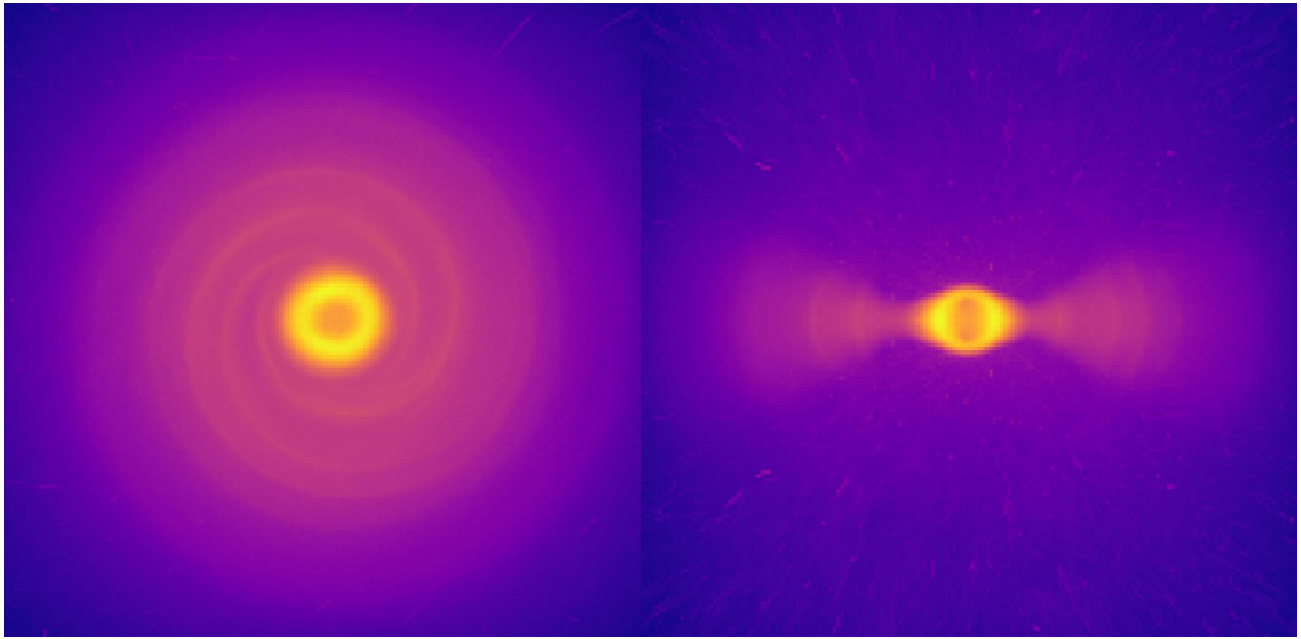
Neutrino-matter interactions in neutron star merger simulations



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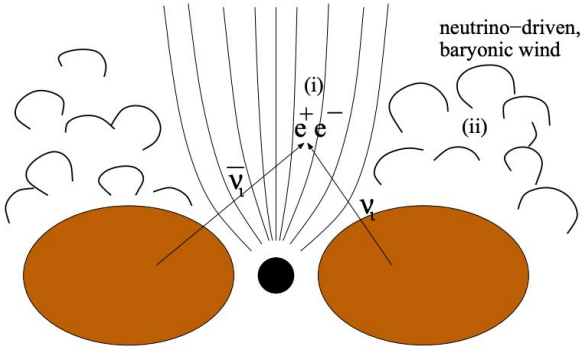
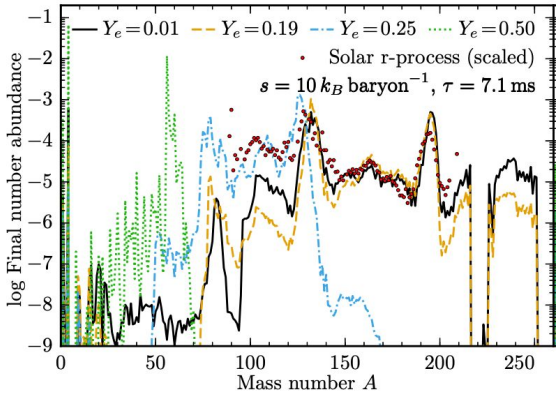
Why care about neutrinos in NS mergers?

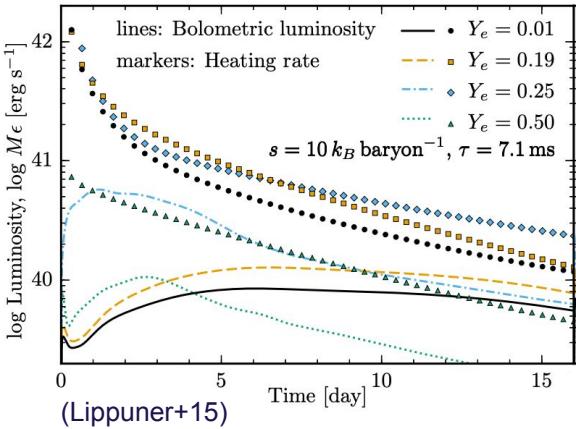
- r-process nucleosynthesis, kilonovae
  (Kasen+19, Eichler+19, Martin+18, Barnes+16, Metzger+10)
- short gamma-ray burst mechanism
  (Perego+17, Just+16, Zalamea+11, Richers+15, Eichler+89)



(Rosswog+03)

Very important to get the neutrino physics right!





(Lippuner+15)

Can we get the neutrino physics right?

Different transport methods

Light bulb, leakage,

FLD, M0, M1

VET, DO, MC

How reliable are the results of approximate methods?

Can we get the neutrino physics right?

Different transport methods
Light bulb, leakage,
FLD, M0, M1
VET, DO, MC

How reliable are the results of approximate methods?

Different interactions
Emission/absorption
Scattering
Oscillations

Which interactions are important to include?

The unreasonable effectiveness of Monte Carlo techniques

- Probabilistic solution, very accurate and very expensive.
  (Miller+19, Foucart+18, Richers+15, Abdikamalov+12, Keil+03, Yamada+99, Janka+91, Tubbs+78)

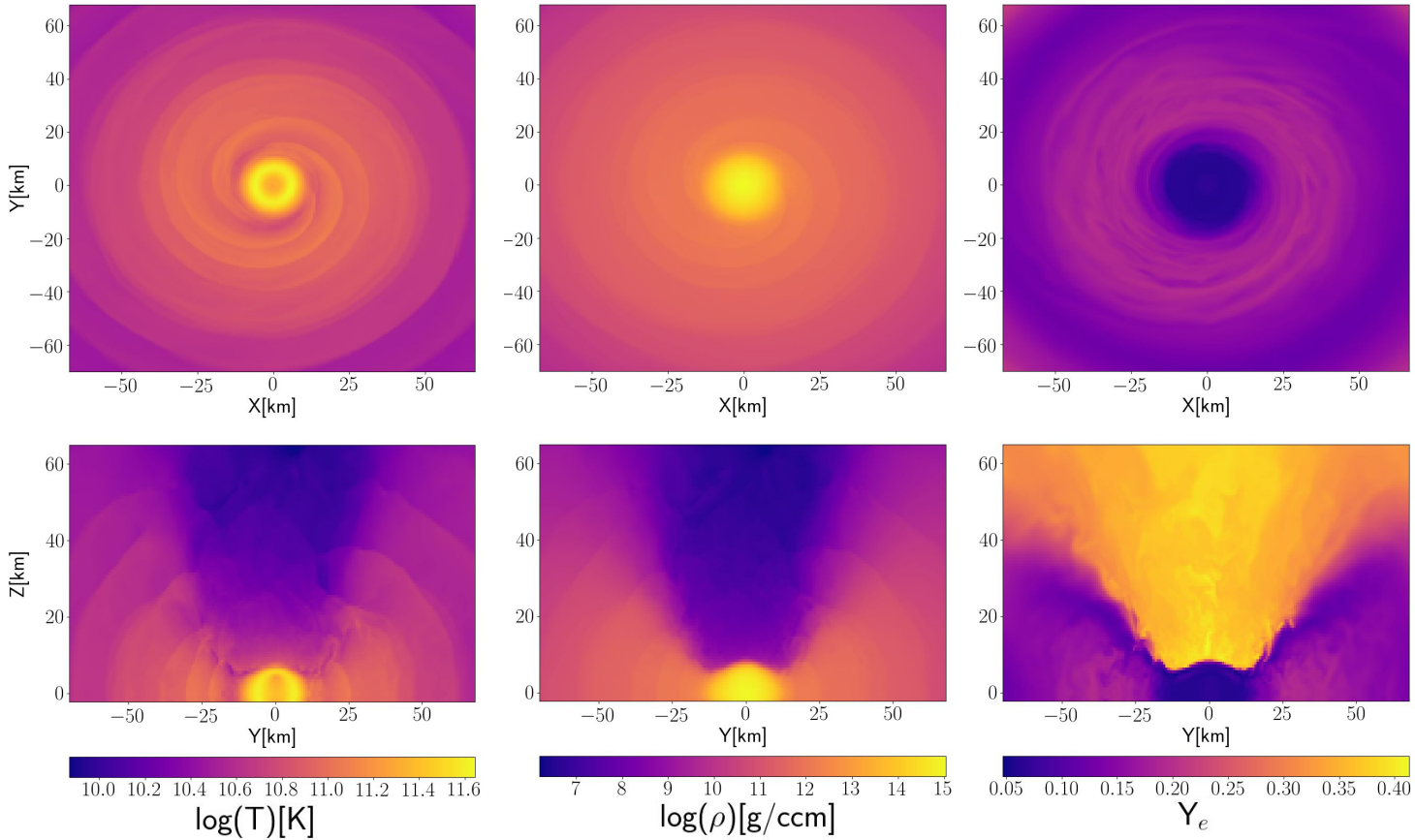
This study:

- MC neutrino transport on fluid snapshots from M0 simulations and compare results.
- Investigate importance of various neutrino interactions over broad parameter space.

SedonuGR: Time-independent MC transport

- General-relativistic Monte Carlo neutrino transport code.
- Emit neutrino ‘packets’. Propagate and scatter (with correct probability density functions!) till they escape or are absorbed.
- Neutrino-fluid interactions depend on (ρ, T, Ye, E_ν, S_ν). Tabulated rates from NuLib (nulib.org), given an EOS and set of interactions.

Fluid Snapshots



Post-merger snapshots

4 EOSs

Equal and unequal mass binaries

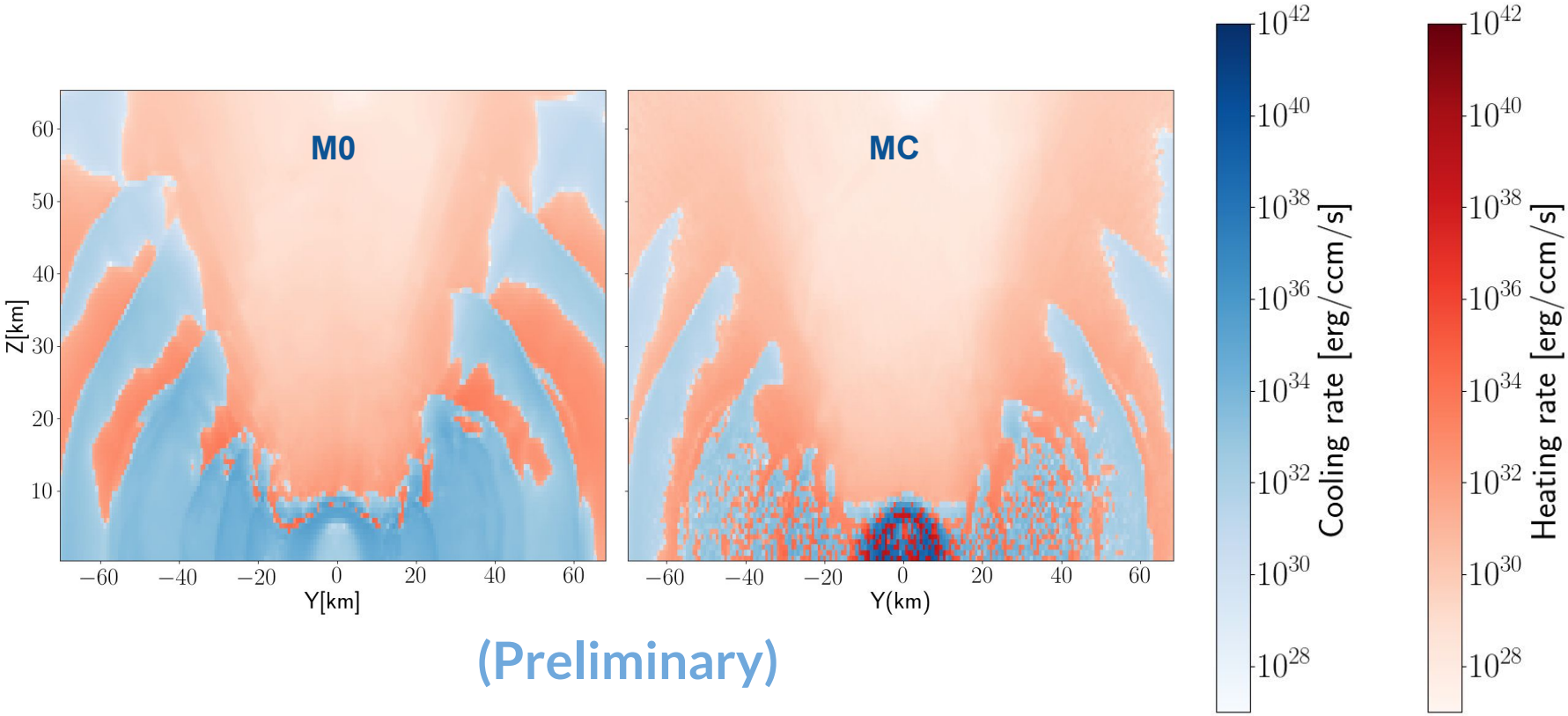
(Radice et al. 2018)

Questions:

1. How do results from dynamical M0 compare to MC?

2. Importance of:
(i) neutrino-electron inelastic scattering
(ii) neutrino pair-annihilation?

M0 and MC: heating and cooling rates



(Preliminary)

Questions:

1. How do results from dynamical M0 compare to MC?

2. Importance of:
(i) neutrino-electron inelastic scattering
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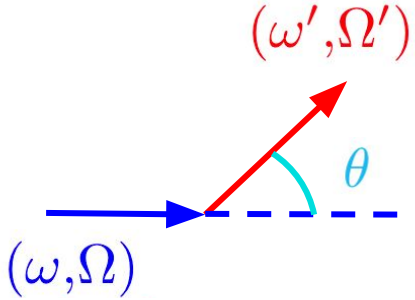
Neutrino-electron inelastic scattering

$$\kappa_s(\omega) = \frac{1}{h^3 c^4} \int d\left(\frac{\omega'^3}{3}\right) \int d\Omega' R(\omega, \omega', \mu)$$

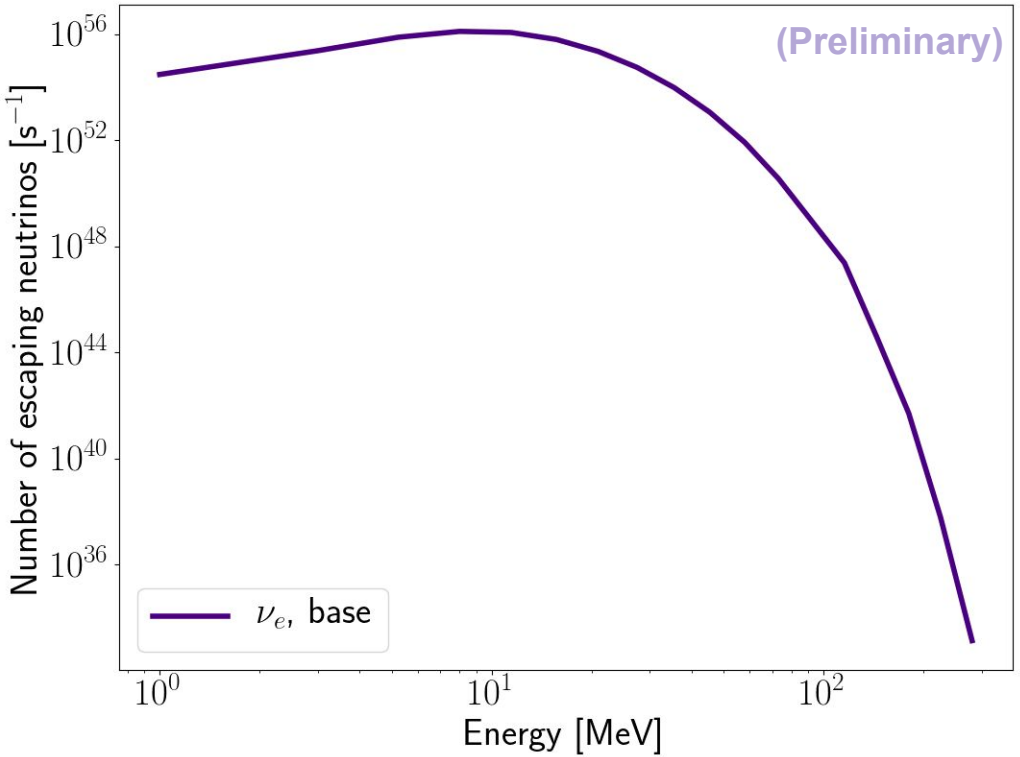
$$R(\omega, \omega', \mu) \approx \frac{1}{2}\Phi_0(\omega, \omega') + \frac{3}{2}\mu\Phi_1(\omega, \omega')$$



1. Pick random new energy (inelastic)
2. Pick random new direction (anisotropic)

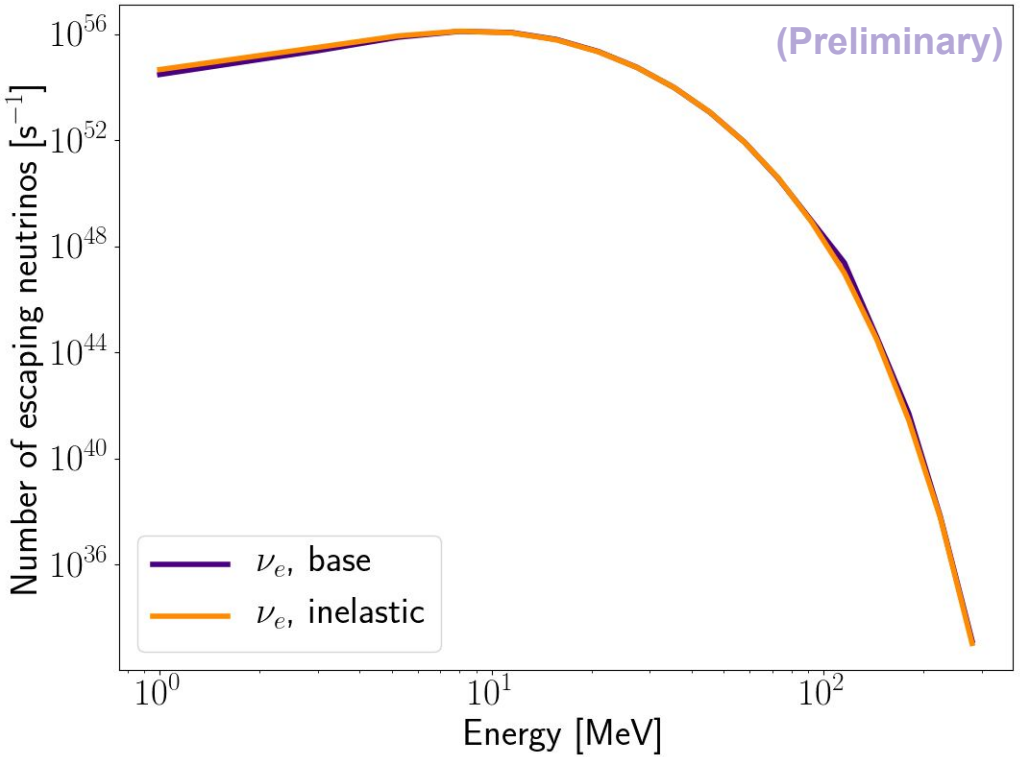
Neutrino-electron inelastic scattering

1. Electron flavor



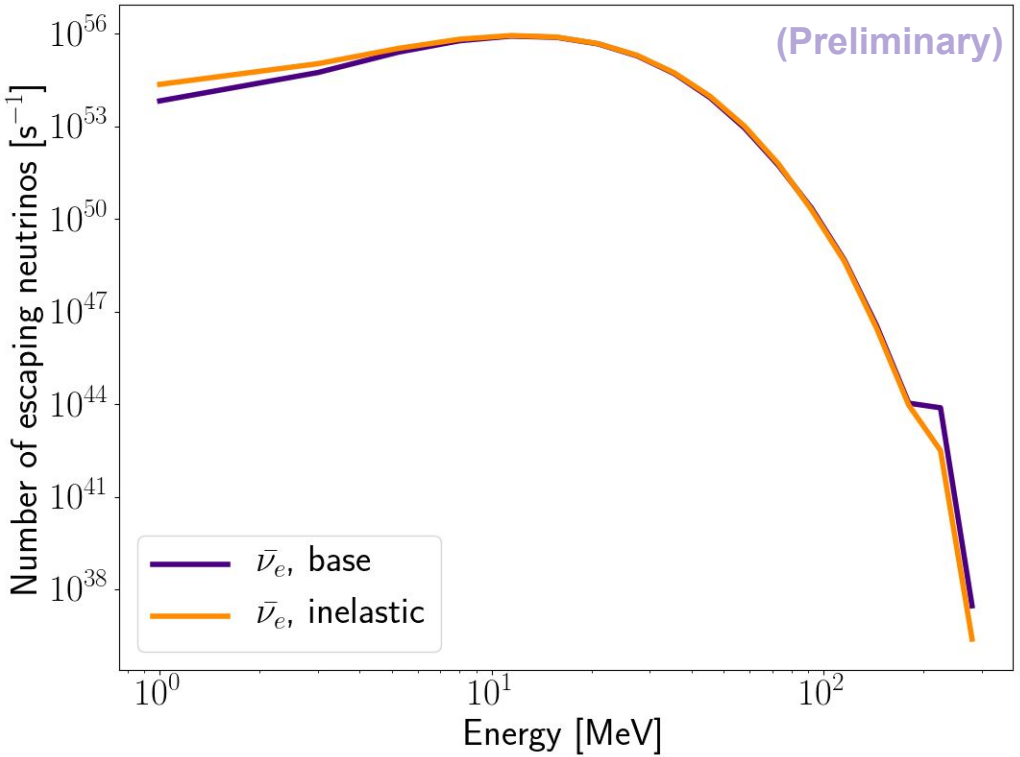
Neutrino-electron inelastic scattering

1. Electron flavor



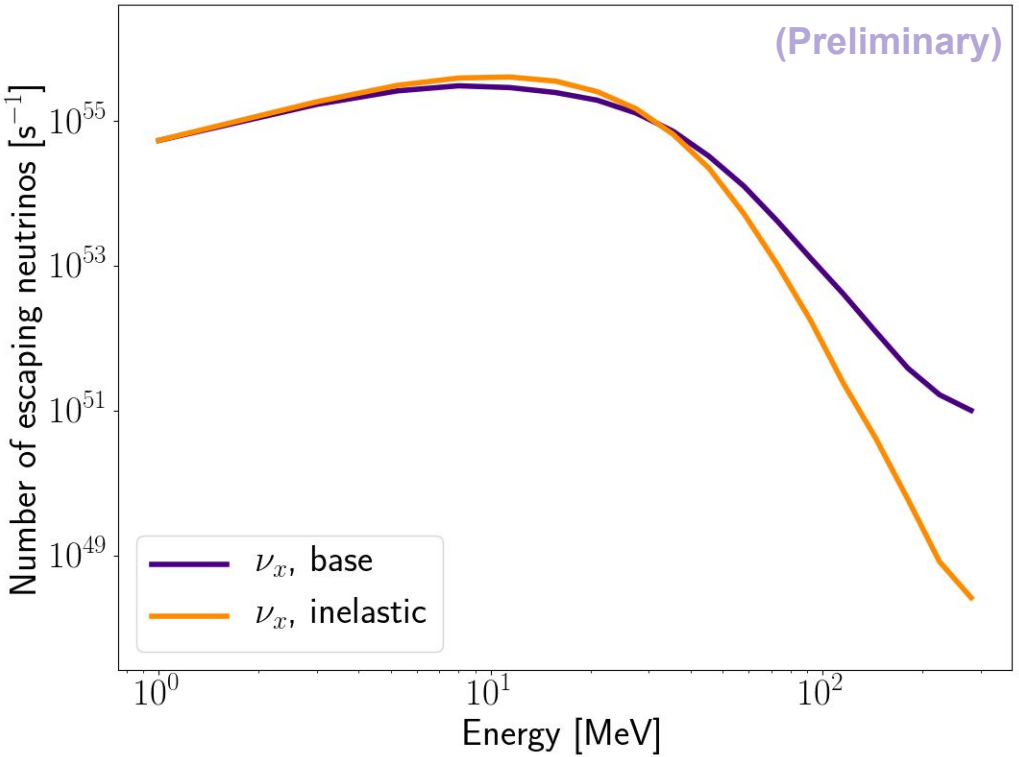
Neutrino-electron inelastic scattering

2. Anti-electron flavor



Neutrino-electron inelastic scattering

3. Heavy flavors



Questions:

1. How do results from dynamical M0 compare to MC?

2. Importance of:
(i) neutrino-electron inelastic scattering
(ii) neutrino pair-annihilation?

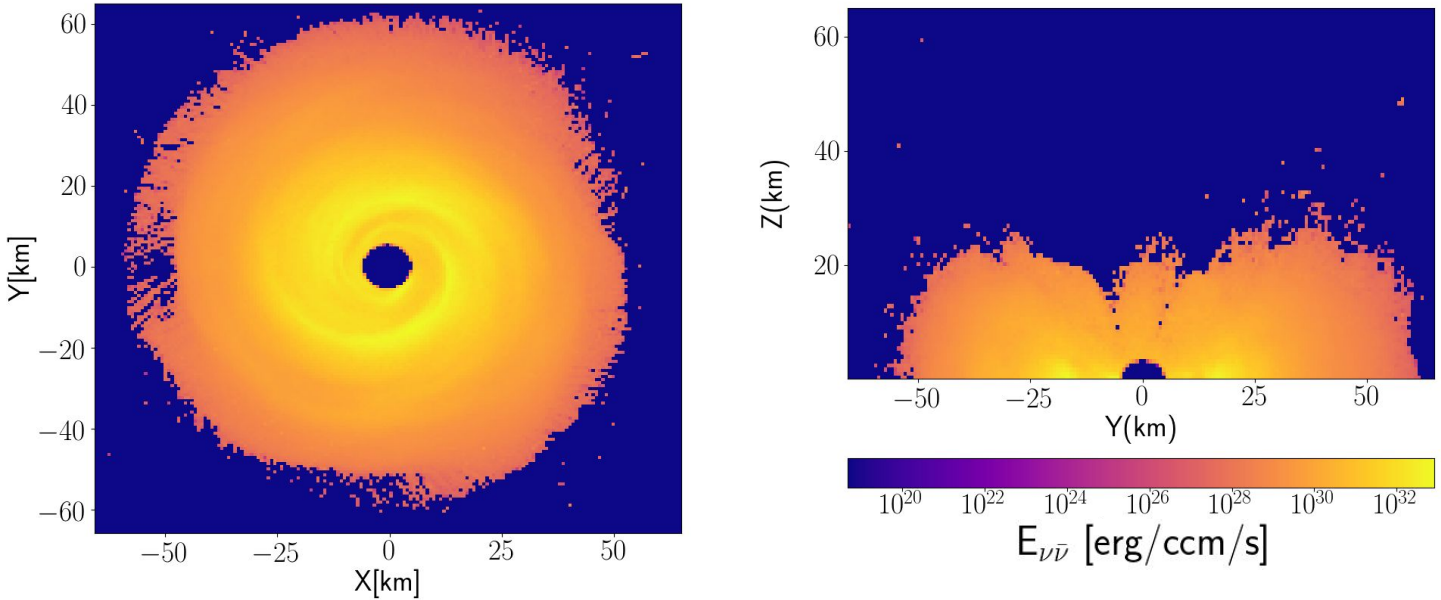
Estimating the energy deposited via neutrino pair-annihilation

$$\mathcal{F}^{\mu}_{\text{annihil}} = \int \widetilde{dp}_{(1)} \int \widetilde{dp}_{(2)} \int d\Omega_{(1)} \int d\Omega_{(2)} f_{(1)} f_{(2)} \left(p^{\mu}_{(1)} + p^{\mu}_{(2)} \right) \Phi(\cos\theta)$$

1. Reconstruct distribution function from moments
2. First two moments of annihilation kernel, guess third
3. Calculate annihilation rate for all species in a given cell
4. Multiply by four-volume of the cell to get energy deposited

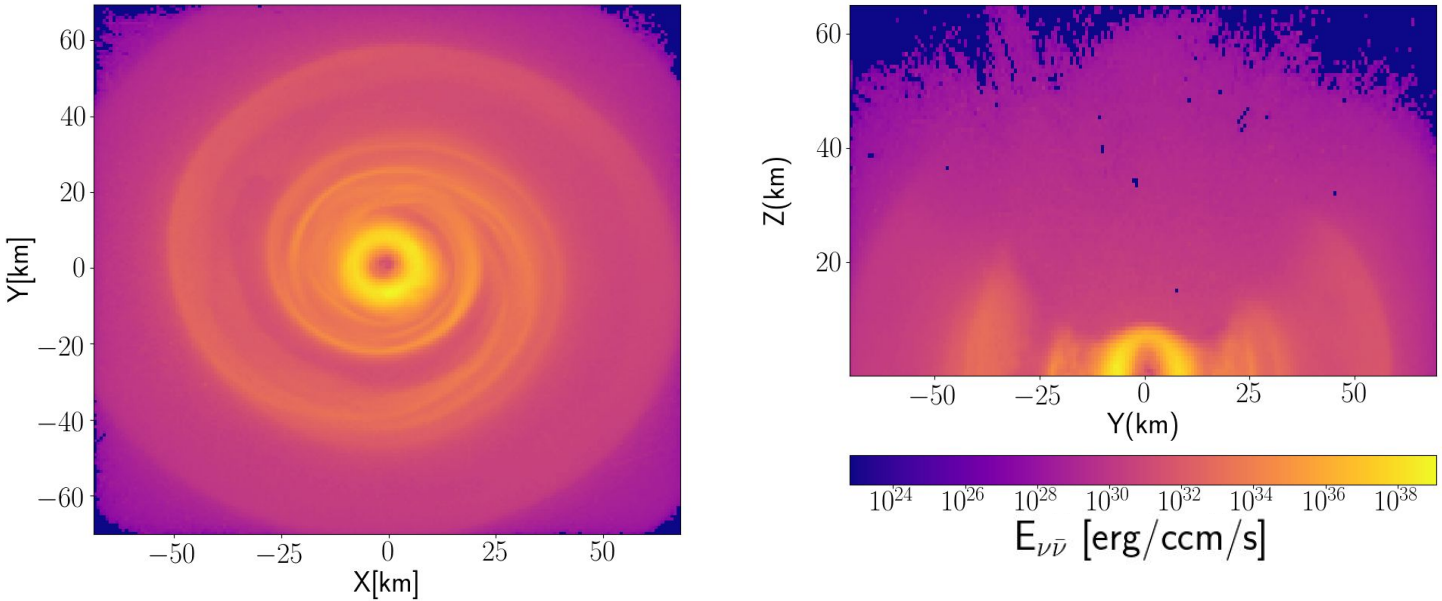
Can pair-annihilation power sGRB jet?

1. **BH case:** SFHo, M=1.35,1.35, t~25.9ms
   E(annihilation) = 1.14 x 10^{48} erg/s **(Preliminary)**
   (Just+16, Zalamea+11, Birkl+07, Kneller+06)



Can pair-annihilation power sGRB jet?

2. **HMNS case:** DD2, M=1.35,1.35, t~27.5ms
   E(annihilation) = 1.16 x 10^{50} erg/s **(Preliminary)**
   (Perego+17, Richers+15, Dessart+09)



Takeaways (and an invitation!)

- MC transport is well-suited for exploring neutrino-matter interactions in NS mergers.
- So far, we have looked at:
  1. MC-M0 comparison: order of magnitude consistent
  2. Neutrino-electron inelastic scattering: heavy flavors most affected
  3. Neutrino pair-annihilation: HMNS case needs further exploration
- In progress: unequal mass binaries, neutrino blocking effects
- **Suggestions?**

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Thank You