Why supernova neutrino oscillations are fun

and why three-flavor analysis is a must

Alex Friedland, LANL

INT neutrino workshop, Feb 10, 2010

Based on A.F., 1001.0996 + in prep.

Movies, etc, are at http://alexfriedland.com/papers/supernova/latecollective/

Supernova neutrinos: key to a big puzzle

- Supernova explosions are some of the most important processes in the Universe that influenced our world
  - “Every one of our chemical elements was once inside a star. The same star. You and I are brothers. We came from the same supernova.”
    - From the NYTimes obituary for Geoffrey Burbidge, Feb 6, 2010
  - Simulations of the galactic disk seem to show the supernova feedback crucial to its structure.
- Neutrinos come to us straight from the central engine, $r \sim 10^1$ km. Could provide the resolution of the 50-year old puzzle -- how the massive stars explode. Unlike SN1987a, 10^4 events -- second-by-second spectra

Flavor transformations

- By now, we know that neutrinos oscillate between flavors
  - solar, atmospheric, reactor, beam
- Supernova neutrinos must also transform flavors, no longer a choice
- To extract physics from the signal, these transformations must be understood!

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  - atmospheric neutrinos: 2-flavor oscillations, $2E/\Delta m^2 \sim 10^4$ km for $E \sim 1$ GeV and $\Delta m^2 \sim 3 * 10^{-3}$ eV^2
  - solar neutrinos: again 2-flavor oscillations, $\Delta m^2/2E \sim G_F\, n_e$ for $E \sim 1$ MeV and n_e in the solar center
  - KamLAND: again 2 flavors, $2E/\Delta m^2 \sim 10^2$ km for $E \sim 10$ MeV and $\Delta m^2 \sim 8 * 10^{-5}$ eV
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- *General principle*: experimental results must conveniently fit in the PRL format?

SN neutrinos: complexity returns with a vengeance!

- Two resonant densities (solar and atm.)
- Neutrinos and antineutrinos of all flavors
- Density profile changing with time:
  - Shock, turbulence
- Neutrino-neutrino interactions (coherent forward scattering)
- ...

Progress?

- Ten years ago, we had a definite prediction for what the supernova signal looks like
- The field has changed radically, as it was shown that many new effects are important for SN neutrino oscillations
- We do not have a clear prediction anymore
- Will complexity render the supernova signal useless?

Yes, progress! Why "complexity" is good

- The "complexity" actually makes the signal more useful, not less useful, as it provides new ways the information about the developing explosion can be imprinted in the neutrino signal

Concrete example

- Shock and turbulence
  - R. Schirato & G. Fuller (2002)
  - A. F. & A. Gruzinov (2006)

3D simulations

- 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,
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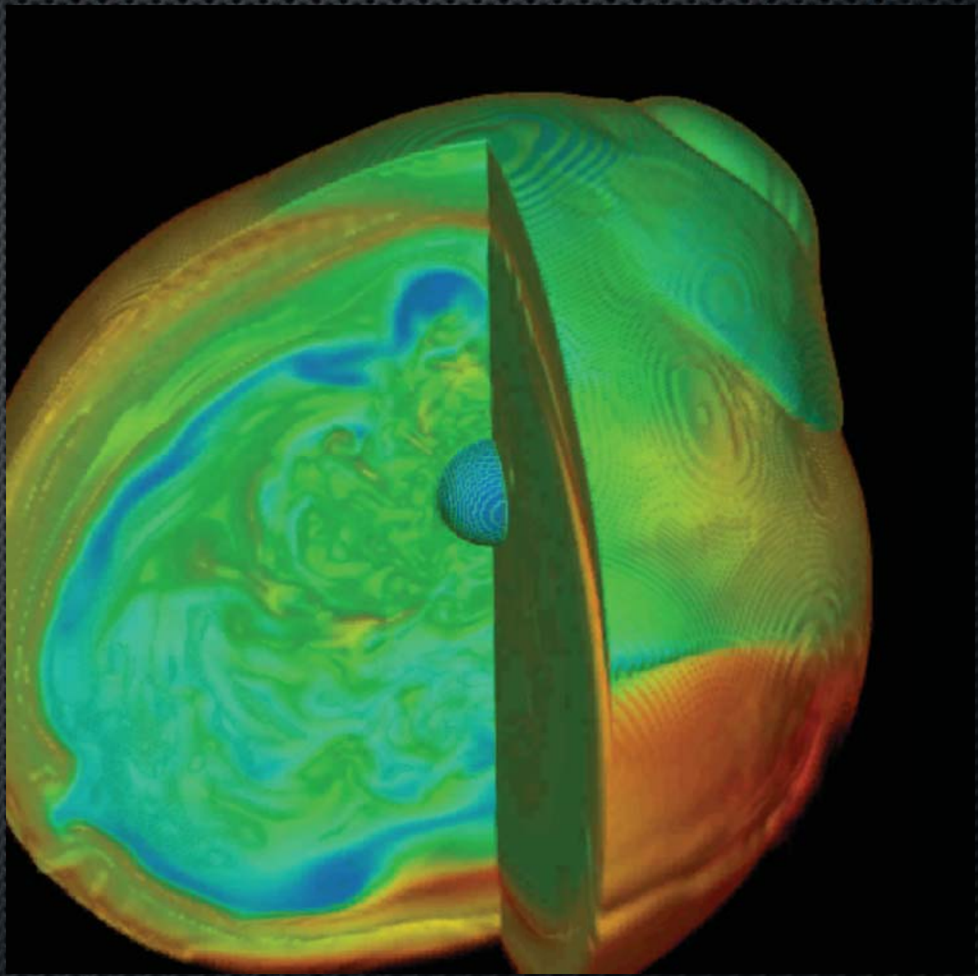

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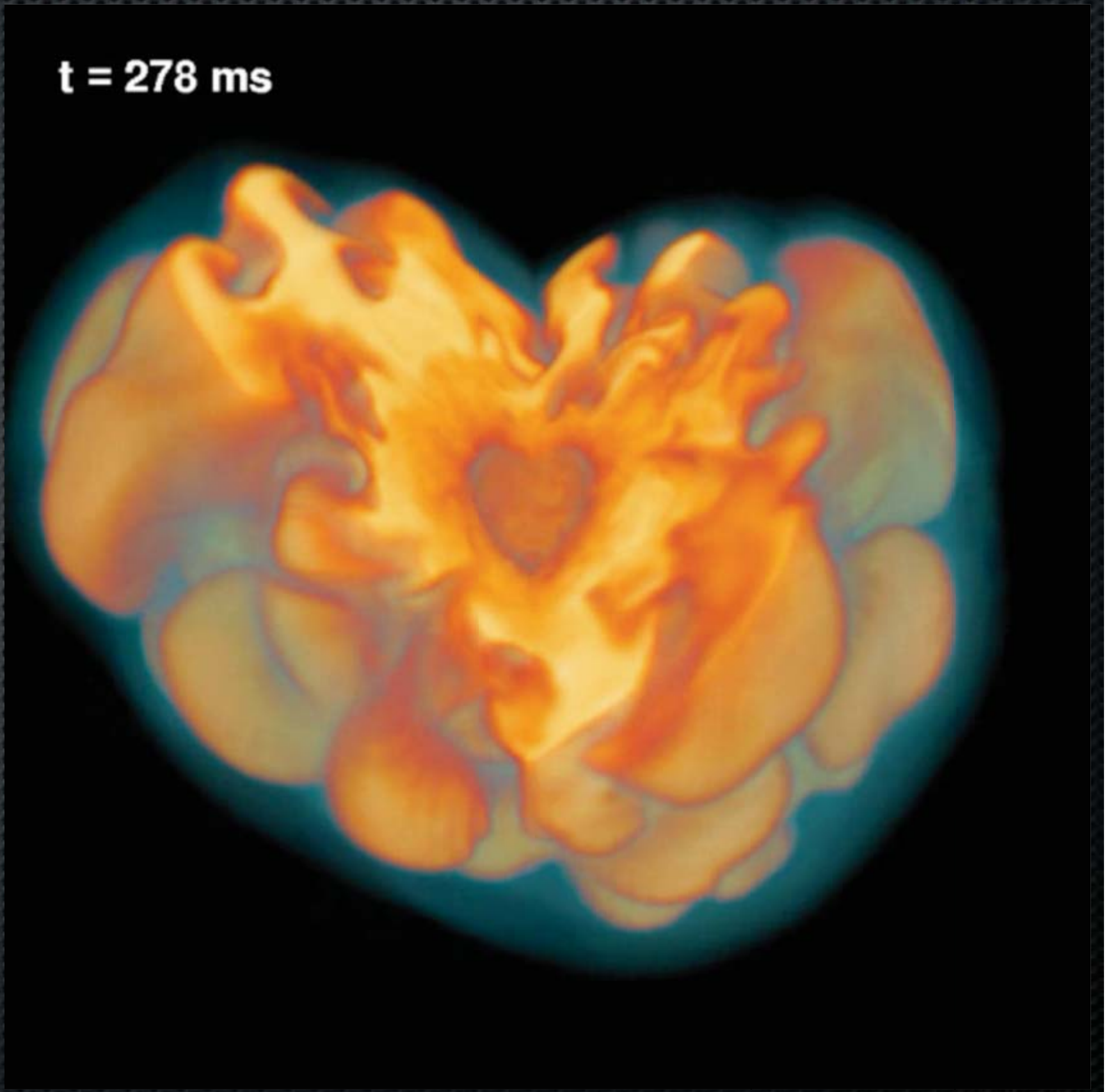
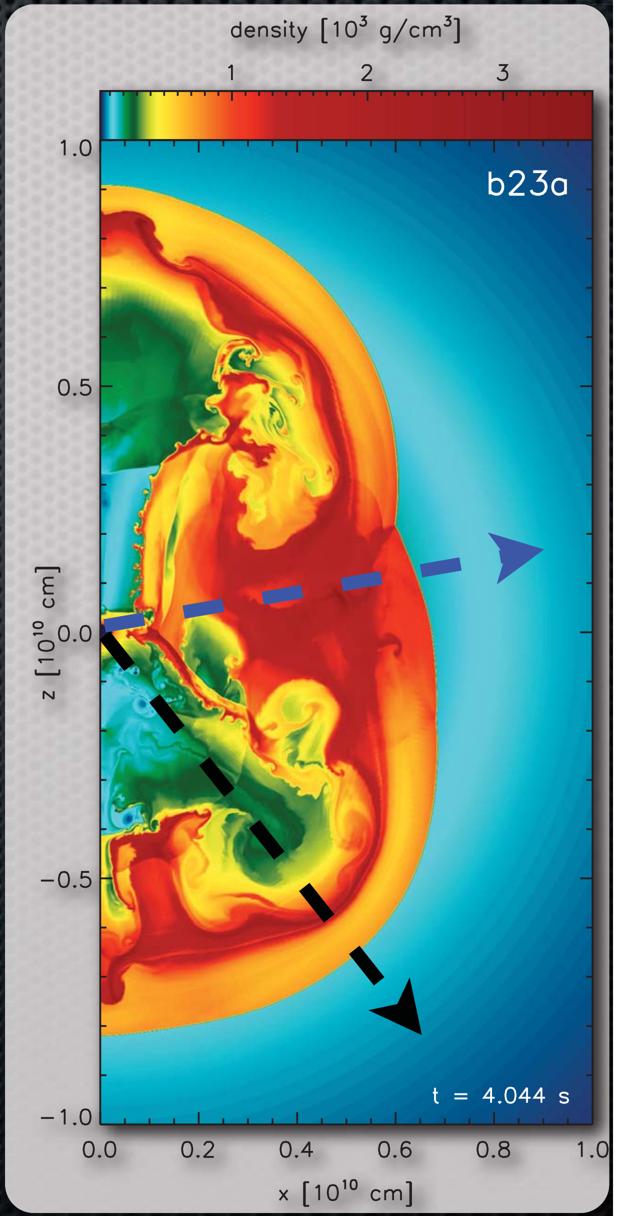


Signatures of shock and turbulence

- Time-varying features sweep through the spectrum several seconds after the onset of explosion
  - The development of the explosion may be observed in real time!



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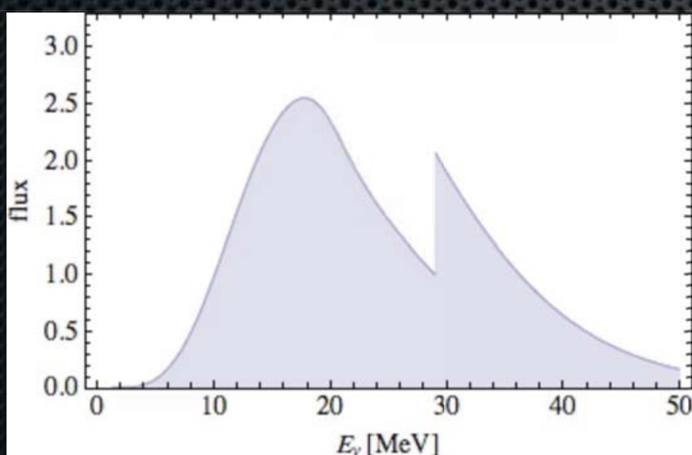
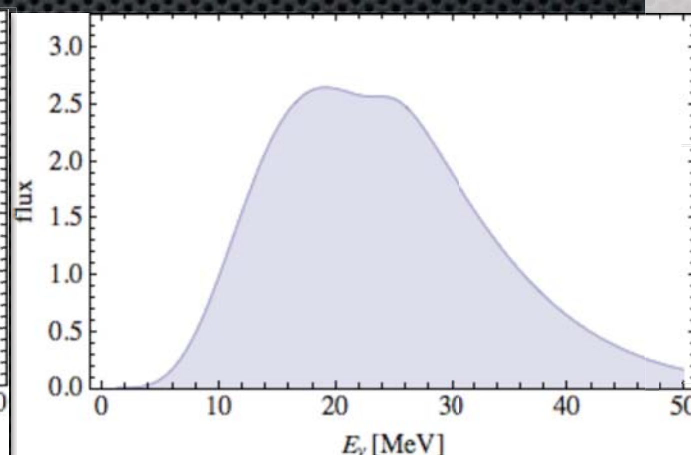
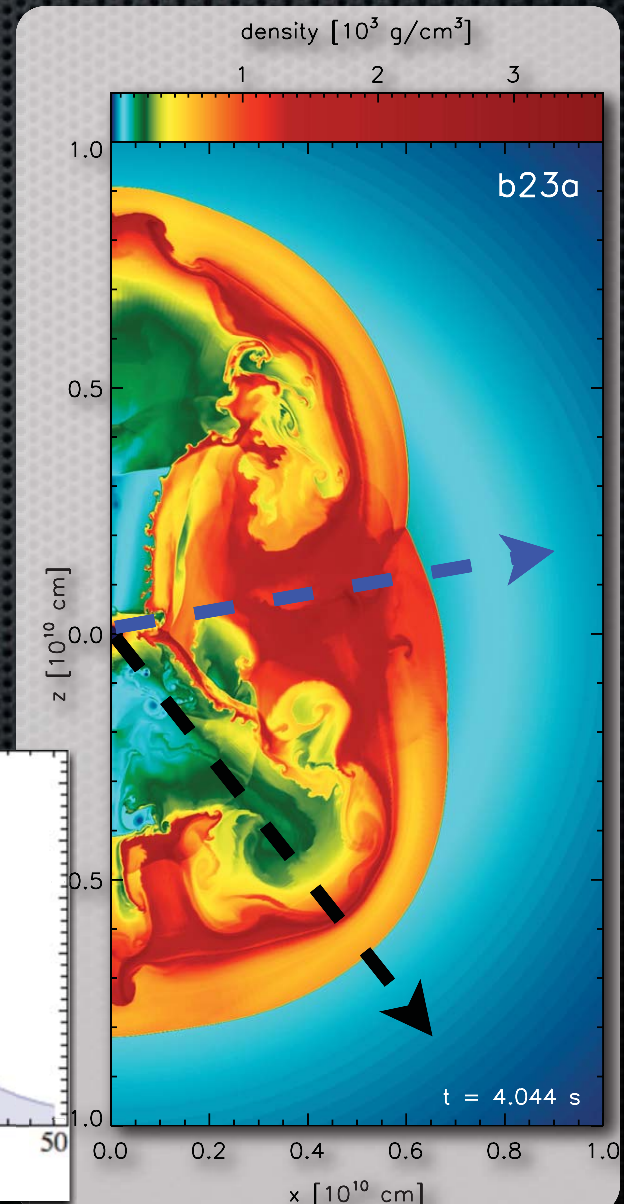




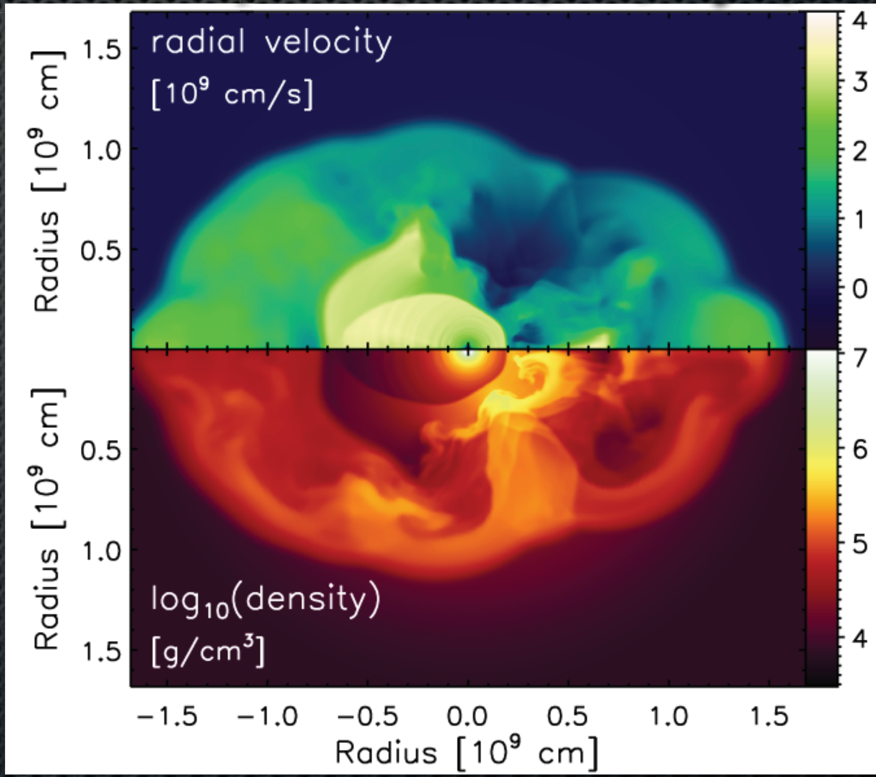


Core-collapse supernova and convection

- Convection behind the shock front is not just a curiosity: essential for the explosion mechanism! (Herant, Benz, Hix, Fryer, Colgate Ap. J. 435, 339 (1994))

Convection brings energy from the dense region near the proto-neutron star to the region behind the shock

Observing it would confirm the basic ingredient in the current paradigm of the SN explosion



Scheck, Plewa, Janka, Kifonidis, and Muller, Phys. Rev. Lett. 92, 011103 (2004), t=1 s

Collective oscillations

- Close to the protoneutron star, the neutrino background itself becomes important in the oscillation Hamiltonian
- The neutrino induced contribution is proportional to the neutrino density matrix, has off-diagonal components

$$\sqrt{2}G_F \sum_i n_i(1 - \cos\theta_{ij})|\psi_i\rangle\langle\psi_i|$$

Pantaleone, 1992

- The problem becomes ***non-linear***: changing the neutrino states also changes the background that drives the evolution
- Recently, detailed numerical calculations of this effect were performed by Duan, Fuller, Carlson, Qian, 2005, 2006 (and followed by others) that led to a realization that complex flavor transformations occur at ~ 100-300 km

Collective oscillations

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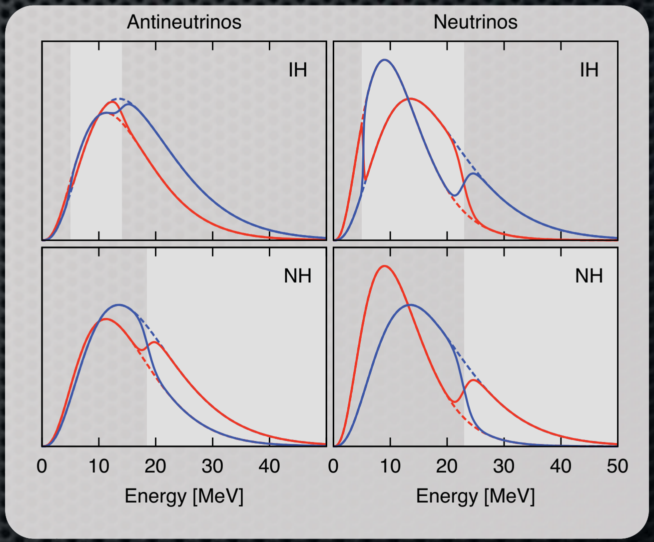
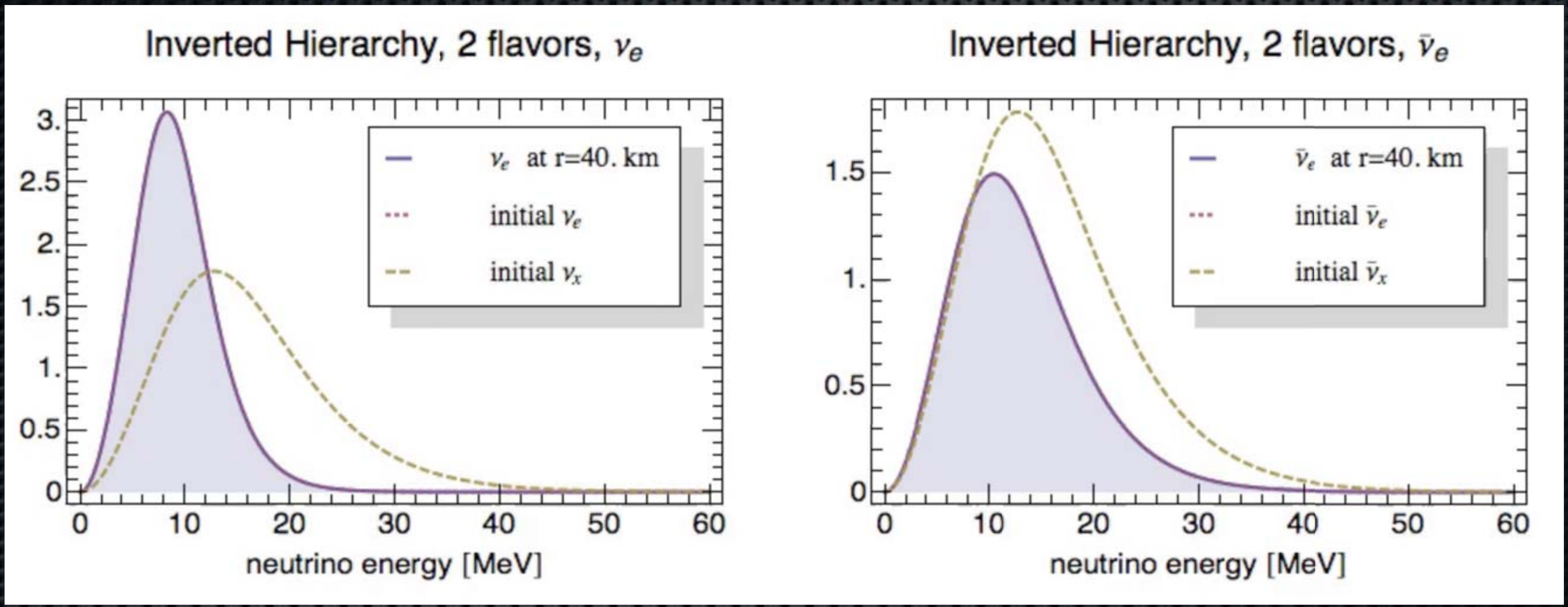
Existing literature

- Existing 3-flavor calculations are done with different fluxes and spectra. Since the problem is nonlinear, different initial conditions may give different results.
- Indeed, calculations with the late-time spectra of the type we are interested in seem to give very curious, novel results, including multiple spectral swaps
    - This can be potentially very significant
    - *But these calculations are done with only 2 flavors.* Is the third state a spectator?



Dasgupta, Dighe, Raffelt, Smirnov, arXiv:0904.3542 [hep-ph] -> PRL (2009)

Start by repeating the 2-flavor calculations



- Complete agreement with 0904.3542

This, and subsequent movies are at

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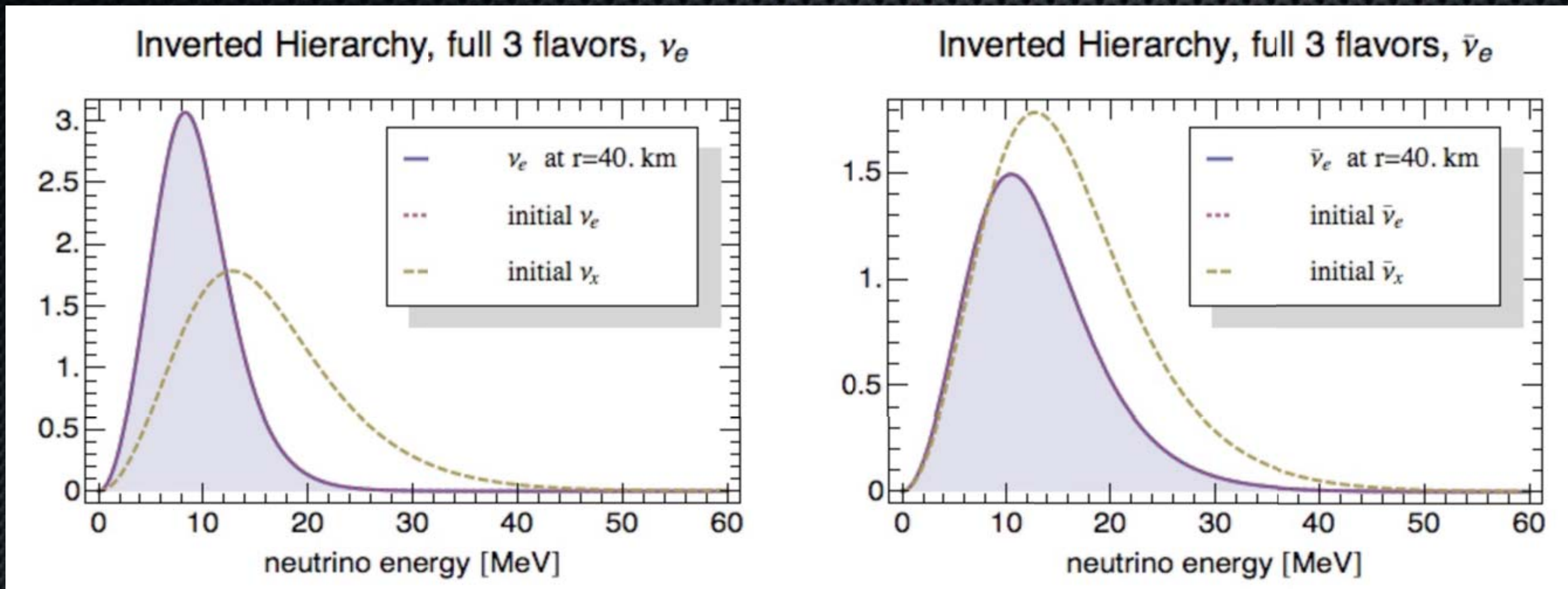

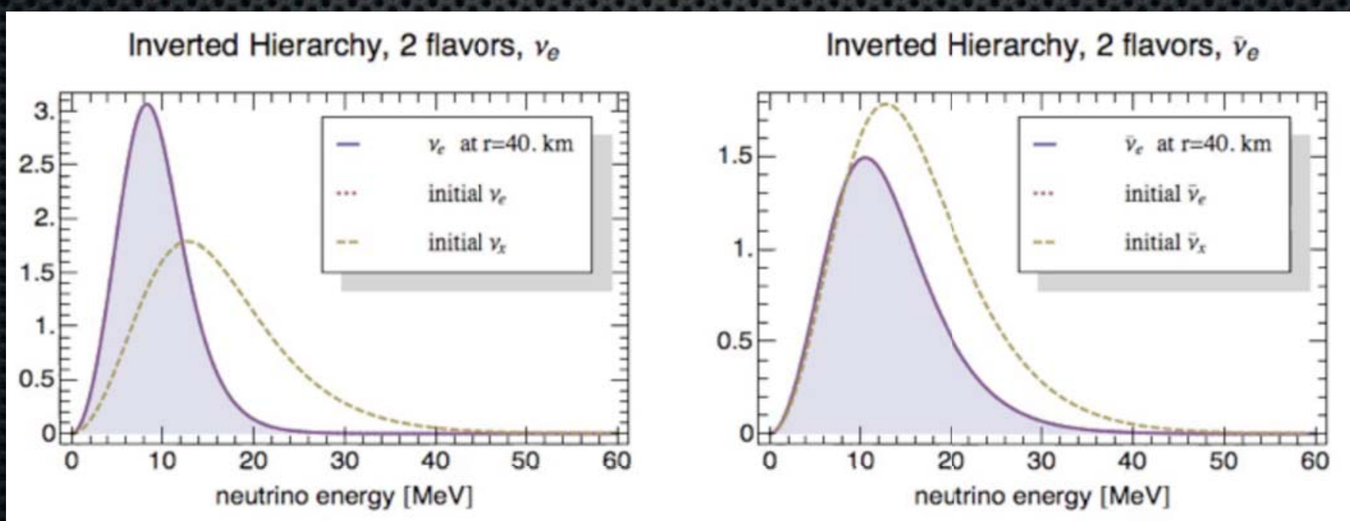

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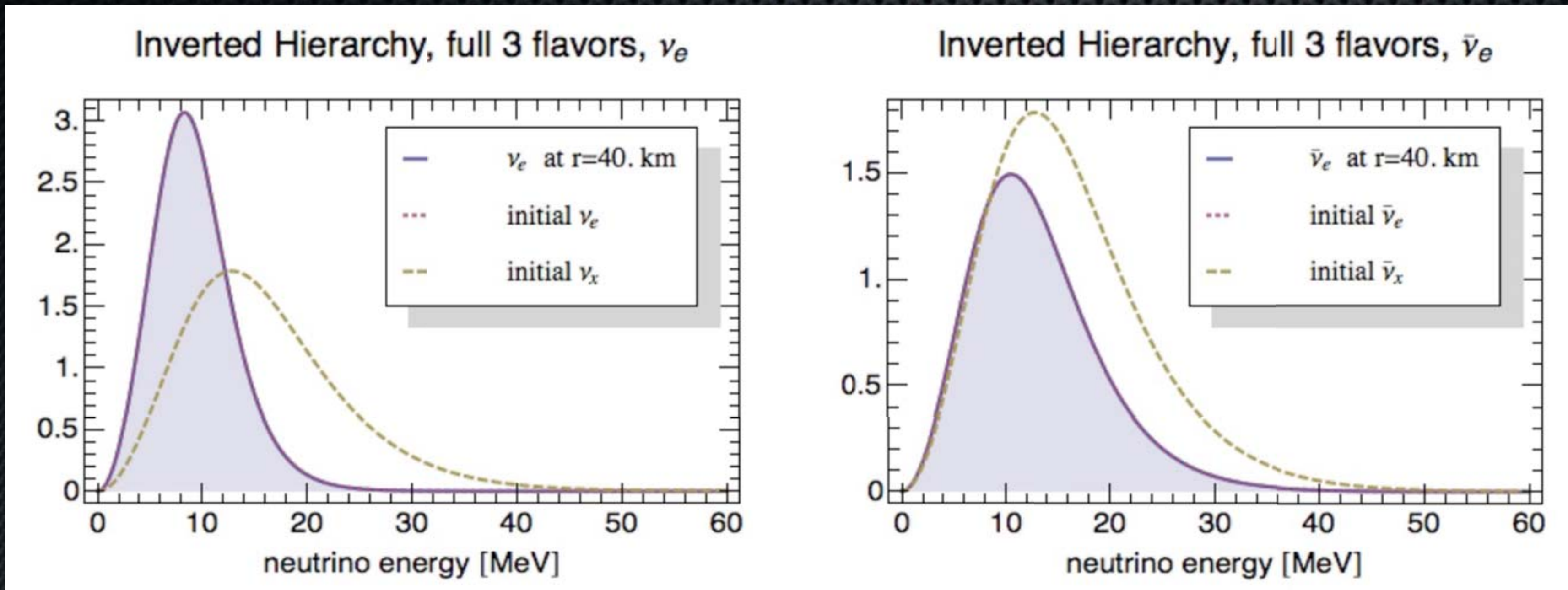
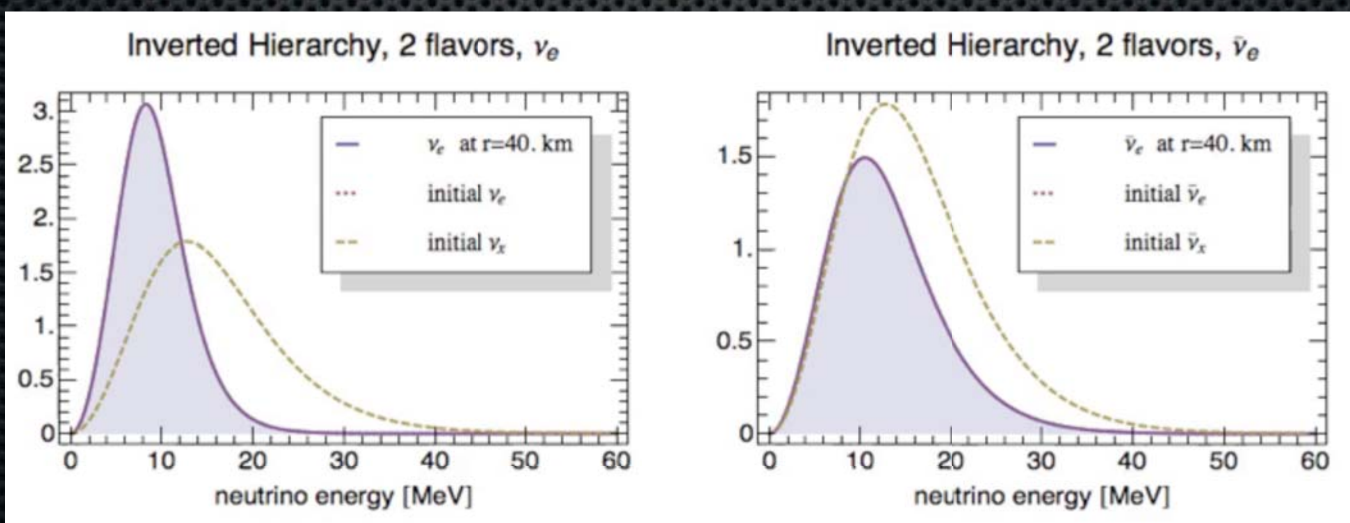
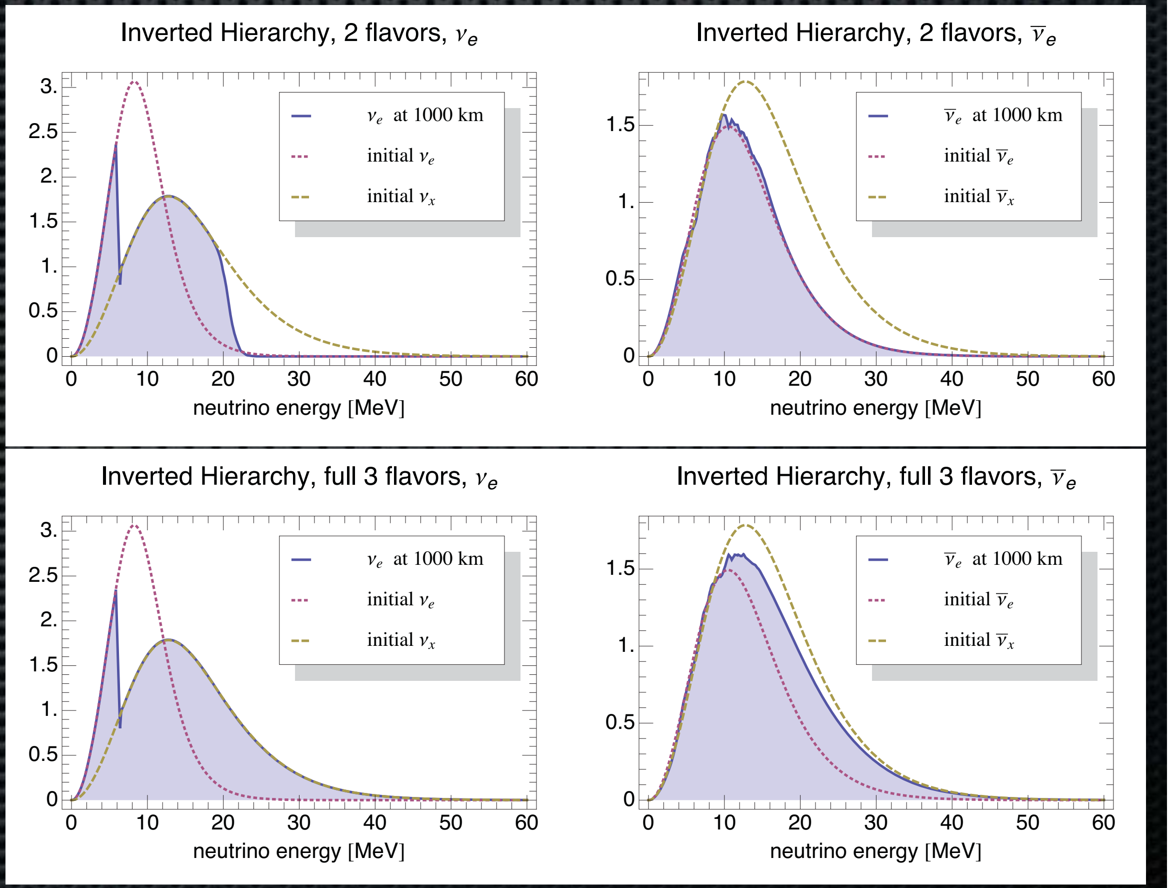




- Entirely different result!?

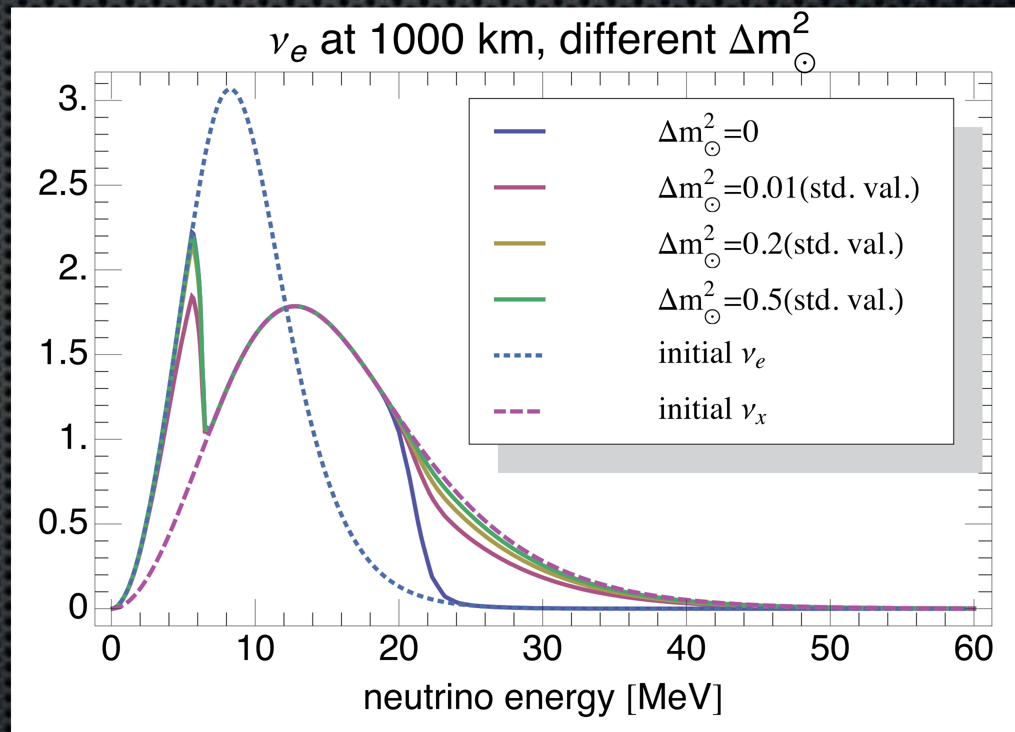
How can this be?

- The high-energy spectral split is gone
  - How can the solar splitting, which is only 1/30 of the atmospheric one, undo the effects of the latter?
- For the antineutrinos, the result is also interesting. The spectral swap is only partial (*mixed spectrum*)



Let's at what $\Delta m_\odot^2$ the differences kick in

- At first glance, this result is strangest of all:
  - At $\Delta m_\odot^2=0$, 2-flavor result is reproduced
  - As soon as $\Delta m_\odot^2\neq 0$, the answer is closer to the realistic $\Delta m_\odot^2$ than to $\Delta m_\odot^2=0$



The answer: instabilities, instabilities

- Recall that the concept of instability is key to understanding collective oscillations
  - The initial configuration is nearly in flavor eigenstates, yet the large flavor mixing develops later

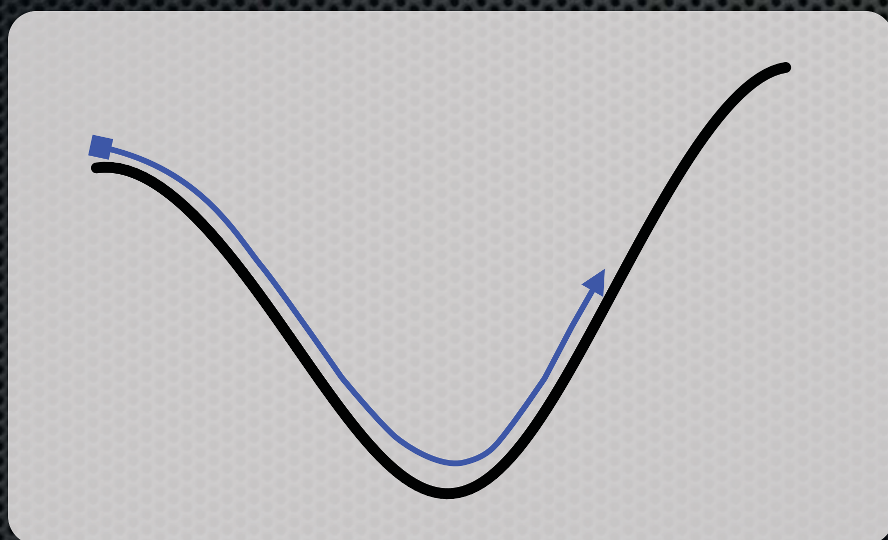
    "However, the nonlinearity of the system creates an instability ... The situation is analogous to a rigid pendulum positioned [...] suddenly inverted."

    Kostelecky & Samuel, *Neutrino oscillations in the early universe with an inverted neutrino mass hierarchy*, PLB 318, 127 (1993).

  - The key role of this instability for supernova neutrinos was only understood in Duan, Fuller, Qian, astro-ph/0511275 (and the fact that dense matter doesn't suppress it)
  - Interestingly, the simple system of two angular momenta is not merely analogous to an inverted pendulum, but in fact turns out to be *exactly* like it (Hannestad, Raffelt, Sigl, Wong, astro-ph/0608695)

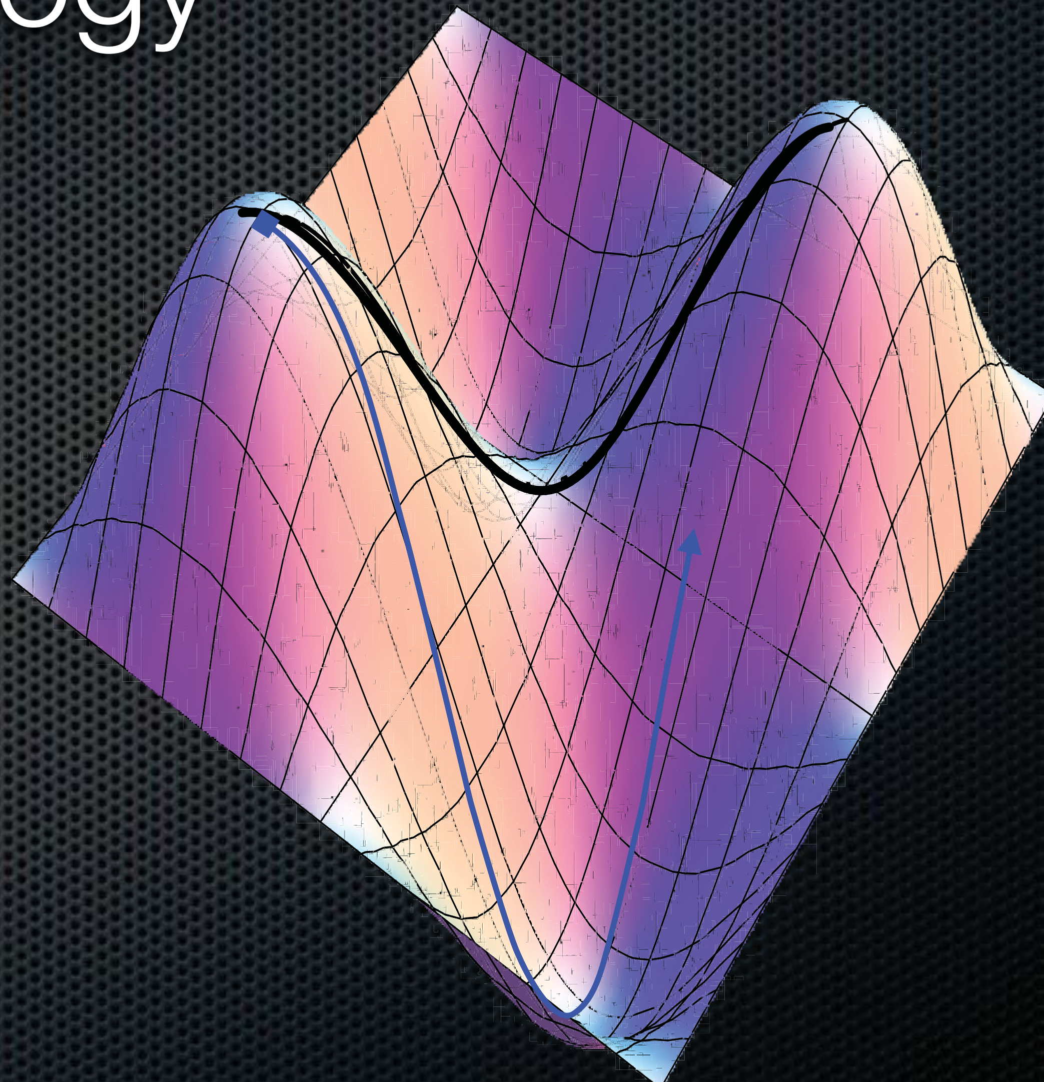
Cartoon analogy

- The 2-flavor instability can be (schematically) pictured like this



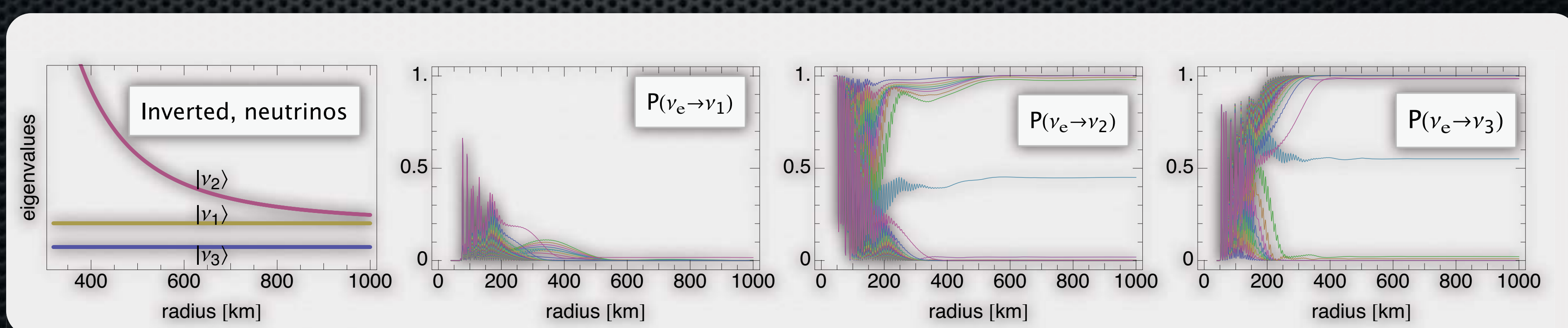
Cartoon analogy

- The 2-flavor trajectory is itself unstable in the 3-flavor space
- Disclaimer: only a cartoon, so that I don't have to draw 8-dim. objects! (SU(3))



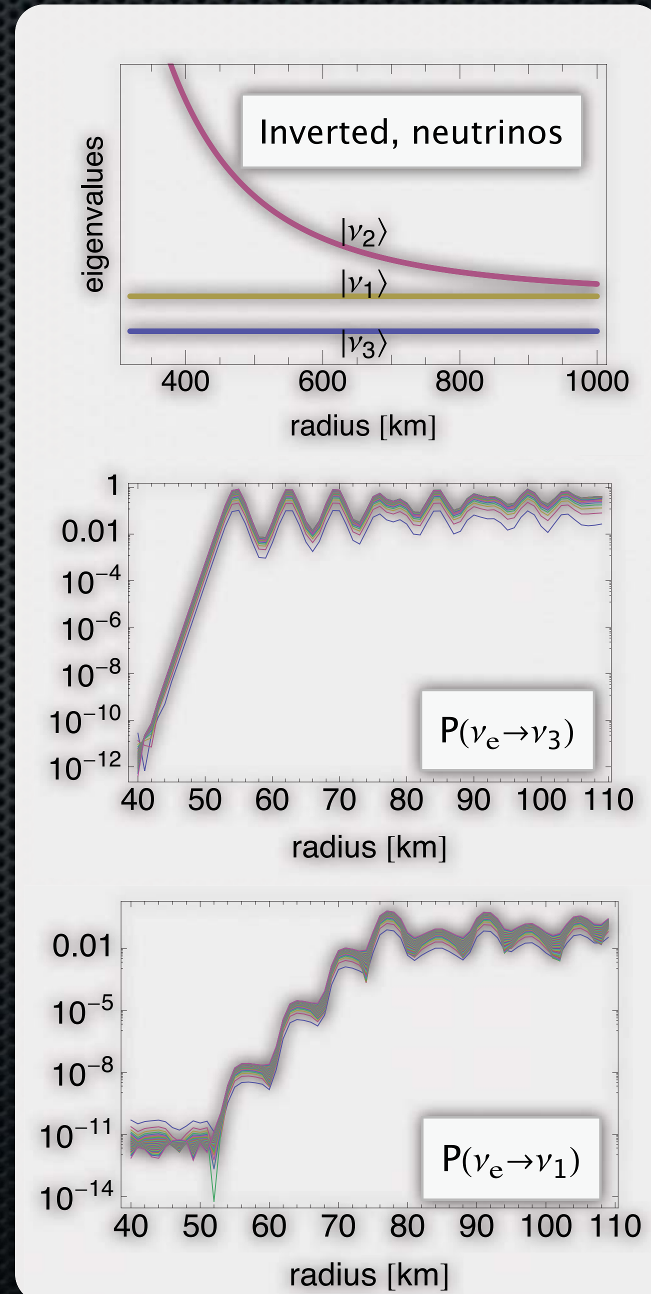
Mass basis

- All three states are seen to participate in the "bipolar-like" oscillations, hence trajectory is very different from 2 flavors
- Atmospheric decouples at ~ 200 km, solar at ~500 km
- Eventually, a single split is formed between ν_2 and ν_3.



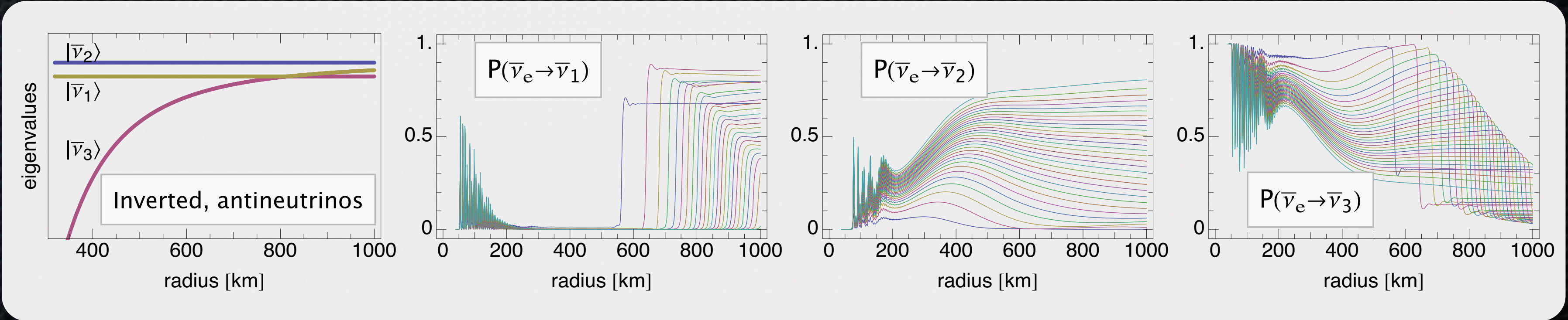
Instability, zoomed in

- The instability first grows between ν_2 and ν_3, but then also between ν_3 and ν_1.
- The growth rates are the same, indicating that the atmospheric splitting is the driving force in both.
- The solar splitting provides the initial mixing, just to kick off the instability
  - Analogous to the role of small θ_{13} for seeding the 2-flavor instability



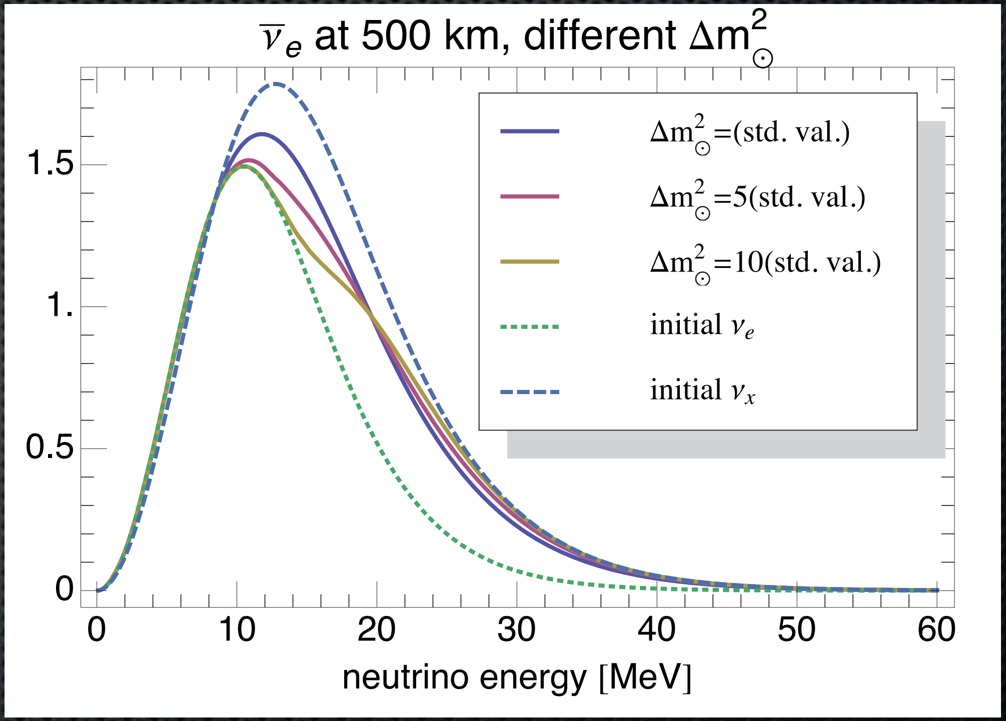
Antineutrinos: mixed spectrum

- The would-be split that is driven by the solar splitting is never completed in this case: adiabaticity violated
- The scale height of the nu-nu potential is $|d \ln H_{\nu\nu}/dr|^{-1} \sim r/4 \sim 75 - 100 \text{ km}$
- The atmospheric distance scale is safely adiabatic $2E/\Delta m^2_{\text{atm}} \sim 2 \text{ km}$
- while the solar scale is only marginally adiabatic $2E/\Delta m^2_{\odot} \sim 77 \text{ km}$



More on adiabaticity

- To illustrate this argument, let's artificially increase the solar splitting
  - broad split forms
- The adiabaticity is reflected in the width of a split. (See Raffelt & Smirnov, 2007) Our finding can be viewed as an extremely broad split.



Normal hierarchy

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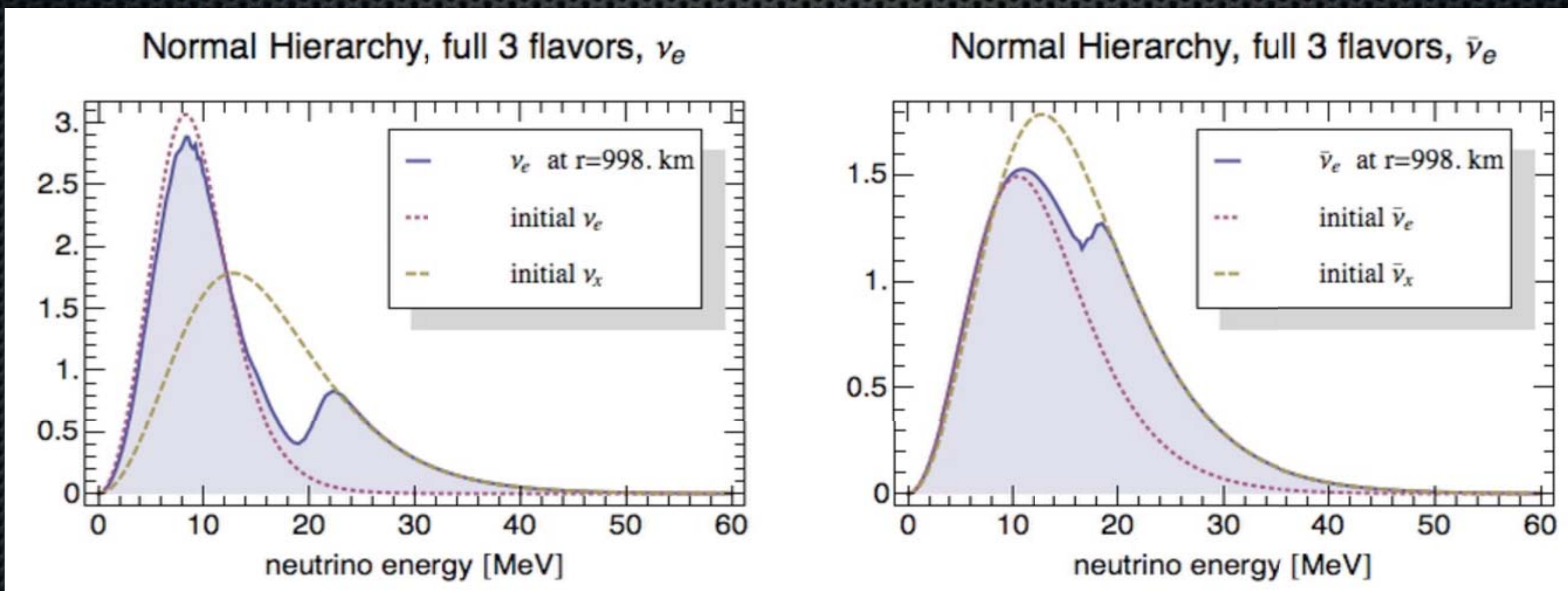

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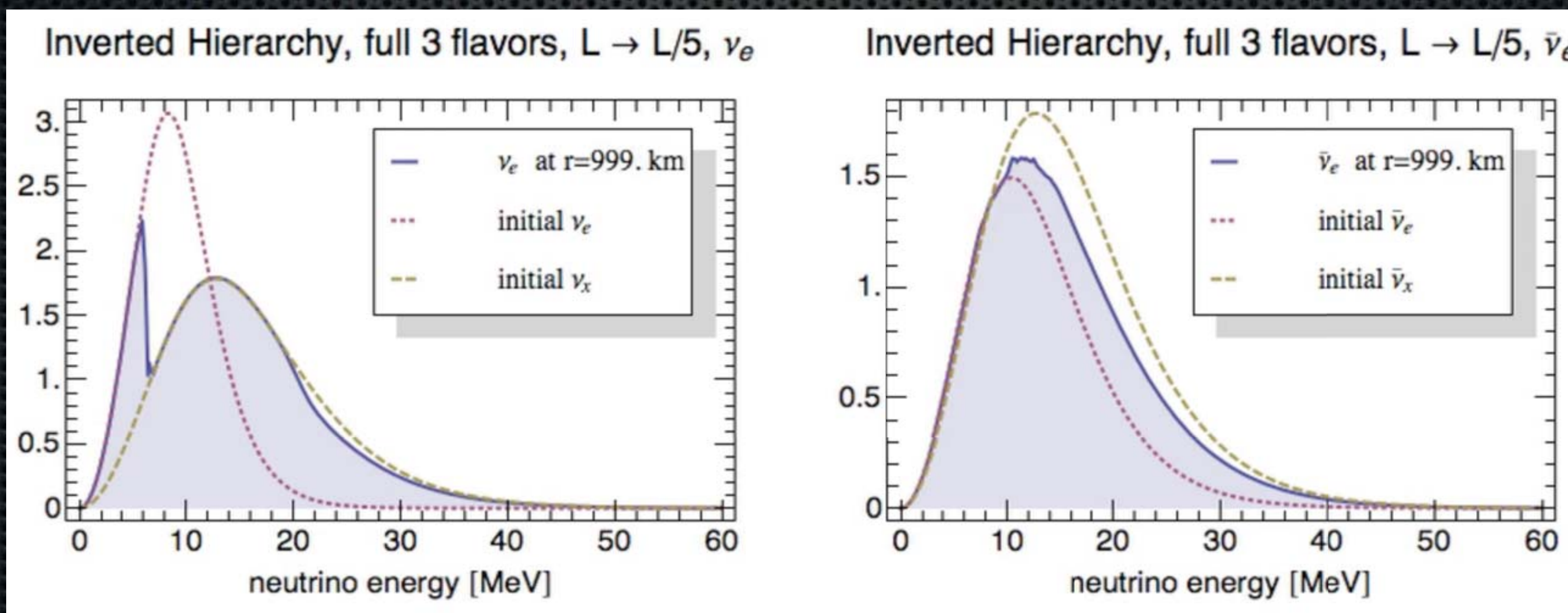

Conclusions

- Unlike 10 years ago, we no longer have a simple prediction for the supernova neutrino signal...
- ... Because the physics turned out to be much more interesting!
- The ingredients are all known physics, so must sort out what's going on
- Genuine 3-flavor effects; non-factorizable
- Potentially unique information about the physics of the explosion + probes of neutrino properties
  - probes of new physics -- not yet understood

P.S. nonlinearity at work, expect more surprises?

- Even simple systems of nonlinear ODEs

$$\begin{aligned} \frac{dx}{dt} &= \sigma(y - x) \\ \frac{dy}{dt} &= x(\rho - z) - y \\ \frac{dz}{dt} &= xy - \beta z \end{aligned}$$

- can have very rich and nontrivial behavior