SN neutrino oscillations: overview

Alex Friedland

SLAC NATIONAL ACCELERATOR LABORATORY

Supernova Meeting, March 11, 2016
Virginia Tech

Imagine designing a wild intensity frontier experiment

- Let's dream! What if we could:
  - Take ~3×10^{29} kg of matter and convert it to pure energy, in the form of 10^{58} neutrinos with energies of 10^{7} eV.
  - Create a ball of matter so dense (10^{12}-10^{14} g/cm^3, nuclear densities) that it is opaque even for neutrinos. Measure its cooling properties as a function of time.
  - 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 just a few tens of km across
- Gravitational binding energy of the collapsed core, $\sim GM^2/R$, equals to about 10% of its rest mass
- It 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
  - $\sim 10^{58}/4\pi r^2 c\delta t \sim 10^{32}$ 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

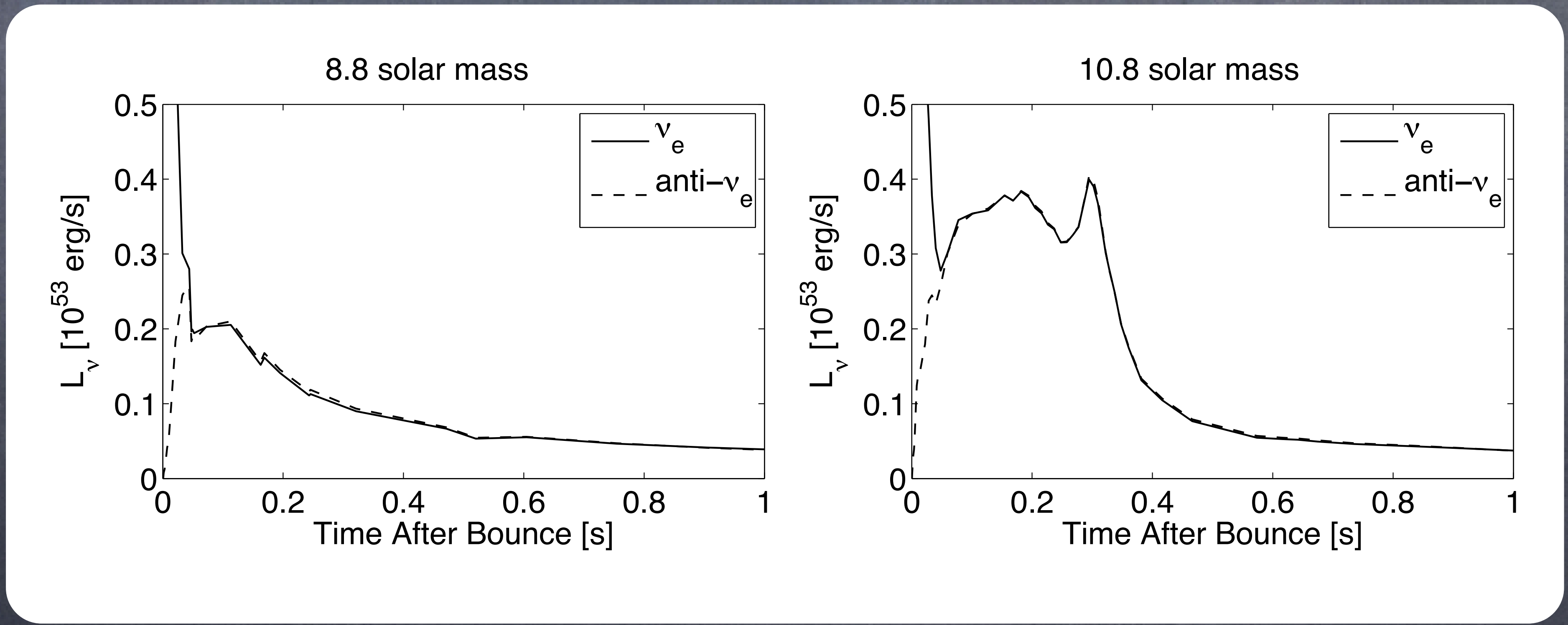


Fig from Fischer, Whitehouse, Mezzacappa, Thielemann, Liebendörfer, arXiv:0908.1871

Measure each of the phases

- The Neutronization burst : the onset of the explosion, shock breakout through the neutrinosphere; also, a 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!
  - Information about progenitor, EOS
- 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!

Cooling bounds on new physics

- Two dozen neutrinos observed from 1987A confirmed the rough picture of core-collapse supernovae as gravity-powered neutrino bombs
- This limited dataset already provides some of the best known constraints on many classes of new physics models with light, weakly interacting degrees of freedom
  - nonstandard neutrinos, axions, KK gravitons, extra-dim photons/unparticles, dark photons ...
- If this can be done with ~20 events, how about thousands of events expected from the next Galactic SN?

Once-in-a-lifetime opportunity

- The next SN likely to give
  - 10^4 electron antineutrinos at SK (10^5 at HyperK)
    - plus hundreds (thousands) of nu-e elastic scattering events
  - several thousand electron neutrinos at DUNE, potentially with good energy resolution
  - Second-by-second evolution of the spectra

Gold mine of physics information

- Information about neutrino trapping, dynamics of the explosion, state of nuclear matter in the center, equation of state as a function of density, new physics contributions to energy transport ...
- Nature does not seem to know or care about the separation between the different DOE offices!

Theory required part of "technology"!

- For example, let's say we would like to measure the total energy release
  - Energy is released in neutrinos and antineutrinos of **all flavors**
  - Just measuring nu-e-bar's is not enough
  - Measuring of neutral current rate helps, but also not enough, if the spectrum of nu-x is unknown
- Fortunately, neutrinos oscillate. If we can understand the oscillation pattern, we can infer the total energy released, second-by-second

The richest and most challenging neutrino oscillations problem known

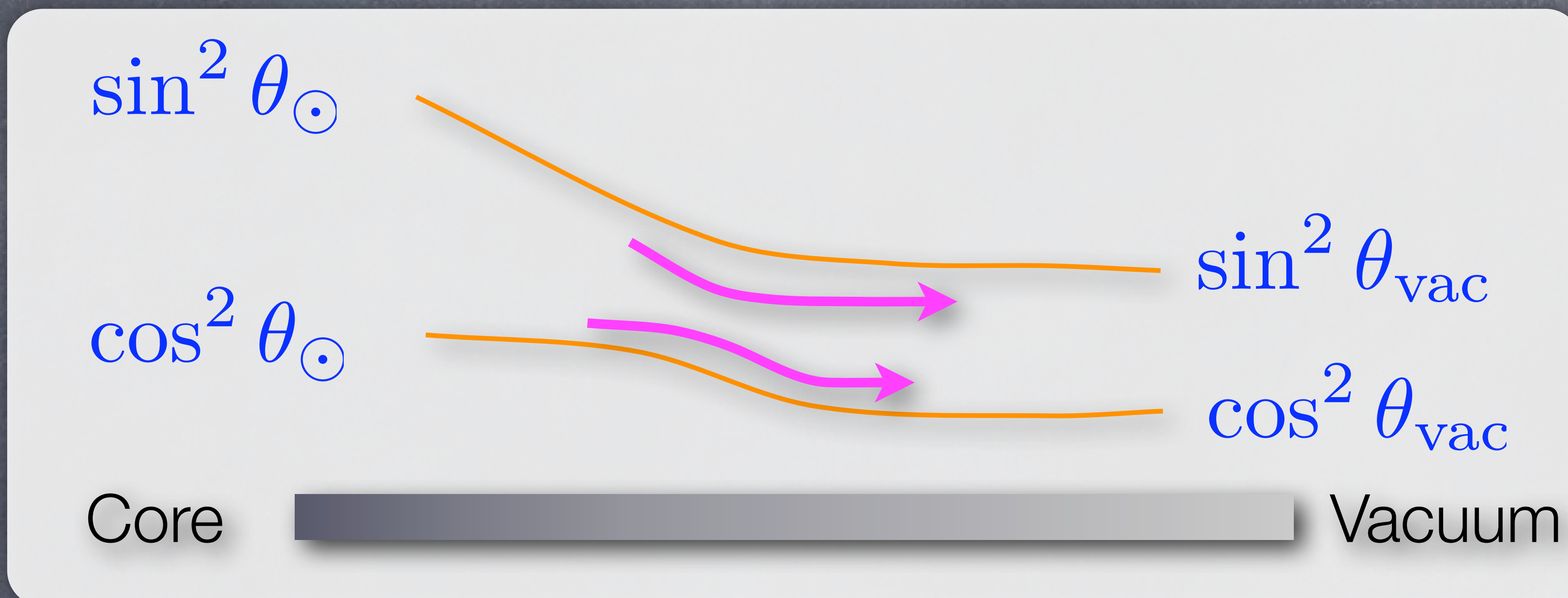
- Possible matter effect in the Earth
- "Solar" MSW in the outer envelope of the progenitor
- "Atmospheric" MSW in the outer envelope of the progenitor
- Turbulent region behind the shock
- Collective oscillations near the neutrino-sphere
- This is schematic, the order of some of these ingredients could 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} << 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)

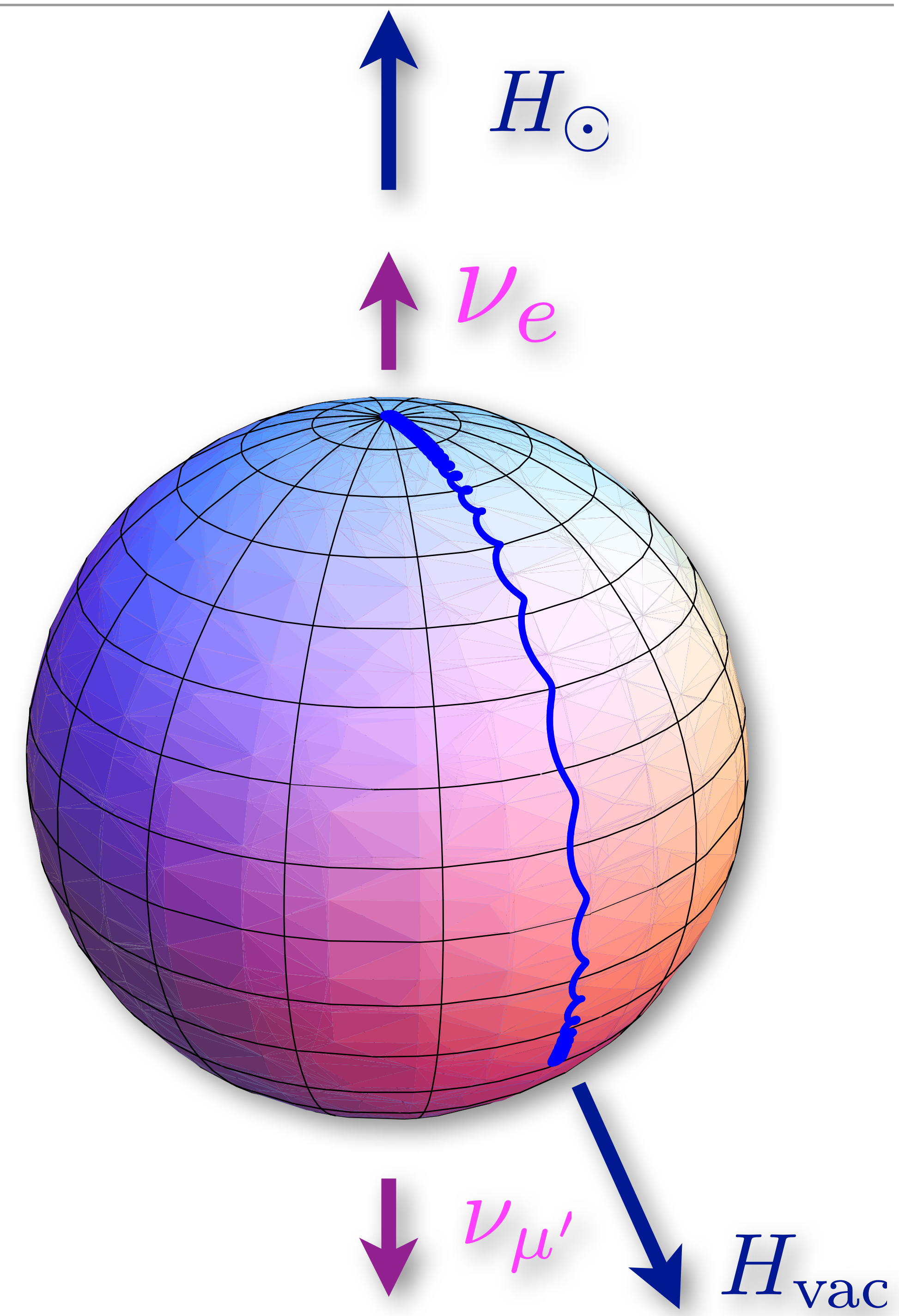
Ordinary MSW in the spin representation

- Like any two-state QM system, the neutrino flavor state can be thought of as a spin. We can depict its evolution by showing the trajectory of the expectation value of the spin, $\langle \nu | \vec{\sigma} | \nu \rangle$, on a sphere

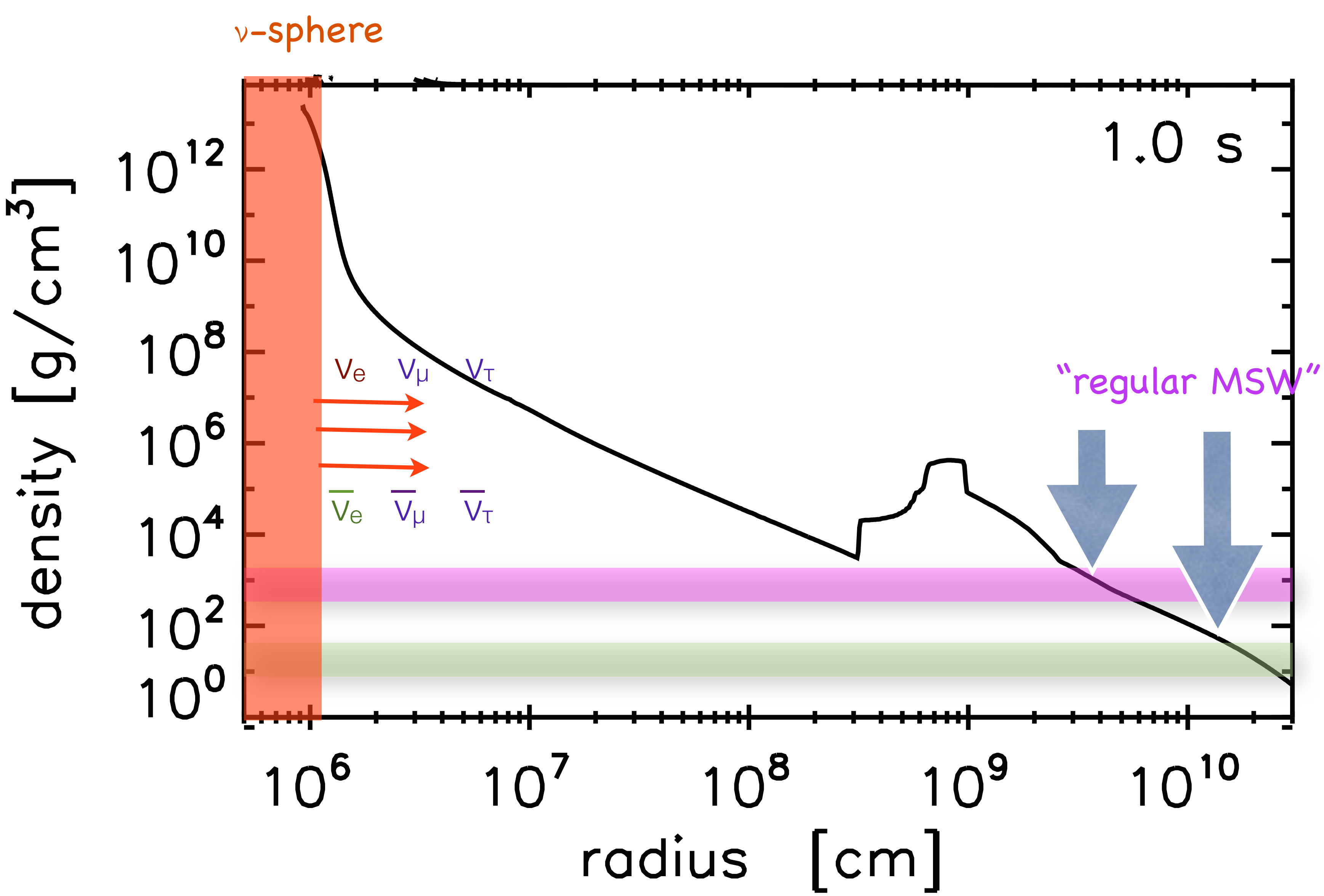
- The oscillation Hamiltonian acts as an external magnetic field. The matter potential changes the z-component of the field.

$$H(r) = \frac{\Delta m^2_{\rm mat}}{2E_\nu} \begin{pmatrix} -\cos 2\theta_{\rm mat} & \sin 2\theta_{\rm mat} \\ \sin 2\theta_{\rm mat} & \cos 2\theta_{\rm mat} \end{pmatrix} = \vec{H}(r) \cdot \vec{\sigma}$$

- In the adiabatic case, the spin follows the changing “magnetic field”.

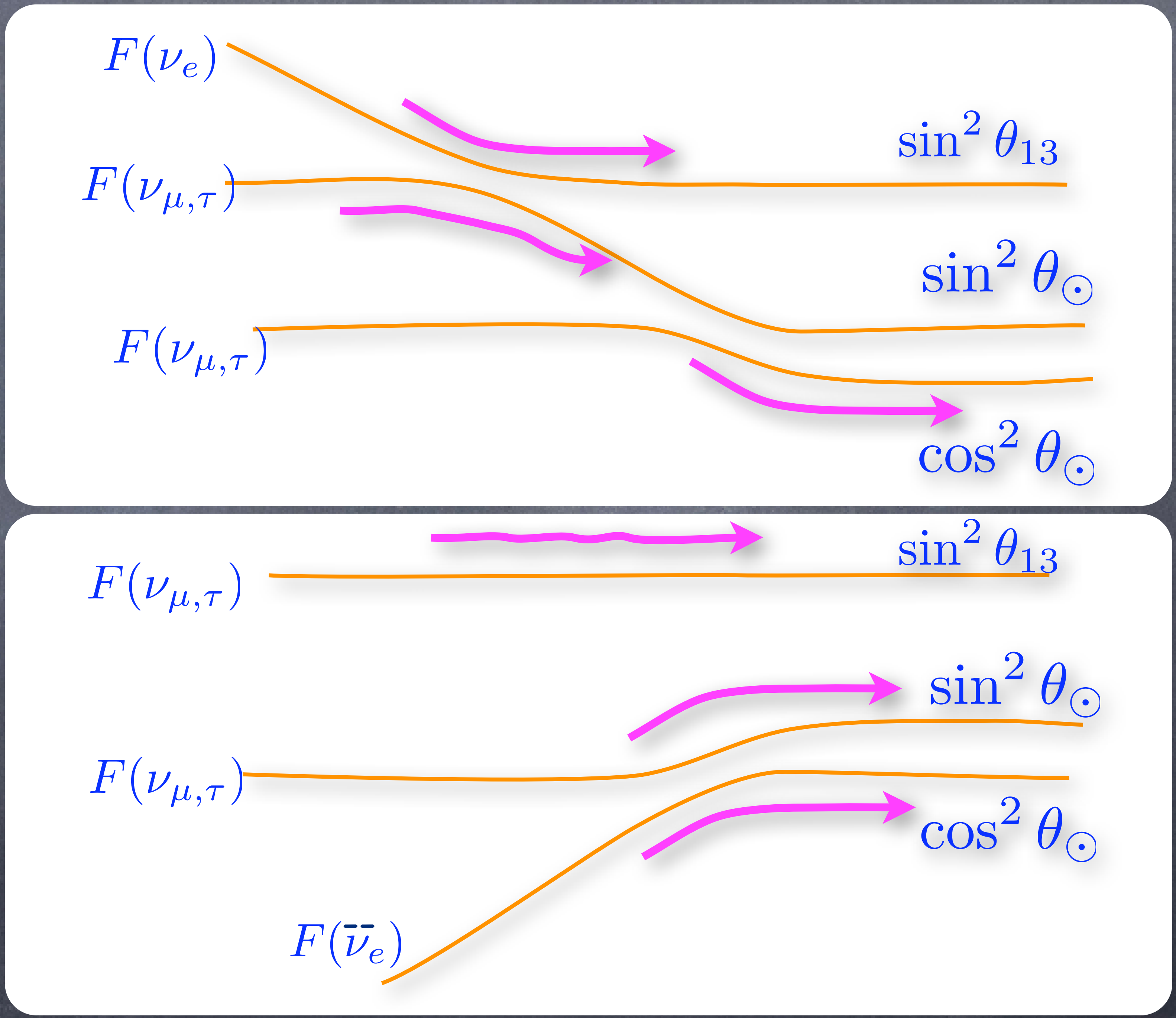


SN ν oscillations: 2 MSW densities



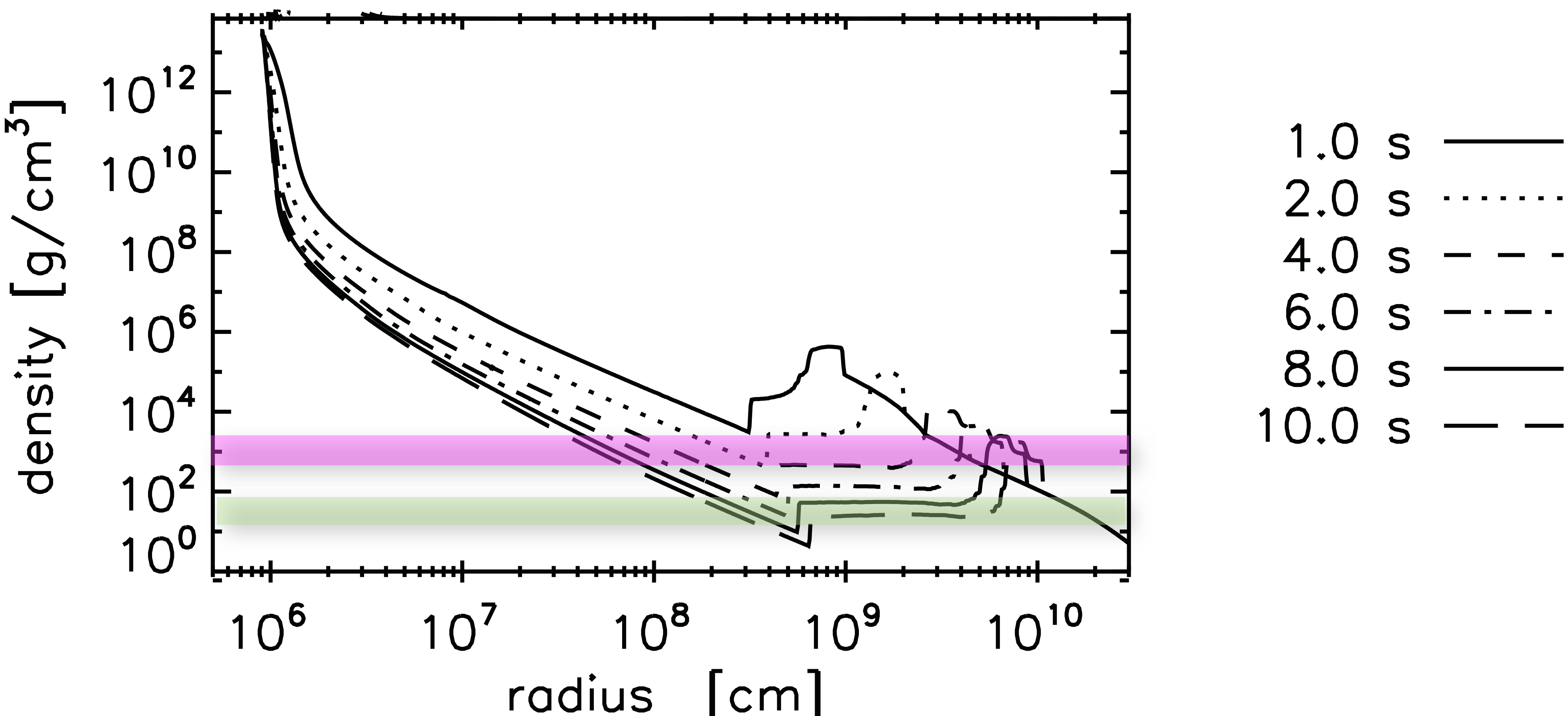
SN MSW transformations, schematics

- Given the scale height in the progenitor, the evolution is very adiabatic
  - the adiabaticity of the atmospheric resonance is controlled by <u>theta13</u>
- 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.

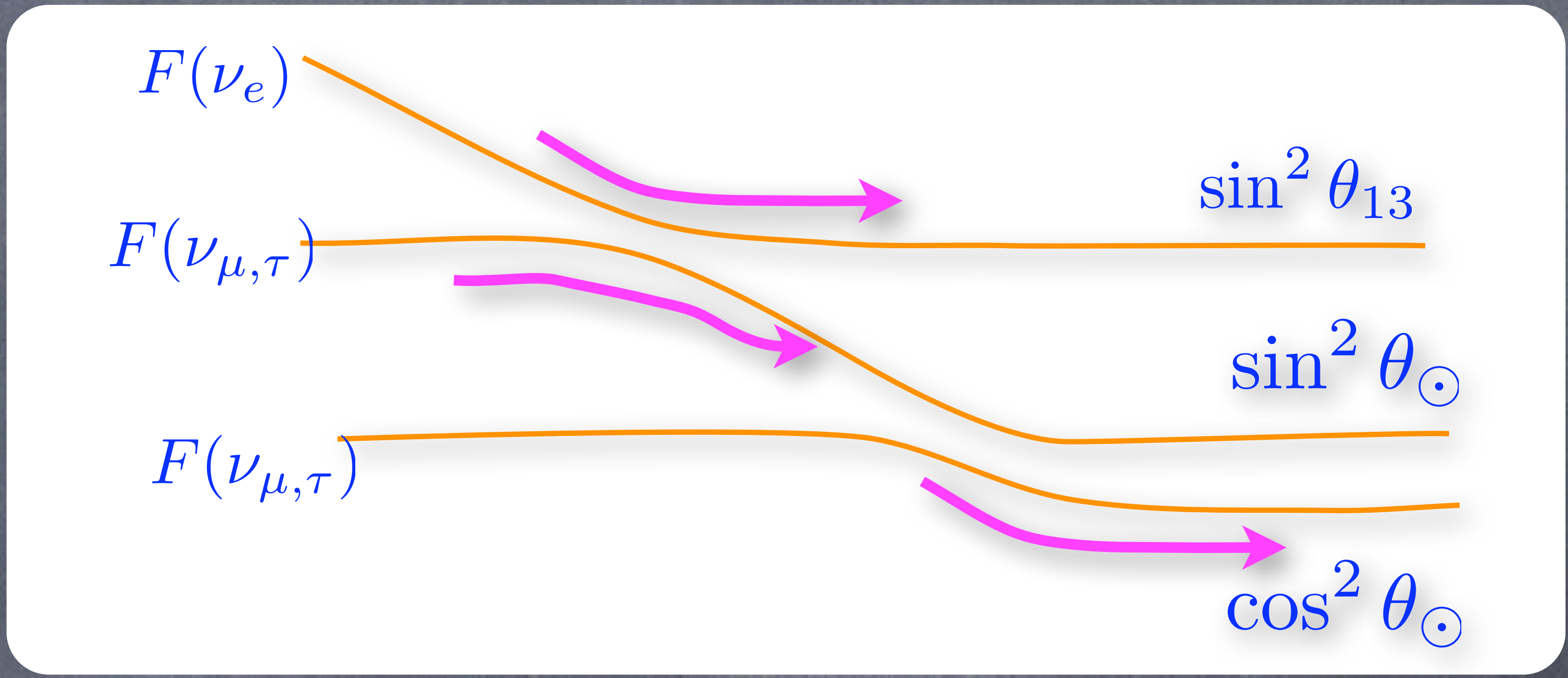
Dynamical density profile

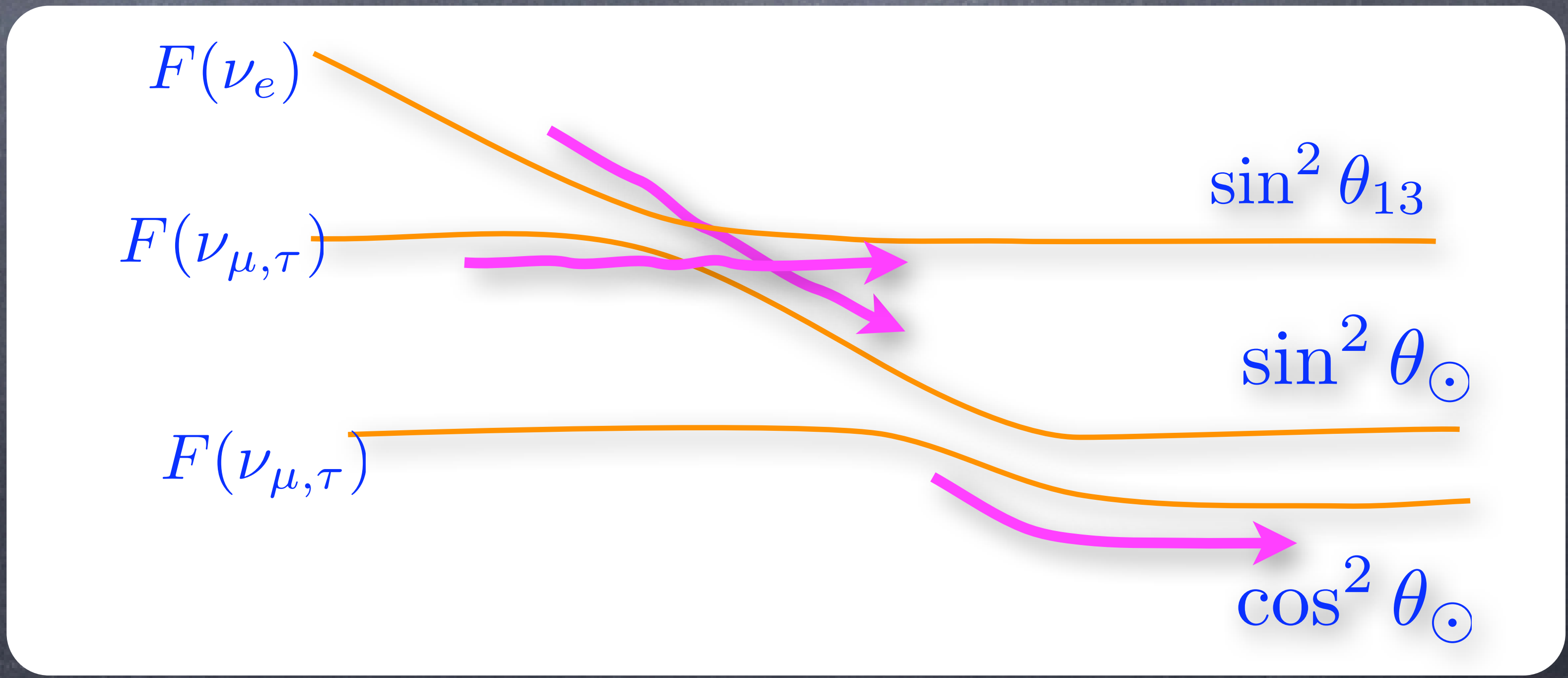


- Front shock reaches the regions where “atmospheric” and “solar” transformations happen, while neutrinos are being emitted
  - See Schirato & Fuller (2002) astro-ph/0205390

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.

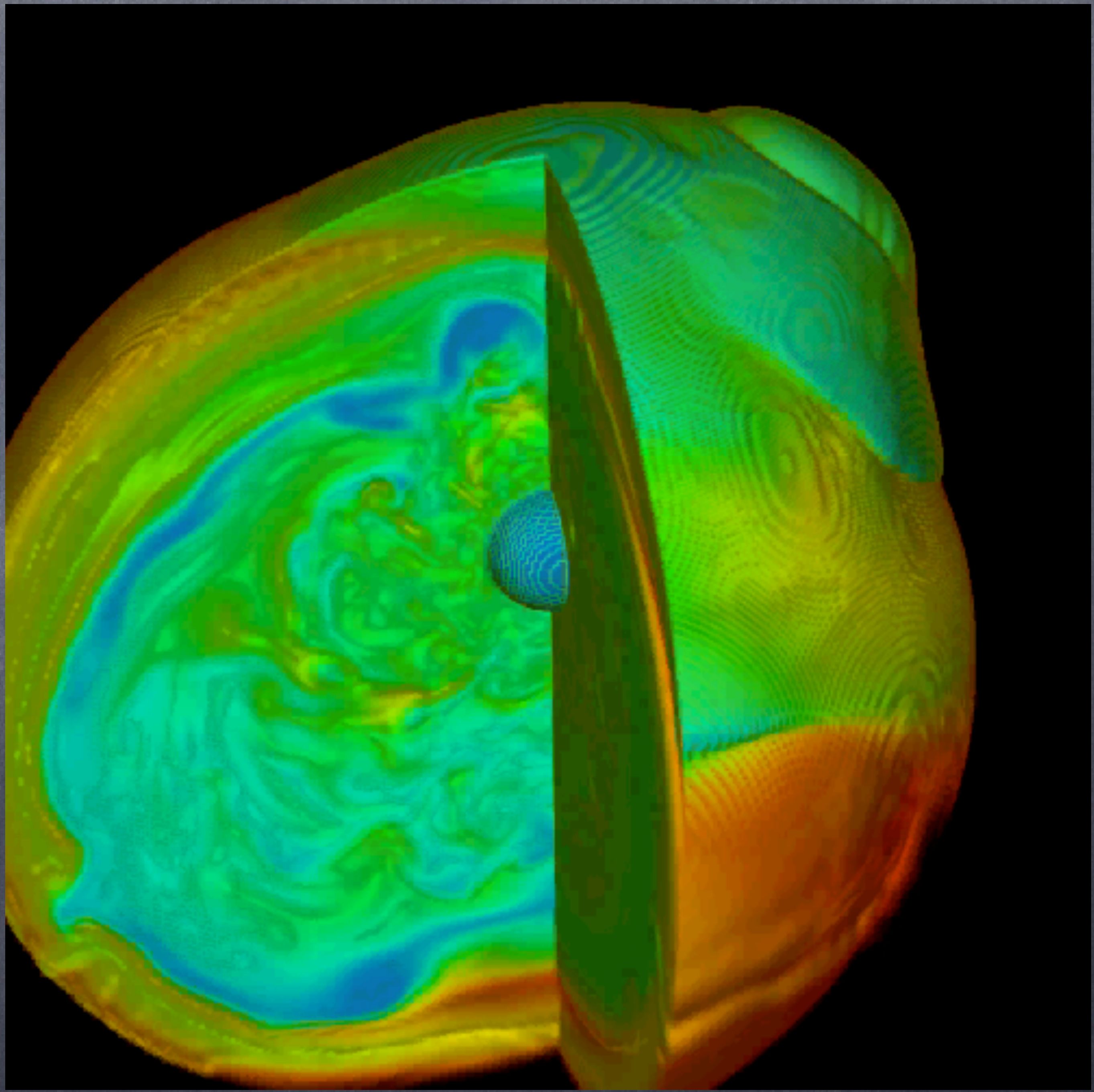




For inverted hierarchy, the same happens in antineutrinos.

3D simulations show turbulence

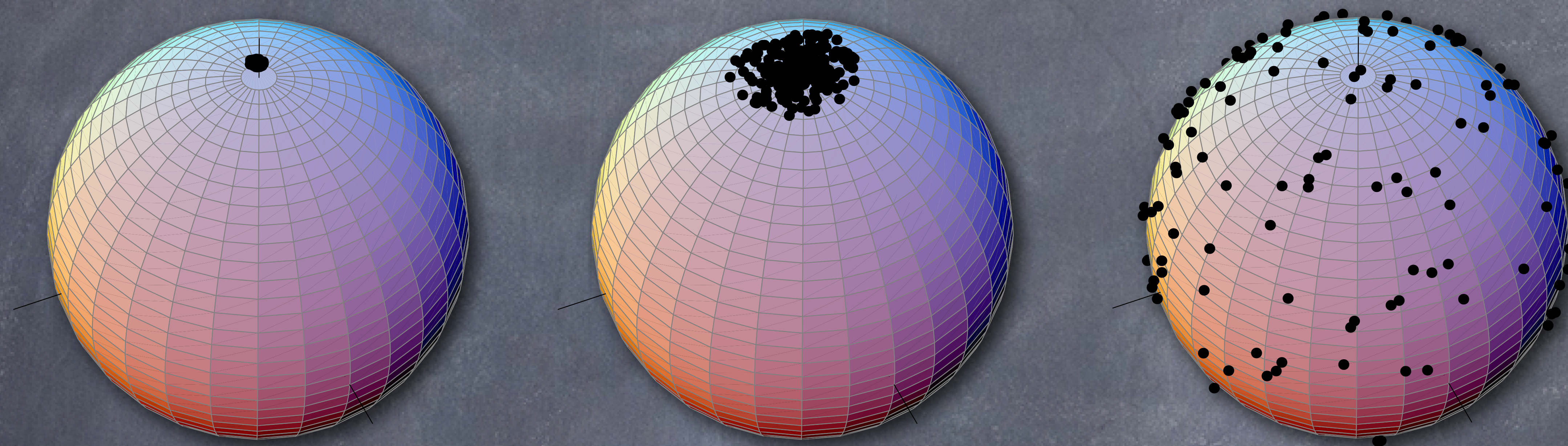
- 3d simulations of the accretion shock instability Blondin, Mezzacappa, & DeMarino (2002)
- See http://www.phy.ornl.gov/tsi/pages/simulations.html
- extensive, well-developed turbulence behind the shock



Reproduced in a backyard water experiment

- Foglizzo, Masset, Guilet, Durand, Phys. Rev. Lett. 108, 051103 (2012)
- Made PRL cover and APS Viewpoint highlight

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

Turbulence in realistic simulations

- 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
  - turbulence should cause observable depolarization, when large-scale fluctuations are

$$\delta n_L/n_L \gtrsim 0.07\theta_{13}^{1/3} \sim 4\%$$

for details, see Friedland & Gruzinov, astro-ph/0607244;
http://public.lanl.gov/friedland/info07/INFO07talks/FriedlandINFO07.pdf

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"

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

- 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

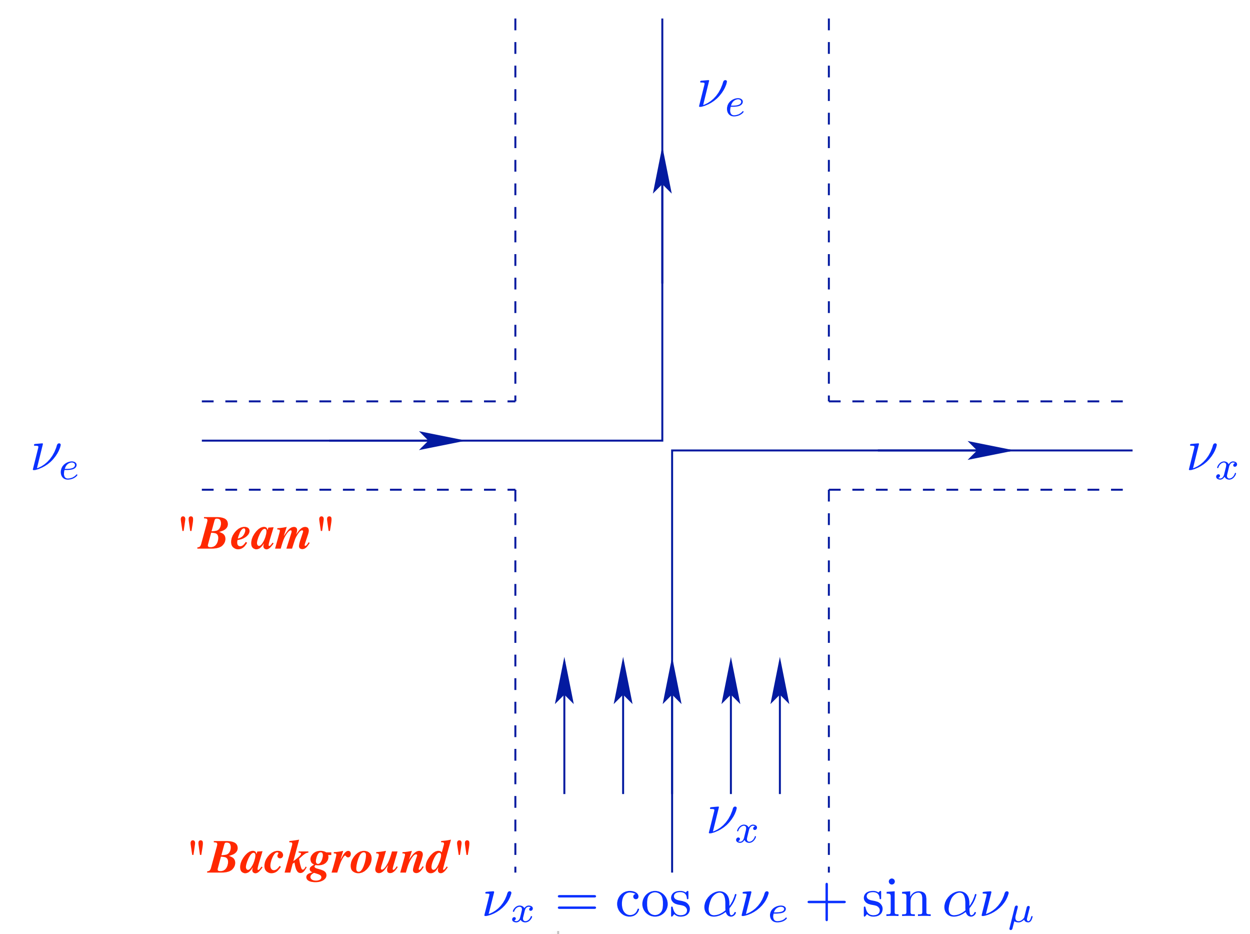
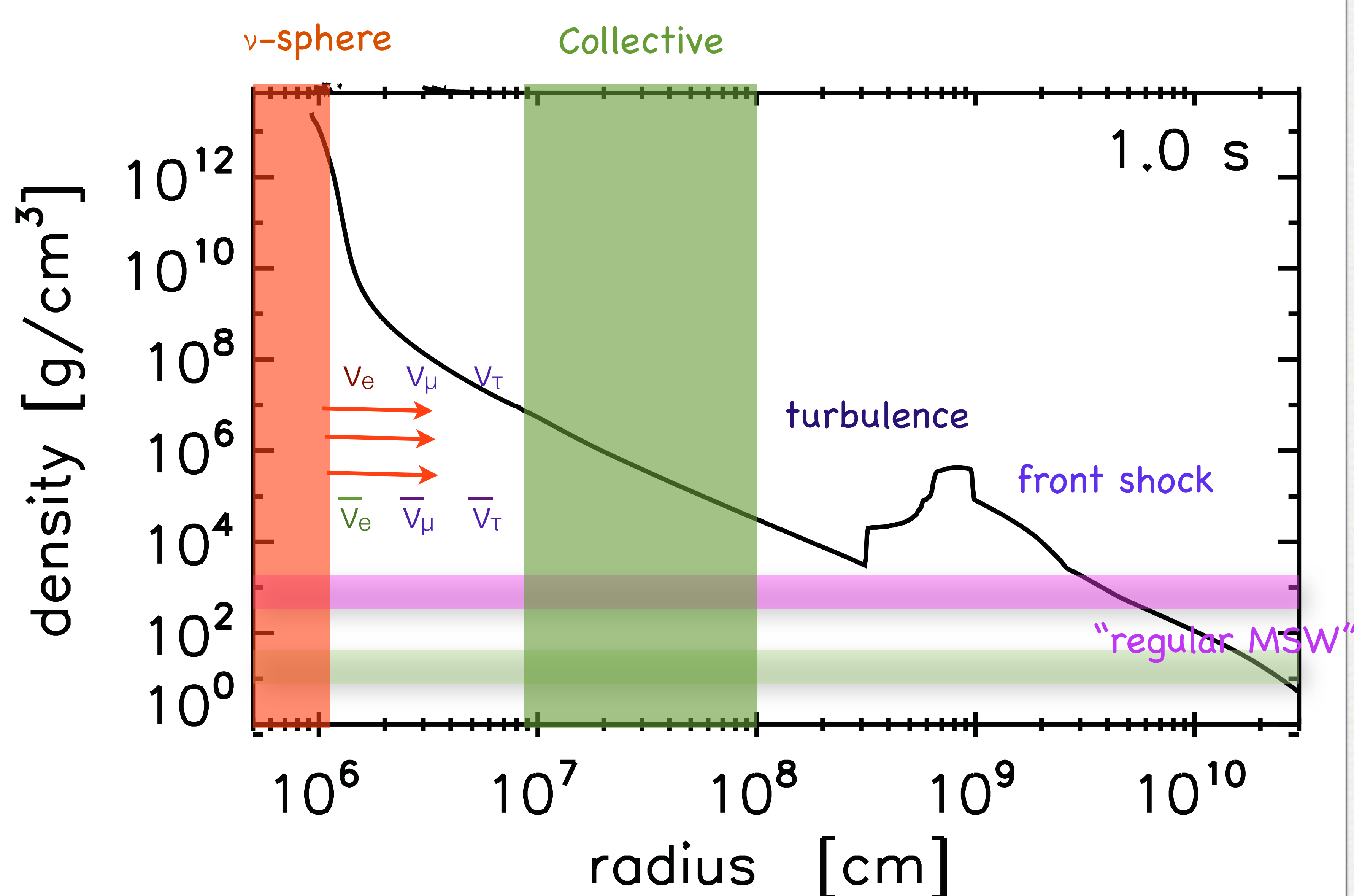


Figure from
Friedland & Lunardini,
Phys. Rev. D 68, 013007 (2003)

SN ν: summary physics cartoon

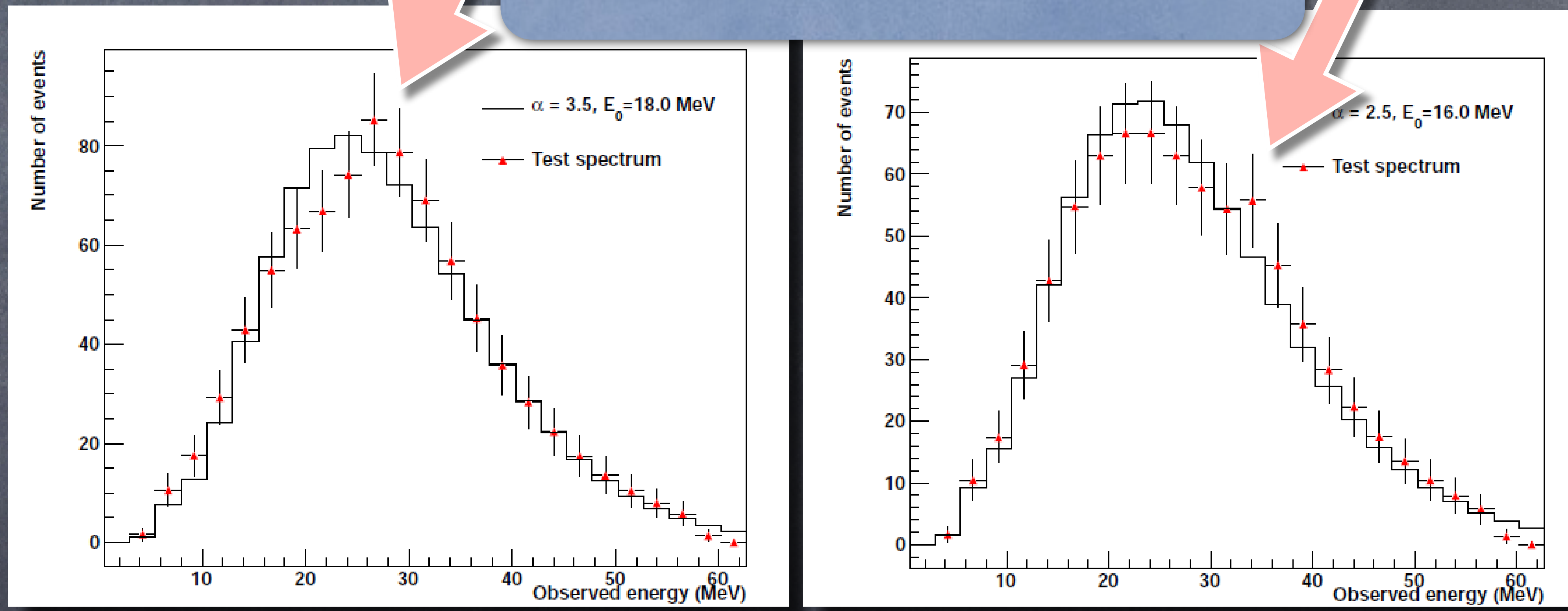


What are we looking for? Smoking-gun features

Modeling multiangle collective + moving shock by A. F.

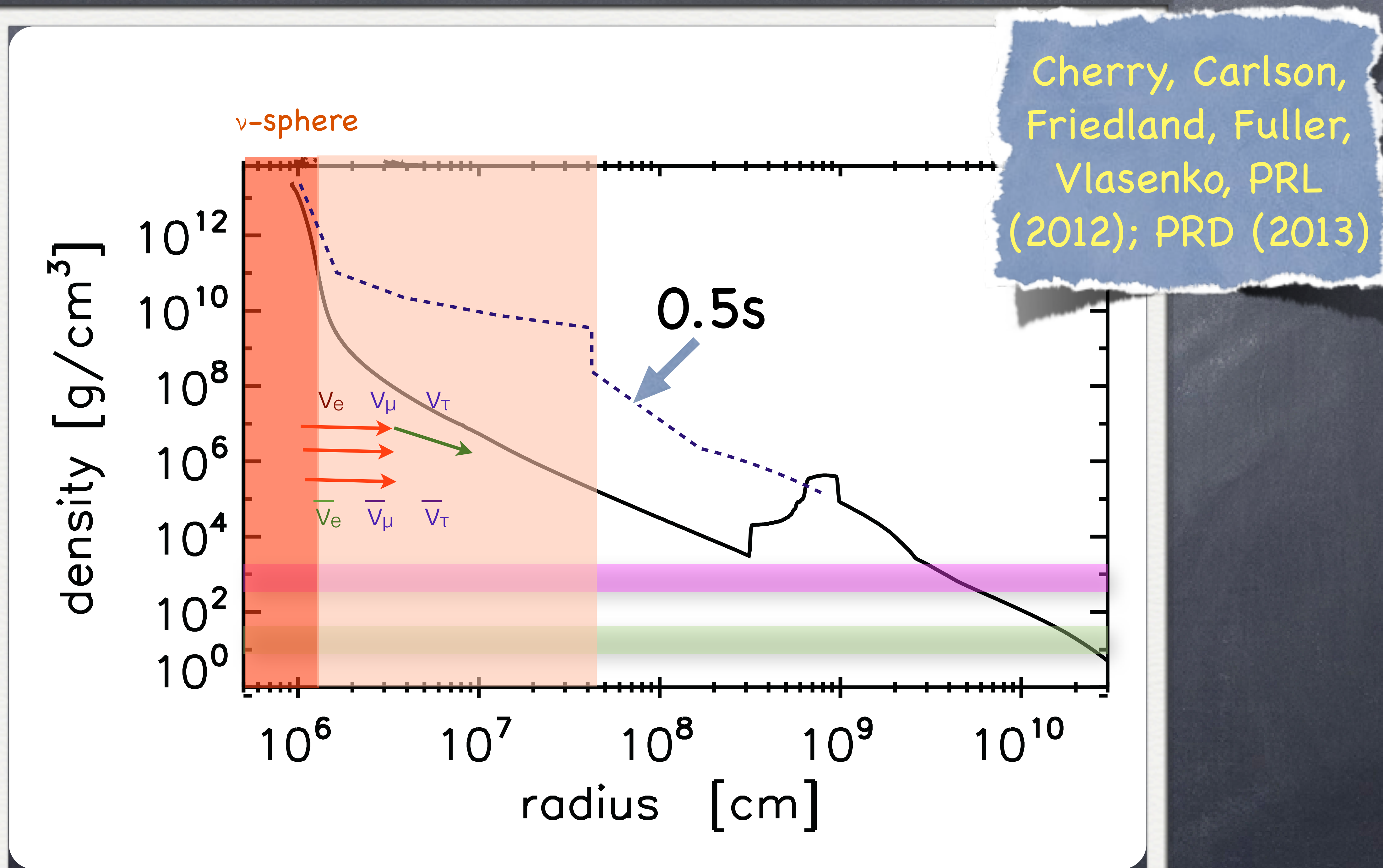
Detector model by K. Scholberg

LBNE science document arXiv:1307.7335v3



- 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)

Summary

- The physics of SN neutrino oscillations is extremely rich, much more interesting than thought 15 years ago!
- Changing, turbulent density profile can modulate the signal in a unique way: tells us about the development of the explosion
- Collective oscillations: qualitatively new phenomenon, inaccessible in the lab
  - Known physics → not optional
- Need to explore and understand different physical regimes