Title: Neutrino oscillations and the CCSN mechanism

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Abstract:

Question: How can we revive the core-collapse supernova shock?

Answer: ??

1. Increased dimensionality (Nordhaus et al. 2010) may be enough to get robust explosion.

2. May be missing some crucial microphysics which could naturally increase the heating rate?

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Outline:

- Formalism neutrino oscillations
- Neutrino heating in the postshock region
- Influence of collective neutrino oscillations on shock revival + prospects of this mechanism

Neutrino Oscillations

$$|\nu_{\text{mass}}\rangle = U_M\,|\nu_{\text{flavour}}\rangle$$

$$U_M = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

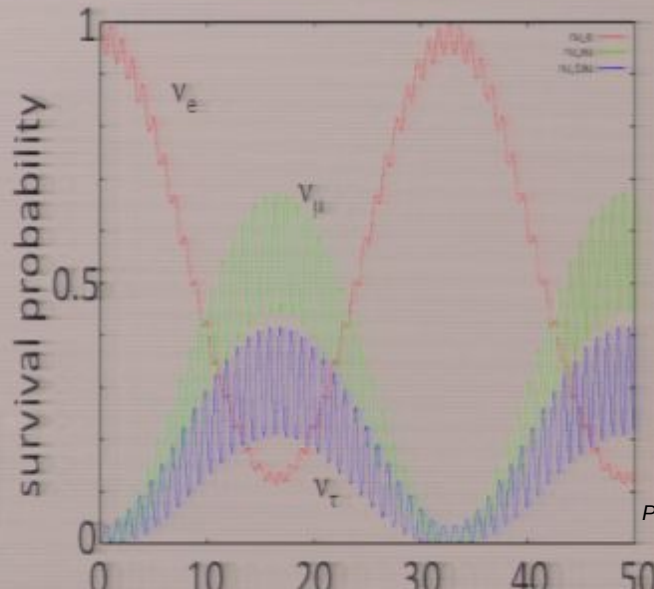
$$|\nu_{\text{mass}}(t)\rangle = e^{-i\mathcal{H}t}\,|\nu_{\text{mass}}\rangle$$

$$|\nu_{\text{flavour}}(t)\rangle = U_M^{-1}\,|\nu_{\text{mass}}(t)\rangle$$

- *Vacuum Oscillations*

$$\begin{pmatrix} |\nu_1(t)\rangle \\ |\nu_2(t)\rangle \\ |\nu_3(t)\rangle \end{pmatrix} =$$

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{-i\Delta m^2_{21}t/2E} & 0 \\ 0 & 0 & e^{-i\Delta m^2_{31}t/2E} \end{pmatrix} \begin{pmatrix} |\nu_1(0)\rangle \\ |\nu_2(0)\rangle \\ |\nu_3(0)\rangle \end{pmatrix}$$



Neutrino Oscillations

- *Matter Oscillations*

  Matter introduces extra potential in Hamiltonian due to forward scattering of electrons and neutrinos, the MSW potential:

$$\mathcal{H}_{\rm matter} = \sqrt{2} G_{\rm F} (N_{e^-} - N_{e^+})$$

- *Collective Oscillations*

  High neutrino densities in the core-collapse supernova environment leads to appreciable neutrino-neutrino forward scattering

$$\mathcal{H}_{\rm collective} = G_{\rm F} \frac{R_{\nu_e}^2}{2r^2 - R_{\nu_e}^2} \int \frac{R_{\nu_e}^2}{r^2} \left[\Phi_{\nu_e} - \Phi_{\bar{\nu}_e}\right] dE$$

interaction angle closes ~$1/r^2$

differential neutrino flux ~$1/r^2$

Neutrino Oscillations

- Hamiltonians give equations of motion of the system

$$\mathcal{H}_{\text{vacuum}} = -\frac{|\Delta m^2_{31}|}{2E} \qquad \mathcal{H}_{\text{matter}} = \sqrt{2} G_{\text{F}} (N_{e^-} - N_{e^+})$$

$$\mathcal{H}_{\text{collective}} = G_{\text{F}} \frac{R^2_{\nu_e}}{2r^2 - R^2_{\nu_e}} \int \frac{R^2_{\nu_e}}{r^2} \left[\Phi_{\nu_e} - \Phi_{\bar{\nu}_e}\right] dE$$

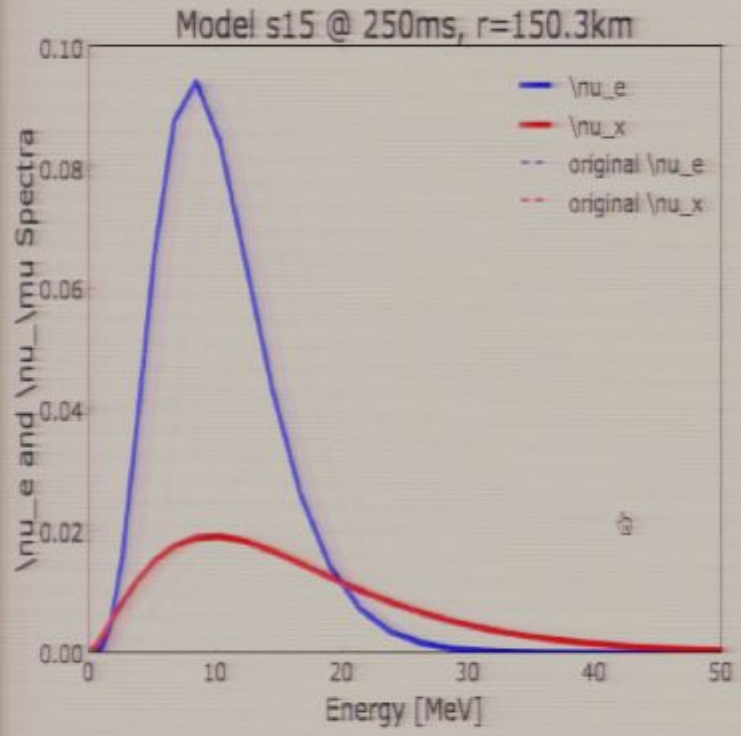
$$\frac{\partial \Phi_\nu}{\partial t} = -\frac{i}{\hbar}\left[+\mathcal{H}_{\text{vacuum}} + \mathcal{H}_{\text{matter}} + \mathcal{H}_{\text{collective}}, \Phi_\nu\right]$$

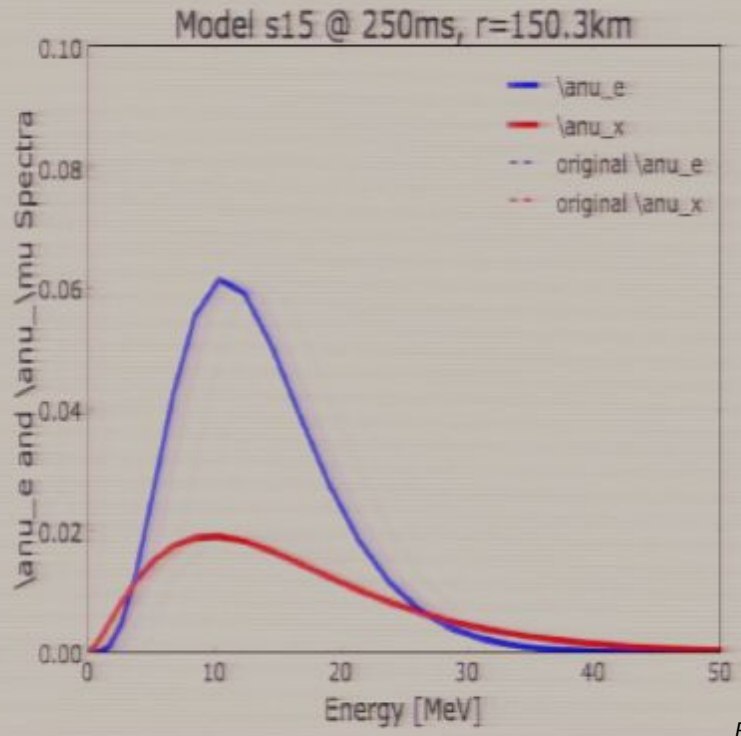
$$\frac{\partial \Phi_{\bar{\nu}}}{\partial t} = -\frac{i}{\hbar}\left[-\mathcal{H}_{\text{vacuum}} + \mathcal{H}_{\text{matter}} + \mathcal{H}_{\text{collective}}, \Phi_{\bar{\nu}}\right]$$

- Evolution is complicated due to non-linear coupling of neutrino and antineutrino fields

Neutrino Evolution

- As an example of oscillations, here is a movie showing the evolution of the ν spectra from the ν-sphere out in radius
- Will describe simulations in more detail





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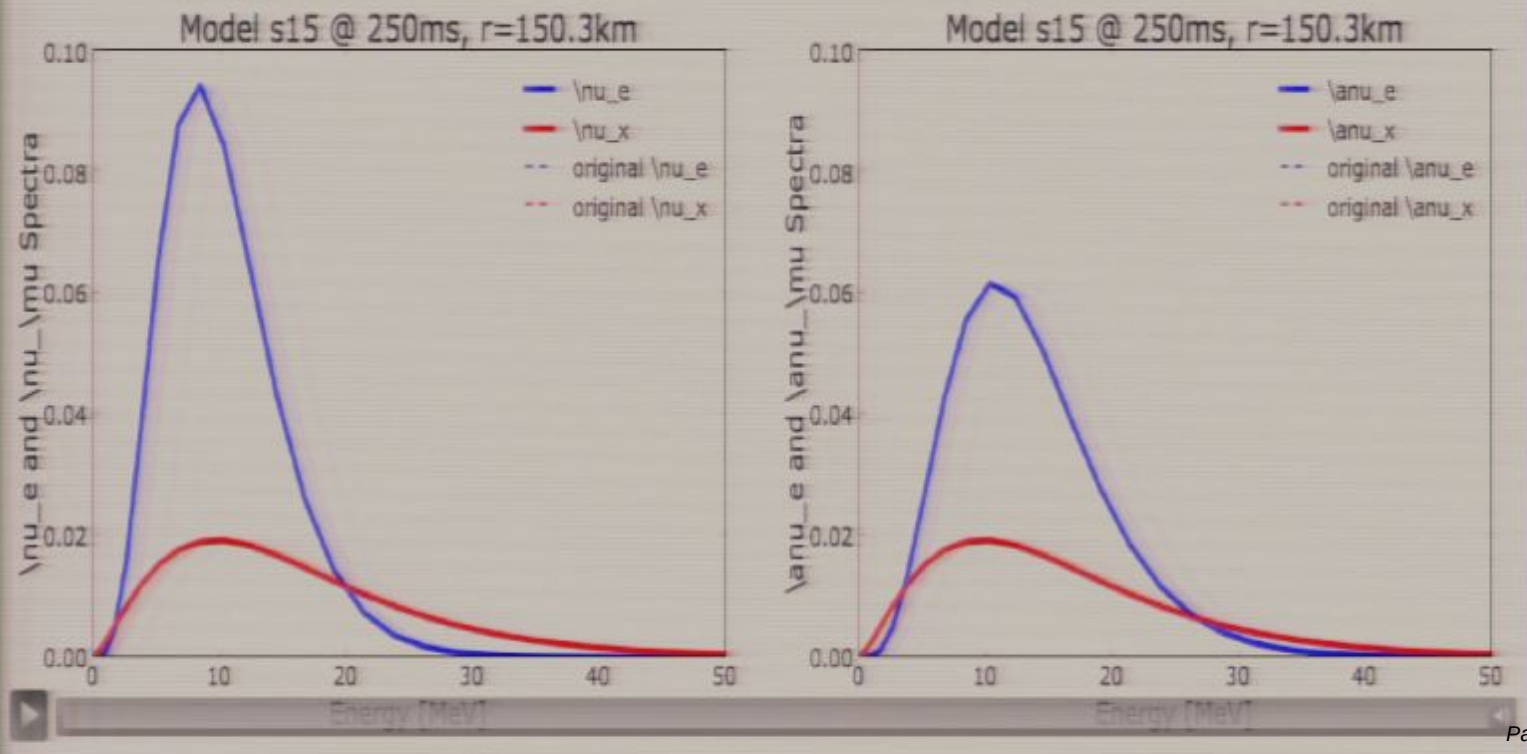

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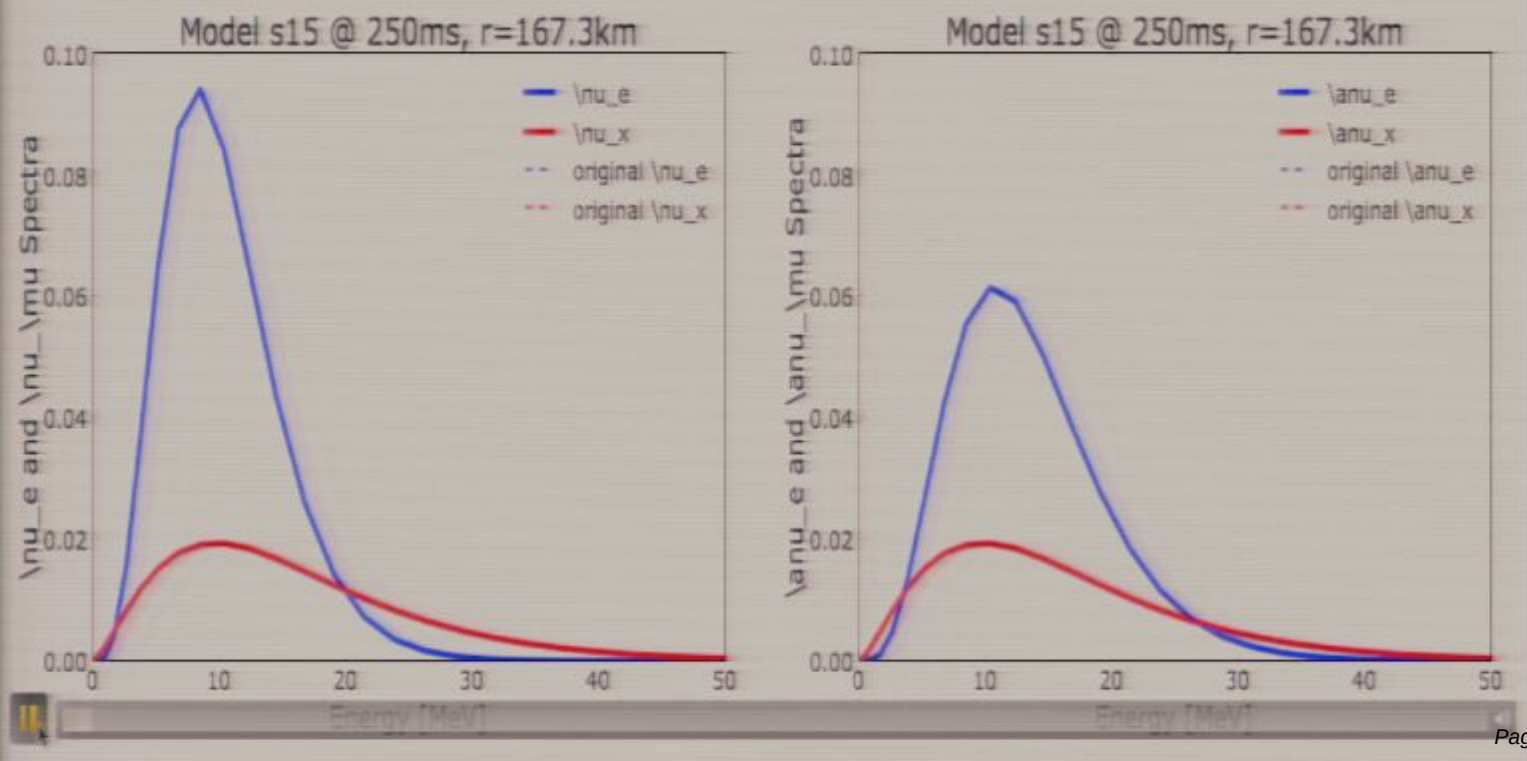

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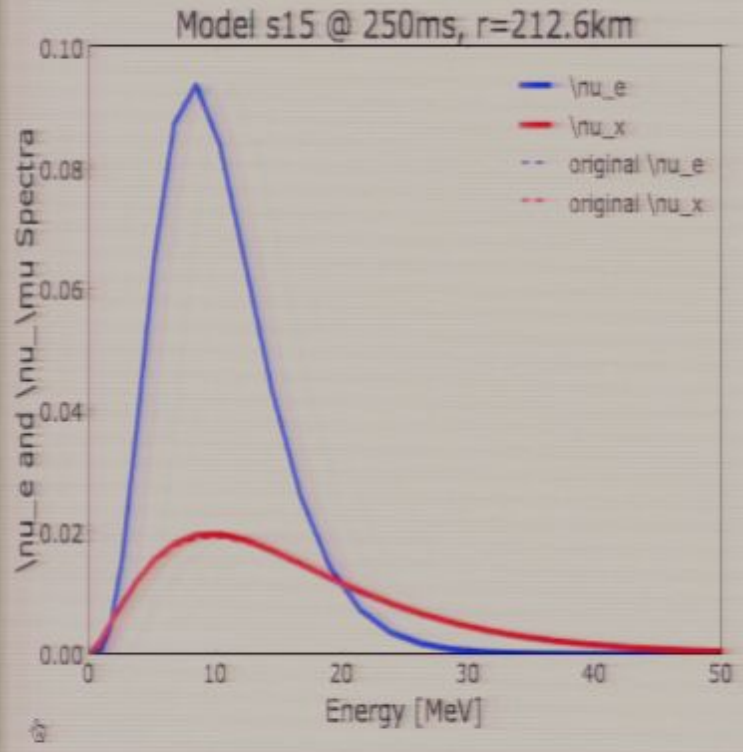

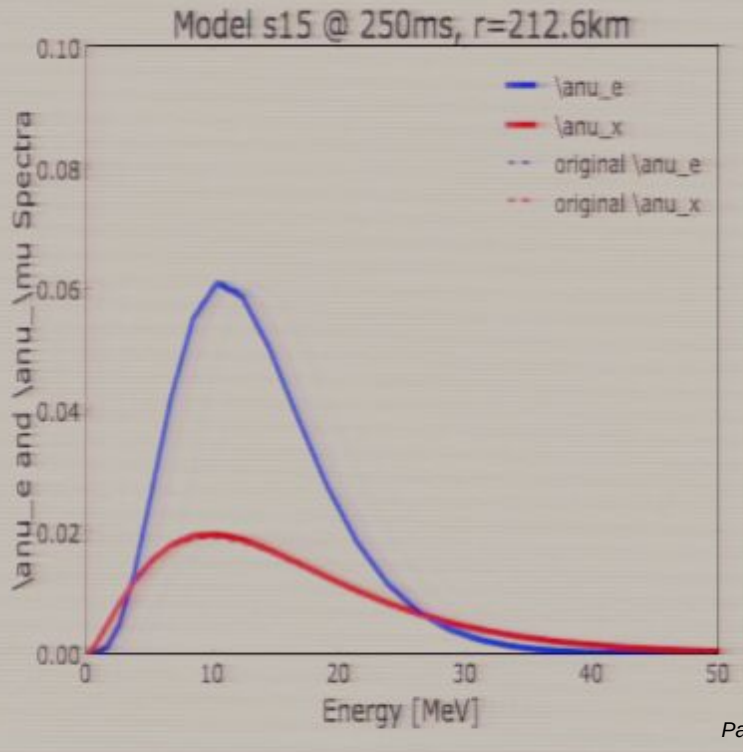

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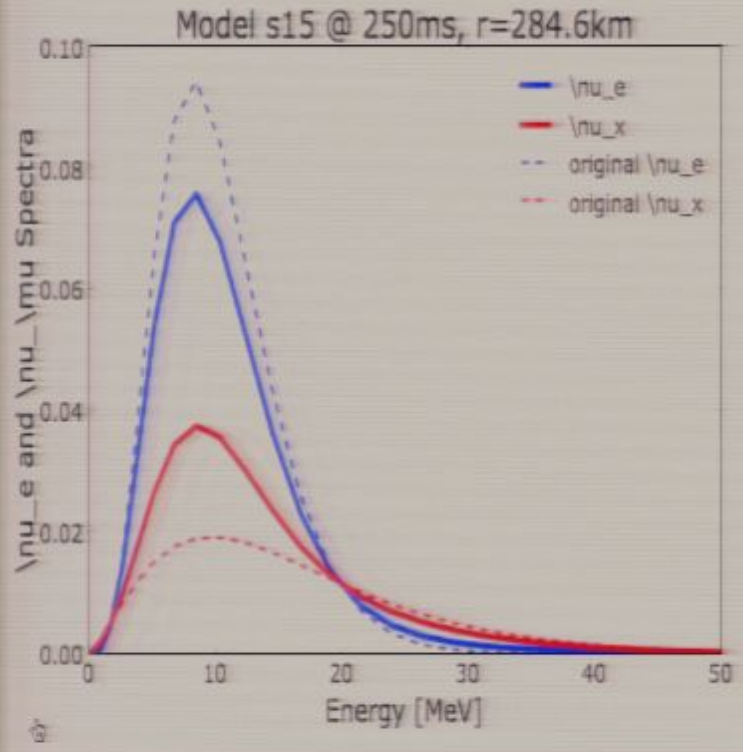

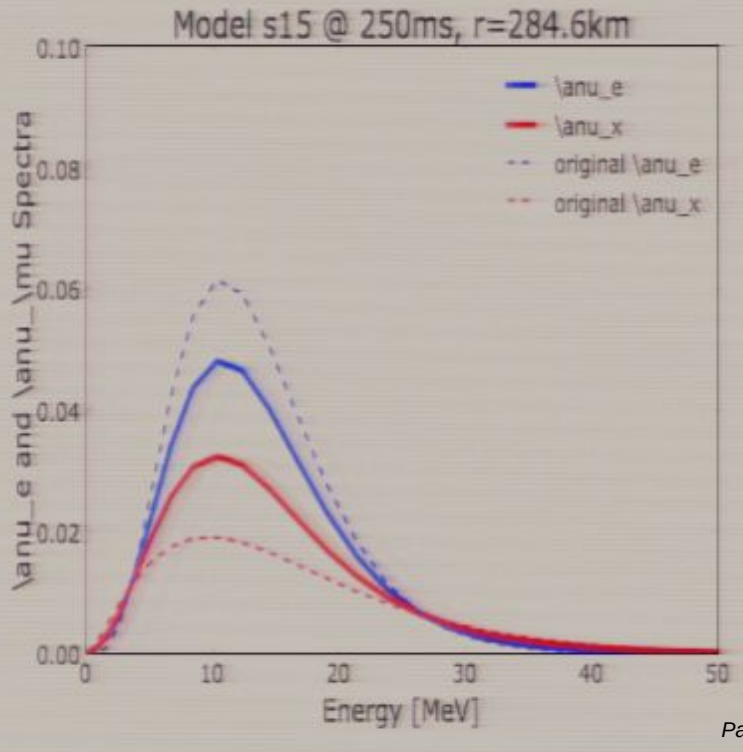

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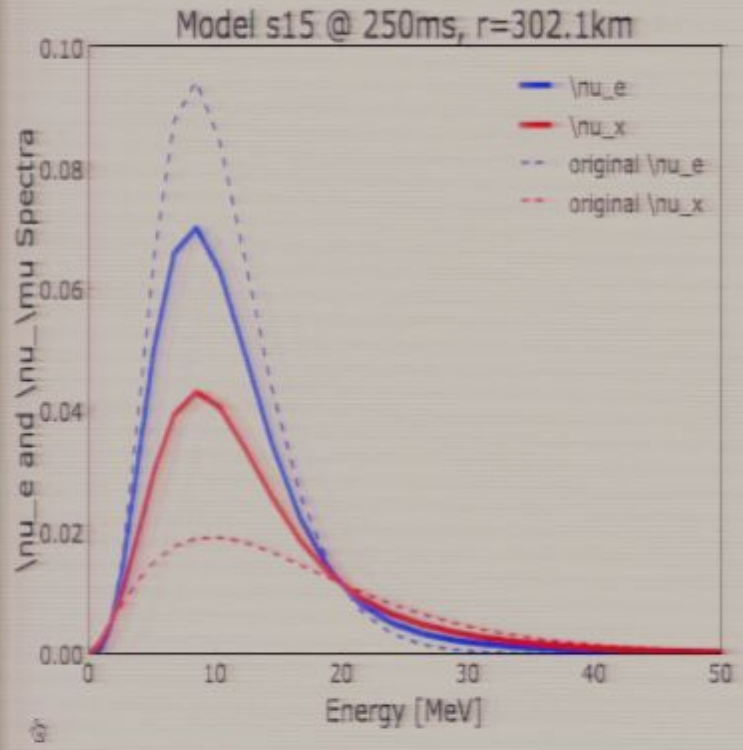

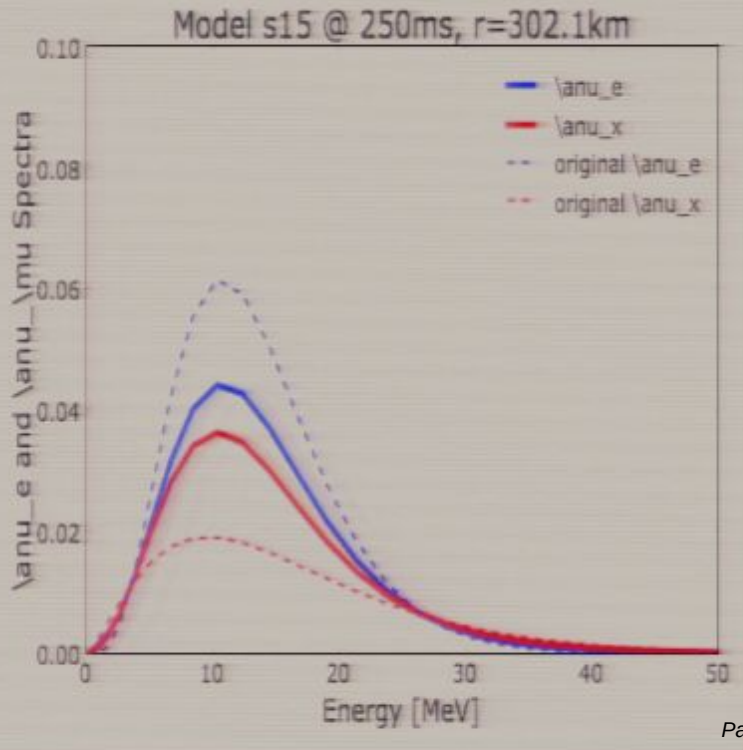

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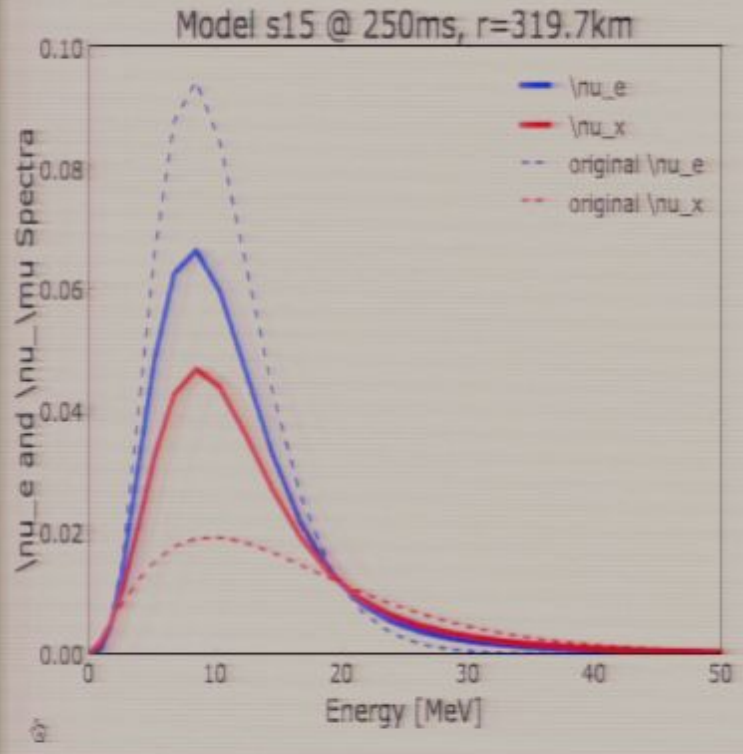

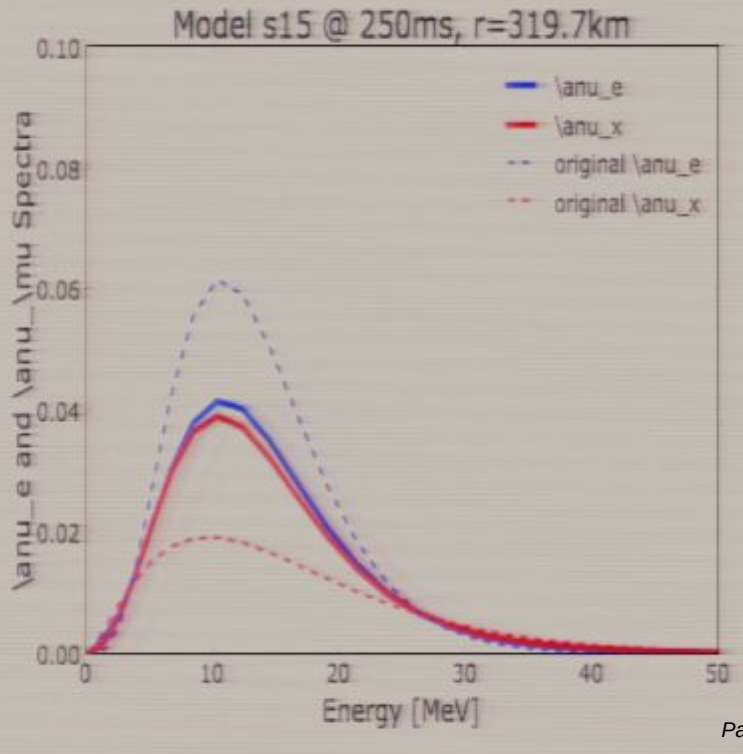

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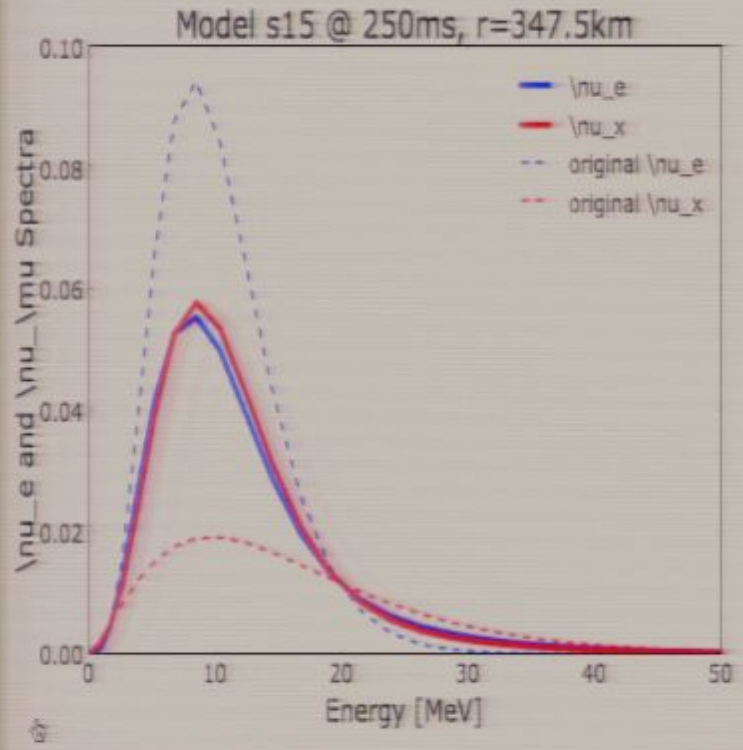

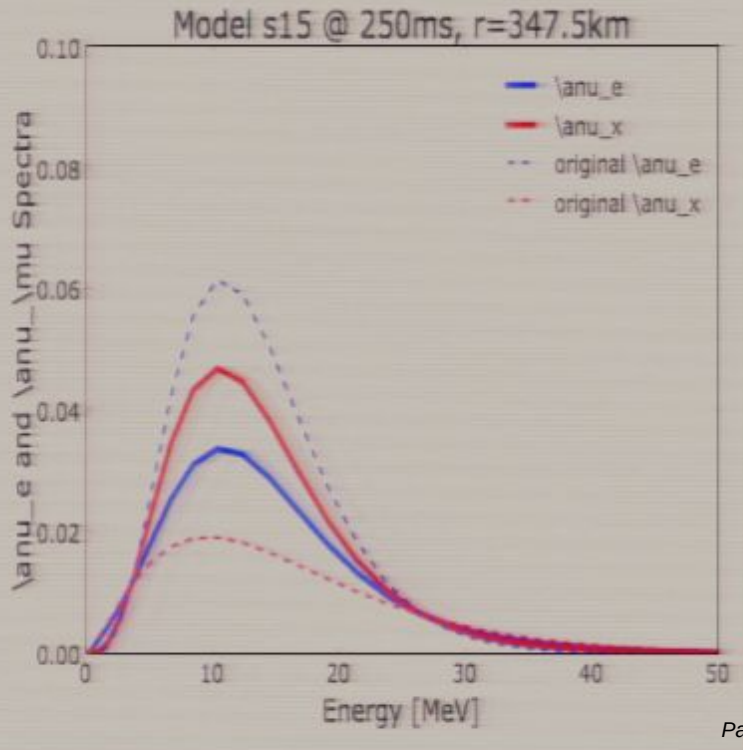

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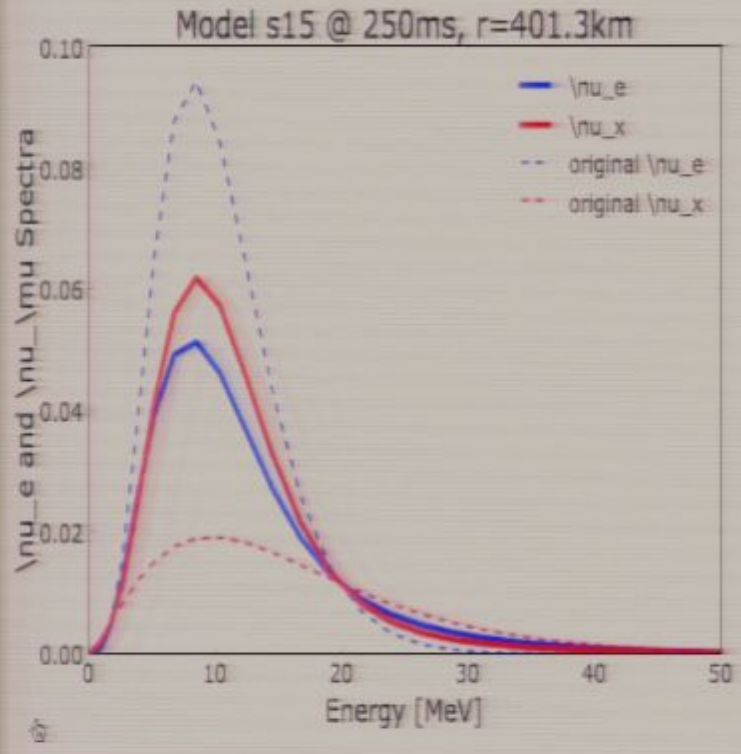

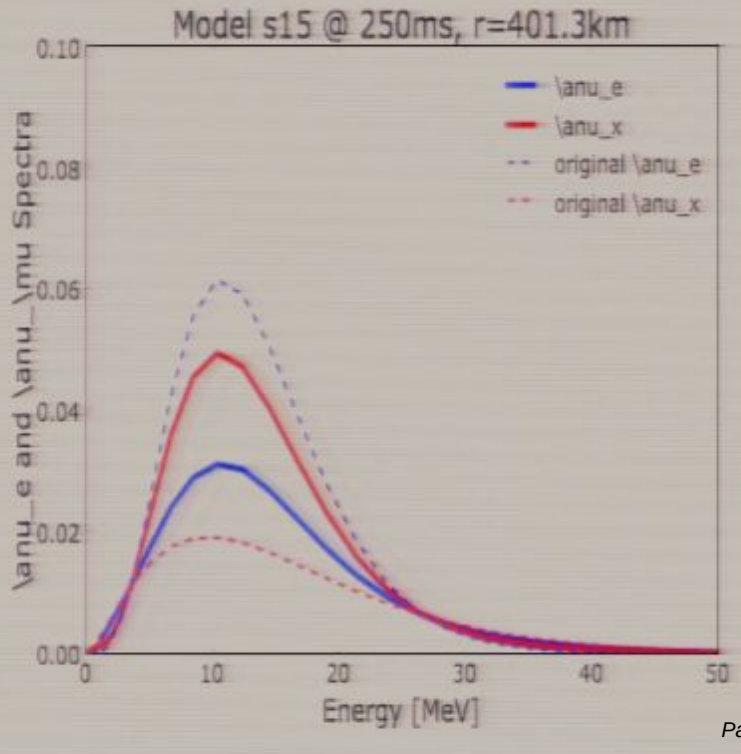

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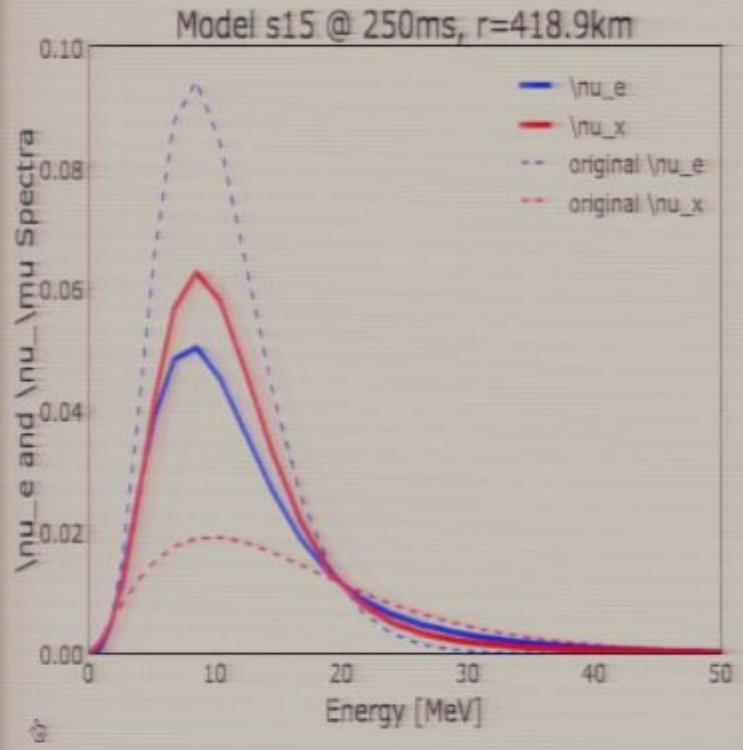

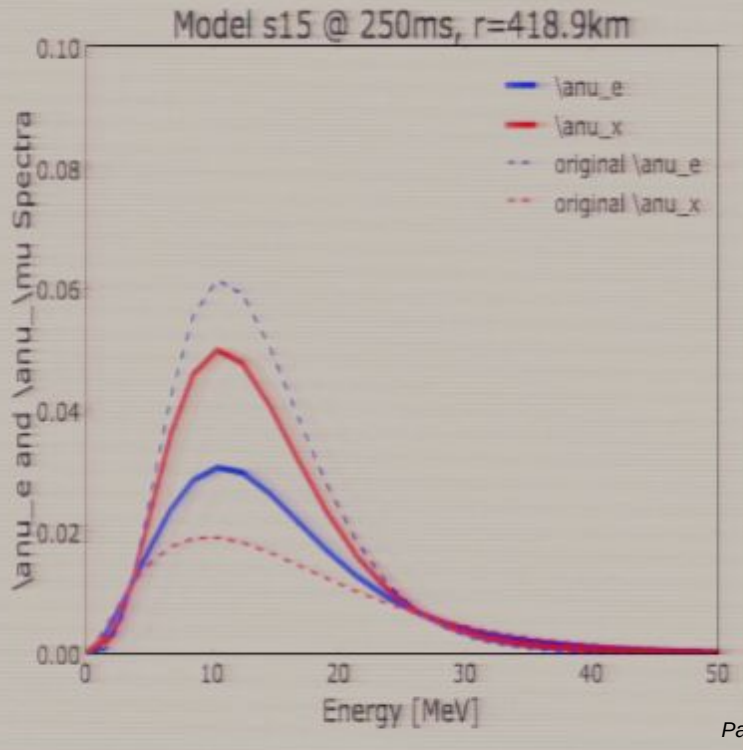

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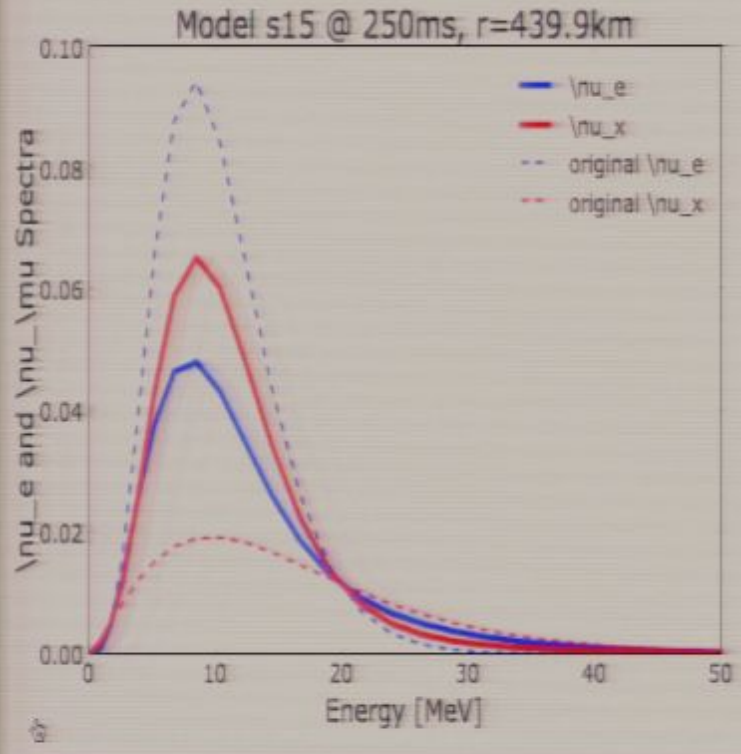

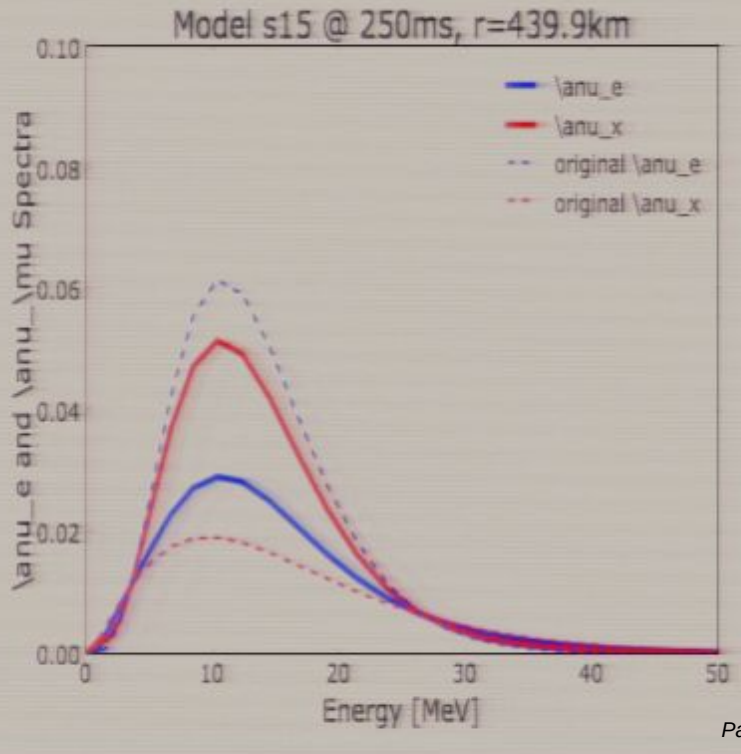

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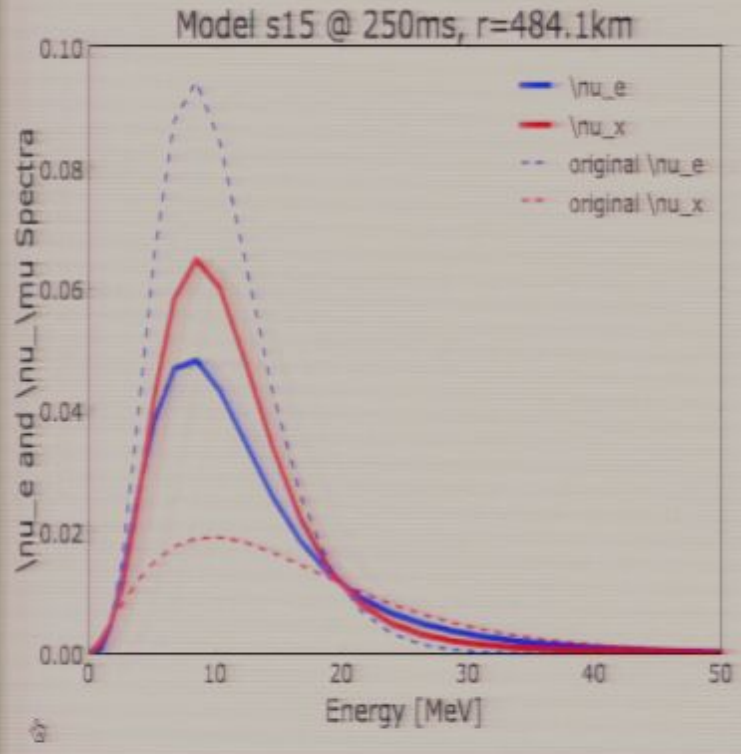

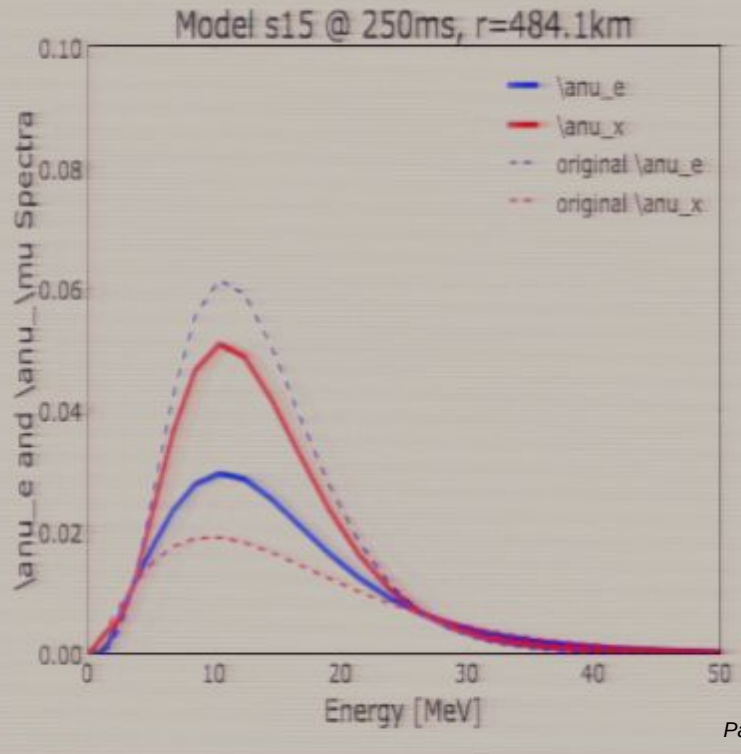

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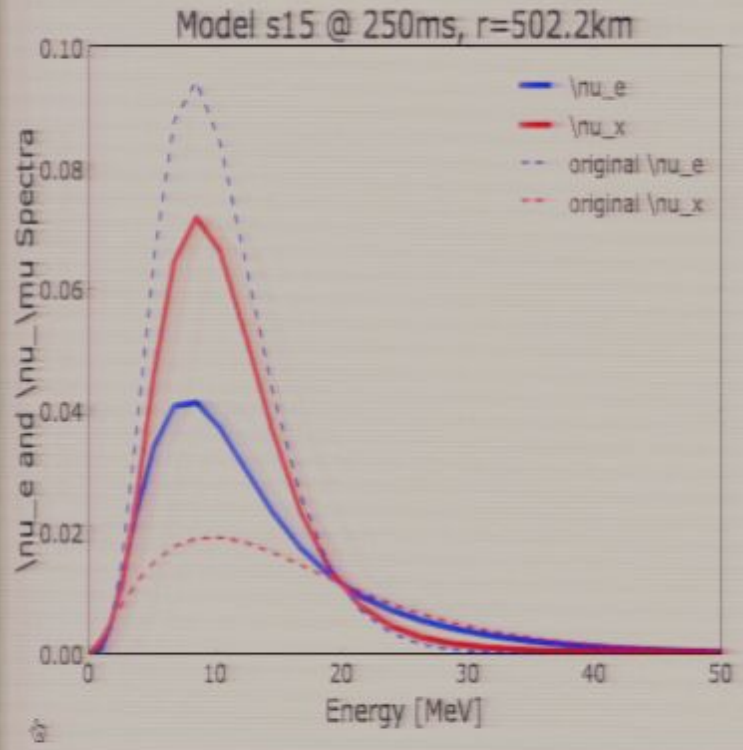

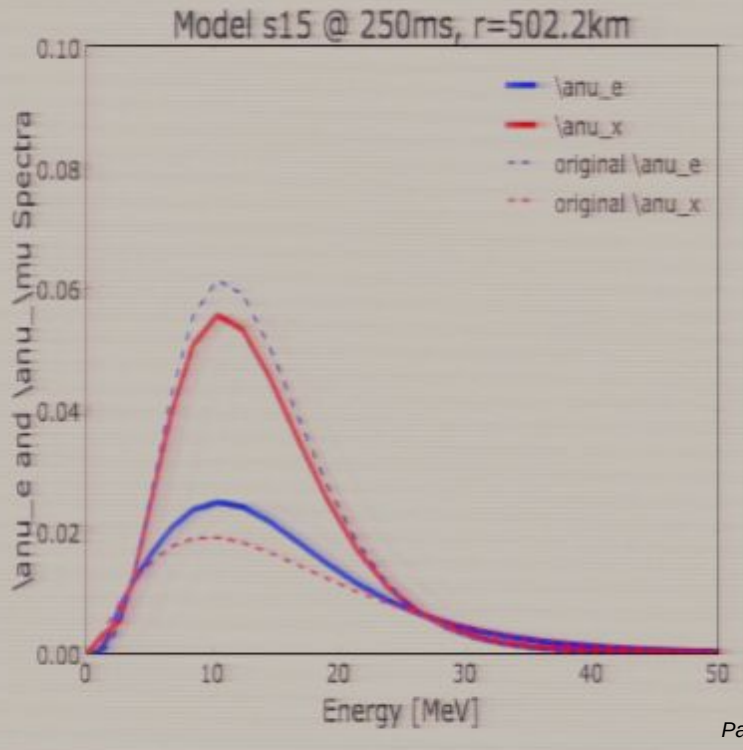

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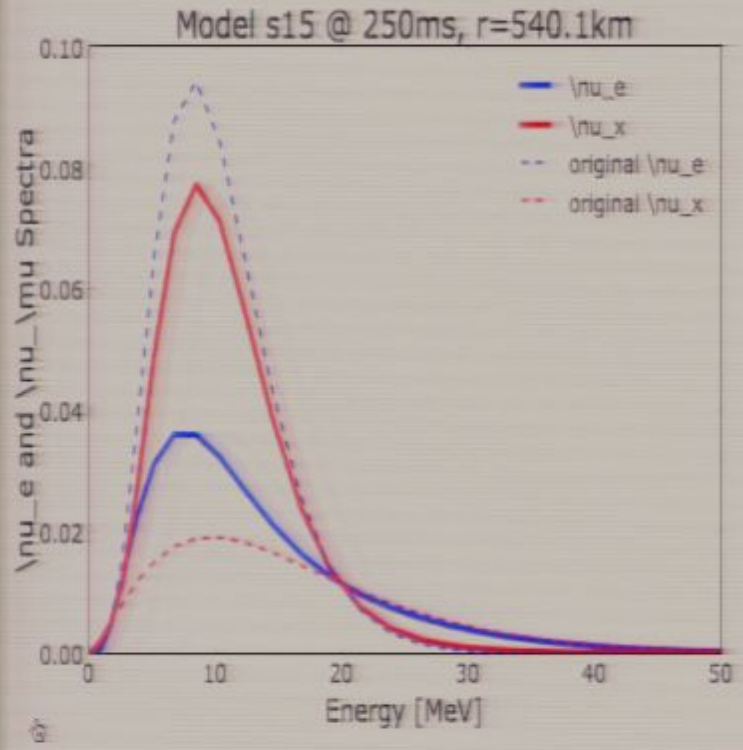

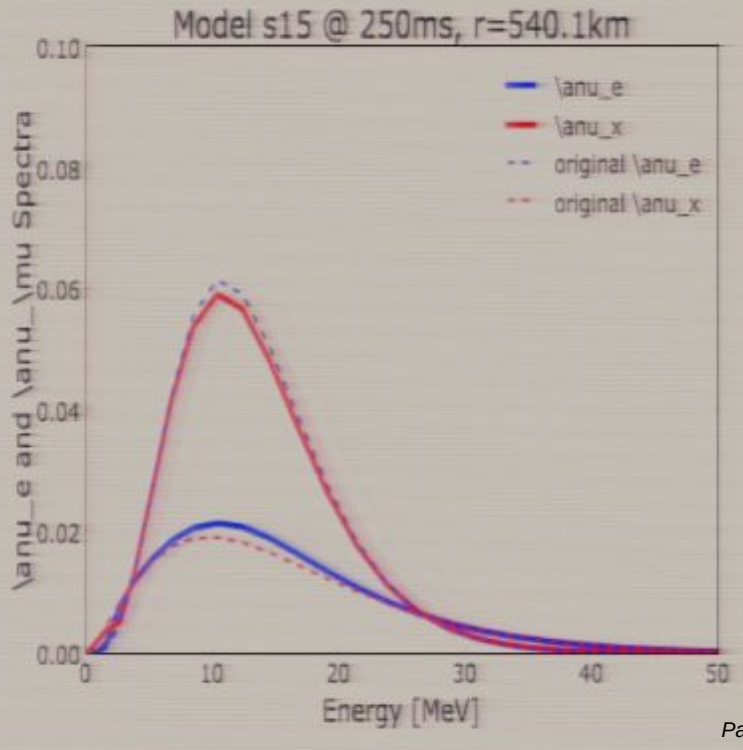

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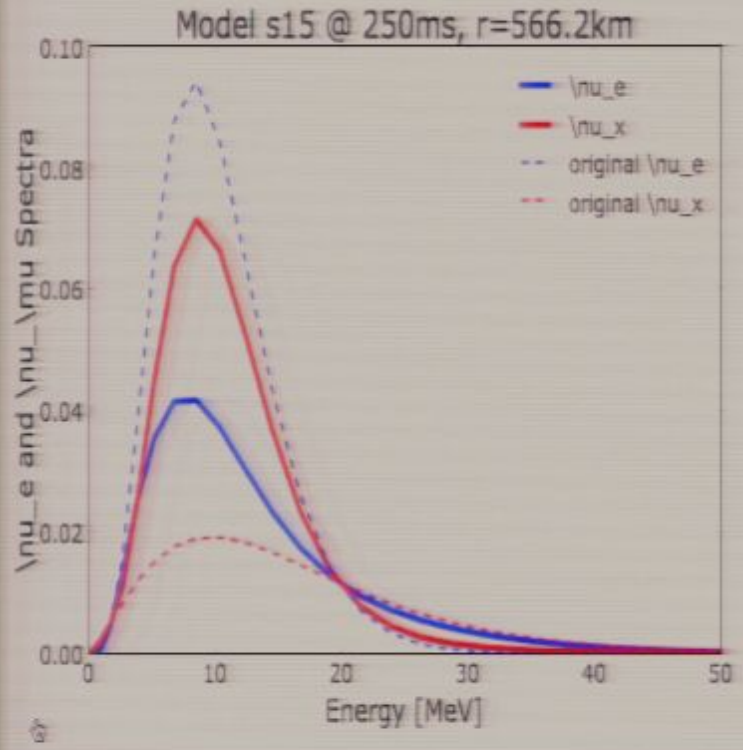

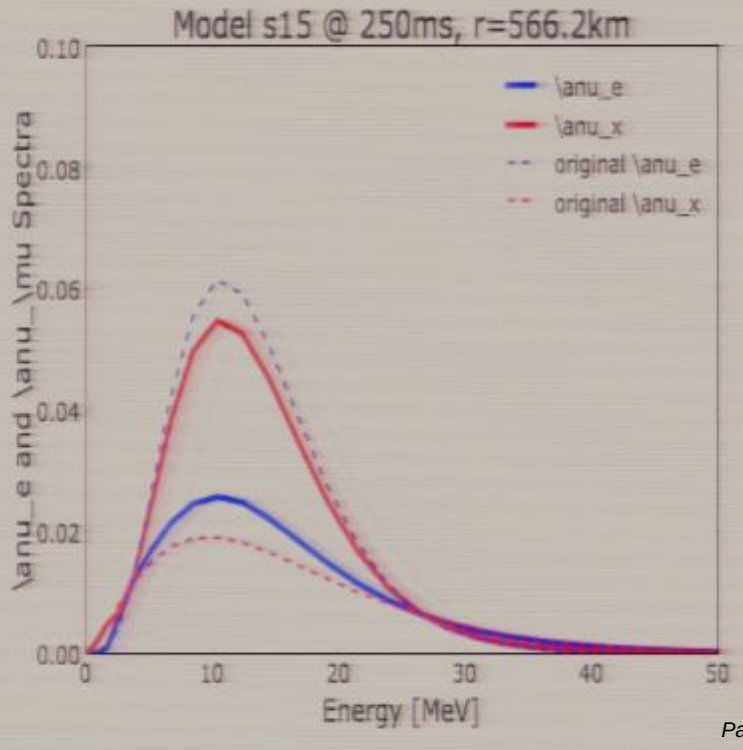

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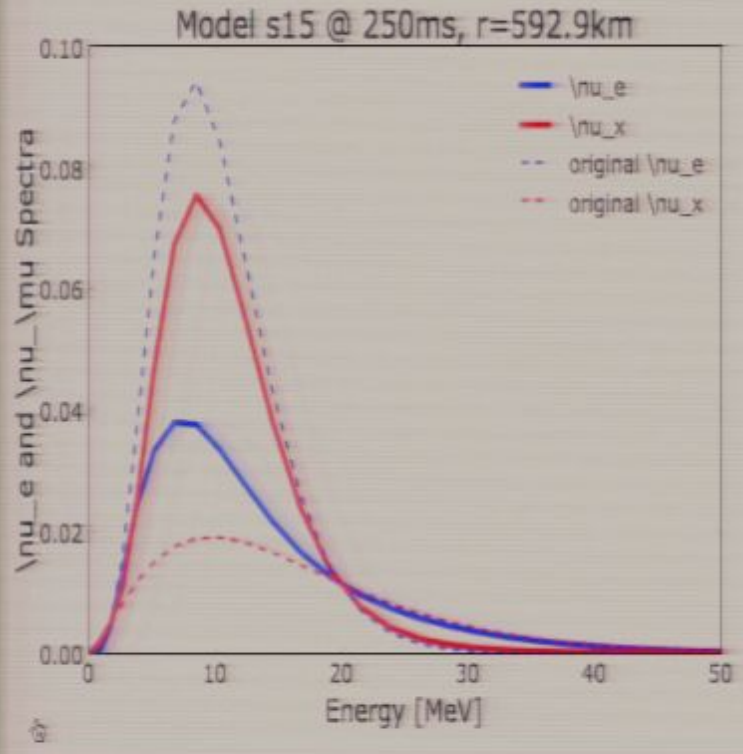

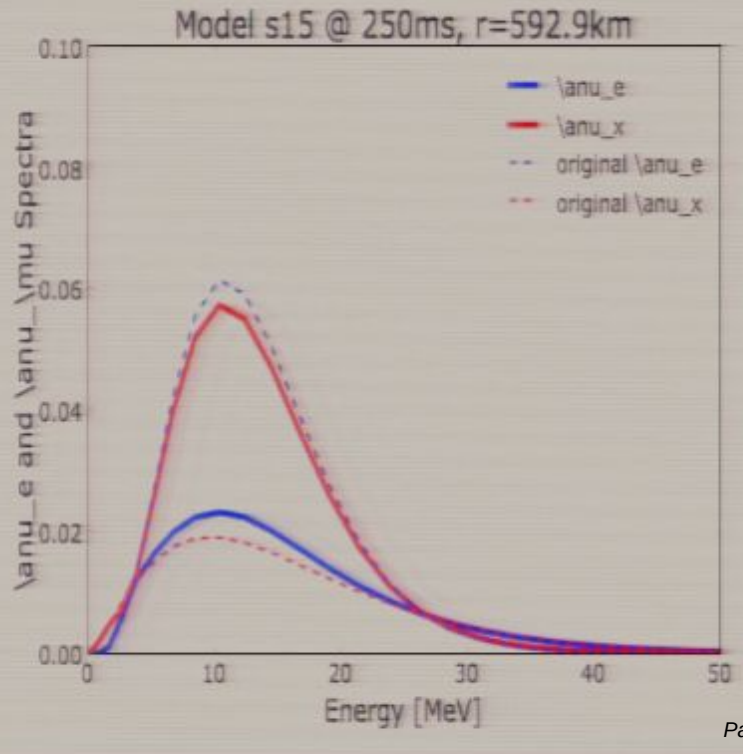

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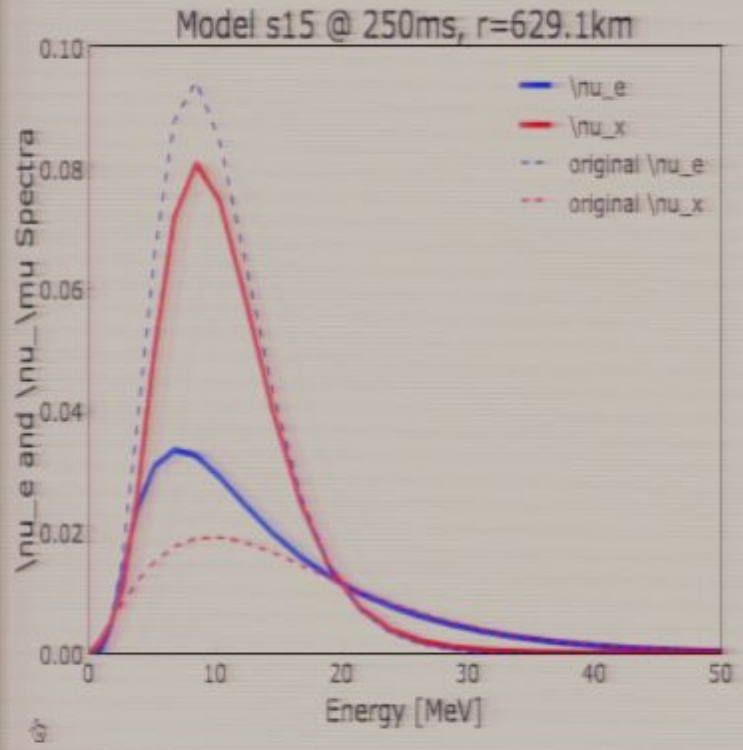

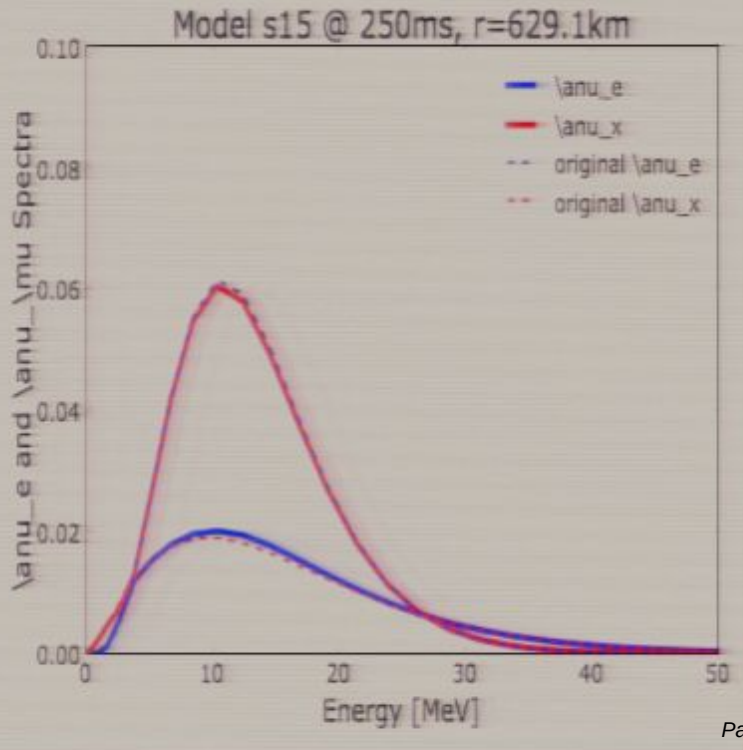

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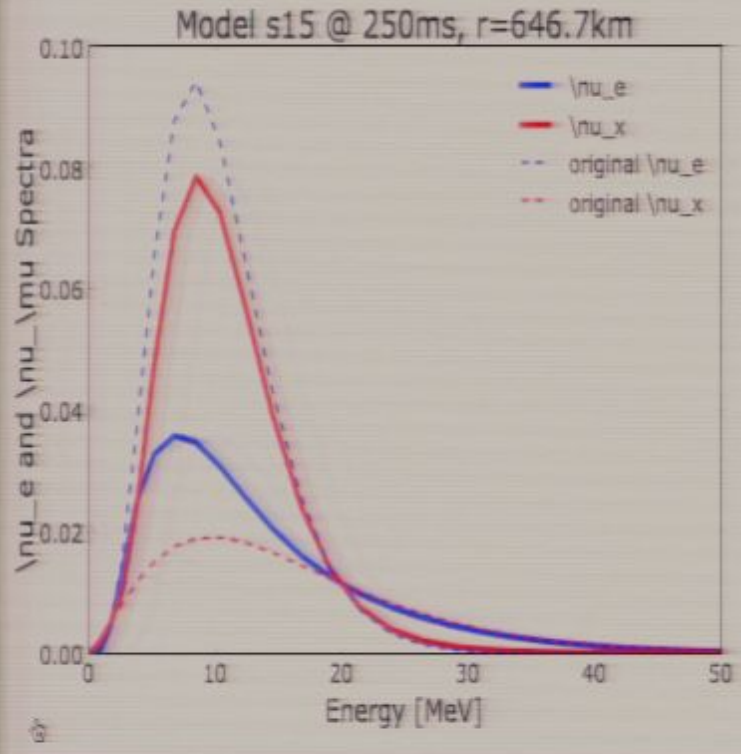

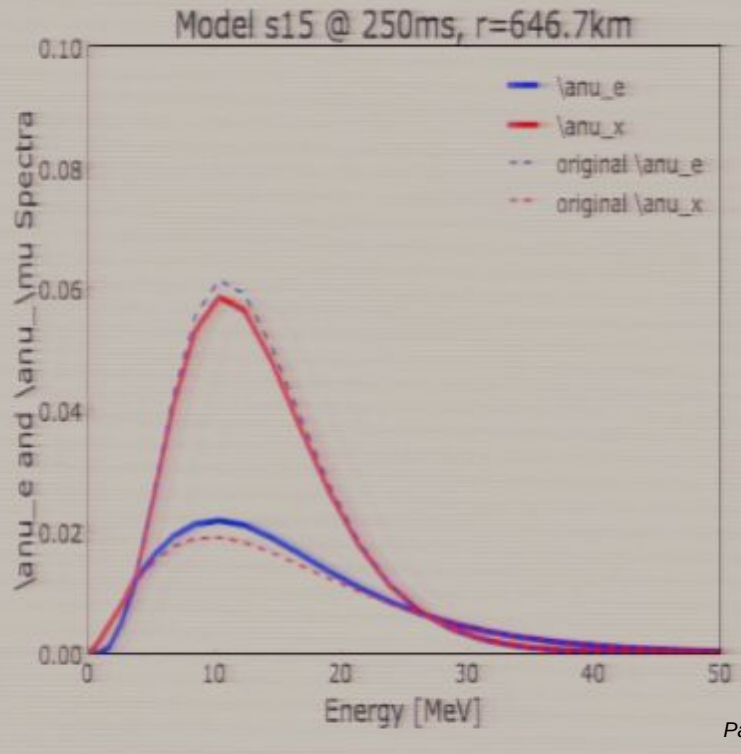

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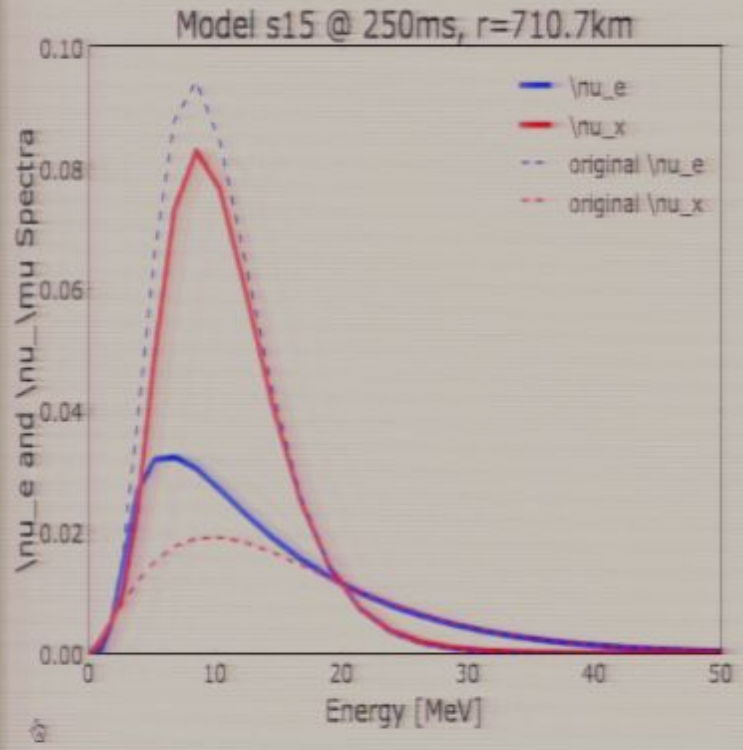

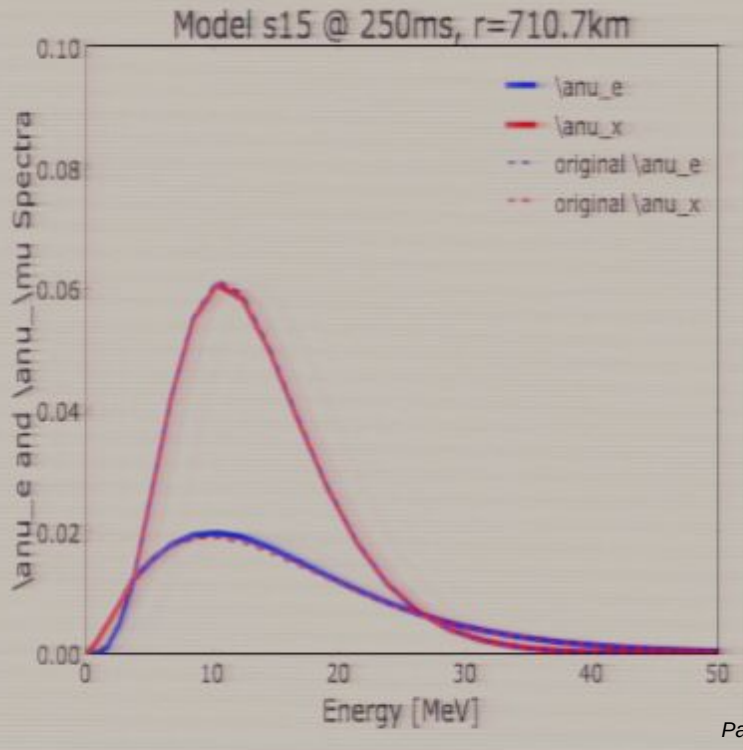

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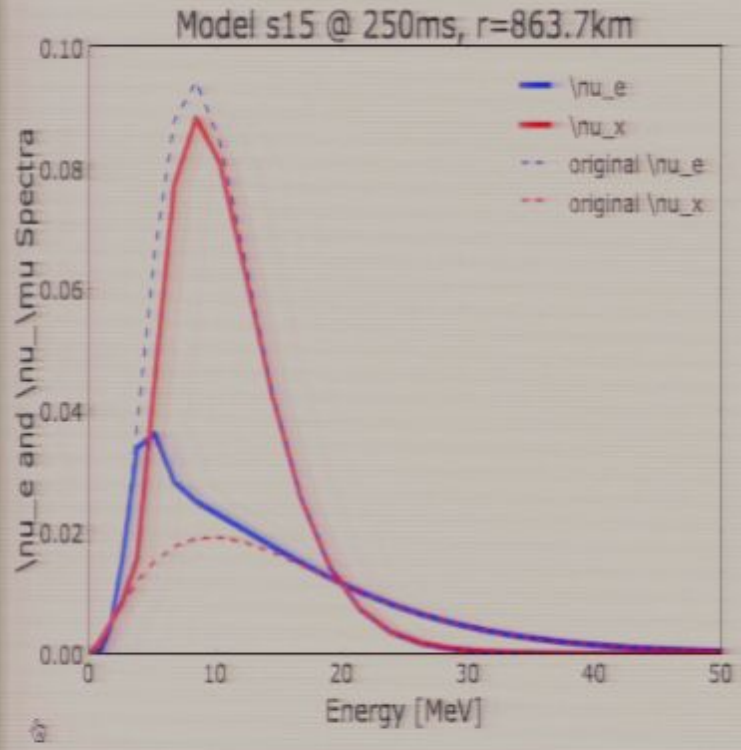

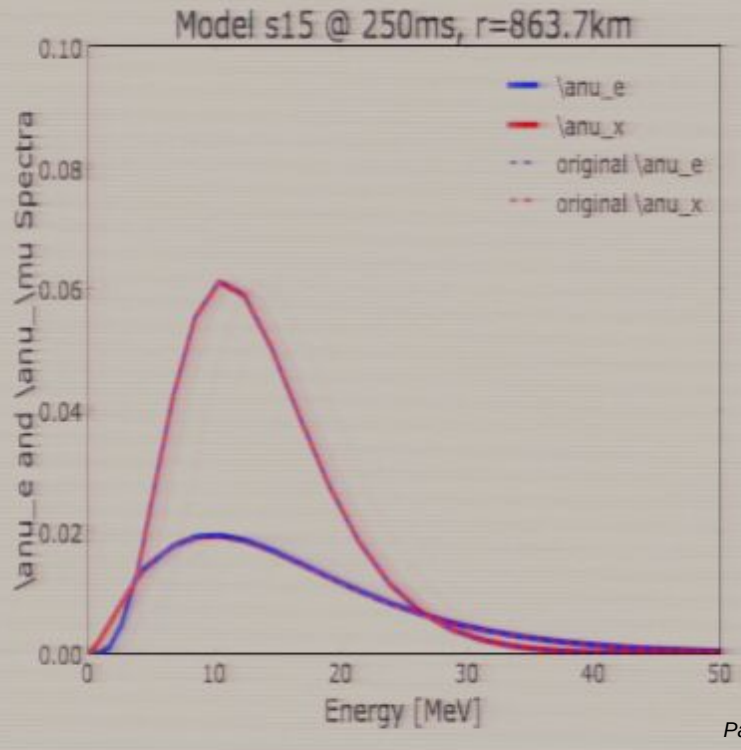

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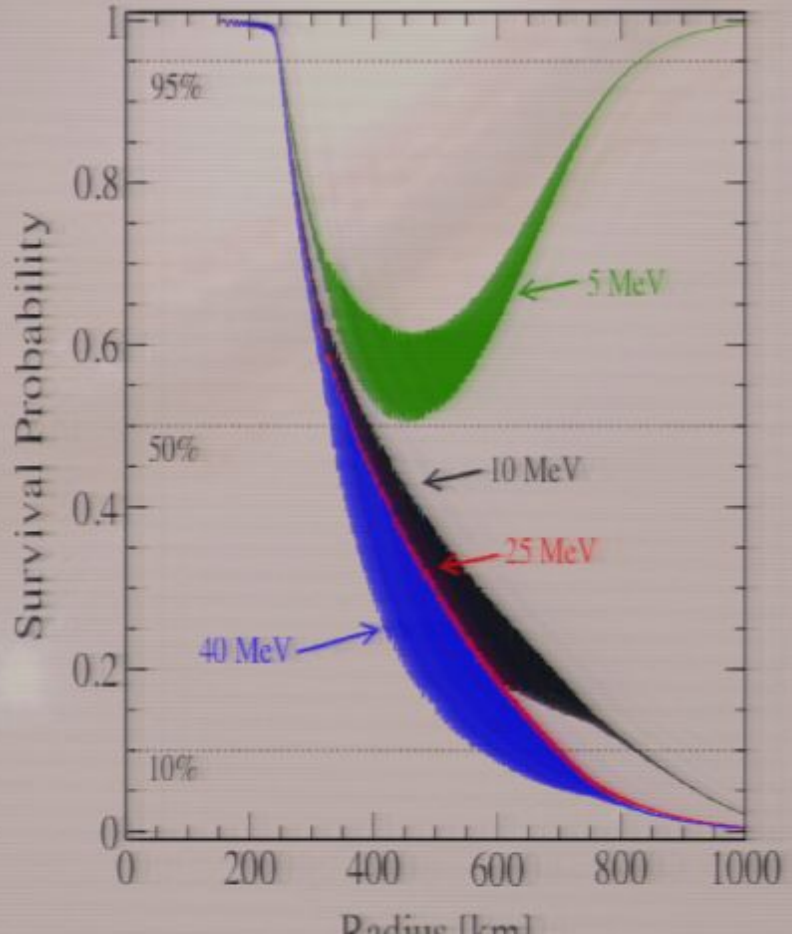
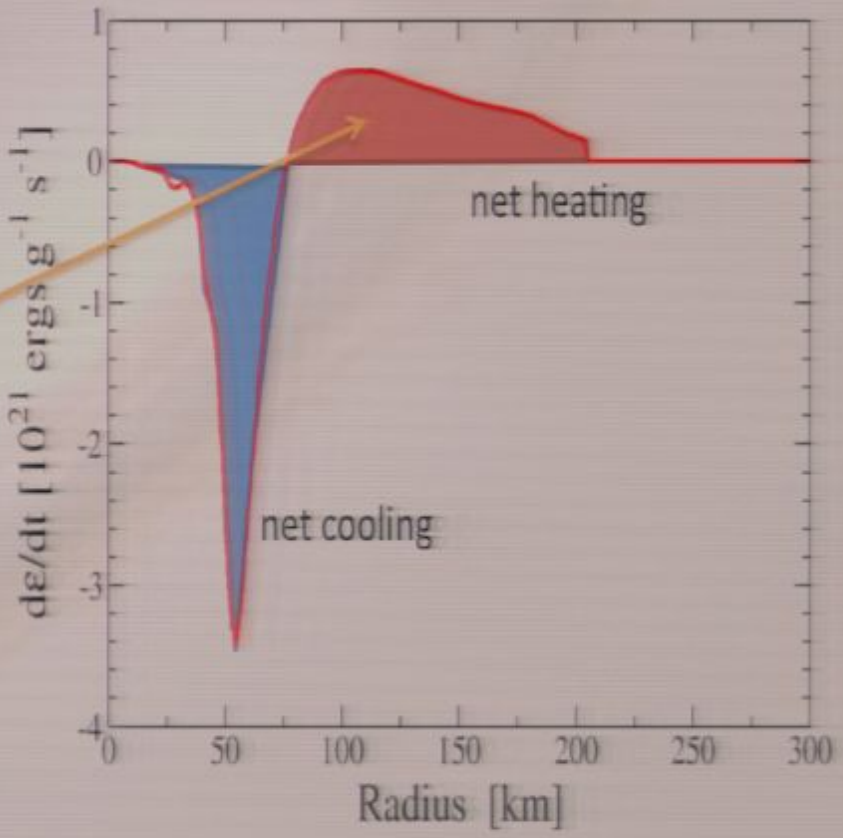


Theory of Neutrino Heating

- Neutrinos diffusing from core have a net energy deposition in the postshock region, the so called `gain region'
- The neutrino mechanism works by having sufficient heating in the gain region to reenergize the shock



$$\mathcal{H} = \sum_{\nu_e,\bar{\nu}_e} \int_{r_g}^{r_s} dr\, 4\pi r^2\, n_i \int_0^{\infty} d\epsilon\, \sigma_{\nu_i}(\epsilon)\, \frac{\epsilon d\Phi_{\nu_i}}{d\epsilon}$$

$$\sim \hat{\sigma}\left[\langle \epsilon_{\nu_e}^2 \rangle \mathcal{L}_{\nu_e} c_N + \langle \epsilon_{\bar{\nu}_e}^2 \rangle \mathcal{L}_{\bar{\nu}_e} c_P\right]$$

Exploratory simulations with VULCAN/2D

Livne, E. 1993, Burrows, A. et al. 2006

- Use 11.2 Msun progenitor from Woosley et al. 2002 and the Shen, H. et al. 1998 EOS
- Extract neutrino spectra at ν-sphere and run through dynamical neutrino evolution taking into account collective oscillations

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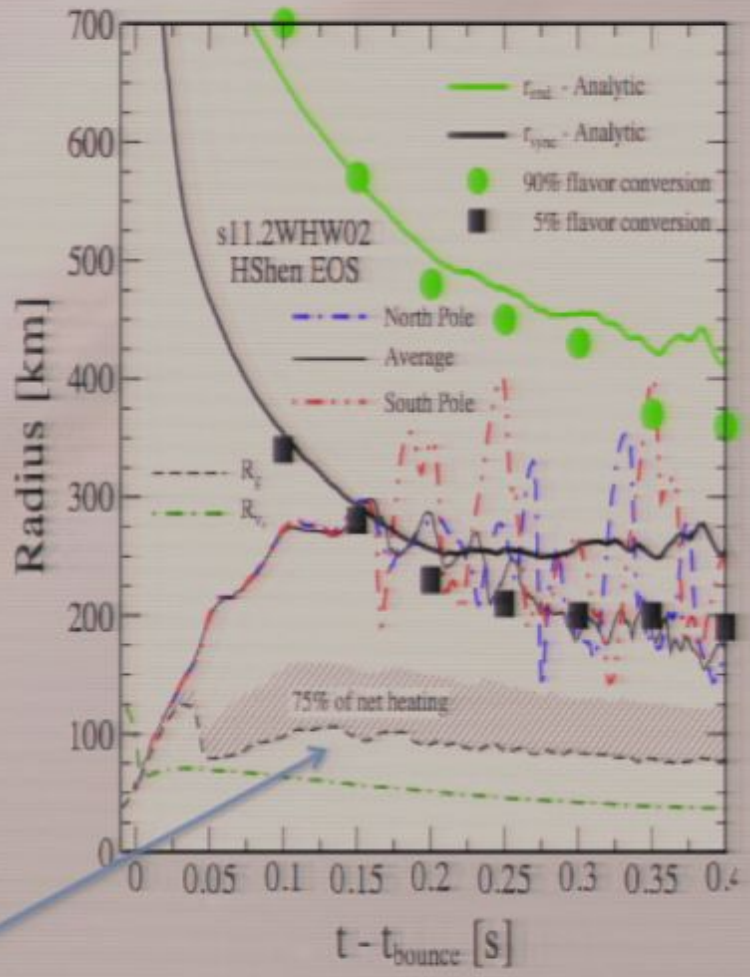
- Even though oscillations being inside shock, not complete until well outside.
- Significant heating will occur only if oscillations occur before gain radius



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The Role of Collective Neutrino Flavor Oscillations in Core-Collapse Supernova Shock Revival

arXiv:1106:1167, submitted to PRD

Evan O'Connor
with Basudeb Dasgupta & Christian Ott
TAPIR, Caltech
MICRA2011, PI

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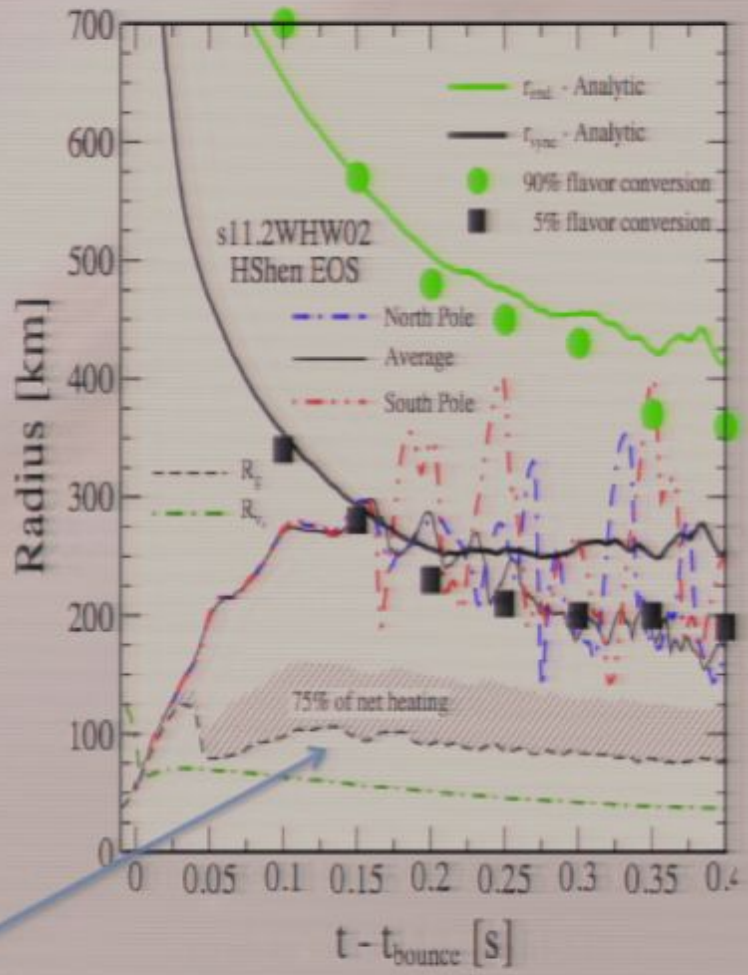

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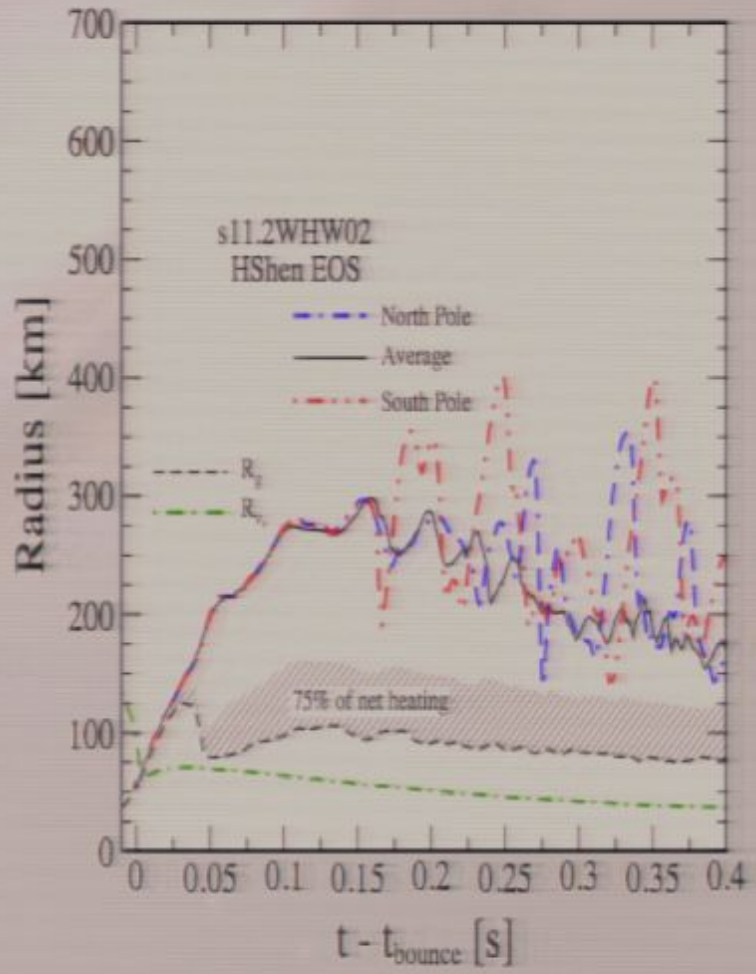

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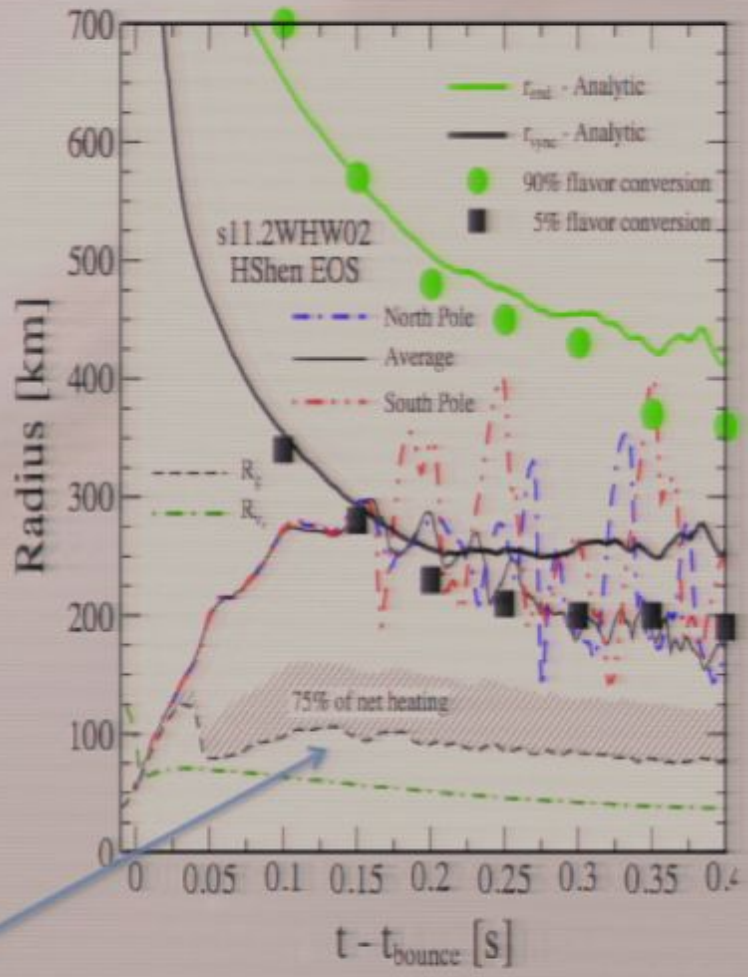

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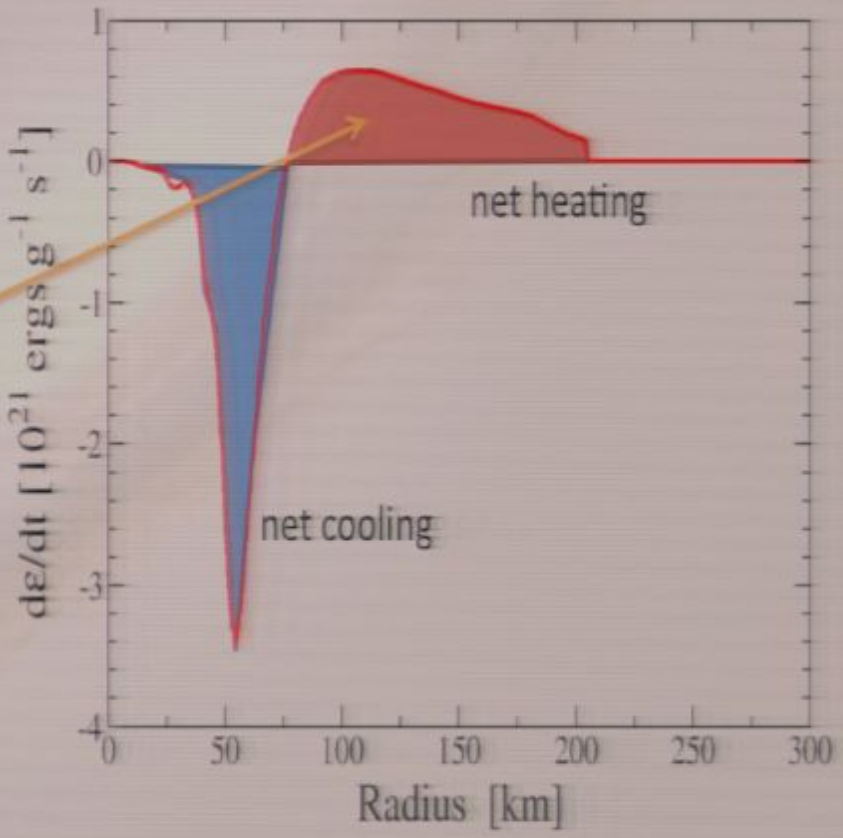

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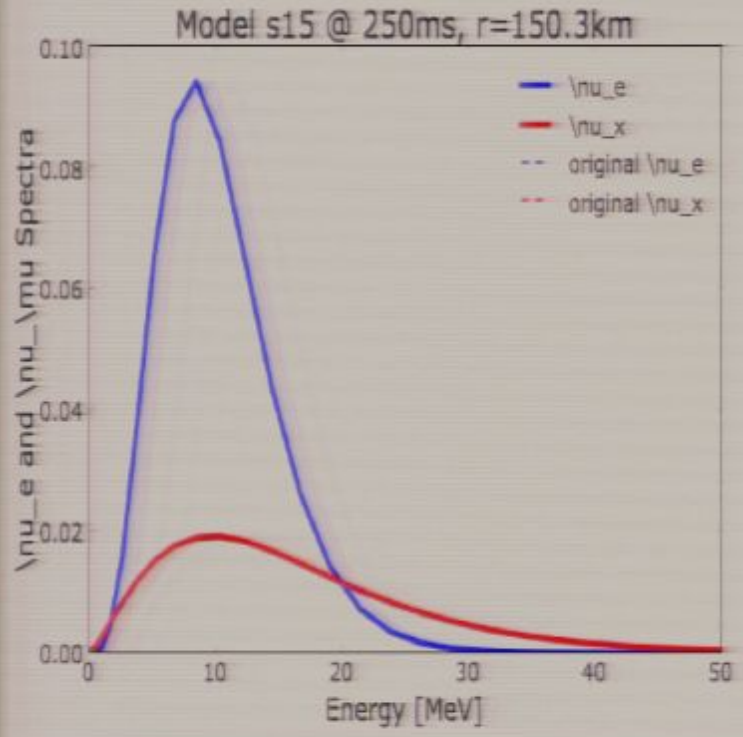

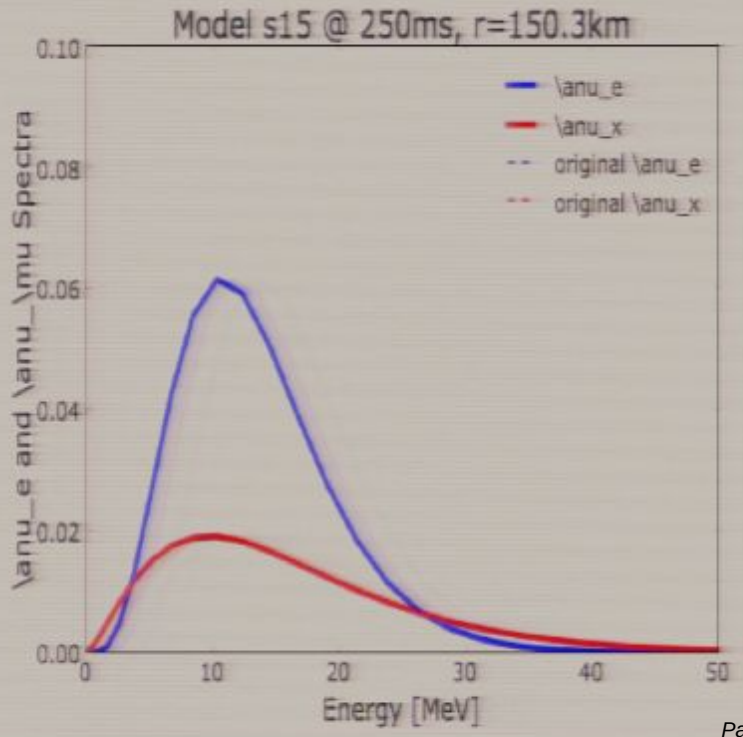

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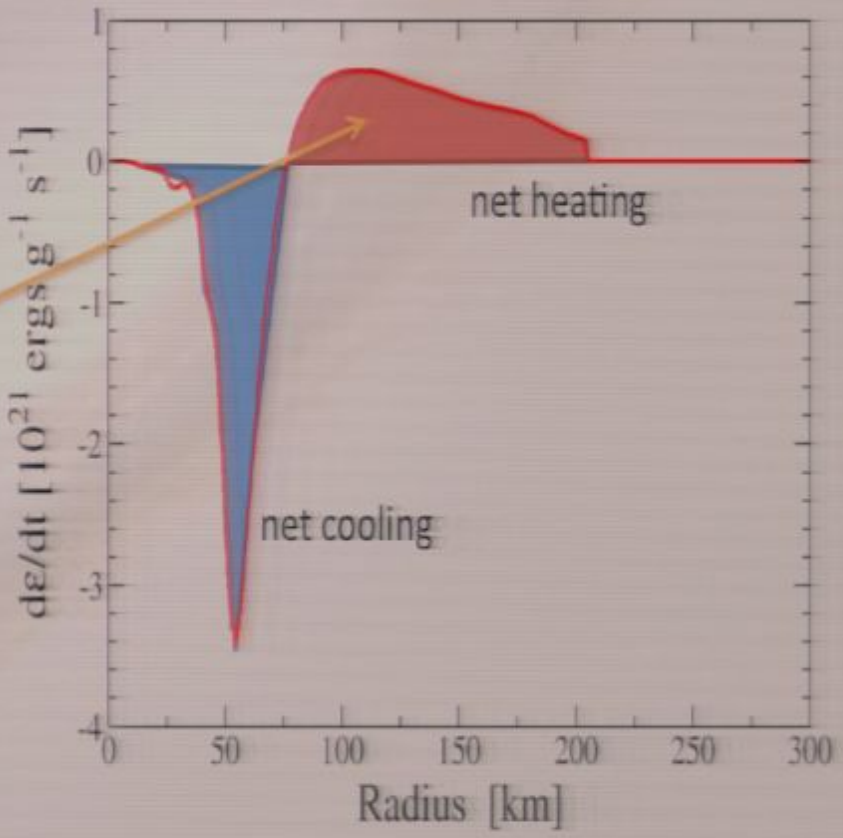

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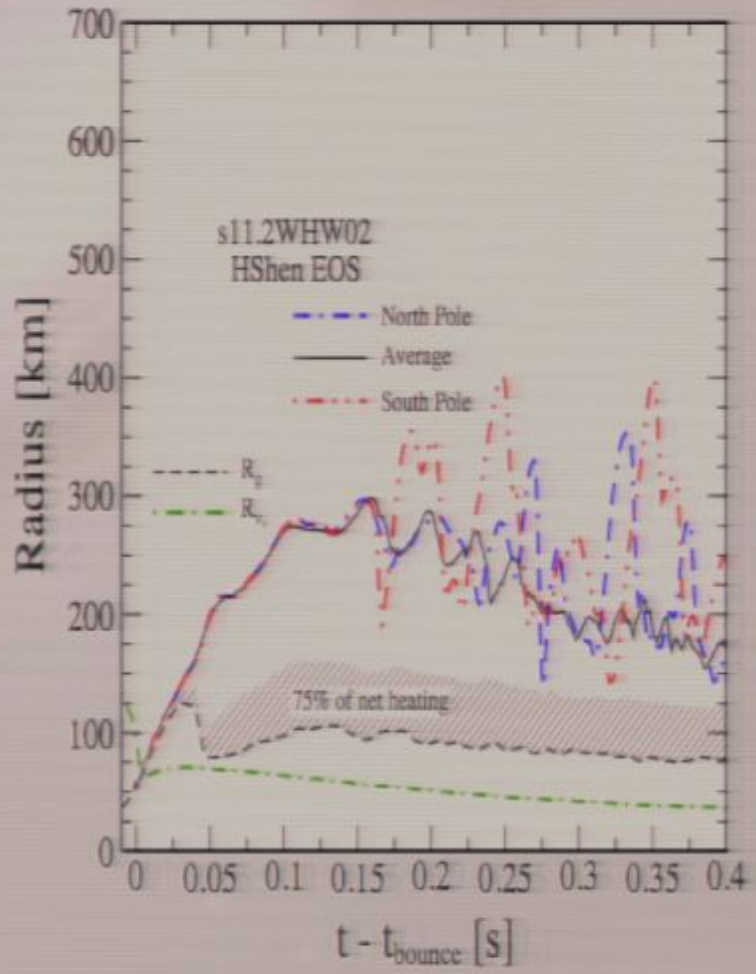

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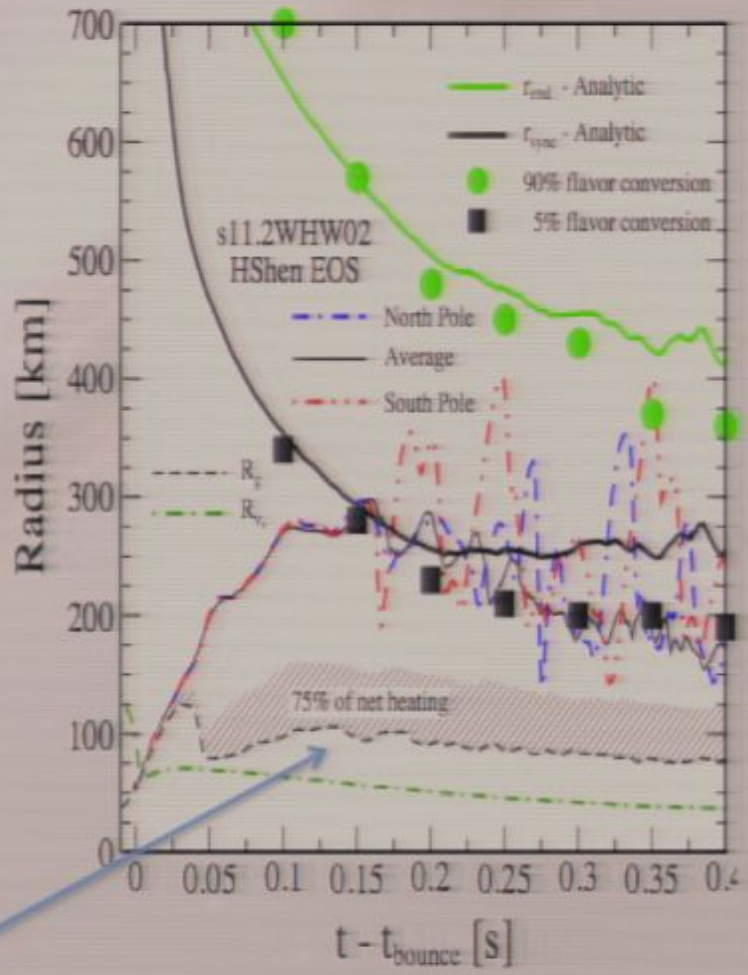

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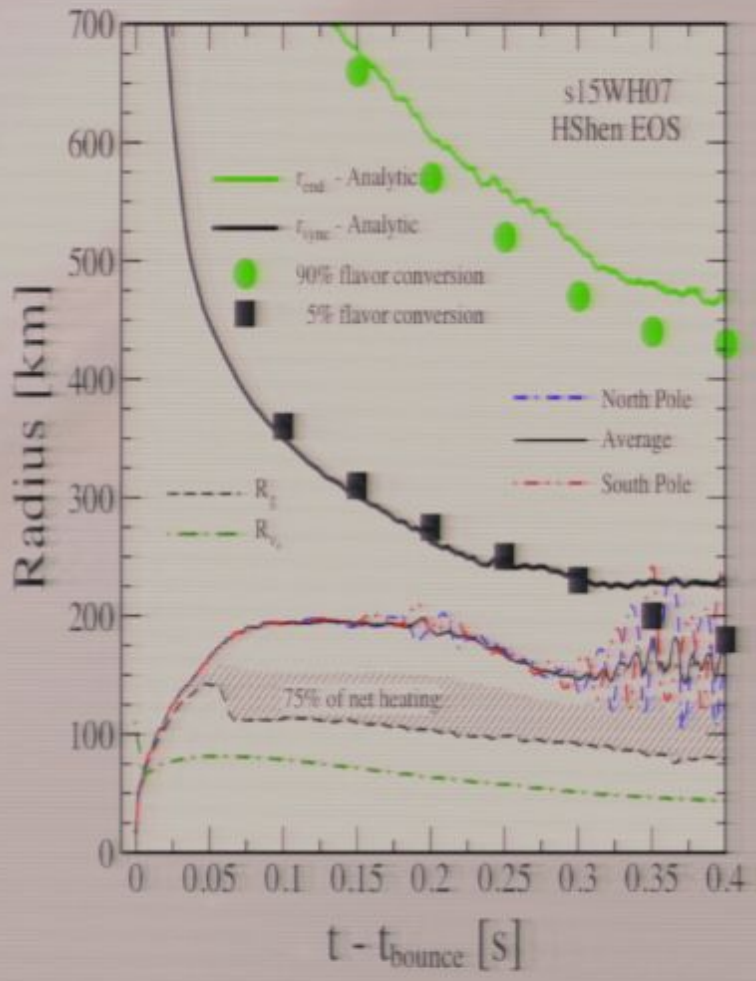
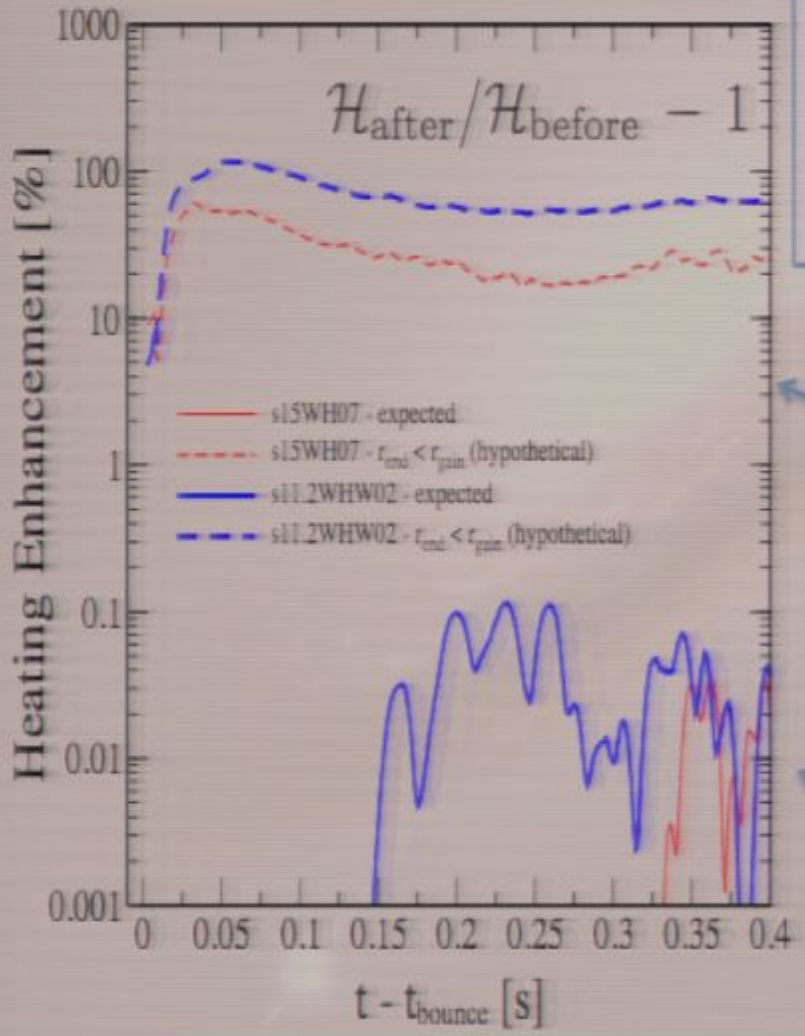


Expected Heating Enhancement



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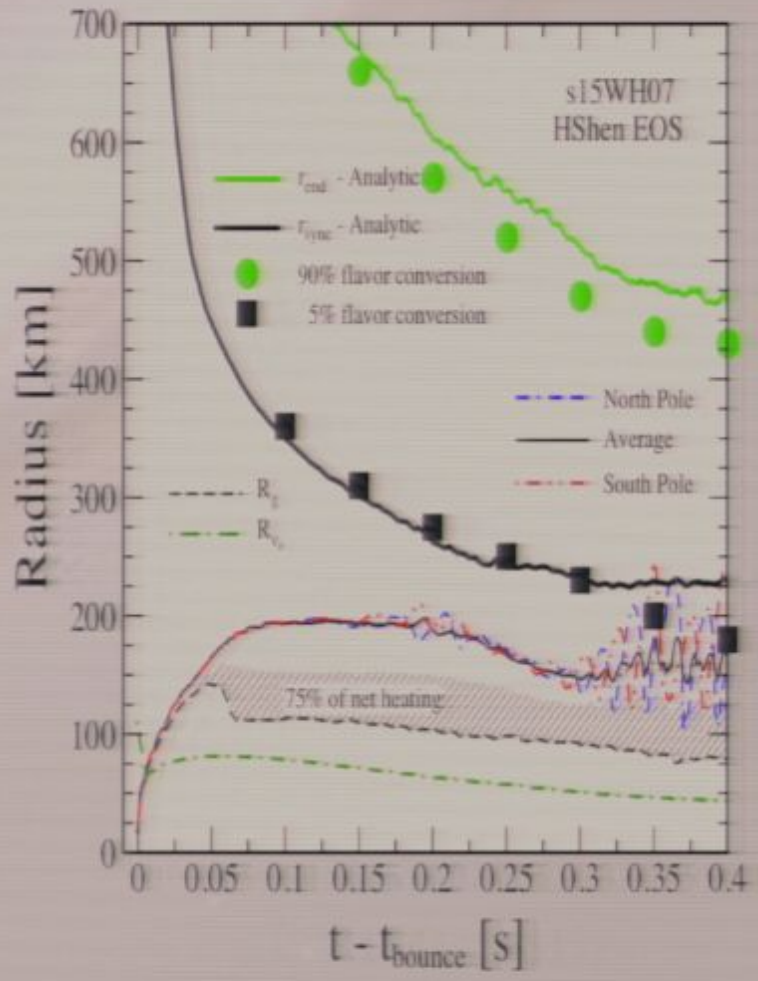

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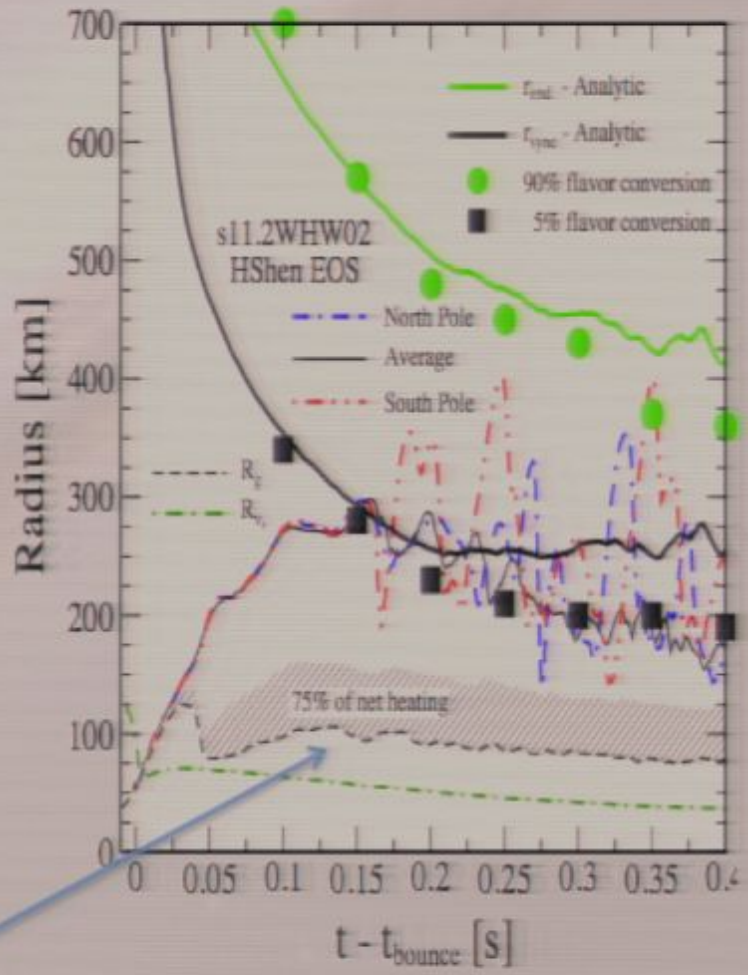

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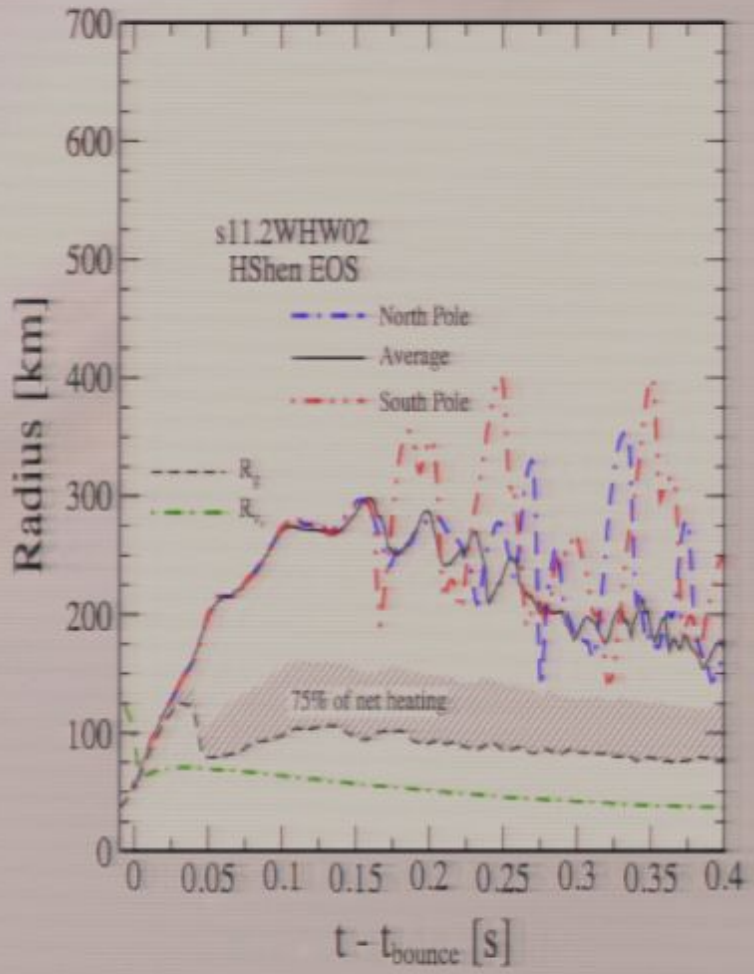

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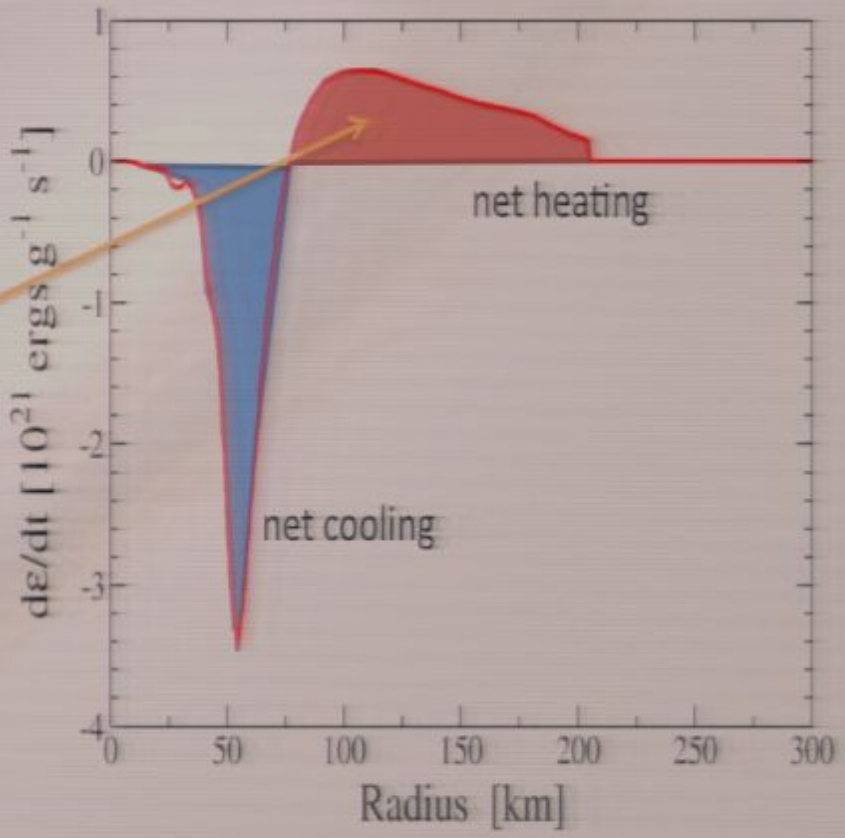

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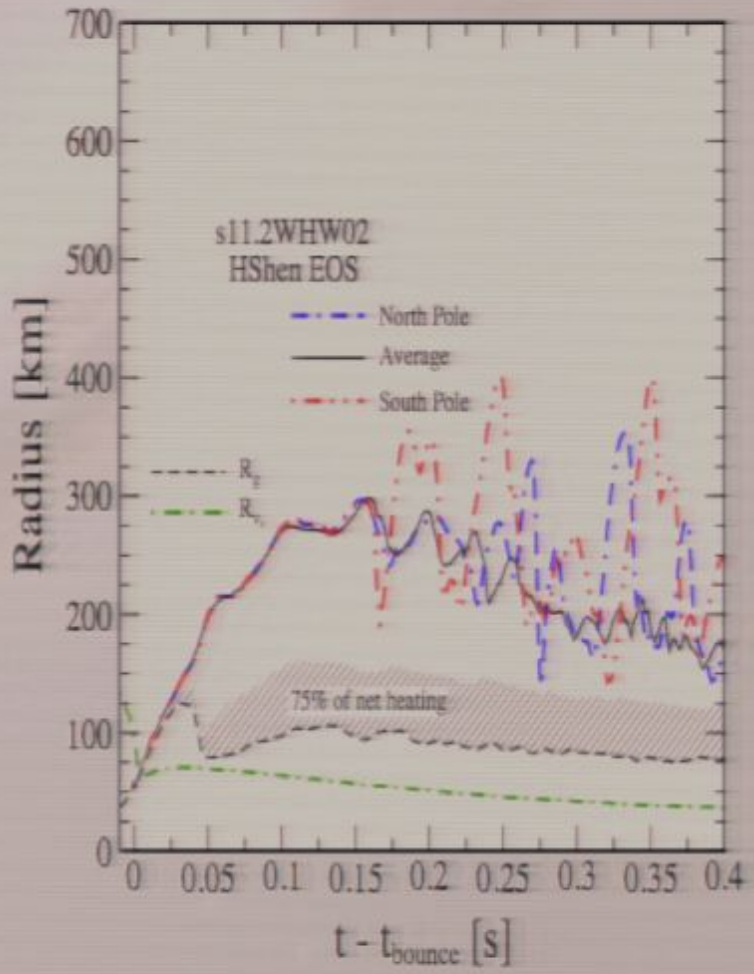

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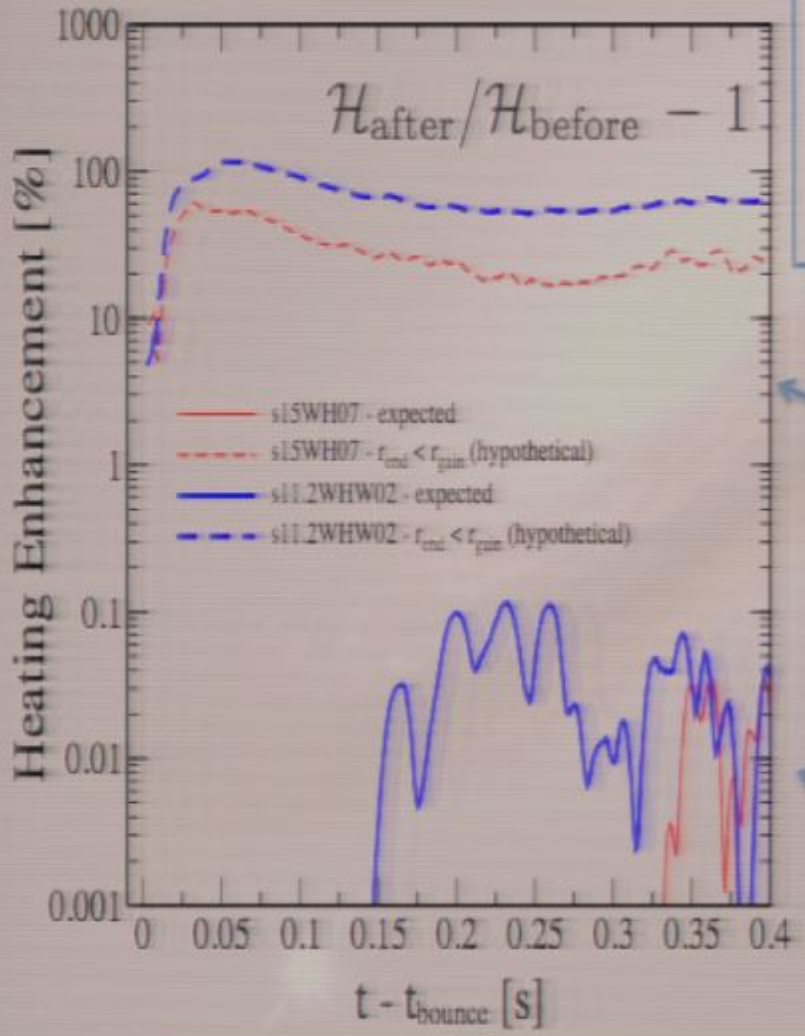

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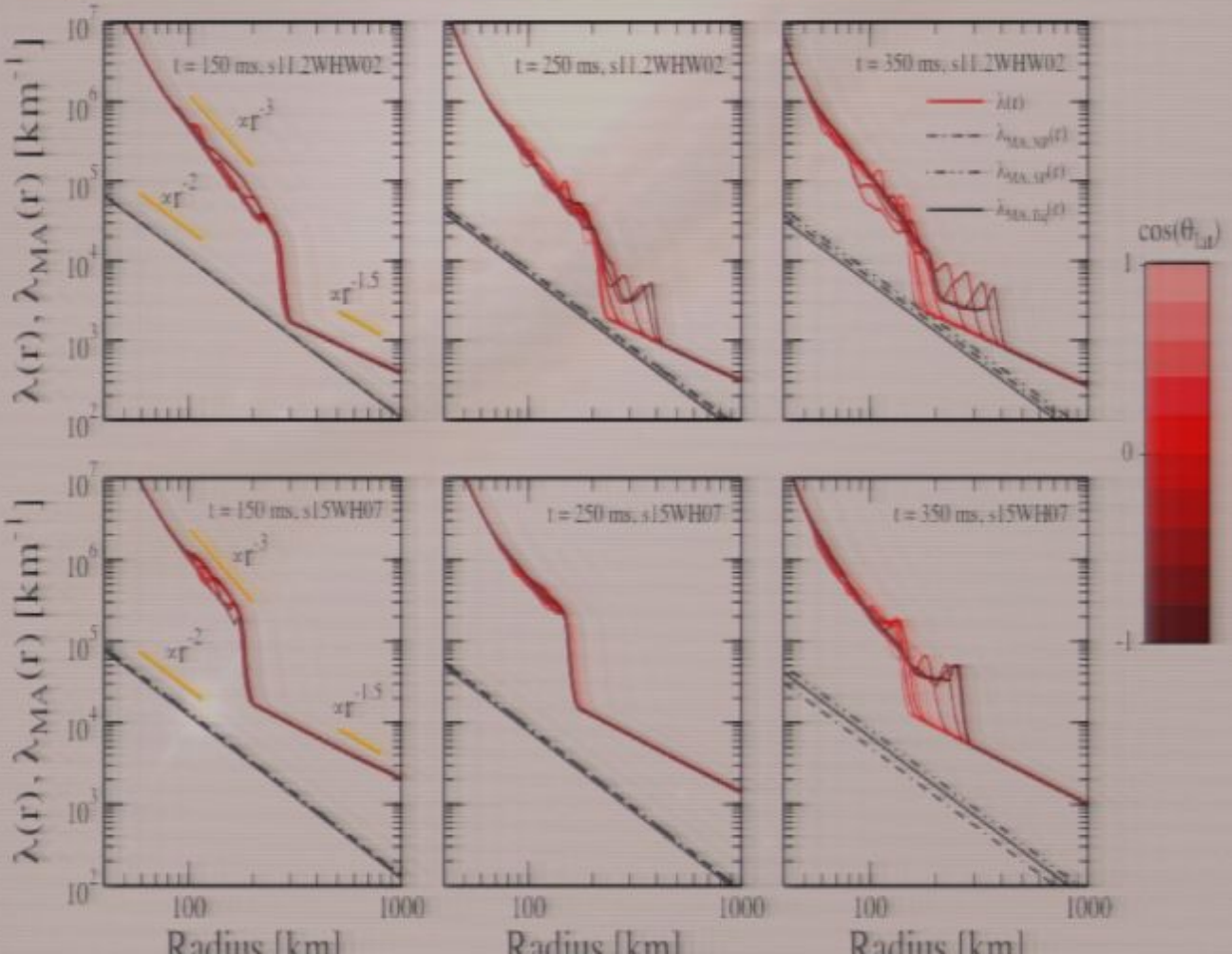
Multiangle suppression of Oscillations

(see also Chakraborty et al. 2011ab)

- In single angle approximation one can `rotate' away the matter potential
- Recent development in multiangle collective neutrino oscillations leads to a suppression of oscillations until the electron density < neutrino density



Should we expect this to be relevant in improved models/EOS/codes/dimensions/neutrinos...?

- Models with higher accretion rates not only suppress SASI but lead to higher ν-sphere radii and neutrino densities. We chose low mass-range models for this reason (...O-Ne-Mg?)

$$r_{\mathrm{sync}} \propto \sqrt{R_{\nu_e}} \left(\Phi_{\nu,\bar{\nu}} R_{\nu_e}^2 \right)^{1/4}$$

- Different EOS do not significantly change R_ν or $\Phi_{\nu\nu}$
- 3D may lead to larger shock radii, however need to get oscillations deep down below gain radius to see significant effect – that's hard

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- Results here in single-angle approximation, multiangle may lead to larger swap radii:
  - multiangle matter effects (Chakraborty et al. 2011)
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- If $\Phi_{ve} \sim \Phi_{ve}$ then multiangle decoherence, spectra equilibrate
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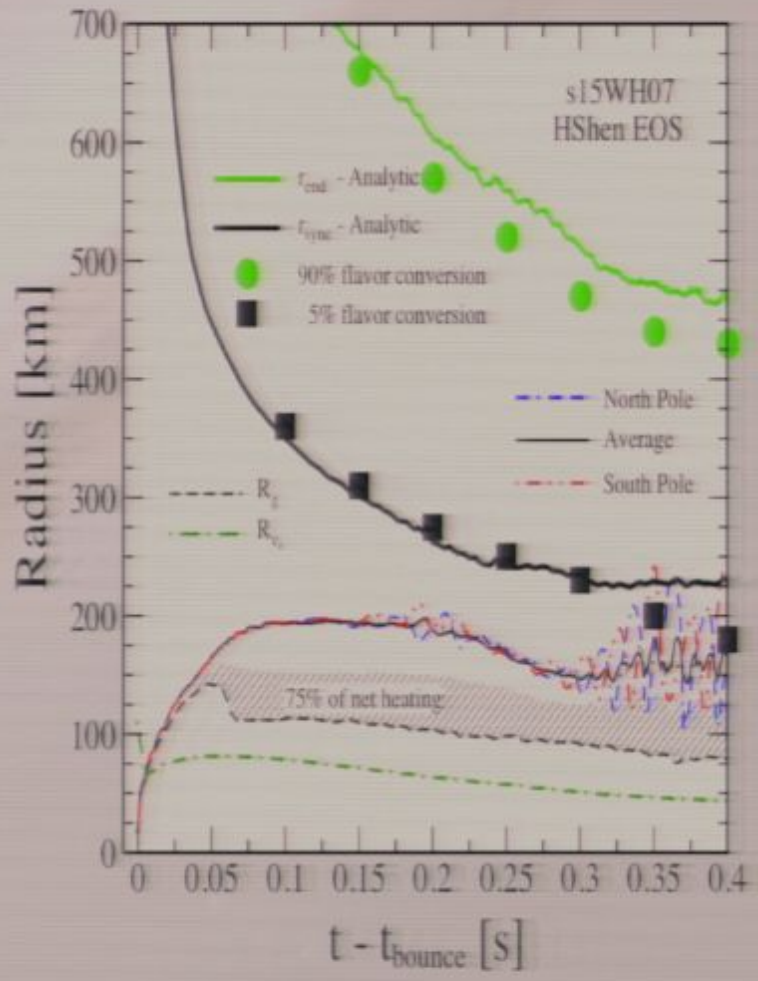

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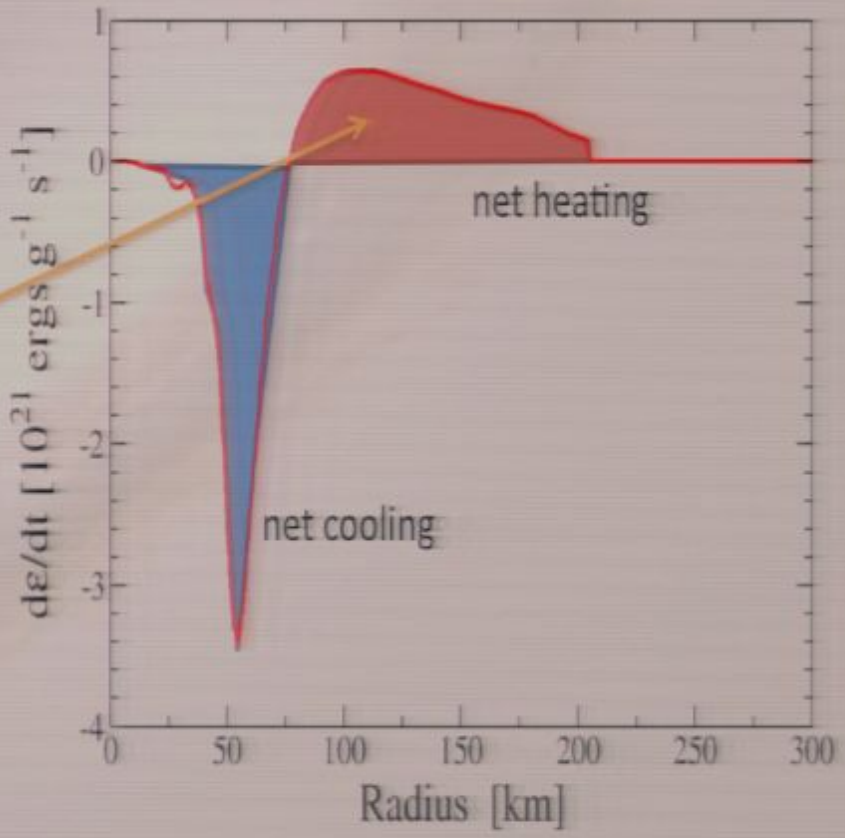

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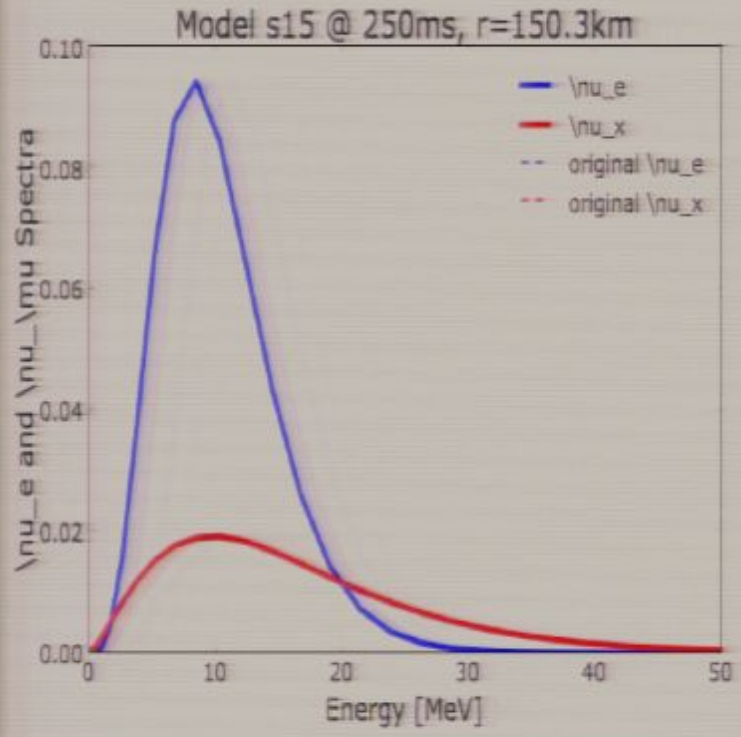

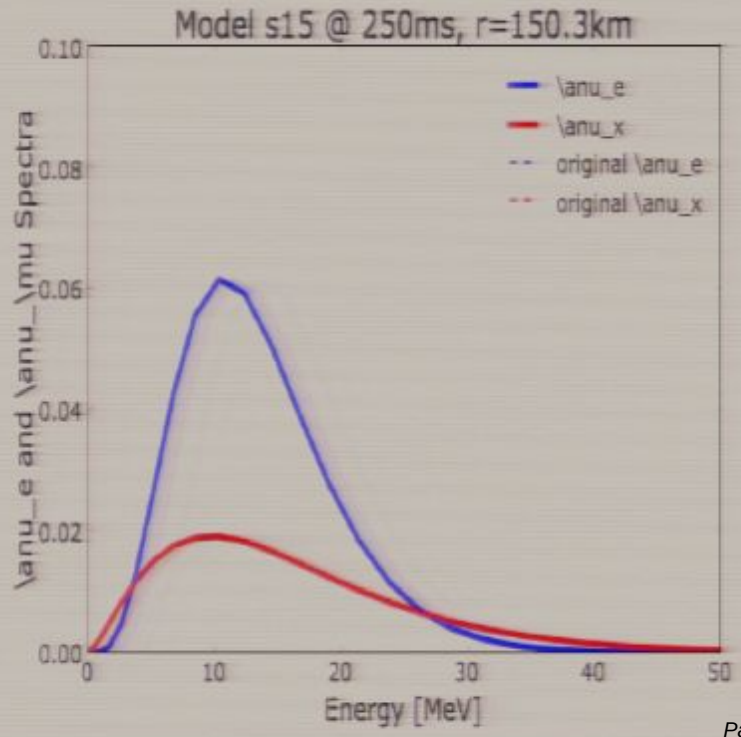

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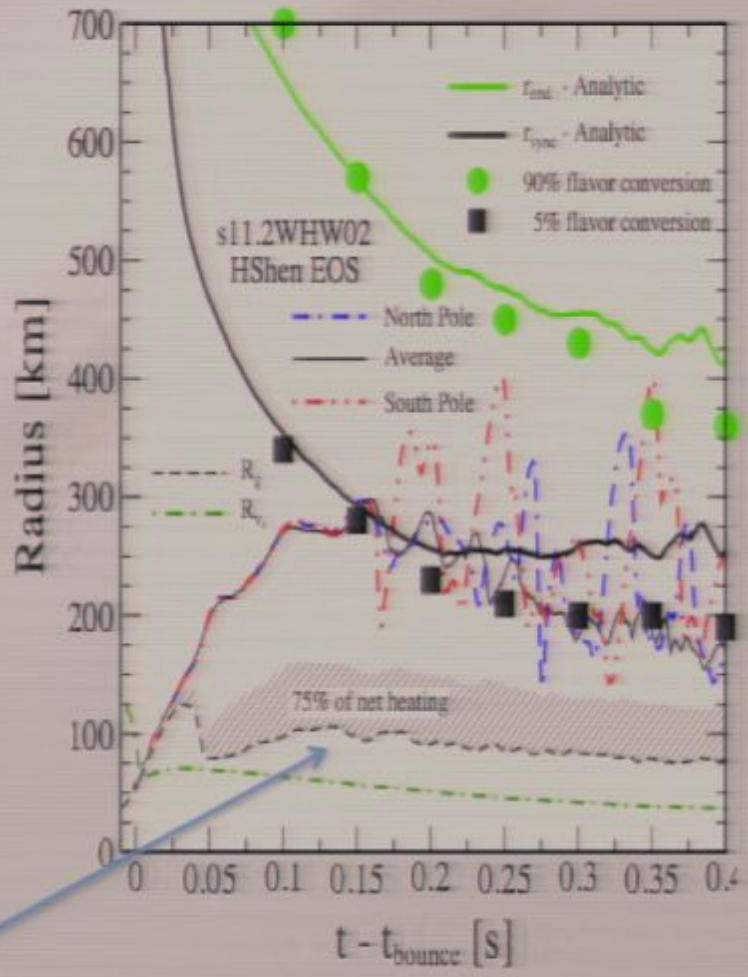

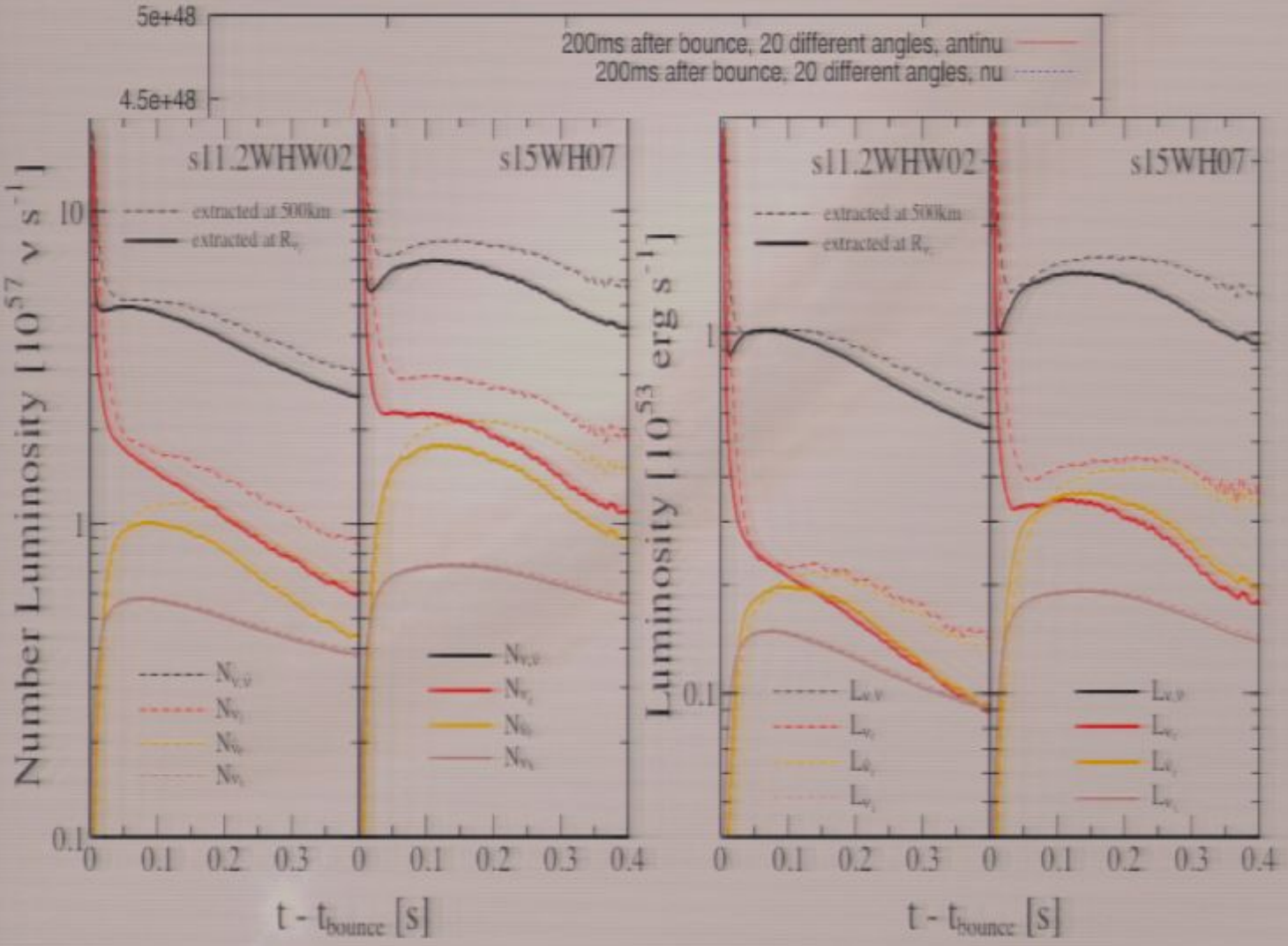
5e+48
4.5e+48
200ms after bounce, 20 different angles, antinu
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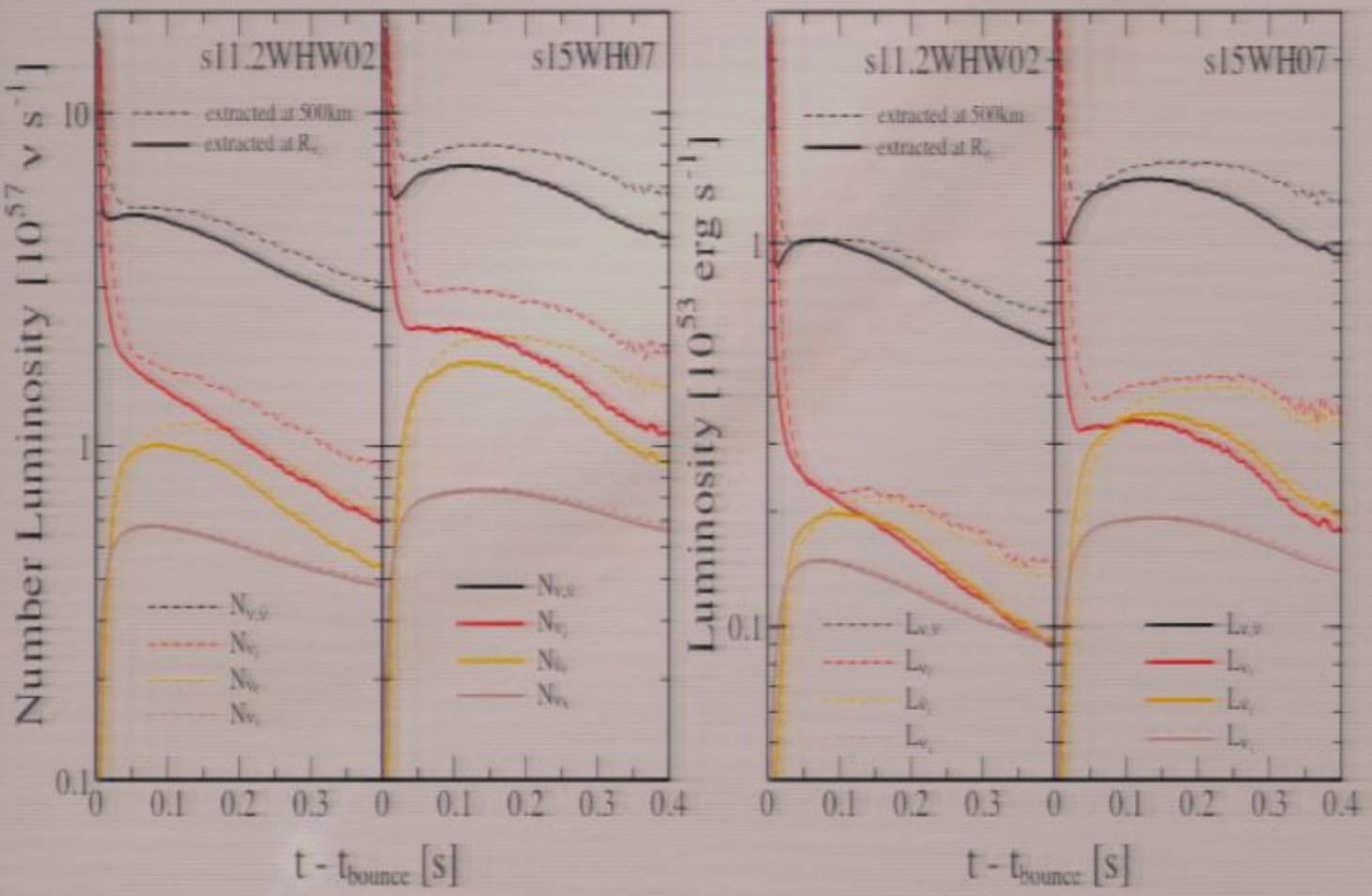
t - t_{bounce} [s]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