Supernova Neutrinos: Challenges & Opportunities

Sovan Chakraborty

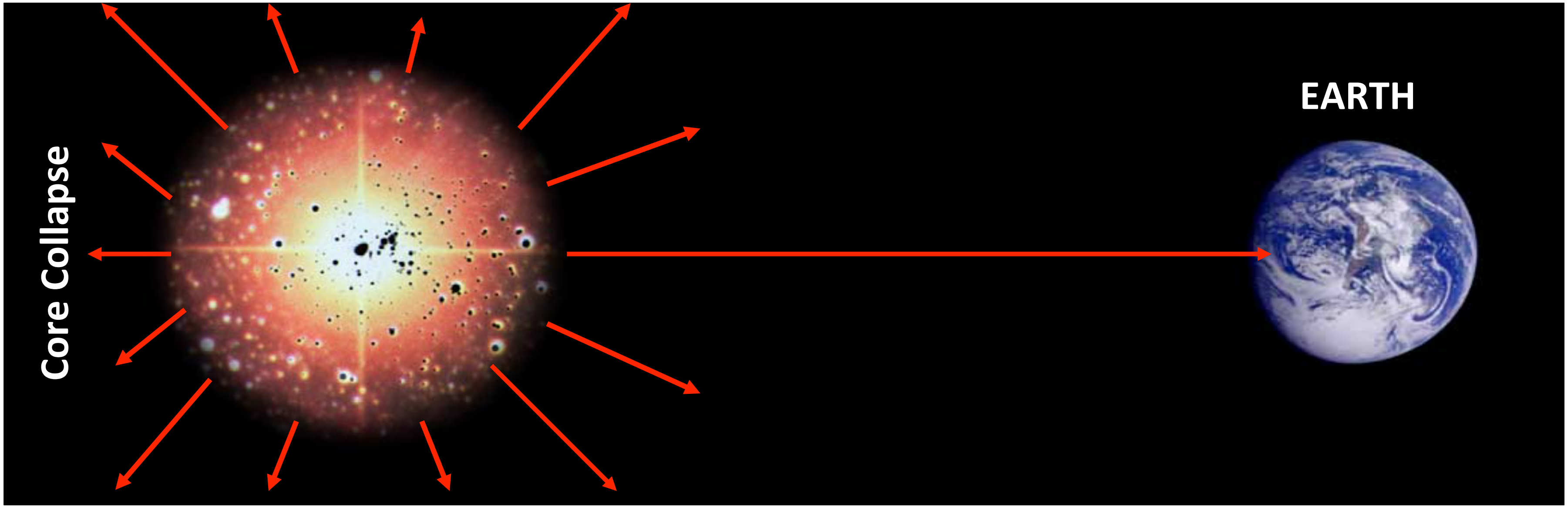
MPI for Physics, Munich

Blois, France, May 26-31, 2013

MARIE CURIE ACTIONS

MAX-PLANCK-GESELLSCHAFT

TYPICAL PROBLEMS IN SUPERNOVA NEUTRINOS



Supernova (SN) as Neutrino Source

Oscillation of SN Neutrinos

Neutrino Signal at Detectors

Plan of the talk

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Conclusions

23 February 1987 SN 1987A

Supernova one of the most energetic events in nature.

Terminal phase of a massive star ($M > 8{\sim}10\ M_{\odot}$)

Collapses and ejects the outer mantle in a shock wave 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**

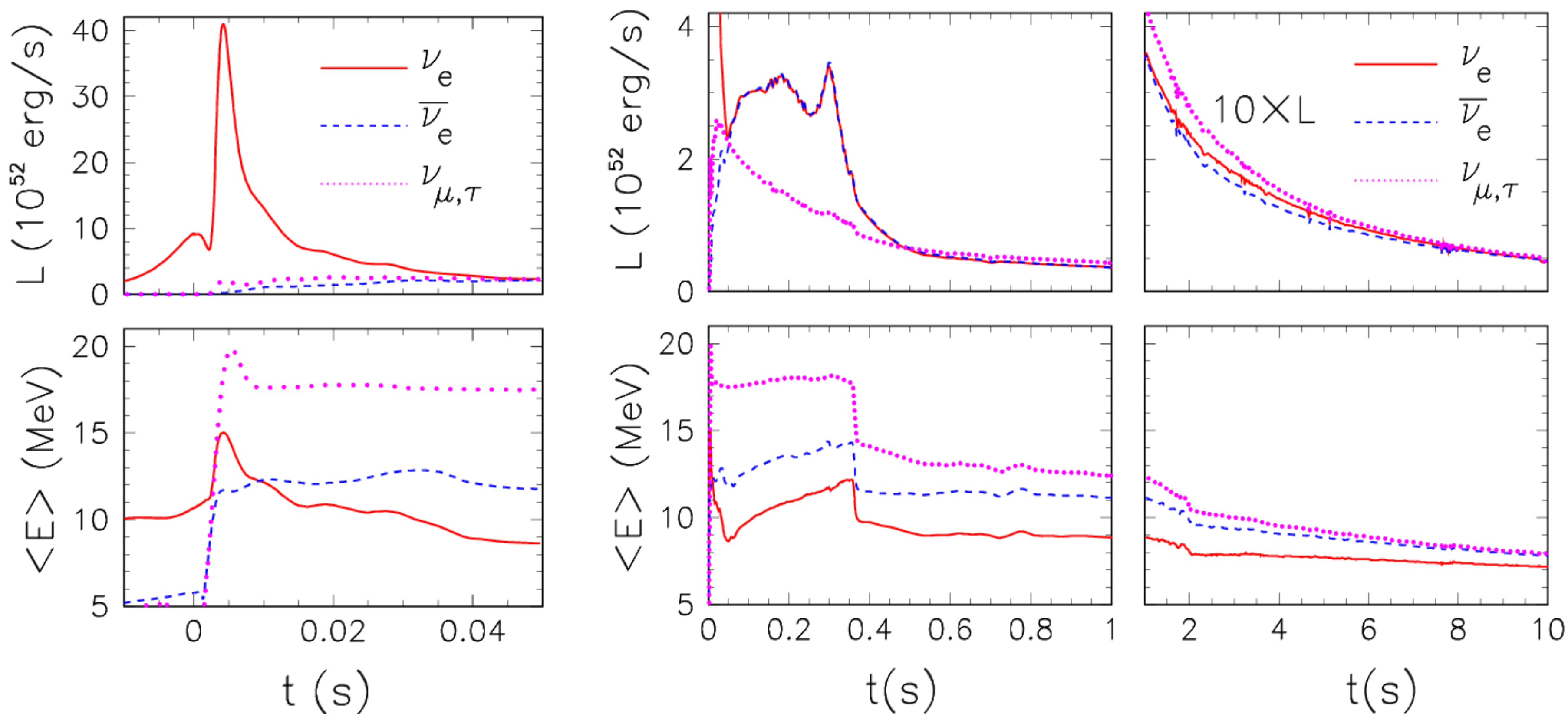
Accretion

- powered by infalling matter
- Stalled shock

Cooling

- Cooling by ν diffusion

Accretion: ~ 0.5 s ; Cooling: ~ 10 s



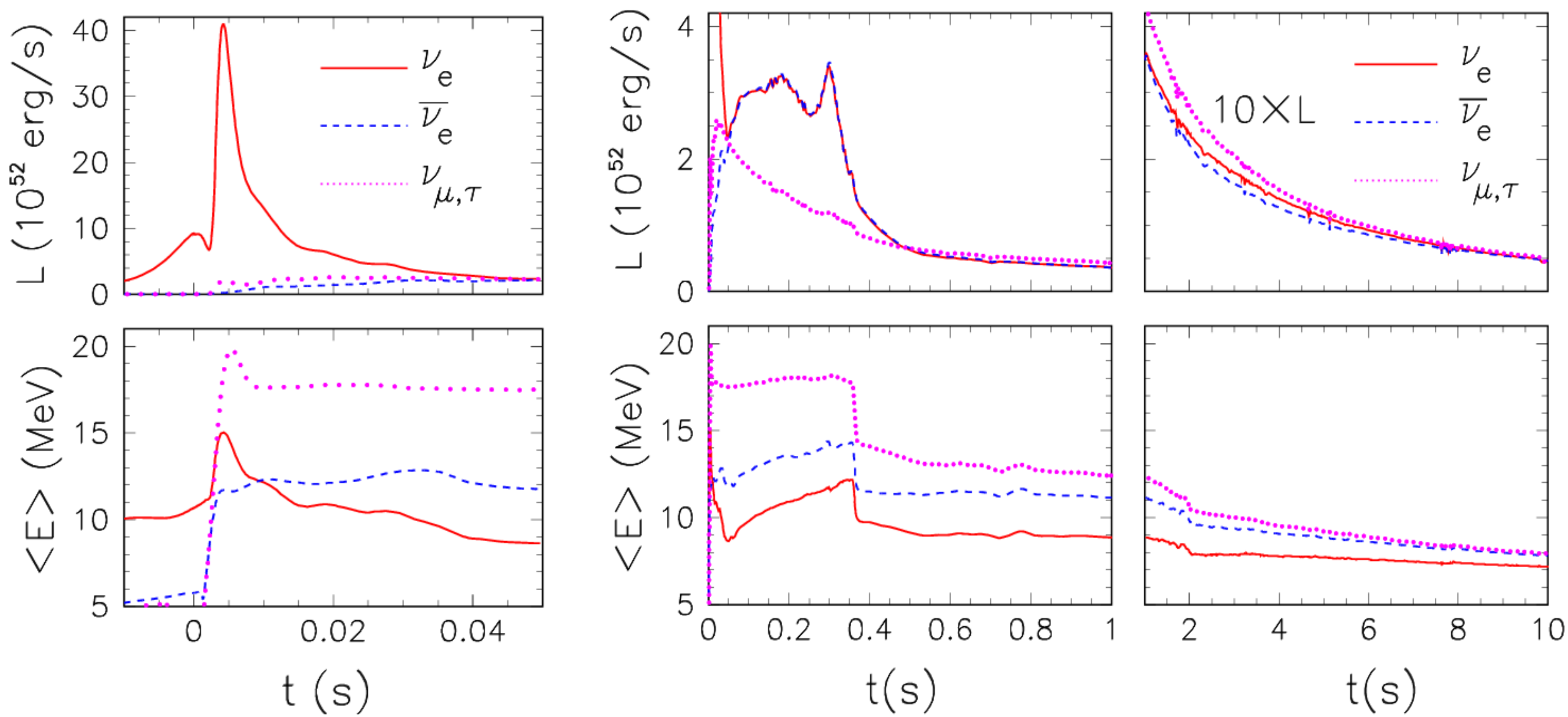
[Fischer et al. (Basel Simulations), A&A 517:A80,2010, 10. 8 M_{sun} progenitor mass]

Neutrino Emission Phases

Neutronization burst **Accretion** **Cooling**

Large flux differences in Accretion Phase (best for oscillation effects!)

Cooling Phase : Equipartition of luminosity + Mild flavor hiearchy in <E>



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SN ν Flavor Transitions

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

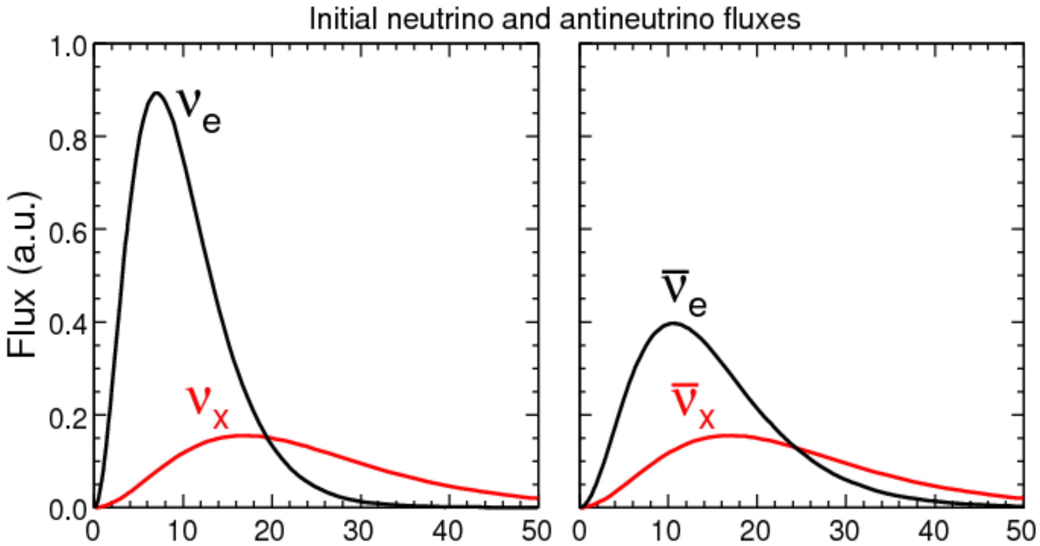
$$i\frac{d}{dx}\psi_\nu = \left(H_{vac} + H_e + H_{\nu\nu}\right)\psi_\nu$$

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

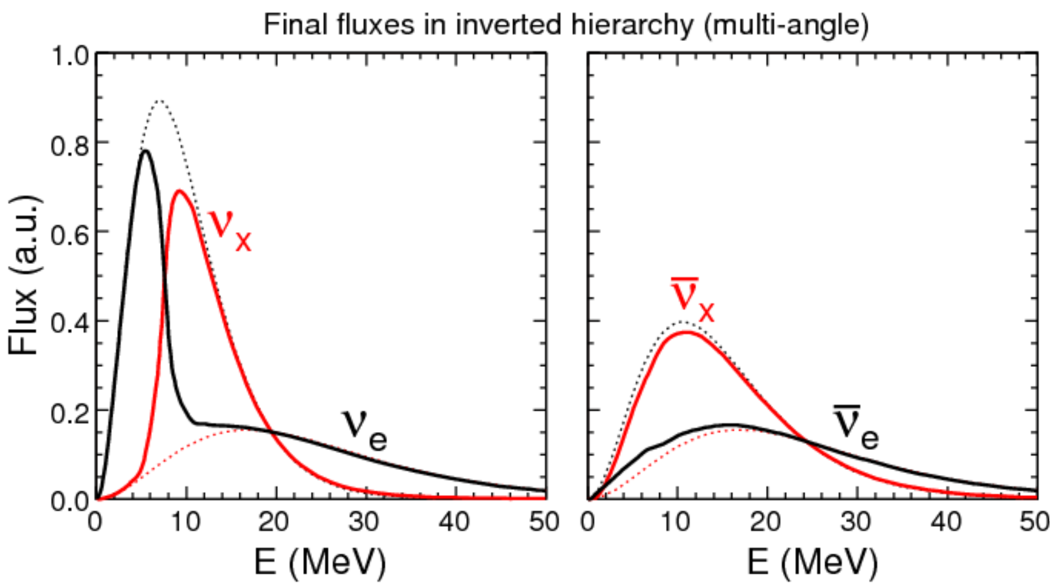
[Fogli, Lisi, Marrone, Mirizzi, arXiV: 0707.1998 [hep-ph]]



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)

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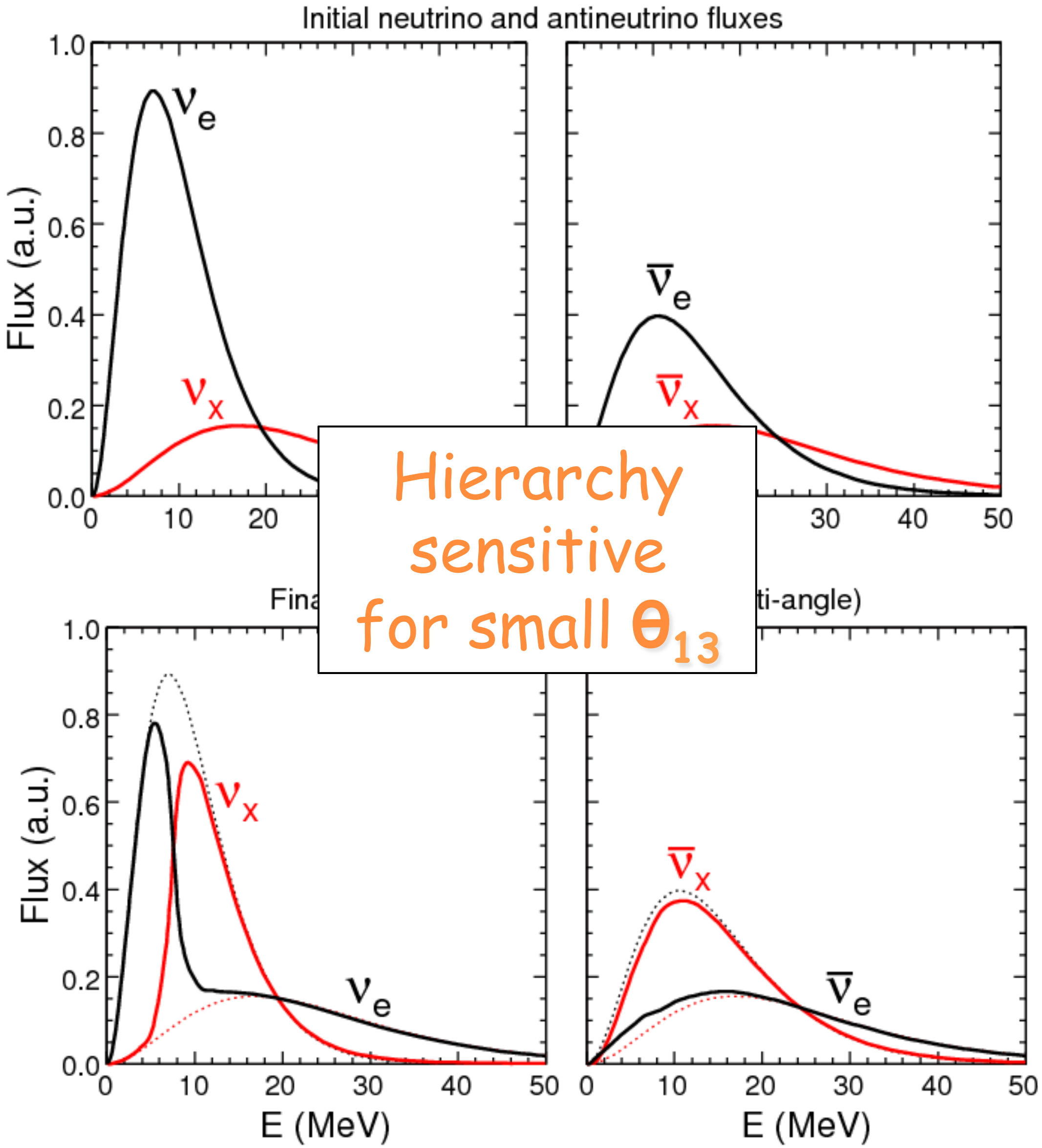

Hierarchy sensitive for small θ_{13}

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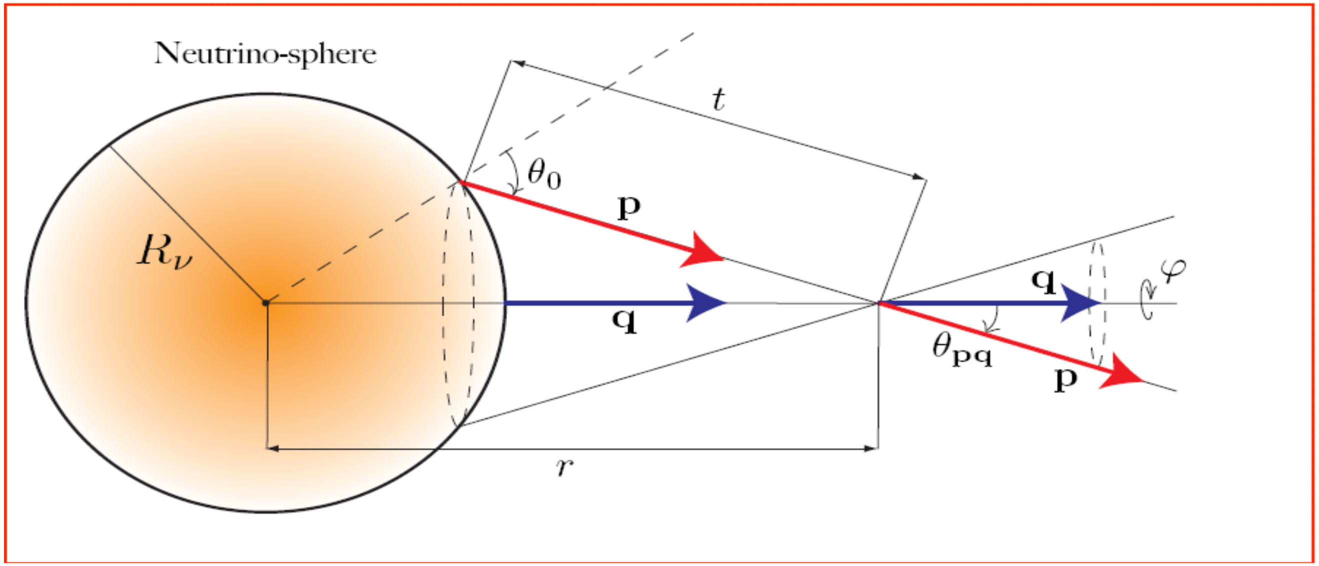
Matter Suppression



•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 : $n_e \ll n_\nu$

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

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

Suppression of Collective effects

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

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

Sarikas, Raffelt, Hüdepohl &
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Dasgupta, P. O'Connor, Ott
PRD 85:065008, 2012]

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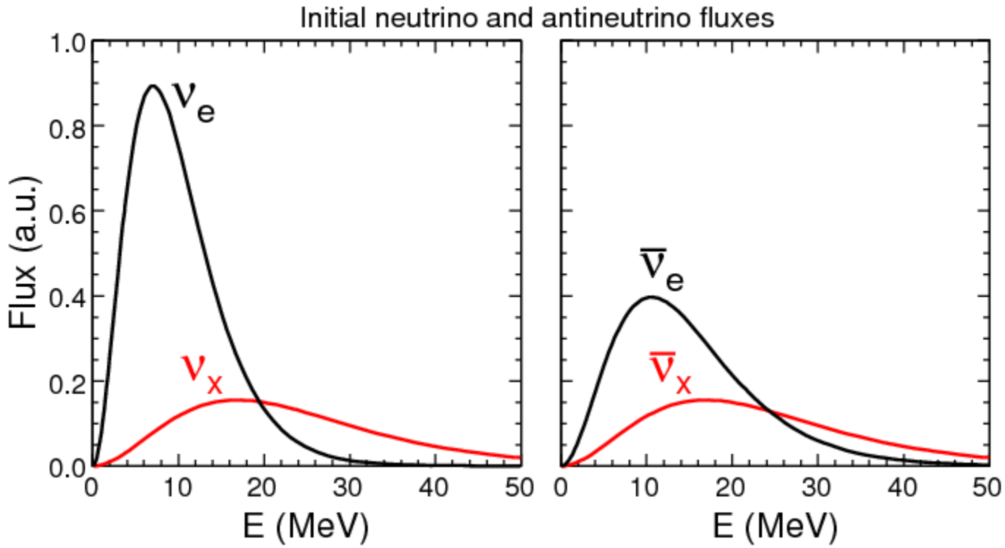

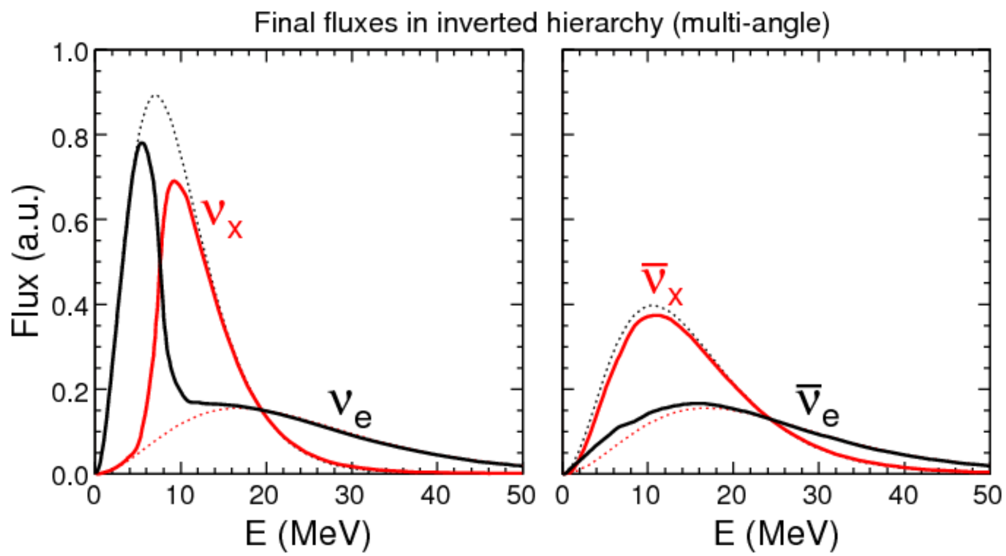

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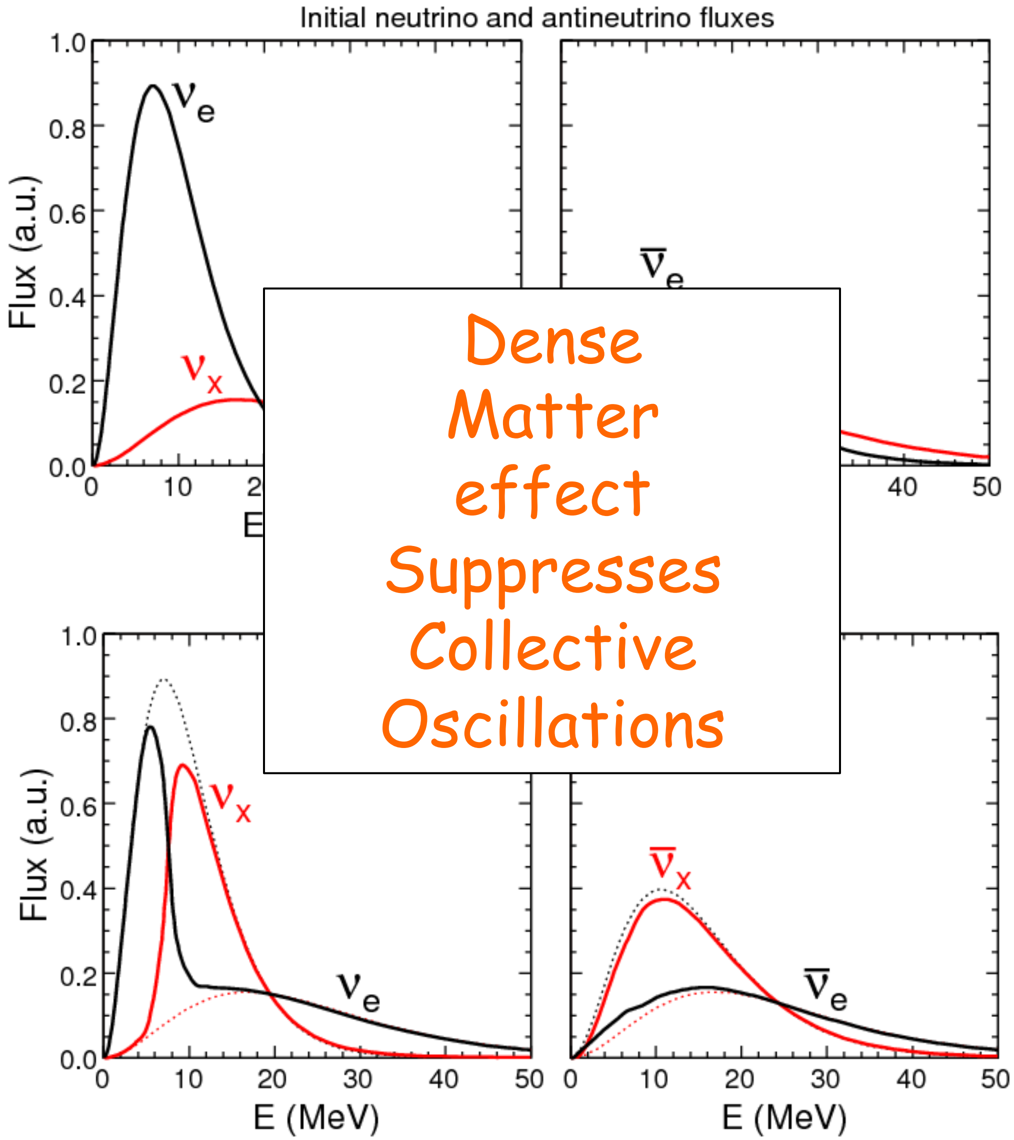

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Suppression of Collective effects

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):

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

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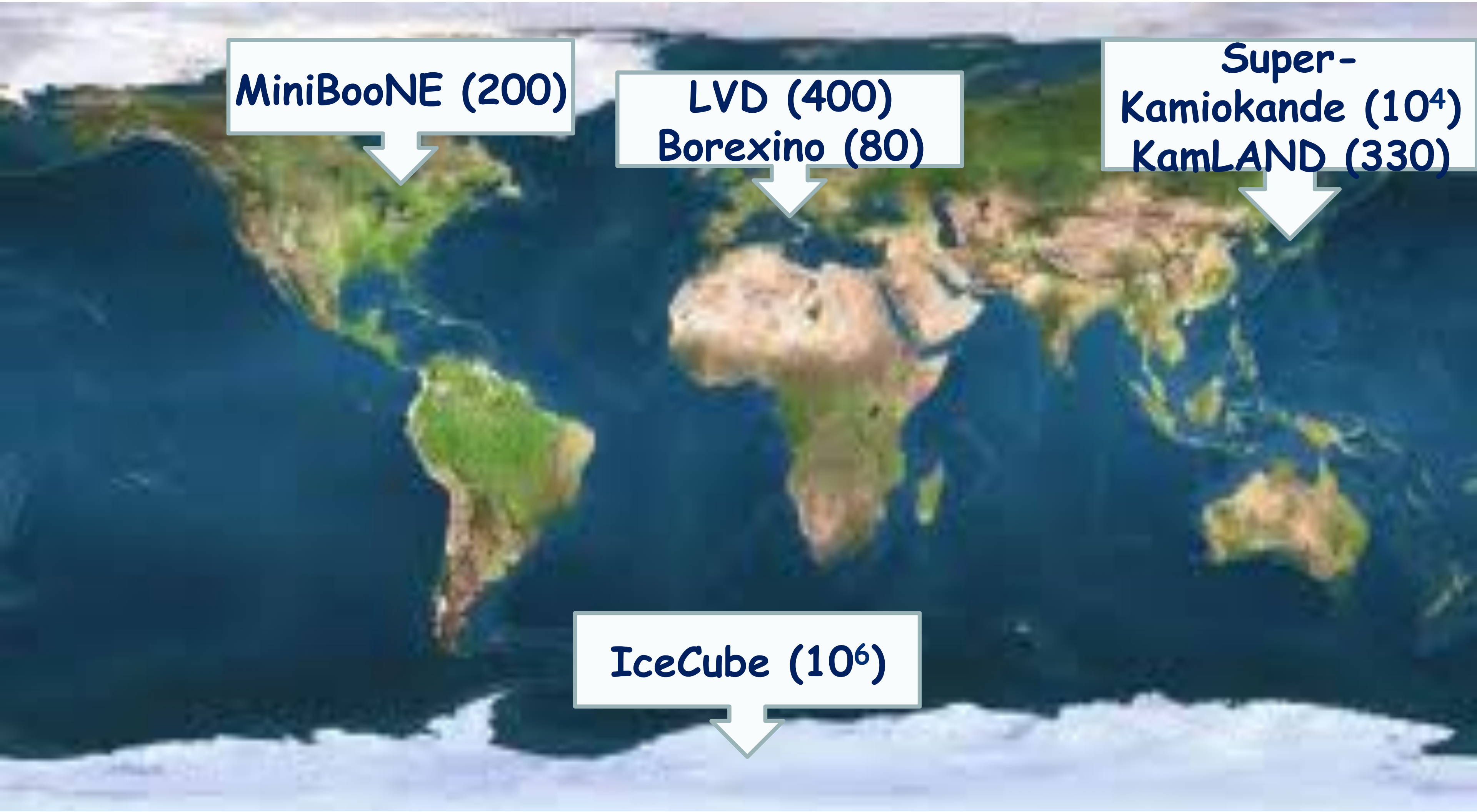
Large Detectors for Supernova Neutrinos



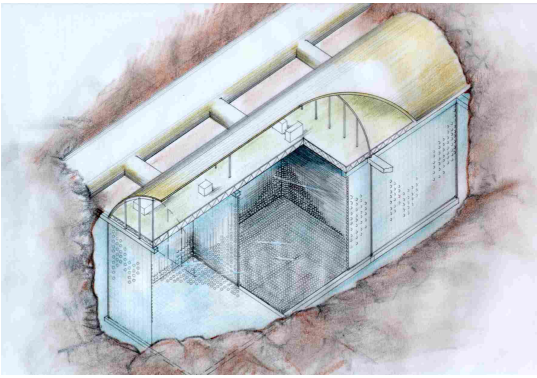
In brackets events for a "fiducial SN" at distance 10 kpc

Next generation Detectors for Supernova Neutrinos

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

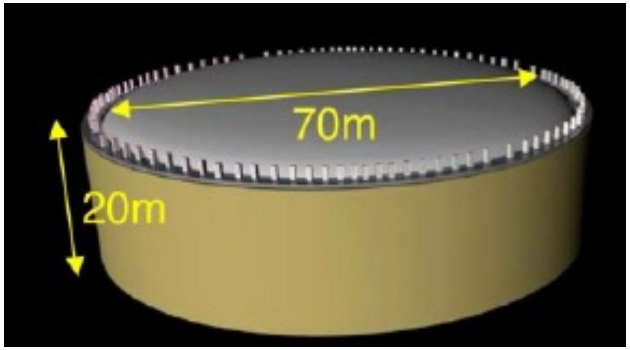
- **0.4 Mton WATER Cherenkov detectors**
- **100 kton Liquid Ar TPC**
- **50 kton scintillator**

Mton Cherenkov



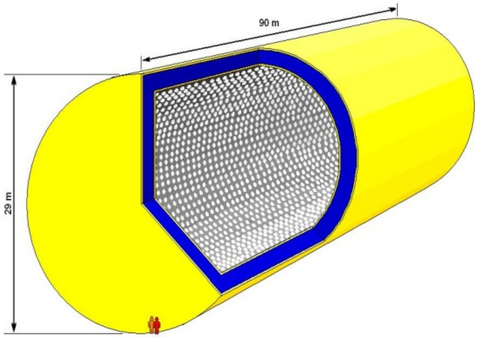
UNO, MEMPHYS, HYPER-K

LAr TPC



GLACIER

Scintillator

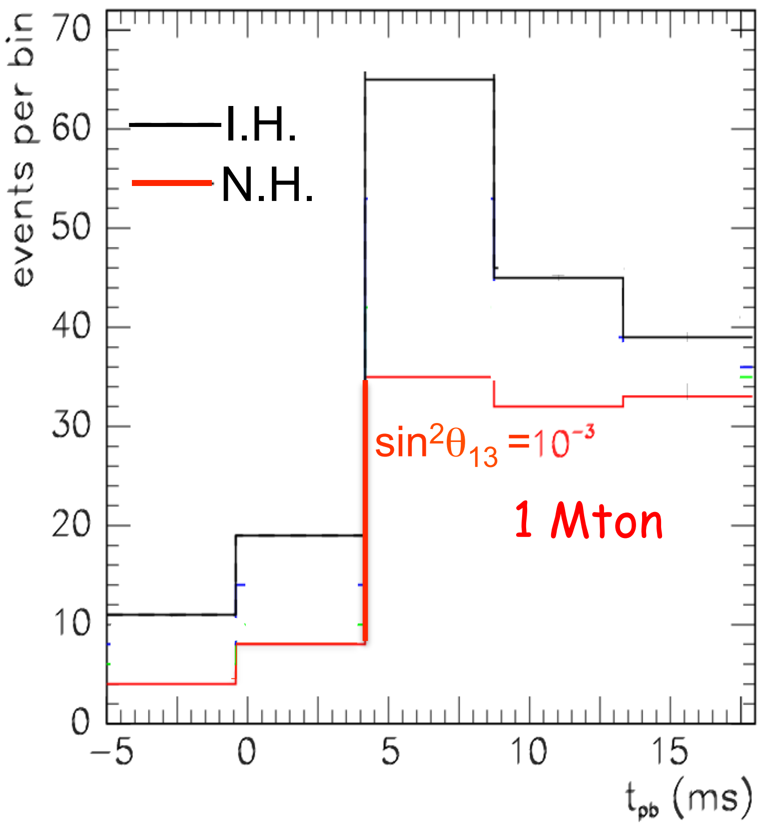


LENA

See LAGUNA Collaboration, "Large underground, liquid based detectors for astro-particle physics in Europe: Scientific case and prospects," arXiV:0705.0116 [hep-ph]

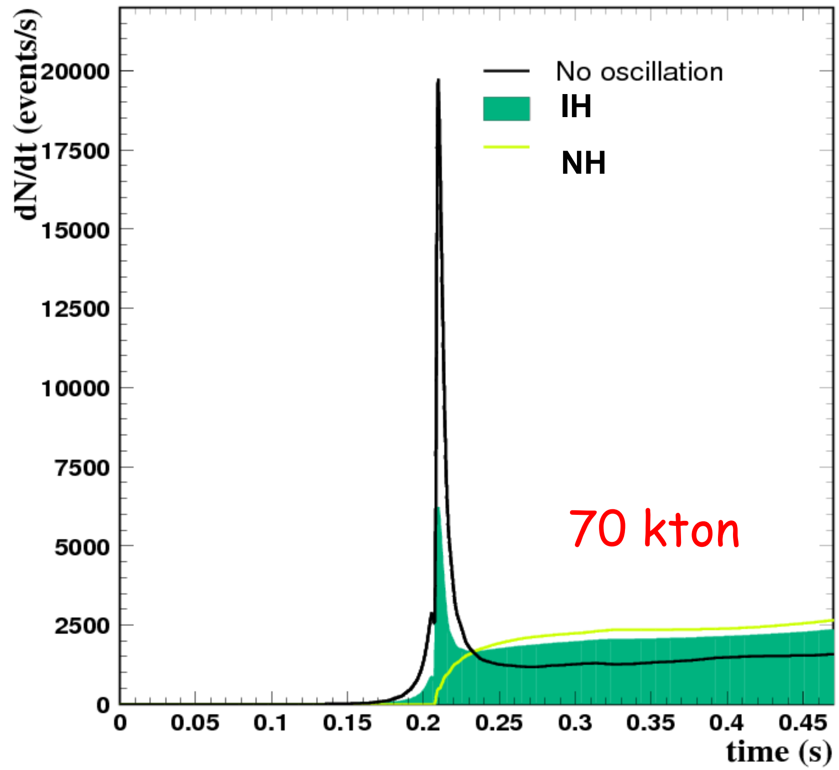
Oscillations in the Neutronization Burst

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]

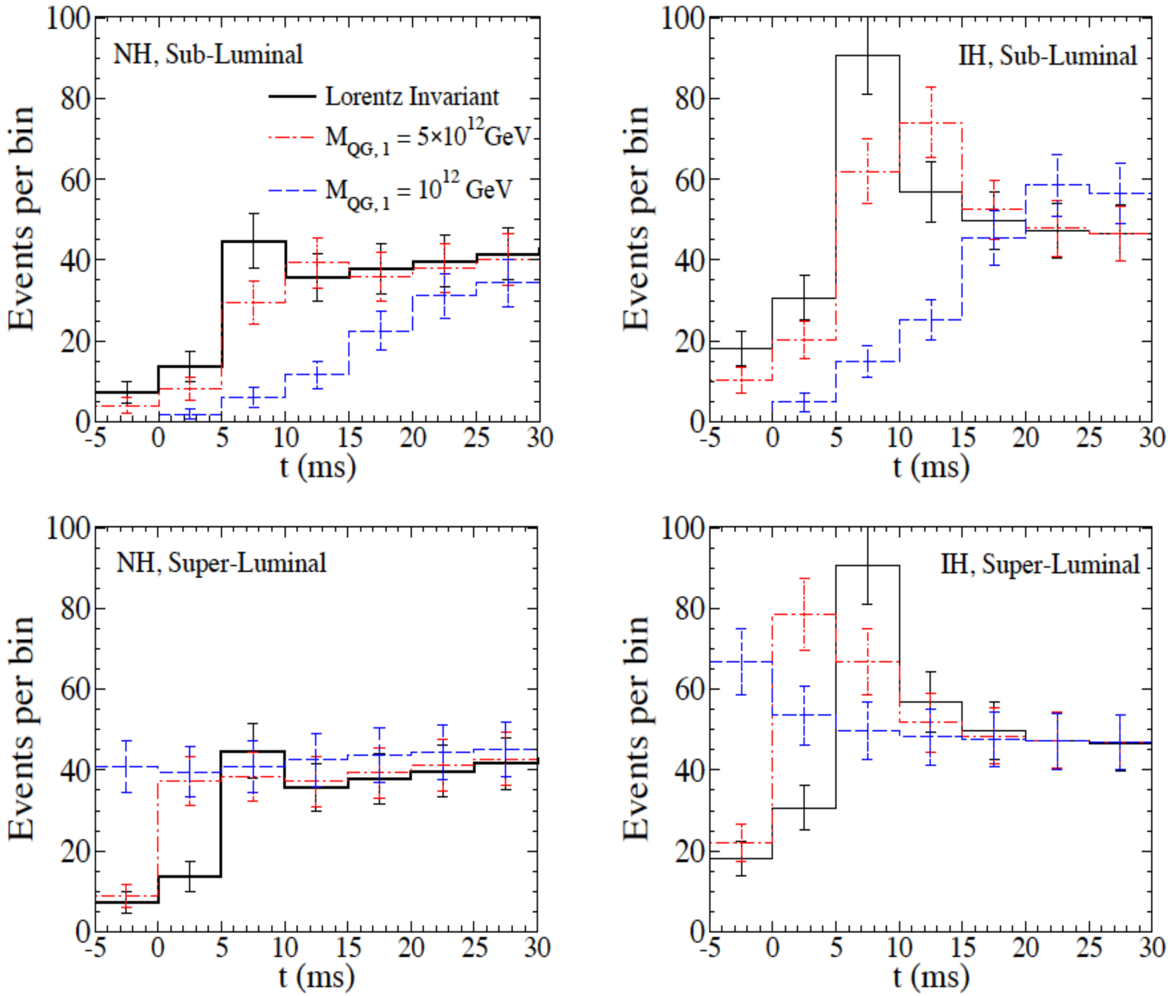
- Peak is absent ⟶ NH ($F_{\nu_e} = F^0_{\nu_x}$)
- Peak is seen ⟶ IH ($F_{\nu_e} = \sin^2\vartheta_{12}(F^0_{\nu_e} - F^0_{\nu_x}) + F^0_{\nu_x}$)

SN Bounds on Neutrino Velocity

Violation of Lorentz invariance

[Ellis et al., 0805.0253 & 1110.4848]

$$\frac{v-c}{c} = \left(\frac{E}{M_{QG}}\right)^{\alpha}$$



The signal would be spread out and shifted in time.

$(v-c)/c < 10^{-14}$ for linear Lorentz violation
$(v-c)/c < 10^{-8}$ for quadratic Lorentz violation

[S.C, Mirizzi & Sigl Phys. Rev. D 87, 017302 (2013)]

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):

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

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

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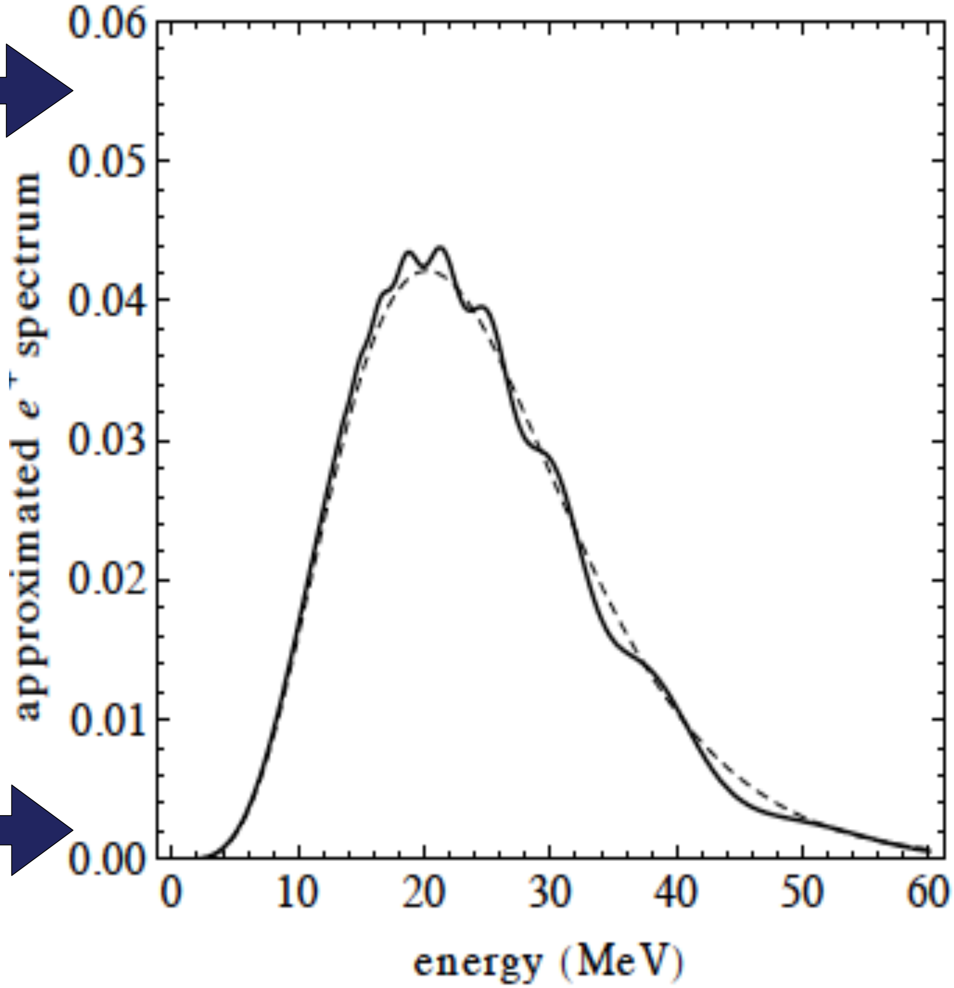

[Dighe, Keil & Raffelt, hep-ph/0304150]

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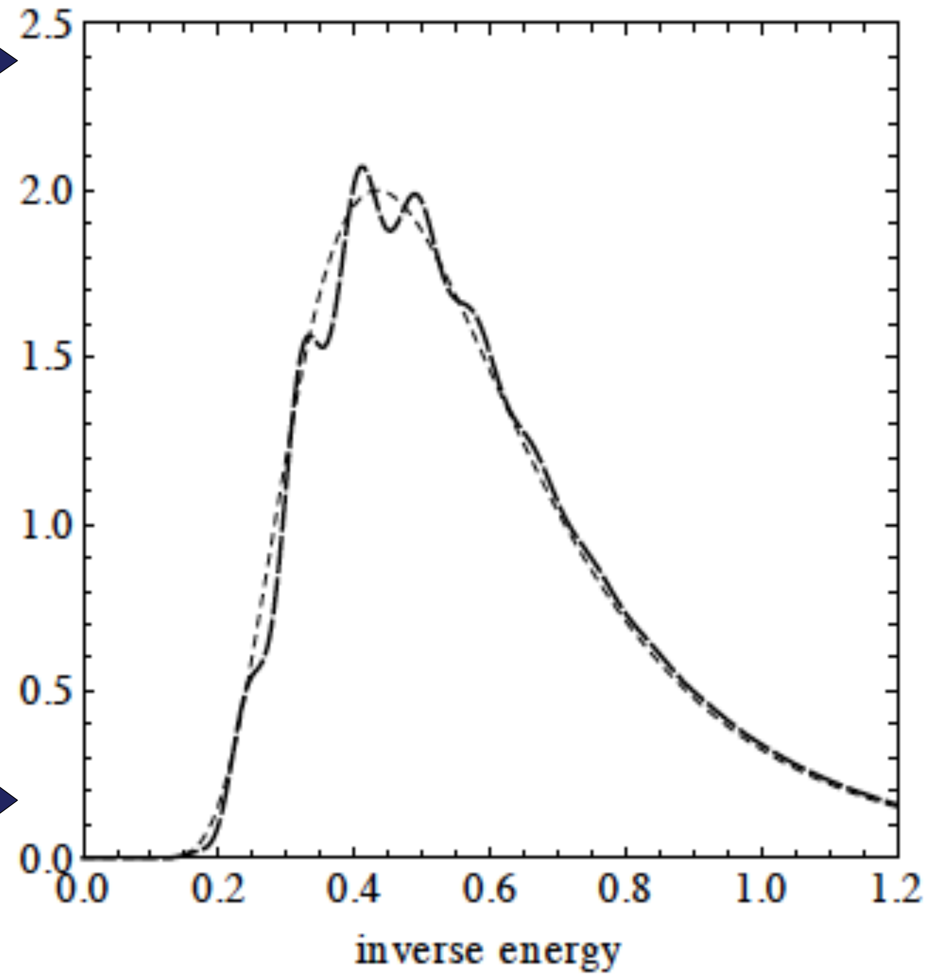

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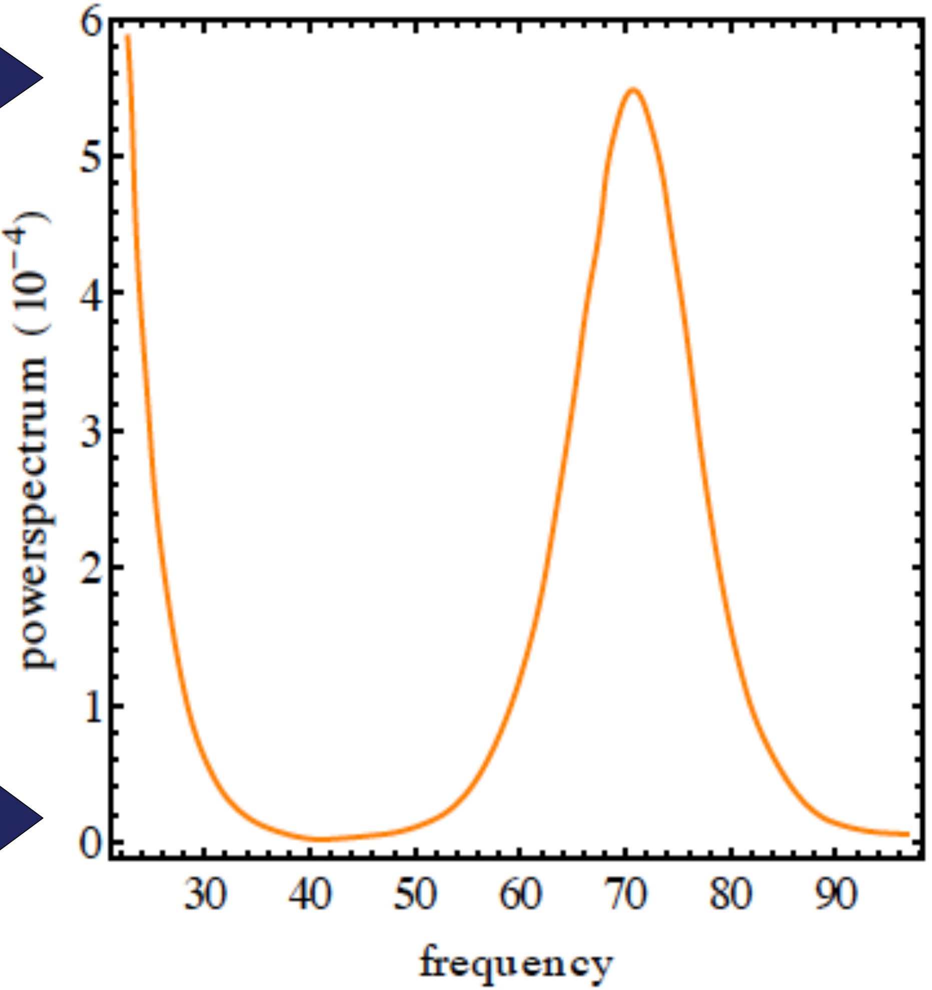

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Normal Hierarchy (NH):

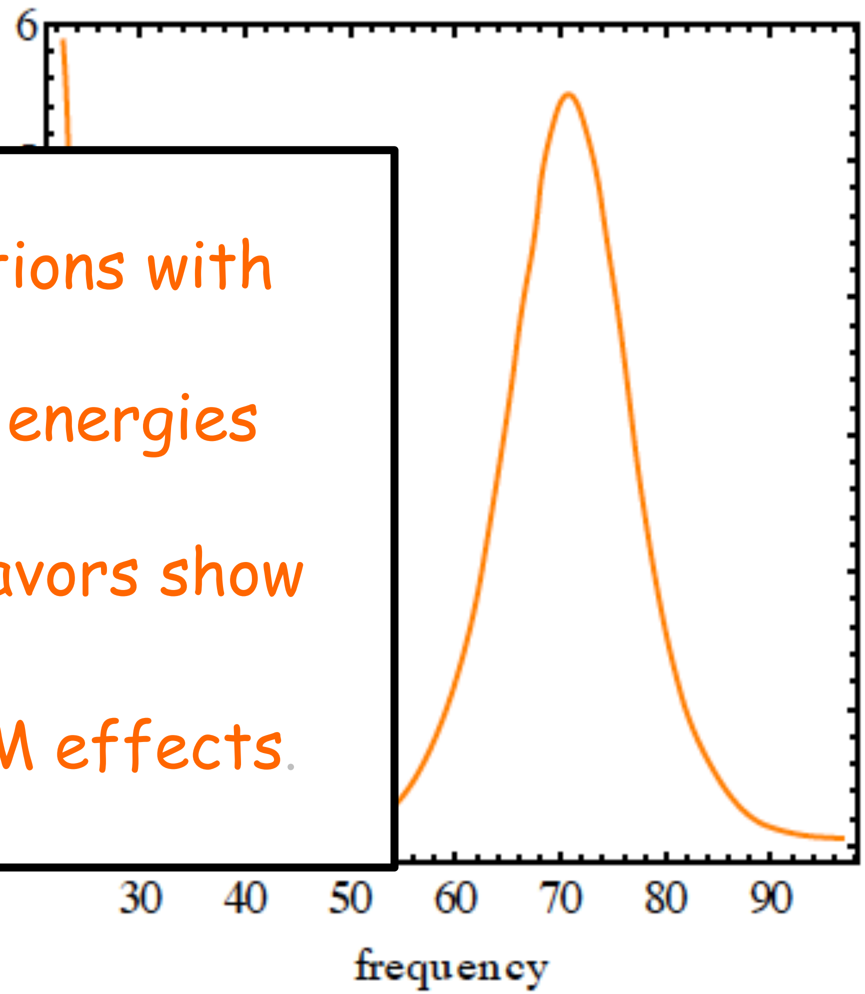
$F_{\nu_e} = F^0_{\nu_x}$

$F_{\bar{\nu}_e} = \cos$

Inverted Hierarchy (

$F_{\nu_e} = \sin^2$

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



Recent simulations with close average energies of different flavors show **negligible** EM effects.

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

SN neutrino Flux at Earth

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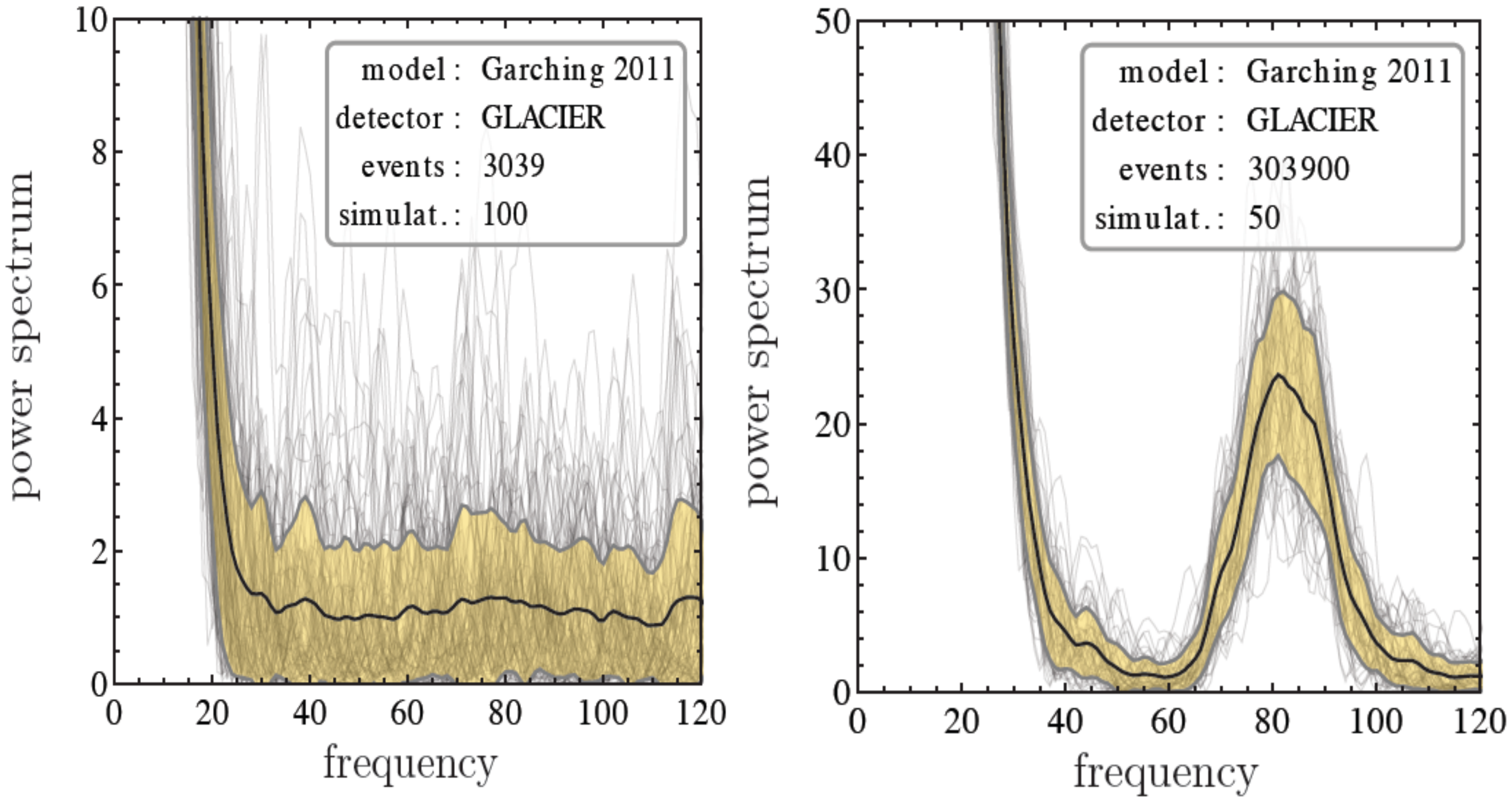
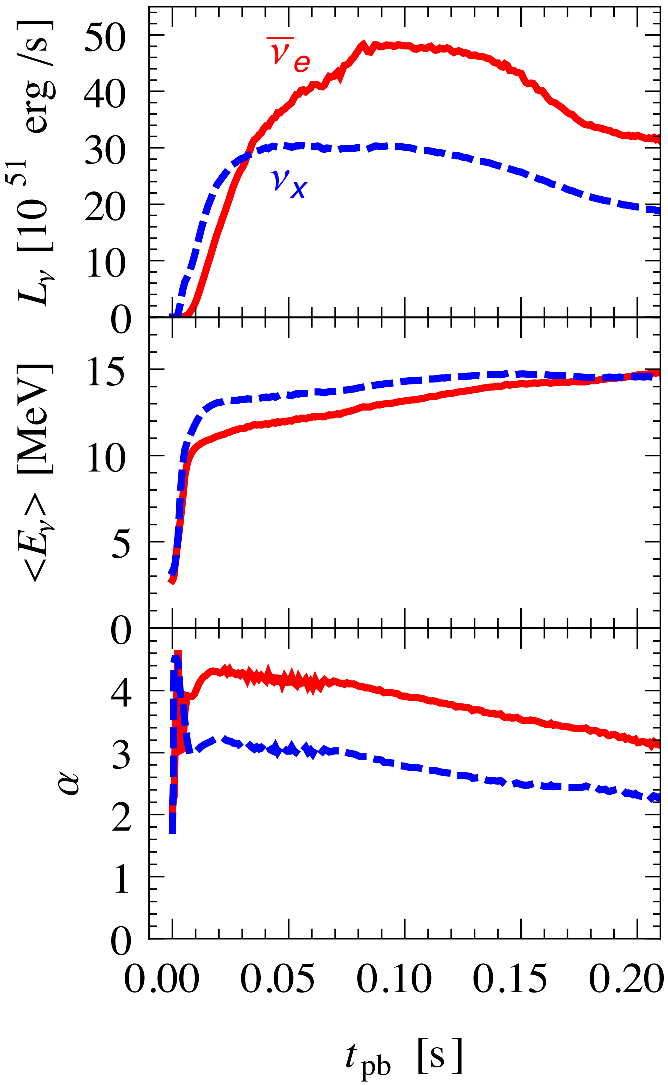


[Borriello, S.C, Mirizzi, Serpico; PRD 86 (2012)]

Rise time Analysis: Hierarchy Determination

Garching

15 Solar Mass



ν_x has only NC, $\bar{\nu}_e$ has both CC+NC.

$\bar{\nu}_e$ more in equilibrium with environment than ν_x

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

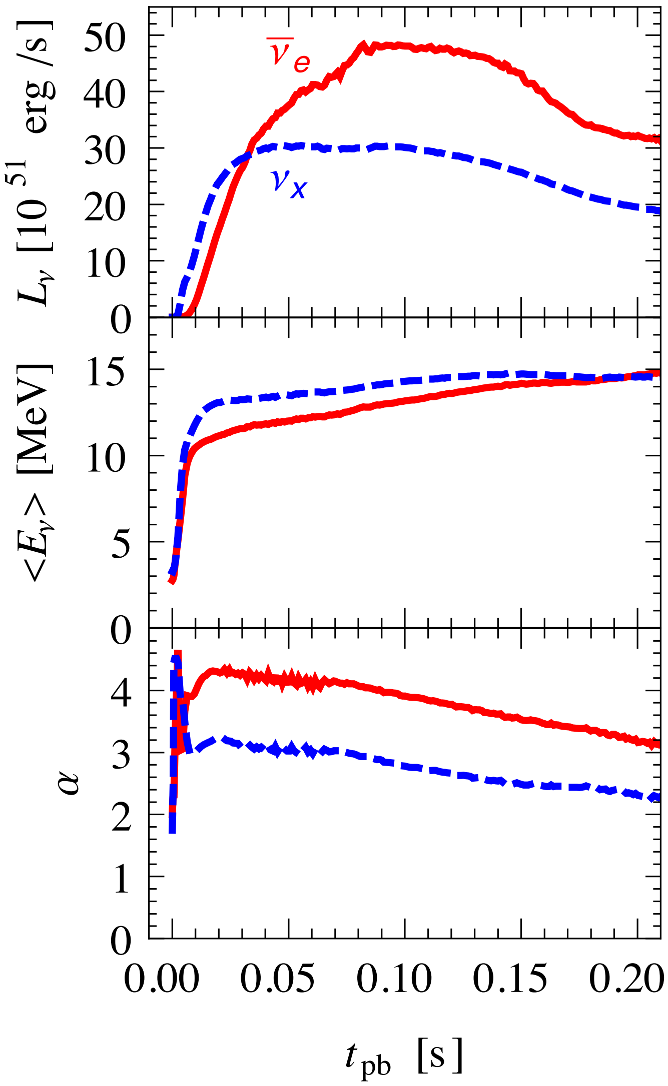
Flux in IH (ν_x) rises faster than NH (ν_x, $\bar{\nu}_e$)

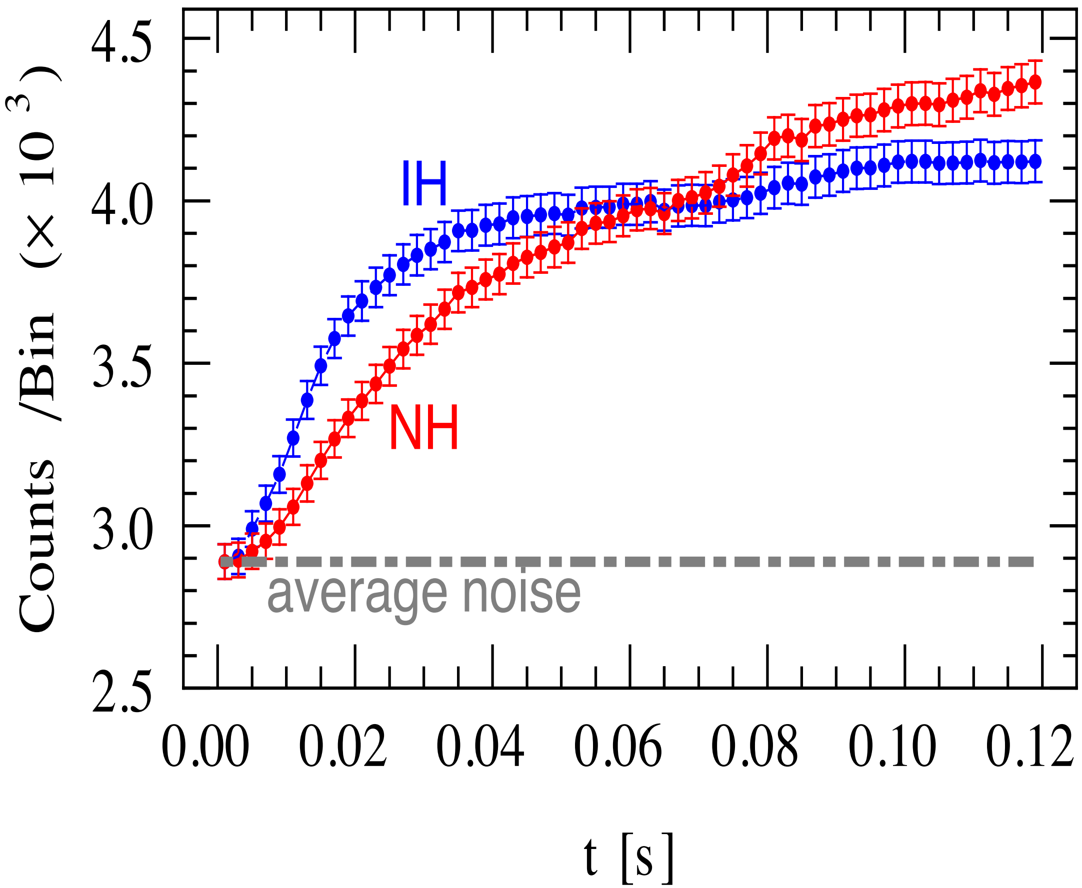
[Serpico, **S.C**, Fischer, Hüdepohl, Janka & Mirizzi
PRD 85:085031,2012]

Rise time Analysis: Hierarchy Determination

Garching

15 Solar Mass
in Ice-Cube





Flux in IH rises faster than NH

[Serpico, **S.C**, Fischer, Hüdepohl, Janka & Mirizzi
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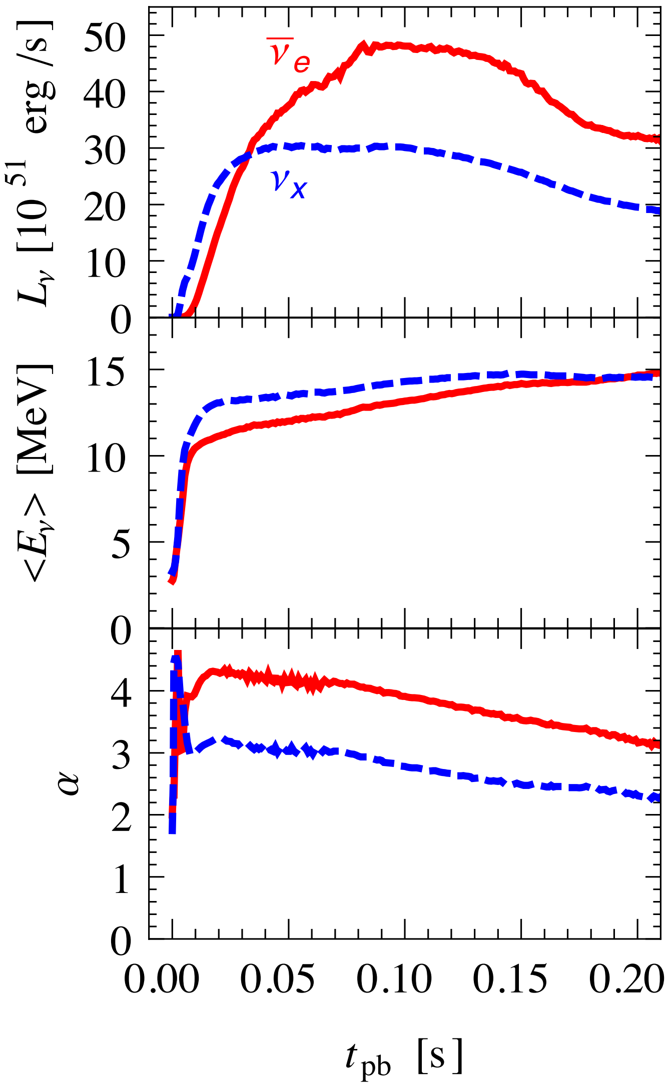
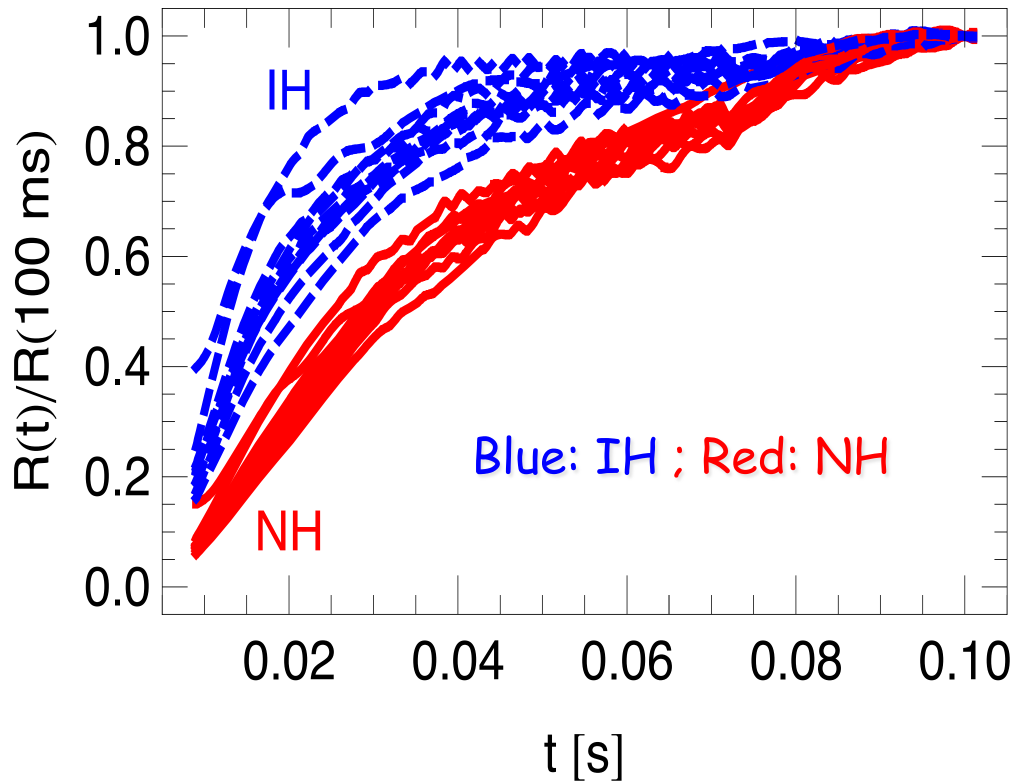


Normalized Count rate :

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



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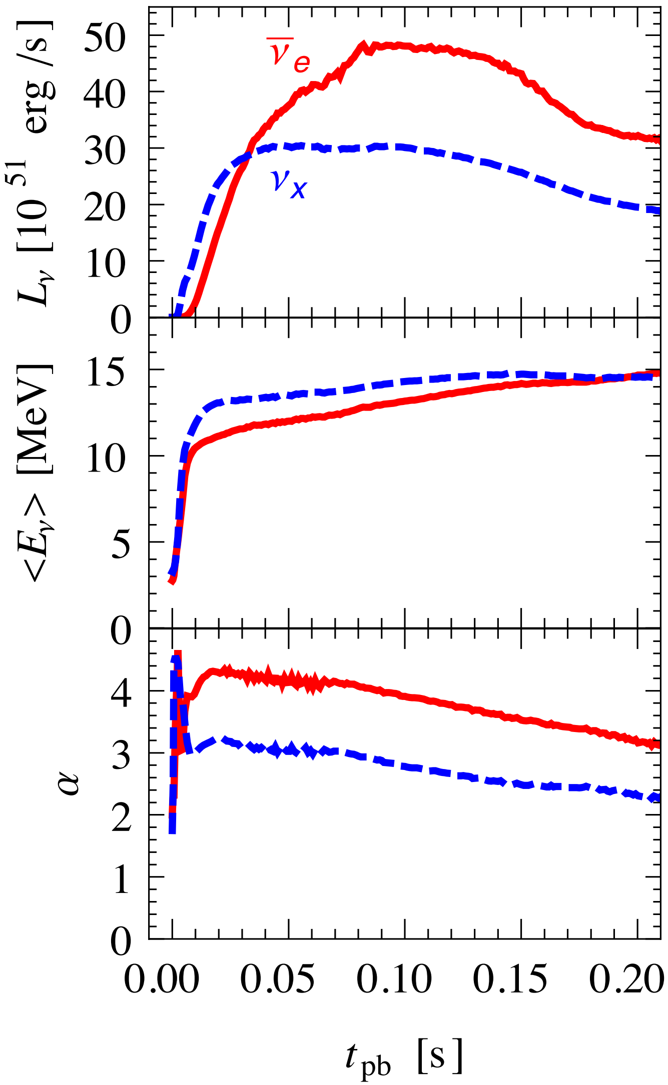
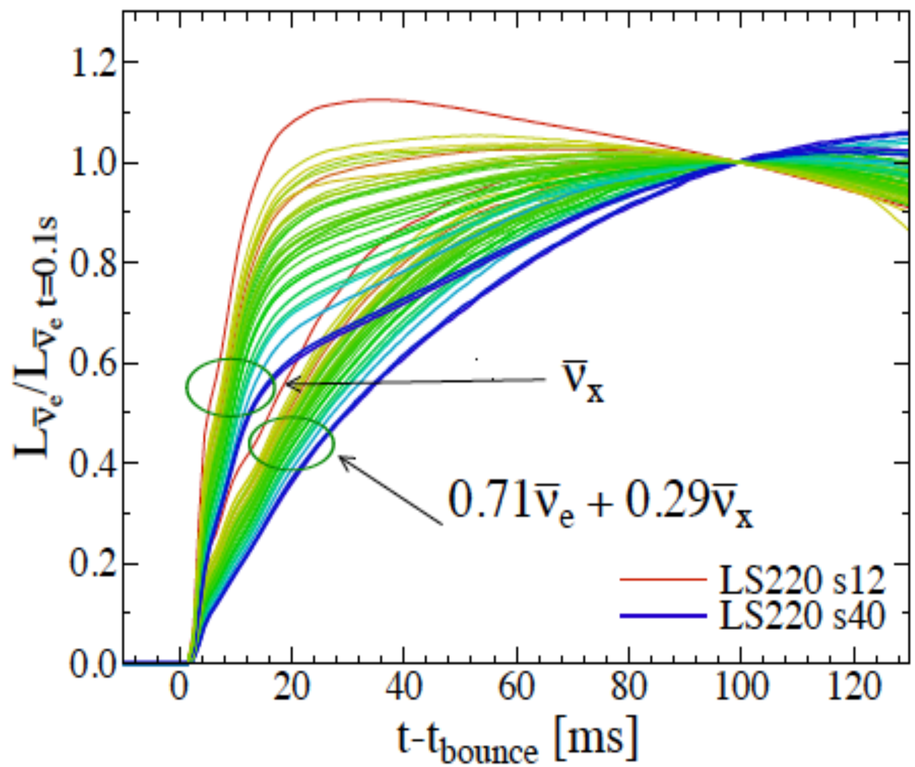


Normalized Count rate : 32 different models



Flux in IH rises faster than NH

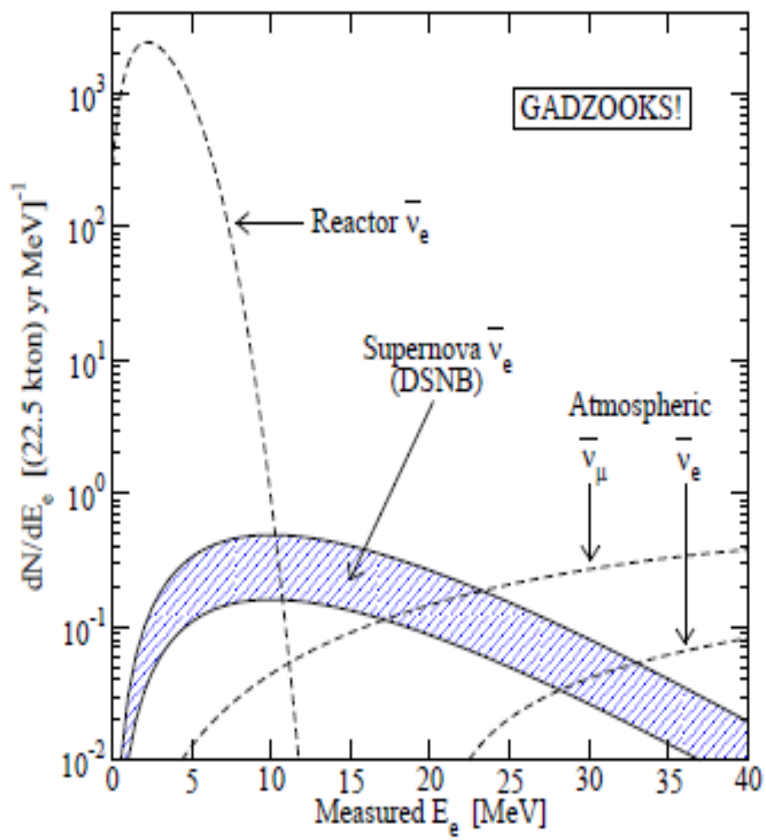
[C.D. Ott et al. Neutrino 2012, Japan]

Diffuse SN Neutrino Background (DSNB)

- Approx. 10 core-collapse/sec in the visible universe
- mostly from redshift z~1
- Confirm star formation rate

Window of opportunity
bkg less than signal

[Beacom & Vagins, hep-ph/0309300]



SK-doped with Gd would detect few clear DSNB $\bar{\nu}$ events/year.

ν astronomy at cosmic distances !

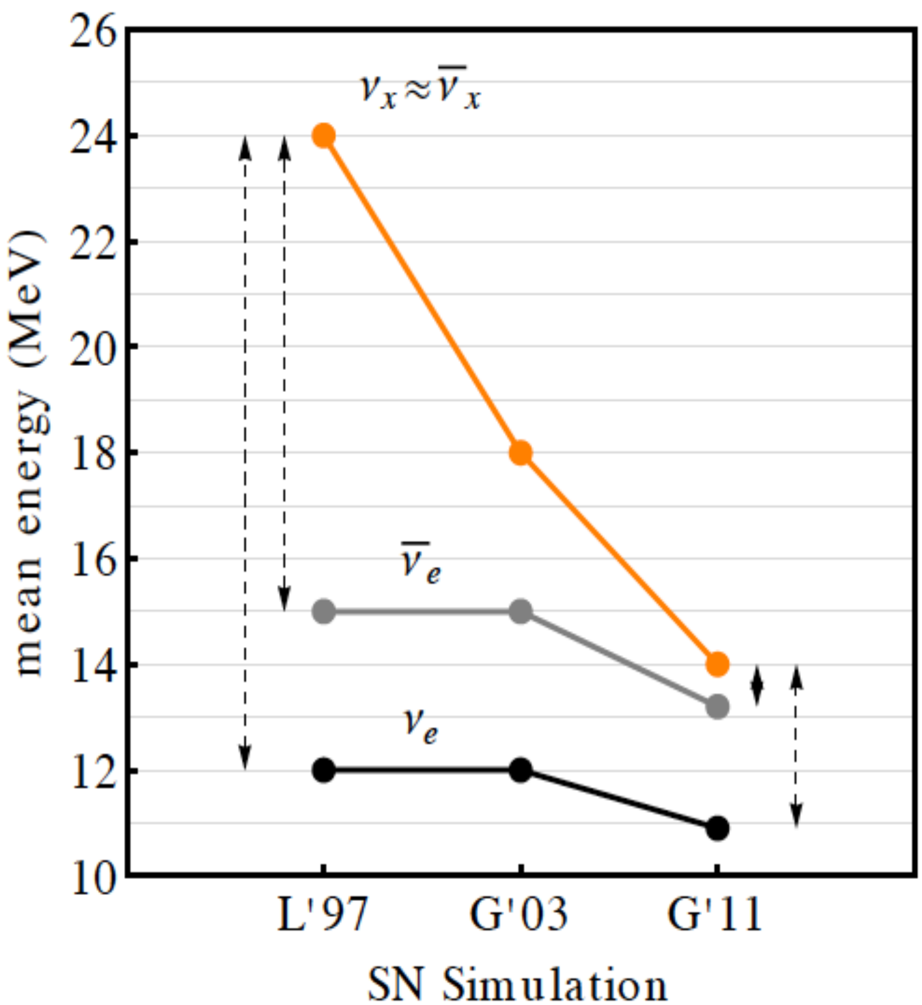
Conclusions

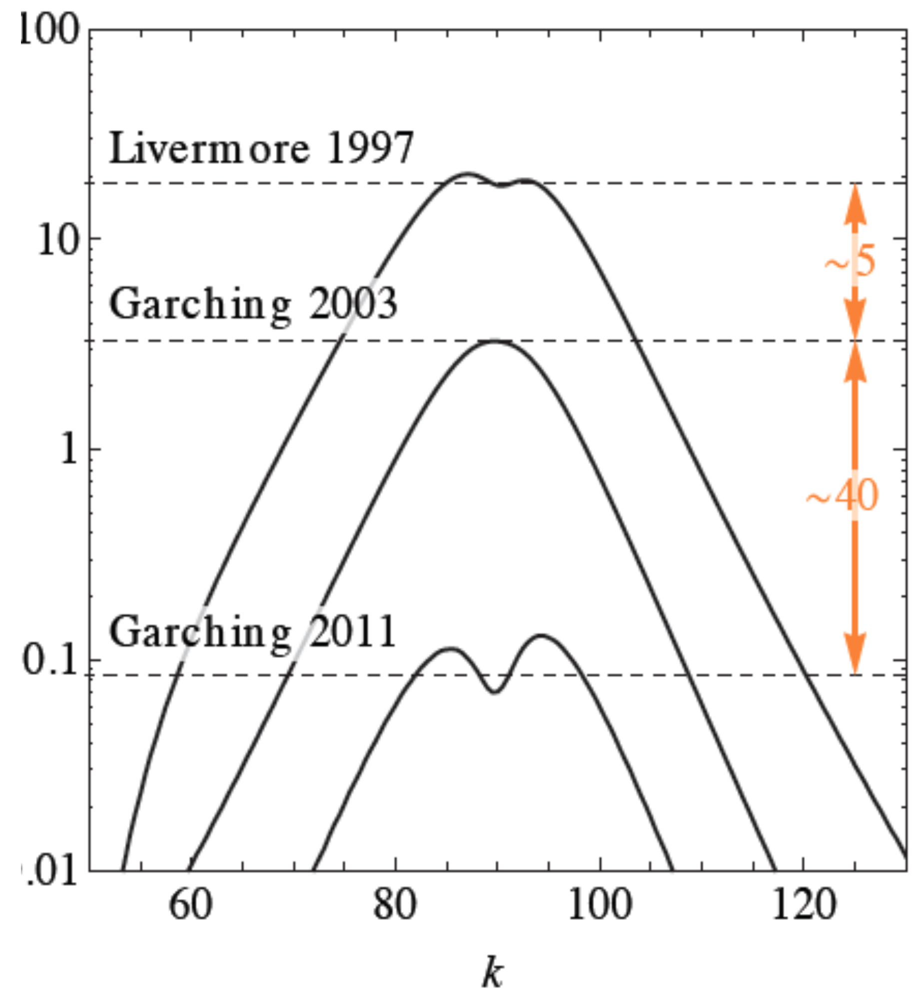
- Observing SN neutrinos is the next frontier of low-energy neutrino astronomy.
- Collective effects are suppressed in early SN phases, implying hierarchy sensitivity at large θ_{13}.
- Earth Matter effect: Detectable for Sub-kpc SNe.
- New physics scenarios can be constrained.
- Rise time of SNe signal contains hierarchy information.


SN 20XX A !
LOOKING FORWARD
FOR THE NEXT
GALACTIC SN !
Thank You !

Appendix: SN antineutrino Flux at Earth

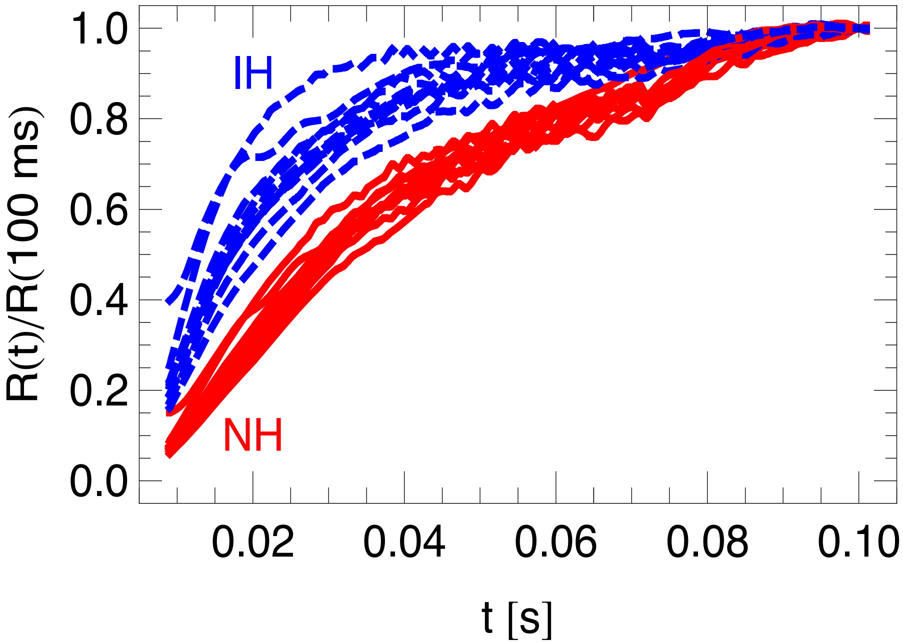
Earth Matter Effect:



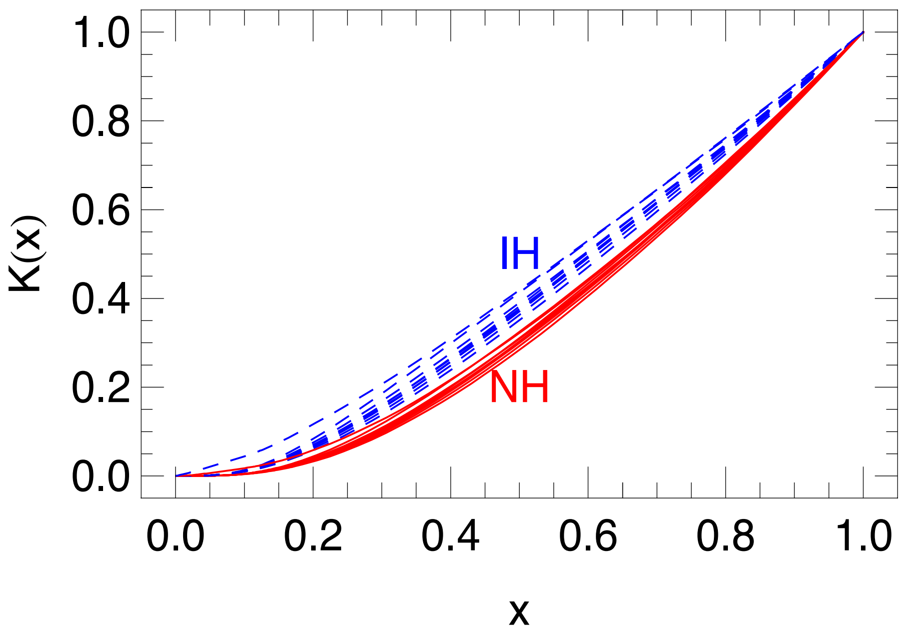


[Borriello, S.C, Mirizzi, Serpico; PRD 86 (2012)]

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]

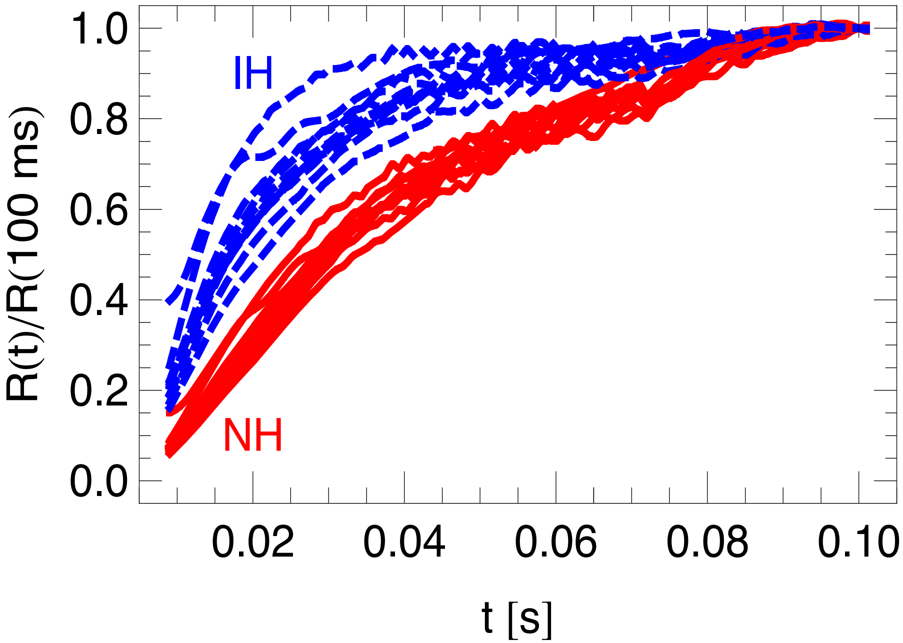


For Statistical analysis introduce
Cumulative Time Distribution K(x)

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

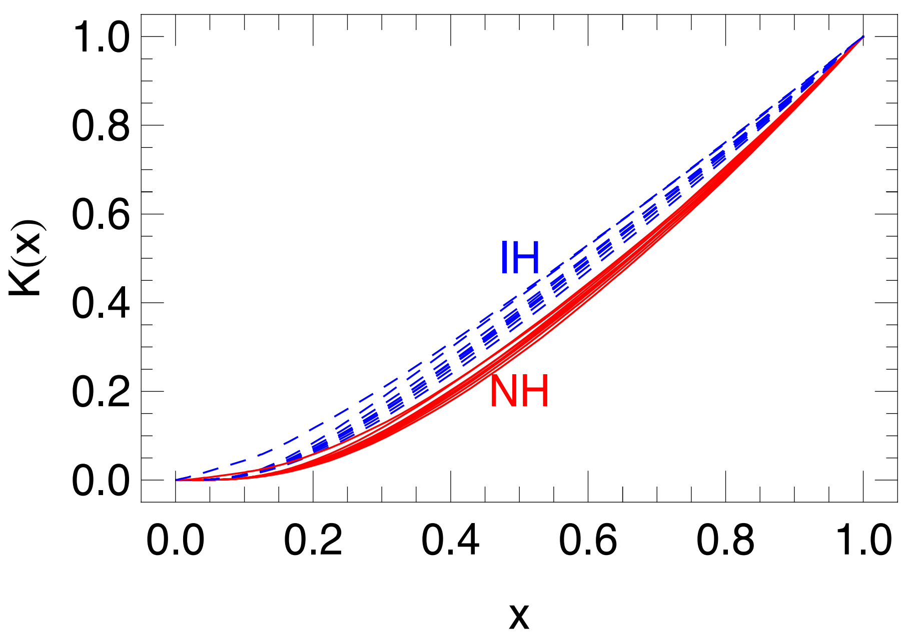
$$K(x) = \frac{\int_0^{x\, t_{\text{end}}} dt\, R(t)}{\int_0^{t_{\text{end}}} dt\, R(t)}$$

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.