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Supernova Lessons from Low- and High-Energy Neutrinos

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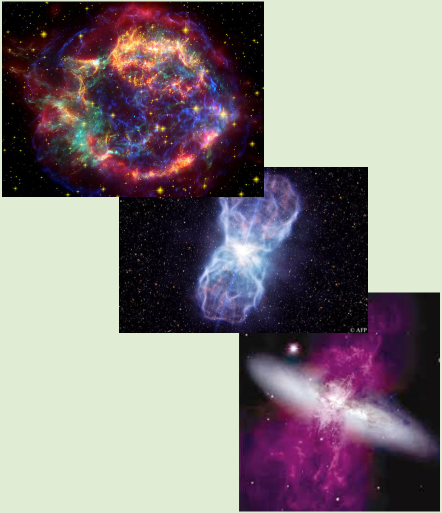
IAUS 331: SN 1987A, 30 Years Later
La Réunion Island, February 24, 2017

Neutrinos from Supernovae

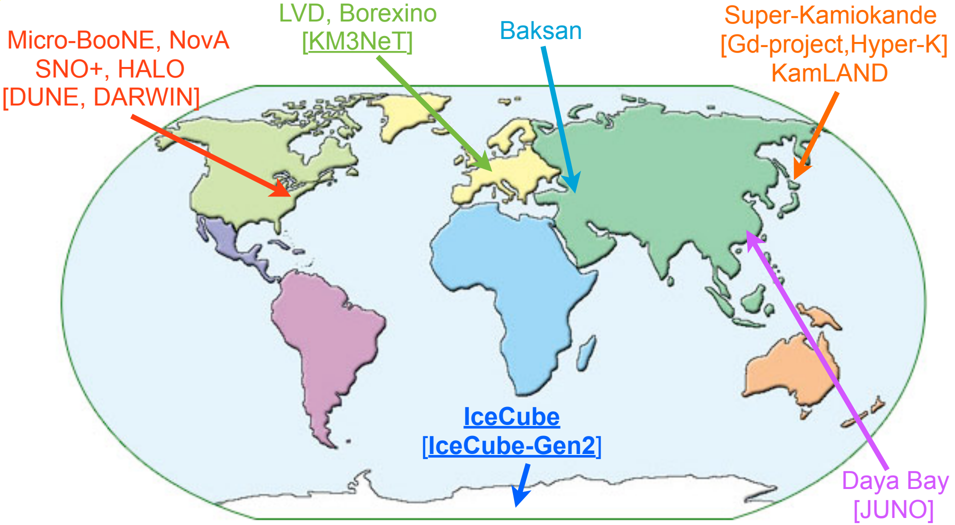
Burst phase
[MeV neutrinos]

Post-burst phase
[TeV-GeV neutrinos]



Neutrino Astronomy

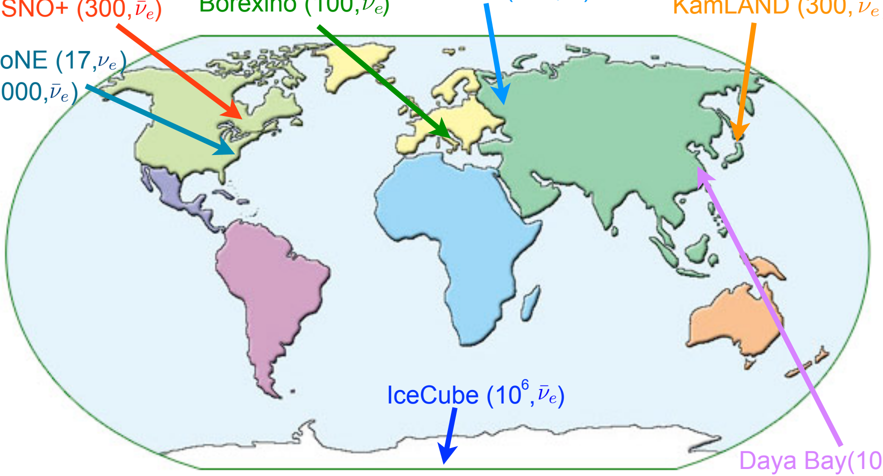
Several detectors are (or will be soon) sensitive to astrophysical neutrinos.



Detectors under planning/construction in parenthesis. Underlined detectors sensitive to HE nus.

MeV Neutrinos
from Core-Collapse Supernovae

Are We Ready For SN 20XXa?



HALO (30, ν_e, ν_x)
SNO+ (300, $\bar{\nu}_e$)

LVD (300, $\bar{\nu}_e$)
Borexino (100, $\bar{\nu}_e$)

Baksan (100, $\bar{\nu}_e$)

Super-Kamiokande (7×10^4, $\bar{\nu}_e$)
KamLAND (300, $\bar{\nu}_e$)

MicroBooNE (17, ν_e)
NovA(4000, $\bar{\nu}_e$)

IceCube (10^6, $\bar{\nu}_e$)

Daya Bay(100, $\bar{\nu}_e$)

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

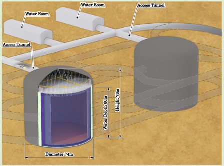
Fundamental to combine the SN signal seen in detectors employing different technologies.

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

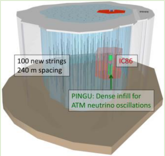
Next Generation Large Scale Detectors

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

Hyper-Kamiokande (10^5)



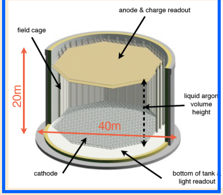
IceCube-Gen2 PINGU (10^6)



KM3NeT ORCA

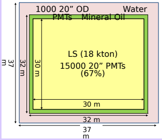
Liquid Argon detectors (ν_e)

DUNE (3000)

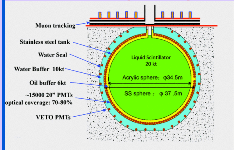


Scintillation detectors ($\bar{\nu}_e$)

RENO-50 (5400)



JUNO (6000)



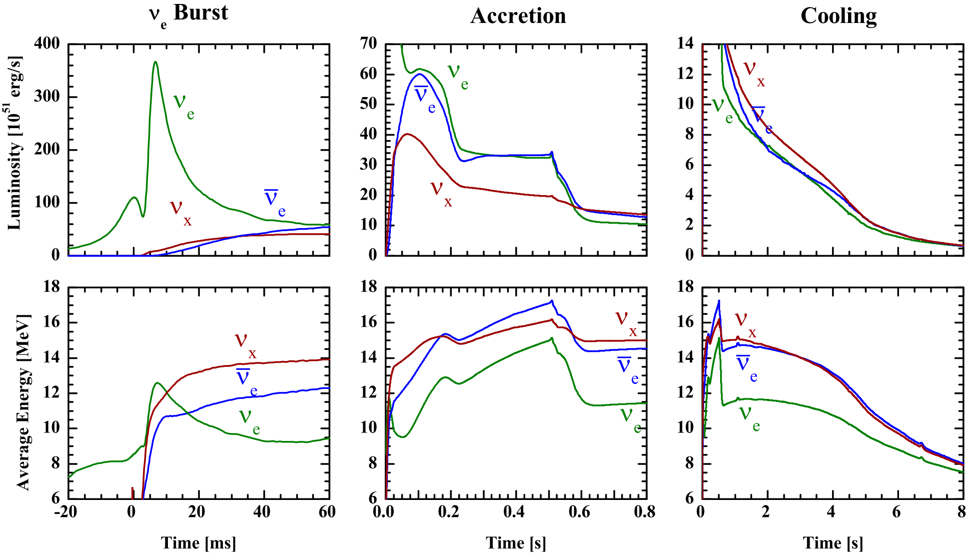
Dark Matter Detectors ($\nu_{e,x}, \bar{\nu}_{e,x}$)

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 et al. (2016).

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.

General features of the neutrino signal as from 1D hydro simulation.

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

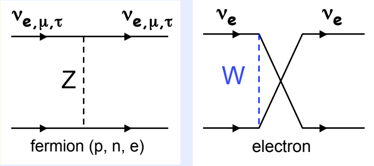
MeV Neutrinos
from Core-Collapse Supernovae

1. Flavor Oscillation Physics Imprints

Neutrino Interactions in Supernovae

Neutrinos in neutrino-dense media interact with matter and among each other.

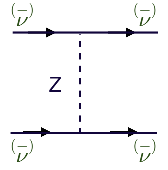
Understood phenomenon.



Neutrinos interact with neutrons, protons and electrons.

Wolfenstein, PRD 17 (1978) 2369

We still need to learn a lot!!

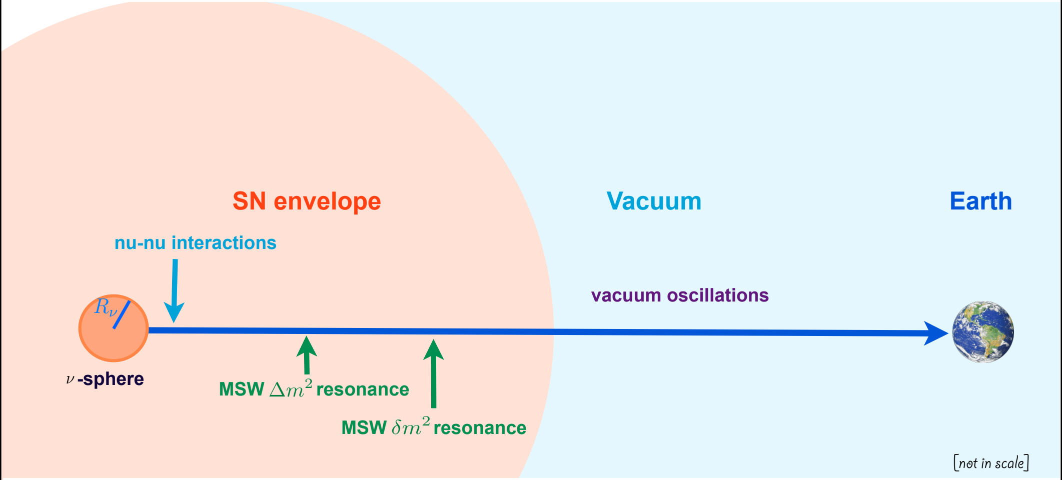


$\nu - \nu$ interactions

Non-linear phenomenon

Pantaleone, PLB 287 (1992) 128

Simplified Picture of SN Fluxes at Earth



Nu-nu interactions and MSW resonances mainly occur in distinct regions.

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

Pairwise Neutrino Conversions

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.

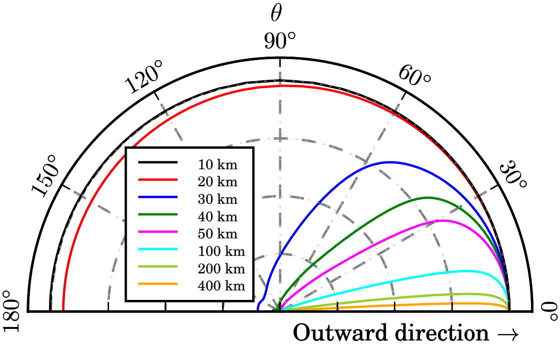
Growth rate: $\sqrt{2}G_F(n_{\nu_e} - n_{\bar{\nu}_e}) \simeq 6.42\ \mathrm{m}^{-1}$ vs. $\dfrac{\Delta m^2}{2E} \simeq 0.5\ \mathrm{km}^{-1}$ ⇒ **“Fast” conversions**

Neutrino angular distributions **crucial** in pairwise flavor conversions.

Sawyer, PRD (2005), Sawyer, PRL (2016), Chakraborty et al., JCAP (2016). Izaguirre, Raffelt, Tamborra, PRL (2017). Dasgupta et al., JCAP (2017).

Pairwise Neutrino Conversions

Neutrinos were assumed to stream forward and freely after the neutrino sphere (~15km).



Non-negligible inward neutrino flux may be responsible for fast conversions.

Flavor equipartition might occur close to neutrino decoupling region.

Existing investigations are simplified case studies. Further work needed.

Sawyer, PRD (2005), Sawyer, PRL (2016), Izaguirre, Raffelt, Tamborra, PRL (2017), Tamborra et al., arXiv: 1702.00060.

MeV Neutrinos from Core-Collapse Supernovae

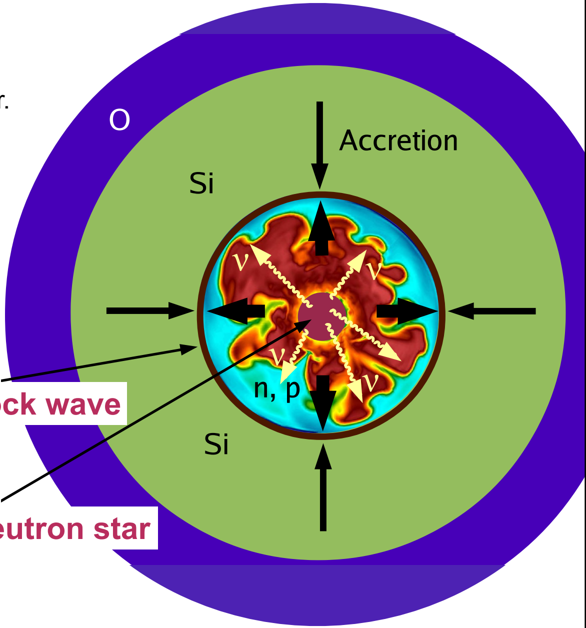
1. Flavor Oscillation Physics Imprints

2. Supernova Dynamics Imprints

Supernova Explosion Mechanism

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

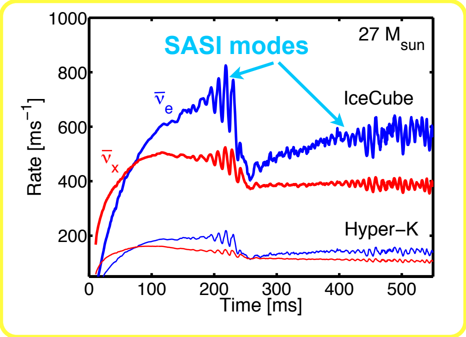
★ **Neutrinos** provide energy to stalled shock wave to start re-expansion. **(Delayed Neutrino-Driven Explosion.)**

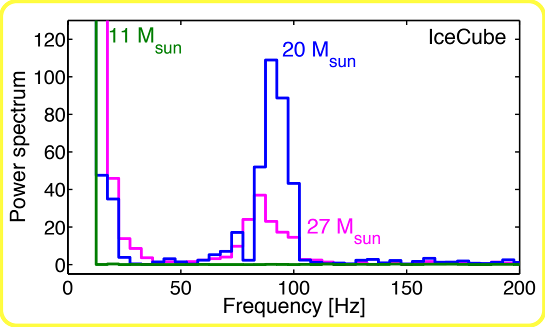


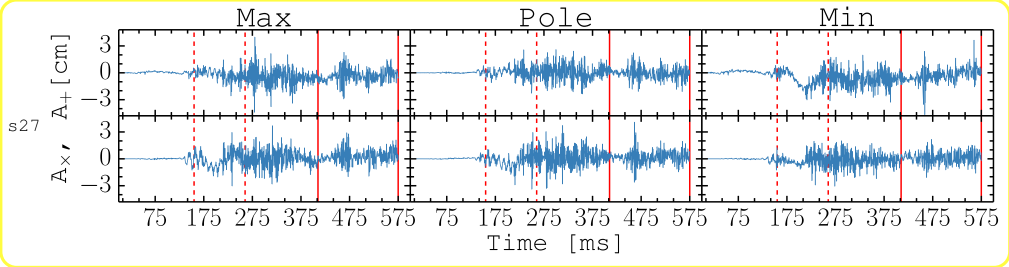
★ **Convection** and **shock oscillations** (standing accretion shock instability, **SASI**) enhance efficiency of neutrino heating and revive the shock.

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

SASI Imprints on Neutrino and GW Signals



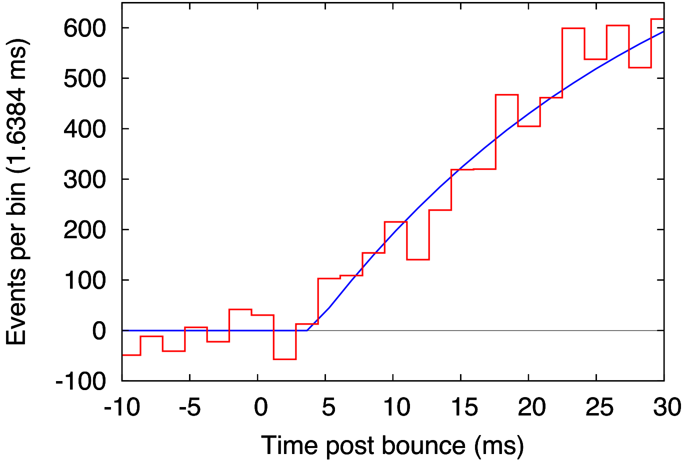




Tamborra, Hanke, Mueller, Janka, Raffelt PRL (2013), Tamborra et al., PRD (2014). Lund et al., PRD (2012).
Andresen, Mueller, Mueller, Janka, arXiv: 1607.05199.

Supernova Core Bounce Time

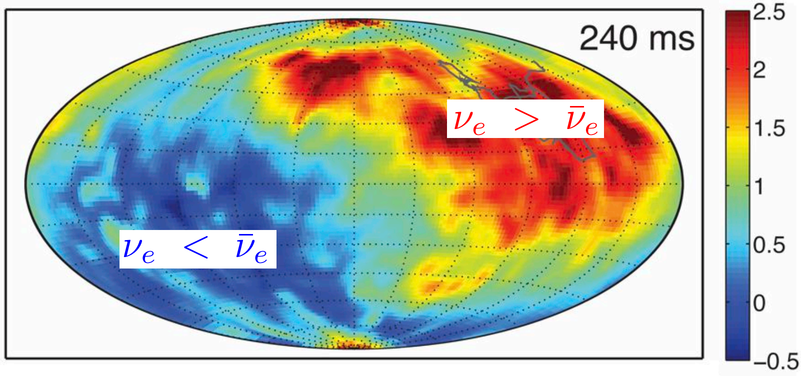
Neutrinos can probe the core bounce time. Coincidence measurement with GW detectors.



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

SN Dynamics: Nu-Driven Instability in 3D

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



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

First nu-driven instability. Neutrino signal may strongly depend on direction.

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

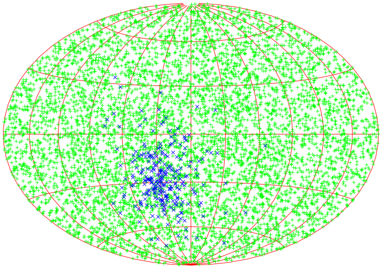
MeV Neutrinos
from Core-Collapse Supernovae

1. Oscillation Physics Imprints
2. Supernova Dynamics Imprints
3. Pinpointing a Supernova in the Sky

Early Alert and Pointing

SuperNova Early Warning System (SNEWS)

Network to alert astronomers of a burst.



SN detected within a cone of O(5^{o}) at Super-K
or via triangulation.

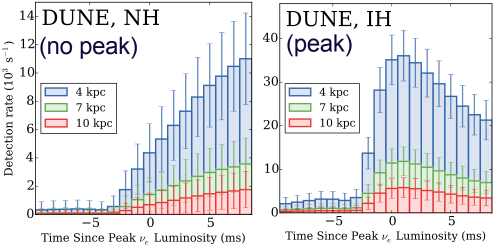
SN location with nu’s crucial for vanishing or weak SNe.

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).

SN Distance and Oscillation Physics

Neutrinos



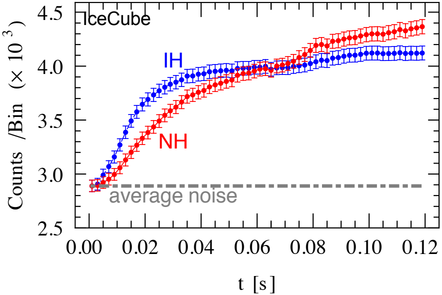
Deleptonization peak is:

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

If mass ordering known:

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

Antineutrinos



Rise time depends on mass ordering.

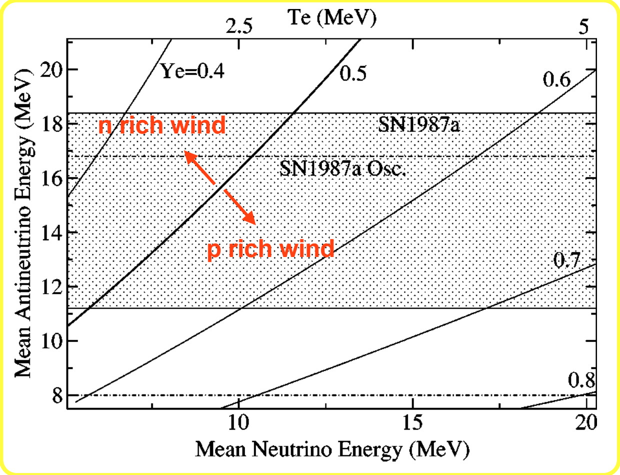
Test oscillations in dense media.

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

MeV Neutrinos from Core-Collapse Supernovae

1. Oscillation Physics Imprints
2. Supernova Dynamics Imprints
3. Pinpointing a Supernova in the Sky
4. Constraints on Nuclear Physics

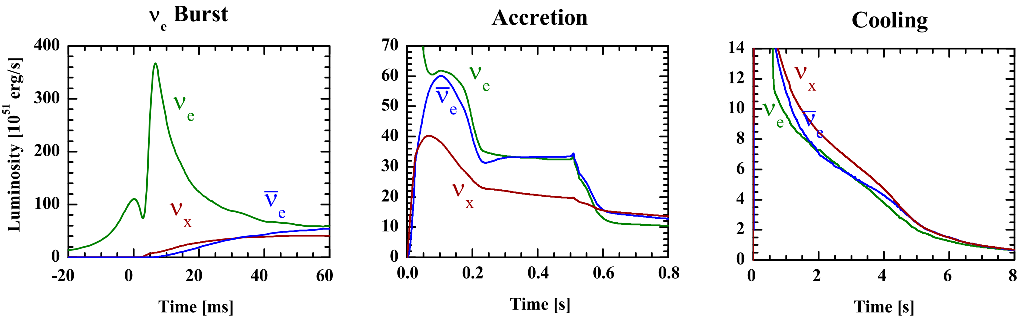
Neutrino Cooling Phase



- Late time signal is strongly sensitive to nuclear physics and progenitor mass.
- Connects supernova physics to neutron-star physics.
- Nucleosynthesis in the neutrino driven wind.

Horowitz, PRD (2002). Roberts et al., PRL (2012). Duan et al., J. Phys. G (2011). Pllumbi, Tamborra et al., ApJ (2015). Mirizzi, Tamborra et al. (2016).

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.

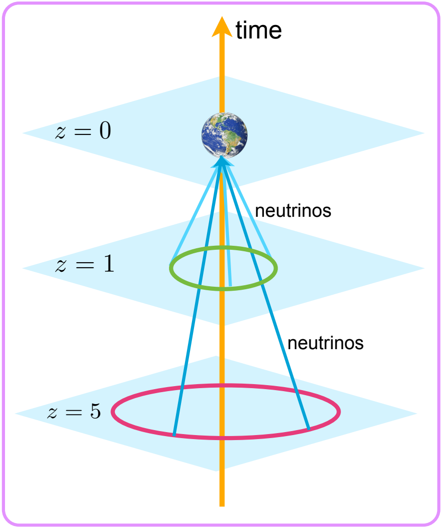
- Test nuclear physics.
- Nucleosynthesis.

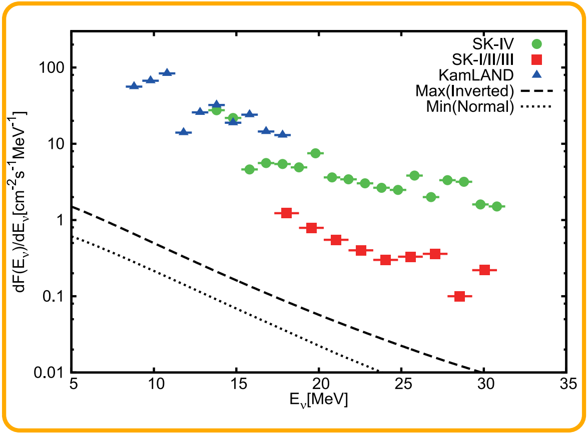
MeV Neutrinos from Core-Collapse Supernovae

1. Oscillation Physics Imprints
2. Supernova Dynamics Imprints
3. Pinpointing a Supernova in the Sky
4. Constraints on Nuclear Physics
5. Constraints on Stellar Population

Diffuse Supernova Neutrino Background

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

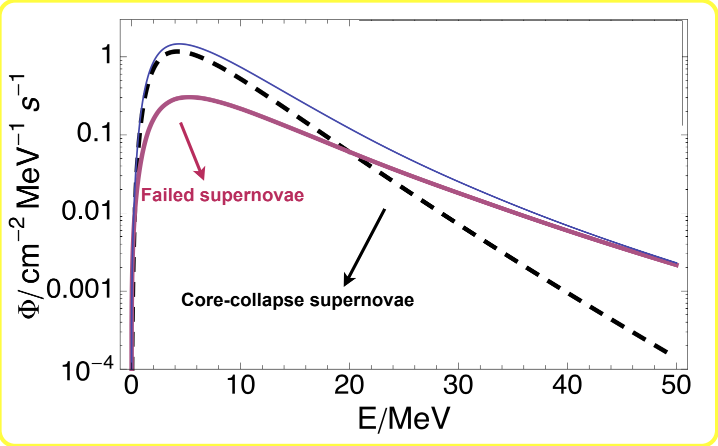




DSNB detection may happen soon with, e.g., upcoming JUNO and Gd-Super-K project.

Recent review papers: Beacom (2010). Lunardini (2010). Mirizzi, Tamborra et al. (2016).
Super-Kamiokande Collaboration, Astropart. Phys. (2015). Nakazato, Mochida, Niino, Suzuki, ApJ (2015).

Diffuse Supernova Neutrino Background



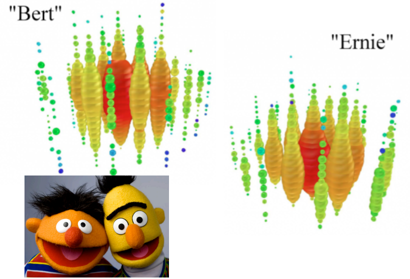
- Constraints on stellar population. Independent test of the global SN rate.
- Constraints on fraction of core-collapse vs. failed supernovae.

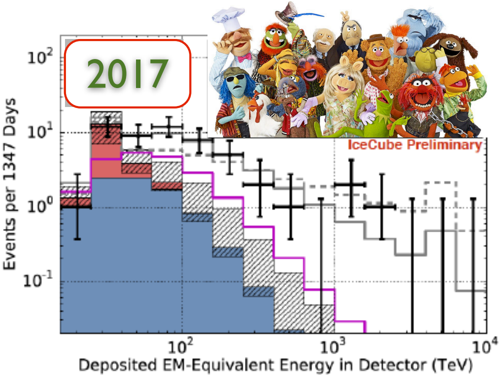
Lunardini (2010). Mirizzi, Tamborra et al. (2016). Nakazato et al., ApJ (2015). Lunardini, Tamborra, JCAP (2012). Lunardini, PRL (2009). Ertl et al., ApJ (2016). Gerke et al., MNRS (2015). Horiuchi et al., MNRSL (2014). O'Connor & Ott, ApJ (2011).

TeV Neutrinos
from Core-Collapse Supernovae

High-energy neutrino astronomy is happening!

2013





- ★ IceCube observed 54 events over four years in the 25 TeV-2.8 PeV range.
- ★ Zenith Distribution compatible with isotropic flux.
- ★ Flavor distribution consistent with $\nu_e : \nu_\mu : \nu_\tau = 1:1:1$.

7σ evidence for astrophysical flux

IceCube Collaboration, Science 342 (2013) 6161, PRL 113 (2014) 101101, PRD 91 (2015) 2, 022001.
IceCube Collaboration, ApJ 809 (2015) 1, 98; PRL 115 (2015) 8, 081102.

TeV Neutrinos from Core-Collapse Supernovae

1. Imprints of SN-GRB Connection

Constraints on SN-GRB Connection

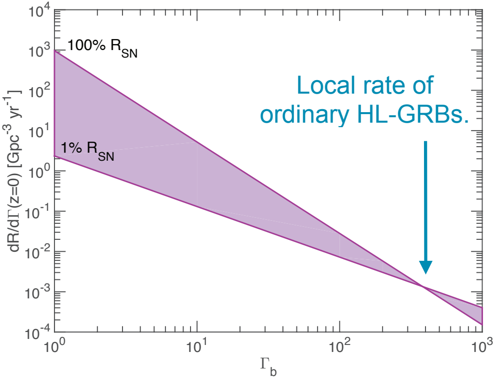
Redshift evolution: $R(z) \propto \left[(1+z)^{p_1 k} + \left(\frac{1+z}{5000}\right)^{p_2 k} + \left(\frac{1+z}{9}\right)^{p_3 k}\right]^{1/k}$

Rate evolution with the Lorentz boost factor:

$$\int_1^{10^3} d\Gamma_b \, \Gamma_b^{\alpha_\Gamma} \beta_\Gamma = R_{\rm SN}(0) \zeta_{\rm SN} \frac{\theta_{\rm SN}^2}{2}$$

$$\int_{200}^{10^3} d\Gamma_b \, \Gamma_b^{\alpha_\Gamma} \beta_\Gamma = \rho_{0,{\rm HL-GRB}} \, ,$$

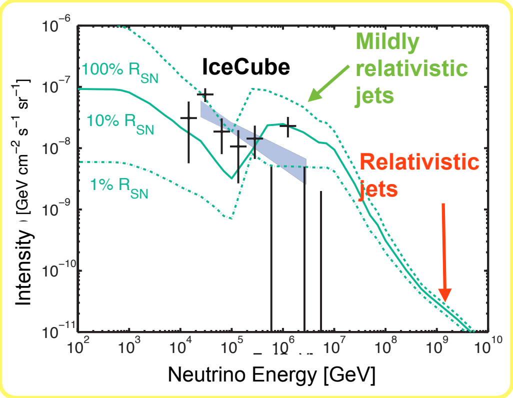
Local Evolution Rate

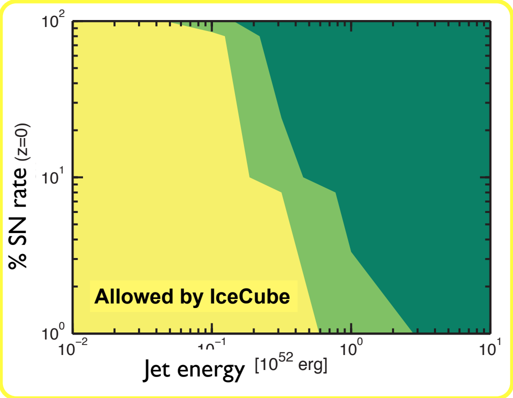


Local rate of ordinary HL-GRBs.

Tamborra & Ando, PRD (2016).

Constraints on SN-GRB Connection





Neutrinos can constrain the fraction of supernovae forming jets and their jet energy.

Tamborra & Ando, PRD (2016). Senno et al. PRD (2016). IceCube and ROTSE Collaborations, A&A (2012). Woosley&Bloom, Ann. Rev.Astron. Astrophys. (2006). Waxman & Bahcall, PRL (1997). Meszaros & Waxman, PRL (2001). Razzaque, Meszaros, Waxman, Mod. Phys. Lett. (2005).

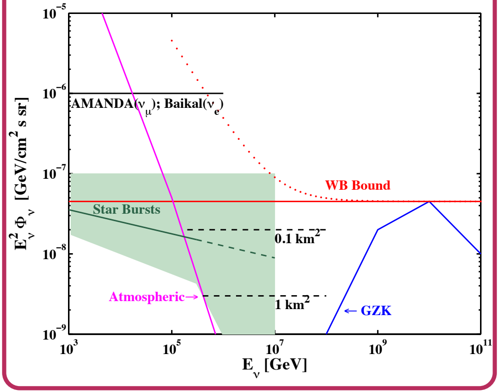
TeV Neutrinos from Core-Collapse Supernovae

1. Imprints of SN-GRB Connection

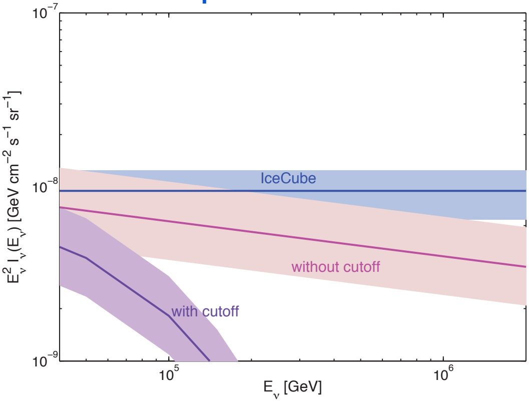
2. Neutrinos from Star-Forming Galaxies

Star-Forming Galaxies

Starbursts efficiently produce neutrinos!



Diffuse neutrino intensity extrapolated from IR data



Neutrino intensity within IceCube band for E<0.5 PeV.

Tamborra, Ando, Murase, JCAP (2014). Strong et al. (1976), Thompson et al. (2006), Fields et al. (2010), Makiya et al. (2011), Stecker&Venters(2011). Loeb&Waxman (2006), Lacki et al. (2011), Murase et al. (2013).

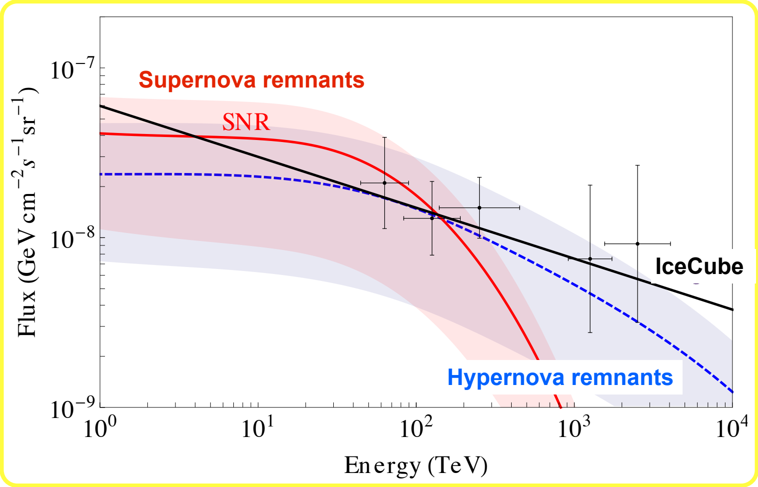
TeV Neutrinos
from Core-Collapse Supernovae

1. Imprints of the SN-GRB Connection

2. Neutrinos from Star-Forming Galaxies

3. Constraints on SNR vs. HNR Physics

Supernova and Hypernova Remnants



If SNR and HNR are main sources of the neutrino flux observed by IceCube, then a spectral break should be expected around 100 TeV.

Neutrino constraints on SNR vs. HNR relative rates possible.

Chakraborty & Izaguirre, PLB (2015). Senno et al., ApJ (2015). Tamborra, Ando, Murase, JCAP (2014).

Conclusions

- Neutrinos play a fundamental role in SNe.

- Each SN phase offers different opportunities to learn about SN (and nu) physics.

- Realistic perspectives to learn about SN population through DSNB in next future.

- Constraints on SN-GRB connection possible via TeV neutrinos.

- Starburst galaxies, supernova and hypernova remnants among possible sources of IceCube neutrinos.

Thank you for your attention!