The Niels Bohr International Academy

DARK

Supernova Theory Review

Irene Tamborra

Niels Bohr Institute, University of Copenhagen

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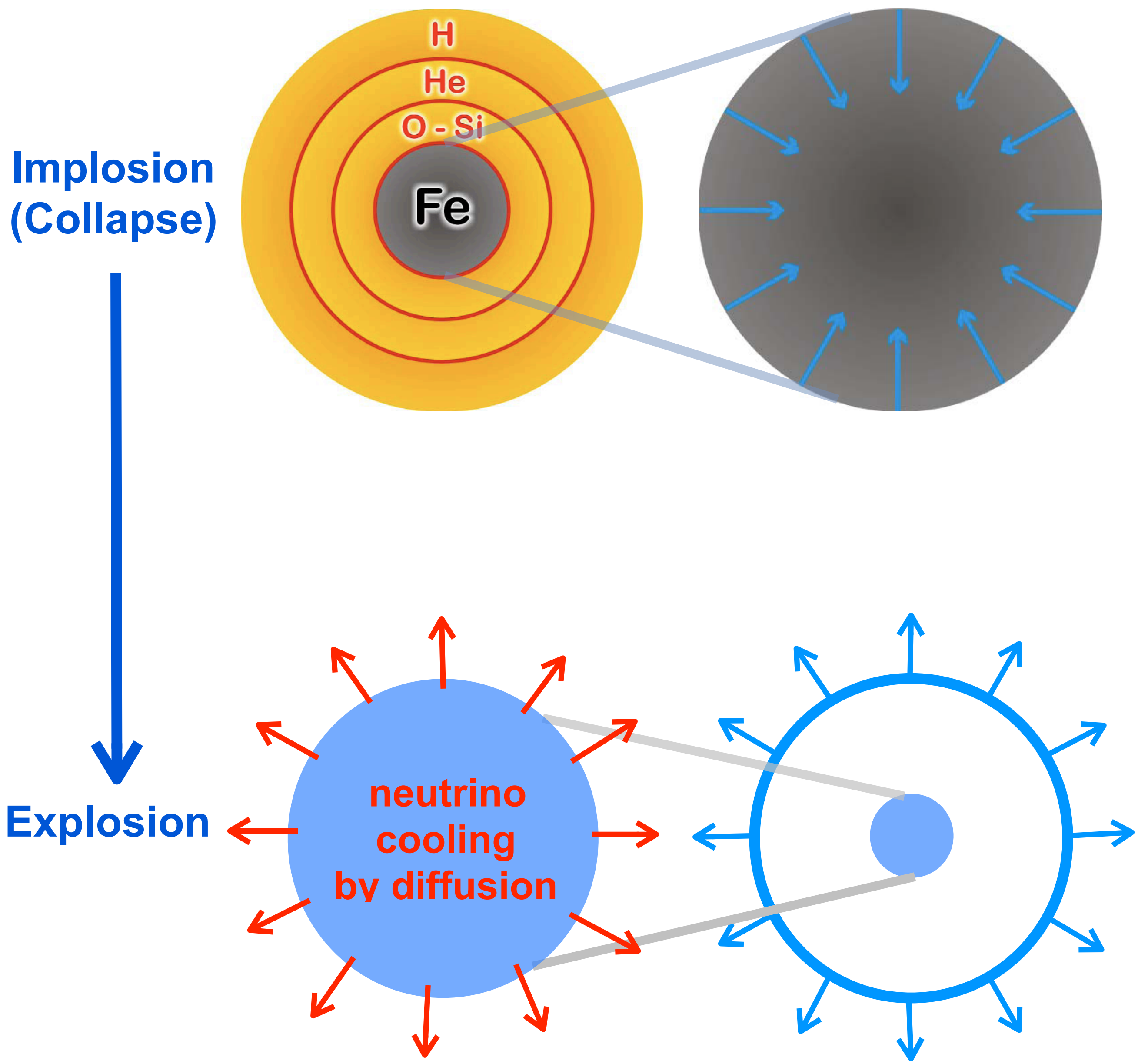
VILLUM FONDEN

Sapere Aude

CARLSBERG FOUNDATION

SFB 1258 Neutrinos Dark Matter Messengers

Core-Collapse Supernova Explosion



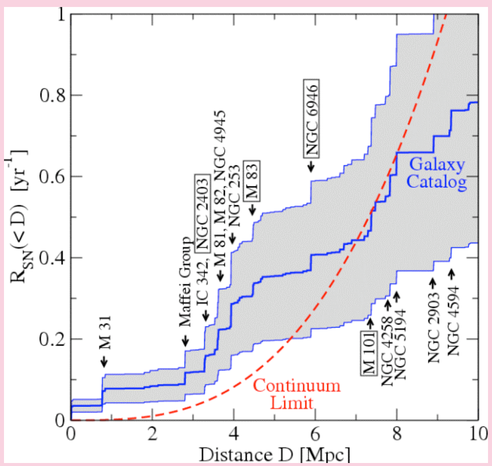
Neutrinos carry 99% of the released energy (~ 10^{53} erg).

Neutrino energies: ~ 10 MeV.
Neutrino emission time: ~ 10 s.

Detection Frontiers

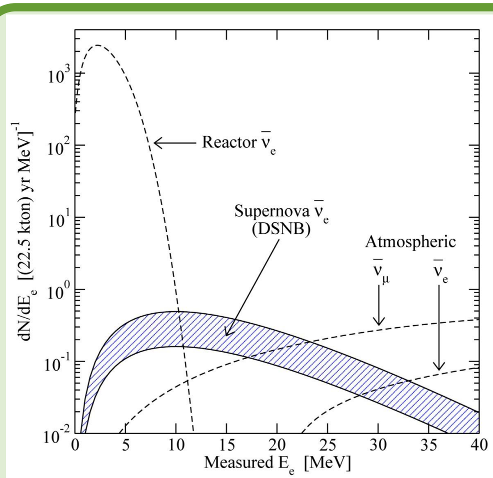
Supernova in our Galaxy (one burst per 40 years).

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.

Multi-Messenger Signatures

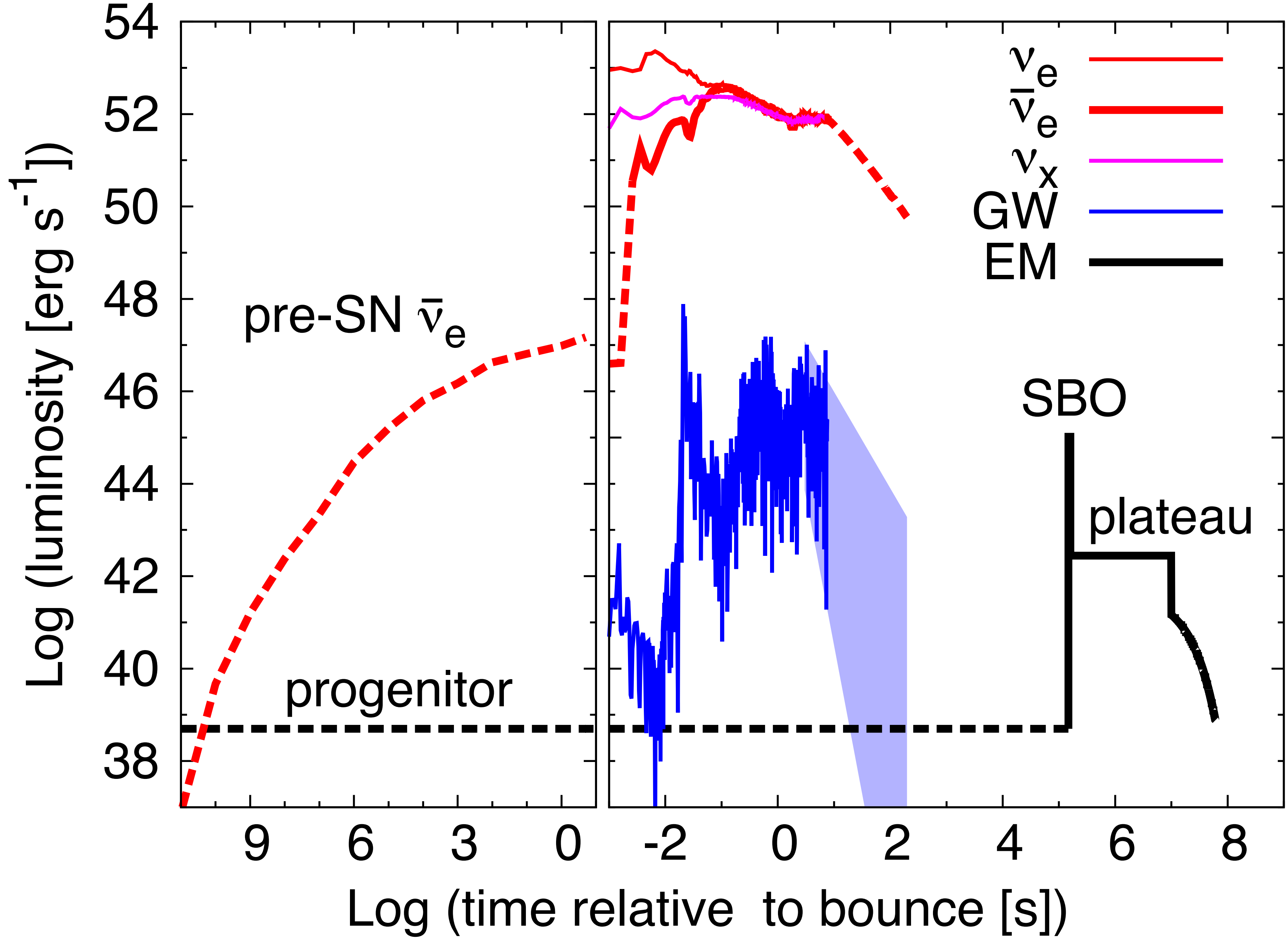


Figure from Nakamura et al., MNRAS (2016).

General Features of Neutrino Signal

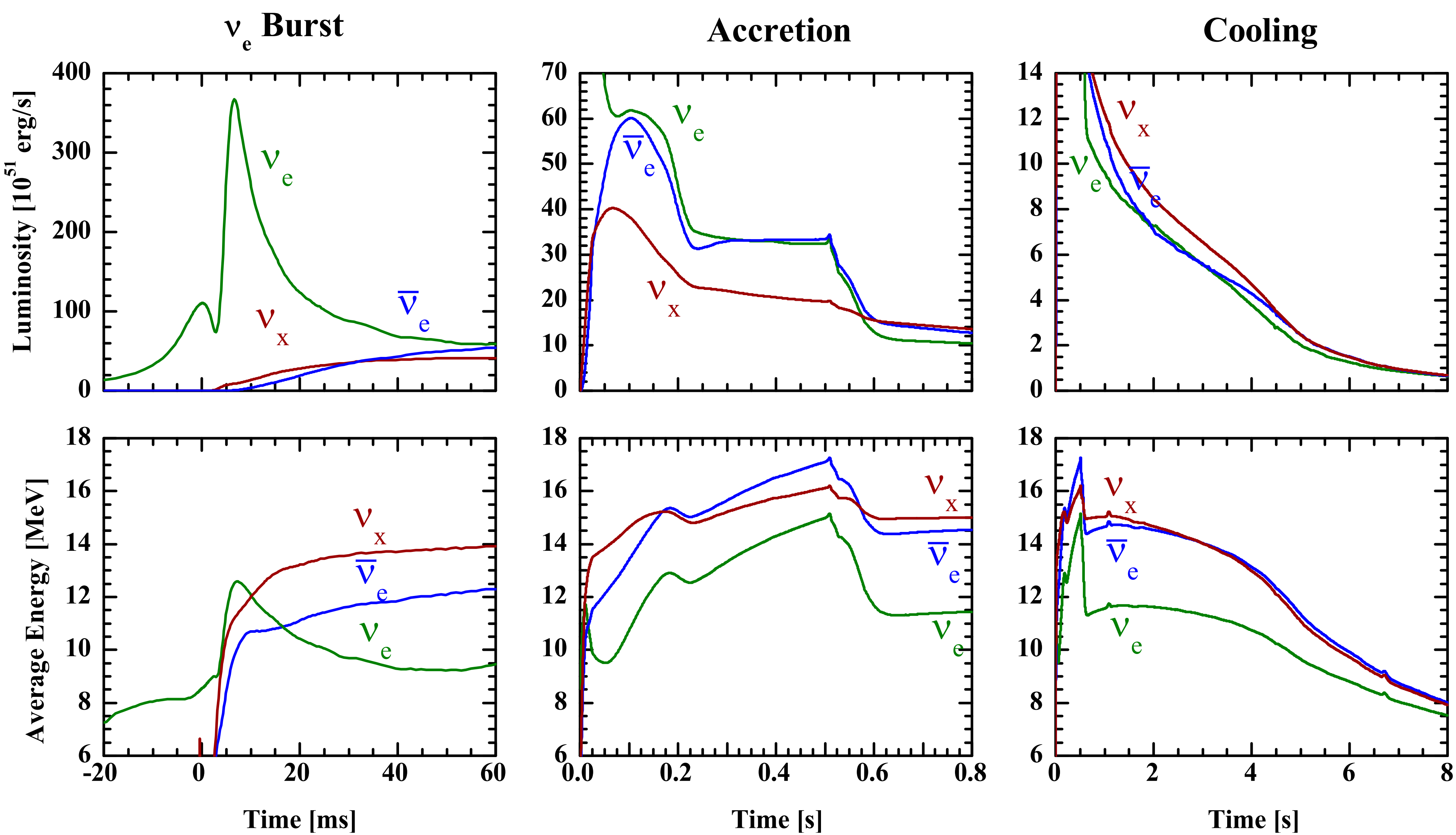
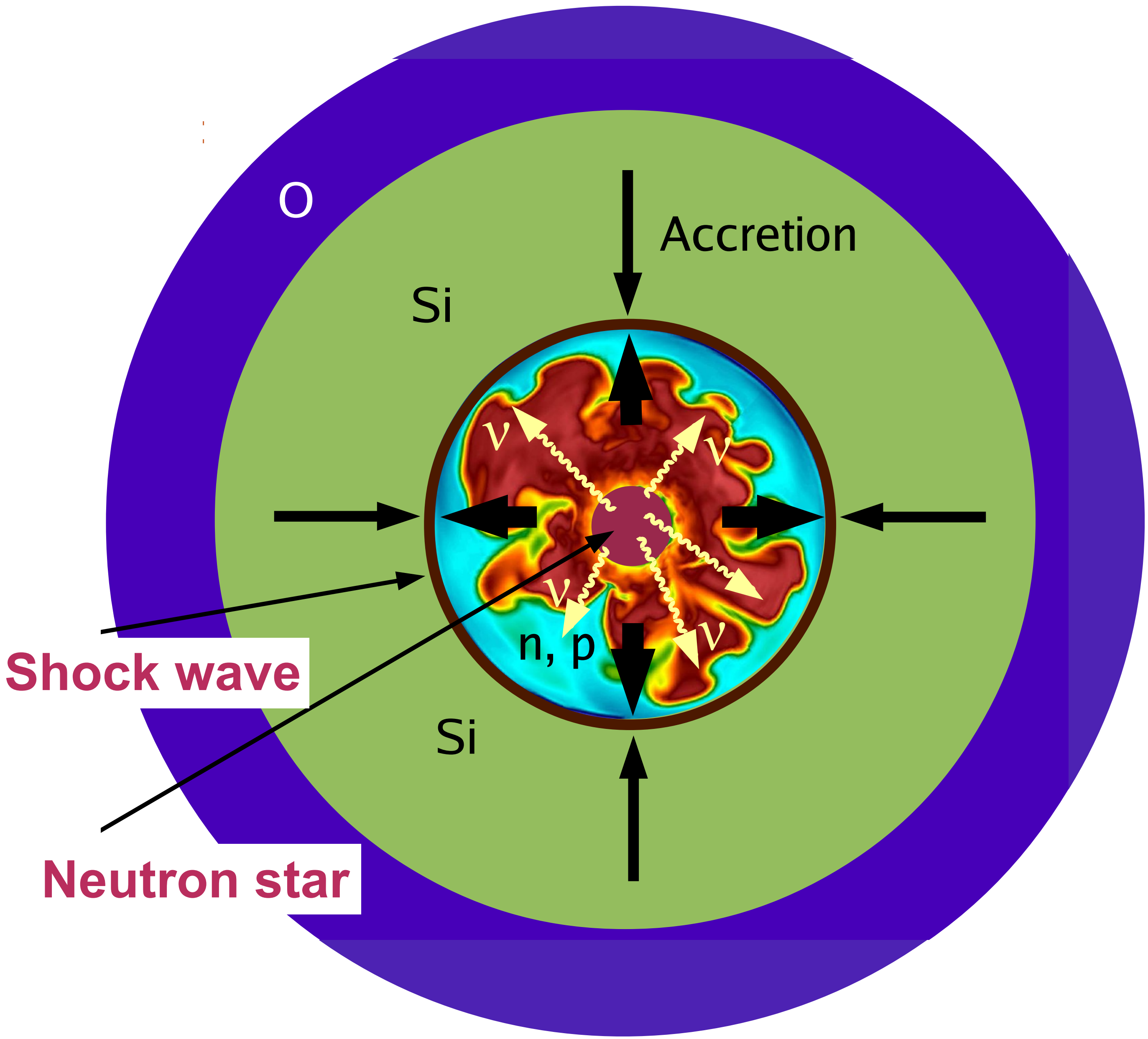


Figure: 1D spherically symmetric SN simulation (M=27 M_{sun}), Garching group.

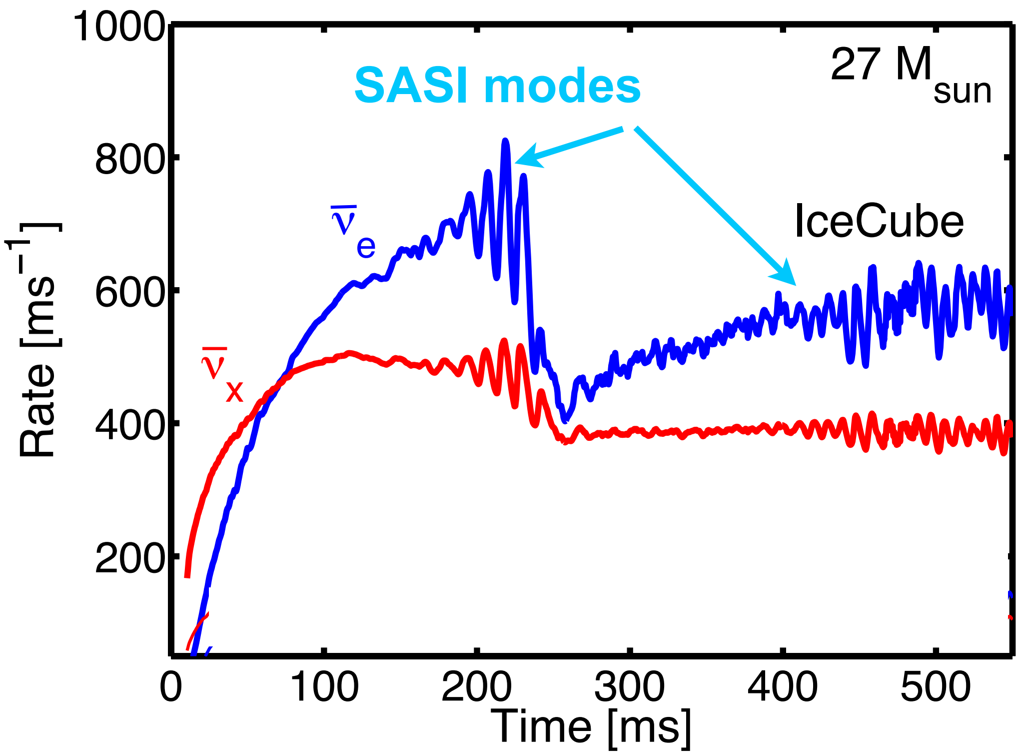
Supernova Explosion Mechanism

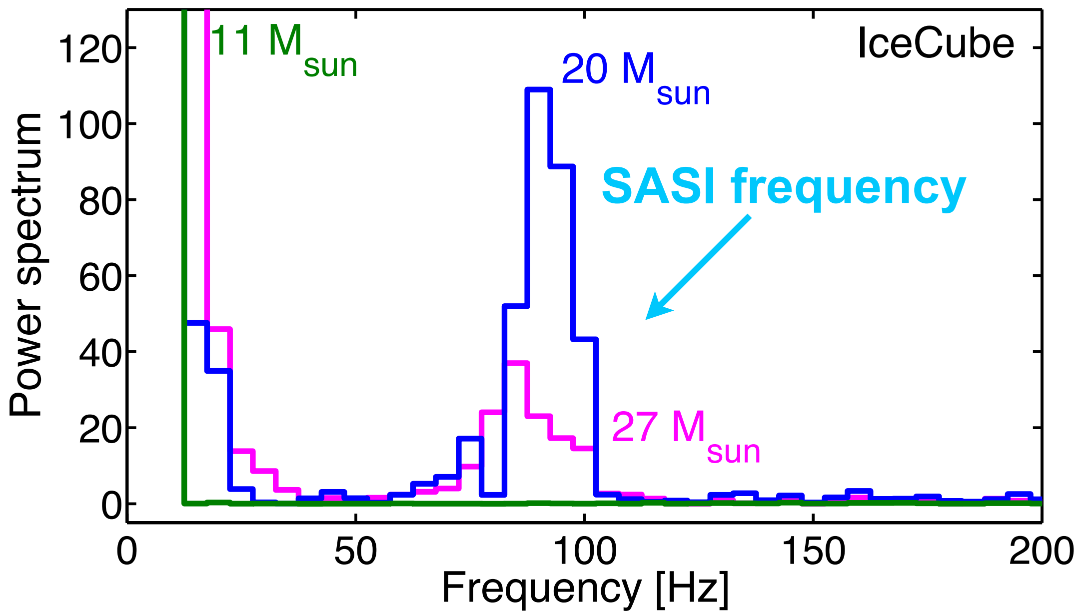
Shock wave forms within the iron core. It dissipates energy dissociating the iron layer.
Neutrinos provide energy to the stalled shock wave to start re-expansion.

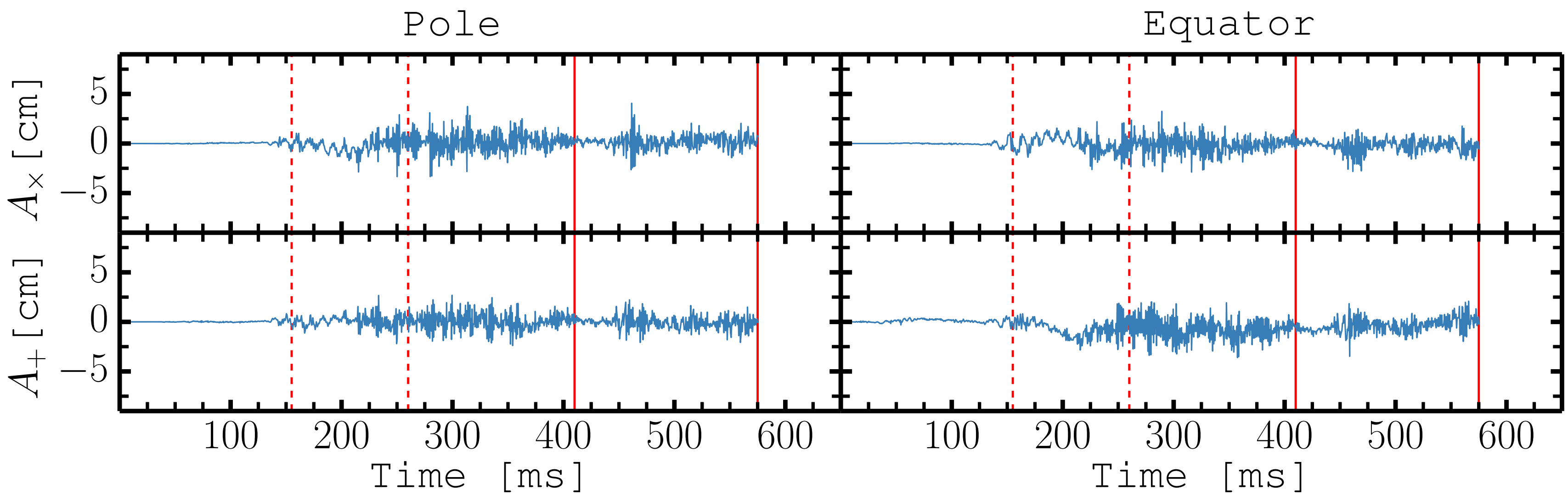


Recent reviews: Janka (2017). Mirizzi, Tamborra et al. (2016).

Fingerprints of the Explosion Mechanism

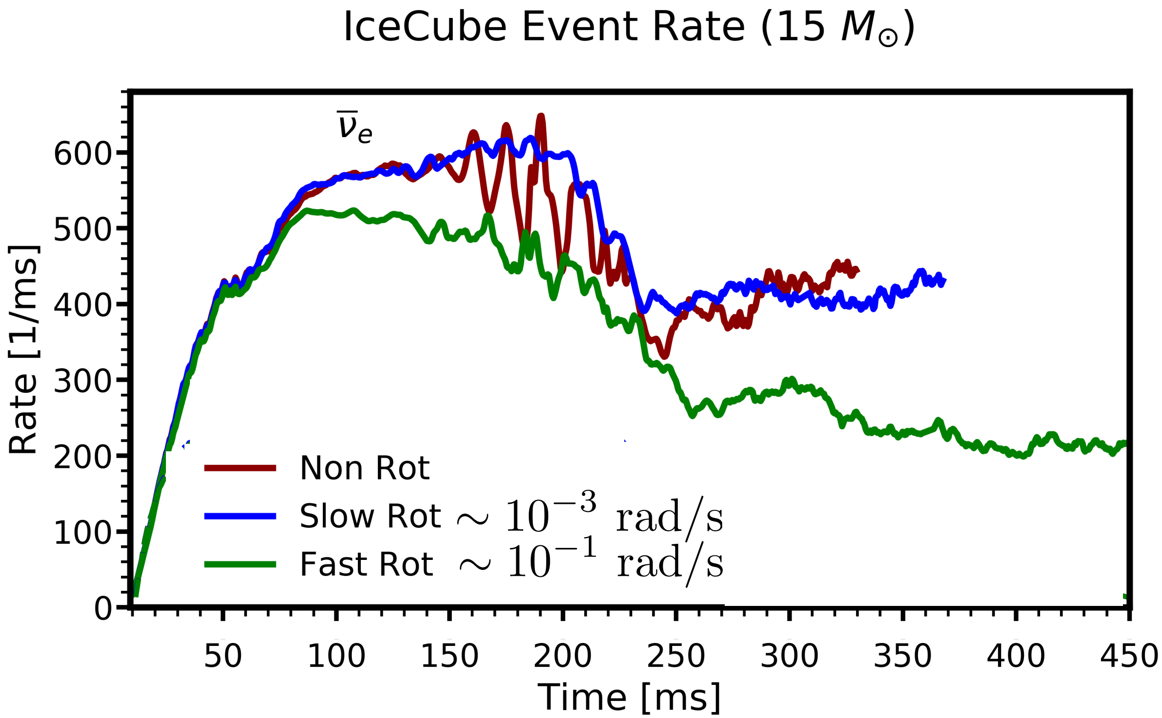




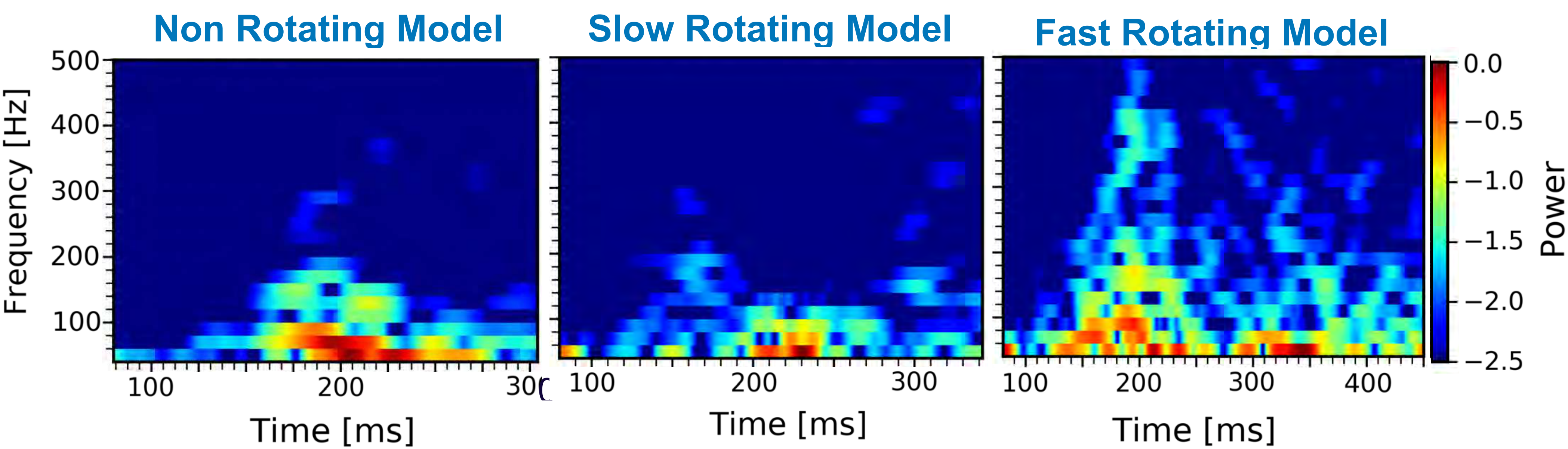


Tamborra et al., PRL (2013), PRD (2014). Andresen et al., MNRAS (2017). Kuroda et al., ApJ (2017).

Fingerprints of Supernova Rotation

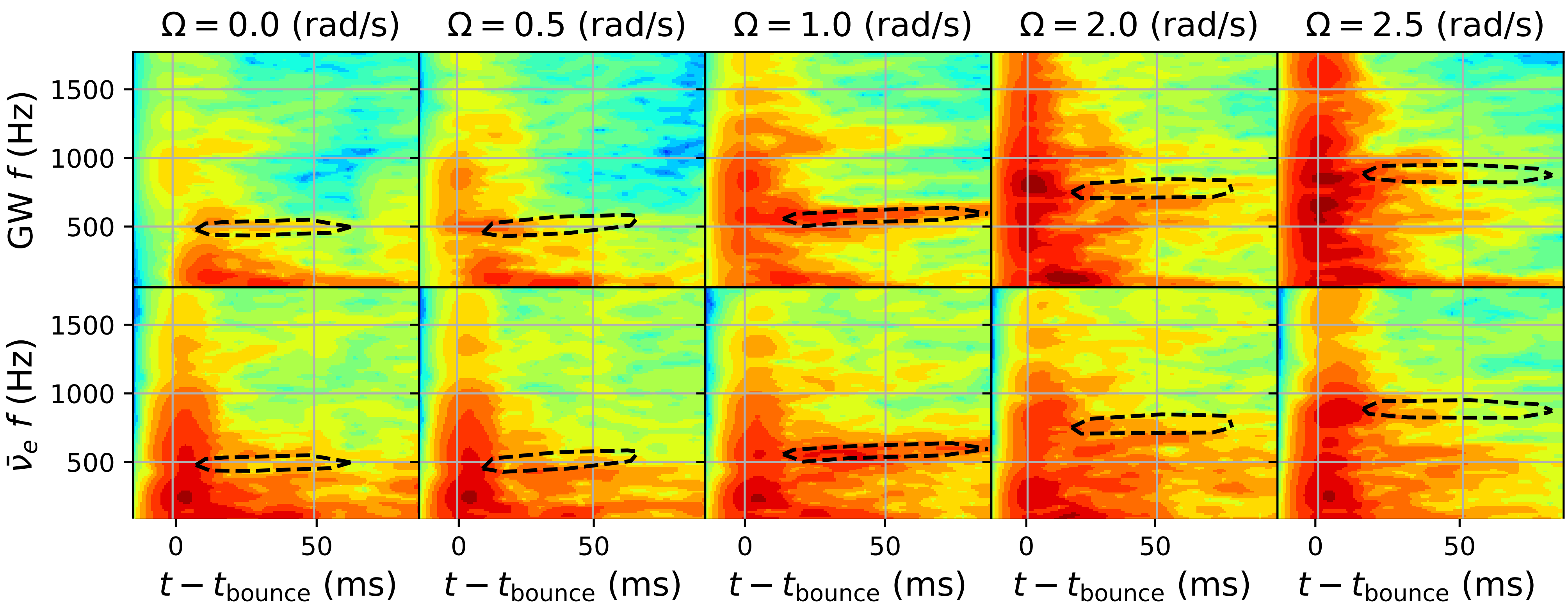


High frequency modulations appear as rotational speed increases.



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

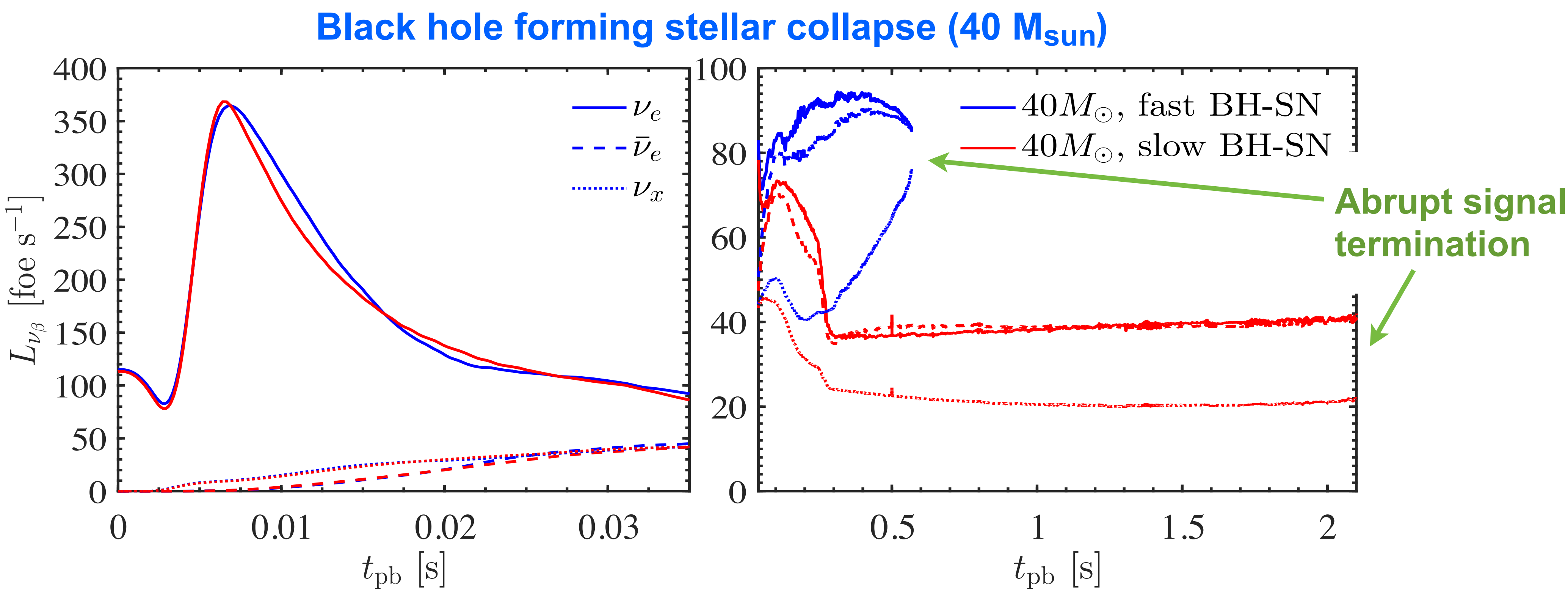
Supernova Astroseismology



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

Westernacher-Schneider, O'Connor, O.Sullivan, Tamborra et al., PRD (2019).
Torres-Forne et al., MNRAS (2017, 2018). Morozova et al., ApJ (2018). Andrersson et al., MNRAS (1998).

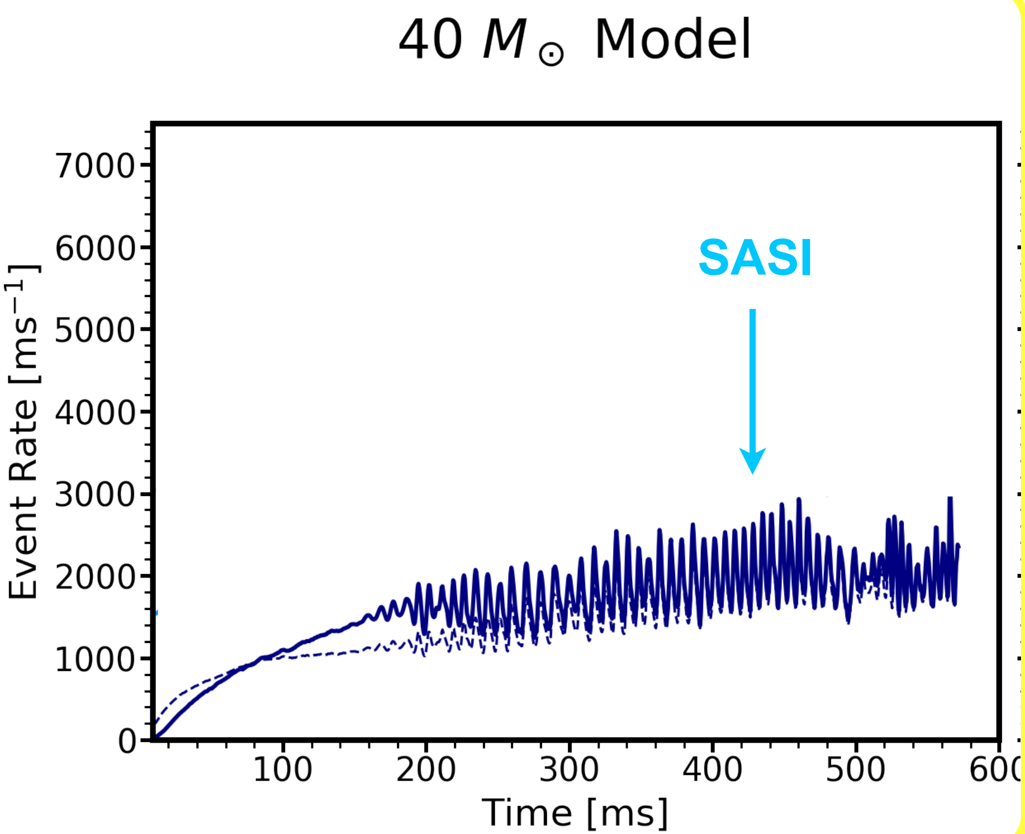
Fingerprints of Black Hole Formation



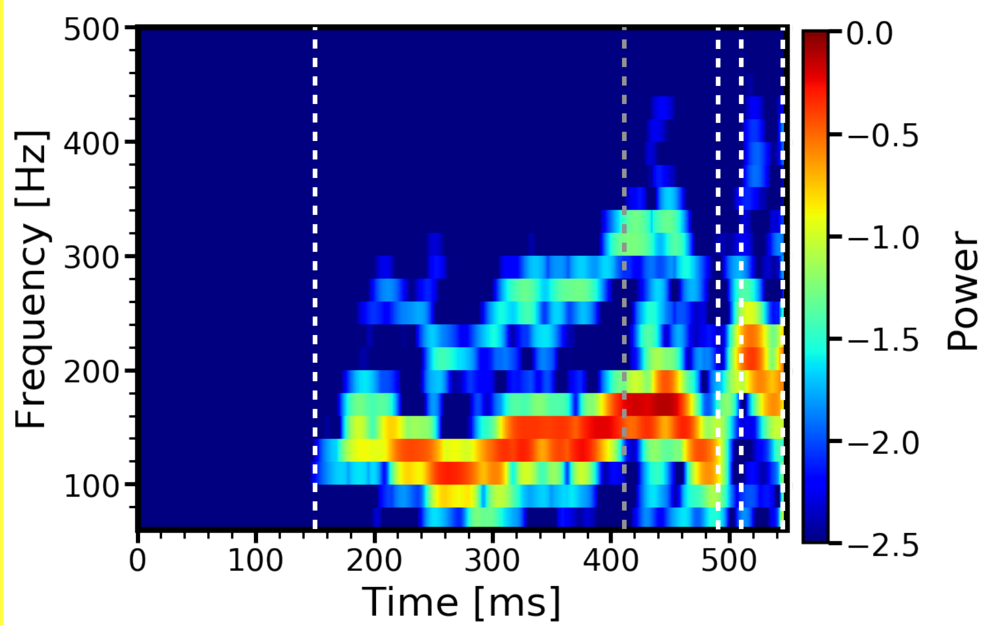
- Failed supernovae up to 20-40% of total (low-mass progenitors can also lead to failed SN).
- Neutrinos (and GW) may be the only probes revealing black hole formation.

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).

Neutrinos Probe Black Hole Formation



Neutrino (and gravitational waves) probe black hole formation.

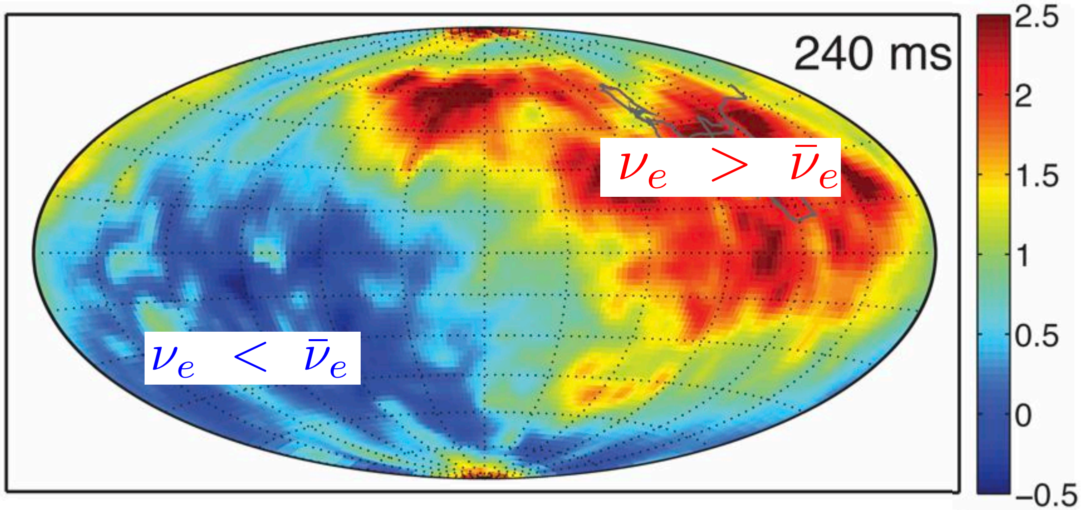


SASI frequency evolution = shock radius evolution

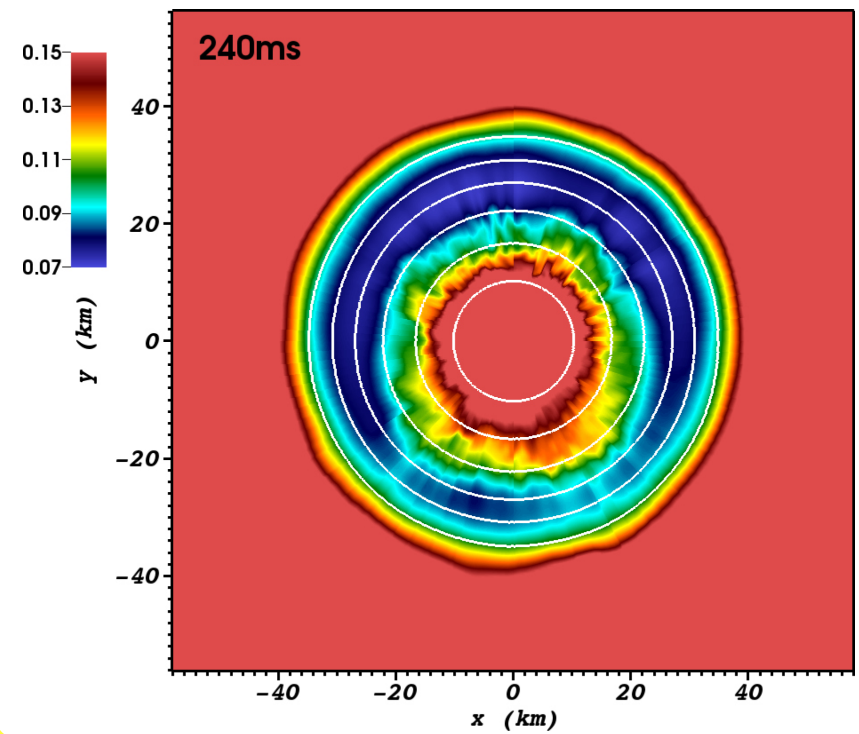
Walk, Tamborra, Janka, Summa, arXiv: 1910.12971.

LESA: Neutrino-Driven Instability

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

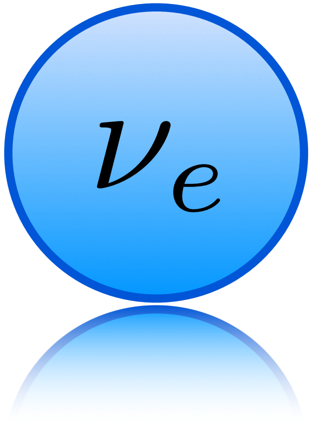


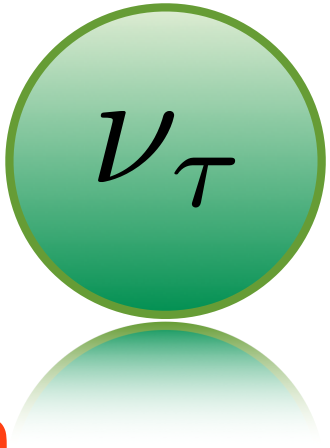
Electron fraction



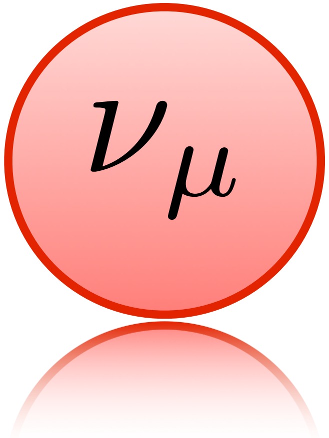
Lepton-number emission asymmetry (**LESA**): Large-scale feature with **dipole character**.

Tamborra, Hanke, Janka, Mueller, Raffelt, Marek, ApJ (2014). Walk et al., PRD (2019). Walk et al., arXiv: 1910.12971.
Janka et al., ARNPS (2016). Glas et al., (2018), Vartanyan et al., MNRAS (2019), O'Connor & Couch, ApJ (2018).

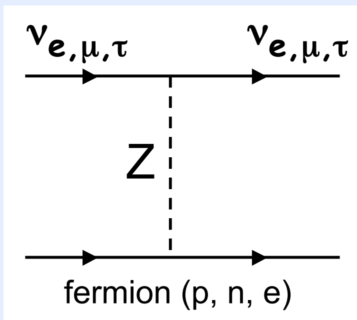


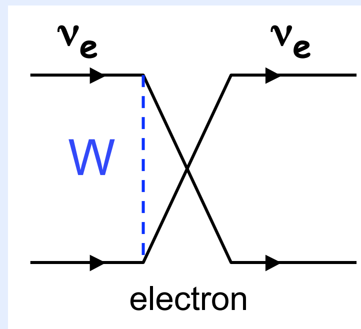


Flavor Evolution

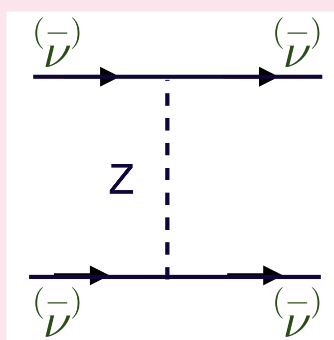


Neutrino Interactions





Neutrinos interact with neutrons, protons and electrons (MSW enhanced conversions).

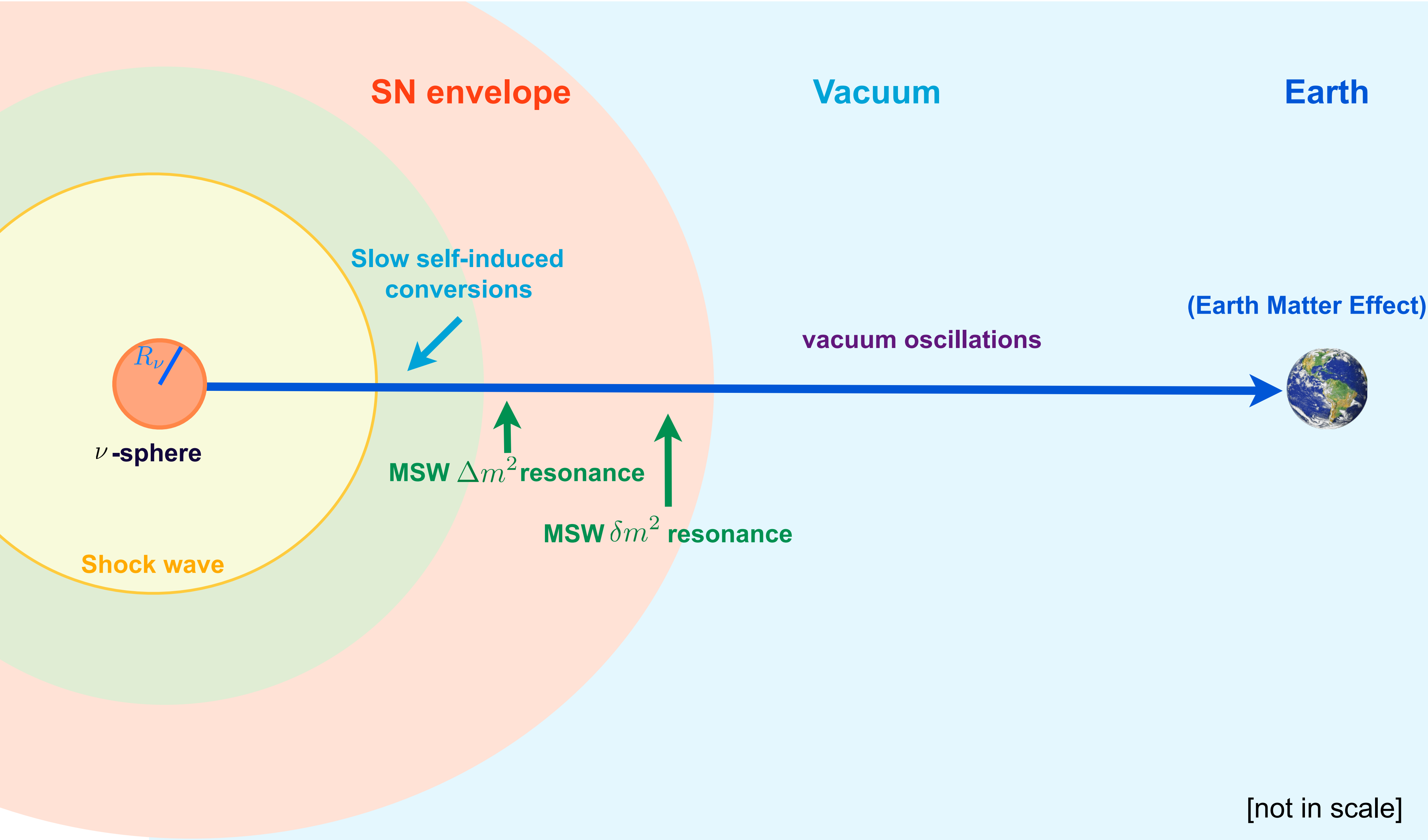


$\nu - \nu$ interactions

Non-linear phenomenon

Angular distributions crucial!

Simplified Picture of Flavor Conversions



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: $\nu_e(p) + \bar{\nu}_e(k) \to \nu_\mu(p) + \bar{\nu}_\mu(k)$
$\nu_e(p) + \nu_\mu(k) \to \nu_\mu(p) + \nu_e(k)$

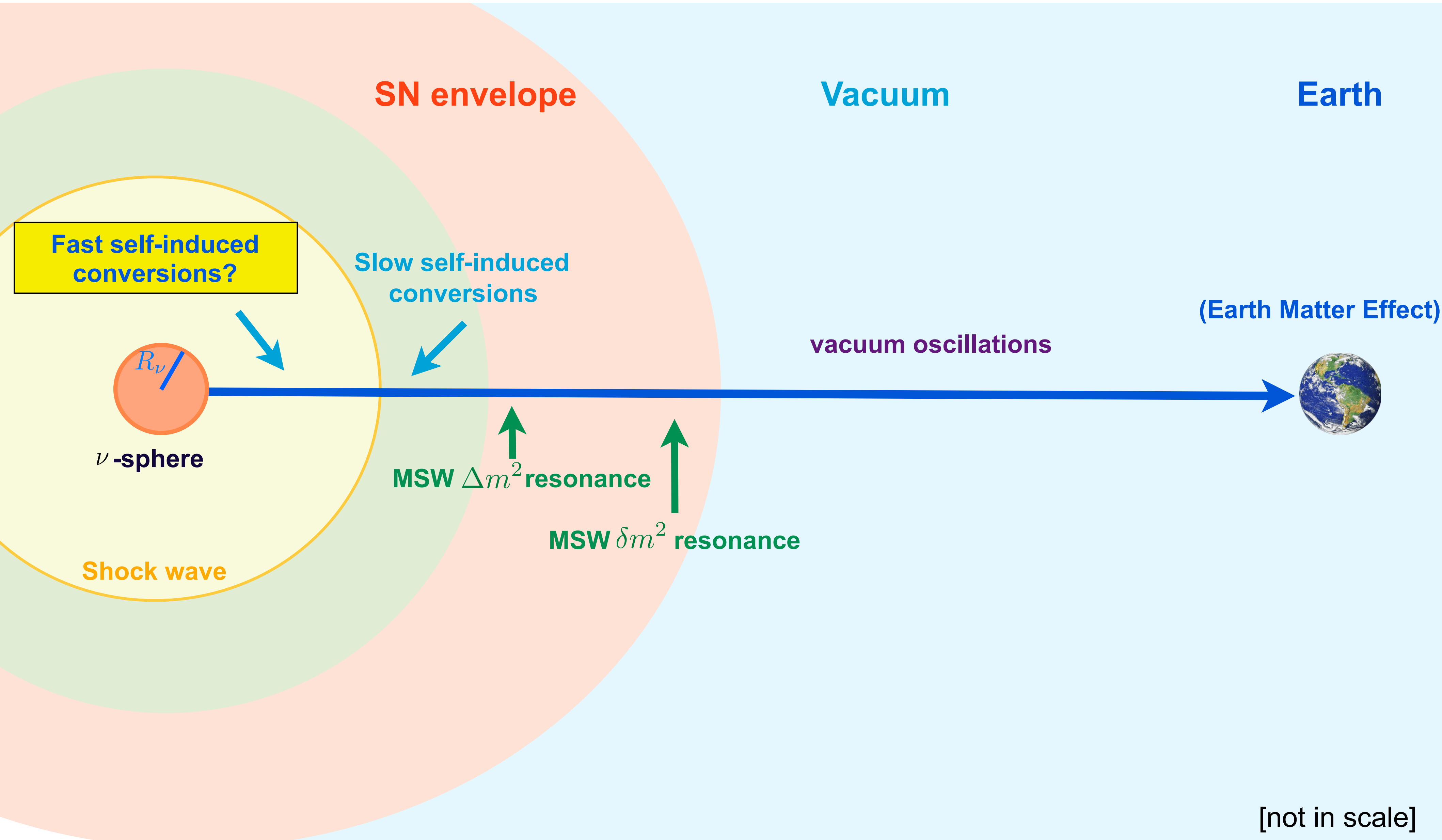
Can occur **without masses/mixing**. No net lepton flavor change.

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

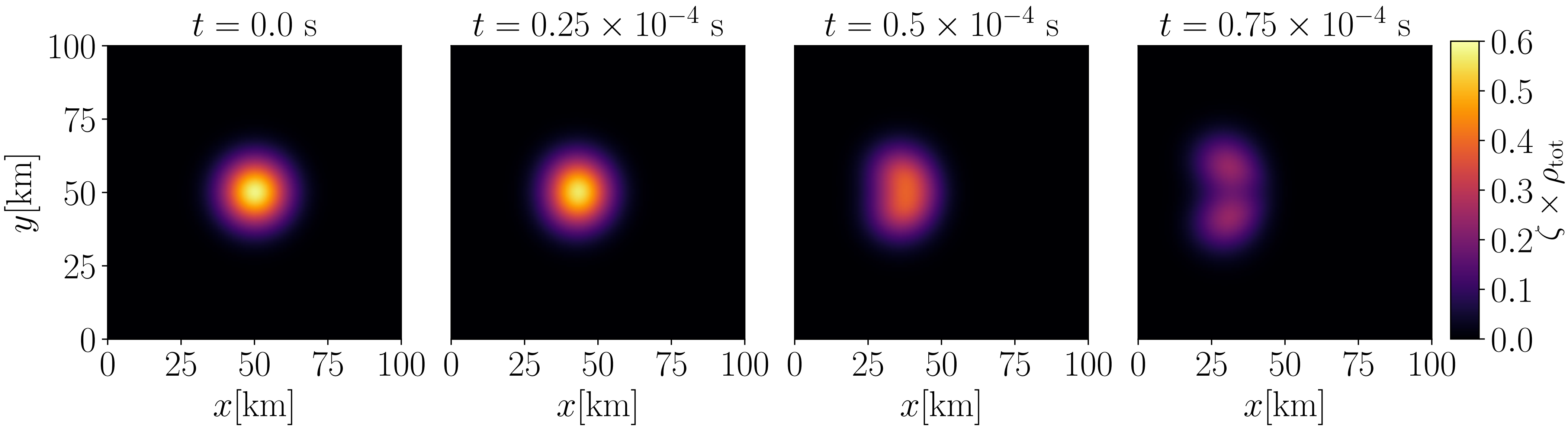
Flavor conversion may occur close to neutrino decoupling region. **Further work needed.**

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).

Simplified Picture of Flavor Conversions



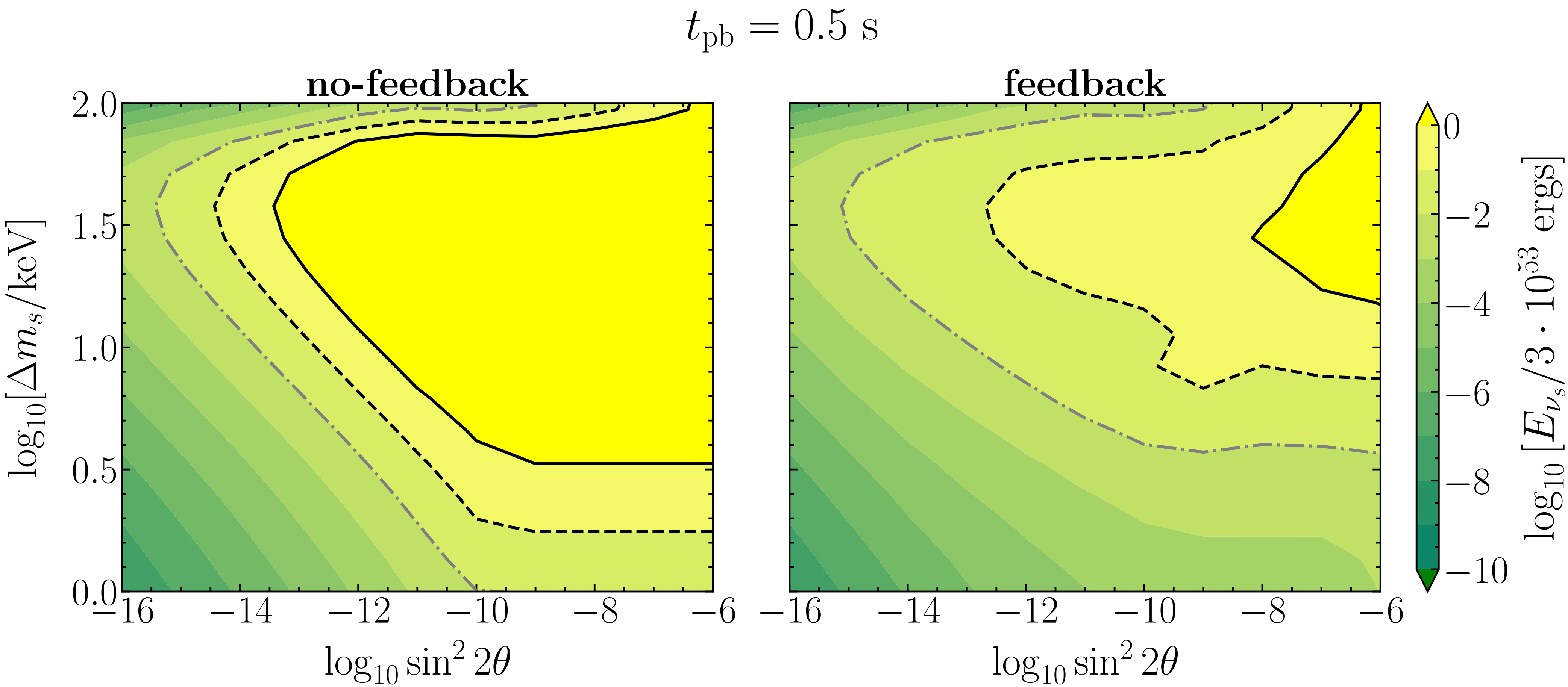
Fast Pairwise Neutrino Conversions



Any flavor instability will be damped by neutrino drifting unless the conditions leading to flavor instabilities are self-sustained in time (e.g. LESA).

Shalgar, Padilla-Gay, Tamborra, arXiv: 1911.09110. Shalgar & Tamborra, ApJ (2019).

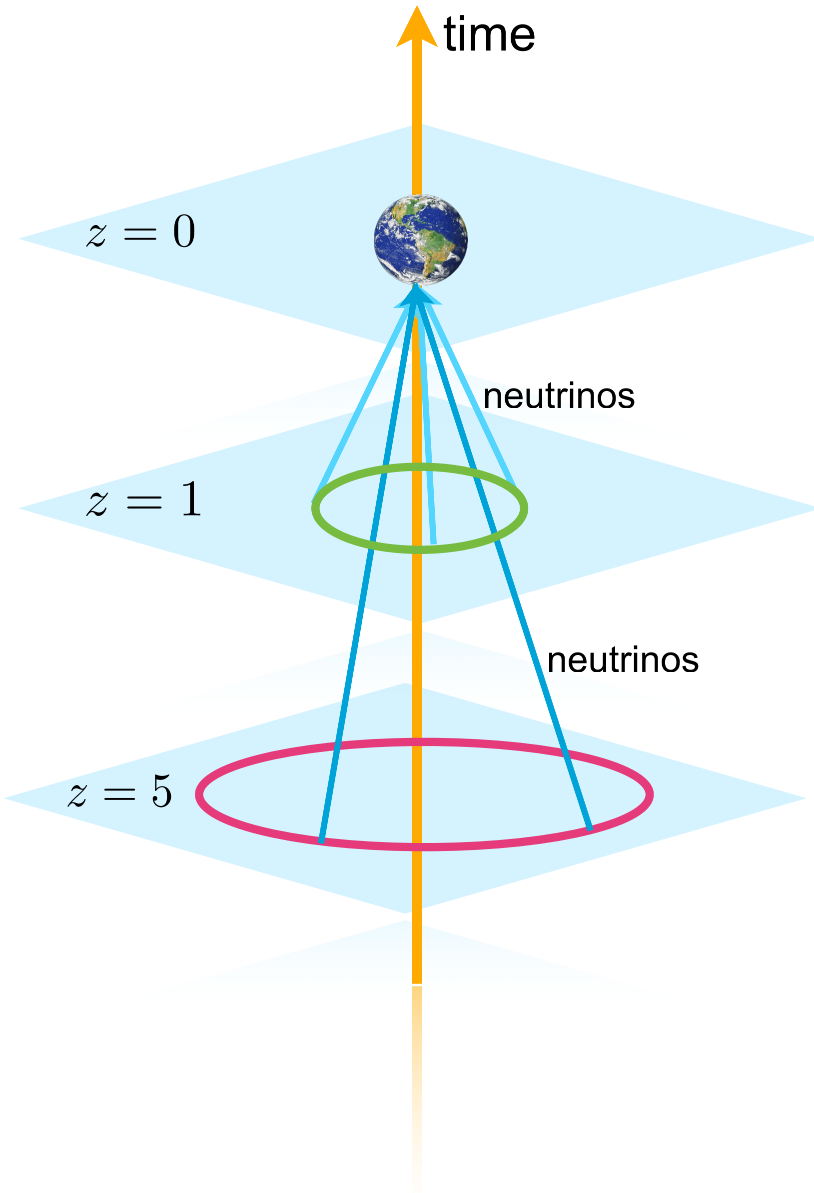
Non Standard Physics in Supernovae



keV-mass sterile neutrinos significantly affect SN physics and observable signal.

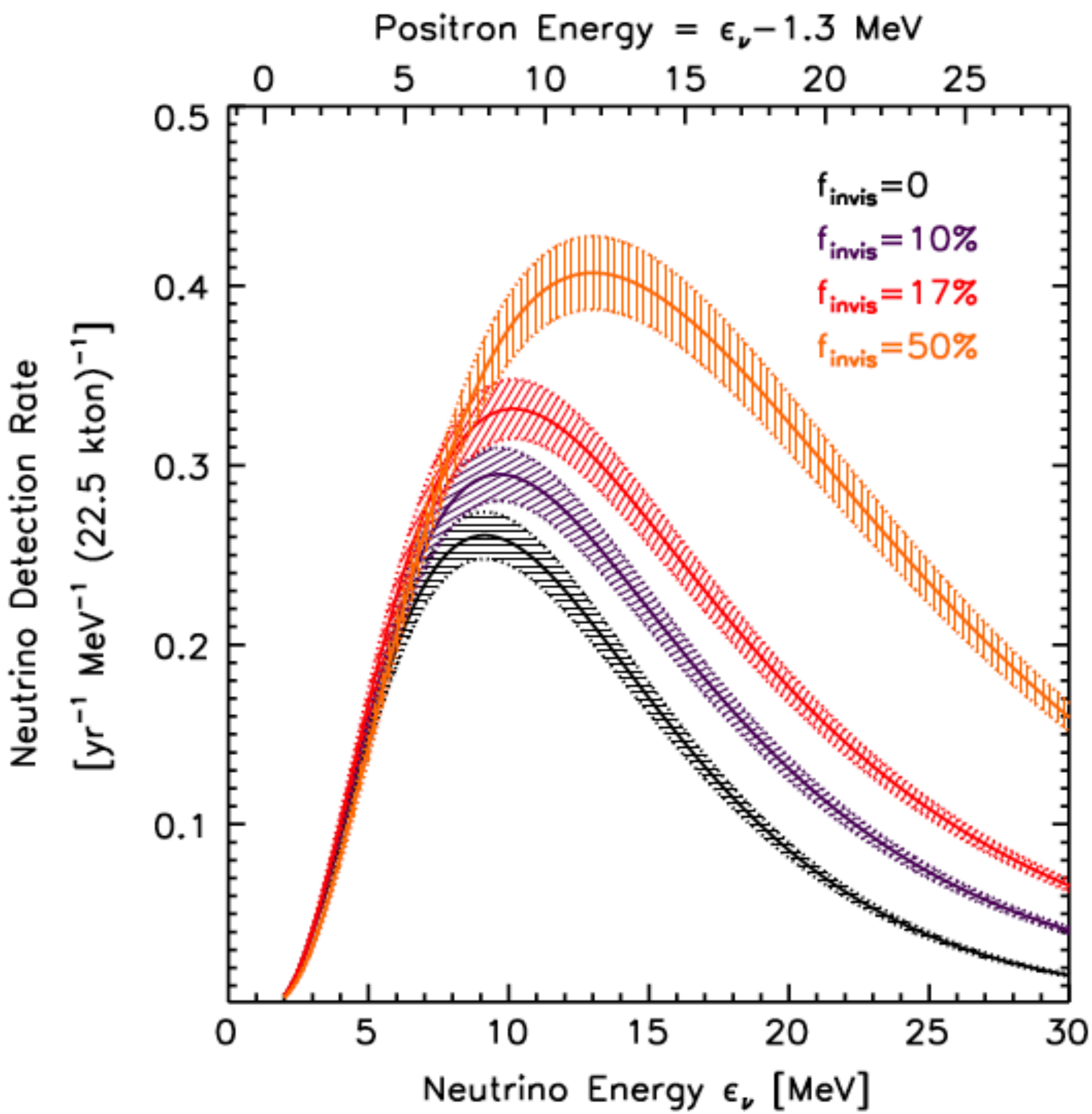
Dynamical feedback on SN physics is crucial!

Suliga, Tamborra, Wu, JCAP (2019).



Diffuse Supernova Neutrino Background

Core-Collapse vs. Failed Supernovae

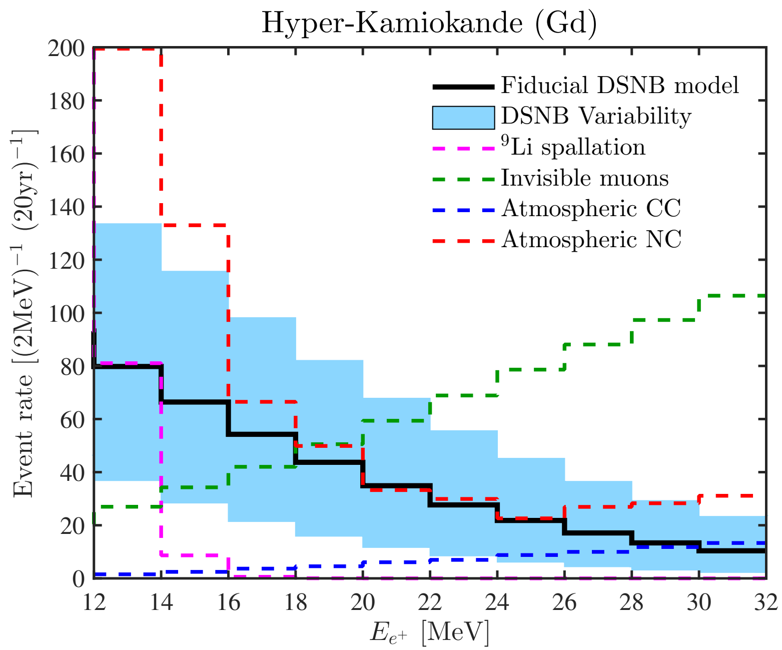


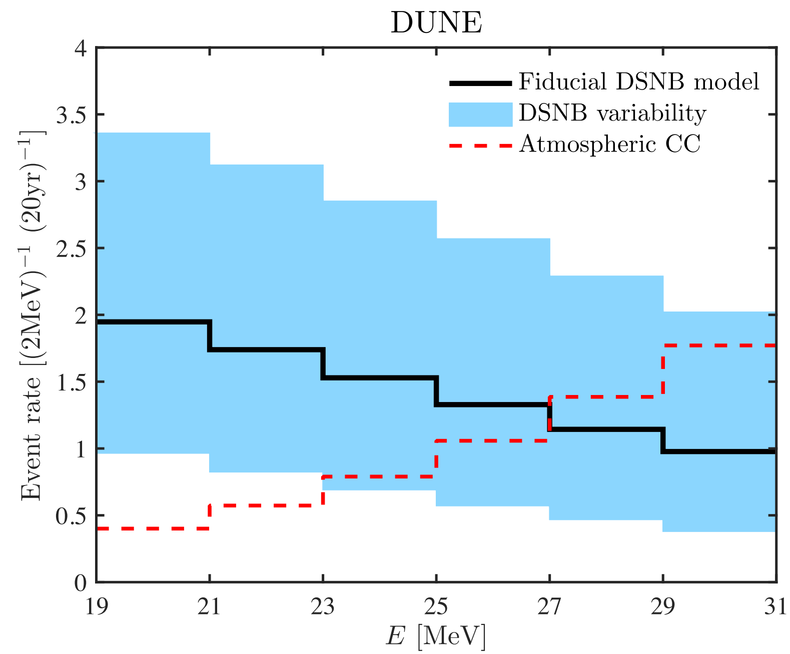
DSNB sensitive to failed SN fraction.

Lunardini, PRL (2009), Nakazato et al., ApJ (2015), Yuksel & Kistler, PLB (2015). Priya & Lunardini, JCAP (2017).

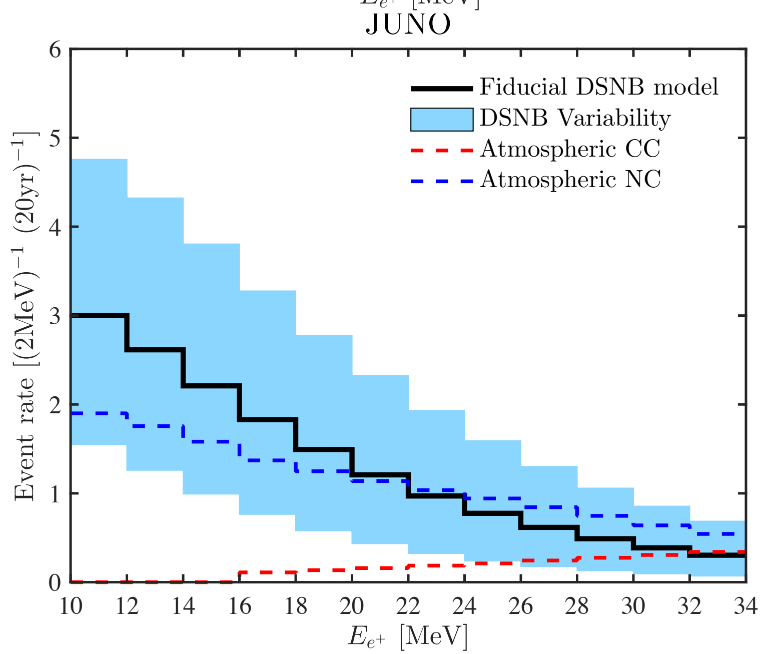
DSNB Forecast

$\bar{\nu}_e$





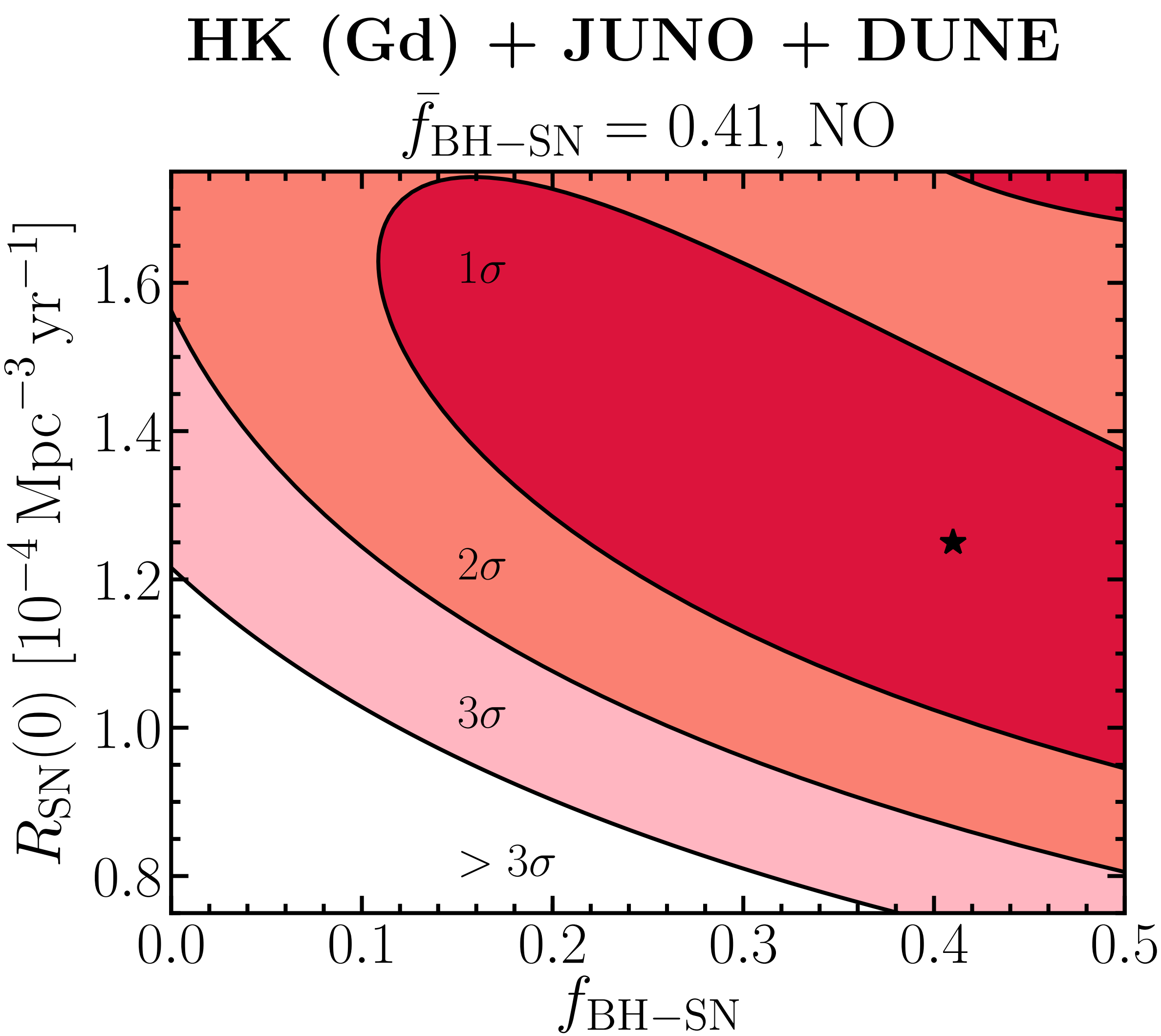
ν_e



Detectors employing different technologies provide complementary information.

Moller, Suliga, Tamborra, Denton, JCAP (2018).

Diffuse Supernova Neutrino Background



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

Moller, Suliga, Tamborra, Denton, JCAP (2018).

Conclusions

- Neutrinos play a fundamental role in supernova mechanism.
- Each SN phase offers different opportunities to learn about SN (and nu) physics.
- Neutrino flavor conversions: Work still needed to grasp their role.
- Realistic perspectives to detect the DSNB in the near future.

Thanks!