The Niels Bohr International Academy

VILLUM FONDEN

SFB 1258 Neutrinos Dark Matter Messengers

Supernova Neutrinos

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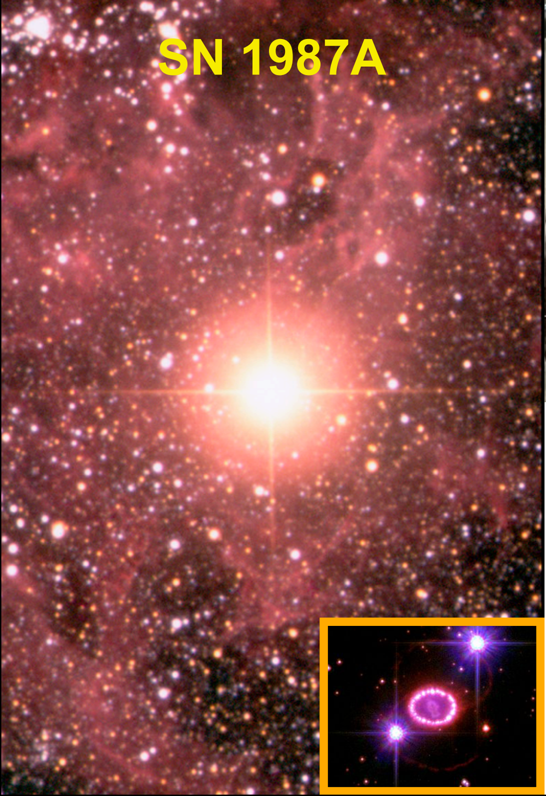
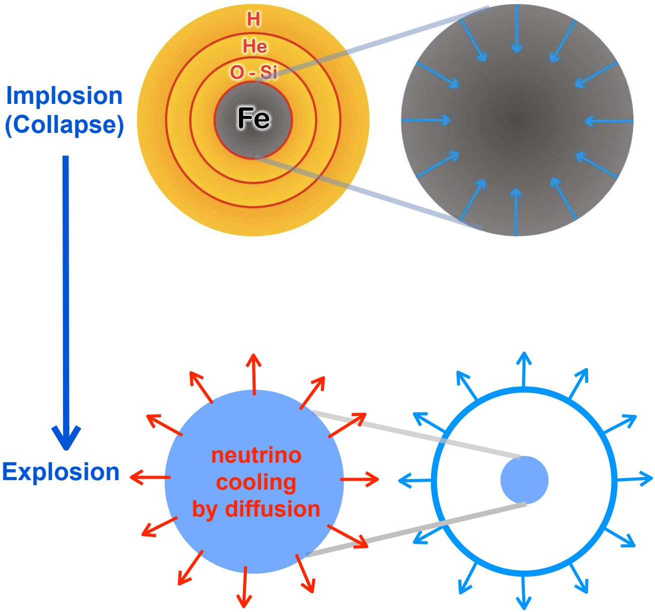
TAUP 2017
Sudbury, July 27, 2017



What can we learn next?

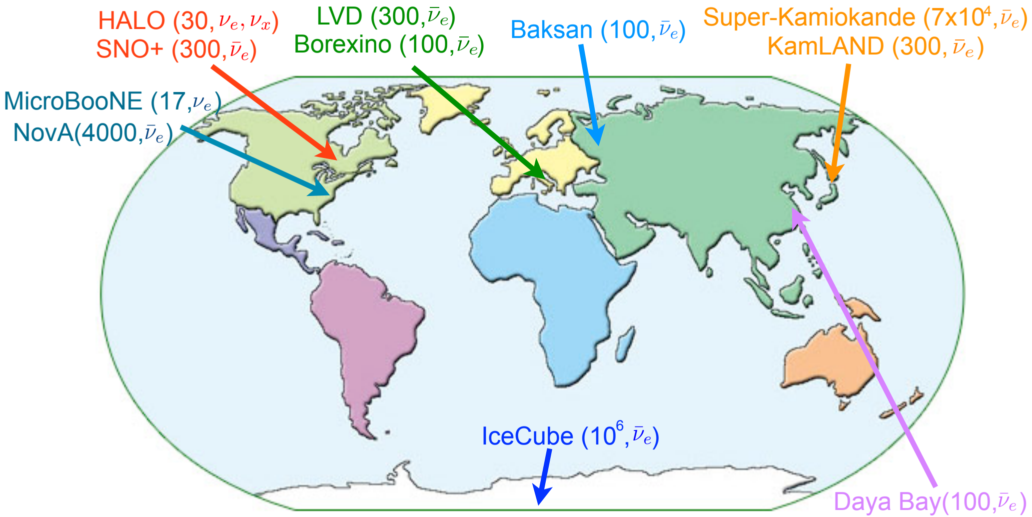
Core-Collapse Supernova Explosion



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

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

Existing Detectors



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

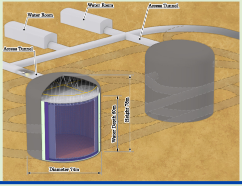
Fundamental to combine the supernova signal from detectors employing different technologies.

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

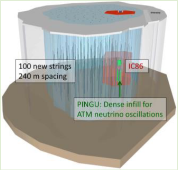
Next Generation Large Scale Detectors

Cherenkov telescopes ($\bar{\nu}_e$)

Hyper-Kamiokande (10^5)

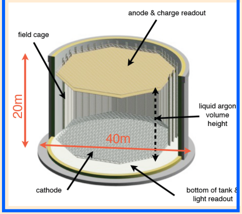


IceCube-Gen2 (10^6)



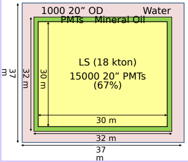
Liquid Argon detectors (ν_e)

DUNE (3000)

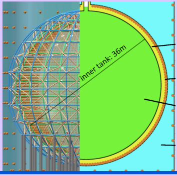


Scintillation detectors ($\bar{\nu}_e$)

RENO-50 (5400)



JUNO (6000)

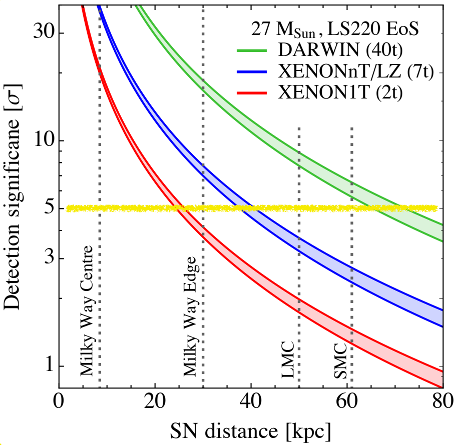


Expected number of events for a SN at 10 kpc and dominant flavor sensitivity in parenthesis.

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

Xenon Dark Matter Detector: Nu Telescope

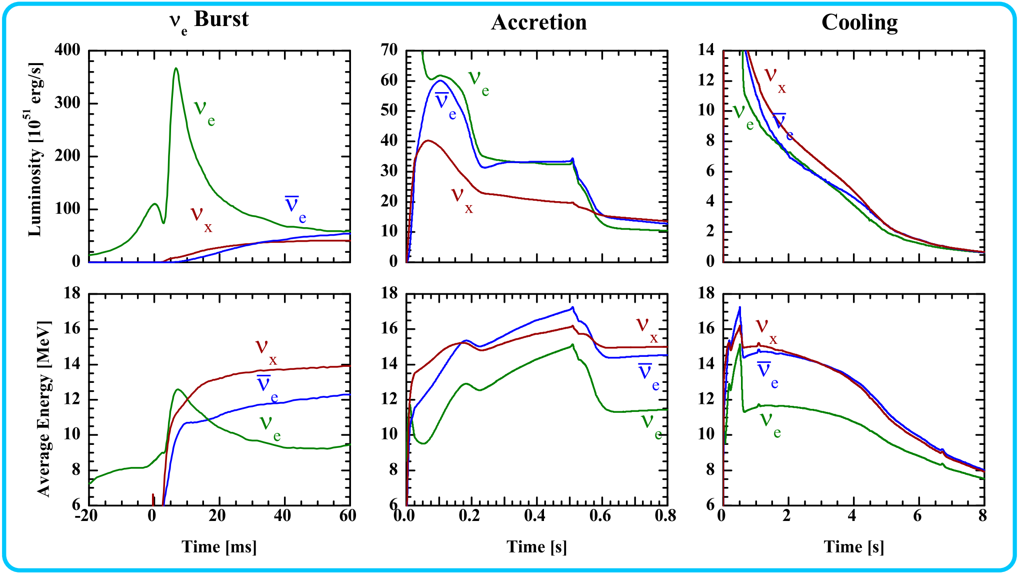
DARWIN, 700 events ($\nu_{e,x}$, $\bar{\nu}_{e,x}$)



- 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).

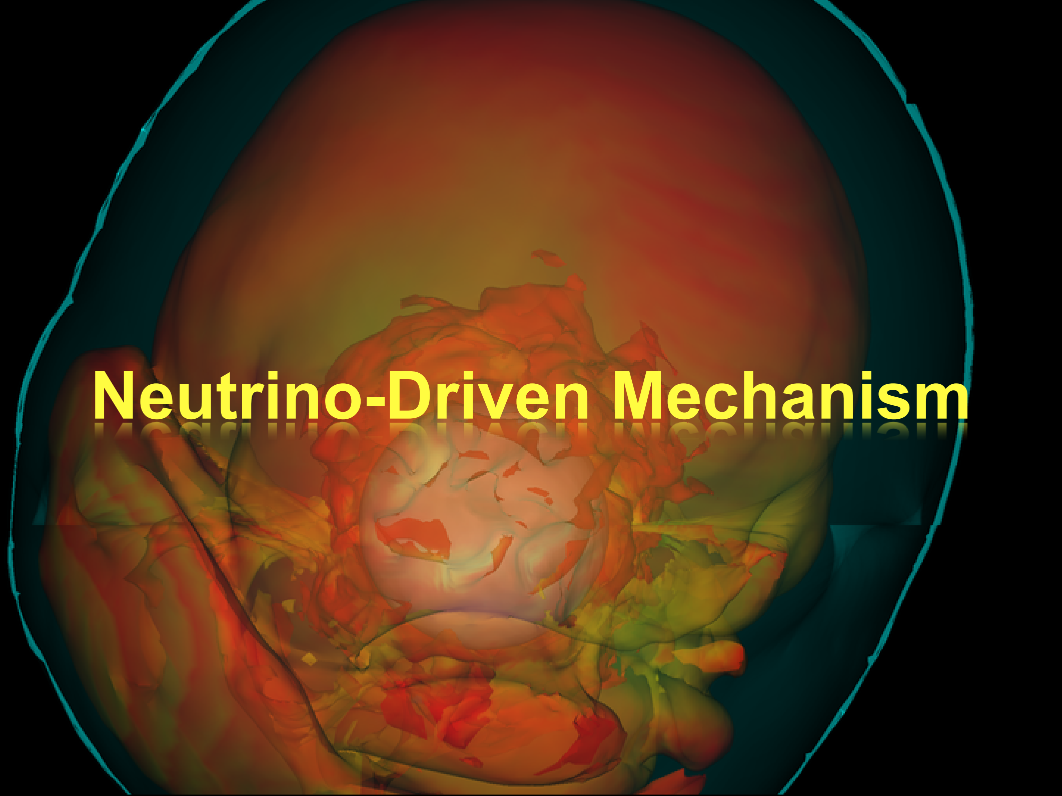
General Features of Neutrino Signal



General features of the neutrino signal well described by 1D hydro simulations.

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

Neutrino-Driven Mechanism



Recent Developments

- Successful 3D SN simulations of low-mass progenitors.
- Several ideas to make neutrino-driven explosions robust:
  - Improved microphysics [Bollig et al. (2017), Burrows et al. (2016), Melson et al. (2015)]
  - Convective seed perturbations [Mueller et al., (2017), Couch et al. 2015, Couch & Ott, (2014)]
  - Explosion favored by rotation [Janka et al. (2016), Takiwaki, Kotake, Suwa (2016)]
  - Explosion affected by resolution and symmetries [Roberts et al. (2016), Lentz et al. (2015)]
  - Missing physics?
  - A combination of the points above.

3D modeling has only begun, no clear picture yet. Still to do ...

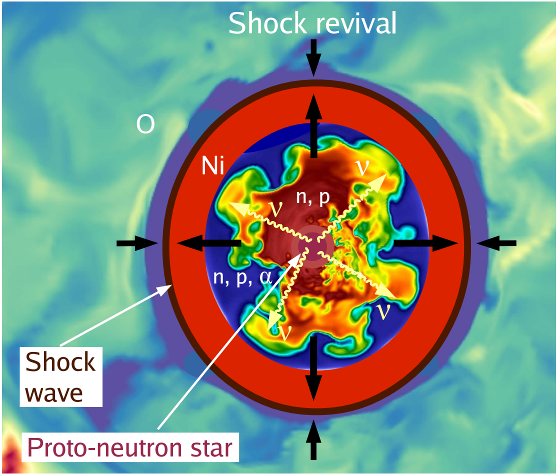
- Role of magnetic field and rotation to be understood.
- Role of stellar companion in SN formation and dynamics.
- First principle, self-consistent simulations (still very premature).

Delayed Neutrino-Driven Explosion

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

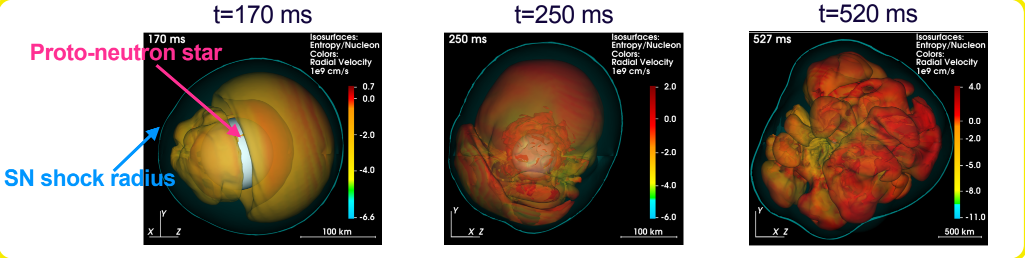
- **Neutrinos** provide energy to stalled shock wave to start re-expansion.

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



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

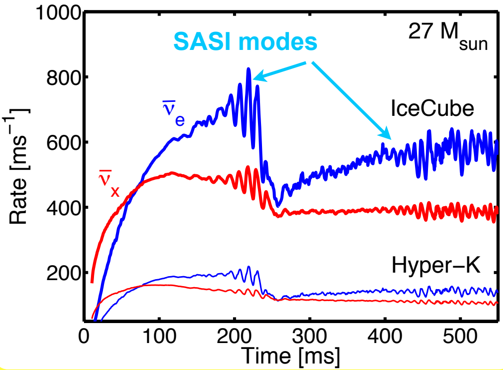
Exploding Progenitor in 3D (20 M_{sun})



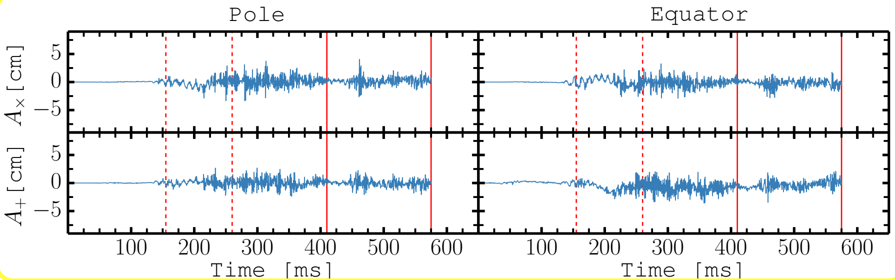
3D SN simulations: Benchmark models to test neutrino-driven mechanism.

Figure adapted from Melson et al., ApJ (2015).

Neutrinos Probe Explosion Mechanism



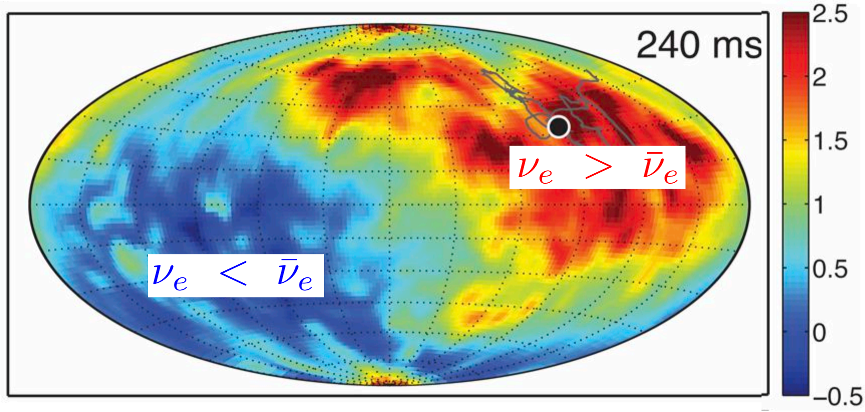
Neutrinos and gravitational waves **probe the explosion mechanism**.



Tamborra et al., PRL (2013), Tamborra et al., PRD (2014). Andresen et al., MNRAS (2017). Lund et al., PRD (2012).

LESA: Intriguing 3D Feature in Neutrinos

Neutrino lepton-number flux (11.2 M_{sun}, $\nu_e - \bar{\nu}_e$)

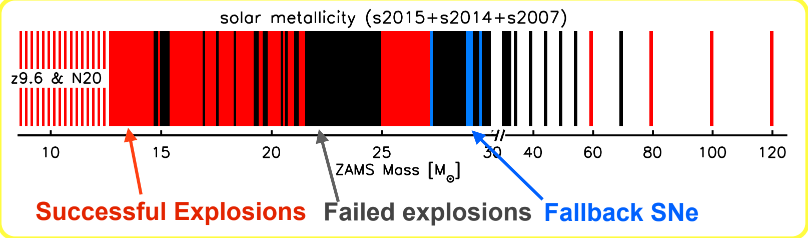


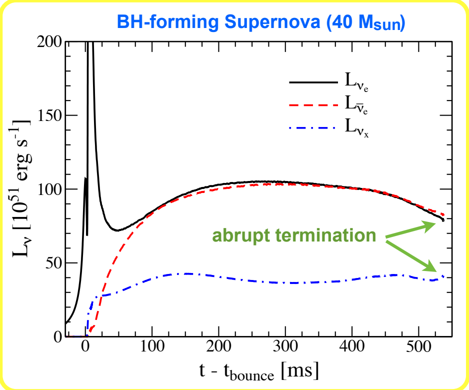
Lepton-number emission asymmetry (**LESA**) is a large-scale feature with **dipole character**.

Relevant implications for flavor oscillations, nucleosynthesis, neutron-star kicks.

Tamborra, Hanke, Janka, Mueller, Raffelt, Marek, ApJ (2014). Janka, Melson, Summa, ARNPS (2016).

Black-Hole Forming Supernovae



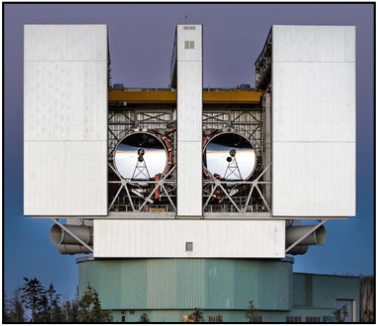


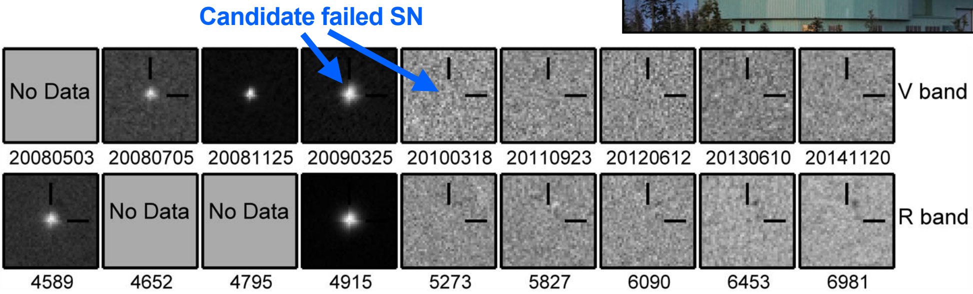
- Low-mass SN progenitors can form black holes.
- Neutrinos reveal black-hole formation.
- Black-hole forming SNe up to 20-40% of total.

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

A Survey About Nothing

- Look for disappearance of red-supergiants in 27 galaxies within 10 Mpc with Large Binocular Telescope.
- 1 core collapse/yr expected.
- 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).

ν_e

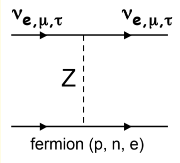
ν_τ

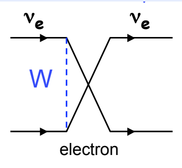
Flavor Evolution in Supernovae

ν_μ

Neutrino Interactions

Understood phenomenon.

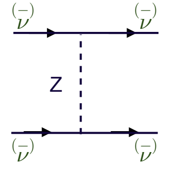




Neutrinos interact with neutrons, protons and electrons.

Wolfenstein, PRD 17 (1978) 2369

We still need to learn a lot!

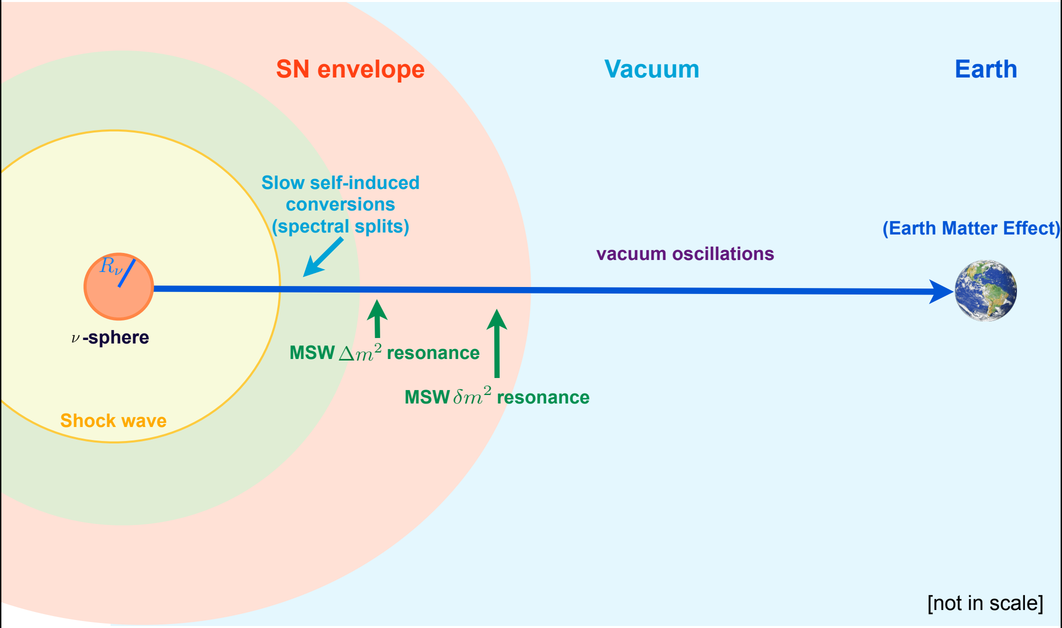


$\nu - \nu$ interactions

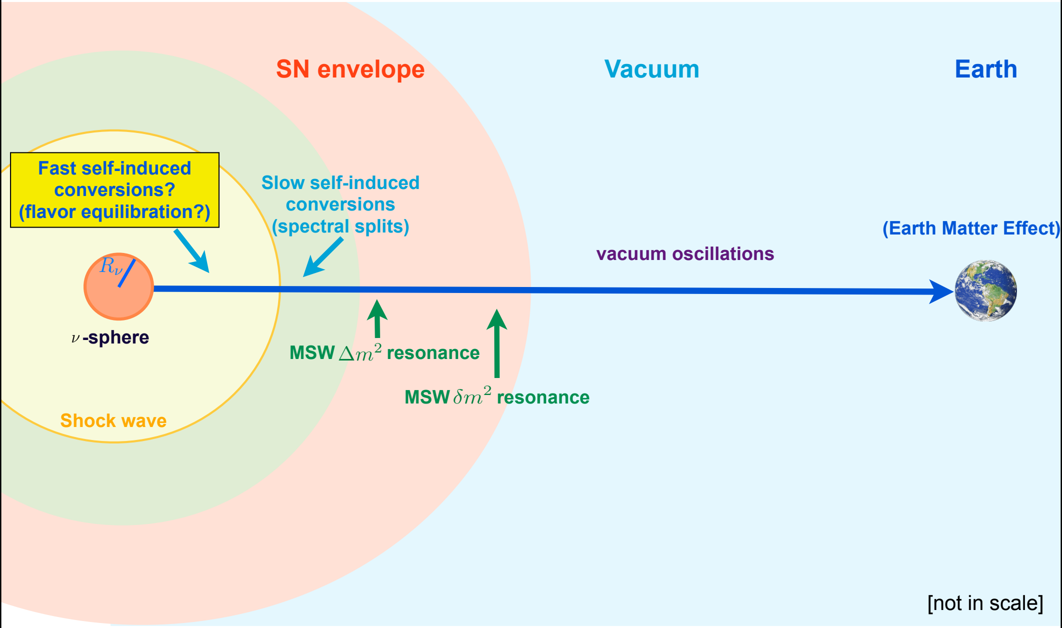
Non-linear phenomenon

Pantaleone, PLB 287 (1992) 128

Simplified Picture of Flavor Conversions



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.

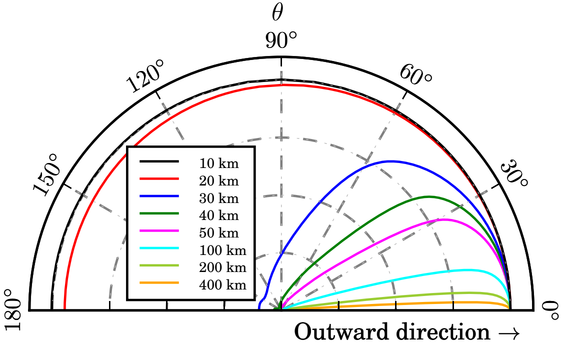
Growth rate: $\sqrt{2}G_F(n_{\nu_e} - n_{\bar{\nu}_e}) \simeq 6.42\ \mathrm{m}^{-1}$ vs. $\dfrac{\Delta m^2}{2E} \simeq 0.5\ \mathrm{km}^{-1}$. ⇨ **"Fast" conversions**

⇧

Neutrino angular distributions **crucial**.

Sawyer, PRD (2005), Sawyer, PRL (2016), Chakraborty et al., JCAP (2016).

Fast Pairwise Neutrino Conversions



Non-negligible inward neutrino flux maybe responsible for fast conversions.

Flavor equipartition might occur close to neutrino decoupling region. Explosion affected?

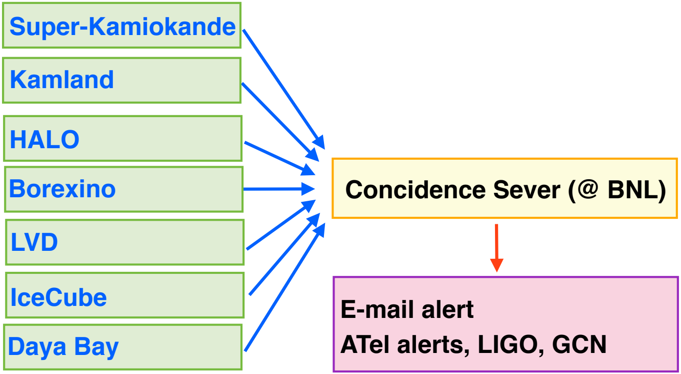
Existing investigations are simplified case studies. Further work needed.

Tamborra et al., ApJ (2017). Izaguirre, Raffelt, Tamborra, PRL (2017). Dasgupta et al., JCAP (2017). Capozzi et al., 2017.

What Can We Learn From a SN Burst?

Neutrinos Tell Us When To Look

SuperNova Early Warning System (SNEWS)



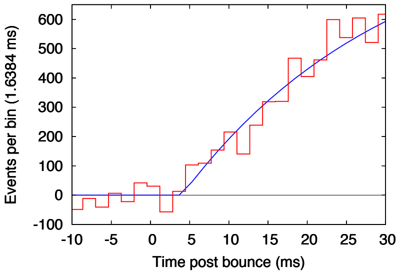
- Shock break out arrives mins to hours after neutrino signal.

Meanwhile, individual detectors, e.g.:

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

http://snews.bnl.gov. Adams et al., ApJ (2013).

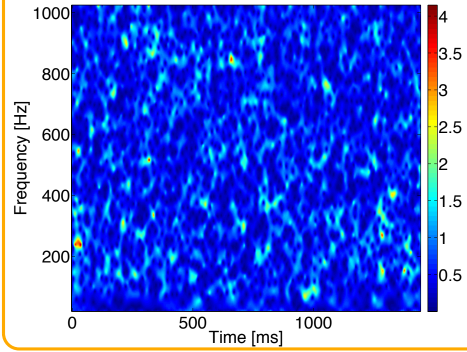
Neutrinos Tell Us When To Look



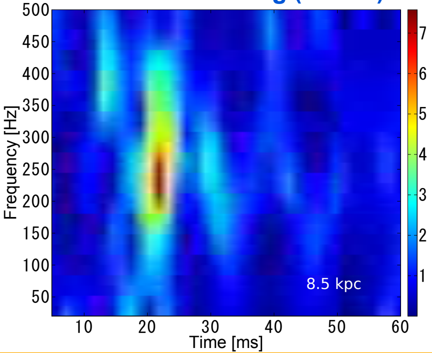
Probe core bounce time with neutrinos.

Help timing for gravitational wave detection.

Without neutrino timing (S/N~3.5)

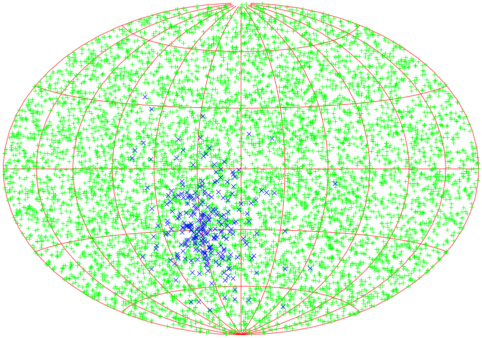


With neutrino timing (S/N ~7)



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

Neutrinos Tell Us Where To Look



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

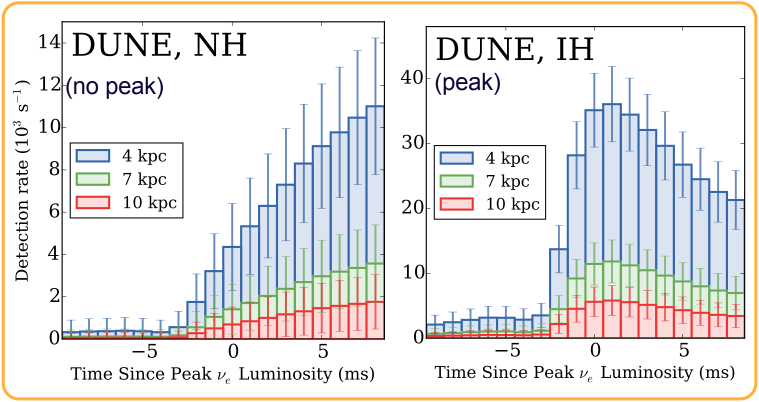
	Super-K	Hyper-K
water	6 deg	1.4 deg
water+Gd	3 deg	0.6 deg

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

Beacom & Vogel, PRD (1999). Tomas et al., PRD (2003). Fisher et al., JCAP (2015). Muehlbeier et al., PRD (2013).

Neutrinos Tell Us Where To Look

Deleptonization peak is independent of progenitor mass & EoS but sensitive to mass ordering.



If mass ordering known:

- Determination of **SN distance**.
- (Test role of oscillations in dense media.)

Kachelriess et al., PRD (2005). Wallace, Burrows, Dolence, ApJ (2016).

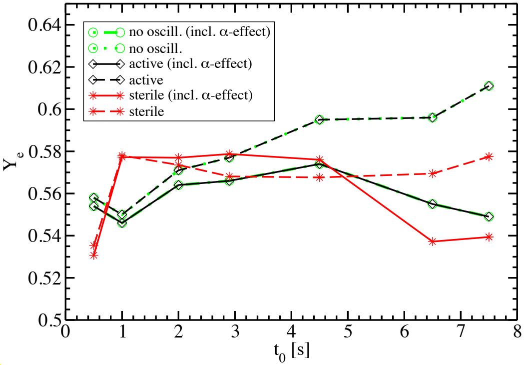
Neutrinos Affect Element Production

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

Flavor oscillations affect element production mainly via

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

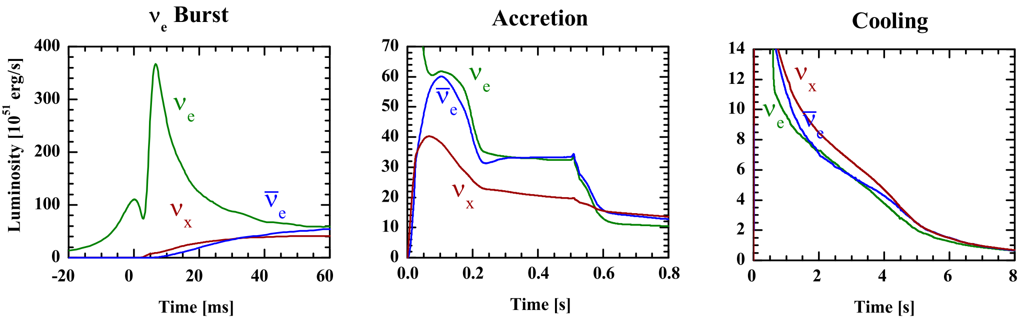
Coupling of oscillation codes to nucleosynthesis networks recently begun.



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

Pllumbi, Tamborra et al., ApJ (2015). Wu et al., PRD (2015). Duan et al., J. Phys. G (2011).

Synopsis



Signal independent on SN mass and EoS.

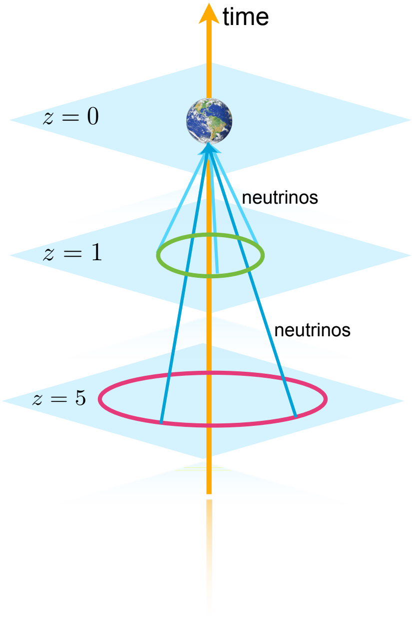
- SN distance.
- (Test oscillation physics.)

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

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

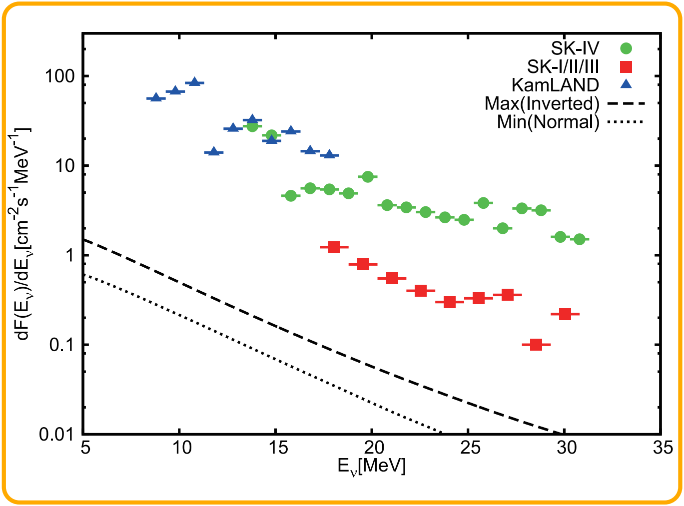
EoS and mass dependence.

- Test nuclear physics.
- Nucleosynthesis.



Diffuse Supernova Neutrino Background

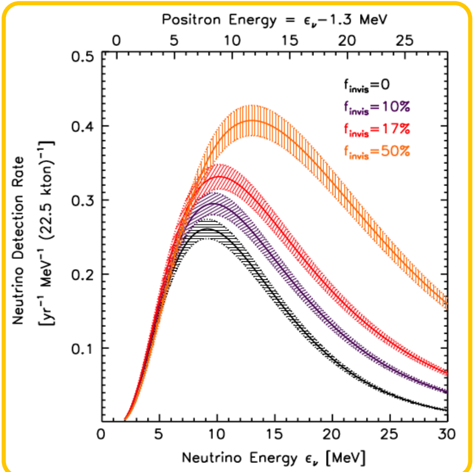
Diffuse Supernova Neutrino Background



DSNB detection may happen soon with, e.g., upcoming JUNO and Gd-Super-K project (sensitivity strongly improved).

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. Priya & Lunardini 2017.

Diffuse Supernova Neutrino Background



DSNB sensitive to failed supernova fraction.

- Independent test of the global SN rate.
- Constraints on the fraction of core-collapse and failed supernovae.
- Constraints on the neutrino emission properties.

Lien et al., PRD (2010), Nakazato et al., ApJ (2015), Yuksel&Kistler, PLB (2015). Priya & Lunardini 2017. Lunardini, PRL(2009),

Conclusions

- Neutrinos play a fundamental role in supernovae.
- Intriguing neutrino features from 3D SN simulations. Steady progress on SN modeling.
- Nu-nu interactions: Work still needed to grasp their role, especially for fast conversions.
- Each SN phase offers different opportunities to learn about SN (and nu) physics.
- Realistic perspectives to learn about supernovae through the DSNB in the next future.

Thank you for your attention!