What should we try to measure at DUNE?

Alex Friedland

SLAC NATIONAL ACCELERATOR LABORATORY

INT Seattle, Aug 18, 2016

DUNE working group

- DUNE has a number of physics working groups. Among them,
  - "SuperNova Burst/Low Energy Physics Working Group"
  - Co-conveners Kate Scholberg, Ines Gil-Botella, A.F.

DUNE working group

- DUNE has a number of physics working groups. Among them,
  - "SuperNova Burst/Low Energy Physics Working Group"
  - Co-conveners Kate Scholberg, Ines Gil-Botella, A.F.

DUNE working group

- DUNE has a number of physics working groups. Among them,
  - "SuperNova Burst/Low Energy Physics Working Group"
  - Co-conveners Kate Scholberg, Ines Gil-Botella, A.F.

Design decisions

- The DUNE experimentalists ask: what should we try to measure?

Recent discussions

- SLAC, November 23-24, 2015
- stanford.edu/~alexfr/SN4DUNE/Nov2015/SN_theory_for_DUNE.htm
  - DUNE experimentalists + external experts in simulations, nuclear physics, oscillations
- Virginia Tech, March 11-12, 2016
  - cnp.phys.vt.edu/SNatDUNE/
  - Externally organized, a number of DUNE participants
- DUNE Collaboration meeting, Rapid City, 19-22 May 2016

Physics list

- Neutrino Physics/Particle Physics
  - Absolute neutrino mass
  - Mass hierarchy
  - Collective oscillations
  - Spin flip
  - Exotic particles, cooling
  - Majorana vs Dirac
  - Collective oscillations
  - Sterile neutrinos
  - Earth matter effect
- Supernova Physics
  - Presupernova evolution
  - Progenitor structure
  - Neutronization, trapping
  - Shock waves, turbulence effects
  - Supernova core type, core mass, EOS
  - Convective transport
  - Black hole formation
  - Explosion
  - Accretion to cooling transition
  - SASI
  - LESA
  - Neutron star "tomography"
  - Quark stars
  - QCD phase transition
  - Lepton number
  - Post BH accretion
- Other Physics
  - Nucleosynthesis
  - ...

To be converted into actionable items

- Basic detector characteristics
  - Photo detection system
  - Charge lifetime (LAr purity)
  - DAQ design: what information is written out, buffer size, etc
  - Time resolution, event reconstruction, etc
- Cross sections on Ar

Stages of the explosion

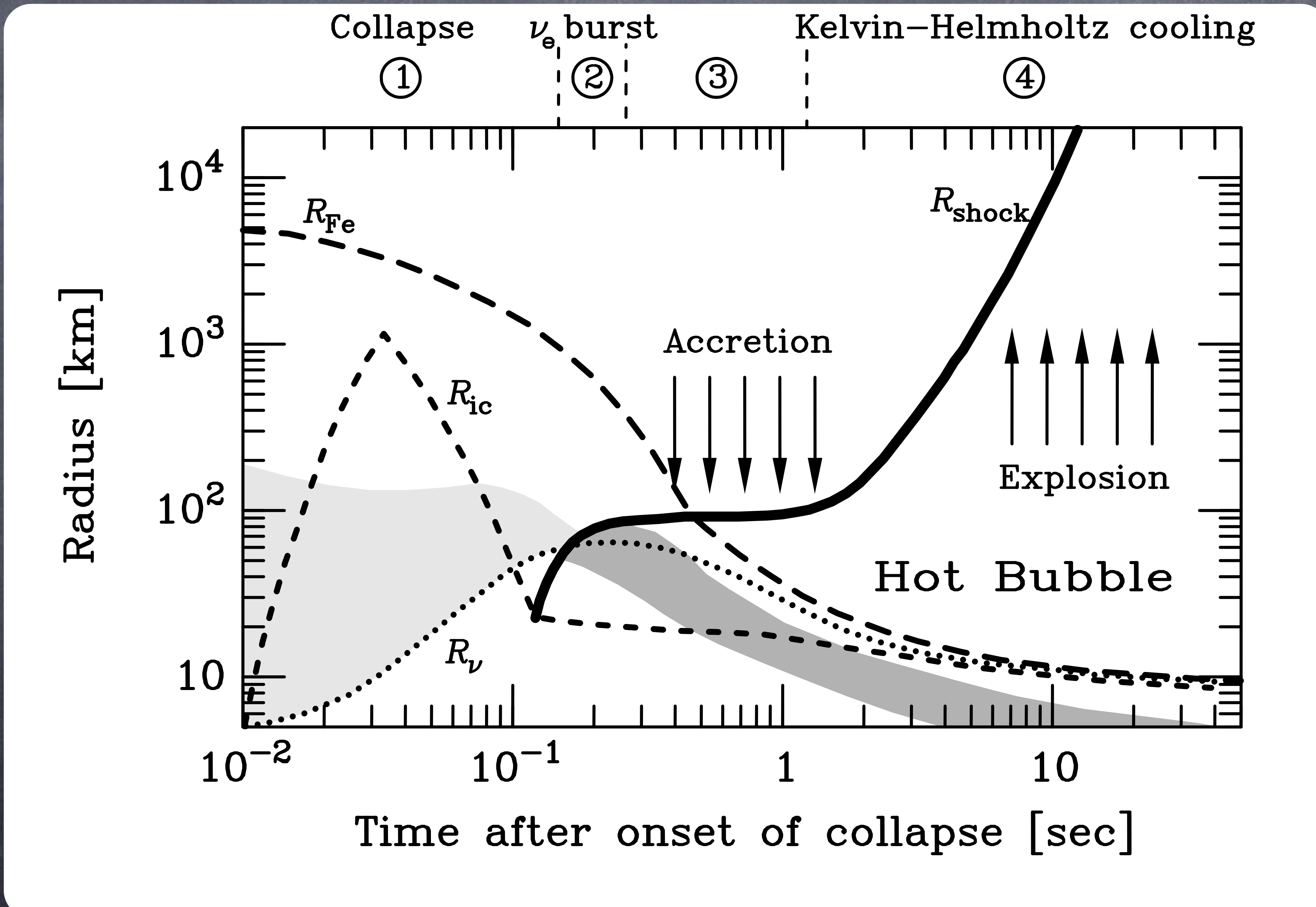


Fig by G. Raffelt, based on T. Janka (1993)

60-year-old problem

- How does the shock get restarted? Why don't people find robust explosions?

THE ASTROPHYSICAL JOURNAL, 766:43 (21pp), 2013 March 20 MÜLLER, JANKA, & MAREK

Table 1
Model Setup

Model	Progenitor	Neutrino Opacities	Treatment of Relativity	Simulated Post-bounce Time	Angular Resolution	Explosion Obtained	Time of Explosion[a]	EOS
G8.1	u8.1	Full set	GR hydro + xCFC	325 ms	1°.4	Yes	175 ms	LS180
G9.6	z9.6	Full set	GR hydro + xCFC	735 ms	1°.4	Yes	125 ms	LS220
G11.2	s11.2	Full set	GR hydro + xCFC	950 ms	2°.8	Yes	213 ms	LS180
G15	s15s7b2	Full set	GR hydro + xCFC	775 ms	2°.8	Yes	569 ms	LS180
S15	s15s7b2	Reduced set	GR hydro + xCFC	474 ms	2°.8	No	...	LS180
M15	s15s7b2	Full set	Newtonian + modified potential	517 ms	2°.8	No	...	LS180
N15	s15s7b2	Full set	Newtonian (purely)	525 ms	1°.4	No	...	LS180
G25	s25.0	Full set	GR hydro + xCFC	440 ms	1°.4	No	...	LS220
G27	s27.0	Full set	GR hydro + xCFC	765 ms	1°.4	Yes	209 ms	LS220

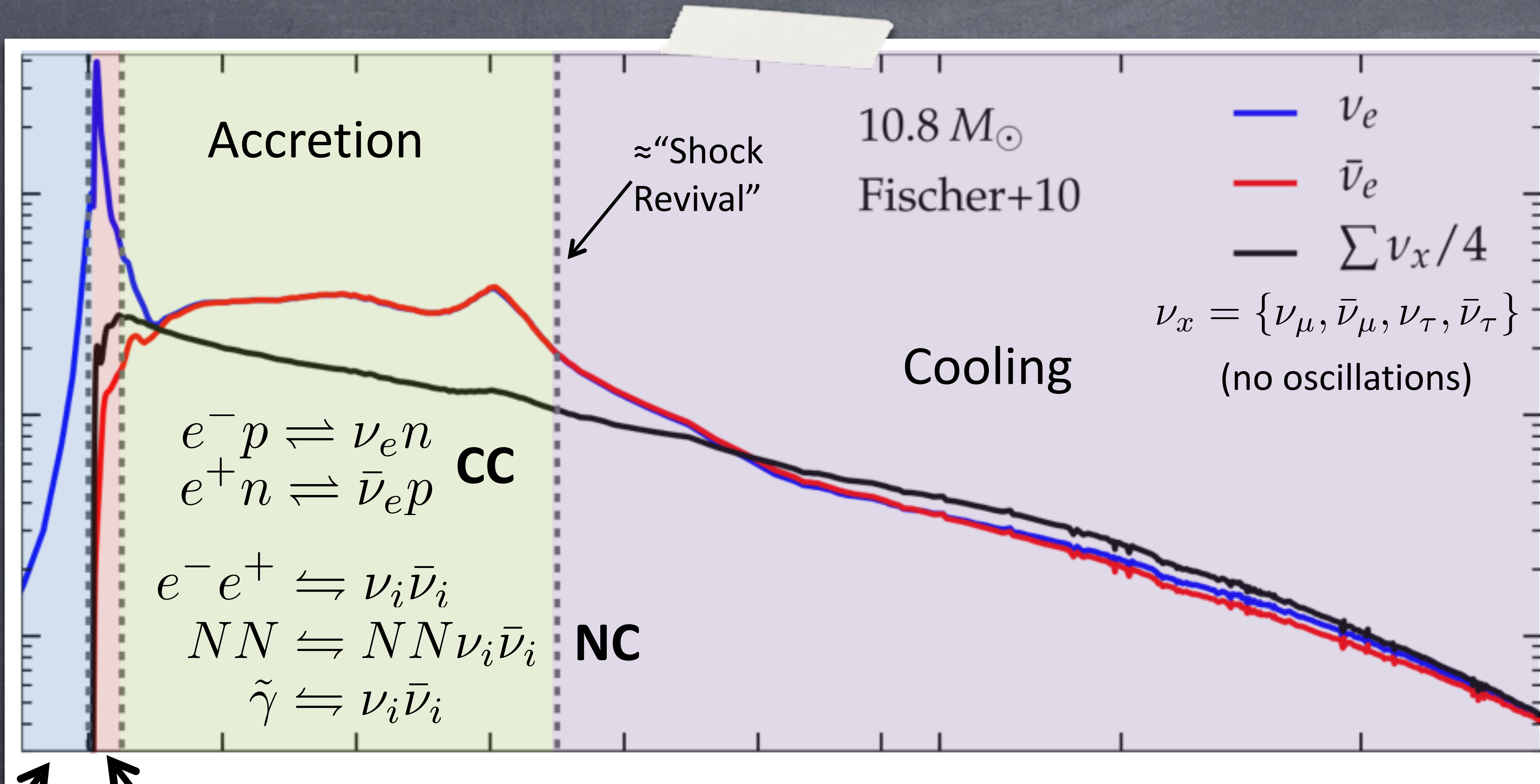
Note. [a] Defined as the point in time when the average shock radius $\langle r_{sh} \rangle$ reaches 400 km.

Need direct probes

- Just observing remnants in photons may not be enough
- Need to look inside the engine as the explosion happens
- In particular, need to observe when the accretion stage ends

Need direct probes

- Just observing remnants in photons may not be enough
- Need to look inside the engine as the explosion happens
- In particular, need to observe when the accretion stage ends

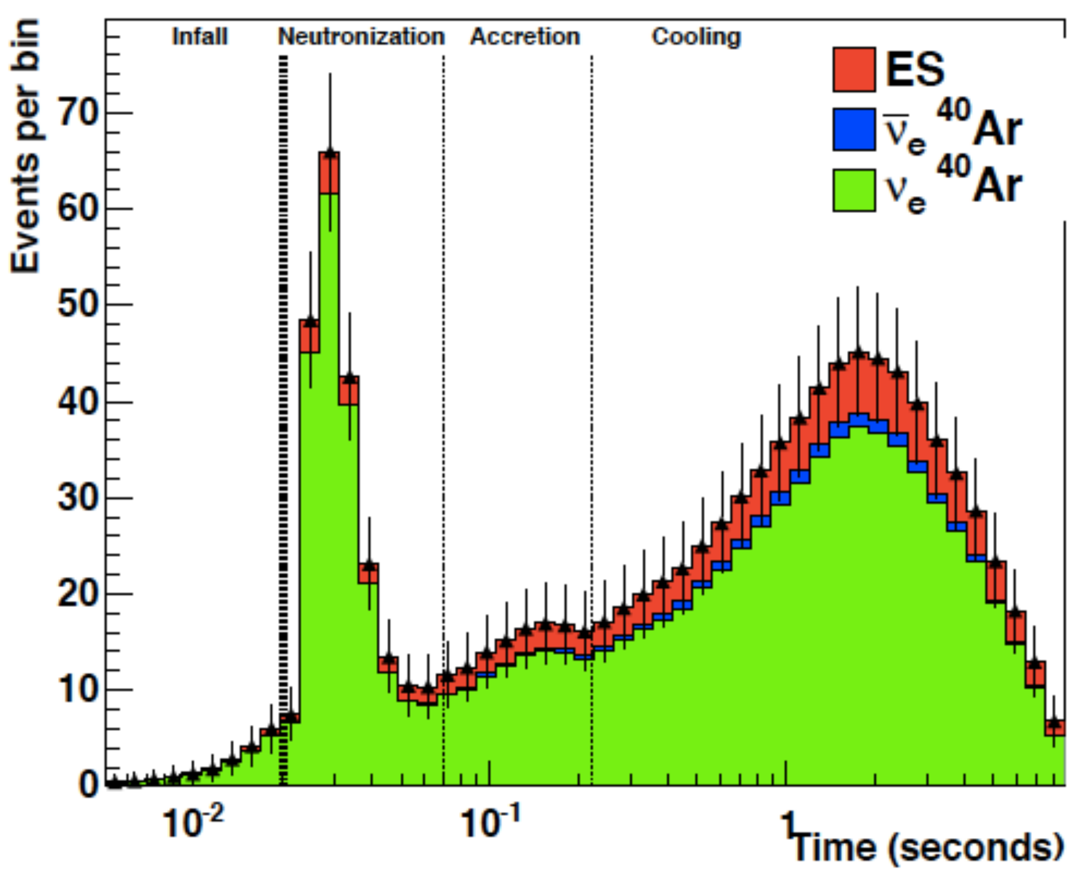


Evolution of the explosion is reflected in neutrinos (illustration from Messer)

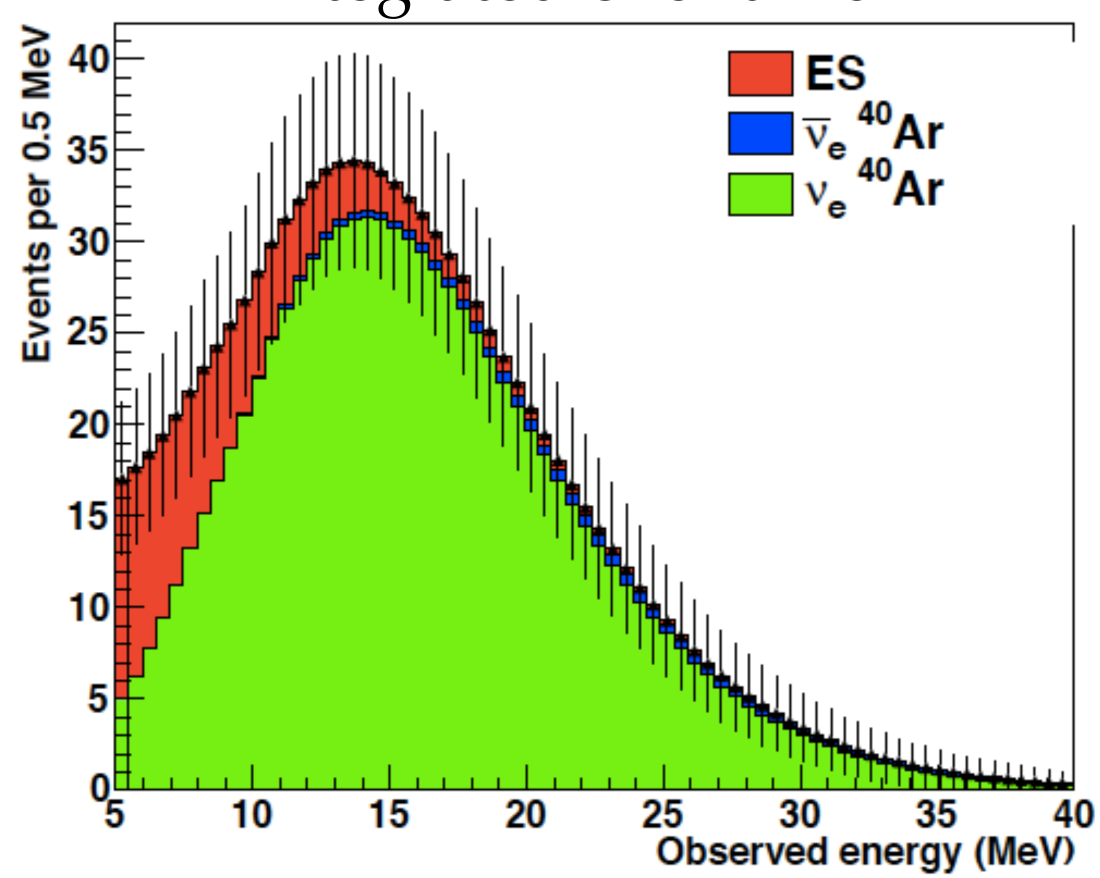
All stages can in principle be seen in neutrinos

DUNE: 40 kton LAr (SN @10 kpc)

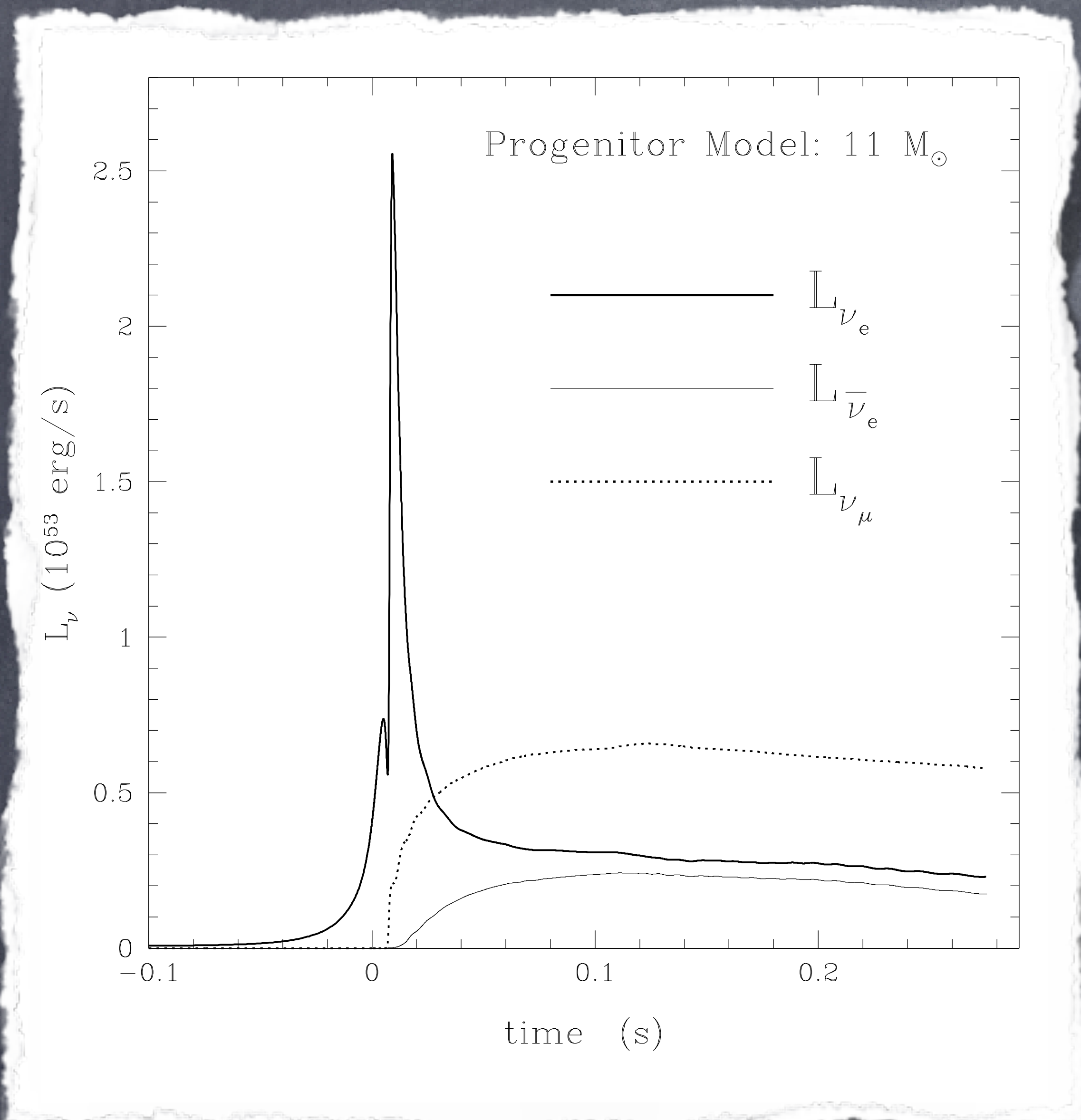
Time-dependent signal

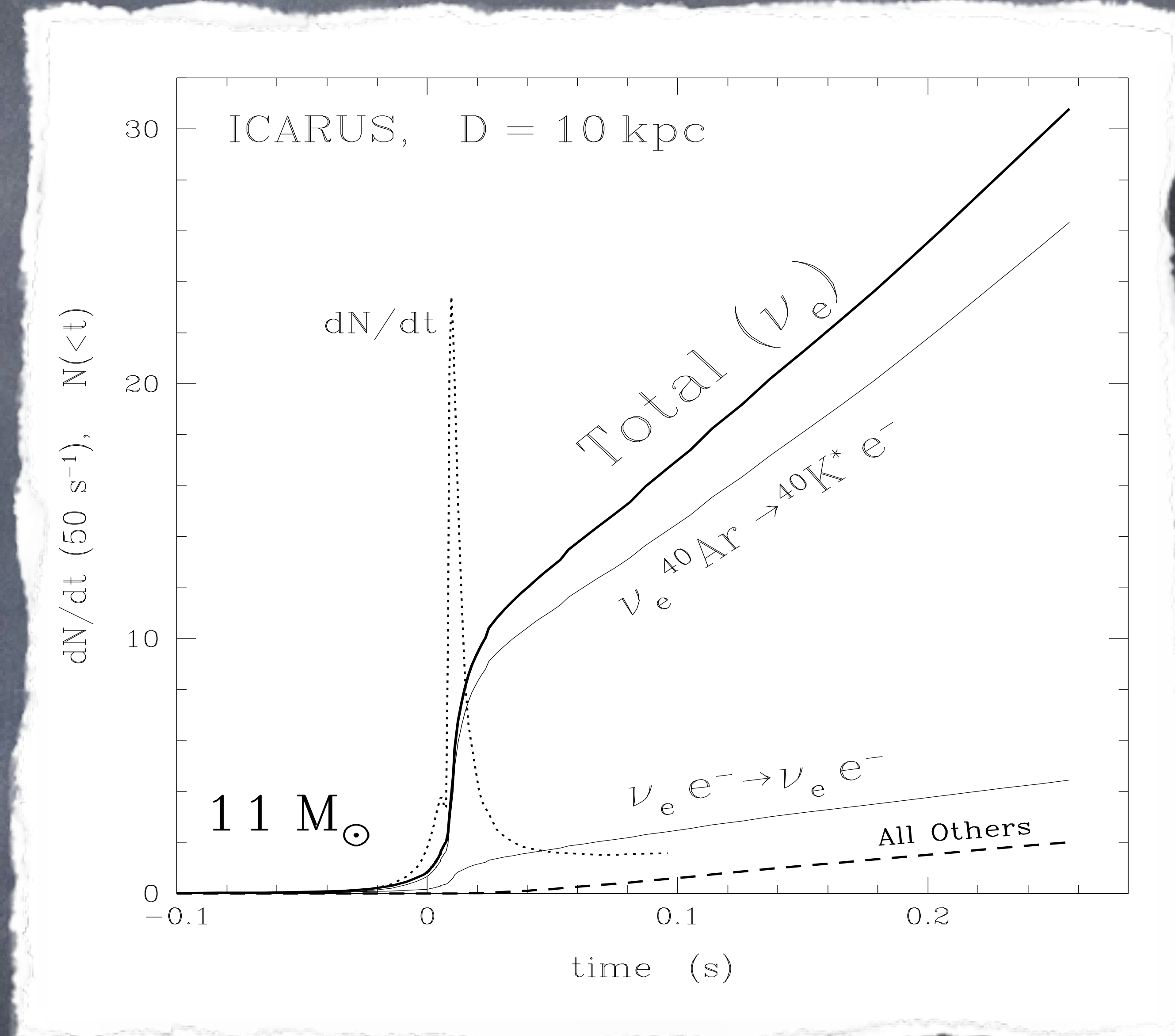


Expected event spectrum integrated over time



Neutronization burst



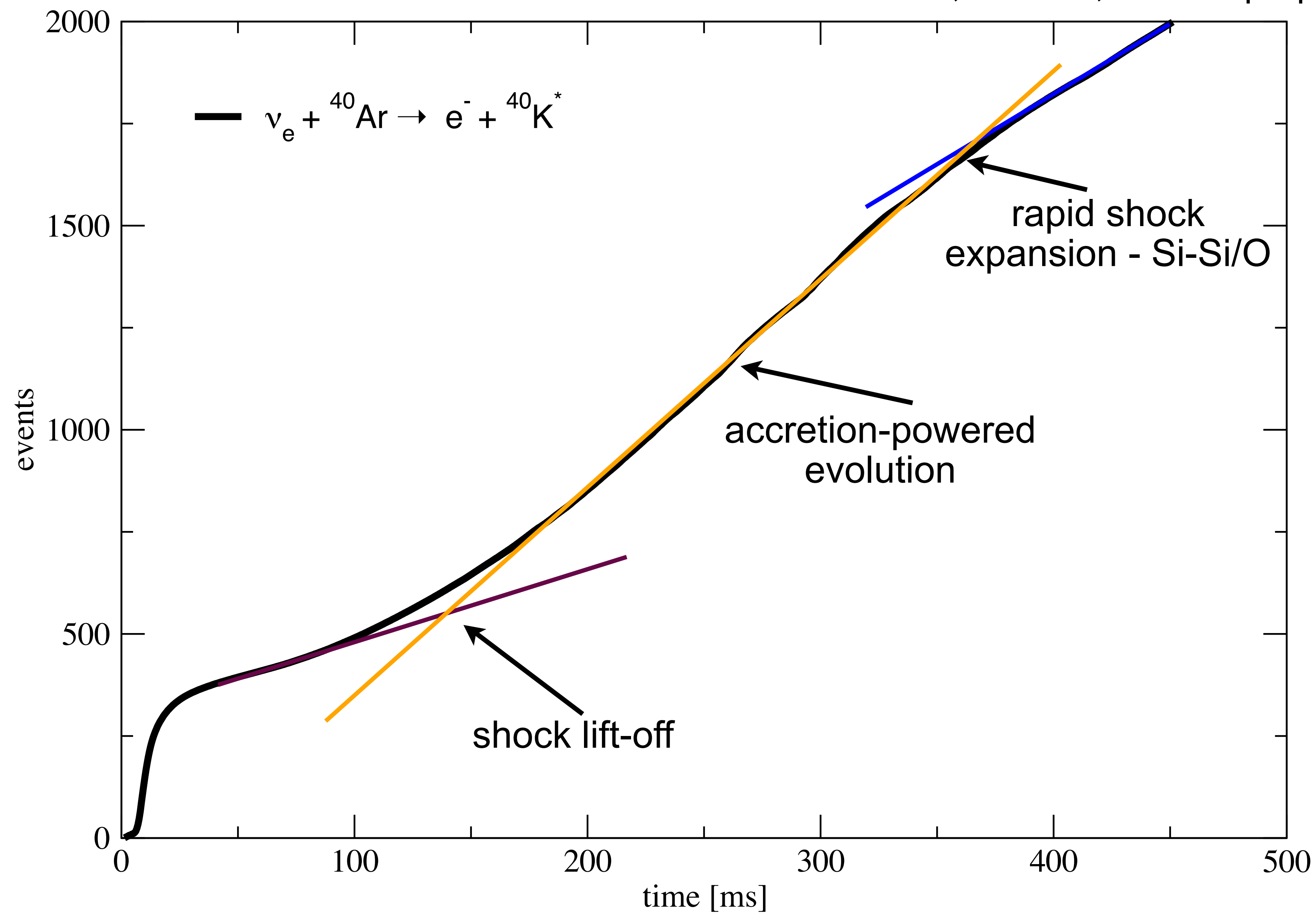


Thompson, Burrows, Pinto, astro-ph/0211194

Update from Oak Ridge

2D - ν_e total counts vs. time

Messer, Devotie, et al. In prep.



C15-2D, angle-averaged, SNOwGLoBES Ar17kt, 10 kpc

OAK RIDGE National Laboratory

Internal evolution

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

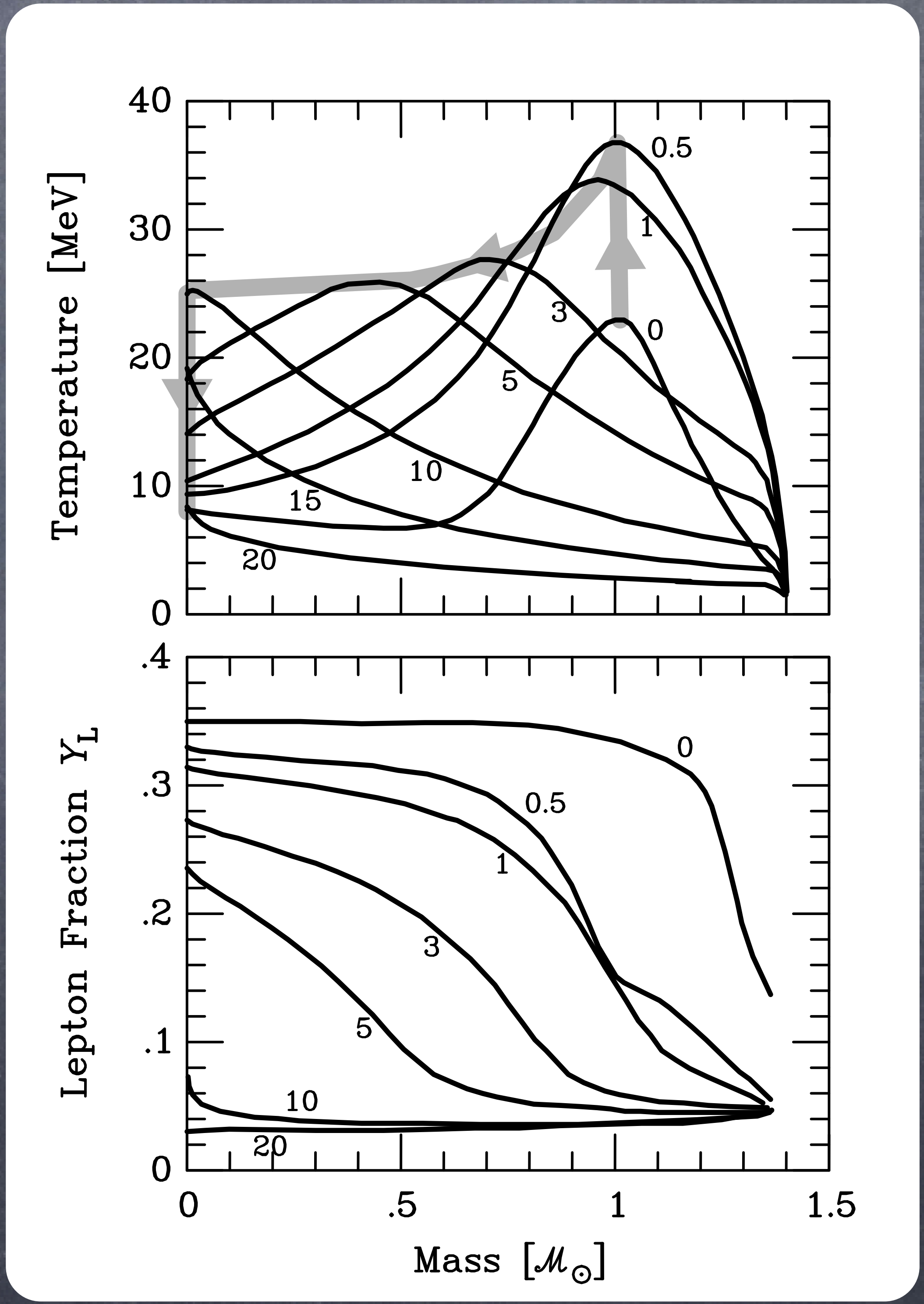
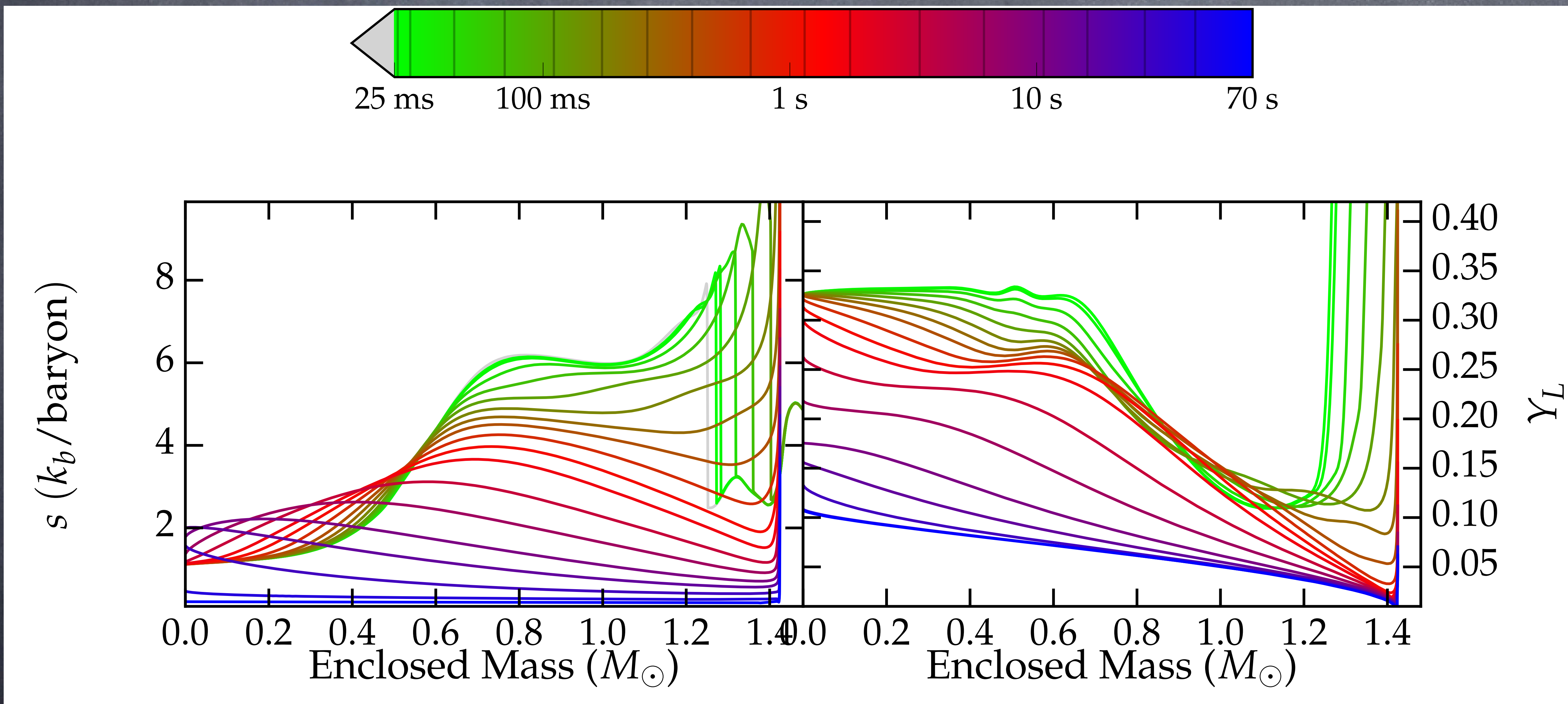
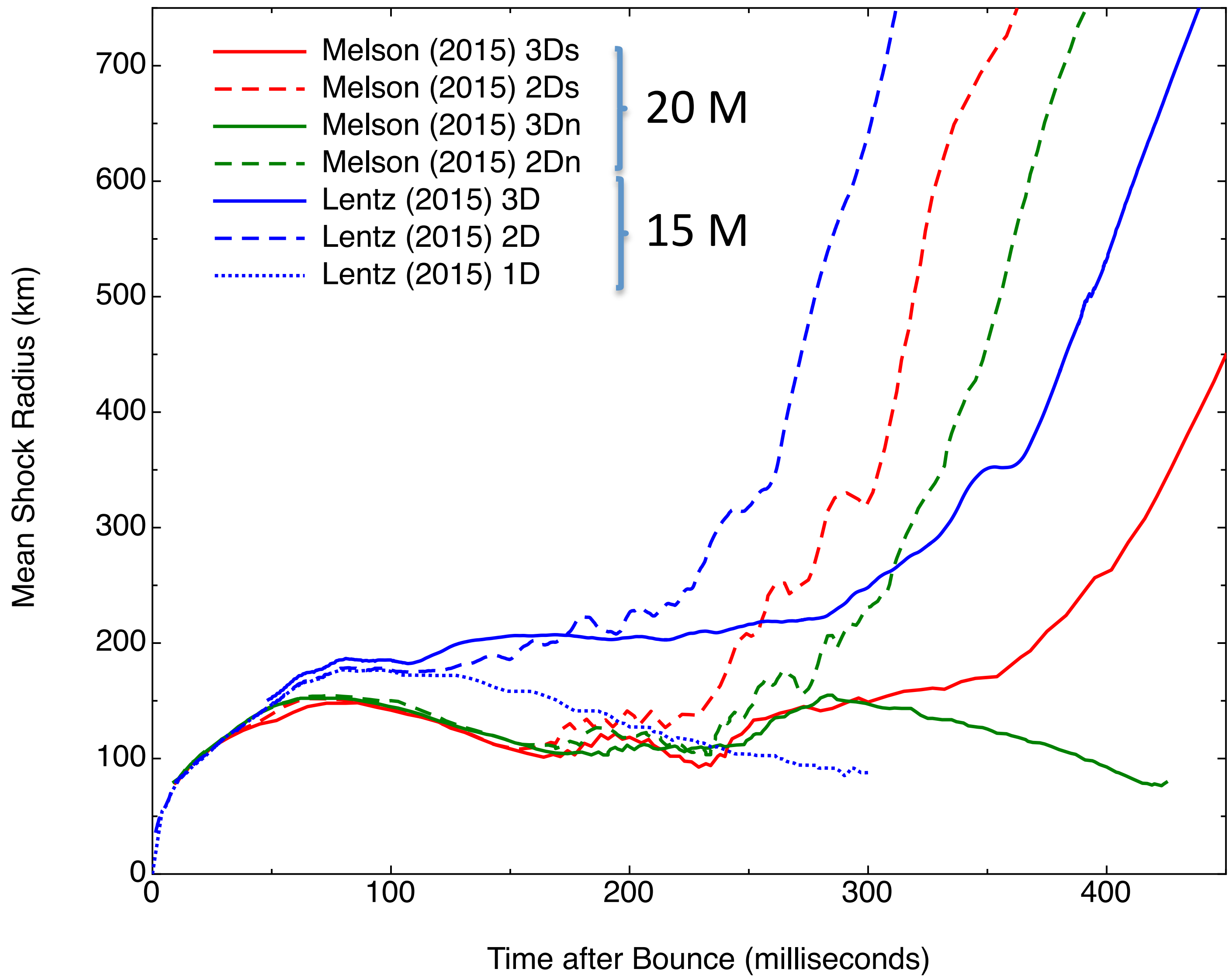


Fig by G. Raffelt based on Borrows & Lattimer (1986)

Update (from Luke Roberts)



Comparing Qualitative Behavior

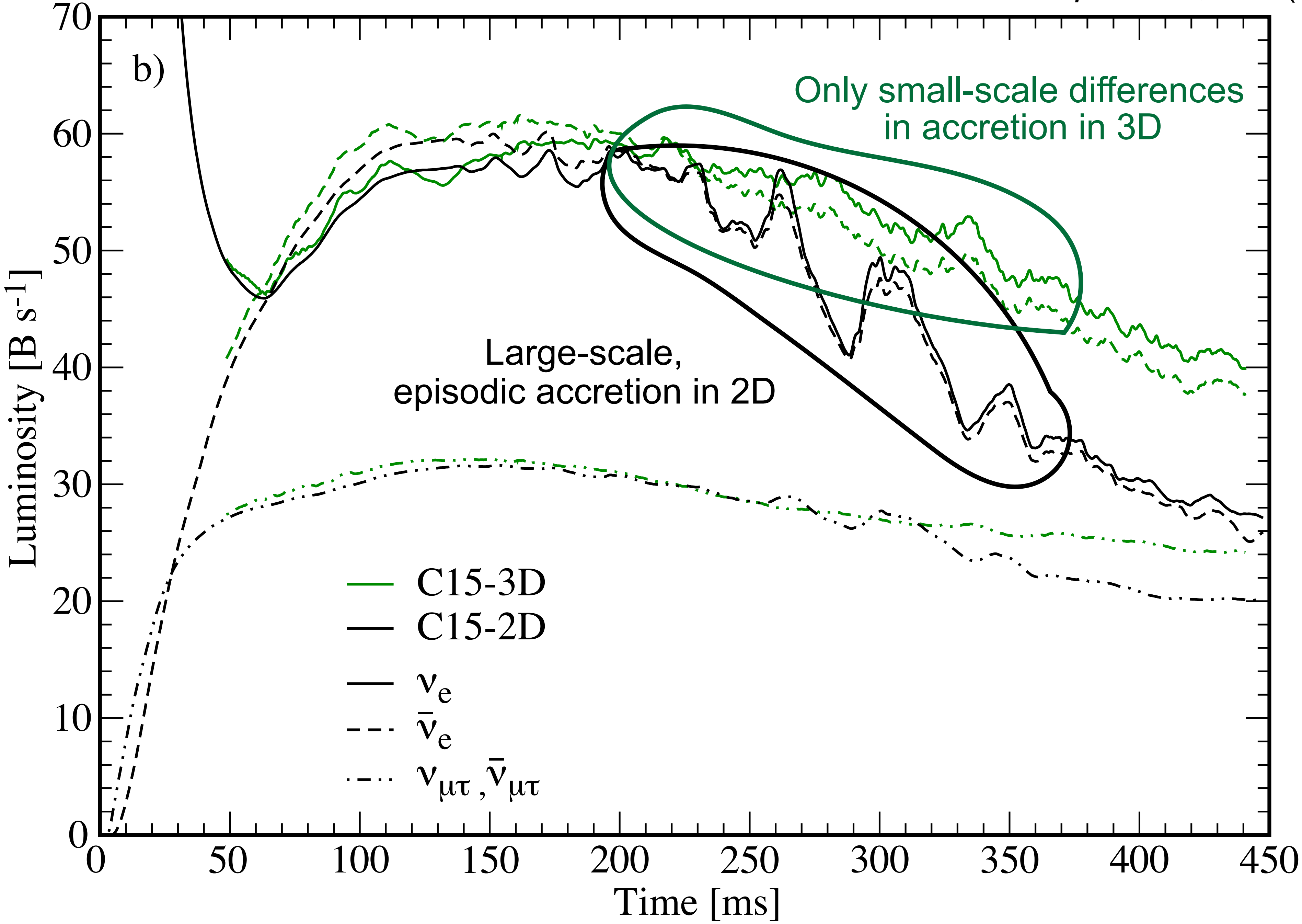


Similarities in the qualitative behavior of 2D models, and 3D models, obtained by the MPA and Oak Ridge groups is evident in the above graph.

3D is harder to explode that 2D (Mezzacappa)

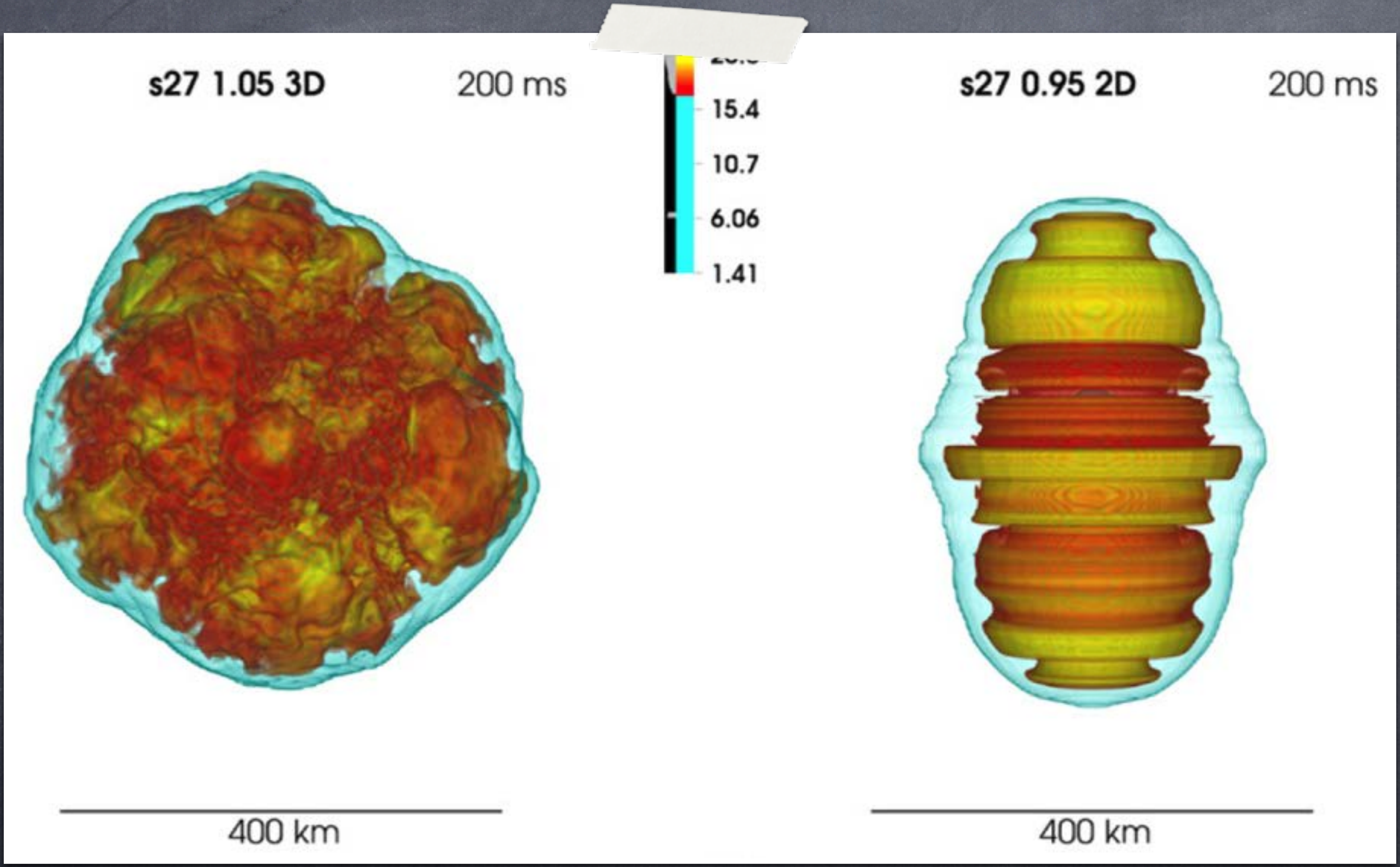
3D vs 2D luminosities

Lentz et al. *ApJL* **807**, L31 (2015)

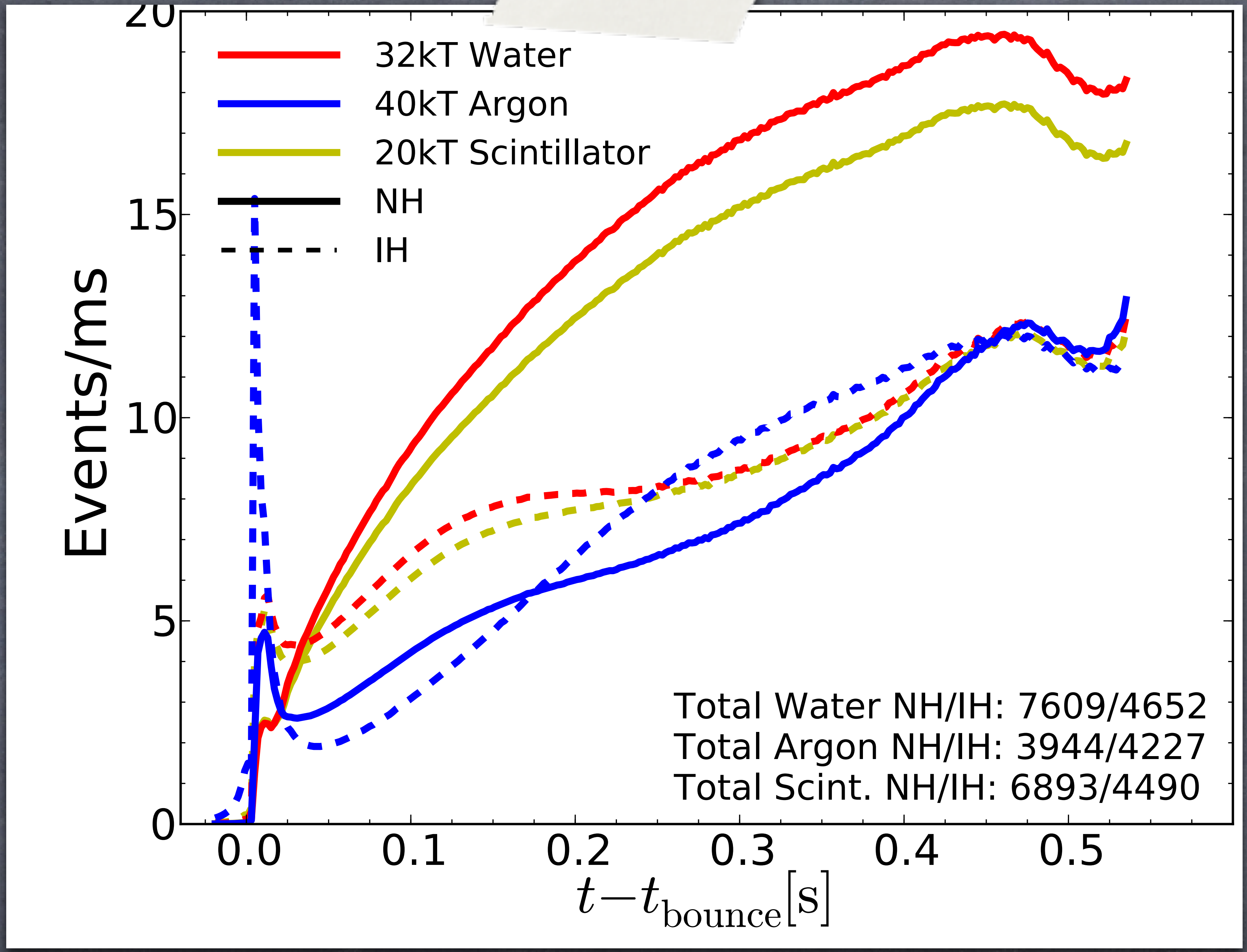


OAK RIDGE National Laboratory | OAK RIDGE LEADERSHIP COMPUTING FACILITY

different time variations in 2D vs 3D (Messer)



2D turbulence is artificial (illustration from Ott)



Or maybe the signal suddenly stops, a black hole forms (O'Connor)

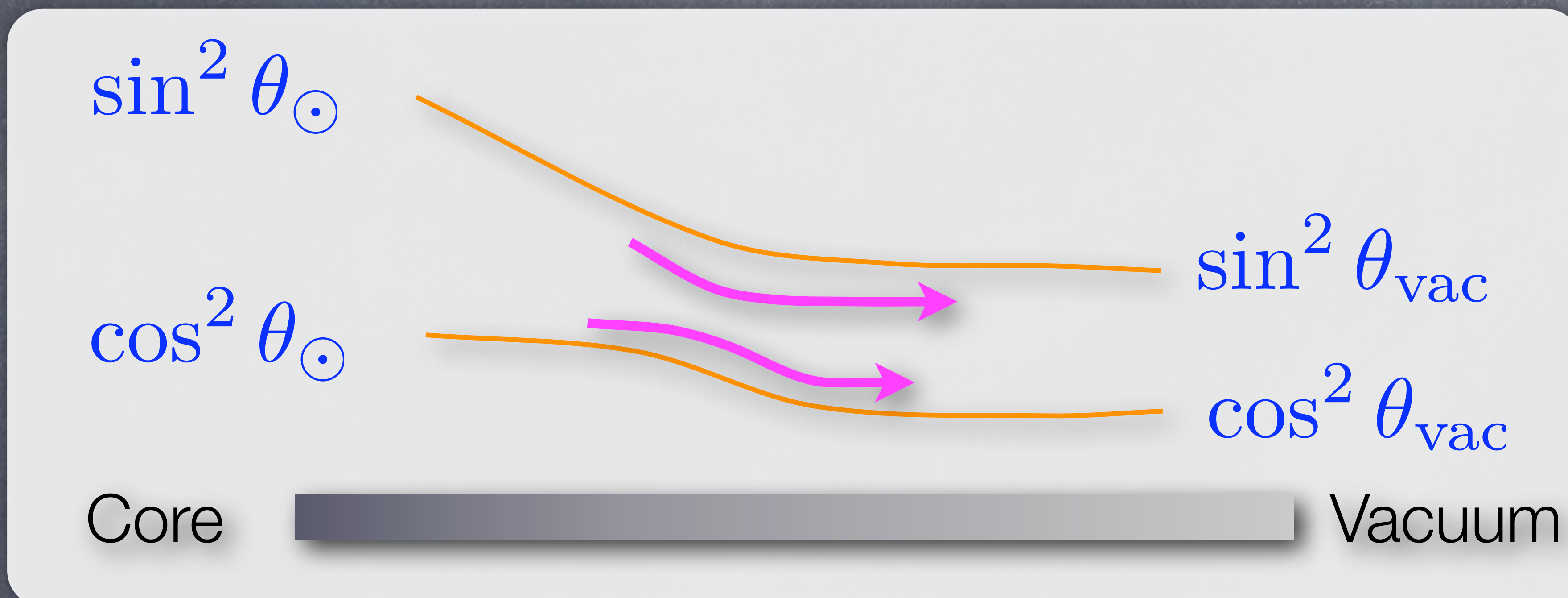
- It is already clear that one needs DAQ with a big enough buffer to store all the events, for at least 20-30 seconds
- Good timing resolution, ~ 1 ms, to study time features (neutronization burst, SASI modulations, etc)
- Next, good energy resolution
    - Good photodetection system
    - Long charge lifetime (Argon purity)

Oscillations

- In the normal hierarchy, almost the entire neutronization burst would oscillate away!
- Why?

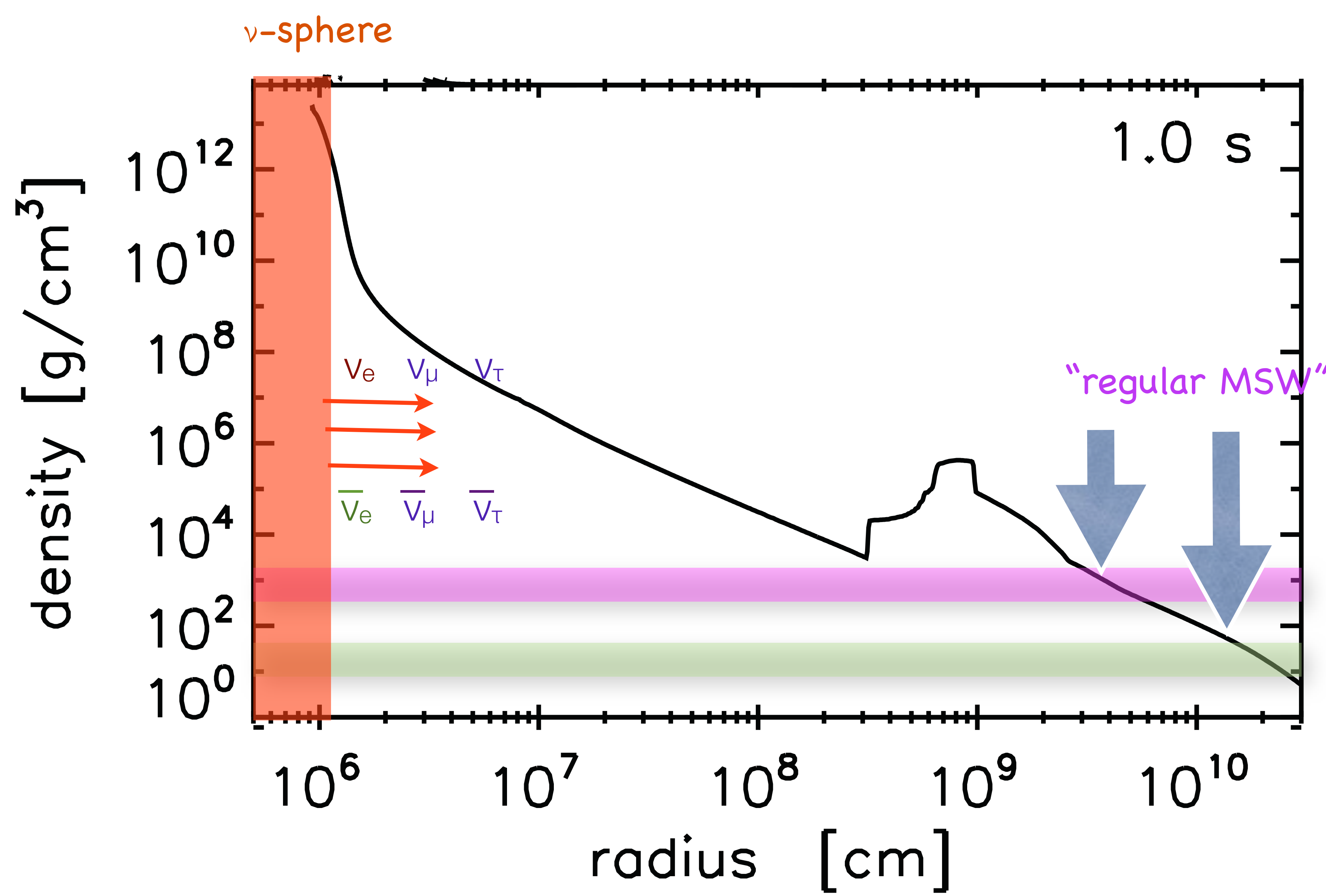
Sun: 2-state oscillations

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



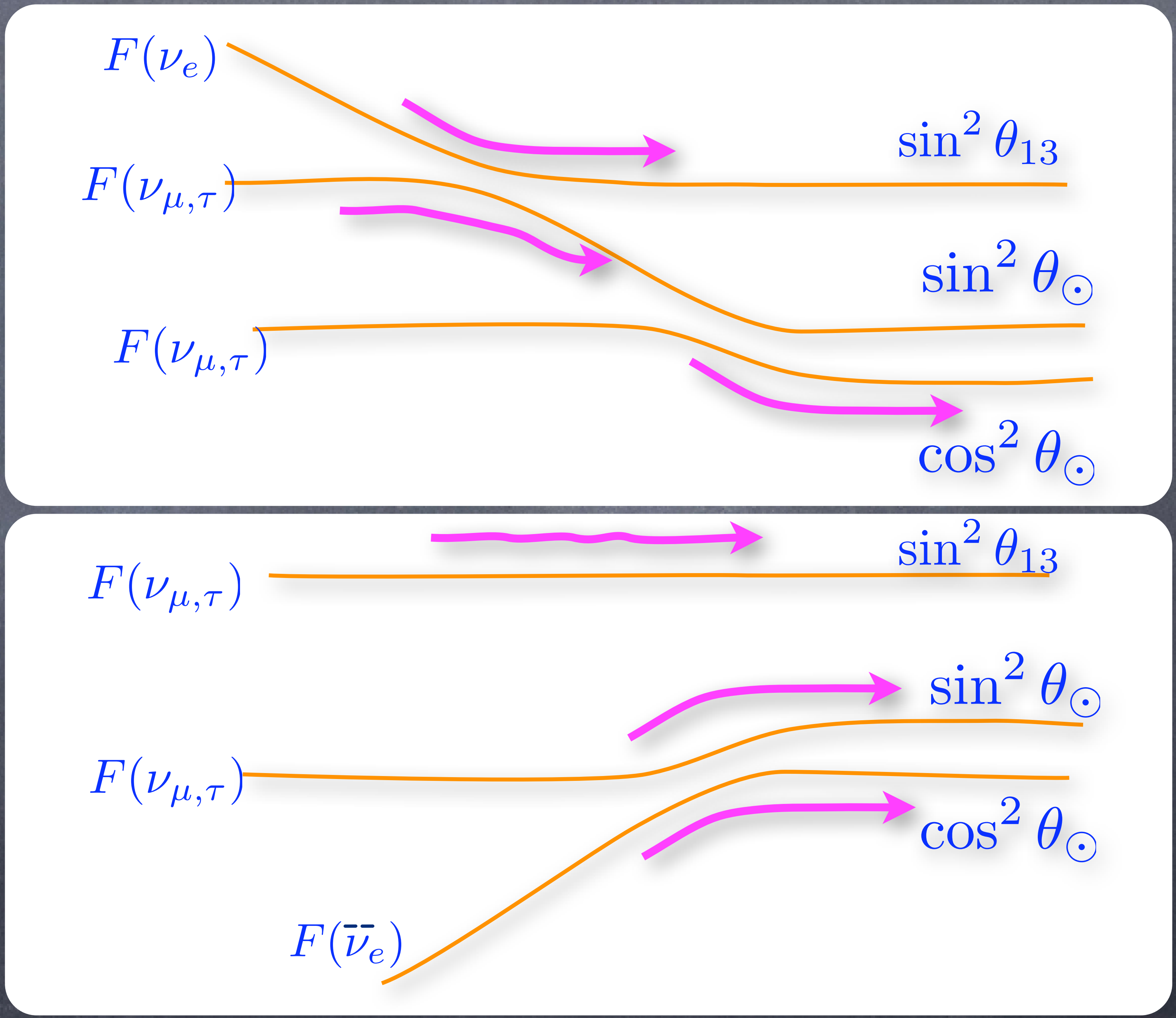
- The evolution is adiabatic (no level jumping), since l_{osc} << density scale height ($|d \ln\rho/dr|^{-1}$)
  - Hint: for most of the Sun, the density scale height is $R_{sun}/10$, while l_{osc} is comparable to the width of Japan (KamLAND)

SN ν oscillations: 2 MSW densities



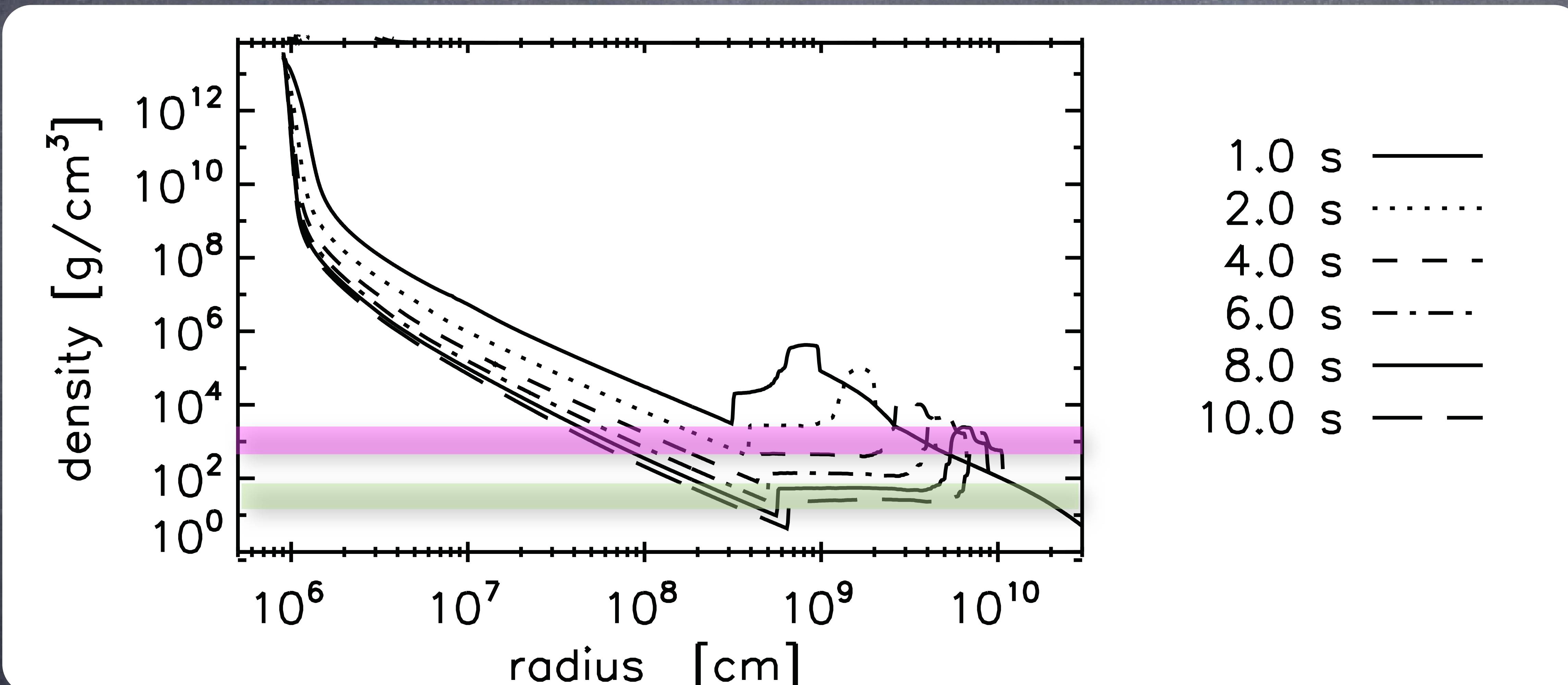
SN MSW transformations, schematics

- Given the scale height in the progenitor, the evolution is very adiabatic
  - the adiabaticity of the atmospheric resonance is controlled by theta13
- Prediction for the nue signal during the **neutronization burst** is critically dependent on the sign of MH



For inverted hierarchy, the same happens in antineutrinos.

Dynamical density profile

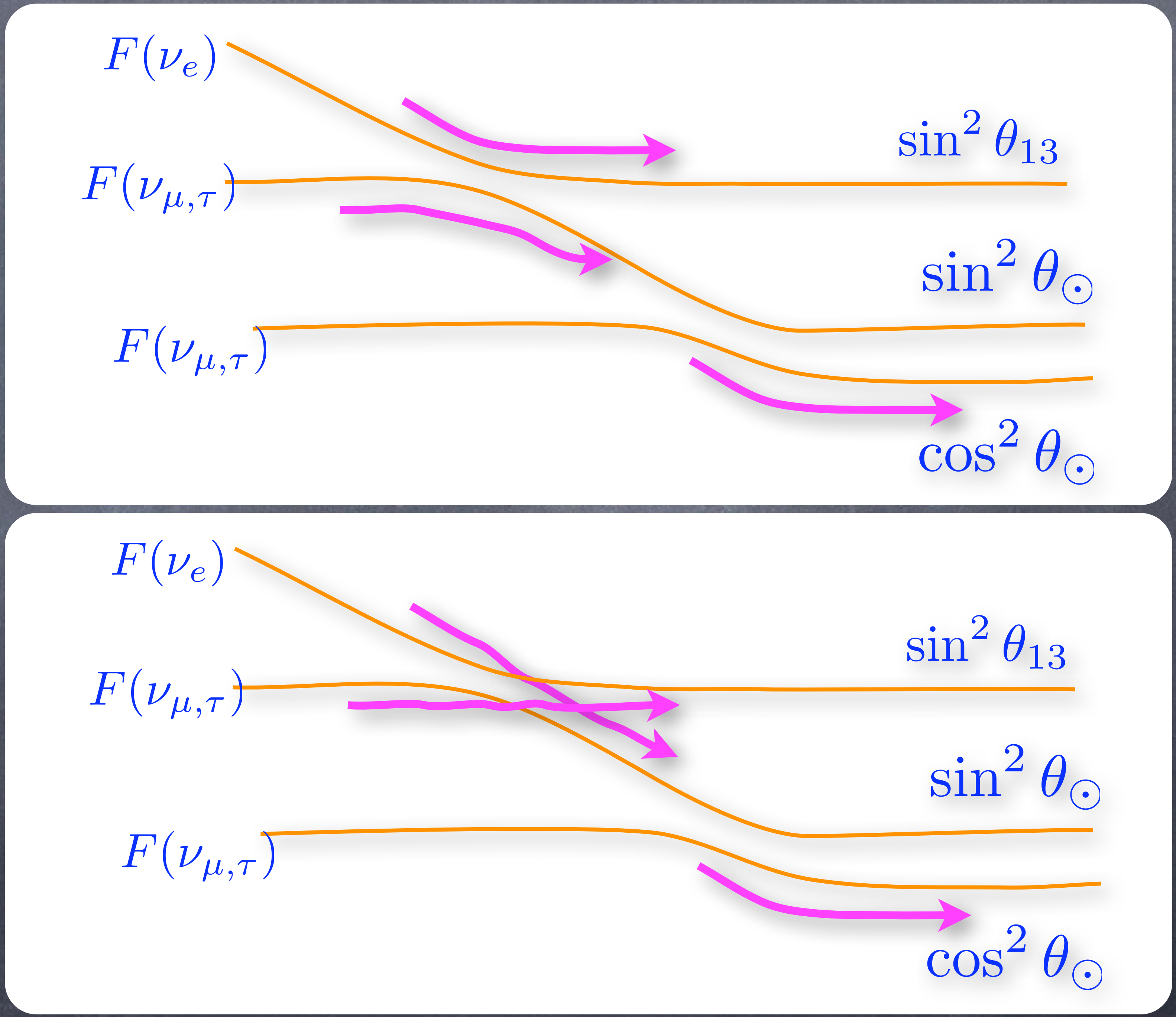


- Front shock reaches the regions where “atmospheric” and “solar” transformations happen, while neutrinos are being emitted

  - 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.



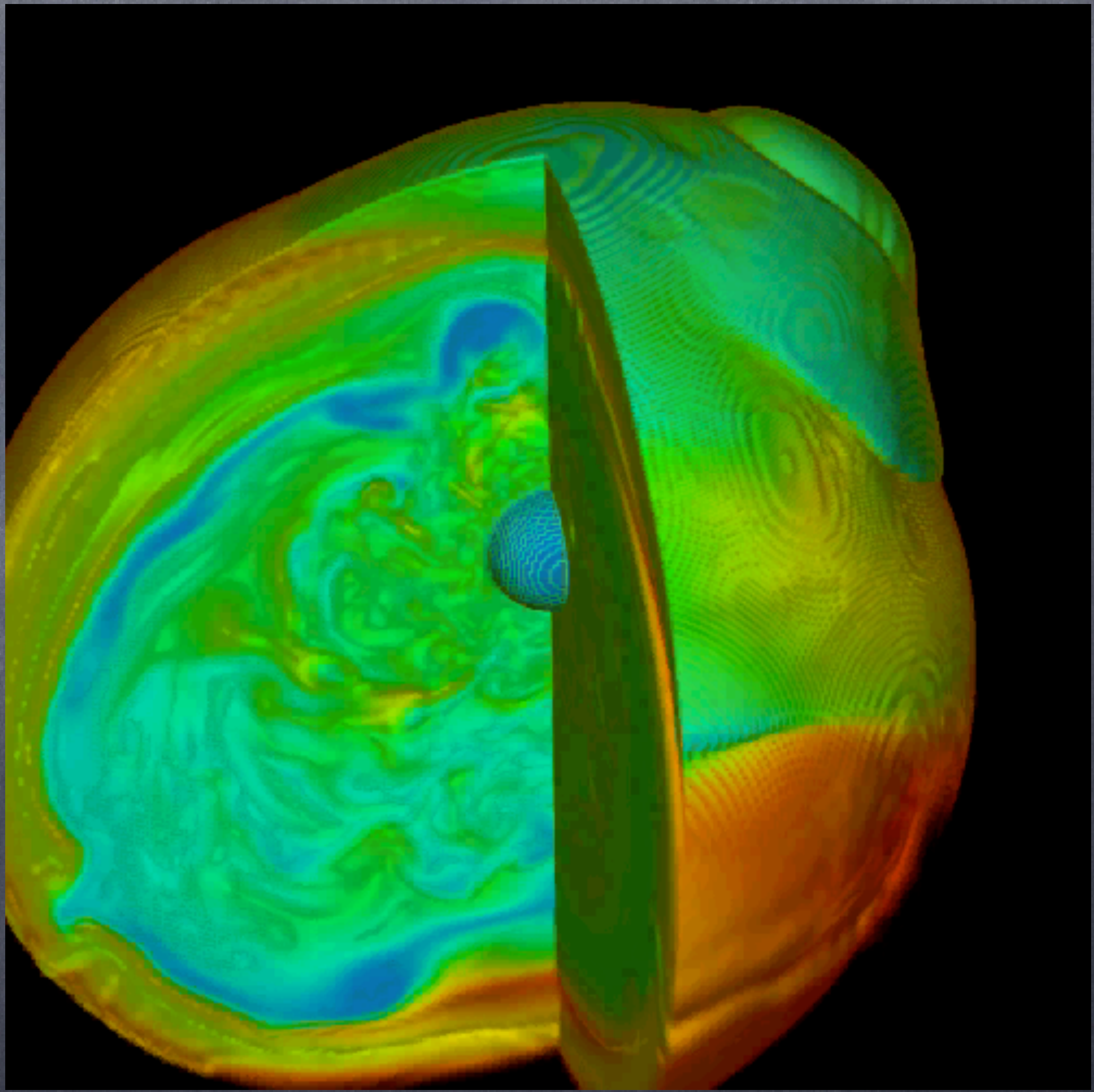
For inverted hierarchy, the same happens in antineutrinos.

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
- extensive, well-developed turbulence behind the shock

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
- 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

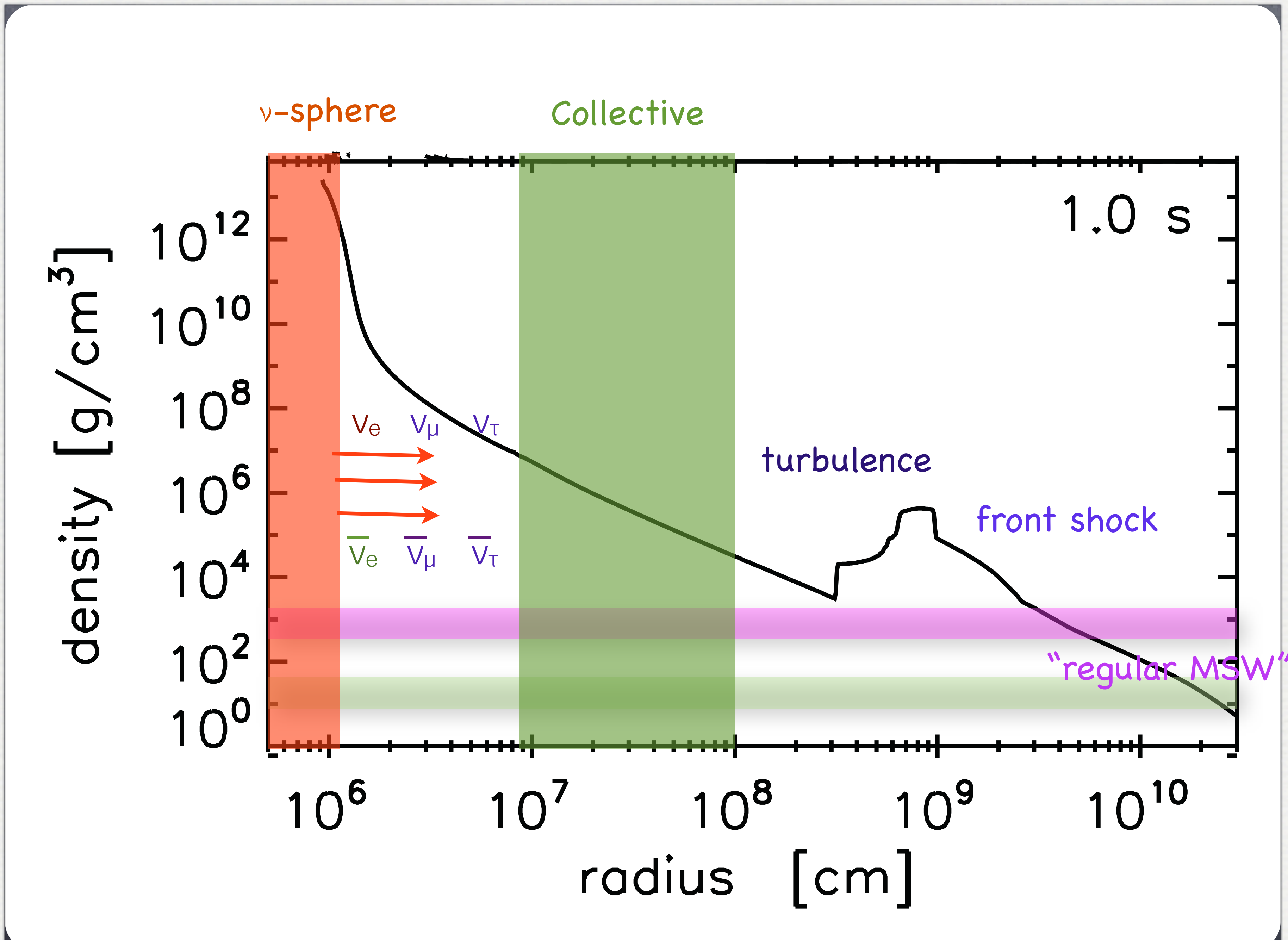
Turbulence in realistic simulations

- 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
  - turbulence should cause observable flavor depolarization, when large-scale fluctuations are

$$\delta n_L/n_L \gtrsim 0.07\theta_{13}^{1/3} \sim 4\%$$

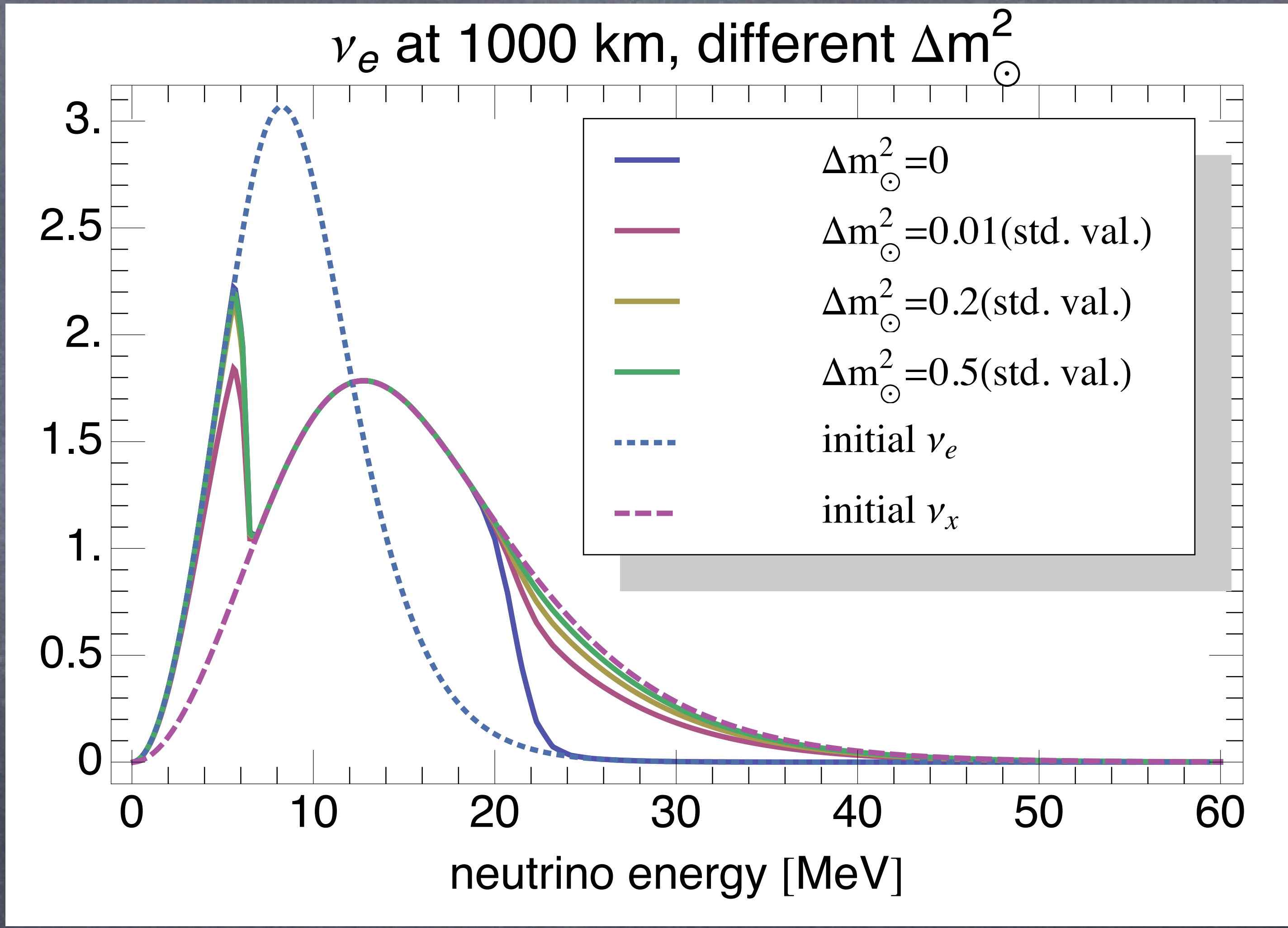
for details, see Friedland & Gruzinov, astro-ph/0607244;
http://public.lanl.gov/friedland/info07/INFO07talks/FriedlandINFO07.pdf

SN ν: summary physics cartoon

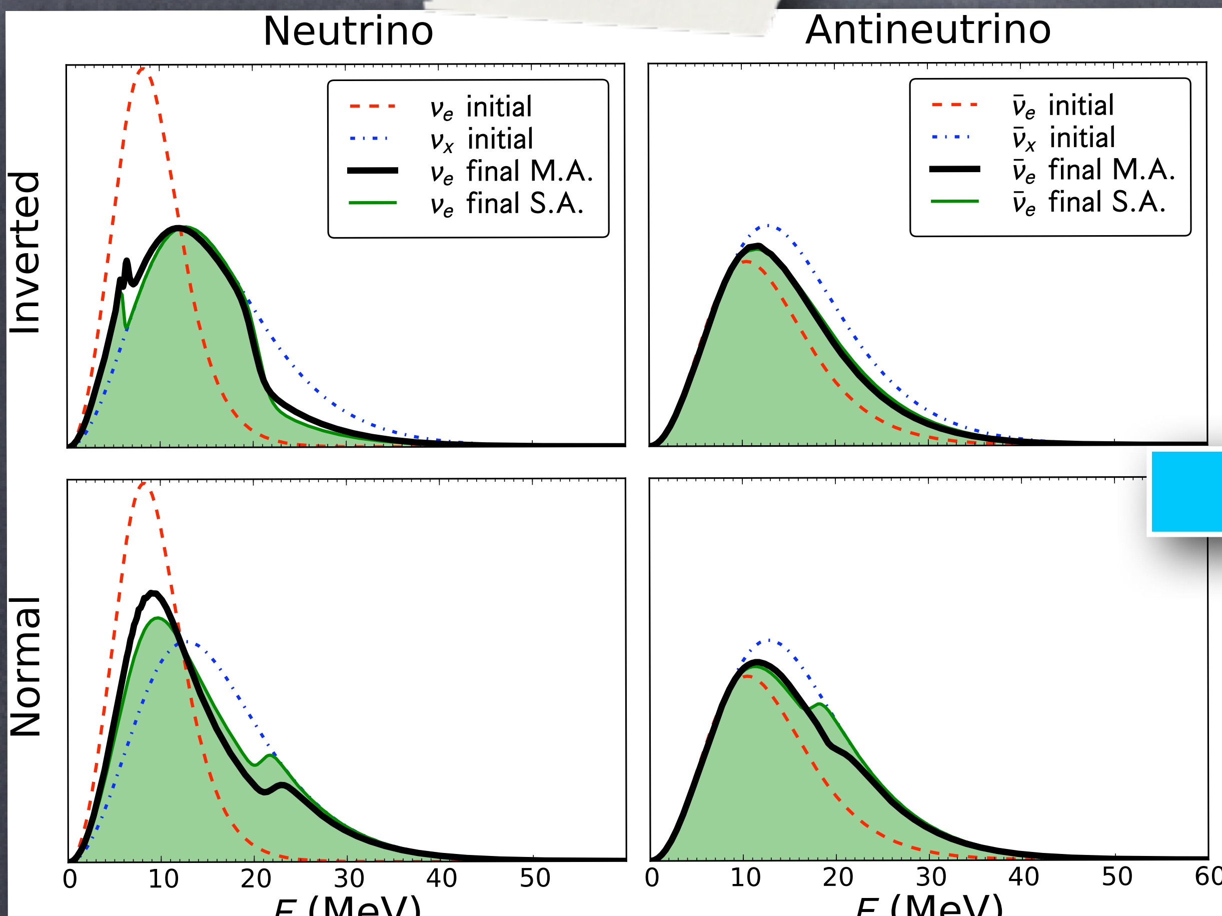


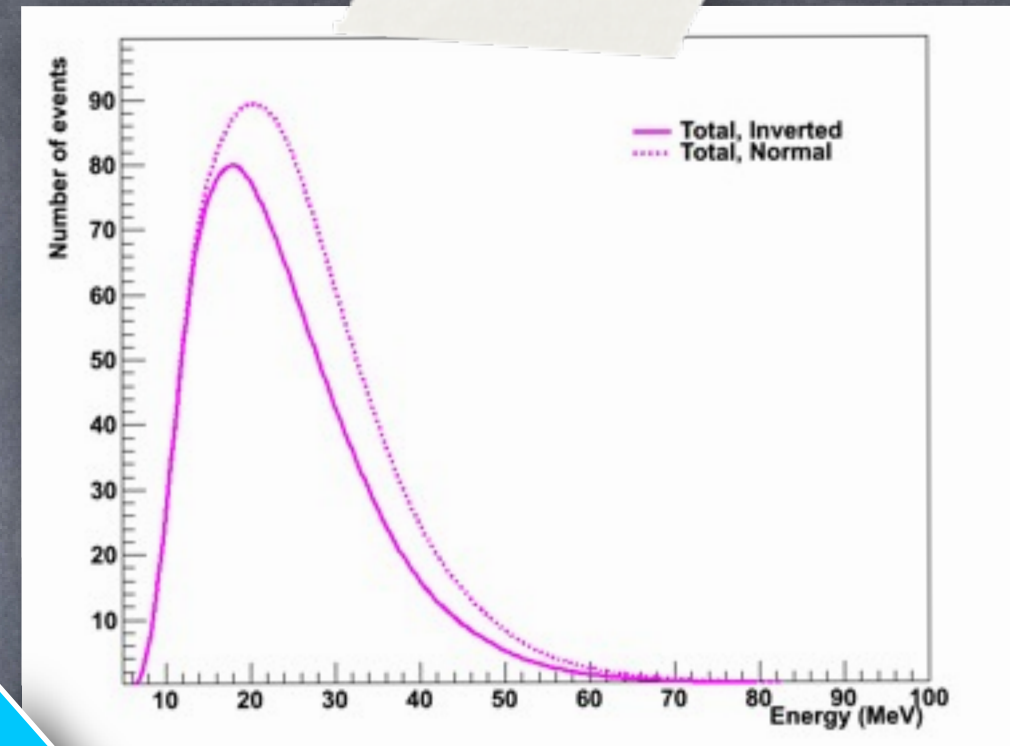
Collective oscillations: new D.O.F.s can lead to new instabilities

- 2-flavor trajectory can be unstable in the 3-flavor space
    - At $\Delta m_\odot^2=0$, 2-flavor result is reproduced
    - As soon as $\Delta m_\odot^2 \neq 0$, the answer jumps
- adding new d.o.f. can lead to new instabilities and very different answers

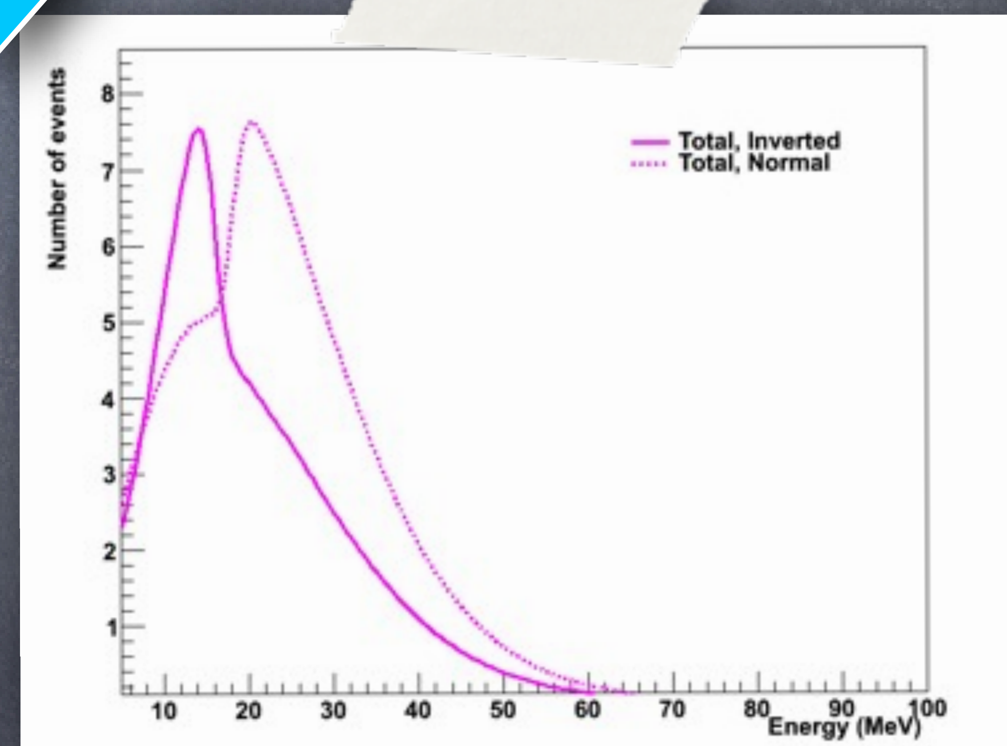


For details, see A.F., PRL (2010);
2-flavor Dasgupta, Dighe, Raffelt, Smirnov, PRL (2009)





WC



LAr

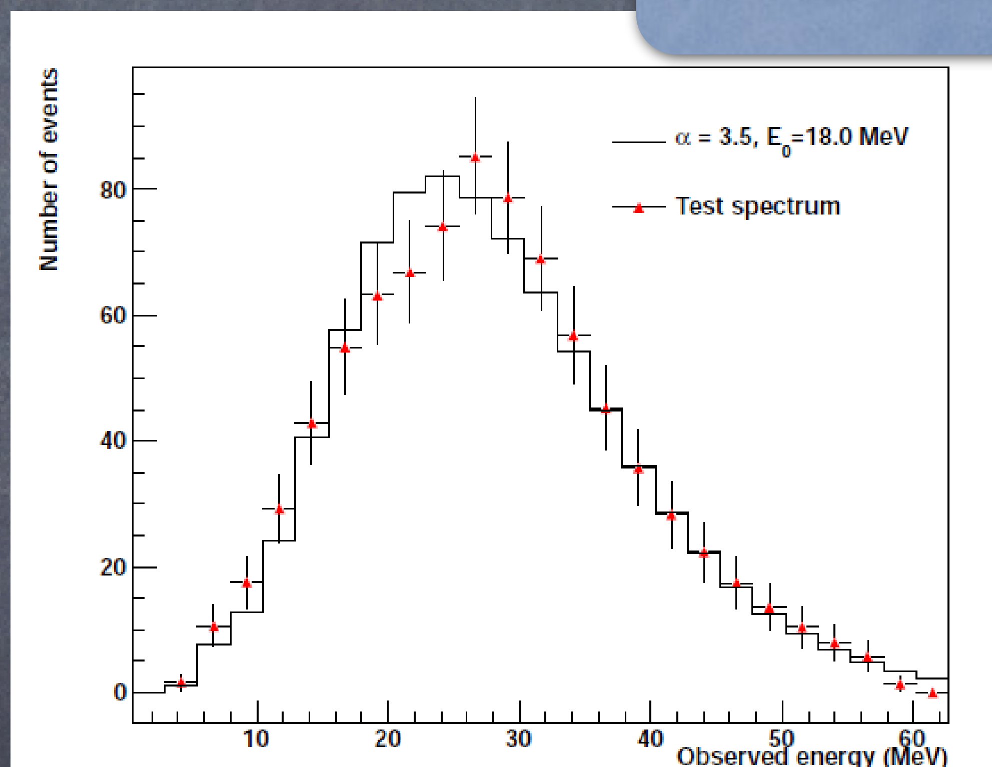
* oscillations by Duan & Friedland, PRL 2011
* detector modeling by Kate Scholberg & team
* See LBNE science document

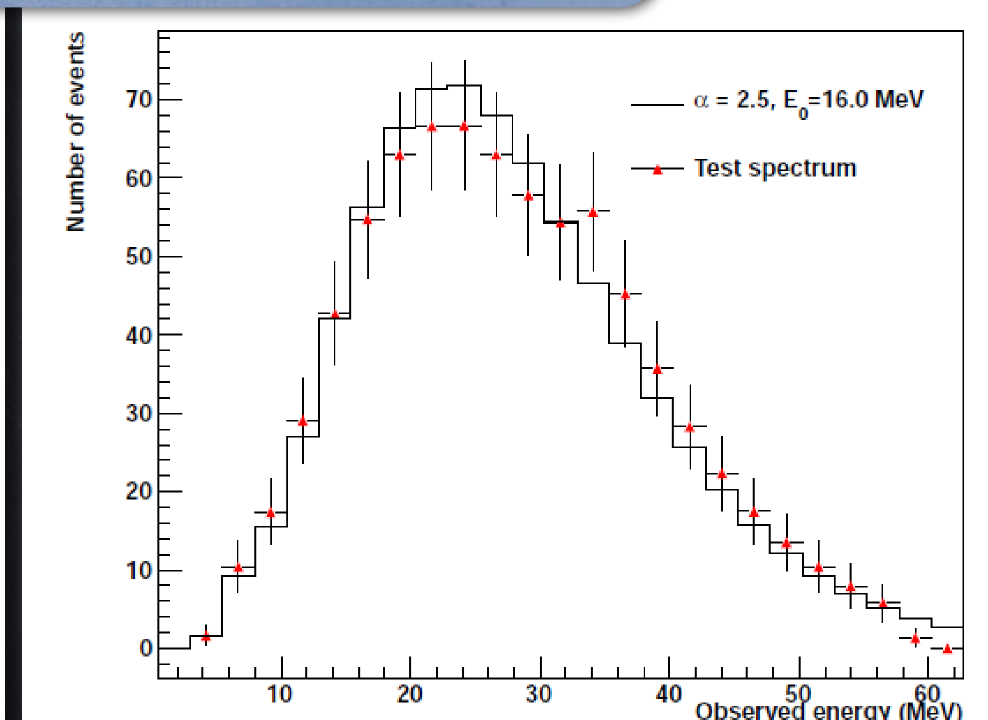
Another smoking-gun feature. Tracking the shock in real time

multiangle collective oscillations + moving shock by A. F.

Detector model by K. Scholberg

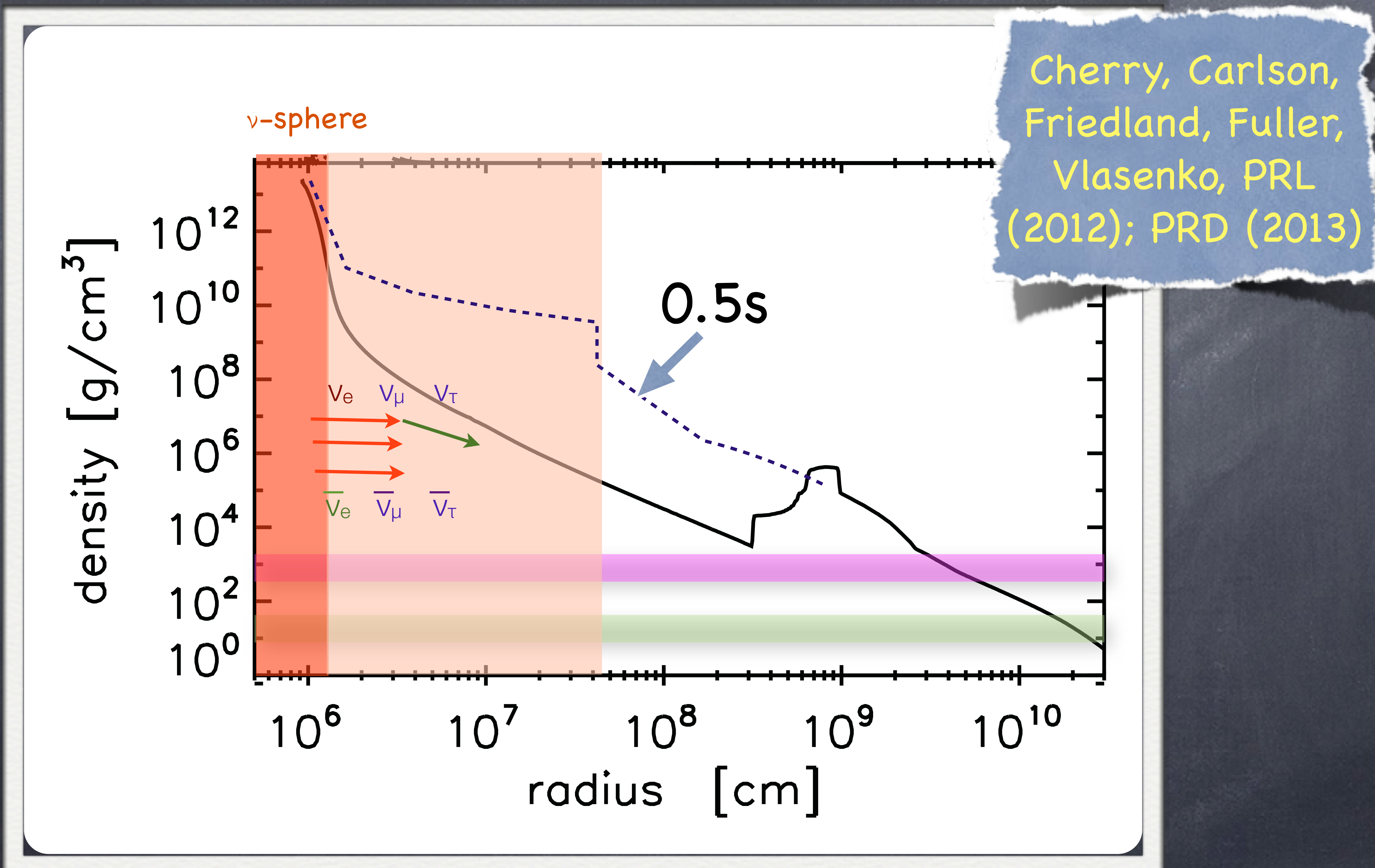
LBNE science document
arXiv:1307.7335v3





- The neutrino spectrum is modulated, but not antineutrinos (simultaneously observed by SK/HK)

Accretion phase: neutrinos scattering above ν-sphere?



More on detection

See talk by Ines Botella at VTech for more

Low-energy neutrino signal in LAr

- Elastic scattering (ES) on electrons

$\nu + e^- \rightarrow \nu + e^-$

- Charged-current (CC) interactions on Ar

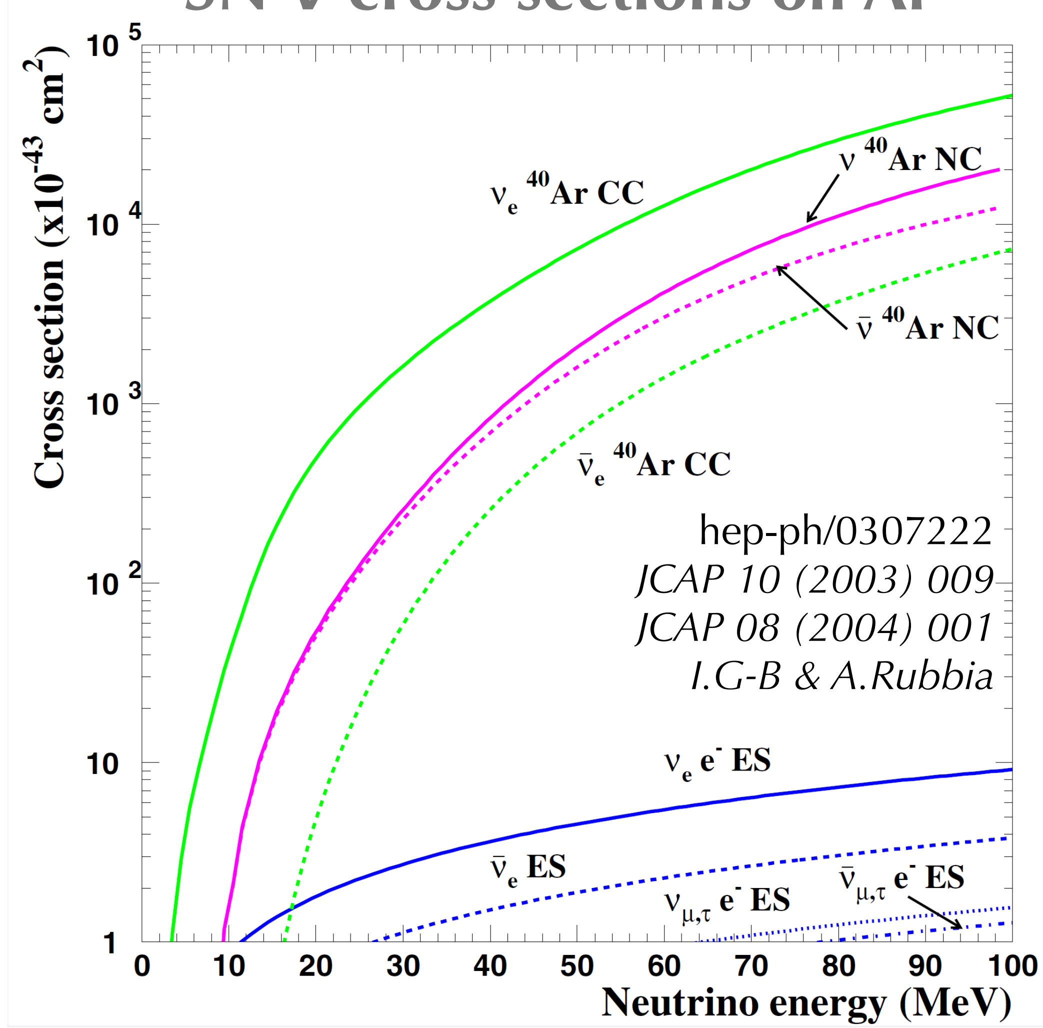
$\nu_e + {}^{40}Ar \rightarrow {}^{40}K^* + e^-$ $\quad E\nu_e > 1.5$ MeV

$\bar{\nu}_e + {}^{40}Ar \rightarrow {}^{40}Cl^* + e^+$ $\quad E\bar{\nu}_e > 7.48$ MeV

- Neutral current (NC) interactions on Ar

$\nu + {}^{40}Ar \rightarrow \nu + {}^{40}Ar^*$ $\quad E\nu > 1.46$ MeV

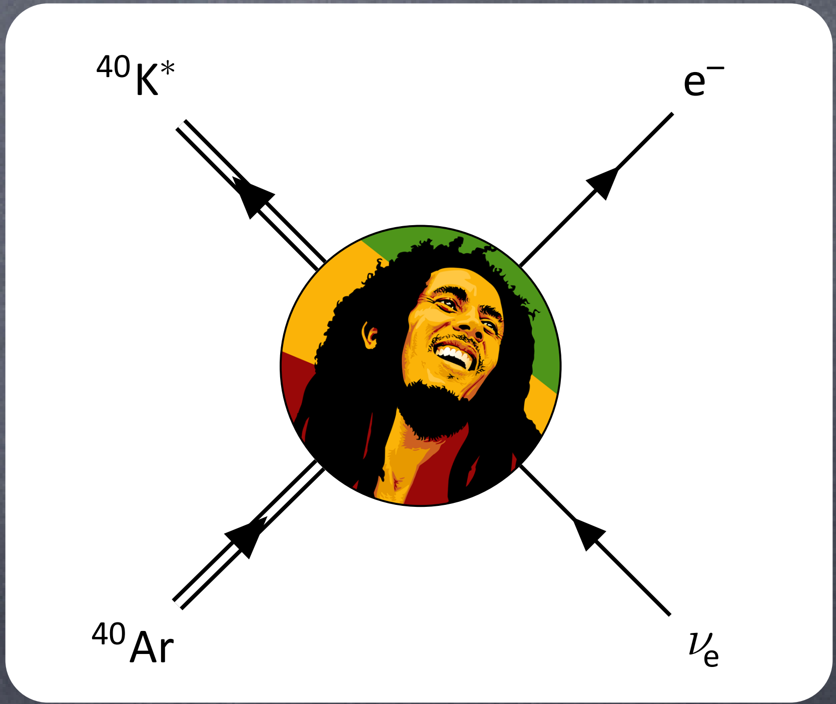
SN ν cross sections on Ar



MARLEY: Model of Argon Reaction Low-Energy Yields

Steven Gardiner
Christopher Grant
Emilija Pantic
Robert Svoboda

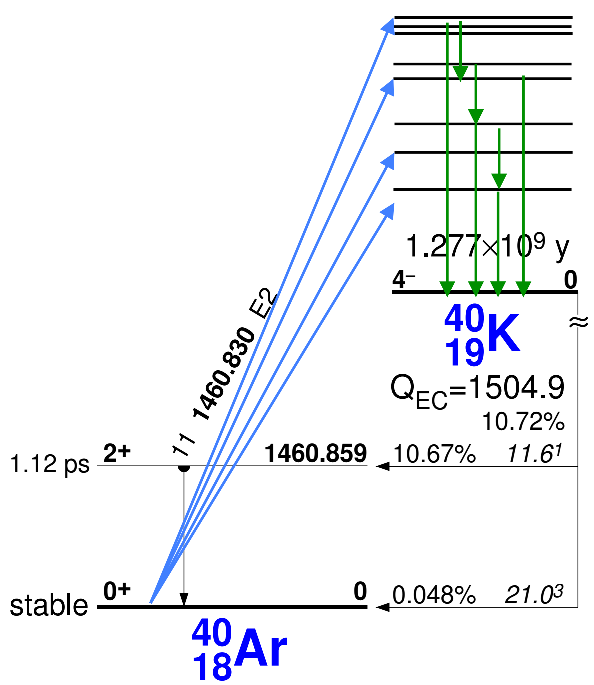
- Talk at the SLAC meeting by Bob Svoboda (+ hours of discussion)
- Talk in Rapid City by Christopher Grant for recent results



Goal: determine whether "every 40K* e- little thing gonna be all right" for SN neutrino physics in LArTPCs

Gammas, neutrons, protons at high E_ν

Creating an accurate model for ν_eArCC events requires confronting several challenges

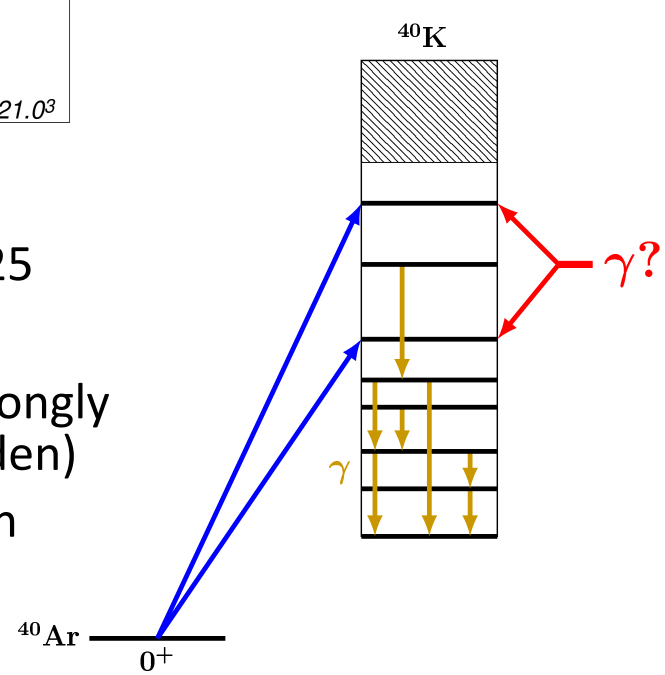


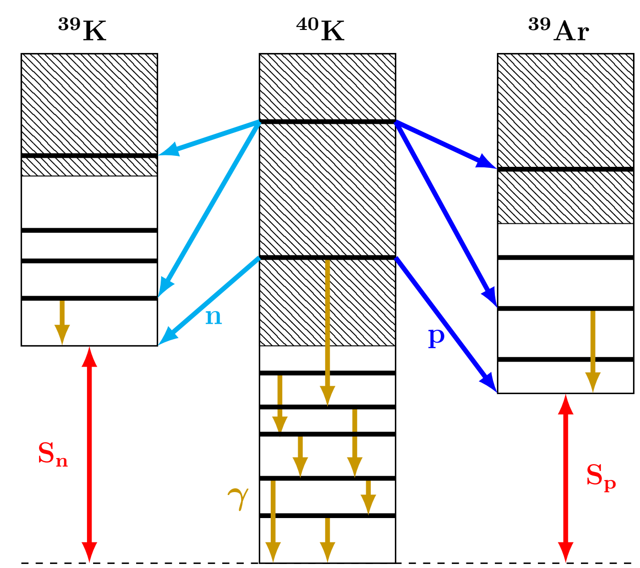
ν_eArCC events access ~25 excited levels in ^{40}K*

Transition to ^{40}K g.s. strongly suppressed (3rd-forbidden)

ν_e energy reconstruction relies on determining accessed level

J^π values and γ-decay data are missing for many relevant ^{40}K* levels





Significant loading of unbound nuclear levels occurs

Large number of de-excitation channels complicates energy reconstruction

4

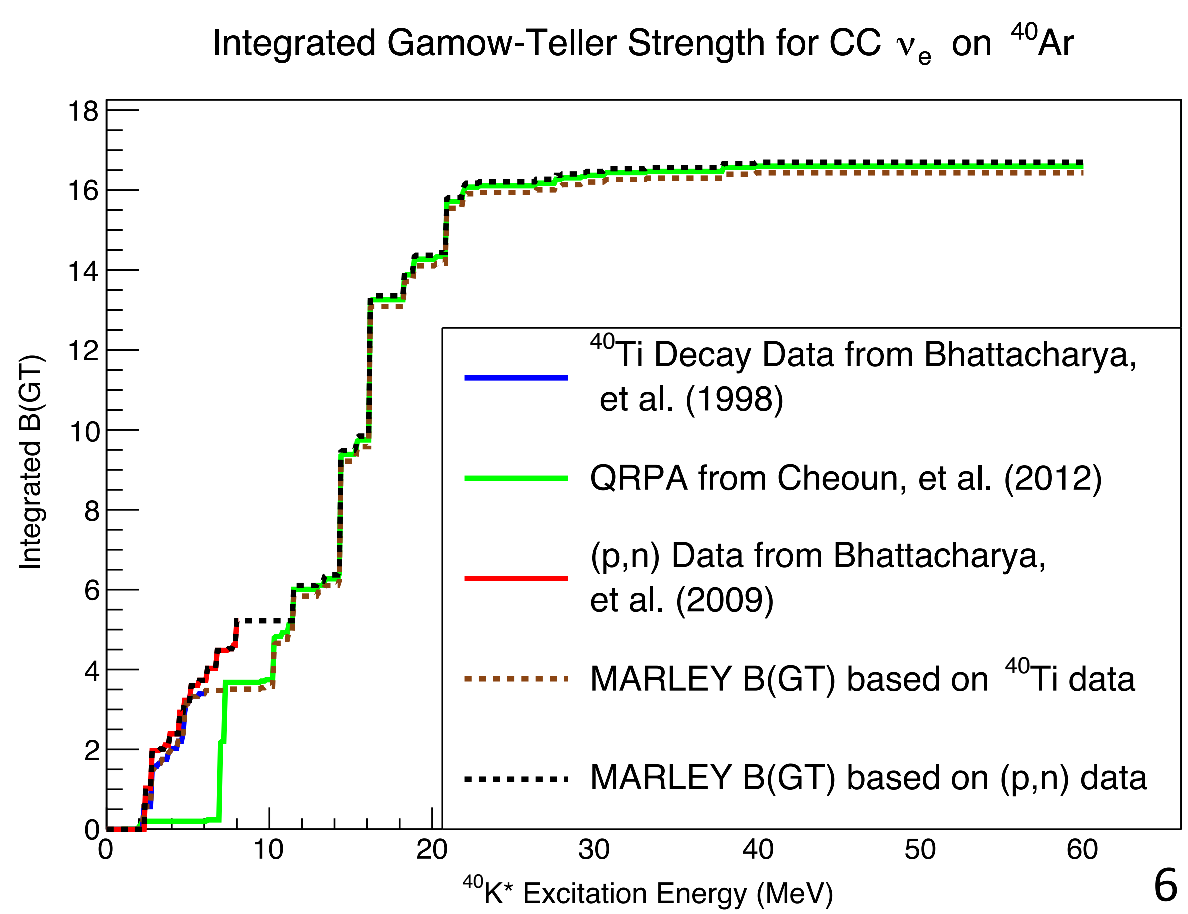
Notice that theory and experiment don't match at all

MARLEY uses tabulated Fermi and GT strengths to compute ν_eArCC cross sections

- Considering only allowed transitions gives us the total cross section

$$\sigma = \sum_{\text{levels}} \frac{G_F^2 \, |V_{ud}|^2}{\pi} \, |\mathbf{p}_\mathrm{e}| \, E_e \, F(Z_f, E_e) \left[B(F) + B(GT) \right]$$

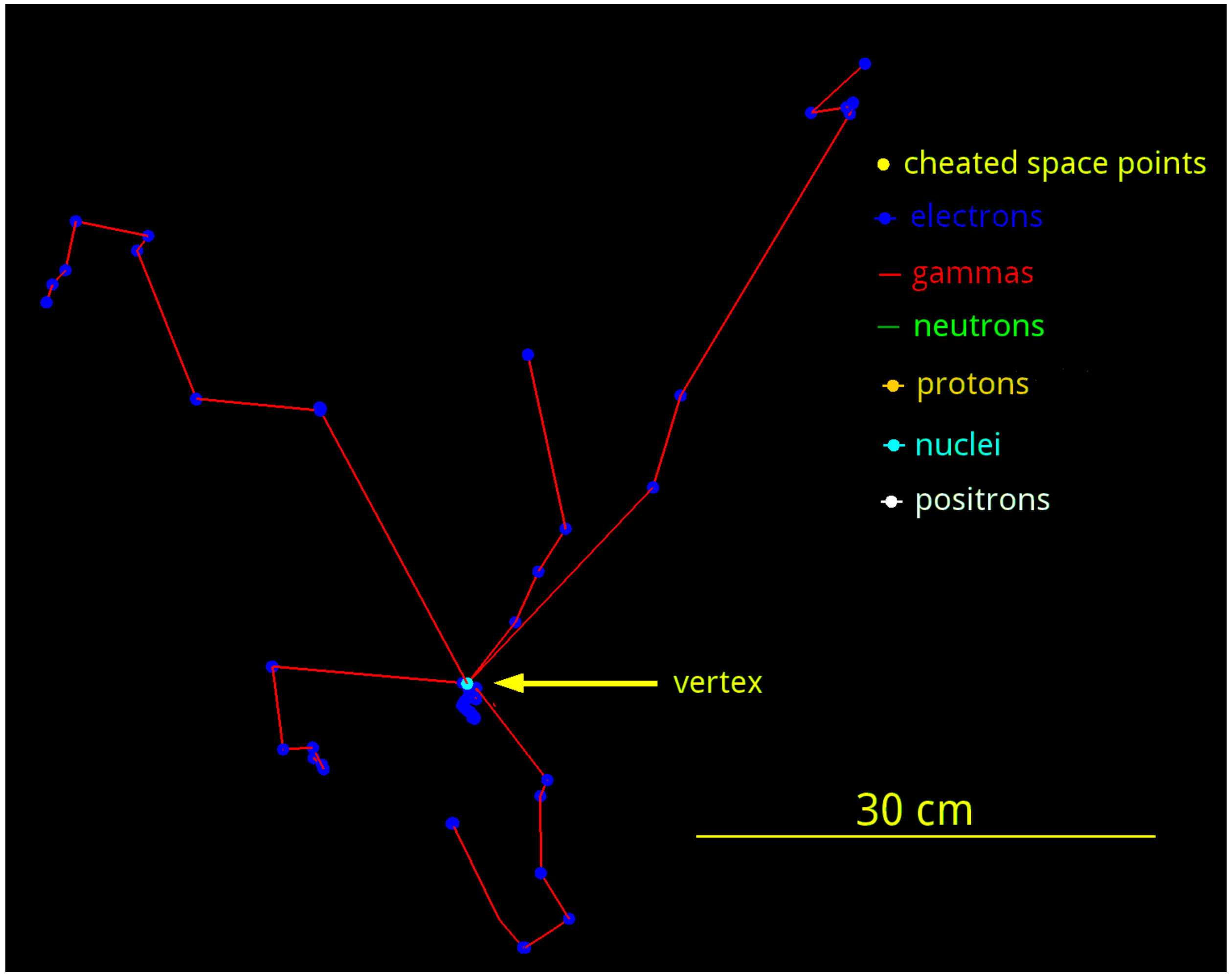
- Experimental strengths available up to $E_x \approx 8$ MeV
  - ^{40}Ti analog decay
  - (p,n) scattering
- Experiments have significant disagreements
- Interpolate to higher-energy QRPA calculation



6

e− + γs Event

- E_ν = 16.1 MeV
- e^- deposited 10.2 MeV
- γs deposited 4.3 MeV
- ^{40}K deposited 3.7 keV
- Total visible energy:
  14.5 MeV
- Visible energy sphere radius:
  48.4 cm
- Electrons are nearly always easy to see
- Gammas leave "blips" plus pair production tracks at high energy



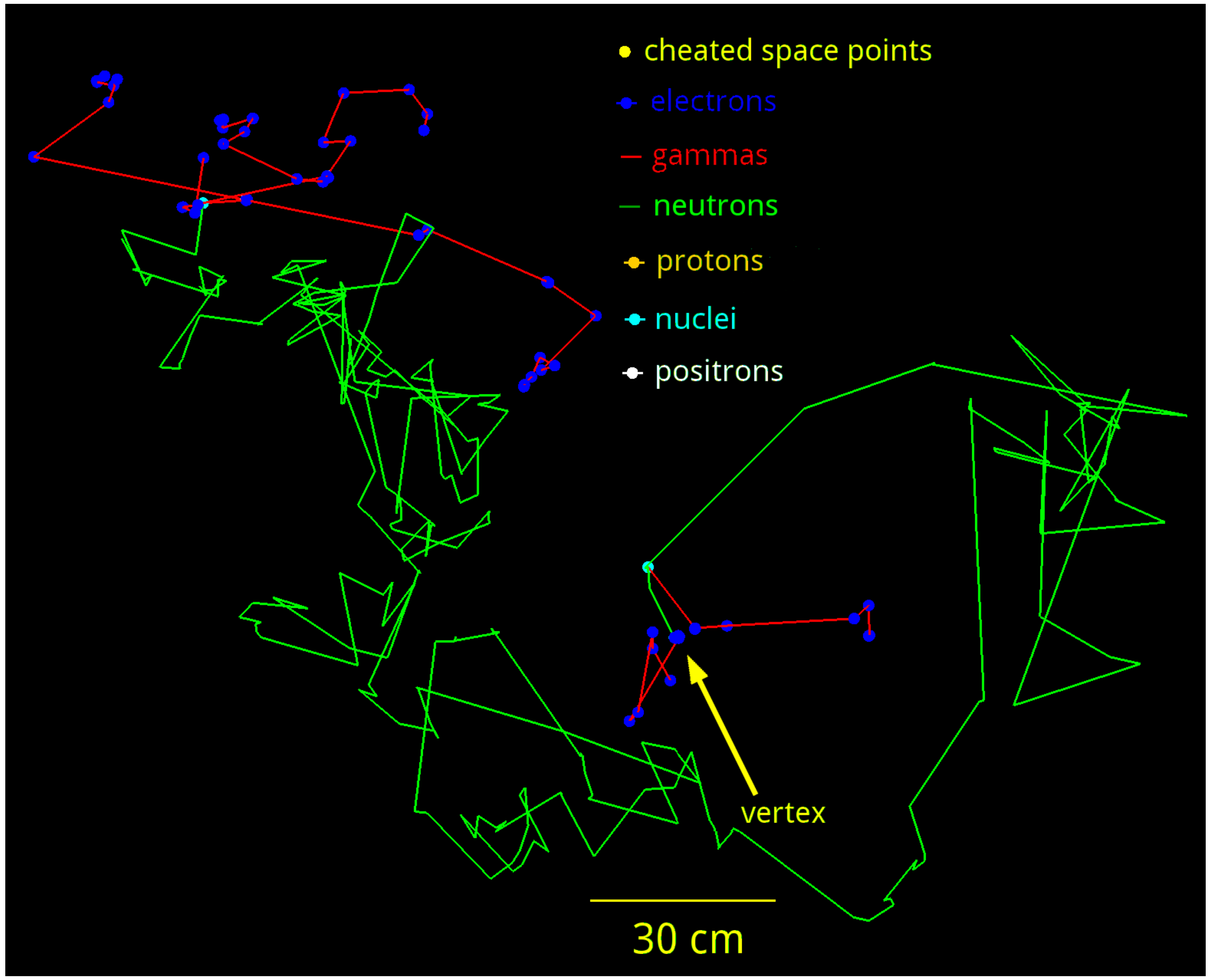
10

Neutron ejected

- E_ν = 16.3 MeV
- e^- deposited 4.5 MeV
- No primary γs from vertex
- ^{39}K deposited 68 keV
- n deposited 7.6 MeV (mostly from capture γs)
- Total visible energy:

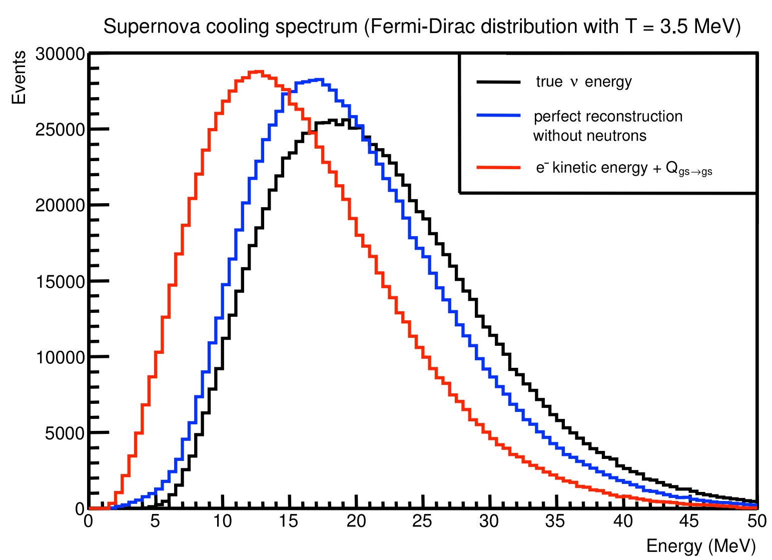
  12.2 MeV
- Visible energy sphere radius:

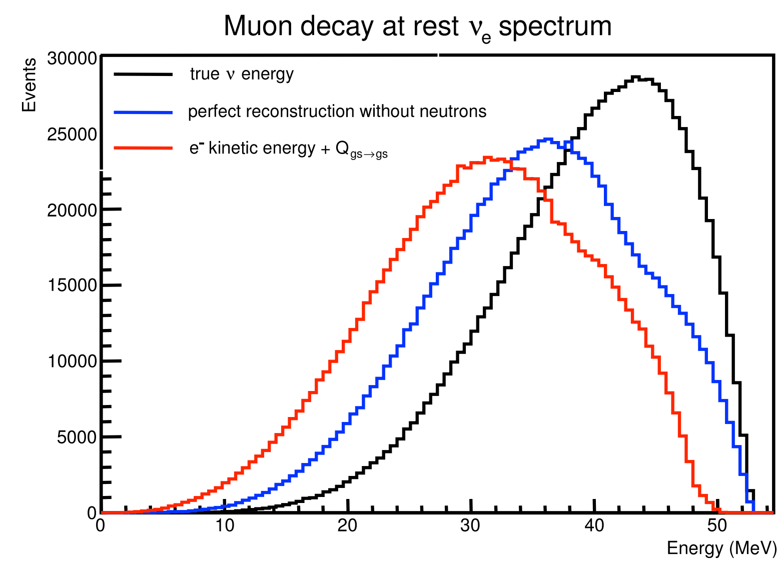
  1.44 m
- Neutrons bounce around for a long time!



Huge distortion at high energy. Looks like a spectral split from collective oscillations!

MARLEY branching ratios for two different source spectra





$^{40}K^*$ de-excitations

- γs only: 82.5%
- single n + γs: 15.9%
- single p + γs: 1.4%
- other: 0.2%

$^{40}K^*$ de-excitations

- γs only: 58.0%
- single n + γs: 36.3%
- single p + γs: 4.6%
- other: 1.1%

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

7

In Summary

- The next supernova will allow us to look inside the core collapse, observing the engine in real time
- This should help unravel the explosion mechanism, while also presenting a laboratory for particle and nuclear physics unavailable on earth
- But we need to be prepared! All stages carry important physics information. Events are complicated; missing photons and gammas could be a big problem
- Measurements of cross sections and robust DAQ design now would pay off handsomely when SN2029a goes off