International Symposium on
Revealing the History of the Universe with Underground Particle and Nuclear Research 2016
University of Tokyo

Neutrinos from Supernovae

Basudeb Dasgupta
TIFR, Mumbai


Sanduleak –69 202
Supernova 1987A
23 February 1987
29 YEARS AGO
IN A GALAXY NEAR US

Kungliga
Svenska Vetenskapsakademien
har den 8 oktober 2002 beslutat
att med det

NOBELPRIS

som detta år tillerkännes den som inom
fysikens område gjort den viktigaste
upptäckten eller uppfinningen
med ena hälften gemensamt belöna

Masatoshi Koshiba

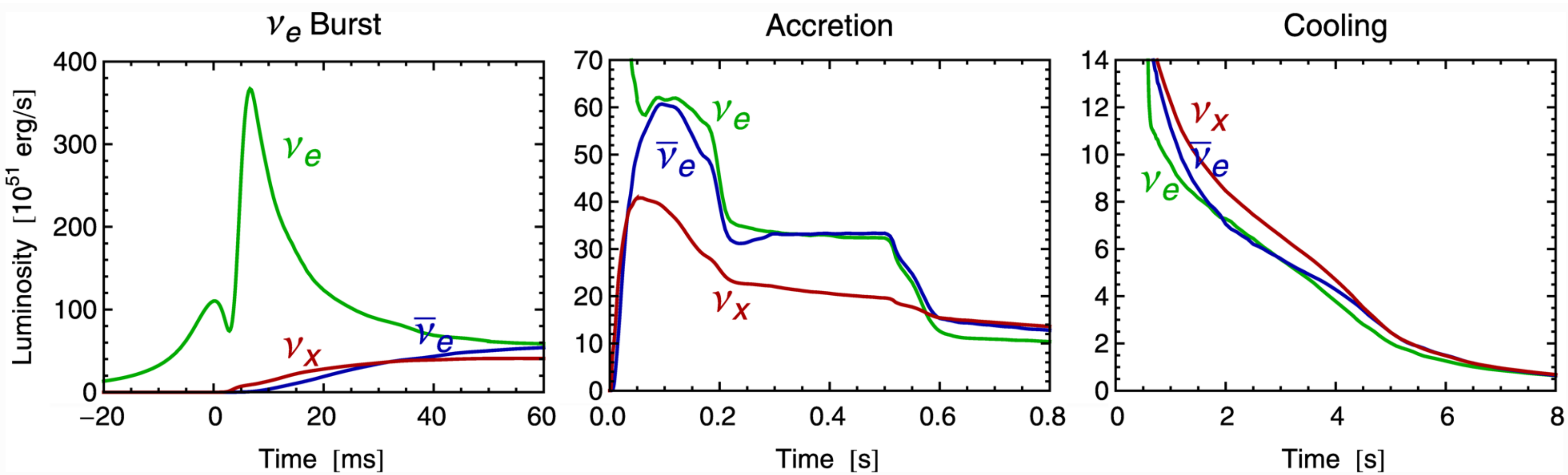
och Raymond Davis Jr.

för banbrytande insatser inom astro-
fysiken, särskilt för detektion av
kosmiska neutriner

STOCKHOLM DEN 10 DECEMBER 2002

So why are we still talking about Supernova Neutrinos?

Opportunities & Challenges



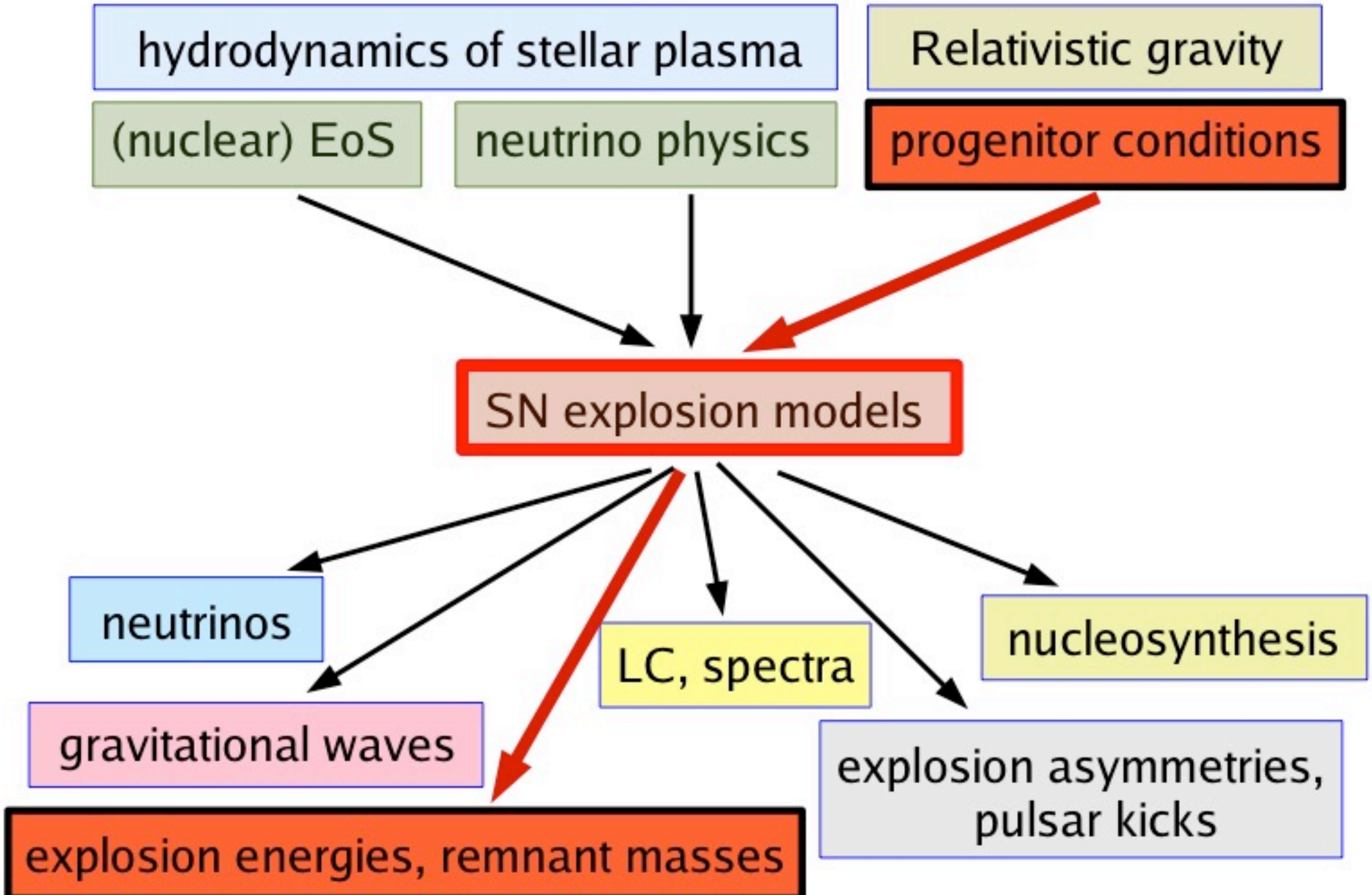
Burst	Accretion	Cooling
SN standard candle?	Astrophysics	Nuclear physics
SN theory	Oscillation effects?	Nucleosynthesis
Timing	Shock revival?	Exotics/Axions
Mass hierarchy	Mass hierarchy?	…
…	…	

Supernova Day!

9:40	30'	Supernova neutrinos and Supernova Relic Neutrinos using a Water Cherenkov Detector	M. Nakahata (ICRR, Tokyo)
10:10	20'	coffee	
chair:M.Wurm (Mainz)			
10:30	40'	Recent progress in supernova progenitor theories	H. Umeda (Tokyo)
11:10	30'	Theoretical study of supernova relic neutrinos	K. Nakazato (Kyushu)
11:40	100'	lunch	
chair:B. Dasgupta (Tata)			
13:20	30'	Supernova as sources of multi-messenger signals	Ko Nakamura (Waseda)
13:50	20'	The final evolution of massive stars observed by pre supernova neutrinos	T. Yoshida(University of Tokyo)
14:10	20'	Properties of pre-supernova neutrino in collapsing phase ~ towards comprehensive neutrino studies	C. Kato(Waseda university)
14:30	20'	coffee	
chair: M.Sakuda			
14:50	40'	Prospects for detecting the Diffuse Supernova Neutrino Background in JUNO	M. Wurm (Mainz)
15:30	30'	Recent Progress on Hyper-Kamiokande Project	T. Sekiguchi (KEK)

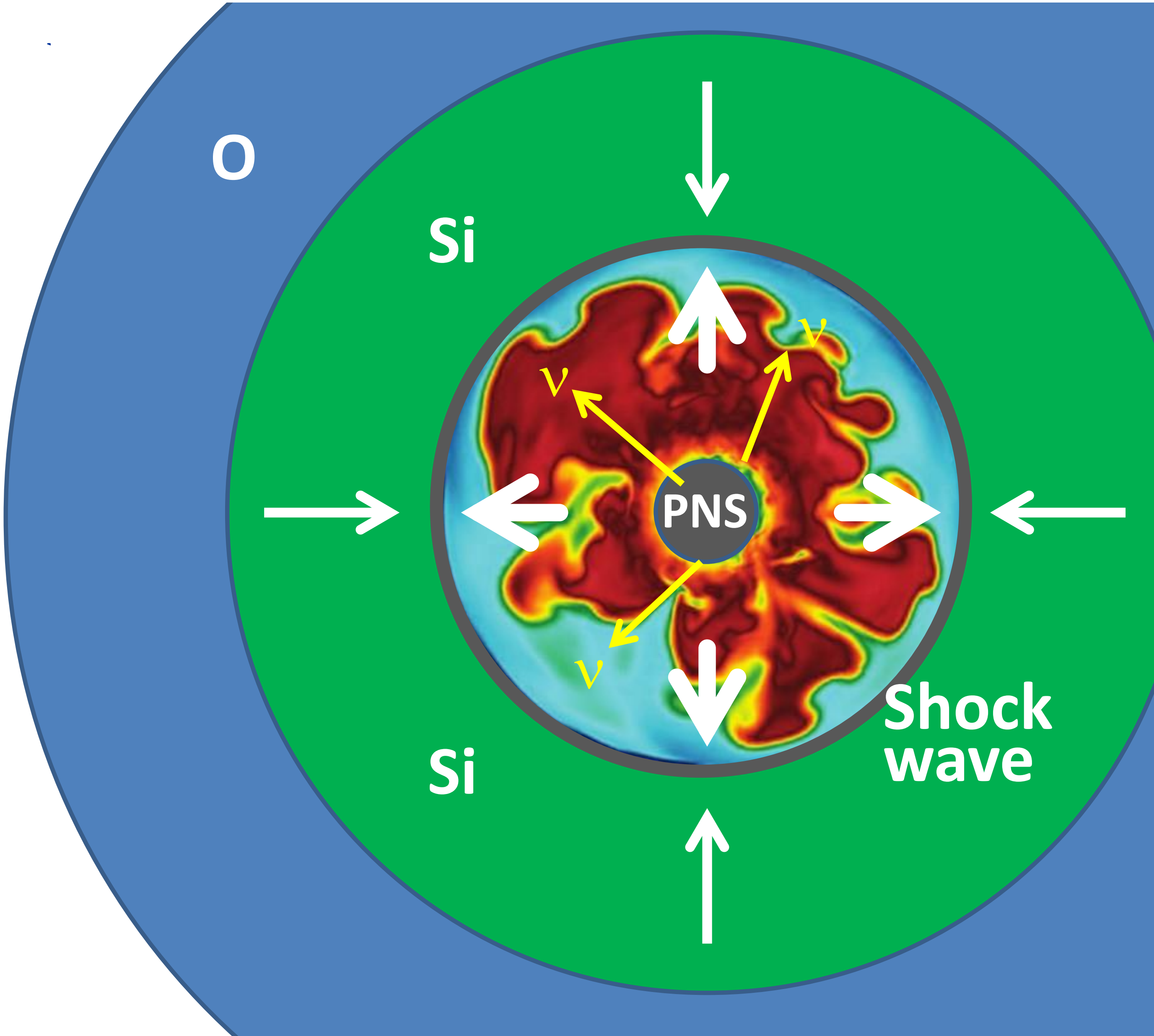
SUPERNOVA PHYSICS

Supernova Theory

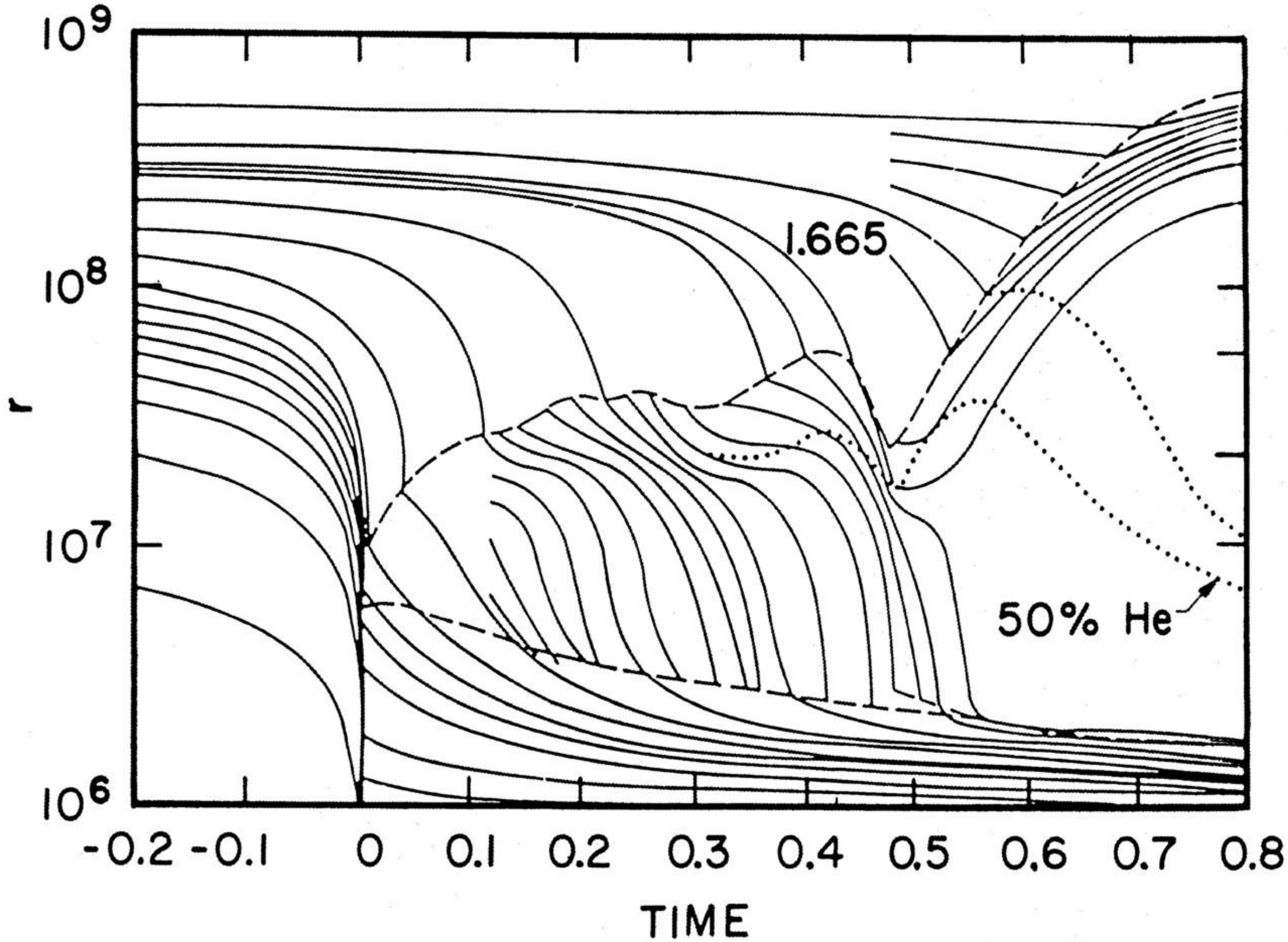


H-T. Janka (TAUP 2013)

Neutrino Mechanism

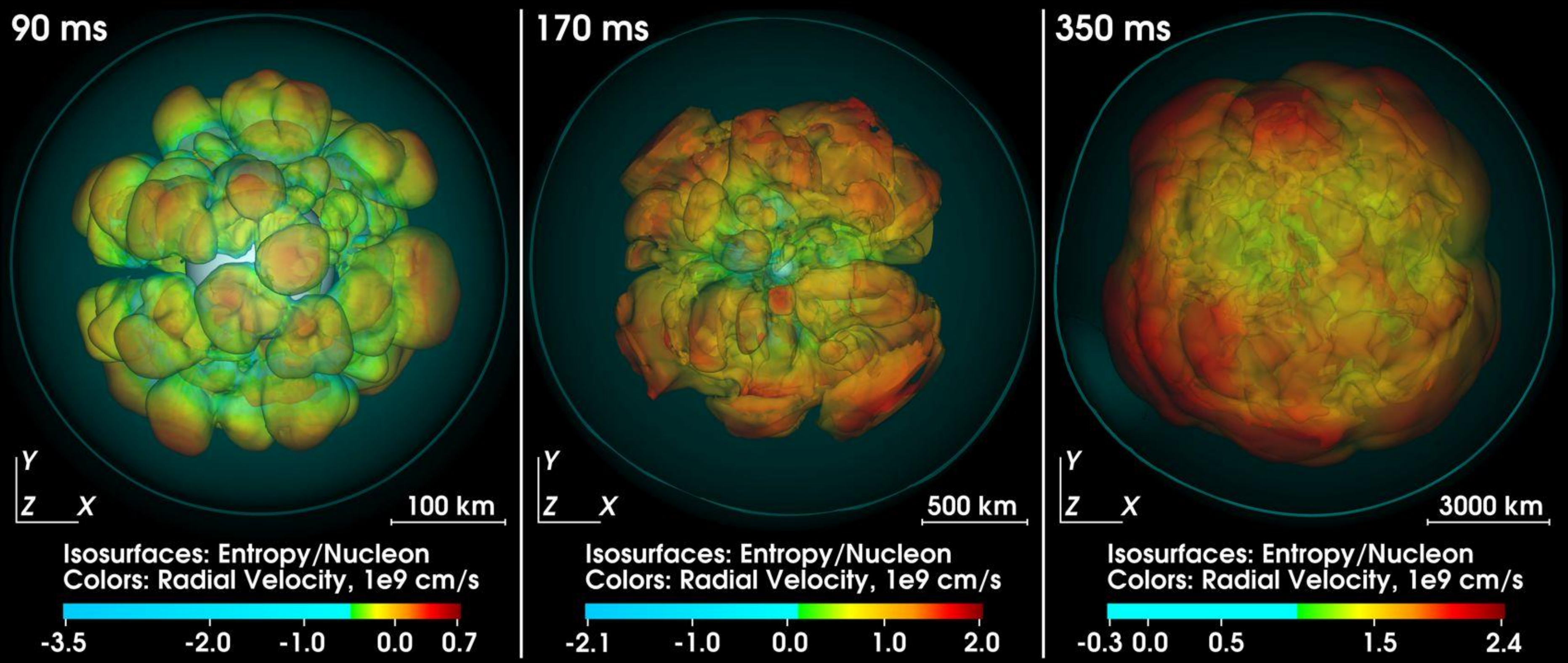


Delayed Explosion



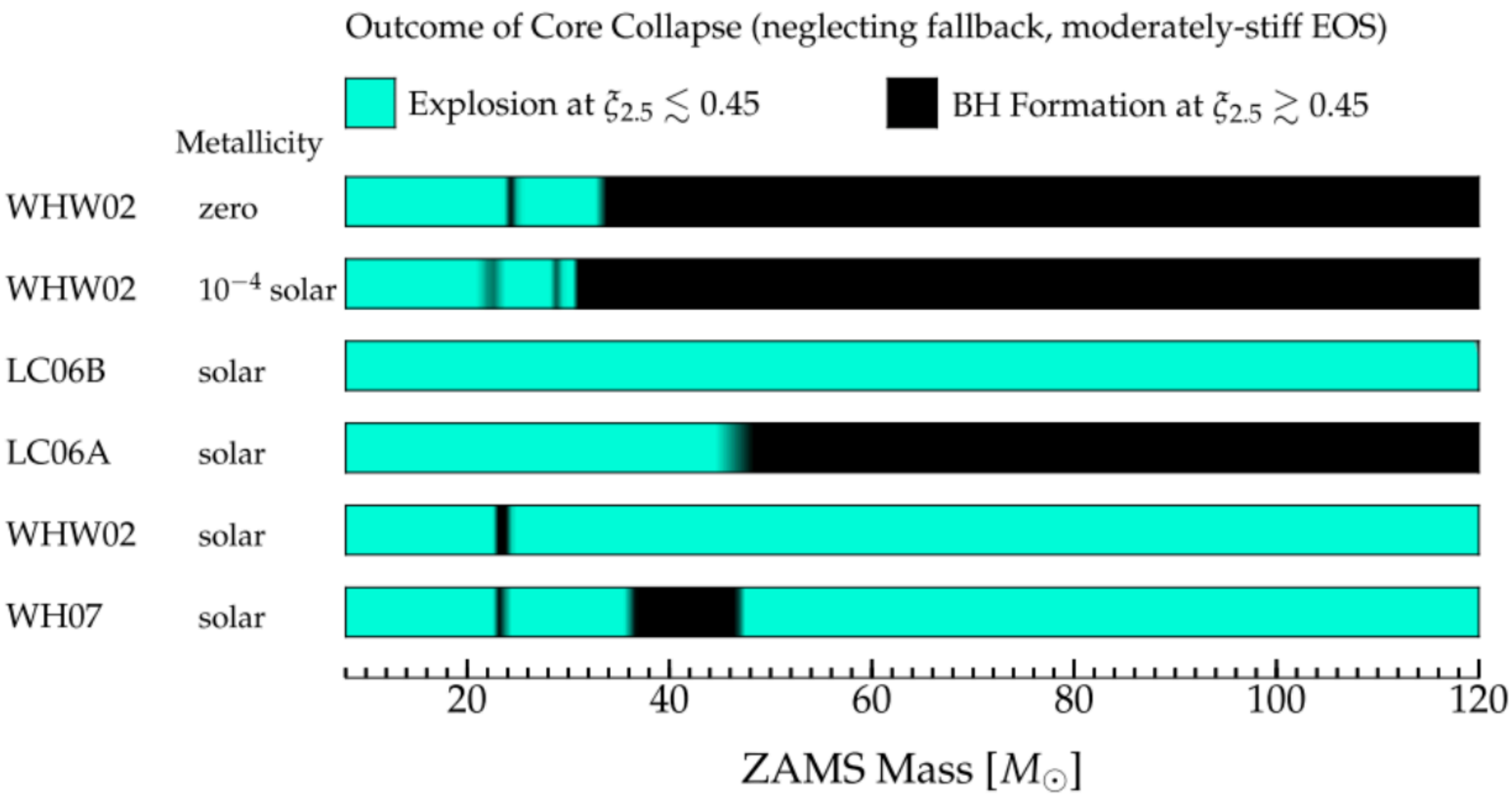
Bethe and Wilson (1985)

First 3D Explosions (9.6 $M_\odot$)



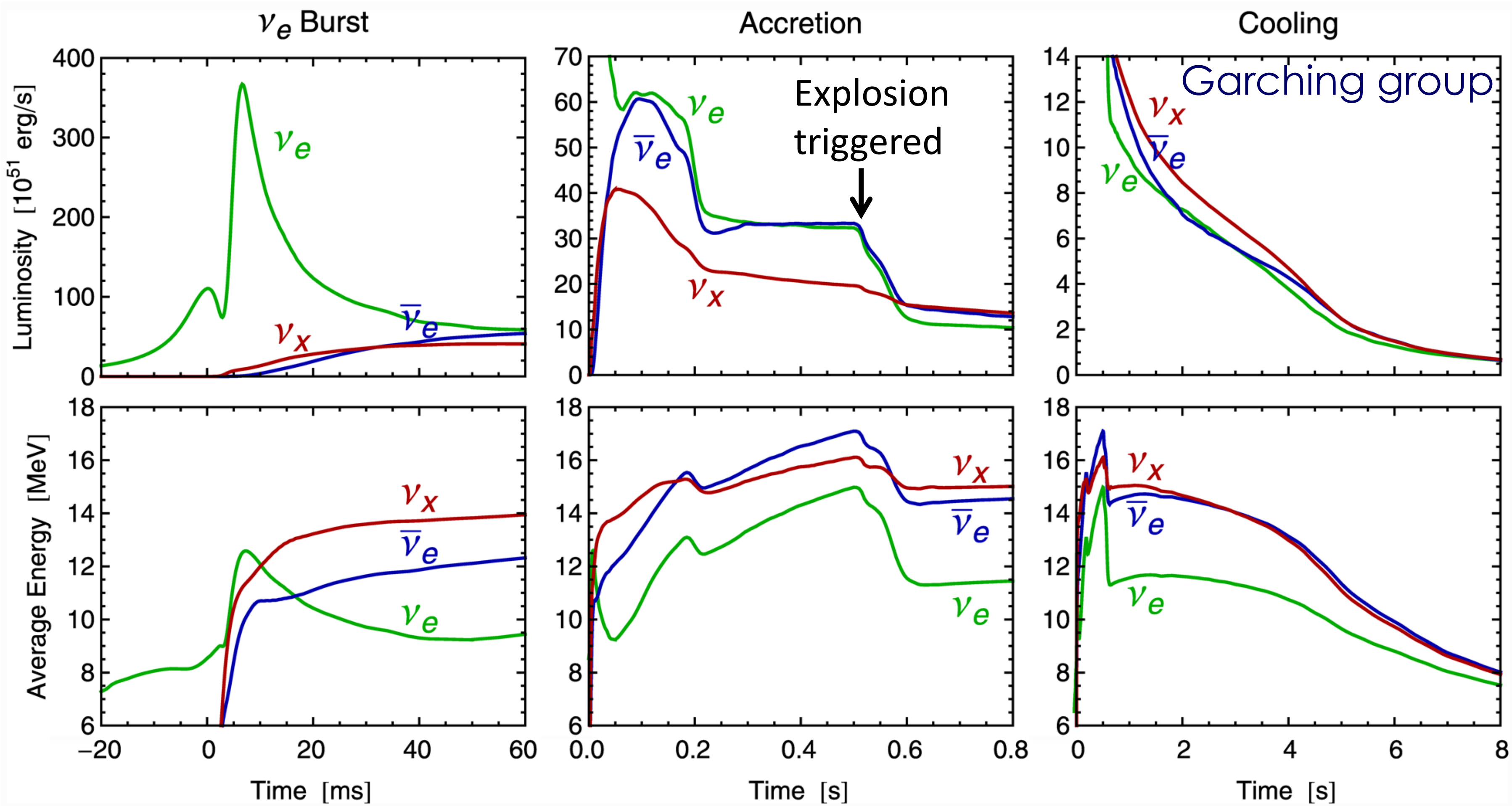
Garching group

Failed SN



O' Connor and Ott

Fluxes and Spectra

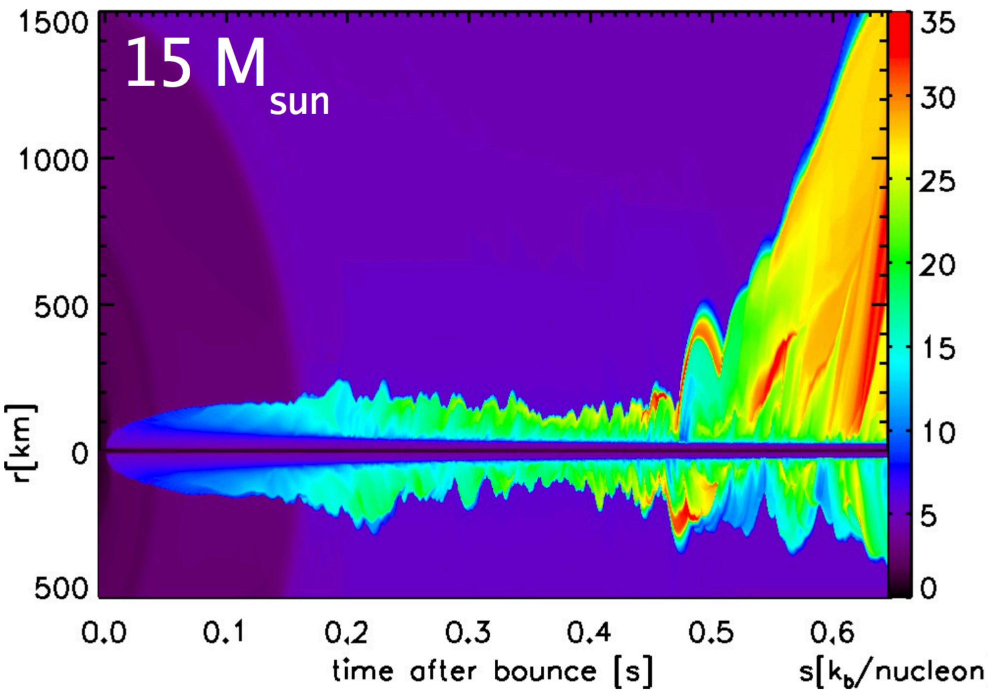


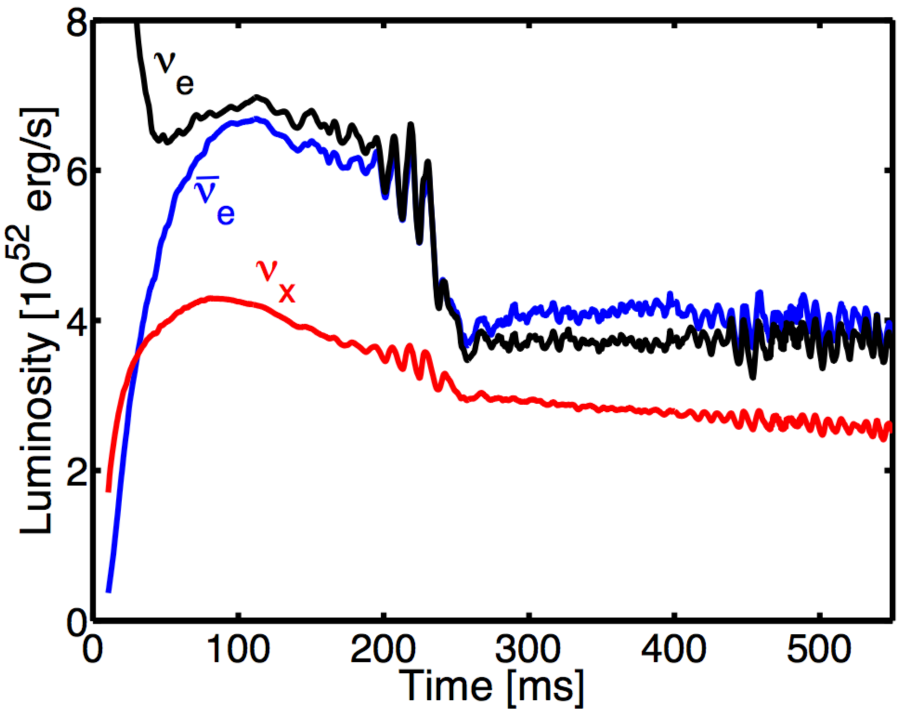
Also, pre-supernova fluxes (Odrywolzcek et al. See talks by Kato, Yoshida)

See also Kato, Azari, Yamada, Takahashi, Umeda, Yoshida, Ishidoshiro

SASI

STANDING ACCRETION SHOCK INSTABILITY

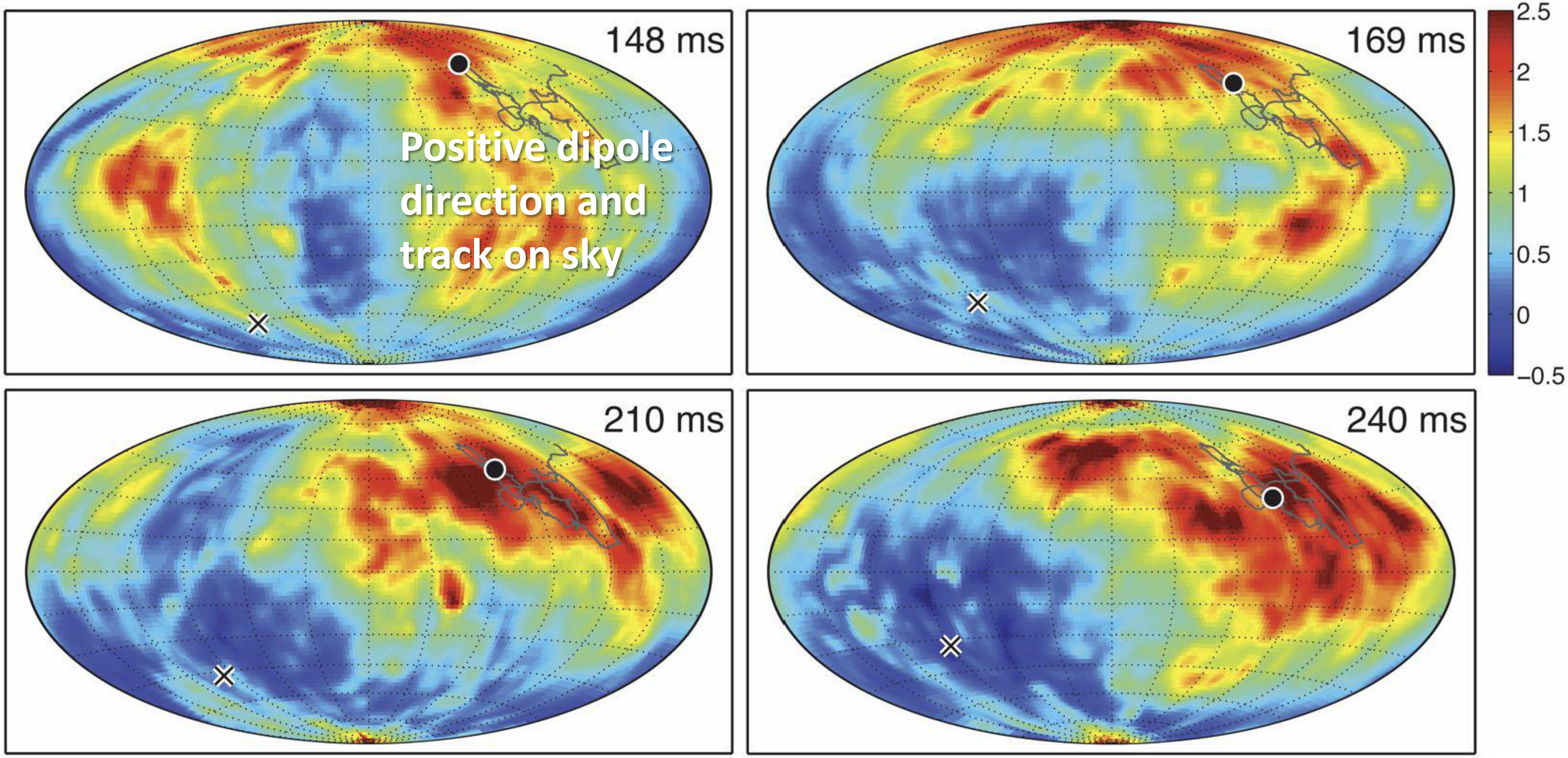




Garching group

LESA

Lepton-# Emission Self-sustained Asymmetry



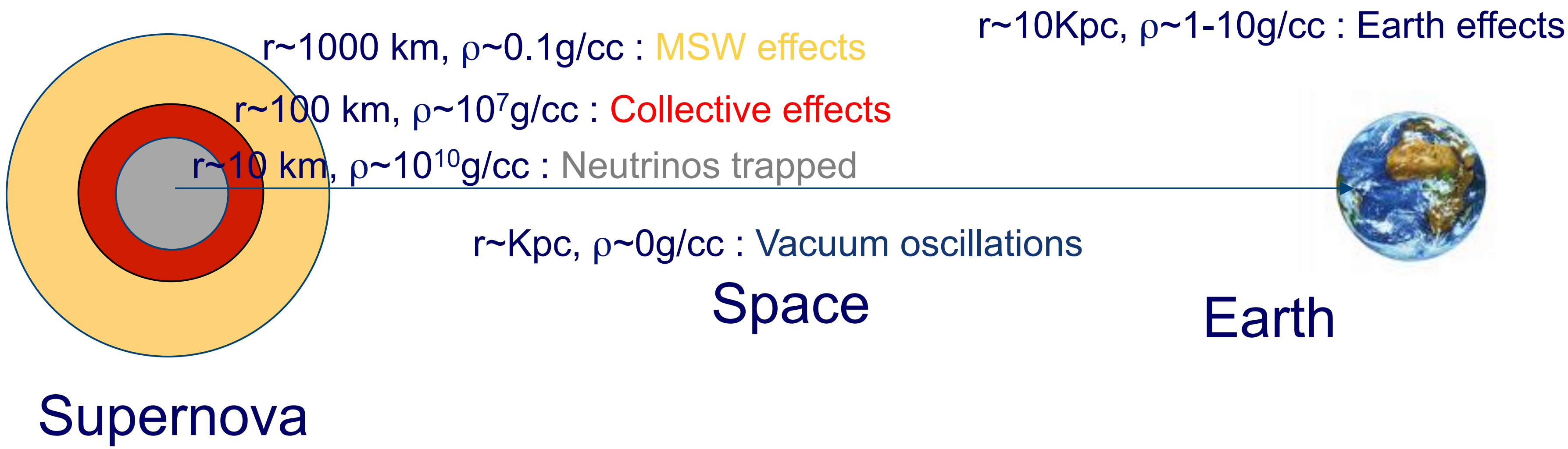
Tamborra, Hanke, Janka, Mueller, Raffelt, Marek

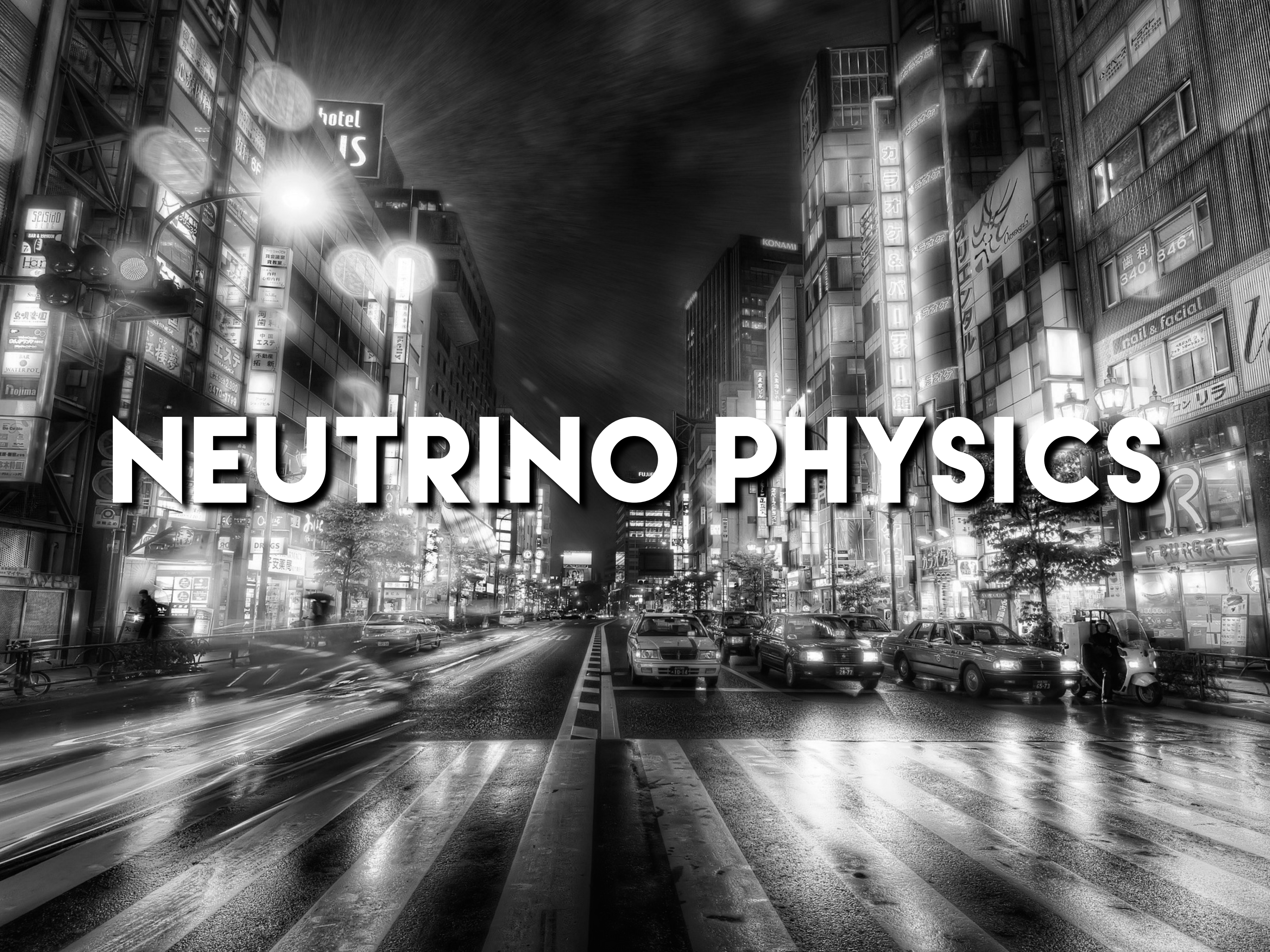
Still a long way to go

Solution approach	Required resources
3D hydro + **6D** direct discretization of Boltzmann Eq. (code development by Sumiyoshi & Yamada '12)	≥ 10–100 PFlops/s (sustained!)
3D hydro + two-moment closure of Boltzmann Eq. (next feasible step to full 3D; O. Just et al. 2013)	≥ 1–10 Pflops/s, TBytes
3D hydro + "**ray-by-ray-plus**" variable Eddington factor method (method used at MPA/Garching)	≥ 0.1–1 PFlops/s, Tbytes
2D hydro + "**ray-by-ray-plus**" variable Eddington factor method (method used at MPA/Garching)	≥ 0.1–1 Tflops/s, < 1 TByte

Janka (TAUP 2013)

Simplified Set-up





NEUTRINO PHYSICS

Formal Aspects

$$i\,D\hat{f} - \left[\hat{\mathcal{H}}, \hat{f}\right] - \hat{U}\left[\hat{\phi}\right]$$

OSCILLATIONS + COLLISIONS

Vlasenko, Fuller, Cirigliano

BEYOND MEAN-FIELD

Vaananen, Volpe, Espinoza
Serrau and Volpe
Kartavtsev, Raffelt and Vogel
Balantekin, Pehlivan,..

TYPICALLY SMALL EFFECTS, BUT $\cdots$

Oscillation Framework

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

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

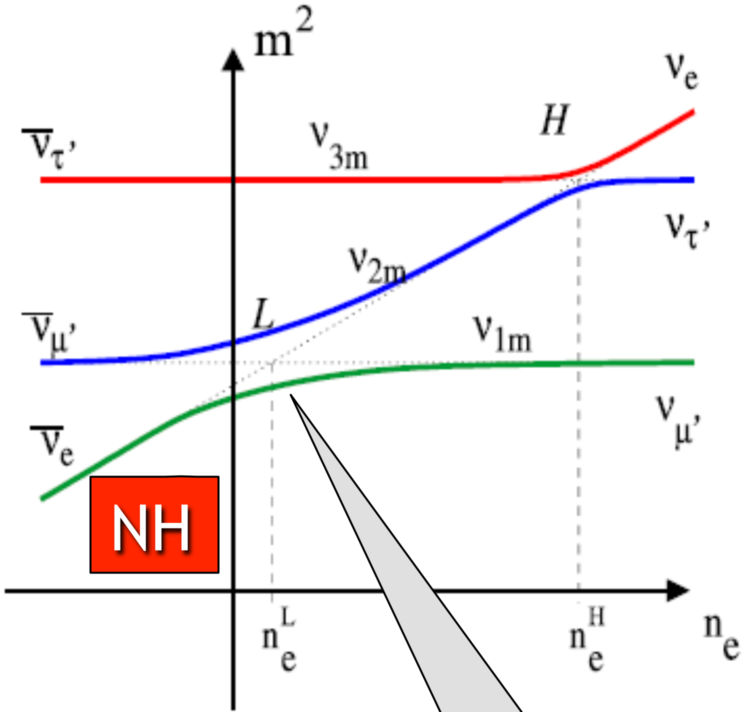
MSW effect depends on ordinary matter density L, i.e. mainly electron density

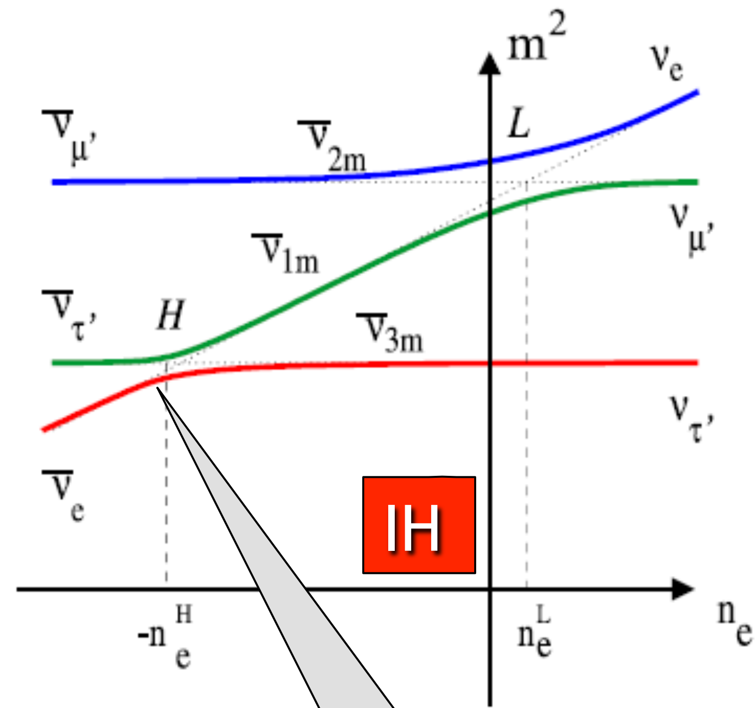
Nonlinear Effects depends on the neutrino density ρ

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

These interactions give rise to “Collective” flavor conversions

MSW Effects





Dighe and Smirnov

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

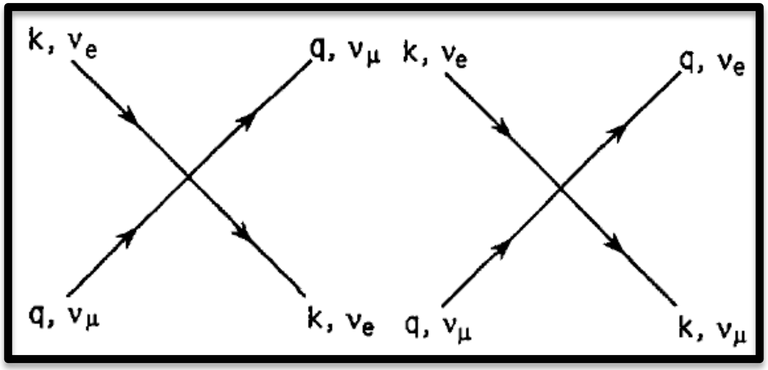
$(\Delta m_{atm}^2 , \theta_{13})$ at 10^3 - 10^4 g/cc

In neutrinos for NH and in antineutrinos for IH.

Adiabaticity ≈ $\sin^2\theta_{13}$

Neutrino-Neutrino Interactions

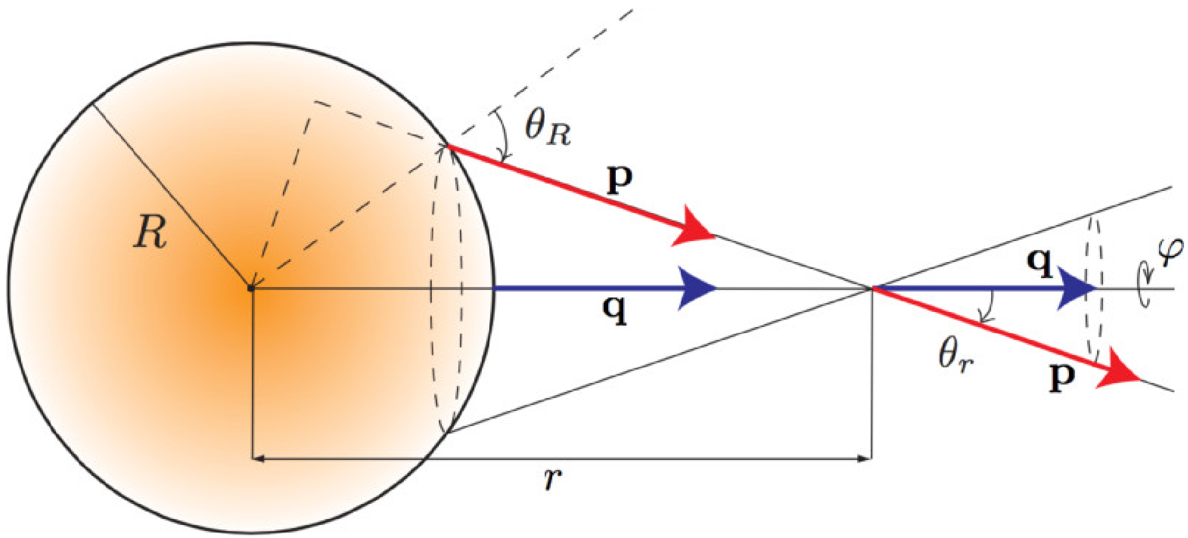
$$i\frac{d}{dt}\begin{pmatrix}|\nu_e(k)\nu_e(q)\rangle\\|\nu_e(k)\nu_\mu(q)\rangle\\|\nu_\mu(k)\nu_e(q)\rangle\\|\nu_\mu(k)\nu_\mu(q)\rangle\end{pmatrix}=V_2\begin{pmatrix}|\nu_e(k)\nu_e(q)\rangle\\|\nu_e(k)\nu_\mu(q)\rangle\\|\nu_\mu(k)\nu_e(q)\rangle\\|\nu_\mu(k)\nu_\mu(q)\rangle\end{pmatrix}$$



Pantaleone (1992)

$$V_{2\nu}=\sqrt{2}G_F\xi\frac{1}{V}\begin{pmatrix}2&0&0&0\\0&1&1&0\\0&1&1&0\\0&0&0&2\end{pmatrix}$$

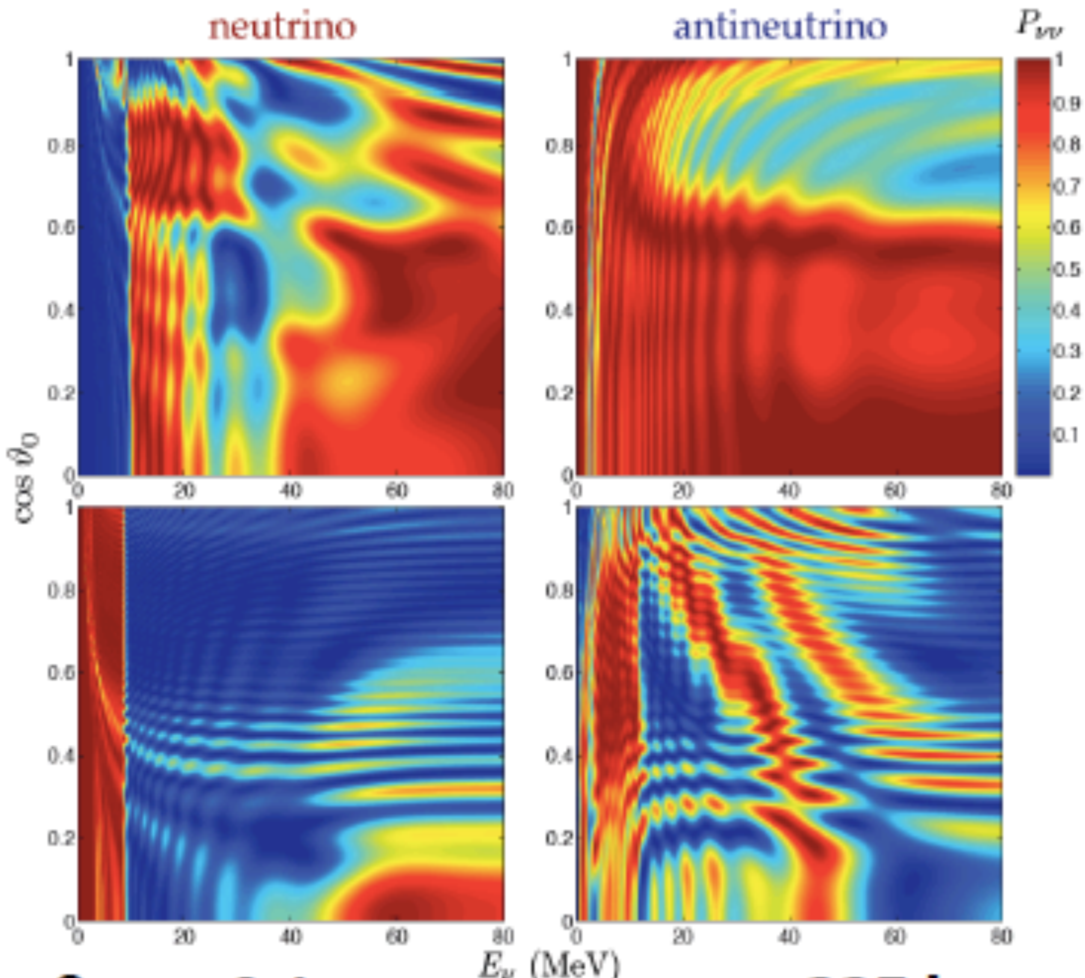
Why so complicated?



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

The density matrix has large dimensionality

Collective Effects



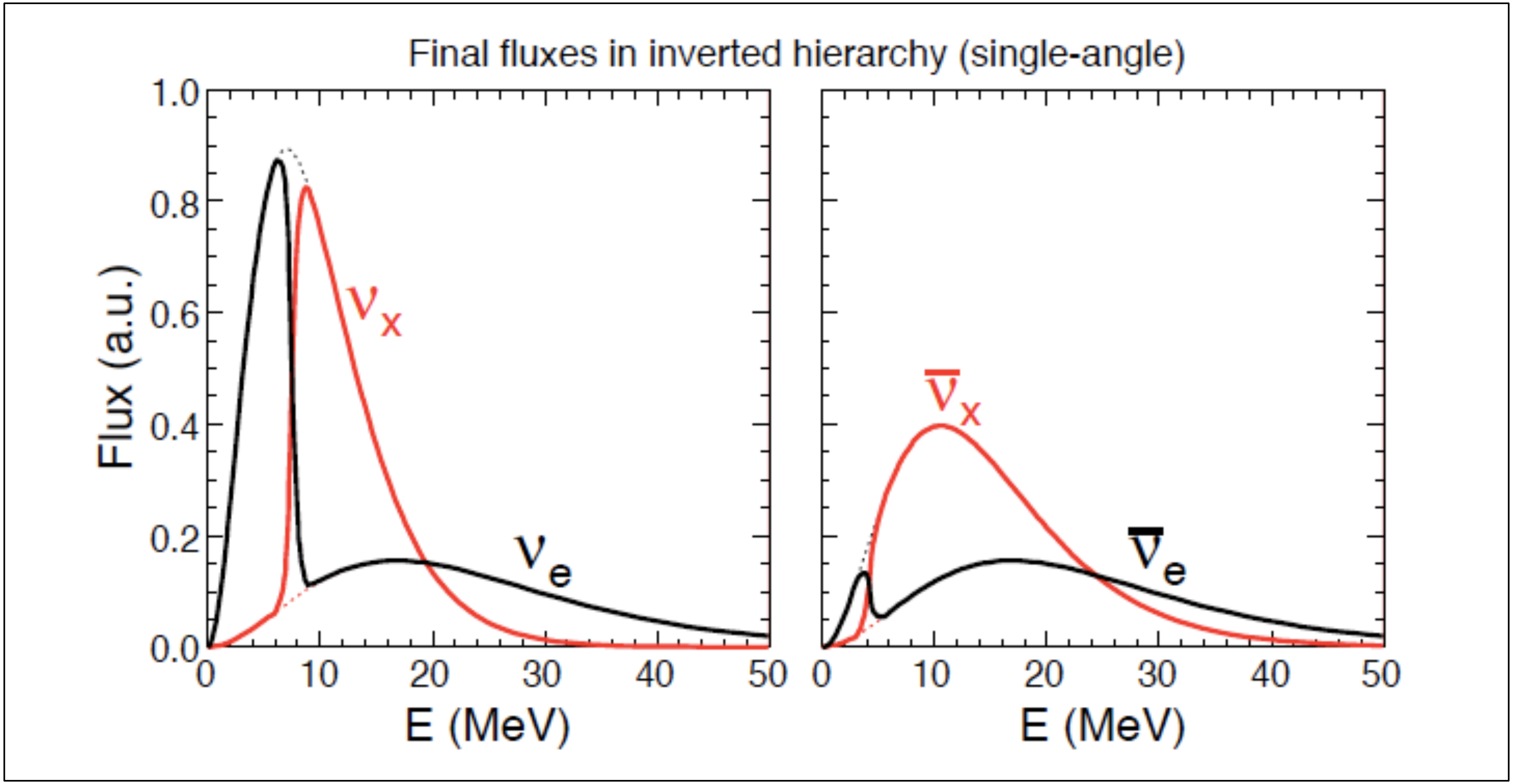
θ_{13} ~ 0.1

r ~ 225 km

Duan, Fuller, Carlson, Qian (2005, 2006,...)

Spectral Splits

Nontrivial Evolution only for Inverted Hierarchy

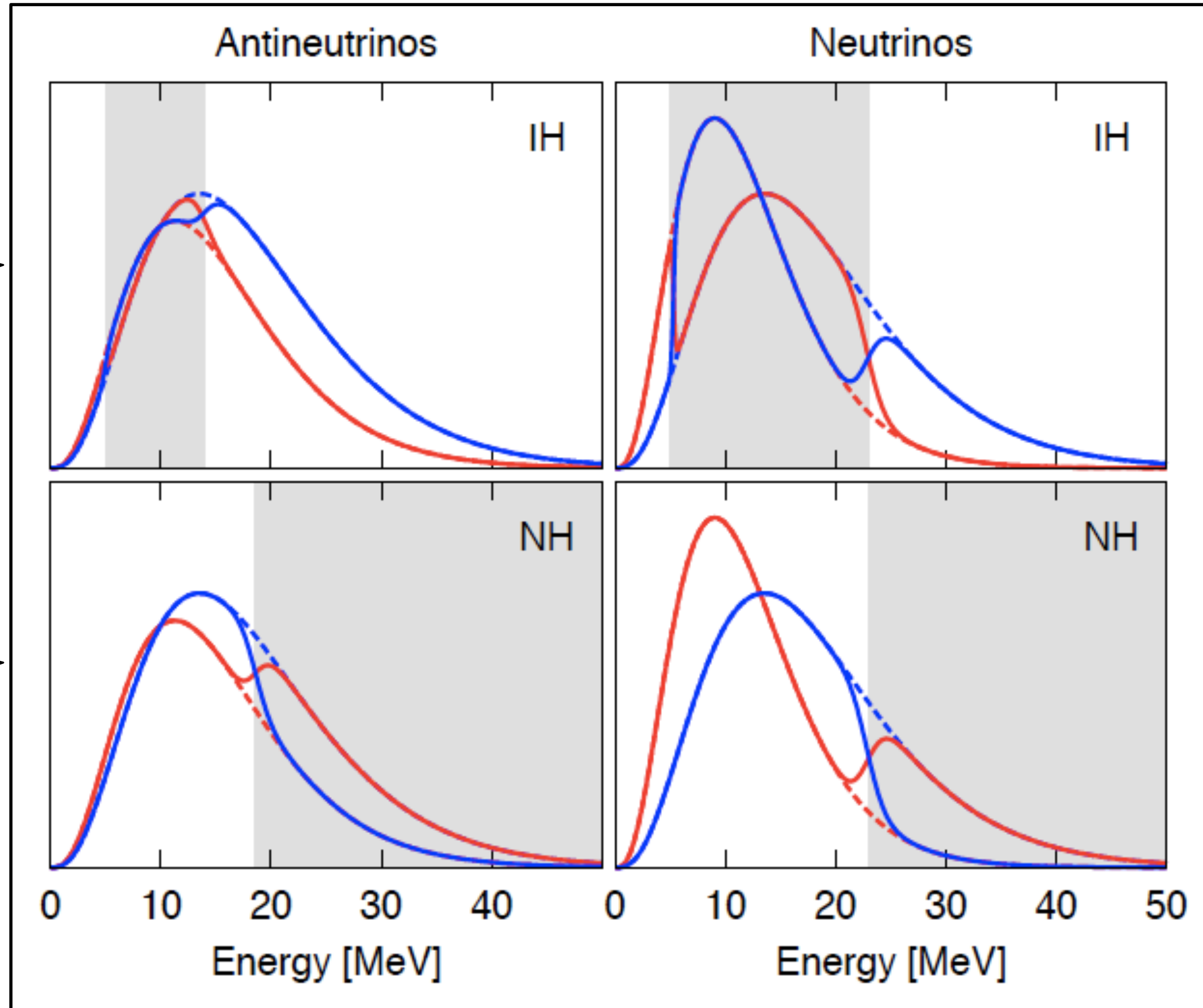


Fogli, Lisi, Marrone and Mirizzi

Why do we get these effects?

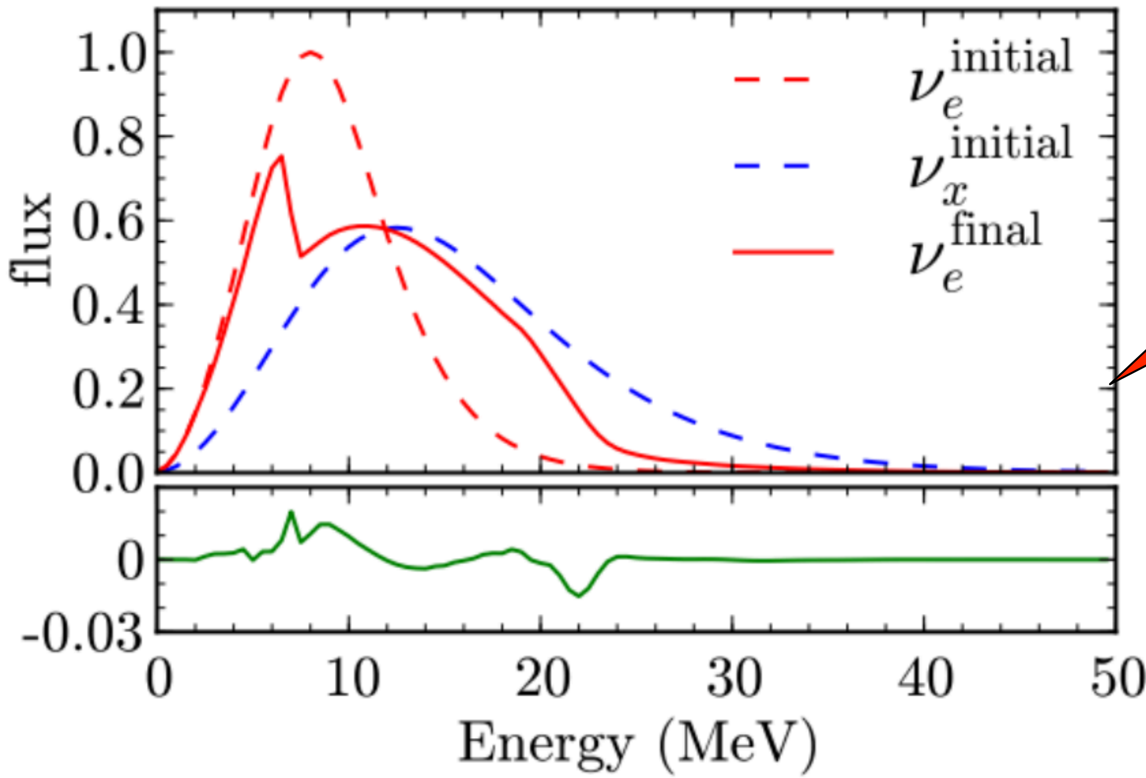
Spectral Splits in Inverted Hierarchy

Spectral Splits in Normal Hierarchy



Dasgupta, Dighe, Raffelt and Smirnov

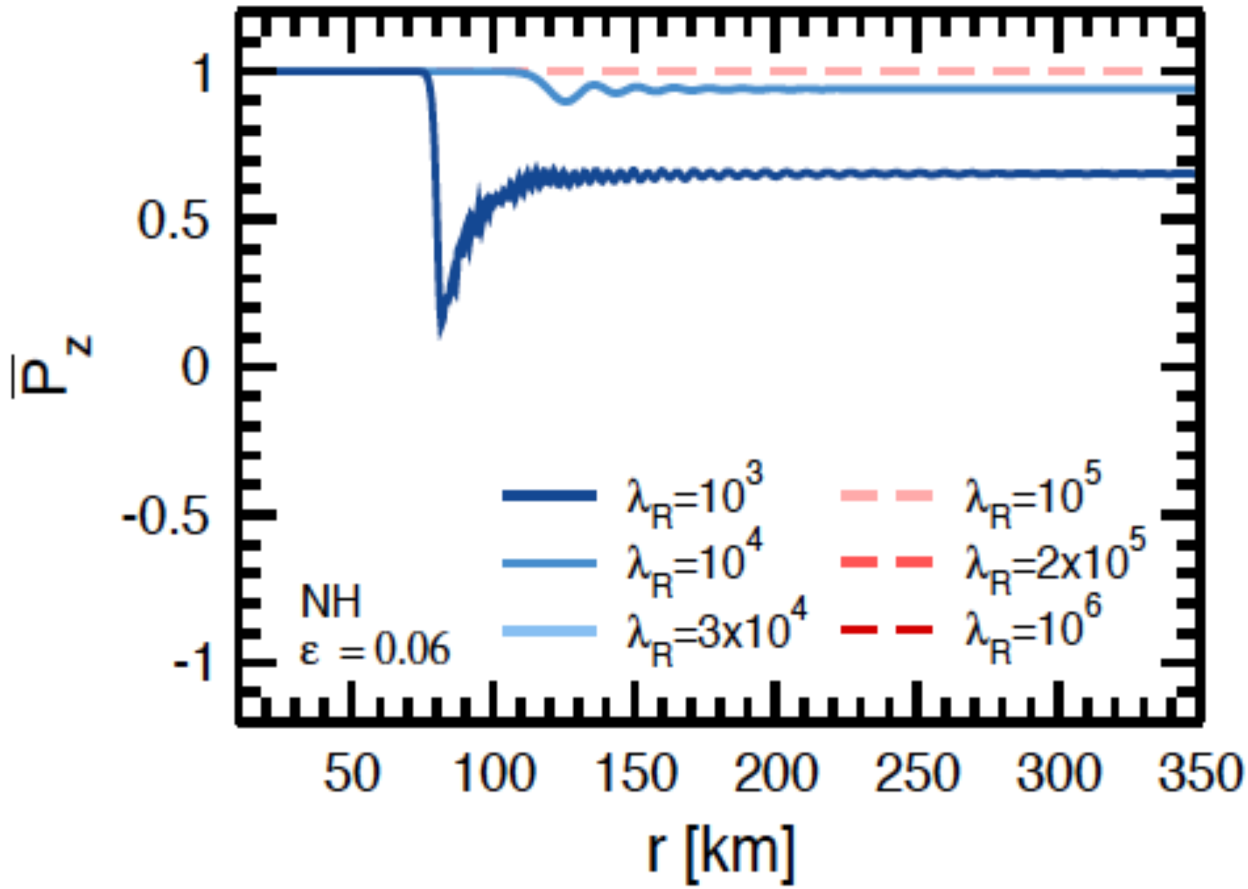
Multi-Angle Effects



Smeared Spectral Splits

Esteban-Pretel et al, Friedland and Duan

Multi-Angle Matter Effect



Esteban-Pretel, Mirizzi, Pastor, Tomas, Raffelt, Serpico, Sigl

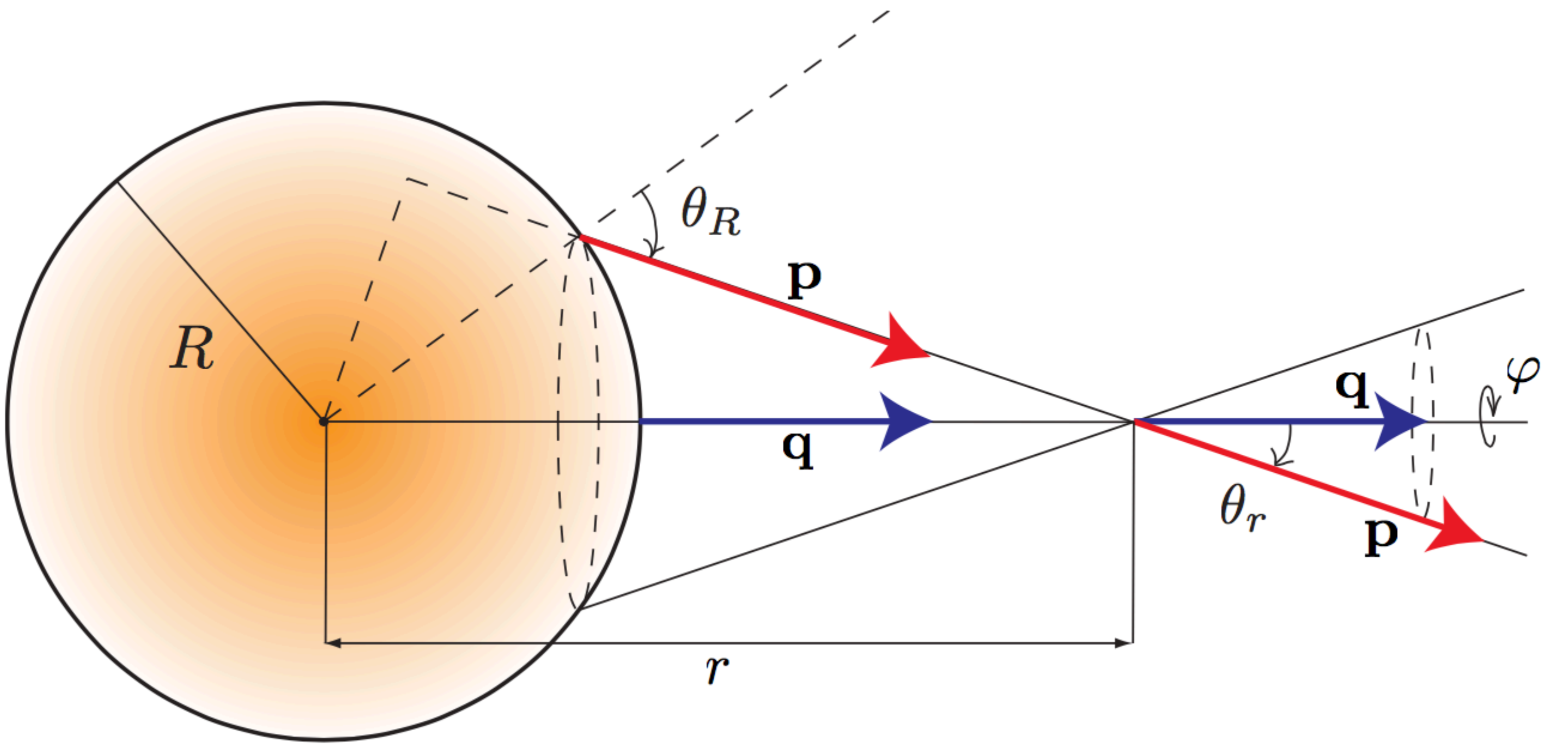
Linear Stability Analysis

$$i\partial_r S_{\omega,u} = [\omega + u(\lambda + \epsilon\mu)]S_{\omega,u} - \mu \int du' d\omega' (u + u') g_{\omega' u'} S_{\omega',u'}.$$

EIGENVALUE PROBLEM

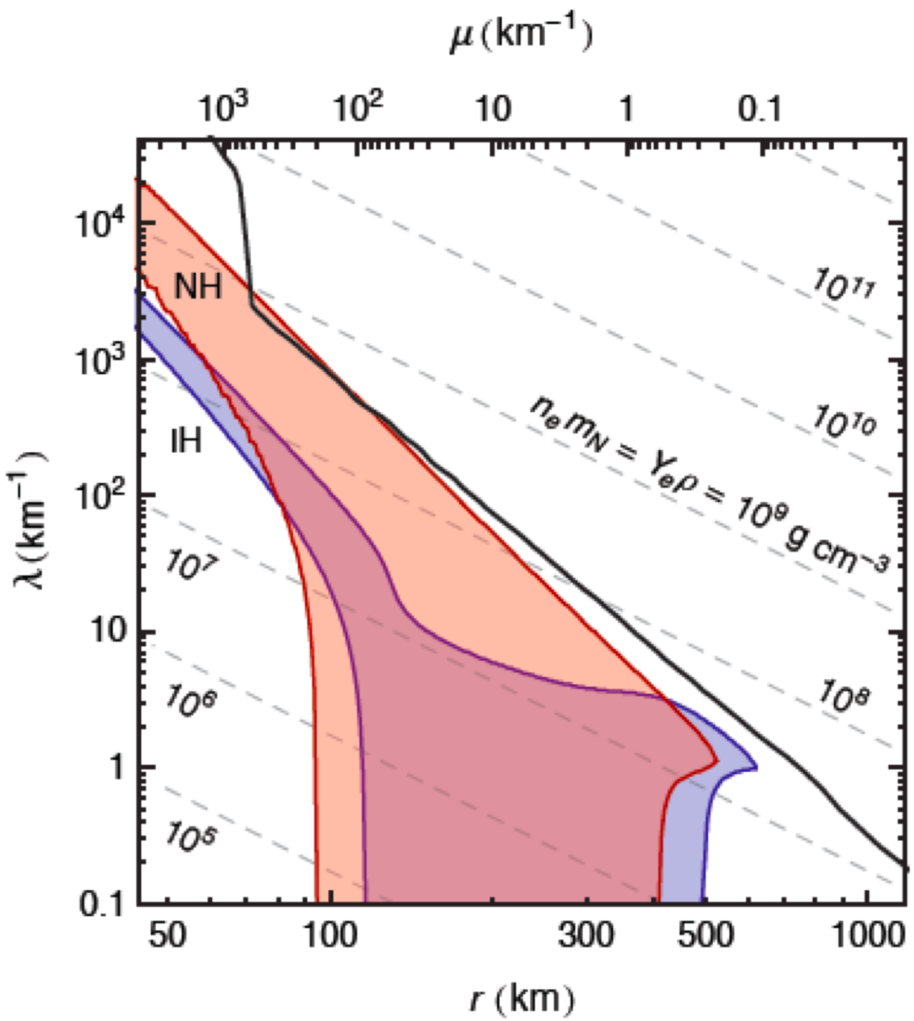
Banerjee, Dighe, Raffelt

Symmetry Breaking



$$iv_r\partial_r \to i(\partial_t + \vec{v}\cdot\nabla)$$

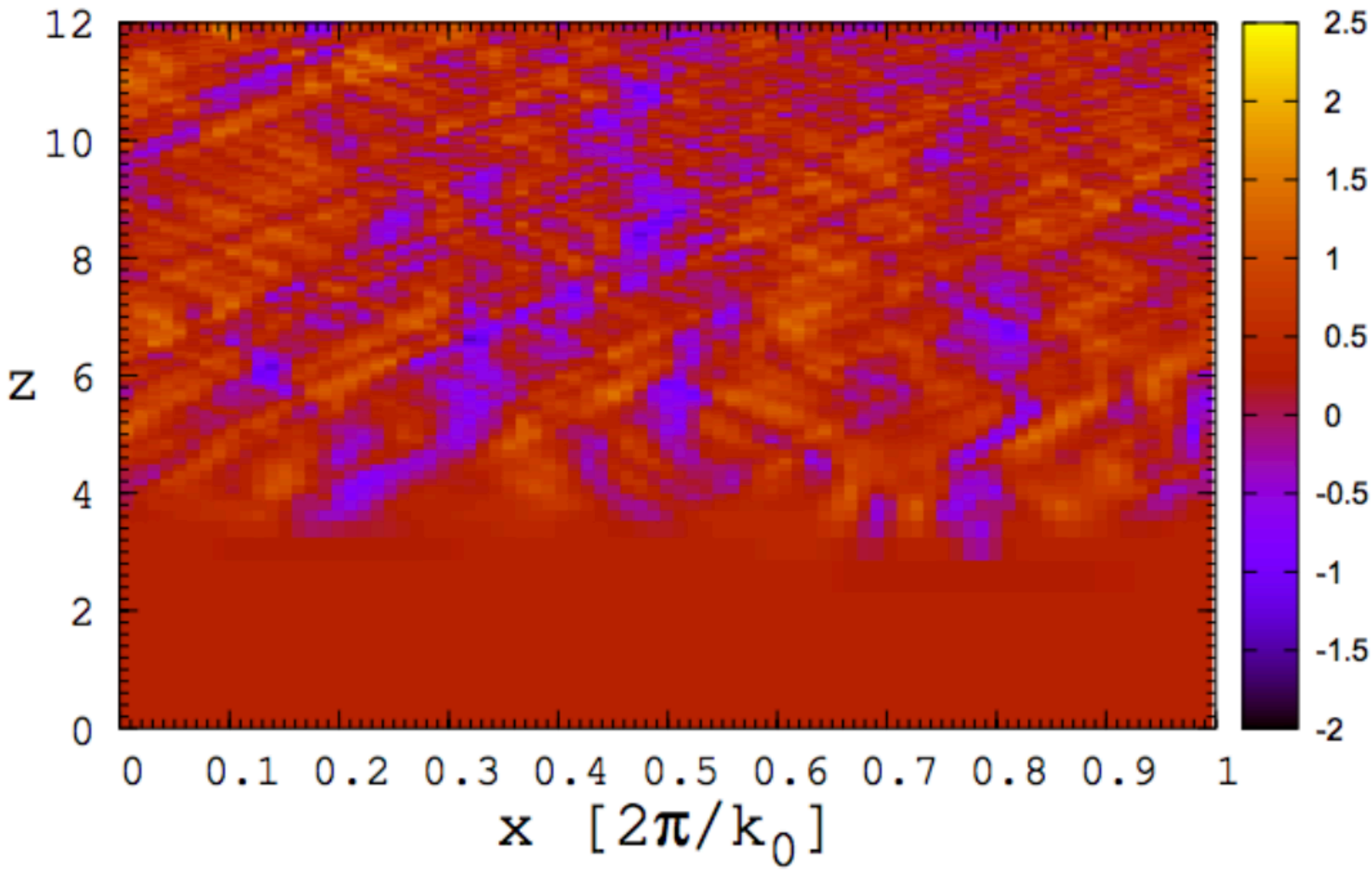
Angular Symmetry Breaking



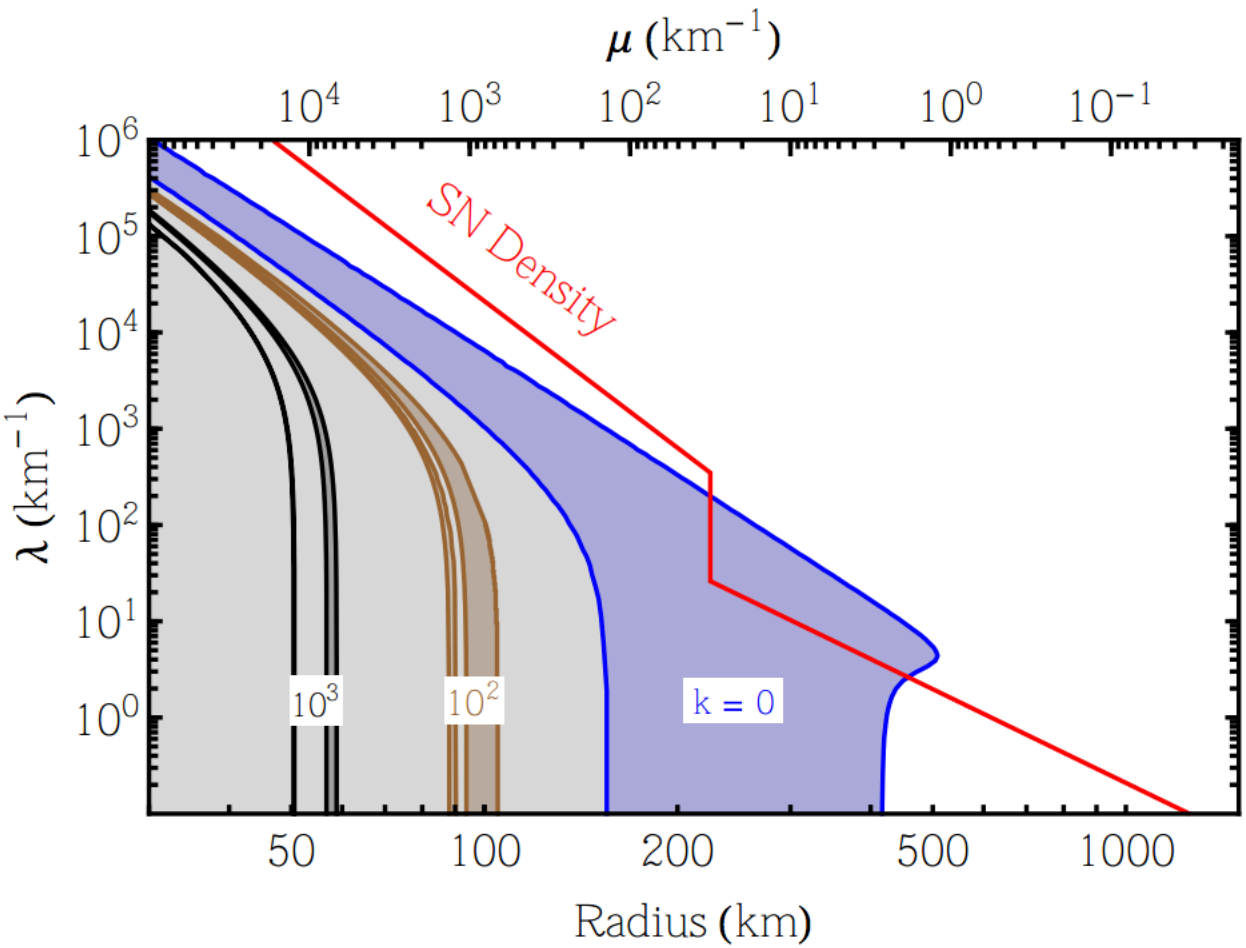
Raffelt, Sarikas, Seixas

Instability from Inhomogeneity

Mirizzi, Mangano, Saviano
Duan and Shalgar

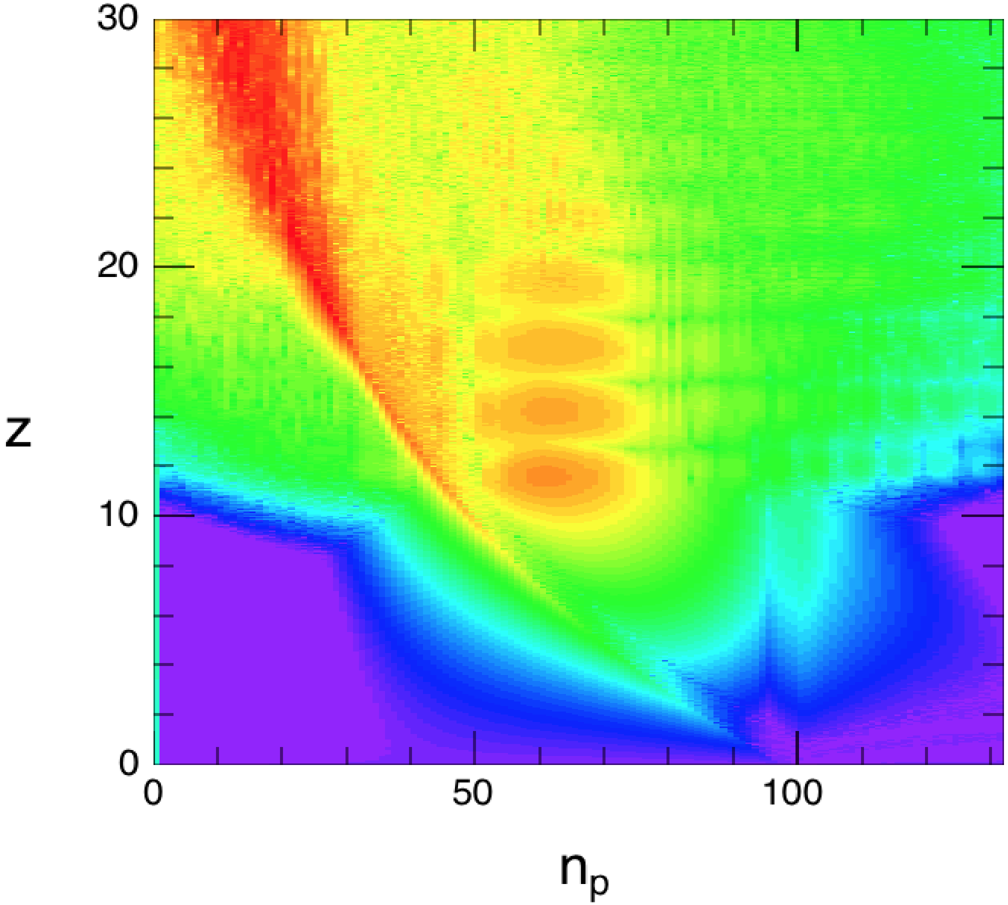


Instability Footprint

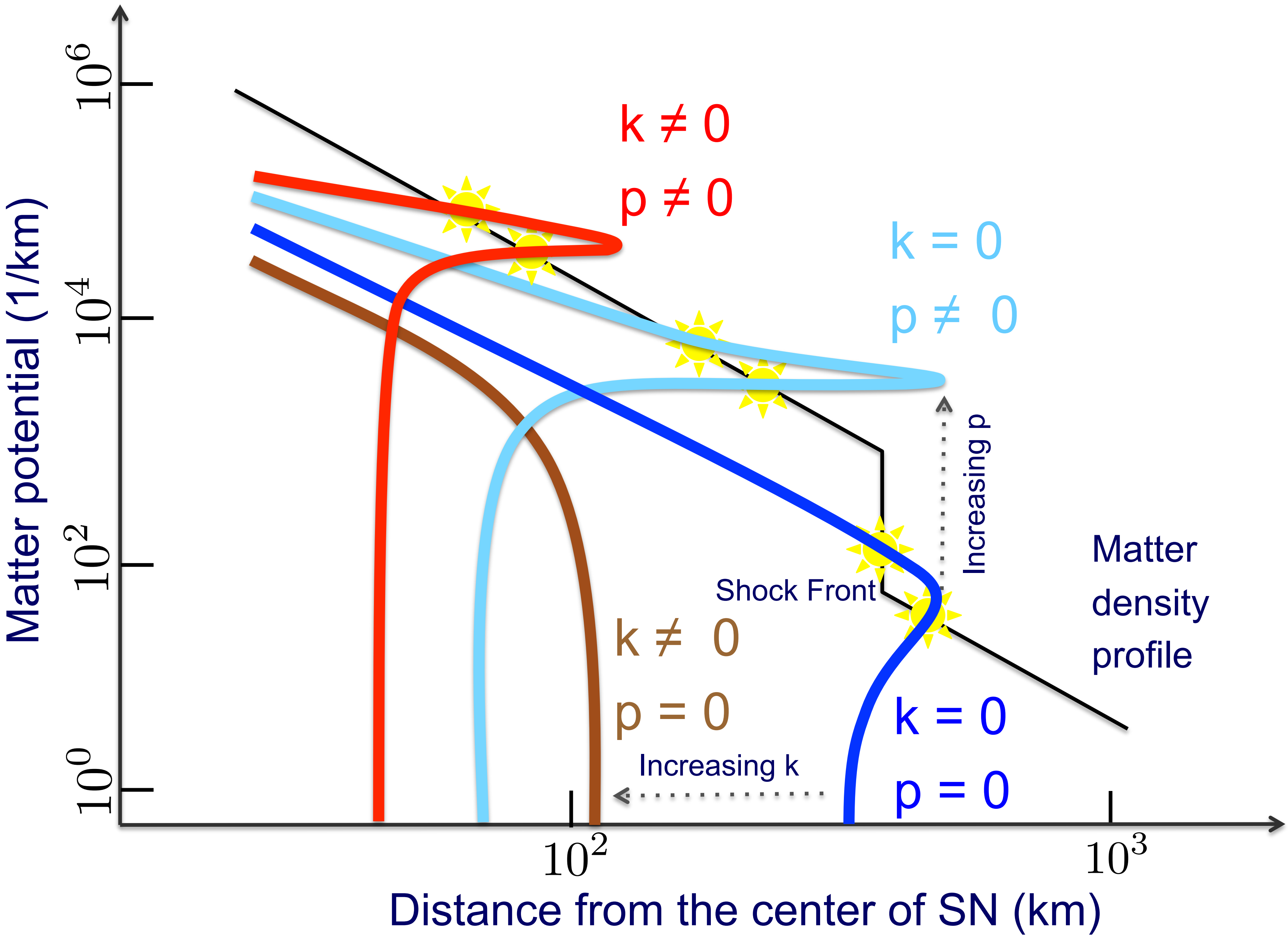


Chakraborty, Hansen, Izaguirre, Raffelt

Temporal Instability

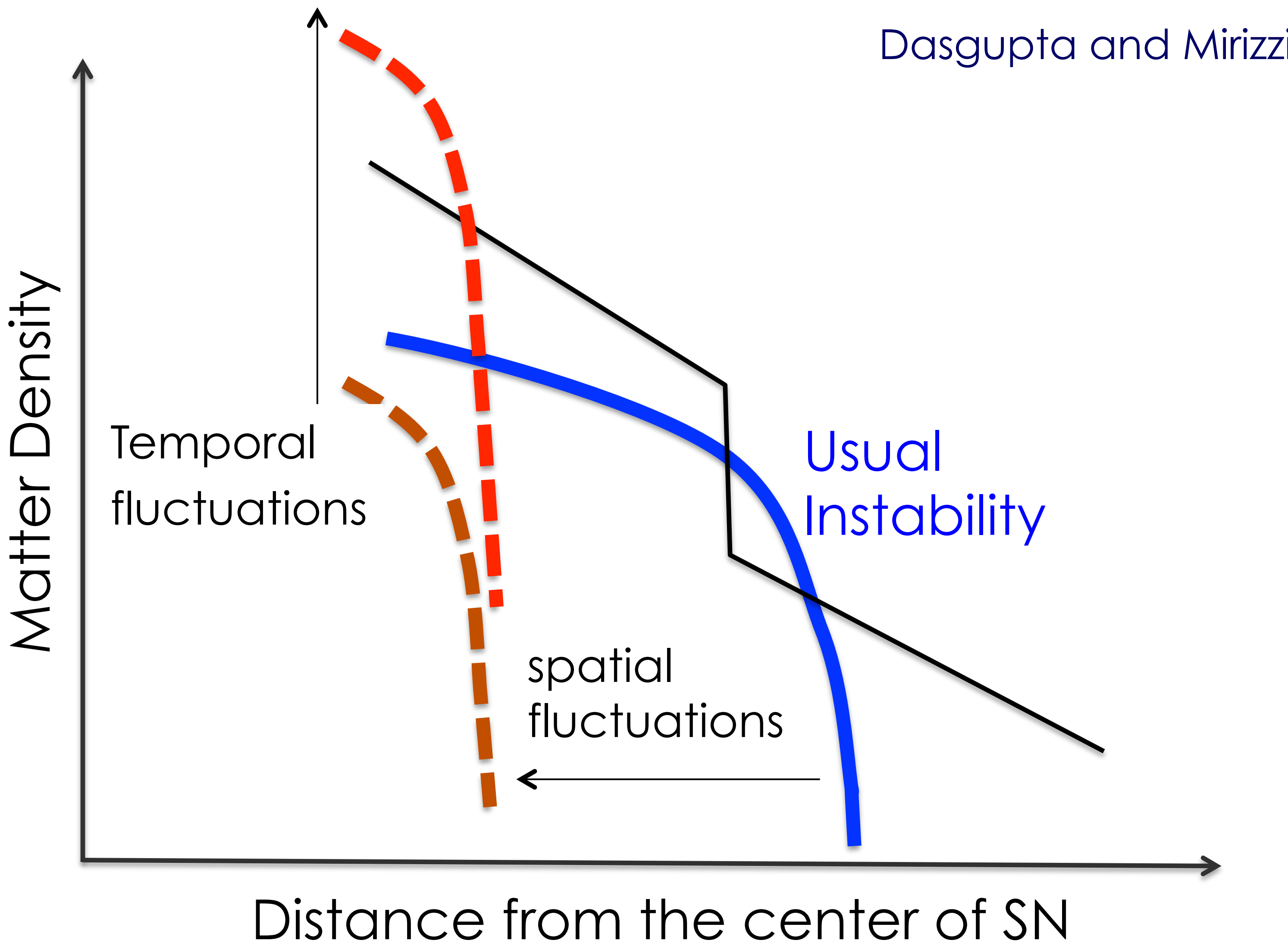


Dasgupta and Mirizzi
Capozzi, Dasgupta, Mirizzi



Matter potential (1/km)
10^6
10^4
10^2
10^0
10^2
10^3
Distance from the center of SN (km)
k ≠ 0
p ≠ 0
k = 0
p ≠ 0
Increasing p
Shock Front
k ≠ 0
p = 0
k = 0
p = 0
Increasing k
Matter
density
profile

Moving Footprints



Fast Conversions

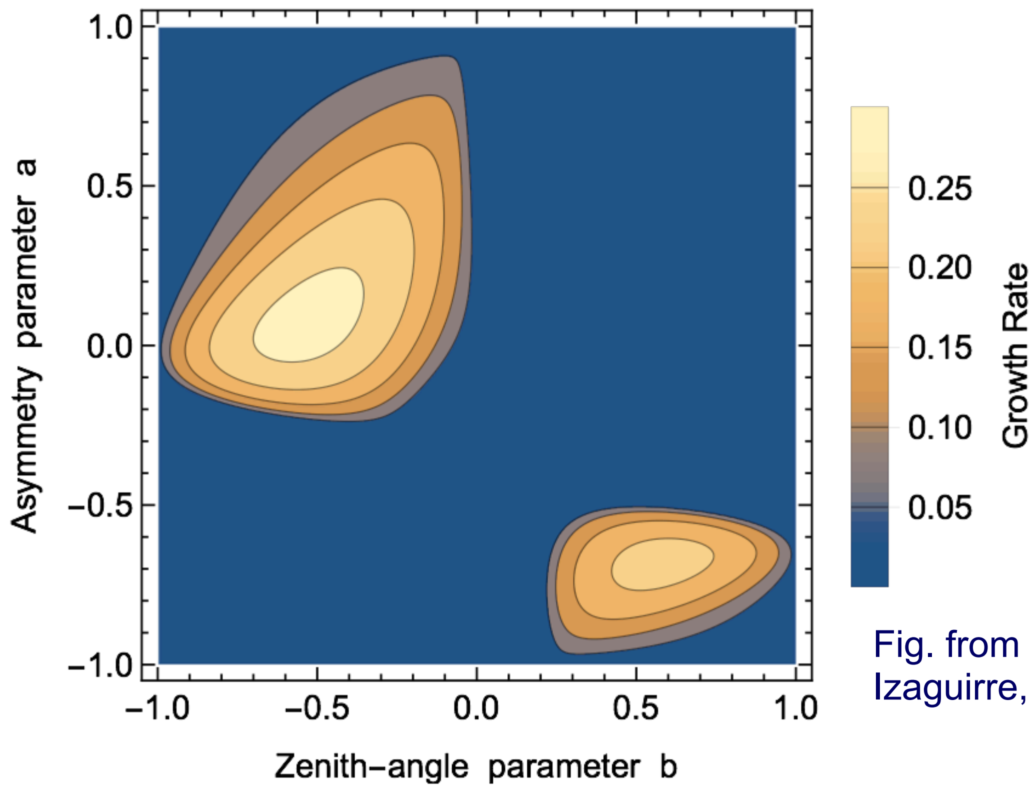


Fig. from Chakraborty, Hansen, Izaguirre, Raffelt

Possibility of even faster flavor conversions, that scale as neutrino density, independent of vacuum oscillation frequency!

Sawyer

Work in progress

PHENOMENOLOGY

Main Channels

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

$$\bar{\nu}_e p \rightarrow n e^+: \approx 7000 - 12000^*$$
$$\nu e^- \rightarrow \nu e^-: \approx 200 - 300^*$$
$$\nu_e + {}^{16}O \rightarrow X + e^-: \approx 150\text{–}800^*$$

SK and IC are the SN neutrino workhorses.

- Scintillation detector

$$\bar{\nu}_e p \rightarrow n e^+$$
$$\nu + {}^{12}C \rightarrow \nu + X + \gamma \ (15.11 \text{ MeV})$$

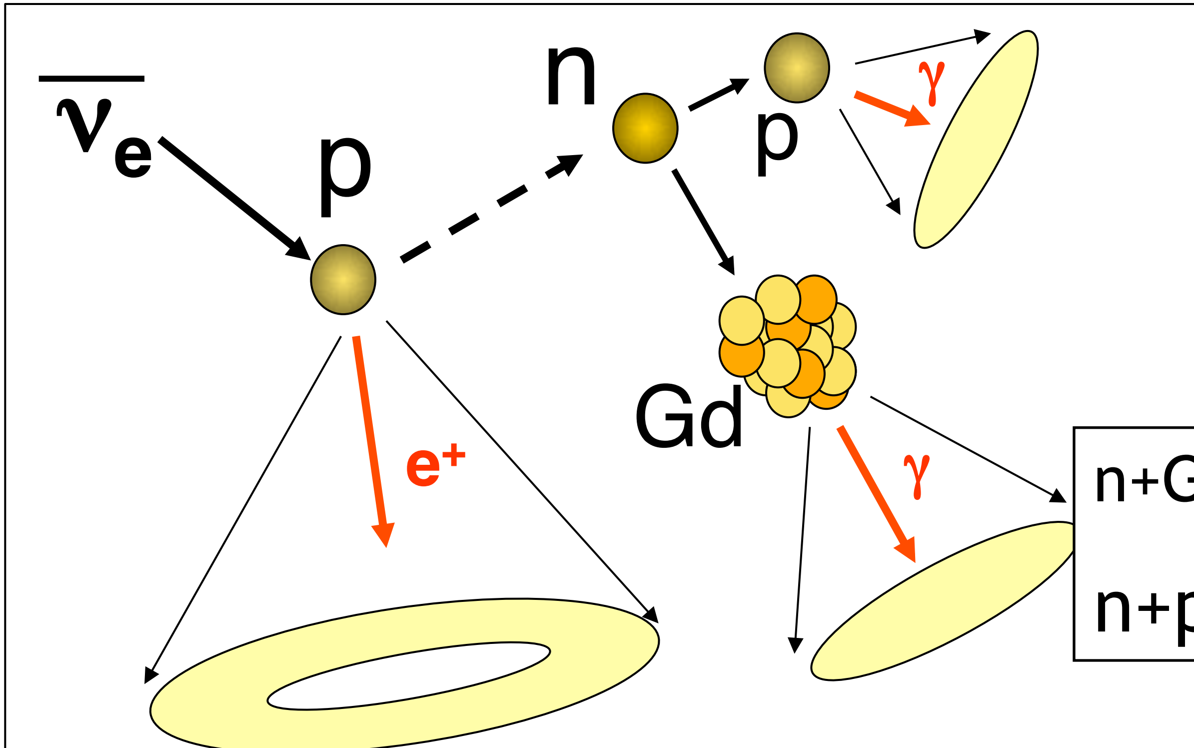
Low threshold. May see non-electron.

- Liquid Argon detector

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

Liquid Argon TPC can see neutrinos, others mostly see antineutrinos

Gadzooks



n+Gd → ~8 MeV γ (90%)

n+p → d + 2.2 MeV γ (10%)

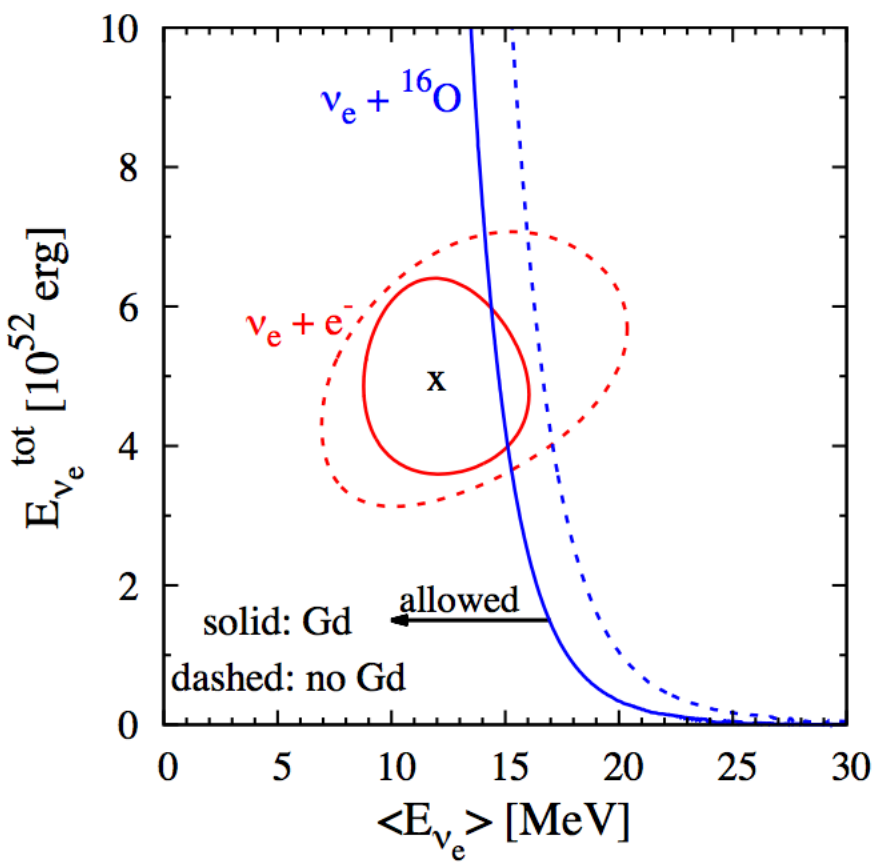
Positron and gamma ray vertices are within ~50cm.

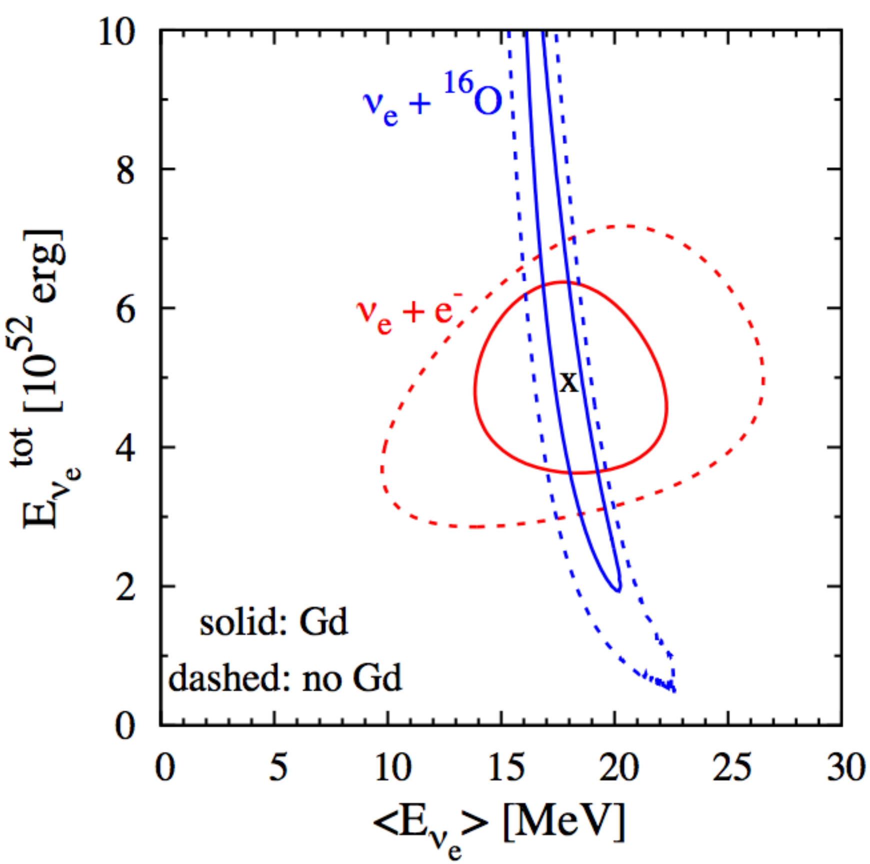
[reaction schematic by M. Nakahata]

Beacom and Vagins

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

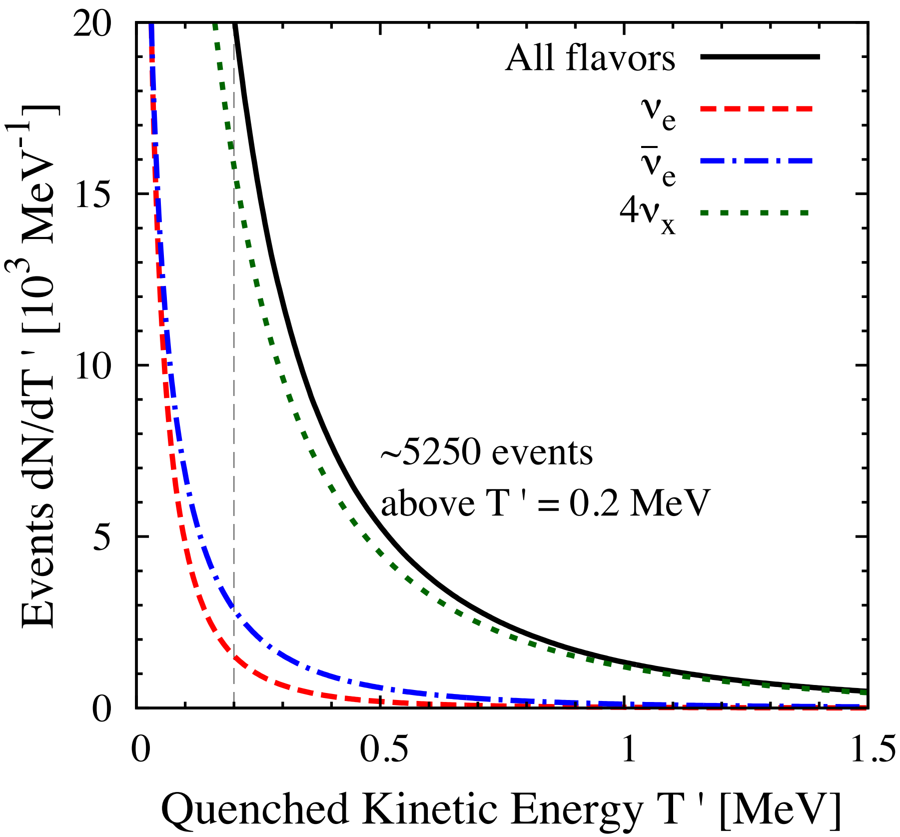
Electron Neutrinos in SK





Laha and Beacom

Non-electron Neutrinos



Beacom, Farr, Vogel

Dasgupta and Beacom

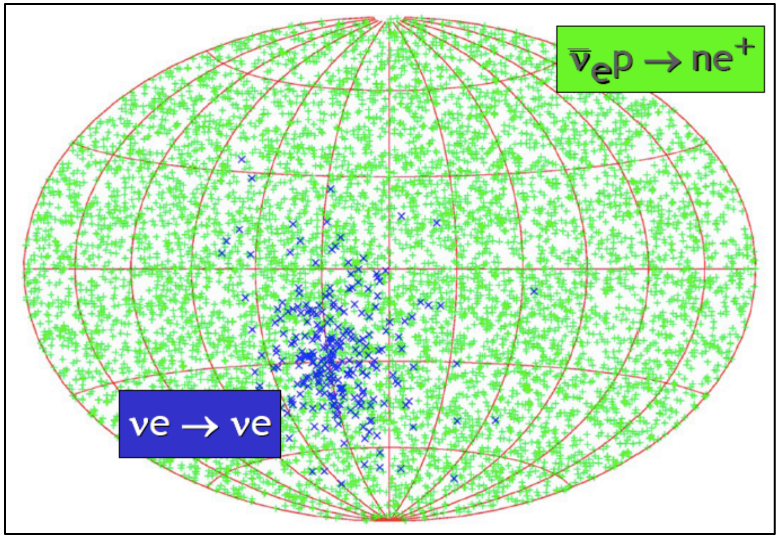
Pointing and Alerts

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

Beacom and Vogel

Tomas, Semikoz, Kachelriess, Raffelt and Dighe

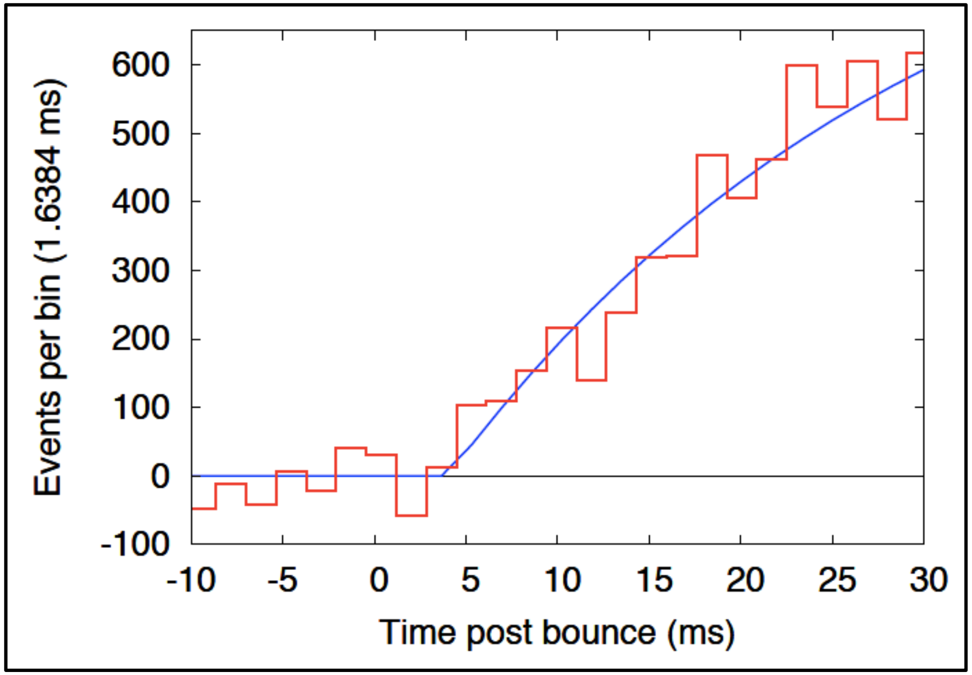


This may be crucial for dust-obscured supernovae!

Coincidence at multiple detectors will trigger an alert for astronomers

SNEWS
http://snews.bnl.gov

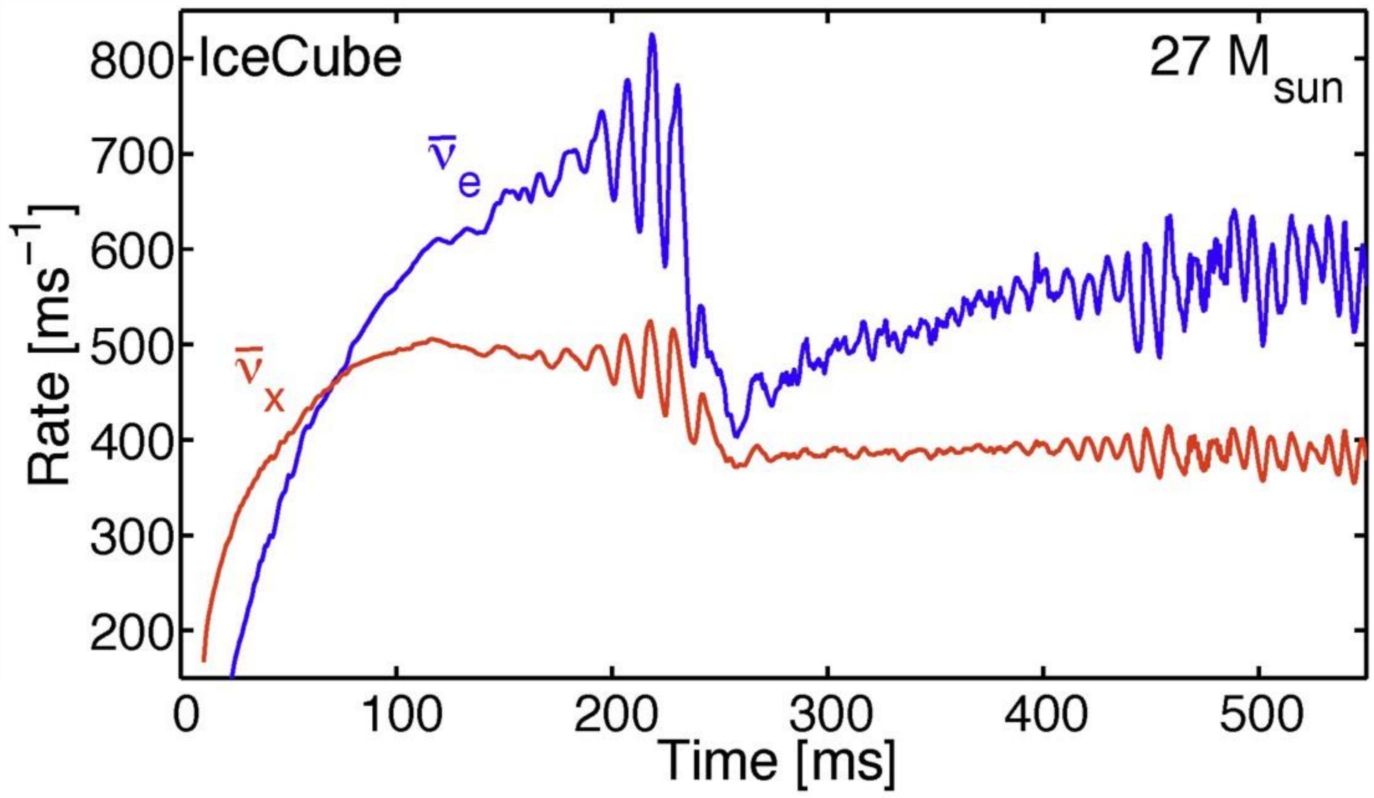
Timing



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
Halzen and Raffelt

SASI



Lund Marek Lunardini Janka Raffelt

Tamborra, Hanke, Mueller, Janka, Raffelt

Earth Matter Effects

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

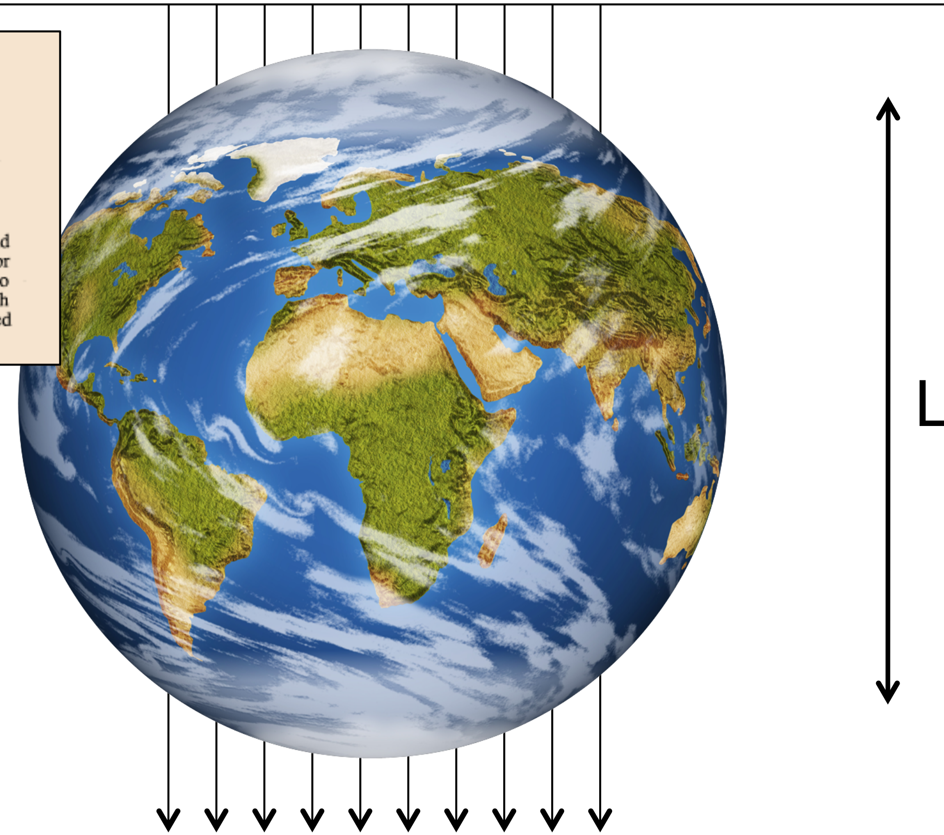
HE 5.1-4

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.



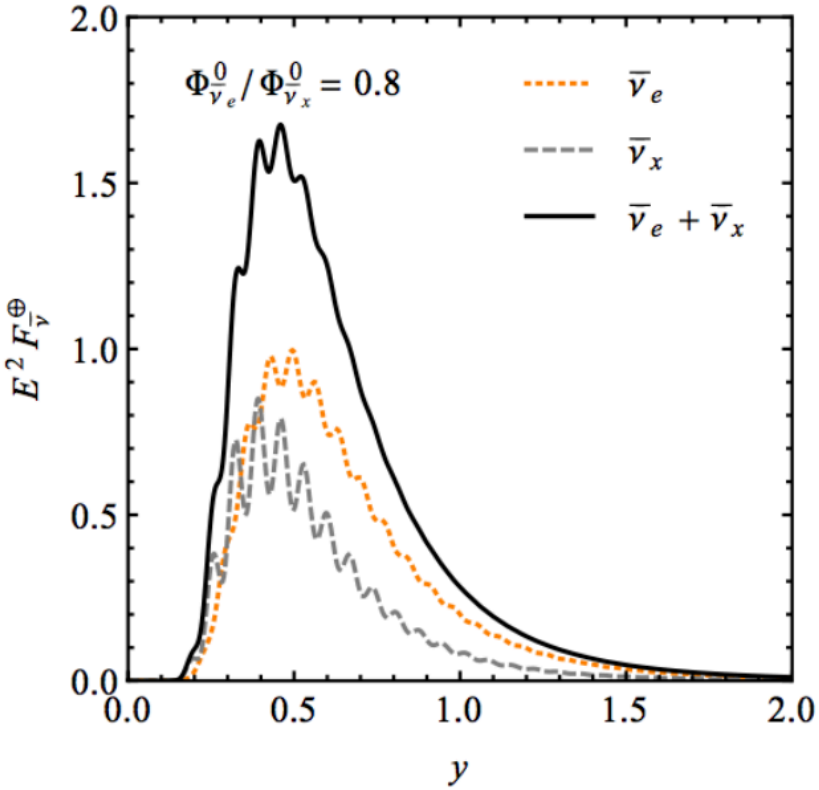
Detector Location Matters!

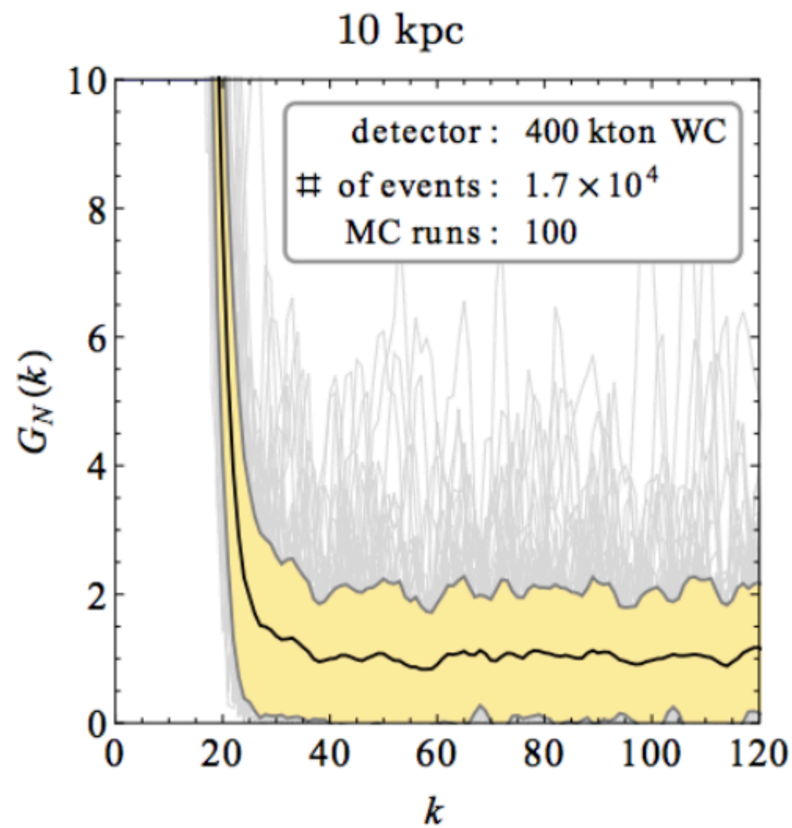
Electron flavor: = $(1-P_{2e})\,\nu_1 + P_{2e}\,\nu_2$

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

which depends on Earth density and L

Earth Matter Effects

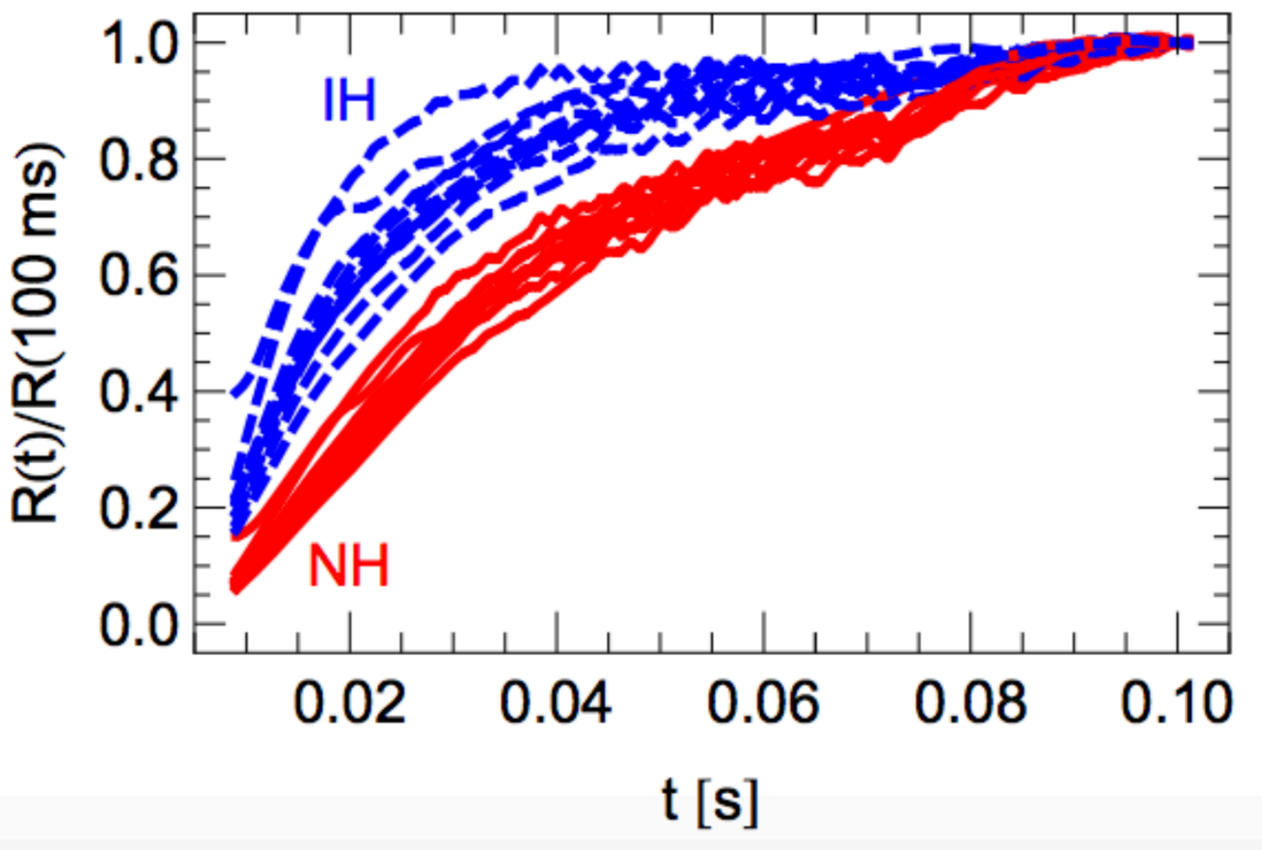




Hard to do…

Boriello, Chakraborty, Mirizzi, Serpico, Tamborra

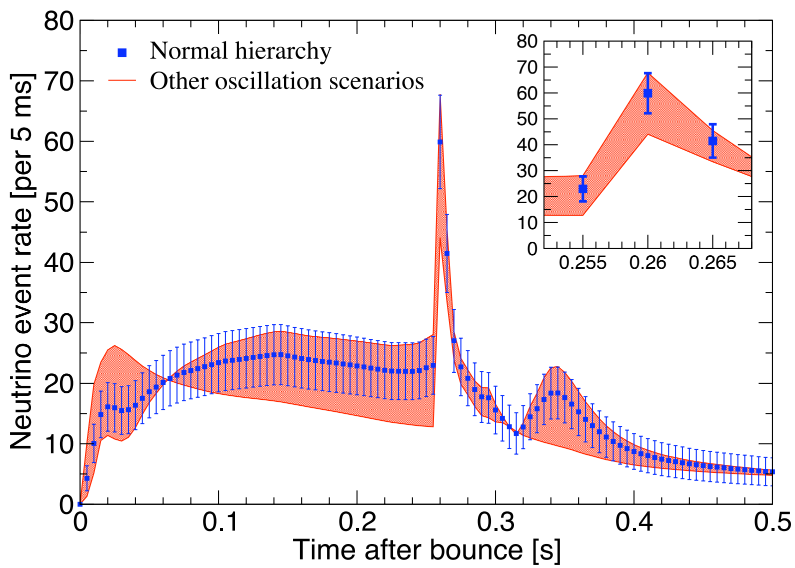
Mass Hierarchy via Risetime



Serpico, Chakraborty, Fischer, Hudepohl, Janka, Mirizzi

Look for new physics…

QCD phase transition

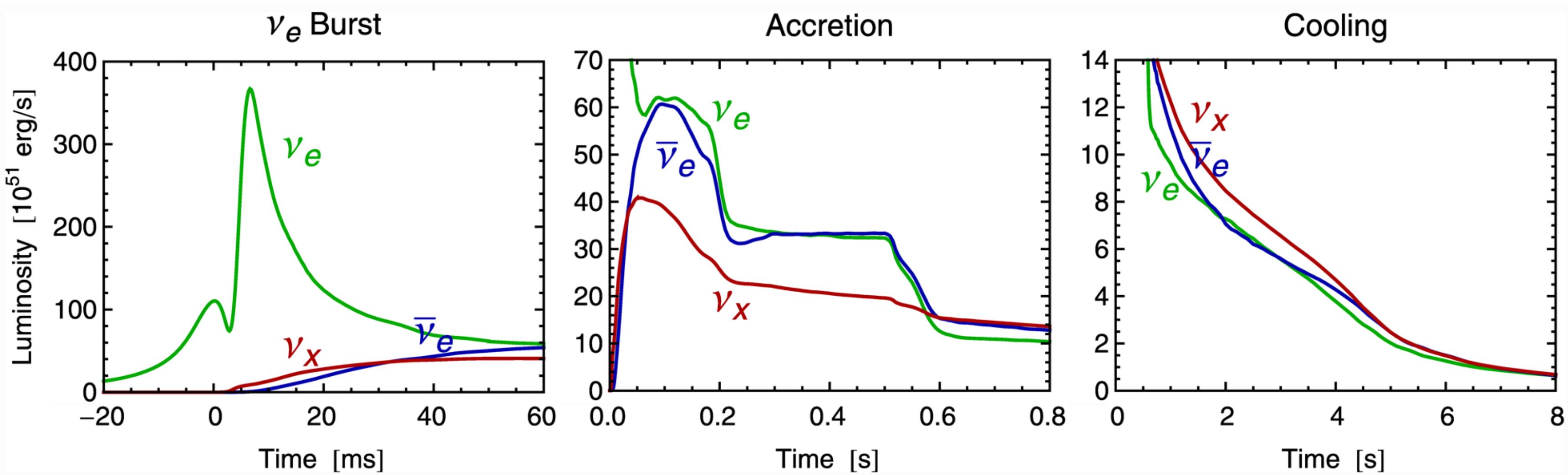


Dasgupta, Horiuchi, Mirizzi + Basel Group

Sterile Neutrinos

Arguelles, Brdar, Kopp

Opportunities & Challenges



Burst	Accretion	Cooling
SN standard candle?	Astrophysics	Nuclear physics
SN theory	Oscillation effects?	Nucleosynthesis
Timing	Shock revival?	Exotics/Axions
Mass hierarchy	Mass hierarchy?	…
…	…	