WIN 2017, Irvine

Supernova Neutrinos Theory and Future Detection

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

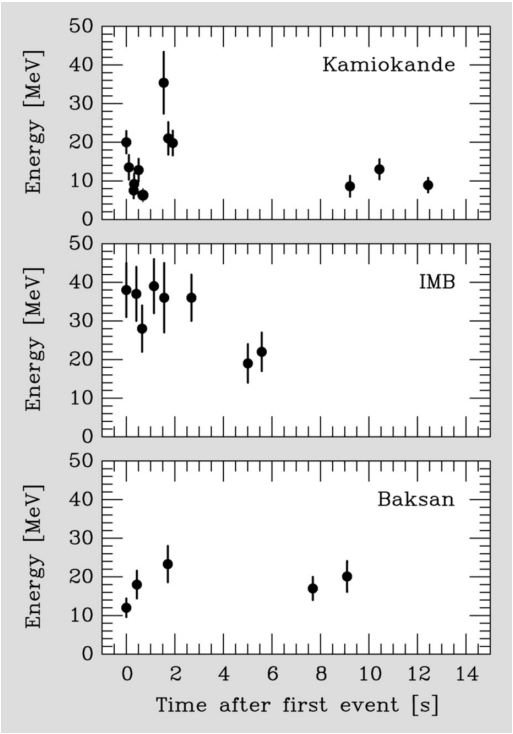
Are we ready for the next supernova?
Review of experimental facilities

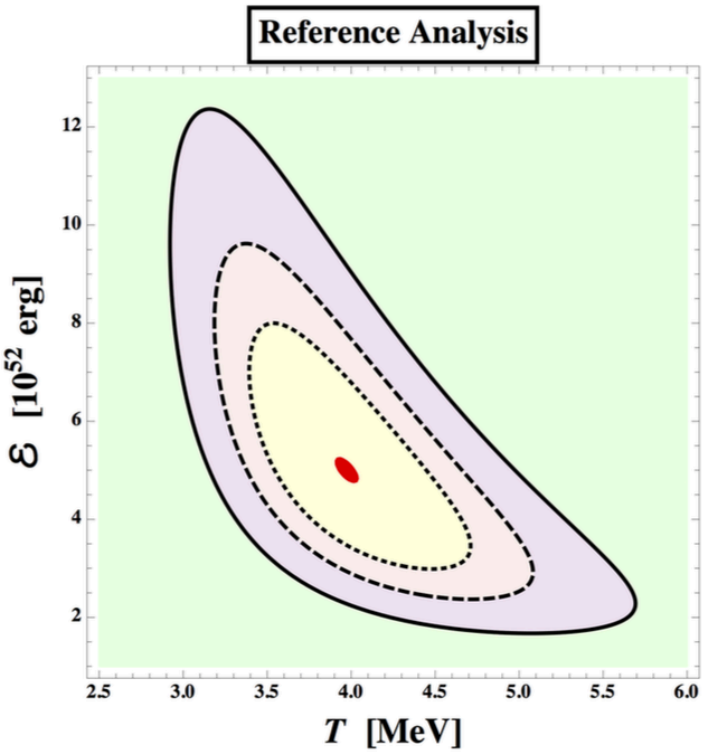
Talk by Prof. Masayuki Nakahata

See also recent review by Mirizzi, Tamborra, Janka, Scholberg (2016)

This talk is mainly about the progress in neutrino theory

What we know





Review by Vissanni (2014)

Average Neutrino Energy = 12 MeV +/- 10%

Total Energy in anti-nue = 5 x 10^{52} erg +50% - 20%

SUPERNOVA PHYSICS

SN Theory

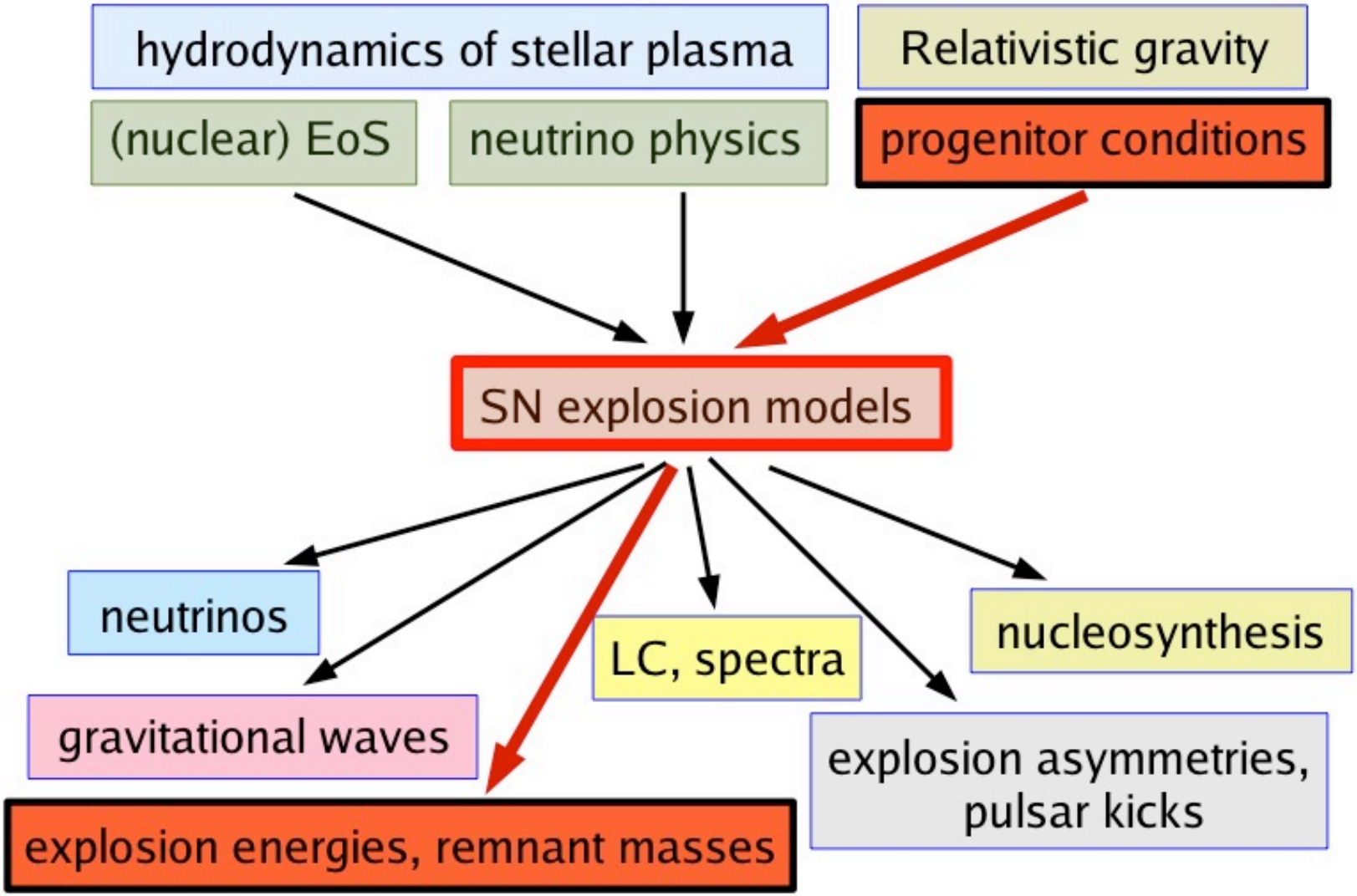
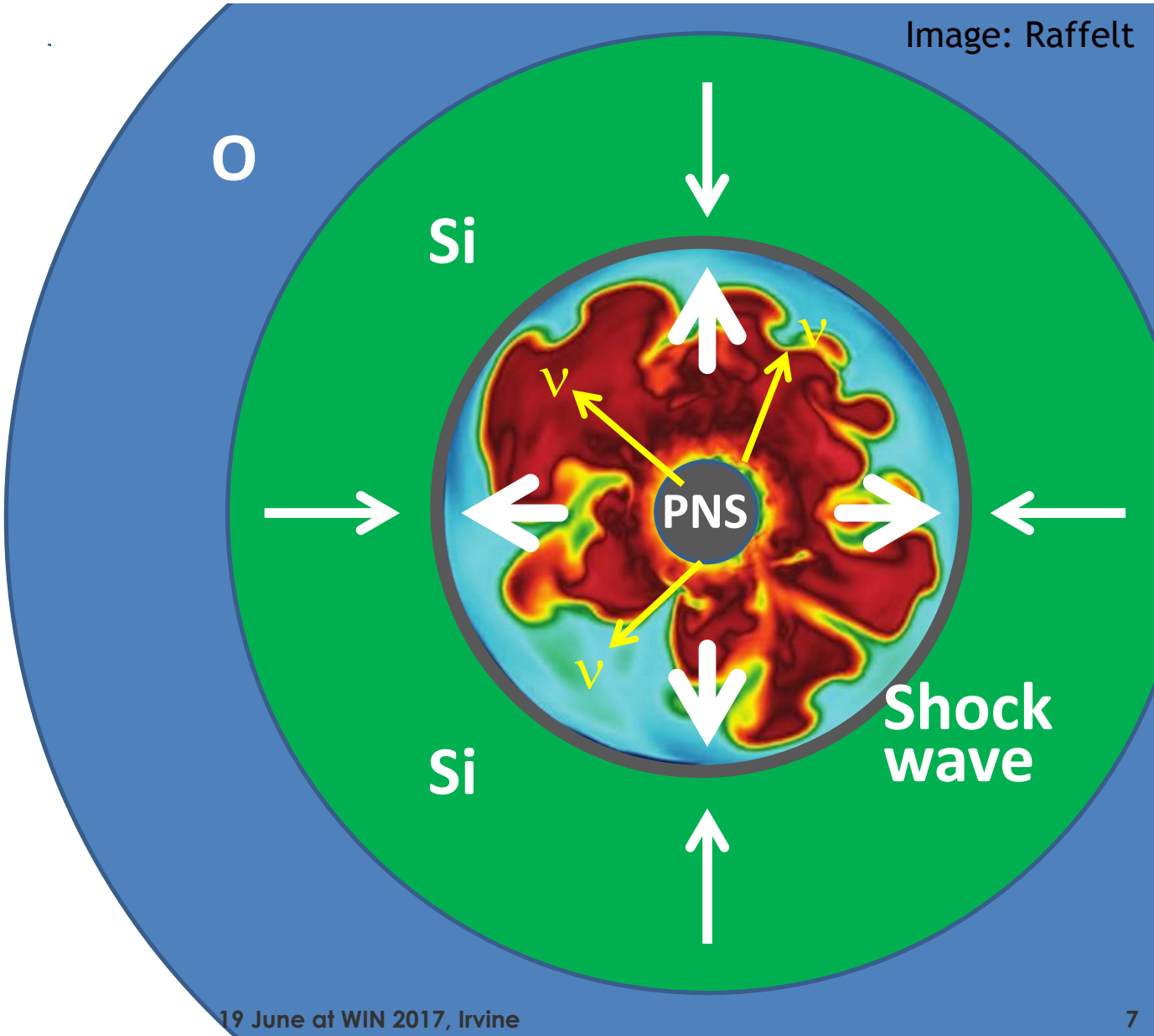
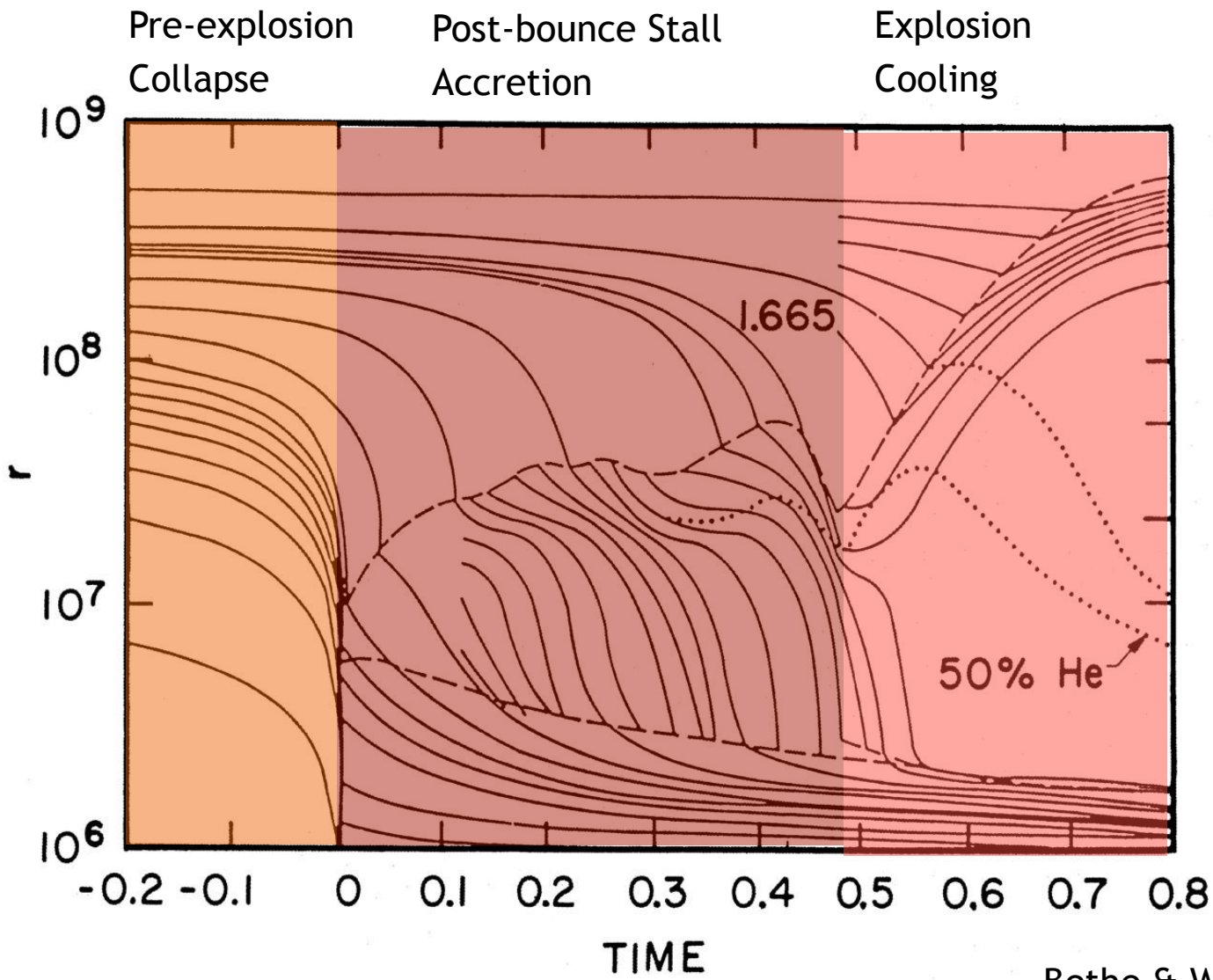


Image:Janka

Neutrino Mechanism

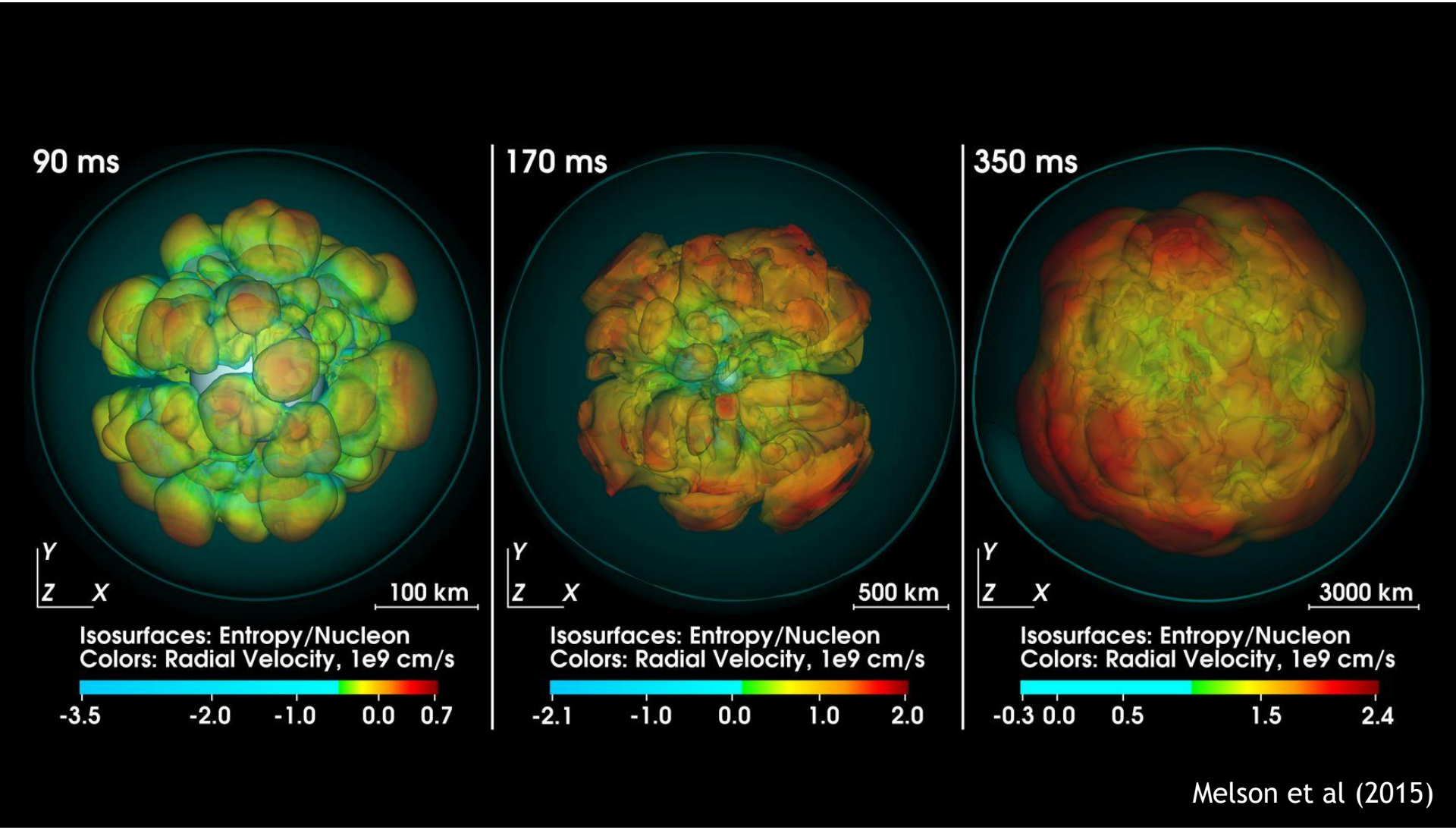


Delayed Explosion



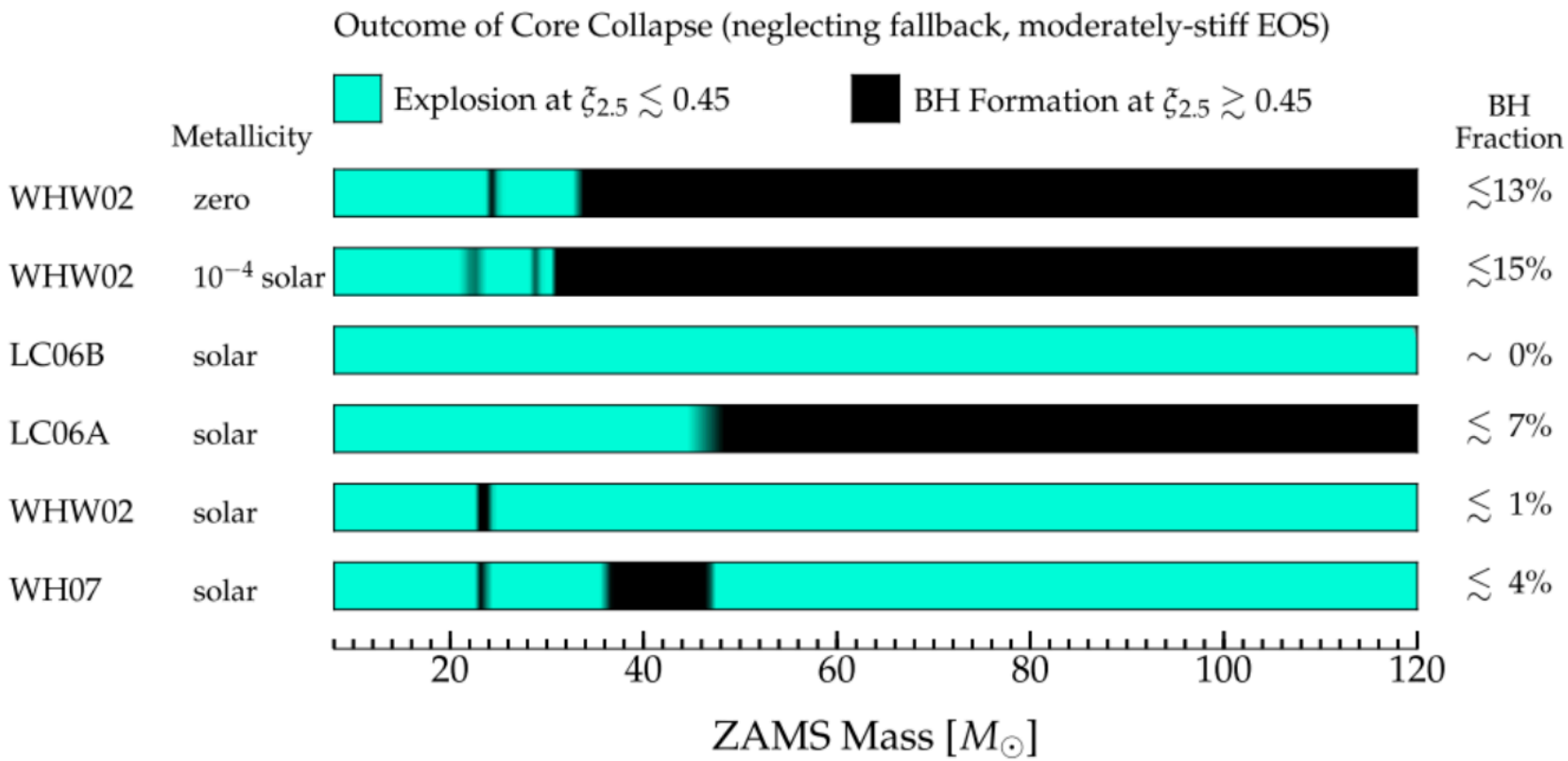
Bethe & Wilson (1985)

3D Explosions



Melson et al (2015)

Failed SN

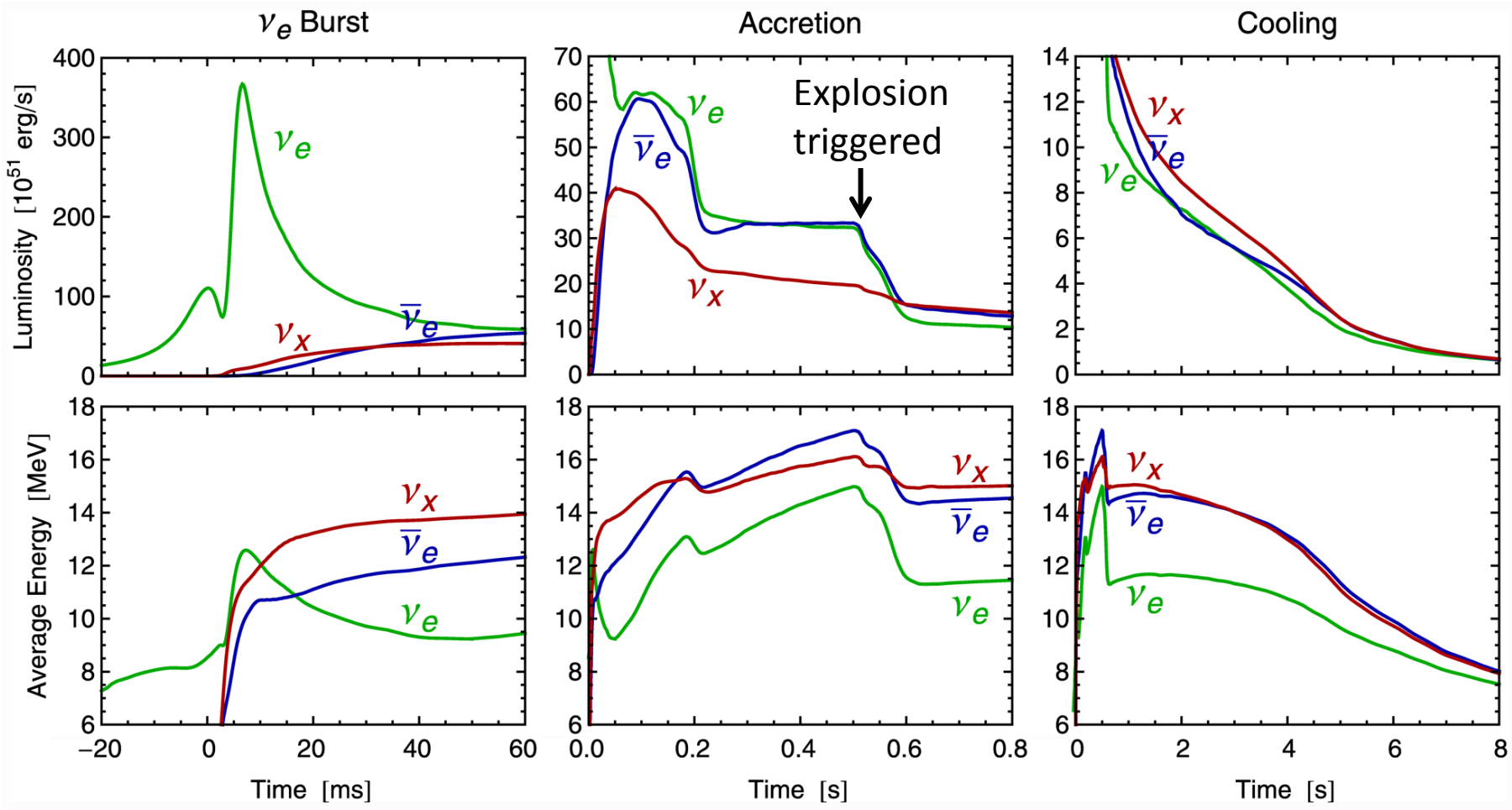


Ott and O'Connor (2011)
Horiuchi et al (2014) …

The Road Ahead

- Systematic 3D simulations and code-comparisons
- Full momentum-space of neutrinos
- Oscillations? (or other “exotic” physics)

Luminosity and Temperature



Garching group simulation of a 27 solar mass SN in 1d

NEUTRINO PHYSICS

Formalism

QFT

Helicity flipping?
Magnetic field due to flow of matter?
Mean field?

-> Boltzmann Eq.

Collisions end before oscillations start
Approximations of convenience

-> Vlasov Eq.

Raffelt and Sigl
Pehlivan, Balantekin Kajino (2011)
Vlasenko, Fuller, Cirilgliano (2013,2014)
Vaanaanen and Volpe (2014), Serrau and Volpe (2014)
Kartavtsev, Raffelt, Vogel (2015)

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**

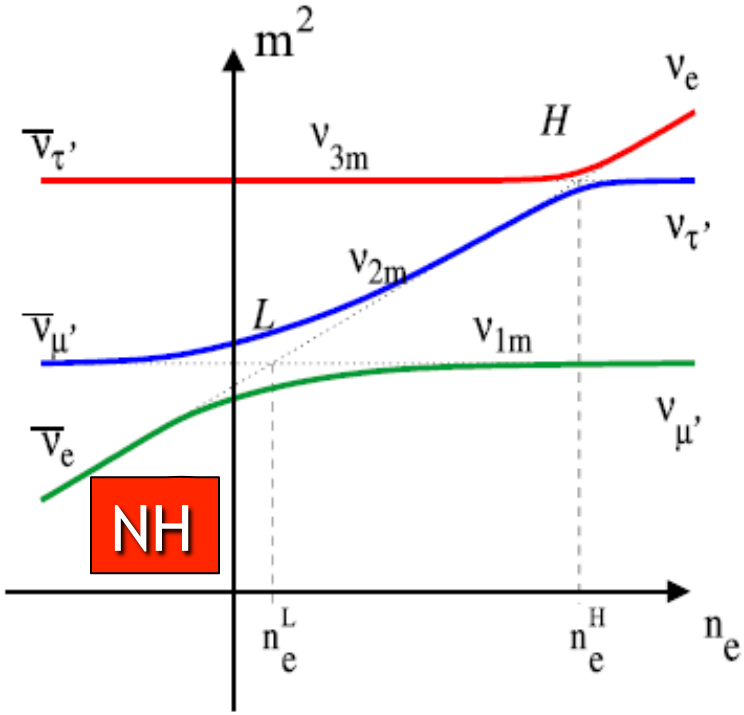
MSW effect depends on ordinary matter density L, i.e. mainly electron density

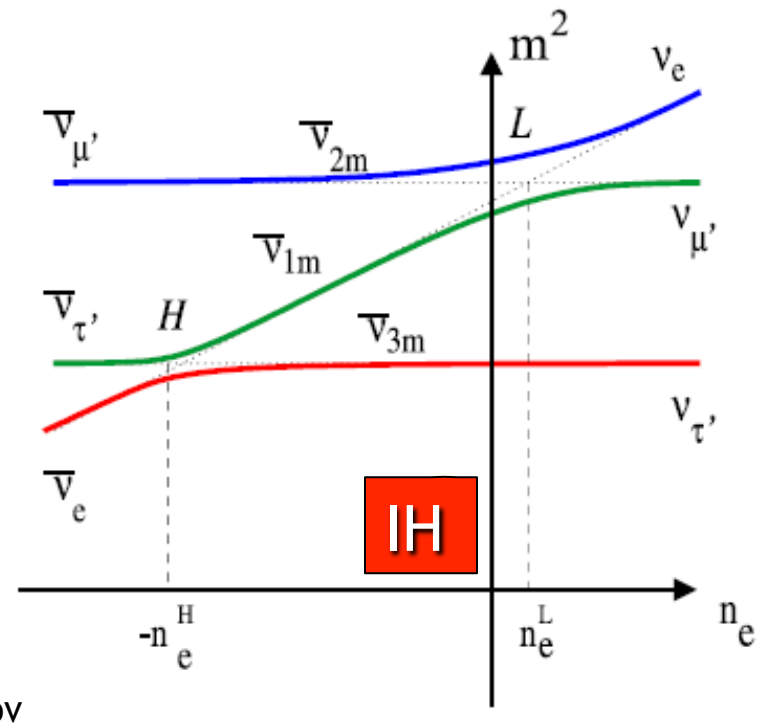
Nonlinear Effects depends on the neutrino density ρ

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 : ν_1 ν_2

(Δm_{sol}^2 , θ_{12}) at 10^1 - 10^2 g/cs

Always in neutrinos

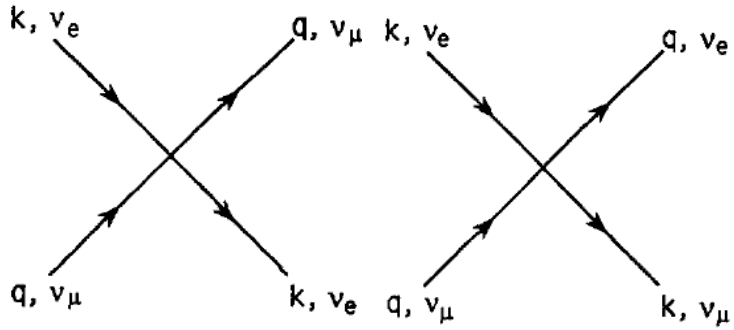
H resonance : ν_1/ν_2 ν_3

(Δm_{atm}^2 , θ_{13}) at 10^3 - 10^4 g/cc

In neutrinos for NH and in antineutrinos for IH.

These effects occur at r~500 km or more

Neutrino-Induced Potential



Two neutrinos forward-scattering off each-other can exchange flavor

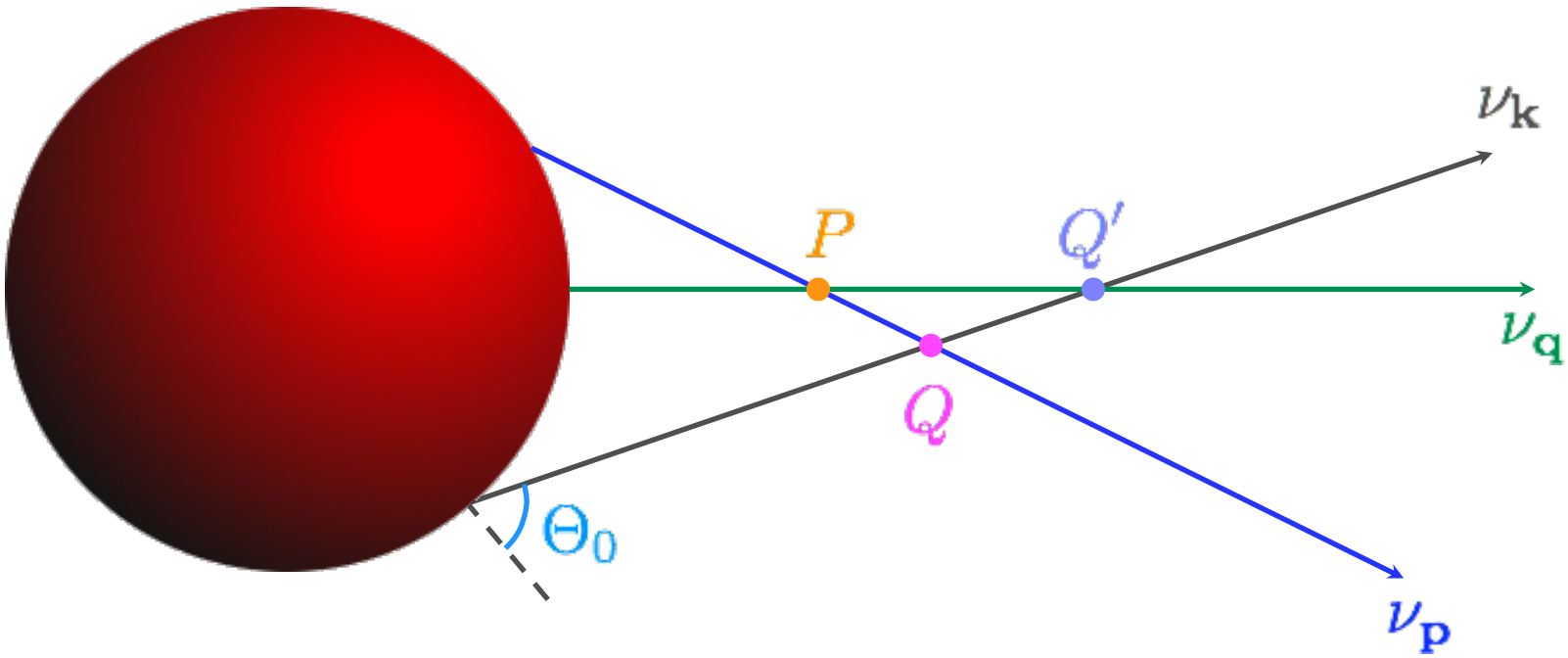
$$i\frac{d}{dt}\begin{vmatrix} |\nu_e(\boldsymbol{k})\nu_e(\boldsymbol{q})\rangle \\ |\nu_e(\boldsymbol{k})\nu_\mu(\boldsymbol{q})\rangle \\ |\nu_\mu(\boldsymbol{k})\nu_e(\boldsymbol{q})\rangle \\ |\nu_\mu(\boldsymbol{k})\nu_\mu(\boldsymbol{q})\rangle \end{vmatrix} = V_2 \begin{vmatrix} |\nu_e(\boldsymbol{k})\nu_e(\boldsymbol{q})\rangle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

where

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

Pantaleone (1992)

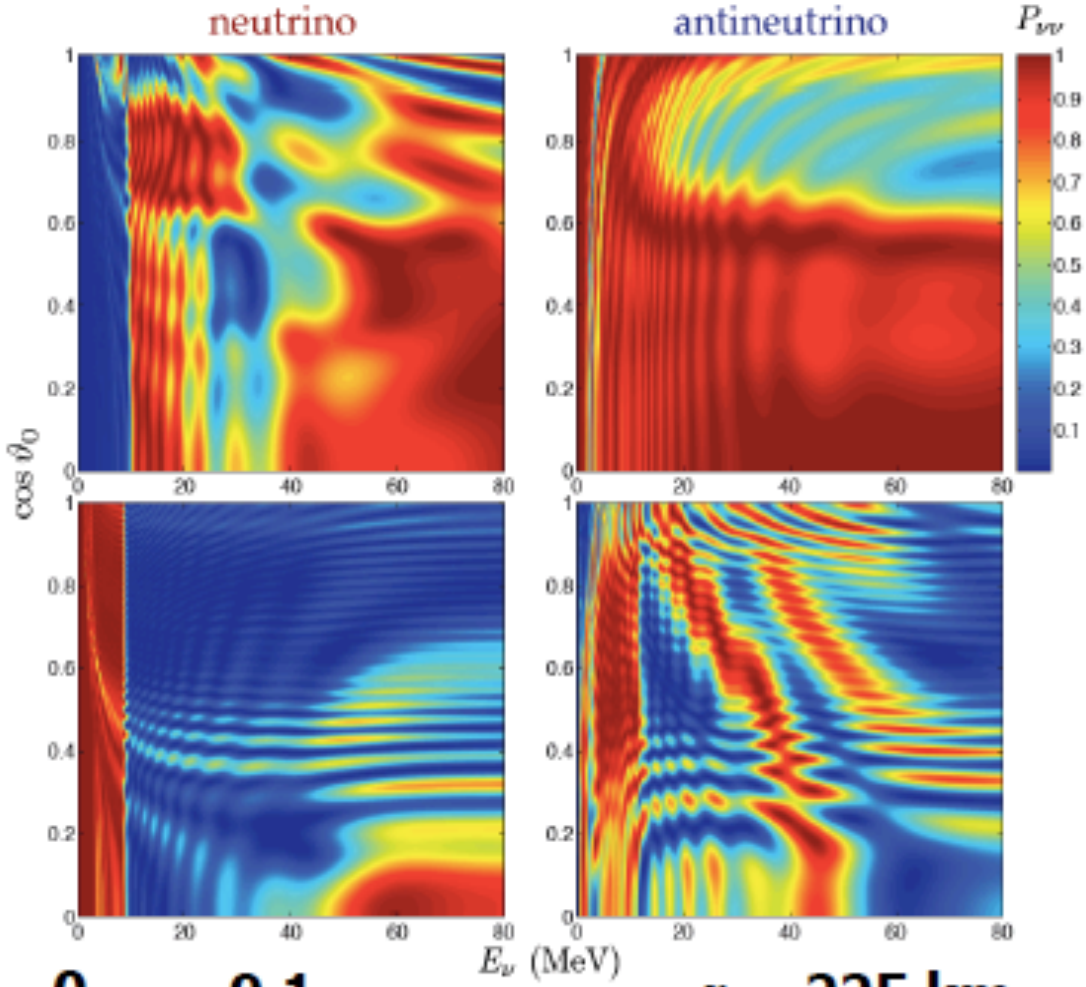
Many-Body Physics



Flavor histories of all neutrinos get coupled

Image: Duan

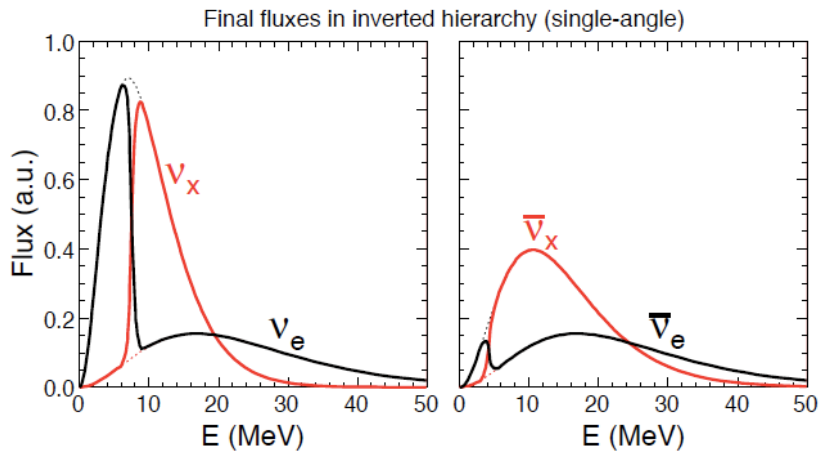
Collective Effects

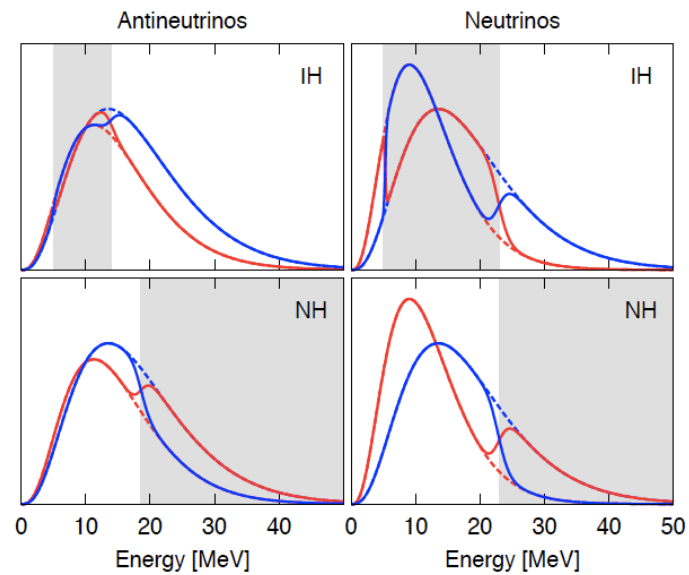


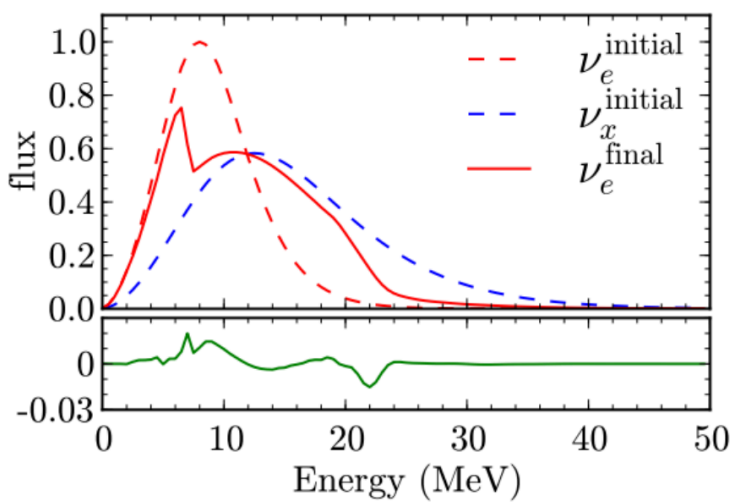
$\theta_{13} \sim 0.1$ $r \sim 225$ km

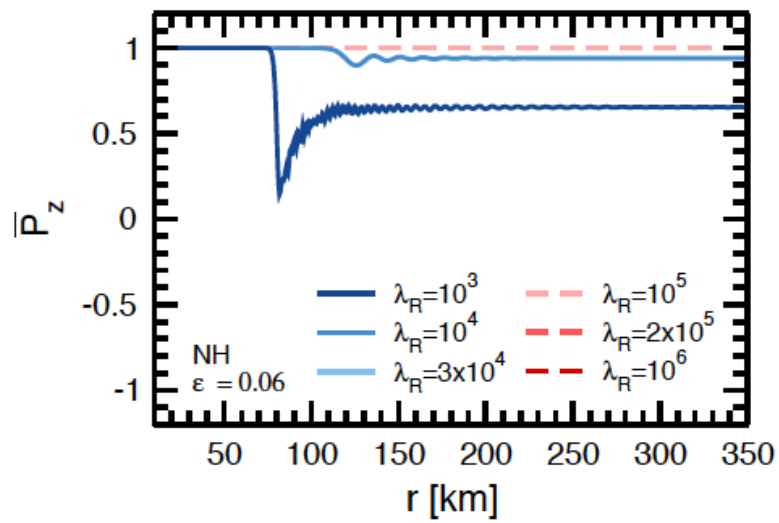
Duan, Fuller, Carlson, and Qian (2005-06)
See review by Duan, Fuller, Carlson, and Qian

Many Interesting Effects









Lot of work in 2005-2010

More than 100 papers on collective effects by:

AbaZajian, Adams, Balantekin, Banerjee, Beacom, Bell, Blennow, Carlson, CapoZZi, Chakraborty, Cherry, Choubey, Dasgupta, DeGouvea, Dighe, Dolgov, Duan, Esteban-Pretel, Fogli, Friedland, Fuller, GaVa, Giles, Hannestad, Hansen, IZaguirre, Kneller, Kostelecky, Lisi, Lunardini, Marrone, McLaughlin, MiriZZi, Pantaleone, Pastor, Pehlivan, Qian, Raffelt, Samuel, Sarikas, Serpico, SemikoZ, Seunarian, Shalgar, Sigl, Smirnov, Stodolsky, Tomas, Vogel, Volpe, Wong...(and you?)

All these effects take place at r~200 km

Linear Stability Analysis

Banerjee, Dighe, and Raffelt (2010)

$$\varrho_{\omega,v_z,\varphi} = \frac{1}{2}\mathrm{Tr}(\varrho_{\omega,v_z,\varphi})\,\mathbb{I} + \Phi_\nu \frac{g_{\omega,v_z,\varphi}}{2}\begin{pmatrix} s_{\omega,v_z,\varphi} & S_{\omega,v_z,\varphi} \\ S^*_{\omega,v_z,\varphi} & -s_{\omega,v_z,\varphi} \end{pmatrix}$$

Off-diagonal part of density matrix = Not flavor eigenstate

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

Look at just the growth of this off-diagonal part

Breaking Spacetime Symmetries

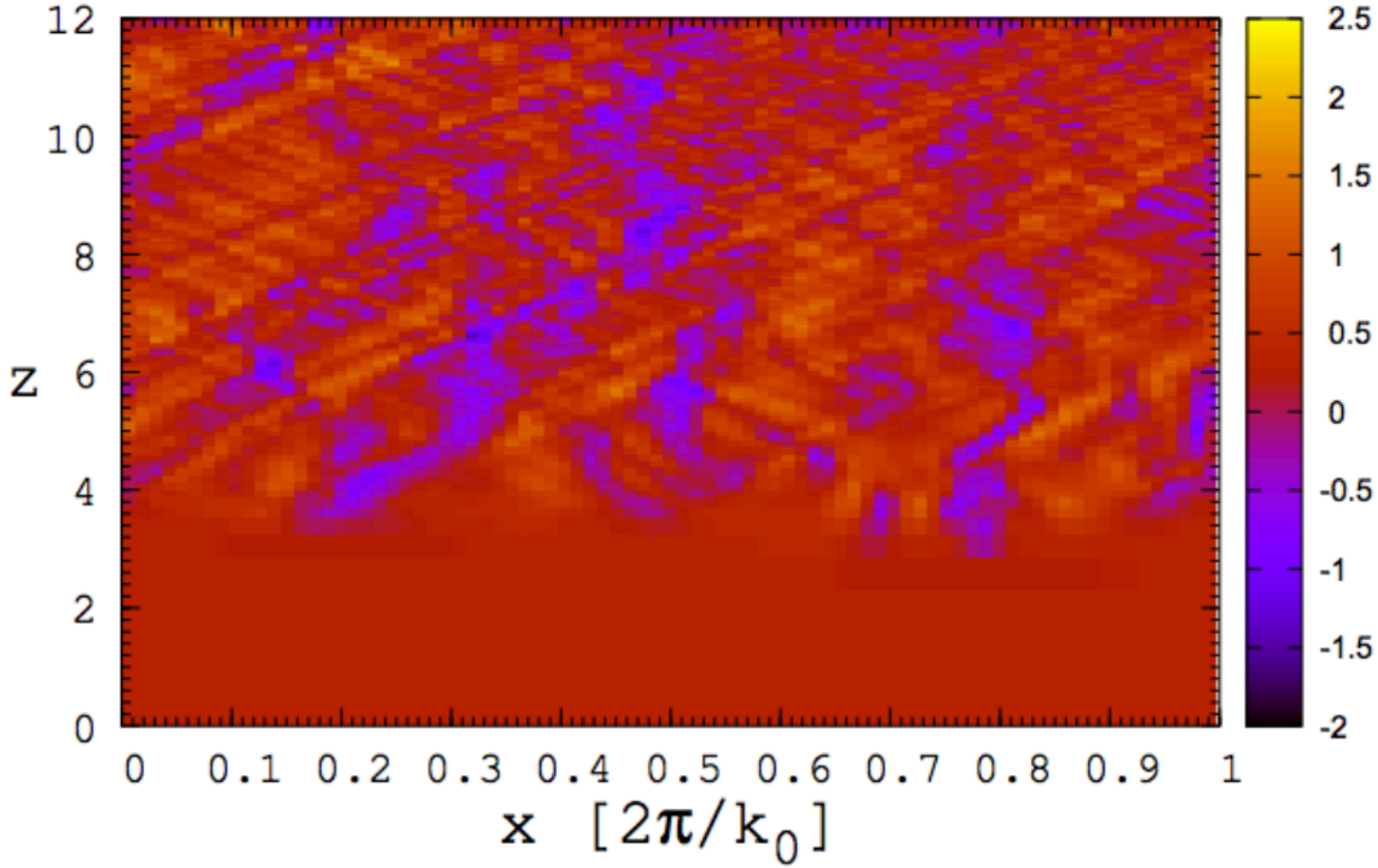
$$i\partial_r \to i(\partial_t + \mathbf{v} \cdot \nabla)$$

- Solution can depend on time
- Solution can depend on angular coordinates even if the source is approximately spherical

Think of the off-diagonal component as a field over x and t

$$S(t, \mathbf{x}) \to Q(\omega, \mathbf{k})$$

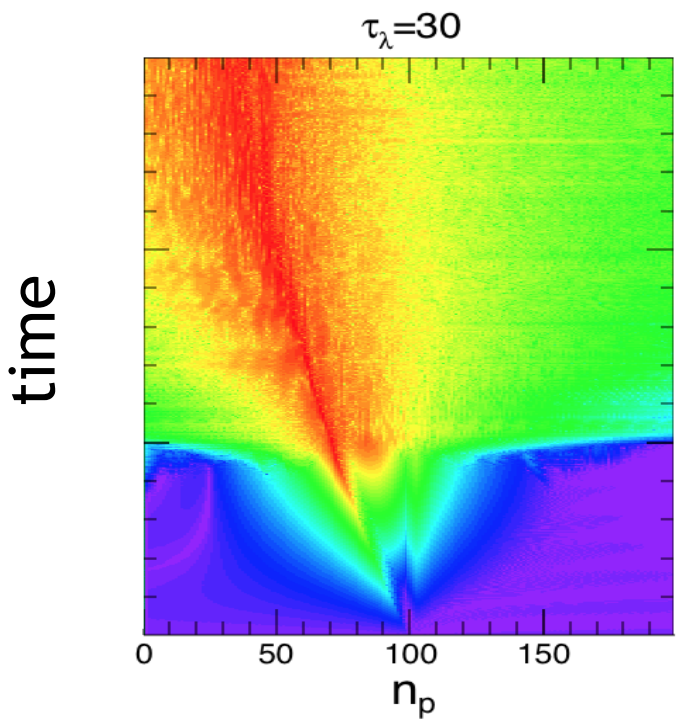
Inhomogeneity

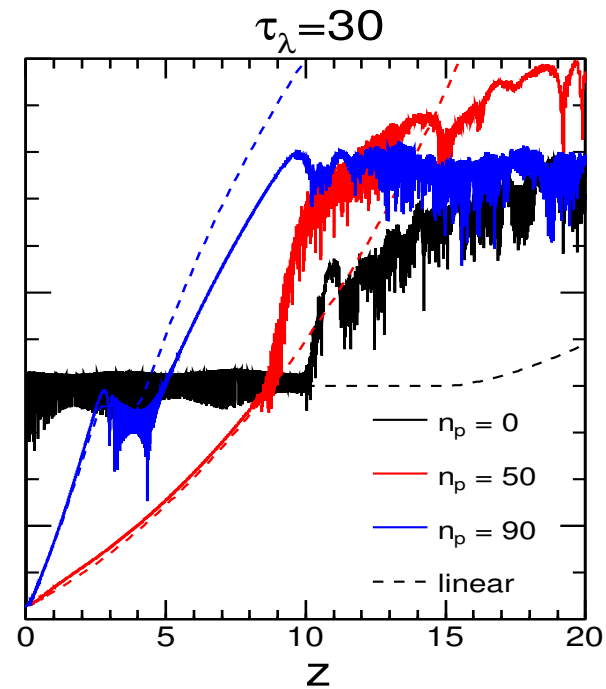


Small inhomogeneities grow larger

Mirizzi, Mangano, Saviano (2014)
Duan and Shalgar (2015)

Nonstationarity





Instability starts as a small pulsating seed, and cascades down to a large steady instability

Duan and Abbar (2015)
Dasgupta and Mirizzi (2015)
Capozzi, Dasgupta, Mirizzi (2016)

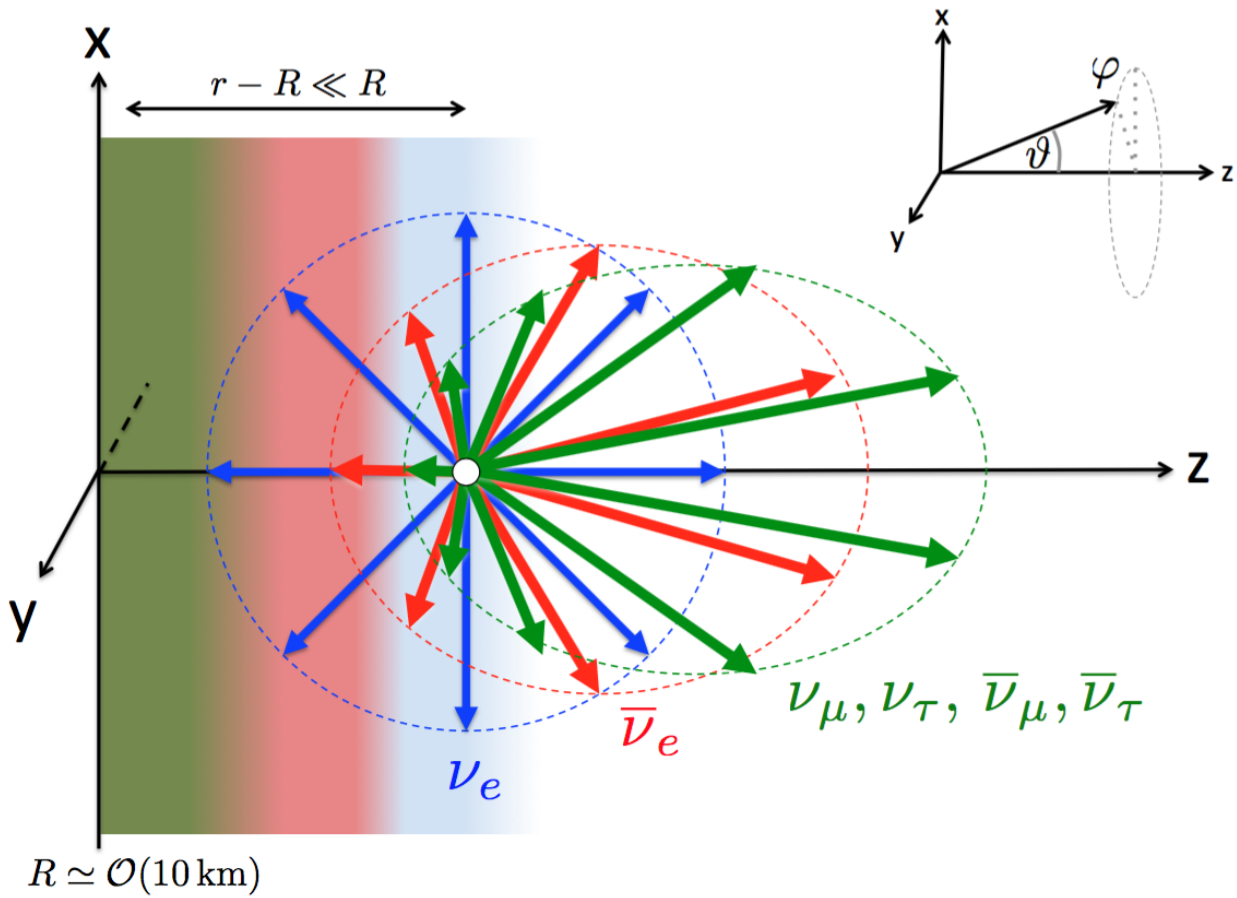
Fast Conversion

Neutrinos change flavor within a few cm or at most a meter from their emission region because of nontrivial angular distribution of neutrinos

Emphasized since 2005 by Ray Sawyer, but clearly understood only in the past few years

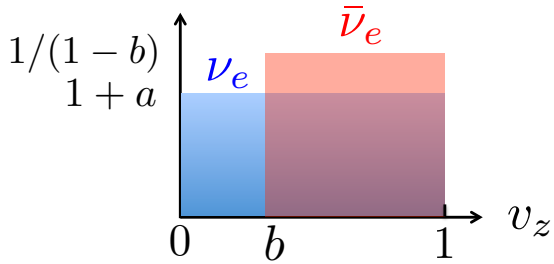
Several papers by R. Sawyer (2005, 2008, 2015)

Why Fast Conversion?

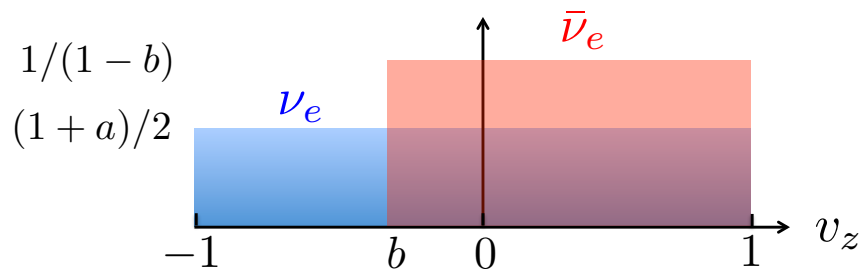


Crossing and Back-flux

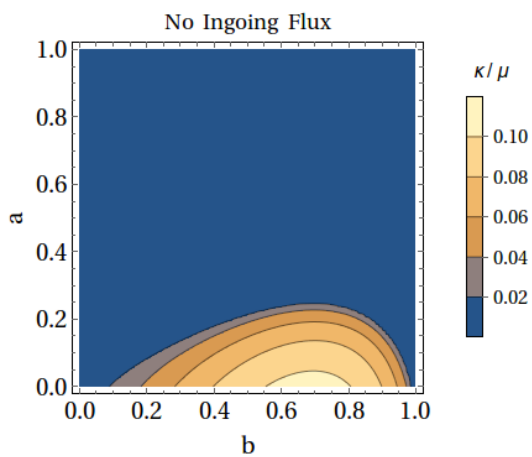
Chakraborty, Hansen, Izagguire, Raffelt (2016)
Dasgupta, Mirizzi, Sen (2016)

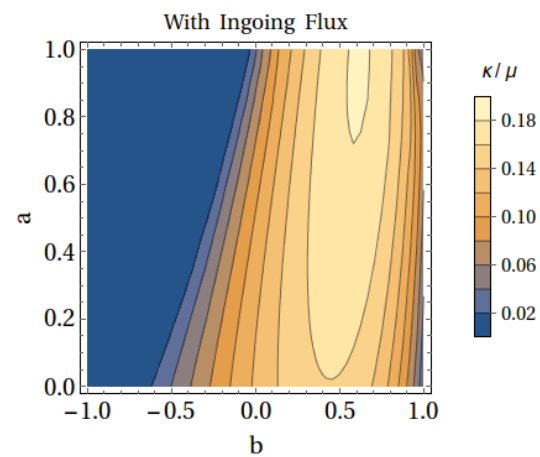


No backward flux



Has backward flux

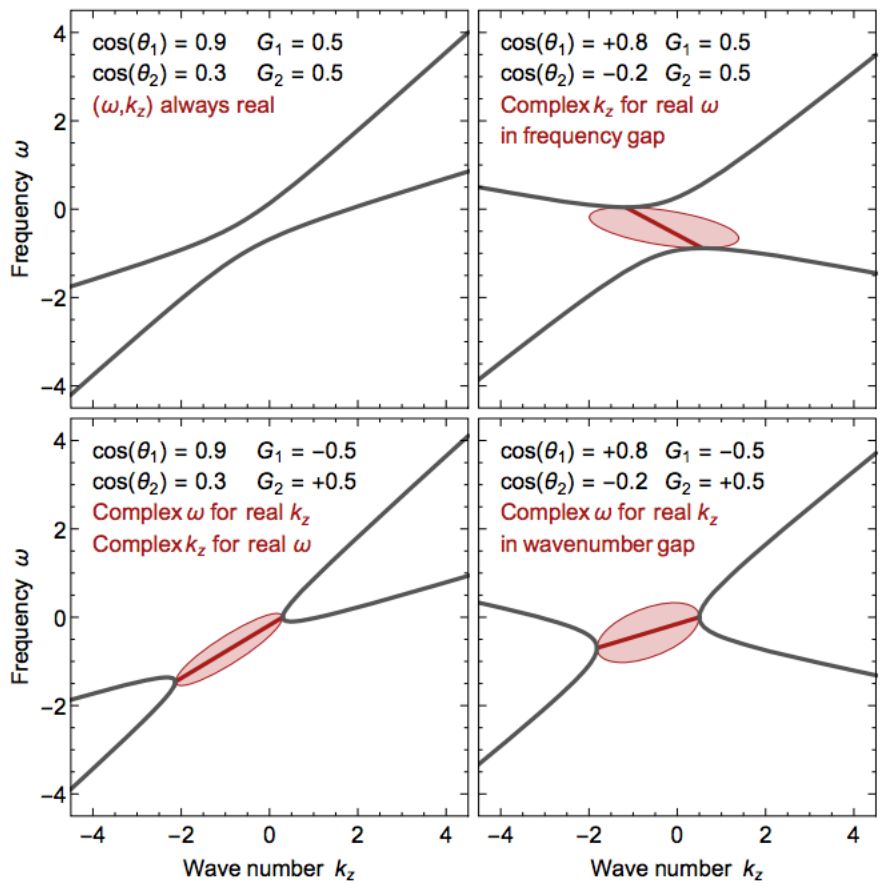




Stronger Instability

Talk by Mirizzi

Dispersion Relations



Some combinations of

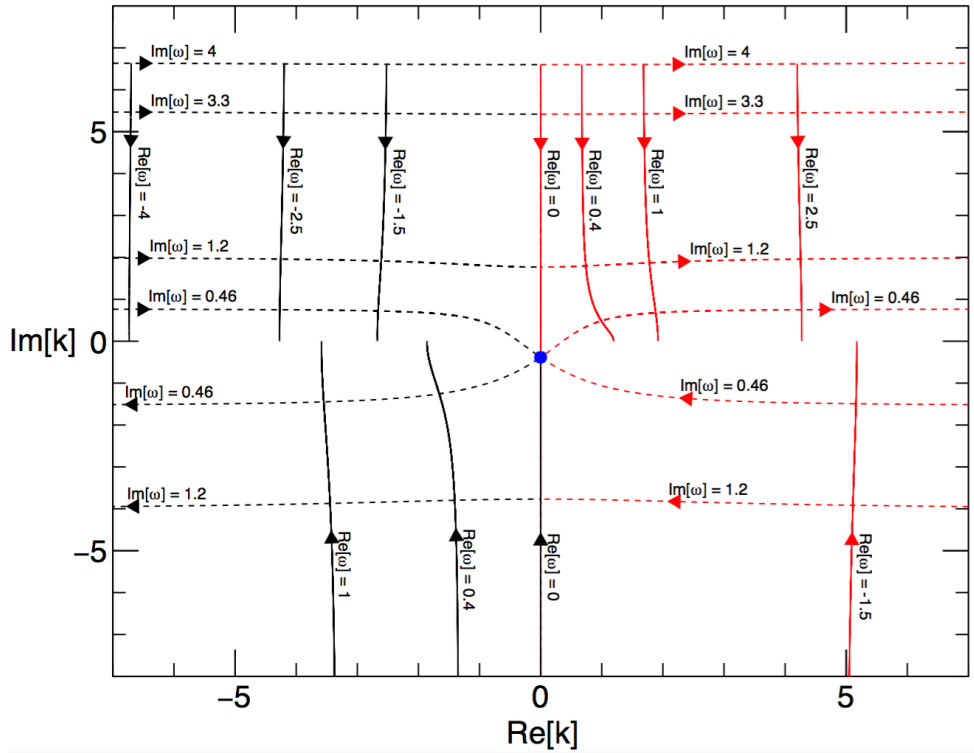
$$(\omega,\ \mathbf{k})$$

not allowed to propagate

Are these all instabilities?

Izagguire, Raffelt, Tambora (2016)

Instability Theory



Detailed understanding of the complex analytic structure of poles of the dispersion relation gives the instabilities

Capozzi, Dasgupta, Lisi, Marrone, Mirizzi (2017)

Work in Progress

Should we worry about fast conversions impacting the SN explosion process itself?

Probably yes.

Do fast conversion happen inside the “core”?

Probably not.

Dasgupta and Sen (2017, to appear)

SN NEUTRINO PHENOMENOLOGY

DSNB

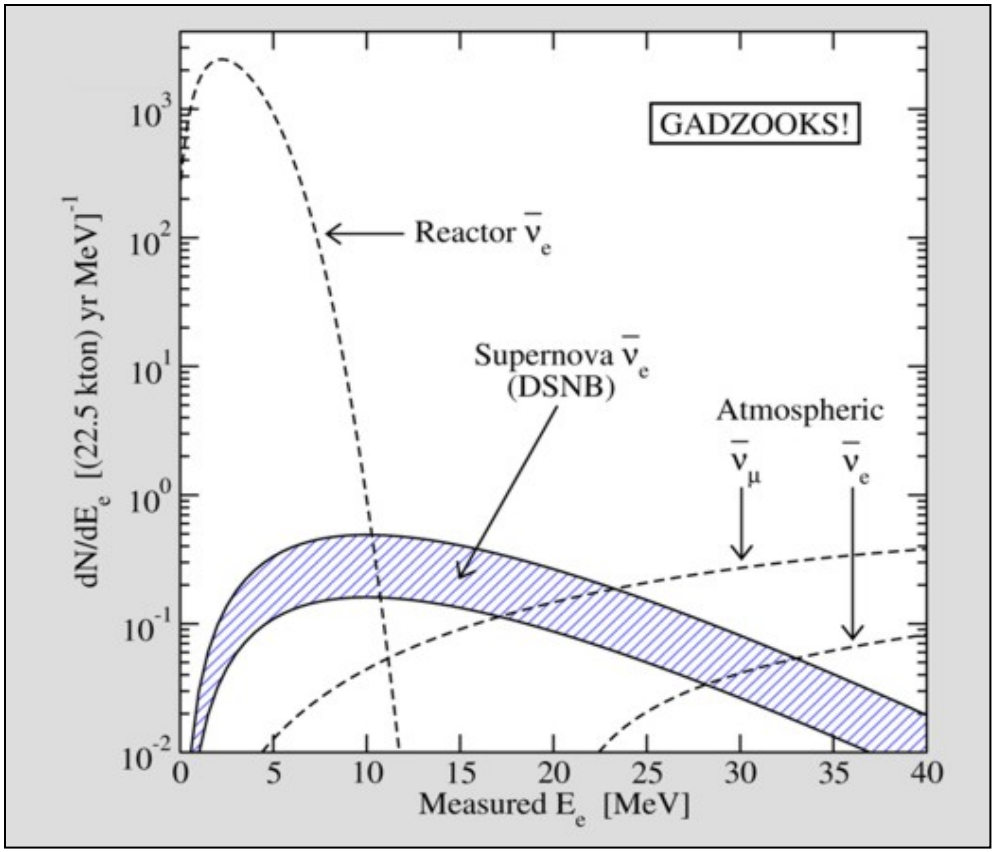
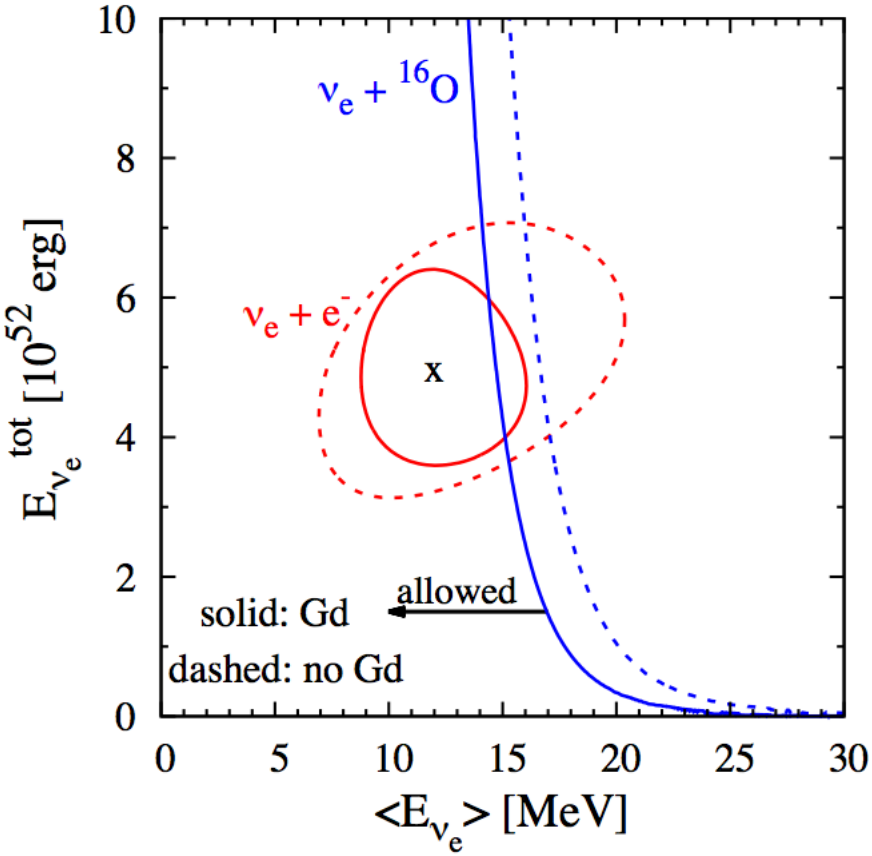


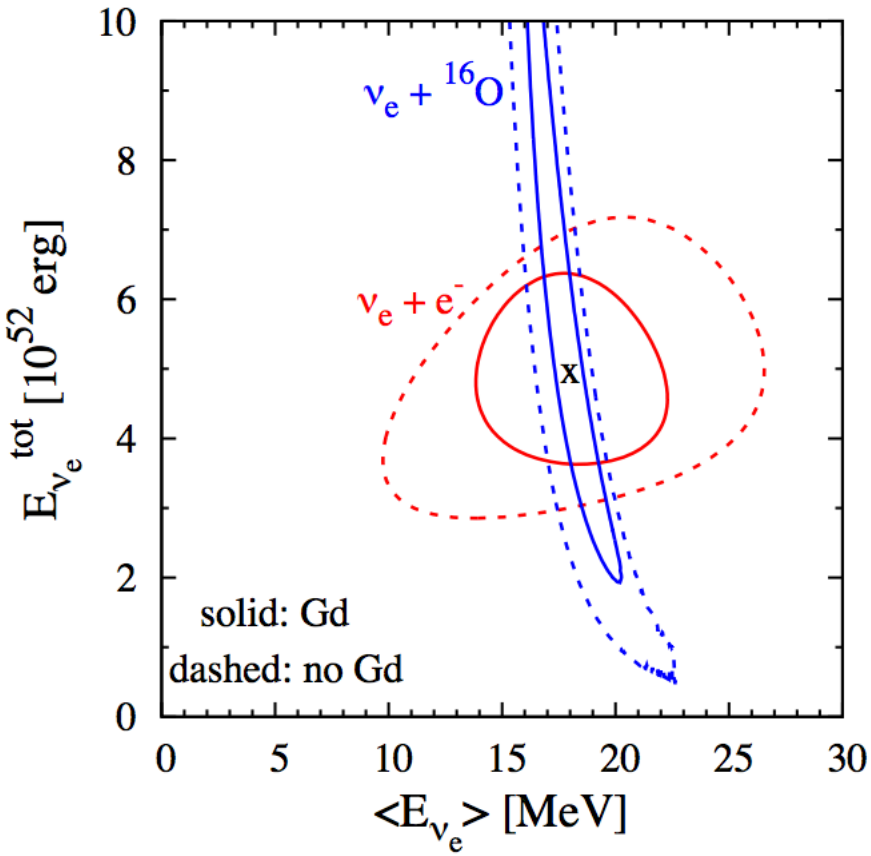
Image: Beacom & Vagins

Coming soon to a detector near you?

See reviews by Beacom and Lunardini

Electron Neutrinos in Super-K

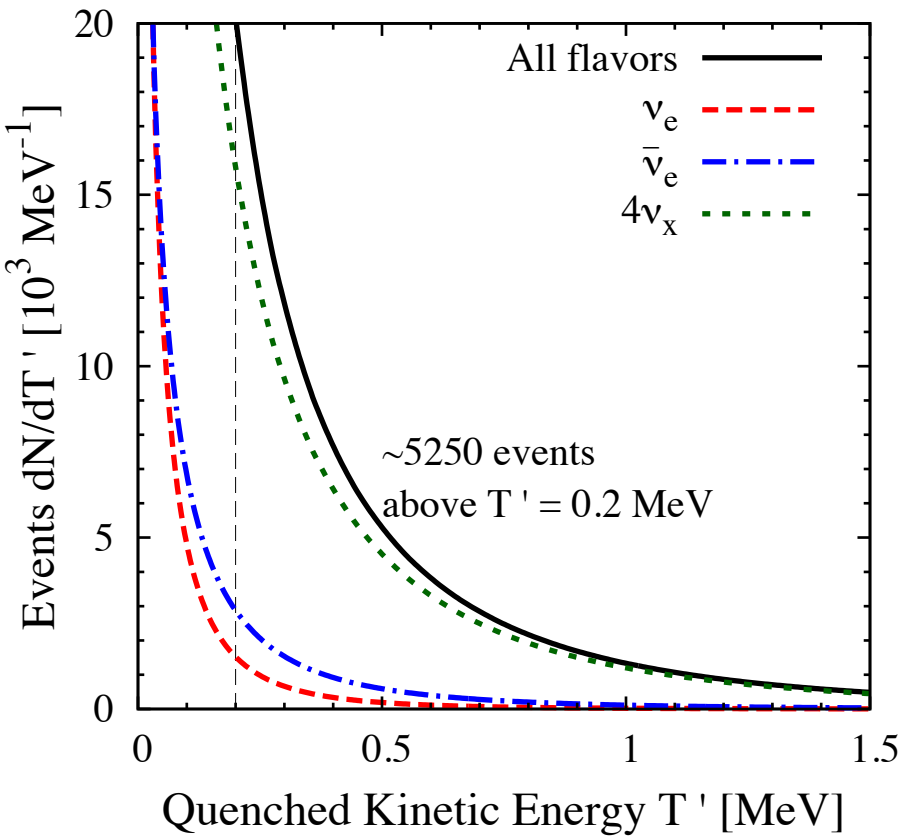




If energies on higher side, inelastic reactions very useful

Laha and Beacom (2015)

Non-electron Neutrinos

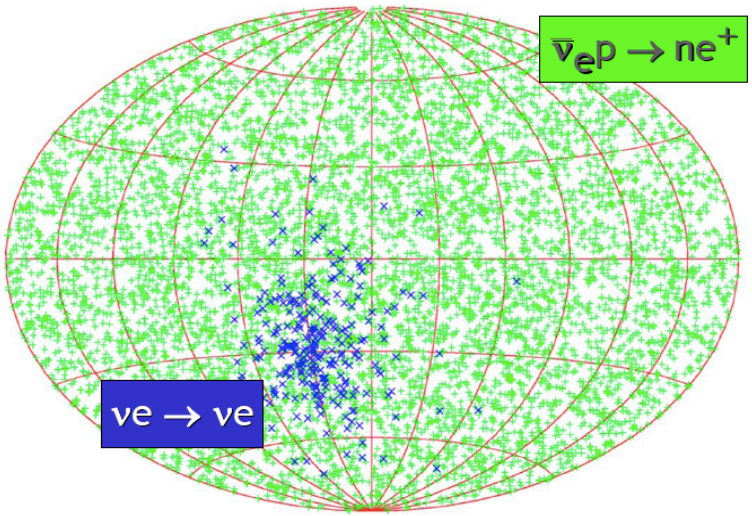


At large upcoming liquid scintillator detectors, e.g., JUNO, RENO

Need low threshold, good energy resolution to detect the neutrino-proton elastic scattering

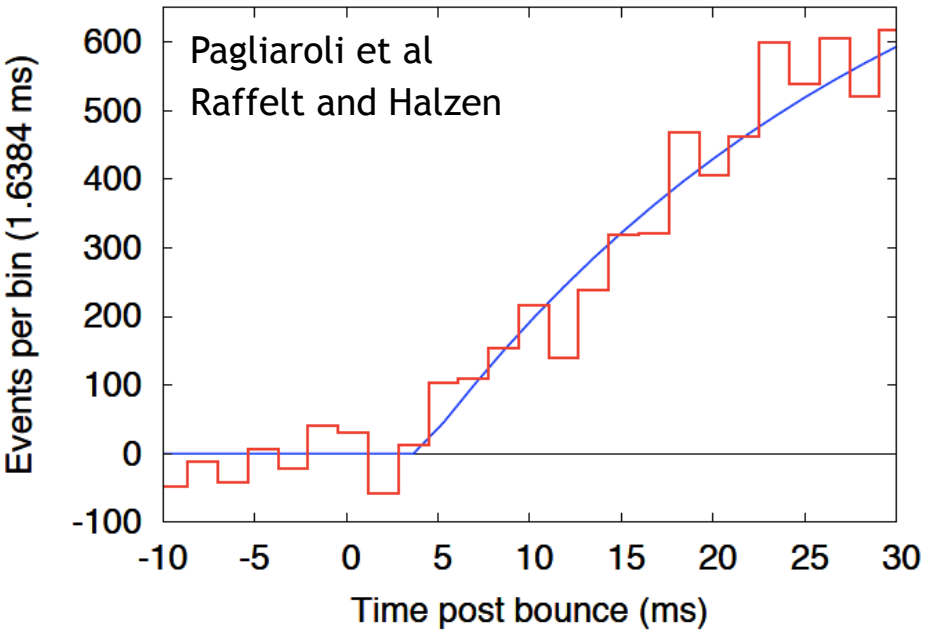
Beacom, Farr, Vogel
See also Dasgupta and Beacom (2010)

Pointing, Timing, and Alerts



Pointing within 5 degrees

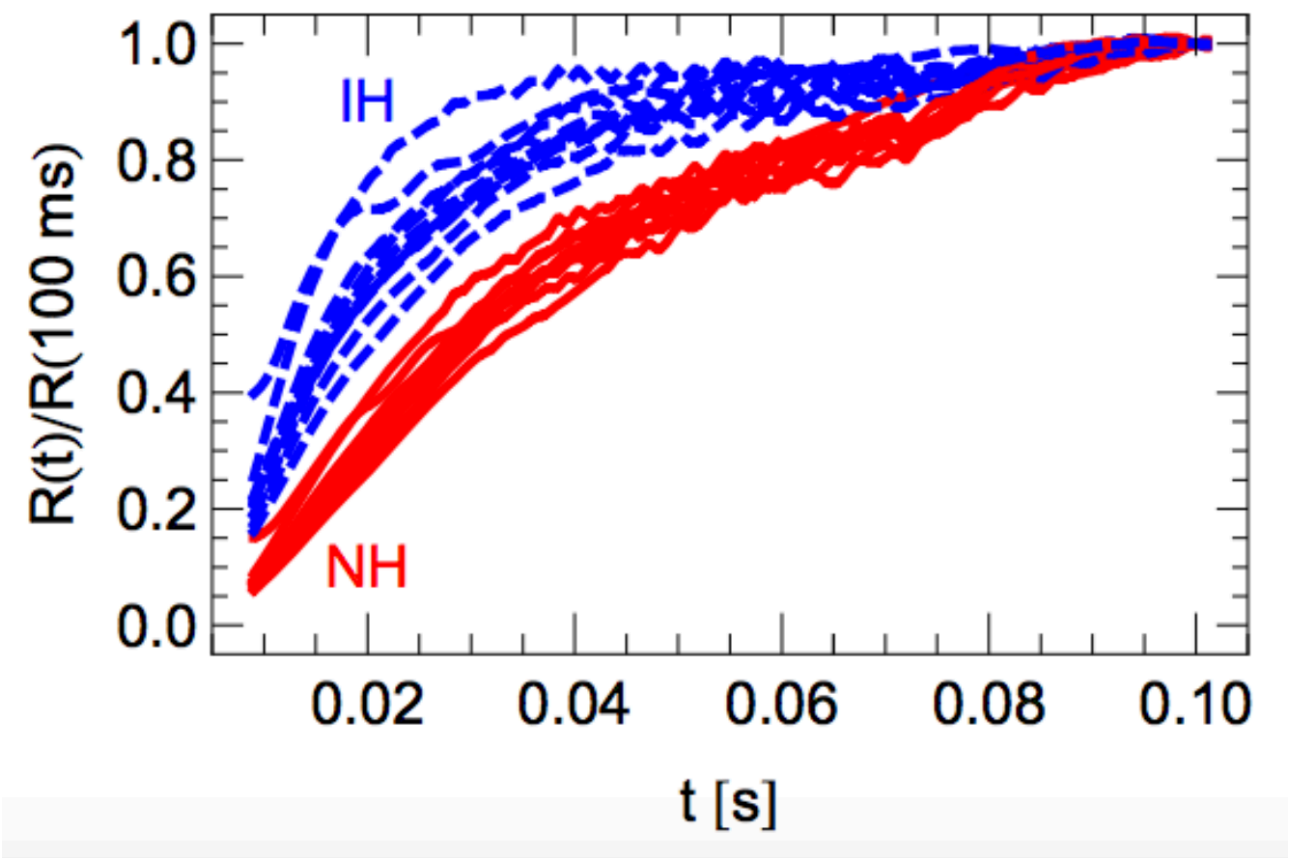
Beacom and Vogel
Tomas et al



Timing within 3 ms

SNEWS
http://snews.bnl.gov

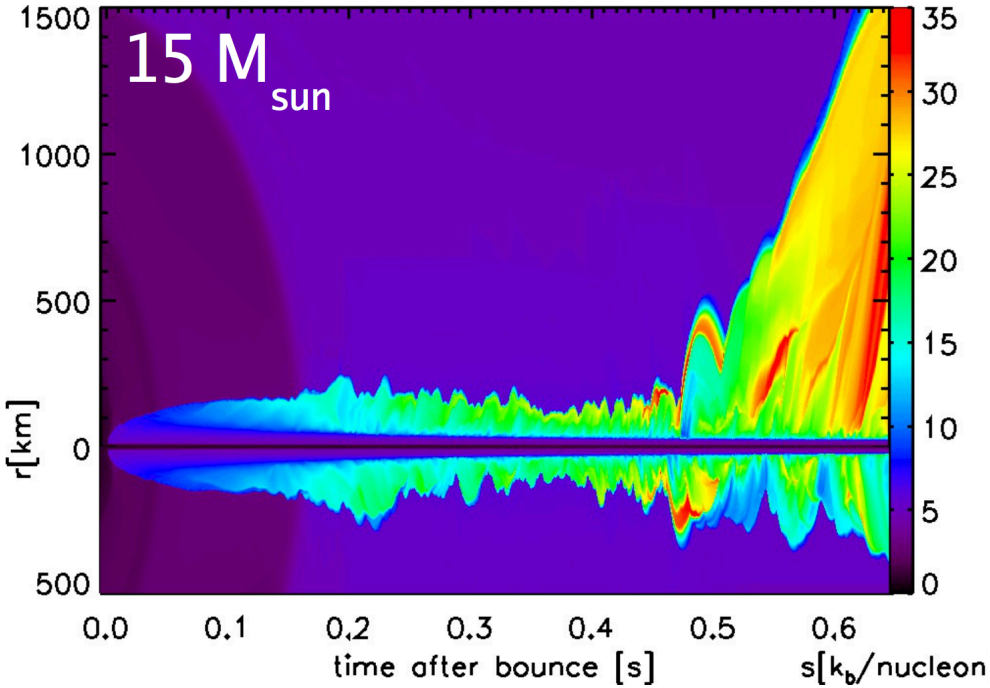
Mass Hierarchy from Risetime

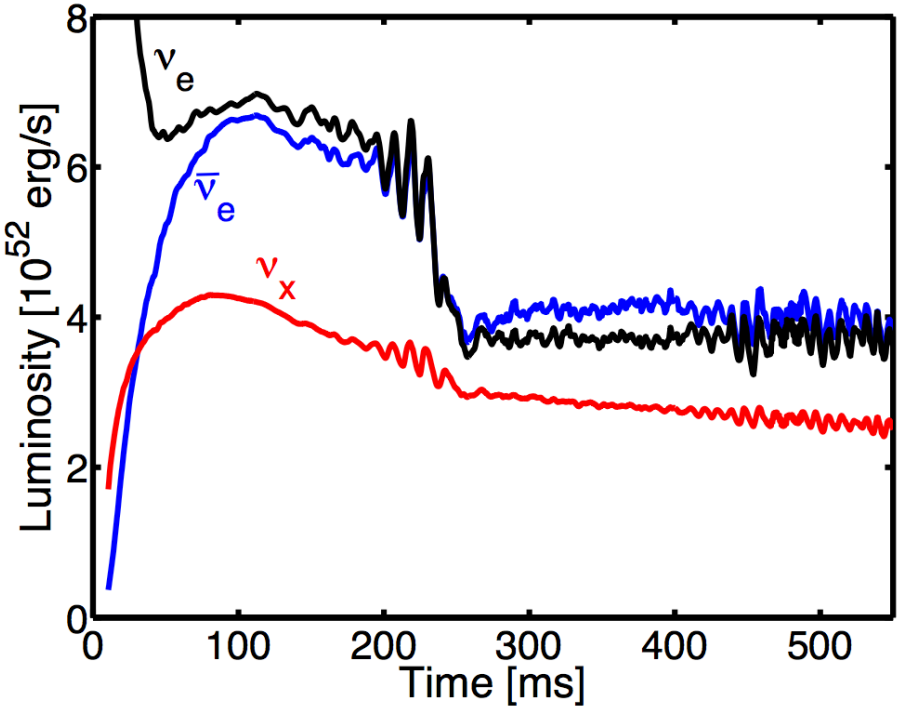


Signal rises faster for Inverted Hierarchy

Serpico et al (2012)

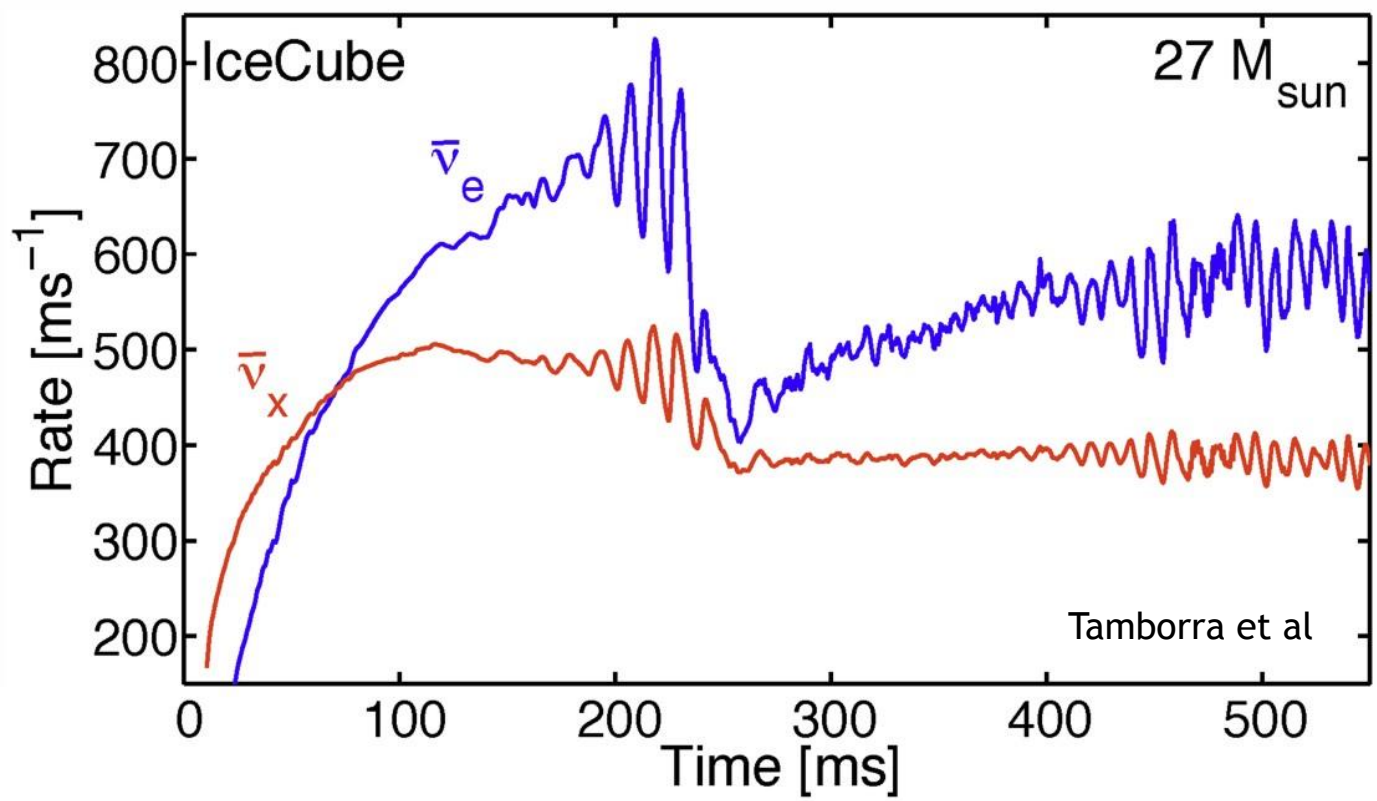
Hydrodynamic Instability





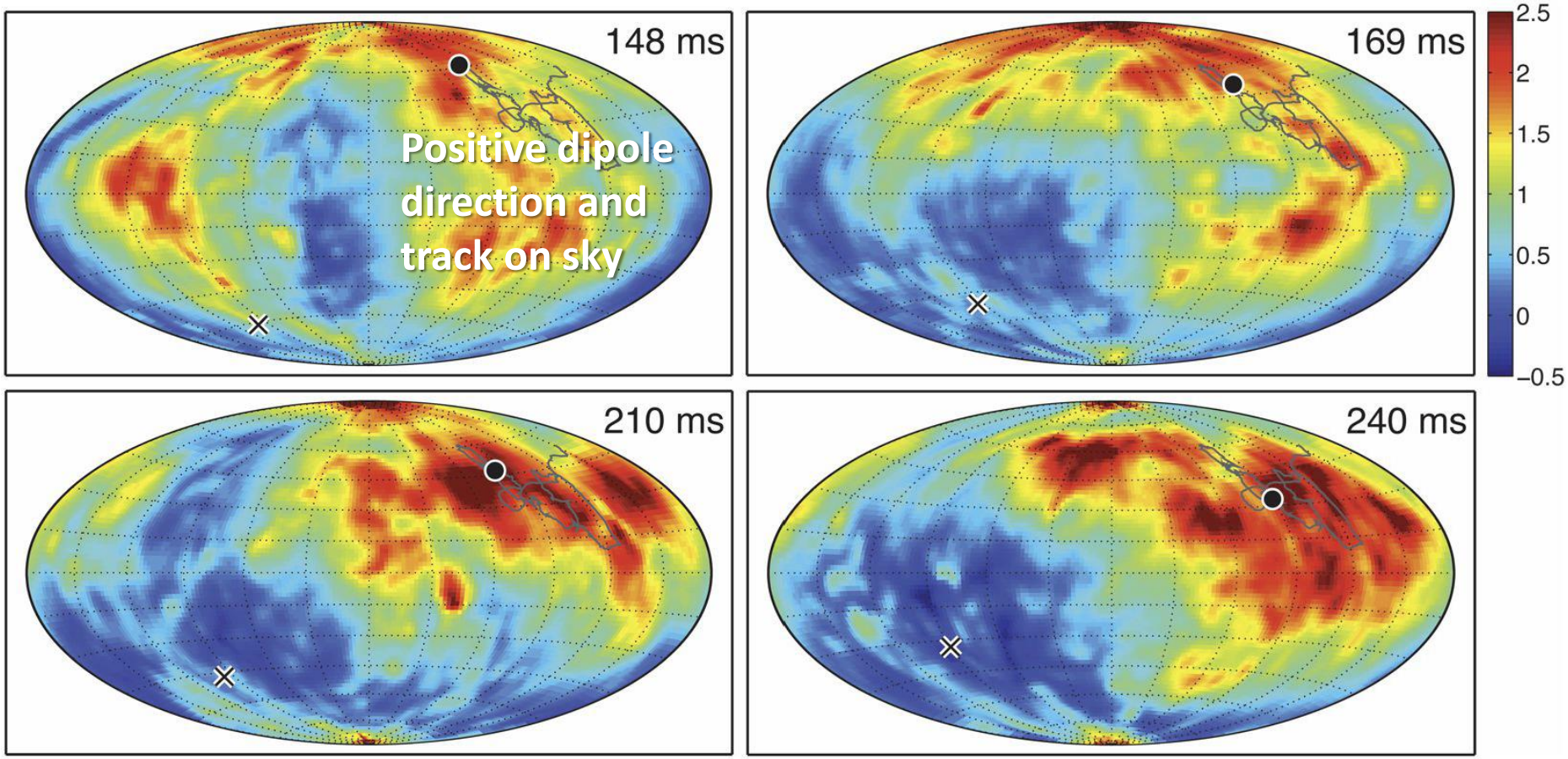
Lund et al (2012)

SASI



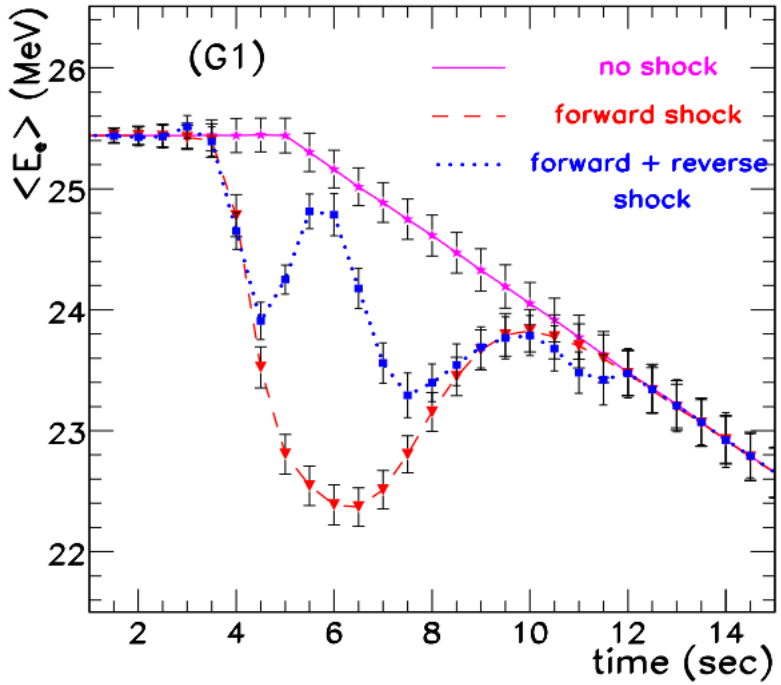
Can see SASI “bubbling” in the neutrino signal

Beaming of Lepton Asymmetry



Tamborra et al (2013, 2014)

Shock Propagation

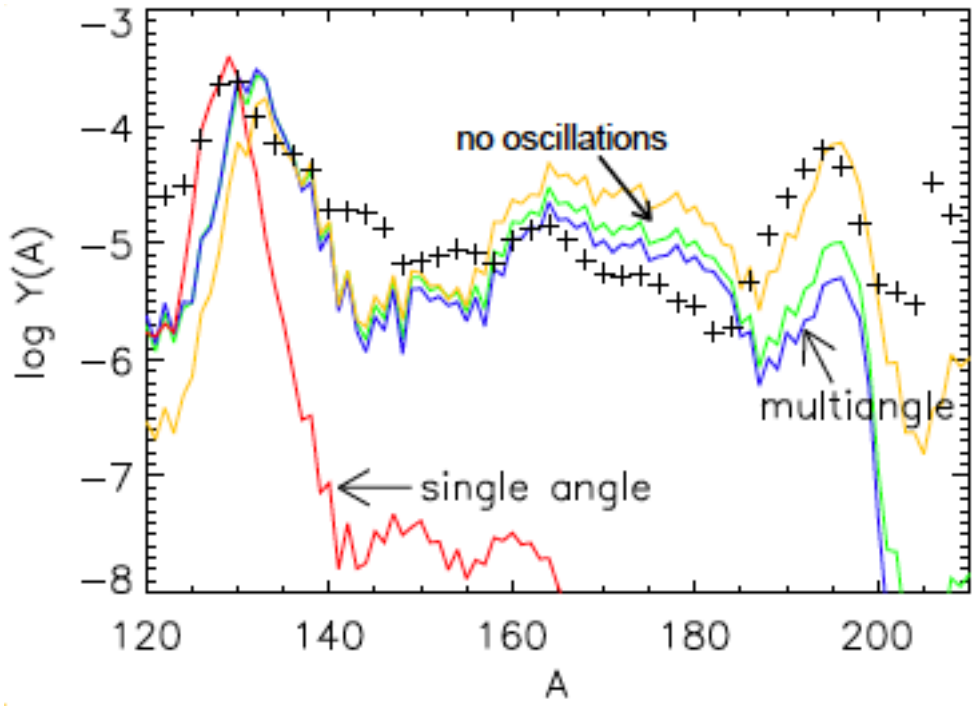


Tomas et al

Imprints of SN hydrodynamics in Neutrino Signal

Many papers during 2000-2007 on shock waves imprint, turbulence, phase effects etc. See review by Mirizzi et al. 2016.

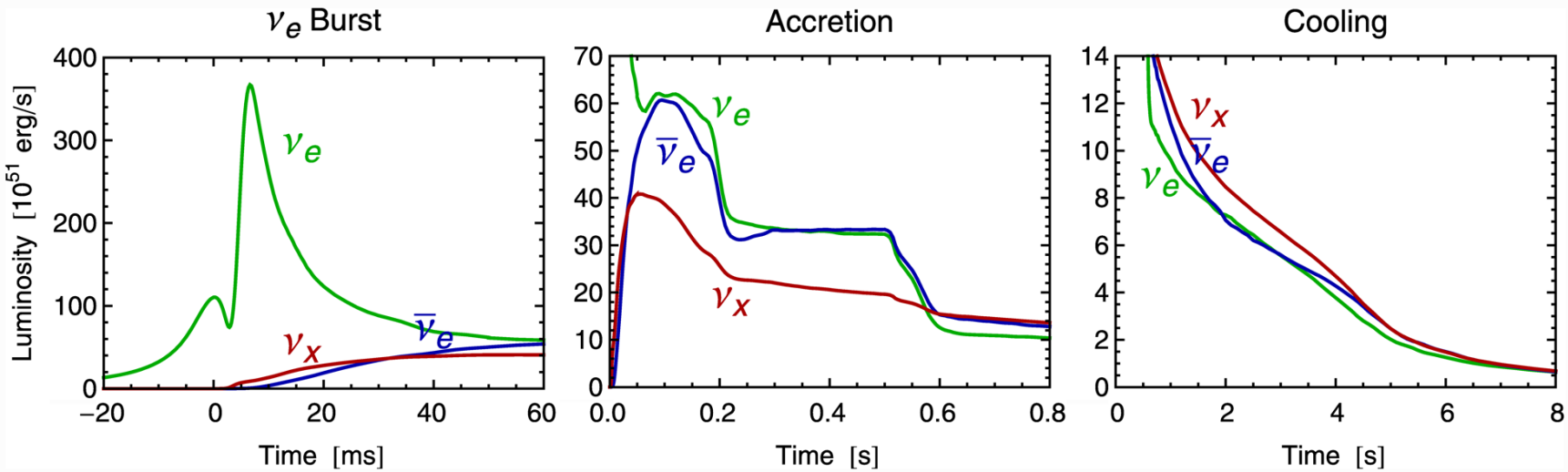
Nucleosynthesis



Recent work suggests r-process unlikely. More work needed.

Duan et al (2011), Wu et al (2015)

Opportunities & Challenges



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