Physics Opportunities with Supernova Neutrinos

Sovan Chakraborty

MPI for Physics, Munich

IOP, Bhubaneswar, January, 2015

MARIE CURIE ACTIONS

MAX-PLANCK-GESELLSCHAFT

WHY SUPERNOVA NEUTRINOS?

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

Neutrino detection

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

Neutrino theory/phenomenology

NEUTRINO OSCILLATIONS in extreme astrophysical environment. Sensitivity to ν mixing

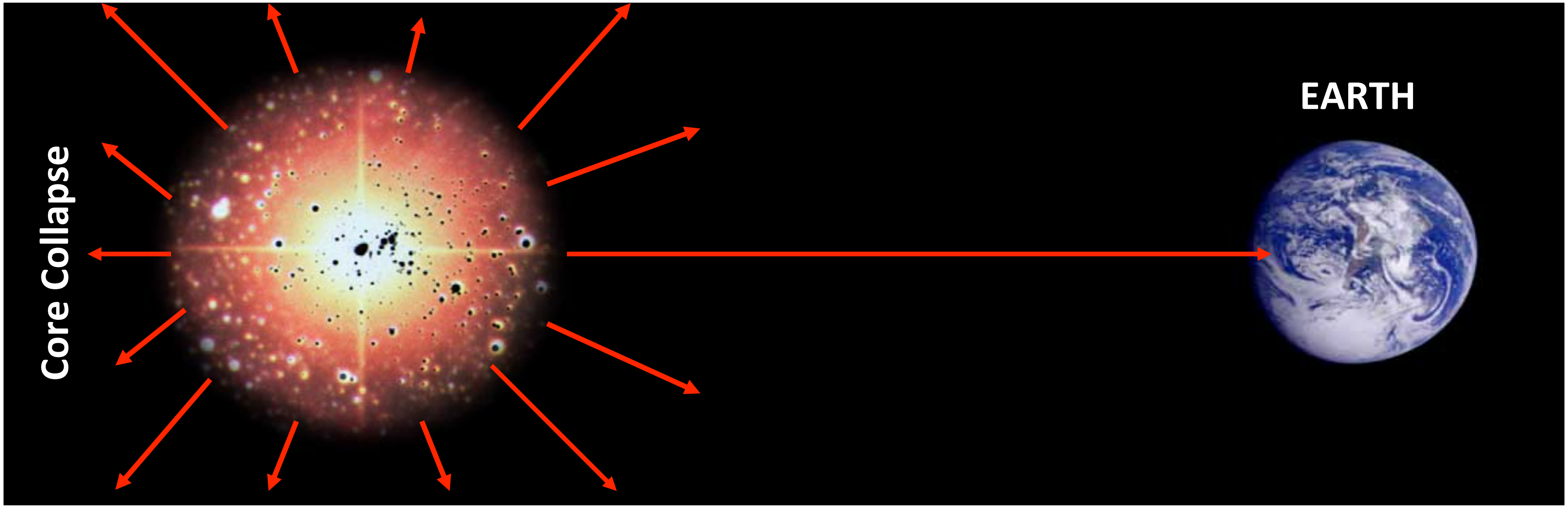
Neutrino astrophysics

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

TYPICAL PROBLEMS IN SUPERNOVA NEUTRINOS



Production (flavor)

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

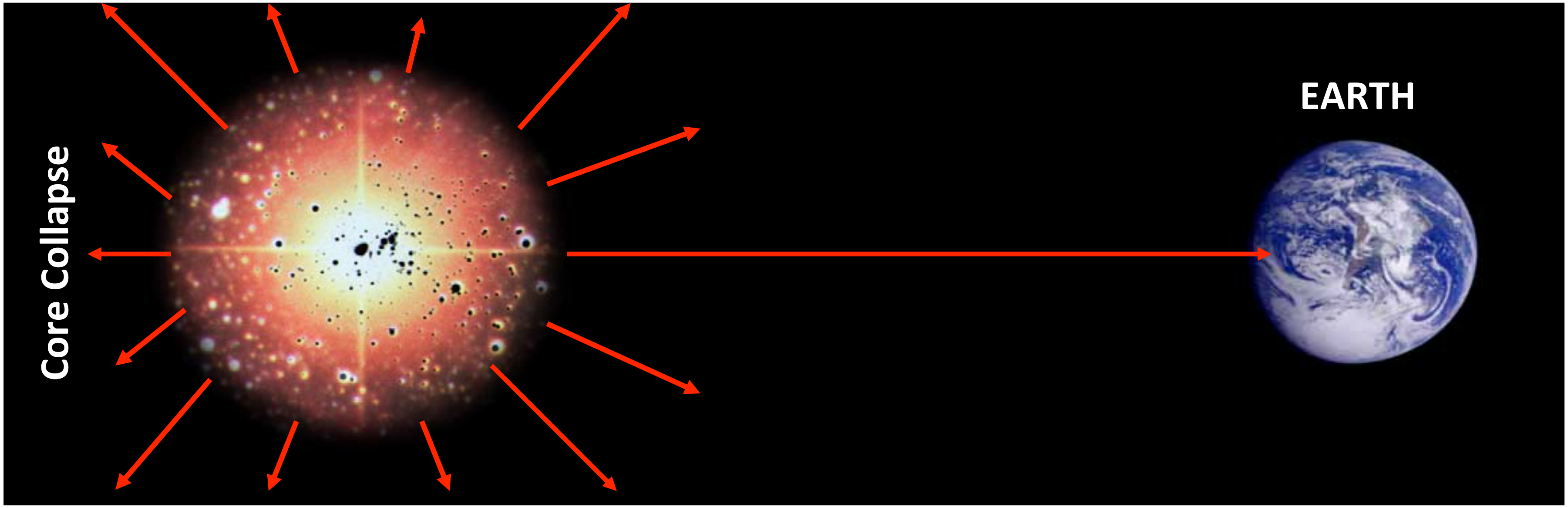
Propagation (mass,mixing)

- 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

TYPICAL PROBLEMS IN SUPERNOVA NEUTRINOS

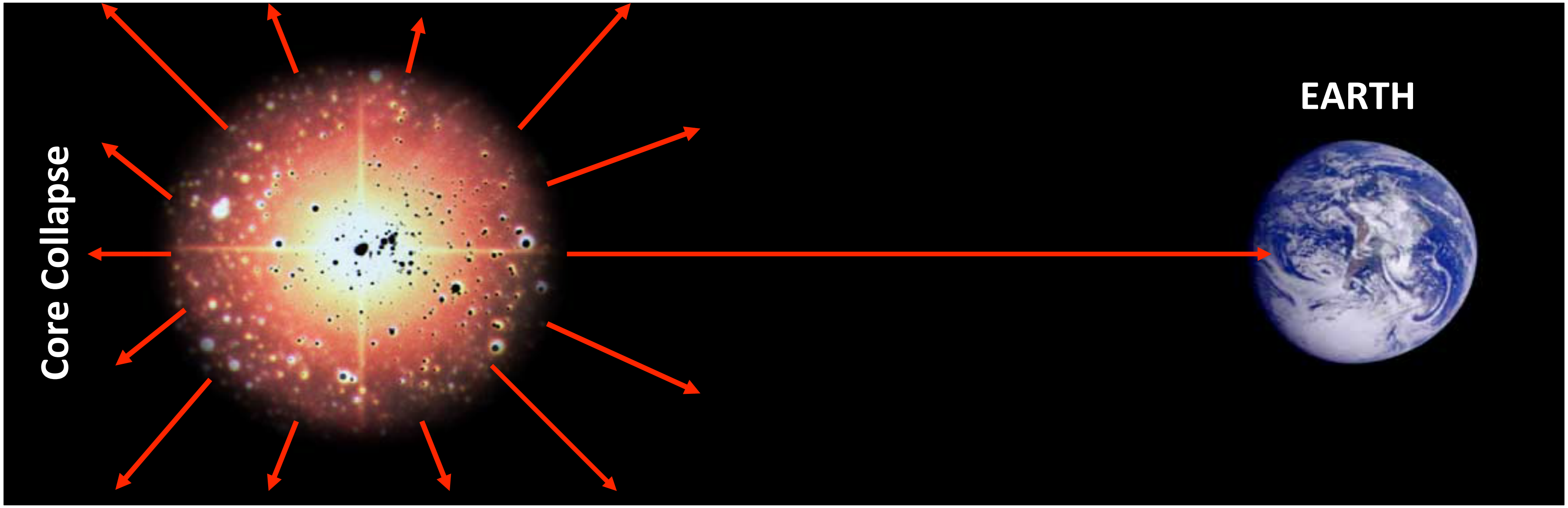


Supernova (SN) as Neutrino Source

Oscillation of SN Neutrinos

Neutrino Signal at Detectors

TYPICAL PROBLEMS IN SUPERNOVA NEUTRINOS



Supernova (SN) as Neutrino Source

Oscillation of SN Neutrinos

Neutrino Signal at Detectors

Supernova one of the most energetic events in nature.

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

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

ENERGY SCALE:

99% energy (10^{53} ergs) 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**

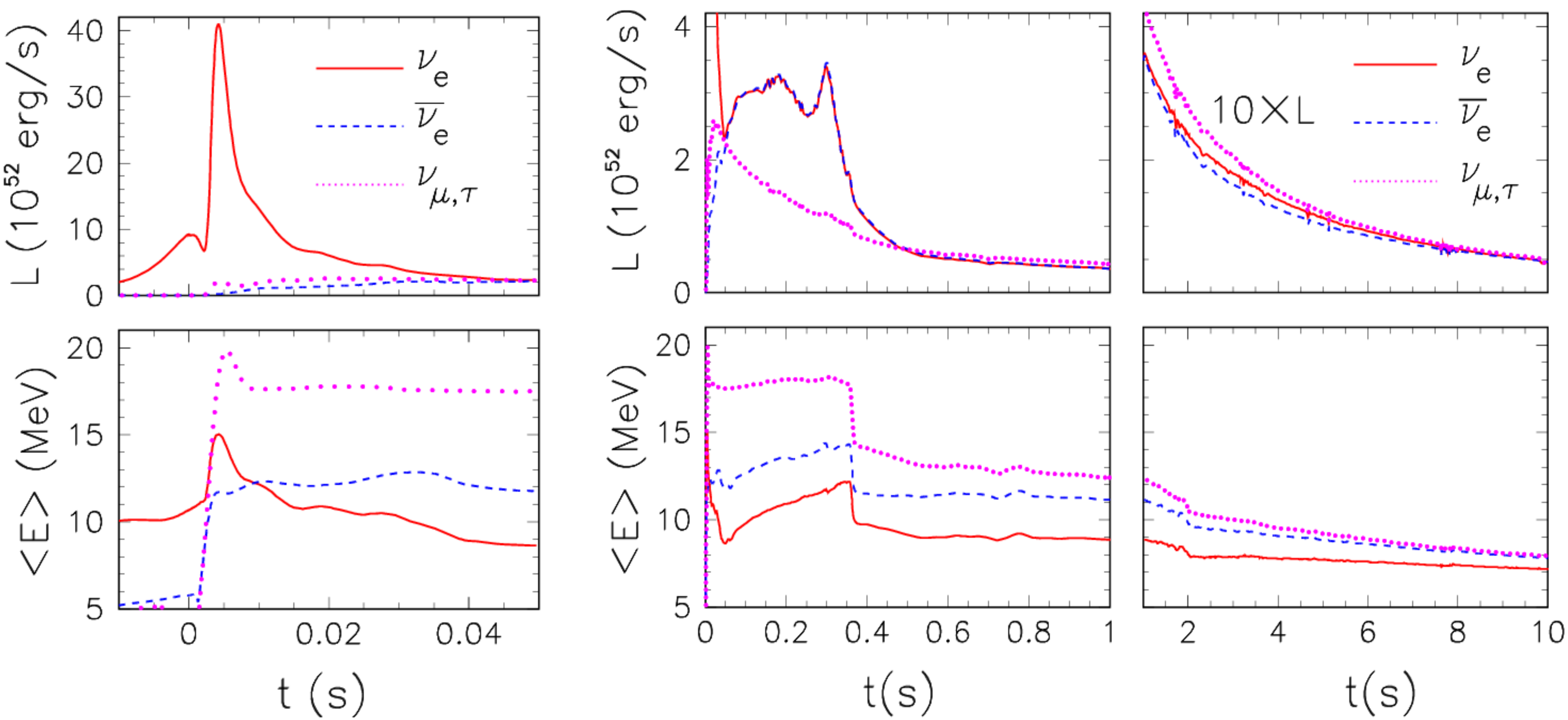
Accretion

- powered by infalling matter
- Stalled shock

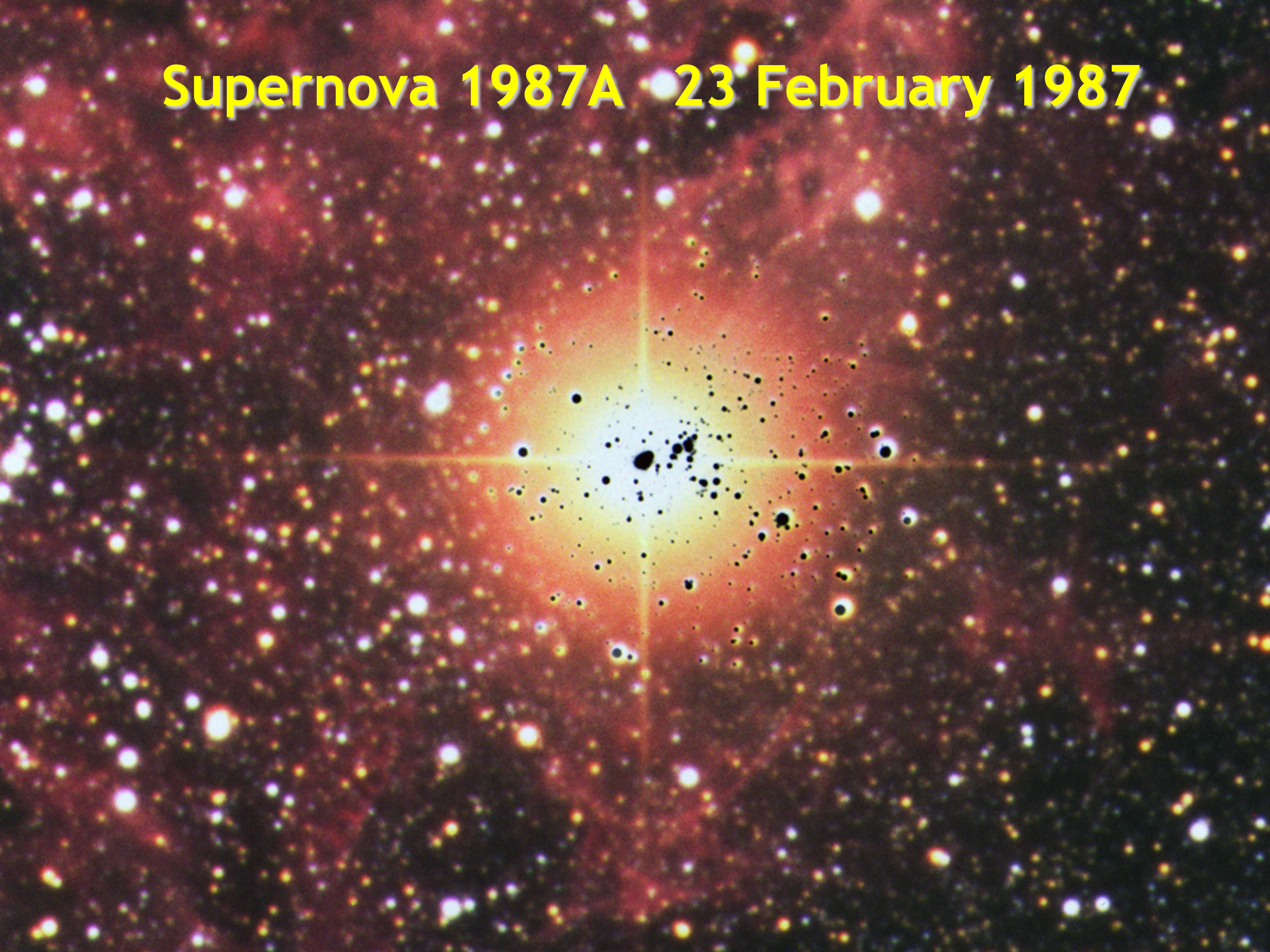
Cooling

- Cooling by ν diffusion

Accretion: ~ 0.5 s ; Cooling: ~ 10 s

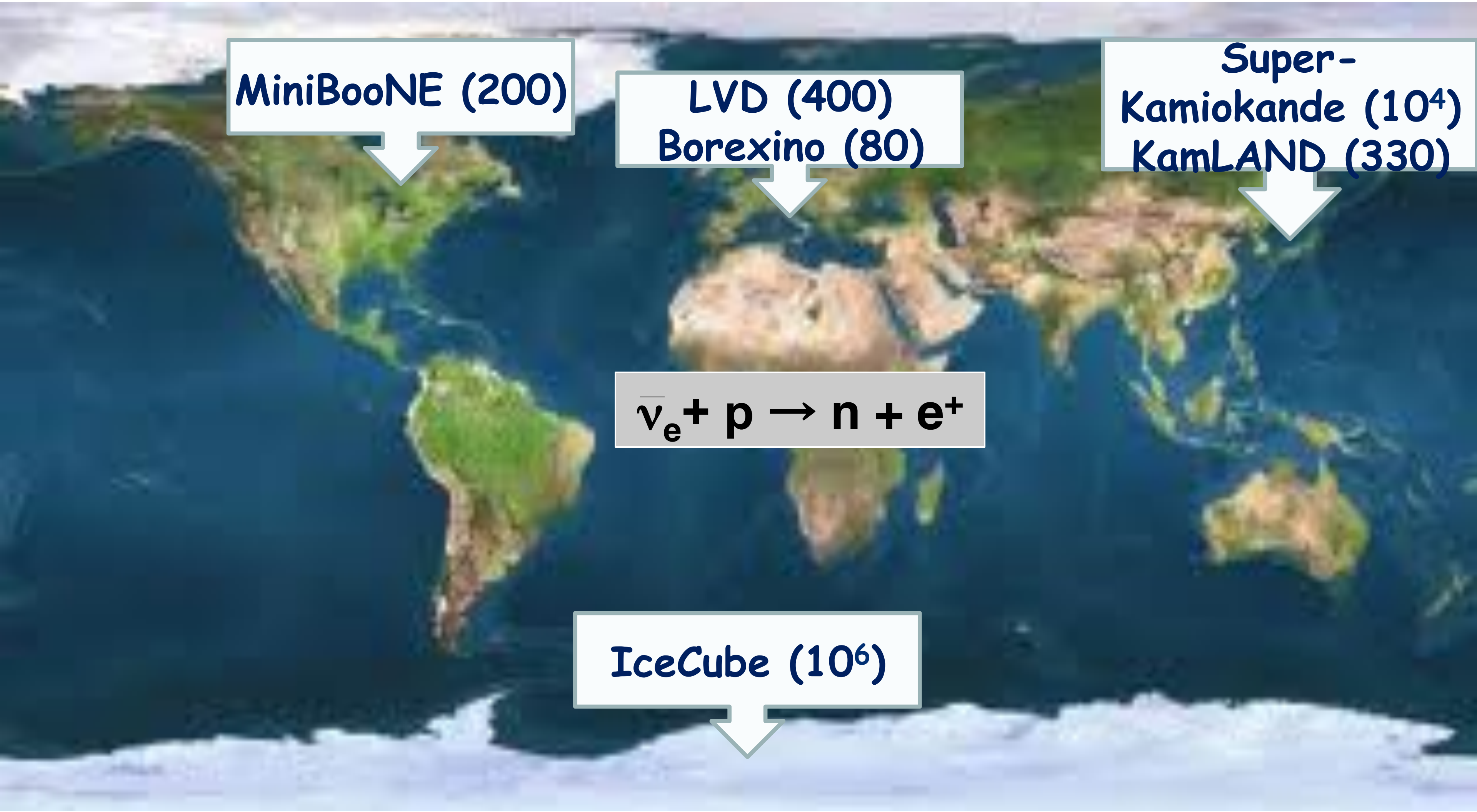


[Fischer et al. (Basel Simulations), A&A 517:A80,2010, 10. 8 M_{sun} progenitor mass]


Supernova 1987A 23 February 1987

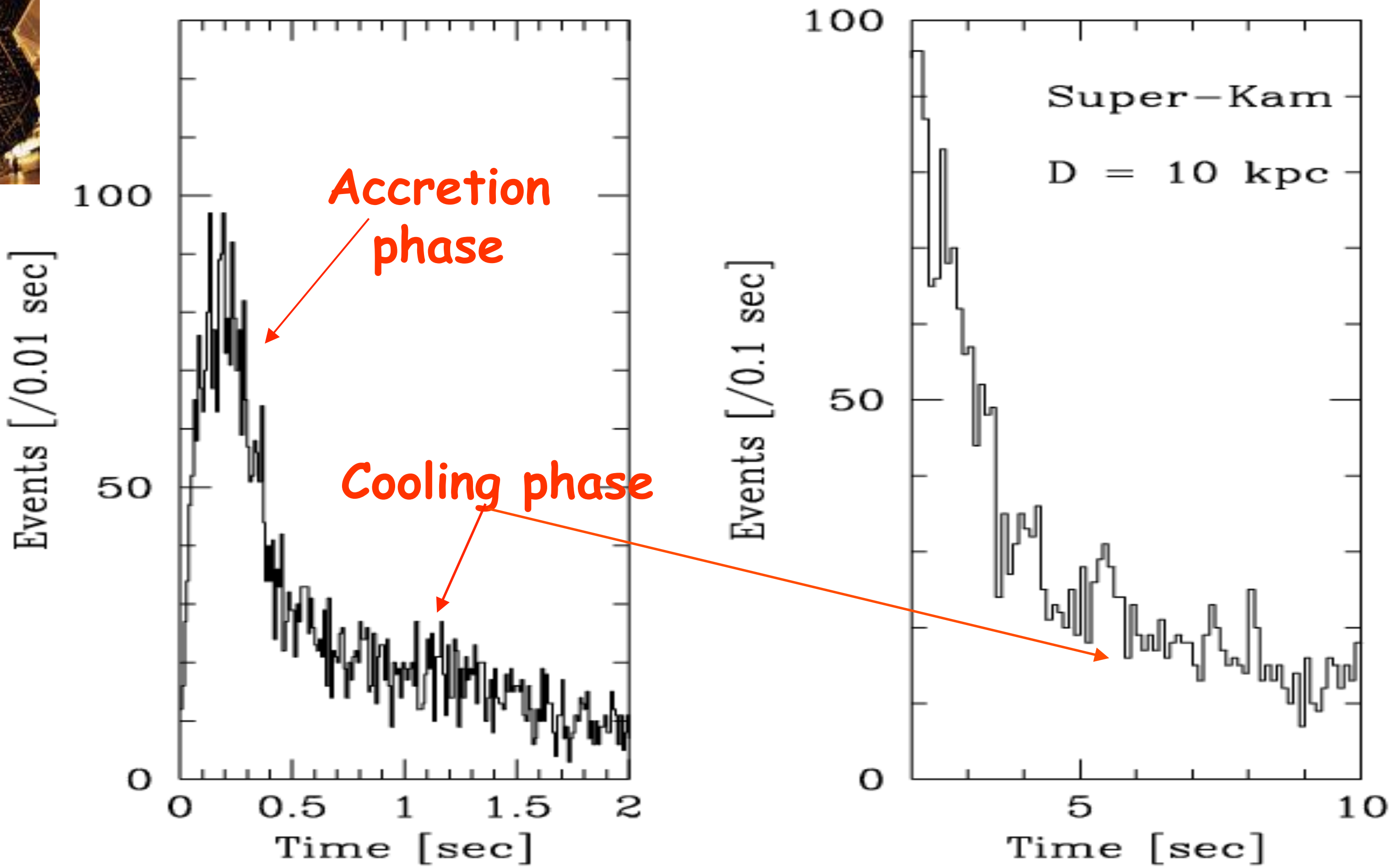

What could we see “tomorrow”?
SN 20XXA !

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

[Totani, Sato, Dalhed & Wilson, ApJ 496 (1998) 216]

Next generation Detectors for Supernova Neutrinos

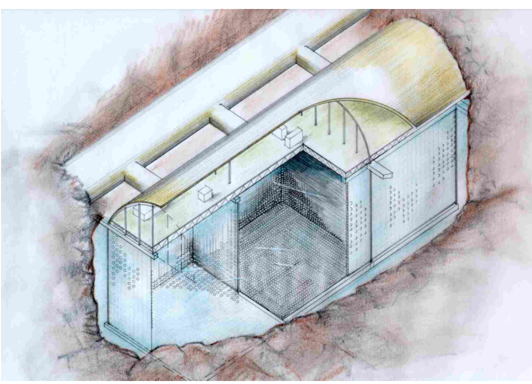
Next-generation large volume detectors will open a new era in SN neutrino detection:

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

$\nu_e + \overline{p} \rightarrow n + e^+$

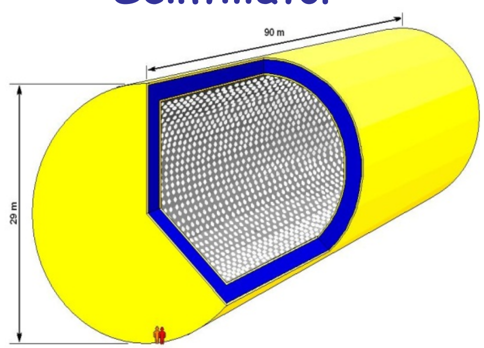
$\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$

Mton Cherenkov



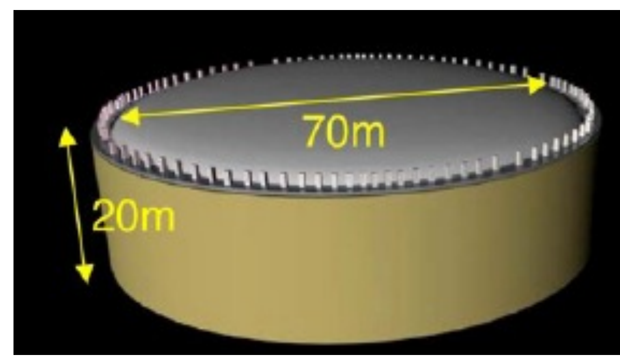
UNO, MEMPHYS, HYPER-K

Scintillator



LENA

LAr TPC



GLACIER

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

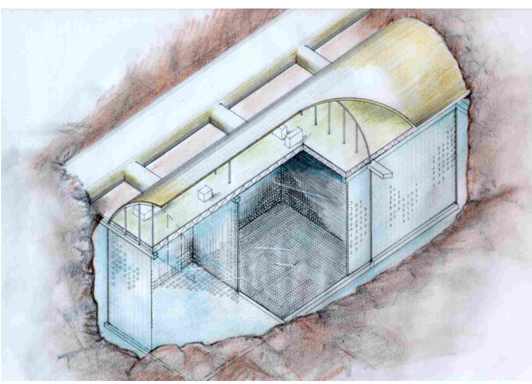
Next generation Detectors for Supernova Neutrinos

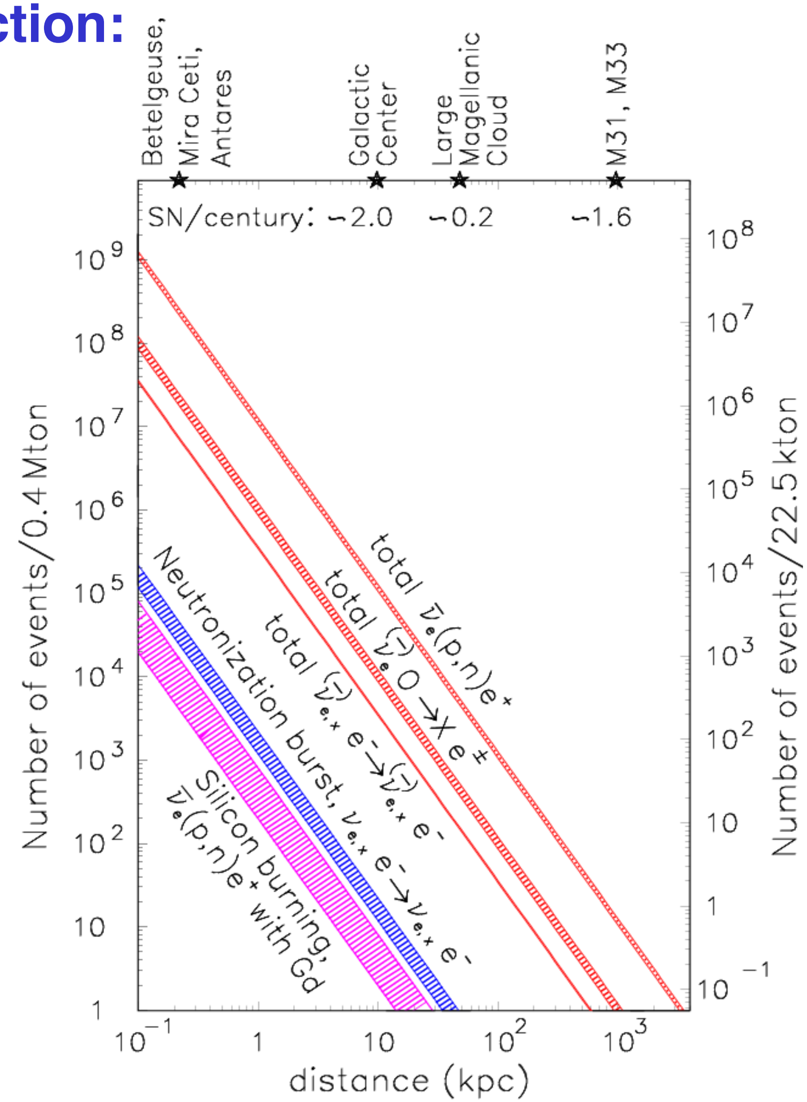
Next-generation large volume detectors will open a new era in SN neutrino detection:

- 0.4 Mton WATER Cherenkov detectors

$\bar{\nu}_e + p \rightarrow n + e^+$

Mton Cherenkov

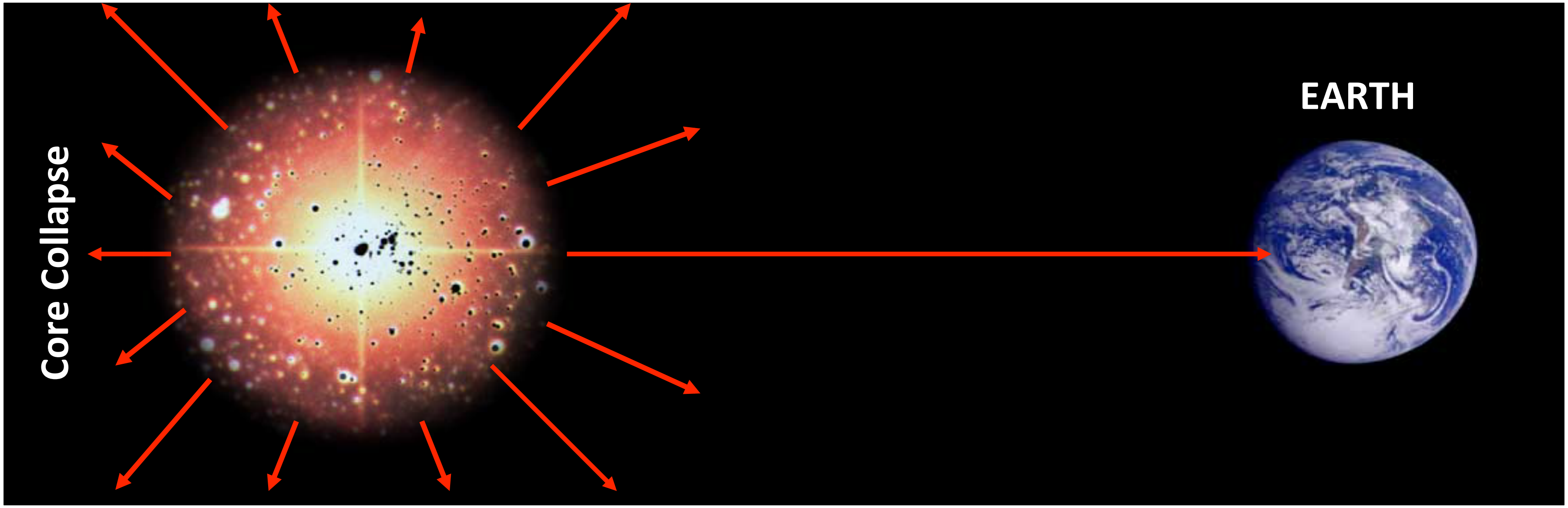




UNO, MEMPHYS, HYPER-K

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

TYPICAL PROBLEMS IN SUPERNOVA NEUTRINOS



Supernova (SN) as Neutrino Source

Oscillation of SN Neutrinos

Neutrino Signal at Detectors

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)

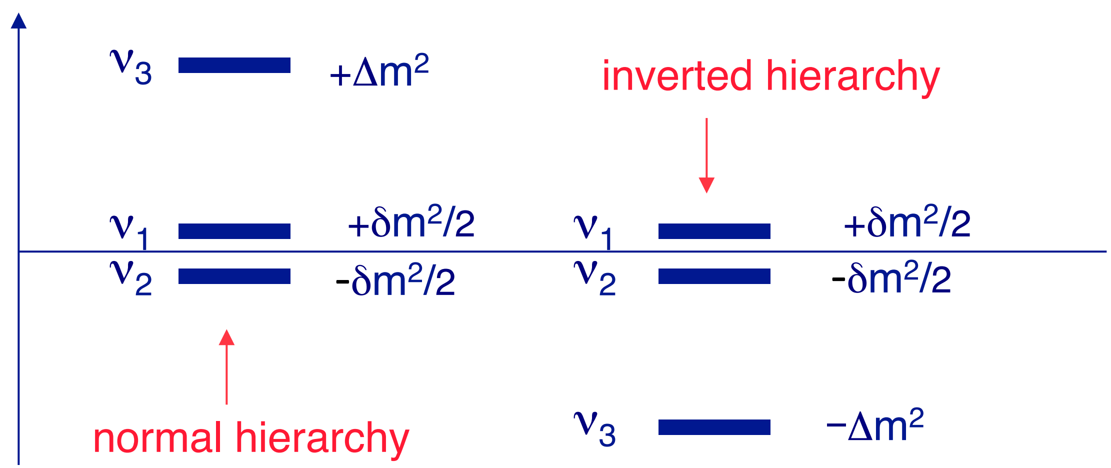
3ν FRAMEWORK

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



SN ν Flavor Transitions

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

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

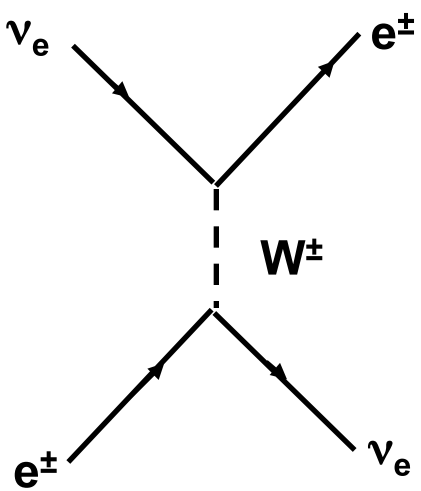
In the standard 3ν framework

- $$H_{vac} = \frac{U\ M^2\ U^\dagger}{2E}$$ **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)**

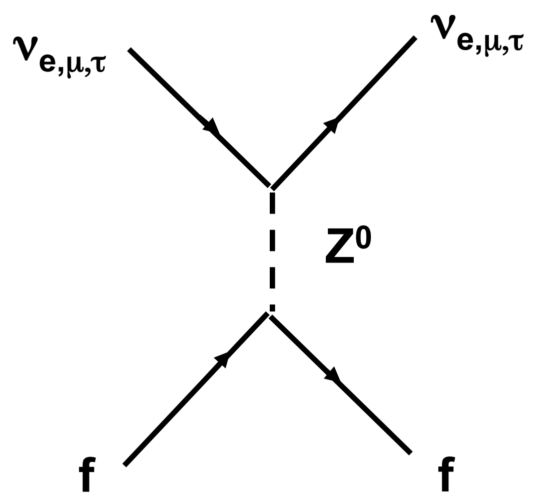
MIKHEYEV-SMIRNOV-WOLFENSTEIN (MSW) EFFECT

[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:

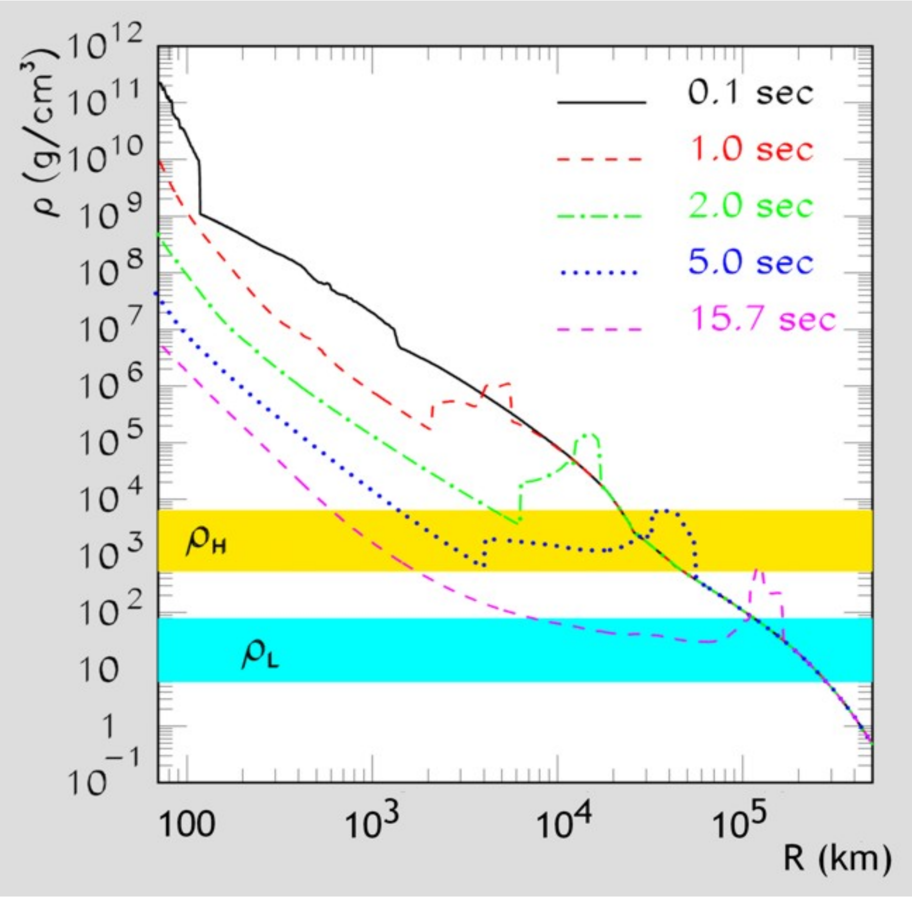
$$i\frac{d}{dx}\psi_\nu = \left(H_{vac} + H_e + H_{\nu\nu}\right)\psi_\nu$$

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)**

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



ν−ν NC interactions important!

- Matter bkg potential

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

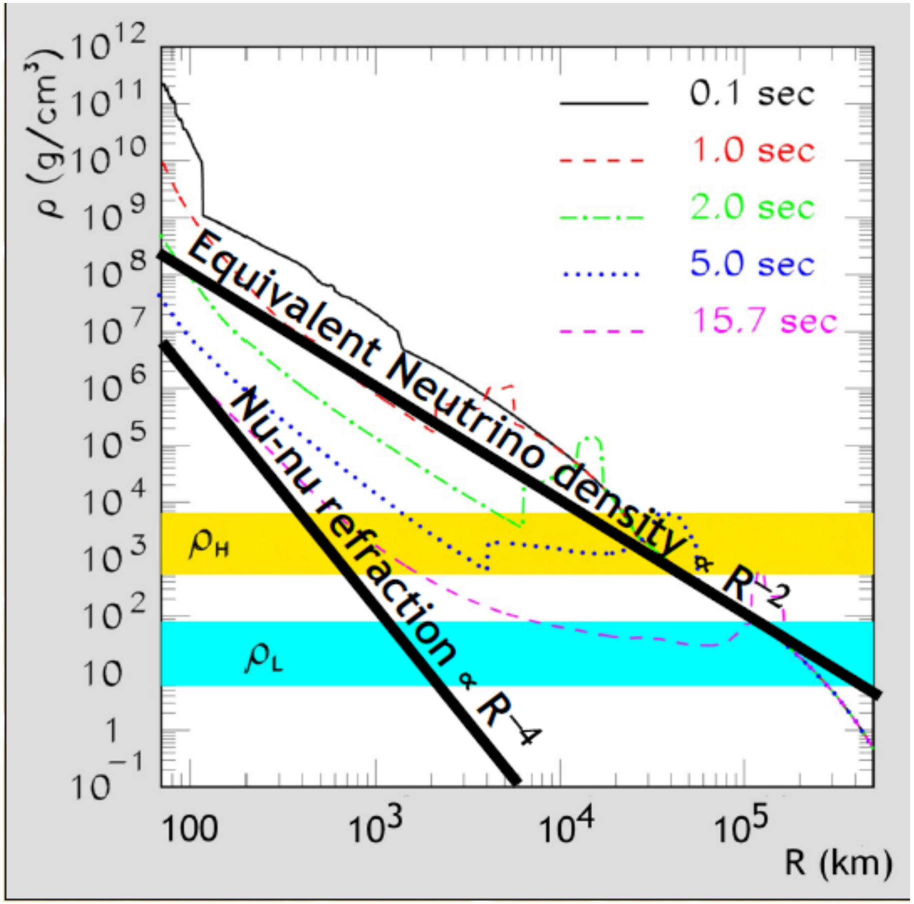
- ν−ν potential

Multi-angle effects

$$\mu = \sqrt{2} G_F n_\nu (1 - \cos\theta_{pq}) \sim R^{-2} \times R^{-2} = R^{-4}$$

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



ν−ν NC interactions important!

- Matter bkg potential

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

- ν−ν potential

Multi-angle effects

$$\mu = \sqrt{2} G_F n_\nu (1 - \cos\theta_{pq})$$

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

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

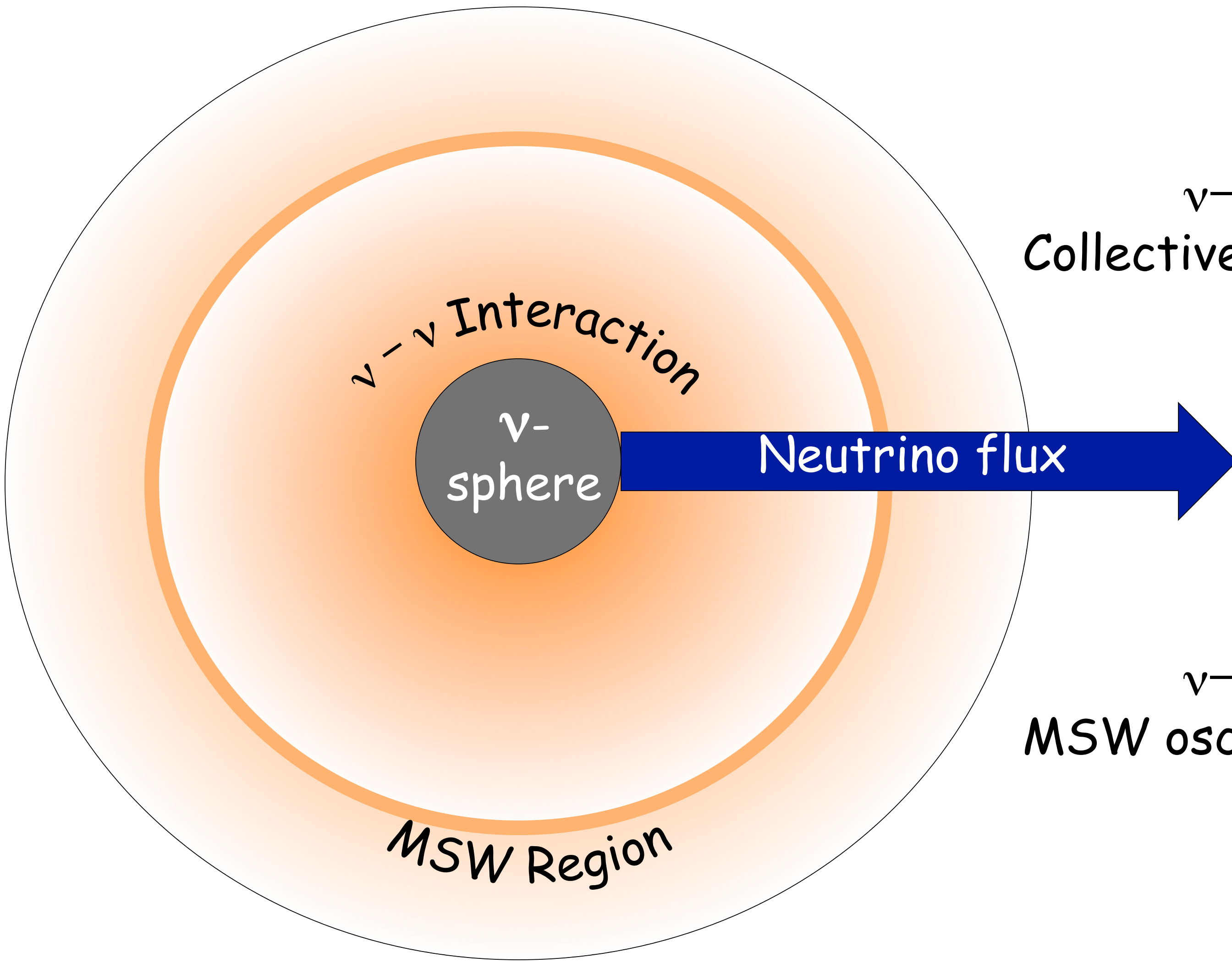
Collective SN Neutrino Oscillations since 2006

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

Duan, Fuller, Carlson & Qian, astro-ph/0608050, 0703776, arXiv:0707.0290, 0710.1271. Duan, Fuller & Qian, arXiv:0706.4293, 0801.1363, 0808.2046. Duan, Fuller & Carlson, arXiv:0803.3650. Duan & Kneller, arXiv:0904.0974. Hannestad, Raffelt, Sigl & Wong, astro-ph/0608695. Balantekin & Pehlivan, astro-ph/0607527. Balantekin, Gava & Volpe, arXiv:0710.3112. Gava & Volpe, arXiv:0807.3418. Gava, Kneller, Volpe & McLaughlin, arXiv:0902.0317. Raffelt & Sigl, hep-ph/0701182. Raffelt & Smirnov, arXiv:0705.1830, 0709.4641. Esteban-Pretel, Pastor, Tomàs, Raffelt & Sigl, arXiv:0706.2498, 0712.1137. Esteban-Pretel, Mirizzi, Pastor, Tomàs, Raffelt, Serpico & Sigl, arXiv:0807.0659. Raffelt, arXiv:0810.1407. Fogli, Lisi, Marrone & Mirizzi, arXiv:0707.1998. Fogli, Lisi, Marrone & Tamborra, arXiv:0812.3031. Lunardini, Müller & Janka, arXiv:0712.3000. Dasgupta & Dighe, arXiv:0712.3798. Dasgupta, Dighe & Mirizzi, arXiv:0802.1481. Dasgupta, Dighe, Mirizzi & Raffelt, arXiv:0801.1660, 0805.3300. Dasgupta, Dighe, Raffelt & Smirnov, arXiv:0904.3542. Sawyer, arXiv:0803.4319. Chakraborty, Choubey, Dasgupta & Kar, arXiv:0805.3131. Blennow, Mirizzi & Serpico, arXiv:0810.2297. Wei Liao, arXiv:0904.0075, 0904.2855.

SN ν Flavor Transitions

Extreme neutrino density close to the neutrino-sphere

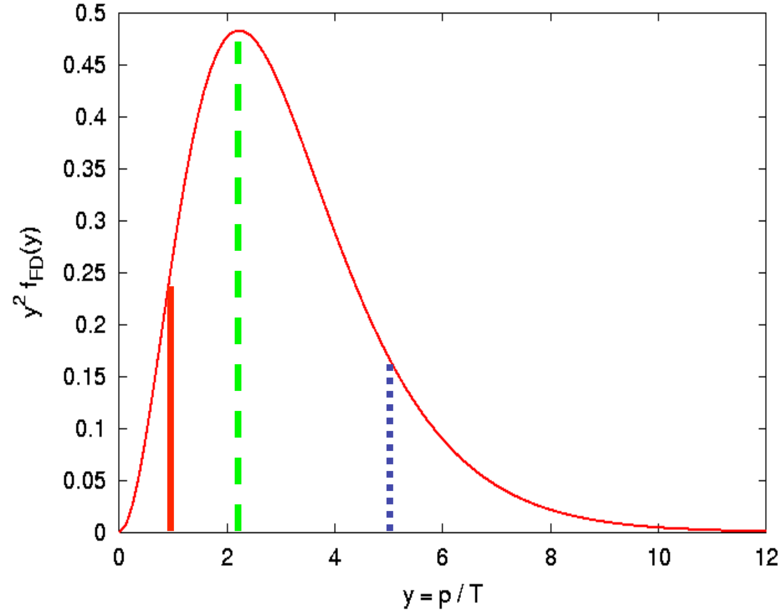


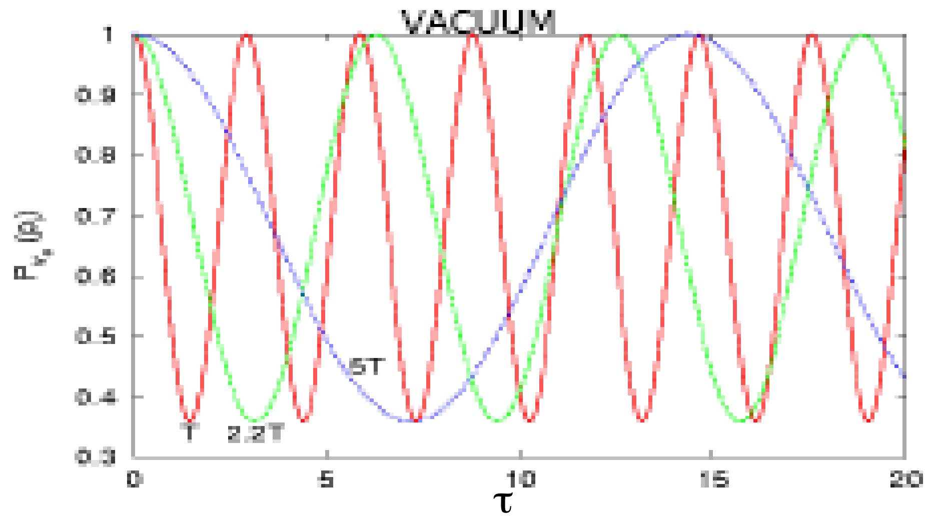
ν–ν interaction
Collective oscillation~ 10^2 km

ν–e^- interaction
MSW oscillation ~ 10^4-10^5 km

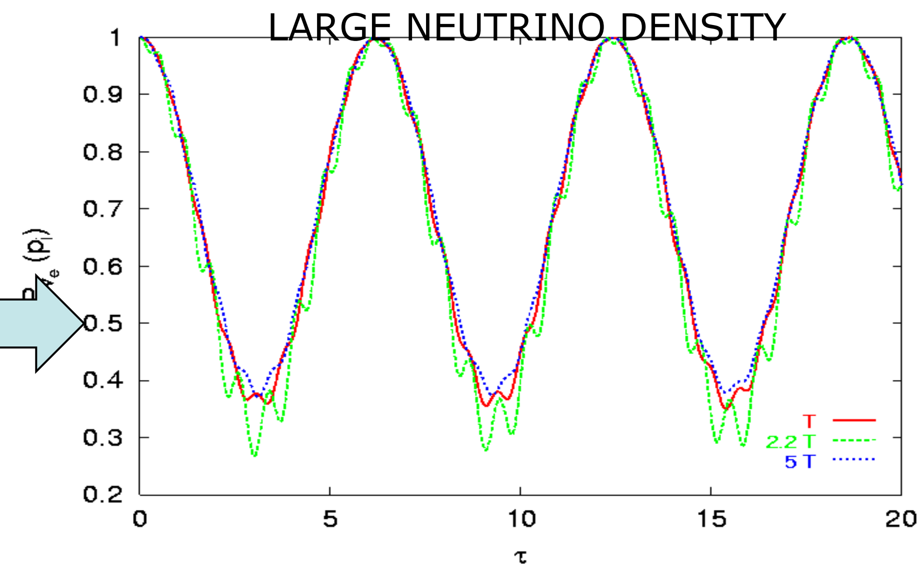
SYNCHRONIZED OSCILLATIONS BY NEUTRINO-NEUTRINO INTERACTIONS

Example: evolution of neutrino momenta with a thermal distribution





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



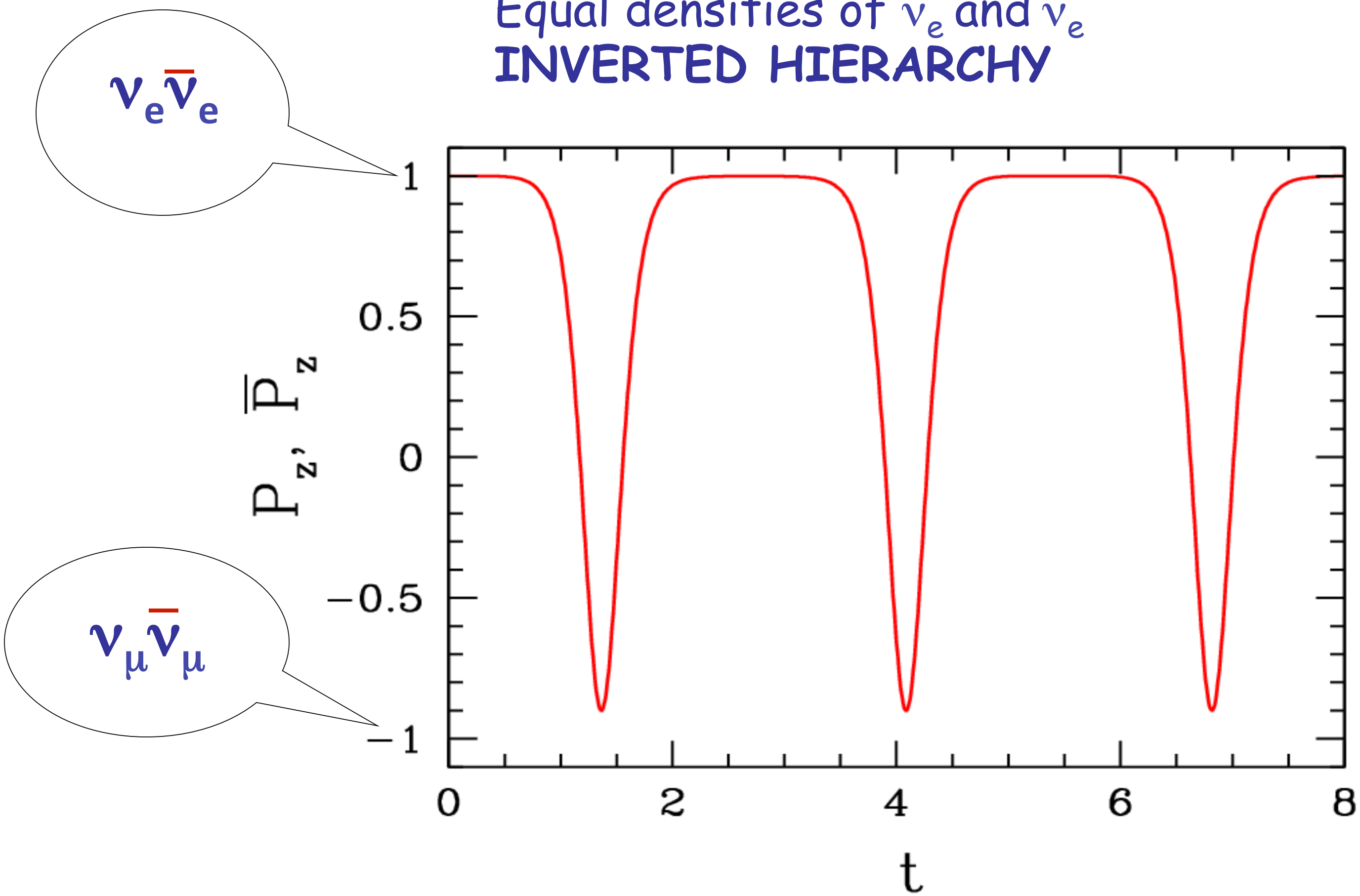
[Pastor, Raffelt, Semikoz, hep-ph/0109033]

PENDULAR OSCILLATIONS

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

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

INVERTED HIERARCHY



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

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

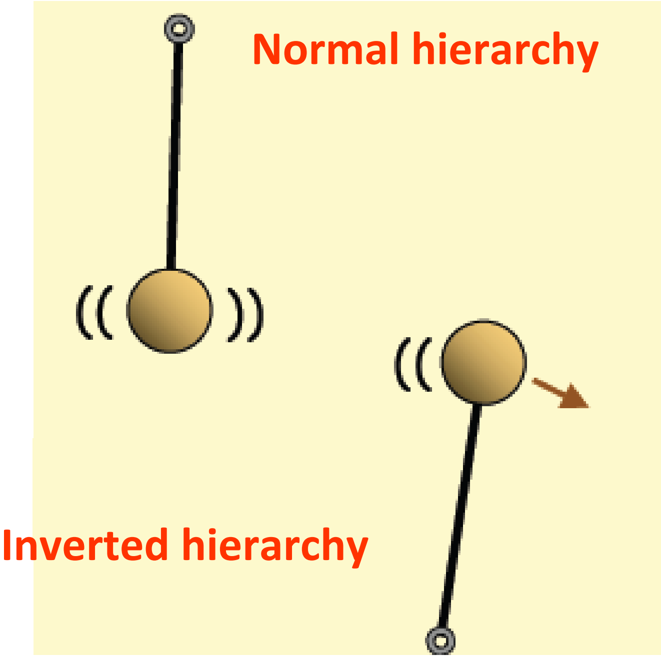
With only initial ν_e and $\bar{\nu}_e$:

- **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.

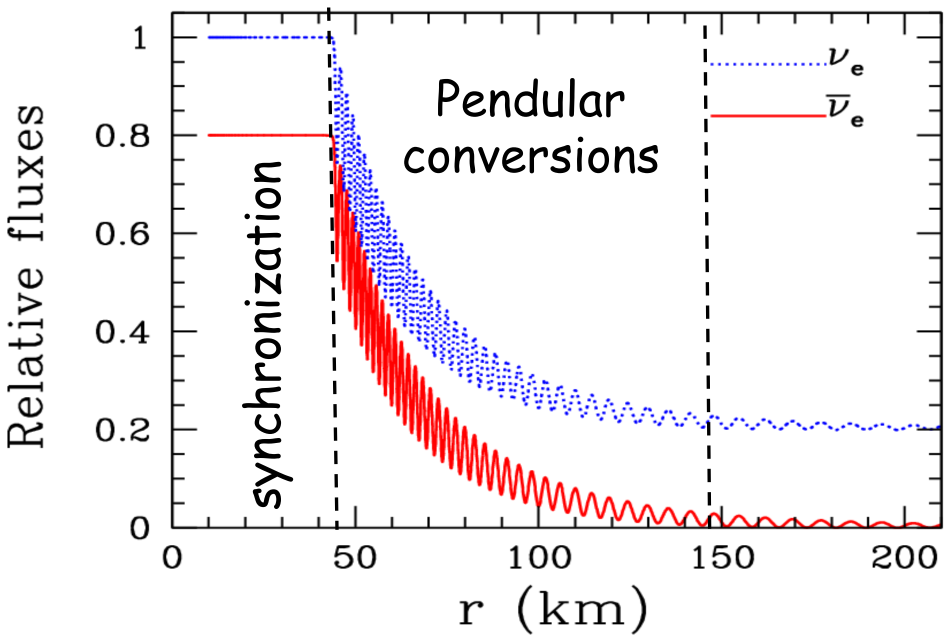


θ_{13} sets initial misalignment with vertical. Specific value not much relevant.

SUPERNOVA TOY-MODEL

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

Only ν_e and $\overline{\nu}_e$



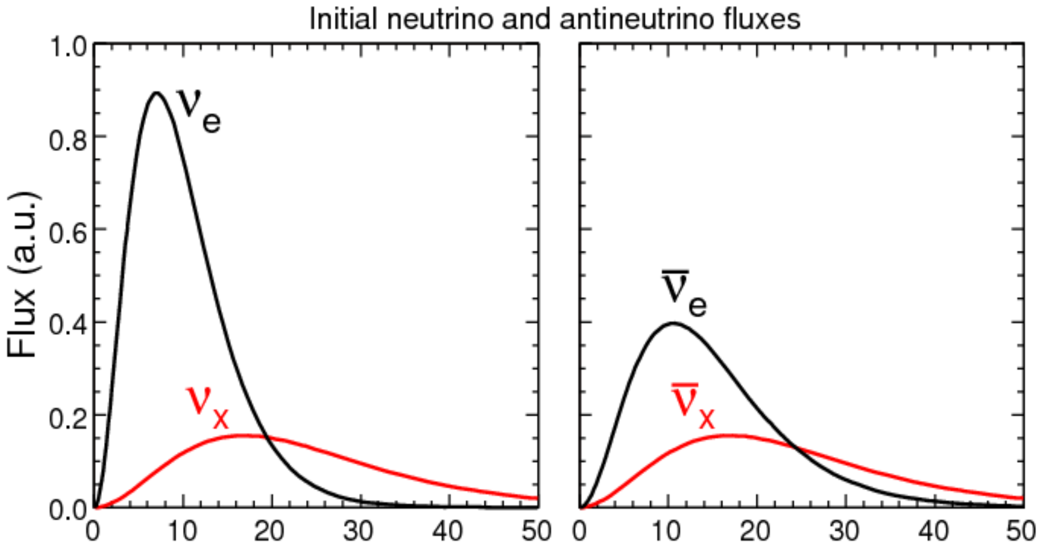
SUPERNOVA: **Non-periodic** since ν density decreases

Complete flavor conversions!

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

Spectral Splits in the Accretion Phase

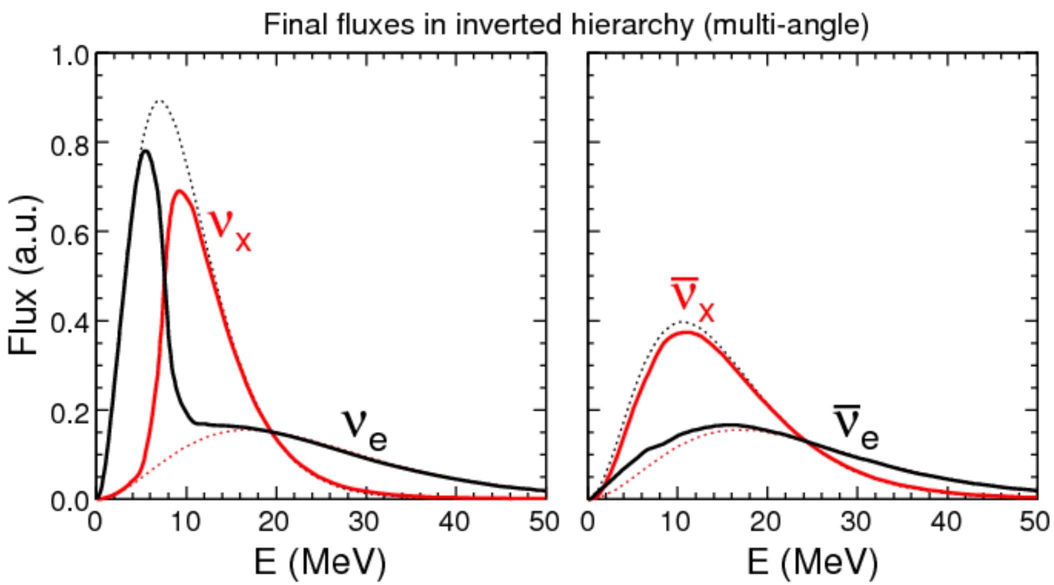
[Fogli, Lisi, Marrone, Mirizzi, arXiV: 0707.1998 [hep-ph]]



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

IH

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



Nothing happens in Normal Hierarchy (NH)

Removal of axial symmetry

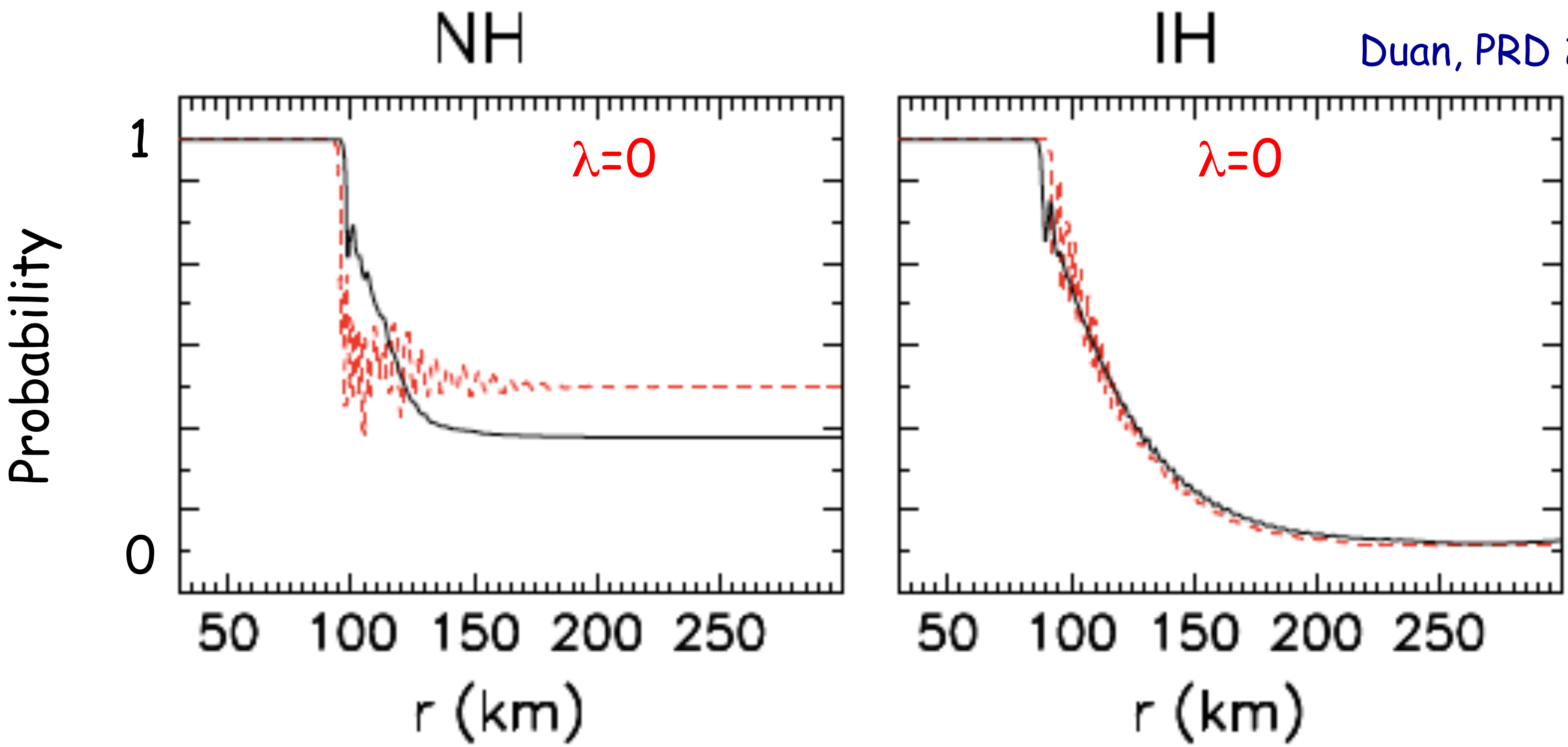
Realistic SN would have axial/azimuthal asymmetry.

Enhance instability of the non-linear system

Sarikas, Raffelt, Hüdepohl & Janka, PRL 2012

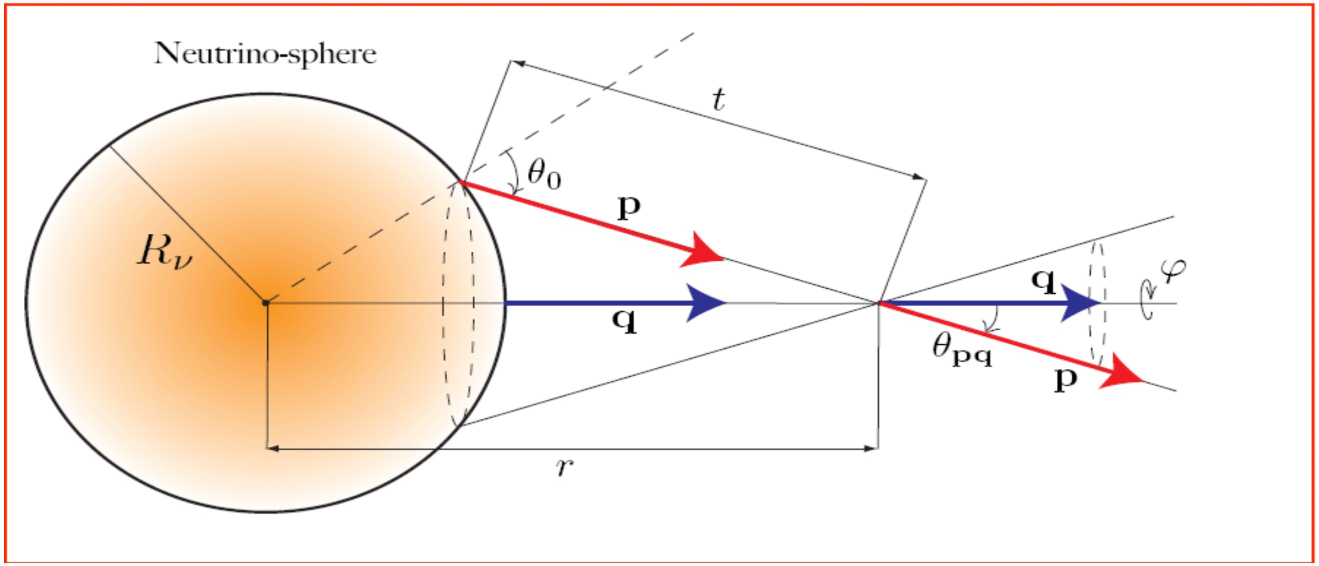
Mirizzi, PRD 2013

Duan, PRD 2013



S.C & Mirizzi, PRD 2014

Multi Angle Matter Suppression



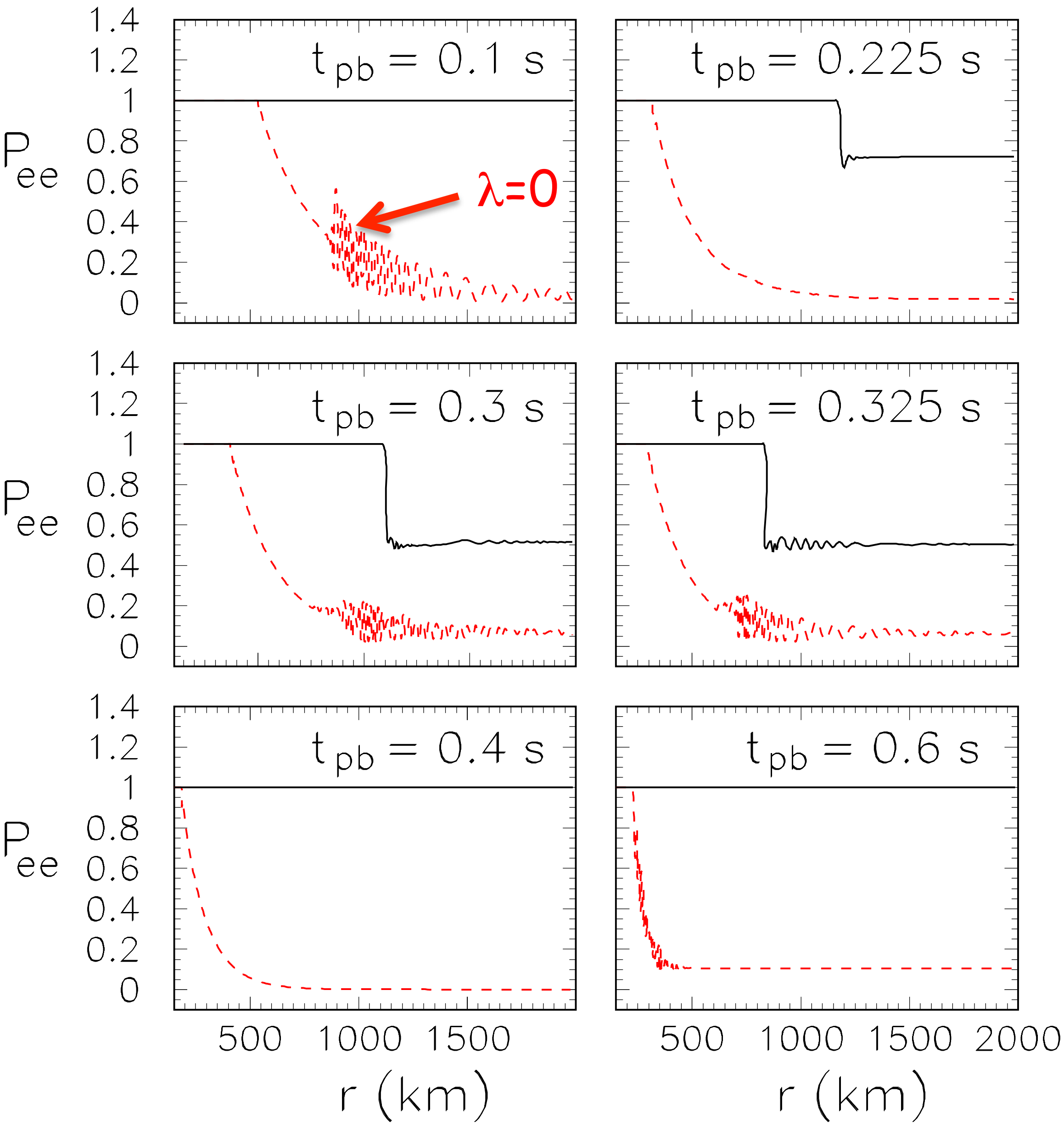
- Neutrinos emitted from spherical source, travel on different trajectories.
- Different oscillation phases for neutrinos traveling in different paths.
- Strong ν–ν interaction can overcome trajectory dependent dispersion.

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 Evolution of Survival Probability

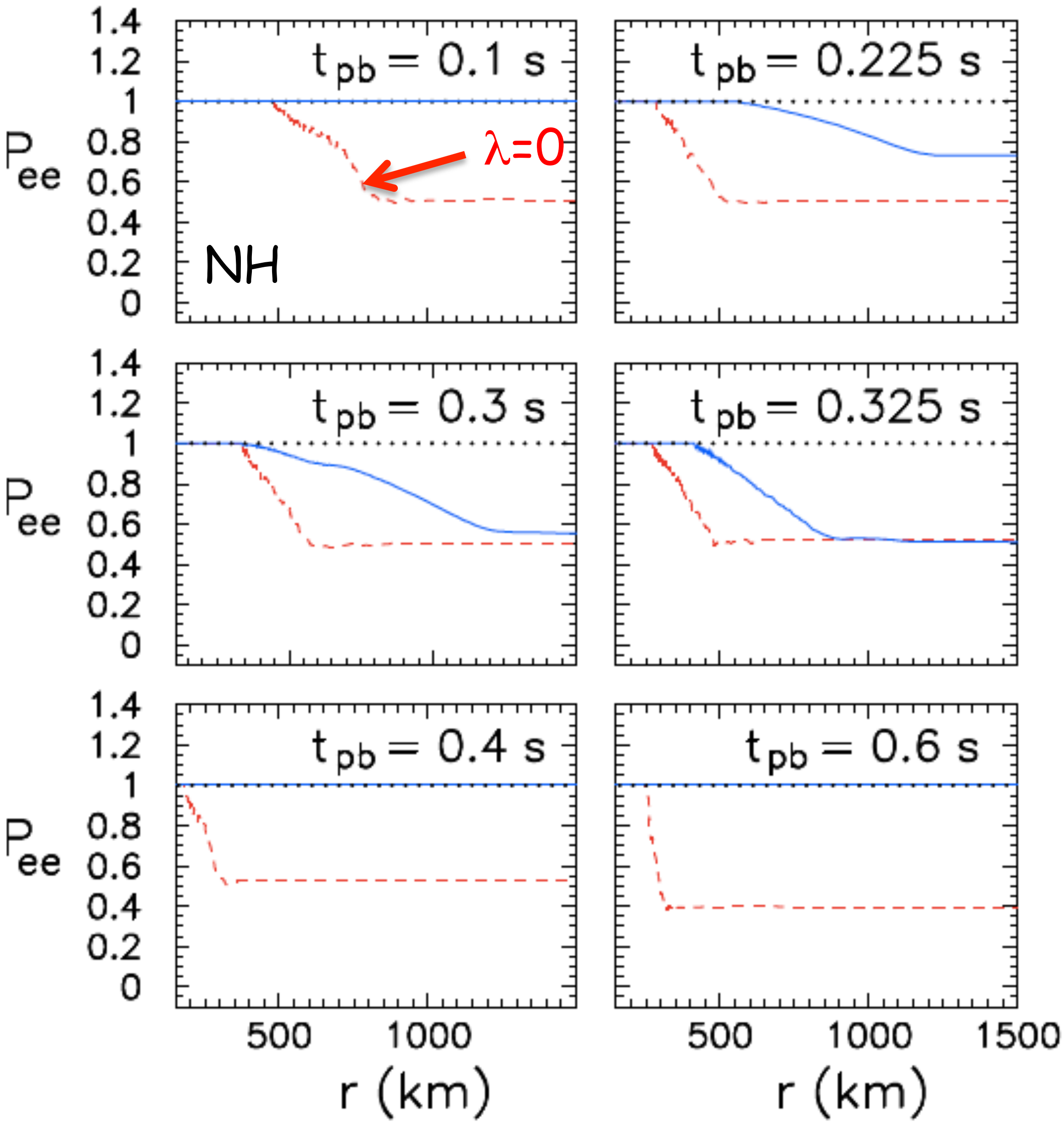


IH

Dense Matter effect Suppresses Collective Oscillations

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

Removal of axial symmetry + Zenith distribution

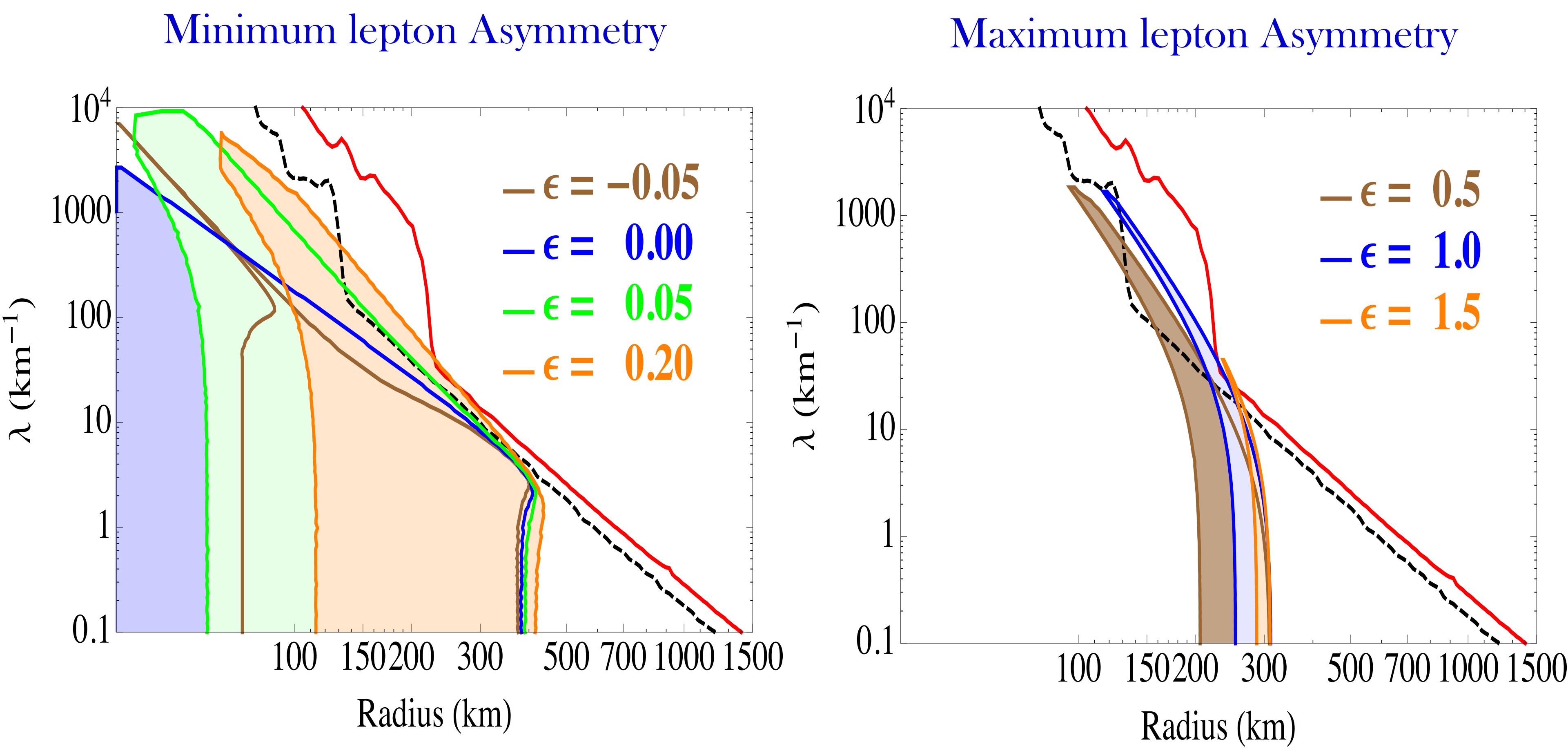


NH

Dense Matter effect Suppresses Collective Oscillations

S.C, Mirizzi, Saviano & Seixas
PRD, 2014

Stability Analysis: LESA



S.C, Raffelt, Janka & Mueller, arXiv:1412.0670

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]

★ ★

LESA: Suppression is generic till 150 ms

S.C, Raffelt, Janka & Mueller, arXiv:1412.0670

SN neutrino Flux at Earth

Neutronization burst & Accretion Phase (150 ms):

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):

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

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

Collective effects in Cooling phase

3) Cooling phase (t < 500 ms)

nu-nu interaction dominates over dense matter term : $n_e << n_\nu$

Collective Oscillation is complex due to

- Multi angle effect
- Dependence on flux ordering
- Initial angular distribution of flavors

+

- Shock Effect & Turbulence

Near Equipartition of flux in different Flavors

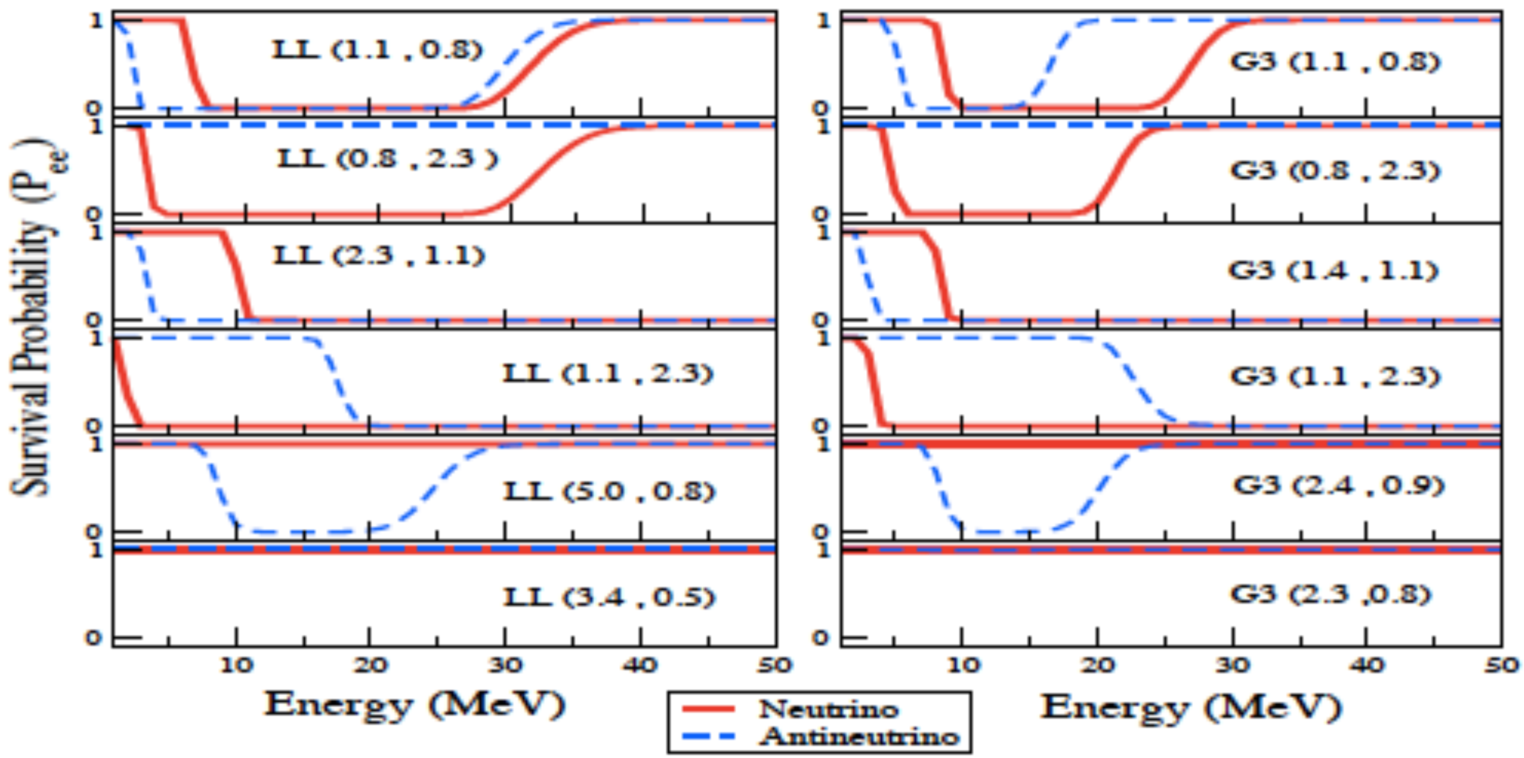
Oscillation Effects are Negligible

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

Collective effects in Cooling phase

3) Cooling phase (t < 500 ms)

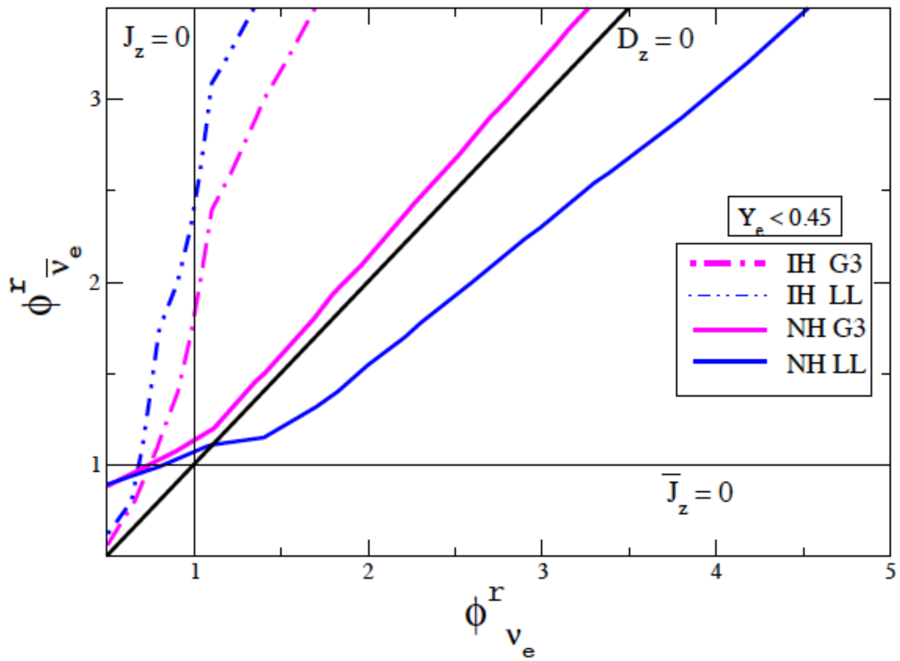
nu-nu interaction dominates over dense matter term : $n_e << n_\nu$



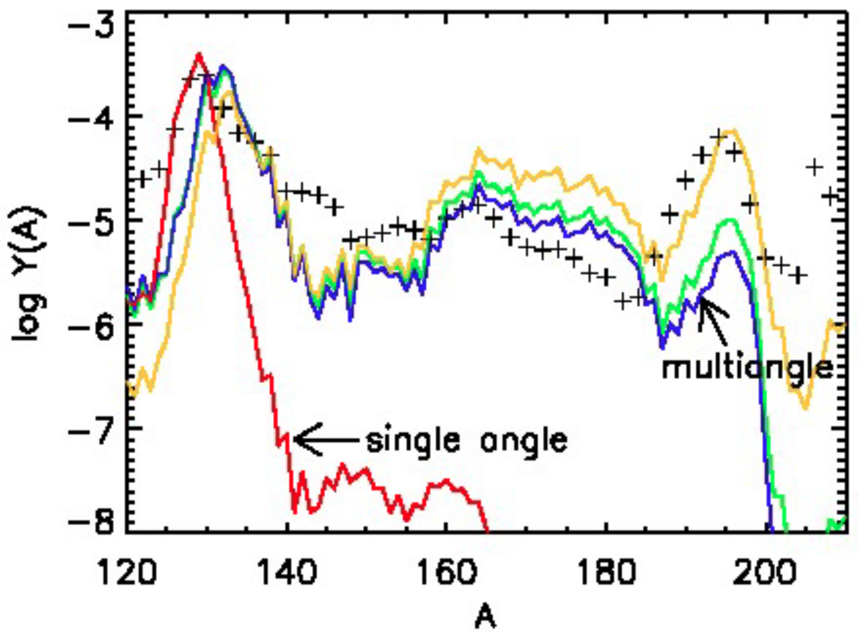
[S.C, Choubey, Goswami & Kar JCAP, 2010]

r-Process Nucleosynthesis

- Heating by neutrino driven wind coming from neutrino-sphere
  $\nu_e + n \rightleftharpoons e^- + p; \ \bar{\nu}_e + p \rightleftharpoons e^+ + n$
- Important quantity whose evolution should be studied is
  Electron fraction (Ye) = No of electrons/No of Baryons
- For Neutron rich conditions Ye < 0.5 (Preferably < 0.45).

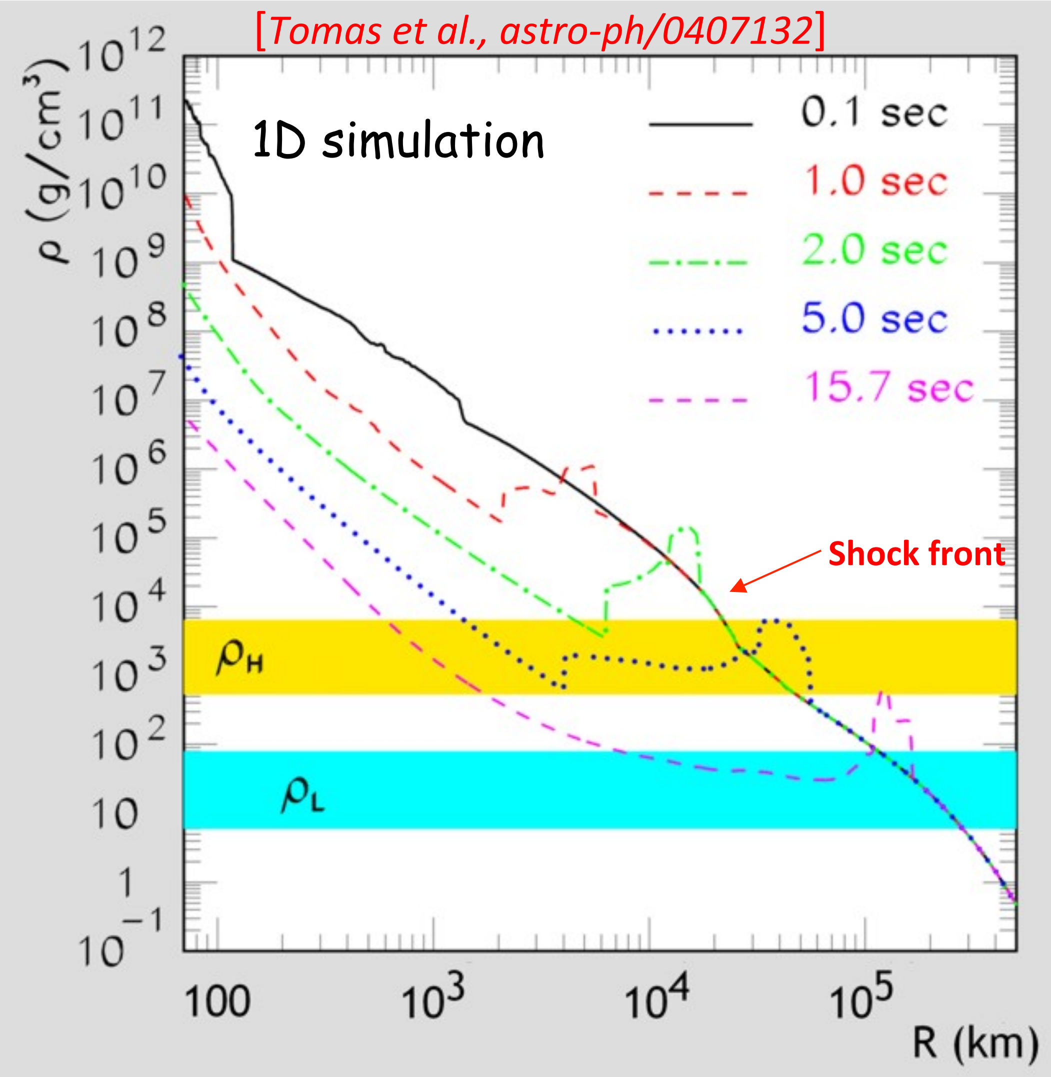


S C, Choubey, Goswami and Kar, JCAP 2010



Duan, et al, JPG (2010)

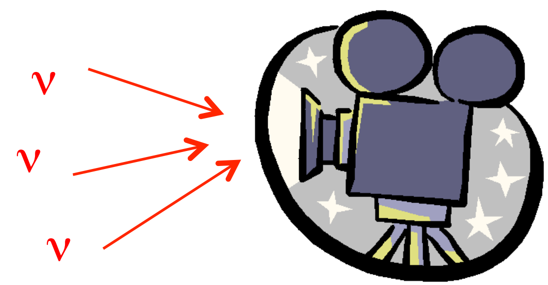
MSW MATTER EFFECT IN SN



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



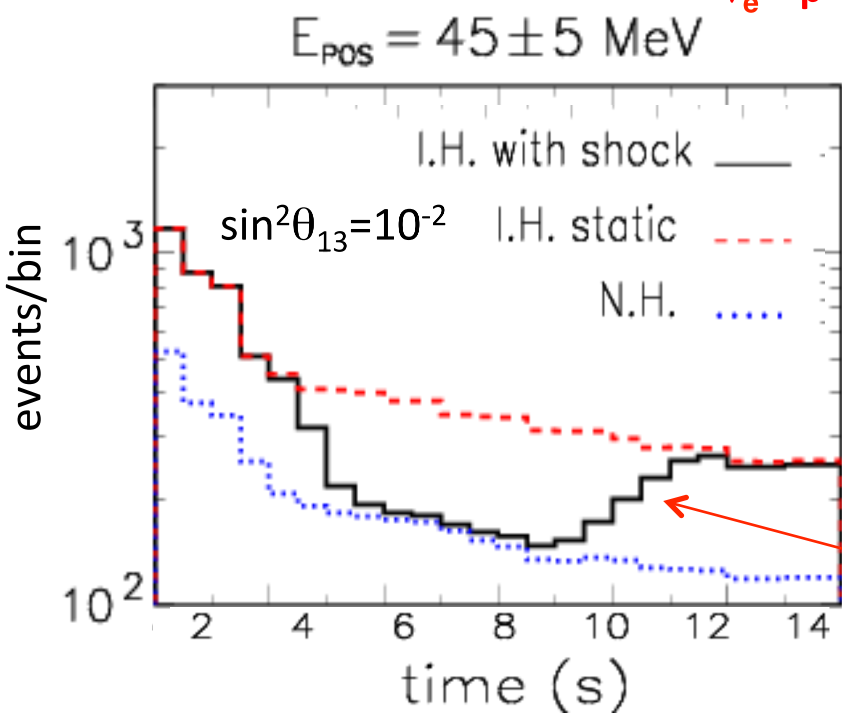
[see, e.g., Fogli, Lisi, A.M., and Montanino, hep-ph/0304056; Fogli, Lisi, A.M., and Montanino, hep-ph/0412046, Tomas et al., astro-ph/0407132, Choubey et al, hep-ph/0605255, Gava et al. 0902.0317,….]

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

0.4 Mton WC

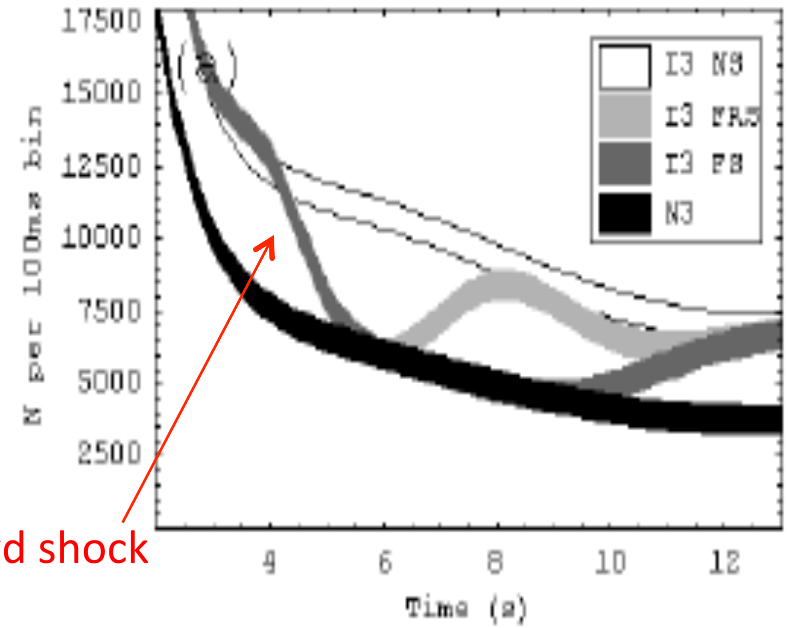
$\bar{\nu}_e + p \rightarrow n + e^+$

Icecube



[Fogli et al., hep-ph/0412046]

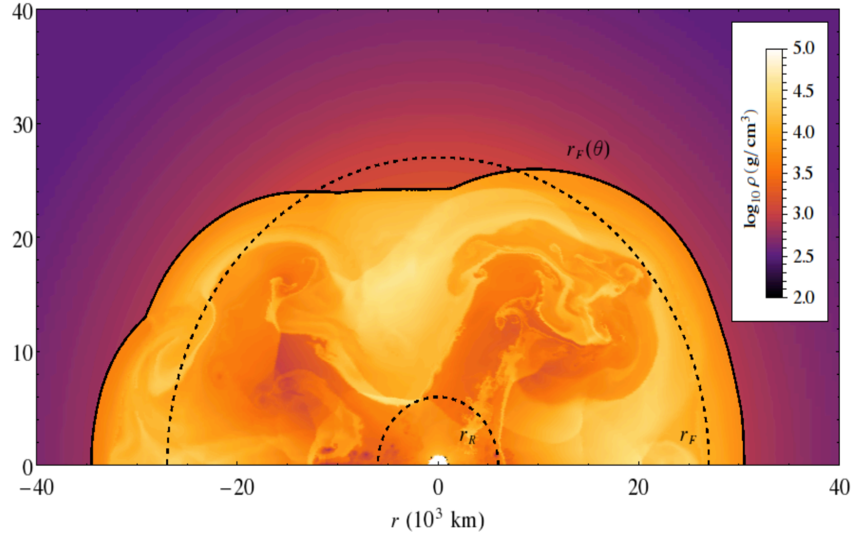
IH fwd shock



[Choubey et al, hep-ph/0605255]

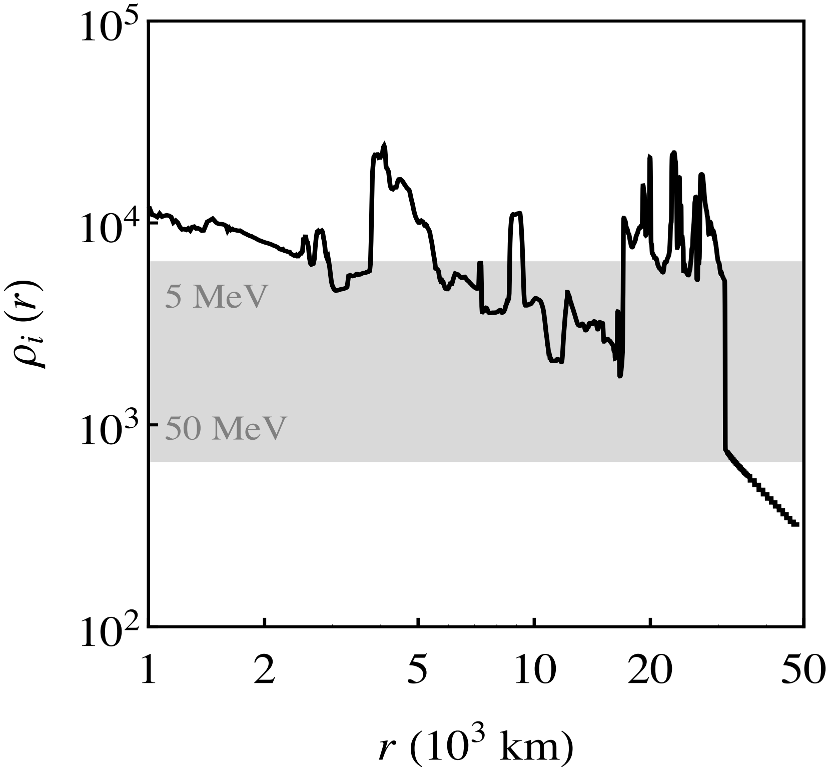
In inverted hierarchy and for θ_{13} not too small, flavor conversions along the shock-waves induce non-monotonic time spectra.

STOCHASTIC DENSITY FLUCTUATIONS



GARCHING 2D simulation

Turbulent convective motions behind the shock front create a fluctuating density field in the post-shock region. A SN neutrino "beam" might thus experience stochastic matter effects while traversing the stellar envelope.

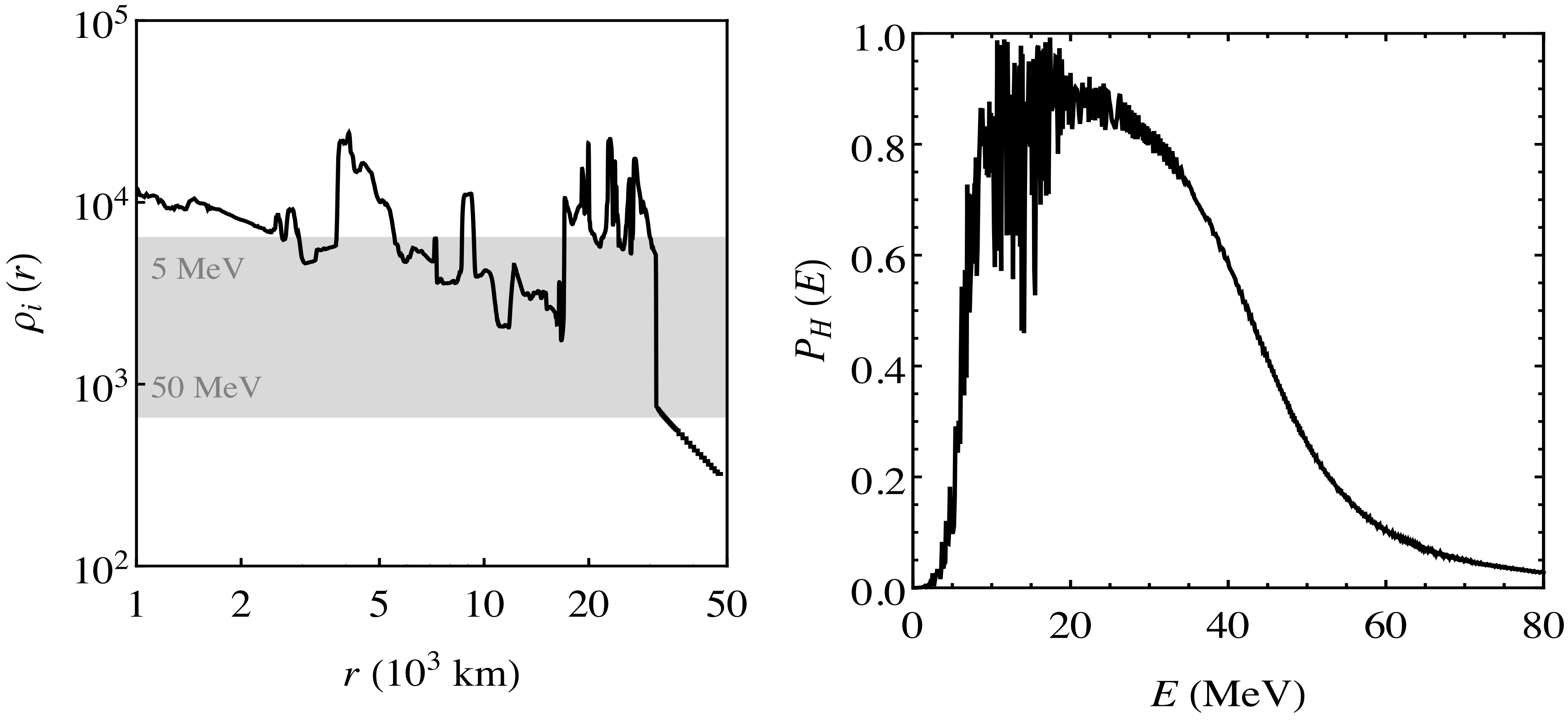


[Fogli, Lisi, A.M. , Montanino, hep-ph/0603033; Friedland, astro-ph/0607244; Choubey, Harries, Ross, hep-ph/0703092, Kneller, 1004.1288, Kneller & Volpe, 1006.0913]

Depolarization ($\langle P_{ee} \rangle \rightarrow \frac{1}{2}$) would replace the shock-signature when turbulence is relevant

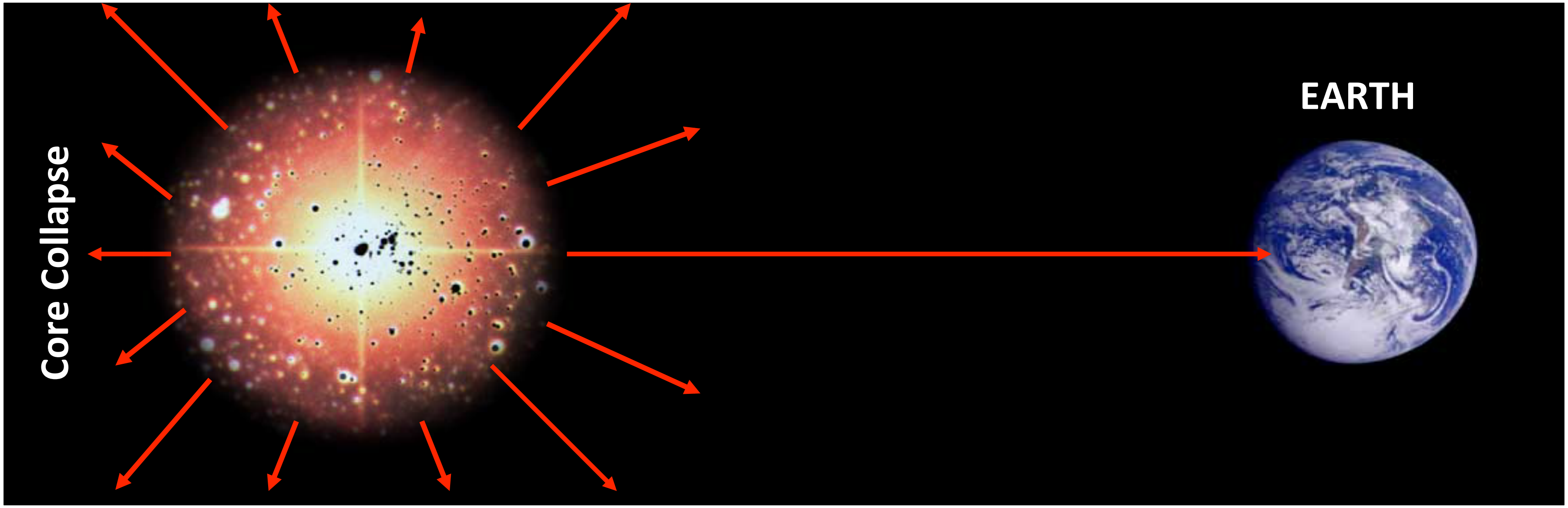
GARCHING 2D simulation

Not enough fluctuation in small length scale



[Borriello, S.C, Janka, Lisi & Mirizzi, JCAP 2014]

TYPICAL PROBLEMS IN SUPERNOVA NEUTRINOS



Supernova (SN) as Neutrino Source

Oscillation of SN Neutrinos

Neutrino Signal at Detectors

Neutrino Emission Phases

Neutronization burst

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

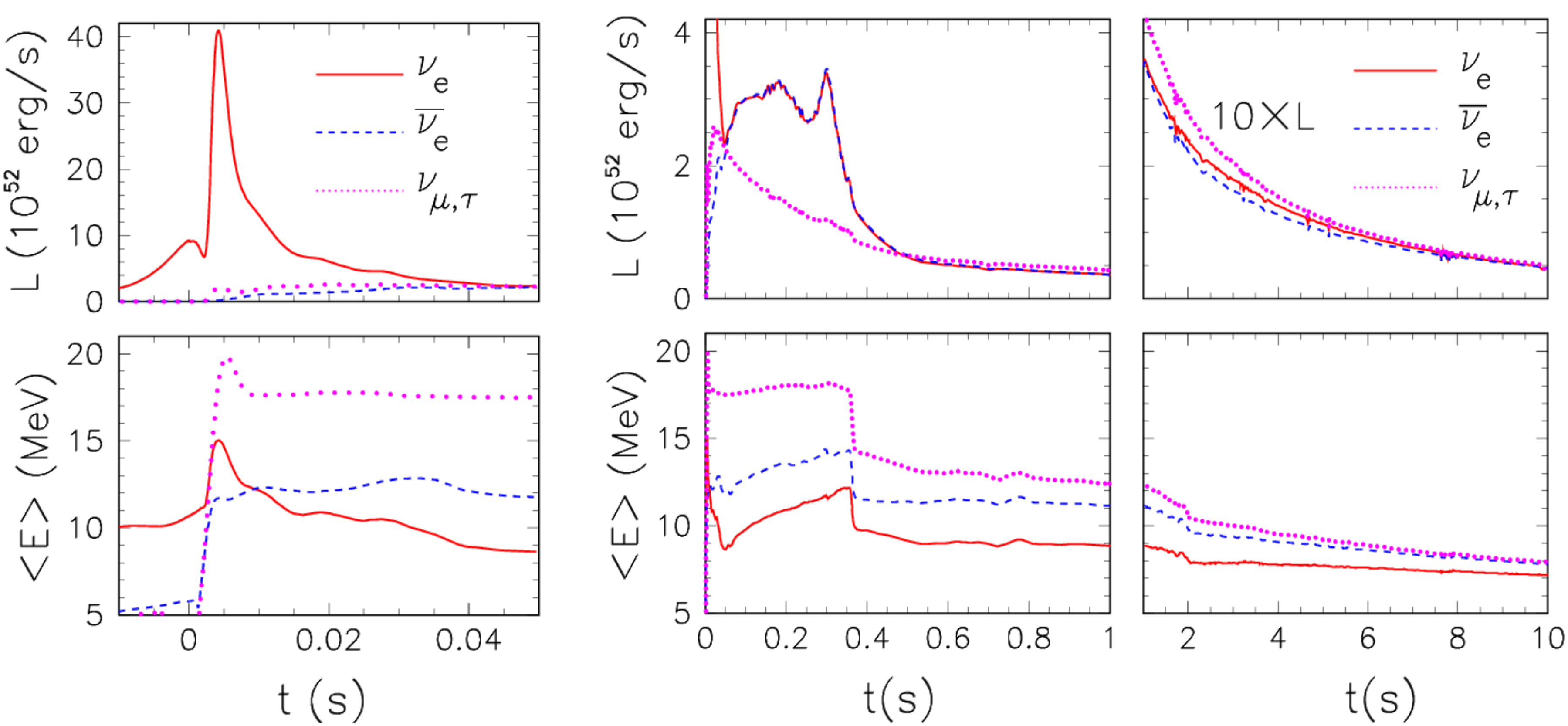
Accretion

- powered by infalling matter
- Stalled shock

Cooling

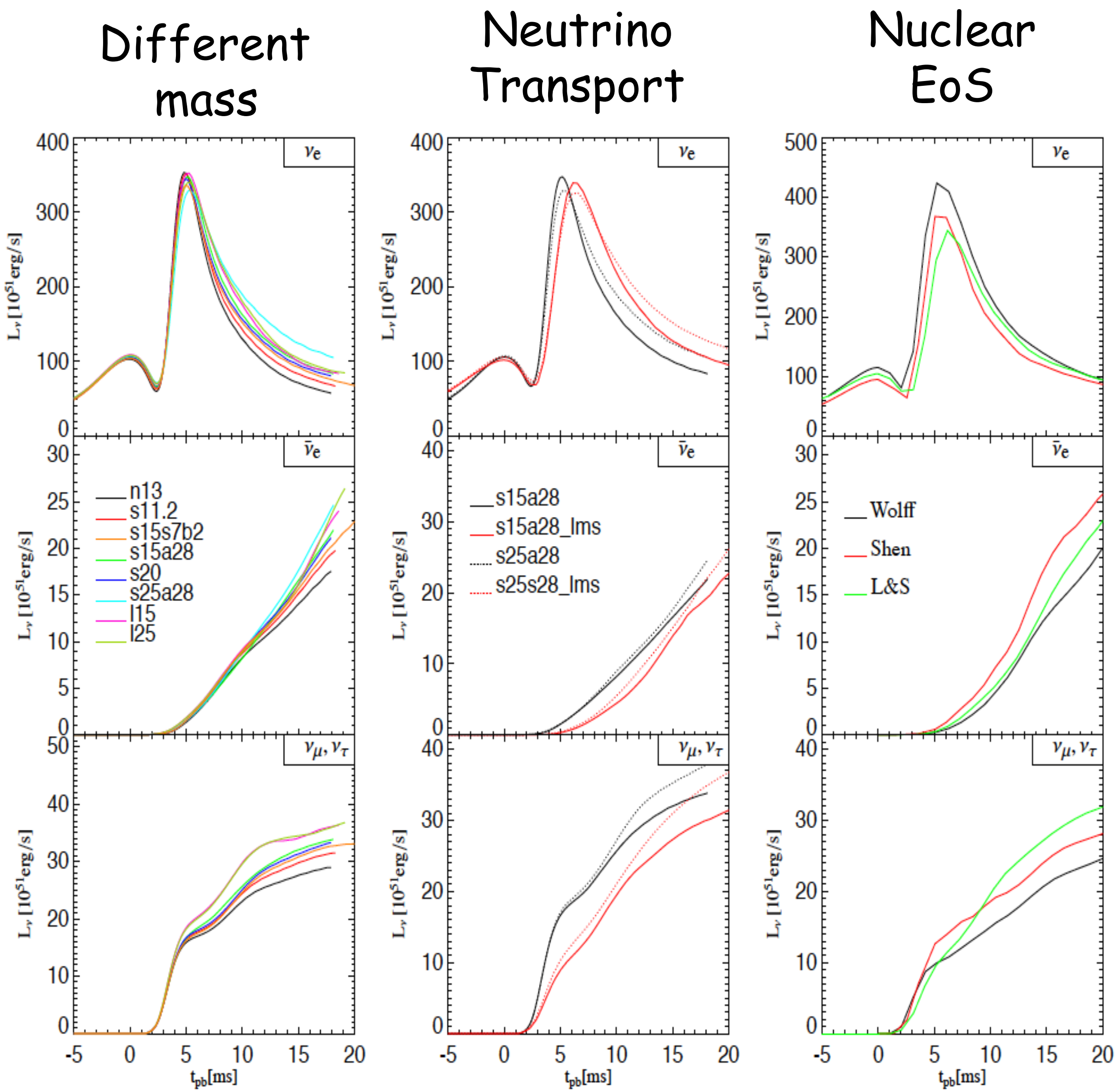
- Cooling by ν diffusion

Accretion: ~ 0.5 s ; Cooling: ~ 10 s



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

Neutronization Burst : Model Independence

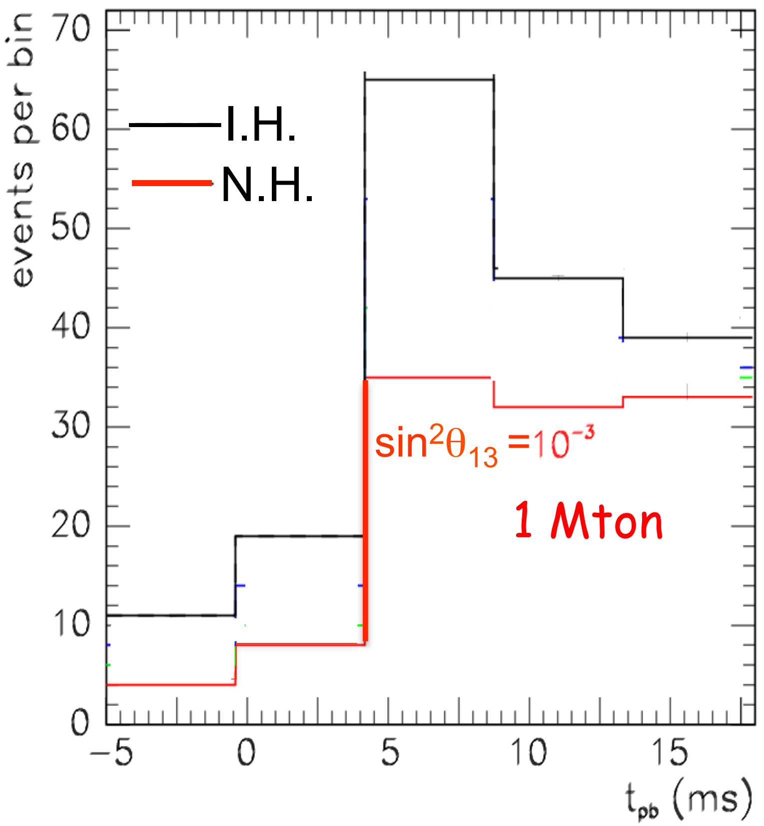


'Standard Candle' for SN Neutrino

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

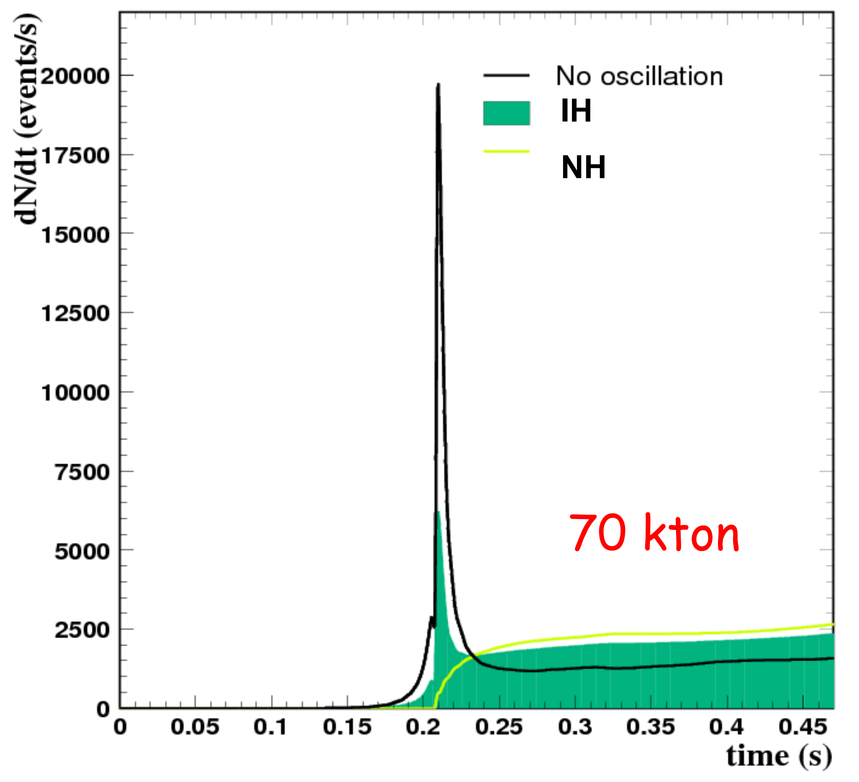
Oscillations in the Neutronization Burst

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]

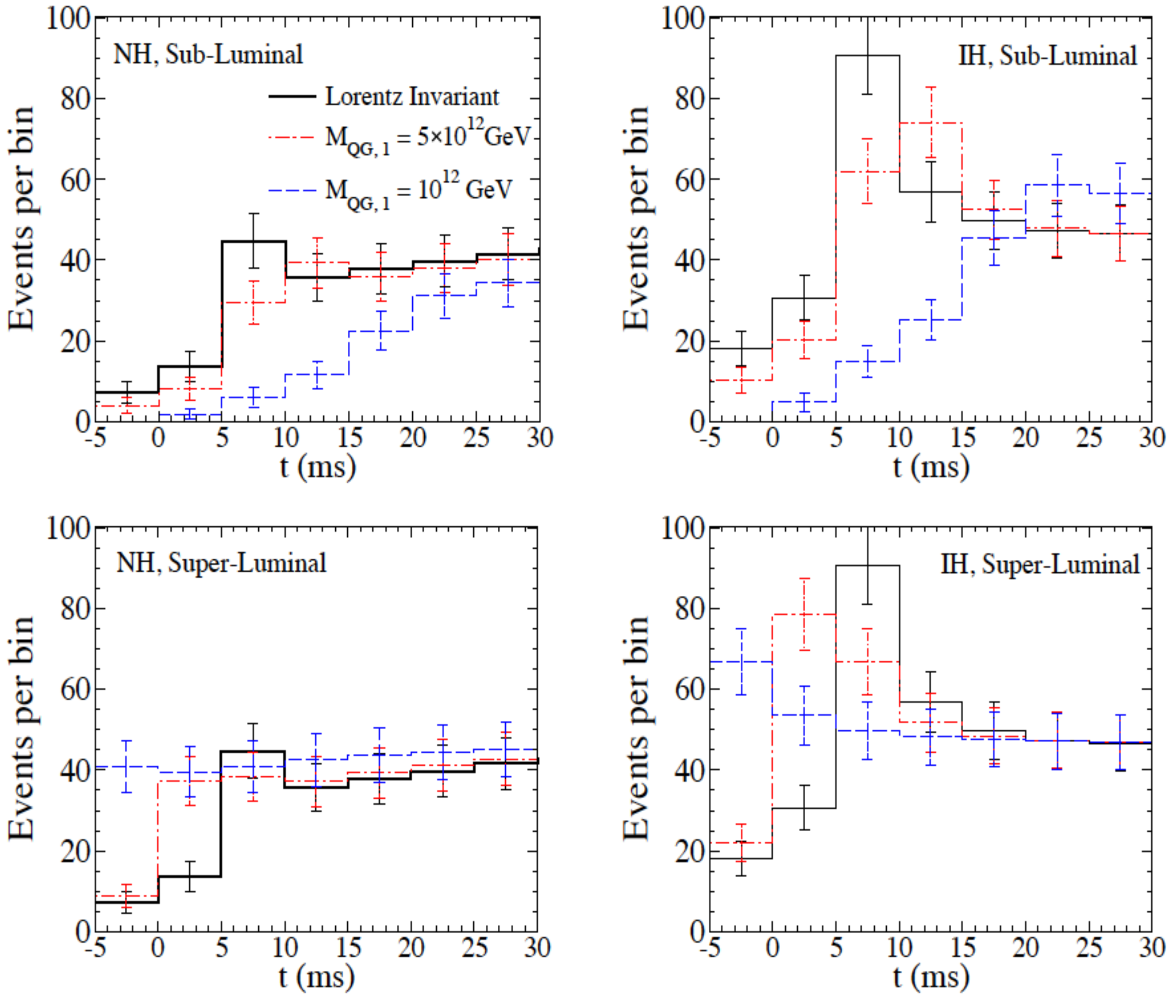
- Peak is absent ⟶ NH ($F_{\nu_e} = F^0_{\nu_x}$)
- Peak is seen ⟶ IH ($F_{\nu_e} = \sin^2\vartheta_{12}(F^0_{\nu_e} - F^0_{\nu_x}) + F^0_{\nu_x}$)

SN Bounds on Neutrino Velocity

Violation of Lorentz invariance

[Ellis et al., 0805.0253 & 1110.4848]

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



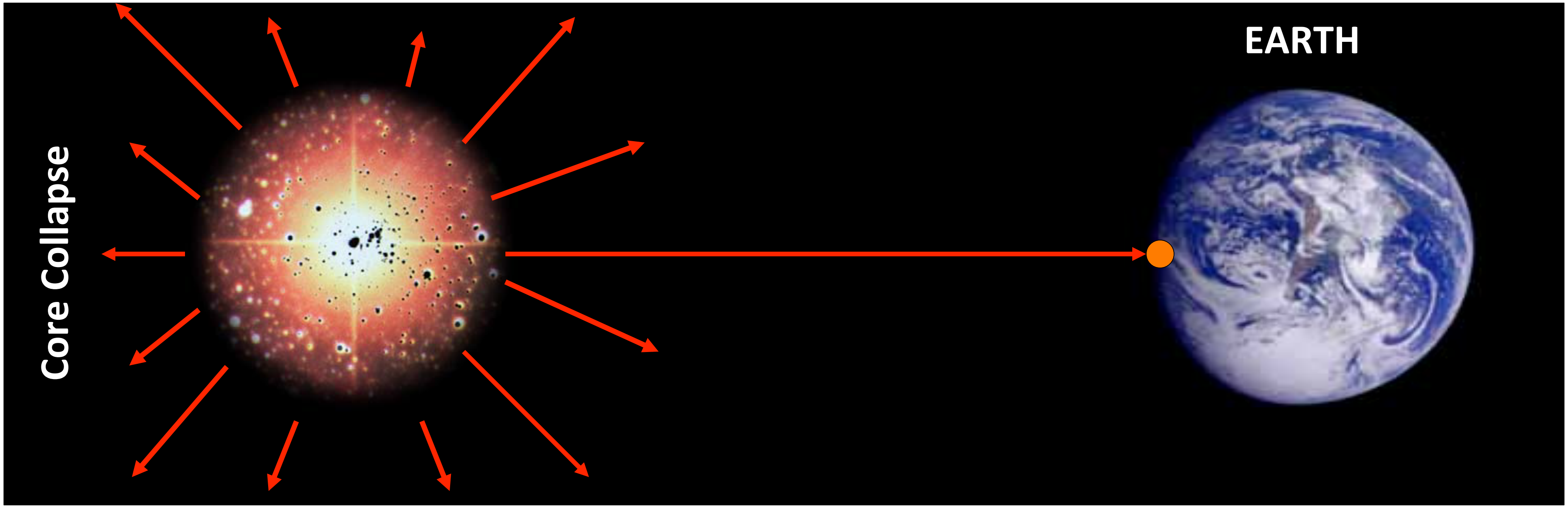
The signal would be spread out and shifted in time.

(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

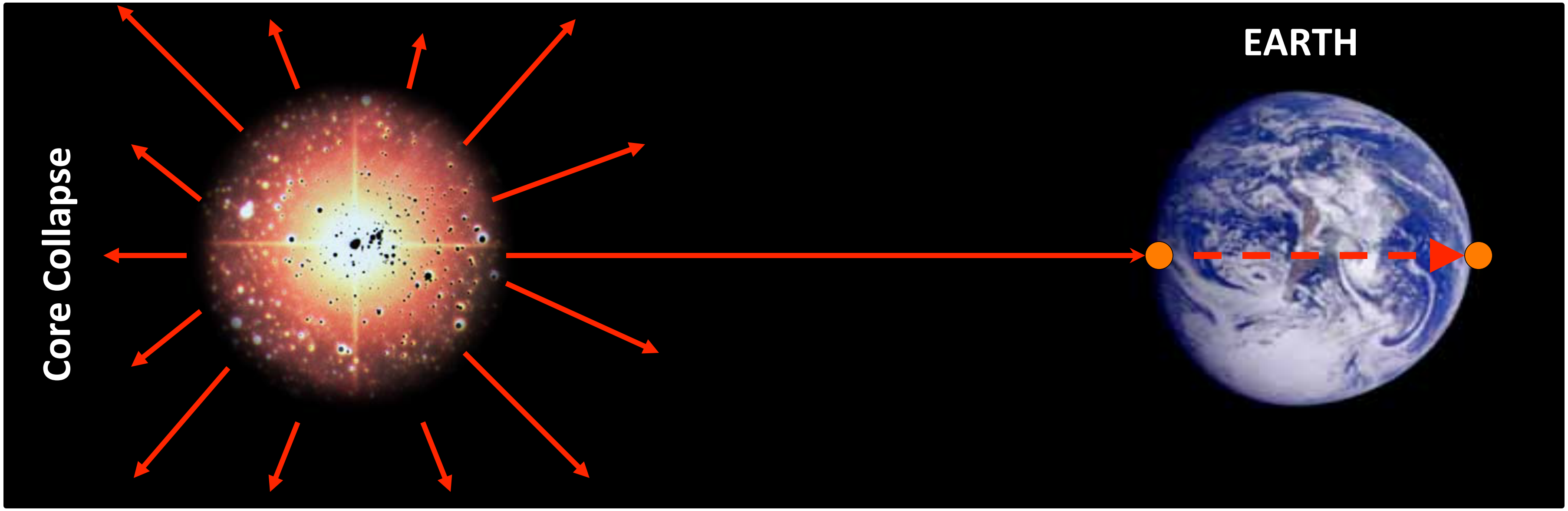
Earth Matter Effect:



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

SN neutrino Flux at Earth

Earth Matter Effect:



[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):

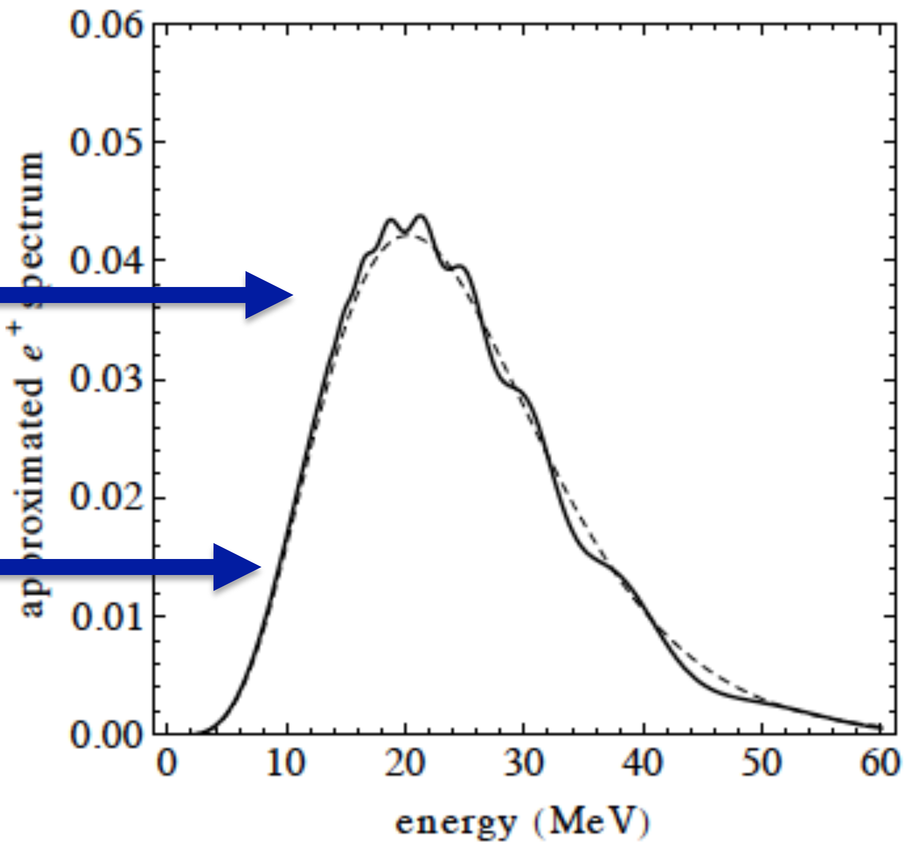
$$F_{\nu_e} = F^0_{\nu_x} \quad \text{(No E.M)}$$

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

Inverted Hierarchy (IH):

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

$$F_{\bar{\nu}_e} = F^0_{\nu_x} \quad \text{(No E.M)}$$



[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):

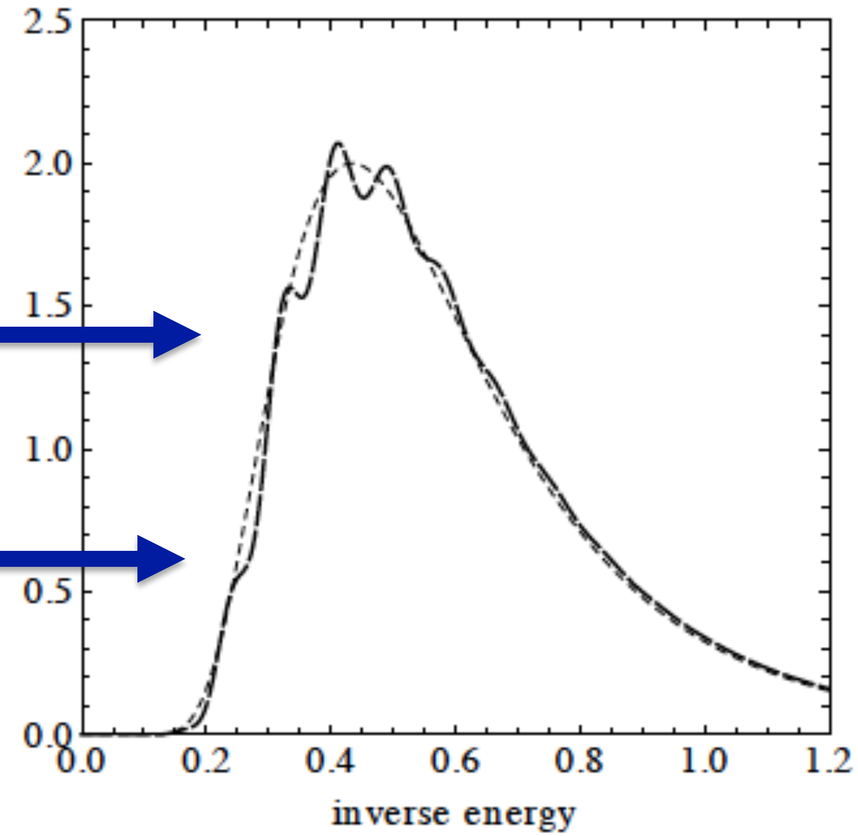
$$F_{\nu_e} = F^0_{\nu_x}$$ (No E.M)

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

Inverted Hierarchy (IH):

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

$$F_{\bar{\nu}_e} = F^0_{\nu_x}$$ (No E.M)



[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):

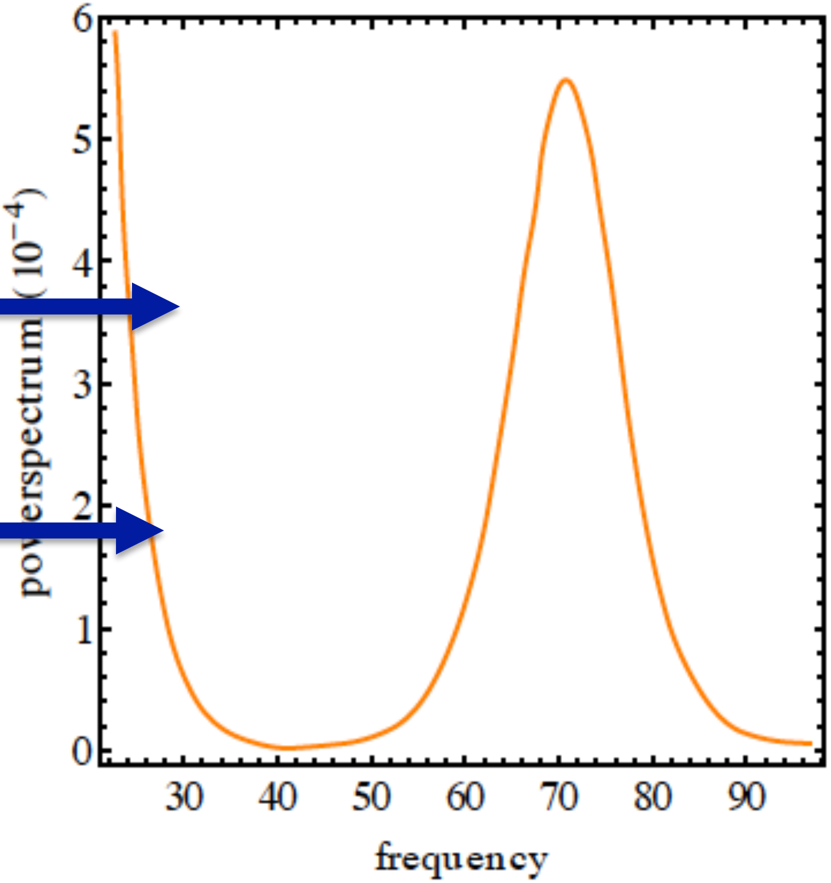
$$F_{\nu_e} = F^0_{\nu_x} \quad \text{(No E.M)}$$

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

Inverted Hierarchy (IH):

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

$$F_{\bar{\nu}_e} = F^0_{\nu_x} \quad \text{(No E.M)}$$



[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 (N

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

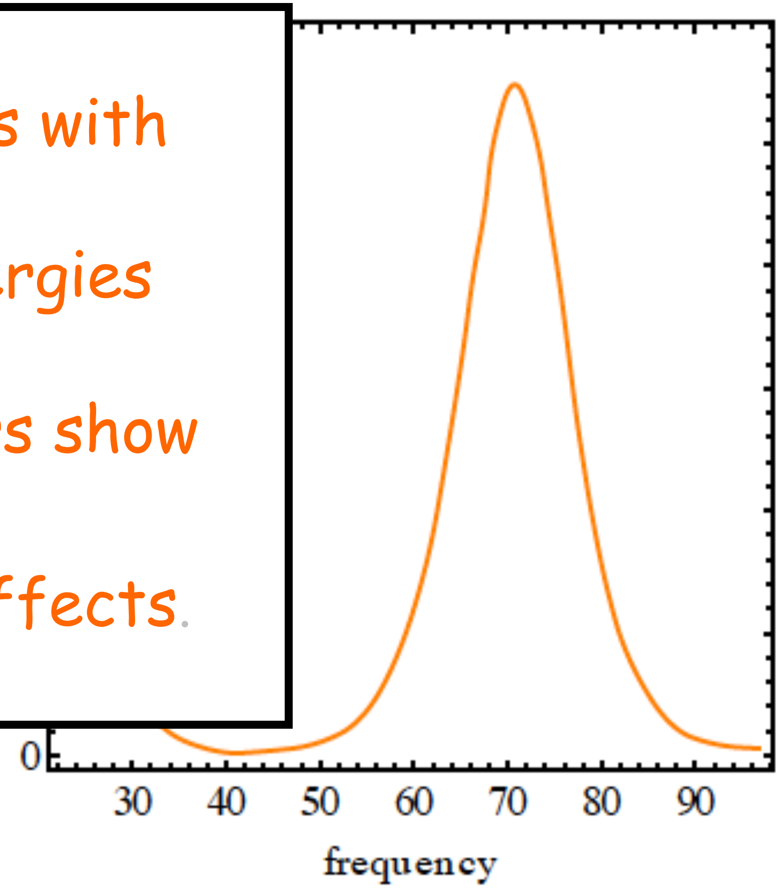
$$F_{\bar{\nu}_e} = \cos^2$$

Inverted Hierarchy (I

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

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

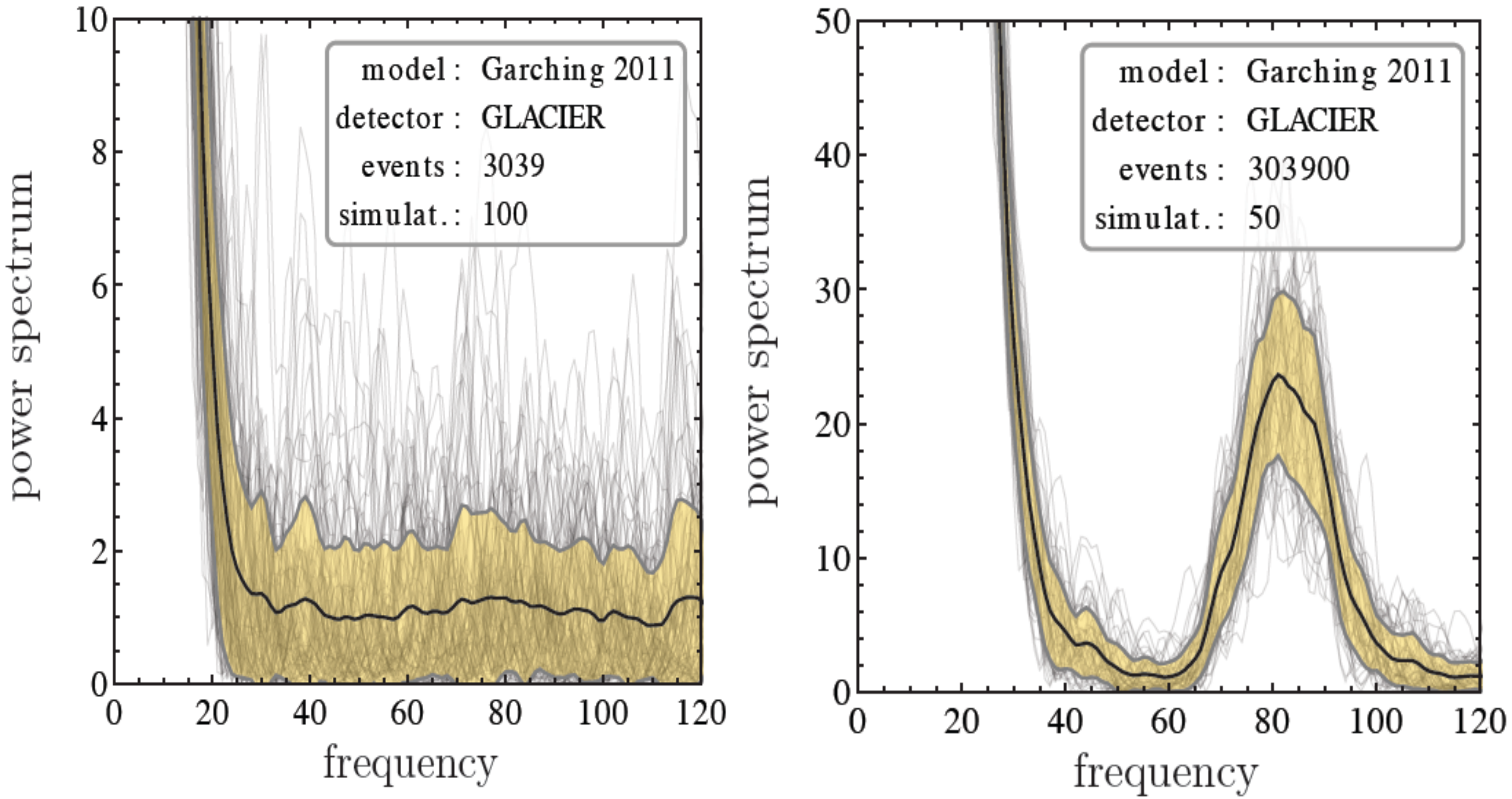
Recent simulations with close average energies of different flavors show **negligible** EM effects.



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

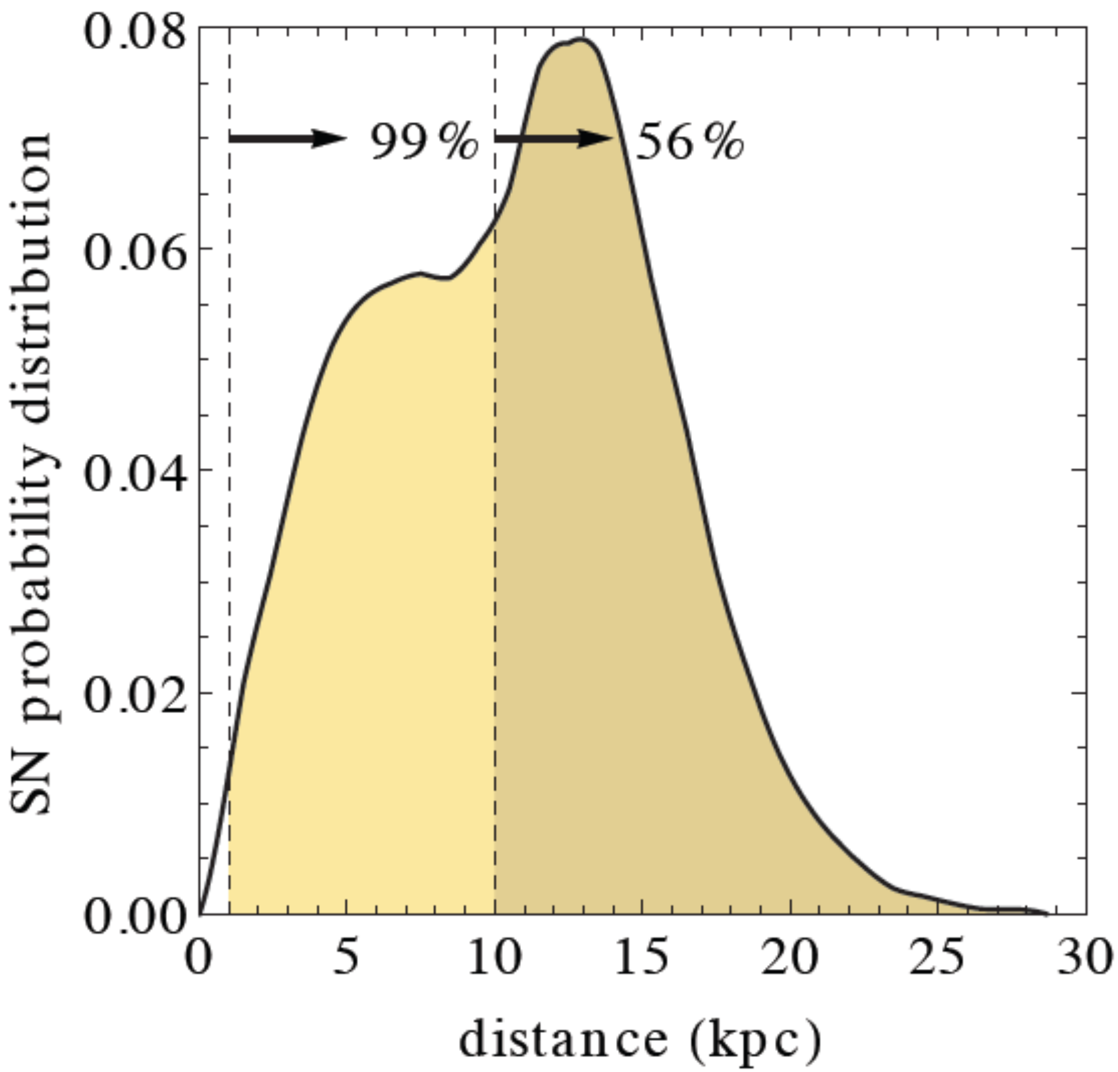
SN neutrino Flux at Earth

Earth Matter Effect:



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

Galactic SN Distribution



Possible sub-kpc candidate:

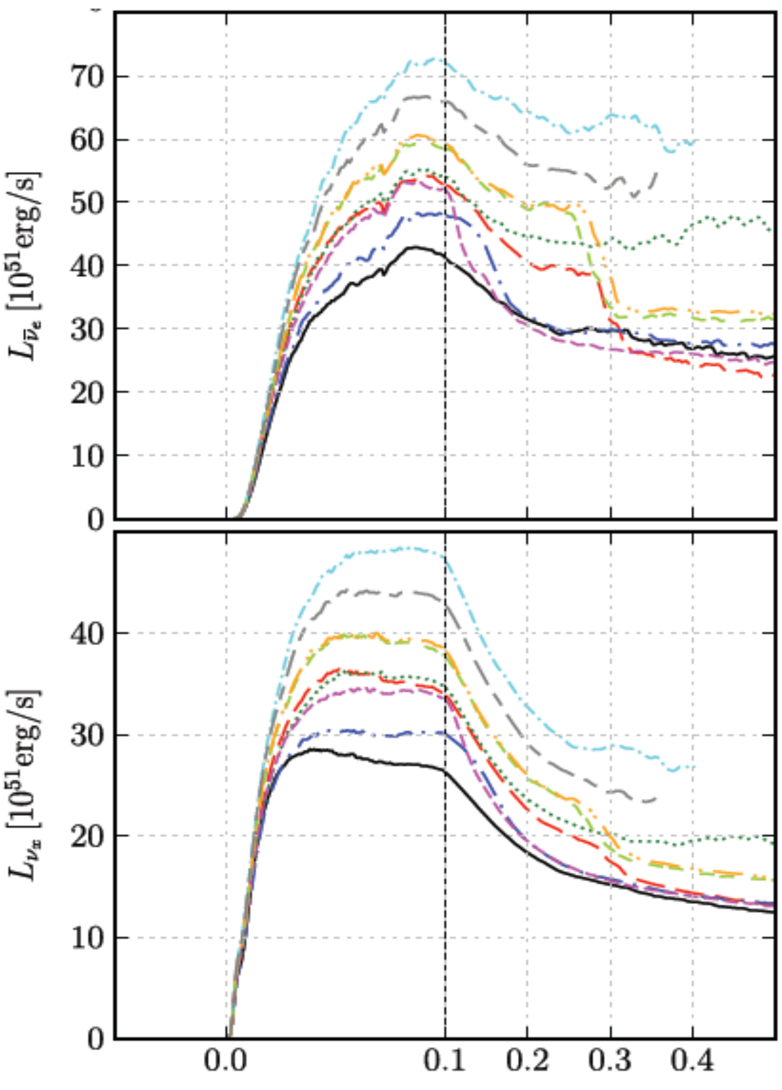
Red supergiant Betelguse

distance~ 0.2 kpc

Event count~ 10s of million

[Mirizzi, Raffelt & Serpico; (2006)]

Rise time Analysis



- High degeneracy of ν_e and e, suppresses $\bar{\nu}_e$ production.
- $\bar{\nu}_e$ more in equilibrium with environment than ν_x

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

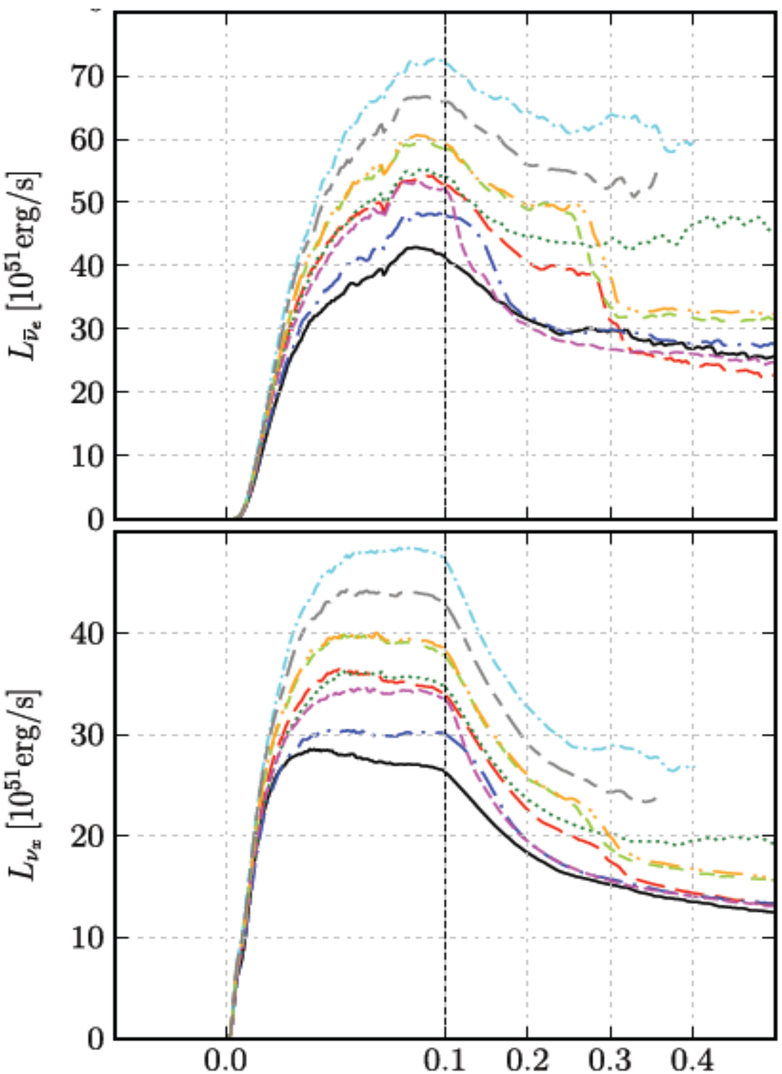
NH: $F_{\bar{\nu}_e} = \cos^2\vartheta_{12}(F^0_{\bar{\nu}_e} - F^0_{\nu_x}) + F^0_{\nu_x}$

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

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]

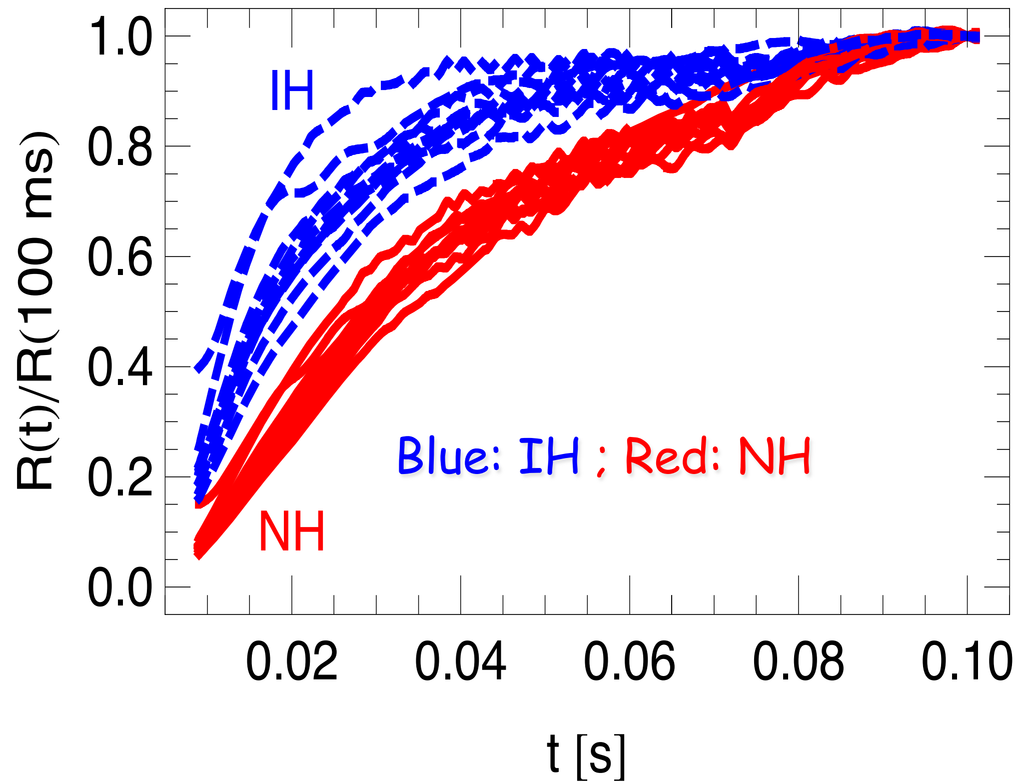
Rise time Analysis: Hierarchy Determination



Garching group, 2011

Normalized Count rate :

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

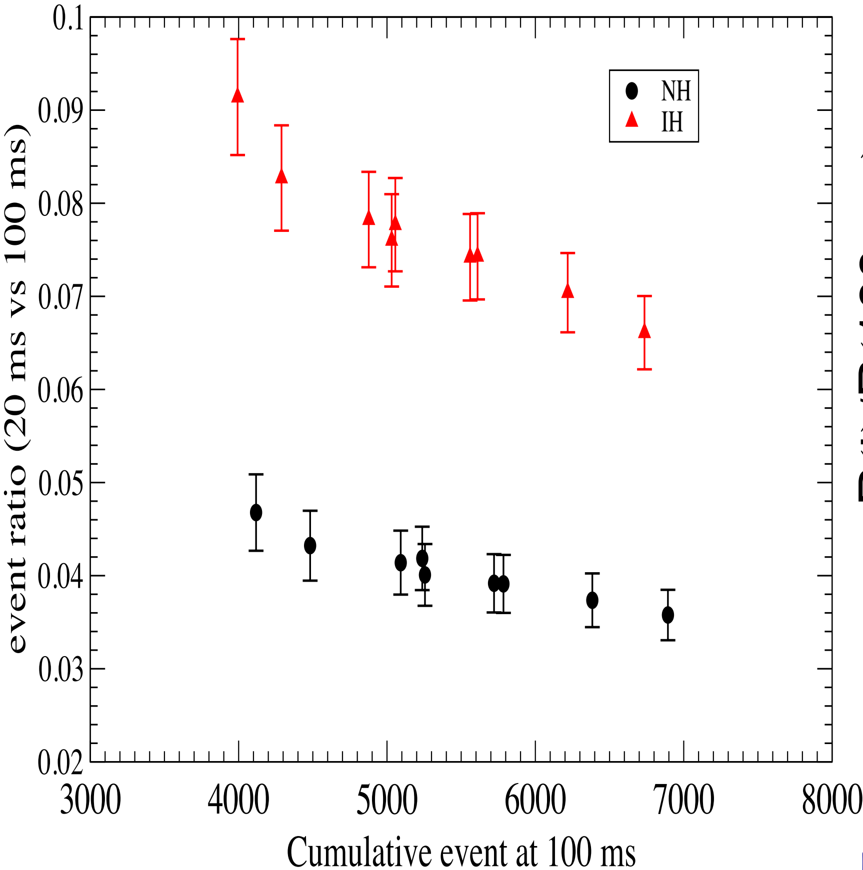


Flux in IH rises faster than NH

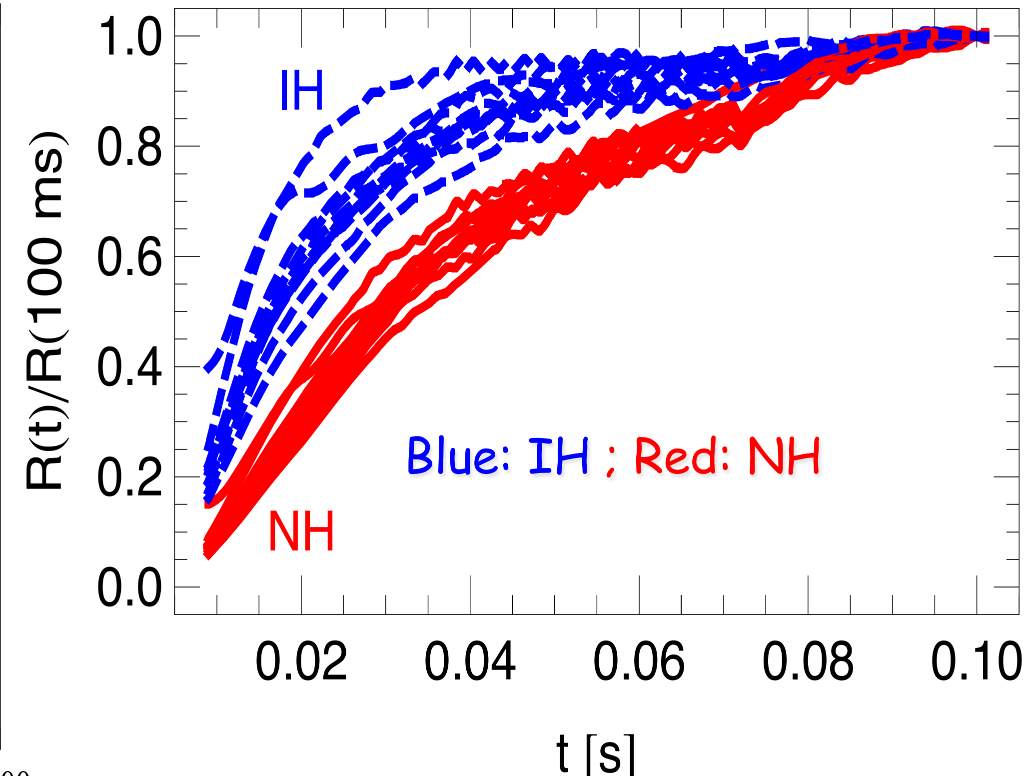
[Serpico, **S.C**, Fischer, Hüdepohl, Janka & Mirizzi
PRD 85:085031,2012]

Rise time Analysis: Hierarchy Determination

Normalized Count rate :
10 different models (12 $M_{\odot}$-40 $M_{\odot}$)



Mton



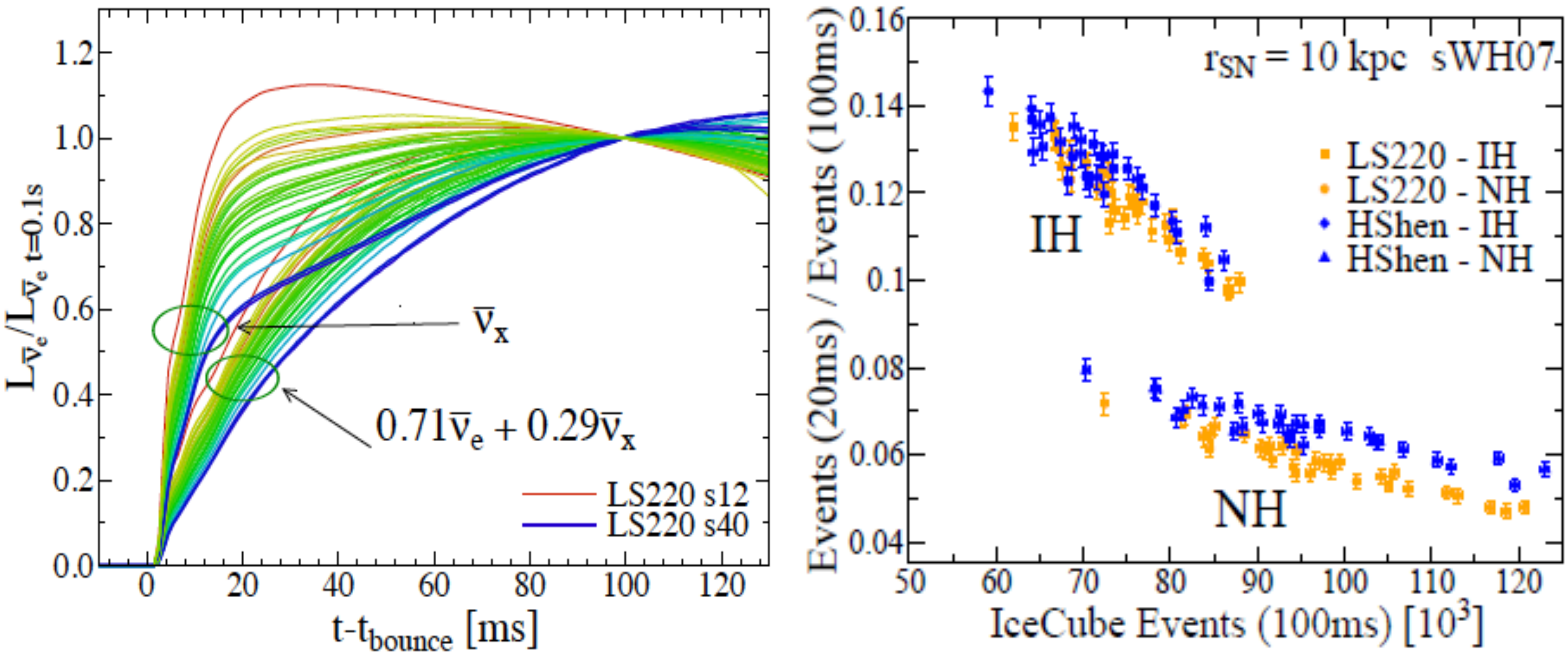
Flux in IH rises faster than NH

SC & Mirizzi, LAGUNA meeting '14

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

Rise time Analysis: Hierarchy Determination

Normalized Count rate :
32 different models



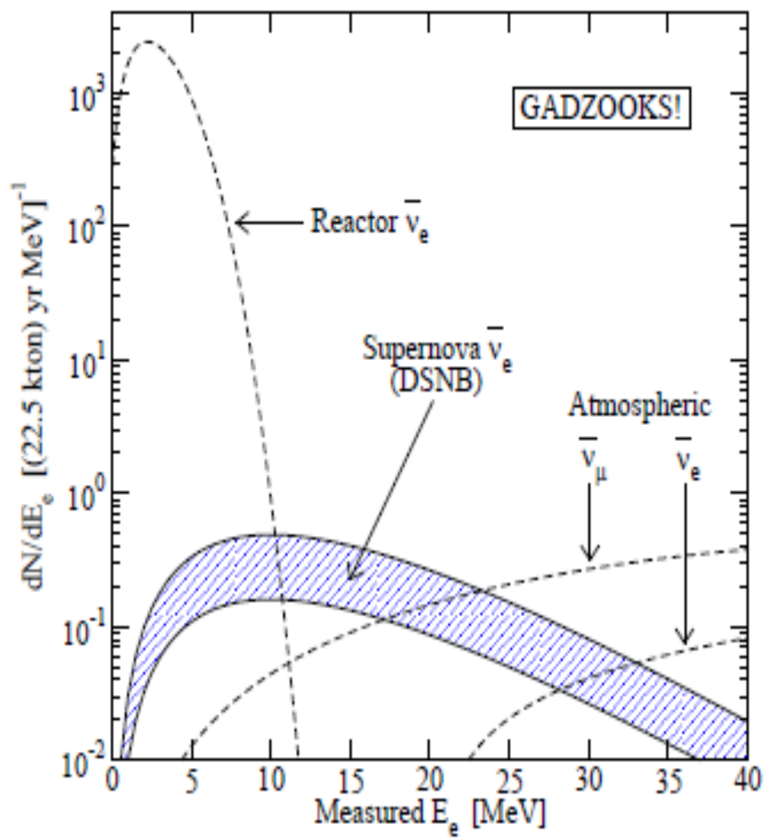
Flux in IH rises faster than NH

[C.D. Ott et al. Neutrino 2012, Japan, 1212.4250]

Diffuse SN Neutrino Background (DSNB)

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

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



Window of opportunity
bkg less than signal

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

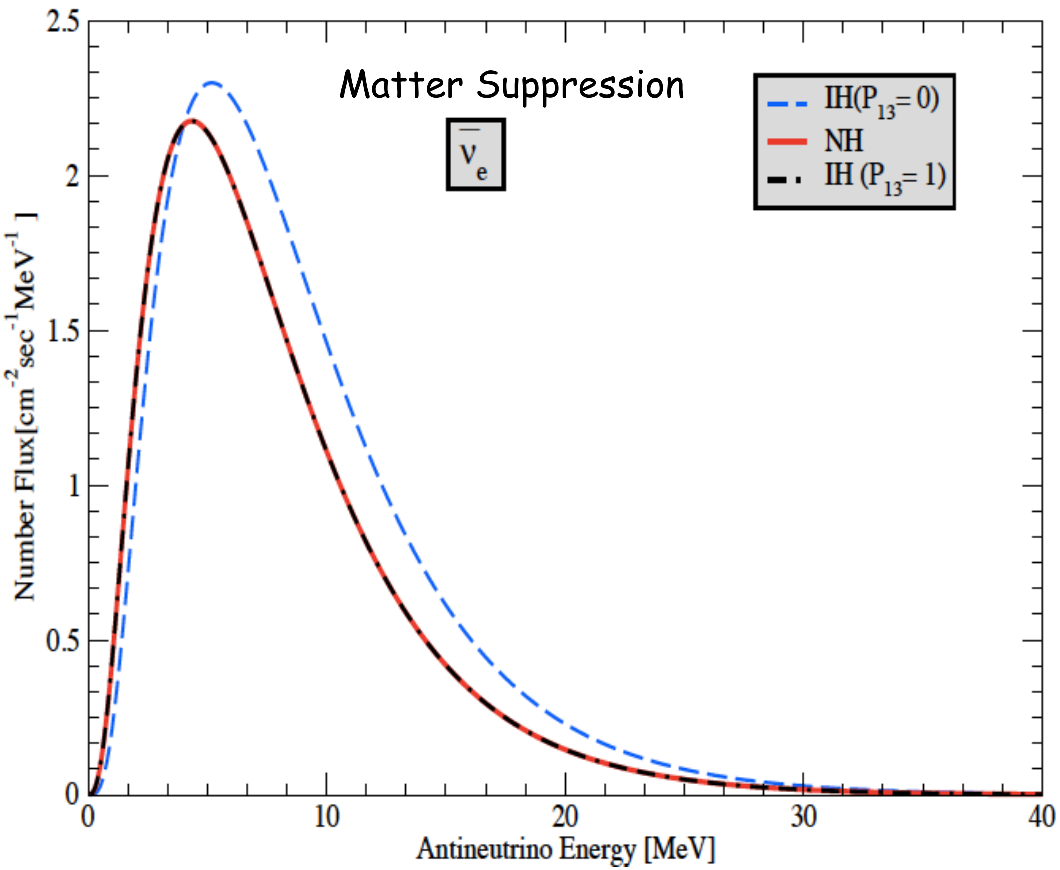
ν astronomy at cosmic distances !

Diffuse SN Neutrino Background (DSNB)

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

Window of opportunity
bkg less than signal

SC, Choubey, Dasgupta, Kar; JCAP. 2008



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

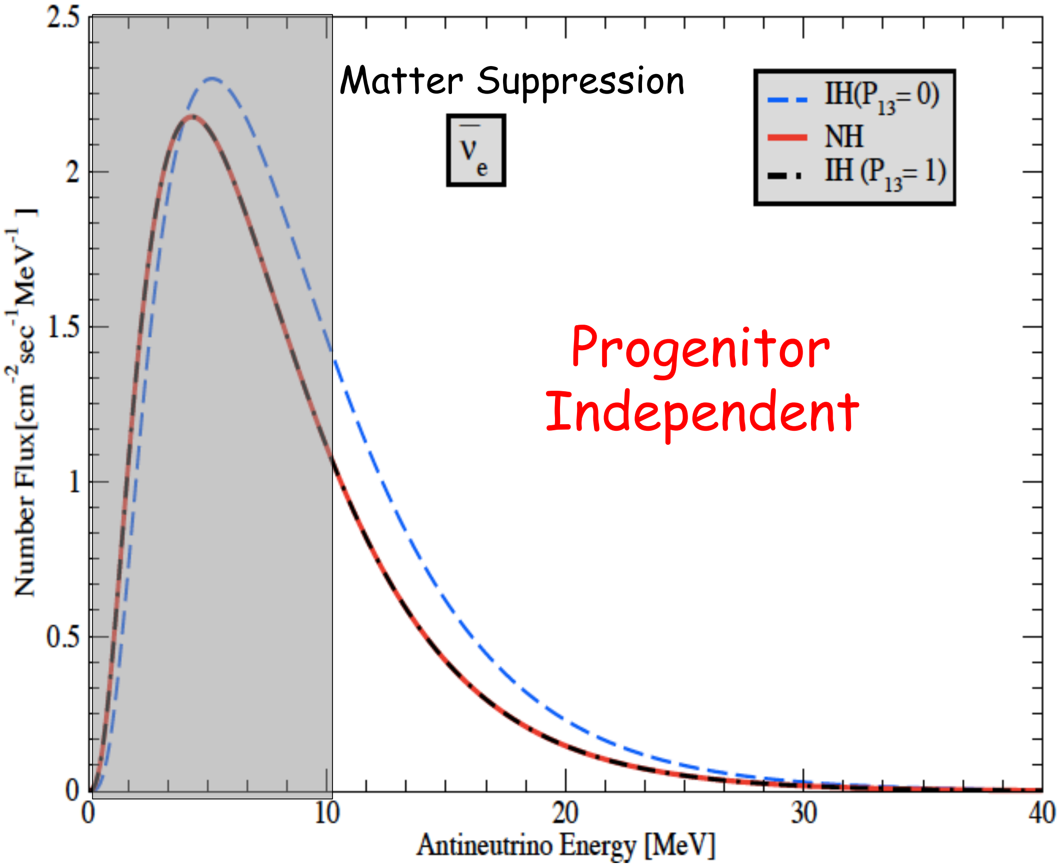
ν astronomy at cosmic distances !

Diffuse SN Neutrino Background (DSNB)

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

Window of opportunity
bkg less than signal

SC, Choubey, Dasgupta, Kar; JCAP. 2008



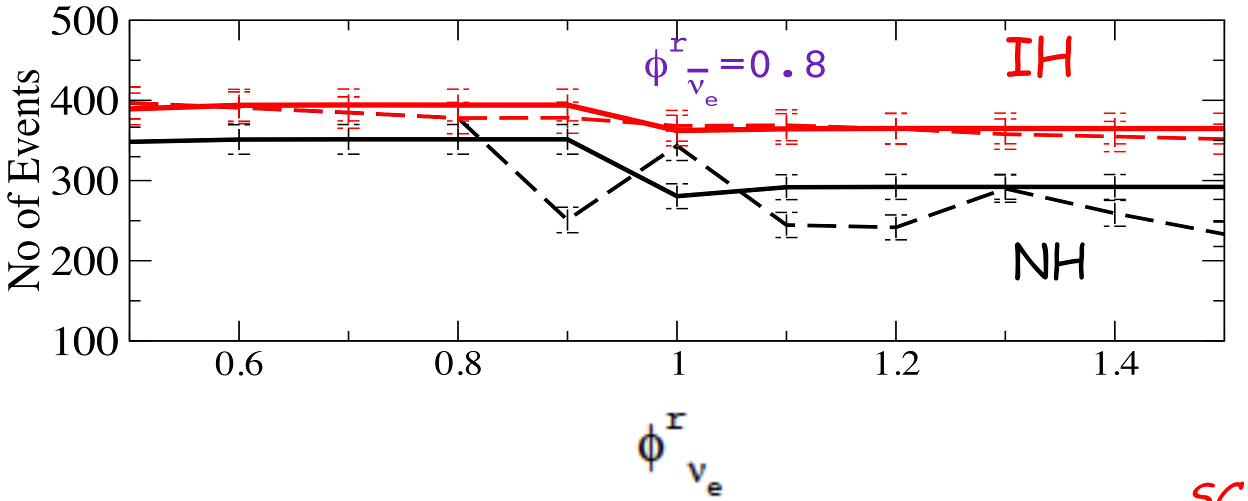
SK-doped with Gd would detect few clear DSNB $\bar{\nu}$ events/year.

ν astronomy at cosmic distances !

Diffuse SN Neutrino Background (DSNB)

All progenitors will not have the same relative neutrino luminosity.

Depend on the mass of the star.



Parametric study on relative luminosities

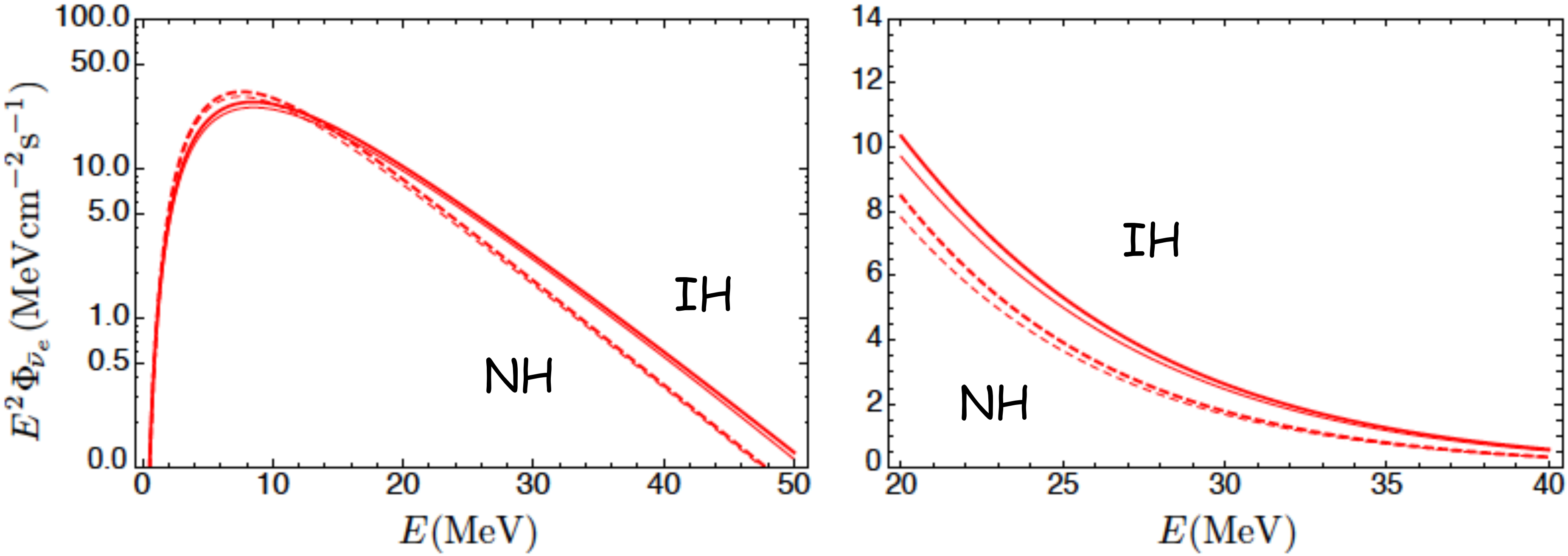
SC, Choubey, Kar PLB. 2011

Diffuse SN Neutrino Background (DSNB)

[Lunerdini & Tamborra, JCAP. 2012

Study based on Basel simulations

However only three progenitor classes for all SNe



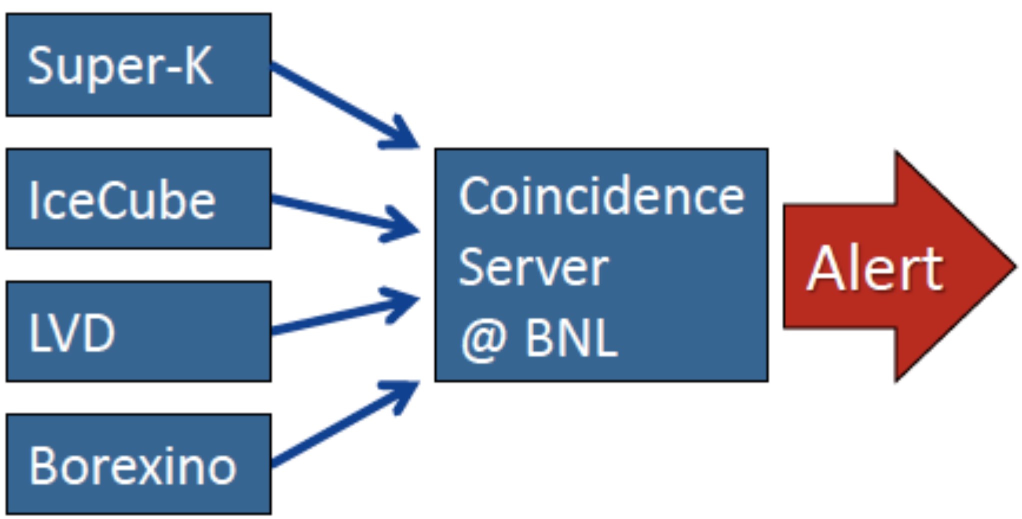
SK-doped with Gd would detect few clear DSNB $\bar{\nu}$ events/year.

ν astronomy at cosmic distances !

SuperNova Early Warning System (SNEWS)

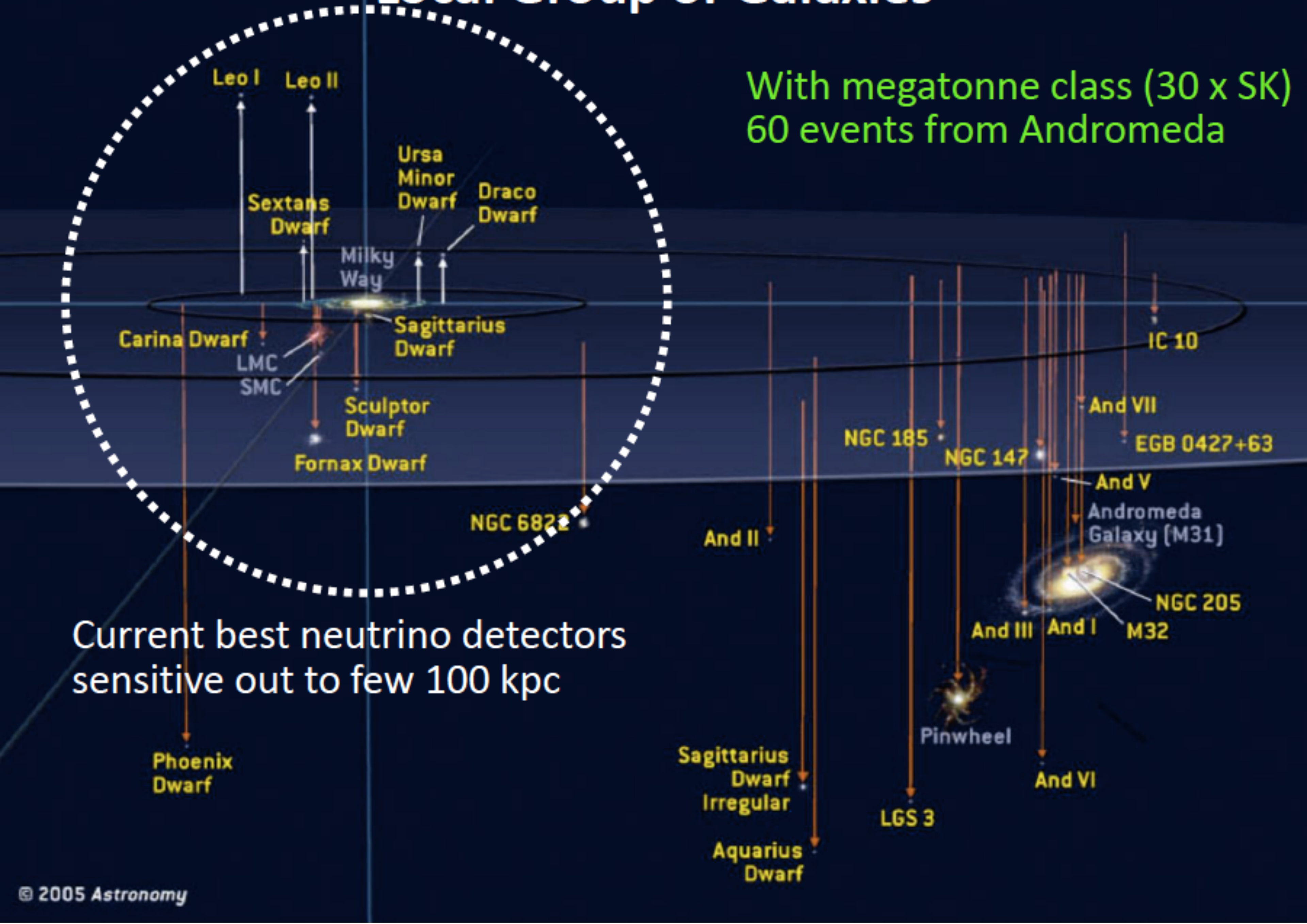
- Neutrinos arrive several hours before photons
- Can alert astronomers several hours in advance

http://snews.bnl.gov



Local Group of Galaxies

With megatonne class (30 x SK)
60 events from Andromeda



Current best neutrino detectors
sensitive out to few 100 kpc

Conclusions

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

- SN provide very extreme conditions, where the neutrino-neutrino interactions prove to be surprisingly important in the n oscillations.

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

- Neutronization is the best phase to probe hierarchy.
- Earth Matter effect: Detectable for Sub-kpc SNe.
- Rise time of SNe signal contains hierarchy information.

- DSNB detection would be unique probe to neutrinos from cosmic distances.

Open Problems

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

- SN provide very extreme conditions, where the neutrino-neutrino interactions prove to be surprisingly important in the n oscillations.

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

- Neutronization is the best phase to probe hierarchy.
- Earth Matter effect: Detectable for Sub-kpc SNe.
- Rise time of SNe signal contains hierarchy information.

- DSNB detection would be unique probe to neutrinos from cosmic distances.


LOOKING FORWARD
FOR THE NEXT
GALACTIC SN !
Thank You !