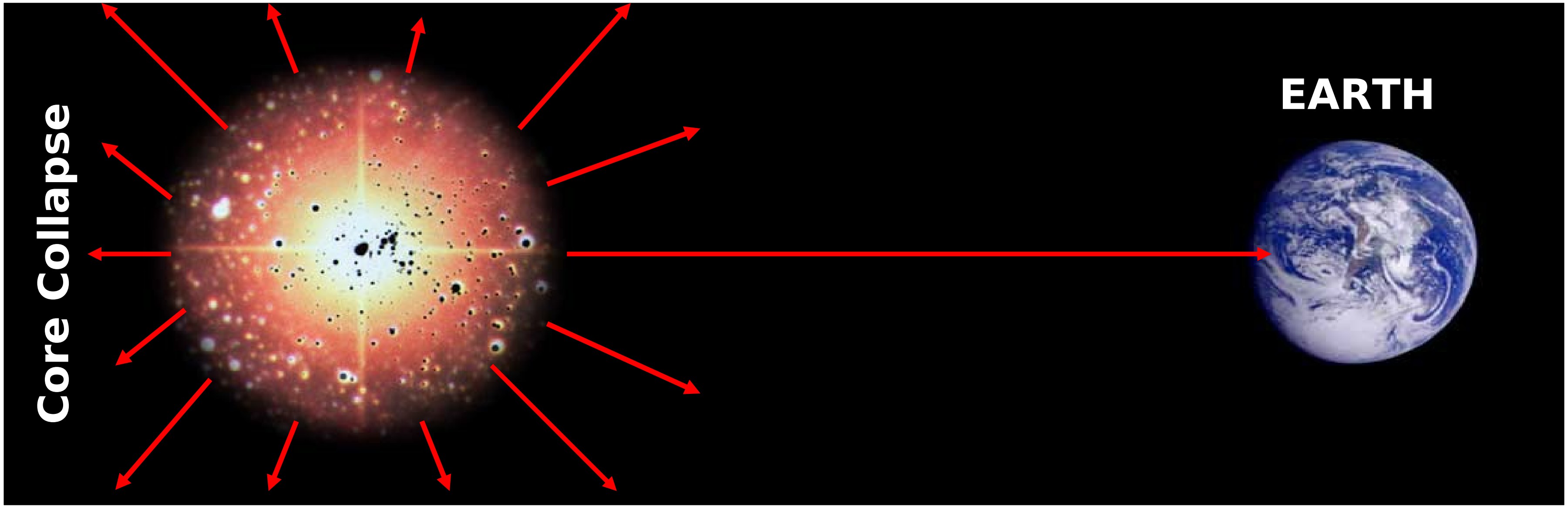
Supernova Neutrinos

Sovan Chakraborty

MPI for Physics, Munich

ICTS, Numerical Relativity, June, 2013

TYPICAL PROBLEMS IN SUPERNOVA NEUTRINOS



Production (flavor)

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

Propagation (mass,mixing)

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

Detection (flavor)

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

Theory

Phenomenology

Supernova one of the most energetic events in nature.

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

Collapses and ejects the outer mantle in a shock wave driven explosion.

ENERGY SCALES: ~ 10^{53} erg : 99% energy is emitted by Neutrinos (Energy ~ 10 MeV).

TIME SCALE: The duration of the burst lasts ~10 s.

Neutrino Emission Phases

Neutronization burst

- Shock breakout
- De-leptonization of outer core layers
- **Duration ~ 25 ms**

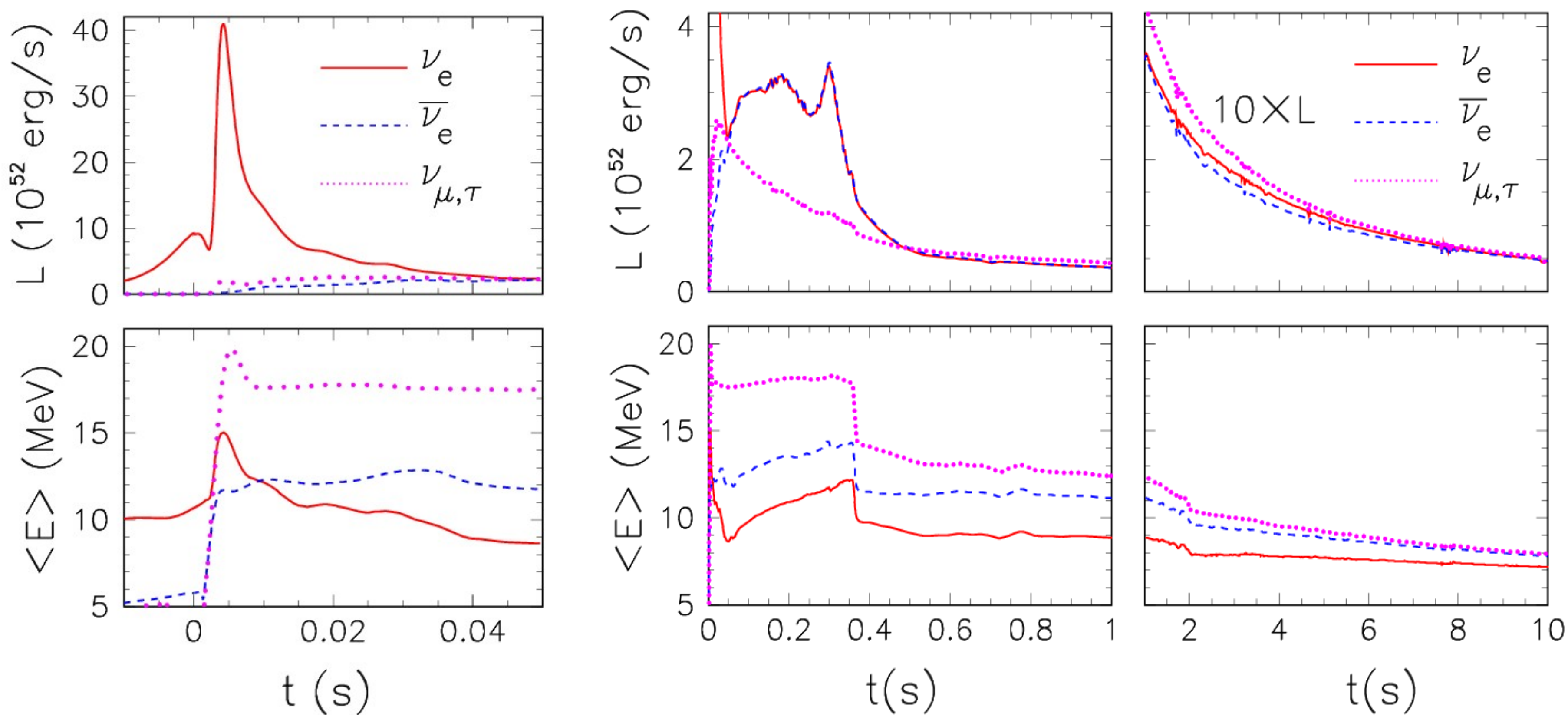
Accretion

- powered by infalling matter
- Stalled shock

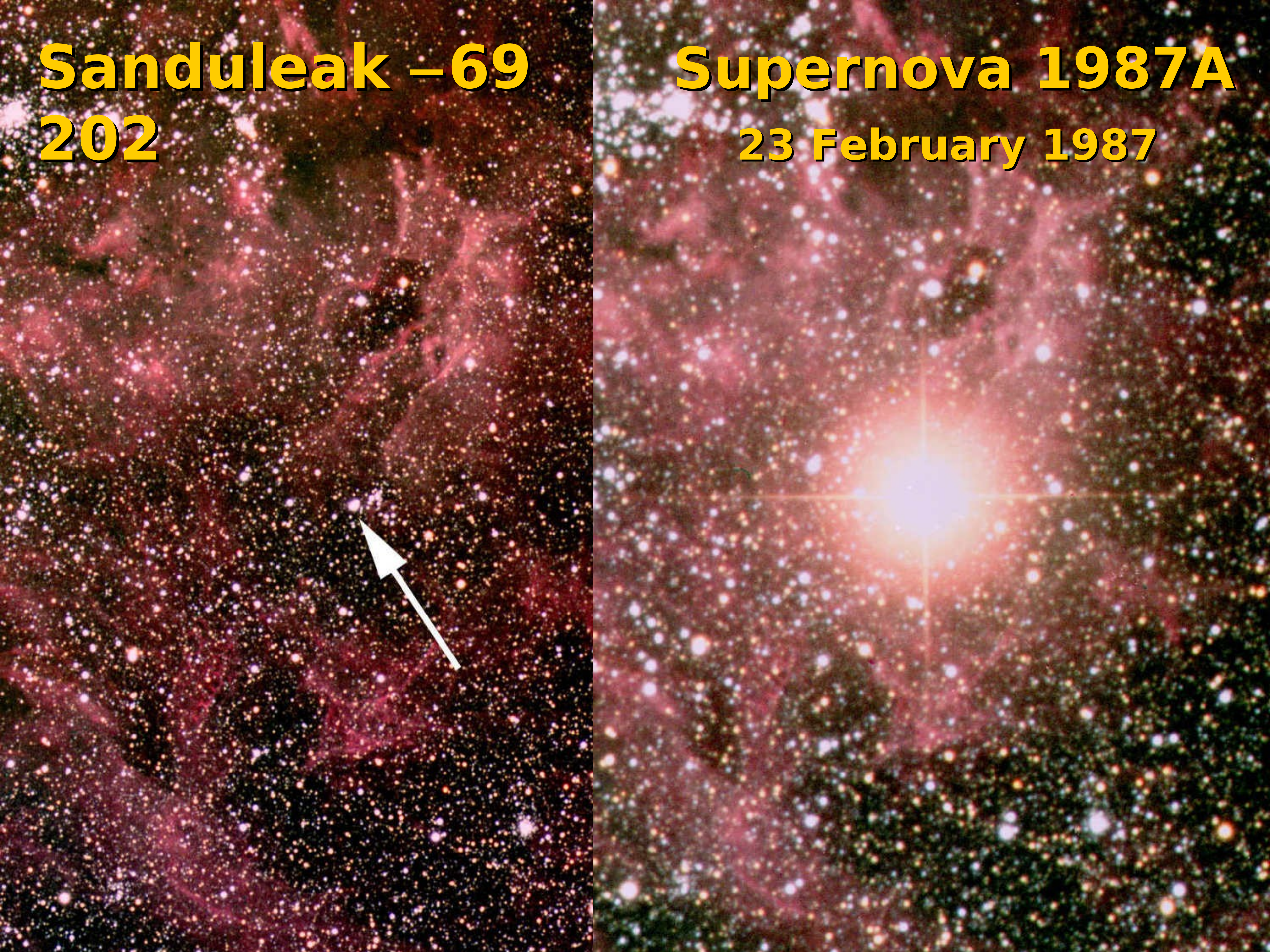
Cooling

- Cooling by ν diffusion

Accretion: ~ 0.5 s ; Cooling: ~ 10 s

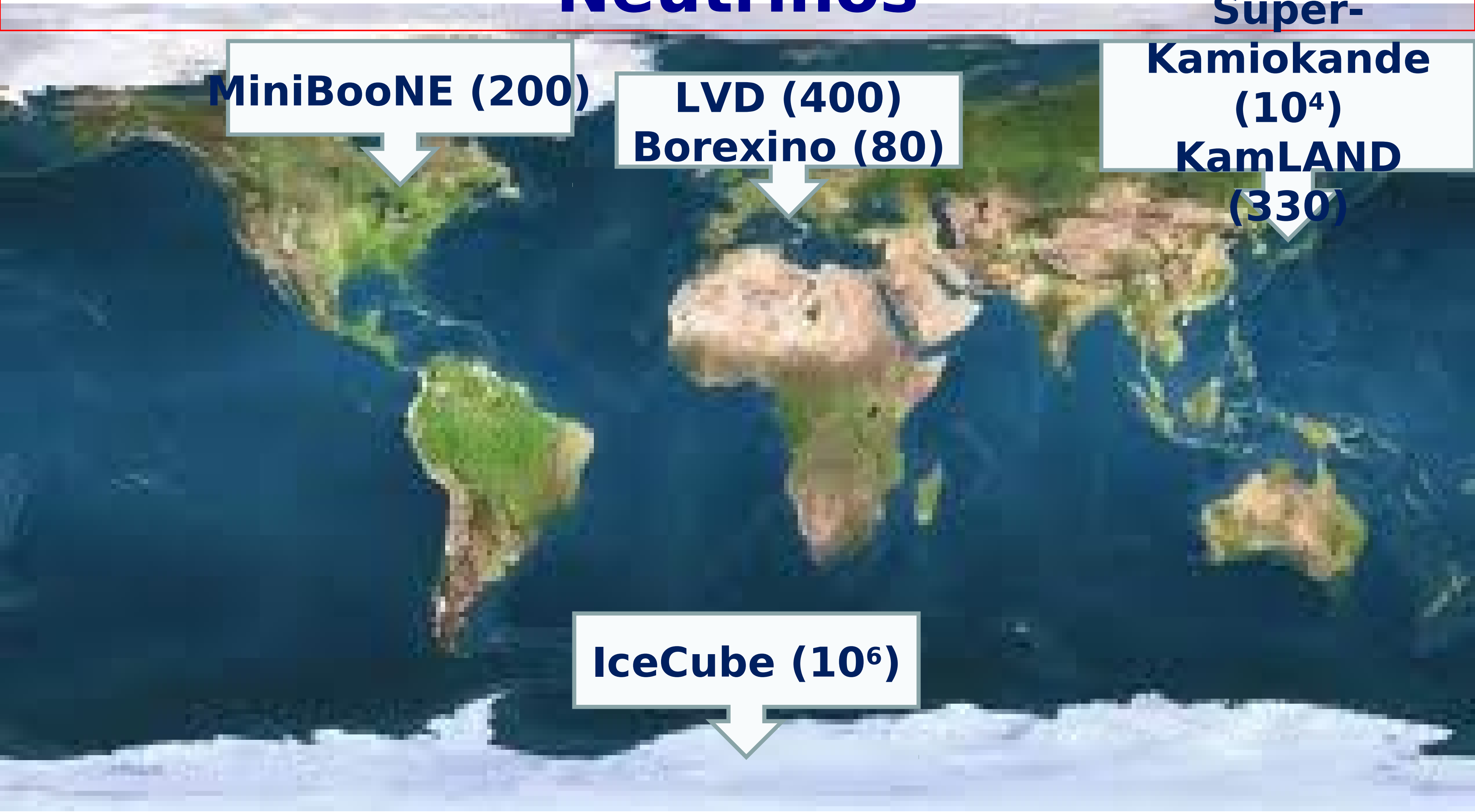


[Fischer et al. (Basel Simulations), **A&A 517:A80,2010,** 10. 8 M_{sun} progenitor mass]


Sanduleak –69
202
Supernova 1987A
23 February 1987

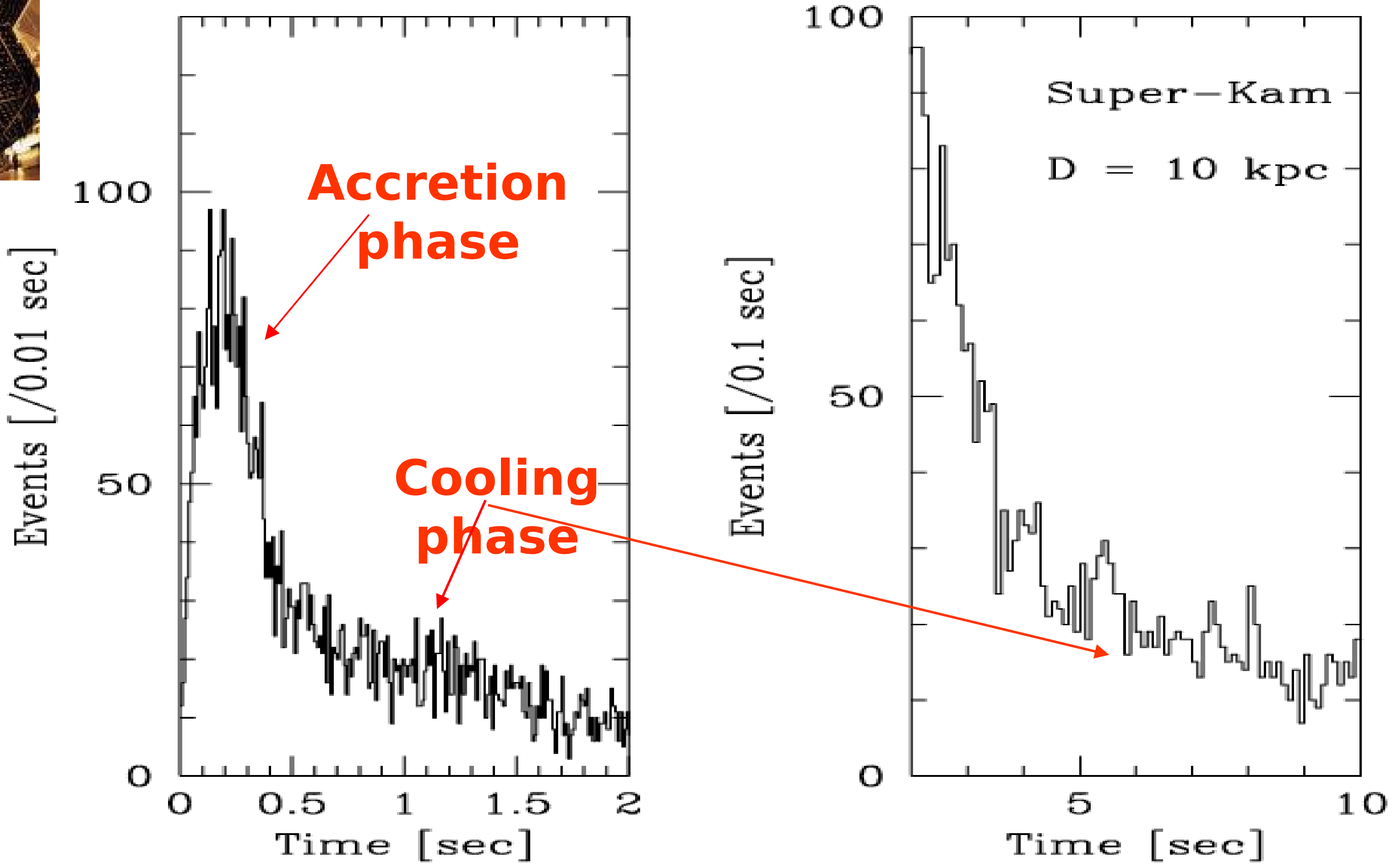

What could we see
“tomorrow”?
SN 20XXA !

Large Detectors for Supernova Neutrinos



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

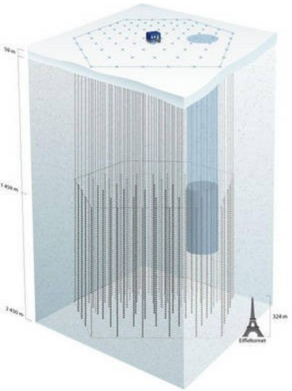
Simulated Supernova Signal at Super-Kamiokande

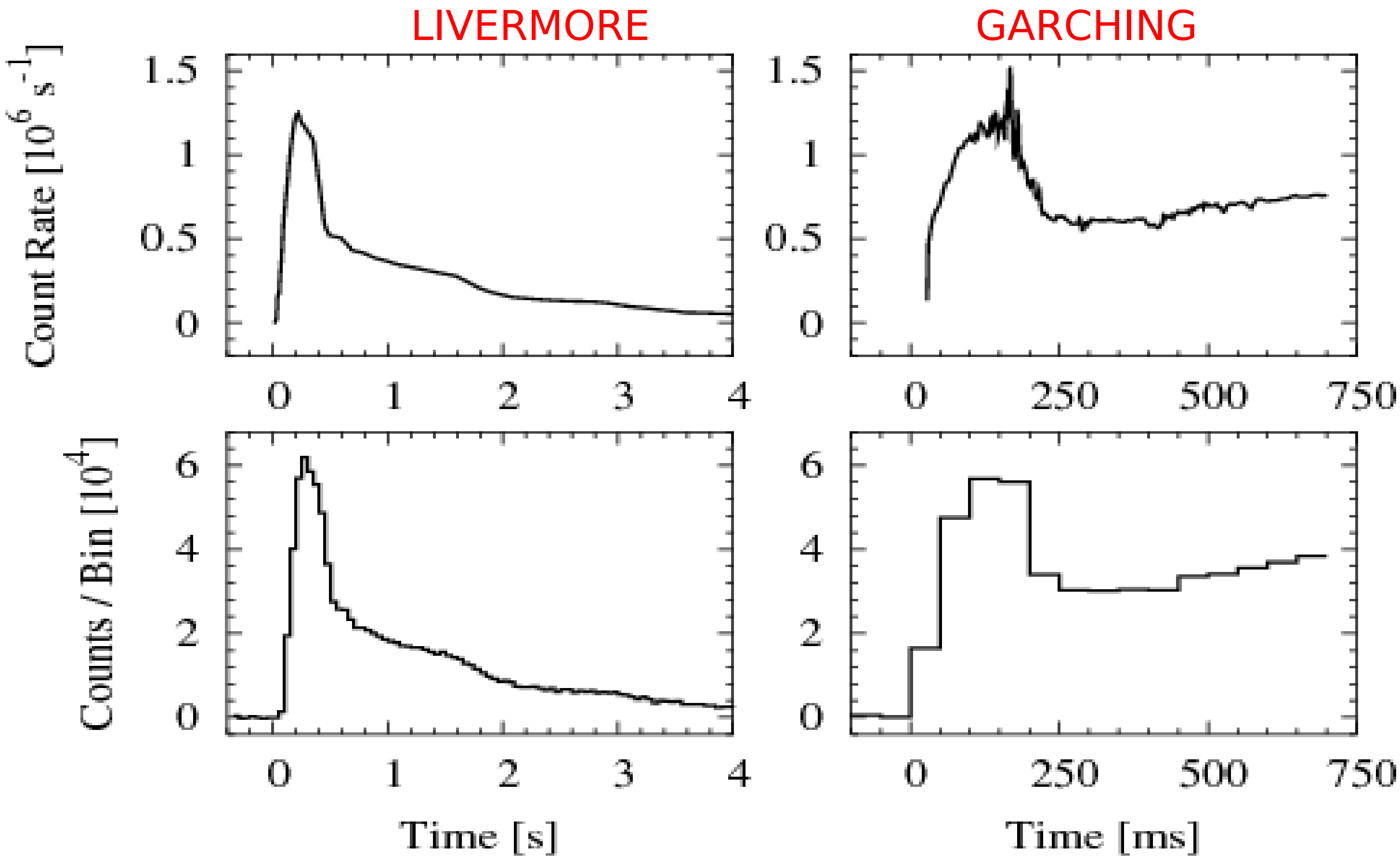


Simulation for Super-Kamiokande SN signal at 10 kpc,
based on a numerical Livermore model

Simulated Supernova Signal at Ice-Cube

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





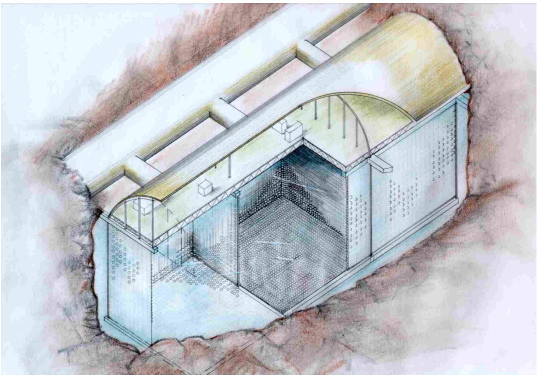
Possible to reconstruct the SN ν lightcurve with current detectors. Discrimination btw different simulations.

Next generation Detectors for Supernova Neutrinos

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

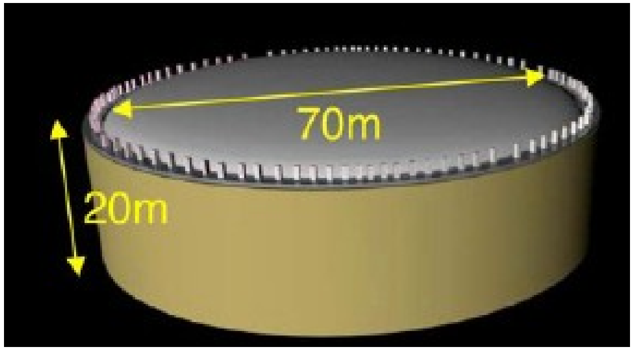
- **0.4 Mton WATER Cherenkov detectors**
- **100 kton Liquid Ar TPC**
- **50 kton scintillator**

Mton Cherenkov



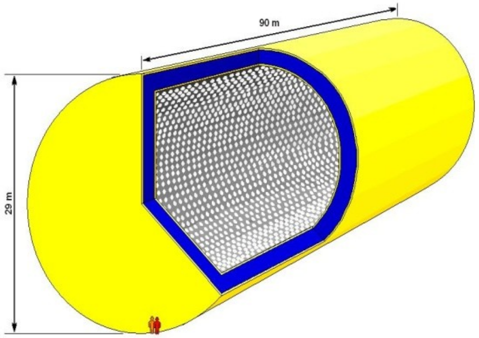
UNO, MEMPHYS, HYPER-K

LAr TPC



GLACIER

Scintillator



LENA

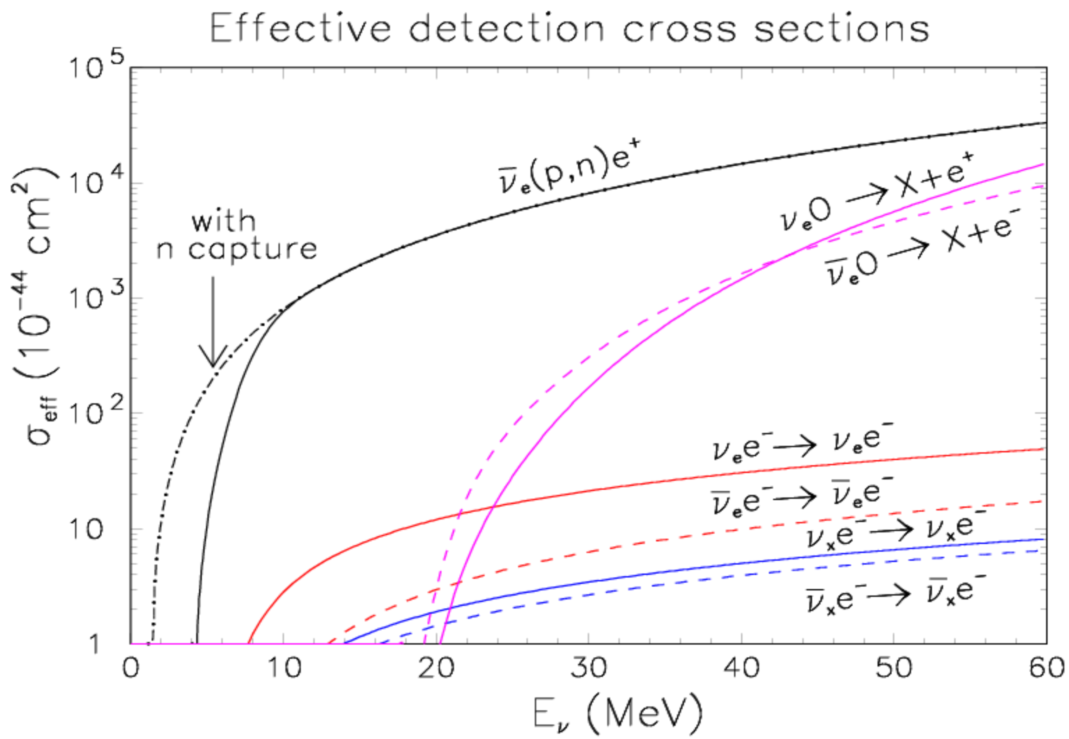
See LAGUNA Collaboration, "Large underground, liquid based detectors for astro-particle physics in Europe: Scientific case and prospects,"

• LAGUNA Detectors for Supernova Neutrinos

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

- **0.4 Mton WATER**

Cherenkov detectors



Interactions	# of events @ 10 kpc
$\bar{\nu}_e + p \rightarrow n + e^+$	2×10^5
$\nu_e + O \rightarrow X + e^\pm$	10^4
$\nu + e^- \rightarrow \nu + e^-$	10^3

Golden channel:

Inverse beta decay (IBD) of $\bar{\nu}_e$

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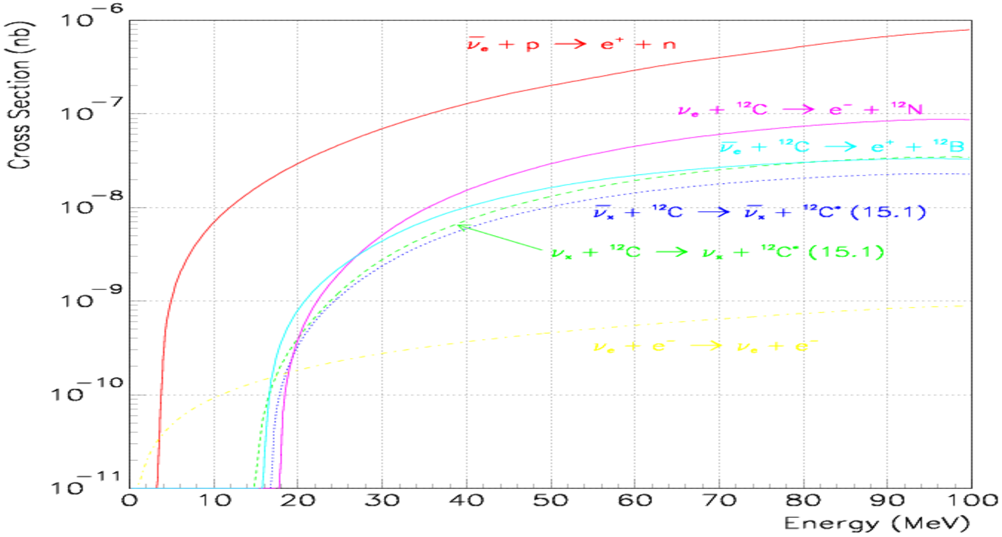
- **50 kton scintillator**



Interactions	# of events at 10 kpc
$\bar{\nu}_e + p \rightarrow n + e^+$	10^4
$\nu + p \rightarrow \nu + p$	10^3
$\bar{\nu}_e + {}^{12}C \rightarrow e^+ + {}^{12}B$	400
$\nu_e + {}^{12}C \rightarrow e^- + {}^{12}N$	500
$\nu + {}^{12}C \rightarrow \nu + {}^{12}C^*$	3×10^3
$\nu + e^- \rightarrow \nu + e^-$	600

Golden channel:

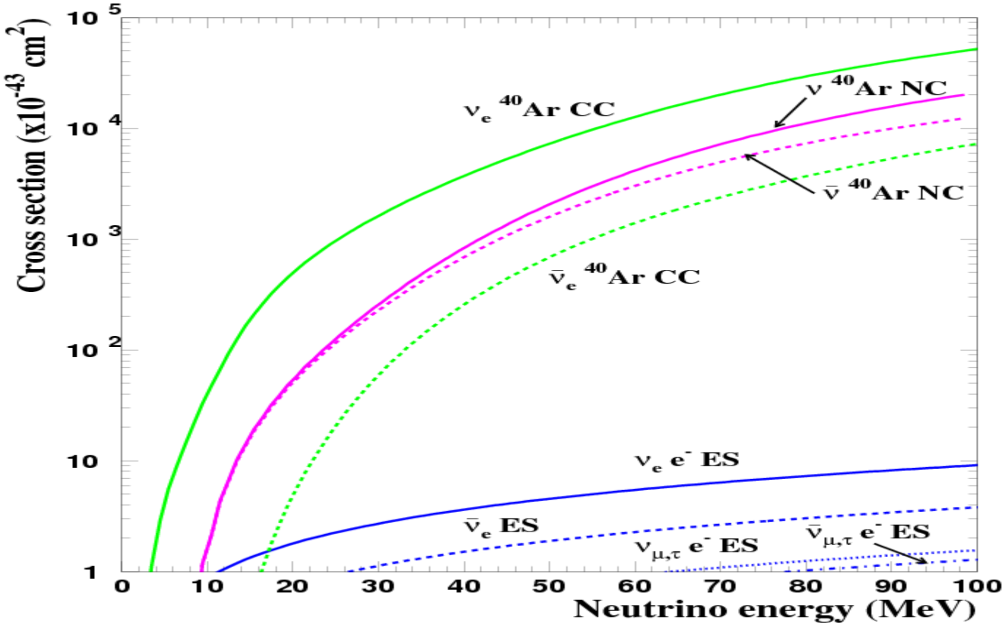
Inverse beta decay (IBD) of $\bar{\nu}_e$

Better energy resolution than a water Cherenkov

• LAGUNA Detectors for Supernova Neutrinos

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

- **100 kton Liquid Ar TP**



Interactions	# of events @ 10 kpc
$\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$	2.5×10^4
$\nu_e + {}^{40}Ar \rightarrow e^+ + {}^{40}Cl^*$	10^3
$\nu + {}^{40}Ar \rightarrow \nu + {}^{40}Ar^*$	3×10^4
$\nu + e^- \rightarrow \nu + e^-$	10^3

Golden channel:

ν_e Ar CC

Complementary to previous techniques

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

- $H_{vac} = \dfrac{U\ M^2\ U^\dagger}{2E}$
- $H_e = \sqrt{2}G_F\,\mathrm{diag}(N_e, 0, 0)$
- $H_{\nu\nu} = \sqrt{2}G_F\int(1-\cos\theta_{pq})\left(\rho_q - \bar{\rho}_q\right)\,dq$

Kinematical mass-mixing term

Dynamical MSW term (in matter)

Neutrino-neutrino interactions term (non-linear)

3ν FRAMEWORK

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

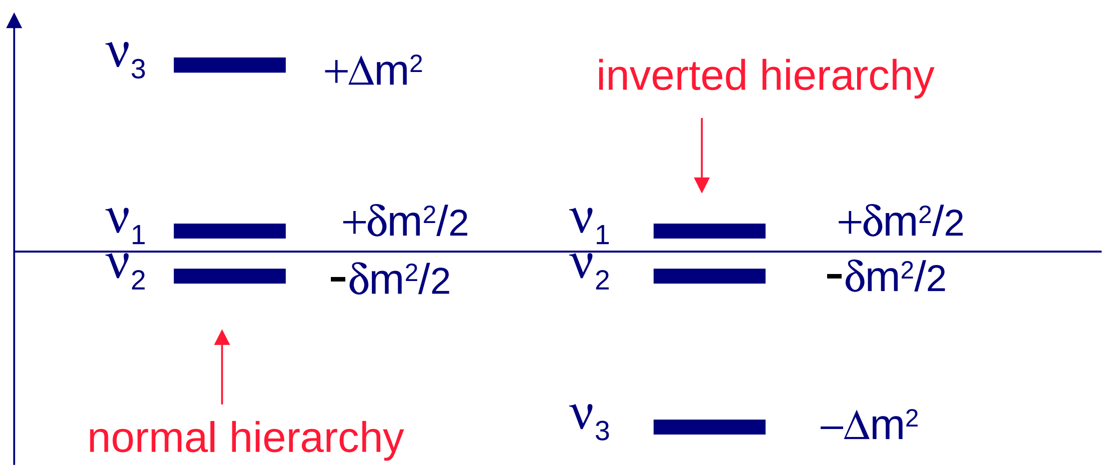
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & e^{-i\delta} s_{13} \\ & 1 & \\ -e^{-i\delta} s_{13} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12}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

$c_{12} = \cos\theta_{12}$, 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"



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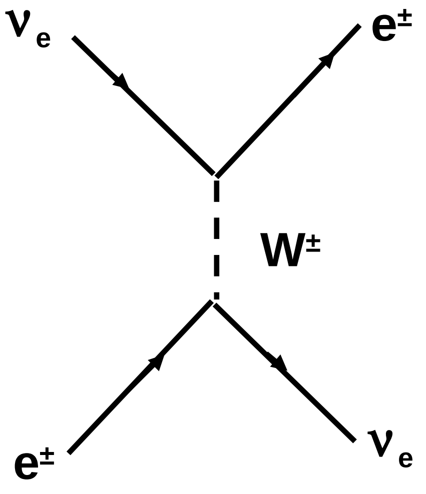
- $$H_{\nu\nu} = \sqrt{2}G_{F}\int(1-\cos\theta_{pq})\left(\rho_{q} - \bar{\rho}_{q}\right)\,dq$$ **Neutrino-neutrino interactions term (non-linear)**

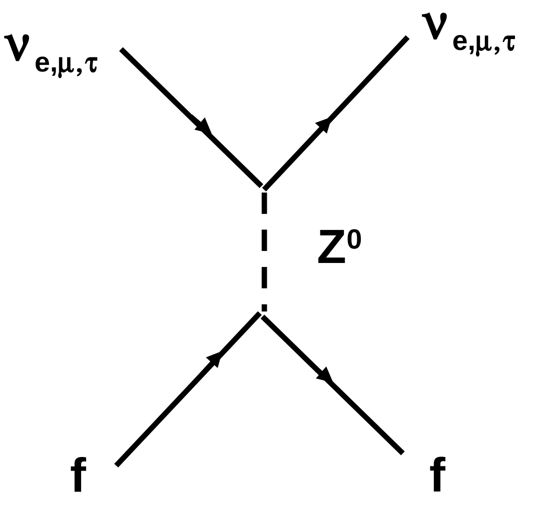
MIKHEYEV-SMIRNOV-WOLFENSTEIN (MSW) EFFECT

[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

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)**

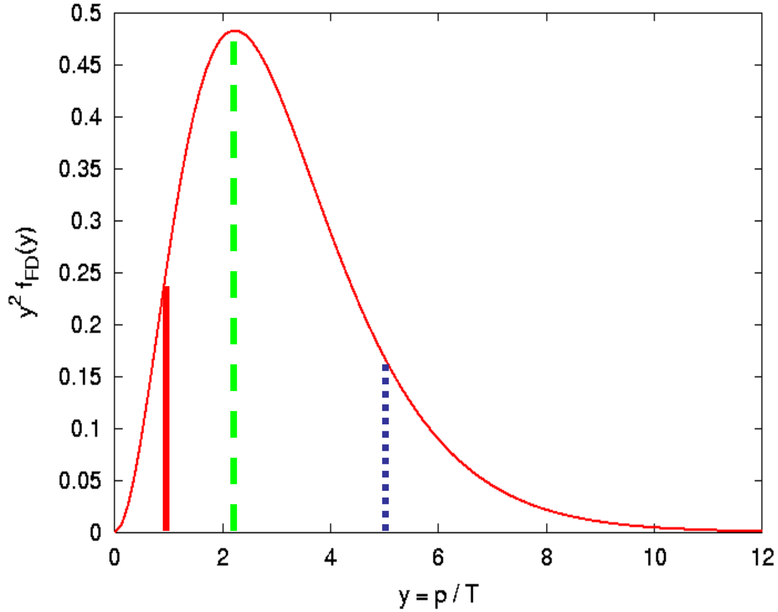
Collective SN Neutrino Oscillations since 2006

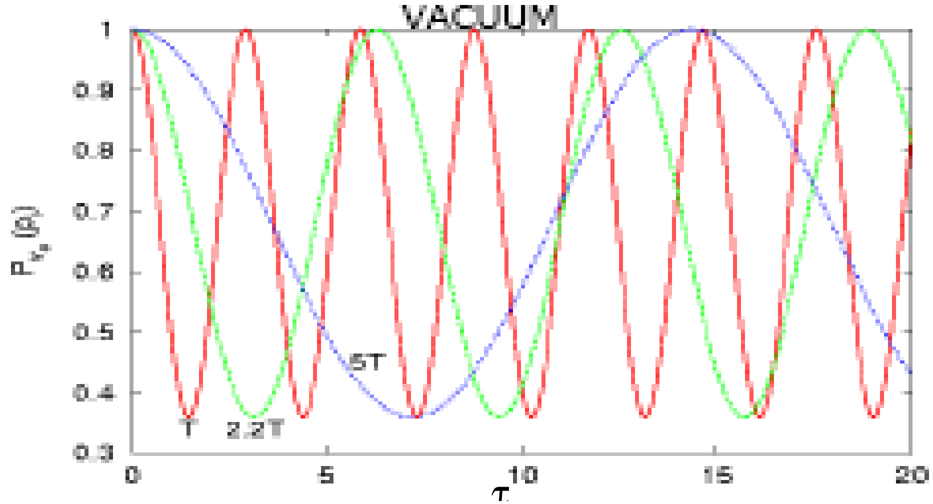
Two seminal papers in 2006 triggered a torrent of activities
Duan, Fuller, Qian, astro-ph/0511275, Duan et al. astro-ph/0606616

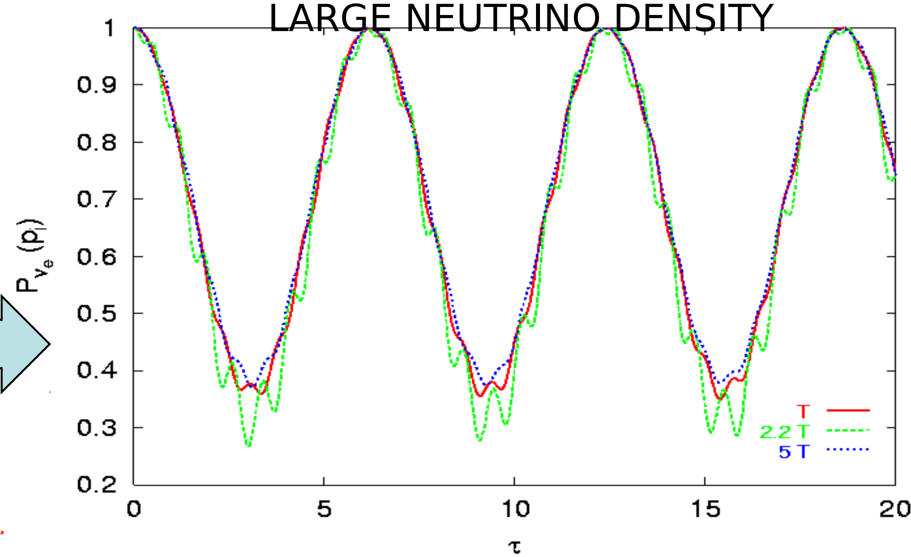
, Fuller, Carlson & Qian, astro-ph/0608050, 0703776, arXiv:0707.02
.1271. Duan, Fuller & Qian, arXiv:0706.4293, 0801.1363, 0808.2046
, Fuller & Carlson, arXiv:0803.3650. Duan & Kneller, arXiv:0904.097
estad, Raffelt, Sigl & Wong, astro-ph/0608695. Balantekin & Pehliva
-ph/0607527. Balantekin, Gava & Volpe, arXiv:0710.3112. Gava & V
:0807.3418. Gava, Kneller, Volpe & McLaughlin, arXiv:0902.0317.
lt & Sigl, hep-ph/0701182. Raffelt & Smirnov, arXiv:0705.1830,
.4641. Esteban-Pretel, Pastor, Tomàs, Raffelt & Sigl, arXiv:0706.249
.1137. Esteban-Pretel, Mirizzi, Pastor, Tomàs, Raffelt, Serpico & Sig
:0807.0659. Raffelt, arXiv:0810.1407. Fogli, Lisi, Marrone & Mirizzi,
:0707.1998. Fogli, Lisi, Marrone & Tamborra, arXiv:0812.3031.
rdini, Müller & Janka, arXiv:0712.3000. Dasgupta & Dighe,
:0712.3798. Dasgupta, Dighe & Mirizzi, arXiv:0802.1481. Dasgupta,
e, Mirizzi & Raffelt, arXiv:0801.1660, 0805.3300. Dasgupta, Dighe,
lt & Smirnov, arXiv:0904.3542. Sawyer, arXiv:0803.4319.
raborty, Choubey, Dasgupta & Kar, arXiv:0805.3131. Blennow, Miriz
co, arXiv:0810.2297. Wei Liao, arXiv:0904.0075, 0904.2855.

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

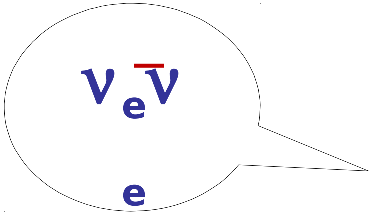
[Pastor, Raffelt, Semikoz, hep-ph/0109033]

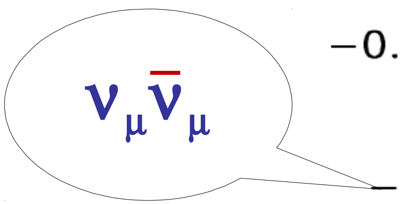
PENDULAR OSCILLATIONS

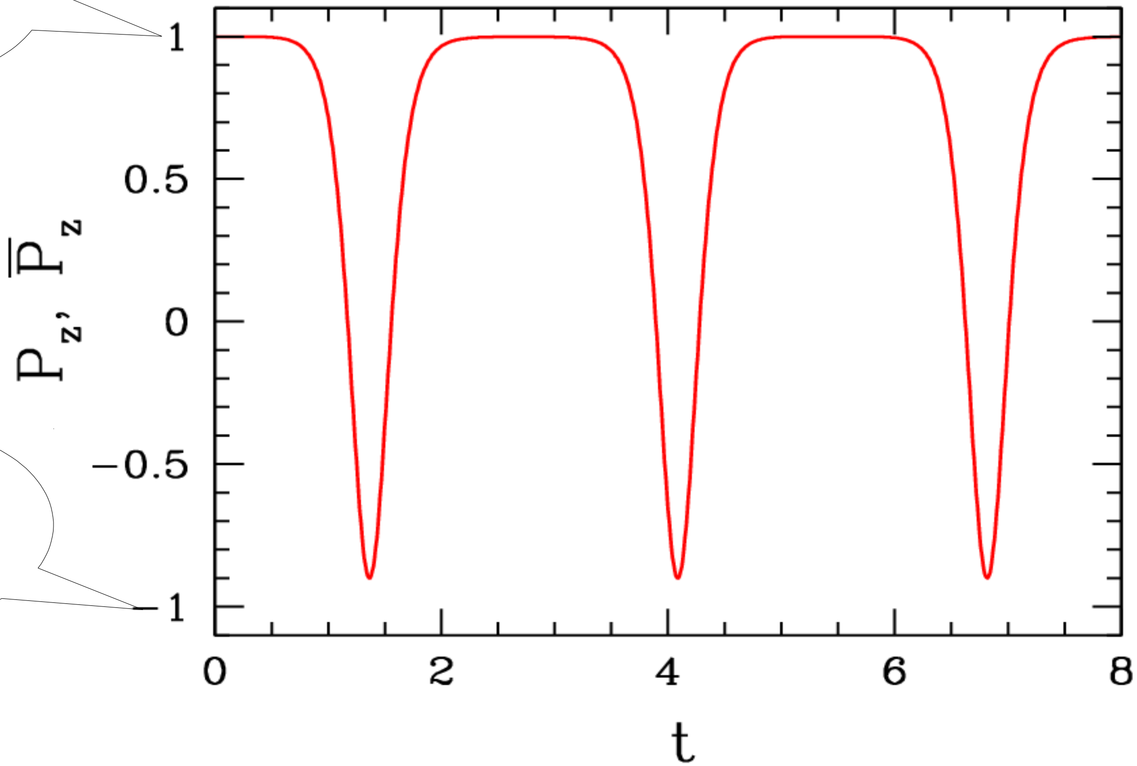
[*Hannestad, Raffelt, Sigl, Wong, astro-ph/0608695*]

Equal densities of ν_e and $\bar{\nu}_e$

INVERTED HIERARCHY + small θ







In inverted hierarchy: coherent “pair conversions” $\nu_e\bar{\nu}_e \rightarrow \nu_\mu\bar{\nu}_\mu$

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

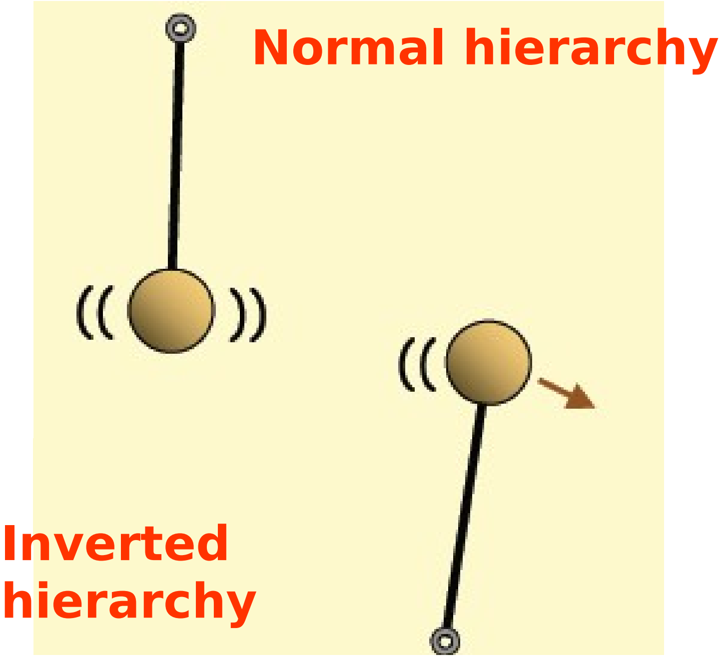
With only initial ν_e and $\bar{\nu}_e$:

- **Normal hierarchy**

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

- **Inverted hierarchy**

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

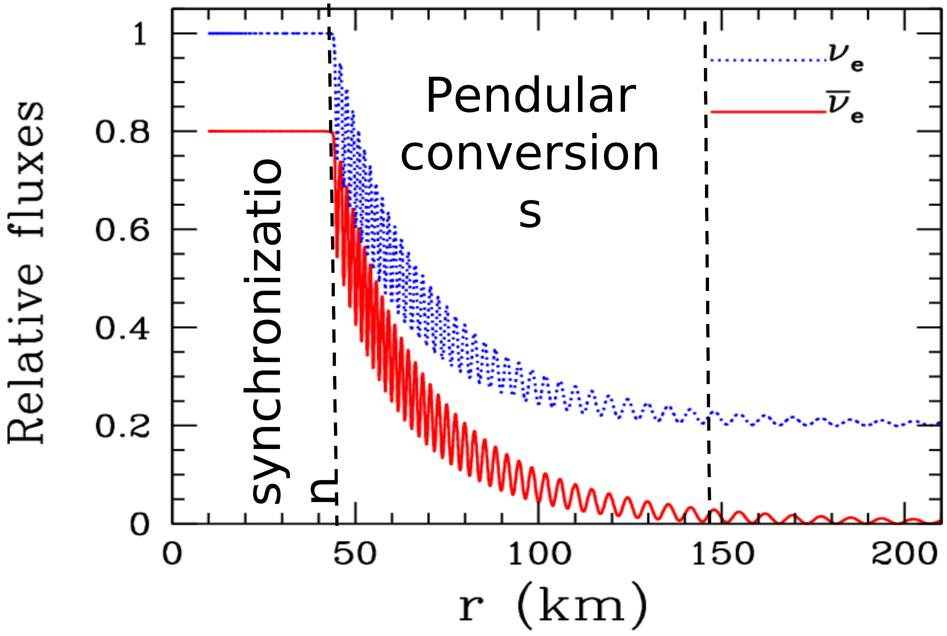


θ_{13} sets initial misalignment with vertical. Specific value not much relevant.

SUPERNOVA TOY-MODEL

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

Only ν_e and $\bar{\nu}_e$



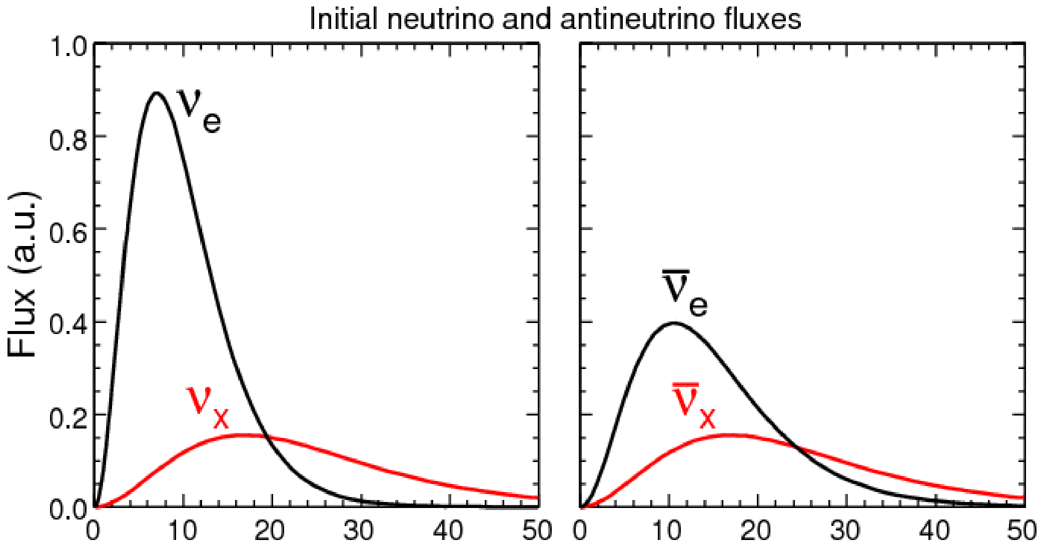
SUPERNOVA: **Non-periodic** since ν density decreases

Complete flavor conversions!

- Occurs for very small mixing angles
- Preserves the initial excess ν_e over $\bar{\nu}_e$ (lepton number conservation)

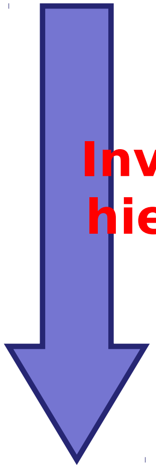
Spectral Splits in the Accretion Phase

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

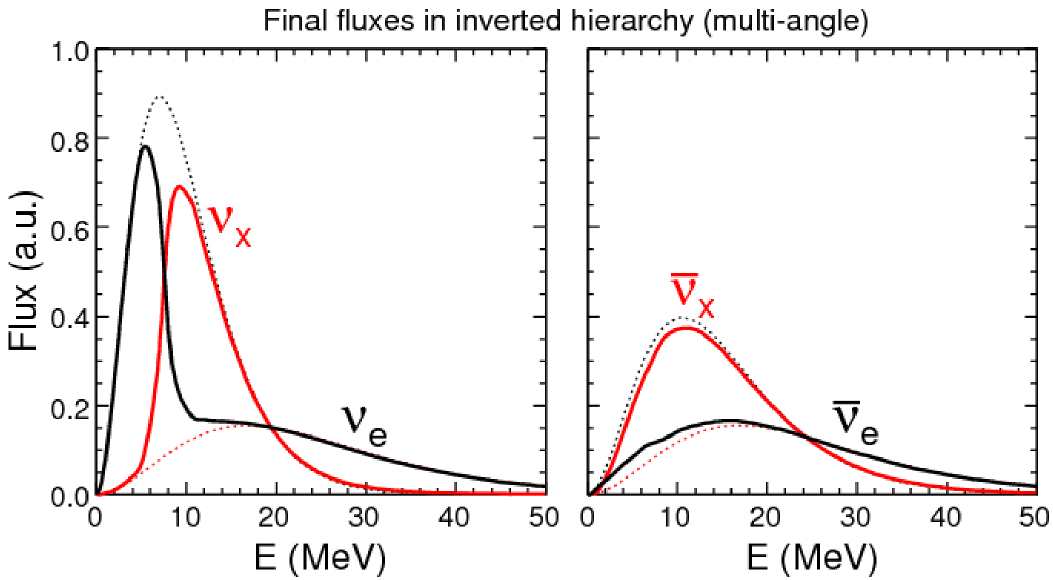


Initial fluxes typical of accretion phase at neutrinosphere (r ~10 km)

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



Inverted mass hierarchy (IH)

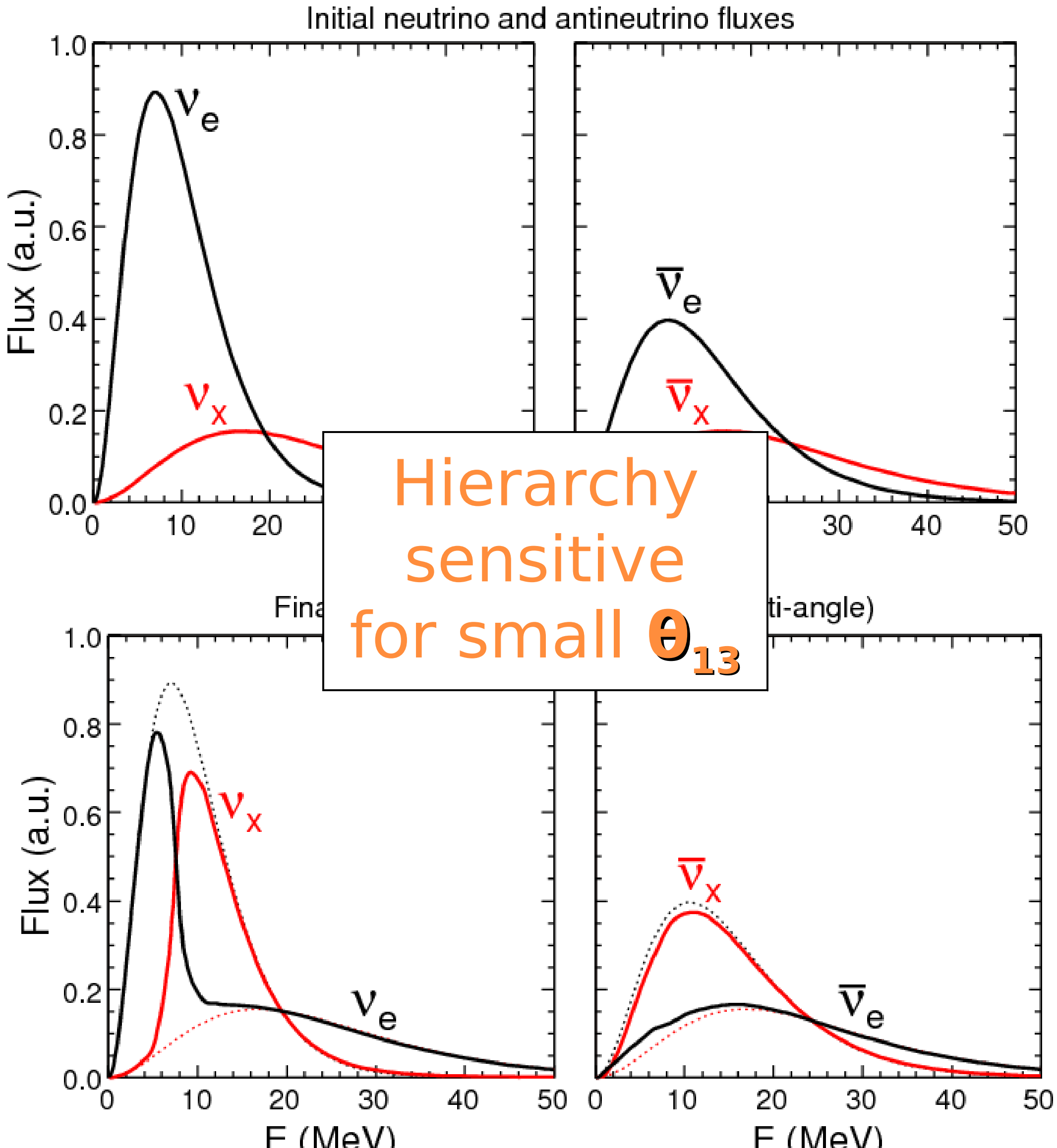


Fluxes at the end of collective effects (r ~200 km)

Nothing happens in Normal Hierarchy (NH)

Spectral Splits in the Accretion Phase

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



Hierarchy sensitive for small θ_{13}

Initial fluxes typical of accretion phase at neutrinosphere (r ~10 km)

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

Inverted mass hierarchy (IH)

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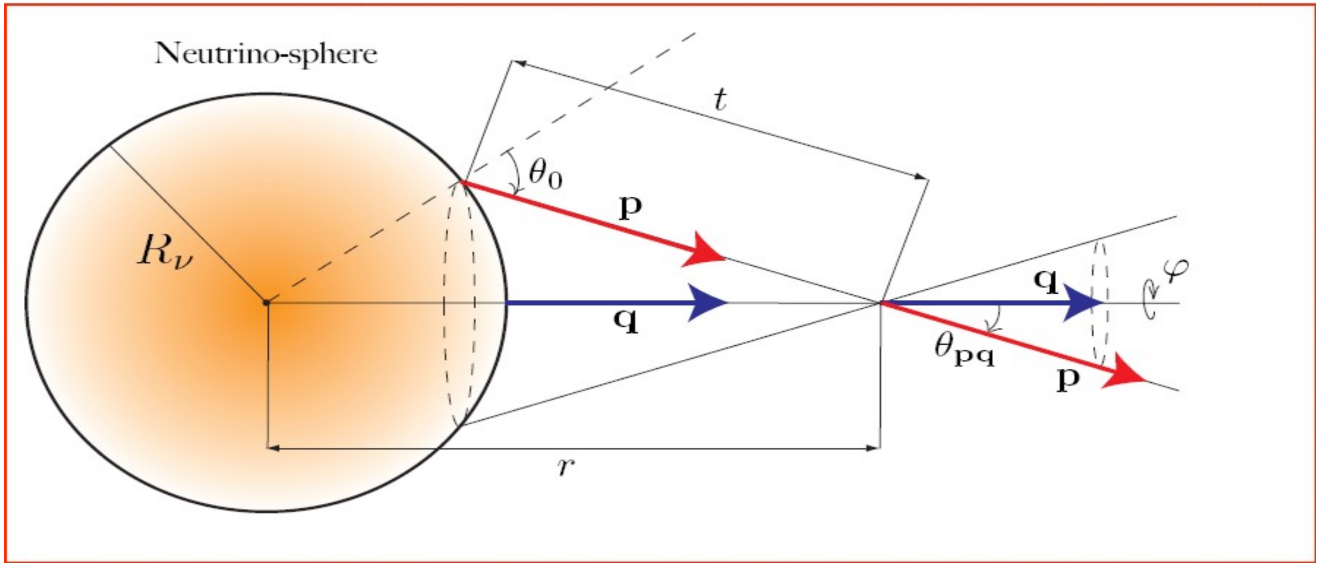
Matter Suppression



- Neutrinos emitted from spherical source, travel on different trajectories.
- Different oscillation phases for neutrinos traveling in different paths.
- Strong $\nu-\nu$ interaction can overcome trajectory dependent dispersion.

Collective conversion requires : $n_e \ll n_\nu$

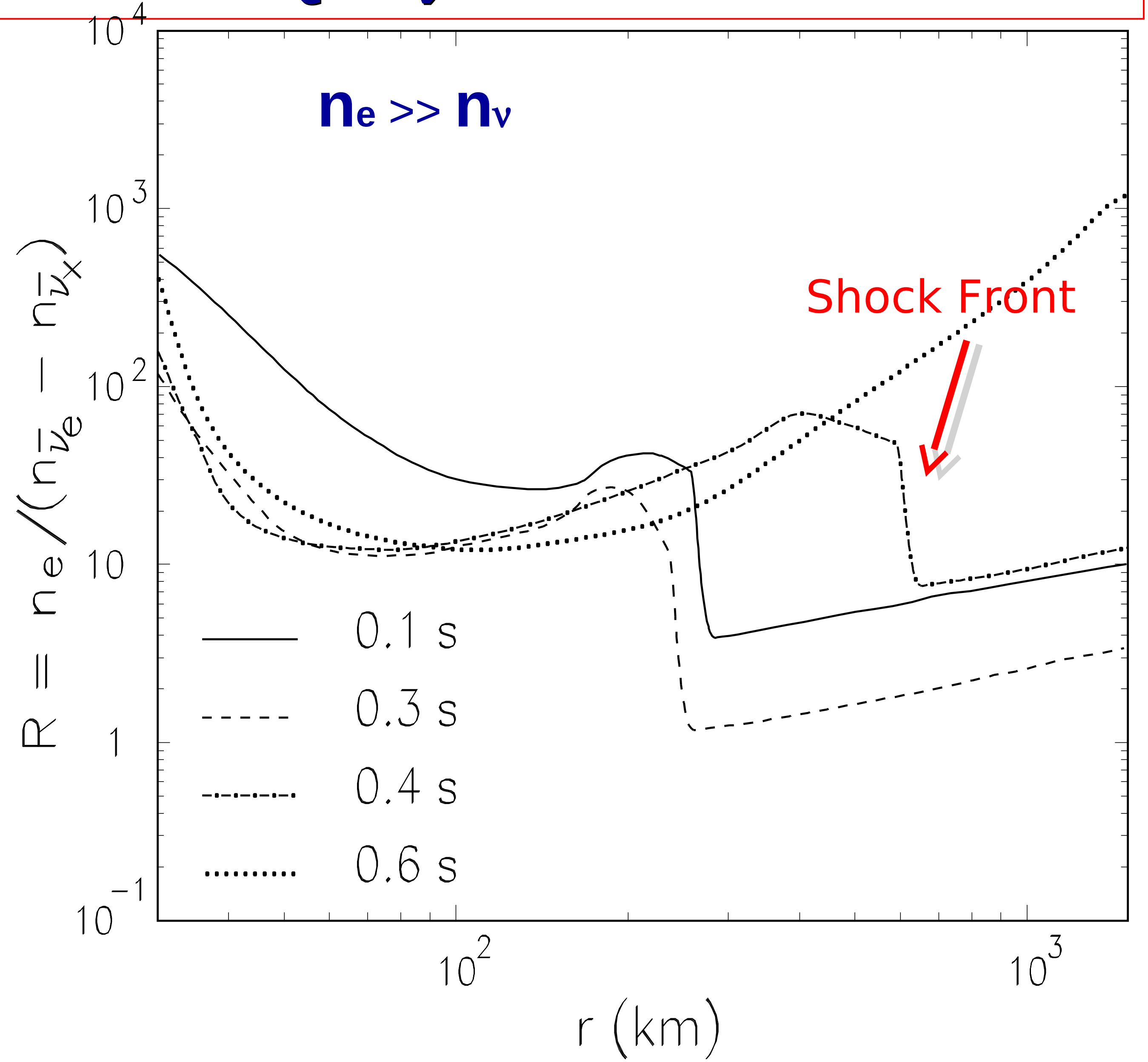
Collective conversion is matter Suppressed : $n_e \gtrsim n_\nu$

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

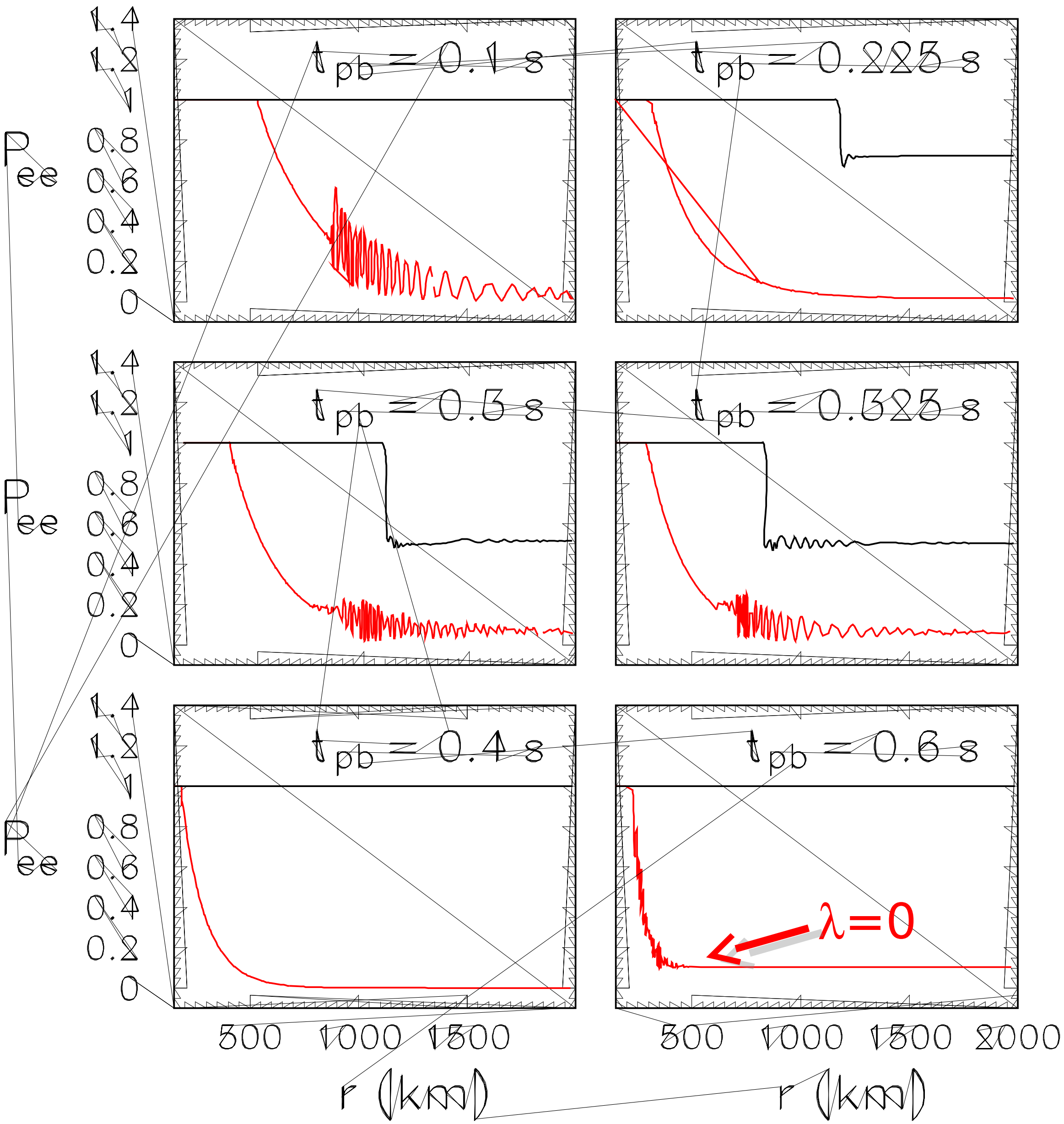
Radial Variation of the Ratio (R) between n_e, n_ν

(10.8 Solar Mass)

Dense Matter effect Suppresses Collective Oscillations



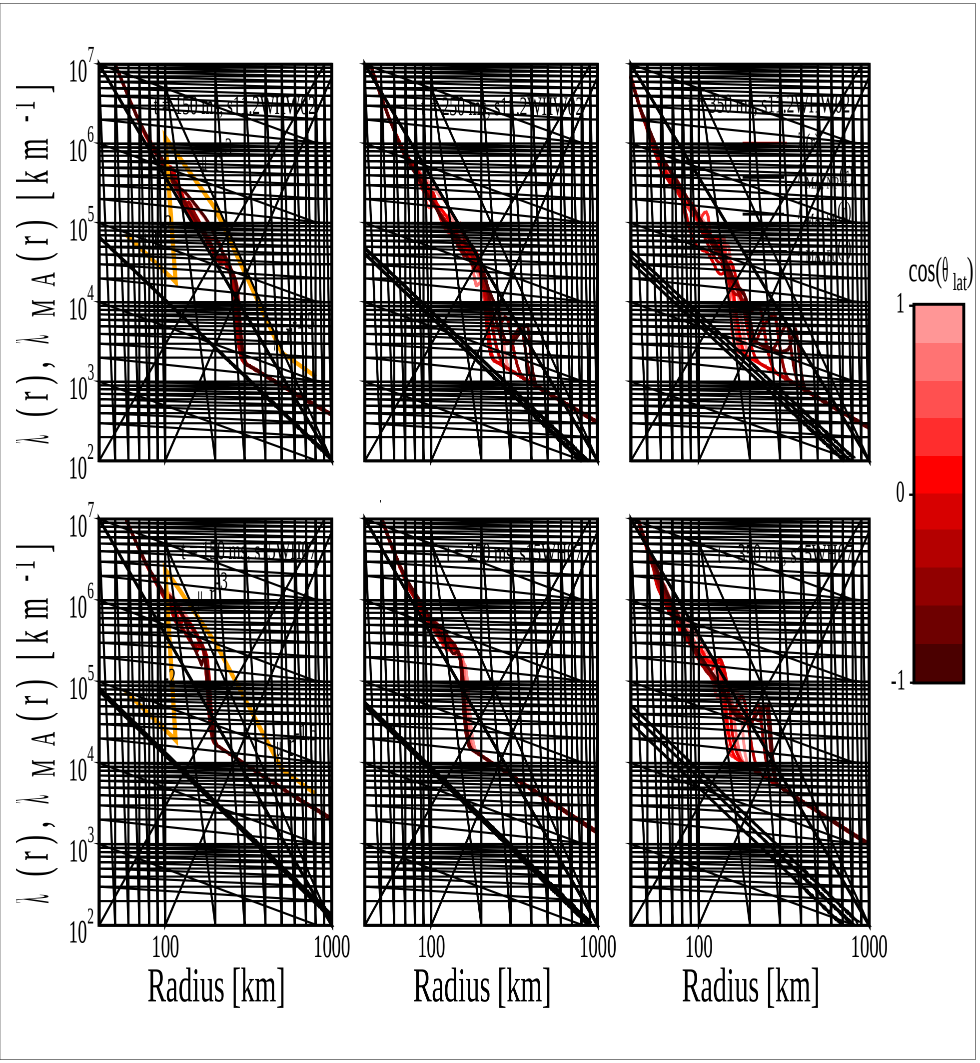
Radial Evolution of Survival Probability

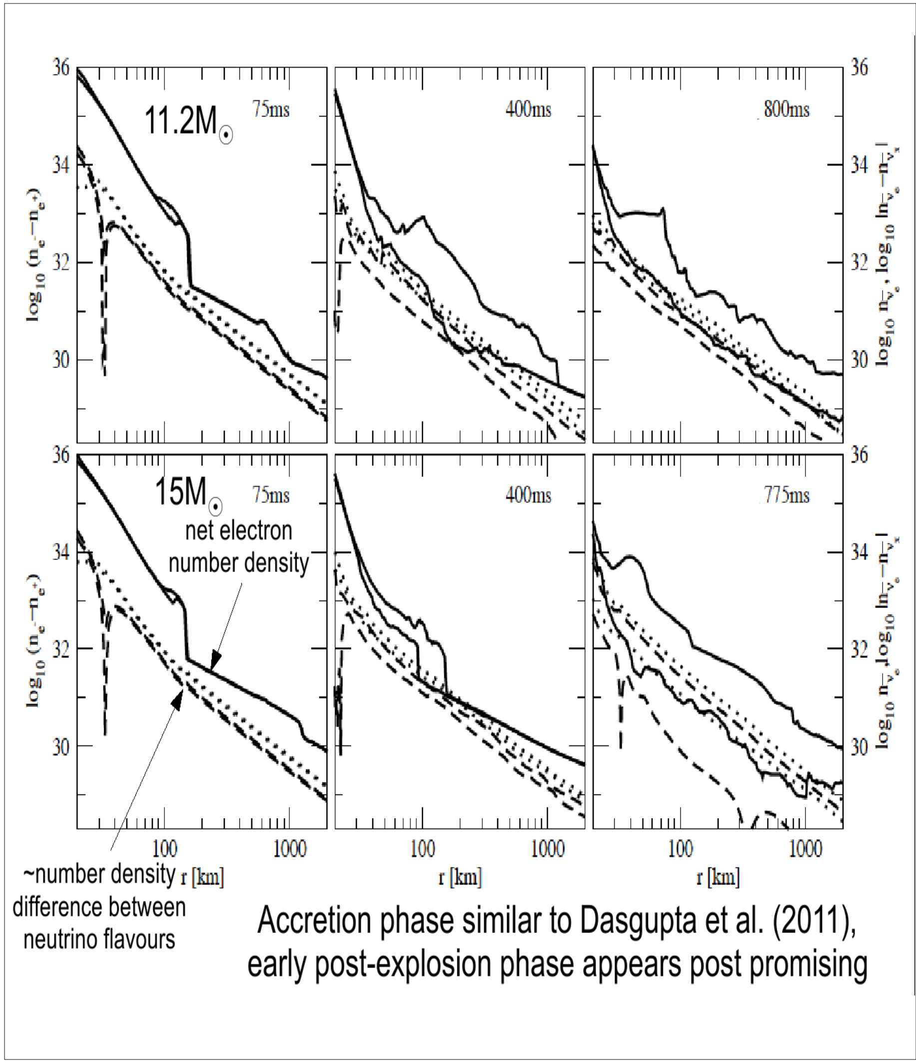


Dense Matter effect Suppresses Collective Oscillations

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

Similar Results from other Groups

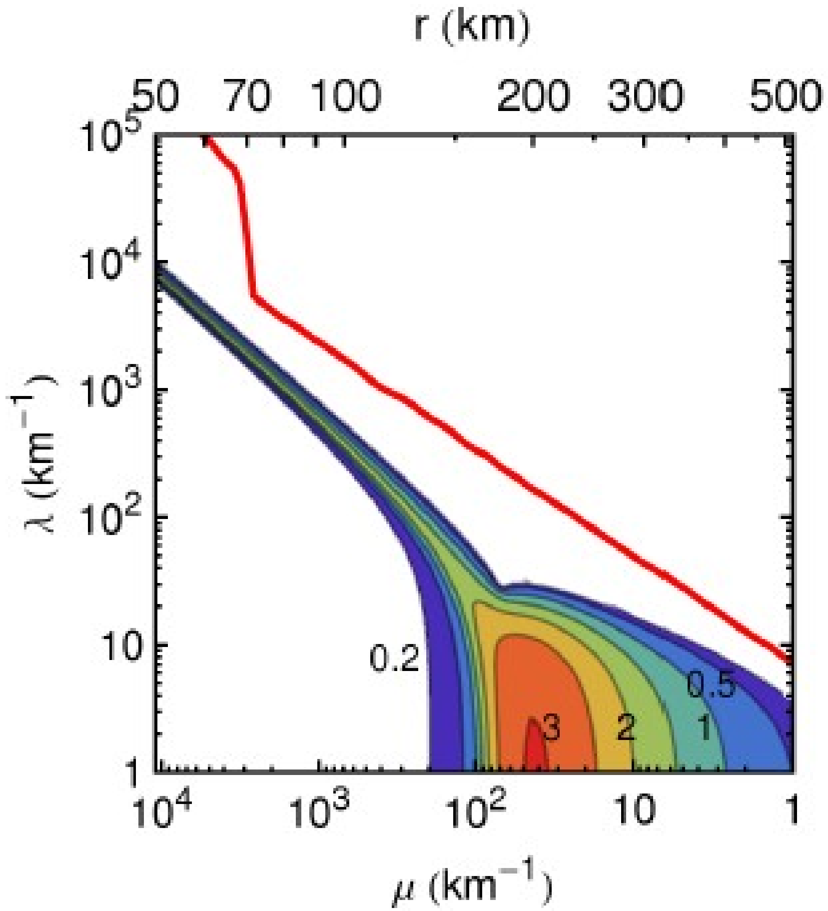




[Dasgupta, P. O'Connor, Ott PRD 85:065008, 2012]

[MPA, Garching Group, slide from B.Muller's talk at Hanse 2011, Hamburg]

Similar Results from Garching Simulations



15 Solar Mass

Contours of instability parameter ‘k’ in the (λ, μ) plane.
&
SN density profile at 280 ms

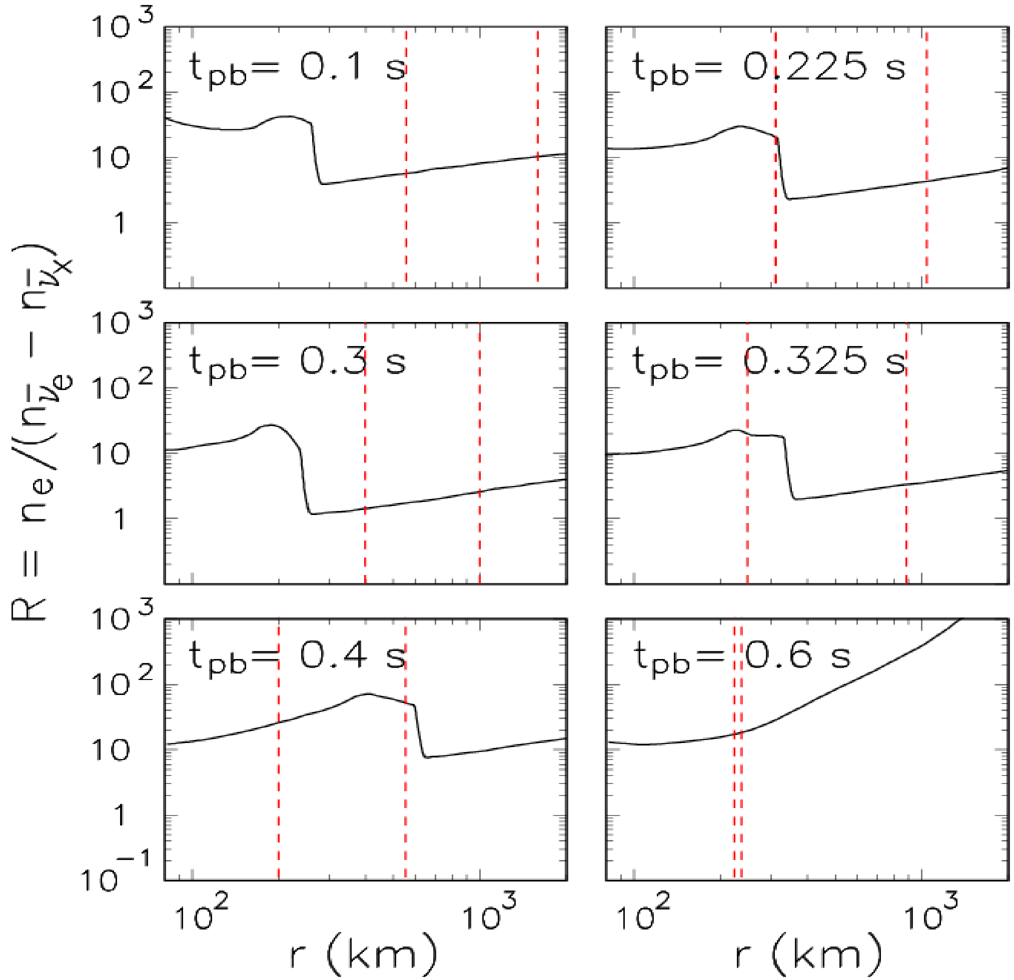
Self Induced flavor conversions do not occur

Sarikas, Raffelt, Hüdepohl & Janka
PRL 108:061101, 2012

Time Evolution of Radial Positions

Oscillation is not important for shock revival

- Oscillation suppressed by dense matter effect.
- Conversion (Synchronization) radius larger than shock radius.



S.C, Fischer, Mirizzi, Saviano &Tomas

PRL 107:151101, 2011

PRD 84:025002, 2011

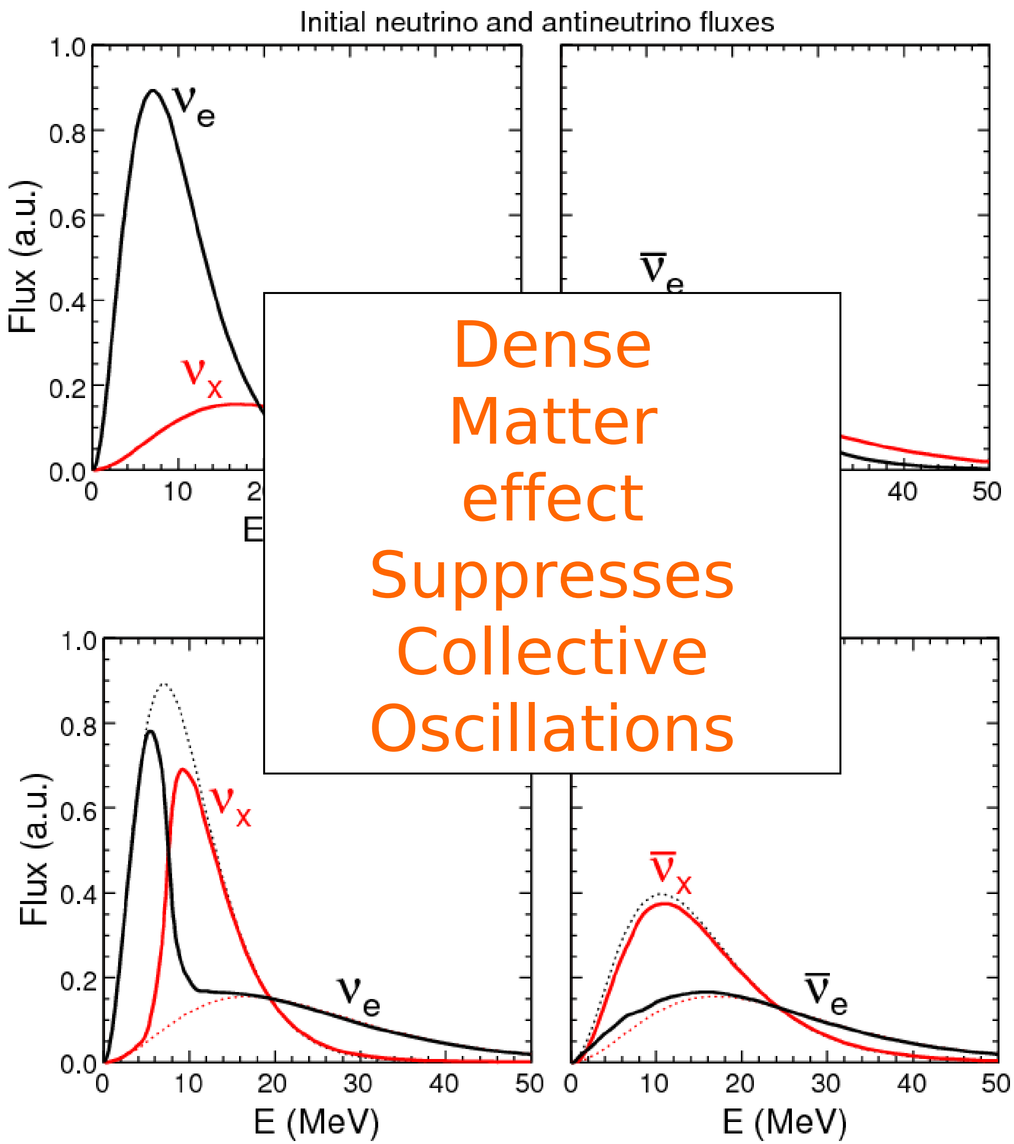
Also see,

Dasgupta, P. O'Connor, Ott

PRD 85:065008, 2012

Suppression of Collective effects

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



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PRD 85:065008, 2012]

Suppression of Collective effects

Predictions are robust when collective effects are suppressed, i.e.:

1) Neutronization burst (t < 20 ms)

large ν_e excess and ν_x deficit

[Hannestad et al., astro-ph/0608695]

2) Accretion phase (t < 500 ms)

Dense matter term dominates over nu-nu interaction term.

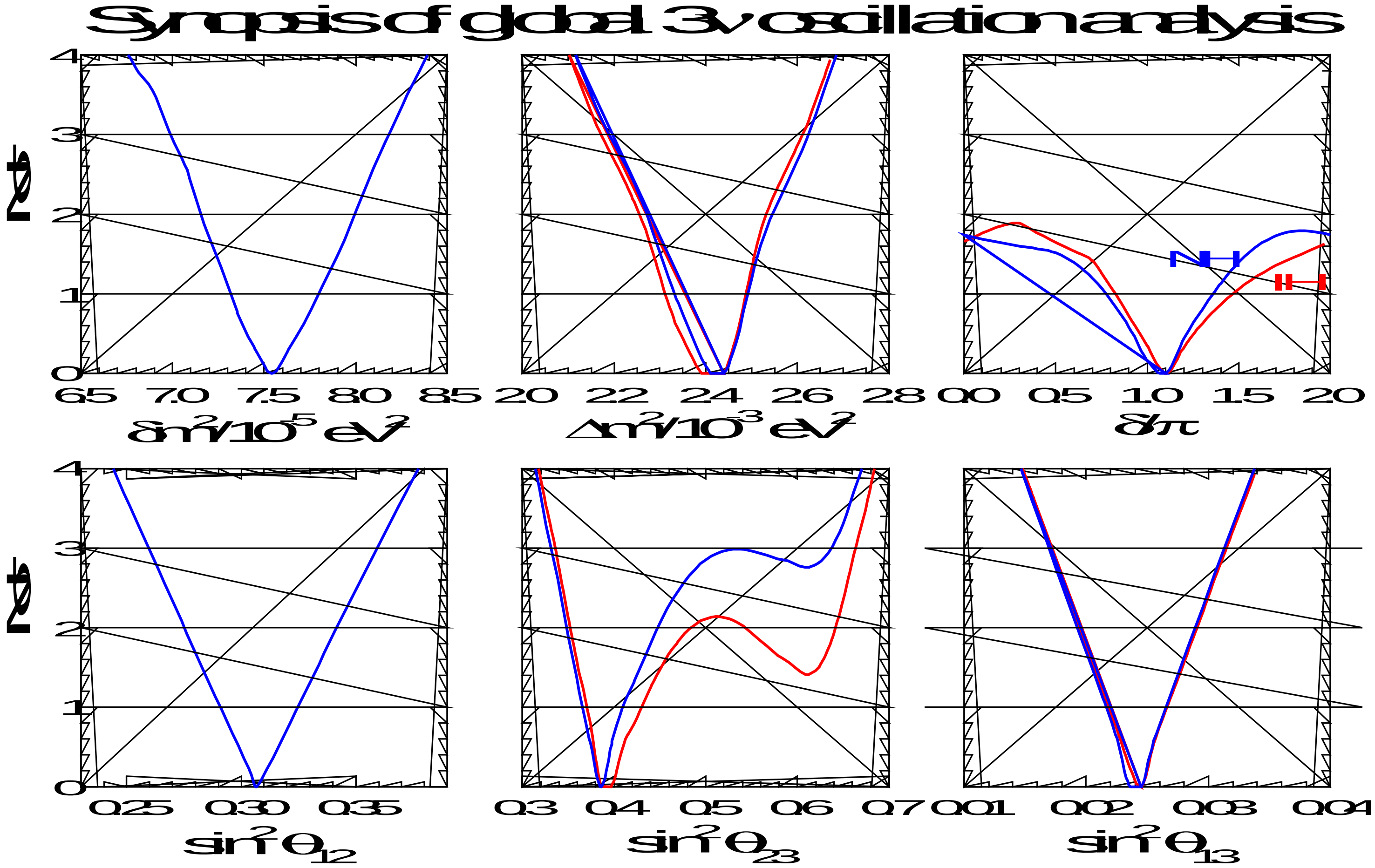
[**S.C**, Fischer, Mirizzi, Saviano &Tomas

PRL 107:151101, 2011
PRD 84:025002, 2011]

Discovery of large θ_{13}

T2K; MINOS; Double Chooz -> Large θ_{13}

Daya Bay-> $\sin^2 2\theta_{13} = 0.092 \pm 0.017$



[Fogli, Lisi, Marrone, Montanino, Palazzo & Rotunno, PRD 86:013012, 2012]

SN neutrino Flux at Earth

Neutronization burst & Accretion Phase:

Normal Hierarchy (NH):

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

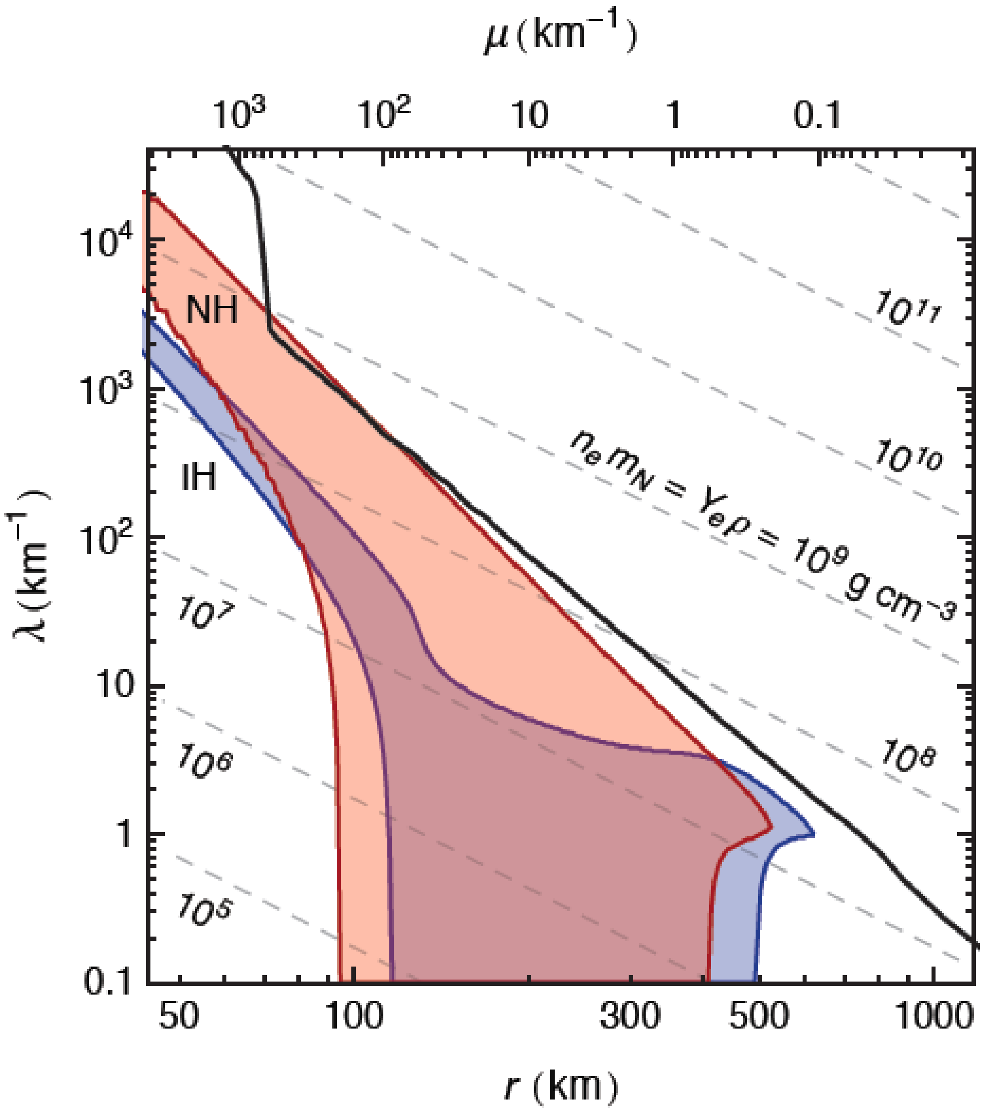
$$F_{\bar{\nu}_e} = \cos^2\vartheta_{12}(F^0_{\bar{\nu}_e} - F^0_{\nu_x}) + F^0_{\nu_x}$$

Inverted Hierarchy (IH):

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

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

Removal of axial symmetry



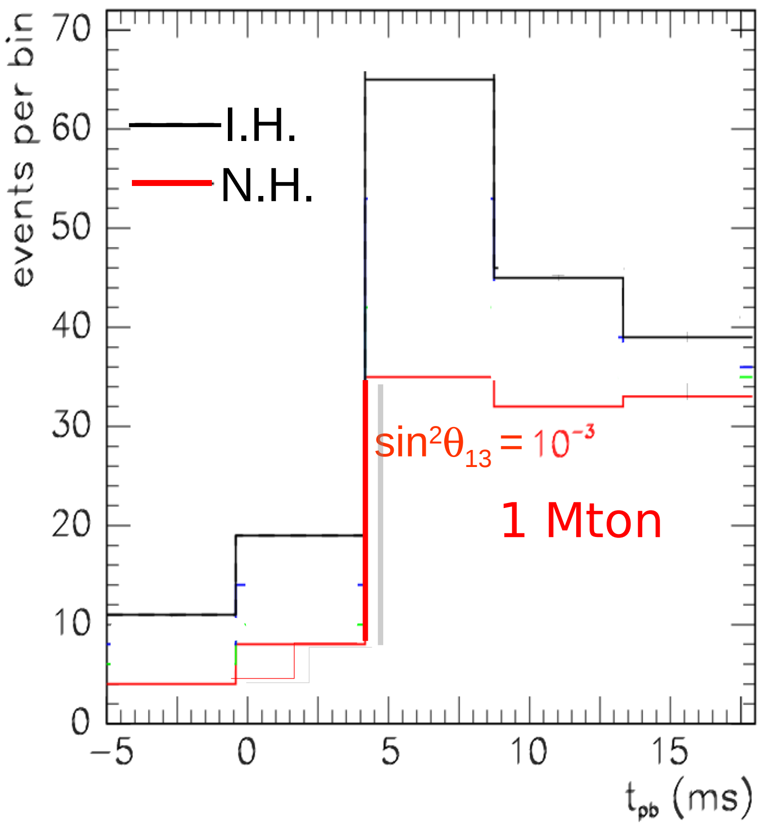
15 Solar Mass

Contours of instability parameter 'k' in the (λ, μ) plane.
&
SN density profile at 280 ms

Sarikas, Raffelt, David arxiv: 1305.7140

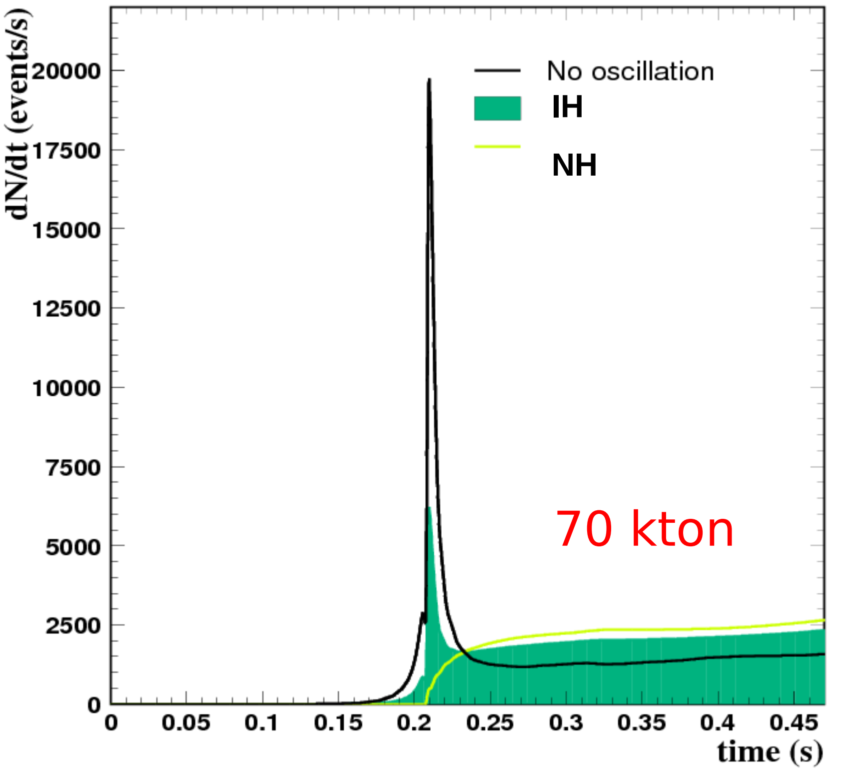
Oscillations in the Neutronization Burst

Water Cherencov $(\nu_{e,x}\ e^- \longrightarrow \nu_{e,x}\ e^-)$



[M.Kachelriess et al, hep-ph/0412082]

Liq Ar TPC $\nu_e\ ^{40}Ar$ CC



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

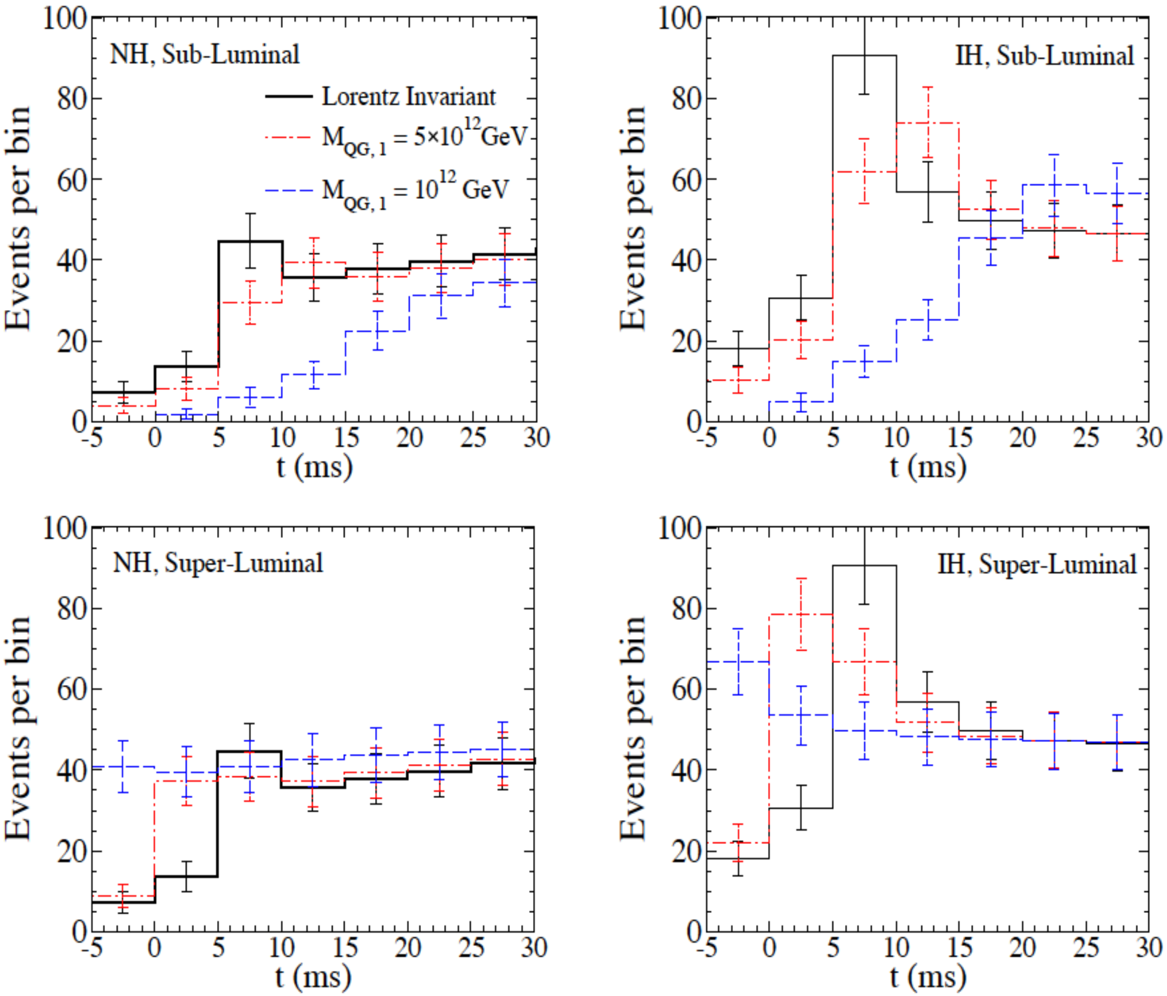
- Peak is absent ⟶ NH $(F_{\nu_e} = F^0_{\nu_x})$
- Peak is seen ⟶ IH $(F_{\nu_e} = \sin^2\vartheta_{12}(F^0_{\nu_e} - F^0_{\nu_x}) + F^0_{\nu_x})$

SN Bounds on Neutrino Velocity

Violation of Lorentz invariance

[Ellis et al., 0805.0253 & 1110.4848]

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



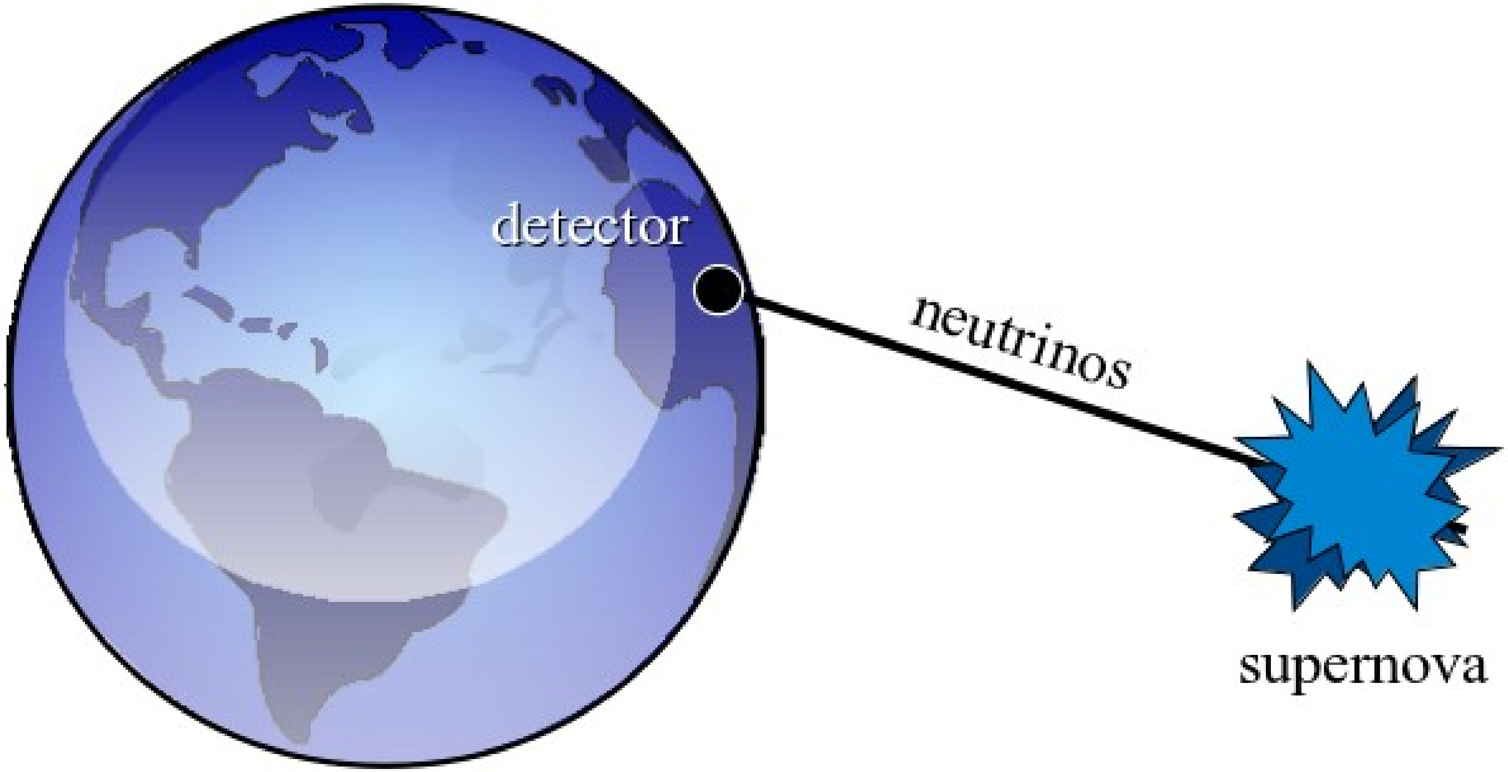
The signal would be spread out and shifted in time.

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

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

SN neutrino Flux at Earth

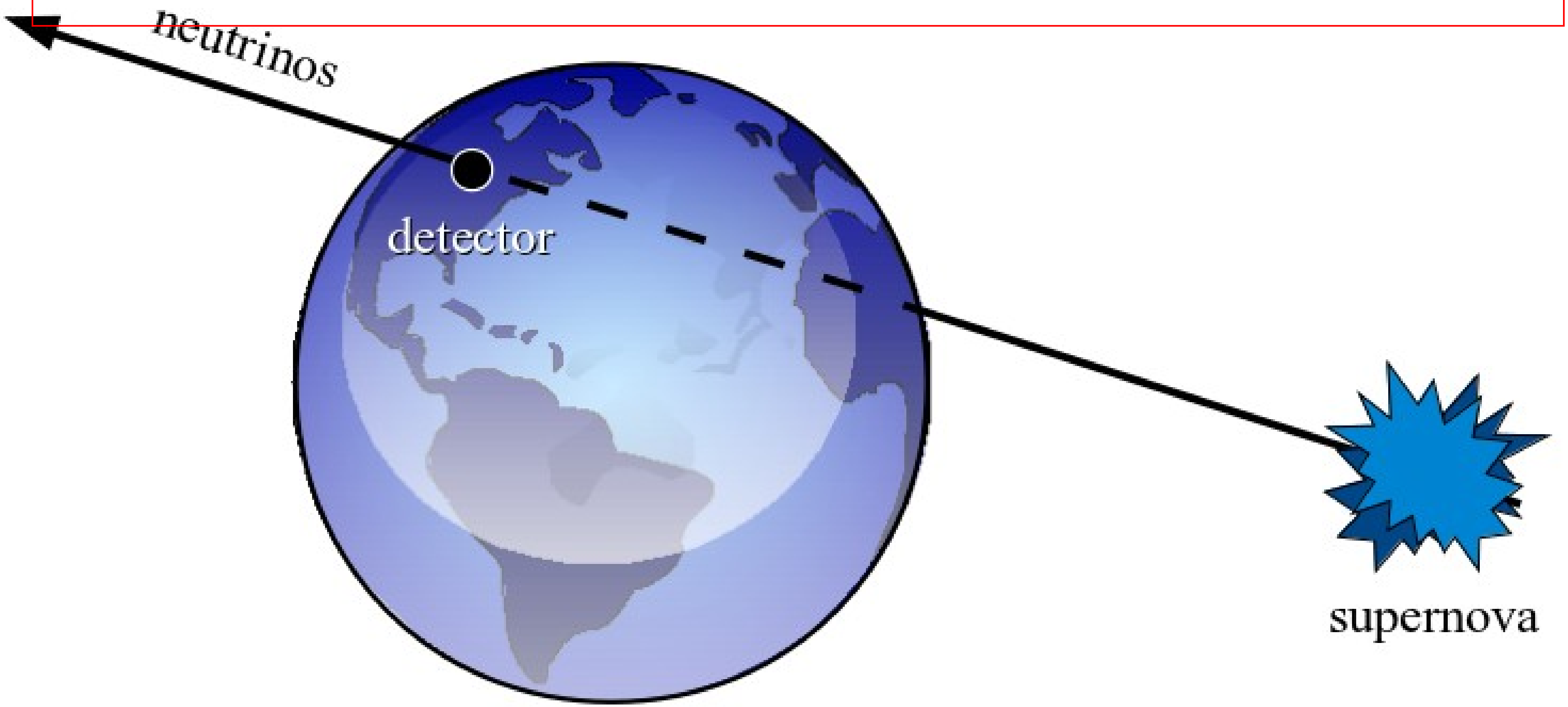
Earth Matter Effect:



LENA?

SN neutrino Flux at Earth

Earth Matter Effect:



LENA?

SN neutrino Flux at Earth

Earth Matter Effect:

$$F_{\bar{e}}^{D} = \sin^2\theta_{12} F_{\bar{x}}^{0} + \cos^2\theta_{12} F_{\bar{e}}^{0} + \Delta F^{0} \bar{A}_{\oplus} \sin^2(12.5\,\overline{\Delta m^2_{\oplus}} L/E)$$

Normal Hierarchy (NH):

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

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

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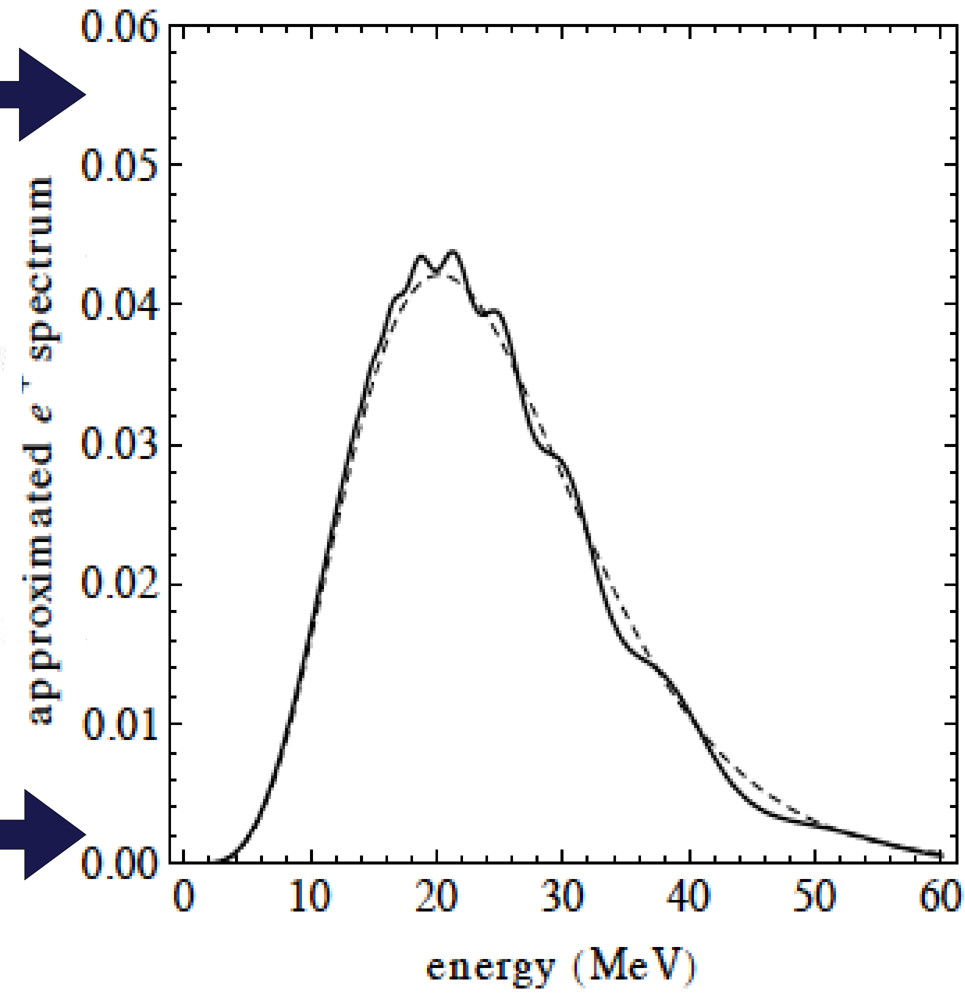

[Dighe, Keil & Raffelt, hep-ph/0304150]

SN neutrino Flux at Earth

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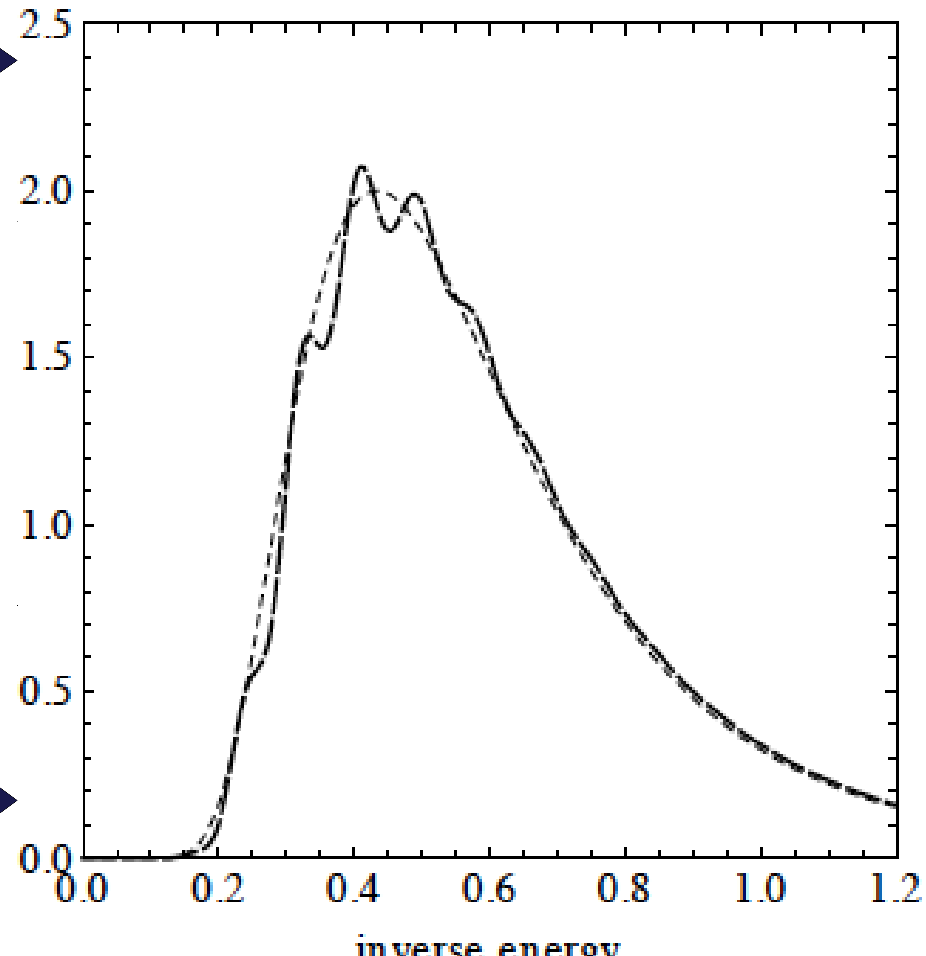

[Dighe, Keil & Raffelt, hep-ph/0304150]

SN neutrino Flux at Earth

Earth Matter Effect:

$$F^D_{\bar{e}} = \sin^2\theta_{12} F^0_{\bar{x}} + \cos^2\theta_{12} F^0_{\bar{e}} + \Delta F^0 \bar{A}_\oplus \sin^2(12.5\,\overline{\Delta m^2_\oplus} L/E)$$

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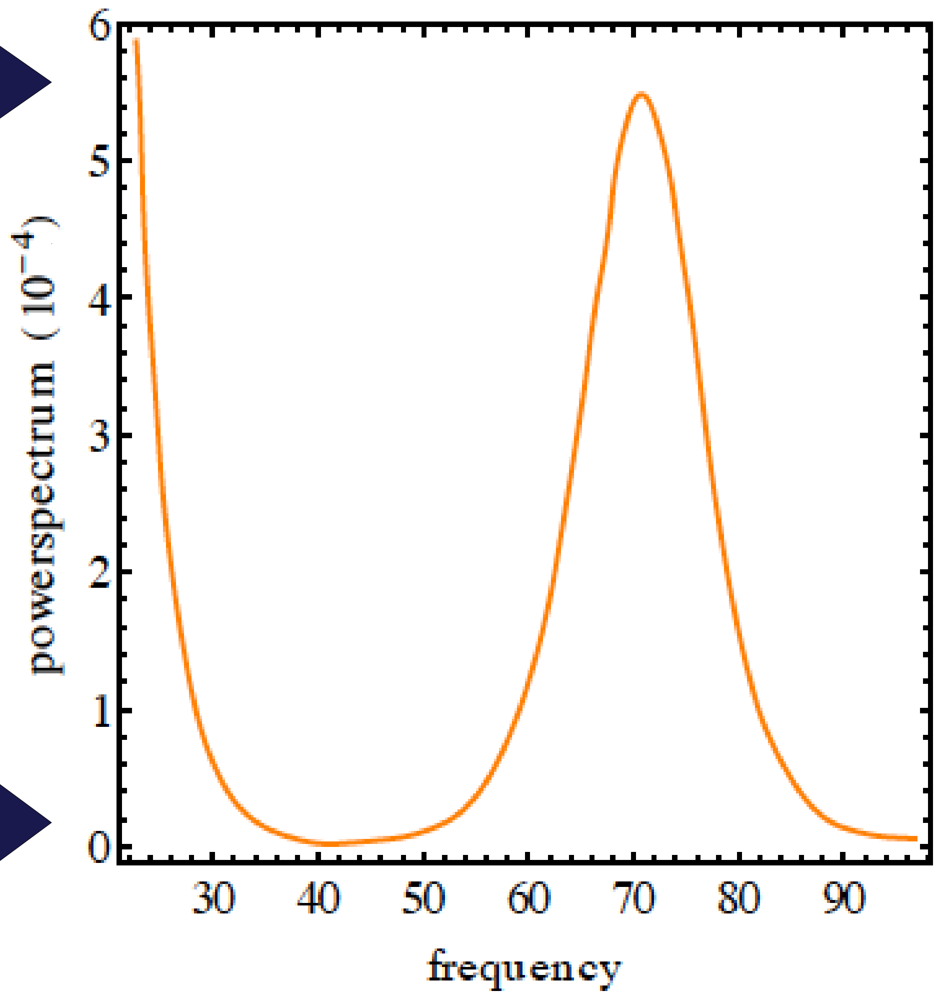


[Dighe, Keil & Raffelt, hep-ph/0304150]

SN neutrino Flux at Earth

Earth Matter Effect:

$$F_{\bar{e}}^{D} = \sin^2\theta_{12} F_{\bar{x}}^0 + \cos^2\theta_{12} F_{\bar{e}}^0 + \Delta F^0 \bar{A}_{\oplus} \sin^2(12.5\,\overline{\Delta m^2_{\oplus}} L/E)$$

Normal Hierarchy (NH):

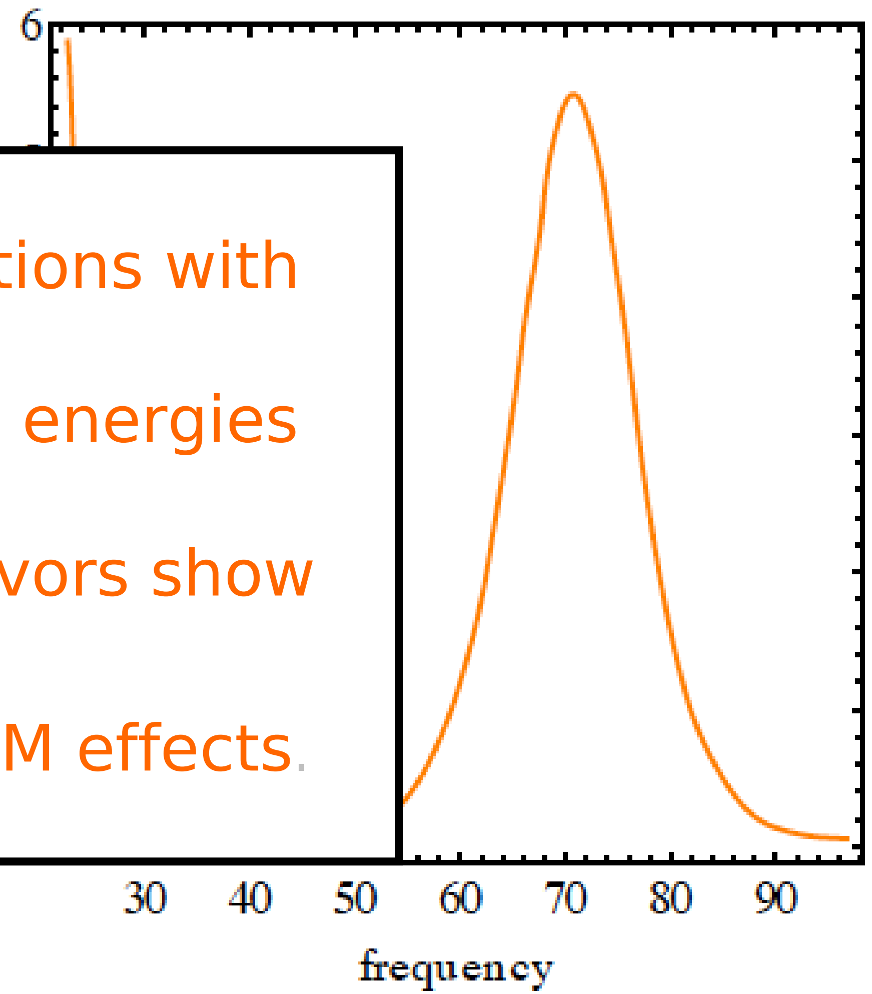
$$F_{\nu_e} = F^0_{\nu_x}$$

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

Inverted Hierarchy (

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

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

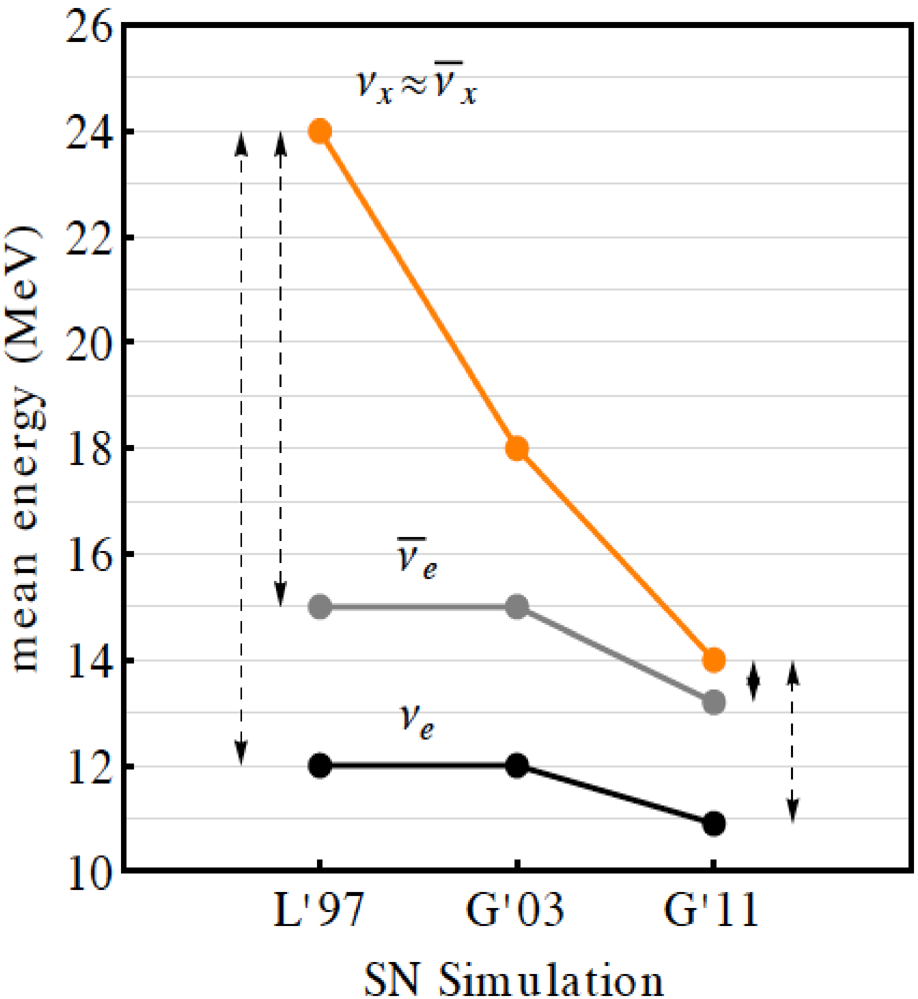


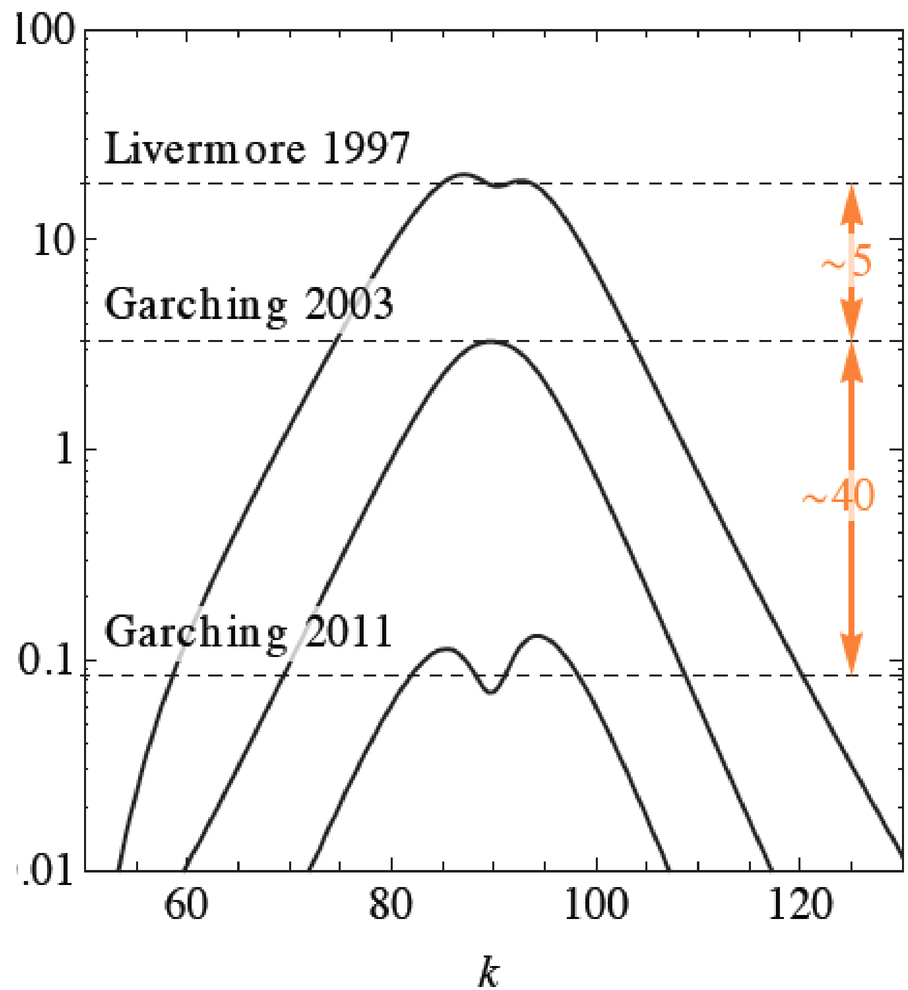
Recent simulations with close average energies of different flavors show **negligible** EM effects.

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

SN antineutrino Flux at Earth

Earth Matter Effect:

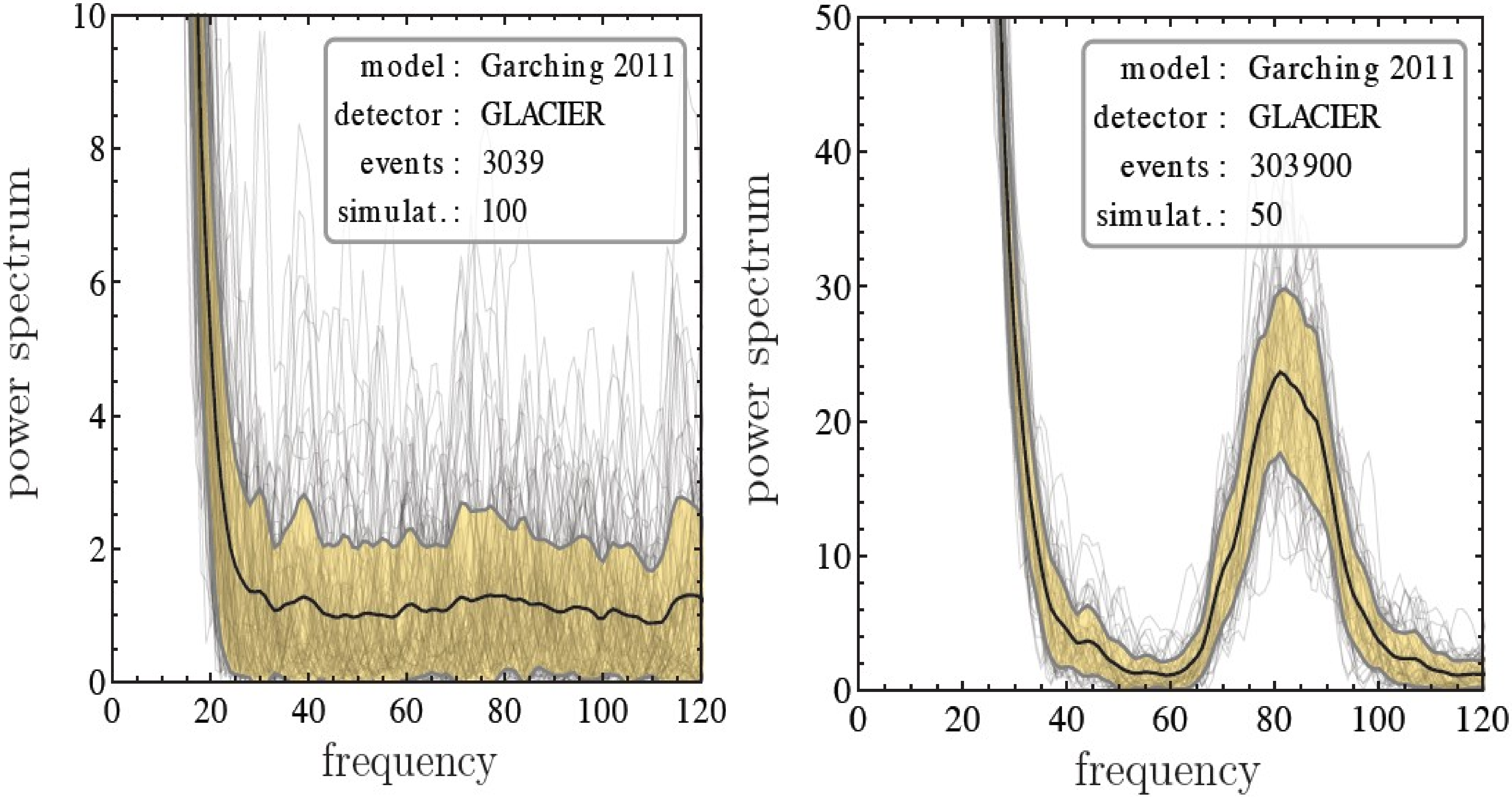




[Borriello, S.C, Mirizzi, Serpico; PRD 86 (2012)]

SN neutrino Flux at Earth

Earth Matter Effect:

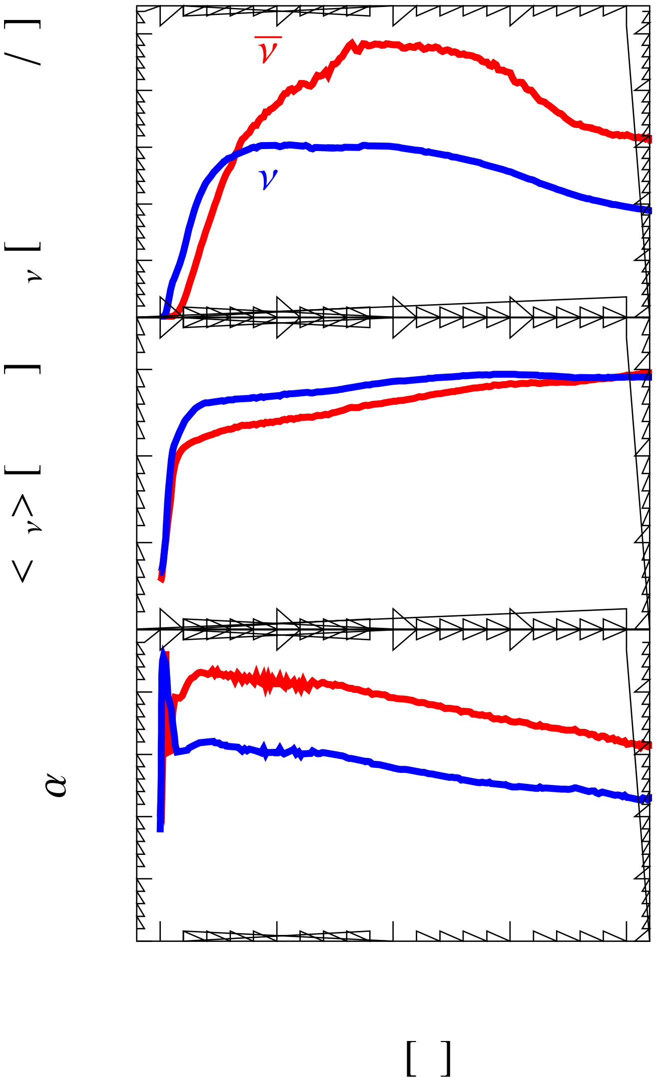


[Borriello, S.C, Mirizzi, Serpico; PRD 86 (2012)]

Rise time Analysis: Hierarchy Determination

15 Solar Mass

Garching



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

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

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

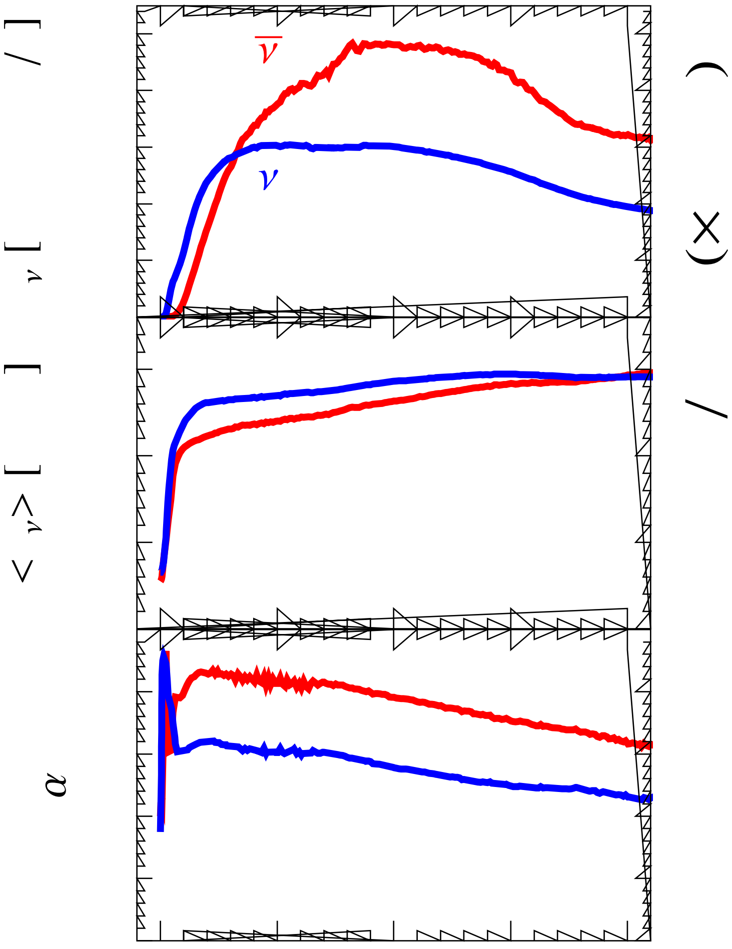
Flux in IH (ν_x) rises faster than NH (ν_x, $\bar{\nu}_e$)

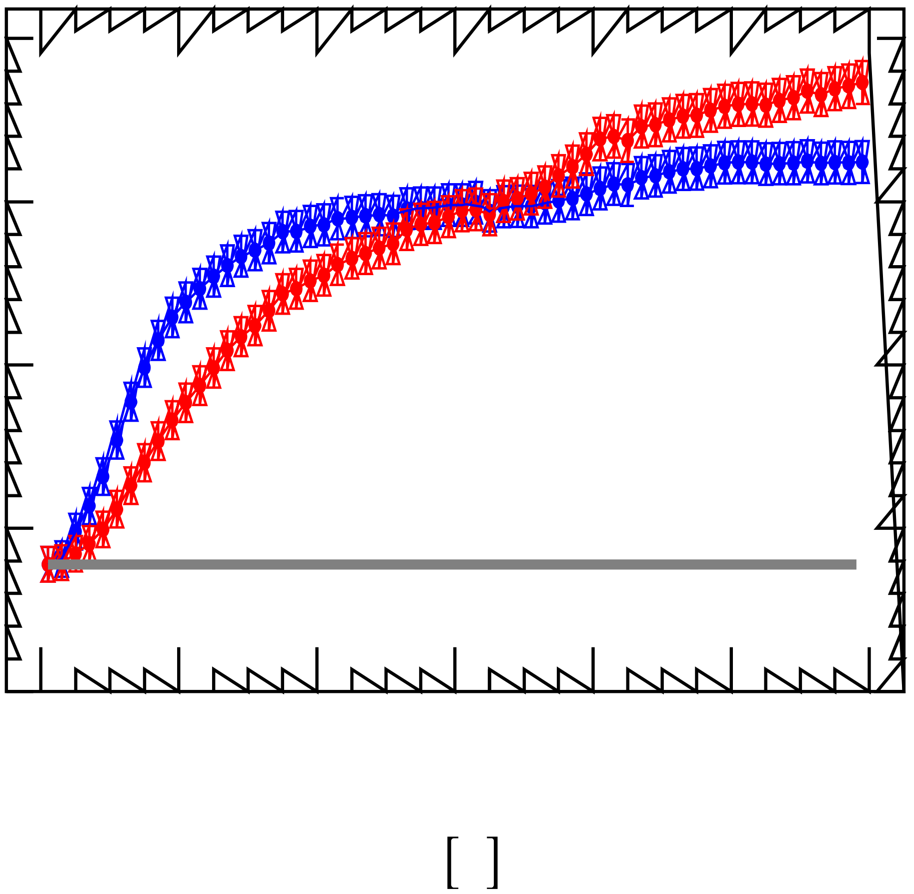
[Serpico, **S.C**, Fischer, Hüdepohl, Janka & Mirizzi
PRD 85:085031,2012]

Rise time Analysis: Hierarchy Determination

Garching

15 Solar Mass
in Ice-Cube





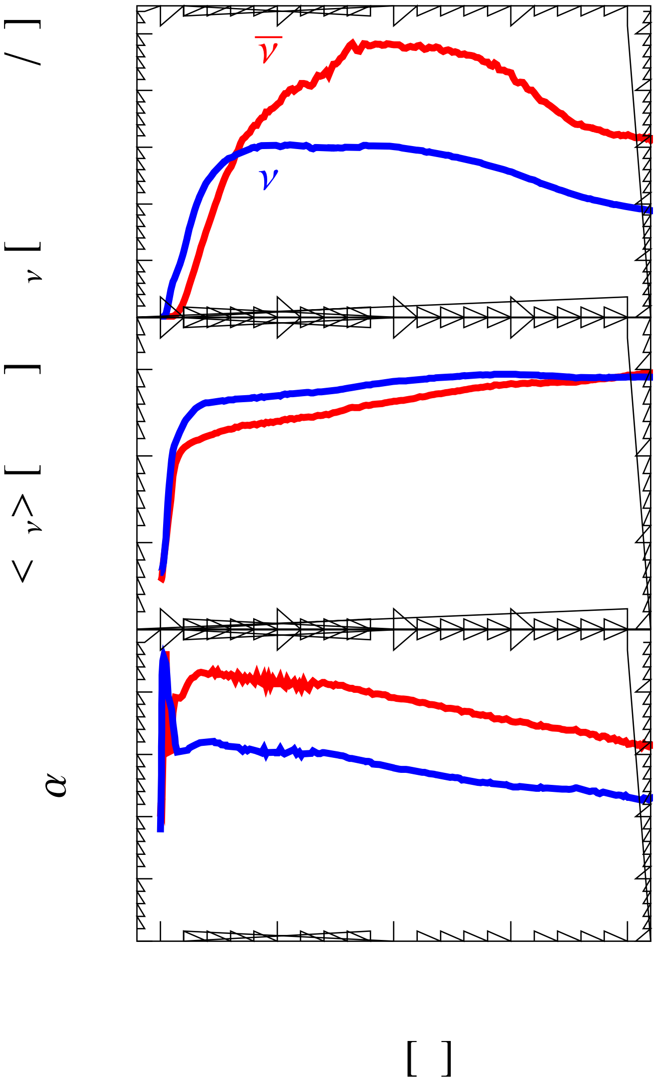
Flux in IH rises faster than NH

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

Rise time Analysis: Hierarchy Determination

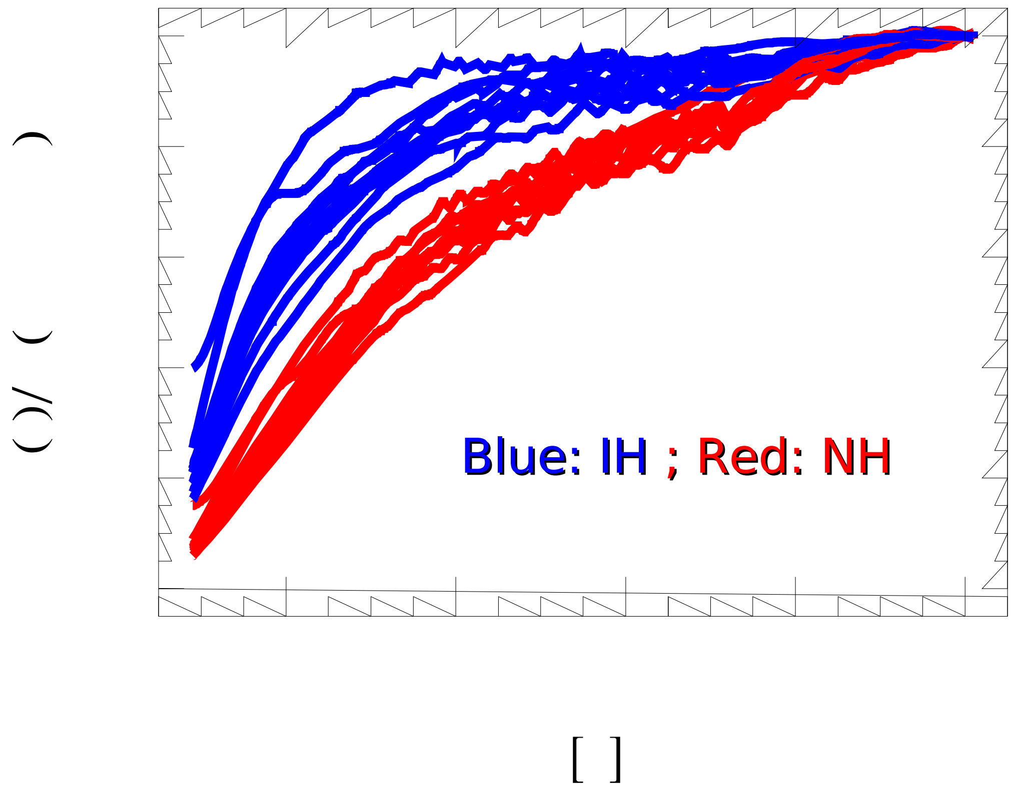
Garching

15 Solar Mass in Ice-Cube



Normalized Count rate :

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



Flux in IH rises faster than NH

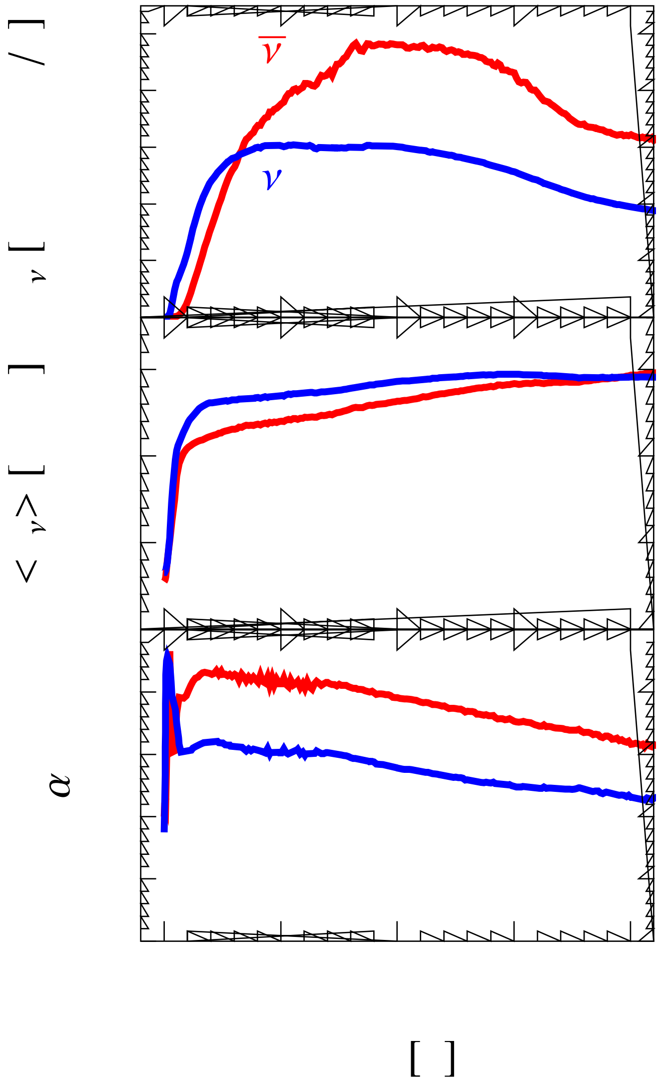
[Serpico, **S.C**, Fischer, Hüdepohl, Janka & Mirizzi **PRD 85:085031,2012**]

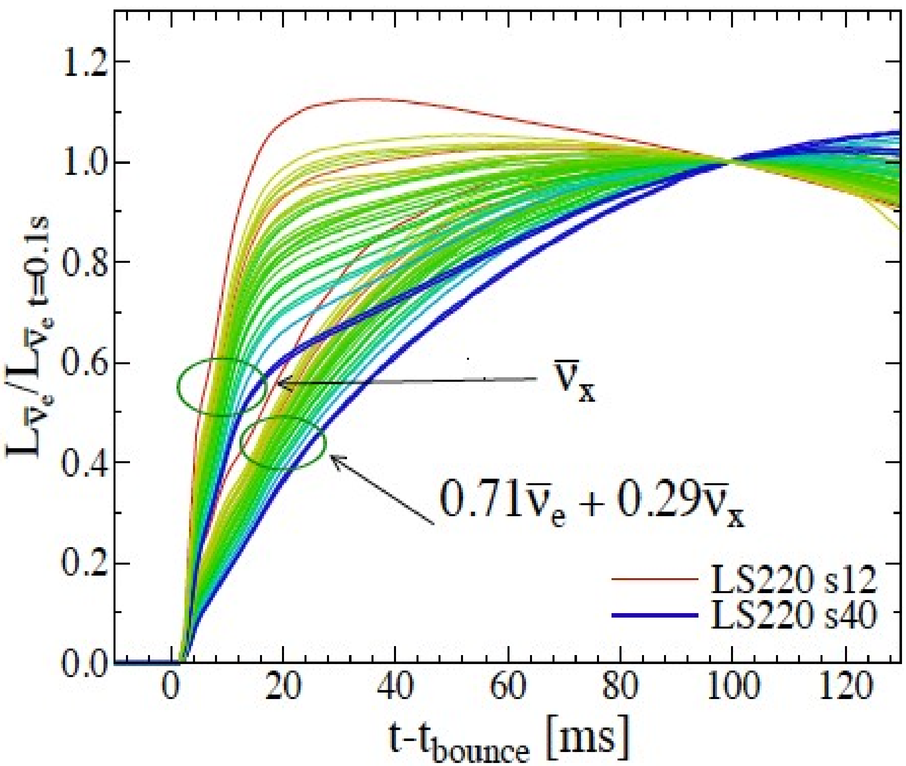
Rise time Analysis: Hierarchy Determination

Garching

15 Solar Mass in Ice-Cube

Normalized Count rate : 32 different models





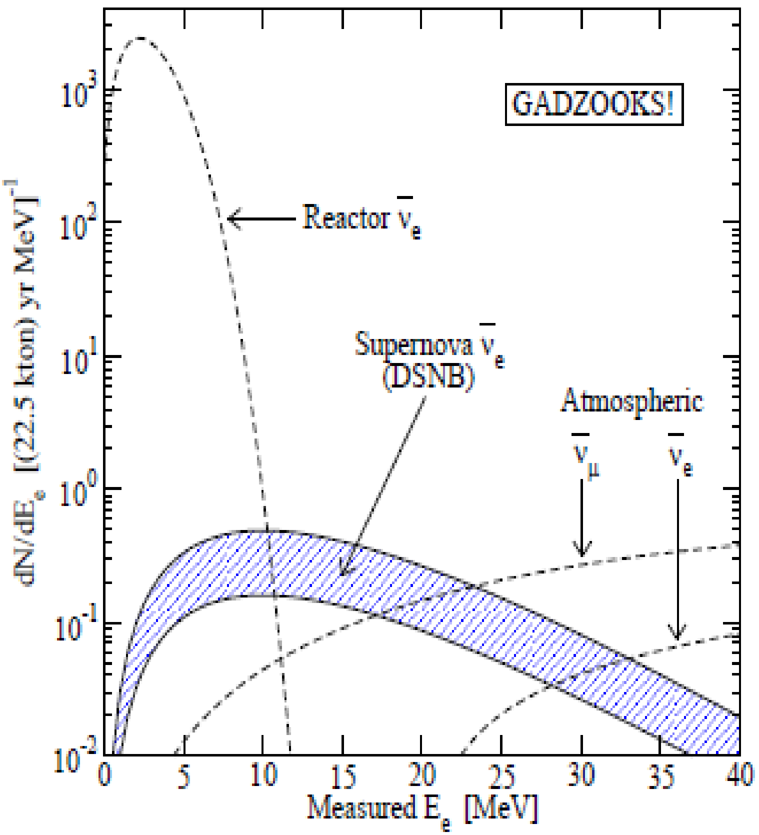
Flux in IH rises faster than NH

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

Diffuse SN Neutrino Background (DSNB)

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

[*Beacom & Vagins, hep-ph/0309300*



Window of opportunity
bkg less than signal

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

ν astronomy at cosmic distances !

Conclusions

- **Observing SN neutrinos is the next frontier of low-energy neutrino astronomy.**

- **Collective effects are suppressed in early SN phases, implying hierarchy sensitivity at large θ_{13}.**

- **Earth Matter effect: Detectable for Sub-kpc SNe.**

- **New physics scenarios can be constrained.**

- **Rise time of SNe signal contains hierarchy information.**


LOOKING FORWARD
FOR THE NEXT
GALACTIC SN !
Thank You !