The Niels Bohr International Academy

Dark Cosmology Centre

VILLUM FONDEN

SFB 1258 Neutrinos Dark Matter Messengers

Supernova Neutrinos

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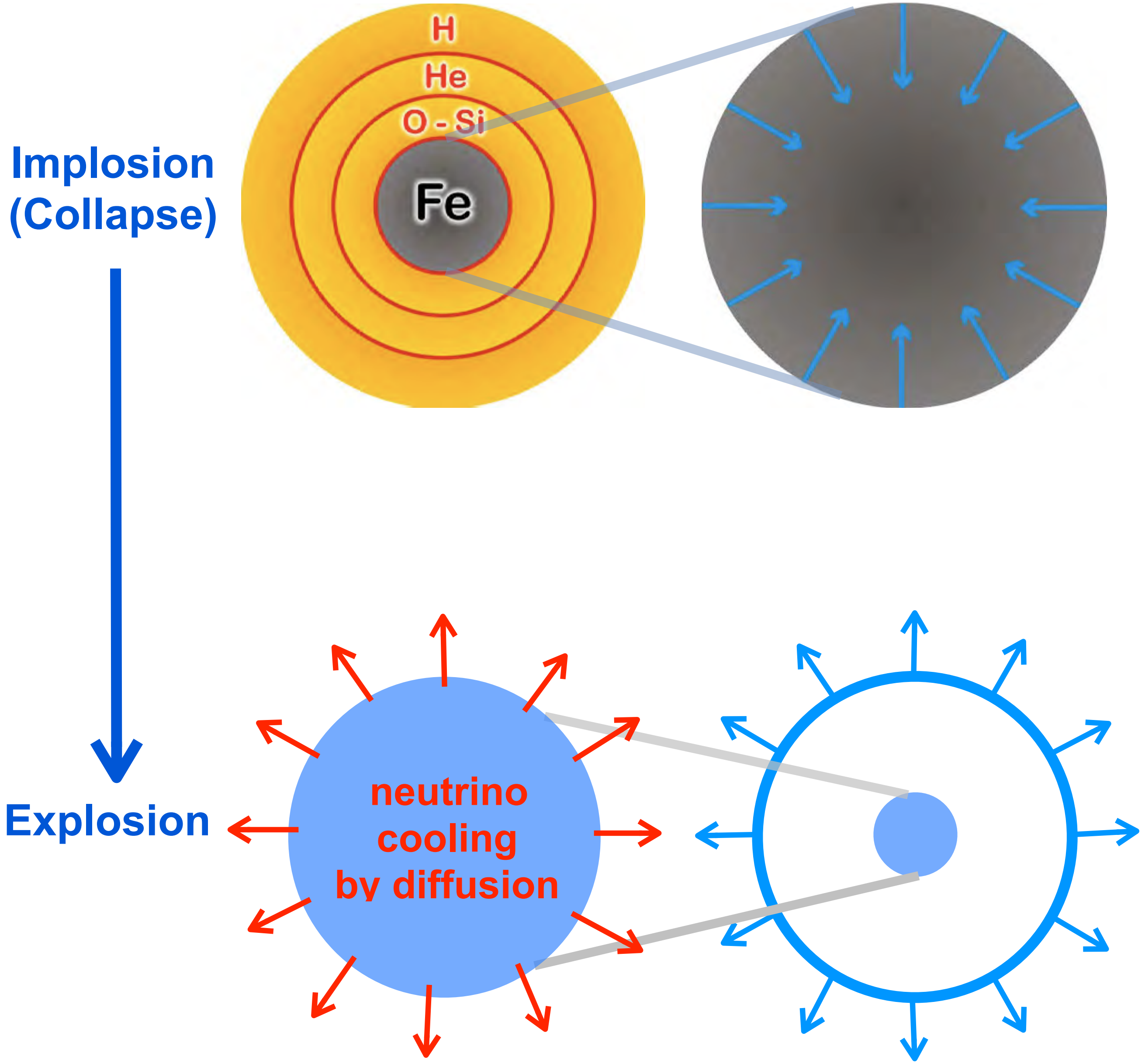
CoCoNuT Meeting 2017
Garching, October 26, 2017

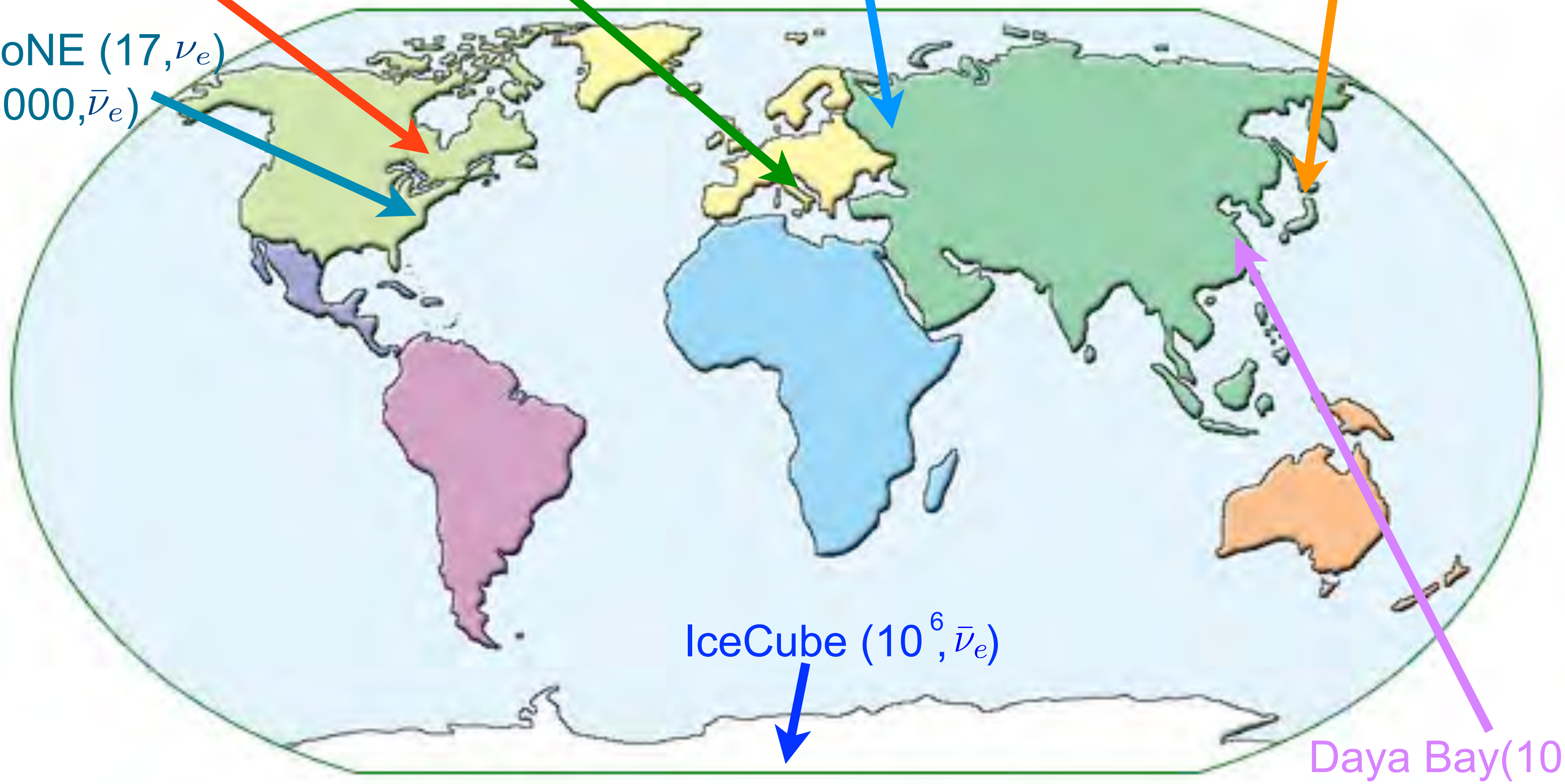
Core-Collapse Supernova Explosion



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

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

Existing Detectors



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 (7x10^{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.

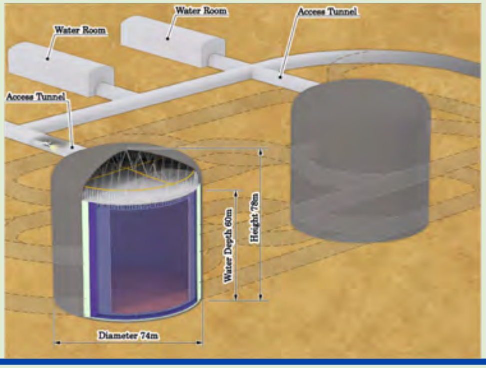
Fundamental to combine the supernova signal from detectors employing different technologies.

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

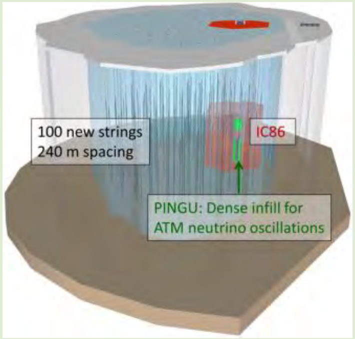
Next Generation Large Scale Detectors

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

Hyper-Kamiokande (10^5)

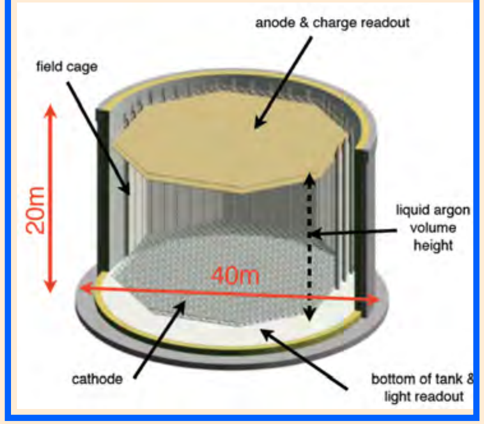


IceCube-Gen2 (10^6)



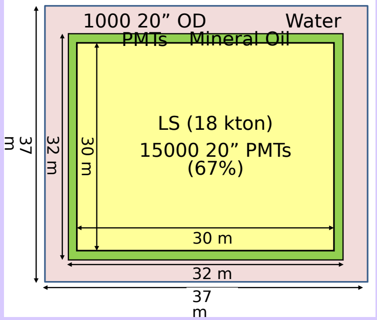
Liquid Argon detectors (ν_e)

DUNE (3000)

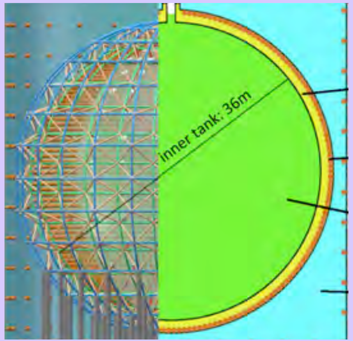


Scintillation detectors ($\bar{\nu}_e$)

RENO-50 (5400)



JUNO (6000)

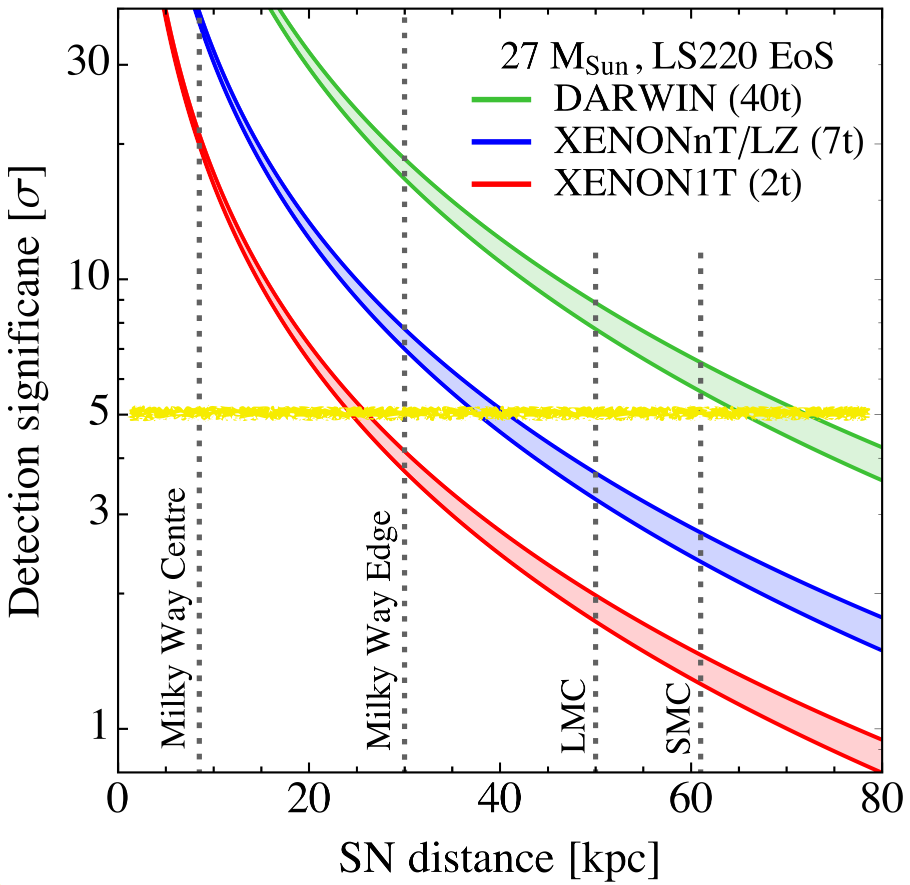


Expected number of events for a SN at 10 kpc and dominant flavor sensitivity in parenthesis.

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

Xenon Dark Matter Detector: Nu Telescope

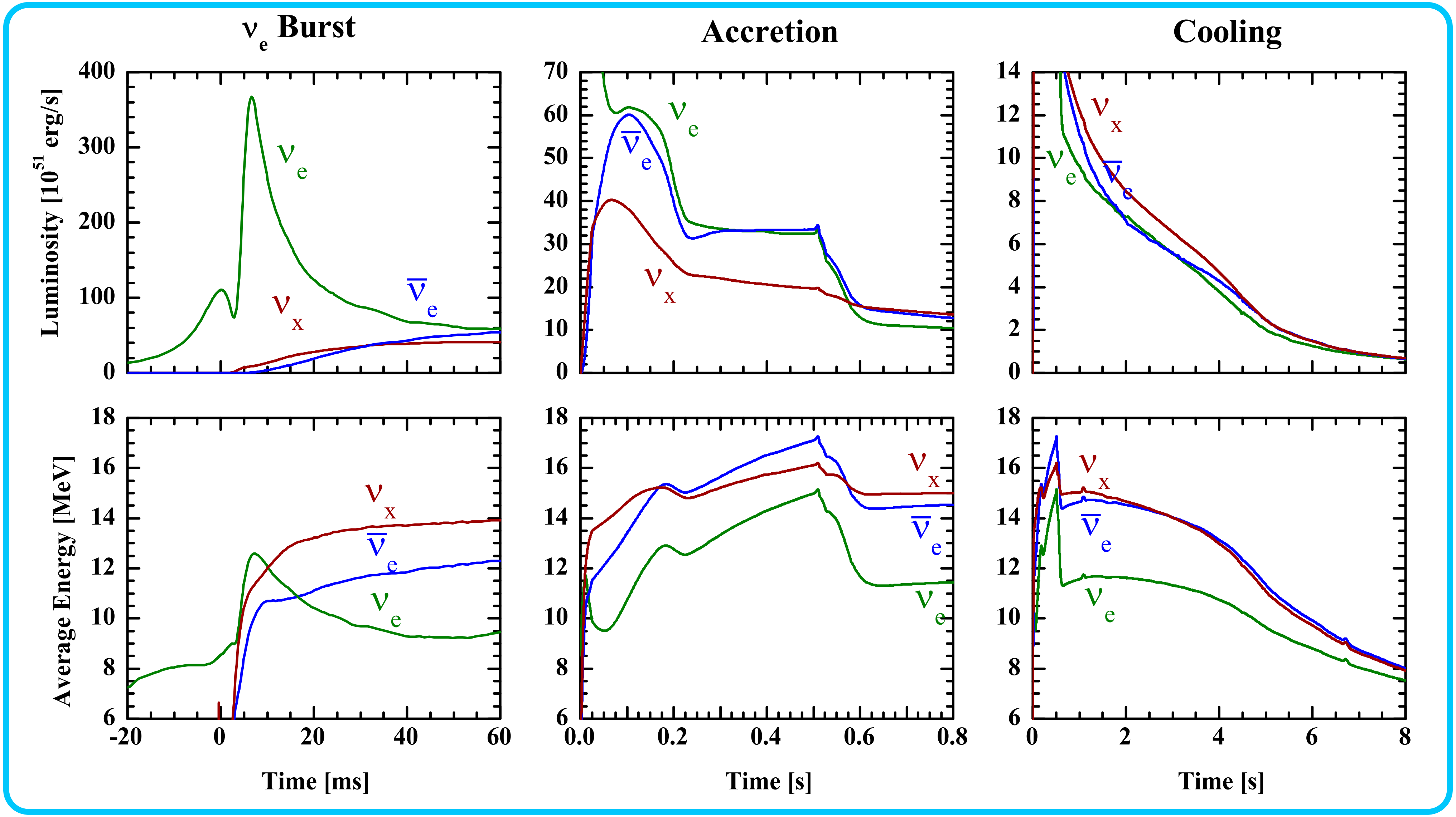
DARWIN, 700 events ($\nu_{e,x}\,, \bar{\nu}_{e,x}$)



- 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.

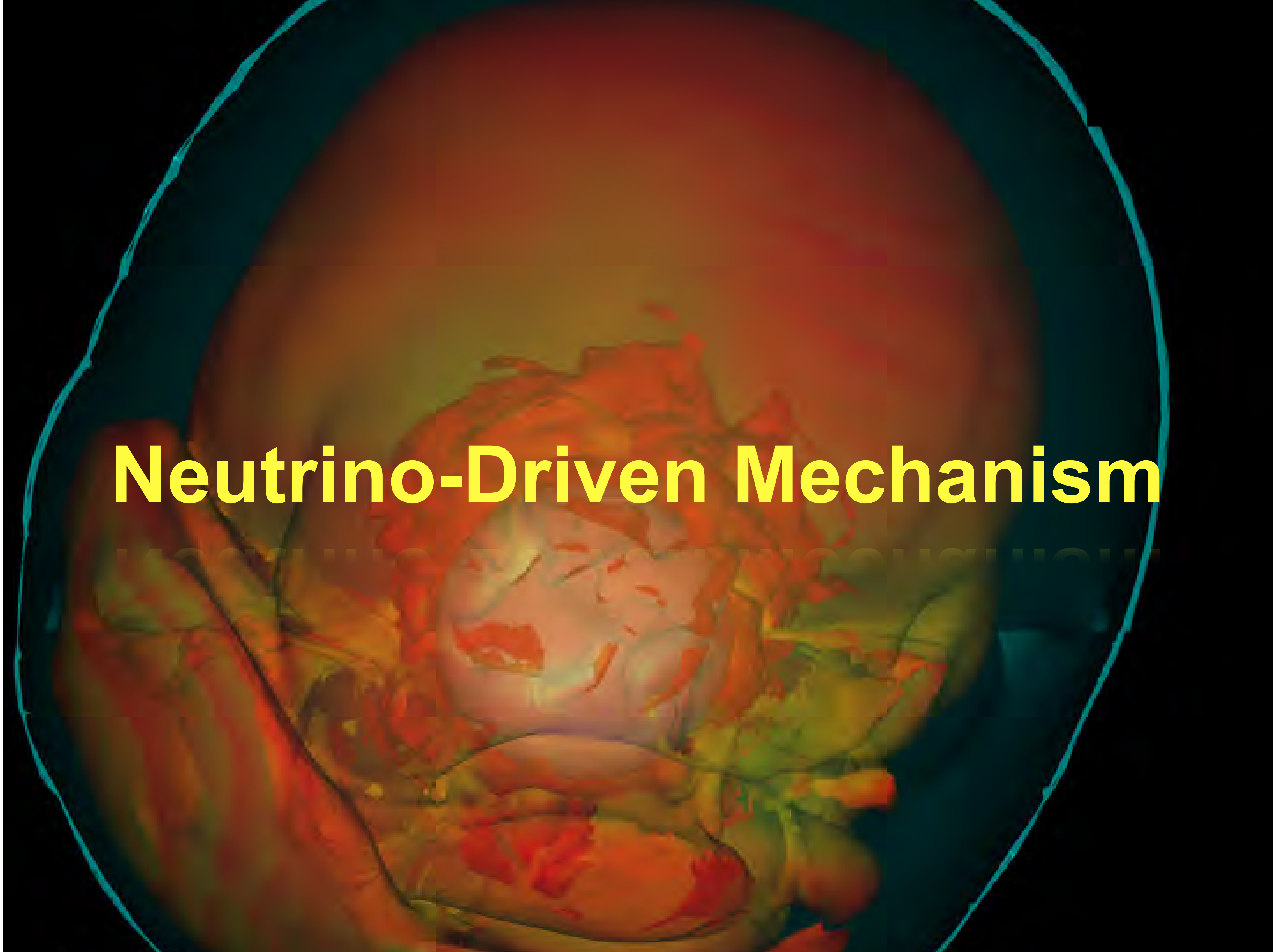
Lang, McCabe, Reichard, Selvi, Tamborra, PRD (2016). Horowitz et al. PRD (2003). Drukier and Stodolsky, PRD (1984).

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.



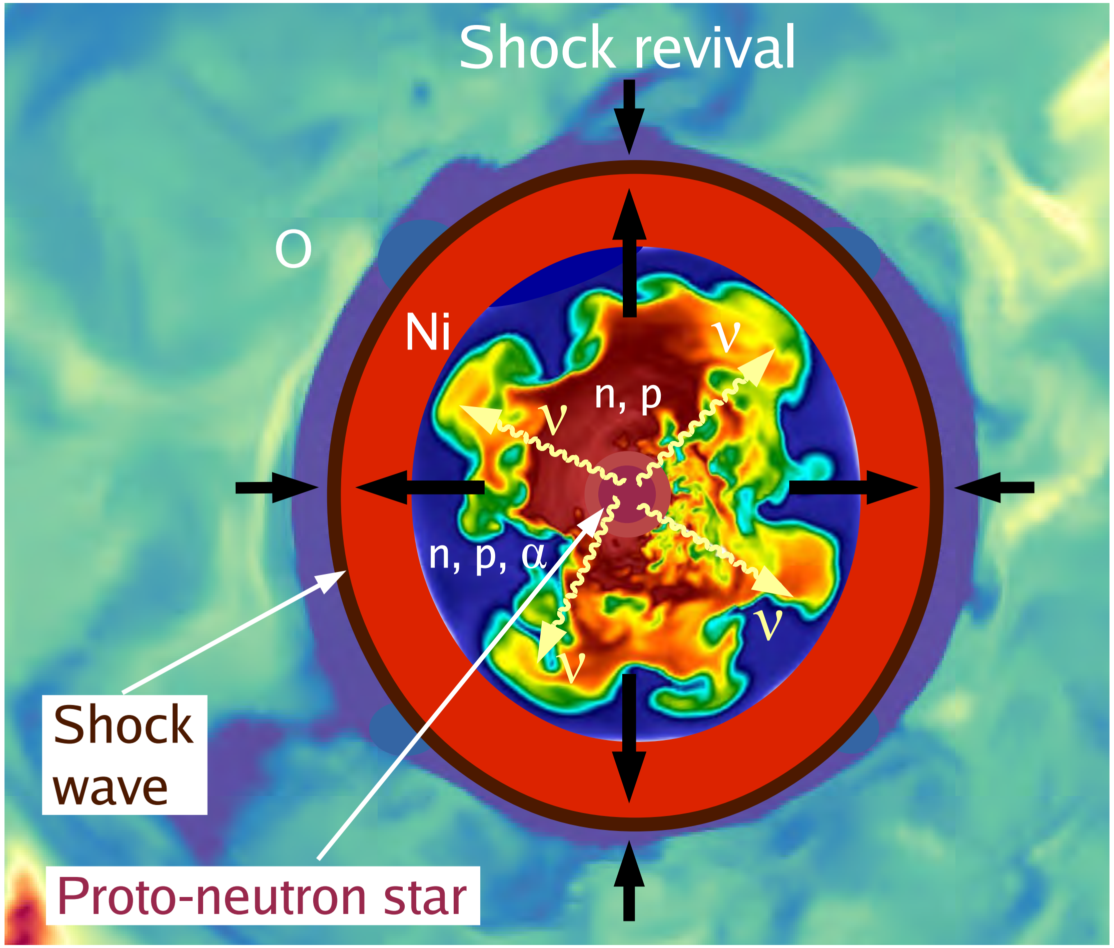
Neutrino-Driven Mechanism

Delayed Neutrino-Driven Explosion

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

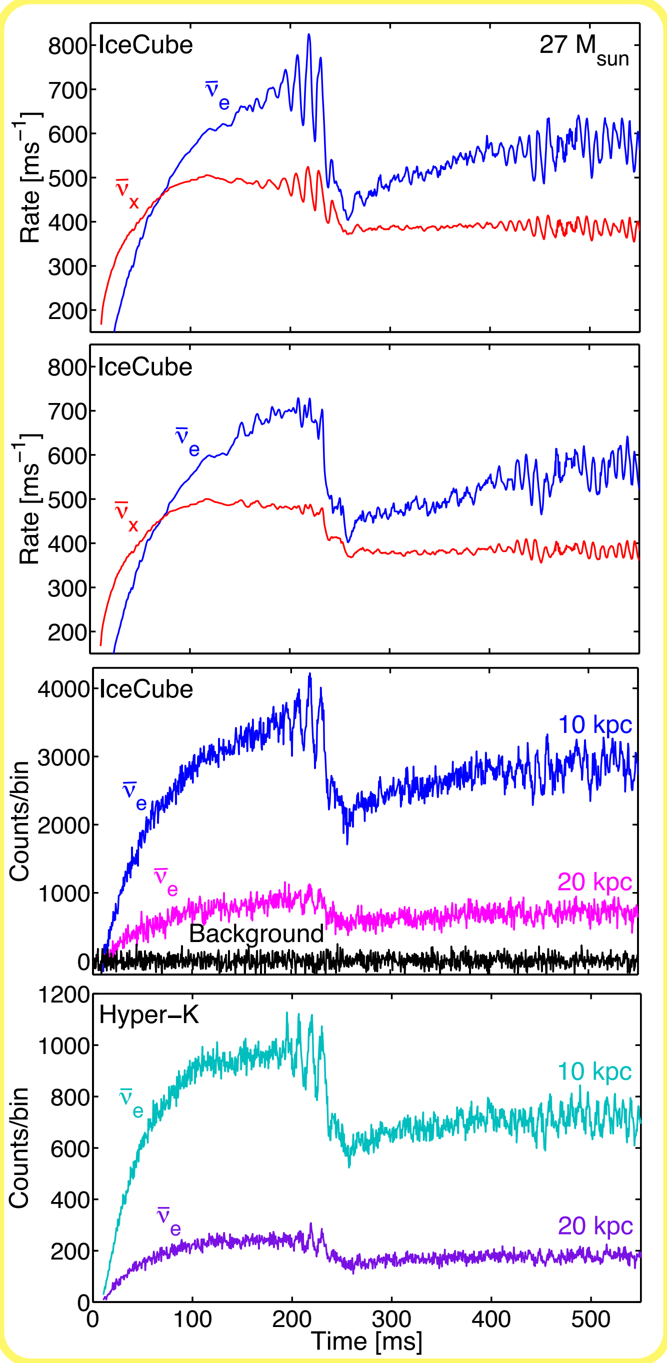
- **Neutrinos** provide energy to stalled shock wave to start re-expansion.

- **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).

SASI Detection Perspectives (27 M_{sun})



Strong signal modulation
(optimistic observer direction)

Weak signal modulation
(pessimistic observer direction)

Expected rate above IceCube background

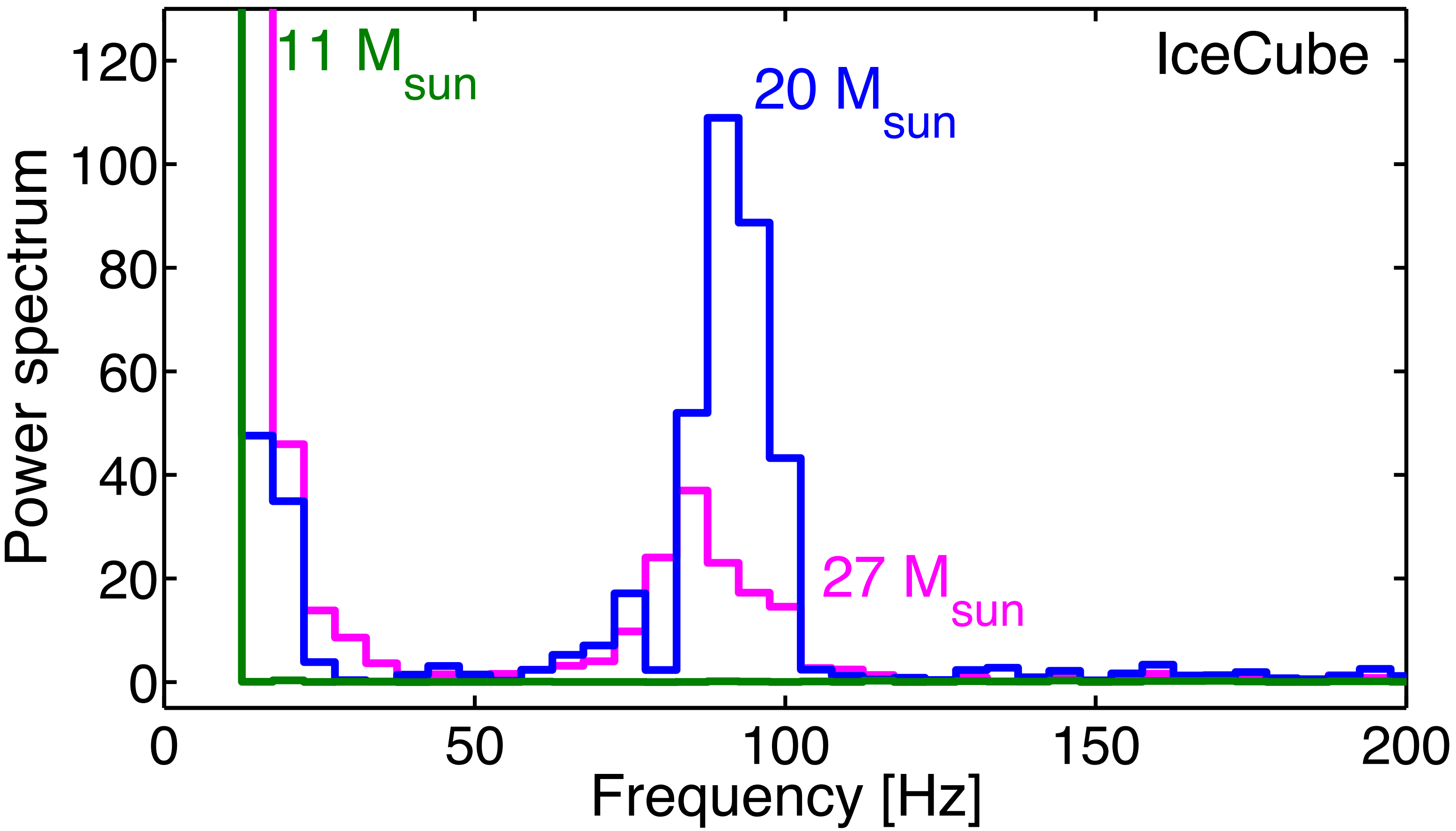
Hyper-K rate = 1/3 IceCube rate

SASI still detectable

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

Power Spectrum of the Event Rate

Power spectrum of the IceCube event rate in [100,300] ms

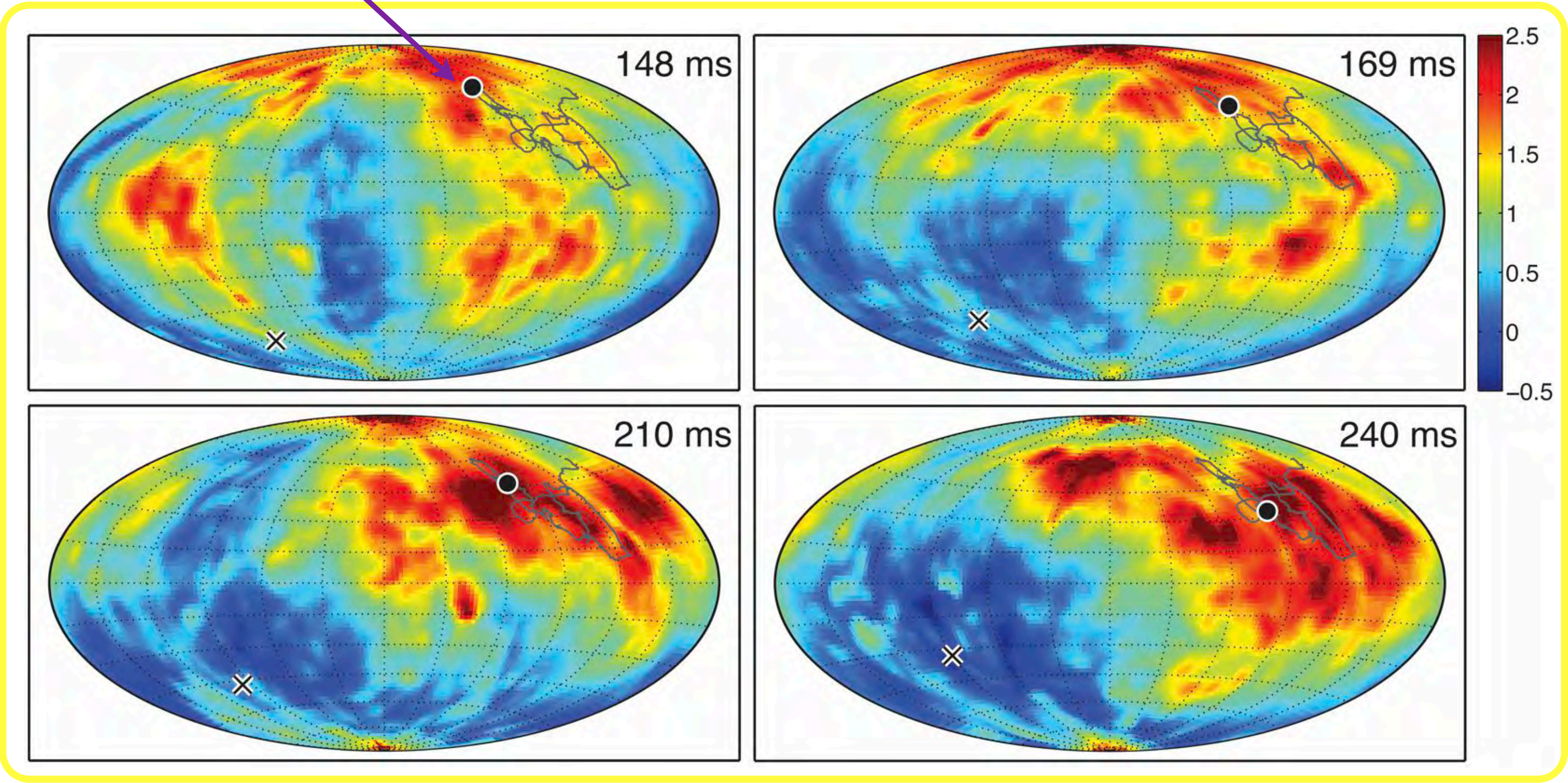


A peak appears at the SASI frequency of ~ 80 Hz for the 20 and 27 M_{sun} SN progenitors.

Tamborra, Hanke, Mueller, Janka, Raffelt, PRL (2013).

LESA Instability

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


positive dipole direction

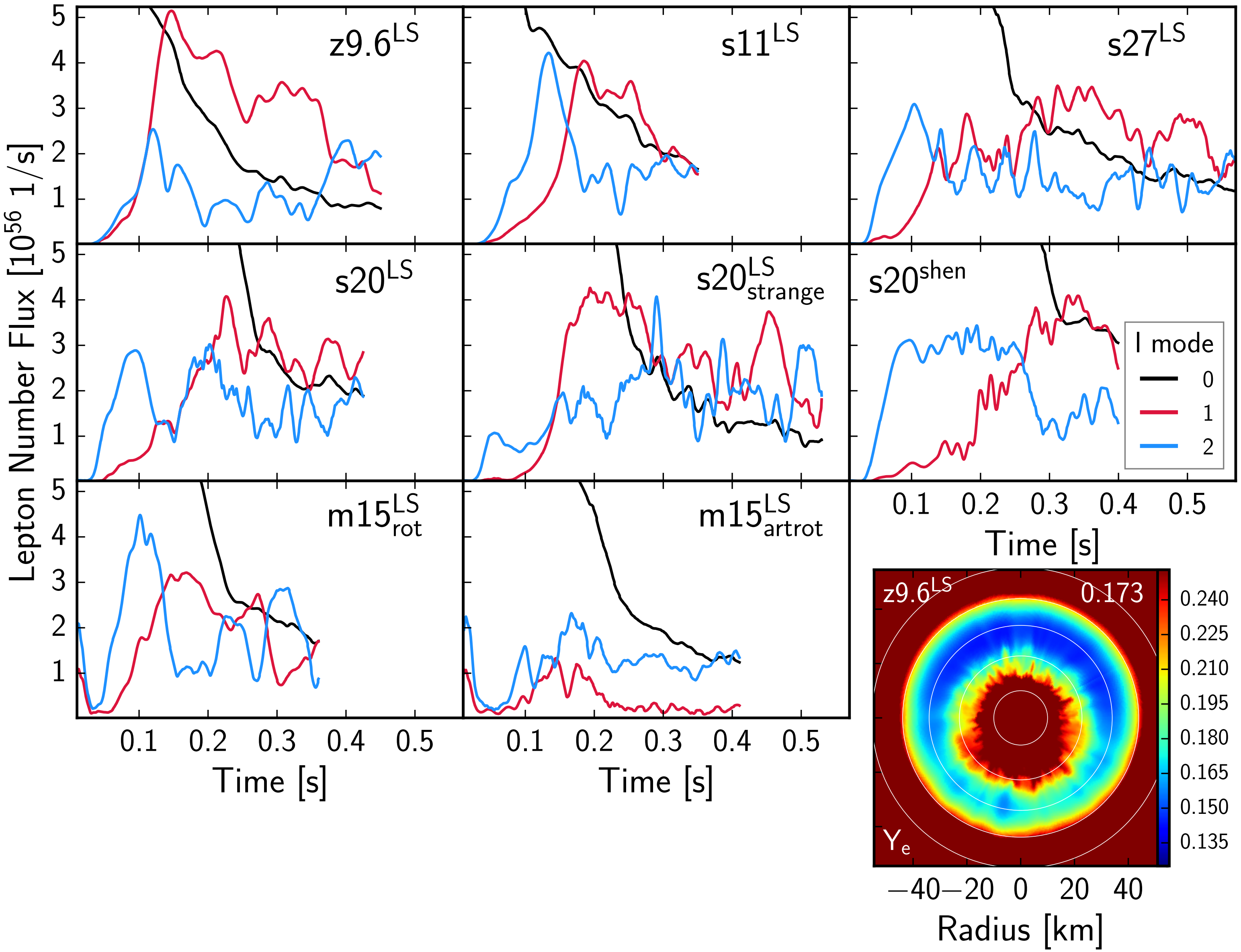
Lepton-number emission asymmetry (**LESA**) is a large-scale feature with **dipole character**.

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, ARNPS (2016).

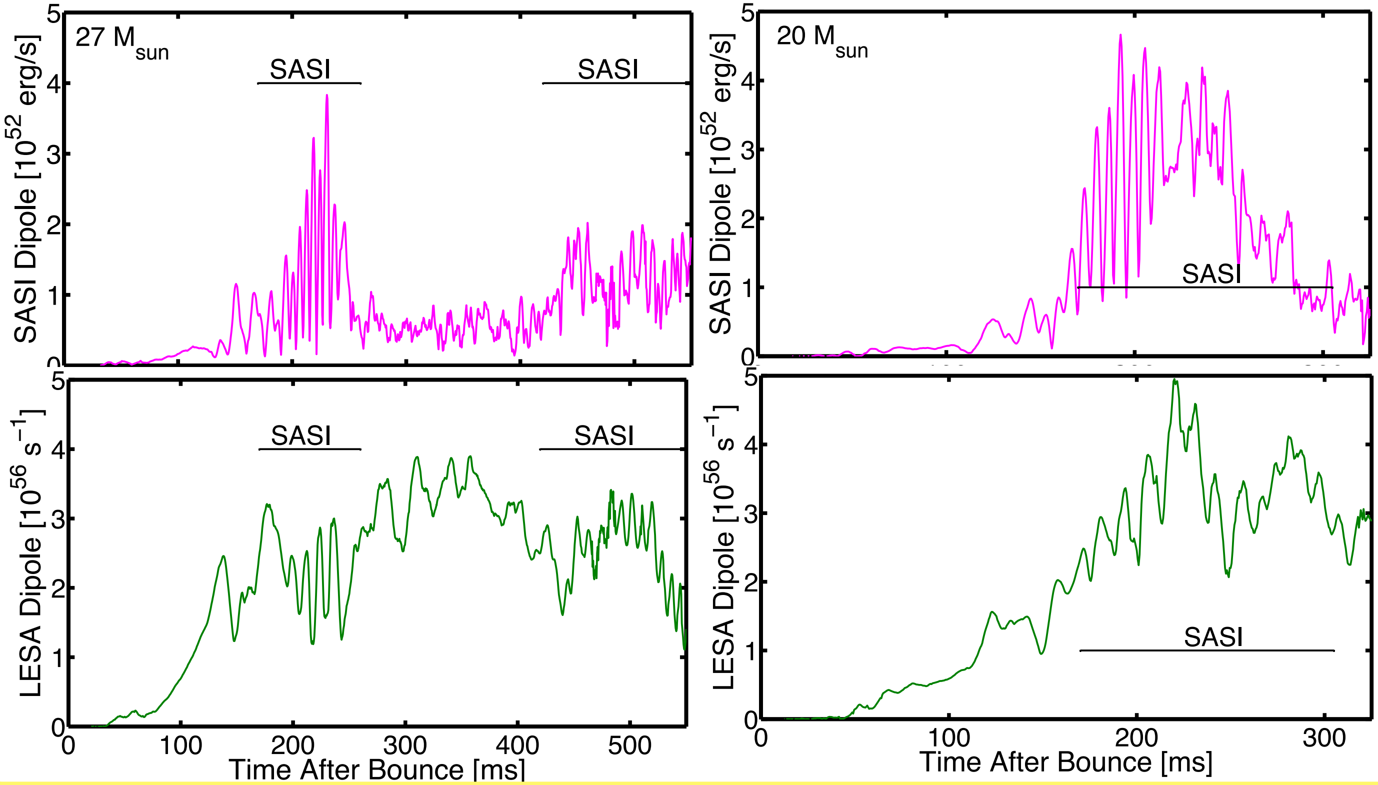
Lepton Number Flux Evolution

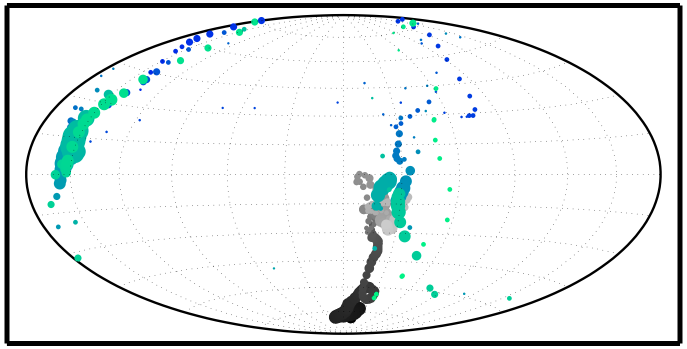
Monopole, dipole and quadrupole of the lepton number flux



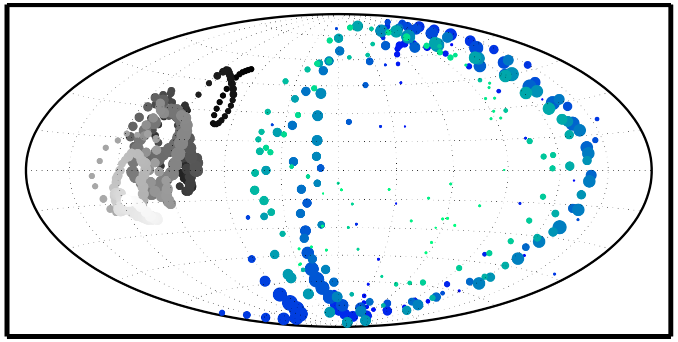
Janka, Melson, Summa, ARNPS (2016). Tamborra, Hanke, Janka, Mueller, Raffelt, Marek, ApJ (2014).

LESA-SASI Interference





LESA dipole close to SASI plane



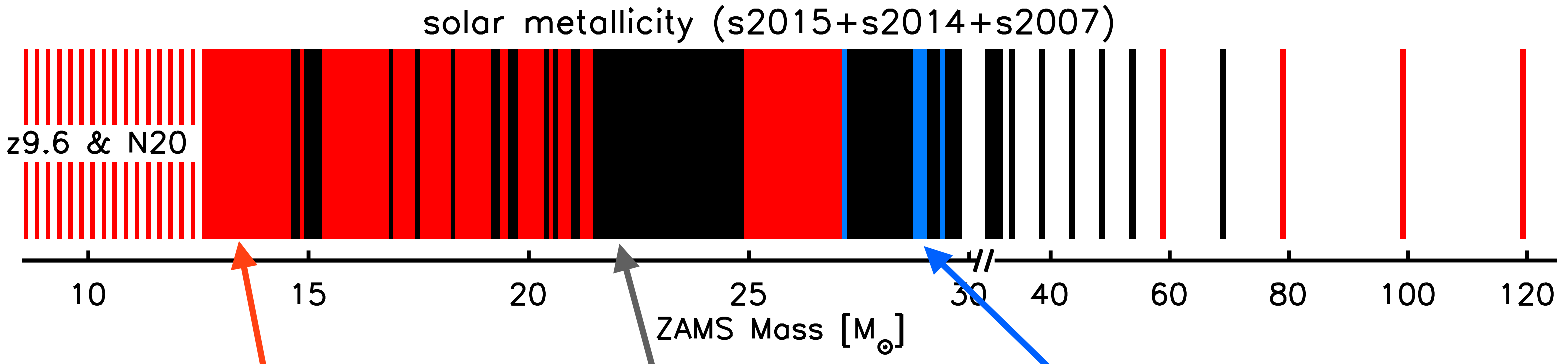
LESA dipole perp. to SASI plane

No clear correlation between LESA and SASI.

Interplay dependent on relative orientations of SASI plane and LESA dipole.

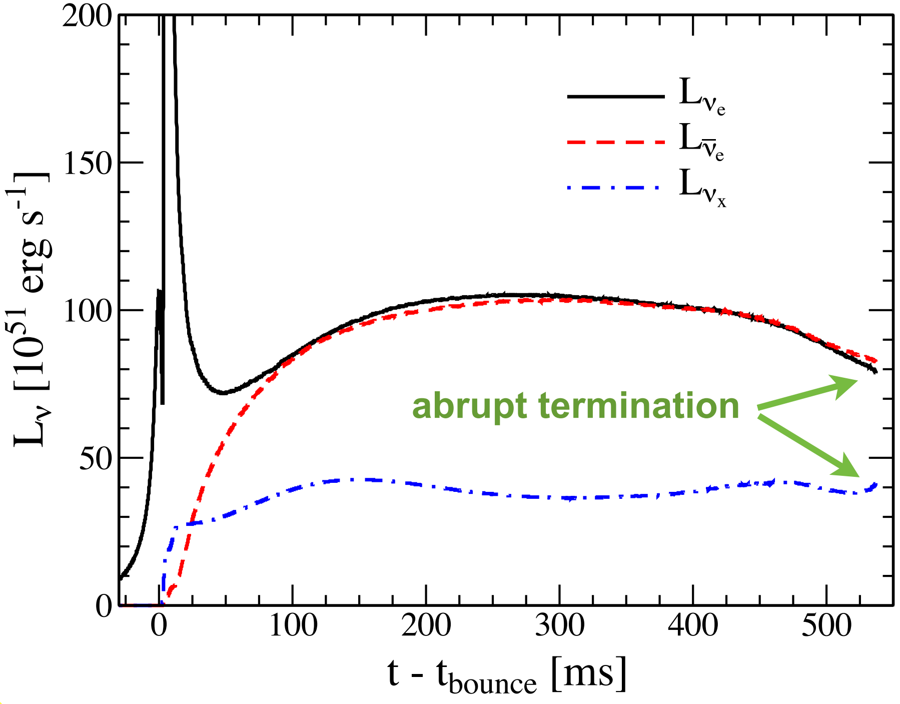
Tamborra et al., ApJ (2014). Tamborra et al., PRD (2014).

Black-Hole Forming Supernovae



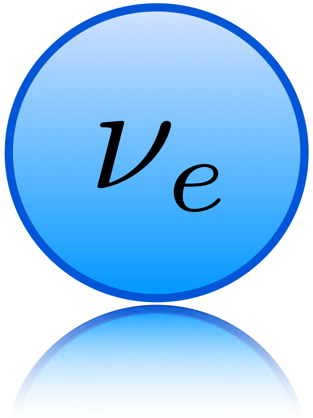
Successful Explosions **Failed explosions** **Fallback SNe**

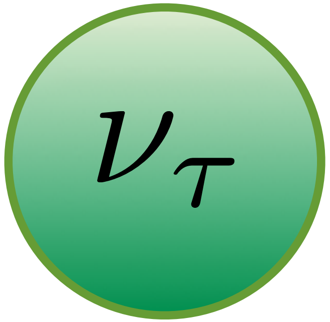
BH-forming Supernova (40 M_{sun})



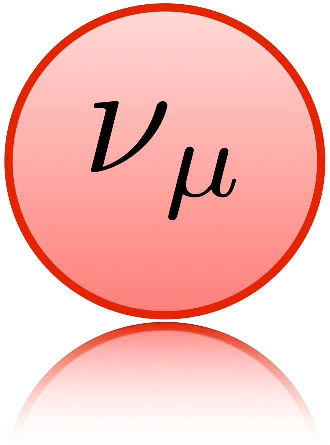
Neutrinos reveal black-hole formation.

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



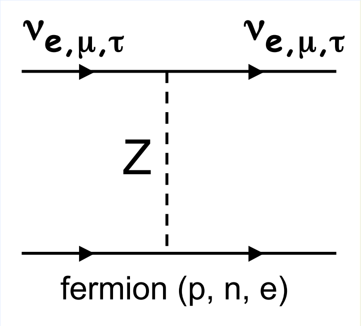


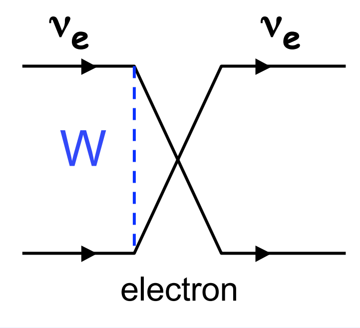
Flavor Evolution in Supernovae



Neutrino Interactions

Understood phenomenon.

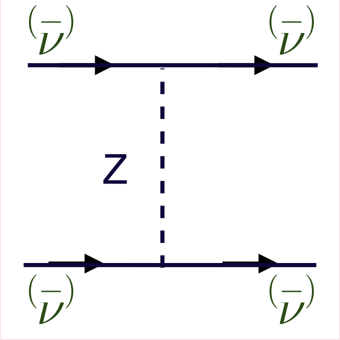




Neutrinos interact with neutrons, protons and electrons.

Wolfenstein, PRD 17 (1978) 2369

We still need to learn a lot!



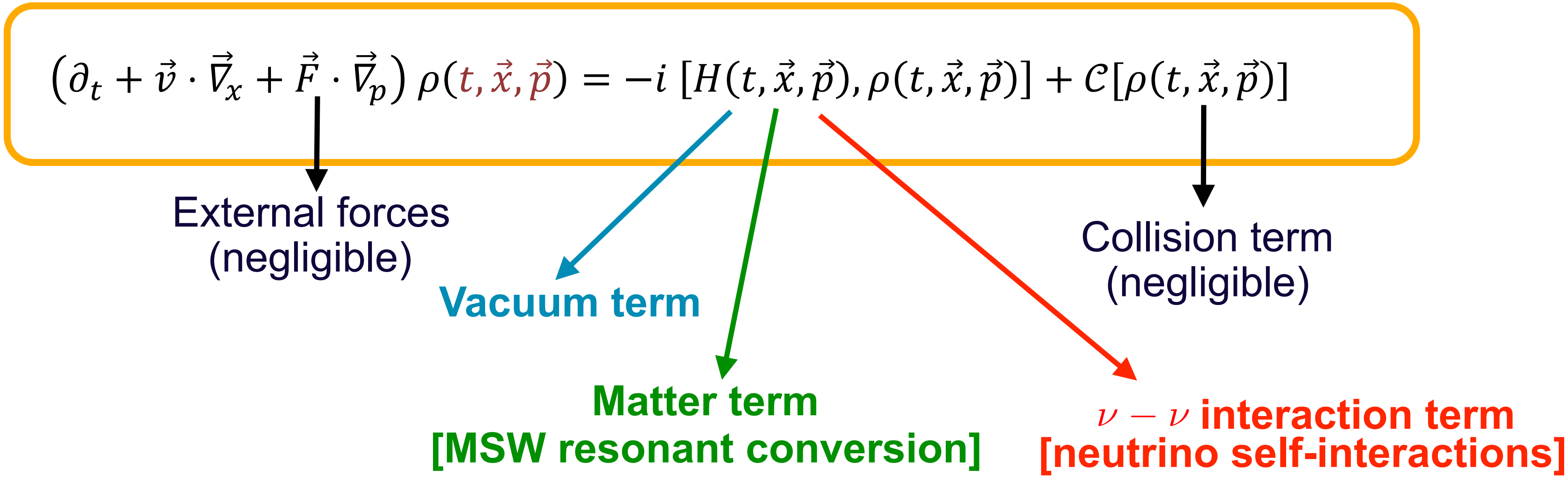
$\nu - \nu$ interactions

Non-linear phenomenon

Pantaleone, PLB 287 (1992) 128

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]

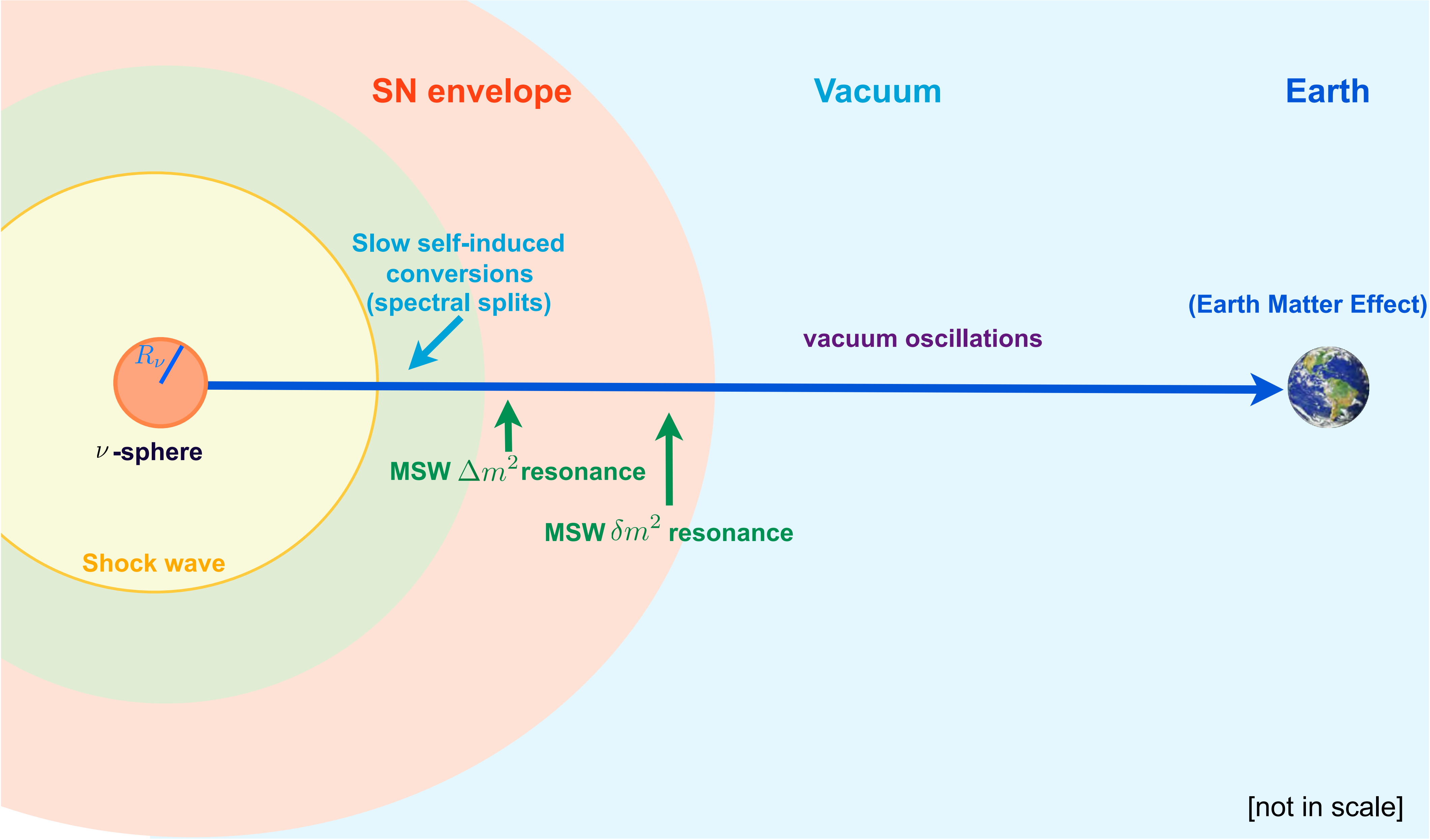
$\nu - \nu$ **interaction term**
[neutrino self-interactions]

Collision term
(negligible)

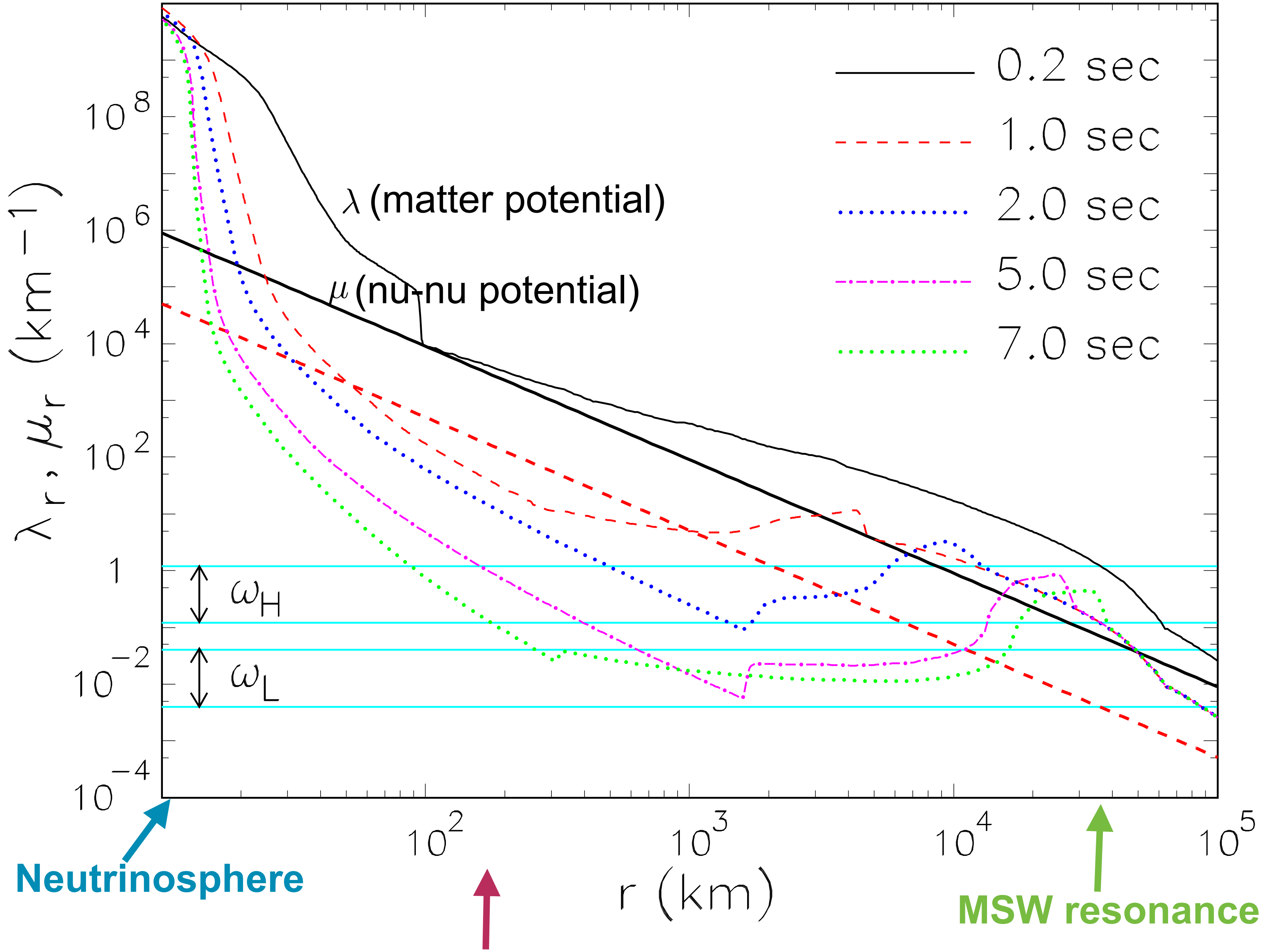
Challenging problem:

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

Simplified Picture of Flavor Conversions



Nu-Nu and Matter Potentials

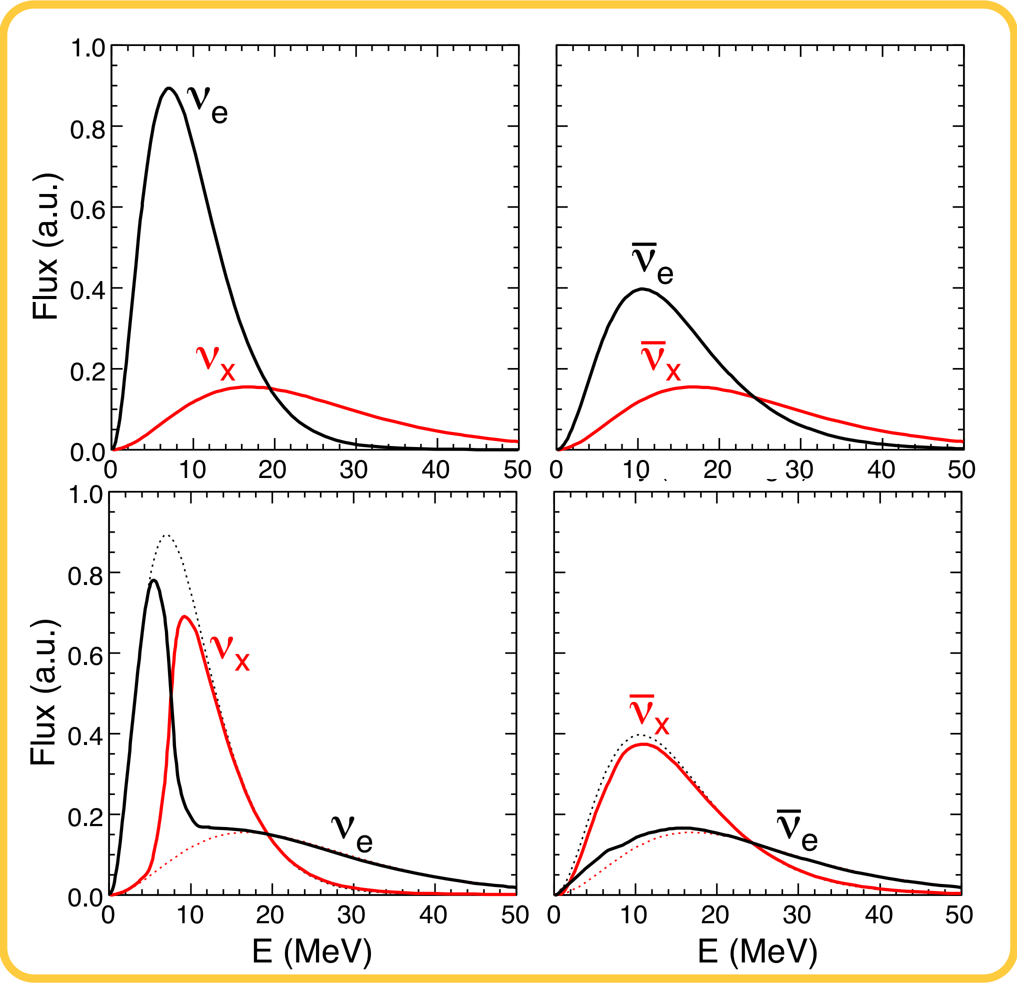


Neutrinosphere

Nu-nu interactions relevant

MSW resonances

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.

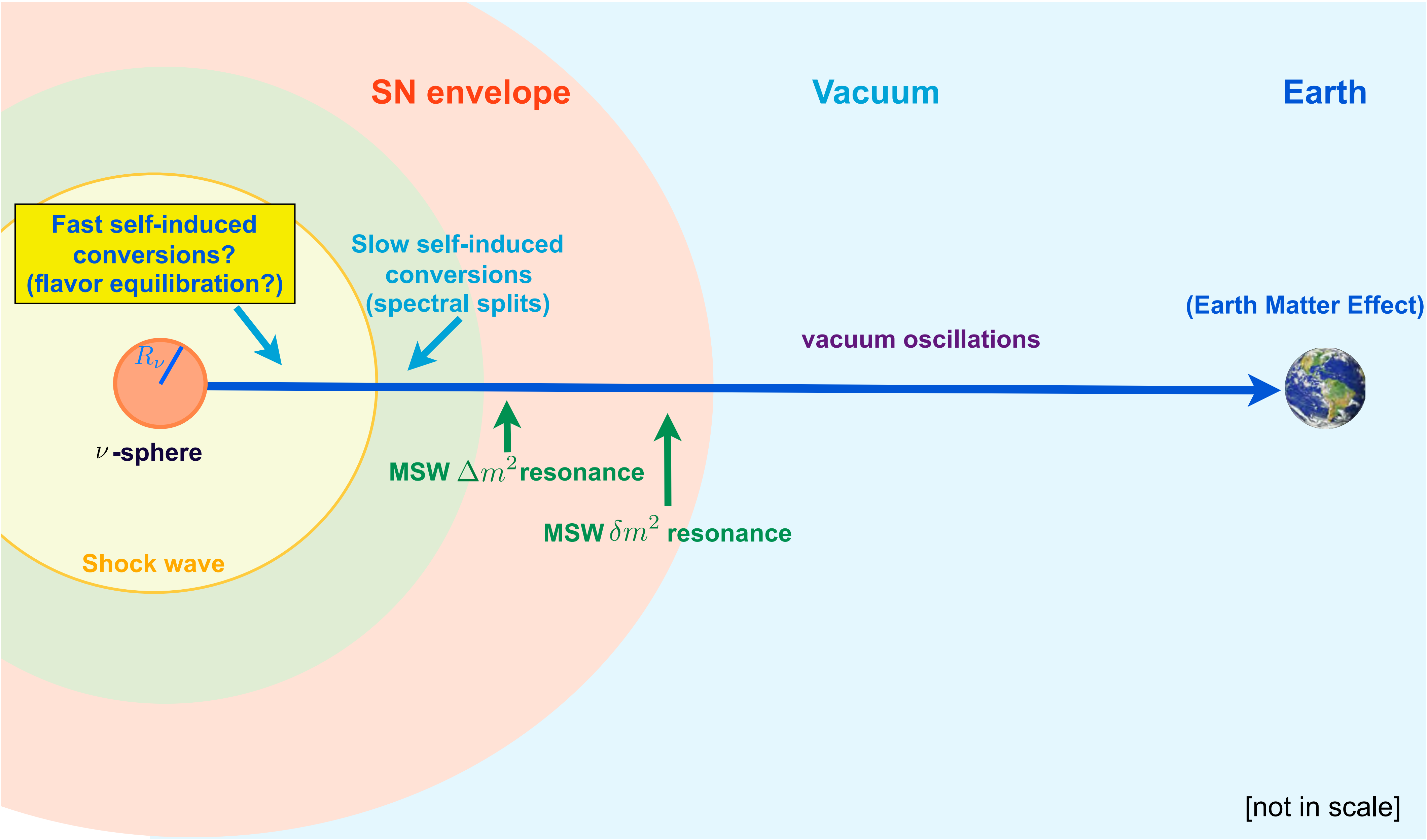
Fogli, Lisi, Marrone, Mirizzi, JCAP (2007), Fogli, Lisi, Marrone, Mirizzi, Tamborra, PRD (2008). Raffelt and Smirnov, PRD (2007), PRD (2007). Duan et al., PRD (2007). Hannestad, Raffelt, Sigl, Wong, PRD (2006).

Real SN is Space-Time Dependent

Spontaneous symmetry breaking may occur when releasing symmetry assumptions.
Caveats: Studies only within 1D/2D toy-models. Numerical implementation very challenging.

- 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)].

Simplified Picture of Flavor Conversions



SN envelope

Vacuum

Earth

Fast self-induced conversions? (flavor equilibration?)

Slow self-induced conversions (spectral splits)

(Earth Matter Effect)

vacuum oscillations

R_ν

ν -sphere

MSW Δm^2 resonance

MSW δm^2 resonance

Shock wave

[not in scale]

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:
$$\begin{gathered} \nu_e(p) + \bar\nu_e(k) \to \nu_\mu(p) + \bar\nu_\mu(k) \\ \nu_e(p) + \nu_\mu(k) \to \nu_\mu(p) + \nu_e(k) \end{gathered}$$

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).

PRL **118,** 021101 (2017) PHYSICAL REVIEW LETTERS week ending 13 JANUARY 2017

Fast Pairwise Conversion of Supernova Neutrinos: A Dispersion Relation Approach

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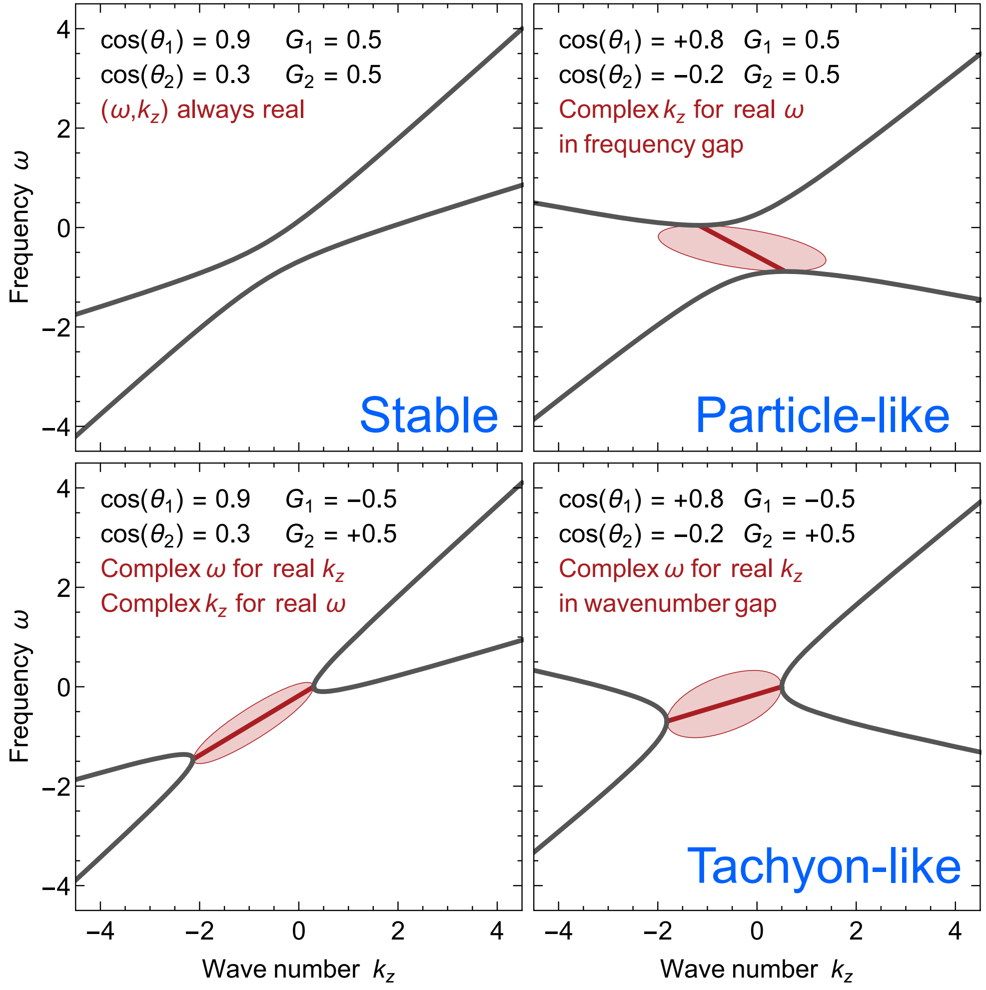
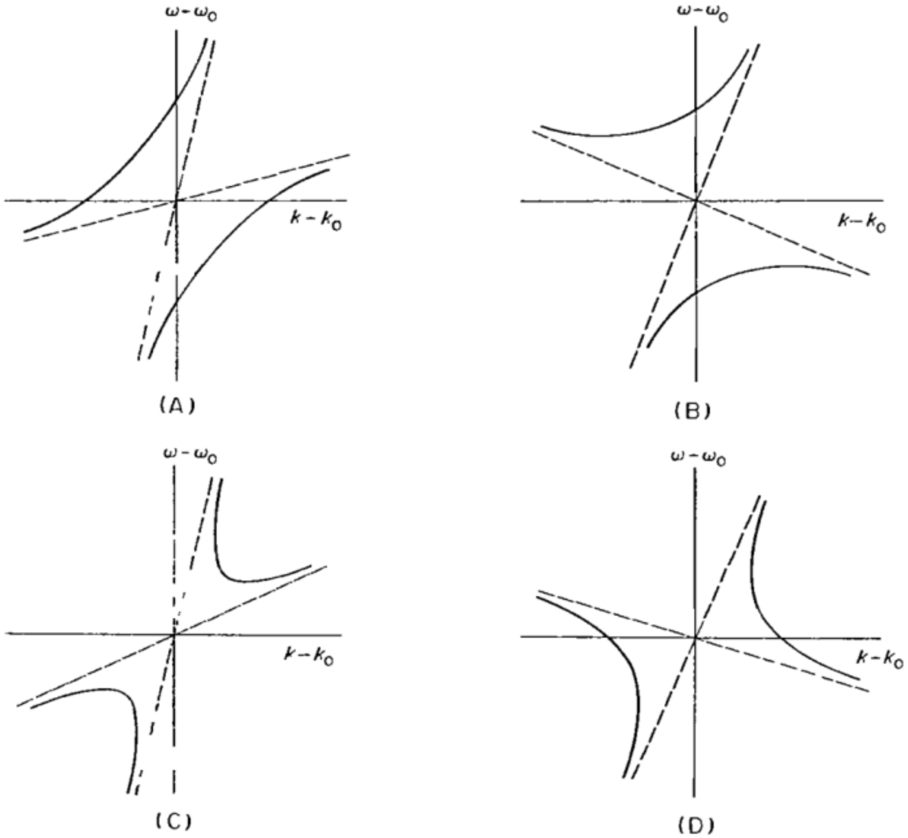
Instabilities of “flavor waves”



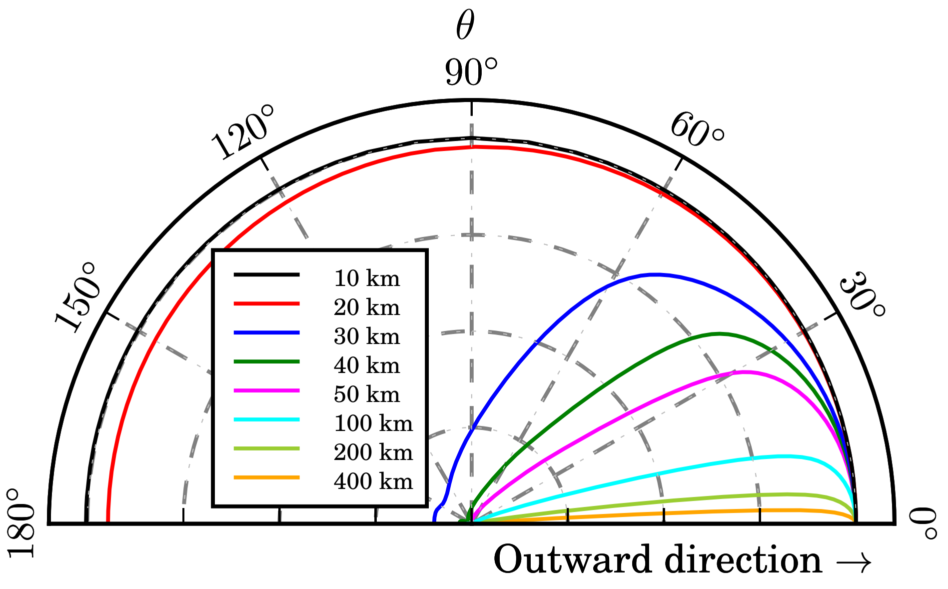
Instabilities of “plasma waves”

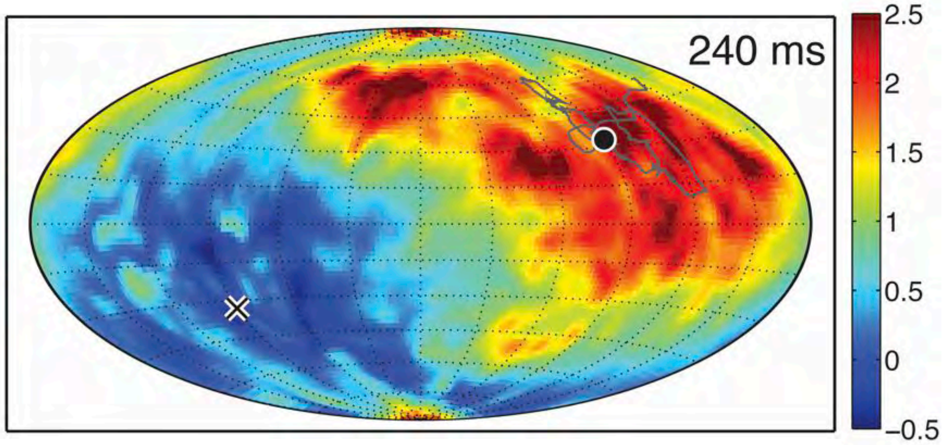


[Landau&Lifshitz, Vol. 10, Physical Kinetics, Chapter VI, Instability Theory]

Izaguirre, Raffelt, Tamborra, PRL (2017). See also Capozzi et al., PRD (2017).

Fast Pairwise Neutrino Conversions





Non-negligible inward neutrino flux may induce fast conversions.

LESA may induce fast conversions.

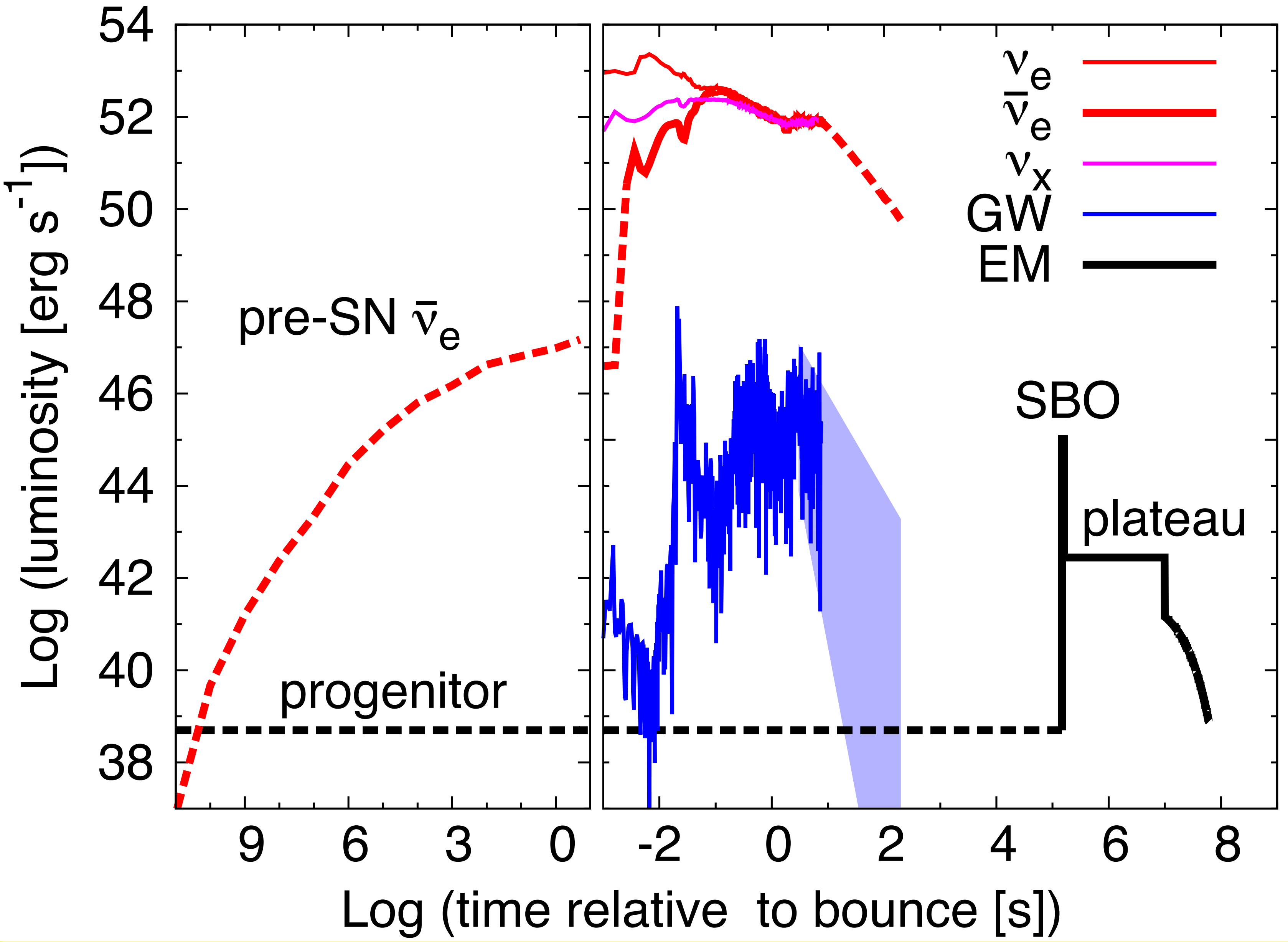
Flavor equipartition might occur close to neutrino decoupling region. Explosion affected?

Existing investigations are simplified case studies. Further work needed.

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

What Can We Learn From a SN Burst?

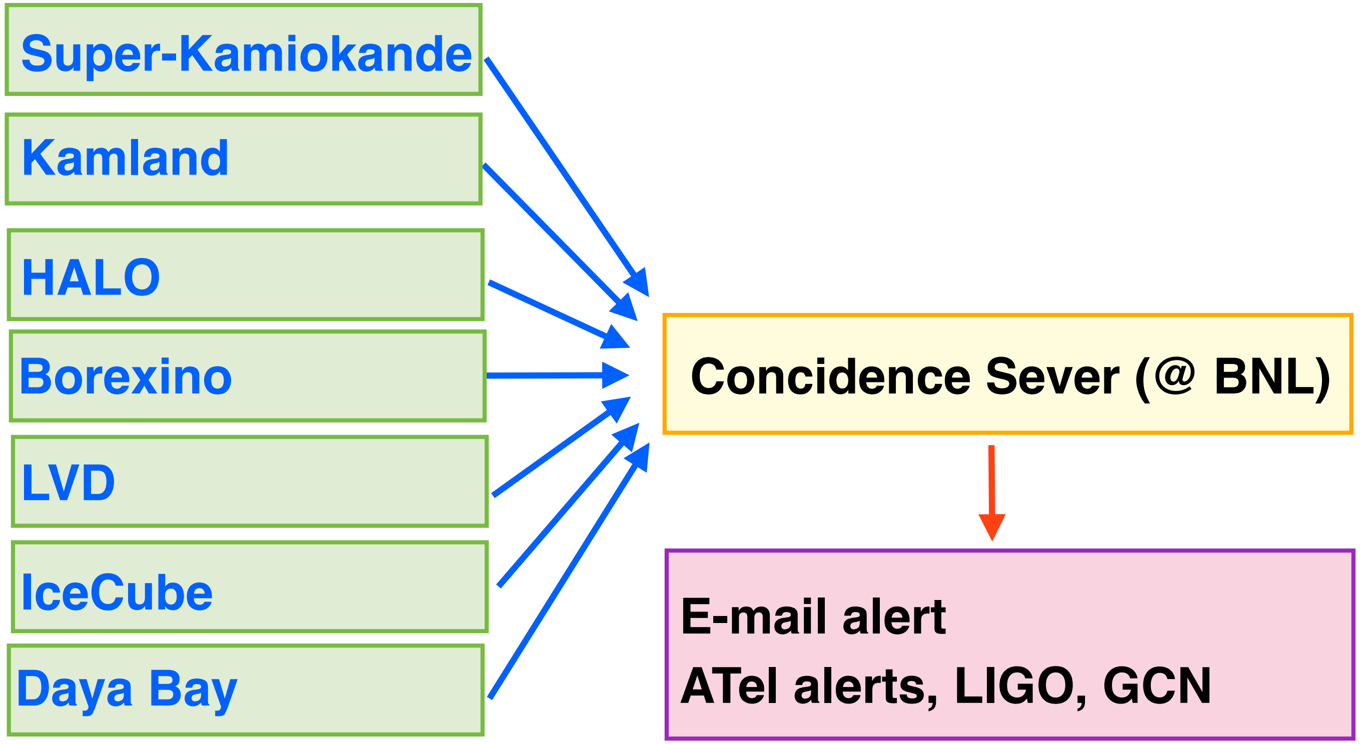
A Multi-Messenger Riddle



Nakamura et al., MNRAS (2016).

Neutrinos Tell Us When To Look

SuperNova Early Warning System (SNEWS)



Super-Kamiokande

Kamland

HALO

Borexino

LVD

IceCube

Daya Bay

Concidence Sever (@ BNL)

E-mail alert
ATel alerts, LIGO, GCN

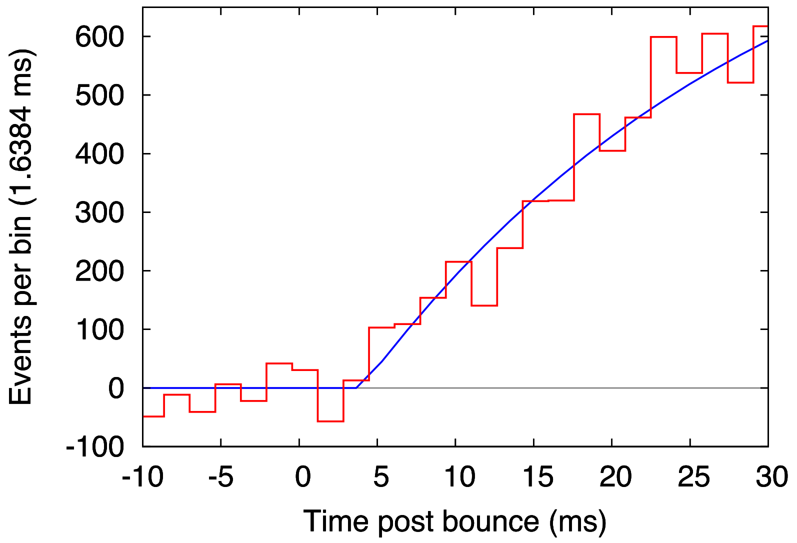
- Shock break out arrives mins to hours after neutrino signal.

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.

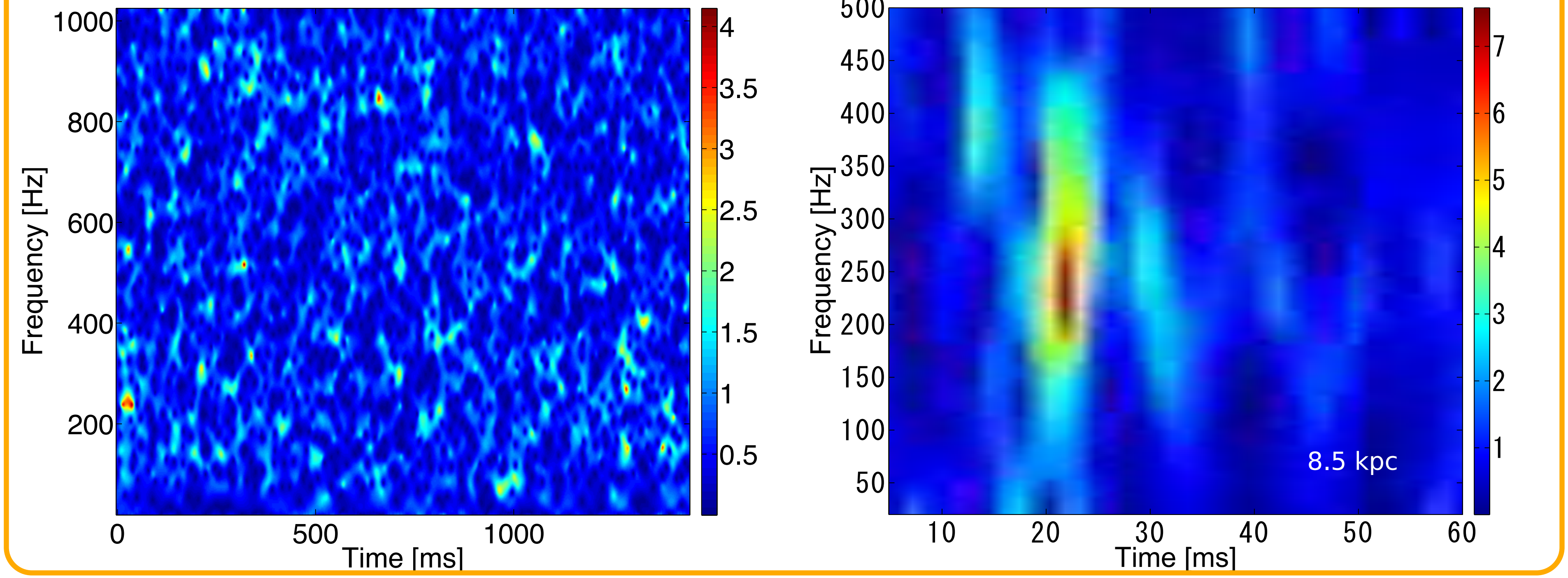
http://snews.bnl.gov. Adams et al., ApJ (2013).

Neutrinos Tell Us When To Look



Probe core bounce time with neutrinos.

Help timing for gravitational wave detection.

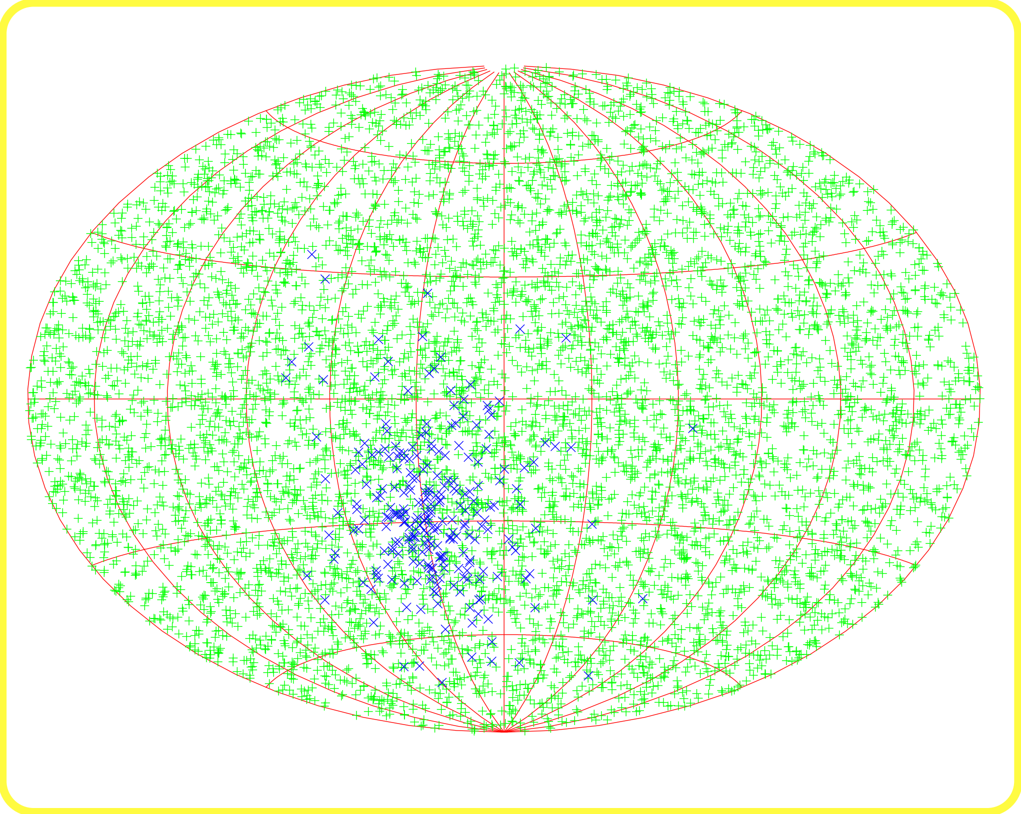


Without neutrino timing (S/N~3.5)

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



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

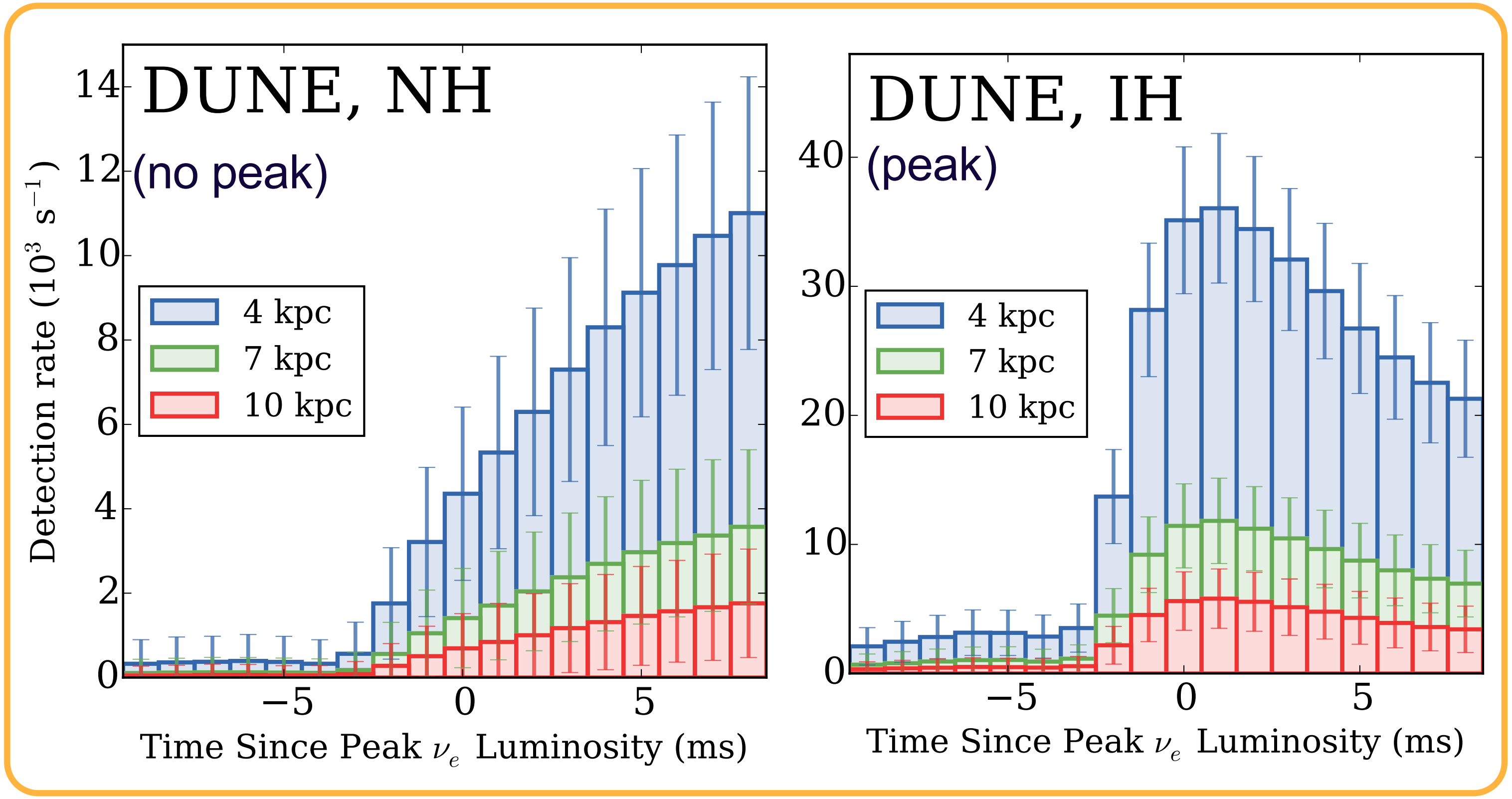
	Super-K	Hyper-K
water	6 deg	1.4 deg
water+Gd	3 deg	0.6 deg

- 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).

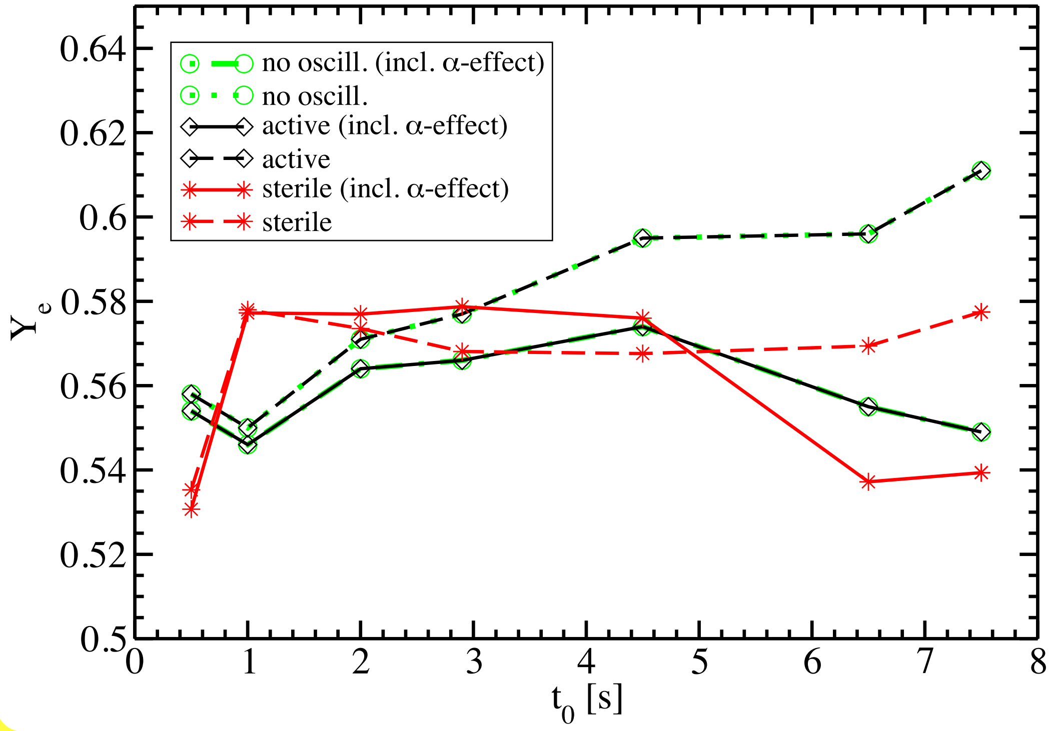
Neutrinos Affect Element Production

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

Flavor oscillations affect element production mainly via

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

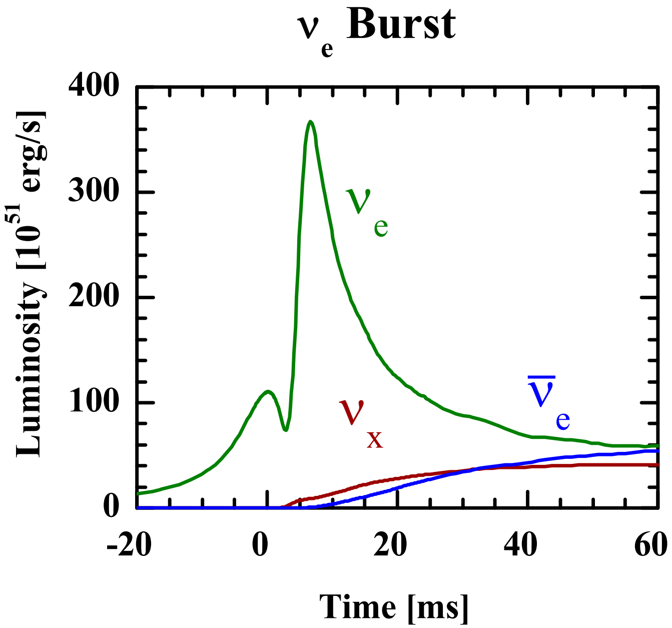
Coupling of oscillation physics to nucleosynthesis networks recently begun.

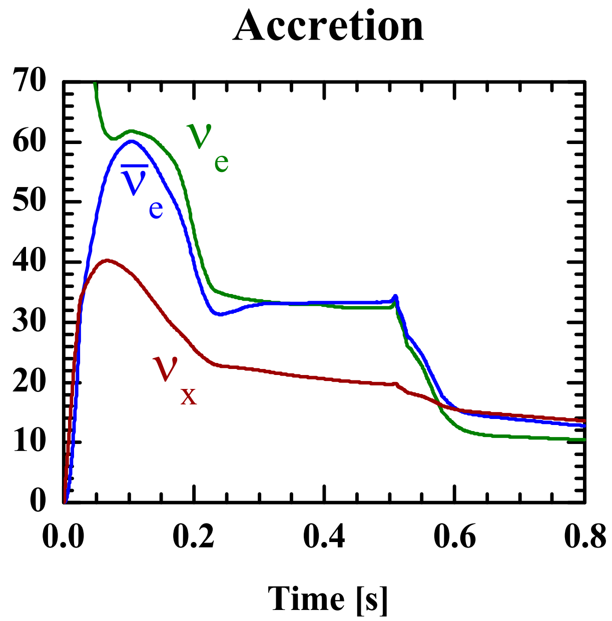


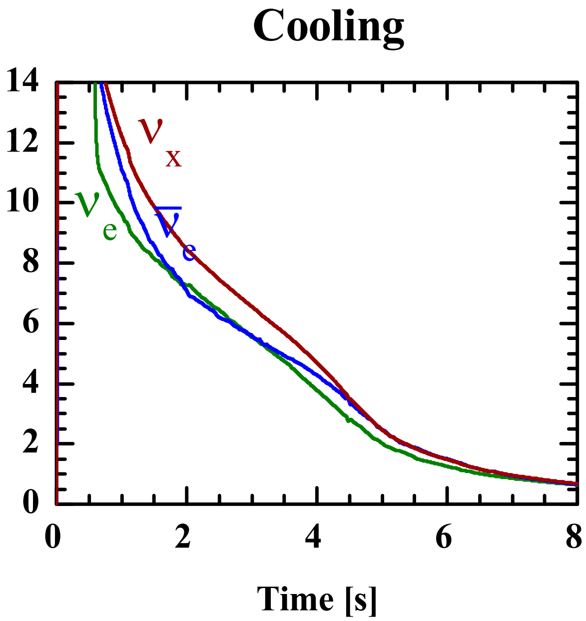
Recent work suggests unlikely r-process conditions in SNe, but further work needed.

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.

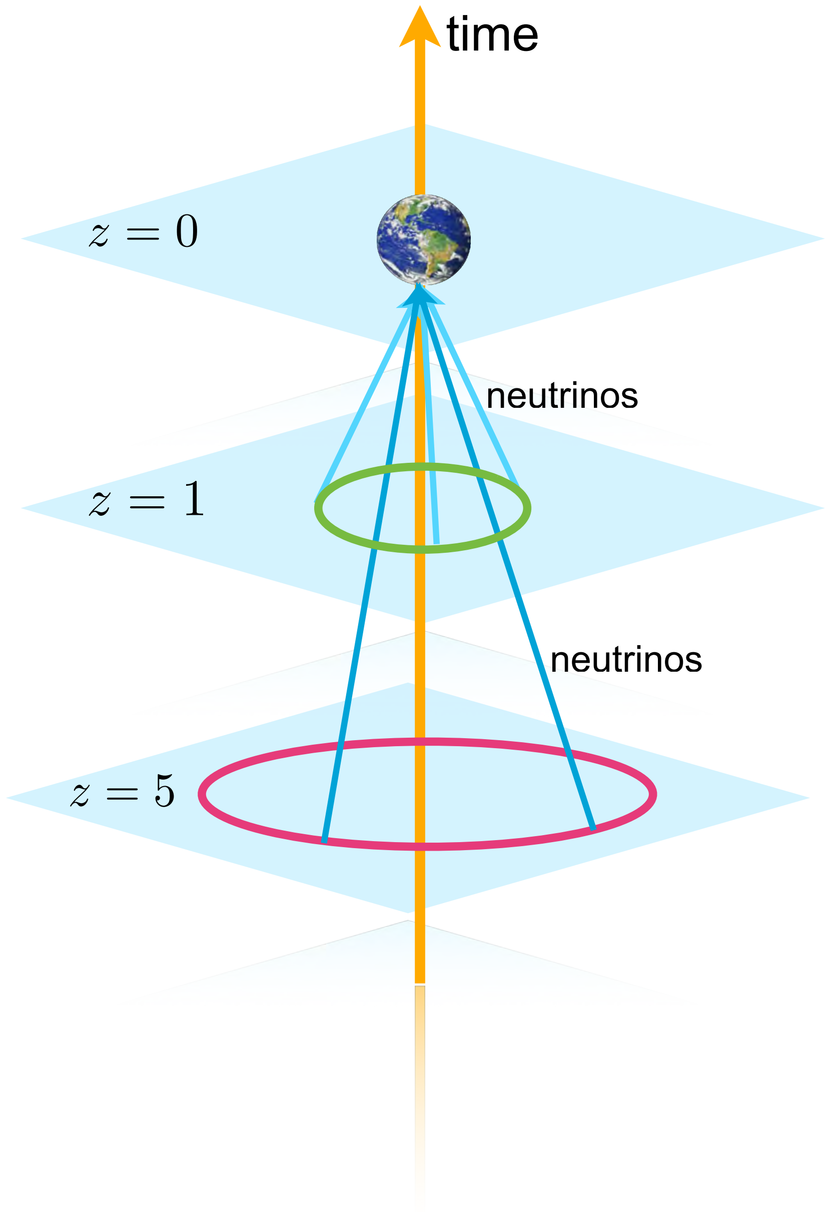
- SN distance.
- (Test oscillation physics.)

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

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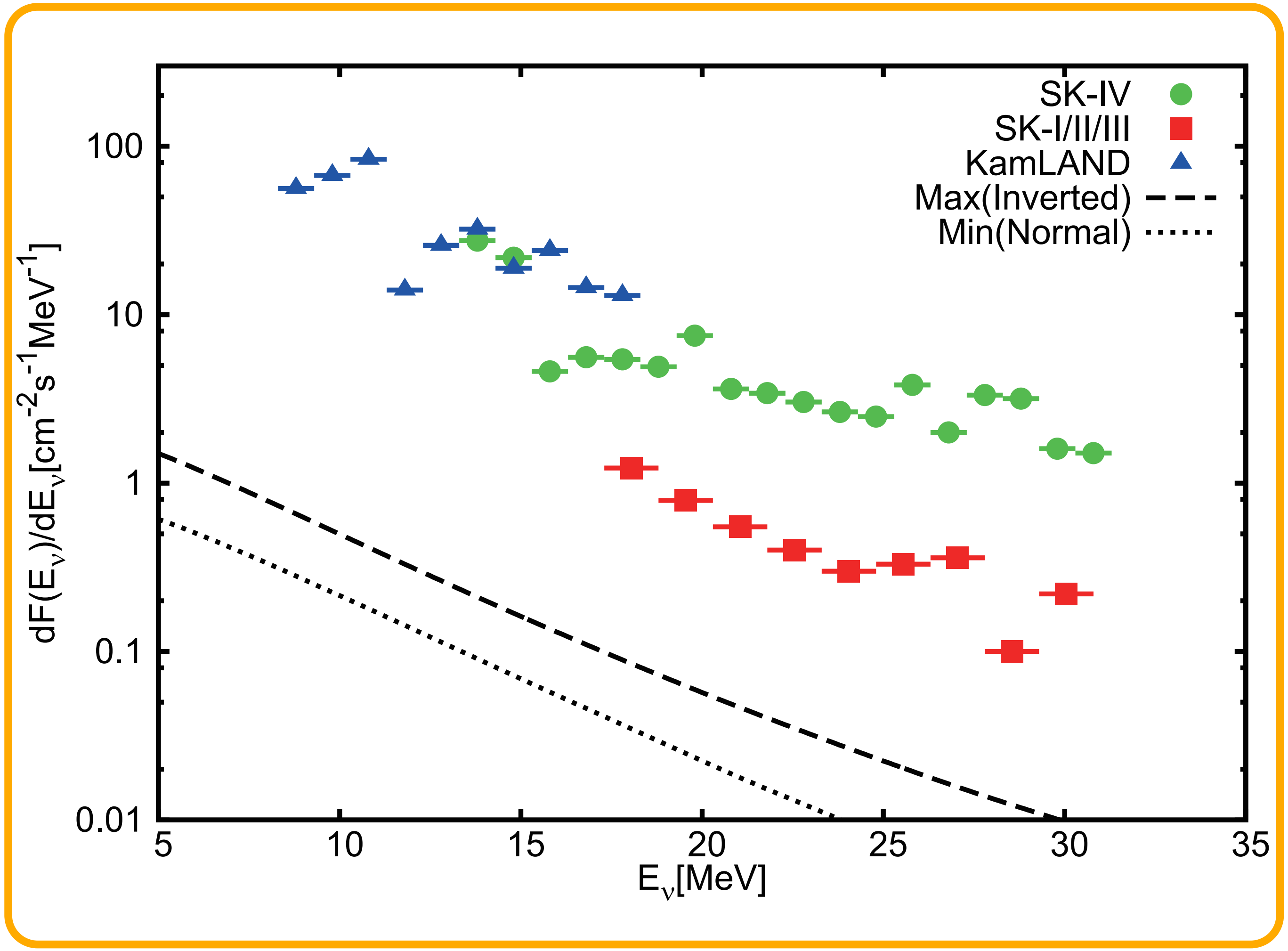
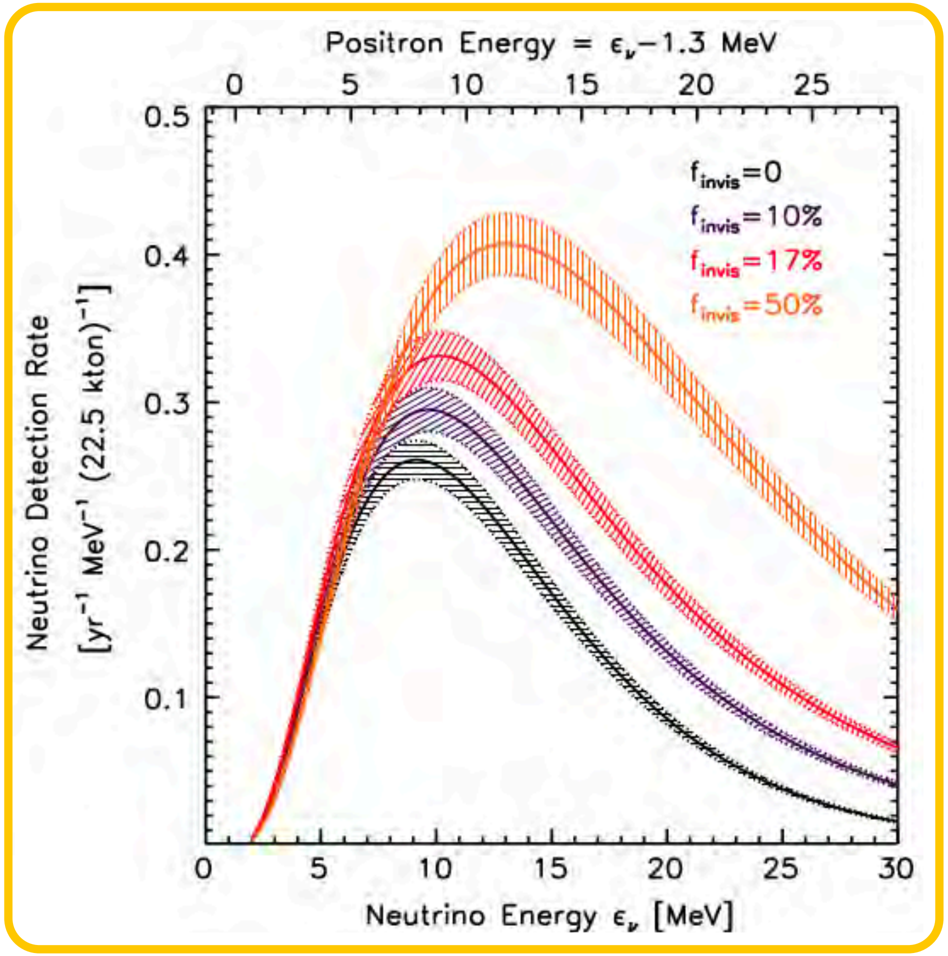


DSNB detection may happen soon with, e.g., upcoming JUNO and Gd-Super-K project (sensitivity strongly improved).

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



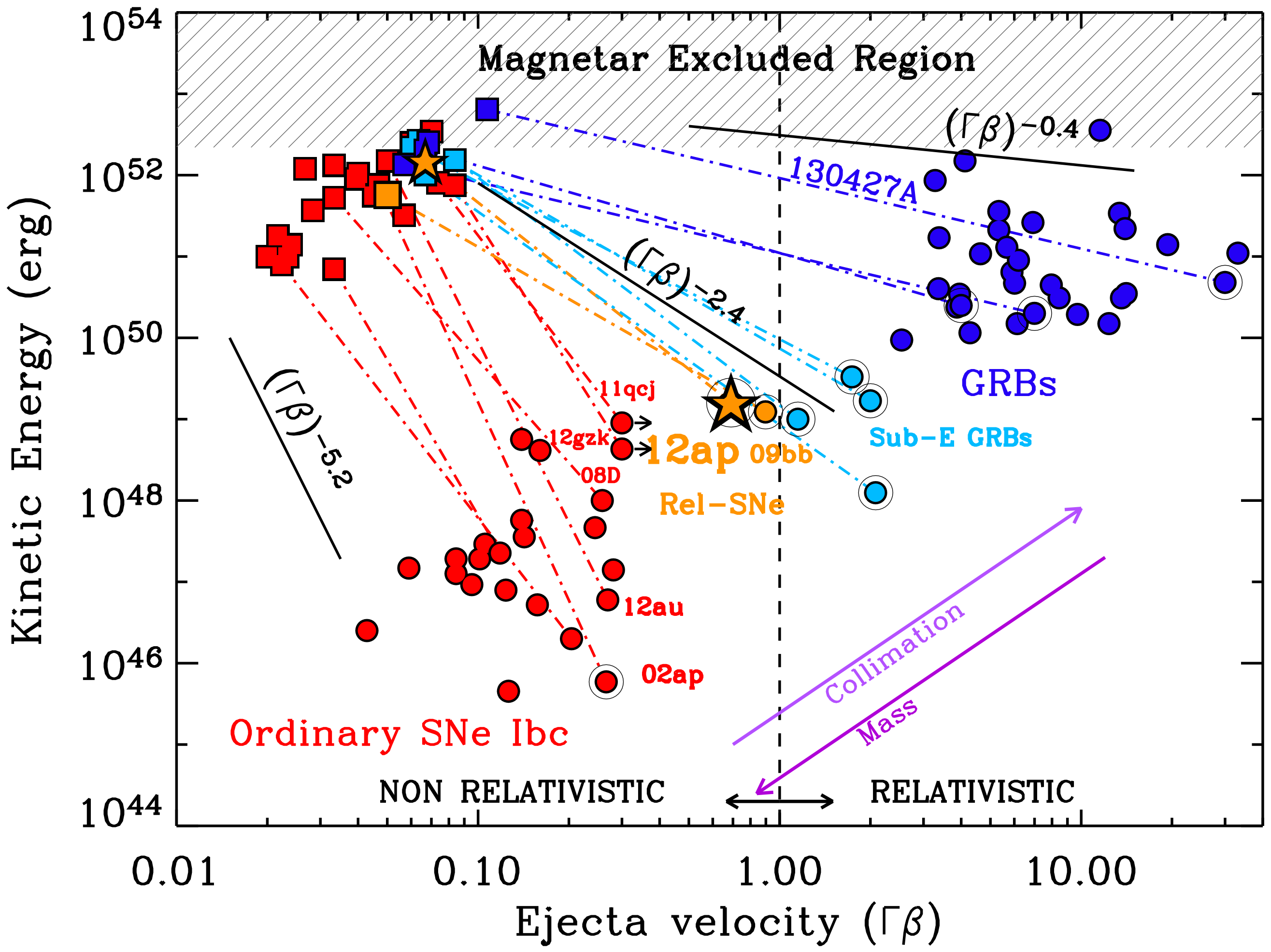
DSNB sensitive to failed supernova fraction.

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

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

SN-GRB Connection

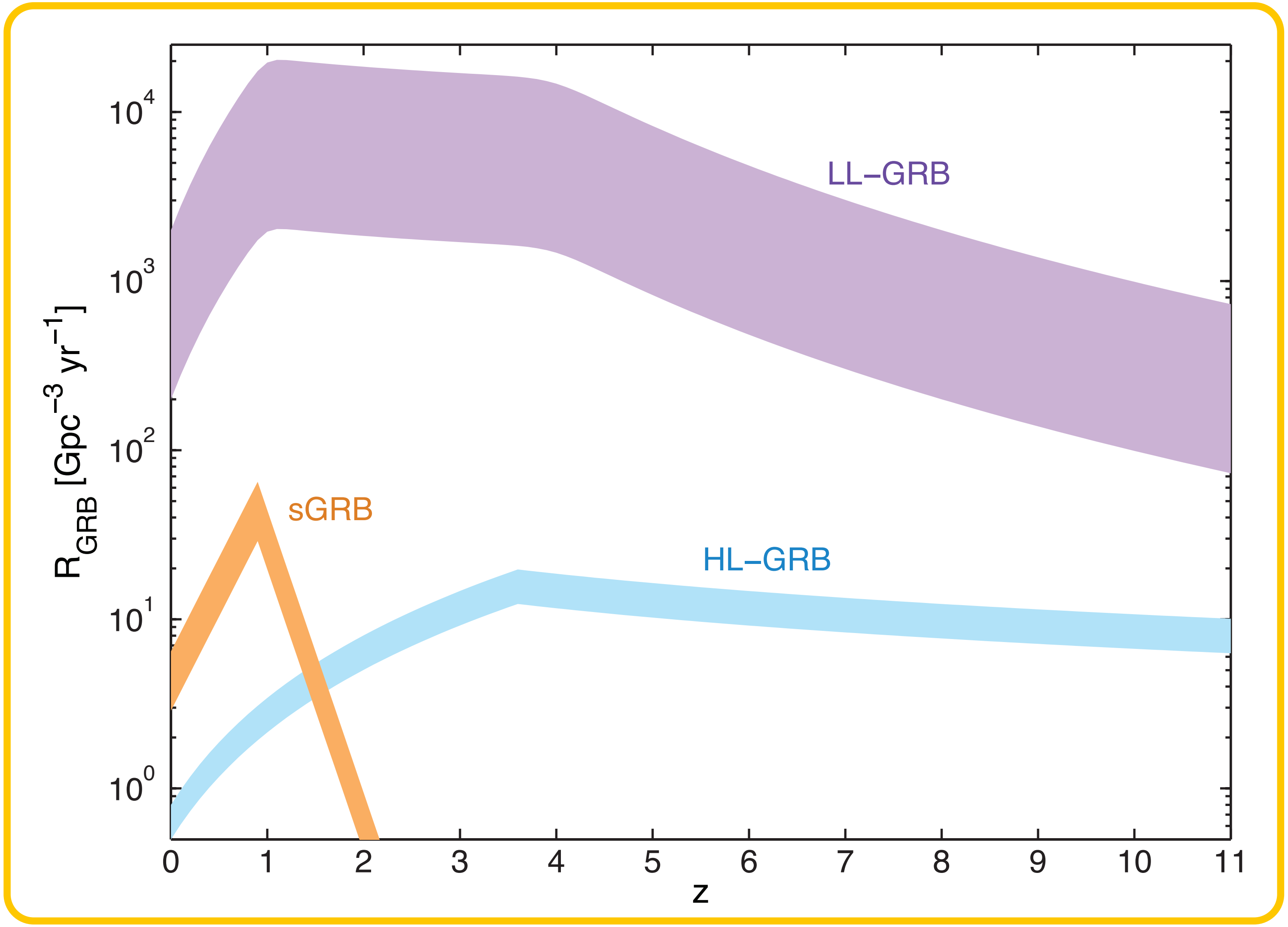
Core-Collapse Supernovae



Evidence towards a continuum of stellar explosions originating from hydrogen-stripped envelopes.

Margutti et al., ApJ (2014). Woosley & Bloom (2006). Bloom & Hjorth (2011). Lazzati et al. (2012). Piran et al., arXiv: 1704.08298. Sobacchi et al., arXiv: 1705.00281.

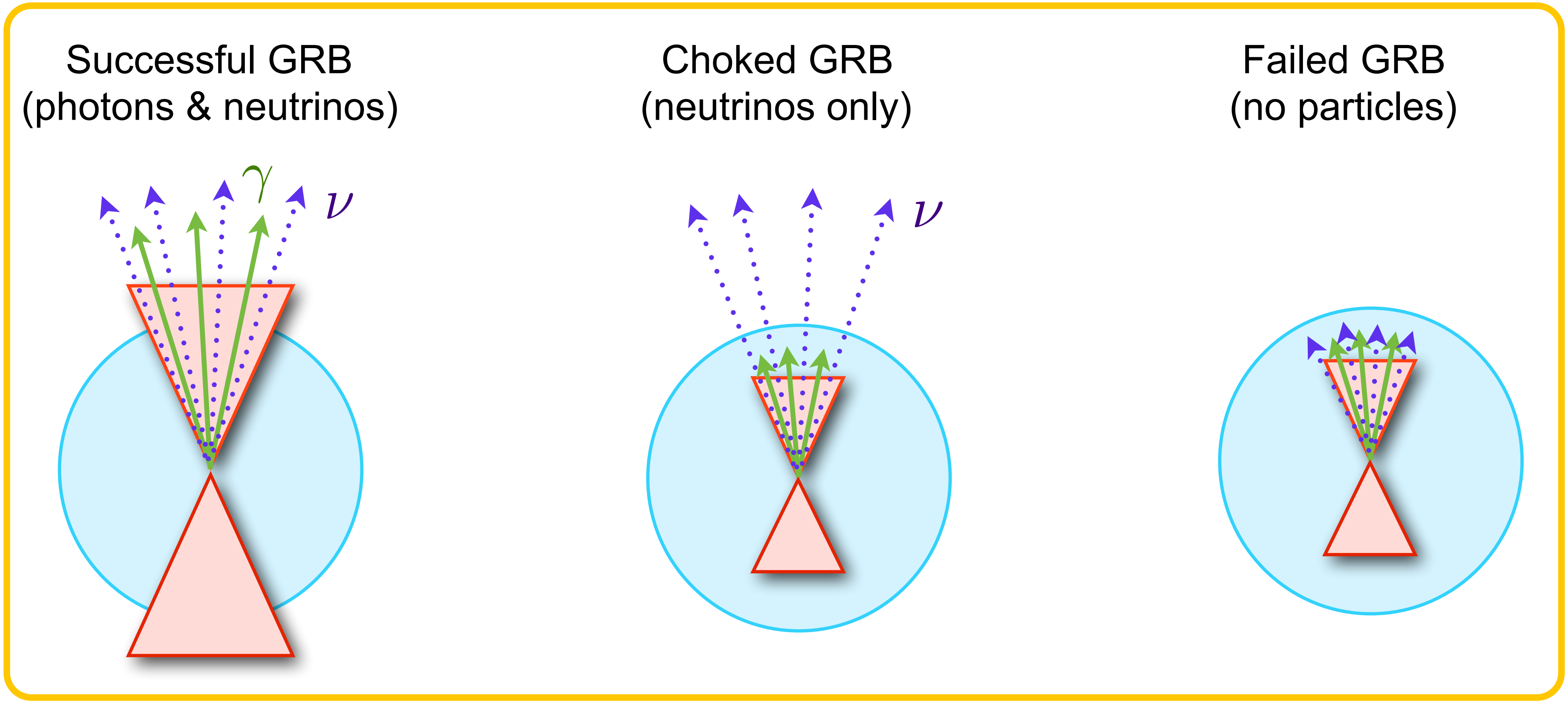
GRB Redshift Evolution



GRBs potentially scarcely visible in photons may be more abundant than ordinary ones.

Figure taken from Tamborra & Ando, JCAP (2015).

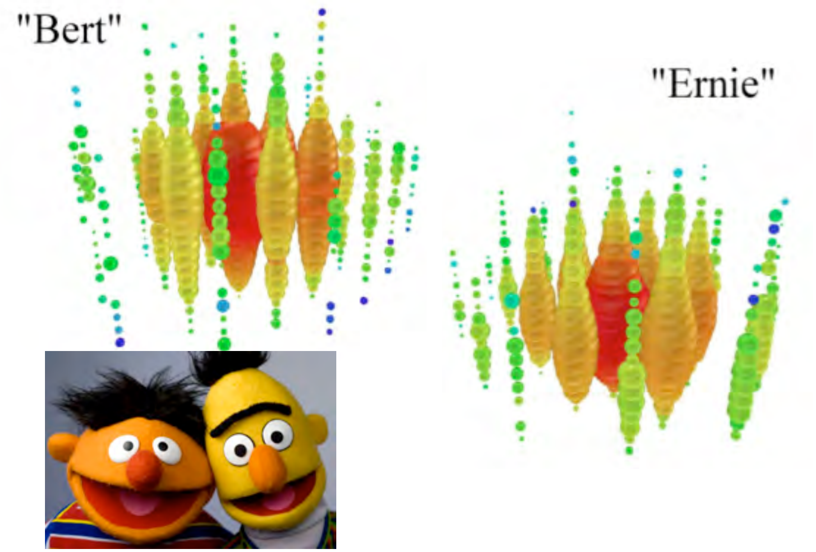
Supernova Aftermath



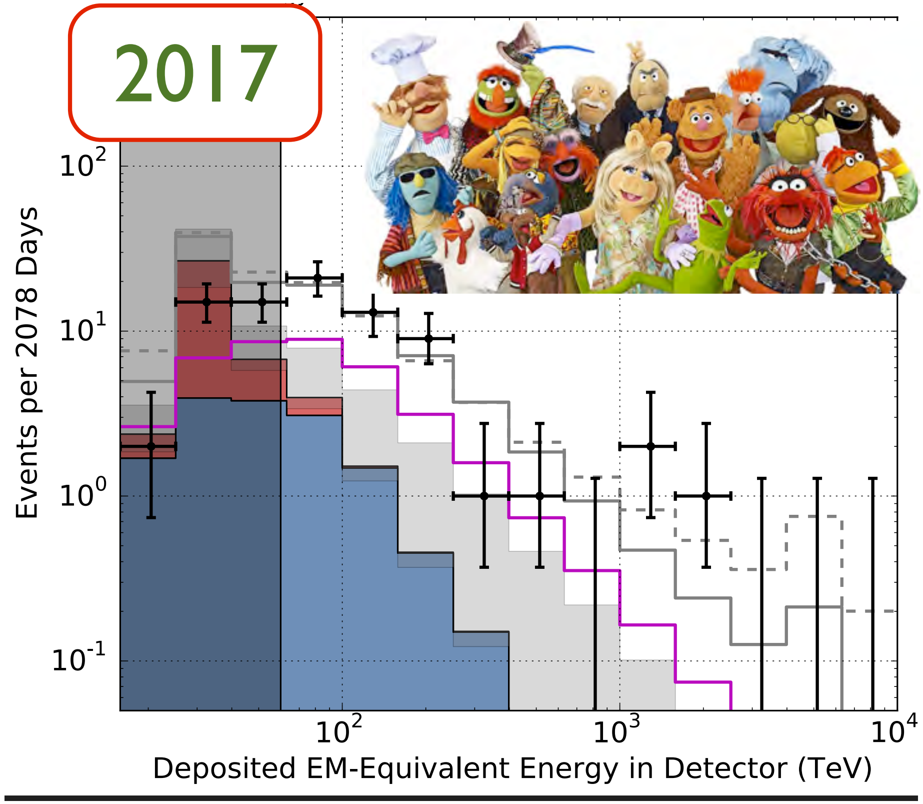
Neutrinos may be the only particles emerging from the stellar envelope.

Upper Limit on Neutrino Emission

2013



2017

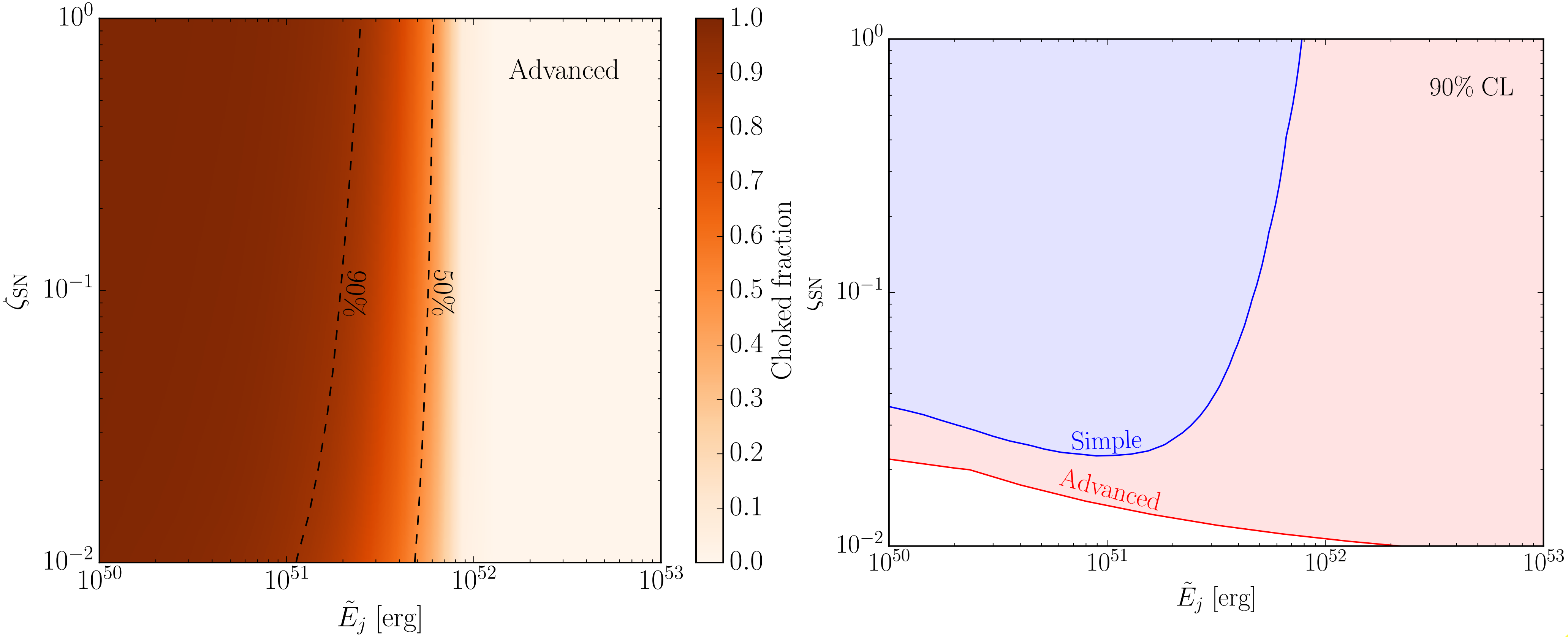


- ★ IceCube observed O(80) events over six years in the TeV-PeV range.
- ★ Zenith Distribution compatible with isotropic flux.
- ★ Flavor distribution consistent with $\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$.

$> 7\sigma$ evidence for astrophysical flux

Talk by Kopper @ ICRC 2017. IceCube Collaboration, Science (2013), PRL (2014), PRD (2015). IceCube Collaboration, ApJ (2015); PRL (2015).

SN-GRB Connection



IceCube flux indirectly constraints the fraction of SNe evolving in jets and their jet energy.

Denton & Tamborra, in preparation. Tamborra & Ando, PRD (2016). Senno et al., PRD (2015). Meszaros & Waxman, PRL (2001).

Conclusions

- Neutrinos play a fundamental role in supernovae.
- Intriguing neutrino features from 3D SN simulations.
- 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 detect the DSNB in the near future.
- Neutrinos are intriguing probes of the supernova aftermath.

Thank you for your attention!