What we can learn from supernova neutrinos

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Intensity Frontier Workshop

Spectacular events

- 10^{28} megaton explosion
  - (Los Alamos units)
  - Mostly in neutrinos (>99%)
- ~ 10^{58} neutrinos per second
  - definitely Intensity Frontier!
  - (in the terminology of this workshop)

Do they emit neutrinos?
We have already observed one explosion with neutrinos

1987A versus the next Galactic SN

- 1987A: two dozen events total at 3 detectors (IMB, Kamiokande, Baksan)
  - confirmed basic paradigm: ~ 20 MeV neutrinos, ~ 10^{53} total energy
    - collapsed core cools by neutrino emission
    - countless bounds on new particle physics: axions, KK gravitons, etc
- Next galactic supernova: ~ 9,000 events in Super-Kamiokande
  - ~ 200,000 in proposed 0.99 MT Hyper-Kamiokande
    - See Hyper-K letter of intent, **arXiv:1109.3262**

Qualitatively new game

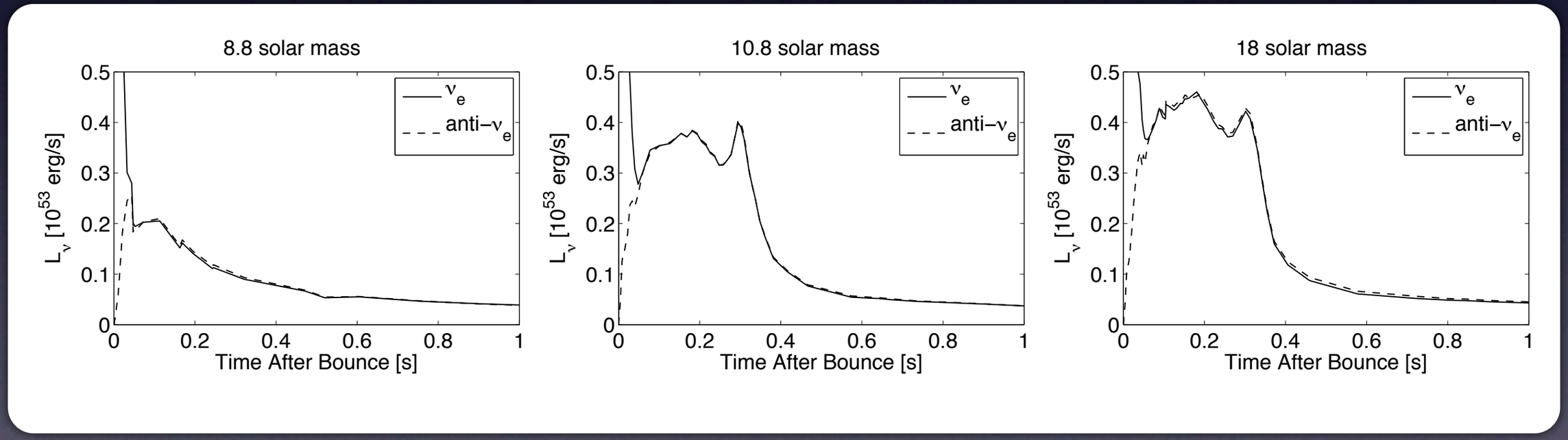
- Detailed spectrum of neutrinos
- Evolving second-by-second
- Potentially treasure trove of information
- How to we read this signal?
  - What detector characteristics are optimal?

Neutrino telescope

- Photons come only after the shock breaks up the star, expands
  - A lot of processing, not obvious. Converting 0.5% of all energy into the visible explosion involves very nontrivial "multi-physics": multi-d hydro, transport ....
- Neutrinos come directly from the central region, during the crucial first ~10 seconds of the explosion
  - *Direct* window into the mechanism of the explosion
    - Combine neutrino and grav. wave signals

Evolution of the explosion is reflected in neutrinos

- Neutronization burst, accretion phase, cooling phase can all be seen in neutrinos
- Different for different progenitor masses



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

Physics of the explosion: Holy Grail for 60 years

- Supernovae are extremely important objects in our universe
- Synthesize and disperse heavy elements
  - Heavy elements around us were once inside a massive star
  - How did they get here?
- Structure of our galaxy
  - Simulations of the galactic disk show supernova feedback is crucial to its structure

What about nuclear and particle physics?

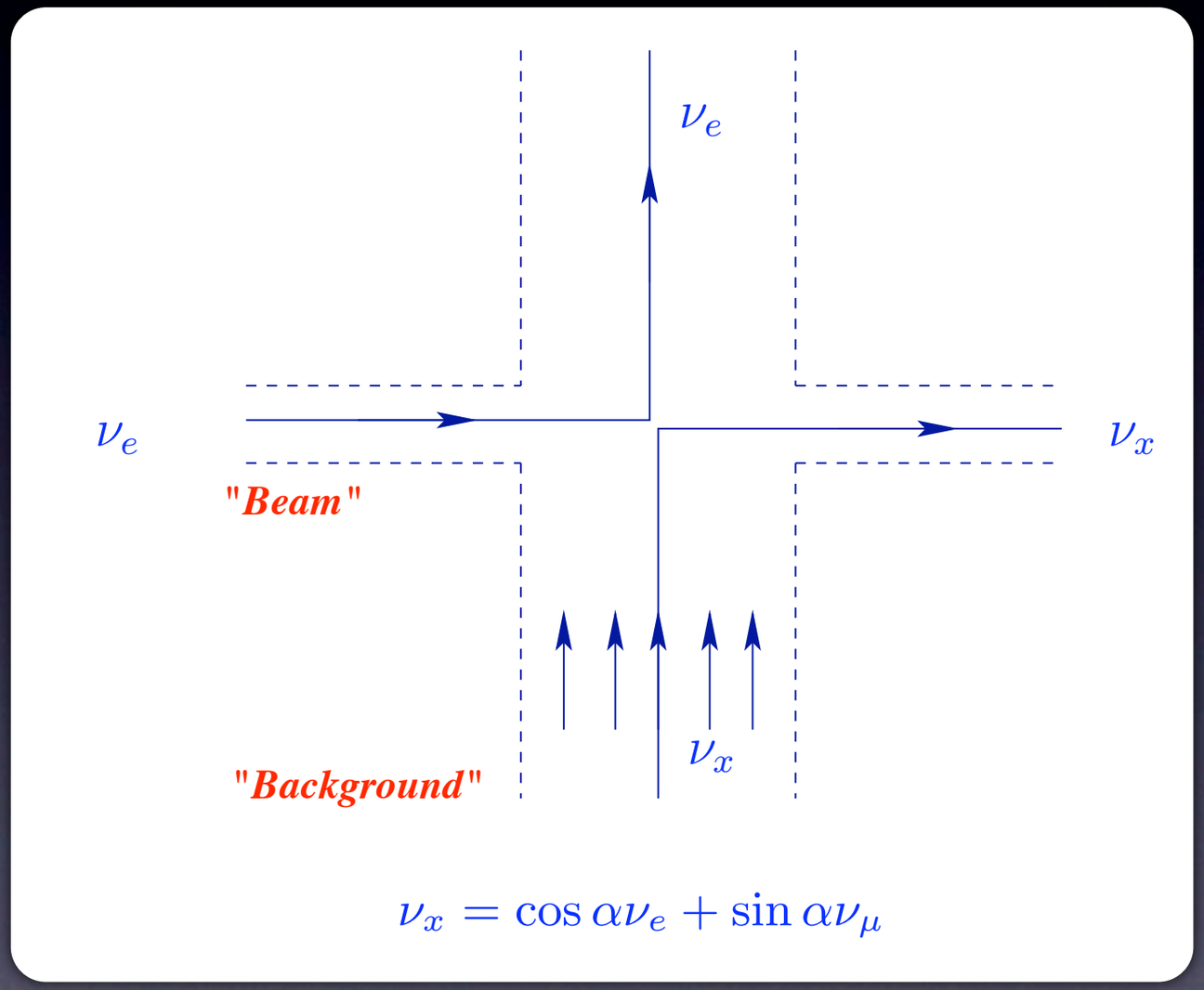
- Nuclear astrophysics
  - Can we explain where and how the r-process elements are synthesized?
- Nuclear physics/QCD:
  - Upon core-collapse, the density in the center reaches ~ 10^{14} g/cm^3 -- nuclear
  - What is the equation of state of matter at such extreme conditions? (and how it depends on T?)
- Particle physics: neutrino oscillations, novel weakly coupled particles (axions/majorons/extra dim/etc), ...

What about oscillations?

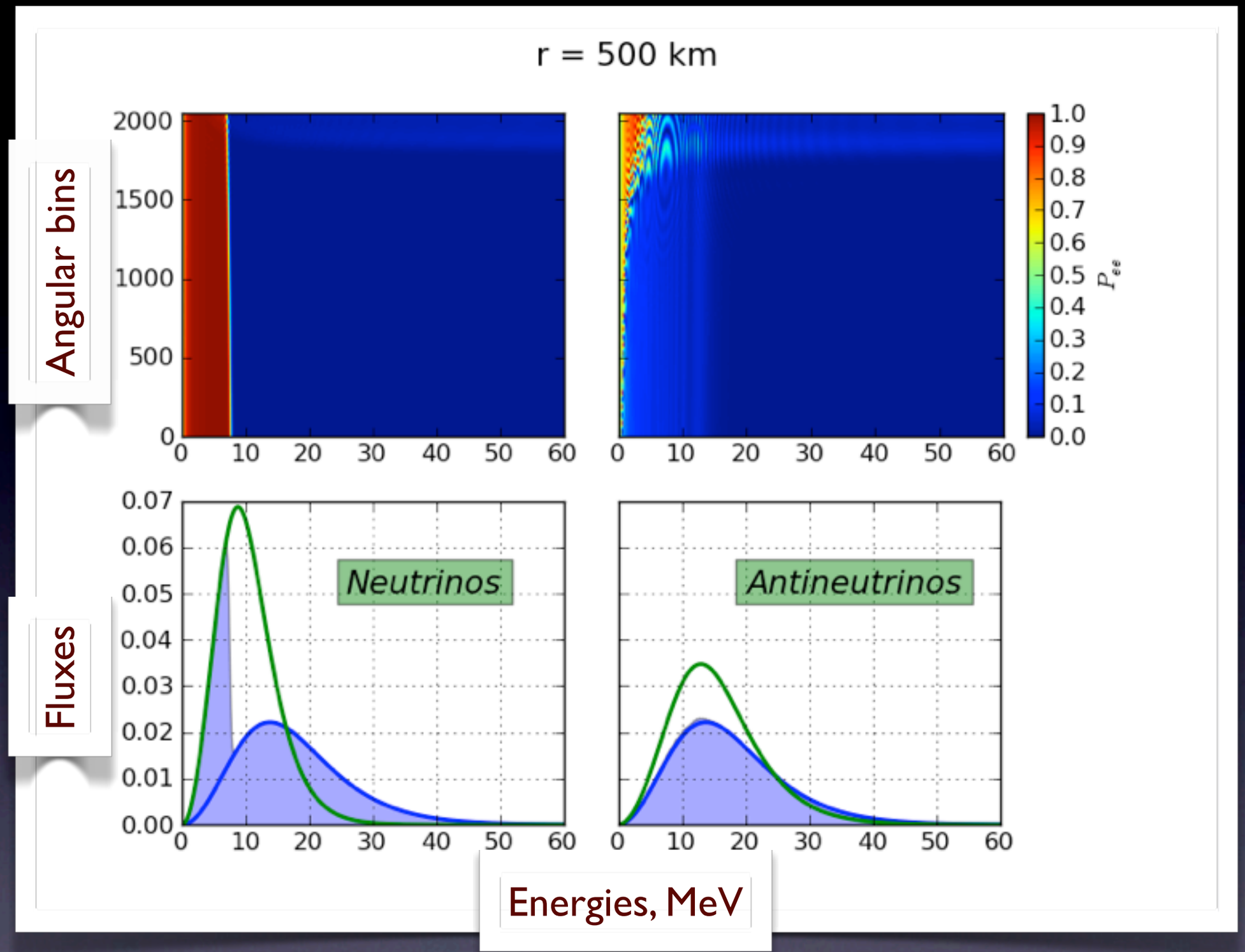
- Oscillations have been observed in atmospheric, solar, reactor, and accelerator beam neutrinos
- Oscillations have to be there in SN, no longer optional!
  - Not only that, but the physics of supernova oscillations is way richer than in any of the terrestrial experiments
  - Study neutrino oscillations in a regime inaccessible in the lab

Neutrino "self-refraction"

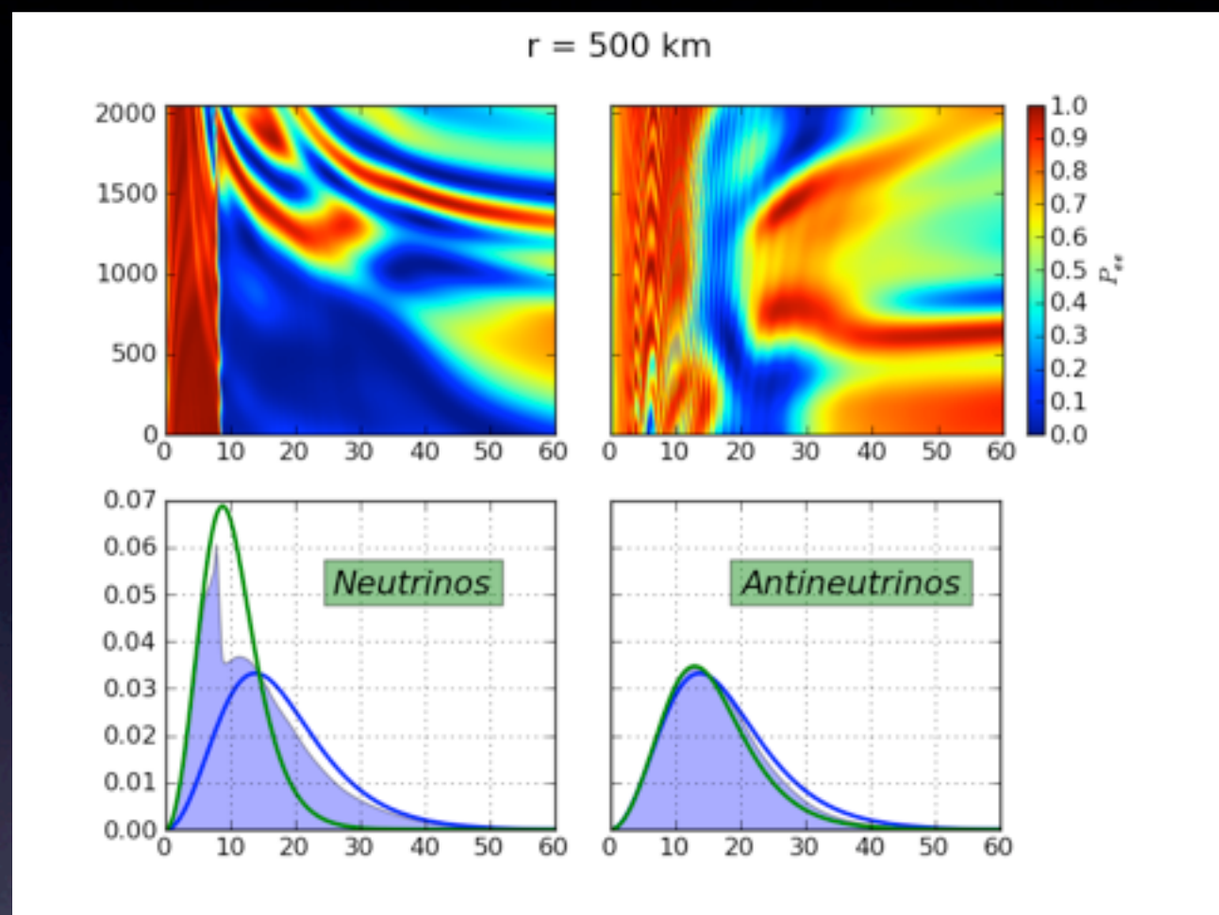
- Above the neutrino-sphere, streaming neutrinos are so dense that their flavor evolutions become coupled
- A given neutrino scatters on an ensemble of the "background" neutrinos
- One has to evolve an ensemble of neutrinos as a whole
- Rich many-body physics, with many regimes
- Supercomputing

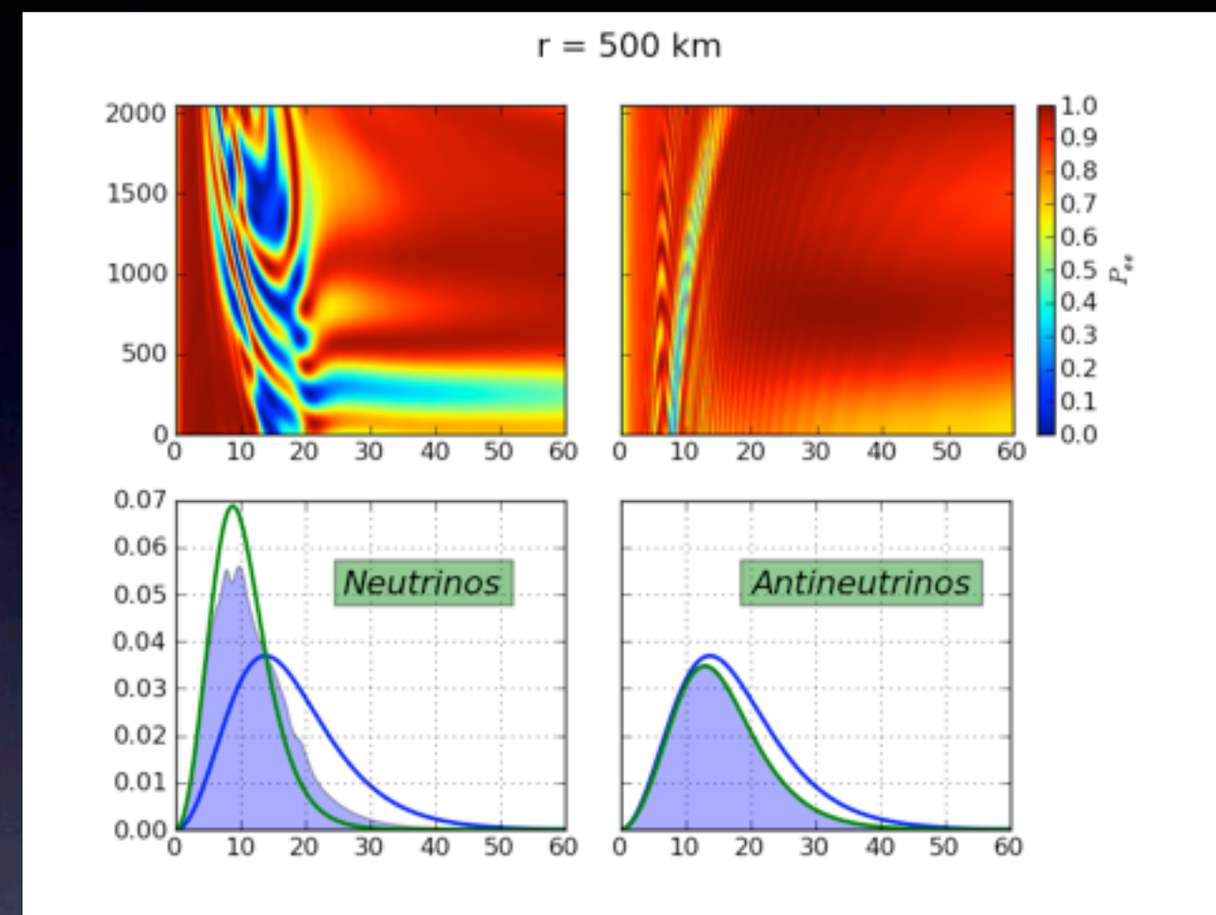


Fuller et al, 1988;
Pantaleone 1992;
Duan, Fuller, Qian, Carlson, 2006;
+ hundreds more

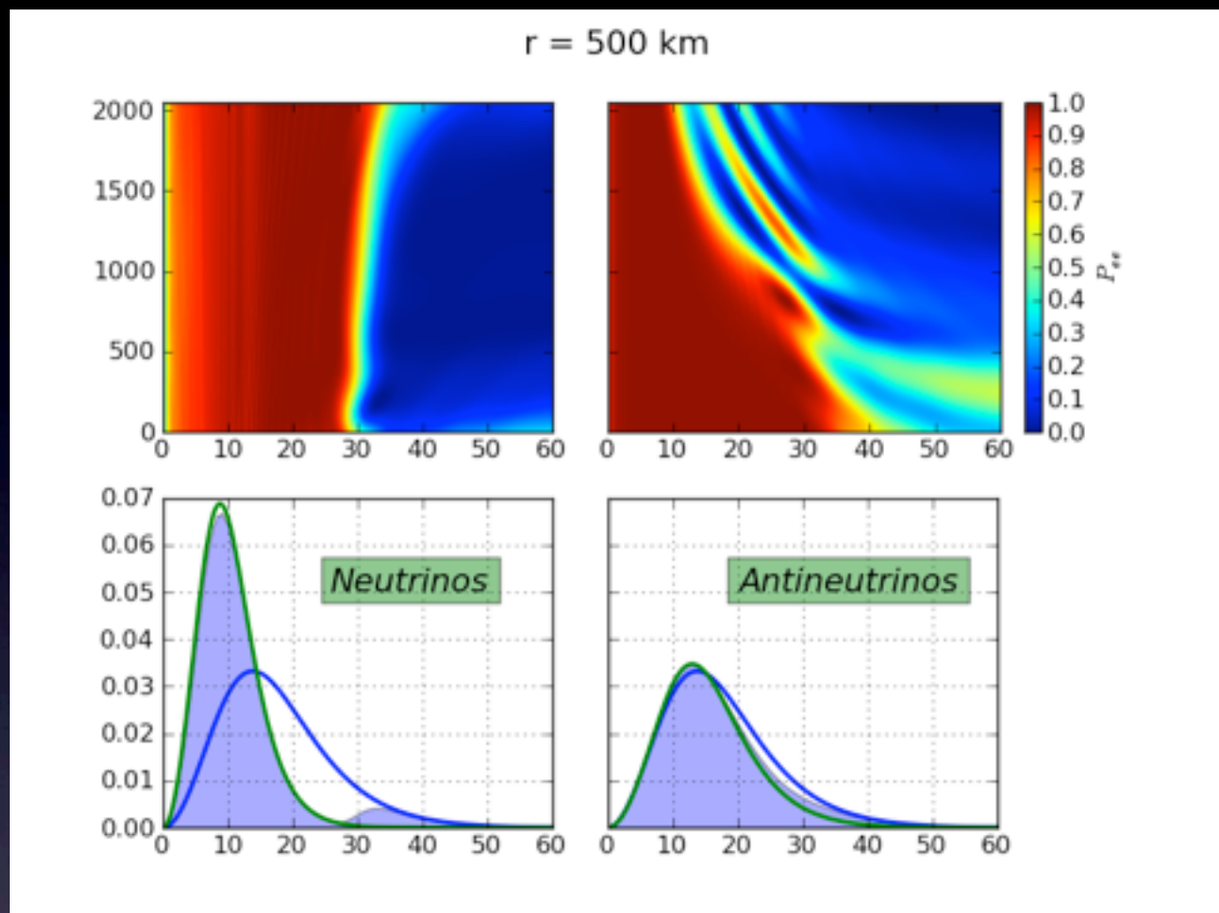


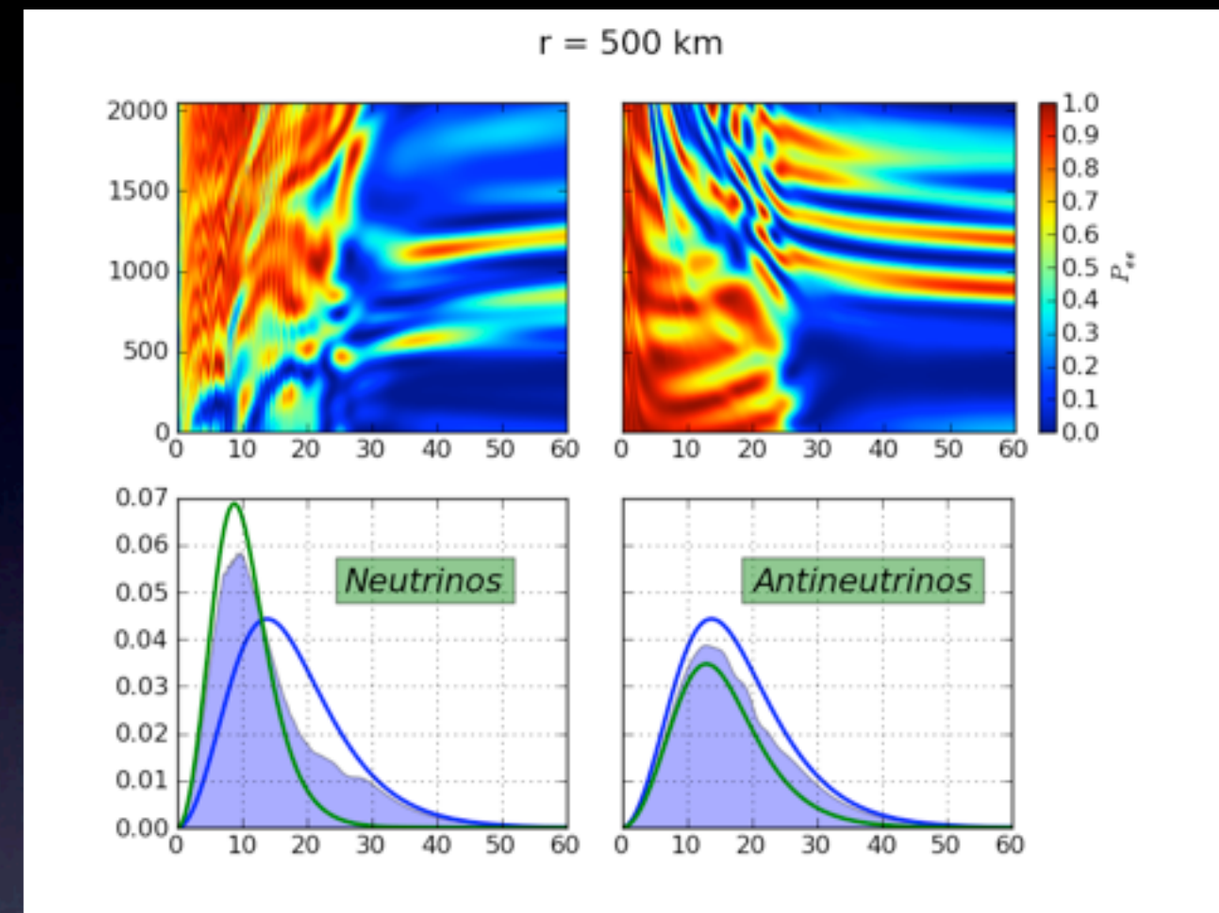
Resulting spectra on Earth have peculiar non-thermal features





The features change with the initial fluxes ➪ ways to measure emitted fluxes of different flavors



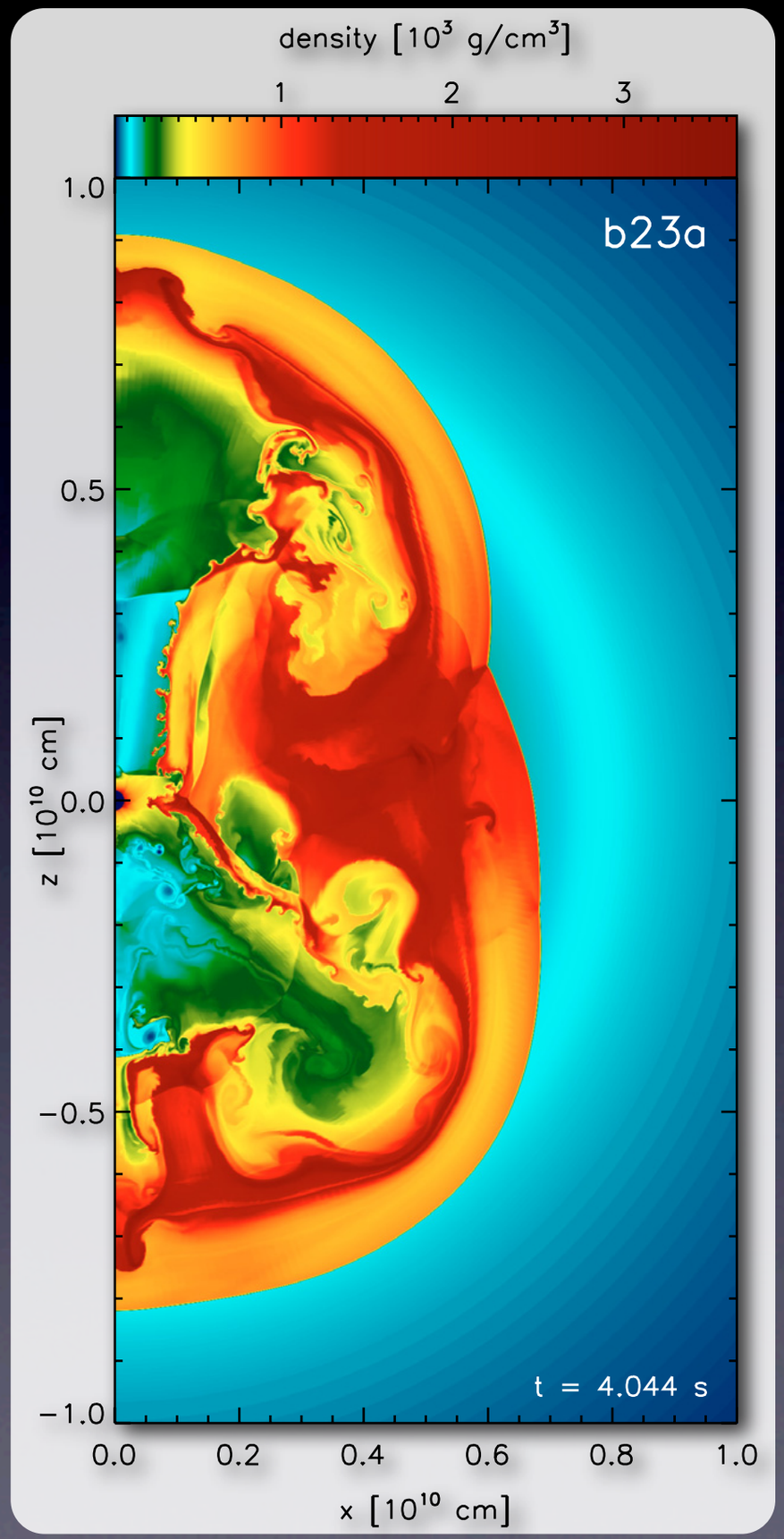


Also, qualitatively different patterns for different mass hierarchy

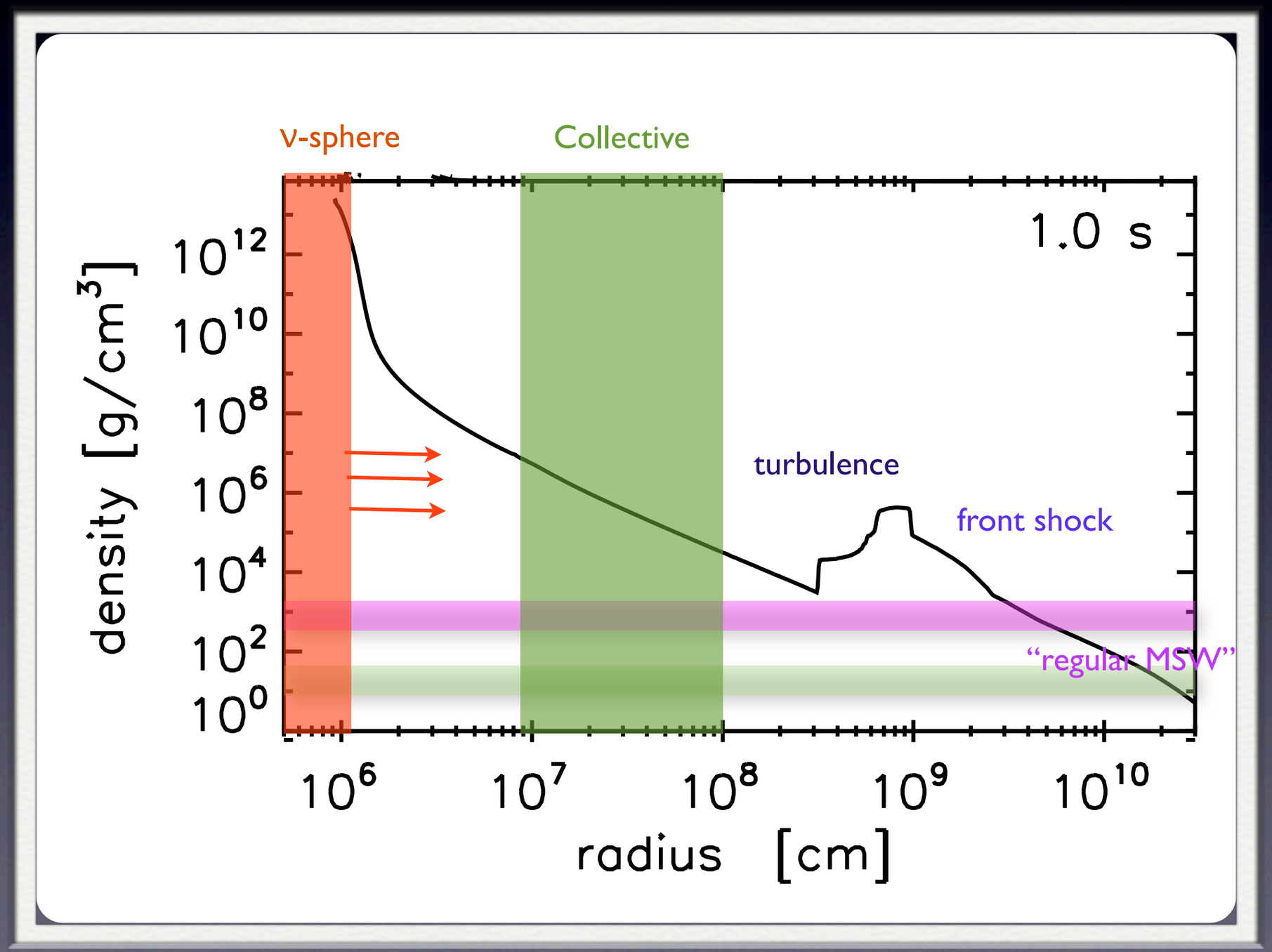
Fig. from K. Kifonidis, T. Plewa, L. Scheck, H.-T. Janka, E. Mueller, astro-ph/0511369

Dynamical, turbulent density profile

- The front shock is moving out, as the explosion develops
  - evolving density profile
- The region behind is turbulent: stochastic density fluctuations on many scales
- Both effects should leave imprints in the neutrino signal
  - This gives another way to observe the developing explosion in real time



Supernova signal: physics cartoon



Bottom line

- The next galactic supernova will be a gold mine for science
  - Particle physics, nuclear physics and astrophysics all stand to benefit greatly
    - How neutrinos oscillate collectively, how nuclear matter responds to being squeezed and how heavy elements got here are just some of the answers
  - Very tight synergy between the fields required, from abstract particle physics models to supercomputing
  - Instead of asking "What field is this?" or "Do we fund astrophysics?" (think Type Ia SN modeling!), seize the moment to lead this intellectually exciting, high-payoff field