# Neutrino-Matter Interactions in Neutron Star Mergers

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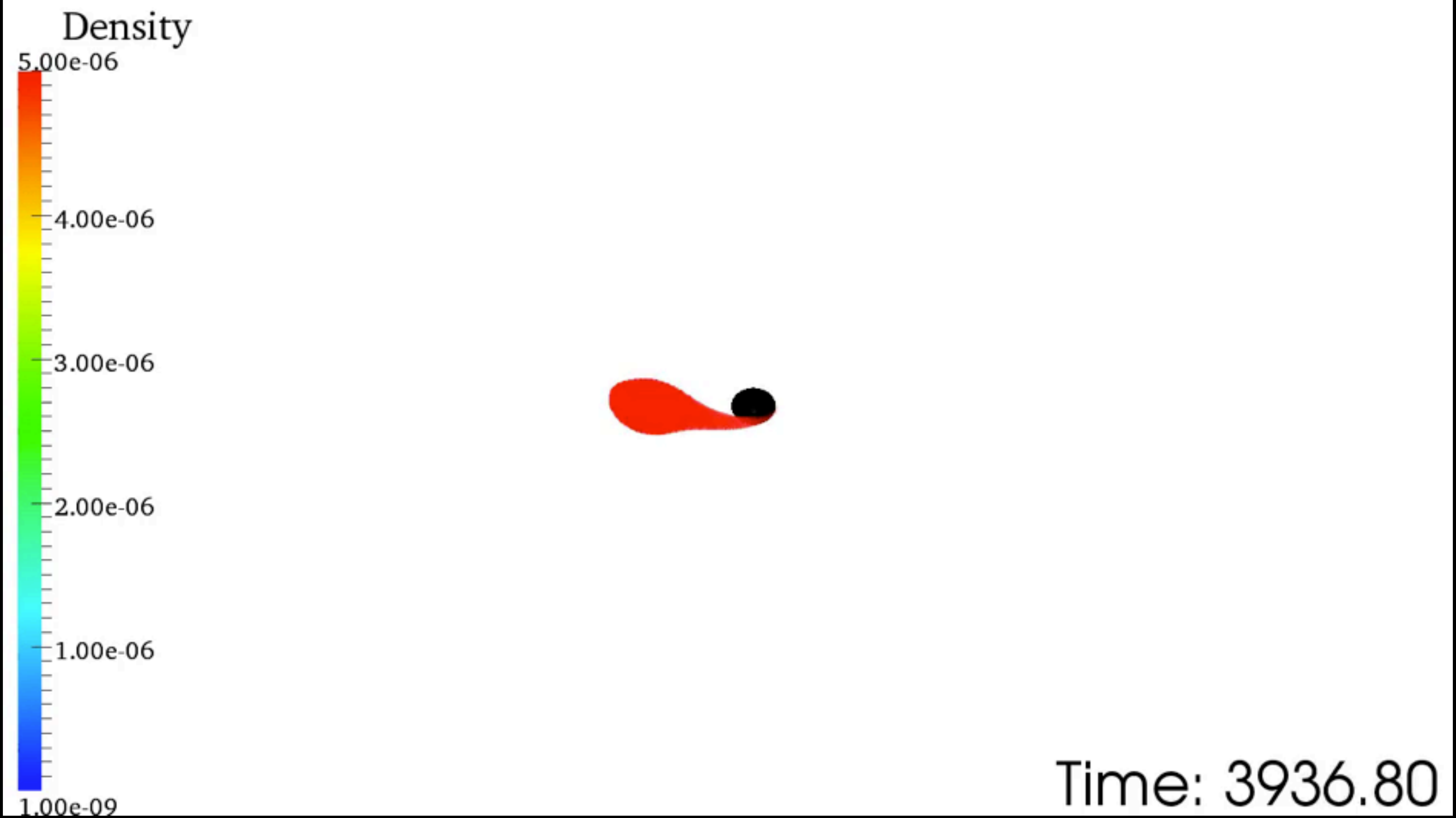
# Physical Setup



Movie from Lovelace et al. 2013

# Where do neutrinos matter?

- Neutrinos:
  - Cool the remnant accretion disk (under control)
  - Drive disk winds (maybe not that important?)
  - Set the composition of the ejecta, and thus
    - the outcome of **r-process nucleosynthesis**
    - the color/amplitude/duration of **kilonovae**
  - Deposit energy in low-density region (SGRB?)

# The neutrino problem

The full problem:

Boltzmann equations

$$p^\alpha \left[ \frac{\partial f_{(\nu)}}{\partial x^\alpha} - \Gamma^\beta_{\alpha\gamma} p^\gamma \frac{\partial f_{(\nu)}}{\partial p^\beta} \right] = \left[ \frac{df_{(\nu)}}{d\tau} \right]_{\mathrm{coll}}$$

with collision terms including
emission / absorption / scattering

**High cost**: (6+1)D problem

$$f_{(\nu)} = f(t, x^i, p^\alpha)$$

and **complex collision terms**, e.g.
Inelastic scattering
Neutrino-antineutrino annihilation

# Approximate Methods

- Cooling function: only in optically thin regime
- Leakage: good in optically thin regime, order of magnitude accurate otherwise
- **Moment formalism**: good in optically thick and semi-transparent regime. In the grey regime, lack of spectral information is an issue
- Beyond moments: **Monte-Carlo**, full transport

# Moment formalism (M1)

Relatively cheap, **approximate transport** method.

See Shibata et al. 2011, Foucart et al. 2015

Define moments (fluid frame):

$$J = \int d\nu \nu^3 \int d\Omega f_{(\nu)}(x^\alpha, \nu, \Omega)$$

$$H^\mu = \int d\nu \nu^3 \int d\Omega f_{(\nu)}(x^\alpha, \nu, \Omega) l^\mu$$

Transform to inertial frame:

$$T^{\mu\nu} = J u^\mu u^\nu + H^\mu u^\nu + H^\nu u^\mu + P^{\mu\nu}$$

$$T^{\mu\nu} = E n^\mu n^\nu + F^\mu n^\nu + F^\nu n^\mu + K^{\mu\nu}$$

**Exact evolution equations:**

$$\partial_t \tilde{E} + \partial_j \mathcal{F}^j = \text{sources}$$

$$\partial_t \tilde{F}_i + \partial_j \mathcal{P}_i^j = \text{sources}$$

**Approximate closure**

$$K^{\mu\nu} = \alpha K^{\mu\nu}_{\text{thick}} + (1-\alpha) K^{\mu\nu}_{\text{thin}}$$

using optically thin/thick limits

Sources include:

Curvature/redshift terms

**Emission/Absorption/Scattering**

Improvement:

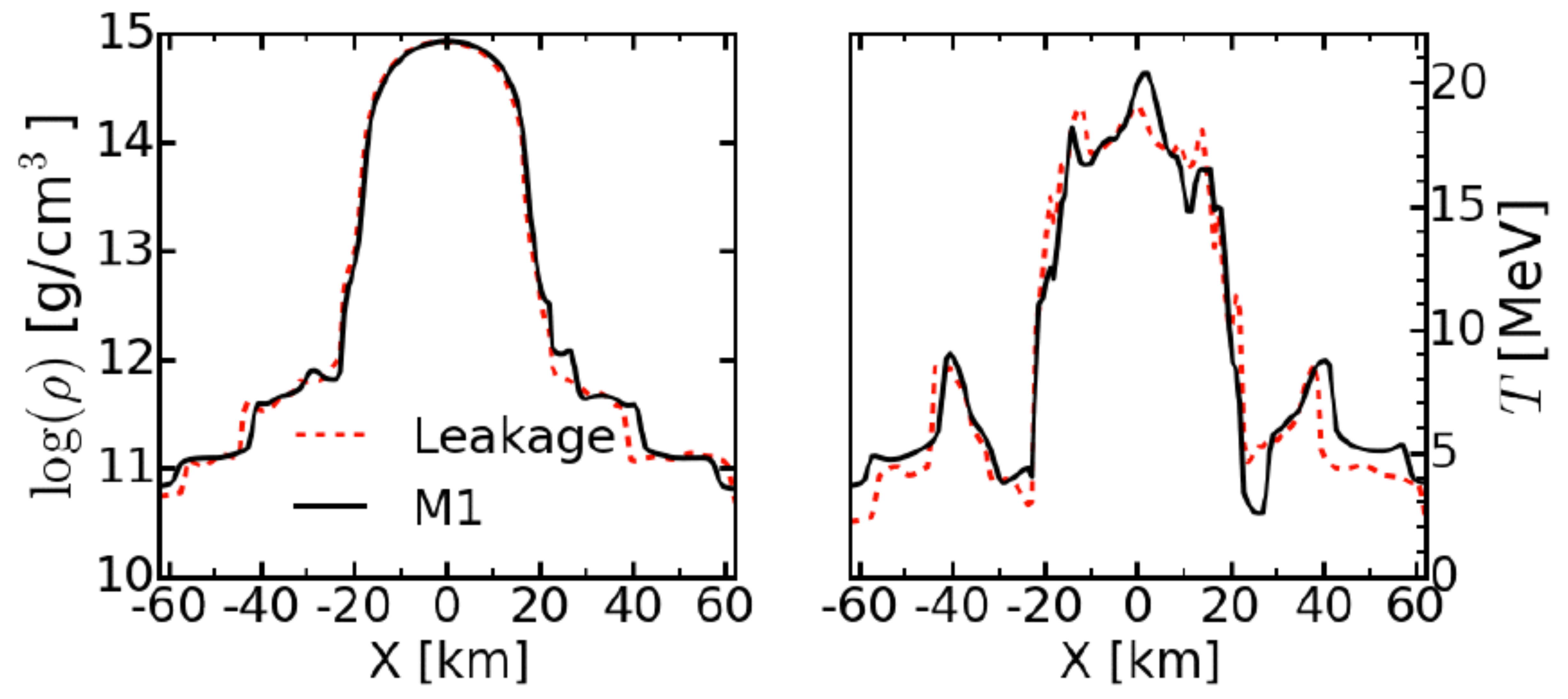
**Evolve number density**.

Provides information about ν

See Foucart et al. 2016b

# Qualified Success: NSNS mergers

1.2M⊙+1.2M⊙, LS220 EoS (Foucart+ 16,17)

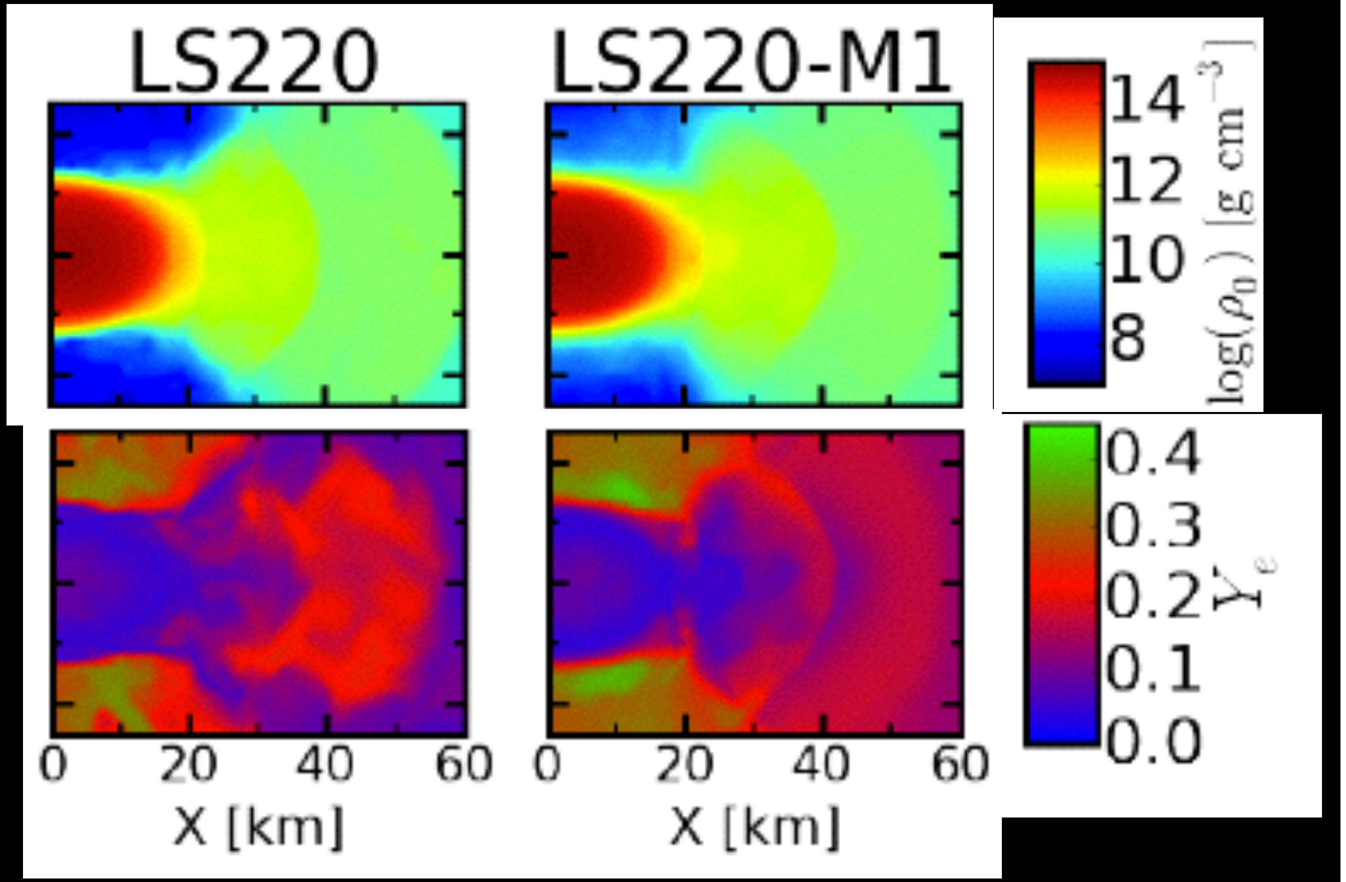


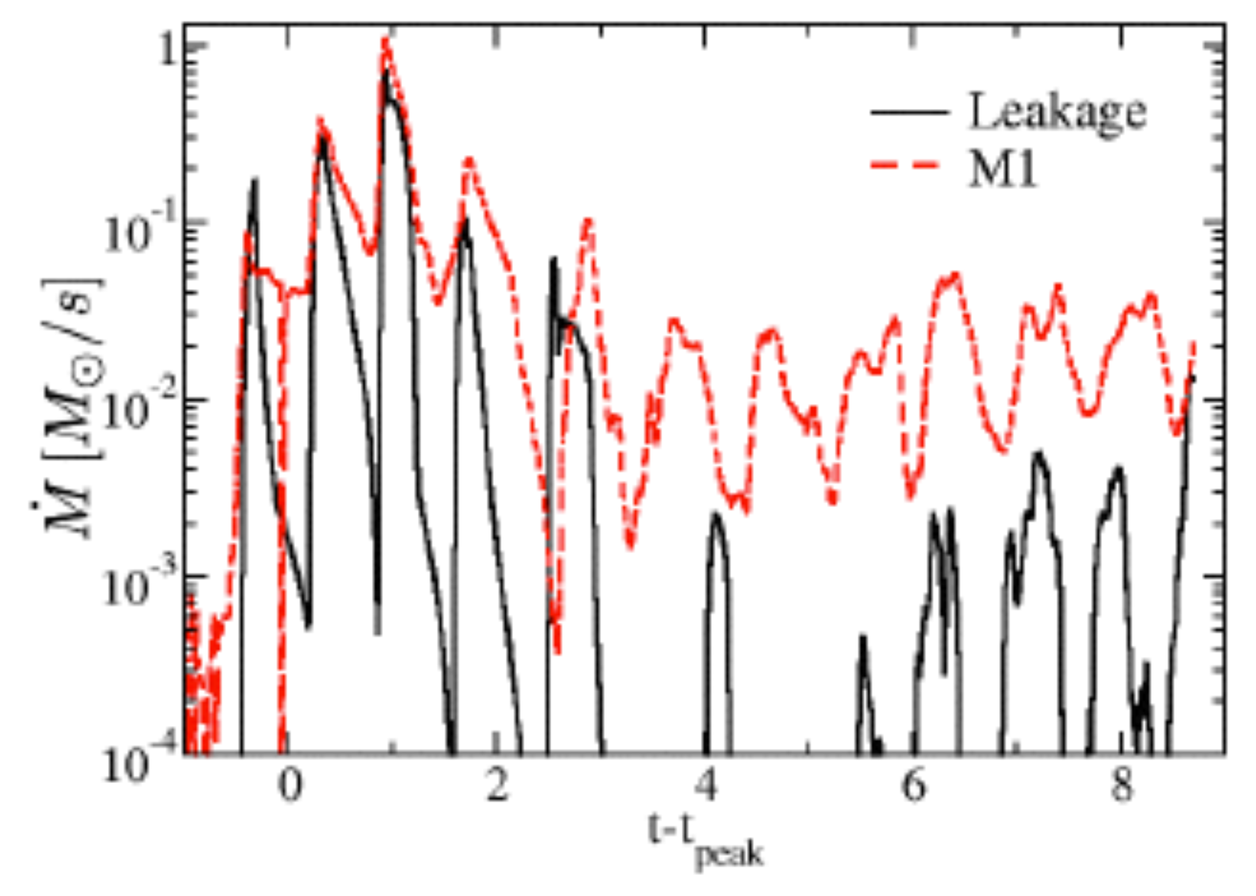
**Density and temperature**

of the remnant are reliable even with leakage

# Qualified Success: NSNS mergers

1.2M$_\odot$+1.2M$_\odot$, LS220 EoS (Foucart+ 16,17)



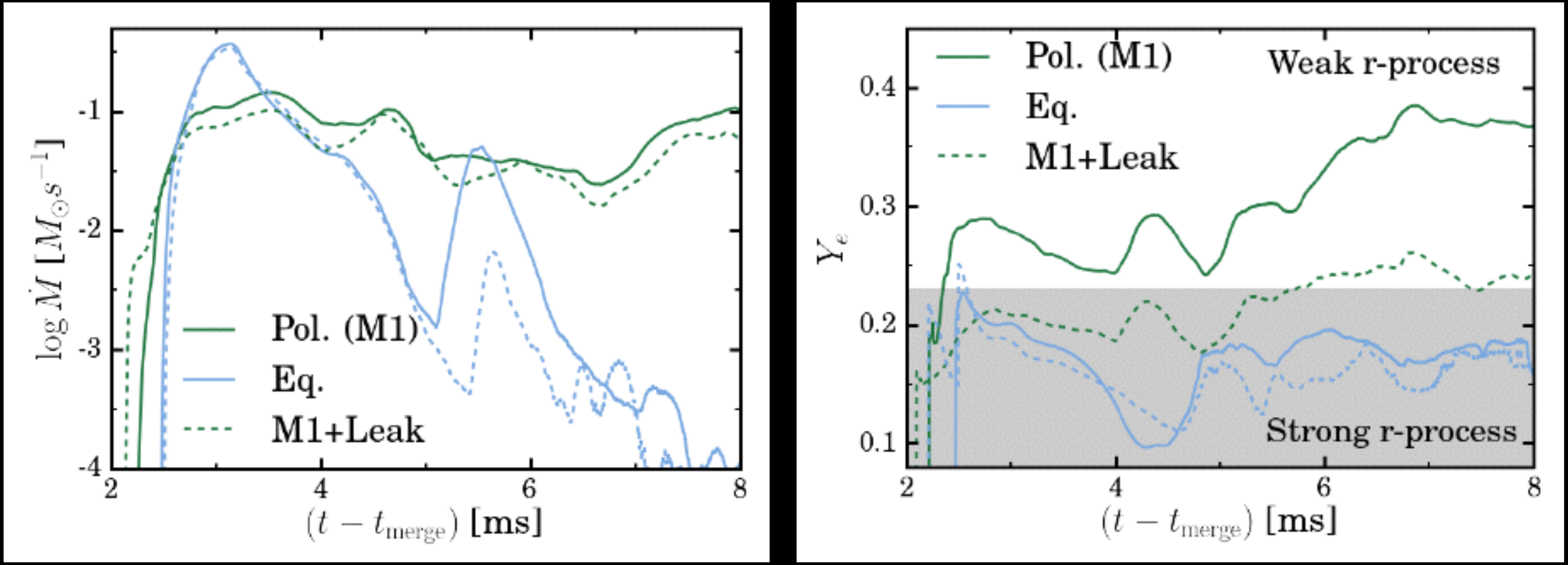


**Electron fraction and polar outflows**
are unreliable when using leakage

# Qualified Success: NSNS mergers

1.2M⊙+1.2M⊙, LS220 EoS (Foucart+ 16,17)

Compare **different energy estimates** in M1:



**Outflow mass, composition of equatorial outflows** now converge. **Composition of polar outflows** is uncertain

# Pair annihilation

- Neutrino-Antineutrino annihilation can deposit ~(0.001-0.01) $L_\nu$ in polar regions
- Annihilation rate depends on neutrino orientations, which is unknown in M1 scheme
- Post-processing with transport codes provides information about energy deposition
- Back-reaction on fluid/jet requires on-the-fly computation!

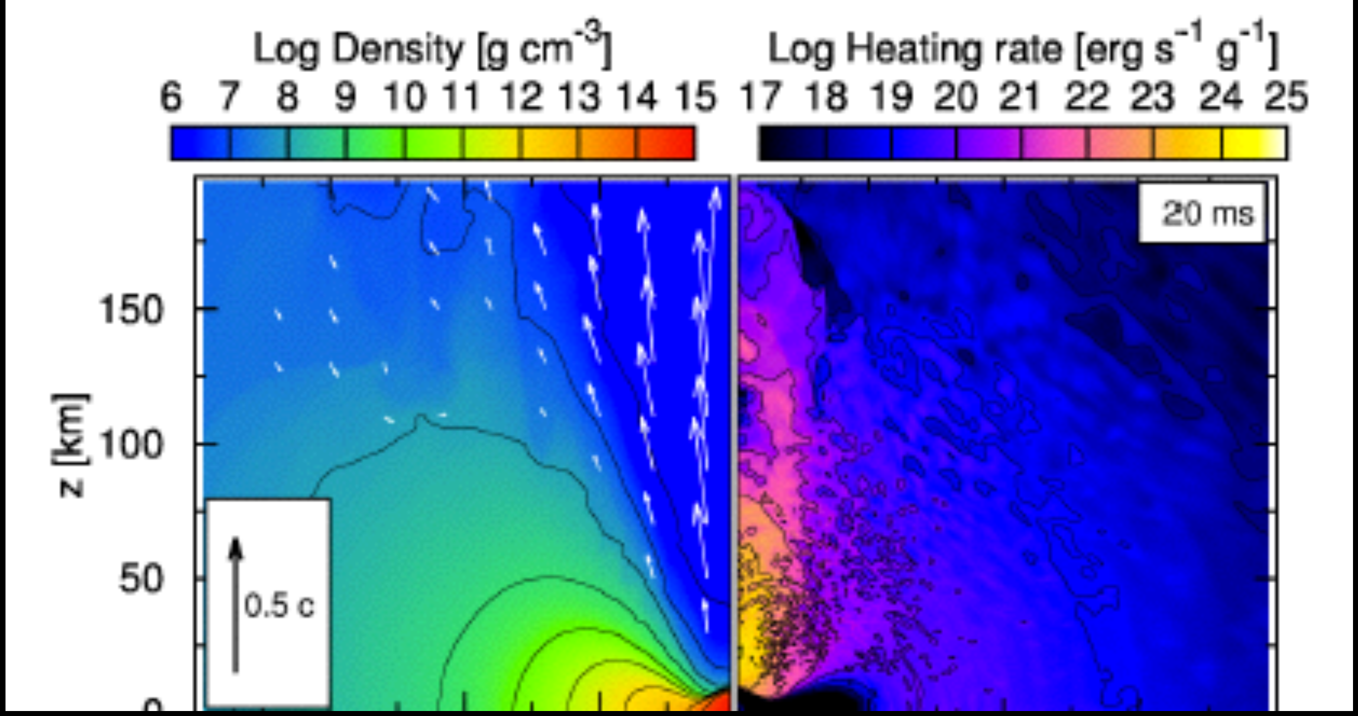


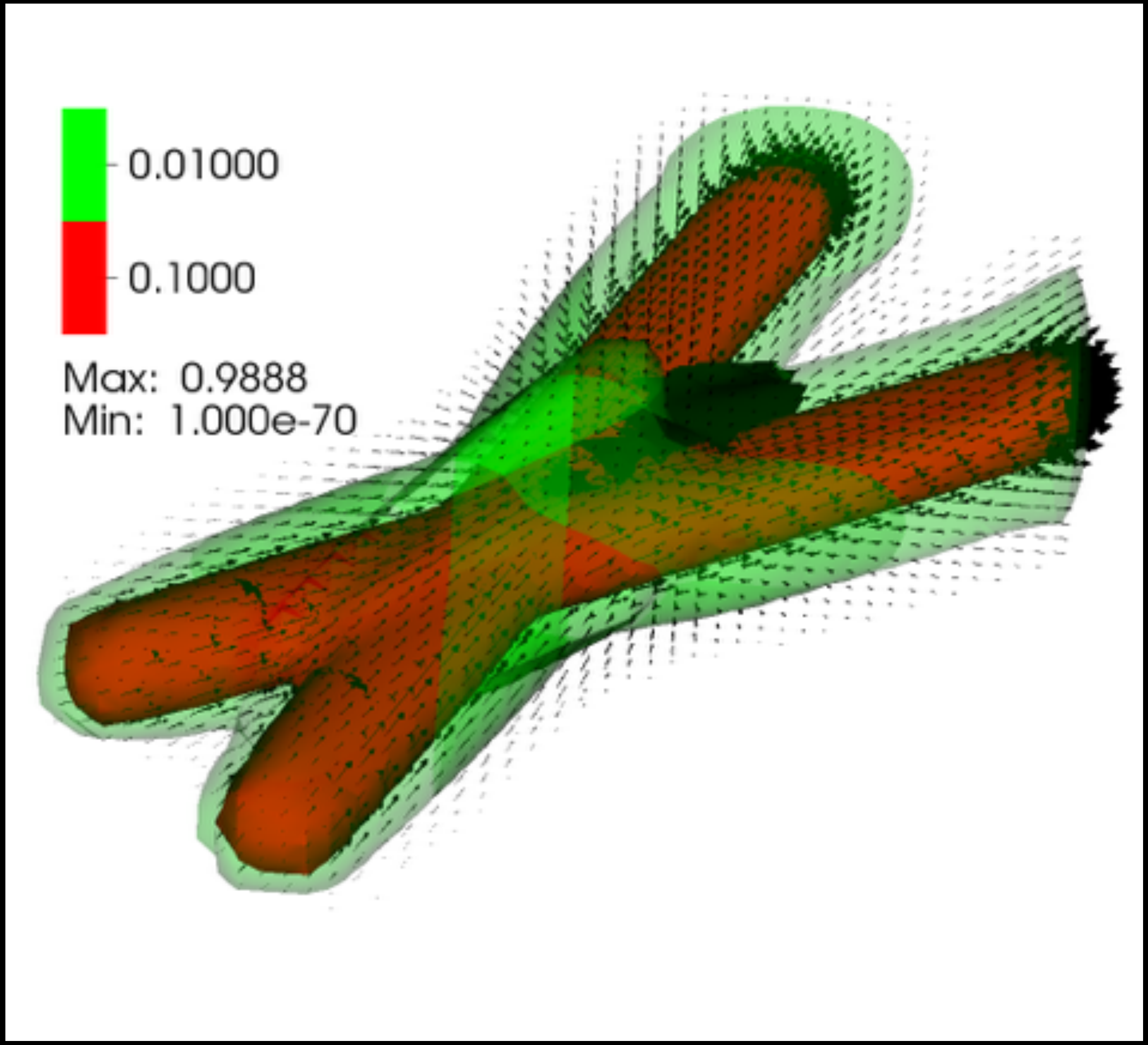
Image: Fujibayashi et al. 2017

# Can we go further?

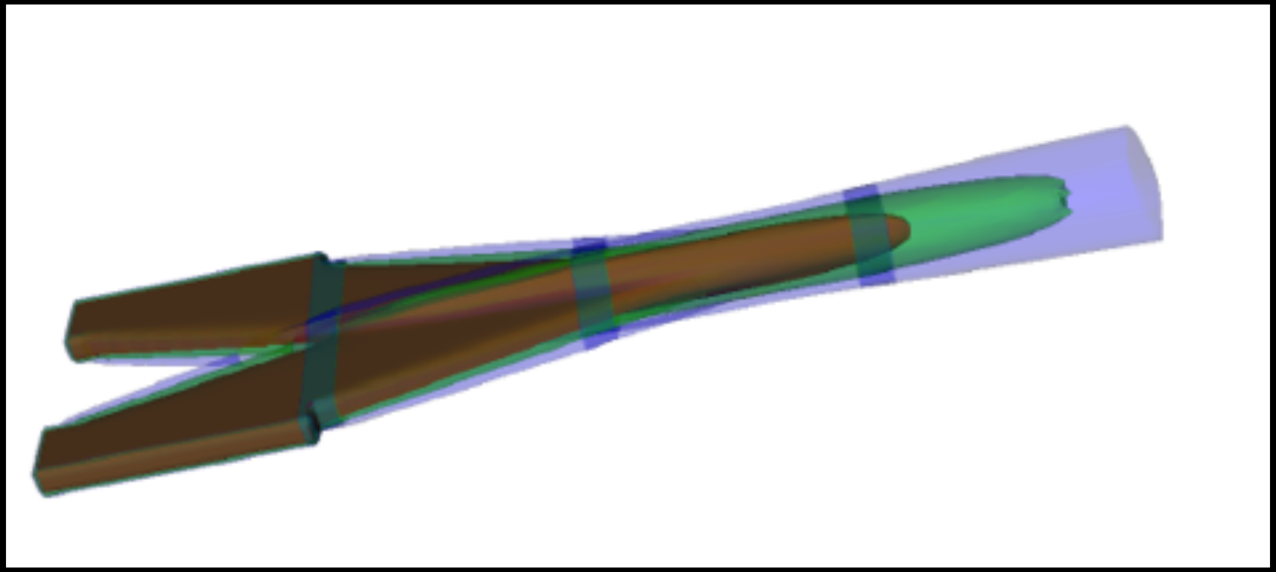
- One possibility: Monte-Carlo (MC) as closure
  - Too expensive to run MC with high-accuracy at all times
  - Noise in low-resolution MC simulation could be an issue
  - Could run MC rarely on time-independent snapshots
  - **Could run MC with low number of particles** and get a time-averaged distribution function
  - **No need to do MC in optically thick regions!**
  - Can provide information needed for pair annihilation

# Proof of principle: two beams problem

MC vs M1



(Foucart, in prep)



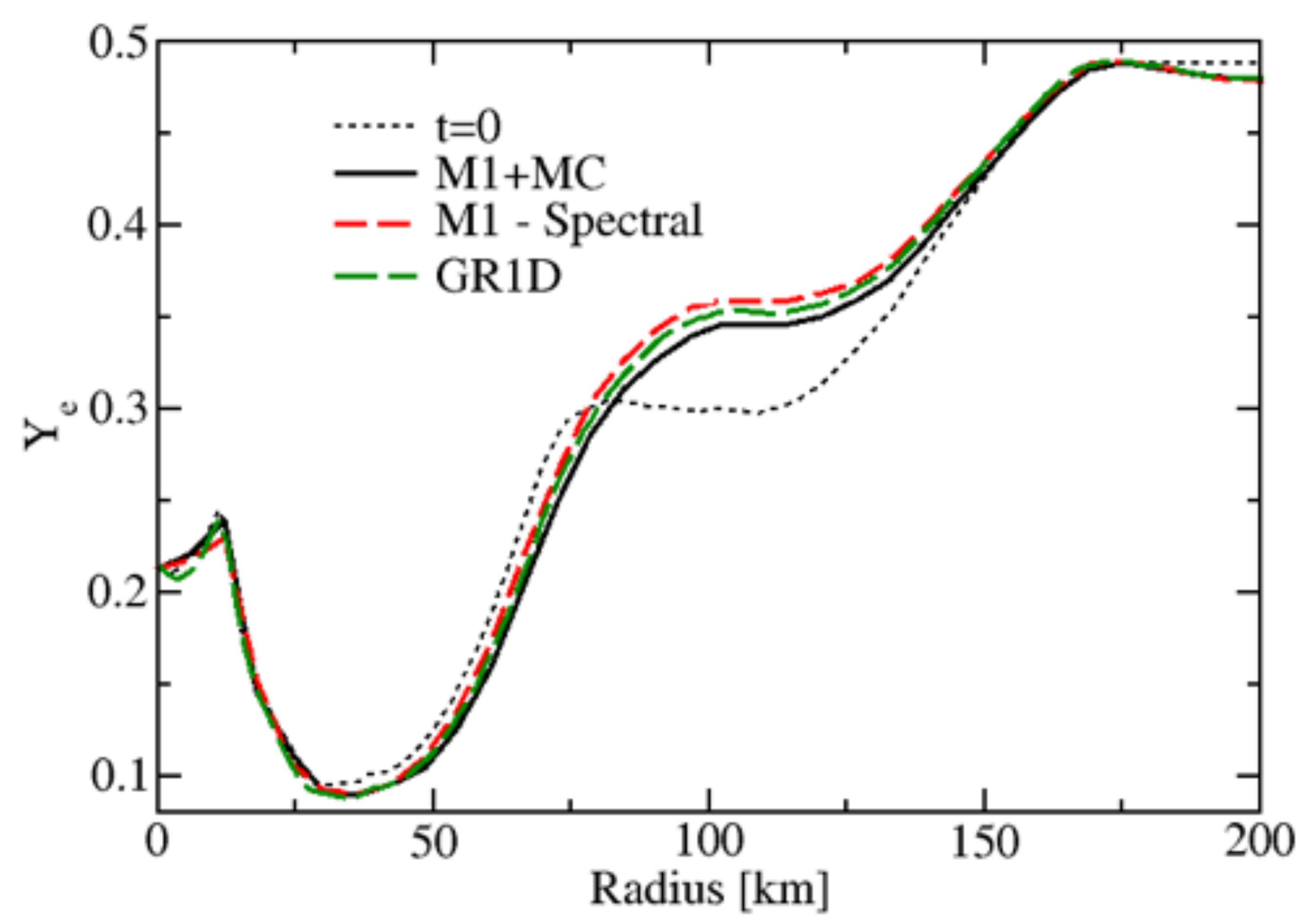
M1 closure causes radiation shock

MC closure (nearly) avoids interactions

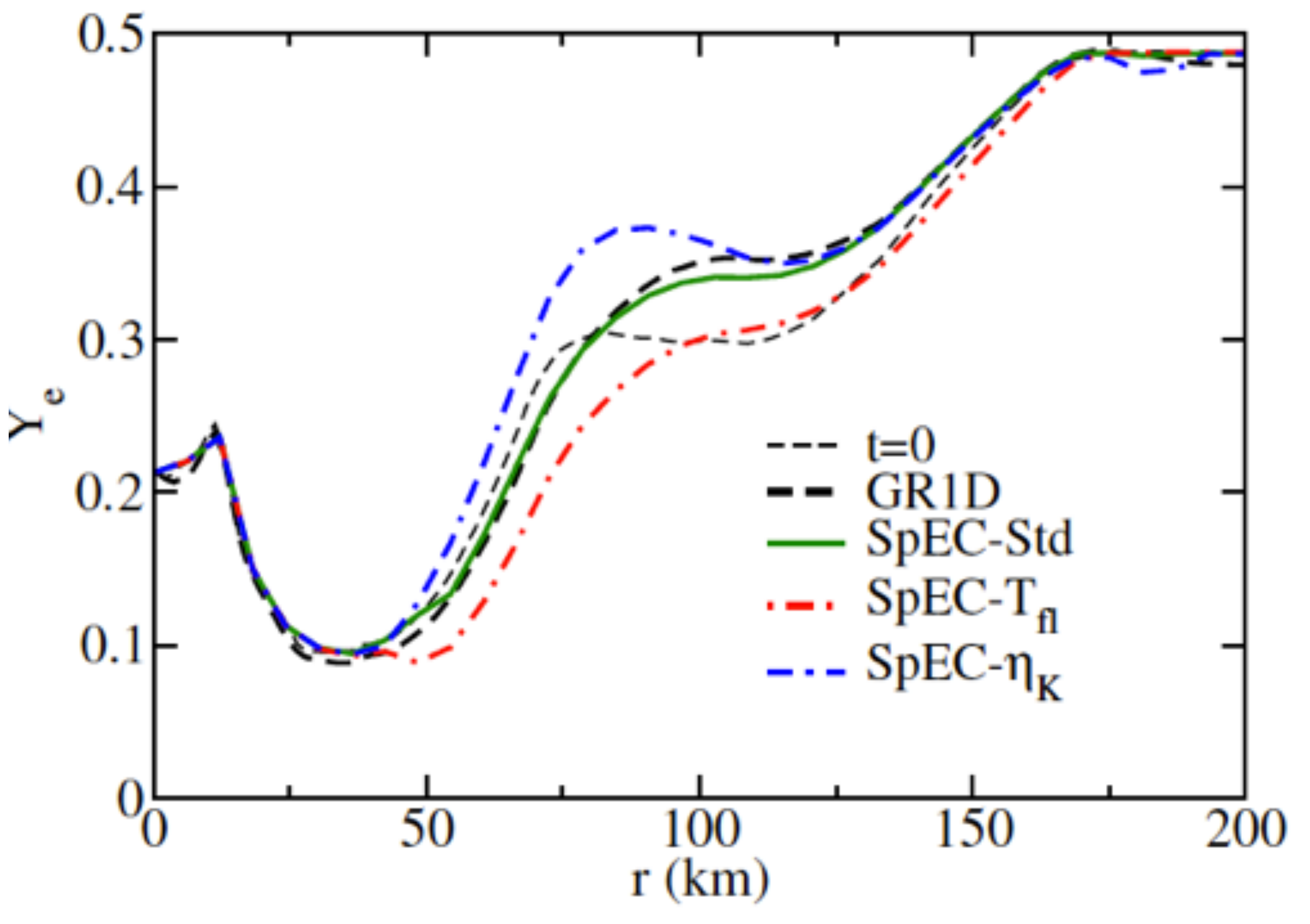
# Proof of principle

Composition after 8ms of evolution of a core-collapse profile
Very low resolution simulations (dx~6km)

M1 vs M1+MC



Different M1 methods

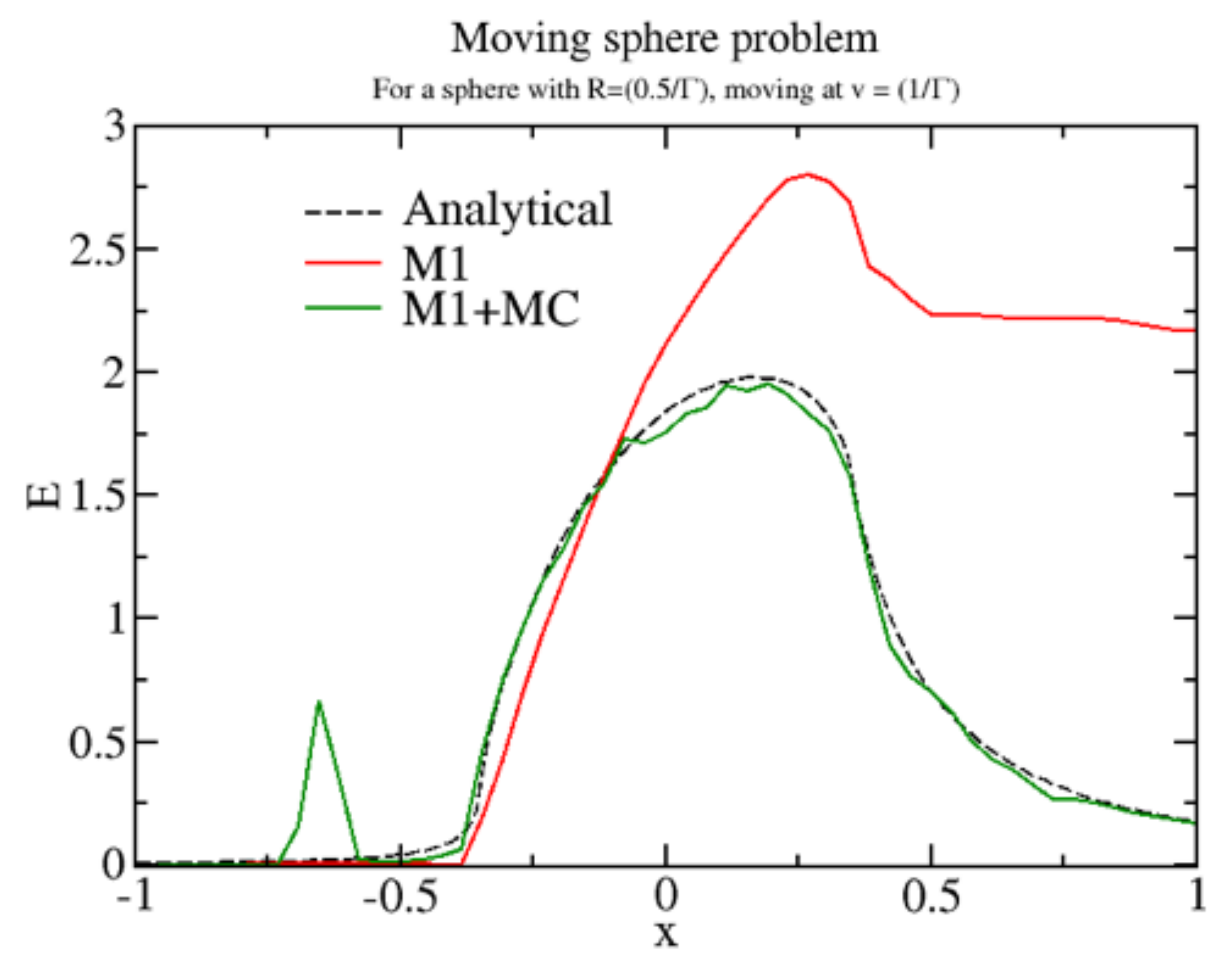


(Foucart, in prep)

MC also provides spectral information,
in good agreement with spectral M1

# Pitfalls and limitations

- Time averaging could introduce artifacts for low number of particles
- Choices made at the interface between optically thick regions (where MC is not active) and regions in which MC is active has to be studied.
- Parallelization will be non-trivial (and hasn't been done)
- M1 and MC can get out of sync, leading to closure inconsistent with M1 evolution



For ~50 part./cell at peak E

(Foucart, in prep)

# Conclusions

- Neutrino-matter interactions are important but expensive to compute
- How much to spend depends on the question asked
  - Remnant properties captured by leakage
  - Outflow masses captured with any M1 scheme
  - Outflow composition needs spectral information
  - Pair annihilation requires MC or full transport
    - To get energy deposition, post-processing is good enough