JIGSAW 2010

Joint Indo-German Supernova Astroparticle Physics Workshop

Mumbai, 22-26 February 2010

SUPERNOVA NEUTRINOS: CHALLENGES AND OPPORTUNITIES

Alessandro MIRIZZI
(Universität Hamburg)

OUTLINE

Supernovae as neutrino source

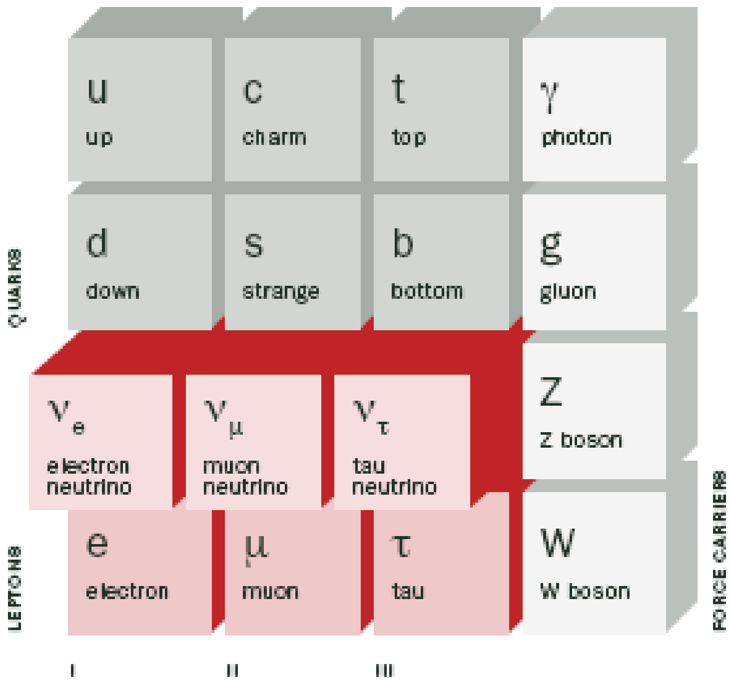
Supernova neutrino observations: SN 1987A and future perspectives

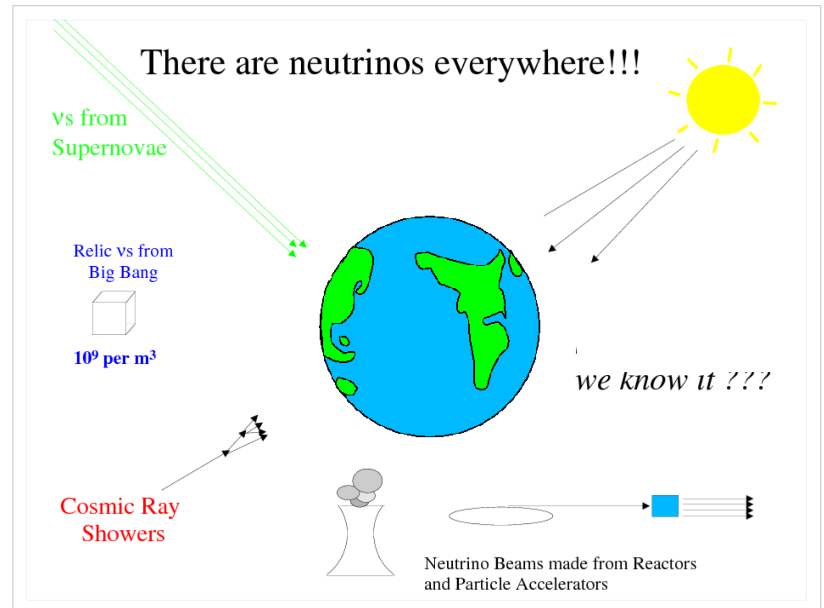
Figure 3: Dubna 1988. Neutrino oscillations.

Supernova neutrino oscillations and observable signatures

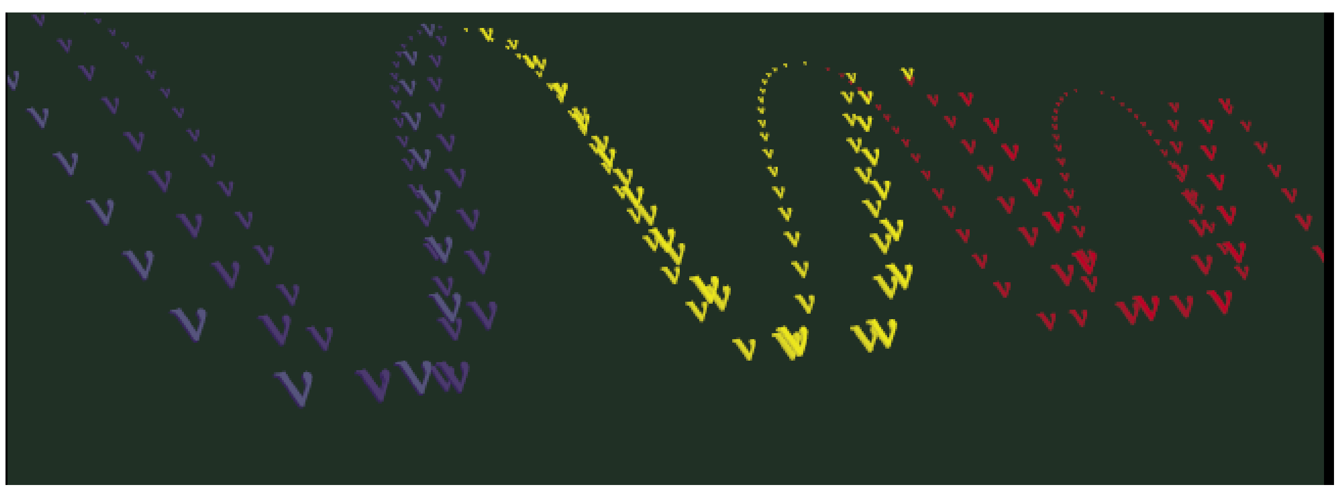
Conclusions

NEUTRINOS

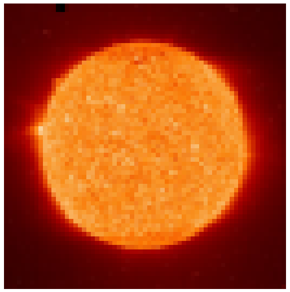




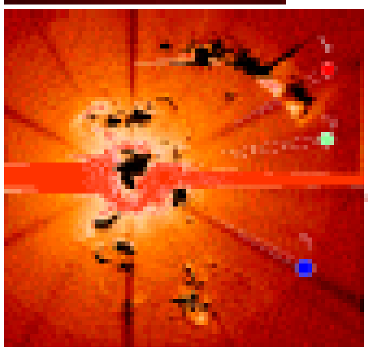
Neutrino oscillations → Neutrinos have a tiny but finite mass



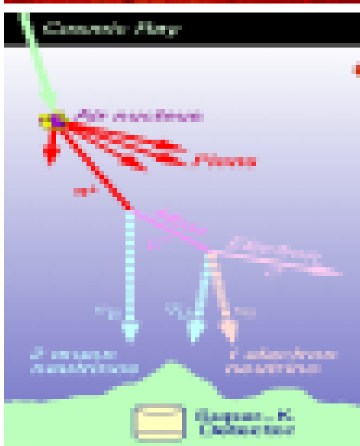
NEUTRINO SOURCES



← Sun



← Cosmology



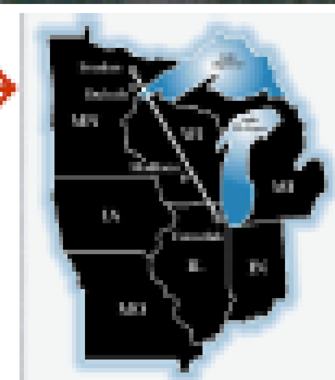
← Atmosphere

← Earth

Astronomy: →
Supernovae
GRBs
UHE ν's

Reactors →

Accelerators →



β-Sources →

WHY SUPERNOVA NEUTRINOS?

SN EXPLOSION: the most powerful neutrino source (10^{57}/10 sec) in the Universe

Neutrino theory/phenomenology

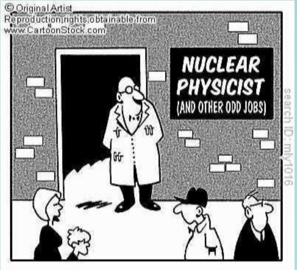
NEUTRINO OSCILLATIONS in extreme astrophysical environment. Sensitivity to ν mixing

Neutrino detection

High-statistics of events in large underground detectors (10^5-10^6 ev/10 sec) for galactic SN

Neutrino astrophysics

Crucial role of ν in the explosion mechanism. Unique probe of the deepest SN regions



Neutrino nuclear astrophysics

Nucleosynthesis in supernovae is a neutrino-driven process

SUPERNOVA NEUTRINOS

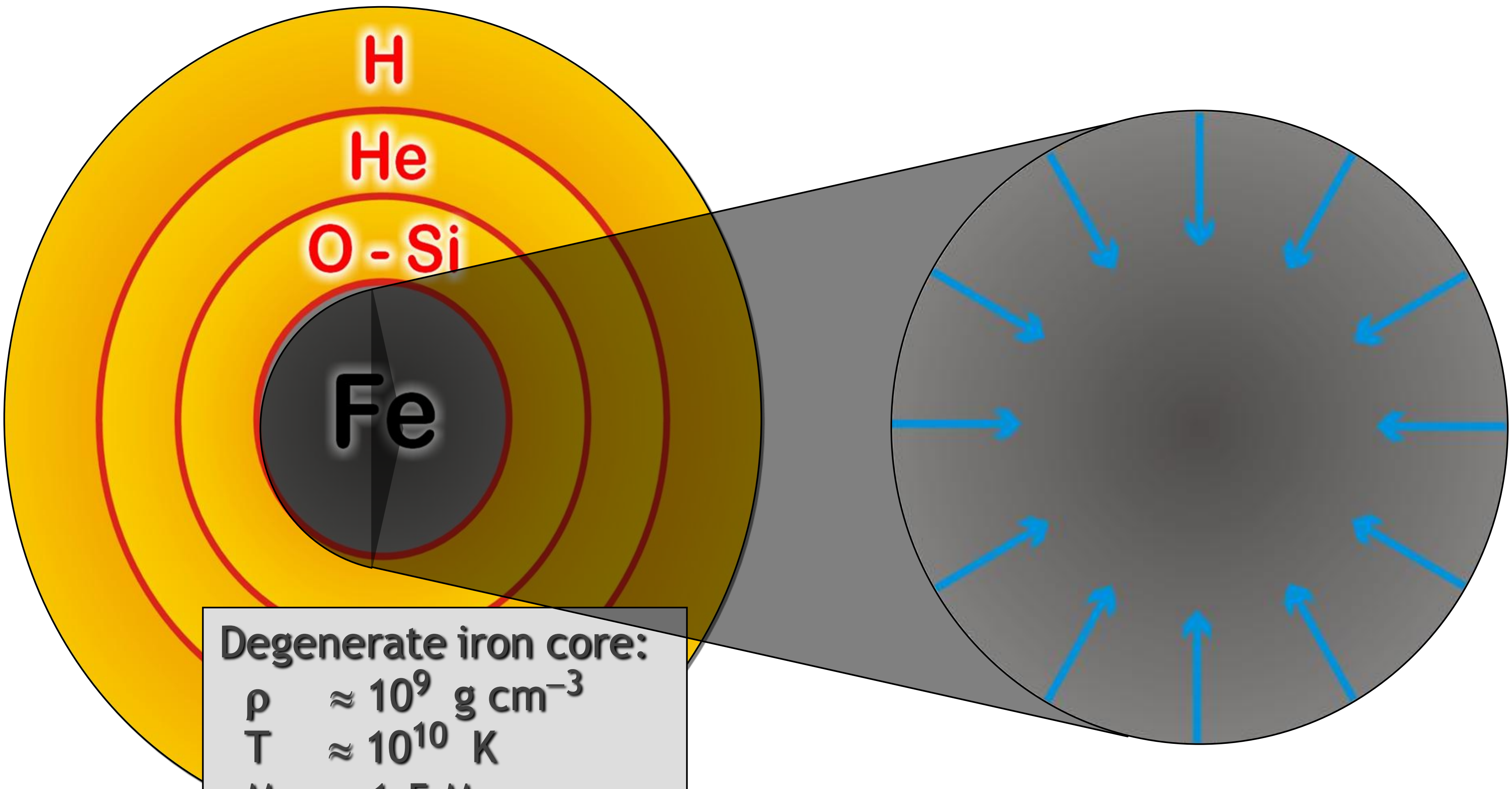
Core collapse SN corresponds to the terminal phase of a massive star [$M \gtrsim 8\ M_{\odot}$] which becomes unstable at the end of its life. It collapses and ejects its outer mantle in a shock wave driven explosion.

- **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).

Stellar Collapse and Supernova Explosion

Onion structure

Collapse (implosion)



Degenerate iron core:

$\rho \approx 10^9$ g cm^{-3}

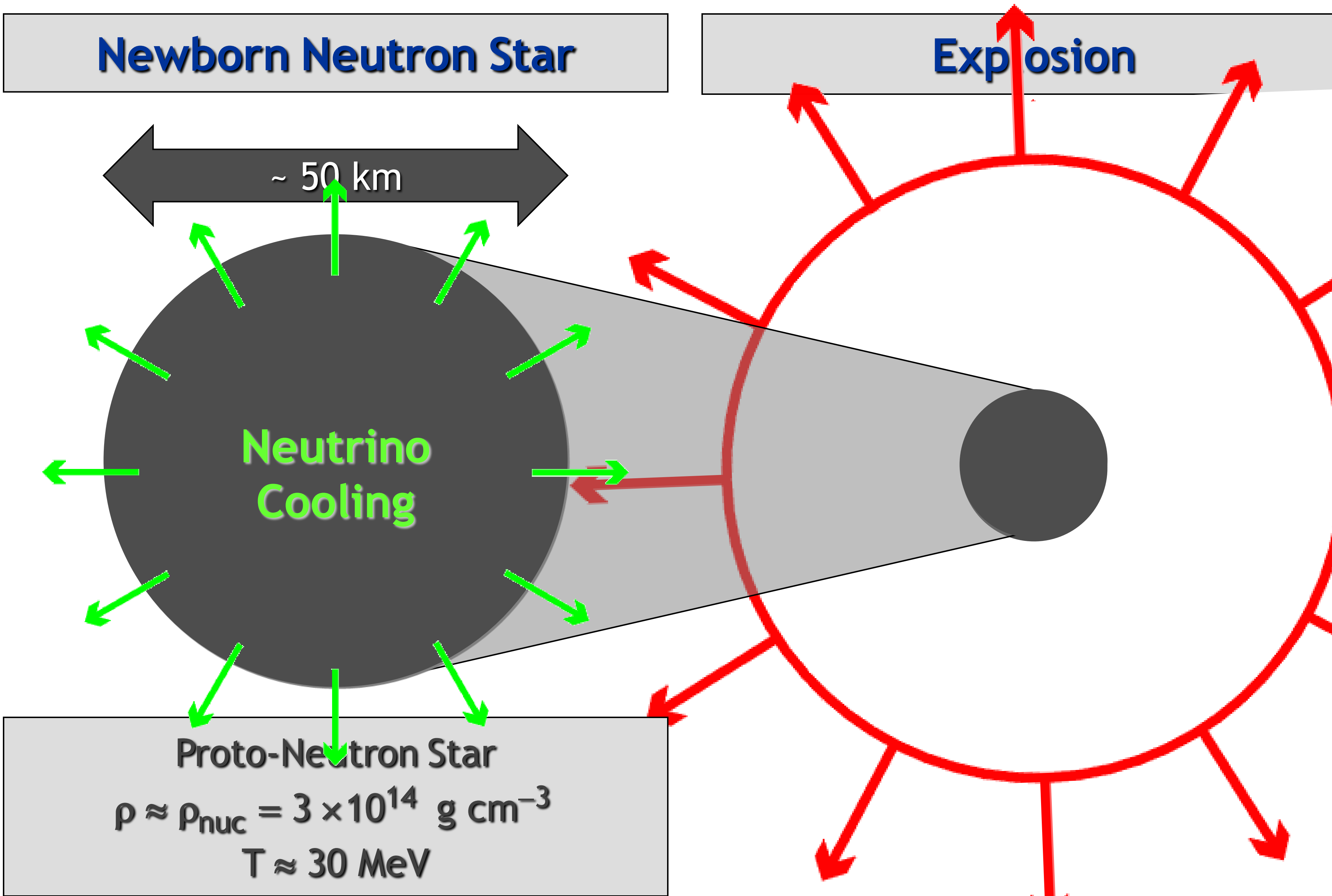
$T \approx 10^{10}$ K

$M_{Fe} \approx 1.5\ M_{sun}$

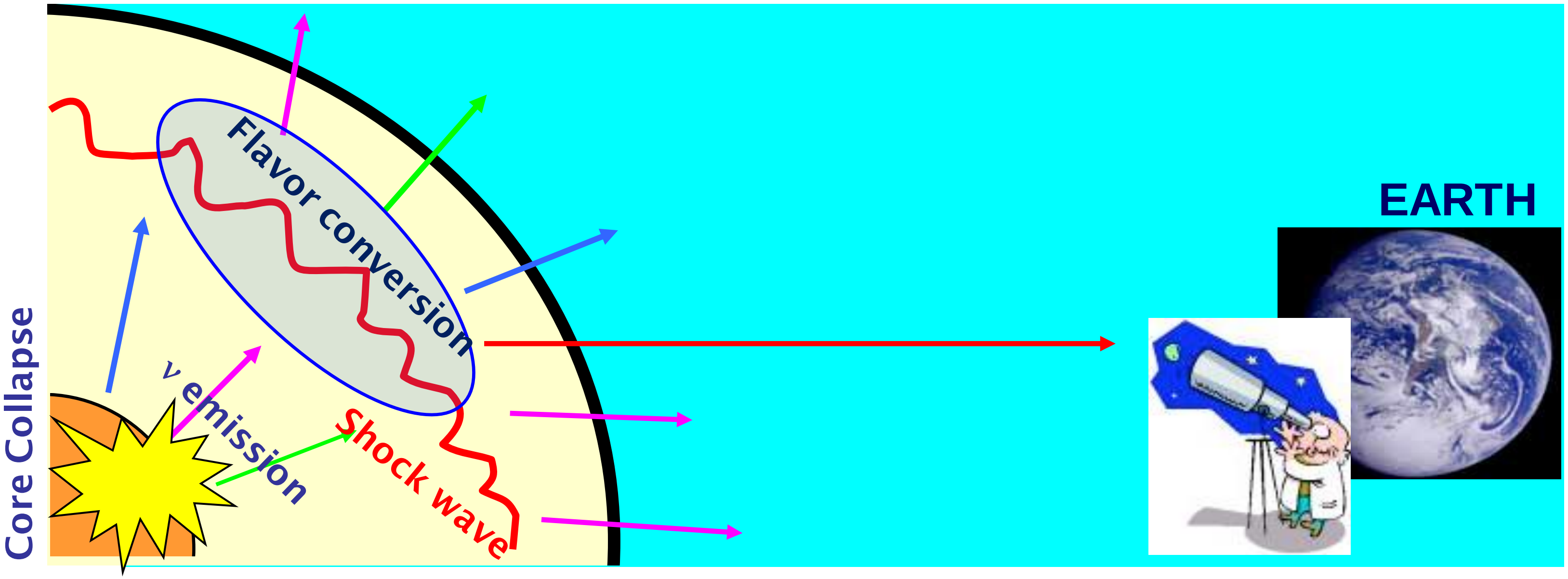
$R_{Fe} \approx 8000$ km

[slides from G. Raffelt]

Stellar Collapse and Supernova Explosion



TYPICAL PROBLEMS IN SUPERNOVA NEUTRINOS



Production (flavor)

Propagation (mass,mixing)

Detection (flavor)

$$\left| \langle \psi_i \right| \int \exp(-iHt) \left| \psi_f \rangle \right|$$

- Simulations of SN explosion
- Initial energy spectra
- Initial time spectra

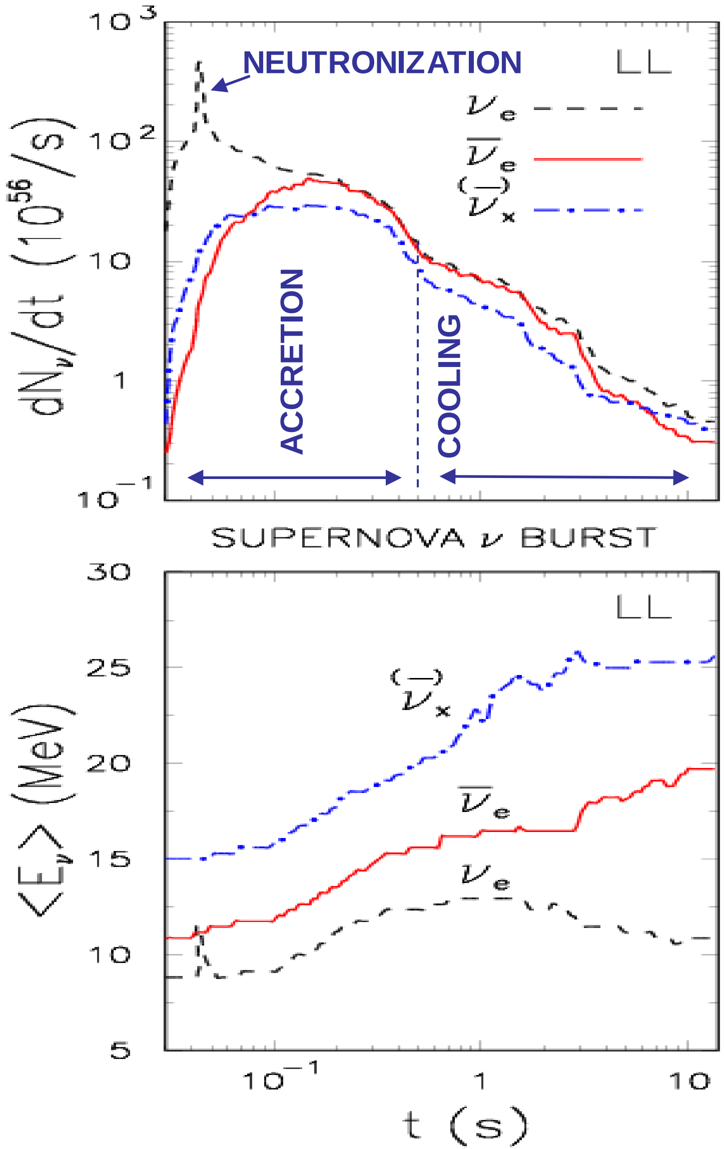
- Matter effects: shock wave,turbulences, Earth crossing, …
- Dense neutrino bkg
- New interactions
- Decays
- ………

- CC & NC interactions
- Different detectors
- Energy spectra
- Angular spectra
- Time spectra

Theory

Phenomenology

Neutrino fluxes (in time)

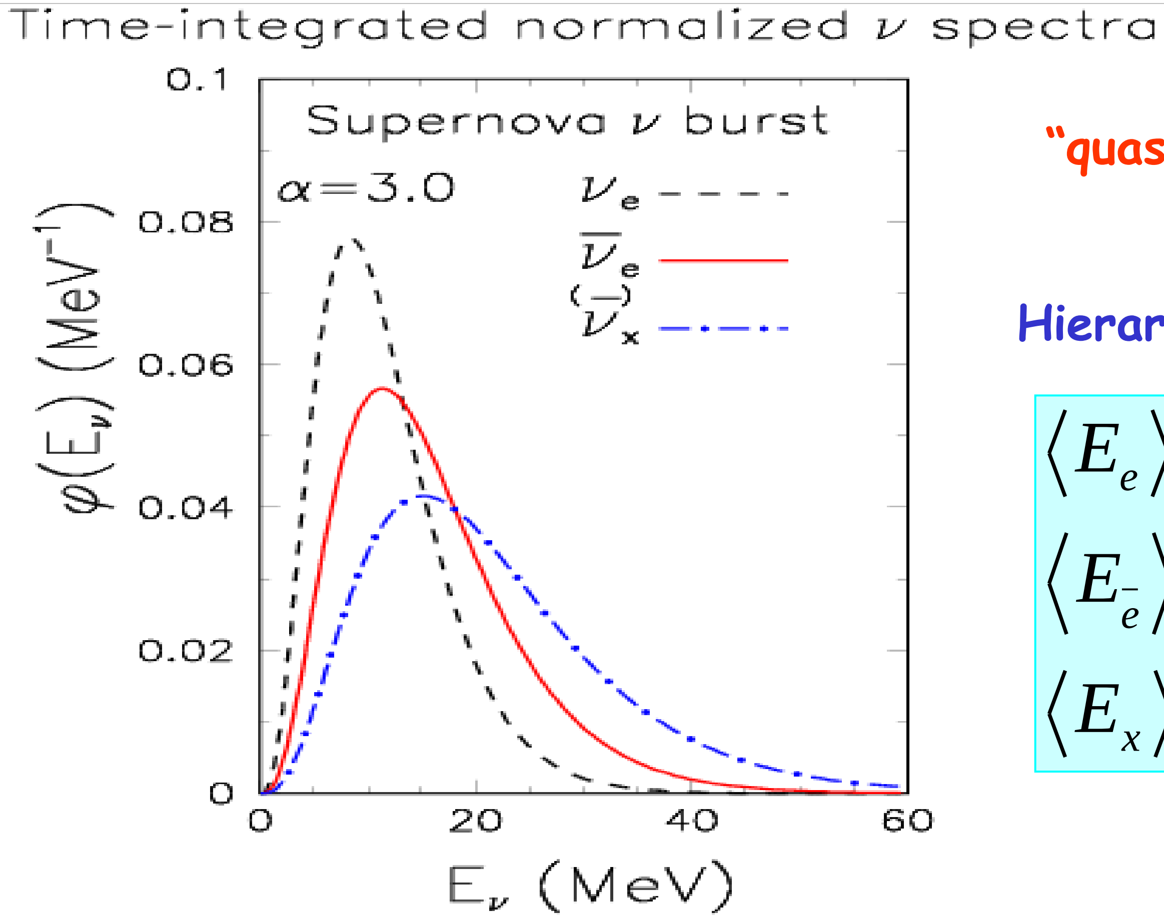


Results of neutrino emission based on the numerical simulations of SN explosion. [see, e.g., T. Totani, K.Sato, H.E. Dalhed, and J.R. Wilson, Astrophys. J. **496**, 216 (1998)].

- **NEUTRONIZATION BURST**: ν_e
  - Duration: ~ 25 ms after the explosion
  - Emitted energy : E~ 10^{51} erg

    (1/100 of total energy)
- **THERMAL BURST (ACCRETION + COOLING)**: ν_e , $\bar{\nu}_e$, ν_x , $\bar{\nu}_x$
  - Accretion: ~ 0.5 s
  - Cooling: ~ 10 s
  - Emitted energy: E~ 10^{53} erg

Neutrino spectra (in energy)



"quasi-thermal" spectra

Hierarchy of the spectra

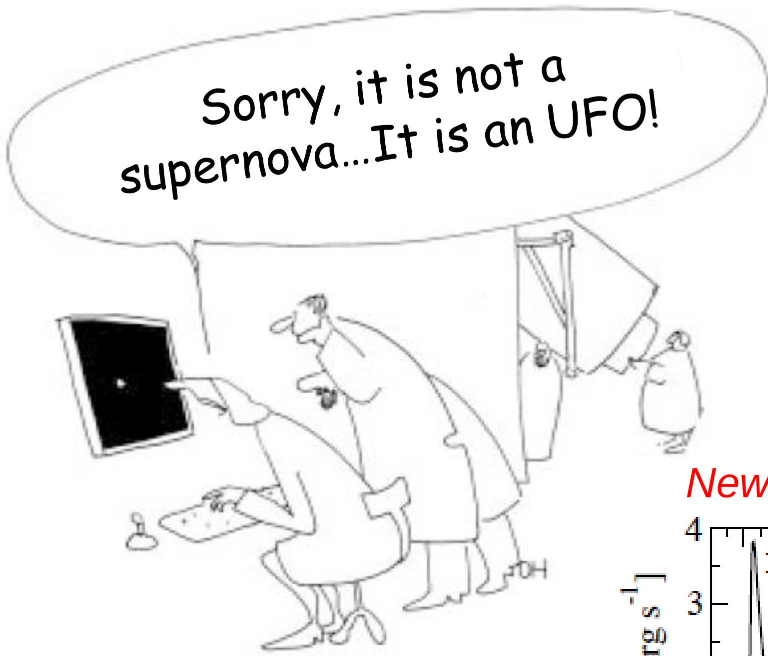
$$\langle E_e \rangle \approx 9-12 \text{ MeV}$$

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

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

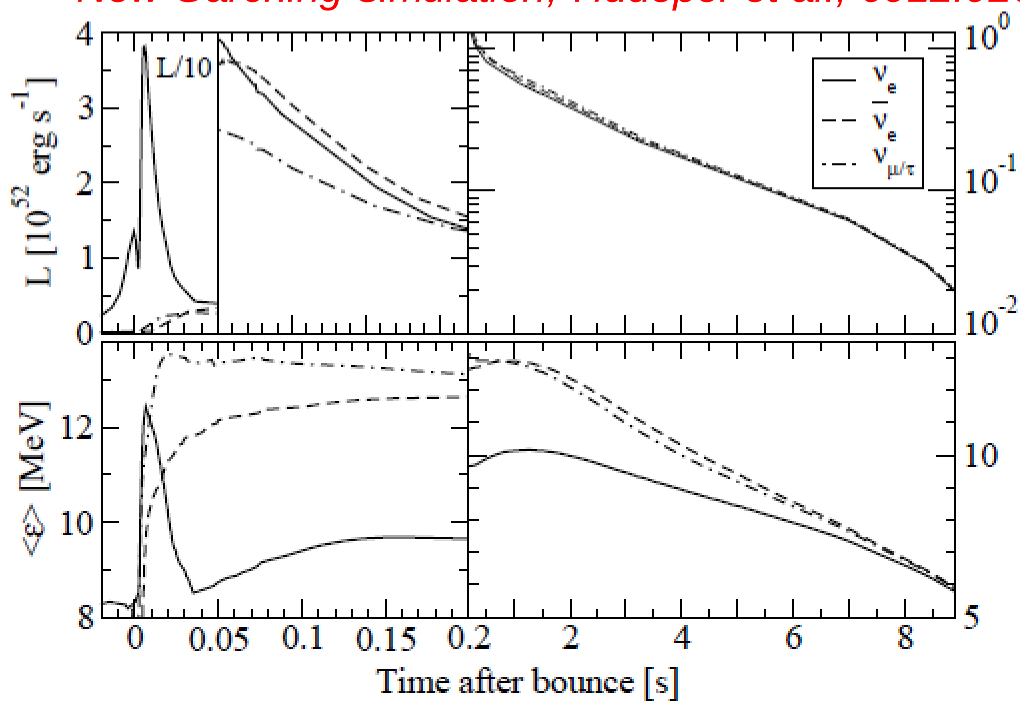
NEW LONG-TERM COOLING CALCULATIONS

[Talks by Cardall, Ott, Raffelt]



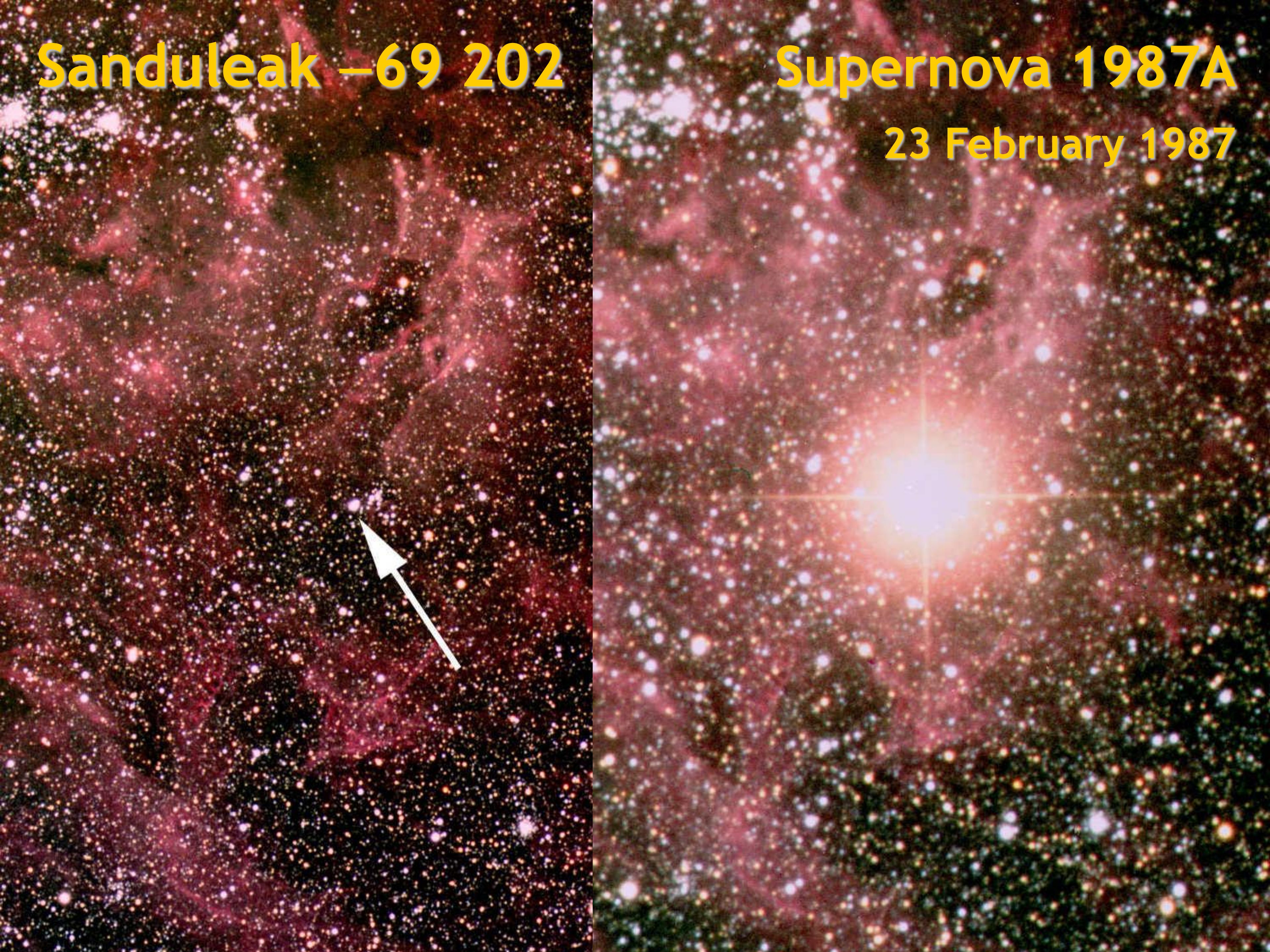
After many efforts ......

New Garching simulation, Hüdepol et al., 0912.0260

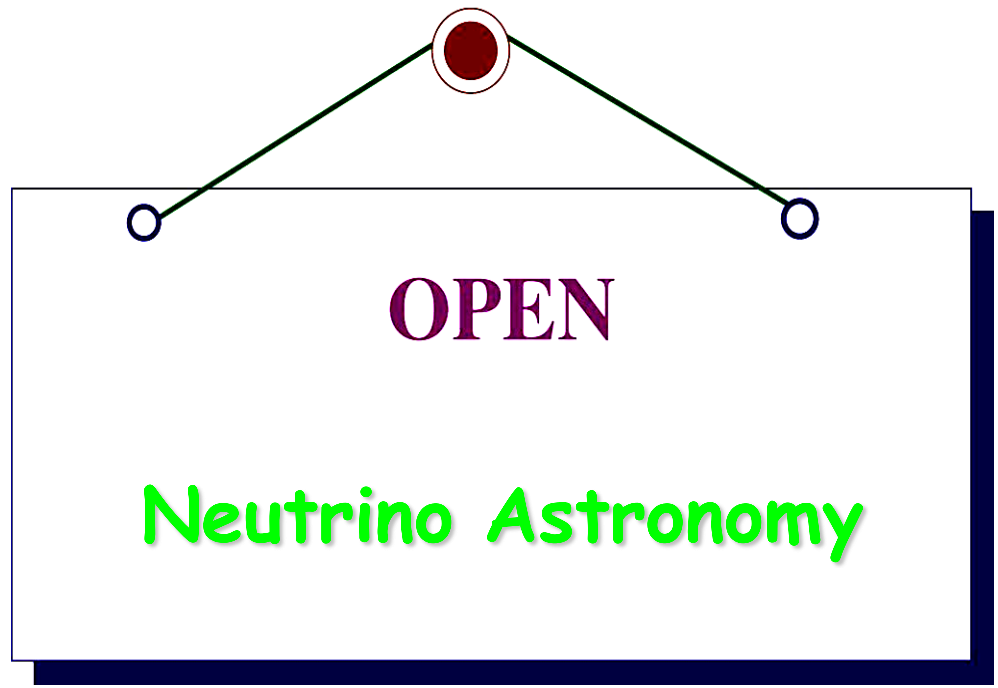


Low-mass (~ 8 $M_\odot$) SNe start to explode also in computer !!

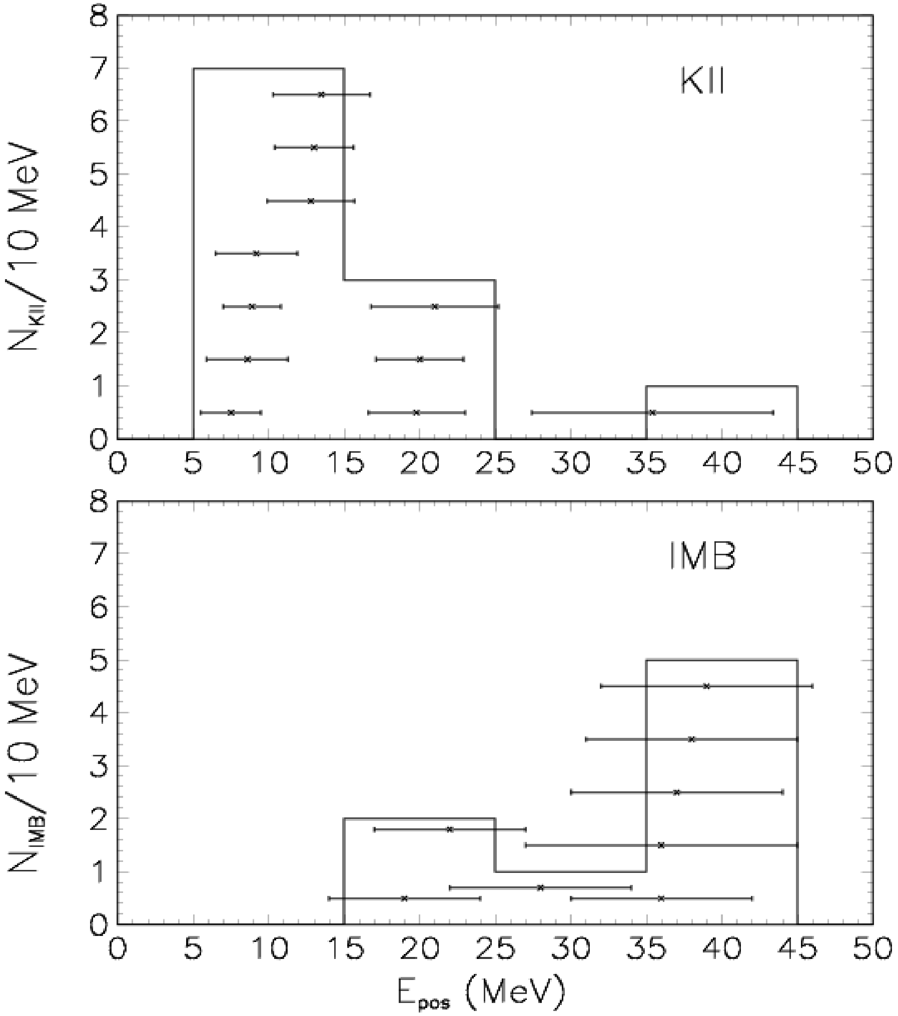
See also new Basel simulations, Fischer et al., 0908.1871


Sanduleak −69 202
Supernova 1987A
23 February 1987

Neutrino Burst Observation :
First verification of stellar evolution mechanism



Energy Distribution of SN 1987A Neutrinos

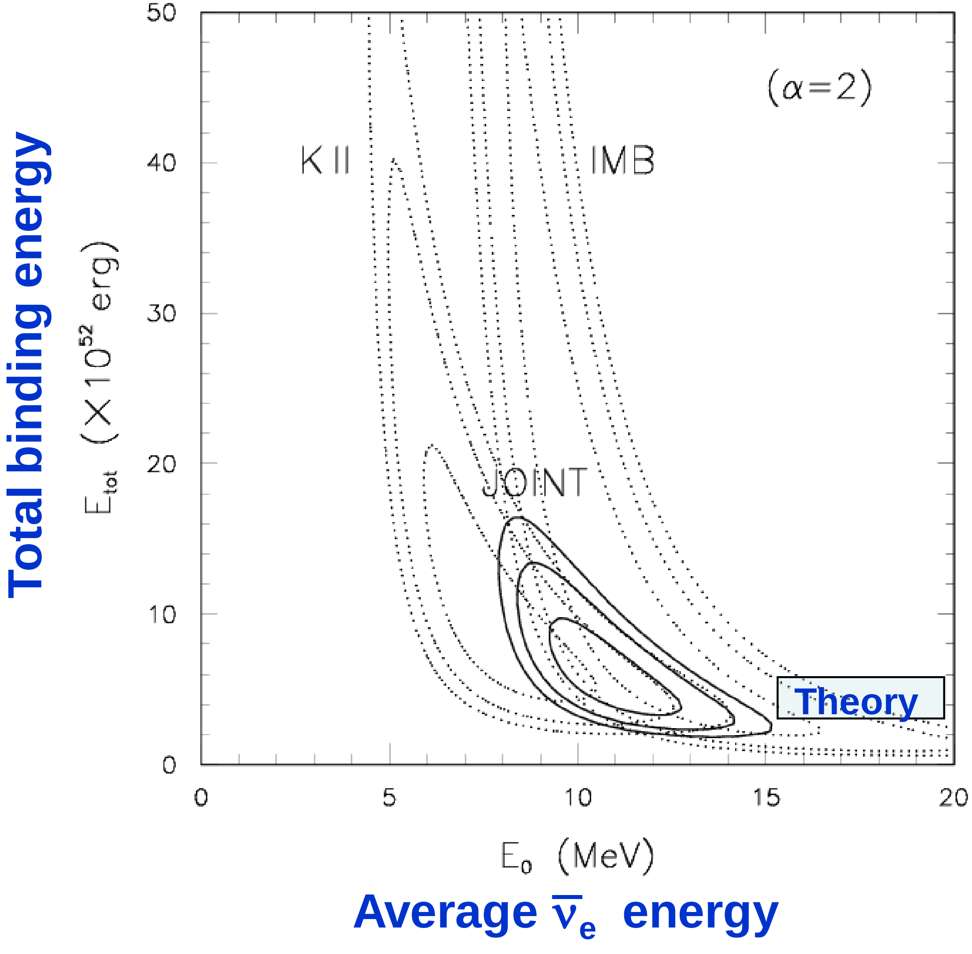


Kamiokande-II (Japan)
Water Cherenkov detector
2140 tons

Irvine-Michigan-Brookhaven (US)
Water Cherenkov detector
6800 tons

Interpreting SN1987A neutrinos

[e.g.,B. Jegerlehner, F. Neubig and G. Raffelt, PRD **54**, 1194 (1996); A.M., and G. Raffelt, PRD **72**, 063001 (2005)]

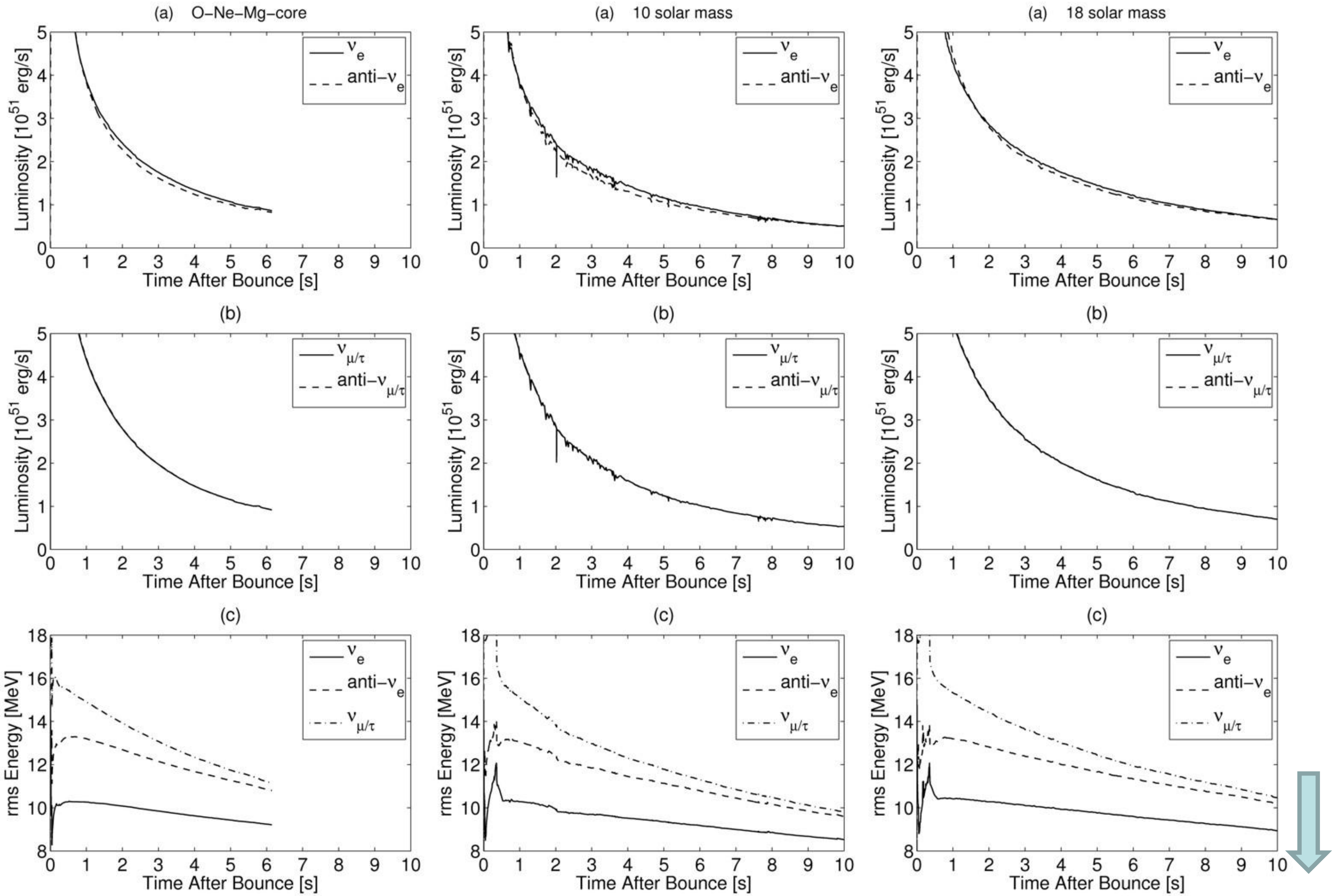


- Imposing thermal ν spectra, tension between the two experiments (marginal overlap between the two separate CL)
- Tension between the experiments and the theory.

But….

NEW LONG-TERM COOLING CALCULATION

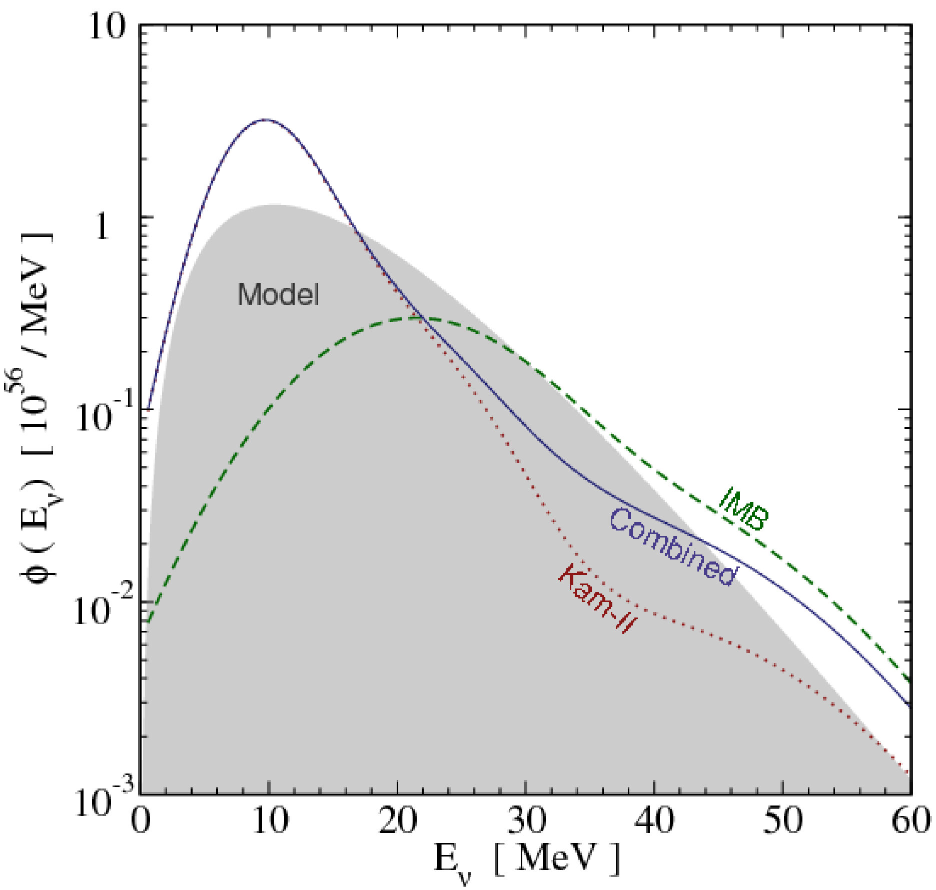
Lower ν average energies…In agreement with SN 1987A data



Fischer et al. (Basel group), arXiv: 0908.1871

SN NEUTRINO SPECTRUM FROM SN1987A

[Yuksel & Beacom, astro-ph/0702613]



Original SN ν energy spectra expected to be quasi-thermal

SN1987A inferred ν energy spectrum shows strong deviations from quasi-thermal distribution:

Possible effects of:

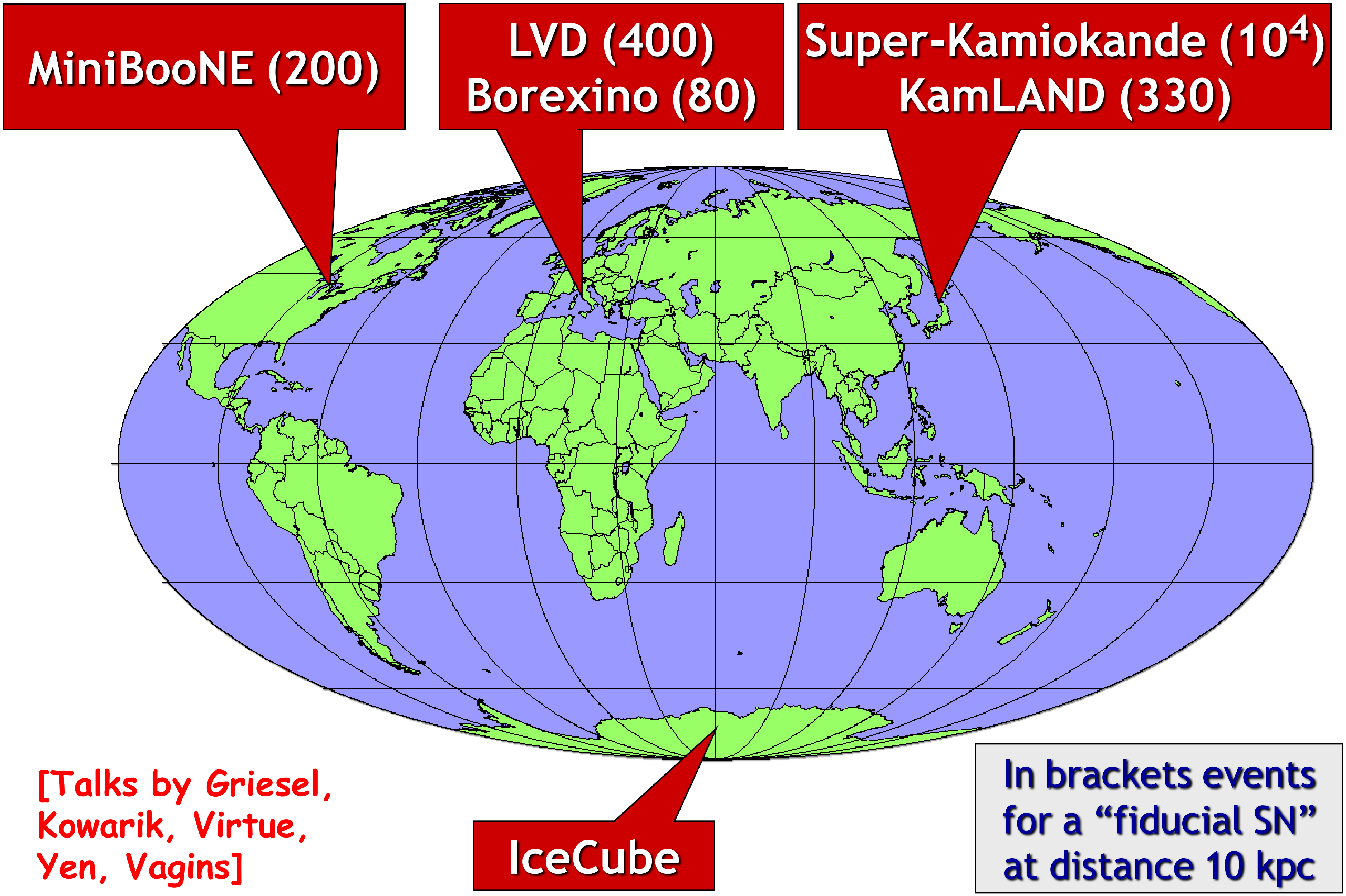
- neutrino mixing
- ν–ν interactions
- ν decay
- nonstandard ν interactions
- additional channels of energy exchange among flavors

?

Possible to reconcile detection and theory… Still many open questions!


What could we see “tomorrow”?
SN 20XXA !

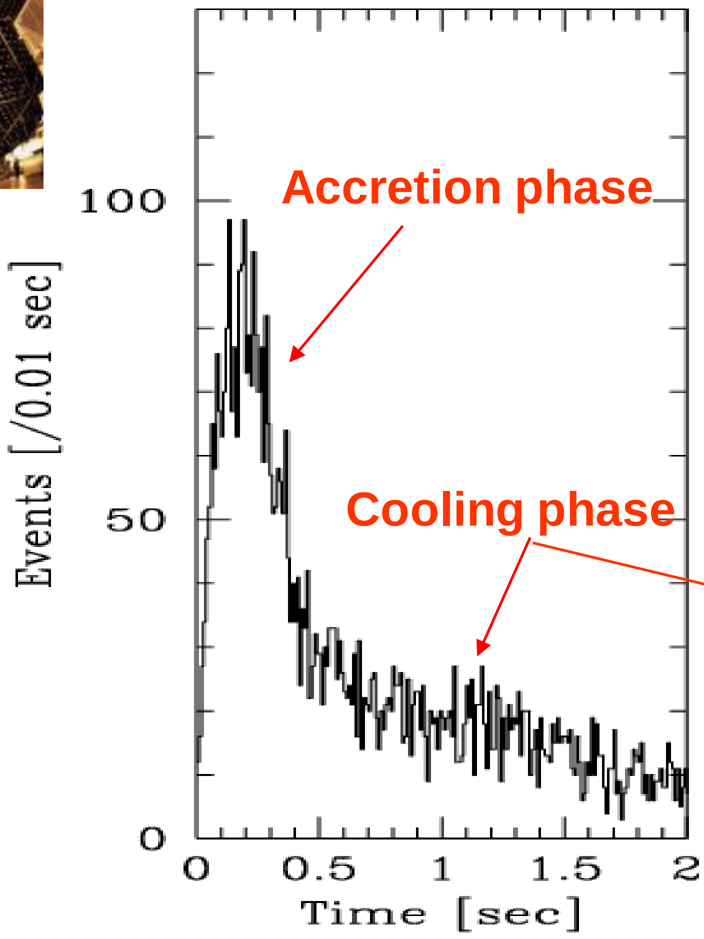
Large Detectors for Supernova Neutrinos

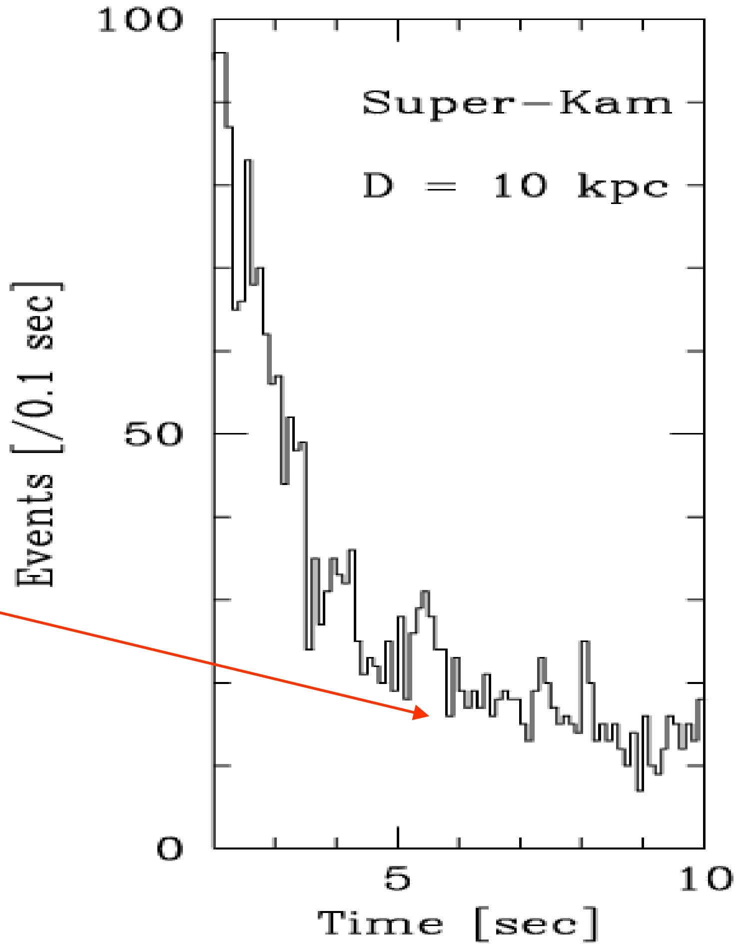


[Talks by Griesel, Kowarik, Virtue, Yen, Vagins]

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

Simulated Supernova Signal at Super-Kamiokande

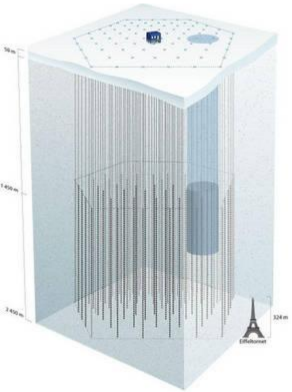


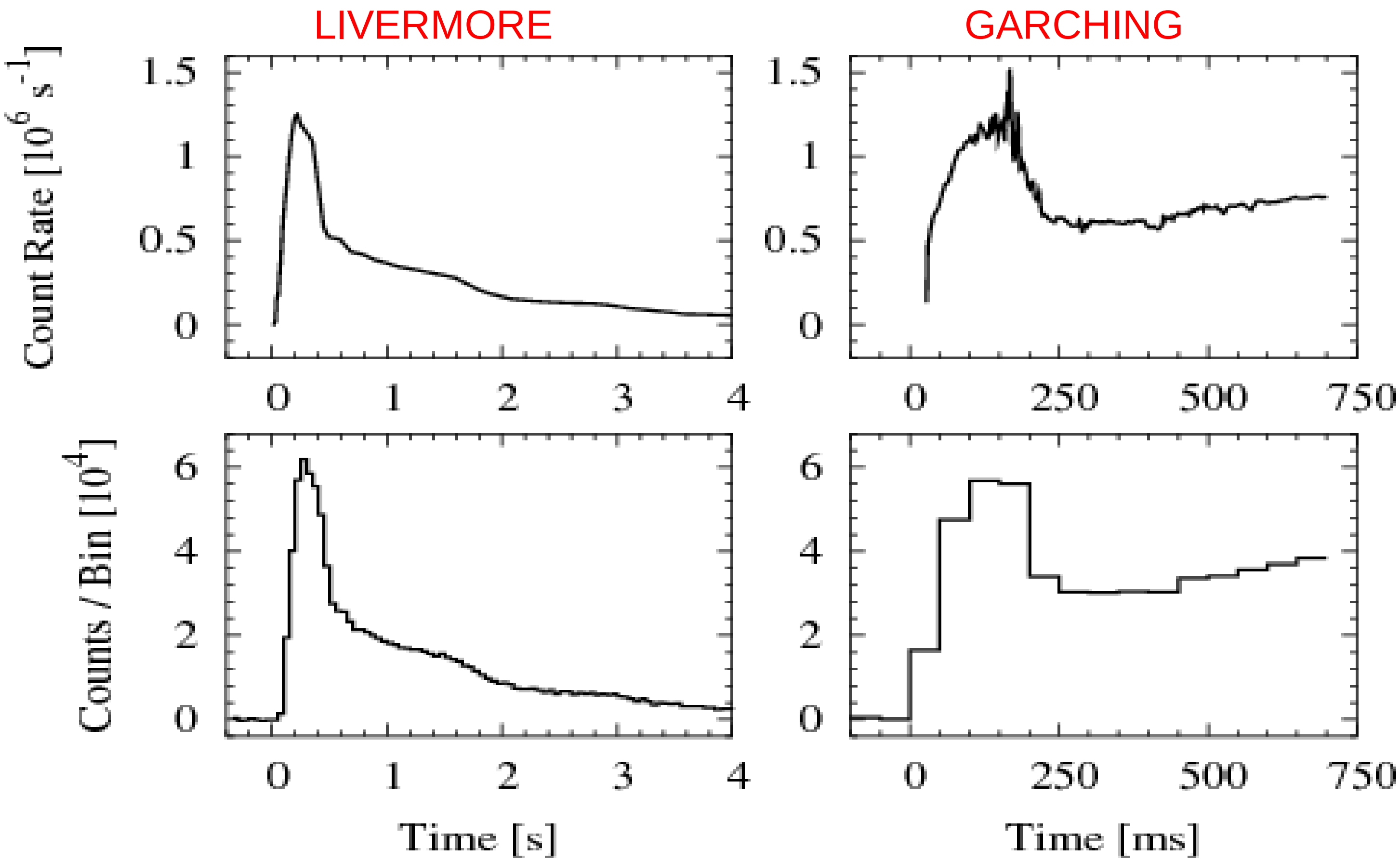


Simulation for Super-Kamiokande SN signal at 10 kpc,
based on a numerical Livermore model
[Totani, Sato, Dalhed & Wilson, ApJ 496 (1998) 216]

Simulated Supernova Signal at Ice-Cube

[Dighe, Keil and Raffelt, hep-ph/0303210]

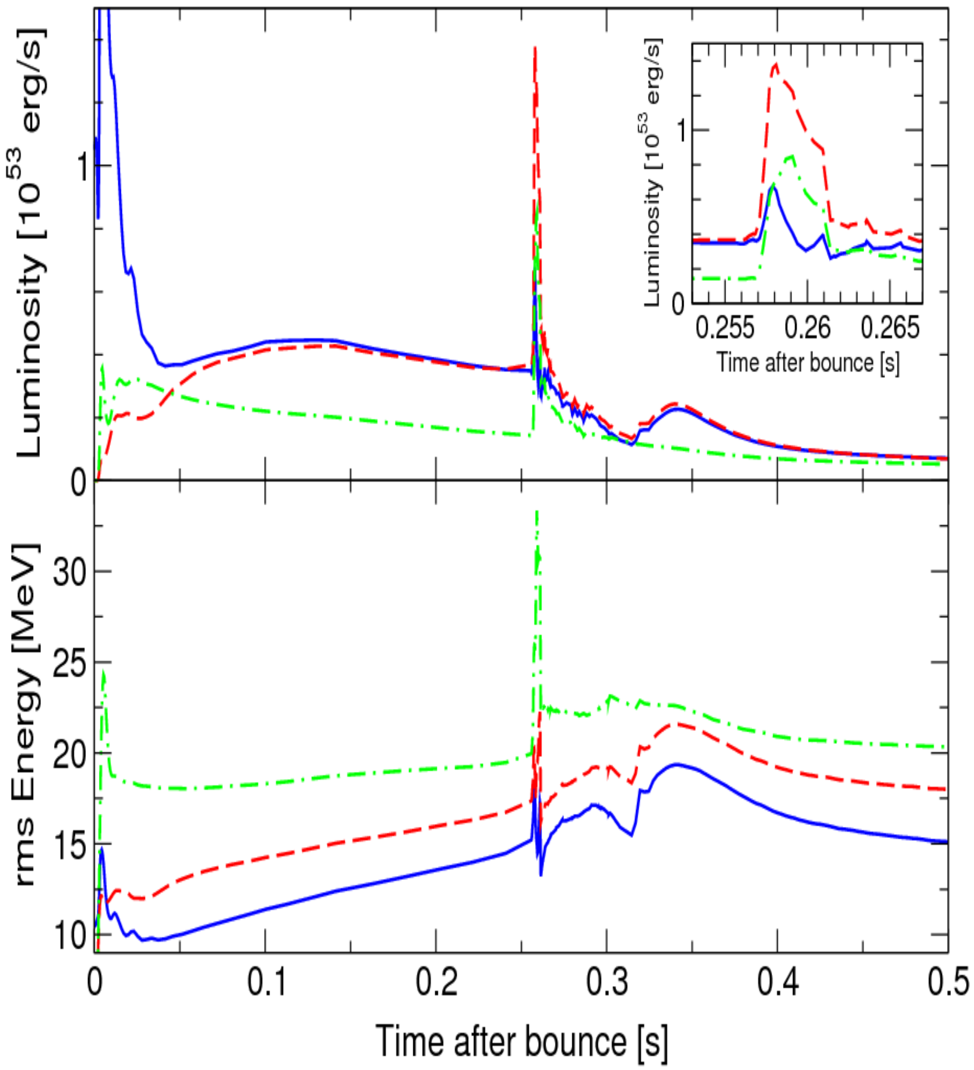




Possible to reconstruct the SN ν lightcurve with current detectors. Discrimination btw different simulations.

SIGNALS OF QCD PHASE TRANSITION IN SN ν

[Sagert et al., arXiv:0809.4225, Dasgupta et al. 0912.2568]



If QCD phase transition happens in a SN $\rightarrow$ second peak in the neutrino signal.

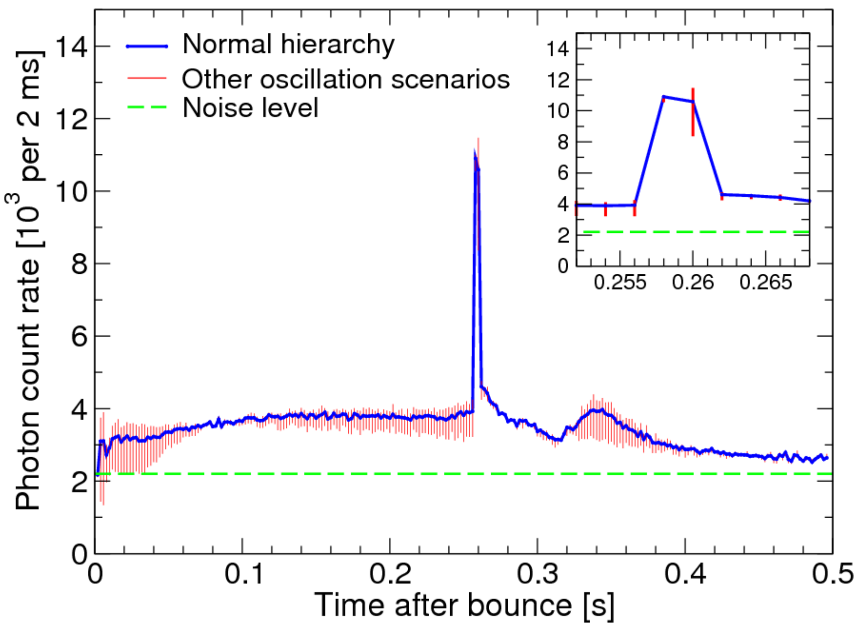
In contrast to the first neutronization burst, second neutrino burst dominated by the emission of anti-neutrinos

SN ν DETECTORS AS QCD EXPERIMENTS

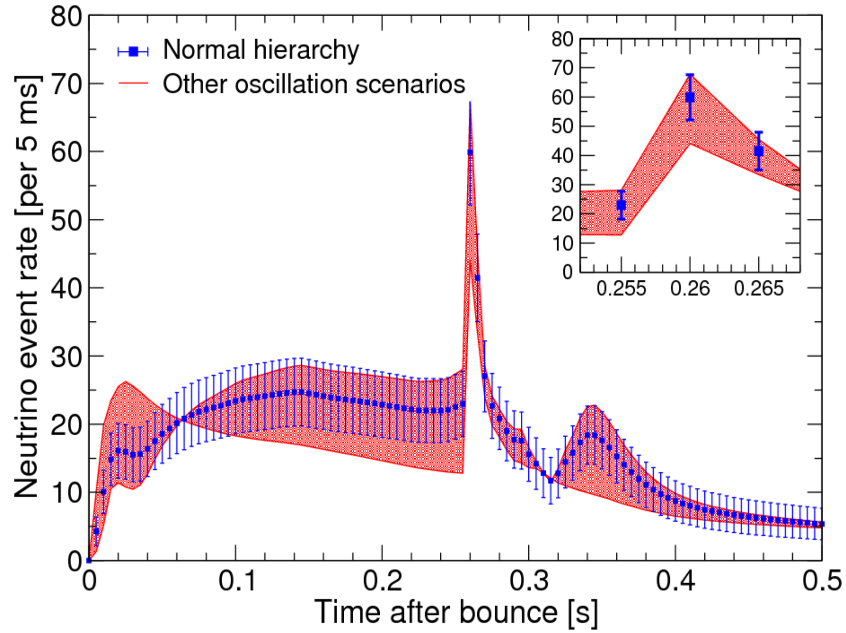
[*Dasgupta et al, arXiv:0912.2568*]

[Talk by Dasgupta]

ICE-CUBE



SUPER-KAMIOKANDE



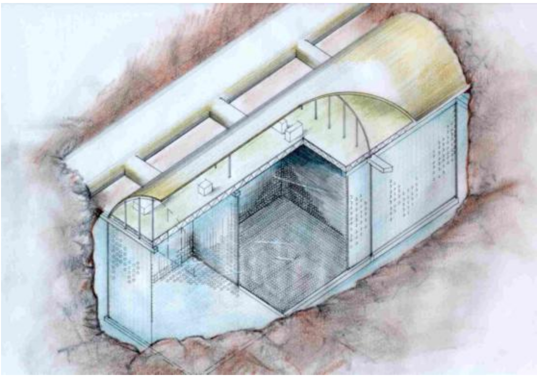
While the standard ν_e neutronization burst is difficult to detect with current detectors, the QCD-induced $\overline{\nu}_e$ peak would be successfully tracked by IBD reactions.

Next generation Detectors for Supernova Neutrinos

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

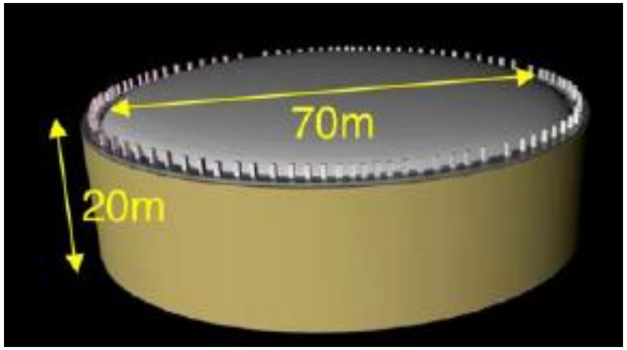
- **0.4 Mton WATER Cherenkov detectors**
- **100 kton Liquid Ar TPC**
- **50 kton scintillator**

Mton Cherenkov



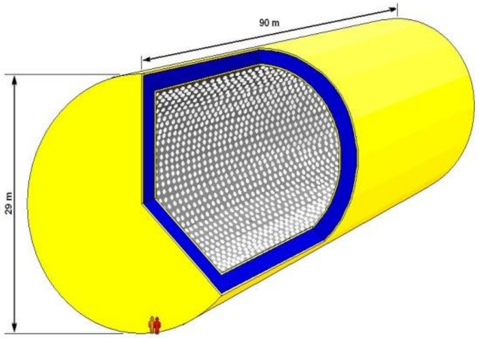
UNO, MEMPHYS, HYPER-K

LAr TPC



GLACIER

Scintillator

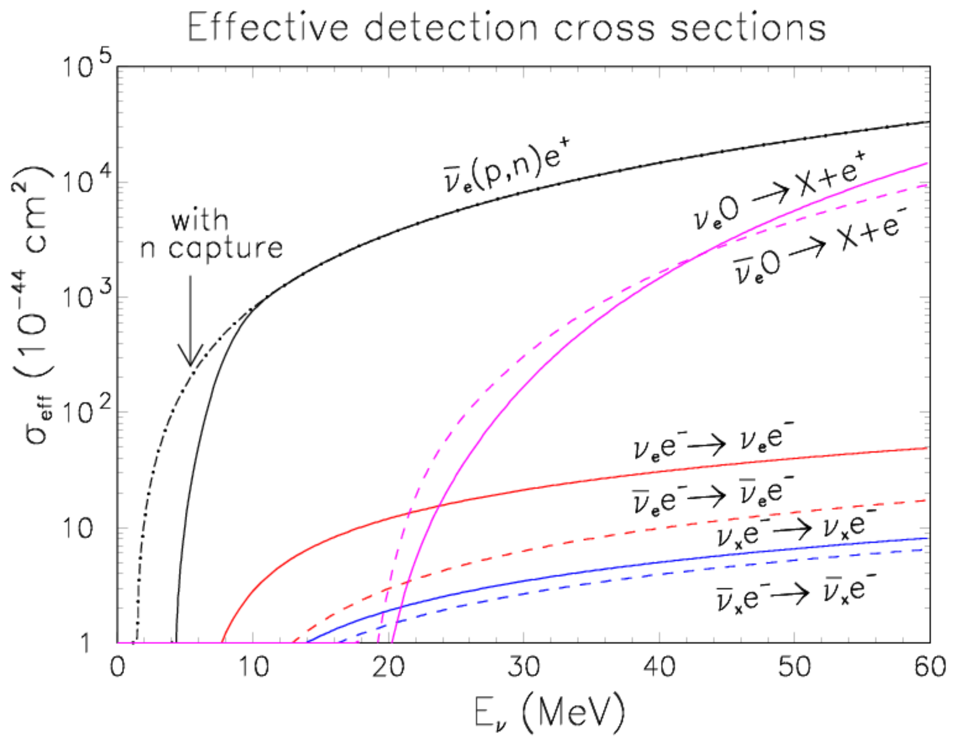


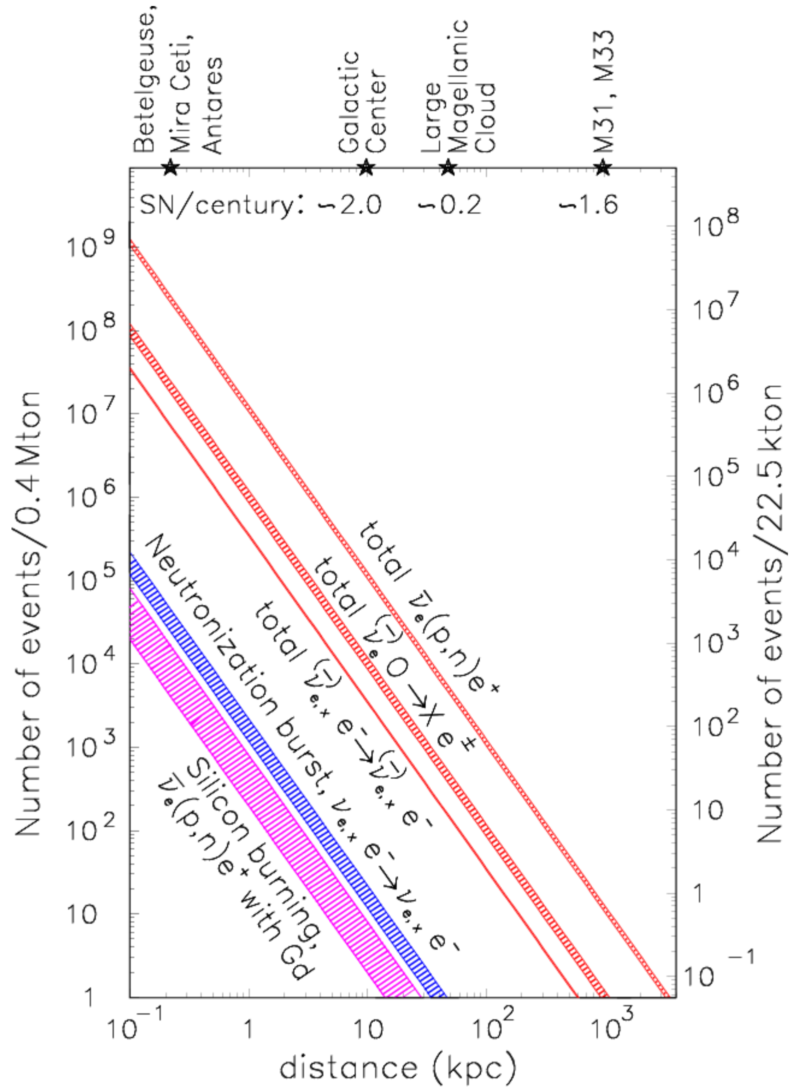
LENA

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

0.4 Mton Water Cherenkov detector

[Fogli, Lisi, A.M., Montanino, hep-ph/0412046**]**

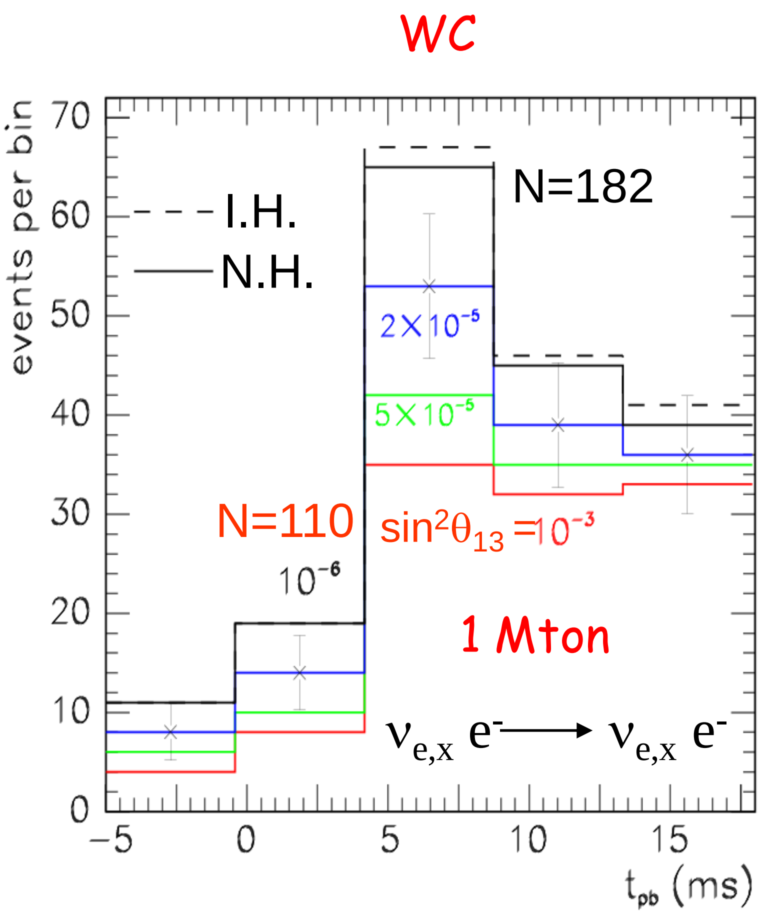




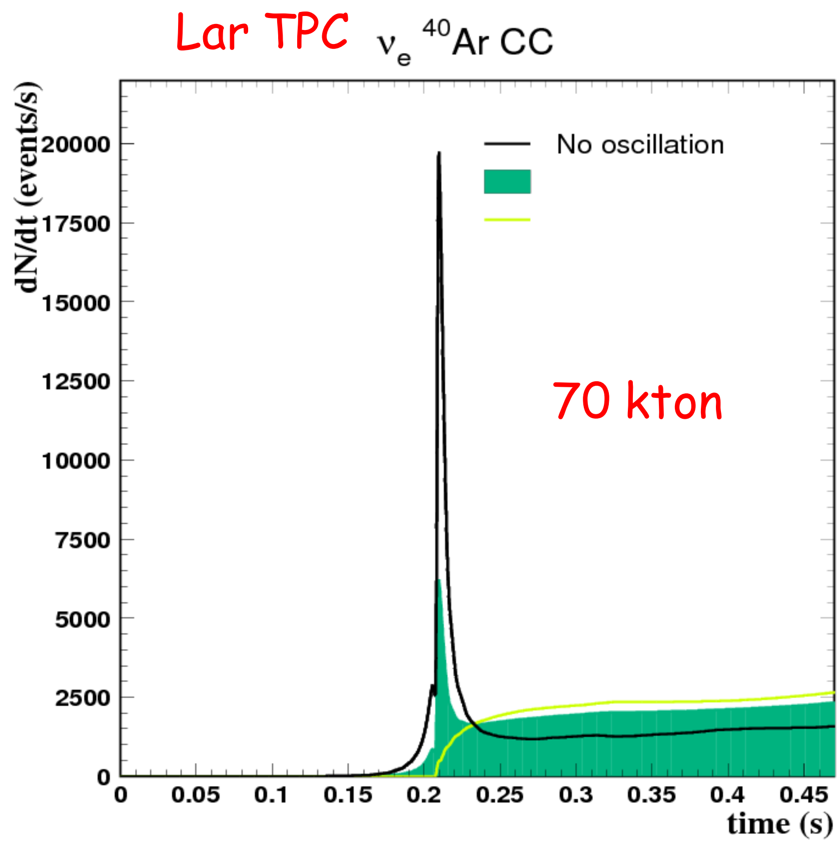
Golden channel: Inverse beta decay (IBD) of $\overline{\nu}_e$

~2.5×10^5 events @ 10 kpc

NEUTRONIZATION BURST



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



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

- Robust feature of SN simulations
- Possibility to probe oscillation physics during early stages of a SN
- SN distance measurement (with a precision of ~5 %): $N \sim 1/d^2$. Useful in case of dust oscuration.

Next-generation detectors would assure a high-statistics measurement of galactic SN neutrinos.

This would allow spectral studies

- **in time**
- **in energy**
- **in different interaction channels**

We will mainly focus on the possibility to detect signatures in the ν signal for a typical galactic SN explosion associated to

SN NEUTRINO OSCILLATIONS

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)**

VACUUM OSCILLATIONS

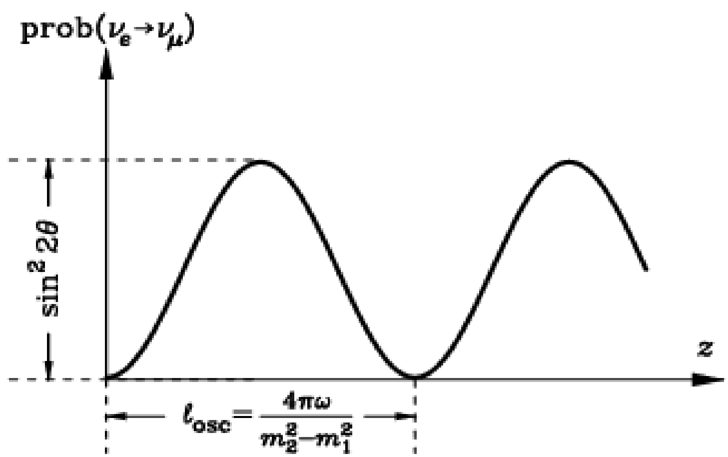
- **Two flavor mixing**

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

Each mass eigenstates propagates as $\mathbf{e^{ipz}}$ with $p_i = \sqrt{E^2 - m^2} \approx E - \frac{m_i^2}{2E}$

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

- **2 ν oscillation probability** $P(\nu_e \to \nu_\mu) = \left|\langle \nu_\mu(z)|\nu_e(0)\rangle\right|^2 = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$



Bruno Pontecorvo (1967)

Dubna 1988. Neutrino oscillations.

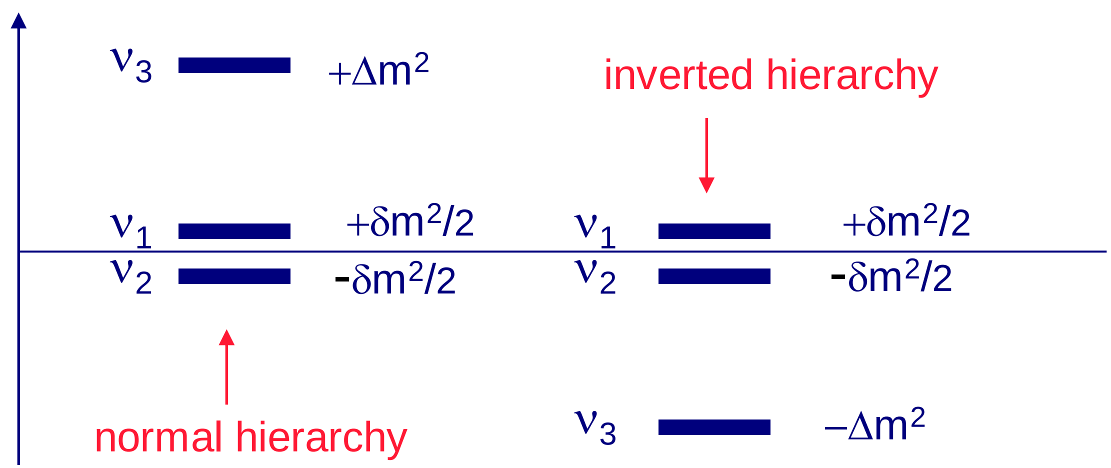
3ν FRAMEWORK

- **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:** $M^2 = \left[\underbrace{-\frac{\delta m^2}{2}, +\frac{\delta m^2}{2}}_{\text{"solar"}}, \underbrace{\pm \Delta m^2}_{\text{"atmospheric"}} \right]$



GLOBAL OSCILLATION ANALYSIS (2008)

[Fogli et al., arXiv:0805.2517]

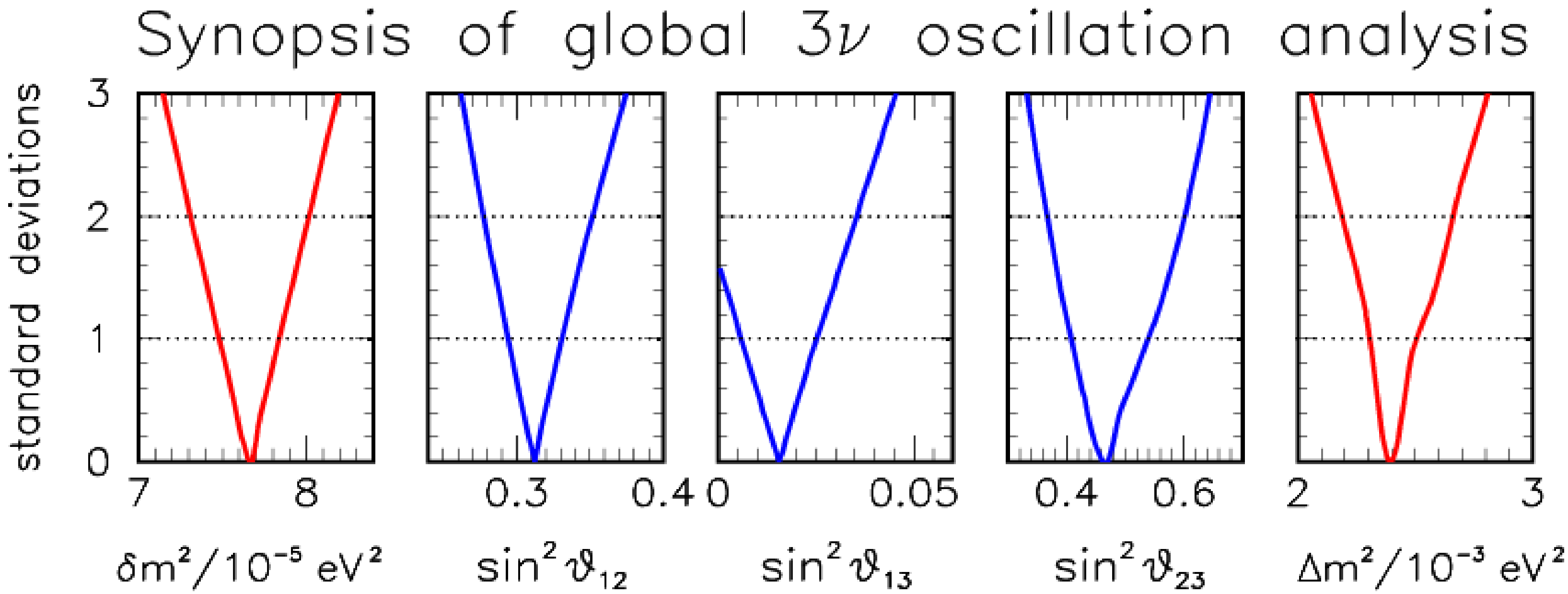


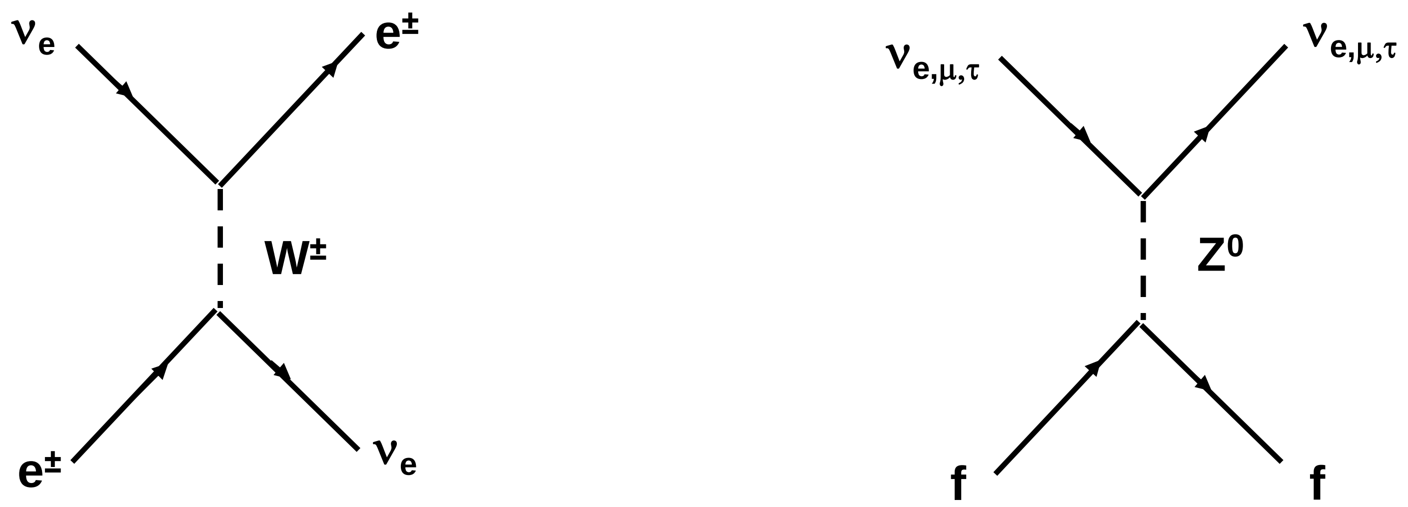
TABLE I: Global 3ν oscillation analysis (2008): best-fit values and allowed n_σ ranges for the mass-mixing parameters.

Parameter	$\delta m^2/10^{-5}$ eV^2	$\sin^2\theta_{12}$	$\sin^2\theta_{13}$	$\sin^2\theta_{23}$	$\Delta m^2/10^{-3}$ eV^2
Best fit	7.67	0.312	0.016	0.466	2.39
1σ range	7.48 – 7.83	0.294 – 0.331	0.006 – 0.026	0.408 – 0.539	2.31 – 2.50
2σ range	7.31 – 8.01	0.278 – 0.352	< 0.036	0.366 – 0.602	2.19 – 2.66
3σ range	7.14 – 8.19	0.263 – 0.375	< 0.046	0.331 – 0.644	2.06 – 2.81

MIKHEYEV-SMIRNOV-WOLFENSTEIN (MSW) EFFECT

[Wolfenstein, PRD 17, 2369 (1978)]

When neutrinos propagate in a medium they will experience a shift of their energy, similar to photon refraction, due to their coherent interaction with the medium constituents



Charged current **Neutral current**

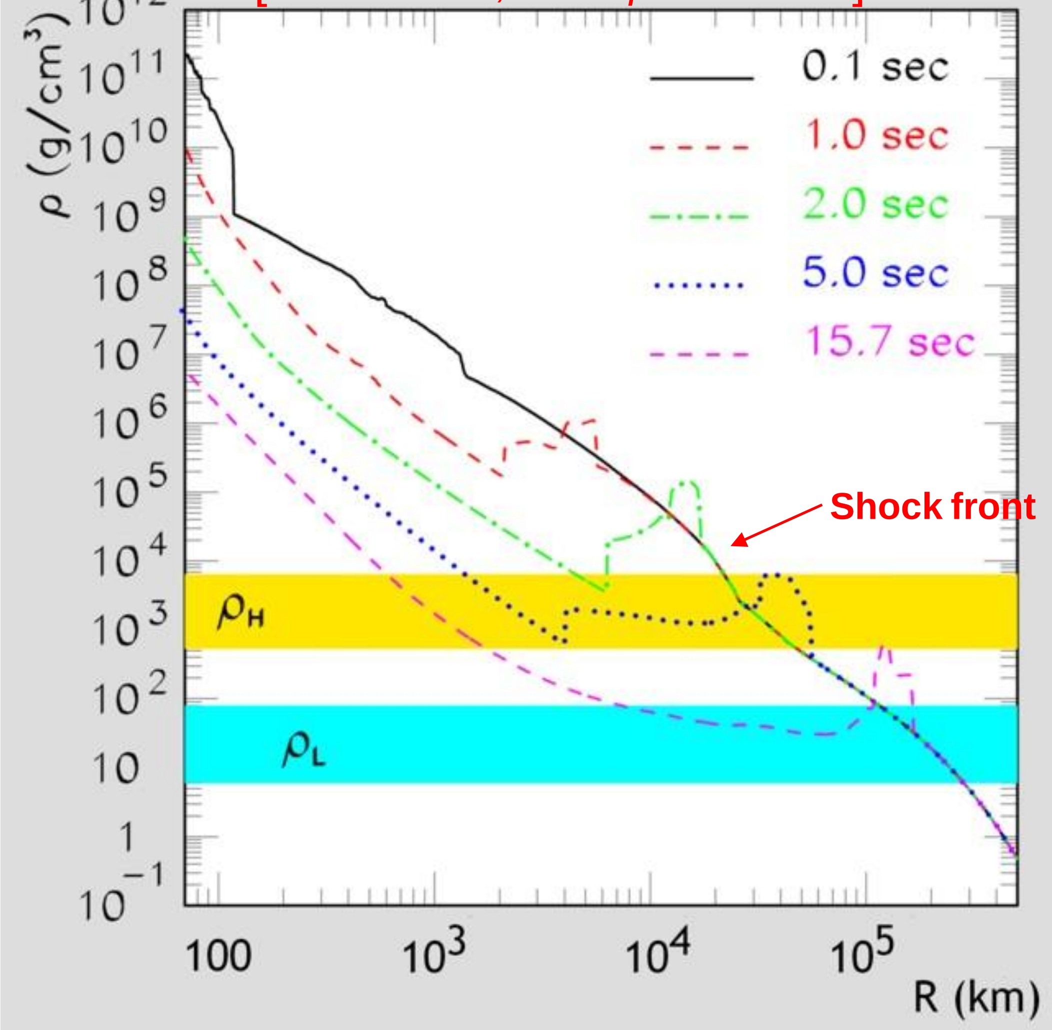
The difference of the interaction energy of different flavors gives an effective potential for electron (anti)neutrinos

$$V(x) = \sqrt{2} G_F N_e$$

net electron density

MSW MATTER EFFECT IN SN

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



A few second after the core bounce, shock wave(s) can induce time-dependent matter effects in neutrino oscillations

[R.Schirato, and G. Fuller, astro-ph/0205390**]**

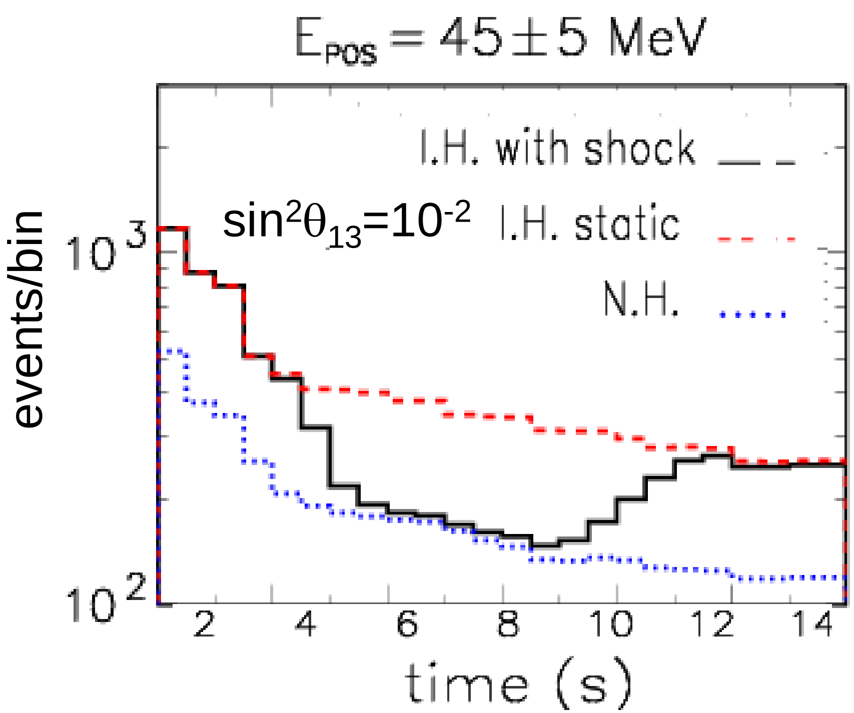
Neutrino oscillations as a "camera" for shock-wave propagation

[see, e.g., Fogli, Lisi, A.M., and Montanino, hep-ph/0304056; Fogli, Lisi, A.M., and Montanino, hep-ph/0412046, Tomas et al., astro-ph/0407132, Choubey et al, hep-ph/0605255 **]**

PROBING SHOCK WAVES AND MASS HIERARCHY AT LARGE θ_{13}

Time spectra of $\bar{\nu}_e(p,n)e^+$ 0.4 Mton Cherenkov

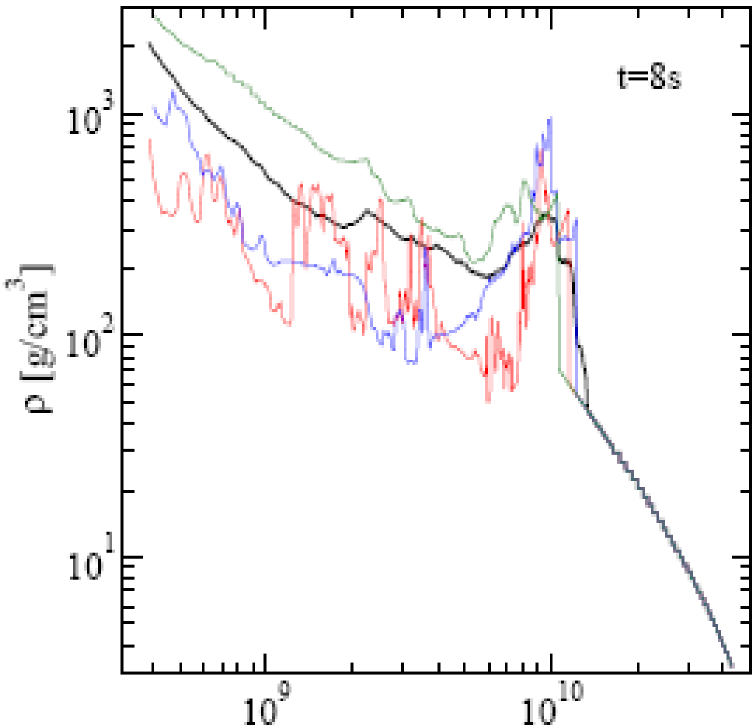
fwd shock



In inverted hierarchy and for θ_{13} not too small, flavor conversions along the shock-waves induce non-monotonic time spectra at "sufficiently high" energy.

[Fogli, Lisi, A.M., and Montanino, hep-ph/0412046]

STOCHASTIC DENSITY FLUCTUATIONS



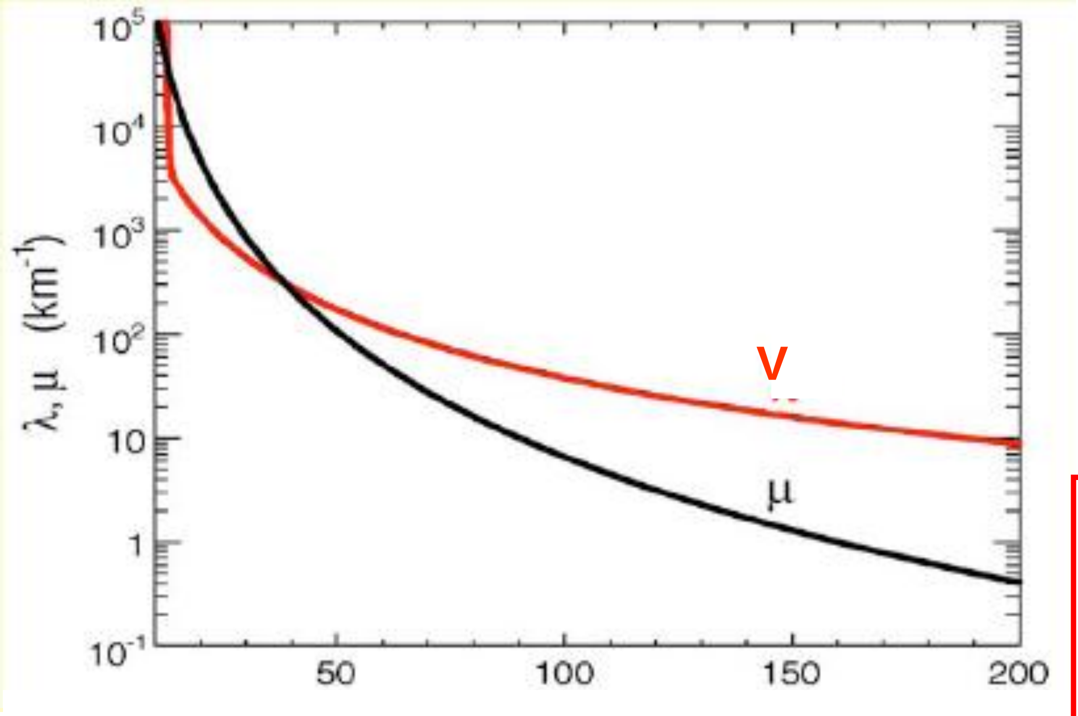
A SN neutrino "beam" might experience stochastic matter effects while traversing the stellar envelope.

SHADOW ON THE SHOCK-WAVE SIGNATURE

[Fogli, Lisi, A.M. , Montanino, hep-ph/0603033; Friedland, astro-ph/0607244; Choubey, Harries, Ross, hep-ph/0703092**]**

NEUTRINO-NEUTRINO INTERACTIONS

In the region just above the neutrino-sphere the neutrino density exceeds the ordinary electron background. Neutrinos themeselves form a background medium



Self-interaction effects studied for ~20 y in SN. But, recent boost of interest after new crucial results by Duan, Fuller, Carlson, Qian '05-'06

ν–ν NC interactions important!

- Matter bkg potential

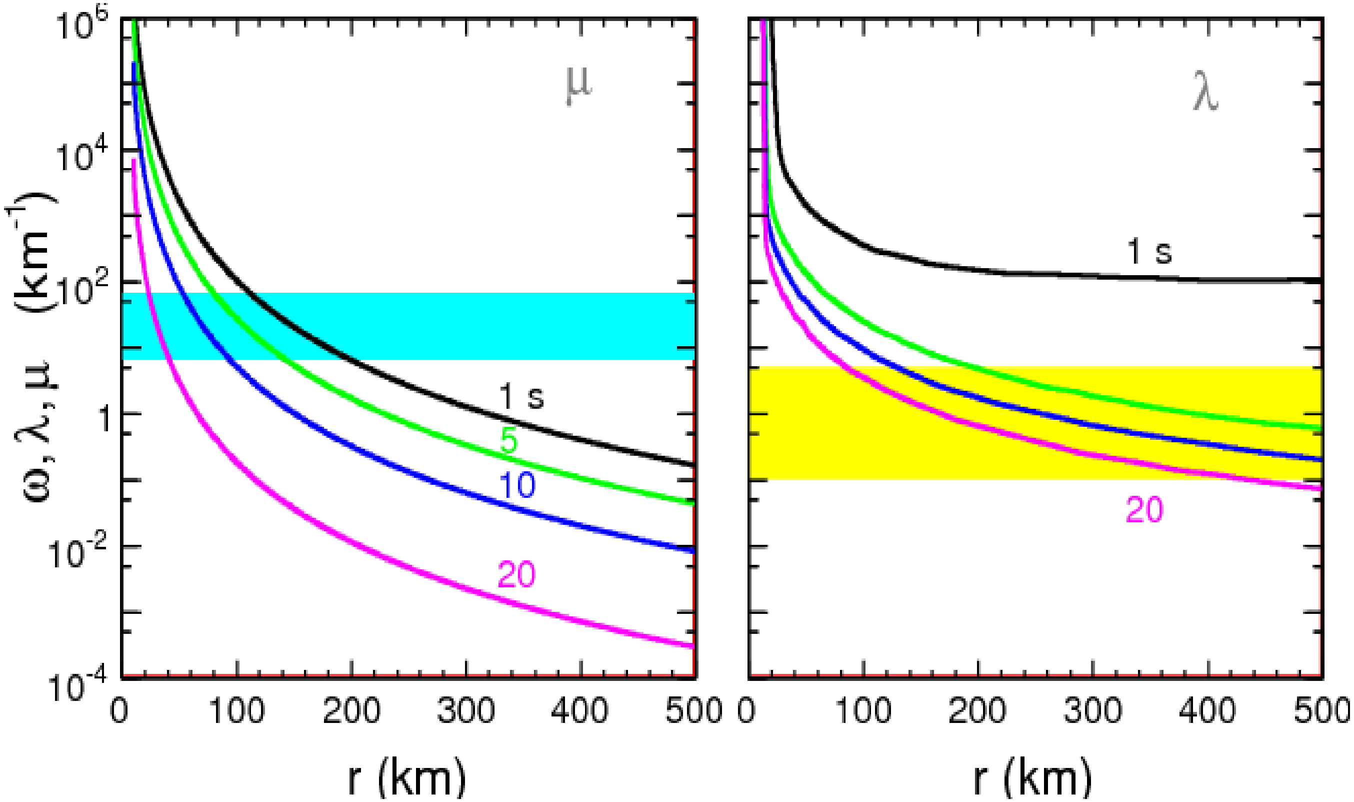
$$V = \sqrt{2} G_F N_e$$

- ν–ν potential

$$\mu = \sqrt{2} G_F n_\nu$$

Lesson: self-interactions (μ) can induce large, non-MSW flavor change at small radii, despite large matter density V

SN SELF-INTERACTION POTENTIAL AND MATTER POTENTIAL

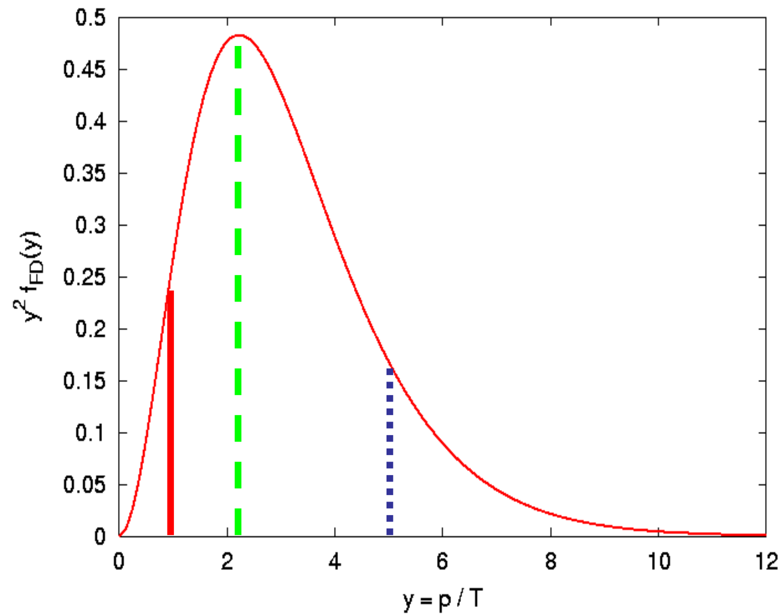


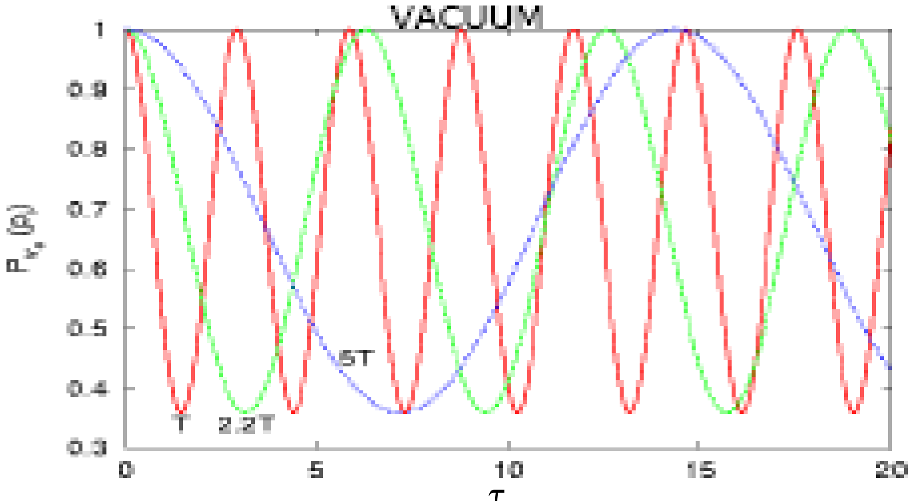
- $\mu \equiv \sqrt{2} G_F (N_\nu + N_{\bar{\nu}})$
- $\lambda \equiv \sqrt{2} G_F N_e$

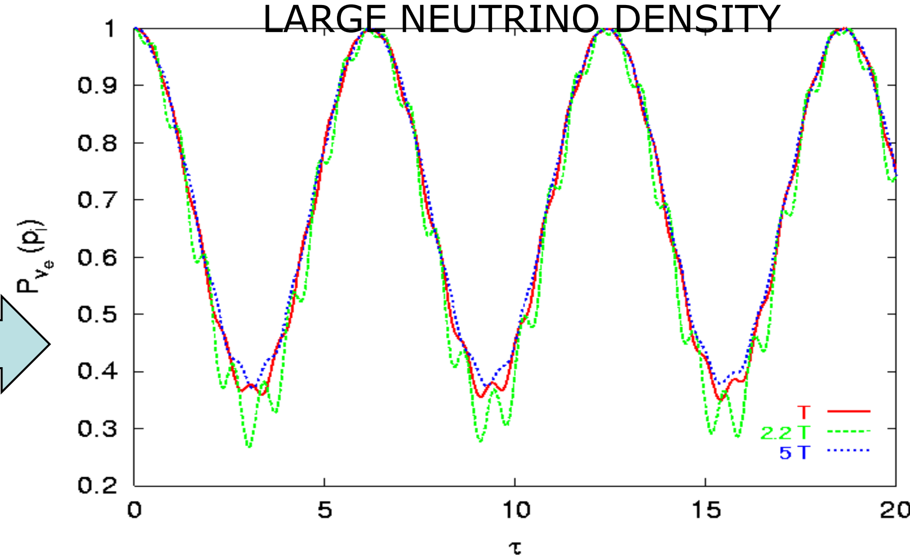
- **r < 200 km : Self-induced collective oscillations**
- **r > 200 km : Ordinary MSW effects**

SYNCHRONIZED OSCILLATIONS BY NEUTRINO-NEUTRINO INTERACTIONS

Example: evolution of neutrino momenta with a thermal distribution







If neutrino density dominates, **synchronized oscillations** with a characteristic common oscillation frequency

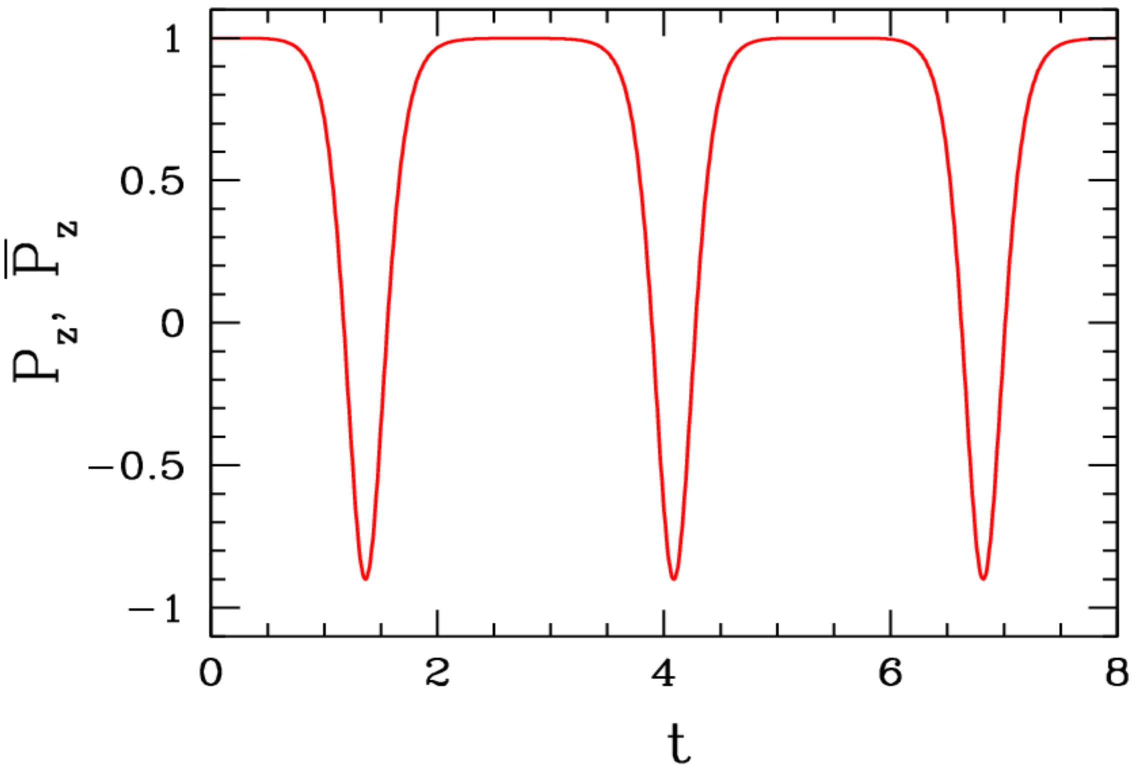
[Pastor, Raffelt, Semikoz, hep-ph/0109033]

PENDULAR OSCILLATIONS

[*Hannestad, Raffelt, Sigl, Wong, astro-ph/0608695*]

Equal densities of ν and $\bar{\nu}$

INVERTED HIERARCHY + small θ



In inverted hierarchy: coherent "pair conversion" $\nu_e \bar{\nu}_e \longrightarrow \nu_\mu \bar{\nu}_\mu$

With constant μ: periodic behaviour

PENDULUM IN FLAVOR SPACE

[*Hannestad, Raffelt, Sigl, Wong, astro-ph/0608695, Duan, Carlson, Fuller, Qian, astro-ph/0703776*]

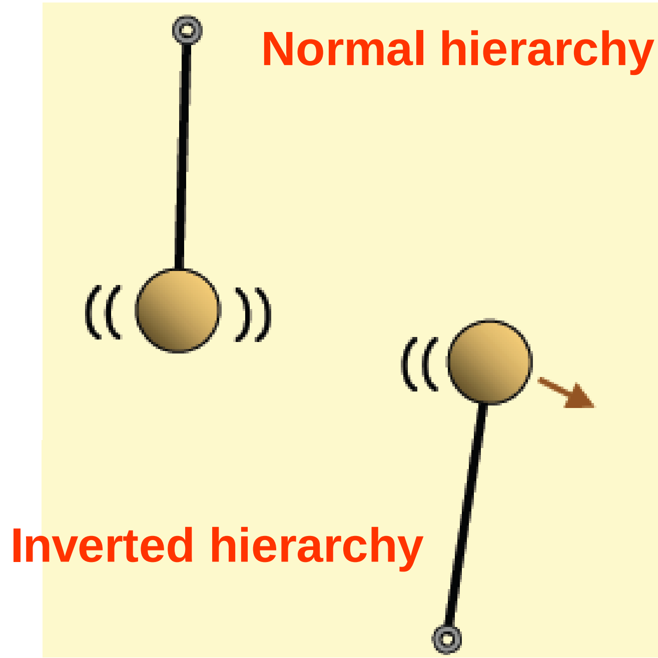
Neutrino mass hierarchy (and θ_{13}) set initial condition and fate

- **Normal hierarchy**

  Pendulum starts in ~ downard (stable) positions and stays nearby. No significant flavor change.

- **Inverted hierarchy**

  Pendulum starts in ~ upward (unstable) positions and eventually falls down. Significant flavor changes.

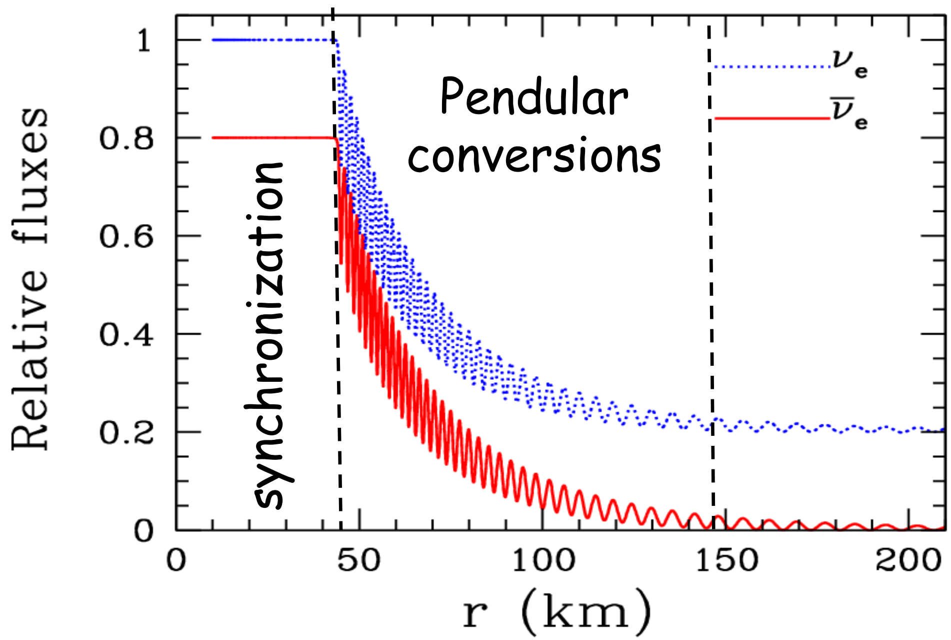


θ_{13} sets initial misalignment with vertical. Specific value not much relevant.

SUPERNOVA TOY-MODEL

[*Hannestad, Raffelt, Sigl, Wong, astro-ph/0608695*]

Only ν_e and $\overline{\nu}_e$



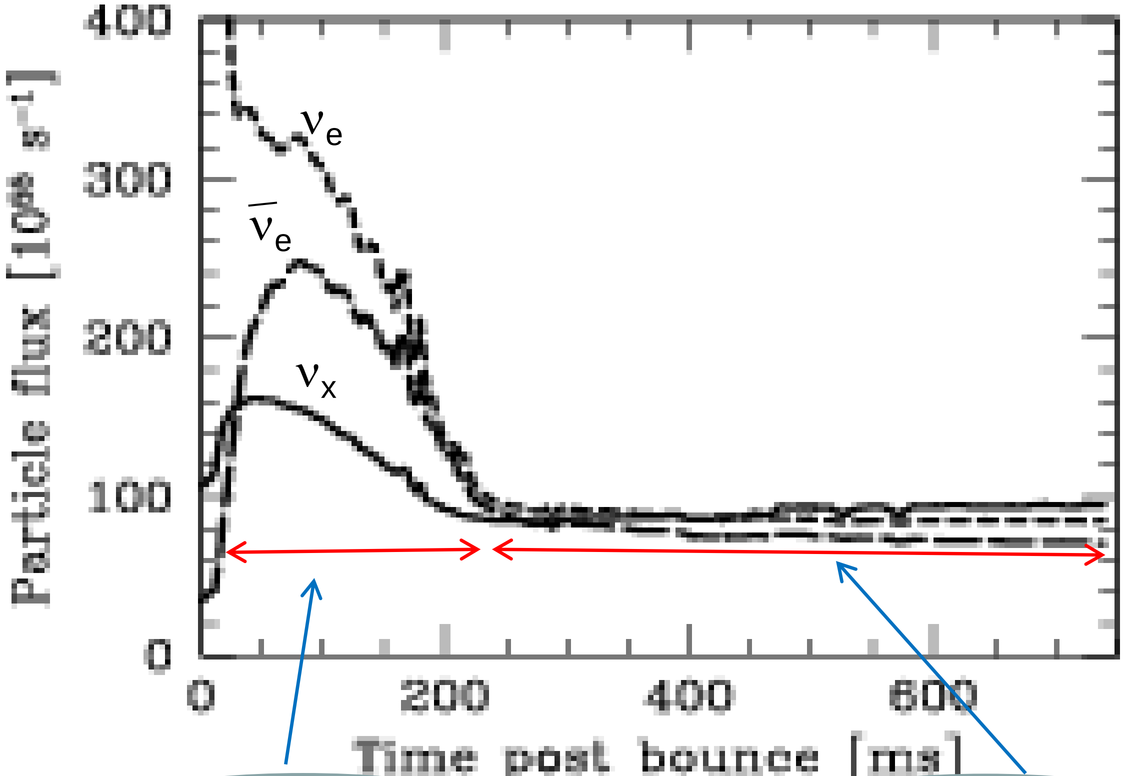
SUPERNOVA: **Non-periodic** since ν density decreases →

Complete flavor conversions!

- Occurs for very small mixing angles
- Almost independent of the presence of dense normal matter
- Preserves the initial excess ν_e over $\overline{\nu}_e$ (lepton number conservation)

NEUTRINO FLUX NUMBERS

[*Raffelt et al. (Garching group), astro-ph/0303226*]



Accretion phase

$$F_{\nu e} > F_{\bar{\nu} e} > F_{\nu x}$$

Excess of ν_e due to deleponization

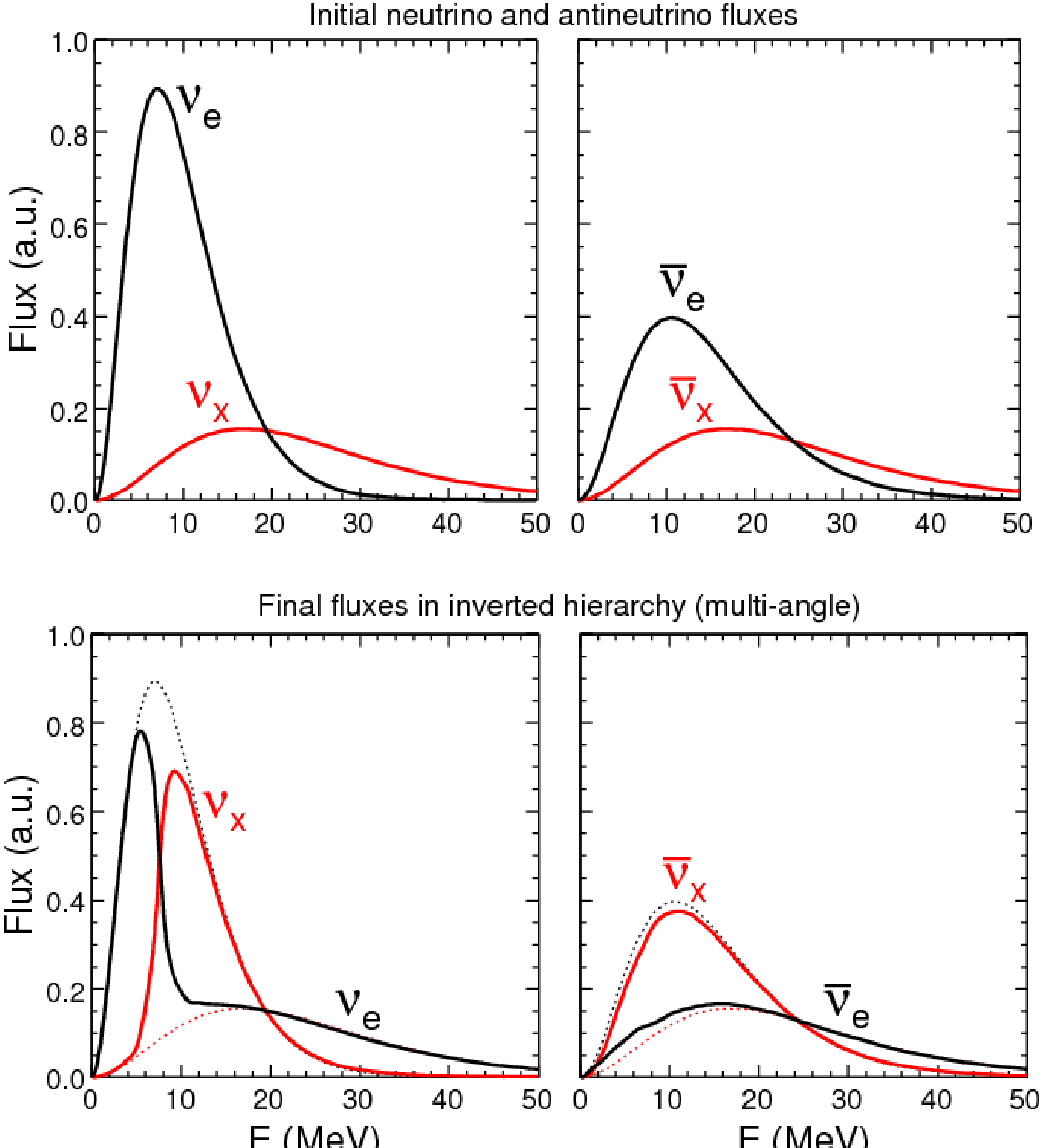
Cooling phase

$$F_{\nu x} \geq F_{\nu e} \geq F_{\bar{\nu} e}$$

Moderate flavor hierarchy, possible excess of ν_x

SPECTRAL SPLITS IN THE ACCRETION PHASE

[*Fogli, Lisi, Marrone, A.M. , arXiV: 0707.1998 [hep-ph], Duan, Carlson, Fuller, Qian, astro-ph/0703776, Raffelt and Smirnov, 0705.1830 [hep-ph]*]



Initial fluxes at neutrinosphere (r ~10 km)

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

(ratio typical of accretion phase)

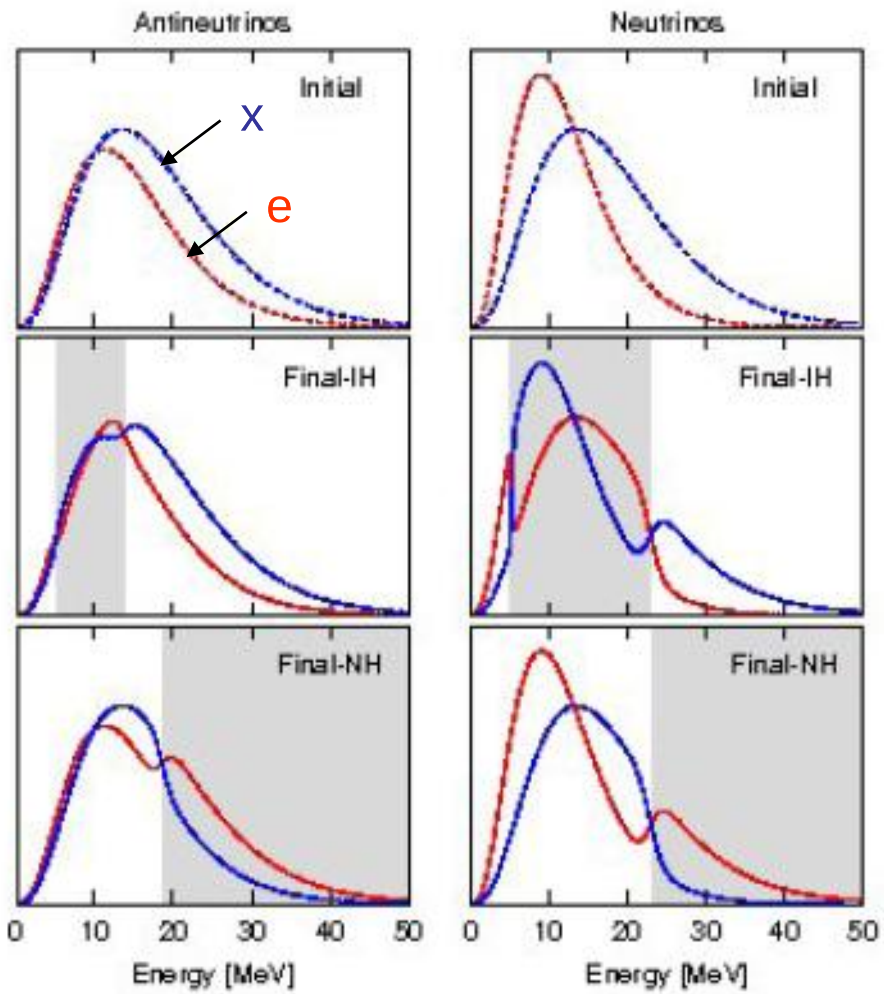
Inverted mass hierarchy

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

Nothing happens in NH

MULTIPLE SPECTRAL SPLITS IN THE COOLING PHASE

[*Dasgupta, Dighe, Raffelt & Smirnov, arXiv:0904.3542 [hep-ph]*]



$$F_{\nu e} : F_{\bar{\nu} e} : F_{\nu x} = 0.85 : 0.75 : 1.00$$

(typical in cooling phase)

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

Possible time-dependent signatures in the SN ν signal

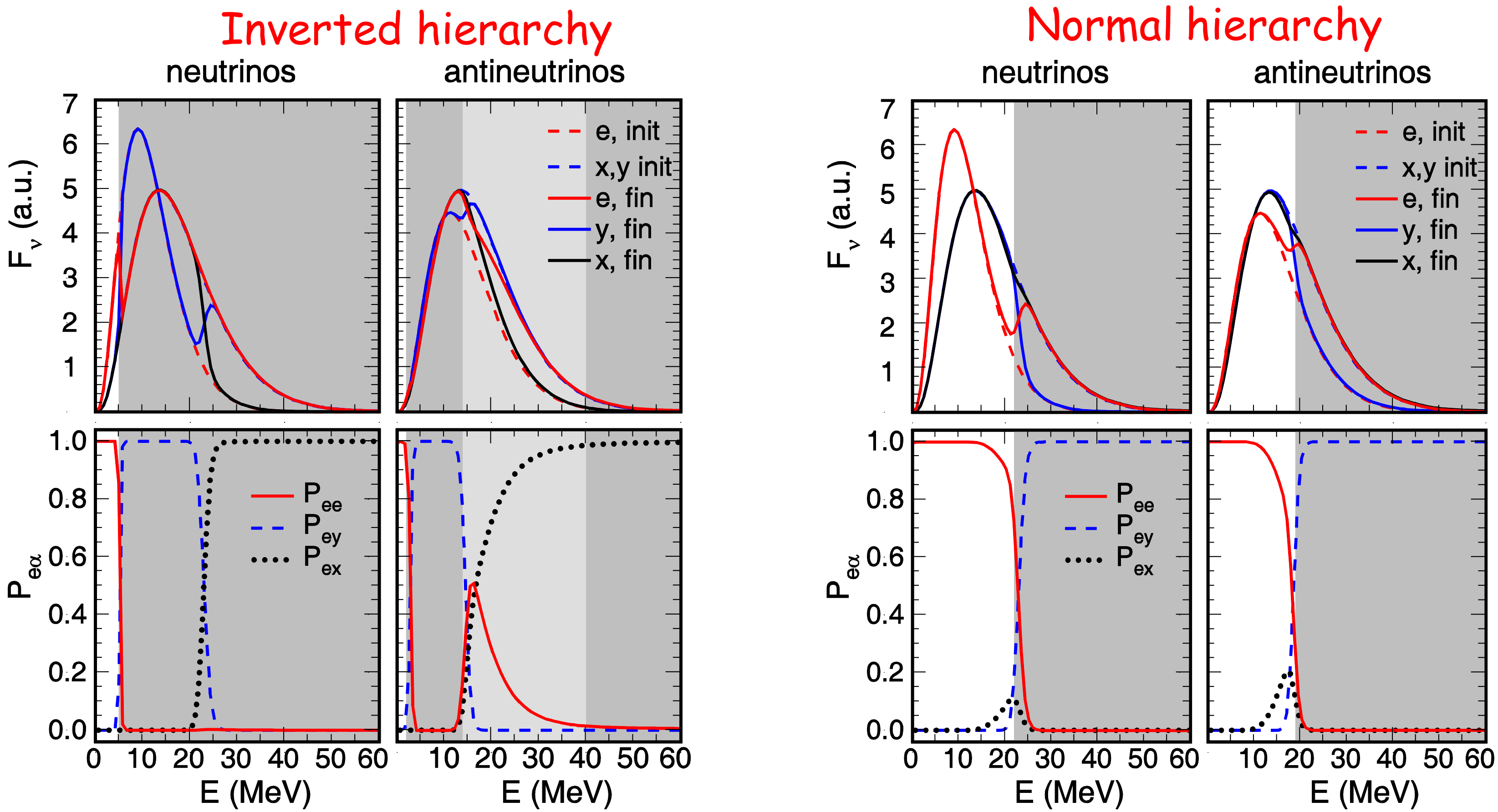
Crucial both ν and $\bar{\nu}$ detection

[Talks by Dasgupta, Marrone]

[See also Fogli, Lisi, Marrone, Tamborra, arXiV:0907.5115]

THREE FLAVOR EFFECTS IN THE COOLING PHASE

[*Friedland, 1001.0996; Dasgupta, A.M., Tamborra, Tomas, 1002.2943*]

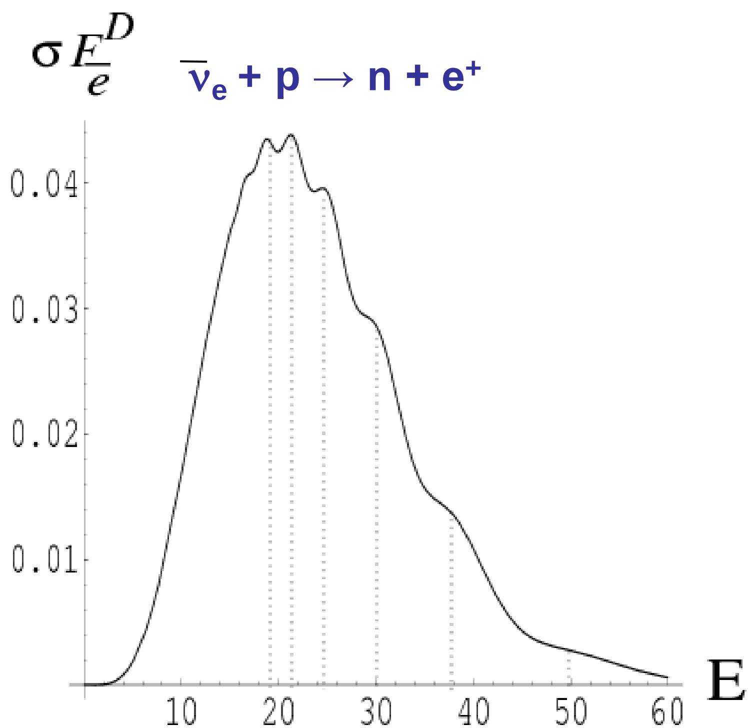


- IN IH hierarchy three-flavor effects associated to the solar mass difference can erase the high-energy spectral split
- Only subleading effect in NH

[Talk by Dasgupta]

USING EARTH EFFECT TO DIAGNOSE COLLECTIVE OSCILLATIONS

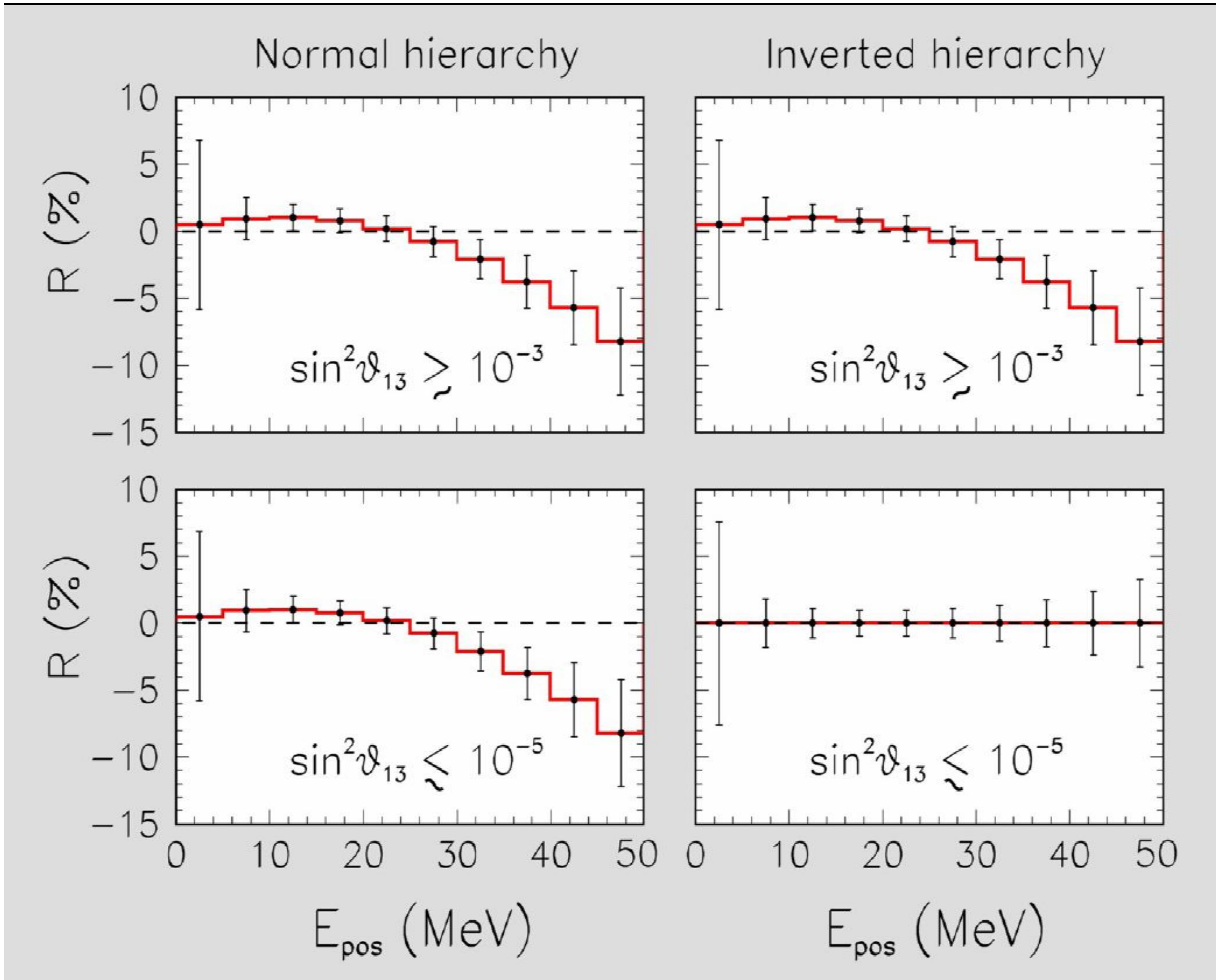
Earth matter crossing induces additional ν conversions between ν_1 and ν_2 mass eigenstates. The main signature of Earth matter effects – oscillatory modulations of the observed energy spectra – is <u>unambiguous</u> since it can not be mimicked by known astrophysical phenomena



MASS HIERARCHY DETERMINATION AT EXTREMELY SMALL θ_{13}

[Dasgupta, Dighe, A.M., arXiv:0802.1481 [hep-ph]]

(Accretion phase)



Ratio of spectra in two water Cherenkov detectors (0.4 Mton), one shadowed by the Earth, the other not.

$$R = \frac{F_e^{shadowed} - F_e^{unshadowed}}{F_e^{unshadowed}}$$

COLLECTIVE SUPERNOVA NEUTRINO OSCILLATIONS (2006-2010)

- "Bipolar" collective transformation important, also for dense matter: *Duan, Fuller & Qian, astro-ph/0511275*
- Numerical simulations including multi-angle effects. Discovery of the spectral split: *Duan, Fuller, Carlson & Qian, astro-ph/0606616, 0608050*
- Pendulum in flavor space: *Hannestad, Raffelt, Sigl & Wong, astro-ph/0608695, Duan, Fuller, Carlson & Qian, astro-ph/0703776*
- Multi-angle decoherence: *Sawyer, hep-ph/0408265, 0503013. Raffelt & Sigl, hep-ph/0701182, Esteban-Pretel, Pastor, Tomas, Raffelt & Sigl, arXiv:0706.2498*
- Theory of spectral split in terms of adiabatic solution: *Raffelt & Smirnov, arXiv: 0705.1830, 0709.0641; Duan, Fuller, Carlson & Qian, arXiv: 0706.4293, 0707.0290*
- Independent multi-angle numerical simulations: *Fogli, Lisi, Marrone & A.M., arXiv: 0707.1998, Fogli, Lisi, Marrone, A.M & Tamborra, arXiv:0808.0807*
- Three flavor effects in O-Ne-Mg SNe: *Duan, Fuller, Carlson & Qian, arXiv: 0710.1271, Dasgupta, Dighe, A.M. &* Raffelt, arXiv: 0801.1660

- Theory of three flavor collective oscillations: *Dasgupta & Dighe, arXiv:0712.3798*
- Secord order μ-τ refractive effect important in the three flavor context: *Esteban-Pretel, Pastor, Tomas, Raffelt & Sigl, arXiv: 0712.1137*
- Three flavor numerical simulations: *Fogli, Lisi, Marrone & Tamborra, arXiv:0812.3031*
- CP violation effects: *Gava & Volpe, arXiv:0807.3418*
- Identifying the mass hierarchy at extremely small θ_{13}: *Dasgupta, Dighe, A.M., arXiv: 0802.1481*
- Formulation for non-spherical geometry: *Dasgupta, Dighe, A.M. & Raffelt, arXiv: 0805.3300.*
- Role of dense matter : *Esteban-Pretel, A.M. , Pastor, Raffelt, Tomas, Serpico, Sigl, arXiv: 0807.0659*
- Nonstandard interactions : *Blennow, A.M. , Serpico, arXiv: 0810.2297, Esteban-Pretel, Tomas & Valle, arXiv: 0909.2196*
- Neutrino flavor spin waves: *Duan, Fuller & Qian, arXiv:0808.2046*
- Combining collective + MSW effect: *Gava,Kneller, Volpe, McLaughlin, arXiv:0902.0317*

- Multiple spectral splits: *Dasgupta, Dighe, Raffelt & Smirnov, arXiv:0904.3543, Fogli, Lisi, Marrone & Tamborra, arXiv: 0907.5115, Friedland, arXiv:1001.0996, Dasgupta, A.M., Tamborra, Tomas, arXiV: 1002.2943*

- Radiative corrections to $\nu-\nu$ refractive index: A.M, *Raffelt, Pozzorini & Serpico, arXiv: 0907.3674*

- SUSY effects: *Gava & Jean-Louis, arXiv:* 0912.5206

- Effects on r-process nucleosynthesis: *Chakraborty, Choubey, Goswami, Kar, arXiv:* 0911.1218

- Triggering collective oscillations at θ_{13}=0: *Dasgupta, Raffelt, Tamborra, arXiv:* 1001.5396

[Talks by Dasgupta, Marrone, Tamborra, Serpico, Tomas, Choubey, Charkaborty]

OPEN ISSUES

Theoretical issues

Robustness of the collective behavior vs. multi-angle decoherence effects. Many-body effects. Reduced symmetries

Realistic SN environment

How asphericities, inhomogeneities, turbulence during the SN explosion might influence neutrino-neutrino interaction effects.

Feedback on SN explosion simulations

Collective effects occur in a crucial region for SN dynamics and for nucleosynthesis. SN explosion simulations do not account for neutrino oscillations.

Beyond the SM

Possible new nu-nu interactions beyond SM might profoundly change the current picture.

CONCLUSIONS

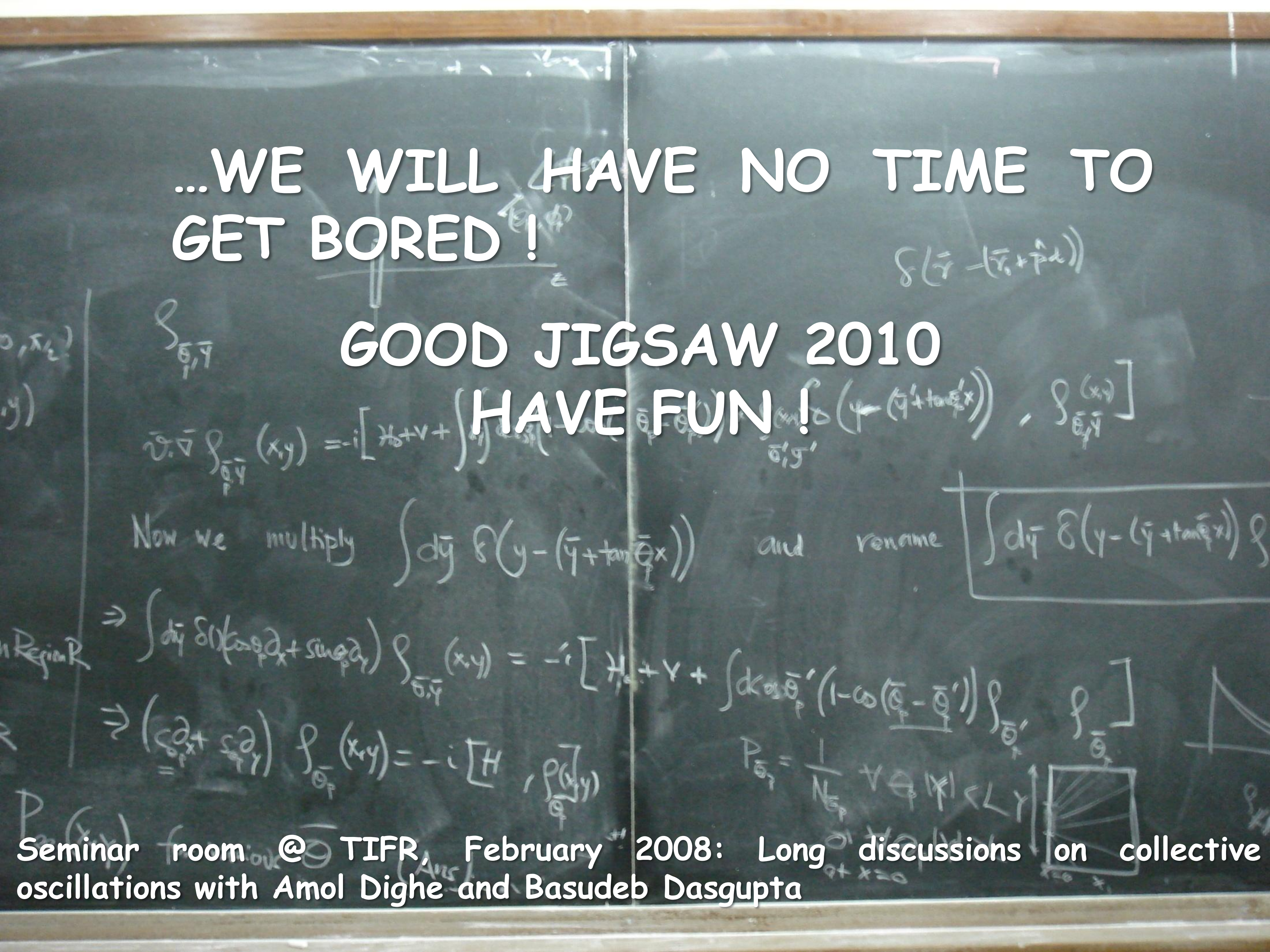
Observing SN neutrinos is the next frontiers of low-energy neutrino astronomy

The physics potential of current and next-generation detectors in this context is enormous, both for particle physics and astrophysics.

SN provide very extreme conditions, where the shock-wave, matter turbulence, neutrino-neutrino interactions prove to be surprisingly important in the ν oscillations.

Further investigations needed to better understand neutrino flavor conversions during a stellar collapse….

WAITING FOR THE NEXT GALACTIC SN….



…WE WILL HAVE NO TIME TO GET BORED !

GOOD JIGSAW 2010

HAVE FUN !

Seminar room @ TIFR, February 2008: Long discussions on collective oscillations with Amol Dighe and Basudeb Dasgupta