Supernova Neutrino Collective Oscillations and Detection

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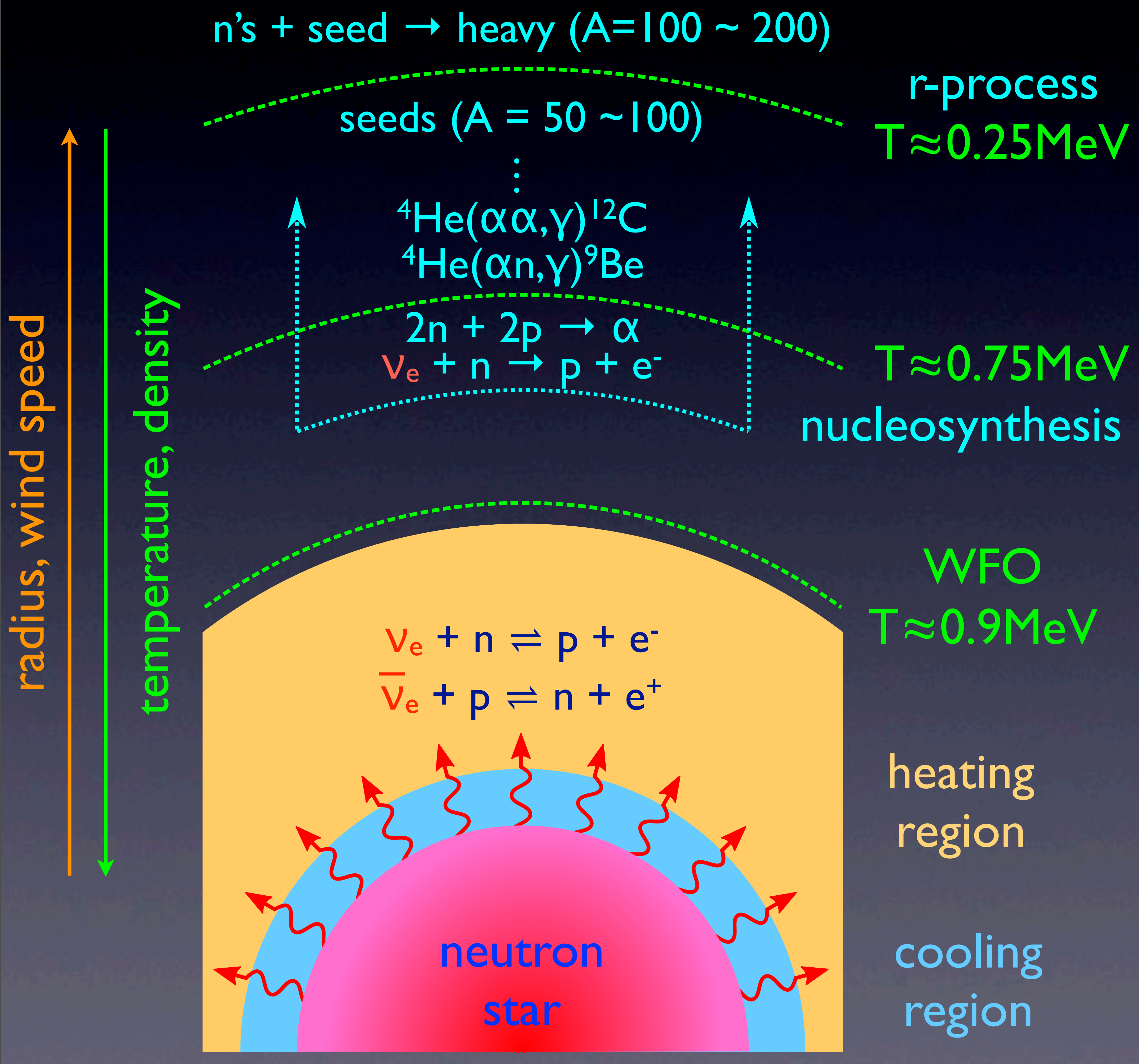
Aspen Winter Workshop, Feb 2013

Neutrinos in Supernovae



n's + seed → heavy (A=100 ~ 200)

seeds (A = 50 ~100)

r-process

T≈0.25MeV

⋮

$^4\mathrm{He}(\alpha\alpha,\gamma)^{12}\mathrm{C}$

$^4\mathrm{He}(\alpha n,\gamma)^{9}\mathrm{Be}$

$2n + 2p \rightarrow \alpha$

$\nu_e + n \rightarrow p + e^-$

T≈0.75MeV

nucleosynthesis

WFO

T≈0.9MeV

$\nu_e + n \rightleftharpoons p + e^-$

$\bar{\nu}_e + p \rightleftharpoons n + e^+$

heating region

cooling region

neutron star

radius, wind speed

temperature, density

- ~10^{53} ergs, 10^{58} neutrinos in ~10 seconds
- All neutrino species, 10~30 MeV
- Dominate energetics
- Influence nucleosynthesis
- Probe into SNe

ν oscillations in SN

$$\mathrm{i}\frac{\mathrm{d}}{\mathrm{d}\lambda}|\psi_{\nu,\mathbf{p}}\rangle = \hat{H}|\psi_{\nu,\mathbf{p}}\rangle$$

mass matrix

electron density

$$\mathrm{H} = \frac{\mathrm{M}^2}{2E} + \sqrt{2}G_{\mathrm{F}}\,\mathrm{diag}[n_e, 0, 0] + \mathrm{H}_{\nu\nu}$$

neutrino energy

ν–ν forward scattering

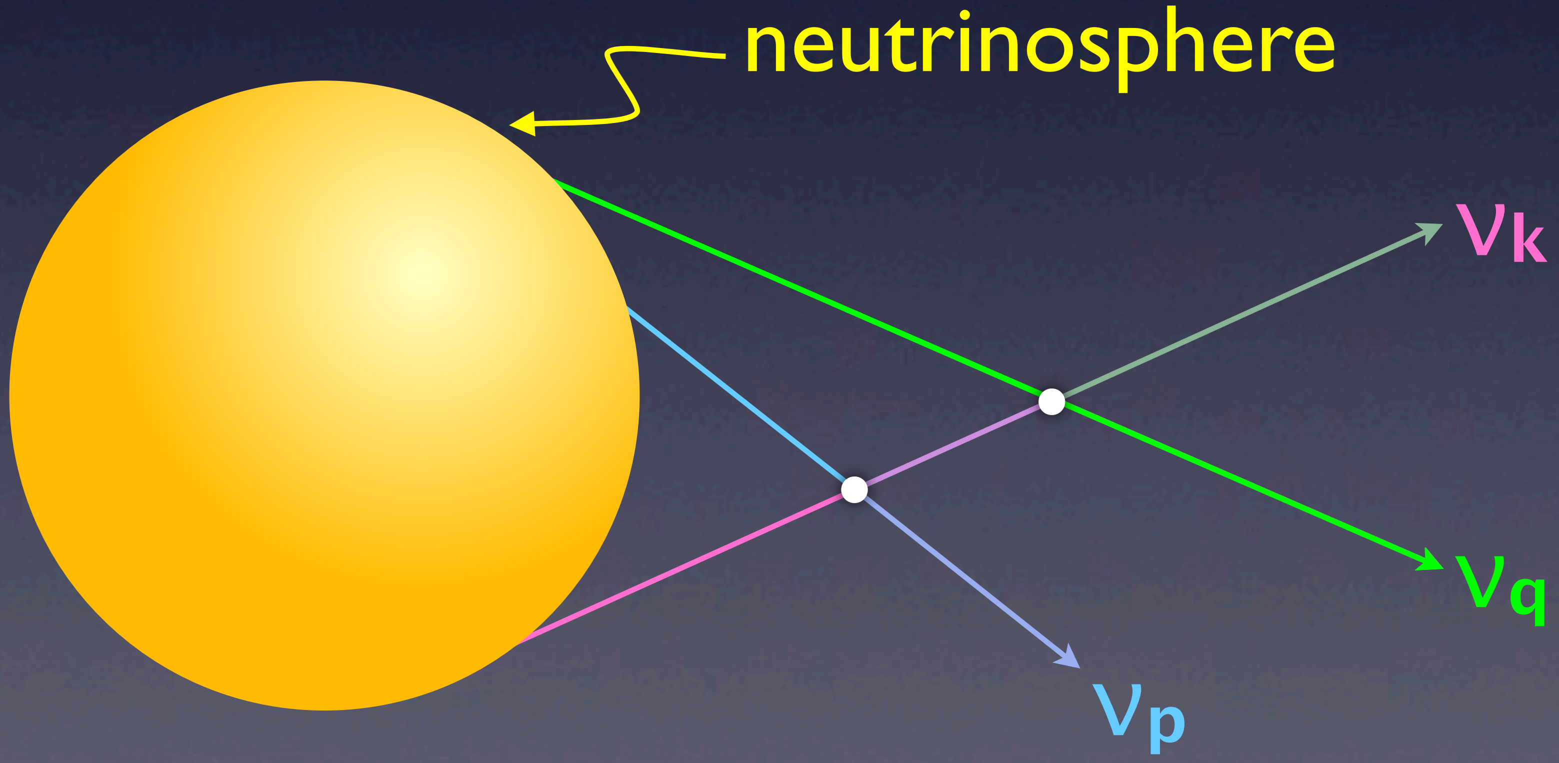
(self–coupling)

$$\mathrm{H}_{\nu\nu} = \sqrt{2}G_{\mathrm{F}}\int \mathrm{d}\mathbf{p}'(1-\hat{\mathbf{p}}\cdot\hat{\mathbf{p}}')(\rho_{\mathbf{p}'}-\bar{\rho}_{\mathbf{p}'})$$

ν oscillations in SN

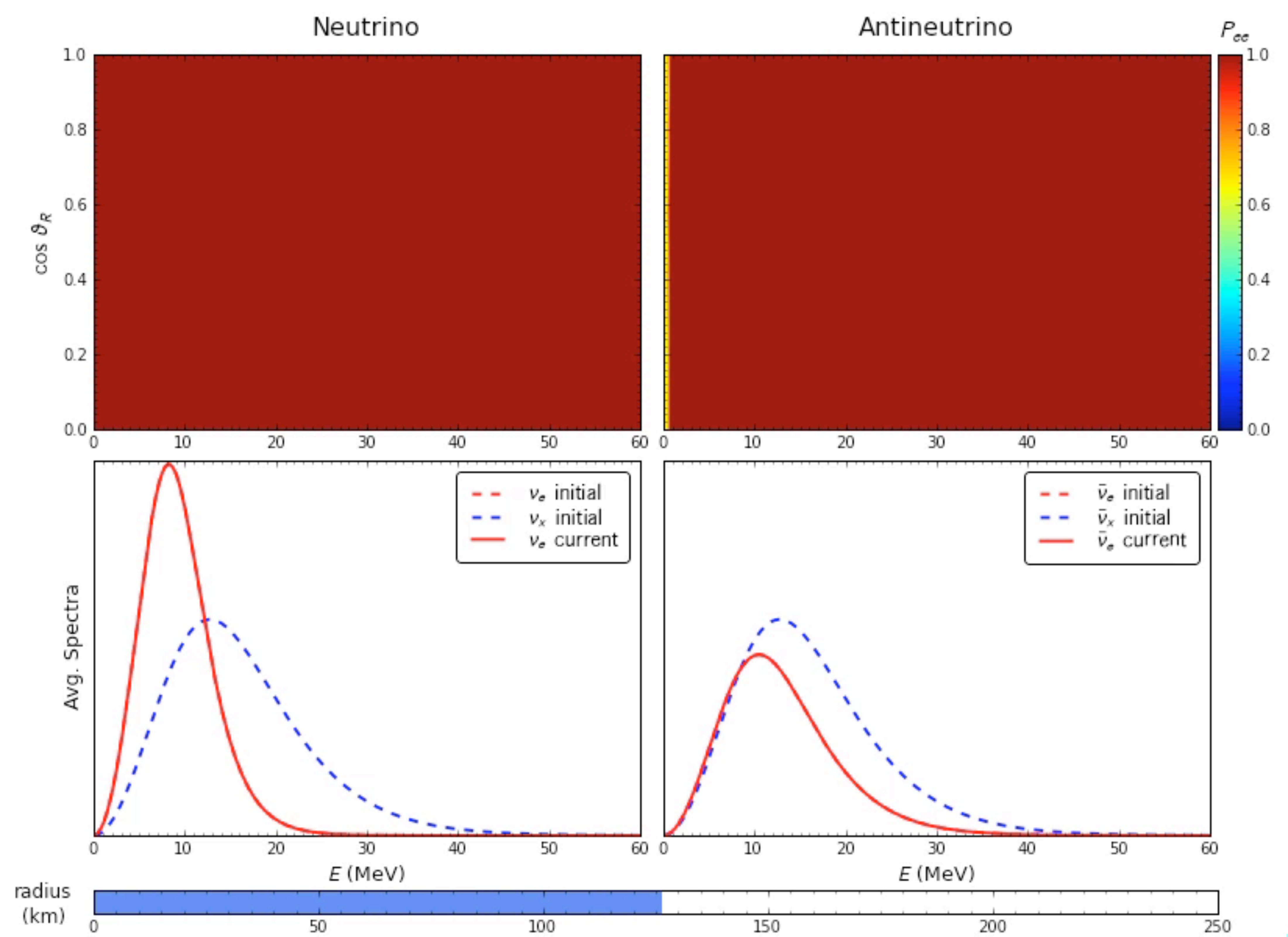
$$\mathrm{i}\frac{\mathrm{d}}{\mathrm{d}\lambda}|\psi_{\nu,\mathbf{p}}\rangle = \hat{H}|\psi_{\nu,\mathbf{p}}\rangle$$

$$\mathrm{H} \quad = \quad \frac{\mathrm{M}^2}{2E} \quad + \quad \sqrt{2}G_{\mathrm{F}}\,\mathrm{diag}[n_e,0,0] \quad + \quad \mathrm{H}_{\nu\nu}$$



$$\langle L_{\nu_e} \rangle = 4.1\,\text{foe},\ \langle L_{\bar{\nu}_e} \rangle = 4.3\,\text{foe},\ \langle L_{\nu_x,\bar{\nu}_x} \rangle = 7.9\,\text{foe}$$

$$\langle E_{\nu_e} \rangle = 9.4\,\text{MeV},\ \langle E_{\bar{\nu}_e} \rangle = 13.0\,\text{MeV},\ \langle E_{\nu_x,\bar{\nu}_x} \rangle = 15.8\text{MeV}$$



Where do neutrino oscillations occur?

$$\mathrm{H} = \frac{\mathrm{M}^2}{2E} + \sqrt{2}G_\mathrm{F}\,\mathrm{diag}[n_e, 0, 0] + \mathrm{H}_{\nu\nu}$$

$$\mathrm{H}_{\nu\nu} = \sqrt{2}G_\mathrm{F}\int \mathrm{d}\mathbf{p}'(1 - \hat{\mathbf{p}}\cdot\hat{\mathbf{p}}')(\rho_{\mathbf{p}'} - \bar{\rho}_{\mathbf{p}'})$$

MSW flavor transformation:

$$\frac{\delta m^2}{2E_\nu} \approx \sqrt{2}G_\mathrm{F}n_e$$

Collective flavor transformation:

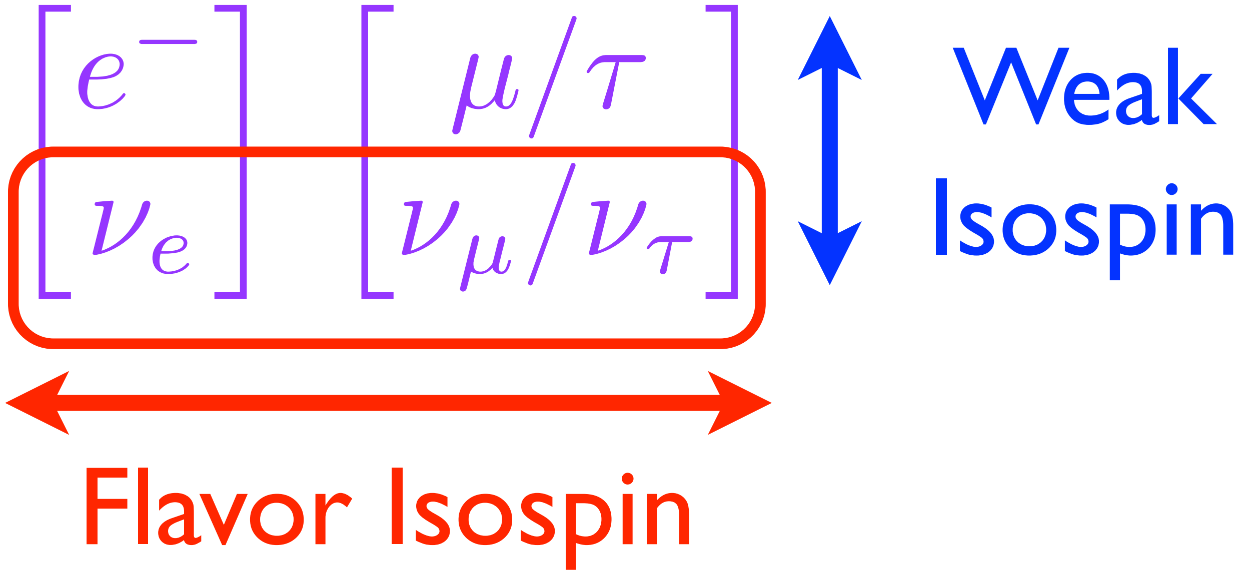
$$\frac{\delta m^2}{E_\nu} \approx G_\mathrm{F}|n_\nu - n_{\bar{\nu}}|\langle 1 - \cos\theta_{\mathbf{p},\mathbf{p}'}\rangle \gtrsim G_\mathrm{F}n_e\langle 1 - \cos\theta_{\mathbf{p},\mathbf{p}'}\rangle$$

Neutrino Flavor Isospin

$$\mathrm{i}\frac{\mathrm{d}}{\mathrm{d}\lambda}\psi_\nu = \mathsf{H}\psi_\nu$$

$$= -\vec{H}\cdot\frac{\vec{\sigma}}{2}\psi_\nu$$

$$\frac{\mathrm{d}}{\mathrm{d}\lambda}\vec{s} = \vec{s}\times\vec{H}$$



$$\begin{bmatrix} e^- \\ \nu_e \end{bmatrix} \quad \begin{bmatrix} \mu/\tau \\ \nu_\mu/\nu_\tau \end{bmatrix}$$

Weak Isospin

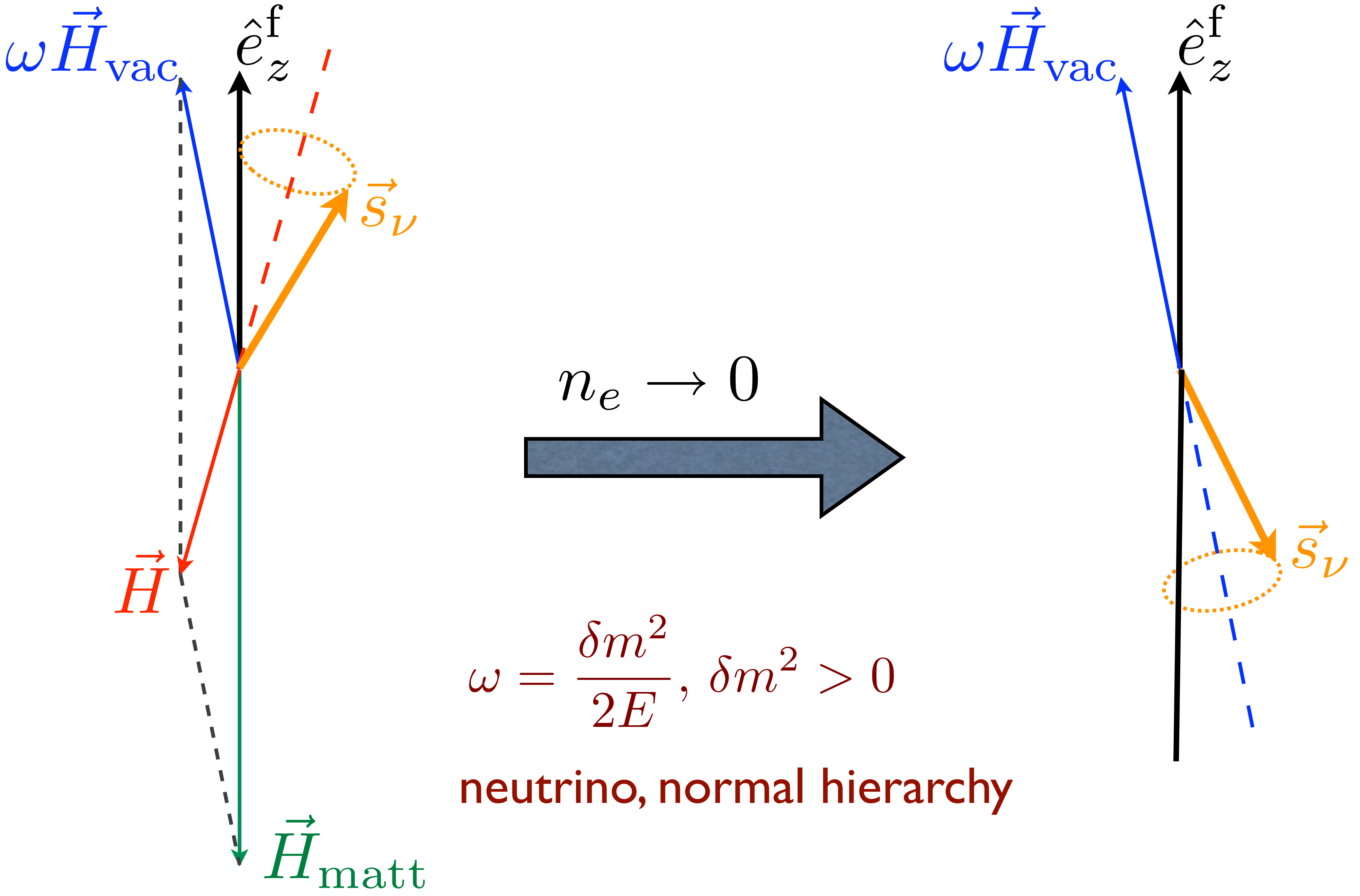
Flavor Isospin

	e-flavor	τ'-flavor	maximally mixed
$\vec{s}_\nu \equiv \psi_\nu^\dagger\frac{\vec{\sigma}}{2}\psi_\nu$	$\uparrow$	$\downarrow$	$\rightarrow$
$\vec{s}_{\bar{\nu}} \equiv (\sigma_y\psi_{\bar{\nu}})^\dagger\frac{\vec{\sigma}}{2}(\sigma_y\psi_{\bar{\nu}})$	$\downarrow$	$\uparrow$	$\rightarrow$

MSW Mechanism

$$\vec{H} = \omega \vec{H}_{\rm vac} + \vec{H}_{\rm matt}$$

$$\vec{H}_{\rm matt} \equiv -\hat{e}_z^{\rm f} \sqrt{2} G_{\rm F} n_e$$



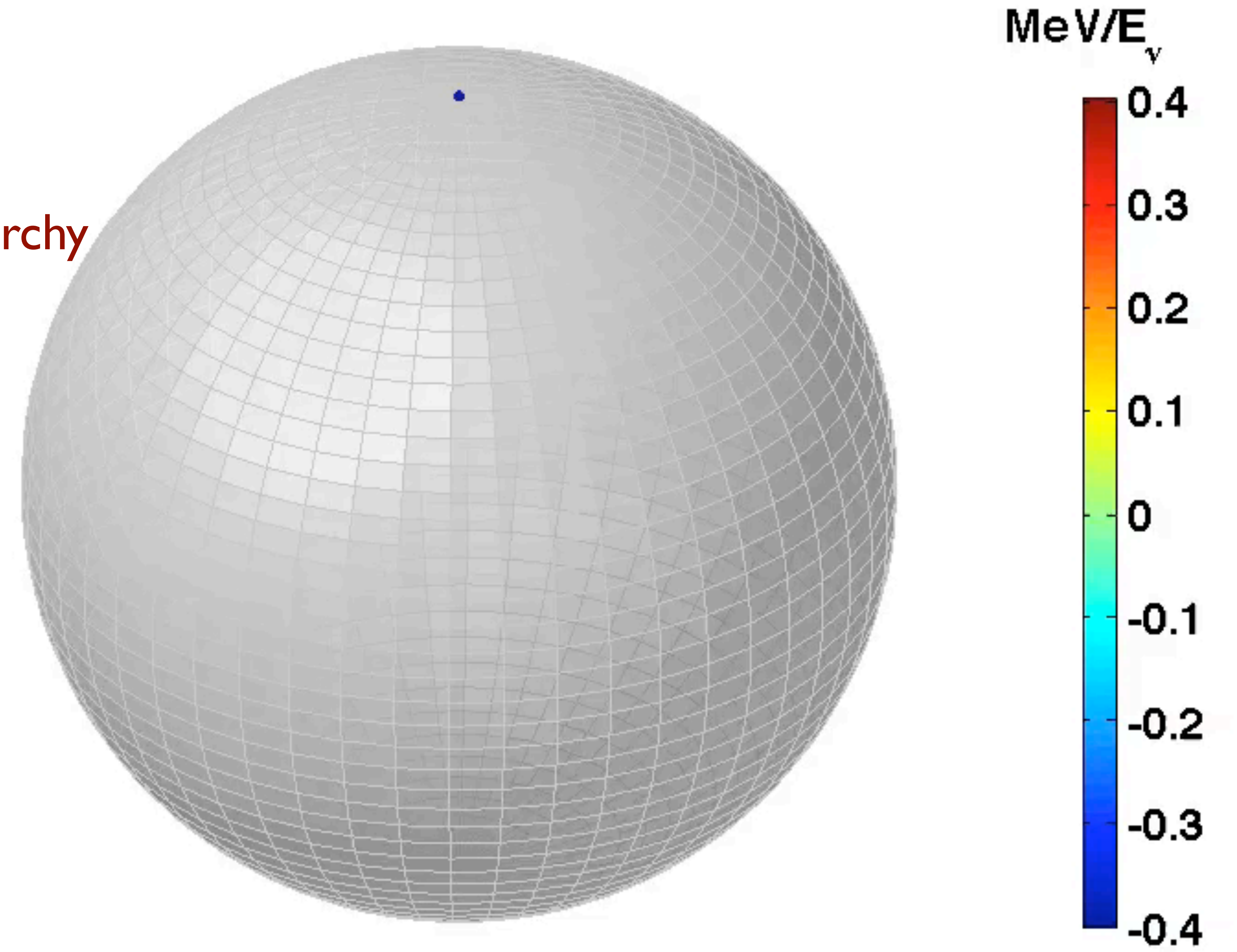
$$\omega = \frac{\delta m^2}{2E}, \ \delta m^2 > 0$$

neutrino, normal hierarchy

MSW Mechanism

$\delta m^2 < 0$

inverted hierarchy



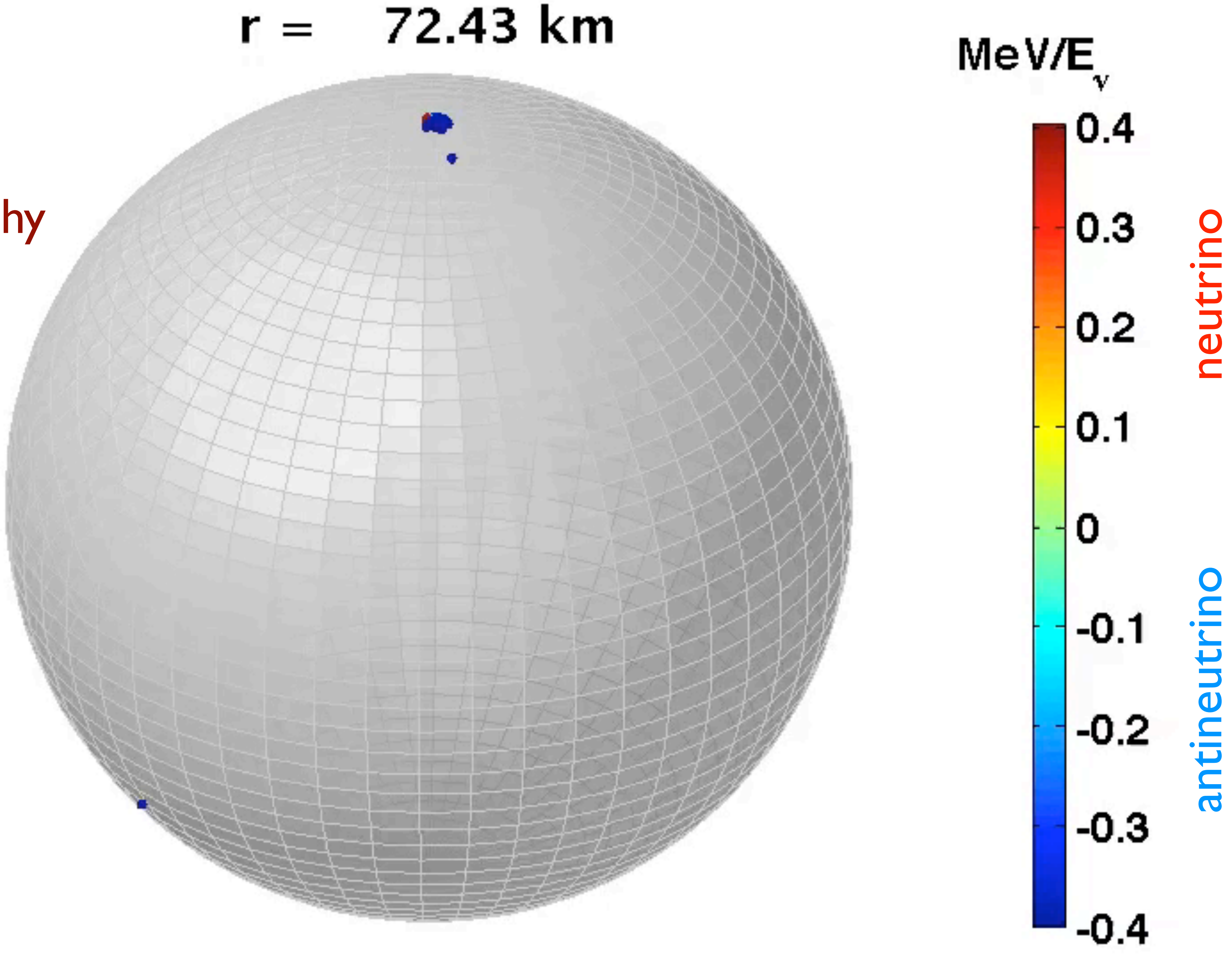
neutrino

antineutrino

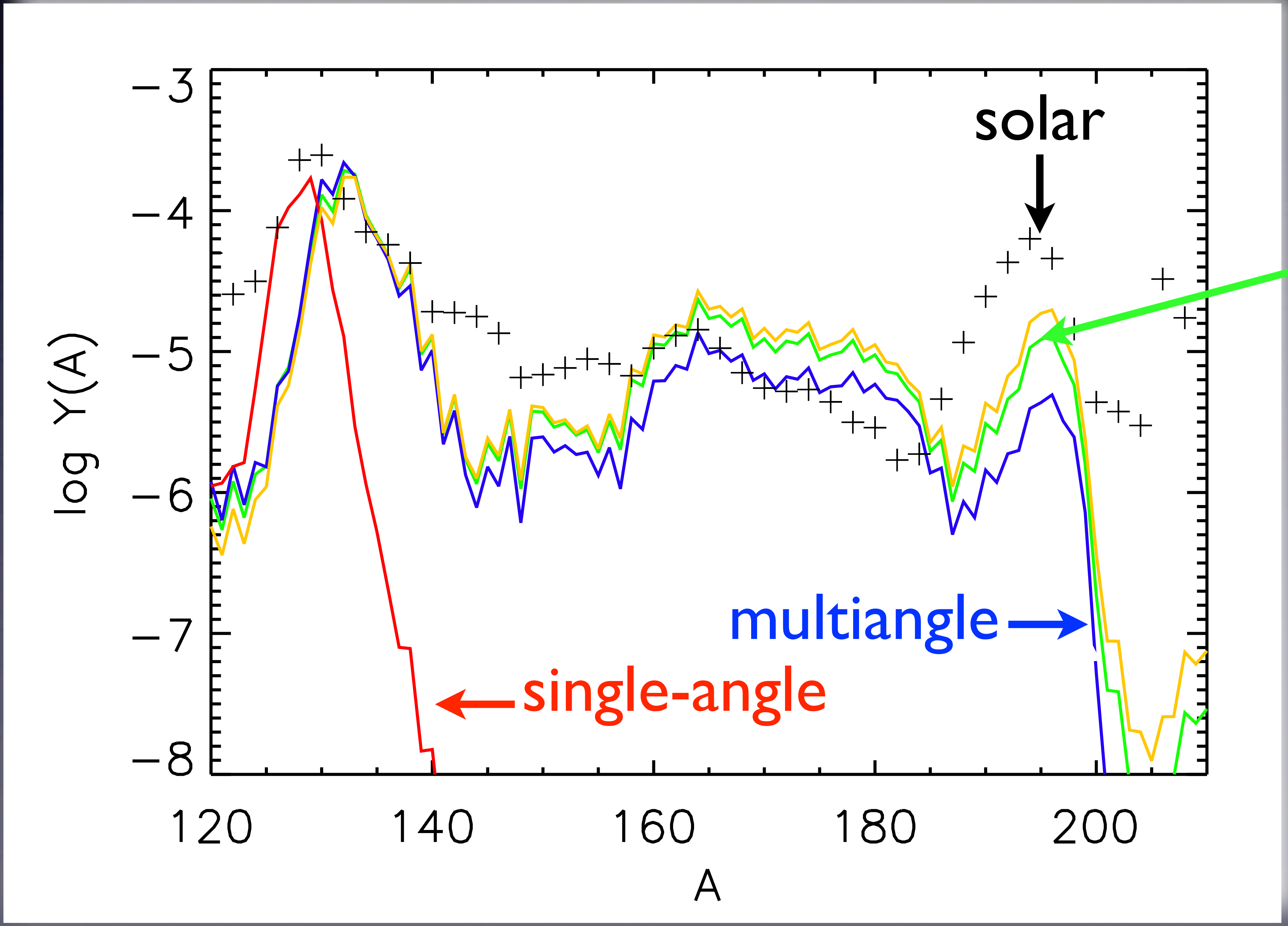
Collective Oscillations

$\delta m^2 < 0$

inverted hierarchy



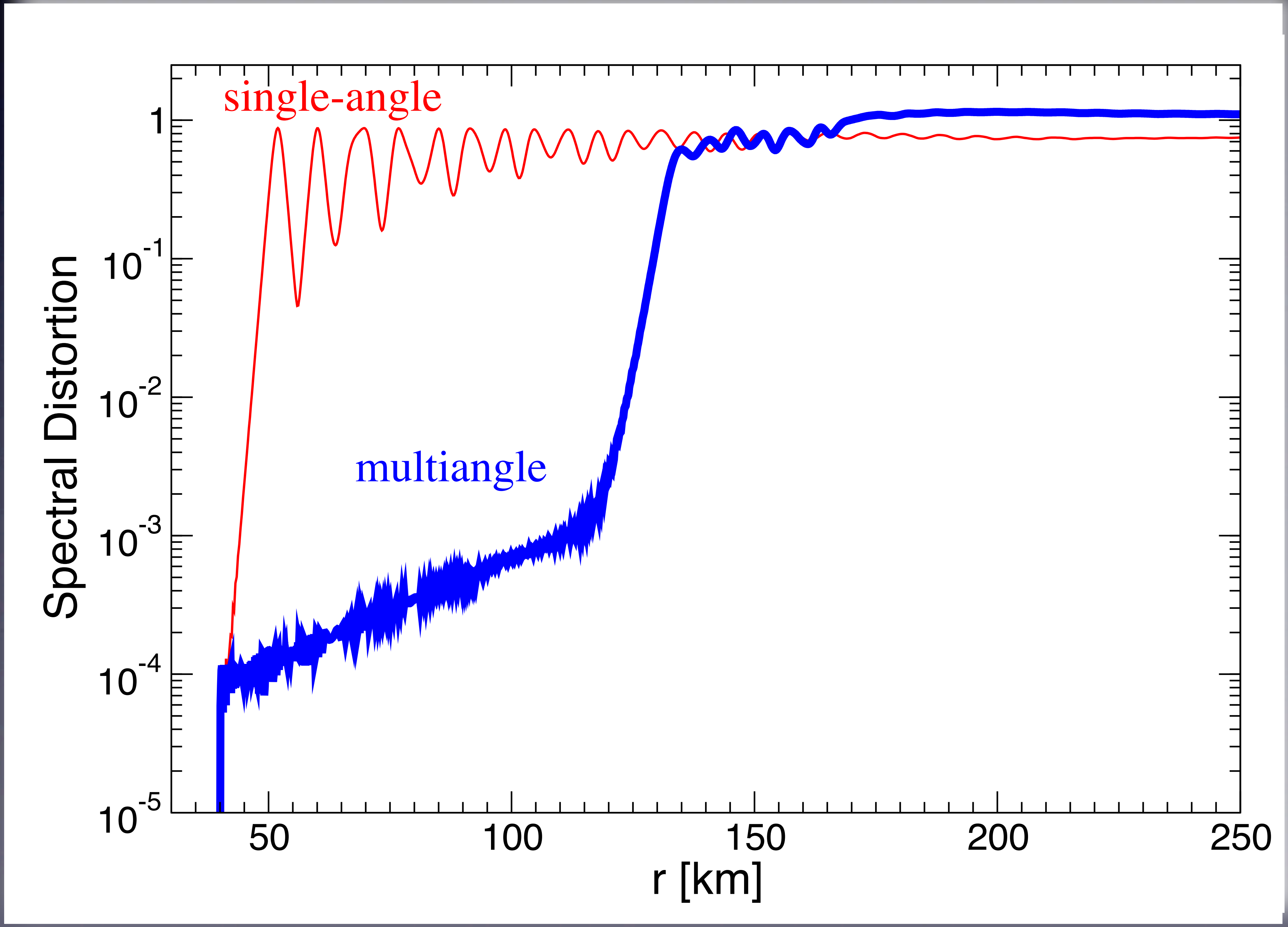
R-process Nucleosynthesis



no osc.

Duan, Friedland, McLaughlin & Surman
JPG 38, 35201 (2011)

Single- or multi-angle?



Duan & Friedland,
PRL 106, 091101 (2010)

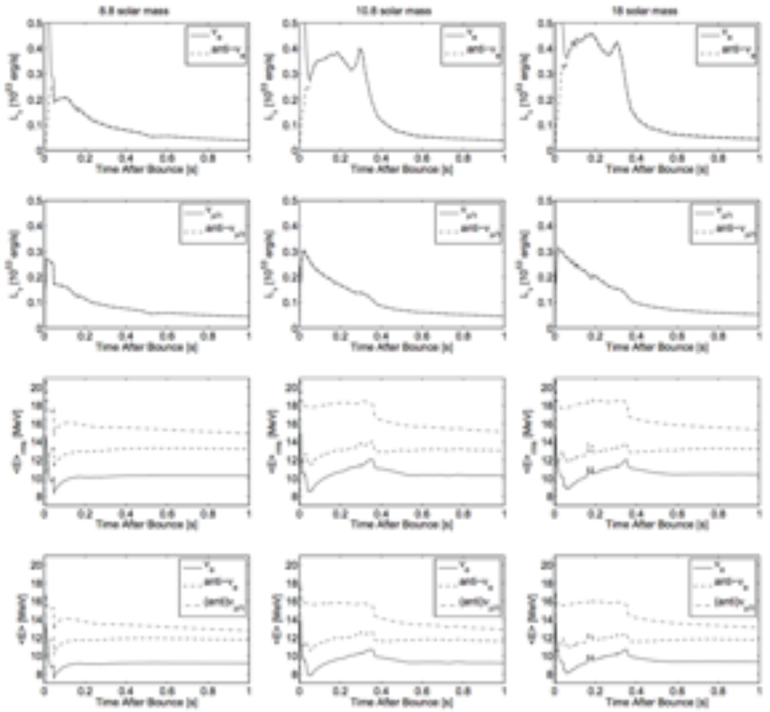
Summary of Part 1

- Neutrino mixing is not optional in computing supernova r-process nucleosynthesis or predicting neutrino signals.
- Neutrinos can experience collective oscillations in supernovae.
- The effects of neutrino oscillations depend on where they occur, which in turn depend on the neutrino mass hierarchy, the initial neutrino spectra and luminosities.
- Can we see them in neutrino signals?

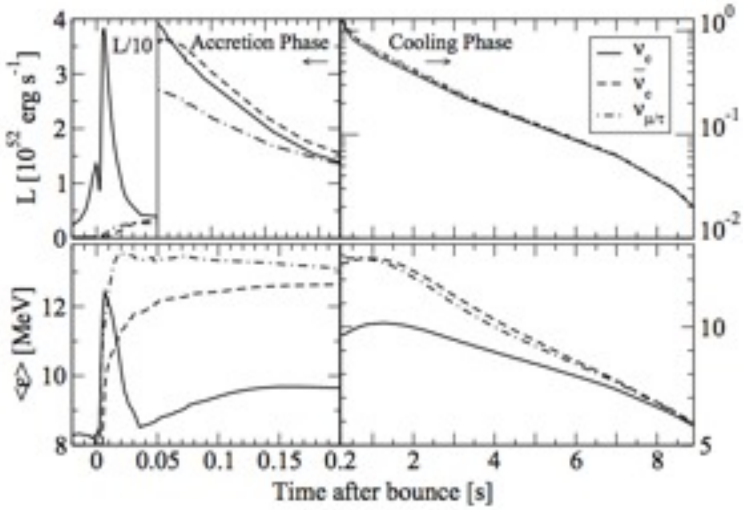
Neutrino Emission from the PNS

- Because physics in the PNS is a bit of a mystery, there is not good agreement on the neutrino emission.

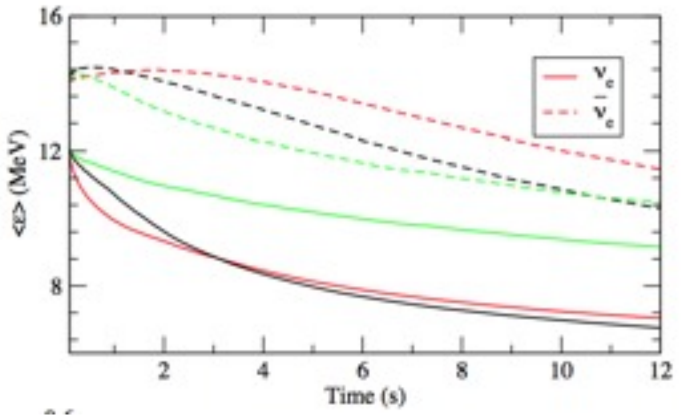
Fischer, et al. (2010)



Hudepohl, et al. (2010)



Roberts, et al. (2012)

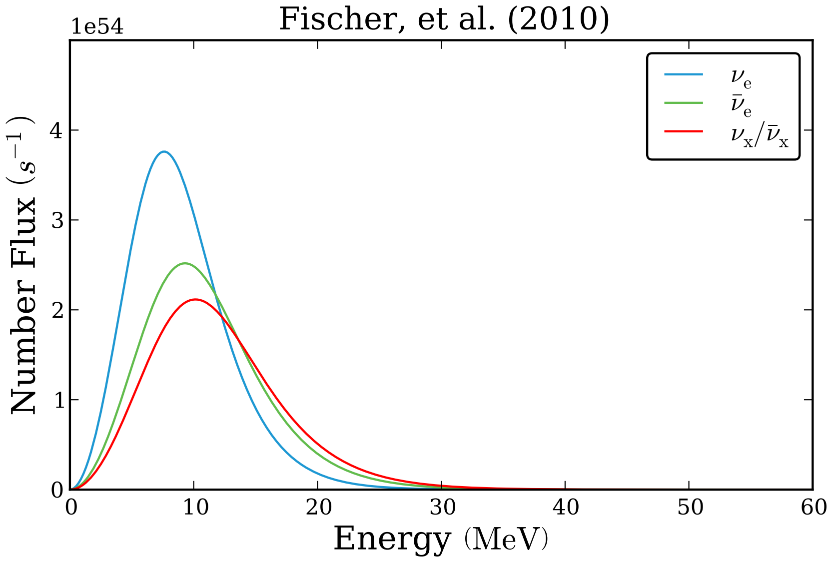


Each group of modelers has their particular strengths

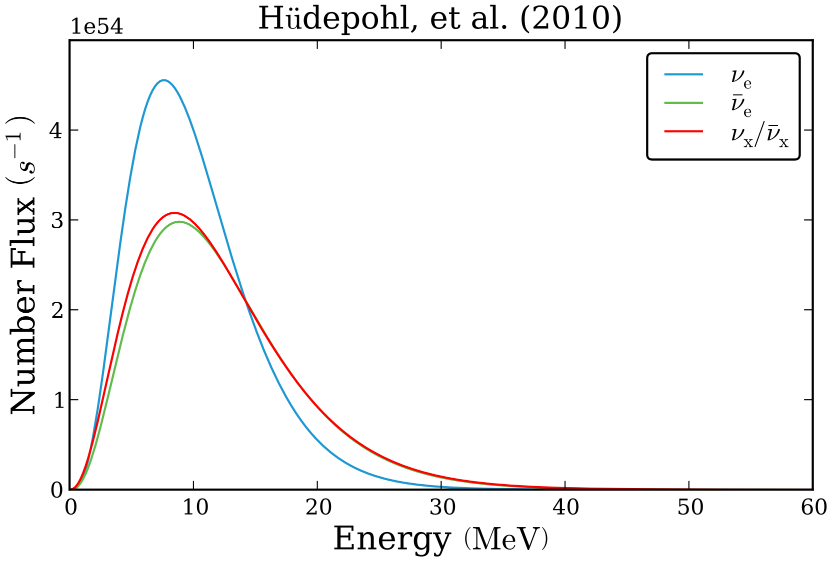
- Fischer, et al. (2010): Full GR radiation transport and hydrodynamics in 1D. Moderately sophisticated neutrino interaction network. Uses standard Shen et al. (1998) EOS for the PNS.
- Hudepohl, et al. (2010): Newtonian radiation transport and hydrodynamics (with corrections) in 1D. Very sophisticated neutrino interaction network. Uses standard Shen et al. (1998) EOS for the PNS.
- Roberts, et al. (2012): Full GR radiation transport and hydrodynamics in 1D. Moderately sophisticated neutrino interaction network. Employs cutting edge EOS for PNS, in particular several that are consistent with recent calculations of the nuclear symmetry energy at high density.

A few typical spectra

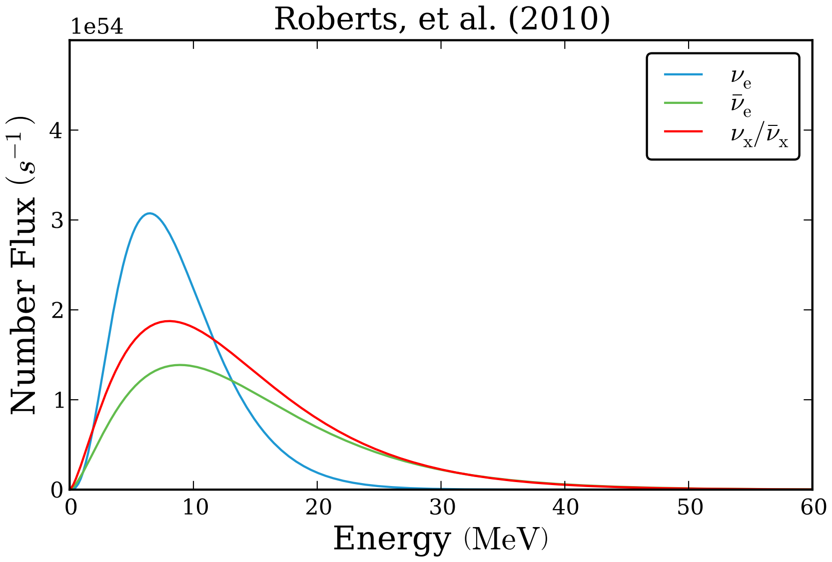
2s post core bounce



Fischer, et al. (2010)
Classic energy hierarchy
Symmetric late time spectra



Hudepohl, et al. (2010)
Anomalously hot $\bar{\nu}_e' s$.
Symmetric late time spectra



Roberts, et al. (2012)
Anomalously hot $\bar{\nu}_e' s$.
Asymmetric late time spectra

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]

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[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`

Event rate calculation only!

- SNoWGLoBES exists for the express purpose of performing this integral:

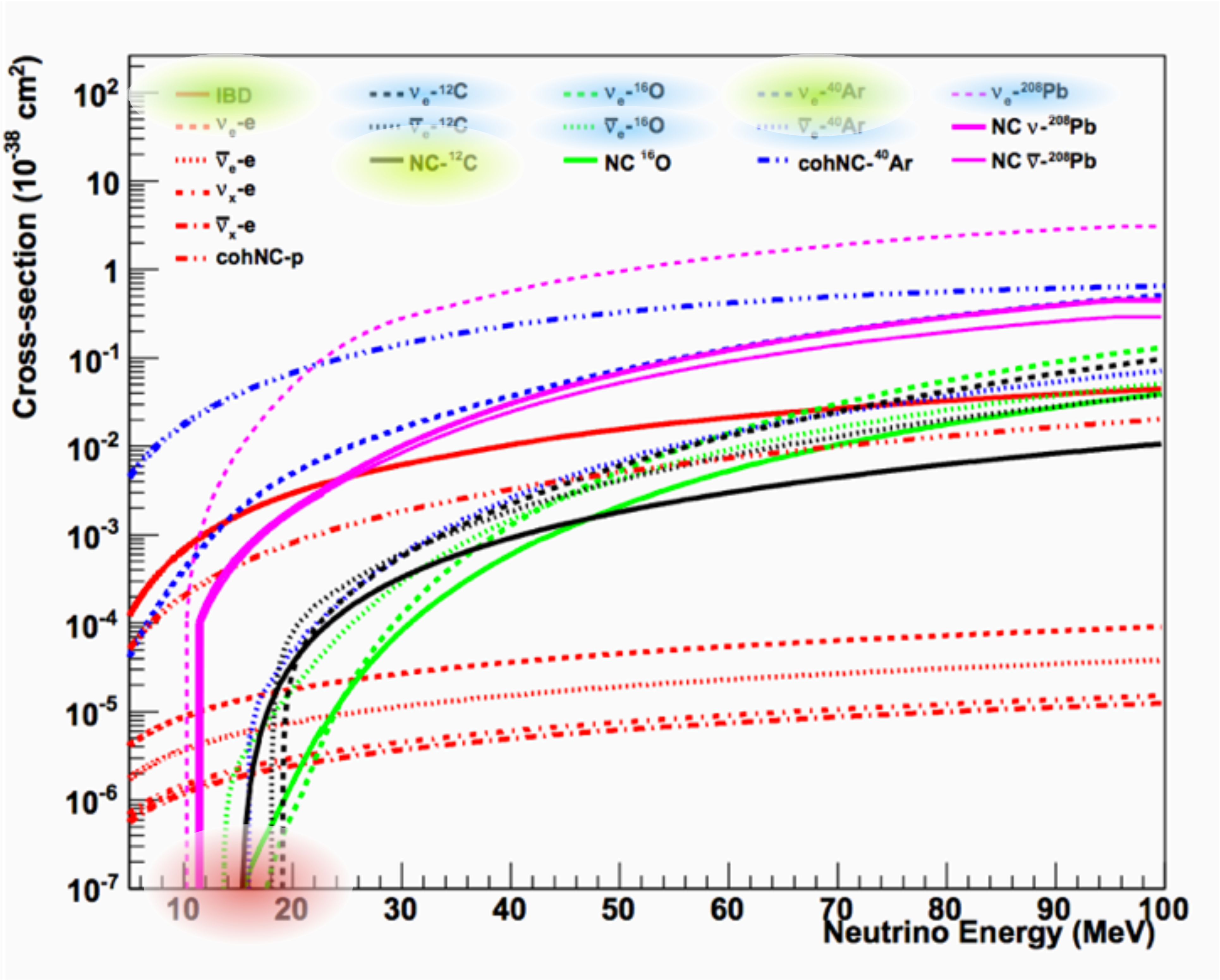
$$\frac{dn}{dE'} = \int_0^\infty \int_0^\infty dE d\hat{E} \Phi(E)\sigma(E)k(E-\hat{E})T(\hat{E})V(\hat{E}-E')$$

- k, T, and V are collected into a single “smearing” matrix.

Basic set up:

- Assume a distance to a galactic supernova of 10 kpc
- Examine several 'proxies' for planned future detectors: 100 kt Water Cherenkov detector, 17kt Liquid Argon detector, 50 kt Liquid Scintillator detector.
- Assume the detectors are buried deep.

A suite of detection channels

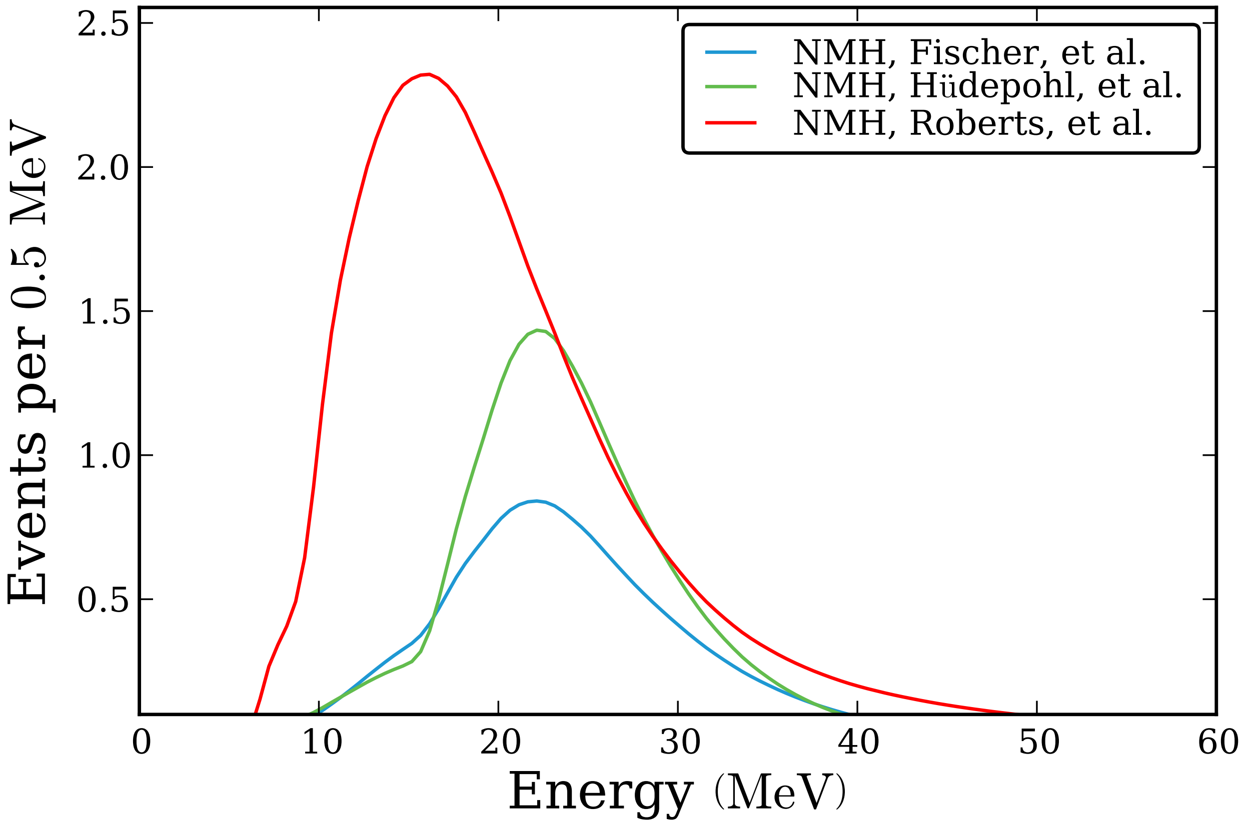


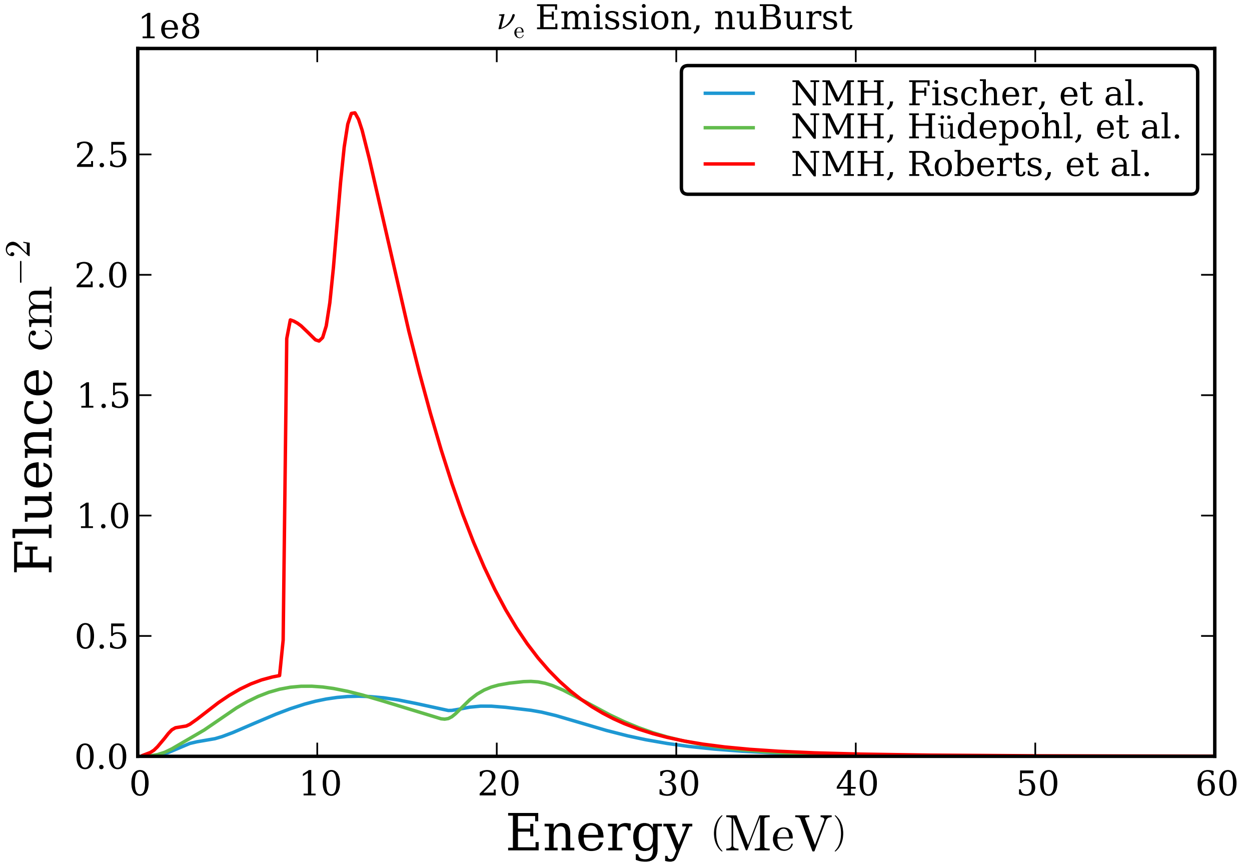
[1] K. Scholberg, Annual Review of Nuclear and Particle Science Vol. 62: 81-103 (2012).

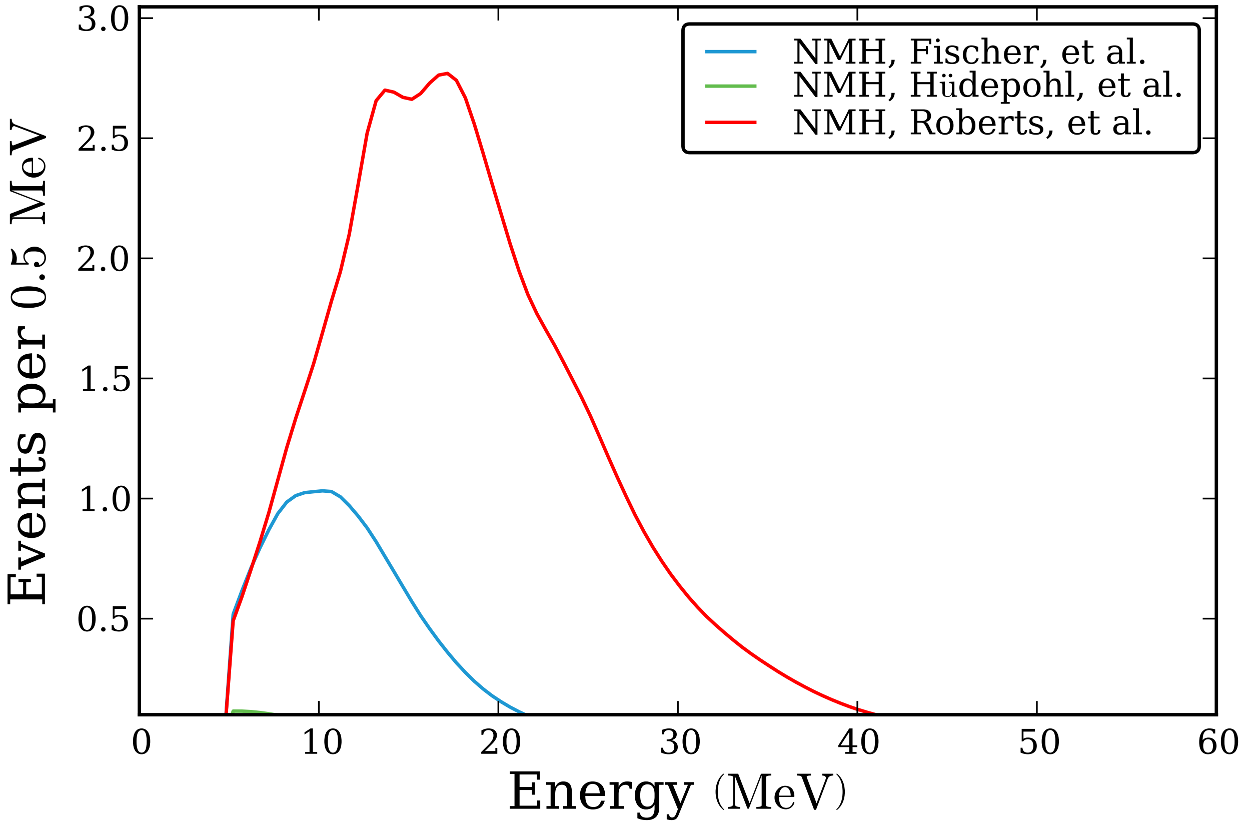
Signals in Liquid Argon

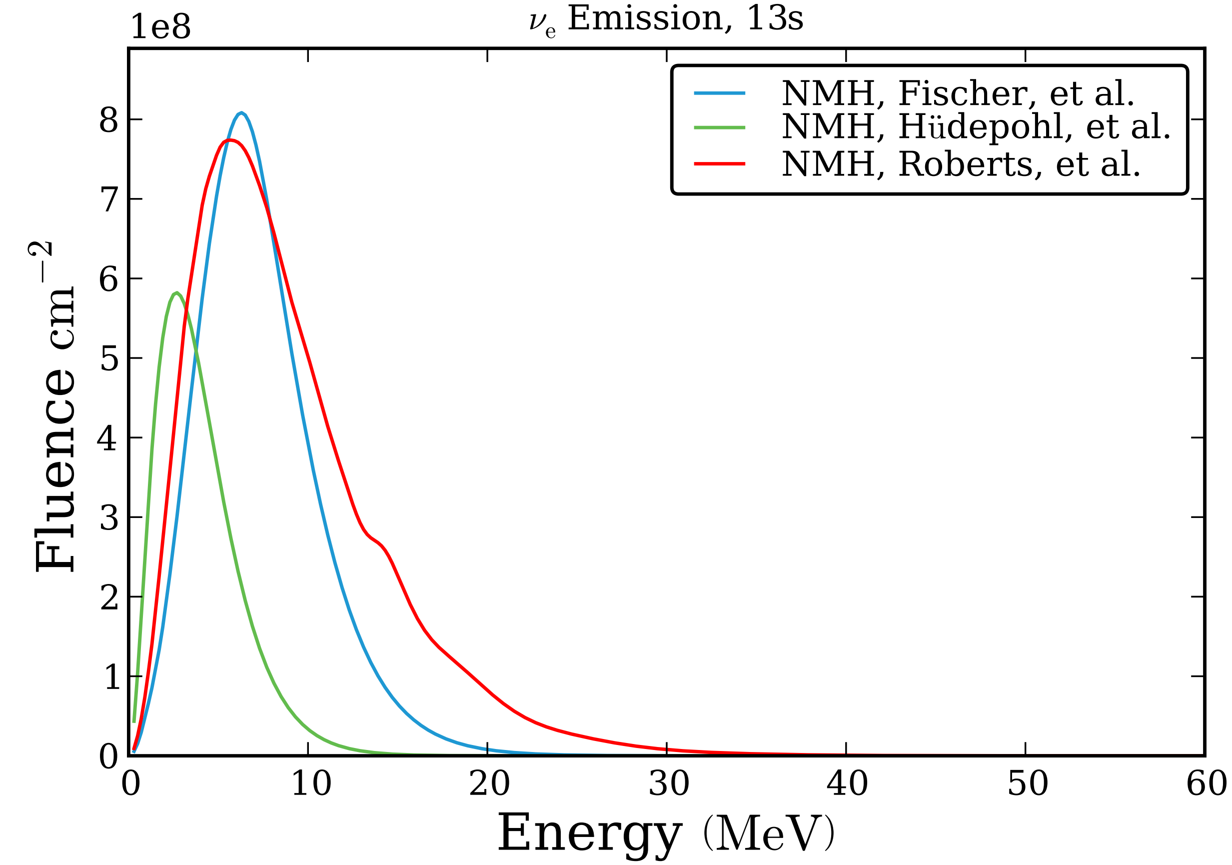
$$\nu_{\mathrm{e}} + {}^{40}Ar \rightarrow e^{-} + {}^{40}K^{*}$$

Normal mass Hierarchy

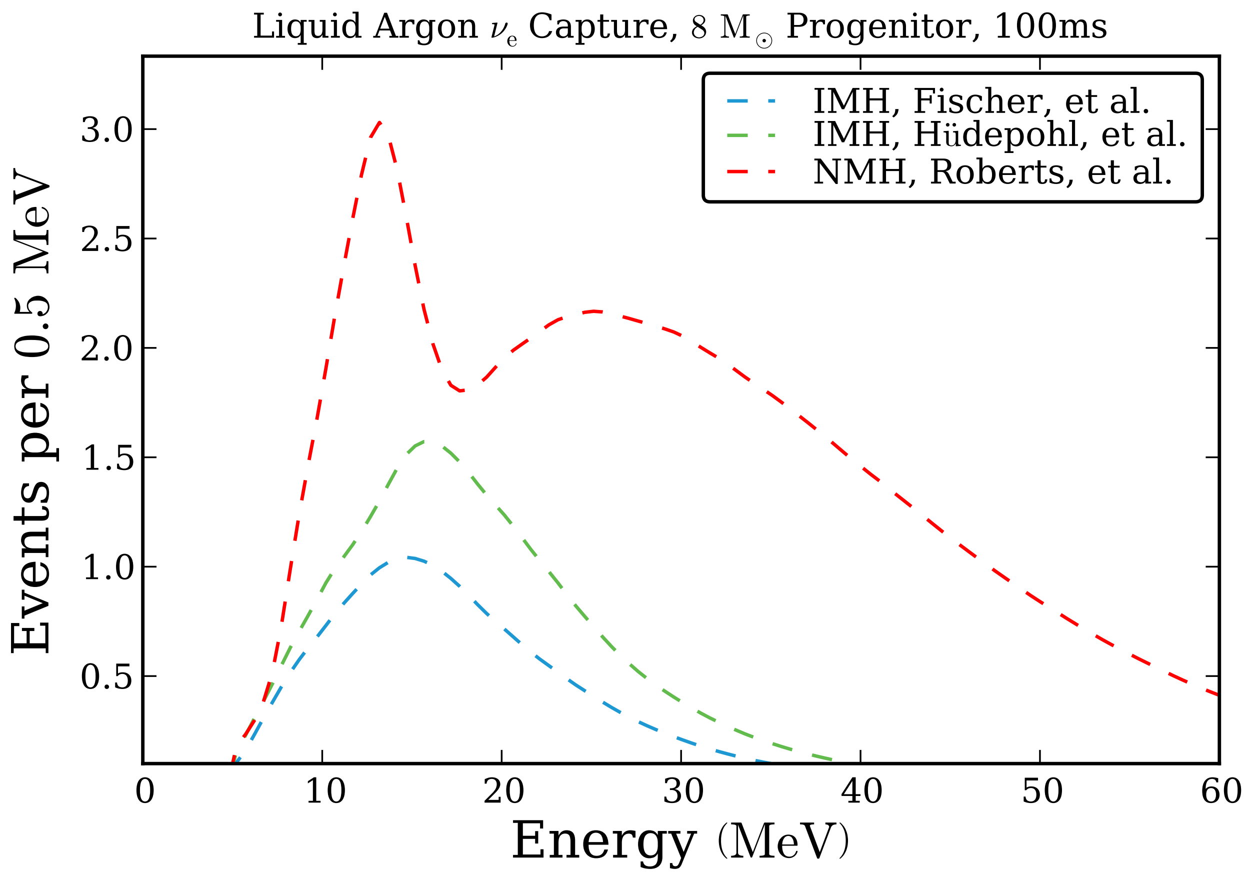

Liquid Argon ν_e Capture, 8 $M_\odot$ Progenitor, nuBurst

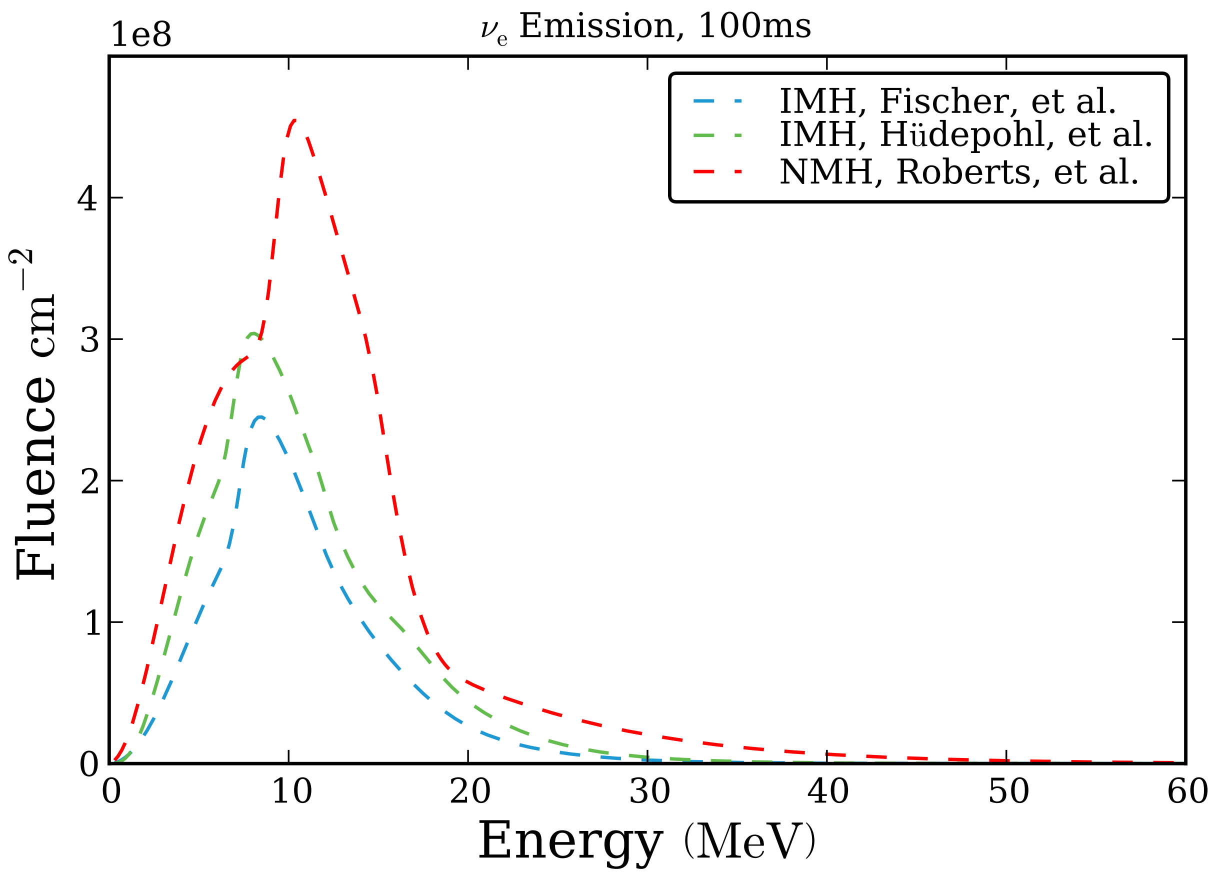

ν_e Emission, nuBurst


Liquid Argon ν_e Capture, 8 $M_\odot$ Progenitor, 13s


ν_e Emission, 13s

Inverted mass Hierarchy

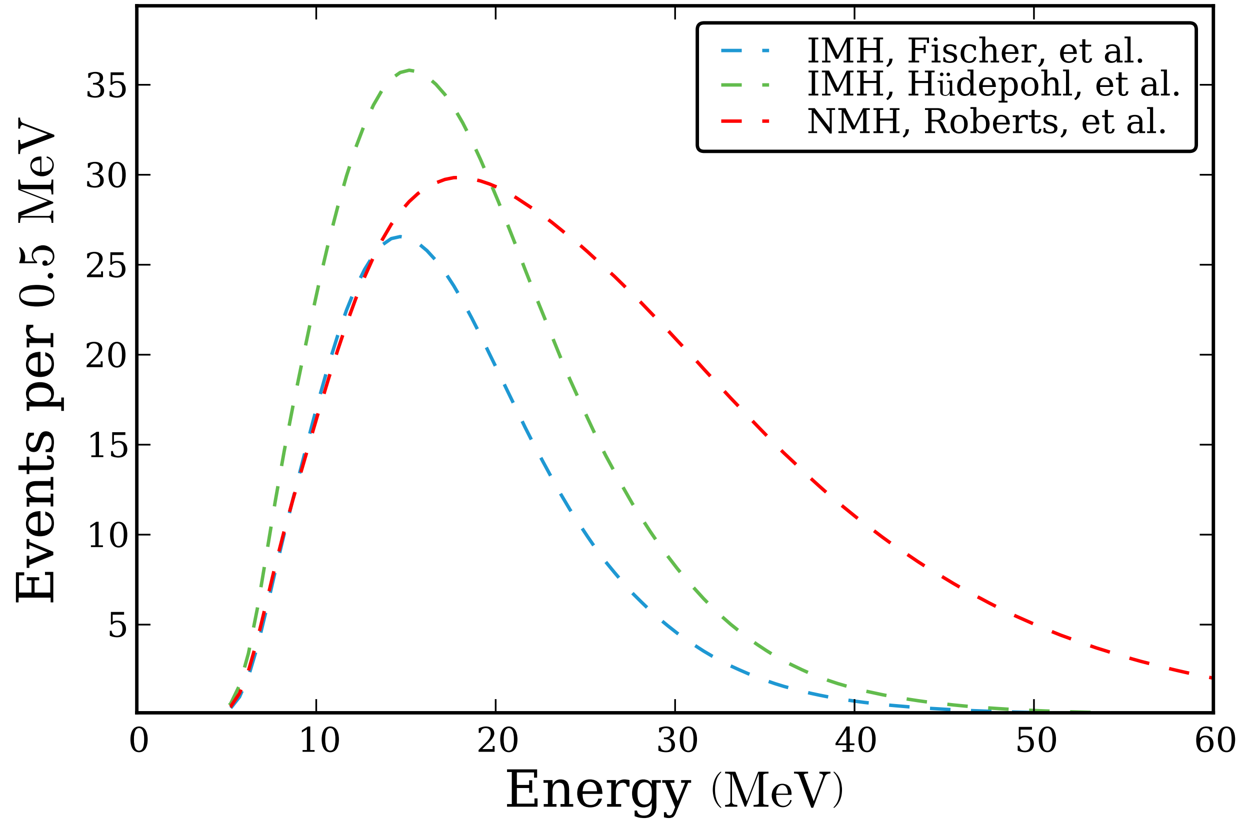


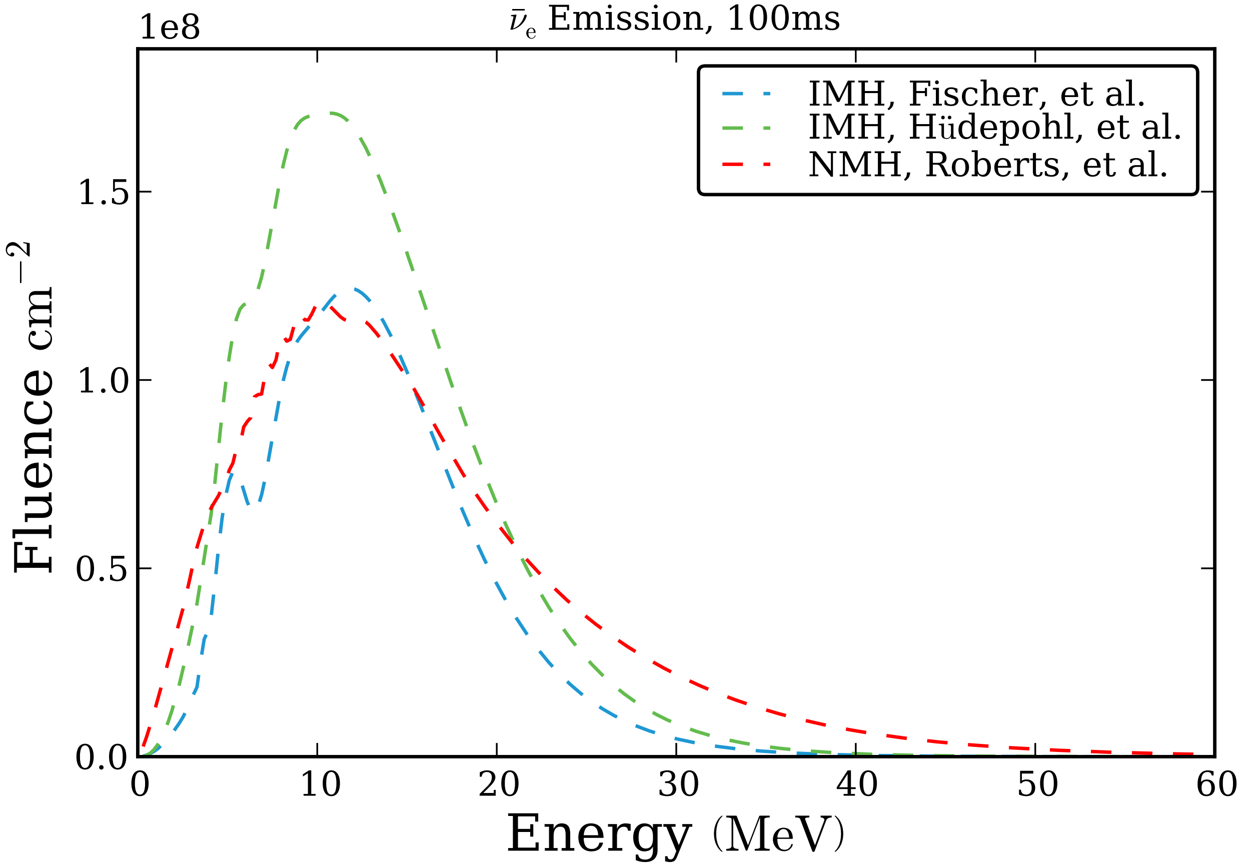


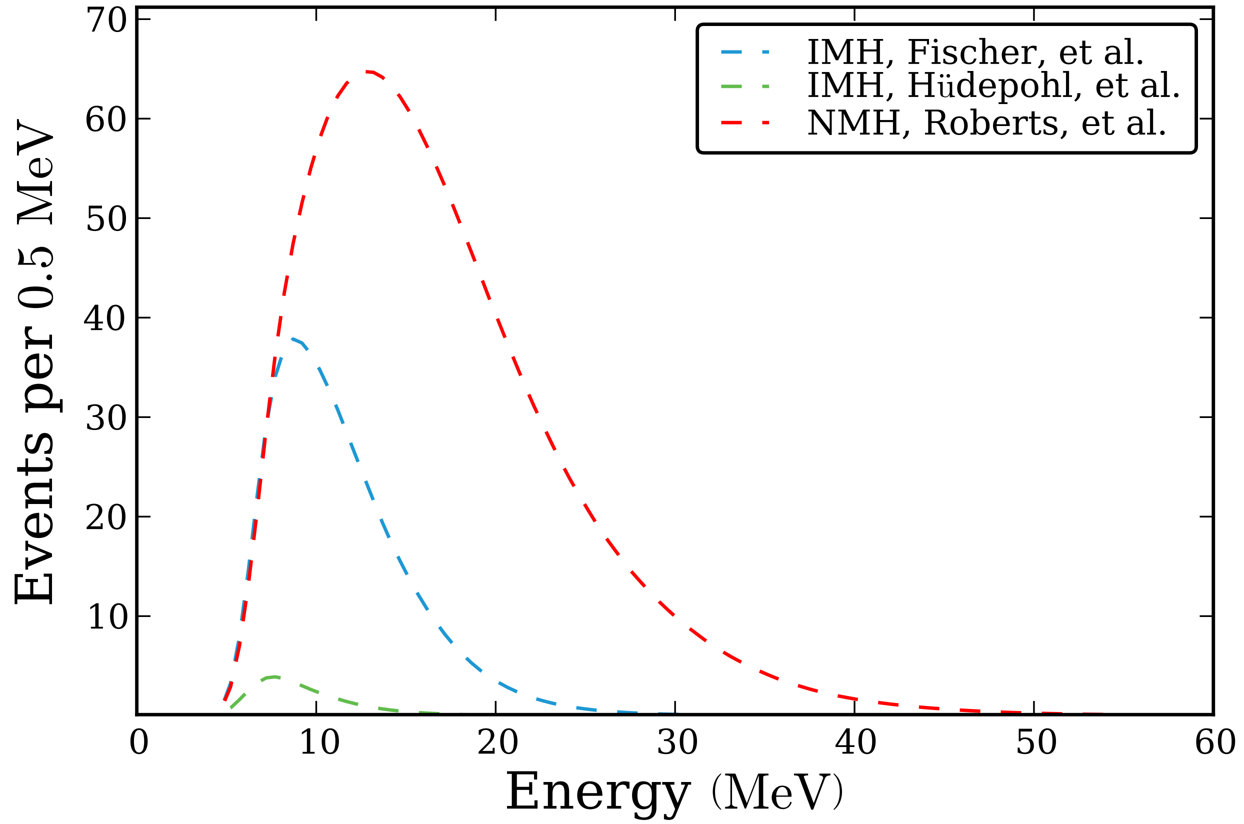
Signals in Water

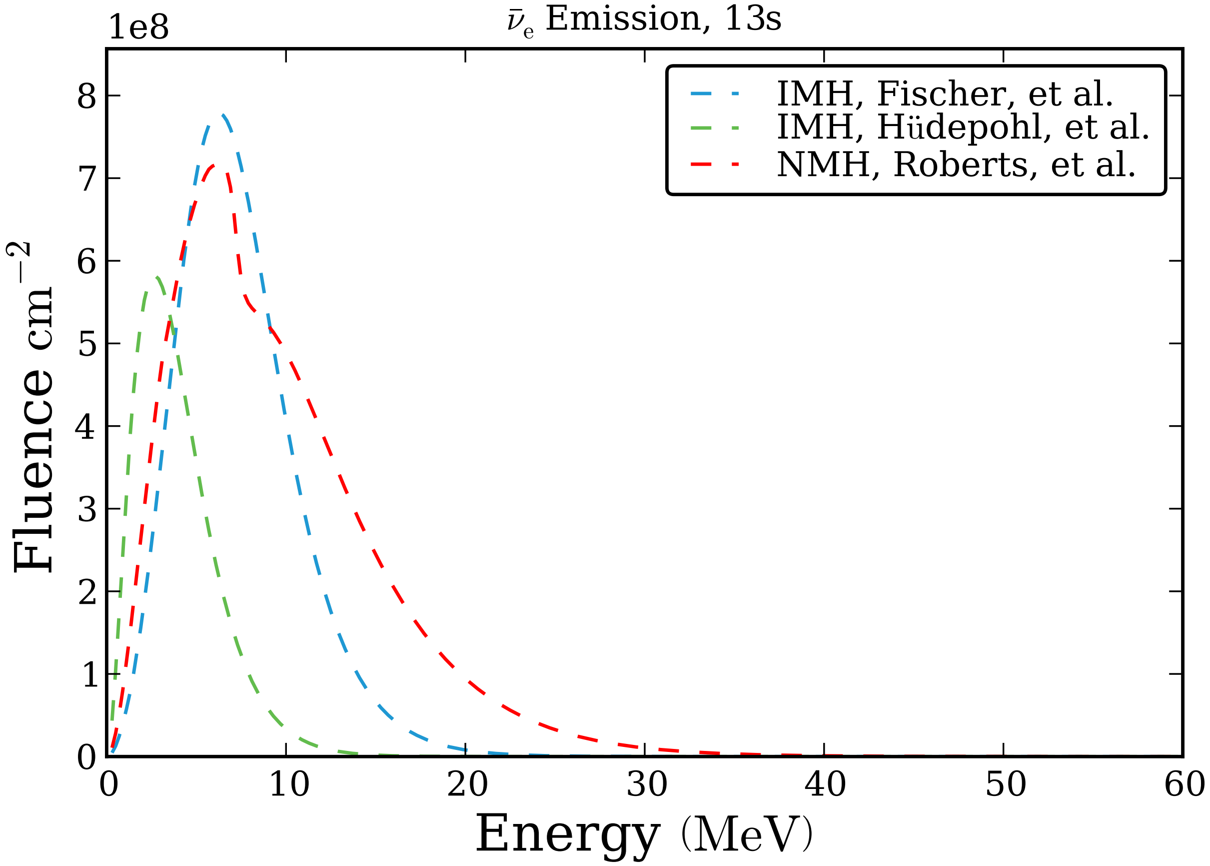
$$\bar{\nu}_{\mathrm{e}} + p \rightarrow e^{+} + n$$

Inverted mass Hierarchy


Water Cherenkov IBD, 8 $M_\odot$ Progenitor, 100ms


$\bar{\nu}_e$ Emission, 100ms

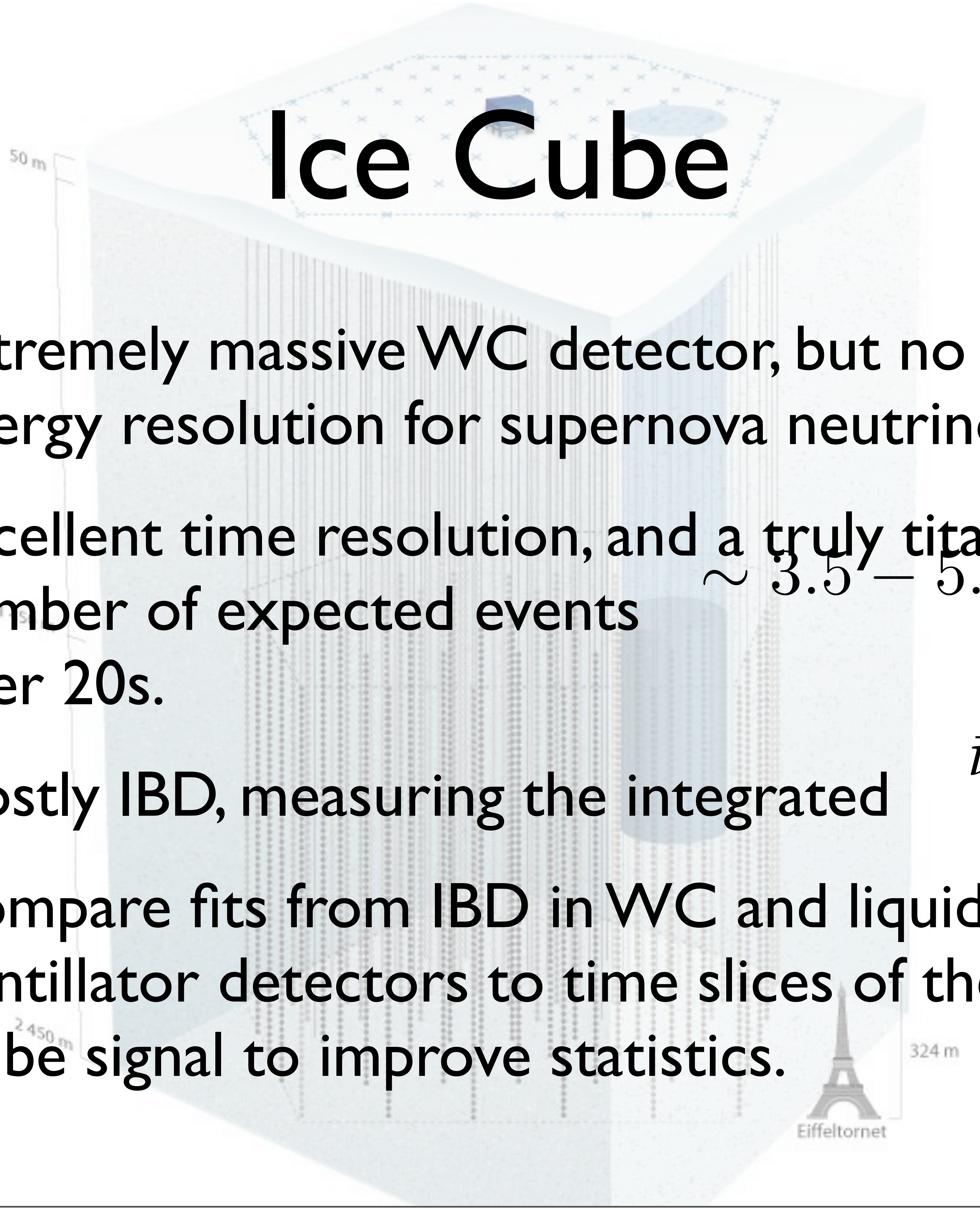

Water Cherenkov IBD, 8 $M_\odot$ Progenitor, 13s


$\bar{\nu}_e$ Emission, 13s

Signals in Liquid Scintillator

$$\nu + {}^{12}C \rightarrow \nu + {}^{12}C + \gamma$$

Ice Cube

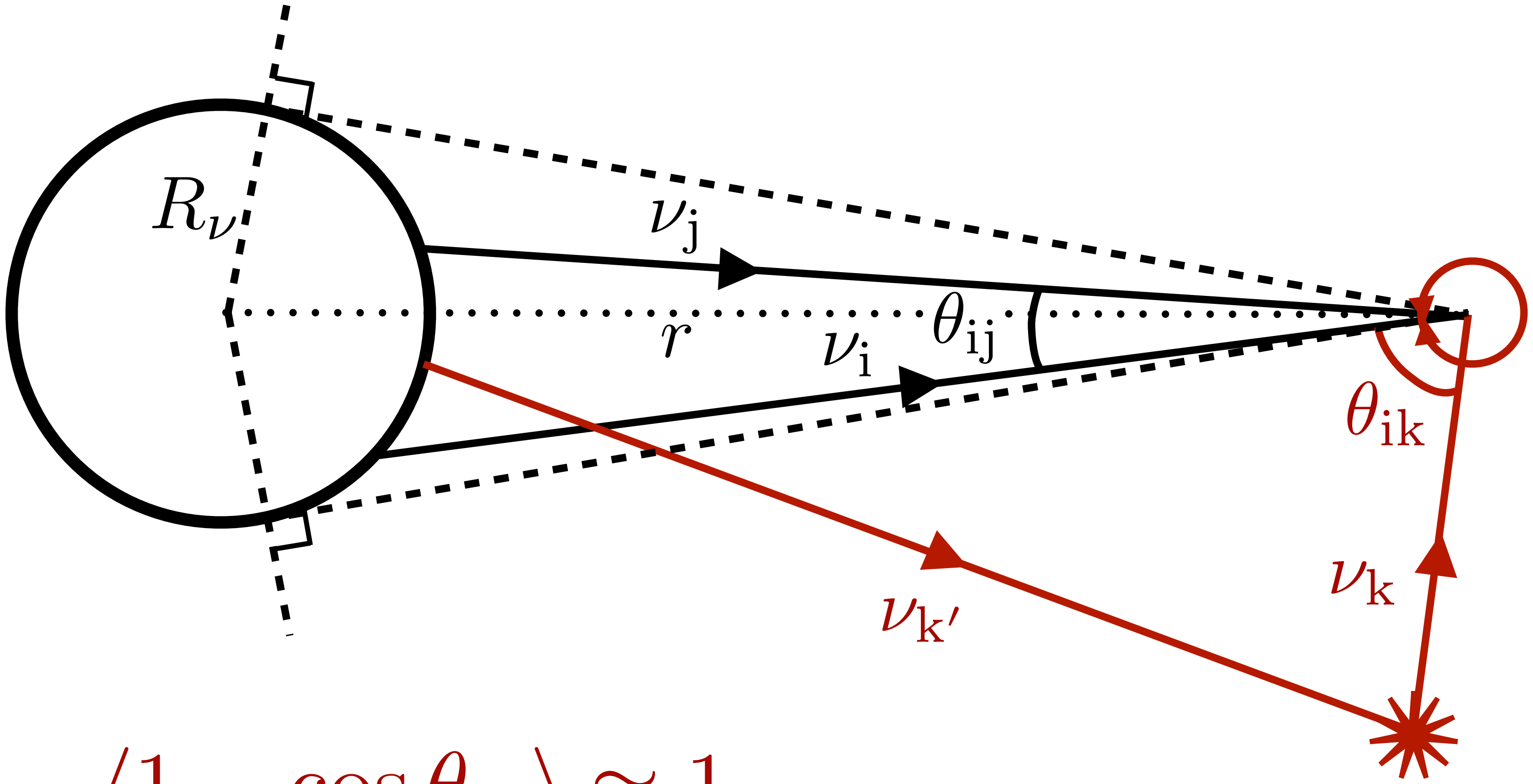


- Extremely massive WC detector, but no energy resolution for supernova neutrinos.
- Excellent time resolution, and a truly titanic number of expected events $\sim 3.5 - 5.3 \times 10^6$ over 20s.
- Mostly IBD, measuring the integrated $\bar{\nu}_\mathrm{e}$ flux.
- Compare fits from IBD in WC and liquid scintillator detectors to time slices of the Ice Cube signal to improve statistics.

Do we fully understand flavor transformation?

J. F. Cherry, A. Friedland, G. M. Fuller, J. Carlson, and A. Vlasenko, Phys. Rev. Lett. **108**, 261104 (2012), 1203.1607.

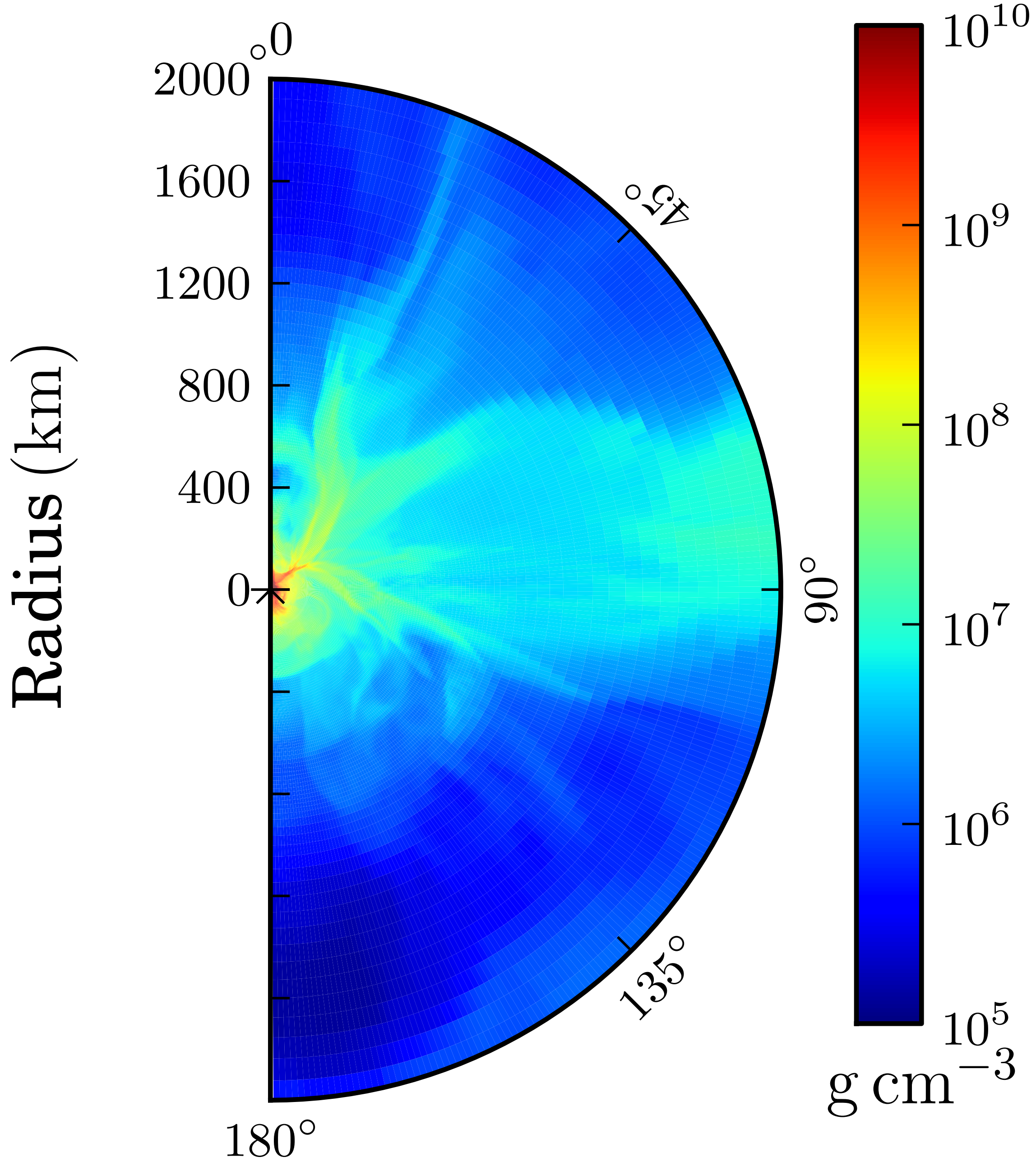
$$r \gg R_\nu \Rightarrow \langle 1 - \cos\theta_{\mathrm{ij}} \rangle \propto \left(\frac{R_\nu}{r} \right)^2$$

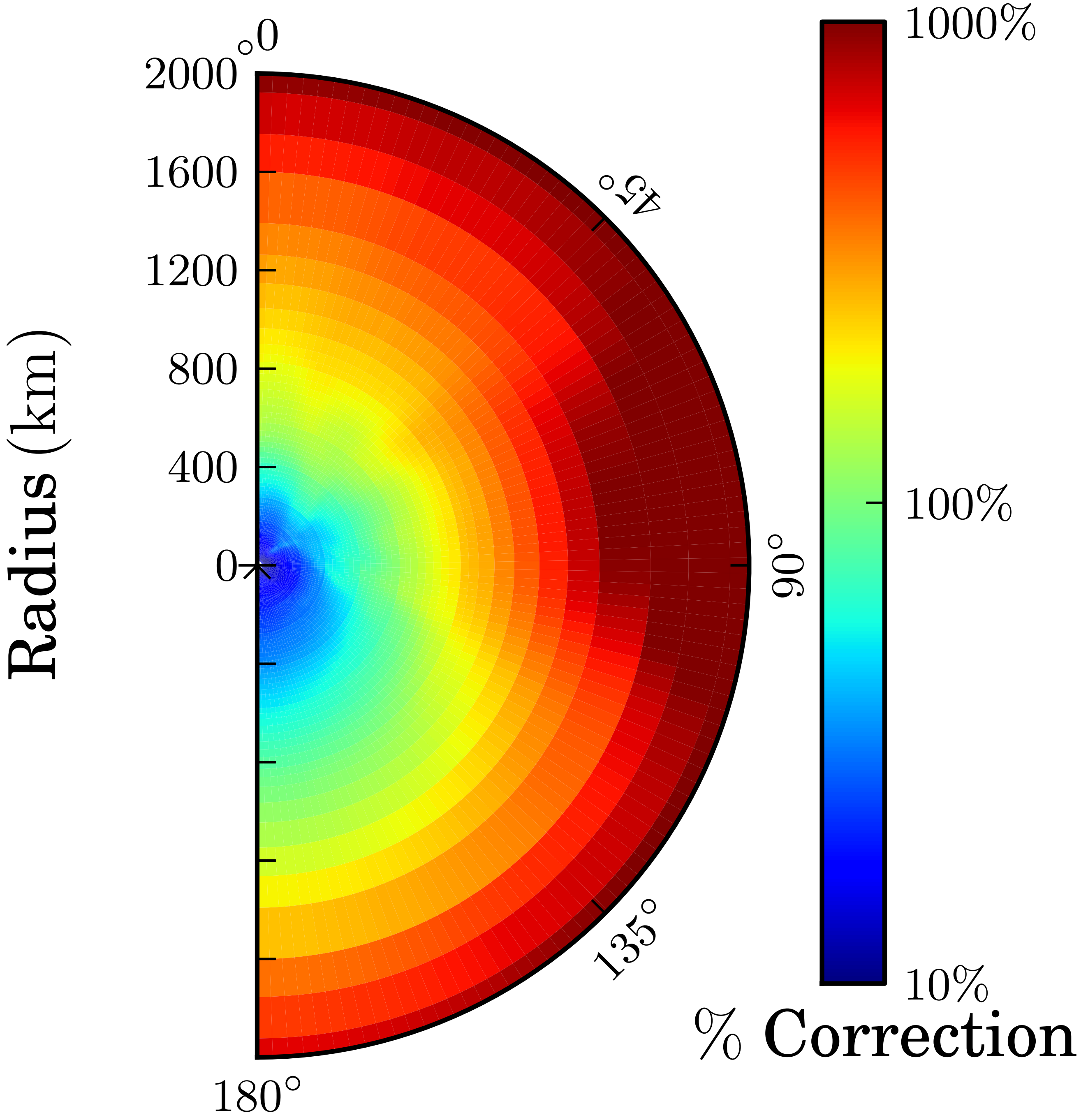


$$\langle 1 - \cos\theta_{\mathrm{ik}} \rangle \approx 1$$

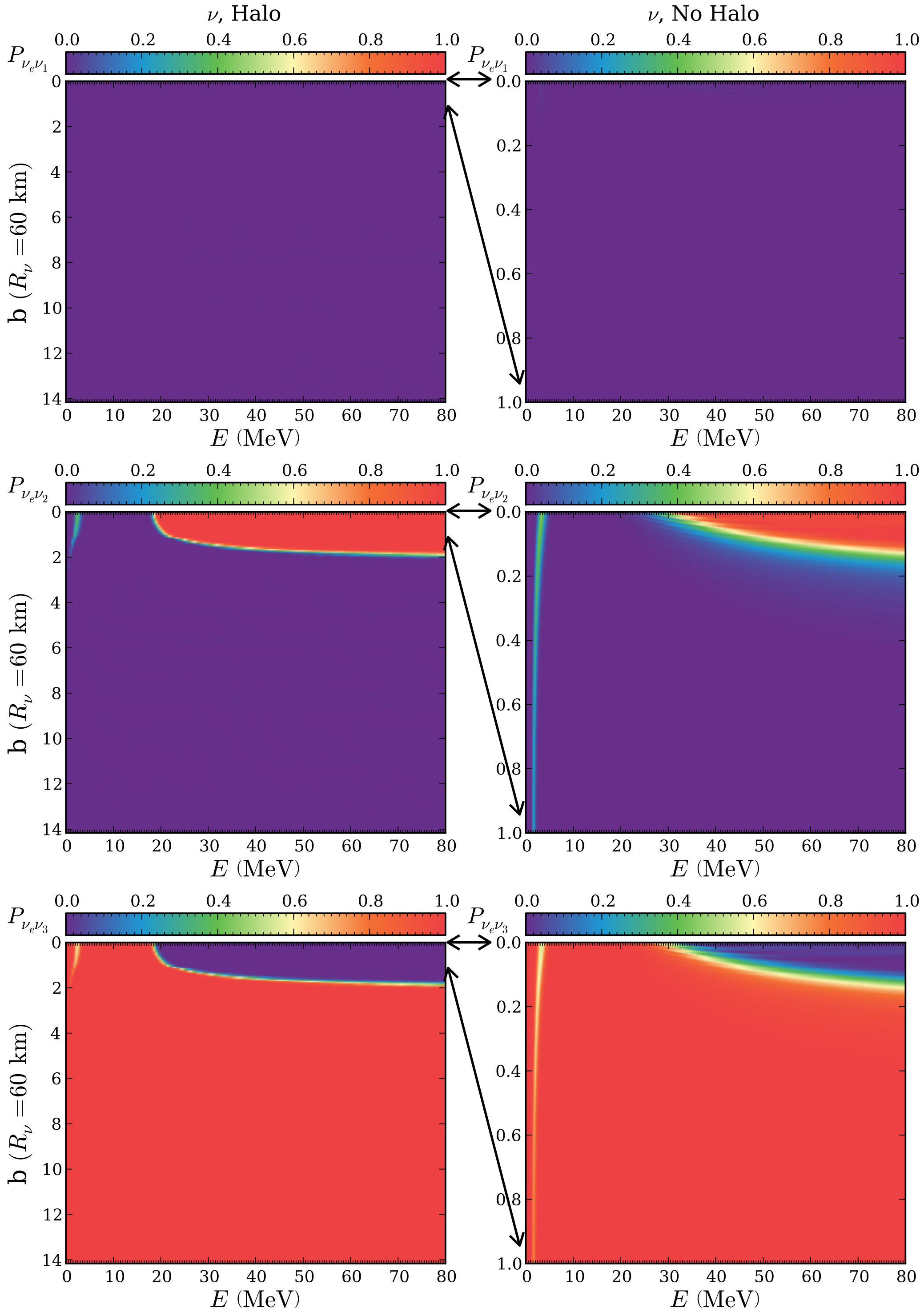
$\sim 10^{-3}$ of all ν's

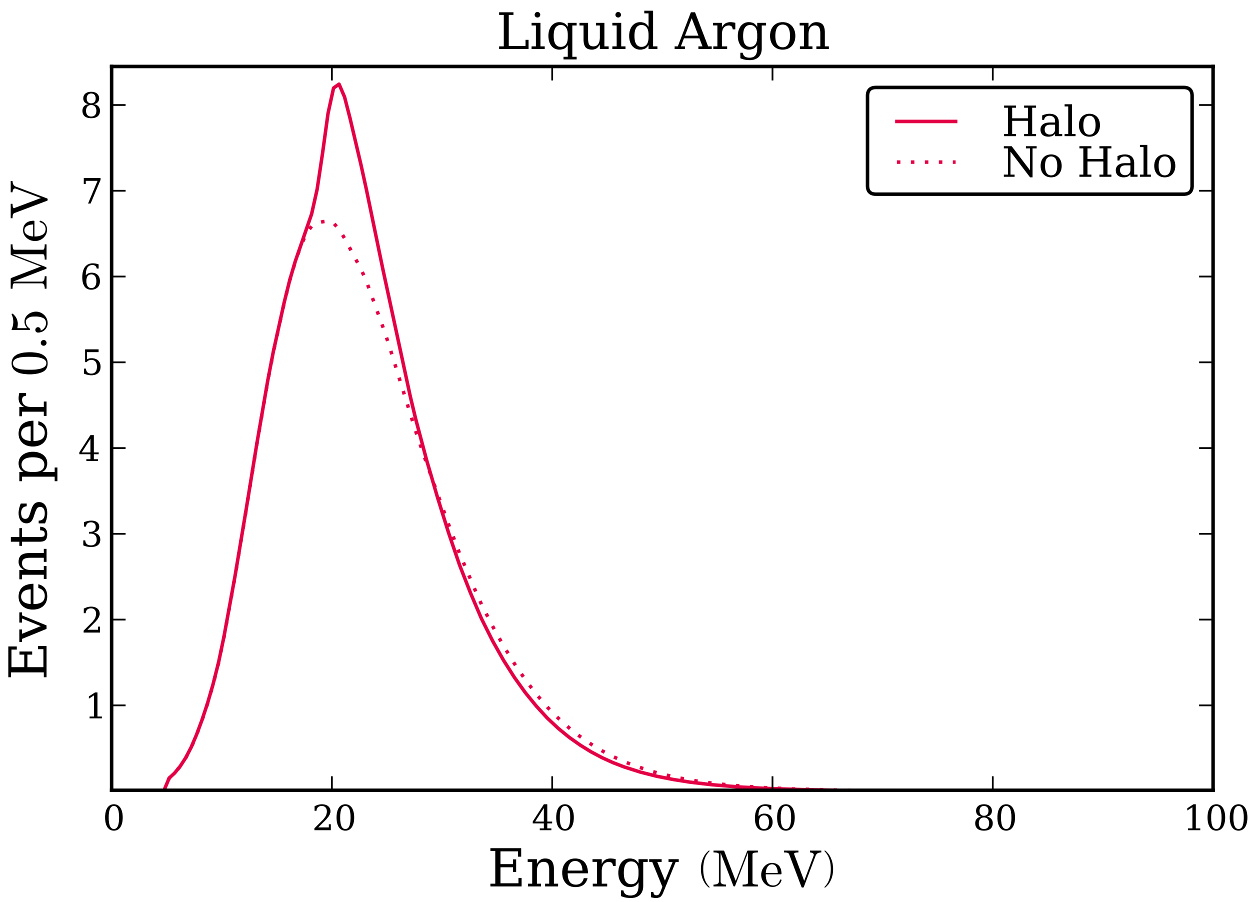
How large is the Halo effect?





Is there an observable effect?





Where does all of this leave us?

- Various detector mediums have their own strengths and, taken as an ensemble, will be able to provide a definite detection of a collective oscillation signal.
- Concrete predictions for observed neutrino signals are still beholden to contentious physics.

Thank you very much!