The Magellan Workshop - Connecting Neutrino Physics and Astronomy

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Physics Opportunities with Supernova Neutrinos

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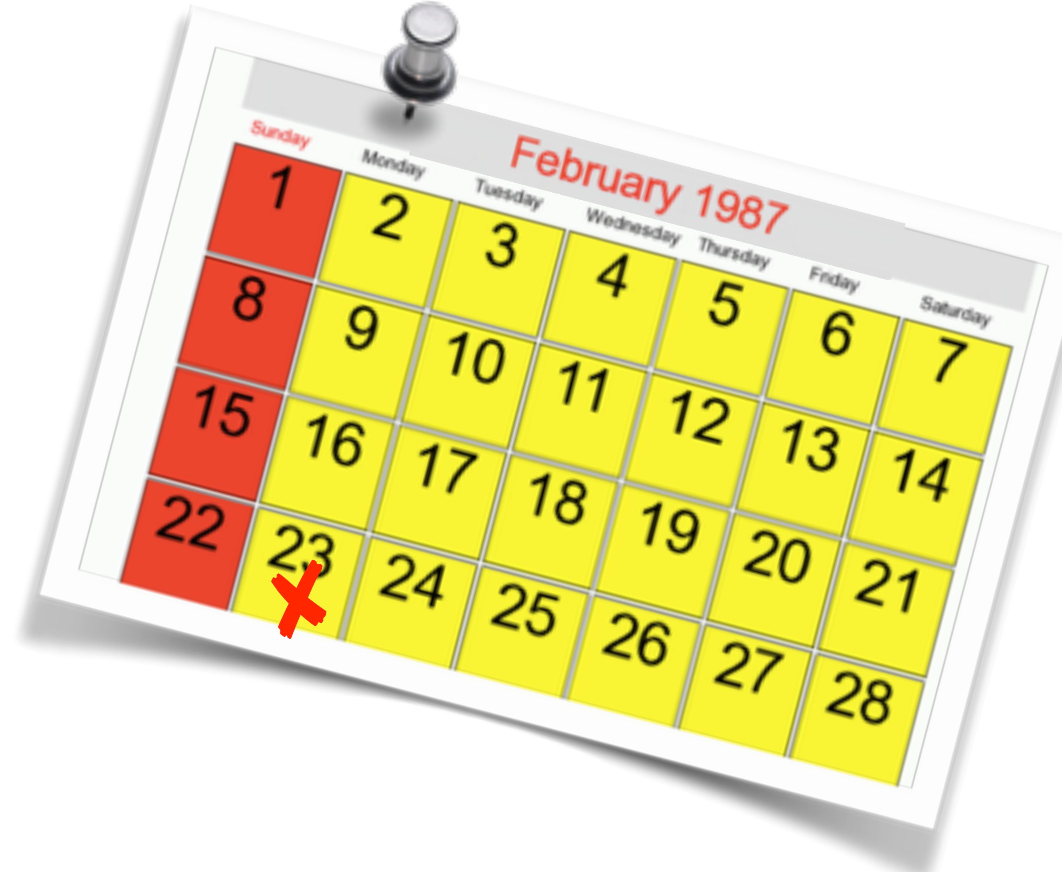
Based on the review:

"Superenova neutrinos: production, oscillations and detection"

Mirizzi , Tamborra, Janka, Saviano, Scholberg, Bollig, Huedepohl, and S. Chakraborty

SN 1987A

March 23, 1987 | Vol. 129 No. 12



In 1987, for the first time it was possible to directly observe, at a distance of 50 kpc, the neutrinos emitted by the explosion of a supernova, **SN 1987A**, in the ***Large Magellanic Cloud***

Supernova Neutrinos

Supernova is one of the most energetic events in nature.

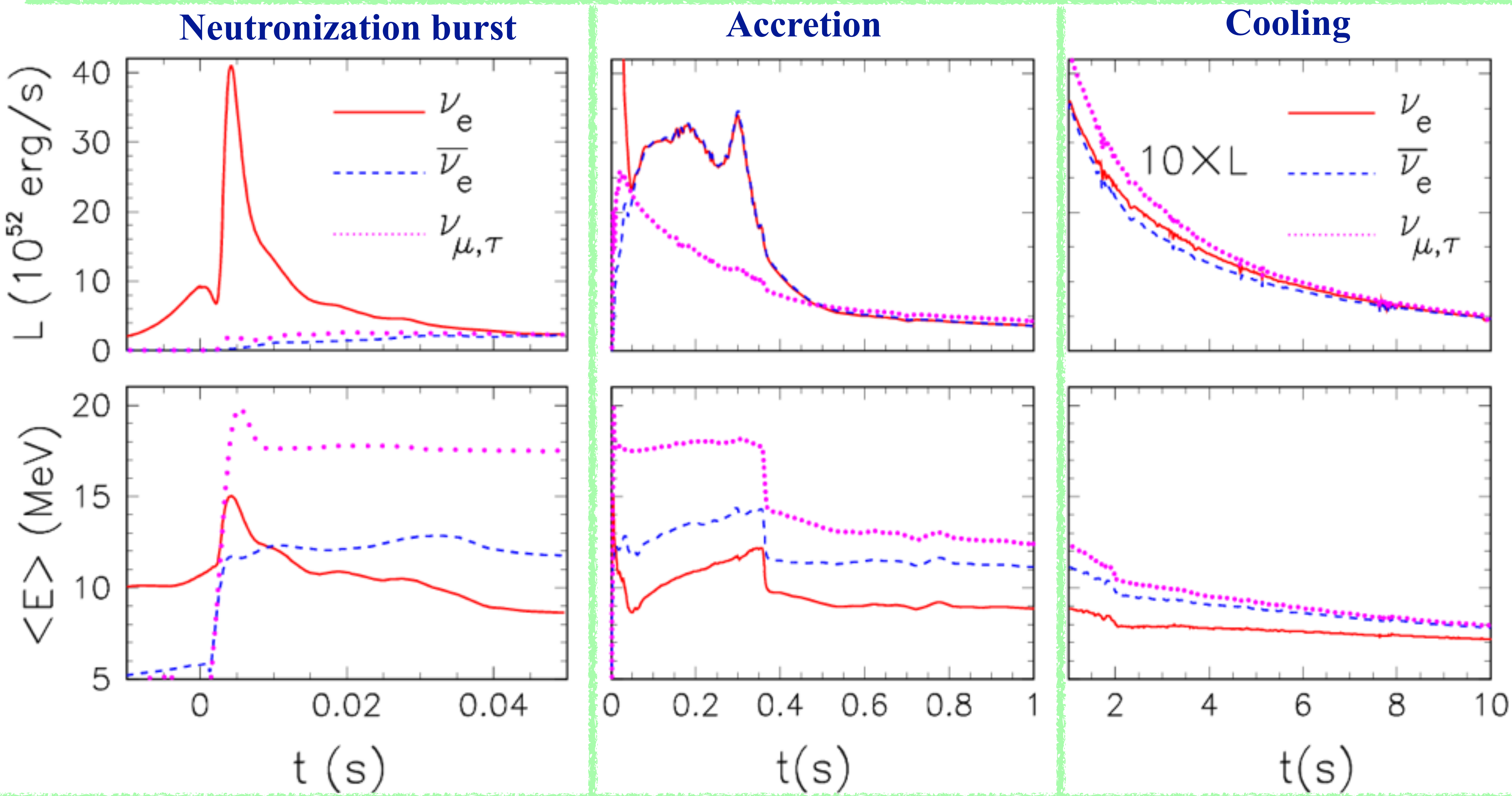
It is the terminal phase of a massive star ($M > 8 \div 10 M_{\odot}$)

It collapses and ejects the outer mantle in a ***shock wave*** driven explosion.

- ✓ **TIME SCALE:** The duration of the burst lasts ~10 s
- ✓ **EXPECTED RATE:** 1-3 SN/century in our galaxy ($d \approx O(10)$ kpc).
- ✓ **ENERGY SCALES:** 99% of the released energy (~10^{53} erg) is emitted by neutrinos and antineutrinos of all flavors with energies $\mathcal{O}$(10 MeV).

The supernova is one of the most powerful ν source in the Universe → crucial tool to study flavor conversions and to get information about the mixing parameters.

Three Phases of Neutrino Emission



Neutronization burst	Accretion	Cooling
• Shock breakout • De-leptonization of outer core layers	• Shock stalls ~ 150 km • ν powered by infalling matter	• Cooling on ν diffusion timescale

10. 8 M_{sun} progenitor mass (spherically symmetric with Boltzmnann ν transport)

(Recently 2D and 3D SN simulations have been performed

[see e.g. A. Wongwathanarat, E. Mueller and Janka,1409.5431, Tamborra et al, 1402.5418]

3ν Framework

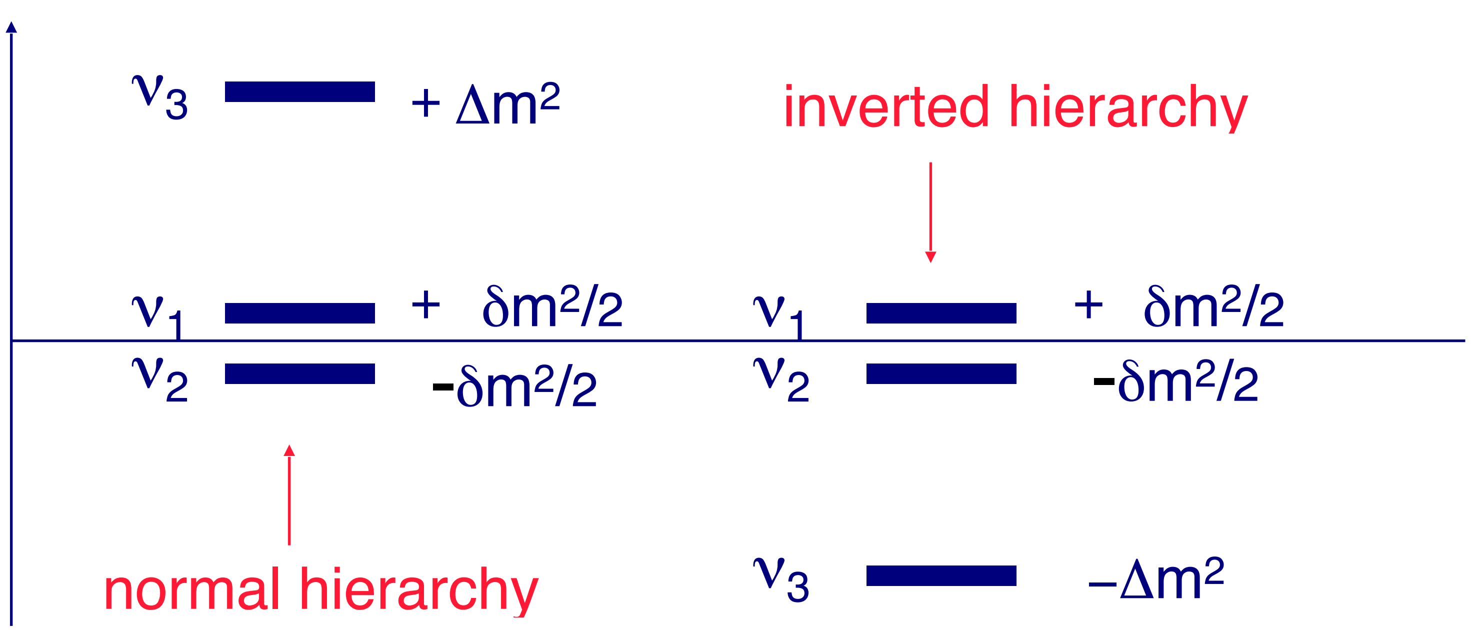
- ***Mixing parameters:*** $U = U(\theta_{12}, \theta_{13}, \theta_{23}, \delta)$ as for CKM matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & e^{-i\delta} s_{13} \\ & 1 & \\ -e^{-i\delta} s_{13} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$c_{12} = \cos\theta_{12}$, etc., δ CP phase

- ***Mass-gap parameters:***

$$M^2 = \Bigg(\underbrace{-\frac{\delta m^2}{2}, +\frac{\delta m^2}{2}}_{\text{“solar”}}, \underbrace{\pm\frac{\Delta m^2}{2}}_{\text{“atmospheric”}}\Bigg)$$

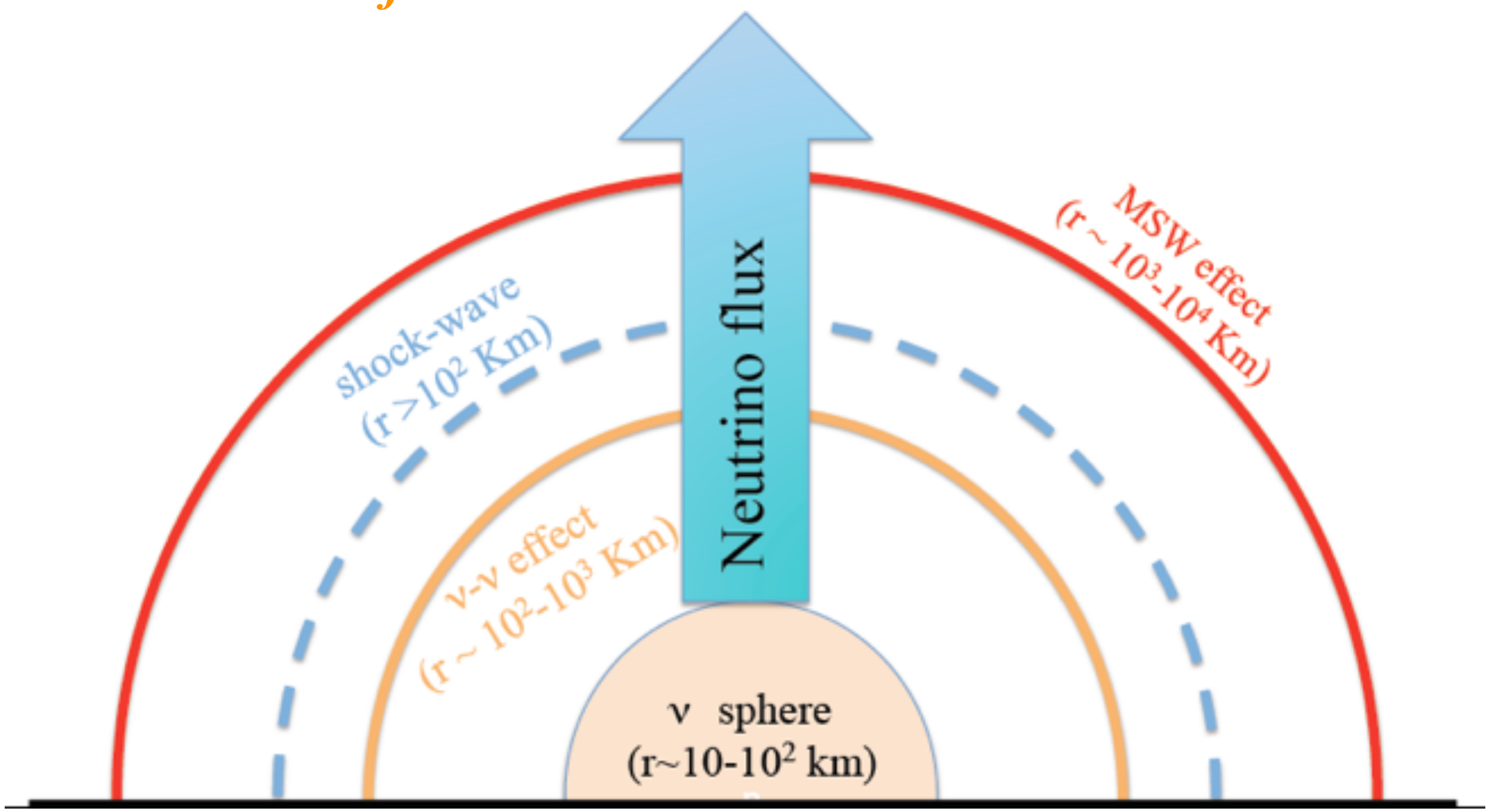


Different Oscillation Regimes in SN

Neutrinos free streaming beyond the neutrinosphere also interact among themselves (neutrino self-interactions)

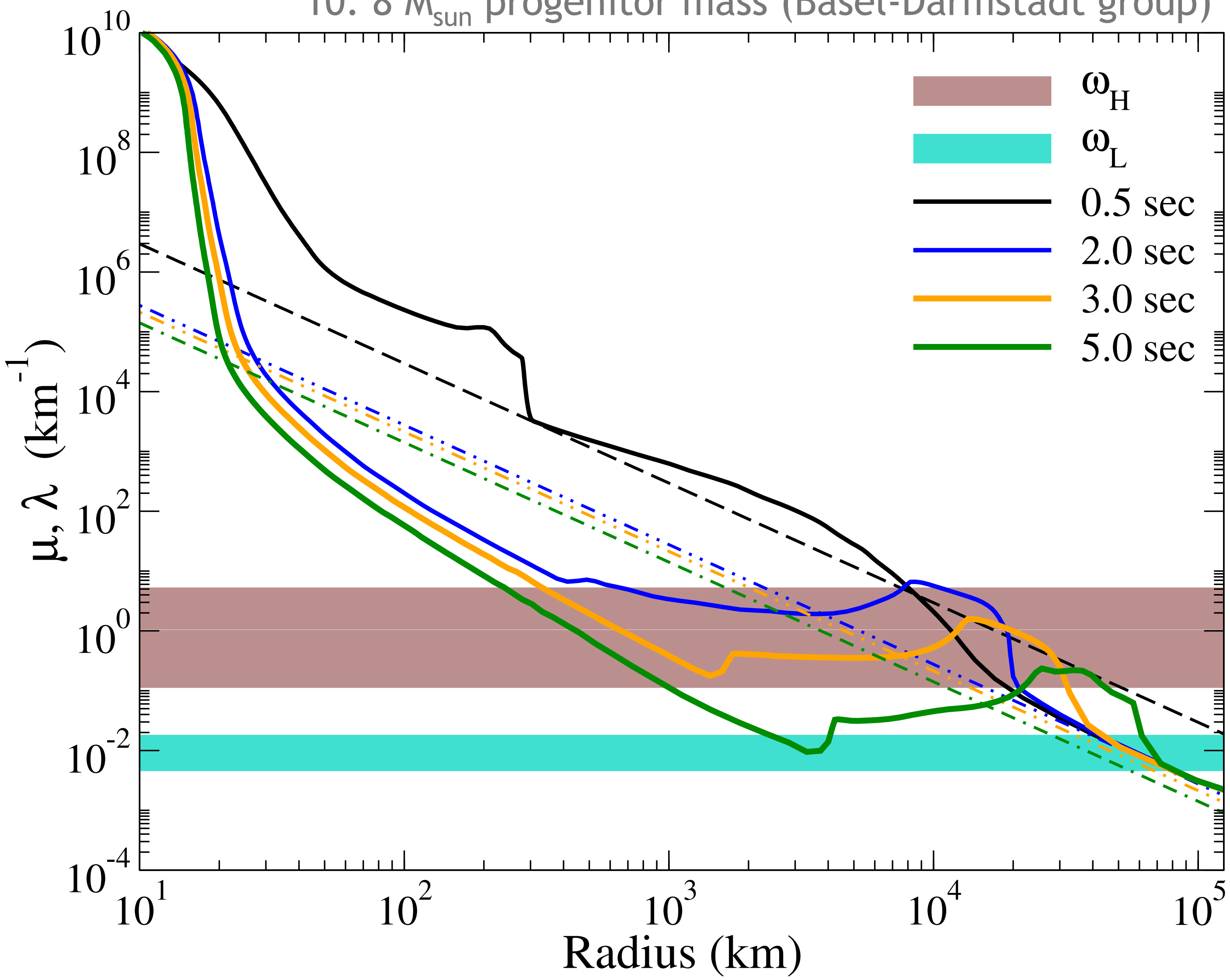
Indeed, in the deepest regions of a SN the neutrino gas is so dense that neutrinos themselves form a background medium leading to intriguing non-linear effects.

Neutrino-neutrino interactions could trigger ***large self-induced flavor conversions*** in the deepest SN regions → ***neutrinos emitted with different energies would be locked to oscillate in a collective fashion.***



Snap-Shots of SN Density Profile

Effects of flavor conversions on supernova neutrinos depend on the different densities encountered by neutrinos in their propagation in the stellar envelope.



- Matter bkg potential

$$\lambda = \sqrt{2} G_F N_e \sim r^{-3} \quad \text{(solid curves)}$$

- $\nu-\nu$ interaction

$$\mu = \sqrt{2} G_F n_\nu \sim r^{-2} \quad \text{(dashed curves)}$$

- Vacuum oscillation frequencies

$$\omega = \frac{\Delta m^2}{2E}$$

When $\mu >> \lambda$, SN ν oscillations dominated by ν-ν interactions

➡ Collective flavor transitions at low-radii [O ($10^2 - 10^3$ km)]

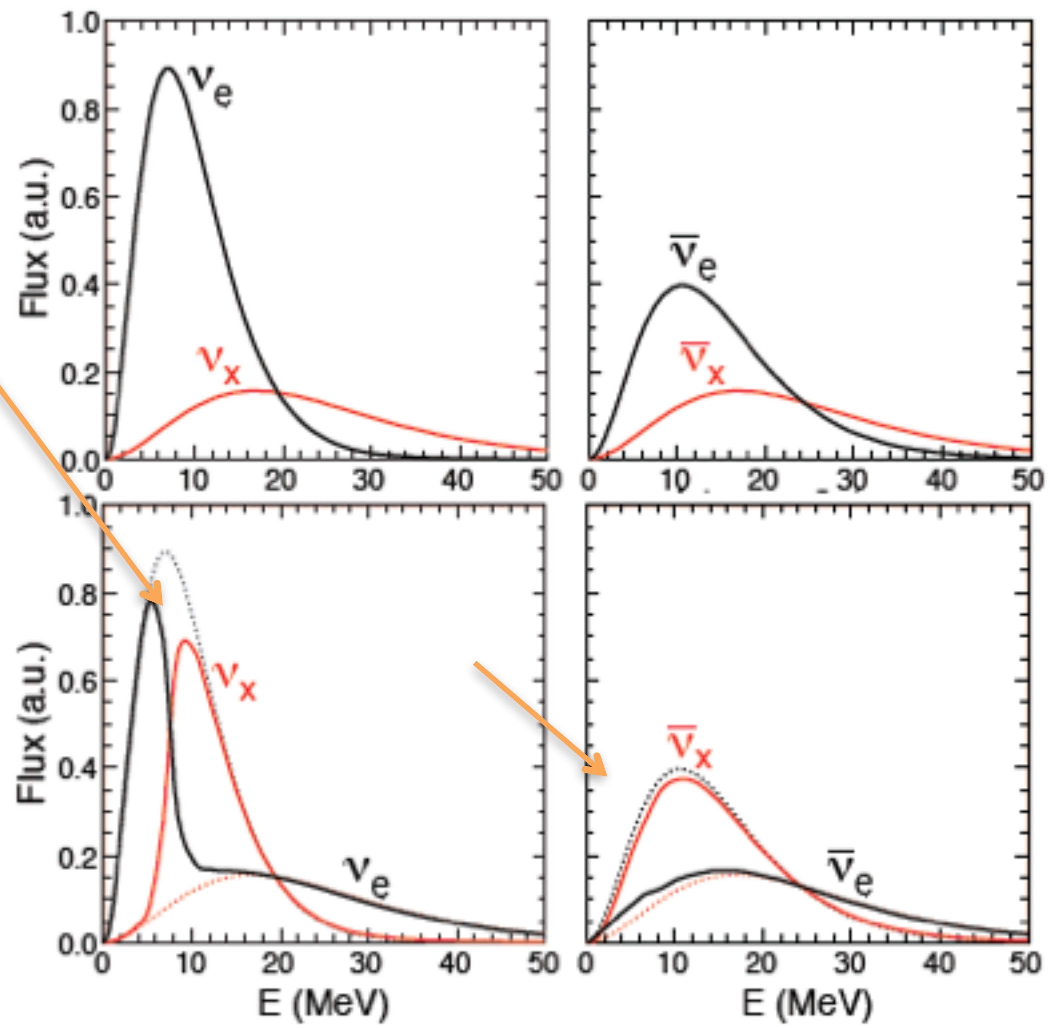
[see Duan, Fuller and Qian arXiv:1001.2799 [hep-ph]]

Collective Behaviour: Self-Induced Spectral Splits

Collective oscillations occur between the ν sphere and the MSW region and can modify the neutrino spectra.

Most important observational consequence:

swap of the ν_e and $\bar{\nu}_e$ spectra with non-electron ν_x and $\bar{\nu}_x$ spectra



Initial fluxes at neutrino sphere

After collective transformation

[Fogli et al., arXiv:0707.1998, 0808.0807 [hep-ph]]

Strong dependence of collective oscillations on mass hierarchy and on the energy (''splits'')

Splits possible in both normal and inverted hierarchy, for ν & $\bar{\nu}$!!

However, still far from generic predictions about signatures of collective effects ....many layers of complications in the description of the flavor evolution!

Self-Induced Flavor Evolution

✓ Recent advances

Matter suppression during the Accretion phase (t < 500 ms): dense matter term dominates over nu-nu interaction term [*Chakraborty, Mirizzi, **Saviano** et al., 1104.4031, 1105.1130, 1203.1484, Sarikas et al., 1109.3601, S. Sarikas, I. Tamborra et al., 1204.0971]*

Linearized Stability analysis of the EOM provides many conceptual insights and practical results: [*Banerjee, Dighe & Raffelt, 1107.2308, **Saviano** et al., 1105.1130, Mirizzi & Serpico, 1110.002, …*]

Axial Symmetry Breaking and Multi-Azimuthal-Angle-Instability: [*Raffelt, Sarikas & de Sousa, 1305.7140; Mirizzi, 1308.1402, Chakraborty, Mirizzi, **Saviano** and Seixas, 1402.1767*]

Spontaneous Breaking of space-time symmetries: *[**time:** Mangano, Mirizzi and **Saviano**1403.1892, Abbar and Duan, 1509.01538, Dasgupta and Mirizzi, 1509.03171, space: Duan and Shalgar, 1412.7097 Mirizzi, Mangano and **Saviano**, 1503.03485, Mirizzi, 1506.06805, Duan, 1506.08629. Chakraborty, Hansen, Izaguirre and Raffelt, 1507.07569]*

✓ Open issues

Numerical treatment without symmetries challenging

Simultaneous time and space dependence important?

Suppression of Collective Oscillations

At the moment, predictions are more robust in the phases where collective effects are suppressed, i.e.:

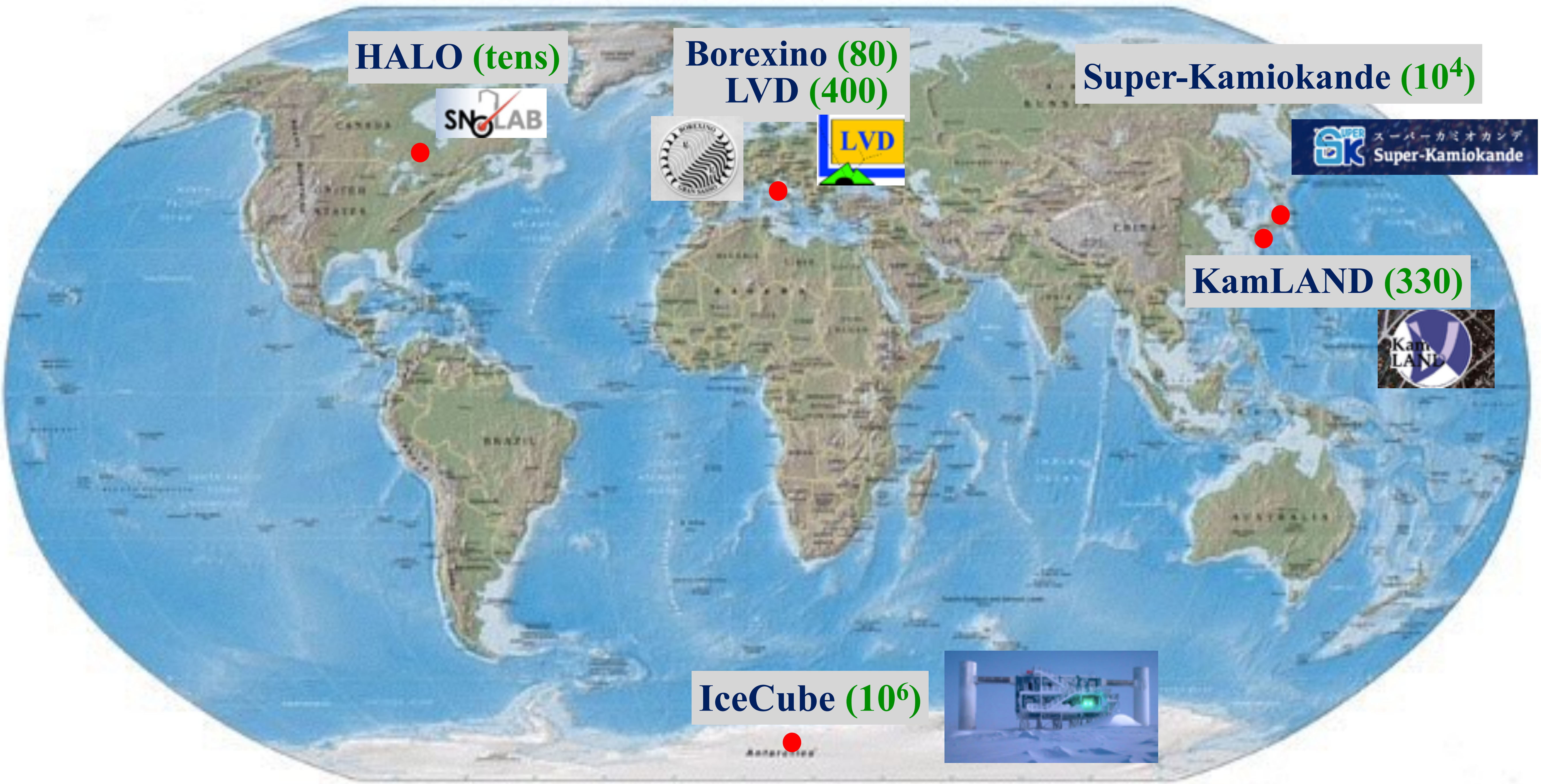
- **Neutronization burst ($t < 20$ ms):** large ν_e excess and ν_x deficit
  [Hannestad et al., astro-ph/0608695]

- **Accretion phase ($t < 500$ ms):** dense matter term dominates over ν-ν interaction term [*Chakraborty, Mirizzi, **Saviano** et al., 1104.4031, 1105.1130, 1203.1484, Sarikas et al., 1109.3601]*

Large flux differences during the neutronization and accretion phase

Best cases for ν oscillation effects !

Large Detectors for SN Neutrinos

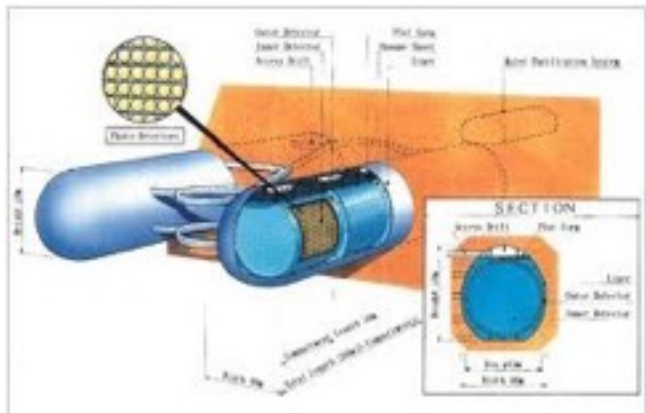


events for a “fiducial SN” at distance 10 kpc

Next Generation Detectors

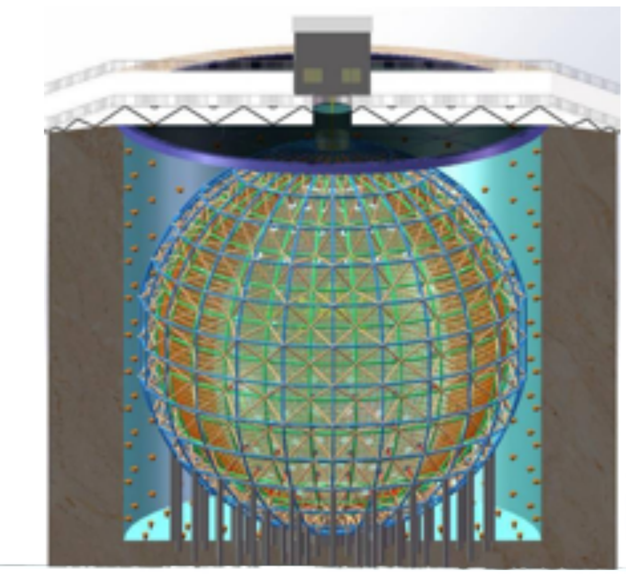
Mton scale water Cherenkov detector

HYPER-KAMIOKANDE



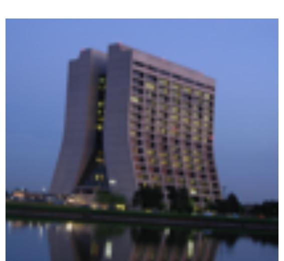
20 kton scintillator

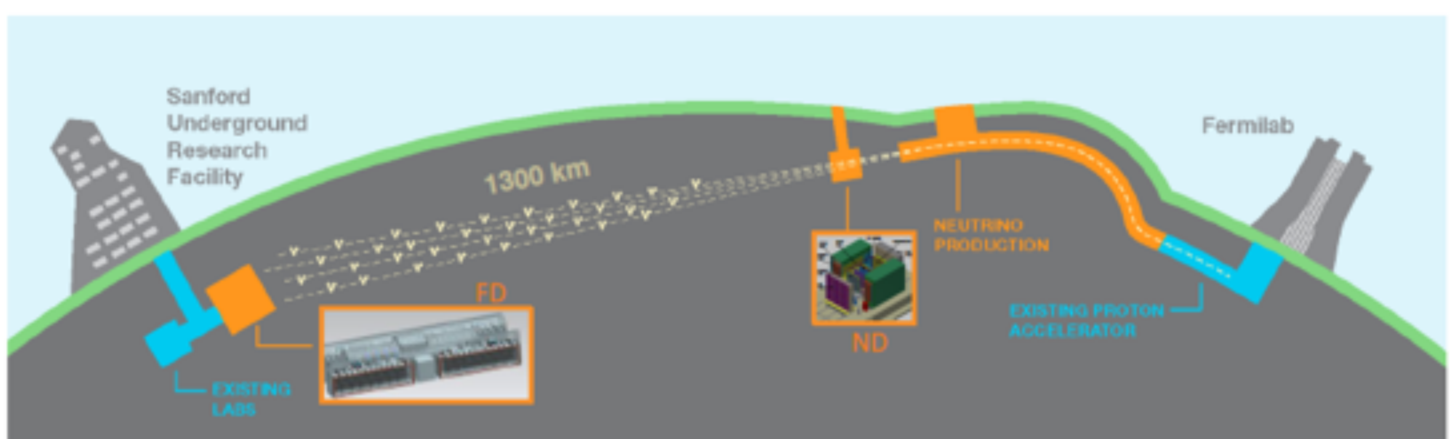
JUNO



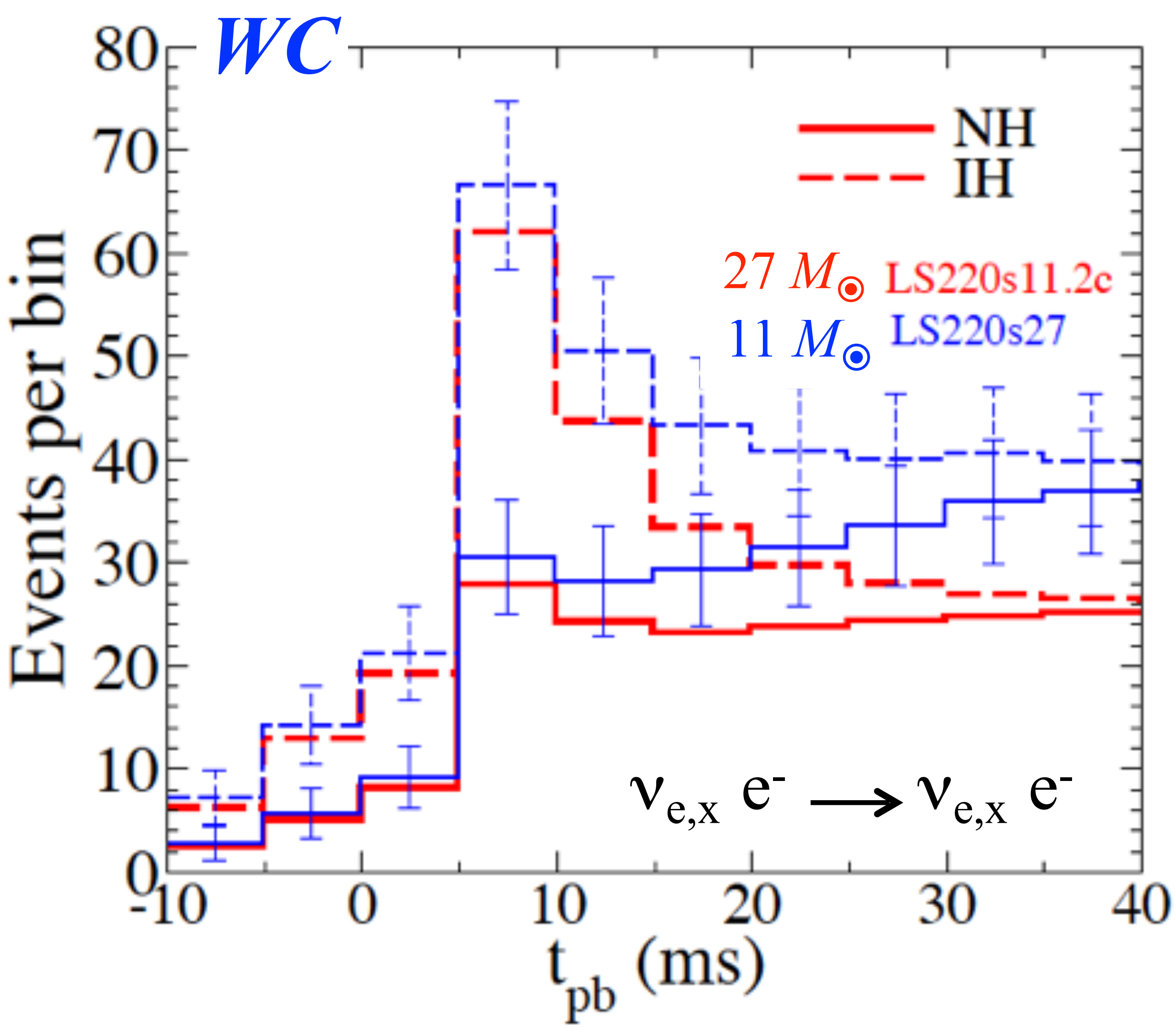
40 kton Liquid Argon TPC

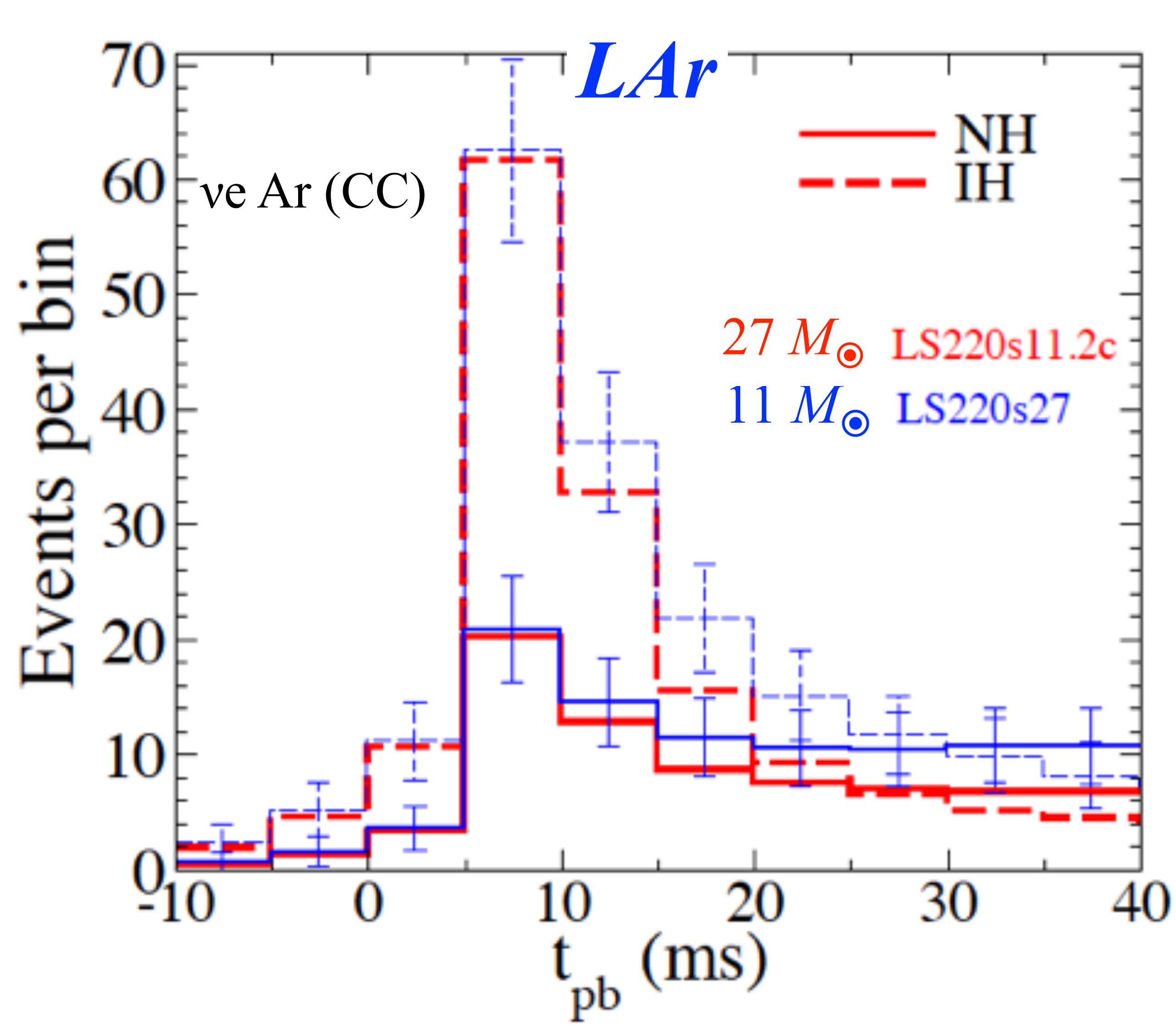
DUNE





Neutronization Burst in WC & LAr Detector





$$F_{\nu_e} = F^0_{\nu_x} \qquad \text{(NH)}$$

$$F_{\nu_e} = \sin^2\theta_{12} F^0_{\nu_e} + \cos^2\theta_{12} F^0_{\nu_x} \qquad \text{(IH)}$$

- The peak <u>is not seen</u> → The hierarchy is normal
- The peak <u>is seen</u> → The hierarchy is inverted (more robust)

Using the Earth Effect to Discriminate Mass Hierarchy

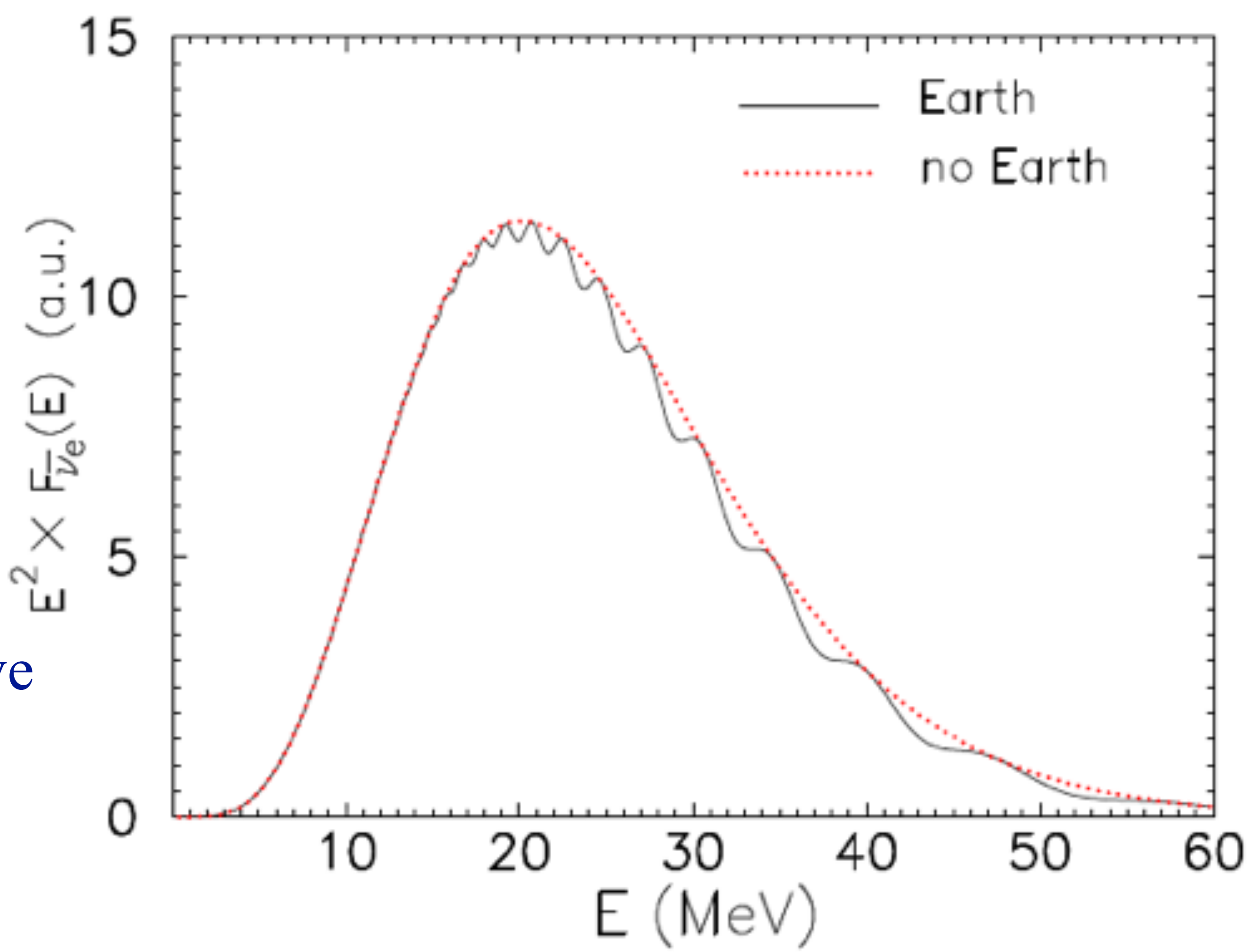
Earth matter crossing induces additional ν conversions between ν_1 and ν_2 mass eigenstates.

The main signature of Earth matter effects – oscillatory modulations of the observed energy spectra – is *unambiguous* since it can not be mimicked by known astrophysical phenomena

EME observed in $\bar{\nu}$ ⟶ Normal hierarchy

EME observed in ν ⟶ Inverted hierarchy

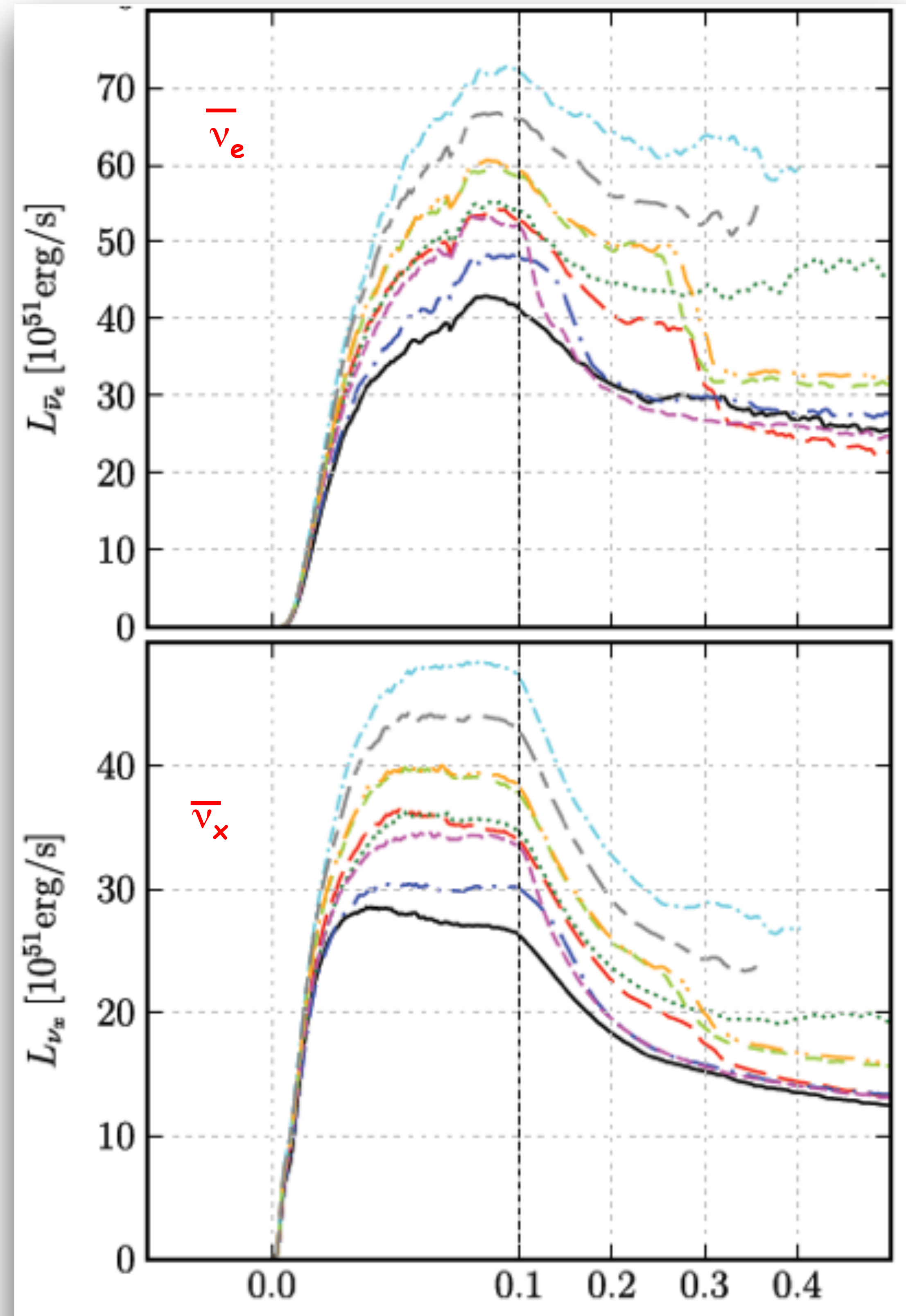
(Assuming complete matter suppression of collective oscillations during the accretion phase)



The observability would be reduced with state of art simulations

[Borriello, Chakraborty, Mirizzi, Serpico and Tamborra, 1207.5049]

Rise Time of SN Neutrino Signals



Garching group, 2011

The production of $\bar{\nu}_e$ is more strongly suppressed than that of ν_x during the first tens of ms after bounce because of the high degeneracy of e and ν_e .

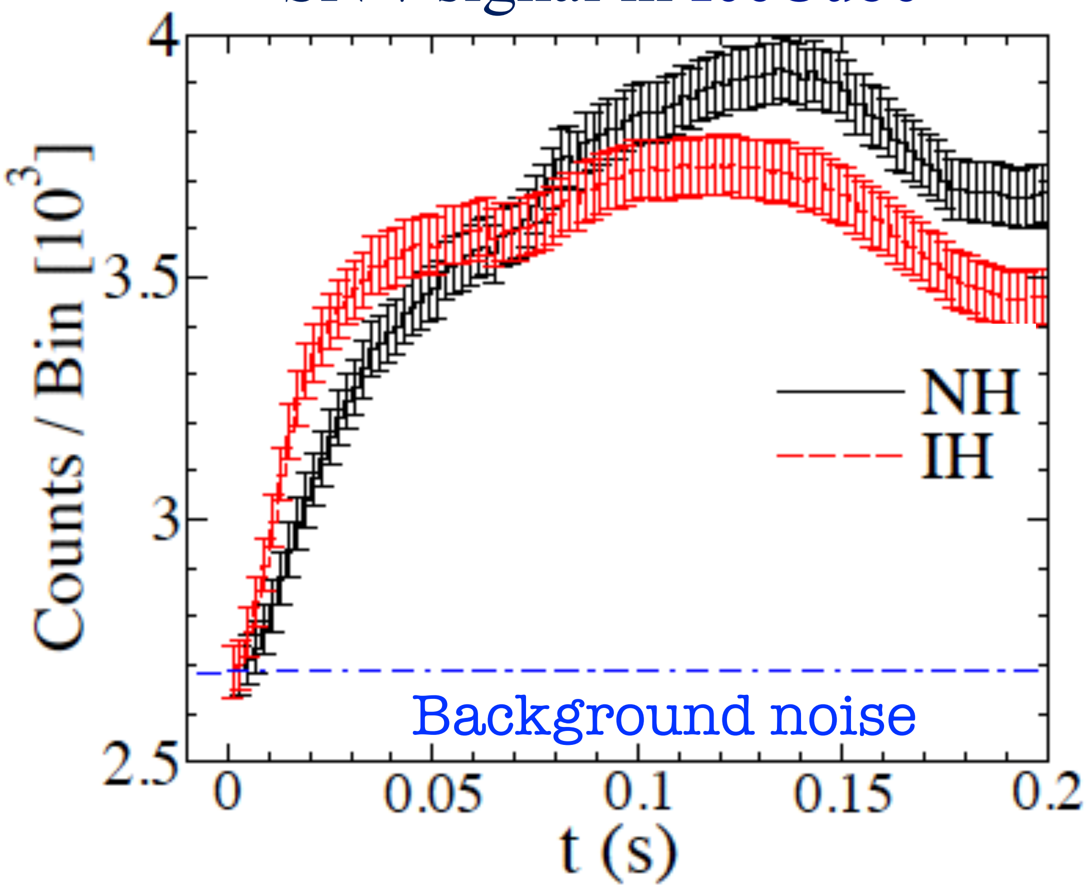
$\bar{\nu}_e$ are produced more gradually via cc processes (e captures on free nucleons) in the accreting matter; ν_x come quickly from a deeper region

The lightcurves of the two species in the first O(100) ms are quite different.

Rise Time Analysis:Hierarchy Determination

[Serpico, Chakraborty, Fischer, Hudepohl, Janka & Mirizzi, 1111.4483]

SN ν signal in IceCube



In accretion phase one has

$$F_{\bar{\nu}_e} = \cos^2\theta_{12} F^0_{\bar{\nu}_e} + \sin^2\theta_{12} F^0_{\bar{\nu}_x} \quad \text{NH}$$

$$F_{\bar{\nu}_e} = F^0_{\bar{\nu}_x} \quad \text{IH}$$

A high-statistics measurement of the rise time shape may distinguish the two scenarios

Are the rise time shapes enough robustly predicted to be useful?

Models with state-of-the art treatment of weak physics (Garching simulations) suggest so: one could attribute a ‘’shape’’ to NH and IH.

Given these promising early results, it would be mandatory in future to explore the robustness of the signature with other simulations. *[see Ott et al., 1212.4250]*

Synopsis of oscillation signatures

Mass Hierarchy	ν_e burst	$\bar{\nu}_e$ rise time	Earth effects
NH	absent	long	$\bar{\nu}_e$
IH	present	short	ν_e

Conclusions

After 29 years from the SN 1987A….

…the physics opportunity from SN neutrino observations is enormous, both for particle physics and astrophysics.

- SNe provide very extreme conditions to test the ν flavor conversions and probe the missing pieces of the neutrino mixing framework.

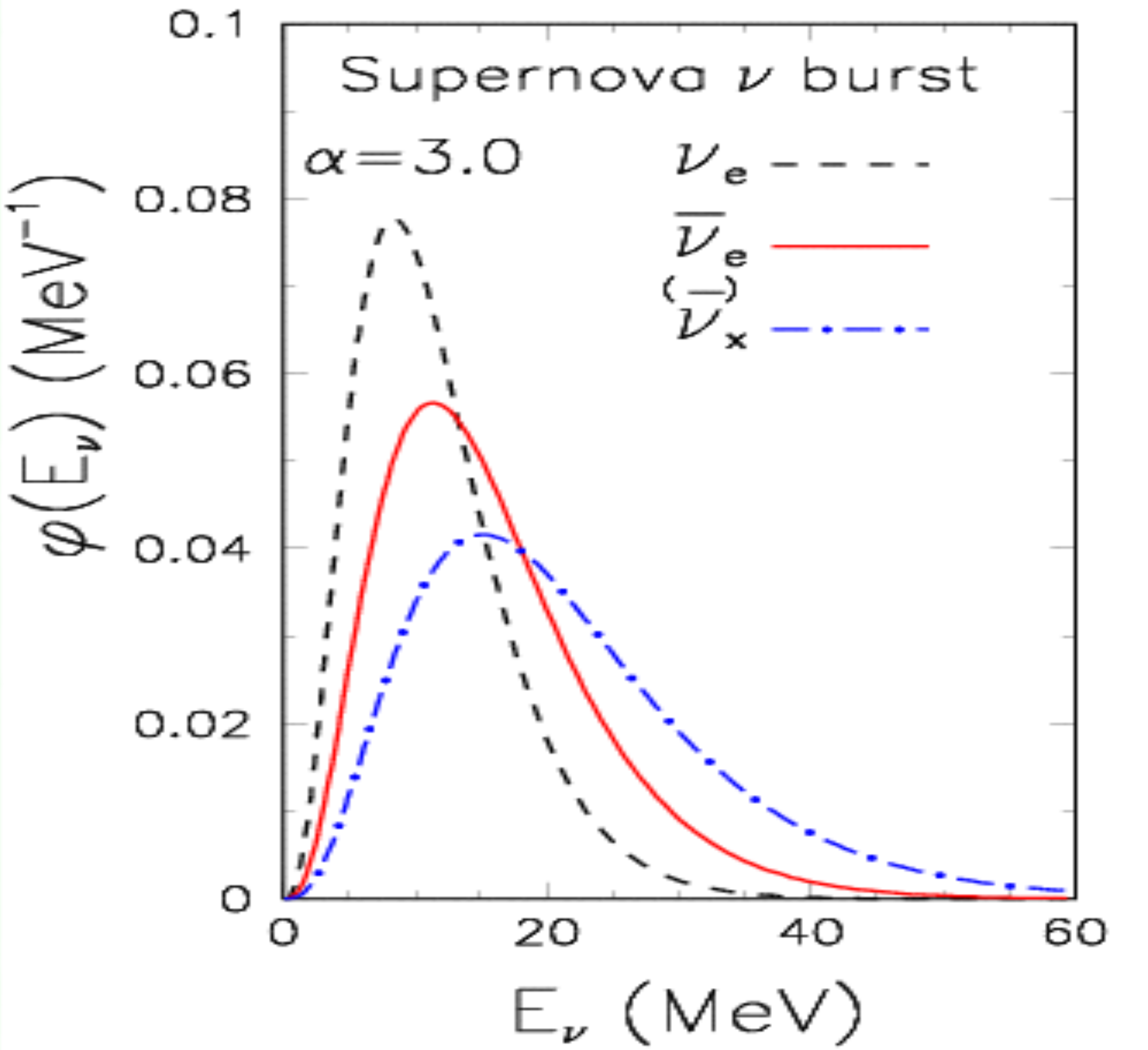
- Models of core-collapse and SN ν production can be "calibrated".

A lot of work is necessary to fully characterise the SN mechanism and the neutrino flavor conversions

Thank you

Neutrino Energy Spectra

Time-integrated normalised ν spectra



"quasi-thermal" spectra

Hierarchy of the spectra

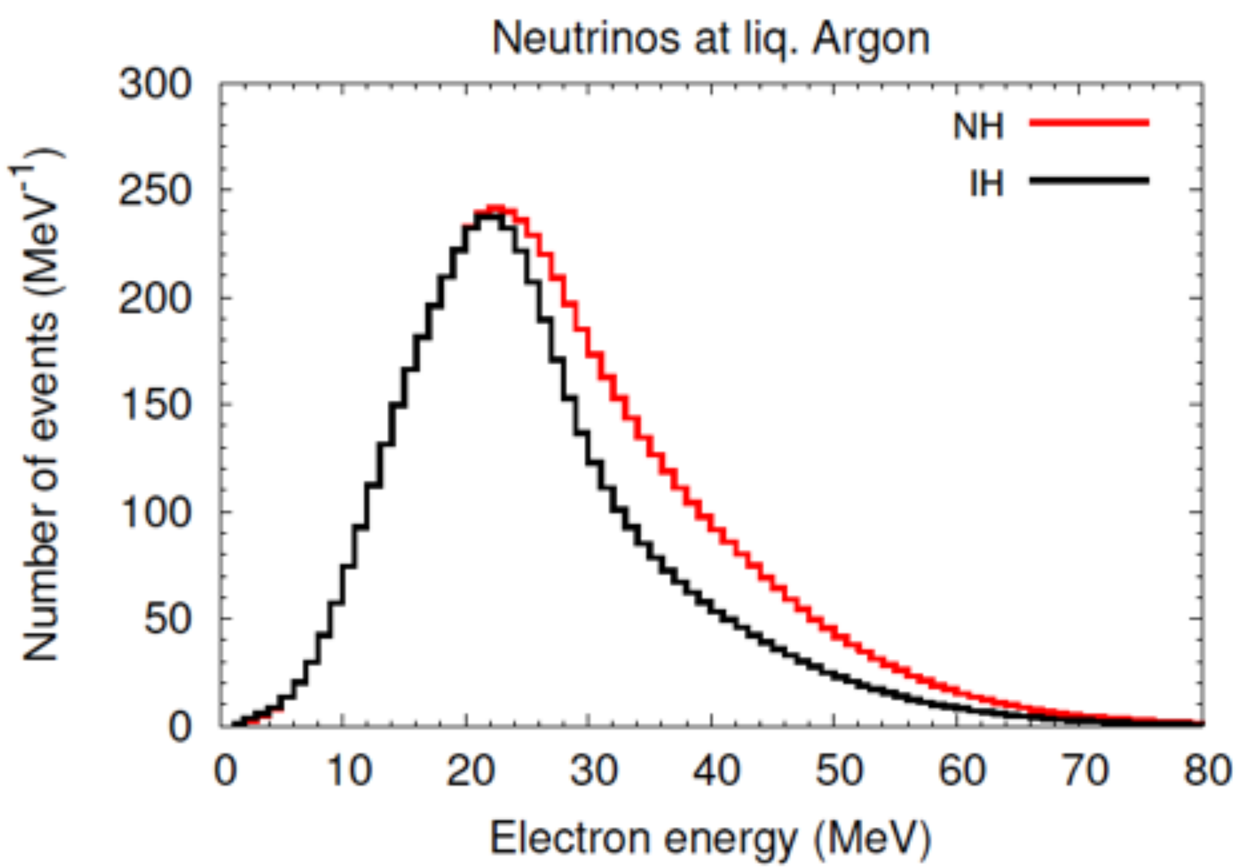
$$\langle E_e \rangle \approx 9 - 12 \text{ MeV}$$

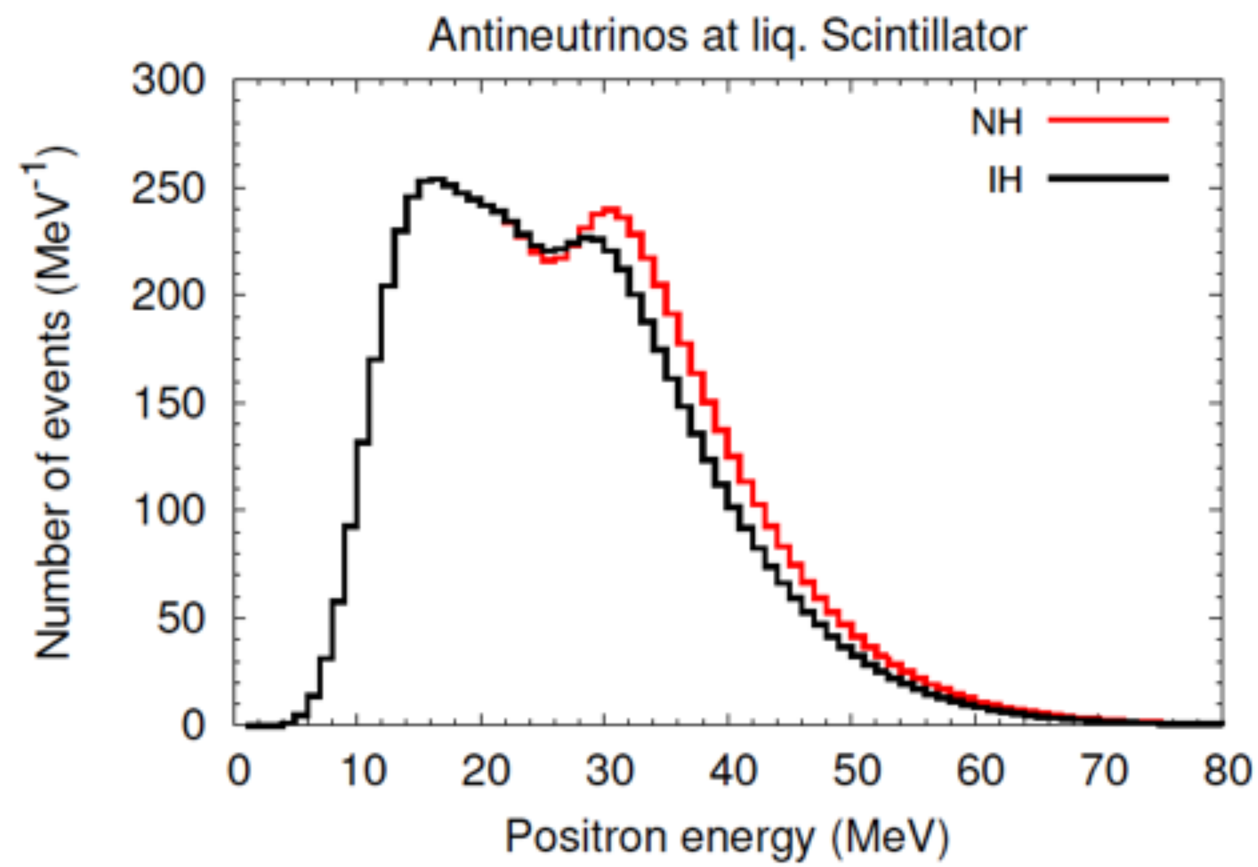
$$\langle E_{\bar{e}} \rangle \approx 14 - 17 \text{ MeV}$$

$$\langle E_x \rangle \approx 18 - 22 \text{ MeV}$$

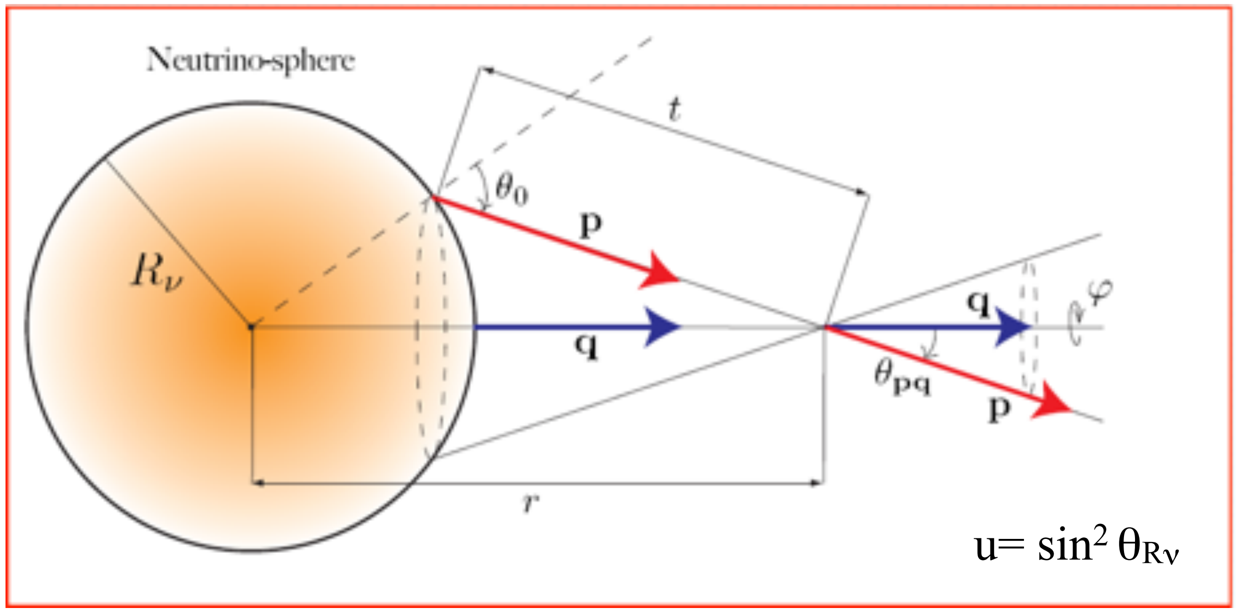
Observables signature?

Spectral split may be visible ad “shoulders”





However, still far from generic predictions about signatures of collective effects....Many layers of complications in the description of the flavor evolution!



- νs emitted from a spherical source acquire different phases at a given radius r.
- Matter effect is not the same for all the modes.
- It would introduce trajectory-dependent multi-angle effects.

Assumptions

- "half-isotropic" ν emission (outward-moving angular modes equally occupied)
- Azimuthal symmetry: physical conditions only depend on the distance r from the center of the star

$$\mathbf{v_p} \cdot \nabla_\mathbf{x} \varrho_{\mathbf{p},\mathbf{x}} \Rightarrow \quad \mathbf{v_p} \cdot \nabla_\mathbf{x} \to v_r \frac{d}{dr} \quad ,$$ (projecting the evolution along the radial direction)

Radiating object → stationary system evolving in space

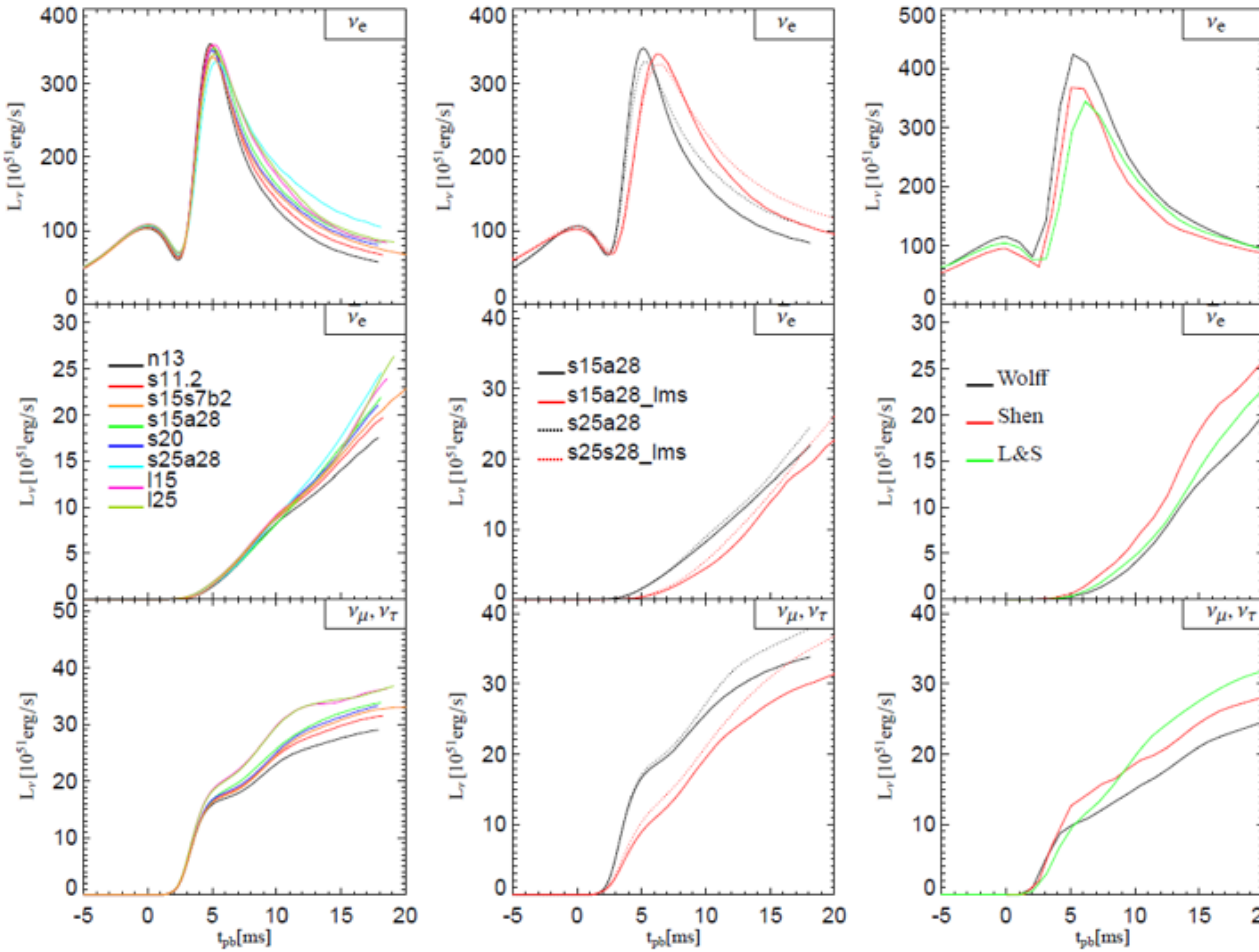
Full kinetics equations

$$\left(\frac{\partial}{\partial t} + \mathbf{v_p} \cdot \nabla_\mathbf{x} \right) \varrho_{t,\mathbf{p},\mathbf{x}} = -i[\Omega_{\mathbf{p},\mathbf{x}}, \varrho_{t,\mathbf{p},\mathbf{x}}]$$

seven-dimensional problem that has never been solved in its complete form.

Neutronization Burst as Standard Candle

Different mass **Neutrino transport** **Nuclear EoS** 3



If mixing scenario is known, perhaps best method to determine SN distance, especially if obscured (better than 5-10%)

[Kachelriess, Tomas, Buras, Janka, Marek & Rampp, astro-ph/0412082]