Invisible13 Workshop
Lumley Castle, 15-19 July 2013

PROBING THE MASS HIERARCHY WITH SUPERNOVA NEUTRINOS

Alessandro MIRIZZI
(Hamburg University)

OUTLINE

- Supernova neutrino flavor oscillations

- Observables sensitive to the mass hierarchy:
  - ✓ Self-induced spectral splits
  - ✓ Neutronization burst
  - ✓ Earth matter effect
  - ✓ Rise time of neutrino signal

- Conclusions

3ν FRAMEWORK

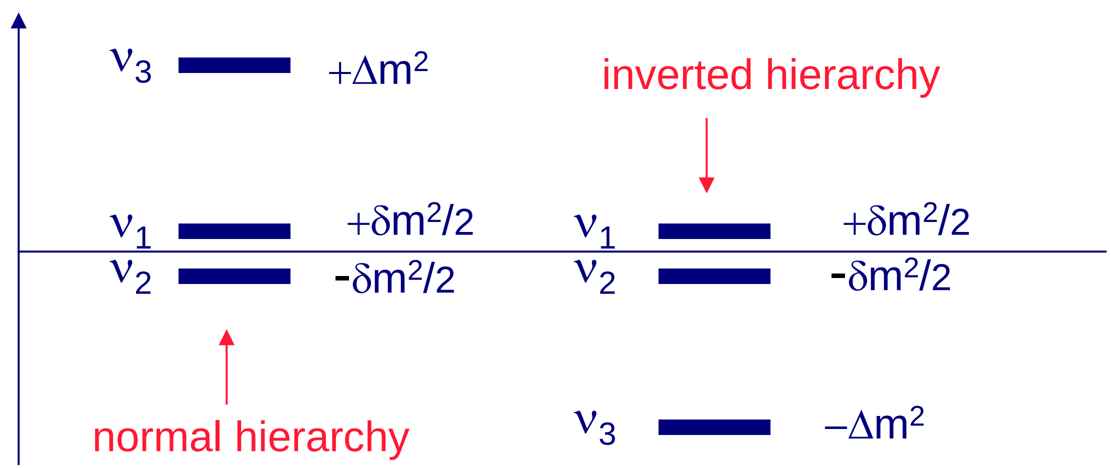
- **Mixing parameters:** $U = U(\theta_{12}, \theta_{13}, \theta_{23}, \delta)$ as for CKM matrix

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

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

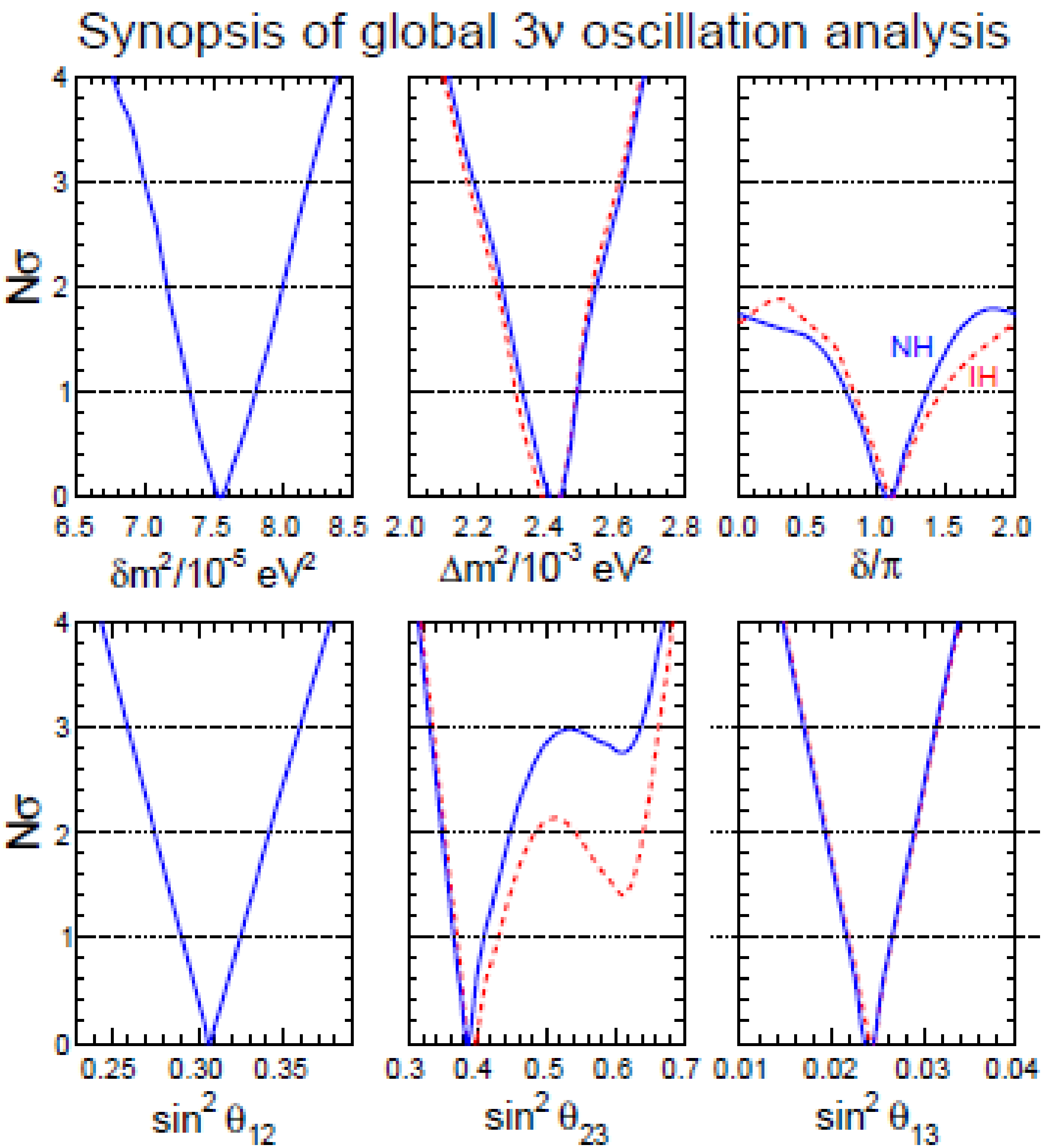
- **Mass-gap parameters:** $M^2 = \left[-\frac{\delta m^2}{2}, +\frac{\delta m^2}{2}, \pm \Delta m^2 \right]$

"solar" "atmospheric"



GLOBAL OSCILLATION ANALYSIS (2012)

[Fogli et al., arXiv:1205.5254]



REMARKS ON MASS HIERARCHY VIA FLAVOR TRANSITIONS

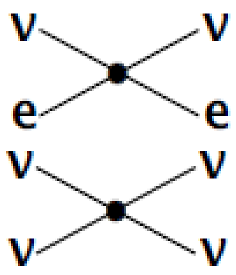
The hierarchy, namely, sign($\pm\Delta m^2$), can be probed (in principle), via interference of Δm^2-driven oscillations with some other Q-driven oscillations, where Q is a quantity with known sign.

Barring new states/interactions, the only known options are:

Q = δm^2 (high-precision oscill. pattern; reactors?)

Q = Electron density (MSW effect in Earth or SNe)

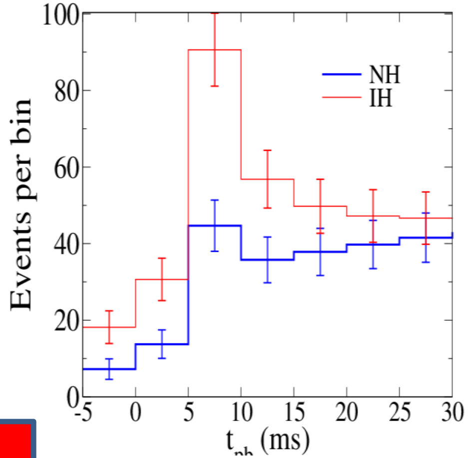
Q = Neutrino density (Collective effects in SNe)



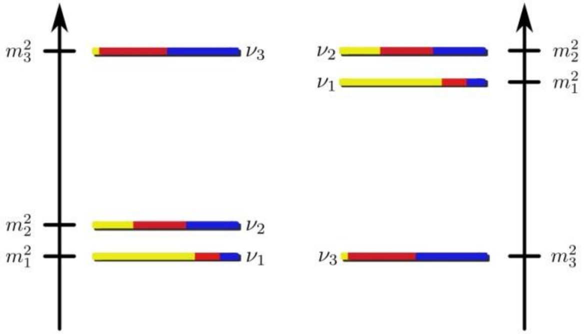
Which of the three... will succeed? Each one is very challenging, for rather different reasons. Non-oscillation observables might provide another handle. In any case: very high accuracy required.

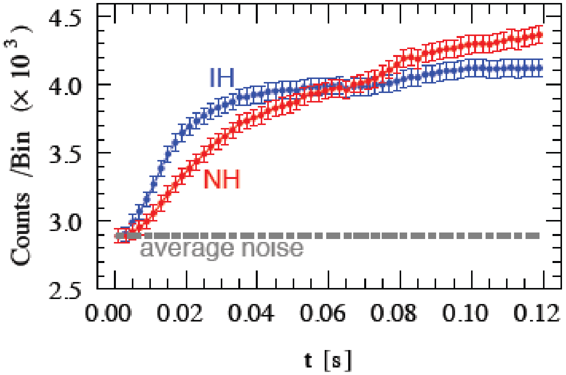
INVERSE SN NEUTRINO PROBLEM

Observe SN ν signal



Extract ν mass hierarchy





"Neutrino Physics: The Art of Learning a Great Deal By Observing Nothing" (Haim Harari)

SUPERNOVA NEUTRINOS

Core collapse SN corresponds to the terminal phase of a massive star [$M \gtrsim 8\, M_\odot$] which becomes unstable at the end of its life. It collapses and ejects its outer mantle in a shock wave driven explosion.

- **ENERGY SCALES:** 99% of the released energy (~ 10^{53} erg) is emitted by ν and $\bar{\nu}$ of all flavors, with typical energies E ~ O(15 MeV).
- **TIME SCALES:** Neutrino emission lasts **~10 s**
- **EXPECTED:** **1-3 SN/century** in our galaxy (d ≈ $\mathcal{O}$(10) kpc).

THREE PHASES OF NEUTRINO EMISSION

[Figure adapted from *Fischer et al. (Basel group), arXiv: 0908.1871*]

10. 8 M_{sun} progenitor mass

(spherically symmetric with Boltzmnann ν transport)

Neutronization burst

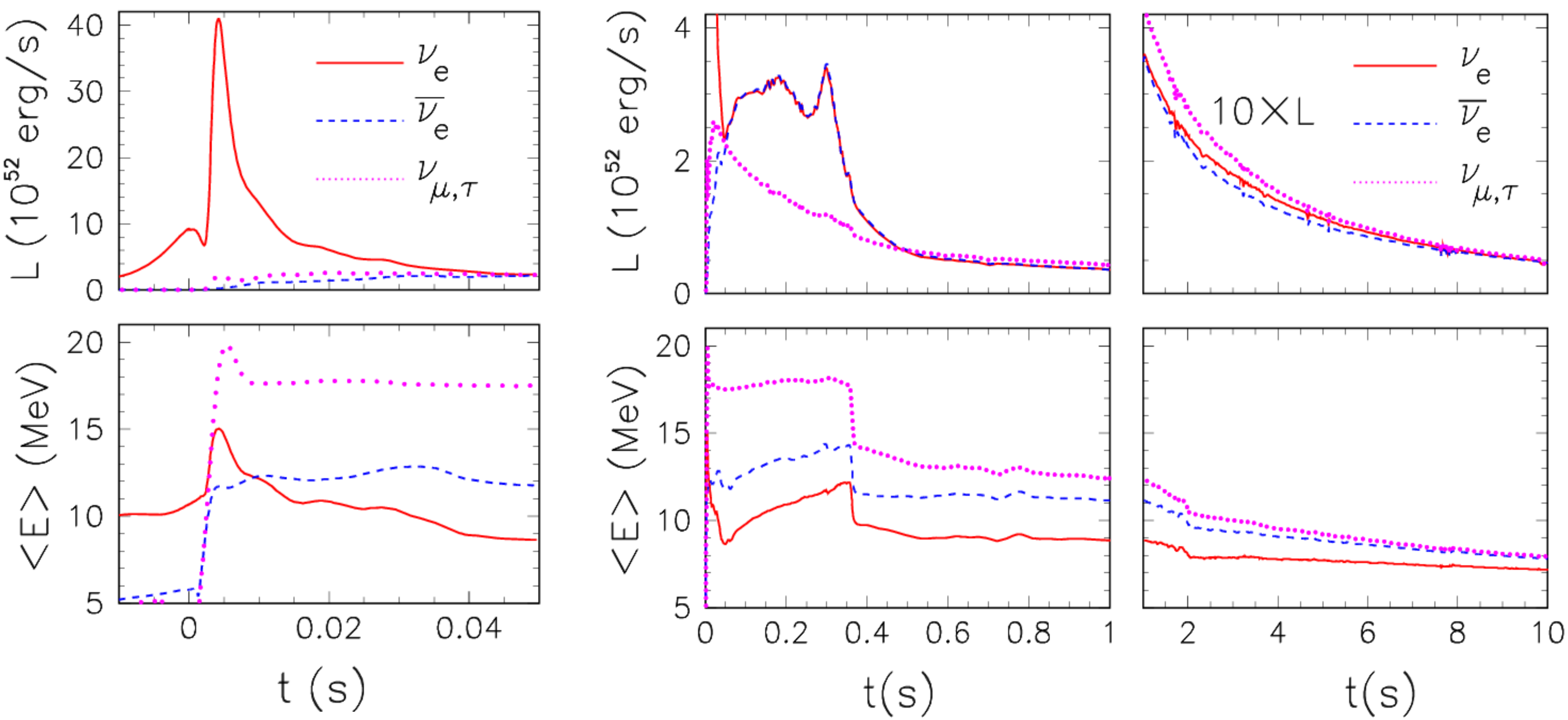
- Shock breakout
- De-leptonization of outer core layers

Accretion

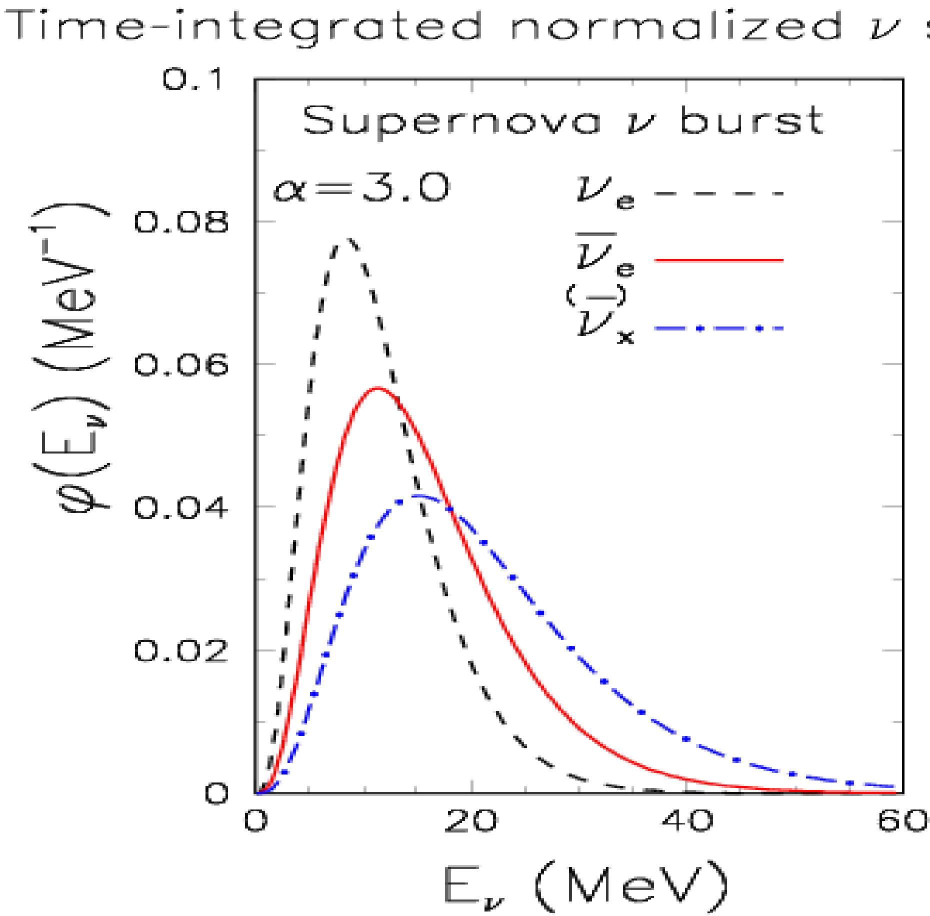
- Shock stalls ~ 150 km
- ν powered by infalling matter

Cooling

- Cooling on ν diffusion time scale



NEUTRINO ENERGY SPECTRA



"quasi-thermal" spectra

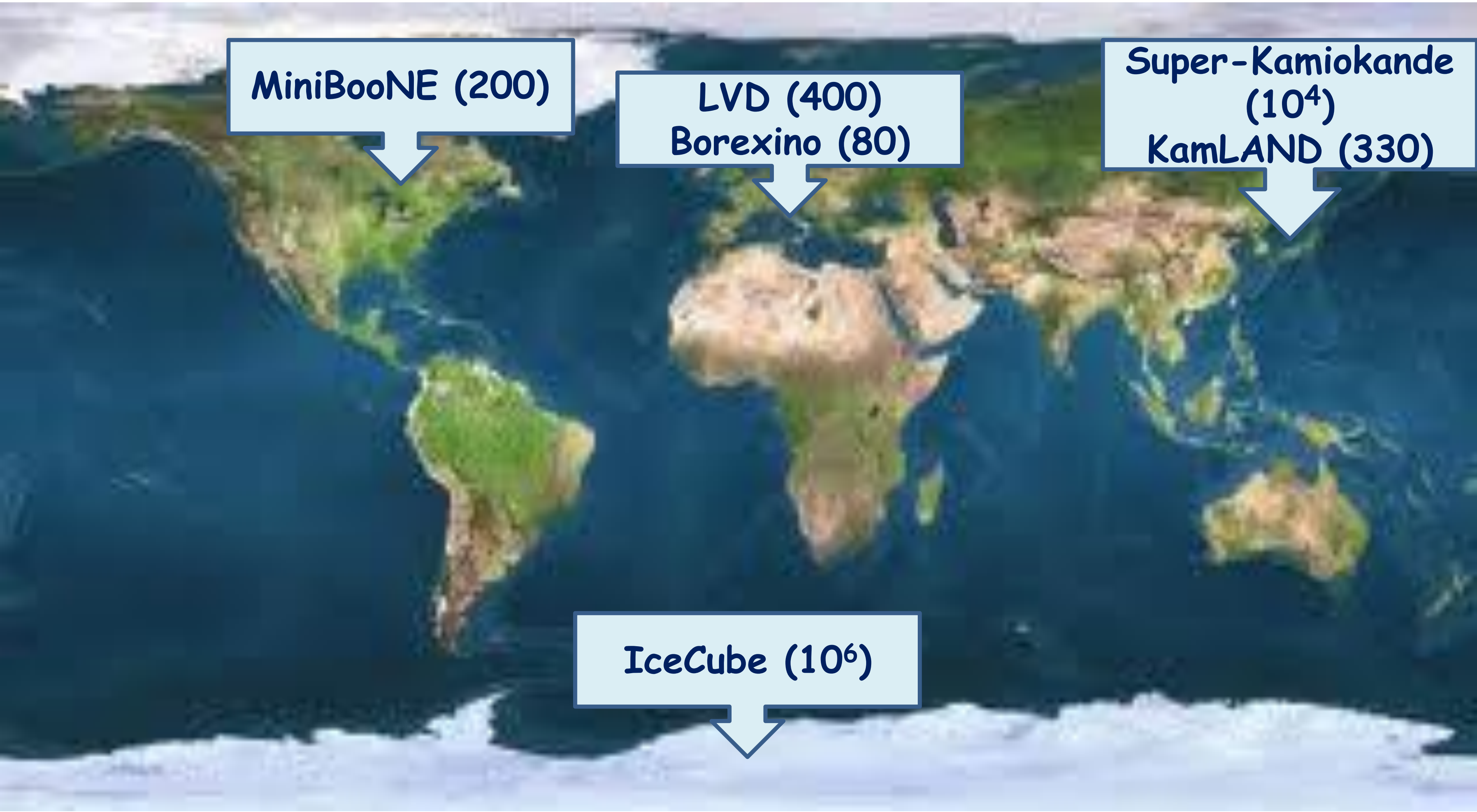
Hierarchy of the spectra

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

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

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

Large Detectors for Supernova Neutrinos

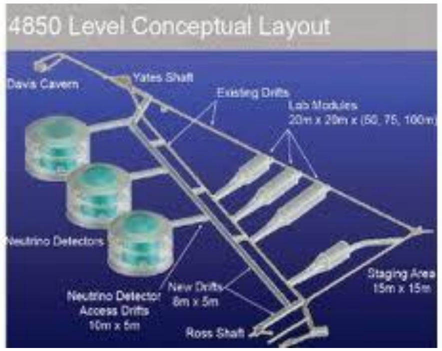


In brackets events for a "fiducial SN" at distance 10 kpc

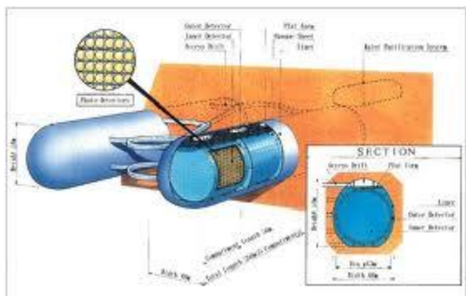
NEXT-GENERATION DETECTORS

Mton scale water Cherenkov detectors

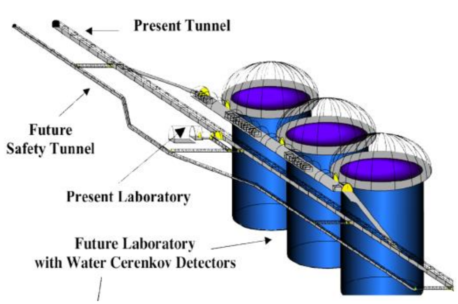
DUSEL LBNE



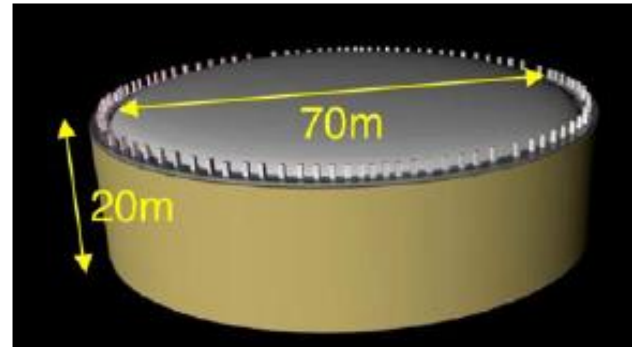
HYPER-KAMIOKANDE



MEMPHYS



5-100 kton Liquid Argon TPC



GLACIER

50 kton scintillator

LENA

Hanohano

SN ν FLAVOR TRANSITIONS

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

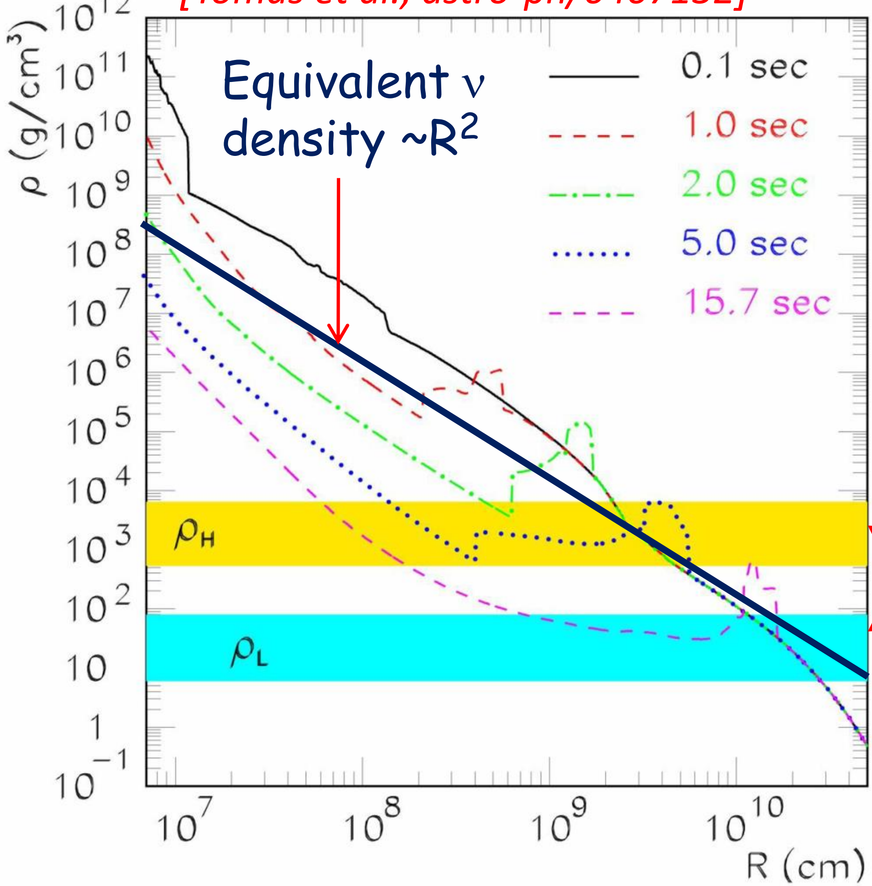
$$i\frac{d}{dx}\psi_{\nu} = \left(H_{vac} + H_{e} + H_{\nu\nu}\right)\psi_{\nu}$$

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)**

SNAPSHOT OF SN DENSITIES

[Tomas et al., astro-ph/0407132]



- Matter bkg potential

$$\lambda = \sqrt{2} G_F N_e \quad \sim R^{-3}$$

- ν–ν interaction

$$\mu = \sqrt{2} G_F n_\nu \quad \sim R^{-2}$$

- Vacuum oscillation frequencies

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

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

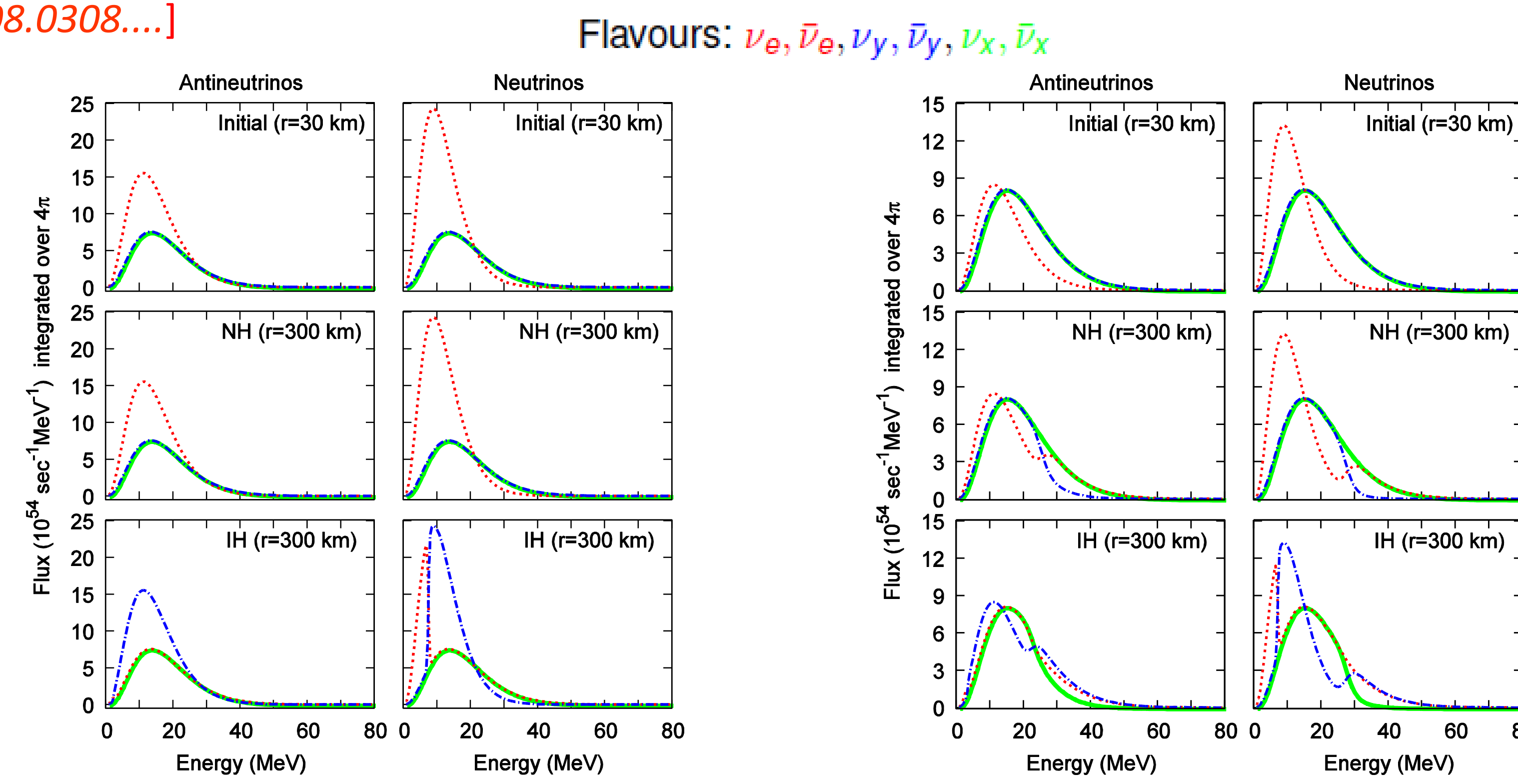
Collective flavor transitions at low-radii [O (10^2 – 10^3 km)]

Two seminal papers in 2006 triggered a torrent of activities
Duan, Fuller, Qian, astro-ph/0511275, Duan et al. astro-ph/0606616

[see Duan et al, arXiv:1001.2799 for a review]

SELF-INDUCED SPECTRAL SPLITS

[Fogli, Lisi, Marrone, A.M. , arXiV: 0707.1998 [hep-ph], Duan, Carlson, Fuller, Qian, astro-ph/0703776, Raffelt and Smirnov, 0705.1830 [hep-ph], Dasgupta, Dighe, Raffelt & Smirnov, arXiv:0904.3542 [hep-ph], Duan & Friedland, arXiv: 1006.2359, A.M. & Tomas, arXiv:1012.1339, Choubey, Dasgupta, Dighe, A.M., 1008.0308....]



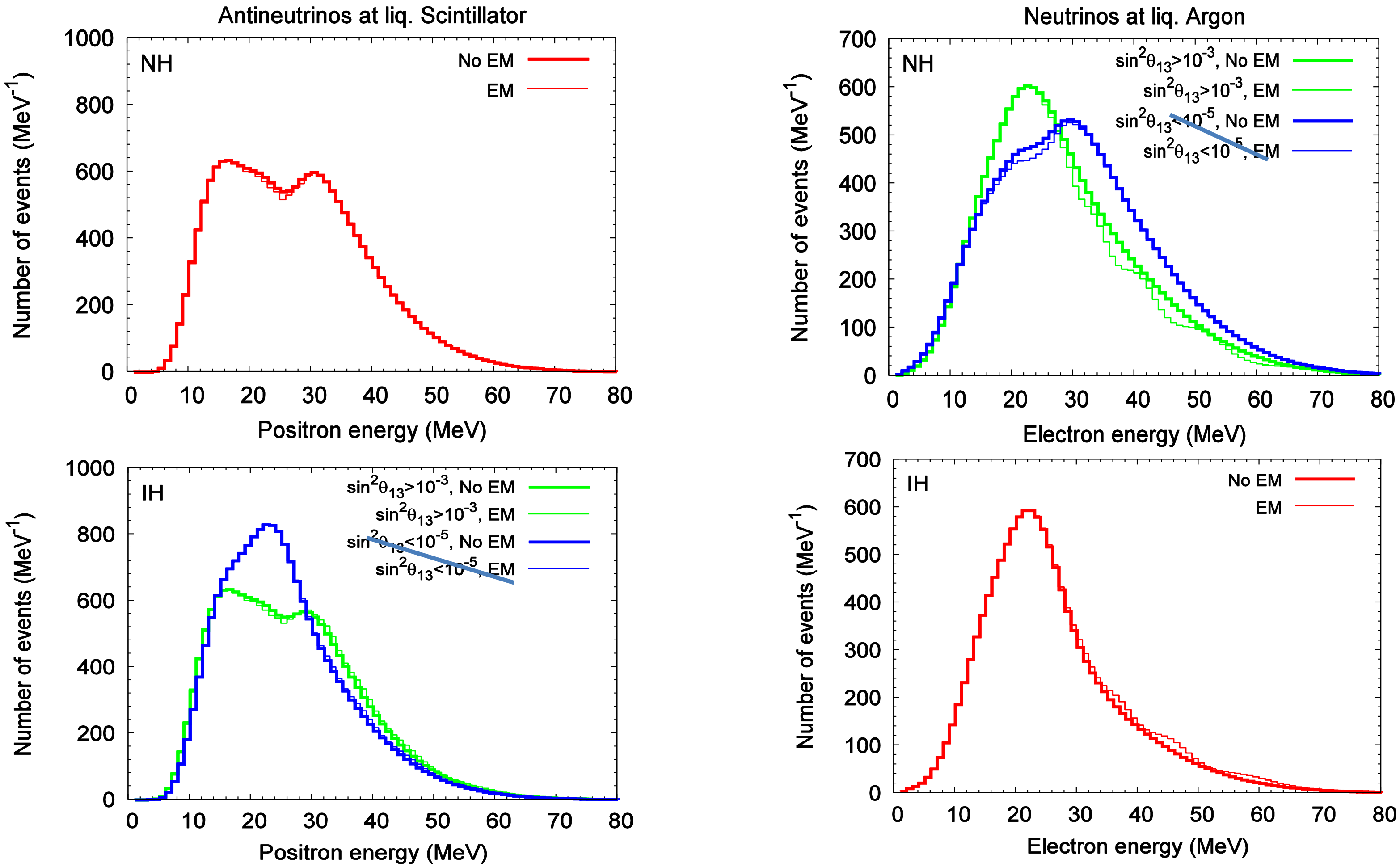
Strong dependence of collective oscillations on mass hierarchy and on the energy ("splits")

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

OBSERVABLE SIGNATURES?

[*Choubey, Dasgupta, Dighe, A.M., 1008.0308*]

- Spectral split may be visible as “shoulders”



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

SUPPRESSION OF COLLECTIVE OSCILLATIONS

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

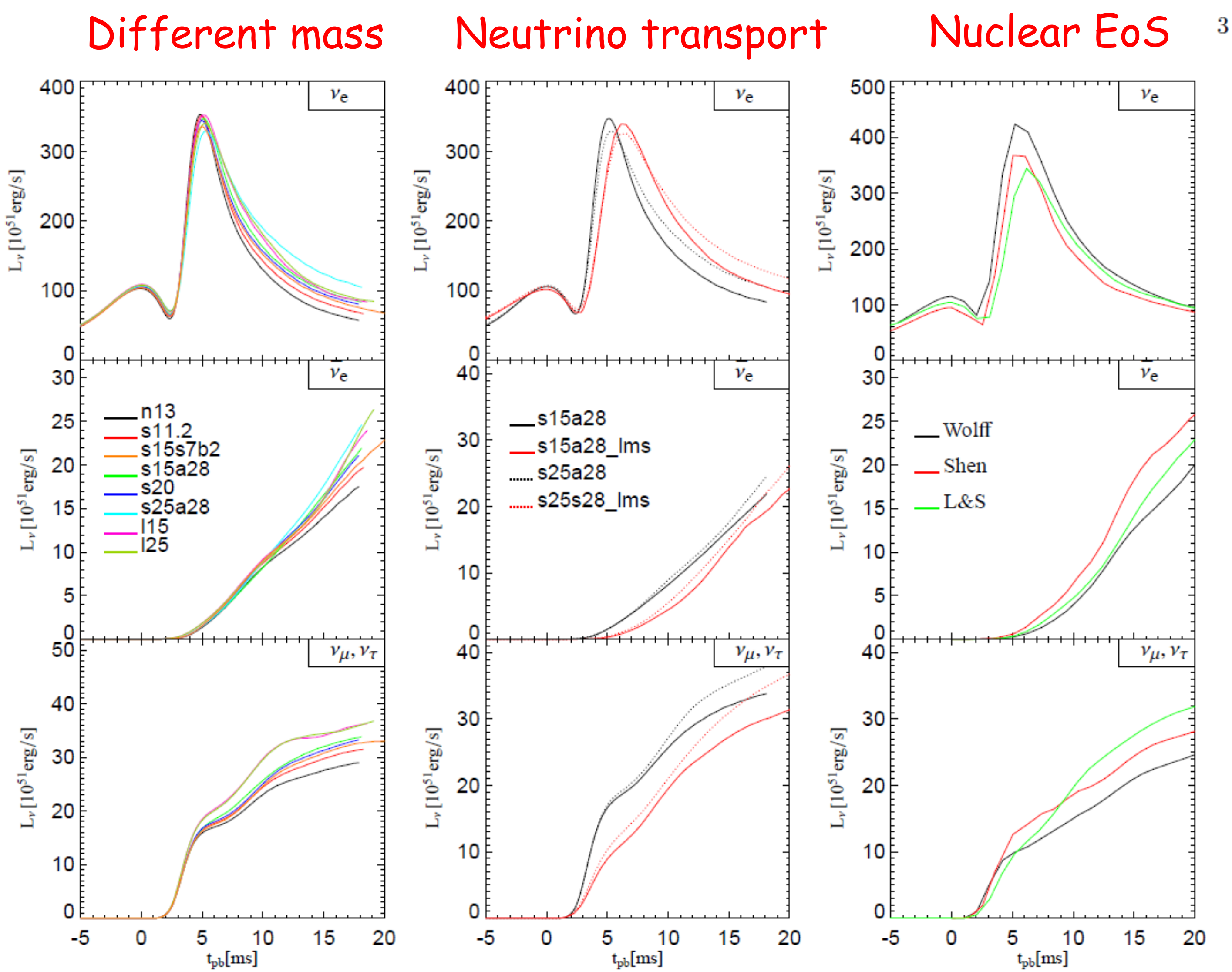
- Neutronization burst ($t < 20$ ms): large ν_e excess and ν_x deficit *[Hannestad et al., astro-ph/0608695]*

- Accretion phase ($t < 500$ ms): dense matter term dominates over nu-nu interaction term *[Chakraborty, A.M. , 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 !

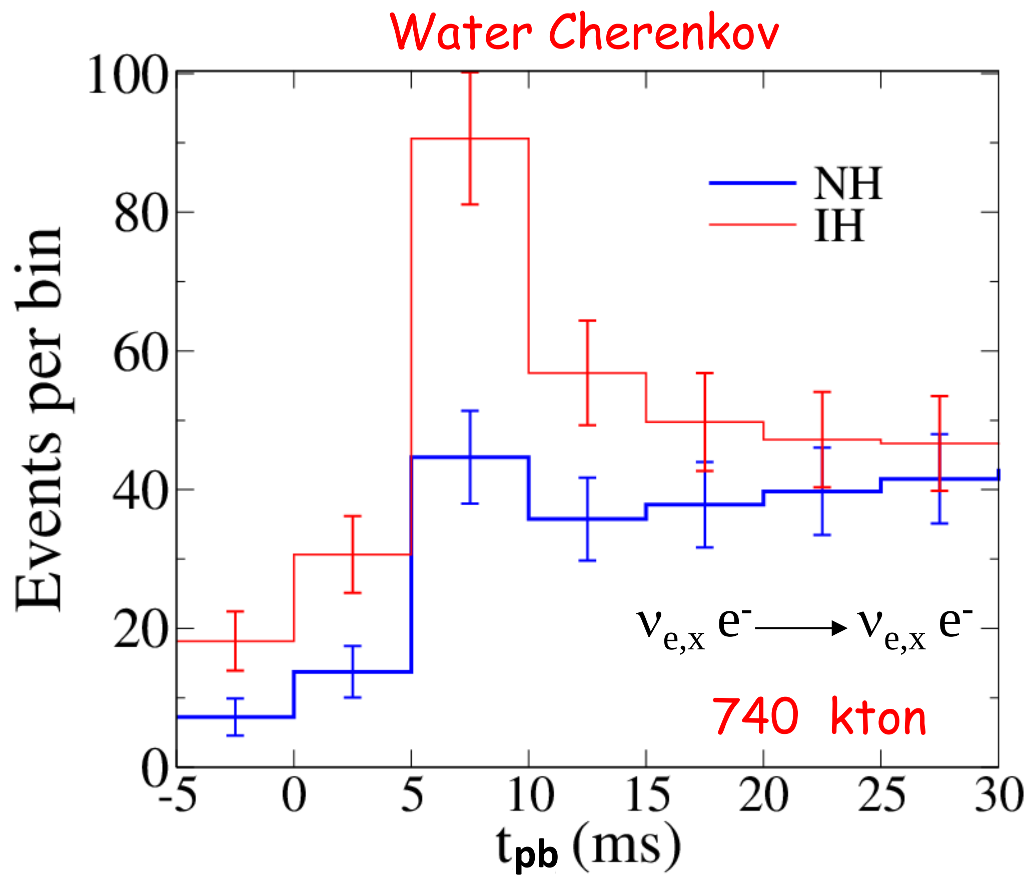
NEUTRONIZATION BURST AS A STANDARD CANDLE



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]

NEUTRONIZATION BURST



[see M.Kachelriess & R. Tomas, hep-ph/0412082]

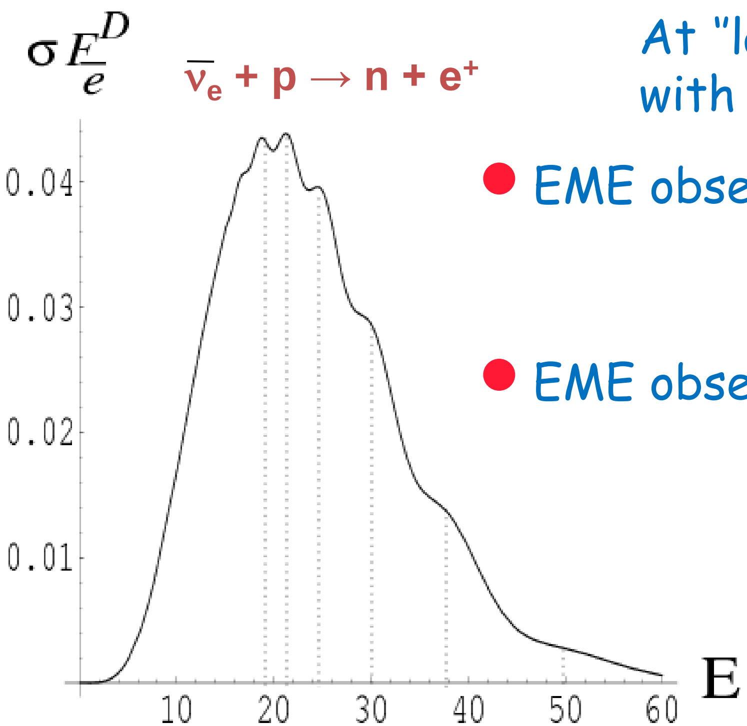
Possible also in a large LAr detector *[I.Gil-Botella & A.Rubbia, hep-ph/0307244]*

At "large" θ_{13} (like recently measured!):

- The peak <u>is not seen</u> → The hierarchy is normal (if one could see it...)
- The peak <u>is seen</u> → The hierarchy is inverted (more robust)

USING EARTH EFFECT TO DIAGNOSE 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



At "large" θ_{13} only one possible scenario compatible with detection of Earth matter effect (EME):

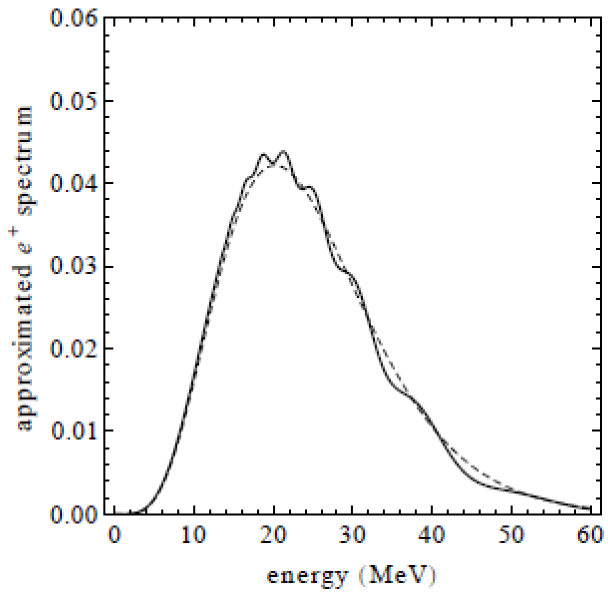
- EME observed in neutrinos ⟶ Normal hierarchy
- EME observed in anti-neutrinos ⟶ Inverted hierarchy

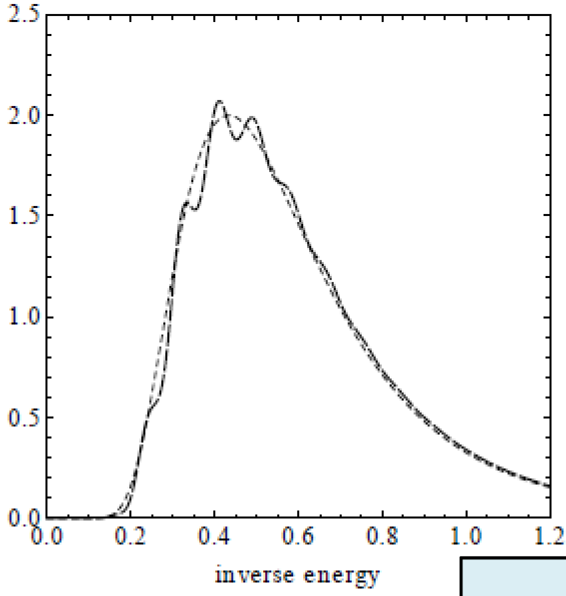
(Assuming complete matter suppression of collective oscillations during the accretion phase)

EARTH MATTER EFFECT

$$F^D_{\bar{e}} = \sin^2\theta_{12} F^0_{\bar{x}} + \cos^2\theta_{12} F^0_{\bar{e}} + \Delta F^0 \overline{A}_{\oplus} \sin^2\left(\overline{\Delta m^2_{\oplus}} L y\right)$$

$$\Delta F^0(E) = F^0_{\bar{e}}(E) - F^0_{\bar{x}}(E)$$





$$y = \frac{12.5\ MeV}{E}$$

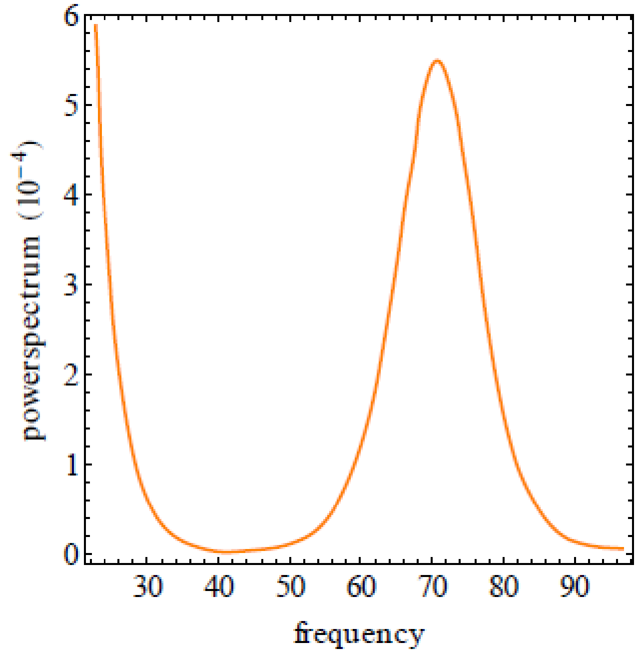
In terms of the " inverse energy " y, there is modulation of the spectrum with a specific wavenumber $k_{\oplus} = 2\Delta m^2_{\oplus} L$ (indipendent of SN physics!)

FOURIER TRANSFORM OF THE SN ν SIGNAL

[see Dighe et al., hep-ph/0304150; 0311172]

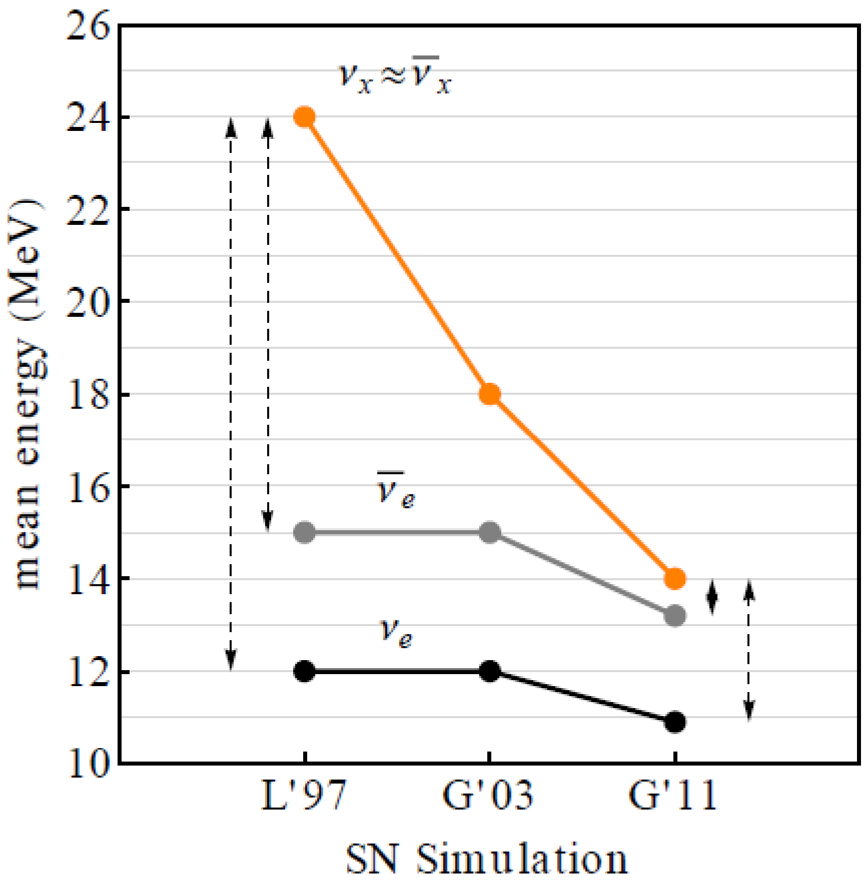
To "tag" the hierarchy, one may search for a known peak in the Fourier Transform (wrt y) of the event rate spectrum (~σF), seemingly independently of SN input!

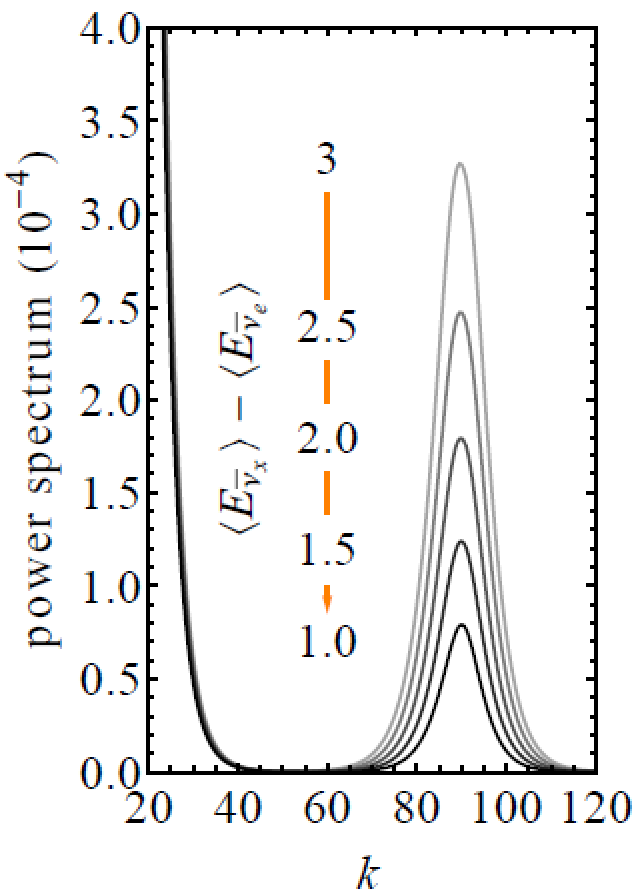
$$G_N(k) \equiv \frac{1}{N}\left|\sum_{i=1}^{N} e^{iky_i}\right|^2$$



DEPENDENCE ON THE FLUX DIFFERENCES

- **CAVEAT:** How important/dominant the "Earth matter" mode is depends also on the flux difference (which is **model-dependent!**)

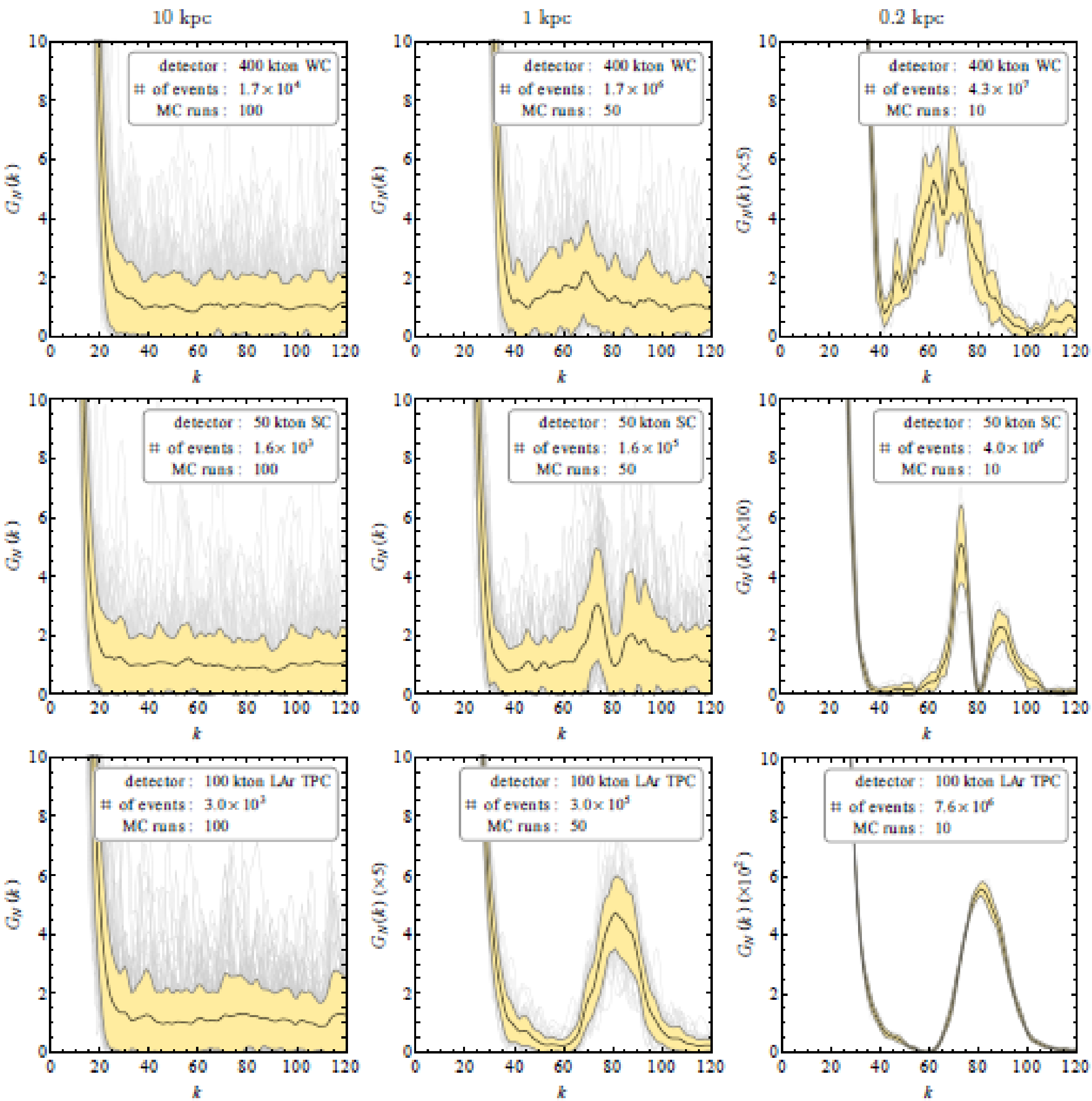




L: Livermore, G: Garching

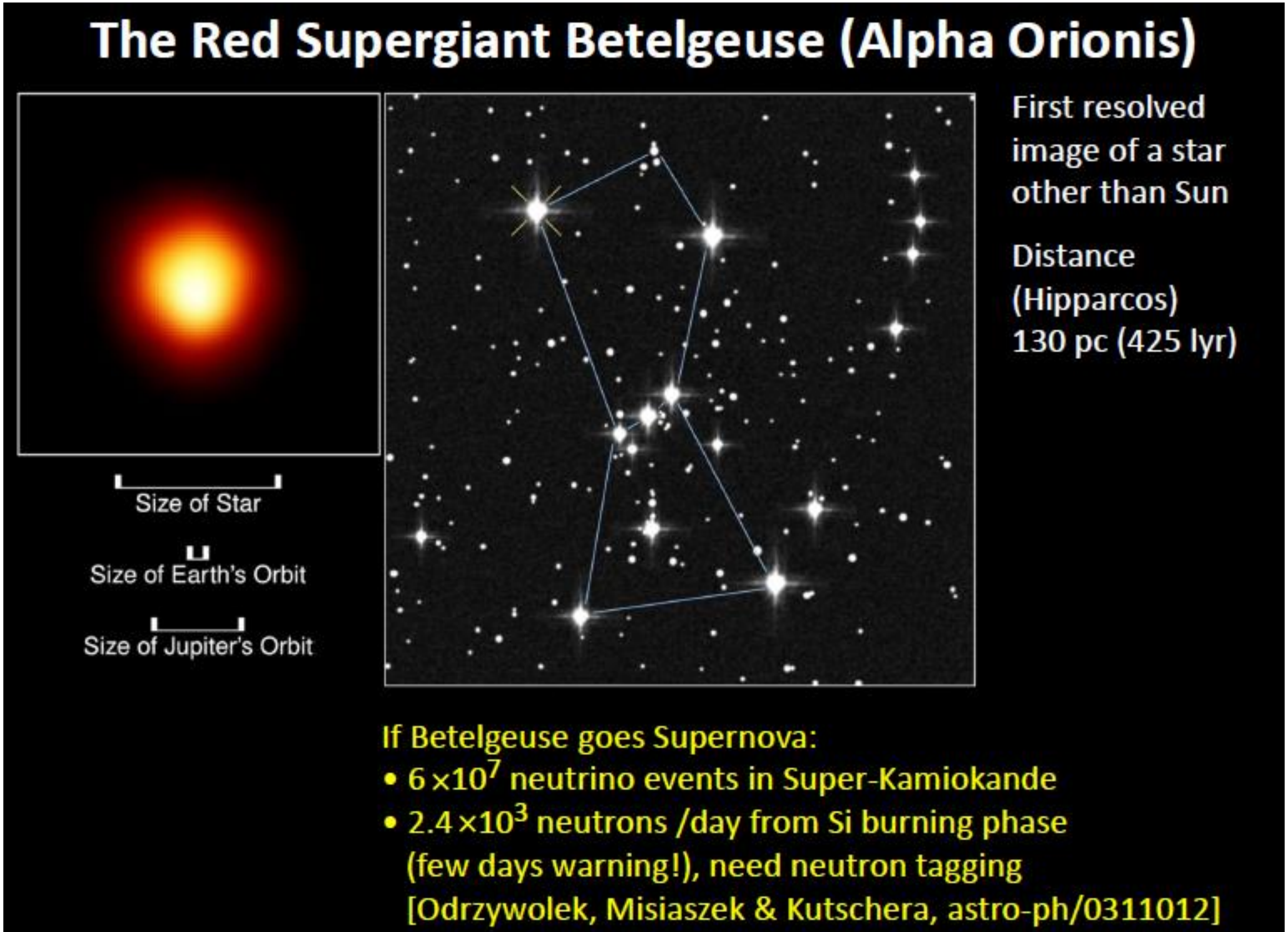
(DOWN-TO-)EARTH MATTER EFFECT

[see Borriello, Chakraborty, A.M., Serpico & Tamborra, 1207.5049]

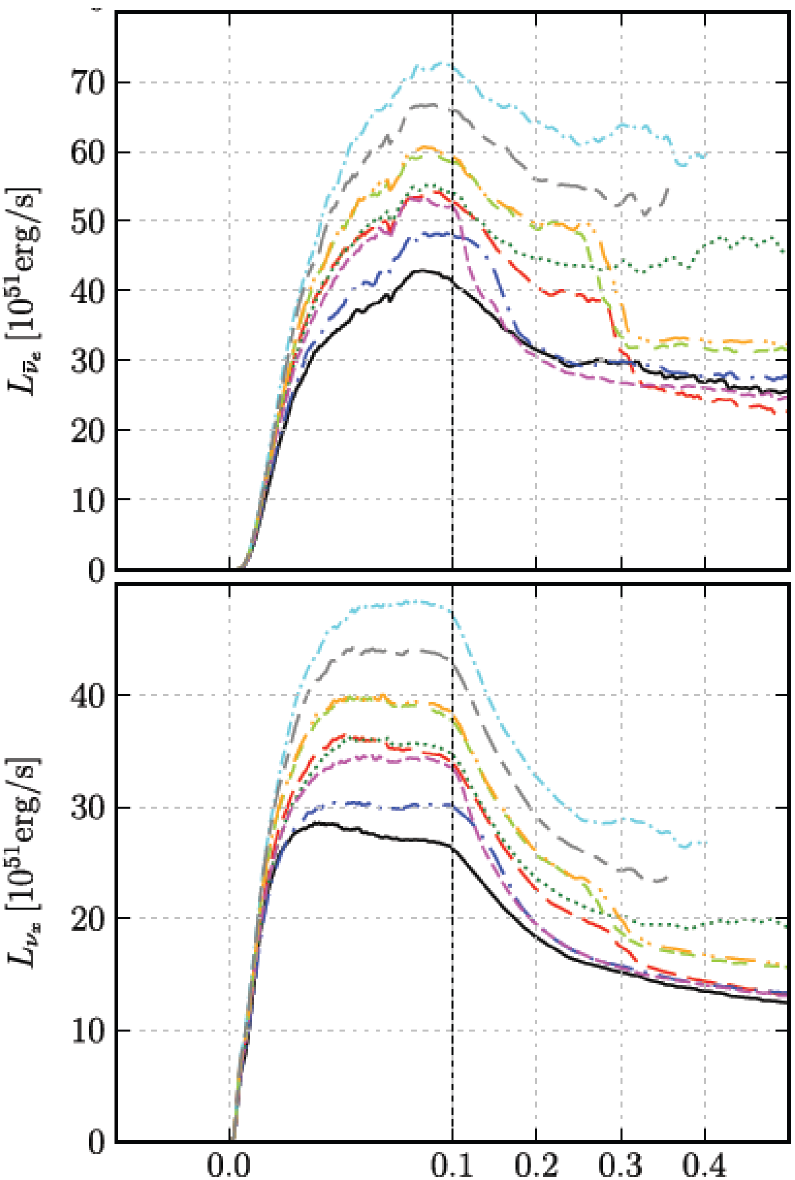


- Sub-kpc distance required in general for unambigous detection (provided electronics can handle those rates!)
- For Liq. Argon, hope up to O(kpc) distances given the larger differences found in the neutrino channel.
- Realistically, no more than a few percent chance to detect EME at next Gal. SN

….However, some candidates at d~ 0.2 kpc exist!



RISE TIME OF SN NEUTRINO SIGNAL



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 .
- The high degeneracy allows only for a low abundance of e^+, the production of $\bar{\nu}_e$ by pair annihilation and e^+ capture on neutrons is not very efficient. Moreover, since in the optical tick regime $\bar{\nu}_e$ are in chemical equilibrium with the matter, their degeneracy also blocks the phase space for the creation of $\bar{\nu}_e$ via nucleon-nucleon bremmstrahlung (which however is operative also for ν_x).
- $\bar{\nu}_e$ are produced more gradually via cc processes (e captures on free nucleons) in the accreting matter; ν_x come fastly from a deeper region

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

RISE TIME ANALYSIS: HIERARCHY DETERMINATION

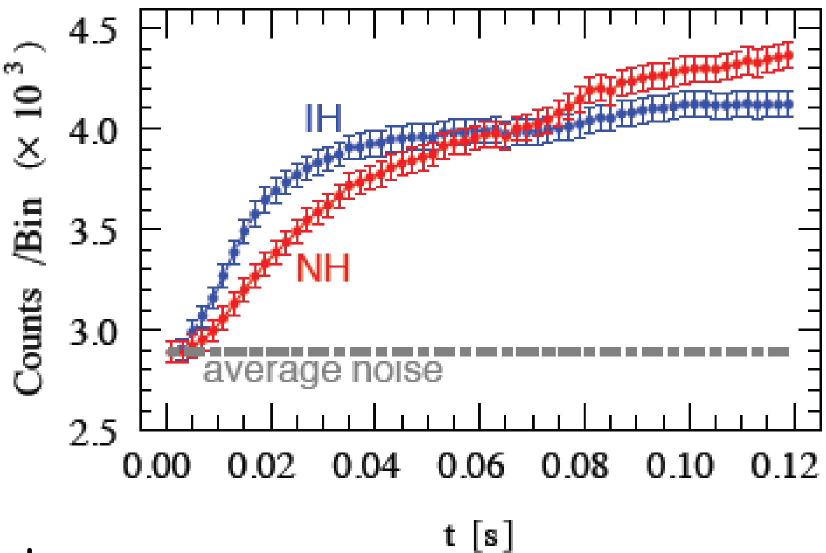
[see Serpico, Chakraborty, Fischer, Hudepohl, Janka & A.M., 1111.4483]

In accretion phase one has

$$F^D_{\bar{\nu}_e} = \cos^2\theta_{12} F_{\bar{\nu}_e} + \sin^2\theta_{12} F_{\bar{\nu}_x}$$ NH

$$F^D_{\bar{\nu}_e} = F_{\bar{\nu}_x}$$ IH

SN ν signal in Icecube

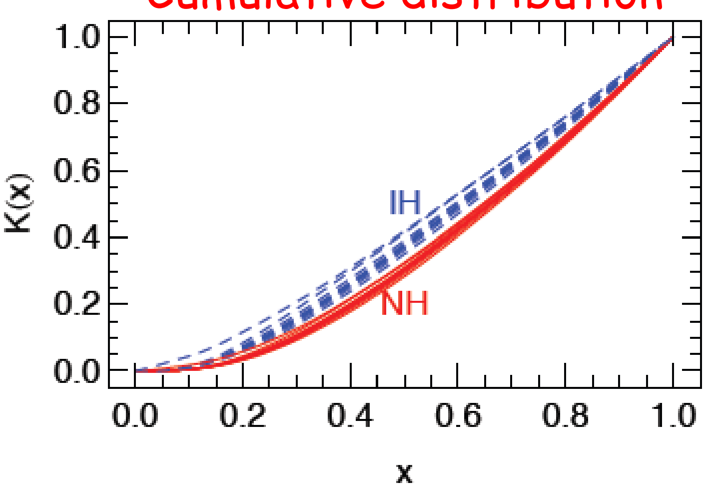


A high-statistics measurment of the rise time shape may distinguish the two scenarios

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

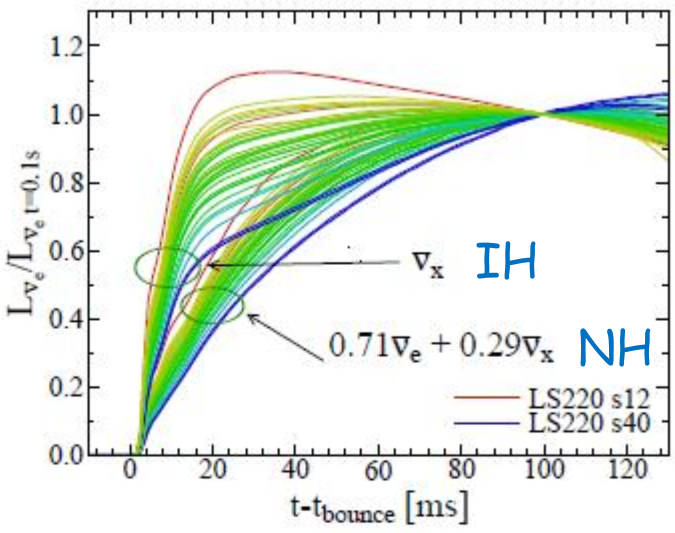
Models with state-of-the art treatment of weak physics (Garching simulations) suggest so: one could attribute a "shape" to NH and IH.

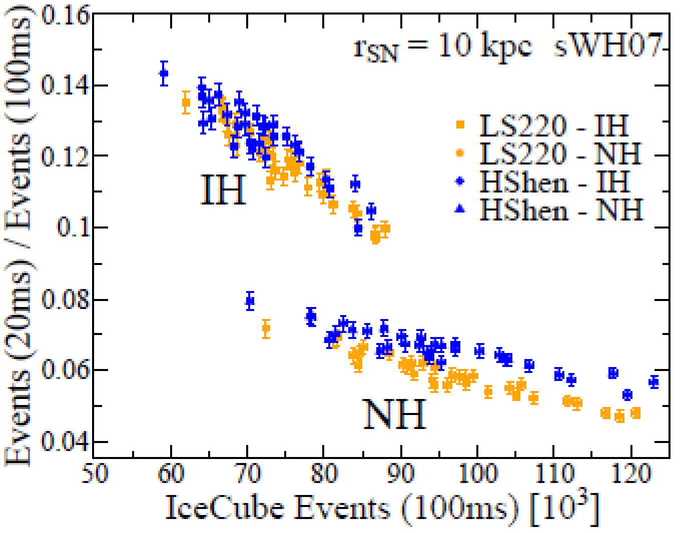
Cumulative distribution



● Result confirmed also with the SN simulations of Caltech group

[see Ott et al., 1212.4250]





Given these promising early results, it would be mandatory in future to explore the robusteness of the signature with more and more accurate simulations.

CONCLUSIONS

- Self-induced and matter effects in SNe are strongly sensitive to the neutrino mass hierarchy

- A high-statistics SN ν detection would allow to observe possible signatures of the mass hierarchy.

- INVERSE SN NEUTRINO PROBLEM

  - ✓ Self-induced spectral splits
  - ✓ Neutronization burst
  - ✓ Earth matter effect
  - ✓ Rise time of neutrino signal

  ⇒ Extract mass hierarchy

Instant identification of the ν mass hierarchy not impossible... but still many gaps to be filled.

Lot of theoretical and experimental work to get the most from the next galactic SN explosion!