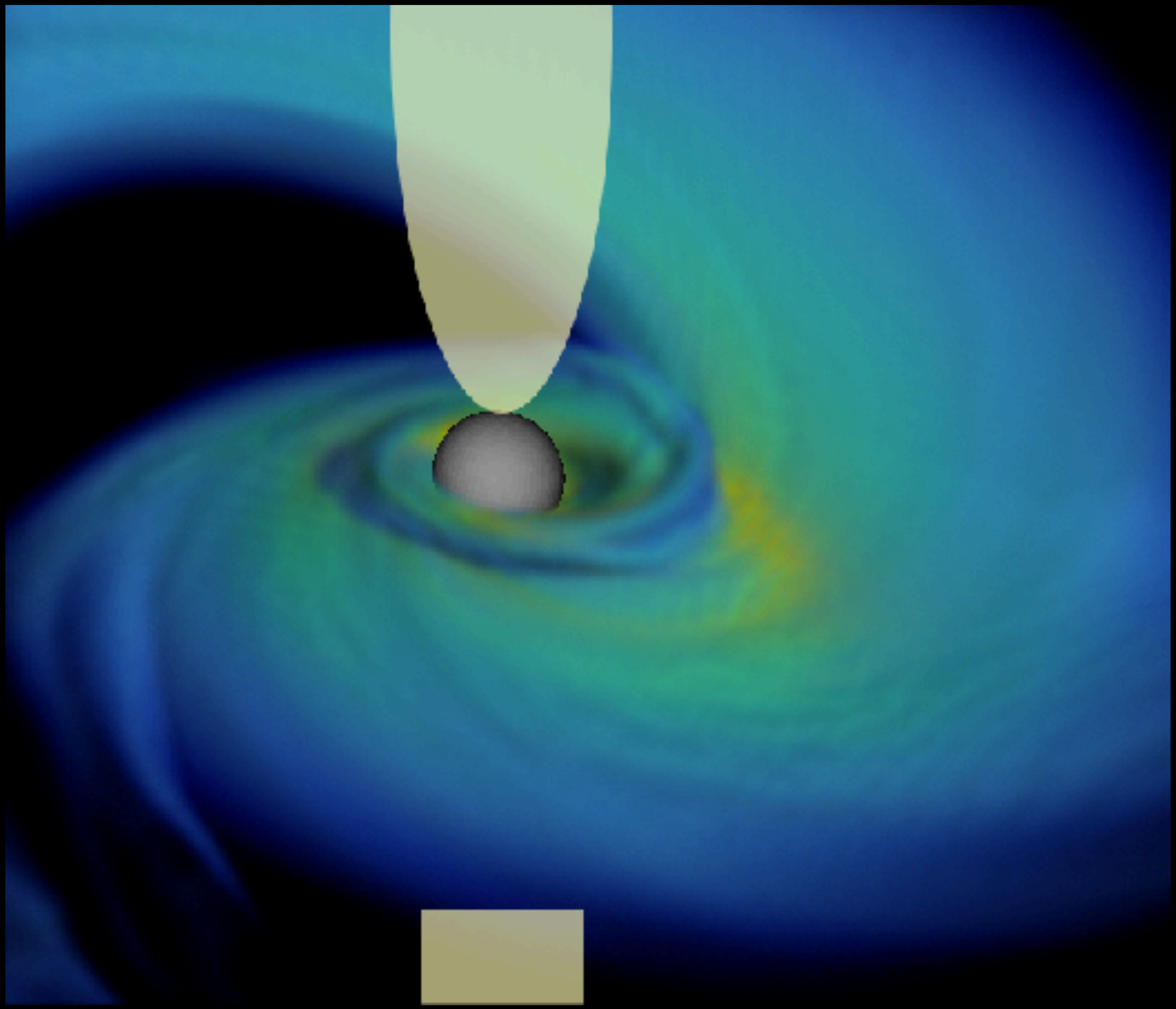
Neutrino transport in neutron star merger simulations

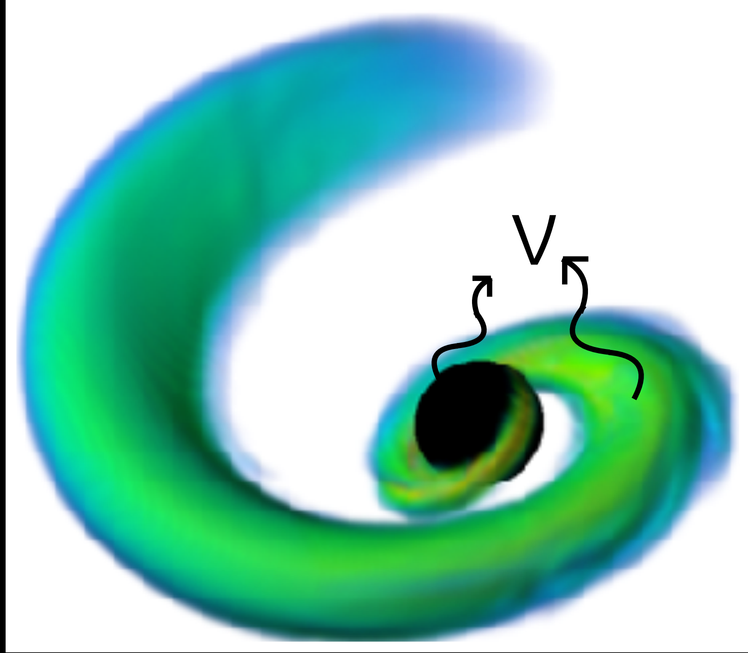


Francois Foucart
University of New Hampshire

Purdue University
May 9th 2018

r-process and kilo novae

Merger event produces **unbound outflows**



r-process nucleosynthesis in neutron rich ejecta produces heavy elements

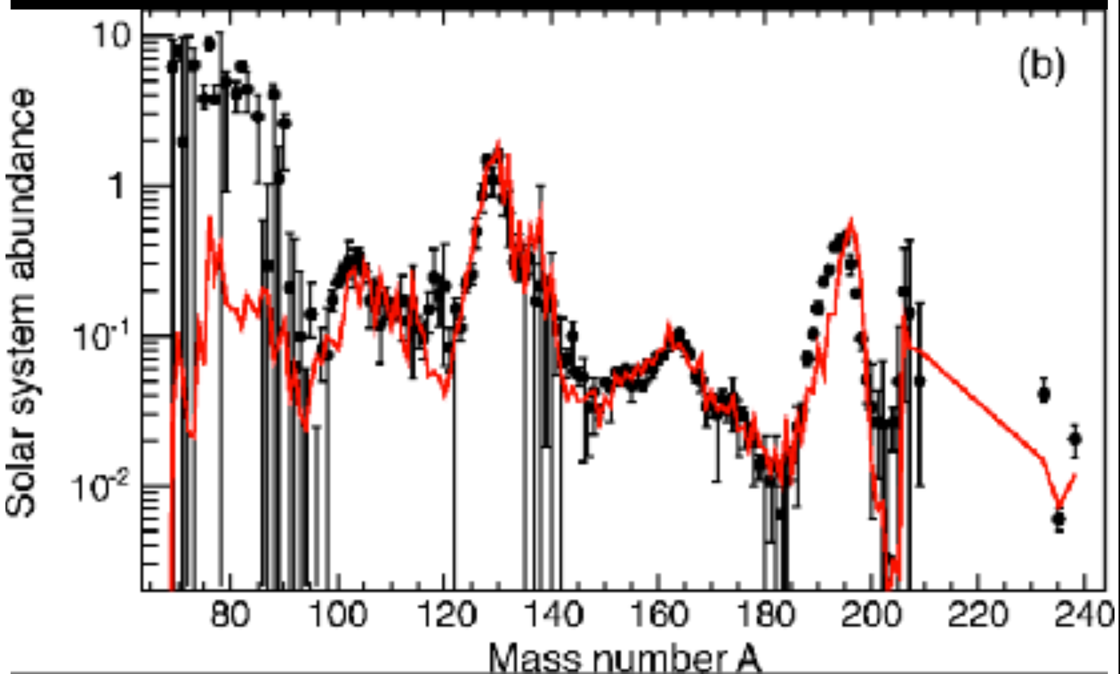
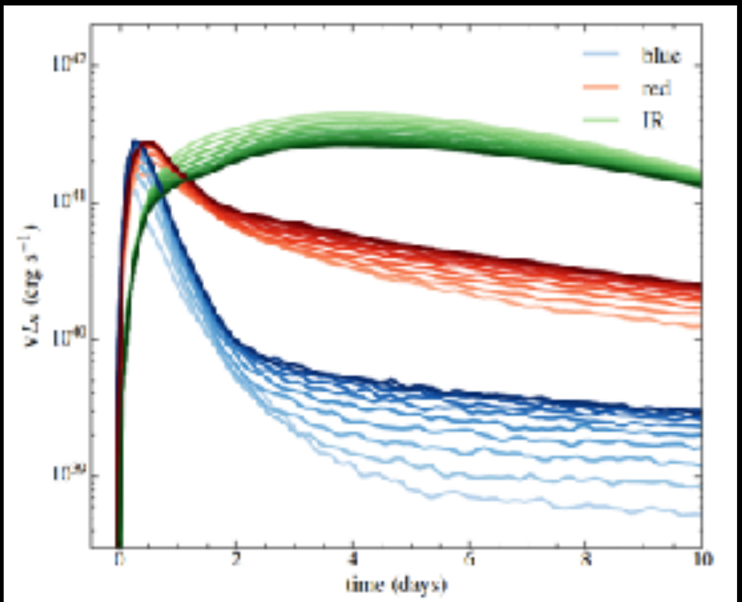


Image: Lorusso et al. 2015

Radioactive decay of heavy elements heats ejecta



Hot ejecta produces **optical/IR transient**

r-process outcome

$$Y_e = \frac{n_p}{n_p + n_n}$$

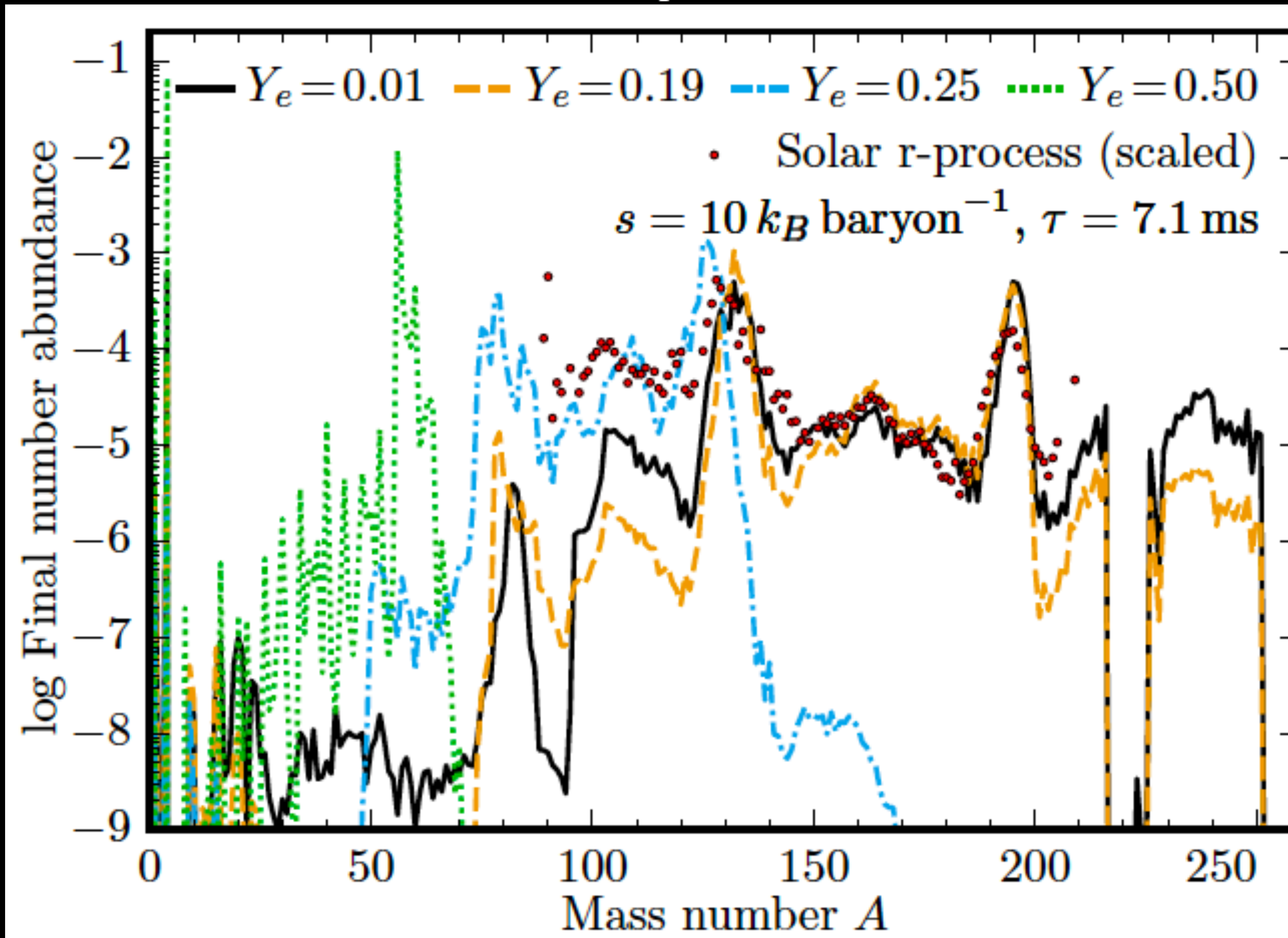
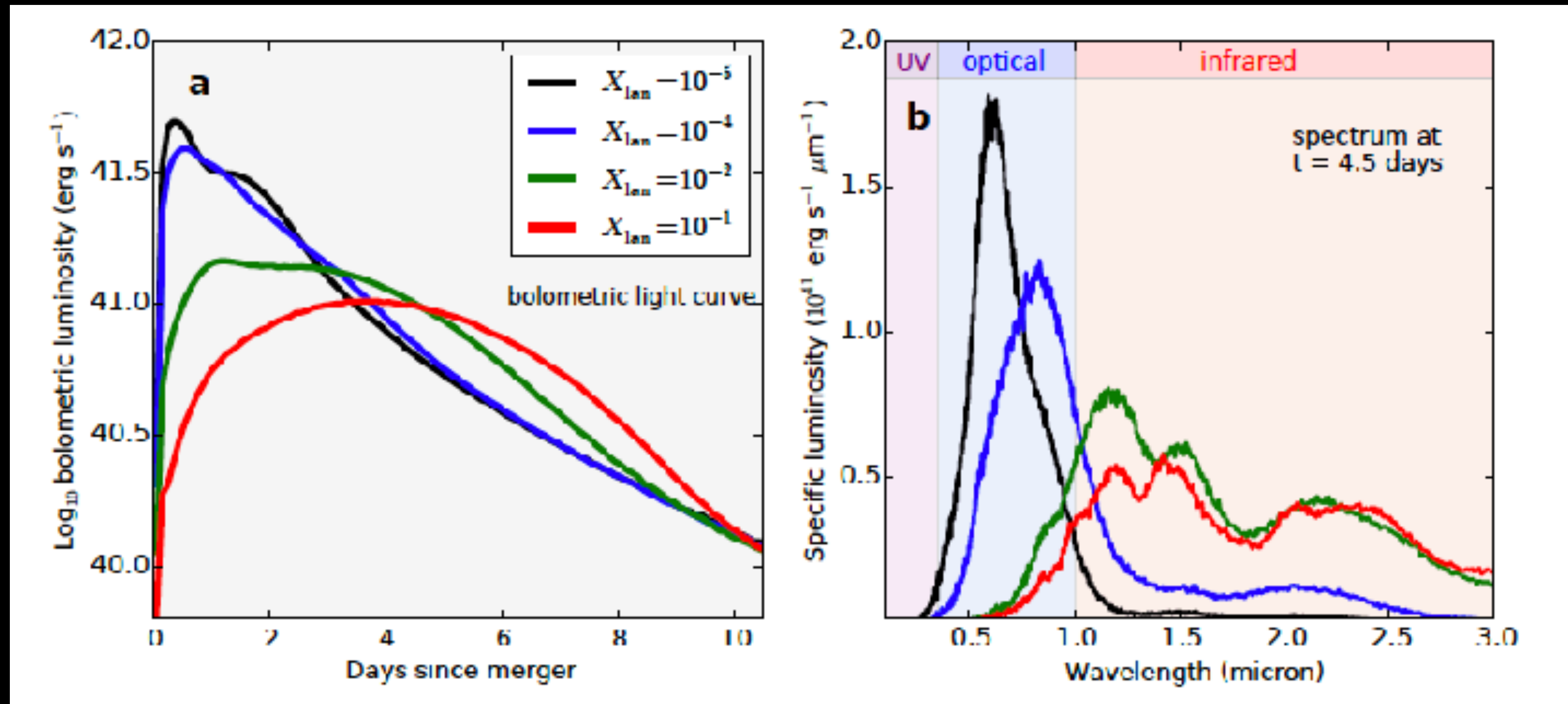


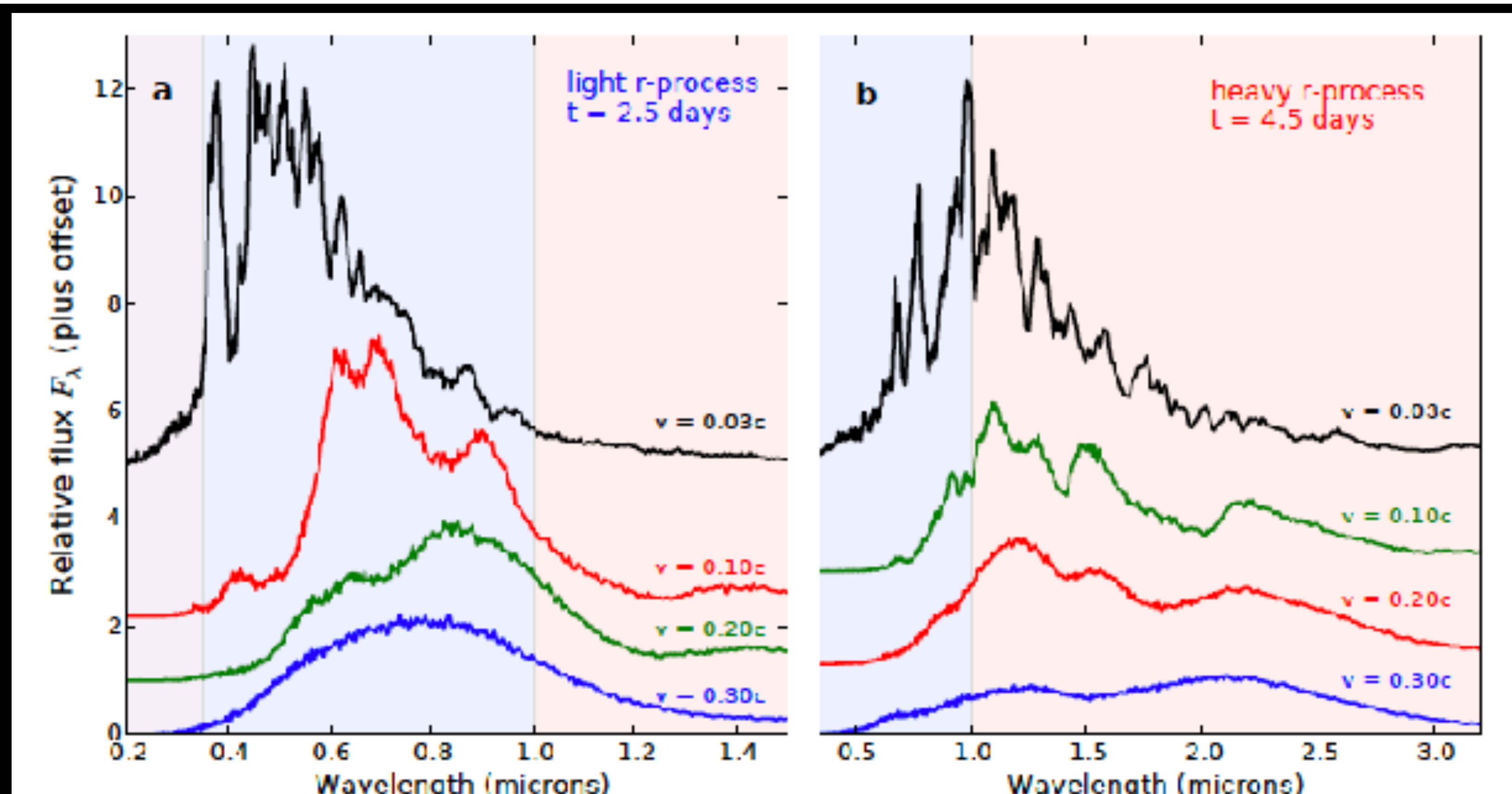
Image: Lippuner & Roberts 2015

Kilonova Properties vs Outflow Properties

Composition :



Velocity :



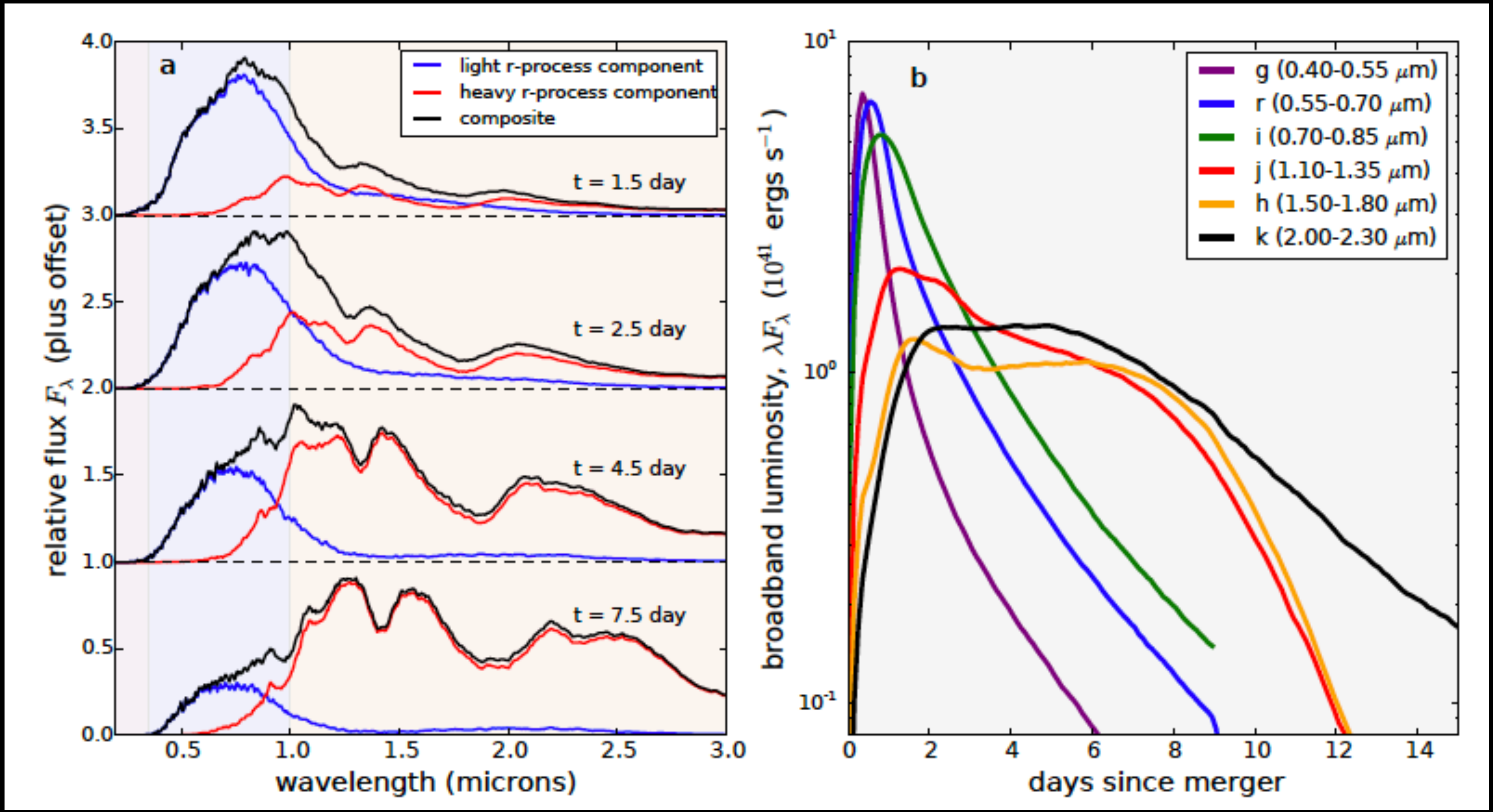
Images: Kasen et al 2017

Kilonova : GW170817

<u>Two-component model</u>

0.025M$_\odot$ at high Y$_e$, v~0.3c

0.04M$_\odot$ at low Y$_e$, v~0.15c



<u>Image:</u> Kasen et al 2017

Kilonova : inferring merger parameters

NSNS -> NS **NSNS -> BH** **BHNS**

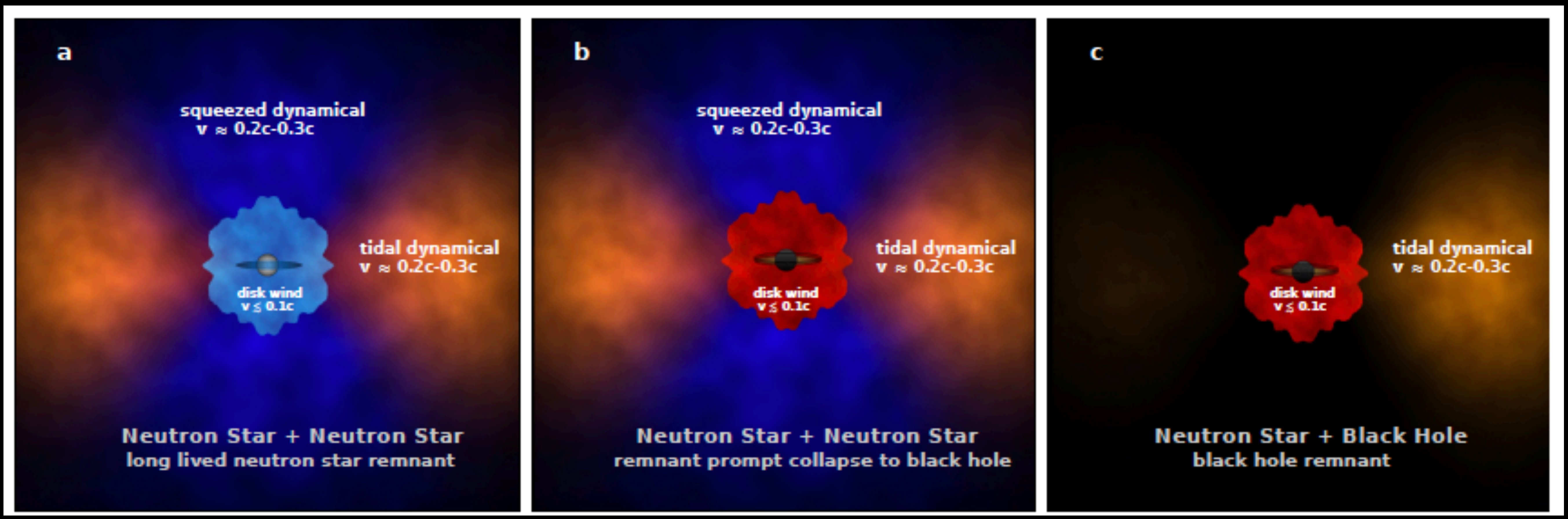
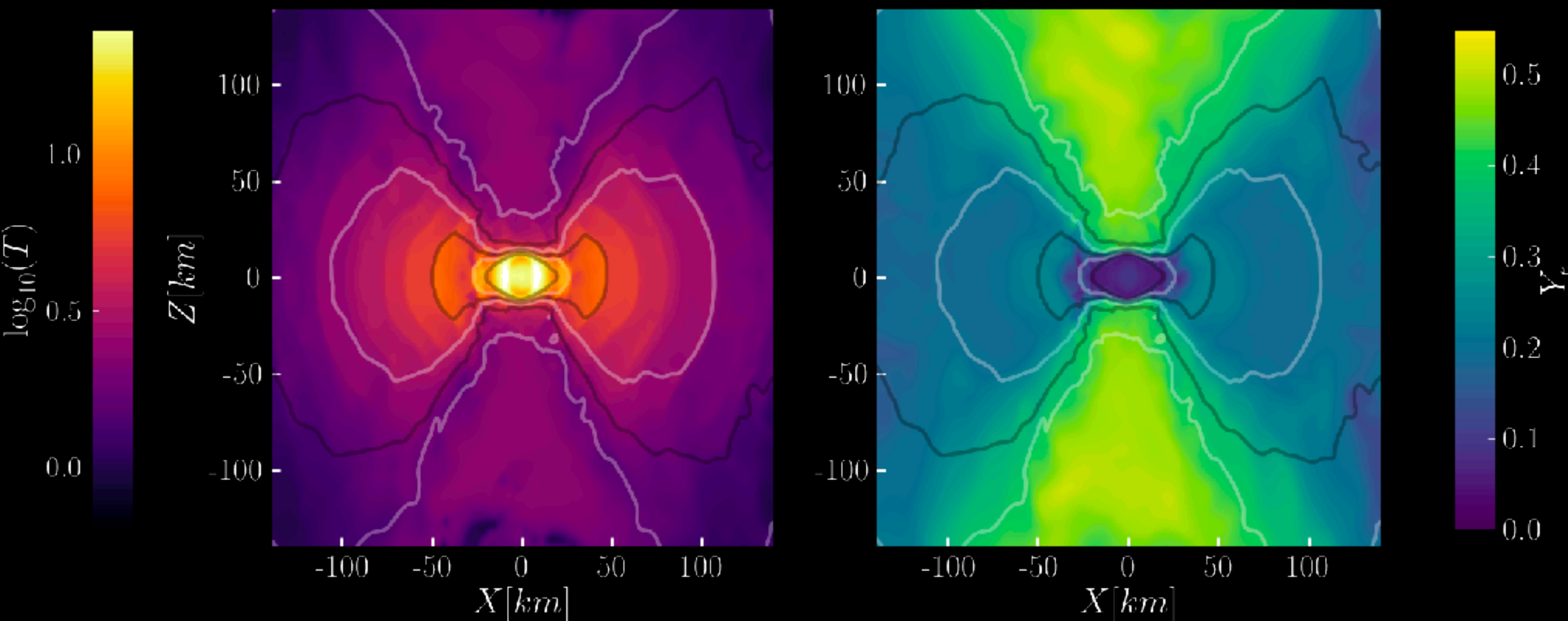


Image: Kasen et al 2017

Neutrinos in mergers

Neutron Star Merger remnant (Foucart et al. in prep)



(1) Neutrinos cool the disk

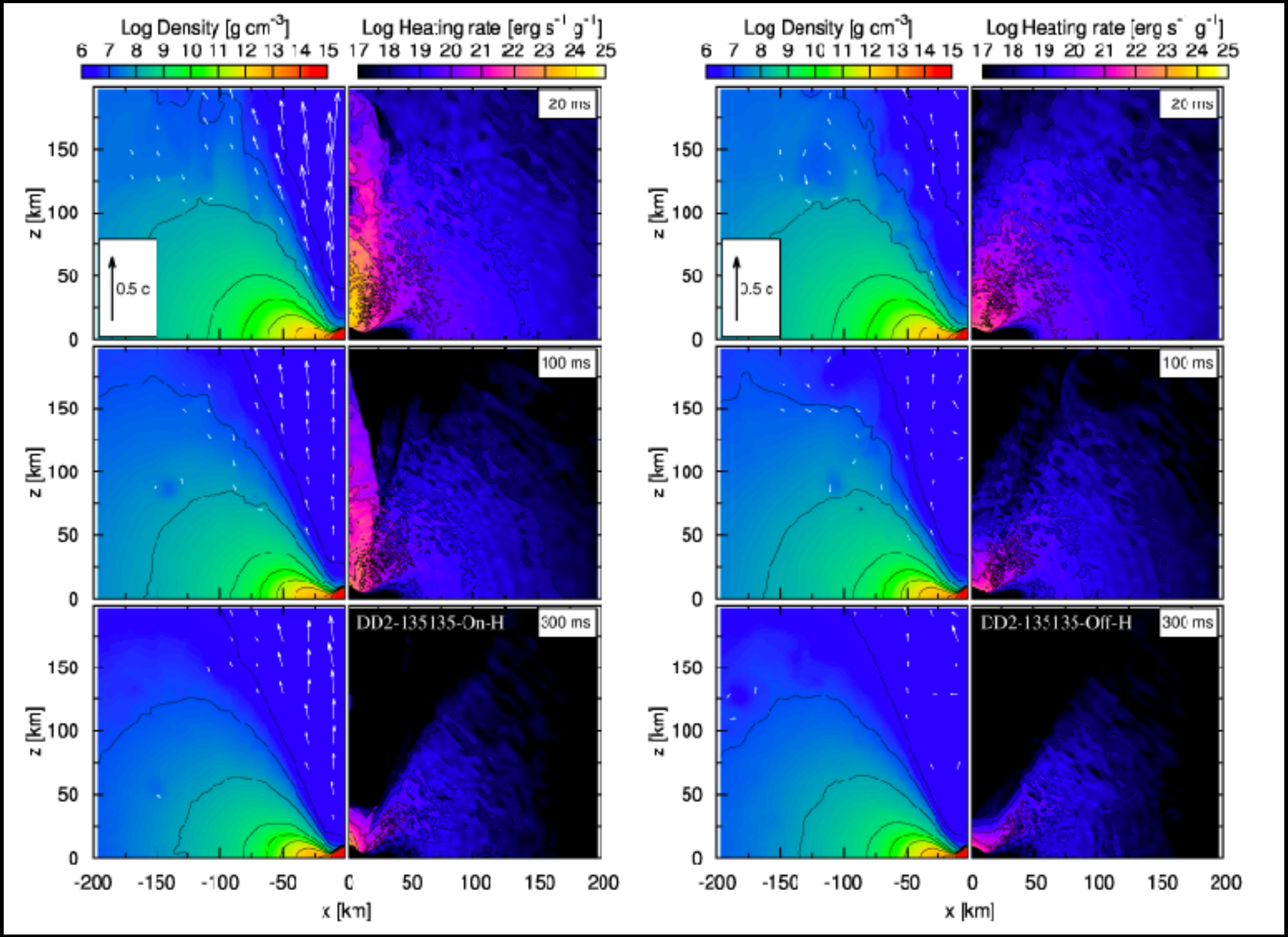
(2) Neutrinos drive polar outflows

(3) Neutrino absorption / Antineutrino emission increase Y_e of outflows

(4) Pair annihilation deposits energy in polar regions

Pair annihilation **(NSNS)**

With annihilation Without annihilation



Images: Fujibayashi et al., 2017

Neutrino transport

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

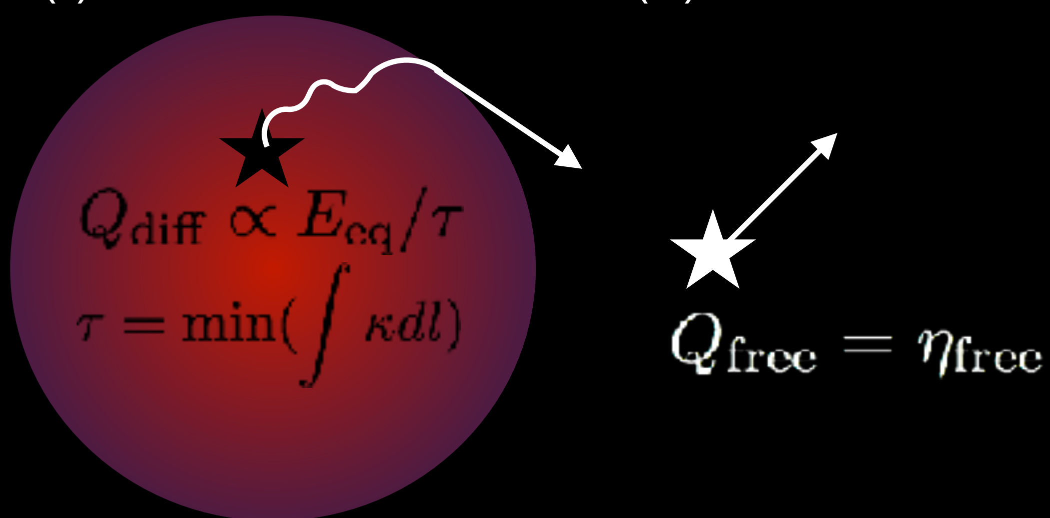
Cross-sections depend strongly on neutrino energy & orientation!

Leakage schemes

Simplest, most common approximation:

Estimate energy and lepton number emission from:

(i) Diffusion limit (ii) Free-streaming



$$Q = \left(\frac{1}{Q_{\rm free}} + \frac{1}{Q_{\rm diff}}\right)^{-1}$$

Optical depth obtained from approximate solution to

$$|\nabla \tau| = (\kappa_A + \kappa_S)$$

Leakage schemes are cheap, **but**
only order-of-magnitude accurate
No absorption/winds/non-local effects

See Ruffert et al. 1997, Rosswog & Liebendorfer 2003, Sekiguchi et al. 2011, **Deaton et al. 2013**, Neilsen et al. 2014, **Foucart et al. 2014**

Moment formalism (M1)

Relatively cheap, **approximate transport** method.

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

Define moments :
Energy Density E
Flux Density F_i
(optionally) Number Density N

Approximate closure

$$P^{\mu\nu} = \alpha P^{\mu\nu}_{\rm thick} + (1-\alpha) P^{\mu\nu}_{\rm beam}$$

using optically thin/thick limits

Exact evolution equations:

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

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

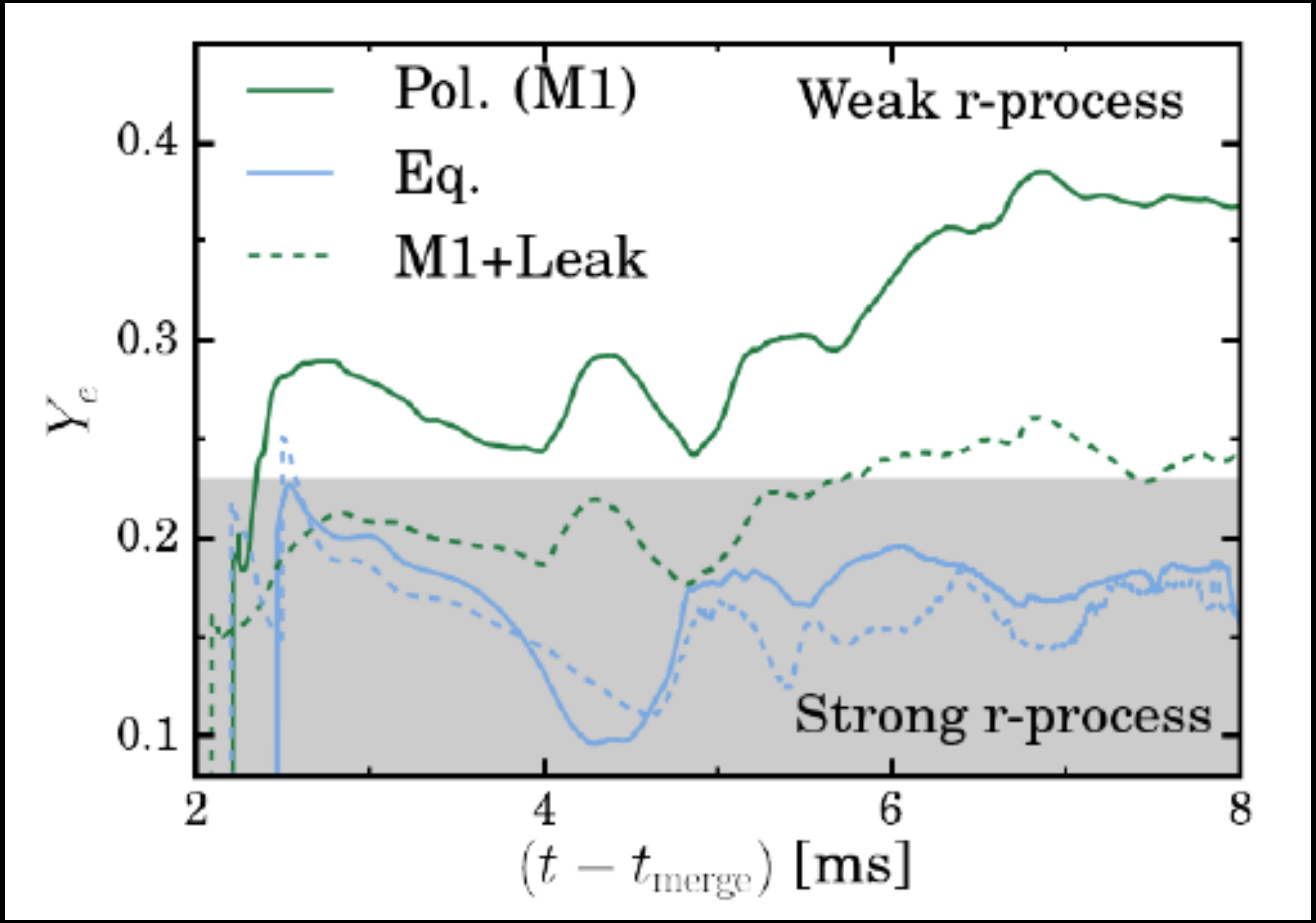
Sources include:
Curvature/redshift terms
Emission/Absorption/Scattering

Improvement:
Evolve number density.

See Foucart et al. 2016b

Impact of gray approximation

Outflow composition (**NSNS**):
Impact of neutrino treatment

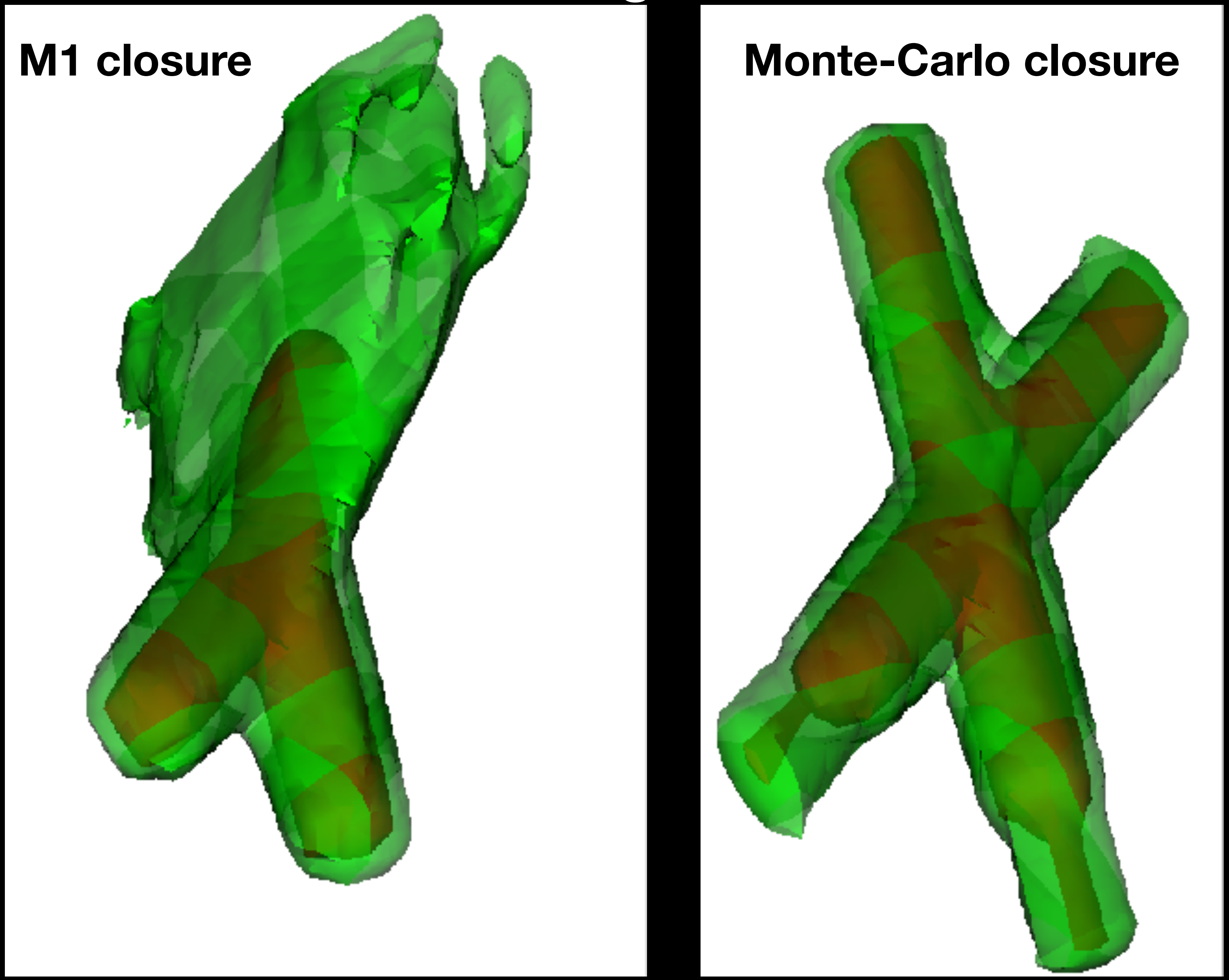


Images: Foucart et al., 2017

Beyond M1 : Monte-Carlo closure

To improve on the M1 closure, use a low-accuracy MC evolution to compute the closure! [Foucart et al. 2018]

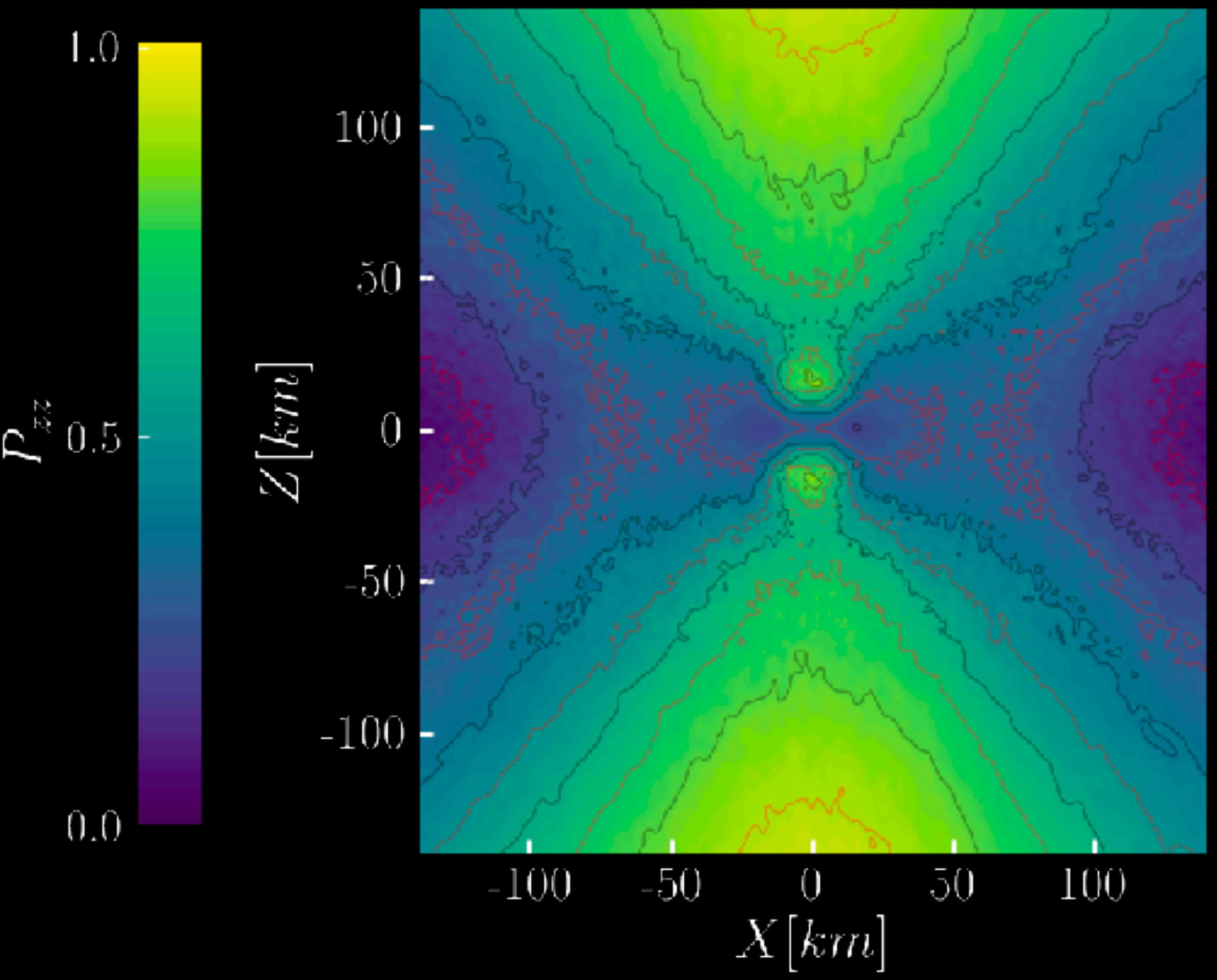
Crossing beams



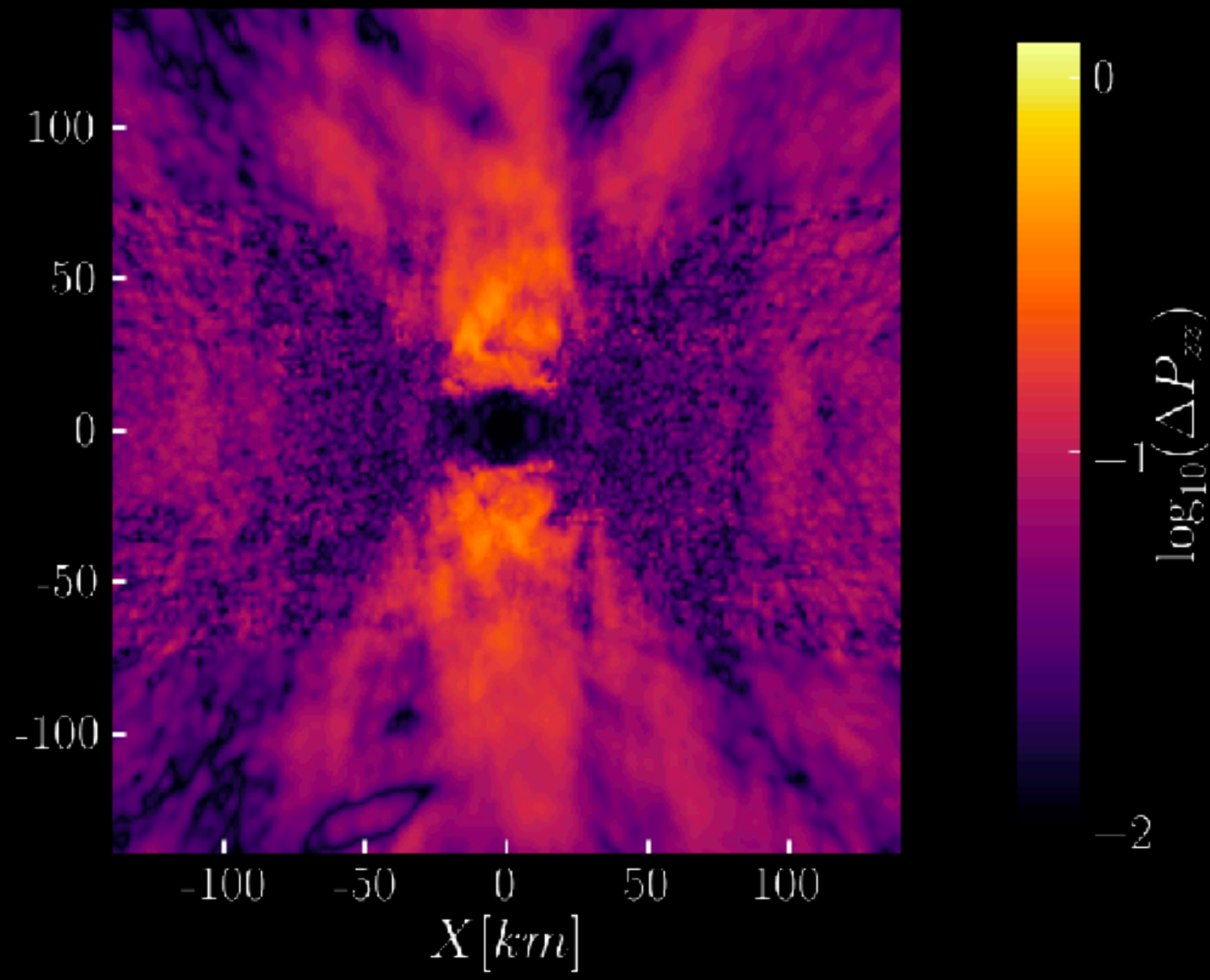
MC vs M1 Closures

Foucart et al. in prep

P_{zz}/E with MC closure



Difference between MC and M1 closures



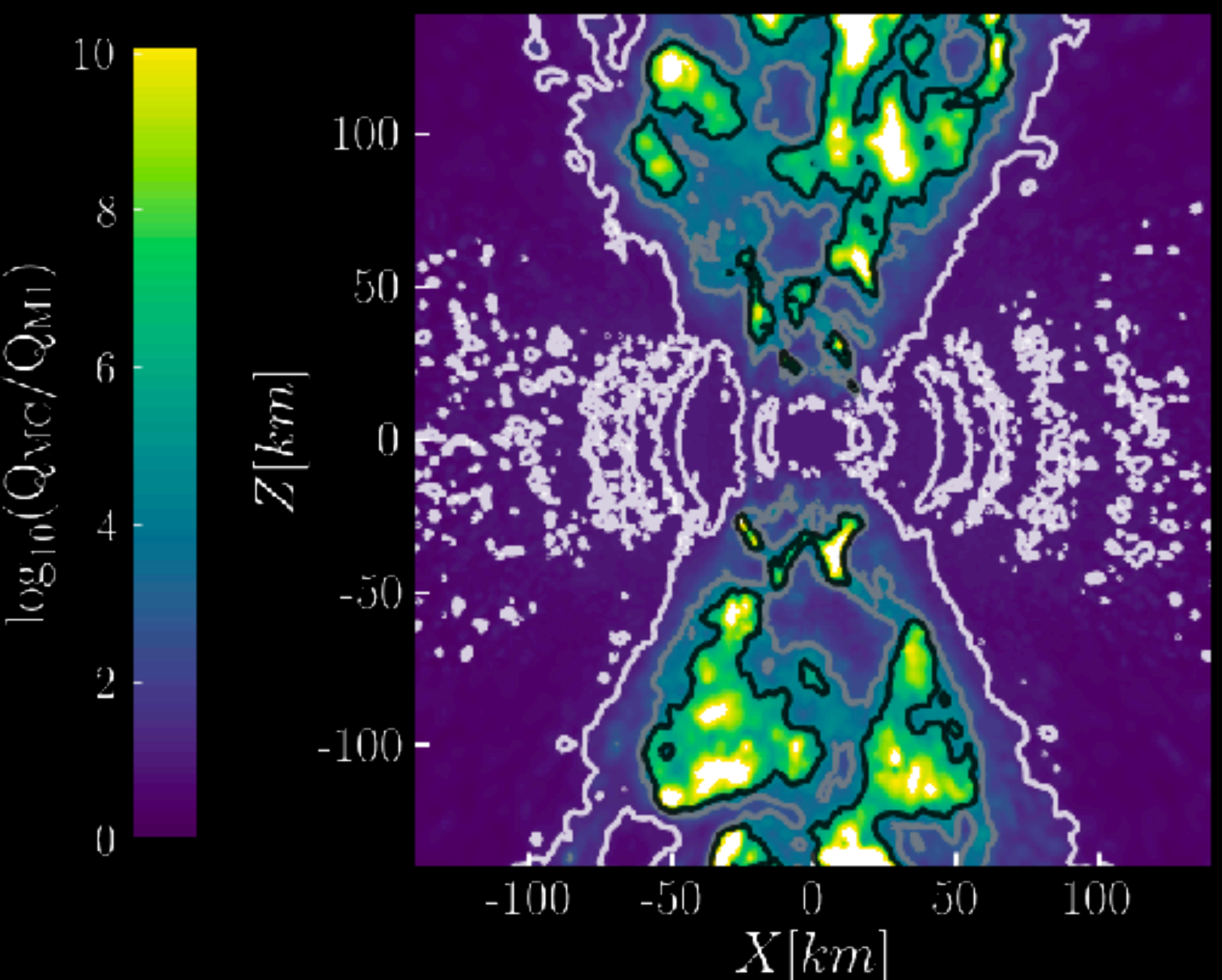
MC vs M1 Closures

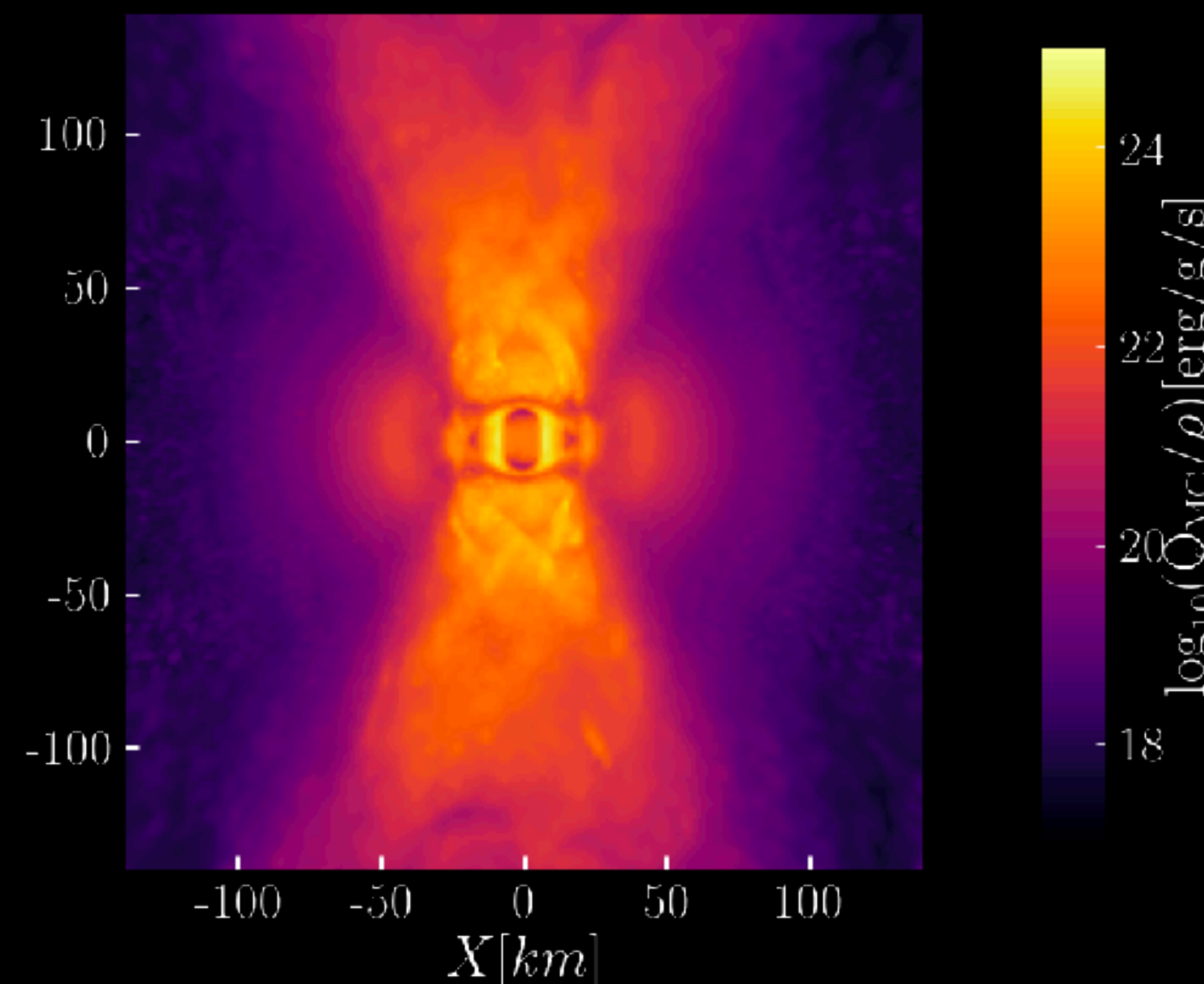
Foucart et al. in prep

<u>Neutrino pair annihilation:</u>

Ratio of heating rates (MC/M1)

Specific heating rate (MC)





Contours at (1,3,5)

Francois Foucart

UNH

Conclusions

- Neutrino transport crucial to model kilonovae / maybe SGRBs
- Leakage schemes ok for qualitative dynamics of remnant, insufficient to study outflows
- Gray M1 schemes capture neutrino-driven outflows, Y_e accuracy uncertain
- Pair annihilation deposits a lot of energy in polar regions, and requires knowledge of neutrino momenta
- Neutrinos are not the only hard part of the problem! MHD is an important issue for kilonova modeling, and the main issue in SGRB modeling!