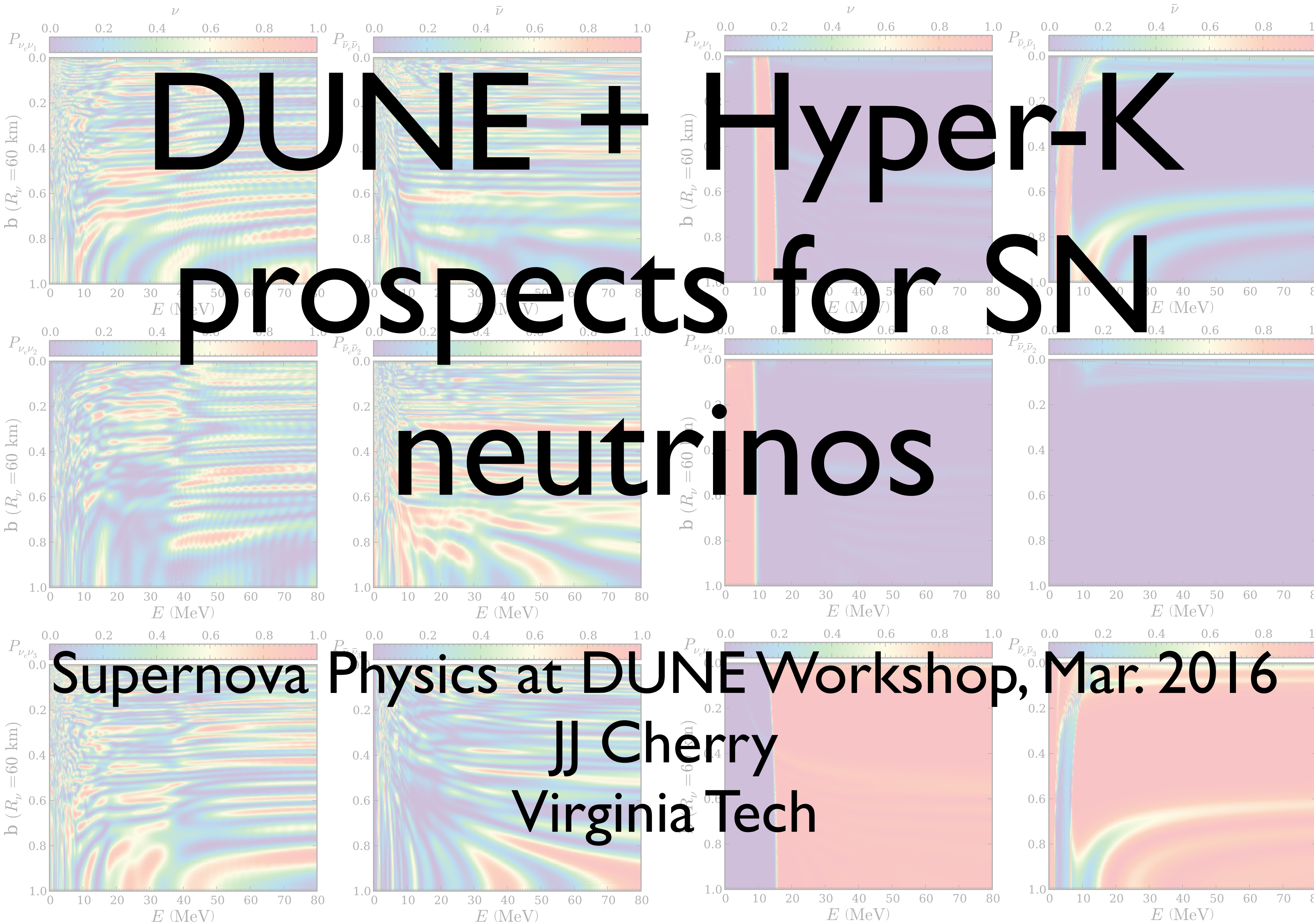


DUNE + Hyper-K prospects for SN neutrinos

Supernova Physics at DUNE Workshop, Mar. 2016

JJ Cherry
Virginia Tech

What do we hope to learn?

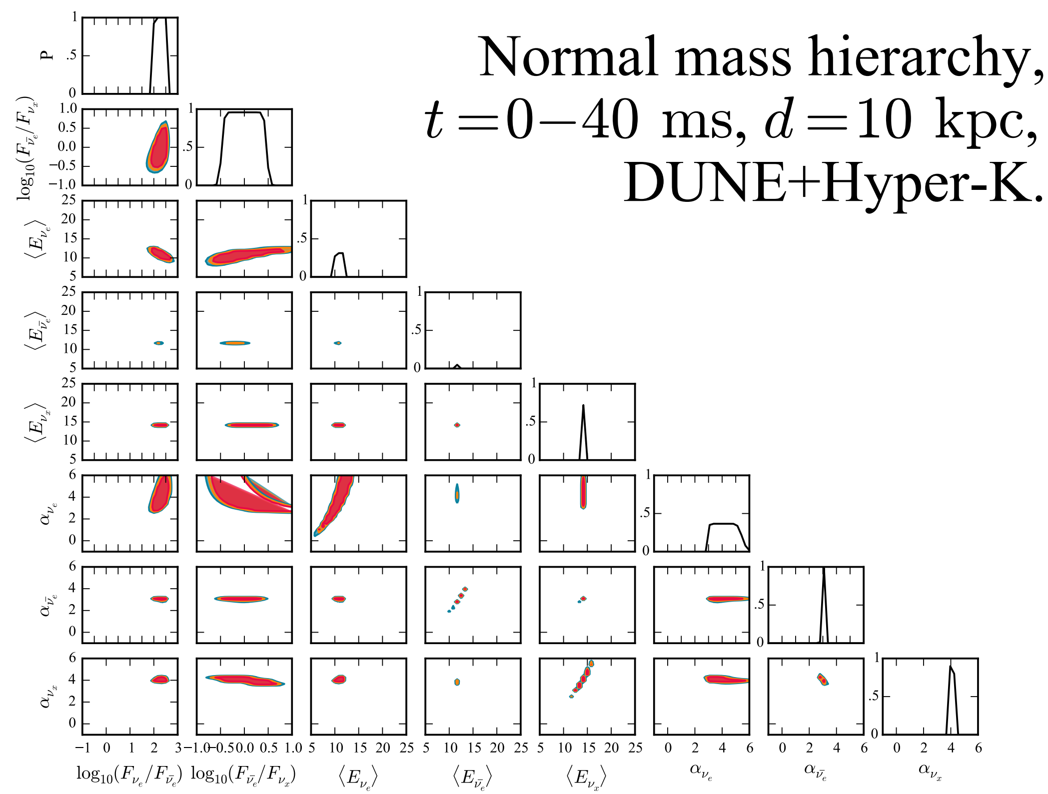
- Fundamental neutrino physics.
- Properties of extended nuclear matter (the hot protoneutron star).
- Supernova explosion mechanics.
- How to structure our experimental program to maximize our ability to explore the above!

Zero-th order considerations

- SN 1987a confirmed that O(0.1 M_sun) energy is released as neutrino energy.
- ~.5 - 1 M_sun/M_p worth of electron lepton number should also be emitted.
- Need detector complementarity to find it!
- Combine 40 kt LAr TPC (DUNE) with 374 kt WC detector (Hyper-K) to find relative fluence of $\nu_e \; vs. \; \bar{\nu}_e$

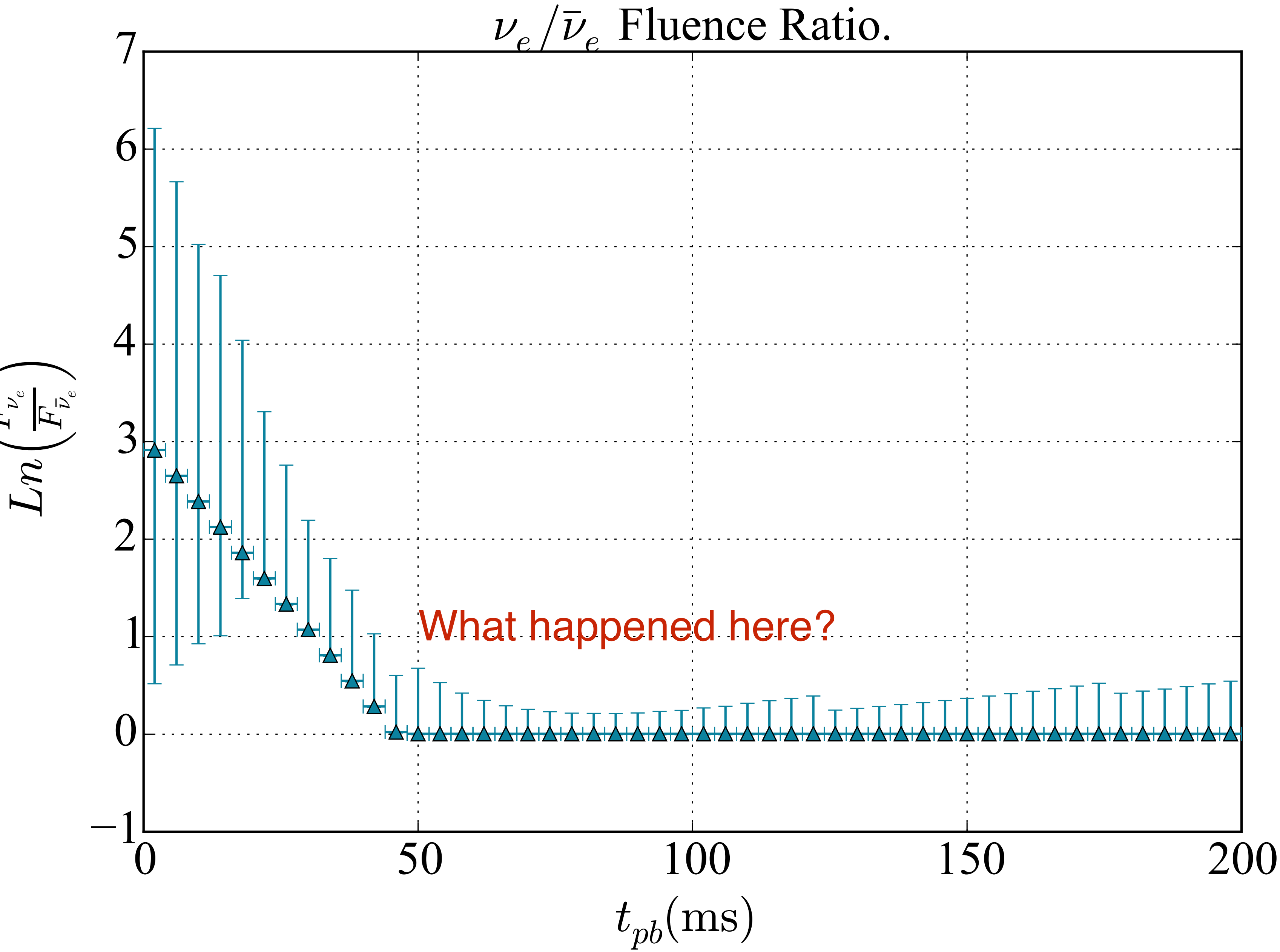
Minimize LL over 8 parameters

- Need to fit all spectral components to get at neutronization fluence.
- Complicated structure, but initially we simply want the $\nu_e/\bar{\nu}_e$ fit.



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

Success!



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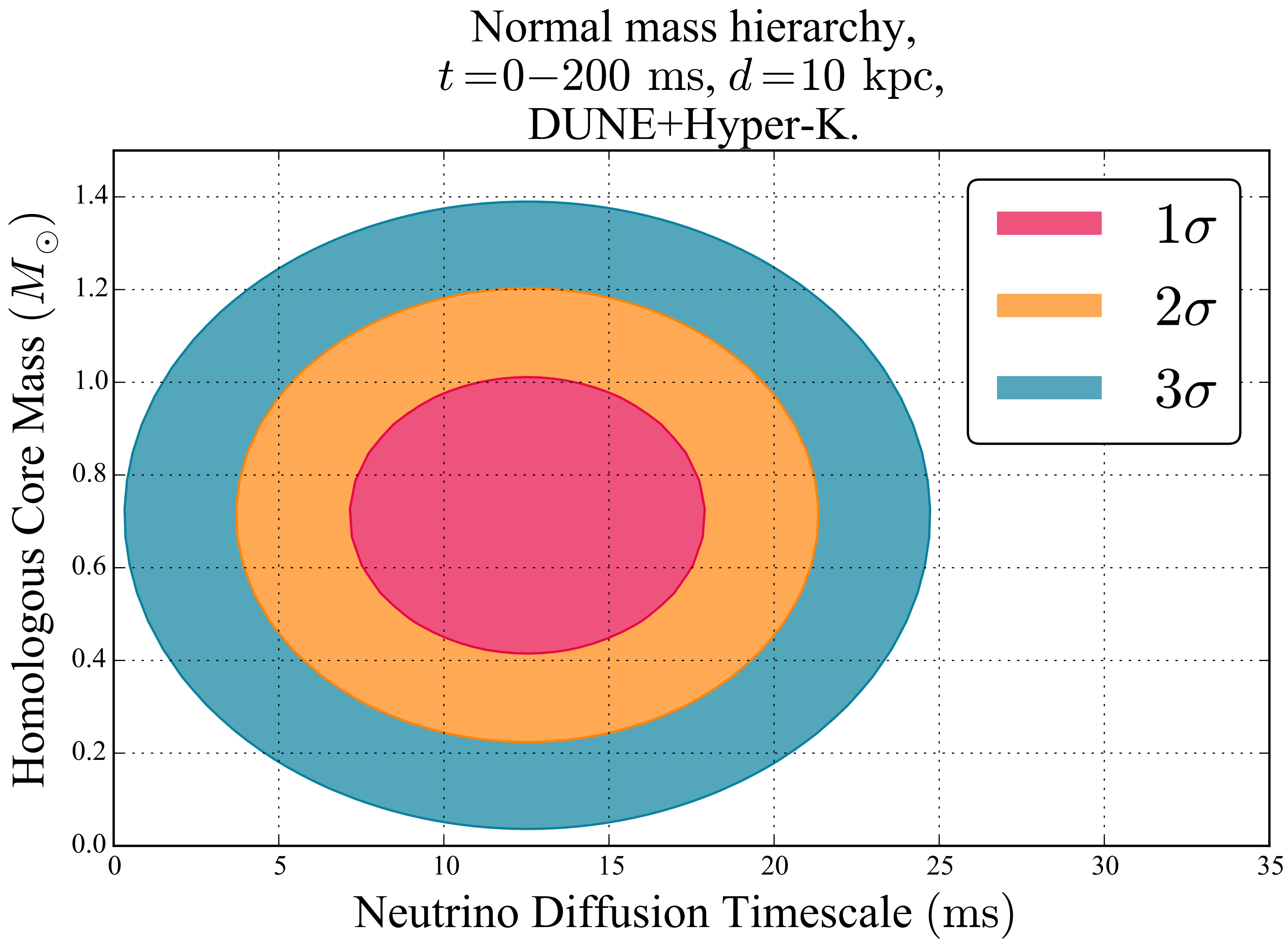


Normal mass hierarchy,
$t = 0-200$ ms, $d = 10$ kpc,
DUNE+Hyper-K.
Homologous Core Mass ($M_\odot$)
Neutrino Diffusion Timescale (ms)
1σ
2σ
3σ
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
0
5
10
15
20
25
30
35

Where are the accretion $\nu_e's$?

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

$$Y_e \sim 0.5 \qquad\qquad P_{ee}^{nm} = .095\,, \;\; P_{ee}^{im} = .24$$

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

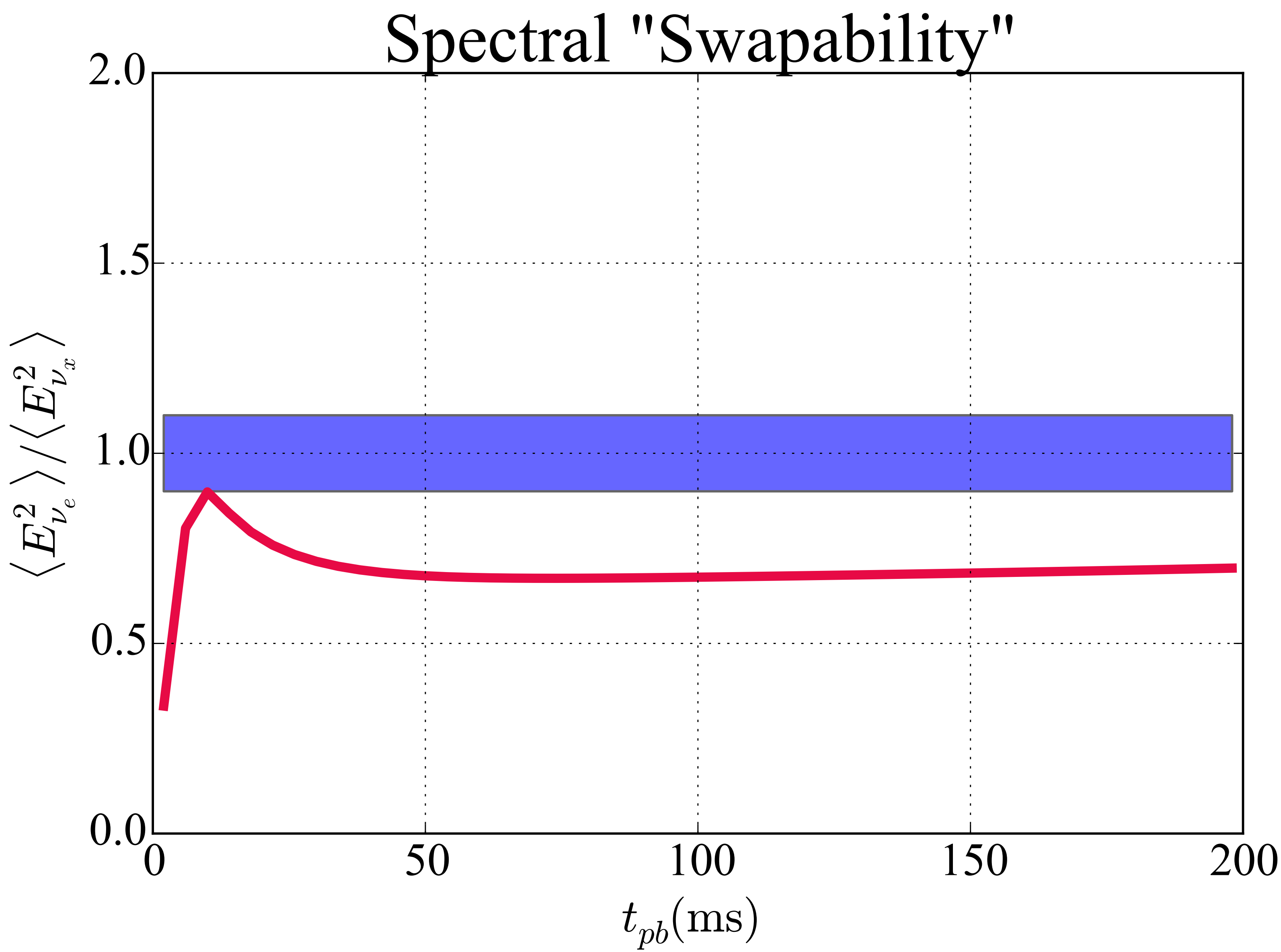
$\sim 10\%$ of that survives as electron flavor, accretion may end early when the shock is launched.

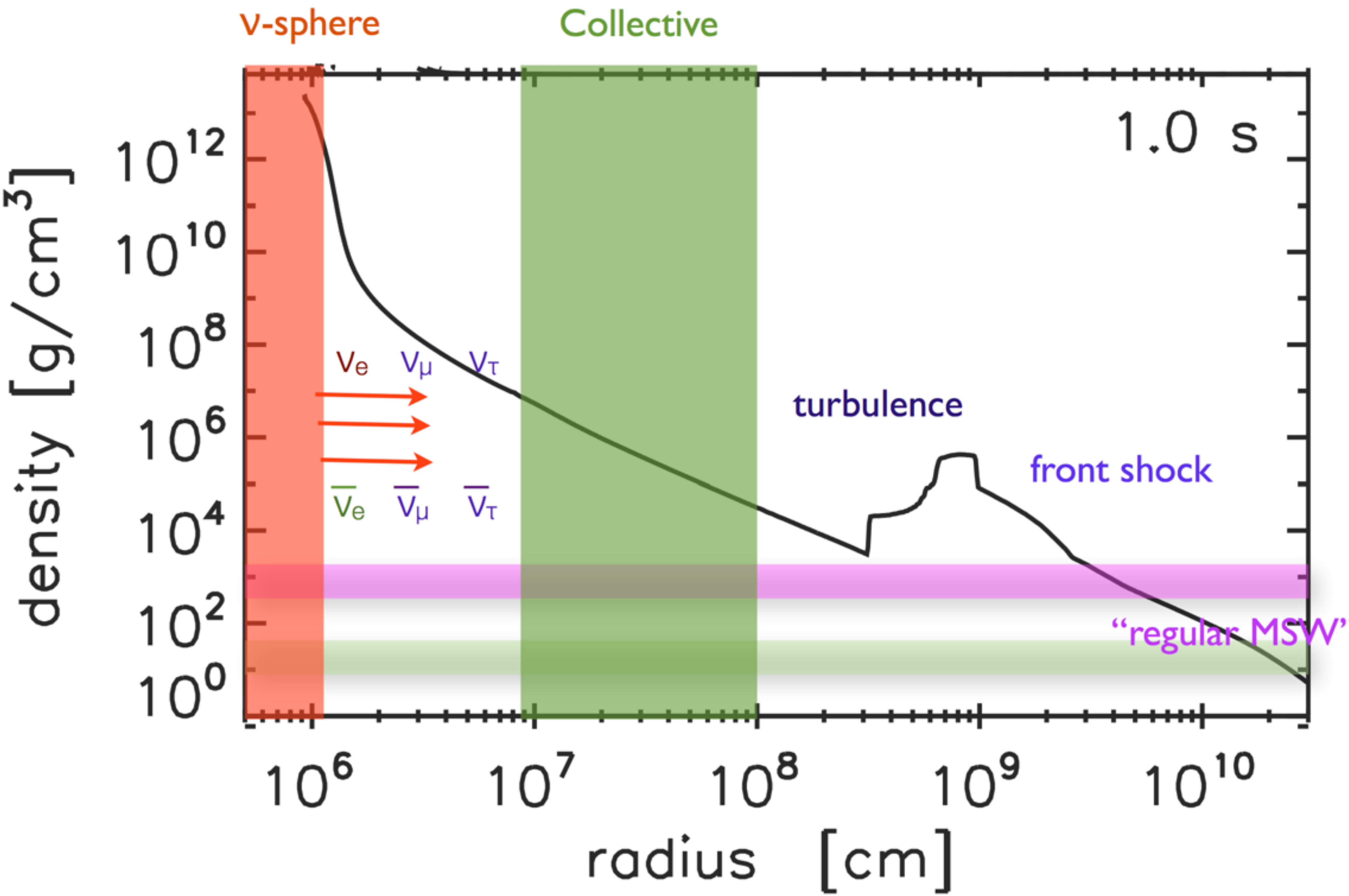
LAr can find the mass Hierarchy in 40 ms

Neutronization burst nu_e burst events are:
50% - 50% original nu_e - nu_x (NM)
75% - 25% original nu_e - nu_x (IM)
NC nu-Ar events at the same time are
90% - 10% original nu_e - nu_other (regardless)

Based on the events collected in CC Ar capture, the different hierarchies predict a factor of ~2 difference in the NC rate. Pessimistic case (Garching) shown earlier exhibits 1 NC event per ms. 40 NC events ~ $3\sigma - 5\sigma$ rejection of opposite hierarchy

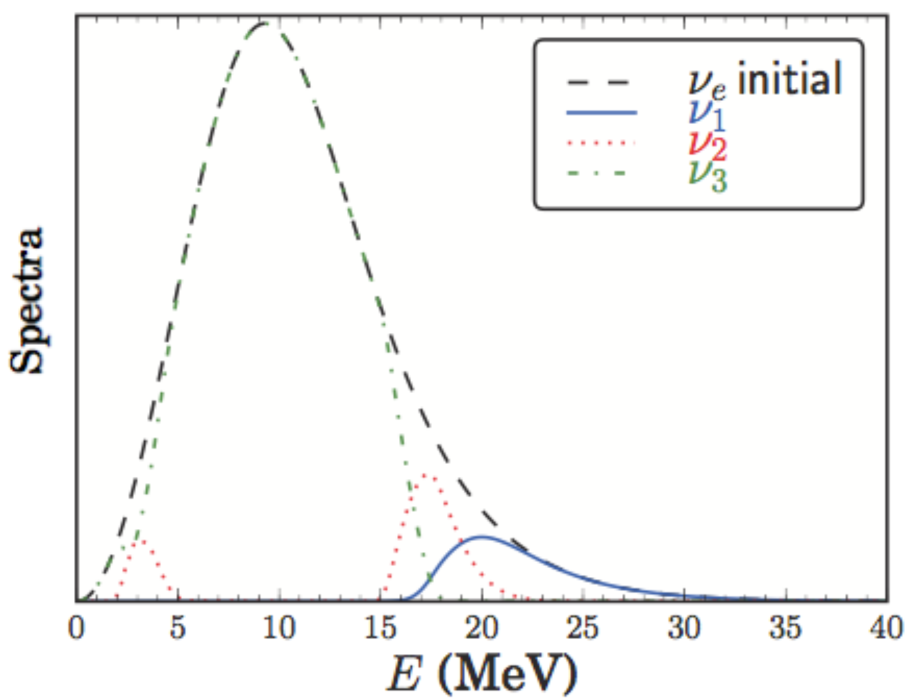
Other signals?



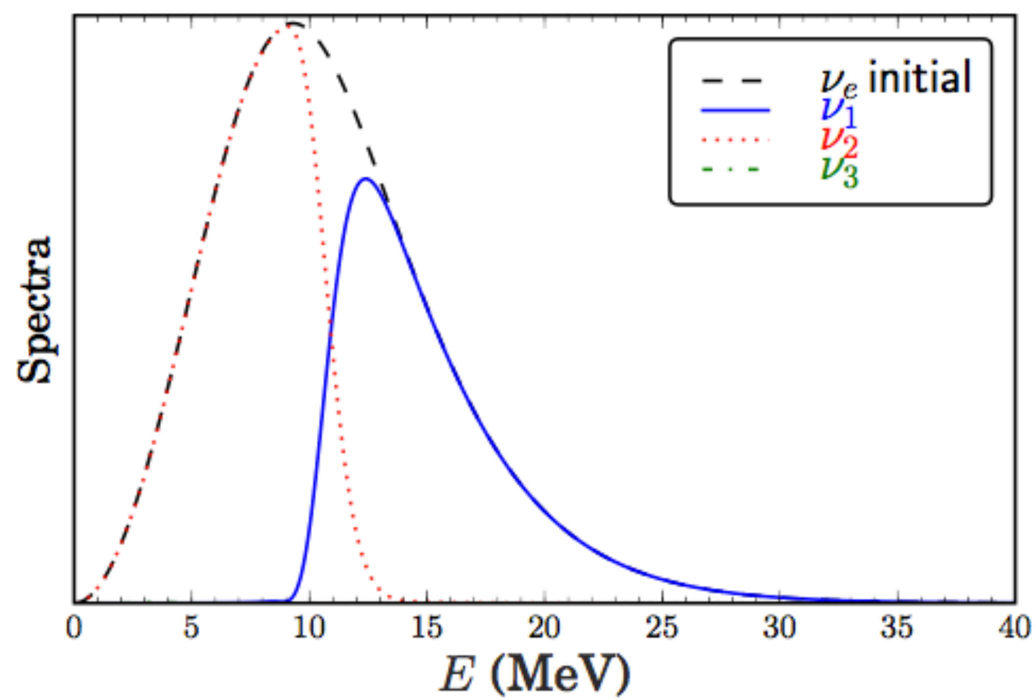

ν-sphere
Collective
1.0 s
ν_e ν_μ ν_τ
$\bar{\nu}_e$ $\bar{\nu}_\mu$ $\bar{\nu}_\tau$
turbulence
front shock
"regular MSW"
density [g/cm^3]
10^{12}
10^{10}
10^8
10^6
10^4
10^2
10^0
10^6
10^7
10^8
10^9
10^{10}
radius [cm]

Collective Oscillation Signatures

Normal Neutrino Mass Hierarchy

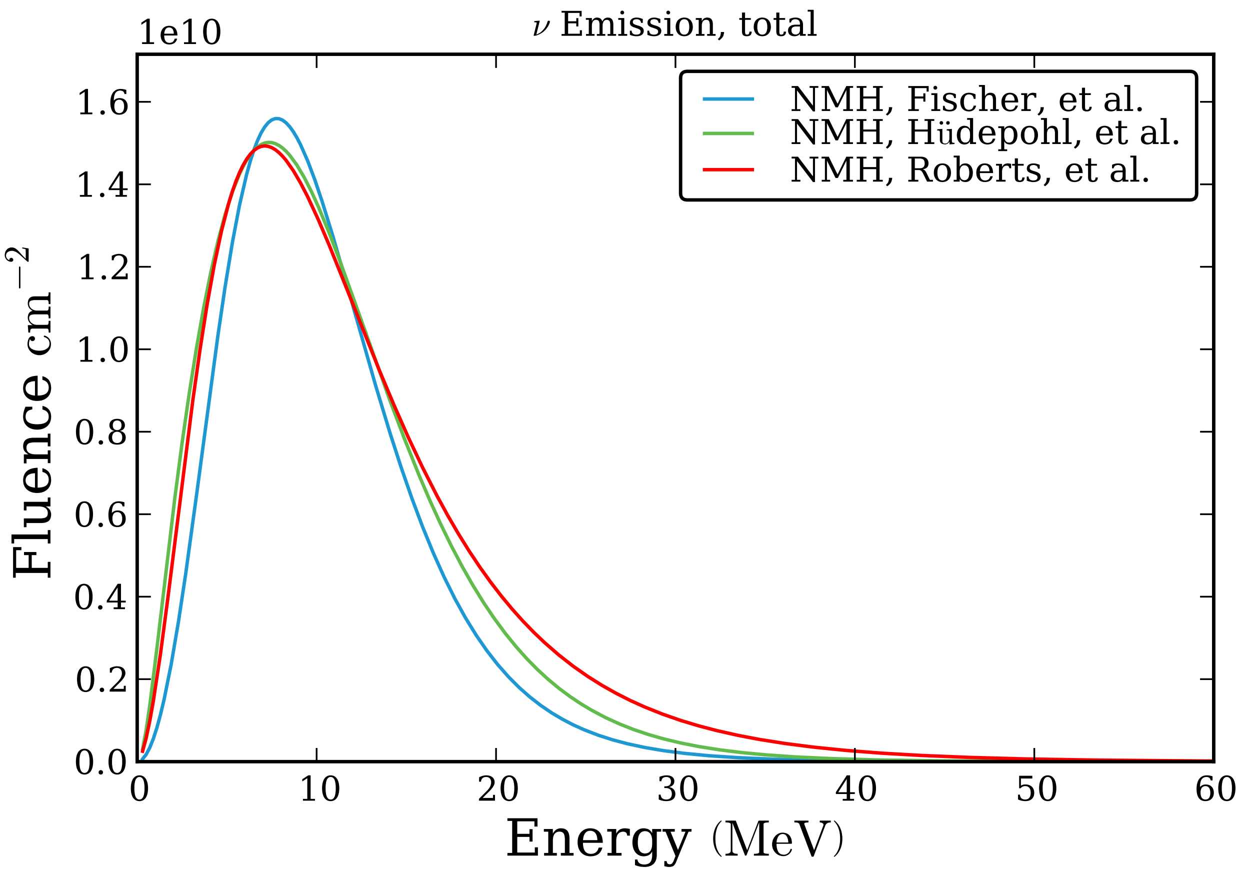


Inverted Neutrino Mass Hierarchy



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

Total Fluences are Nearly Identical to the Eye



Do not be fooled, the pinching / degeneracy is critical to the event rate.

At 10kpc, a 35kt LAr detector sees:

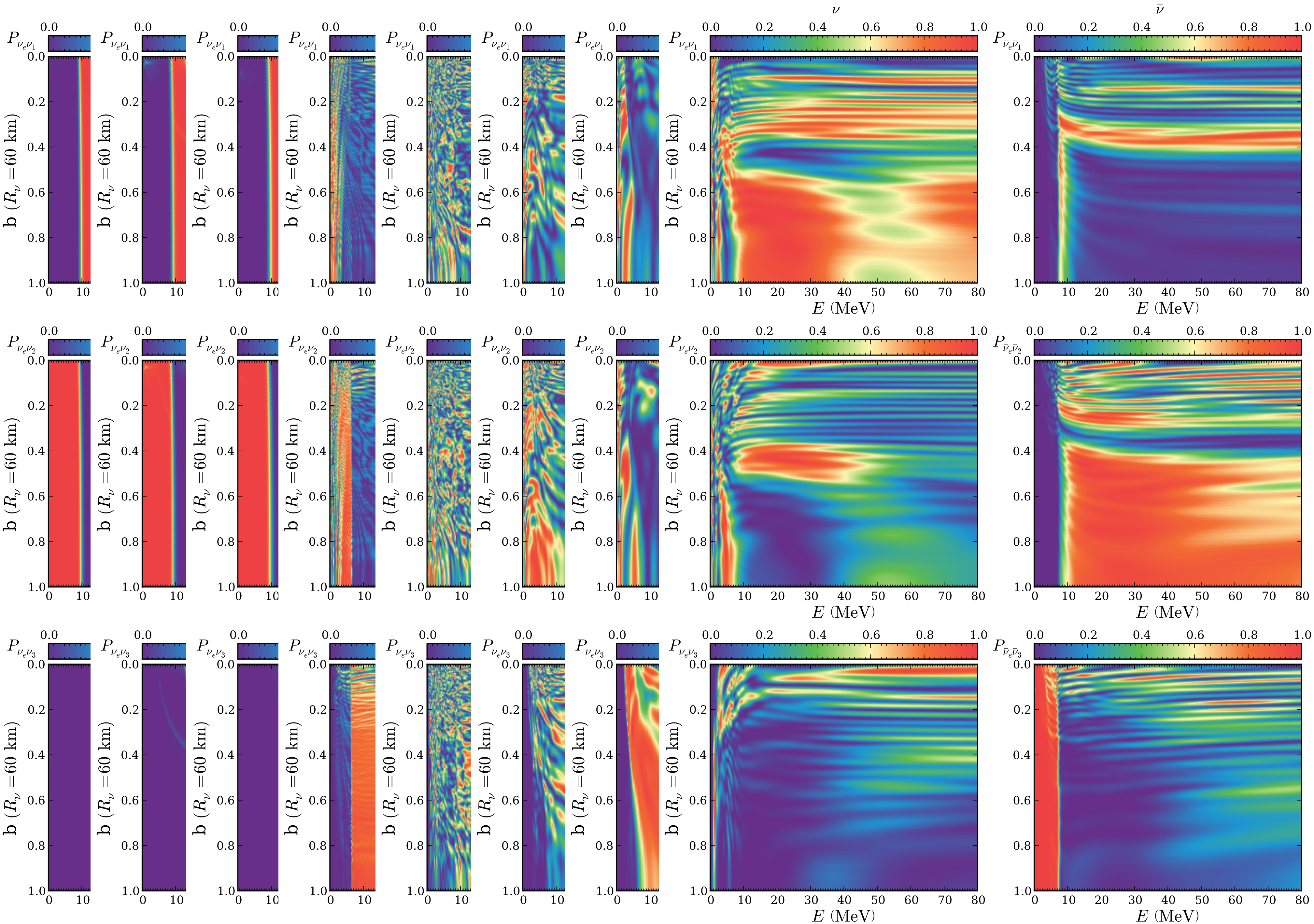
2200 Events for Roberts, et al.

900 Events for Fischer, et al.

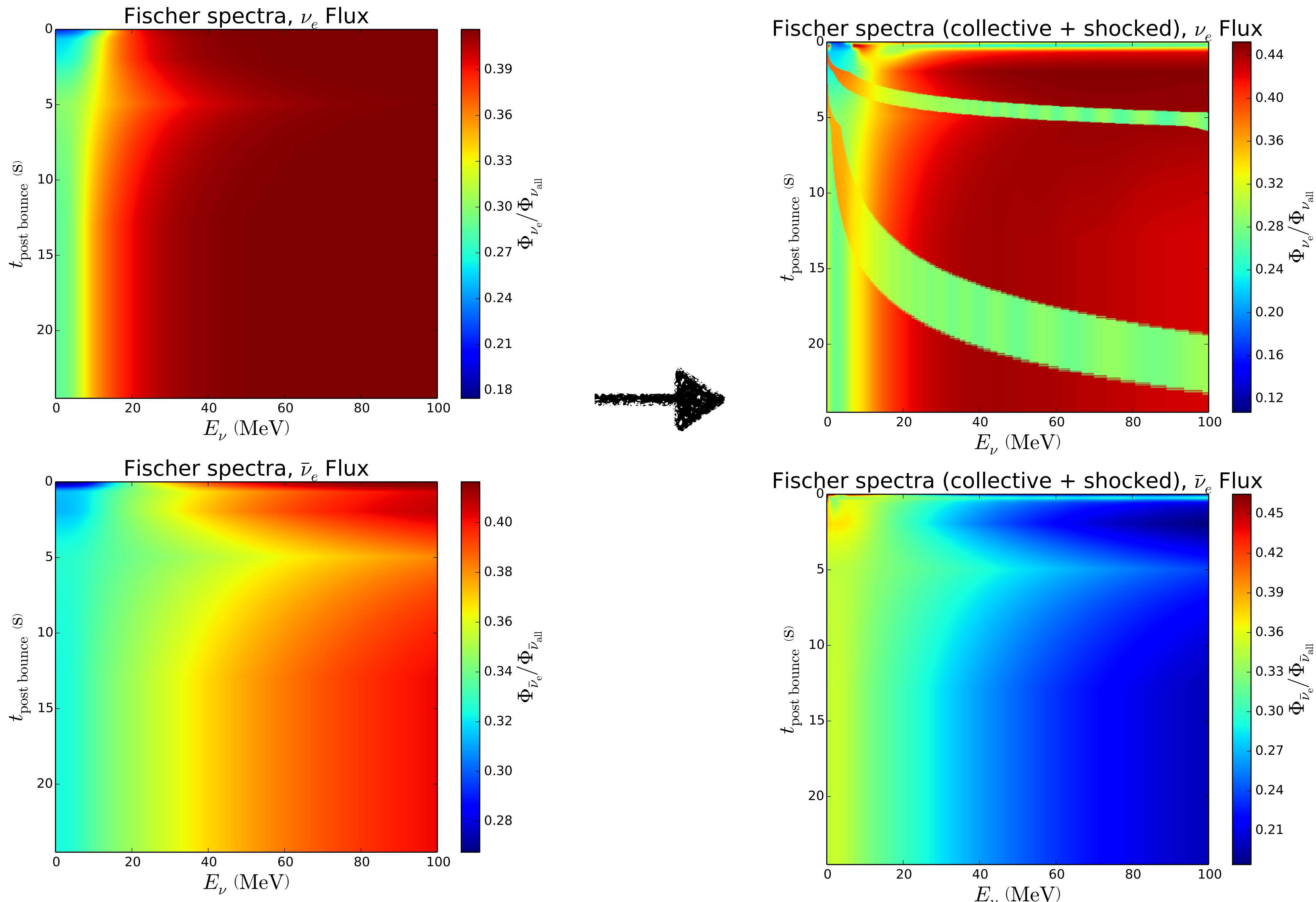
It is not enough to look at static spectra!

- 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.

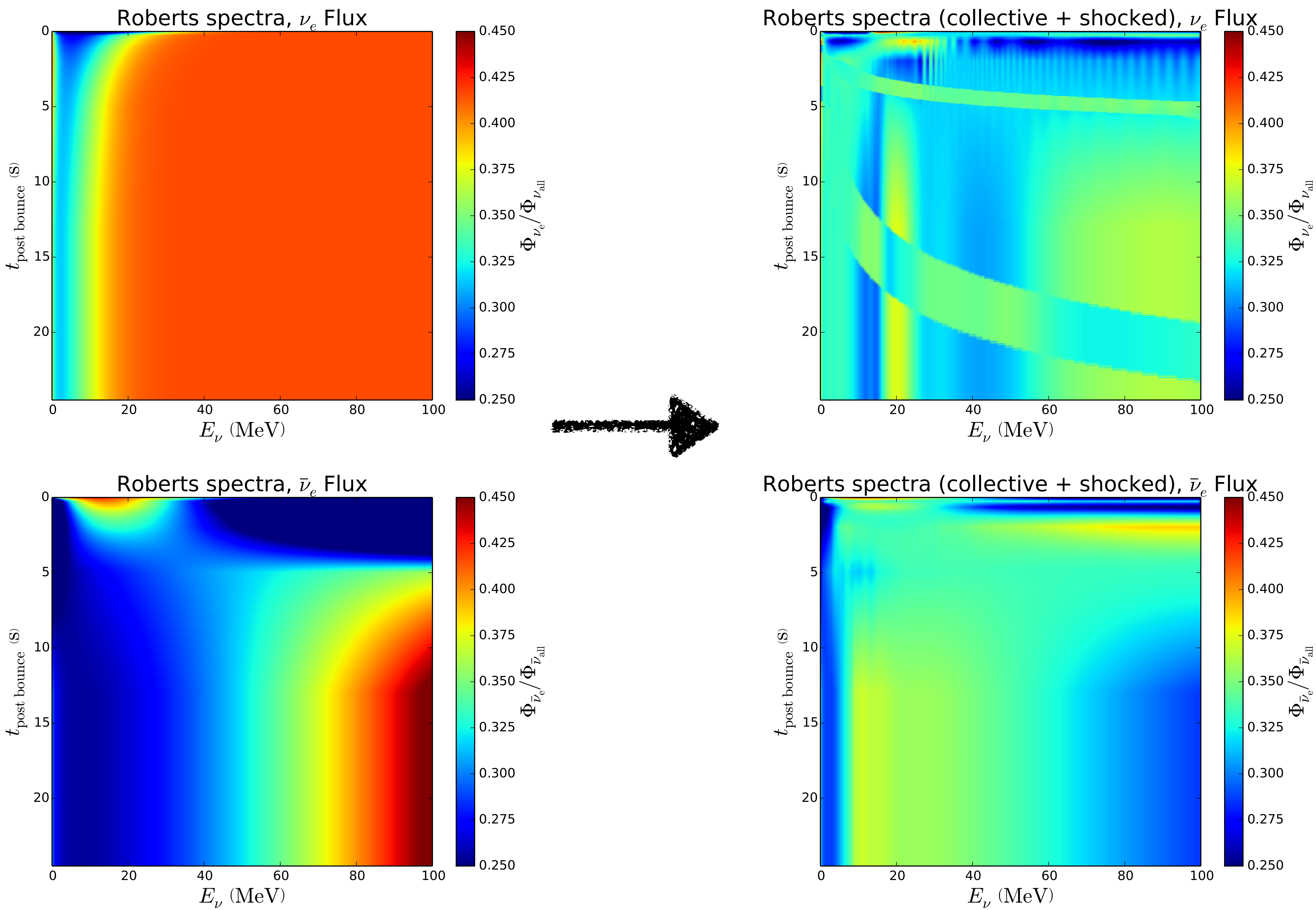
Roberts, et al.



Stitch Snapshots Together



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

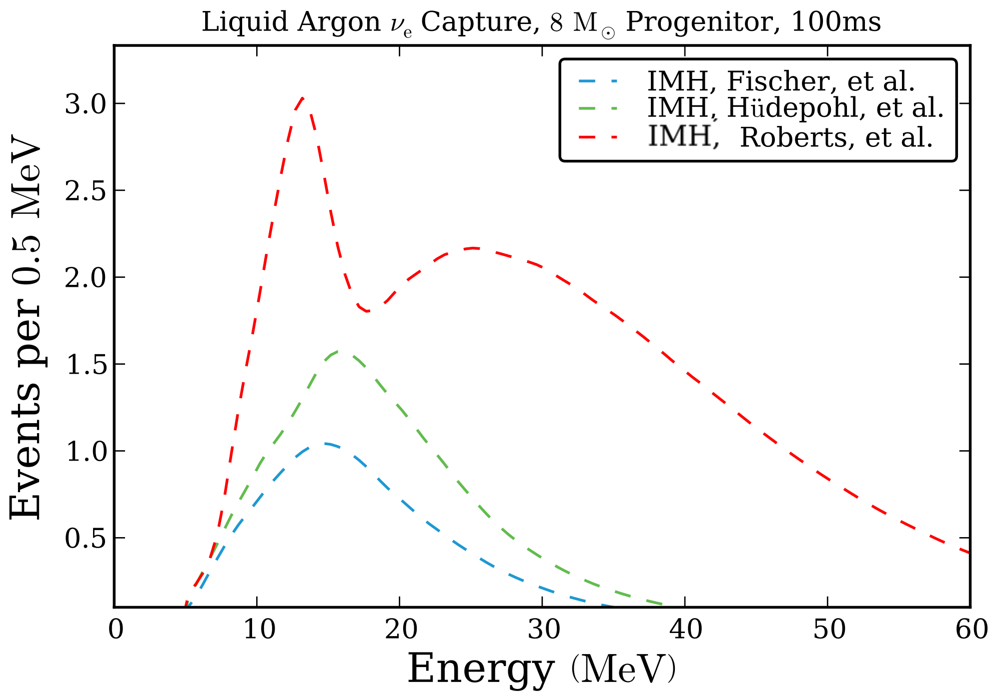
[6] Department of Physics, North Carolina State University, Raleigh, NC, 27695

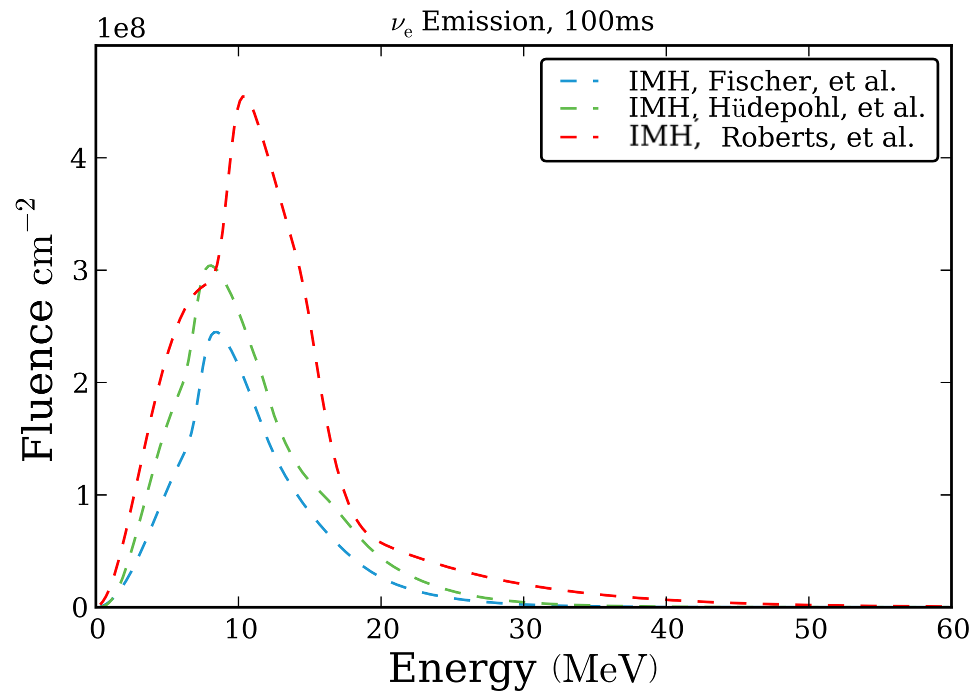
[7] Fermilab, Batavia, IL, 60510-5011

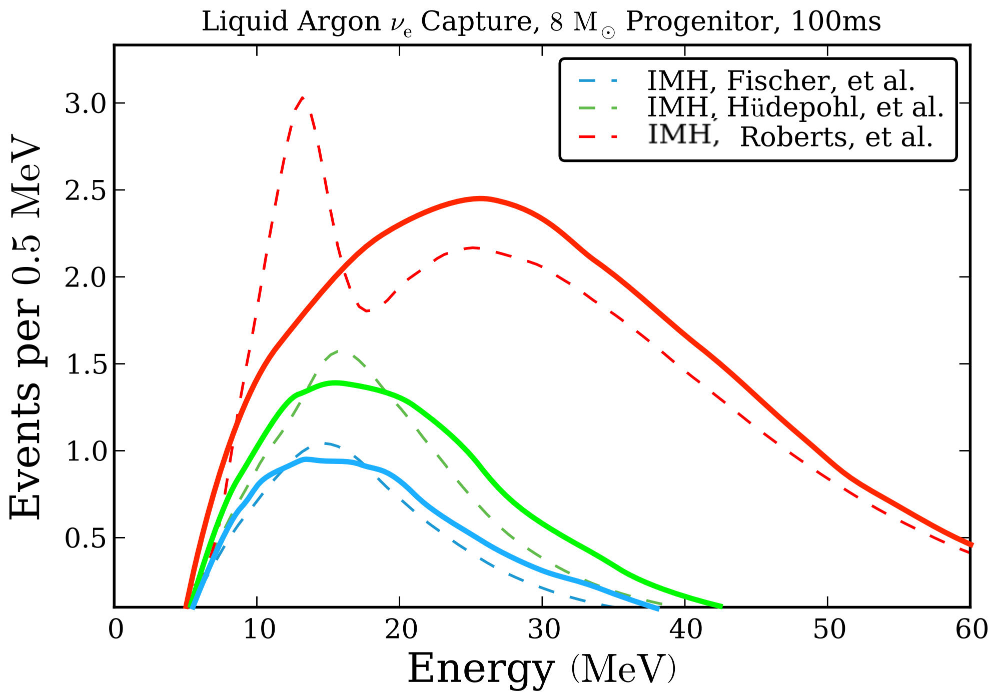
[8] Department of Physics, University of Wisconsin, Madison, WI, 53706-1390

[*] schol@phy.duke.edu

Typical Result of the Chi-squared test



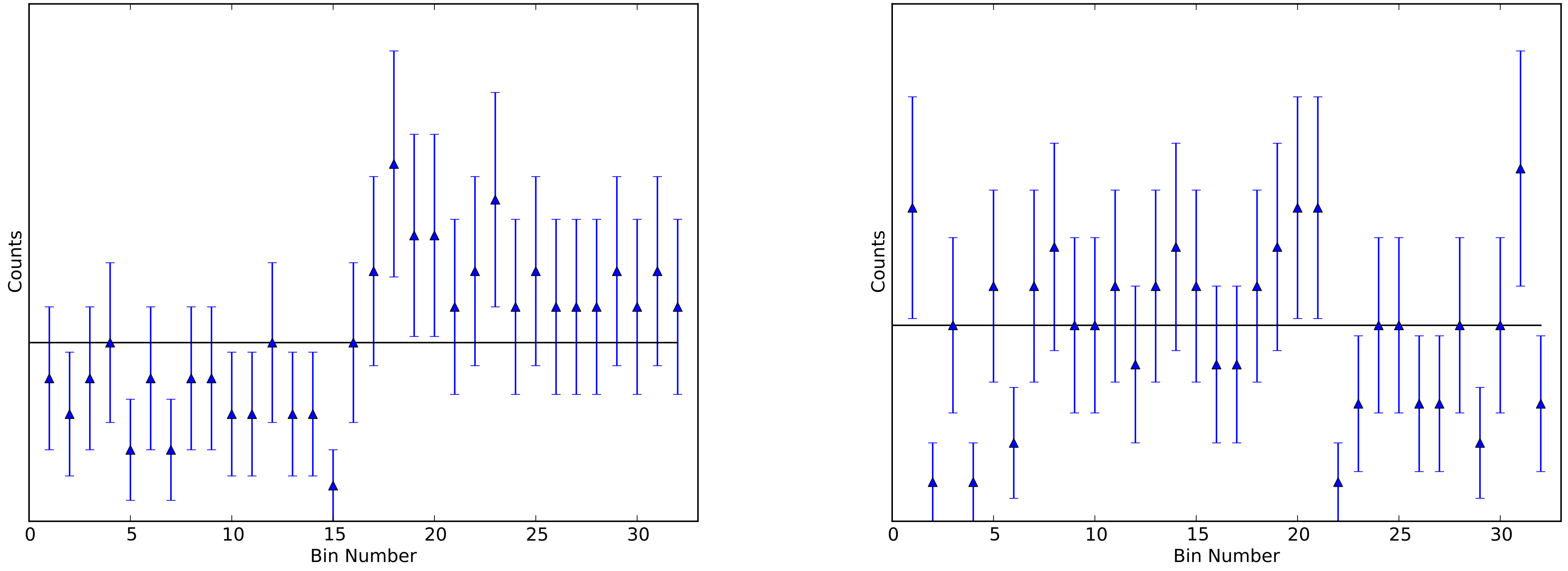




In spite of strong spectral features, fits of single component thermal spectra are not strongly in tension with event models.

χ^2 does not capture all the information

Both data sets have identical χ^2



Correlation Matrix

$$r_{ij} = \frac{(x_i - \bar{x}_i)\,(x_j - \bar{x}_j)}{\sigma_i \sigma_j}$$

$$\hat{r} = \begin{pmatrix} r_{11} & r_{12} & r_{13} & \cdots & r_{1n} \\ \vdots & r_{22} & r_{23} & \cdots & r_{2n} \\ & & \ddots & & \\ & & & & r_{nn} \end{pmatrix}$$

For Poisson random data:

$$\mathrm{Tr}\,(\hat{r}) = \chi^2$$

Pearson's Correlation Coefficient

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

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

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

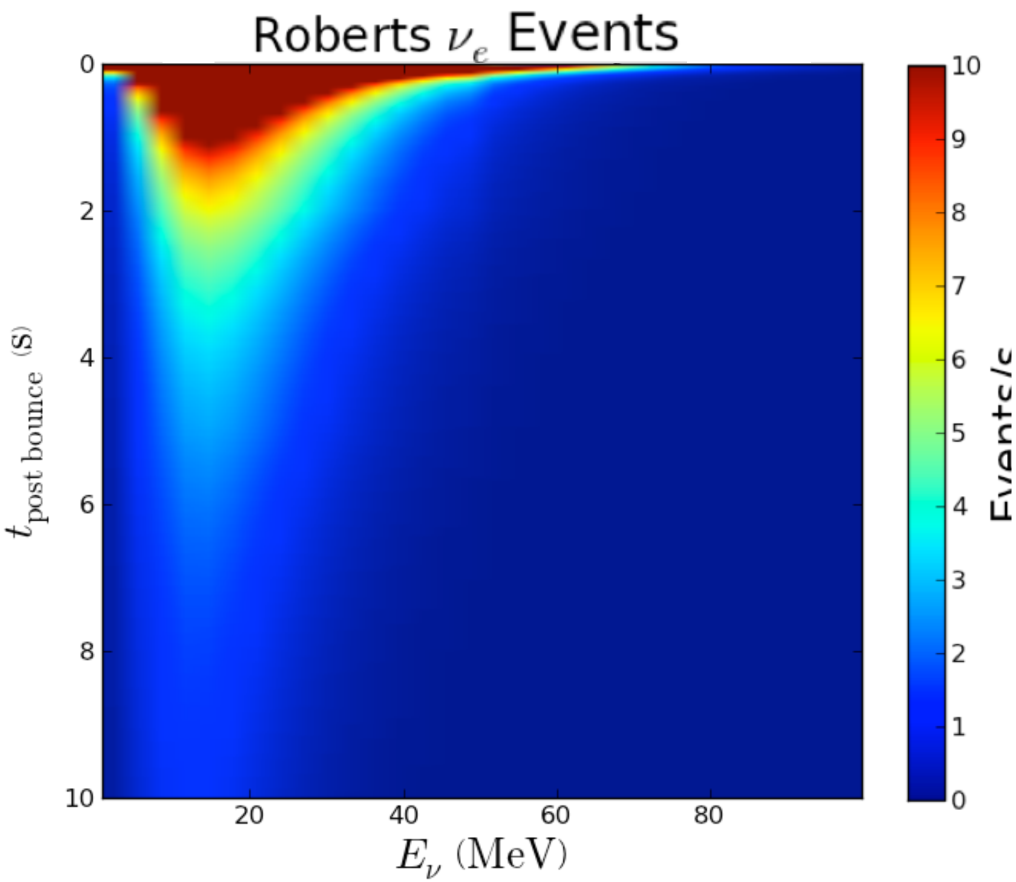
$$SE = \frac{1}{\sqrt{DOF - 3}}$$

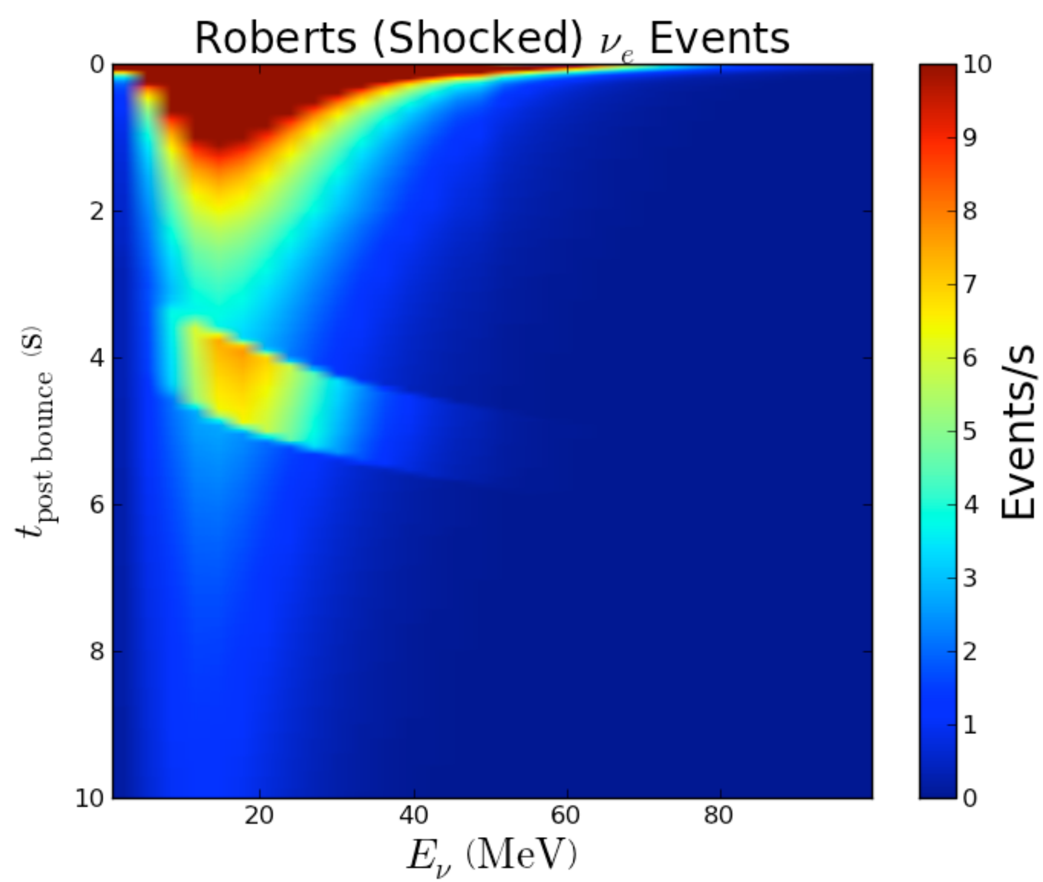
$$z = \left[F(r) - F(r0)\right]\sqrt{DOF - 3}$$

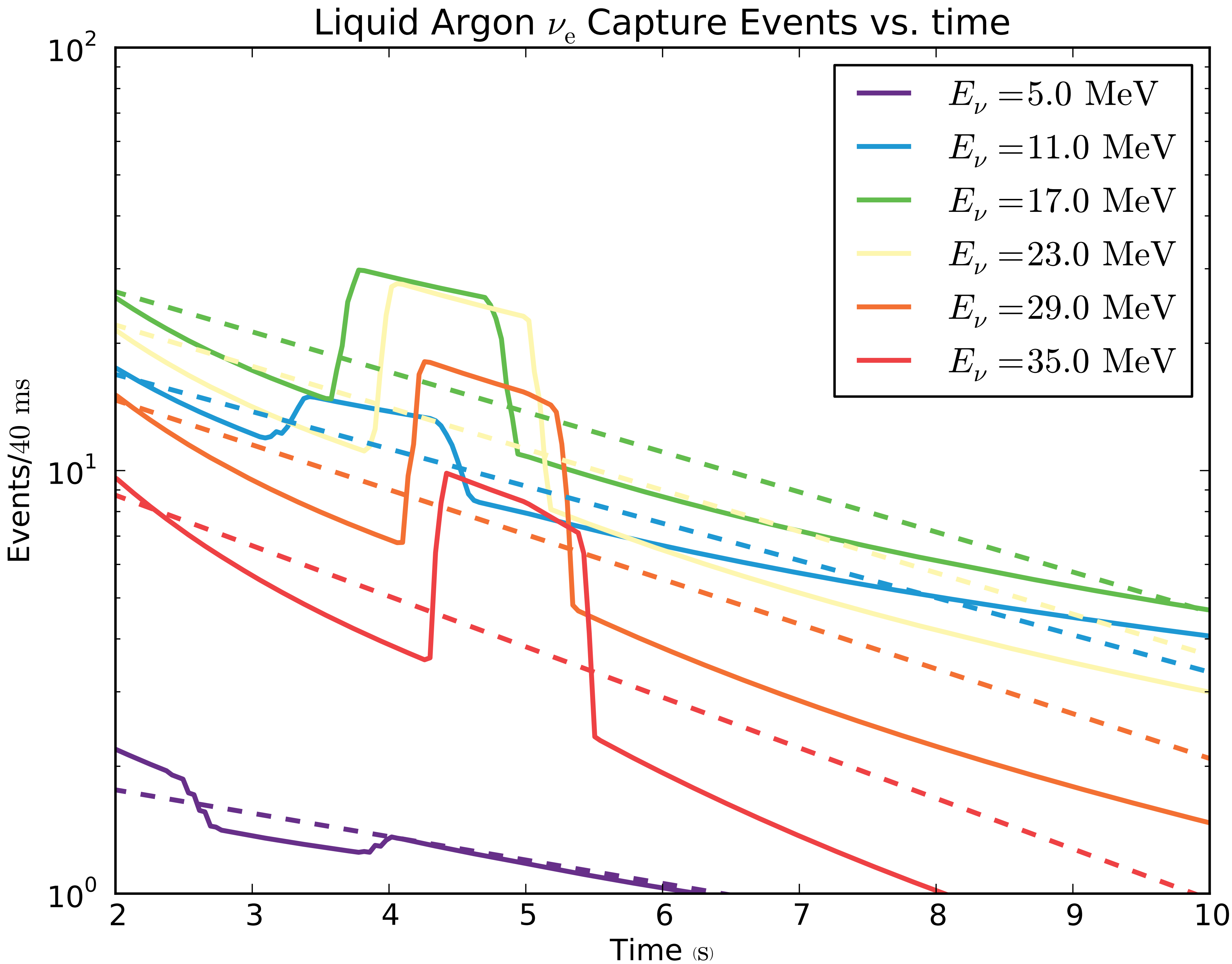
$$P(z) = 1 + Erf\left(\frac{-z}{\sqrt{2}}\right)$$

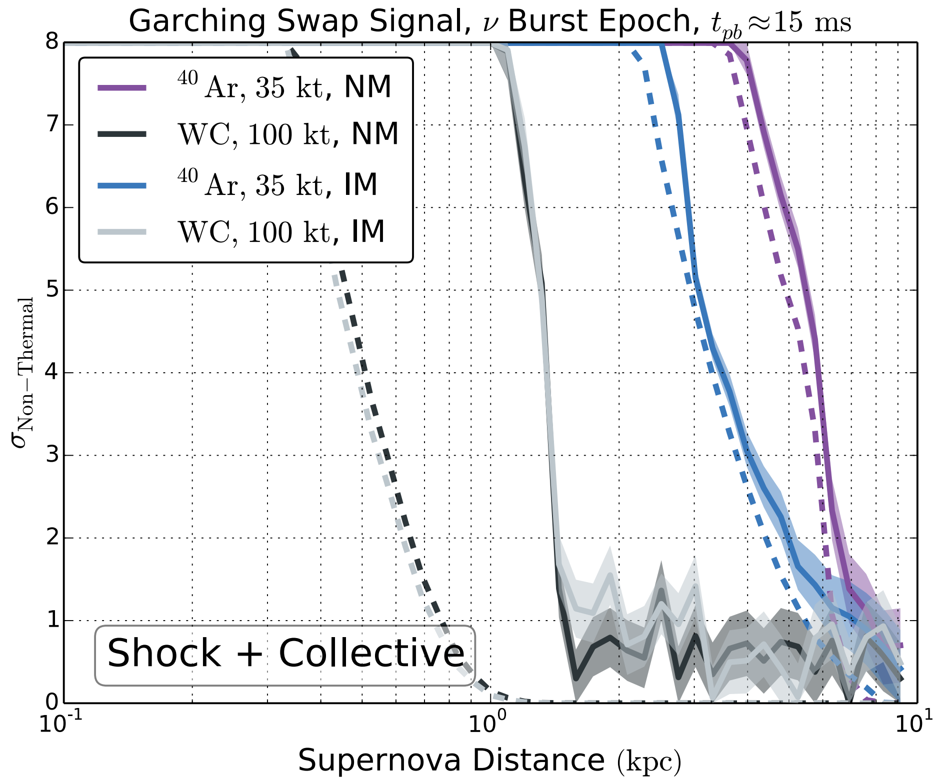
Shock signal:

Integrate over energy and scan temporally!

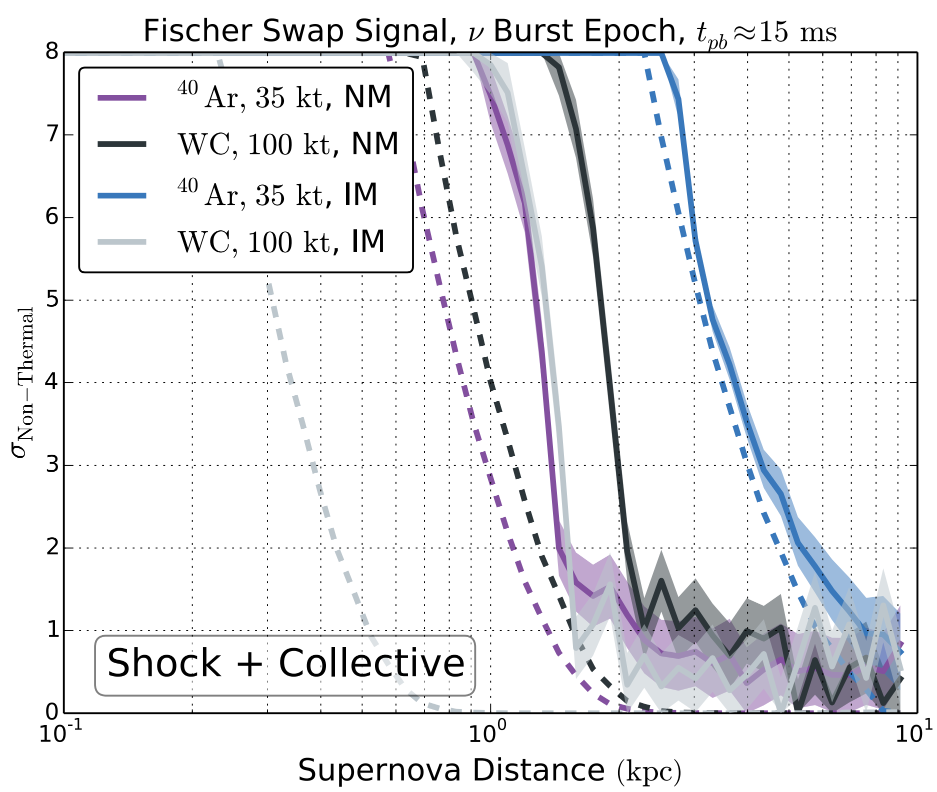


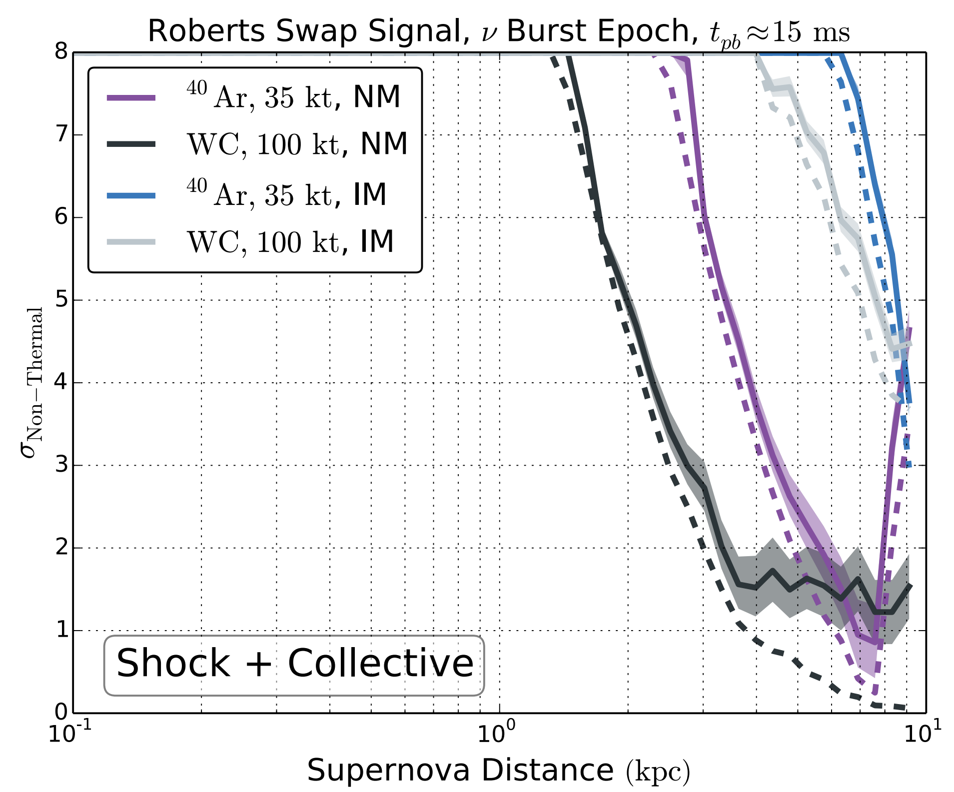


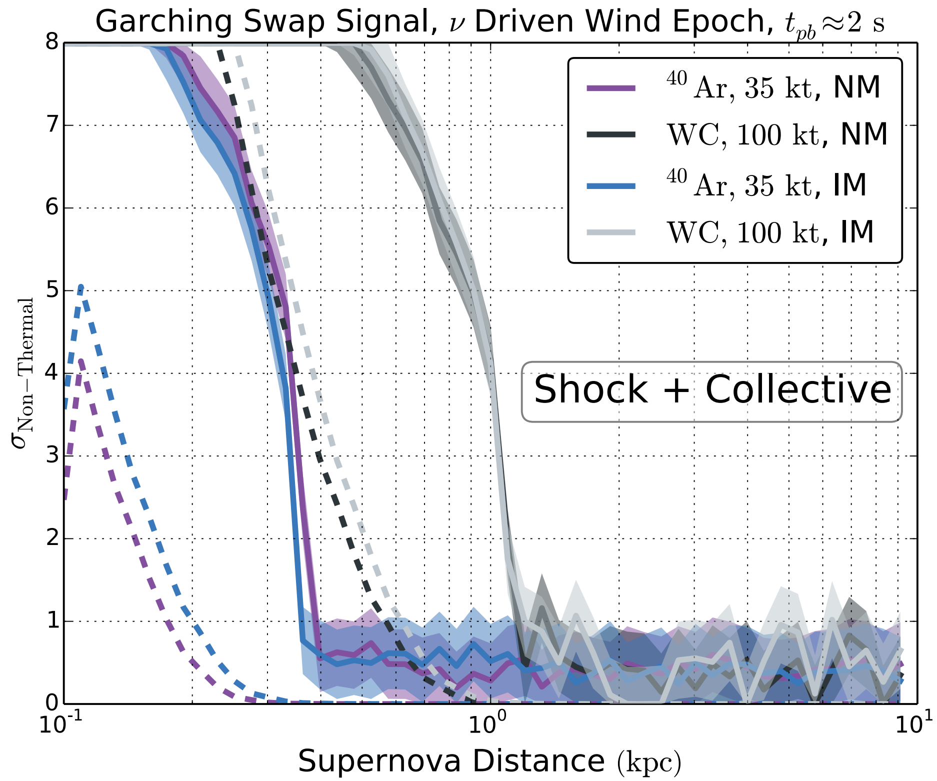

Liquid Argon ν_e Capture Events vs. time
E_ν =5.0 MeV
E_ν =11.0 MeV
E_ν =17.0 MeV
E_ν =23.0 MeV
E_ν =29.0 MeV
E_ν =35.0 MeV
Events/40 ms
Time (s)
10^0
10^1
10^2
2
3
4
5
6
7
8
9
10



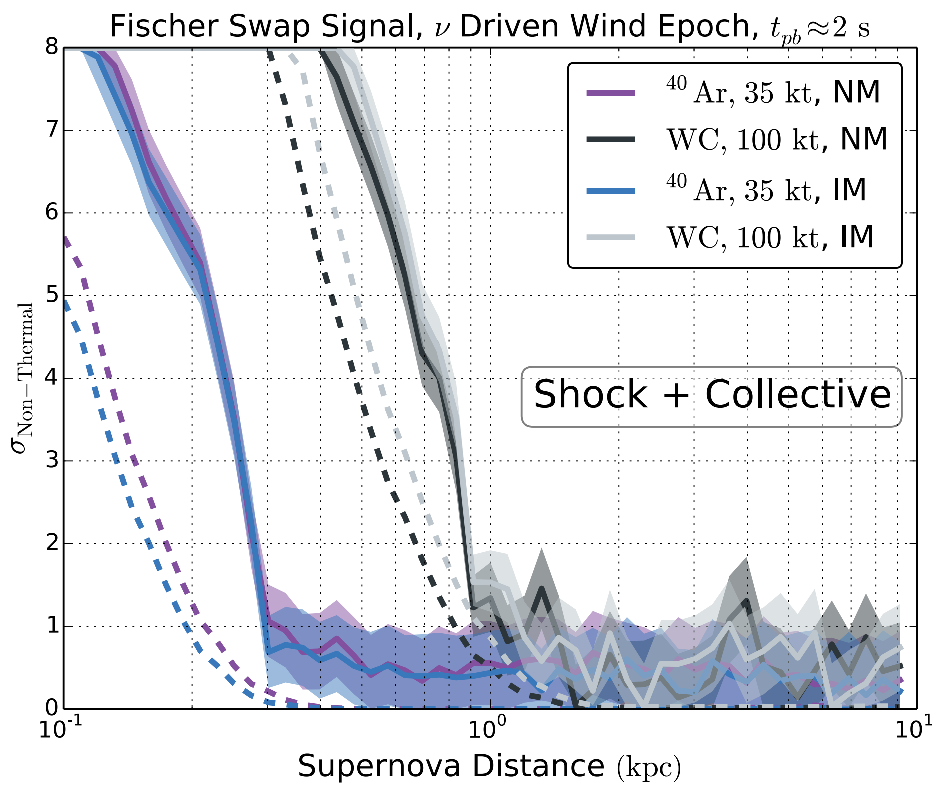
Neutronization Burst: The signal with the best discrimination power.

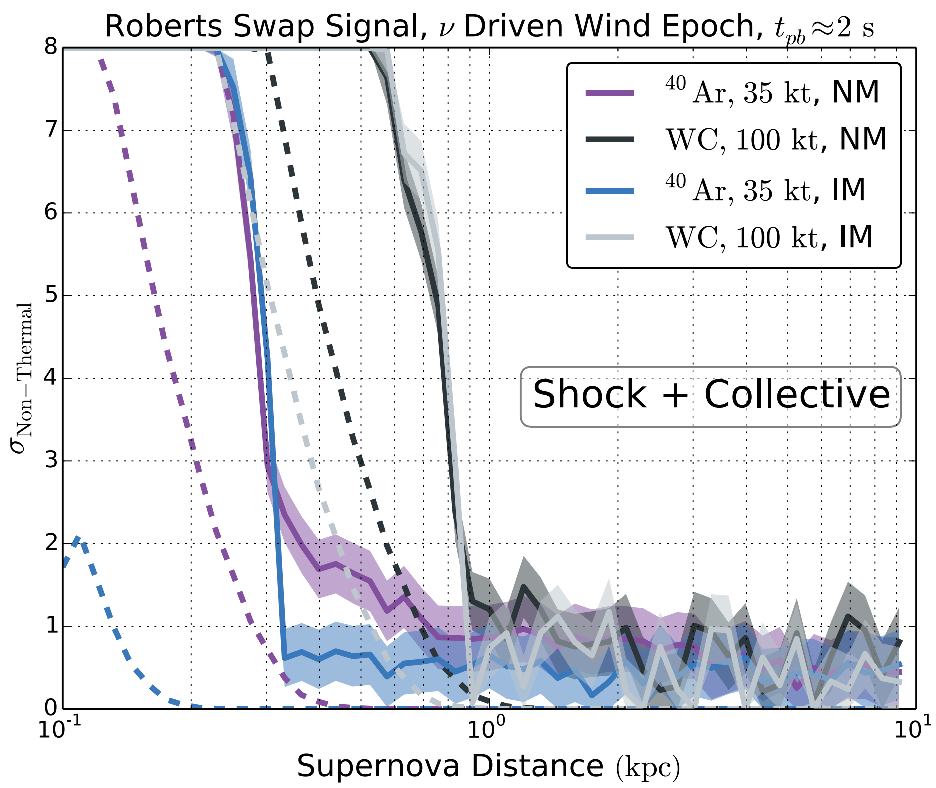




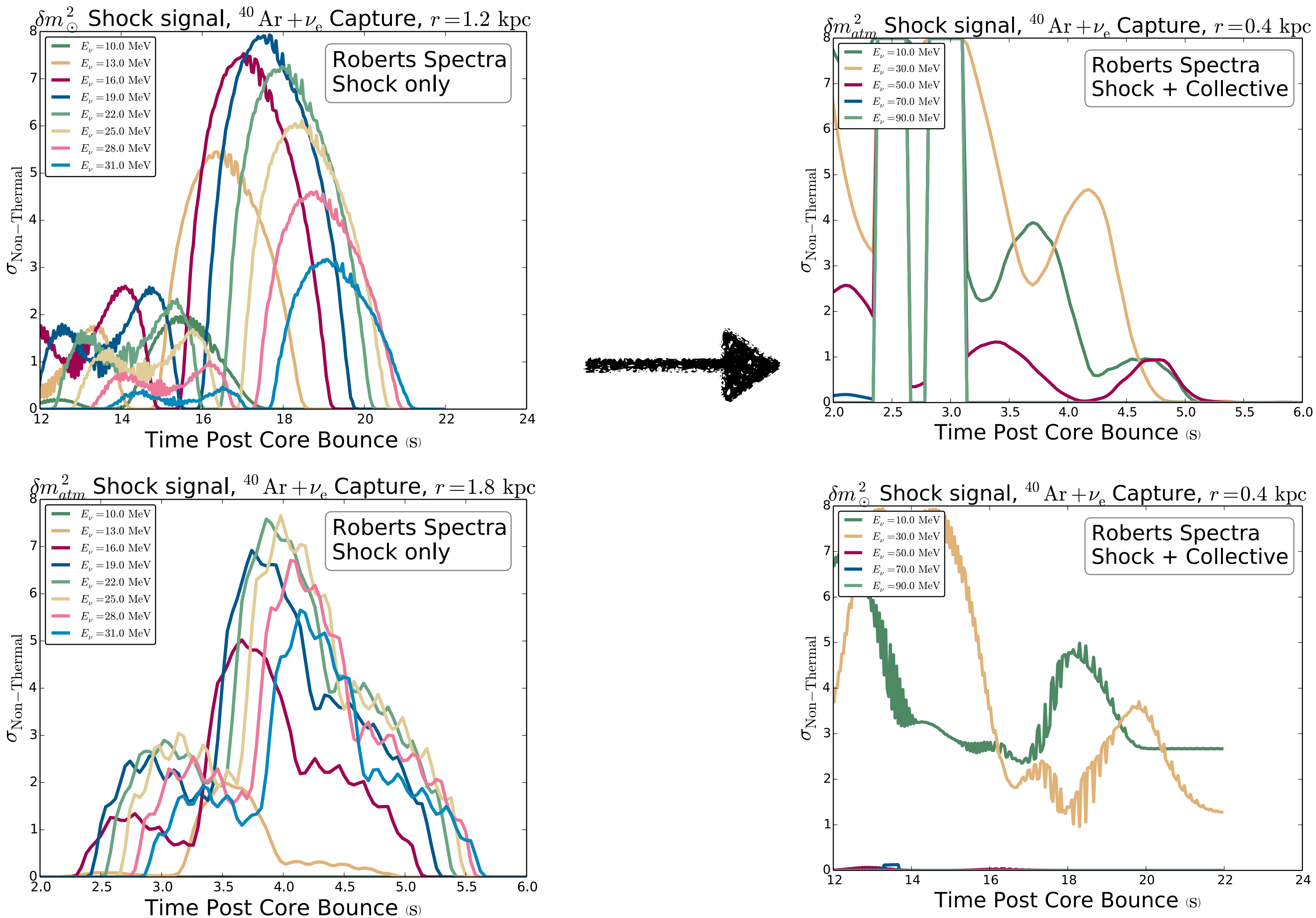


Neutrino Driven Wind: The supernova needs to be very close.





Collective Oscillations tend to ruin the shock signal to noise ratio



Conclusions

- Flavor tagging in LAr makes the neutronization burst a guaranteed 10kpc science target when used in concert with Hyper-K (Super-K/Juno works too). Gamma tagging in DUNE would clinch the mass hierarchy.
- Rapid time variability of collective oscillations makes the 'treasure' to be found in other oscillation signatures statistically troublesome.
- Lack of a strong temperature hierarchy also hinders the range at which thermal emission may be ruled out for shocks.
- Observable net lepton fluence after ~50 ms = Treasure.