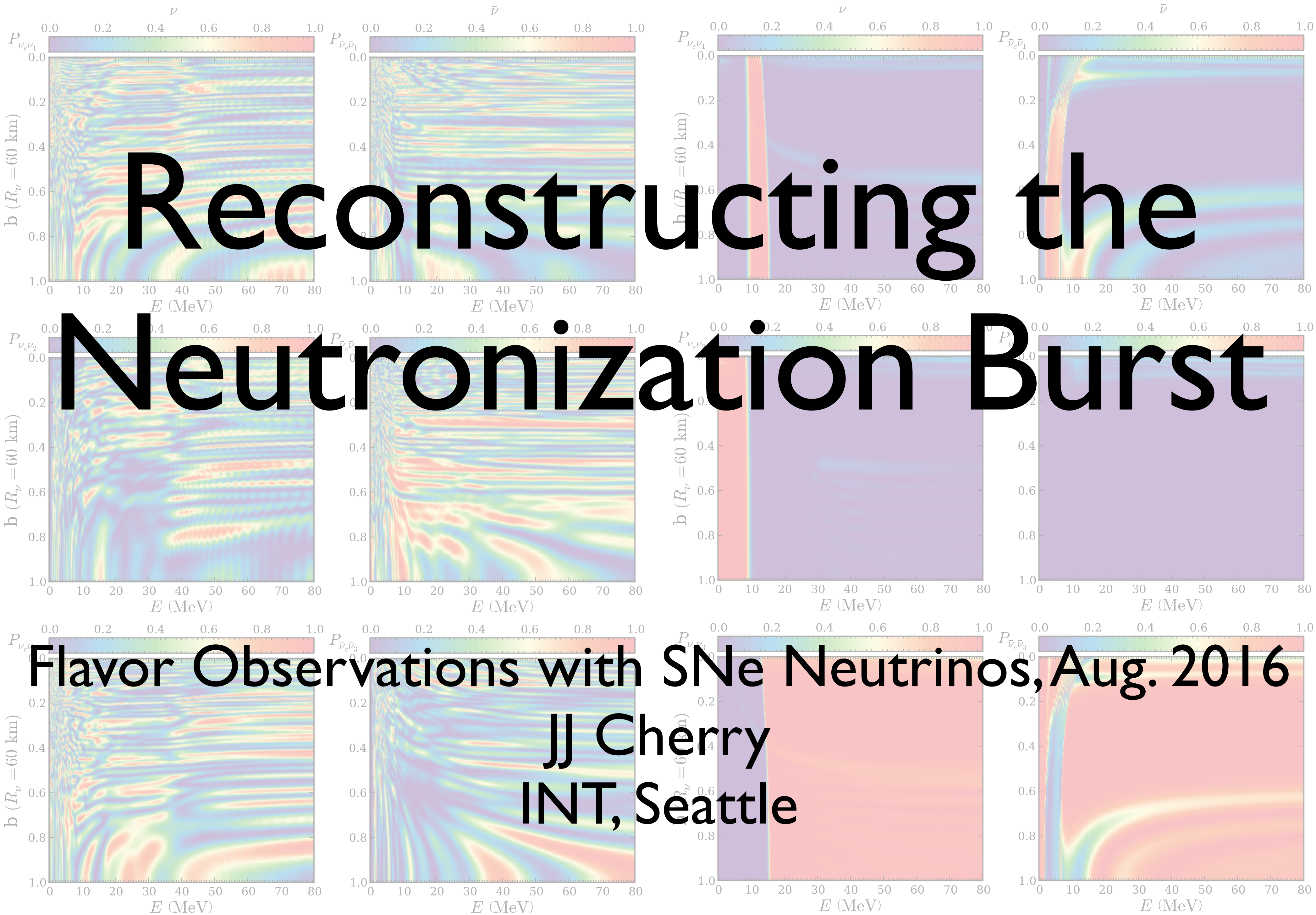
Reconstructing the Neutronization Burst



Flavor Observations with SNe Neutrinos, Aug. 2016

JJ Cherry
INT, Seattle

What do we hope to learn?

- Fundamental neutrino physics.
- Properties of the hot proto-neutron star: EOS.
- Supernova explosion mechanics: mass accretion.
- How to structure our experimental program to maximize our ability to explore the above!

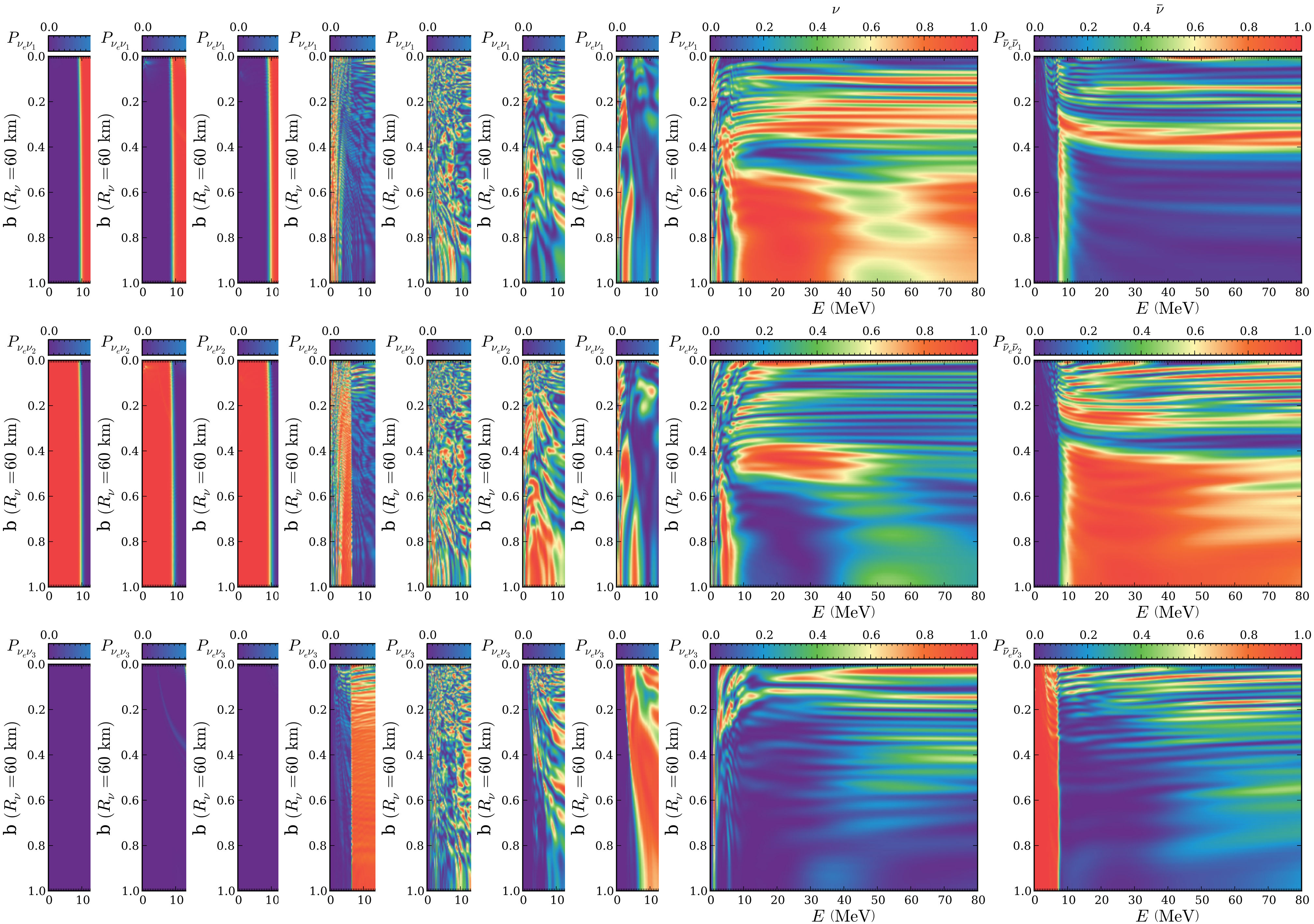
Zero-th order considerations

- SN 1987a confirmed that O(0.1 M_sun) energy is released as neutrino energy.
- ~.5 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 $\nu_e \; vs. \; \bar{\nu}_e$

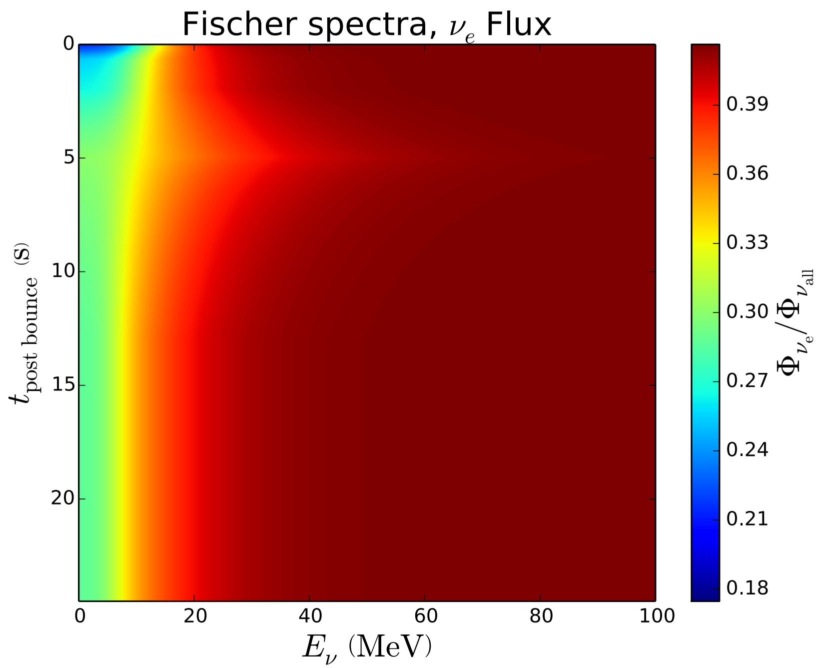
It is not enough to look at static spectra

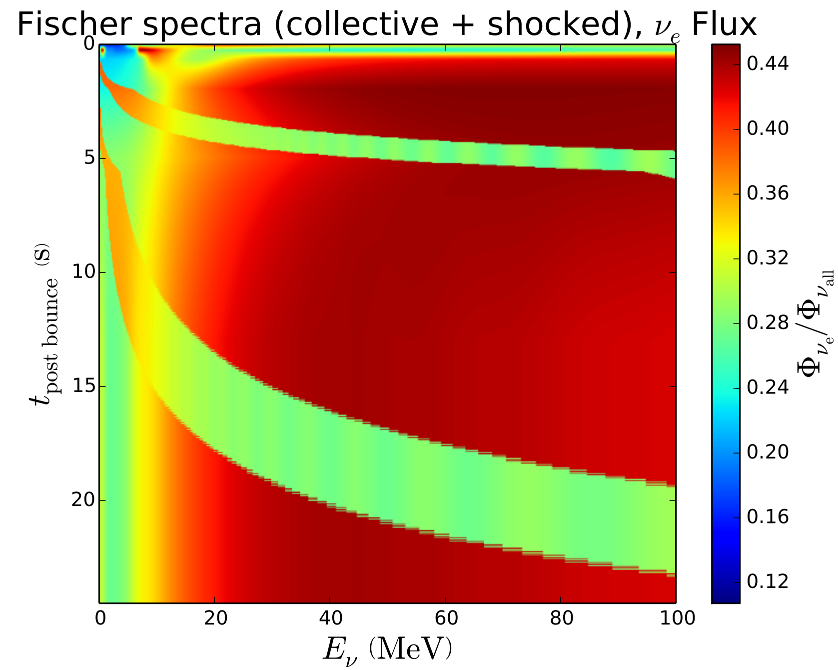
- Supernova are dynamical!
- The neutrino emission evolves rapidly with time, so we must establish a time series of different spectra for each model.
- Space snapshots roughly evenly in terms of neutrino fluence and stitch them together with curve fitting for fine time resolution.

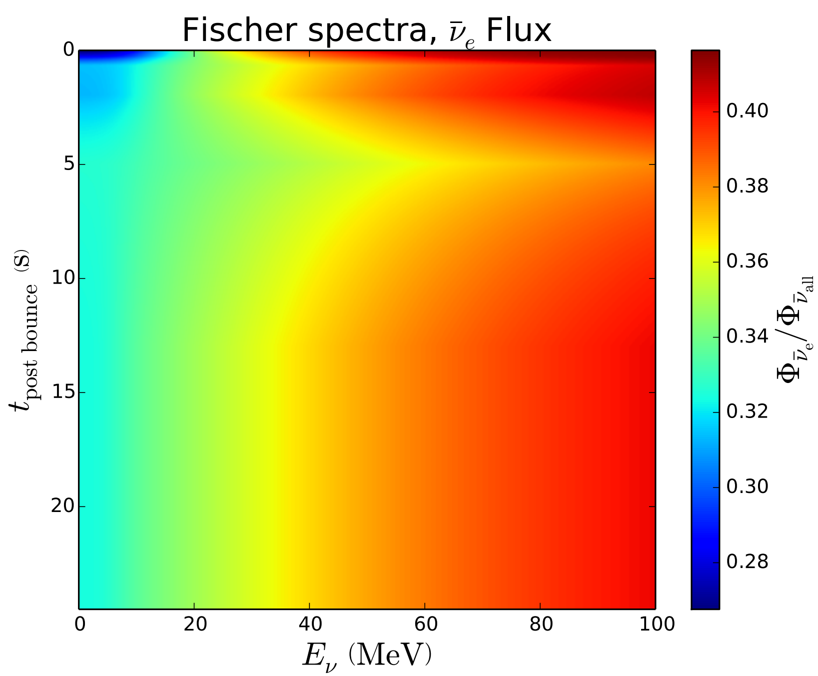
Roberts, and Reddy (2012)

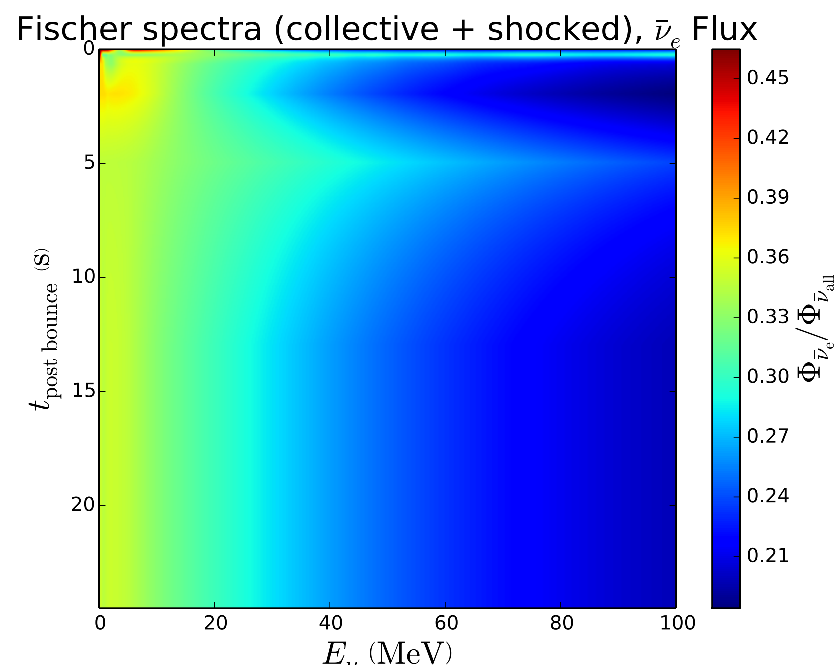


Stitch Snapshots Together

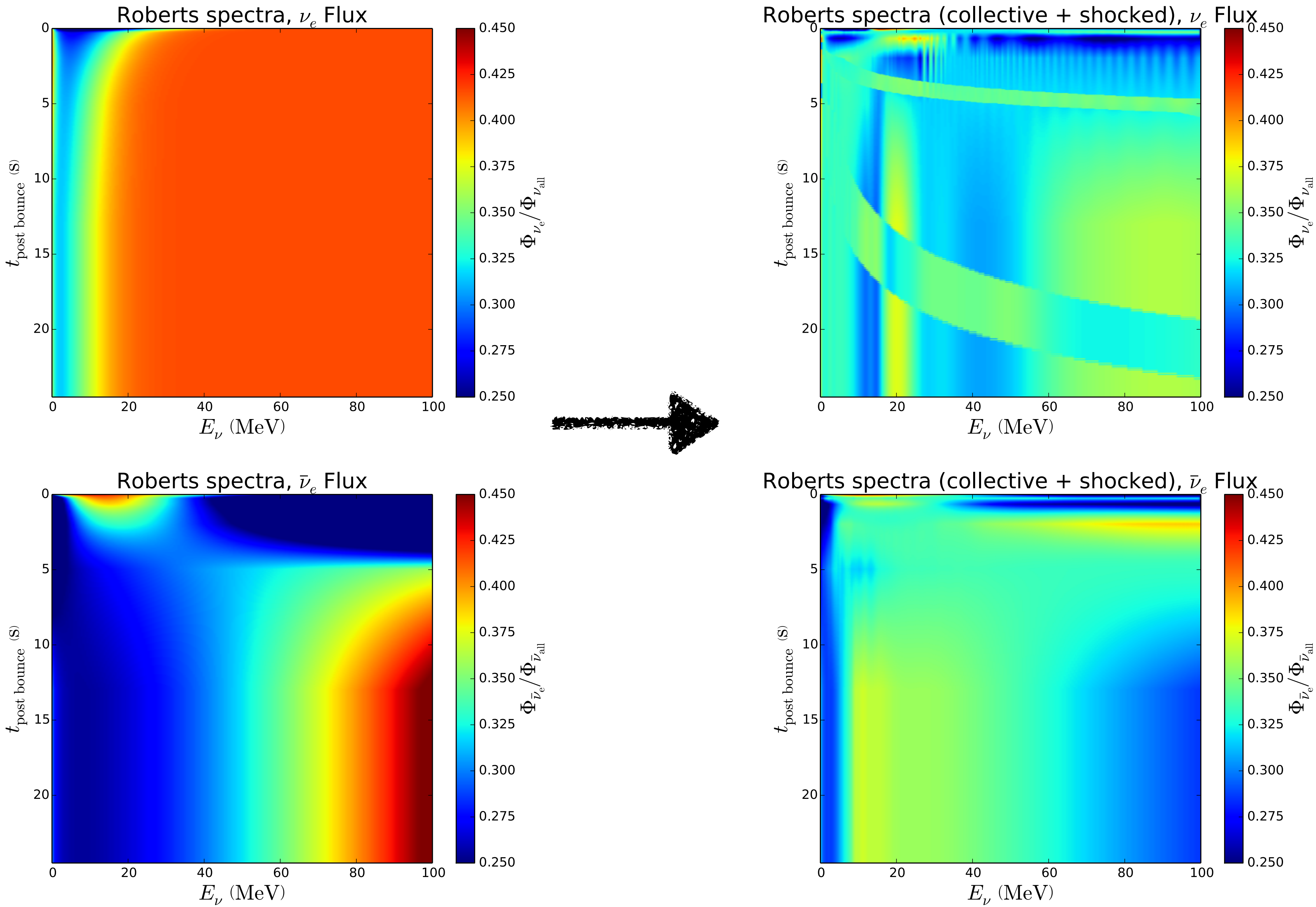








Stitch Snapshots Together



A simple test: rule out thermal emission

- Use our emission toy models to *exclude* thermal fits to the received spectra.
- Run SNOwGLoBES on many tiny slices of the times series and stack the reconstruction.
- 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]

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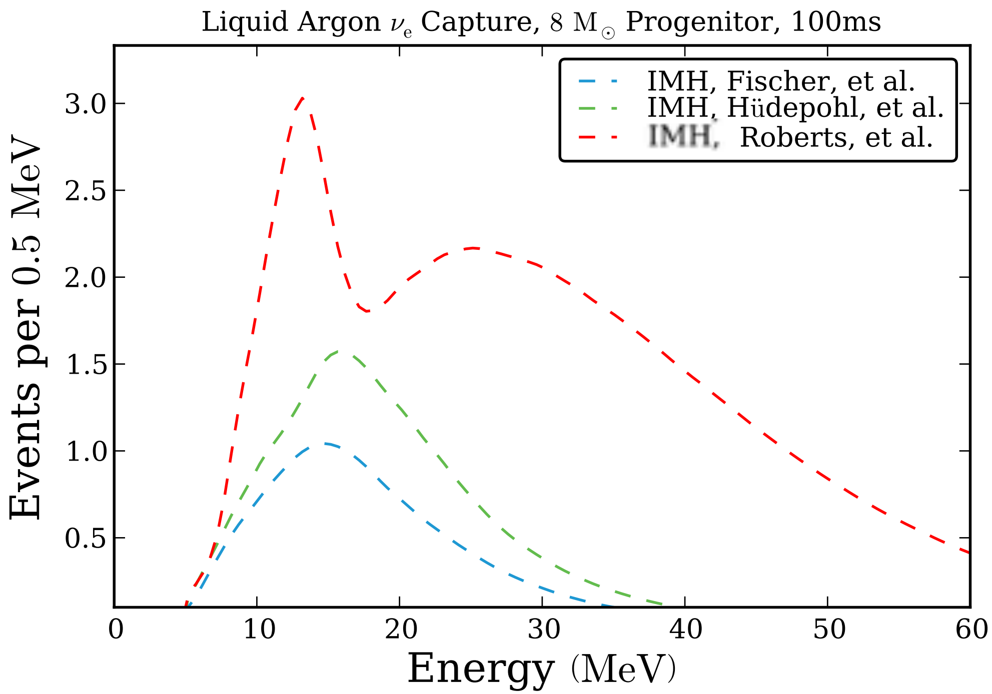
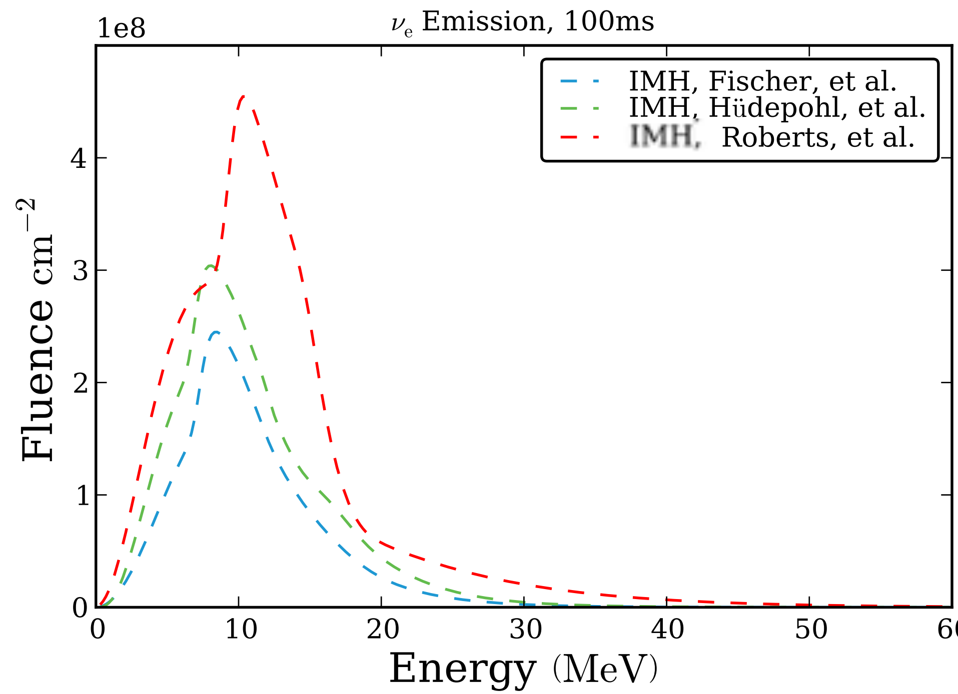
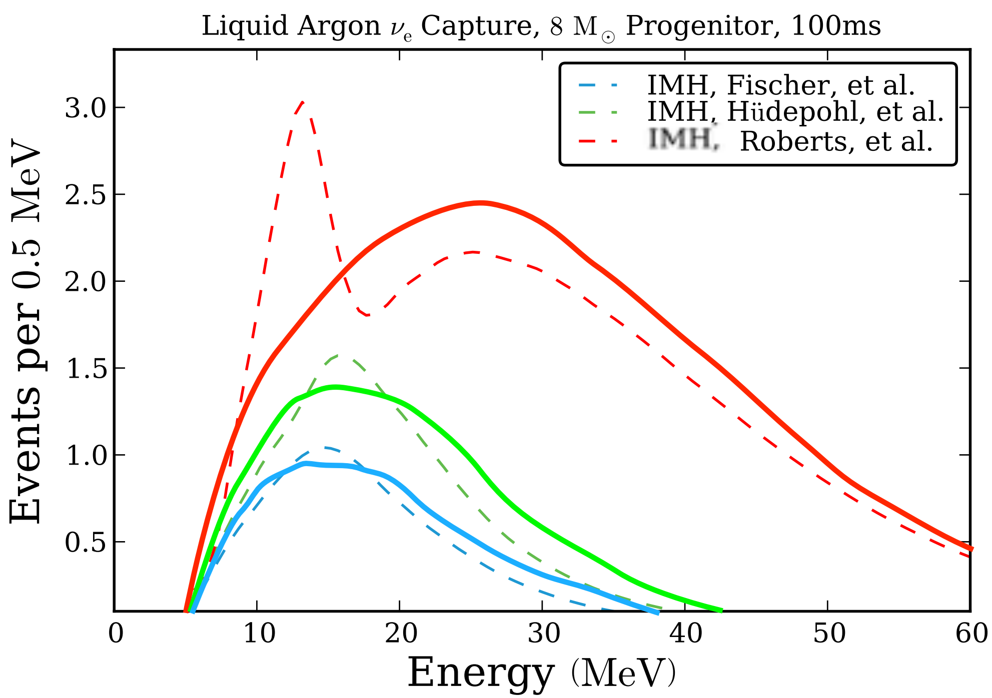
Typical Result of the Chi-squared test



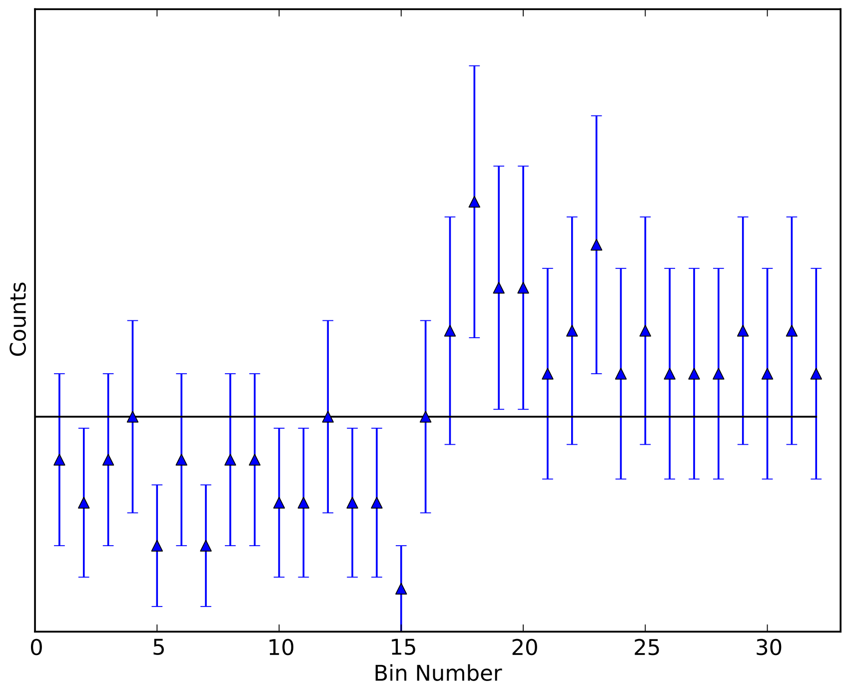


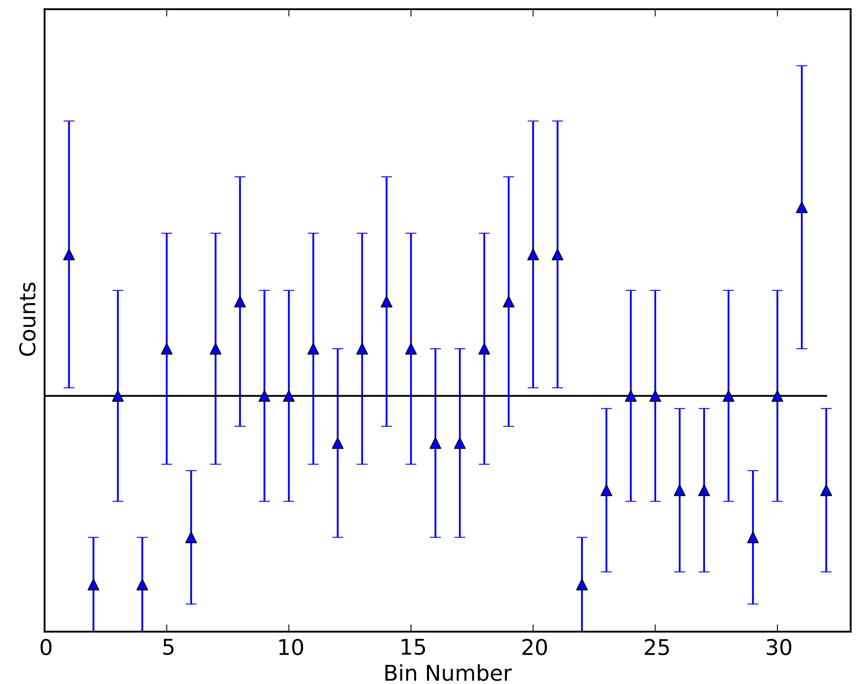


In spite of strong spectral features, fits of multi-component thermal spectra are not strongly in tension with event models.

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

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

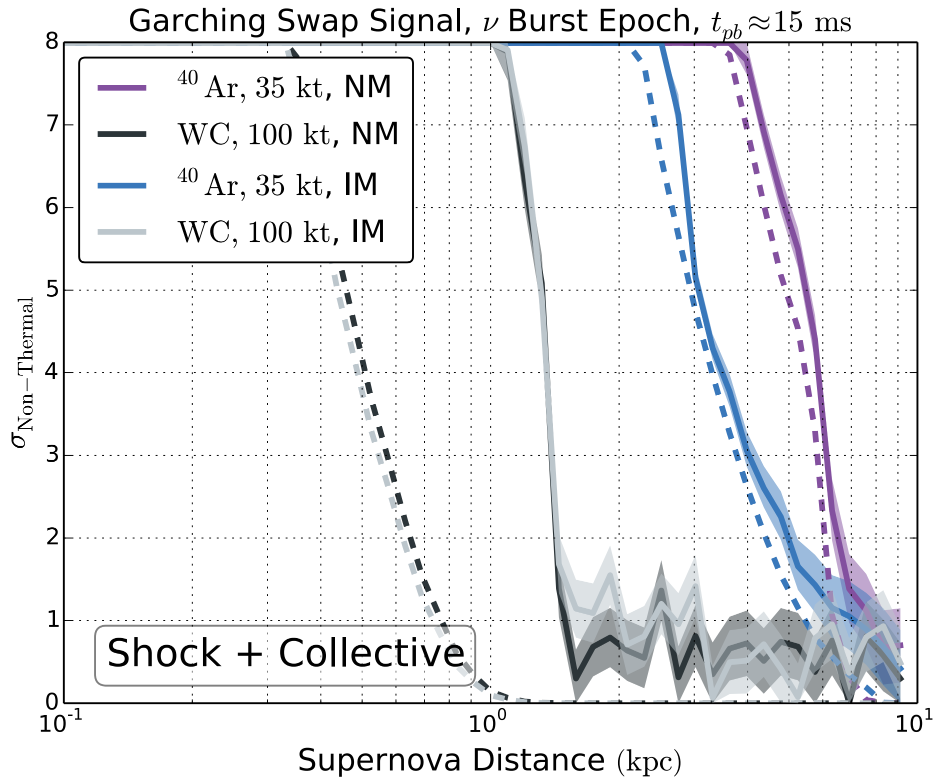
Fisher Transformation: $F(r) = \mathrm{arctanh}(r)$

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

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

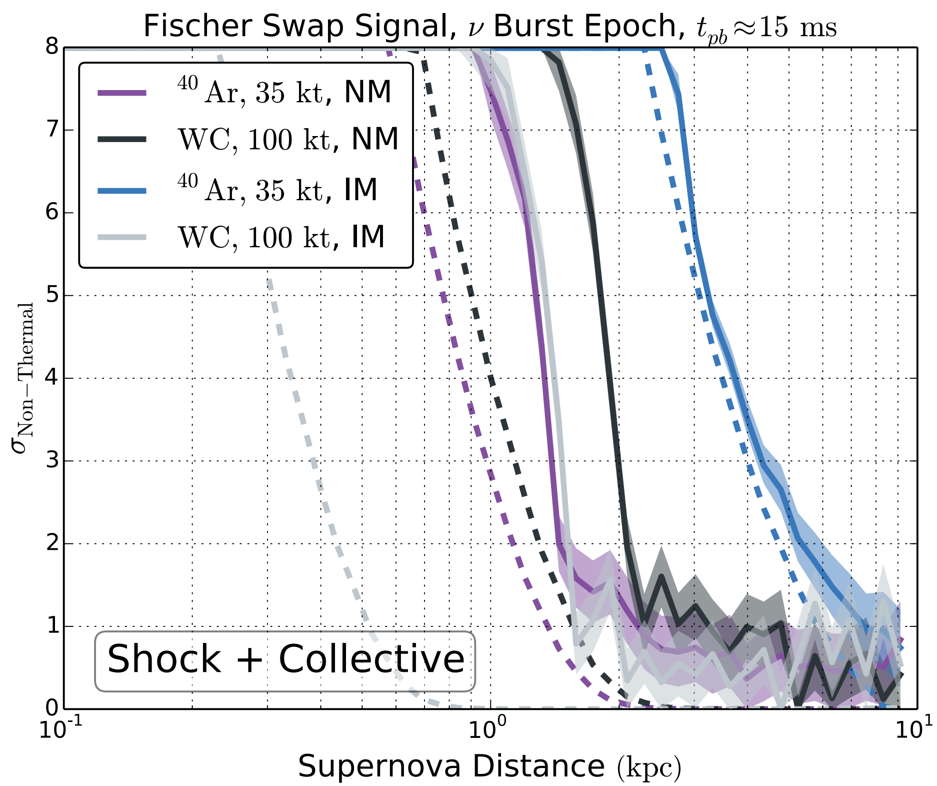
$$z = [F(r) - F(r0)]\sqrt{DOF - 3}$$

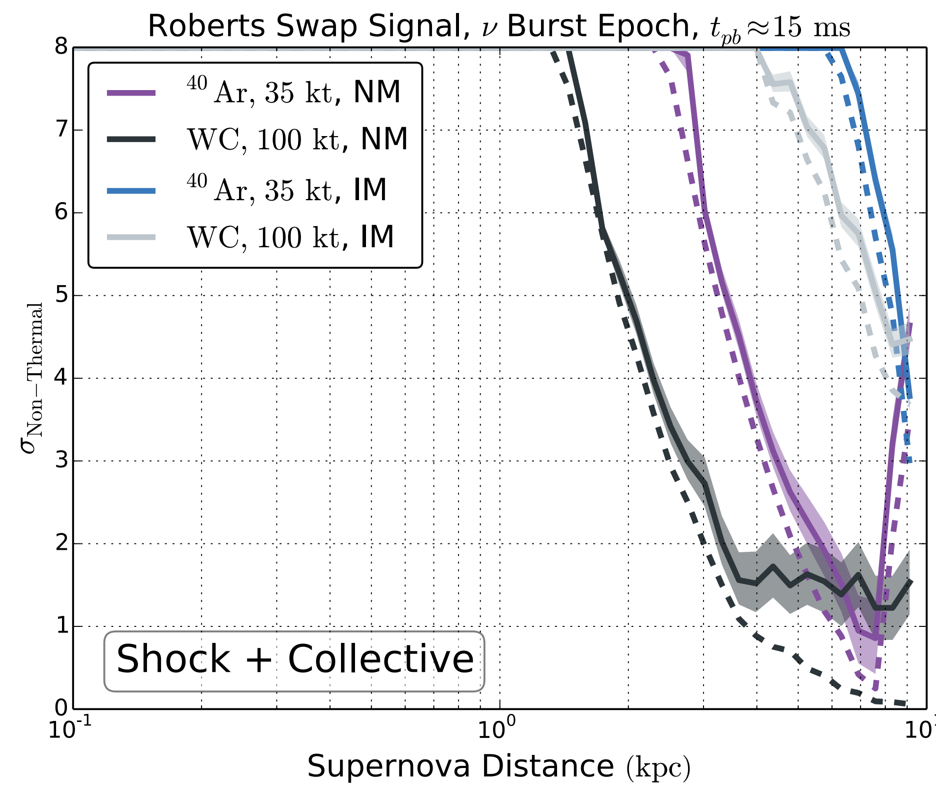
$$P(z) = 1 + Erf\left(\frac{-z}{\sqrt{2}}\right)$$



Neutronization Burst: The signal with the best discrimination power.

Cherry, Duan, Friedland, Scholberg
(in preparation)





Let's say we observe thermal emission

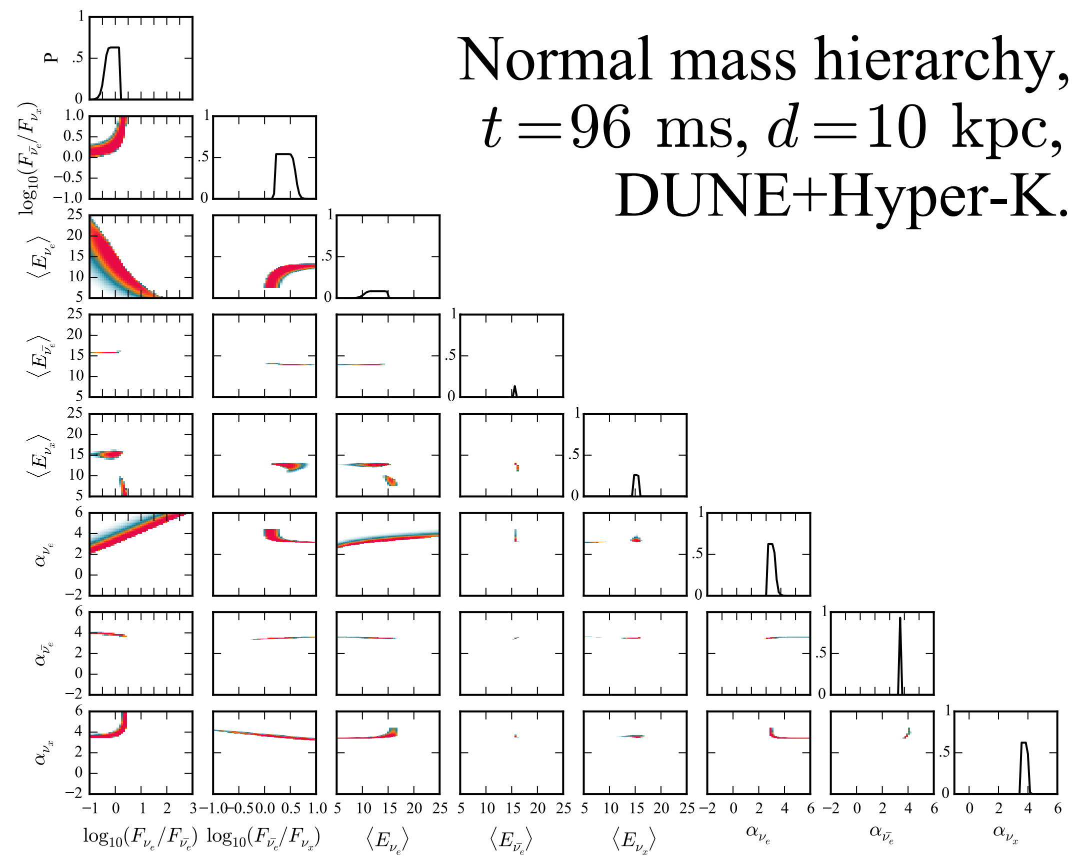
- Preclude complicated oscillation physics during the neutronization burst.
- Try to properly fit the simplest case scenario: adiabatic MSW flavor conversion in the envelope.

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

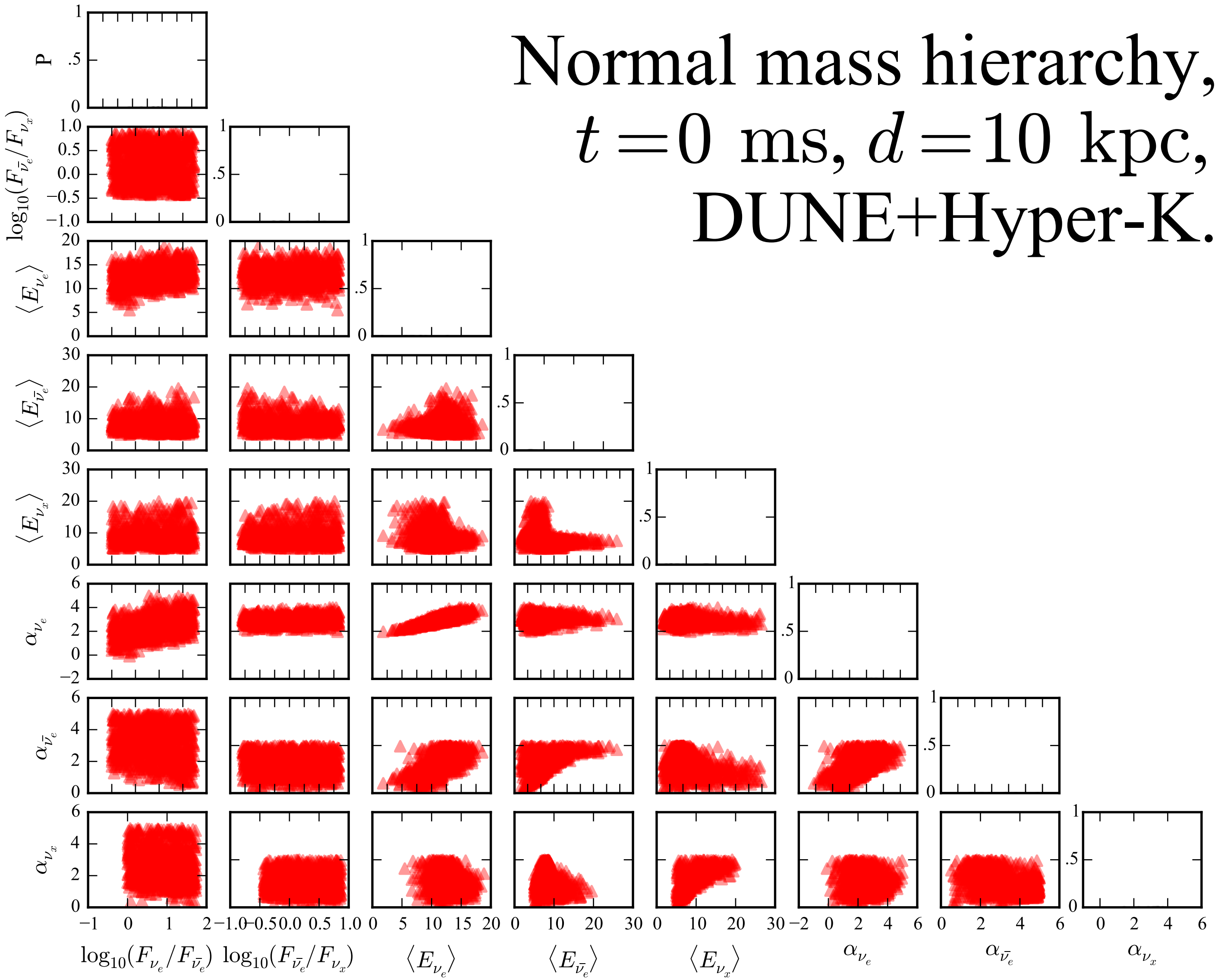
A parameter space rife with local minima

- 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.
- Requires non-deterministic, diffusion-like methods, e.g. genetic algorithms.

Computationally Intensive!

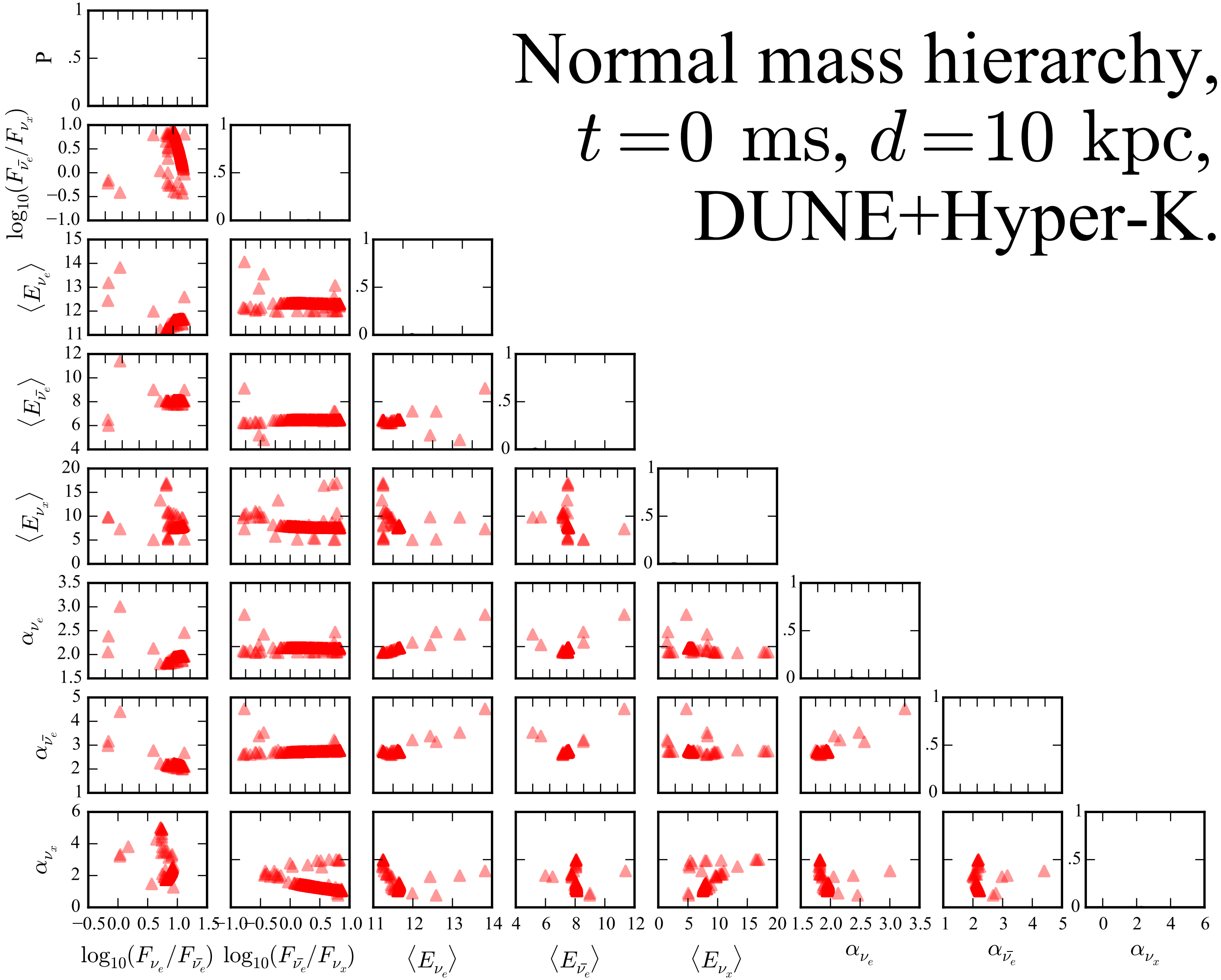
3 Generations

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

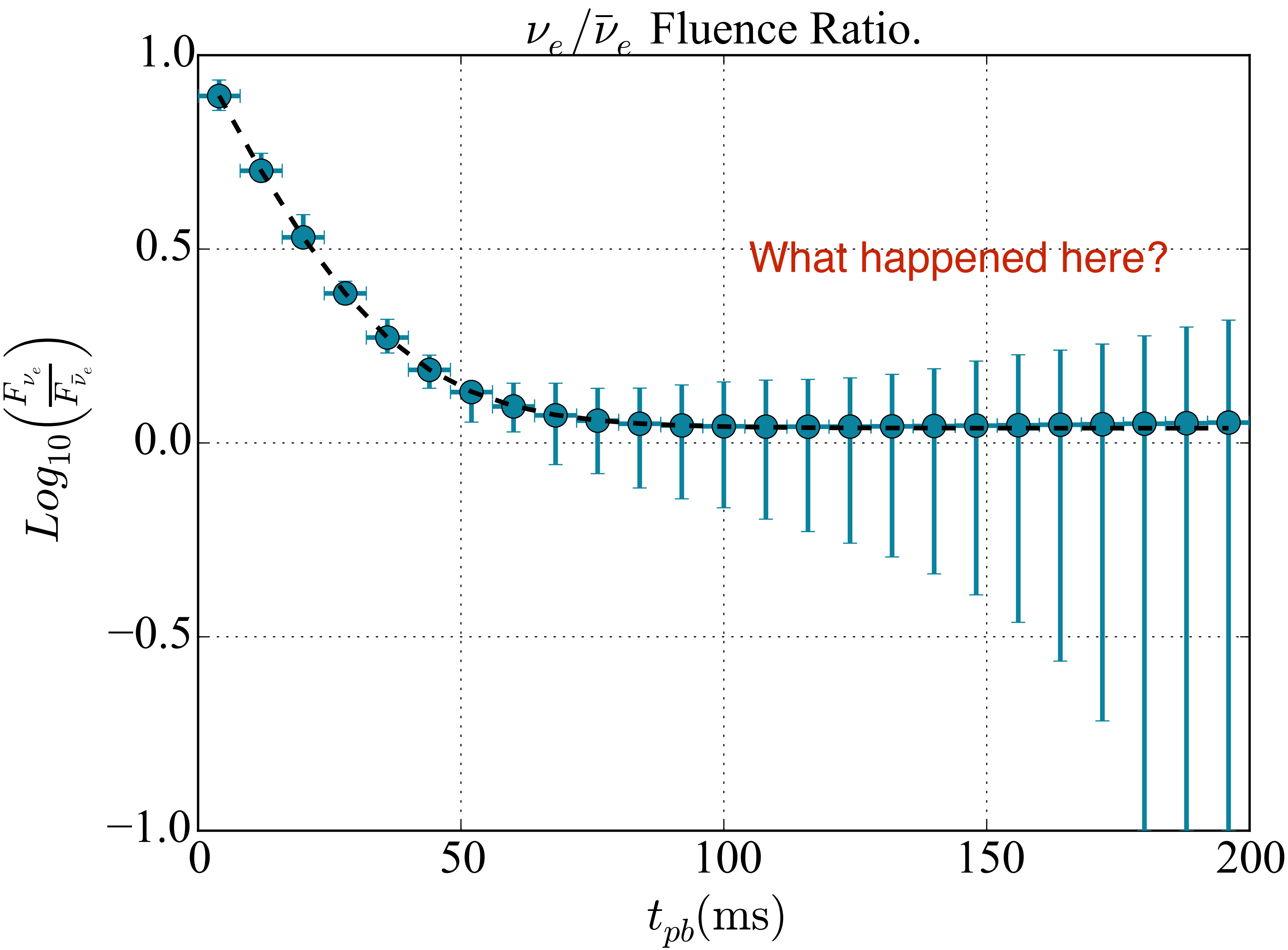


20 Generations

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



Success!



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Where are the accretion $\nu_e's$?

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

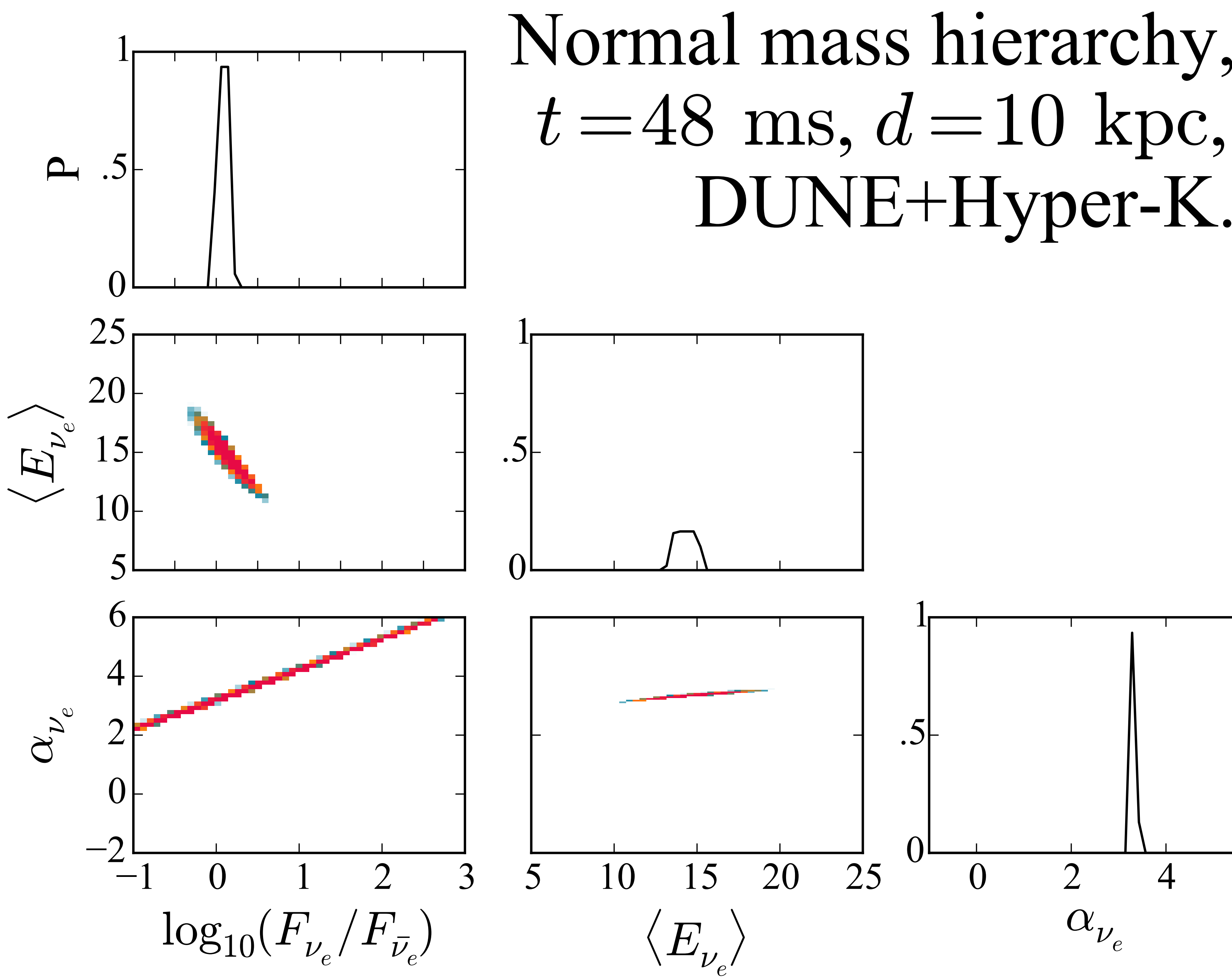
$Y_e \sim 0.5$ $\quad P_{ee}^{nm} = .095\,,\ \ P_{ee}^{im} = .24$

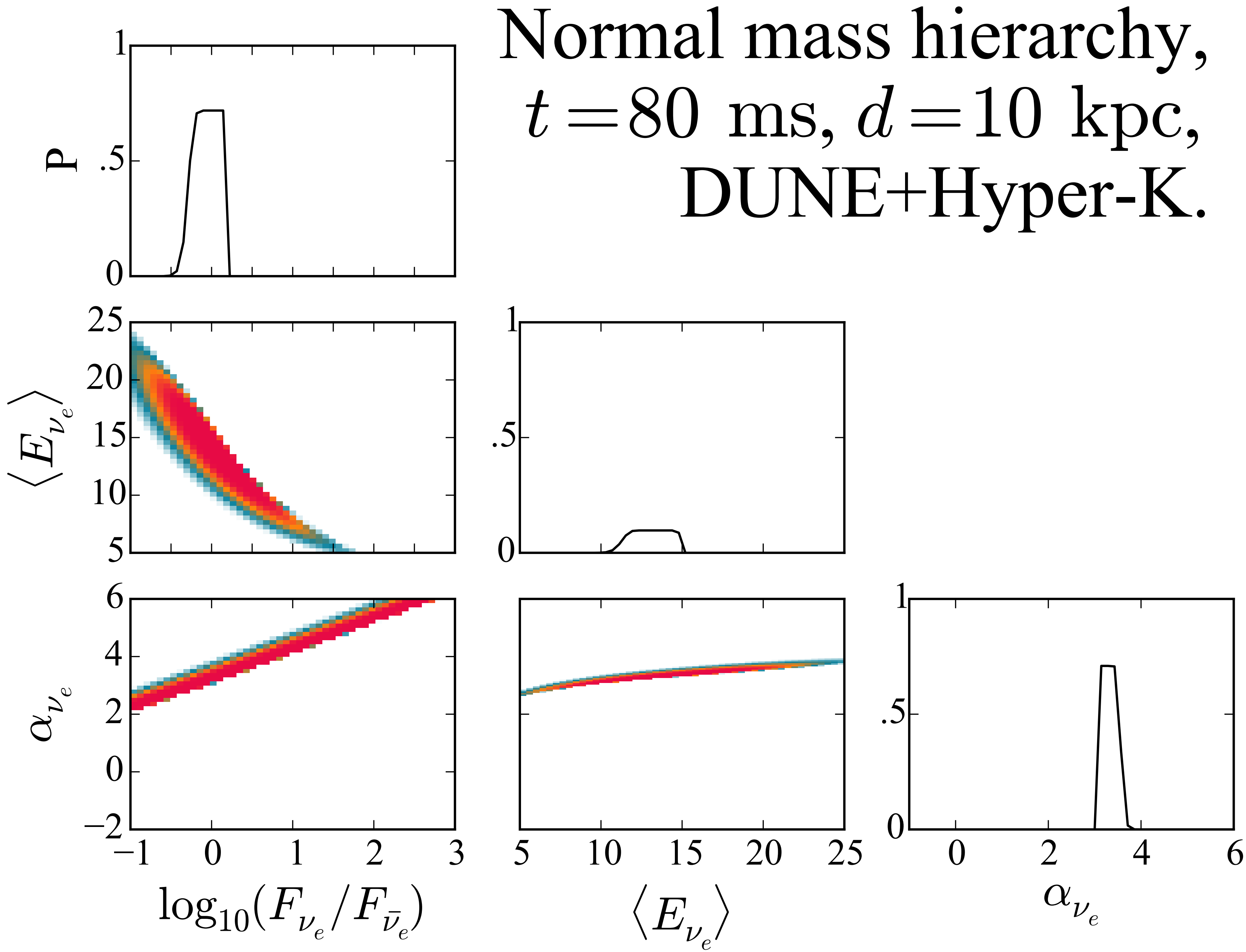
Energetics of accretion:

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

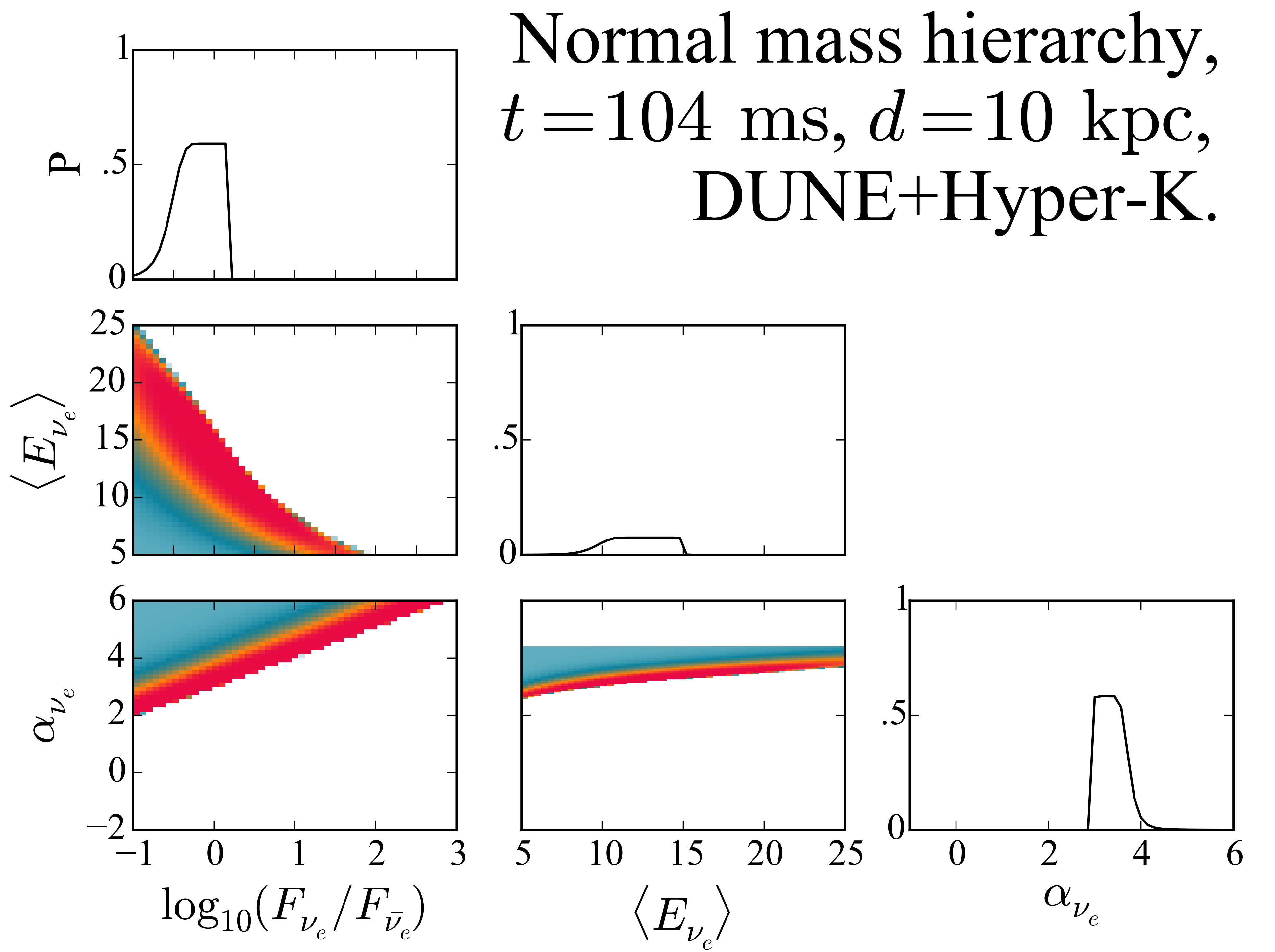
$\Longrightarrow\ 5\%$ of accretion neutrinos carry lepton number

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

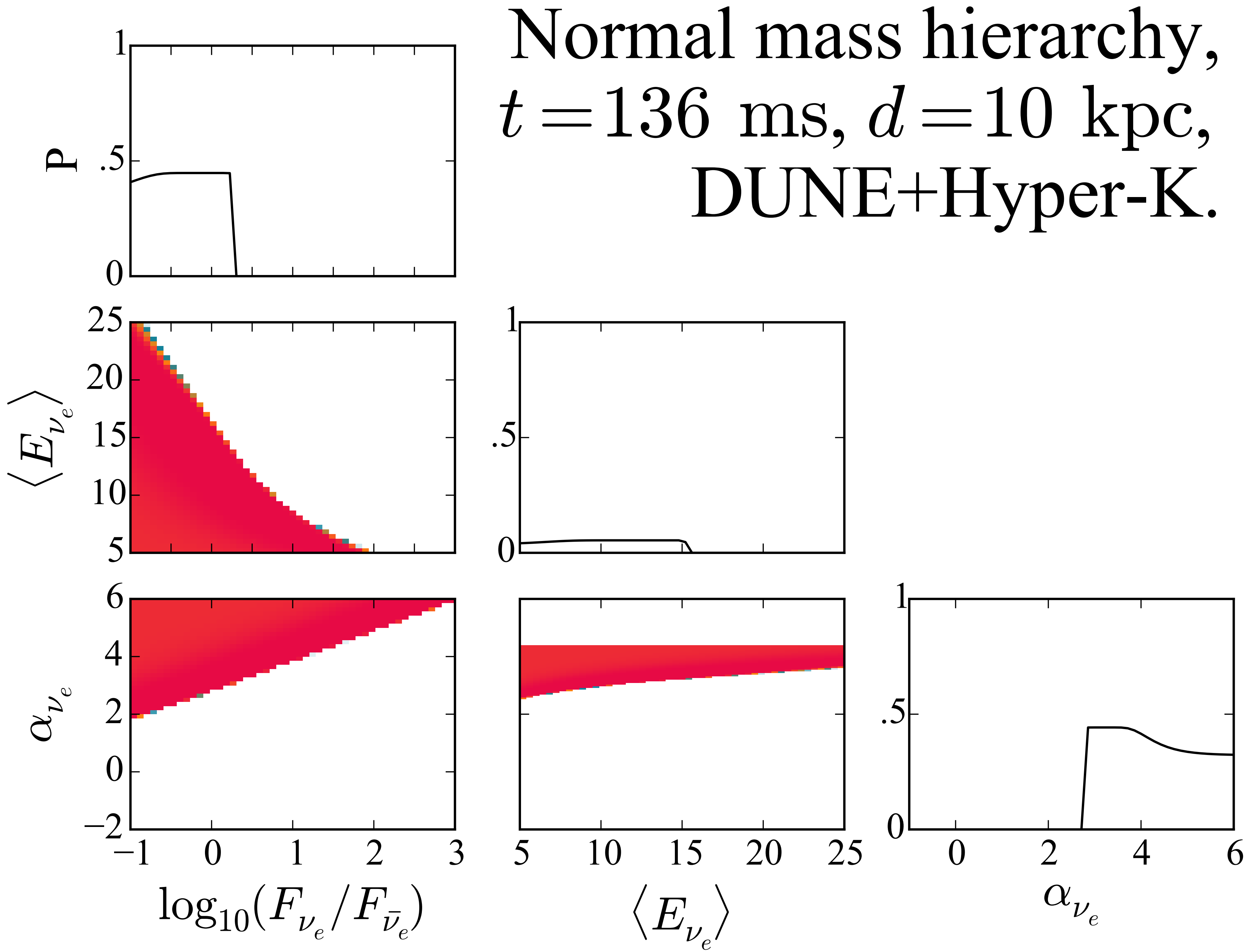

Normal mass hierarchy,
$t = 48$ ms, $d = 10$ kpc,
DUNE+Hyper-K.
P
$\langle E_{\nu_e} \rangle$
α_{ν_e}
$\log_{10}(F_{\nu_e}/F_{\bar{\nu}_e})$
$\langle E_{\nu_e} \rangle$
α_{ν_e}



Normal mass hierarchy,
$t = 80$ ms, $d = 10$ kpc,
DUNE+Hyper-K.
P
$\langle E_{\nu_e} \rangle$
α_{ν_e}
$\log_{10}(F_{\nu_e}/F_{\bar{\nu}_e})$

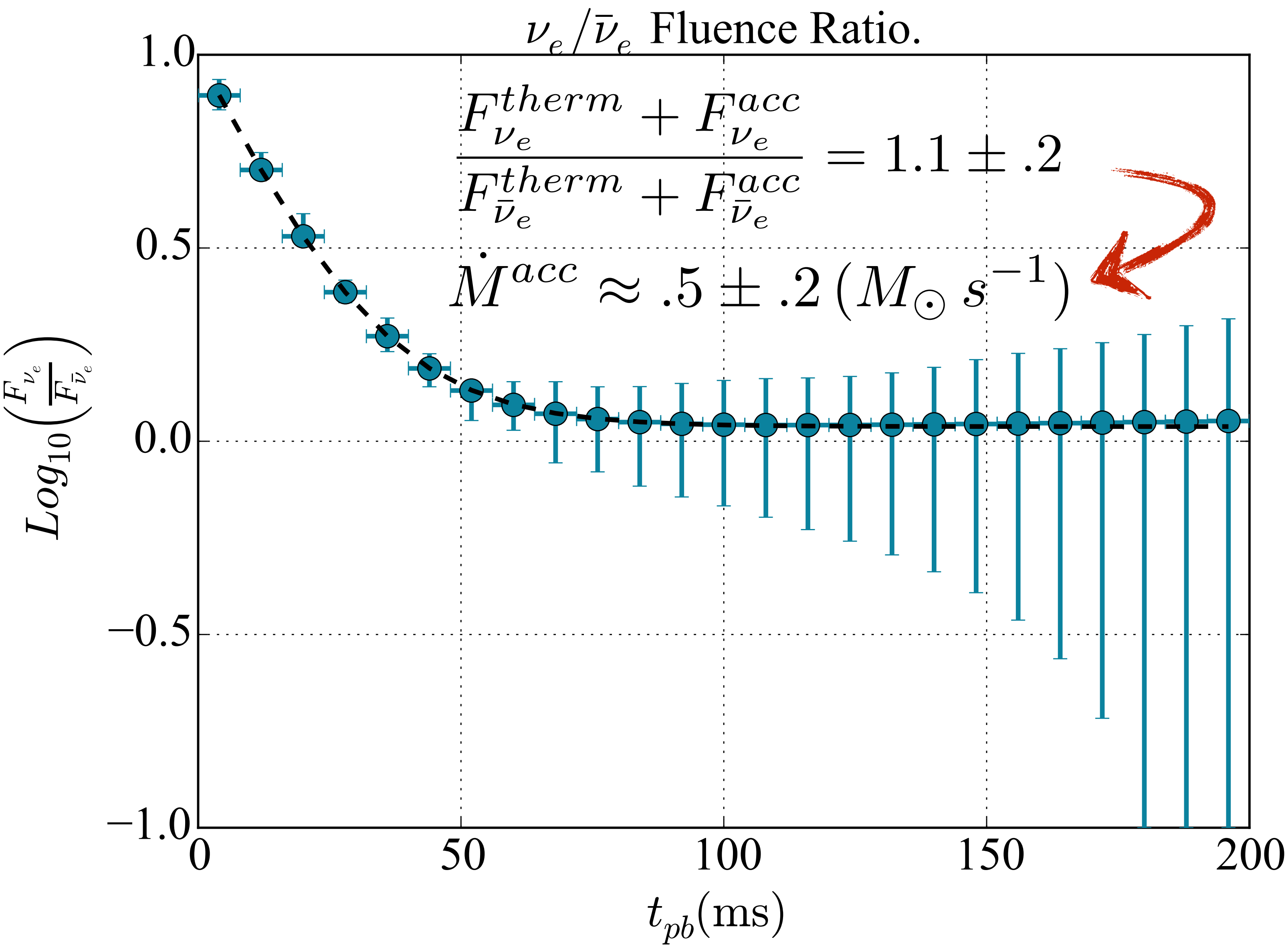


Normal mass hierarchy,
$t = 104$ ms, $d = 10$ kpc,
DUNE+Hyper-K.
P
$\langle E_{\nu_e} \rangle$
α_{ν_e}
$\log_{10}(F_{\nu_e}/F_{\bar{\nu}_e})$

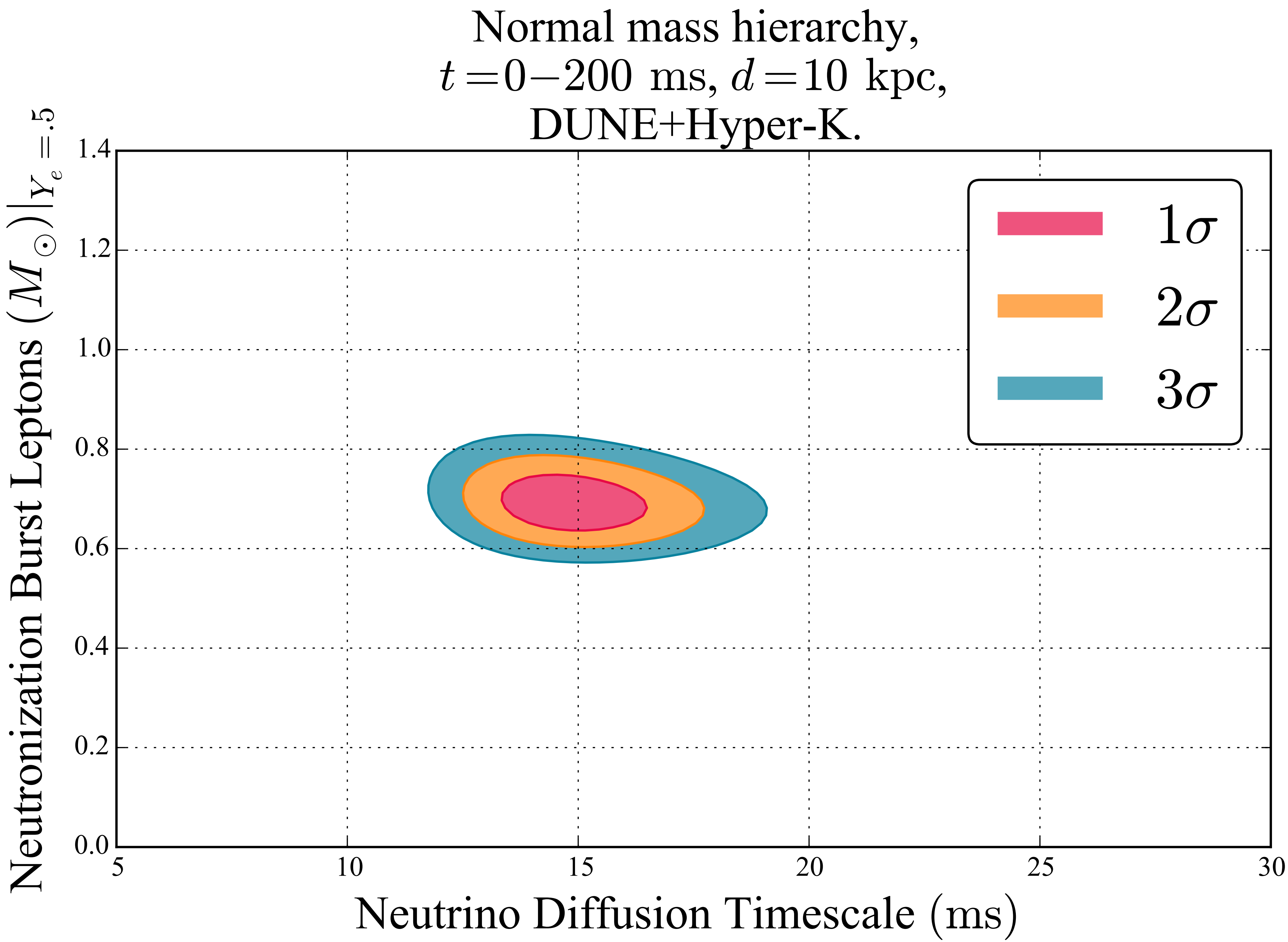


Normal mass hierarchy,
$t = 136$ ms, $d = 10$ kpc,
DUNE+Hyper-K.
P
1
.5
0
25
20
15
10
5
$\langle E_{\nu_e} \rangle$
6
4
2
0
−2
α_{ν_e}
−1
0
1
2
3
$\log_{10}(F_{\nu_e}/F_{\bar{\nu}_e})$
5
10
15
20
25
$\langle E_{\nu_e} \rangle$
0
2
4
6
α_{ν_e}

Accretion Flux



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



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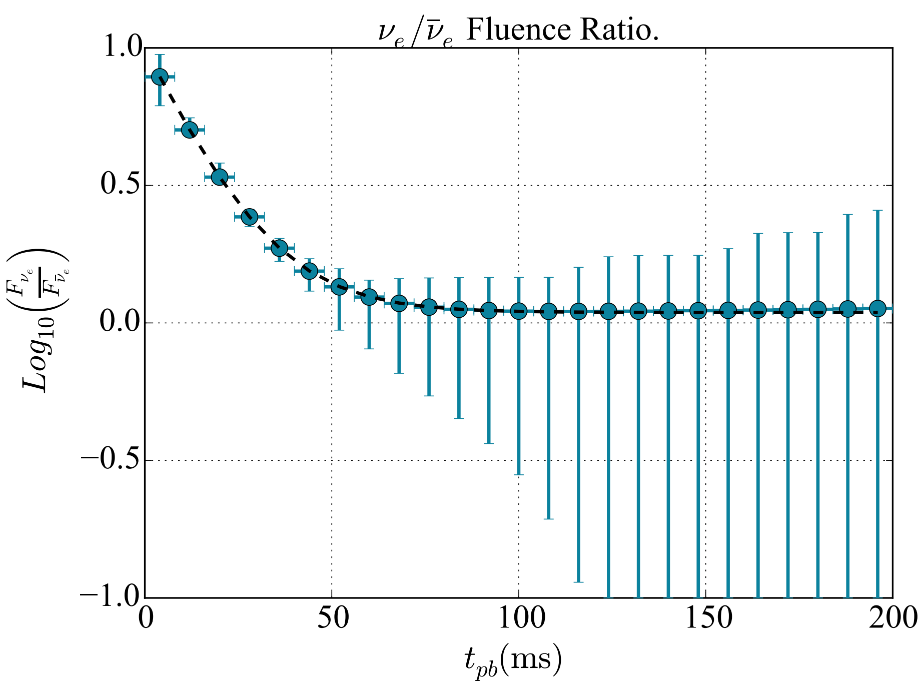
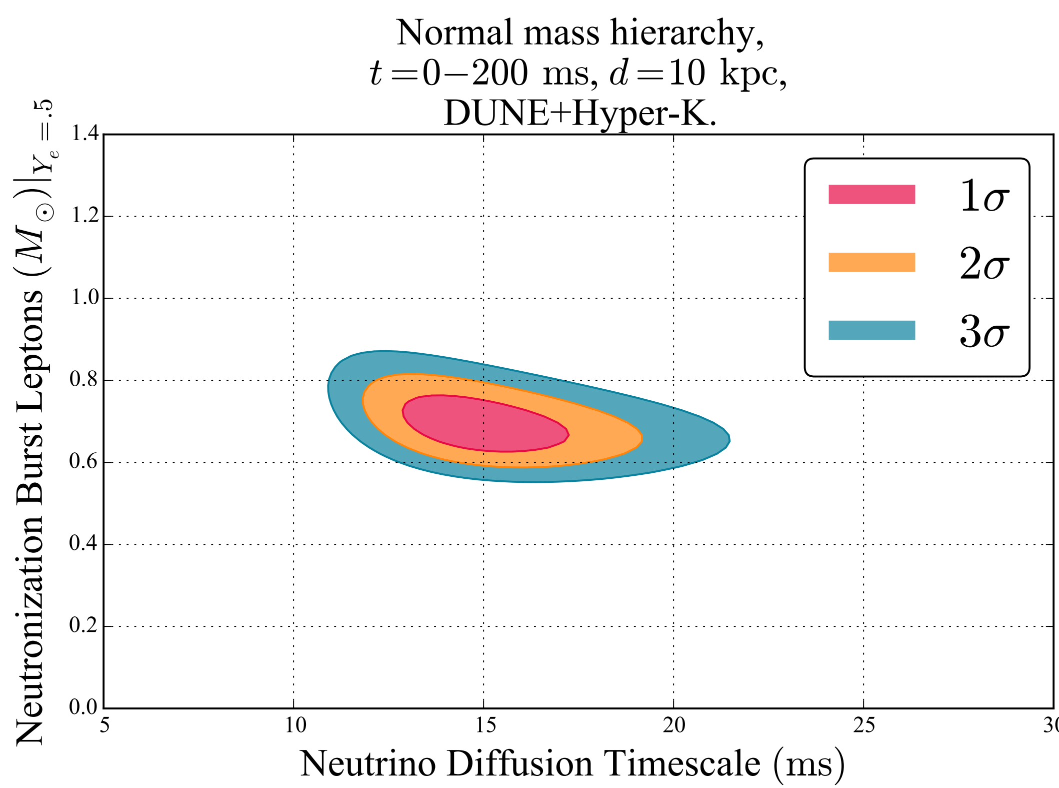
Bare Bones Detectors?

How are the fits changed if, for instance, DUNE has no ability to tag the de-excitation photons from CC-Ar40 and NC-Ar40 events?





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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

Conclusions

- Electron flavor sensitivity 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.
- 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 on the in the range needed to constrain neutron star EOS's.