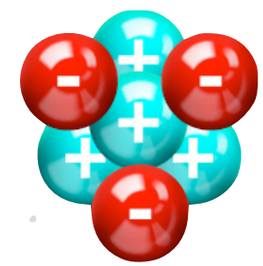
Because of anti-nu excess, the nu-nu potential enters in resonance with the matter one.

Figure from Malkus et al., PRD (2012).

How Are Elements> Fe Produced in Supernovae and Mergers?



Stage	Timescale
H burning	7 million years
He Burning	0.5 million years
C Burning	600 years
Ne Burning	1 year
O Burning	6 months
Si Burning	1 day



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).

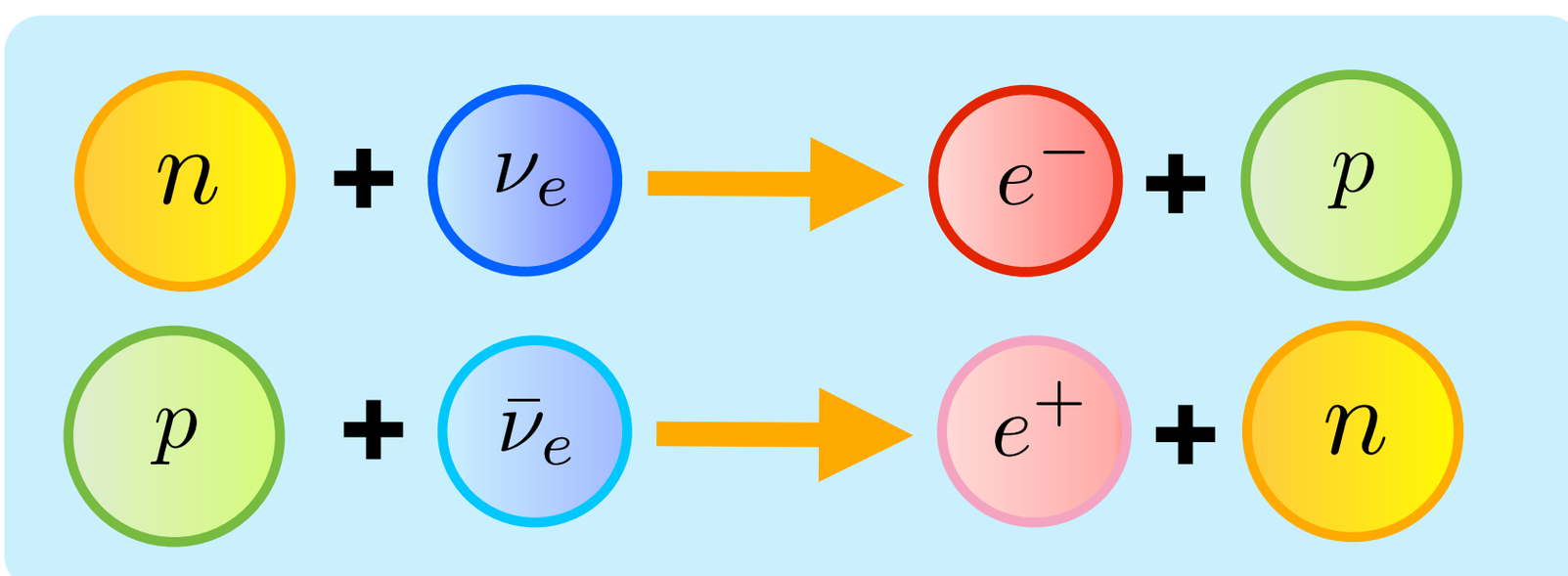
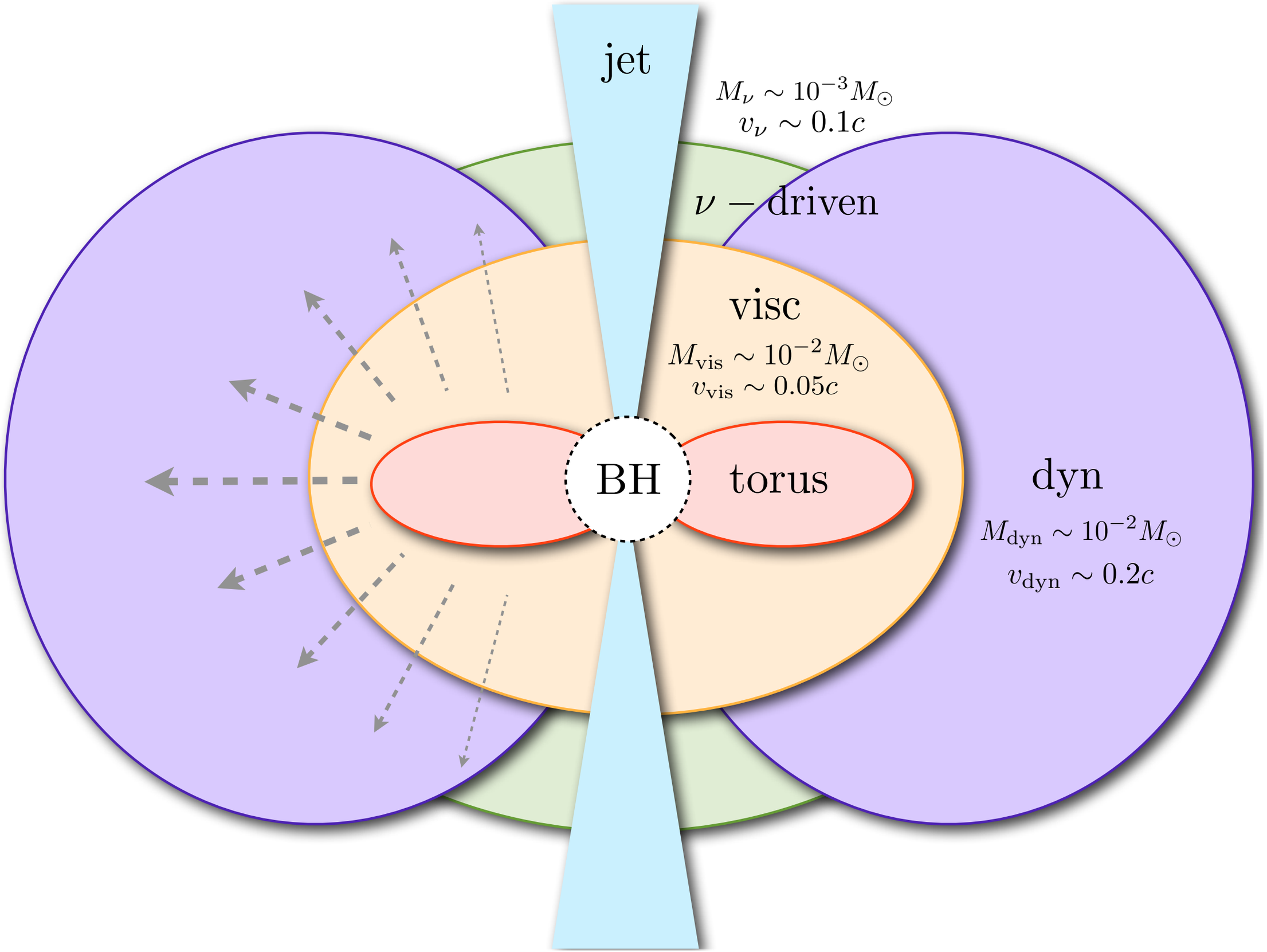
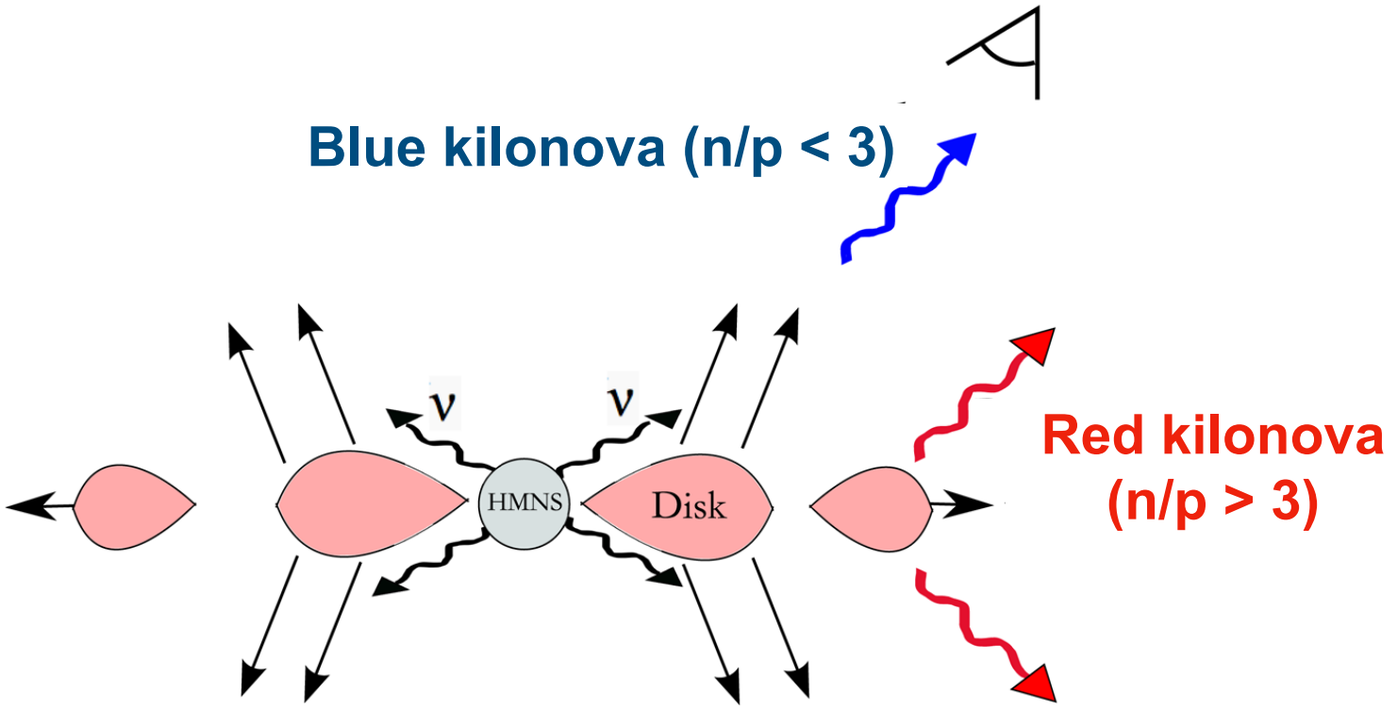


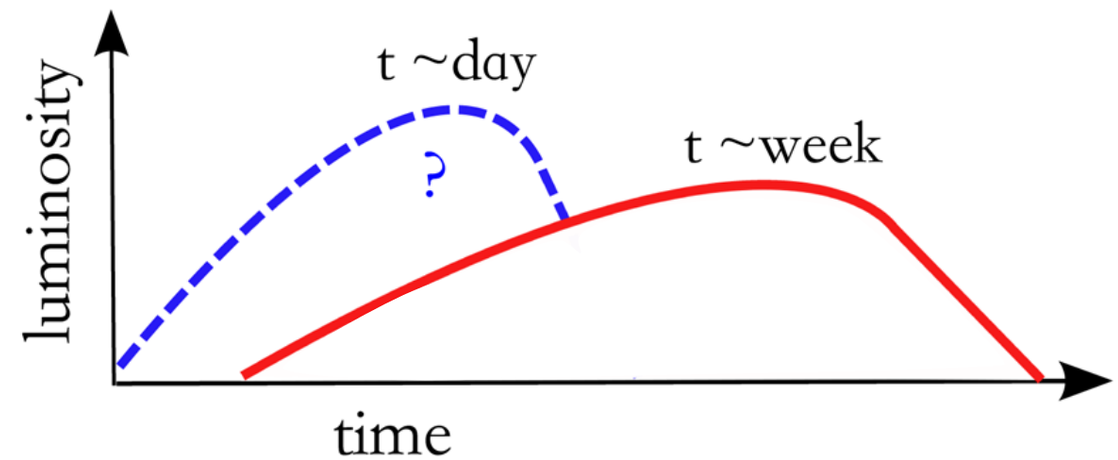
Figure credits: A. C. Phillips, The Physics of Stars, 2nd Edition (Wiley, 1999).

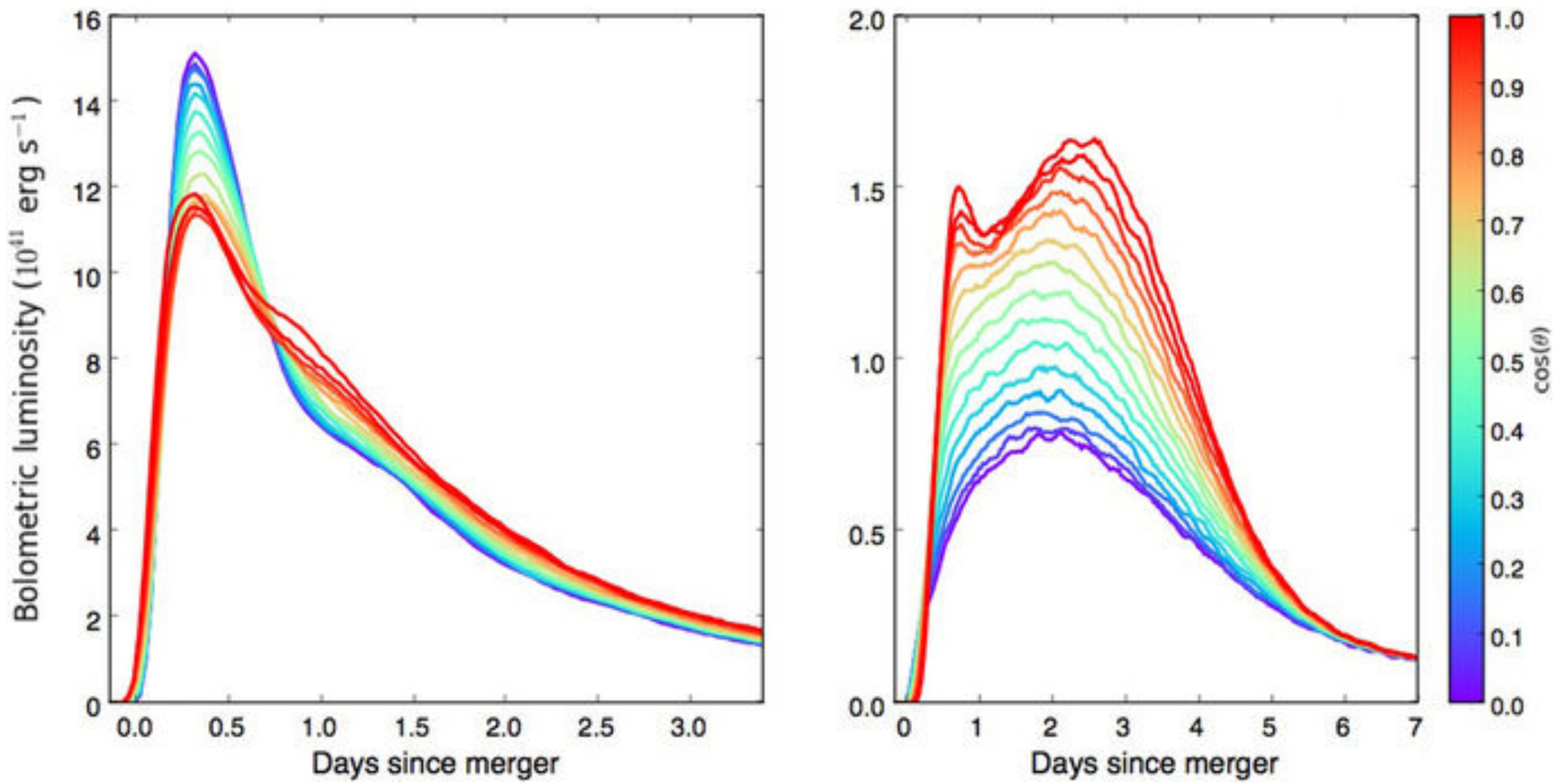
Do Neutrinos Affect Element Production?



Red and Blue Kilonova Components

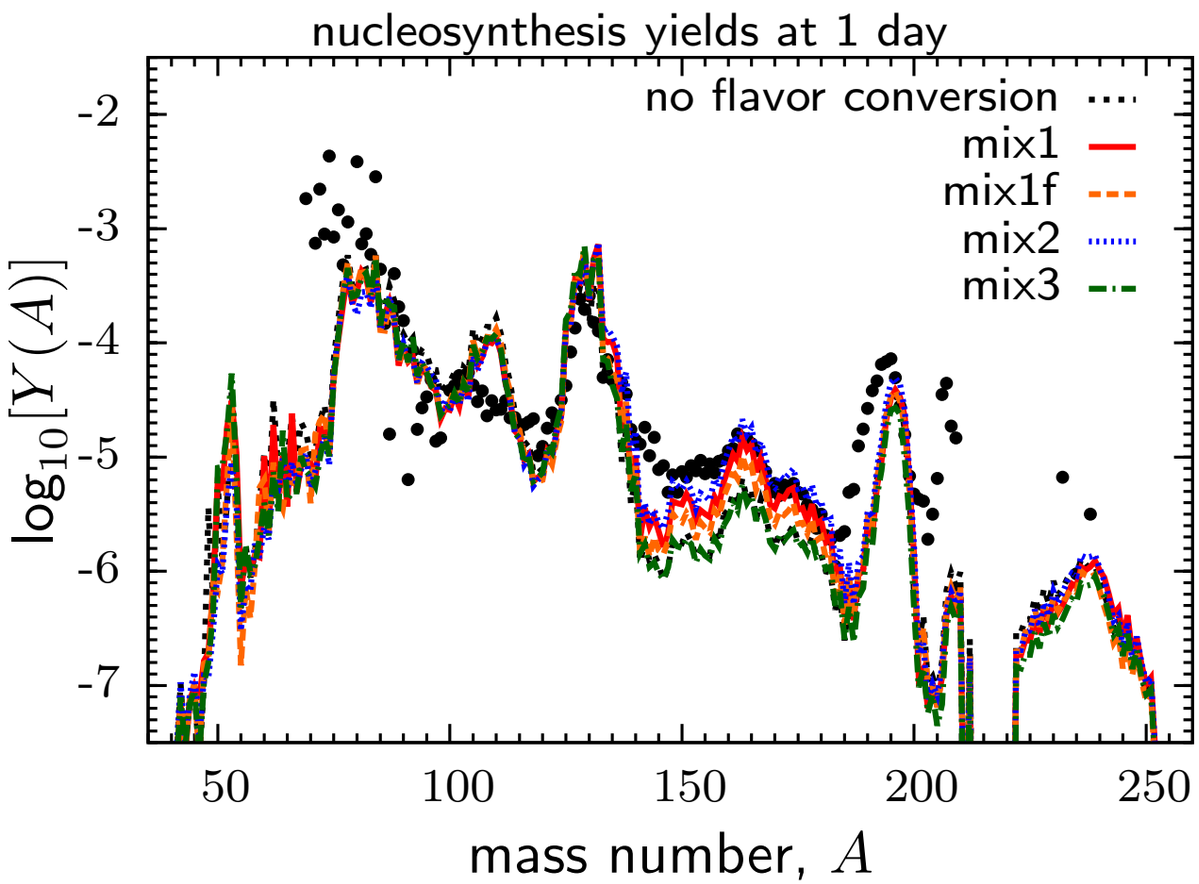


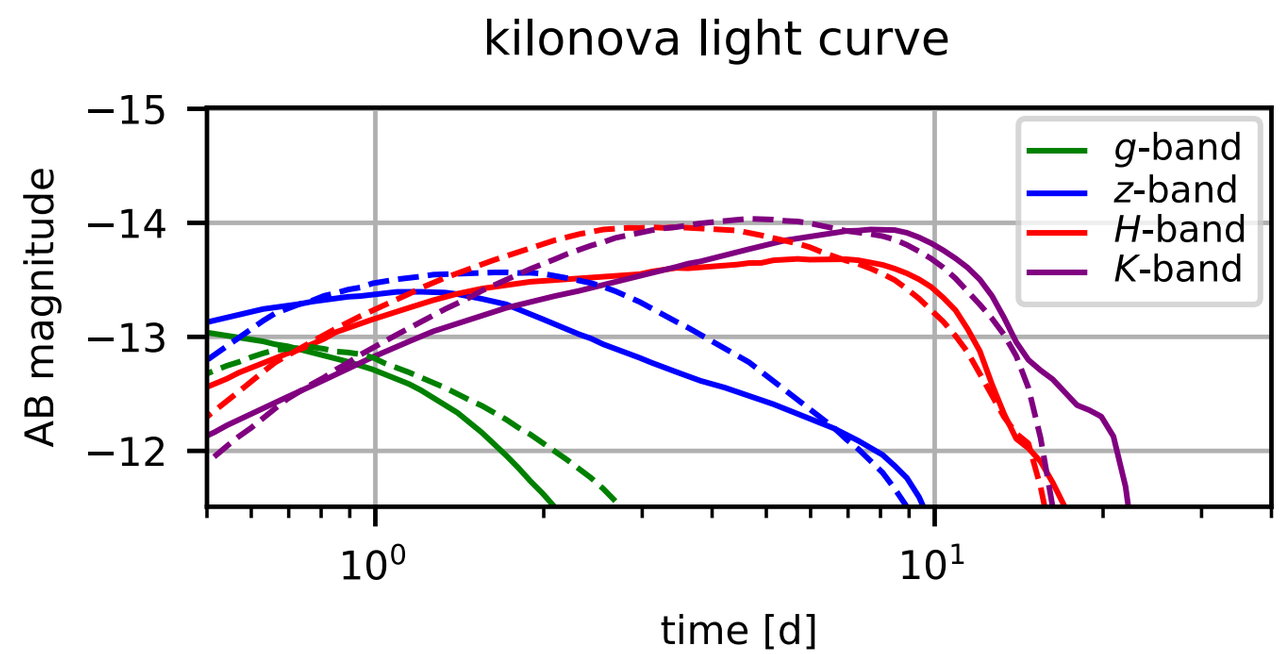




Figures taken from: Metzger & Fernandez, MNRAS (2014); Kasen et al., Nature 2017.

Neutrinos and Nucleosynthesis





Flavor conversion affects the cooling of the disk and enhances synthesis of elements with A>130 by a factor 2-3.

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 et al., PRD (2022).

Summary

- Neutrinos play a fundamental role in the supernova explosion mechanism.

- Neutrino flavor conversion in compact astrophysical sources is not understood yet.

- Neutrinos provide information on supernova properties and trigger multi-messenger detection.

- The diffuse supernova neutrino background will allow us to investigate the supernova population.

- Neutrinos have an impact on the synthesis of the heavy elements in compact binary mergers and disk cooling rate.

Additional references:

- 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
- A. Burrows, D. Vartanyan, https://arxiv.org/abs/2009.14157
- Tamborra & Shalgar, https://arxiv.org/abs/2011.01948
- B. Metzger, https://arxiv.org/abs/1910.01617