# Supernova neutrinos: time-dependent features

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CERN NEUTRINO PLATFORM WEEK

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# Prelude and disclaimer

- I come to CERN wearing two hats
  - I'm a theorist interested in neutrino physics and astrophysics

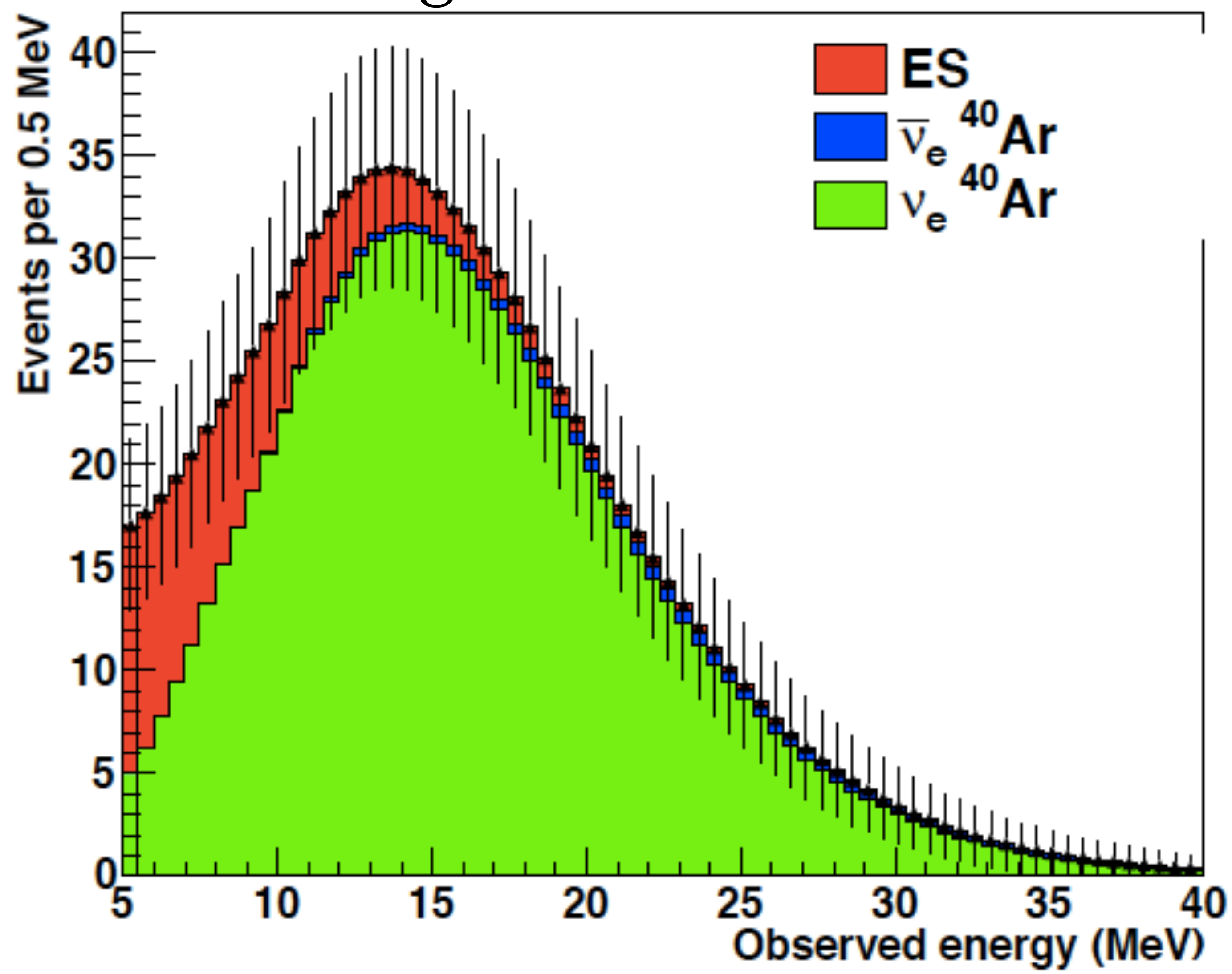
  - I'm also a convener (w/ Kate Scholberg and Ines Gil-Botella) of the SNB/LE working group on DUNE

- **This is not a DUNE talk**
  - I won't show any ongoing, internal work or plots from the WG or the collaboration (DUNE members in the audience, please come tomorrow morning!)
  - Here, I want to discuss some of the physical signatures that would be great to see in the next SNB. The focus is on the time-dependent features of the signal.

# Setup

- Suppose a large, modern experiment is in the final design stages
- They come to you and ask:
    - *We know there is no standard model of the explosion. We want to learn about the explosion from our data. Can you give us some simulated fluxes with interesting features, so that we may benchmark different design decisions?*
- You start with the obvious: *Measure total number of events, energy spectrum*
- But then you think: *Since they have enough statistics to make time slices of the data, they definitely should look for the time evolution of the signal*

Expected event spectrum integrated over time




DUNE 40 kt LAr (SN @10kpc)

Disclaimers: one particular simulation, perfect detection, no oscillations

# Evolution of the explosion is reflected in neutrinos

- The neutrino signal clearly shows different stages of the explosion: neutronization burst, accretion through stalled shock, PNS cooling

- Importantly, these are different for different progenitor masses

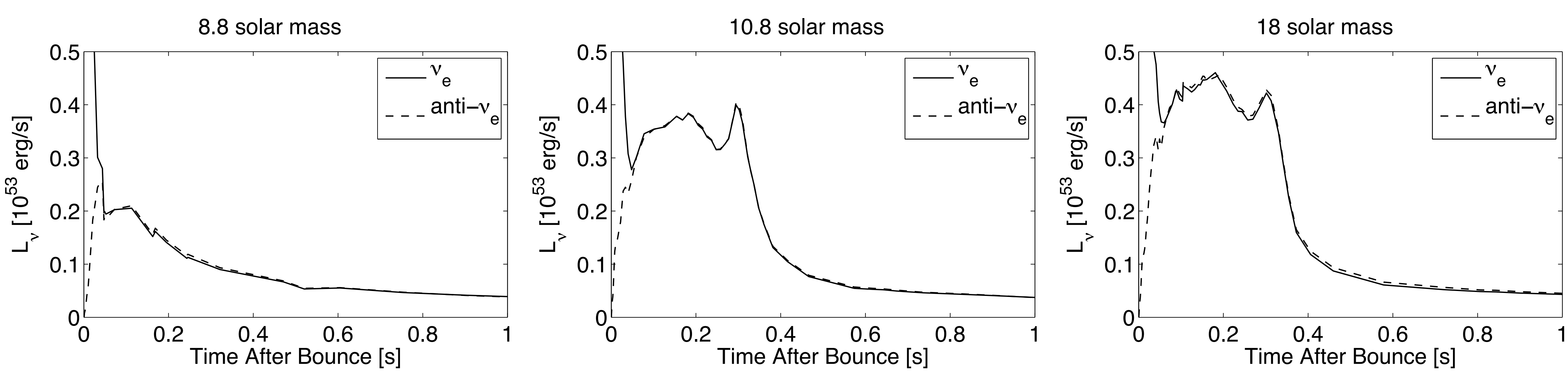
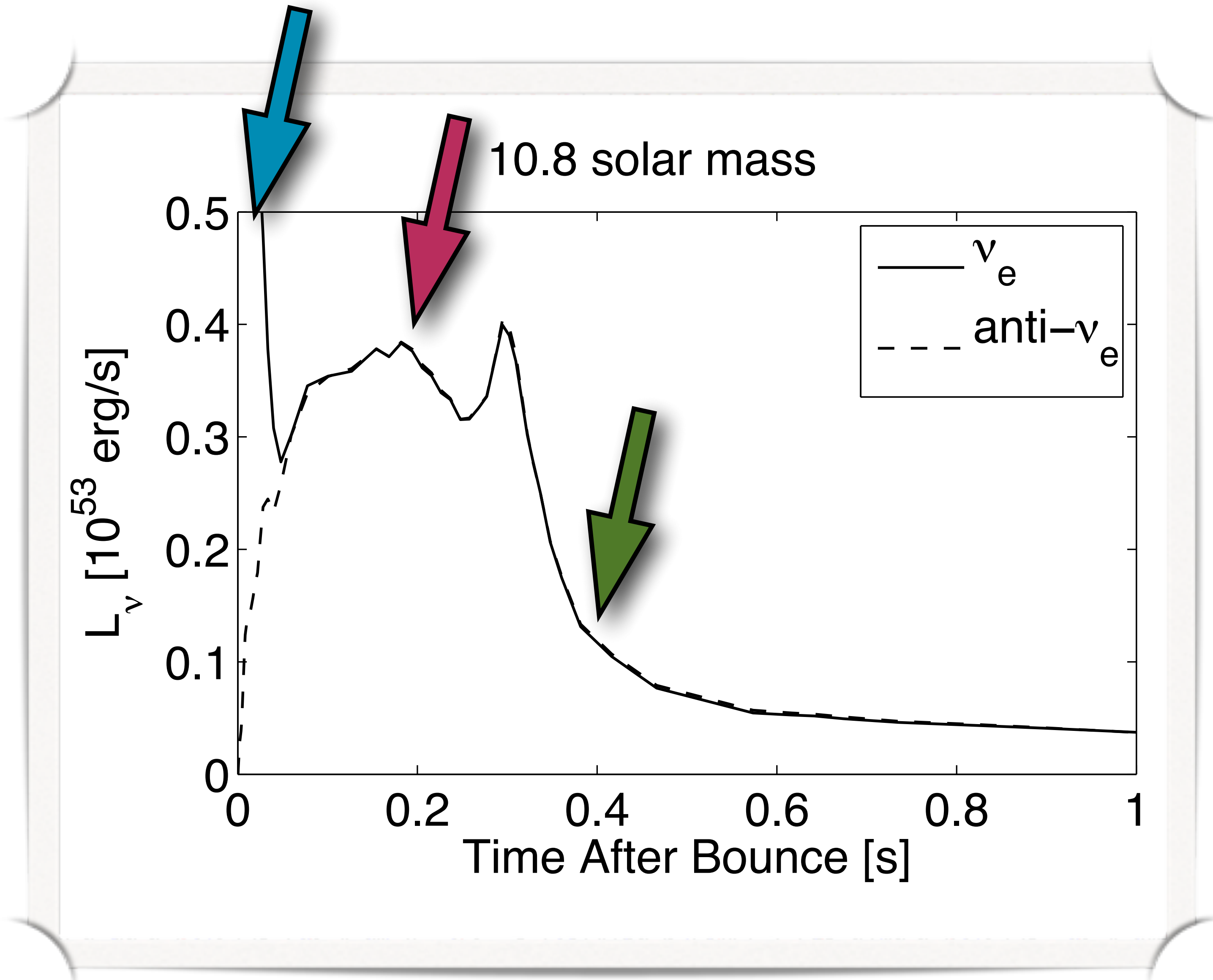


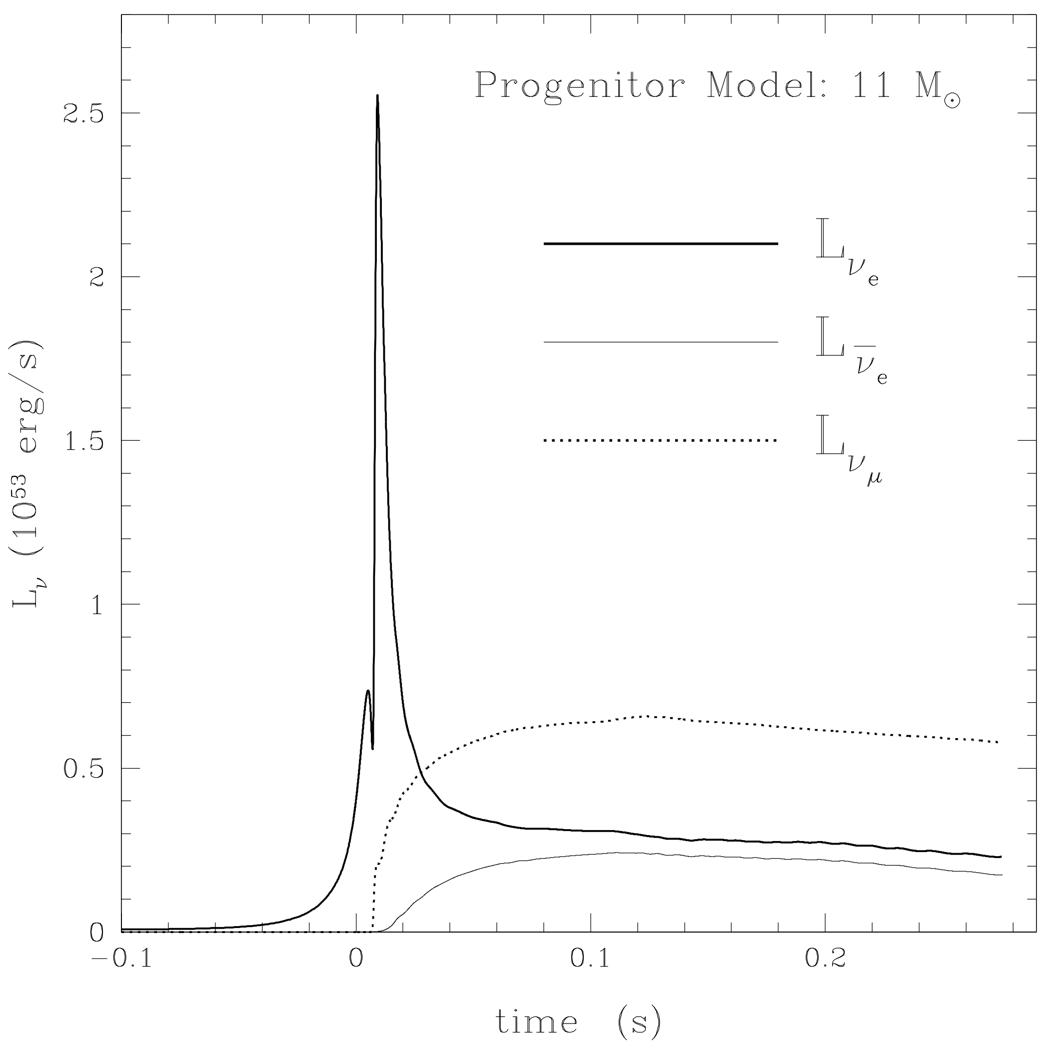

Fig from Fischer, Whitehouse, Mezzacappa, Thielemann, Liebendörfer, arXiv:0908.1871

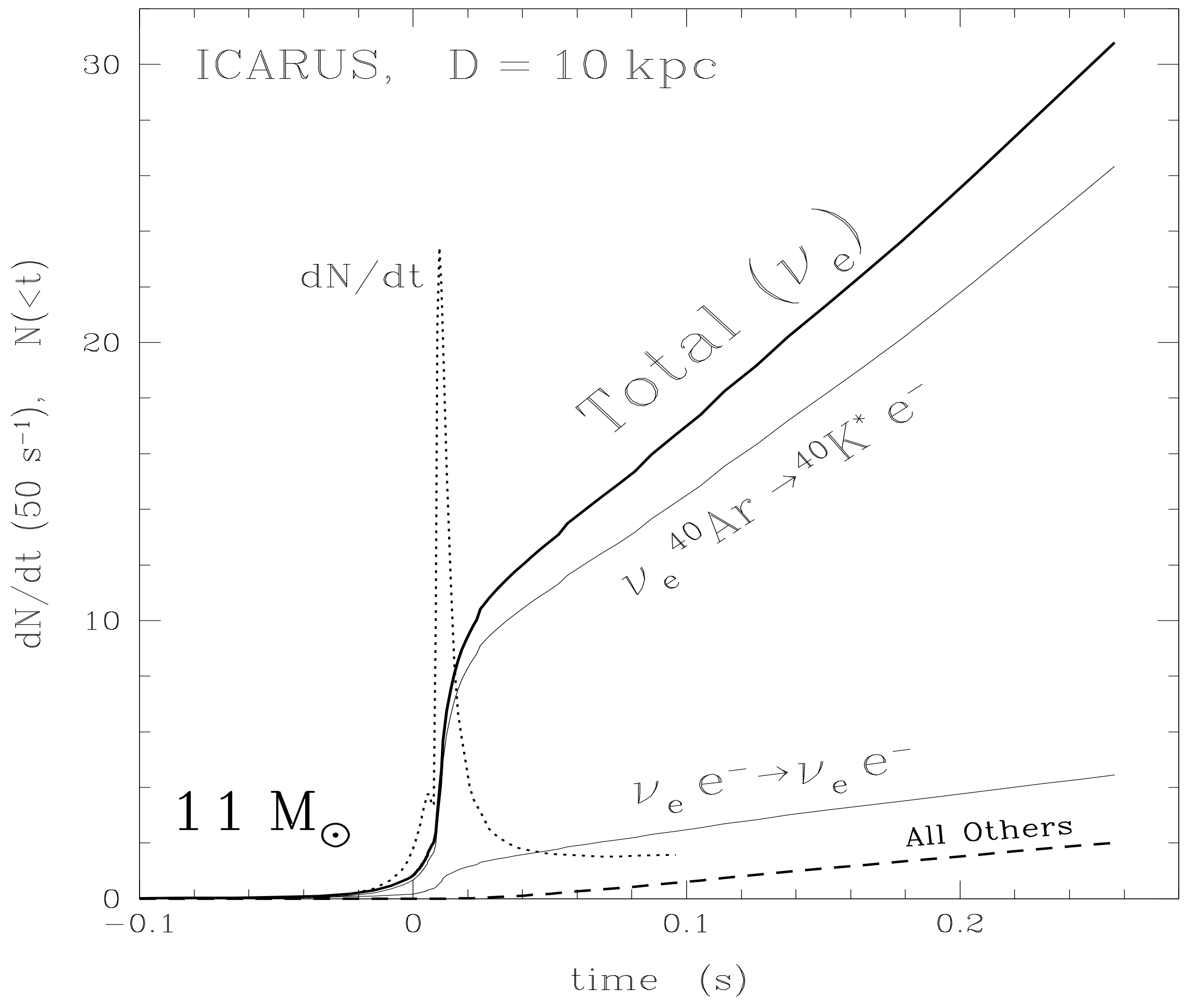
# What are these stages?

- **Shock forms** inside collapsing core, breaks through the neutrino-trapping sphere
- **Shock stalls** at ~ 200 km, while the material keeps raining onto the core, releasing graviational binding energy in neutrinos
- **Shock is pushed out**, the central, dense region cools, losing energy and trapped lepton number; settles into a neutron star (or a BH!)



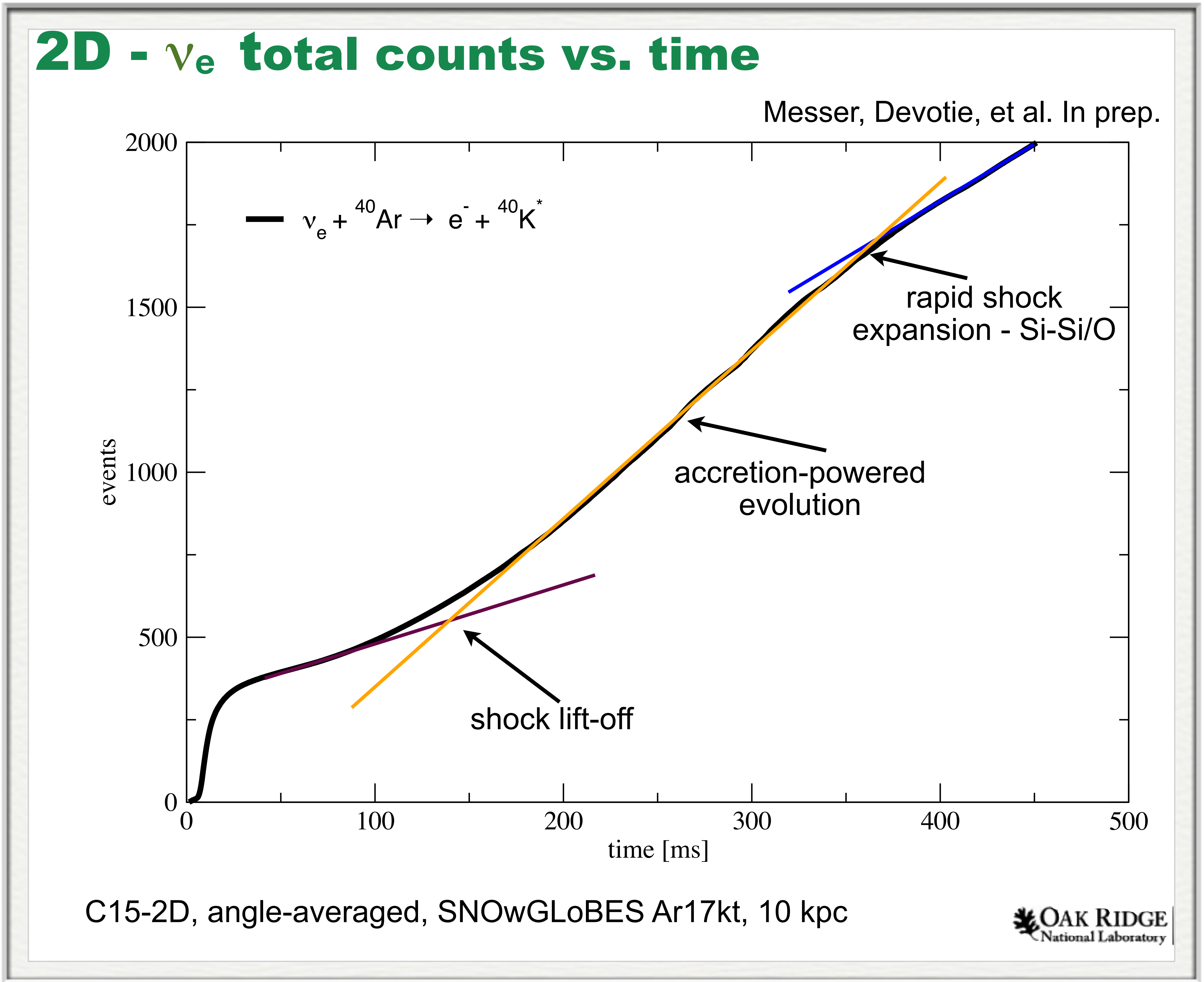
# Neutronization burst



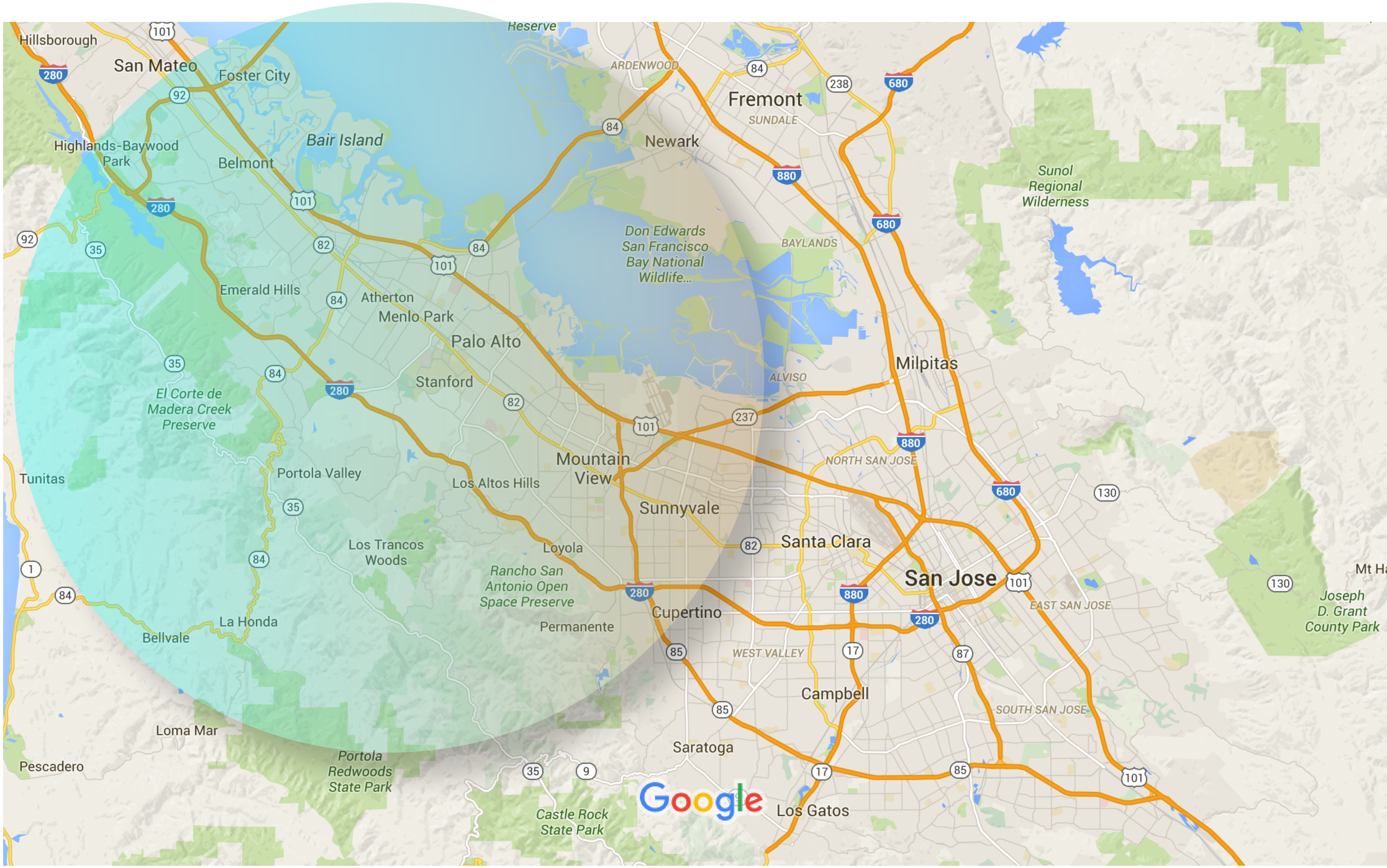




Thompson, Burrows, Pinto, astro-ph/0211194

# Update from the Oak Ridge group



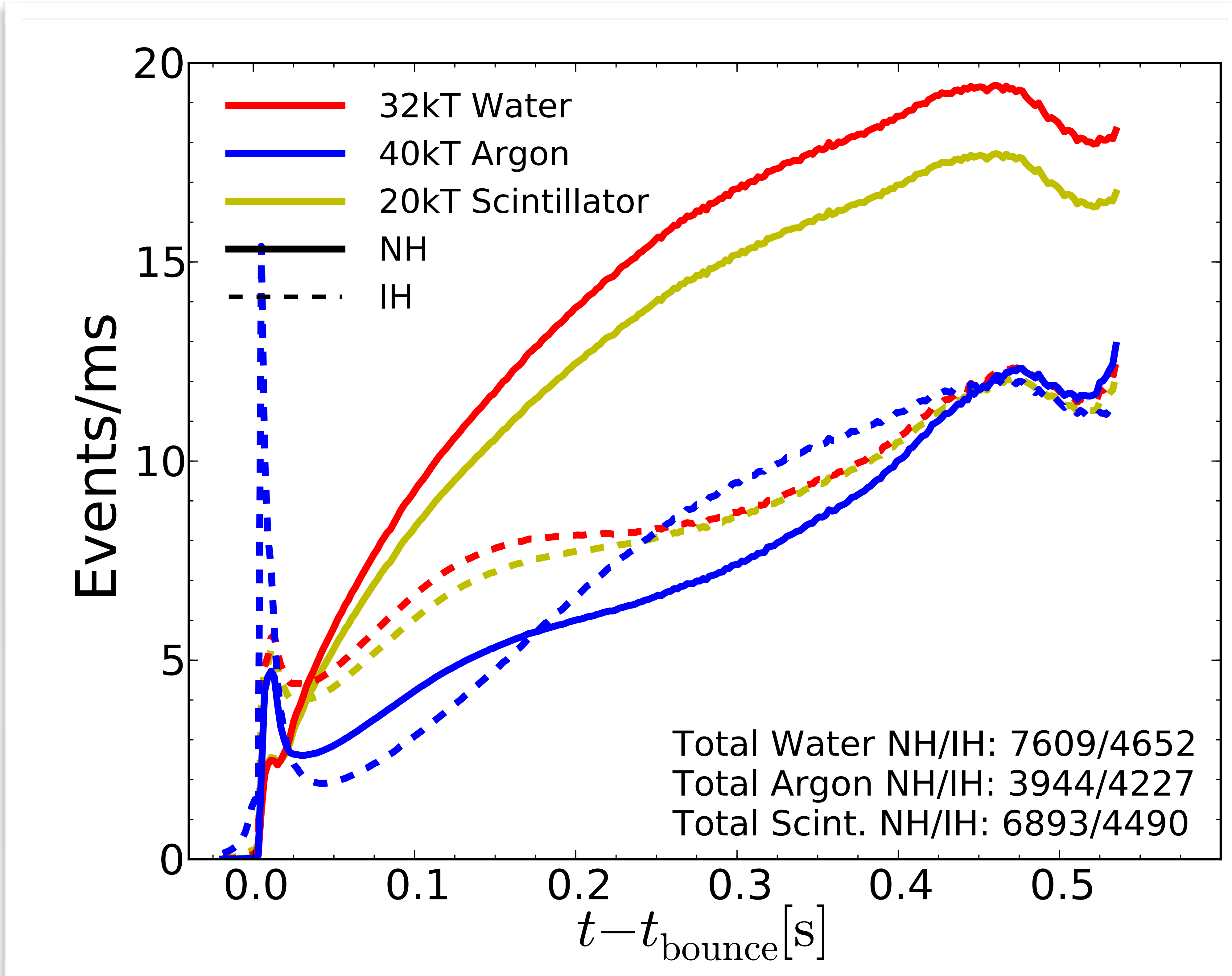
Google Maps




Map data ©2016 Google 2 mi

# Final Neutron Star, M~1-2 $M_\odot$

Grav. binding energy ~ 10% of its rest mass, getting close to BH




Or maybe a black hole forms: the signal is very bright and suddenly stops

(credit: Evan O'Connor)

# Evolution of the explosion is reflected in neutrinos

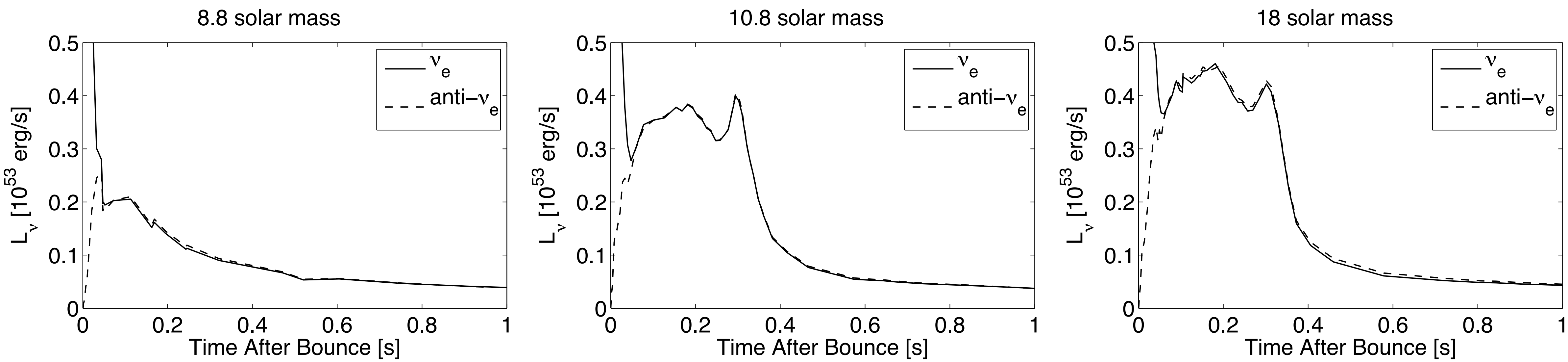
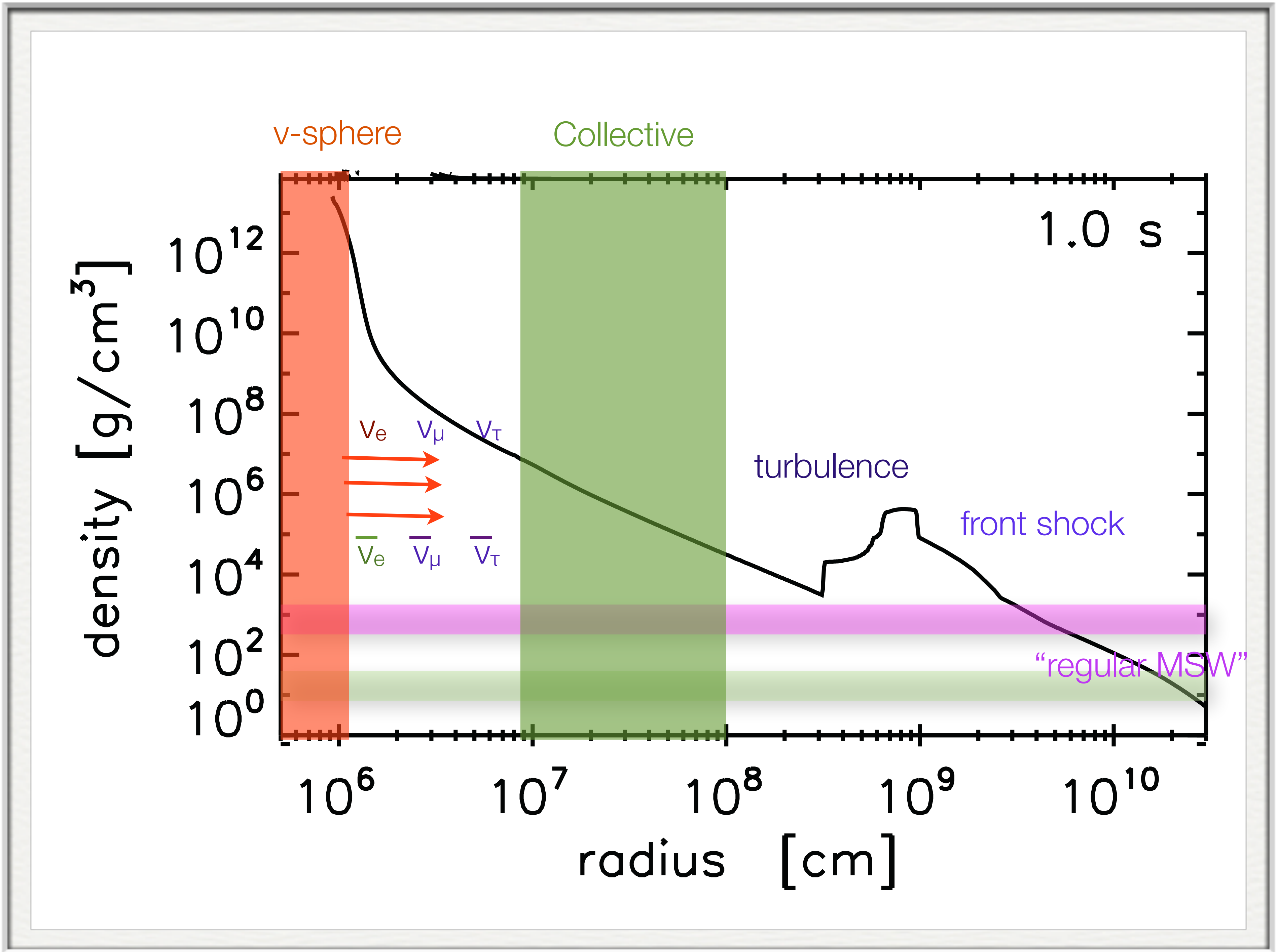



Fig from Fischer, Whitehouse, Mezzacappa, Thielemann, Liebendörfer, arXiv:0908.1871

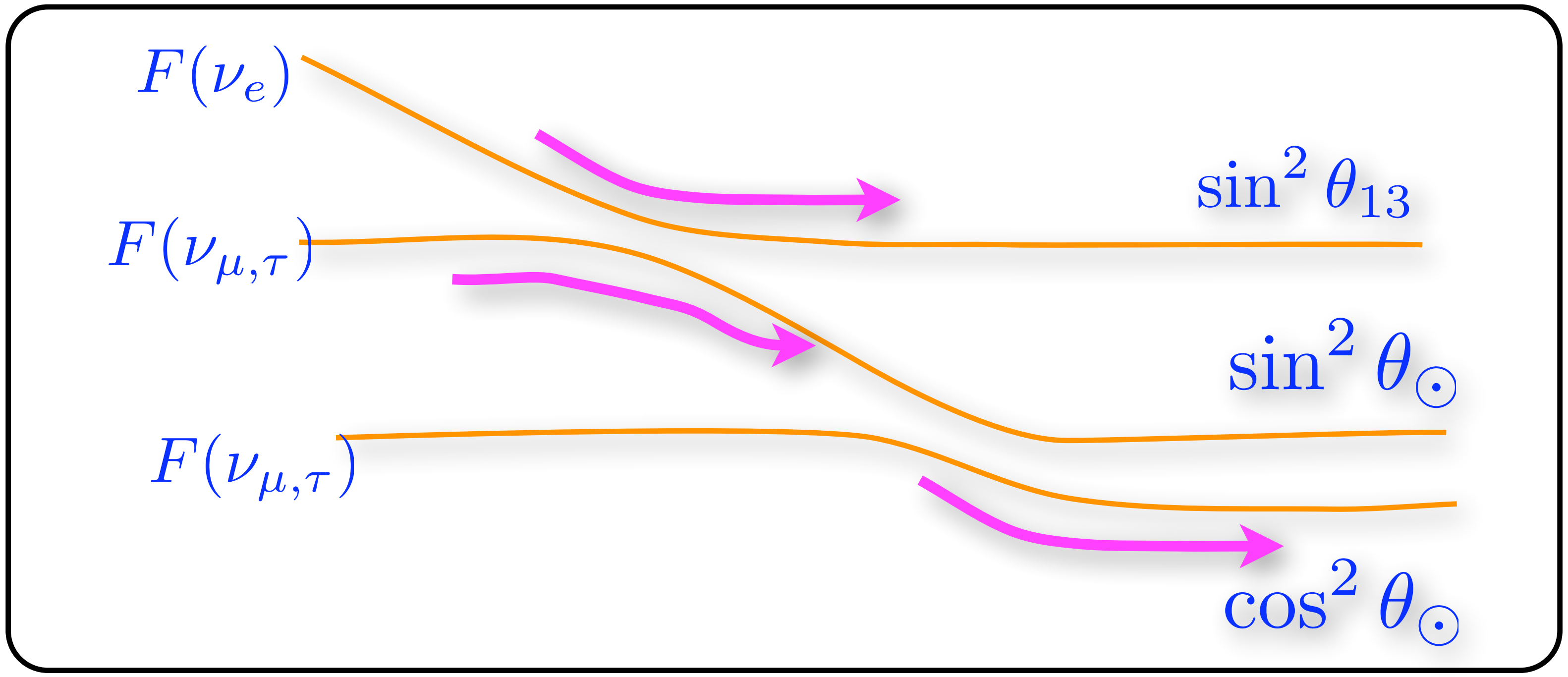
- Caution I: toy models! 1d simulations, artificially exploded
    - There is no 3d model w/ state-of-the-art nu transport and hydro that computes nu fluxes for the duration of the burst
- Caution II: no oscillation effects included!

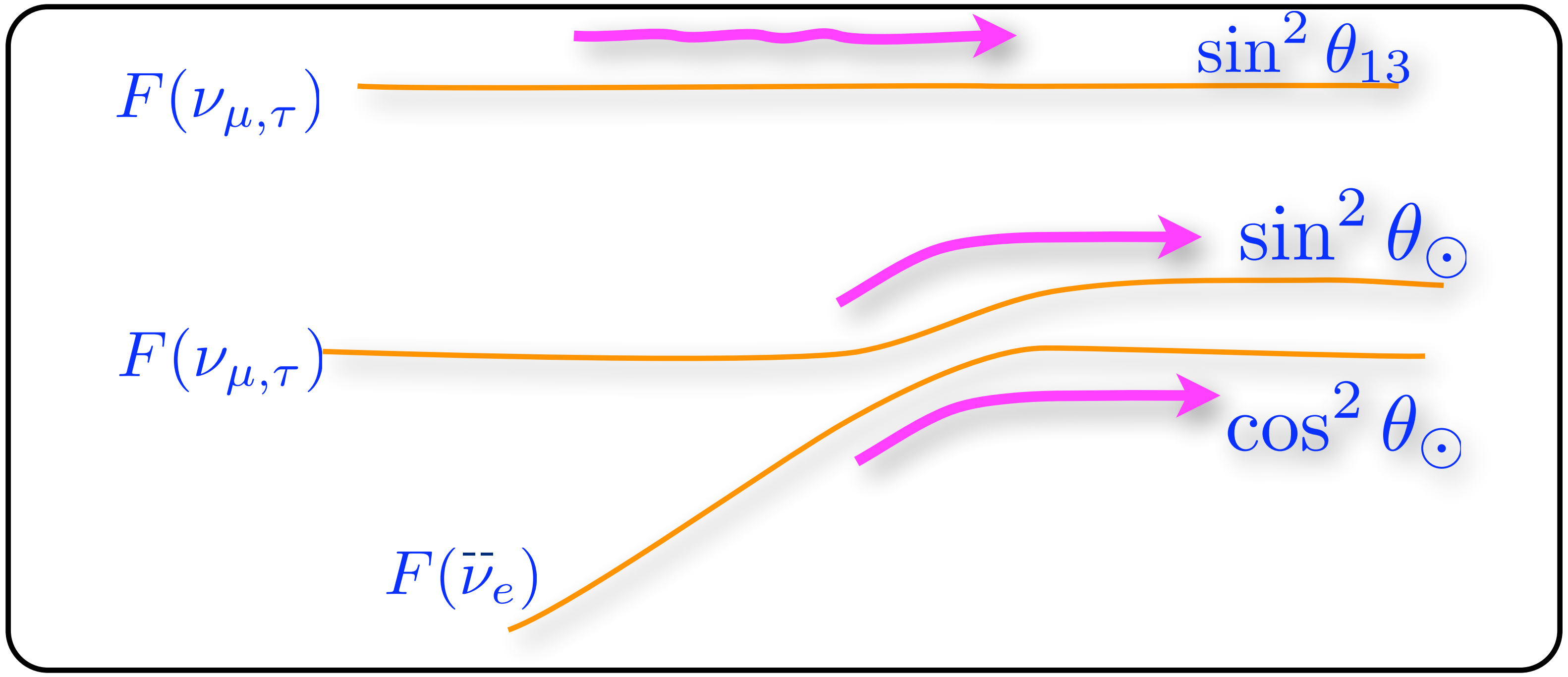
# SN ν oscillations: very rich physics



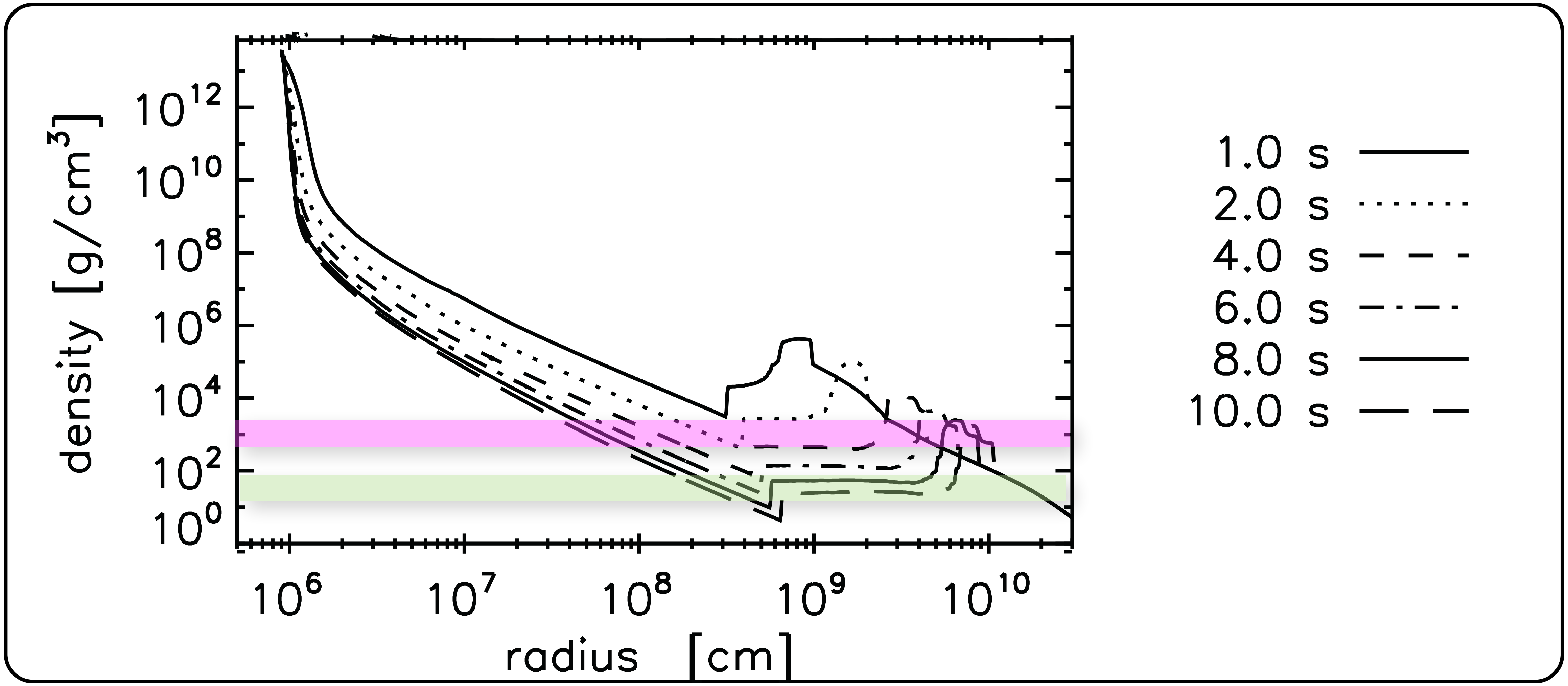
# Part I: MSW transformations, 2 level crossings

- ➡Given the scale height in the progenitor, initially the MSW evolution is very adiabatic
  - ➡the adiabaticity of the atmospheric resonance is controlled by <u>theta13</u>
- ➡For NH, the nue flux during the **neutronization burst** is swept into the nu3 state, largely disappears, from ~300 to ~6 events (by $\sin^2\theta_{13}$)
  - ➡For IH, from ~300 to ~90



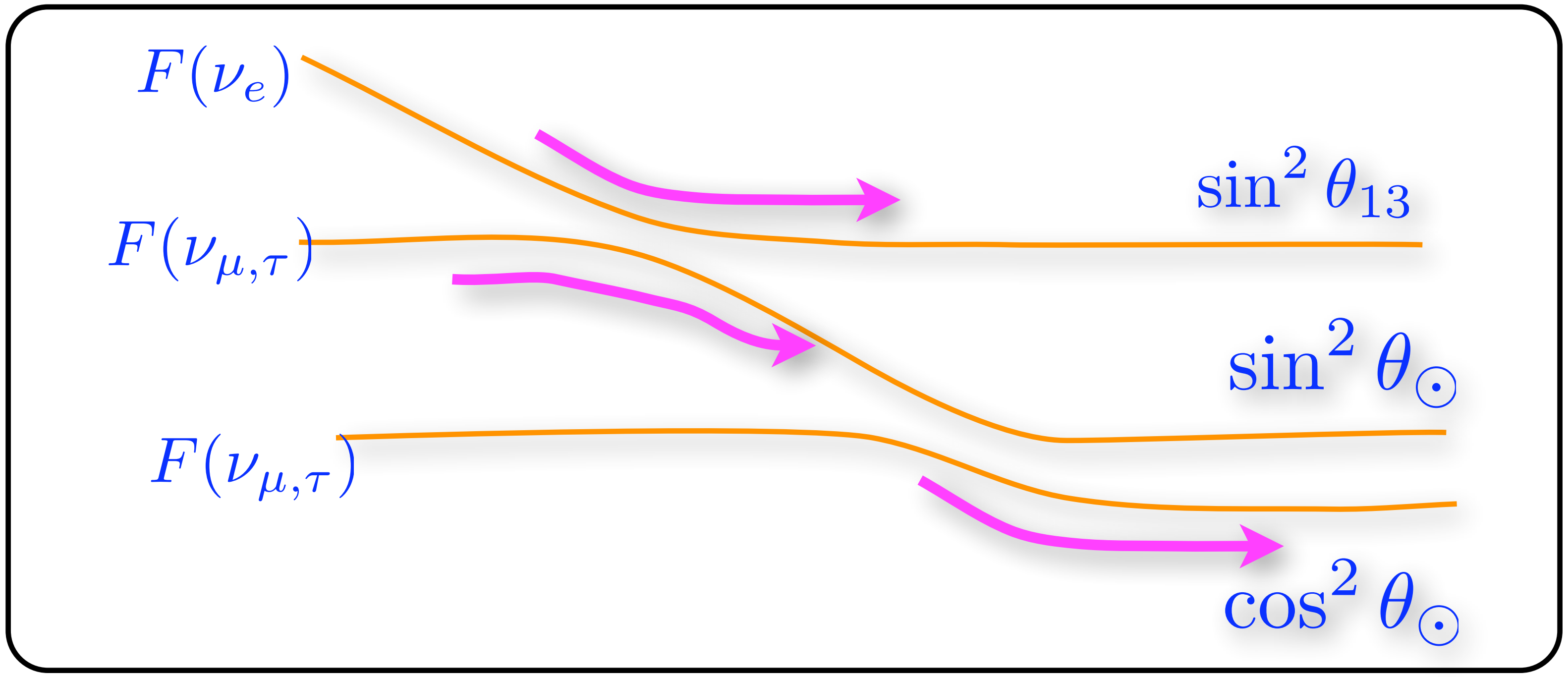
# The key word there was “initially”

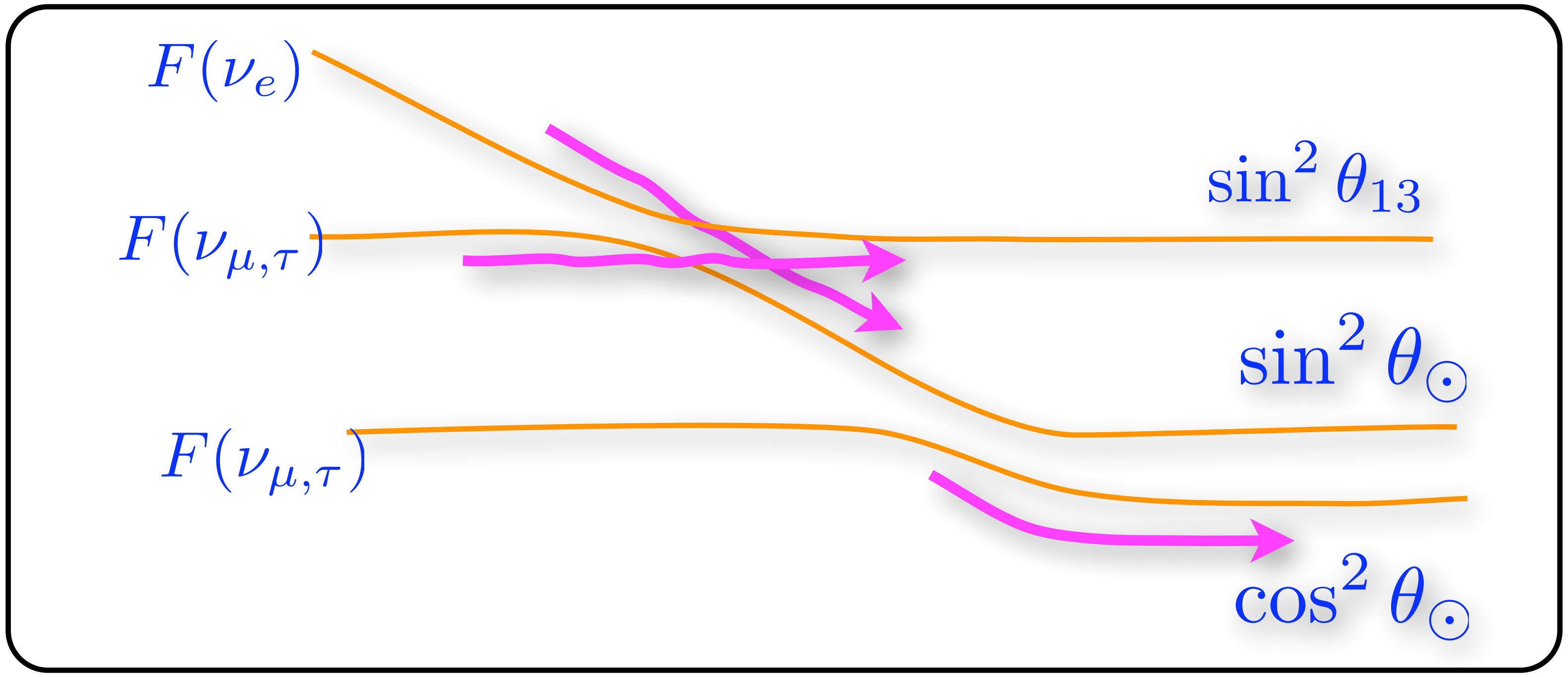



- Front shock reaches the regions where “atmospheric” and “solar” transformations happen, while neutrinos are still being emitted
  - See Schirato & Fuller (2002)  astro-ph/0205390

# Part II:Moving shock and MSW transformations

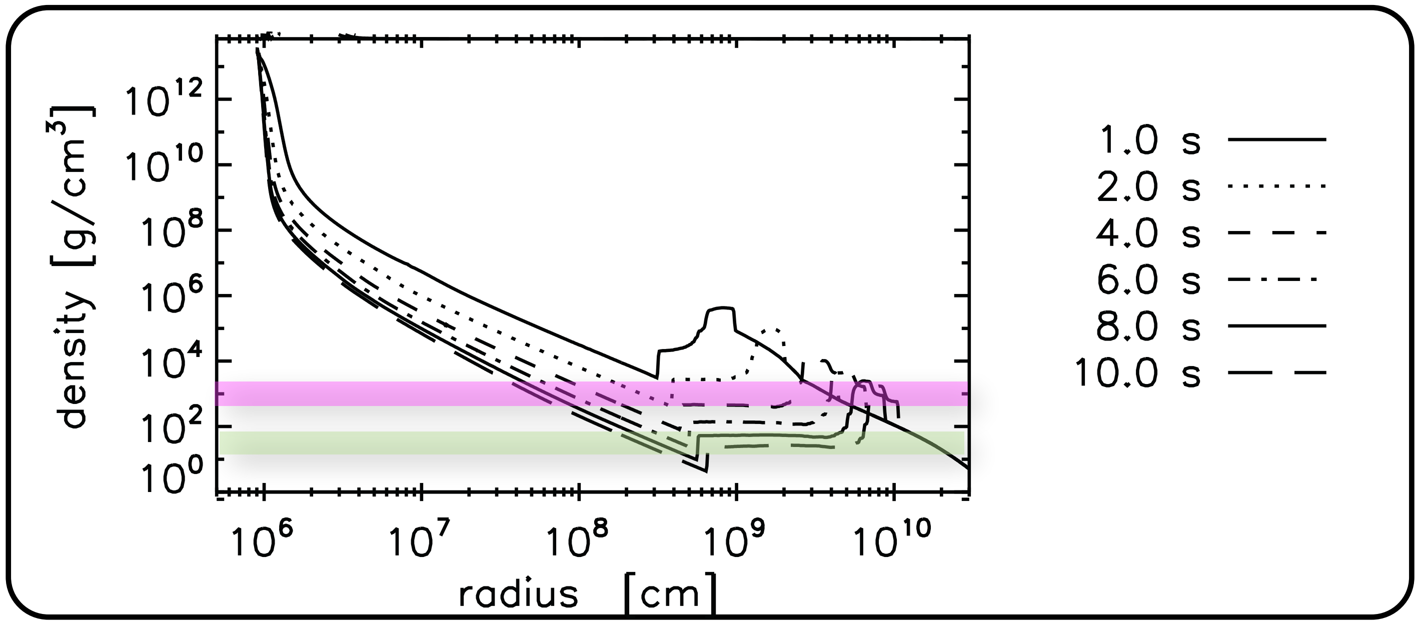
- ➡ The shock is infinitely sharp from the neutrinos' point of view (photon mean free path).
- ➡When it arrives at the resonance, the evolution becomes non-adiabatic
- ➡Now, original $\nu_e$ spectrum mixes in the $\nu_2$ mass state, making it colder
- ➡The transition sweeps from low to high energies, in about a second



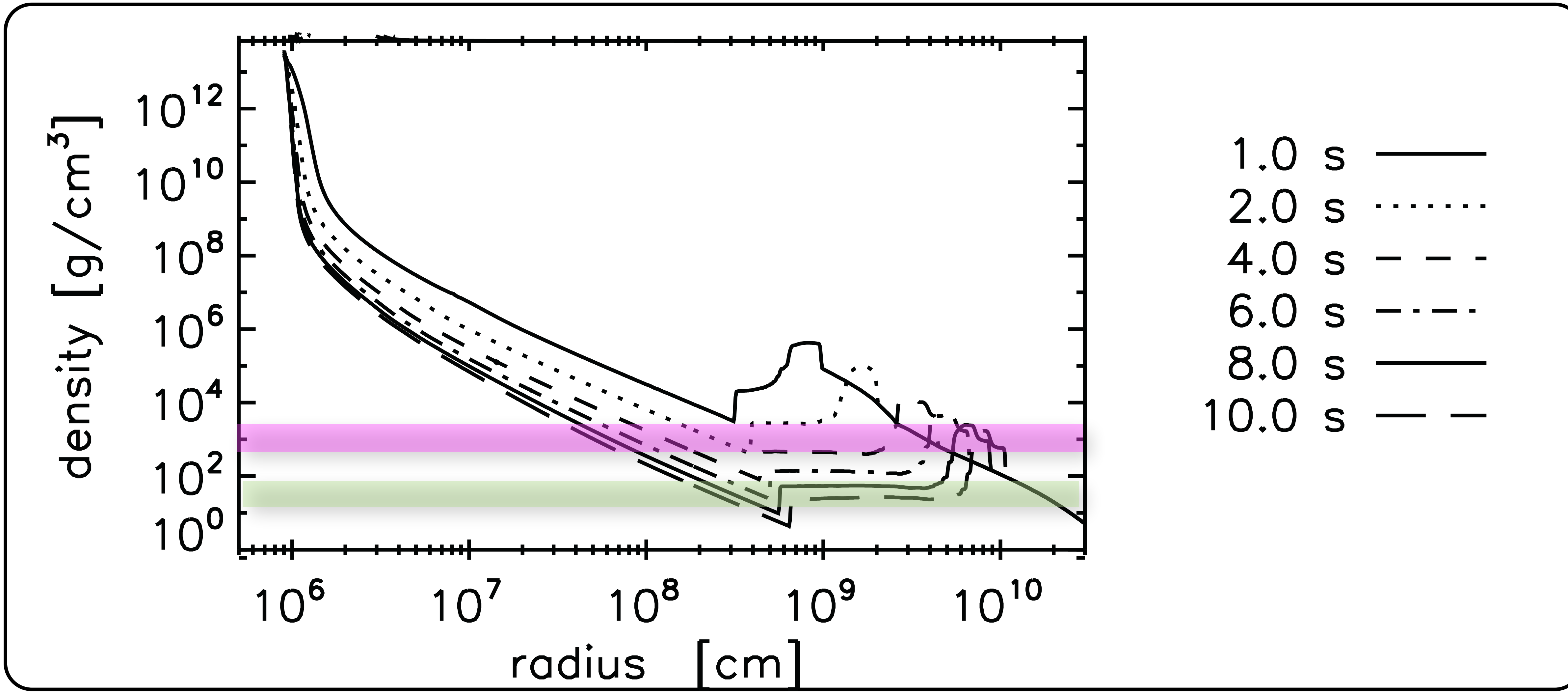

For IH, the same happens in antineutrinos.

# If we observe this modulation




- We would be monitoring shock propagation in real time, measure its speed and the stellar density profile (-> the type of the progenitor star)
- Would immediately know the mass hierarchy
  - Seen either in neutrinos or in antineutrinos, hence need both LAr and WC
- With both channels, by observing modulation in one while not in the other, can exclude the effect of thermal physics at the neutrinosphere.

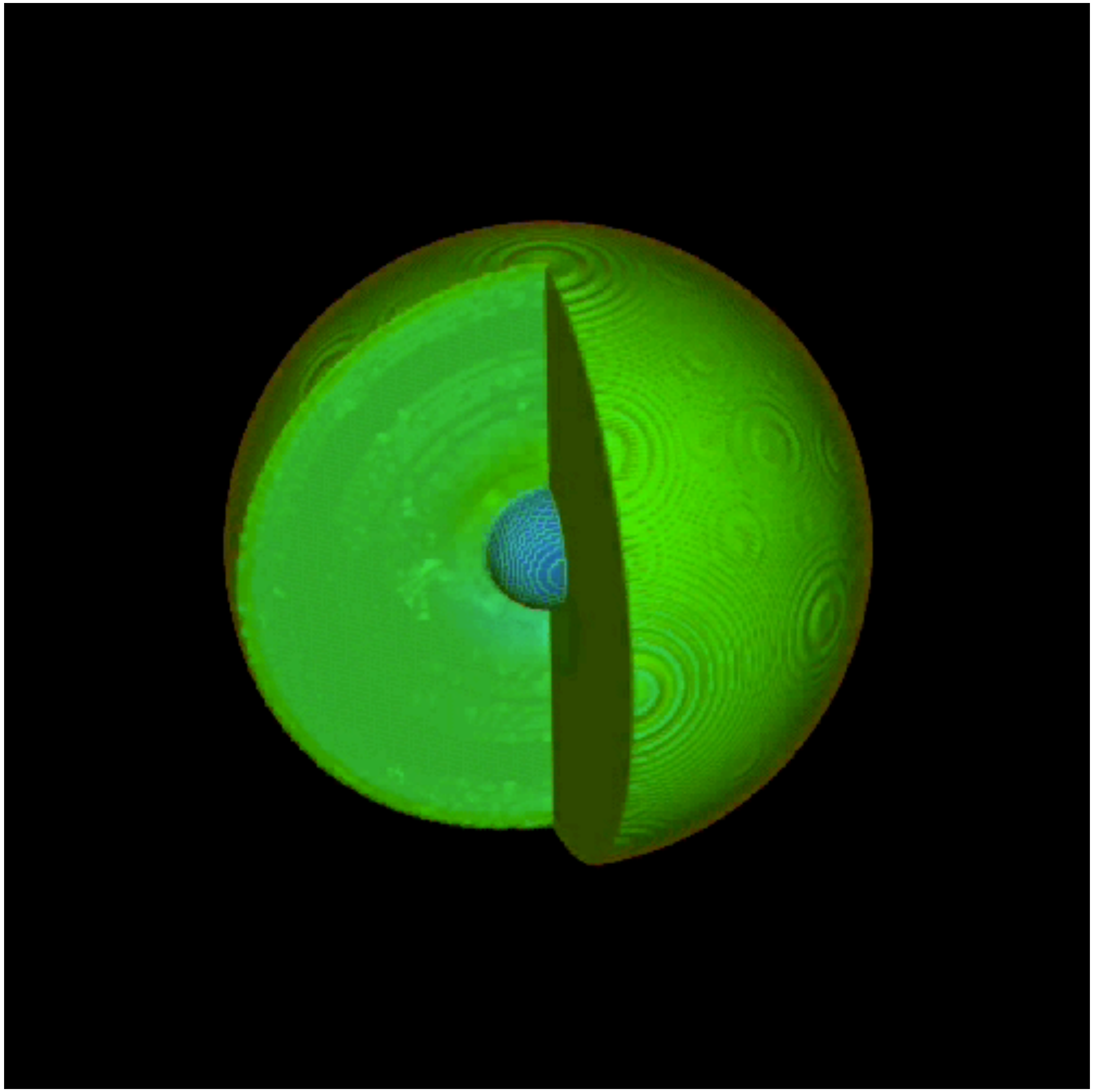
# But what about the region behind the shock?



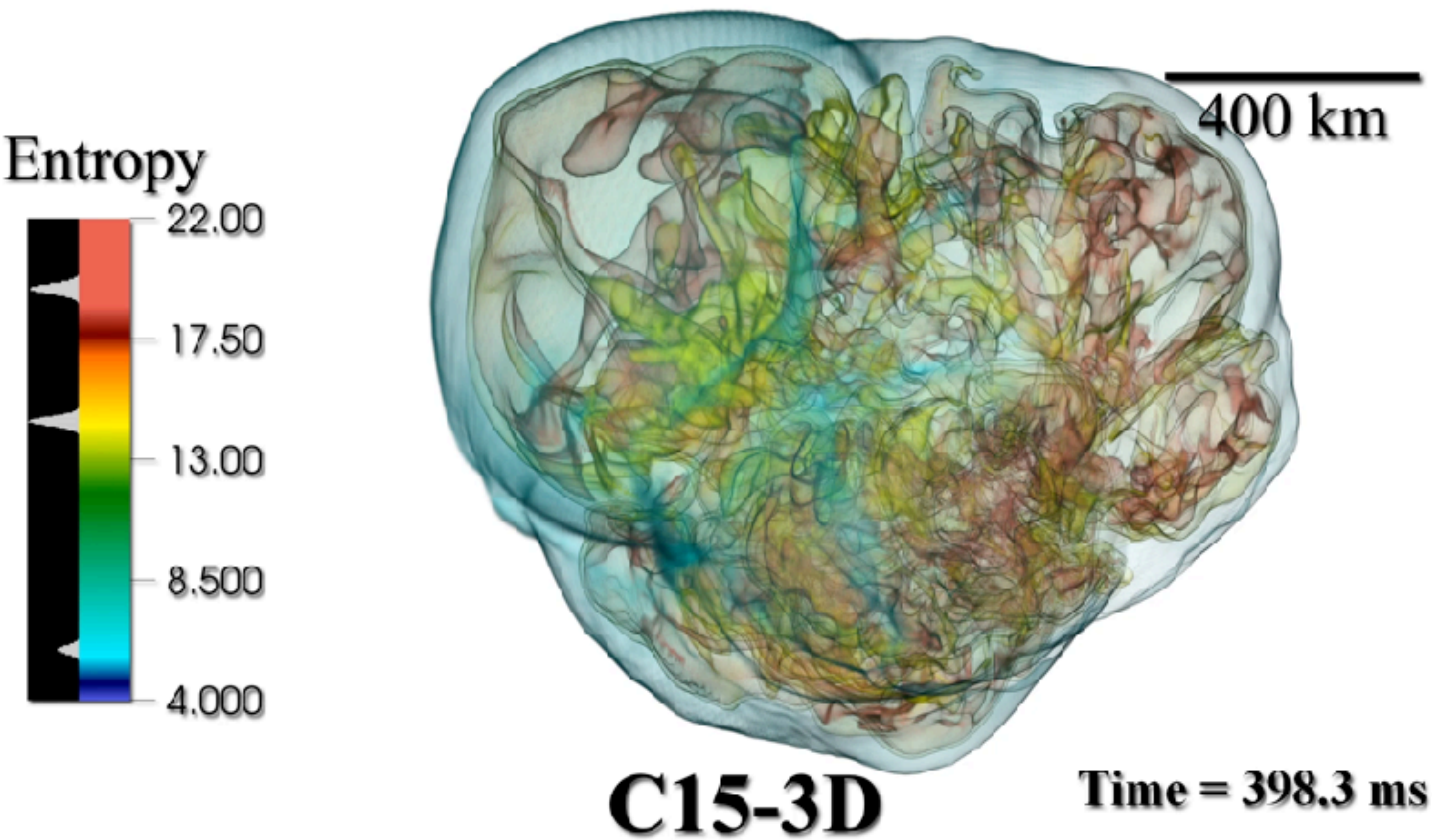

- The resonance is potentially crossed more than once

# Multi-d simulations show extensive turbulence behind the expanding shock

Blondin, Mezzacappa, & DeMarino (2002)



# Update in Lentz et al, ApJ (2015)

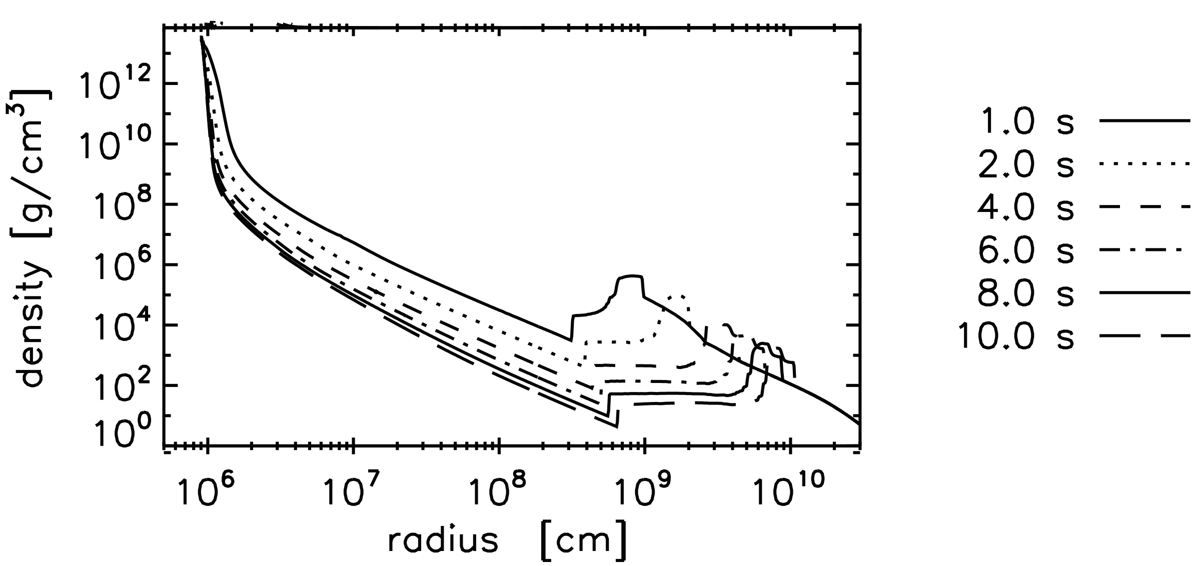


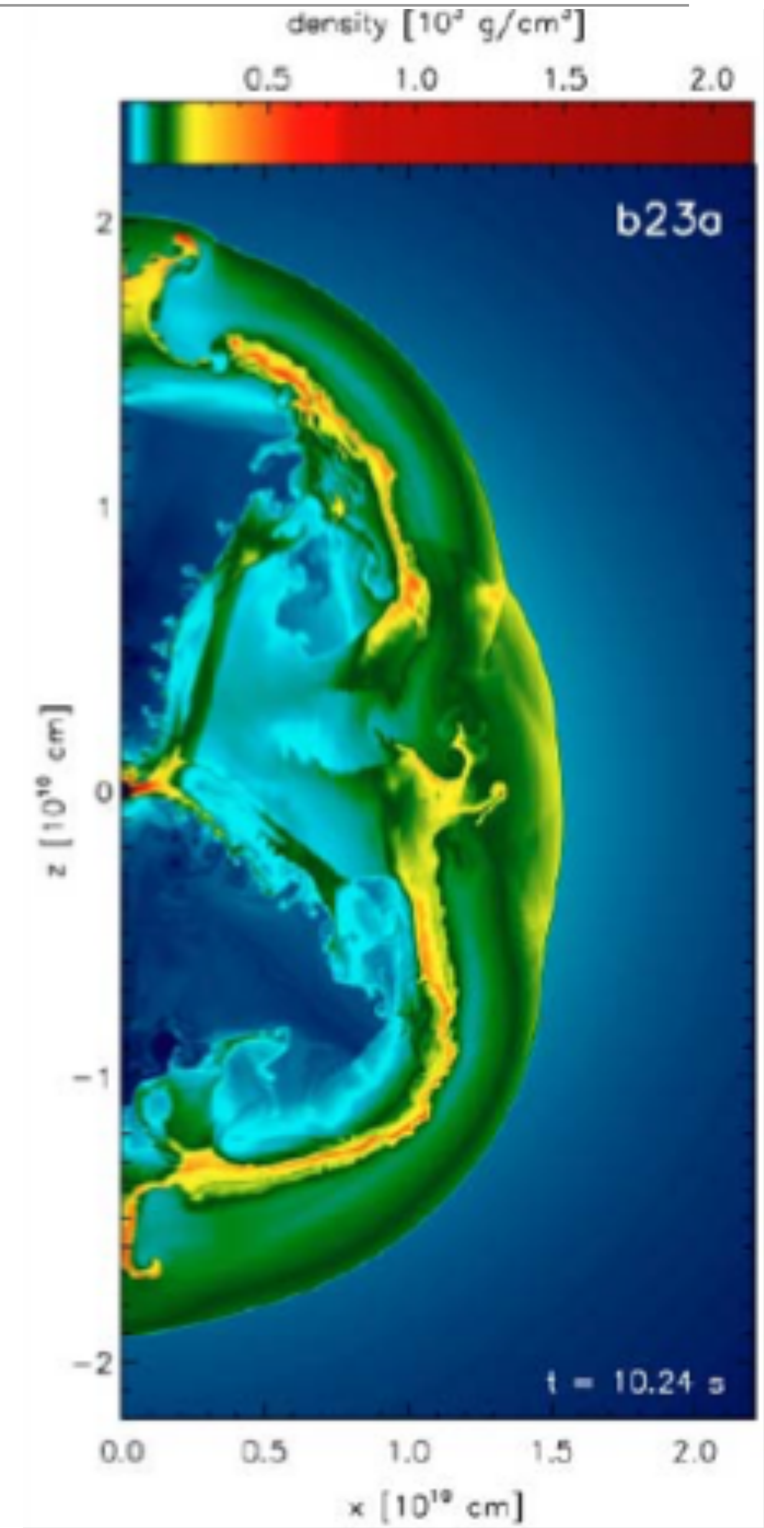
# Multi-d simulations show extensive turbulence behind the expanding shock

Foglizzo, Masset, Guilet, Durand (2012)

# Neutrino signal at a few seconds

- Neutrino transformations depend on the how densities behind and in front of the shock compare.
- Can be even different for different directions in the same simulations.
- Needed: high-resolution simulations the explosion to several seconds!



# Part III: Neutrino oscillations in turbulent matter

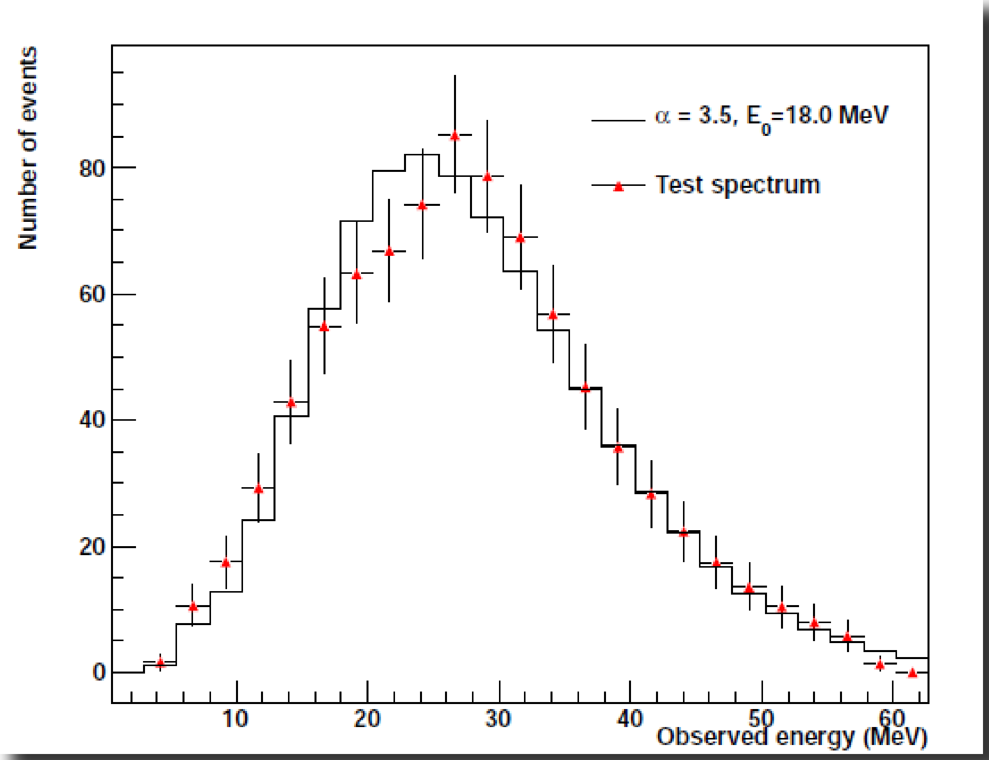
- In 3D, energy is pumped on large scales, dissipated on small scales
- Between these two scales (in the "inertial range"), a turbulent cascade is formed, carrying energy from large to small scales
    - **Fluctuations scale as a power law of their size**
- The relevant scales for neutrinos are tens of km (neutrino osc. length) and shorter
- These are not going to be resolved directly, but the existence of the cascade could be verified in a good simulation
- Given the cascade the problem can be treated analytically, see Friedland & Gruzinov, astro-ph/0607244

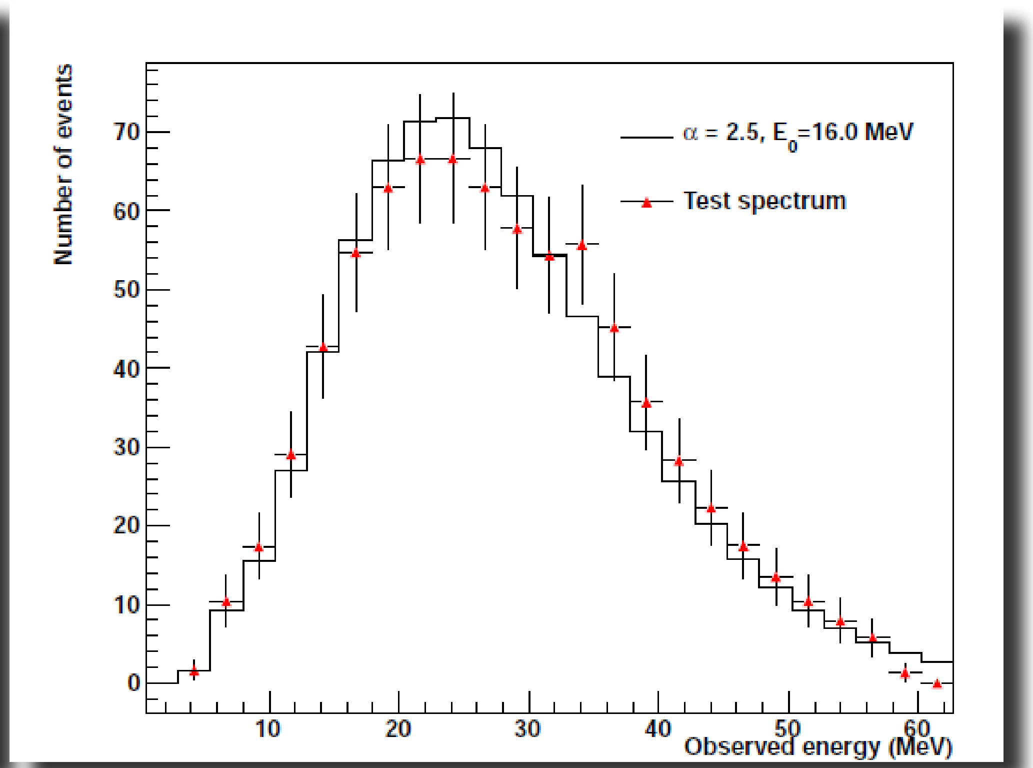
# What are we looking for?

Modeling multiangle collective + shock and turbulence by A. F.

Detector model by K. Scholberg

LBNE Science document, arXiv: 1307.7335v3 (April 22, 2014)




- Time-varying modulation of the signal, neutrinos vs antineutrinos

# 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

- Very rich many-body physics, with many regimes

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

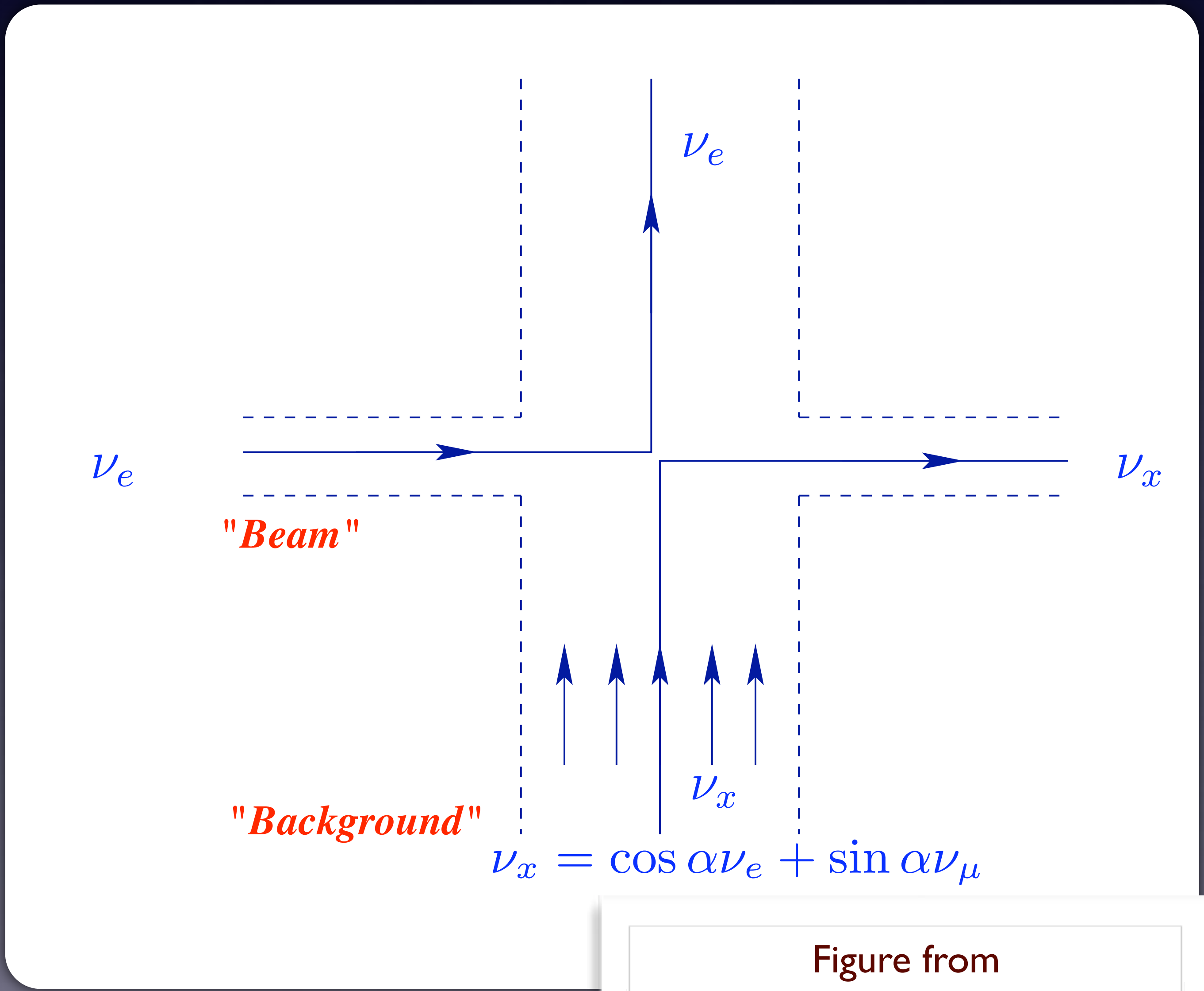
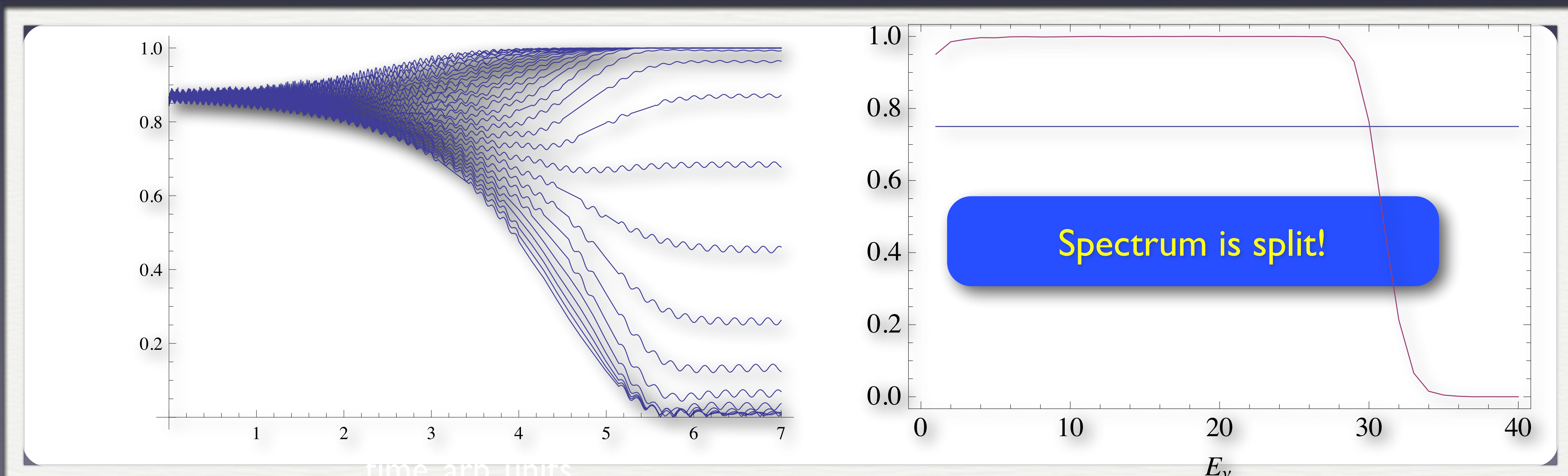



Figure from
Friedland & Lunardini,
Phys. Rev. D 68, 013007 (2003)

# Simplest toy problem

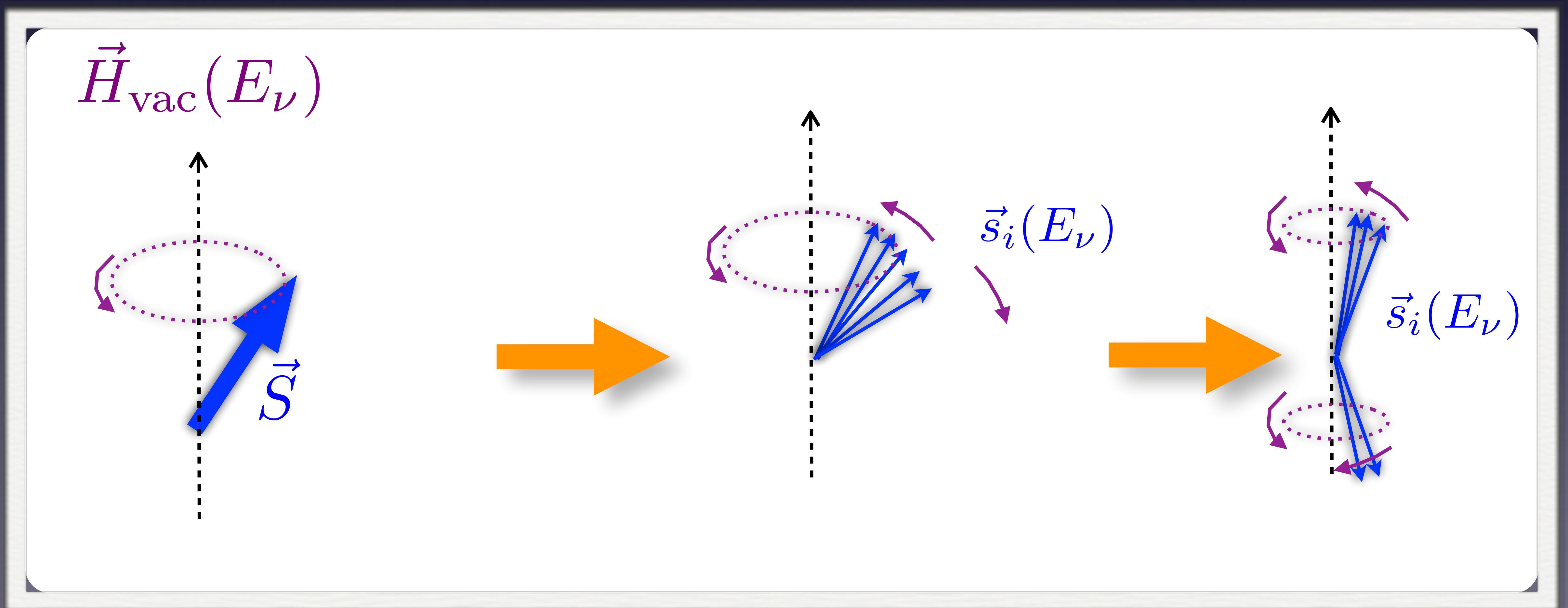
(after Raffelt & Smirnov, 2007)

- Start with neutrinos of different energies, all initially in the same flavor superposition state $\cos\theta_0\ |\nu_e> + \sin\theta_0\ |\nu_\mu>$
- Take the self-coupling to be large initially (much larger than the vacuum oscillation terms for these neutrinos).
- Gradually relax the self-coupling to zero. What is the final state of this system?

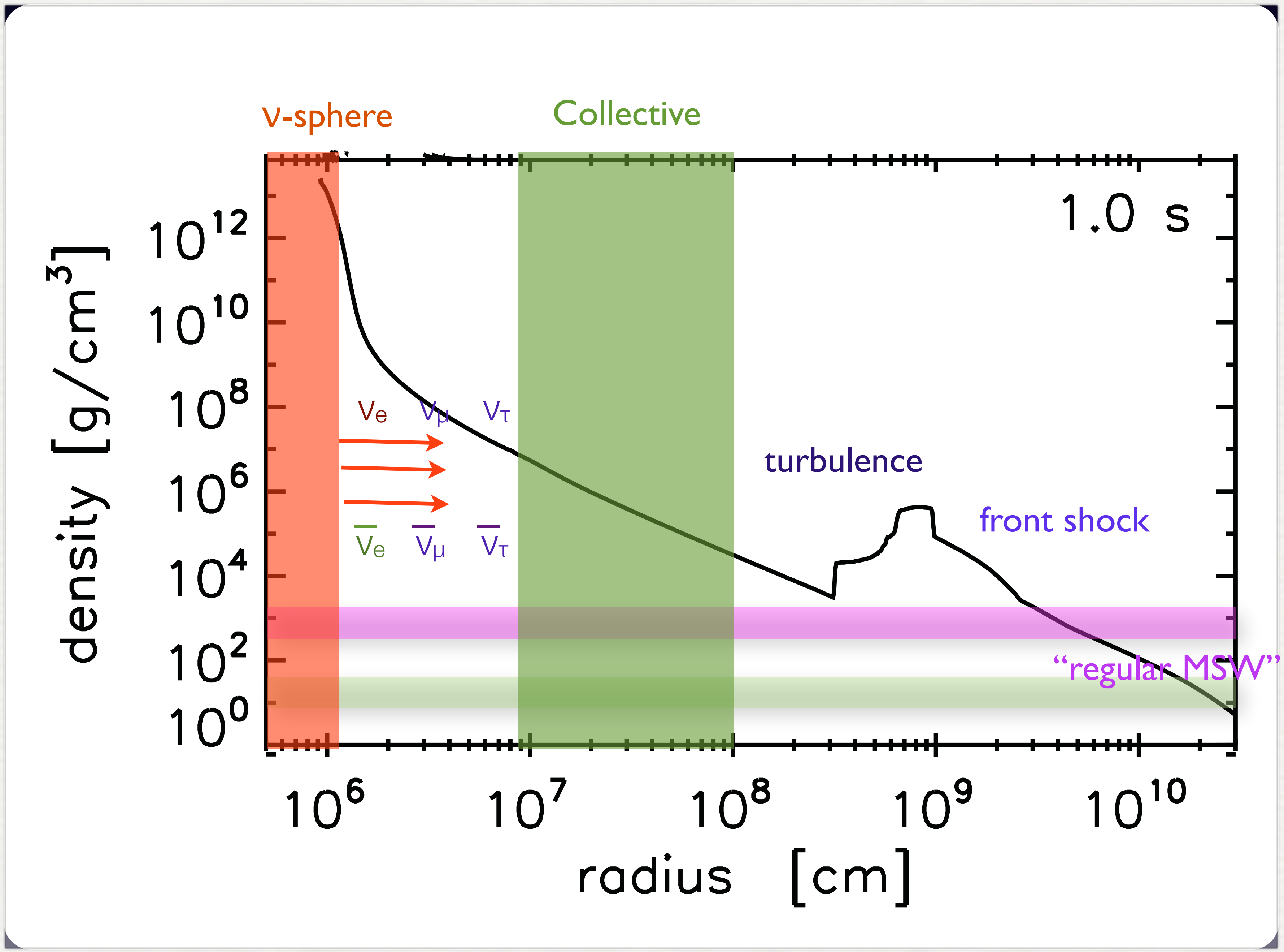


# Simplest toy problem: spin picture

- as self-coupling is gradually taken to zero, spins align or anti-align along the external field



# SN ν oscillation cartoon again

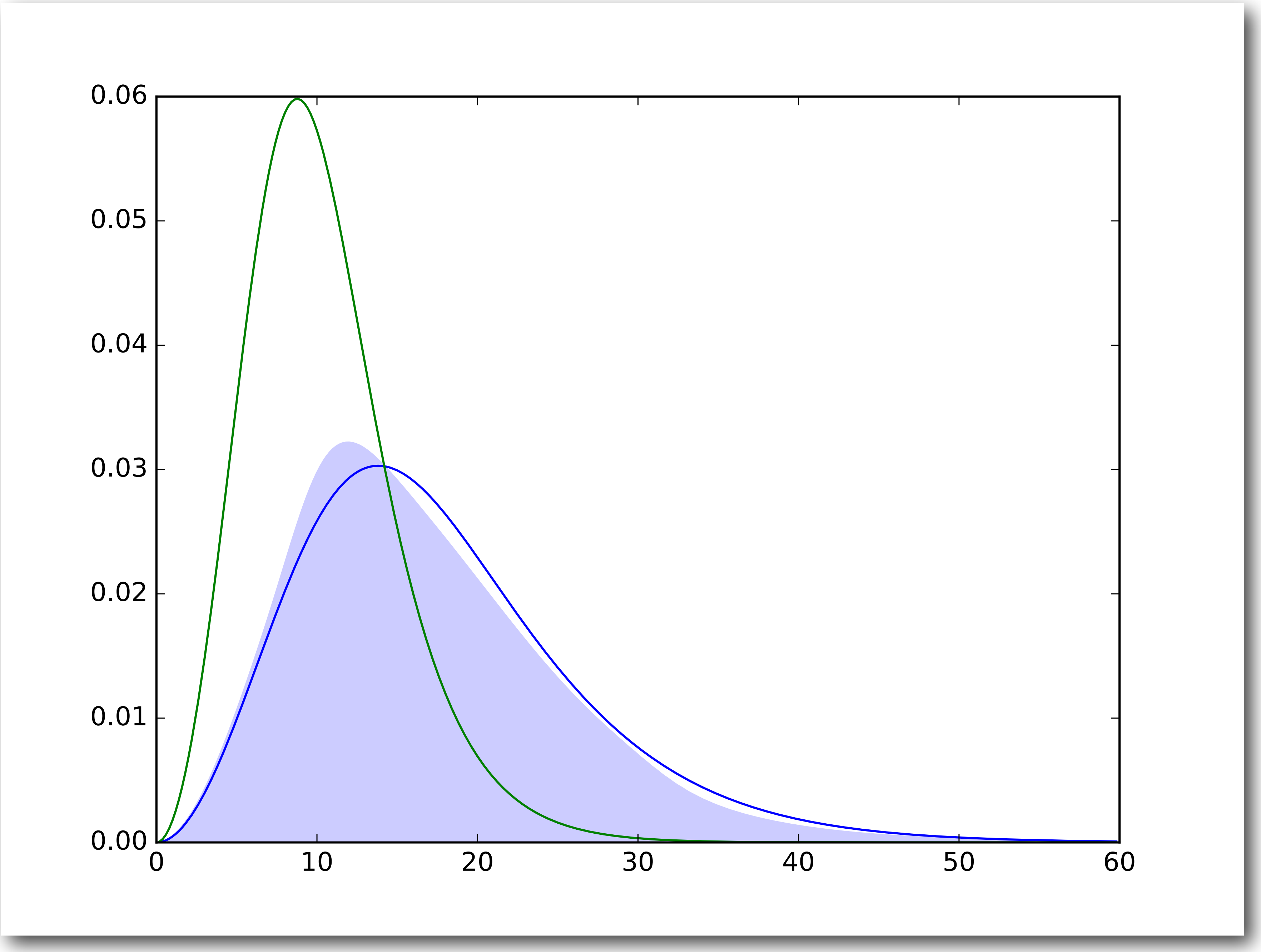


# Part IV: collective oscillations

- Collective oscillations are usually computed for a fixed moment in time
    - A single such calculation by itself is already a serious computing project
- Question: can’t the changing conditions in an evolving supernova lead to interesting modulations of the signal by collective oscillations, just like the shock/turbulence effects?

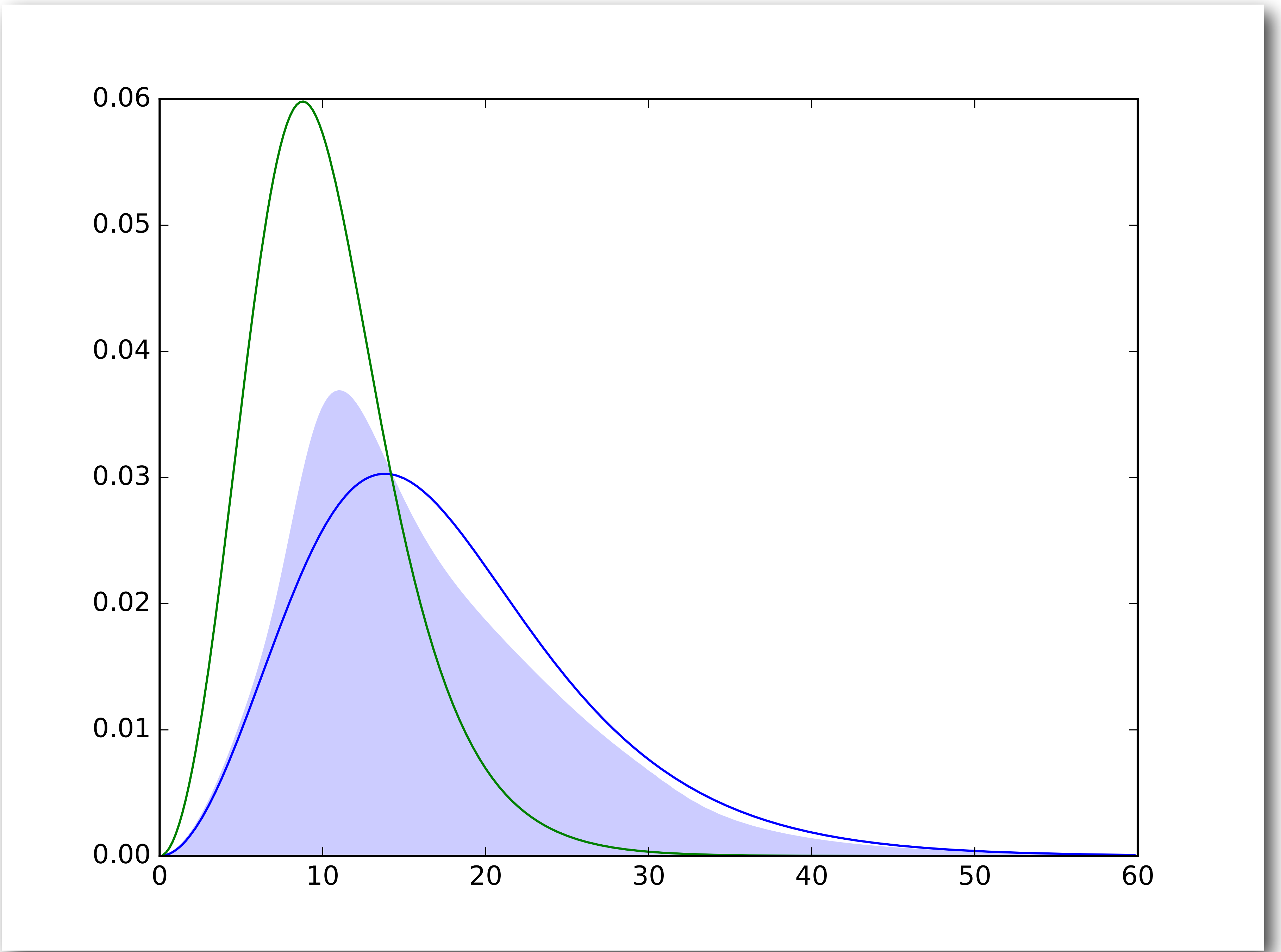
# Yes, and here is an explicit example

- t=1.2 s



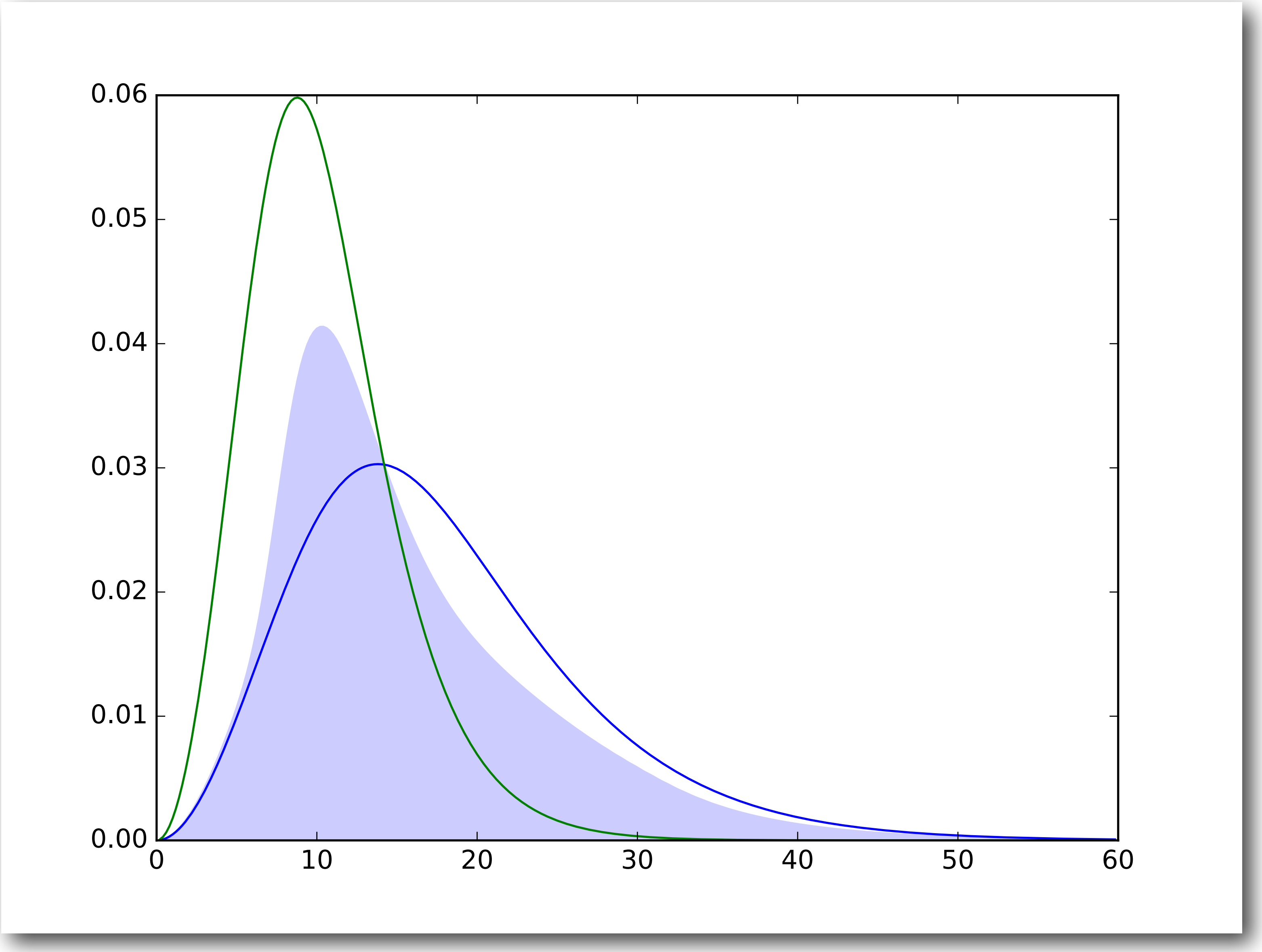
# Yes, and here is an explicit example

- t=1.4 s



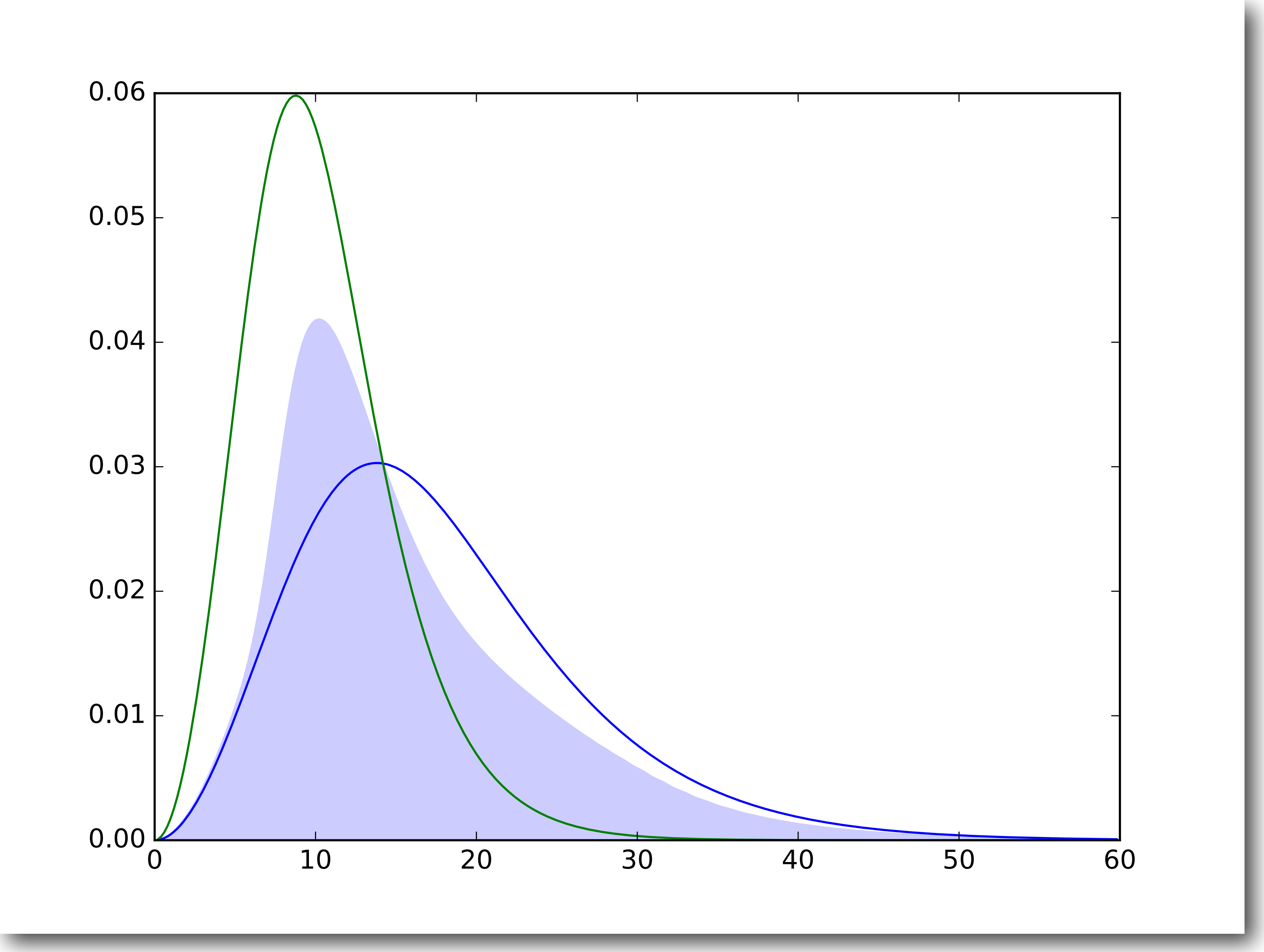
# Yes, and here is an explicit example

- t=1.6 s



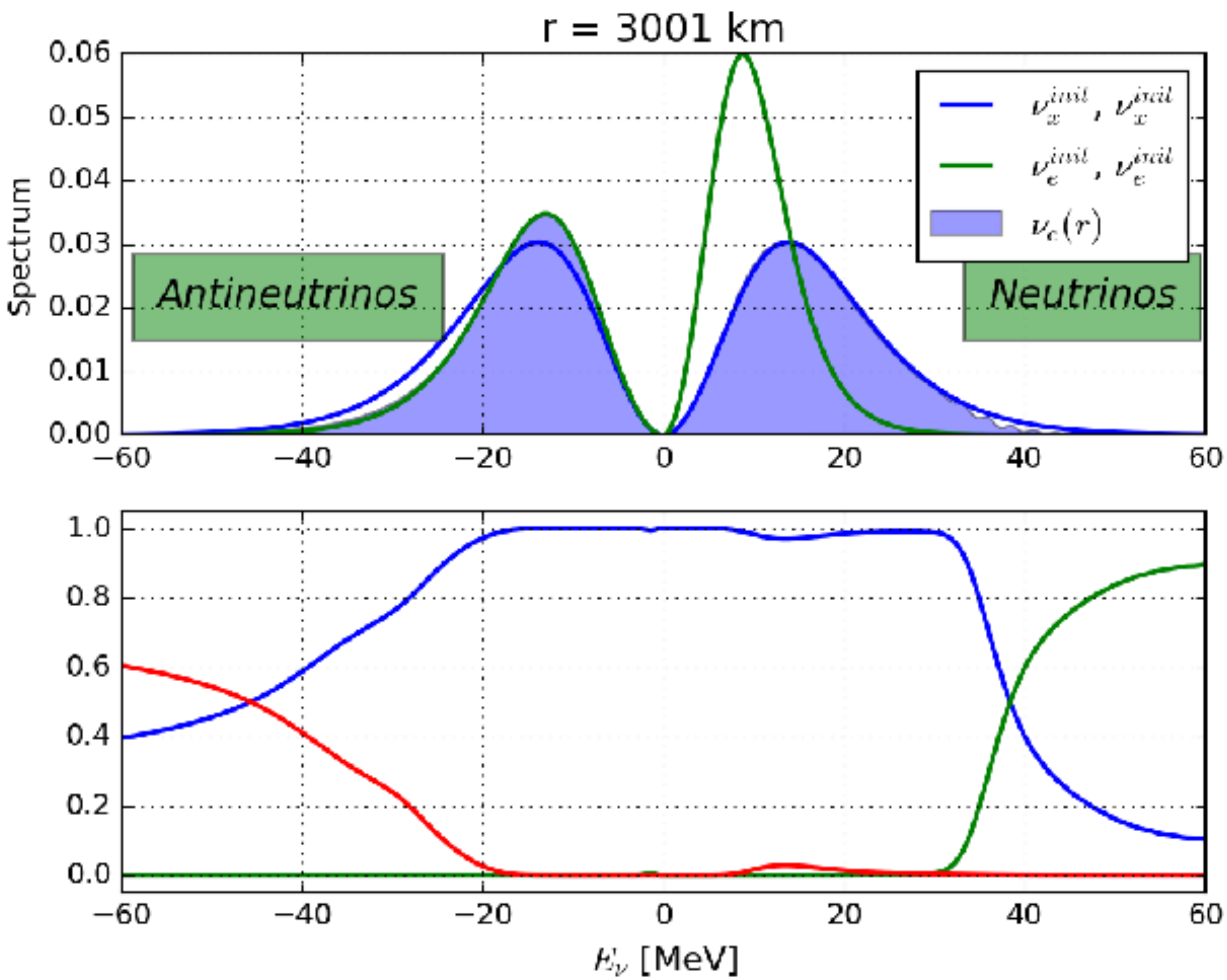
# Yes, and here is an explicit example

- t=2.0 s



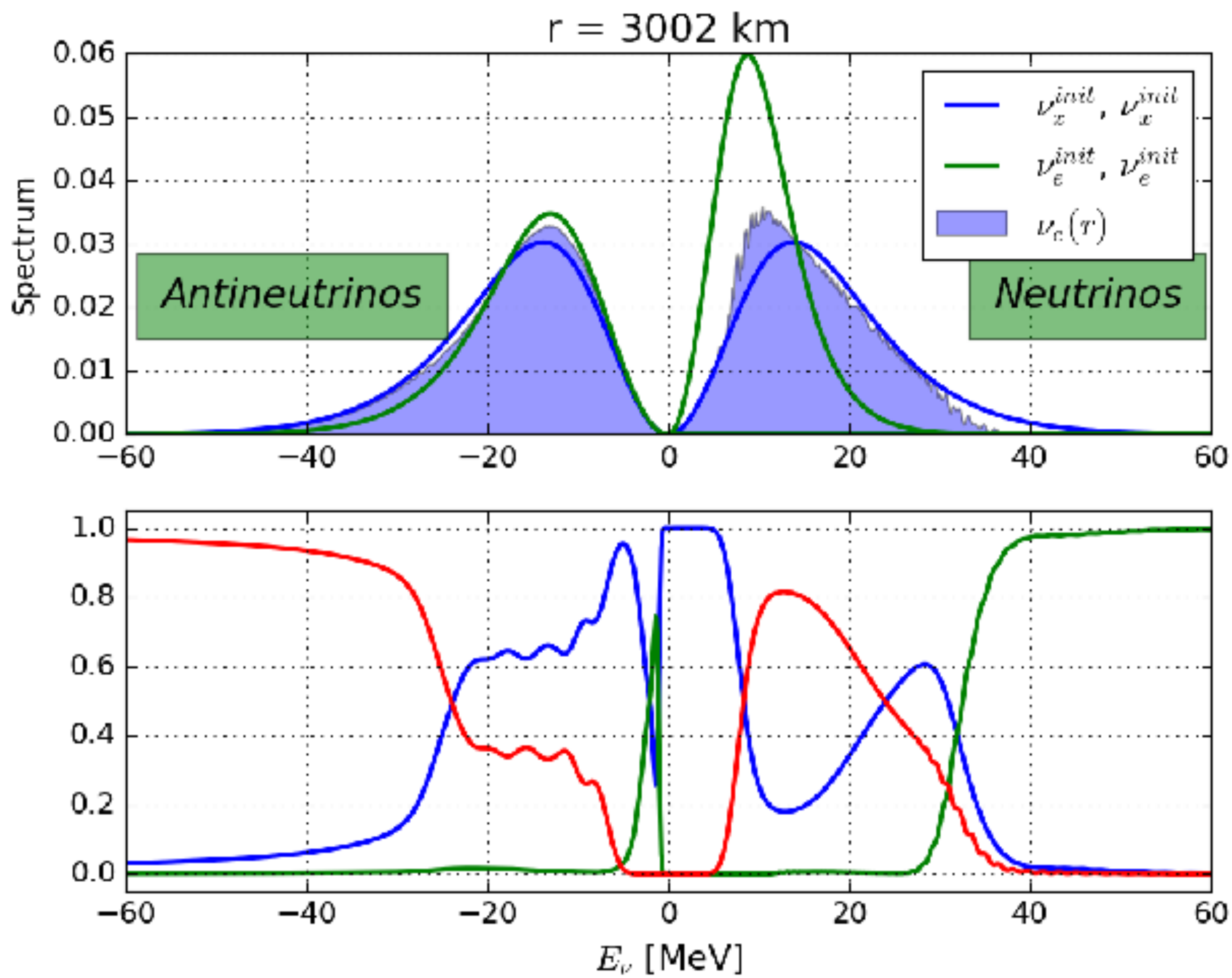
# Different pattern in the mass basis (for aficionados)

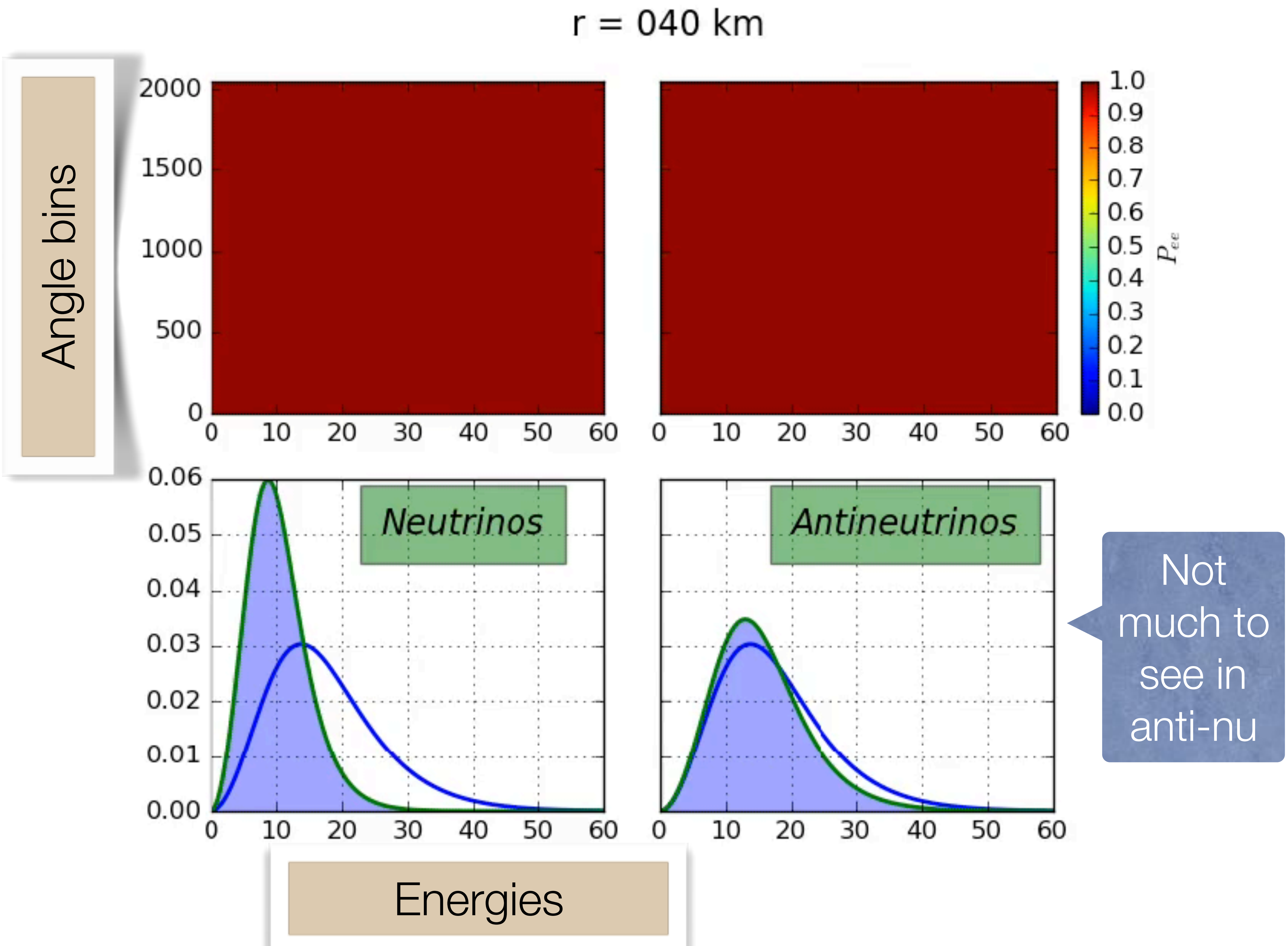
- t=1 sec



# Different pattern in the mass basis (for aficionados)

- t=2 sec

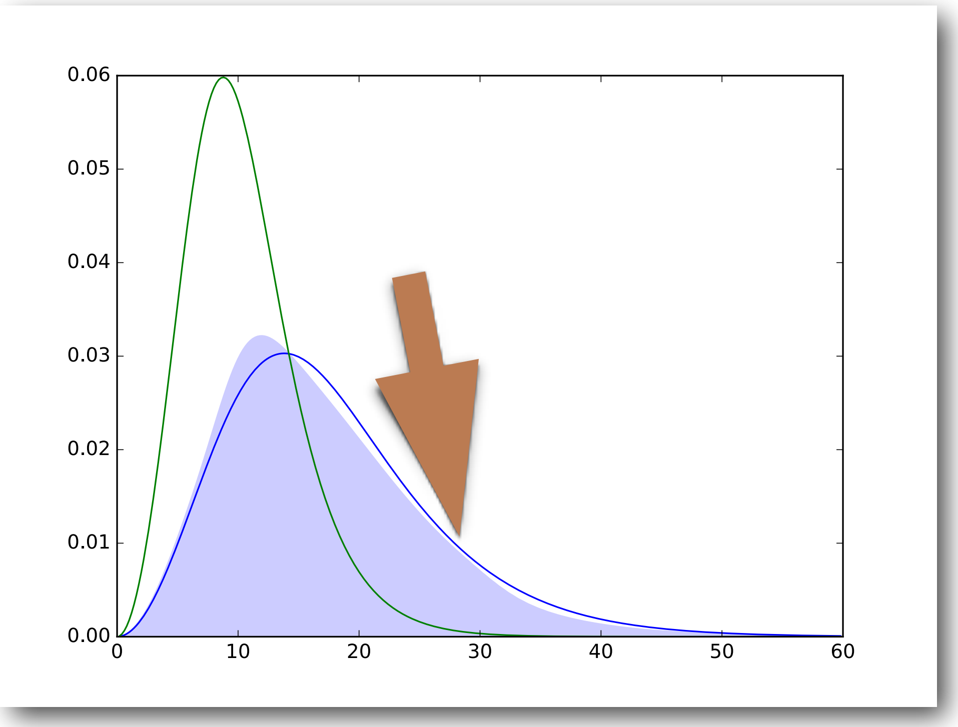


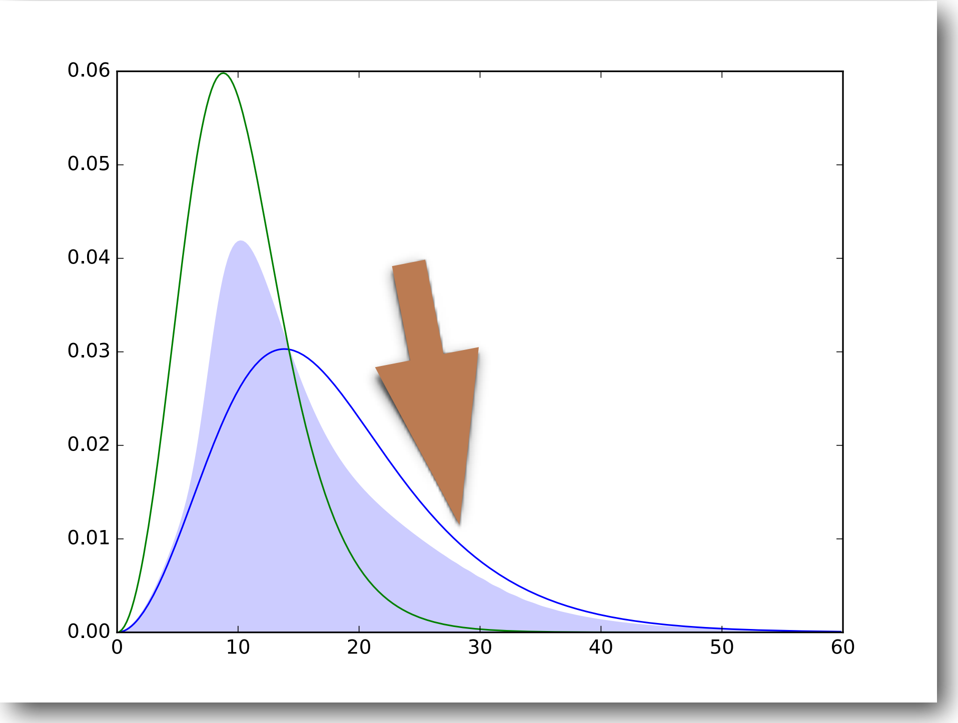


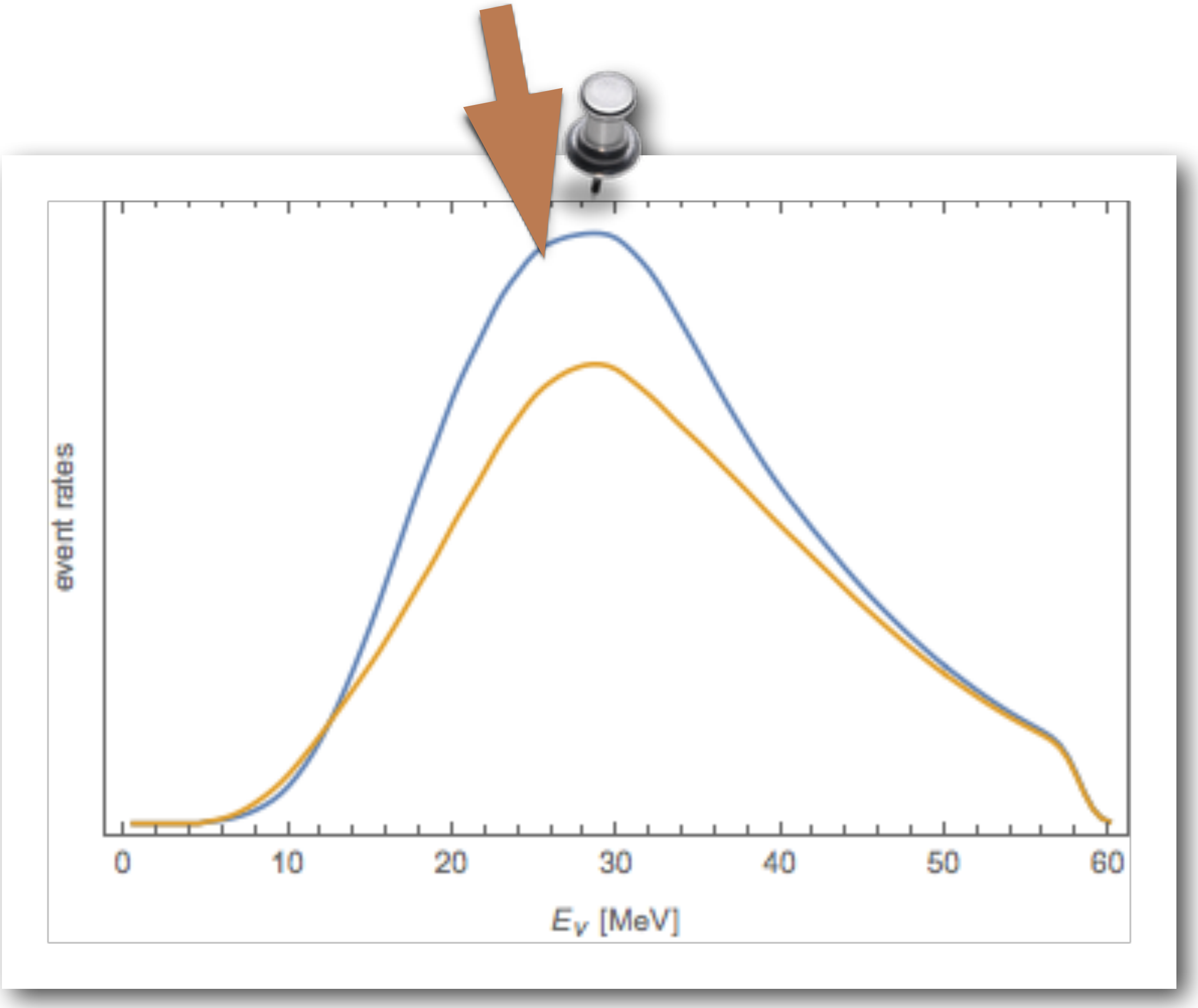

# Development of the oscillations

t=1.4 sec shapshot
Multiangle, spherical symmetry

# What does this mean for detection?



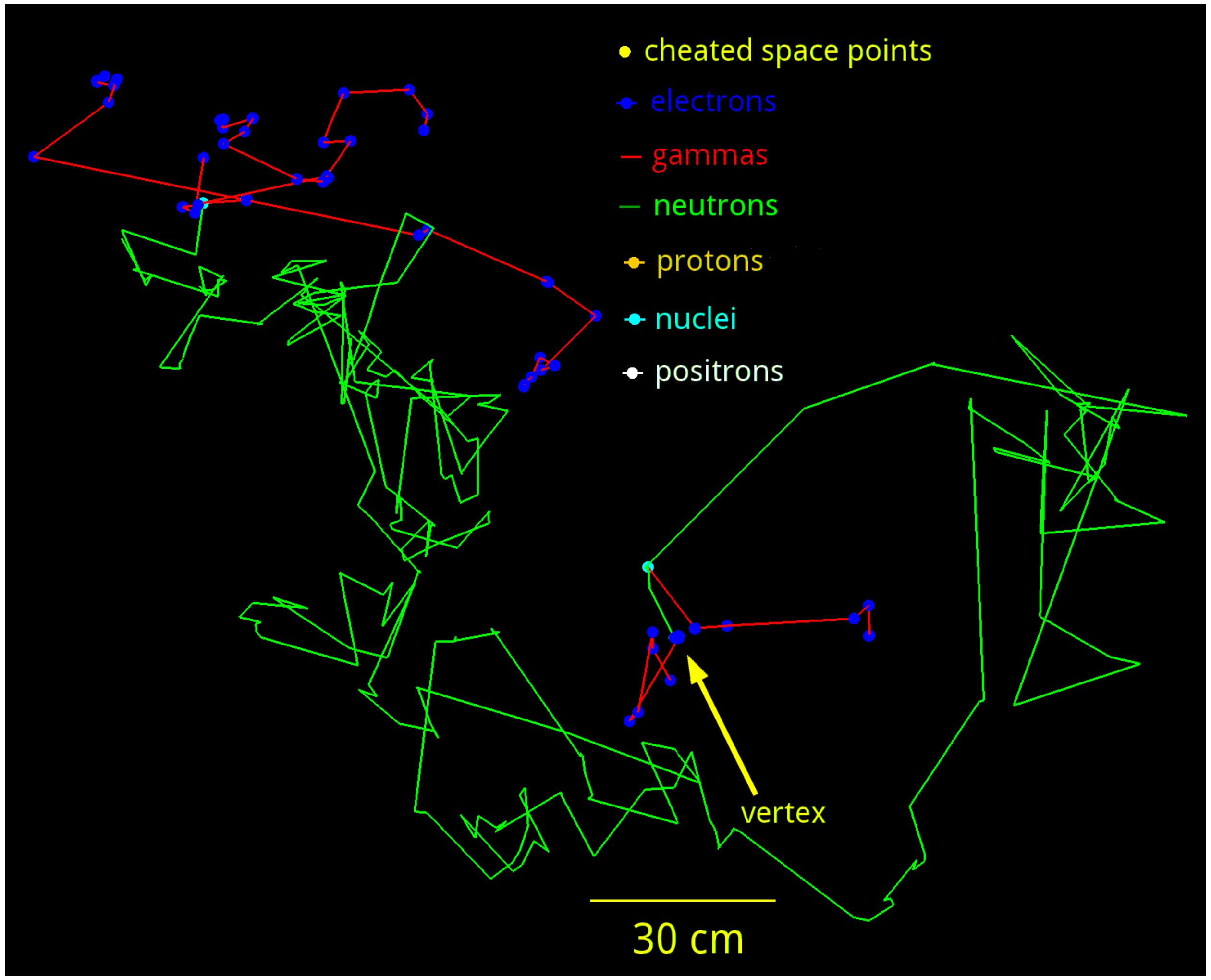




SNOwGLoBES, Ar17kt,
stock smearing matrices

# Detection in LAr 101

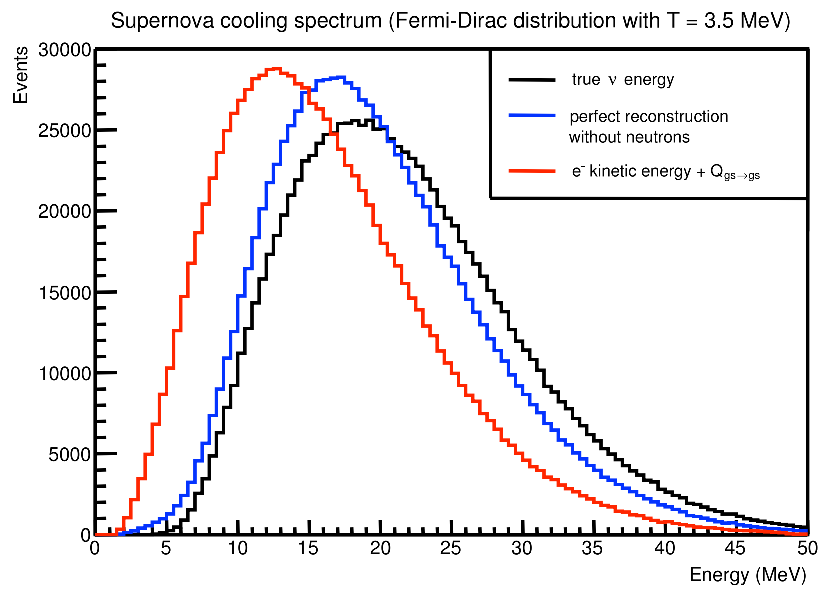
# MARLEY Simulation by UC Davis group (Credit: S. Gardener et al)

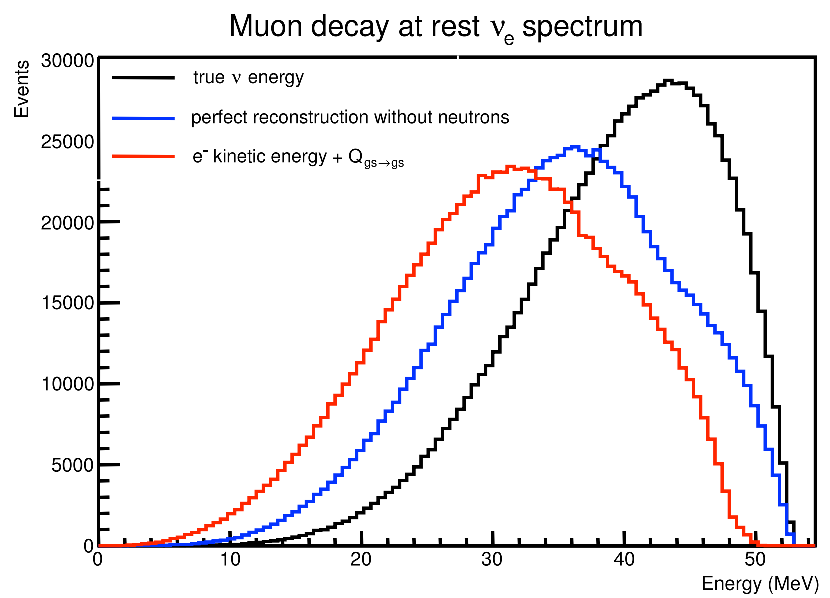
- $E_\nu$ = 16.3 MeV
- $e^-$ deposited 4.5 MeV
- No primary $\gamma$s from vertex
- $^{39}K$ deposited 68 keV
- n deposited 7.6 MeV (mostly from capture $\gamma$s)
- Total visible energy:
  12.2 MeV
- Visible energy sphere radius:
  1.44 m
- Neutrons bounce around for a long time!



# Different observed spectra, depending on what's detected

## MARLEY branching ratios for two different source spectra




$^{40}$K* de-excitations

- $\gamma$s only: 82.5%
- single n + $\gamma$s: 15.9%
- single p + $\gamma$s: 1.4%
- other: 0.2%

$^{40}$K* de-excitations

- $\gamma$s only: 58.0%
- single n + $\gamma$s: 36.3%
- single p + $\gamma$s: 4.6%
- other: 1.1%

**A simple table of branching ratios is inadequate due to this energy dependence**

# So, what’s the strategy?

- One can supply experimentalists a library of oscillated fluxes
  - choosing simulations with different interesting time signatures encoded
- They can then process them under different detector performance assumptions
  - Energy resolution, efficiency as a function of energy, different reconstruction abilities (only electrons, also some de-exitation gammas, also some neutrons, etc)
- See if this is different from another possible extreme scenario: complete incoherent mixture of all flavors (for example, due to fast collective oscillations)
- You contributions very welcome here!

# Final thoughts

- Supernova neutrino burst contains in it imprints of the developing explosion
  - You may see when the shock stalls and restarts, what happens in the post-shock region, different patterns of collective oscillations, etc
  - Having both LAr and WC is essential to read these signals
  - Need a library of benchmark scenarios to assess how detector performance affects physics that can be extracted
- No Standard Supernova model. The plan is to use the data to tell us what happens. The question is how to read the signal and what characteristics of the detector are desirable
- Decisions now will affect what we will see for SN2025