Mainz Institute for Theoretical Physics

SN neutrino oscillations, new physics effects, etc: a few thoughts and requests

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SNOBS2017, MITP, Mainz

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SN and new physics: vast subject

- Numerous scenarios of new particles physics can impact SN neutrino signals
- Axions, Majorons, Extra-dim KK modes, “Unparticles”, Dark Photons, Dark Matter, Sterile Neutrinos, Nonstandard Interactions, Neutrino Magnetic moments, etc, etc
- Can create energy losses, modify transport, composition, EOS, affect each explosion stage

- Flavor oscillations in SN
  - Extremely rich physics: MSW, shocks and turbulence, collective oscillations, and their interplays
  - Many questions still unanswered
- Signal detection
  - Argon presents a great opportunity, but also challenges

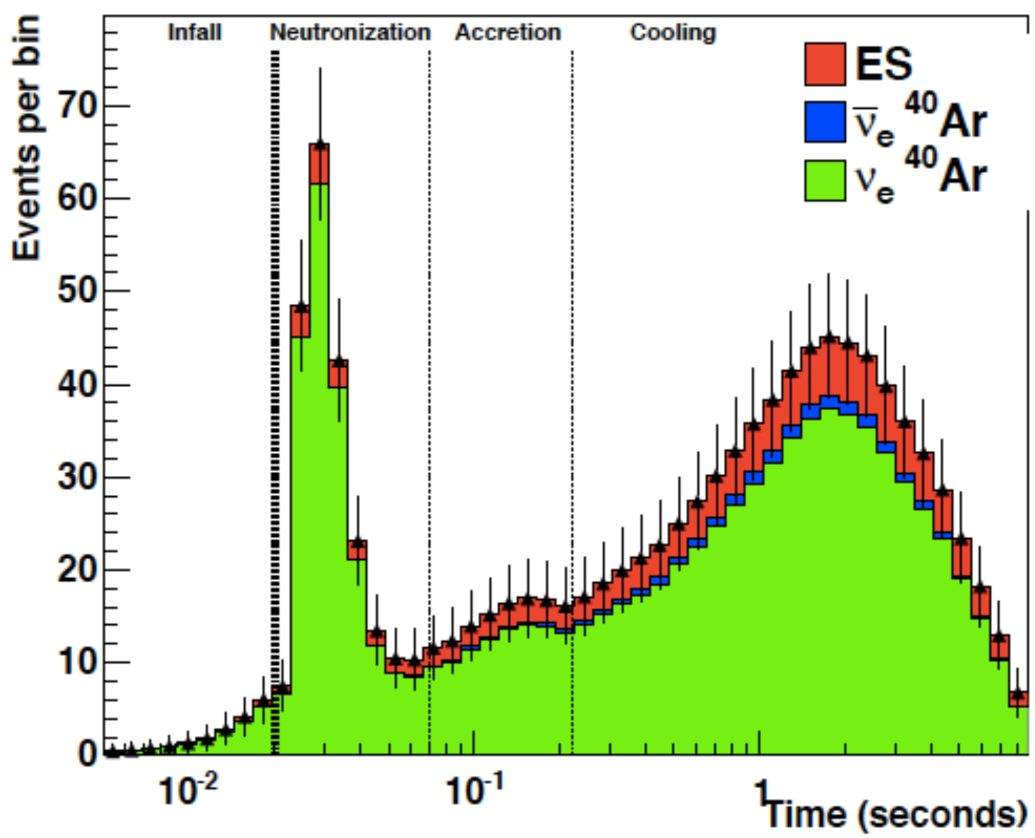
What could be done in such a short talk?

- A few points, hopefully complementary to other talks
- A few things experts could simulate/provide data for
  - Neutrino signals up to 10 sec in consistent 2D simulations
  - Neutrino-Argon interactions (better nuclear physics)

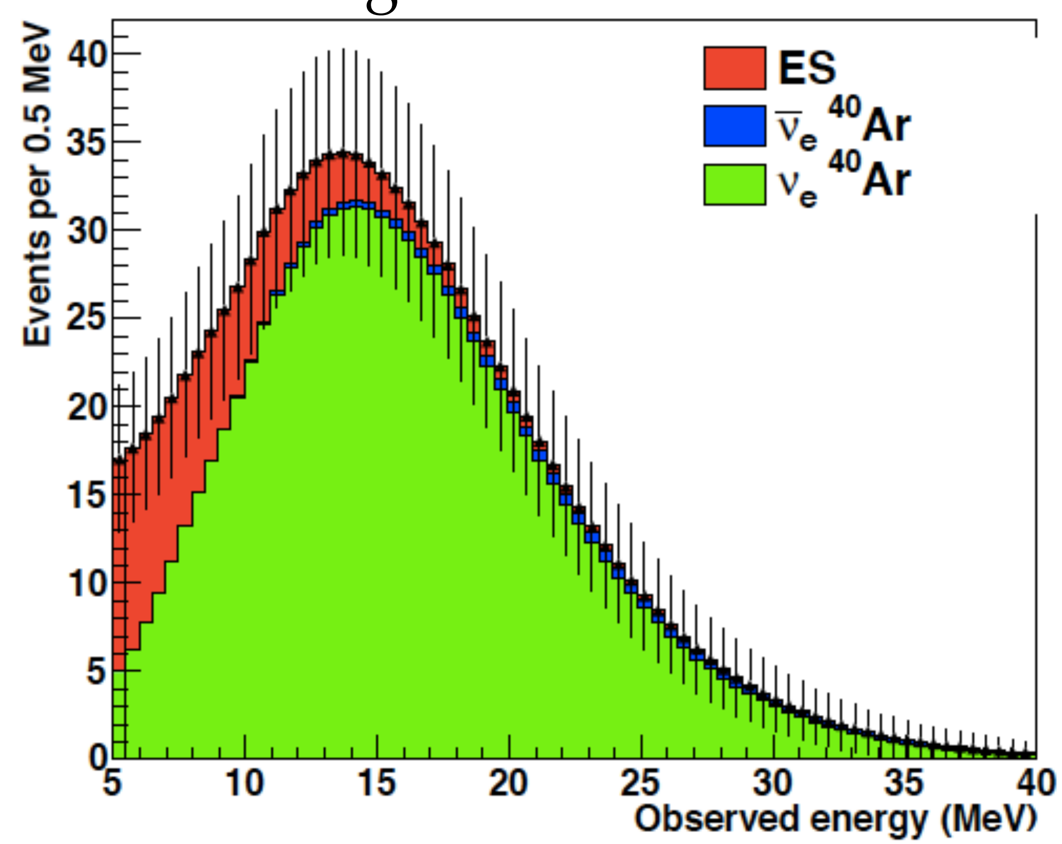
1. Detailed matter distributions behind the expanding shock
2. Detailed distributions of streaming neutrinos (energies, impact parameters)
3. Explosion simulations with modified neutrino-neutrino scattering

DUNE: 40 kton LAr (SN @10 kpc)

Time-dependent signal



Expected event spectrum integrated over time

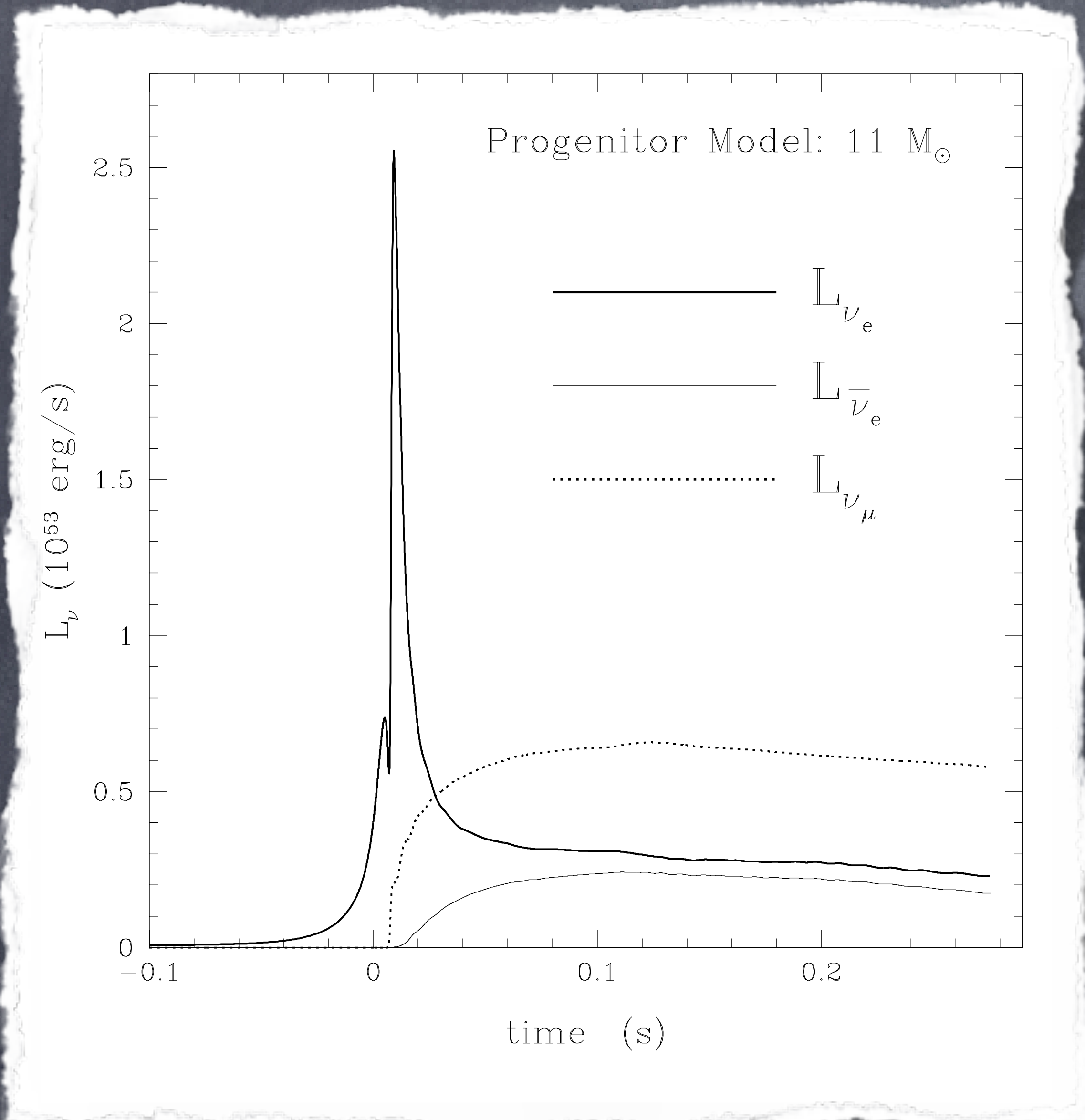


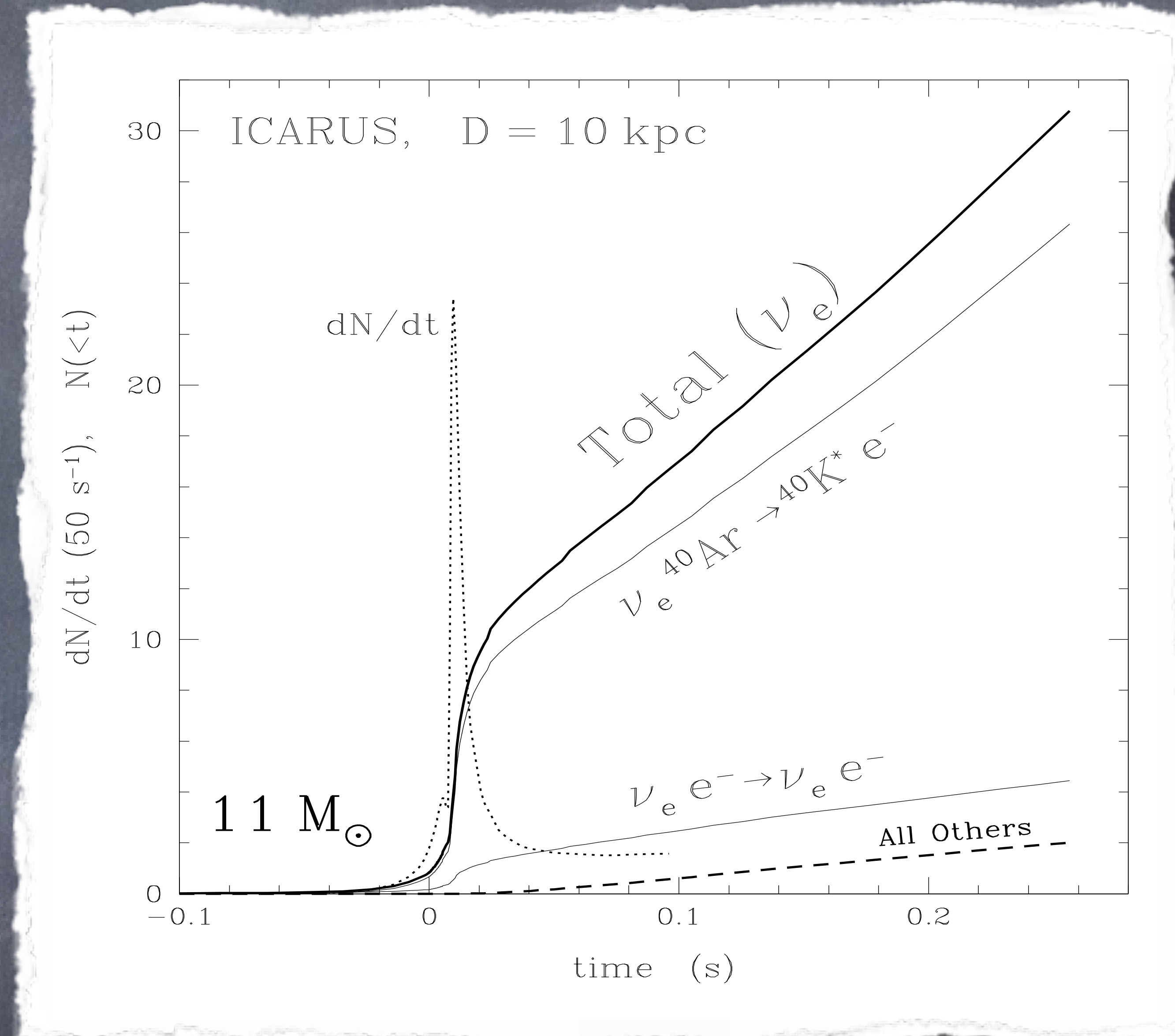
See talk by Kate for more

A lot of neutrinos come after 1 second

Disclaimers: perfect detection, no oscillations

Neutronization burst



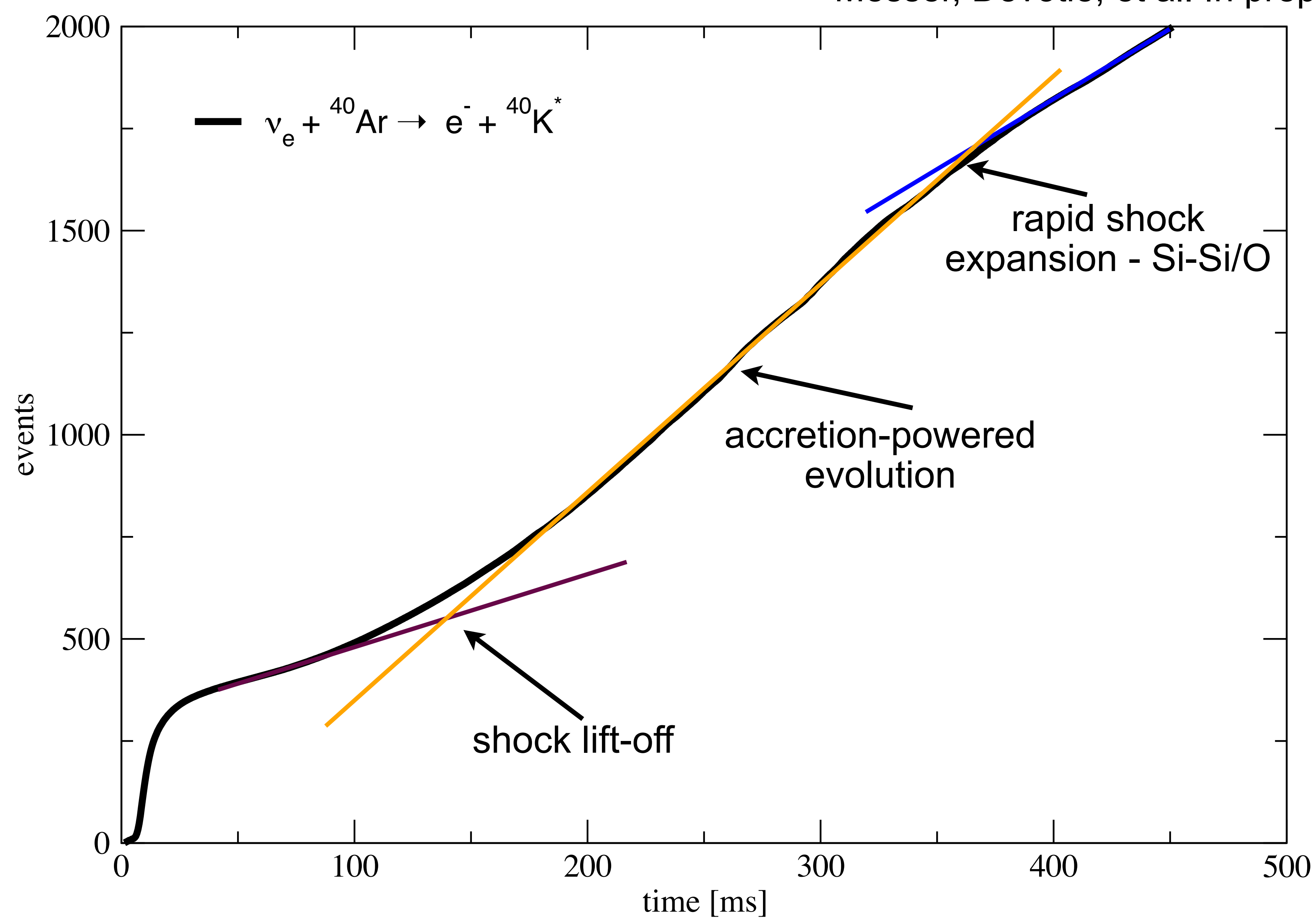


Thompson, Burrows, Pinto, astro-ph/0211194

Update from Bronson

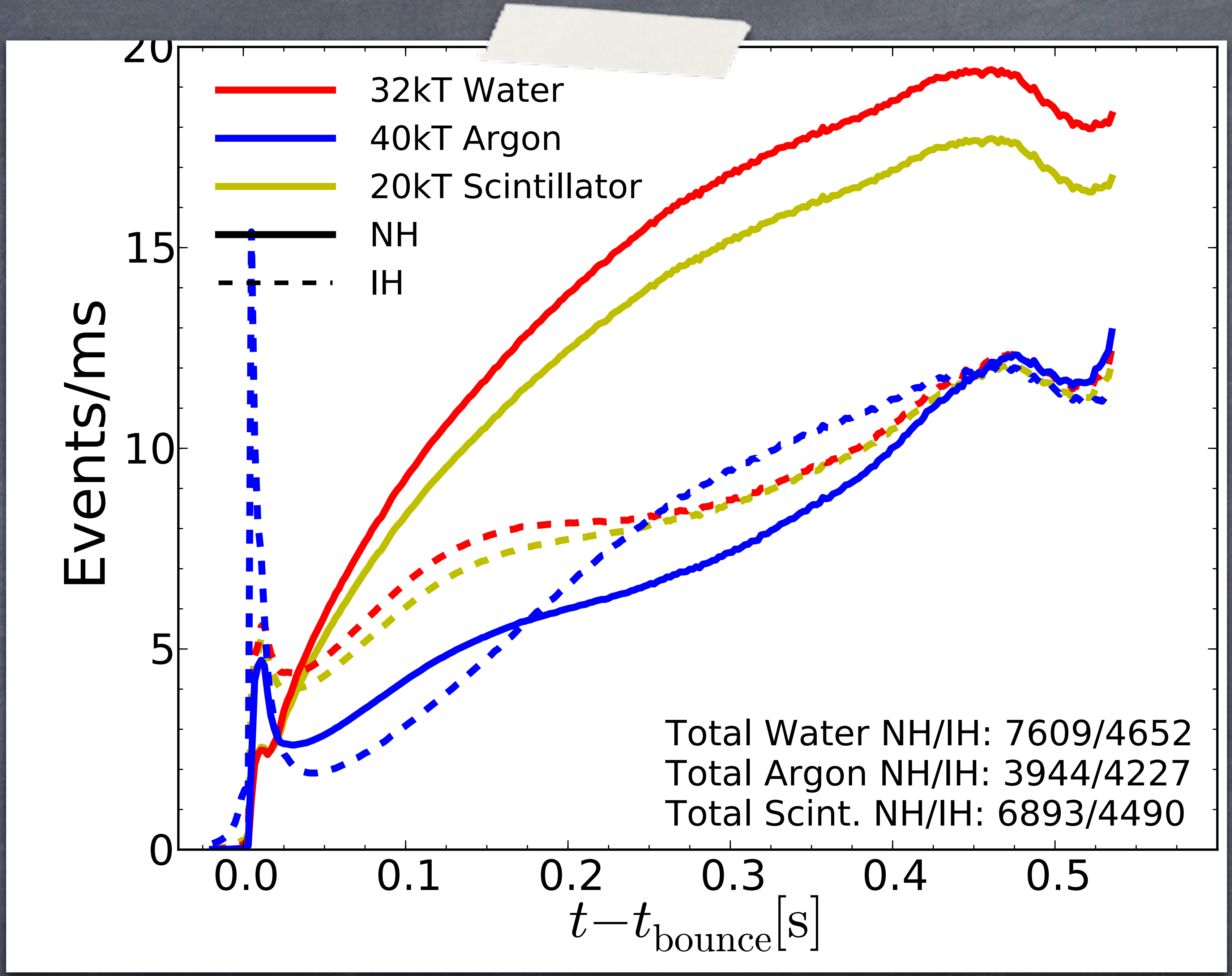
2D - ν_e total counts vs. time

Messer, Devotie, et al. In prep.



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

OAK RIDGE National Laboratory

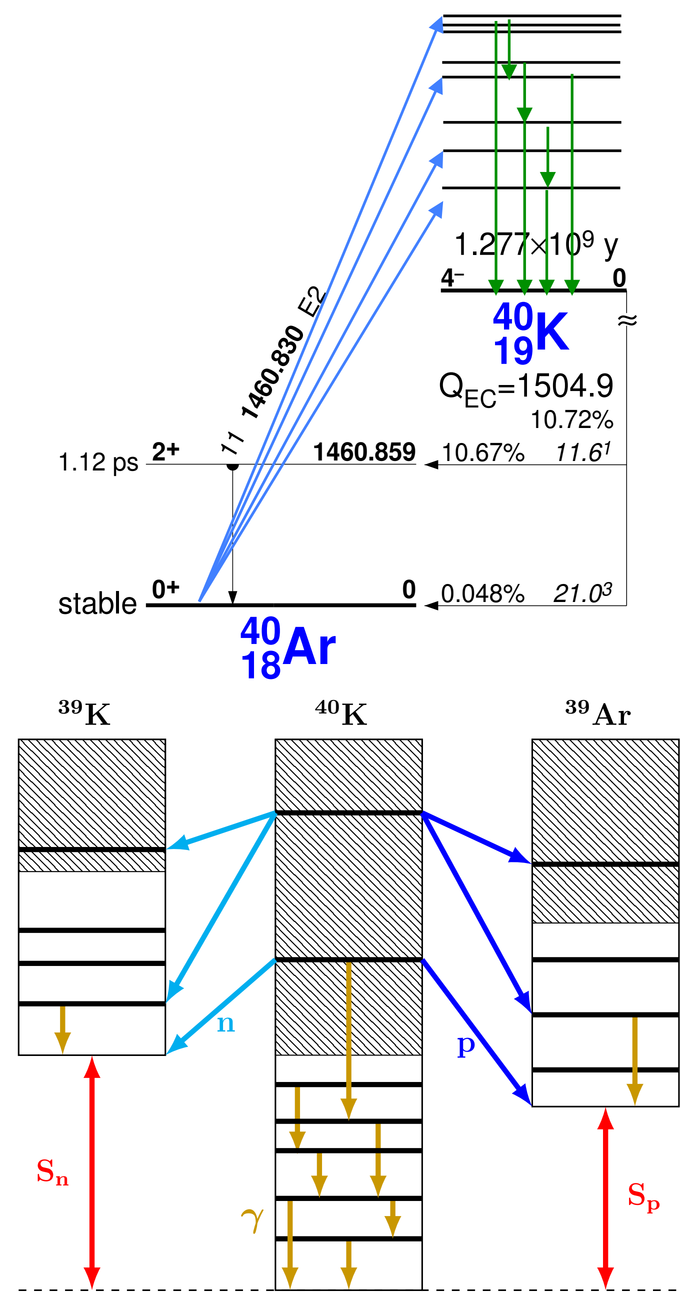


Or maybe the signal is very bright and suddenly stops, a black hole forms (from Evan O'Connor)

Detection

The interaction physics of SN neutrinos in Ar is nontrivial

- The reaction $\nu_e + {}^{40}Ar \rightarrow e + {}^{40}K^*$ creates ${}^{40}K$ in an excited state
- De-excitation gammas, plus at high energies n or p emission

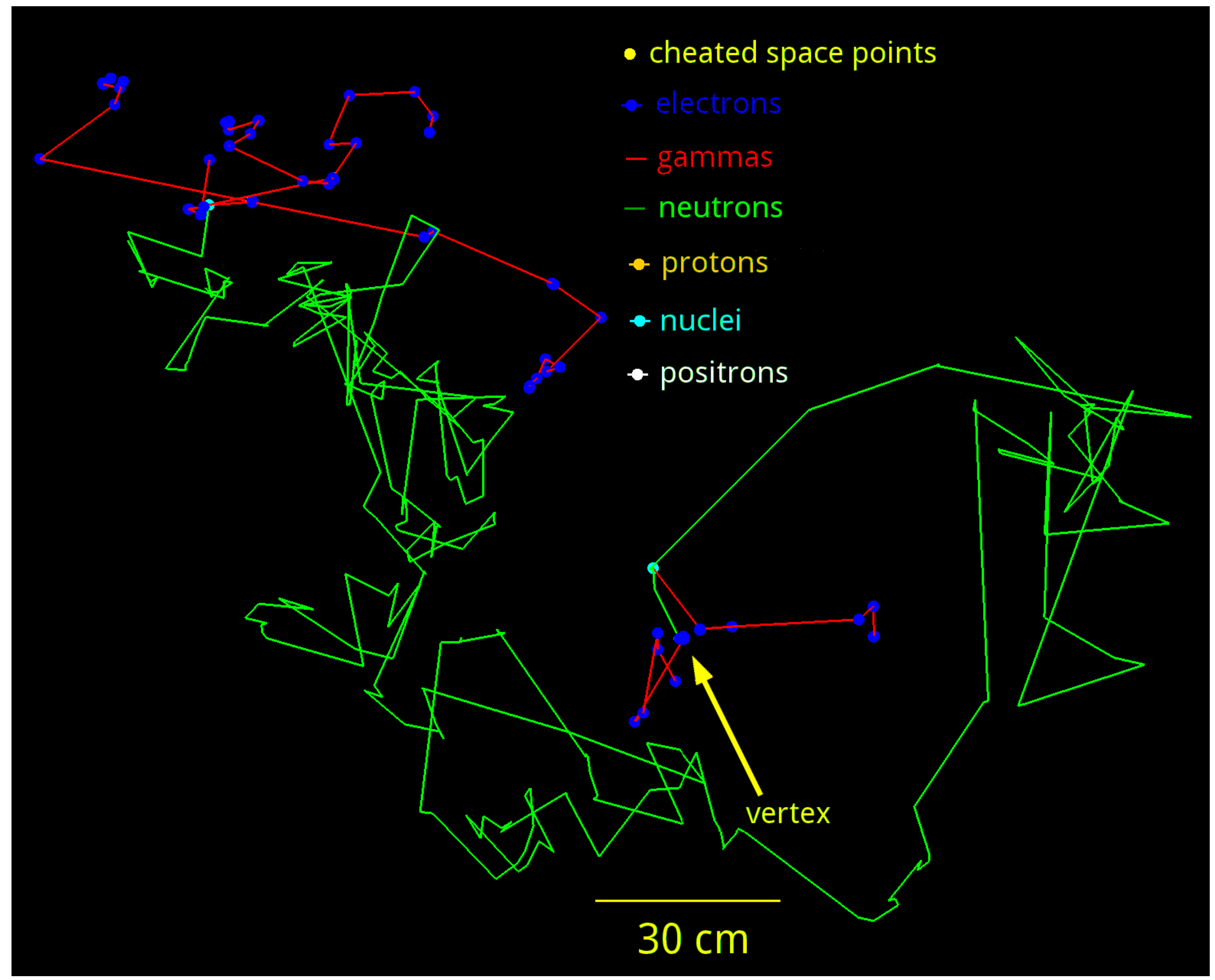


Simulation by UC Davis group (Gardener, Grant, Svoboda, et al)

- 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:

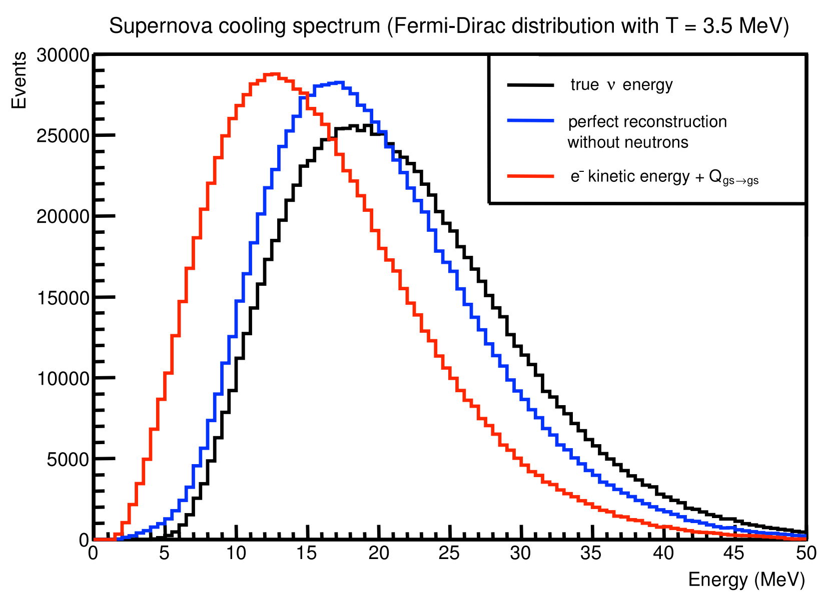
  12.2 MeV
- Visible energy sphere radius:

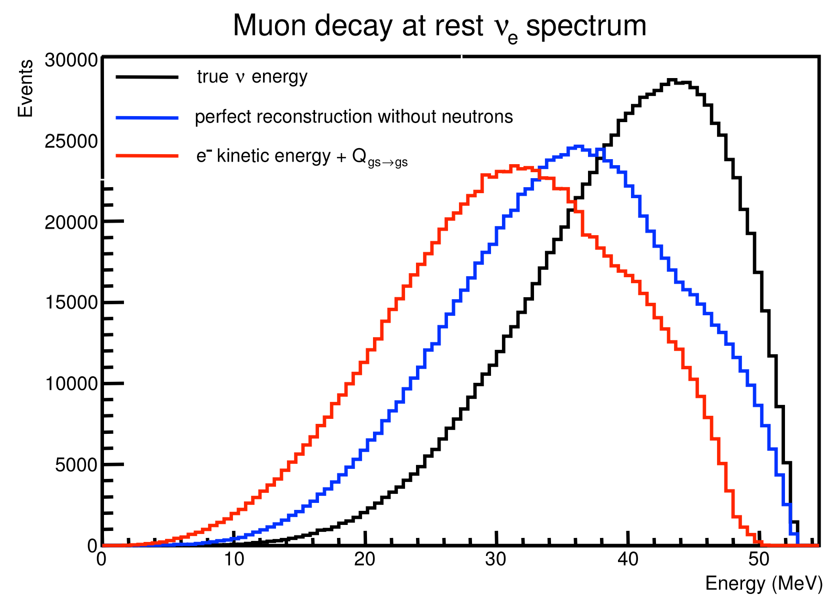
  1.44 m
- Neutrons bounce around for a long time!



Spectral distortion, esp. at high energy. (Not 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

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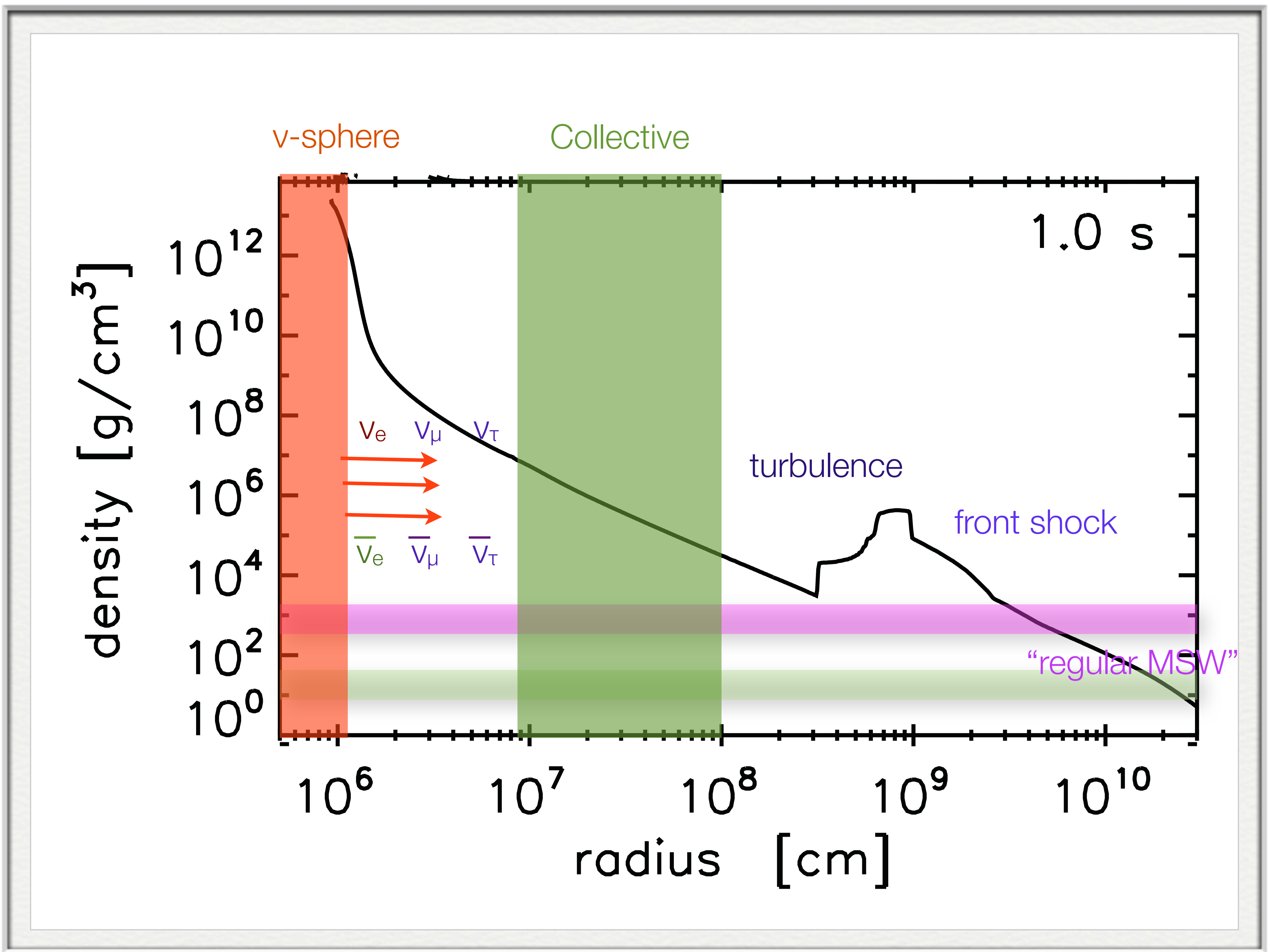
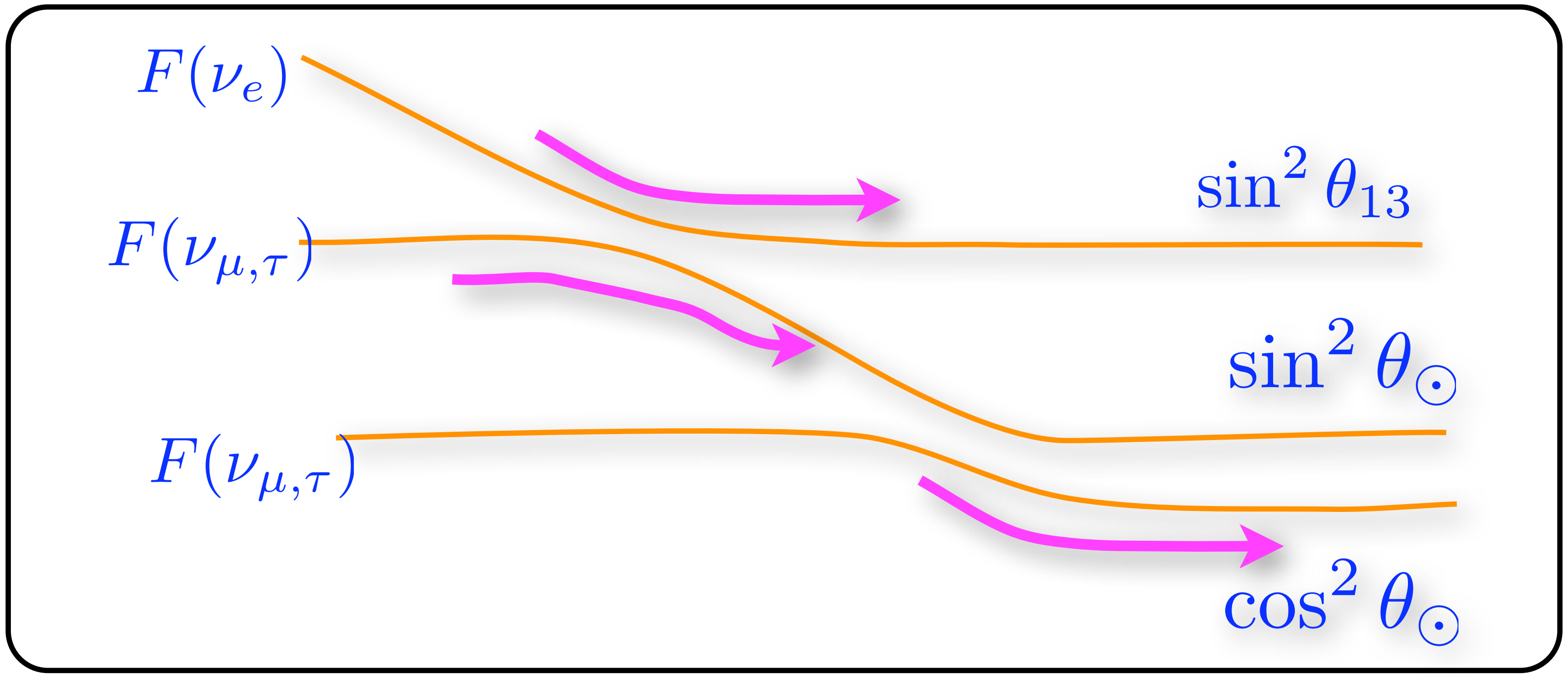
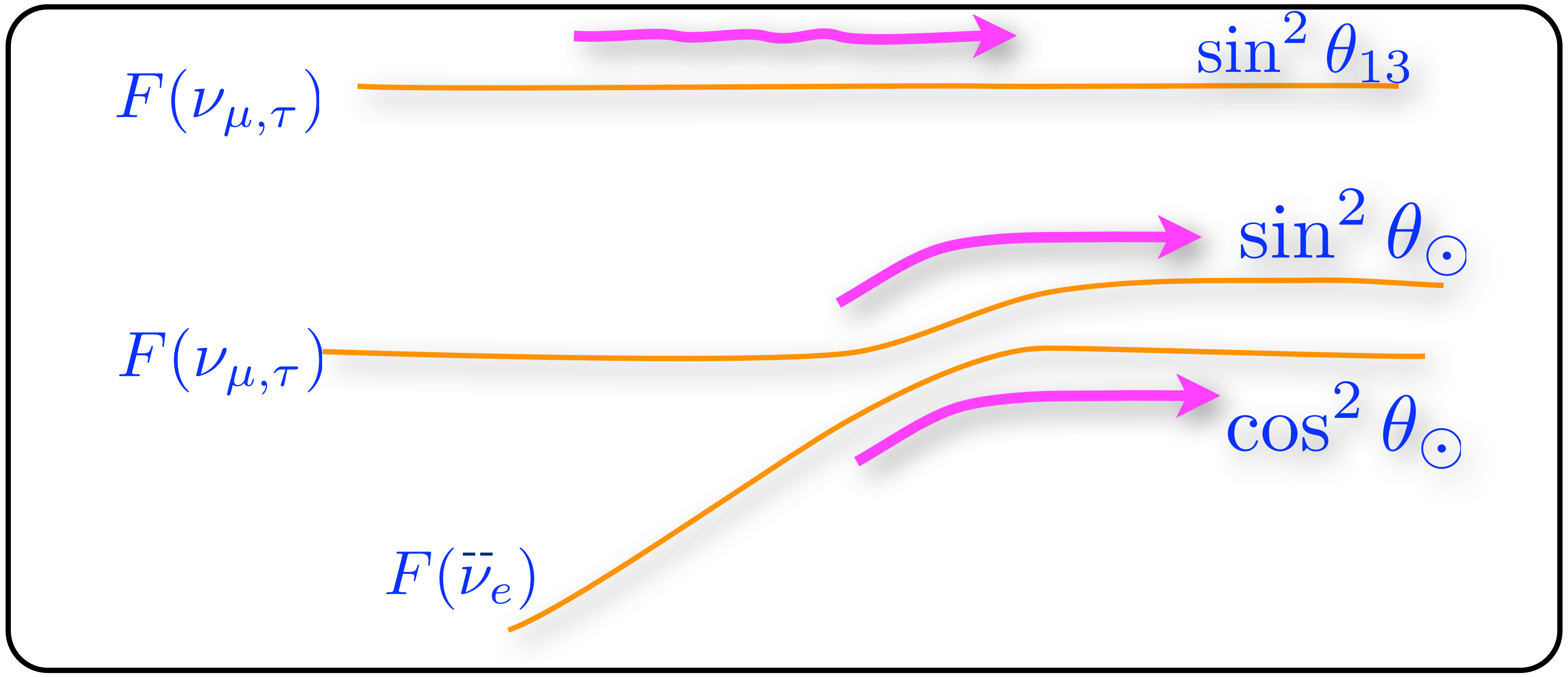
SN ν oscillations: very rich physics



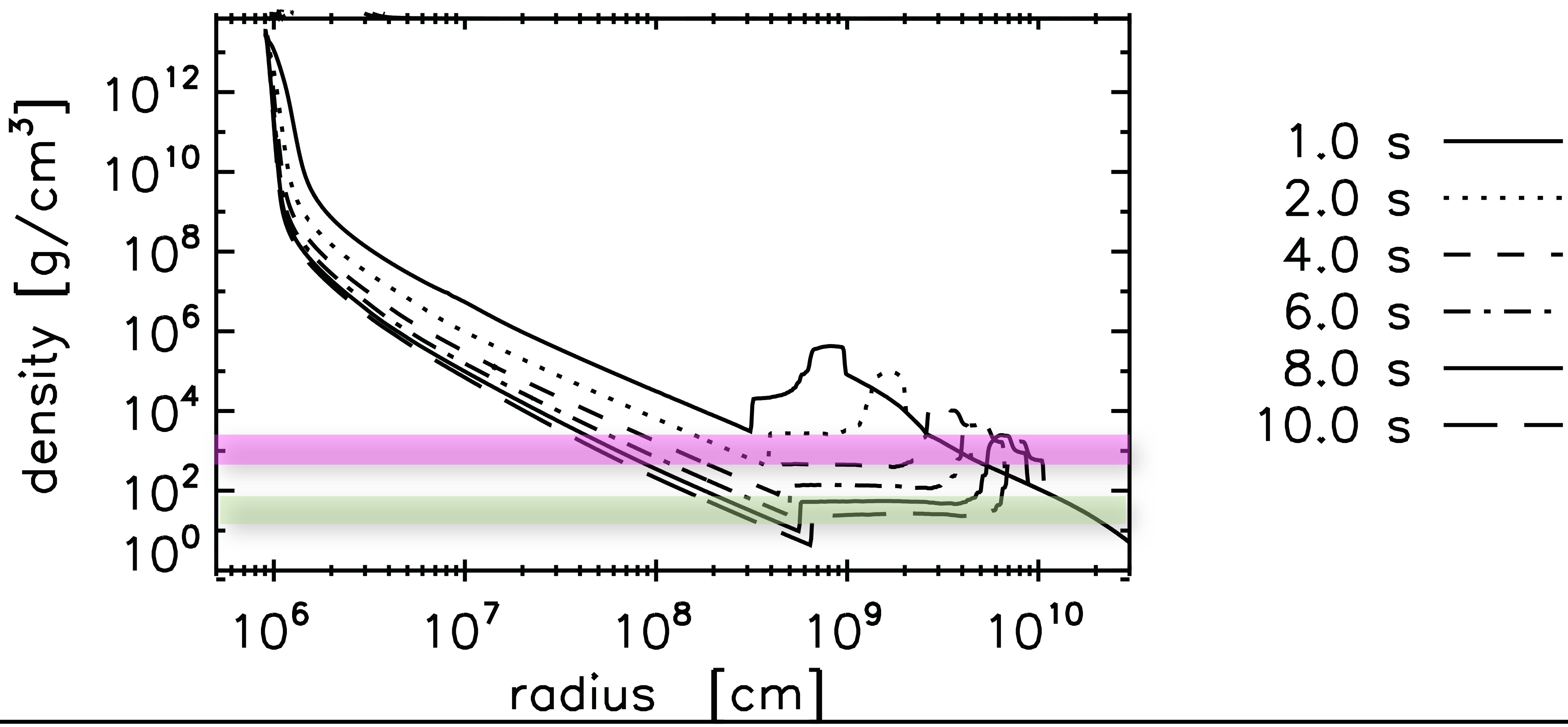
Trivial part: MSW transformations

- ➡Given the scale height in the progenitor, the MSW evolution is very adiabatic
  - ➡the adiabaticity of the atmospheric resonance is controlled by theta13
- ➡For NH, the nue flux during the **neutronization burst** swept into the nu3 state, largely disappears (and nux give the final nue signal)





Dynamical density profile, modulated MSW

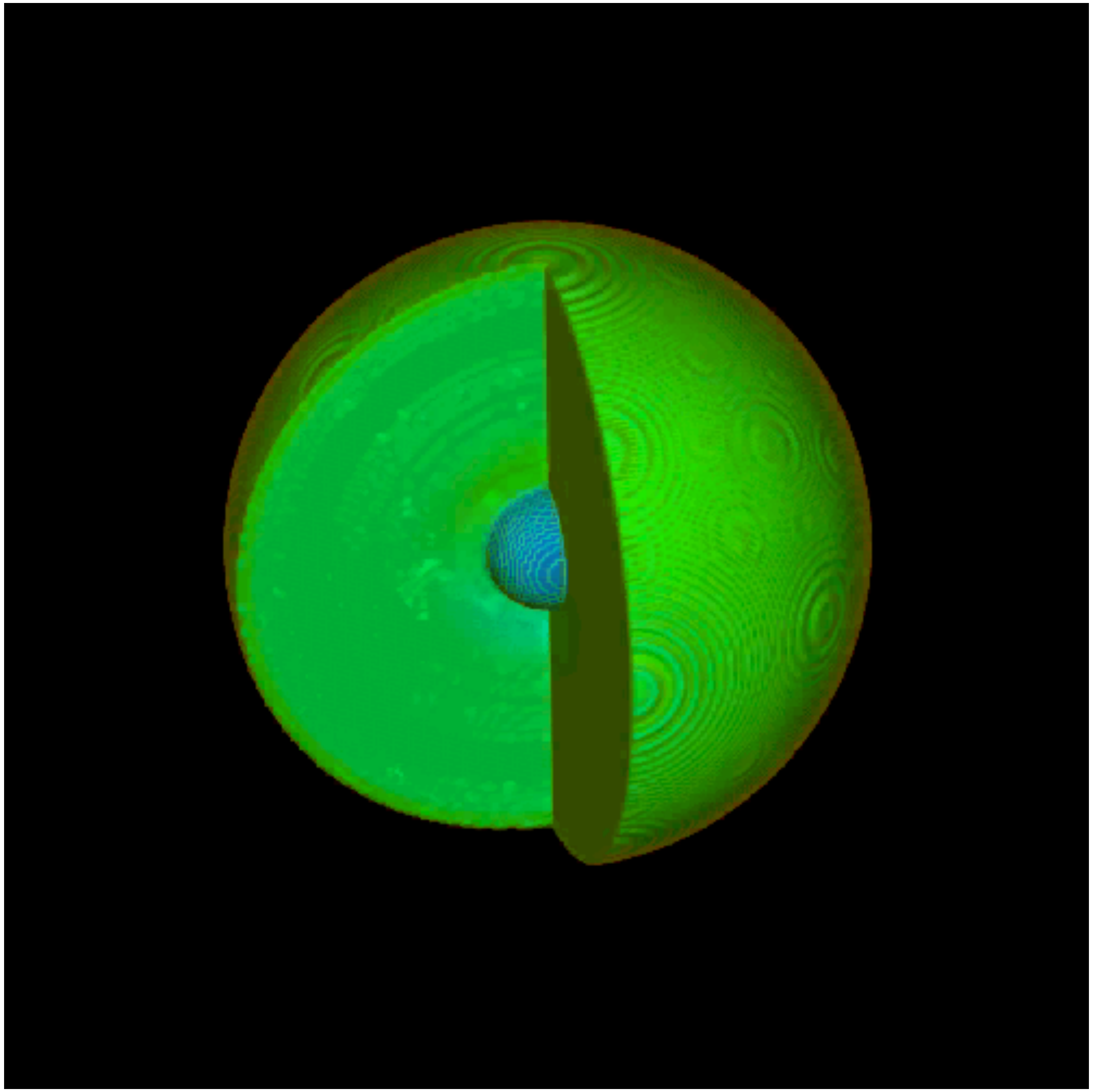


- Front shock reaches the regions where “atmospheric” and “solar” transformations happen, while neutrinos are being emitted

  - See Schirato & Fuller (2002) astro-ph/0205390

Multi-d simulations show extensive turbulence behind the expanding shock

Blondin, Mezzacappa, & DeMarino (2002)

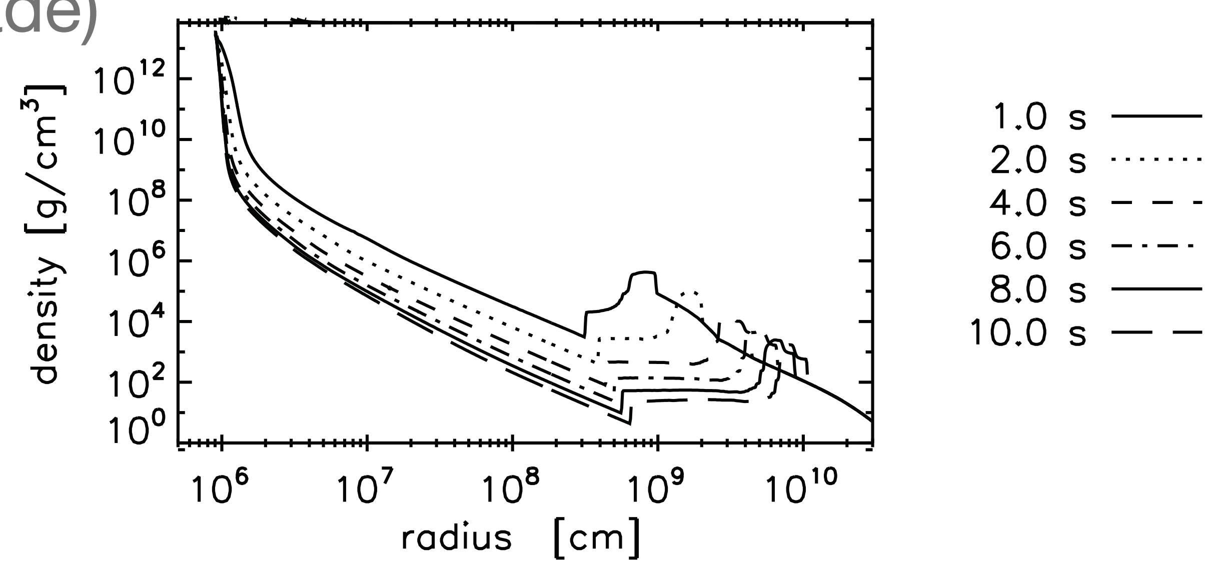


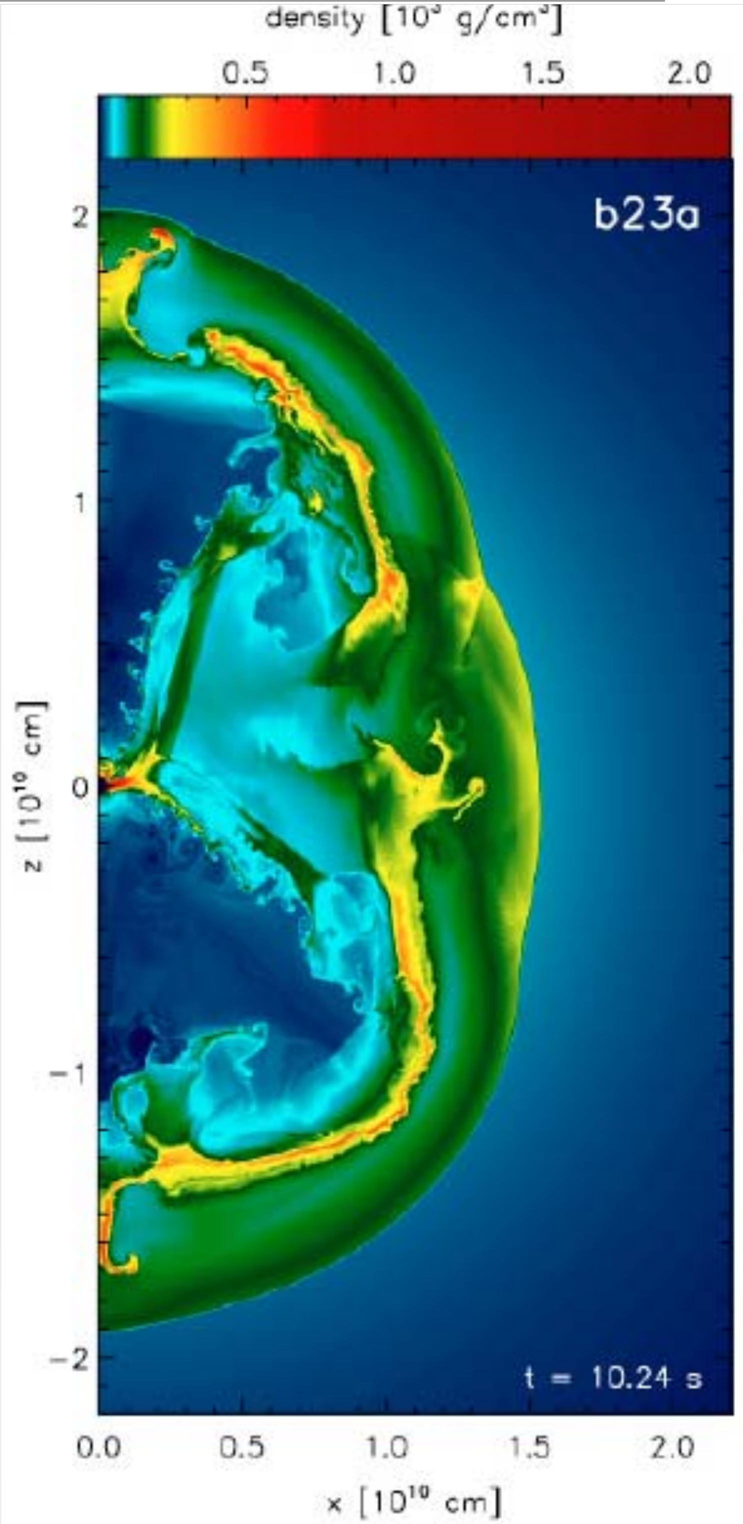
Multi-d simulations show extensive turbulence behind the expanding shock

Foglizzo, Masset, Guilet, Durand (2012)

Neutrino signal at a few seconds

- Neutrino transformations depend on the how densities behind and in front of the shock compare.
- Can be even different for different directions in the same simulations.
- Please simulate the explosion to several seconds!
- High-resolution simulations preferred (to check turbulent cascade)





Neutrino oscillations in turbulent matter

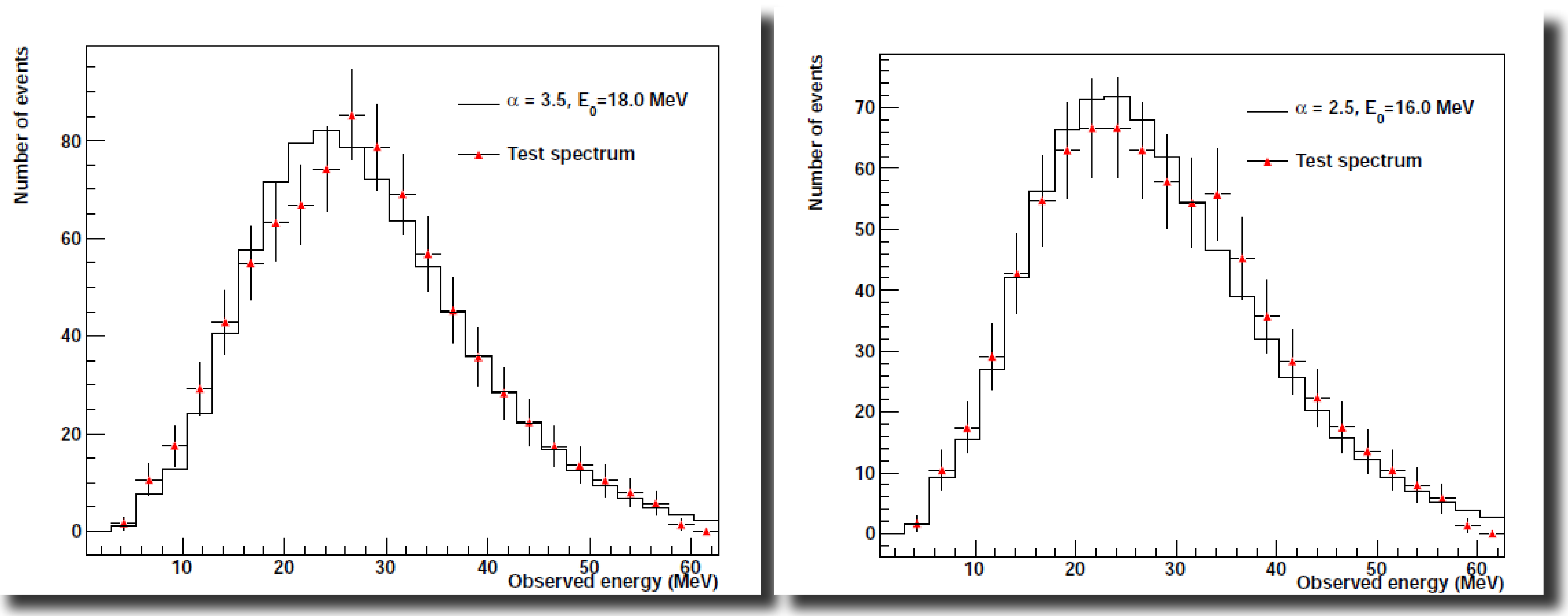
- In 3D, energy is pumped on large scales, dissipated on small scales
- Between these two scales (in the “inertial range”), a turbulent cascade is formed, carrying energy from large to small scales
    - Fluctuations scale as a power law of their size
- The relevant turbulent scales for neutrinos are tens of km (neutrino osc. length) and shorter
- These are not going to be resolved directly, but the existence of the cascade could be verified in a good simulation
- Given the cascade the problem can be treated analytically, see Friedland & Gruzinov, astro-ph/0607244

What are we looking for?

Modeling multiangle collective + shock and turbulence by A. F.

Detector model by K. Scholberg

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



- Time-varying modulation of the signal, neutrinos vs antineutrinos

Neutrino "self-refraction"

- Neutrinos undergo flavor conversion in the background of other neutrinos

Fuller et al, Notzold & Raffelt 1988;
Pantaleone 1992; ...
Duan, Fuller, Qian, Carlson, 2006;
+ hundreds more

- The neutrino induced contribution depends on the flavor states of the background neutrinos

$$\sqrt{2}G_F \sum_{\vec{p}} n_i (1 - \cos\Theta_{\vec{p}\vec{q}}) |\psi_{\vec{p}}\rangle\langle\psi_{\vec{p}}|$$

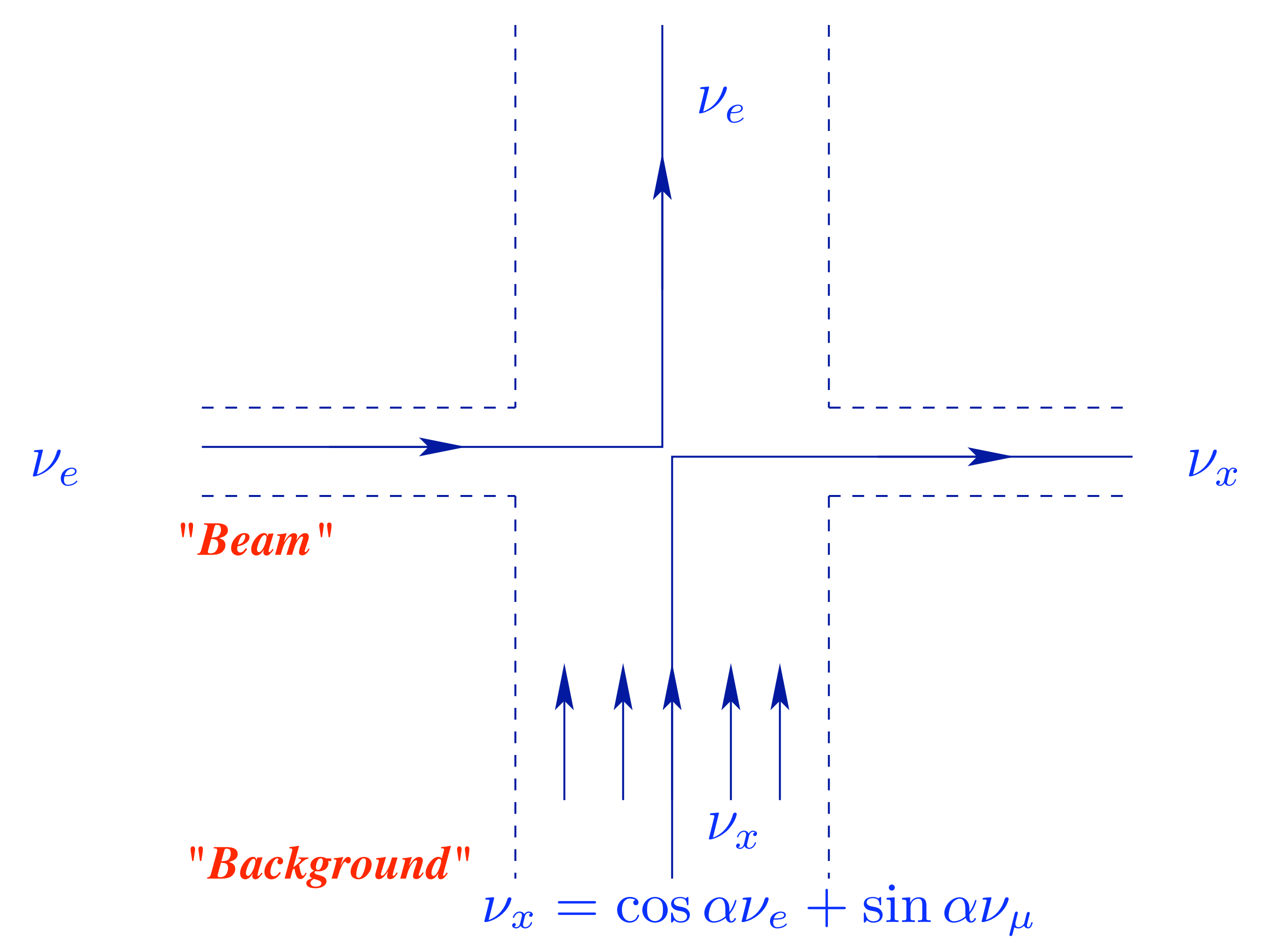
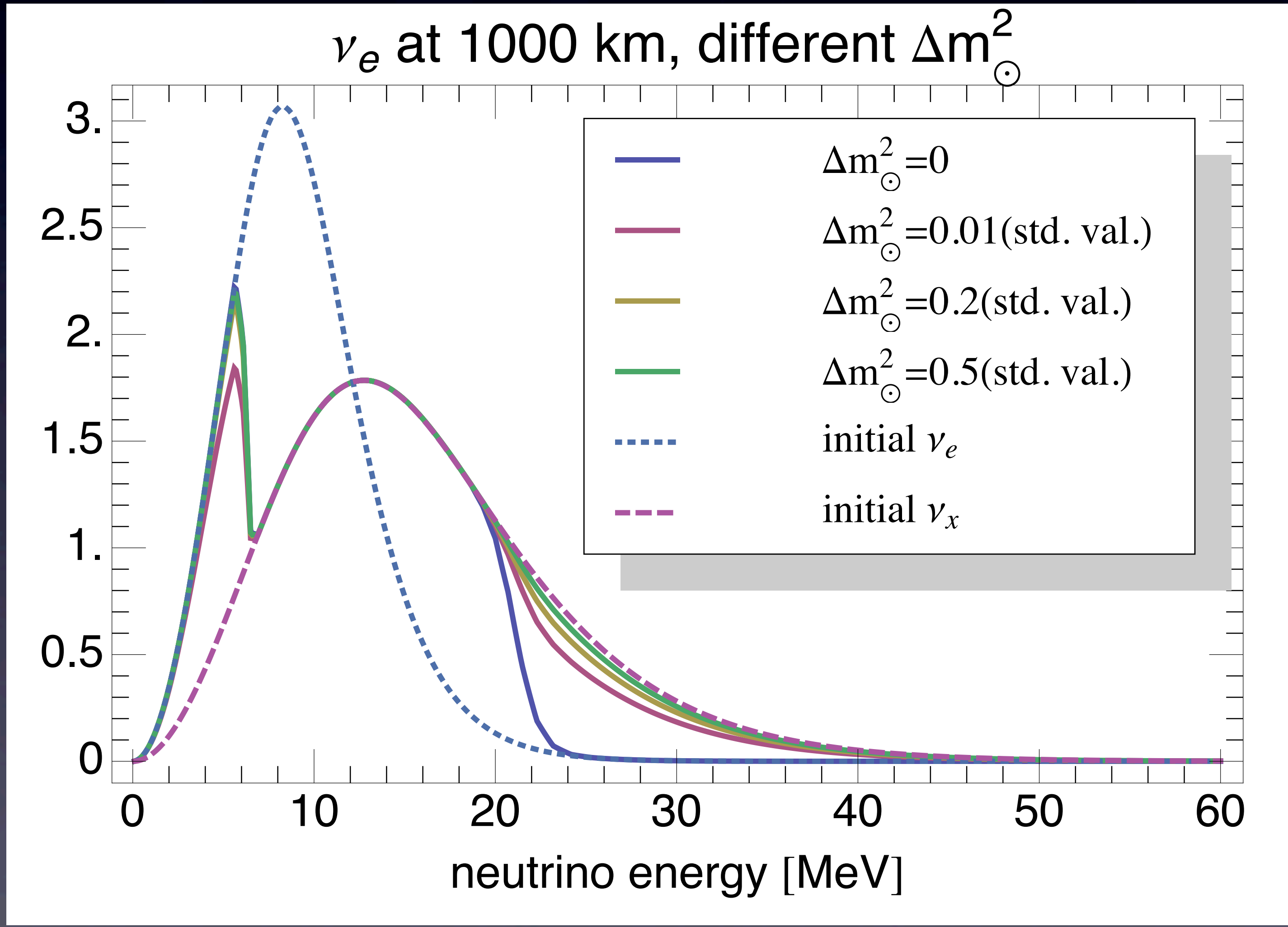


Figure from
Friedland & Lunardini,
Phys. Rev. D 68, 013007 (2003)

- One has to evolve the neutrino ensemble as a whole
- Rich many-body physics, with many regimes

Instabilities: adding a tiny parameter (additional d.o.f.) has a large effect

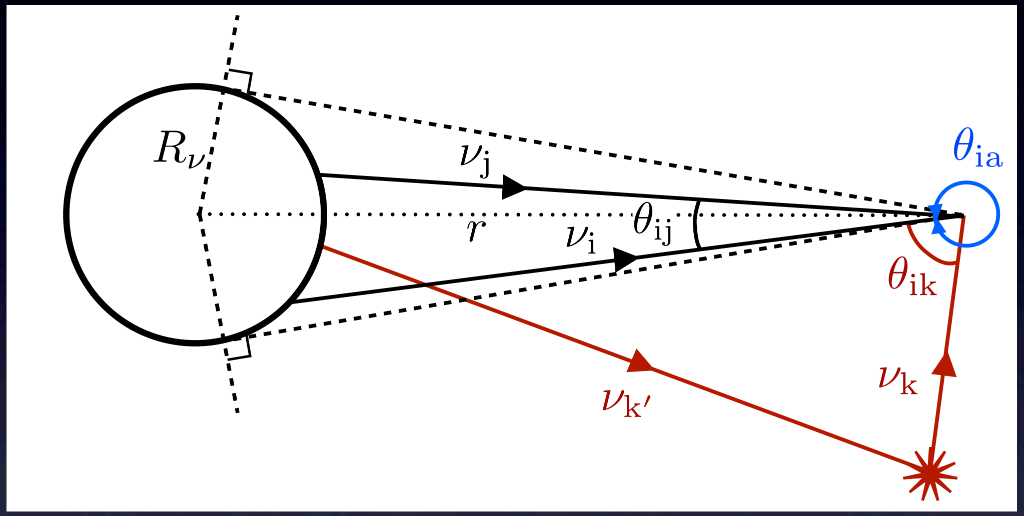
- Example where the solar mass splitting is turned on gradually
  - At $\Delta m_\odot^2=0$, 2-flavor result is reproduced
  - As soon as $\Delta m_\odot^2 \neq 0$, the answer is closer to the realistic $\Delta m_\odot^2$ than to $\Delta m_\odot^2=0$
- 2-flavor trajectory can be unstable in the 3-flavor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



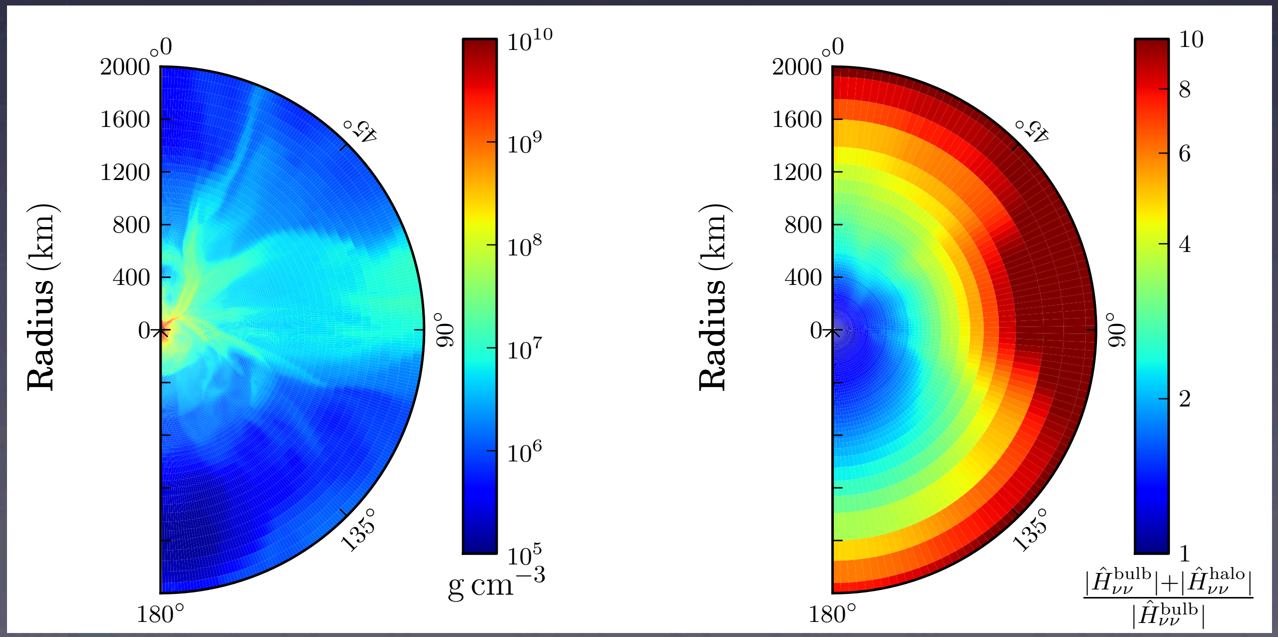
For details, see A. F., Phys. Rev. Lett.104, 191102 (2010);
cf Dasgupta, Dighe, Raffelt, Smirnov, PRL (2009)

What happens during the first second?

Cherry, Carlson, Friedland, Fuller, Vlasenko, arXiv:1203.1607

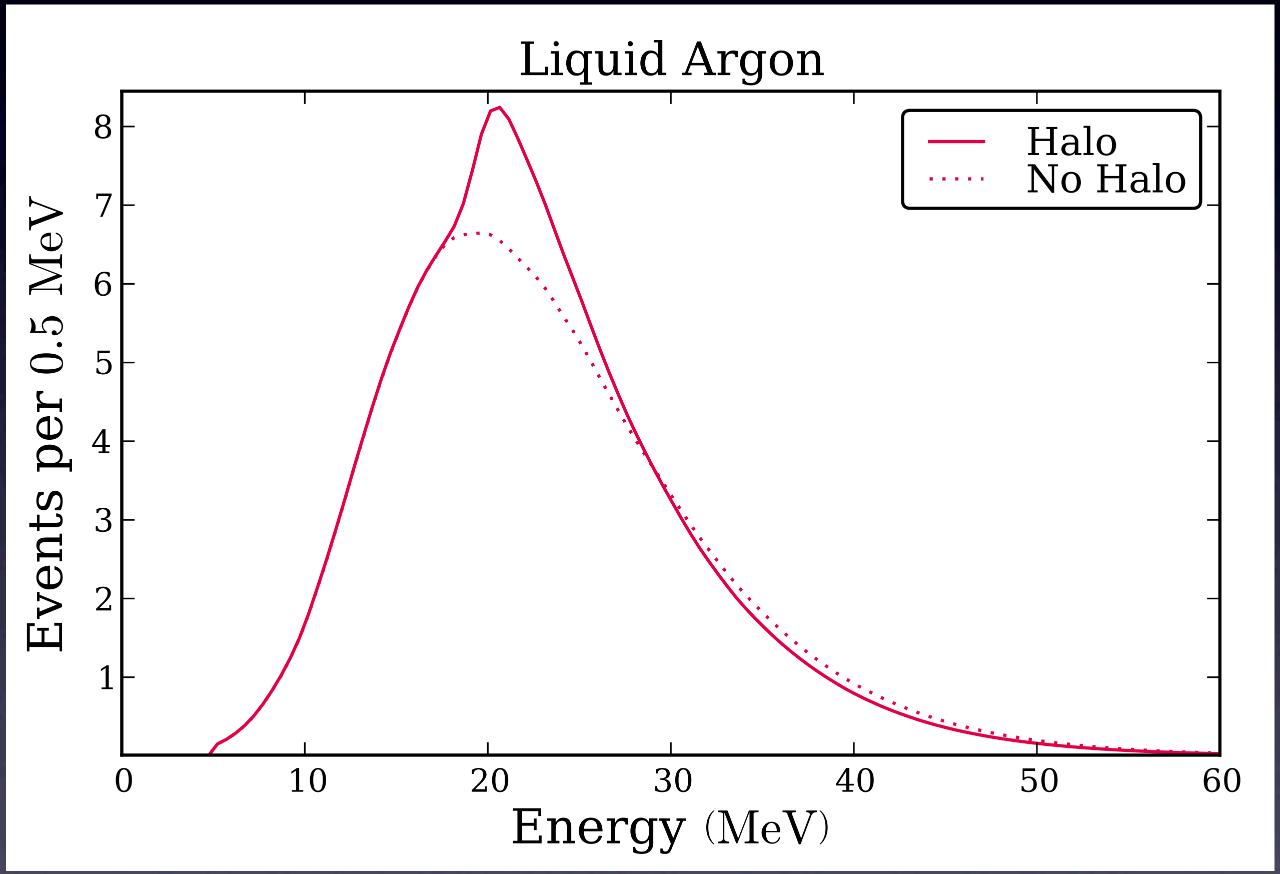


- Scattered "halo" neutrinos dominate oscillation Hamiltonian
- When the matter is inhomogeneous, multi-D, extremely tough
- Need "super-supercomputing"?



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
- Simulations with halo neutrinos wanted!



Cherry, Carlson, Friedland, Fuller, Vlasenko, arXiv:1302.1159

Neutrino-neutrino interactions?

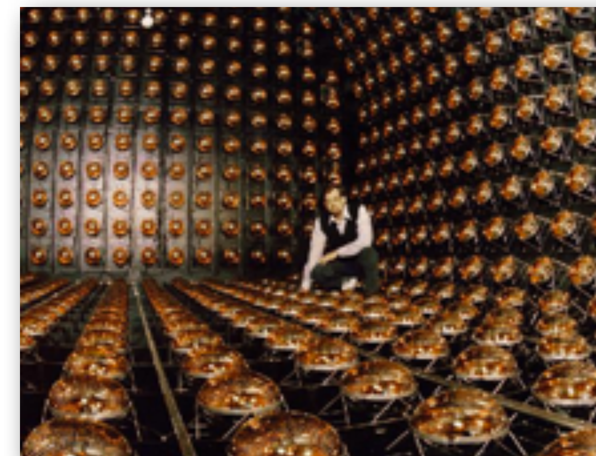
- The preceding discussion assumed that neutrinos interact only via the SM Z-exchange
- How do we know this is true? Impossible to measure in the lab
- Who would want to modify neutrino-neutrino interactions?!
  - Dasgupta and Kopp; Hannestad, Hansen, and Tram; Mirizzi, Mangano, Pianti, and Saviano; Archidiacono, Hannestad, Hansen, and Tram; Chu, Dasgupta, Kopp; Cherry, Friedland, Shoemaker
  - Why would we do this?

Experimental evidence? Sterile neutrinos at oscillation experiments

VOLUME 77, NUMBER 15 PHYSICAL REVIEW LETTERS 7 OCTOBER 1996

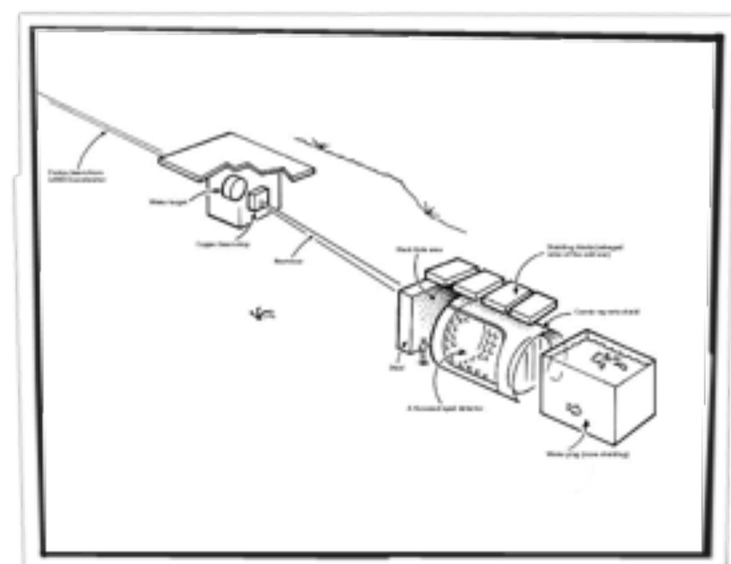
Evidence for $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ Oscillations from the LSND Experiment at the Los Alamos Meson Physics Facility

C. Athanassopoulos,[12] L. B. Auerbach,[12] R. L. Burman,[7] I. Cohen,[6] D. O. Caldwell,[3] B. D. Dieterle,[10] J. B. Donahue,[7] A. M. Eisner,[4] A. Fazely,[11] F. J. Federspiel,[7] G. T. Garvey,[7] M. Gray,[3] R. M. Gunasingha,[8] R. Imlay,[8] K. Johnston,[9] H. J. Kim,[8] W. C. Louis,[7] R. Majkic,[12] J. Margulies,[12] K. McIlhany,[1] W. Metcalf,[8] G. B. Mills,[7] R. A. Reeder,[10] V. Sandberg,[7] D. Smith,[5] I. Stancu,[1] W. Strossman,[1] R. Tayloe,[7] G. J. VanDalen,[1] W. Vernon,[2,4] N. Wadia,[8] J. Waltz,[5] Y-X. Wang,[4] D. H. White,[7] D. Works,[12] Y. Xiao,[12] S. Yellin[3]
LSND Collaboration



(Received 9 May 1996)

A search for $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ oscillations has been conducted at the Los Alamos Meson Physics Facility by using $\overline{\nu}_\mu$ from μ^+ decay at rest. The $\overline{\nu}_e$ are detected via the reaction $\overline{\nu}_e\, p \rightarrow e^+\, n$, correlated with a γ from $np \rightarrow d\gamma$ (2.2 MeV). The use of tight cuts to identify e^+ events with correlated γ rays yields 22 events with e^+ energy between 36 and 60 MeV and only 4.6 ± 0.6 background events. A fit to the e^+ events between 20 and 60 MeV yields a total excess of $51.0^{+20.2}_{-19.5} \pm 8.0$ events. If attributed to $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ oscillations, this corresponds to an oscillation probability of $(0.31 \pm 0.12 \pm 0.05)\%$.



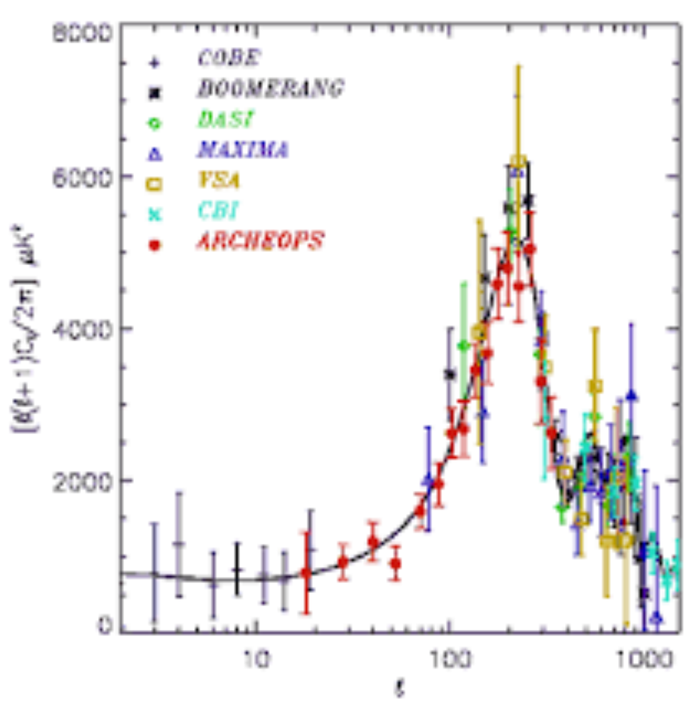
Since then, MiniBOONE, Reactor flux anomaly, gallium source anomaly. See, e.g., C. Giunti, arXiv:1609.04688 for review

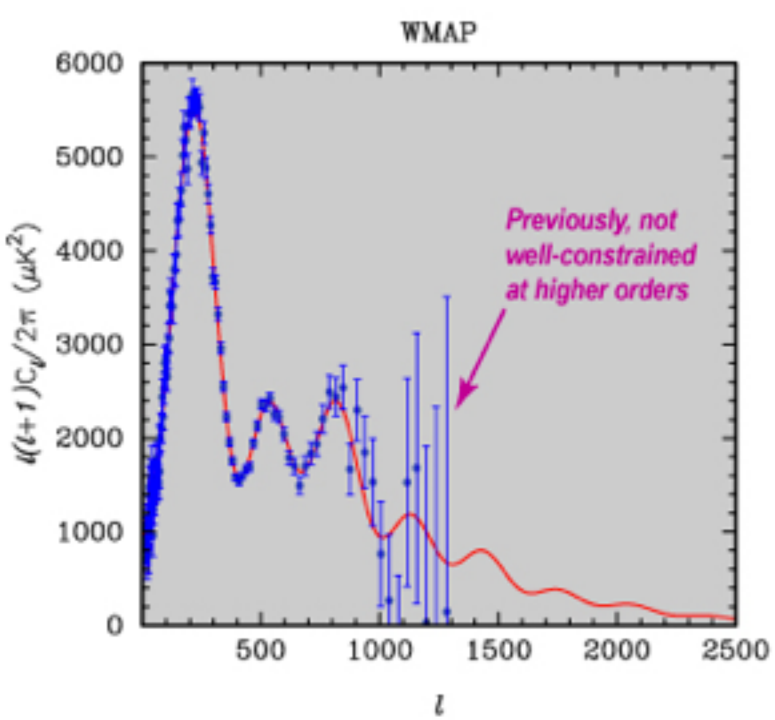
Sterile neutrinos: cosmological problems?

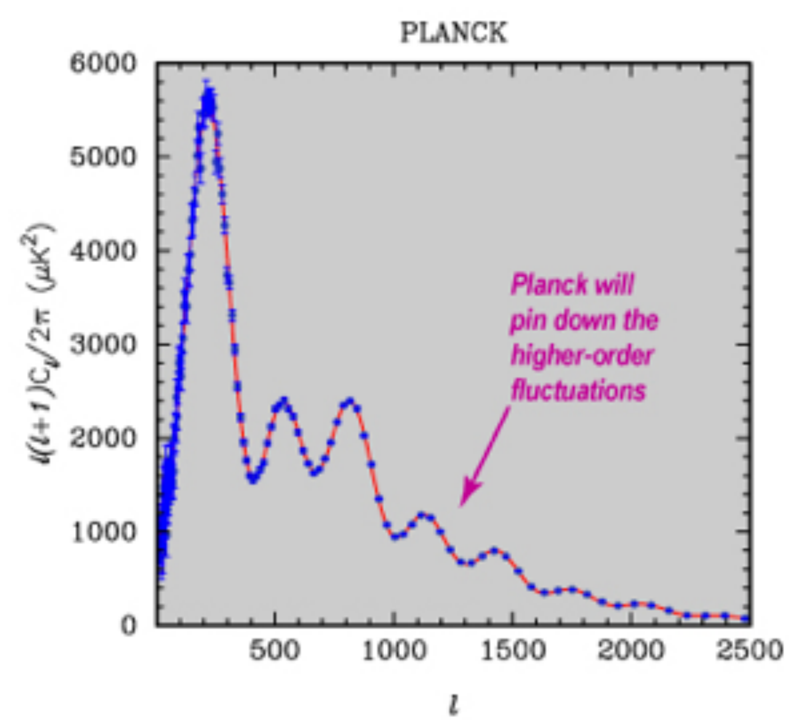
- Recent results from Planck measure relativistic energy density in the universe at matter/rad equality -> CMB decoupling

- Planck 2015 [arXiv:1502.01589] reports N_{eff}=3.15±0.23 and for the mass m_ν < 0.23 eV

- *Are sterile neutrinos that the SBN program plans to search for already ruled out by cosmology?*







Hidden interactions to the rescue?

- What if sterile neutrinos were actually not sterile, but interacting through their own force?
- Once there is some population of hidden neutrinos, this would induce an MSW potential that would suppress mixing between ν_a and ν_h . Would that shut off $\nu_a \to \nu_h$ thermalization?
- This is the Babu-Rothstein framework
  - Babu & Rothstein, Phys.Lett. B275 (1992) 112-118

Why is suppression of mixing not enough?

- New interactions, while solving one problem, introduce another
- While they suppress collisions due to Weak Interactions, they themselves mediate collisions
- Can flavor recoupling due to the new force can be delayed until T ~ 1 MeV?
- Quantitative question: compare rates

Let's do an example calculation

- Light mediator, recoupling at temperatures above the mediator mass

$$\sin^2 2\theta_m \sigma(T) T^3 \sim \frac{T^2}{M_{pl}}$$

$$\sin 2\theta_m \simeq \frac{\Delta m^2 \sin 2\theta_v}{E|V_m|}.$$

$$V_m \sim +\frac{g^2 T^2}{E}, \;\; T, E \gg M$$

$$\left(\frac{\Delta m^2 \sin 2\theta_v}{E g^2 T^2 / E}\right)^2 \frac{g^4}{M^2} T^3 \sim \frac{T^2}{M_{pl}}$$

$$\boxed{T_{recoupling} \sim T_0^{5/3} M^{-2/3}}$$

$$T_0 = [(\Delta m^2 \sin 2\theta_v)^2 M_{pl}]^{1/5} \sim 10^5 \text{ eV} \left(\frac{\Delta m^2}{1 \text{ eV}^2}\right)^{2/5} \left(\frac{\sin 2\theta_v}{0.1}\right)^{2/5}.$$

Careful analysis required, many effects

- Heavy mediator, Light mediator, Resonant, Oscillation dominated, Collision dominated, Non-freestreaming at CMB epoch ...

- We find that for the oscillation parameters suggested by the oscillation "anomalies" the thermalization temperature has a fundamental lower limit

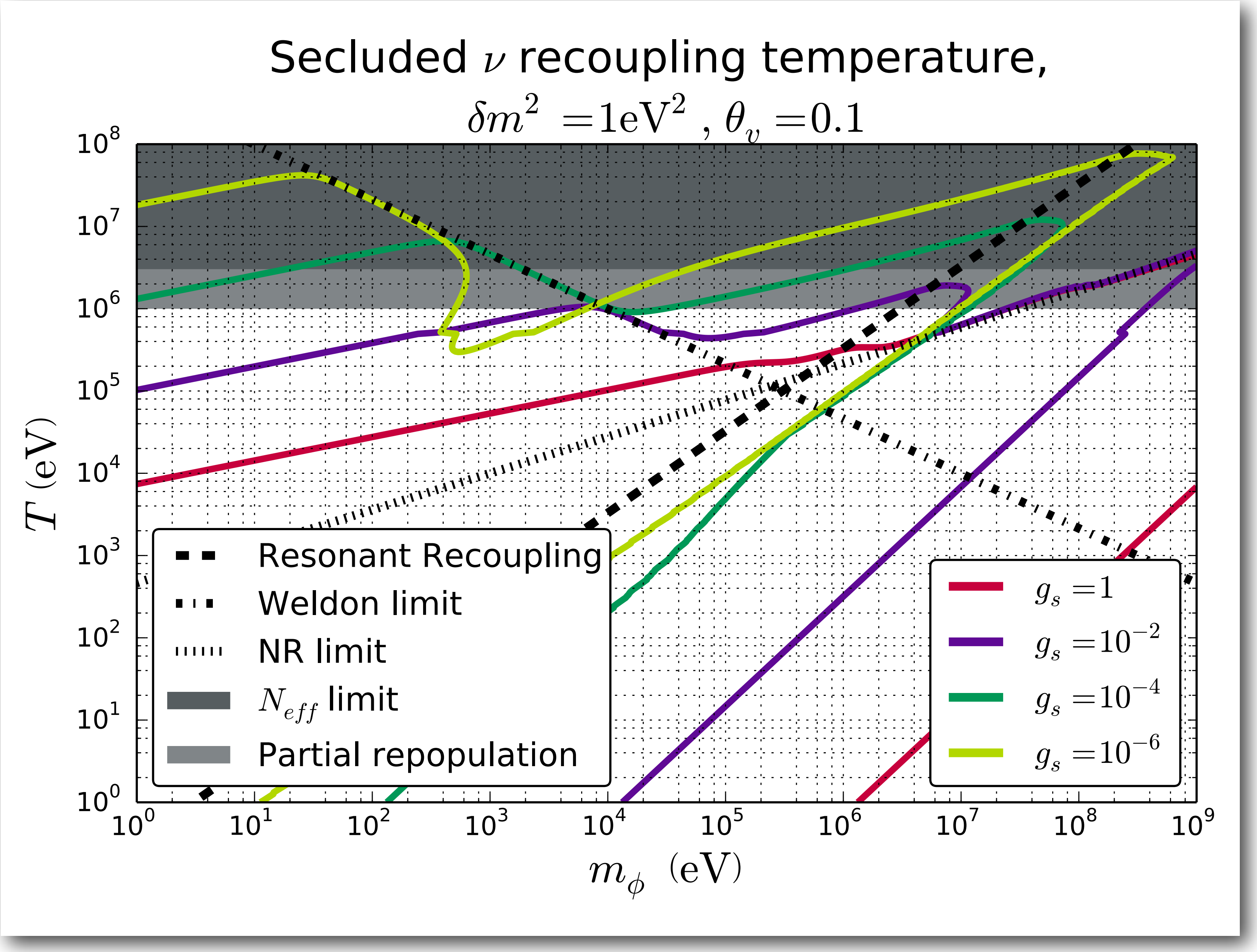
$$T_0 \sim (\sin^2 2\theta(\Delta m^2)^2 M_{pl})^{1/5} \sim 200 \text{ keV}$$

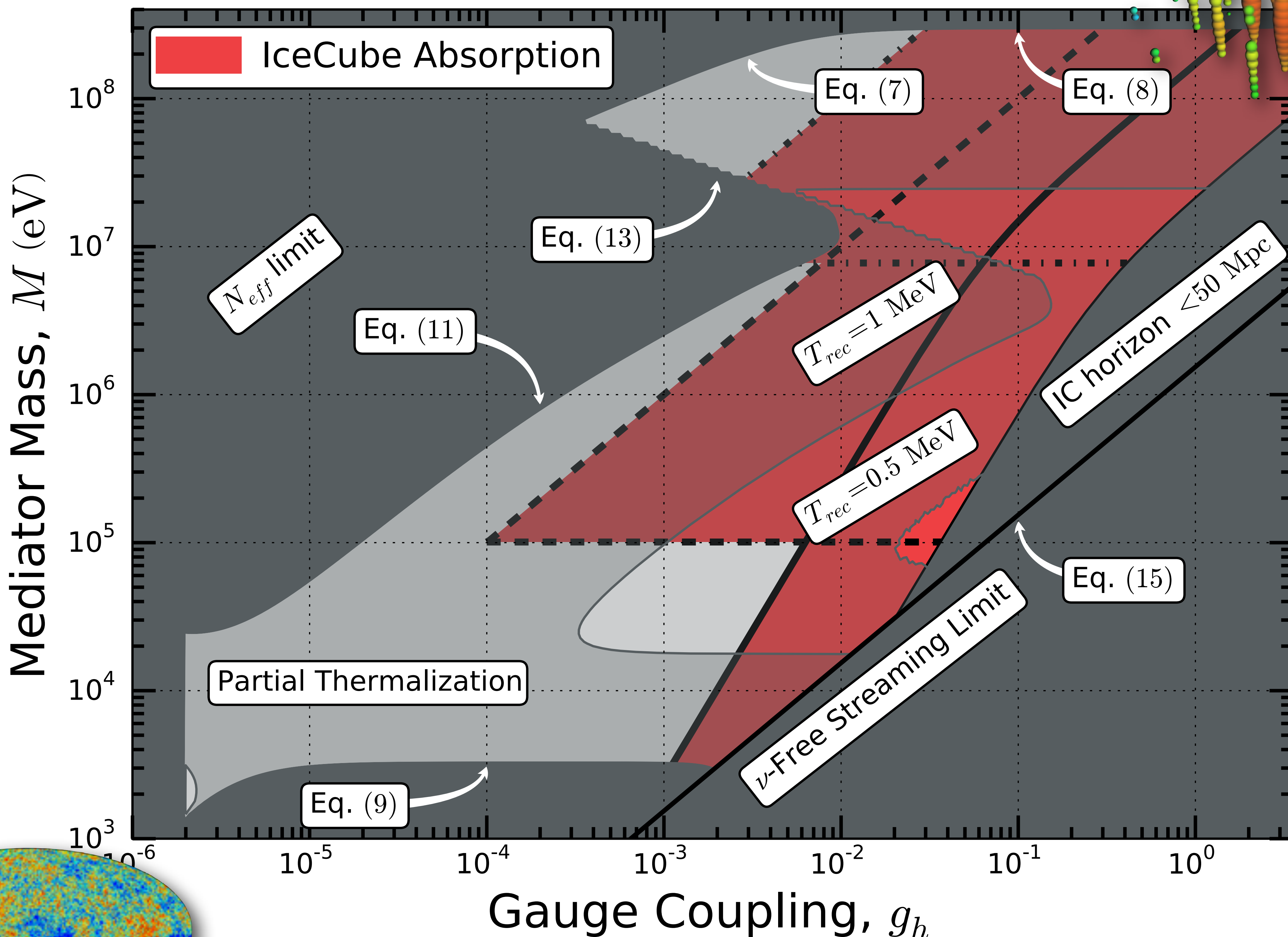
- This is close to 1 MeV of weak decoupling. The BR mechanism is thus only marginally successful.

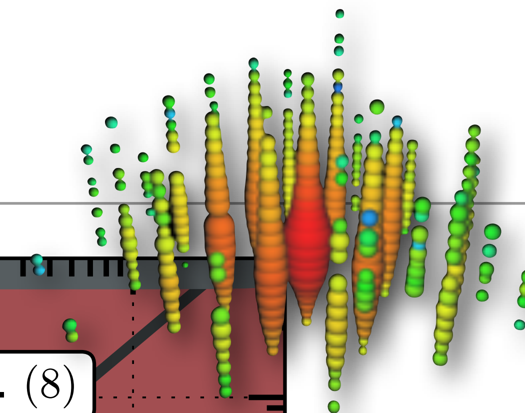
Cherry, A. F., Shoemaker, arXiv:1605.06506

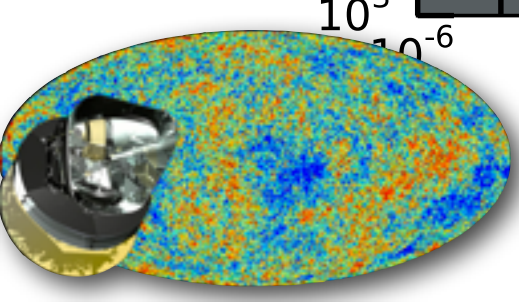
Recoupling isocontours

arXiv:1605.06506 for details



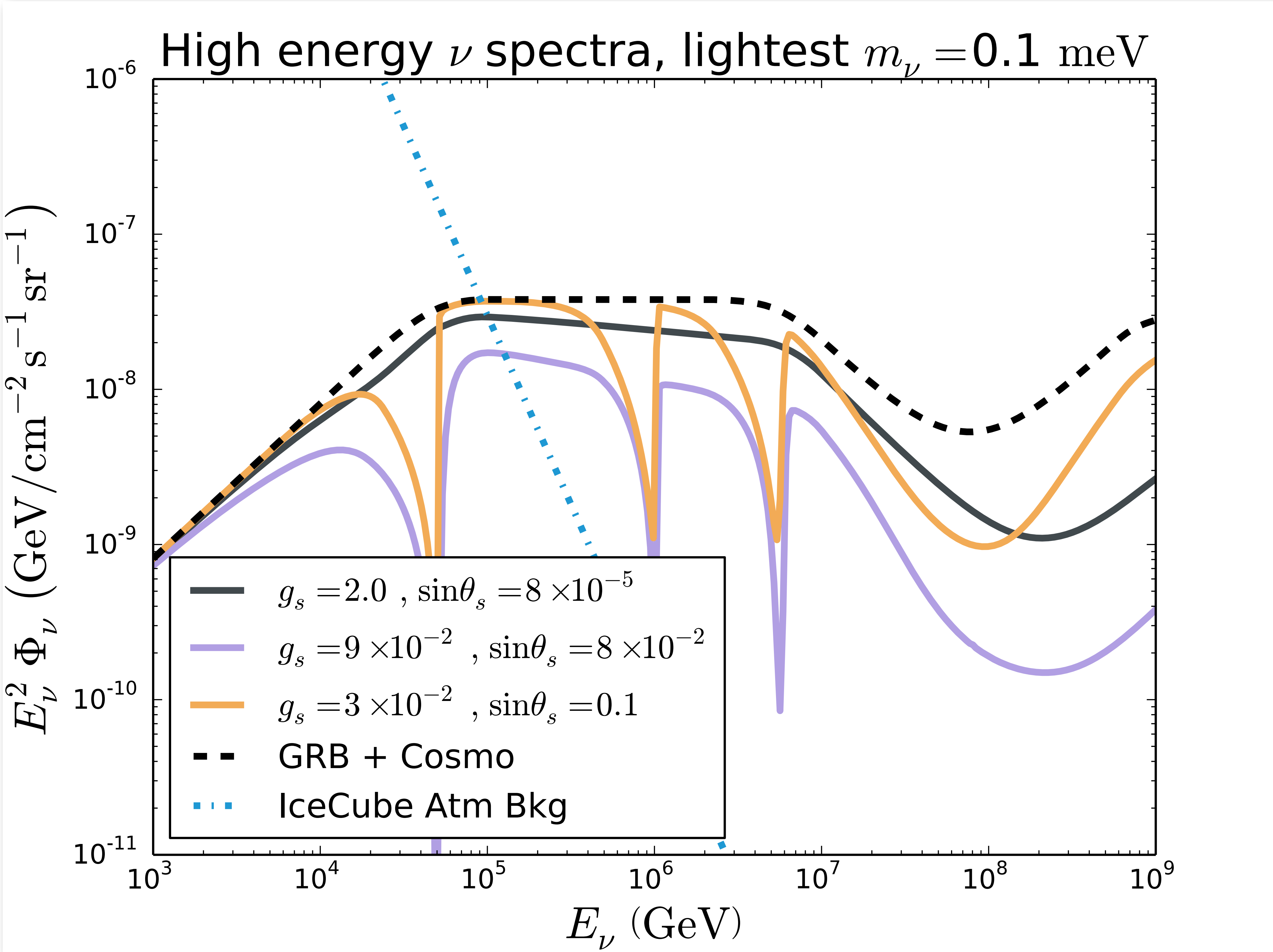

IceCube Absorption
Eq. (7)
Eq. (8)
Eq. (13)
N_{eff} limit
Eq. (11)
T_{rec}=1 MeV
IC horizon <50 Mpc
T_{rec}=0.5 MeV
Eq. (15)
Partial Thermalization
ν-Free Streaming Limit
Eq. (9)
Mediator Mass, M (eV)
Gauge Coupling, g_h
10^3
10^4
10^5
10^6
10^7
10^8
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^0





Neutrino-neutrino collider?

- We need to collide neutrino mass eigenstates, which have admixture of the “sterile” component that gives them new interactions
- Not feasible in the lab, but we can use the universe as the experimental setup
- **Icecube** has observed neutrinos in the PeV energy range, that likely originate from cosmological distances. These neutrinos on their way to us travel through the relic neutrino background.
- Inside a **core-collapse supernova?** It would be good to understand what this does to the explosion/ neutrino signal



Example calculation

See talk at Miami 2014:
https://cgc.physics.miami.edu/Miami2014/Friedland2014.pdf

Final thoughts

- A number of requests
  - Neutrino signals up to 10 sec in consistent 2D simulations
  - Neutrino-Argon interactions (better nuclear physics)
  - Detailed matter distributions behind the expanding shock
  - Detailed distributions of streaming neutrinos (energies, impact parameters)
  - Explosion simulations with modified neutrino-neutrino scattering
- “Supernovae are very complicated systems, nonlinear and with a lot of feedbacks. When you put your favorite effect in, the answer comes out 10 times smaller than what you thought. And with the opposite sign.” Paraphrasing Georg Raffelt