Supernovae and Neutrinos

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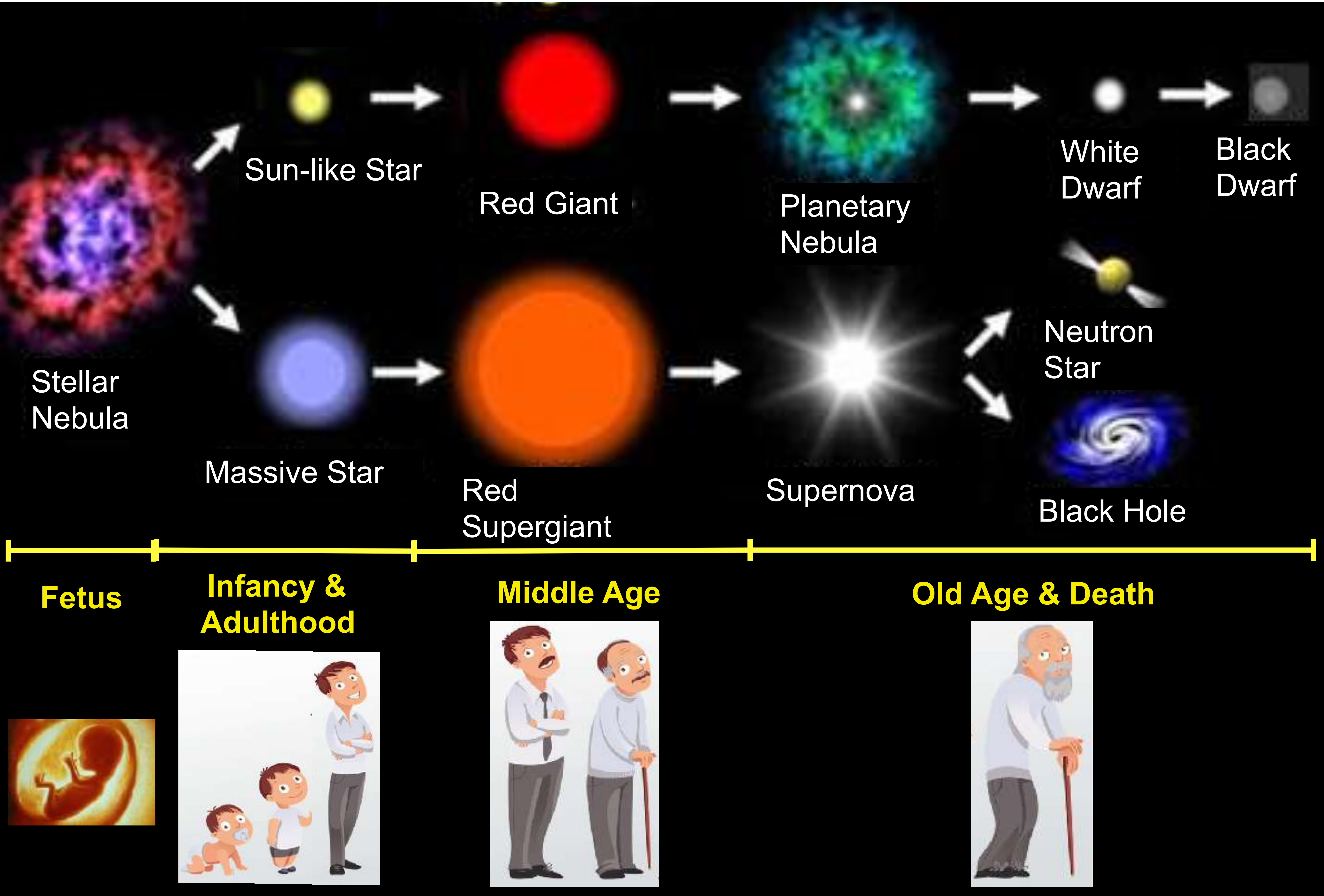
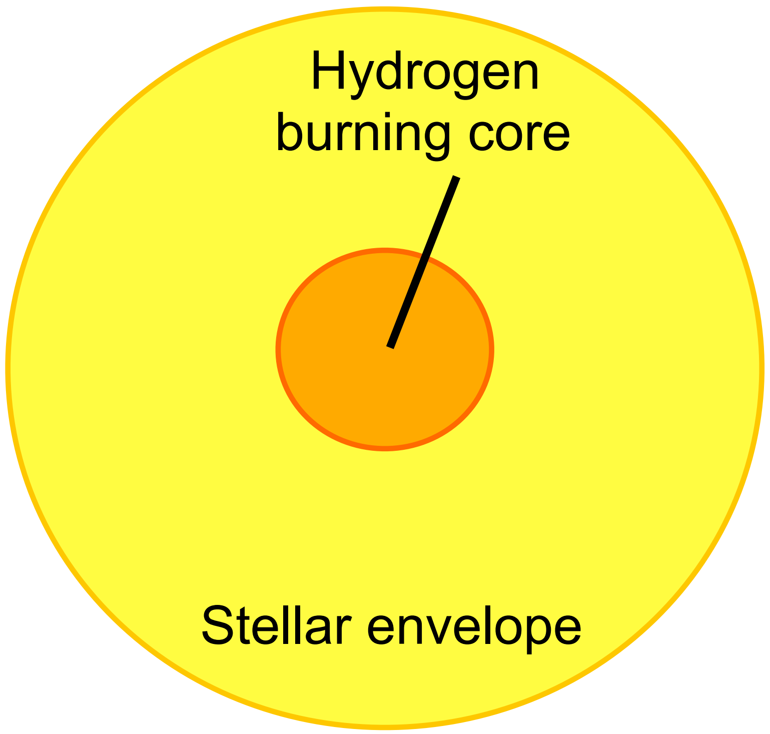
Outline

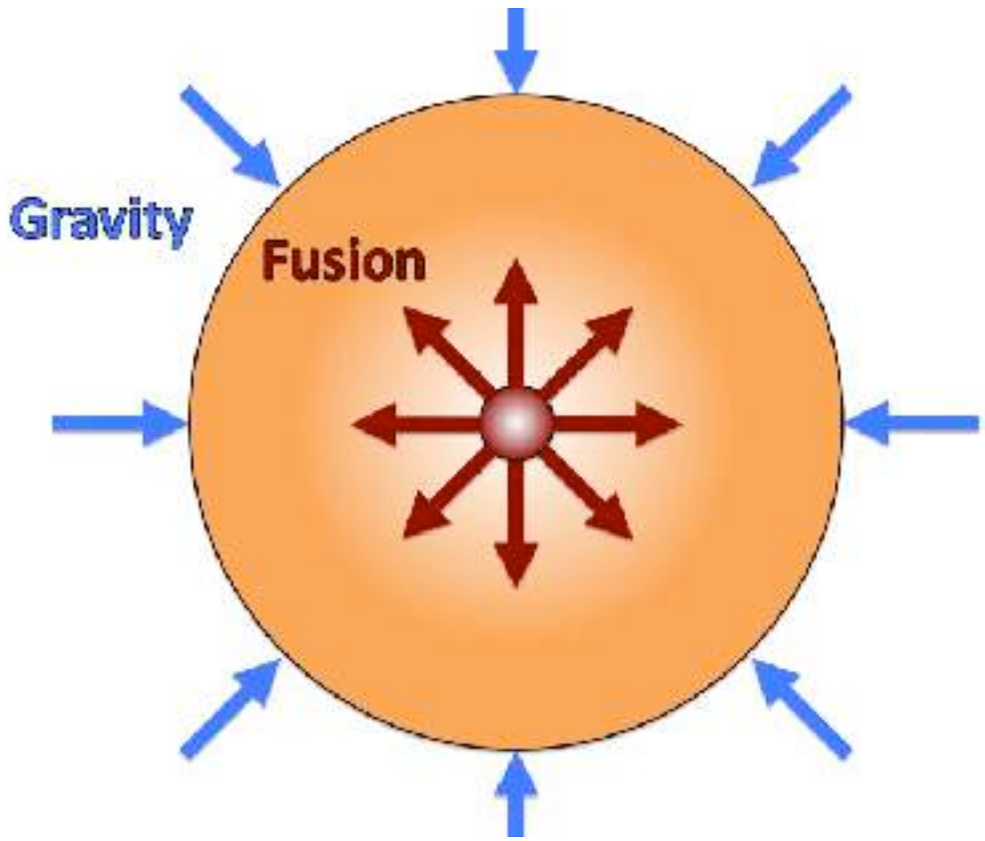
- Core-collapse supernovae
- Neutrinos, gravitational waves, and photons
- Probes of supernova physics and detection perspectives
- Neutrino flavor conversions
- Diffuse supernova neutrino background

Lifecycle of a Star

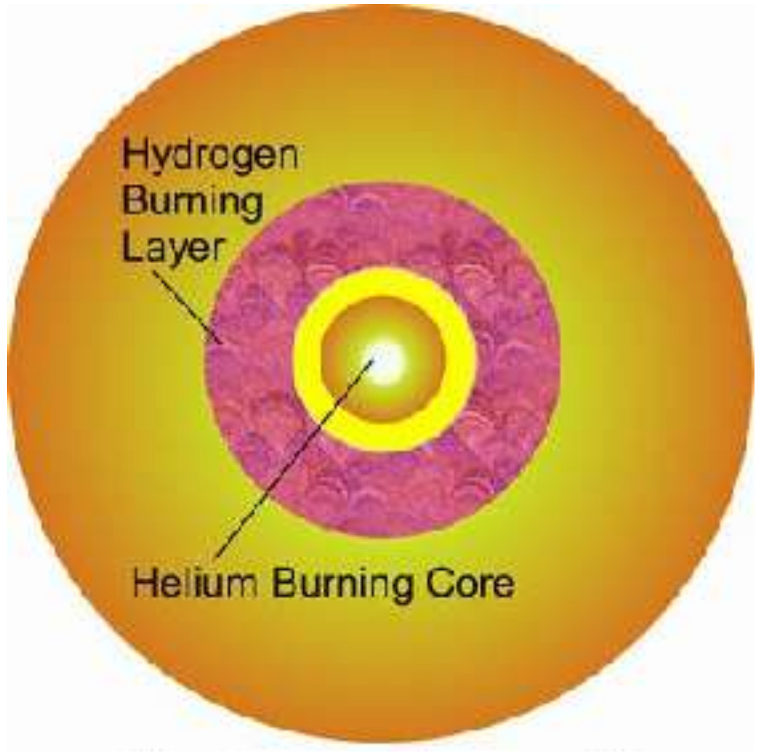


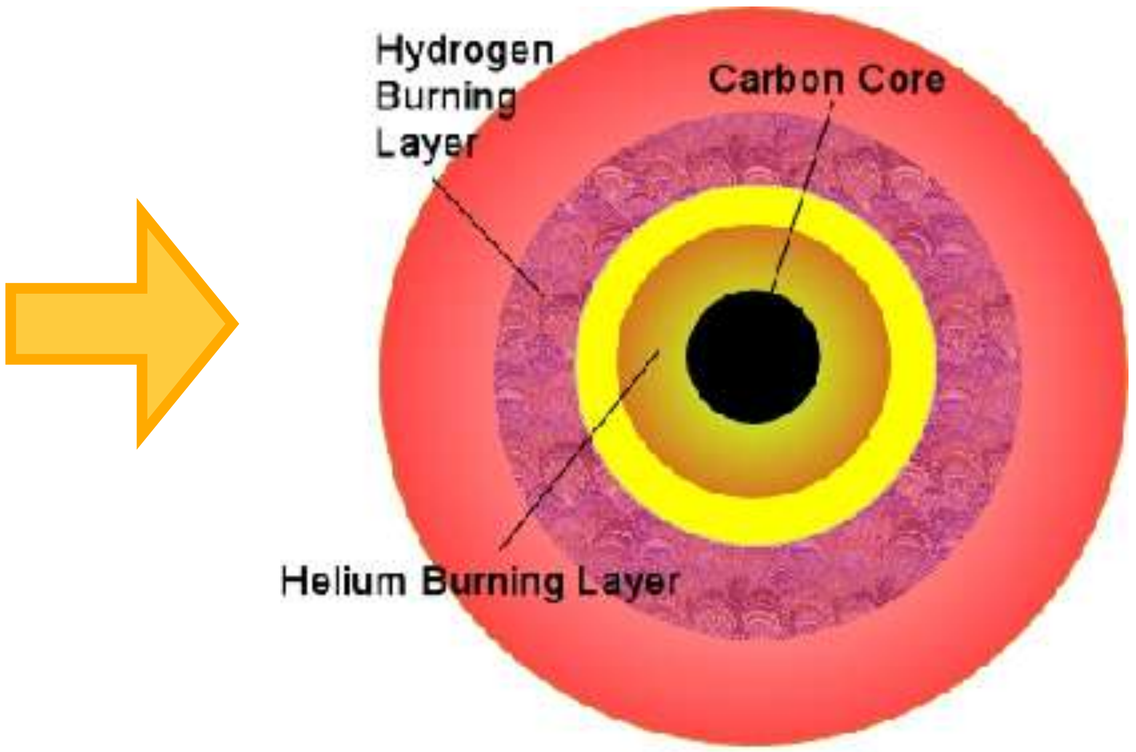
Lifecycle of a Massive Star





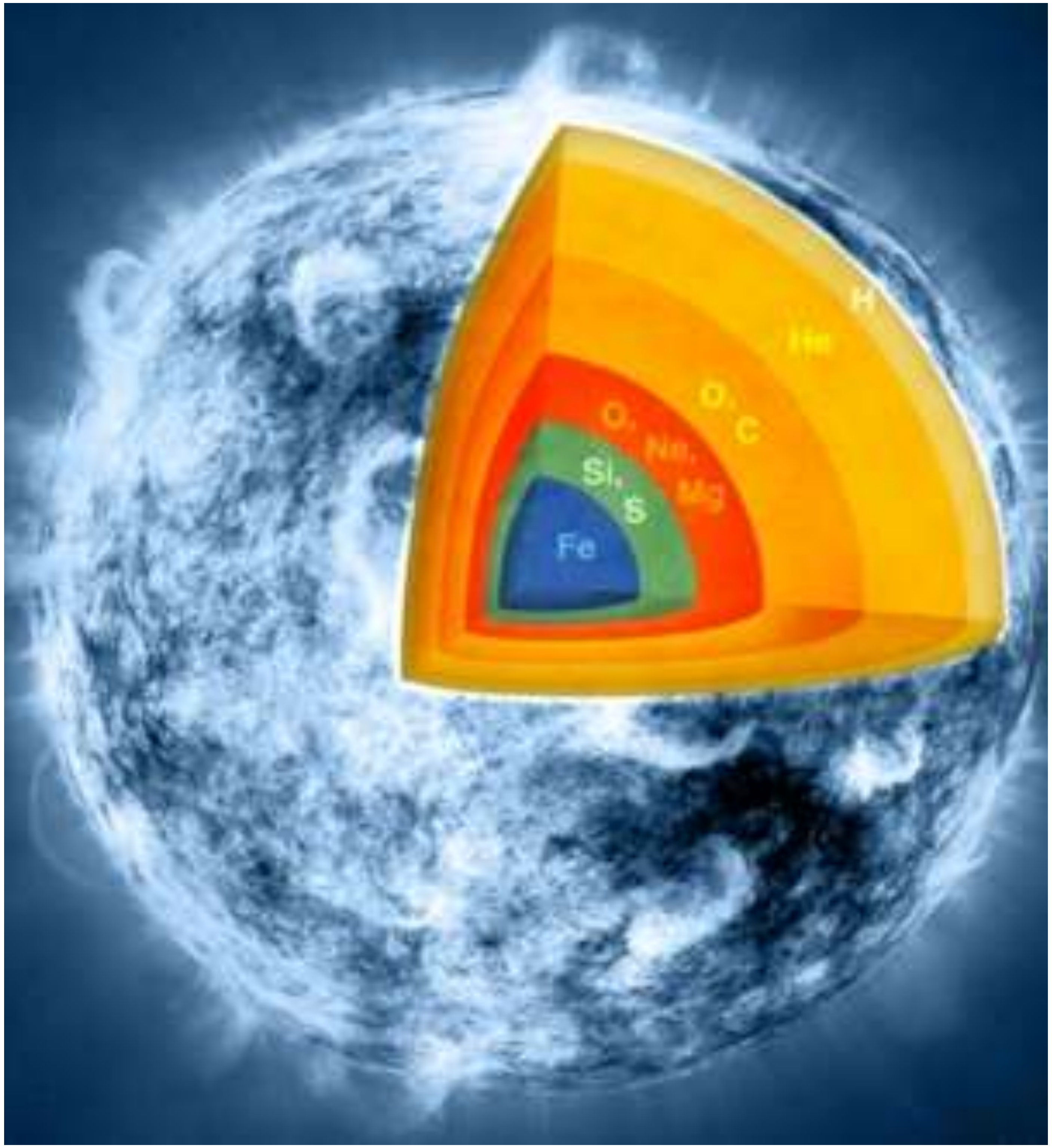
When the star exhausts hydrogen, the core drops its pressure. Gravity compresses the core and the latter heats up. Helium burning starts. It continues for all elements up to Iron.



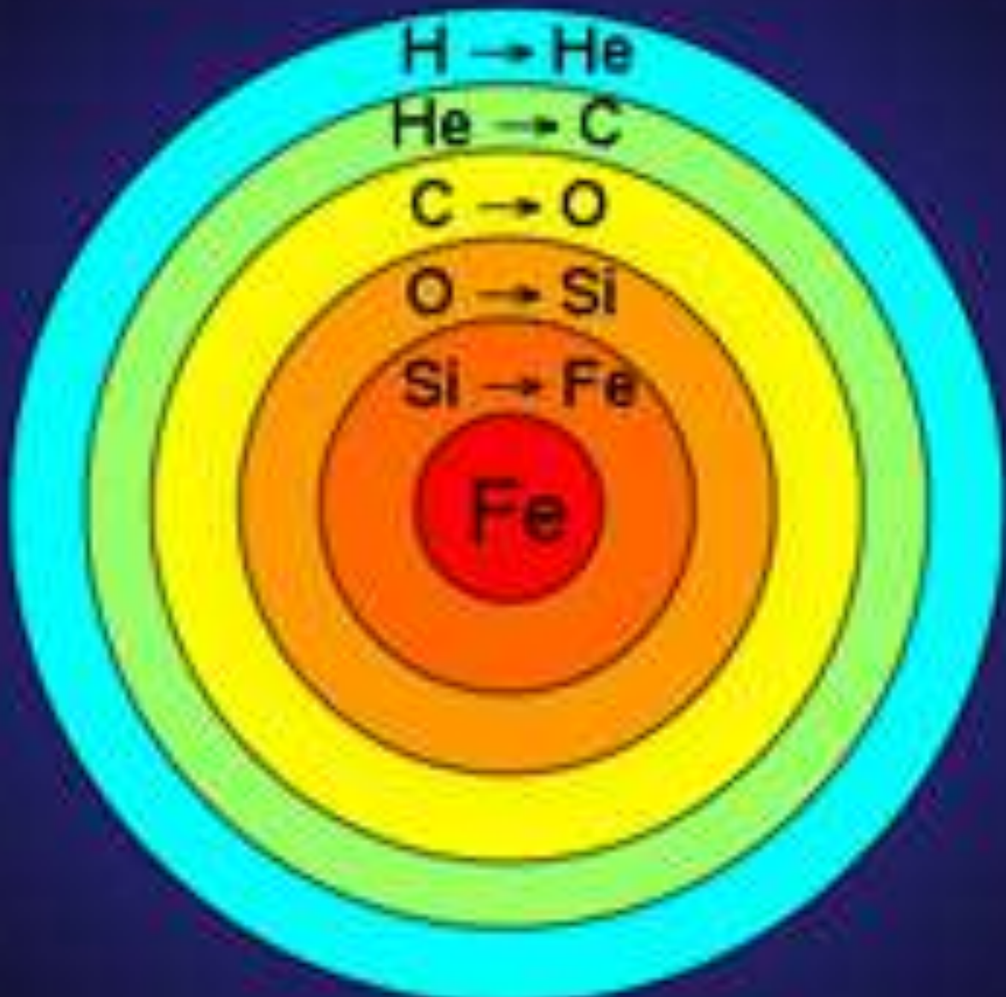


Lifecycle of a Massive Star

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



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

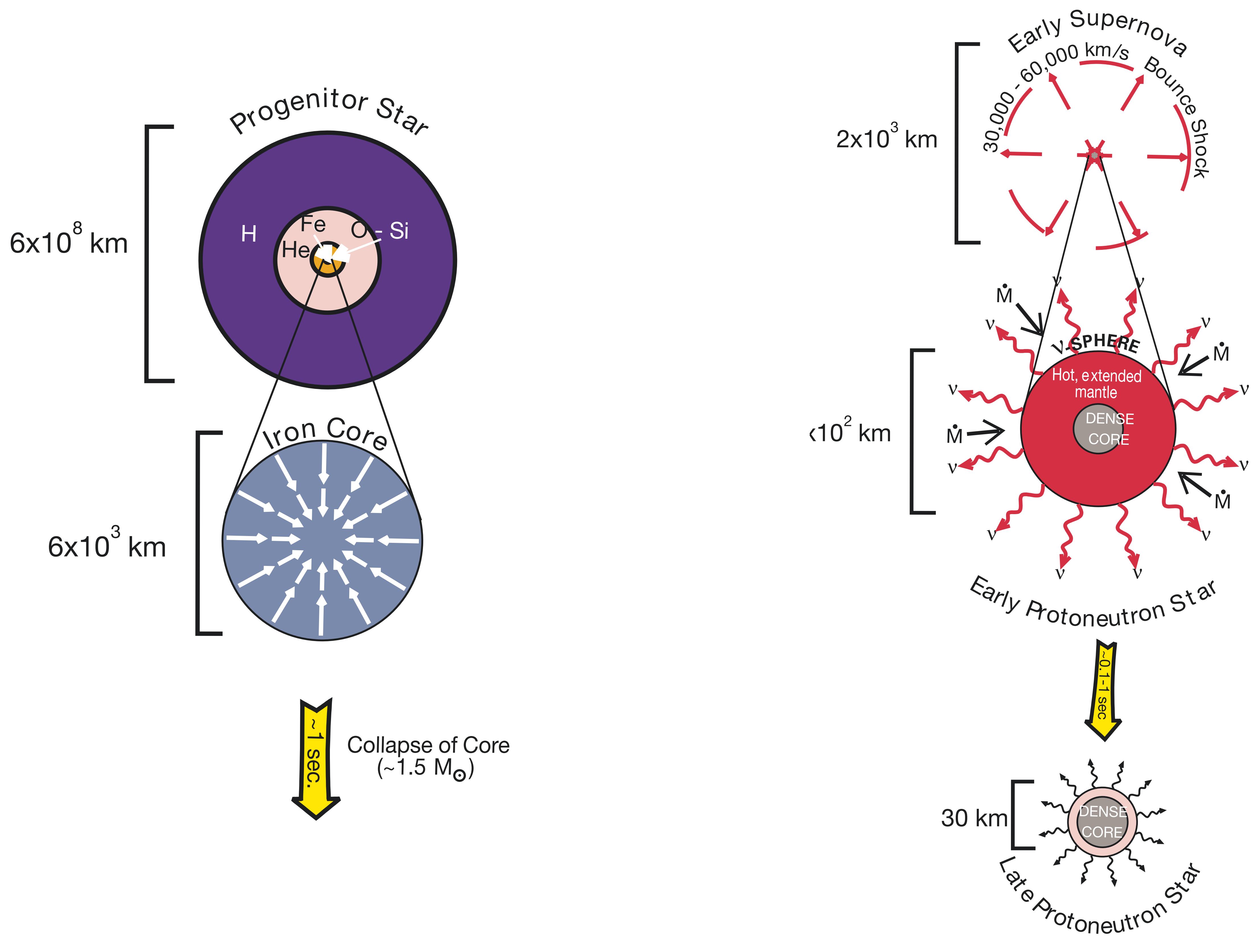


Figure from Burrows, Nature (2000).

Numbers

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

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

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

kinetic explosion energy

99% neutrinos

photons

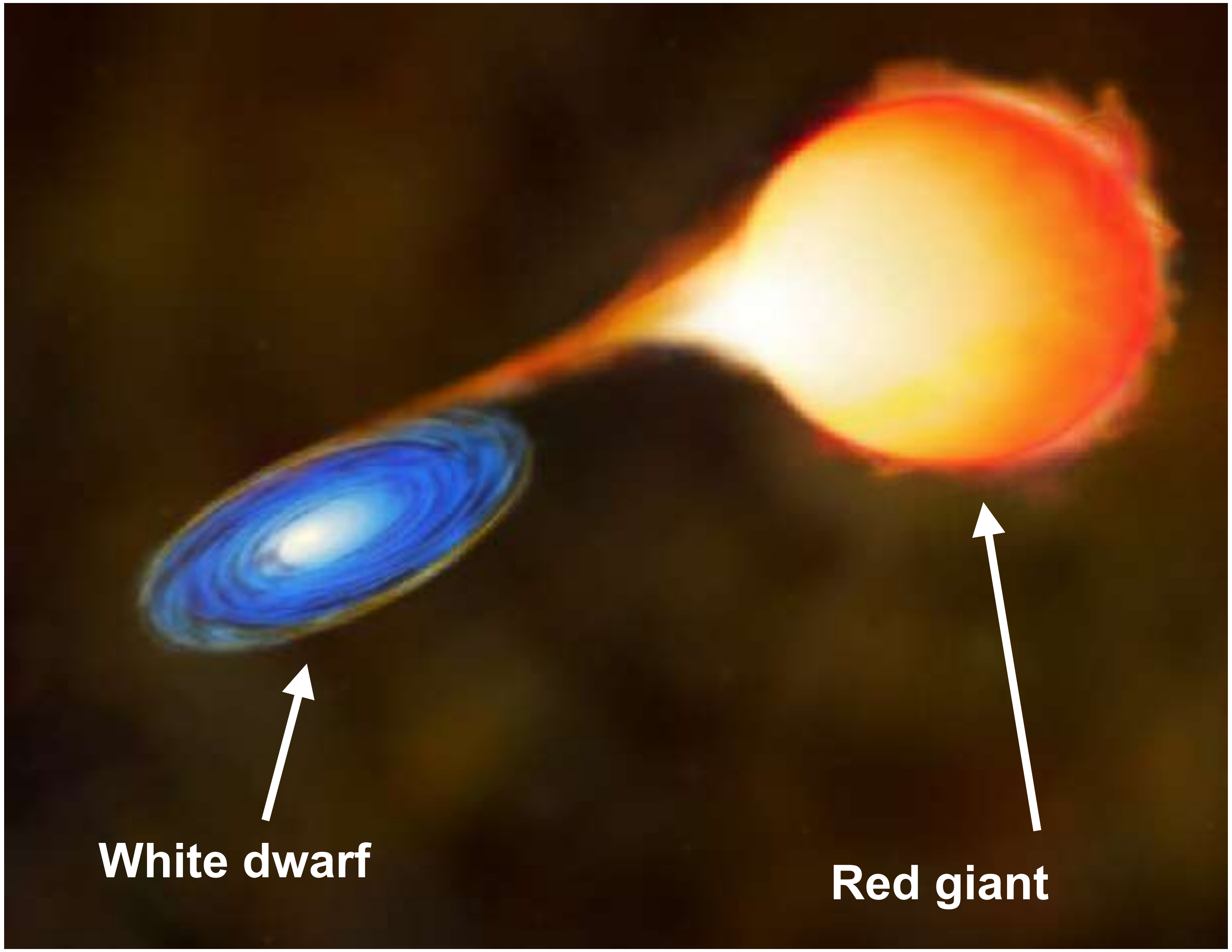
$$L_\nu \simeq \frac{3 \times 10^{53} \text{ erg}}{3 \text{ s}} \simeq 3 \times 10^{19} L_{\text{sun}}$$

Core-collapse supernovae explode because of

NEUTRINOS!

10^{58} neutrinos are emitted!

Alternative Path to Explosion

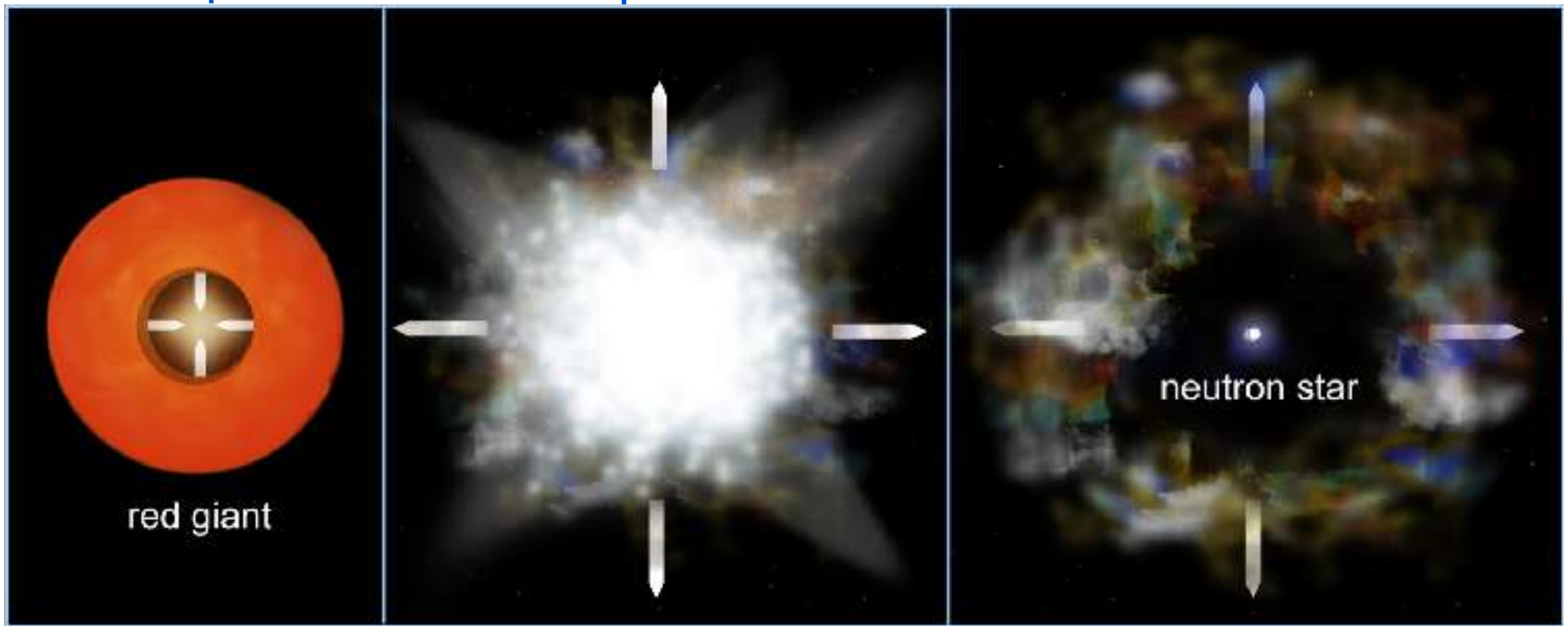


- Many stars live in binary systems.
- A white dwarf may accumulate material from a companion star (often a red giant).
- **Thermo-nuclear supernova explosion**.

Supernova Types

Core-collapse or type II supernova

Core implosion | Explosion | Remnant with neutron star



Thermonuclear or type I supernova

Accretion onto a white dwarf | Explosion | Remnant without neutron star

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

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.

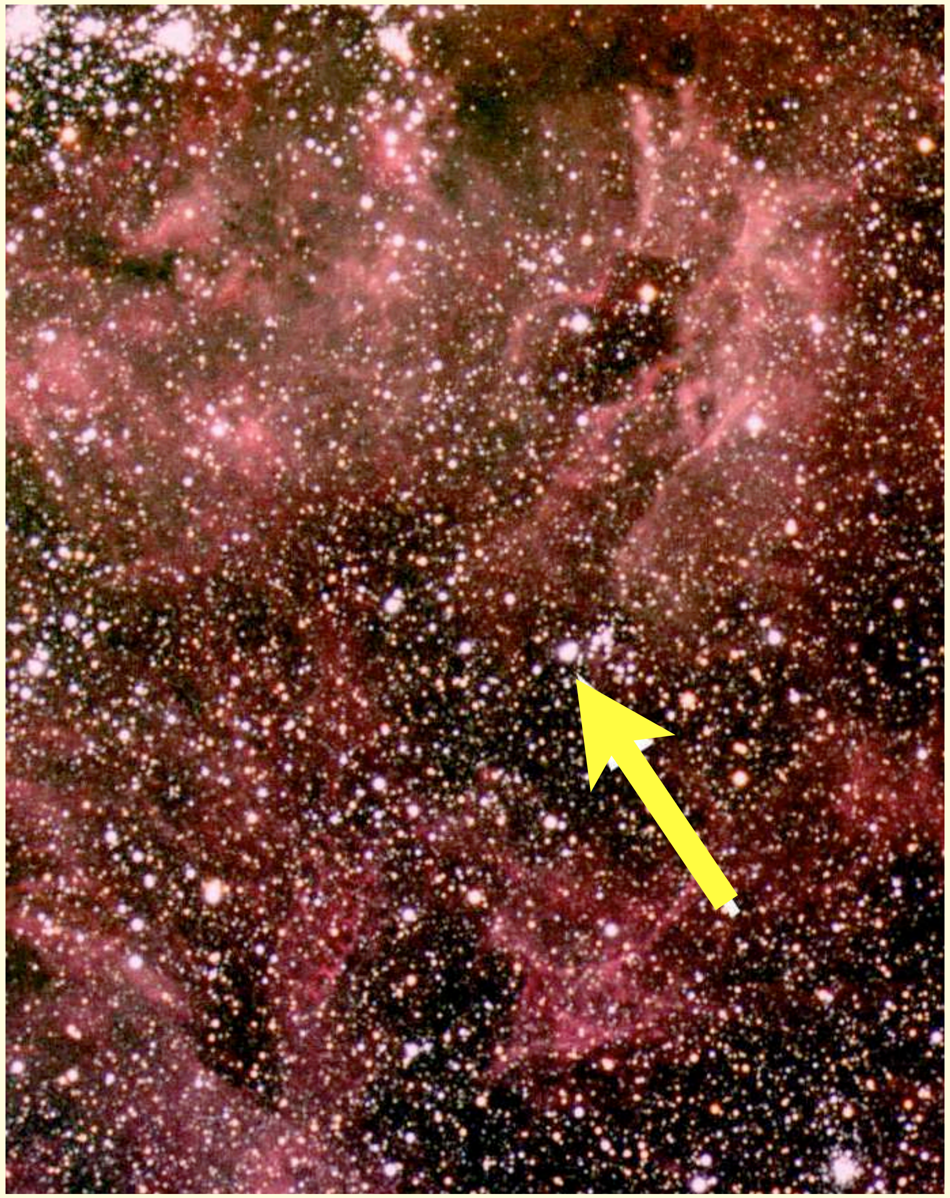
- Neutrinos provide information inaccessible to other kinds of astronomy.

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

SN 1987A

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

Sanduleak -69° 202

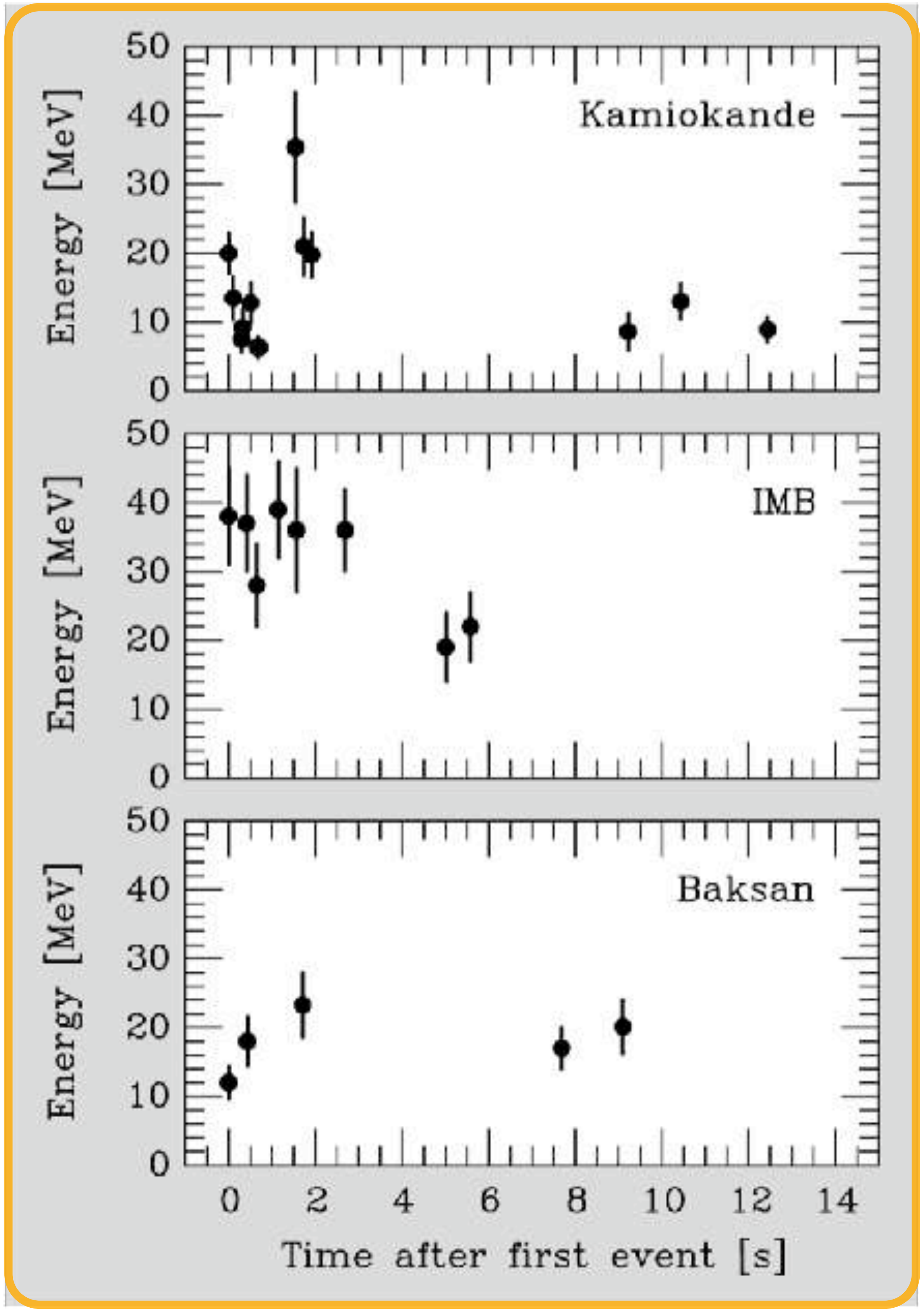


SN 1987A (Feb. 23, 1987)

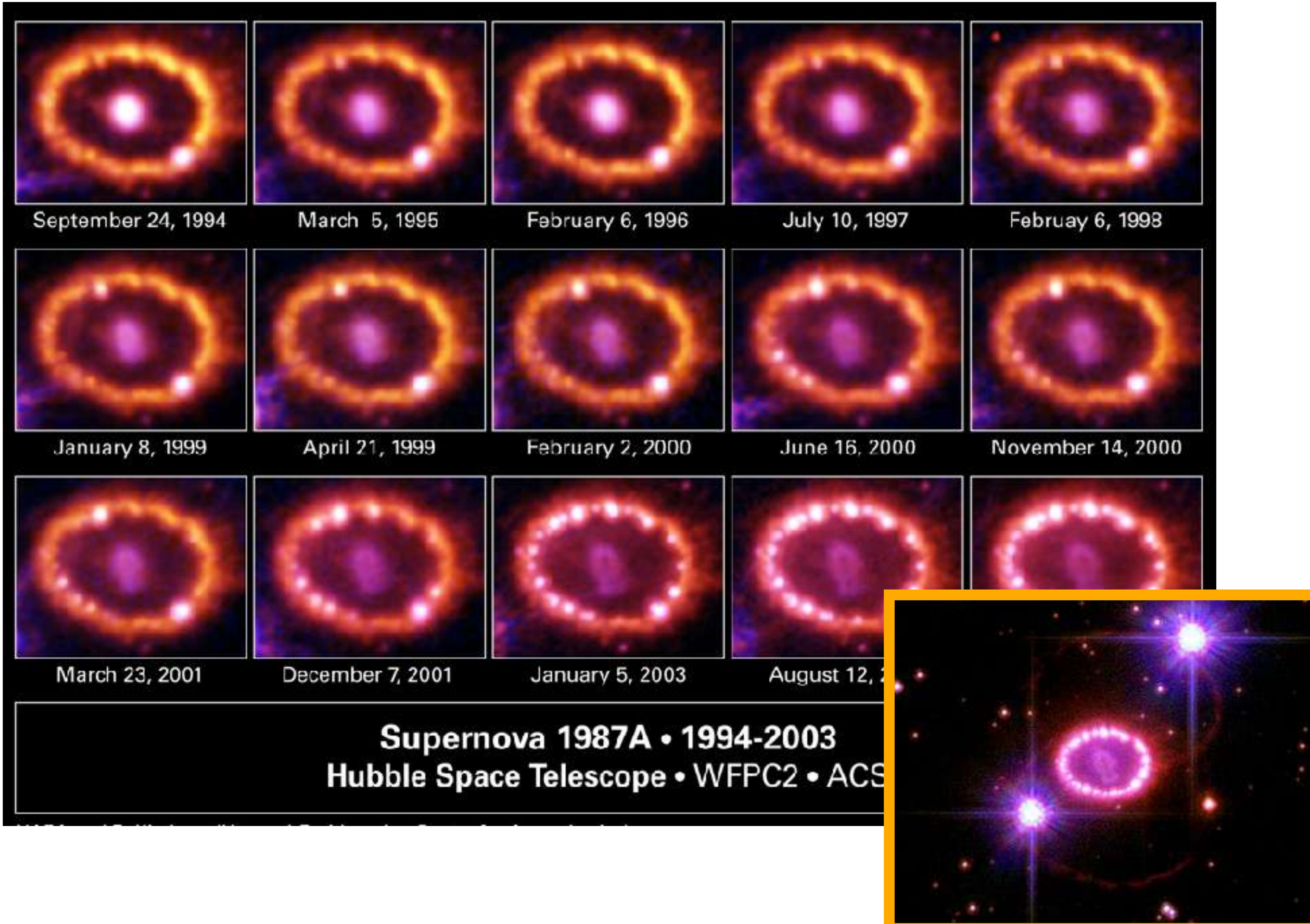
First and only supernova observed in neutrinos.
First verification of stellar evolution mechanism.

SN 1987A

Few detectors were able to detect SN 1987A neutrinos.



Remnant, SN 1987A



Neutrinos, EM Radiation, and GWs

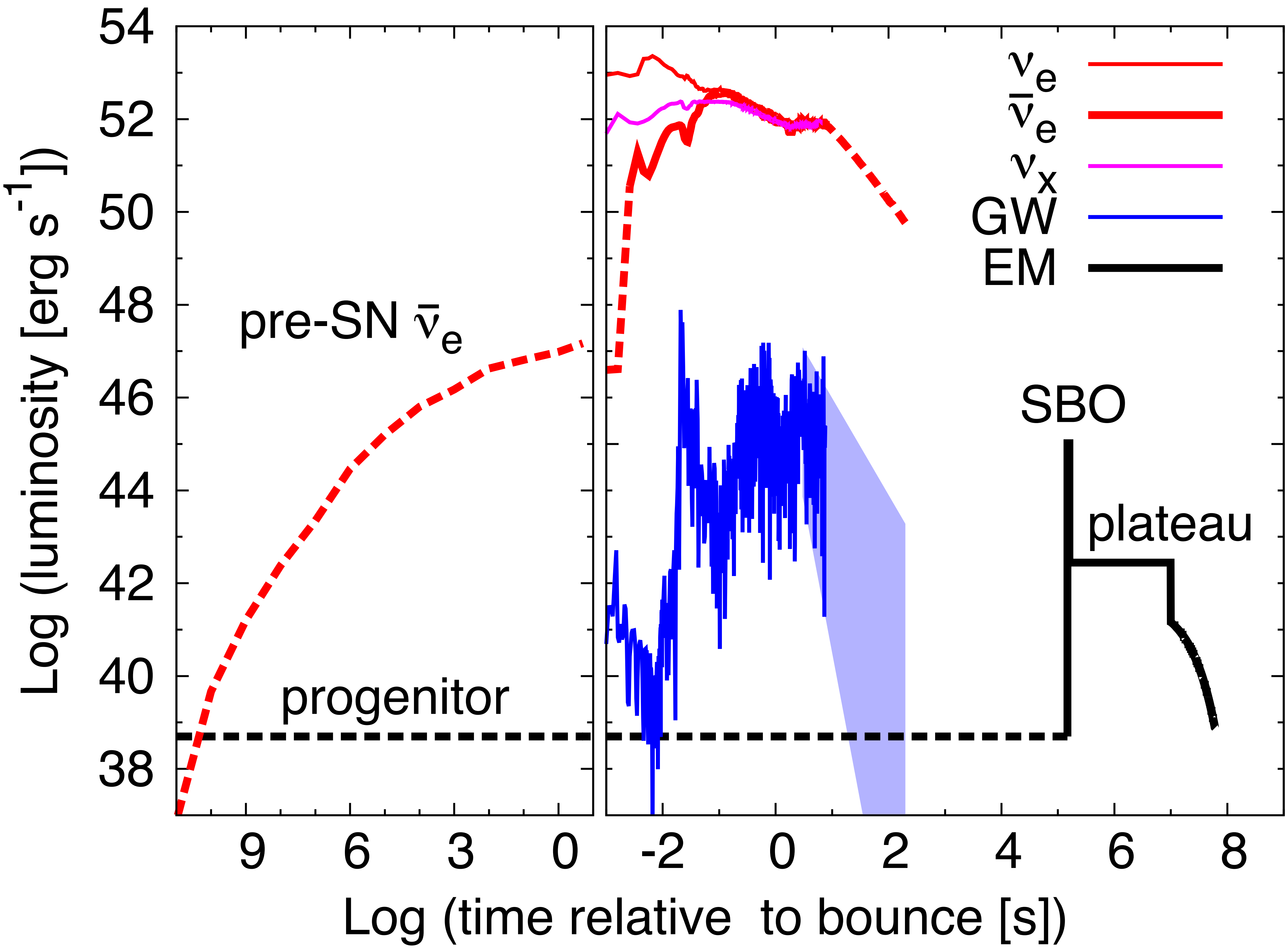
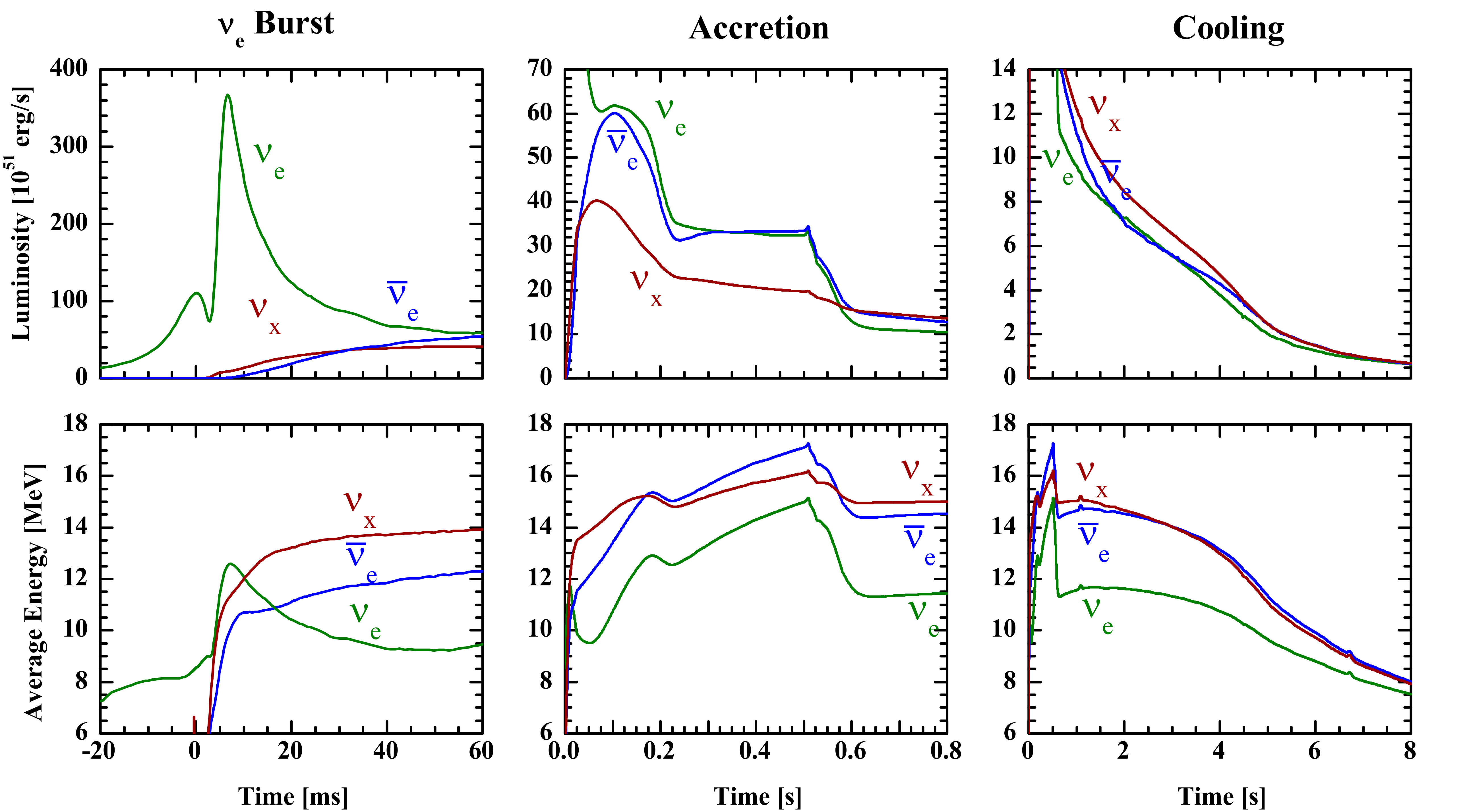


Figure from Nakamura et al., MNRAS (2016).

Neutrino Signal



Large ν_e luminosity peak

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

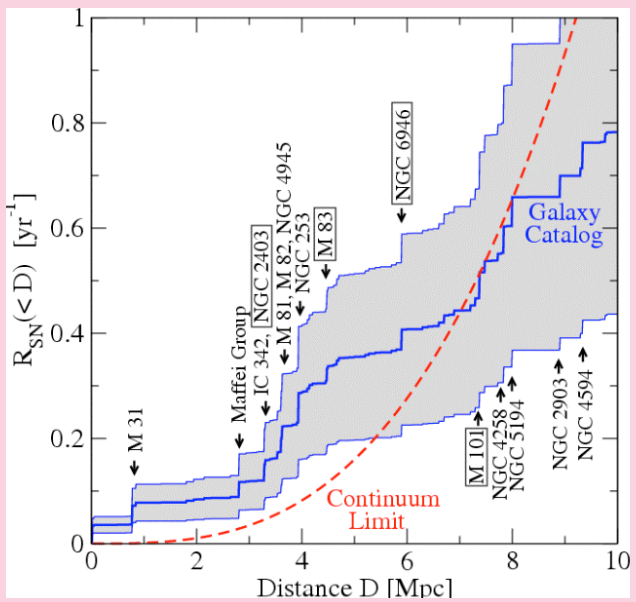
Smaller fluxes.
Small $\overset{(-)}{\nu}_e - \overset{(-)}{\nu}_x$ flux difference.

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

Detection Frontiers

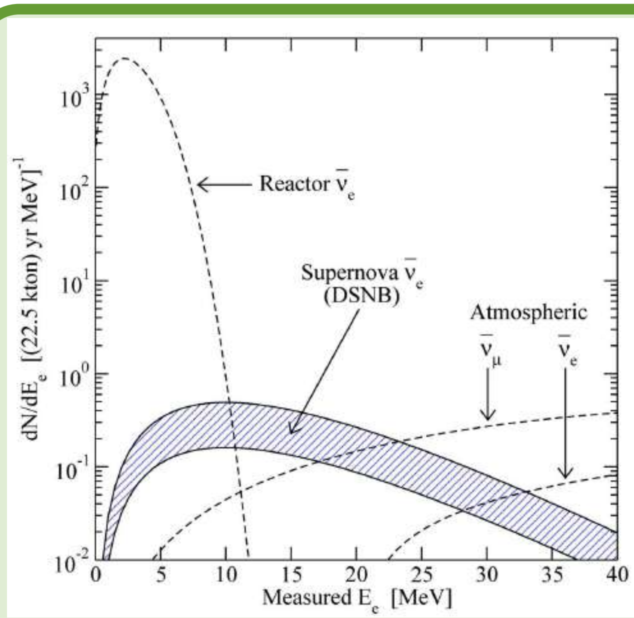
Supernova in our Galaxy (one burst per 40 years).

Excellent sensitivity to details.



Supernova in nearby Galaxies (one burst per year).

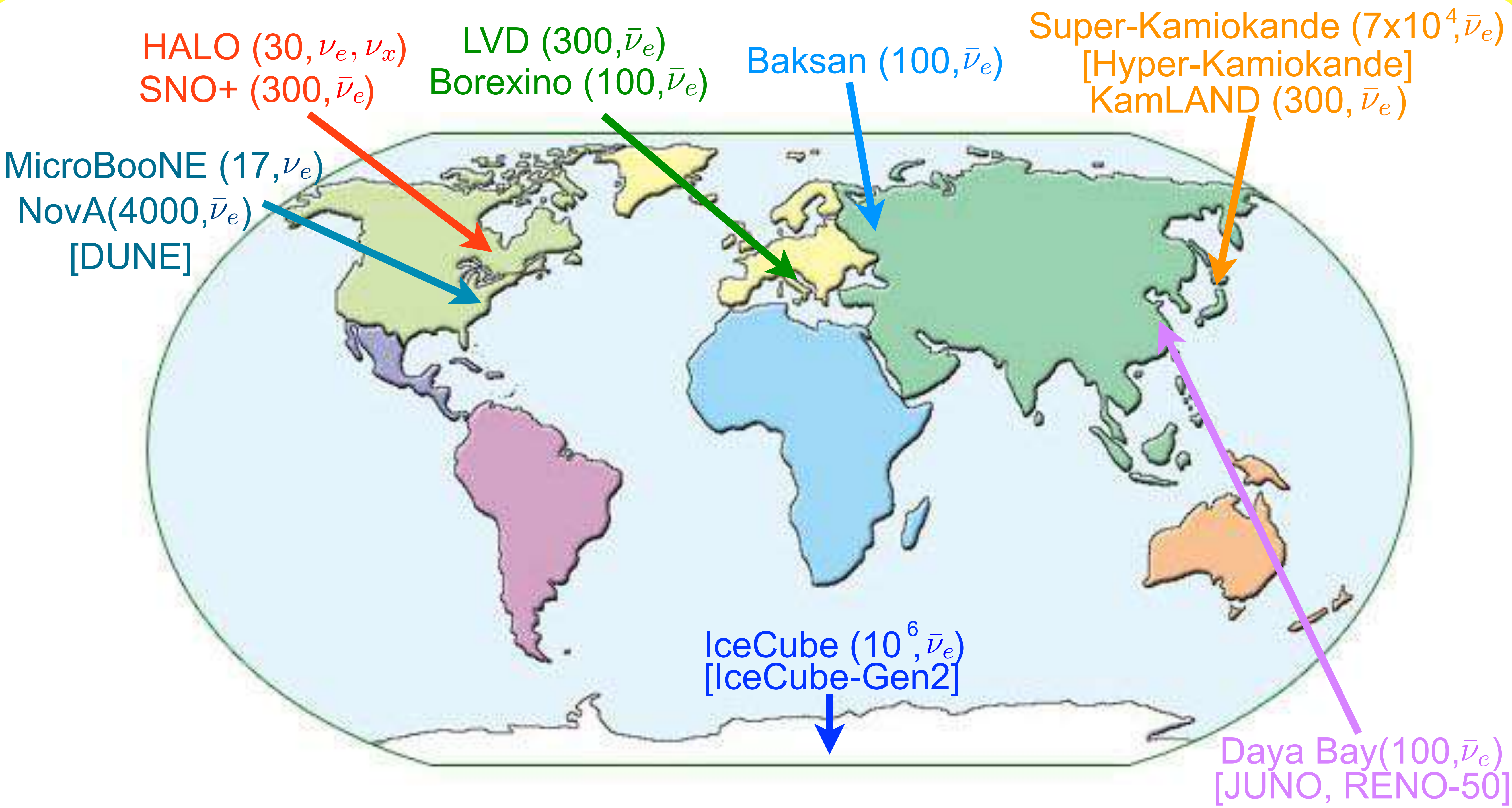
Sensitivity to general properties.



Diffuse Supernova Background
(one supernova per second).

Average supernova emission. Guaranteed signal.

Supernova Neutrino Detectors



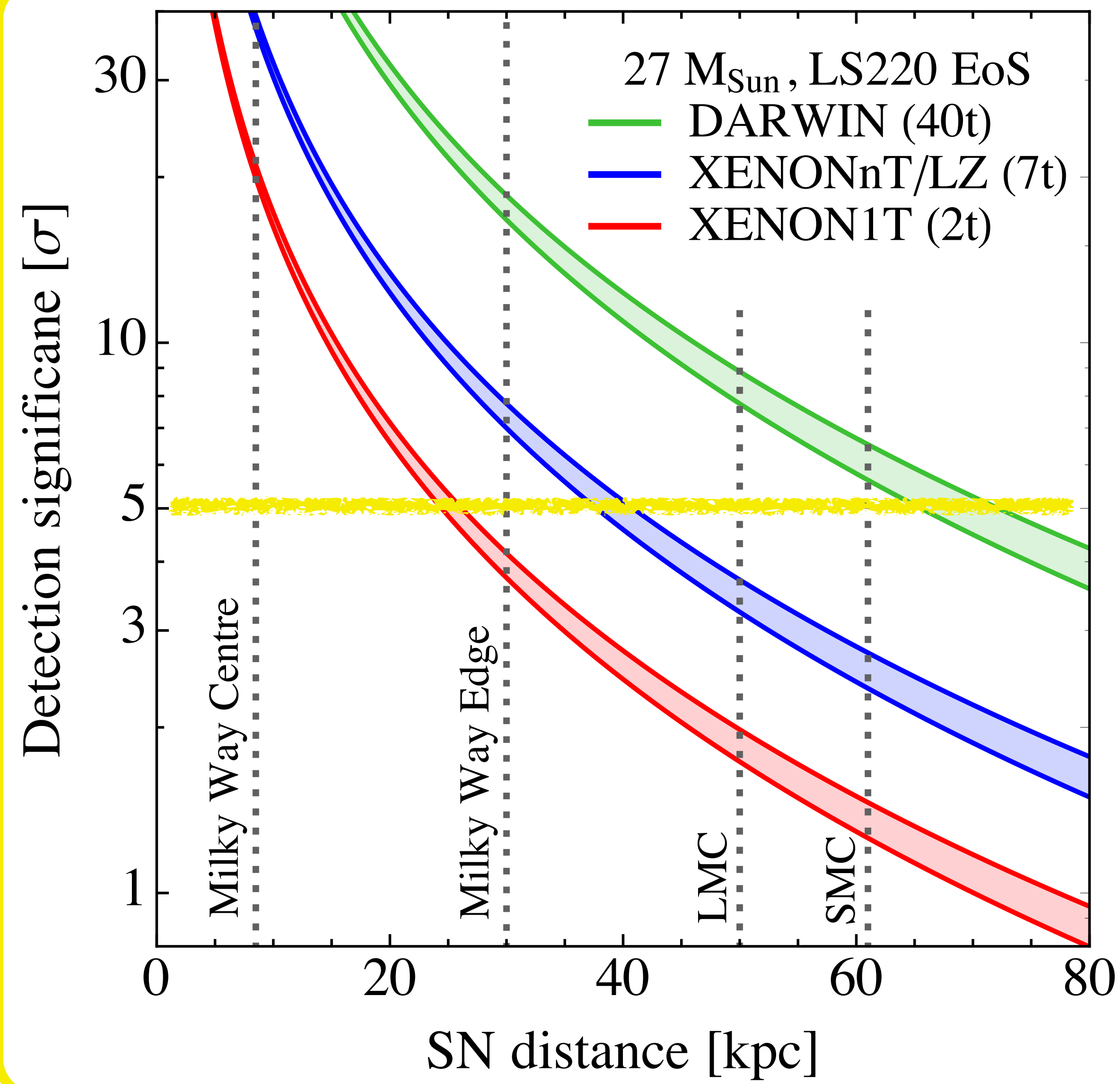
Expected number of events for a SN at 10 kpc and dominant flavor sensitivity in parenthesis.

Fundamental to combine the supernova signal from detectors employing different technologies.

Recent review papers: Scholberg (2017). Mirizzi, Tamborra, Janka, Scholberg et al. (2016).

Xenon Dark Matter Detector: Nu Telescope

DARWIN, 700 events ($\nu_{e,x}\,,\bar{\nu}_{e,x}$)

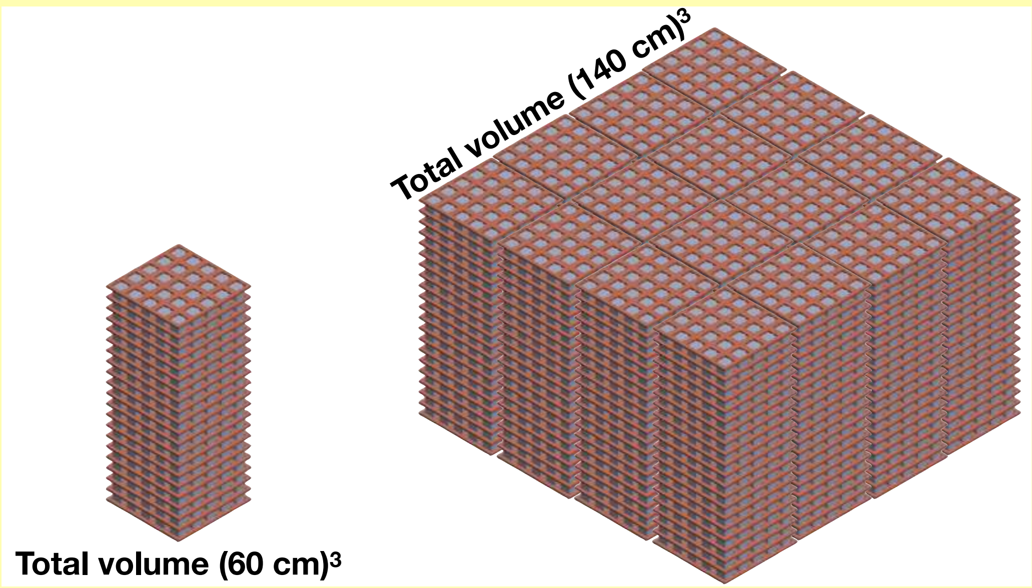


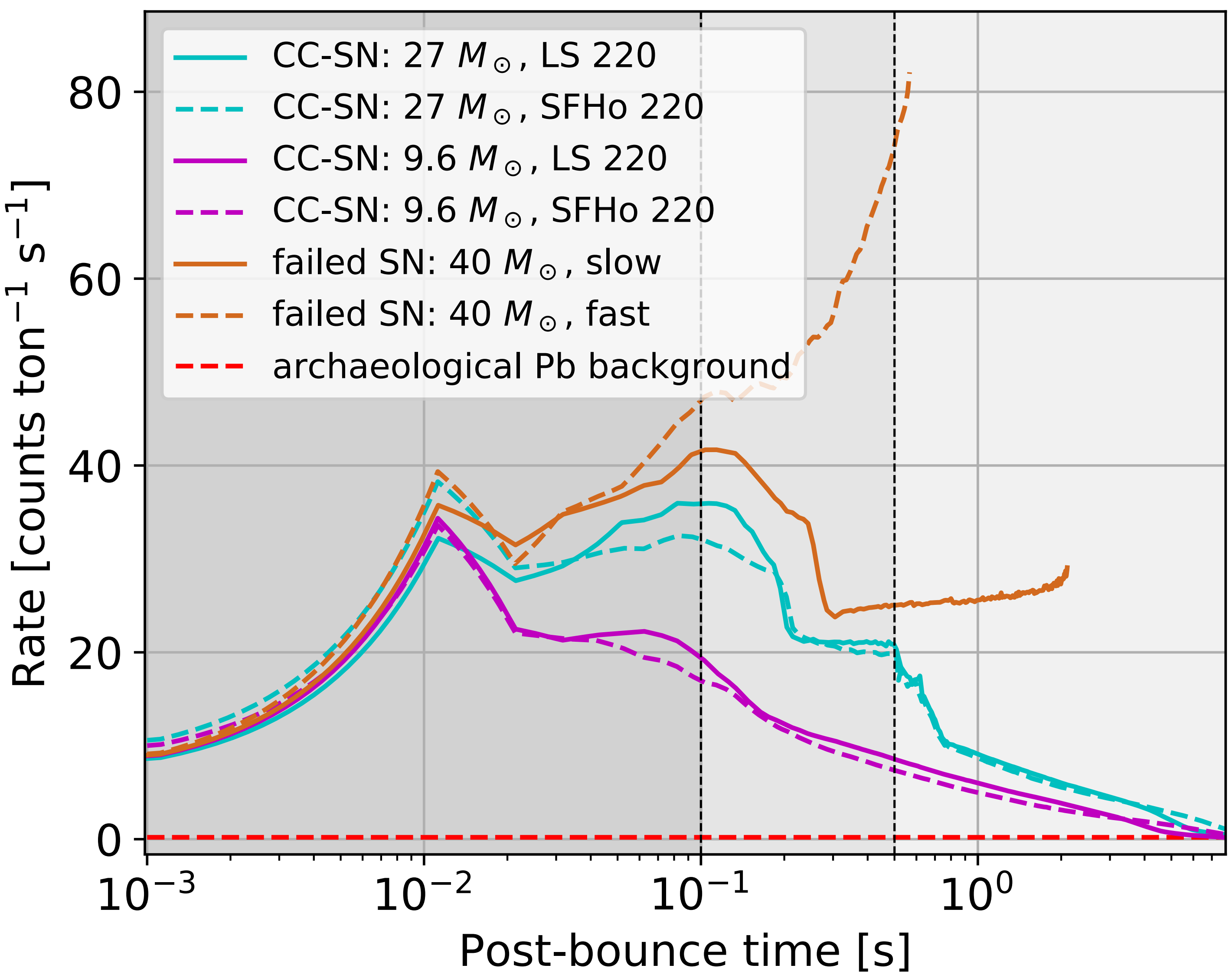
- Flavor insensitive (no uncertainties due to oscillation physics).
- Very low background and excellent time resolution.
- Good reconstruction of neutrino light-curve and neutrino emission properties.

Lang, McCabe, Reichard, Selvi, Tamborra, PRD (2016). Horowitz et al. PRD (2003). Drukier and Stodolsky, PRD (1984).

RES-NOVA: A New Lead-Based Observatory

	Linear dimension	Detector mass	Energy threshold	Background index
RN-1	60 cm	2.4 t	1 keV	0.1 c/keV/t/10 s
RN-2	140 cm	31 t	1 keV	0.1 c/keV/t/10 s
RN-3	15× 140 cm	465 t	1 keV	0.1 c/keV/t/10 s



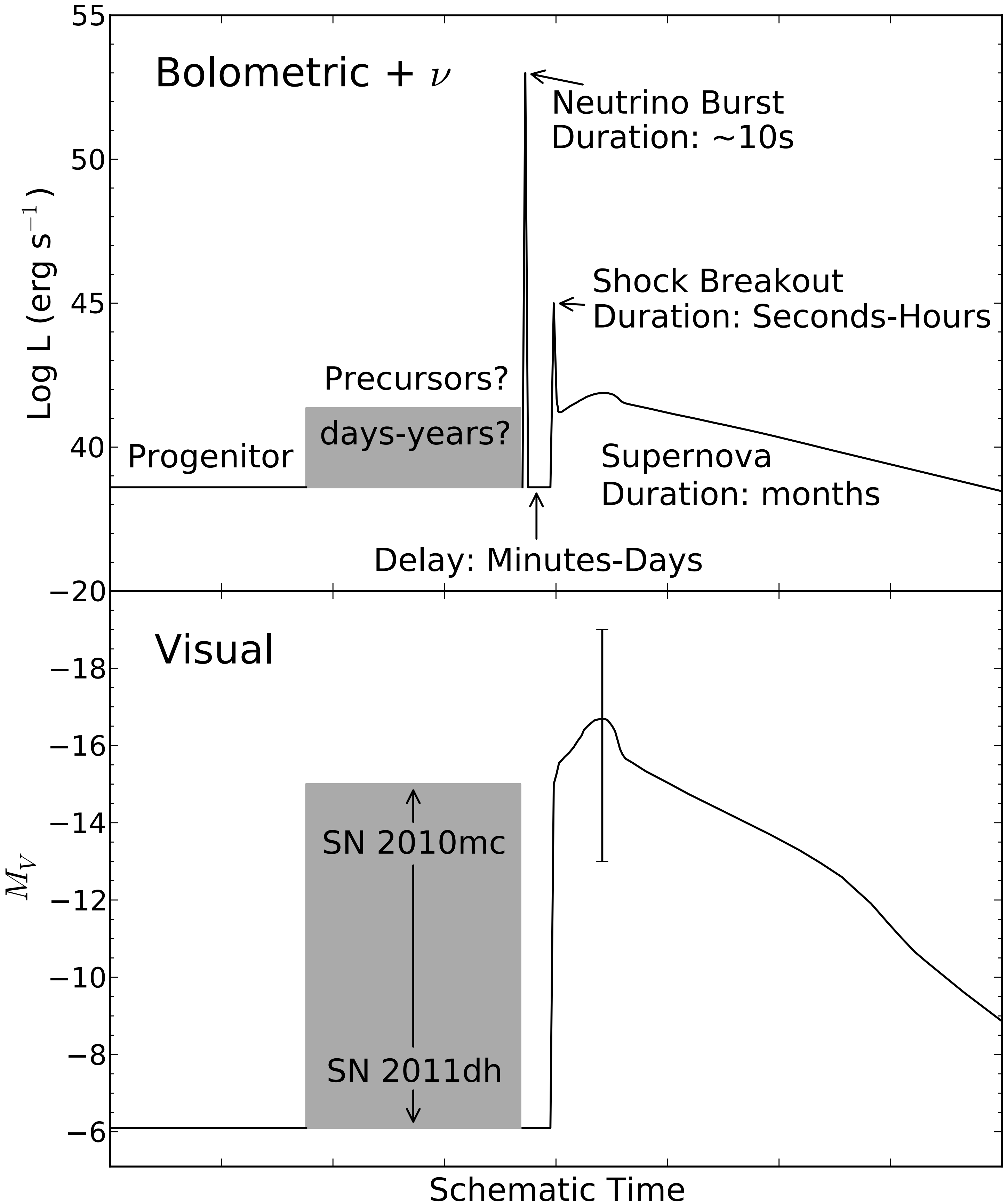


- Flavor insensitive.
- Large cross-section, simple setup, easy scalability to larger detector volumes.
- Excellent reconstruction of neutrino light-curve and neutrino emission properties.

Pattavina, Ferreiro Iachellini, Tamborra, arXiv: 2004.06936.

Neutrinos as Supernova Probes

Neutrinos & EM Radiation

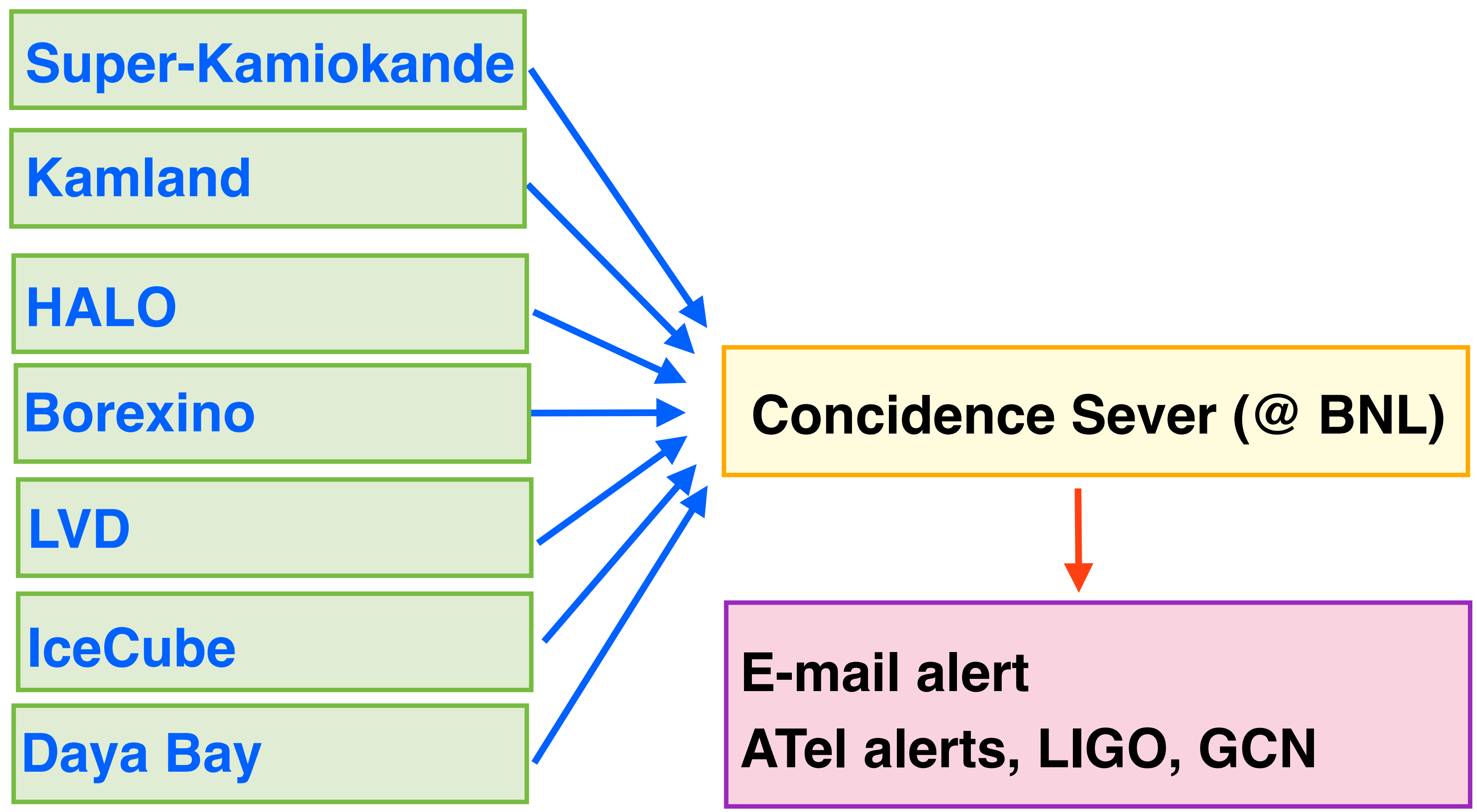


Neutrinos could allow early EM detection of SN signal.

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

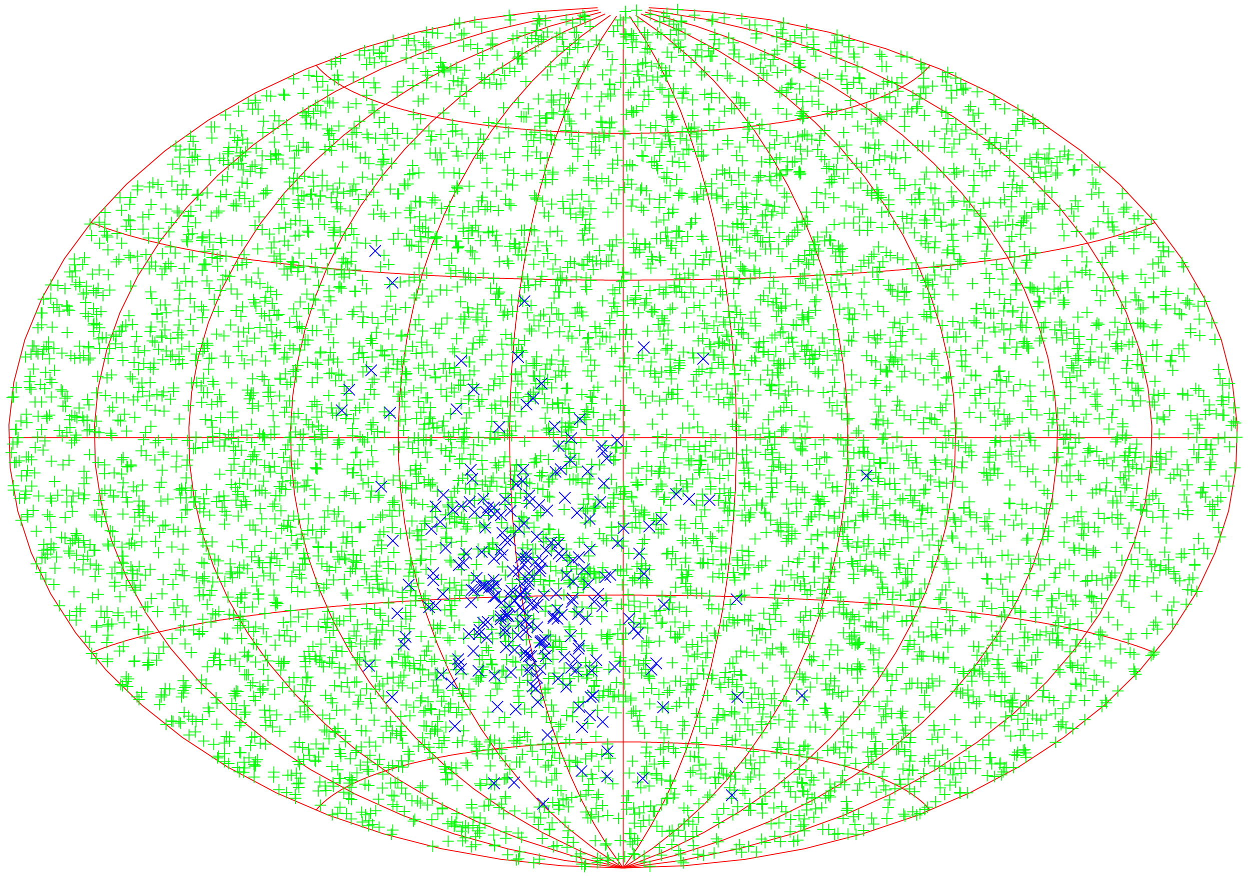
Supernova Early Warning System

SuperNova Early Warning System (SNEWS —> SNEWS 2.0)



Shock breakout arrives mins to hours after neutrino signal.

Supernova Pointing



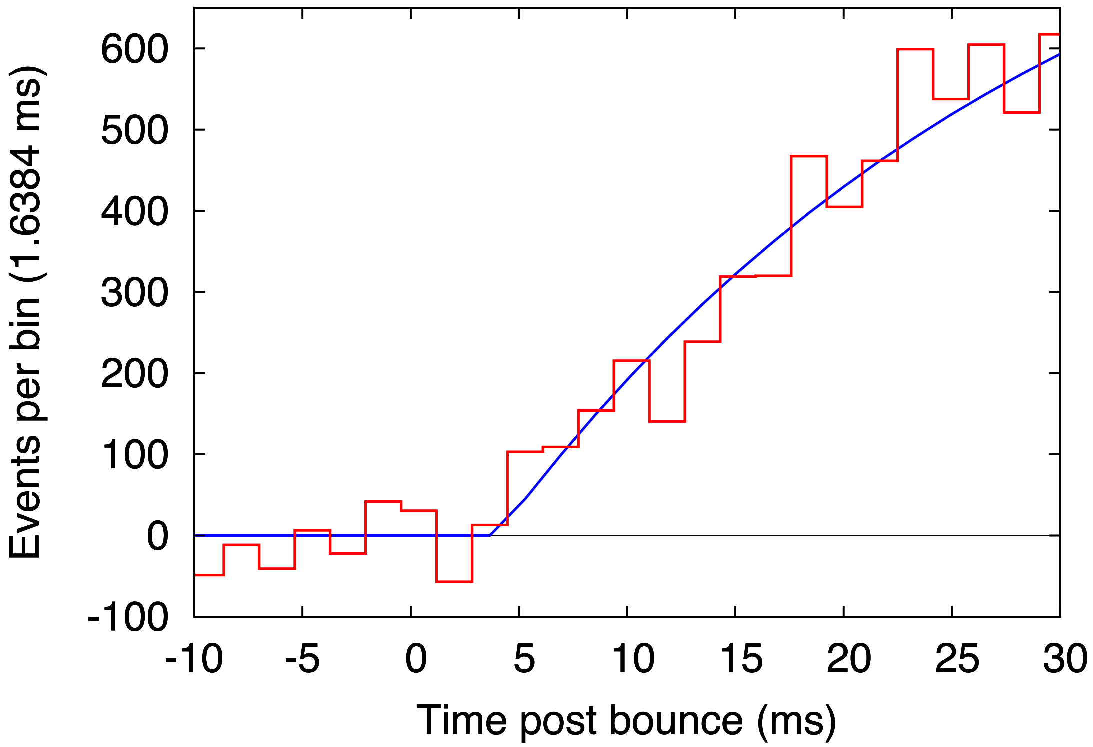
$$\nu + e^- \rightarrow \nu + e^-$$

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

- SN location with neutrinos crucial for vanishing or weak SNe.
- Fundamental for multi-messenger searches.
- Angular uncertainty comparable to e.g., ZTF, LSST potential.
- Triangulation is another option.

Beacom & Vogel (1999). Tomas et al. (2003). Fisher et al. (2015). Linzer & Scholberg, PRD (2019). Brdar, Lindner, Xu, JCAP (2018). Muehlbeier et al., PRD (2013).

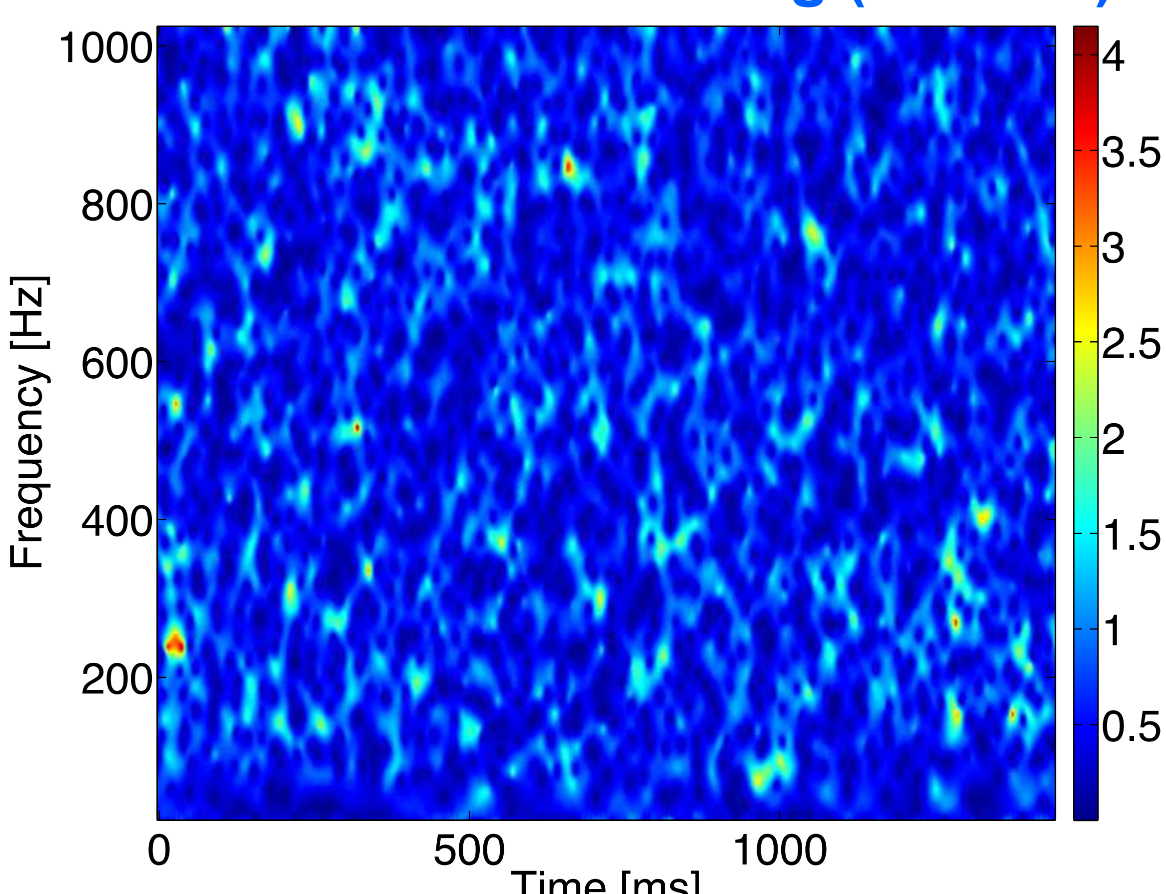
Neutrino Timing for Gravitational Waves



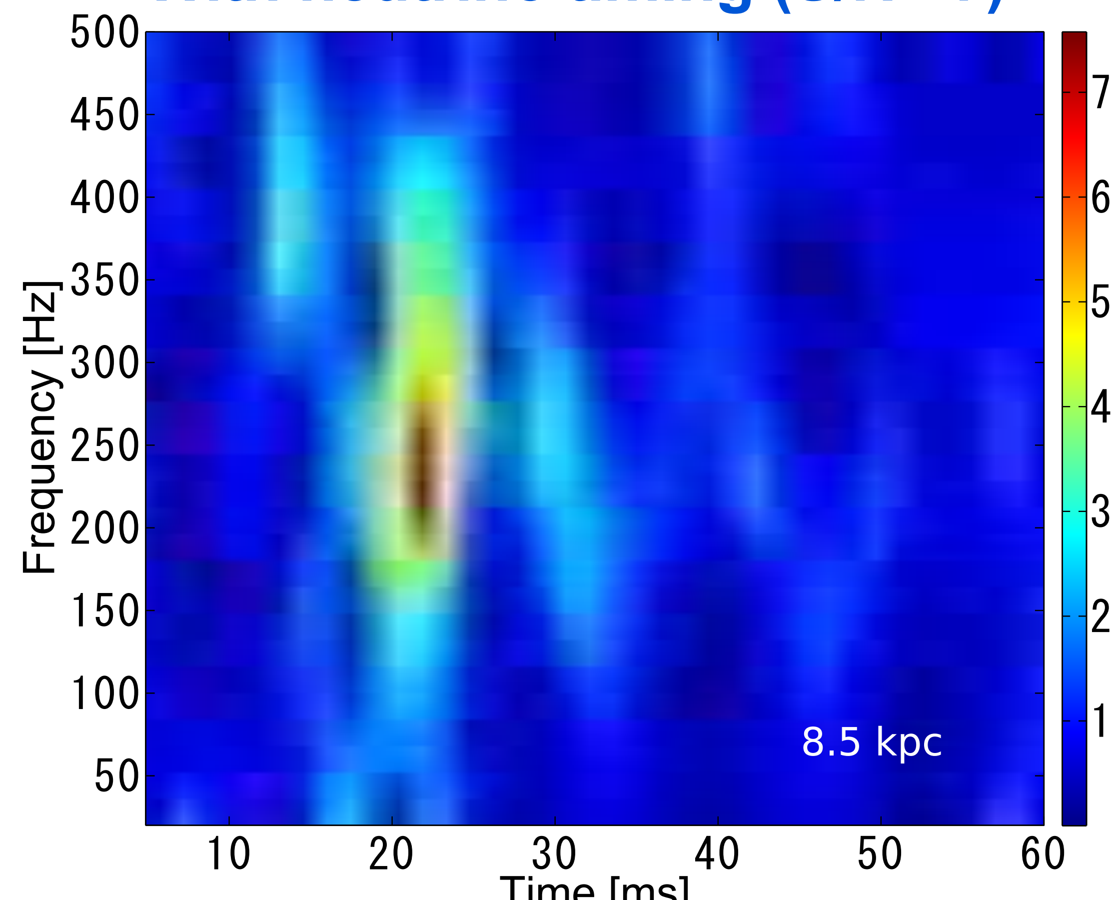
Probe core bounce time with neutrinos.

Help timing for gravitational wave detection.

Without neutrino timing (S/N~3.5)



With neutrino timing (S/N ~7)



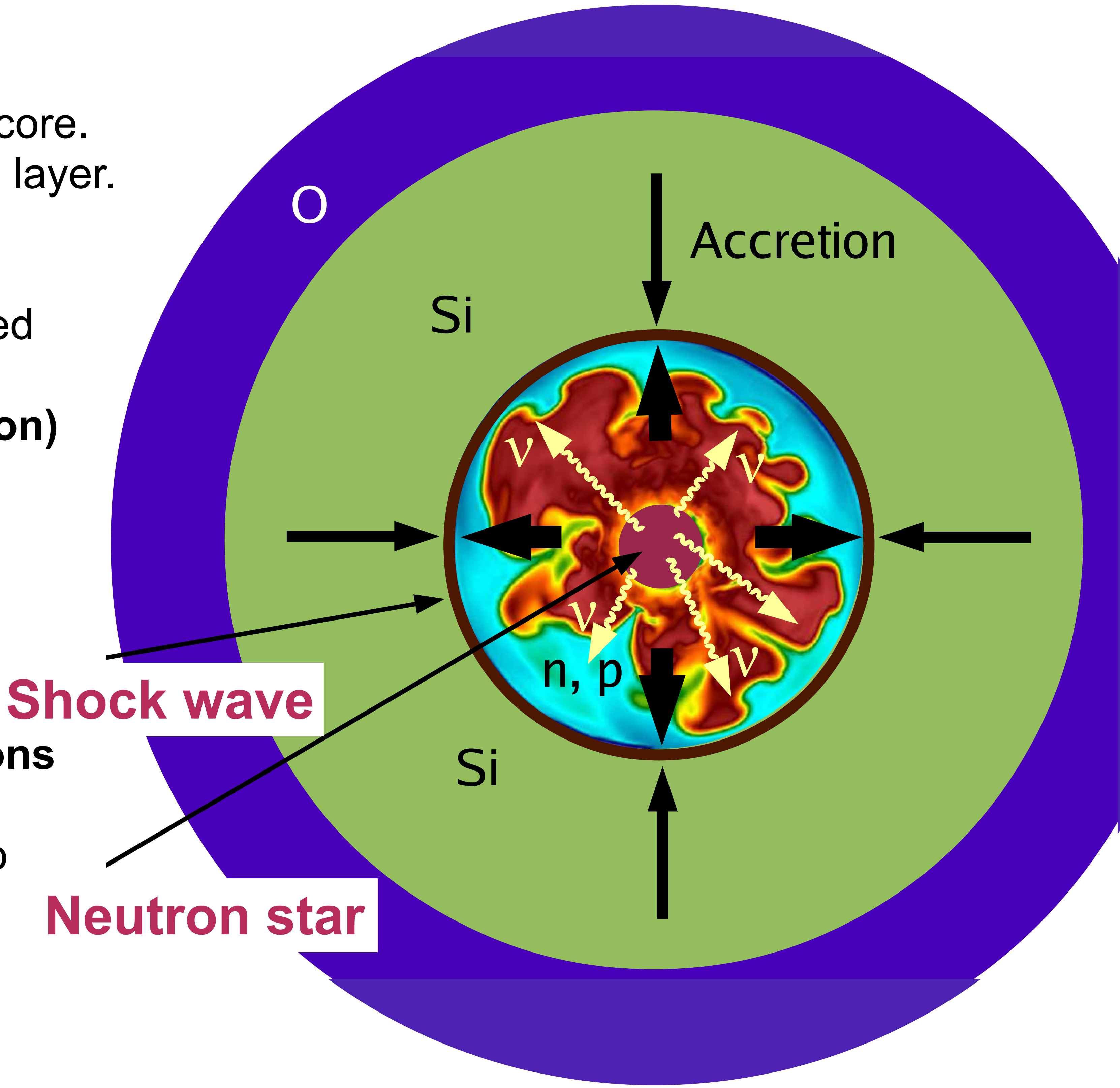
Pagliaroli et al., PRL (2009), Halzen & Raffelt PRD (2009). Nakamura et al., MNRAS (2016).

Supernova Explosion Mechanism

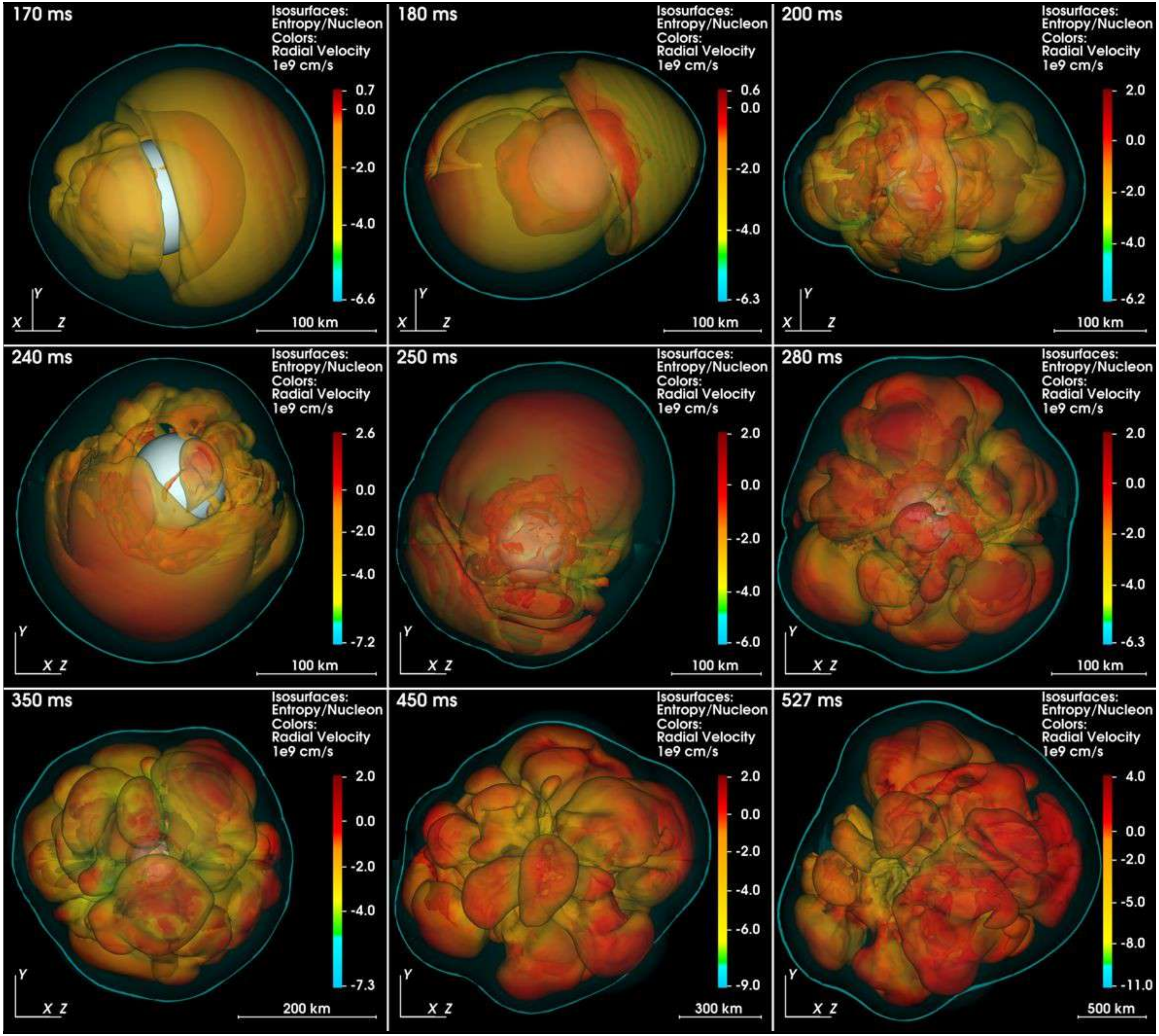
★ Shock wave forms within the iron core. It dissipates energy dissociating iron layer.

★ **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.

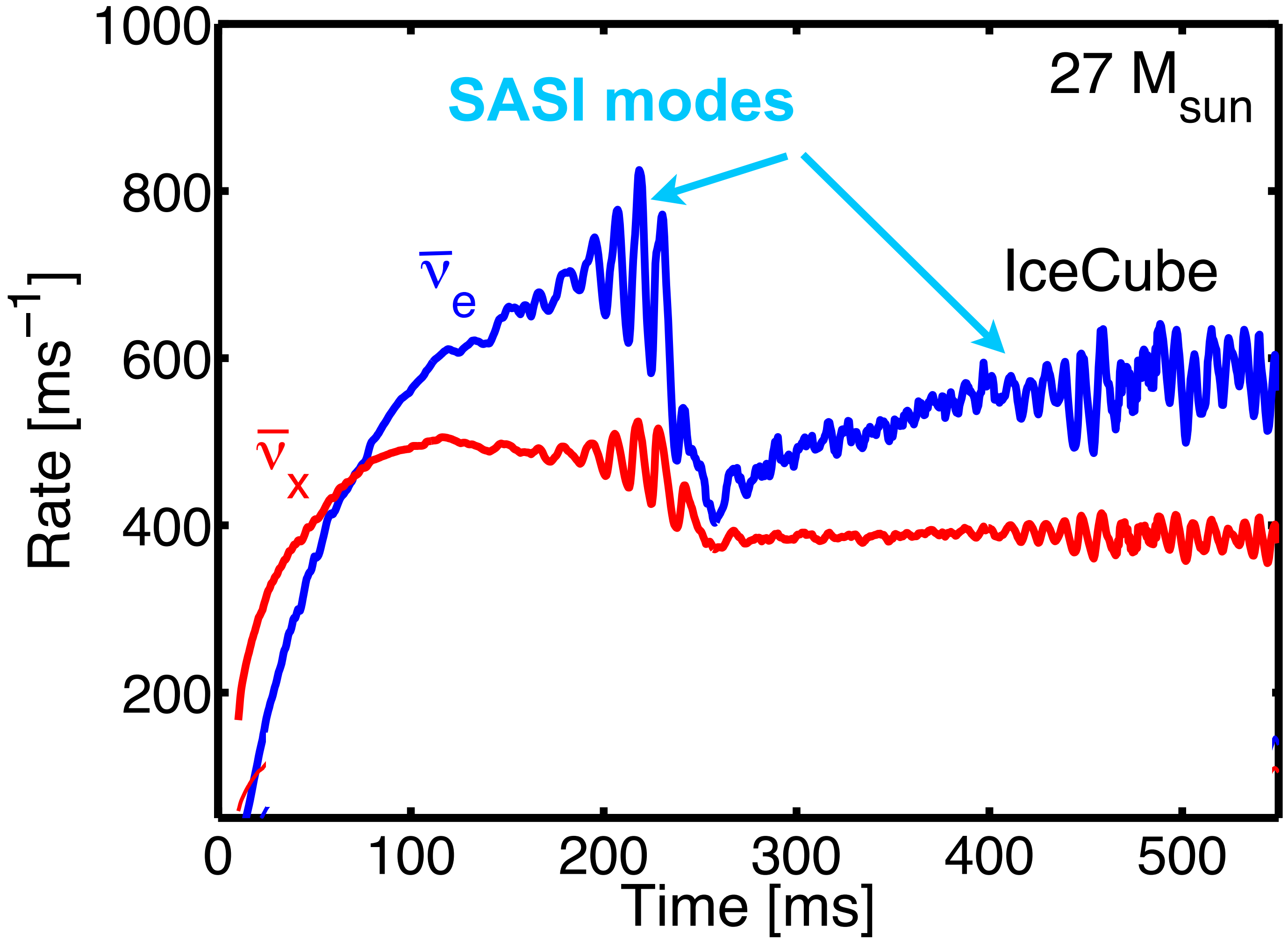


$20\ M_{sun}$ Supernova Model

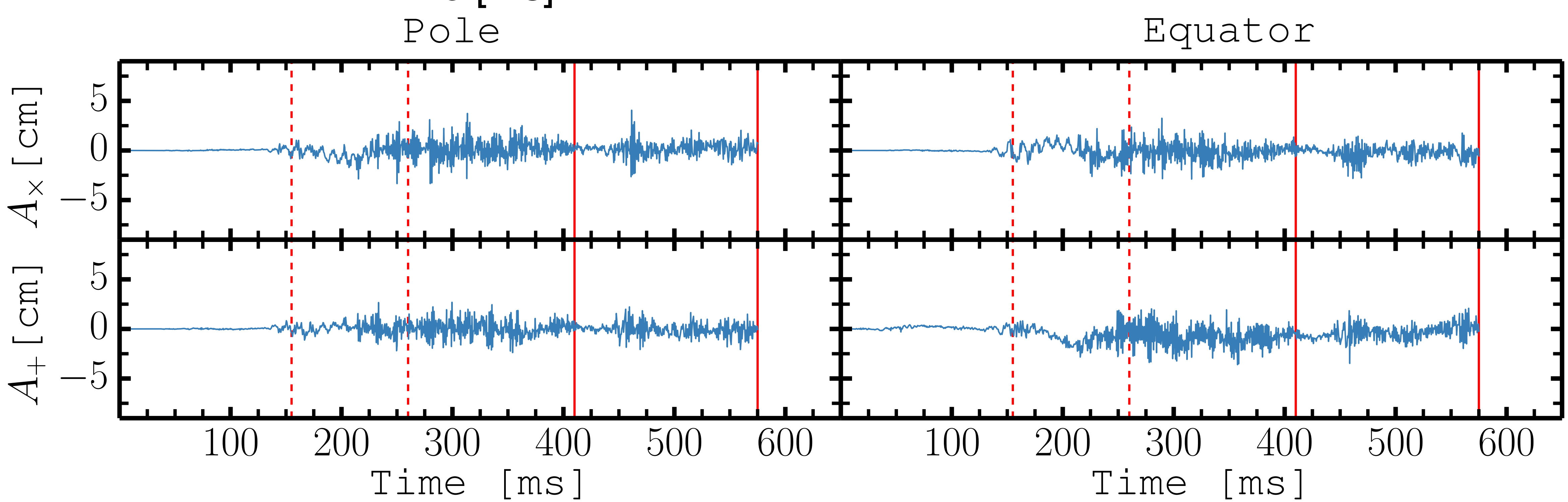


3D SN simulation ($M=20\ M_{sun}$). Melson et al., ApJL (2015)

Standing Accretion Shock Instability

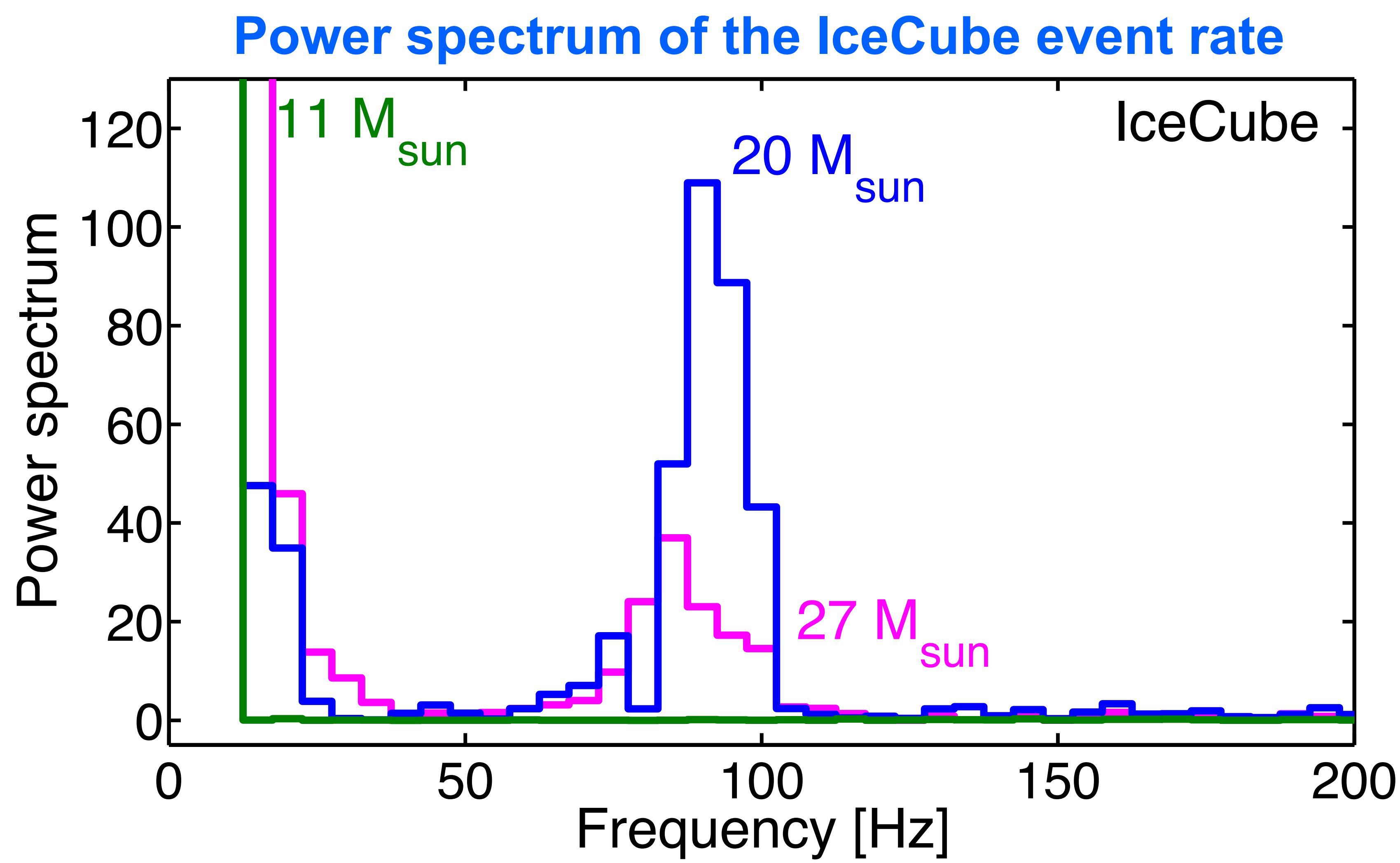


SASI imprints visible in neutrinos and gravitational waves.



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

Standing Accretion Shock Instability

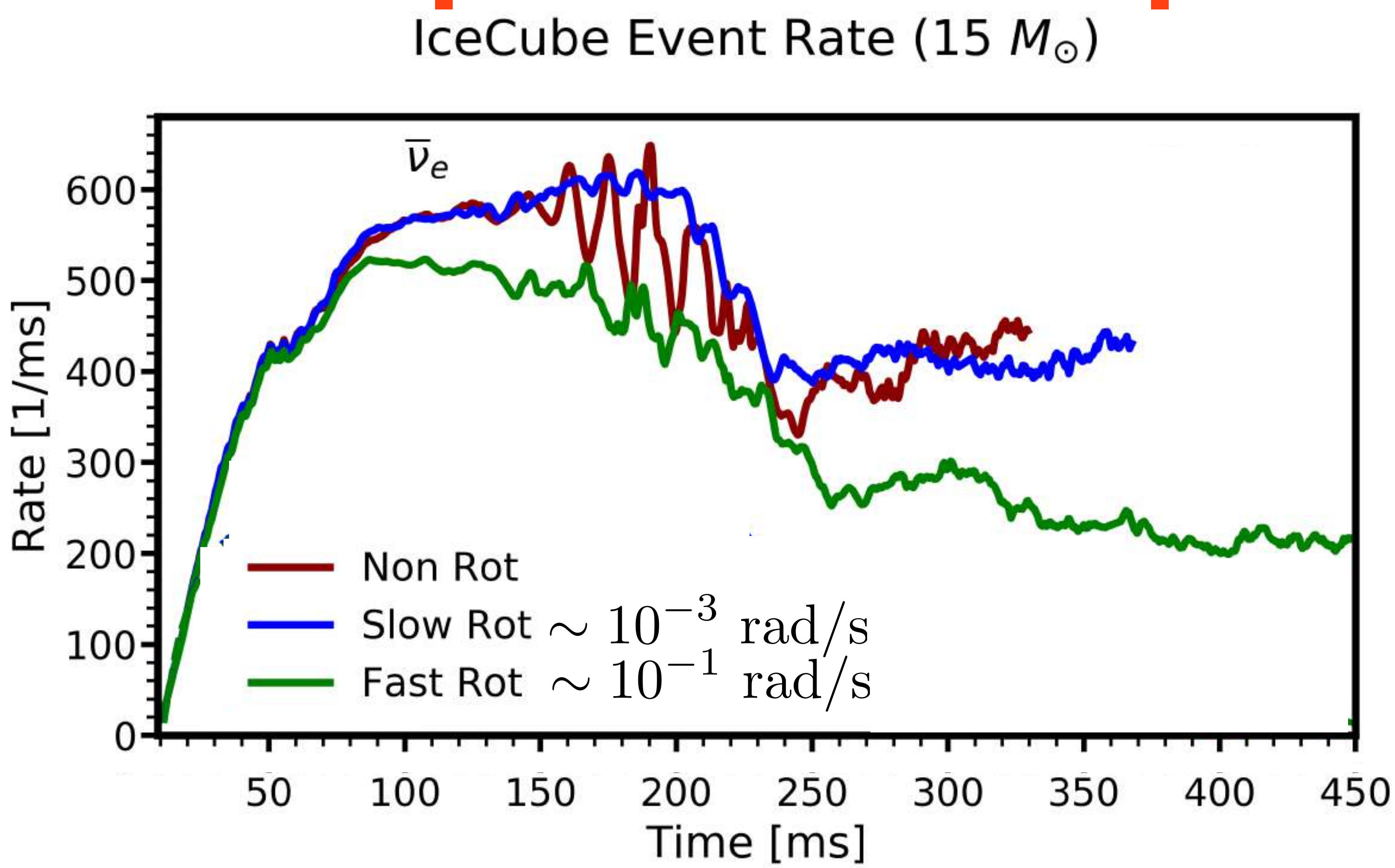


A peak appears in the power spectrum at the SASI frequency.

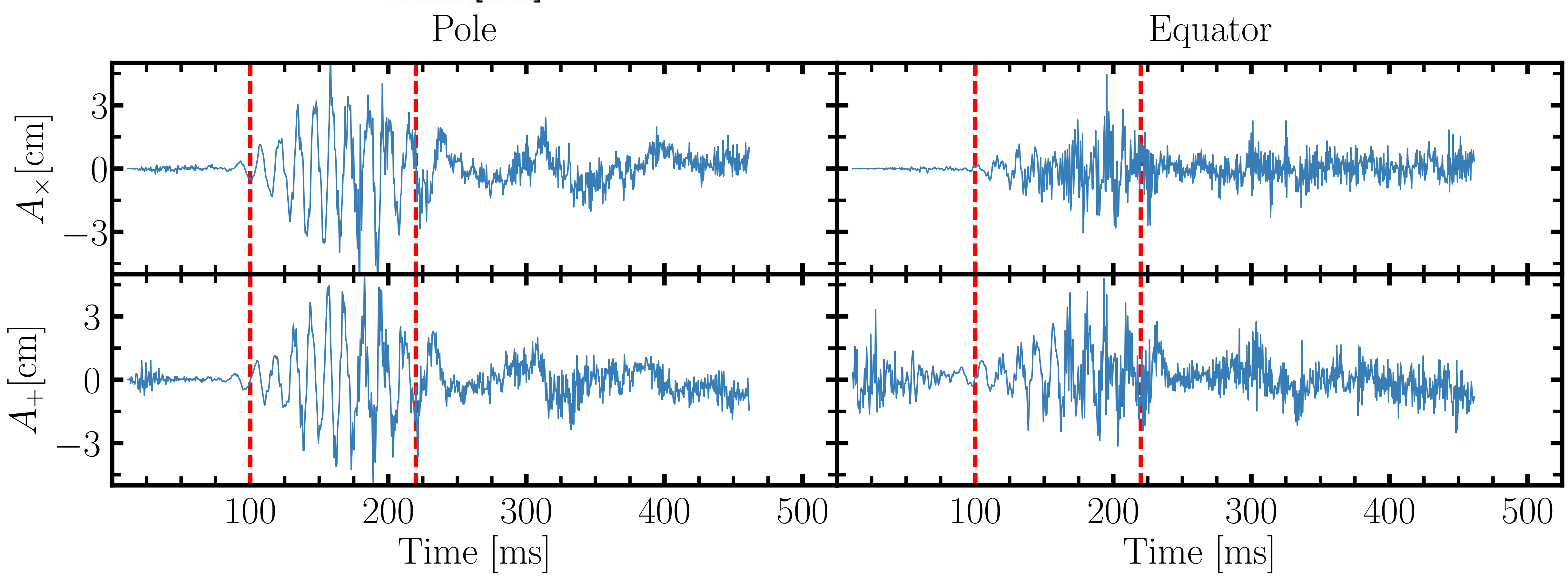
$$T_{\mathrm{SASI}} = 19\,\mathrm{ms}\left(\frac{r_{\mathrm{sh}}}{100\,\mathrm{km}}\right)^{3/2}\ln\left(\frac{r_{\mathrm{sh}}}{r_{\mathrm{PNS}}}\right).$$

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

Imprints of Supernova Rotation

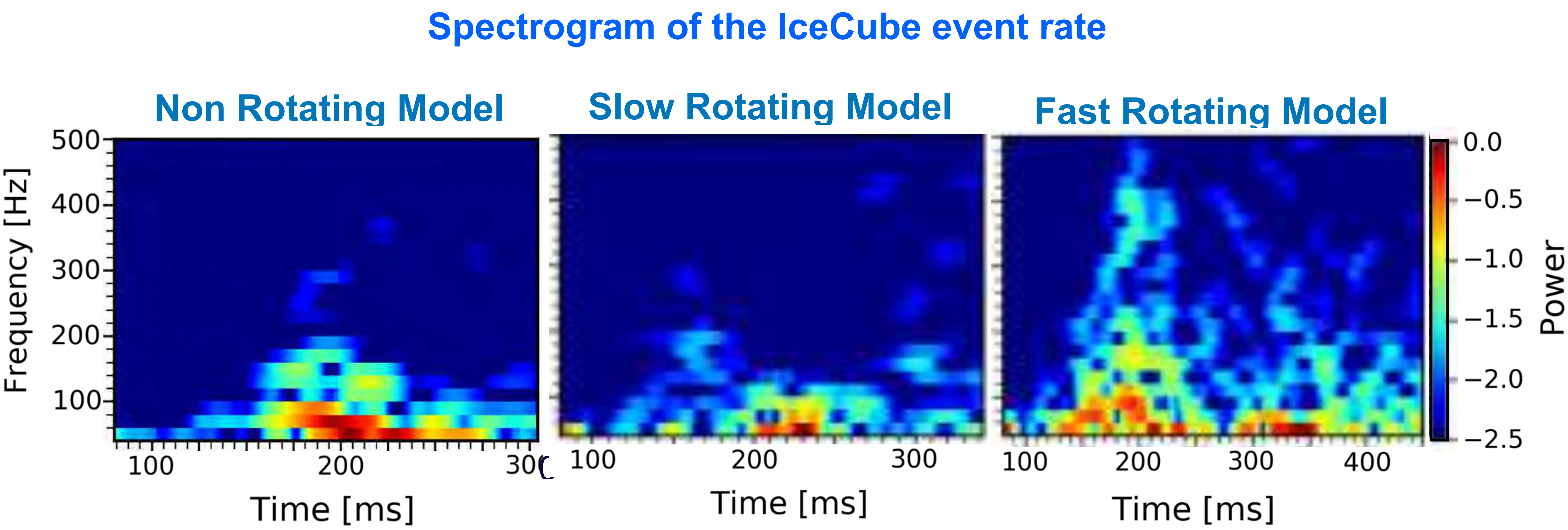


Rotation smears SASI modulations in neutrino signal.



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

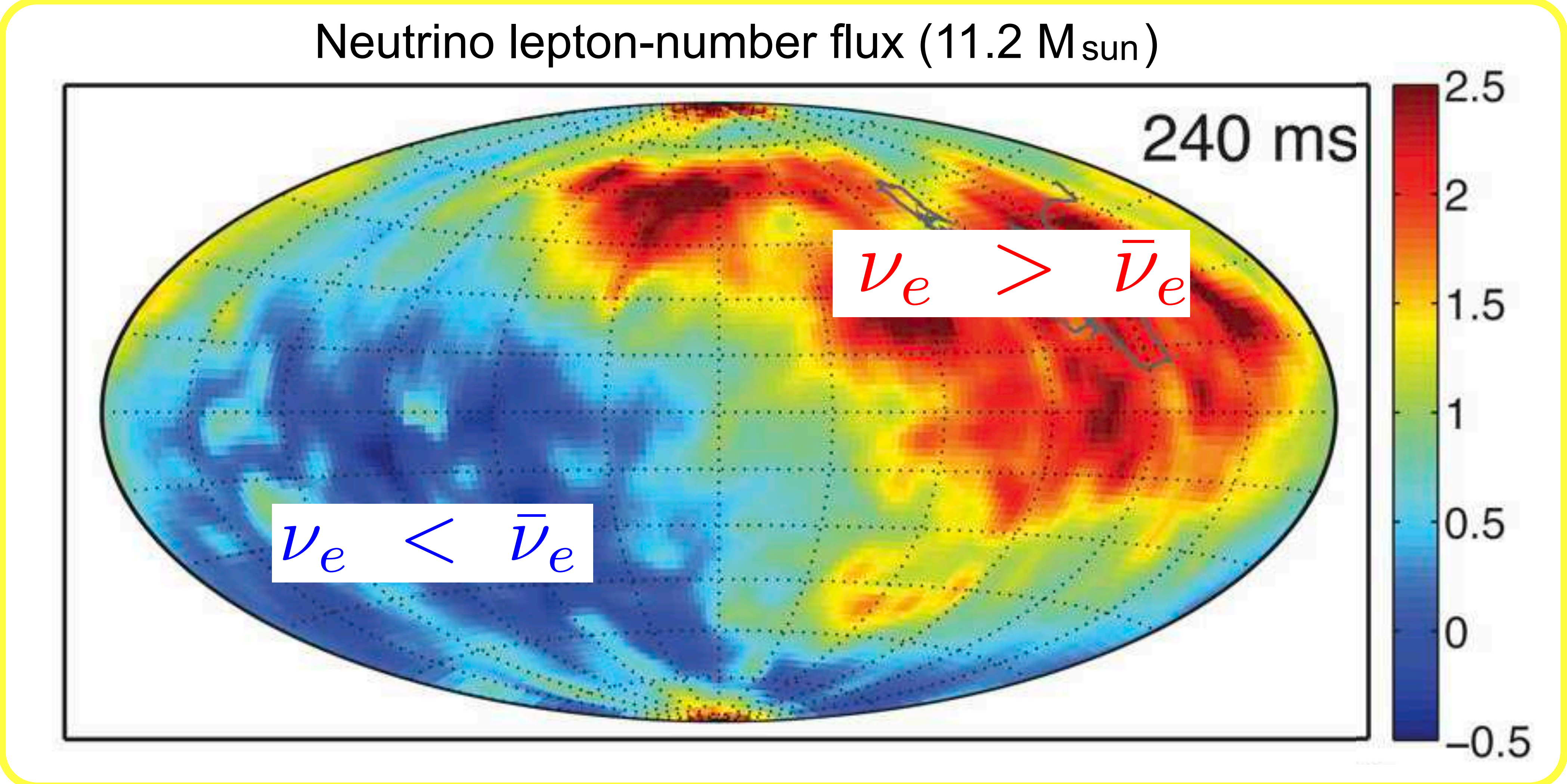
Imprints of Supernova Rotation



High frequency modulations appear as the rotational speed increases.

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

LESA: Neutrino-Driven Instability

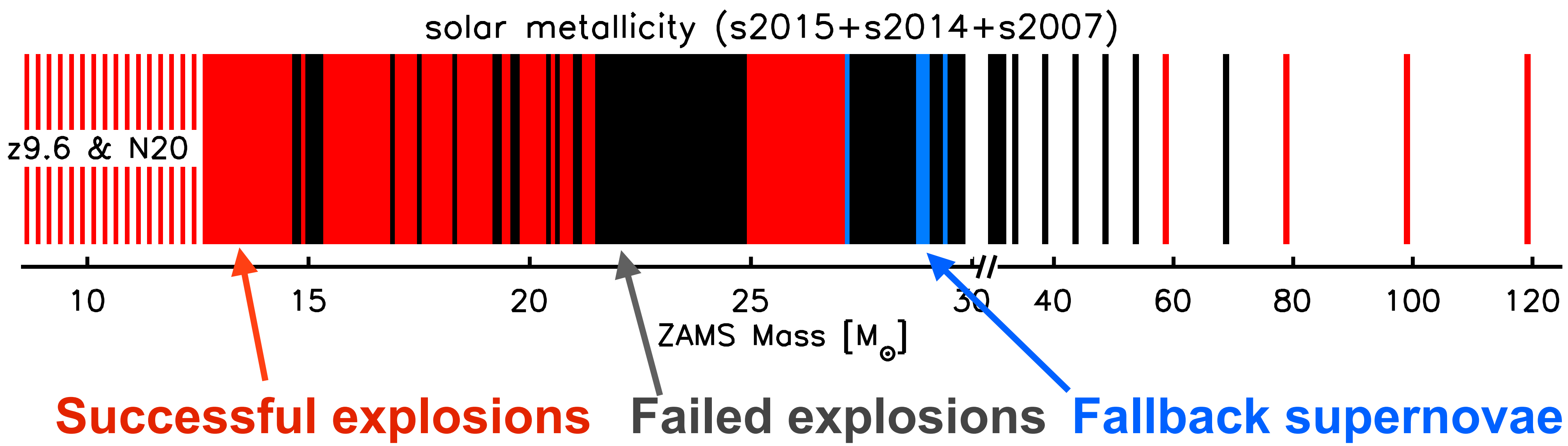


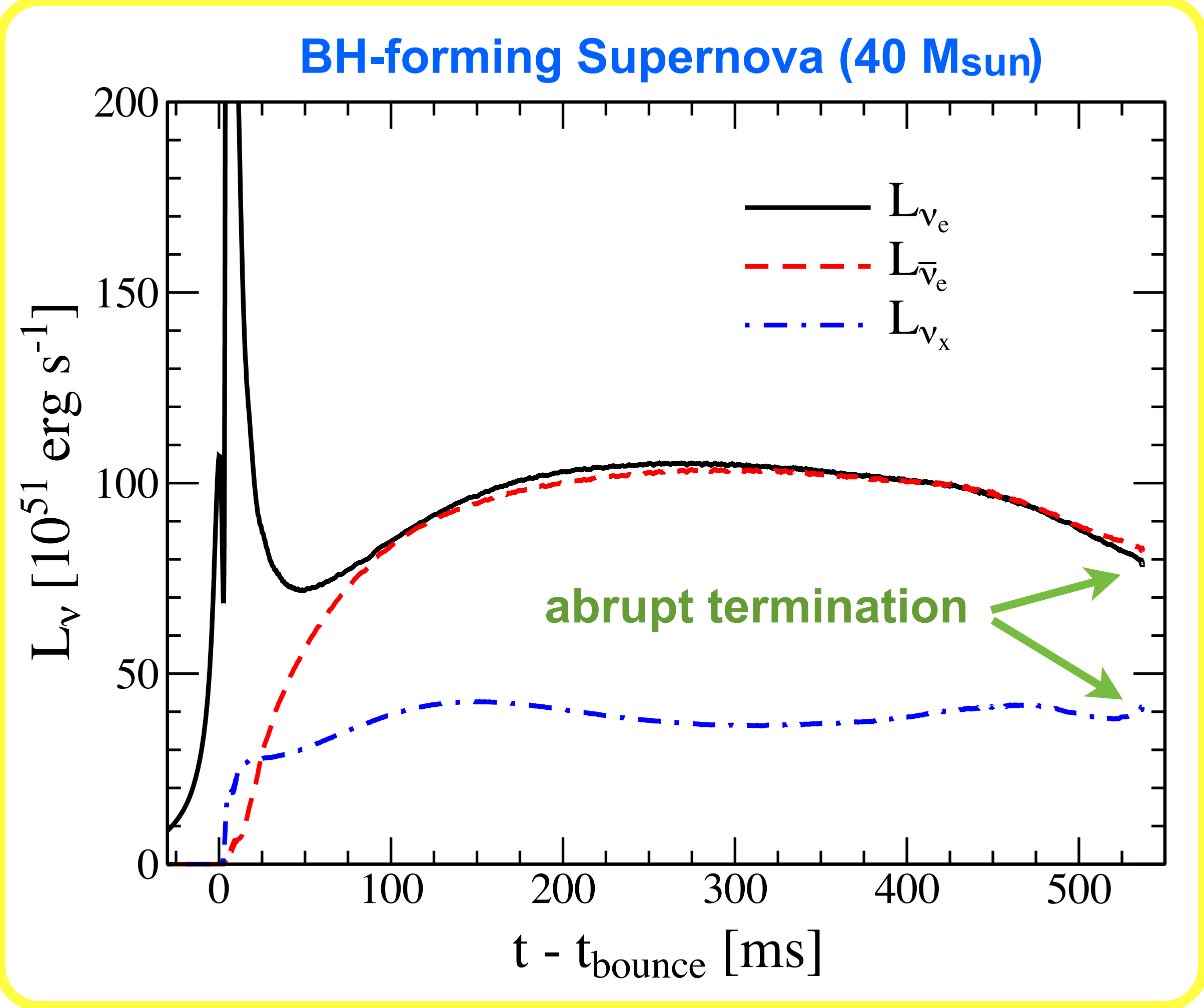
Lepton-number emission asymmetry (**LESA**). Possible major implications for

- 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).

Neutrinos Probe Black Hole Formation

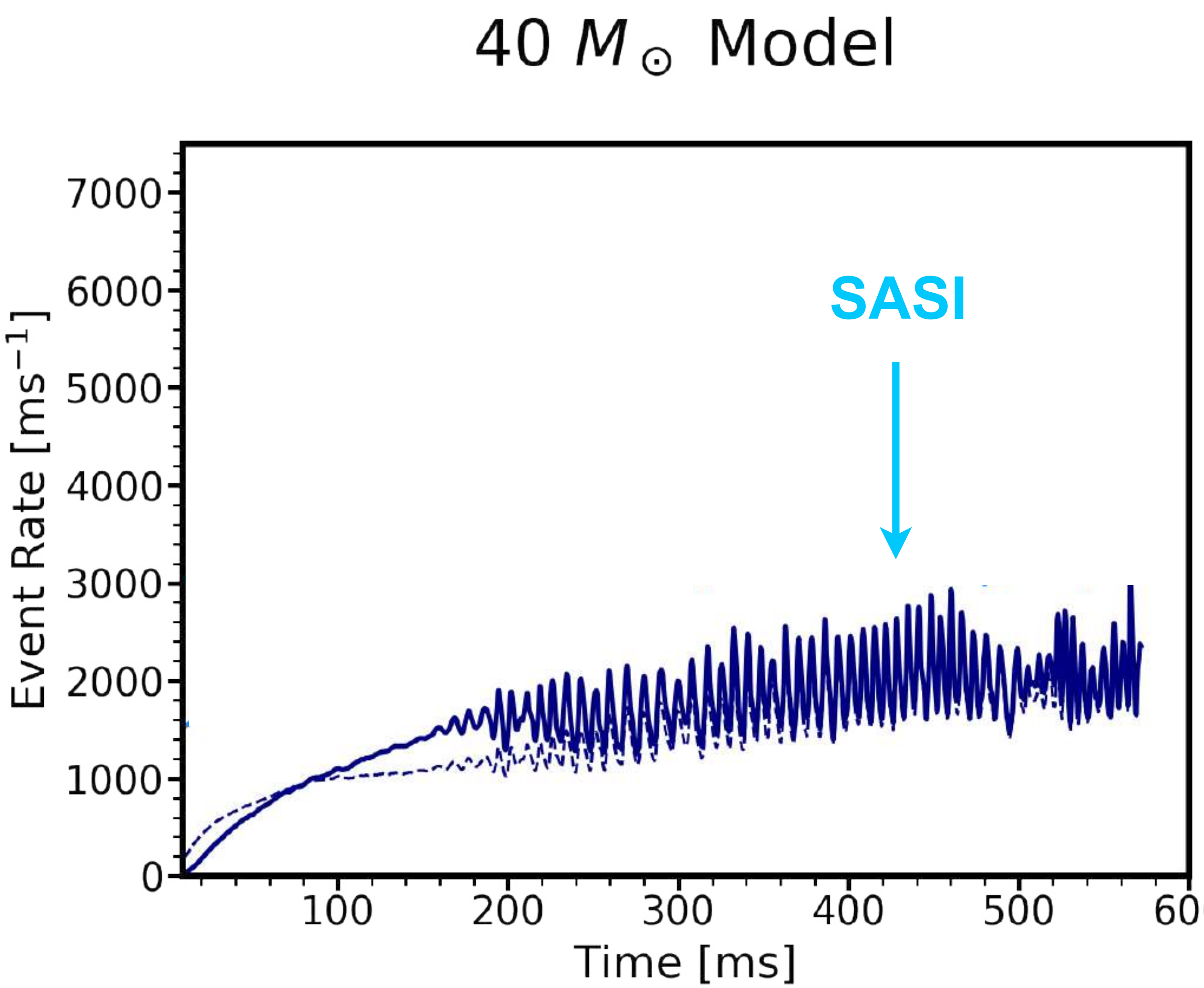




- Low mass supernovae can form black holes.
- Neutrinos reveal black hole formation.
- Failed supernovae up to 20-40% of total.

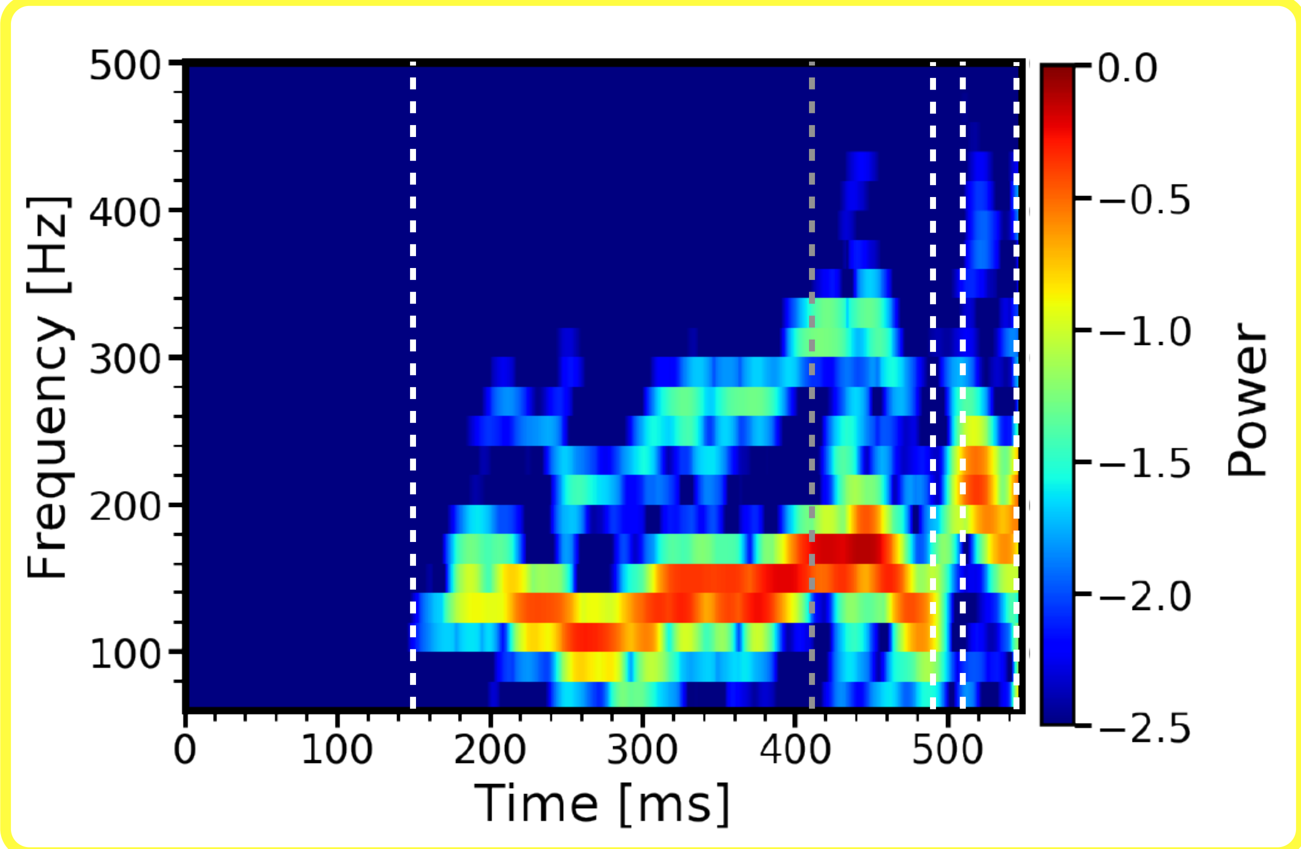
Sukhbold et al., ApJ (2016). Ertl et al., ApJ (2016). Horiuchi et al., MNRSL (2014). O'Connor & Ott, ApJ (2011). O'Connor, ApJ (2015). Kuroda et al., MNRAS (2018).

Neutrinos Probe Black Hole Formation



Neutrinos (and gravitational waves) probe black hole formation.

SASI frequency evolution
= Shock radius evolution

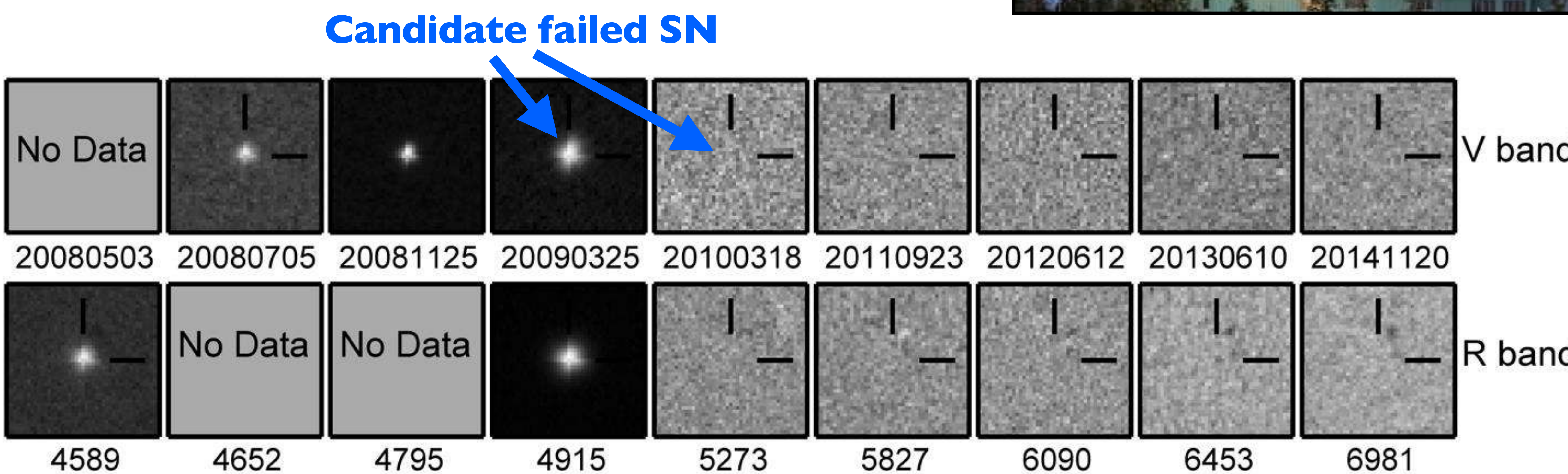


Walk, Tamborra, Janka, Summa, Kresse, PRD (2020).

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)

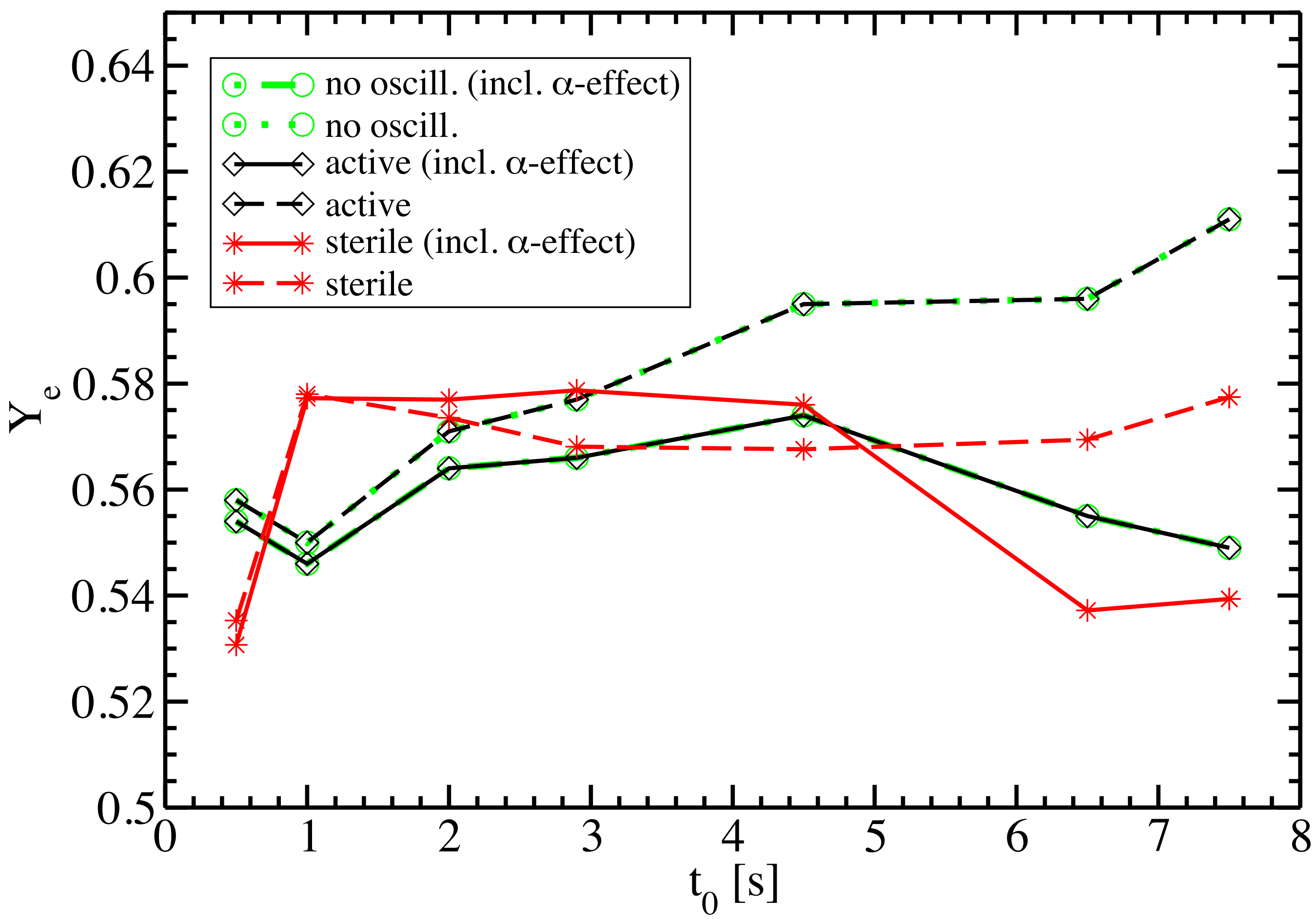
Adams et al., MNRAS (2017), MNRAS (2017). Gerke, Kochanek & Stanek, MNRAS (2015). Kochanek et al., ApJ (2008). Allan et al., MNRAS (2020).

Neutrinos Affect Element Production

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

Flavor oscillations affect element production mainly via

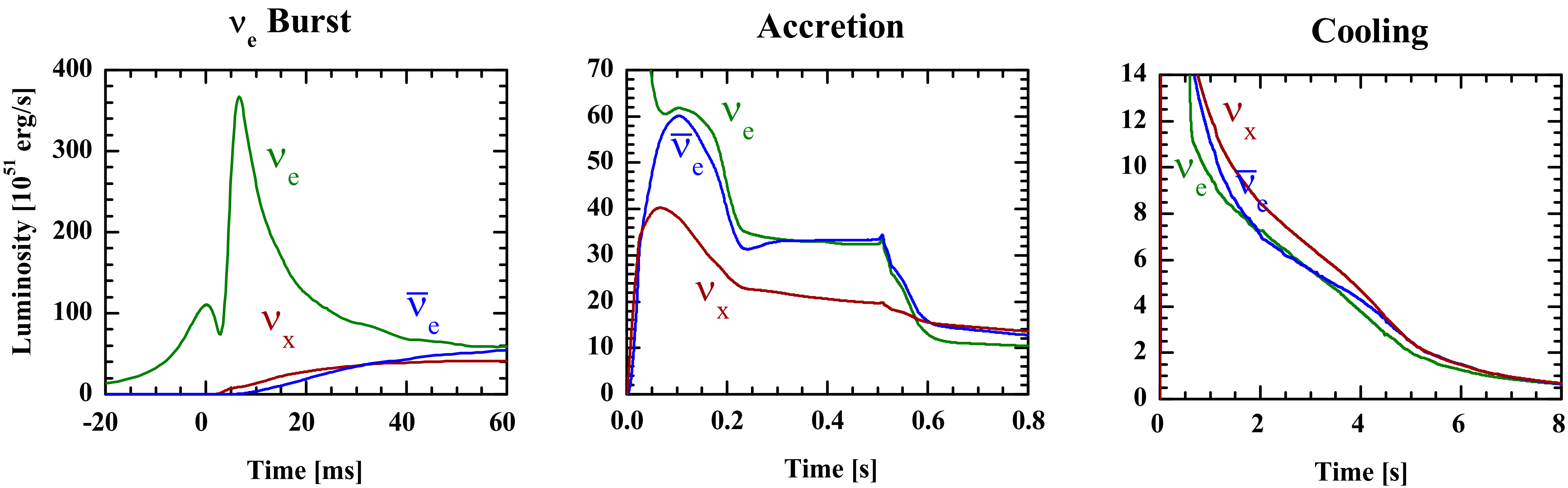
$$\nu_e + n \rightleftharpoons p + e^-$$
$$\bar{\nu}_e + p \rightleftharpoons n + e^+$$



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.

ν_e

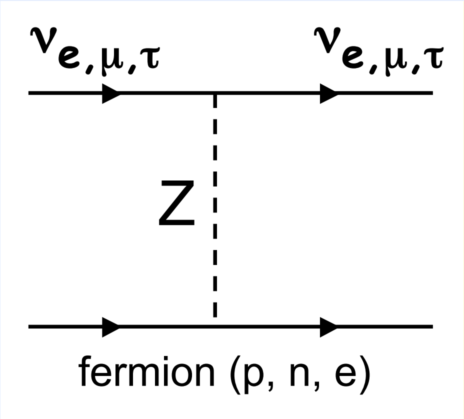
ν_τ

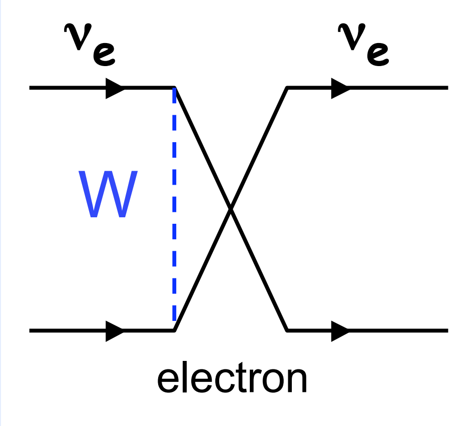
Flavor Evolution

ν_μ

Neutrino Interactions

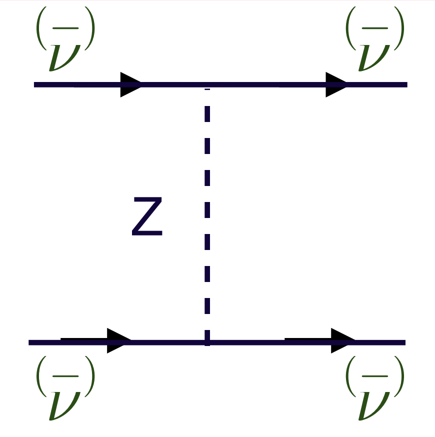
Neutrinos in supernovae interact with matter and among each other.





Neutrinos interact with neutrons, protons and electrons.

(MSW effects)



$\nu - \nu$ interactions

Non-linear phenomenon

Neutrino Equations of Motion

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 (negligible)

Vacuum term

Matter term [MSW resonant conversion]

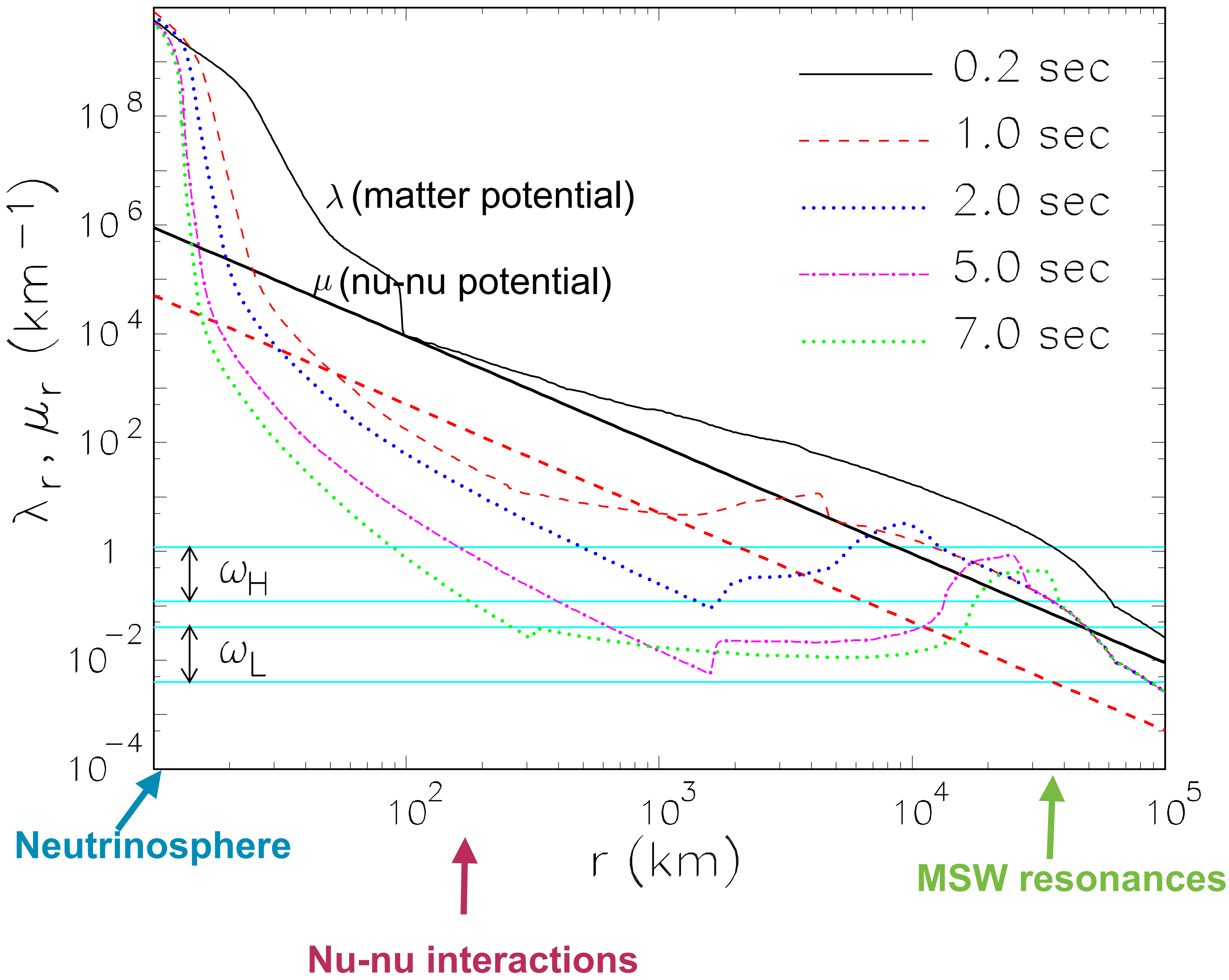
$\nu - \nu$ interaction term [neutrino self-interactions]

Collision term

Challenging problem:

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

Nu-Nu and Matter Potentials



Fast Pairwise Neutrino Conversions

Flavor conversion (vacuum or MSW): $\nu_e(p) \to \nu_\mu(p)$.

Lepton flavor violation by mass and mixing.

Pairwise flavor exchange by $\nu - \nu$ scattering: $\nu_e(p) + \bar{\nu}_e(k) \to \nu_\mu(p) + \bar{\nu}_\mu(k)$
$\nu_e(p) + \nu_\mu(k) \to \nu_\mu(p) + \nu_e(k)$

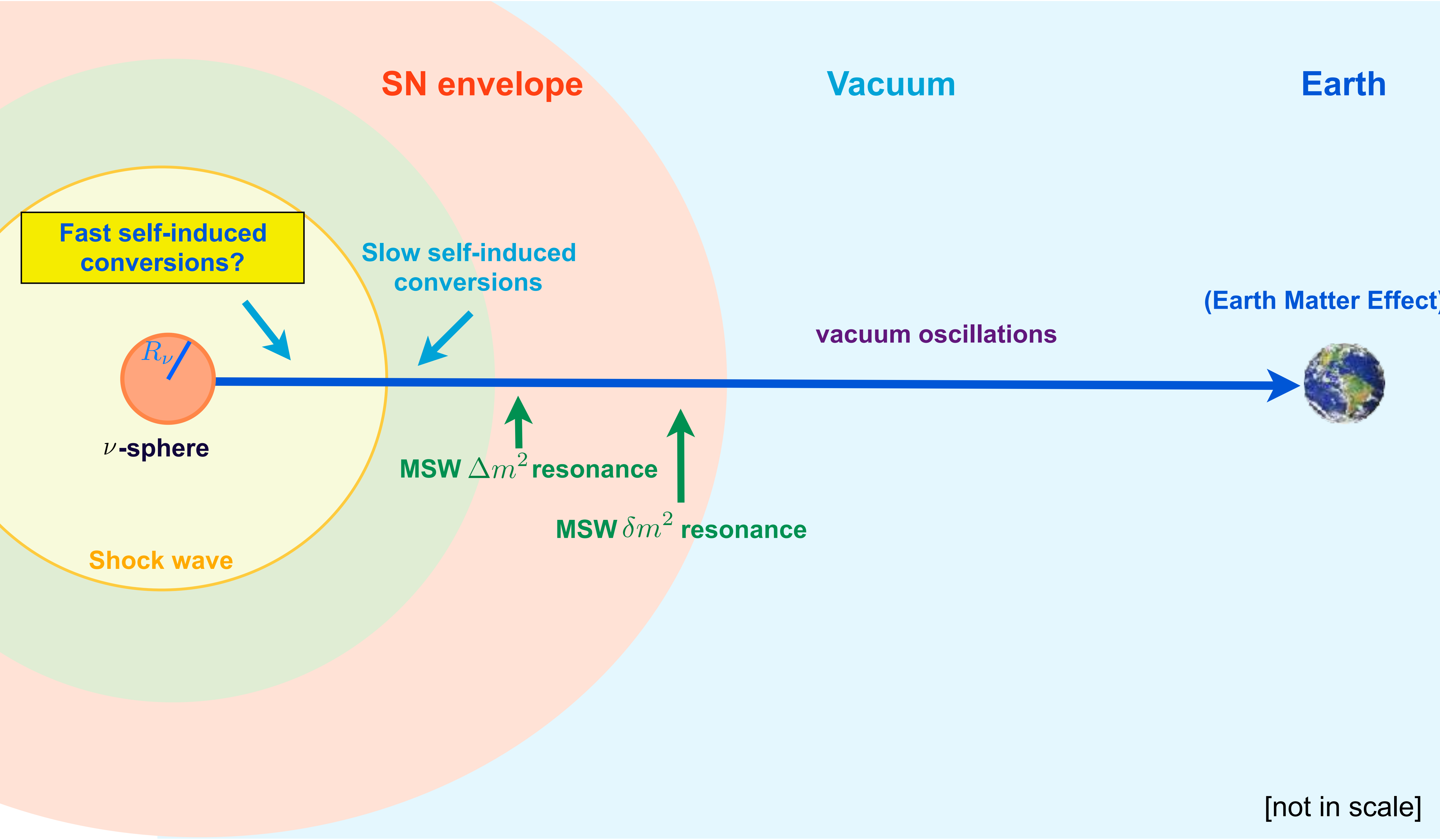
No net lepton flavor change.

Growth rate: $\sqrt{2}G_F(n_{\nu_e} - n_{\bar{\nu}_e}) \simeq 6.42\ \mathrm{m}^{-1}$ vs. $\dfrac{\Delta m^2}{2E} \simeq 0.5\ \mathrm{km}^{-1}$ ⇒ **"Fast" conversions**

Flavor conversion may occur close to neutrino decoupling region. **Further work needed!**

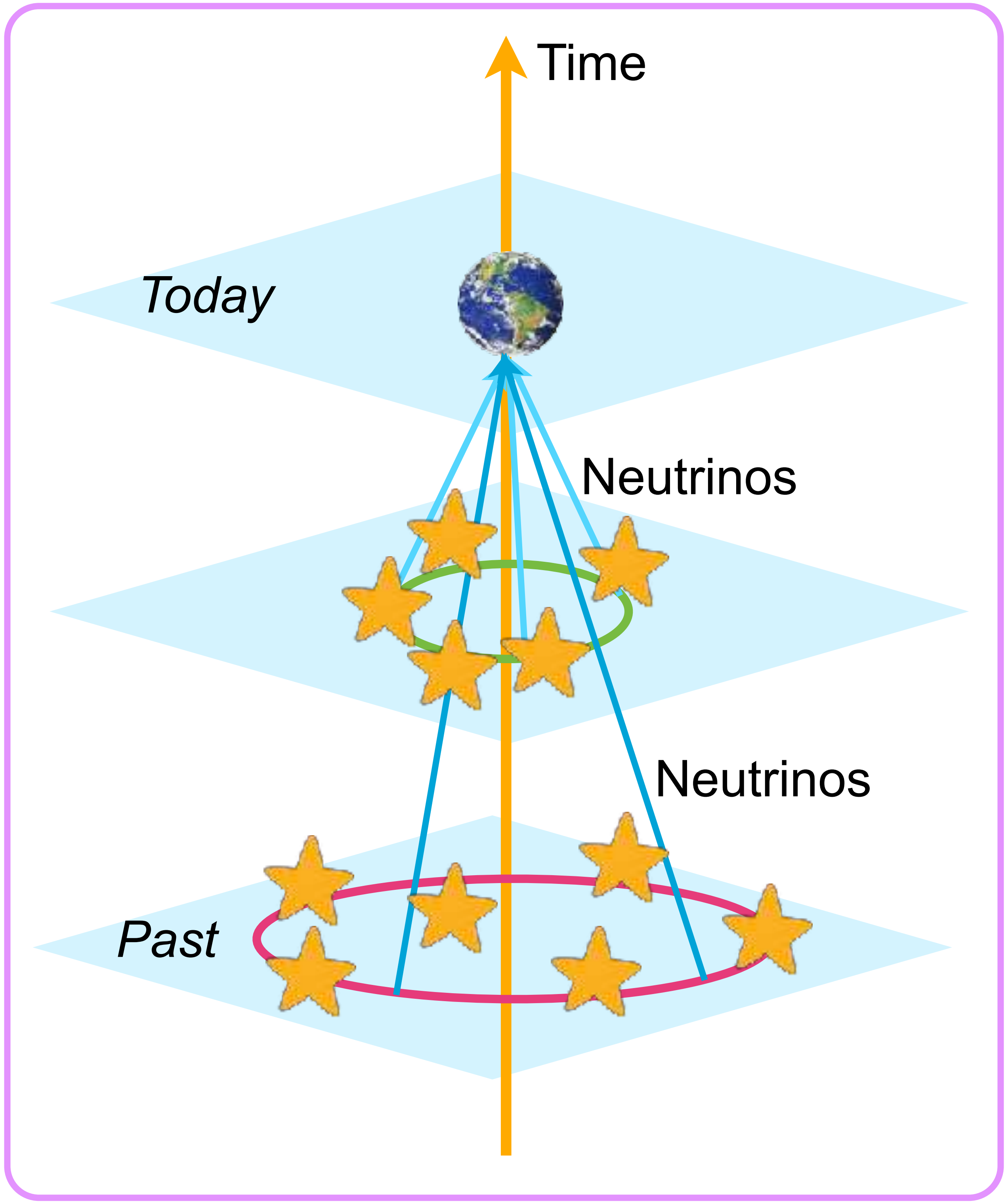
Izaguirre, Raffelt, Tamborra, PRL (2017). Tamborra et al., ApJ (2017). Shalgar & Tamborra, ApJ (2019). Capozzi et al., PRD (2017). Dasgupta et al., PRD 2018. Sawyer, PRD (2005), Sawyer, PRL (2016). Azari et al., PRD (2019, 2020). Dasgupta et al., JCAP (2017). Abbar et al., PRD (2019), PRD (2020). Morinaga et al., PRR (2020). Glas et al., PRD (2020). Nagakura et al., ApJ (2019). Martin et al., PLB (2020). Yi et al., 2019. Shalgar & Tamborra, arXiv: 2007.07926. Shalgar & Tamborra, ApJ (2019). Shalgar, Padilla-Gay, Tamborra, JCAP (2020). …

Simplified Picture of Flavor Conversions



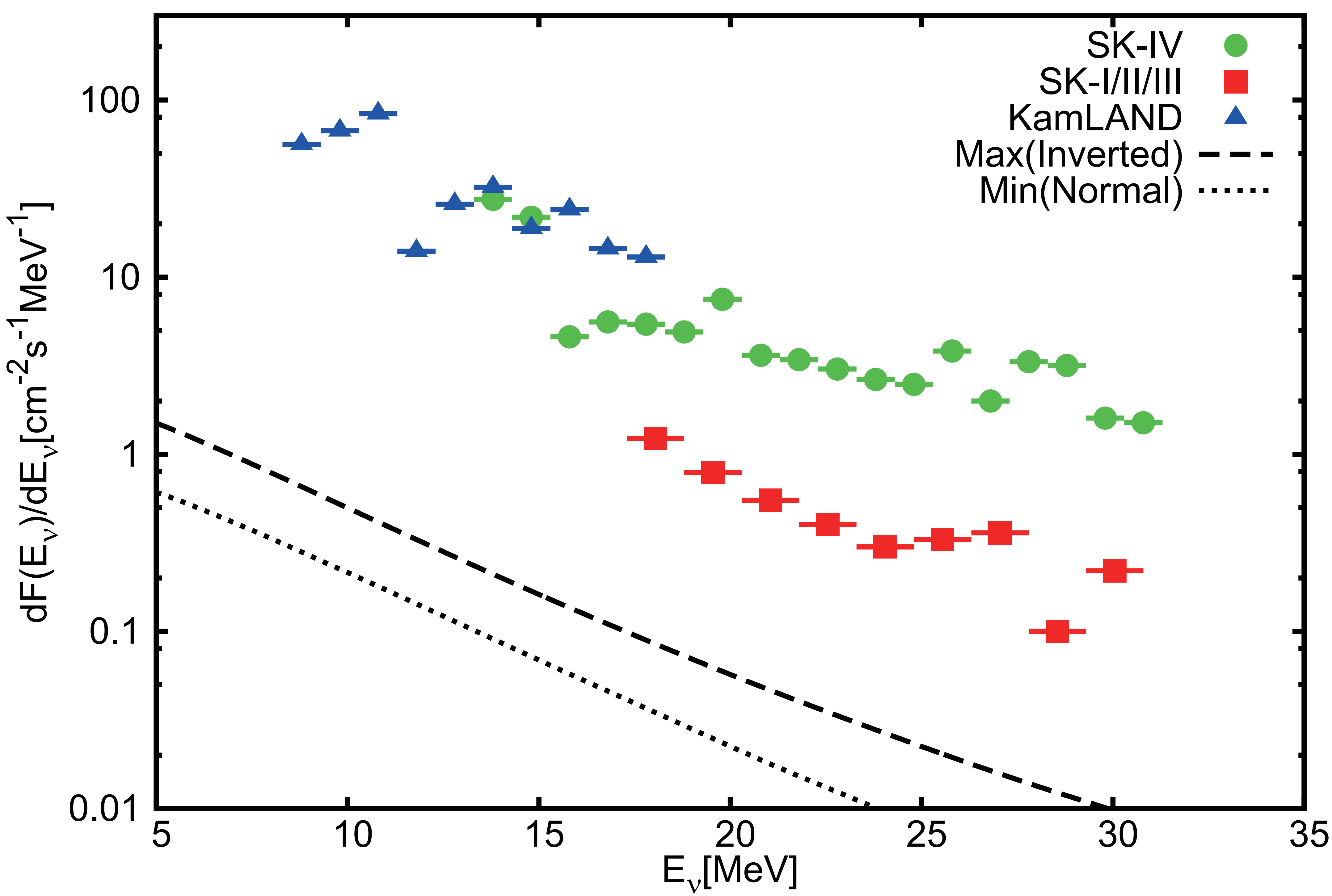
Diffuse Supernova Neutrino Background

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



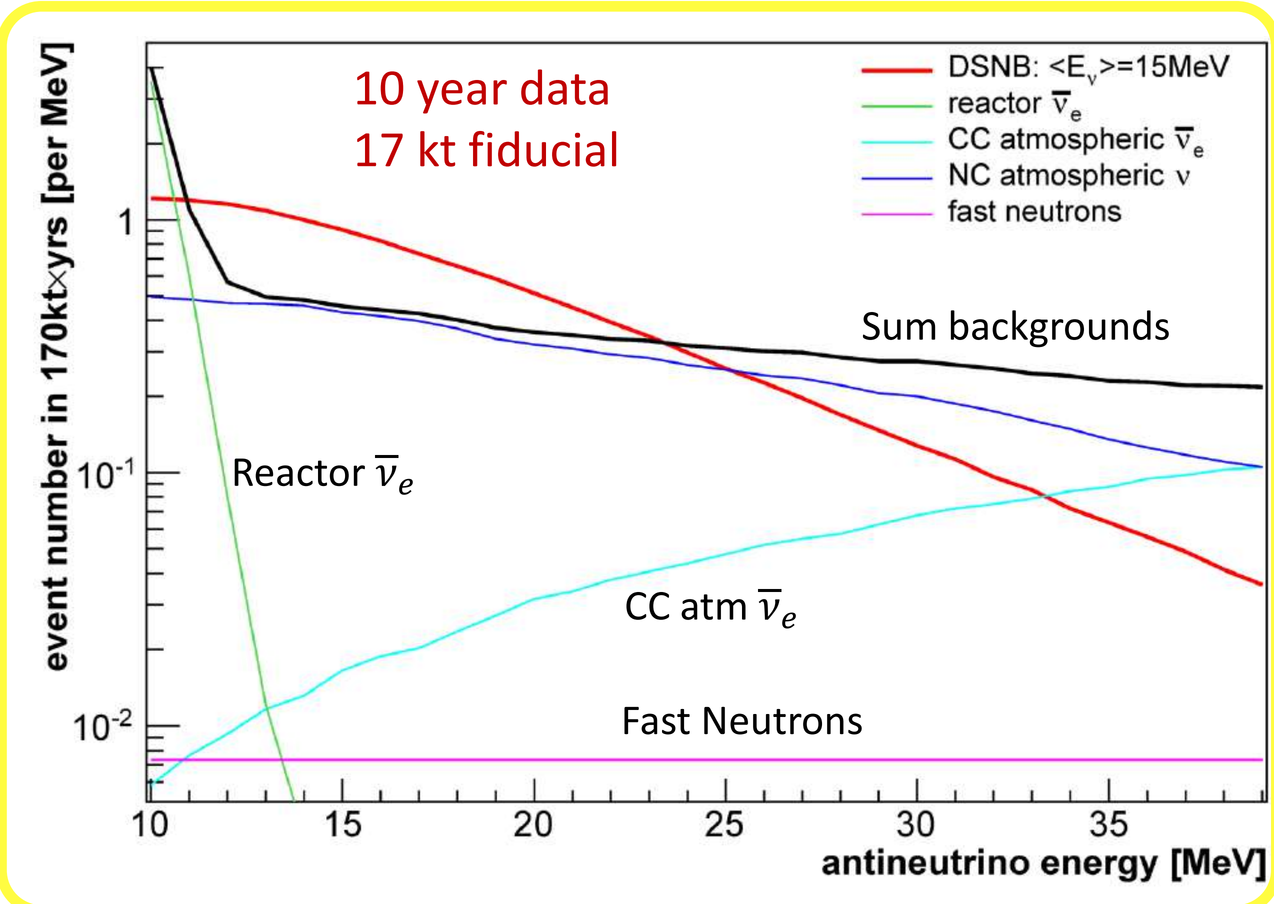
DSNB Detection Perspectives

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



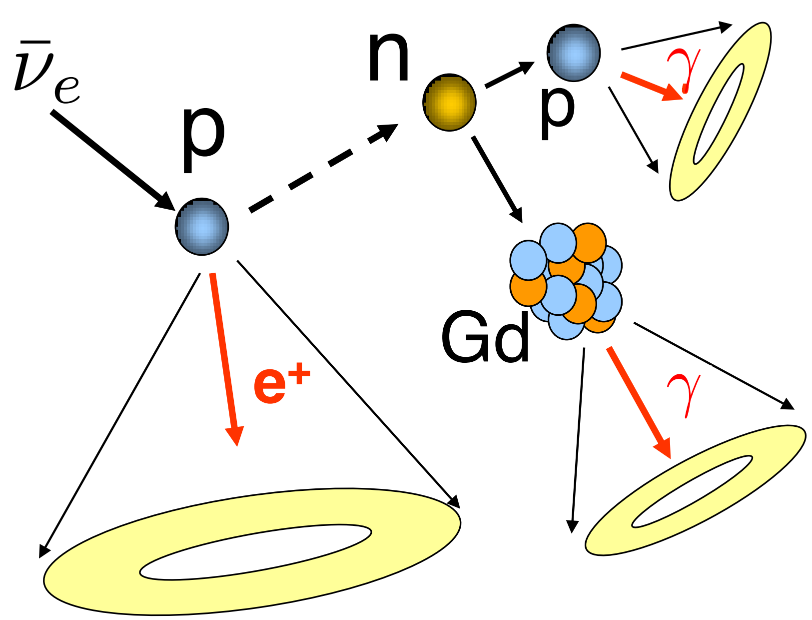
Recent review papers: Mirizzi, Tamborra et al. (2016). Lunardini (2010). Beacom (2010).
Super-Kamiokande Collaboration, Astrop. Phys. (2015). Beacom & Vagins, PRL (2004). JUNO Coll., 2015.

DSNB Detection



JUNO detection perspectives

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



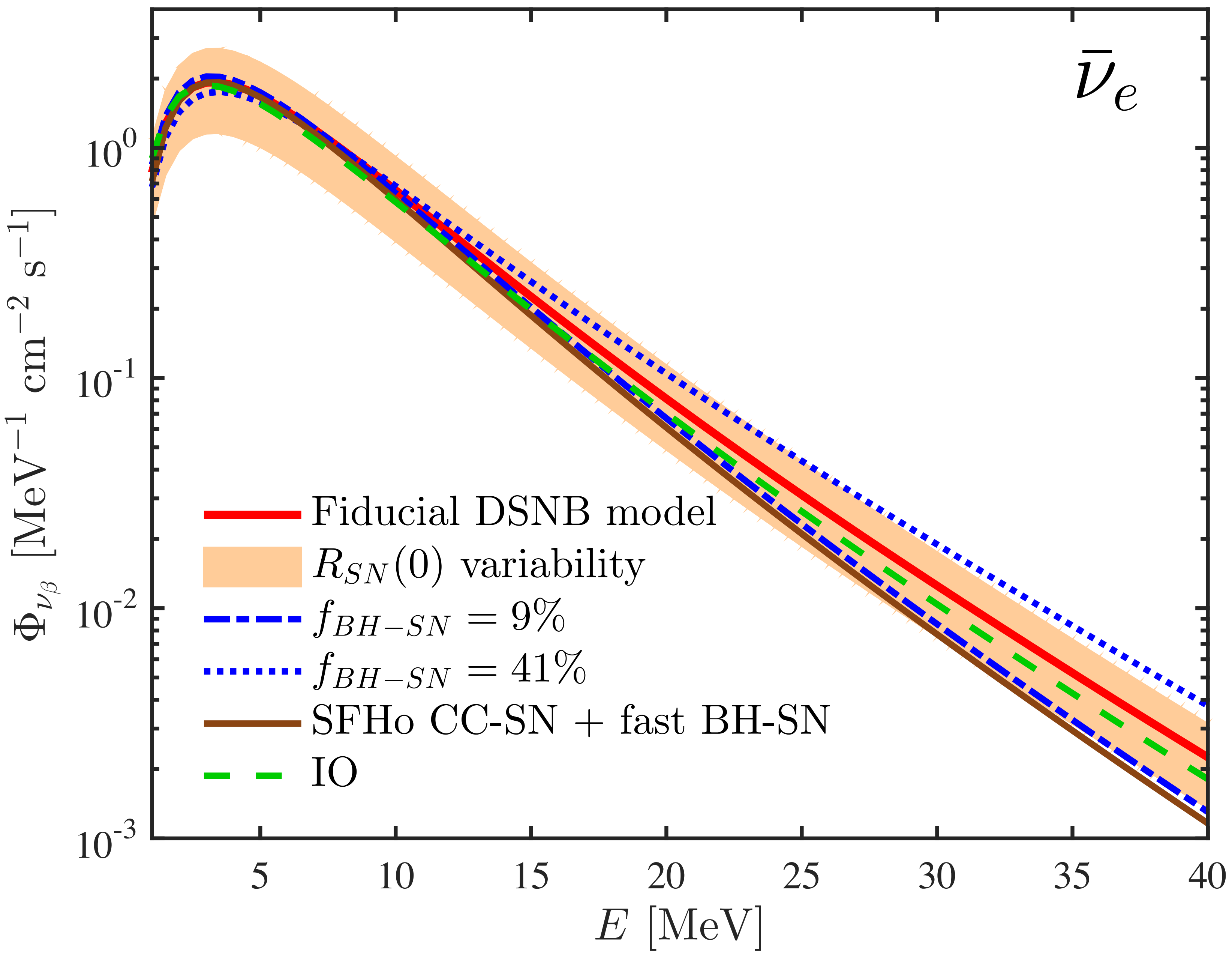
Positron and gamma ray vertices are within ~50cm.

Neutron tagging in Gd-enriched WC detector (Super-K with 100 tons Gd to trap neutrons).

$\bar{\nu}_e$ identified by delayed coincidence

Gd-loading ongoing!

Fingerprints of the Supernova Population



- Independent test of the supernova rate (~30% precision).
- Constraints on fraction of black hole forming collapses.

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

Take Home Messages

- **Neutrinos are fundamental in core-collapse supernovae.**
- **Neutrinos are ideal messengers.**
- **Neutrinos carry imprints of source inner workings.**
- **Neutrinos rule the synthesis of heavy elements.**
- **Neutrino conversions relevant, not yet complete understanding.**
- **Upcoming DSNB detection will allow to explore SN population.**

Thank you!