Supernova neutrinos 101

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Rich, multidisciplinary subject

- Core-collapse supernova explosions involve extremely rich physics
  - Hydrodynamics (MHD), radiation transport, nuclear equation of state, neutrino oscillations in conditions not reproducible on Earth, possible effects of new particle physics, ...
- Half a century of efforts to understand them
  - Presently some of the most ambitious supercomputing simulations in the world
- This 1-hour lecture will not give a comprehensive overview of the subject
  - I will only introduce some general concepts using a few estimates and give you a flavor of current research

Outline

- What are core-collapse supernovae?
    - Progenitor stars, basic energetics, role of neutrinos, etc
- Stages of the explosion
- Neutrino oscillations in SN-like environments
    - Rich physics: known knowns
    - Rich physics: known unknowns

Why should we care? “Theory of everything”!

- Origin of stuff: Supernovae synthesize and disperse heavy elements.
    - BBN created hydrogen and helium. Chemical elements around us were once inside a star
- The universe around us: Simulations of the galactic disk show that supernova feedback is crucial to its structure.
- Conditions not reproducible on Earth make them unique laboratories for particle and nuclear physics

Types of supernovae

- According to astronomers: type I or type II (type II has hydrogen lines)
- Type I is further subdivided into Ia, Ib, Ic
    - Ia: singly ionized silicon (Si II)
    - Ib: no SI, but Helium (He I)
    - Ic: no helium

Types of supernovae

- According to physicists:
  - thermonuclear explosion of an accreting white dwarf start (Type Ia)
  - or collapse of a core inside a massive star (Types Ib, Ic, II)
    - Subclasses:
      - Canonical Fe core collapse (>10 $M_\odot$)
      - Electron capture in O-Ne-Mg cores (8-10 $M_\odot$)
      - Exotic: pair instability (>130 $M_\odot$), photo-disintegration (>250 $M_\odot$)

A lot of neutrinos!

Where supernovae come from: Stars 101

Stellar evolution: hydrostatic balance

- Stars are blobs of gas held together by gravity
- If gravity was not balanced, the object would collapse on a very short time scale

$$v^2 \sim GM_*/R_* \;\rightarrow\; t \sim R_*/v \sim R_*^{3/2}/\sqrt{GM_*} \sim 1/\sqrt{G\rho_*} \sim 10^3 \mathrm{sec}$$

- Gravity must be counteracted by pressure, thermal and/or electron degeneracy

Energy generation and escape

Kelvin, Helmholtz, 19th century

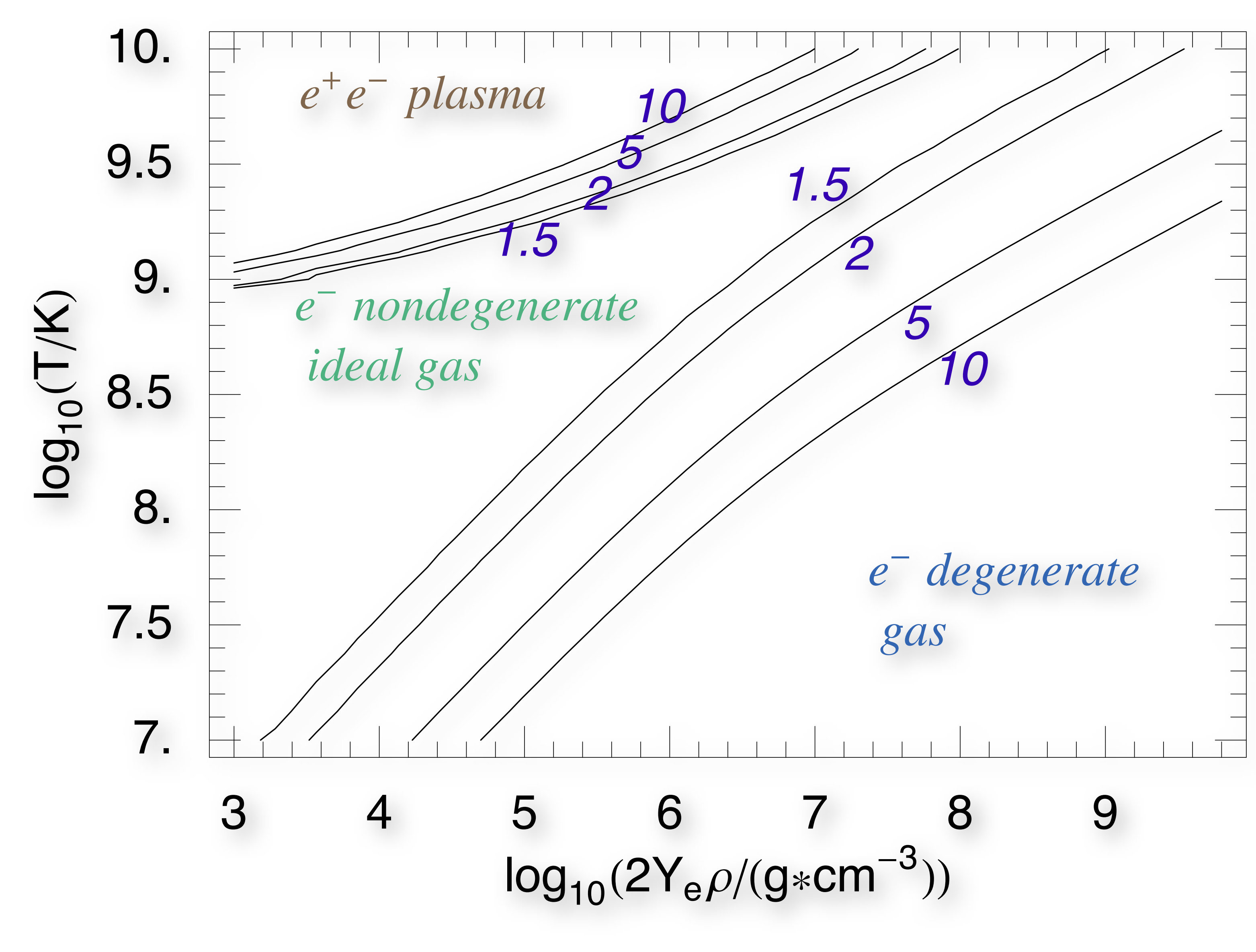
- Energy escapes through the surface as photons or through the volume as neutrinos; without sources of energy the Sun would cool

$$U_\odot \sim \frac{1}{2}\frac{GM_\odot^2}{R_\odot} \sim 10^{48}\mathrm{erg} \rightarrow \frac{U_\odot}{L_\odot} \sim \frac{10^{48}\mathrm{erg}}{10^{33}\mathrm{erg/s}} \sim 10^7\mathrm{yr}$$

Eddington, Gamow, Bethe ...

- Need internal sources of energy, to compensate for energy lost
  - Nuclear reactions, H -> He ->C,O ->...
  - **Loss rate determines the burning (evolution!) rate**

Equation of state



Stars with masses 12 M☉ ≲ M ≲ 50 M☉ spend most of their lives in the "ideal gas" window

Sources of pressure

- Thermal and/or degeneracy
  - If electron degeneracy, the object can just sit there …
    - … unless the mass of the degenerate core reaches a certain threshold, ~ 1.4 $M_\odot$ (see later)
  - If pressure is thermal, the interior must be hot $\frac{3}{2}kT \sim \frac{1}{2}\frac{GM_* m_p}{R_*} \rightarrow T_\odot \sim 10^7 K$

Stellar evolution: opacity and lifetime

- If energy is lost through photons, the luminosity is given by

$$\mathcal{L}_r = -\frac{4\pi r^2}{3\kappa\rho}\frac{d(aT^4)}{dr}$$ where the opacity $$\kappa^{-1} = \kappa_\gamma^{-1} + \kappa_e^{-1} + \kappa_x^{-1}$$

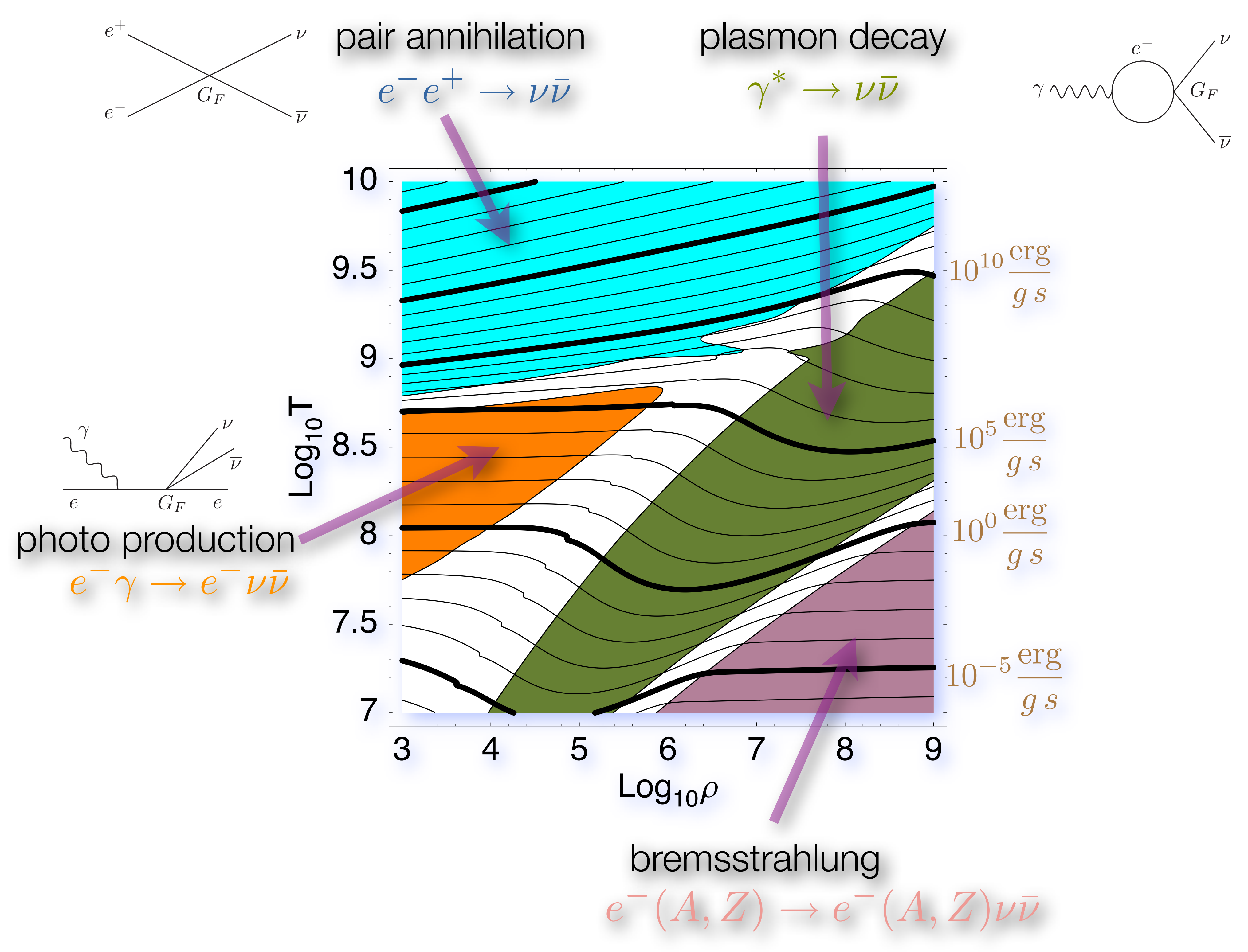
  - More massive stars are hotter inside, burn faster, have shorter lives

$$\mathcal{L}_* \sim \frac{R_*^2}{\kappa M_*/R_*^3}\frac{a(GM_*m_p/R_*k)^4}{R_*} \propto M_*^3$$

  - If a novel particle x is trapped in a star, the smaller the opacity k_x, the more important it is for cooling

  - If x is free-streaming, compute production through the volume (e.g., neutrinos, except in SN)

Energy loss II: neutrino cooling



pair annihilation

$e^-e^+ \to \nu\bar\nu$

plasmon decay

$\gamma^* \to \nu\bar\nu$

photo production

$e^-\gamma \to e^-\nu\bar\nu$

bremsstrahlung

$e^-(A,Z) \to e^-(A,Z)\nu\bar\nu$

Life of massive stars

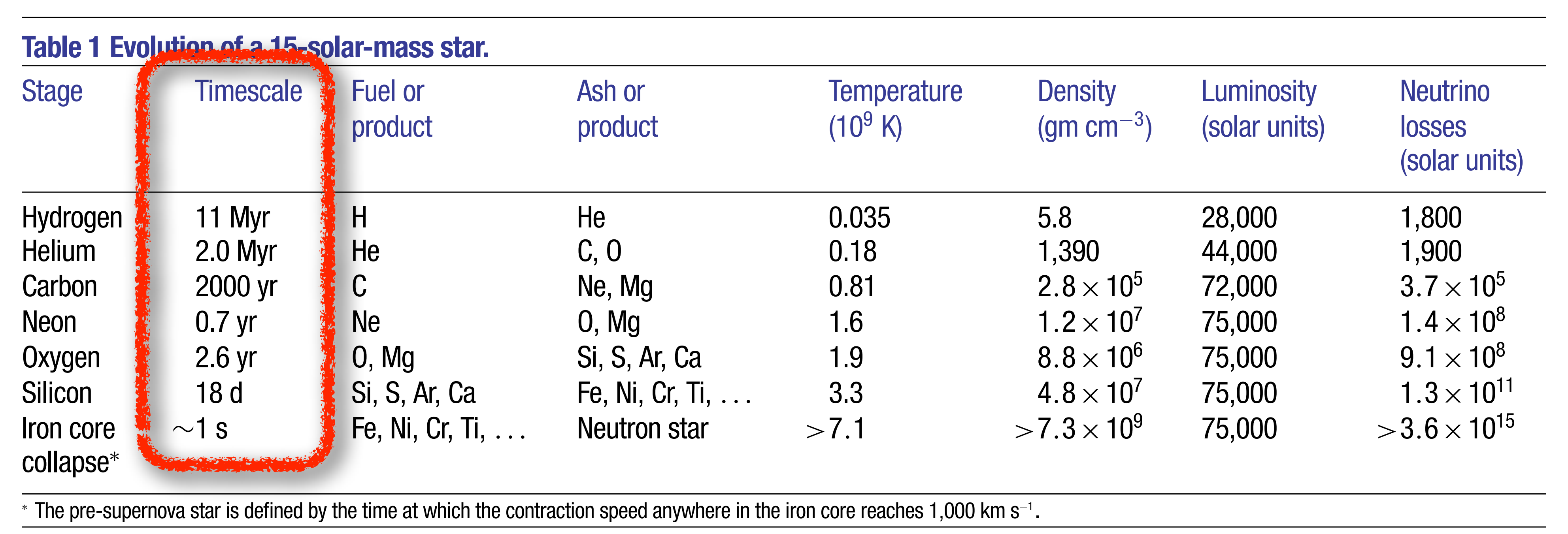
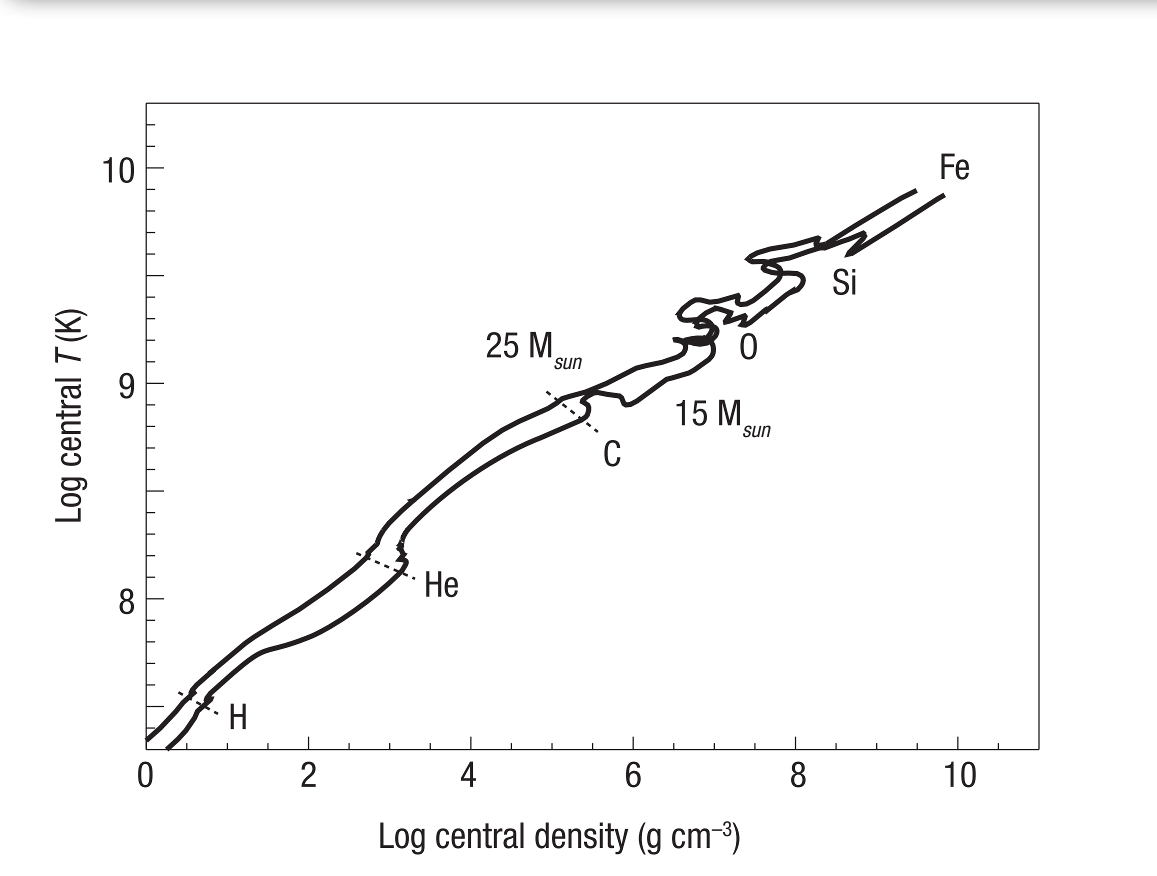


Table 1 Evolution of a 15-solar-mass star.

Stage	Timescale	Fuel or product	Ash or product	Temperature (10^9 K)	Density (gm cm^{-3})	Luminosity (solar units)	Neutrino losses (solar units)
Hydrogen	11 Myr	H	He	0.035	5.8	28,000	1,800
Helium	2.0 Myr	He	C, O	0.18	1,390	44,000	1,900
Carbon	2000 yr	C	Ne, Mg	0.81	2.8×10^5	72,000	3.7×10^5
Neon	0.7 yr	Ne	O, Mg	1.6	1.2×10^7	75,000	1.4×10^8
Oxygen	2.6 yr	O, Mg	Si, S, Ar, Ca	1.9	8.8×10^6	75,000	9.1×10^8
Silicon	18 d	Si, S, Ar, Ca	Fe, Ni, Cr, Ti, . . .	3.3	4.8×10^7	75,000	1.3×10^{11}
Iron core collapse*	~1 s	Fe, Ni, Cr, Ti, . . .	Neutron star	>7.1	$>7.3 \times 10^9$	75,000	$>3.6 \times 10^{15}$

* The pre-supernova star is defined by the time at which the contraction speed anywhere in the iron core reaches 1,000 km s^{-1}.



Woosley,
Janka,
Nature Physics
V. 1, p. 147 (2005)

Digression: hermetic detector!

- The branching ratio for e^+e^- -> neutrino pair is
  - ~ 10^{-18} for ~ 1 MeV energies
  - The main annihilation mode is e^+e^- -> γ γ
- Plasmon decay γ -> neutrino pair probability between collisions is ~ 10^{-26}
- Yet, effects of neutrino energy losses clearly seen in stellar evolution (advanced burning stages)

What happens when all fuel is exhausted?

- Can't the star always cool and settle to a configuration supported by the electron degeneracy pressure?
  - Sometimes YES, but sometimes NO
- To understand when this can and cannot happen, we need the concept of the Chandrasekhar mass

Degenerate electron gas: nonrelativistic case

- Energy density of a NR degenerate gas

$$\epsilon_{NR} \sim \int_0^{p_F} d^3p \frac{p^2}{m_e} \sim \frac{p_F^5}{m_e} \sim \frac{n^{5/3}}{m_e} \qquad n \sim \int_0^{p_F} d^3p \sim p_F^3$$

- Since n ~ M/R^3, this energy density depends on the 5th power of the stellar radius

$$\epsilon_{NR} \sim \frac{1}{m_e}\left(\frac{M}{m_N R^3}\right)^{5/3} = \frac{1}{m_e}\frac{(M/m_N)^{5/3}}{R^5}$$

- This is good since the gravitational binding energy depends on the 4th power of R (stable configuration!)

$$\epsilon_{GR} \sim -\frac{G_N M^2}{R}\frac{1}{R^3}$$

Degenerate electron gas: relativistic case

- The ultra-relativistic case, E=p, is, however, a problem:

$$\epsilon_{UR} \sim \int_0^{p_F} d^3p\, p \sim p_F^4 \qquad n \sim \int_0^{p_F} d^3p \sim p_F^3$$

- The energy density now depends only on the 4th power of the stellar radius

$$\epsilon_{UR} \sim \left(\frac{M}{m_N R^3}\right)^{4/3} = \frac{(M/m_N)^{4/3}}{R^4} \qquad \epsilon_{GR} \sim -\frac{G_N M^2}{R}\frac{1}{R^3}$$

- The degeneracy energy no longer grows faster than the gravitational energy is released

- Moreover, $(M_\odot/M_N)^{4/3} \sim (10^{30}\text{ kg}/10^{-27}\text{ kg})^{4/3} \sim 10^{76}$, while $G_N(M_\odot)^2 \sim (M_\odot/M_{Pl})^2 \sim (10^{30}\text{ kg}/10^{-8}\text{ kg})^2 \sim 10^{76}$. Same order!!

Critical stellar mass

- Since gravity goes like $(M_*/M_{Pl})^2$, while degeneracy energy $(M_*/M_N)^{4/3}$, for a sufficiently massive star, gravity wins!
- Consider a star M_*, which is a borderline case, $(M_*/M_N)^{4/3} \sim (M_*/M_{Pl})^2$.
- This gives $M_* \sim (M_{Pl}/M_N)^2 \, M_{Pl} \sim M_\odot$!! We live in an amazing universe!
- An accurate calculation with all coefficients yields 1.4 $M_\odot$! An object more massive than this cannot be supported by electron degeneracy pressure.

Different stellar fates

- All stars start qualitatively similar, burning Hydrogen on the Main Sequence, where luminosity and color are continuous functions of the stellar mass.
- Stars like our Sun evolve into white dwarfs. These degenerate objects then sit there for a very long time. If further material is accreted (e.g., from a companion star), the object may eventually reach the Chandrasekhar limit and undergo a thermonuclear explosion (Carbon burning).
    - This is Type Ia SN
- A different fate awaits massive stars. When their Iron cores collapse, there is nothing left to burn!

A gravity-powered neutrino bomb

- Central Fe core ($\sim 1.4\ M_{SUN}$) of a massive star collapses in free fall, at $v \sim c/4$, until reaching (supra)nuclear densities, $10^{10}\ g/cm^3 \rightarrow 10^{14}\ g/cm^3$
- The resulting central dense object (~ a few * 10 km in radius) traps neutrinos: $\lambda \sim (G_F^2\ E^2\ n)^{-1} \sim$ a few cm
  - Since electron neutrinos can't get out, the lepton number also becomes trapped.
- The gravitational binding energy $G_N M^2/R$ (~10% of rest mass!) is initially stored mostly in the Fermi seas of electrons & electron neutrinos

A gravity-powered neutrino bomb

- The gravitational binding energy $G_N M^2/R$ ~ $3*10^{53}$ ergs (~10% of rest mass!) is initially stored mostly in the Fermi seas of electrons & electron neutrinos

- Photons are hopelessly stuck inside this dense object

- Neutrinos have an easier time diffusing out. They do so on the time scale of a few seconds:
    - $t \sim R^2/c\lambda \sim 10^{12}$ cm^2/(3 cm $3*10^{10}$cm/s) ~ 10 s

- For comparison, solar luminosity is $3.8*10^{33}$ ergs/s. A core-collapse supernova shines in neutrinos as bright as 10^{20} Suns. Instantaneously outshines the visible universe.

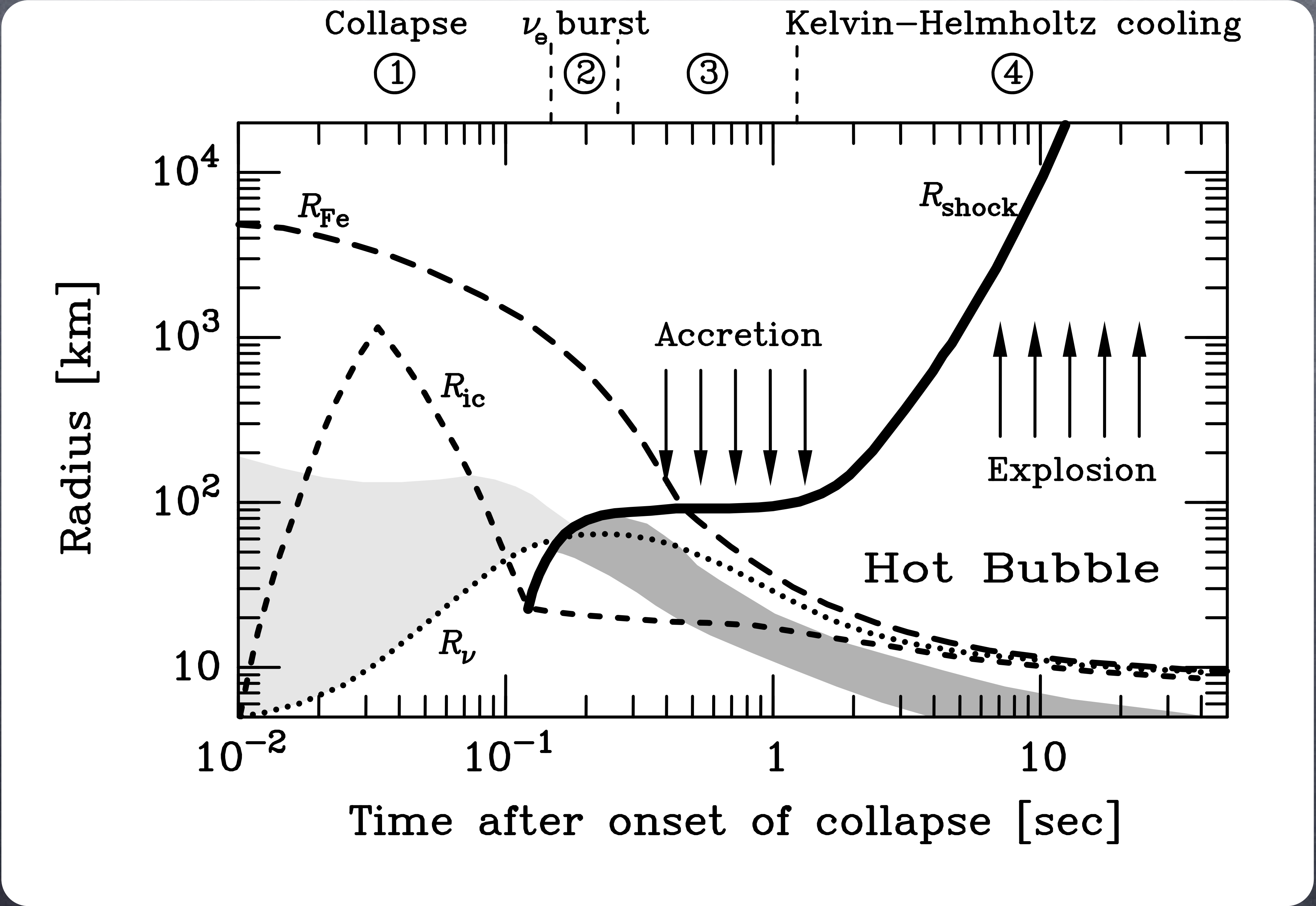
A gravity-powered neutrino bomb

- Thanks to reactions like e+e- annihilation and neutrino pair bremsstrahlung, neutrinos and antineutrinos are emitted in all flavors. (Generally, with different temperatures, because of different cross sections.)
- Neutrinos carry away > 99% of all released gravitational energy. Approximately 15% of the solar mass is converted into neutrinos of ~10 MeV energies
  - 10^{58} neutrinos in a few seconds is definitely intensity frontier!
    - 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} (10^8 moles of neutrinos/cm^3!)
      - Comparable to the electron number density there.
- The object cools and settles to a neutron star (back hole?)

Visible explosion

- Along the way, the shock is formed, first inside the neutrinosphere.
- It moves out, breaks through the neutrinosphere, then loses energy by neutrino emission and disintegration of Iron.
- It stalls at ~ 200 km, then revives, all during ~1 sec.
- Blows off the rest of the star with energy of about 10^{51} ergs, about the binding energy of the envelope. This gives rise to a visible explosion.

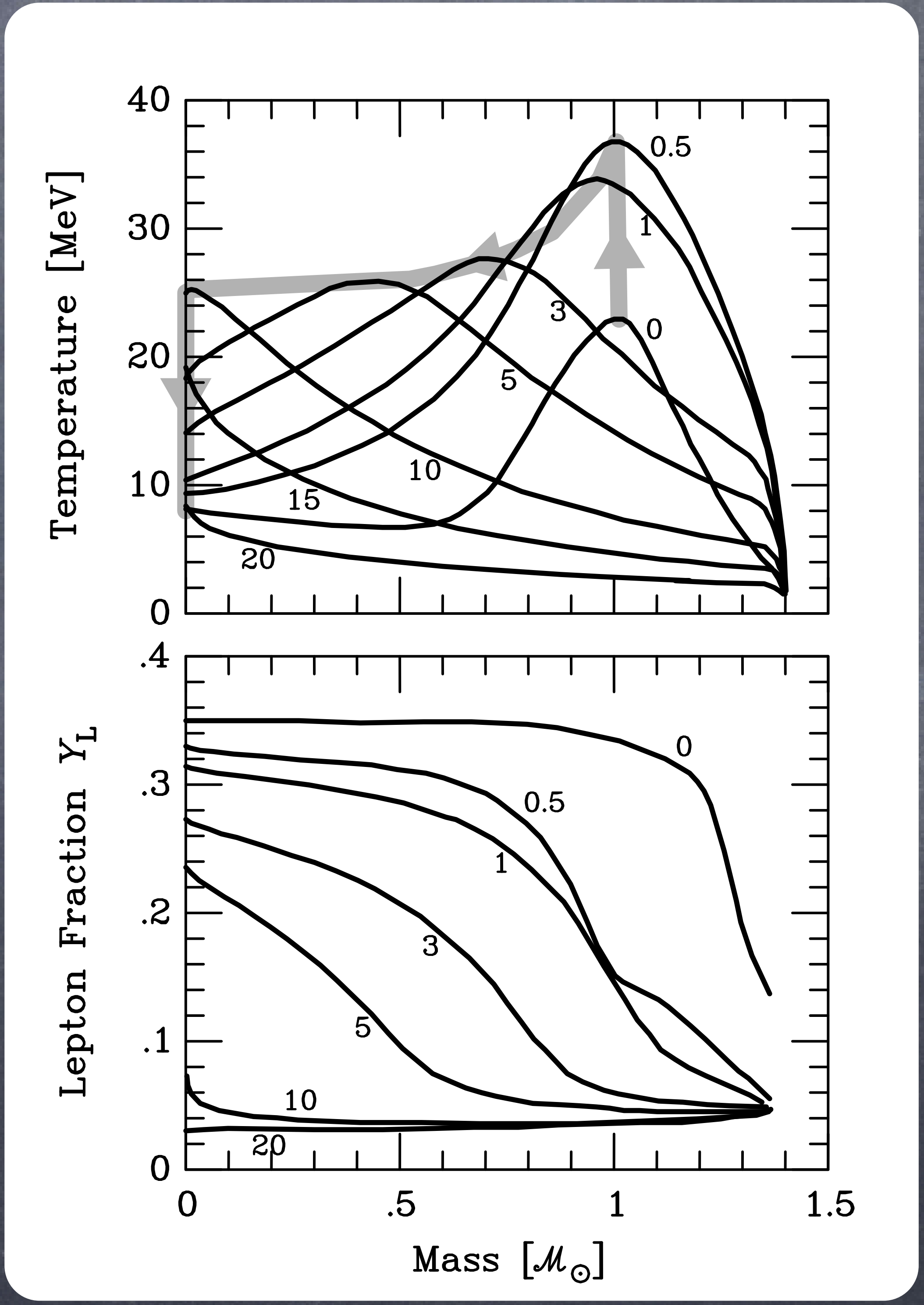
Stages of the explosion



T. Janka (1993)

Internal evolution

Notice that the center is initially cold (low entropy per baryon)
It heats up as lepton number diffuses out



Borrows & Lattimer (1986)

Evolution of the explosion is reflected in neutrinos

- Neutronization burst, accretion and cooling phases can all be seen in neutrinos
- Importantly, this signal depends on the progenitor mass

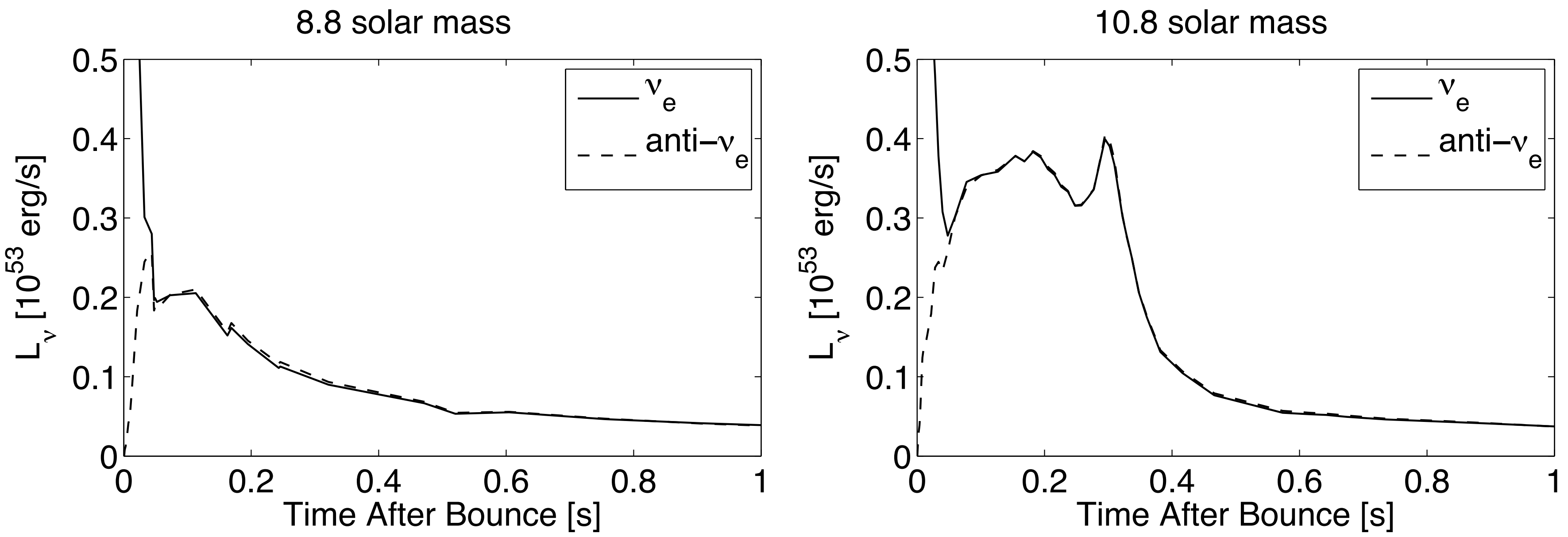


Fig from Fischer, Whitehouse, Mezzacappa, Thielemann, Liebendörfer, arXiv: 0908.1871

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!

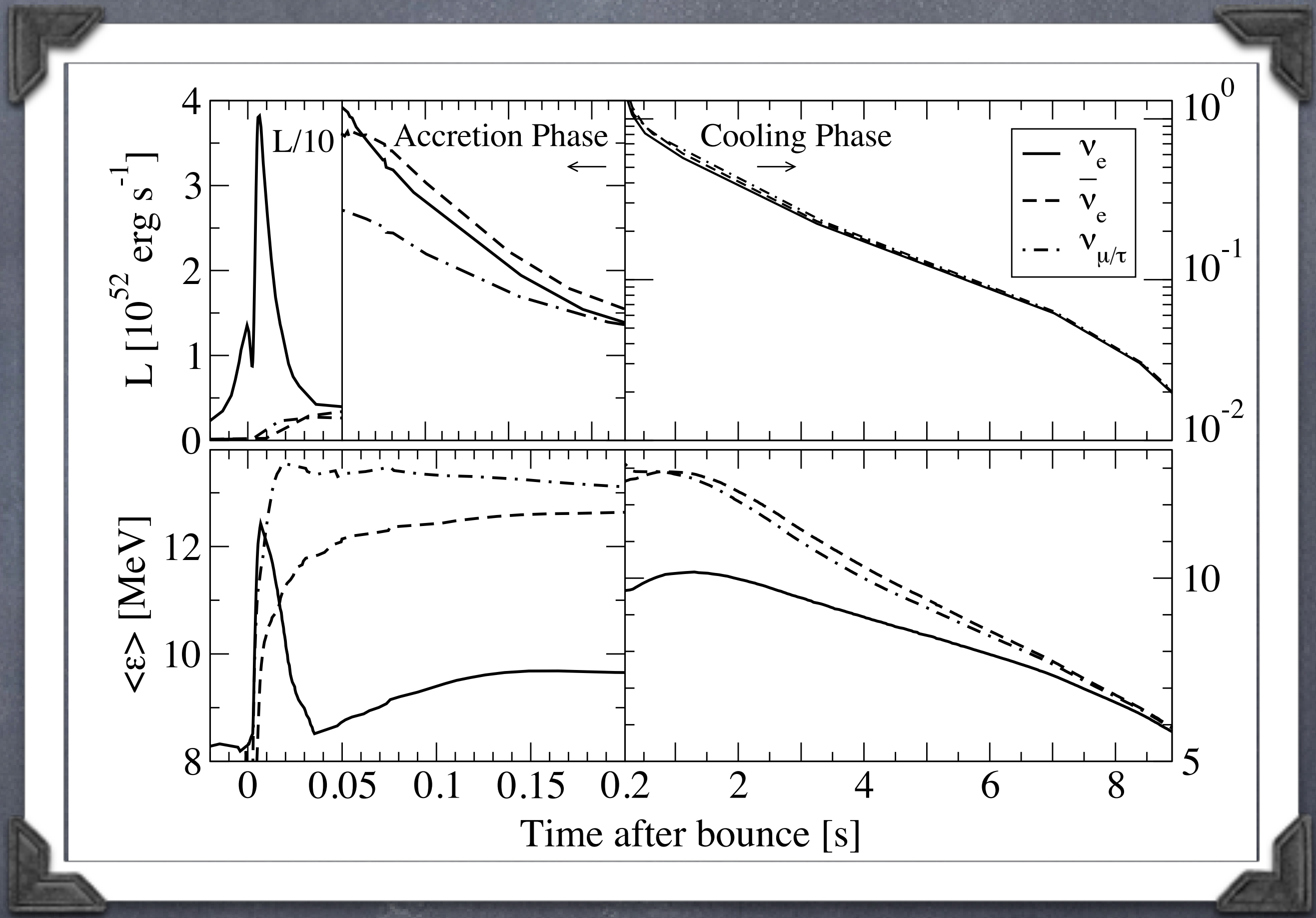
- **Cooling stage** ends with the formation of a neutron star or a black hole. The signal is sensitive to new physics contributions to cooling (light hidden sector!). Monitor how the shock travels out and the turbulent bubble behind expands.
  - May be possible thanks to neutrino oscillations!

Detectors, very briefly

- Water-Cherenkov (Super-K/Hyper-K): nue-bars through inverse beta decays. 10^4 events in Super-K, 10^5 in Hyper-K.
  - + Elastic scattering on electrons (a few hundred at SK). Other flavors contribute. Pointing.
- IceCube, no energy resolution, but a lot of statistics (millions of hits)!
- Liquid Argon (DUNE): primarily electron neutrinos! Several thousand events, with good energy resolution
- Liquid scintillator (JUNO): primarily inverse beta decays. Thousands of events.
- Second-by-second information about the emitted neutrinos, in different channels. Need to figure out how to read this signal

Neutrino mass measurement

- Neutronization burst is a sharp time feature ~ 10 ms
- Massive neutrino time delay $\Delta t=(l/c)(\Delta m^2/2E^2)$
- For 10 kpc Galactic SN, $l/c = 10^{12}$ s. Then $\Delta t=10^{-2}$ s implies $\Delta m^2 \sim 1$ eV
- For comparison, for SN1987a, duration of burst is ~ 10 s, but the distance is 50 kpc (LMC!). This gives $\Delta m^2 \sim 20$ eV.



Hudepohl, Muller, Janka, Marek, Raffelt, PRL (2010)

Total energy output

- How well can we measure total energy output?
  - Useful, for example, in looking for additional energy losses due to new physics
- Problem: can't measure neutrinos in all flavors,
  - only in electron antineutrinos in water (SuperK, IceCube)
  - or electron neutrinos in Argon (DUNE)
- Need to understand oscillations
  - Other excellent reasons to understand oscillations, for example, to model nucleosynthesis or perhaps even the impact on the explosion itself.

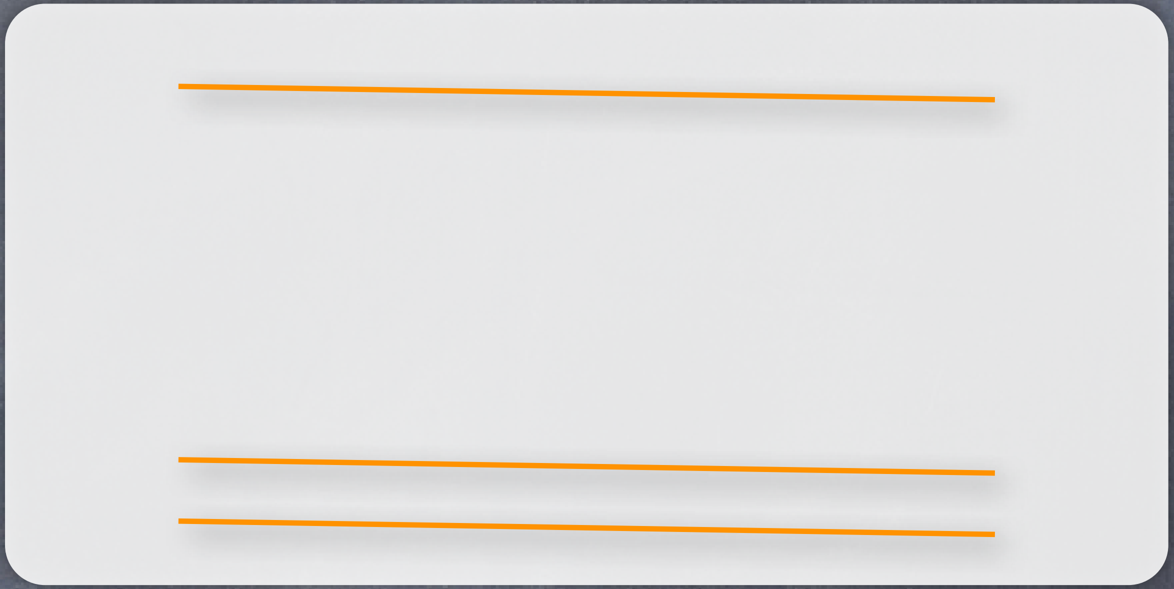
Tracing neutrinos back

- Vacuum oscillations over O(10 kpc)
  - 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

Vacuum oscillations

- The oscillation length in vacuum, $E/\Delta m^2 \sim 10^2$ km $\ll$ 10 kpc = $3*10^{17}$ km
- Therefore, energies different by $\delta E/E \sim 10^{-15}$ will have different oscillation phases
- $\Rightarrow$complete decoherence between mass eigenstates
- Also, wavepacket separation
  - which is the same
- The result is an incoherent sum of spectra of vacuum mass eigenstates

NH



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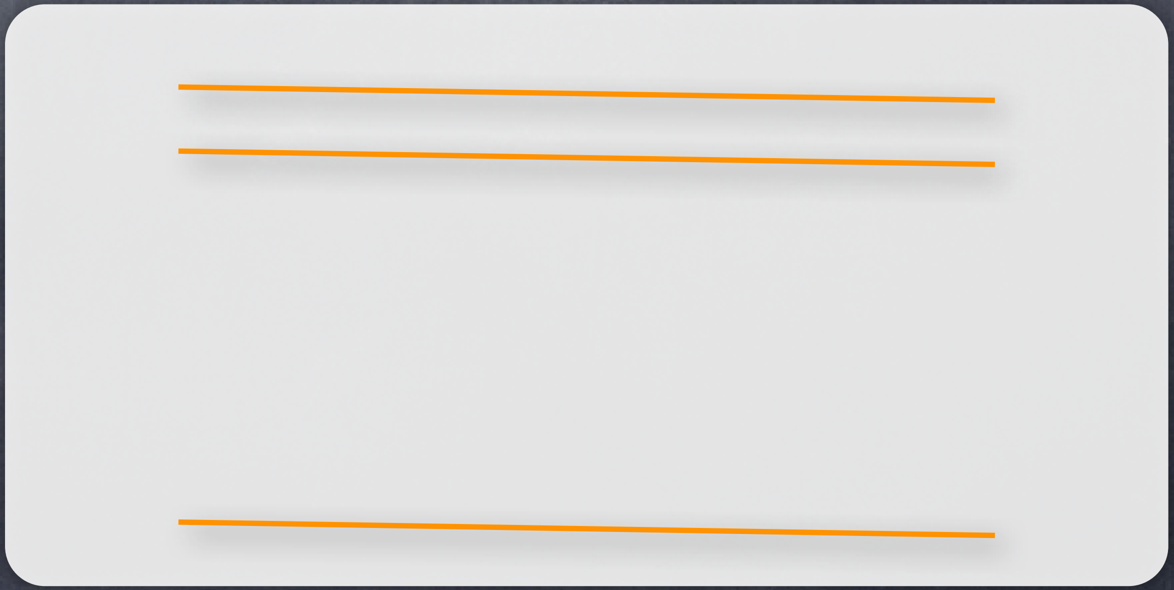


Possible Earth effect

- 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

Next ingredient: MSW effect, caused by changing matter density

- Solar neutrinos: quantum mechanics problem

$$i\partial_t|\psi_i\rangle = H_{\rm osc}|\psi_i\rangle$$

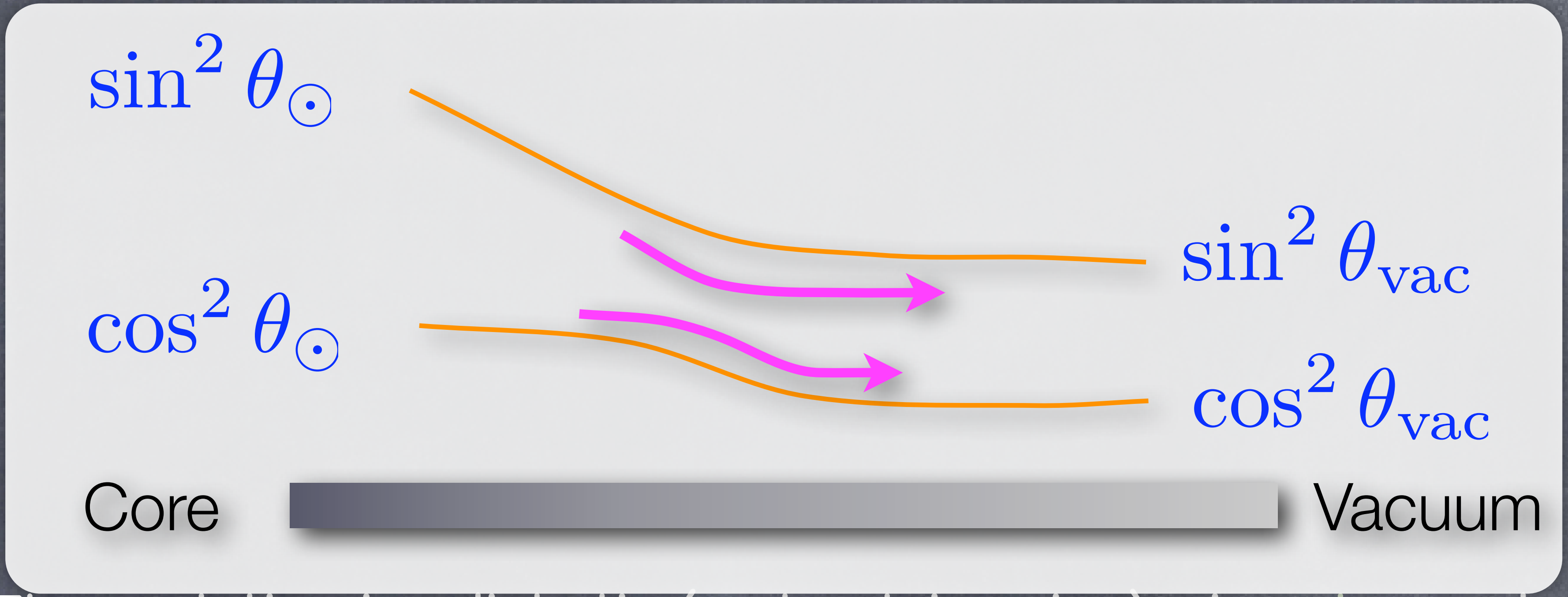
$$H_{\rm osc} = H_{\rm vac} + H_{\rm matter}$$

$$U\mathrm{Diag}(\Delta m^2_{\rm atm}, \Delta m^2_{\odot})U^\dagger$$

$$H_{\rm ee} = \sqrt{2}G_F N_e$$

Sun: 2-state oscillations

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



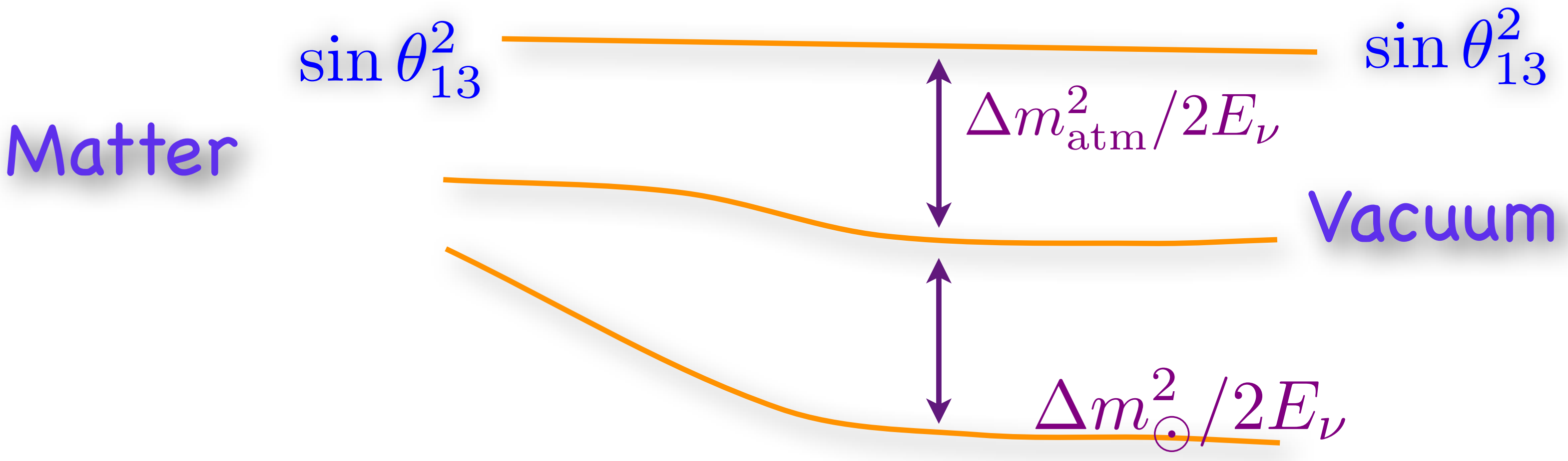
- The evolution is adiabatic (no level jumping), since l_{osc} << density scale height ($|d \ln\rho/dr|^{-1}$)
  - Hint: for most of the Sun, the density scale height is $R_{sun}/10$, while l_{osc} is comparable to the width of Japan (KamLAND)
- Also, the coherence between the states is lost
  - The oscillation length ≪ the size of the production region

Sun:3-state oscillations

- The third state provides a ~ 4.5% correction

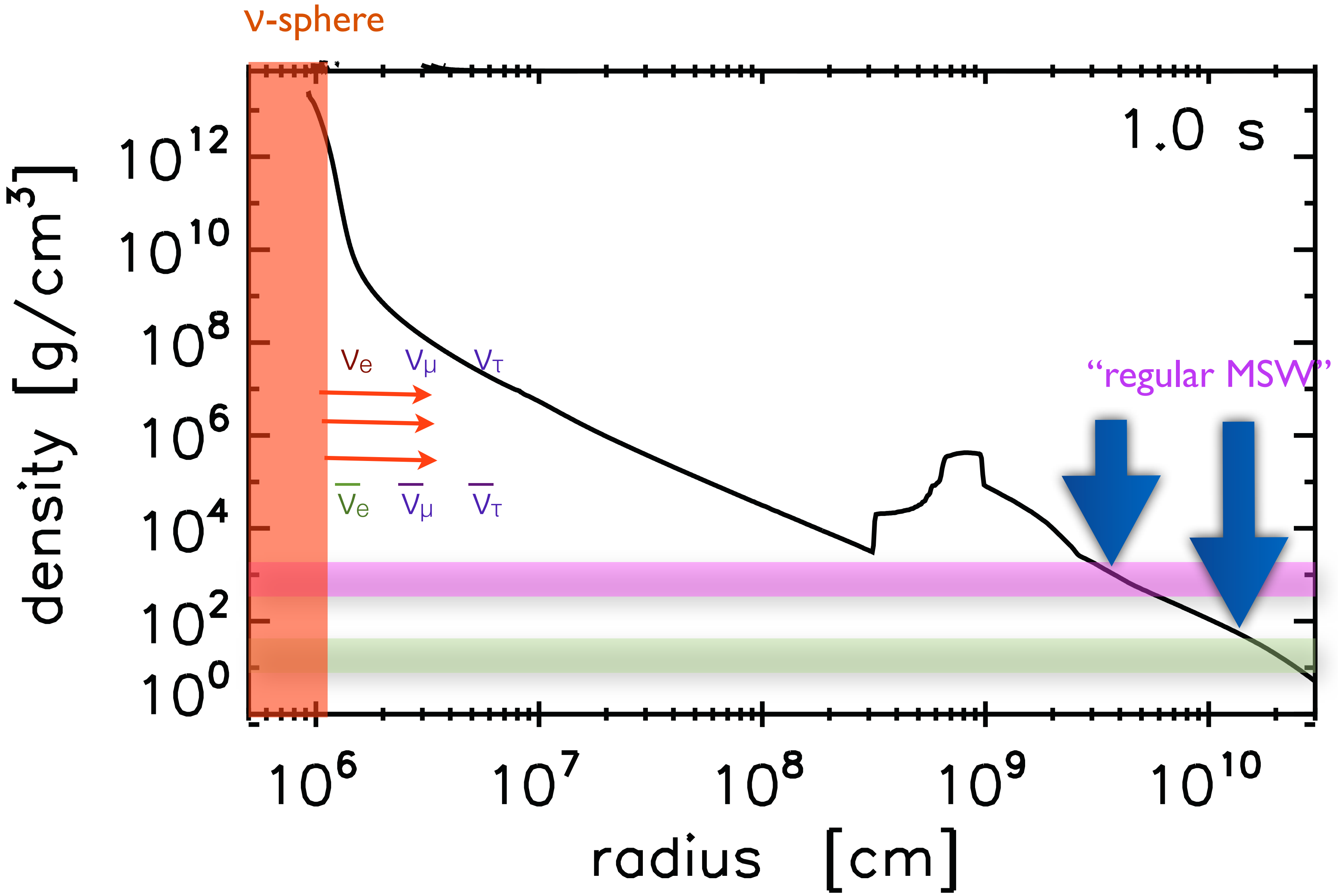
$$\begin{aligned} P_3(\nu_i \to \nu_i) &= \sin\theta_{13}^4 + \cos\theta_{13}^4 P_2(\nu_i \to \nu_i) \\ &\simeq 0.955 P_2(\nu_i \to \nu_i) \end{aligned}$$

Not to scale!



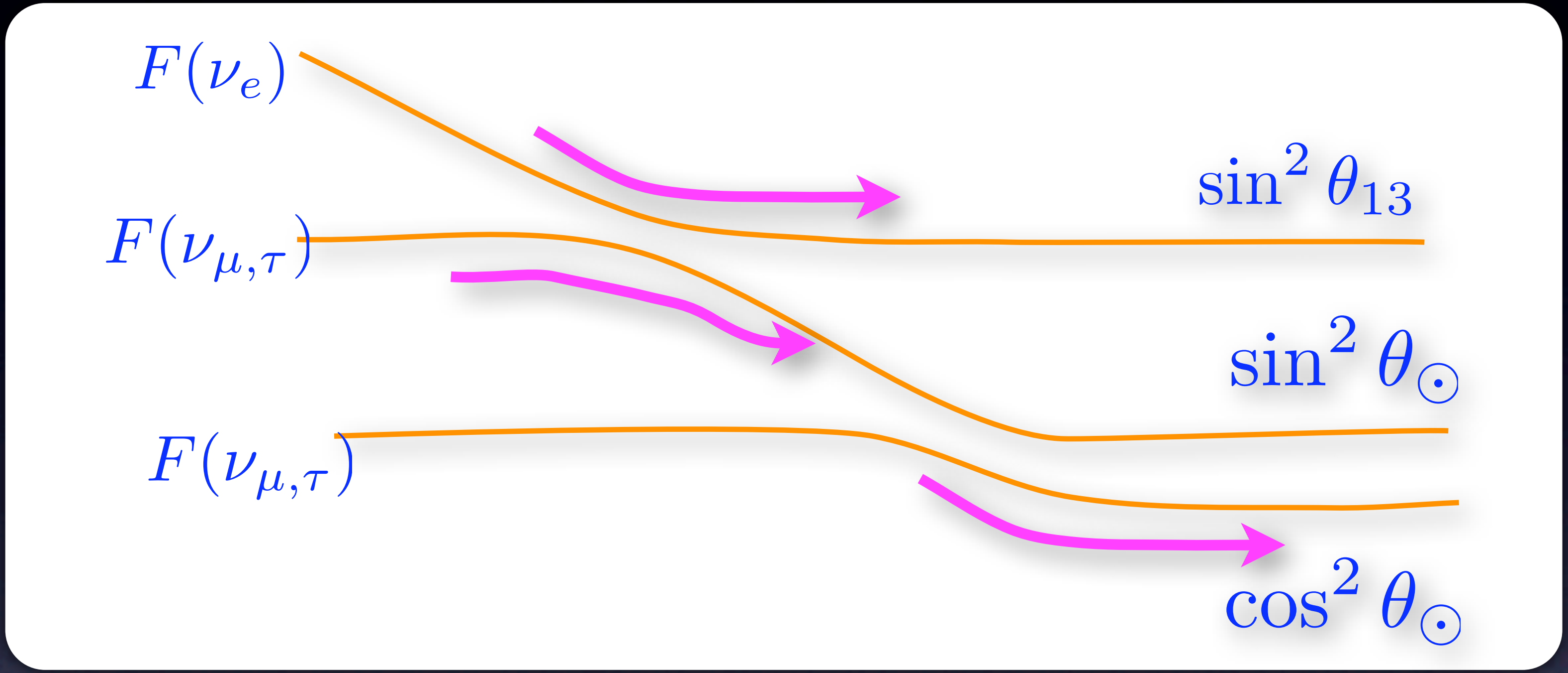
- Notice that the projection of the electron neutrino on the third state is $\sin\theta_{13}^2$, unaffected by matter

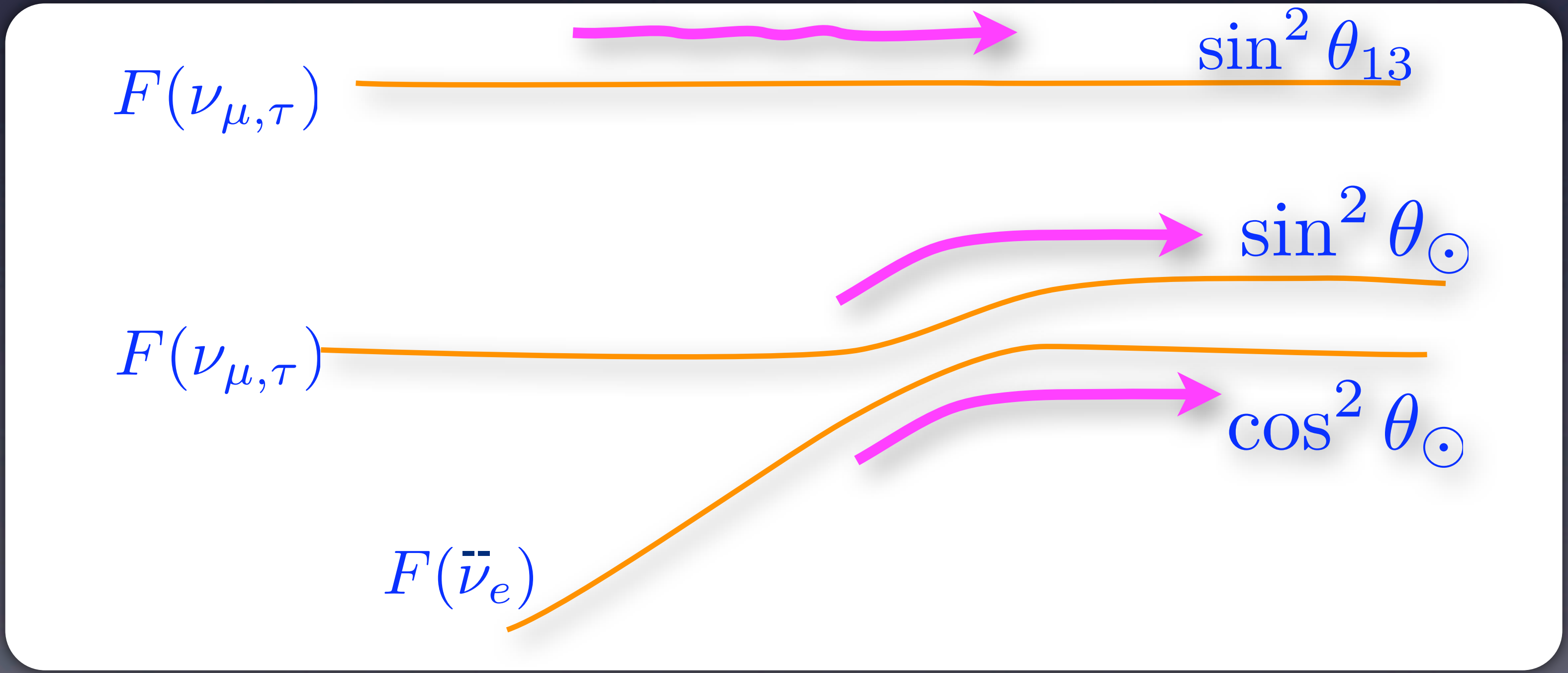
SN ν oscillations: 2 MSW densities



SN MSW transformations, schematics

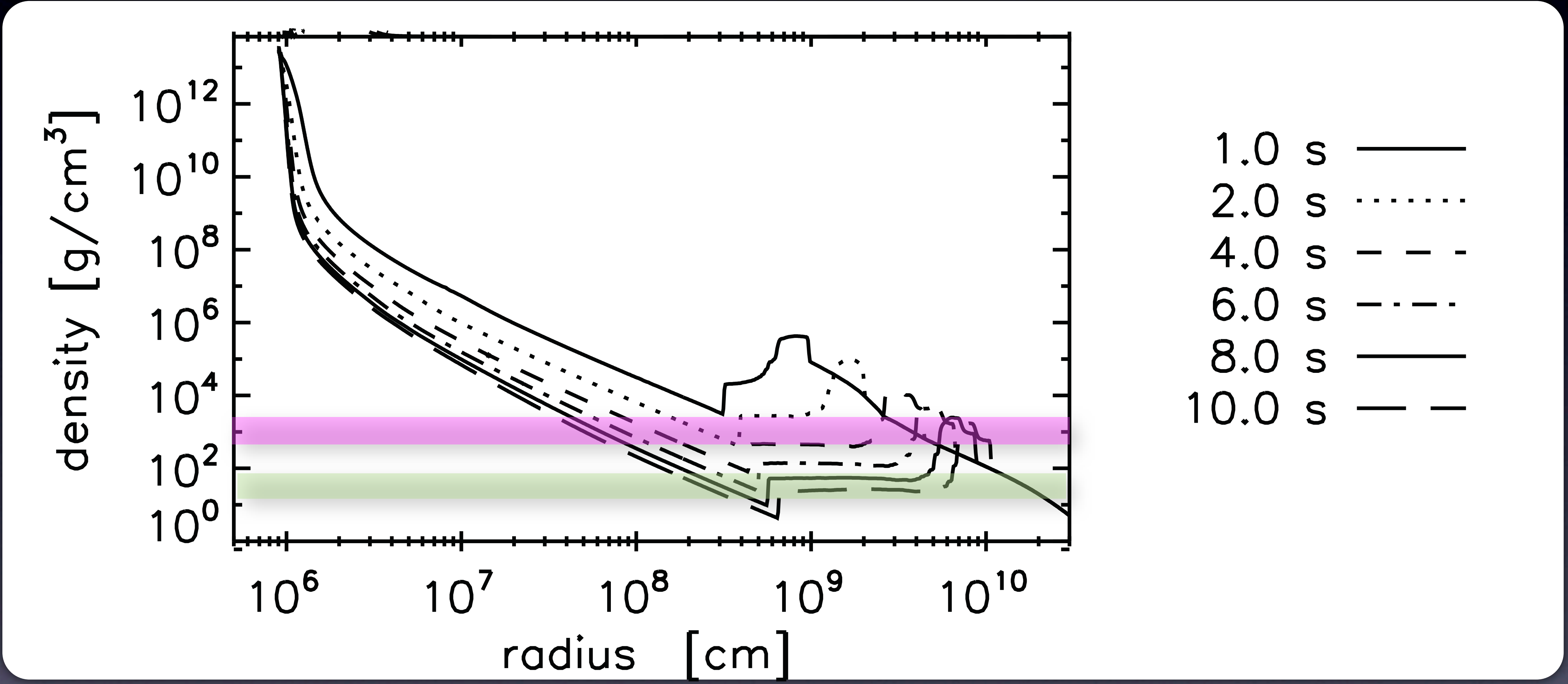
- The neutrinos and antineutrinos have different level crossings
  - Matter potential changes sign
- Given the scale height in the progenitor, the evolution is very adiabatic
  - the adiabaticity of the atmospheric resonance is controlled by theta13





For inverted hierarchy, the same happens in antineutrinos.

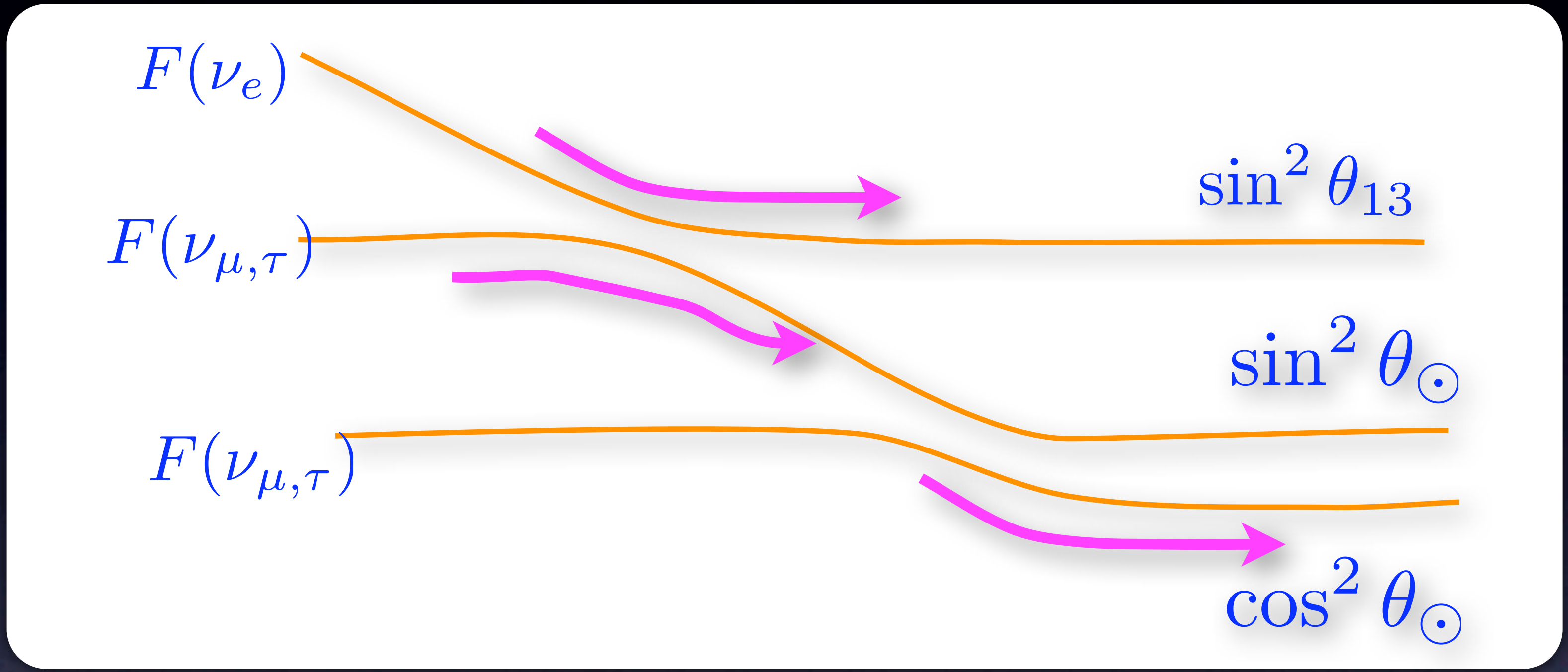
Dynamical density profile

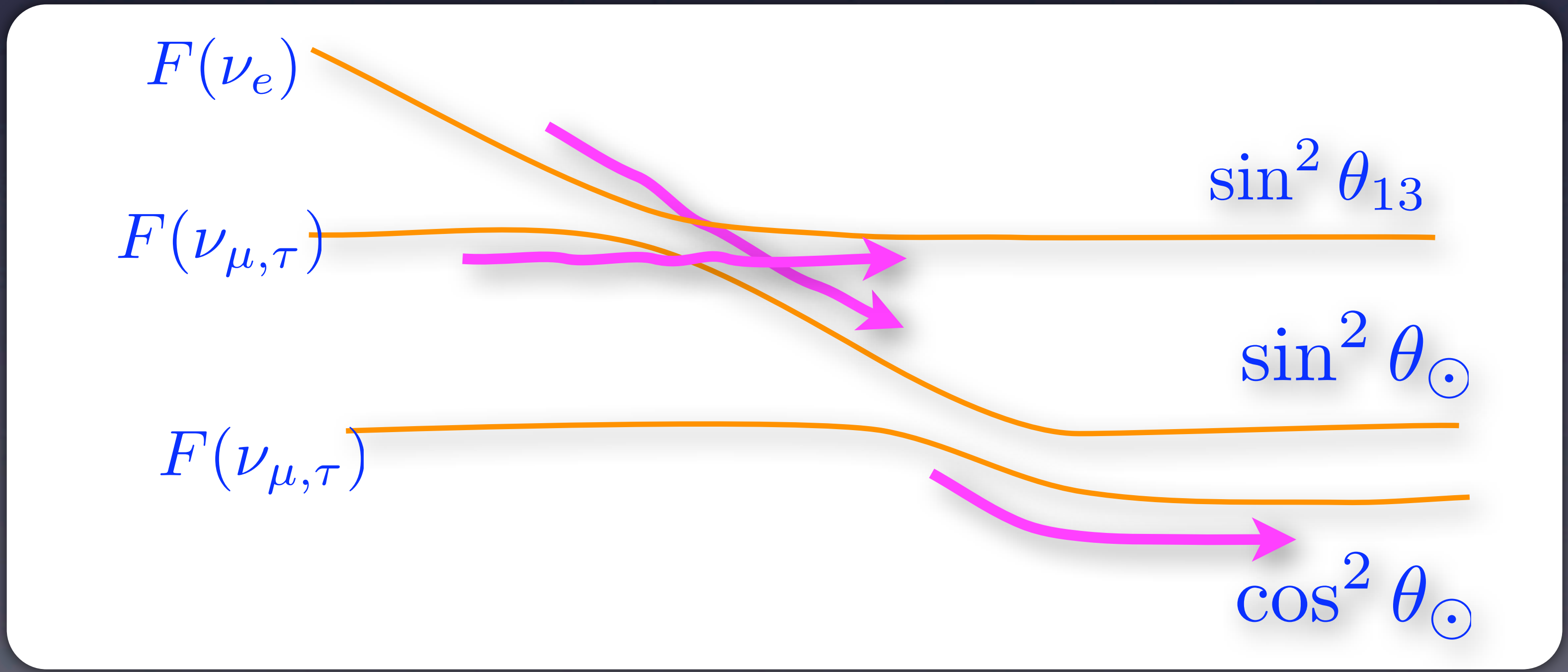


- Front shock reaches the regions where “atmospheric” and “solar” transformations happen, while neutrinos are being emitted
  - See Schirato & Fuller (2002) astro-ph/0205390

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.

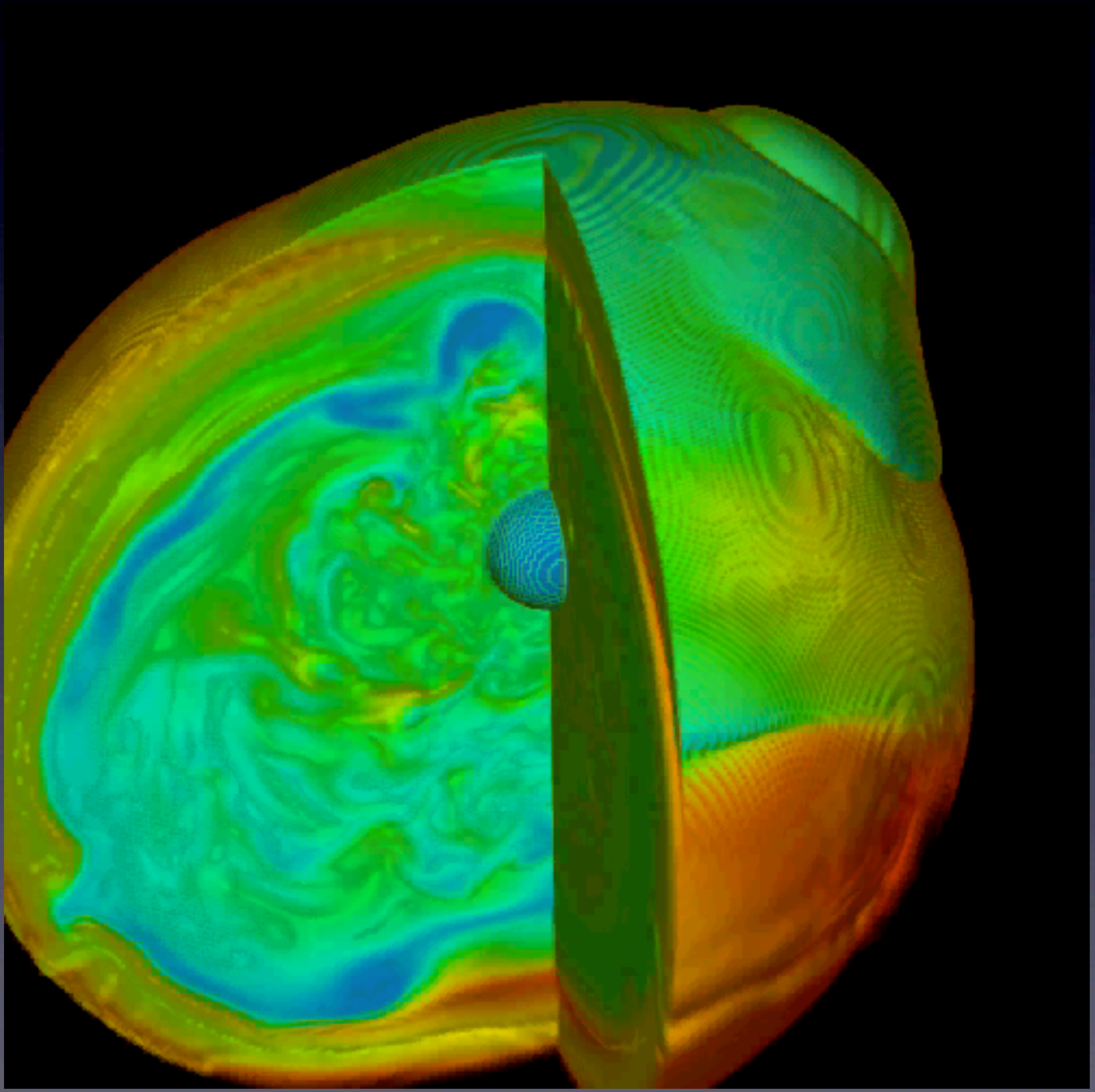




For inverted hierarchy, the same happens in antineutrinos.

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
- No central heating. Still,
  - extensive, well-developed turbulence behind the shock

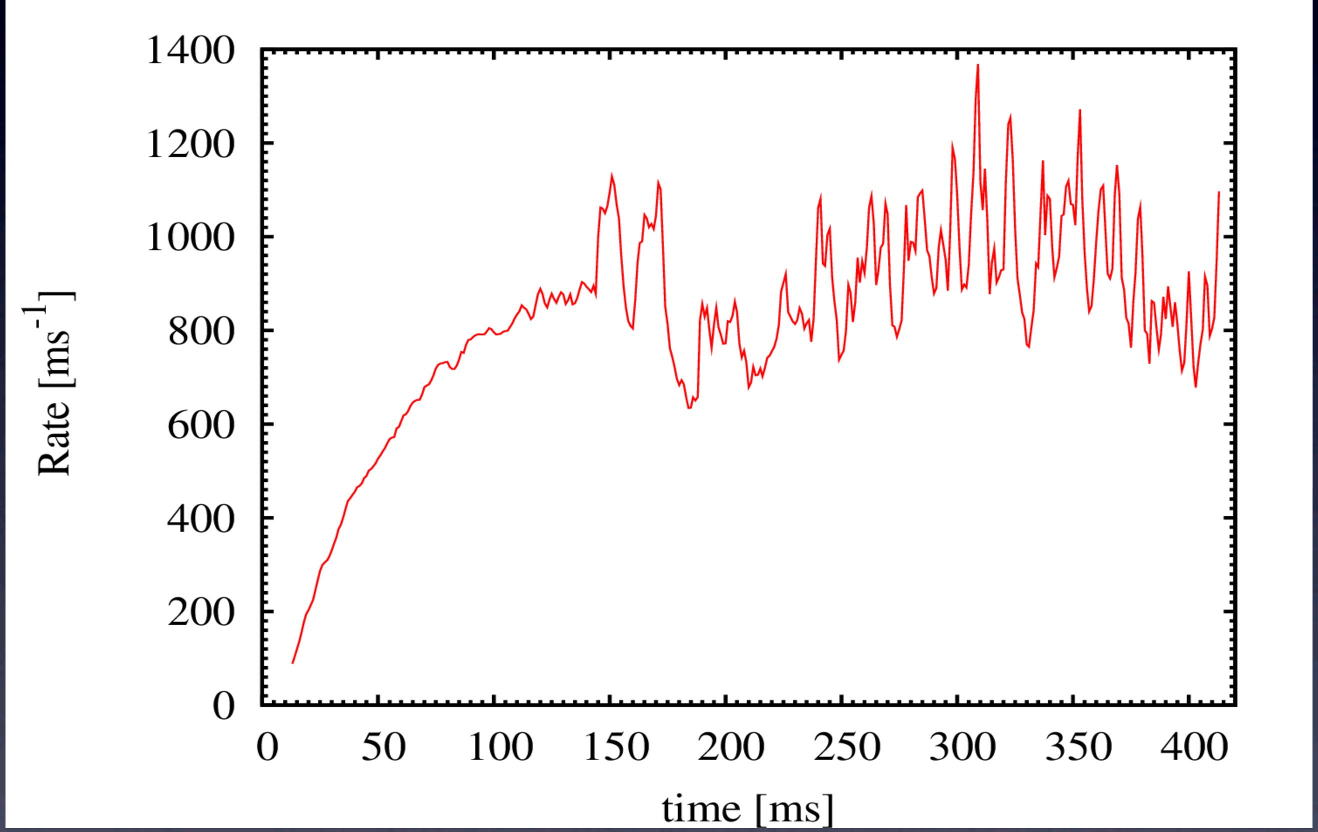


Reproduced in a backyard water experiment

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

Neutrino signature of SASI

- The large sloshing motion could result in rapid variation of the neutrino event rate during the accretion phase
- It was suggested to look for this with IceCube



Lund, Marek, Lunardini, Janka, Raffelt, arXiv:1006.1889

Turbulence and MSW

- 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

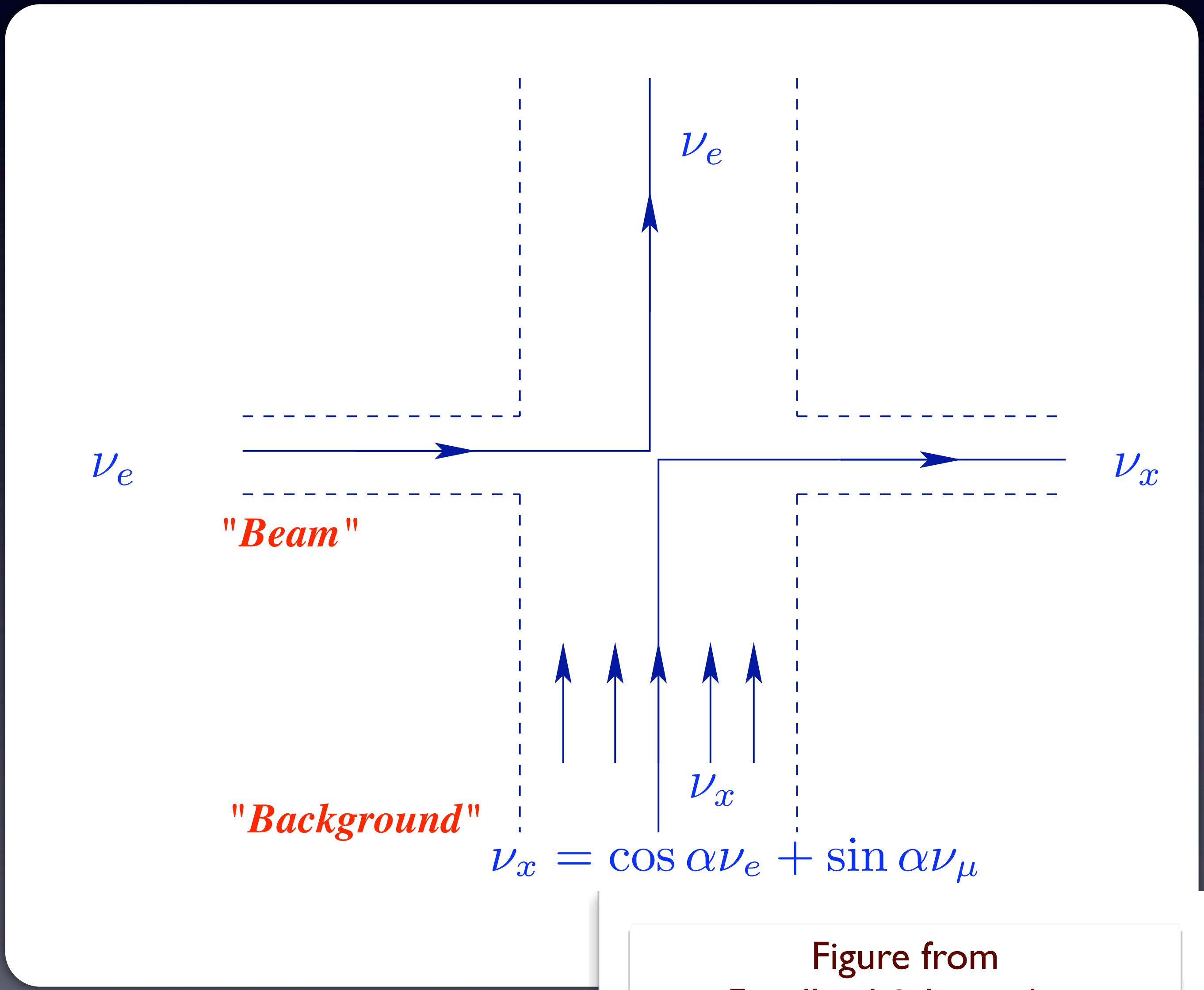
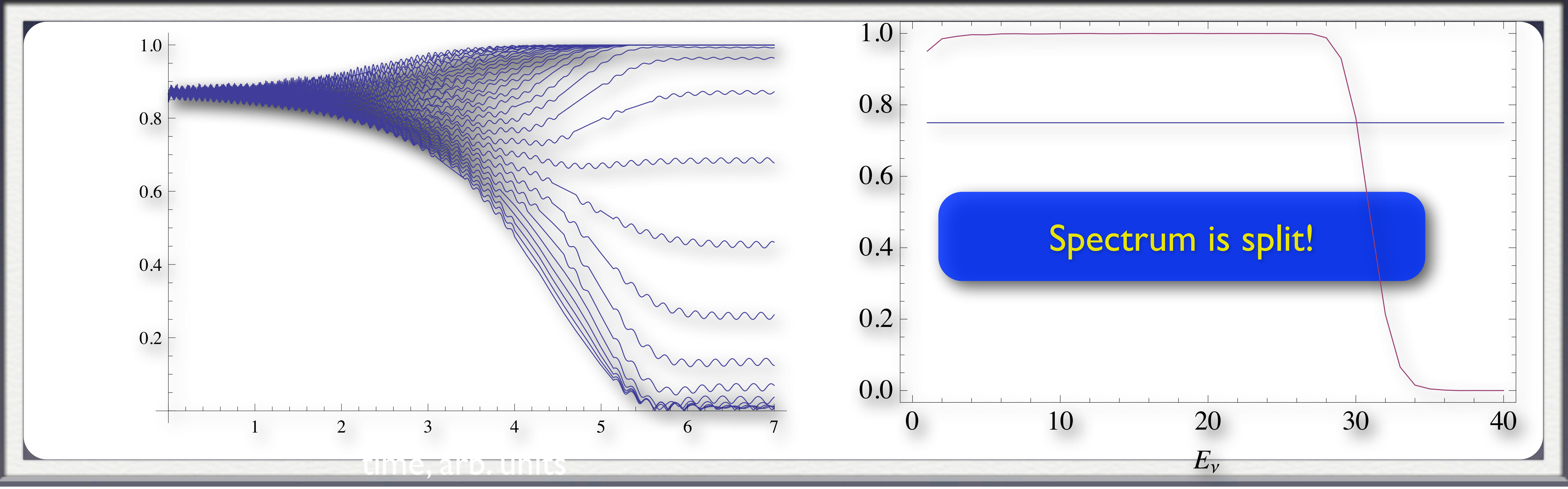


Figure from
Friedland & Lunardini,
Phys. Rev. D 68, 013007 (2003)

Simplest toy problem

(after Raffelt & Smirnov, 2007)

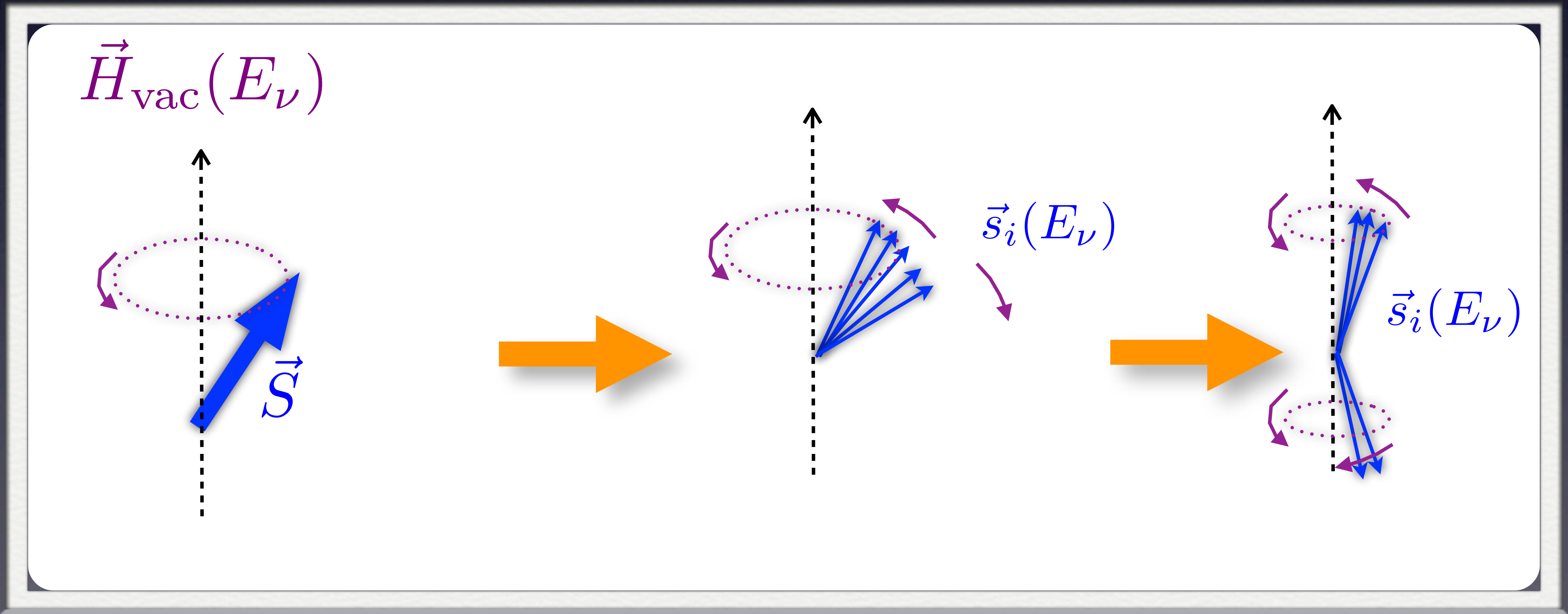
- Start with neutrinos of different energies, all initially in the same flavor superposition state $\cos\theta_0 \, |\nu_e> + \sin\theta_0 \, |\nu_\mu>$
- Take the self-coupling to be large initially (much larger than the vacuum oscillation terms for these neutrinos).
- Gradually relax the self-coupling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



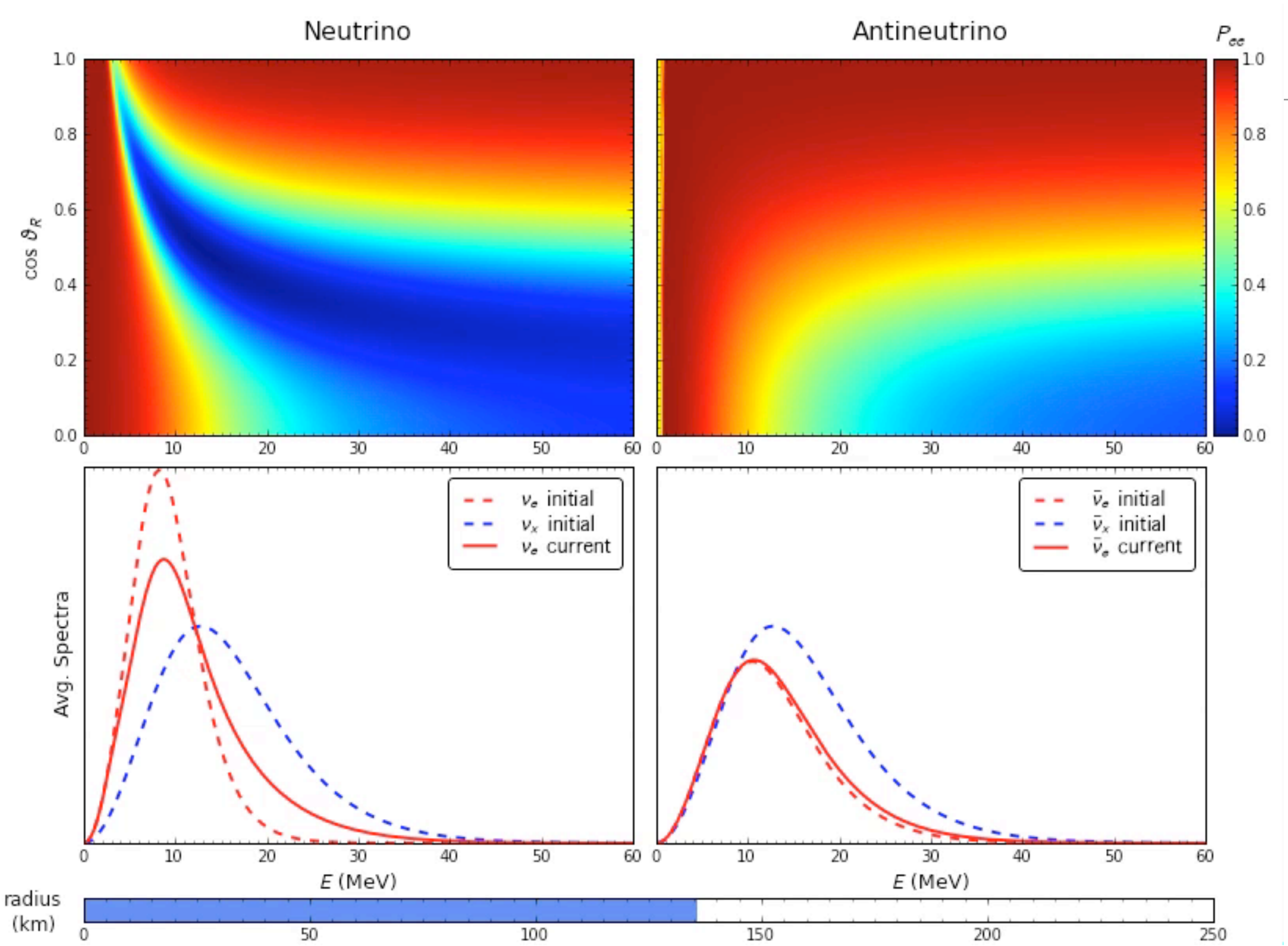
Spectrum is split!

Simplest toy problem: spin picture

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

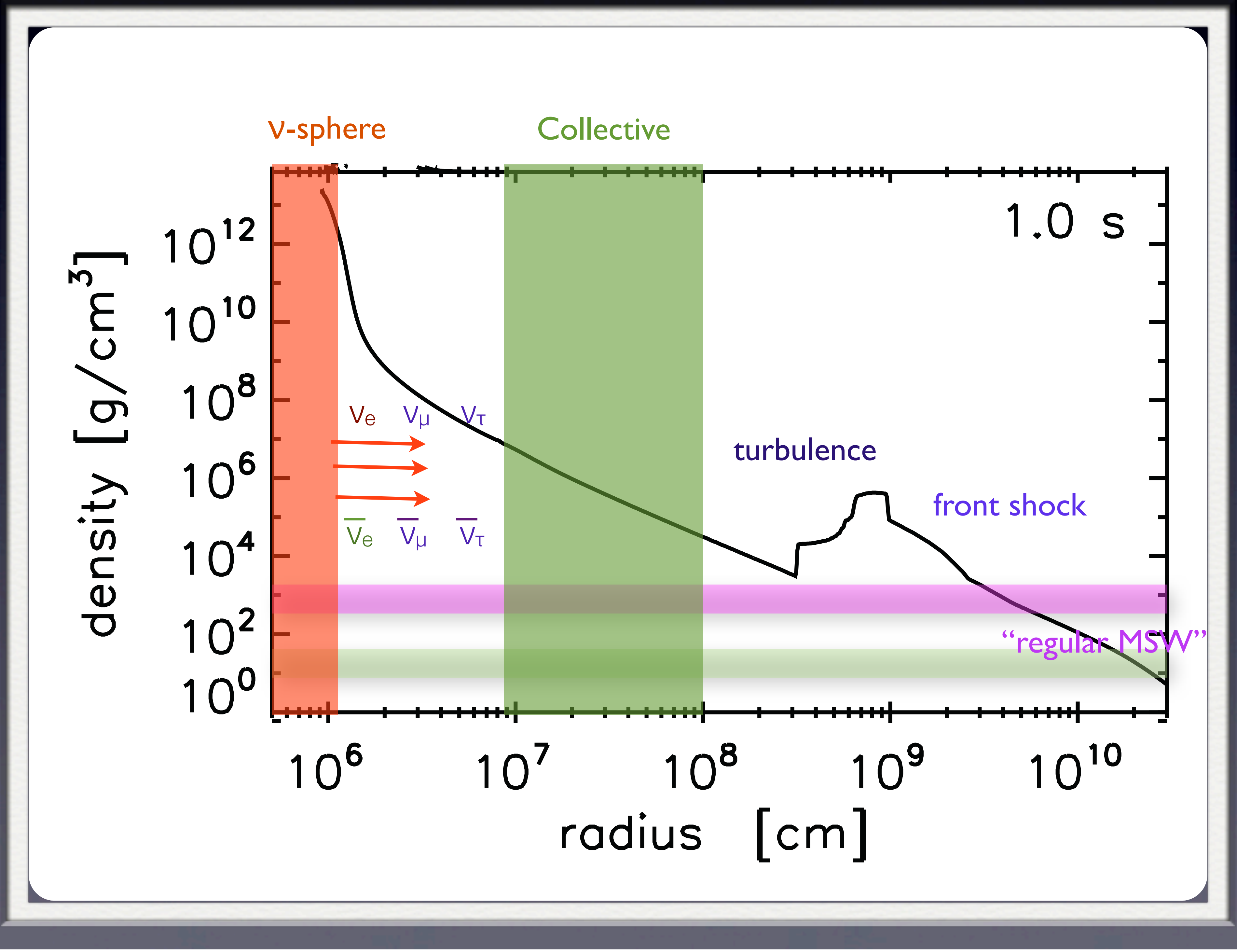


Duan & Friedland, PRL (2011)



Observe that the motion is collective, involving neutrinos and antineutrinos of different energies on different trajectories

SN ν oscillations: physics cartoon



Order-of-magnitude estimates

- "Standard" MSW: transition from matter-to vacuum domination

$$\Delta m^2/2E_\nu \sim \sqrt{2} G_F N_e.$$

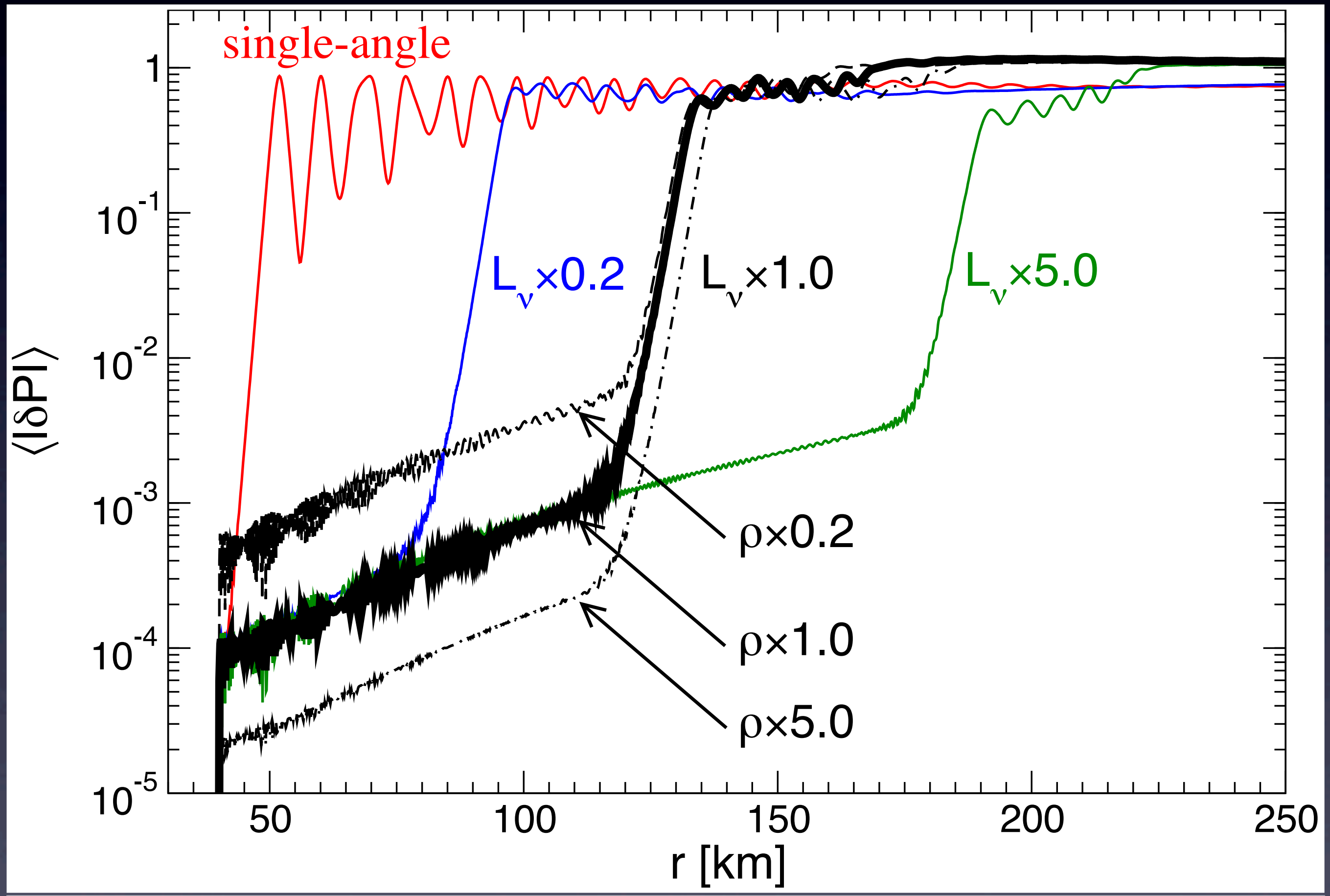
- Turbulence: relevant density fluctuations on the scale of the neutrino osc. length on resonance

- Collective effects: transition from synchronized regime (strong self-coupling) to vacuum

$$G_F |N_\nu - N_{\bar{\nu}}| \langle 1 - \cos\Theta(r_{\nu\nu}) \rangle \gtrsim \Delta m^2/E_\nu.$$

This picture is very neat, perhaps too much so

- Do collective oscillations happen close to, or even inside the neutrino-sphere?
- Crucial for the validity of the supernova models!



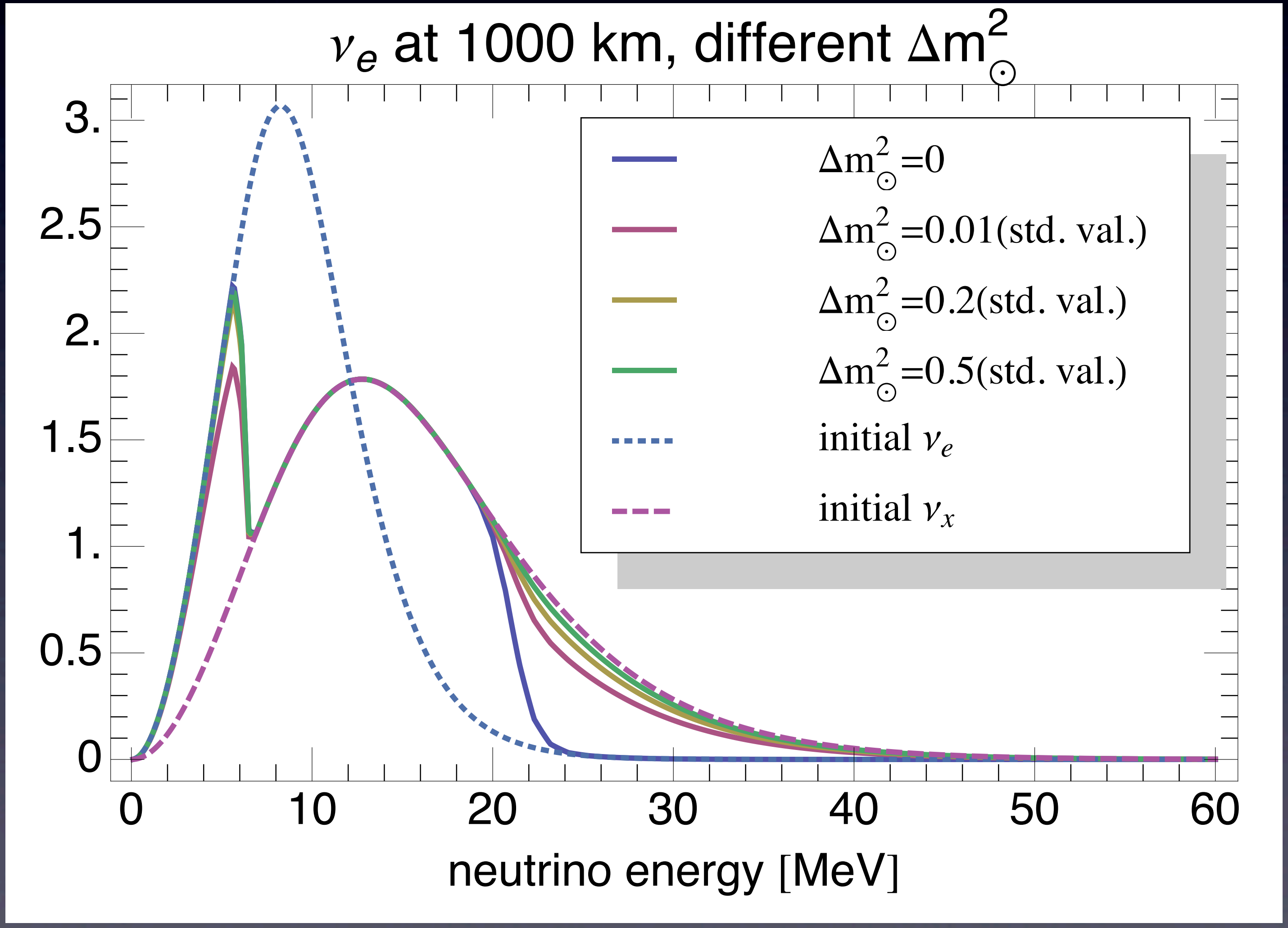
H. Duan & A.F., Phys. Rev. Lett. 106, 091101 (2011)

Breaking of spherical symmetry

- The system could be unstable to axial symmetry breaking
  - Raffelt, Sarikas de Sousa Seixas, PRL 111, 091101 (2013)
  - Mirizzi, PRD 88, 073004 (2013); arXiv: 1308.5255
- Also, potentially to symmetry breaking along the surface of emission (Duan & Shalgar, 2015)

Can adding a tiny parameter (additional d.o.f.) have a large effect?

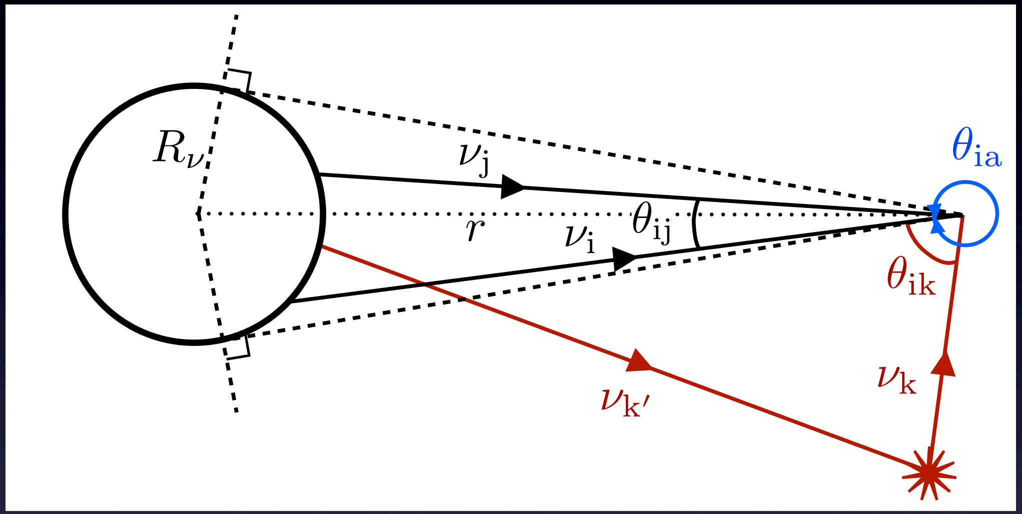
- Example where the solar mass splitting is turned on gradually
  - At $\Delta m_\odot^2=0$, 2-flavor result is reproduced
  - As soon as $\Delta m_\odot^2\neq0$, the answer is closer to the realistic $\Delta m_\odot^2$ than to $\Delta m_\odot^2=0$
- 2-flavor trajectory can be unstable in the 3-flavor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



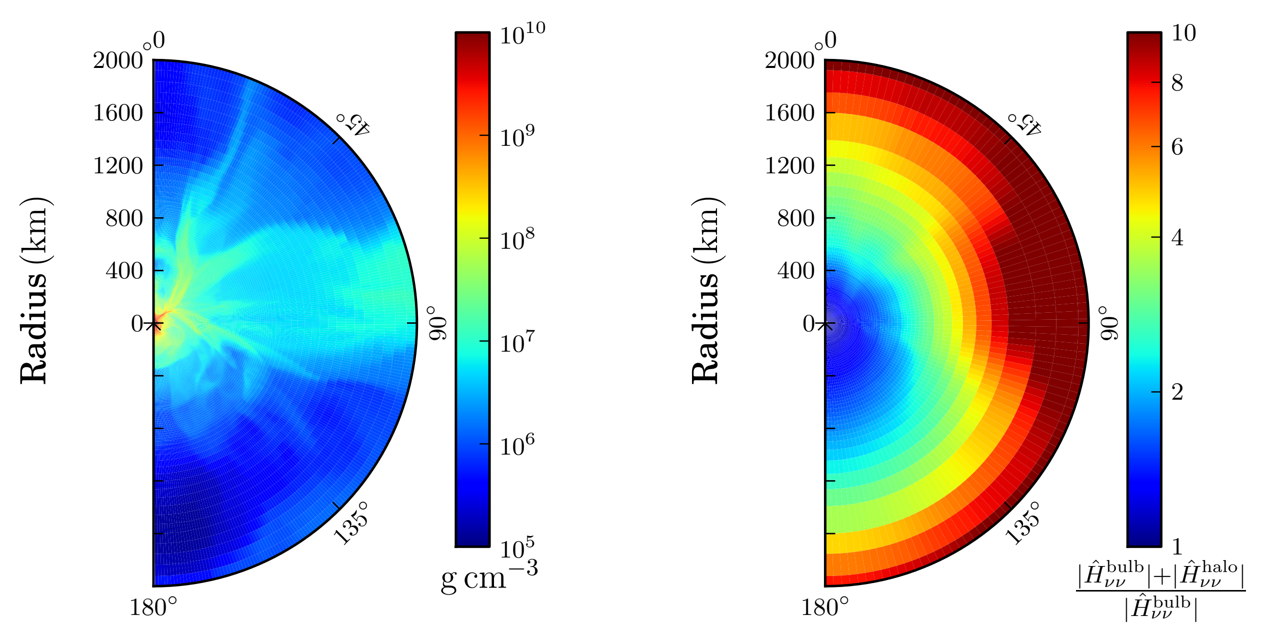
For details, see A. F., Phys. Rev. Lett.104, 191102 (2010);
also Dasgupta, Dighe, Raffelt, Smirnov, PRL (2009)

What happens during the first second?

Cherry, Carlson, A.F., Fuller, Vlasenko, PRL (2012)

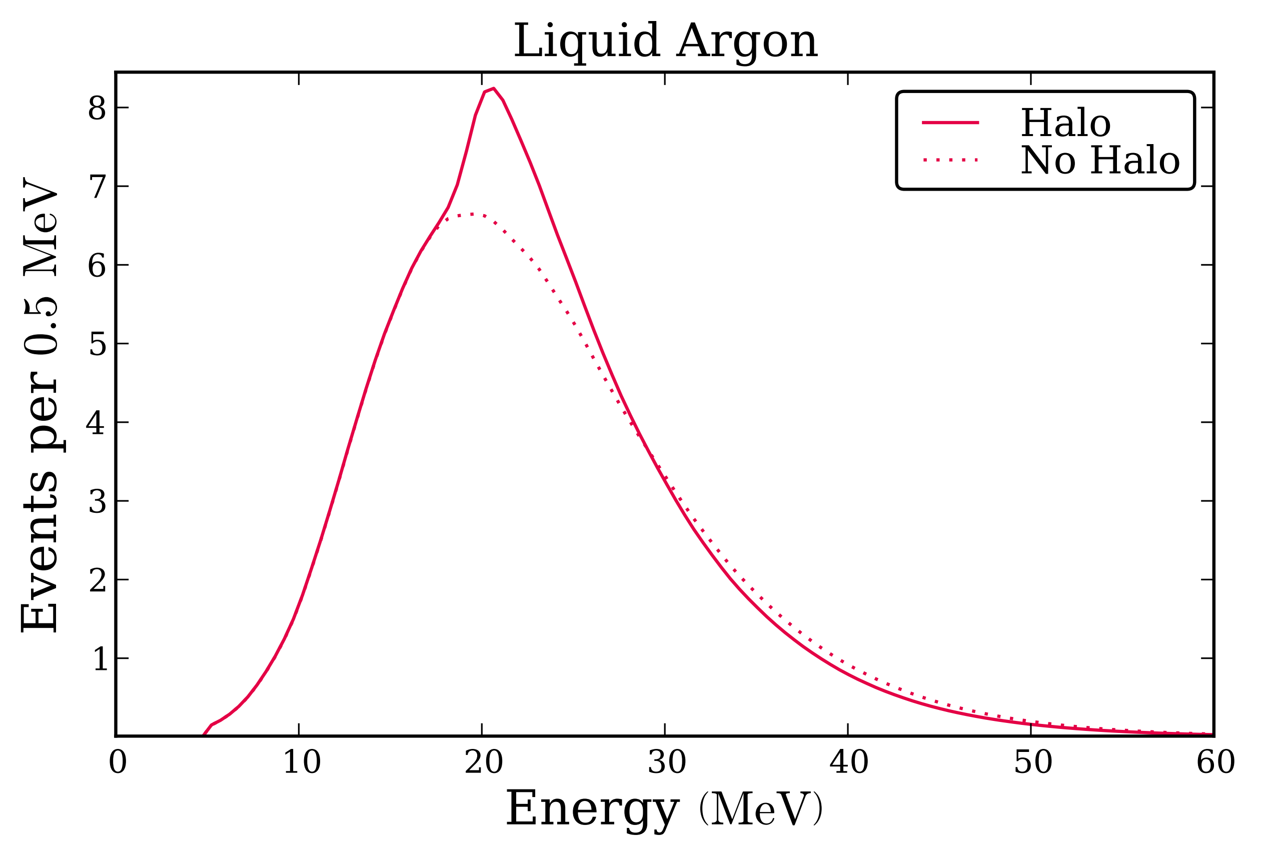


- Scattered "halo" neutrinos dominate oscillation Hamiltonian
- Matter inhomogeneous, plus some scattering is backward
- Nobody knows how to do this problem at the moment: need "super-supercomputing"?



Early in the explosion, computable

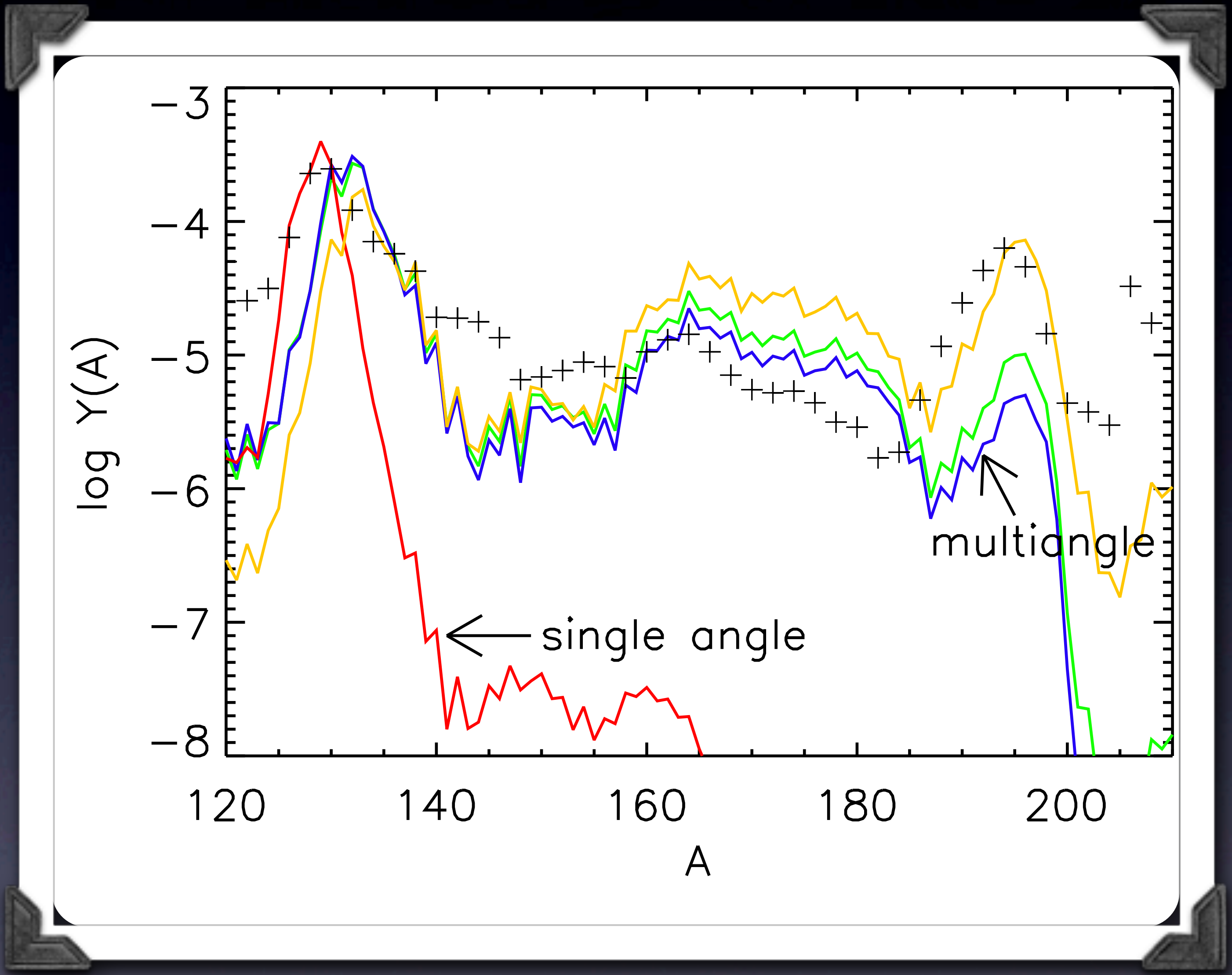
- Early in the explosion, large-scale density fluctuations haven't developed yet
- The problem can be modeled numerically and the halo can be shown to have an effect



Cherry, Carlson, A.F., Fuller, Vlasenko, PRD (2013)

Direct impact on the r-process

- Where exactly the oscillations start and how they develop early on is crucial for the r-process

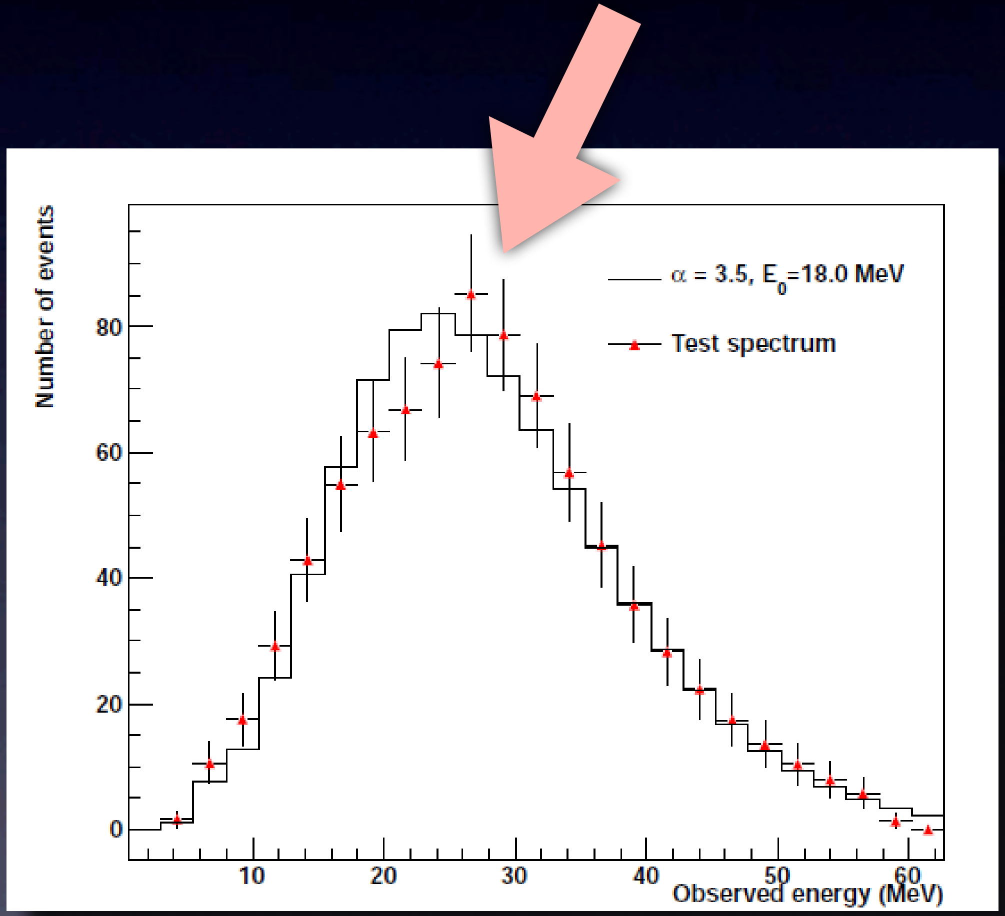


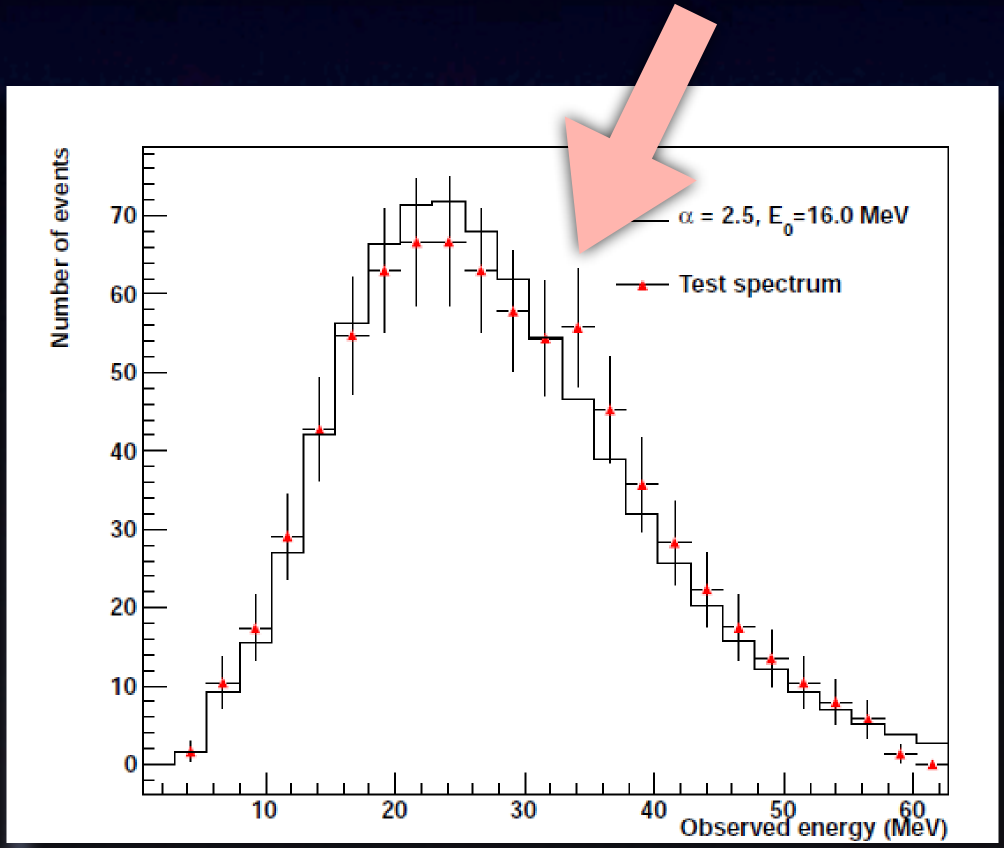
Duan, A.F., McLaughlin & Surman,
The influence of collective neutrino oscillations on a supernova r-process,
J. Phys. G 38, 035201 (2011)

What are we looking for?

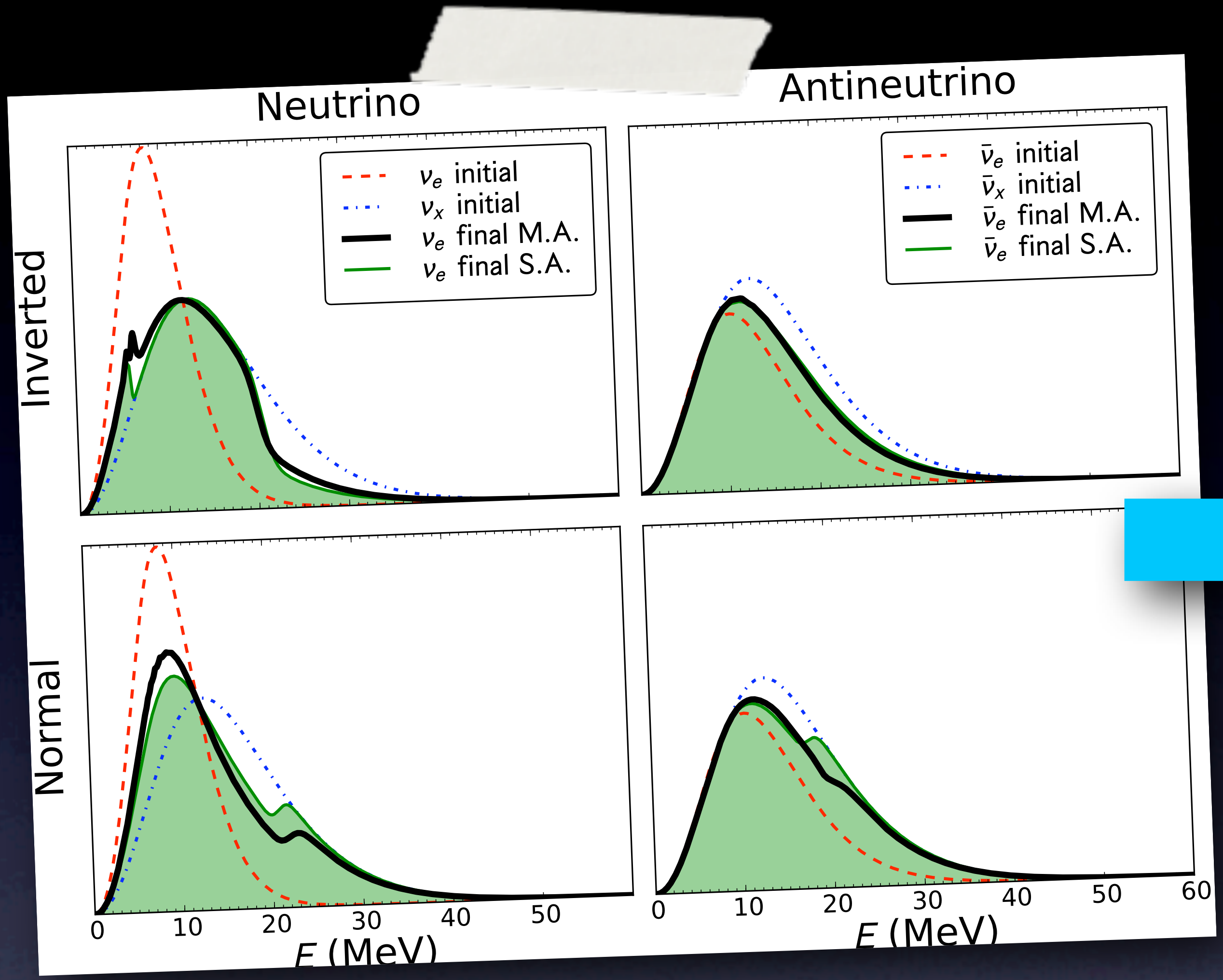
Modeling multiangle collective + moving shock by A. F.

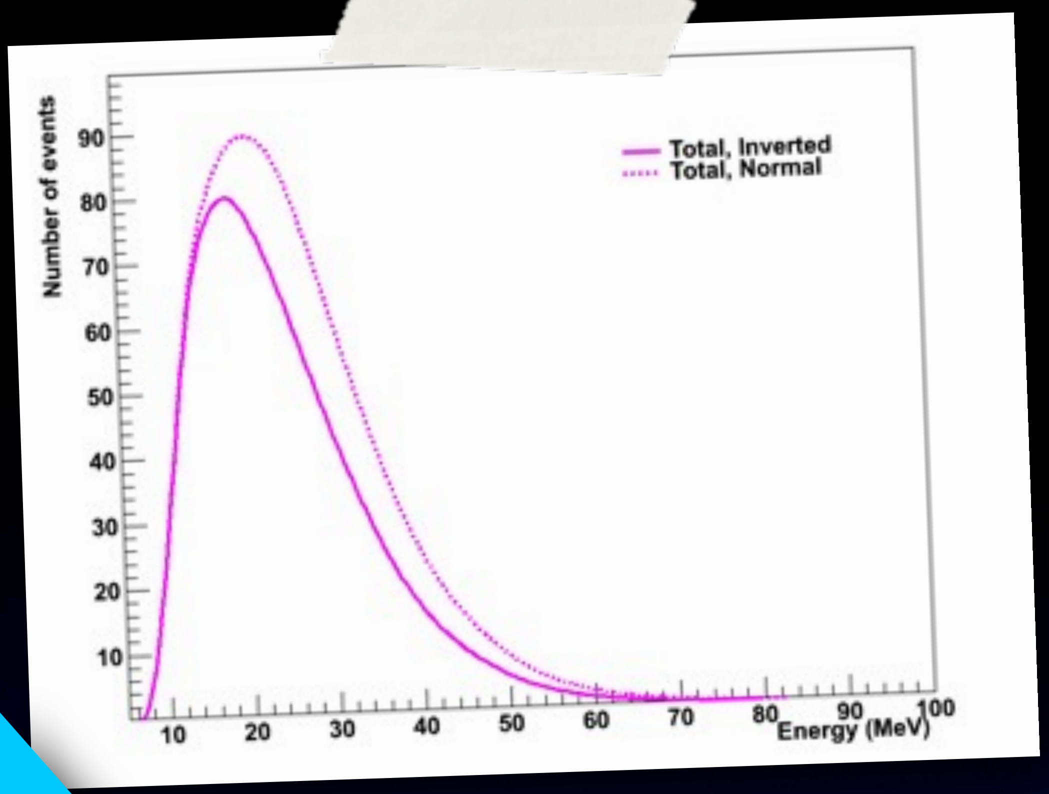
LAr detector model by K. Scholberg



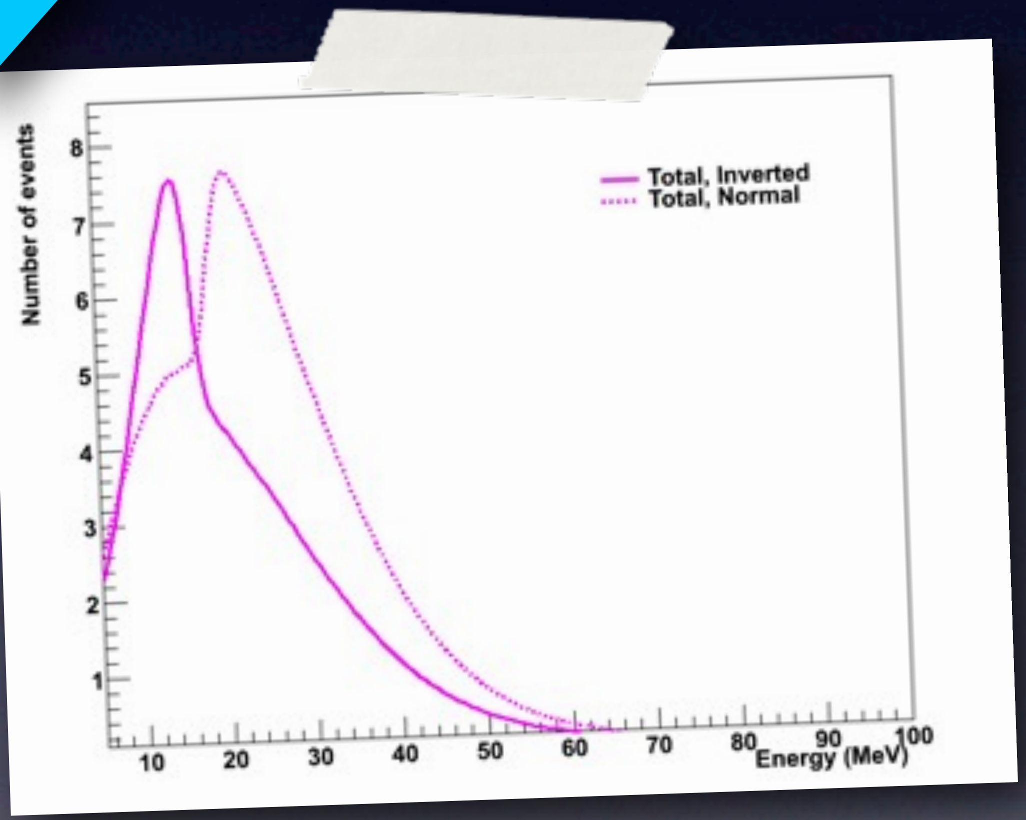


- Experimentally, of special value are phenomena that can give nonthermal, time-varying features in the spectrum





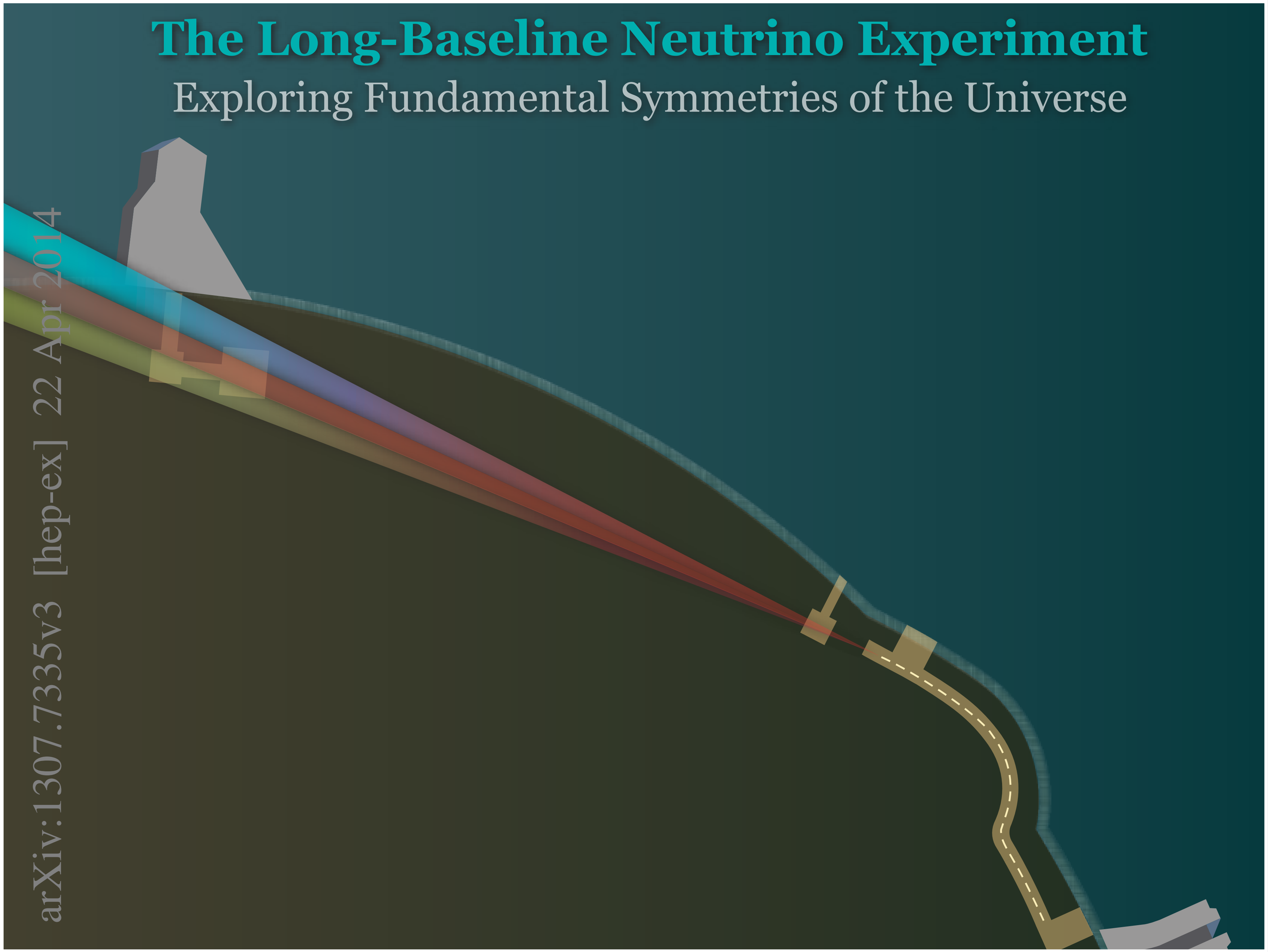
WC



LAr

* spectra by Duan & Friedland

* detector modeling by Kate Scholberg & co



The Long-Baseline Neutrino Experiment

Exploring Fundamental Symmetries of the Universe

arXiv:1307.7335v3 [hep-ex] 22 Apr 2014

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

Summary

- The next galactic SN will be observed with high statistics in neutrinos (DUNE) and antineutrinos (Hyper-K/IceCube). Also in liquid scintillator (JUNO). Thousands of events, with second-by-second spectra.
- Potentially a treasure trove of information: real-time development of the explosion, oscillation dynamics, new physics sensitivity, etc
- The physics of SN neutrino oscillations is extremely rich, much more interesting than thought 10 years ago! Qualitatively new phenomena, inaccessible in the lab
  - Known physics → not optional
- Need to understand these effects better; identify clean signatures; see if detector design can be optimized.
- Nuclear and particle physics, astrophysics and supercomputing all come together. Fantastic subject to learn for graduate students and postdocs. ;-)