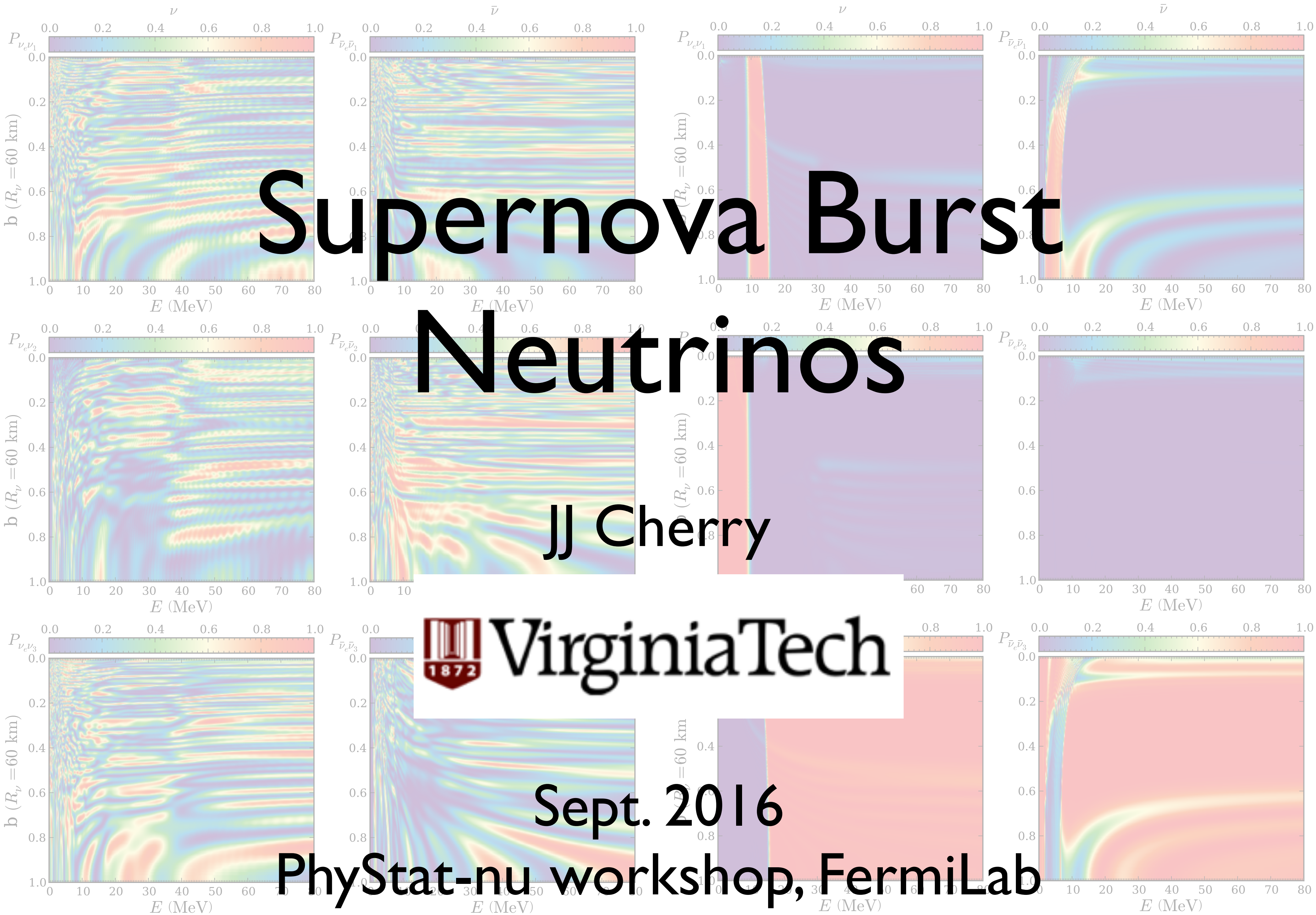


Supernova Burst Neutrinos

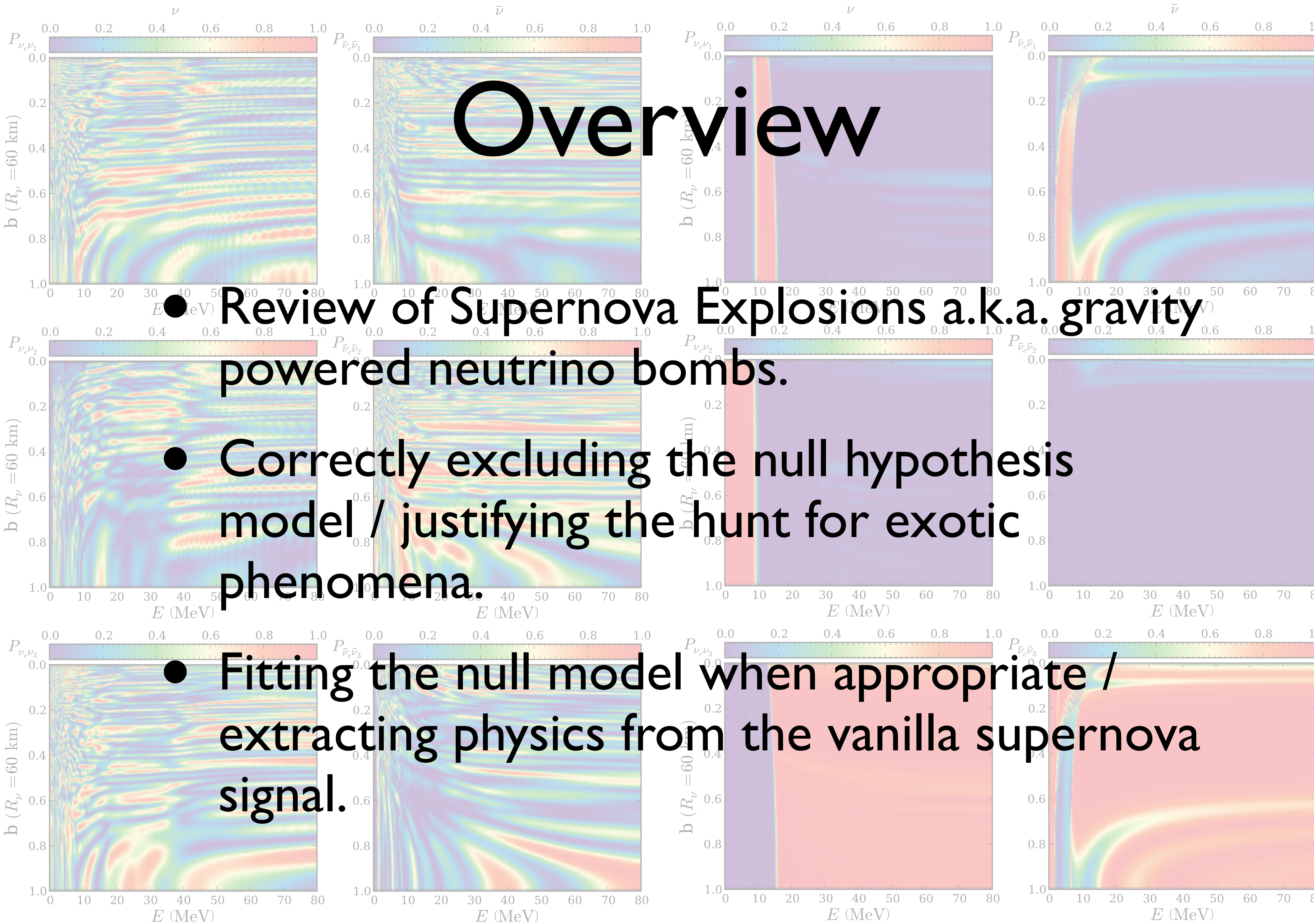
JJ Cherry

VirginiaTech

Sept. 2016

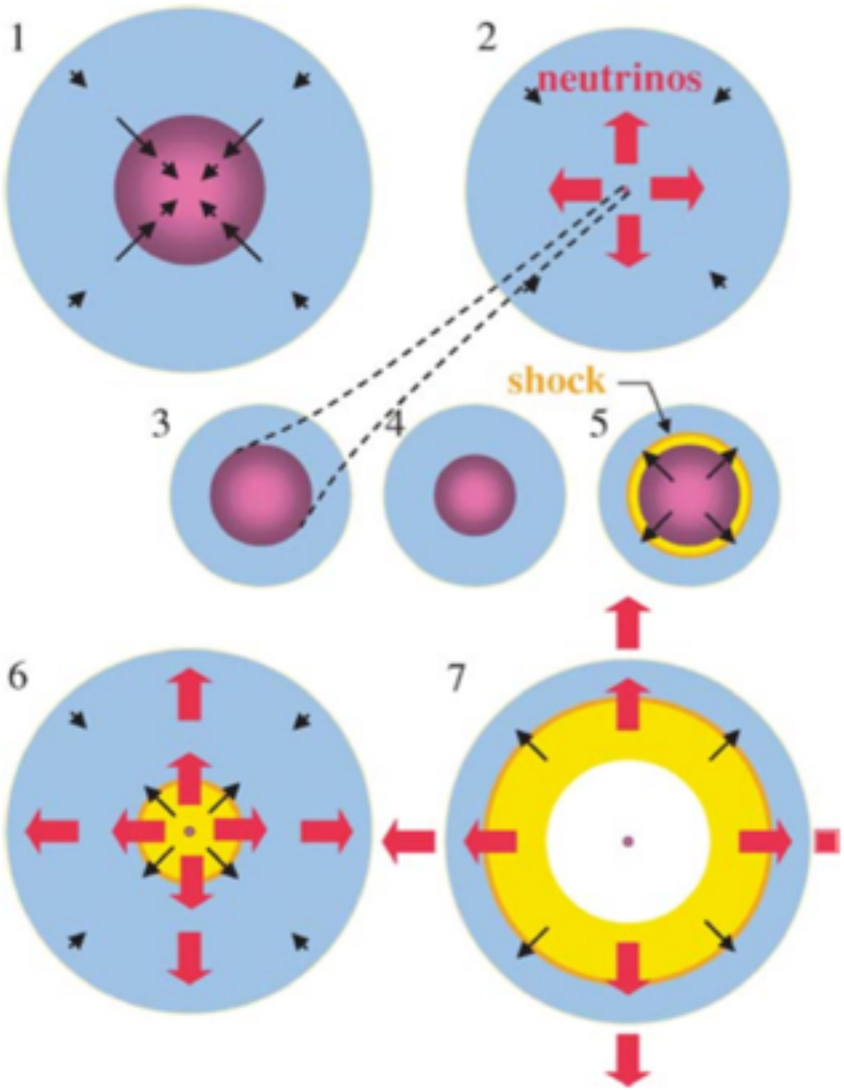
PhyStat-nu workshop, FermiLab

Overview



- Review of Supernova Explosions a.k.a. gravity powered neutrino bombs.
- Correctly excluding the null hypothesis model / justifying the hunt for exotic phenomena.
- Fitting the null model when appropriate / extracting physics from the vanilla supernova signal.

Core Collapse



Collapse releases .14 $M_\odot$ of gravitational binding energy, 99% of which is trapped as thermal energy in the core. This thermal energy is then re-radiated as neutrinos of all flavors.

What does it take to blow up a star?

- About one Bethe of energy.

$$1\,\mathrm{B} = 10^{51}\,\mathrm{erg}$$

- The initial shock has this much energy, but is stalled by photodissociation.

- The thermal energy trapped in the core is huge! $\sim 300B$

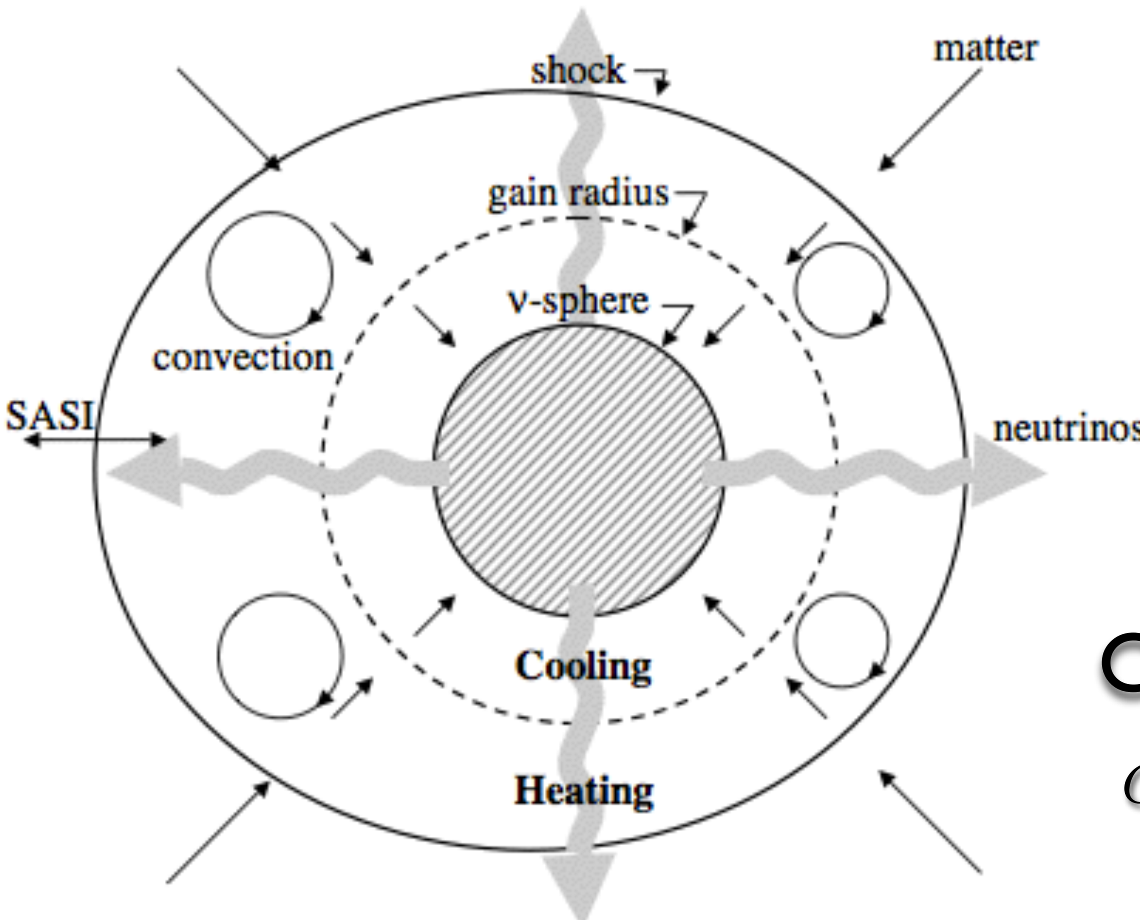
Shock Reheating

- Thermal energy of the PNS emerges as neutrinos of all flavors.

$$L_\nu \sim 10^{51} - 10^{53}\,\mathrm{erg\,s^{-1}}$$

- Neutrino cross sections are just too small to effectively heat the shocked region alone. Large scale convection is necessary to increase the efficiency of the neutrino heating.

Standing Accretion Shock Instability



Neutrino heating and cooling work very differently:

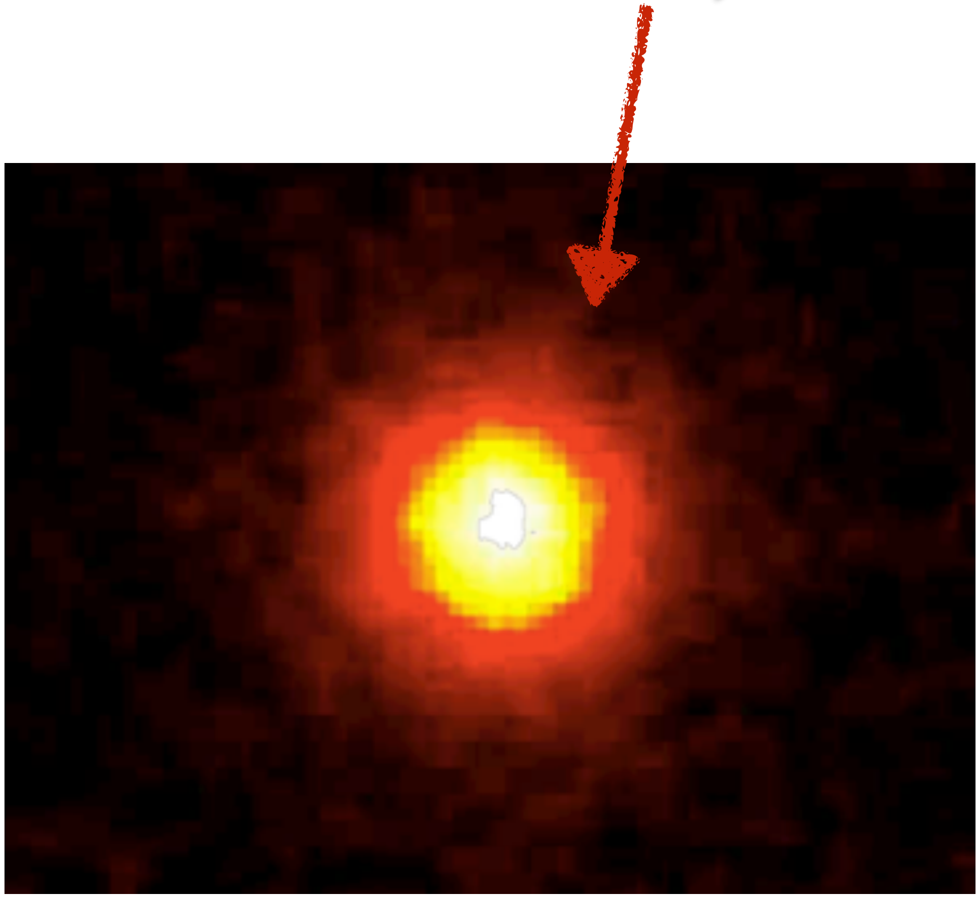
Heating: $$H \propto \frac{L_\nu \langle E^2 \rangle}{r^2}$$

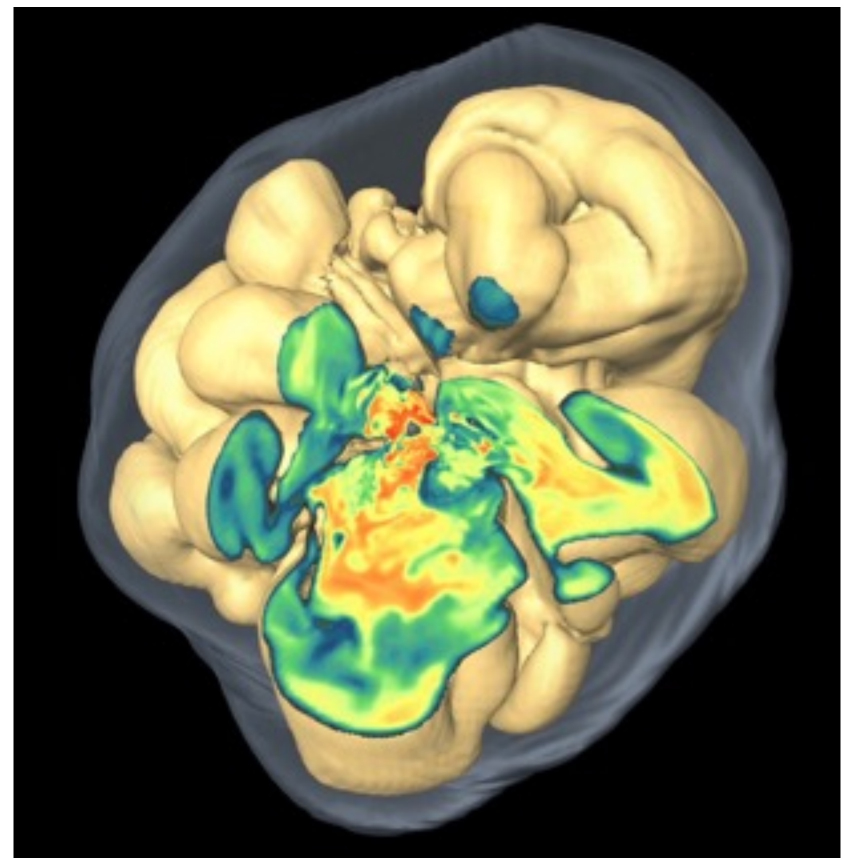
Cooling:
$$C \sim 1.4 \times 10^{20} \left(\frac{T}{2\,\mathrm{MeV}} \right)^6 \mathrm{erg\,g^{-1}\,s^{-1}}$$

Neutrino eyes?

Neutrinos can see through to the heart of the explosion.

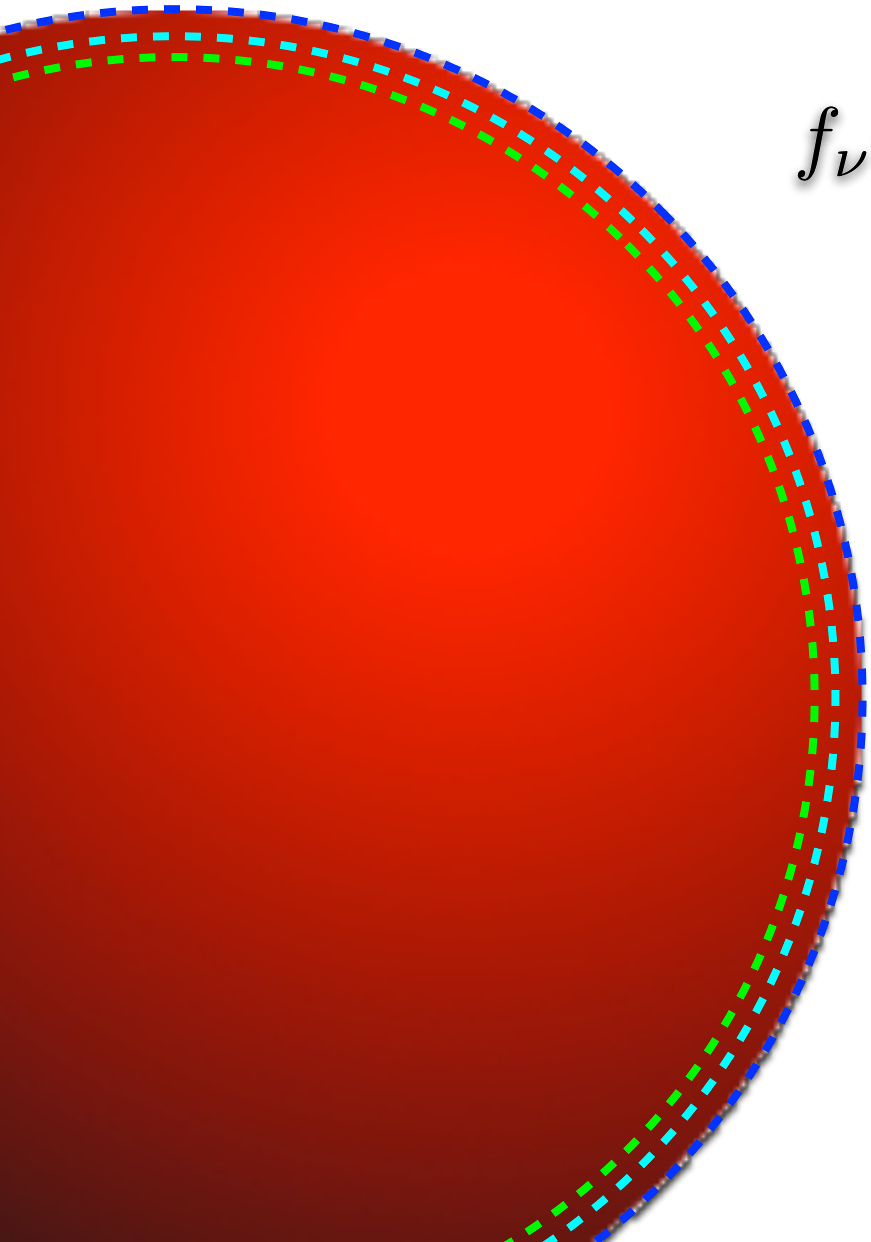
The sun, in neutrinos (via Super-K)





F. Hanke, A. Marek, B. Müller & H. Th. Janka, Astrophys. J. **775**, 138H (2012), 1108.4355.

The Neutrinosphere



$$f_\nu(E_\nu) = \left(\frac{E_\nu}{\langle E_\nu \rangle}\right)^{\alpha_\nu} \exp^{-(\alpha_\nu+1)\frac{E_\nu}{\langle E_\nu \rangle}}$$

$\nu_{\mu/\tau}$ and $\bar{\nu}_{\mu/\tau}$, NC only

ν_{e} and $\bar{\nu}_{\mathrm{e}}$, NC and CC

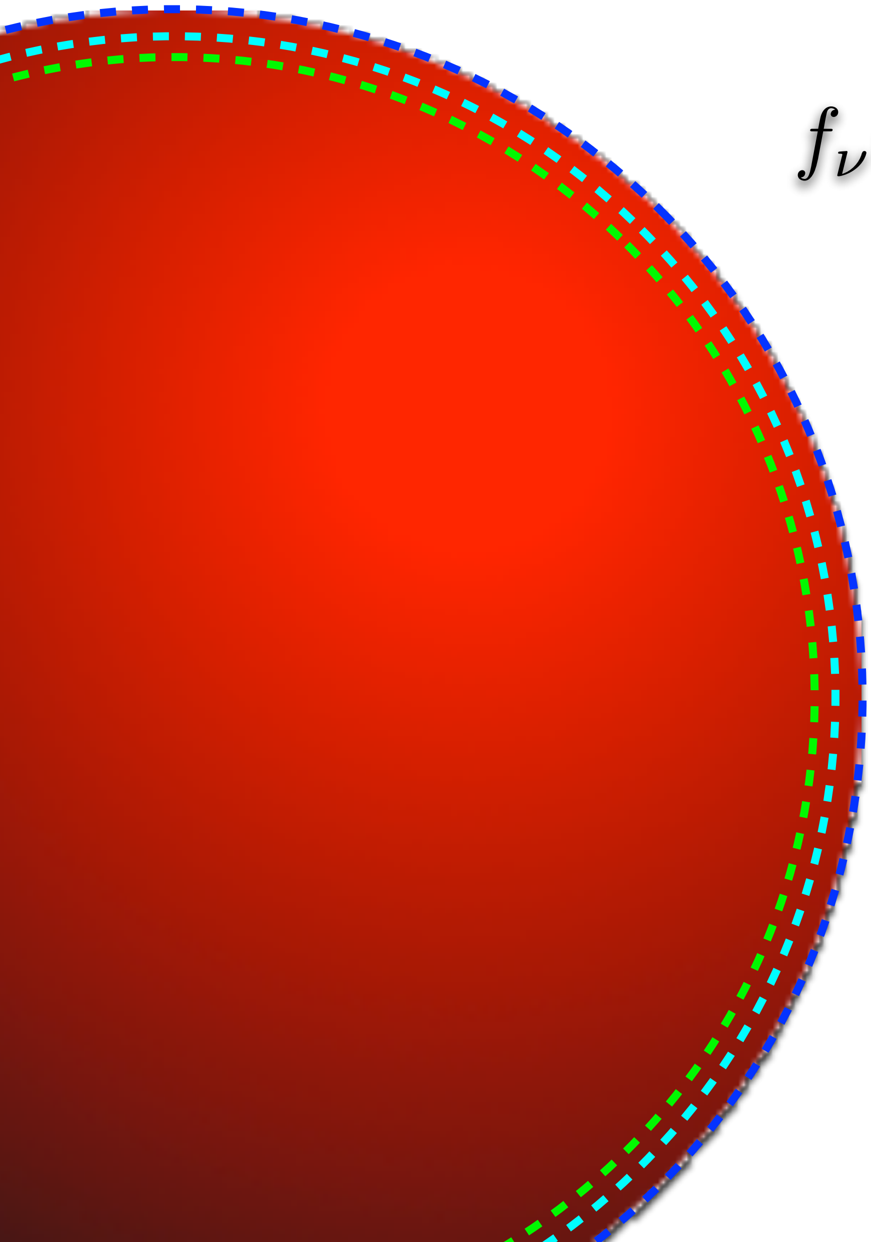
$$\langle E_{\nu_{\mu/\tau},\bar{\nu}_{\mu/\tau}} \rangle > \langle E_{\bar{\nu}_e} \rangle > \langle E_{\nu_e} \rangle$$

Decreasing $T \rightarrow$

Decreasing $\rho \rightarrow$

Model, H_0

The ~~Neutrinosphere~~



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Decreasing $T \rightarrow$

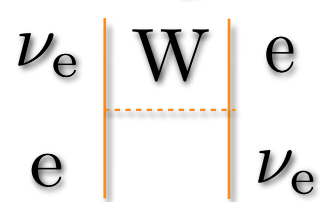
Decreasing $\rho \rightarrow$

Coherent Forward Scattering in Supernovae

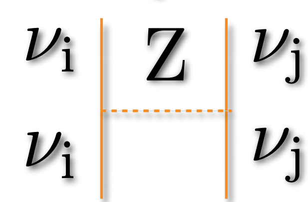
$$\psi_{\nu,\mathrm{i}} = \begin{bmatrix} \text{amplitude to be } \nu_\mathrm{e} \\ \text{amplitude to be } \nu_\mu \\ \text{amplitude to be } \nu_\tau \end{bmatrix}$$

$$i\frac{\partial}{\partial t}\psi_{\nu,\mathrm{i}} = \left(H_{\mathrm{vac,i}} + H_{\mathrm{e,i}} + H_{\nu\nu,\mathrm{i}}\right)\psi_{\nu,\mathrm{i}}$$

neutrino-electron
charged current
forward exchange
scattering



neutrino-neutrino
neutral current
forward scattering



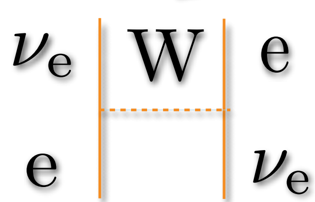
Coherent Forward Scattering in Supernovae

$$\psi_{\nu,\mathrm{i}} = \begin{bmatrix} \text{amplitude to be } \nu_\mathrm{e} \\ \text{amplitude to be } \nu_\mu \\ \text{amplitude to be } \nu_\tau \end{bmatrix}$$

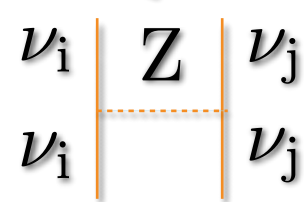
Model, H_1

$$i\frac{\partial}{\partial t}\psi_{\nu,\mathrm{i}} = \left(H_{\mathrm{vac,i}} + H_{\mathrm{e,i}} + H_{\nu\nu,\mathrm{i}}\right)\psi_{\nu,\mathrm{i}}$$

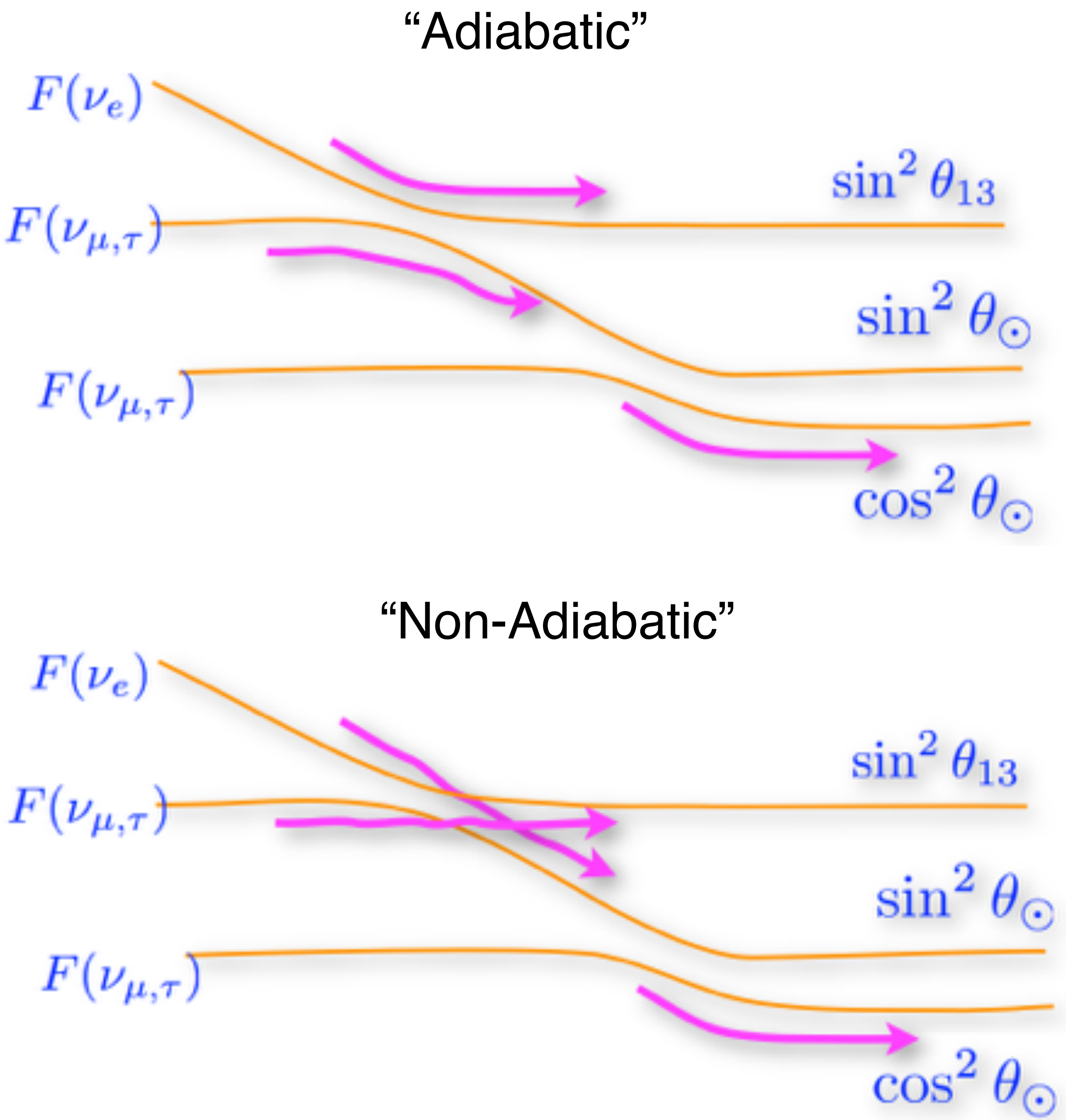
neutrino-electron charged current forward exchange scattering



neutrino-neutrino neutral current forward scattering



Matter Effects



Matter effects via the MSW mechanism:

Adiabatic Transformation

Shock induced flavor transformation

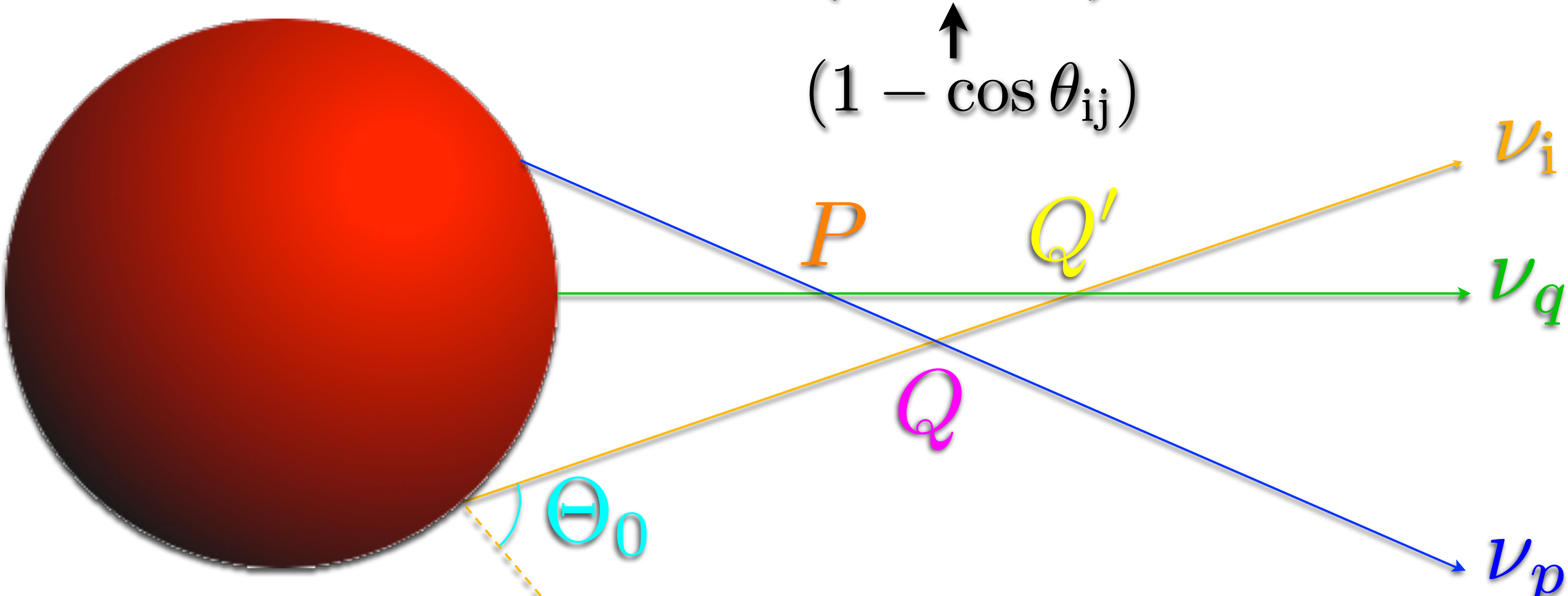
Turbulence driven flavor decoherence

Neutrino Self-Coupling: Flavor States and Geometry

$$H_{\nu\nu,\mathrm{i}} = \sqrt{2}G_{\mathrm{F}} \sum_{\mathrm{j}} \left(1 - \hat{k}_{\mathrm{i}} \cdot \hat{k}_{\mathrm{j}}\right) n_{\nu,\mathrm{j}} \psi_{\nu,\mathrm{j}} \psi^{\dagger}_{\nu,\mathrm{j}}$$
$$-\sqrt{2}G_{\mathrm{F}} \sum_{\mathrm{j}} \left(1 - \hat{k}_{\mathrm{i}} \cdot \hat{k}_{\mathrm{j}}\right) n_{\bar{\nu},\mathrm{j}} \psi_{\bar{\nu},\mathrm{j}} \psi^{\dagger}_{\bar{\nu},\mathrm{j}}$$

↑

$$(1 - \cos\theta_{\mathrm{ij}})$$

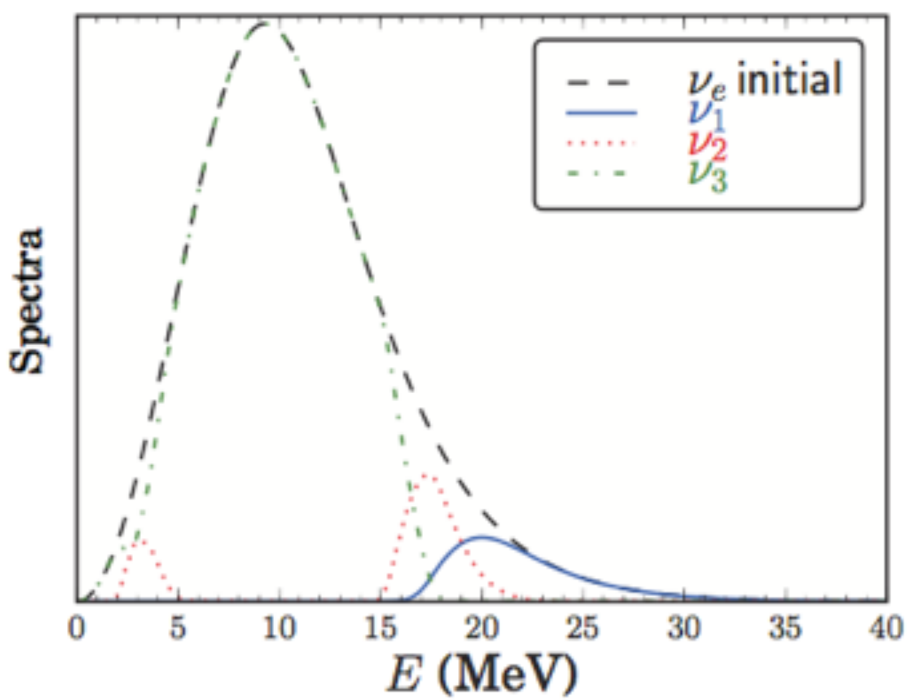


All together, we solve about $10^6 - 10^7$ non-linearly coupled differential equations at each radial step.

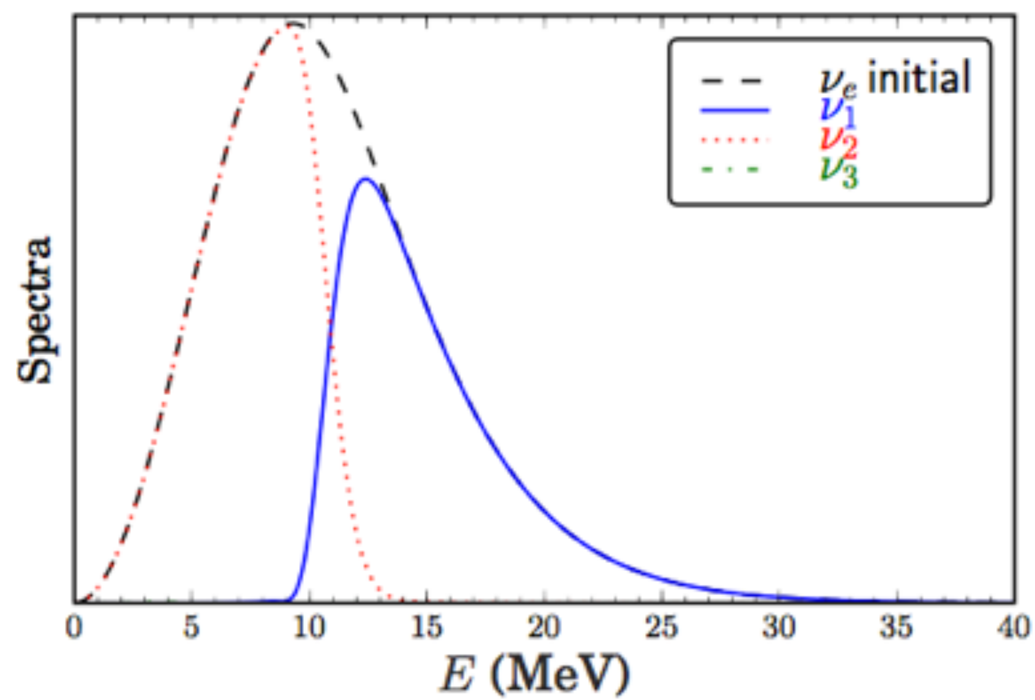
Huaiyu Duan, George M. Fuller, J. Carlson, and Yong-Zhong Qian, Phys. Rev. D 74,105014 (2006)

Collective Oscillation Signatures

Normal Neutrino Mass Hierarchy



Inverted Neutrino Mass Hierarchy



J. F. Cherry, G. M. Fuller, J. Carlson, H. Duan, and Y.-Z. Qian, Phys. Rev. D, **82**, 085025 (2010), 1006.2175.

Progenitor dependent evolution and signals

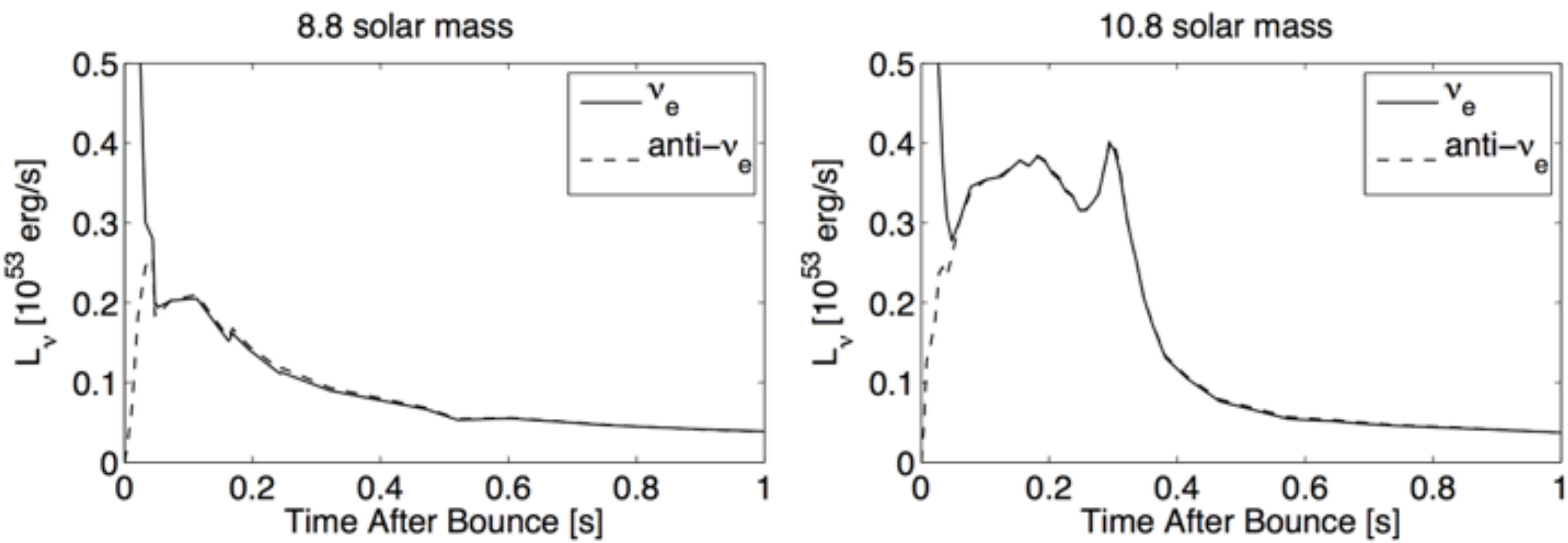
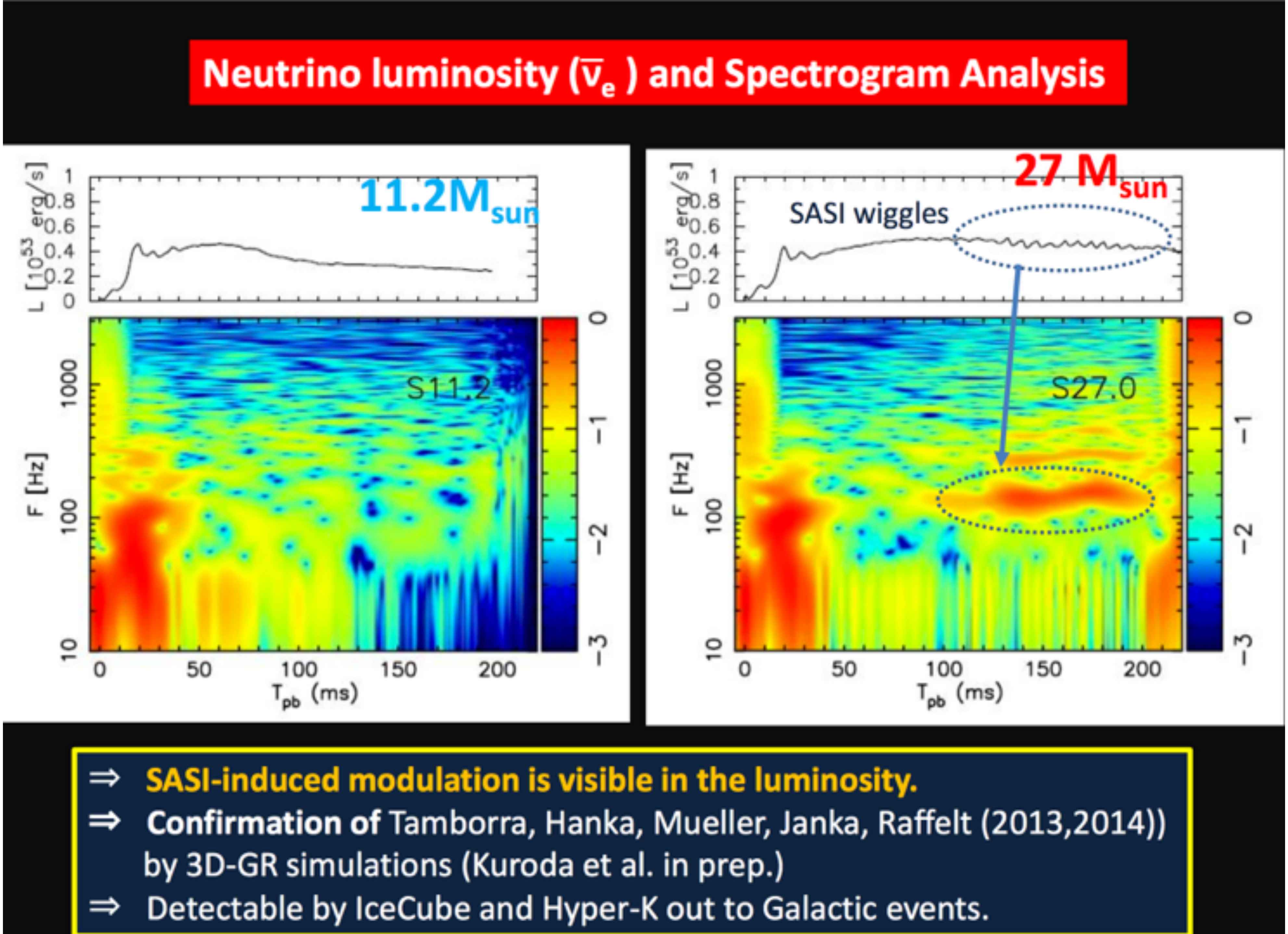
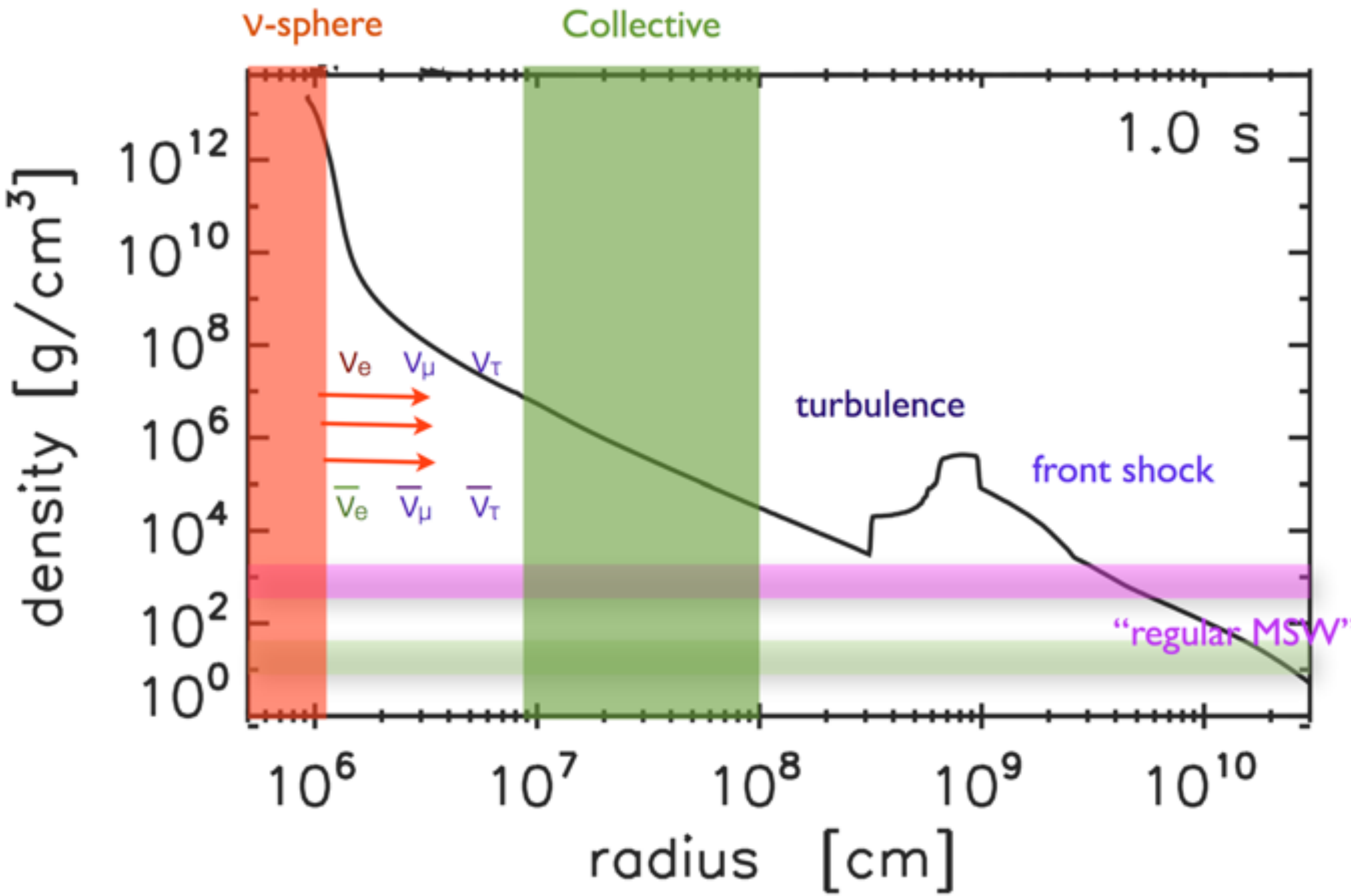


Fig from Fischer, Whitehouse, Mezzacappa, Thielemann, Liebendörfer, arXiv:0908.1871

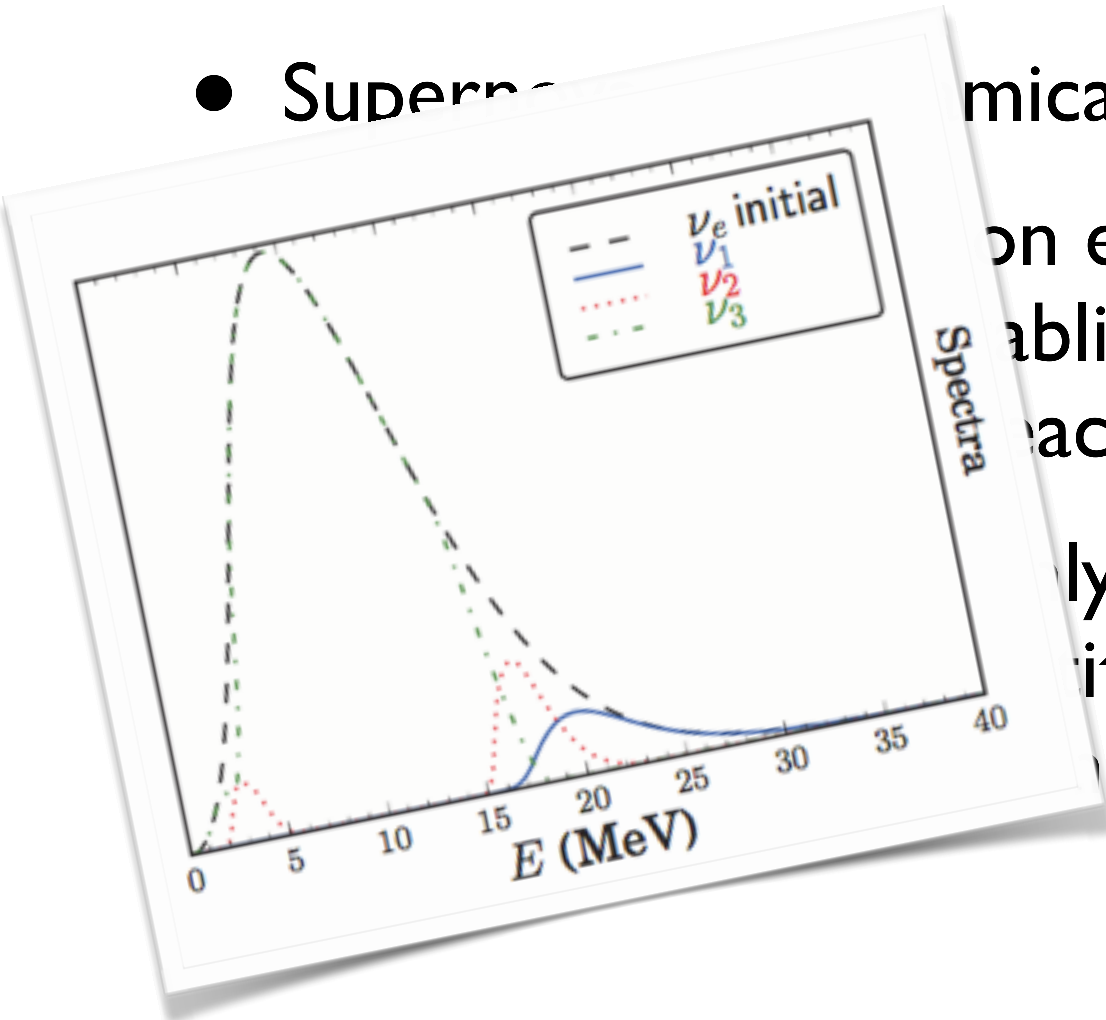


Slide and Data Courtesy of: Kei Kotake, INT Workshop INT-16-61W
Flavor Observations with Supernova Neutrinos

Cartoon Supernova Environment



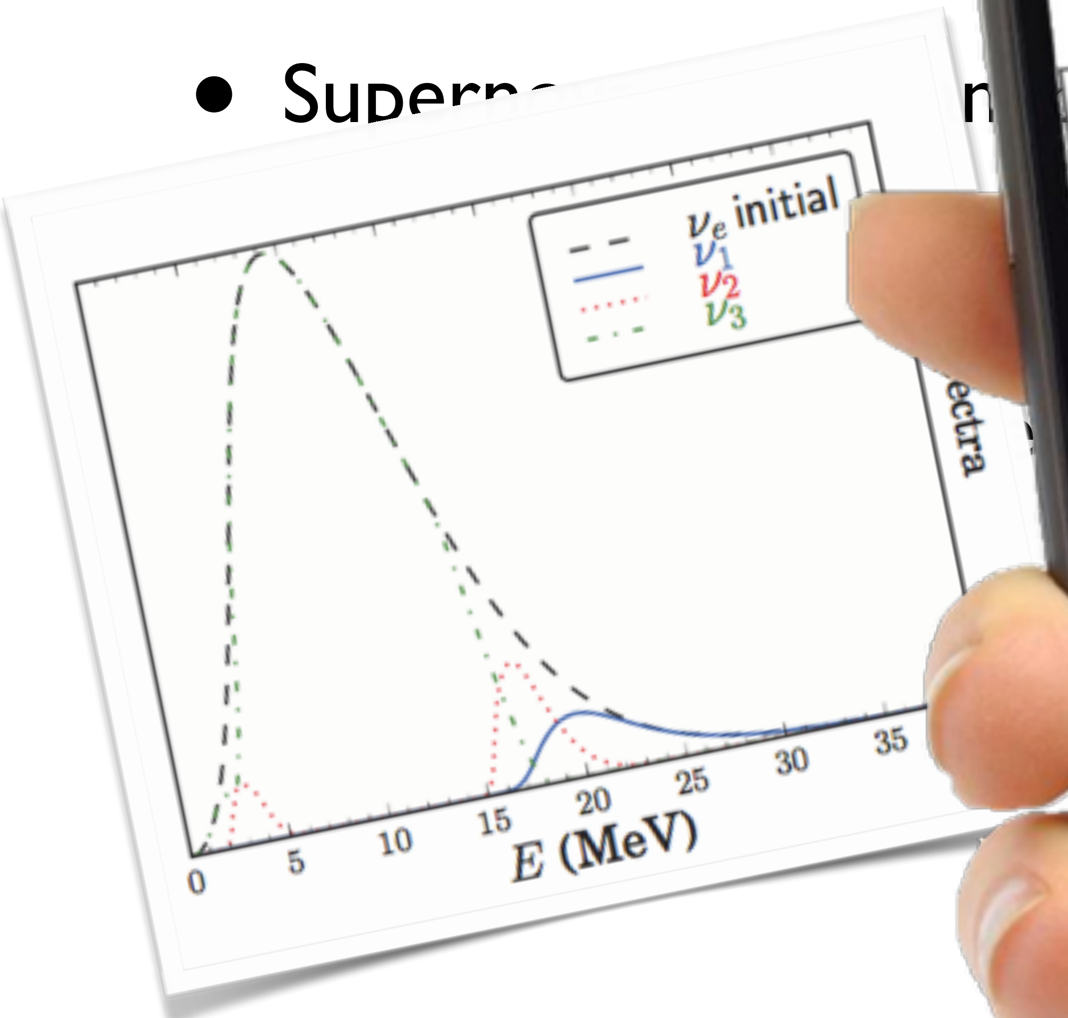
It is not enough to look at static spectra



- Supern... mical!
- ...on evolves rapidly with ...ablish a time series of ...each model.
- ...ly evenly in terms of ...titch them together ...e time resolution.

It is not eno k
at static

- Supern n



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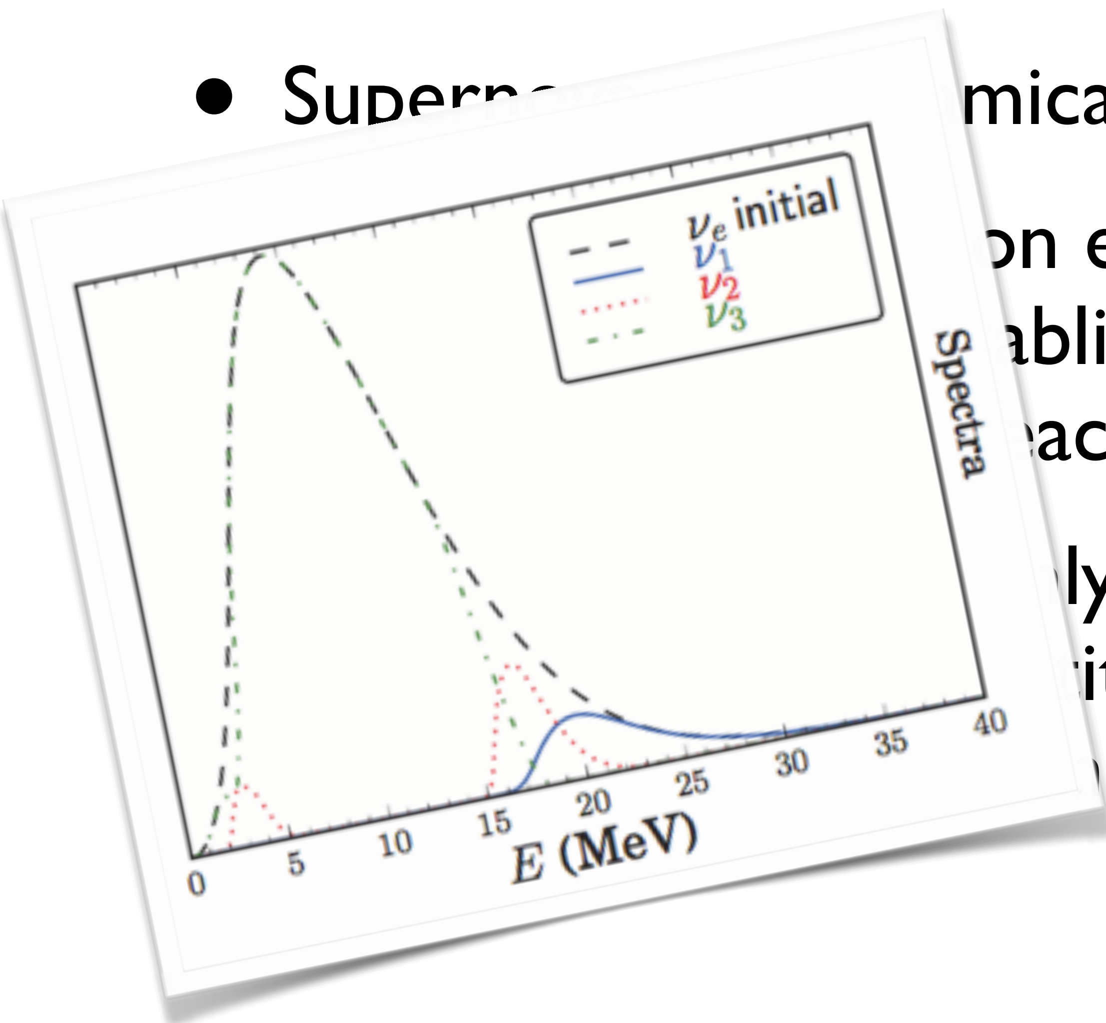
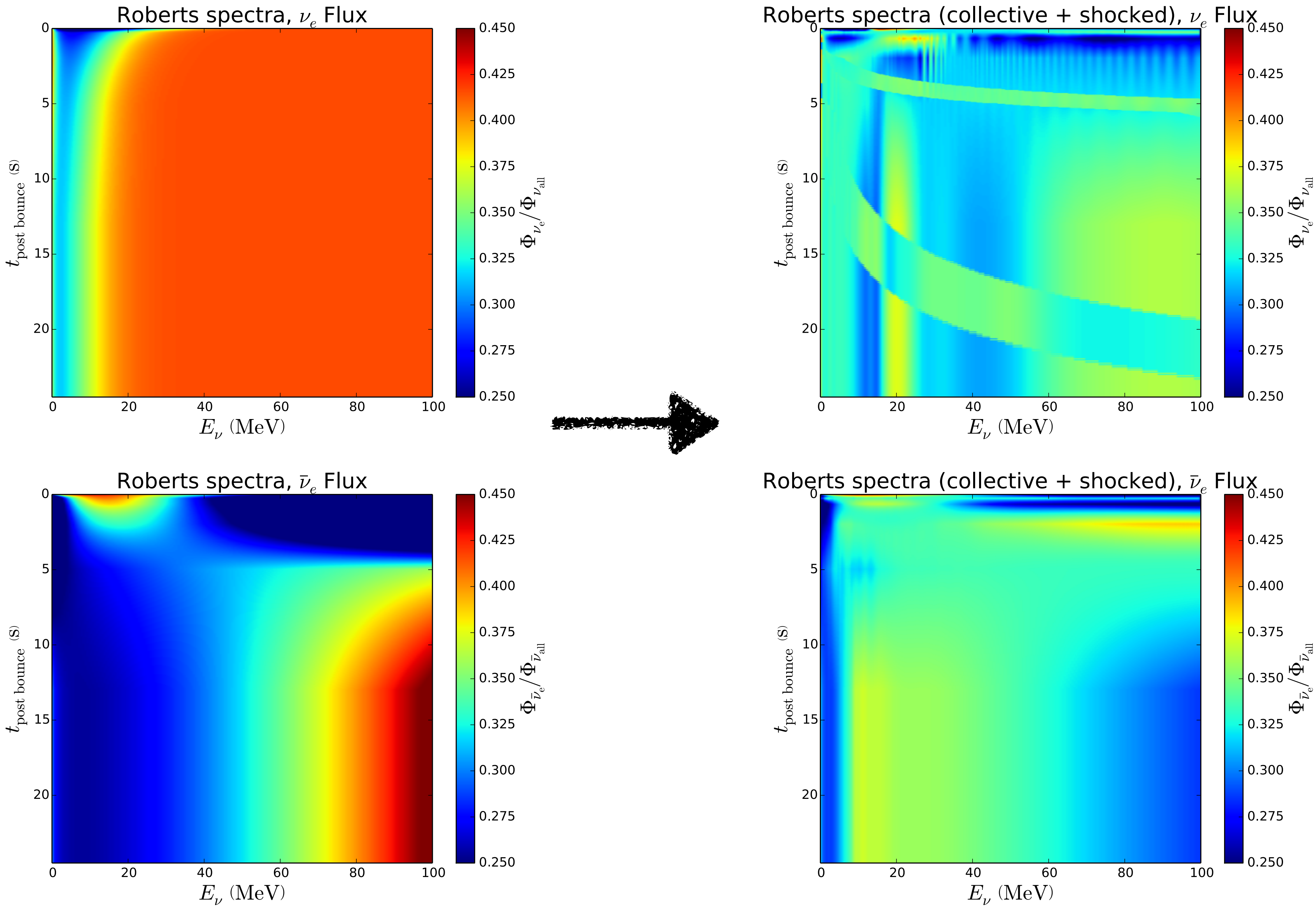


It is not enough to look at static spectra

- Supernova are dynamical!
- The neutrino emission evolves rapidly with time, so we must establish a time series of different spectra for each model.
- Space snapshots roughly evenly in terms of neutrino fluence and stitch them together with curve fitting for fine time resolution.

Stitch Snapshots Together



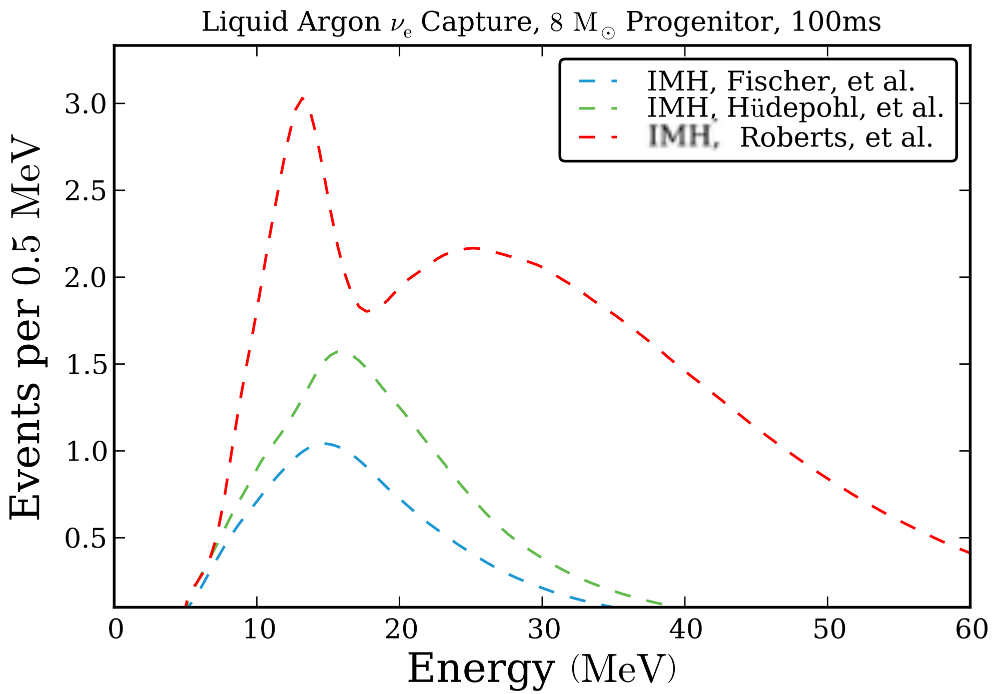
SNOwGLoBES

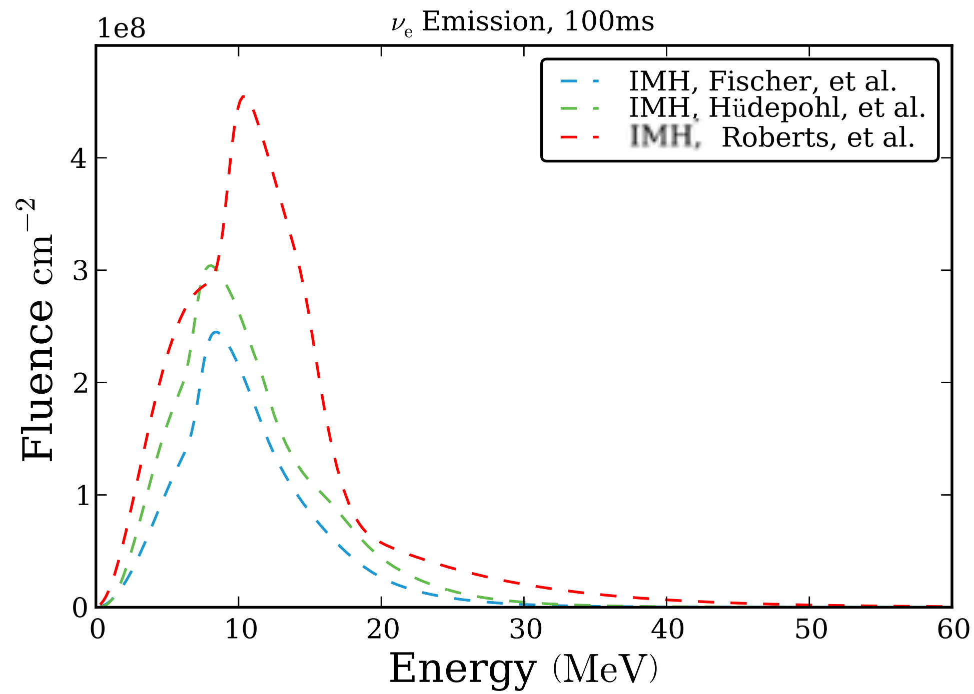
- Software tool designed to model neutrino events from core-collapse supernovae in terrestrial neutrino detectors.
- Developed by:

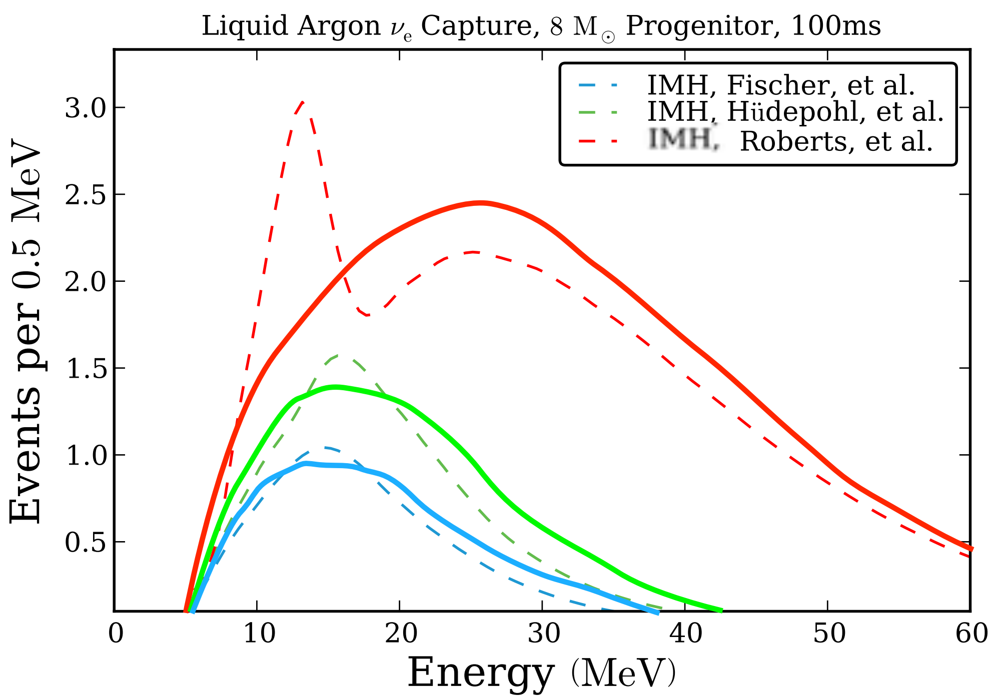
Alex Beck[1], Farzan Beroz[1], Rachel Carr[2], Huaiyu Duan[3], Alex Friedland[4], Nicolas Kaiser[5,1], Jim Kneller[6], Alexander Moss[1], Diane Reitzner[7], Kate Scholberg[1*], David Webber[8], Roger Wendell[1]

[1] Department of Physics, Duke University, Durham, NC 27705
[2] Department of Physics, Columbia University, New York, NY 10027
[3] Department of Physics, University of New Mexico, Albuquerque, NM, 87131
[4] Los Alamos National Laboratory, Los Alamos, NM, 87545
[5] Department of Physics, Karlsruhe Institute of Technology, Germany
[6] Department of Physics, North Carolina State University, Raleigh, NC, 27695
[7] Fermilab, Batavia, IL, 60510-5011
[8] Department of Physics, University of Wisconsin, Madison, WI, 53706-1390
[*] schol@phy.duke.edu

Errors of the 2nd Kind



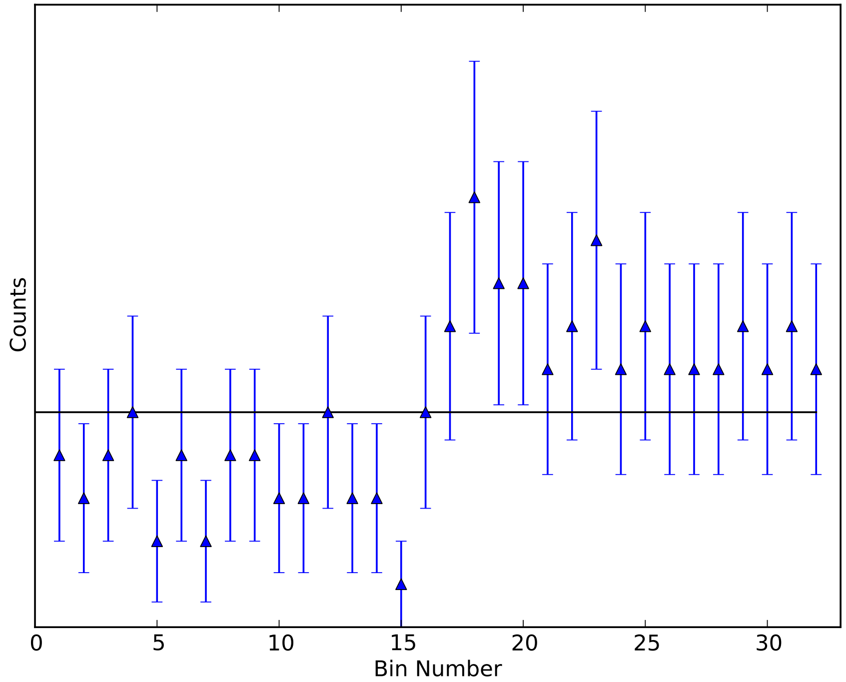


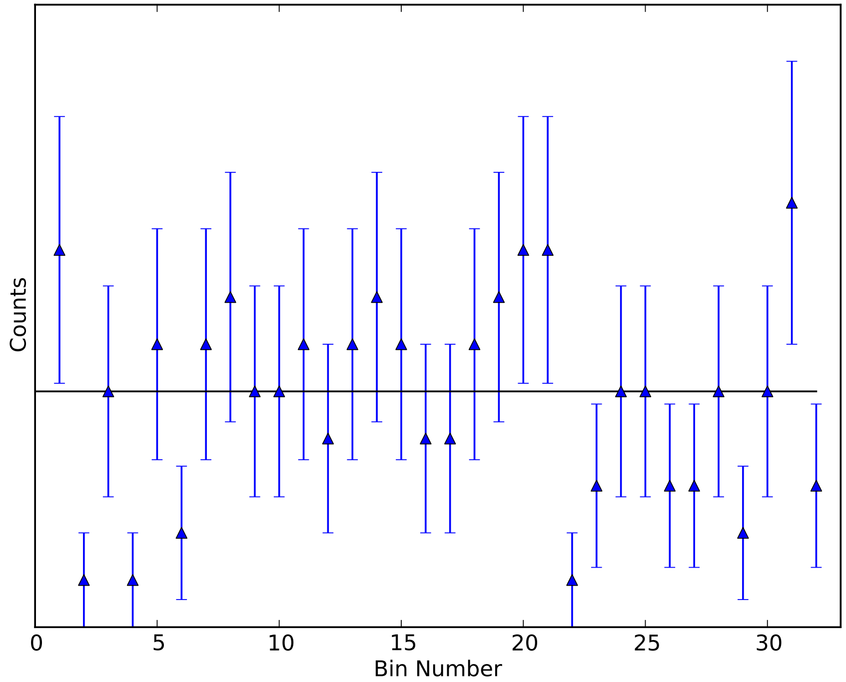


In spite of strong spectral features, fits of multi-component thermal spectra are not strongly in tension with event models.

Correlated Noise Should be Absent

Both data sets have identical χ^2





Correlation Coefficient

$$r = \frac{\sum_{i \neq j}^{n} (x_i - \bar{x}_i)(x_j - \bar{x}_j)}{\sqrt{\sum_{i \neq j}^{n} (x_i - \bar{x}_i)^2} \sqrt{\sum_{j \neq i}^{n} (x_j - \bar{x}_j)^2}}$$

Fisher Transformation: $F(r) = \text{arctanh}(r)$

F(r) has a Gaussian normal distribution about F(r0).

$$SE = \frac{1}{\sqrt{DOF - 3}}$$

$$z = [F(r) - F(r0)] \sqrt{DOF - 3}$$

$$P(z) = 1 + Erf\left(\frac{-z}{\sqrt{2}}\right)$$

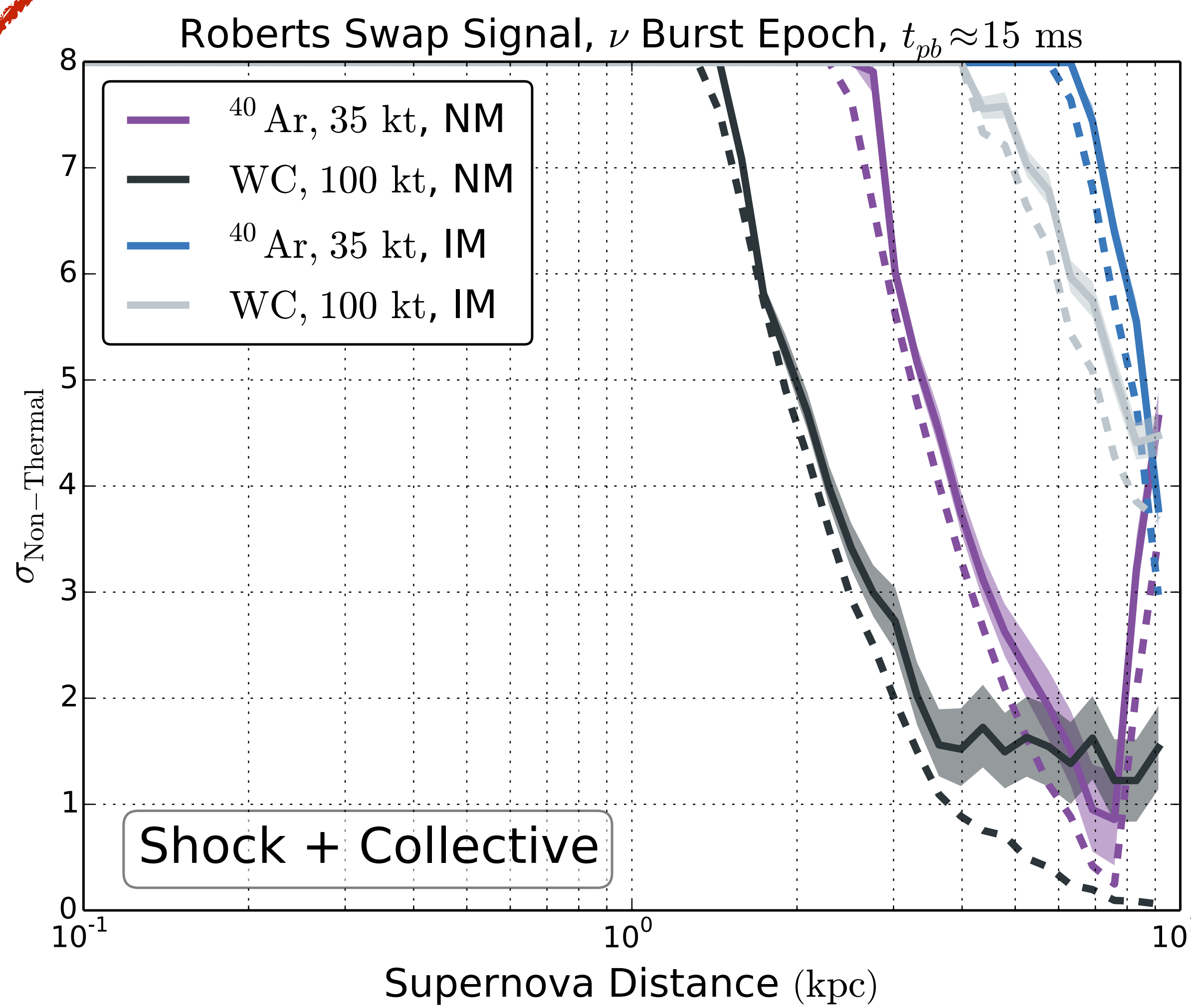
Null Hypothesis Exclusion

$$H_0\left(R, \langle E_{\nu_e,\bar{\nu}_e}\rangle, \langle E_{\nu_x}\rangle, \alpha_{\nu_e,\bar{\nu}_e}, \alpha_{\nu_x}\right)$$

$$\beta = P(\chi^2) \times P(z)$$

Minimize χ^2

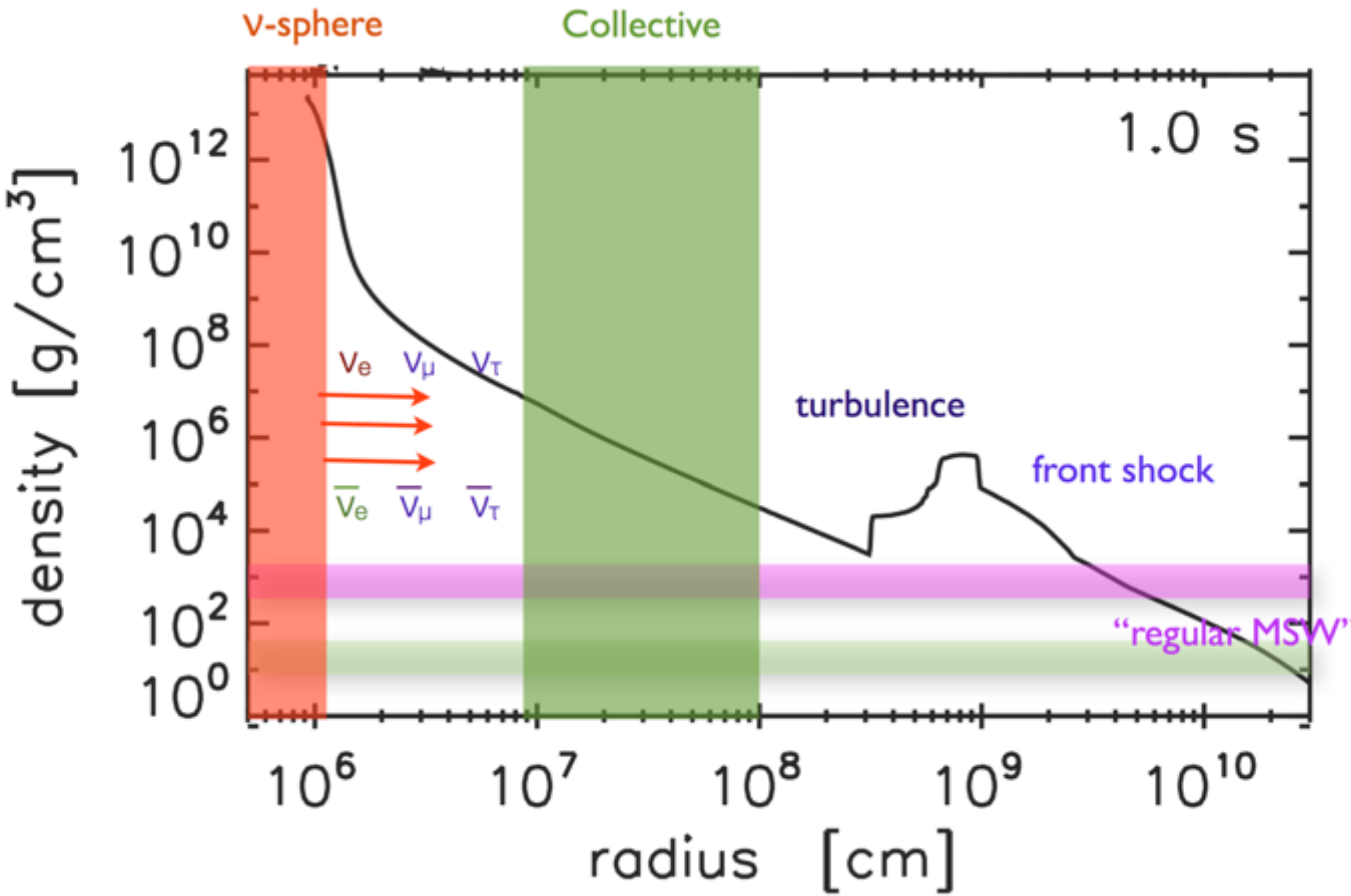
Compute z



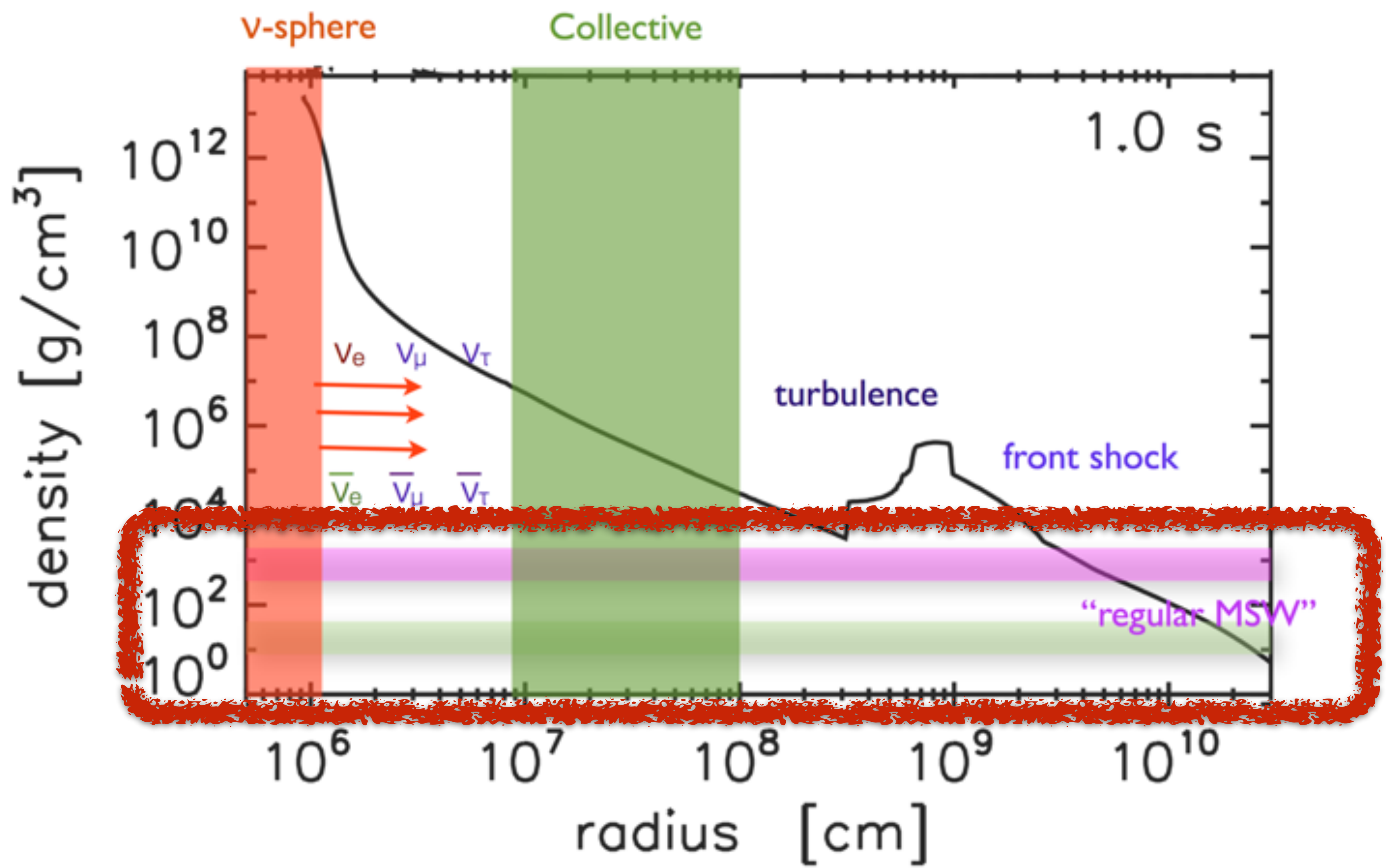
Let's say we observe thermal emission

- Preclude complicated oscillation physics early in the explosion.
- Try to properly fit the simplest case scenario: adiabatic MSW flavor conversion in the envelope.

Cartoon Supernova Environment



Cartoon Supernova Environment

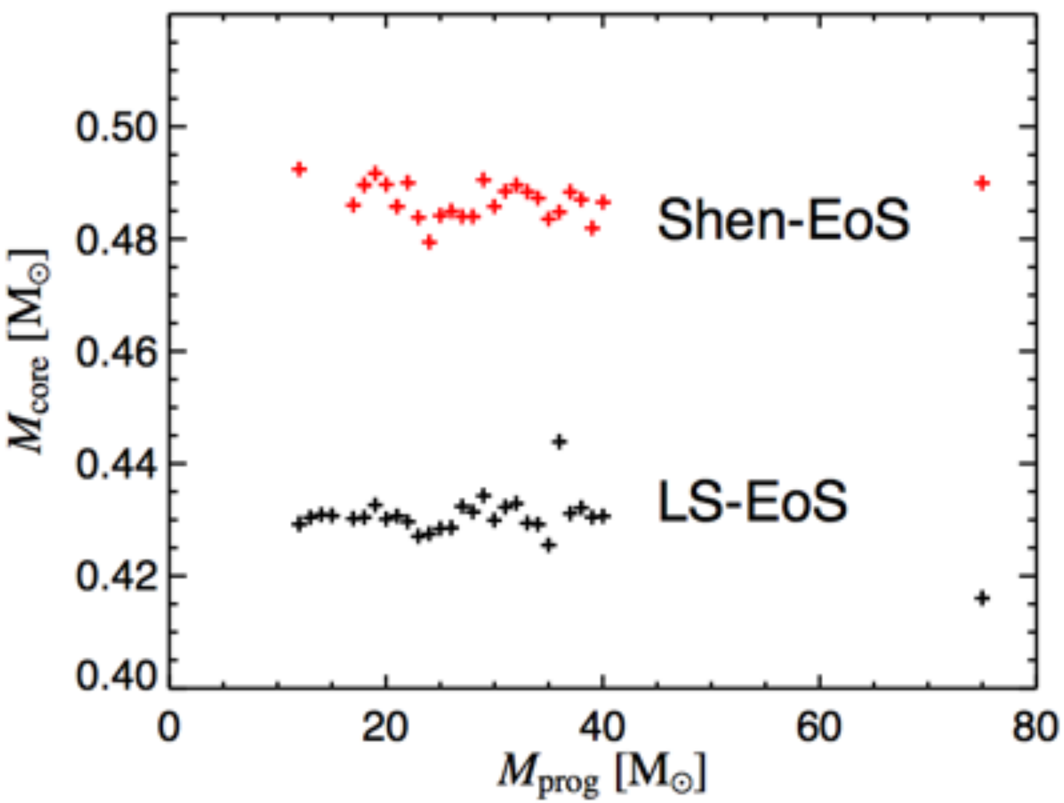


What are some likely Observables?

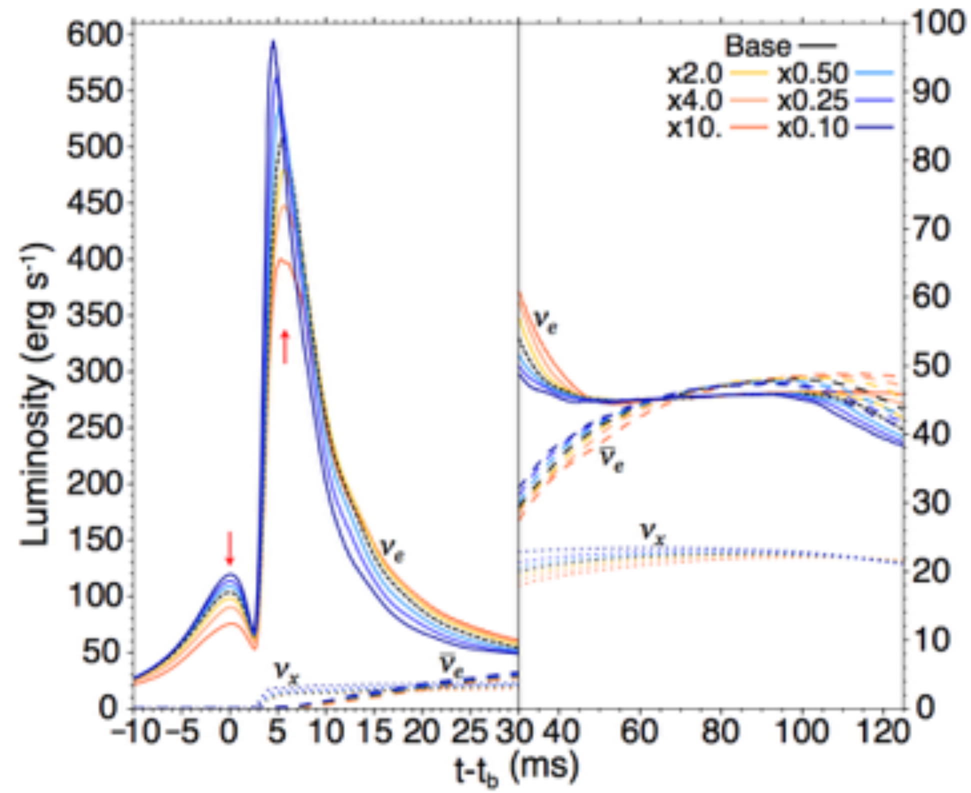
- ~.5 M_sun/M_p worth of electron lepton number should also be emitted.
- ~1 M_sun per second of matter is accreting on the surface of the PNS.
- Need detector complementarity to find it!
- Combine 40 kt LAr TPC (DUNE) with 374 kt WC detector (Hyper-K) and 50 kt Scintillator detector (Juno) to find relative $\nu_e \ vs. \ \bar{\nu}_e$

Lepton Fluence

10% precision or better needed to start doing science



Janka, H.-T., et al. (2013)

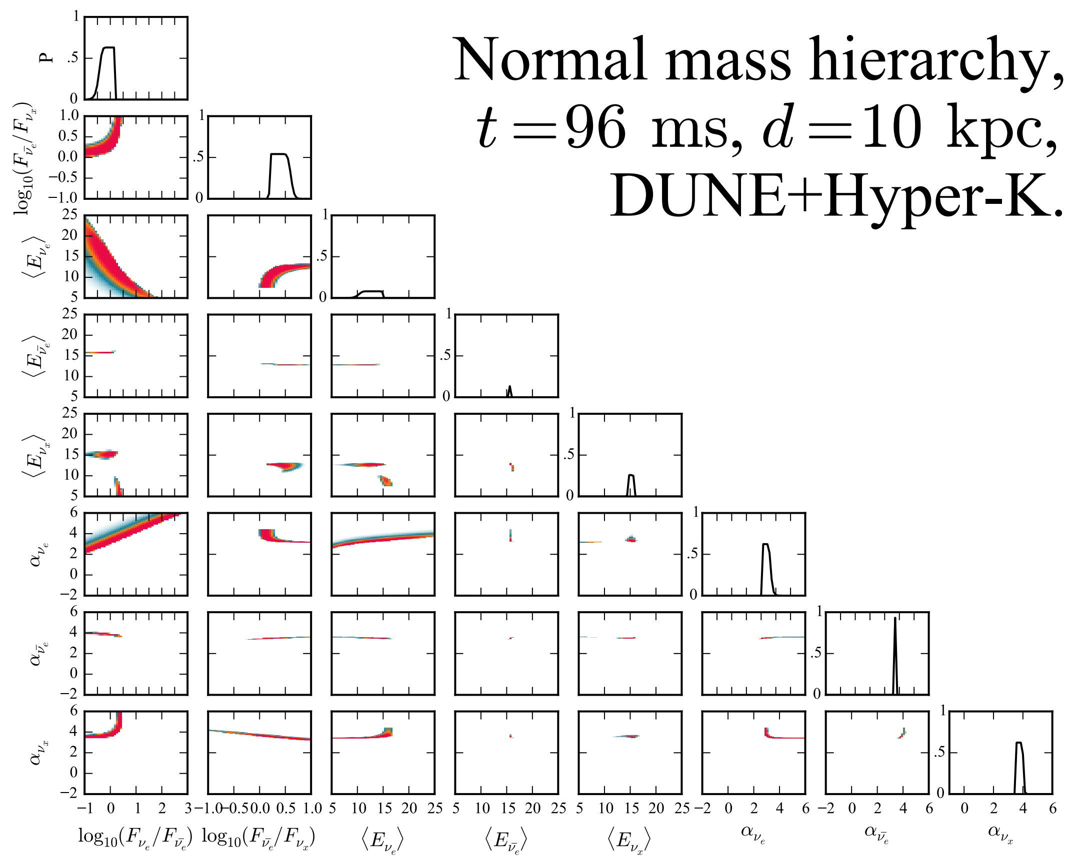


Sullivan, C., et al. (2015)

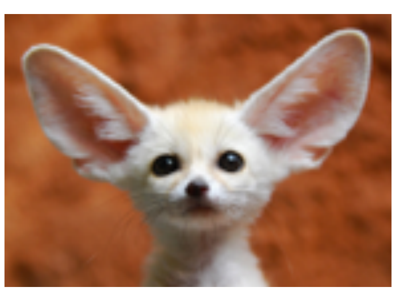
Minimize χ^2 over 8 parameters

- Need to fit all spectral components to get at neutronization fluence.

$$\frac{F_{\nu_e}}{F_{\bar{\nu}_e}}, \frac{F_{\bar{\nu}_e}}{F_{\nu_x}} \quad E_{\nu_e}, E_{\bar{\nu}_e}, E_{\nu_x} \quad \alpha_{\nu_e}, \alpha_{\bar{\nu}_e}, \alpha_{\nu_x}$$



- Complicated structure, but initially we simply want the $\nu_e/\bar{\nu}_e$ fit.



Cherry, J., Horiuchi, S., in preparation

A parameter space rife with local minima

- Deterministic, steepest descent methods take infeasible lengths of time to finish due to the density of L. M.
- Some non-deterministic minimization methods also fail (MCMC) due to large potential barriers $(\Delta\chi^2)$ between L. M.
- May require non-deterministic, diffusion-like methods, e.g. genetic algorithms.

A parameter space rife with local minima

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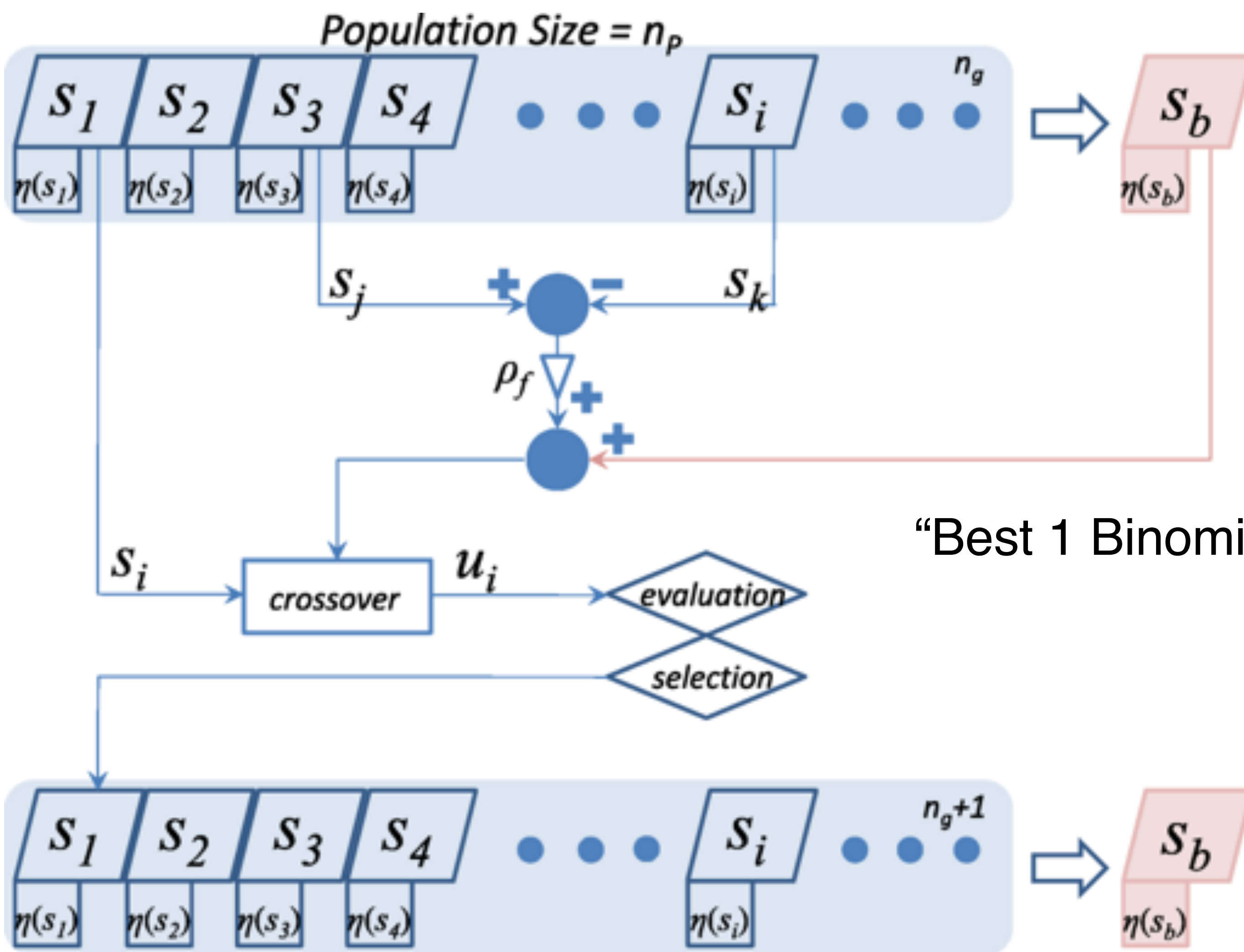
- ~~Some non-deterministic minimization methods also fail (MCMC) due to large potential barriers $(\Delta\chi^2)$ between L. M.~~ ?
- May require non-deterministic, diffusion-like methods, e.g. genetic algorithms.

Differential Evolution

Storn, R.; Price, K. (1994)



"Best 1 Binomial" method

Figure: Wang, Ligang, et al., J. Energy Resour. Technol. 136(3), 031601 (2014)

Differential Evolution

Storn, R.; Price, K. (1994)

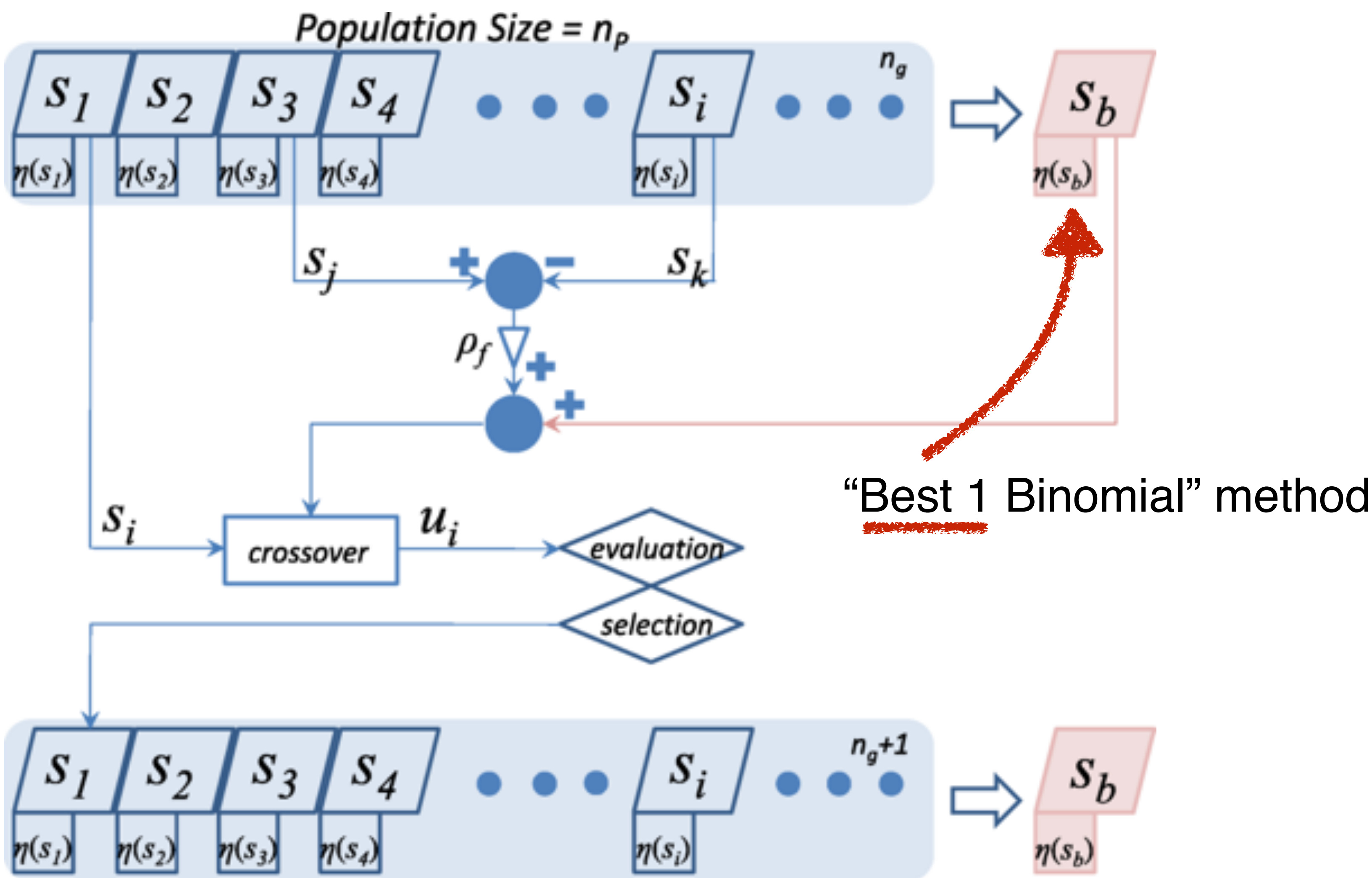


Figure: Wang, Ligang, et al., J. Energy Resour. Technol. 136(3), 031601 (2014)

Differential Evolution

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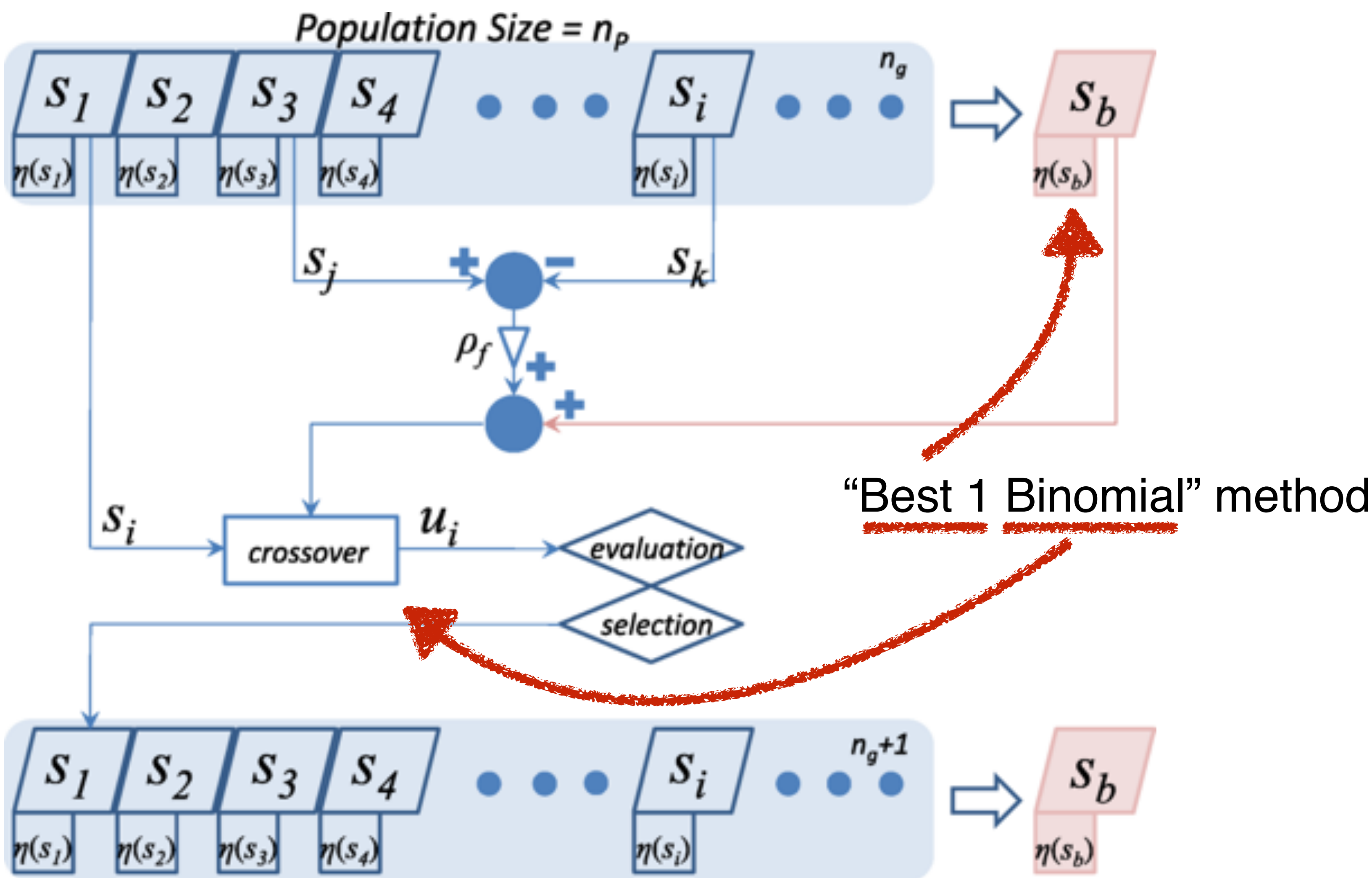
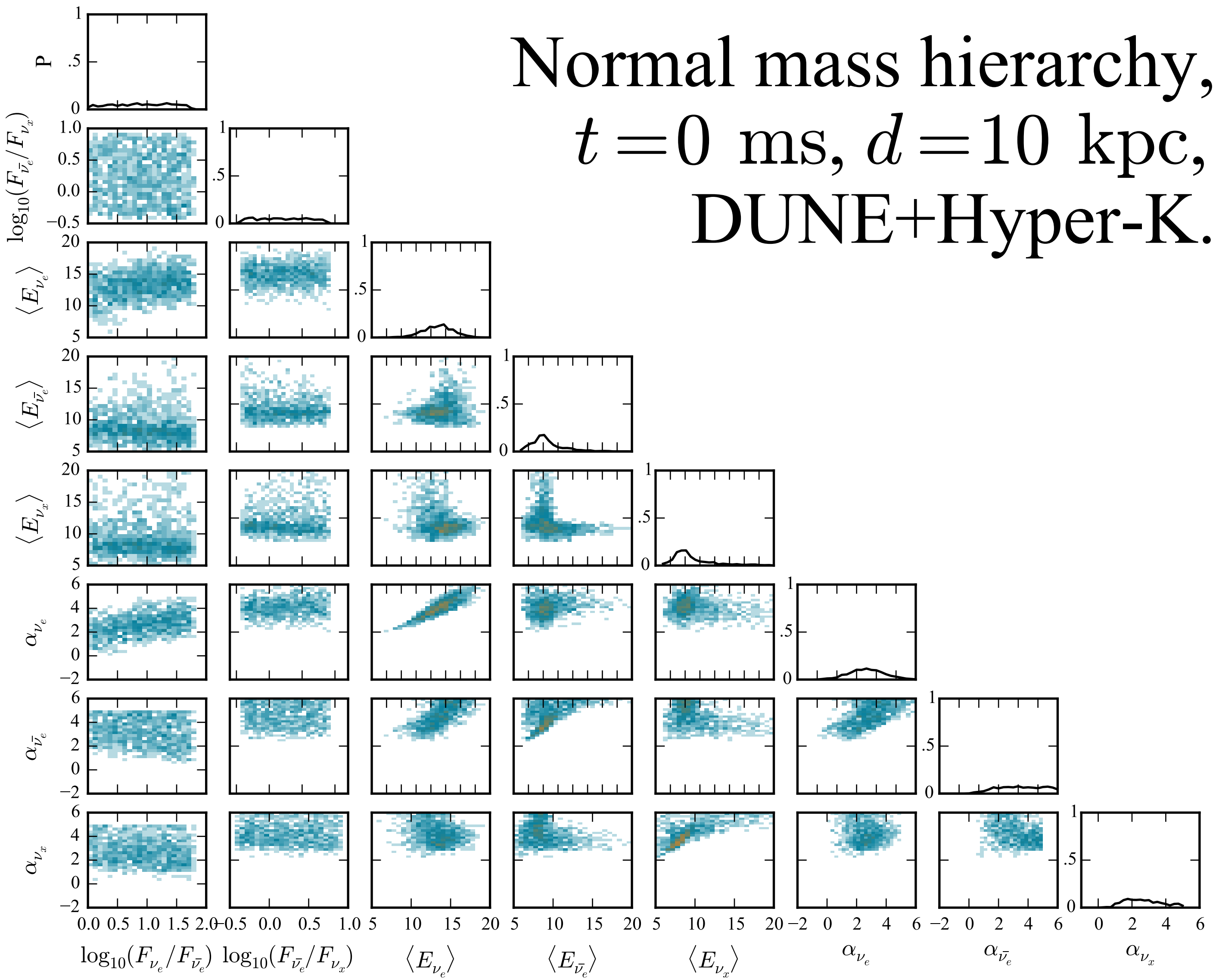


Figure: Wang, Ligang, et al., J. Energy Resour. Technol. 136(3), 031601 (2014)

3 Generations

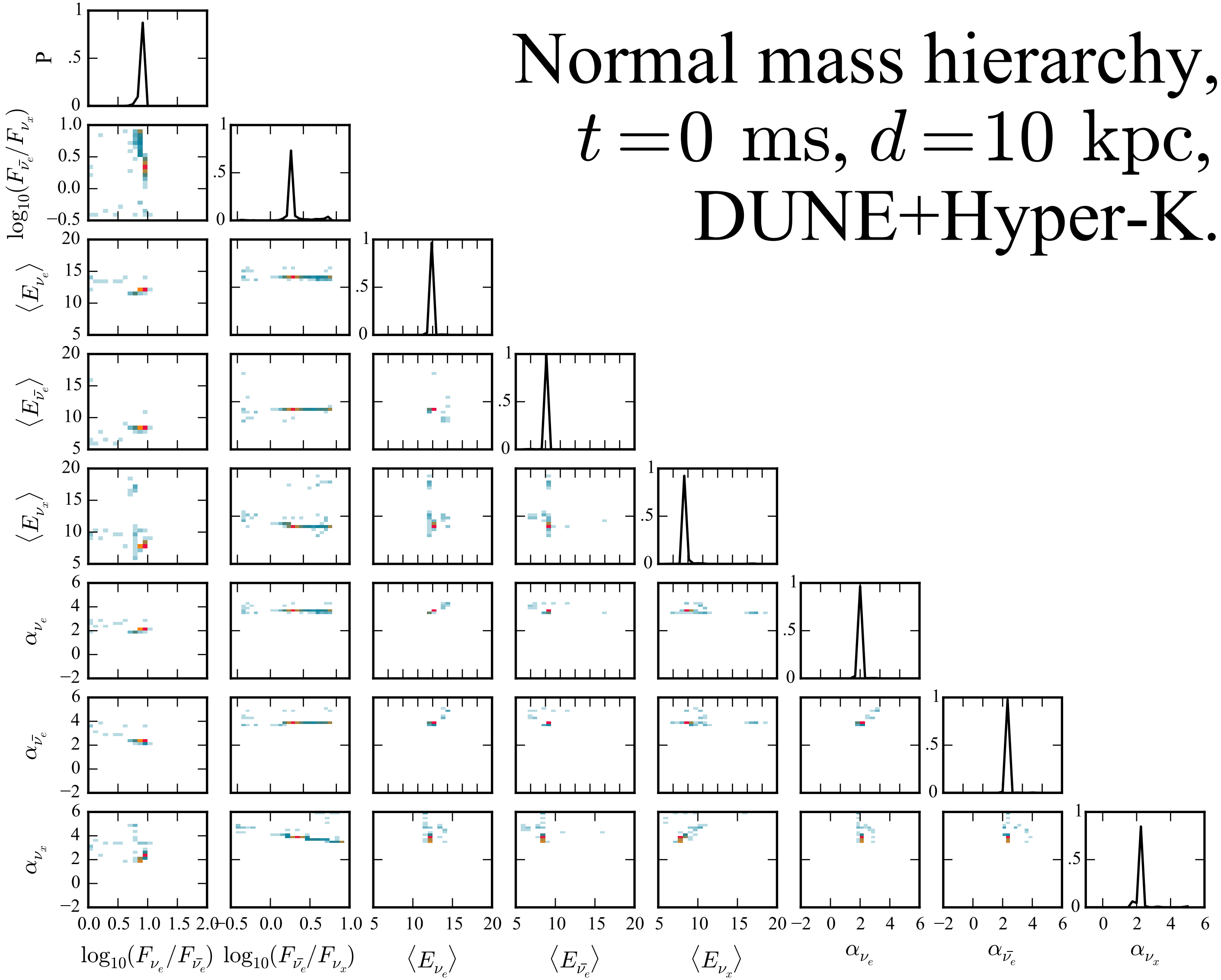


Normal mass hierarchy,
$t = 0$ ms, $d = 10$ kpc,
DUNE+Hyper-K.

Cherry, J., Horiuchi, S., in preparation

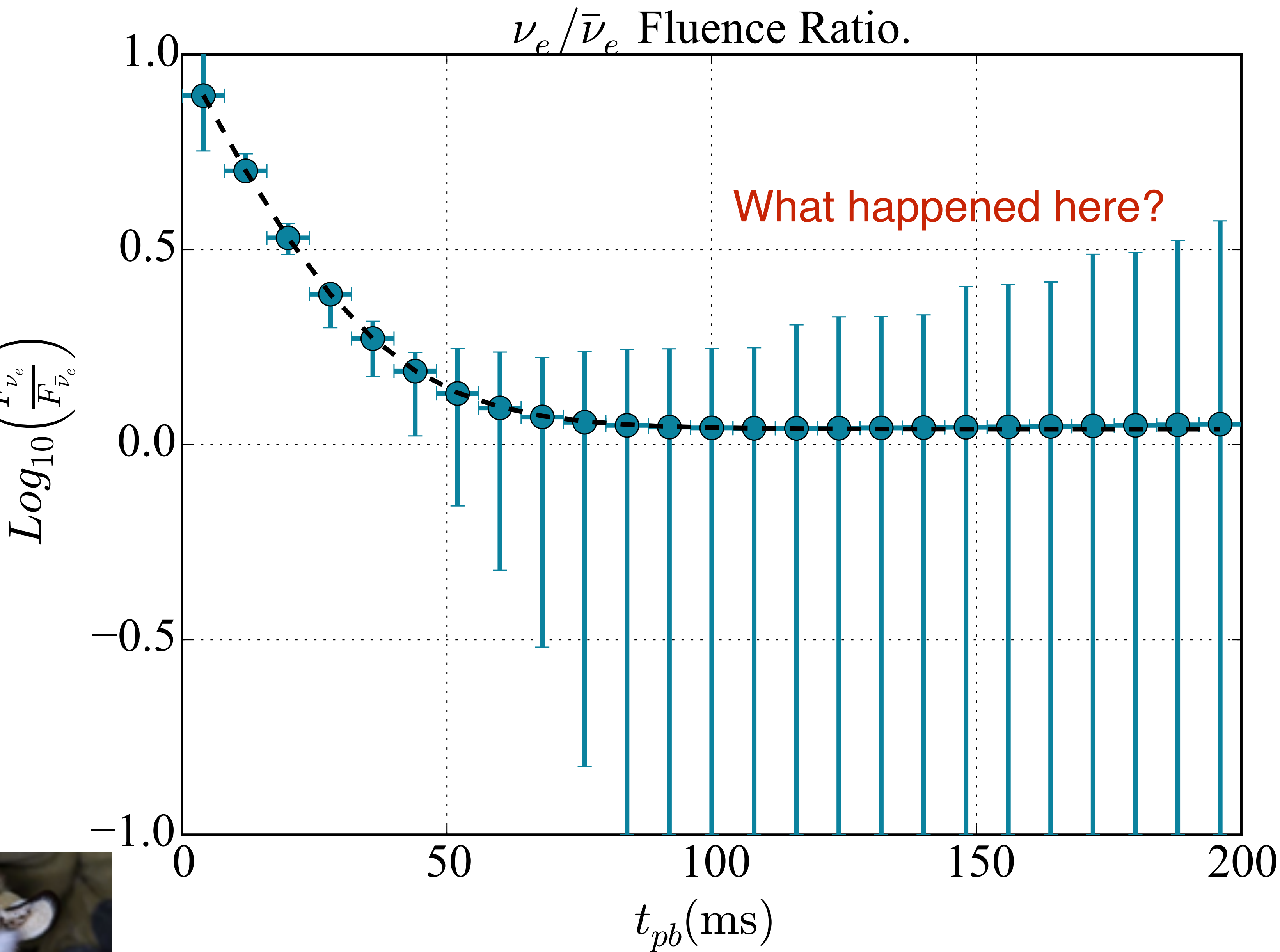
20 Generations

Normal mass hierarchy,
$t = 0$ ms, $d = 10$ kpc,
DUNE+Hyper-K.



Cherry, J., Horiuchi, S., in preparation

Success?



Cherry, J., Horiuchi, S., in preparation

Where are the accretion $\nu_e's$?

$$Y_e \sim 0.5 \qquad \dot{M} \sim 1 M_\odot s^{-1}$$

$$P_{ee}^{nm} = .02\,, \;\; P_{ee}^{im} = .31$$

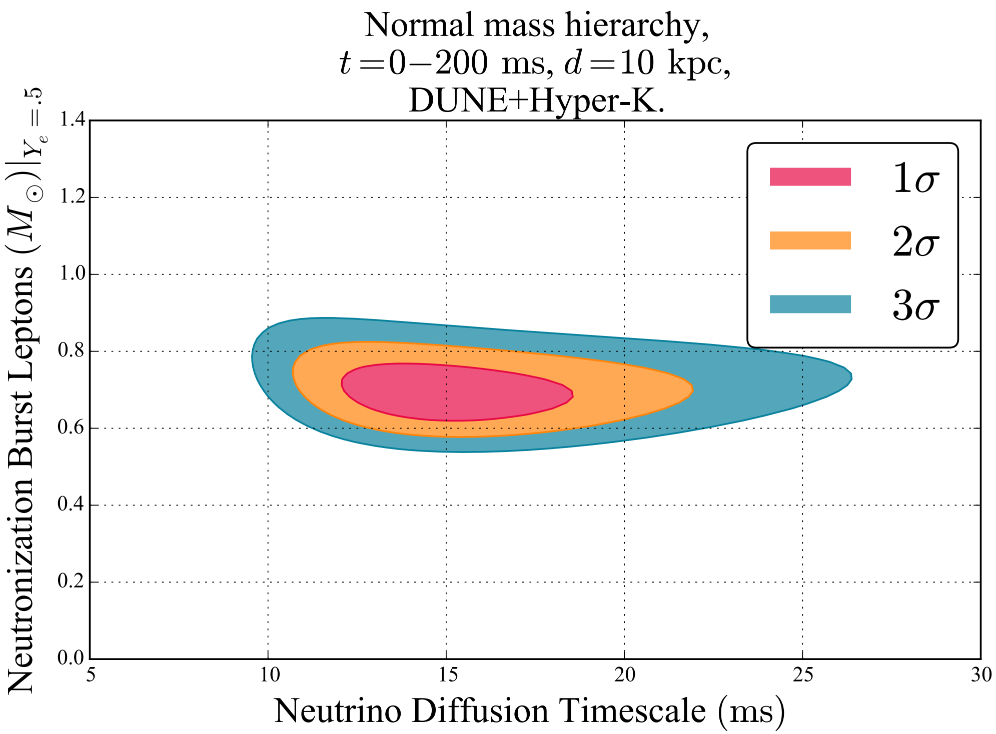
Energetics of accretion:

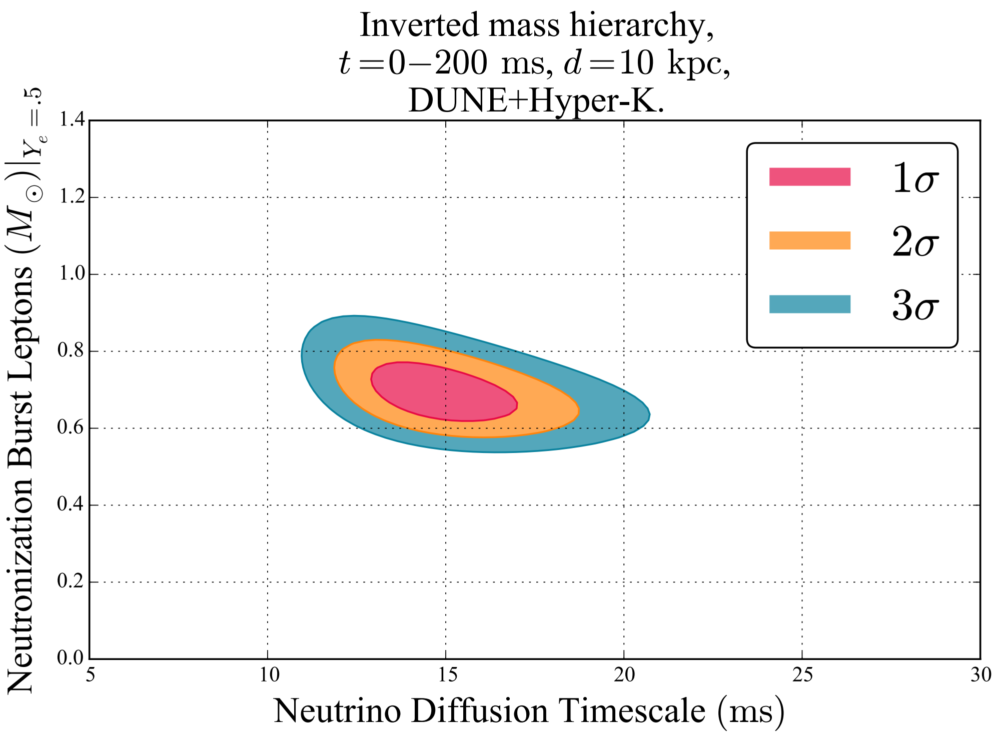
$$E_{dep} \sim 0.1 \times m_{p/n} \sim 100\,\mathrm{MeV} \sim 10\nu/\mathrm{nucleon}$$

$\implies 5\%$ of accretion neutrinos carry lepton number

$\sim 2\%$ of that survives as electron flavor, accretion may end early when the shock is launched.

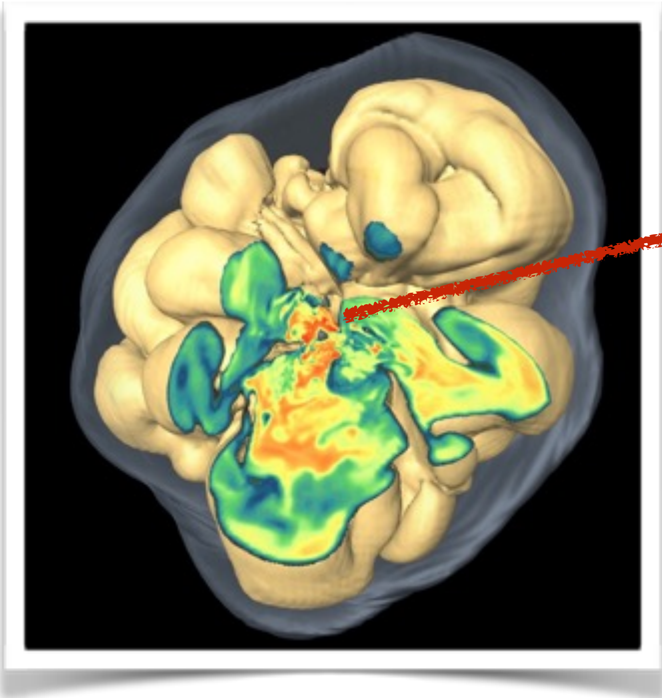
Comparing Mass Hierarchies





Cherry, J., Horiuchi, S., in preparation

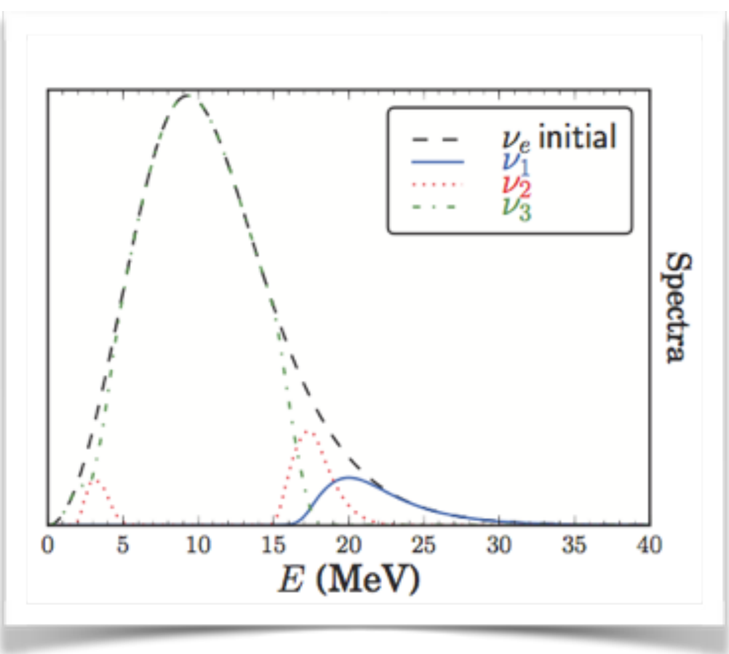
Revenge of θ_{13}



ν_3

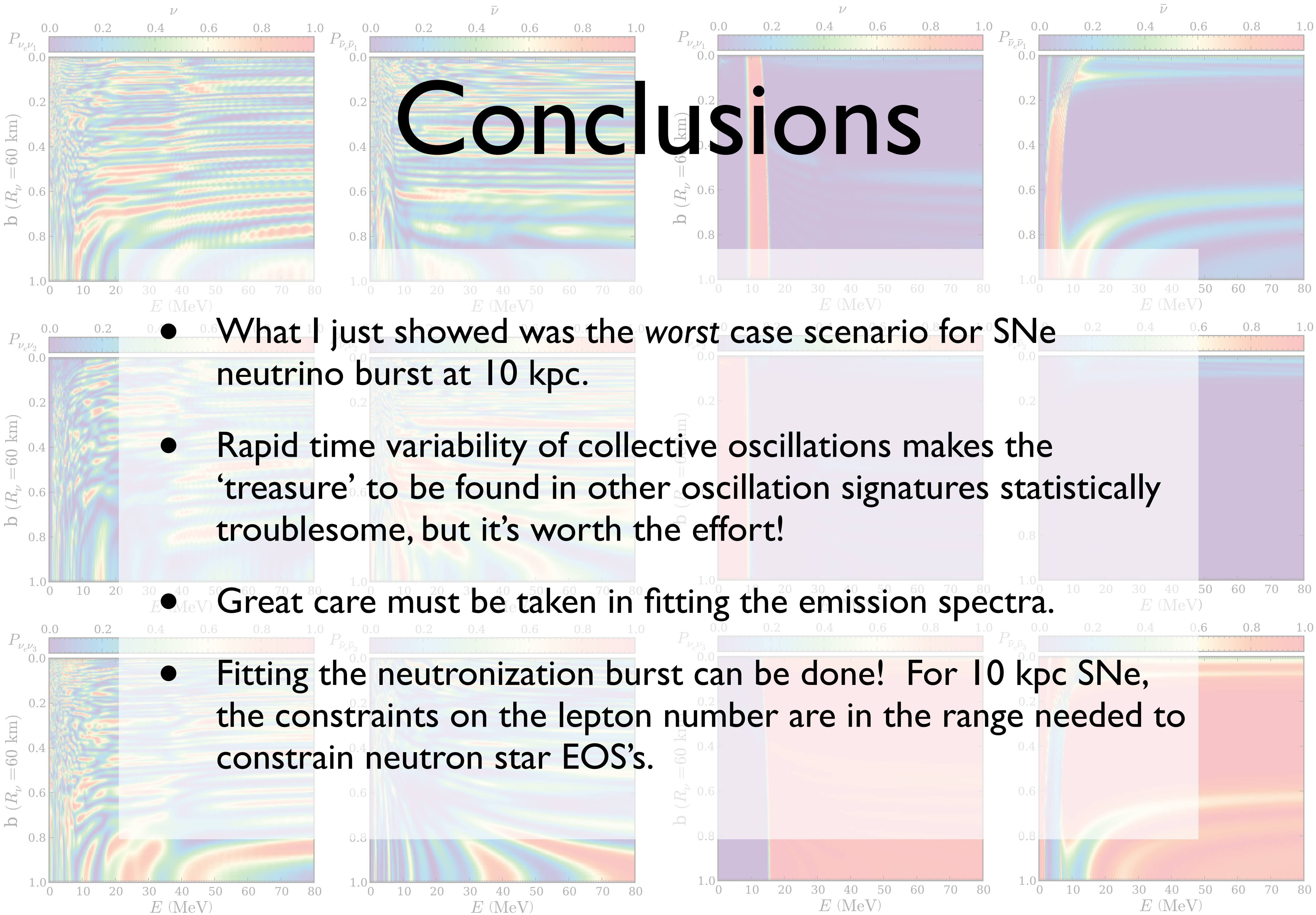
NMH	IMH
ν_e	$\bar{\nu}_e$

2% Survival probability



Upside: any exotic phenomena from supernova dynamics or collective oscillations (H_1) come with a large signal enhancement.

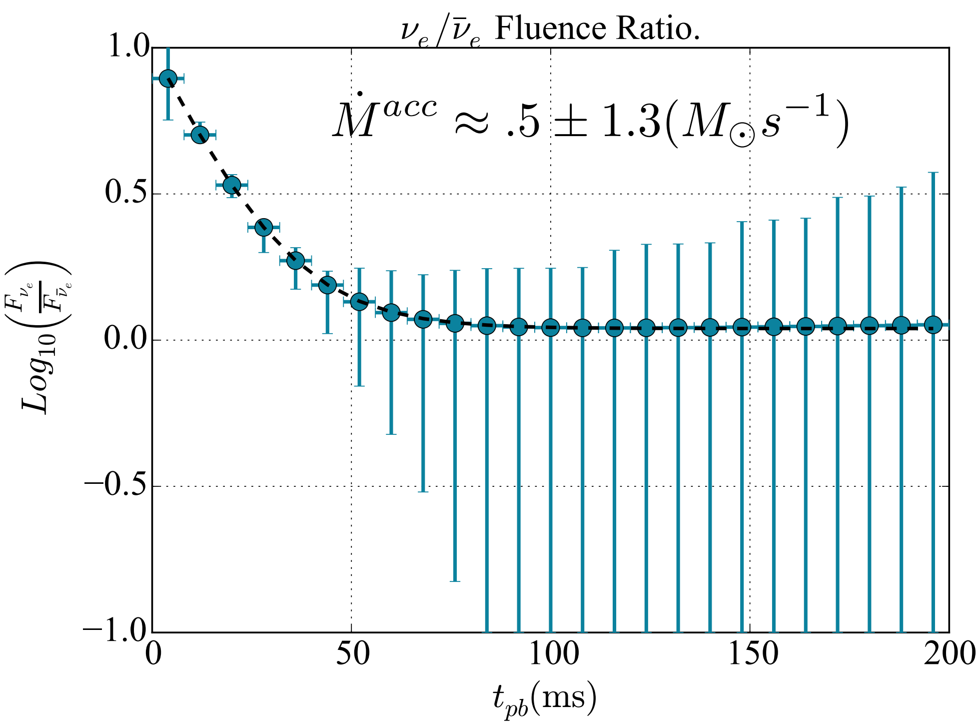
Conclusions

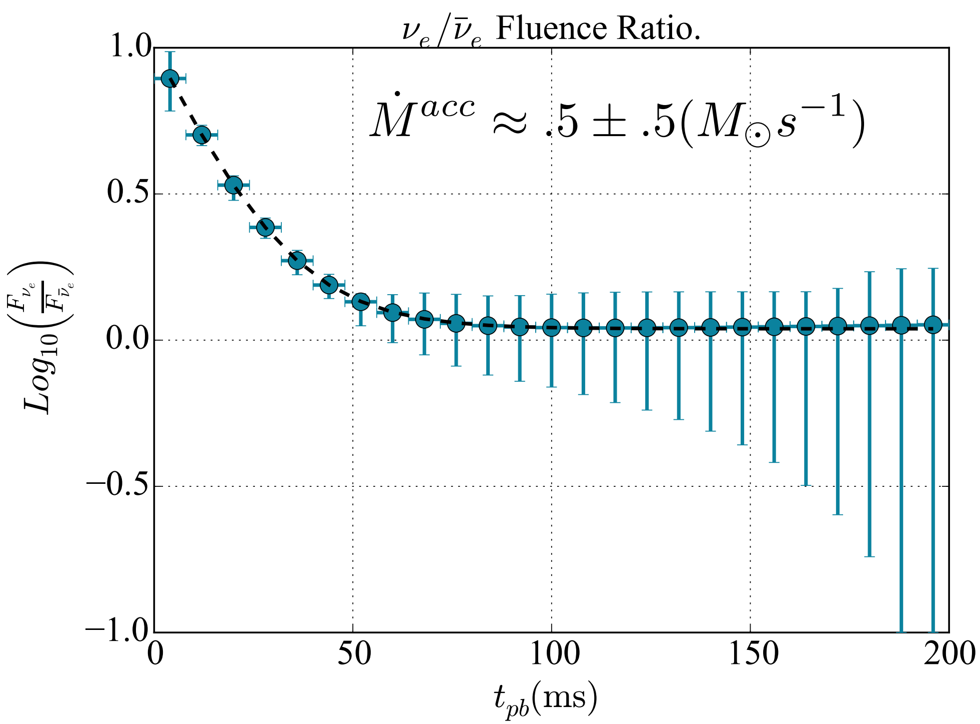


- What I just showed was the *worst* case scenario for SNe neutrino burst at 10 kpc.
- Rapid time variability of collective oscillations makes the 'treasure' to be found in other oscillation signatures statistically troublesome, but it's worth the effort!
- Great care must be taken in fitting the emission spectra.
- Fitting the neutronization burst can be done! For 10 kpc SNe, the constraints on the lepton number are in the range needed to constrain neutron star EOS's.

$$\frac{F^{therm}_{\nu_e} + F^{acc}_{\nu_e}}{F^{therm}_{\bar{\nu}_e} + F^{acc}_{\bar{\nu}_e}} = 1.1 \pm .3$$

$$\frac{F^{therm}_{\nu_e} + F^{acc}_{\nu_e}}{F^{therm}_{\bar{\nu}_e} + F^{acc}_{\bar{\nu}_e}} = 1.1 \pm .1$$





Cherry, J., Horiuchi, S., in preparation