Neutrino Mass Hierarchy from Supernova Neutrinos

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MPI for Physics, Munich

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MARIE CURIE ACTIONS

MAX-PLANCK-GESELLSCHAFT

Outline

Supernova (SN) as Neutrino Source

Oscillation of SN Neutrinos

Signatures of Neutrino Mass Hierarchy

Conclusions

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Supernova (SN) as Neutrino Source

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Conclusions

Supernova one of the most energetic events in nature.

Terminal phase of a massive star ($M > 8\sim10\ M_{\odot}$)

Collapses and ejects the outer mantle in a <u>shock wave</u> driven explosion.

ENERGY SCALES: ~ 10^{53} erg : 99% energy is emitted by Neutrinos (Energy ~ 10 MeV).

TIME SCALE: The duration of the burst lasts ~10 s.

Neutrino Emission Phases

Neutronization burst

- Shock breakout
- De-leptonization of outer core layers
- **Duration ~ 25 ms**

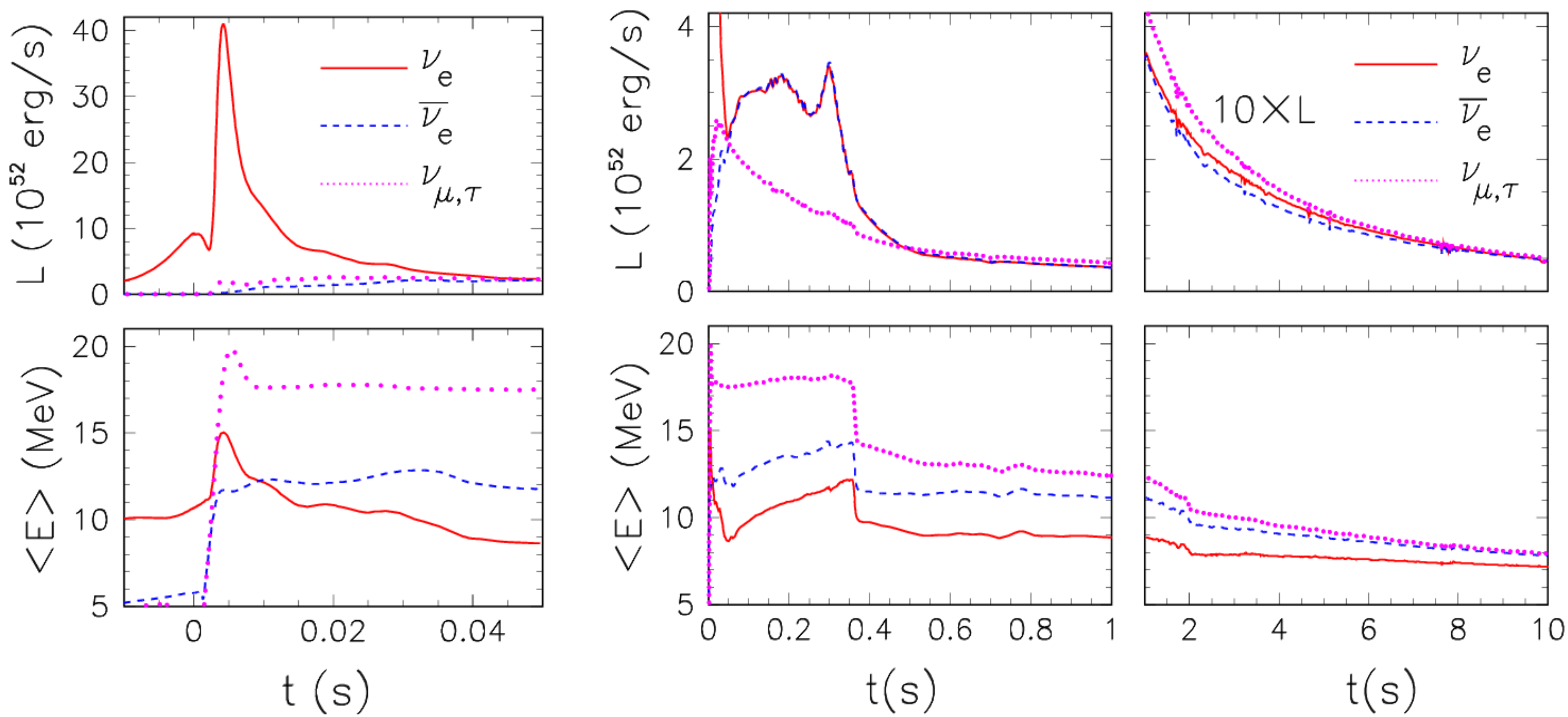
Accretion

- powered by infalling matter
- Stalled shock

Cooling

- Cooling by ν diffusion

Accretion: ~ 0.5 s ; Cooling: ~ 10 s



[Fischer et al. (Basel Simulations), A&A 517:A80,2010, 10. 8 M_{sun} progenitor mass]

Plan of the talk

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SN ν Flavor Evolution

The flavor evolution in matter is described by the non-linear MSW equations:

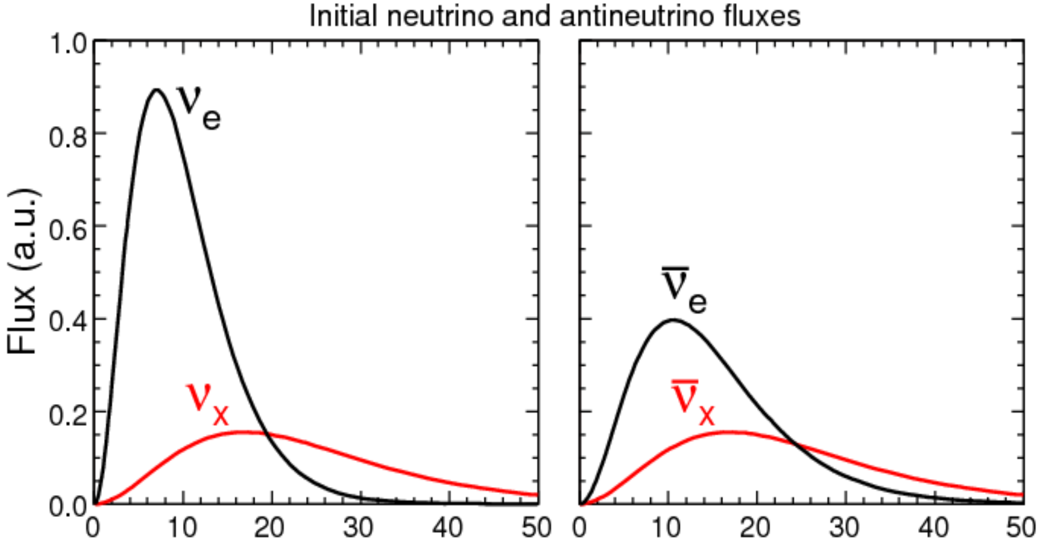
$$i\frac{d}{dx}\psi_\nu = \left(H_{vac} + H_e + H_{\nu\nu}\right)\psi_\nu$$

In the standard 3ν framework

- $$H_{vac} = \frac{U\ M^2\ U^\dagger}{2E}$$ **Kinematical mass-mixing term**
- $$H_e = \sqrt{2}G_F \,\mathrm{diag}(N_e, 0, 0)$$ **Dynamical MSW term (in matter)**
- $$H_{\nu\nu} = \sqrt{2}G_F \int (1-\cos\theta_{pq})\left(\rho_q - \bar{\rho}_q\right) dq$$ **Neutrino-neutrino interactions term (non-linear)**

Spectral Splits in the Accretion Phase

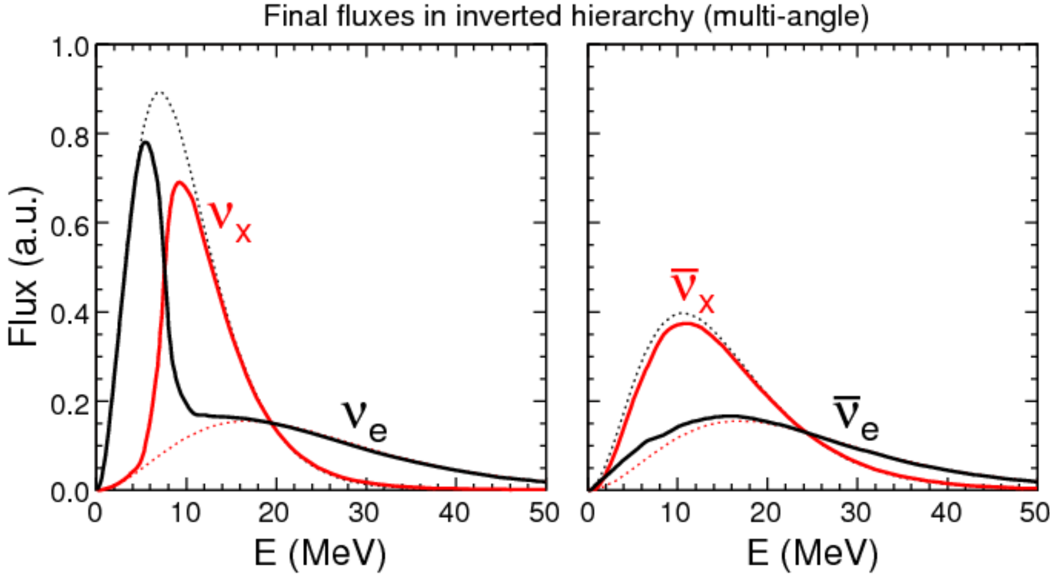
[Fogli, Lisi, Marrone, Mirizzi, arXiV: 0707.1998 [hep-ph]]



Initial fluxes typical of accretion phase at neutrinosphere (r ~10 km)

$$F_{\nu e} : F_{\bar{\nu} e} : F_{\nu x} = 2.4 : 1.6 : 1.0$$

Inverted mass hierarchy (IH)

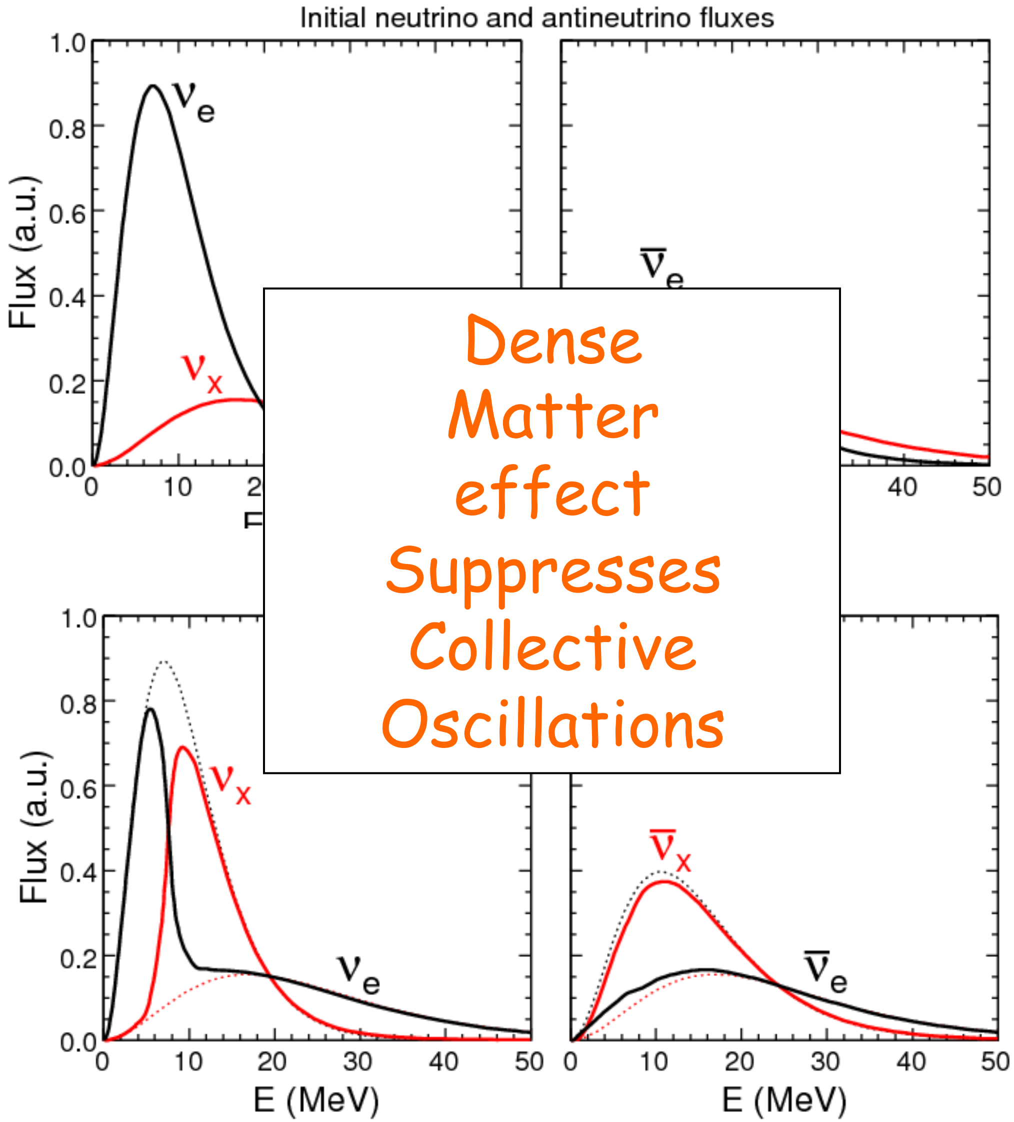


Fluxes at the end of collective effects (r ~200 km)

Nothing happens in Normal Hierarchy (NH)

Suppression of Collective effects

Dense matter (n_e) dominates over nu-nu interaction (n_ν).



Dense Matter effect Suppresses Collective Oscillations

[**S.C**, Fischer, Mirizzi, Saviano &Tomas
PRL 107:151101, 2011
PRD 84:025002, 2011

Sarikas, Raffelt, Hüdepohl & Janka
PRL 108:061101, 2012

Dasgupta, P. O'Connor, Ott
PRD 85:065008, 2012]

Suppression of Collective effects

Predictions are robust when collective effects are suppressed, i.e.:

1) Neutronization burst (t < 20 ms)

large ν_e excess and ν_x deficit

[Hannestad et al., astro-ph/0608695]

2) Accretion phase (t < 500 ms)

Dense matter term dominates over nu-nu interaction term.

[S.C, Fischer, Mirizzi, Saviano &Tomas

PRL 107:151101, 2011
PRD 84:025002, 2011]

SN neutrino Flux at Earth

Neutronization burst & Accretion Phase:

Normal Hierarchy (NH):

$$F_{\nu_e} = F^0_{\nu_x}$$

$$F_{\bar{\nu}_e} = \cos^2\vartheta_{12}(F^0_{\bar{\nu}_e} - F^0_{\nu_x}) + F^0_{\nu_x}$$

Inverted Hierarchy (IH):

$$F_{\nu_e} = \sin^2\vartheta_{12}(F^0_{\nu_e} - F^0_{\nu_x}) + F^0_{\nu_x}$$

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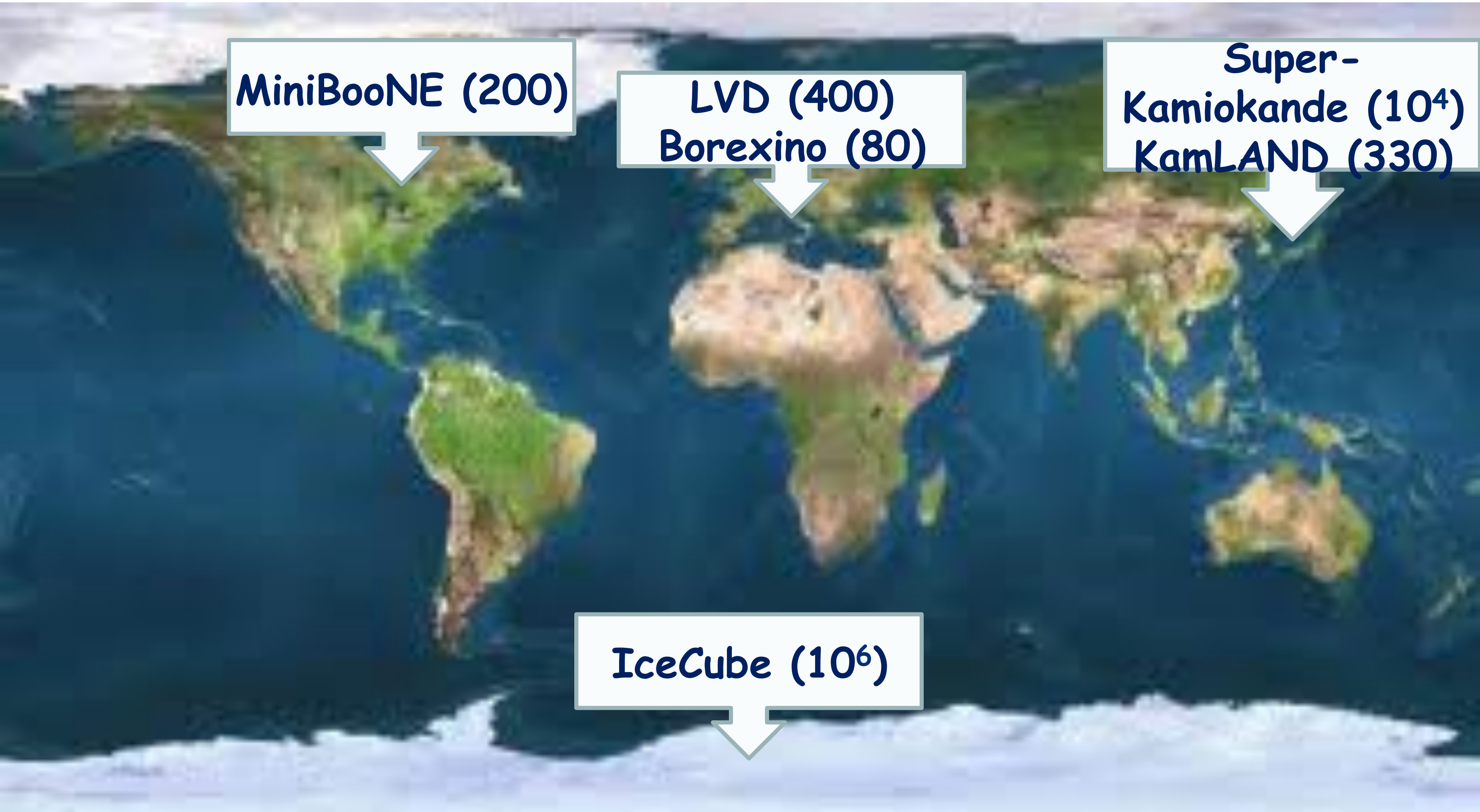
Large Detectors for Supernova Neutrinos

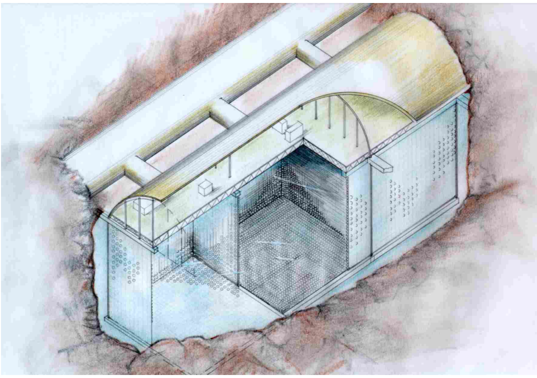


In brackets events for a “fiducial SN” at distance 10 kpc

Next generation Detectors for Supernova Neutrinos

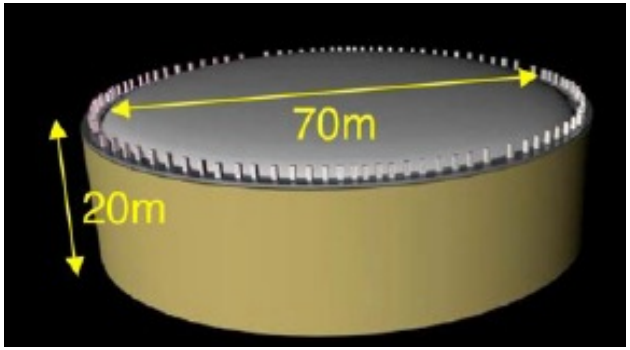
Next-generation large volume detectors might open a new era in SN neutrino detection:

Mton Cherenkov



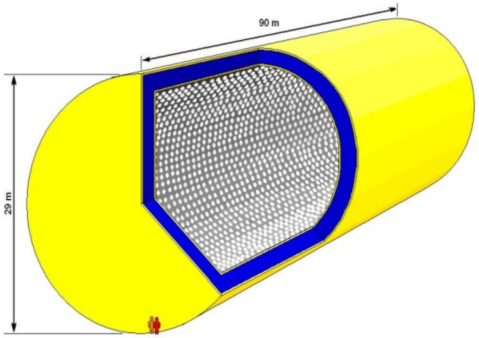
UNO, MEMPHYS, HYPER-K

LAr TPC



GLACIER

Scintillator



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Neutrino Emission Phases

Neutronization burst	Accretion	Cooling
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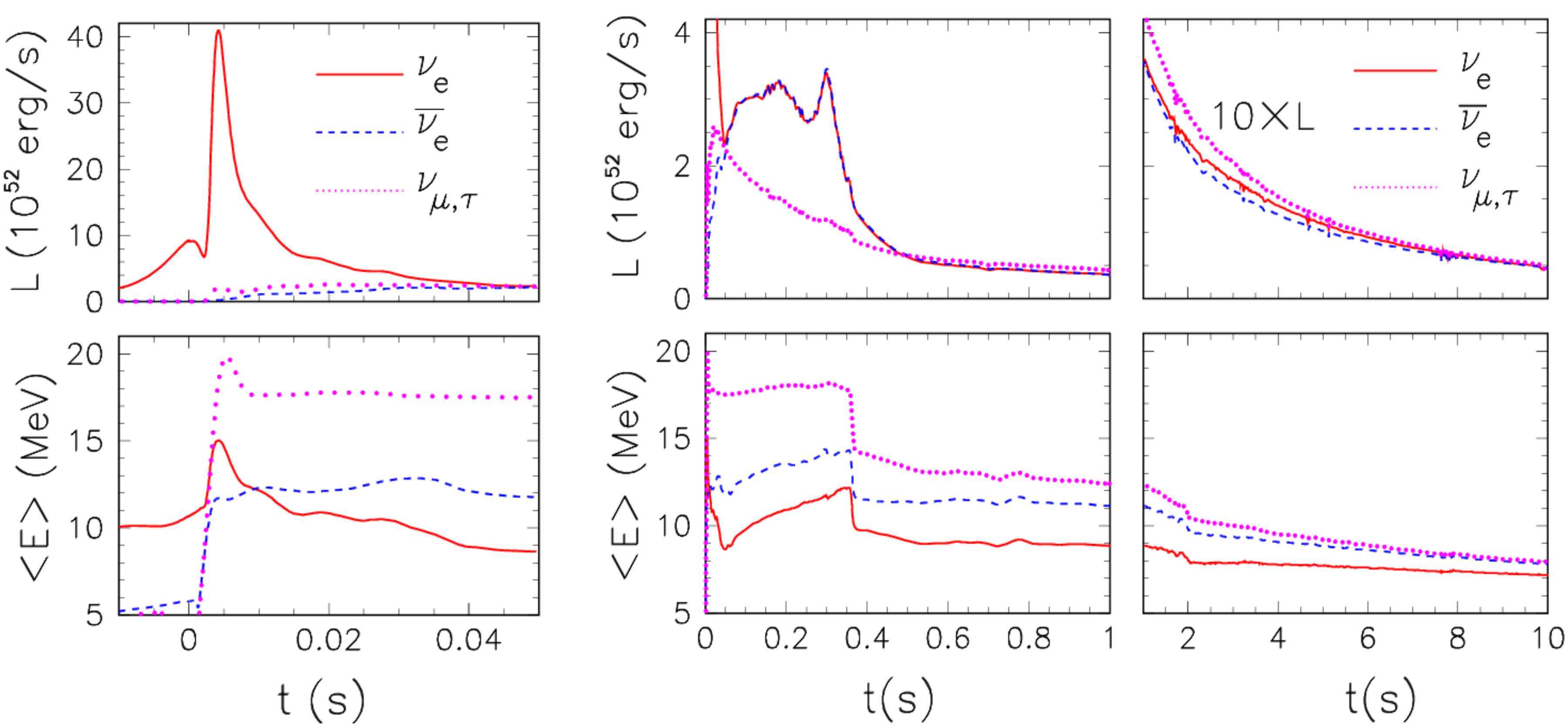
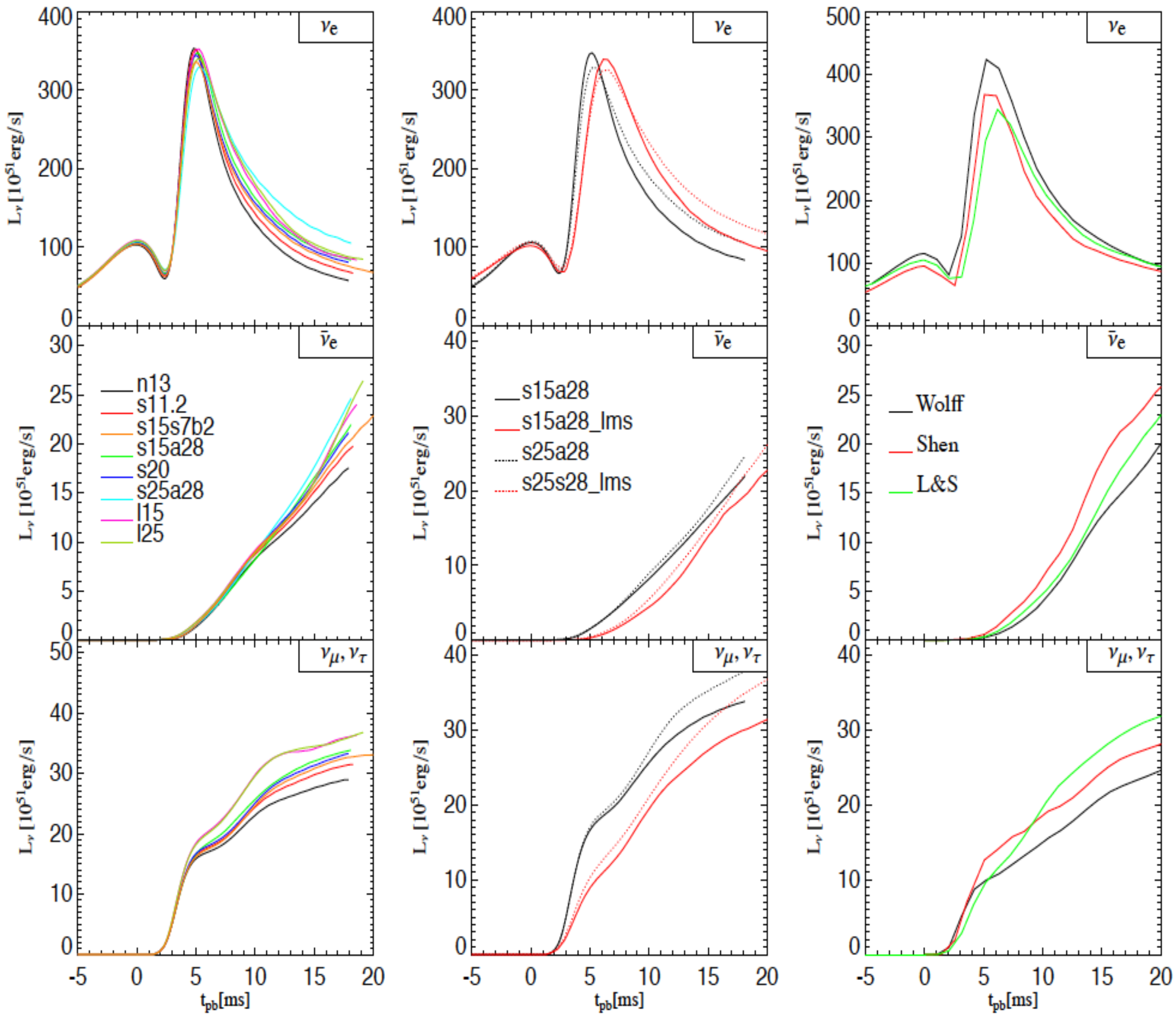


[Fischer et al. (Basel Simulations), A&A 517:A80,2010, 10. 8 M_{sun} progenitor mass]

Neutronization Burst : Model Independence

Different mass | Neutrino Transport | Nuclear EoS

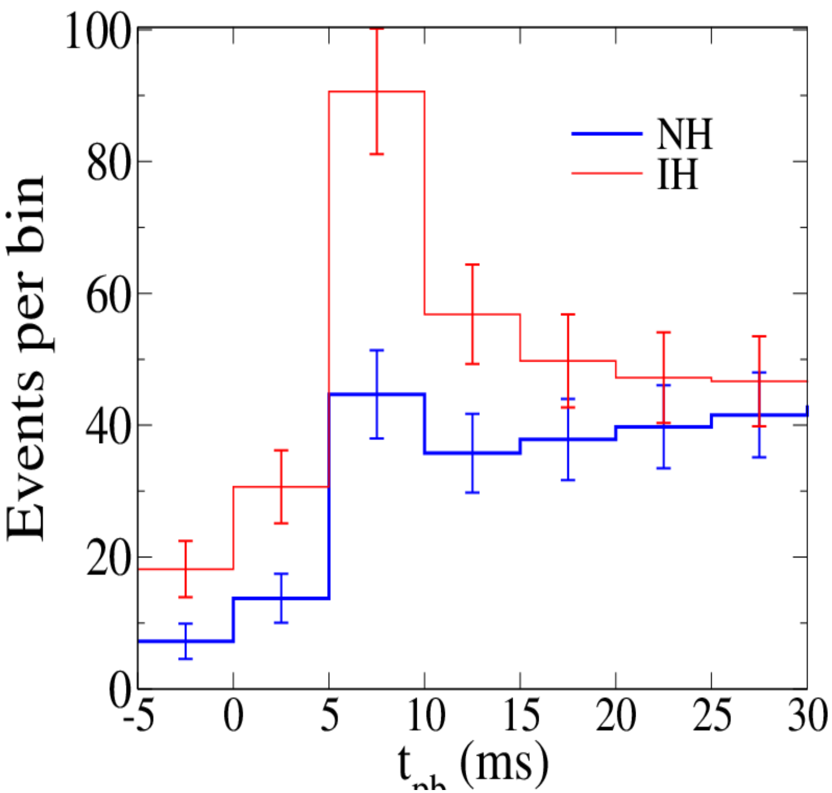


'Standard Candle' for SN Neutrino

[M.Kachelriess et al, hep-ph/0412082]

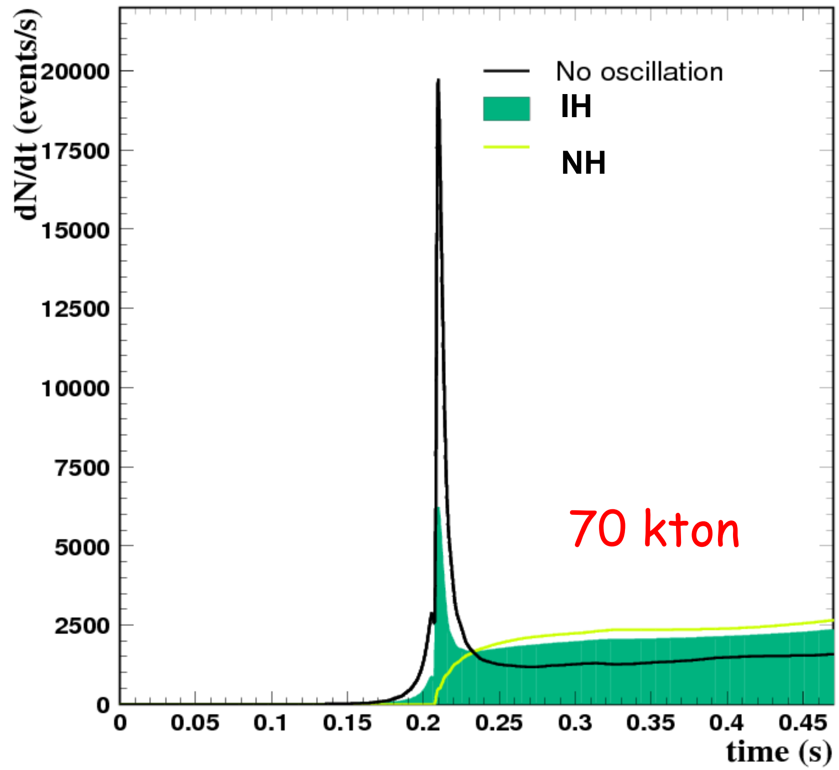
Oscillations in the Neutronization Burst

Water Cherencov ($\nu_{e,x}\, e^- \longrightarrow \nu_{e,x}\, e^-$)



[M.Kachelriess et al, hep-ph/0412082]

Liq Ar TPC $\nu_e\,^{40}Ar$ CC

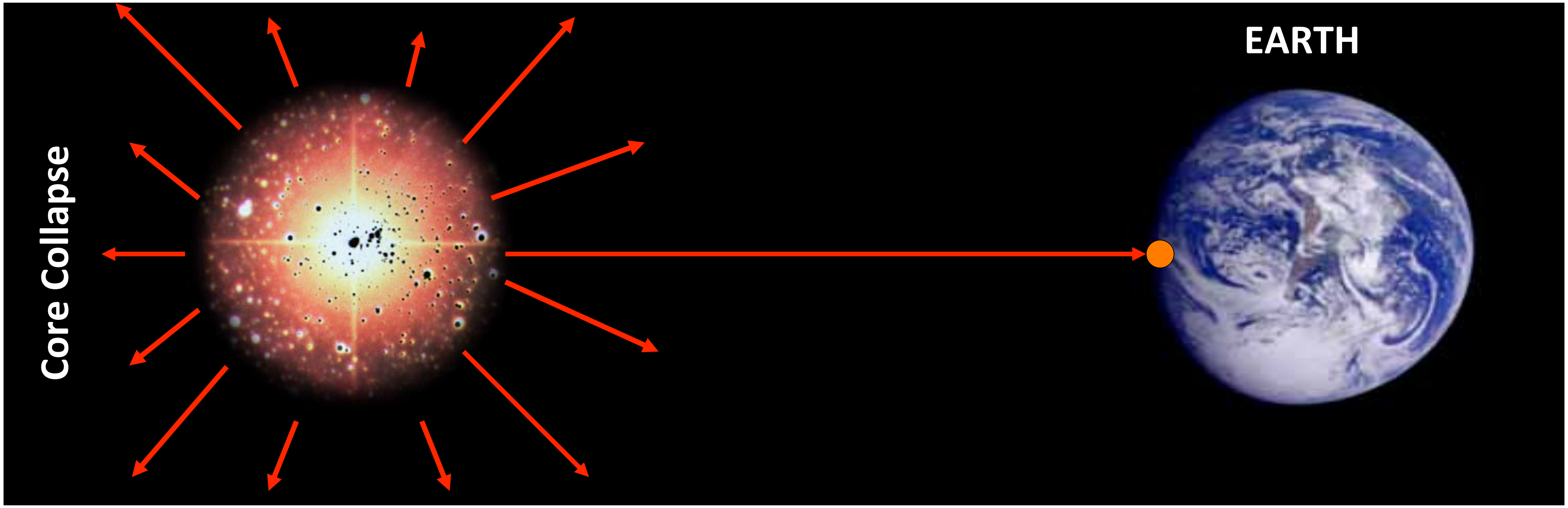


[I.Gil-Botella & A.Rubbia, hep-ph/0307244]

- Peak is absent ⟶ NH ($F_{\nu_e} = F^0_{\nu_x}$)
- Peak is seen ⟶ IH ($F_{\nu_e} = \sin^2\vartheta_{12}(F^0_{\nu_e} - F^0_{\nu_x}) + F^0_{\nu_x}$)

SN neutrino Flux at Earth

Earth Matter Effect:



[Dighe, Keil & Raffelt, hep-ph/0304150]

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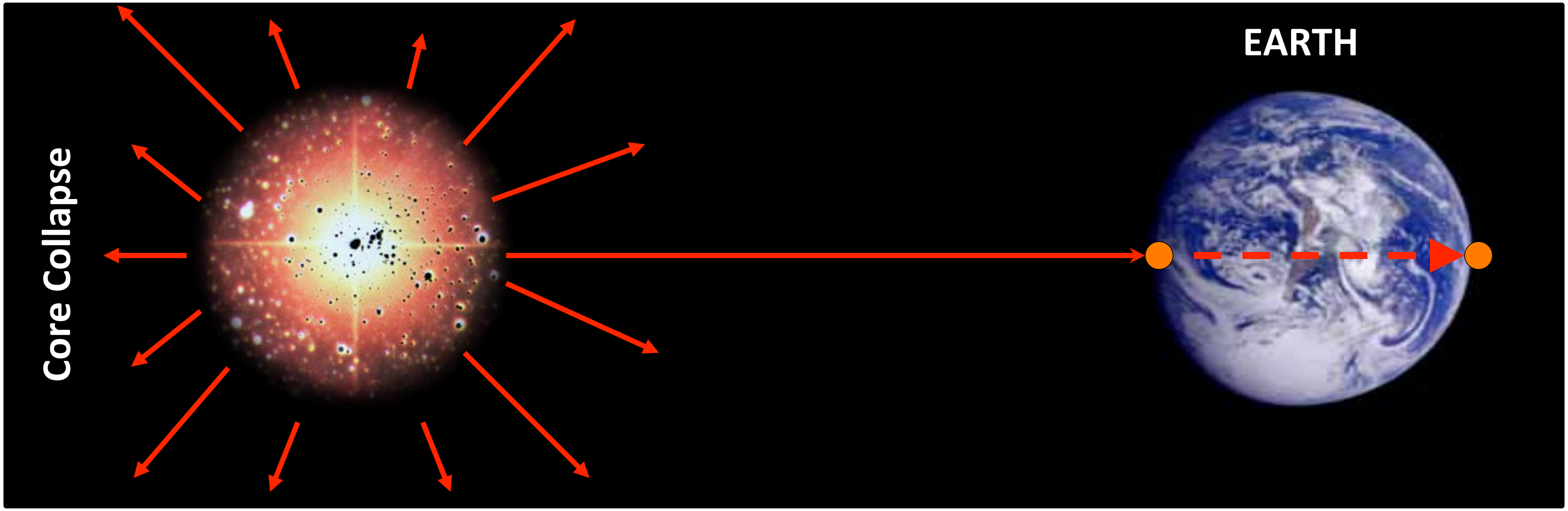

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SN neutrino Flux at Earth

Earth Matter Effect:

$$F_{\bar{e}}^{D} = \sin^2\theta_{12} F_{\bar{x}}^0 + \cos^2\theta_{12} F_{\bar{e}}^0 + \Delta F^0 \bar{A}_\oplus \sin^2(12.5\,\overline{\Delta m^2_\oplus} L/E)$$

Normal Hierarchy (NH):

$$F_{\nu_e} = F^0_{\nu_x} \quad \text{(No E.M)}$$

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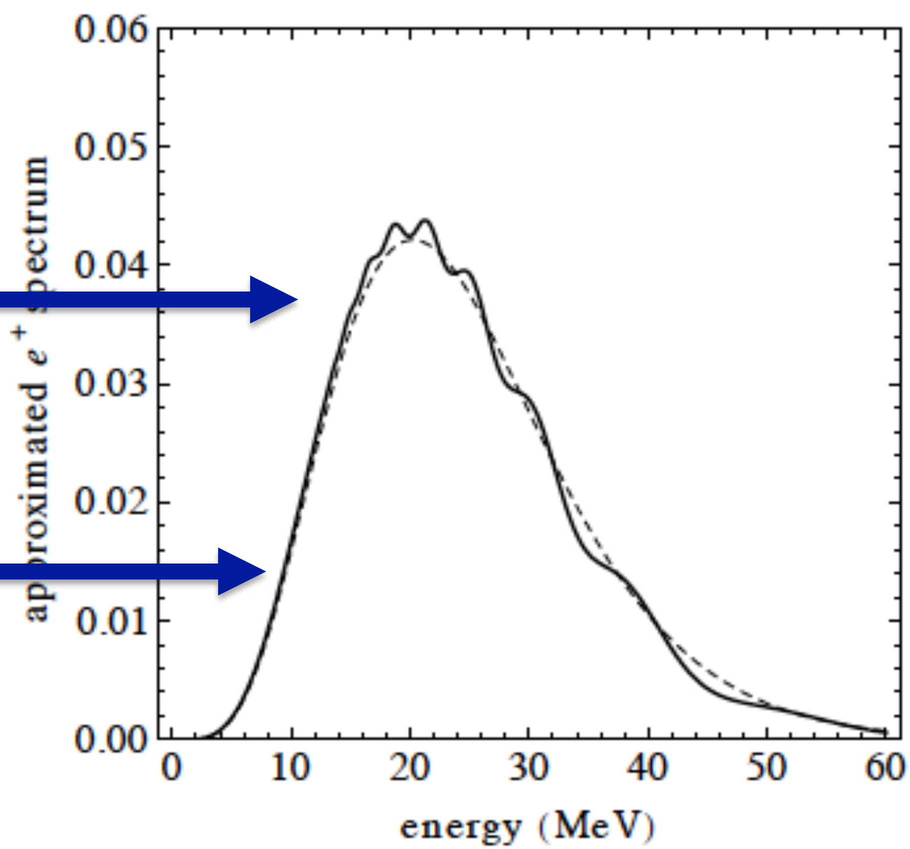

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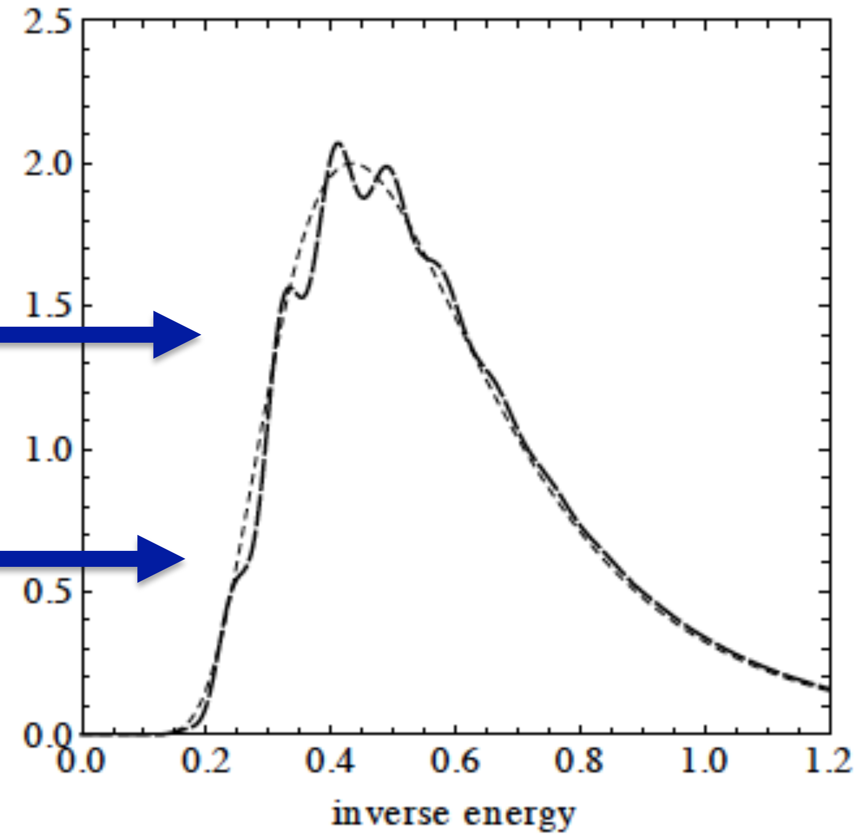

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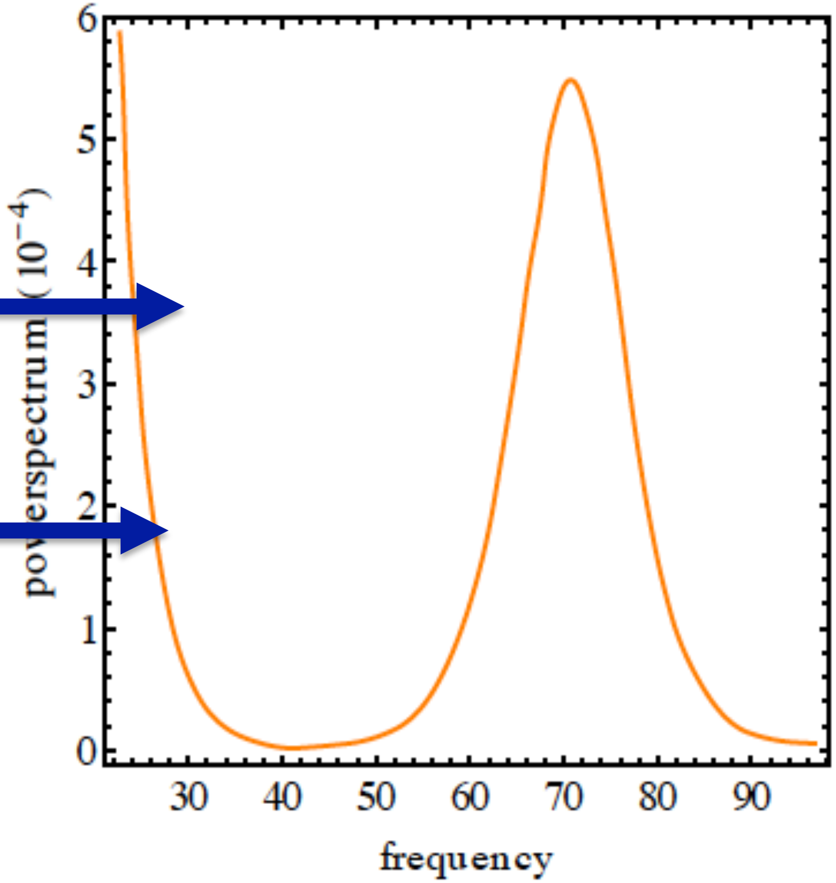

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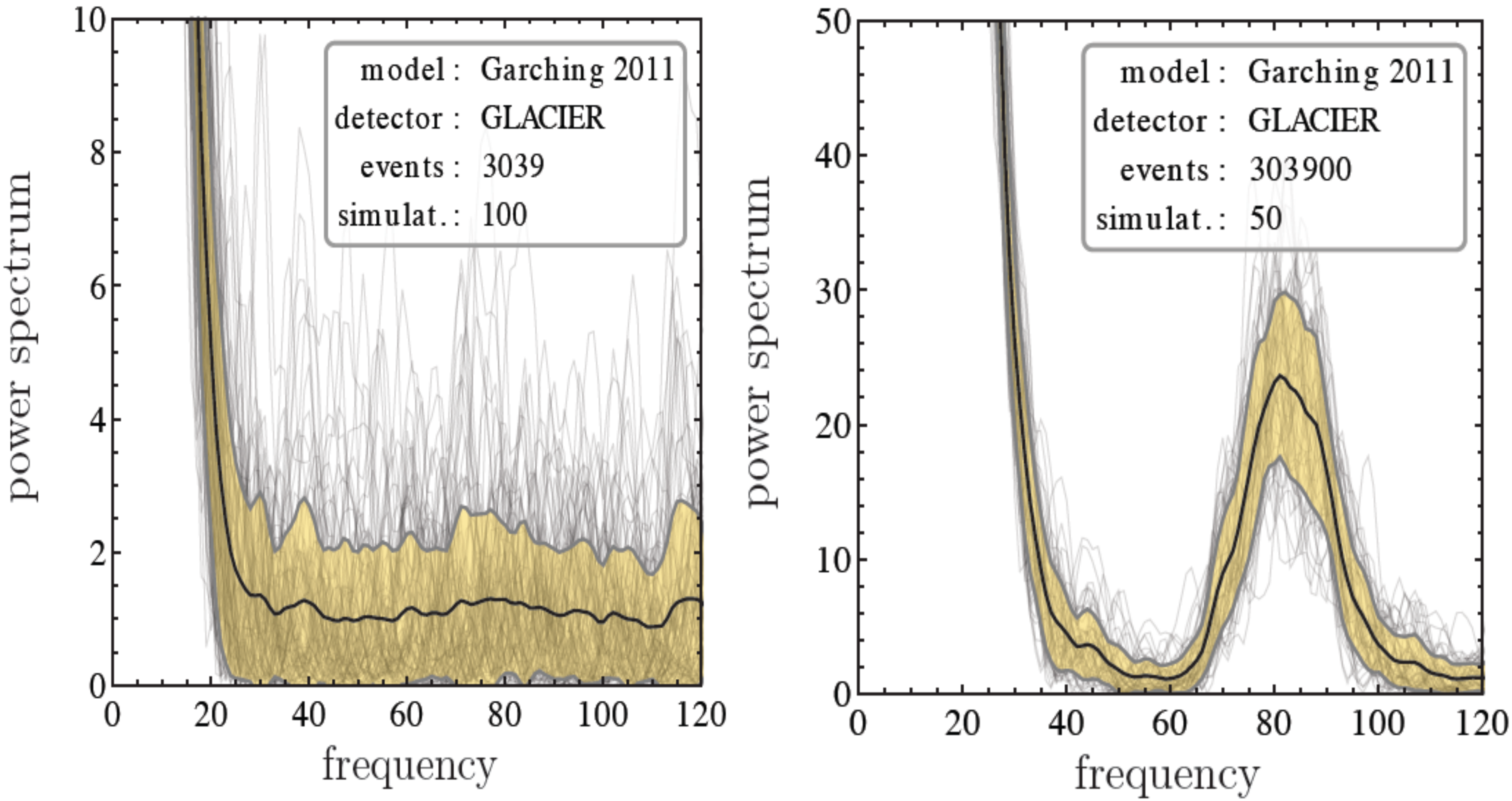
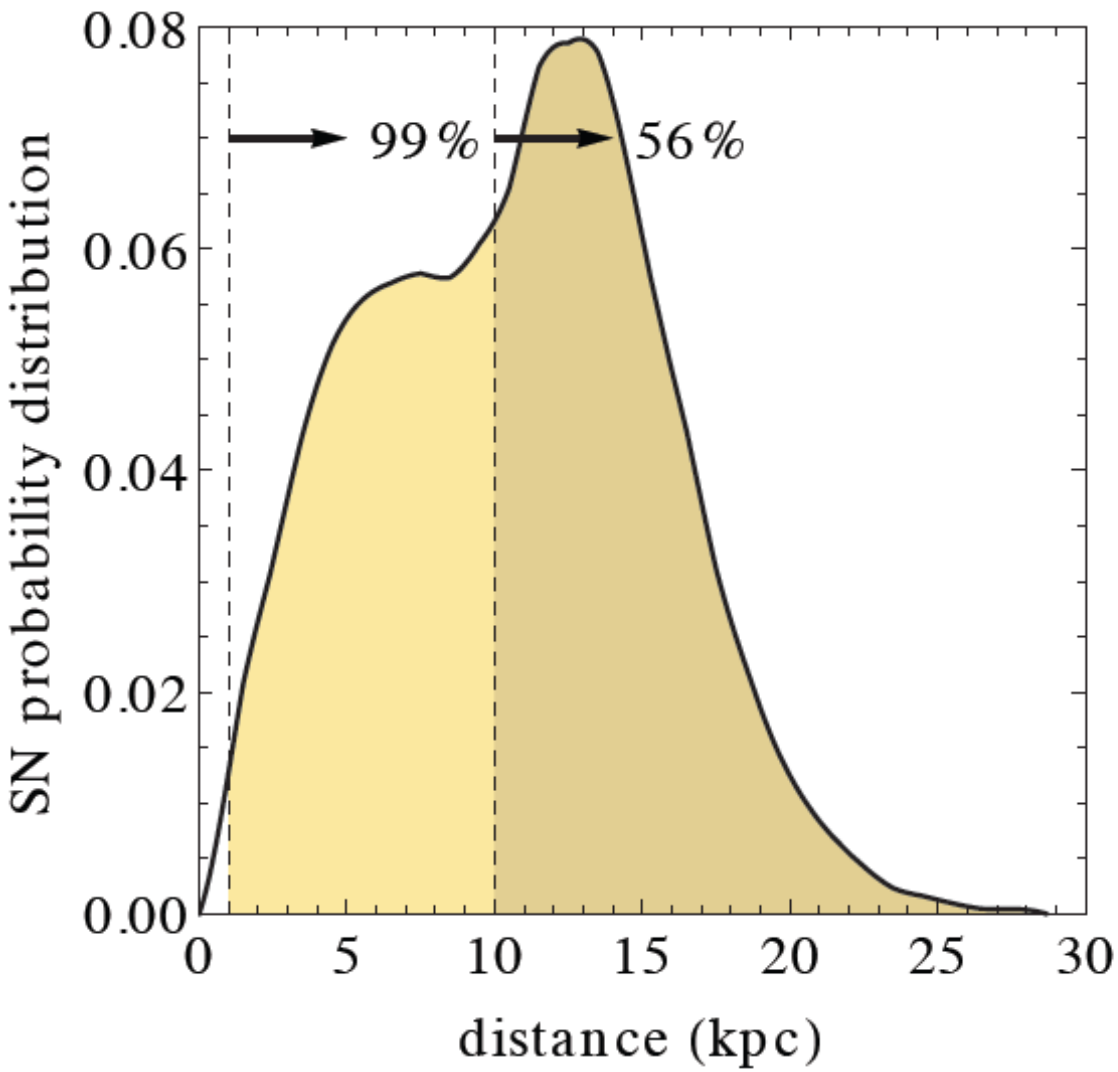


[Borriello, S.C, Mirizzi, Serpico; PRD 86 (2012)]

Galactic SN Distribution



Possible sub-kpc candidate:

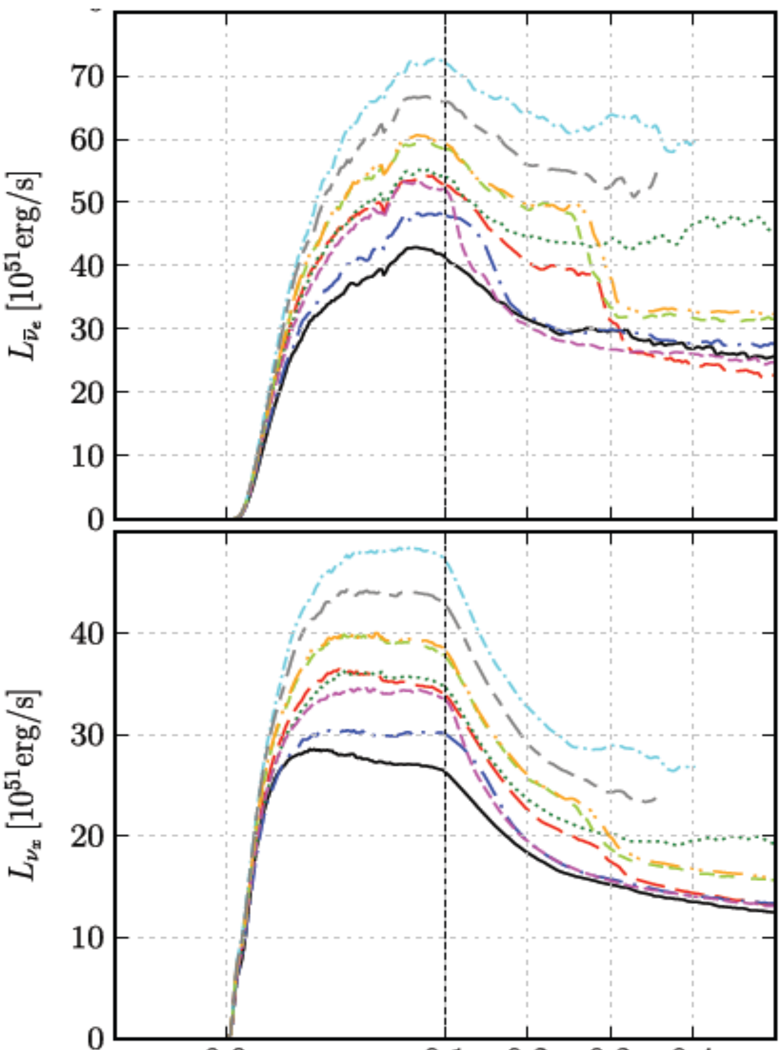
Red supergiant Betelguse

distance~ 0.2 kpc

Event count~ 10s of million

[Mirizzi, Raffelt & Serpico; (2006)]

Rise time Analysis: Hierarchy Determination



- High degeneracy of ν_e and e, suppresses $\bar{\nu}_e$ production.
- $\bar{\nu}_e$ more in equilibrium with environment than ν_x.

Flux of ν_x rises faster than $\bar{\nu}_e$

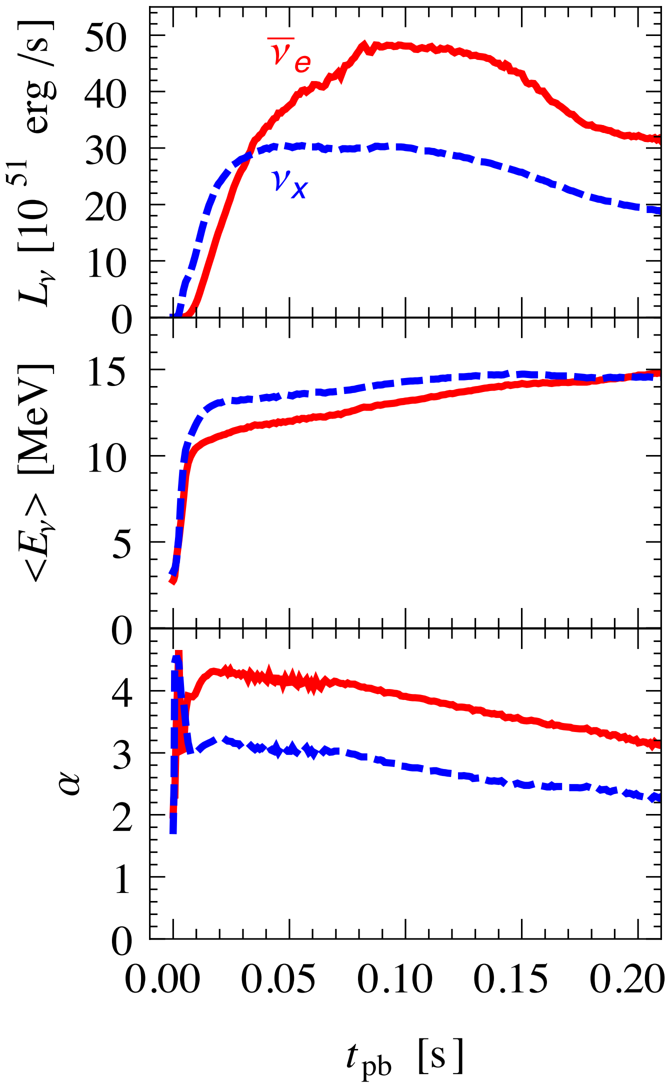
NH: $$F_{\bar{\nu}_e} = \cos^2\vartheta_{12}(F^0_{\bar{\nu}_e} - F^0_{\nu_x}) + F^0_{\nu_x}$$

IH: $$F_{\bar{\nu}_e} = F^0_{\nu_x}$$

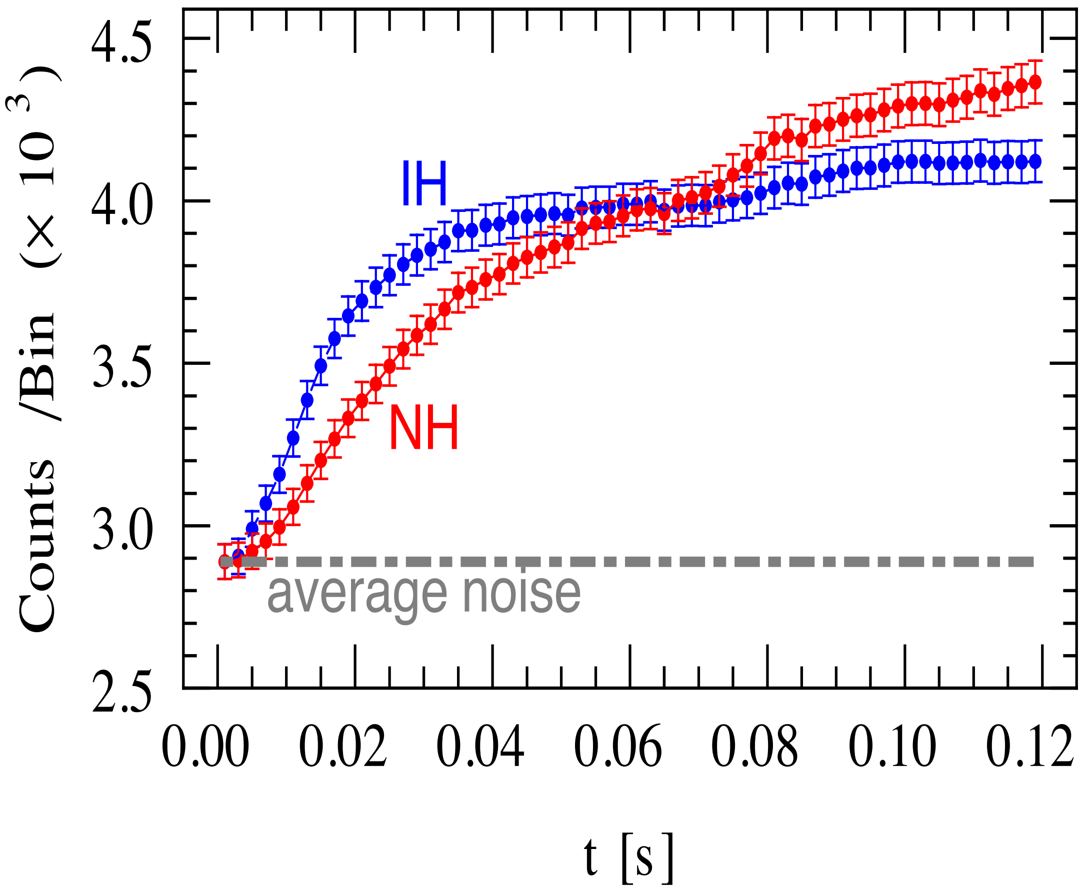
Flux in IH (ν_x) rises faster than NH (ν_x, $\bar{\nu}_e$)

[Serpico, S.C, Fischer, Hüdepohl, Janka & Mirizzi
PRD 85:085031,2012]

Rise time Analysis: Hierarchy Determination



15 Solar Mass
in Ice-Cube



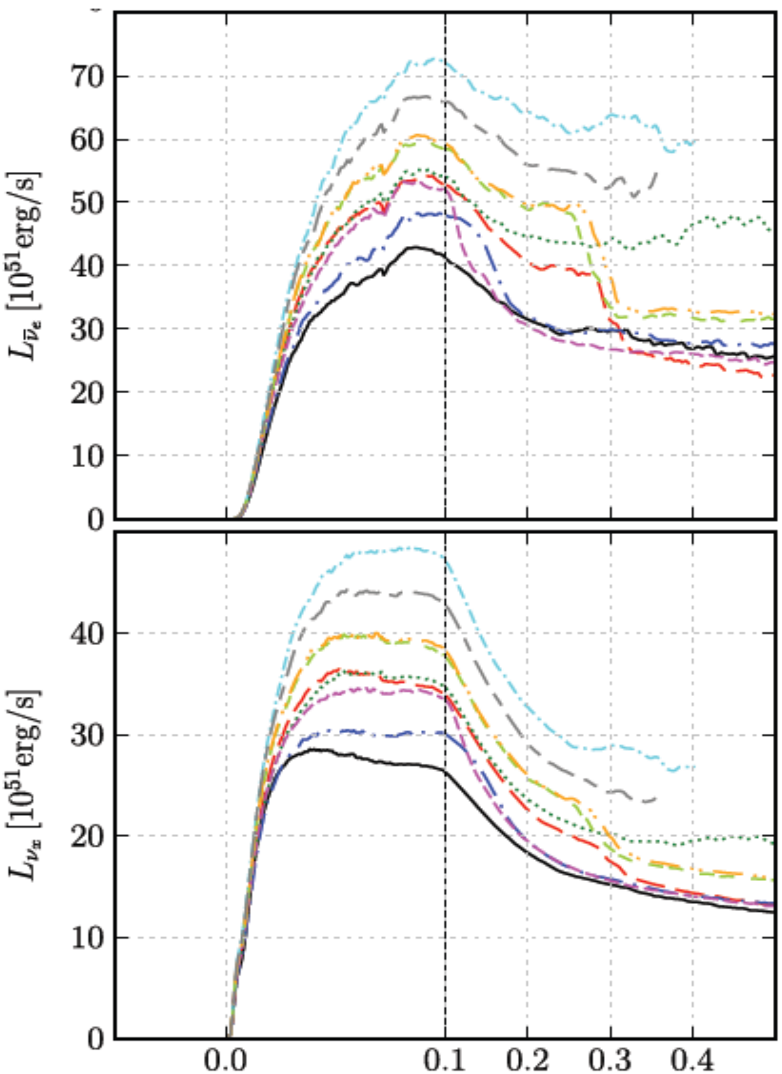
Flux in IH rises faster than NH

[Serpico, **S.C**, Fischer, Hüdepohl, Janka & Mirizzi
PRD 85:085031,2012]

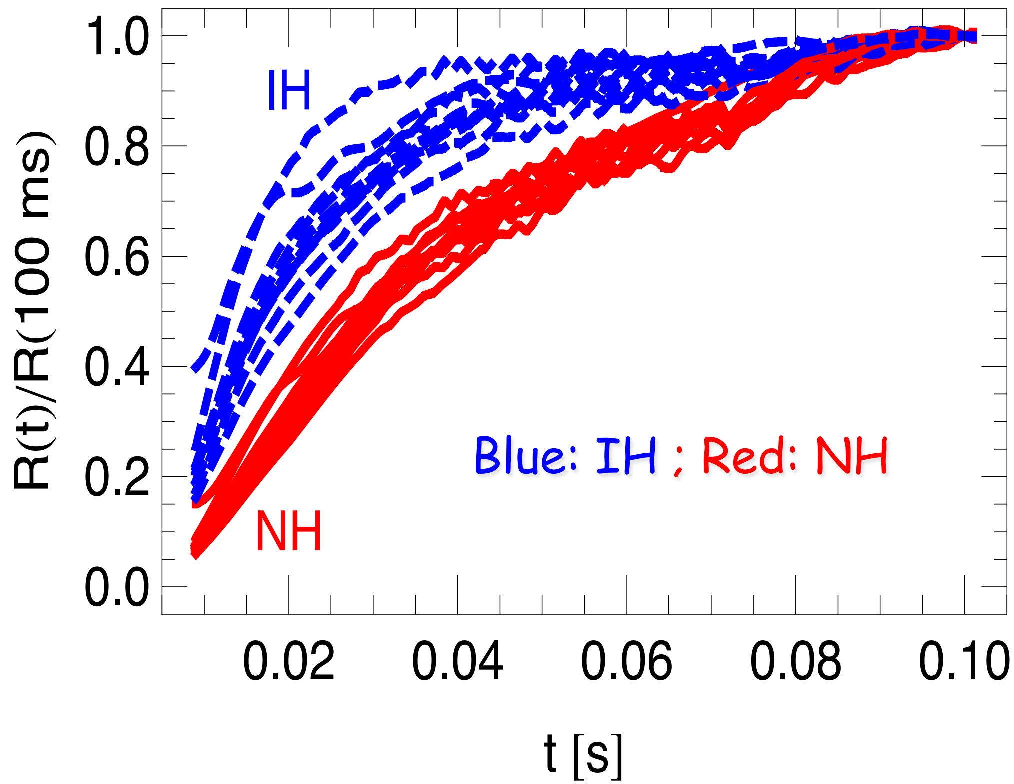
Rise time Analysis: Hierarchy Determination

Normalized Count rate :

10 different models (12 $M_\odot$-40 $M_\odot$)



Garching group, 2011



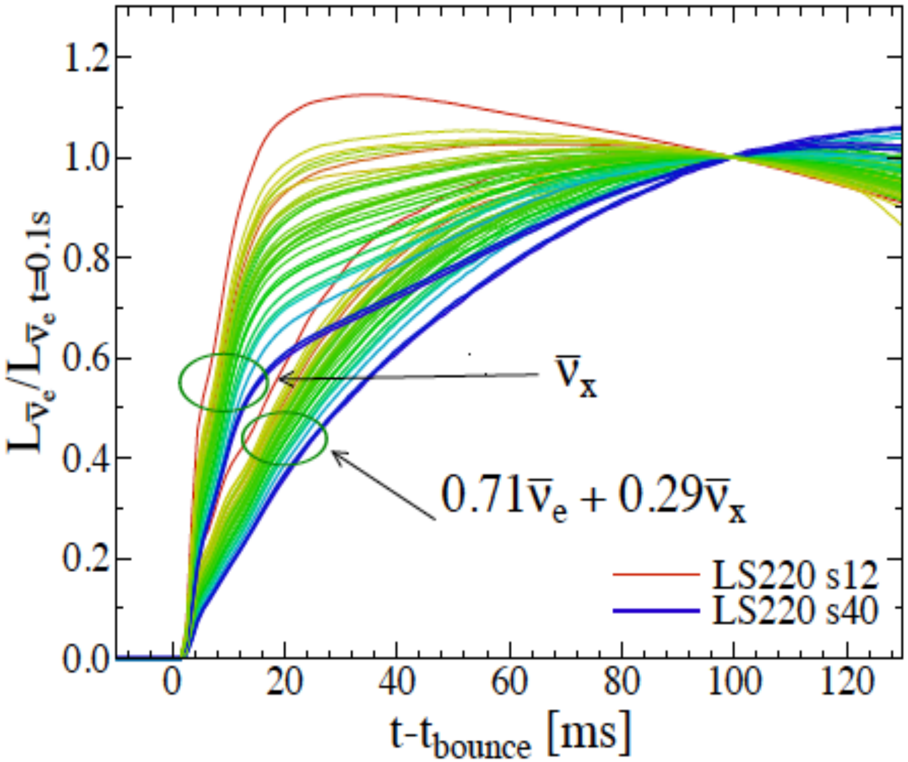
Flux in IH rises faster than NH

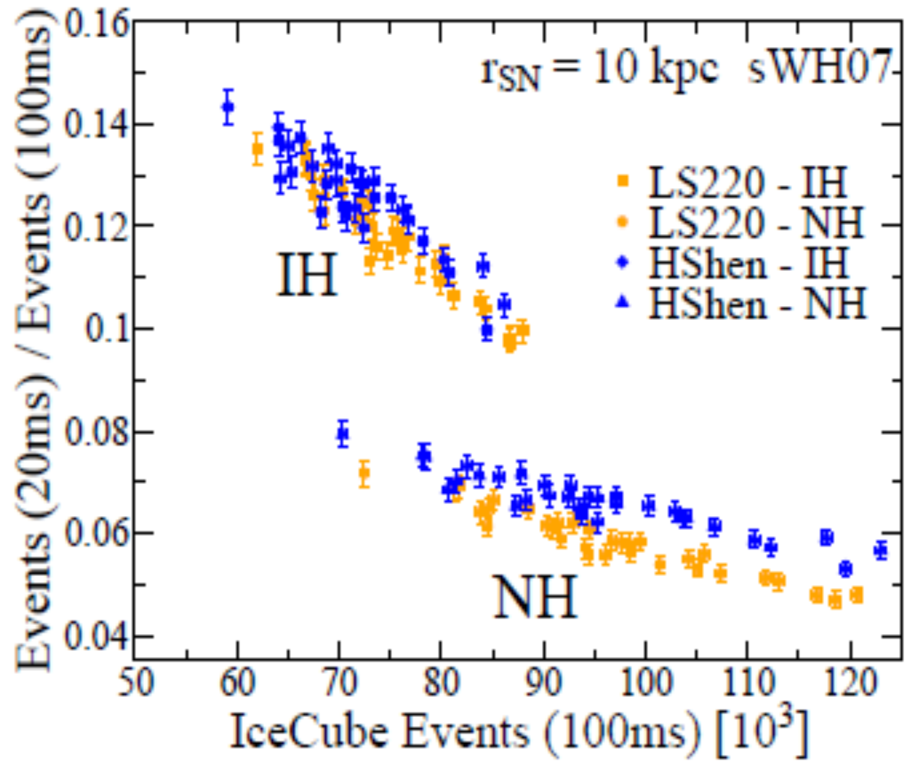
[Serpico, **S.C**, Fischer, Hüdepohl, Janka & Mirizzi
PRD 85:085031,2012]

Rise time Analysis: Hierarchy Determination

Normalized Count rate :
32 different models

[C.D. Ott et al. Neutrino 2012, Japan, 1212.4250]





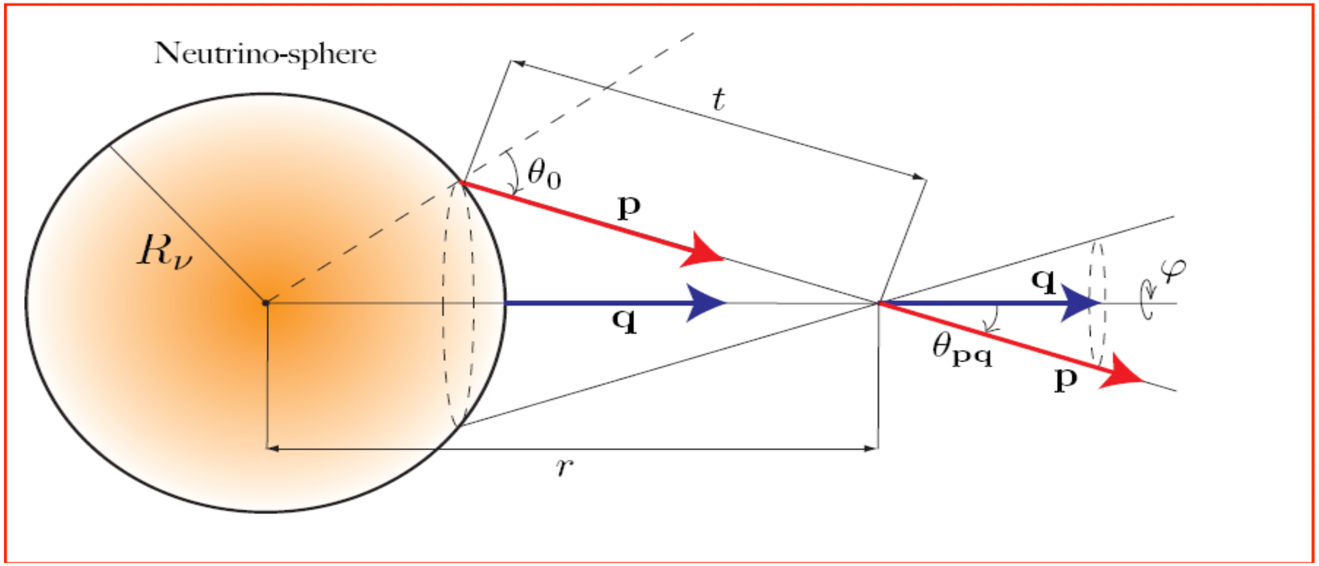
It would be important in future to study the robustness of the rise time signature with more and more accurate simulations.

Conclusions

- Observing SN neutrinos is the next frontier of low-energy neutrino astronomy.
- Collective effects are suppressed in early SN phases, implying hierarchy sensitivity at large θ_{13}.
- Neutronization phase is the best phase to probe mass hiearchy.
- Earth Matter effect: Detectable for Sub-kpc SNe.
- Rise time of SNe signal contains hierarchy information.


LOOKING FORWARD
FOR THE NEXT
GALACTIC SN !
Thank You !

Appendix: Matter Suppression



- Neutrinos emitted from spherical source, travel on different trajectories.
- Different oscillation phases for neutrinos traveling in different paths.
- Strong ν–ν interaction can overcome trajectory dependent dispersion.

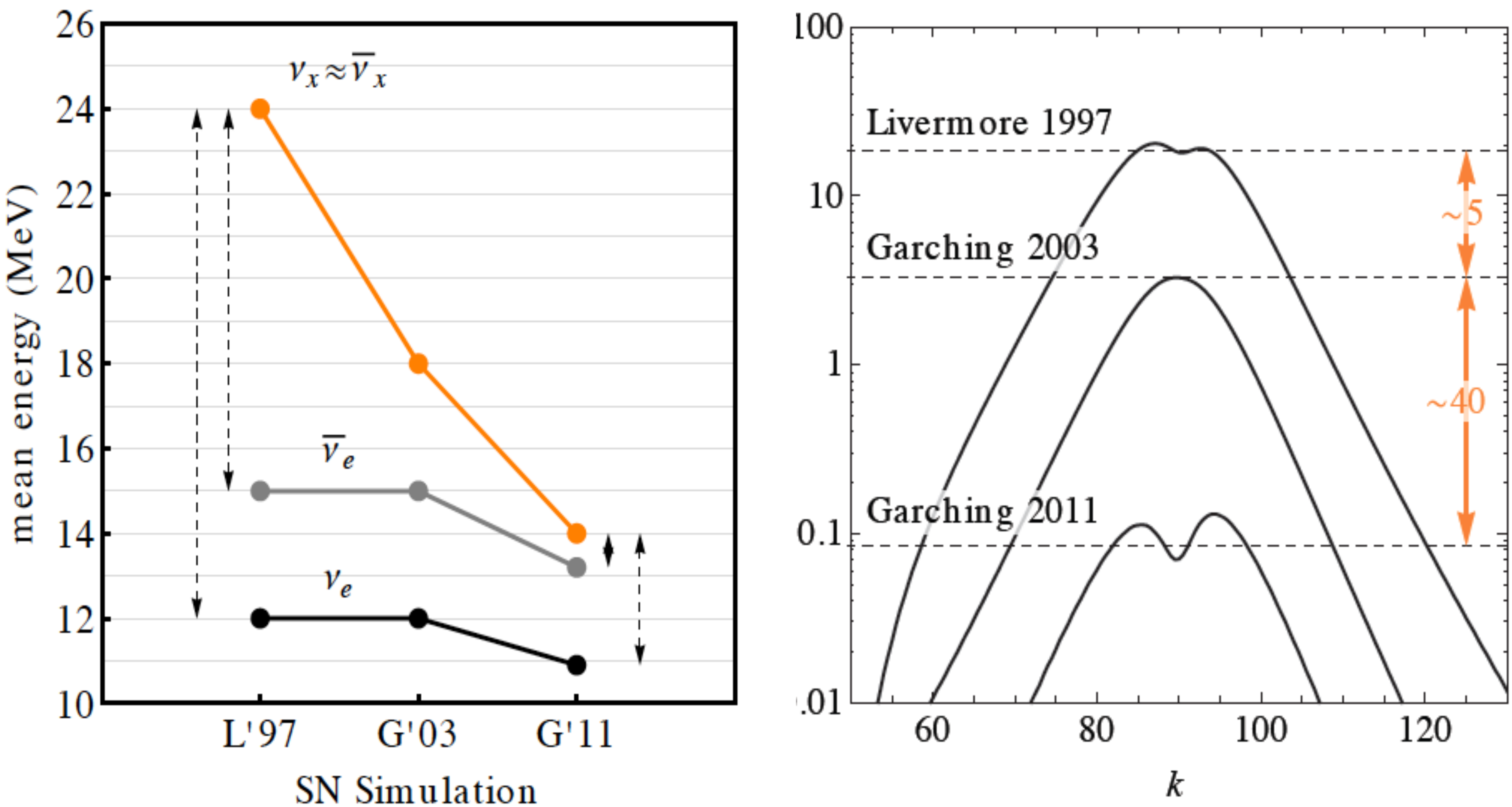
Collective conversion requires : $n_e << n_\nu$

Collective conversion is matter Suppressed : $n_e \gtrsim n_\nu$

[Esteban-Pretel, Mirizzi, Pastor, Tomas, Raffelt, Serpico & Sigl, arxiv: 0807.0659]

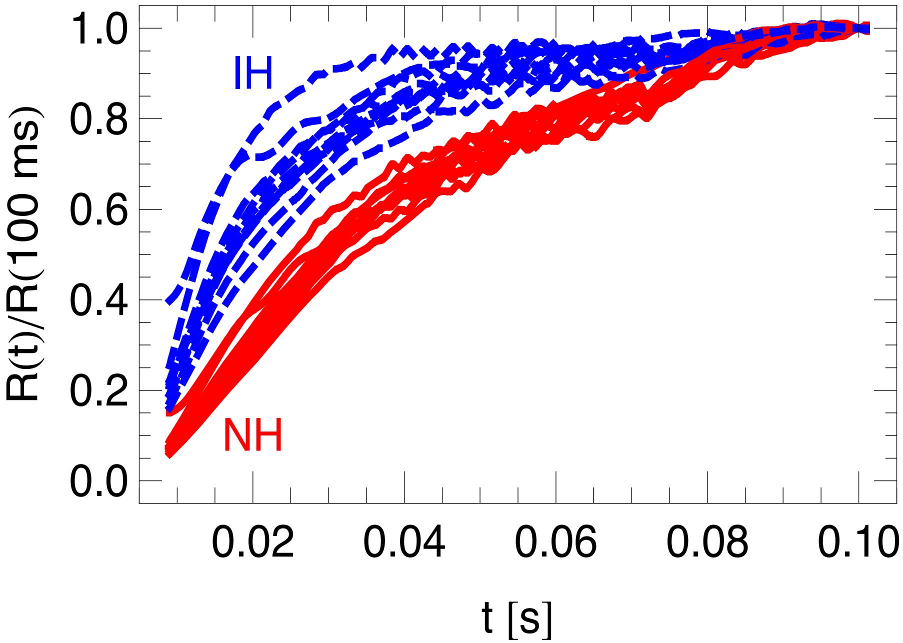
Appendix: SN antineutrino Flux at Earth

Earth Matter Effect:

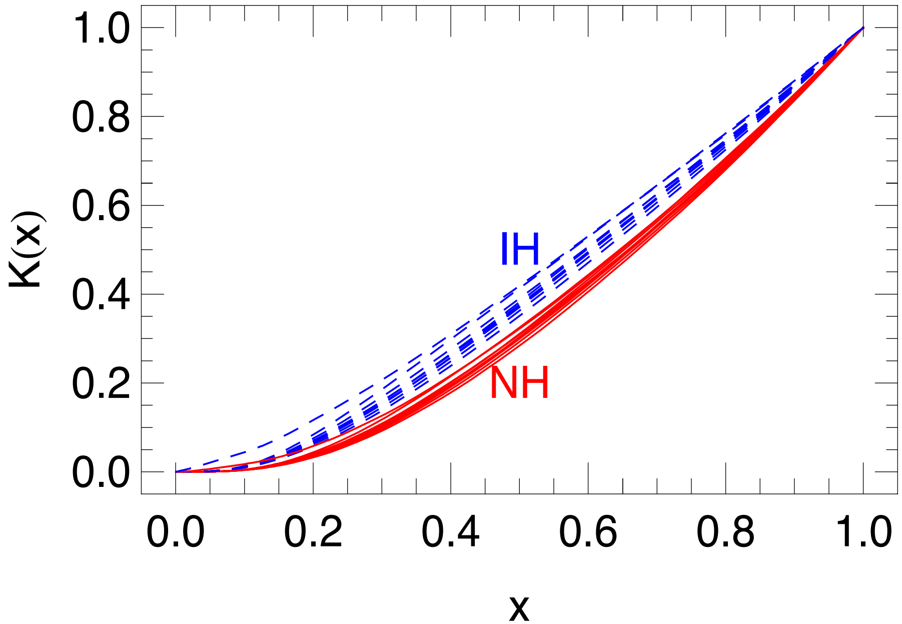


[Borriello, S.C, Mirizzi, Serpico; PRD 86 (2012)]

Appendix: Rise time Analysis: Hierarchy Determination



Count rate (normalized to value at 100 ms)
10 different models, masses 12 to 40 Msun
[Blue: IH ; Red: NH]

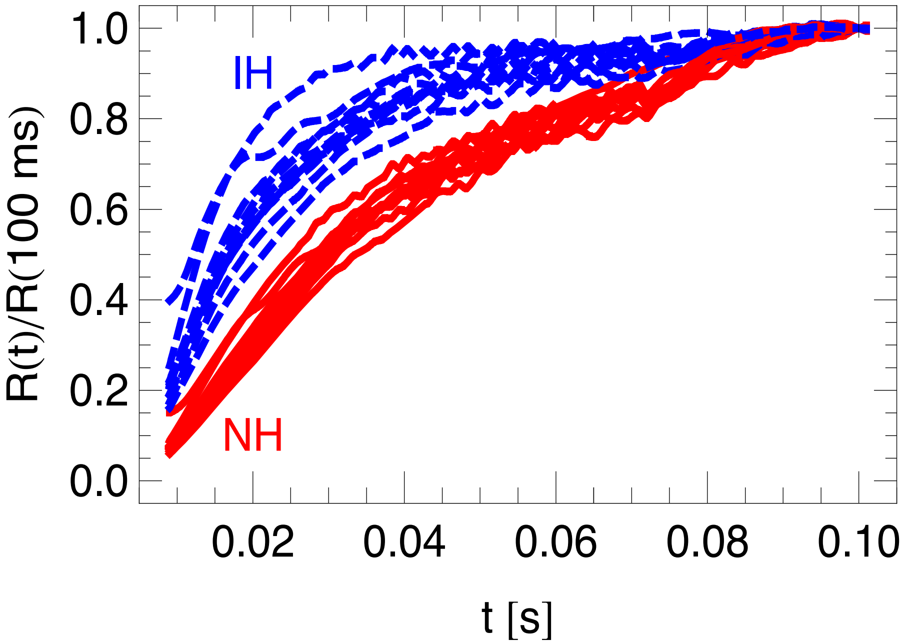


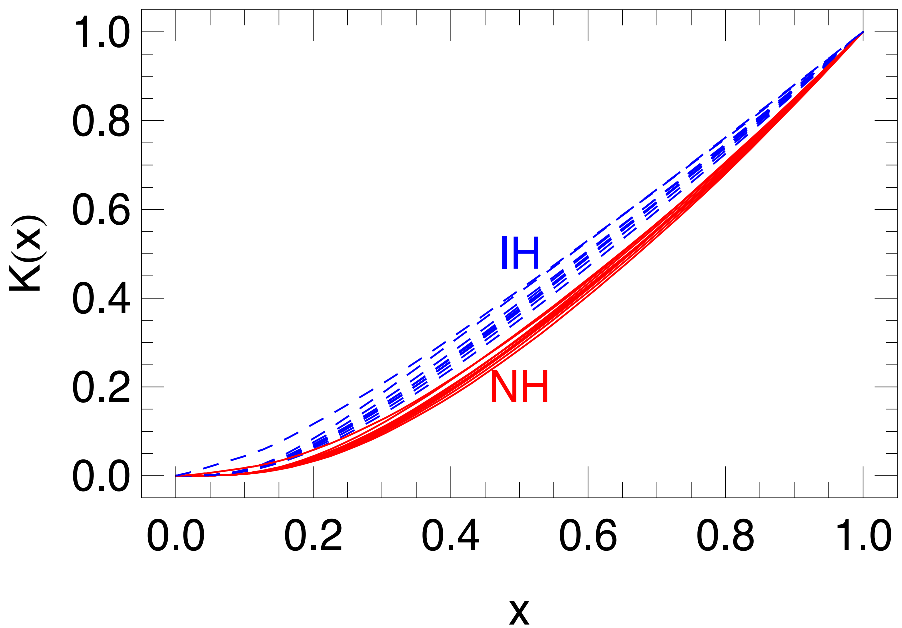
For Statistical analysis introduce
Cumulative Time Distribution K(x)

$$x = R(t)/R(t_{\text{end}})$$

$$K(x) = \frac{\int_0^{x\, t_{\text{end}}} dt\, R(t)}{\int_0^{t_{\text{end}}} dt\, R(t)}$$

Appendix: Rise time Analysis: Hierarchy Determination





Kolmogorov-Smirnov Statistics :

$$\mathcal{D}_\infty(K_i^A, K_j^B) = \max_{x\in[0;1]} \left|K_i^A(x) - K_j^B(x)\right|$$

Distance between any randomly picked NH "model" from average IH one is significantly above the one from average NH ones and well expected statistical errors.

Assessing "theory/numerical" error requires detailed study over other simulations with comparable sophistication.