The Niels Bohr International Academy

UNIVERSITY OF COPENHAGEN

Neutrinos from Supernovae

Irene Tamborra
Niels Bohr Institute, University of Copenhagen

Topical Seminar @ NBIA PhD School
Niels Bohr Institute, Copenhagen, August 5, 2016

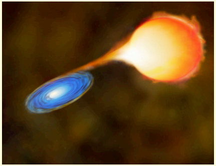
Outline

- Core-collapse supernovae.
- Explosion mechanism and neutrino signatures.
- Neutrino flavor oscillations in the supernova envelope.
- Supernova neutrino detectors and detection perspectives.
- Pre-supernova neutrinos.
- Supernova neutrino diffuse background.

Thermonuclear vs. Core-Collapse SNe

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

Thermo-nuclear SN (type Ia)



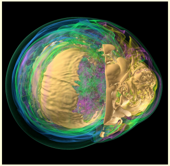
- Binary system with one white dwarf (remnant of low-mass star)
- Accretes mass from companion

Nuclear burning of C and O ignites nuclear deflagration.

Powered by nuclear binding energy.

Negligible amount of neutrinos.

Core collapse SN (type II, Ib/c)



- Degenerate iron core of massive star
- Accretes matter by nuclear burning at its surface.

Collapse to nuclear density.
Implosion and explosion.

Powered by gravity.

99% of energy into neutrinos.

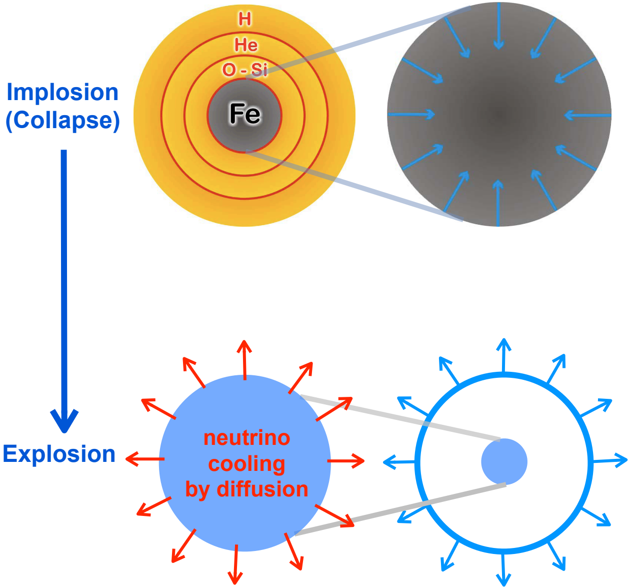
Supernova Spectral Classification

Spectral Type	Ia	Ib	Ic	II
Spectrum	No Hydrogen			Hydrogen
	Silicon	No Silicon		
		Helium	No Helium	
Light Curve	Reproducible	Large variations		
Neutrinos	Insignificant	$\sim 100 \times$ Visible energy		
Compact Remnant	None	Neutron star (typically appears as pulsar) Sometimes black hole		
Rate / h^2 SNu	0.36 ± 0.11	0.14 ± 0.07		0.71 ± 0.34

Table from G. Raffelt.

Core-Collapse Supernova Explosion

Massive stars collapse ejecting the outer mantle by means of shock-wave driven explosions.



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

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

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

1% kinetic explosion energy

99% neutrinos

0.01% photons

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

SN 1987A

The last known core-collapse supernova near our galaxy is the SN 1987A.

Its neutrino burst observation was the first verification of stellar evolution mechanism.

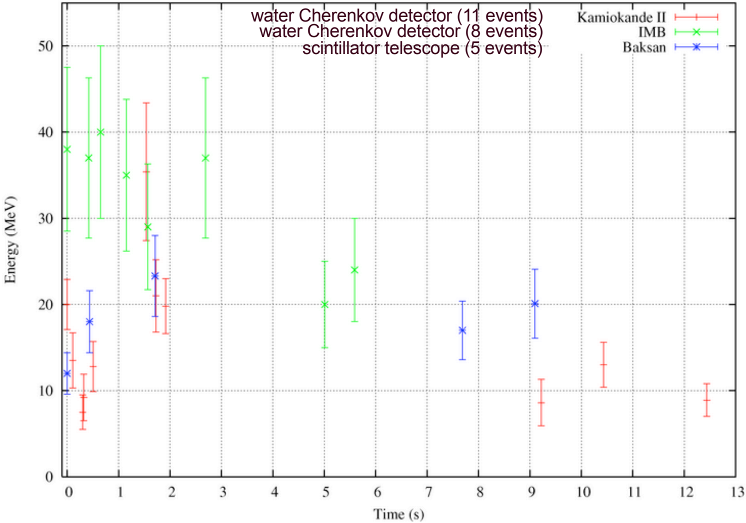
Sanduleak -69° 202

SN 1987A (Feb. 23, 1987)

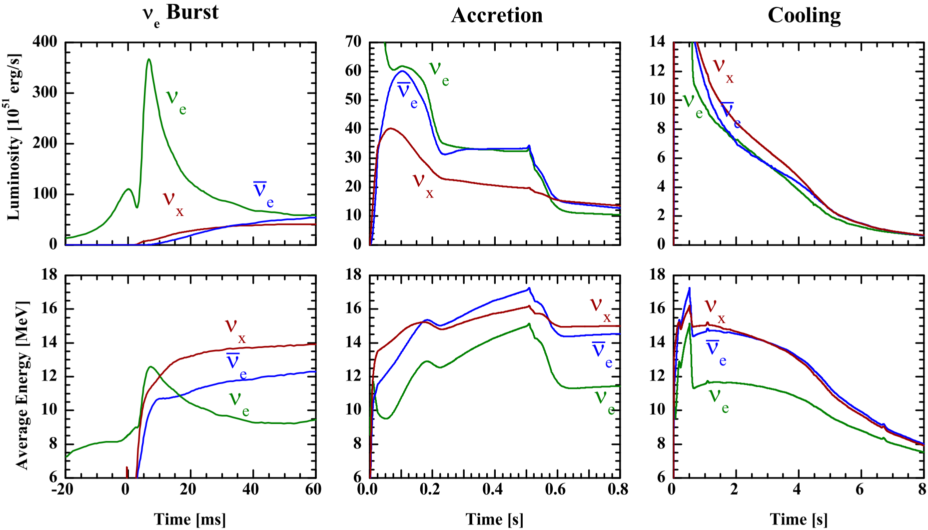
SN 1987A

Few detectors were able to detect SN 1987A neutrinos.

Time distribution of SN 1987A events



General Features of Neutrino Signal



Large ν_e luminosity peak

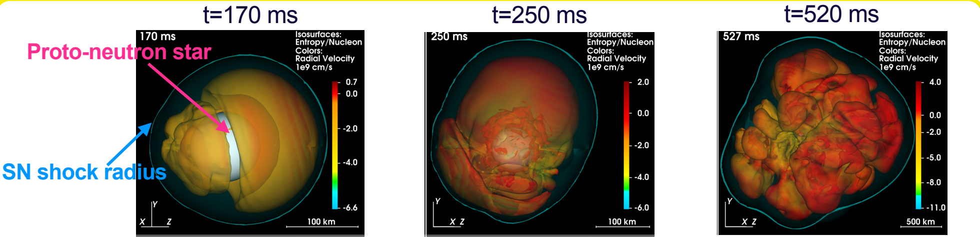
Large fluxes.
Large $\overset{(-)}{\nu}_e - \overset{(-)}{\nu}_x$ flux difference.

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

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

Explosion Mechanism

Supernova Simulations: 3D Frontier



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

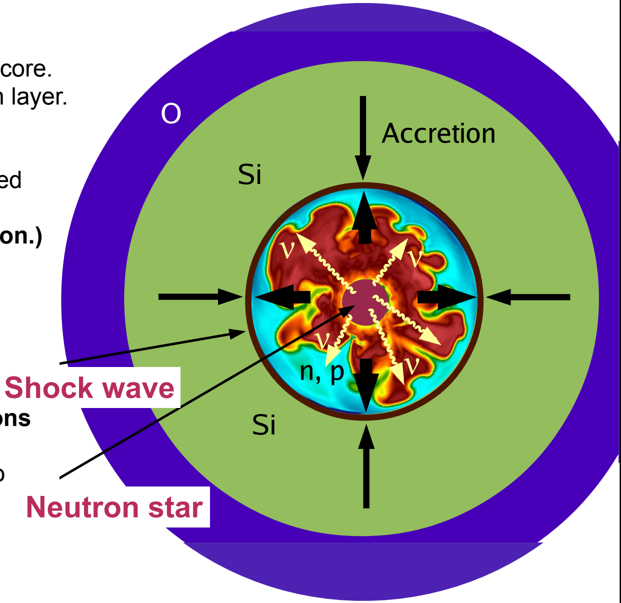
Figure adapted from Melson et al., ApJ (2015).

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.)**

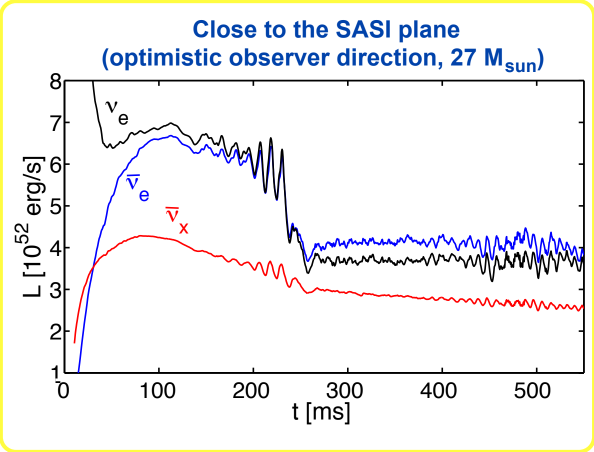
★ **Convection** and **shock oscillations** (standing accretion shock instability, **SASI**) enhance efficiency of neutrino heating and revive the shock.



Review papers: Janka (2012). Mirizzi, Tamborra et al. (2016).

SASI Modulations

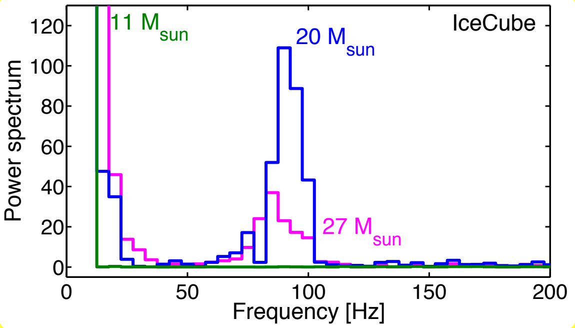
3D SN simulations show that SASI and convection leave imprints on the neutrino signal.

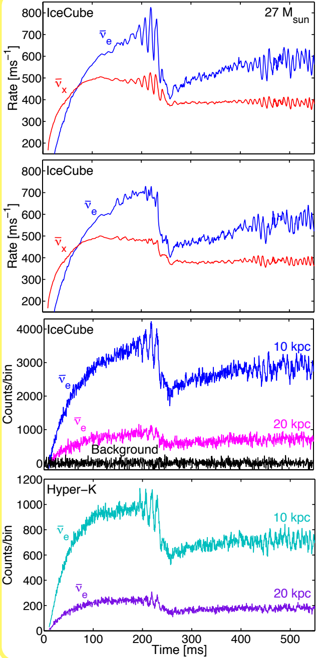


Tamborra, Hanke, Mueller, Janka, Raffelt, PRL (2013), PRD (2014). Hanke et al., ApJ 770 (2013) 66.

SASI Modulations

Power spectrum of the IceCube event rate





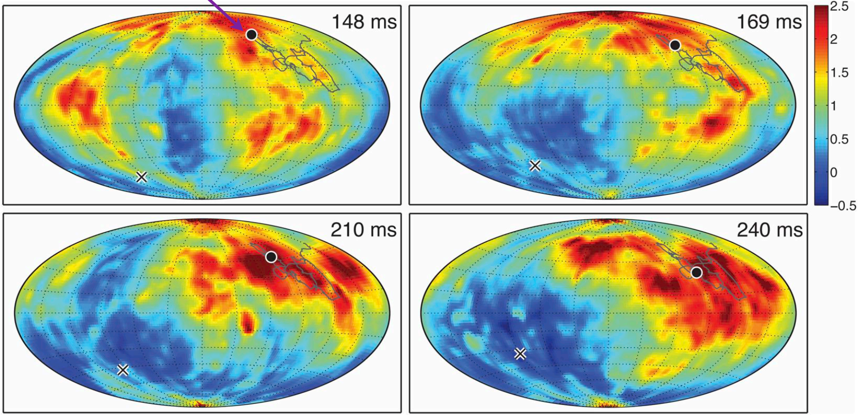
Neutrinos test dynamics of supernova explosion.

Tamborra et al., PRL (2013), PRD (2014). Lund et al., PRD (2010).

Intriguing New Features in 3D

Neutrino lepton-number flux for the 11.2 M_{sun} progenitor $[(F_{\nu_e} - F_{\bar{\nu}_e})/\langle F_{\nu_e} - F_{\bar{\nu}_e}\rangle]$.

positive dipole direction



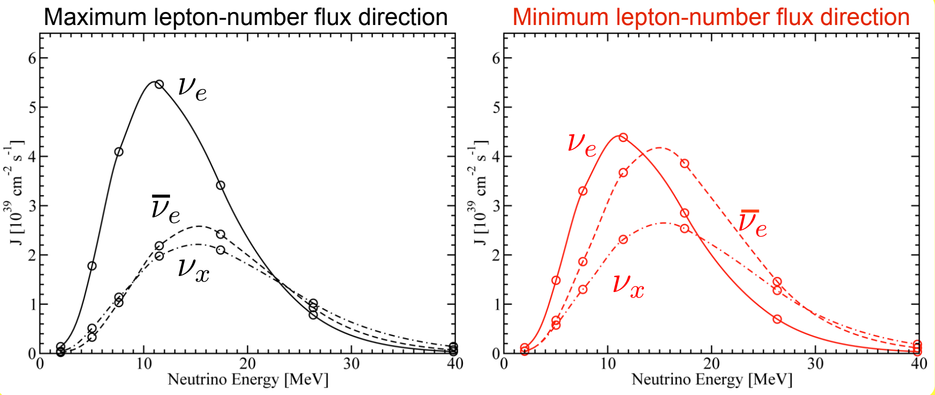
Lepton-number emission asymmetry (**LESA**) is a large-scale feature with **dipole character**.

Once the dipole develops, its direction remains stable. No-correlation with numerical grid.

Tamborra, Hanke, Janka, Mueller, Raffelt, Marek, ApJ (2014). See also: Janka, Melson, Summa, arXiv: 1602.05576.

Neutrino Energy Spectra

Neutrino flux spectra in opposite LESA directions (11.2 Msun, t = 210 ms)



Fluxes strongly vary with the observer direction.

Potential relevant implications for SN nucleosynthesis, neutron-star kicks, flavor conversions.

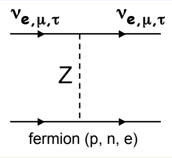
Tamborra, Hanke, Janka, Mueller, Raffelt, Marek, ApJ (2014). See also: Janka, Melson, Summa, arXiv: 1602.05576.

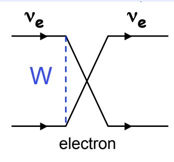
Flavor Oscillations in Supernovae

Neutrino Interactions in Supernovae

Neutrinos in supernovae interact with matter and among each other.

Understood phenomenon.

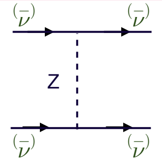




Neutrinos interact with neutrons, protons and electrons.

Wolfenstein, PRD 17 (1978) 2369

We still need to learn a lot!



$\nu - \nu$ interactions

Non-linear phenomenon

Pantaleone, PLB 287 (1992) 128

SN Neutrino Equations of Motion

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

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

External forces (negligible)

Vacuum term

Matter term
[MSW resonant conversion]

Collision term (negligible)

$\nu-\nu$ **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.

Simplifications required!

Stationary & Spherically-Symmetric SN

We assume to have a system that is stationary, spherically symmetric, evolving with radius.

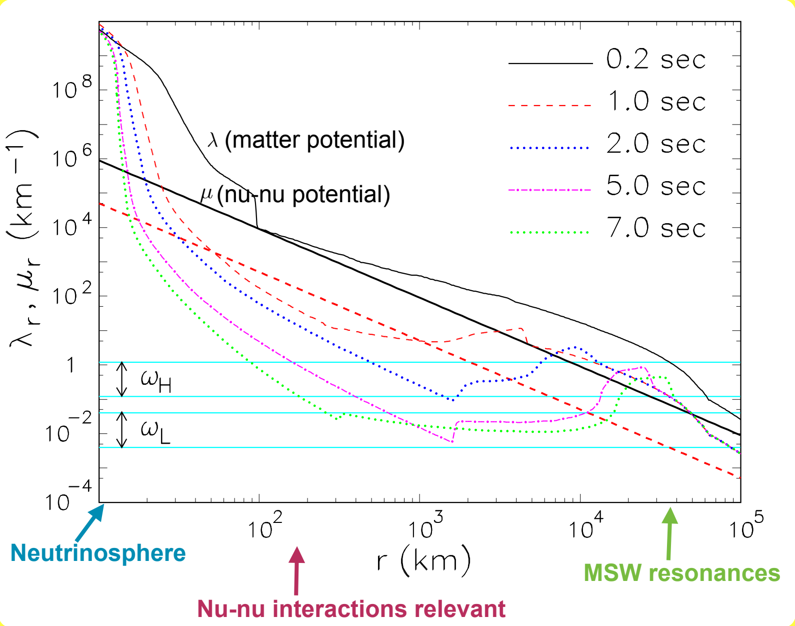
$$i\,\dot{\varrho}_{E,\vartheta} = [\mathsf{H}_{E,\vartheta}, \varrho_{E,\vartheta}] \quad \text{and} \quad i\,\dot{\bar{\varrho}}_{E,\vartheta} = [\bar{\mathsf{H}}_{E,\vartheta}, \bar{\varrho}_{E,\vartheta}]$$

with the Hamiltonian defined as

$$\mathsf{H}_{E,\vartheta} = \underbrace{\frac{\mathsf{U}\mathsf{M}^2\mathsf{U}^\dagger}{2E}}_{\text{vacuum term}} + \underbrace{\sqrt{2}G_\mathrm{F}\,\mathsf{N}_l}_{\text{matter term [MSW resonant conversion]}} + 2\pi\sqrt{2}G_\mathrm{F}\int dE' \int d\cos\vartheta' \; \underbrace{(\varrho_{E',\vartheta'} - \bar{\varrho}_{E',\vartheta'})\,(1-\cos\vartheta\cos\vartheta')}_{\nu-\nu\text{ interaction term [neutrino self-interactions]}}$$

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

Nu-Nu and Matter Potentials

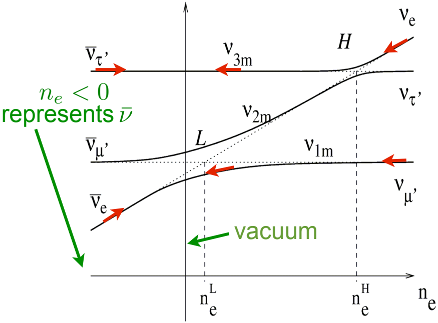


Neutrino Interactions with Matter (MSW)

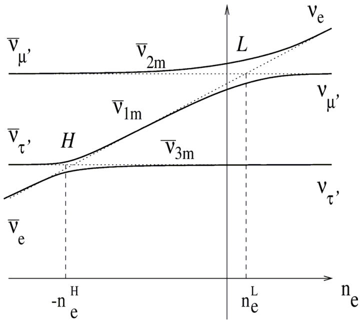
Vacuum term in resonance with the matter term: Maximal flavor conversions (MSW effect).

Eigenvalue diagram of 3 x 3 Hamiltonian matrix for 3-flavor oscillations

Normal hierarchy



Inverted hierarchy



Δm^2 resonance for neutrinos
δm^2 resonance for neutrinos

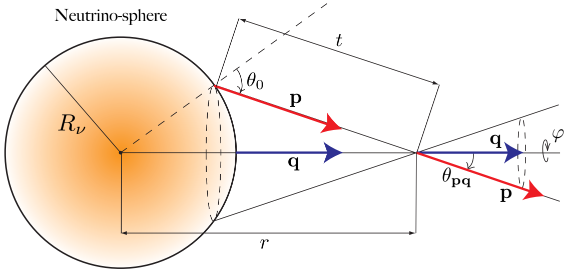
Δm^2 resonance for antineutrinos
δm^2 resonance for neutrinos

Dighe and Smirnov, PRD (2000).

Nu-Nu Interactions:
Stationary & Spherically-Symmetric SN

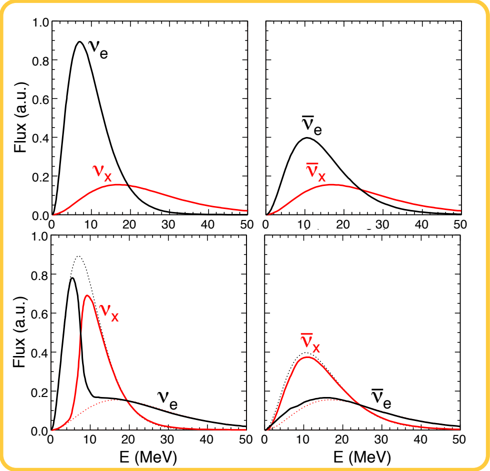
The $\nu - \nu$ term is **non linear**. It depends on the relative angle between colliding neutrinos

$$\mathsf{H}_{E,\nu-\nu} = 2\pi\sqrt{2}G_{\mathrm{F}} \int dE' \int d\cos\vartheta' \;\left(\varrho_{E',\vartheta'} - \bar{\varrho}_{E',\vartheta'}\right)\left(1 - \cos\vartheta\cos\vartheta'\right)$$



Neutrino light-bulb model

Stationary & Spherically-Symmetric SN



Fluxes before oscillations

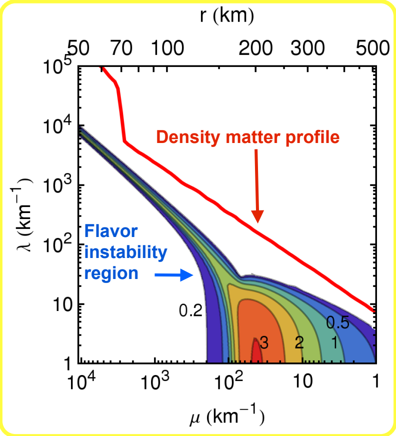
Fluxes after neutrino self-interactions

"**Spectral splits**": For energies above a critical value, a full flavor swap occurs.

Generic features found in highly symmetric framework.

Review papers: Duan, Fuller, Qian (2010). Mirizzi, Tamborra et al. (2016).

Stationary & Spherically-Symmetric SN



Stability analysis: Splits suppressed under certain conditions (e.g. high-matter potential).

Sarikas, Raffelt, Huedepohl, Janka, PRL (2012).

Real SN is Space-Time Dependent

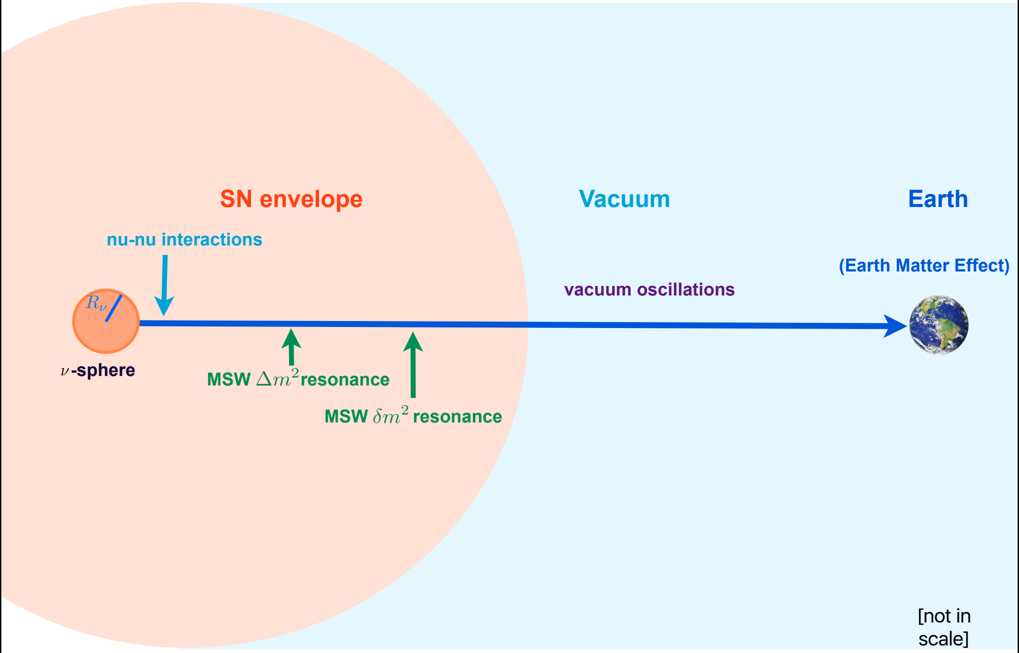
Flavor instabilities may occur when releasing symmetry assumptions.
Caveats: Studies only within 1D/2D toy-models. Challenging numerical implementation.

- Breaking of axial symmetry.
[Raffelt, Sarikas, de Sousa Seixas, PRL (2013)]
- Spatial and directional symmetry breaking (inhomogeneity).
[Mirizzi et al., PRD (2015); Duan&Shalgar, PLB (2015); Hansen&Hannestad, PRD (2014), Chakraborty et al., JCAP (2016)].
- Temporal instability (non-stationarity).
[Abbar & Duan, PLB (2015), Dasgupta & Mirizzi, PRD (2015)].
- Neutrino momentum distribution not limited to outward direction (nu halo).
[Cherry et al., PRL (2012). Sarikas, Tamborra, Raffelt, Huedepohl, Janka, PRD (2012)].
- Large-scale 3D effects (SASI, LESA).
[Tamborra et al., PRL (2013) & ApJ (2014), Chakraborty et al., PRD (2015)].
- Fast flavor conversions close to the nu-sphere.
[Sawyer, PRD (2005) & PRL (2016), Chakraborty, Hansen, Izaguirre, Raffelt, JCAP (2016)].

Some of these studies suggest **flavor equipartition** might occur already close to the SN core.

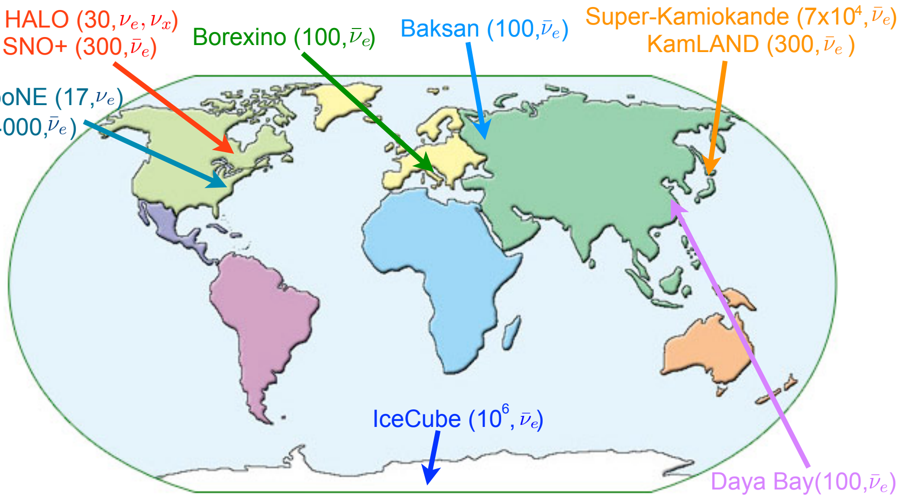
Existing investigations are simplified case studies. Real SN may be different.

Simplified Picture of SN Fluxes at Earth



Supernova Neutrino Detectors

Detectors Sensitive to SN Neutrinos



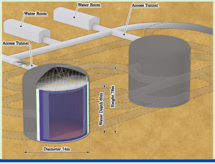
Expected number of events for a SN at 10 kpc and dominant flavor sensitivity in parenthesis.

Recent review papers: Scholberg (2012). Mirizzi, Tamborra, Janka, Scholberg et al. (2016).

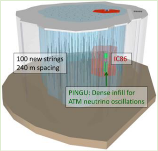
Next Generation Large Scale Detectors

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

Hyper-Kamiokande (10^5)

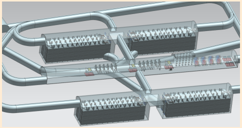


IceCube-Gen2 PINGU (10^6)



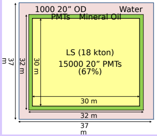
Liquid Argon detectors (ν_e)

DUNE (3000)

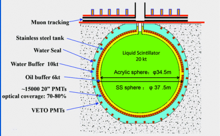


Scintillation detectors ($\bar{\nu}_e$)

RENO-50 (5400)



JUNO (6000)



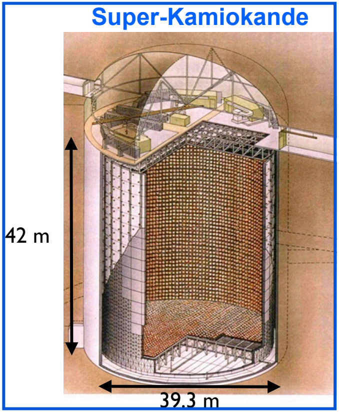
Dark Matter Detectors ($\nu_{e,x}$, $\bar{\nu}_{e,x}$)

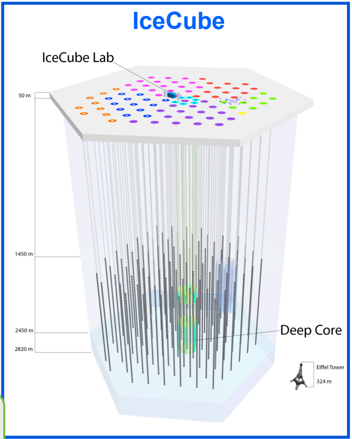
e.g., DARWIN (700)

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

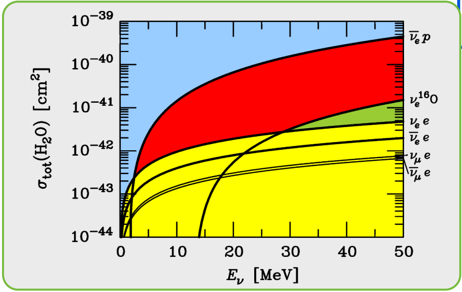
Recent review papers: Scholberg (2012). Mirizzi, Tamborra, Janka, Scholberg et al. (2016).

Main Technologies: Cherenkov Telescopes





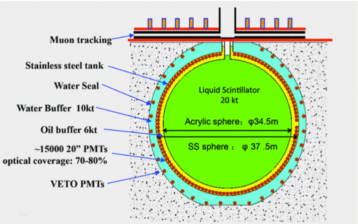
SN detected in IceCube as correlated noise.



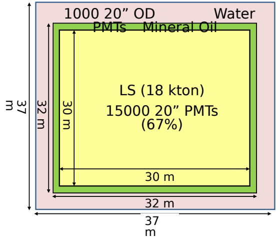
Main interaction channel: Inverse beta decay.

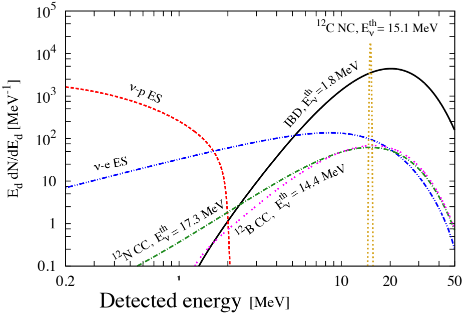
Main Technologies: Scintillators

e.g., JUNO



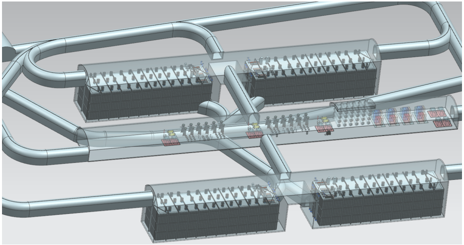
e.g., RENO-50

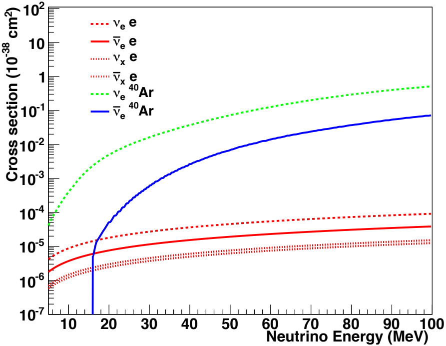




Main Technologies: Liquid Argon

DUNE



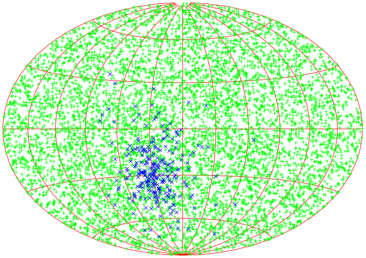


What Can We Learn From a SN Burst?

Early Alert and Pointing

SuperNova Early Warning System (SNEWS)

Network to alert astronomers of a burst.



SN detected within a cone of $O(5^0)$ at Super-K
or via triangulation.

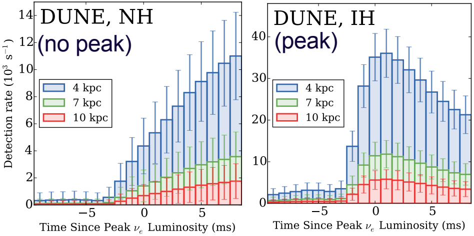
SN location with nu's crucial for vanishing or weak SNe.

Fundamental for multi-messenger searches.

http://snews.bnl.gov.
Beacom & Vogel, PRD (1999). Tomas et al., PRD (2003). Fisher et al., JCAP (2015). Muehlbeier et al., PRD (2013).

Oscillation Physics and SN Distance

Neutrinos



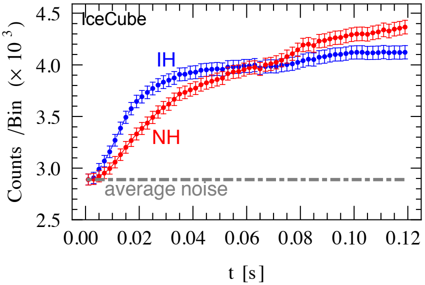
Deleptonization peak is:

- Independent of progenitor mass and EoS
- Sensitive to mass ordering.

If mass ordering known:

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

Antineutrinos

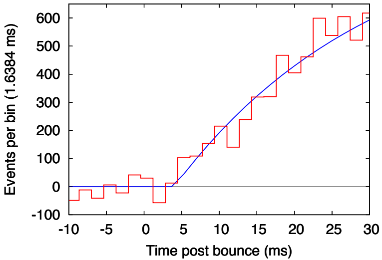


Rise time depends on mass ordering.

Test role of oscillations in dense media.

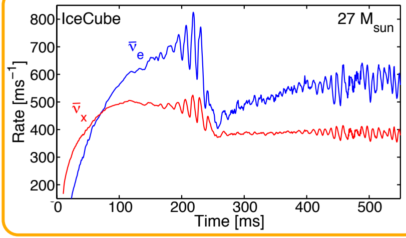
Kachelriess et al., PRD (2005). Wallace, Burrows, Dolence, ApJ (2016). Serpico et al., PRD (2012).

Supernova Explosion Dynamics



Probe the core bounce time.

Coincidence measurement with GW detectors.



Test of SN explosion mechanism.

Complementary measurements with GW detectors.

Pagliaroli et al., PRL (2009), Halzen & Raffelt PRD (2009). Tamborra et al., PRL (2013), PRD(2014), Lund et al., PRD (2010).

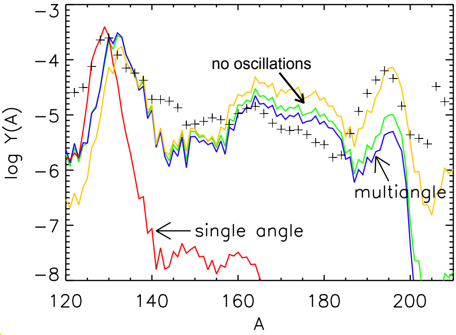
Nucleosynthesis

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

Flavor oscillations affect element production mainly via

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

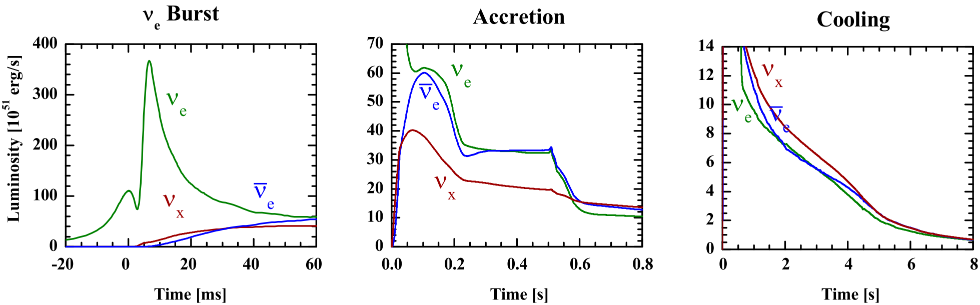
Coupling of oscillation codes to nucleosynthesis networks recently begun.



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

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

Synopsis: What Can We Learn?



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.

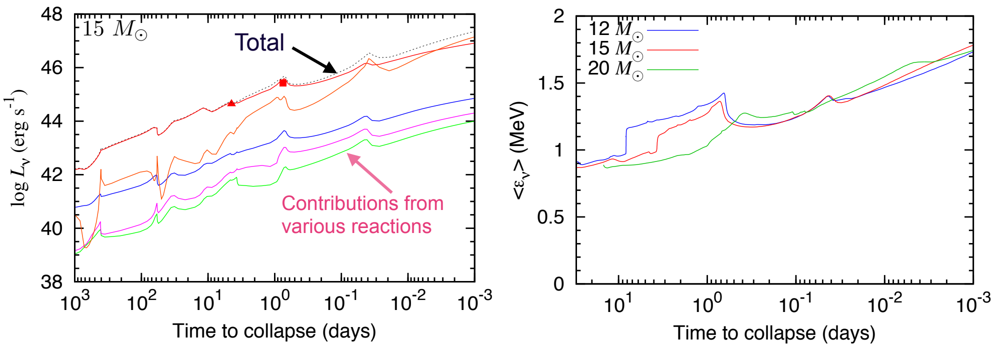
- Test nuclear physics.
- Nucleosynthesis.

Pre-Supernova Neutrinos

Pre-Supernova Neutrinos

Neutrinos are emitted also **before** the SN explosion.

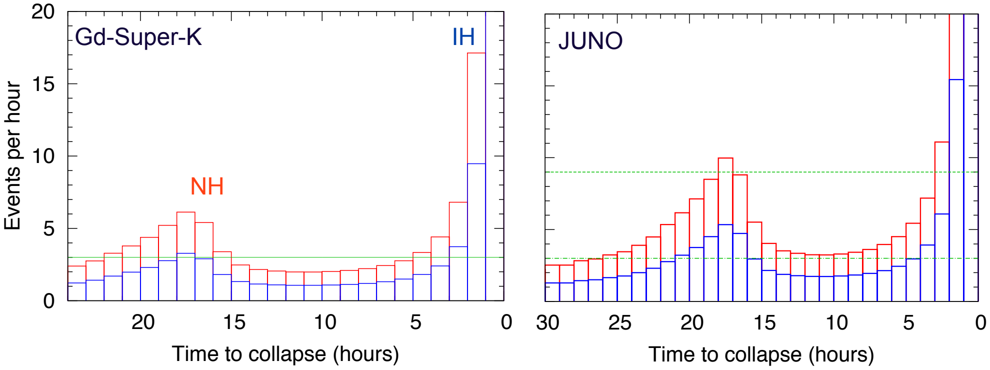
Neutrino emission is most efficient cooling process after He burning ($L_\nu \simeq 10^{47}$ erg/s).



Yoshida et al., arXiv: 1606.04915.

Pre-Supernova Neutrinos

Pre-supernova neutrinos are detectable and tell us that a supernova is exploding.



Yoshida et al., arXiv: 1606.04915.

Diffuse Supernova Neutrino Background

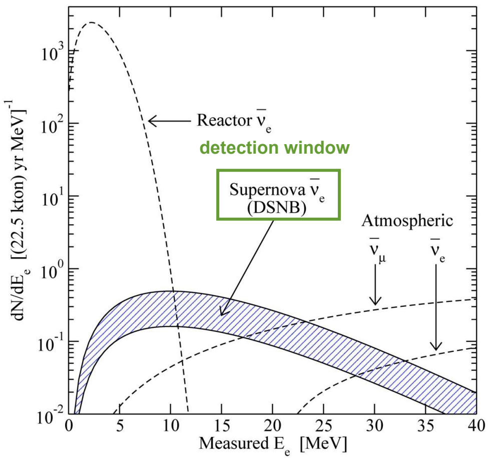
Diffuse Supernova Neutrino Background

Galactic supernova (SN) rare, but SN explosions are quite common.
On average 1 SN/s somewhere in the universe ⟶ Diffuse neutrino background (**DSNB**).

★ Detectable $\bar{\nu}_e$ flux at the Earth (mostly from z ~ 1)

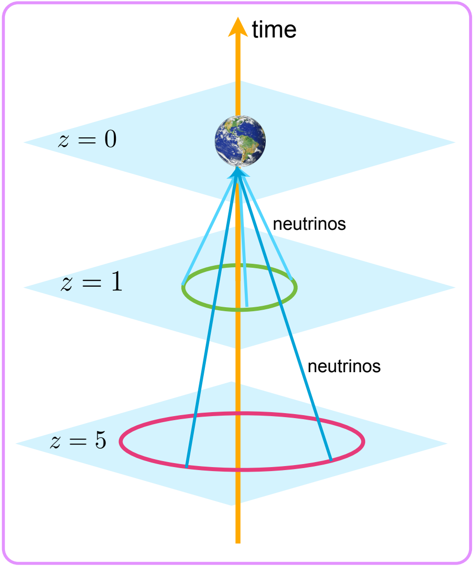
★ Test of supernova astrophysics

★ New frontiers for neutrino astronomy



Recent review papers: Beacom (2010). Lunardini (2010). Mirizzi, Tamborra et al. (2016).

Ingredients



$$\Phi(E) = \frac{c}{H_0}\int_0^{z_{max}} R_{SN}(z)\frac{dN(E')}{dE'}\frac{dz}{\sqrt{\Omega_m(1+z)^3+\Omega_\Lambda}}$$

cosmological supernova rate

oscillated neutrino flux
[$E' = E(1+z)$]

cosmology

Supernova Rate

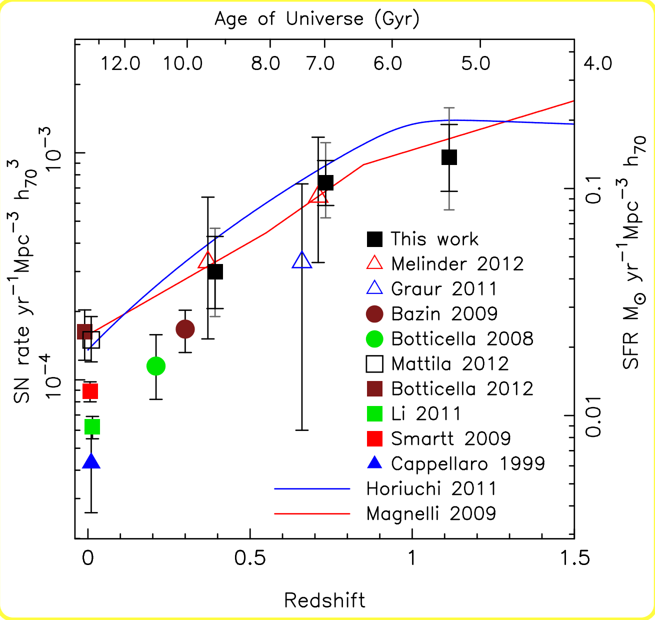
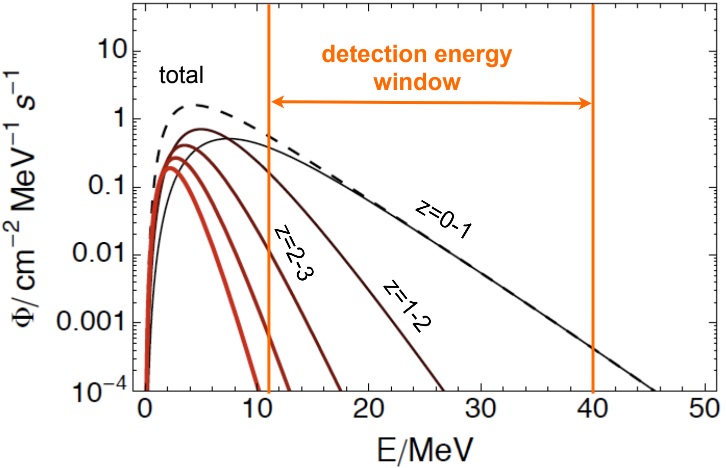


Figure from Dahlen et al., ApJ (2012).

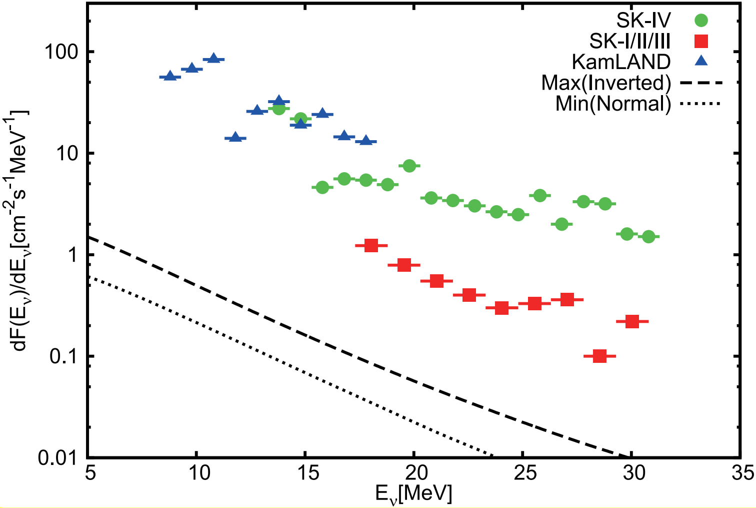
Redshift Correction

The energy redshift correction accumulates neutrinos of higher redshift at lower energies.



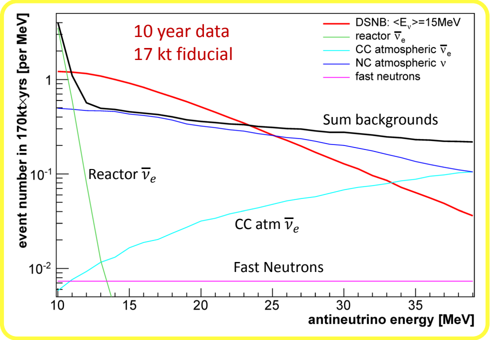
DSNB Detection Perspectives

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



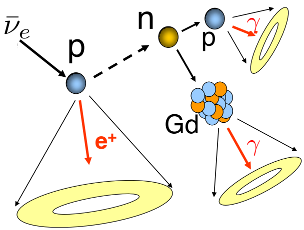
Super-Kamiokande Collaboration, Astropart. Phys. 60 (2015) 41. Nakazato, Mochida, Niino, Suzuki, ApJ 804 (2015) 1, 75.

DSNB Detection - Next Generation



JUNO detection perspectives

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



Positron and gamma ray vertices are within ~50cm.

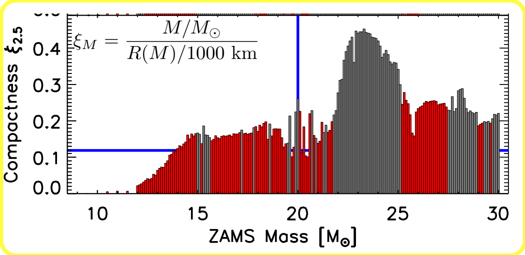
Neutron tagging in Gd-enriched WC detector (Super-K with 100 tons Gd to trap neutrons).

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

Gd-project approved!

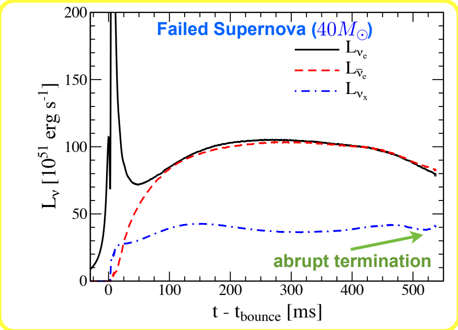
JUNO Collaboration, arXiv: 1507.5613. Beacom&Vagins, PRL 93 (2004) 171101.

Failed Supernovae



Core compactness non-monotonic function of progenitor mass.

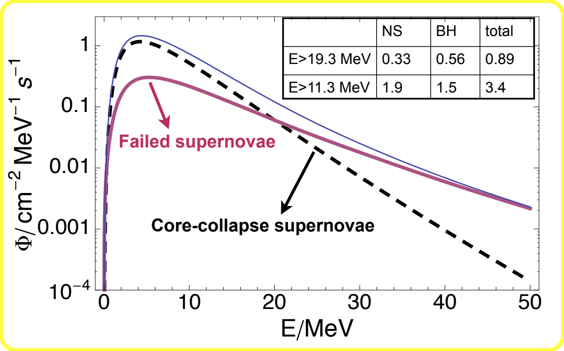
Black hole formation for $\xi_{2.5} > 0.35$ and sometimes for $0.15 < \xi_{2.5} < 0.35$.



Probably higher abundance of failed SNe than previously thought. The DSNB can probe fraction of failed SNe.

Ertl et al., ApJ (2016). Gerke, Kochanek, Stanek, MNRS (2015). Horiuchi et al., MNRSL (2014). Ugliano et al., ApJ (2012). O'Connor & Ott, ApJ (2011). O'Connor, ApJ (2015).

Diffuse Supernova Neutrino Background



	NS	BH	total
E>19.3 MeV	0.33	0.56	0.89
E>11.3 MeV	1.9	1.5	3.4

- ★ Constraints on the stellar population. Independent test of the global SN rate.
- ★ Constraints on the fraction of core-collapse and failed supernovae.
- ★ Constraints on the neutrino emission properties.
- ★ Exotic physics and background modeling for direct dark matter experiments.

Conclusions

- Neutrinos play a fundamental role in SNe.
- Intriguing neutrino features in SN simulations at the 3D frontier.
- Neutrino-neutrino interactions are not negligible. Work still needed to grasp their role.
- Each SN phase offers different opportunities to learn about SN (and nu) physics.
- Realistic perspectives to learn about SNe through the DSNB in the next future.

Thank you for your attention!

References

- Supernova Neutrinos: Production, Oscillations and Detection.
  https://arxiv.org/abs/1508.00785

- Collective neutrino flavor conversion: Recent developments.
  https://arxiv.org/abs/1602.02766

- Explosion Mechanisms of Core-Collapse Supernovae.
  https://arxiv.org/abs/1206.2503

- Supernova Neutrino Detection.
  https://arxiv.org/abs/1004.3311

- The Diffuse Supernova Neutrino Background.
  https://arxiv.org/abs/1004.3311