Perspectives on mass hierarchy determination with supernova ν's

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Lyon - 23 October 2012

Outline

✤ I will first review the feasibility of using the Earth Matter Effect (EME) on Supernova neutrinos as a probe of neutrino mass hierarchy

✤ Based on state of the art simulations and current understanding of neutrino flavour evolution in supernovae, I will explain why it is way less promising (and in a sense less "model-independent") that initially thought.

✤ I will then argue that some other signatures of hierarchy may nonetheless survive: I will briefly discuss one which we have tentatively identified recently.

based on:

Enrico Borriello, Sovan Chakraborty, Alessandro Mirizzi, PS, and Irene Tamborra, Phys. Rev. D 86, 083004 (2012)

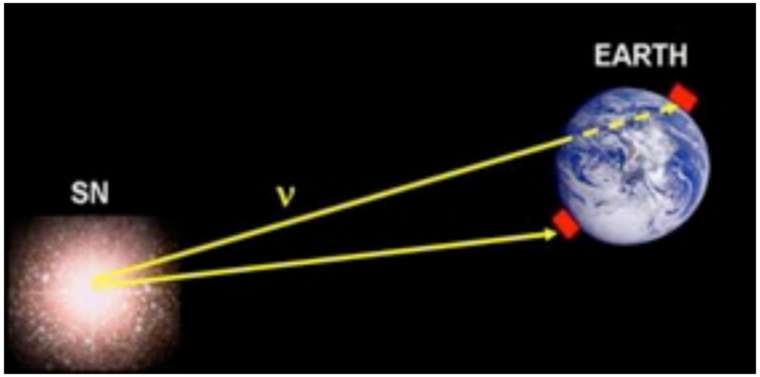
PS, Sovan Chakraborty, Tobias Fischer, Lorenz Hüdepohl, Hans-Thomas Janka, and Alessandro Mirizzi. Phys. Rev. D 85, 085031 (2012)

Part I: EME in SN neutrinos

One slide summary of the situation

- Core-collapse SNe emit *flavour-dependent fluxes of* ν's, in large enough numbers to be *measurable in detail* with current technology for a future Galactic event. *G. Raffelt's talk*
(Emitted fluxes actually do depend on the hierarchy... back to this point later.)

- Assume one measures such a flux for a SN *crossing (enough mantle of) the Earth*.



- Then, the flux of ν's *of a given flavour* is a **peculiar combination (="EME")** of input fluxes.

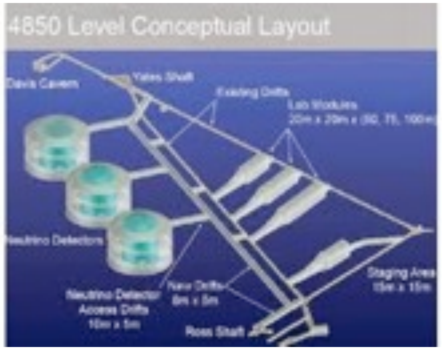
- In which channel EME manifests depends on the (still unknown) mass hierarchy: neutrinos for IH, antineutrinos for NH. Knowing the detection channel, **detection or absence of Earth Matter effects gives information on the hierarchy**.

- **Good news:**

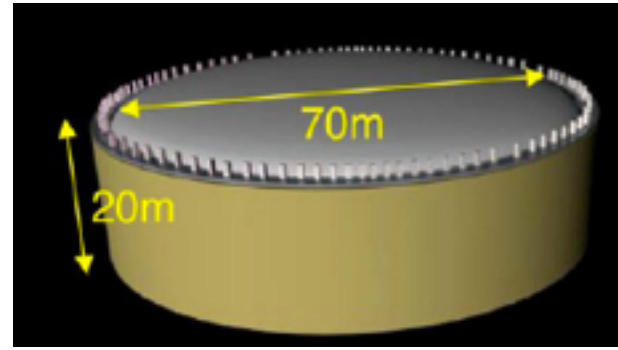
✦ ambiguity between large θ_{13} and small θ_{13} cases now resolved; if a measurement can be performed, it is unambiguous (at least theoretically)
✦ improved simulations exist (transport, GR effects, etc.) with respect to a decade ago.
✦ several detector options

next generation detectors in R&D phase

10-100 kton Liquid Argon TPC



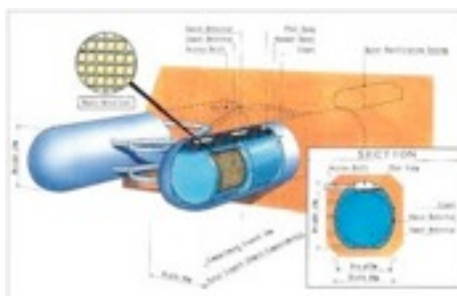
DUSEL LBNE Detector



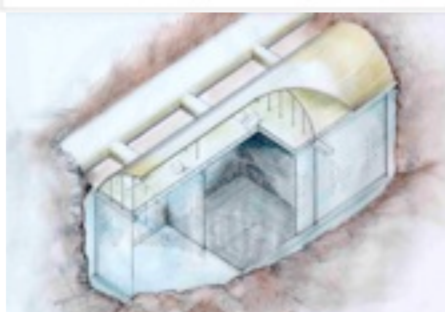
GLACIER*

Mton scale water Cherenkov detectors

HYPER-KAMIOKANDE



MEMPHYS*



50 kton scintillator

LENA*

*=(European LAGUNA research infrastructure)

Complementary channels and features

	"MEMPHYS"	"LENA"	"GLACIER"
Main channels	$\bar{\nu}_e + p \to n + e^+$	$\bar{\nu}_e + p \to n + e^+$	$\nu_e + {}^{40}Ar \to {}^{40}K^* + e^-$
Size	400 kton	50 kton	100 kton
E-Resolution	$\frac{\Delta}{\mathrm{MeV}} = 0.47\sqrt{\frac{E_e}{\mathrm{MeV}}}$	$\frac{\Delta}{\mathrm{MeV}} = 0.07\sqrt{\frac{E_e}{\mathrm{MeV}}}$	$\frac{\Delta}{\mathrm{MeV}} = 0.11\sqrt{\frac{E_e}{\mathrm{MeV}}} + 0.02\frac{E_e}{\mathrm{MeV}}$
Expected # of events	10 kpc: 2×10^4 1 kpc: 2×10^6 0.2 kpc: 4×10^7	10 kpc: 2×10^3 1 kpc: 2×10^5 0.2 kpc: 4×10^6	10 kpc: 3×10^3 1 kpc: 3×10^5 0.2 kpc: 8×10^6

In the following, illustrative results obtained with above parameters

Apologies: Of course, a theorist's simplification...

Flavour-dependent SN neutrino fluxes

Figures adapted from Fischer et al., arXiv: 0908.1871, 10. 8 M_{sun} progenitor mass (spherically symmetric with Boltzmnann ν transport, no oscillations!)

Neutronization Burst

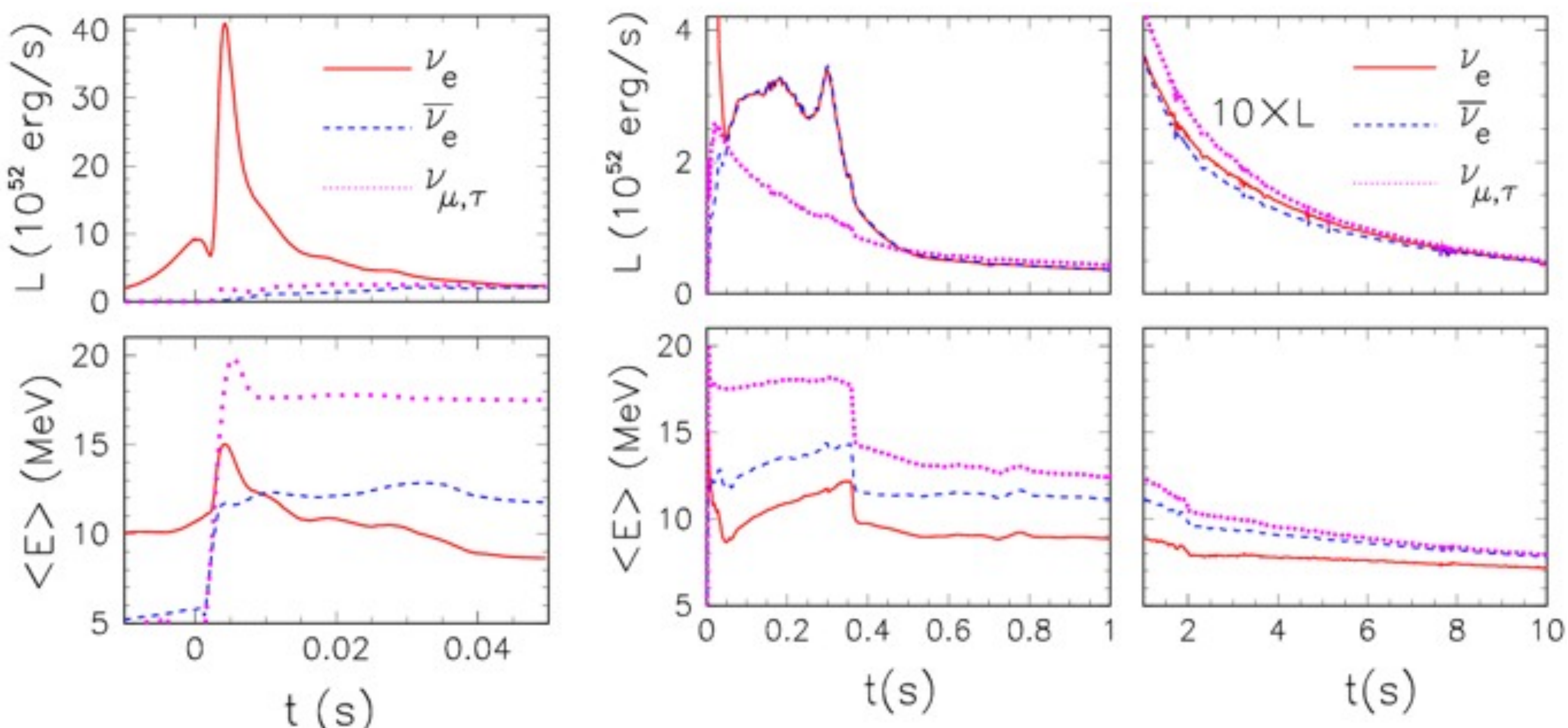
- Shock breakout
- De-leptonization of outer core layers

Accretion

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

Cooling

- Cooling on ν diffusion time scale



Effects of oscillations on the input fluxes: sketch

• In the **cooling phase**, fluxes are much closer and collective oscillations can have an impact.

Generic expectation: almost flavor-independent fluxes at the Earth, with small residual differences that might depend on details (for example, relatively poorly known angular distribution function may favor decoherence... see *A. Mirizzi's talk*)

We cannot/should not rely upon that for flavour diagnostics (expect little effects anyway).

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• **In the accretion phase,** at least for Fe-core collapse SN, we expect matter multi-angle effects (see *A. Esteban-Pretel et al. 0807.0659*) to freeze any alteration due to collective effects (see *S. Chakraborty et al. 1104.4031, 1105.1130, S. Sarikas et al. 1109.3601* for checks with actual simulation outputs).

The well-known MSW-like effects studied for over a decade (e.g. *A. S. Dighe and A.Y..Smirnov, hep-ph/9907423*) apply.

We recover predictability and "large" flux differences, albeit for a signal lasting few hundreds ms. For example, for anti-ν_e:

$$F^D_{\bar{\nu}_e} = \bar{p}^D_e(E) F^0_{\bar{\nu}_e} + [1 - \bar{p}^D_e(E)] F^0_{\bar{\nu}_x}$$

Normal mass hierarchy

$$\bar{p}^D_e \approx \cos^2\theta_{12}$$

Inverted mass hierarchy

$$\bar{p}^D_e \approx 0$$

Earth Matter effect

The probability gets modified (for antineutrinos in NH) as

$$\bar{p}_e^D \to \bar{p}_e^D - \kappa(E)\sin^2\left(\frac{\overline{\Delta m^2_\oplus}}{10^{-5}\,\mathrm{eV}^2}\,\frac{L}{10^3\,\mathrm{km}}\,\frac{12.5\,\mathrm{MeV}}{E}\right)$$

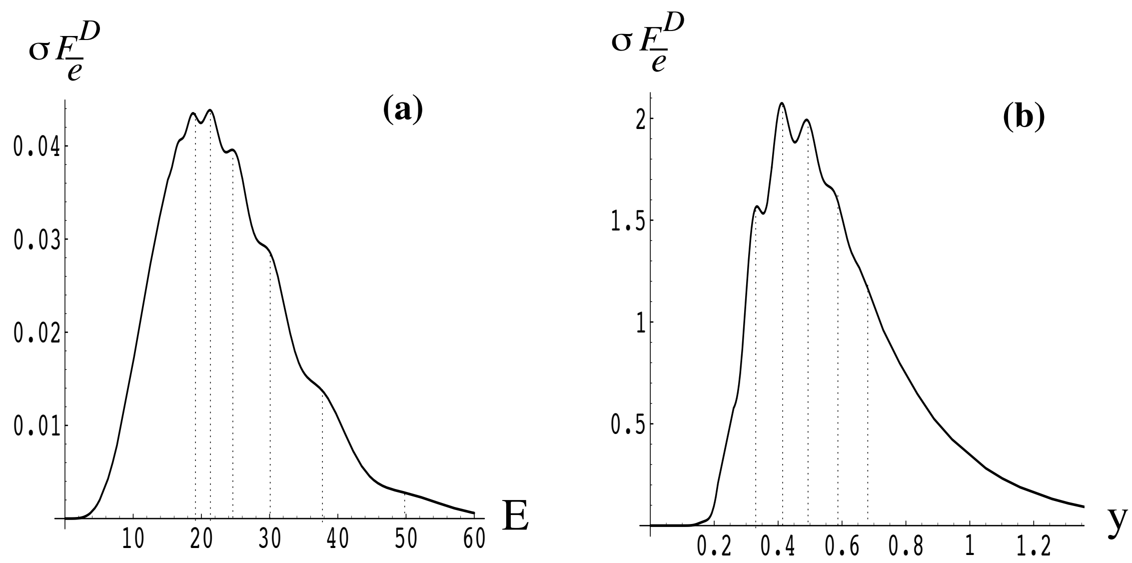
0≤|κ|≤1, depends on mixing angle in matter

$$\overline{\Delta m^2_\oplus} = \Delta m^2_\odot\left[\sin^2 2\theta_\odot + (\cos 2\theta_\odot + 2\,V E/\Delta m^2_\odot)^2\right]^{1/2}$$

In terms of ***y=12.5 MeV/E***, there is modulation of the spectrum with a specific wavenumber (indipendent of SN physics!)

$$F^\oplus_{\bar{\nu}_e} = F^D_{\bar{\nu}_e} - \kappa\,(F^0_{\bar{\nu}_e} - F^0_{\bar{\nu}_x})\sin^2\left(\frac{k_\oplus y}{2}\right) \qquad k_\oplus \equiv 2\overline{\Delta m^2_\oplus}\,L$$

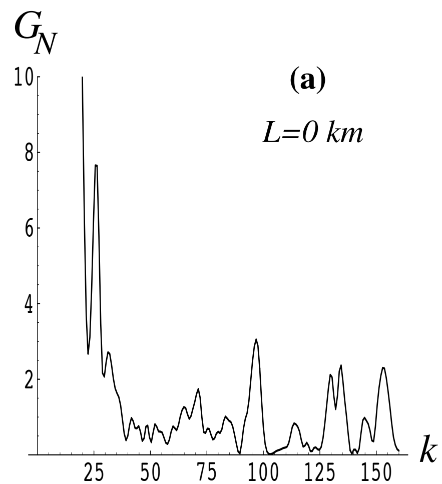
A. S.Dighe, M. T. Keil and G. G.Raffelt, hep-ph/0304150

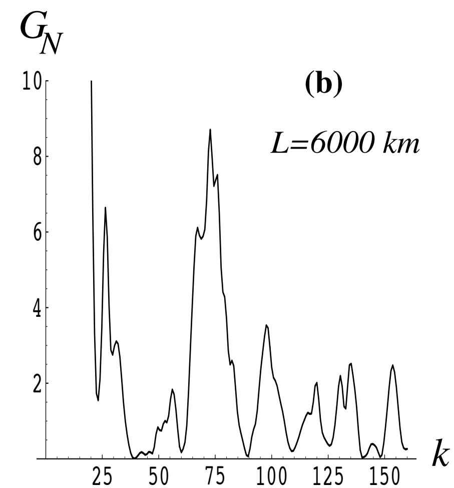


Idea nr. 1

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

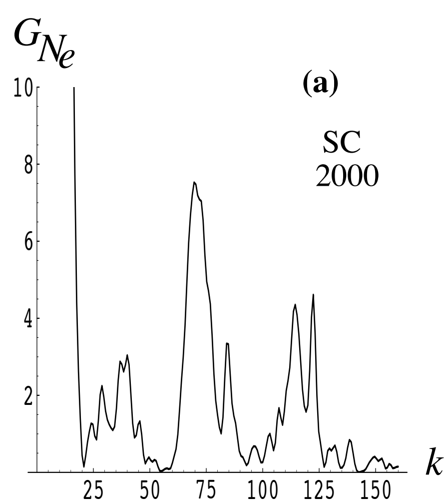
The peak clearly emerges from the finite-statistics (and E-range) "noise" when neutrinos cross the Earth

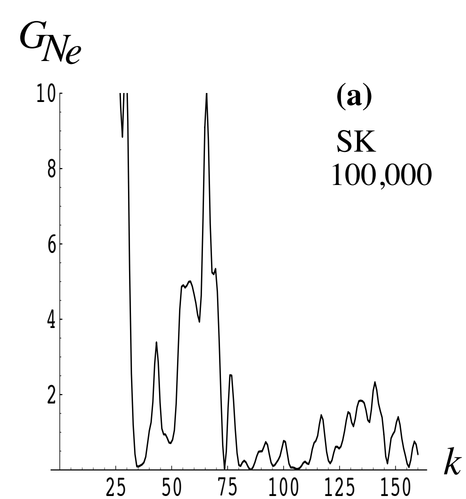




A. S.Dighe, M. T. Keil and G. G.Raffelt, hep-ph/0304150

Good perspectives found for Scintillators of the "LENA" size (exploit E-resolution) or even megaton class Cherenkov detectors (exploit statistics)



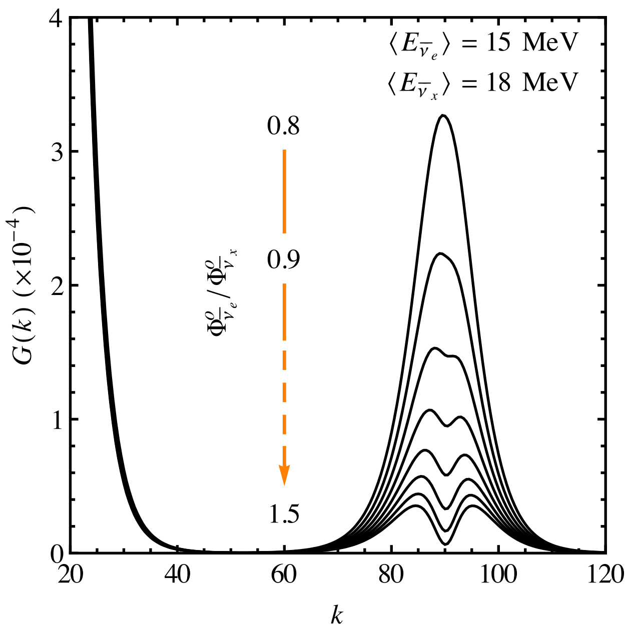


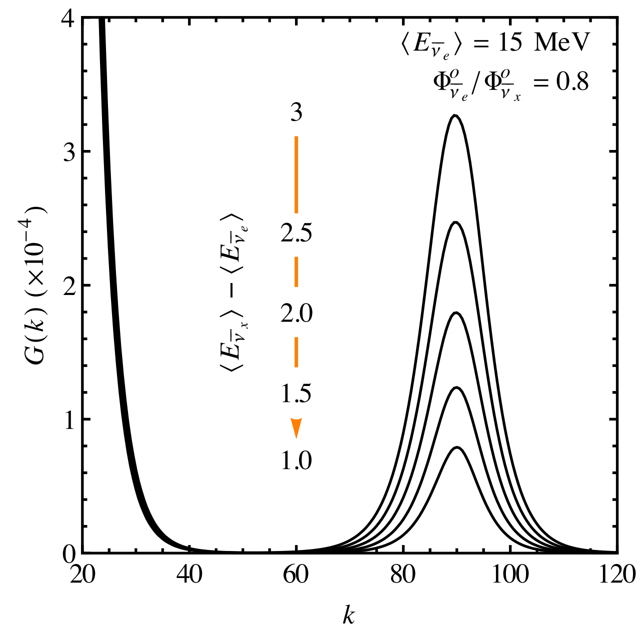
Too good to be true?
Beware of some caveats...

(Some) Caveats

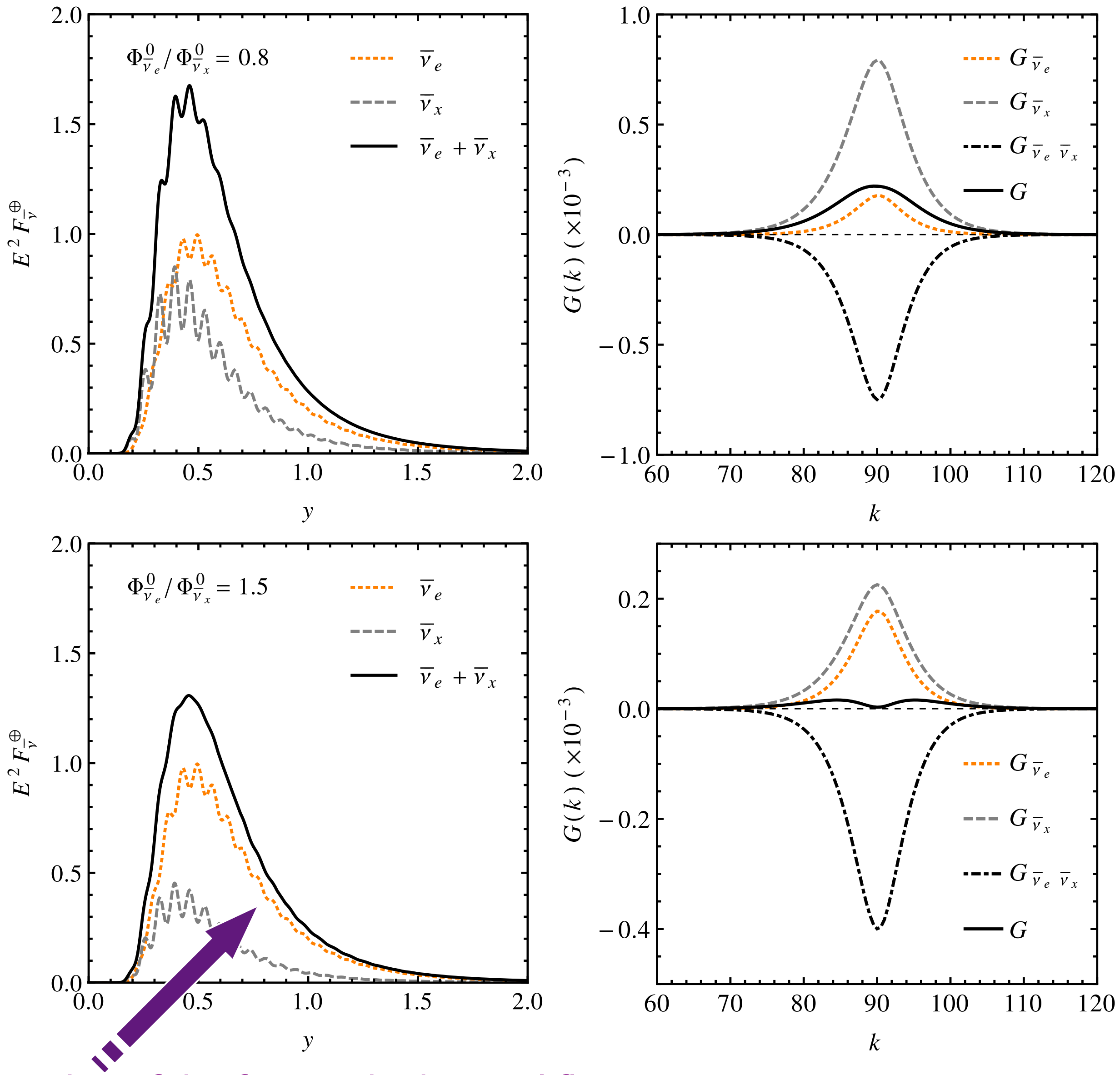
- To predict this wavenumber reasonably well we should be sure to have a decent pointing of the SN (otherwise e.g. L is badly determined)
- Errors in the cross-sections, detector E-resolution, PREM, mismatch between neutrino and electron energy... all affect the precision, hence the “model-independence”.
- How important/dominant the “Earth matter” mode is depends also on the flux difference (which is **model-dependent!**): according to the normalization and E-distribution of fluxes, relevant cross-correlation terms in FT can alter the spectrum of modes...

$$F^{\oplus}_{\bar{\nu}_e} = F^{D}_{\bar{\nu}_e} - \kappa \,(F^{0}_{\bar{\nu}_e} - F^{0}_{\bar{\nu}_x}) \sin^2\left(\frac{k_{\oplus} y}{2}\right)$$



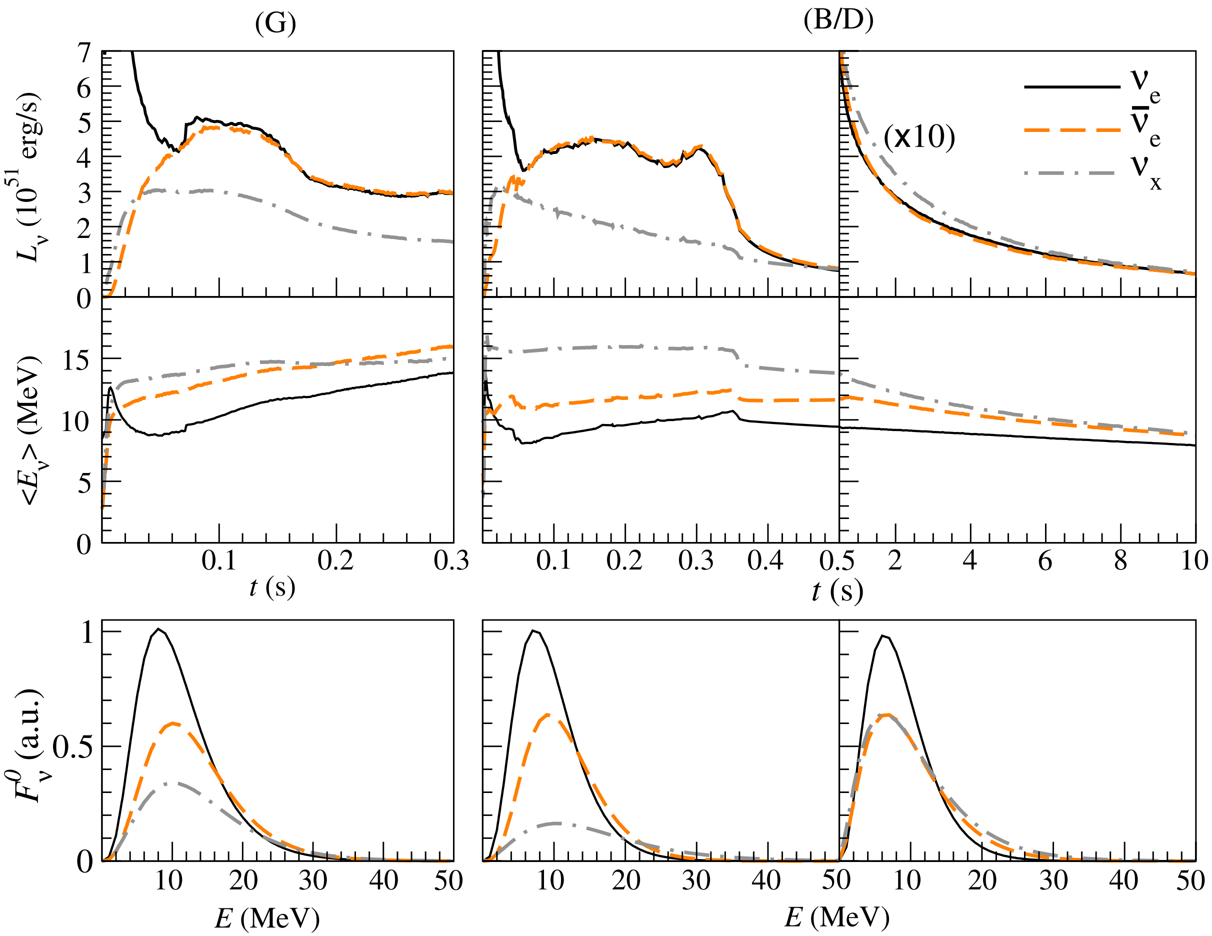


Caveats ("double peak" in a toy model)



note the smearing of the feature in the total flux

Latest simulations show reasons to worry....



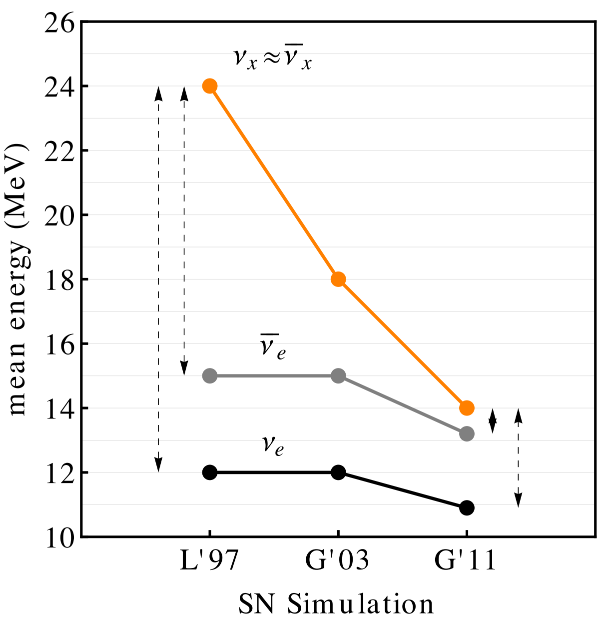
Especially in anti-ν, less prominent spectral differences than in older models

Also, only a fraction of the flux (i.e. accretion) is available for reasonably robust flavour studies

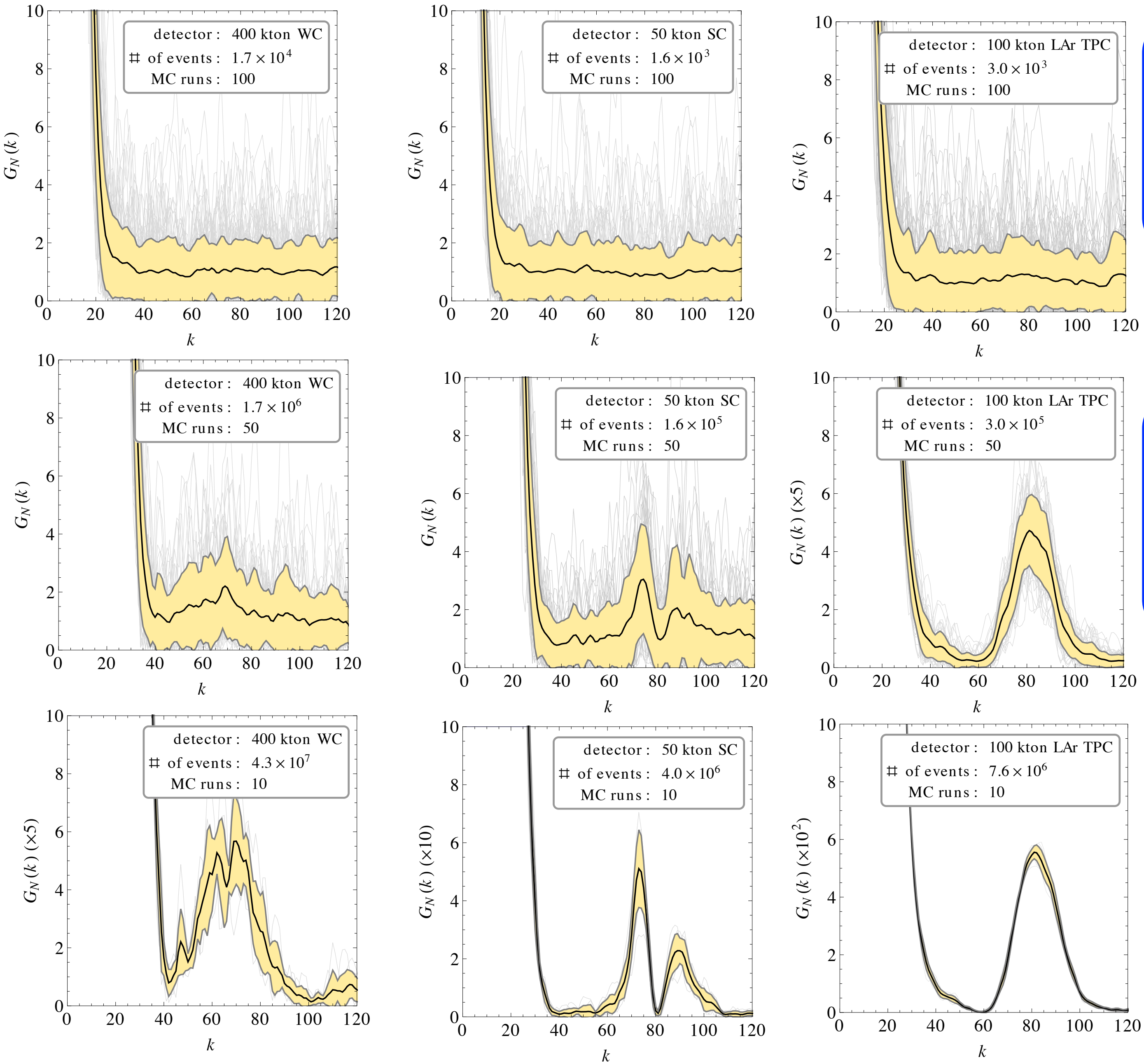
Left: Garching simulation for a 15.0 M_{sun} progenitor (integrated signal for t<0.25 s used in the following).
Right: Basel/Darmstadt simulation for a 18.0 M_{sun} progenitor.

http://www.mpa-garching.mpg.de/ccsnarchive

T. Fischer, S. C. Whitehouse, A. Thielemann, and M. Liebendörfer, 517, A80 (2010)



Our results

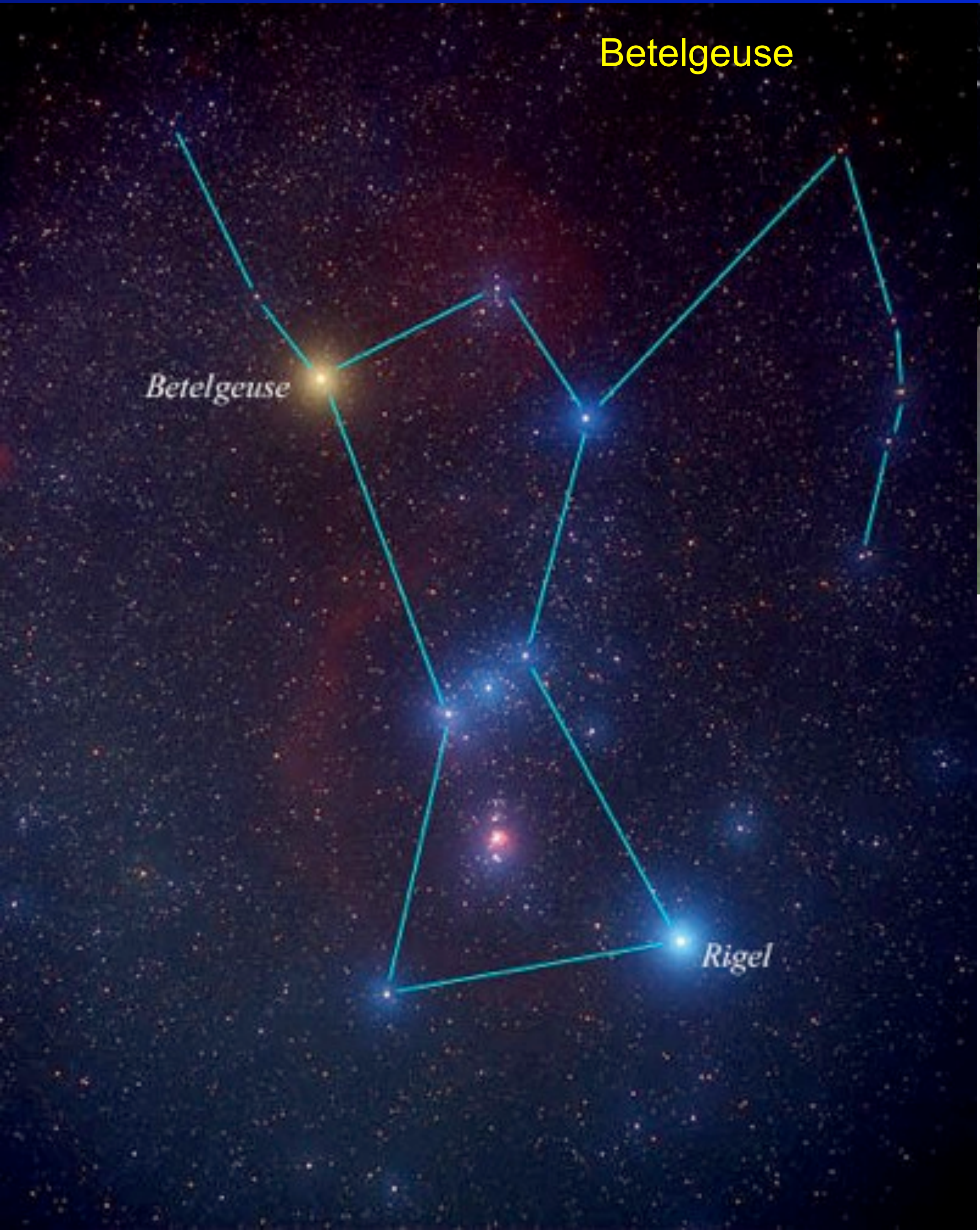


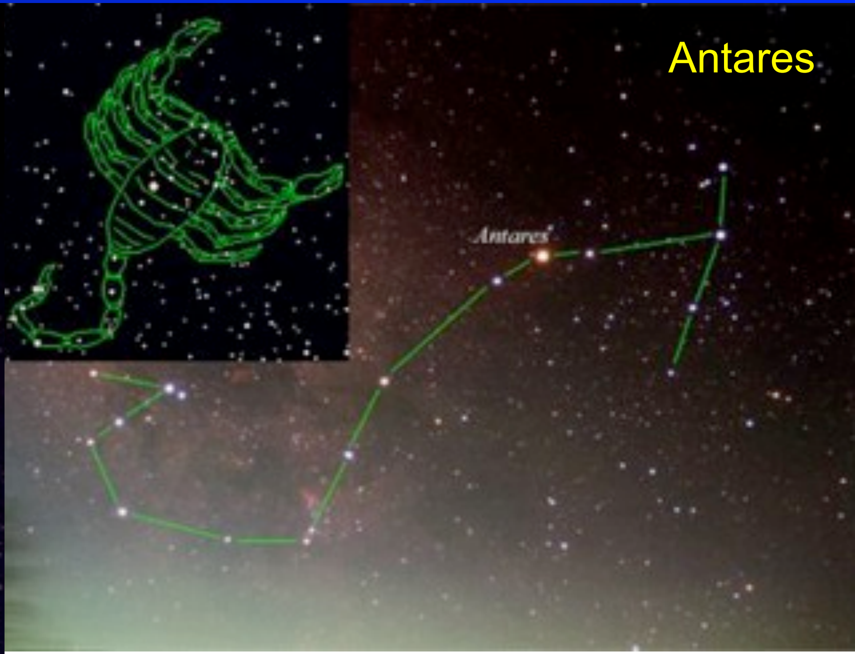
Sub-kpc distance required in general for unambigous detection (provided electronics can handle those rates!)

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!





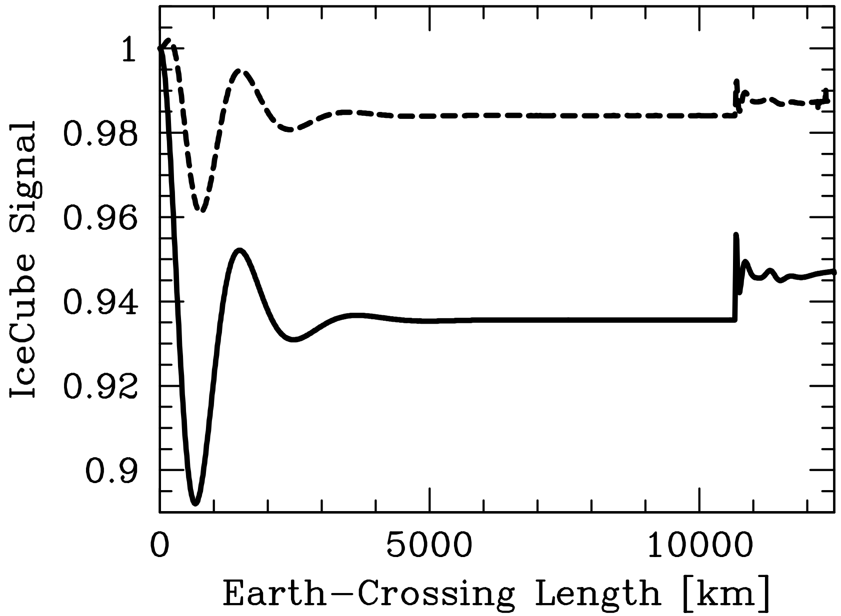
Orion was an old-age gigantic hunter that was killed by a giant scorpion sent by upset Artemis to kill him.

Let's hope then to receive a gift from one of those "primordial enemies"... but are we ready to profit of it?

Idea nr. 2

The EME would produce a modification in the SN anti-ν_e light-curve (time signal, E-integrated) between a "shadowed" detector and an unshadowed one, like IceCube & SK

A. S.Dighe, M. T. Keil and G. G.Raffelt, hep-ph/0303210



ratio of shadowed/ unshadowed signal in IceCube (different SN phases)

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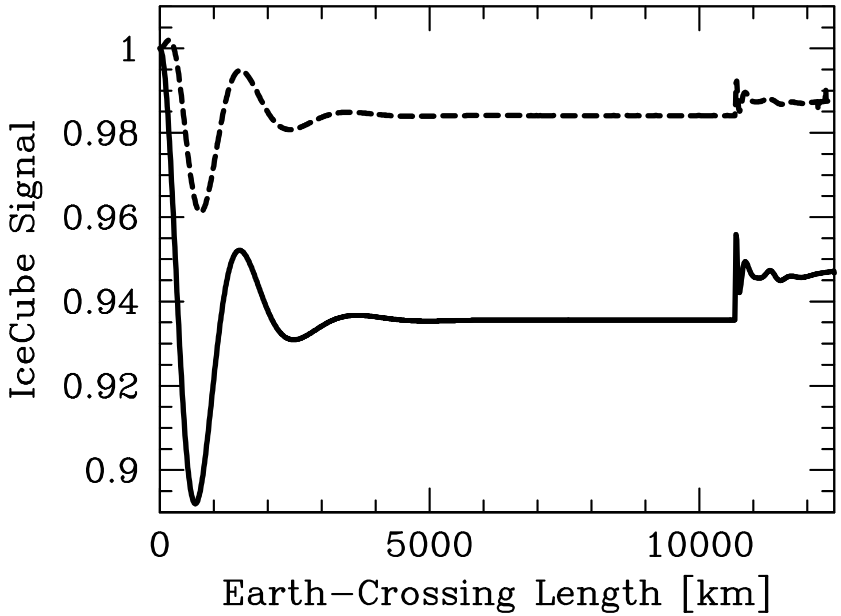


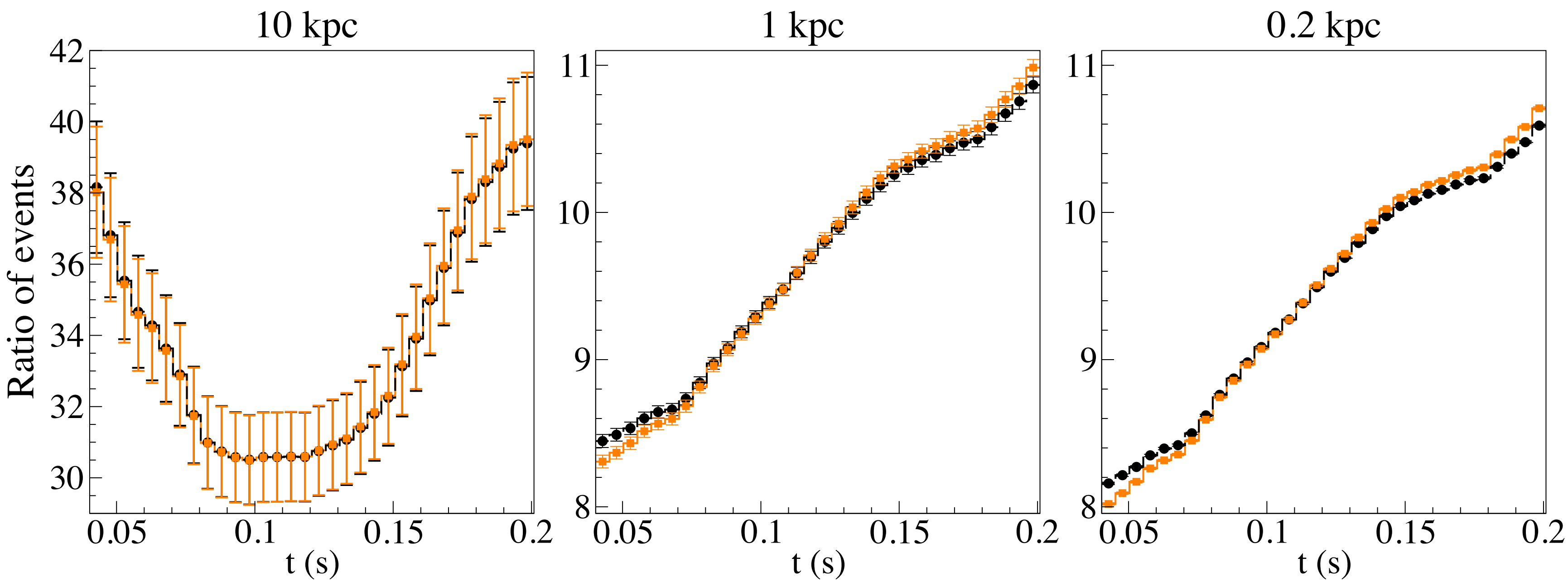
ratio of shadowed/ unshadowed signal in IceCube (different SN phases)

Problem I: detectors are not identical.
The luminosity curve detected in one can only be used indicatively to "predict" what one should see in a different detector in absence of EME. Is the EME larger than this error?

Older expectations where up to 10% differences, easily O(5%)
We now find never more than ~1.7%.

Idea nr. 2, cont'd

Problem II: distance matters.
the shape of the ratio IceCube/SK changes with the distance of the SN, since the measured signal in IceCube is the sum of a time-independent background rate (independent of the distance) and a true SN lightcurve whose normalization depends on the distance.



It does not seem to be working, either...

Comments on Part I

- The EME has been often thought as the most promising and “model-independent” way to infer ν-mass hierarchy from a future observation of a Galactic SN (Yet, it does require at least one *shadowed* detector and lots of statistics!)

- It turns out that the actual chance of observing a significant signal wrt the noise/errors is quite low and its features less model-independent than once believed.

- This is mostly due to much more similar fluxes (especially in the anti-ν sector) suggested by the current generation of SN simulations (including state of the art in ν-opacities, for example).

- In general, a ν (rather than anti-ν) detector offers better chances, still probably not above a few %.

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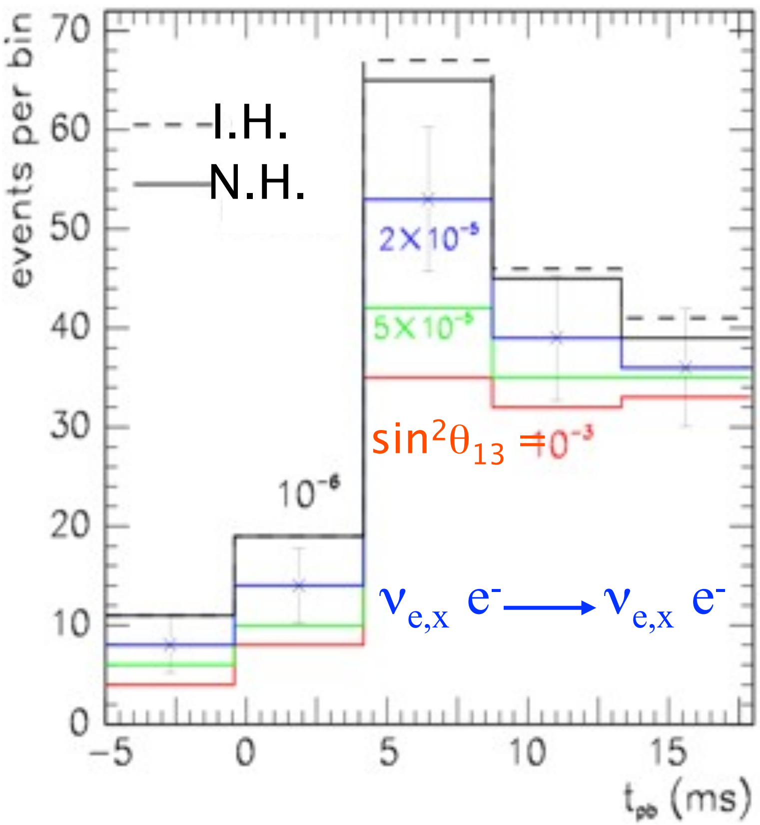
That said, it does not mean that it is hopeless to infer hierarchy from SN ν!!!

Part II: alternative diagnostics

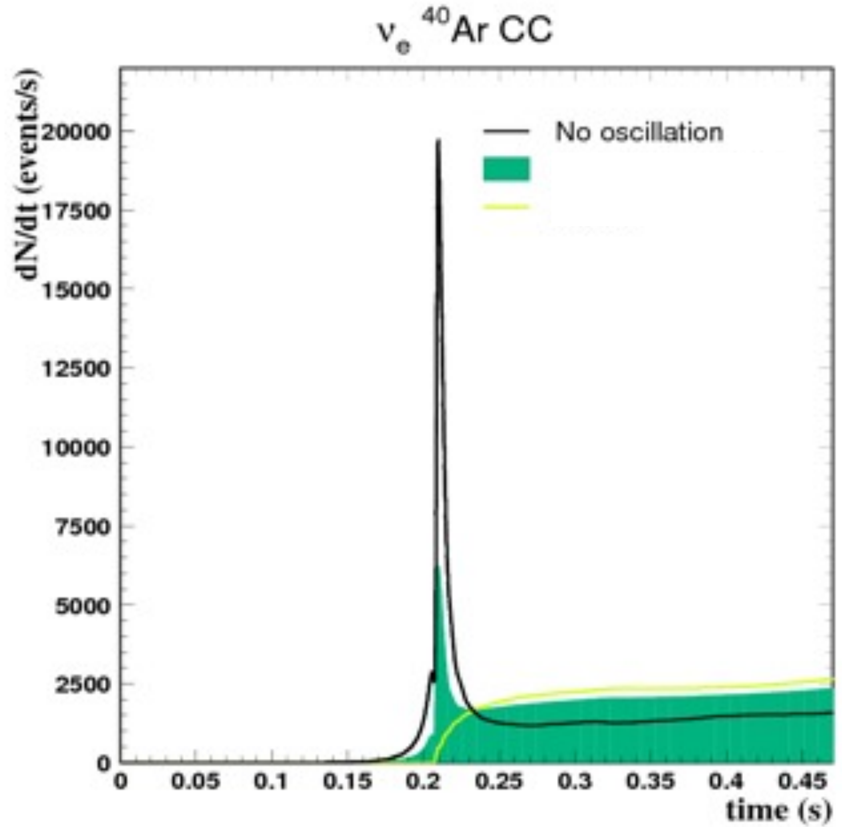
the neutronization burst

1 Mton Water Cherenkov



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

70 kton Lar TPC

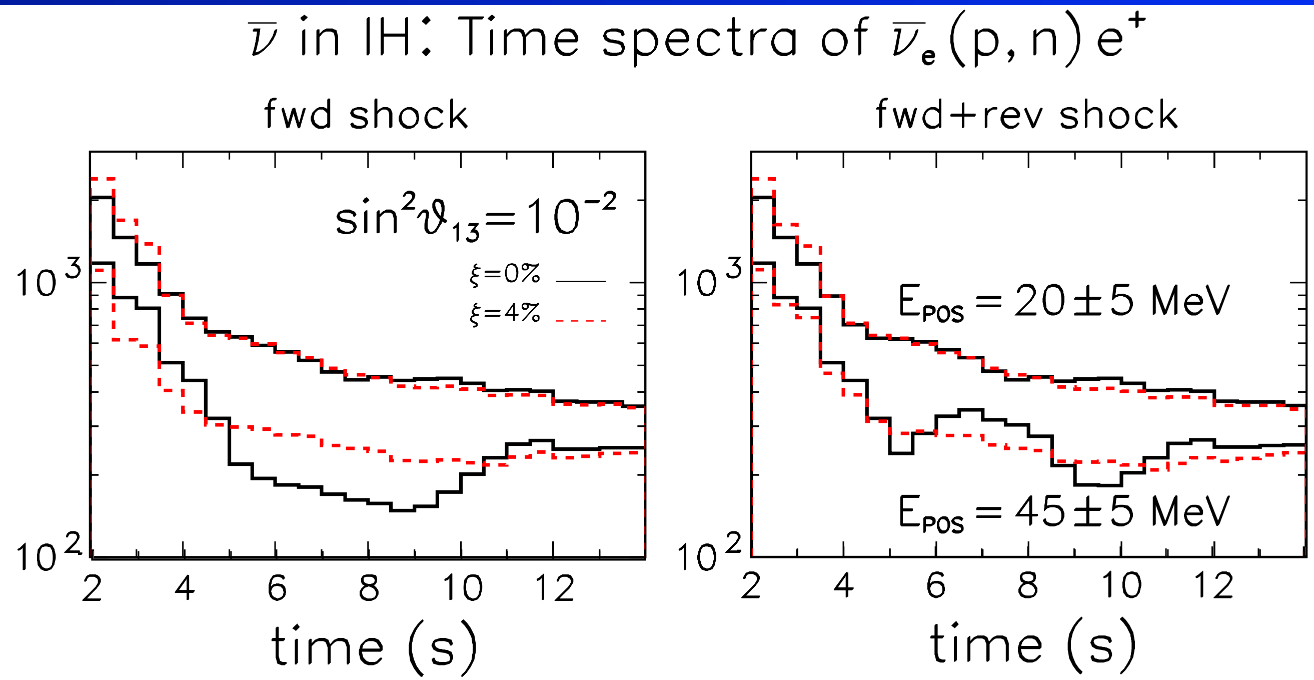


I.Gil-Botella & A.Rubbia, hep-ph/0307244

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)

shock wave effect... and turbulence



In principle, the presence of the forward (plus reverse) shock can leave peculiar imprints on the time (and energy) structure of the signal (e.g. inverse beta decay in Mton detectors).

On the other hand, these patterns are affected by the level and properties of the turbulence in the SN mantle. More likely to infer something on SN astrophysics if hierarchy is known than vice-versa....

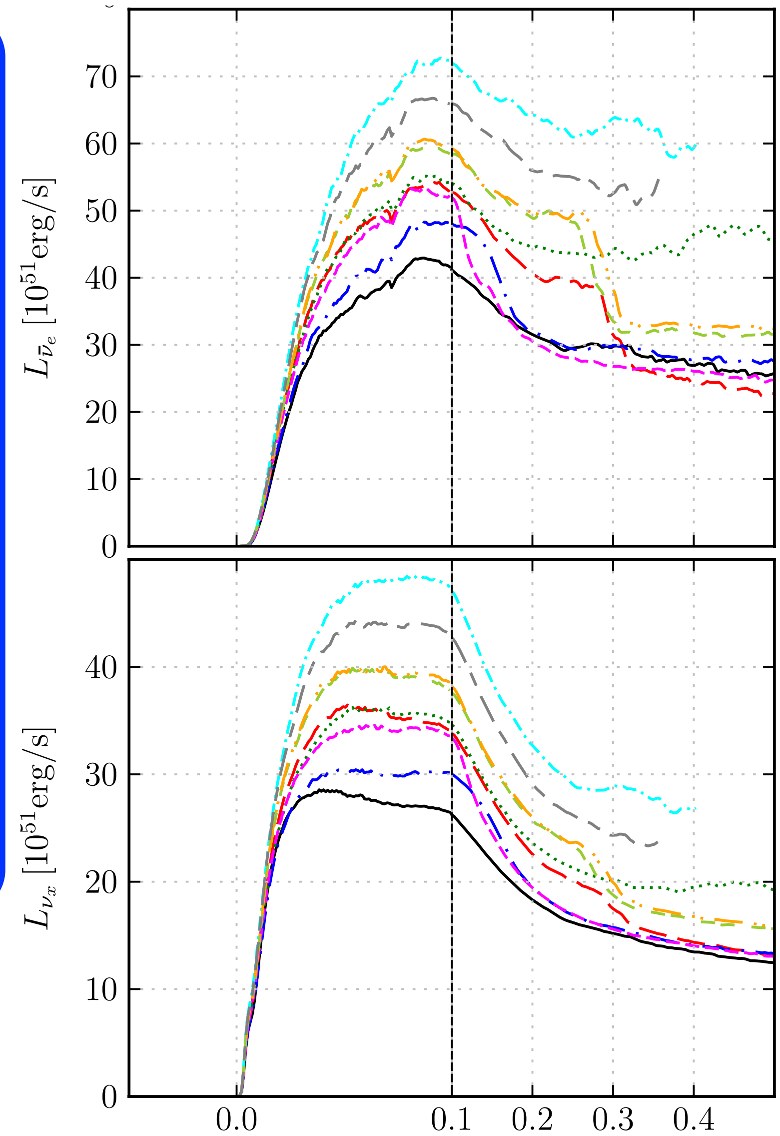
A (limited) list of references:
R. C. Schirato and G. M. Fuller, astro-ph/0205390 K. Takahashi et al.astro-ph/0212195,
C. Lunardini C and A. Y. Smirnov, hep-ph/0302033 G. L. Fogli et al. hep-ph/0304056
R. Tomàs et al. astro-ph/0407132, G. L. Fogli et al. hep-ph/0412046,
G. L. Fogli et al. hep-ph/0603033, J. P. Kneller and C. Volpe, arXiv:1006.091

What about current detectors (mostly anti-ν_e)?

The production of anti-ν_e is more strongly suppressed than that of (anti)ν_x during the first tens of ms after bounce because of the high degeneracy of e and ν_e.

The high e-degeneracy allows only for a low abundance of e^+, the production of anti-ν_e by pair annihilation and e^+ captures on neutrons is not efficient. Moreover, since in the optically thick regime ν_e are in chemical equilibrium with the matter their degeneracy also blocks the phase space for the creation of anti-ν_e via nucleon-nucleon bremsstrahlung (which is however operative for ν_x...)

anti-ν_e are produced more gradually via via charged-current processes (electron and positron captures on free nucleons) in the accreting matter that forms a thick, hot mantle around the newly born proto-neutron star; ν_x come fastly from a deeper region.



Garching group, 2011

The lightcurve of the two species is quite different in the first O(100 ms) and the shape keep significant differences independently of the progenitor and dimensionality of simulation

NH vs IH is roughly anti-ν_e vs anti-ν_x!

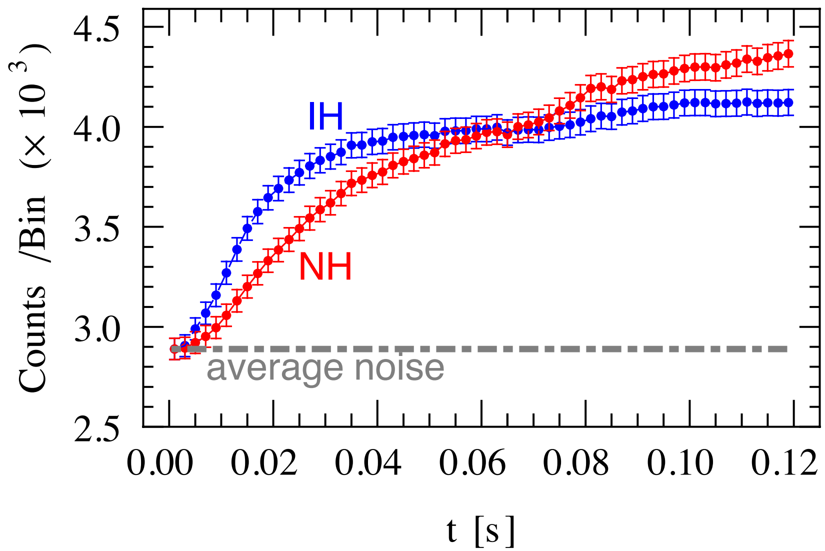
In the accretion phase, one has

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

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

A high-statistics measurement of the risetime *shape* may distinguish the two scenarios!

IceCube is a wonderful calorimetric detector, for that purpose!



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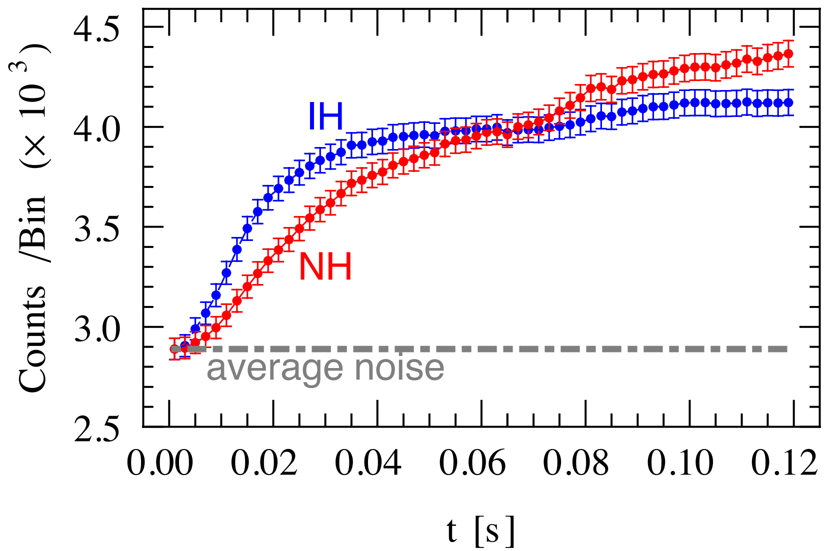
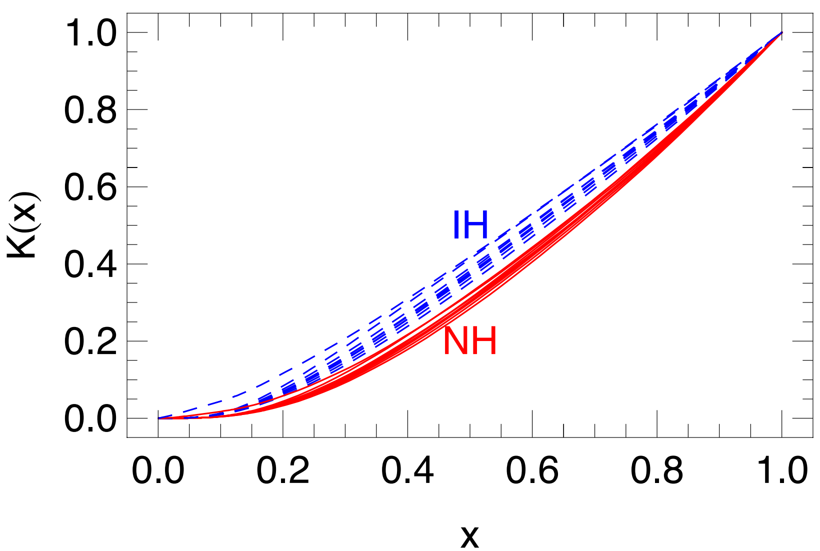


Are the risetime shapes "enough" robustly predicted to be useful?

Models with state-of-the art treatment of weak physics (Garching simulations were used) suggest so: with infinite precision, one could unambigously attribute the "shape" to a NH or IH type.

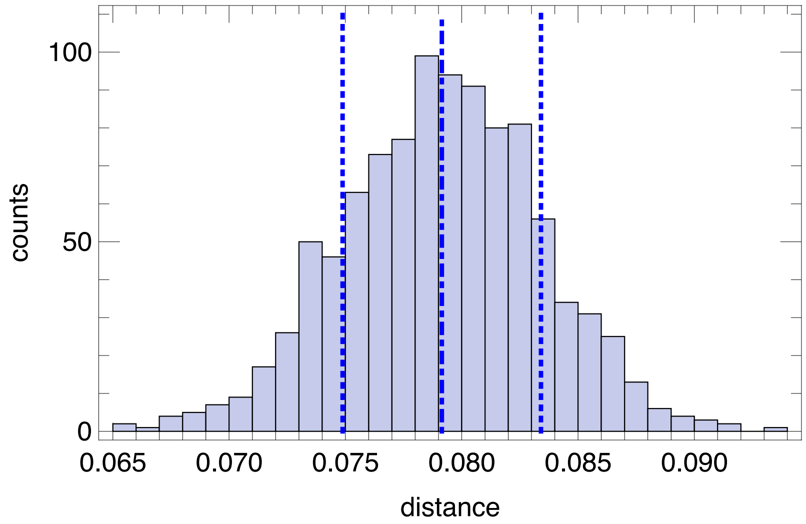
Note: Basel/Darmstadt simulations show even sharper differences...



What about realistic statistics from a Gal. SN?

Question 2. Are the expected theoretical shape differences large or small compared to the expected statistical errors?

We run MonteCarlo simulations, finding that in at least 99% of the cases the right hierarchy could be identified (for 10 kpc distances) even if we exclude the **right template** from the set we compare the mock data to.



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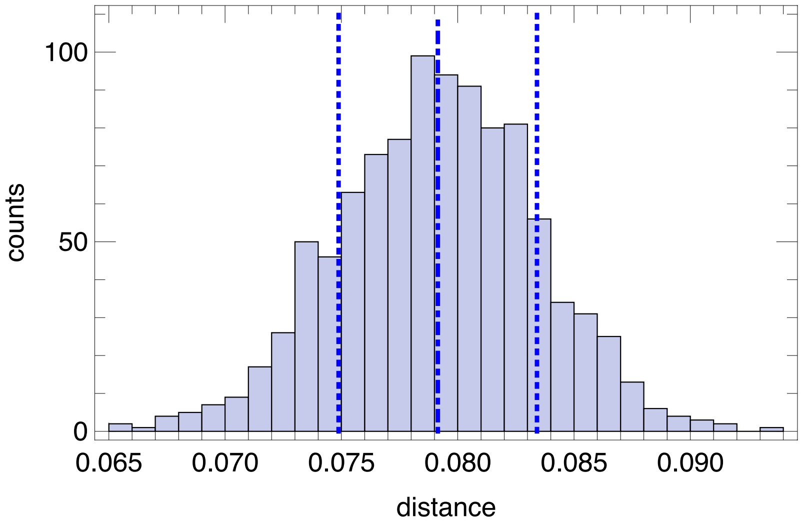

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(our work was a "proof-of-principle")

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Note 3: in 1108.0171, IceCube performed a likelihood analysis for O-Ne-Mg progenitors signals, finding good hierarchy discrimination up to ~6 kpc... qualitatively ok (little accretion there!), but little reliability since collective effects may be important...

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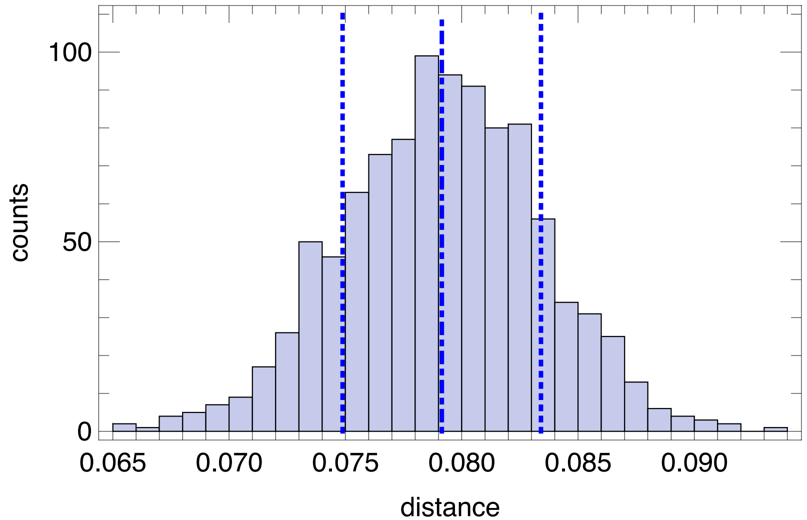

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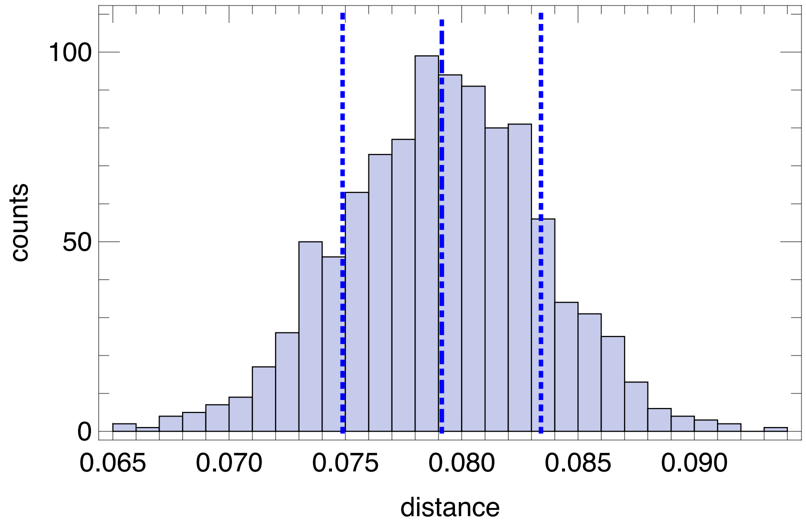
CAVEAT: Despite the fact that the difference between two cases is qualitatively robust (<u>always</u> IH risetime found to be faster than NH one) and the promising early results, it remains to be seen if the relative quantitative robustness of this signature is confirmed by more and more realistic simulations in the future.

What about realistic statistics from a Gal. SN?

Question 2. Are the expected theoretical shape differences large or small compared to the expected statistical errors?

We run MonteCarlo simulations, finding that in at least 99% of the cases the right hierarchy could be identified (for 10 kpc distances) even if we exclude the **right template** from the set we compare the mock data to.



Note 1: We did not try to optimize the "statistical estimators"
(our work was a "proof-of-principle")

Note 2: We did not use E-information, which will be available (e.g. from SK!), to reduce the likelihood of "wrong hierarchy" templates

Note 3: in 1108.0171, IceCube performed a likelihood analysis for O-Ne-Mg progenitors signals, finding good hierarchy discrimination up to ~6 kpc... qualitatively ok (little accretion there!), but little reliability since collective effects may be important...

CAVEAT: Despite the fact that the difference between two cases is qualitatively robust (<u>always</u> IH risetime found to be faster than NH one) and the promising early results, it remains to be seen if the relative quantitative robustness of this signature is confirmed by more and more realistic simulations in the future.

For the time being, best compromise we could find between model-independence & detectability in an existing experiment, for a large fraction of expected gal. SN events.

Conclusions

- Expectations based on state-of-the-art SN simulations and current understanding of neutrino flavour conversions in Fe-core progenitors suggest that the EME signature is very difficult to detect (and less sharply defined that once thought)

- Of course, checking that no EME signature is present in a future signal is "per se" of some interest, especially if hierarchy is known: for example to check that no major departure from expectations based on current simulations takes place.

- ***It does not mean necessarily that it is hopeless to infer hierarchy from SN ν:*** *in particular a large detector sensitive to ν_e would be useful (also for neutronization burst!)*

- **Studies are on-going to find alternative diagnostic tools**
we showed that early encouraging results exist for the risetime signal in IceCube

- ***In any case, terrestrial experiment will eventually measure neutrino mass hierarchy.*** *Independent of when it happens, we have to make sure that the next galactic SN event is recorded in neutrinos in the best possible way.*

- ***It will surely be a bonanza for astrophysics****, and neutrinos may offer a view of the behaviour of matter under extreme conditions, impossible to probe otherwise.*

- ***Be ready for surprises! Neutrinos did it more than once...***