EIPS Lyon, 24 October 2014

Core Collapse Supernovae and neutrinos

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Outline

- ➡ What are (Core-Collapse) Supernovae & the role of neutrinos
- ➡ Back of the envelope estimates and lessons from SN1987A
- ➡ What could we learn next? Detectors and expectations
- ➡ The case of ν mass hierarchy & some proposed strategies for its determination via SN
- ➡ Room for surprises? One "BSM" case and... one within SM?!
- ➡ Conclusions

Supernovae

Crab nebula, remnant of SN1054 in the constellation of Taurus

Supernovae

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凡十一日沒三年三月乙巳出東南方大中祥符四
年正月丁丑見南斗魁前天禧五年四月丙辰出軒轅
前星西北大如桃速行經軒轅太星入太微垣掩右執
法犯次將歷屏星西北凡七十五日入濁沒明道元
年六月乙巳出東北方近濁有芒彗至丁巳凡十三
日沒至和元年五月己丑出天關東南可數寸歲餘
稍沒熙寧二年六月丙辰出箕度中至七月丁卯犯
箕乃散三年十一月丁未出天囷元祐六年十一月
辛亥出參度中犯掩側星壬子犯九游星十二月癸
酉入奎至七年三月辛亥乃散紹興八年五月守婁

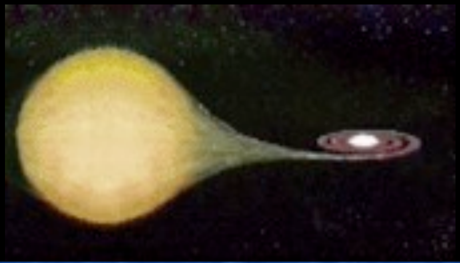
宋史志卷九

Possible SN 1054 Petrograph by the Anasazi people (Chaco Canyon, New Mexico)

When this spectacular star appeared in the Gemini sign […], it provoked the beginning of the plague in Fostat, when Nile waters were low in 445[6]. Ibn Butlan

Two main kinds of beasts

Thermonuclear (Type Ia)	Core Collapse (Type II, Ib/c)
Carbon-oxygen white dwarf (remnant of low-mass star) accretes matter	Degenerate core of evolved massive star accretes matter by nuclear burning at its surface



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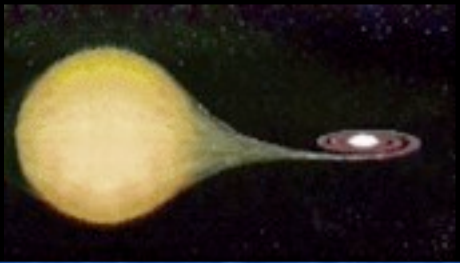

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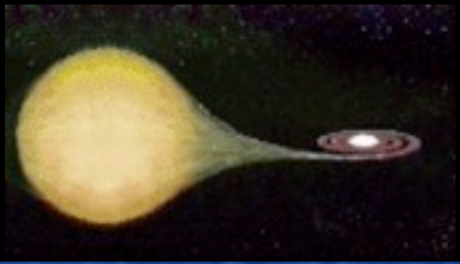

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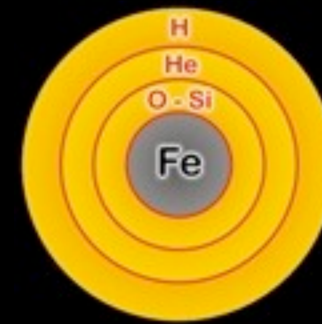

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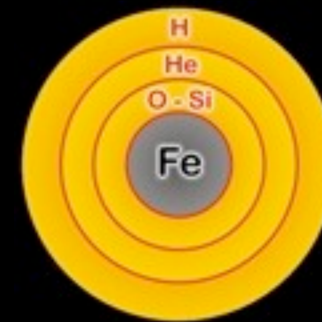

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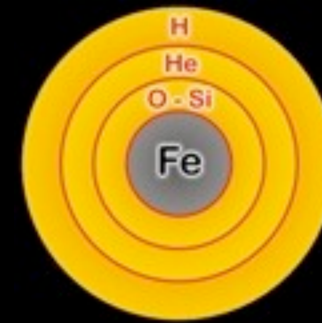

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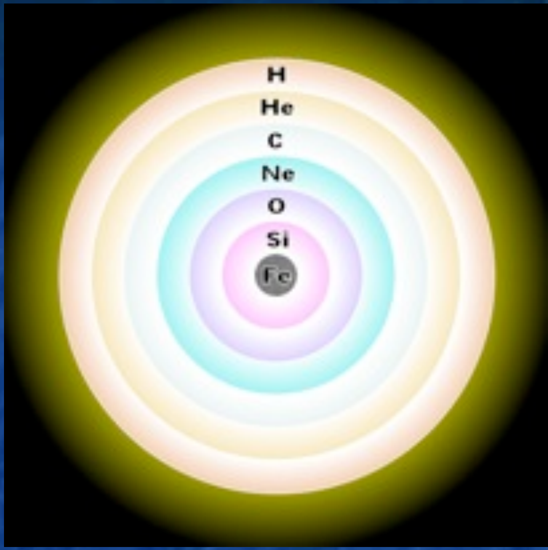
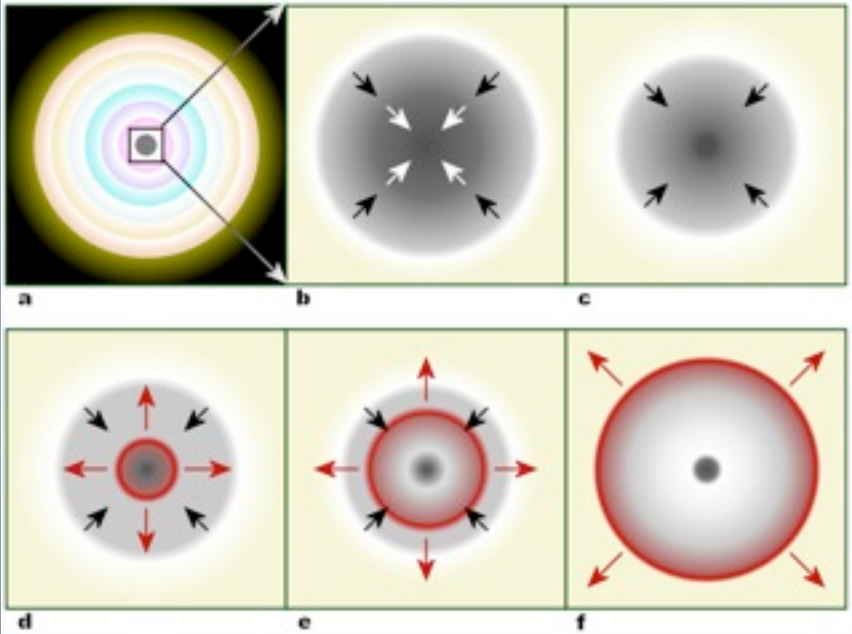
Comparable "visible" energy release of $\sim 3 \times 10^{51}$ erg, ~0.2% M_{SUN} in E!

Stellar Collapse & SN explosion

- The core of a massive star cannot sustain equilibrium by thermonuclear fusion beyond A~56 (Ni-Fe).
- The degenerate iron core starts to collapse, halting when nuclear densities are reached (~incompressible).
- A shock wave (SW) propagates outwards.
- The SW energy is mostly dissipated by dissociating the outer layer of iron, and no explosion happens





What happens, next?

Core-Collapse Supernova Mechanisms

Introduced by:

Mechanism	Introduced by
Neutrino Mechanism	[Colgate & White '66, Arnett '66, Wilson '85, Bethe & Wilson '85]
Magnetorotational Mechanism	[LeBlanc & Wilson '70, Bisnovatyi-Kogan et al. '76, Meier et al. '76, Symbalisty '84]
Acoustic Mechanism	[proposed by Burrows et al. '06, '07; not yet confirmed by other groups/codes]

Magneto-Viscous Mechanism

[Akiyama et al. '03, Thompson et al. '05]

Phase-Transition-Induced Mechanism

[Migdal et al. '71, Sagert et al. '09]

Slide by C.D. Ott (not updated, indicative only!)

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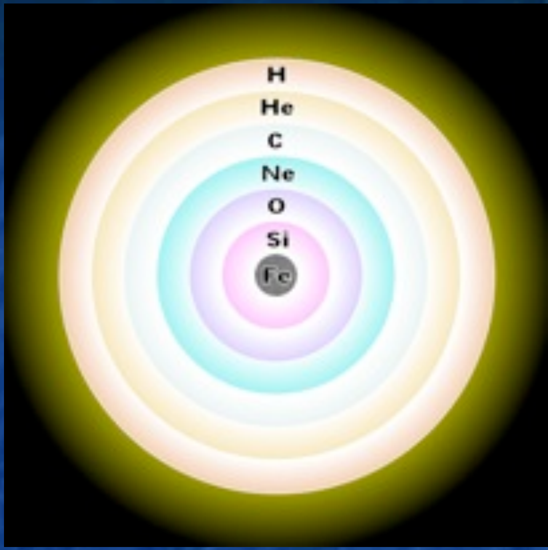

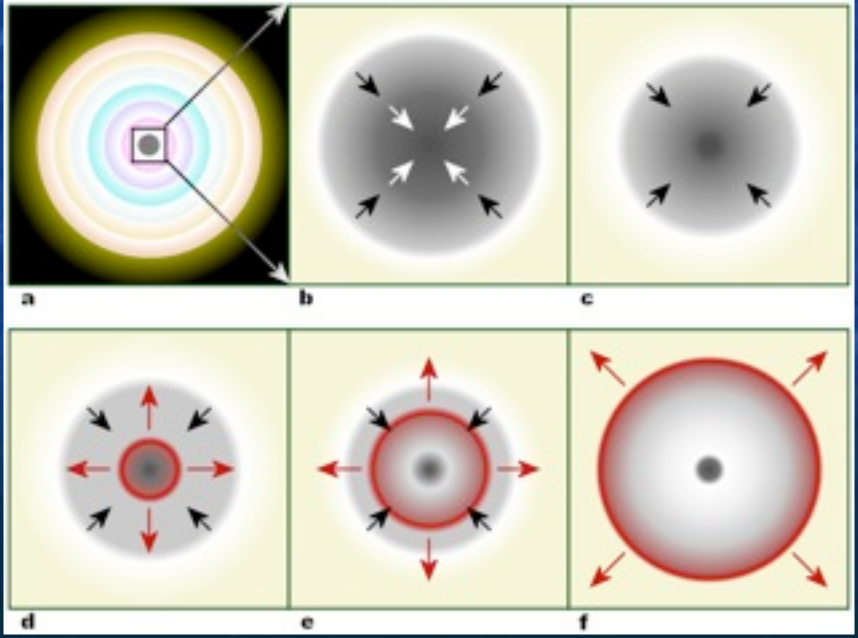

Neutrinos to the rescue!

The core (now a "T~O(10) MeV" p-n star) dissipates its binding energy into ν's

ν heating increases pressure behind shock front, rescuing stalled shock. Eventually ejects star's outer mantle (explosion). While it lasts, L_ν outshines whole universe!

Emission timescales

Neutrinos are trapped in the core, emitted "diffusively", i.e.

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$$t_\mathrm{diff} \sim 1\,\mathrm{s}\left(\frac{R}{10\,\mathrm{km}}\right)^2\left(\frac{E}{100\,\mathrm{MeV}}\right)^2$$

Nuclear densities and weak interactions are a key element!

Energy scale "set by gravity"

Applying the virial theorem (for a self-gravitating system)

$$\langle E_{\rm kin} \rangle = -\frac{1}{2}\langle \Phi_{\rm grav} \rangle$$

For a nucleon at the center of a neutron star-like system
(M~1.5 M_{sun}, R~15 km)

$$\langle \Phi_{\rm grav} \rangle \simeq -\frac{3}{2}\frac{G_{\rm N} M\, m_N}{R} \simeq -200\,{\rm MeV}$$

hence (think of E-losses while diffusing
and production far from the center)

$$E_\nu \lesssim 100\,{\rm MeV}$$

"Figures of merit"

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Gravitational binding energy

$E_b \approx 3 \times 10^{53}$ erg $\approx$ 17% $M_{SUN}\, c^2$

Showing up as

99% Neutrinos

1% Kinetic energy of explosion (10% of this into CRs?)

0.01% γ, outshine host galaxy

Sanduleak -69 202

Supernova 1987A 23/02/1987

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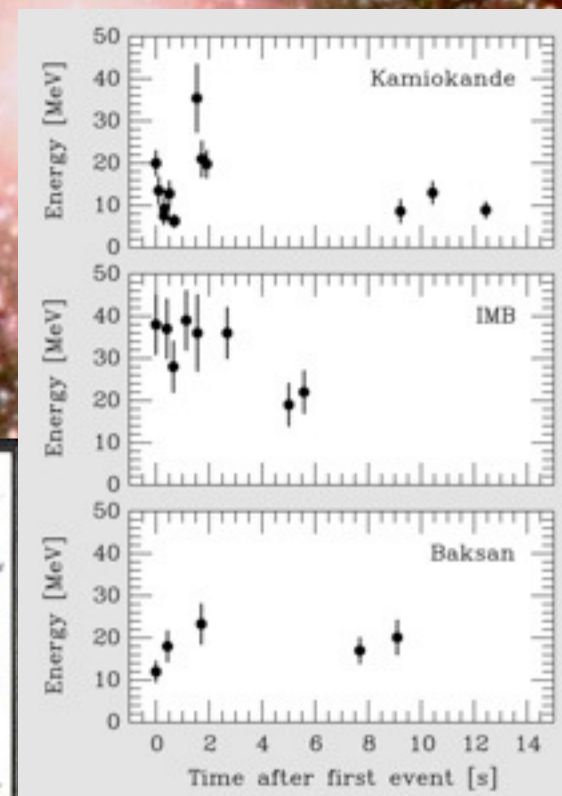

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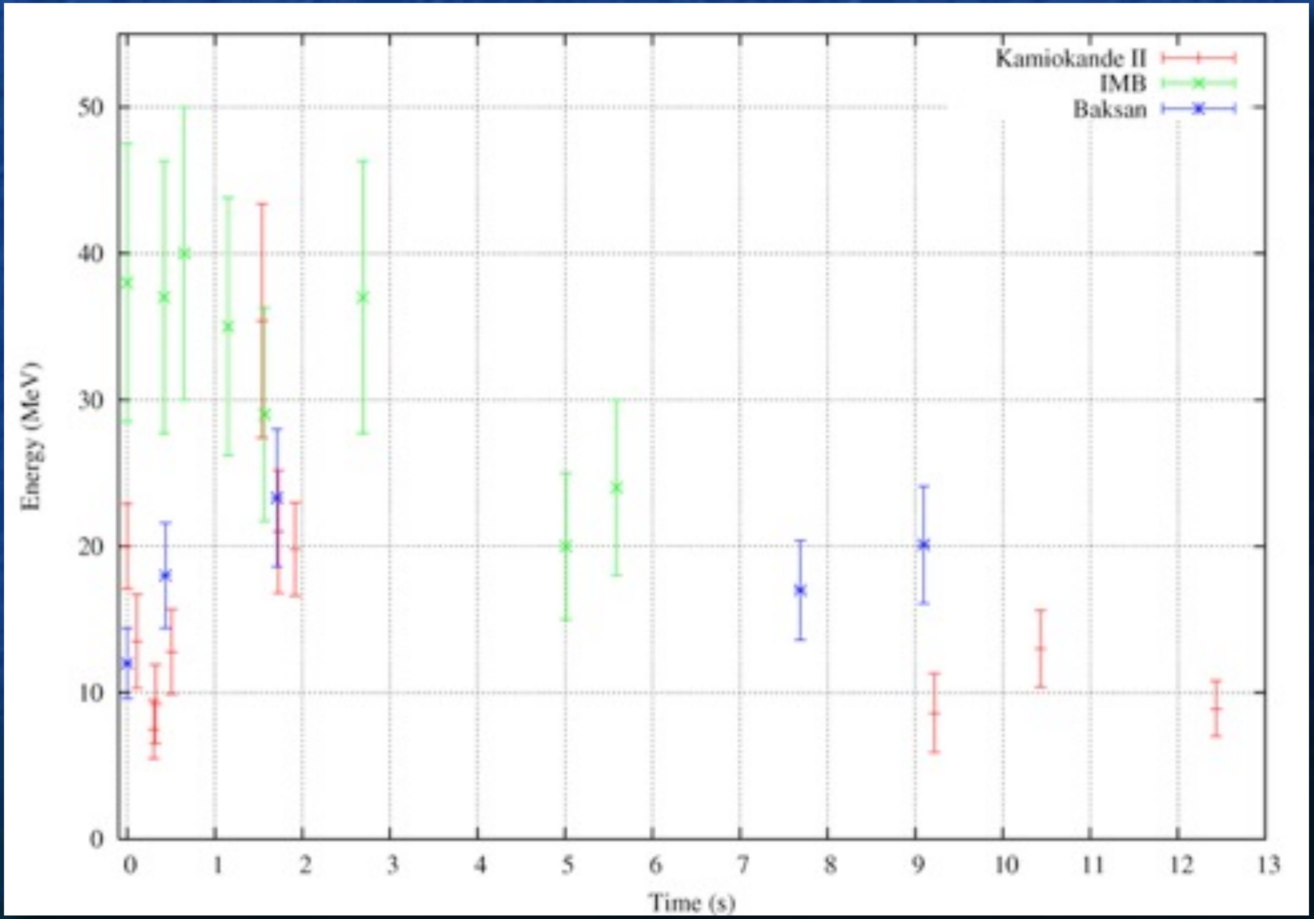
Validation of the basic picture of massive stars' death

Ingredients for "flux-energy-timescale": powered by gravitational collapse, signal from diffusion via weak reactions in medium with nuclear densities



Also useful for constraints to new physics

Example If ν's had minuscule electric charges, their path from SN1987A would have been bent by galactic B-field, inducing a time delay larger than the observed duration of signal.

$$\frac{\Delta t}{t} = \frac{e_\nu^2 (B_\perp \ell_B)^2}{6\, E_\nu^2} < \frac{10\, s}{d_{\rm SN}/c} \approx 3 \times 10^{-12}$$

$$\frac{e_\nu}{e} < 3 \times 10^{-17} \left(\frac{1\,\mu\mathrm{G}}{B_\perp}\right) \left(\frac{1\,\mathrm{kpc}}{\ell_B}\right)$$

G. Barbiellini and G. Cocconi, "Electric Charge of the Neutrinos from SN1987A," Nature 329 21 (1987).

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Similarly, one can constraint "secret interactions" of neutrinos, violations of Lorentz Invariance, lifetime, etc.

A nice overview in G. Raffelt, "Stars as Laboratories for Fundamental Physics", Chapter 13 "What have we learned from SN1987A?"

What have we learned? What could we learn?

SN 1987A	Future SN
General confirmation of CC SN paradigm (E_{tot}, spectra, time scale)	**Detailed test by high-statistics signal. Unexpected features?**

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No unexpected energy-loss channel: Restrictive limits on axions, large extra dimensions, right-handed neutrinos (couplings, mixings, dipole moments), Majorons, light SUSY particles, …	**Confirm & make previous bounds more robust (low-statistics enough!), Uncertainty dominated by theory (processes in dense nuclear medium)**

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Nothing useful about oscillations. Hints that flavor dependence of spectra indeed is not large	**Multi-flavour measurements? Neutrino mass hierarchy?**

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Neutrino Oscillations

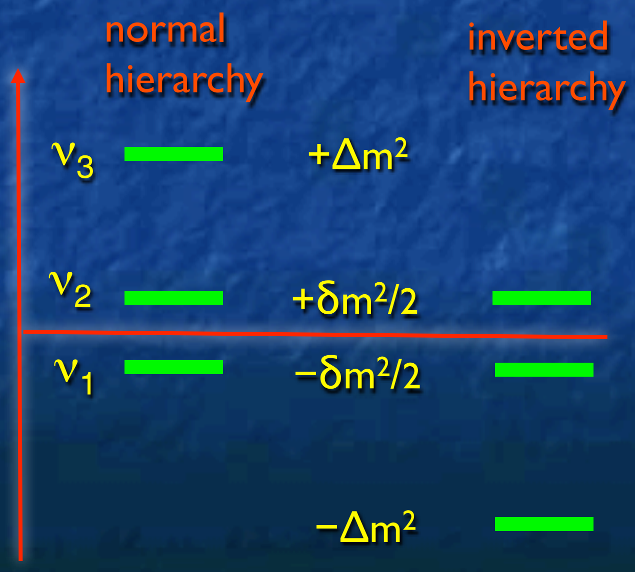
Basics of Neutrino Oscillations

Compelling evidence that ν evolution Hamiltonian non-diagonal in flavour space. (Almost?) all data are consistent with 3ν oscillation framework

$$H = \frac{U\,M^2 U^\dagger}{2\,p} + \mathrm{diag}(V,0,0)$$

Vacuum mixing term

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



MSW term (matter potential)

Energy shift due to different interactions of different flavours

$$V = \sqrt{2} G_F \,(n_{e^-} - n_{e^+})$$

arises at tree level due to the "extra" charged current interaction for ν_e in medium (− for anti)

[Wolfenstein, PRD 17, 2369 (1978), Mikheev & Smirnov, Sov. J. Nucl. Phys. 42, 913 (1985)]

ν oscillations in vacuum

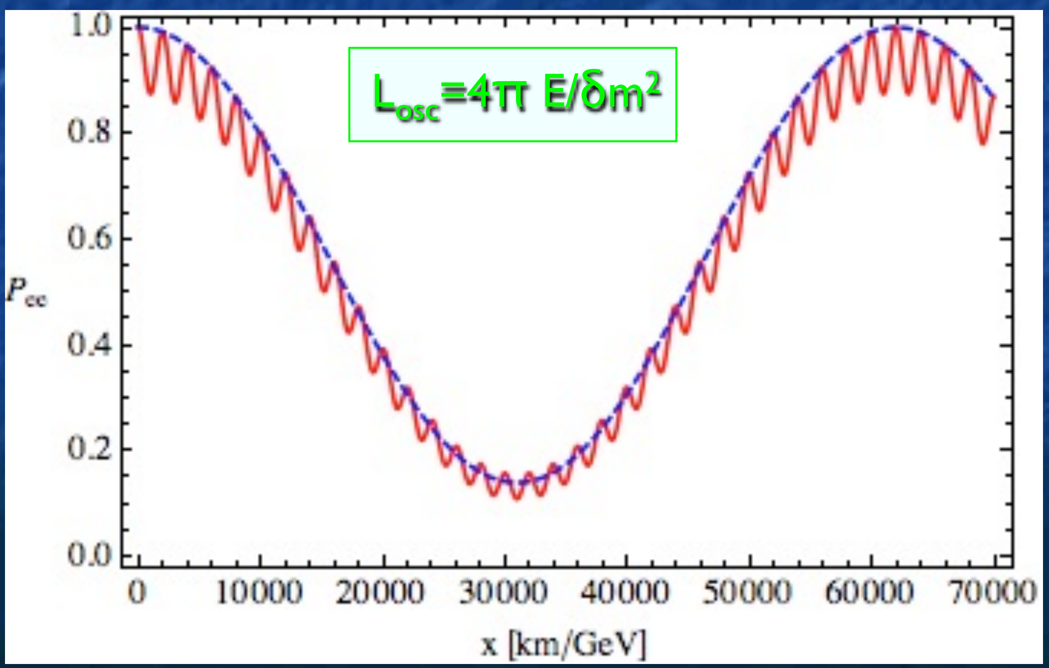
- Two flavour mixing
- Each mass eigenstates propagates as ~ e^{ipz}
- 2 ν oscillation probability

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$$|\nu_\mu(\ell)\rangle = -\sin\theta\, e^{-ip_1\ell}|\nu_1\rangle + \cos\theta\, e^{-ip_2\ell}|\nu_2\rangle$$

$$p_i = \sqrt{E^2 - m^2} \approx E - \frac{m_i^2}{2E}$$

$$P_{ee}(\ell) = 1 - \sin^2 2\theta \sin^2\left(\frac{\delta m^2 \ell}{4E}\right)$$



$\sin^2 2\theta$

Bruno Pontecorvo et al.

(1957→ 1967)

Basics of (resonant) matter effect

$$i\frac{\mathrm{d}}{\mathrm{dt}}\begin{pmatrix}\nu_e\\ \nu_x\end{pmatrix} = \begin{pmatrix}\frac{\Delta m^2\cos 2\theta_0}{4E} - \sqrt{2}G_F n_e & -\frac{\Delta m^2\sin 2\theta_0}{4E}\\ -\frac{\Delta m^2\sin 2\theta_0}{4E} & -\frac{\Delta m^2\cos 2\theta_0}{4E}\end{pmatrix}\begin{pmatrix}\nu_e\\ \nu_x\end{pmatrix}$$

- There's a resonance density at which diagonal elements are equal

$$n_r = \frac{\Delta m^2 \cos 2\theta_0}{2\sqrt{2}G_F E}$$

- The 2 states are "instantaneously" mixed with an angle

$$\tan 2\tilde{\theta} = \frac{\tan 2\theta_0}{1 - n/n_r}$$

Propagation from $n>n_r$ to $n < n_r$ (or vice versa) can lead to an efficient flavour transition, as long the evolution is sufficiently slow ("adiabatic"). Since masses of anti-particles and particles are equal, whereas the lepton numbers change sign under charge conjugation, resonances in matter occur either for ν or for anti-ν

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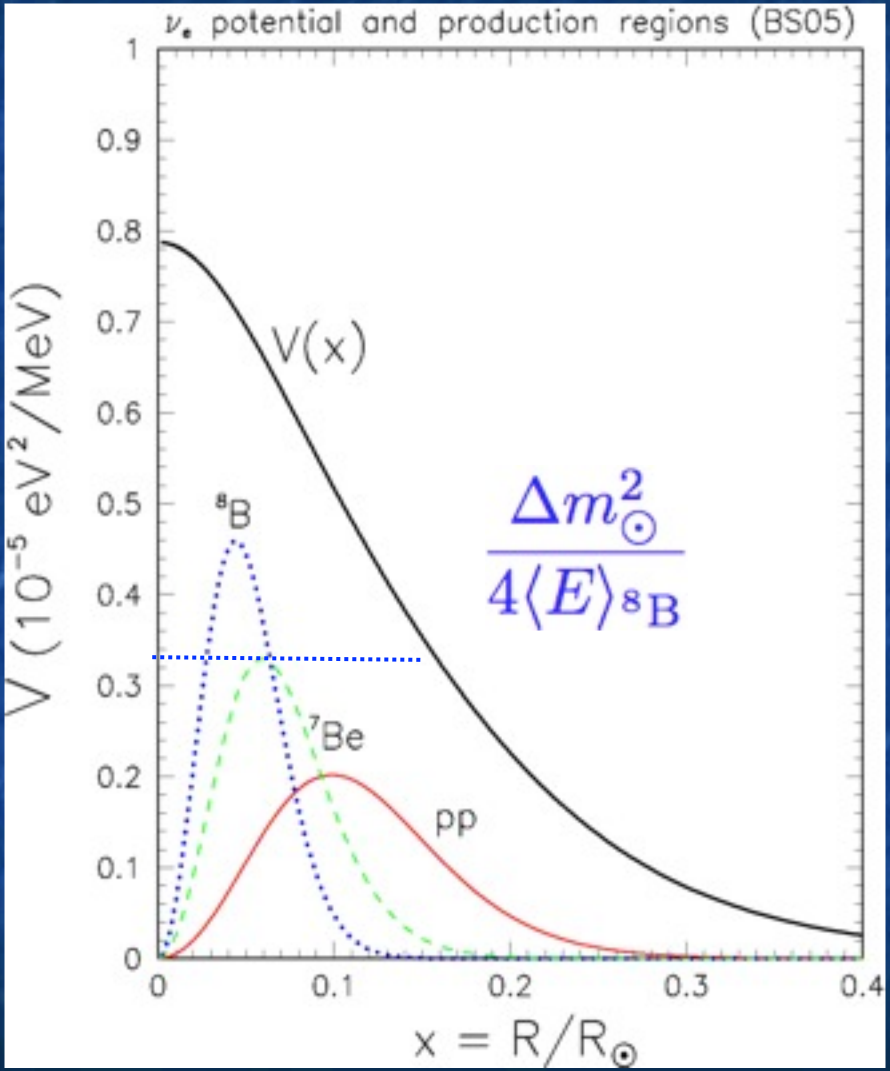
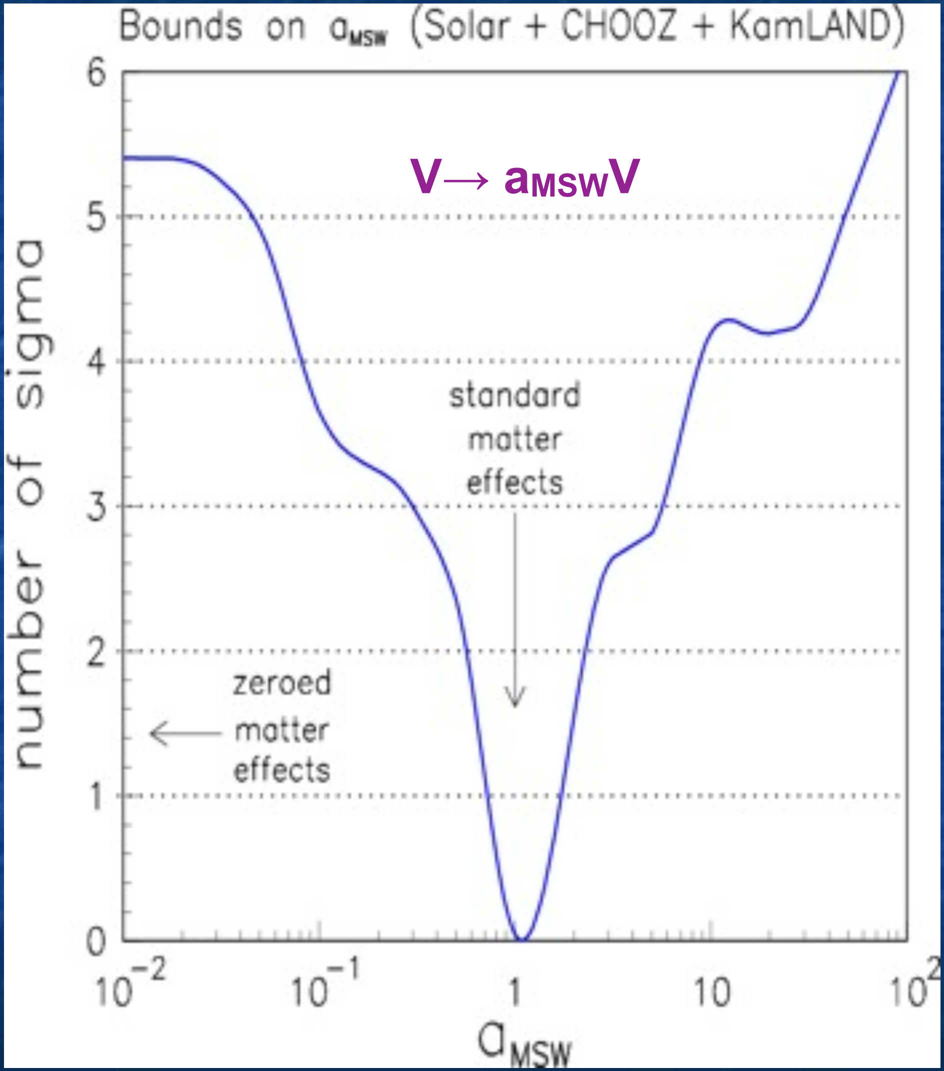
This mechanism is operational for high-E tail of Solar ν's!

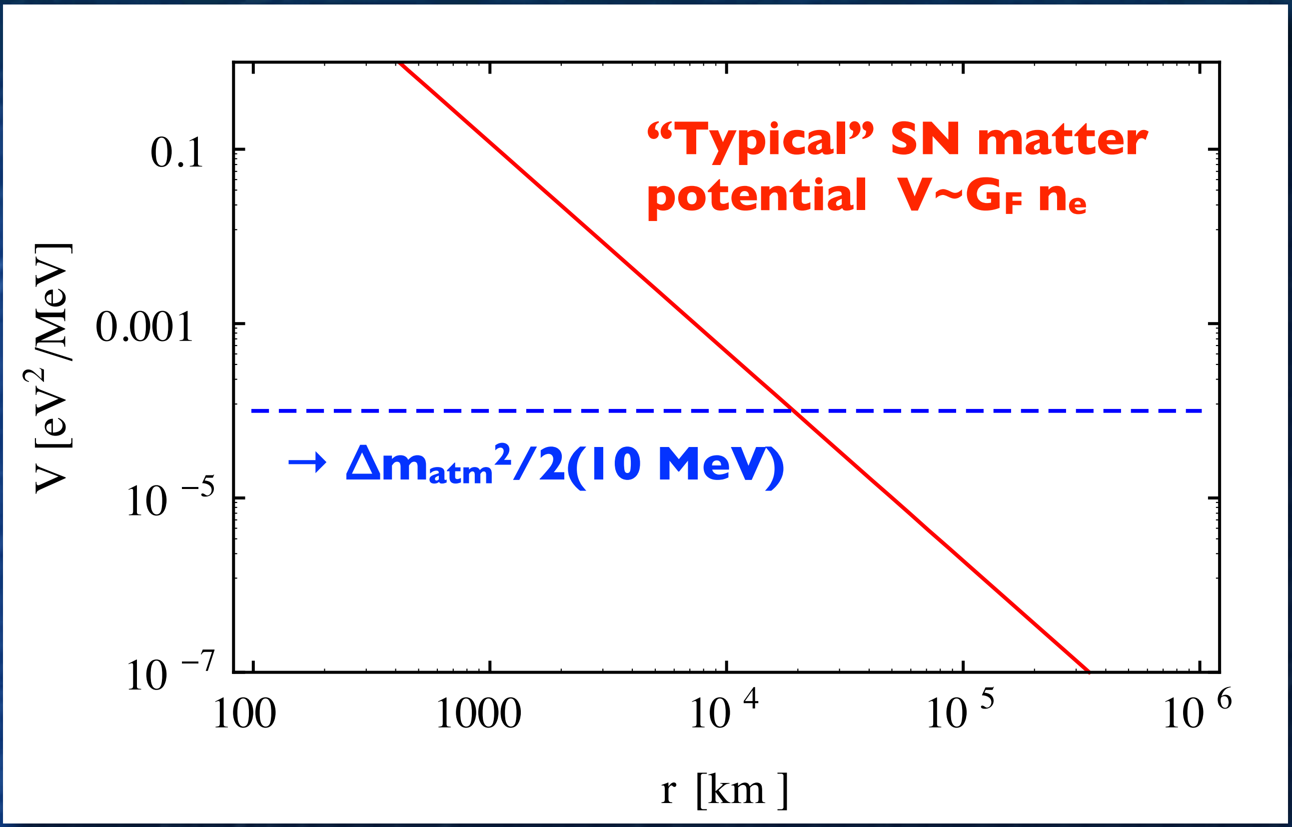
Evidence of MSW effect in the Sun

Fogli, Lisi, Marrone, Palazzo, Prog.Part.Nucl.Phys.57:742-795,2006





SN densities much higher than solar!



$\lambda = \sqrt{2} G_F n_e \sim \omega_H = \Delta m^2 / 2E$

(potential)~(osc. frequency)

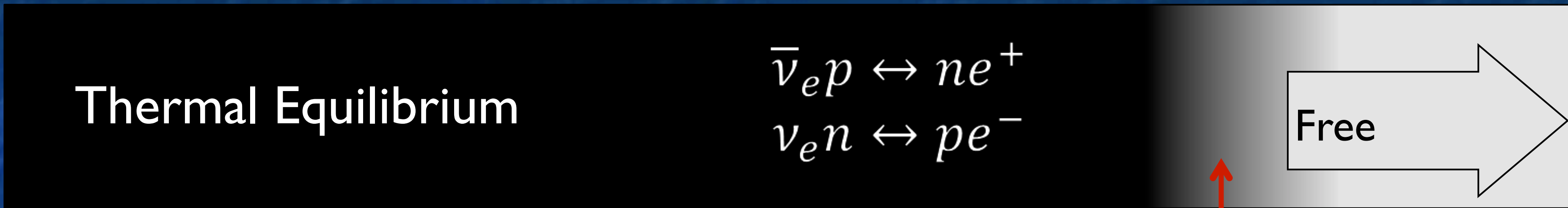
Not surprisingly, one may "repeat the trick" that worked with solar neutrinos and use SN ones to determine the mass hierarchy (sign of Δm_{atm}^2)!

→ requires generalization to 3 generations (you saw that)

→ Flux calculation is more subtle/uncertain than solar one

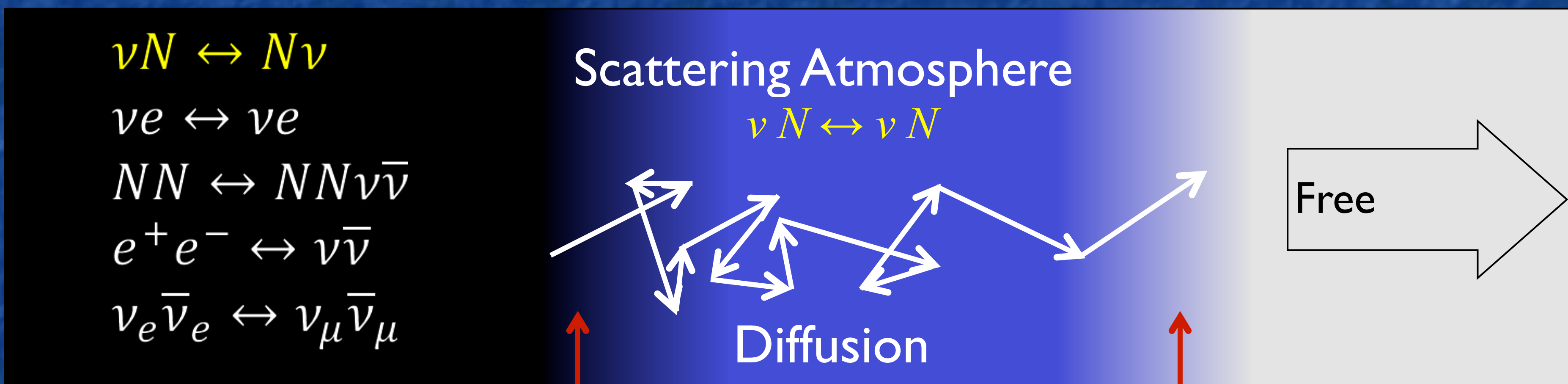
Neutrino emission

Electron flavor (ν_e and $\bar{\nu}_e$) Note that $n_p \neq n_n$ (neutron star forming...)



Neutrino sphere (T_{NS})

Other flavors ($\nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau$)



Energy sphere (T_{ES}) (determining production & chemical equilibrium)

Transport sphere (regulated by different processes!)

Expect differences between ν_e and ν_e, and e vs. other flav.

M. T. Keil, G. G. Raffelt and H. T. Janka, "Monte Carlo study of supernova neutrino spectra formation," Astrophys. J. 590, 971 (2003) [astro-ph/0208035].

Three Phases of ν emission

Figures adapted from Fischer et al., arXiv: 0908.1871, 10. 8 M_{sun} progenitor mass (spherically symmetric with Boltzmnann ν transport)

Neutronization Burst

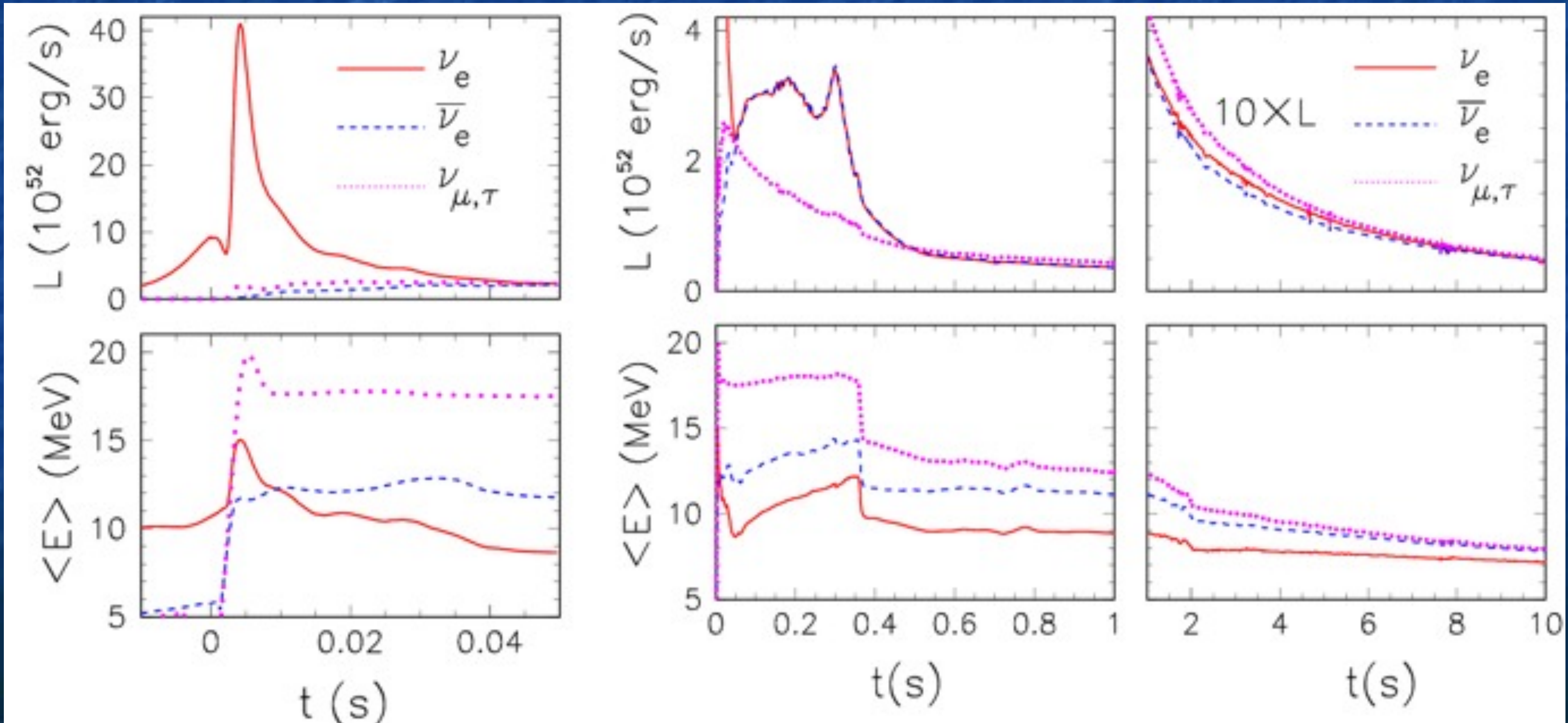
- Shock breakout
- De-leptonization of outer core layers

Accretion

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

Cooling

- Cooling on ν diffusion time scale

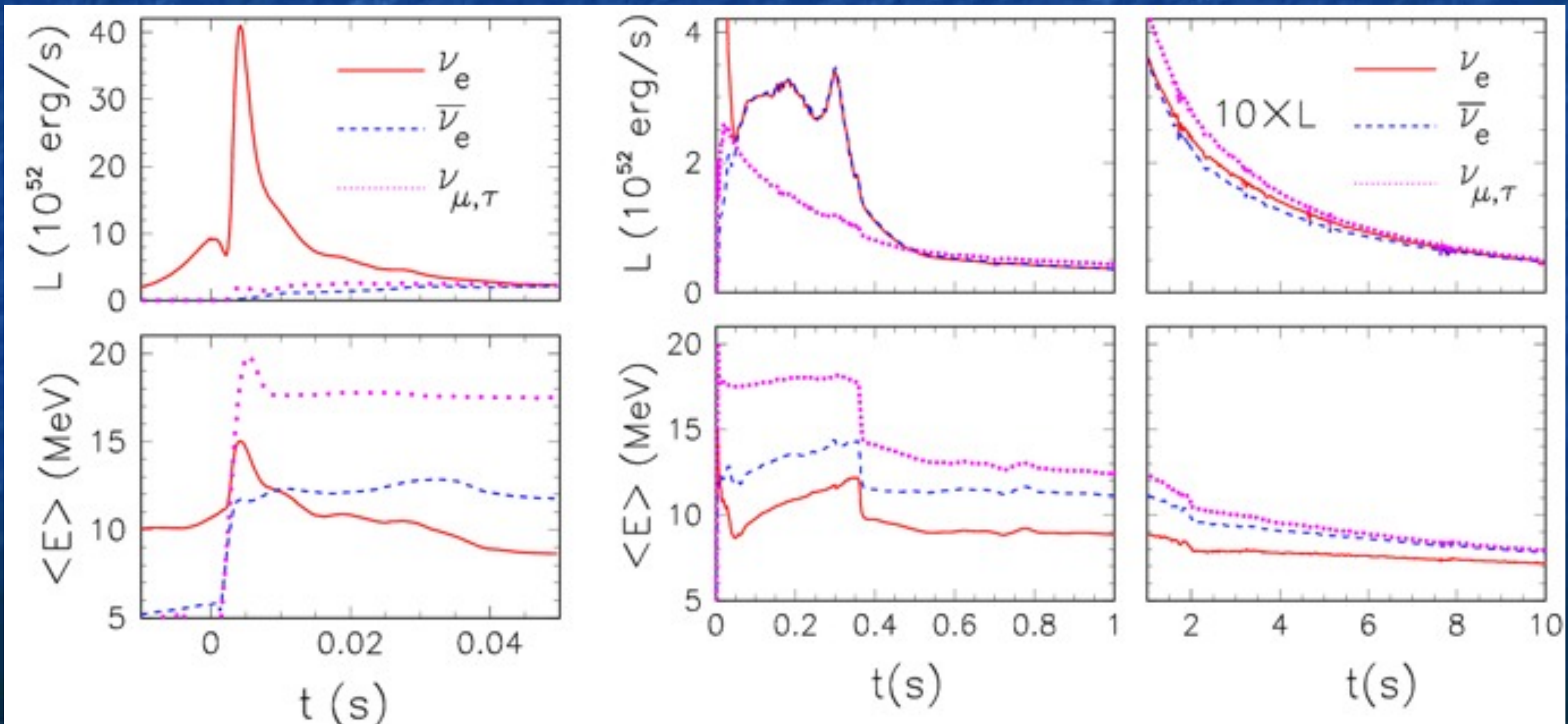


Three Phases of ν emission

almost ν_e-only

$$\langle F_{\nu_e}\rangle \gtrsim \langle F_{\bar{\nu}_e}\rangle \gtrsim \langle F_{\nu_x}\rangle$$
$$\langle E_{\nu_e}\rangle \lesssim \langle E_{\bar{\nu}_e}\rangle \lesssim \langle E_{\nu_x}\rangle$$

almost equipartition



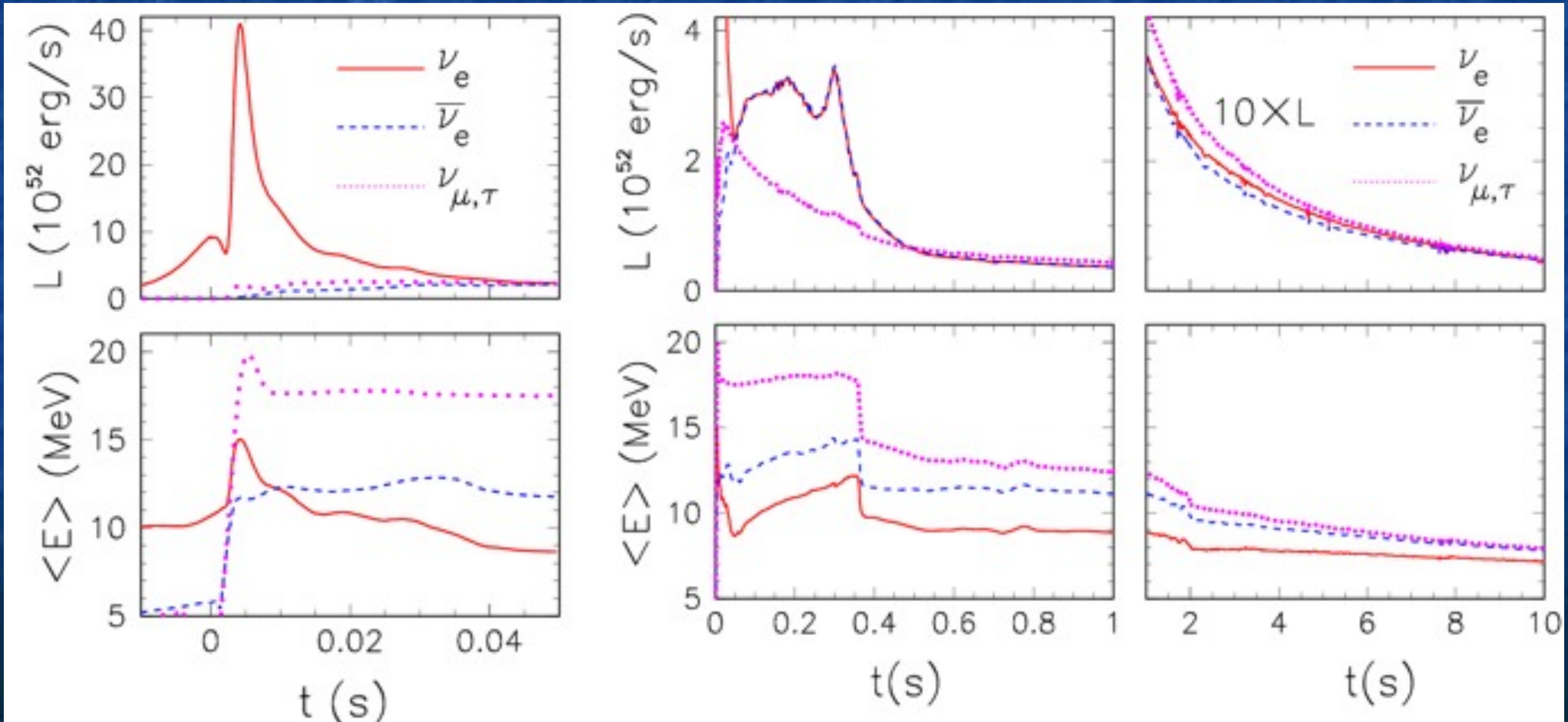
Three Phases of ν emission

But this does not account for oscillations (not to speak of NP!)

almost ν_e-only

$$\langle F_{\nu_e}\rangle \gtrsim \langle F_{\bar{\nu}_e}\rangle \gtrsim \langle F_{\nu_x}\rangle$$
$$\langle E_{\nu_e}\rangle \lesssim \langle E_{\bar{\nu}_e}\rangle \lesssim \langle E_{\nu_x}\rangle$$

almost equipartition



Oscillated fluxes

Taking into account the matter effect, one can evaluate the oscillated SN neutrino fluxes at Earth, and for "large θ_{13}" (as recently measured)

$$F_{\bar{\nu}_e} = \bar{c}_{ee} F^0_{\bar{\nu}_e} + \bar{c}_{xe} F^0_{\bar{\nu}_x}$$

	3ν	
	NH	IH
$\bar{c}_{ee}$	$\lvert U_{e1}\rvert^2 = 0.68$	$\lvert U_{e3}\rvert^2 = 0.02$
$\bar{c}_{xe}$	$1 - \lvert U_{e1}\rvert^2 = 0.32$	$1 - \lvert U_{e3}\rvert^2 = 0.98$

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(Flux conservation gives the non-electron fluxes)

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(Flux conservation gives the non-electron fluxes)

In short, one has

- **Normal mass hierarchy**

$$F^D_{\bar\nu_e} = \cos^2\theta_{12} F_{\bar\nu_e} + \sin^2\theta_{12} F_{\bar\nu_x}$$

- **Inverted mass hierarchy**

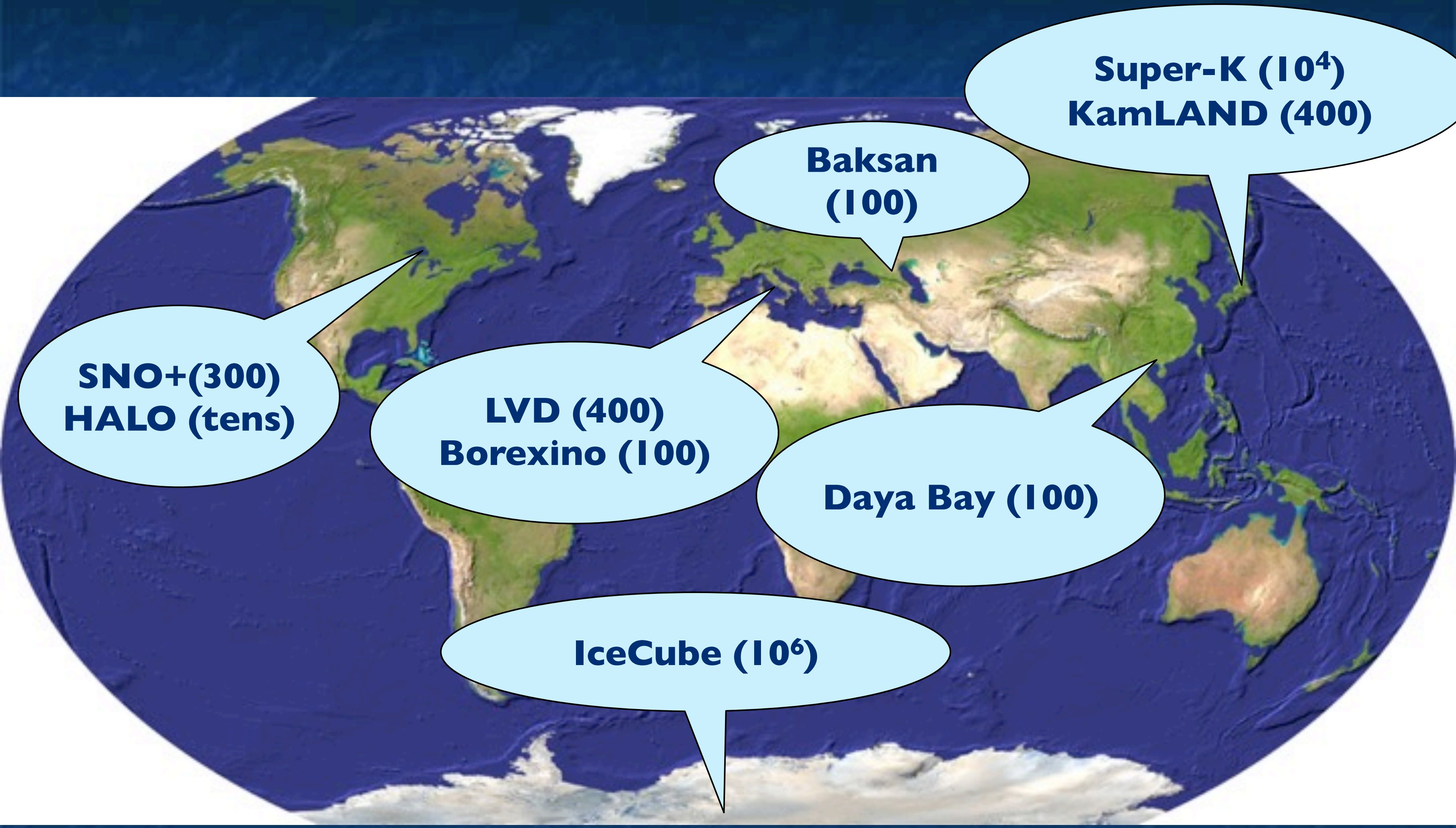
$$F^D_{\bar\nu_e} = F_{\bar\nu_x}$$

Seminal paper

A. S. Dighe and A. Y. Smirnov, "Identifying the neutrino mass spectrum from the neutrino burst from a SN," Phys. Rev. D 62, 033007 (2000) [hep-ph/9907423]

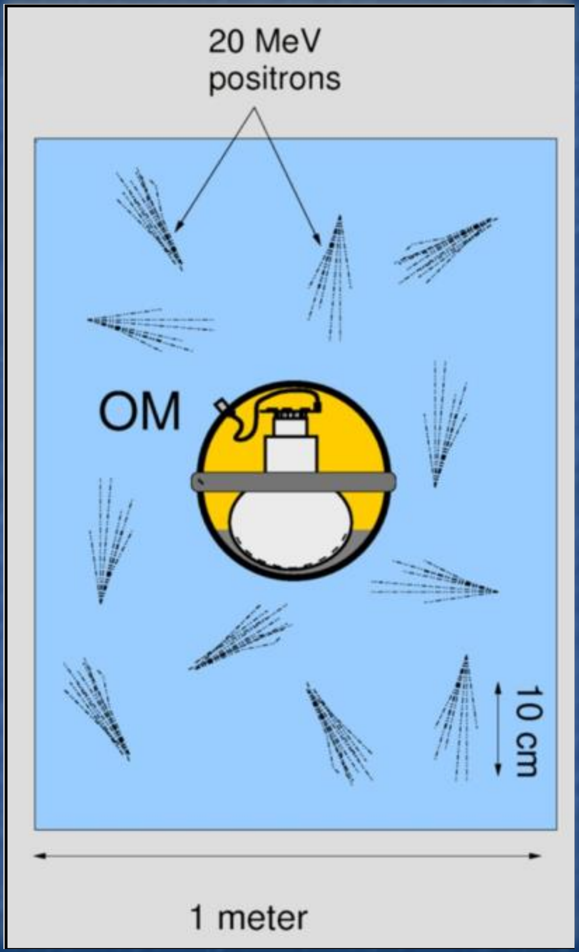
Observational Perspectives

Current detectors for SN neutrinos



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

IceCube as SN detector



- **Each optical module (OM) picks up Cherenkov light from its neighborhood**
- **300 Cherenkov photons per OM from SN at 10 kpc, bkgd rate in one OM < 300 Hz**
- **SN appears as "correlated noise" in ~ 5000 OMs**
- **Some energy information from time correlated hits**

Pryor, Roos & Webster, ApJ 329:355, 1988, Halzen, Jacobsen & Zas, astro-ph/9512080. Demirörs, Ribordy & Salathe, arXiv:1106.1937.

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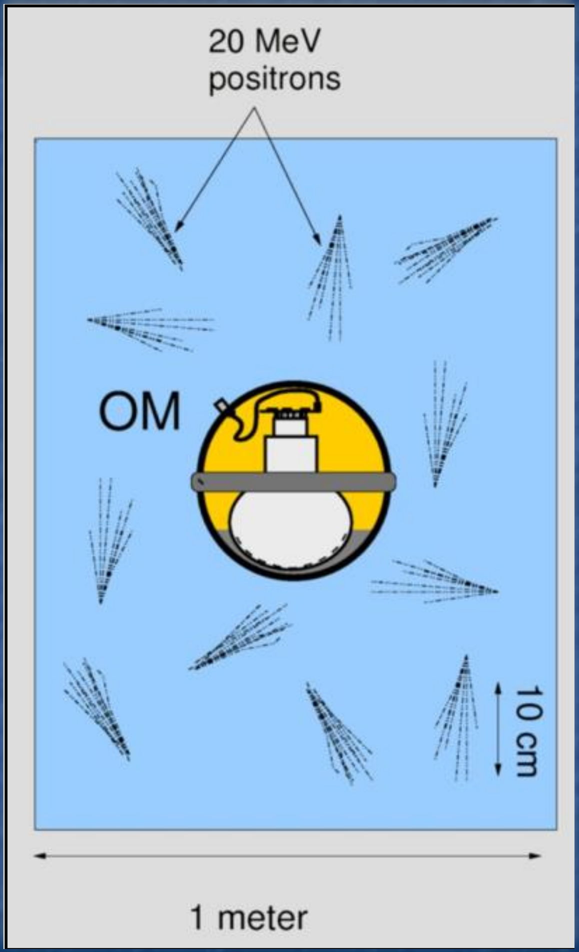

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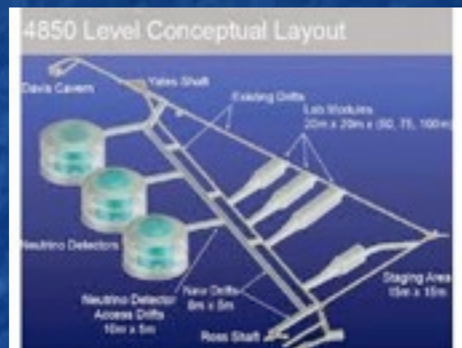
No pointing, poor E-information, but wonderful "lightcurve" t-dependent calorimetric measurement (mostly sensitive to anti-ν_e)

Pryor, Roos & Webster, ApJ 329:355, 1988, Halzen, Jacobsen & Zas, astro-ph/9512080. Demirörs, Ribordy & Salathe, arXiv:1106.1937.

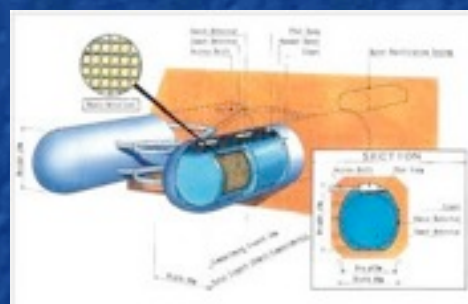
Next Generation Detectors

Mton scale water Cherenkov detectors

DUSEL LBNE (old)

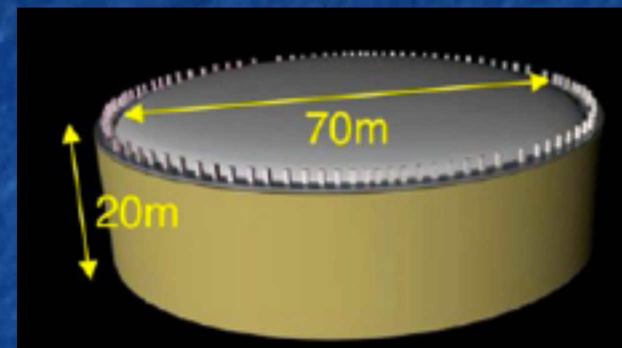


HYPER-KAMIOKANDE



MEMPHYS*

50-100 kton Liquid Argon TPC



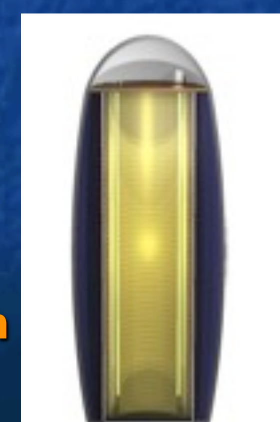
GLACIER*

50 kton scintillator

LENA*,

JUNO

***=(European LAGUNA research infrastructure)**



Complementary channels & features

	"MEMPHYS"	"LENA"	"GLACIER"
Main channels	$\bar{\nu}_e + p \rightarrow n + e^+$	$\bar{\nu}_e + p \rightarrow n + e^+$	$\nu_e + {}^{40}Ar \rightarrow {}^{40}K^* + e^-$
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

How to measure hierarchy?

Inference should possibly rely on robust features about flux differences and SN environment. Some ideas

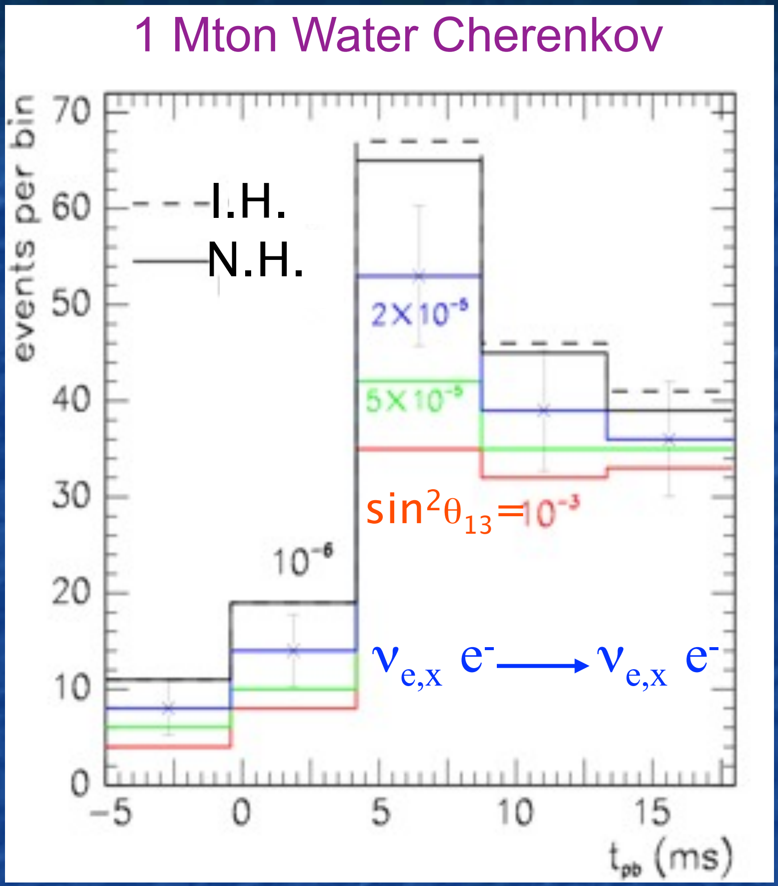
1) Presence/absence of neutronization burst
✓ robust (both qualitatively and quantitatively)
◉ requires large ν_e detector

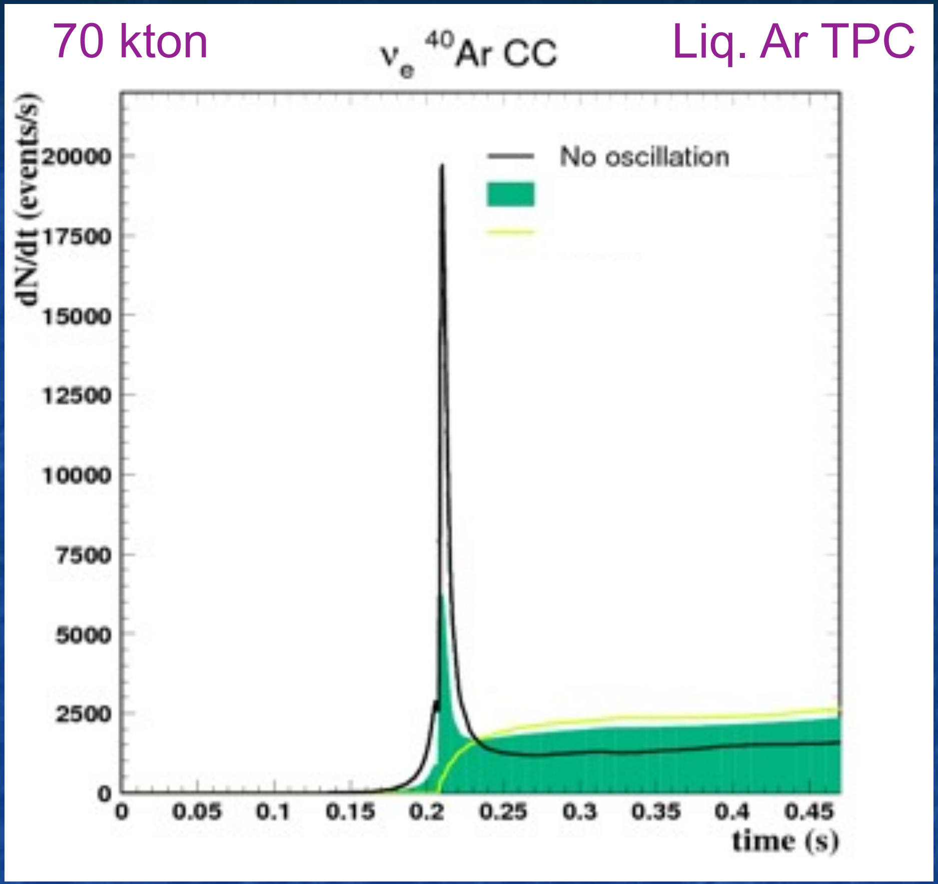
2) Flavor "reprocessing" due to crossing of Earth mantle/core
✓ qualitatively robust, just uses SN as huge ν candle
◉ requires "chance of Earth shadowing", quantitative differences may be small (hard to detect), good E resolution usually needed.

3) Effects of astrophysical robust features, like the shock-wave
✓ presence guaranteed (qualitatively robust)
◉ properties of turbulence in the SN medium unclear, presence/absence of signals is dependent on that.

4) Something else?

Neutronization burst





M.Kachelriess & R. Tomas, hep-ph/0412082   *I.Gil-Botella & A.Rubbia, hep-ph/0307244*

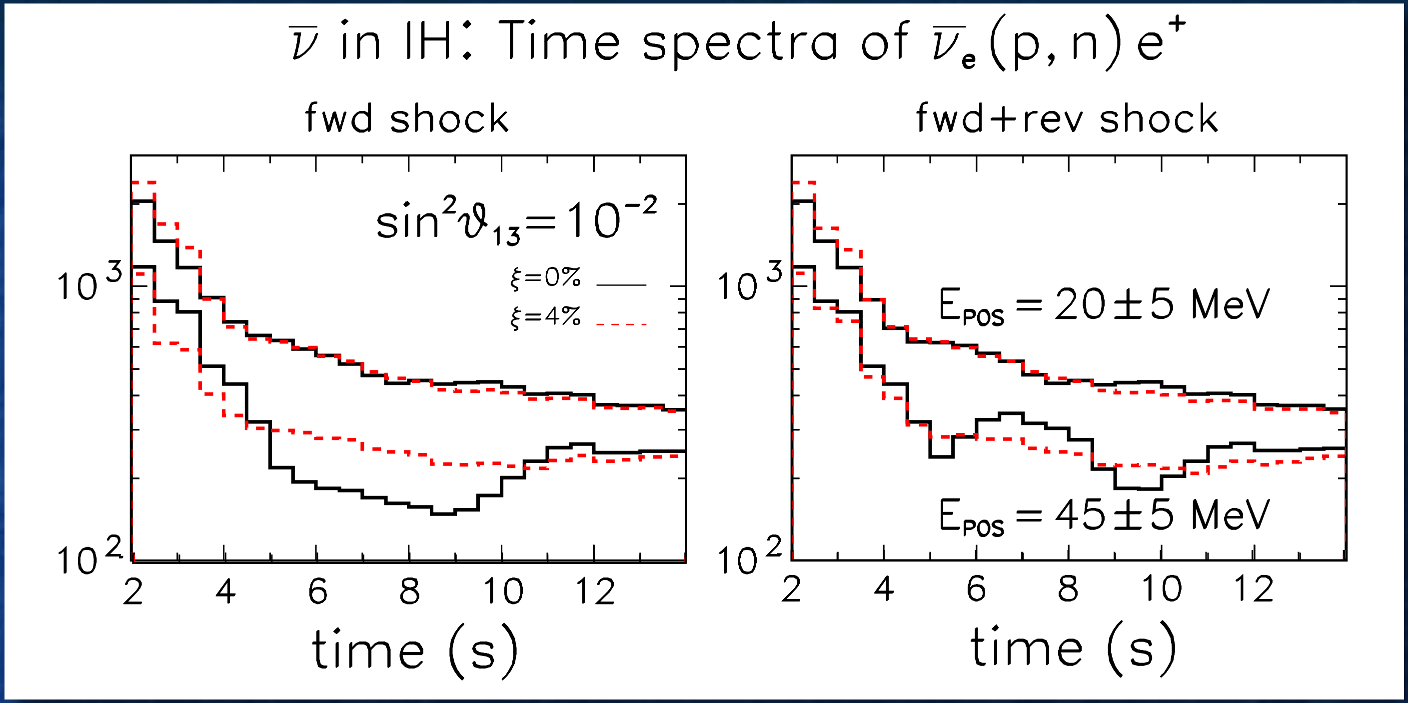
At "large" θ_{13} (as recently measured!):

- **The peak <u>is not seen</u> → NH**
- **The peak <u>is seen</u> → IH**

Experimental challenge:

build instrument that could see a peak, if there!

Shock wave effect and turbulence



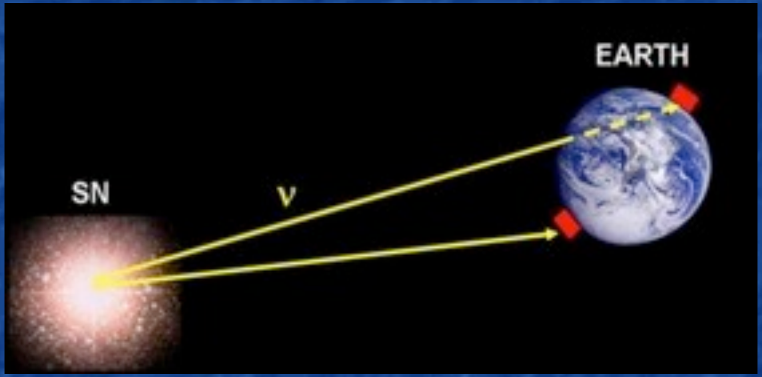
In principle, presence of the forward (+ reverse) shock can leave peculiar imprints on t & E signal (e.g. inverse beta decay in Mton detectors).

But patterns affected by level & properties of turbulence in 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, Borriello et al, 1310.7488

Earth Matter Effect

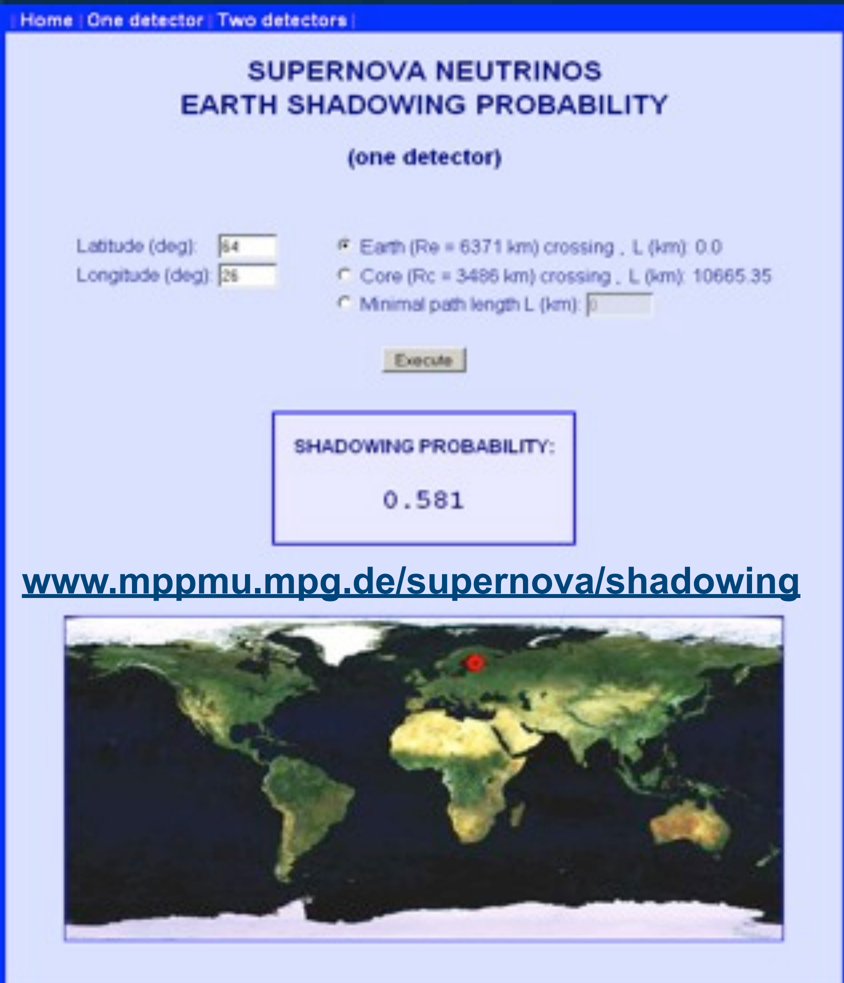
Assume one measures flux for a SN *crossing (enough mantle of) the Earth*.
The "weights" of different input flavours making a given observed flux of ν's *are altered in a peculiar E-dependent way.*



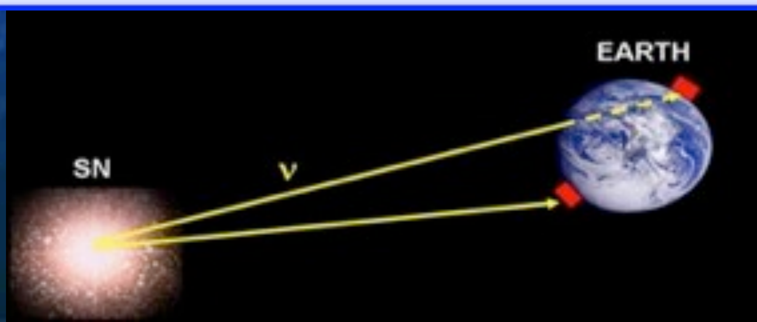
- **In which channel EME manifests depends on the (still unknown) mass hierarchy: neutrinos for IH, antineutrinos for NH. Knowing the detection channel, detection or absence of Earth Matter effects gives information on the hierarchy.**

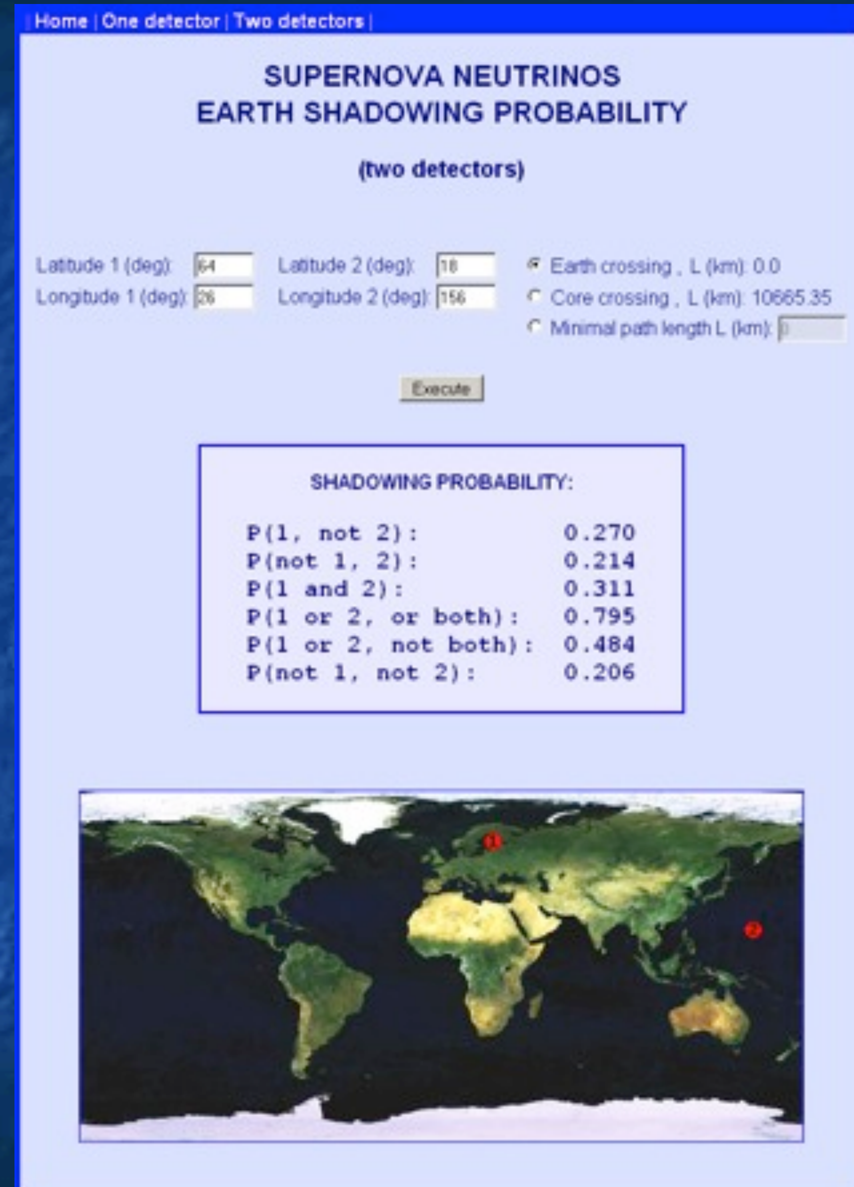
- **Good news:**
  - **ambiguity between large θ_{13} and small θ_{13} cases now resolved; if a measurement can be performed, it is unambiguous (at least theoretically)**
  - **improved simulations exist (transport, GR effects, etc.) wrt a decade ago.**
  - **several detector options**

A web tool to play with...



www.mppmu.mpg.de/supernova/shadowing





Mirizzi, Raffelt, PS astro-ph/0604300

Earth Matter Effect

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

Normal mass hierarchy

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

Inverted mass hierarchy

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

The probability gets modified (for antineutrinos in NH) as

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

$0 \leq |\kappa| \leq 1$, depends on mixing angle in matter

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

"periodic" energy modulation expected!

Wiggles?!

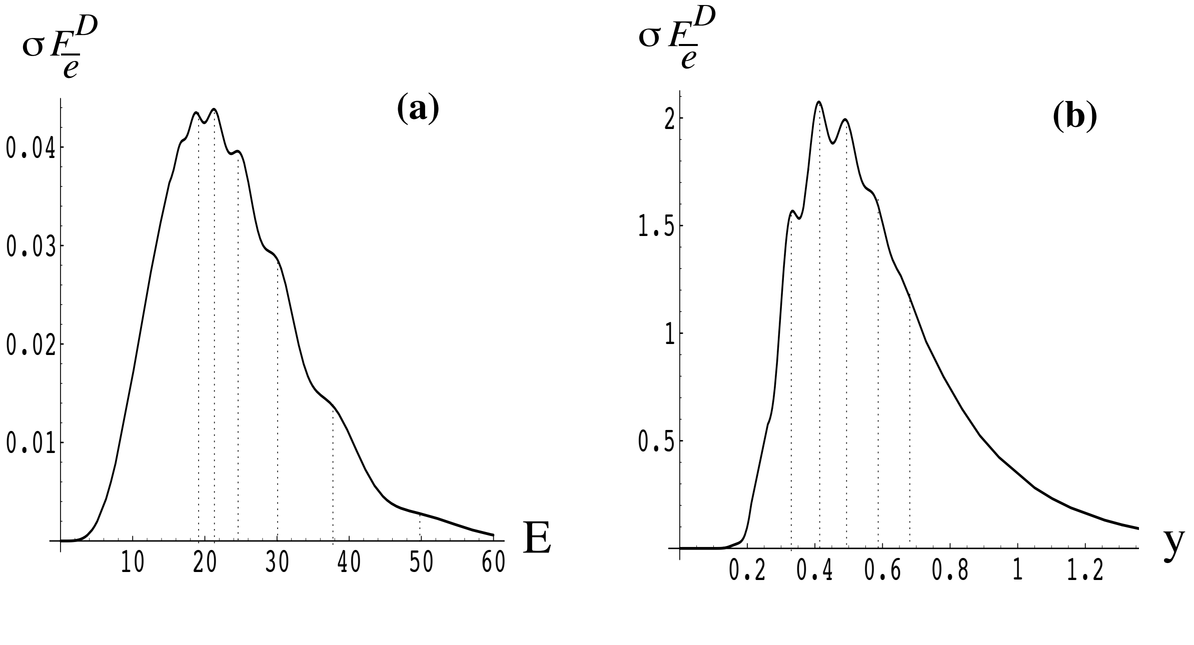
In terms of ***y=12.5 MeV/E***, there is modulation of the spectrum with a specific wavenumber (indipendent of SN physics!)

$$F_{\bar{\nu}_e}^{\oplus} = F_{\bar{\nu}_e}^{D} - \kappa\,(F_{\bar{\nu}_e}^{0} - F_{\bar{\nu}_x}^{0})\,\sin^2\left(\frac{k_{\oplus} y}{2}\right) \qquad k_{\oplus} \equiv 2\overline{\Delta m_{\oplus}^2}\,L$$

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

Accounting for realistic errors, and for new simulations (showing “closer” fluxes), realistically, no more than a few percent chance to detect EME at next Gal. SN.

(Comparing shadowed and unshadowed signals typically suffers from systematics)



E. Borriello, S. Chakraborty, A. Mirizzi, PS, & I. Tamborra, Phys. Rev. D 86, 083004 (2012)

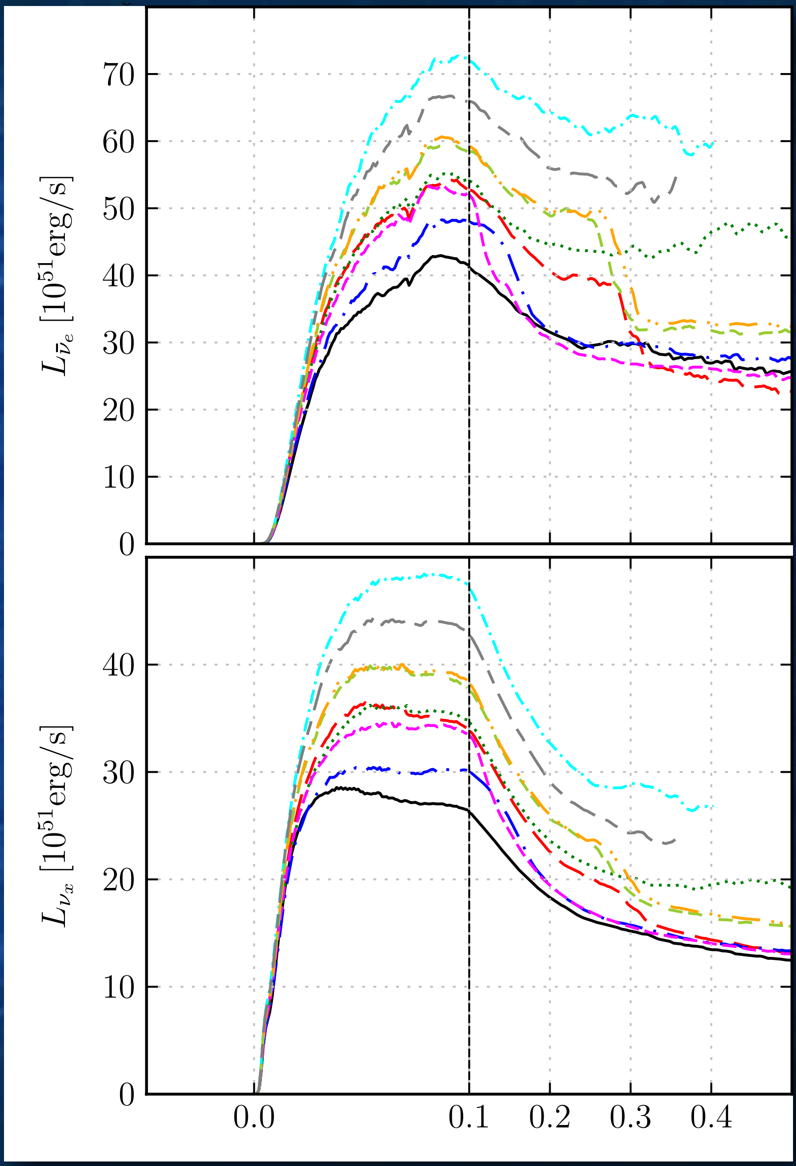
What about current detectors?

anti-ν_e production more suppressed than (anti) ν_x during first tens of ms after bounce because of high e degeneracy

High degeneracy only allows for a low abundance of e^+, (anti-ν_e production by pair annihilation & e^+ captures on neutrons not efficient).
In optically thick regime ν_e are in chemical equilibrium with matter; their degeneracy also blocks the phase space for anti-ν_e creation via NN bremsstrahlung, which is allowed for ν_x...

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

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



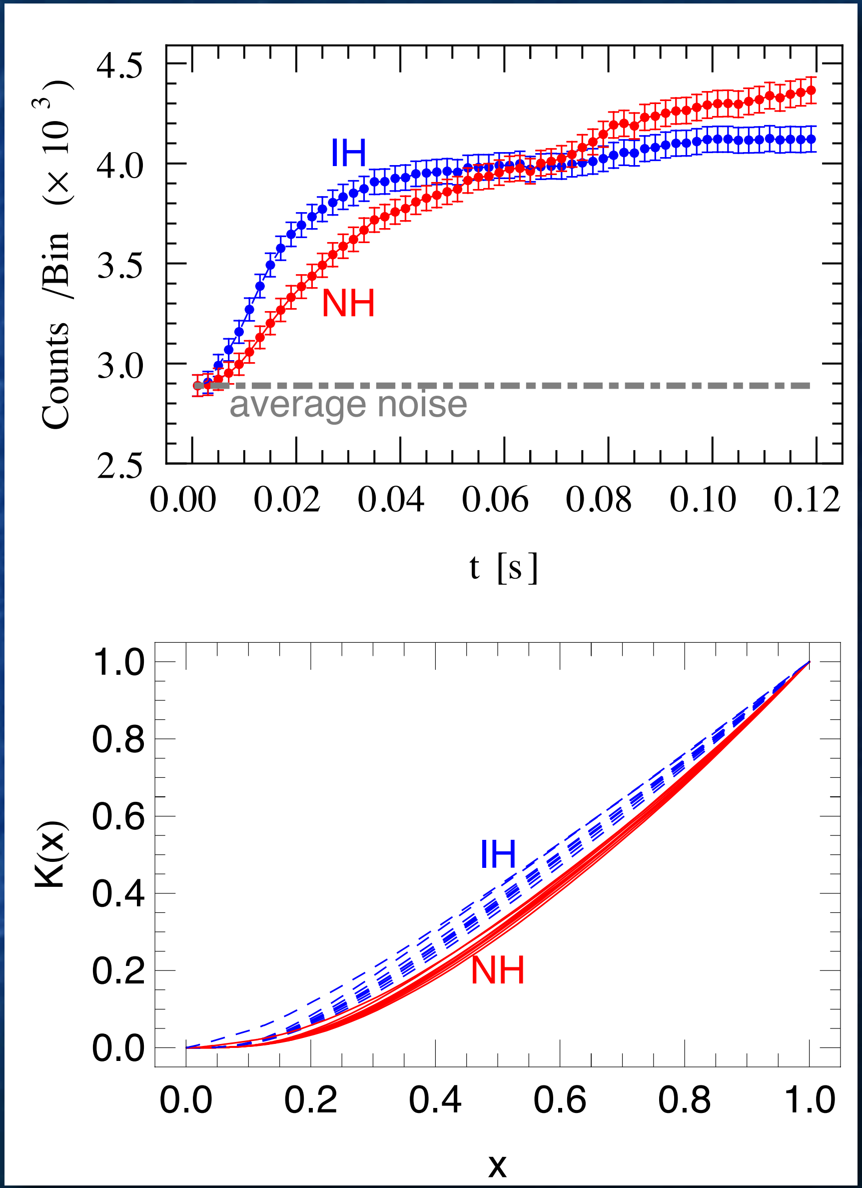
Garching group, 2011

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

IceCube is a wonderful calorimetric detector, for that purpose!

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

PS et al. Phys. Rev. D 85, 085031 (2012) [arXiv:1111.4483].



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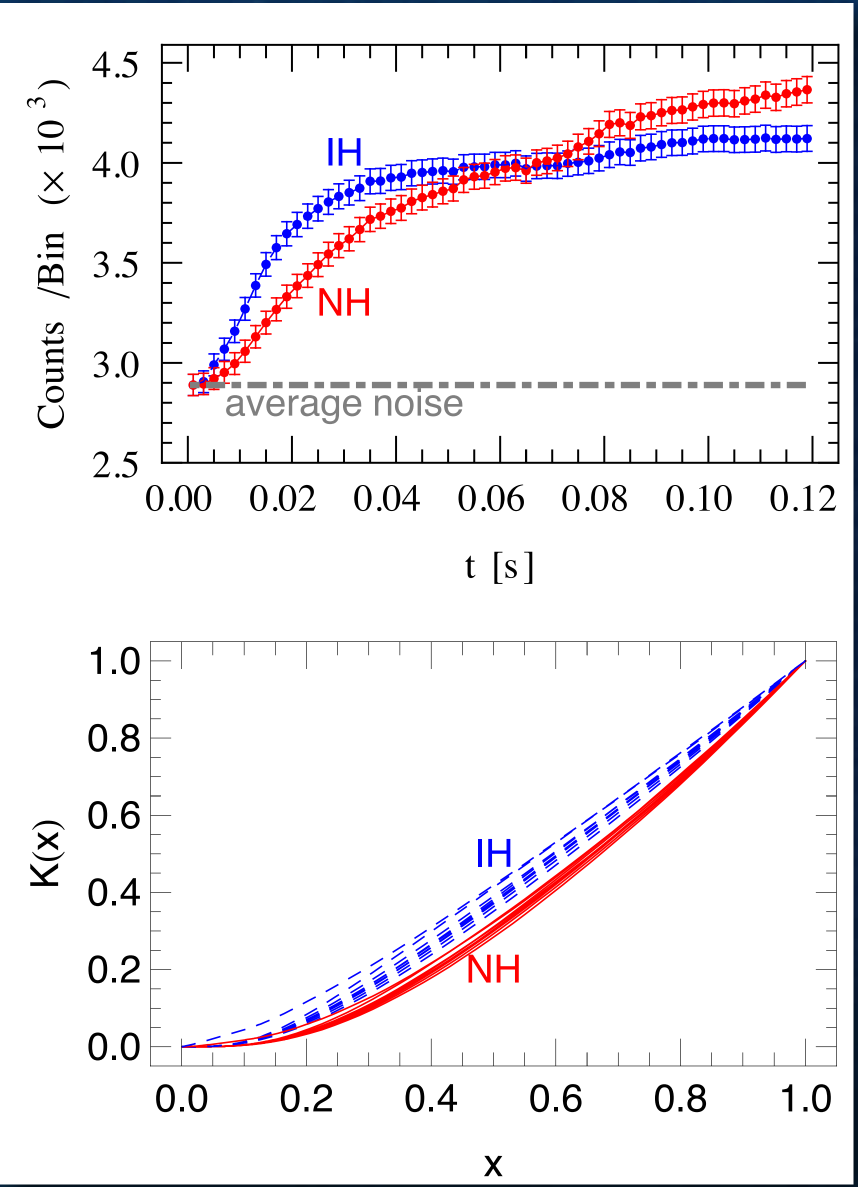
Are the risetime shapes predicted robustly enough to be useful?

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, C. Ott's (1207.1100) ones seem to confirm these trends.



What about realistic statistics?

Are theoretical shape differences large compared to expected statistical errors?

We run MonteCarlo simulations, finding that in >99% of 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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(our work was a "proof-of-principle")

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CAVEAT: Despite the fact that the difference between two cases is qualitatively robust (always 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.

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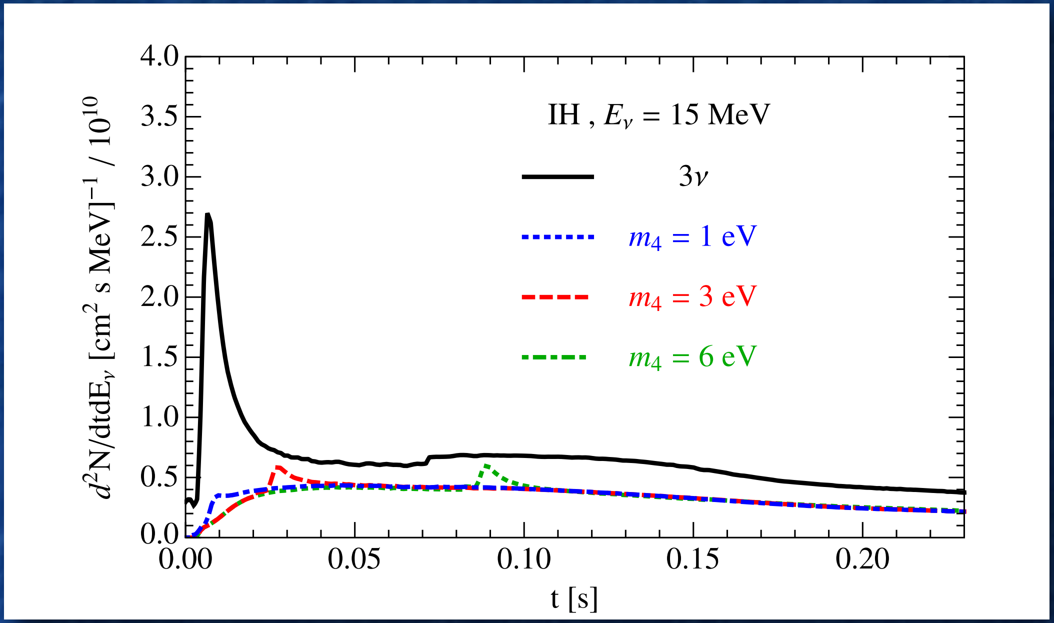
For the time being, best compromise we could find between model-independence & detectability in an existing experiment, for a large fraction of expected gal. SN events.

Room for surprises? (BSM)

What if a sterile neutrino exists, with parameters in the ball-park of what hinted by the "reactor anomaly"?



Might make the neutronization burst "disappear"!

A. Esmaili, O. L. G. Peres, & PS, "Impact of sterile neutrinos on the early time flux from a galactic supernova," PRD 90, 033013 (2014) [1402.1453].

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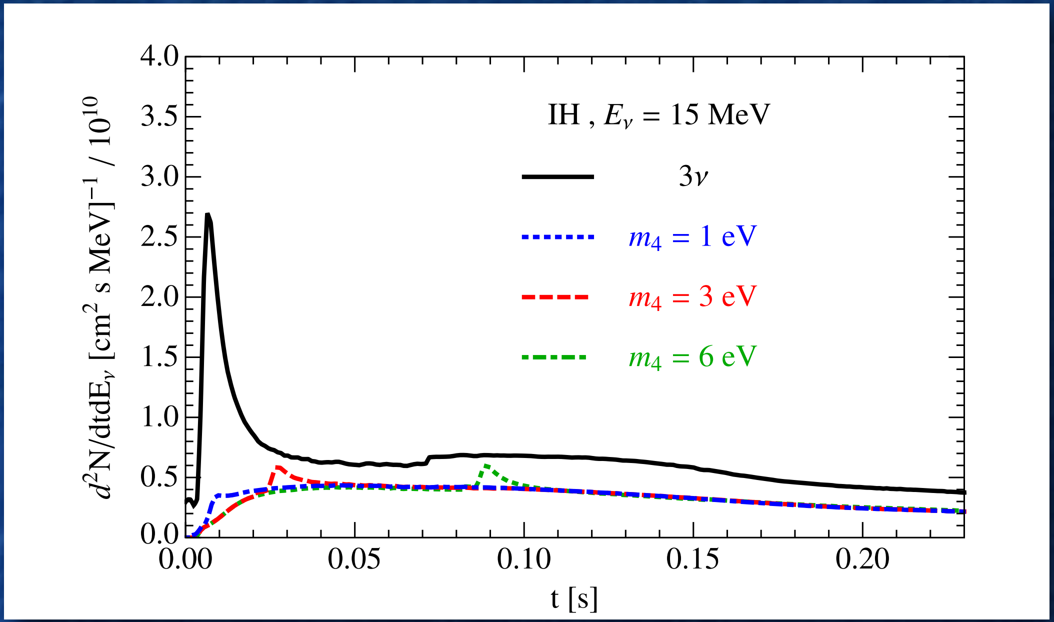

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	NH	IH	NH	IH
c_{ee}	$\|U_{e3}\|^2 = 0.02$	$\|U_{e2}\|^2 = 0.30$	$\|U_{e4}\|^2 = 0.02$	$\|U_{e4}\|^2 = 0.02$
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c_{se}	...	...	$\|U_{e3}\|^2 = 0.02$	$\|U_{e2}\|^2 = 0.29$

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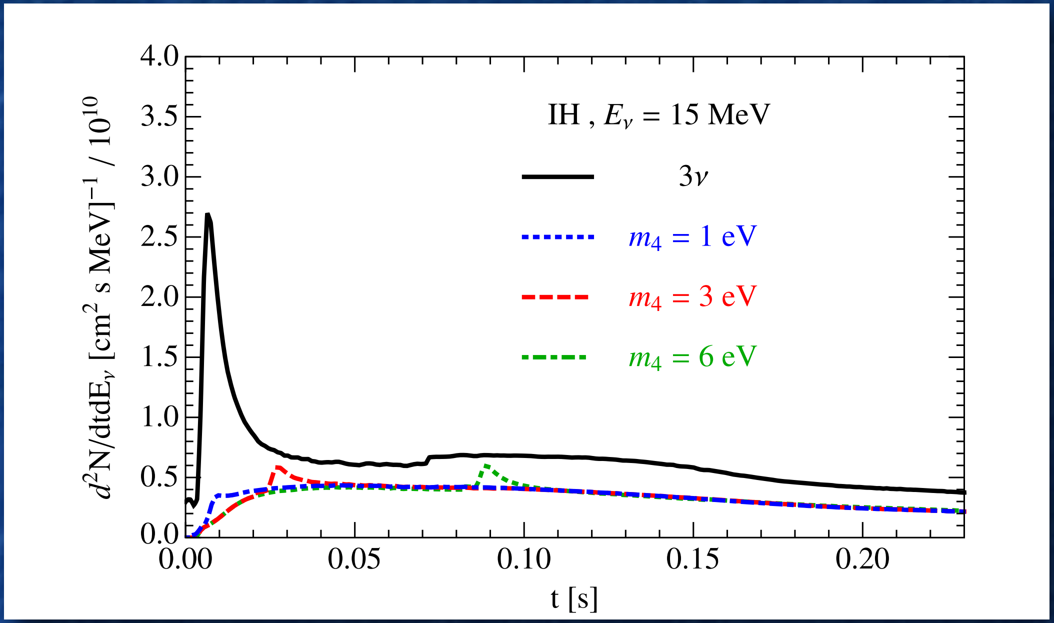

	3ν		$3+1$	
	NH	IH	NH	IH
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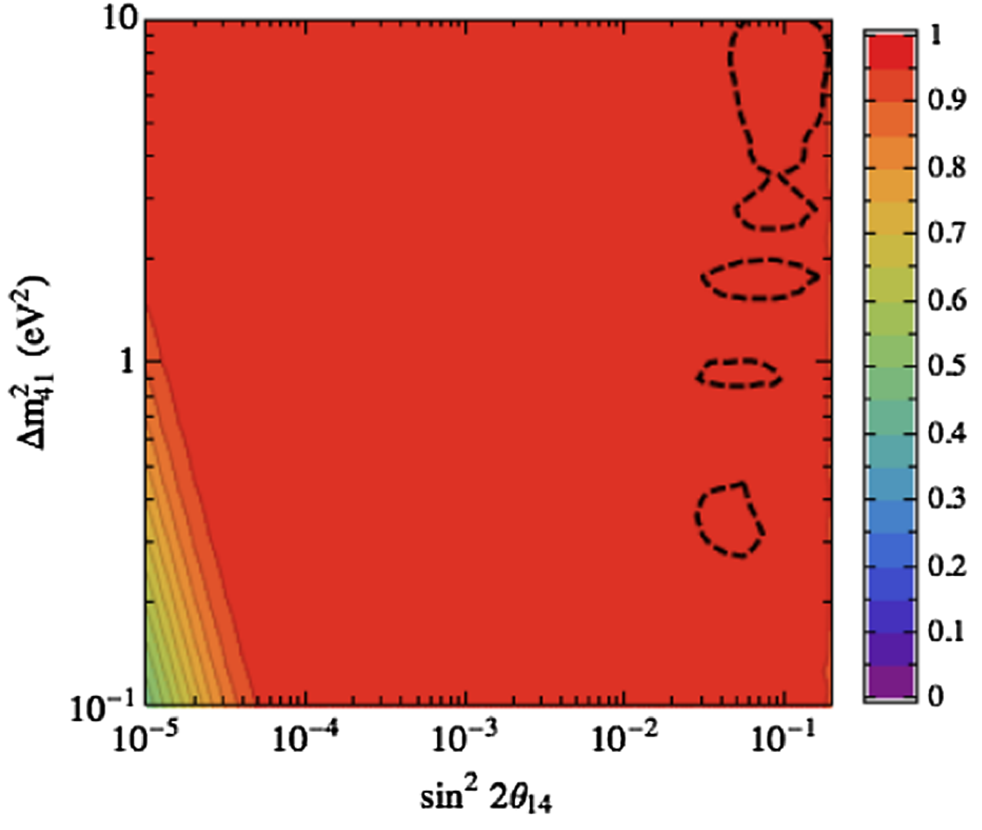
c_{se}	$\cdots$	$\cdots$	$\lvert U_{e3}\rvert^2 = 0.02$	$\lvert U_{e2}\rvert^2 = 0.29$

Imagine now that we will know from the lab (or even hinted by cosmology!) that IH is right...

...We would gain a new tool!



(a) $P(\nu_e \to \nu_s)$, both NH and IH

"Disappearance" of the signal over large parameter space (in principle, new probe of light sterile neutrinos...)

A. Esmaili, O. L. G. Peres and P. D. Serpico, "Impact of sterile neutrinos on the early time flux from a galactic supernova," Phys. Rev. D 90, 033013 (2014) [arXiv:1402.1453].

Room for surprises? (in the SM!?!)

- Well-known MSW effect can occur in a SN envelope when

$$\lambda = \sqrt{2} G_F n_e \sim \omega_H = \Delta m^2 / 2E$$

(potential)~(osc. frequency)

- For t~few sec after bounce, $\lambda \sim \omega$ at $r >> 10^2$ km (large radii) MSW-resonance(s) possible and their effects studied for~20 years

- What happens at small radius? Popular wisdom:

$\lambda >> \omega_H$ at $r < O(10^2 \text{ km})$

→ flavor transition suppressed.

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  → flavor transition suppressed.

Not necessarily correct !!!

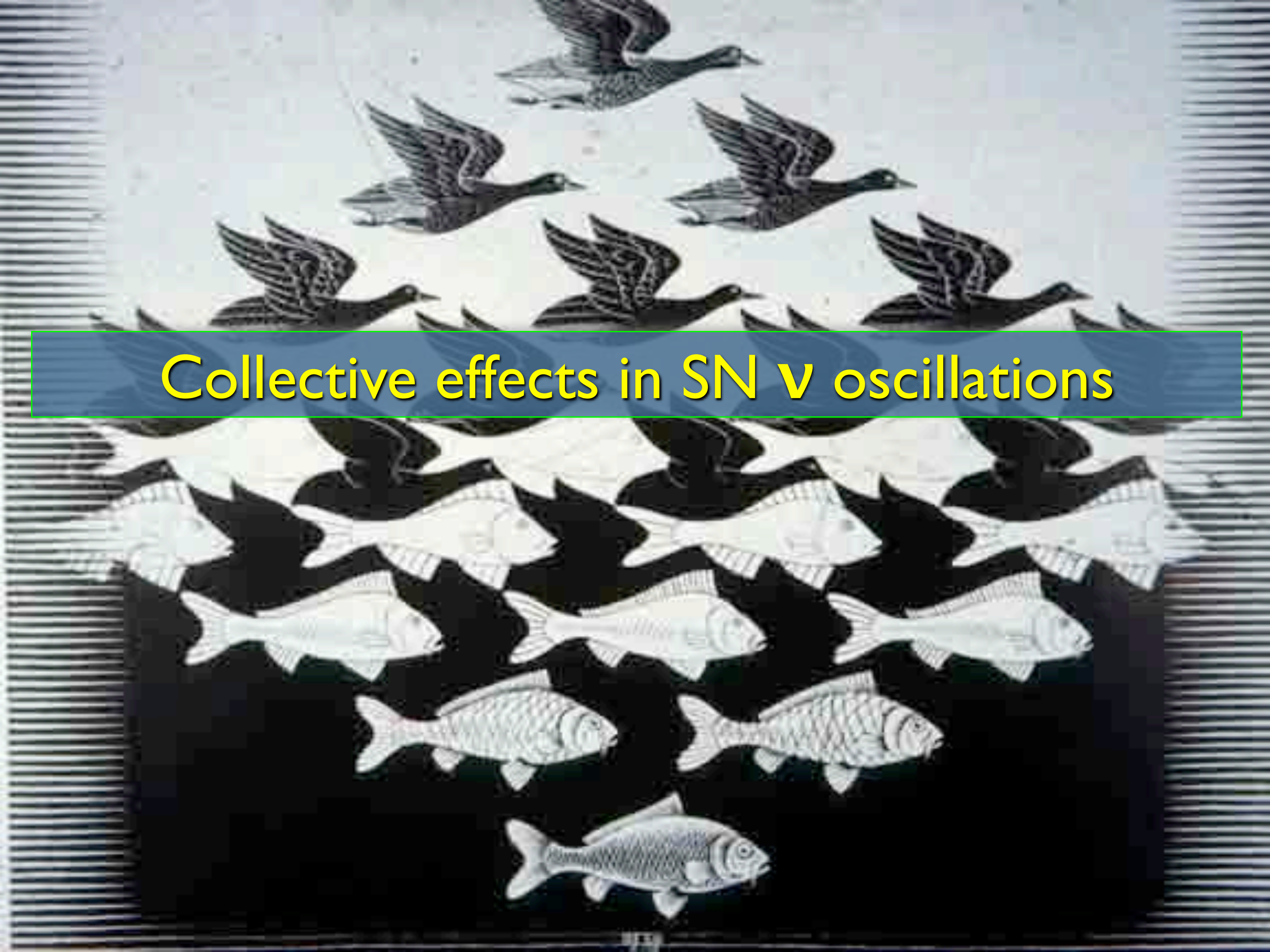
In a SN, beside CC

it is crucial to include also NC

- **At small radius, ν density is high enough that ν self-potential $\mu=\sqrt{2}G_F n_\nu > \omega$ crucial (even if $\lambda > \mu$)**

- **The importance of these (longtime known) terms has been appreciated only after the (mostly numerical) results by Duan, Fuller, Carlson, Qian 05-06 O(200) papers!**

Collective effects in SN ν oscillations



Instability in flavour space

- Some flavour flux configurations may be actually not be the most "stable" ones (linked to mass hierarchy)
- Neutrino self-refraction effects may drive the system to a stable configuration
- Phenomenologically, this can translate in "collective" conversions of the type

$$\bar{\nu}_x \nu_x \leftrightarrow \bar{\nu}_e \nu_e$$

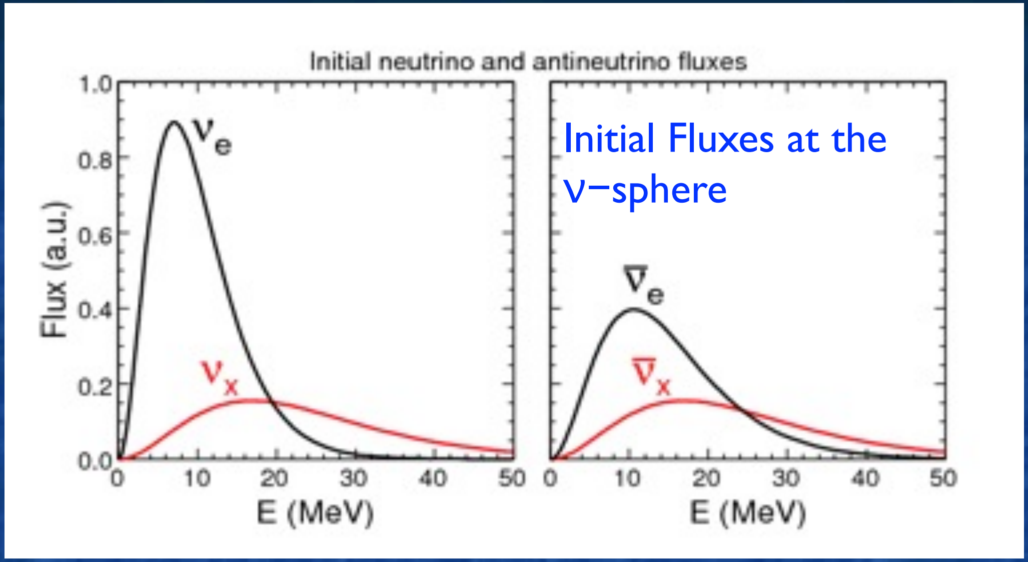
(no flavour violation, new type of conversions)

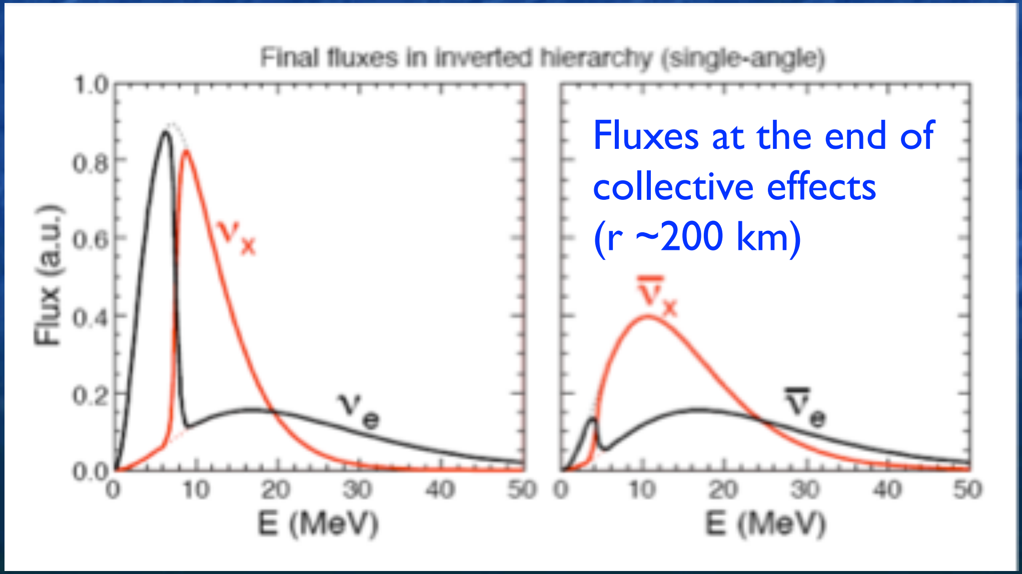
- "Around spectral crossings" (E at which different flavour flux cross) fluxes can completely swap (maximally consistent with L-conservation)
- In some limits, formal analogy with classical non-linear systems (like coupled pendulums).

Some analytical understanding possible

Hannestad, Raffelt, Sigl, Wong astro-ph/0608695

“Spectral Splits”





Typically obtained within some approximations:

spherical symmetry

half-isotropic distribution functions for the neutrinos

overall matter effect for all modes

...

→ may alter E-deposition to layers (explosion itself!)
→ may alter nucleosynthesis in outer layers
→ may alter flavour of fluxes observed at the Earth

Most recent theoretical efforts linked to clarify what happens in more and more realistic cases

Current understanding (tentative)

Neutronization Burst

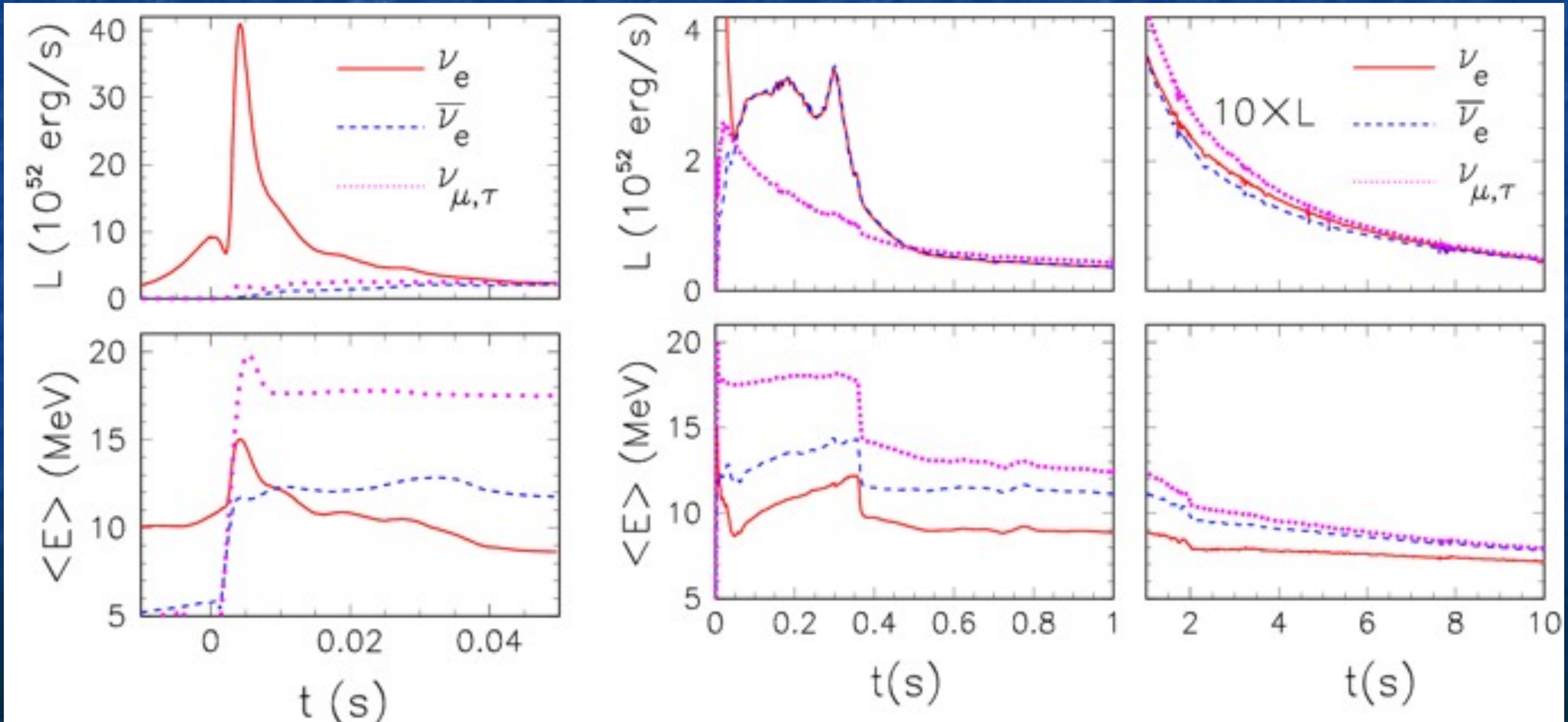
- Almost only ν_e , the effect cannot be there (but at few % level)

Accretion

"Multi-angle effects" *(Esteban-Pretel, PS et al. 0807.0659, S. Chakraborty et al. 1104.4031, 1105.1130, S. Sarikas et al. 1109.3601)* inhibit those processes, standard picture should hold (Fe-SN, unclear for O-Ne-Mg)

Cooling

Effects could be relevant (no robust prediction by now!) but flux differences much smaller, should be hard to see!)



Conclusions

- The current solution of the long-standing solar ν problem can be seen as a "first test" of ν refraction properties in matter
- We know that ν's play a crucial role in the core-collapse Supernova (SN) mechanism: a few ν's observed from SN1987A (part of motivations for Nobel Prize 2002 to Koshiba)
- We know that environmental conditions in a CC SN are extreme and not accessible otherwise in the Lab. Lots of "astroparticle constraints" follow!
- With current/next generation of detectors, it might be possible to infer some unknown properties, like mass hierarchy (challenging but possible... as other methods btw!)
- On the other hand, clarifying the neutrino mixing pheno in the lab could turn next Gal. SN into a unique, powerful tool to explore new features, hard or impossible to test otherwise!

Thank You!


Thank You!
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