SN neutrino theory: lightning overview

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Fermilab

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  - Create a dense neutrino gas (10^{8}-10^{10} moles of neutrinos/cm^3). Let this system expand. Measure the resulting collective flavor oscillation dynamics.

This experiment is carried out in a core-collapse supernova!

- Inner ~ 1.4 $M_\odot$ of material collapses to a super-dense object a few tens of km across
- 10% of the rest mass of the collapsed core is emitted in 10^{58} neutrinos in a burst lasting δt ~ seconds
    - Neutrino diffusion time scale
- At ~ 100 km, the number density of streaming neutrinos is
    - ~ $10^{58}/4\pi r^2 c\delta t \sim 10^{32}$ cm^{-3}
    - Comparable to the number density of matter

Evolution of the explosion is reflected in neutrinos

- Neutronization burst, accretion and cooling phases can all be seen in neutrinos
- Importantly, different for different progenitor masses

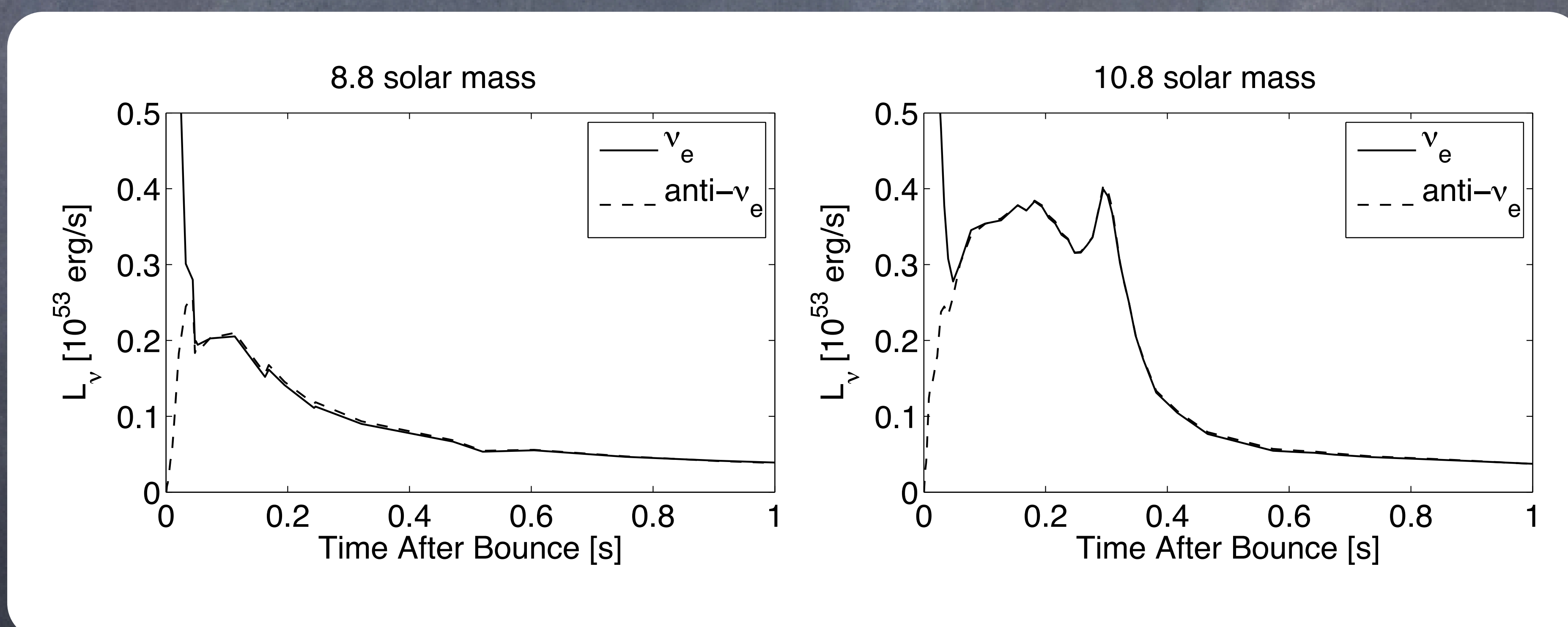


Fig from Fischer, Whitehouse, Mezzacappa, Thielemann, Liebendörfer, arXiv:0908.1871

Measure each of the phases

- The **Neutronization burst** provides information about the onset of the explosion, shock breakout through the neutrinosphere; also, a useful sharp time structure
- During the **Accretion stage** the shock stalls at a few hundred km; we need to know when and how it is reenergized
  - 50-year question in SN theory!
- **Cooling stage** ends with the formation of a neutron star or a black hole. The signal is sensitive to new physics contributions to cooling (light hidden sector!). Monitor how the shock travels out and the turbulent bubble behind expands.
  - May be possible thanks to neutrino oscillations!

The richest and most challenging neutrino oscillations problem known

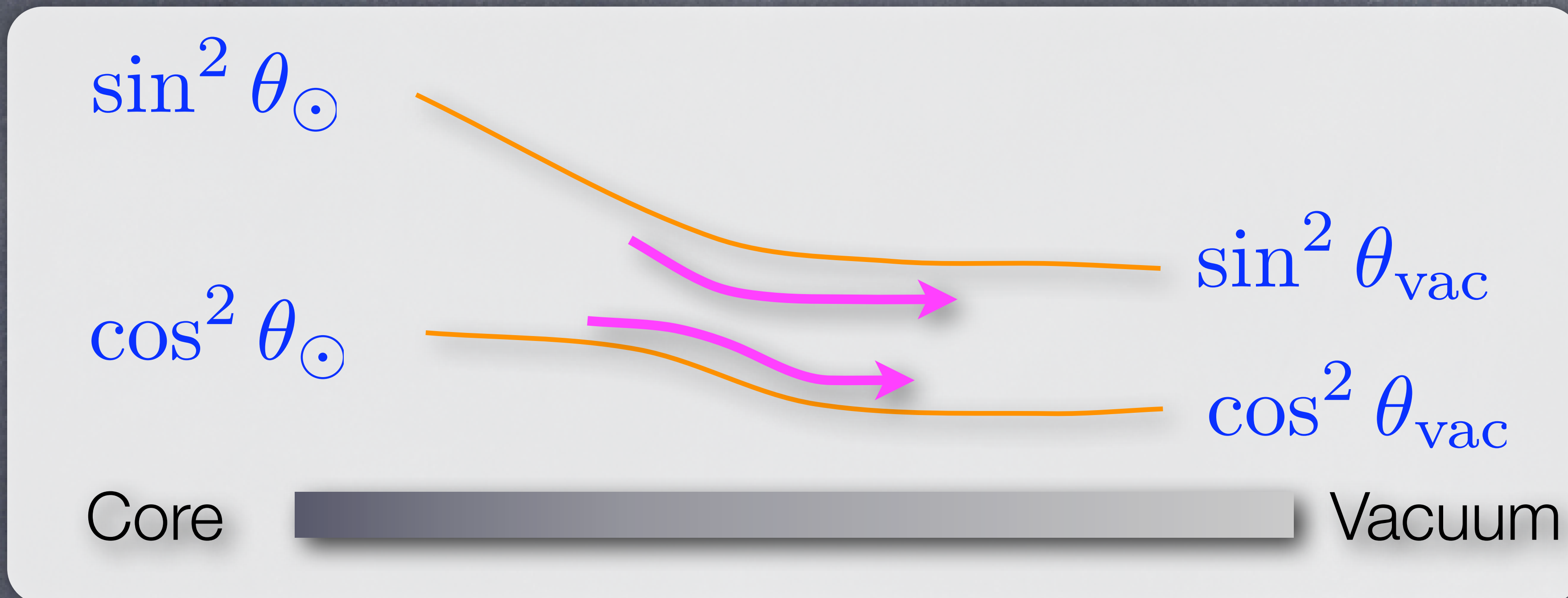
- Possible matter effect in the Earth
- "Solar" MSW in the outer envelope of the progenitor
- "Atmospheric" MSW in the outer envelope of the progenitor
- Turbulent region behind the shock
- Collective oscillations near the neutrino-sphere
- This is schematic, the order of some of these ingredients could be interchanged, depending on the progenitor mass, stage of the explosion

Earth effect

- The density of the Earth is close to resonant for the "solar" splitting and 20-40 MeV SN neutrinos
  - cf. the D/N effect in ^{8}B solar neutrinos is expected at high energies
- Can help to distinguish between different mixing scenarios
- See, e.g.,
  - Smirnov, Spergel & Bahcall, PRD 1994
  - Lunardini & Smirnov, arXiv:hep-ph/0009356
  - Dighe, Kachelriess, Raffelt & Tomas, arXiv:hep-ph/0311172

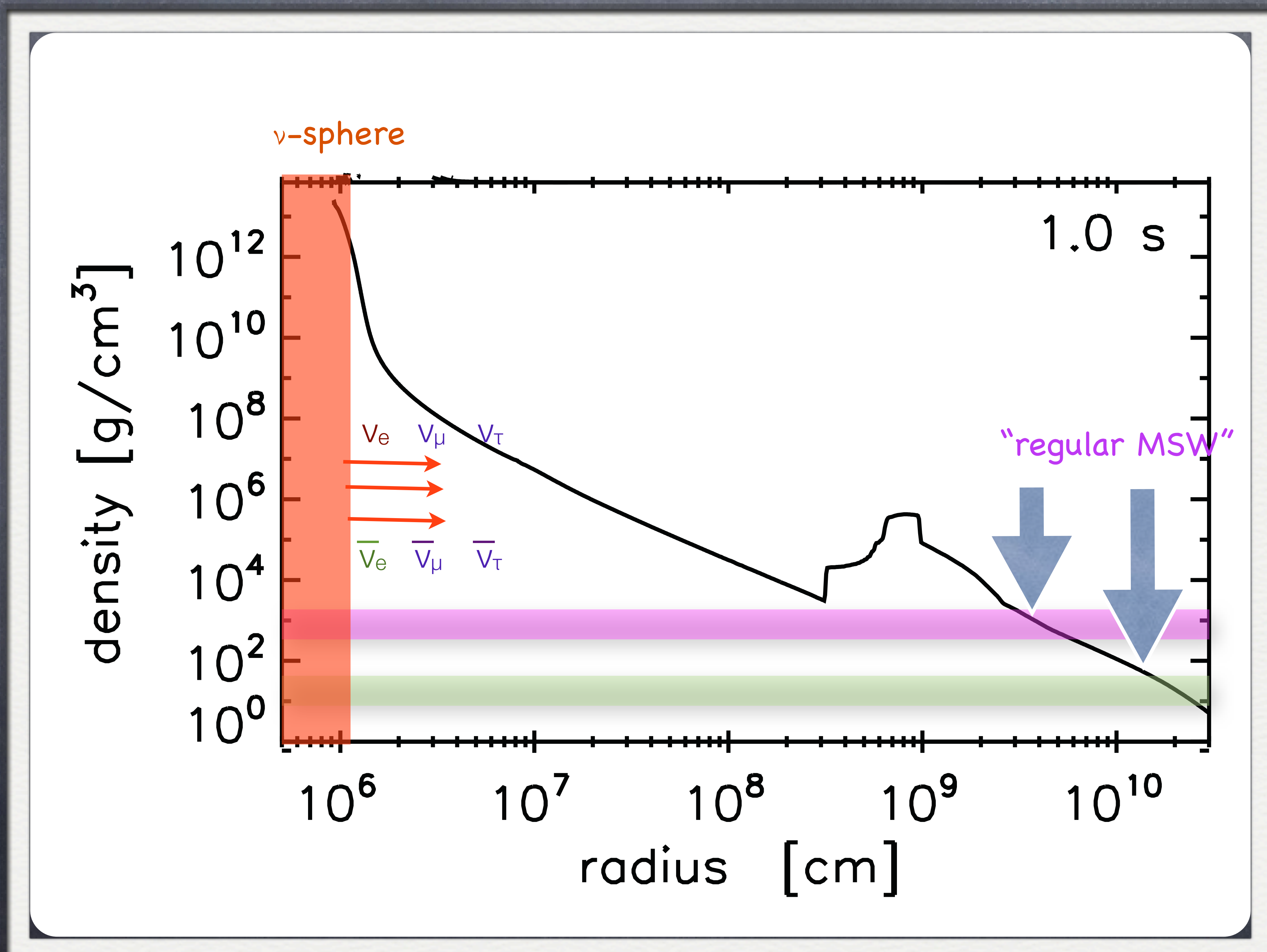
Sun: 2-state oscillations

$$P_2(\nu_e \to \nu_e) \quad = \quad \sin^2\theta \sin^2\theta_\odot + \cos^2\theta \cos^2\theta_\odot$$



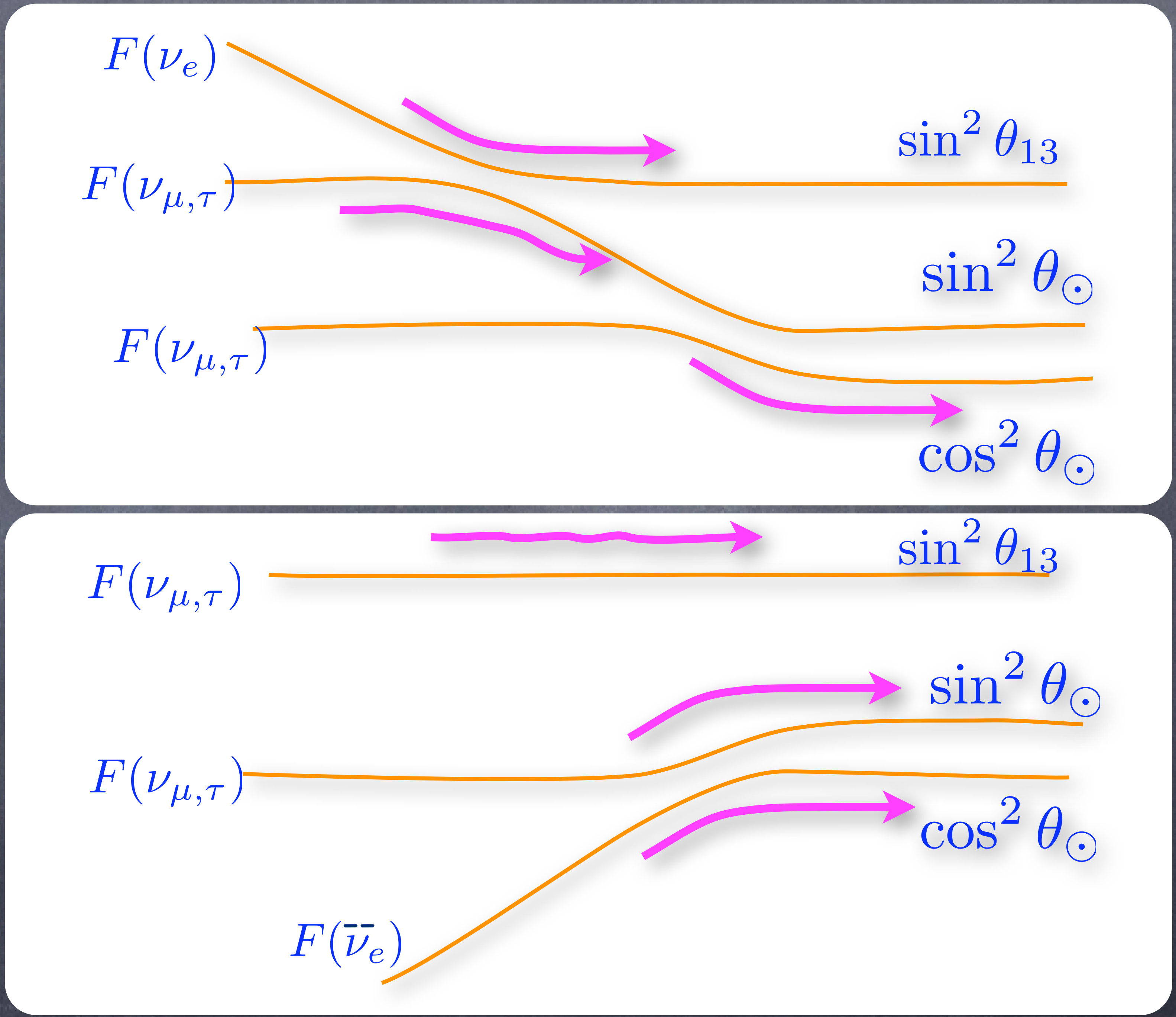
- The evolution is adiabatic (no level jumping), since $l_{osc} \ll$ density scale height ($|d \ln\rho/dr|^{-1}$)
  - Hint: for most of the Sun, the density scale height is $R_{sun}/10$, while l_{osc} is comparable to the width of Japan (KamLAND)

SN ν oscillations: 2 MSW densities



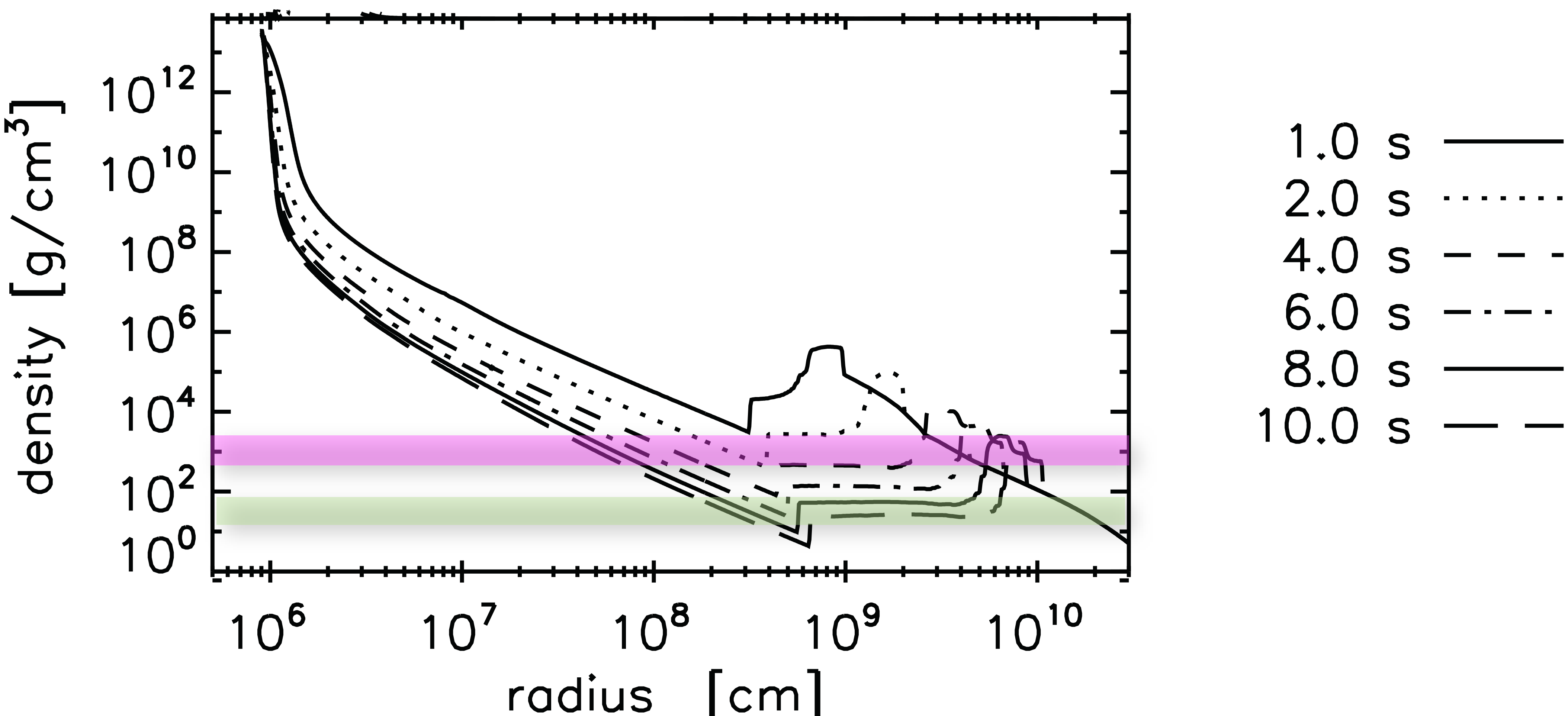
SN MSW transformations, schematics

- Given the scale height in the progenitor, the evolution is very adiabatic
  - the adiabaticity of the atmospheric resonance is controlled by theta13
- Prediction for the nue signal during the **neutronization burst** is critically dependent on the sign of MH



For inverted hierarchy, the same happens in antineutrinos.

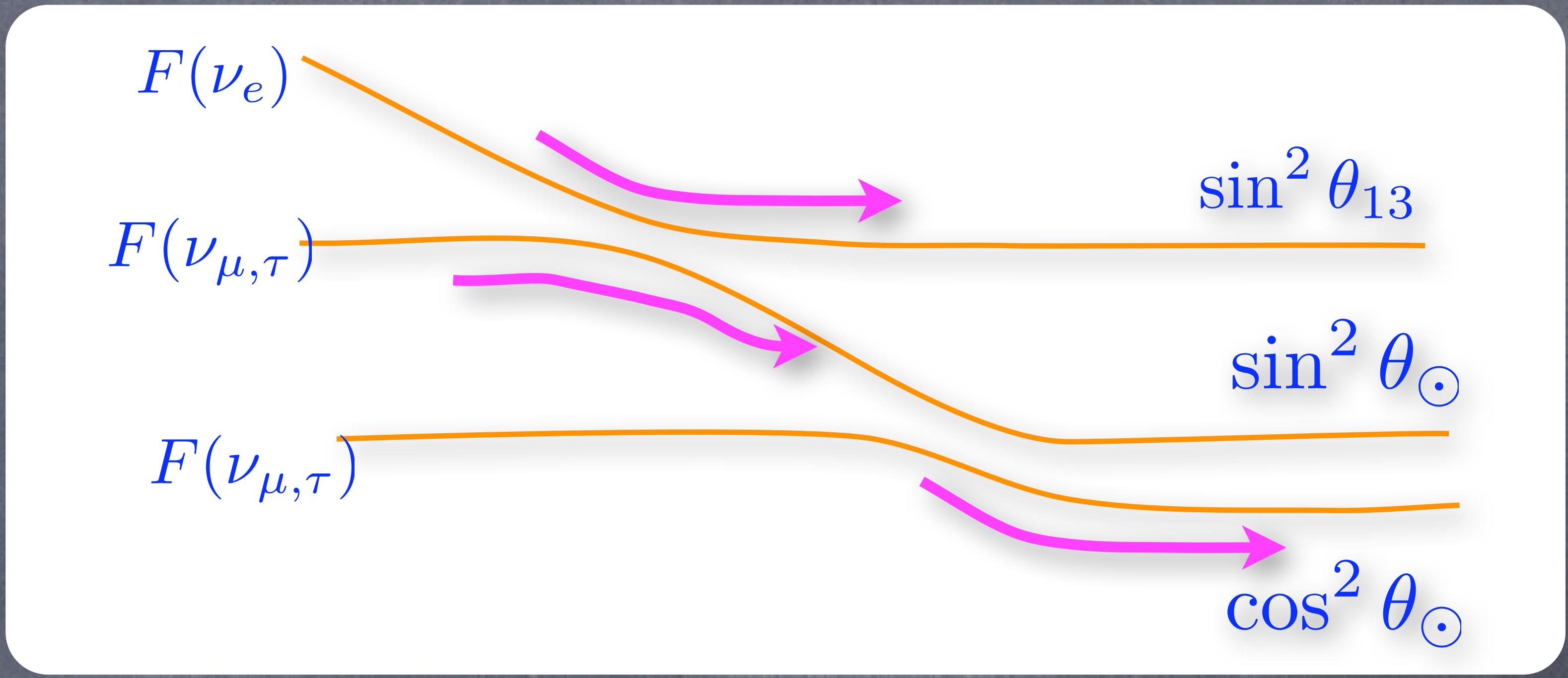
Dynamical density profile

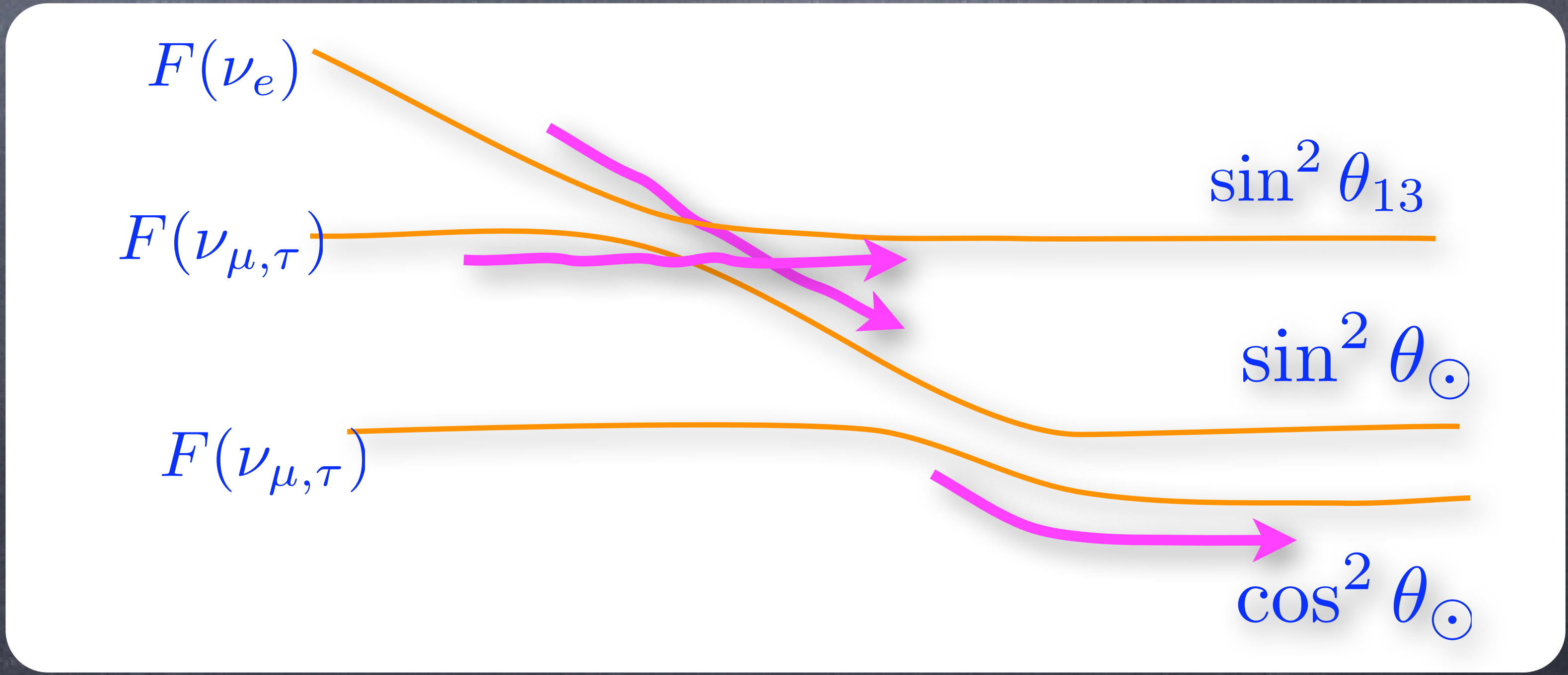


- Front shock reaches the regions where “atmospheric” and “solar” transformations happen, while neutrinos are being emitted
  - See Schirato & Fuller (2002) astro-ph/0205390

Moving shock and MSW transformations

- The shock is infinitely sharp from the neutrinos' point of view (photon mean free path).
- When it arrives at the resonance, the evolution becomes non-adiabatic.

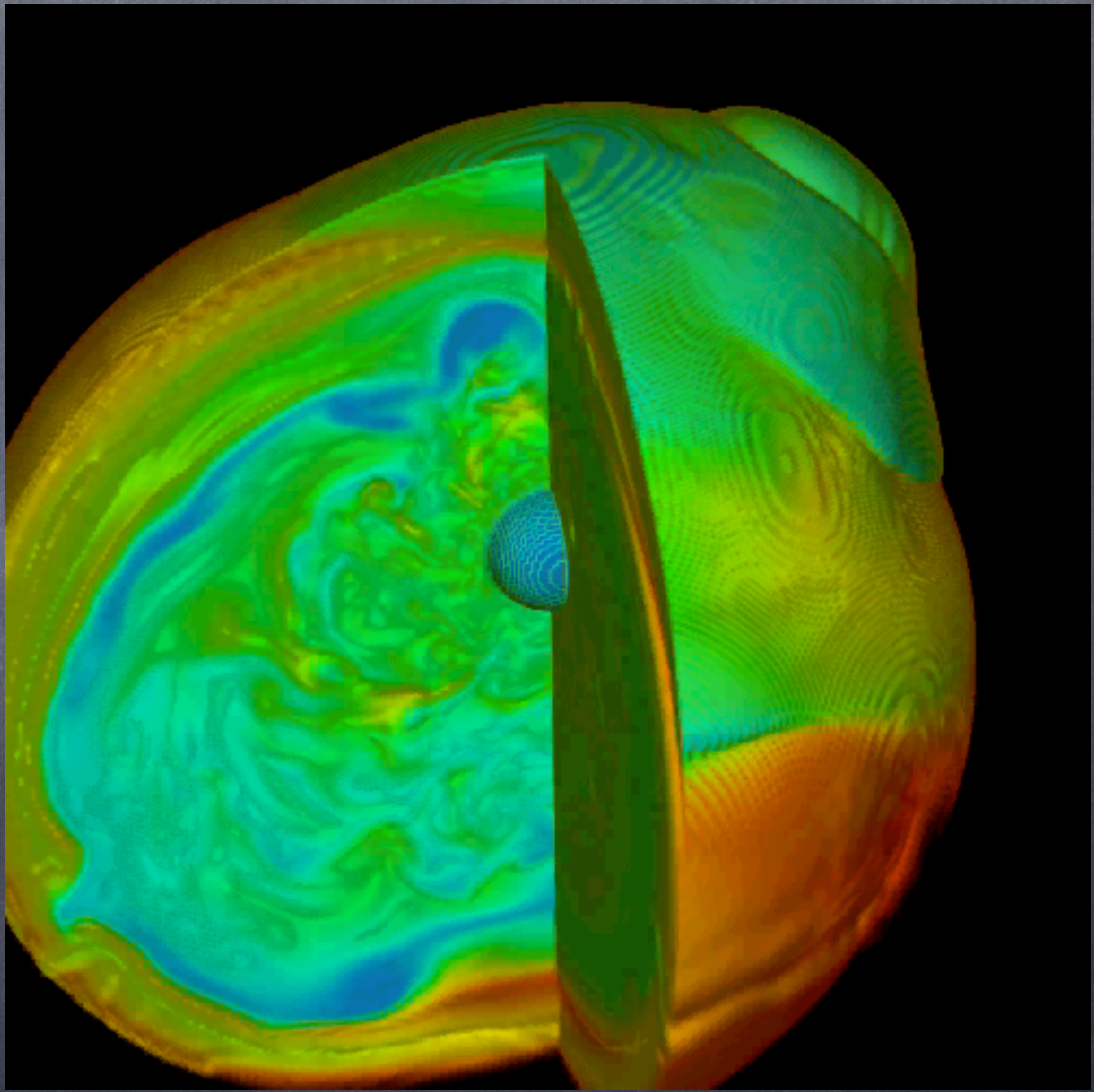




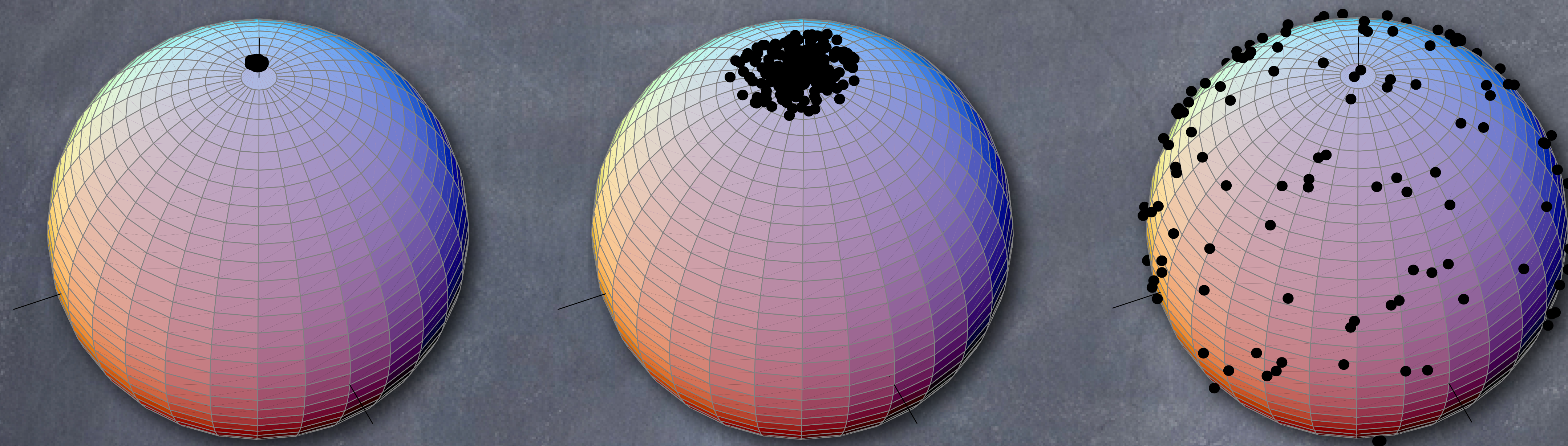
For inverted hierarchy, the same happens in antineutrinos.

3D simulations show turbulence

- 3d simulations of the accretion shock instability Blondin, Mezzacappa, & DeMarino (2002)
- See http://www.phy.ornl.gov/tsi/pages/simulations.html
- extensive, well-developed turbulence behind the shock



Turbulence makes neutrinos diffuse in the flavor space



- Need to estimate the rate of diffusion
    - Given large-scale fluctuations in published simulations (order 1) and the large measured value of theta13, observable signal expected a few seconds into the explosion

Some technical details

- The level-jumping probability depends on fluctuations
  - relevant scales are small, O(10 km)
  - take large-scale fluctuations from simulations, scale down with a Kolmogorov-like power law
  - contributions of different scales to the level-jumping probability are given by the following spectral integral

$$P \simeq \frac{G_F}{\sqrt{2} n_0'} \int dk C(k) G\left(\frac{k}{2\Delta \sin 2\theta}\right), \qquad G(p) \simeq \frac{\Theta(p-1)}{p\sqrt{p^2-1}}.$$

for details, see Friedland & Gruzinov, astro-ph/0607244

Neutrino "self-refraction"

- Neutrinos undergo flavor conversion in the background of other neutrinos
- The neutrino induced contribution depends on the flavor states of the background neutrinos

$$\sqrt{2}G_F \sum_{\vec{p}} n_i (1 - \cos\Theta_{\vec{p}\vec{q}}) |\psi_{\vec{p}}\rangle\langle\psi_{\vec{p}}|$$

- One has to evolve the neutrino ensemble as a whole
- Rich many-body physics, with many regimes

Fuller et al, Notzold & Raffelt 1988;
Pantaleone 1992; ...
Duan, Fuller, Qian, Carlson, 2006;
+ hundreds more

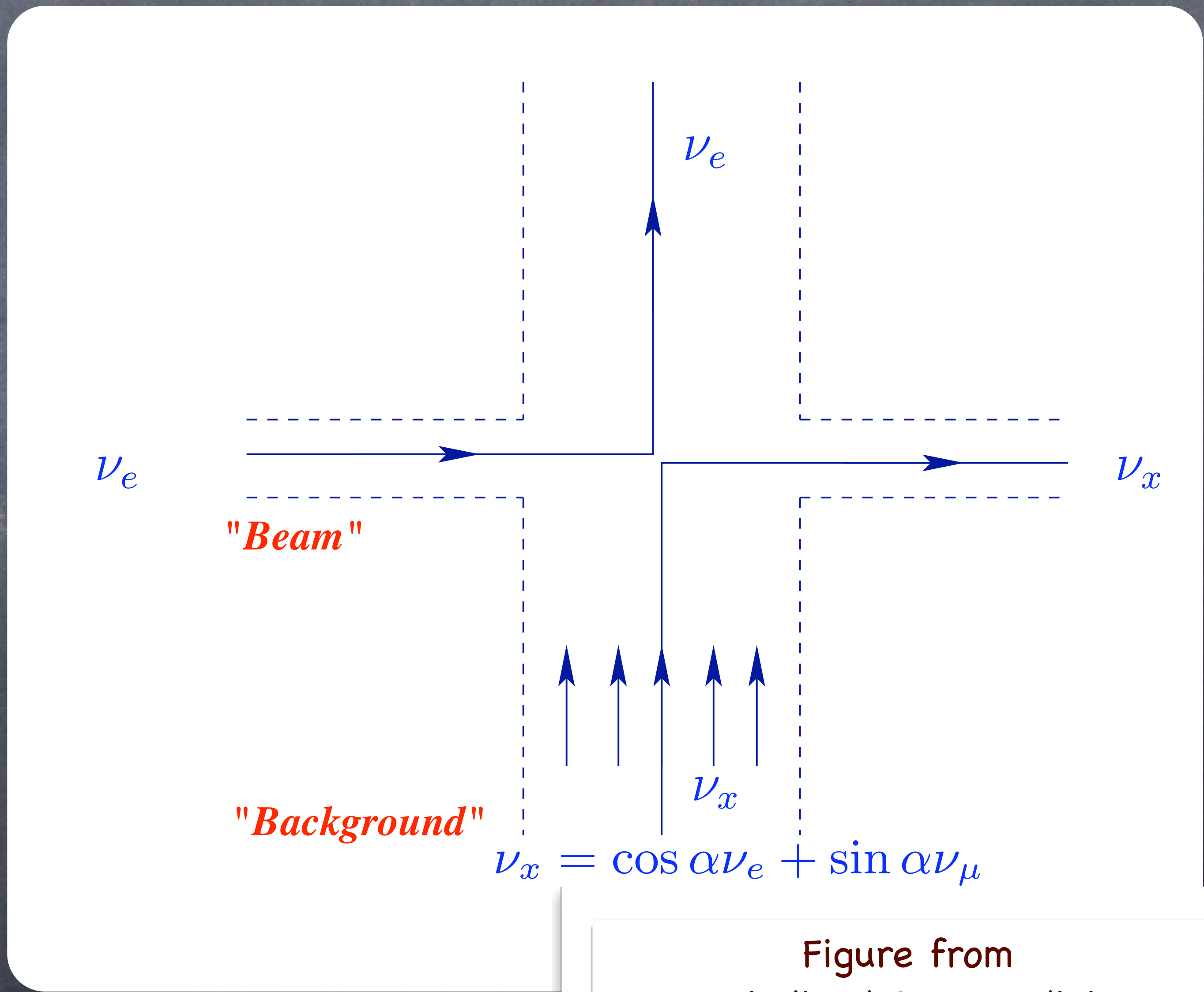
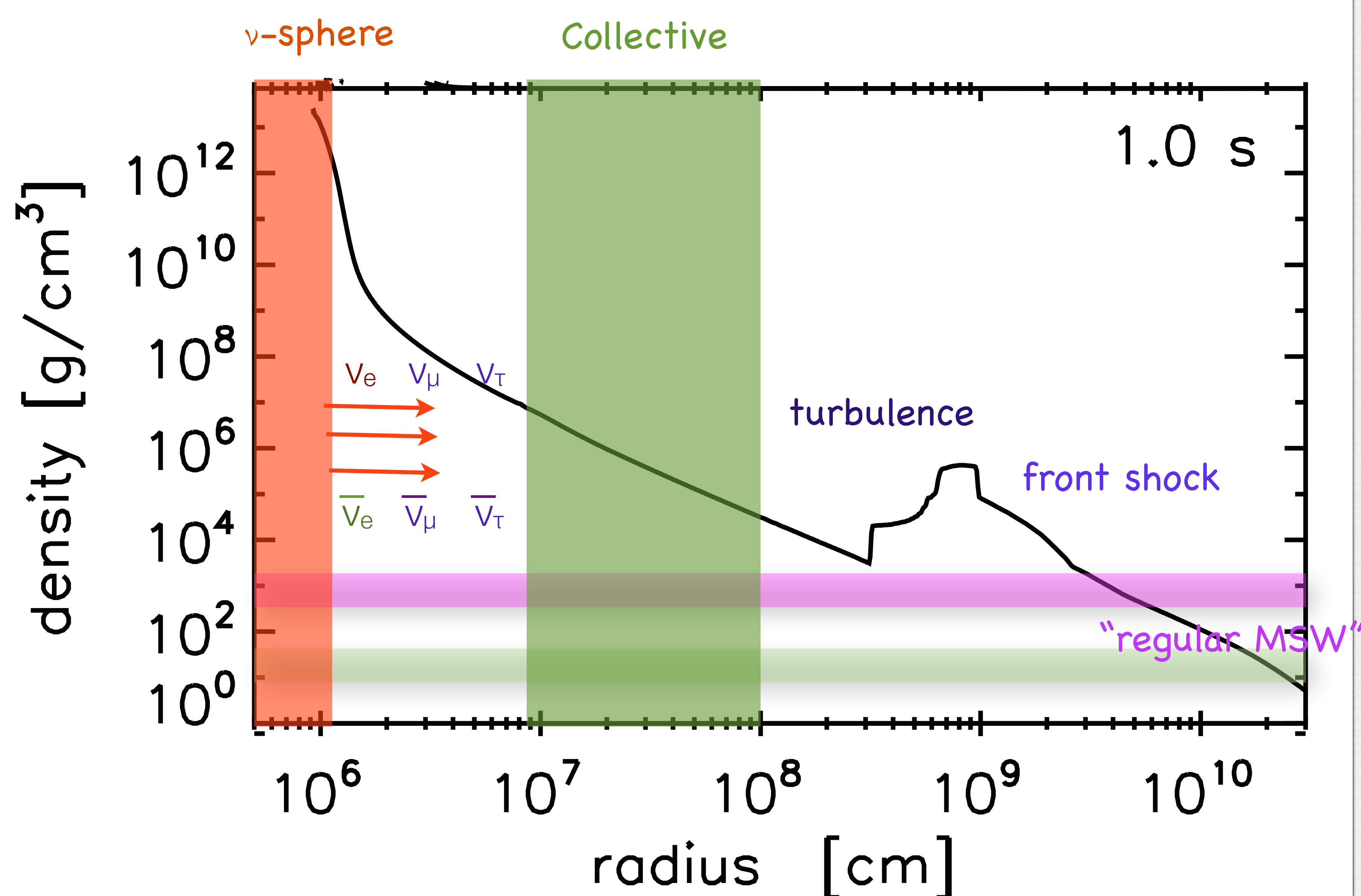
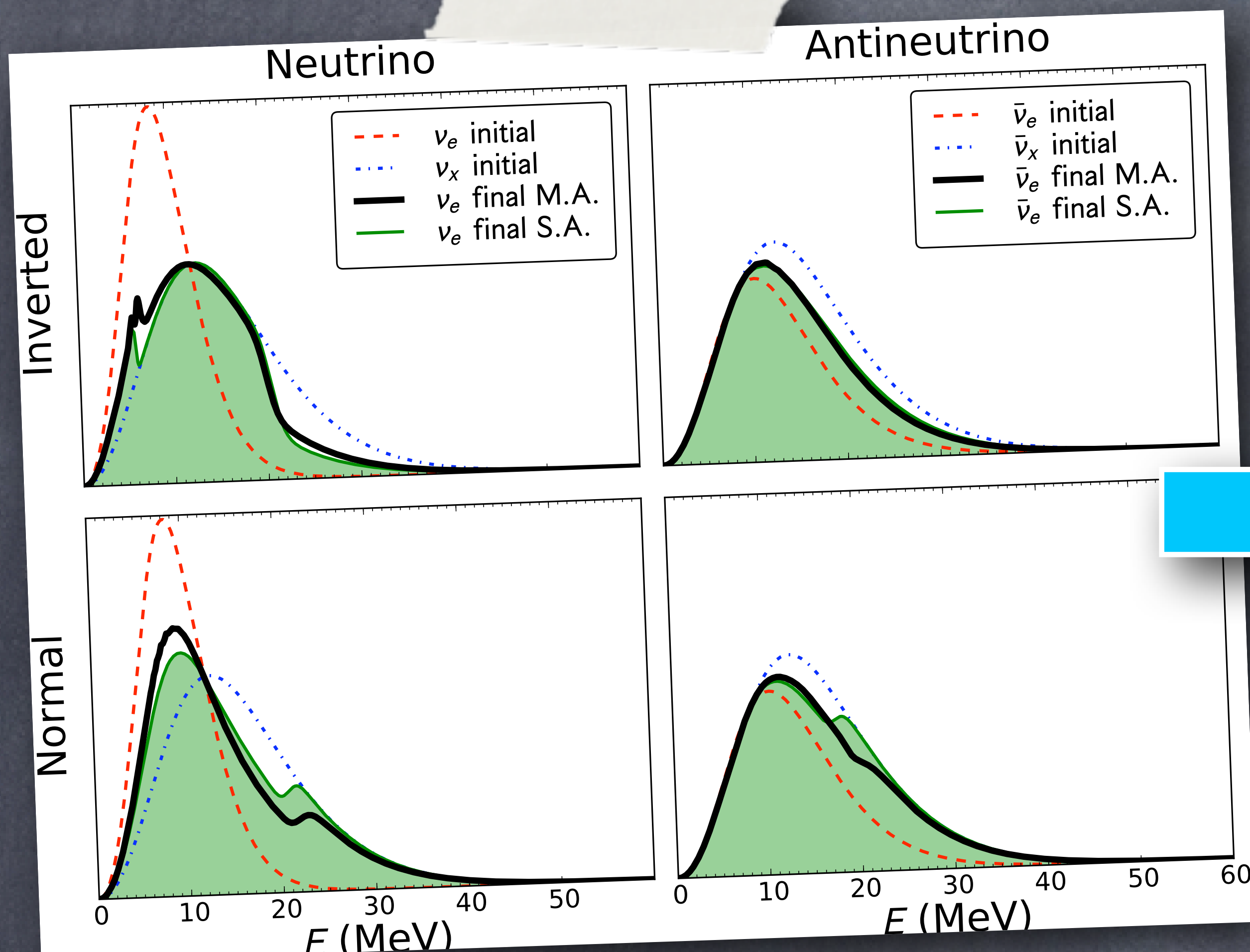
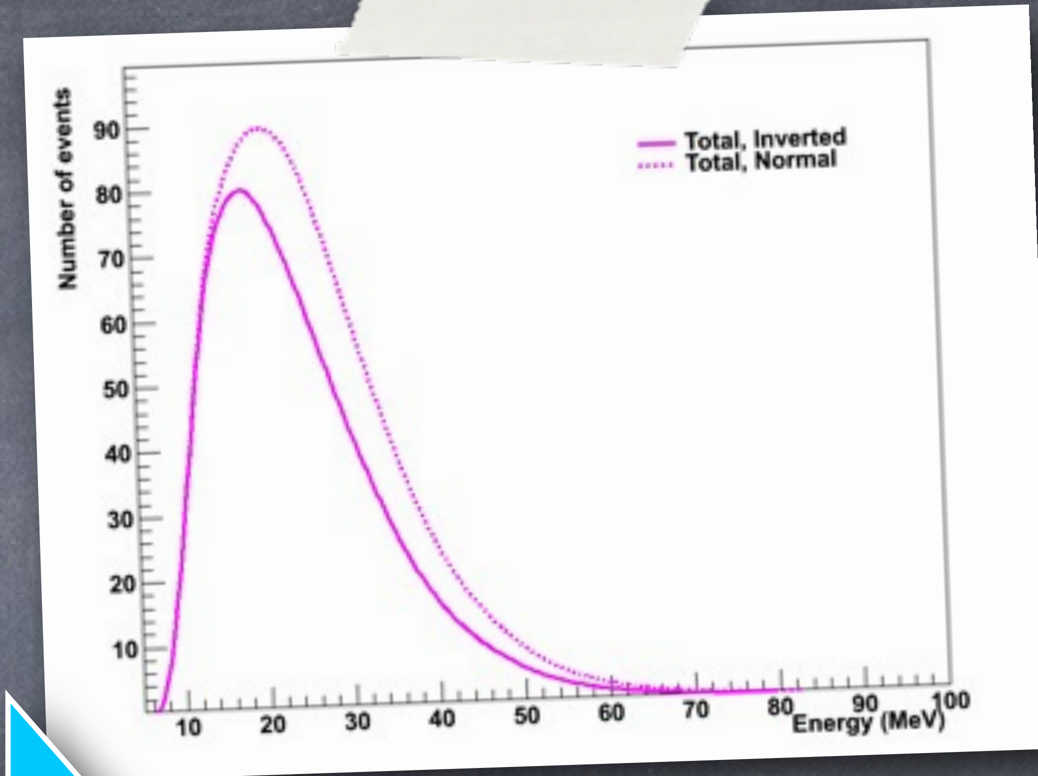


Figure from
Friedland & Lunardini,
Phys. Rev. D 68, 013007 (2003)

SN ν: summary physics cartoon







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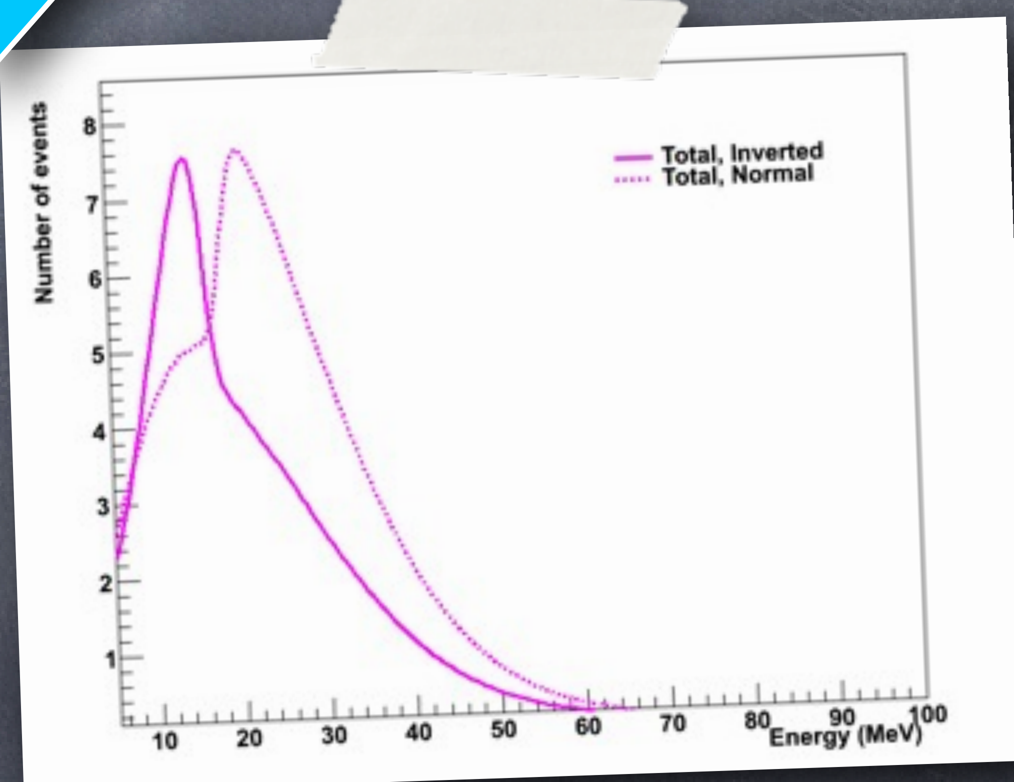
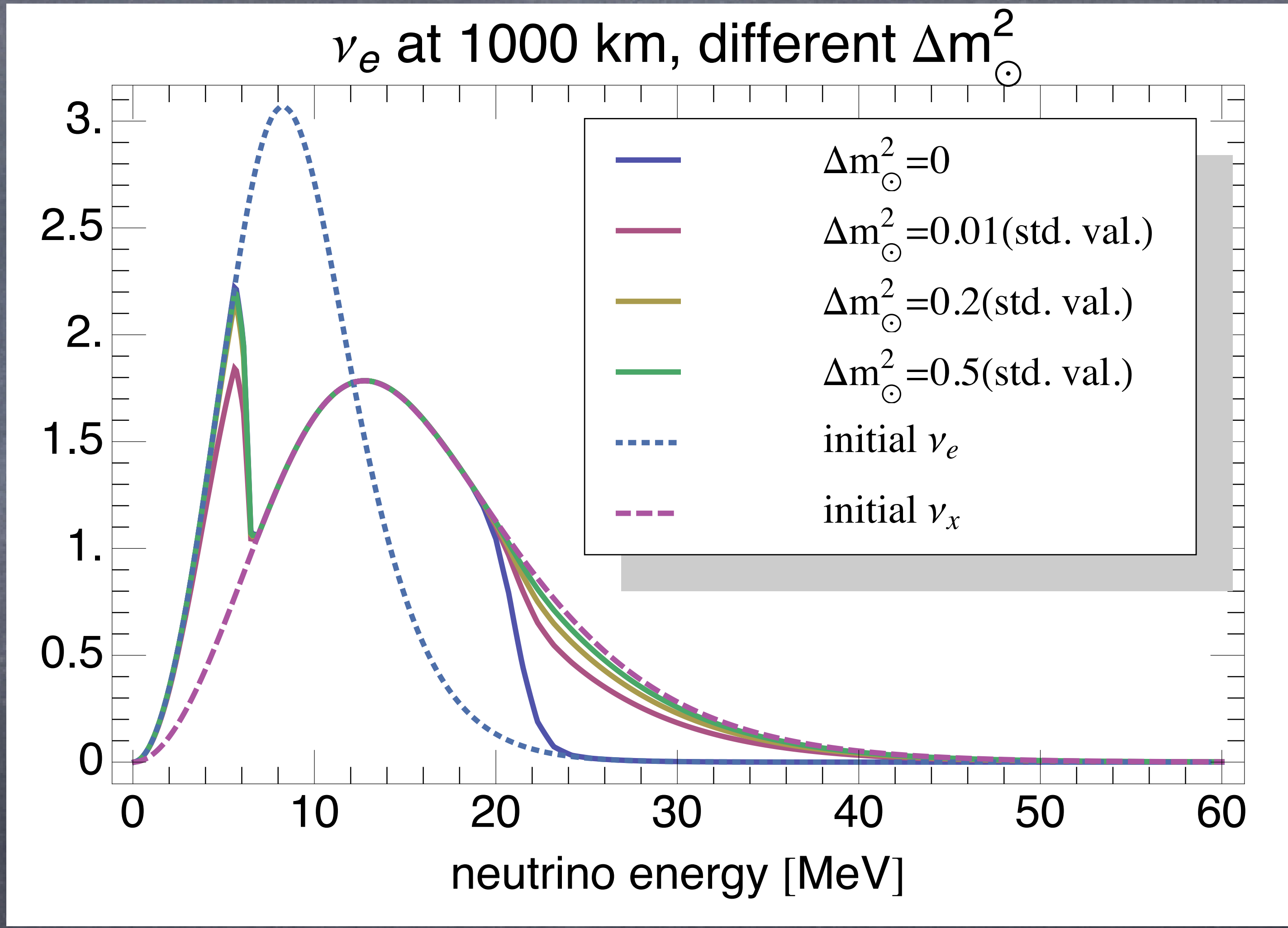


LAr

* spectra by Duan & Friedland, PRL 2011
* detector modeling by Kate Scholberg & co

Collective oscillations must be done in 3 flavors

- Example where the solar mass splitting is turned on gradually
  - At $\Delta m_\odot^2=0$, 2-flavor result is reproduced
  - As soon as $\Delta m_\odot^2\neq0$, the answer is closer to the realistic $\Delta m_\odot^2$ than to $\Delta m_\odot^2=0$
- 2-flavor trajectory can be unstable in the 3-flavor space

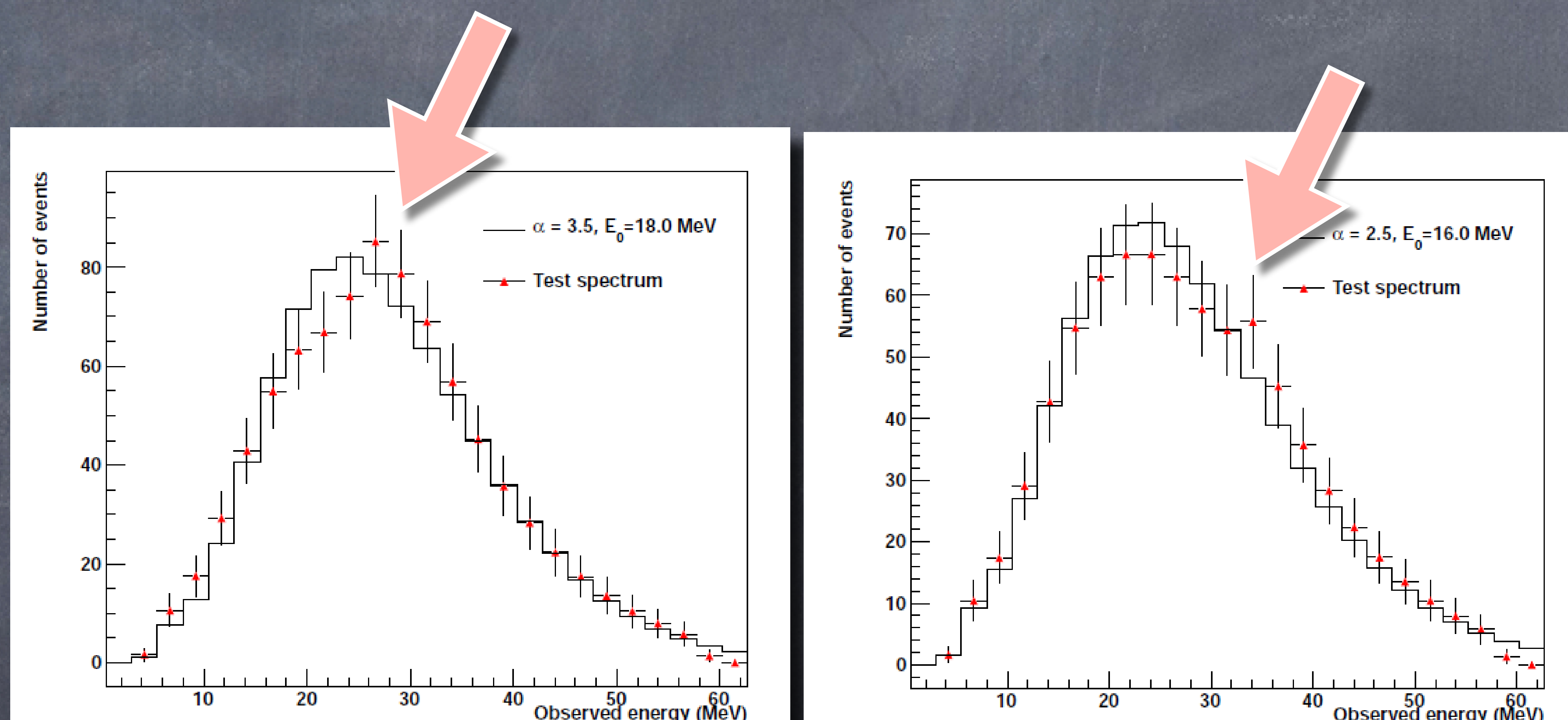


For details, see Friedland, PRL (2010);
also Dasgupta, Dighe, Raffelt, Smirnov, PRL (2009)

What are we looking for? Smoking-gun features

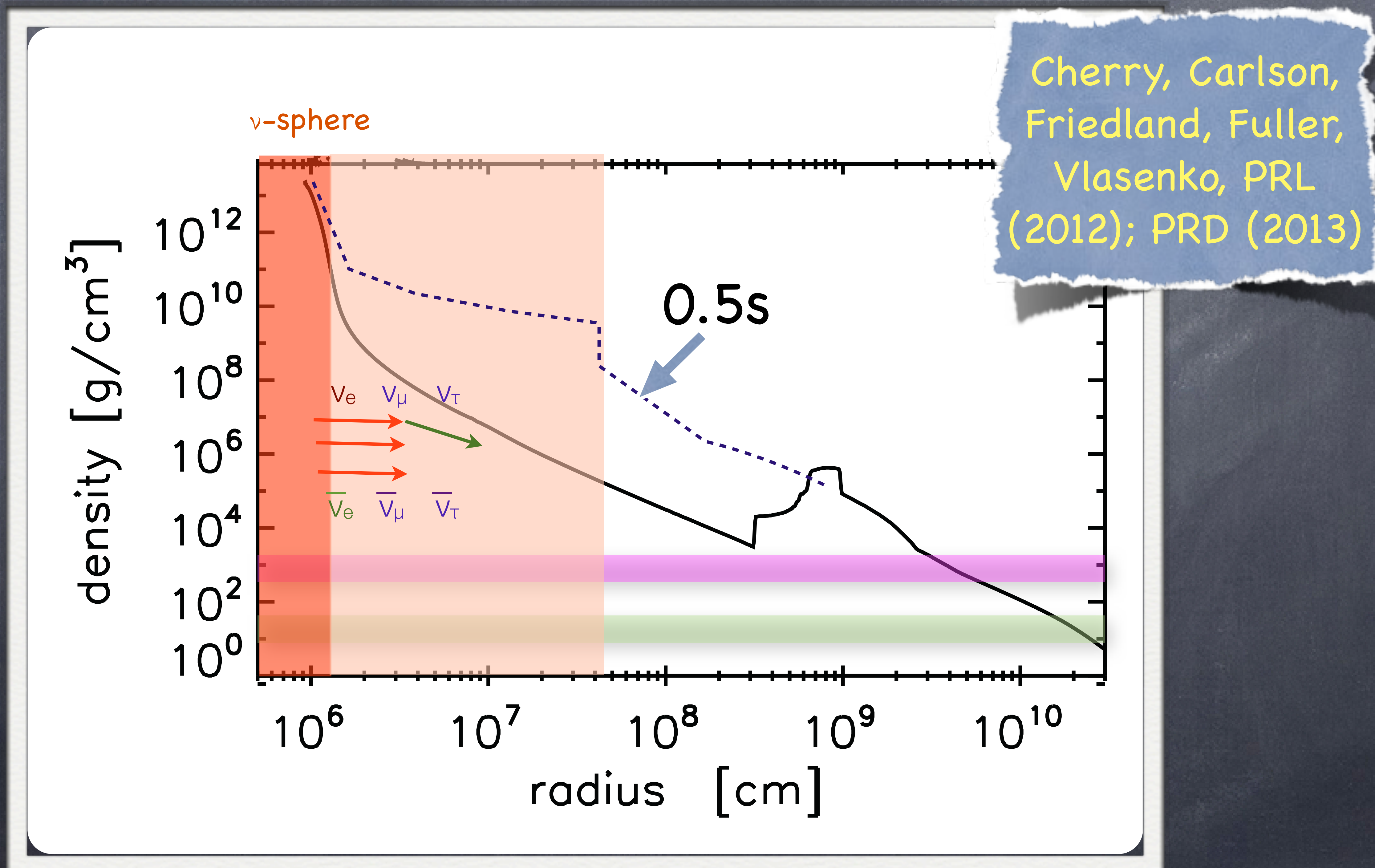
Modeling multiangle collective + moving shock by A. F.

Detector model by K. Scholberg



- The neutrino spectrum is modulated, but not antineutrinos (simultaneously observed by SK/HK)

Accretion phase: neutrinos scattering above ν-sphere?



Much work is still to be done!

- The role of matter in collective oscillations
  - Do they always factorize?
- Dependence of collective transformations on luminosities and temperatures of different components
  - Transition from sharp spectral splits to decoherence
- Breaking of spherical symmetry
  - e.g., Raffelt, Sarikas de Sousa Seixas, PRL 111, 091101 (2013)
- Effects of nonstandard physics
  - e.g., de Gouvea and Shalgar, JCAP (2012, 2013)