Why do Supernova Burst Neutrinos at LBNE?

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Los Alamos

July 31, 2013

Snowmass on the Mississippi, Minneapolis, MN

Galactic core-collapse supernovae as a beam

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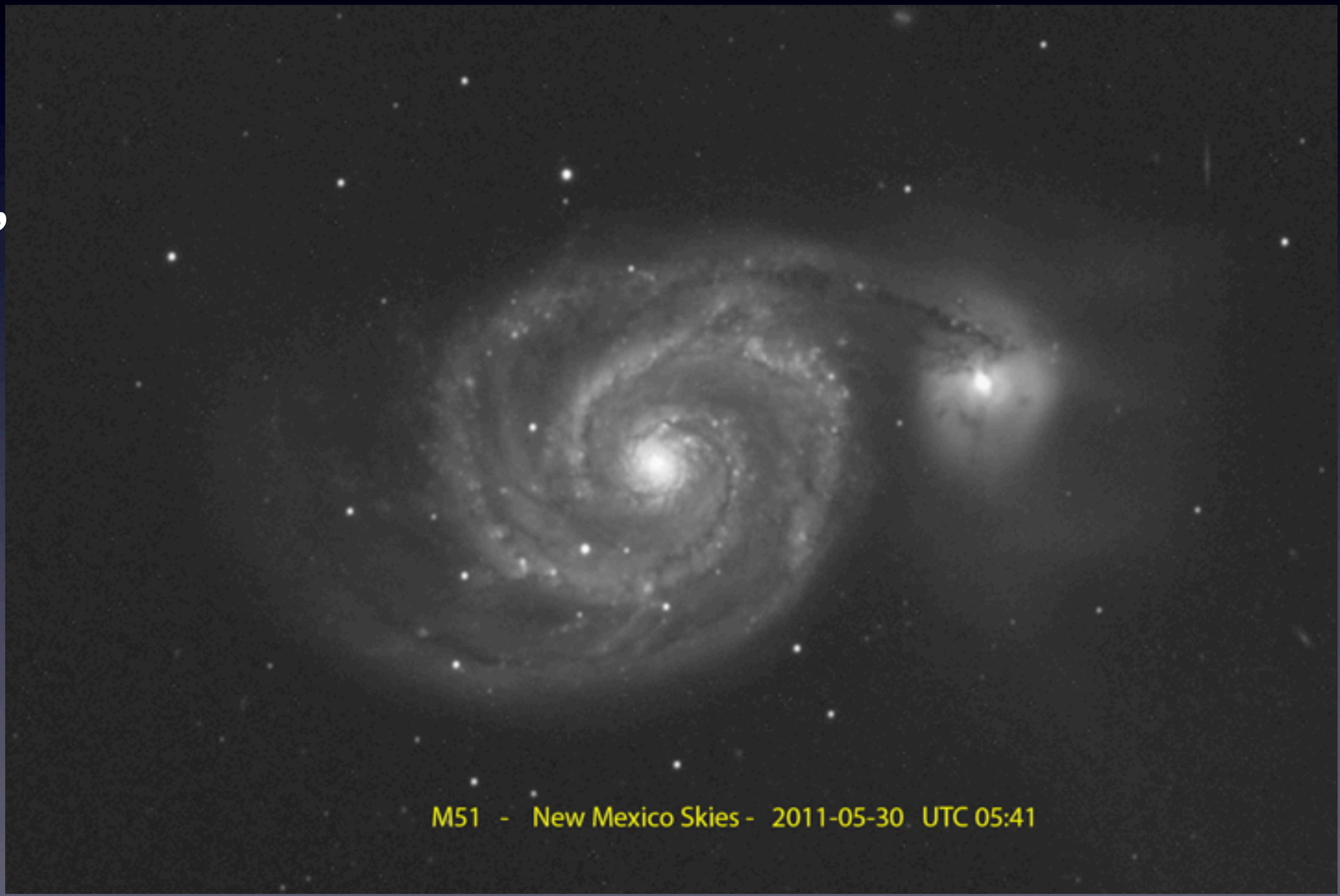
Galactic core-collapse supernovae as a beam

- There's an exciting element of unpredictability
  - just like with science funding in the US in general!
- Although, in fairness to supernovae, it should be acknowledged that a galactic SN is at least guaranteed to happen at some point
  - The beam will be there, we just need to set up the detectors

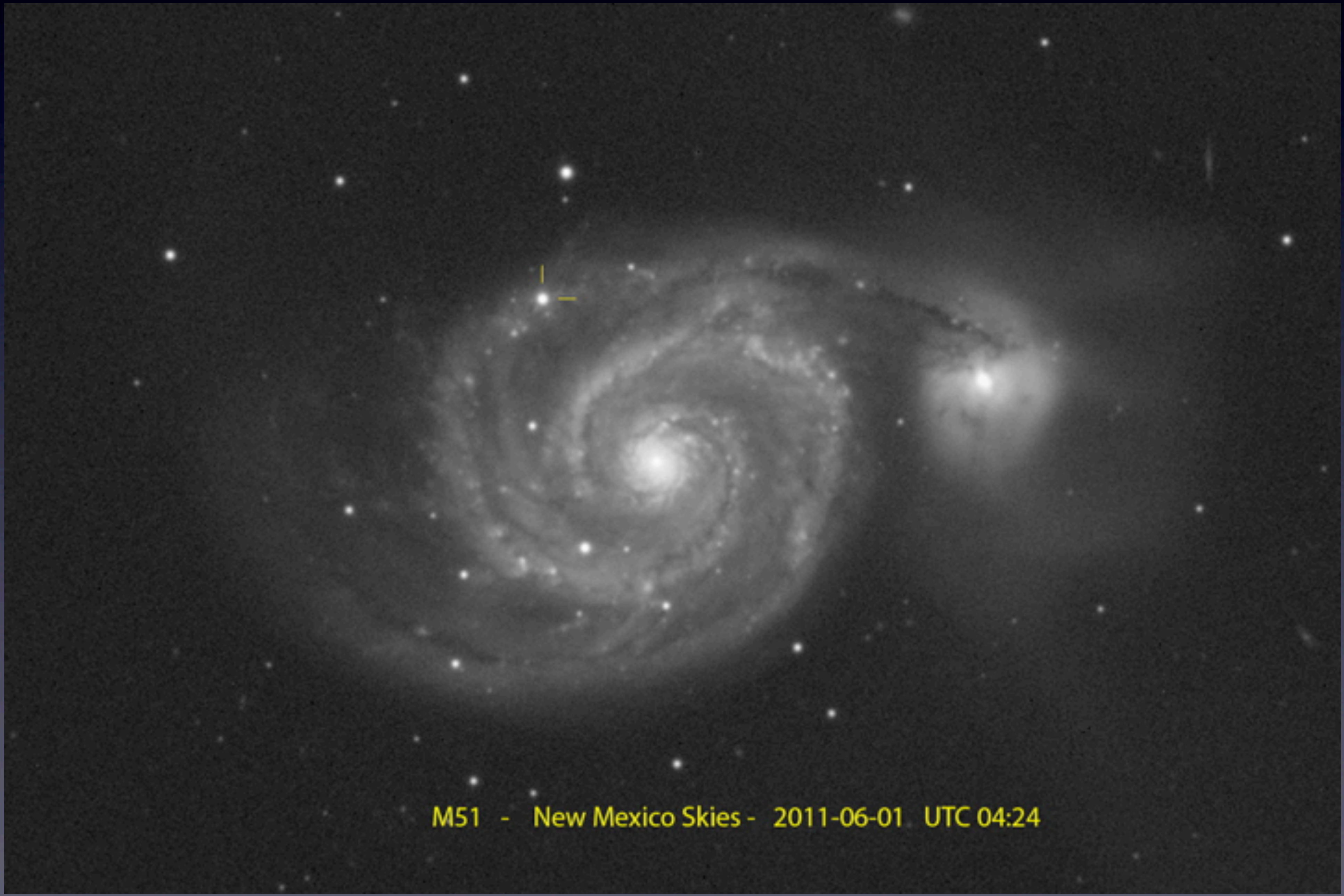
Nearby Whirlpool galaxy (M51)

May 30, 2011



Nearby Whirlpool galaxy (M51)

June 1, 2011



SN 2011dh

- ~20 $M_{\odot}$ progenitor
- The third supernova in M51 in only 17 years
  - earlier one in 2005, another in 1994
- Note locations in the spiral arms
  - Massive stars are very short-lived, hence CCSN occur in star forming regions

SN 2005cs vs SN 2011dh

Our Galaxy

- We want to detect neutrinos from an event like that in our Galaxy
- Our own Galaxy is thought to have a somewhat slower SN rate
  - estimated once every ~ 40 ± 10 yrs
  - ~ 85% of these are from core collapses of massive progenitors (*and hence come with neutrinos!*)

THE GALACTIC SUPERNOVA RATE

G. A. Tammann, W. Löffler, and A. Schröder
Astronomisches Institut der Universität Basel, Venusstrasse 7, CH-4102 Binningen, Switzerland
Received 1993 April 12; accepted 1993 August 2

ABSTRACT

The combined evidence from external galaxies and from the historical SNe in our Galaxy gives a best estimate of the Galactic SN frequency of one event every 40 ± 10 yr. About 85% of these SNe come from massive progenitors and are expected to cause neutrino bursts. The result is in agreement with additional evidence from the number of progenitor stars, radio SN remnants, the Galactic iron abundance, the Galactic γ-ray flux, the absence of a neutrino detection so far, and the birthrate of pulsars. It is also consistent with the observation that the very largest late-type spirals produce ~10 SNe per century. The combined SN rate of the Magellanic Clouds is 0.6, that of M31 plus M33 1.8 SNe per century.

We know for sure they emit neutrinos!
We have already observed one explosion with neutrinos (SN 1987A)

Gravity-powered neutrino bombs

- Central *Fe* core (~ 1.4 $M_\odot$) of a massive star collapses until reaching (supra)nuclear densities, 10^{10} g/cm^3 → 10^{14} g/cm^3
- The gravitational binding energy, $G_N M^2/R$ (~10% of rest mass!), is initially stored mostly in the Fermi seas of trapped electrons & electron neutrinos
- The object loses its lepton number and energy on the time scale of a few seconds by neutrino diffusion
  - 10^{53} ergs explosion (10^{28} megaton in Los Alamos units)
  - This energy comes out mostly (>99%) in 10^{58} neutrinos, emitted in all flavors
    - definitely Intensity Frontier!

Digression: SN neutrinos vs DOE Frontiers

- Actually, SN neutrinos have little regard for boundaries between Frontiers, or between different DOE Offices
- Require physics input from HEP, Nuclear Physics, Astrophysics, and Supercomputing
- Promise fundamental results in all these fields

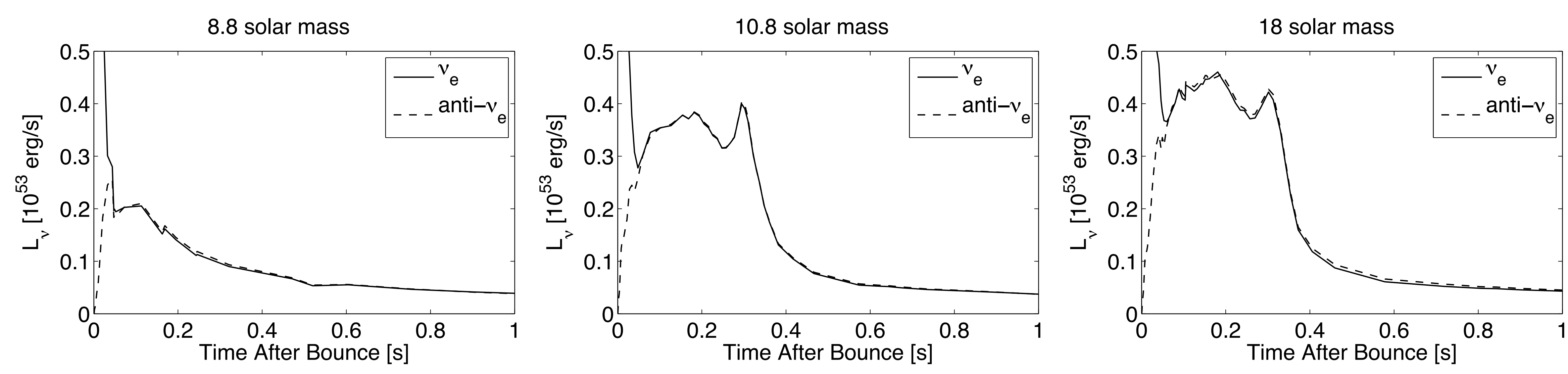
What are some of these fundamental results?

Physics of the explosion: Holy Grail for 60 years

- Supernovae are extremely important objects in our universe
  - They disperse metals and create shock that affect formation of stars
  - They impact the structure of our galaxy
    - Simulations of the galactic disk show supernova feedback is crucial
  - They may synthesize the r-process elements

Neutrinos provide a direct window into the explosion

- Neutronization burst, accretion phase, cooling phase can all be seen in neutrinos



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

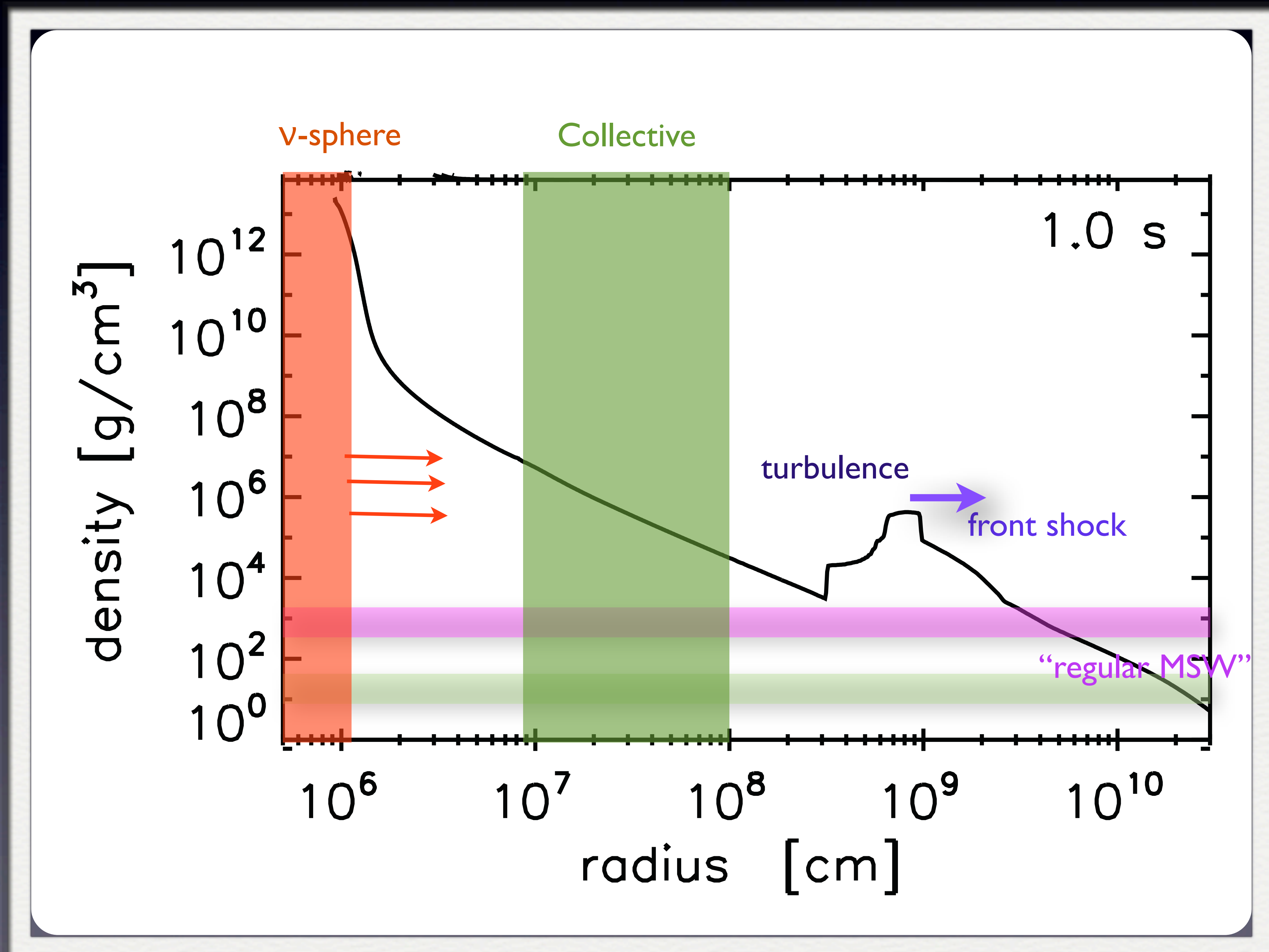
Nuclear physics

- *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?)
  - What are the neutrino transport properties of this medium?

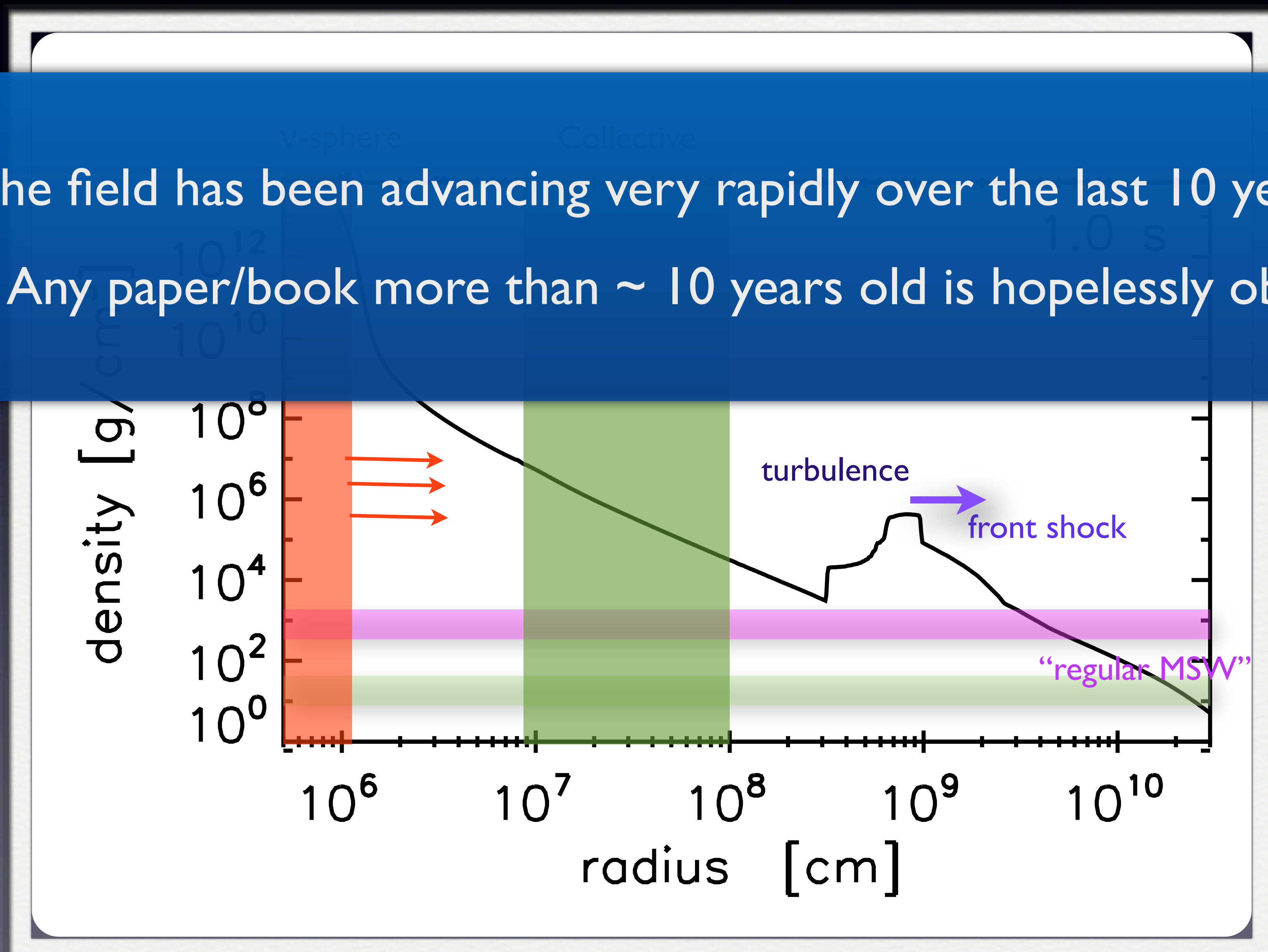
What about particle physics?

- *Particle physics*:
  - bounds on the whole host of novel weakly coupled particles (axions/majorons/extra dim/etc), ...
  - Sensitivity to tiny nonstandard neutrino effects (e.g., flavor changing processes)
  - Richest known neutrino oscillation problem
    - Realizes neutrino oscillations in a regime inaccessible in the lab
    - With the discovery of oscillations, no longer optional!

Supernova nu oscillations: a physics cartoon

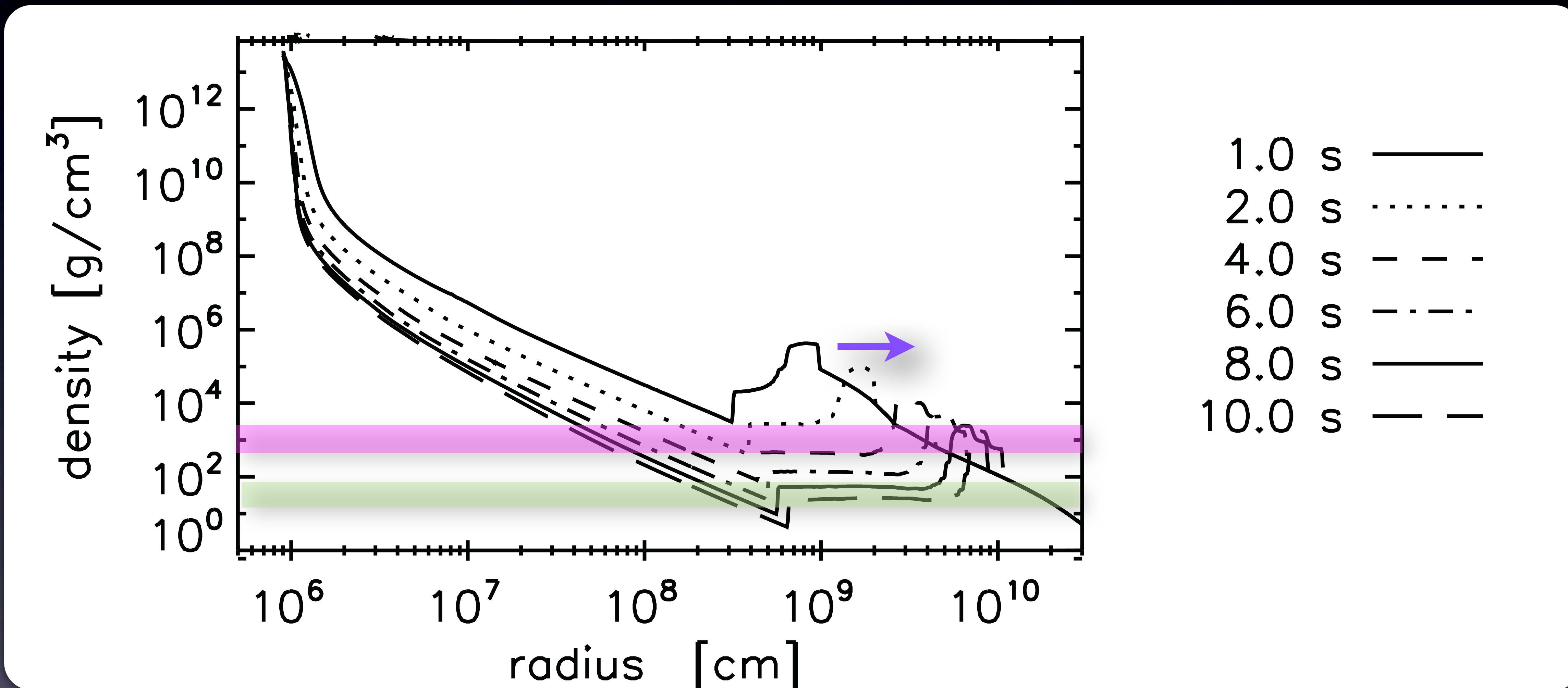


Supernova nu oscillations: a physics cartoon



- The field has been advancing very rapidly over the last 10 years
- ...Any paper/book more than ~ 10 years old is hopelessly obsolete!

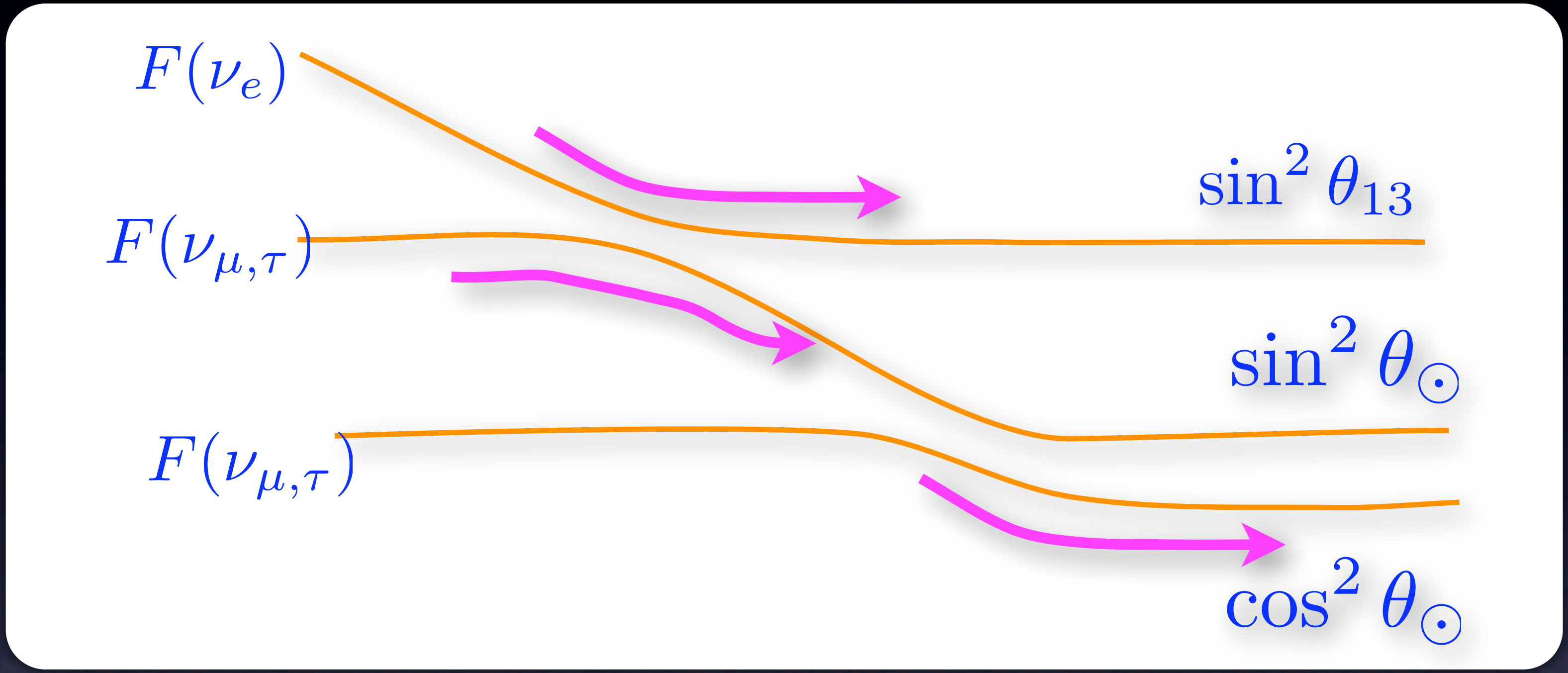
Effect I: moving shock front

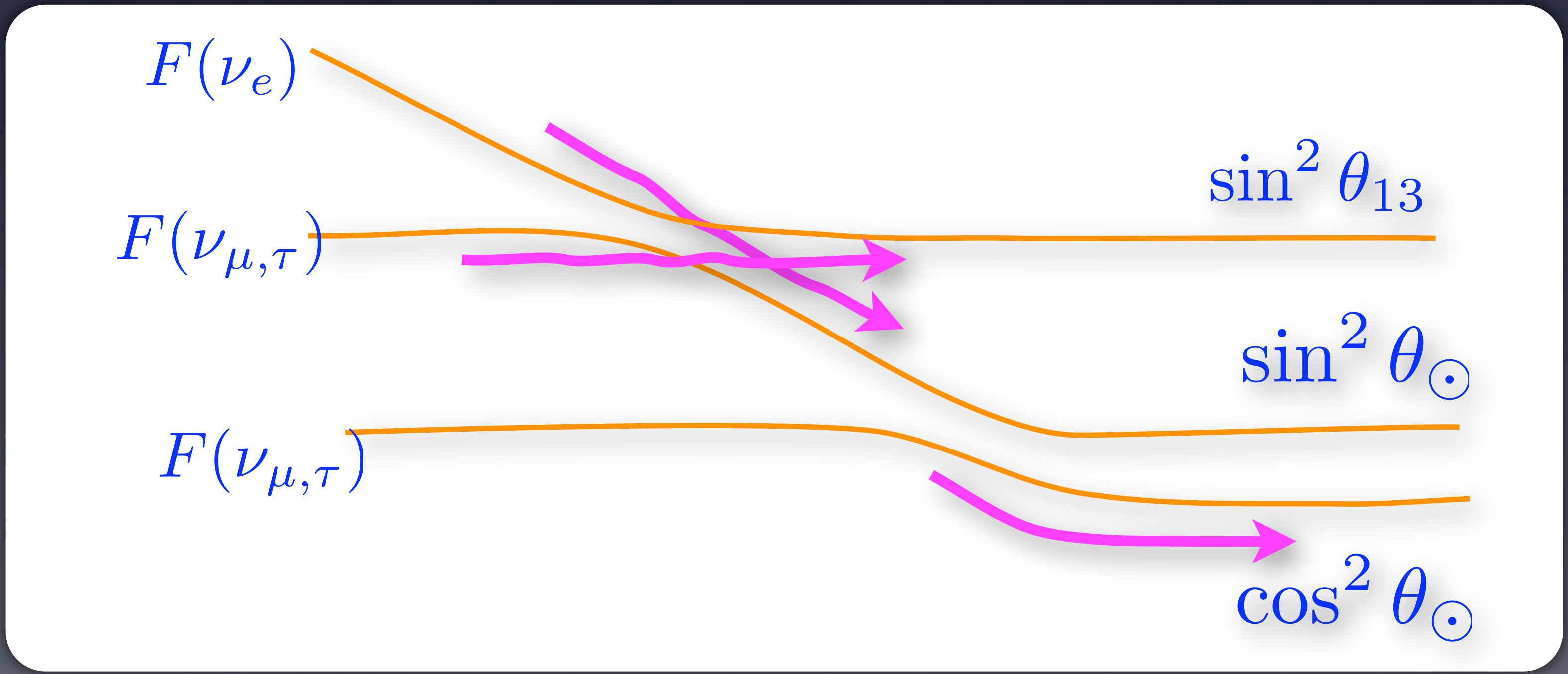


- Front shock reaches the regions where “atmospheric” and “solar” transformations happen, while neutrinos are being emitted
  - See Schirato & Fuller (2002) astro-ph/0205390

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.



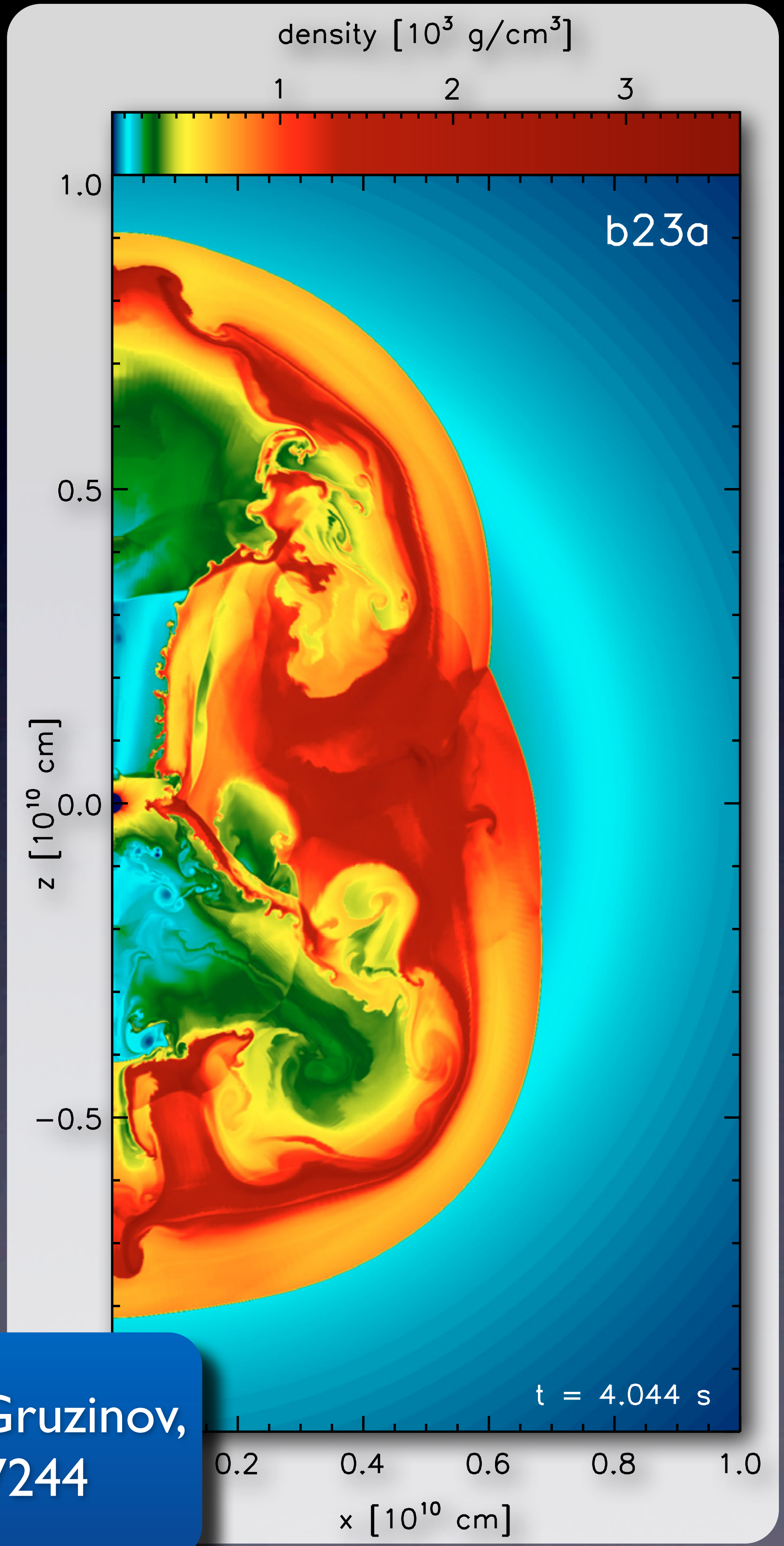


For inverted hierarchy, the same happens in antineutrinos.

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

Effect II: turbulent density fluctuations

- The region behind the shock is turbulent: has stochastic density fluctuations on many scales
    - Turbulence creates a cascade, with fluctuations on all scales, including ~ 10 km neutrinos osc. length
- Simulations see order one large fluctuations + theta13 has since been measured to be large!
    - Under these conditions, turbulence should leave a measurable imprint



Details in A.F., A. Gruzinov, astro-ph/0607244

Effect III: Neutrino "self-refraction"

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

- Above the neutrino-sphere, streaming neutrinos are so dense that their flavor evolutions become coupled
- A given neutrino *coherently* scatters on the ensemble of "background" neutrinos
- One has to evolve an ensemble of neutrinos as a whole

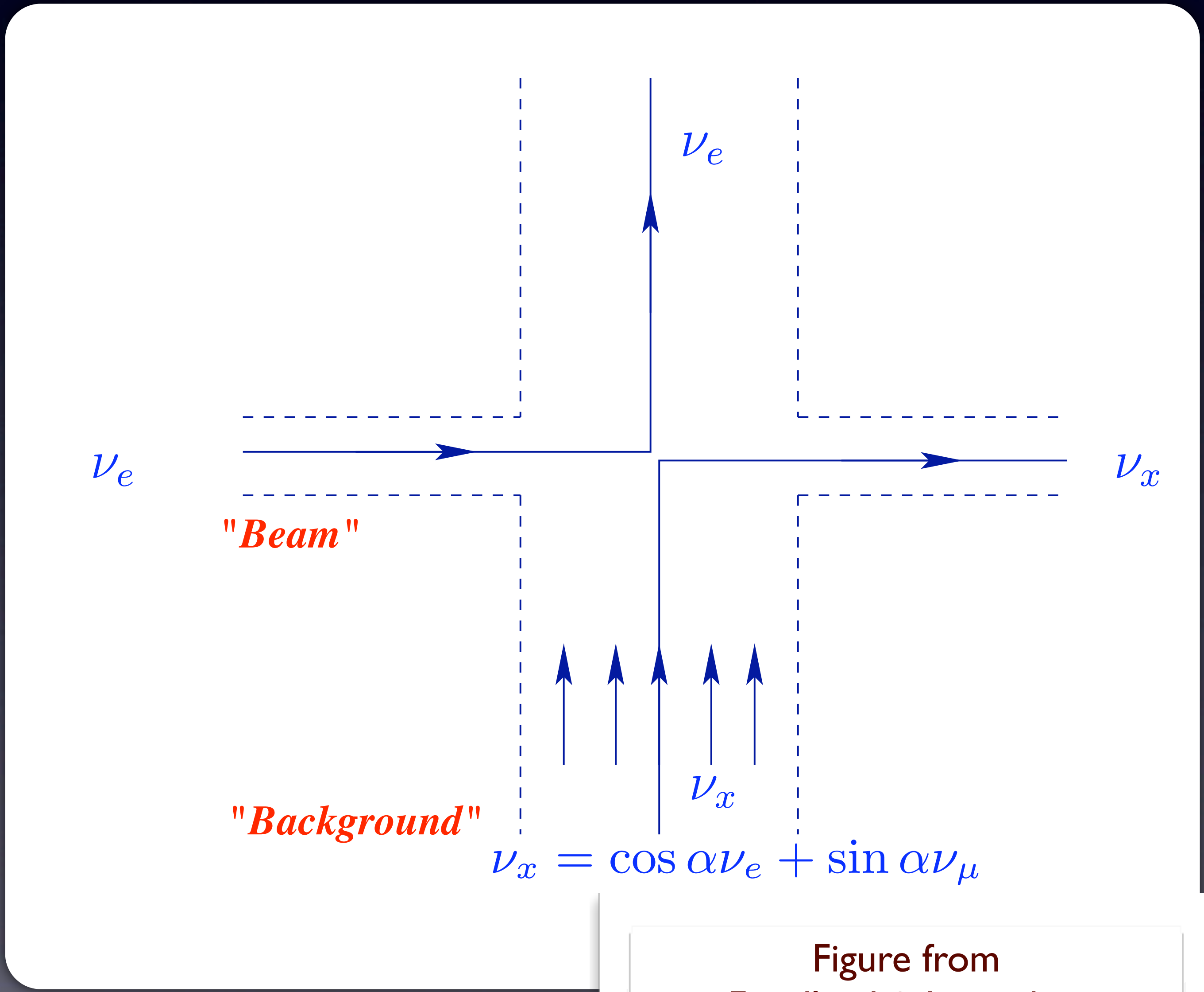
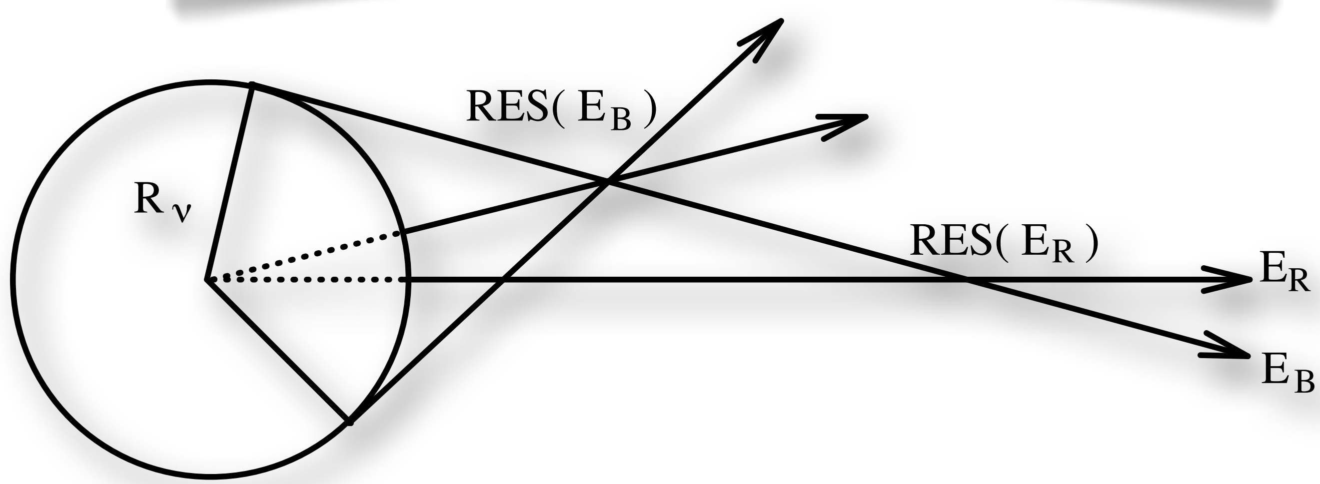


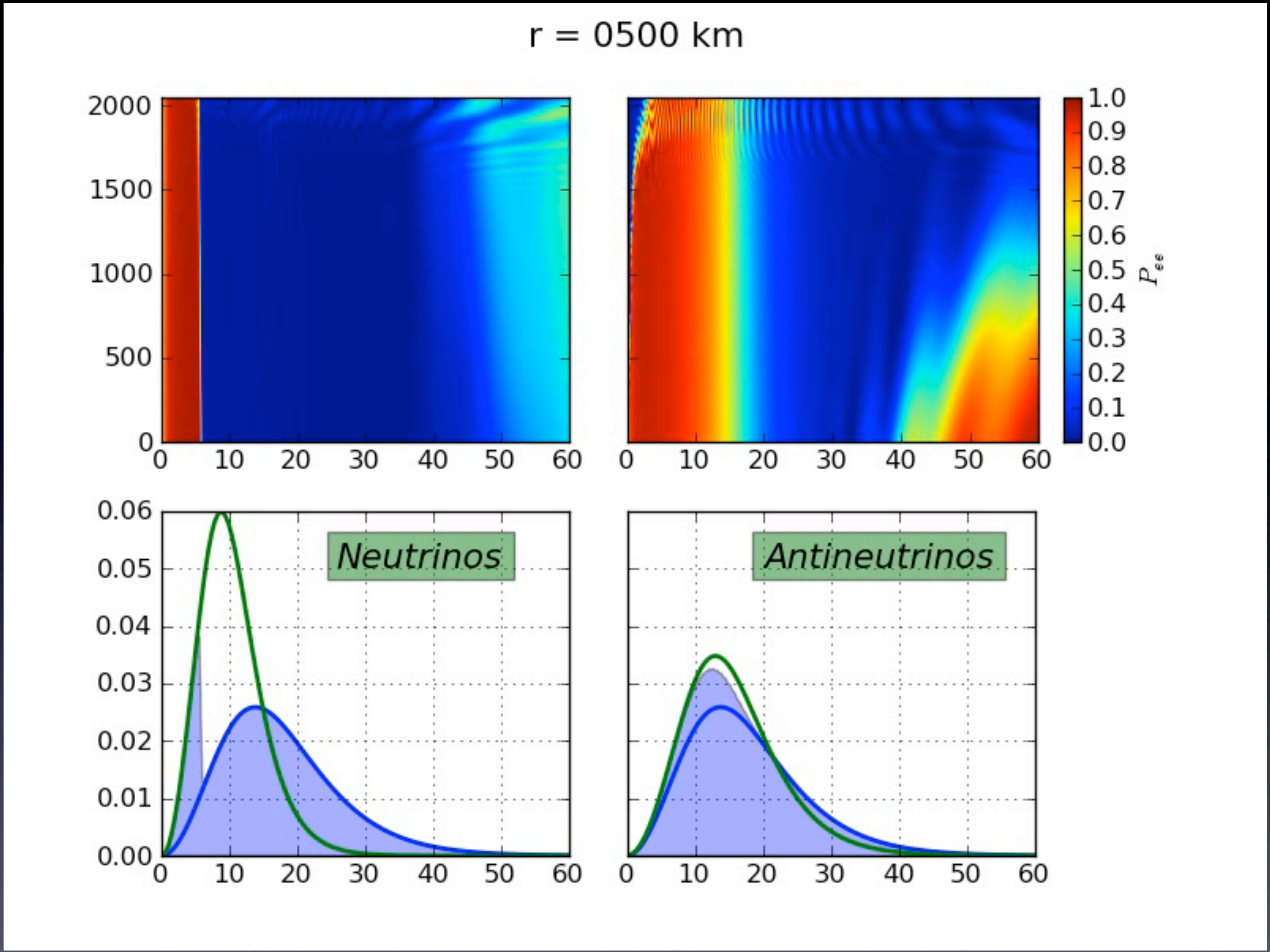
Figure from
Friedland & Lunardini,
Phys. Rev. D 68, 013007 (2003)

Many angles, many energies

Figure from Qian & Fuller, astro-ph/9406073

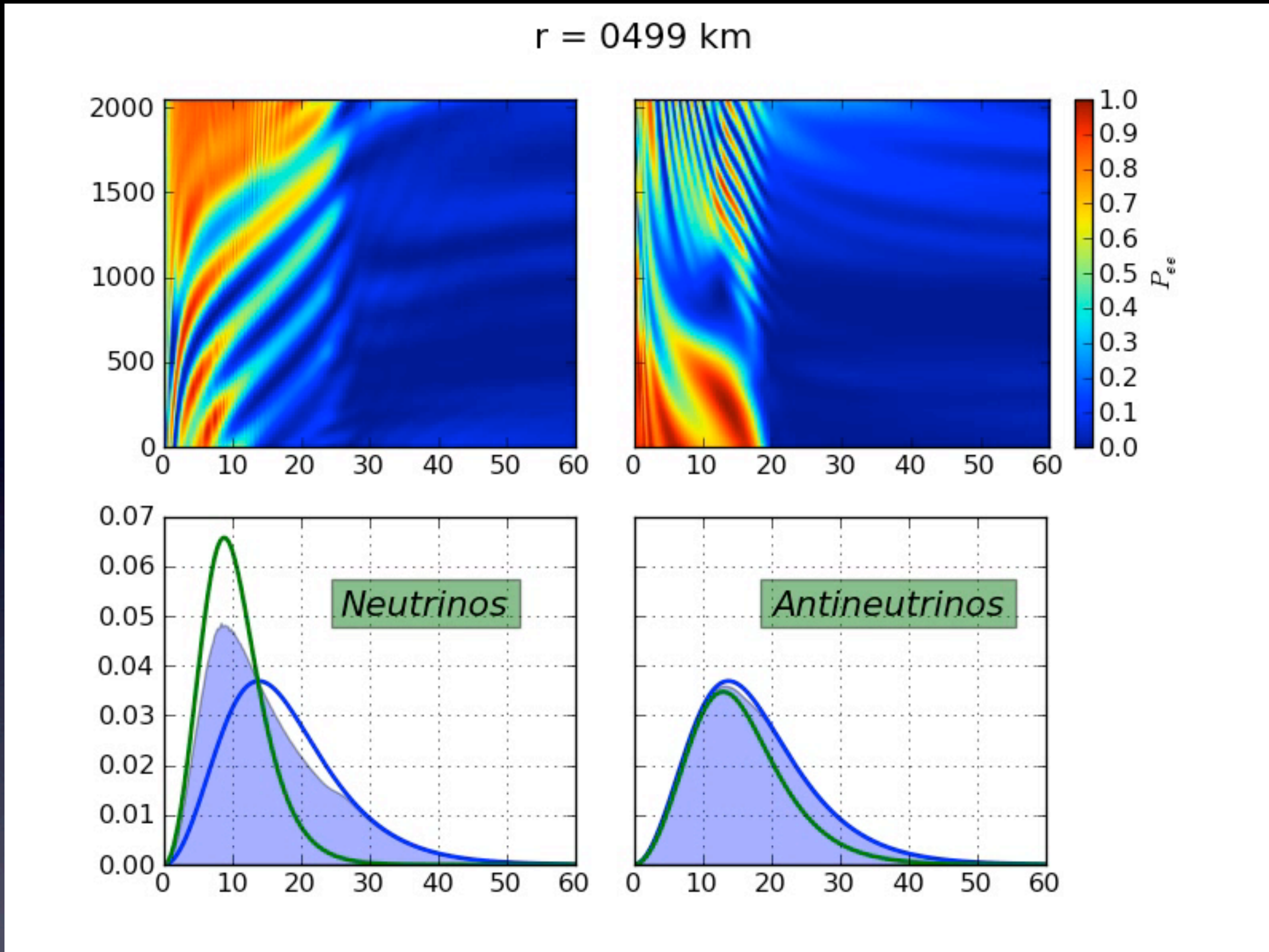


- Multiangle calculations: 10^3 energy bins and 10^4 angle bins
  - Rapid oscillations in all bins, supercomputing
- Nonlinear many-body phenomenon, many different regimes



Inverted hierarchy example

Duan, A.F., *to appear*



Normal hierarchy, qualitatively different pattern

What can detectors see?

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, Majorons, KK gravitons, etc, etc
- Next galactic supernova: precision physics!
  - Several thousands in 34 kt of LAr (LBNE)

Why do we need the LAr signal at all?

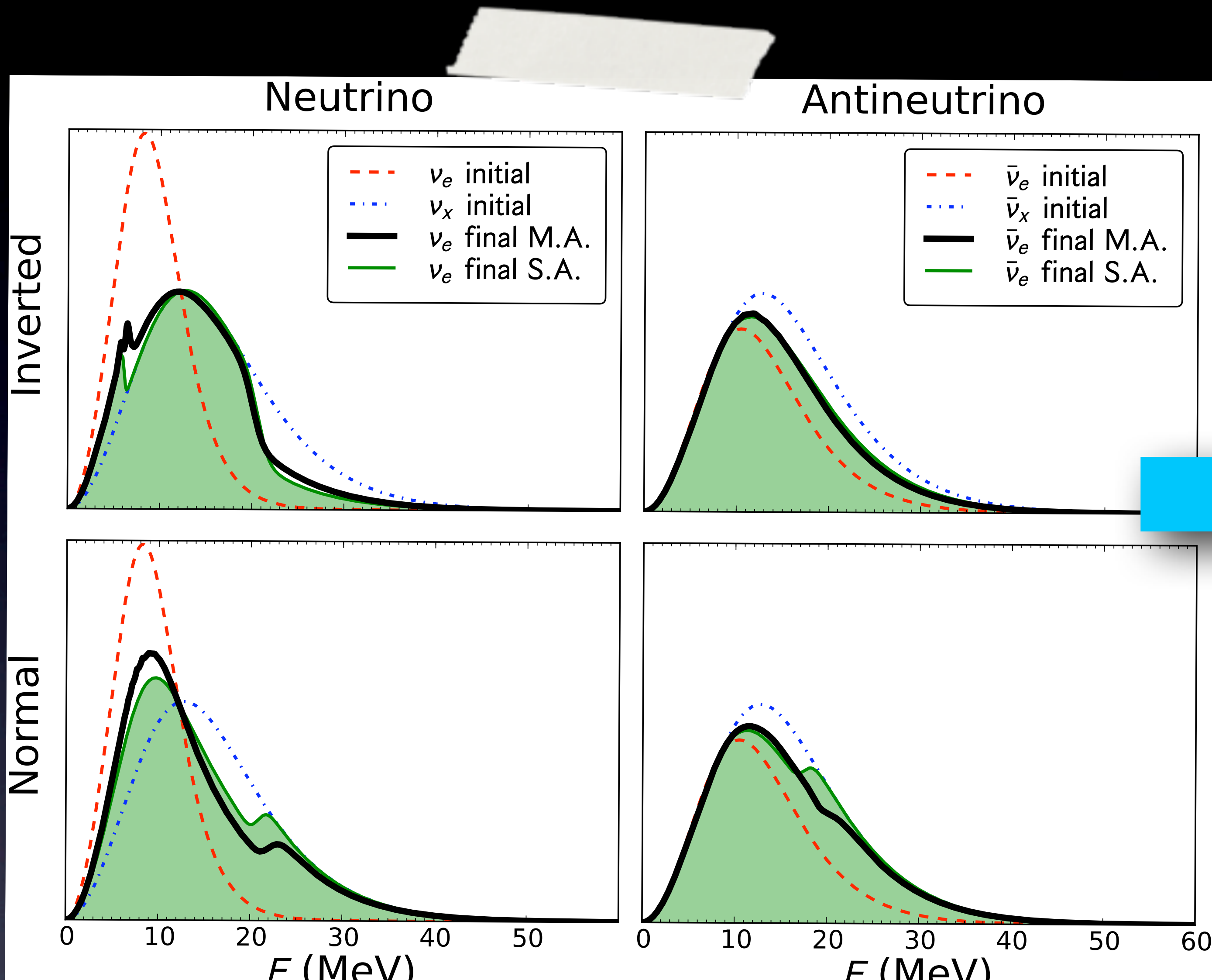
- ~ 10^4 events in Super-Kamiokande
- ~ 10^5 in proposed 0.99 MT Hyper-Kamiokande, see **arXiv:1109.3262**
- ~ 10^6 in IceCube
  - Isn't bigger always better?
- The answer is no, not always
  - Different detectors have different characteristics and excel at different questions
  - Let's see a couple of examples

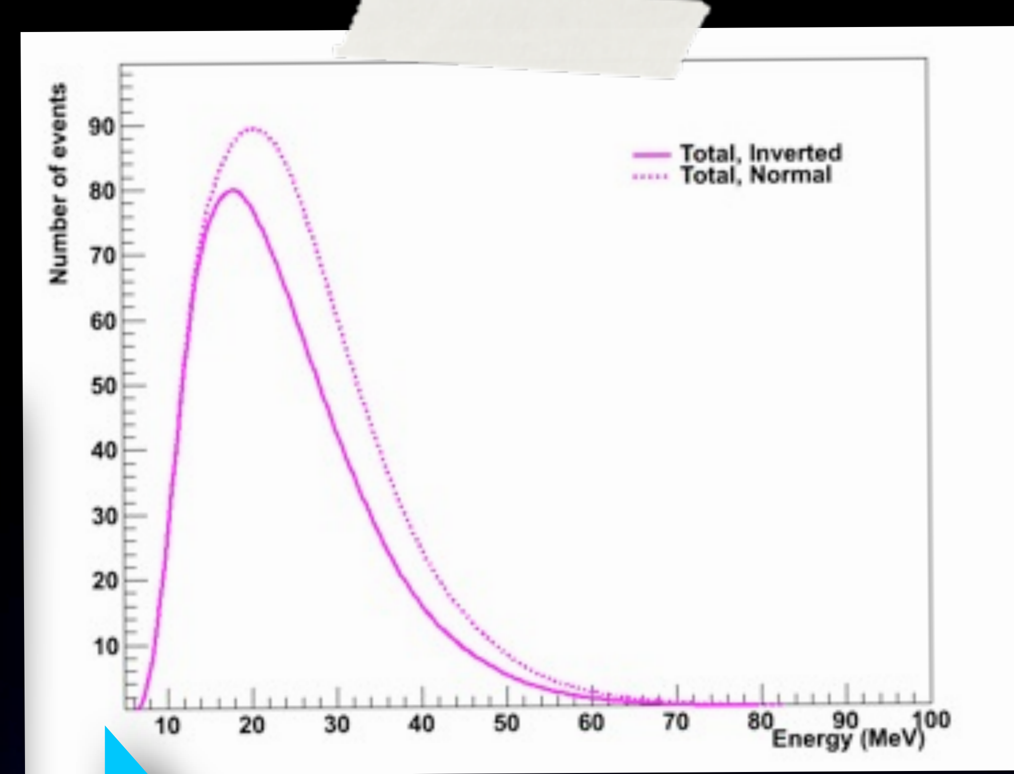
Liquid Argon: strengths

- The main detection channel for SN neutrinos in LAr is the CC reaction

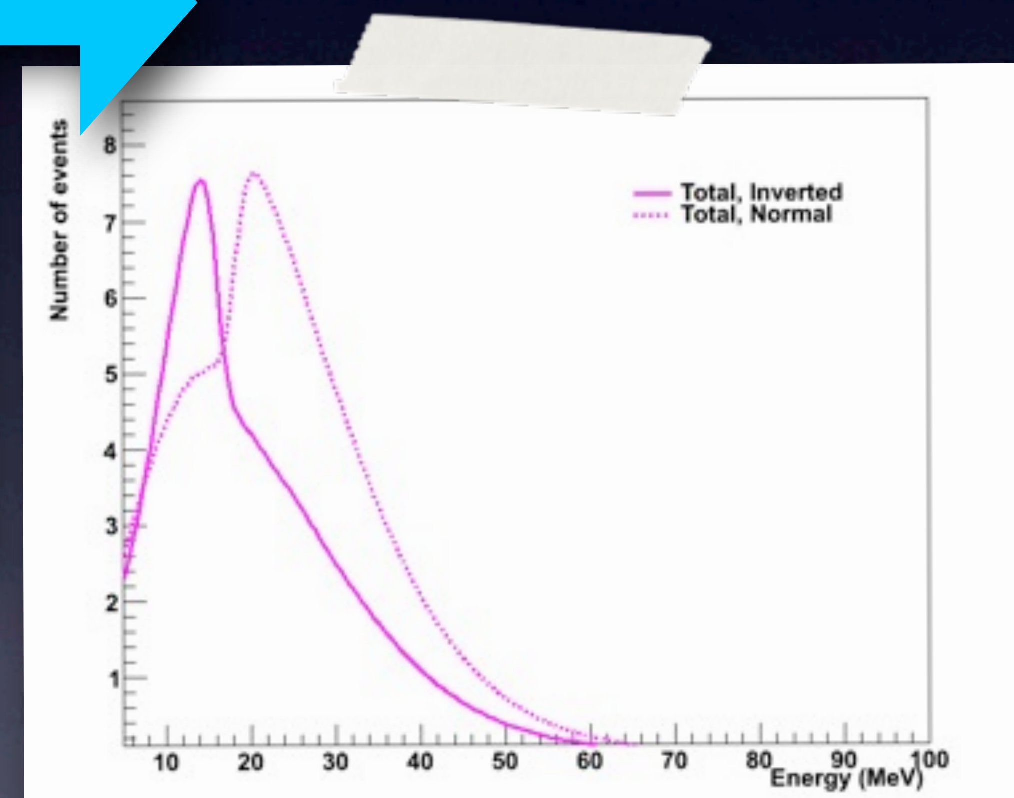
$$\nu_e + ^{40}\mathrm{Ar} \rightarrow e^- + ^{40}\mathrm{K}^*$$

- This reaction is sensitive to neutrinos, while at water detectors most of the signal comes from antineutrinos
- Neutrino and antineutrino signals are very different, moreover the neutrino channel often contains more pronounced features
- In a water detector, there does exist a subdominant nue-electron elastic scattering component, but spectral information is washed out
- In contrast, LAr detector can provide accurate spectral information





WC



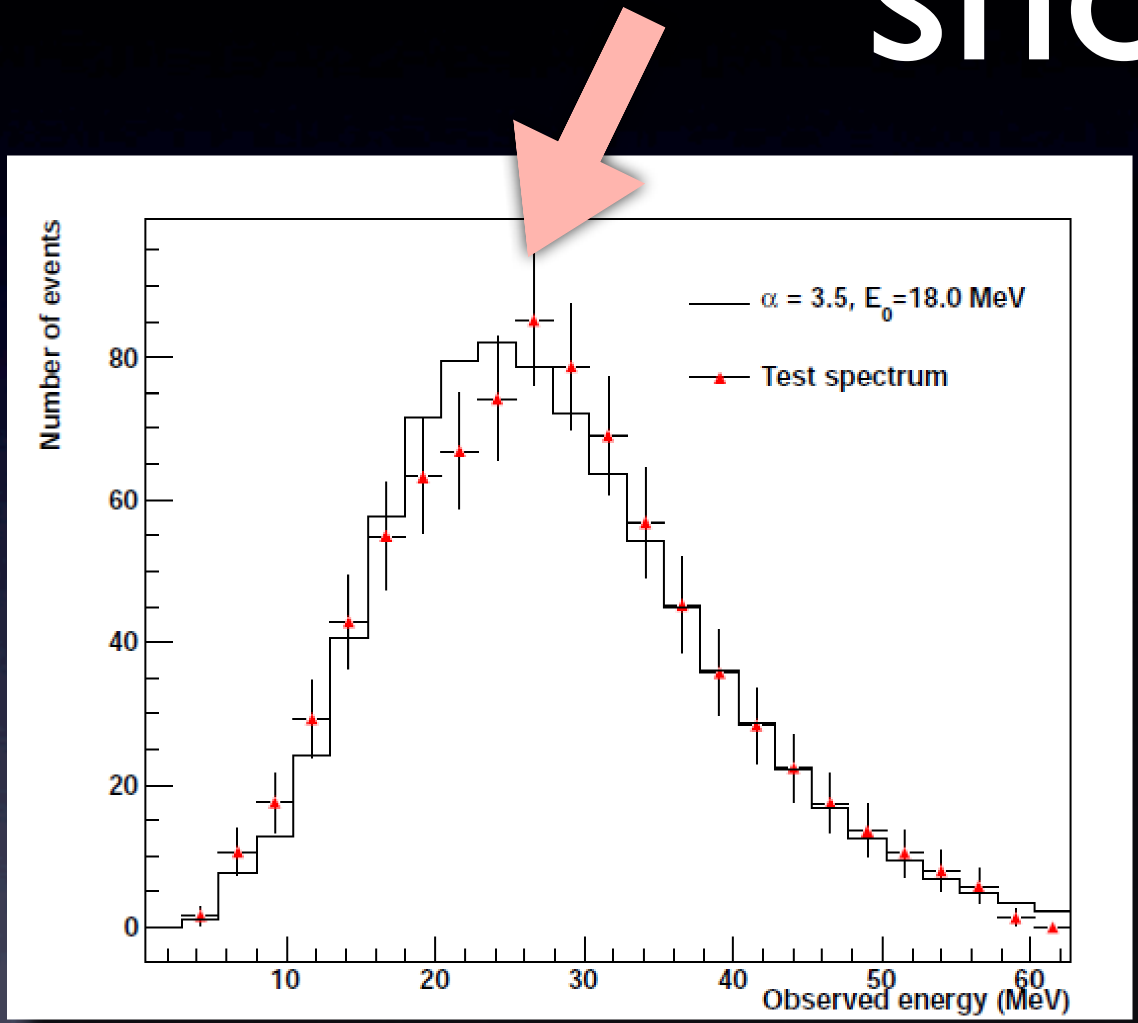
LAr

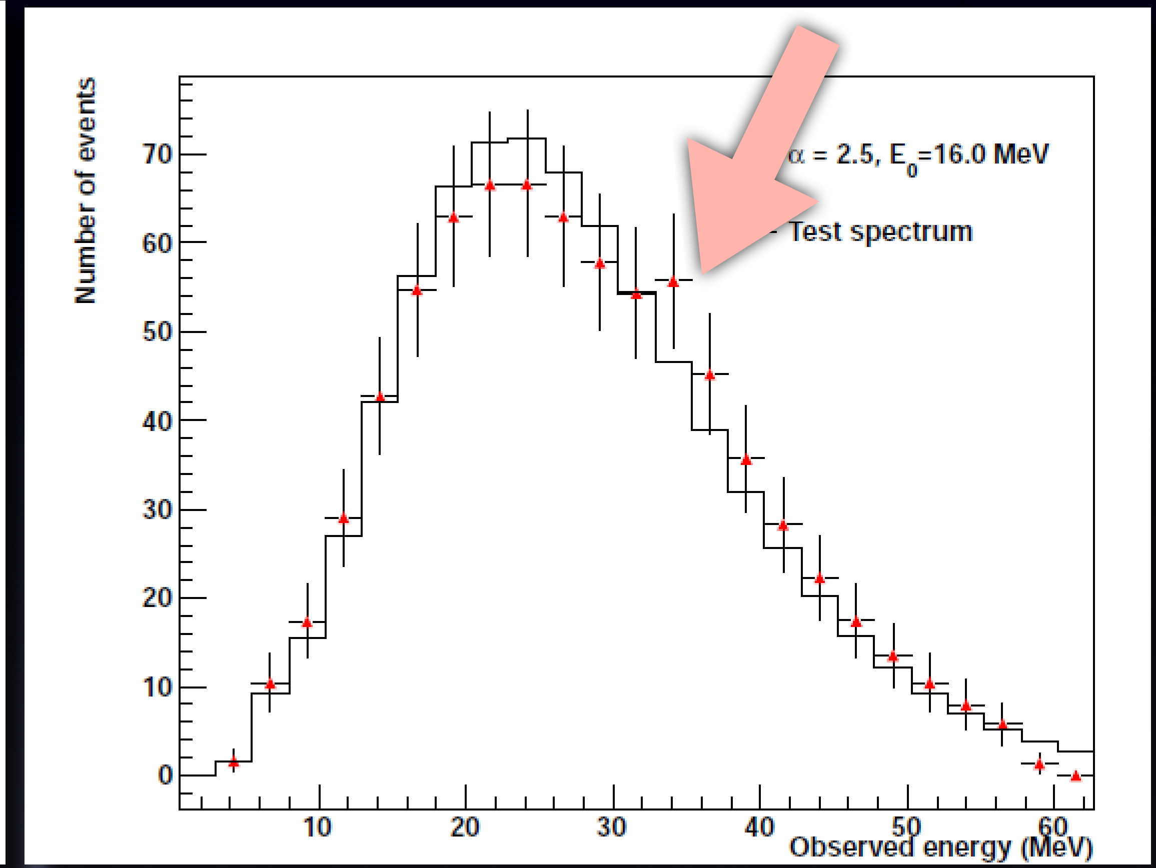
LBNE physics report: SN working group (arXiv:1110.6249)

* collective oscillations by Duan & Friedland, Phys. Rev. Lett. (2011)

* detector modeling by Kate Scholberg & collaborators

Moving imprint of the shock



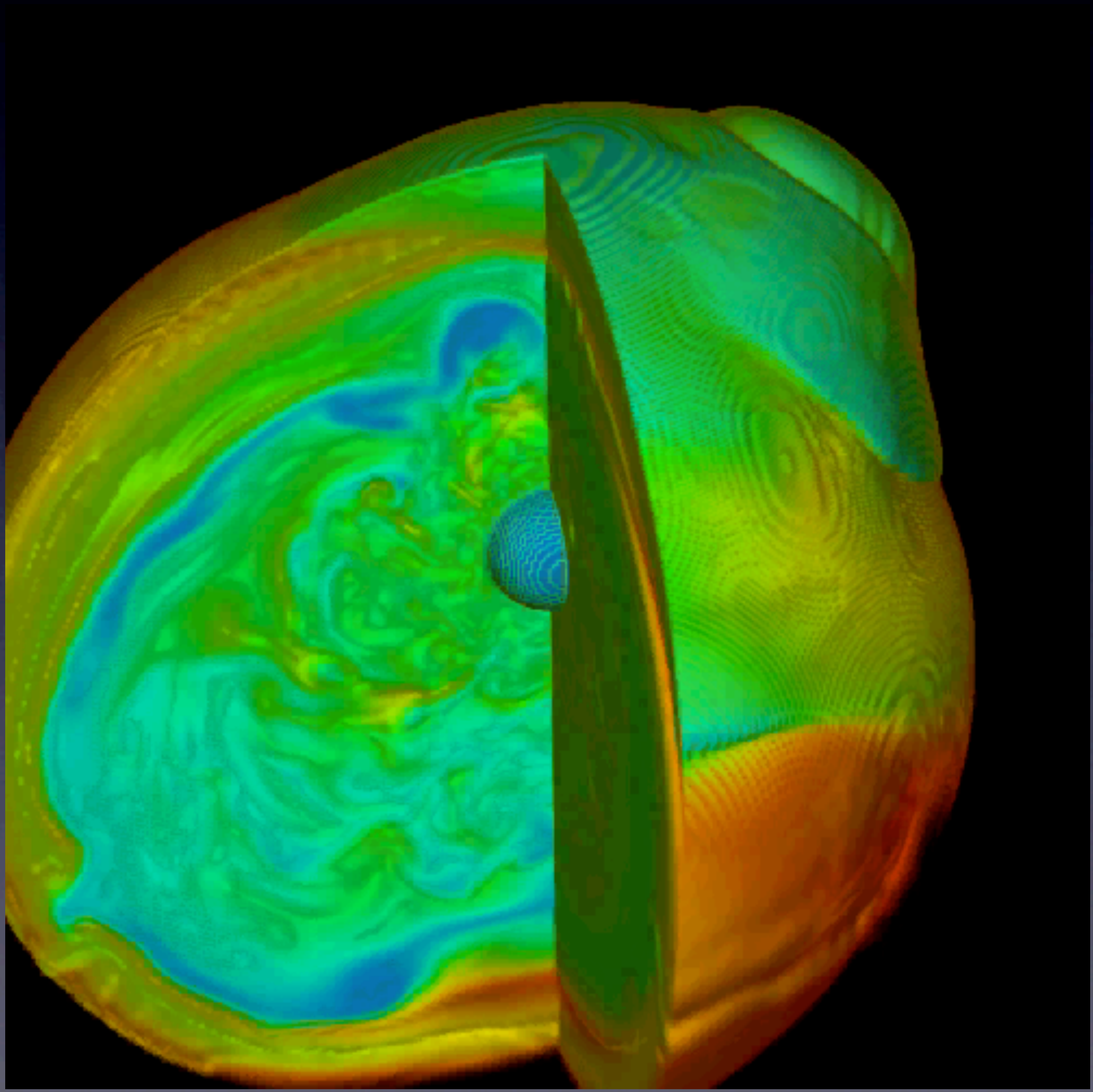


J. Cherry, H. Duan, A.F., K. Scholberg, *in progress*

See *arXiv:1307.7335* (LBNE Snowmass document)

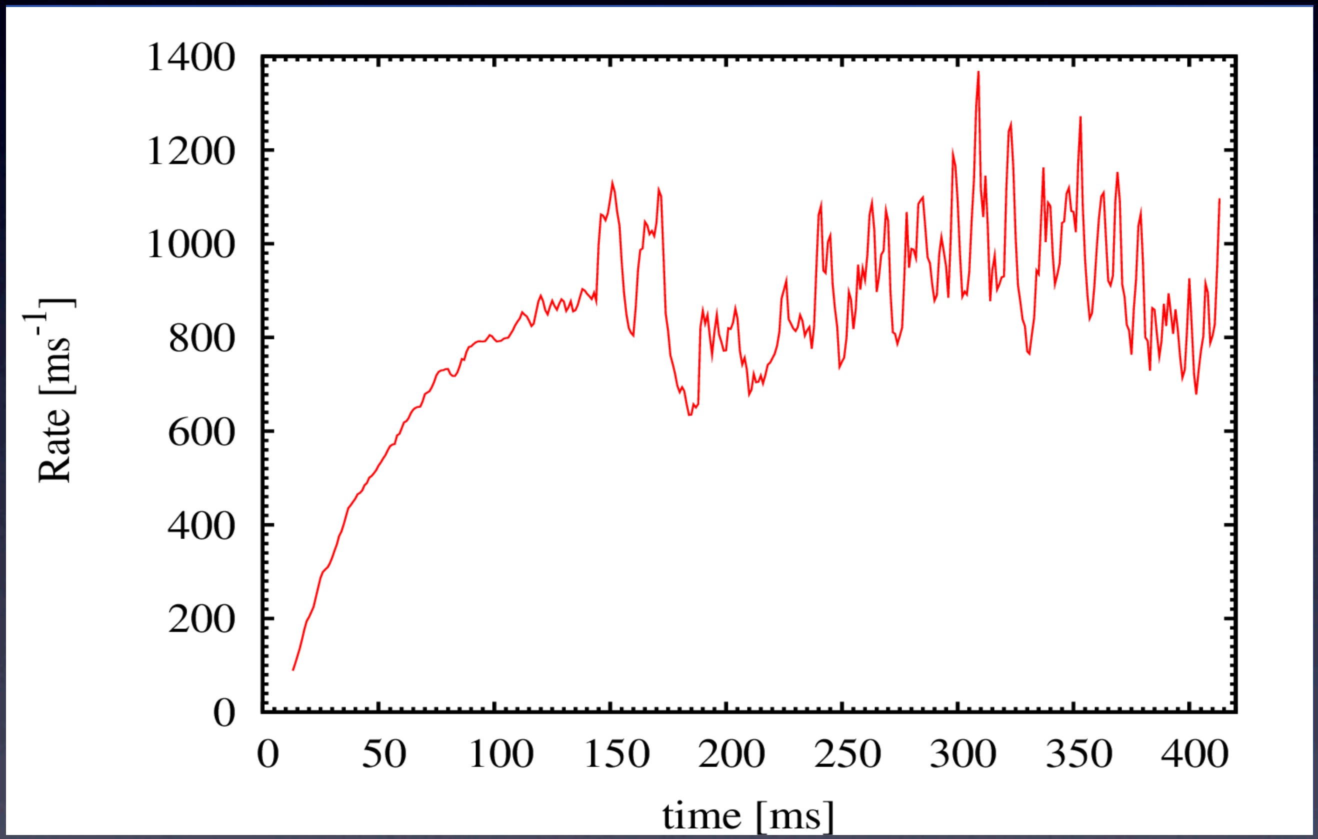
Example when large event rates matter: SASI

- Discovered in 3d supercomputer simulations of the accretion shock by Blondin, Mezzacappa, & DeMarino (2002)
- See http://www.phy.ornl.gov/tsi/pages/simulations.html
  - Standing accretion shock instability (SASI)



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

Reproduced in a backyard water experiment

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

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 heavy elements got here, and whether there are light axion-like particles are just some of the questions that may be answered
  - Very tight synergy between the fields required, from particle physics models to astrophysics and supercomputing

Bottom line II

- 40 ± 10 yrs is a reasonable timescale to target with the LBNE far detector, which is anyway likely to run for several decades, in various beams + searching for nucleon decay
- This will be "a once in a lifetime opportunity" (G. Raffelt)
  - Would be a shame to not have good detectors standing by!

Very active area, help wanted!

- Detailed spectra of neutrinos, evolving second-by-second
- Potentially treasure trove of information
- How should we read this signal?
  - What are the relevant physical effects?
  - What detector characteristics are optimal?