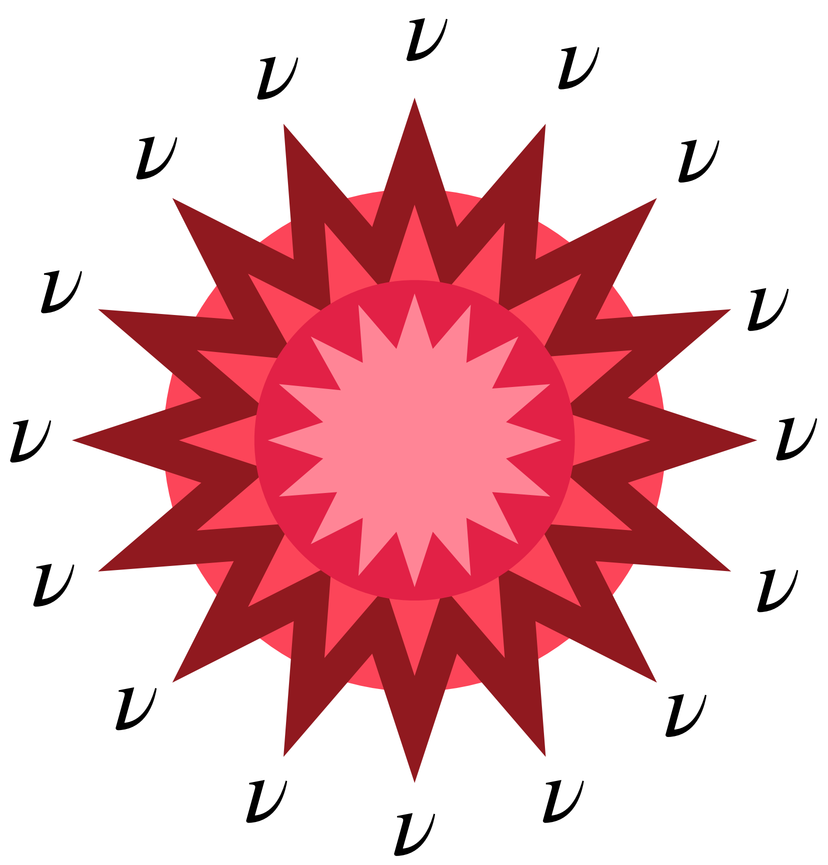
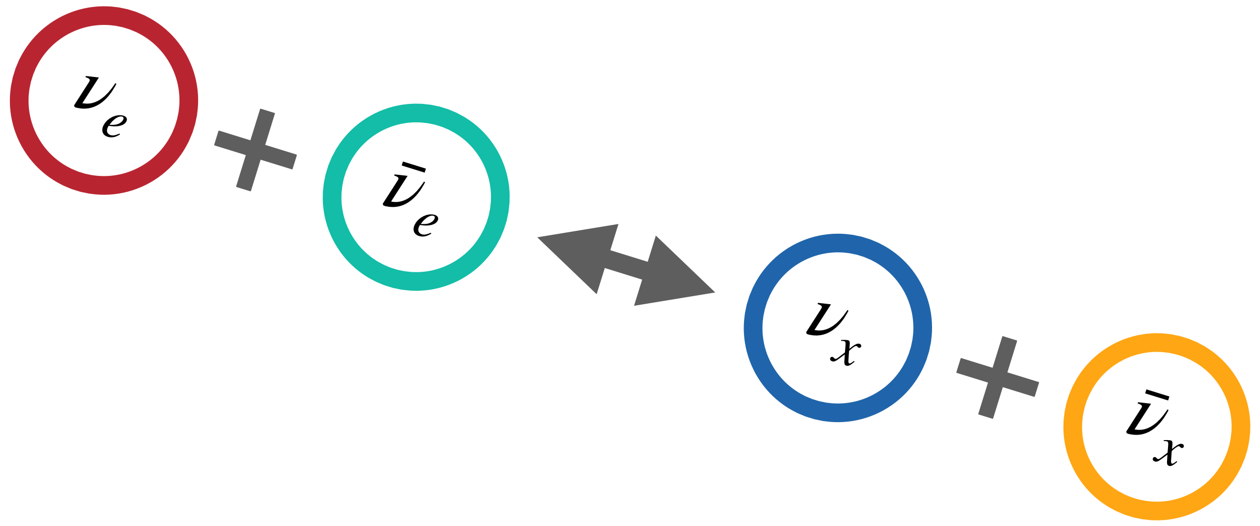
UNIVERSITY OF COPENHAGEN

VILLUM FONDEN

Hunting for electron-neutrino lepton number crossings in core-collapse supernovae

IV PhD Summer School on Neutrinos





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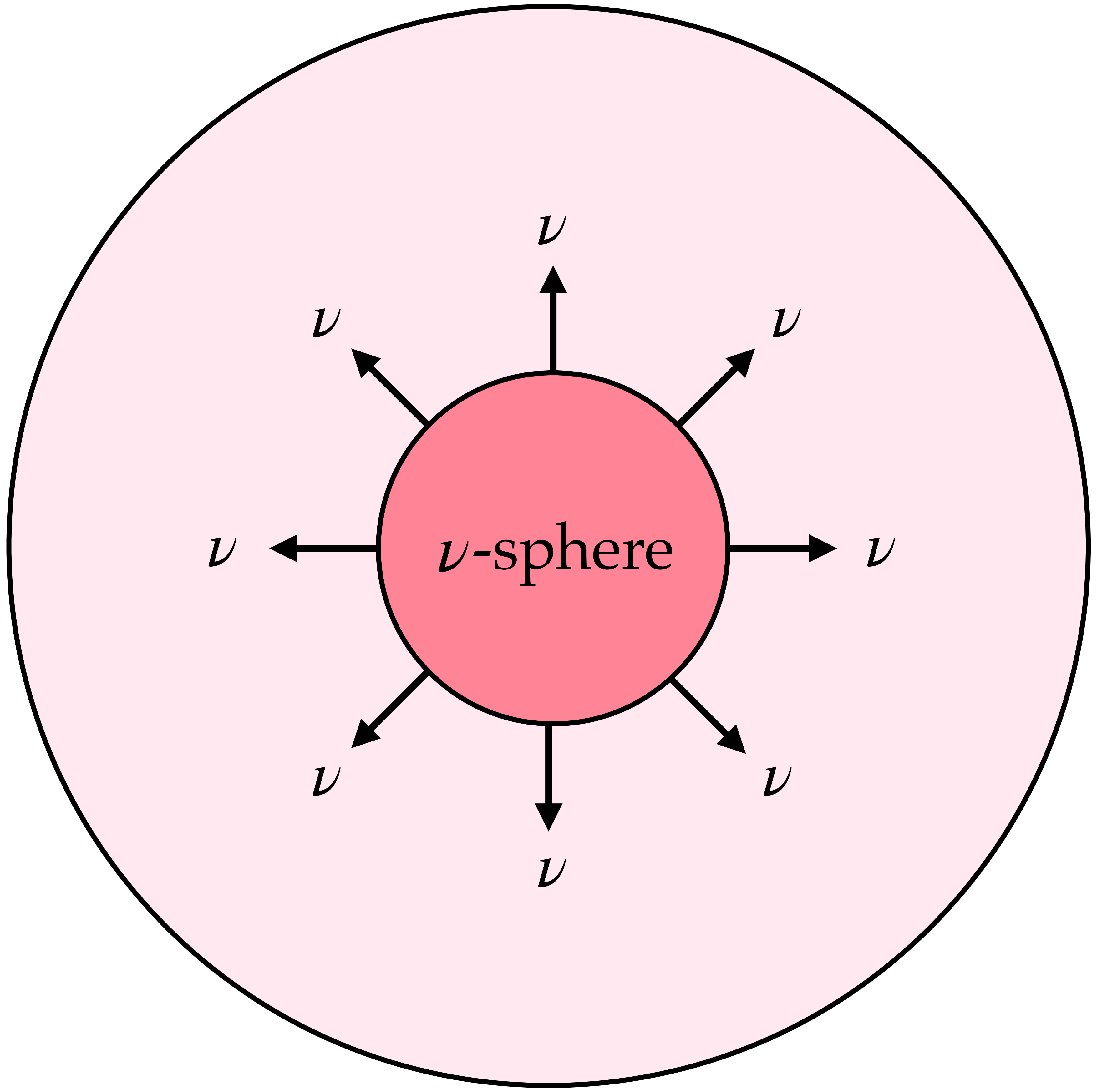
With collaborators
Irene Tamborra (NBI), Malte Heinlein (TUM & MPA Garching), Shashank Shalgar (NBI), Hans-Thomas Janka (MPA Garching)

Neutrinos in core-collapse supernovae

- Neutrinos are abundantly produced during a core-collapse supernova
- They drive the explosion dynamics and shape nucleosynthesis
- **Fast neutrino flavor conversions** become dominant in the extremely dense core

$$\nu_e + \bar{\nu}_e \leftrightarrow \nu_x + \bar{\nu}_x$$



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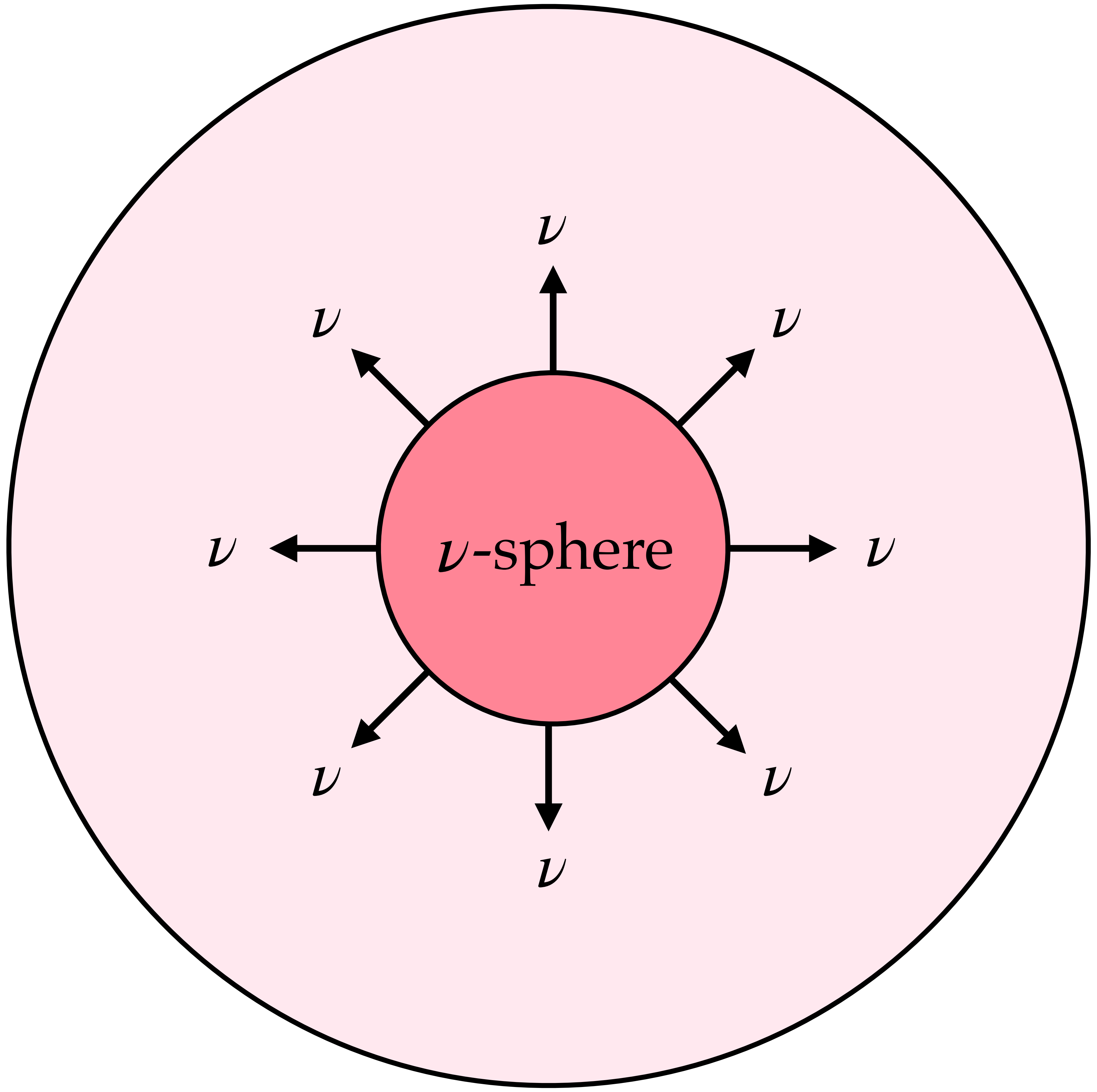
Changing these!



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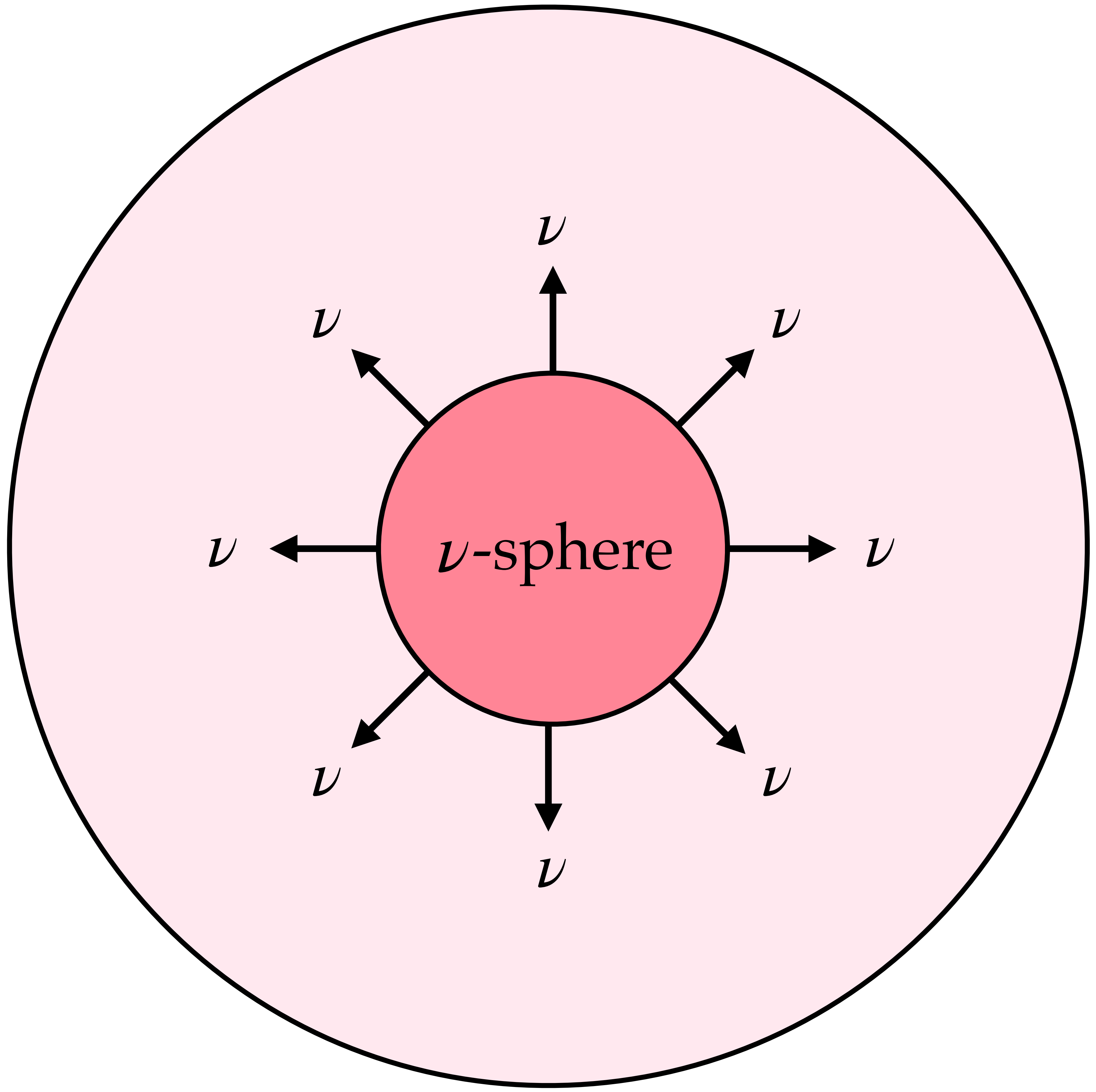
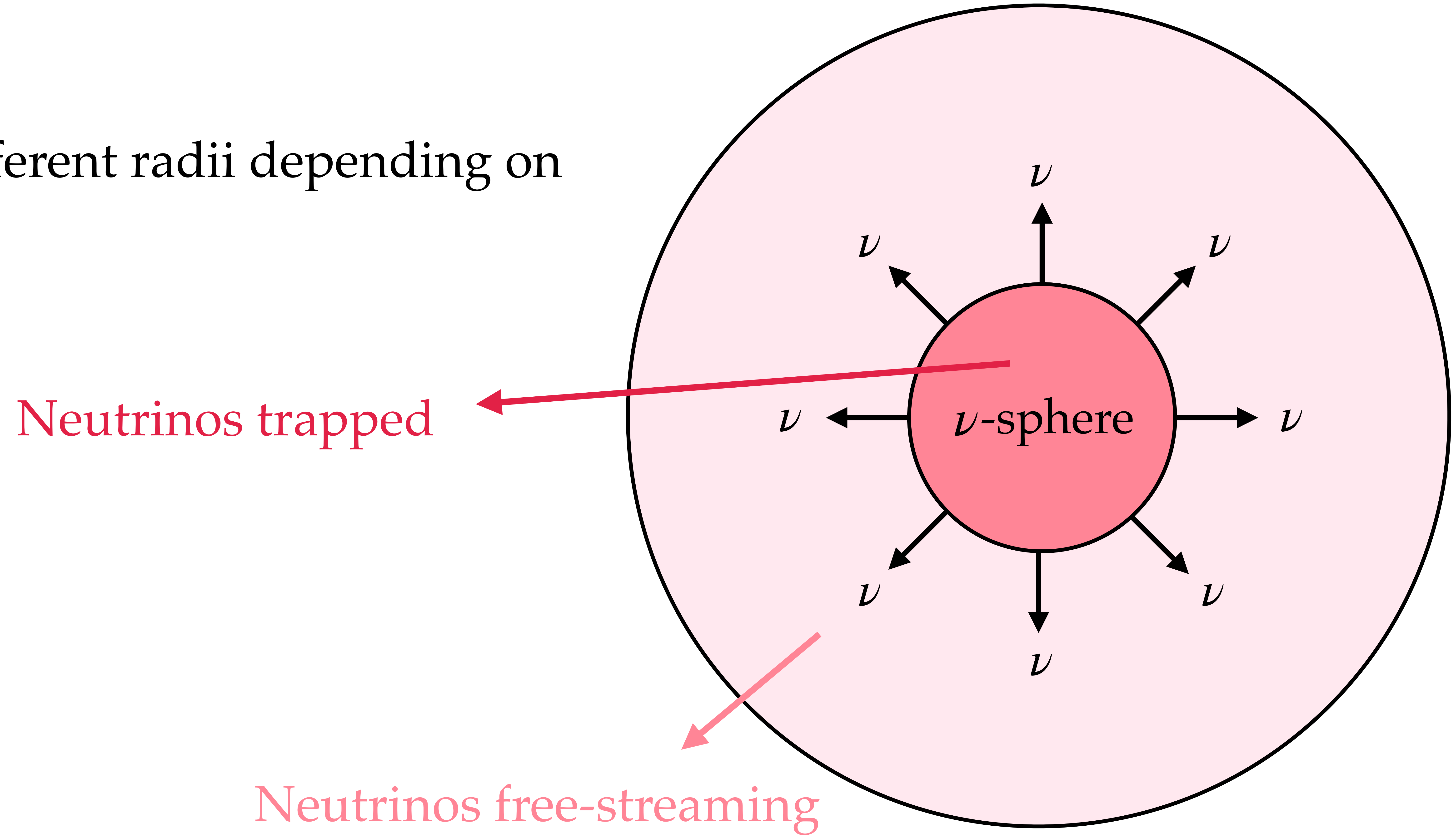
But they require special conditions!



Conditions for fast neutrino flavor conversions

- Neutrinos decouple at different radii depending on flavor and energy



Tamborra & Shalgar, *Ann. Rev. Nucl. Part. Sci.* **71** (2021) 165-188

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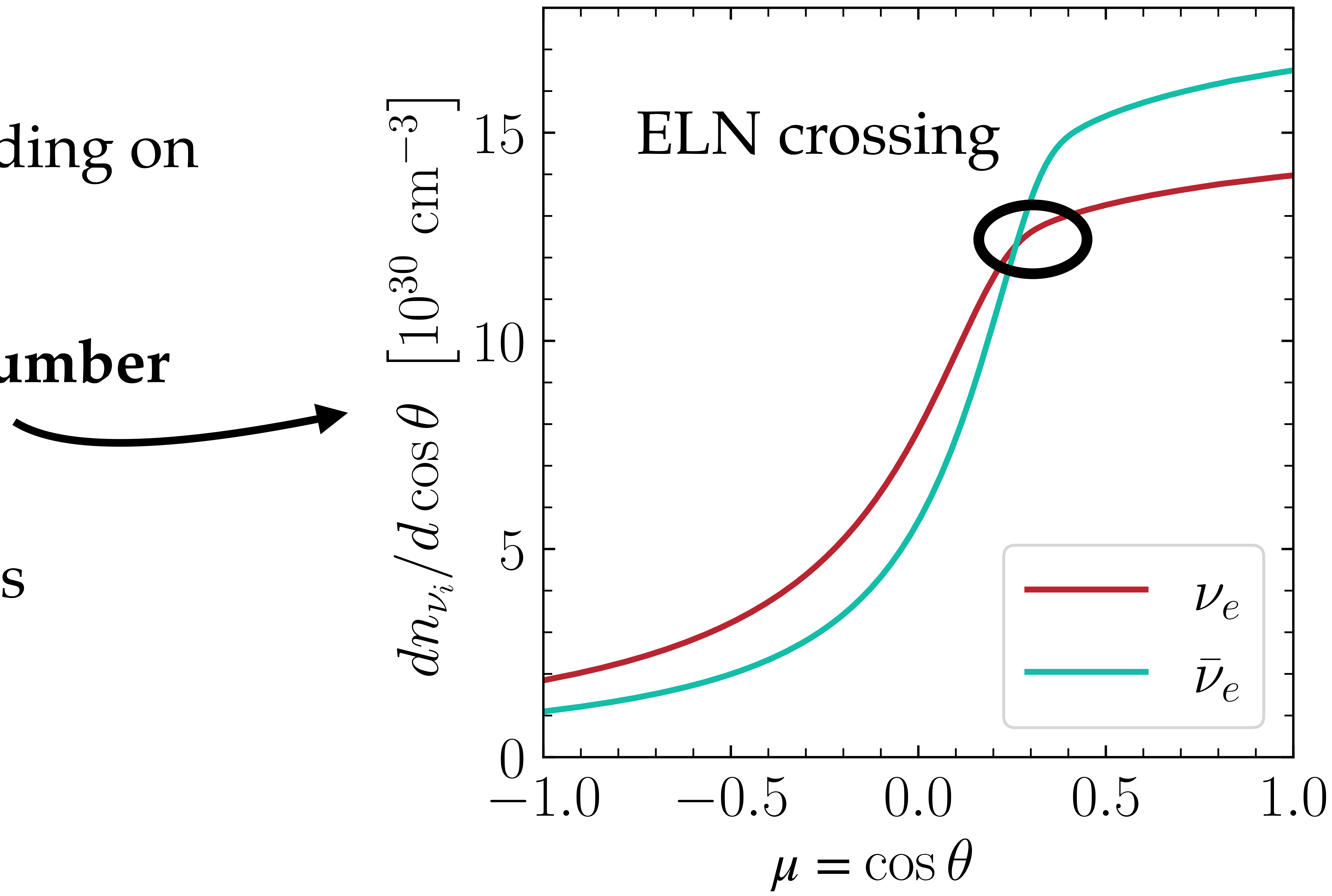
- This can lead to **electron-neutrino lepton number (ELN) crossings**
- ELN crossings trigger fast flavor conversions



Propagation angle

Cornelius, Shalgar & Tamborra, *JCAP* 02 (2024) 038

Conditions for fast neutrino flavor conversions

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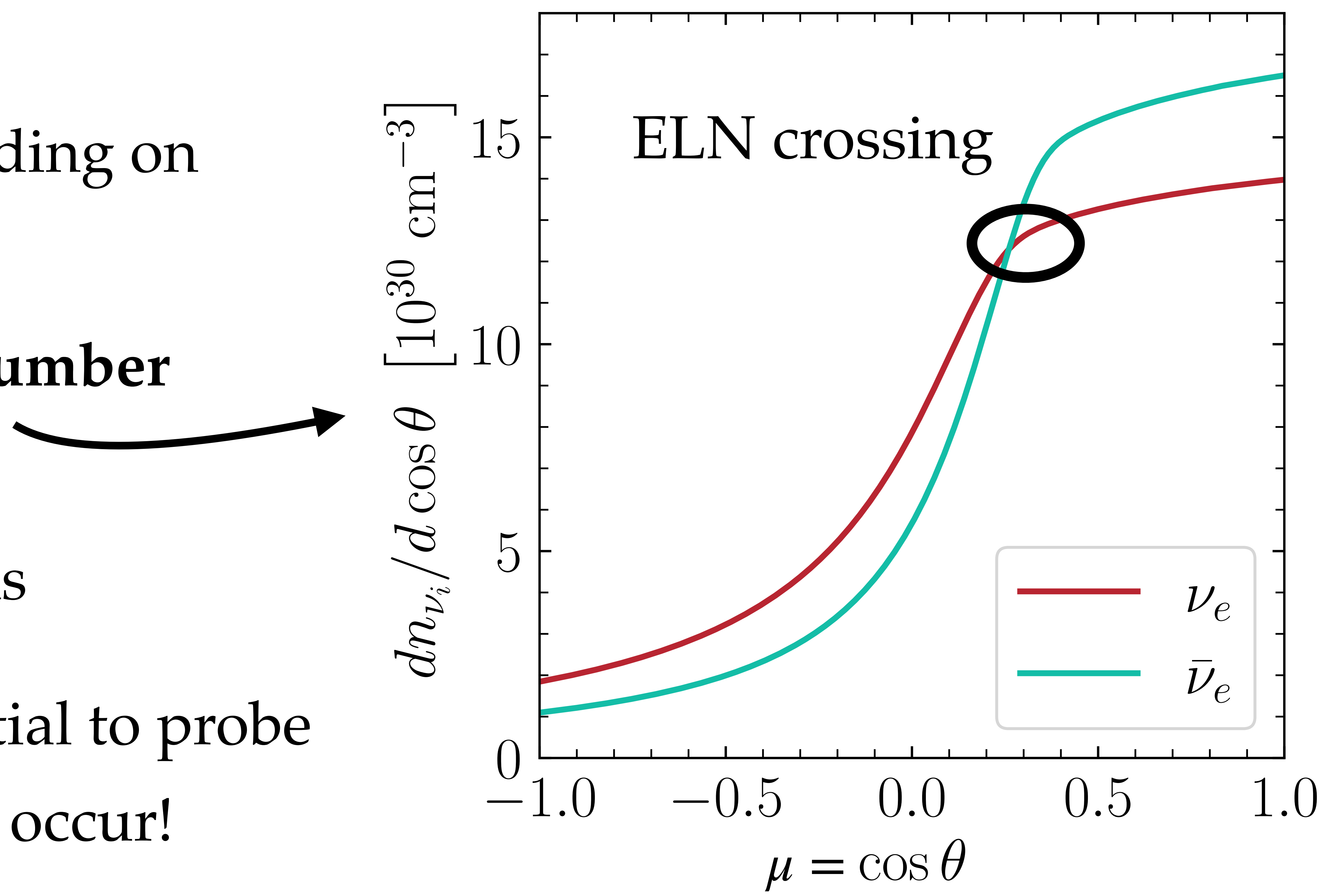
→ Knowing the angular distributions is essential to probe the regions where neutrino flavor conversions occur!



Propagation angle

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Supernova models

- Most supernova simulations have no angular information (too computationally expensive)
- They evolve only angular moments:

0th moment: number density, $n_{\nu_i}(r)$
1st moment: flux, $F_{\nu_i}(r)$

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→ So how do we obtain angular distributions?

Boltzmann equation of neutrino transport

Advection

Collisions between neutrinos and matter

$$\left(\frac{\partial}{\partial t} + \vec{c} \cdot \vec{\nabla}\right) \rho \;=\; \mathcal{C}[\rho, \bar{\rho}]$$

Information from SN simulations

Density matrix, $\rho(r, \mu, E)$

ν_e, ν_x ($\bar{\nu}_e$, $\bar{\nu}_x$)

Boltzmann equation of neutrino transport

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Collisions between neutrinos and matter

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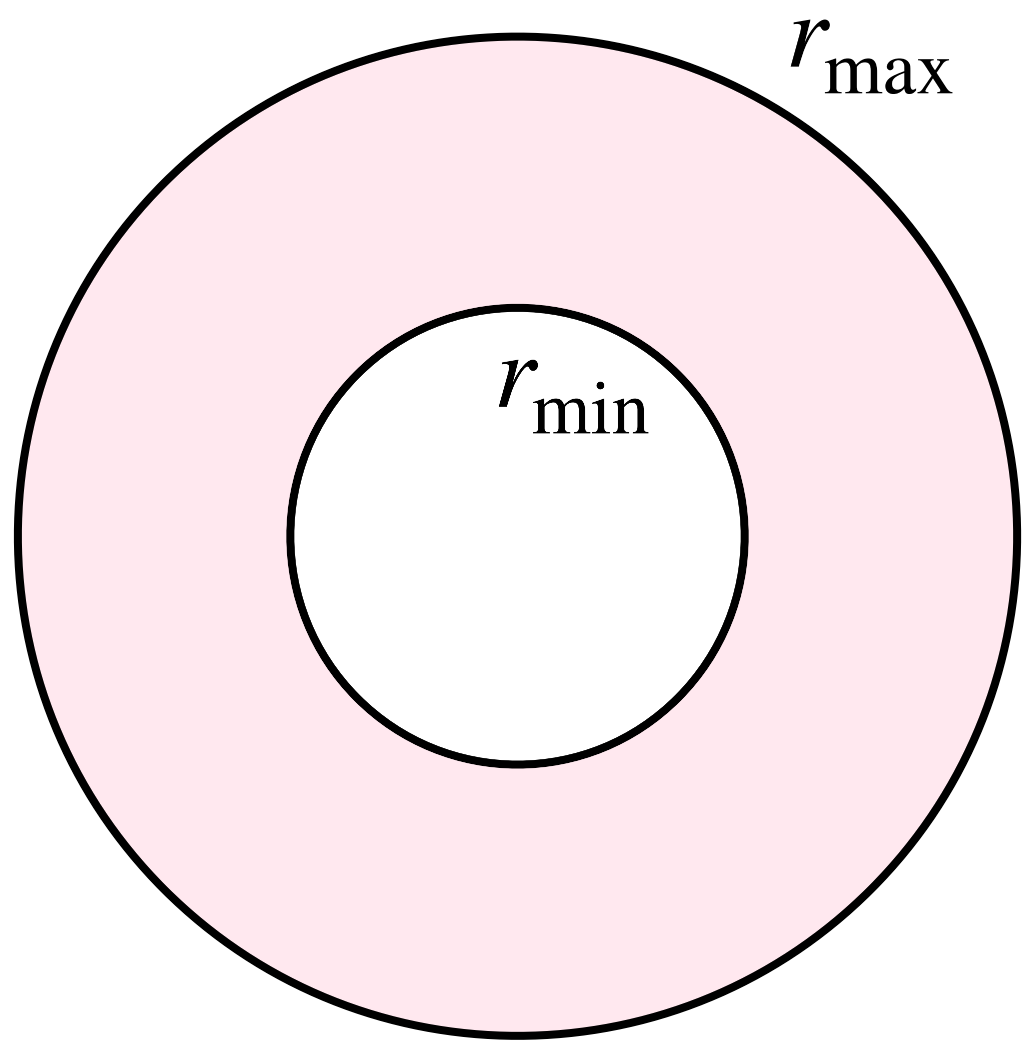
$\nu_e,\ \nu_x\ (\bar{\nu}_e,\ \bar{\nu}_x)$



- Simulation domain: spherical shell enclosing the neutrinosphere
- Boltzmann equation evolved in time until a steady state is reached

Supernova models

Hydrodynamical profiles from SN simulations at chosen post-bounce times
(density, temperature, mass fractions, chem. potentials)

We compare three 1D core-collapse supernova models:

Model 1: without muons and convection

Model 2: without muons, with convection

Model 3: with convection and muons

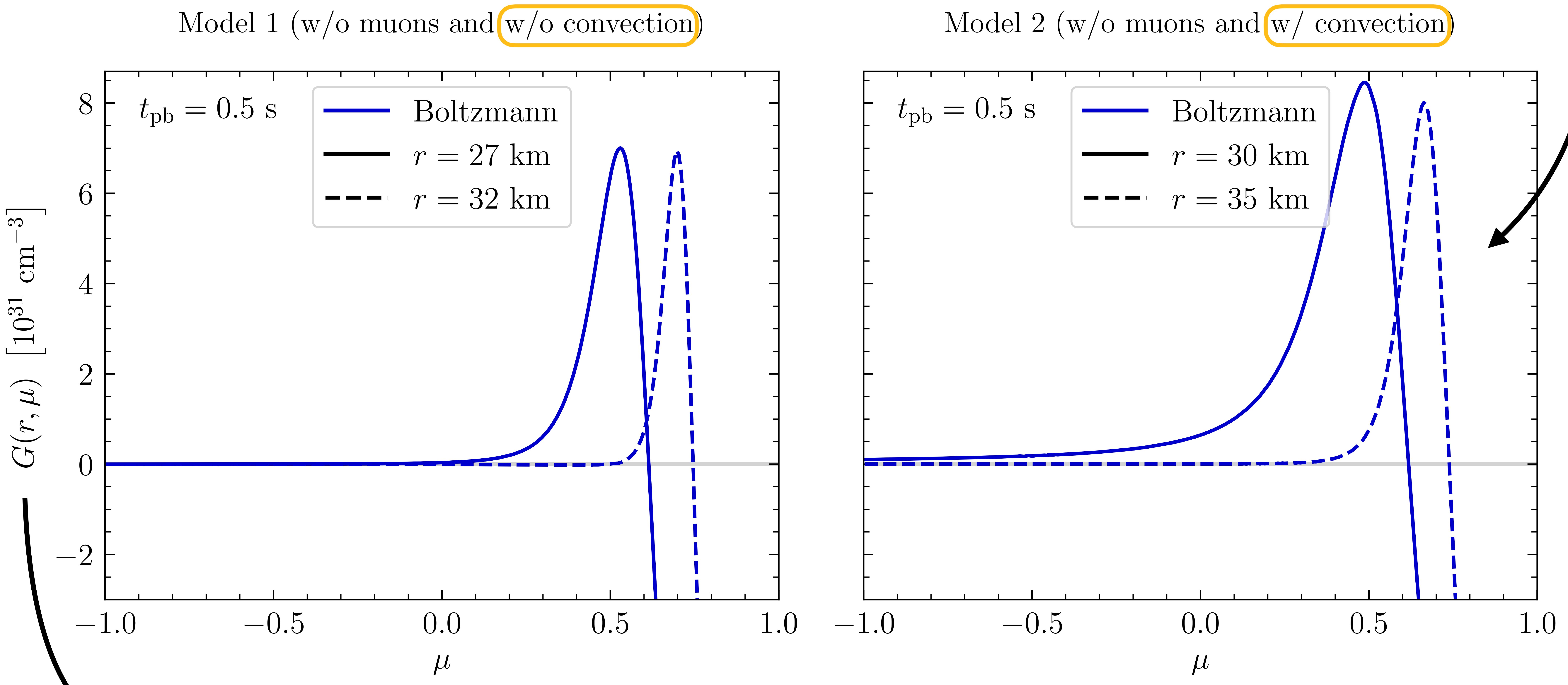
Do muons and convection affect the formation of ELN crossings?

The Garching Core-Collapse Supernova Archive

ELN angular distributions

Boltzmann solution

Forward-peaked distributions



ELN distribution, $G(r,\mu) = \int dE \left[\rho_{ee}(r,\mu,E) - \bar{\rho}_{ee}(r,\mu,E)\right]$

Cornelius, Tamborra, Heinlein, Janka, arXiv:2506.20723

Alternative method:
Use provided moments to reconstruct angular distributions

Maximum entropy distribution

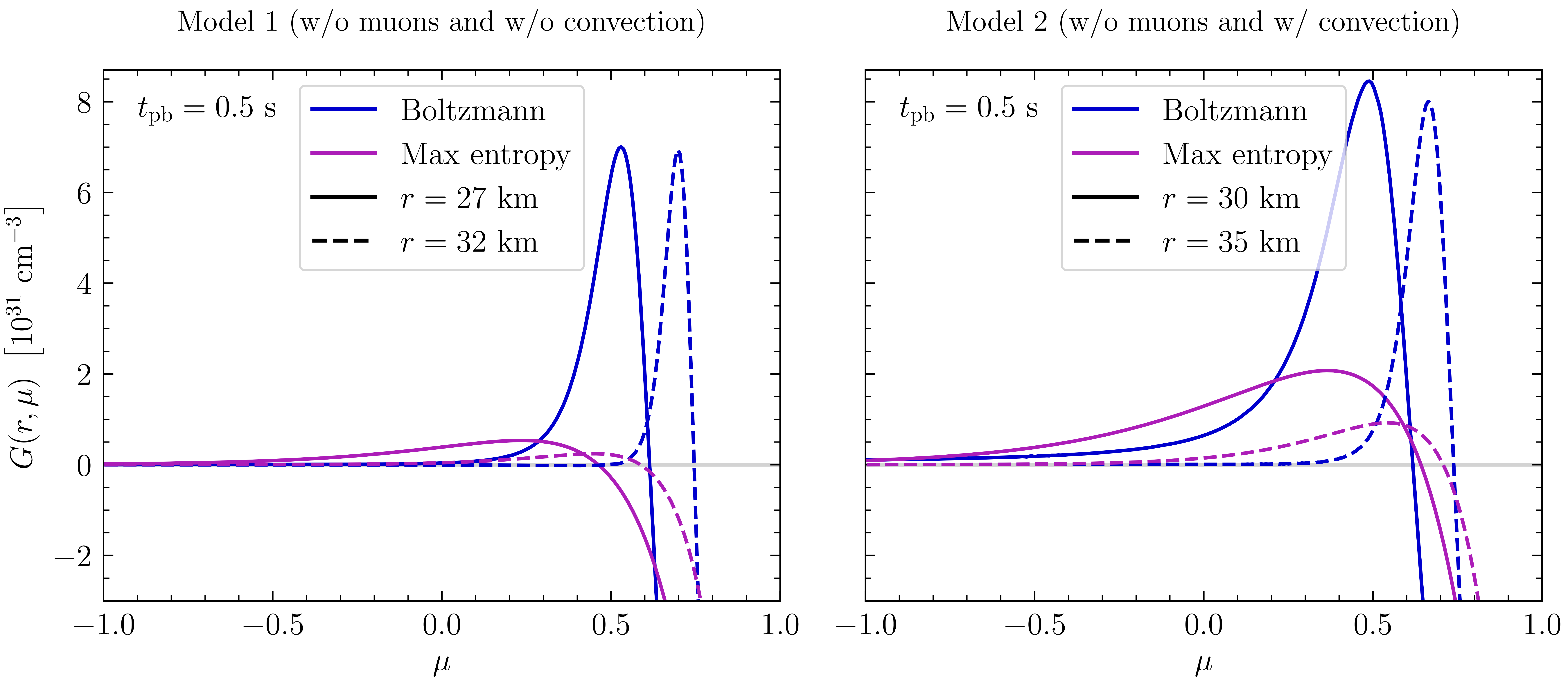
$n_{\nu_i}(r)$, $F_{\nu_i}(r)$ → Z

$$f_{\nu_i}^{\mathrm{ME}}(r,\mu) = \frac{n_{\nu_i}(r)}{4\pi}\frac{Z}{\sinh(Z)}e^{Z\mu}$$

Cornelius, Tamborra, Heinlein, Janka, arXiv:2506.20723

Reconstructing ELN angular distributions

Maximum entropy



- Crossings reproduced, but distributions less forward peaked

Cornelius, Tamborra, Heinlein, Janka, arXiv:2506.20723

Reconstructing ELN angular distributions

Minerbo closure

Using moments and the Minerbo closure:

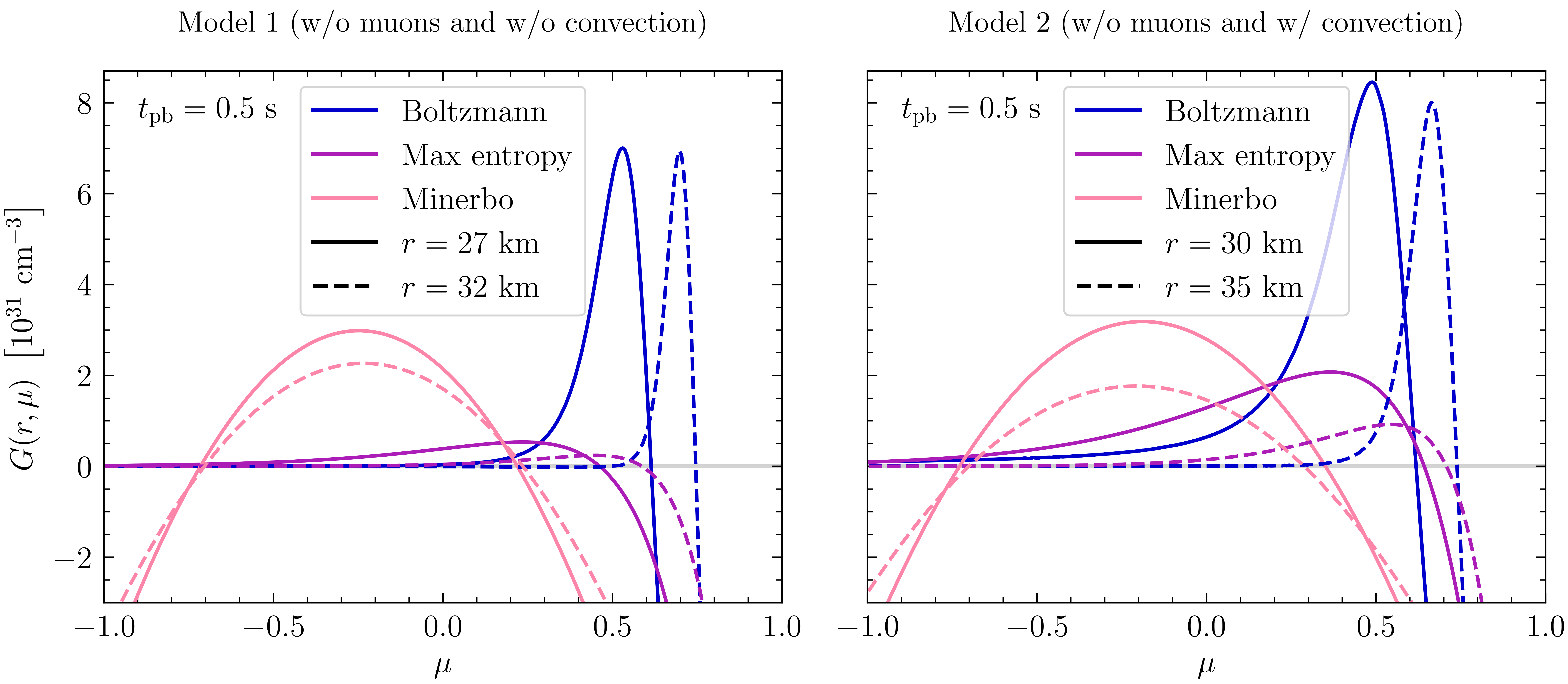
$$f_{\nu_i}^{\text{Minerbo}}(\mu) = a_0 + a_1\mu + a_2\mu^2$$

$n_{\nu_i}(r)$, $F_{\nu_i}(r)$, 2nd moment $M_{\nu_i}^2$ calculated from closure

Cornelius, Tamborra, Heinlein, Janka, arXiv:2506.20723

Reconstructing ELN angular distributions

Minerbo closure



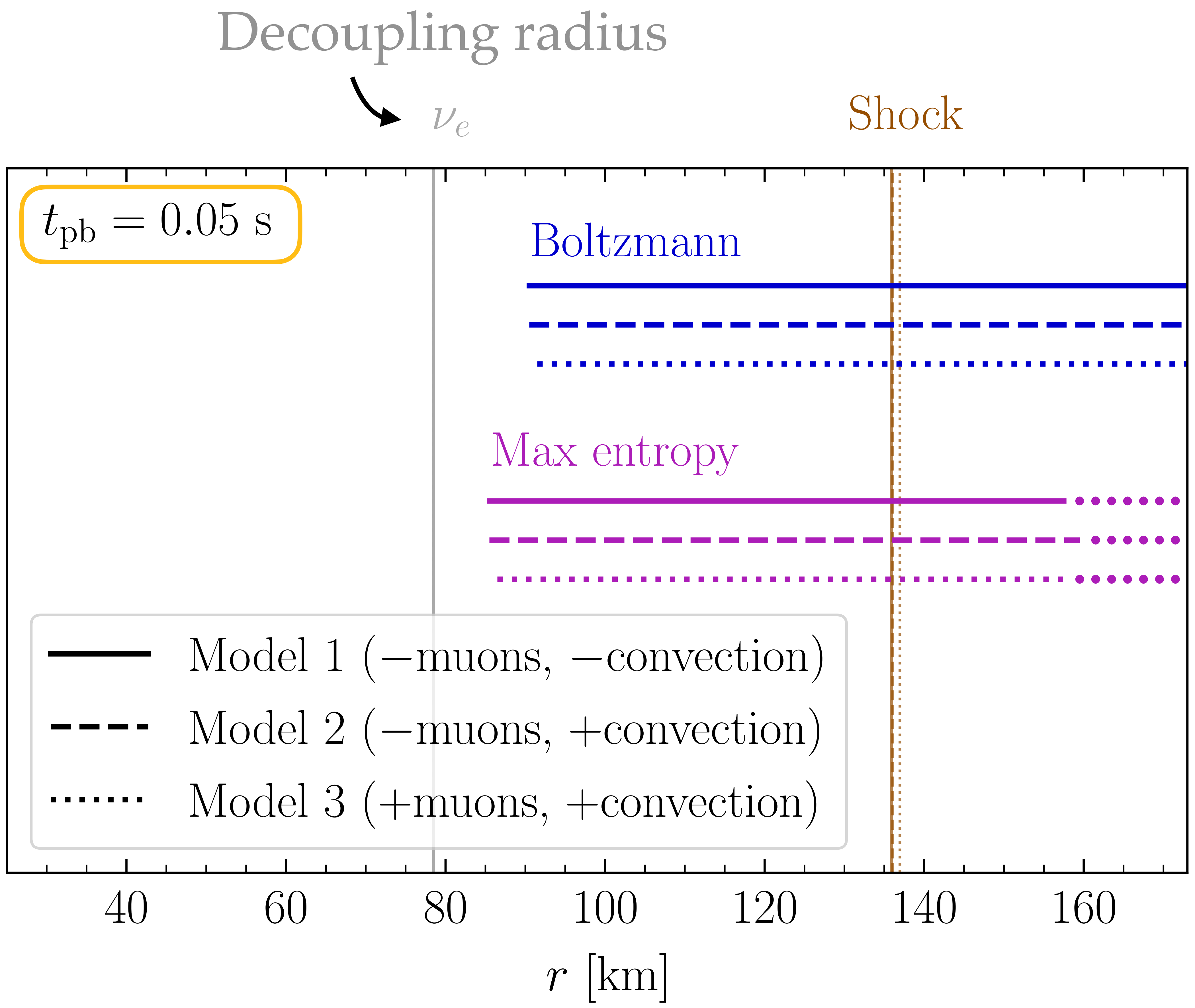
- Double crossings, distributions have wrong shape

Cornelius, Tamborra, Heinlein, Janka, arXiv:2506.20723

How well does each method perform?

(Forward crossings only)

- Boltzmann: crossings occur after neutrino decoupling and also above the shock
- Maximum entropy: reproduces most crossings
- Minerbo: detects no crossings



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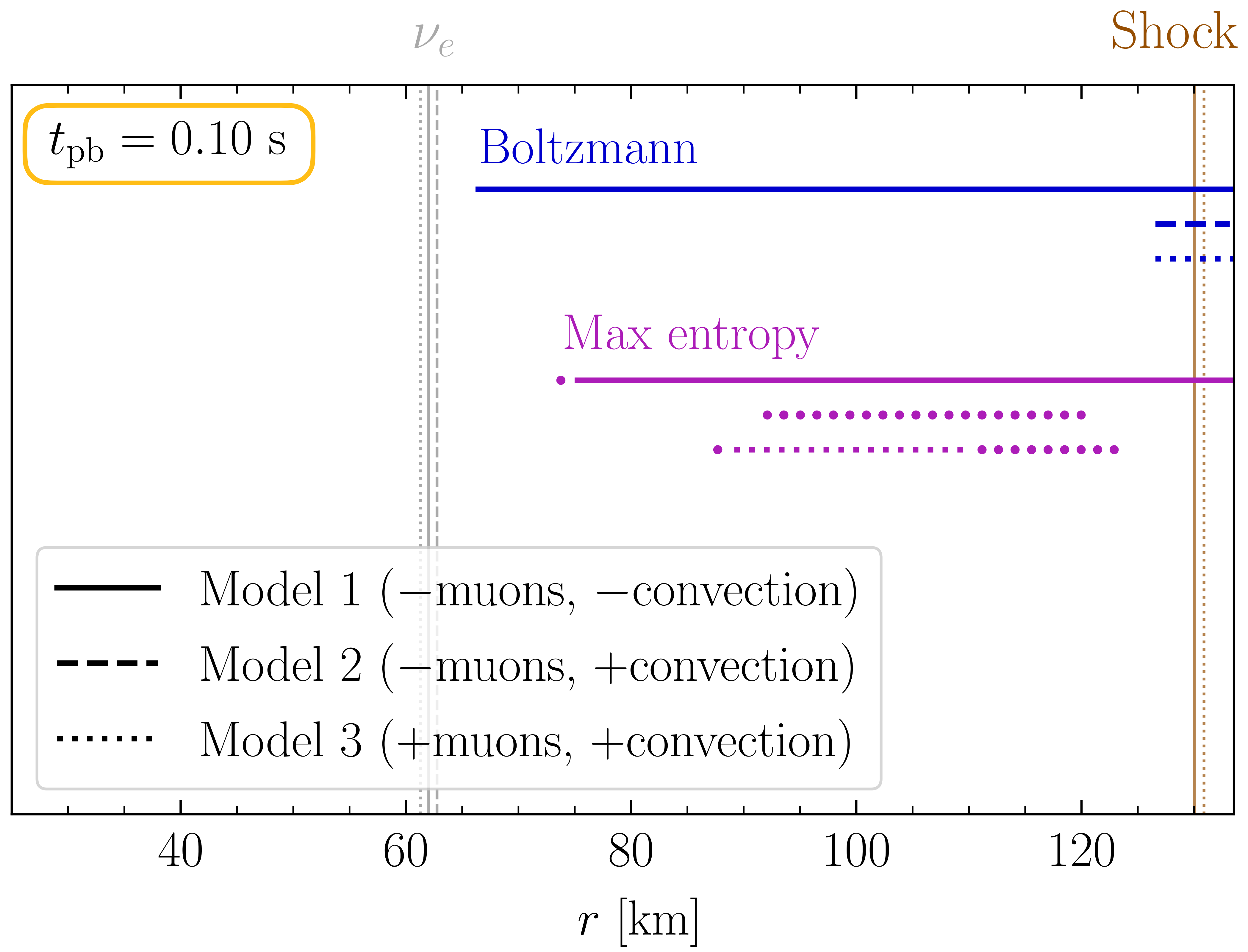
How well does each method perform?

(Forward crossings only)

- Boltzmann: crossings occur after neutrino decoupling for Model 1 → convection causes them to disappear!
- Maximum entropy: reproduces crossings for Model 1, misidentifies crossings for Model 2 and 3
- Minerbo: detects no crossings

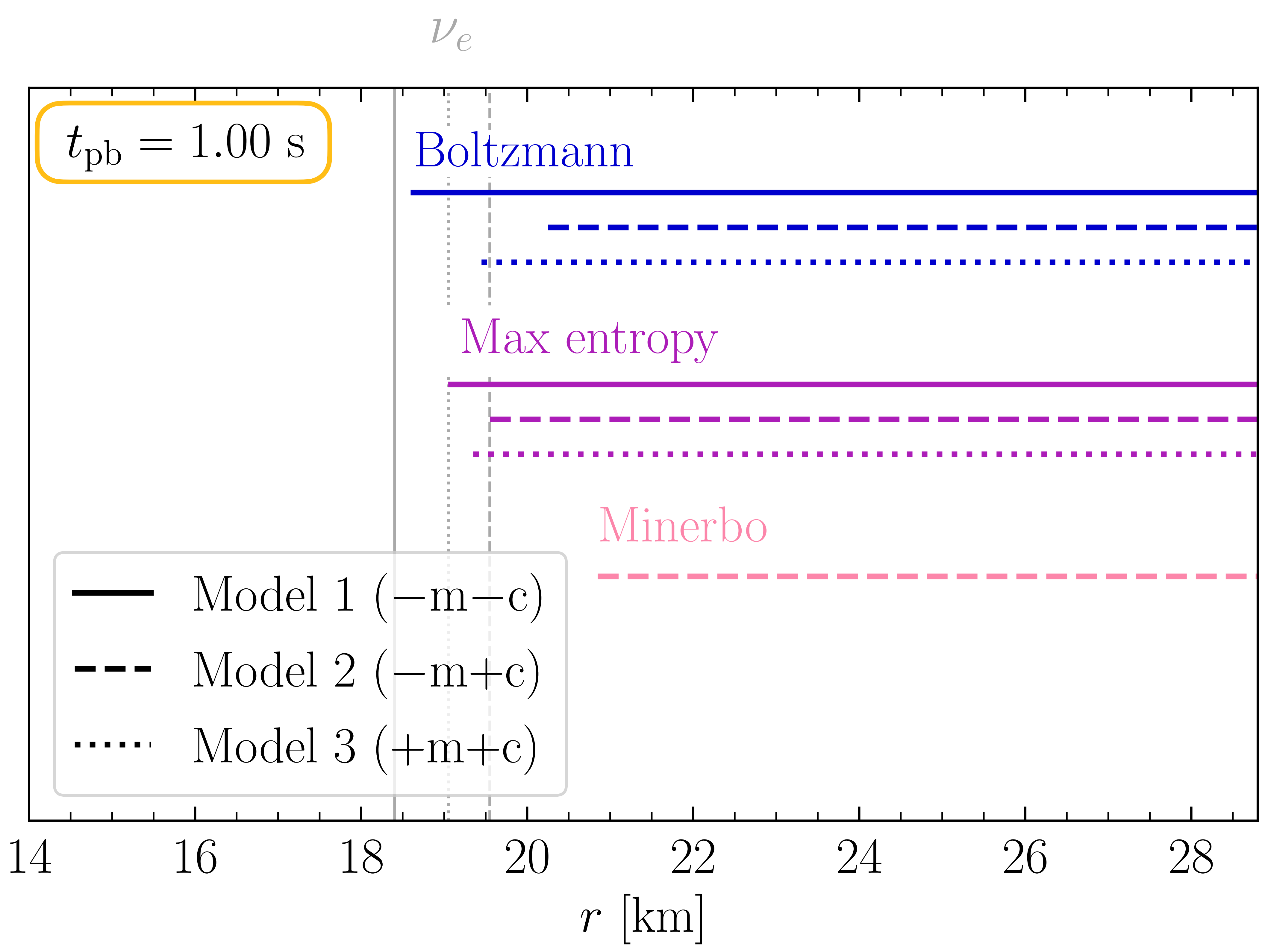


Cornelius, Tamborra, Heinlein, Janka, arXiv:2506.20723

How well does each method perform?

(Forward crossings only)

- Boltzmann: crossings after neutrino decoupling
- Maximum entropy: reproduces most crossings
- Minerbo: crossings for only Model 2



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Conclusions

- Fast neutrino flavor conversions can crucially impact the SN evolution
- They can develop when ELN crossings exist $\rightarrow$ we need angular information, or to reconstruct it in some way

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Conclusions

- Fast neutrino flavor conversions can crucially impact the SN evolution
- They can develop when ELN crossings exist → we need angular information, or to reconstruct it in some way
- Boltzmann: convection removes crossings at $t_{pb} = 0.1$ s, muons play no role
- Maximum entropy outperforms Minerbo method but it fails or misidentifies crossings in some cases
- Method accuracy depends on post-bounce time but is independent of muons and convection → overall, **none of the moment-based methods are trustworthy**

Back-up slides

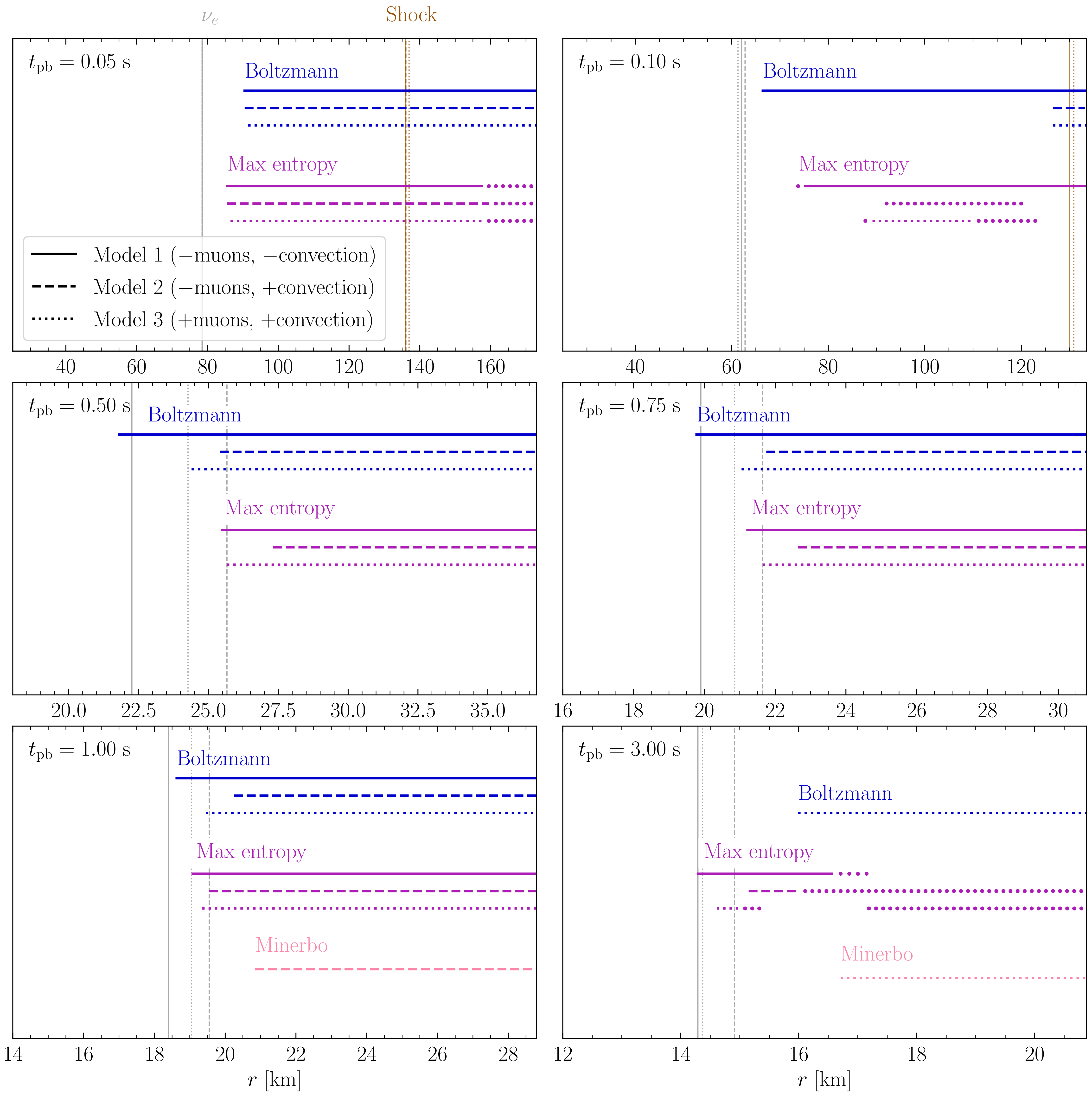
Boltzmann equation of neutrino transport

Neutrinos $$\left(\frac{\partial}{\partial t} + \vec{c} \cdot \vec{\nabla}\right) \rho \ = \ \mathcal{C}[\rho, \bar{\rho}]$$

Antineutrinos $$\left(\frac{\partial}{\partial t} + \vec{c} \cdot \vec{\nabla}\right) \bar{\rho} \ = \ \mathcal{C}[\rho, \bar{\rho}]$$

How well does each method perform?

(Forward crossings only)



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