# Abstract

A nearby supernova will carry an unprecedented wealth of information about astrophysics, nuclear physics, and particle physics. Because supernova are fundamentally neutrino driven phenomenon, our knowledge about neutrinos – particles that remain quite elusive – will increase dramatically with such a detection. One of the biggest open questions in particle physics is related to the masses of neutrinos. Here we show how a galactic supernova provides information about the masses of each of the three mass eigenstates *individually*, at some precision, and is well probed at JUNO. This information comes from several effects including time delay and the physics within the supernova. The time delay feature is strongest during a sharp change in the flux such as the neutronization burst; additional information may also come from a QCD phase transition in the supernova or if the supernova forms a black hole. We consider both standard cases as dictated by local oscillation experiments as well as new physics motivated scenarios where neutrino masses may differ across the galaxy.

# Individual Neutrino Masses From a Supernova

Peter B. Denton

Mitchell Conference

May 16, 2025

2411.13634 with Yves Kini

Brookhaven National Laboratory

# Outline

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1. **Introduction**
2. Possibility of spatially evolving neutrino masses
3. Neutrinos from a supernova
4. Time delay features
5. Detection
6. Sensitivities
7. Conclusions

# Rich New Physics Sector

We want to find BSM!

- Many scenarios have $\sim 2$ low energy effective parameters: $m$, $g$
- In many richer scenarios the ways we may discover the hint of BSM in the first place doesn't inform us about many of the parameters
- Are there rich ($> 2$ effective and impactful parameters) models where the discovery approaches can probe many/all of them?

neutrino oscillations

- At least 7 low energy parameters independent of mass generation
- Discovery channels probe 3-4 parameters:
  - Solar: $\sin^2\theta_{12}$ (and sort of $\Delta m^2_{21}$)
  - Atmospheric: $\sin^2 2\theta_{23}$ and $|\Delta m^2_{32}|$
- Reactors were used to detect first neutrinos: $\sin^2 2\theta_{13}$, $|\Delta m^2_{31}|$, $|\Delta m^2_{21}|$
- Rich sector is established before building dedicated sources: accelerators $\Delta m^2_{32}$, $\sin^2\theta_{23}$, $\sin\delta$

# Absolute Mass Scale

Absolute neutrino mass scale needs other data

- Cosmology looks promising: $\sum_{i=1}^{3} m_i$ too good?

See Joel Meyers's talk on Wednesday

- KATRIN is less sensitive: $\sqrt{\sum_{i=1}^{3} |U_{ei}|^2 m_i^2}$
- Neutrinoless double beta decay: model dependent, generally less sensitive than cosmology
- Supernova?

See also e.g.:
T. Pitik, D. Heimsoth, A. Suliga, B. Balantekin 2208.14469
F. Pompa, et al 2203.00024
G. Parker, M. Wurm 2311.10682
V. Brdar, X.-J. Xu 2204.13135

Can a galactic SN tell us the individual neutrino masses?

# Outline

# Possibility of spatially evolving neutrino masses

- Cosmology is pushing down on neutrino masses below the oscillation limit
- Cosmological constraints come dominantly from $10 \lesssim z \lesssim 100$
- Neutrino masses may vary depending on the DM distribution

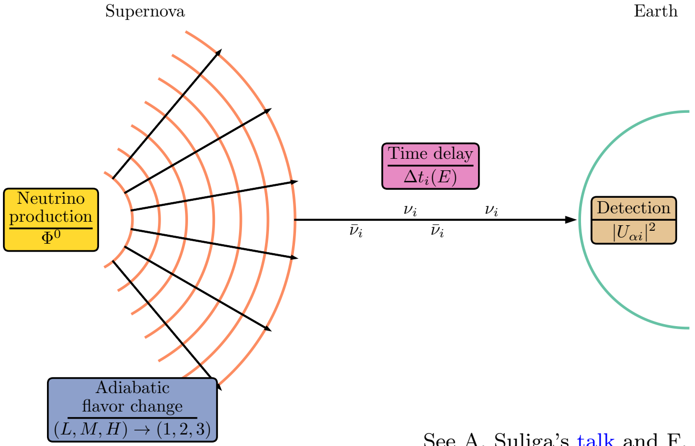
H. Davoudiasl, G. Mohlabeng, M. Sullivan 1803.00012
S.-F. Ge, H. Murayama 1904.02518

$\vdots$

- Neutrinos could be massless in the vacuum of space $\Rightarrow \sum_{i=1}^{3} m_i = 0$
- Within solar system reproduce oscillation measurements
- Masses may be different through the galaxy

# Outline

# Neutrinos From a Supernova




See A. Suliga's talk and F. Hajkarim's talk yesterday

# Flavor Mixing

NO:

$$\Phi_{\nu_e}(E,t)=s_{13}^2\Phi_{\nu_e}^0(E,t)+c_{13}^2\Phi_{\nu_x}^0(E,t)$$

A. Dighe, A. Smirnov hep-ph/9907423

# Flavor Mixing

NO:

$$\Phi_{\nu_e}(E,t) = s_{13}^2\Phi^0_{\nu_e}(E,t) + c_{13}^2\Phi^0_{\nu_x}(E,t)$$
$$\Phi_{\bar\nu_e}(E,t) = c_{12}^2c_{13}^2\Phi^0_{\bar\nu_e}(E,t) + (1-c_{12}^2c_{13}^2)\Phi^0_{\bar\nu_x}(E,t)$$
$$2\Phi_{\nu_x}(E,t) = c_{13}^2\Phi^0_{\nu_e}(E,t) + (1+s_{13}^2)\Phi^0_{\nu_x}(E,t)$$
$$2\Phi_{\bar\nu_x}(E,t) = (1-c_{12}^2c_{13}^2)\Phi^0_{\bar\nu_e}(E,t) + (1+c_{12}^2c_{13}^2)\Phi^0_{\bar\nu_x}(E,t)$$

IO:

$$\Phi_{\nu_e}(E,t) = s_{12}^2c_{13}^2\Phi^0_{\nu_e}(E,t) + (1-s_{12}^2c_{13}^2)\Phi^0_{\nu_x}(E,t)$$
$$\Phi_{\bar\nu_e}(E,t) = s_{13}^2\Phi^0_{\bar\nu_e}(E,t) + c_{13}^2\Phi^0_{\bar\nu_x}(E,t)$$
$$2\Phi_{\nu_x}(E,t) = (1-s_{12}^2c_{13}^2)\Phi^0_{\nu_e}(E,t) + (1+s_{12}^2c_{13}^2)\Phi^0_{\nu_x}(E,t)$$
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A. Dighe, A. Smirnov hep-ph/9907423

# Flavor Mixing Redux

NO:

$$\Phi_{\nu_e}(E,t) = |U_{e3}|^2 \Phi^0_{\nu_e}(E,t) + (|U_{e1}|^2 + |U_{e2}|^2)\Phi^0_{\nu_x}(E,t)$$

# Flavor Mixing Redux

NO:

$$
\begin{aligned}
\Phi_{\nu_e}(E,t) &= |U_{e3}|^2\Phi^0_{\nu_e}(E,t) + (|U_{e1}|^2 + |U_{e2}|^2)\Phi^0_{\nu_x}(E,t)\\
\Phi_{\bar\nu_e}(E,t) &= |U_{e1}|^2\Phi^0_{\bar\nu_e}(E,t) + (|U_{e2}|^2 + |U_{e3}|^2)\Phi^0_{\bar\nu_x}(E,t)\\
2\Phi_{\nu_x}(E,t) &= (|U_{\mu3}|^2 + |U_{\tau3}|^2)\Phi^0_{\nu_e}(E,t) + (|U_{\mu1}|^2 + |U_{\tau1}|^2 + |U_{\mu2}|^2 + |U_{\tau2}|^2)\Phi^0_{\nu_x}(E,t)\\
2\Phi_{\bar\nu_x}(E,t) &= (|U_{\mu1}|^2 + |U_{\tau1}|^2)\Phi^0_{\bar\nu_e}(E,t) + (|U_{\mu2}|^2 + |U_{\tau2}|^2 + |U_{\mu3}|^2 + |U_{\tau3}|^2)\Phi^0_{\bar\nu_x}(E,t)
\end{aligned}
$$

IO:

$$
\begin{aligned}
\Phi_{\nu_e}(E,t) &= |U_{e2}|^2\Phi^0_{\nu_e}(E,t) + (|U_{e1}|^2 + |U_{e3}|^2)\Phi^0_{\nu_x}(E,t)\\
\Phi_{\bar\nu_e}(E,t) &= |U_{e3}|^2\Phi^0_{\bar\nu_e}(E,t) + (|U_{e1}|^2 + |U_{e2}|^2)\Phi^0_{\bar\nu_x}(E,t)\\
2\Phi_{\nu_x}(E,t) &= (|U_{\mu2}|^2 + |U_{\tau2}|^2)\Phi^0_{\nu_e}(E,t) + (|U_{\mu1}|^2 + |U_{\tau1}|^2 + |U_{\mu3}|^2 + |U_{\tau3}|^2)\Phi^0_{\nu_x}(E,t)\\
2\Phi_{\bar\nu_x}(E,t) &= (|U_{\mu3}|^2 + |U_{\tau3}|^2)\Phi^0_{\bar\nu_e}(E,t) + (|U_{\mu1}|^2 + |U_{\tau1}|^2 + |U_{\mu2}|^2 + |U_{\tau2}|^2)\Phi^0_{\bar\nu_x}(E,t)
\end{aligned}
$$

# Mass States

We define the three mass states by the electron neutrino fraction:

$$|U_{e1}|^2 > |U_{e2}|^2 > |U_{e3}|^2$$

$$0.65 > 0.33 > 0.02$$

New definition:

$$m_H > m_M > m_L$$

NO: $L = 1$, $M = 2$, $H = 3$
IO: $L = 3$, $M = 1$, $H = 2$
Other orderings possible in GC with new physics

# Flavor Mixing Final

Hierarchy independent:

$$\Phi_{\nu_e}(E,t)=|U_{eH}|^2\Phi^0_{\nu_e}(E,t)+(|U_{eL}|^2+|U_{eM}|^2)\Phi^0_{\nu_x}(E,t)$$

Necessary for self-consistent statistical tests

# Flavor Mixing Final

Hierarchy independent:

$$\begin{aligned}
\Phi_{\nu_e}(E,t) &= |U_{eH}|^2\Phi^0_{\nu_e}(E,t) + (|U_{eL}|^2 + |U_{eM}|^2)\Phi^0_{\nu_x}(E,t)\\
\Phi_{\bar\nu_e}(E,t) &= |U_{eL}|^2\Phi^0_{\bar\nu_e}(E,t) + (|U_{eM}|^2 + |U_{eH}|^2)\Phi^0_{\bar\nu_x}(E,t)\\
2\Phi_{\nu_x}(E,t) &= (|U_{\mu H}|^2 + |U_{\tau H}|^2)\Phi^0_{\nu_e}(E,t) + (|U_{\mu L}|^2 + |U_{\tau L}|^2 + |U_{\mu M}|^2 + |U_{\tau M}|^2)\Phi^0_{\nu_x}(E,t)\\
2\Phi_{\bar\nu_x}(E,t) &= (|U_{\mu L}|^2 + |U_{\tau L}|^2)\Phi^0_{\bar\nu_e}(E,t) + (|U_{\mu M}|^2 + |U_{\tau M}|^2 + |U_{\mu H}|^2 + |U_{\tau H}|^2)\Phi^0_{\bar\nu_x}(E,t)
\end{aligned}$$

Necessary for self-consistent statistical tests

# Jump probabilities aren't a problem

I promise

See backups

# Outline

# Time delay features

Massive neutrinos lead to time delay relative to light (& higher energy $\nu$s):

$$\Delta t_i(E) = t_{\nu_i} - t_c = D\left(\frac{1}{v_i} - 1\right) \simeq \frac{D}{2}\left(\frac{m_i}{E}\right)^2$$

Modify flavor transformations:

$$|U_{\alpha i}|^2 \Phi^0_{\nu_\beta}(E,t) \to |U_{\alpha i}|^2 \Phi^0_{\nu_\beta}(E, t - \Delta t_i(E))$$

Need a sharp effect in the signal

# Time delay features

1. Neutronization burst
   - Has been in all simulations since the early days
   - Lasts $\sim 25$ ms
   - Highest $L_\nu$, but not the dominant source of neutrinos
   - Turns on/off fairly sharply
   - Depends on true oscillation parameters
2. QCD (quark/hadron) phase transition
   - A FOPT from nuclear to quark matter
   - May restart stalled shocks
   - May produce very sharp enhancement in the neutrino flux
   - Unclear if it happens
3. BH formation
   - Some CCSN form BHs
   - Probably $\mathcal{O}(10\%)$
   - Leads to a sharp truncation of the signal
4. Other things like standing accretion shock instability (SASI)

# Outline

# Detection

JUNO

See backups

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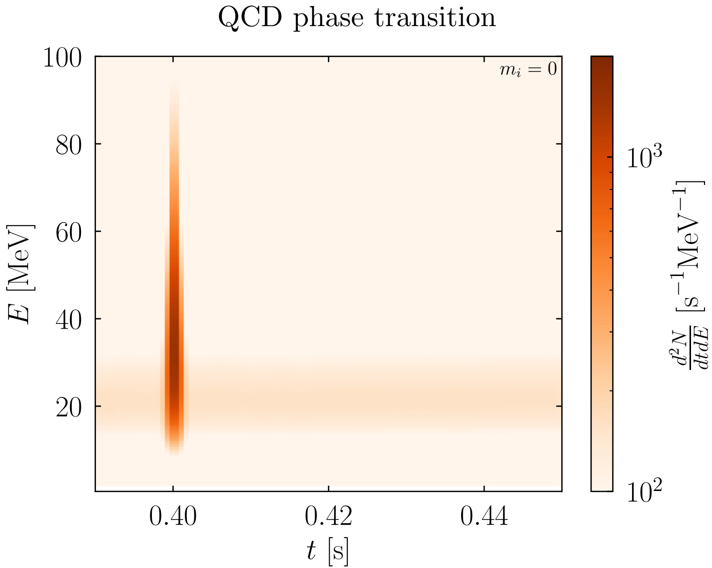
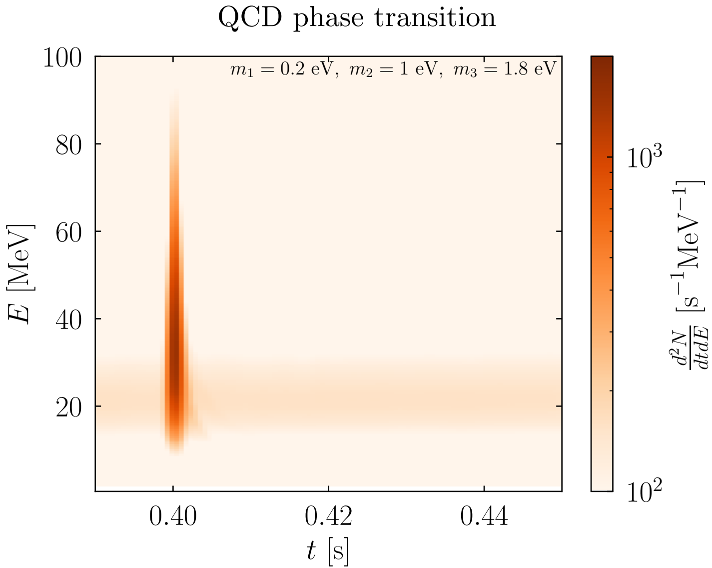
# Events

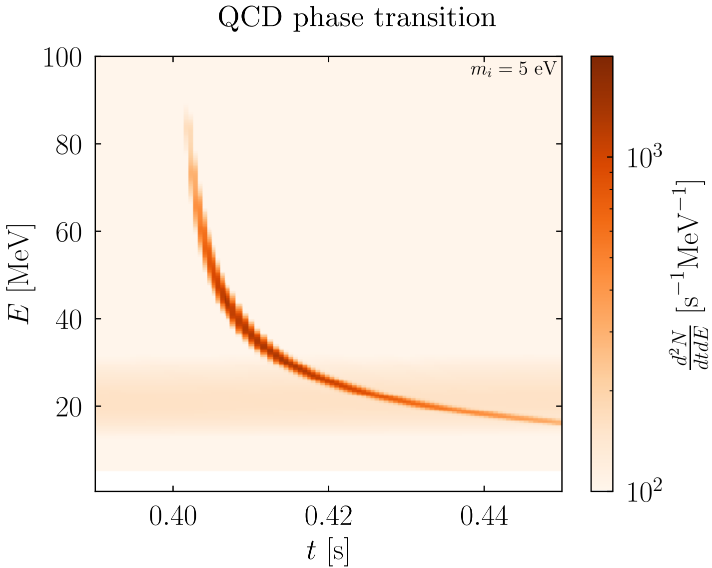


QCD phase transition
$m_i = 0$
$E$ [MeV]
100
80
60
40
20
0.40
0.42
0.44
$t$ [s]
$10^3$
$10^2$
$\frac{d^2N}{dtdE}$ [$s^{-1}$MeV$^{-1}$]

# Events

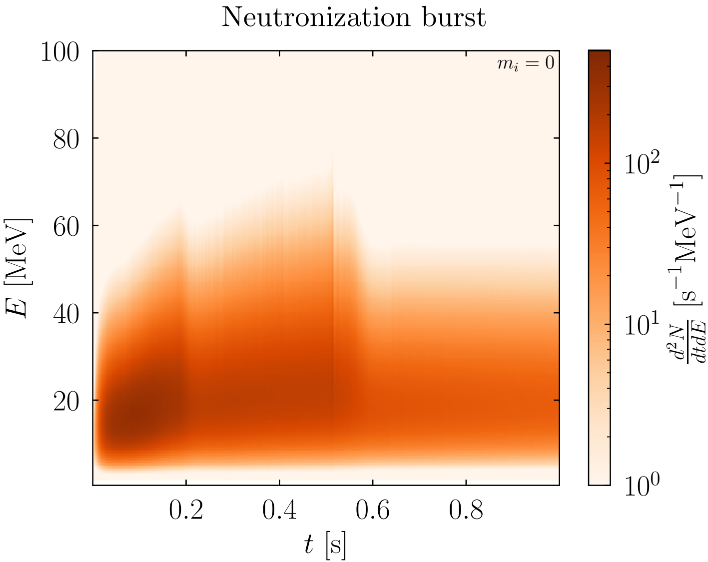

QCD phase transition
$m_1 = 0.2$ eV, $m_2 = 1$ eV, $m_3 = 1.8$ eV
100
80
60
40
20
$E$ [MeV]
0.40
0.42
0.44
$t$ [s]
$10^3$
$10^2$
$\frac{d^2N}{dtdE}$ [$s^{-1}MeV^{-1}$]

# Events



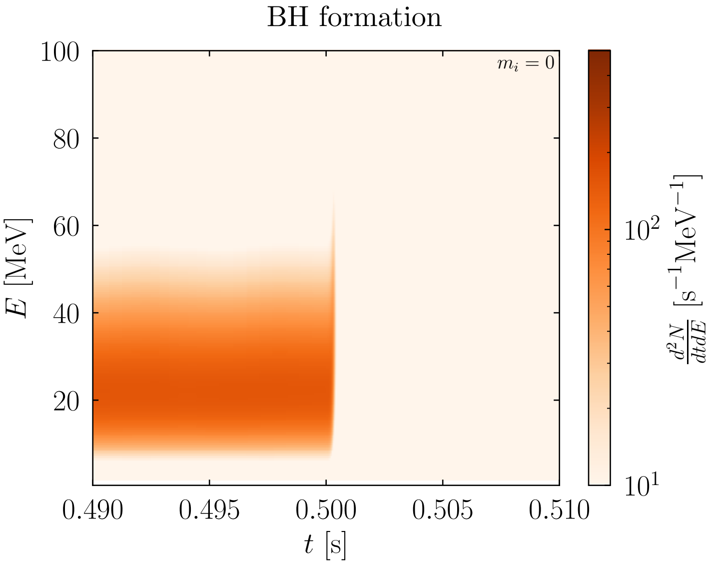
QCD phase transition
$m_i = 5$ eV
100
80
60
40
20
$E$ [MeV]
0.40
0.42
0.44
$t$ [s]
$10^3$
$10^2$
$\frac{d^2N}{dtdE}$ [s$^{-1}$MeV$^{-1}$]

# Events



Neutronization burst
$m_i = 0$
100
80
60
40
20
$E$ [MeV]
0.2
0.4
0.6
0.8
$t$ [s]
$10^2$
$10^1$
$10^0$
$\frac{d^2N}{dtdE}$ [$s^{-1}MeV^{-1}$]

# Events



BH formation
$m_i = 0$
100
80
60
40
20
$E$ [MeV]
0.490
0.495
0.500
0.505
0.510
$t$ [s]
$10^2$
$10^1$
$\frac{d^2N}{dtdE}$ [s$^{-1}$MeV$^{-1}$]

# Benchmarks for Sensitivities

- Oscillations:

$$|\Delta m^2_{31}| = 2.5 \times 10^{-3}\ \text{eV}^2\,, \quad \Delta m^2_{21} = +7.4 \times 10^{-5}\ \text{eV}^2$$

  Two benchmarks: lightest allowed in NO, IO
- Planck and oscillations only (NO, IO) as other cosmological data is very tight:

$$\sum_i m_i < 0.24\ \text{eV}$$

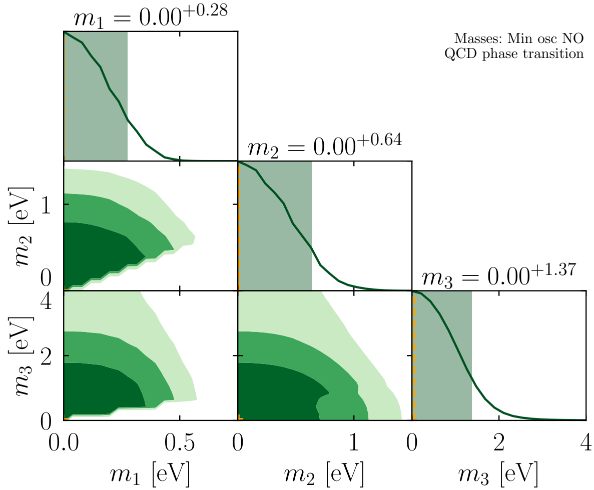
- KATRIN and oscillations only:

$$m_{\beta\beta} < 0.45\ \text{eV}$$

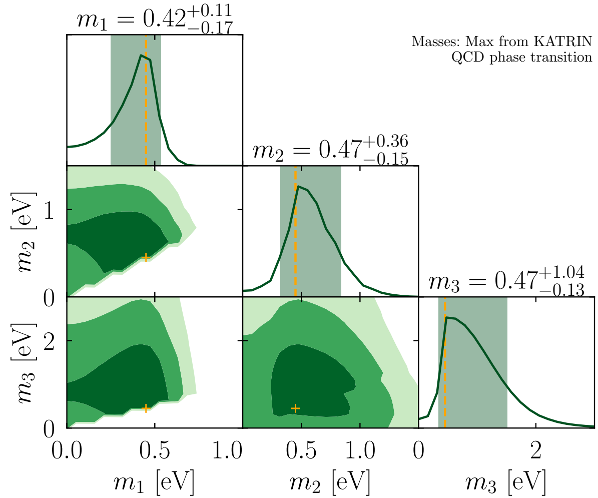
- High mass scenario (new physics):

$$m_1 = 0.2\ \text{eV}\,, \quad m_2 = 1\ \text{eV}\,, \quad m_3 = 1.8\ \text{eV}$$

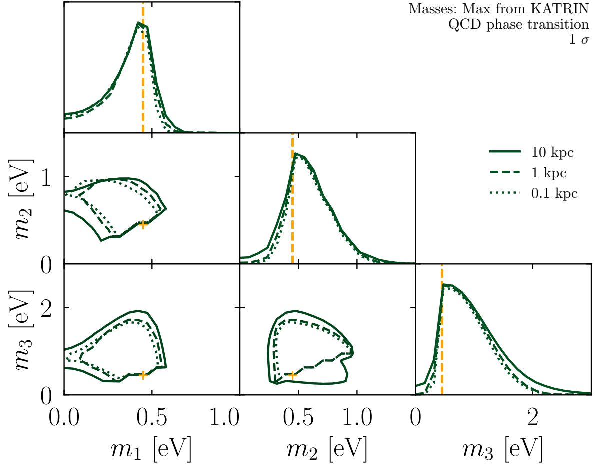
# Sensitivities



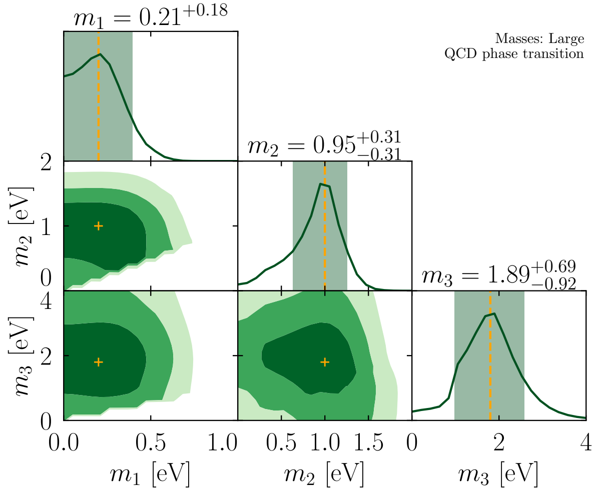
# Sensitivities



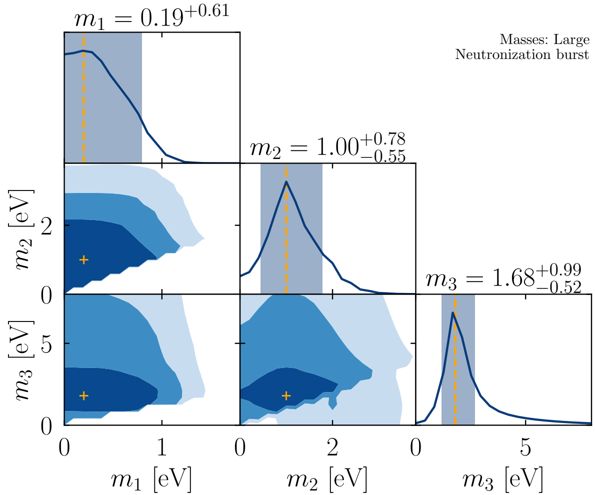
# Sensitivities



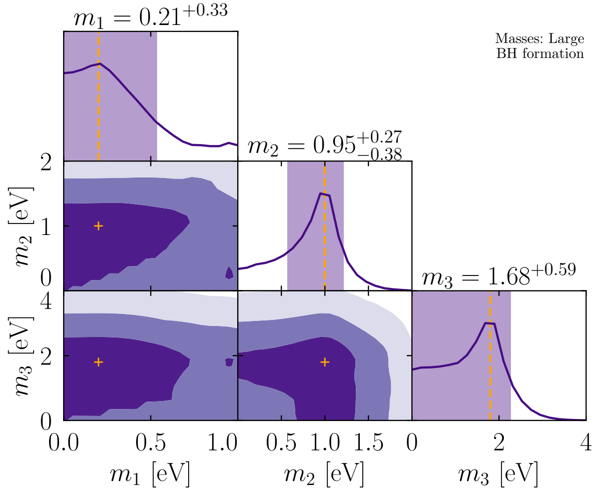
# Sensitivities



# Sensitivities



# Sensitivities



# Caveats

- If DM provides mass to neutrinos, they evolve during propagation

  S.-F. Ge, C.-F. Kong, A. Smirnov 2404.17352
- Terrestrial matter effect may further modify this picture; possible to account for
- Assumes we know the mixing parameters and they are unchanged
  - Can you measure the masses *and* mixing parameters?

# Outline

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# Conclusions

- Galactic supernova can probe the absolute neutrino mass scale
- Likely only possible if masses are anomalously large, or cosmology is more complicated
- Multiple possible timing features to leverage
- Combinations of features and of detectors (e.g. DUNE/HK) will improve the numerical results
- Individual neutrino masses can be reconstructed

# Thanks!

Rice & Texas A&M:

https://aggypedia.com/aggypedia/aggy-embarrassments/sammy-the-owl/

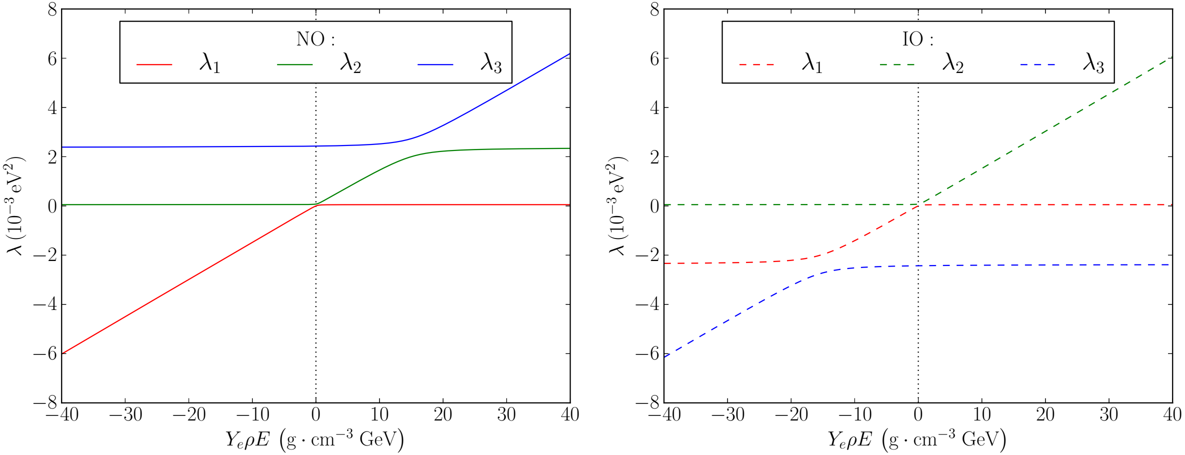
# Supernova Neutrinos

- SN1987A confirmed that $\sim 99\%$ of gravitational energy of large stars $\to \nu$'s
- CCSN produce $\sim 10^{58}$ neutrinos with $E_\nu \sim 10$s MeV
- We believe that stars $8 \lesssim M/M_\odot \lesssim 125$ form CCSN
- Larger progenitors form BHs (?) while smaller form NSs
- Neutrino spectrum generally seems to follow a pinched Fermi-Dirac distribution:

$$\phi_{\nu_i}(E_{\nu_i}, t) = \xi_{\nu_i}(t) \left( \frac{E_{\nu_i}}{\langle E_{\nu_i}(t) \rangle} \right)^{\alpha_{\nu_i}(t)} \exp\left( -\frac{(\alpha_{\nu_i}(t) + 1) E_{\nu_i}}{\langle E_{\nu_i}(t) \rangle} \right)$$

- Mean energy and pinching parameter time dependence fit to simulations

# Eigenvalues



# Eigenvalues

All of the above assumes neutrinos are produced well above both resonances

Neutrinos decouple at

$$\rho \sim 10^{11} - 10^{12} \text{ g/cc}$$

Higher resonance is at

$$\rho_{\text{res}} \simeq 10^{6} \text{ g/cc} \times \left(\frac{\Delta m^2}{1 \text{ eV}^2}\right) \left(\frac{10 \text{ MeV}}{E}\right) \left(\frac{0.5}{Y_e}\right) \cos 2\theta$$

So neutrinos are produced well above upper resonance for any relevant masses

# Jump probabilities

The above discussion assumes neutrinos adiabatically transform from production to the surface

In reality there is a chance of jumping from one eigenvalue to another $\Rightarrow$ vastly complicates the above expressions

Simple picture:

$$P_j = \exp\left(-\frac{\pi}{2}\gamma\right)$$

where the adiabaticity parameter is

$$\gamma = \frac{\Delta m^2}{2E}\frac{s_2^2}{c_2}\frac{1}{\dot{n}_e/n_e|_{\rm res}}$$

For larger angles need to use

$$P_j = \frac{\exp\left(-\frac{\pi}{2}\gamma f\right) - \exp\left(-\frac{\pi}{2}\gamma\frac{f}{s^2}\right)}{1-\exp\left(-\frac{\pi}{2}\gamma\frac{f}{s^2}\right)}$$

# Jump probabilities

where $s$ is $\sin\theta$ and

$$f = {}_2F_1\left(1-\frac{1}{2n},\frac{n-1}{2n},2,-t_2^2\right)$$

which $\to 1$ as $s\to 0$ and $\rho\propto r^n$

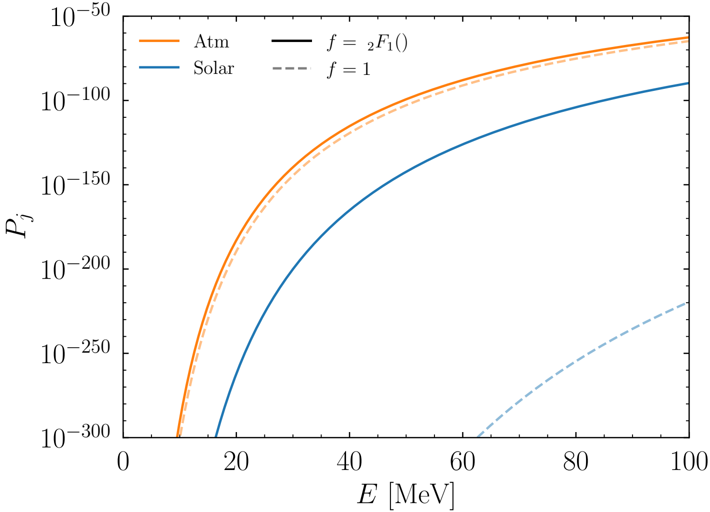
A number of additional caveats here as well: multiple jump, off resonance jumps, nearby resonances, ...

Is this small enough?

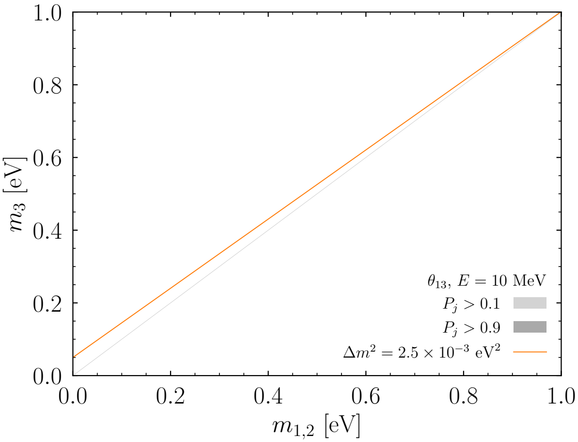
For regular $\Delta m^2$'s, yes

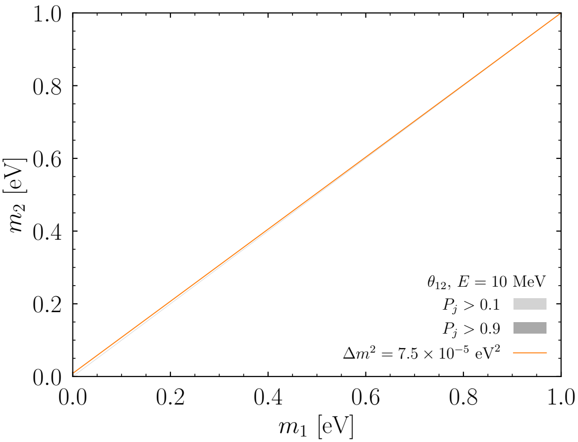
For arbitrary $\Delta m^2$'s: probably

# Jump Probabilities

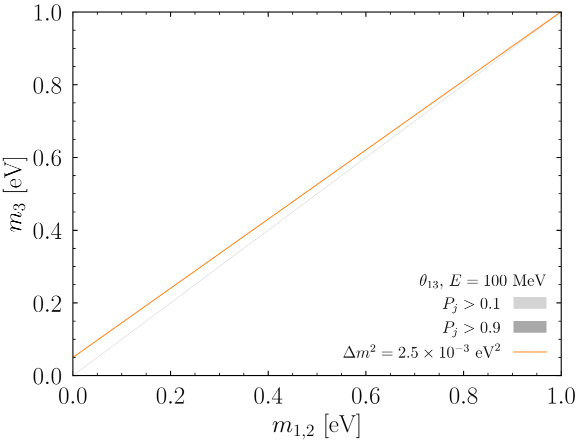


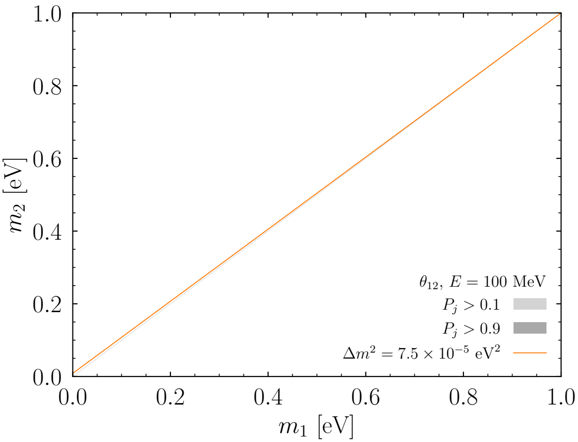
# Jump Probabilities



# Jump Probabilities



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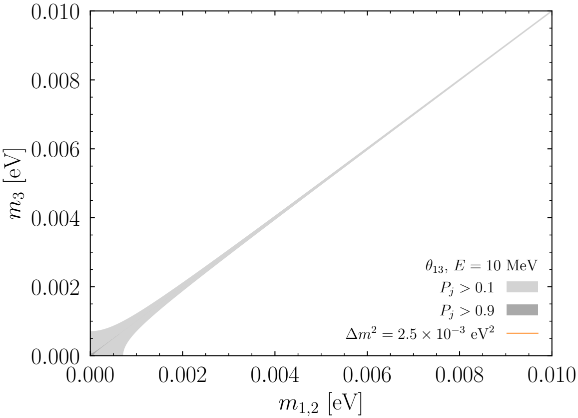
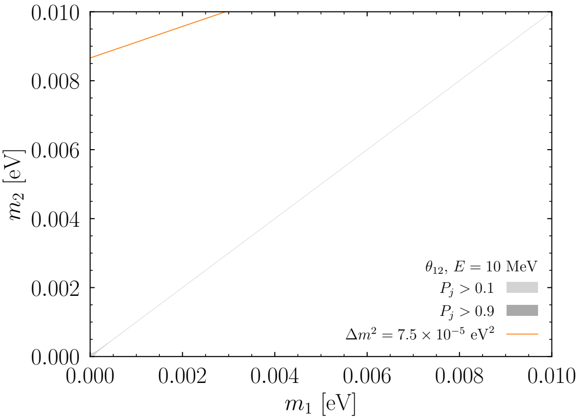
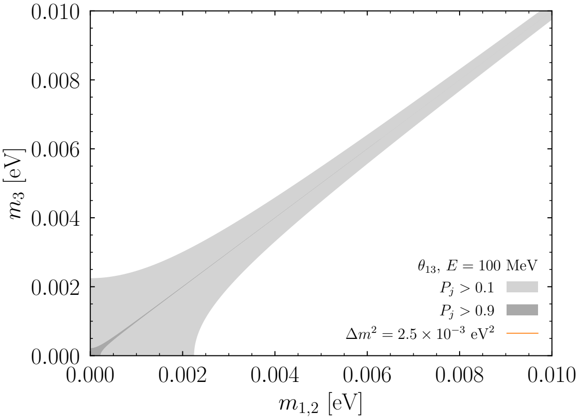
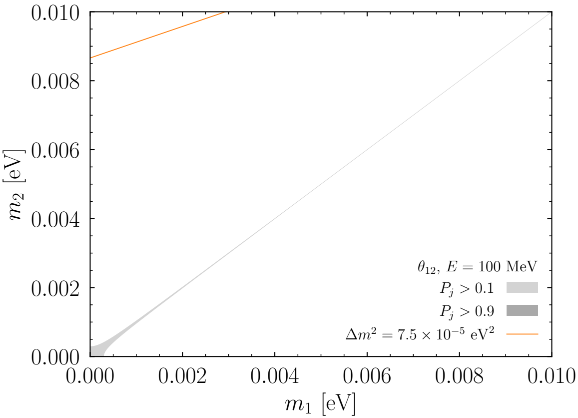


# Jump Probabilities



# Supernova neutrinos

There are many simulations
Focus on features that are largely simulation independent
Use a 27 $M_\odot$ SN at 10 kpc

# Detection

Many current and upcoming detectors that are sensitive to SN neutrinos
Focus on JUNO due to low thresholds, good timing, large volume, and online in $\sim 1$ year
Cross sections:

- IBD: primary, but threshold $E_\nu > 1.8$ MeV
- eES
- $^{12}$C
- $^{13}$C
- NC
- pES: uncertain cross section, plus quenching effects, not included