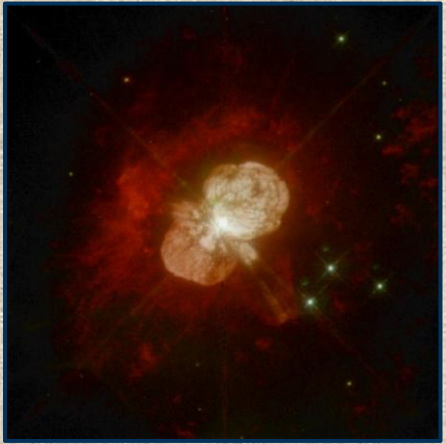
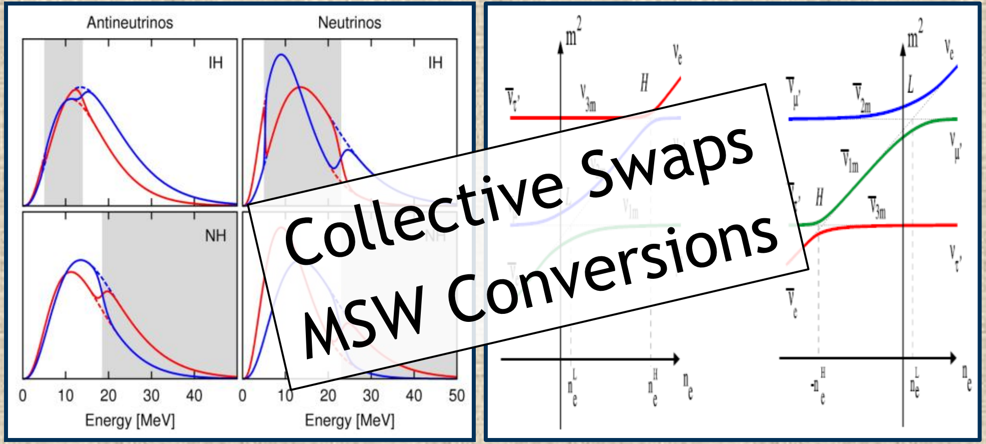
Basudeb Dasgupta

Neutrinos from Supernovae

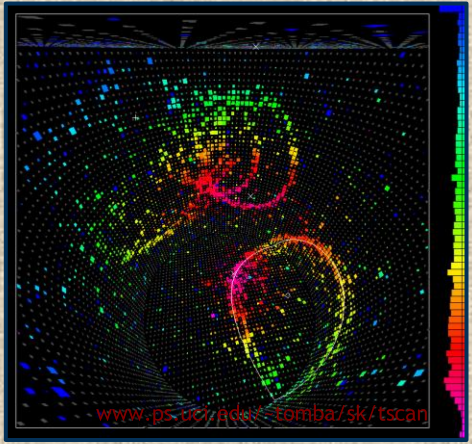
International Conference in High Energy Physics
ICHEP 2010, 22-28 July 2010, Paris, France

Menu du jour





Collective Swaps
MSW Conversions



Neutrino Production

Neutrino Propagation and Flavor Conversion

Neutrino Detection

Neutrino Astronomy Supernova Astrophysics

1. Pointing in advance/SN alerts
2. Signatures of stellar dynamics
3. Tracking the local SN rate
4. Timing/GW-coincidence

Neutrino properties and particle physics

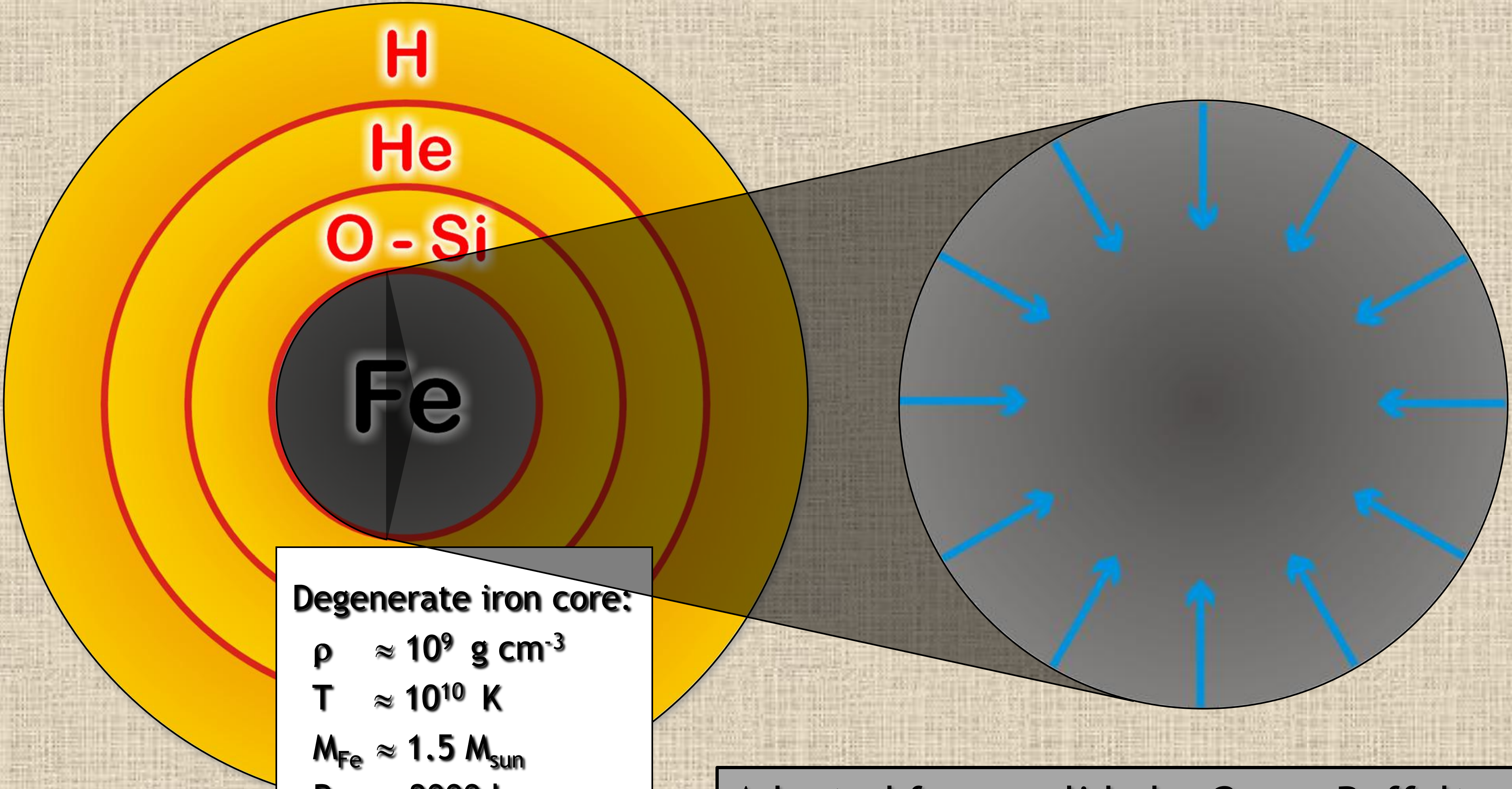
1. Neutrino Mass Hierarchy
2. Θ_{13} estimate
3. QCD phase transition

Neutrino Production in Supernovae

SN Explosion and Neutrino Emission

Onion structure

Collapse (implosion)



Degenerate iron core:

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

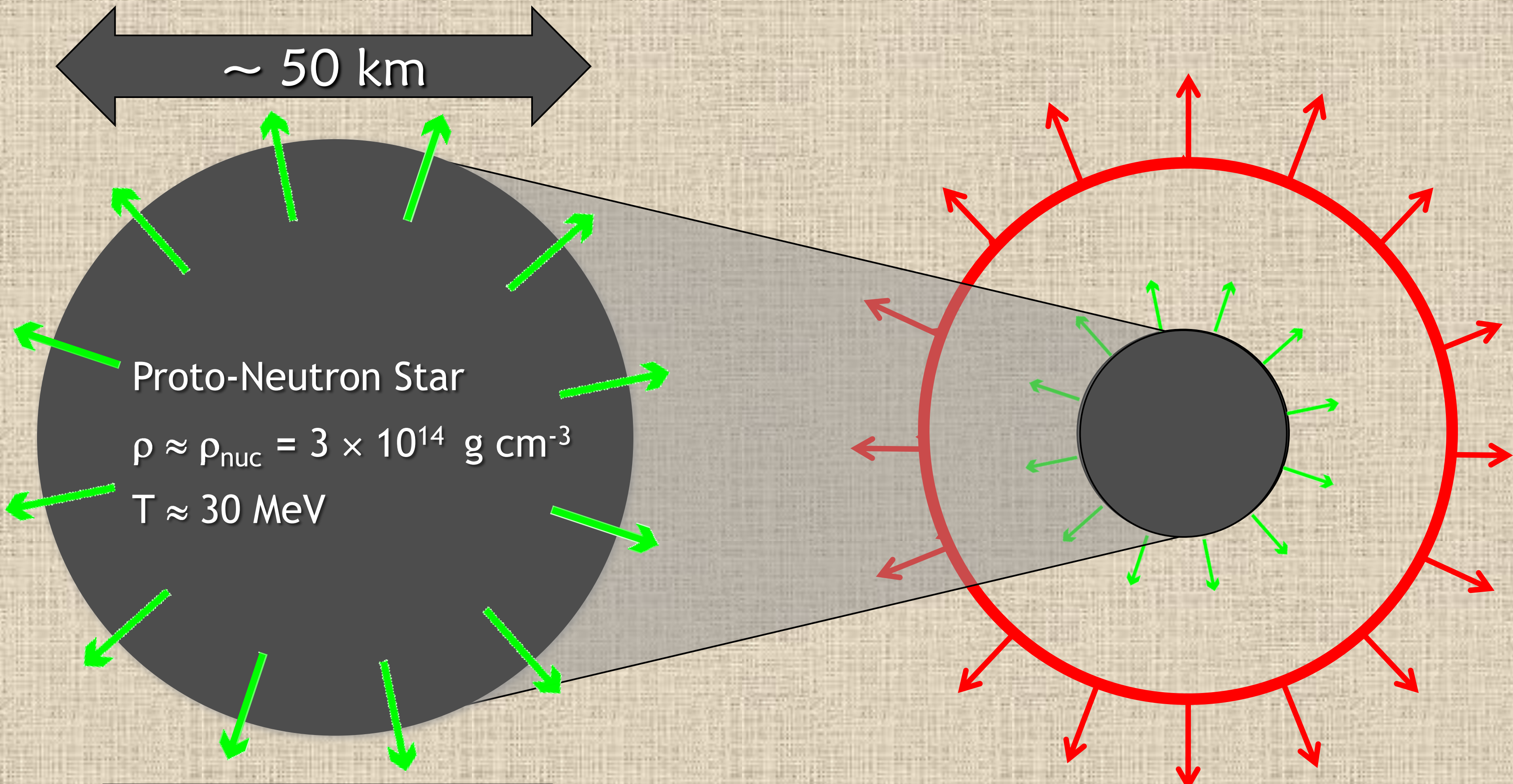
$T \approx 10^{10}$ K

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

$R_{Fe} \approx 8000$ km

Adapted from a slide by Georg Raffelt

SN Explosion and Neutrino Emission



Newborn Neutron Star

Neutrino Driven Explosion

~ 50 km

Proto-Neutron Star

$\rho \approx \rho_{nuc} = 3 \times 10^{14}$ g cm^{-3}

T ≈ 30 MeV

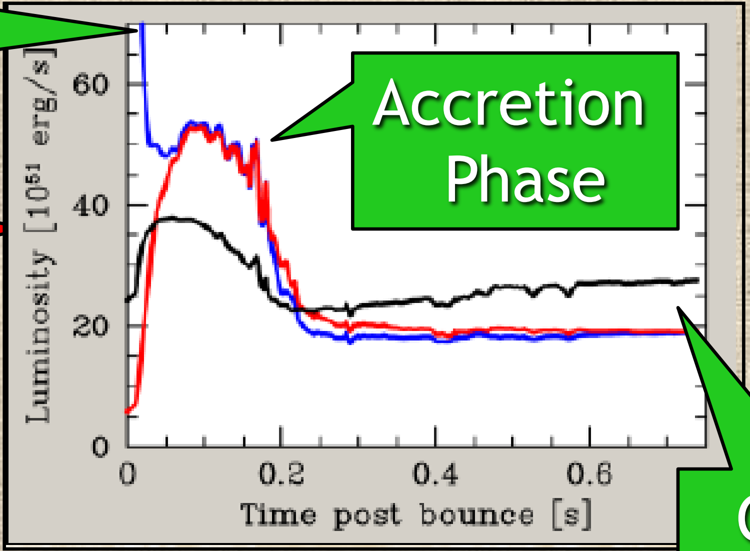
Neutrino Cooling

Neutrino Luminosities and Energies

Burst Phase

Luminosity in 10^{51}erg/s

For ν_e, anti-ν_e and ν_x

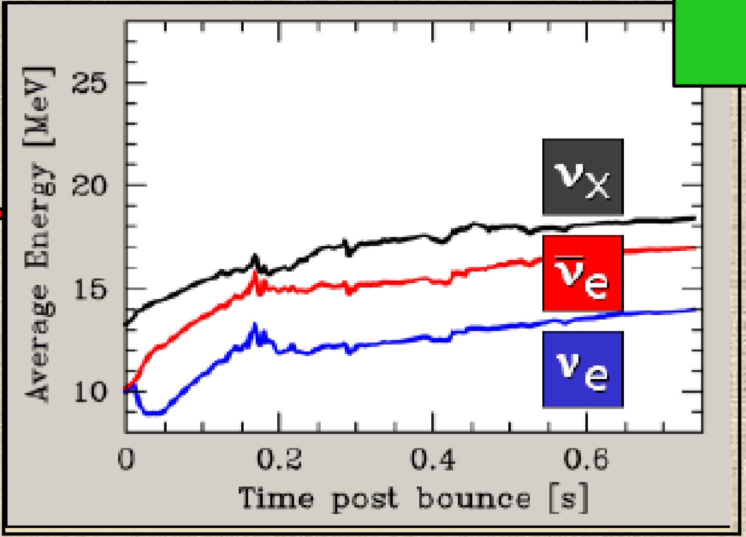


Accretion Phase

Cooling Phase

Average Energy in MeV

For ν_e, anti-ν_e and ν_x



Raffelt, Keil, Buras, Janka and Rampp, arXiv:astro-ph/0303226

Neutrino Propagation and Flavor Conversions

Free-Streaming Neutrinos

$$i\partial_t \rho_{\vec{p}} = \pm\left[\frac{M^2}{2p}, \rho_{\vec{p}}\right] \pm \sqrt{2}G_F[L, \rho_{\vec{p}}] \pm \sqrt{2}G_F \int \frac{d^3\vec{q}}{(2\pi)^3}(1-\cos\theta_{\vec{p}\vec{q}})[(\rho_{\vec{q}} - \bar{\rho}_{\vec{q}}), \rho_{\vec{p}}]$$

Vacuum oscillations
- M is neutrino mass matrix
- minus sign for antineutrinos

Pontecorvo

MSW effect depends on ordinary matter density L, i.e. mainly e density

Mikheev, Smirnov, Wolfenstein

Nonlinear Effects depends on the neutrino density ρ

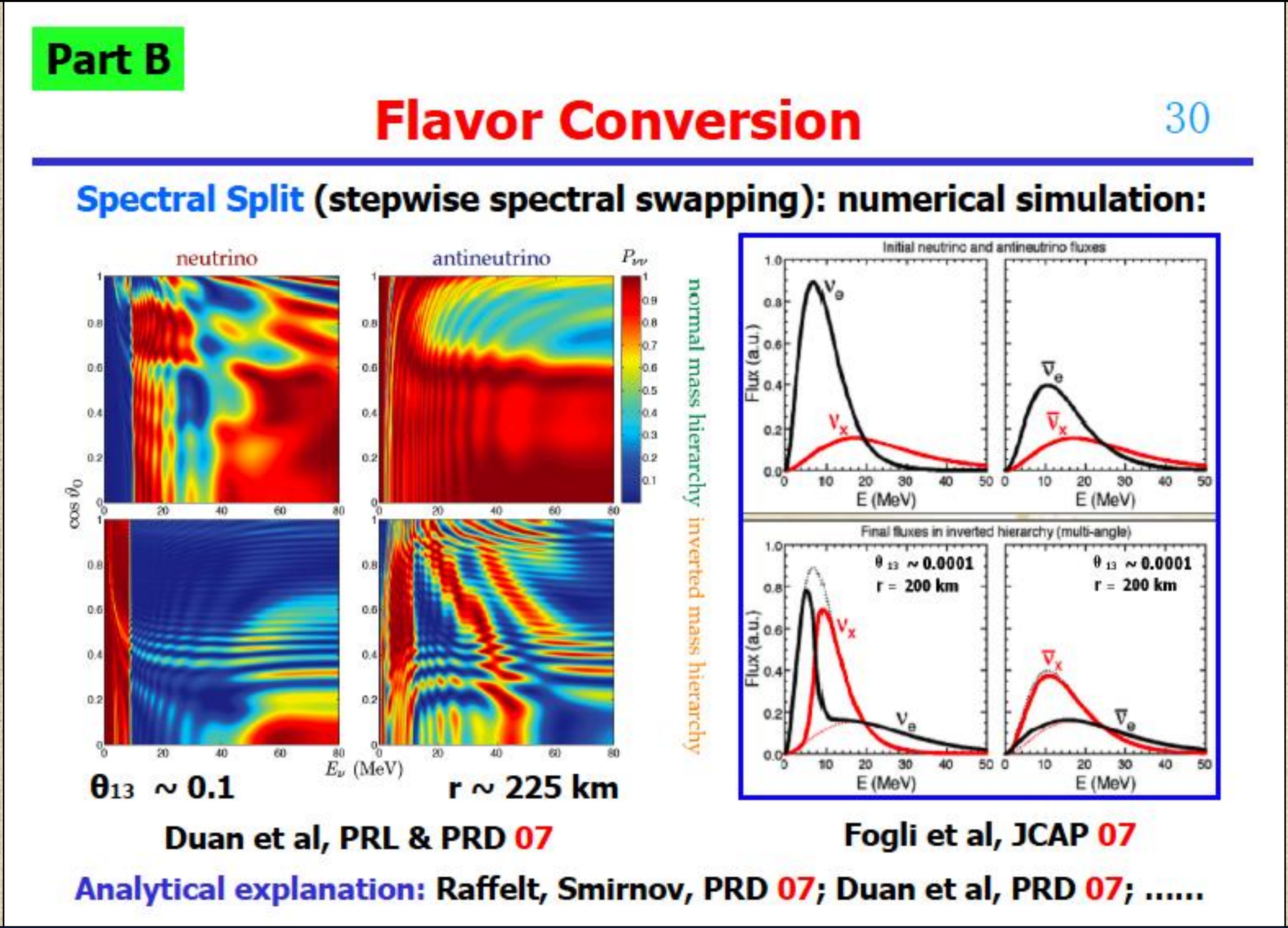
Pantaleone

Nonlinear nu-nu effects are important when nu-nu interaction energy exceeds the typical vacuum oscillation frequency

These interactions give rise to “Collective” flavor conversions

Talk by Antonio Marrone, ICHEP-2010

Status Report at ICHEP 2008



Part B

Flavor Conversion

30

Spectral Split (stepwise spectral swapping): numerical simulation:

$\theta_{13} \sim 0.1$ r ~ 225 km

Duan et al, PRL & PRD 07

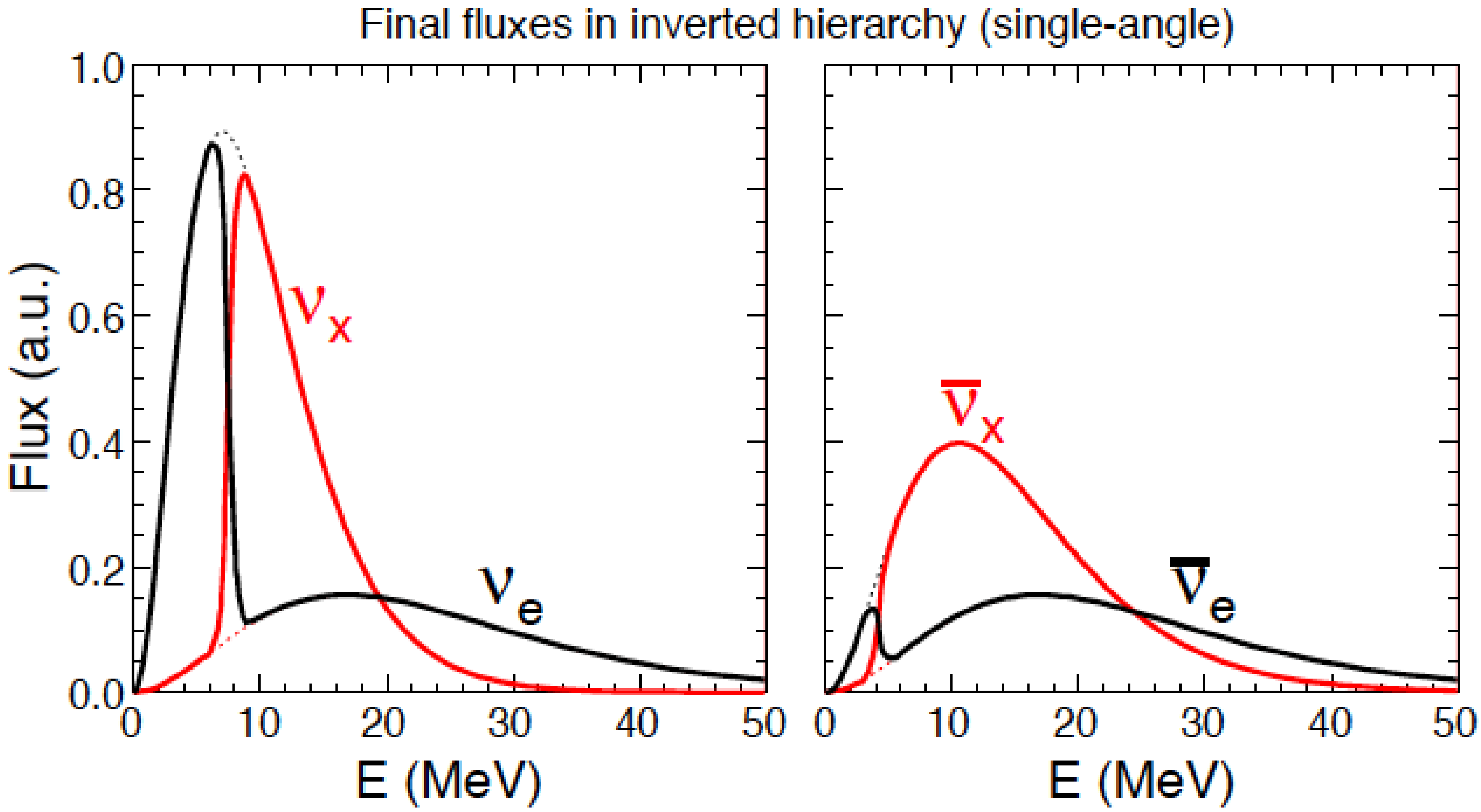
Fogli et al, JCAP 07

Analytical explanation: Raffelt, Smirnov, PRD 07; Duan et al, PRD 07; ……

Neutrinos Plenary Talk by Zhi-Zhong Xing, ICHEP-2008

Spectral Swaps: Accretion Phase

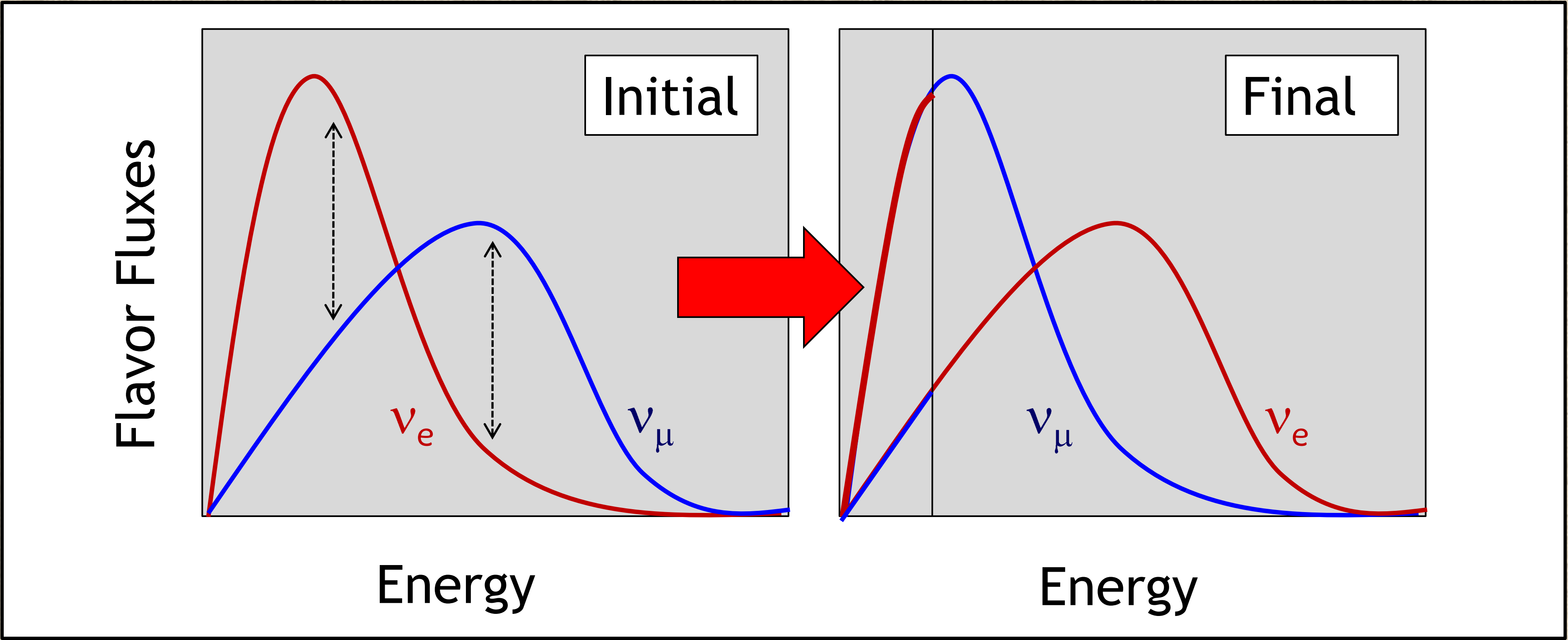
Nontrivial Evolution only for Inverted Hierarchy



Fogli, Lisi, Marrone and Mirizzi, arXiv: 0707.1998

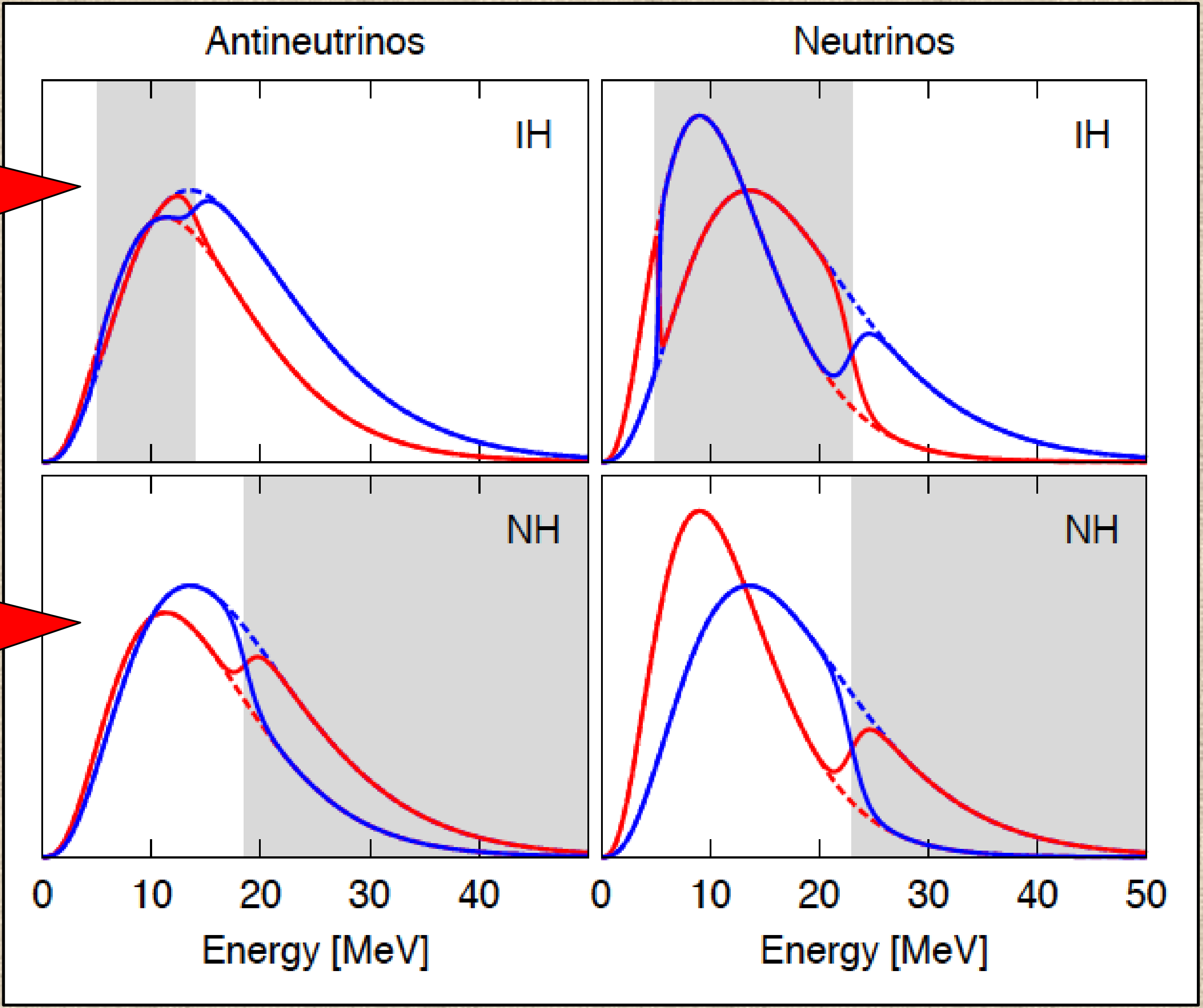
Collective Flavor Conversion

Instability in Flavor Space → Swap around spectral crossings



Swap cannot be complete, because of Total Lepton Number Conservation

Spectral Swaps: Cooling Phase

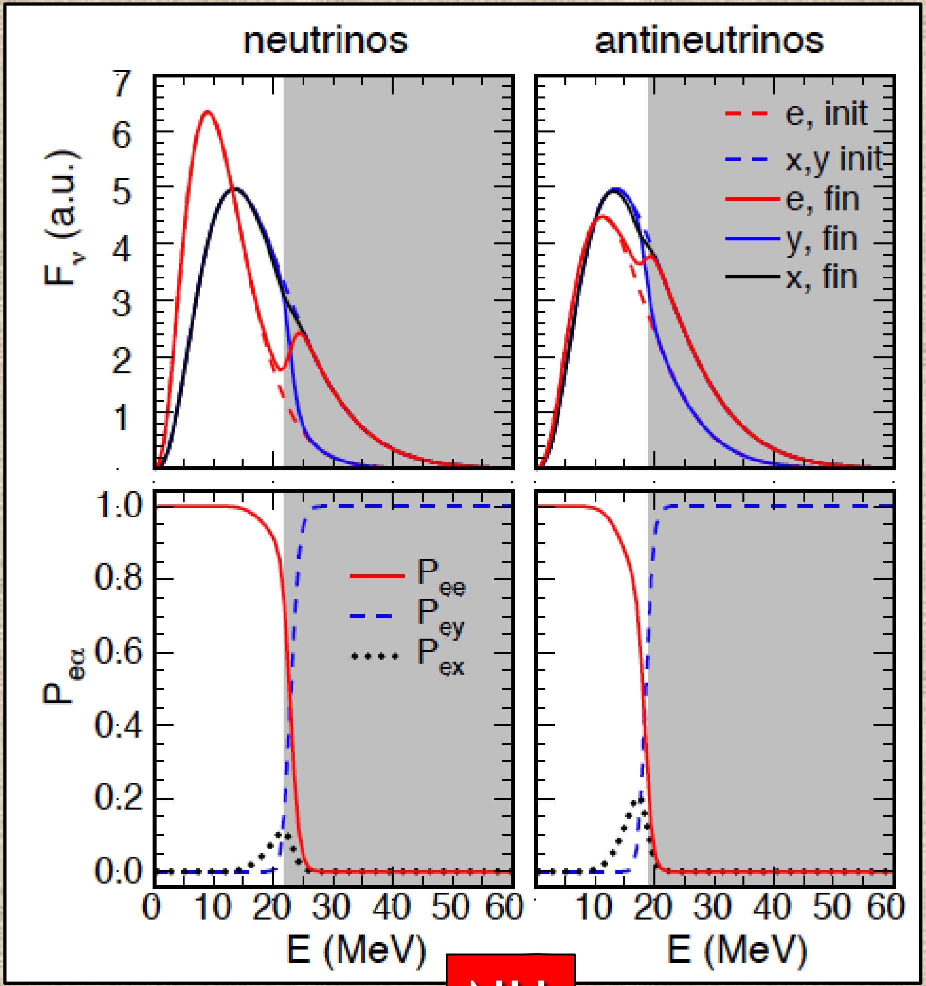


Spectral Splits in Inverted Hierarchy

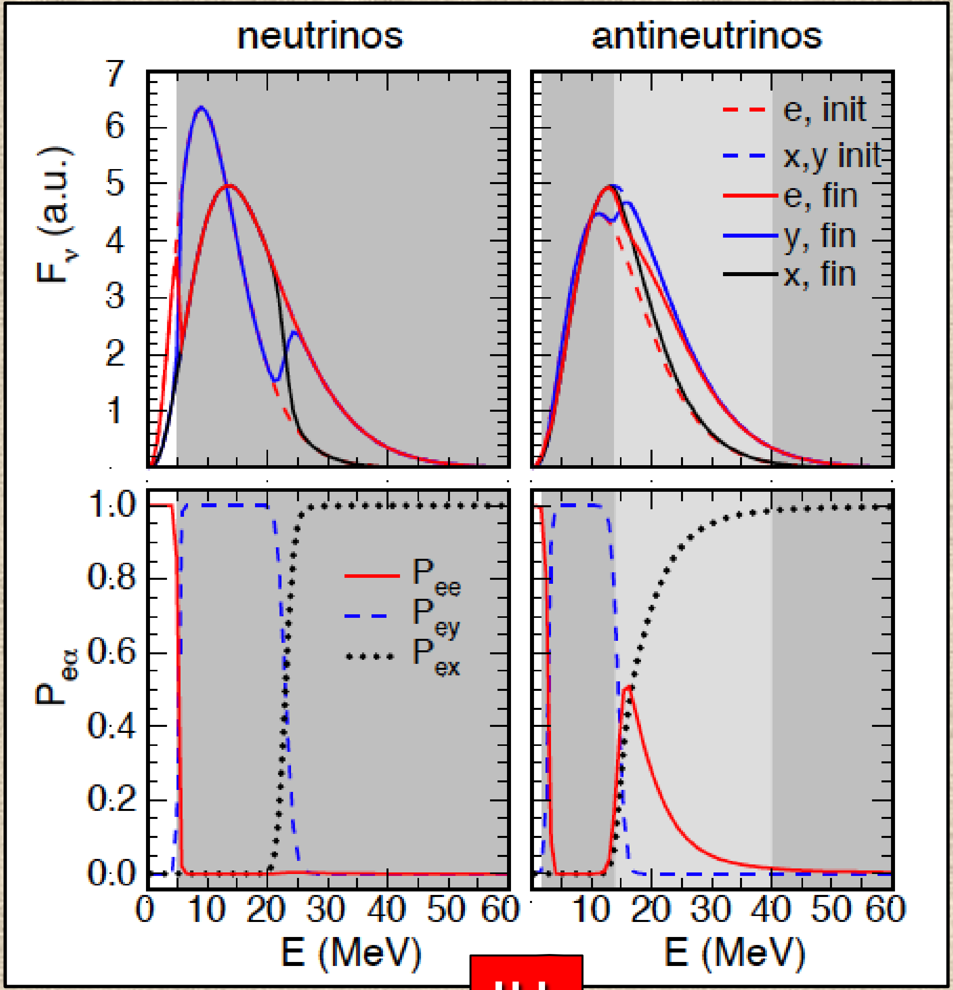
Spectral Splits in Normal Hierarchy

Dasgupta, Dighe, Raffelt and Smirnov, arXiv: 0904.3542 (PRL)

3 Flavor Spectral Swaps: Cooling Phase



NH

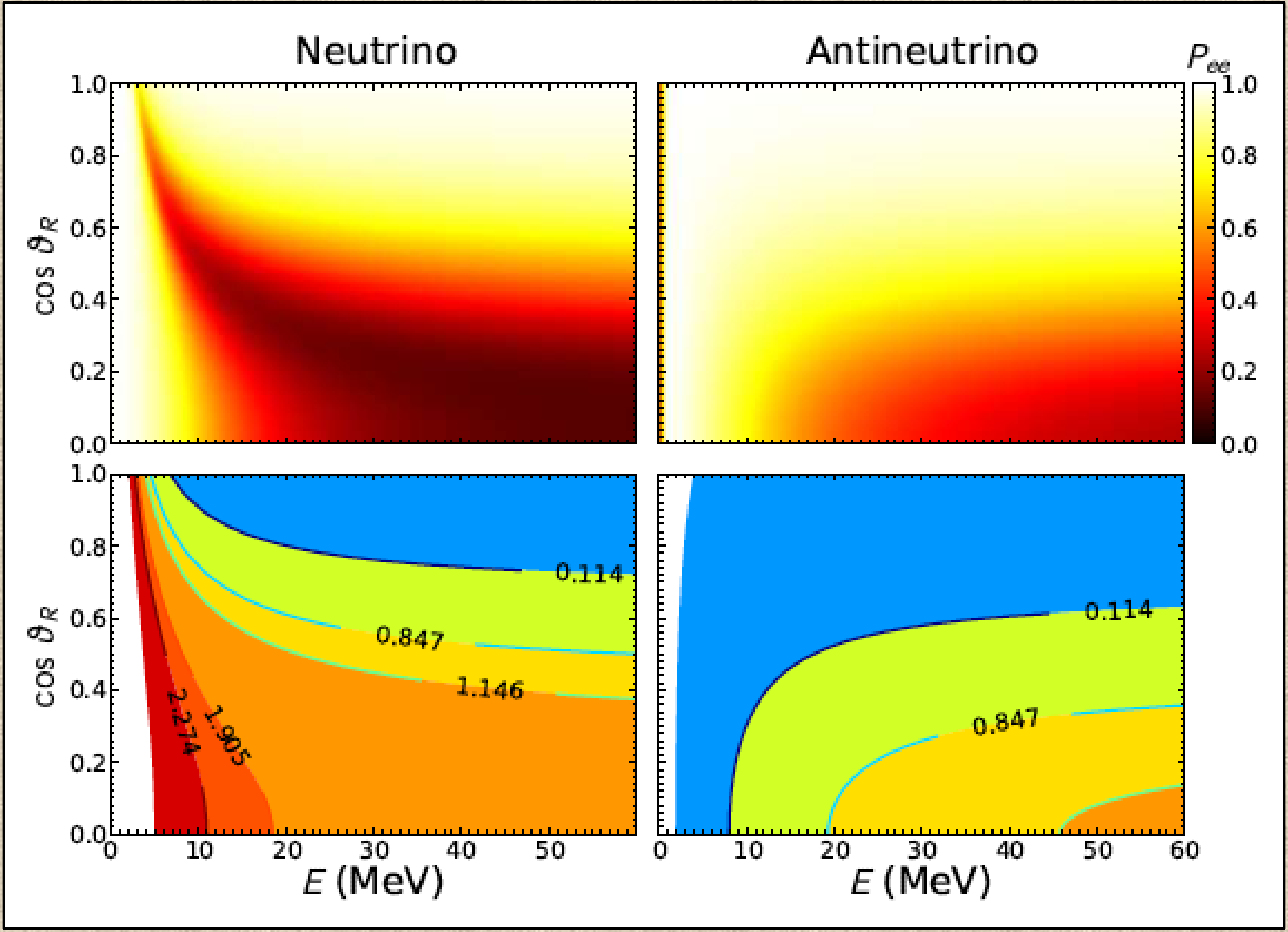


IH

Friedland, arXiv:1001.0996 (PRL)

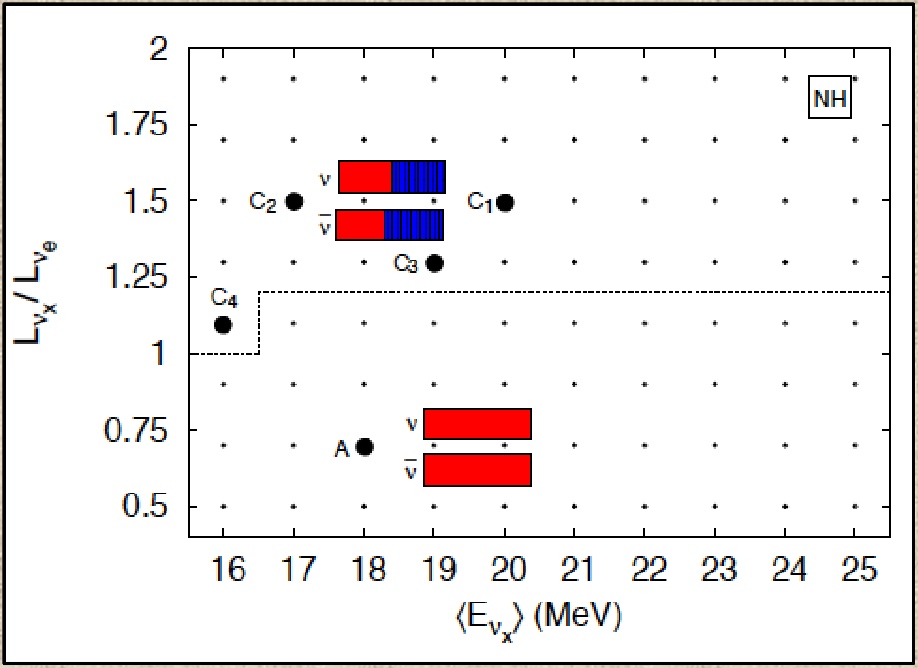
Dasgupta, Mirizzi, Tamborra and Tomas, arXiv:1002.2943

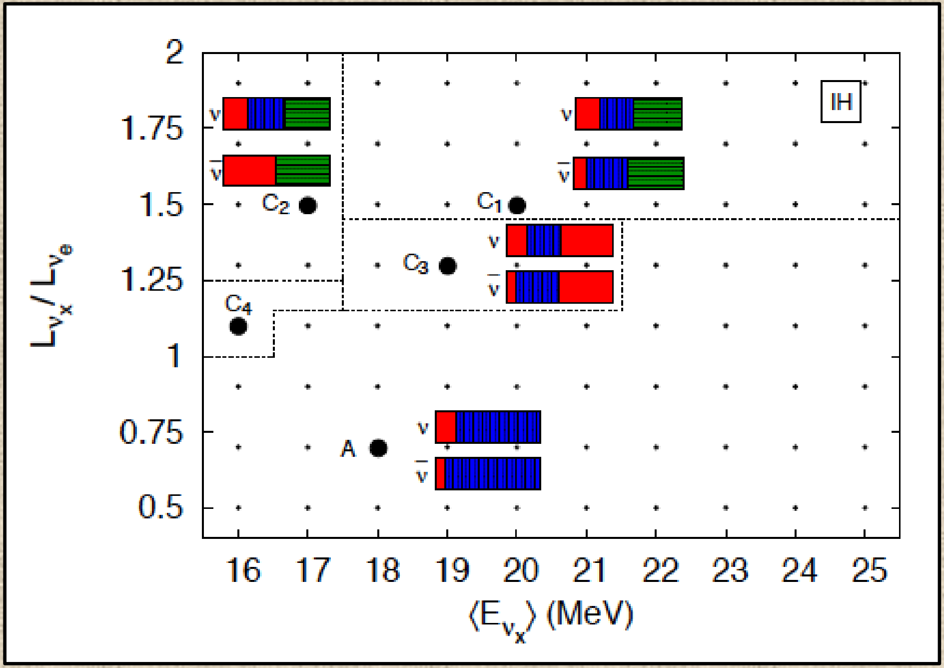
Late-time + Angle-dependent + 3 flavors



Duan and Friedland, arXiv: 1006.2359

Survey of Flux Models

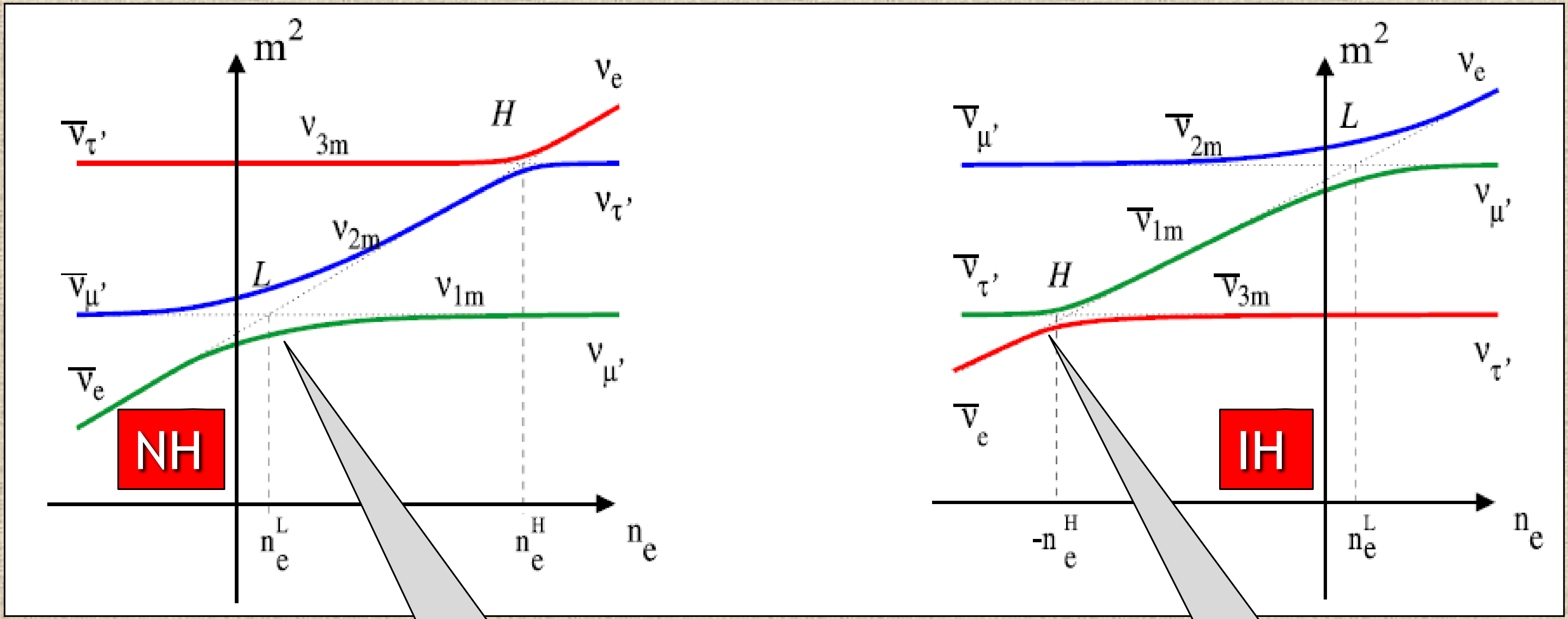




Fogli, Lisi, Marrone and Tamborra, arXiv:0907.5115

Choubey, Dasgupta, Dighe and Mirizzi, arXiv:1008.xxxx

MSW conversions in SN



Dighe and Smirnov, arXiv: hep-ph/9907423

L resonance : $\nu_1 \Leftrightarrow \nu_2$

$(\Delta m_{sol}^2, \theta_{12})$ at $10^1 - 10^2$ g/cc

Always in neutrinos.

Always adiabatic.

H resonance : $\nu_1/\nu_2 \Leftrightarrow \nu_3$

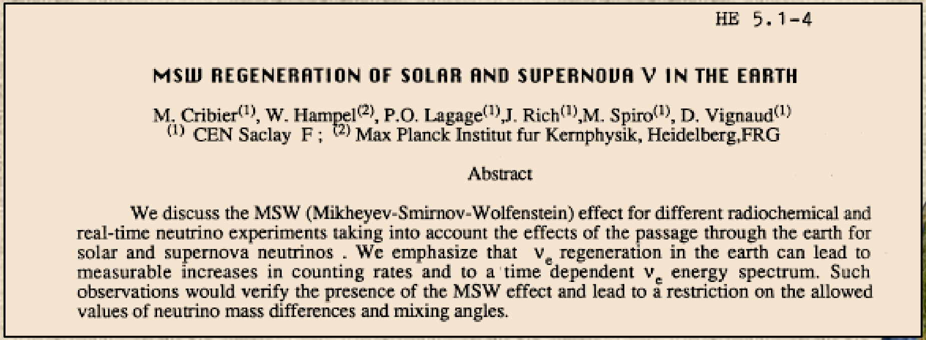
$(\Delta m_{atm}^2, \theta_{13})$ at $10^3 - 10^4$ g/cc

In neutrinos for NH and in antineutrinos for IH.

Adiabaticity ≈ $\sin^2\theta_{13}$

Regeneration in Earth Matter

Electron flavor flux = $\cos^2\theta_{12}\,\nu_1 + \sin^2\theta_{12}\,\nu_2$



HE 5.1-4

MSW REGENERATION OF SOLAR AND SUPERNOVA ν IN THE EARTH

M. Cribier(1), W. Hampel(2), P.O. Lagage(1), J. Rich(1), M. Spiro(1), D. Vignaud(1)
(1) CEN Saclay F ; (2) Max Planck Institut fur Kernphysik, Heidelberg, FRG

Abstract

We discuss the MSW (Mikheyev-Smirnov-Wolfenstein) effect for different radiochemical and real-time neutrino experiments taking into account the effects of the passage through the earth for solar and supernova neutrinos. We emphasize that ν_e regeneration in the earth can lead to measurable increases in counting rates and to a time dependent ν_e energy spectrum. Such observations would verify the presence of the MSW effect and lead to a restriction on the allowed values of neutrino mass differences and mixing angles.

Detector Location Matters!

Electron flavor: = $(1-P_{2e})\,\nu_1 + P_{2e}\,\nu_2$

P_{2e} is the probability of ν_2 to ν_e

which depends on Earth density and L

Survival Probabilities

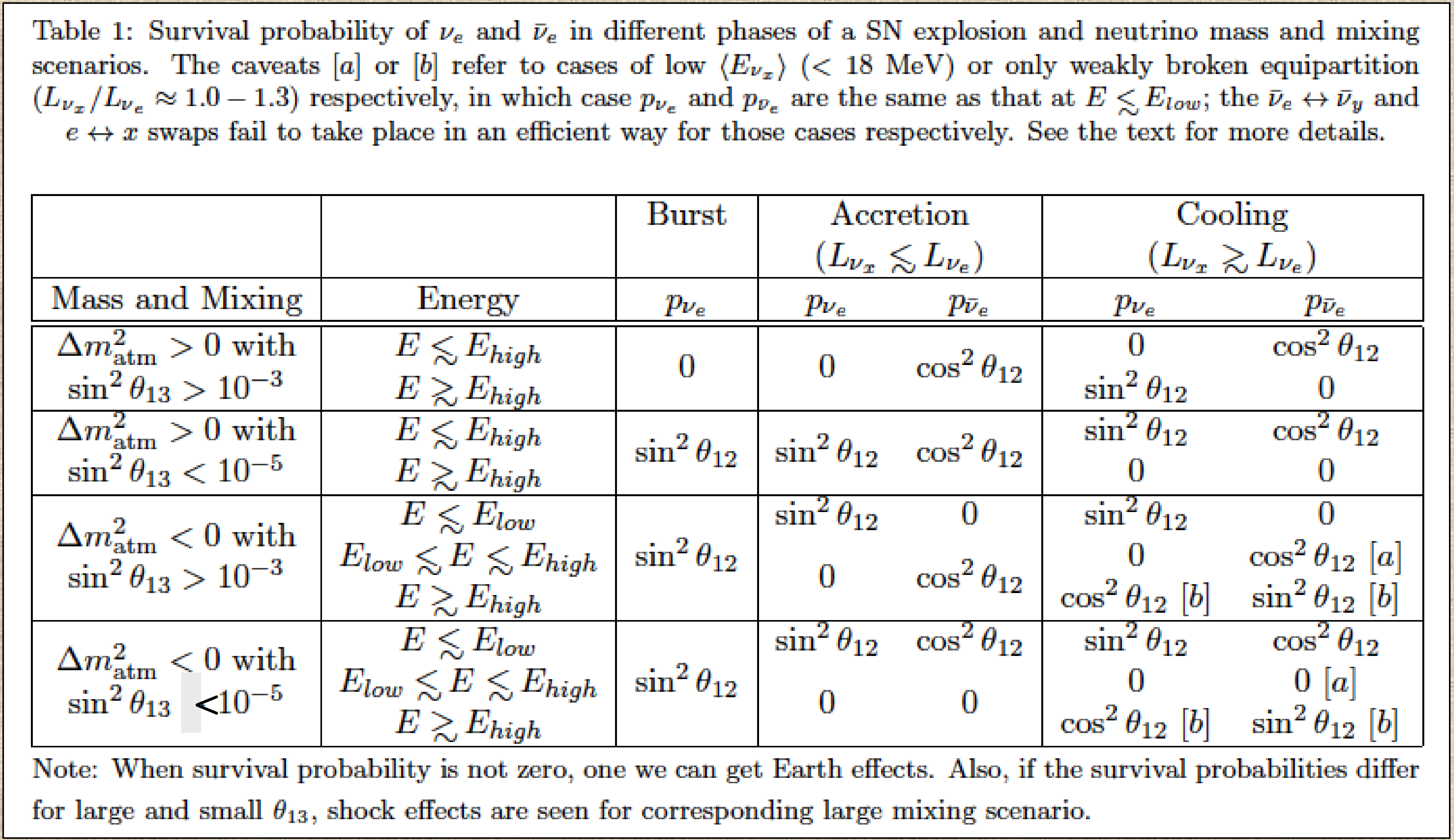
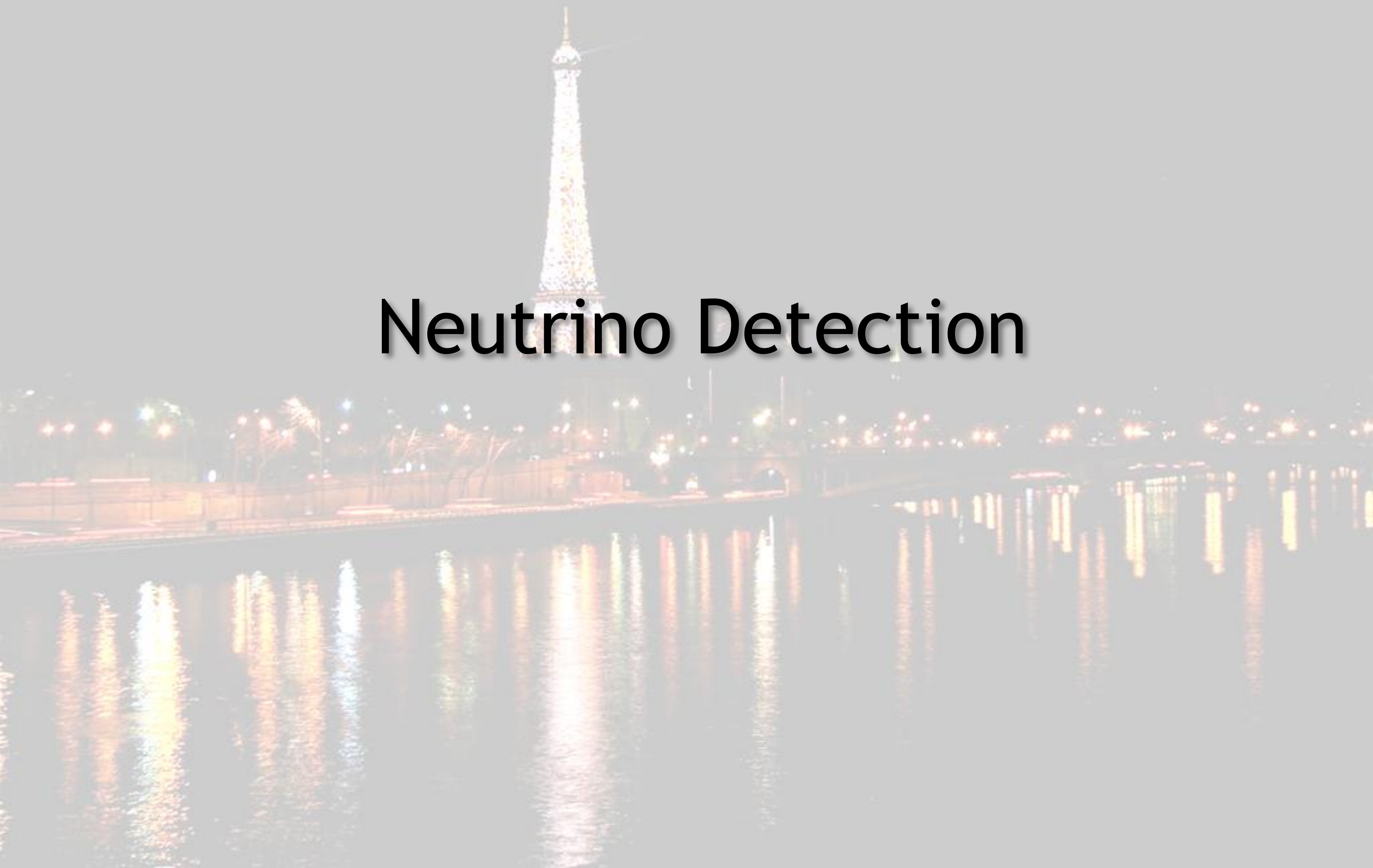


Table 1: Survival probability of ν_e and $\bar{\nu}_e$ in different phases of a SN explosion and neutrino mass and mixing scenarios. The caveats [a] or [b] refer to cases of low $\langle E_{\nu_x} \rangle$ ($<$ 18 MeV) or only weakly broken equipartition ($L_{\nu_x}/L_{\nu_e} \approx 1.0 - 1.3$) respectively, in which case p_{ν_e} and $p_{\bar{\nu}_e}$ are the same as that at $E \lesssim E_{low}$; the $\bar{\nu}_e \leftrightarrow \bar{\nu}_y$ and $e \leftrightarrow x$ swaps fail to take place in an efficient way for those cases respectively. See the text for more details.

		Burst	Accretion ($L_{\nu_x} \lesssim L_{\nu_e}$)		Cooling ($L_{\nu_x} \gtrsim L_{\nu_e}$)	
Mass and Mixing	Energy	p_{ν_e}	p_{ν_e}	$p_{\bar{\nu}_e}$	p_{ν_e}	$p_{\bar{\nu}_e}$
$\Delta m^2_{\rm atm} > 0$ with $\sin^2\theta_{13} > 10^{-3}$	$E \lesssim E_{high}$	0	0	$\cos^2\theta_{12}$	0	$\cos^2\theta_{12}$
	$E \gtrsim E_{high}$				$\sin^2\theta_{12}$	0
$\Delta m^2_{\rm atm} > 0$ with $\sin^2\theta_{13} < 10^{-5}$	$E \lesssim E_{high}$	$\sin^2\theta_{12}$	$\sin^2\theta_{12}$	$\cos^2\theta_{12}$	$\sin^2\theta_{12}$	$\cos^2\theta_{12}$
	$E \gtrsim E_{high}$				0	0
$\Delta m^2_{\rm atm} < 0$ with $\sin^2\theta_{13} > 10^{-3}$	$E \lesssim E_{low}$	$\sin^2\theta_{12}$	$\sin^2\theta_{12}$	0	$\sin^2\theta_{12}$	0
	$E_{low} \lesssim E \lesssim E_{high}$		0	$\cos^2\theta_{12}$	0	$\cos^2\theta_{12}$ [a]
	$E \gtrsim E_{high}$				$\cos^2\theta_{12}$ [b]	$\sin^2\theta_{12}$ [b]
$\Delta m^2_{\rm atm} < 0$ with $\sin^2\theta_{13} < 10^{-5}$	$E \lesssim E_{low}$	$\sin^2\theta_{12}$	$\sin^2\theta_{12}$	$\cos^2\theta_{12}$	$\sin^2\theta_{12}$	$\cos^2\theta_{12}$
	$E_{low} \lesssim E \lesssim E_{high}$		0	0	0	0 [a]
	$E \gtrsim E_{high}$				$\cos^2\theta_{12}$ [b]	$\sin^2\theta_{12}$ [b]

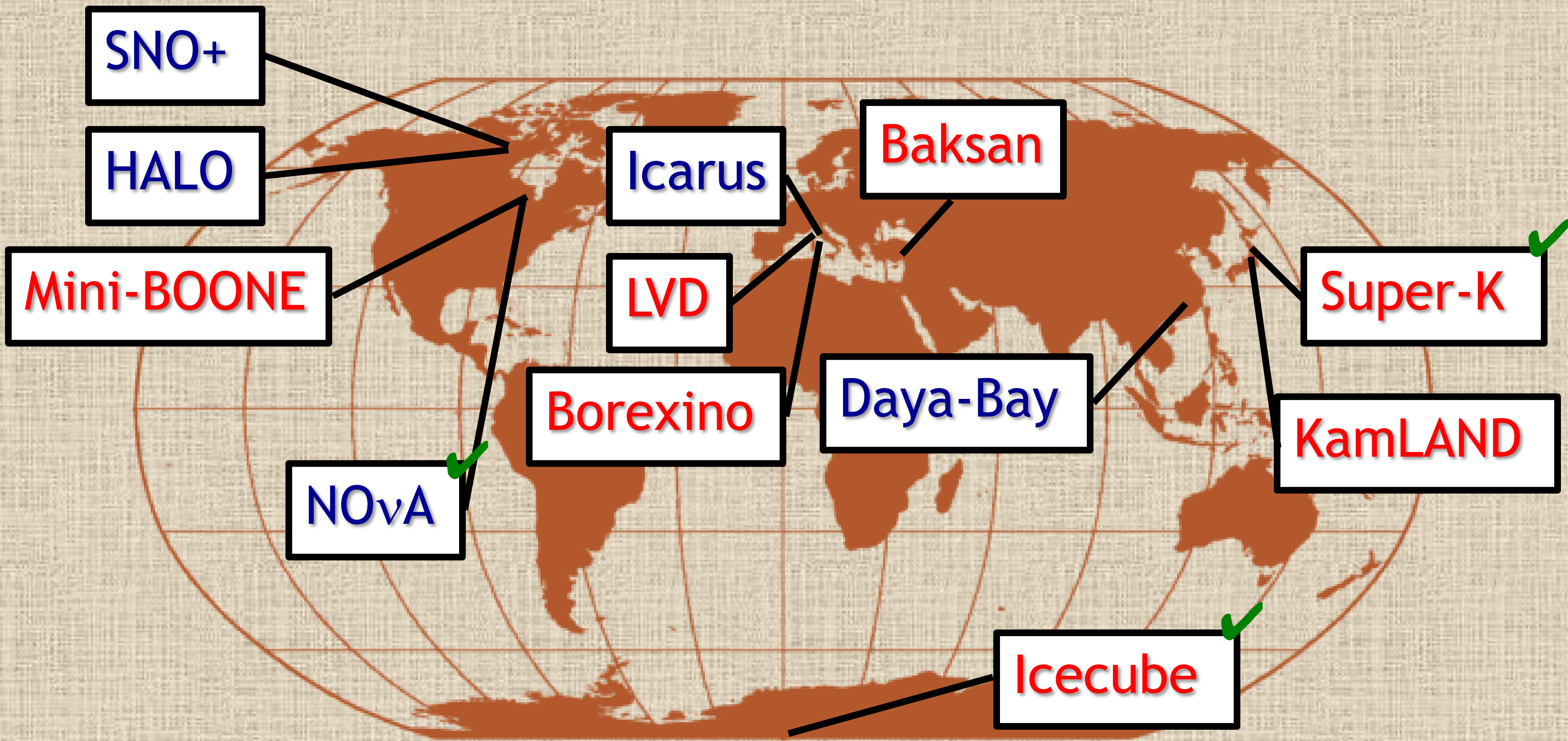
Note: When survival probability is not zero, one we can get Earth effects. Also, if the survival probabilities differ for large and small θ_{13}, shock effects are seen for corresponding large mixing scenario.

B. Dasgupta, arXiv:hep-ph/1005.2681 [Moriond-2010, Proceedings]



Neutrino Detection

Running (soon) SN Neutrino Detectors



SNO+

HALO

Icarus

Baksan

Mini-BOONE

LVD

Super-K ✓

Daya-Bay

Borexino

KamLAND

NOνA ✓

Icecube ✓

✓=Large (>10^3 events for 10kpc SN)

Hyper-K/UNO/MEMPHYS/LENA/Km3NET/…

Main Detection Channels

- SK-like water Cherenkov detector (30 kt, SN at 10kpc)

$$\bar{\nu}_e p \to n e^+ : \approx 7000 - 12000^*$$

$$\nu e^- \to \nu e^- : \approx 200 - 300^*$$

$$\nu_e + {}^{16}\mathrm{O} \to X + e^- : \approx 150\text{–}800^*$$

Super-Kamiokande and Icecube are at present our largest detectors for SN neutrinos.

- Scintillation detector

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

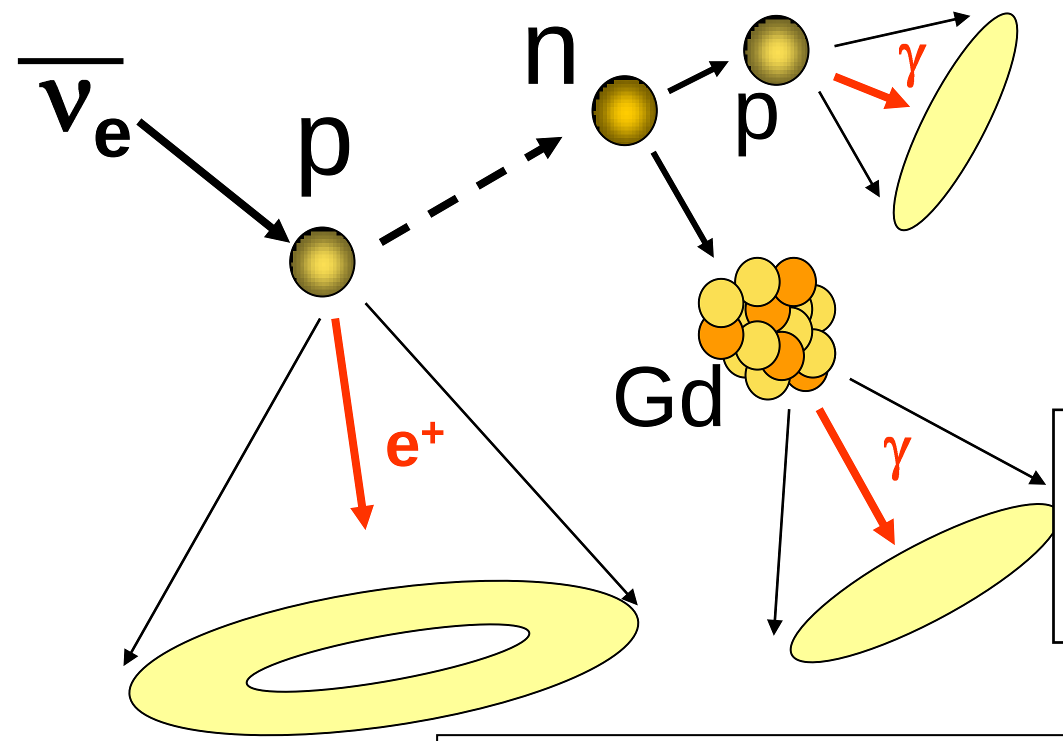
$$\nu + {}^{12}\mathrm{C} \to \nu + X + \gamma\ (15.11\ \mathrm{MeV})$$

- Liquid Argon detector

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

Liquid Argon TPC can see neutrinos, others mostly see antineutrinos

Gadzooks



$n + Gd \to \sim 8$ MeV γ (90%)

$n + p \to d + 2.2$ MeV γ (10%)

Positron and gamma ray vertices are within ~50cm.

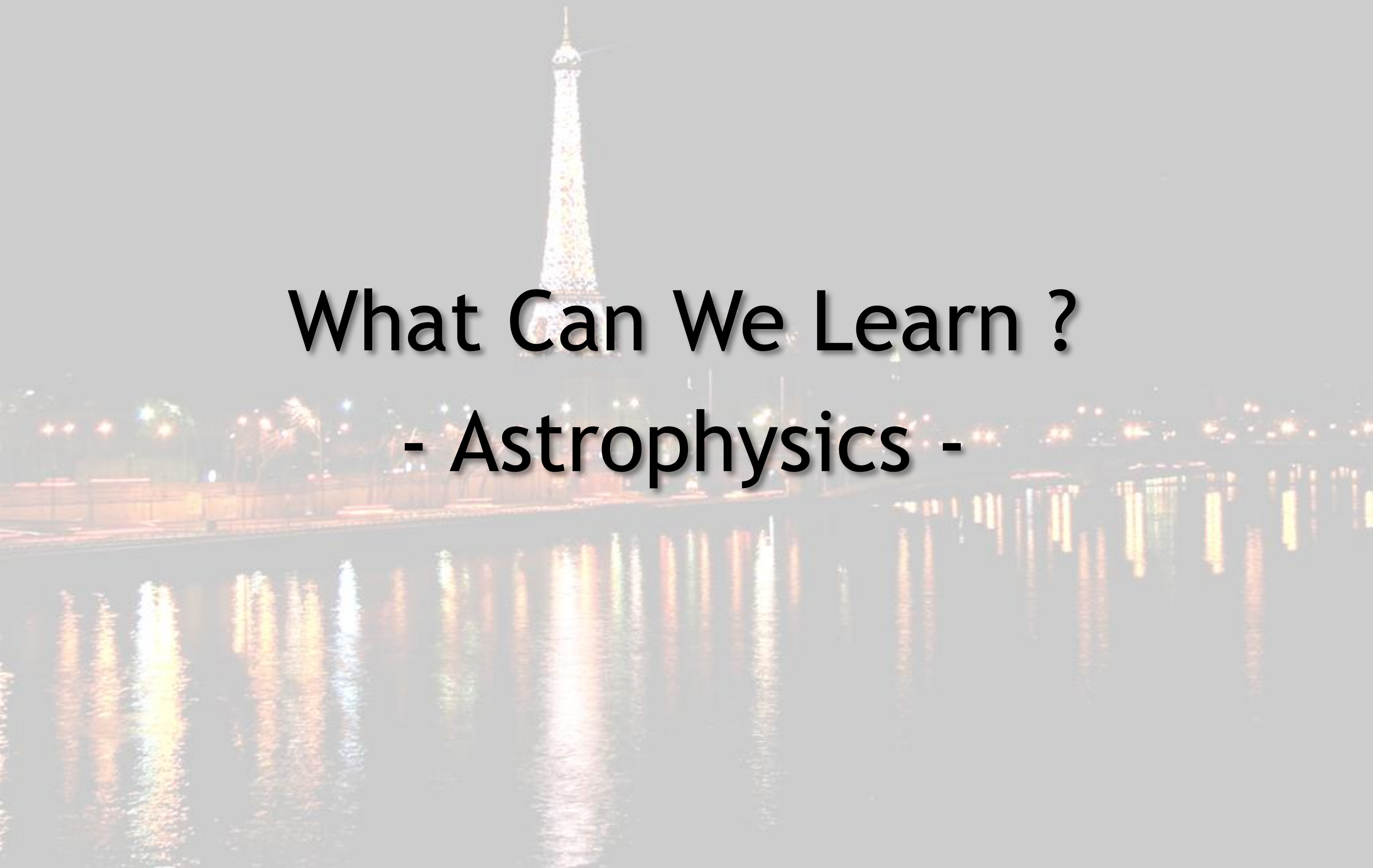
[reaction schematic by M. Nakahata]

Beacom and Vagins, arXiv:hep-ph/0309300 (PRL)

Gadolinium Anti-nu Detector Zealously Outperforming Old Kamiokande. Super!

Can identify each antineutrino on an event-by-event basis

$\bar{\nu}_e$ can be identified by delayed coincidence.



What Can We Learn ?

- Astrophysics -

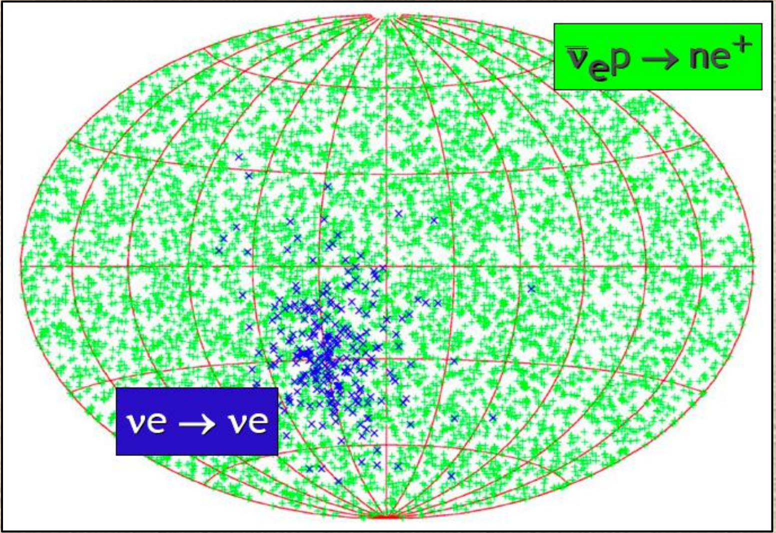
SN pointing alerts/SNEWS

Neutrinos reach ~24 hours before the light from SN explosion

SN at 10 kpc may be detected within a cone of ~ 5° at SK, factor of 3 better with Gd, and factor of 10 better with a 30xSK

Beacom and Vogel, arXiv: astro-ph/9811350

Tomas, Semikoz, Kachelriess, Raffelt and Dighe, arXiv: hep-ph/0307050

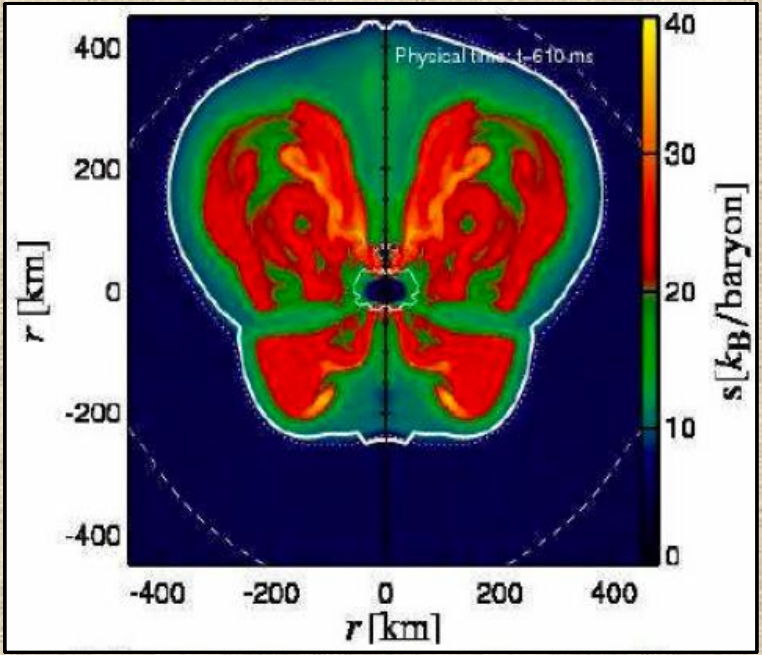


This may be crucial for dust-obscured supernovae!

Coincidence at multiple detectors will trigger an alert for astronomers

SNEWS
http://snews.bnl.gov

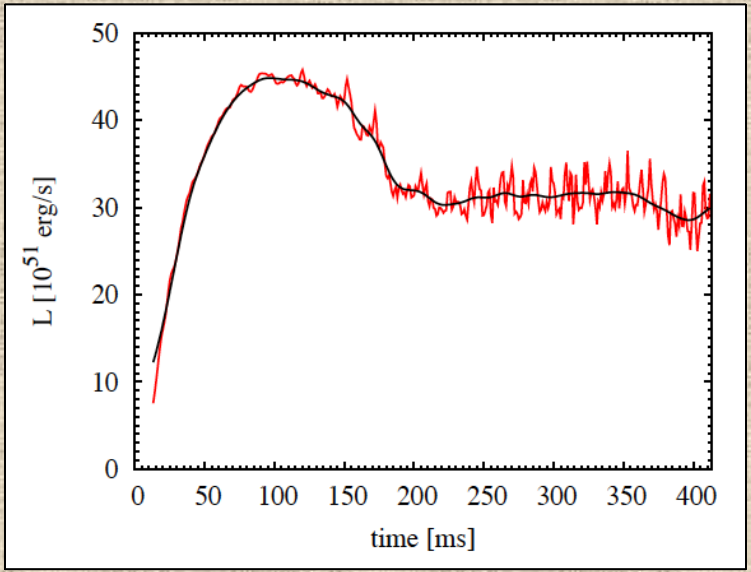
Stellar Explosion Dynamics

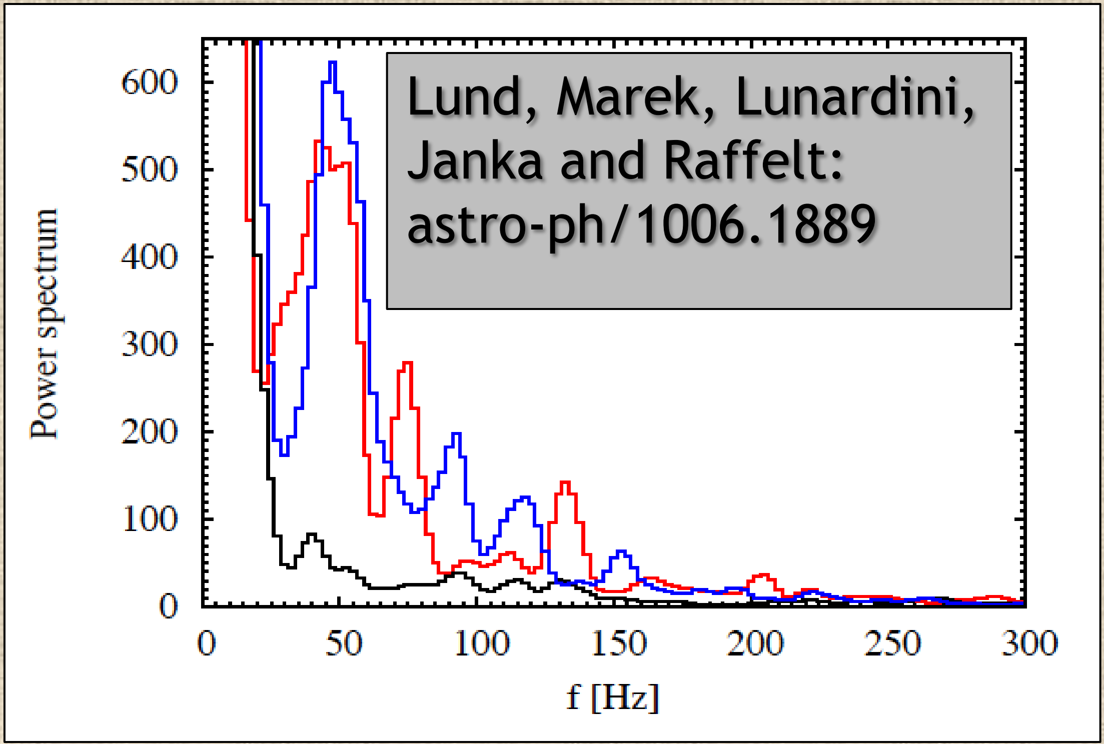


Standing Accretion Shock Instability

Large scale motion of the stellar material on a millisecond timescale

Fluctuations in the neutrino signal, luminosities and energies

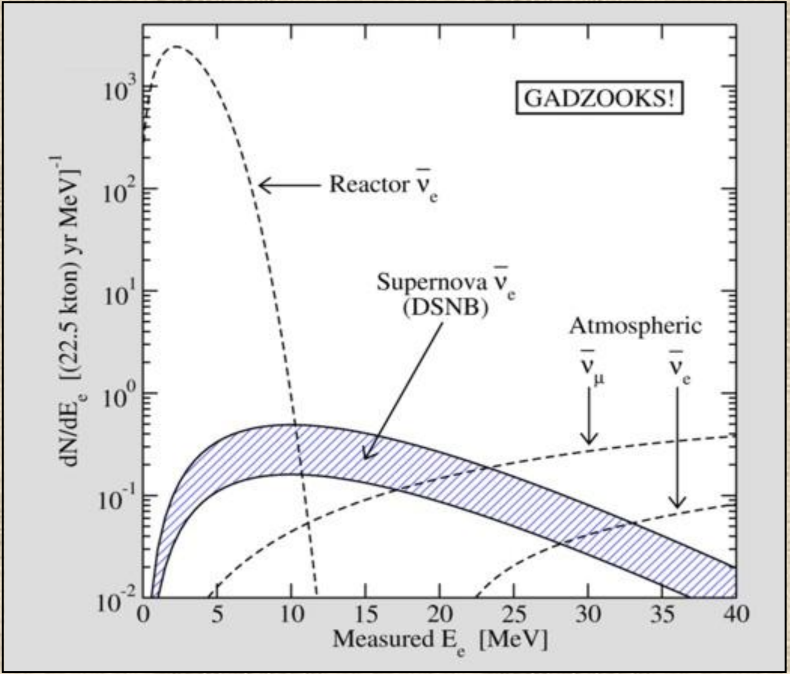


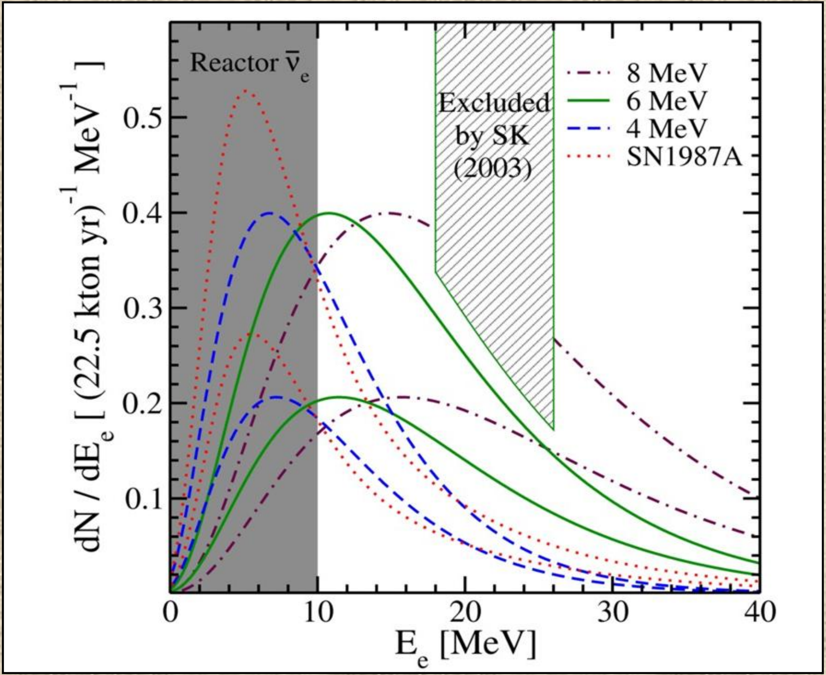

Lund, Marek, Lunardini, Janka and Raffelt: astro-ph/1006.1889

Diffuse Neutrino Background

Estimated present-day $\bar{\nu}_e$ flux from all SN in our past~ 10 cm^{-2} s^{-1}

Guaranteed source of neutrinos from cosmological distances



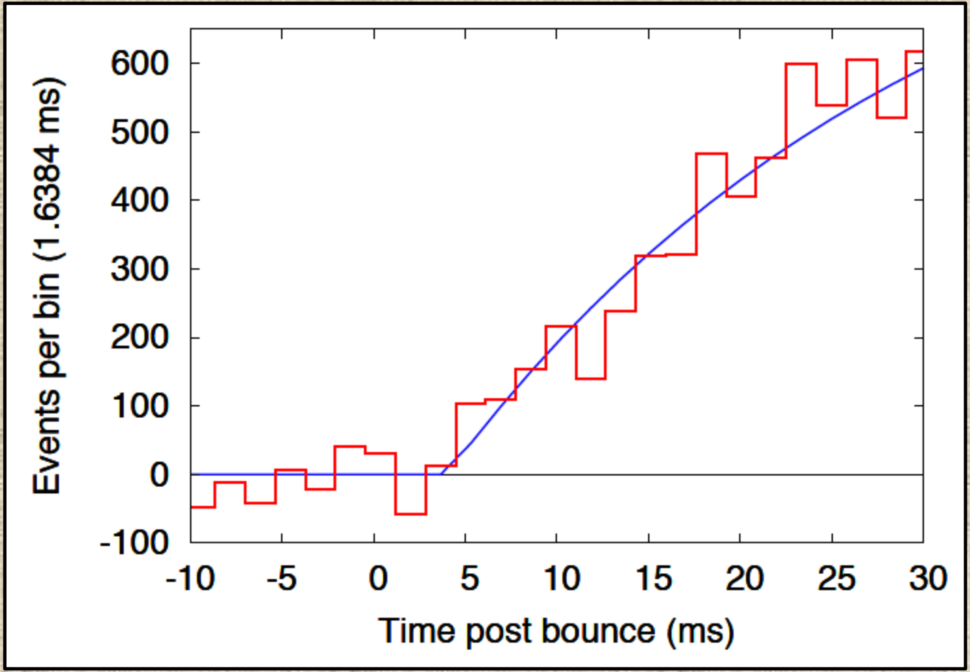


Beacom and Vagins,
hep-ph/0309300 (PRL)

Horiuchi, Beacom and Dwek,
arXiv:0812.3157

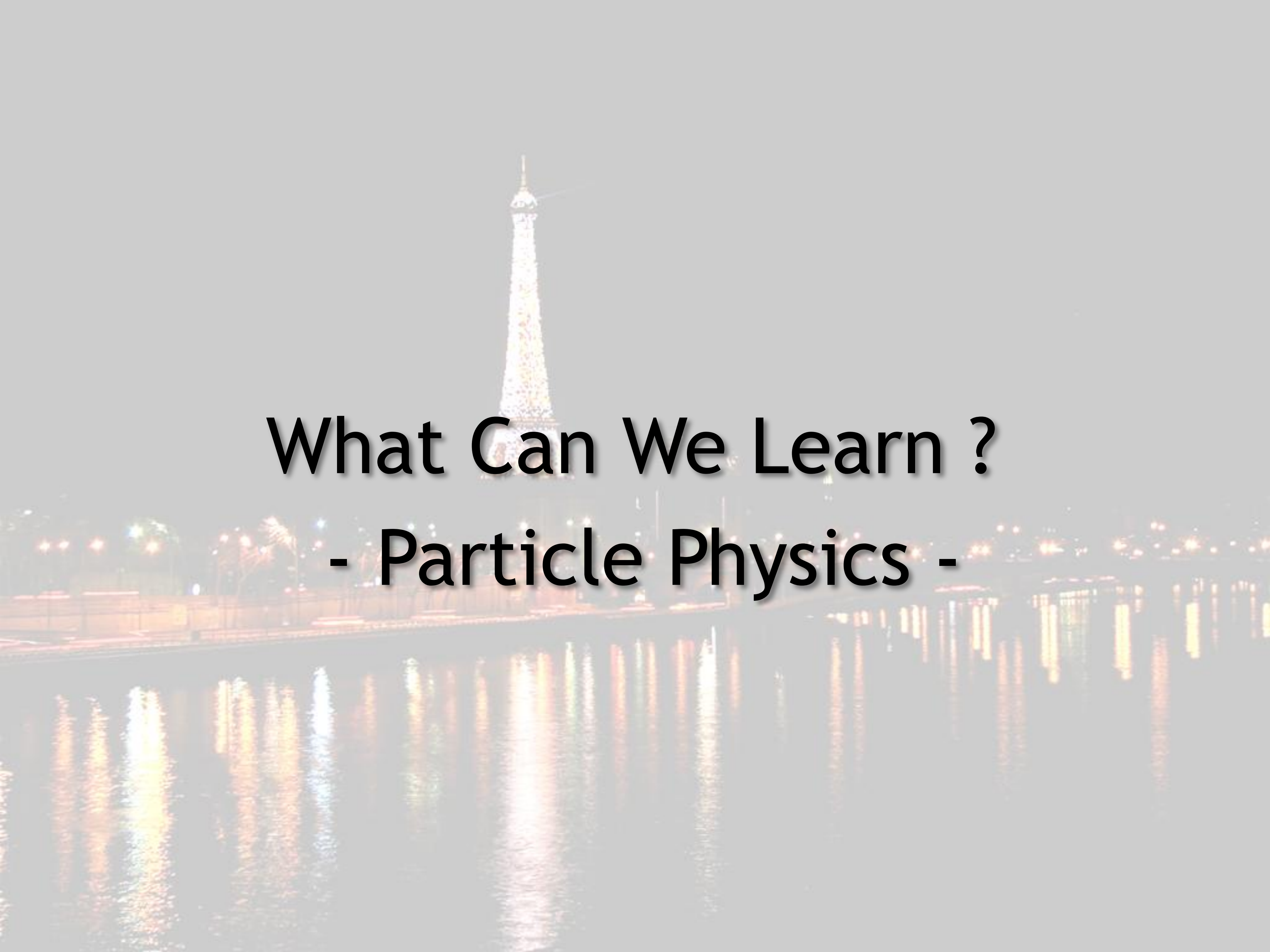
See also Chakraborty, Choubey, Dasgupta and Kar, arXiv:0805.3131
for effect of collective oscillations on DSNB

Coincidence with Gravity Wave Expts



SN neutrino-curve is an excellent probe of the bounce time. This can be used to great advantage for coincidence measurement with gravitational wave detectors

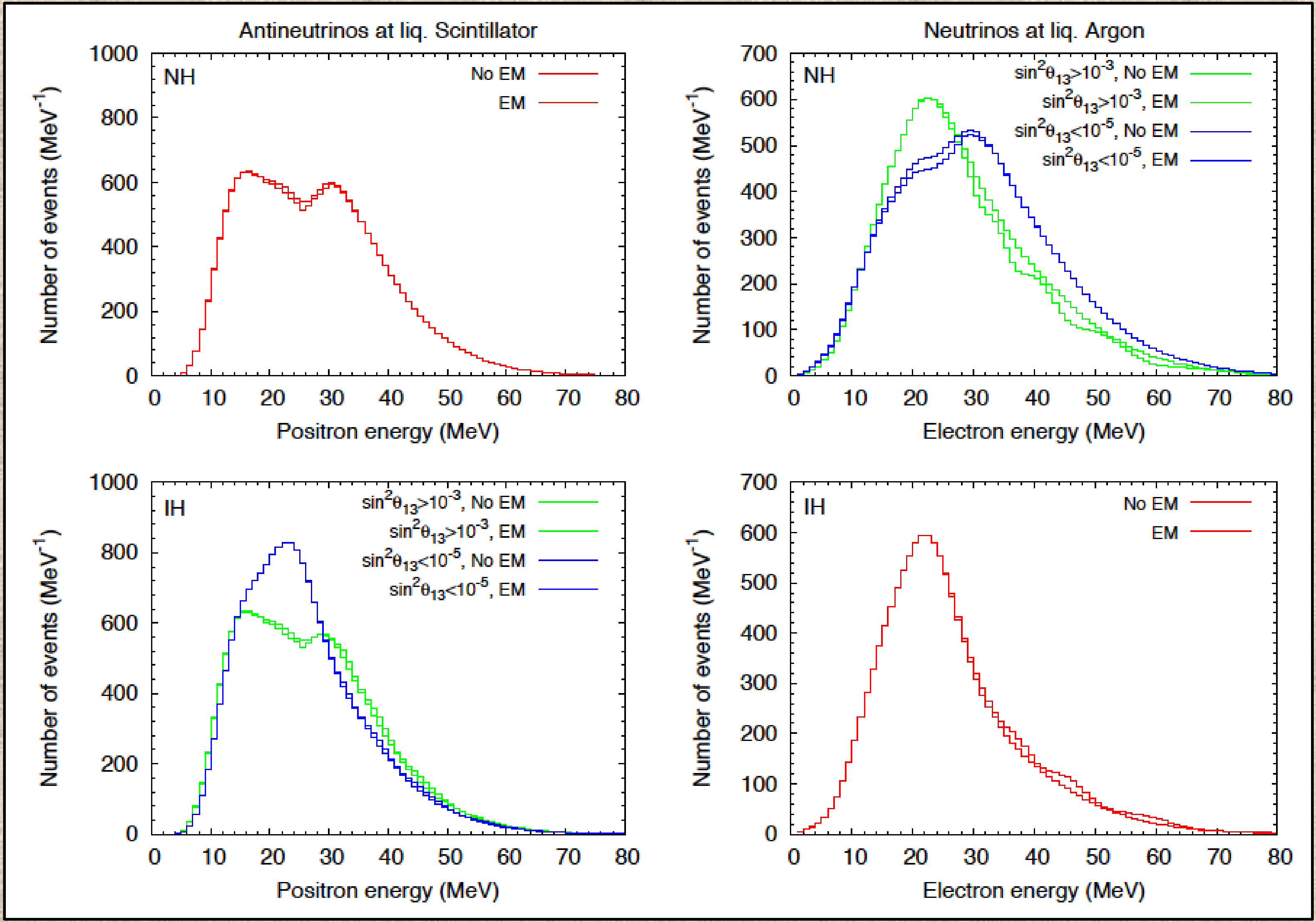
Pagliaroni, Vissani, Coccia and Fulgione, arXiv:0903:1191 (PRL)
Halzen and Raffelt, arXiv:0908.2317



What Can We Learn ?

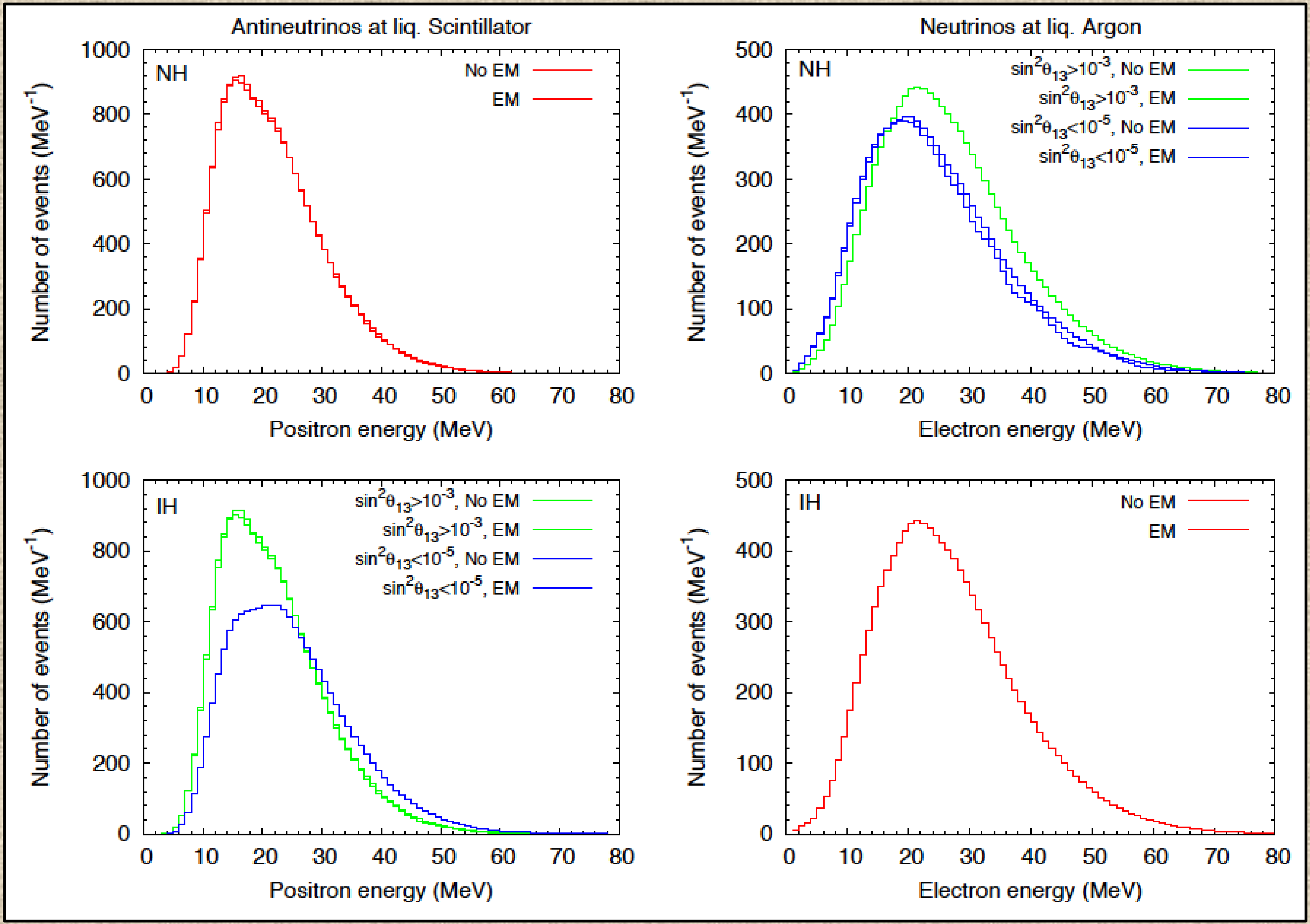
- Particle Physics -

Can we see the splits? Perhaps…for Cooling.



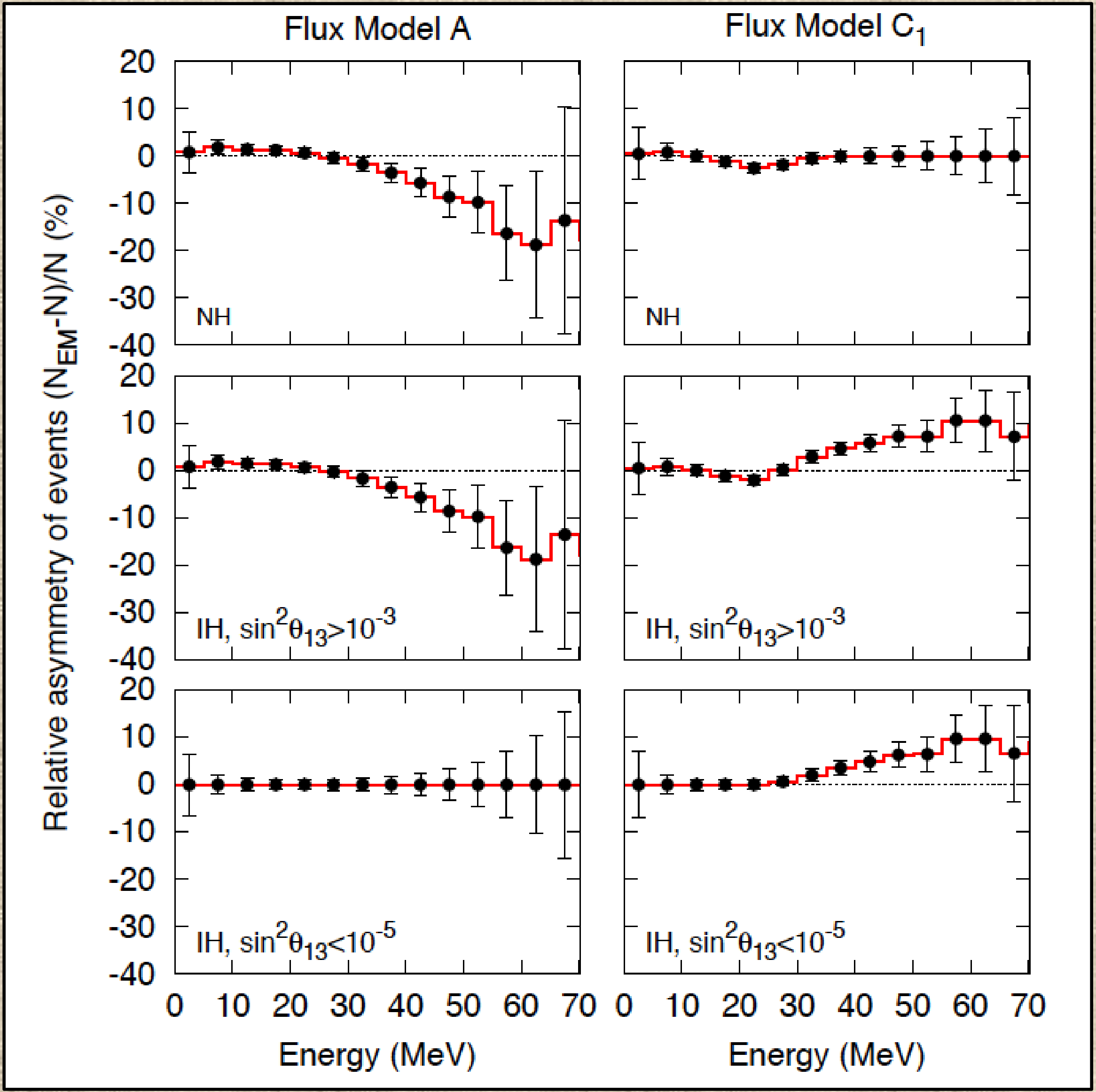
Choubey, Dasgupta, Dighe and Mirizzi, arXiv:1008.xxxx

Accretion phase signals…a bit weaker.



Choubey, Dasgupta, Dighe and Mirizzi, arXiv:1008.xxxx

Earth Matter Effects

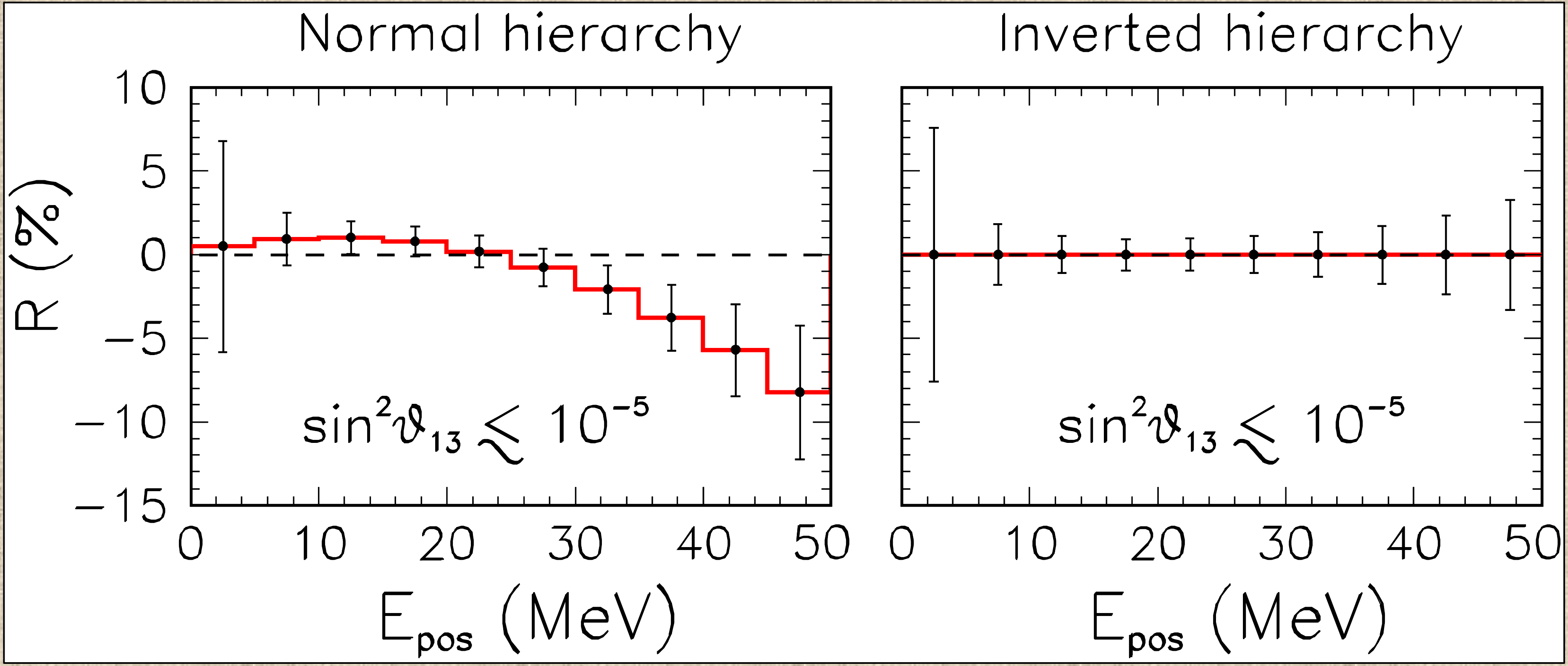


Ratio of events between shadowed and unshadowed WC detectors is an excellent probe of the Neutrino Mass Hierarchy

Fourier analysis of the event rate reveals earth effect oscillations for a single Liq. Argon/Scintillator detector.

Choubey, Dasgupta, Dighe and Mirizzi, arXiv:1008.xxxx

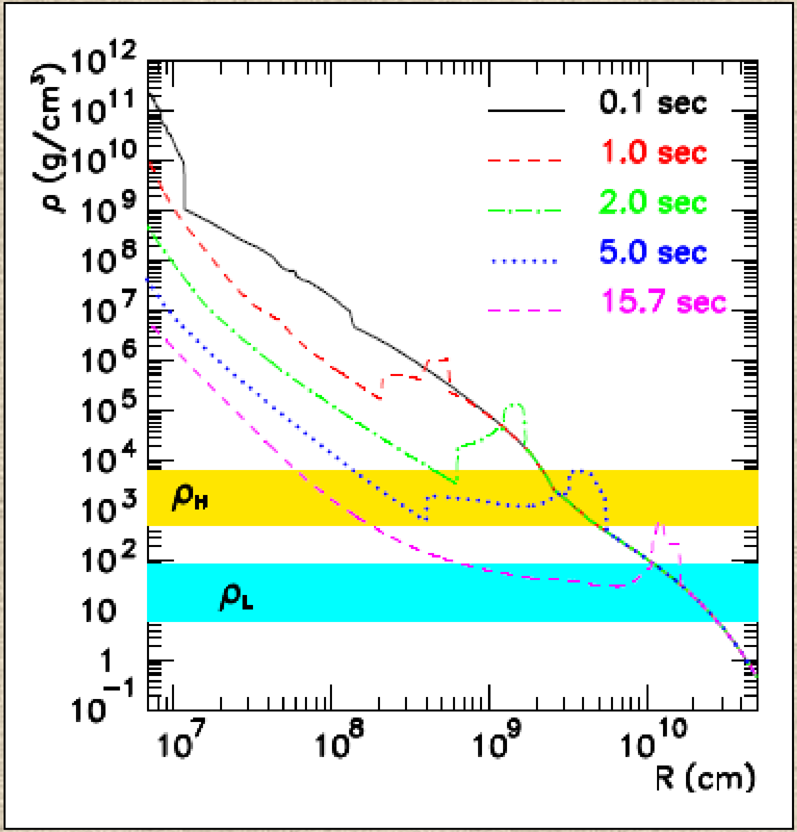
Neutrino Mass Hierarchy

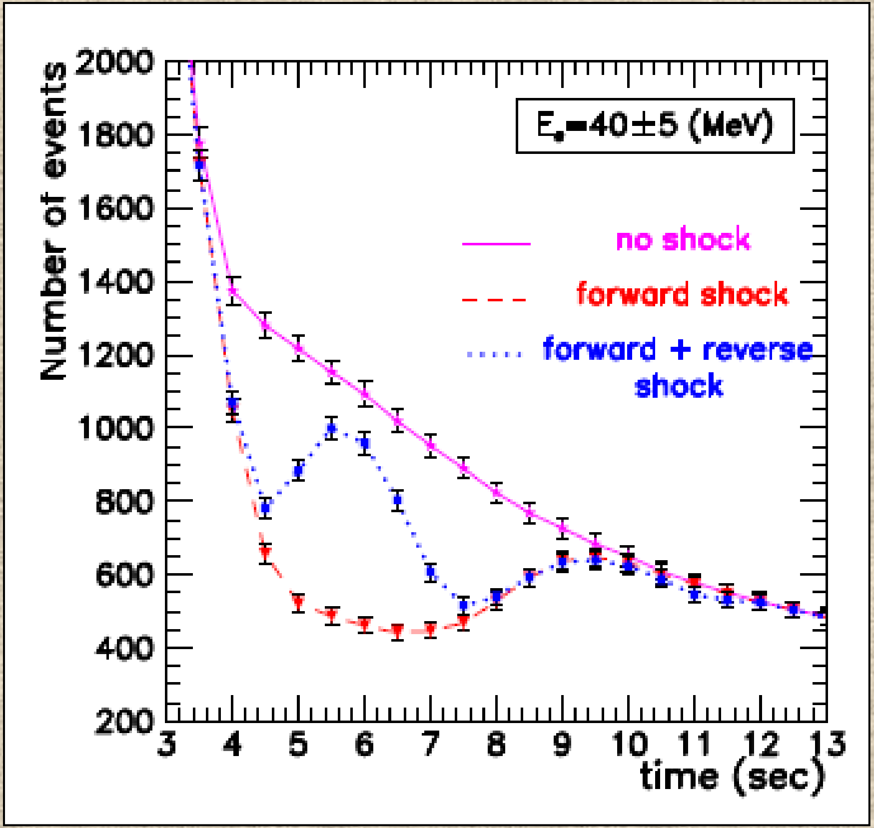


Ratio of events at two 0.4 MT WC detectors, one shadowed and other not. SN taken at 10 kpc.

Dasgupta, Dighe and Mirizzi, arXiv: arXiv:0802.1481 (PRL)

Θ_{13} Estimate/Shockwave effects

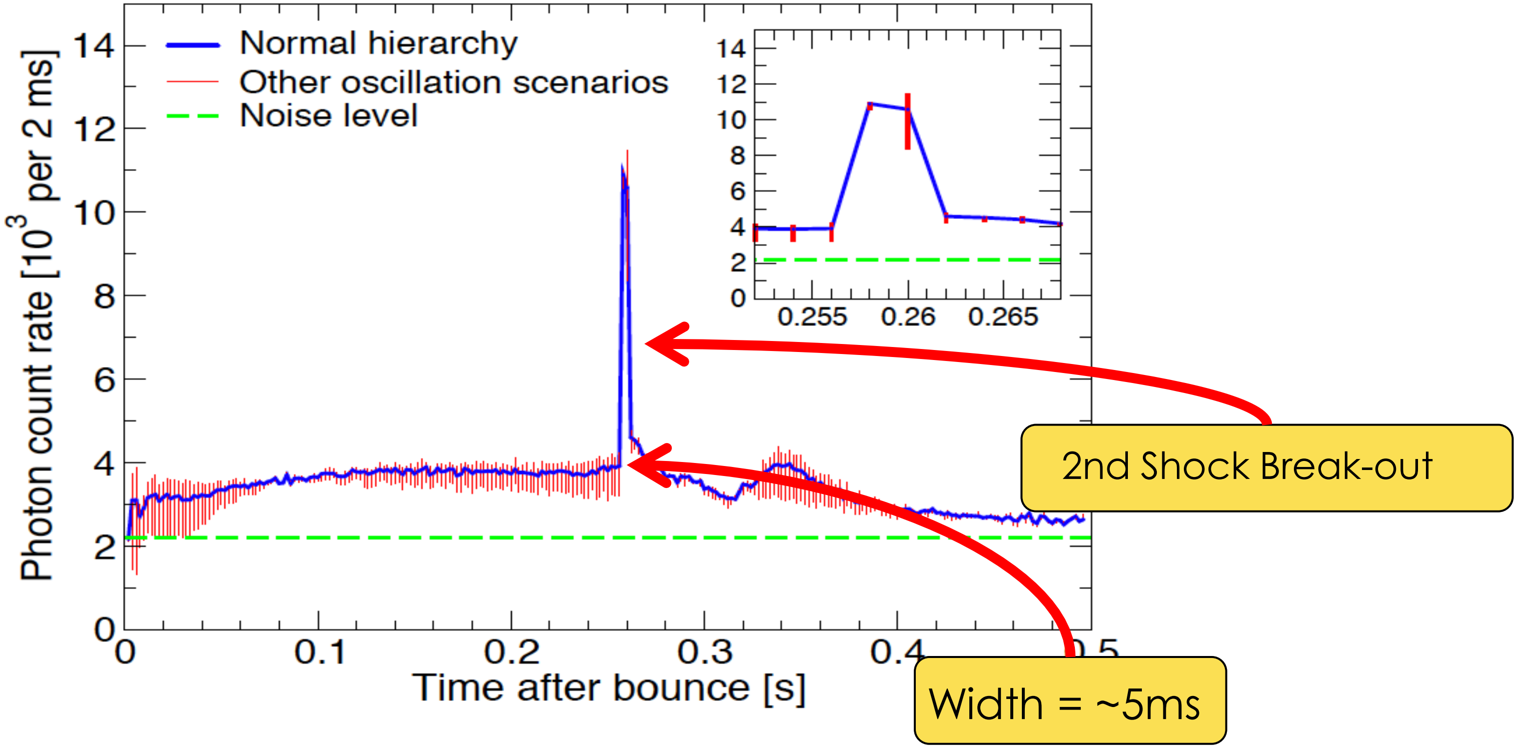




Tomas, Kachelriess, Dighe, Raffelt and Janka,
arXiv:astro-ph/0407132

Most of the work on this was done around 2000-2004
After including collective effects …
e.g. Gava, Kneller, Volpe and Mc Laughlin, arXiv:0902.0317 (PRL)

QCD anti-nu burst detectable from SN



2nd Shock Break-out

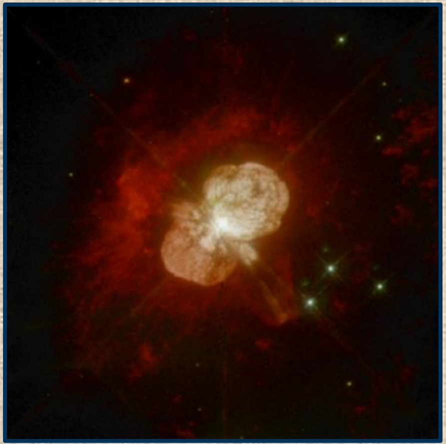
Width = ~5ms

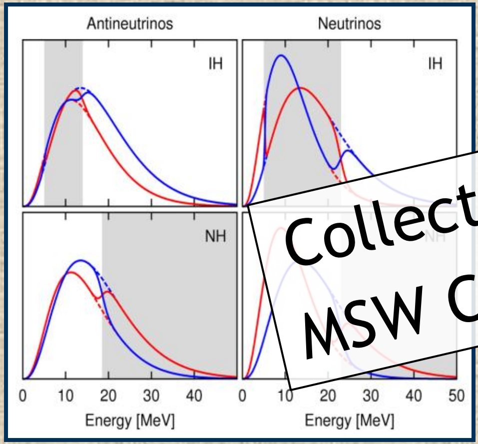
Sagert, Fischer, Hempel, Pagliara, Schaffner-Bielich, Mezzacappa, Thielemann, and Liebendoerfer, arXiv:0809.4225 (PRL)

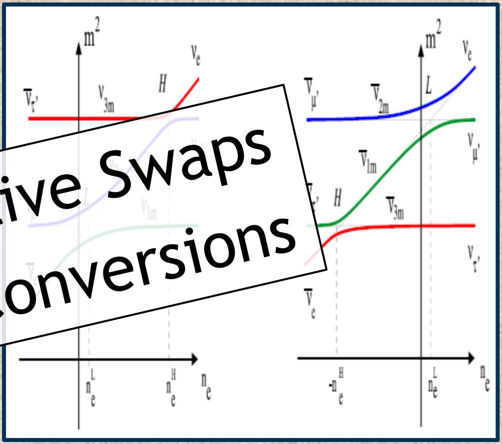
Dasgupta, Fischer, Horiuchi, Liebendorfer, Mirizzi, Sagert and Schaffner-Bielich

arXiv:0912.2568

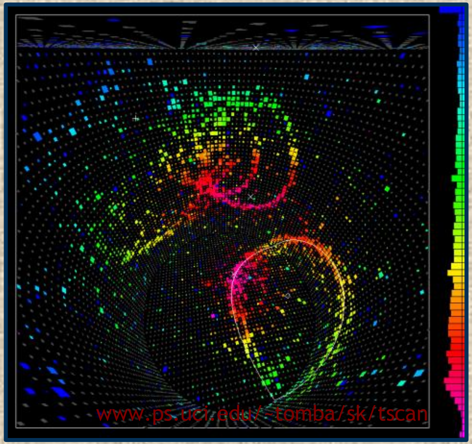
Summary







Collective Swaps
MSW Conversions



Neutrino Production

Neutrino Propagation and Flavor Conversion

Neutrino Detection

Neutrino Astronomy Supernova Astrophysics

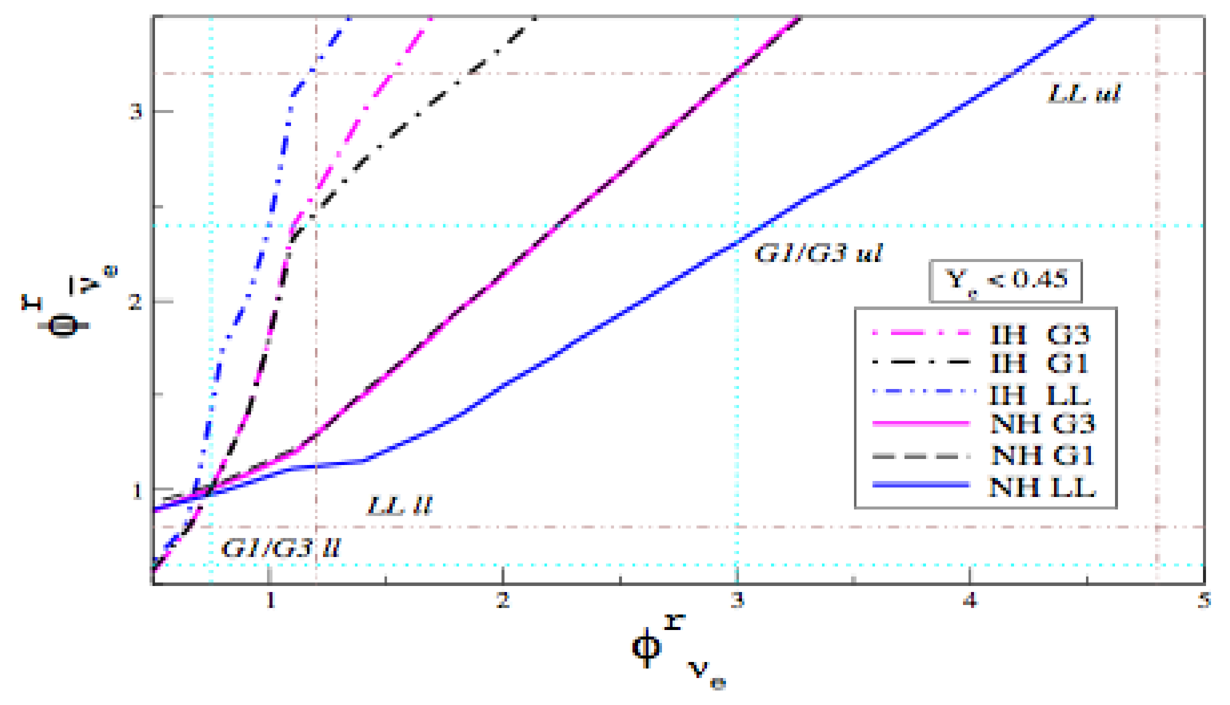
1. Pointing in advance/SN alerts
2. Signatures of stellar dynamics
3. Tracking the local SN rate
4. Timing/GW-coincidence
5. …

Neutrino properties and particle physics

1. Neutrino Mass Hierarchy
2. Θ_{13} estimate
3. QCD phase transition
4. …

Back-up Slide 1: R-process nucleosynthesis

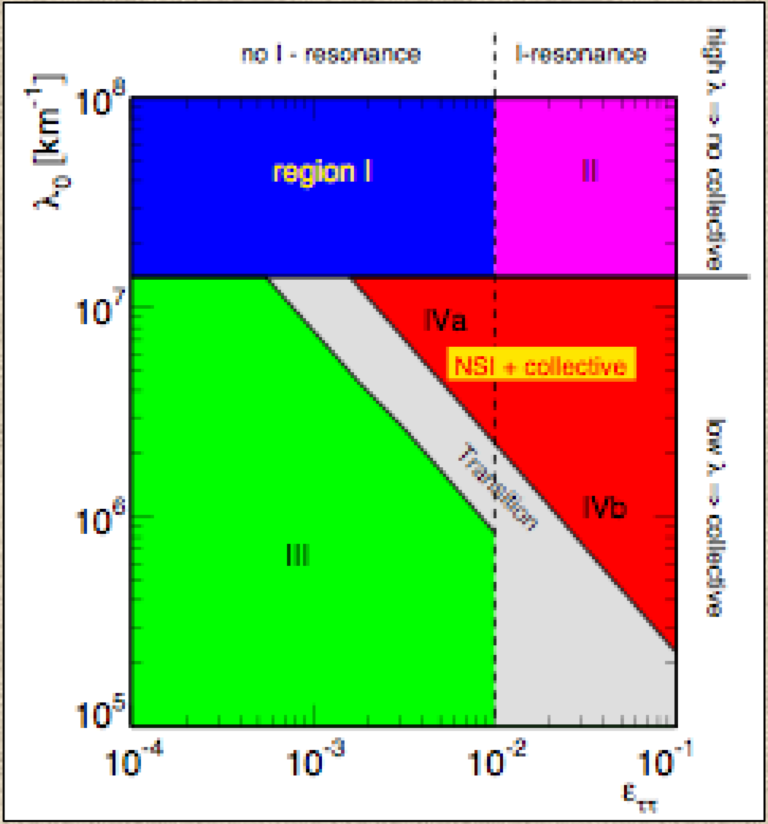
Demanding successful R-process nucleosynthesis puts non-trivial constraints on possible SN fluxes.



Chakraborty, Choubey, Goswami and Kar, arXiv: arXiv:0911.1218

Back-up Slide 2: Non-Standard effects

Non-Standard Interactions can give rise to a rich set of possibilities, and make things more complicated.



Esteban-Pretel, Tomas and Valle, arXiv:0909.2196