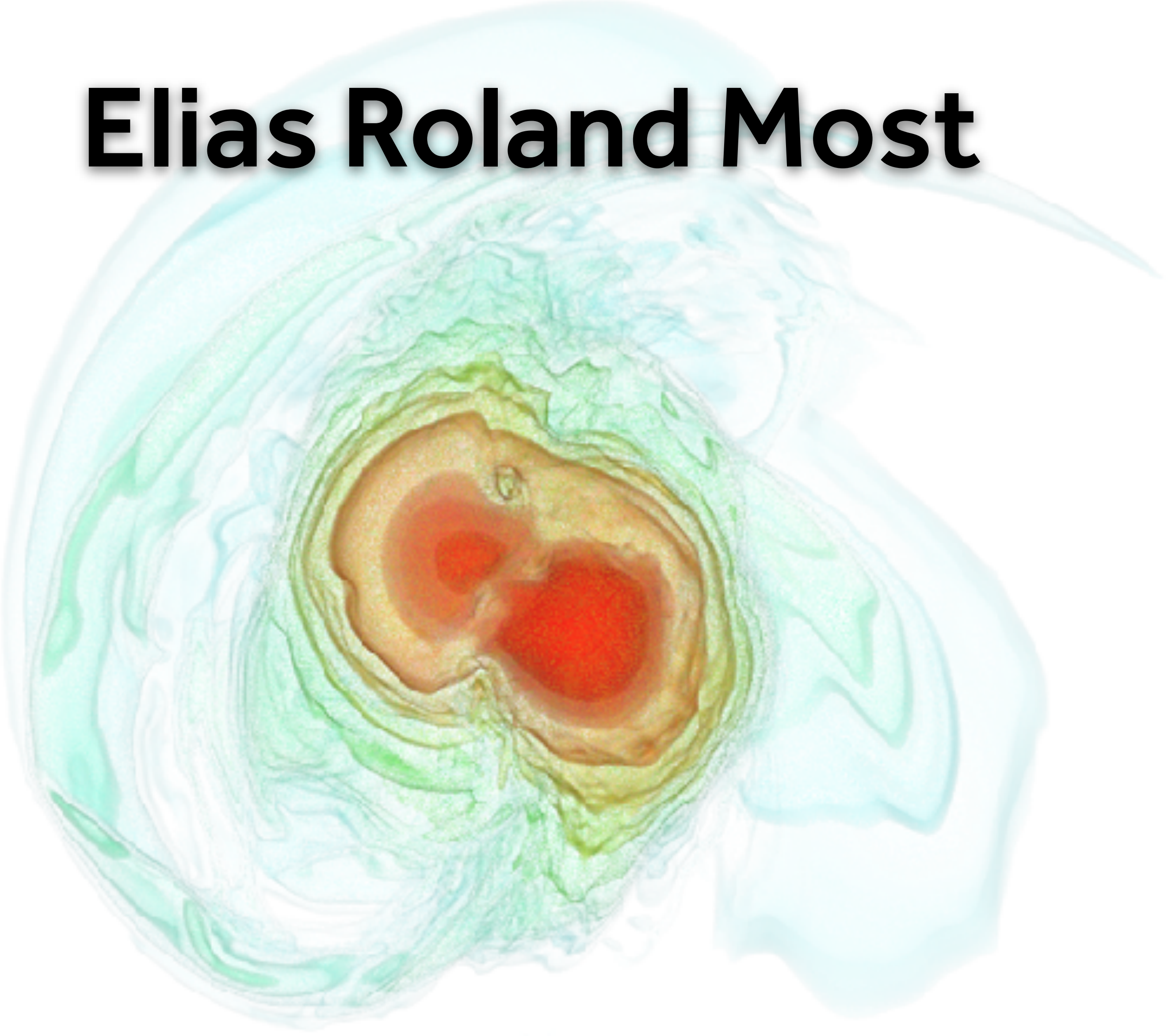
Neutron Star Mergers:

Aspects of nuclear and plasma physics



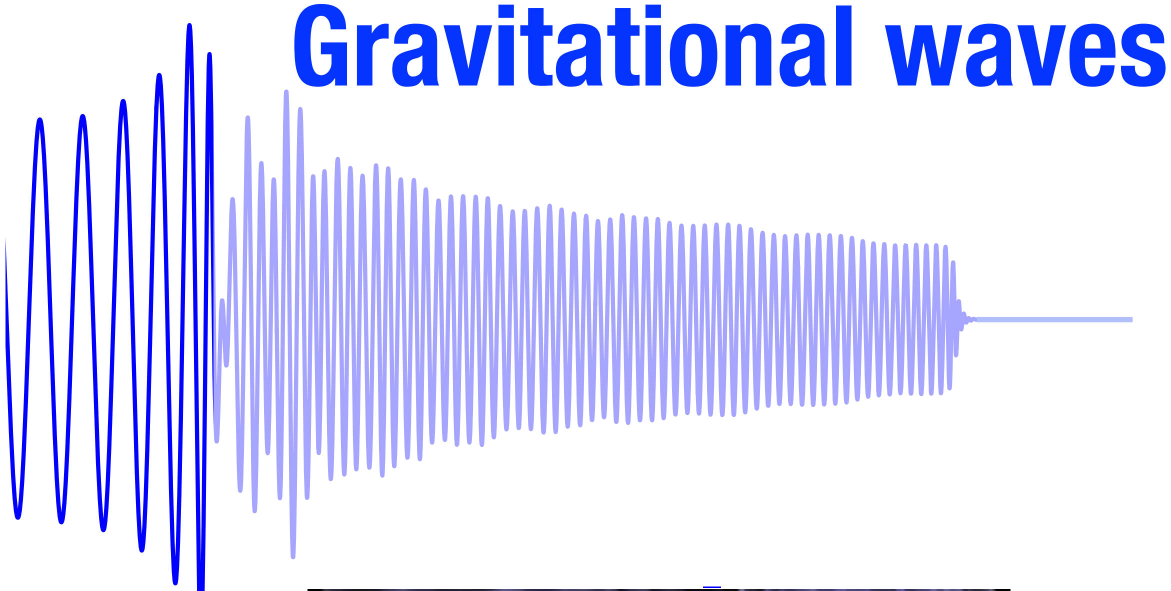
Elias Roland Most

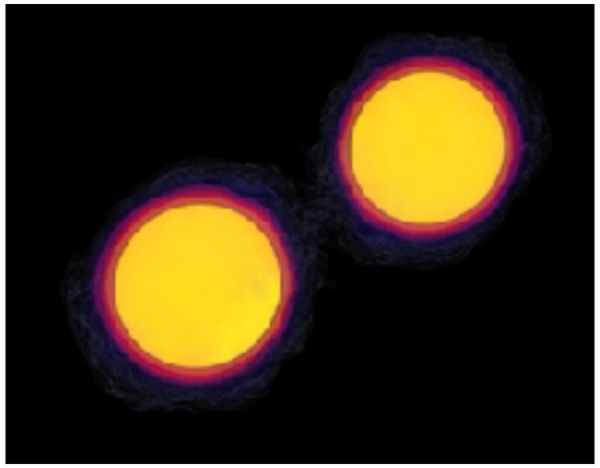
Princeton gravity Initiative

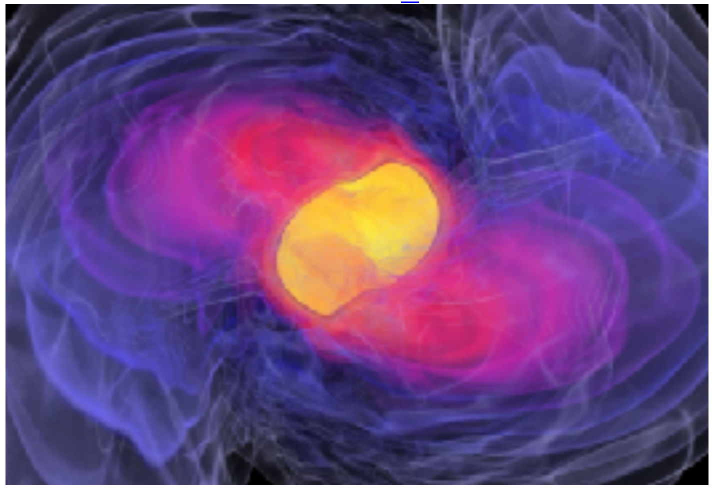
The ultimate fate of a neutron star binary

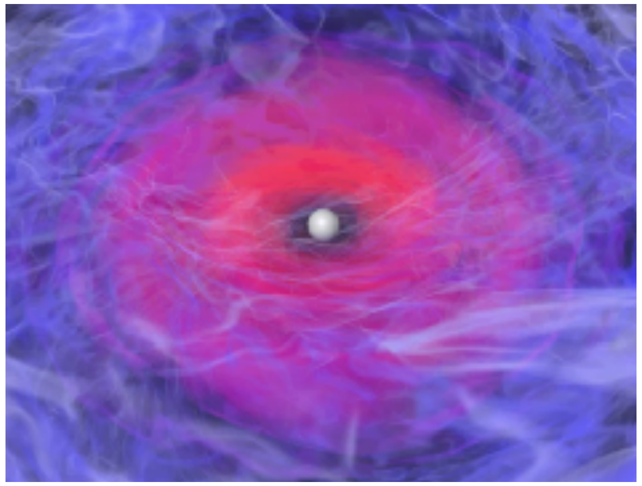
Gravitational waves

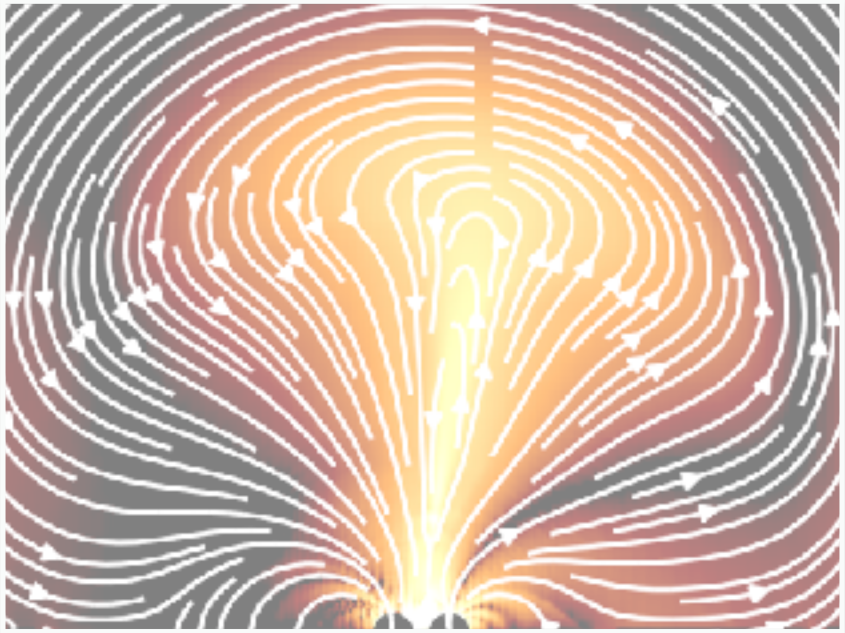
sGRB



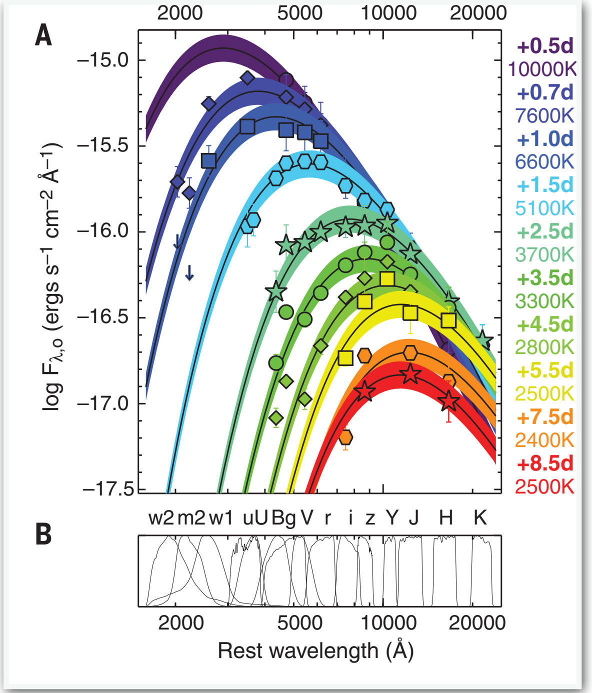






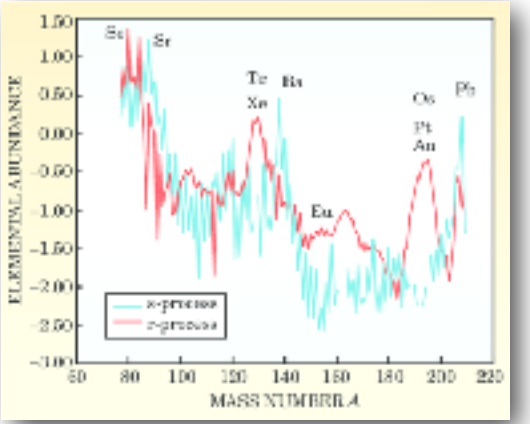


Precursor Emission??



Kilonova

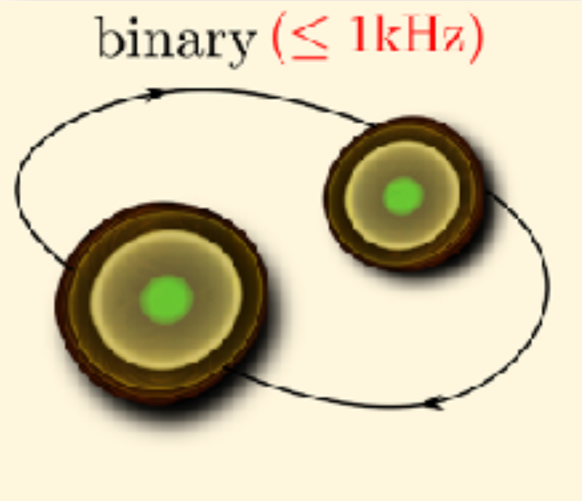
Afterglow

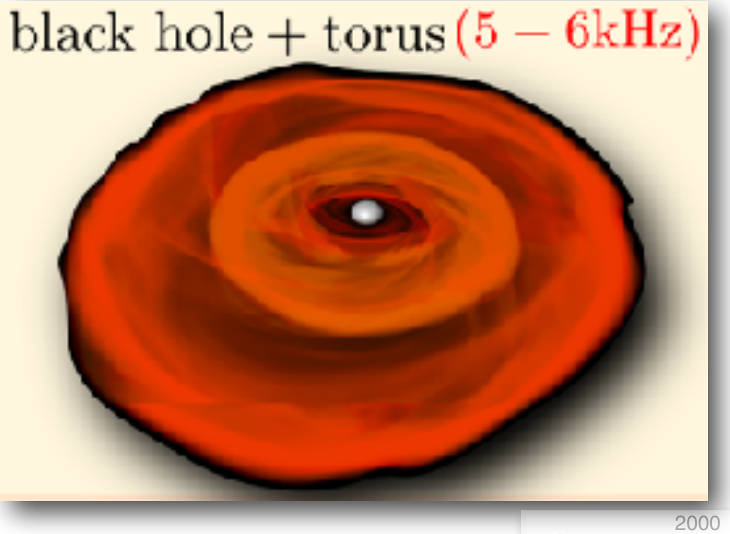


The final fate of a neutron star binary

Gravitational waves

sGRB

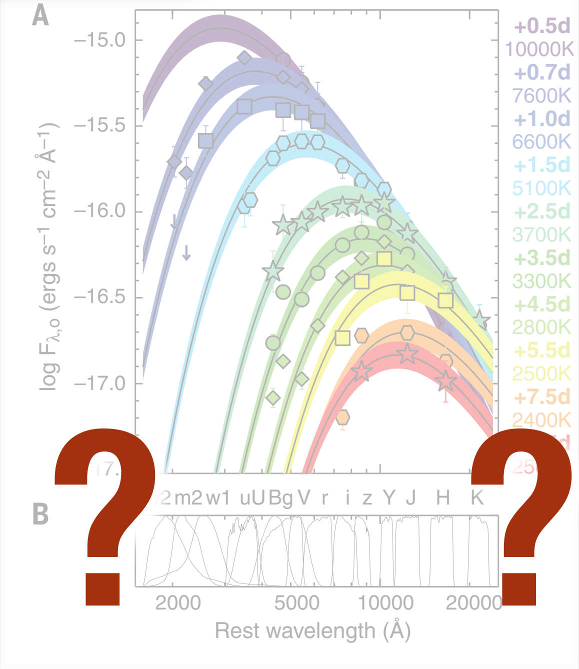


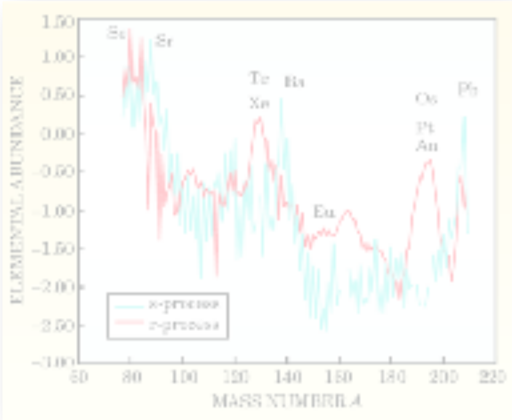


See talks by Fujibayashi, Fahlman, Murguia-Berthier, Miller

Kilonova

Afterglow

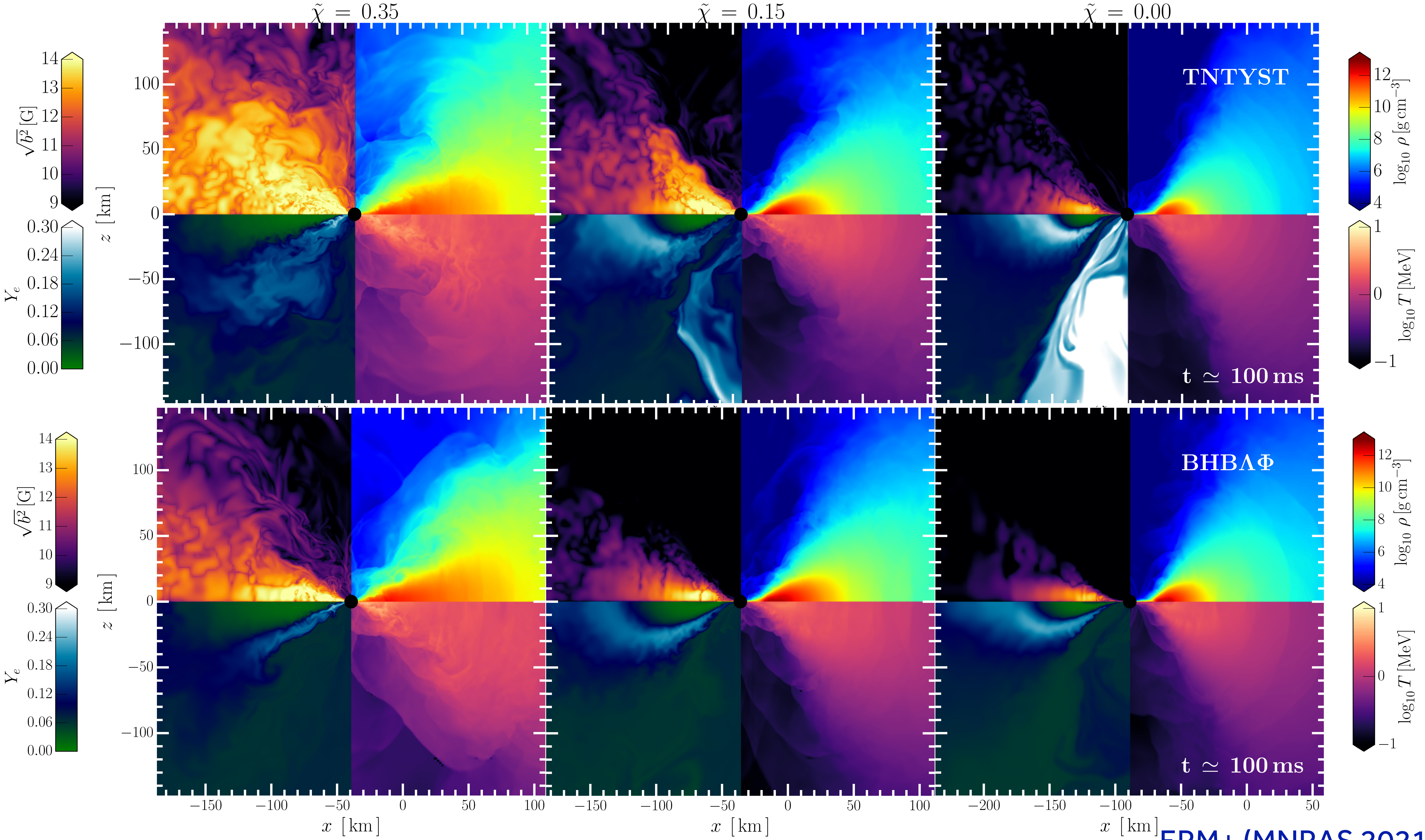




How well do we understand disks formed in this process?

Comment on: *Realistic accretion disks*

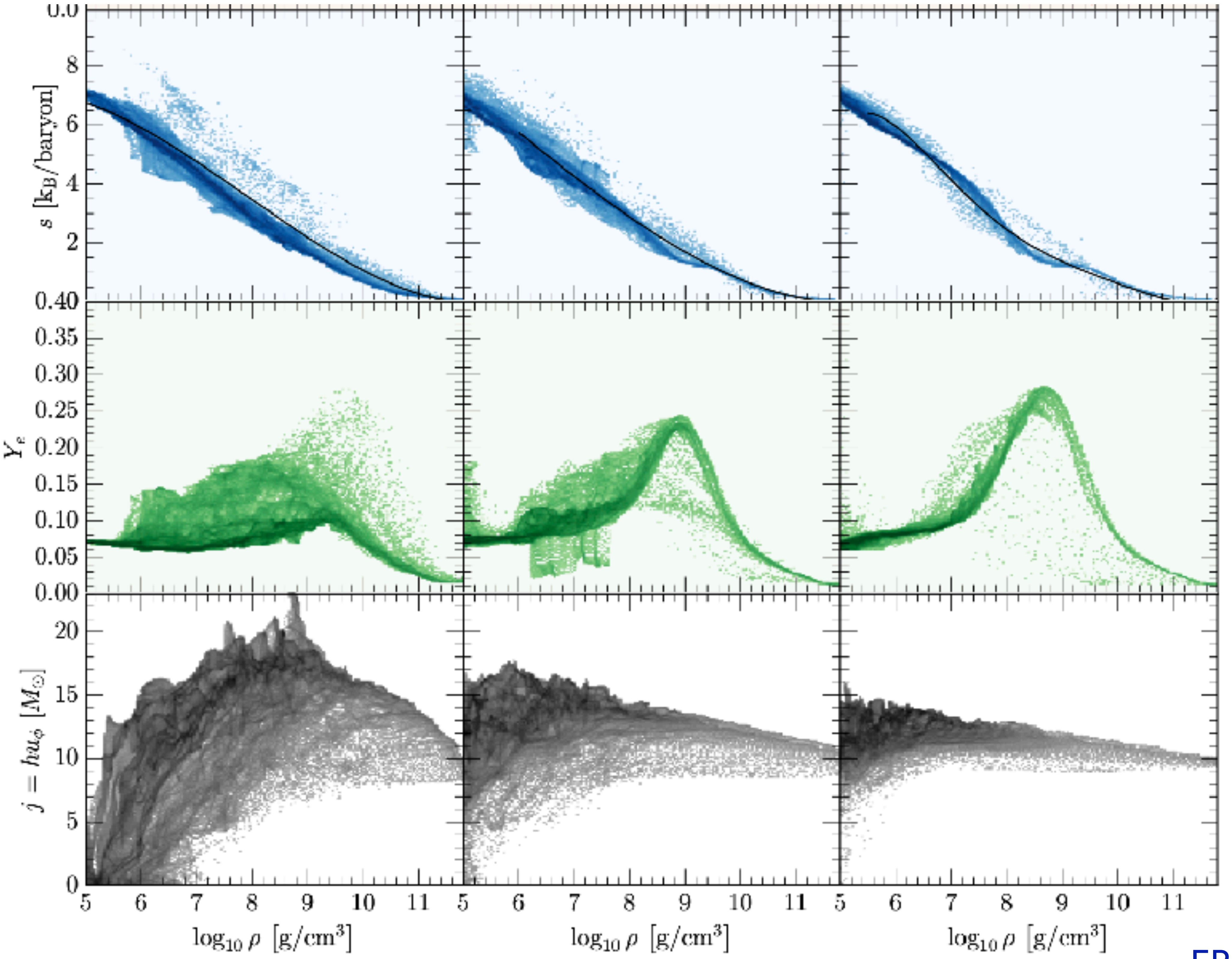
Numerical relativity simulations of BH-NS (with MHD + leakage)



ERM+ (MNRAS 2021)

What do real disks look like?

Standard lore



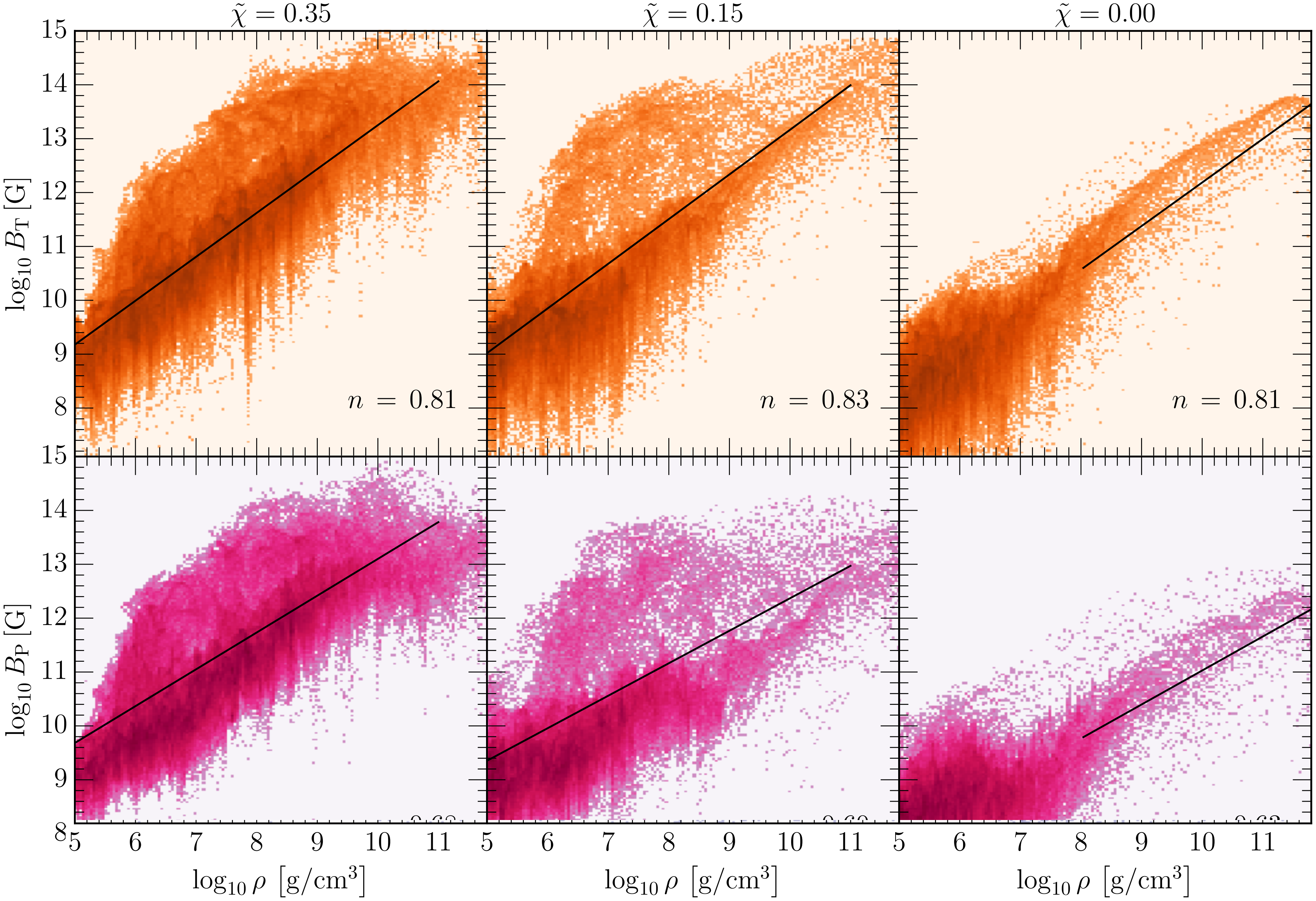
Constant entropy / temperature?

Electron fraction $Y_e \simeq 0.1$??

Constant specific angular momentum

ERM+ (MNRAS 2021)

What about magnetic fields?

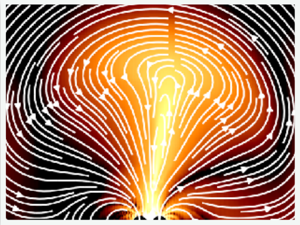


Caveat:

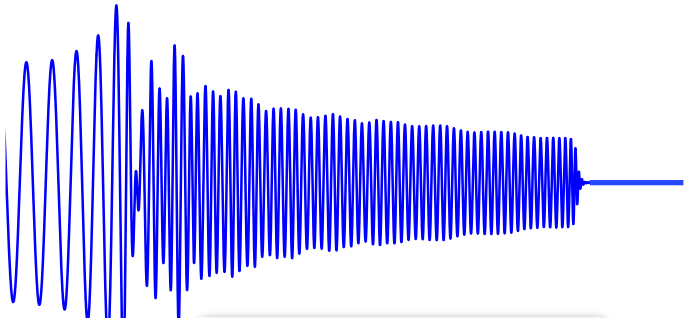
Initial field topology

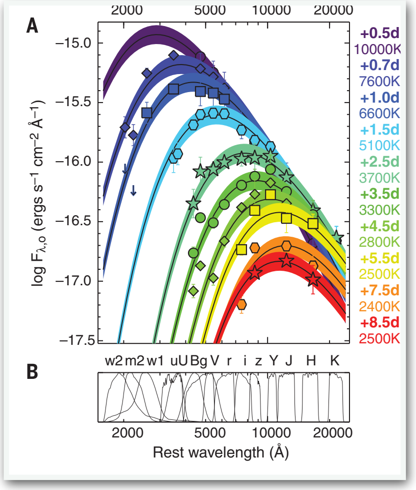
ERM+ (MNRAS 2021)

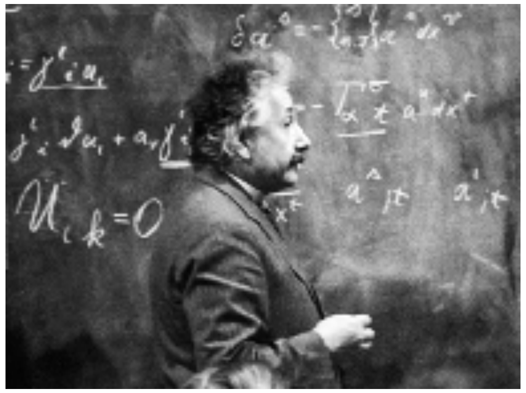
- The poloidal and toroidal field components on average satisfy simple power laws $B_{T/P} \propto \rho^n$

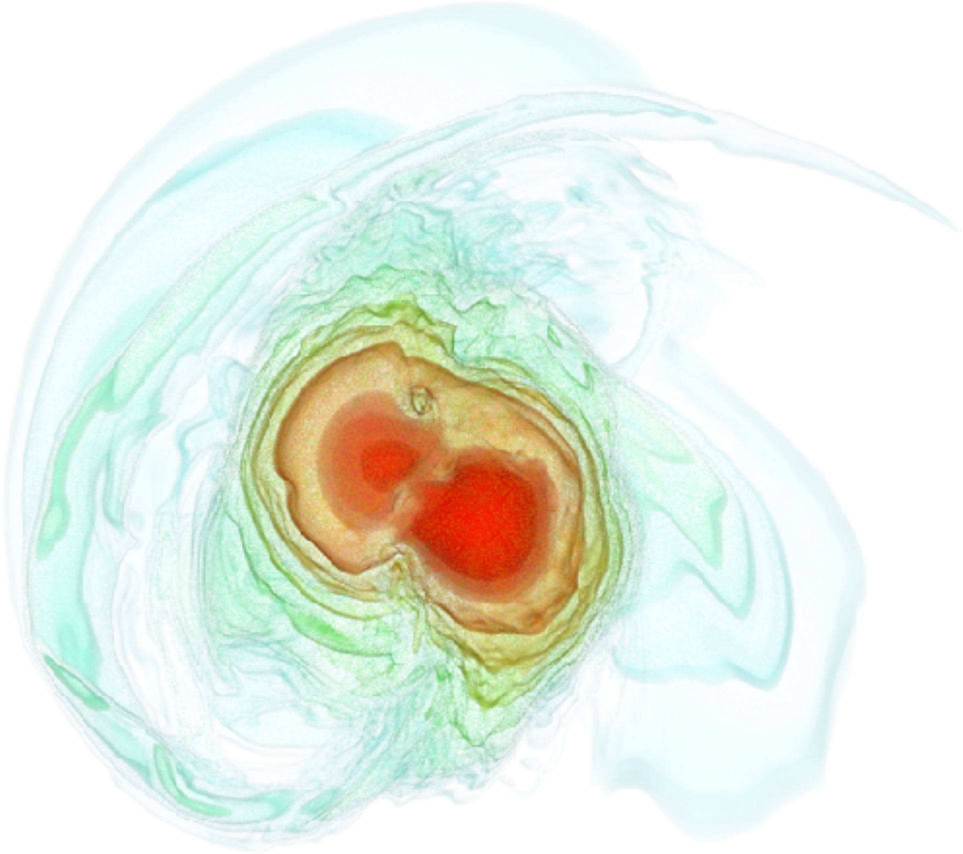


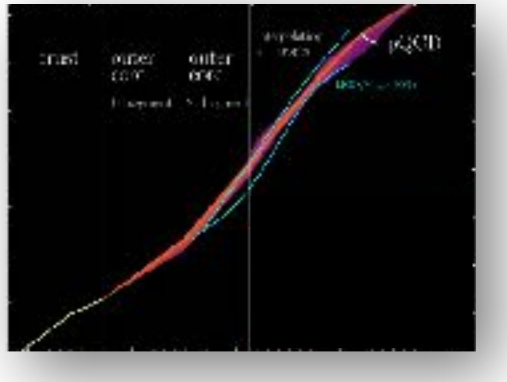
A challenge for computational relativistic astrophysics

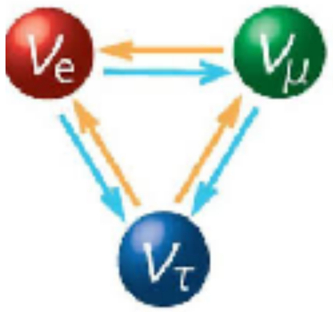


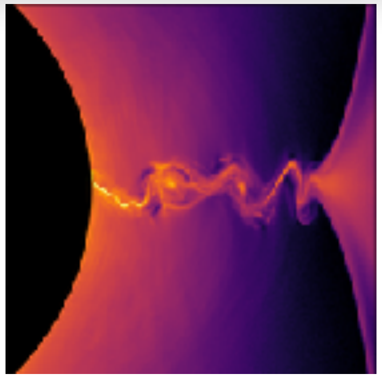






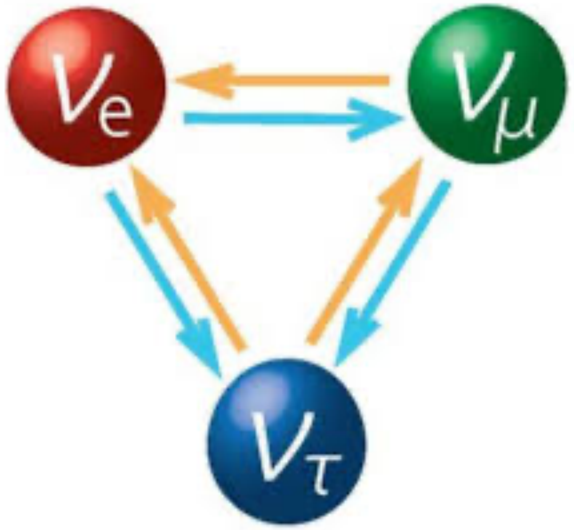




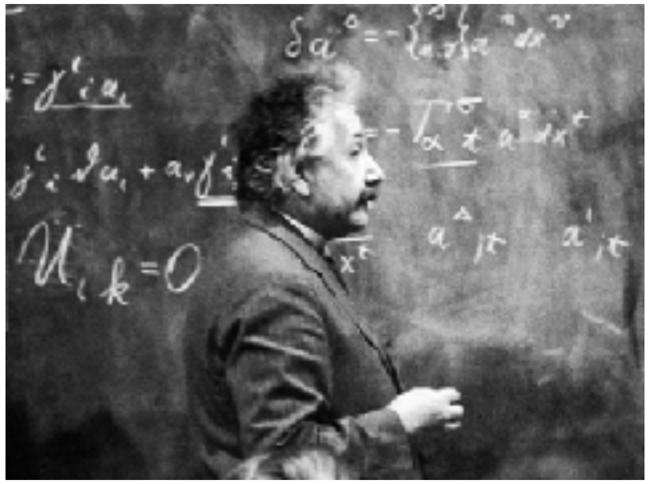


Need a multi-scale, multi-physics approach to interpret multi-messenger events!

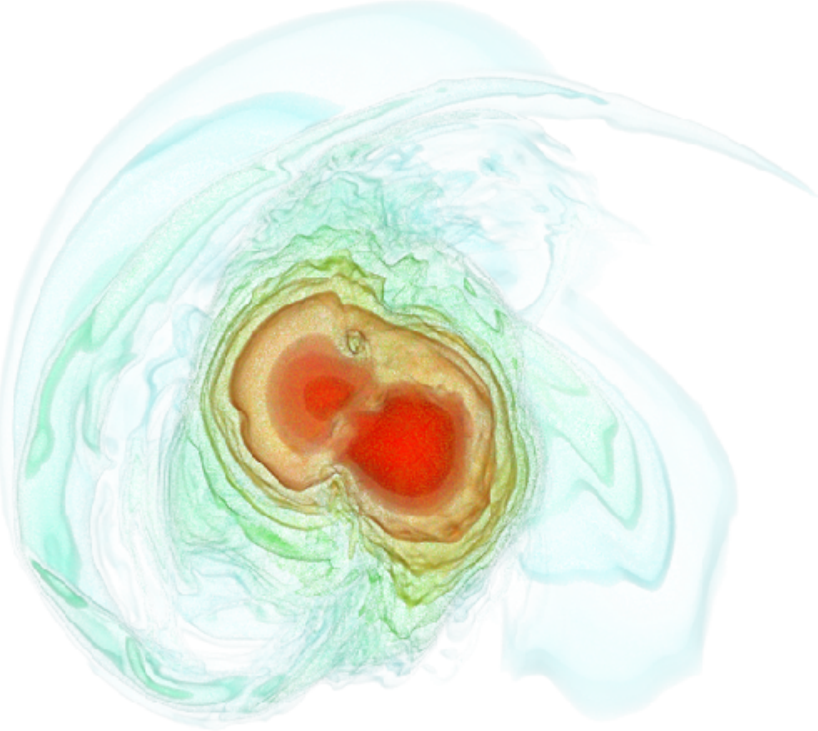
The many faces of neutron star mergers

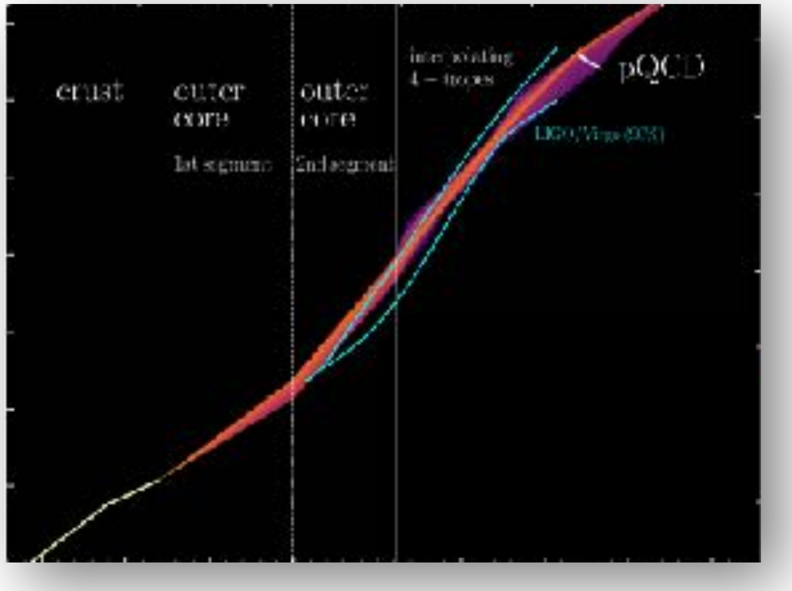


Neutrino physics

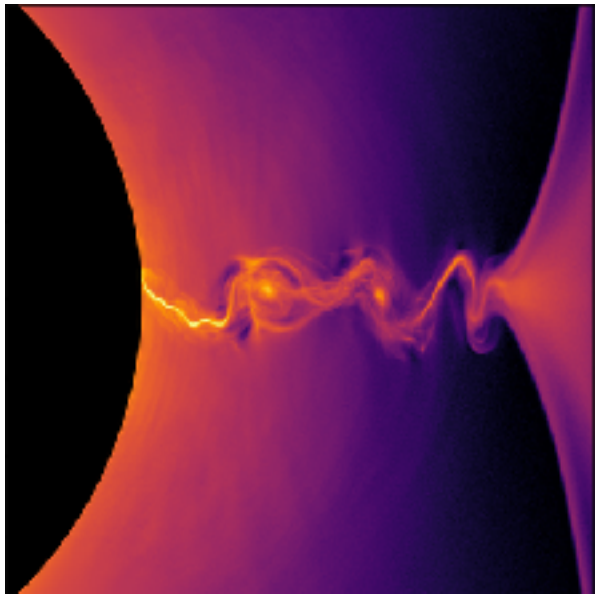


Gravitational physics



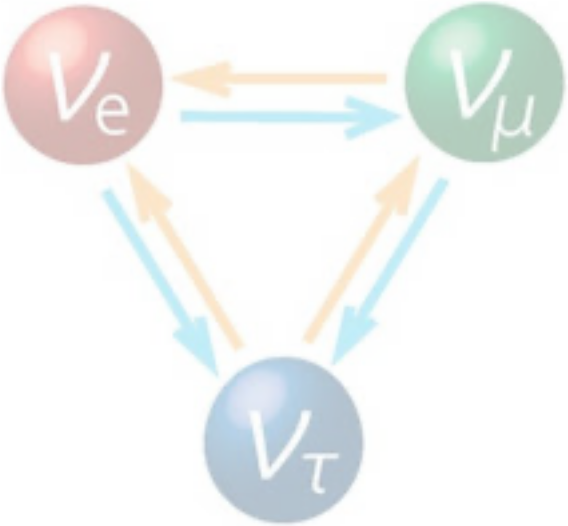


Nuclear physics

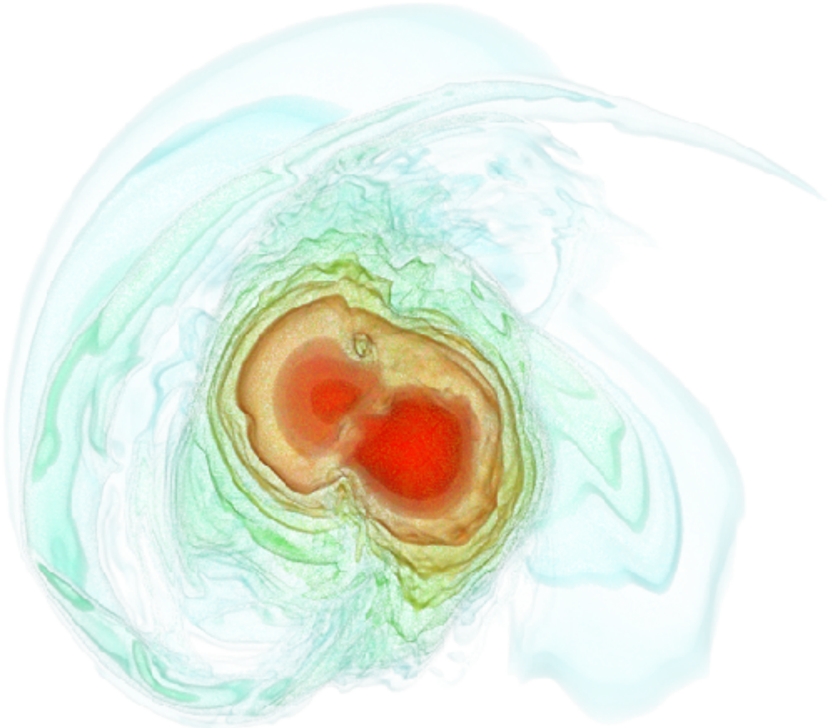


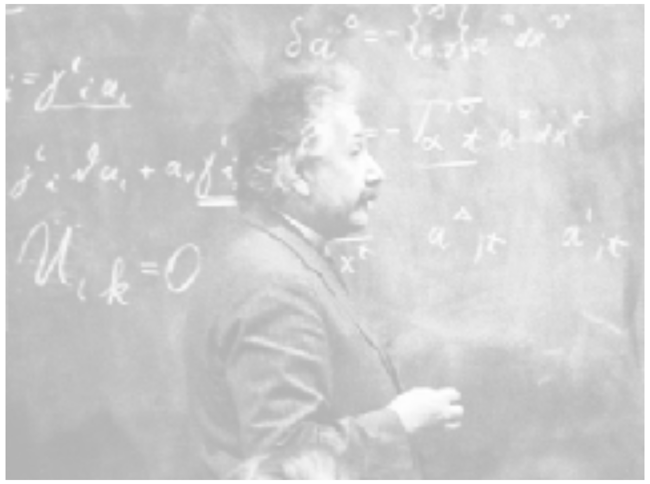
Plasma physics

The many faces of neutron star mergers

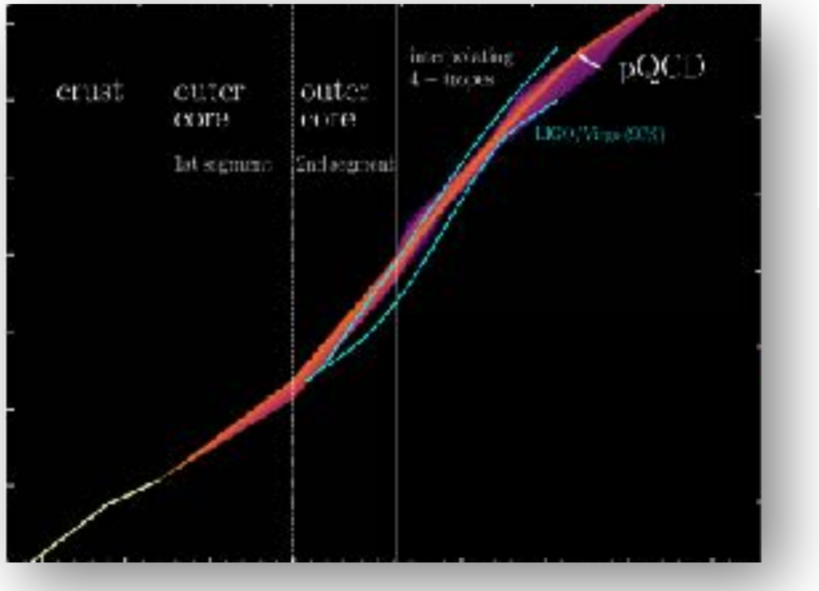


Neutrino physics

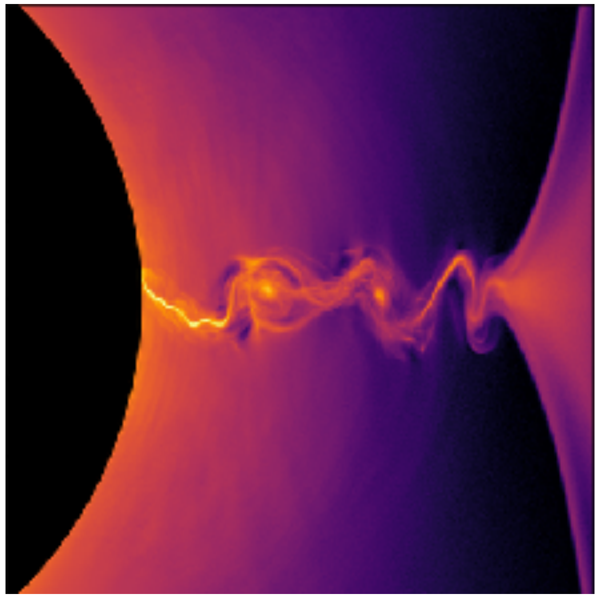




Gravitational physics

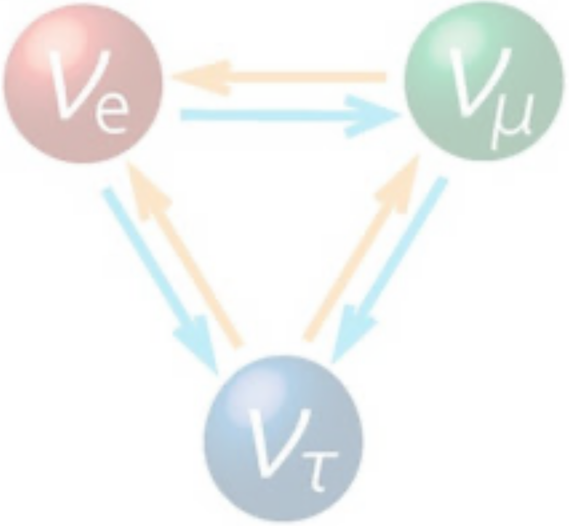


Nuclear physics

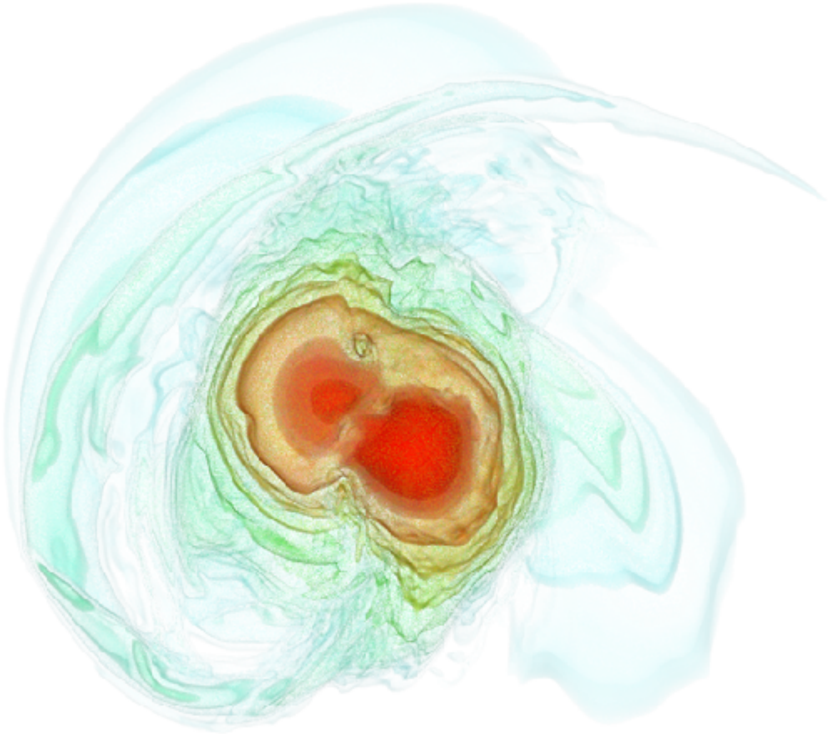


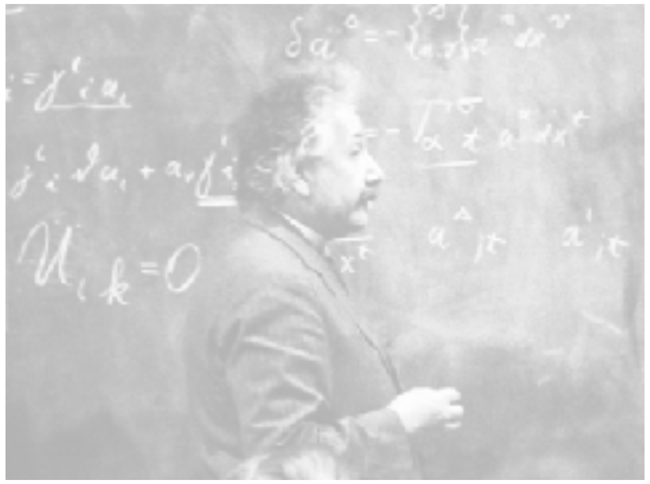
Plasma physics

The many faces of neutron star mergers

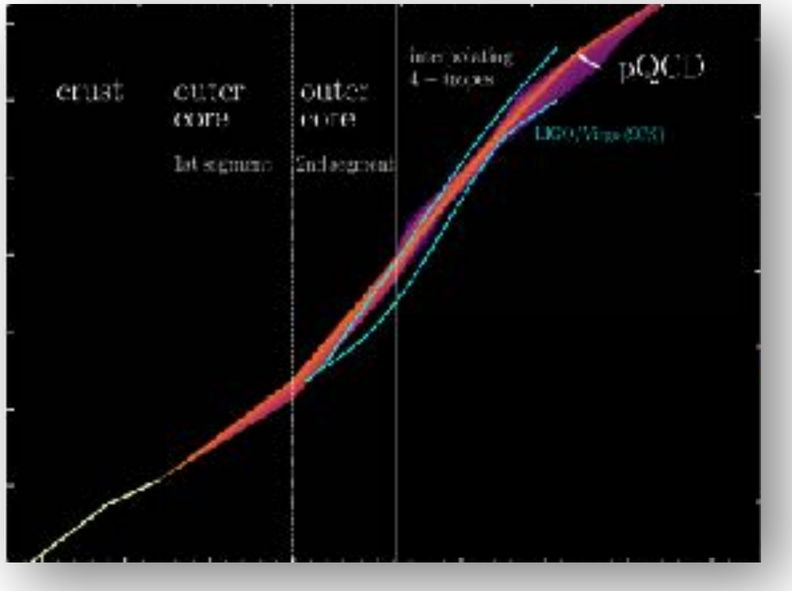


Neutrino physics

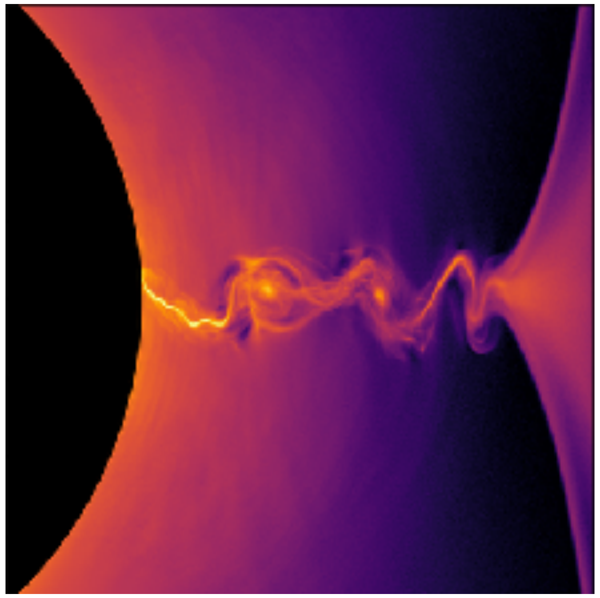




Gravitational physics



Nuclear physics

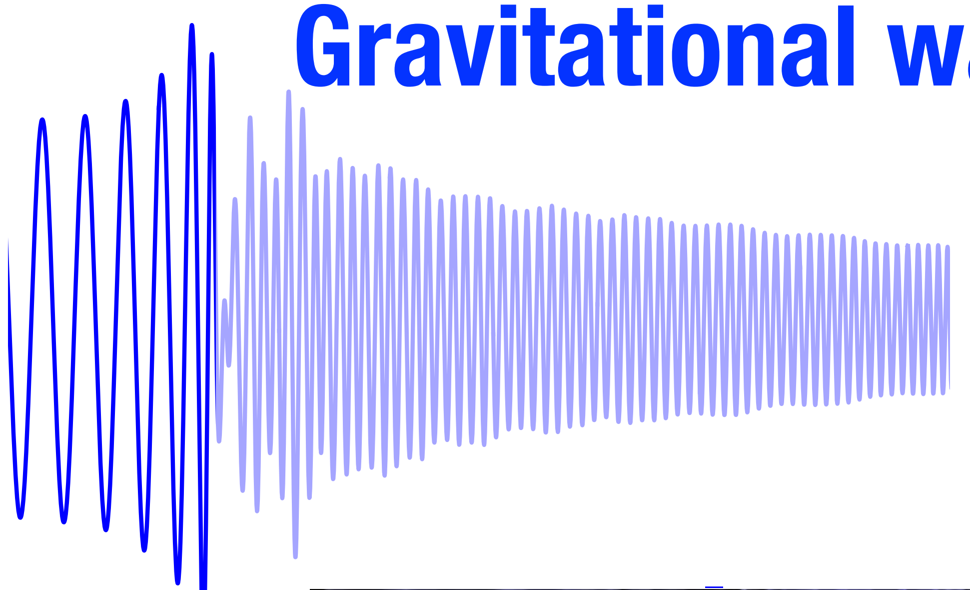


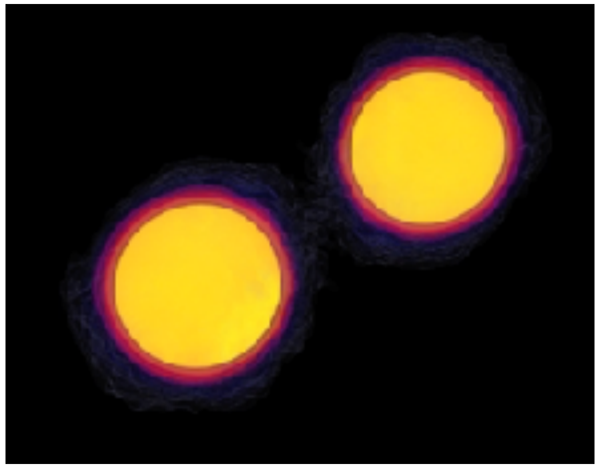
Plasma physics

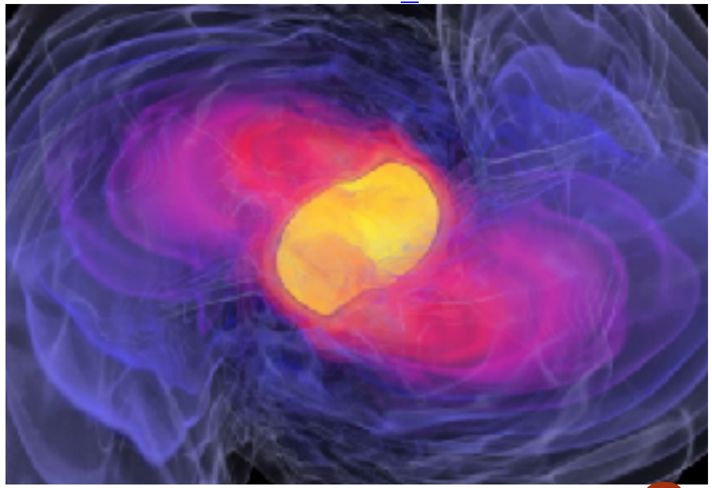
Since we are at GSI…

Gravitational waves

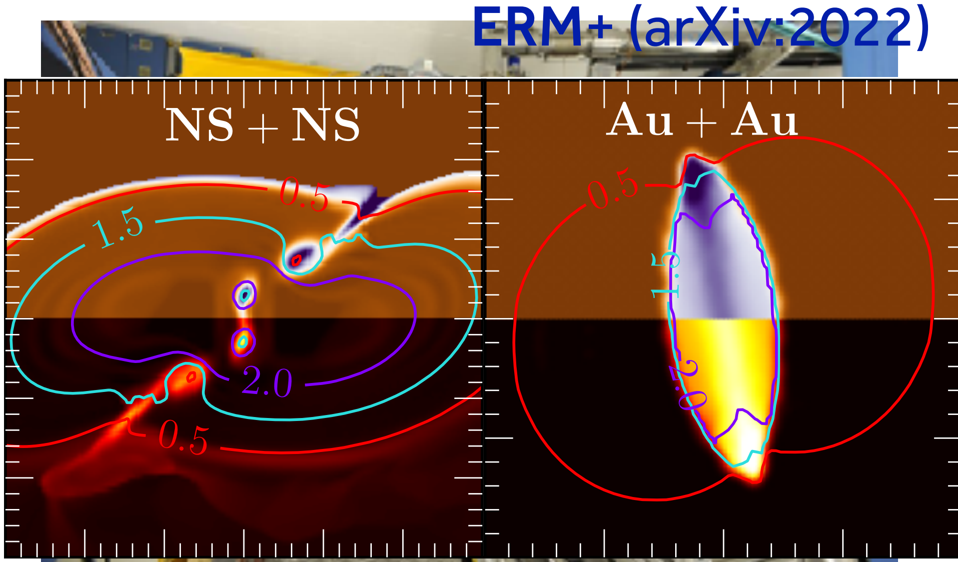
Neutron star mergers as cosmic colliders?



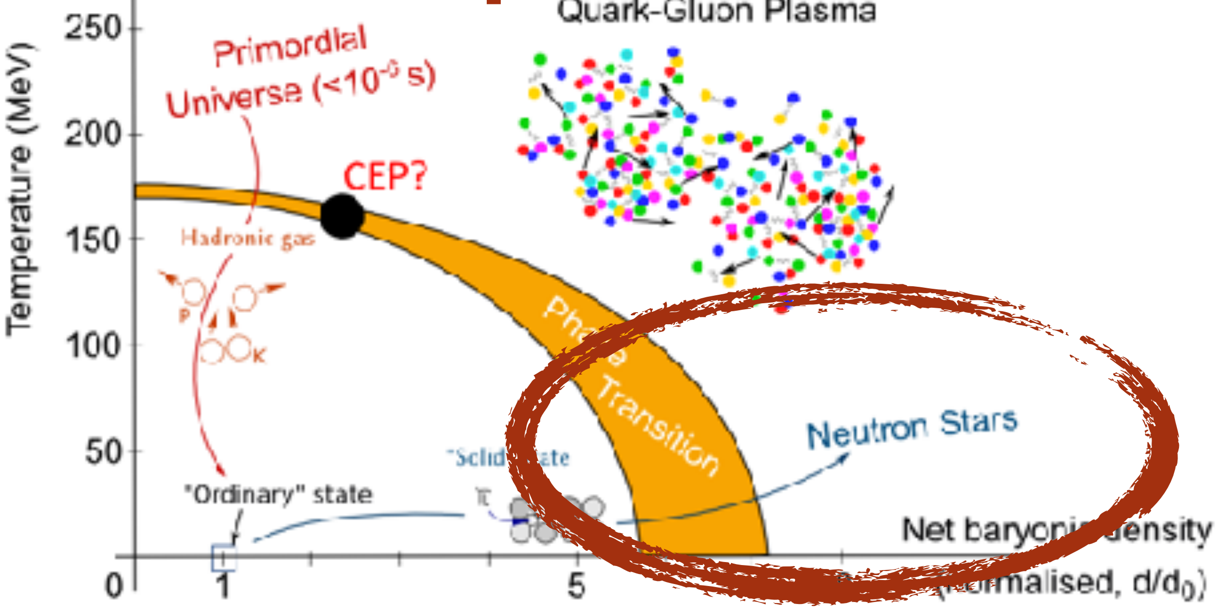




ERM+ (arXiv:2022)



Comparison with Au+Au!

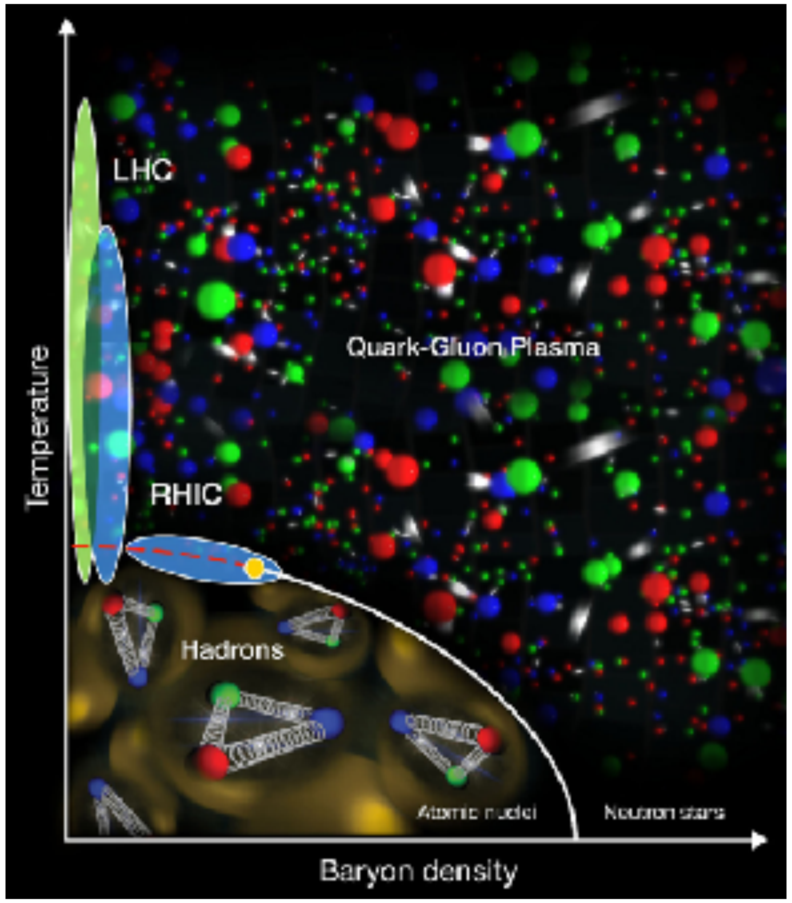


Can these events reveal extreme states of matter?

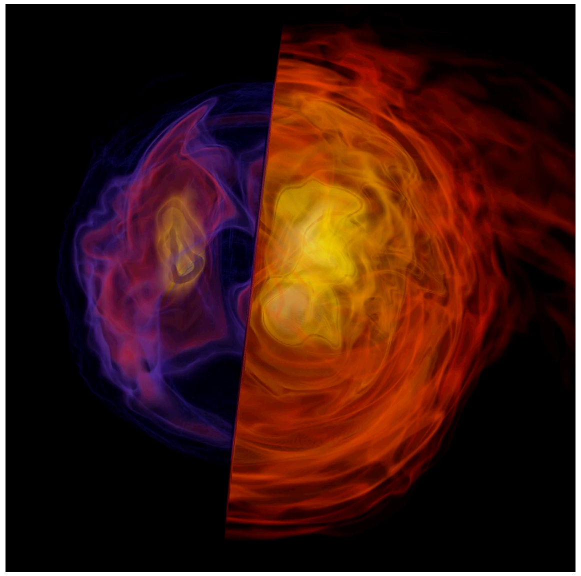
e.g. Bauswein+; **ERM**+; Prakash+; Liebling+;Radice+, Sekiguchi+ and others

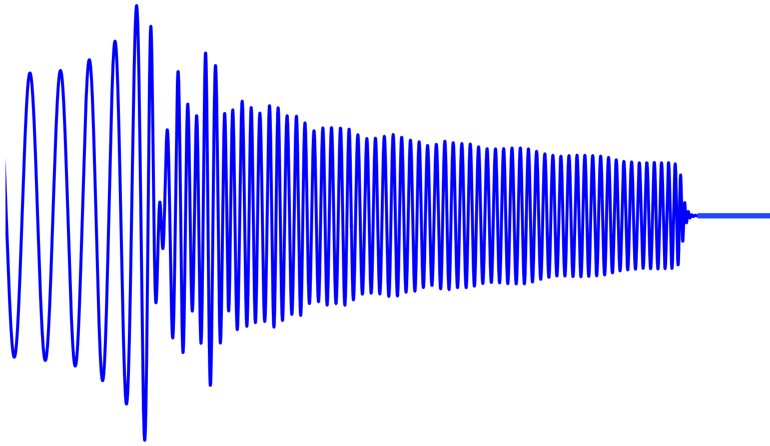
Systematically probing dense matter

Nuclear theory

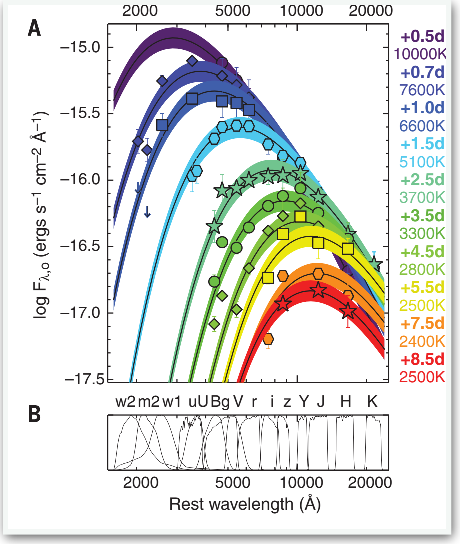


Numerical relativity simulations





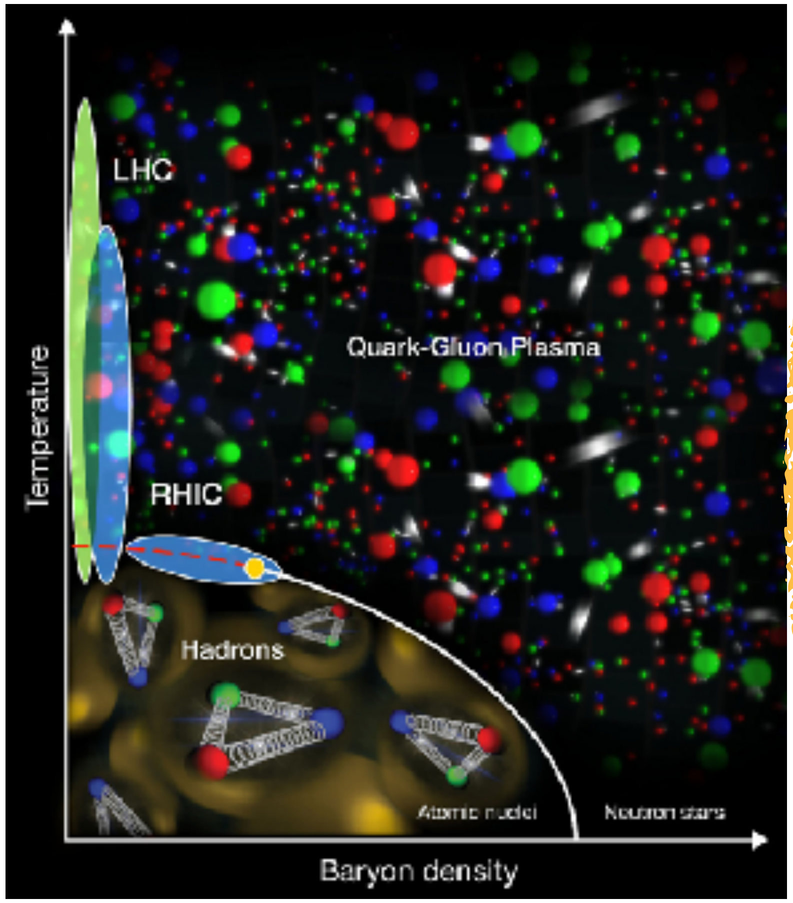
Observables



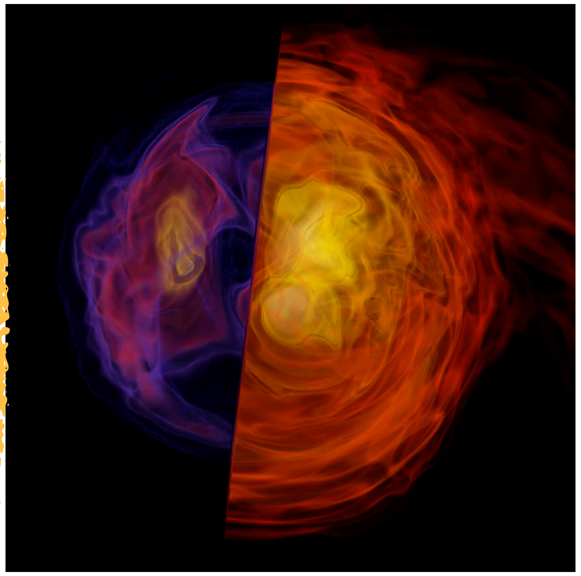
Can we systematically survey dense matter imprints?

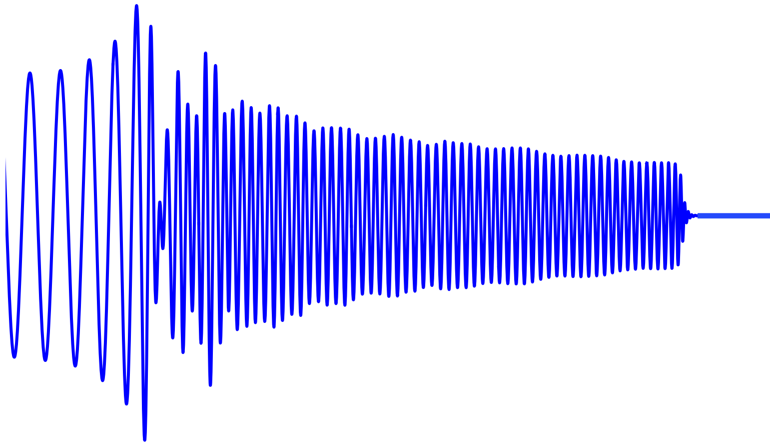
Systematically probing dense matter

Nuclear theory

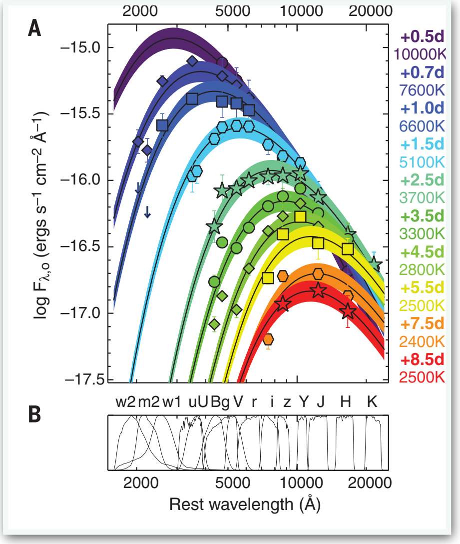


Numerical relativity simulations





Observables



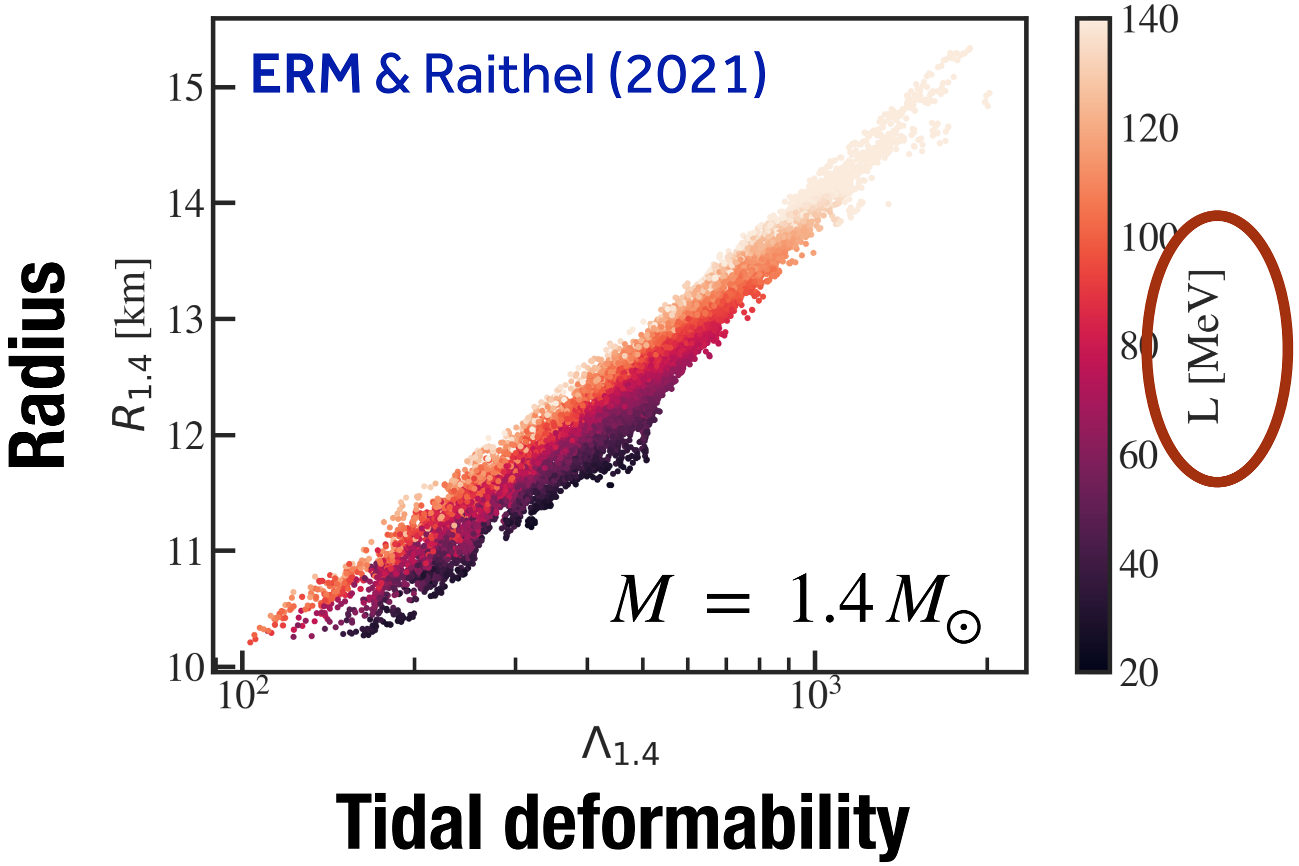
Breakthrough computing:

Modular **U**nified **S**olver
of the **E**quation of **S**tate

muses

https://musesframework.io

Systematically probing dense matter



Degeneracy roughly correlated with slope of the symmetry energy L.

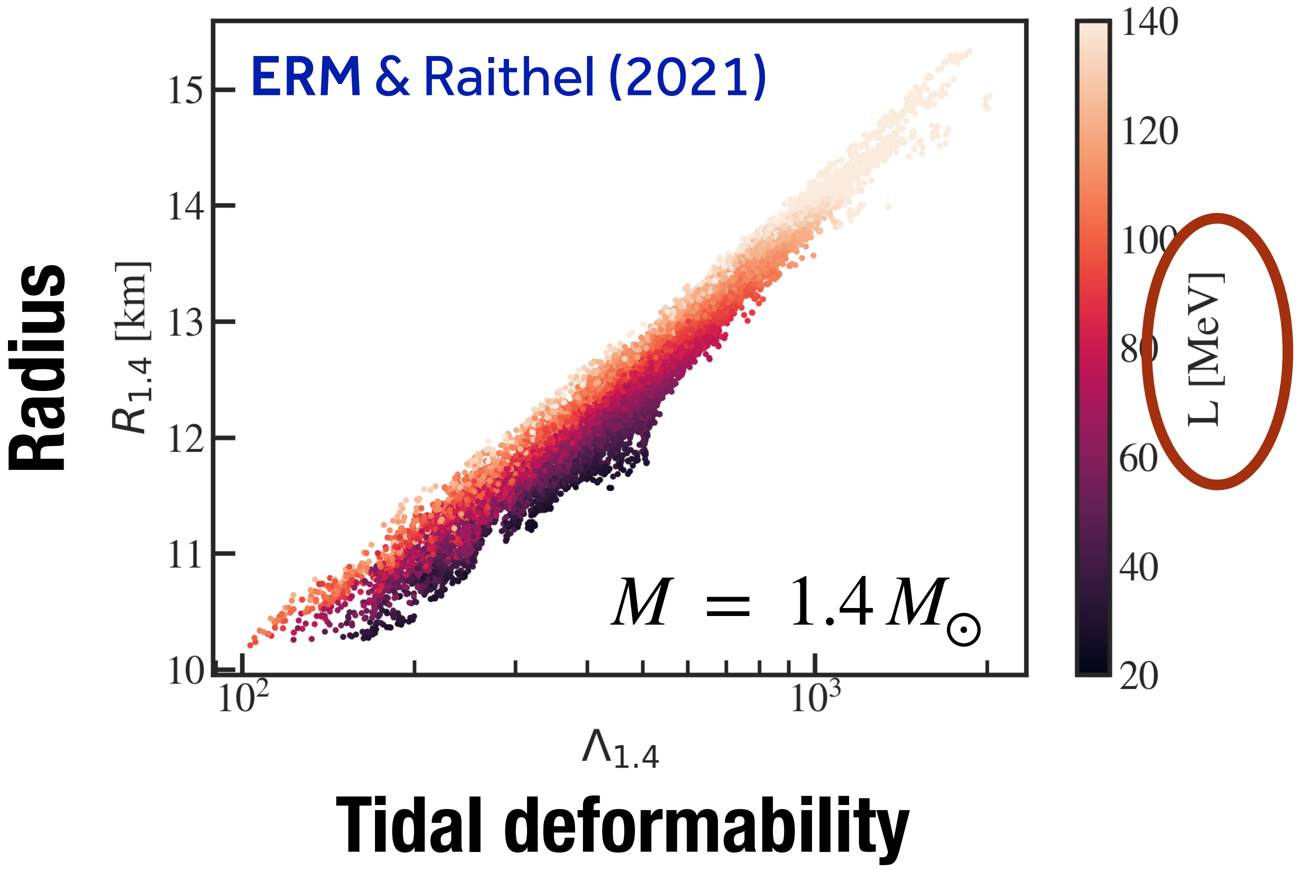
Binding energy per nucleon

$$\frac{E}{A}(n, Y_p) = \frac{E}{A}(n, \frac{1}{2}) + E_{\mathrm{sym}}(n)\left[1 - 2Y_p\right]^2 + \ldots$$

Symmetry energy

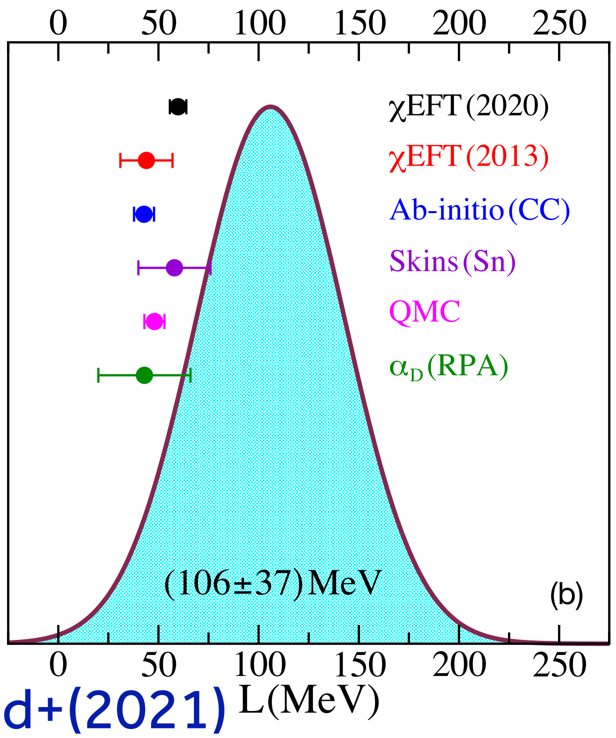
$$E_{\mathrm{sym}}(n) = S + \frac{L}{3}\left[\frac{n}{n_{\mathrm{sat}}} - 1\right] + \mathcal{O}\left[\left(\frac{n}{n_{\mathrm{sat}}}\right)^2\right]$$

Systematically probing dense matter



Degeneracy roughly correlated with slope of the symmetry energy L.

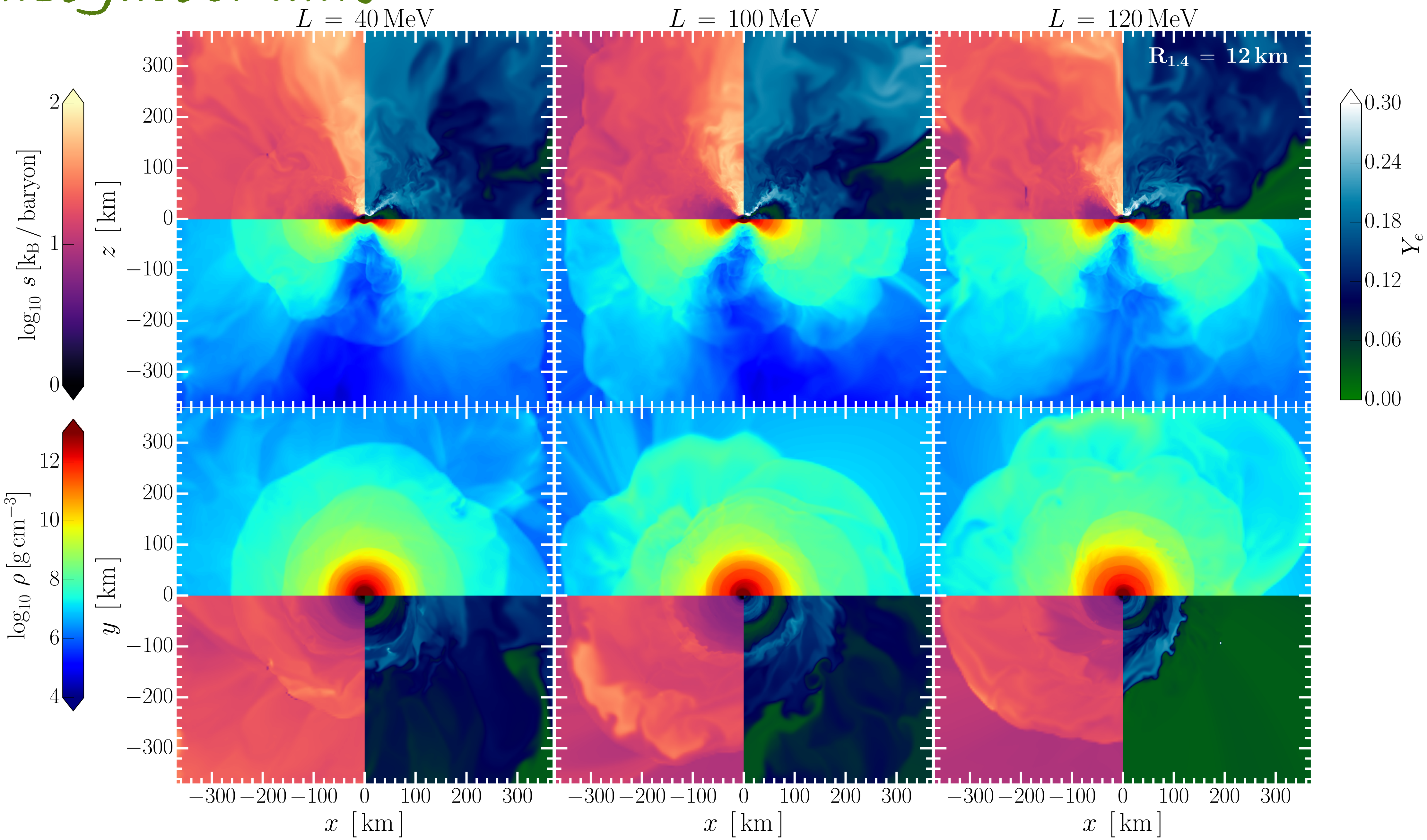
Deciphering the post-merger gravitational wave emission will require systematic investigations of nuclear parameters (e.g., L , S,…).



Reed+(2021)

Probing nuclear matter parameters with post-merger gravitational waves

See also Jacobi talk



Proof-of-principle!

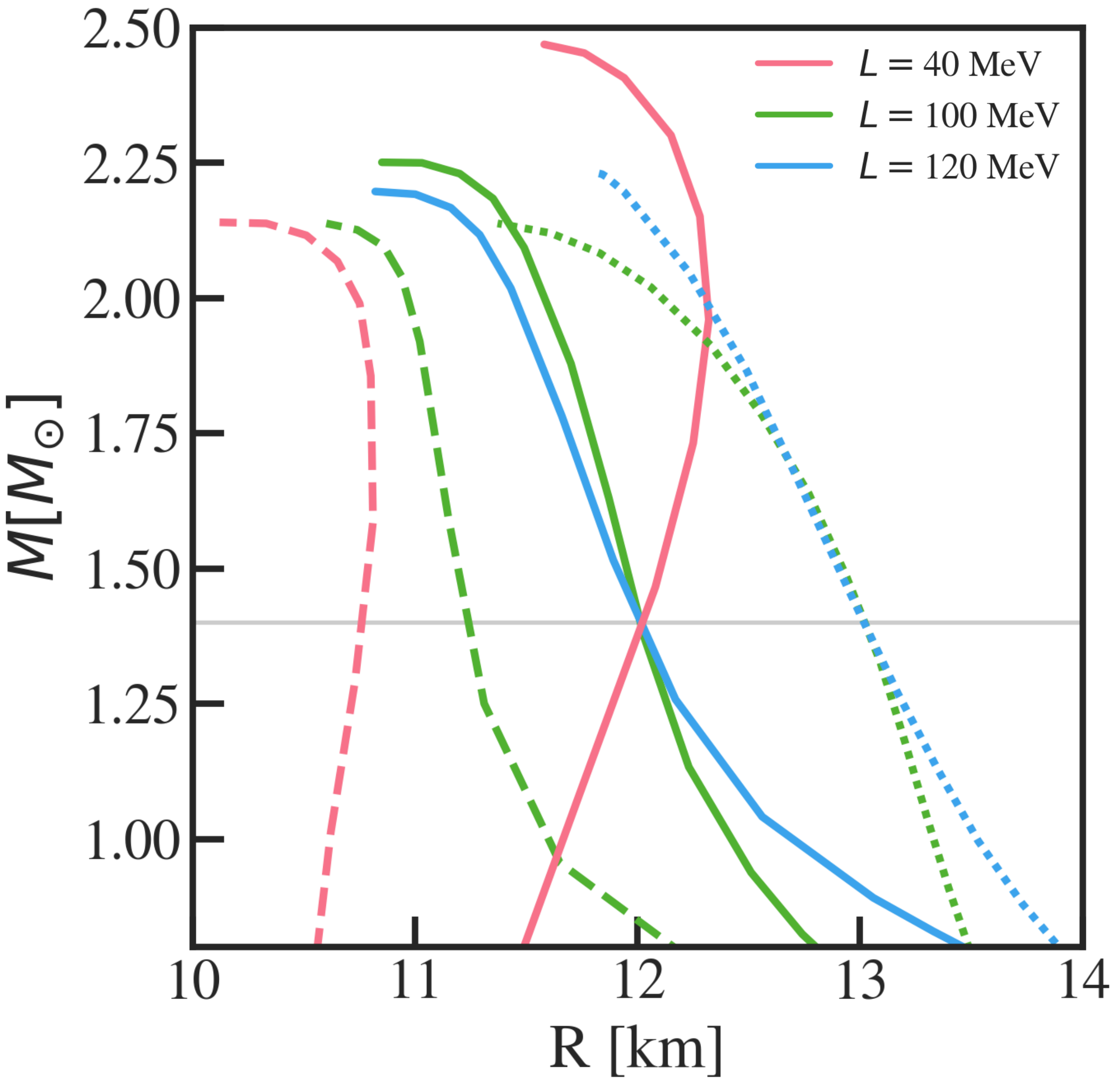
ERM & Raithel (2021)

A parametric approach

Constructed a set of polytropic equations of state that systematically vary L.

Most of them tuned to have either the same tidal deformability $\Lambda_{1.4}$ or radius $R_{1.4}$ for $1.4\,M_\odot$ neutron stars.

ERM & Raithel(2021)



$$L = \frac{3P(n_{\rm sat}, Y_{e,\beta}, T=0)}{a n_{\rm sat}}$$

Extension to finite-temperatures

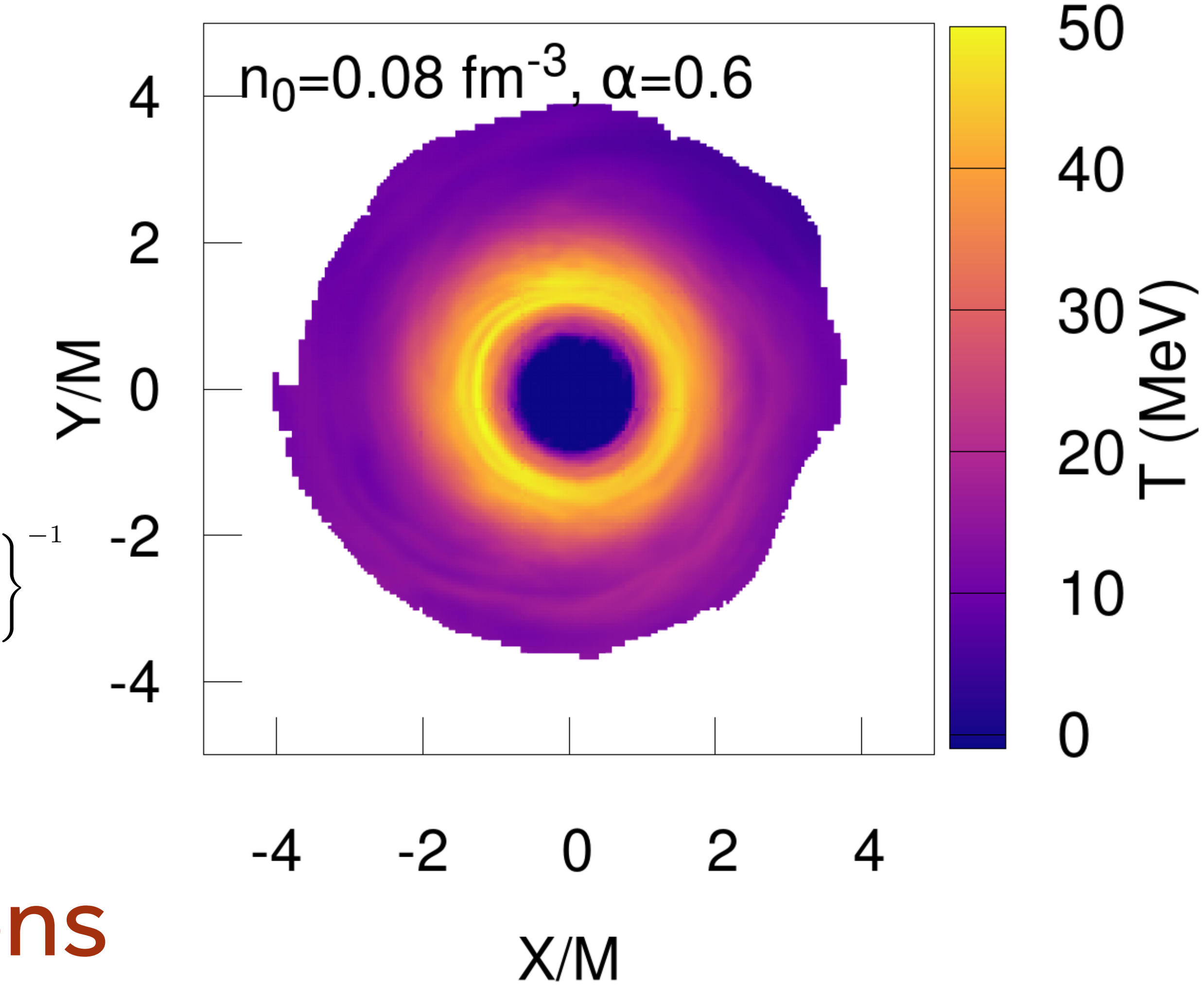
Extended the cold polytropes to finite temperatures using the M^* framework

Raithel+(2019,2021)

$$P = P_{\rm cold} + P_{\rm th}$$

$$P_{\rm th}(n,T,Y_p) = \frac{4\sigma f_s T^4}{3c} + \left\{ (nk_BT)^{-1} - \left[\frac{\partial a(0.5n, M^*_{\rm SM})}{\partial n} + \frac{\partial a(Y_p n, m_e)}{\partial n} Y_p \right]^{-1} n^{-2} T^{-2} \right\}^{-1}$$

Raithel+(2021)



Include out-of-β-eq. corrections by extrapolating chemical potentials ERM & Raithel (2021)

$$\hat{\mu}(n, Y_p, T) \equiv \mu_n(n, Y_p, T) - \mu_p(n, Y_p, T)$$

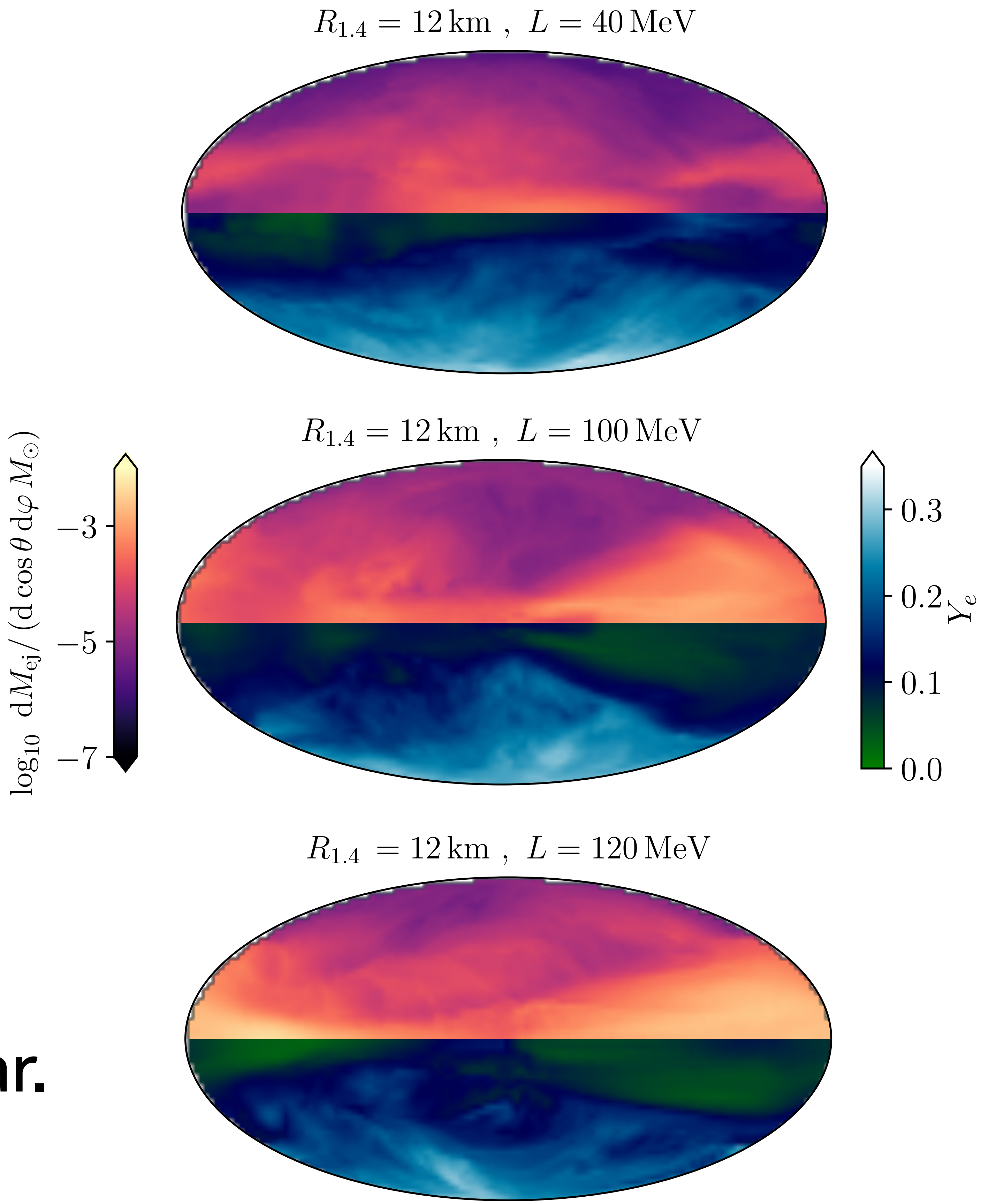
$$\hat{\mu}(T=0) = 4(1-2Y_p)E_{\rm sym}(n)$$

Approach to customize EoS is unique in merger simulations!

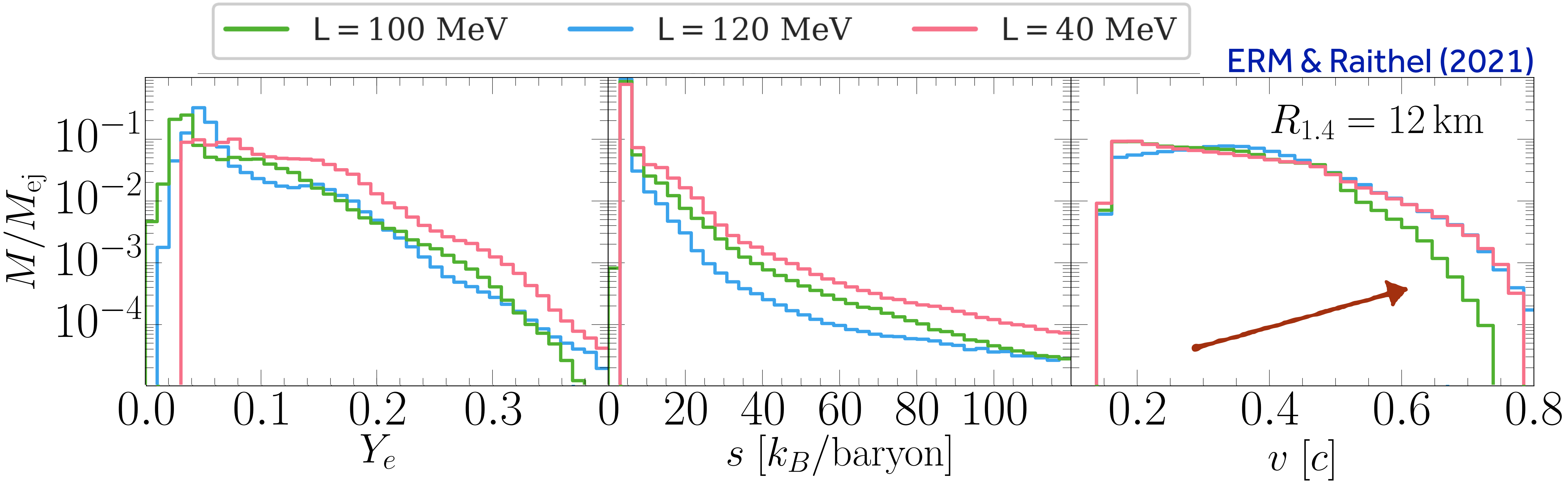
Dynamical mass ejection

ERM & Raithel (2021)

- Mass ejection shows correlation with L.
- Higher L leads to overall more ejecta.
- Spatial distribution and composition very similar.

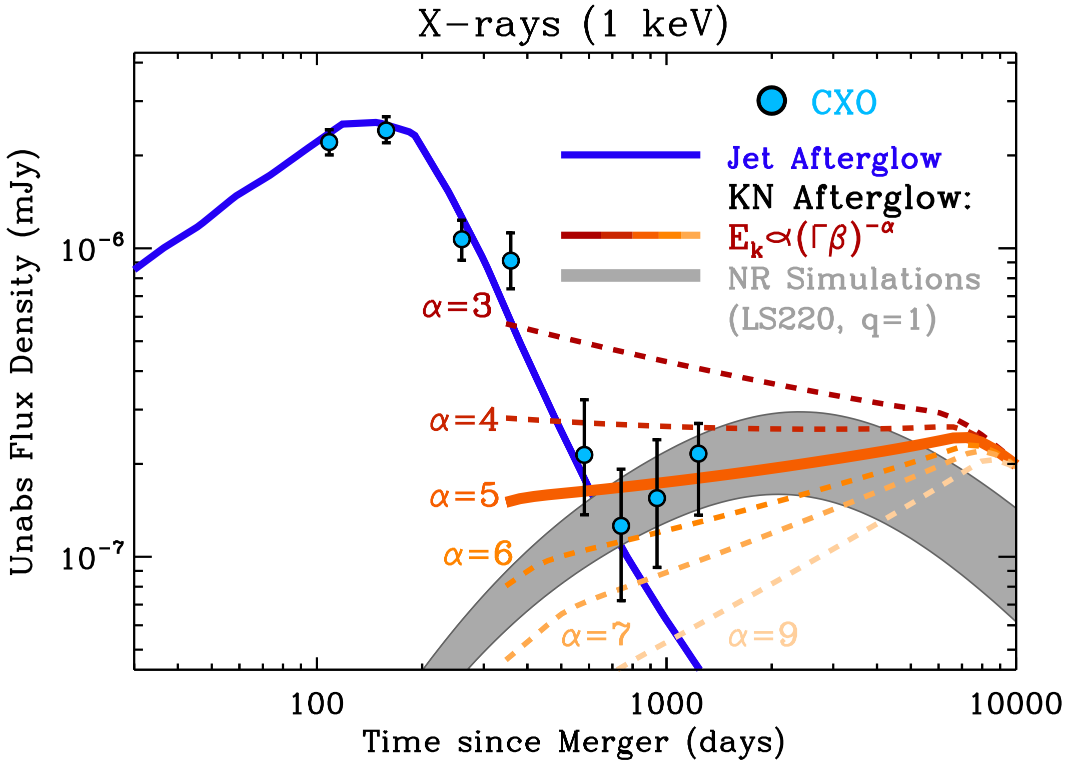


Ejecta properties



ERM & Raithel (2021)

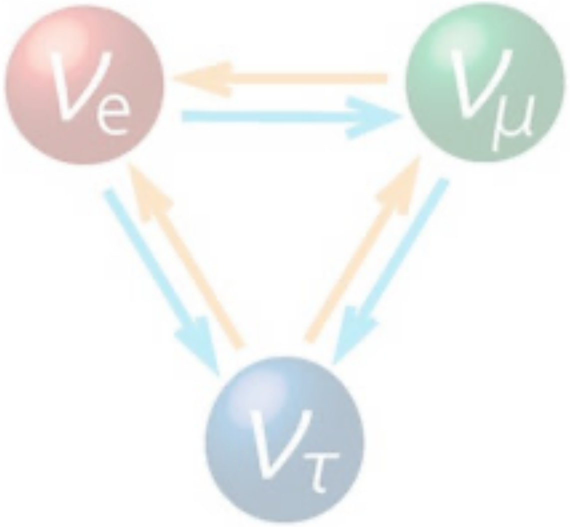
- Fast ejecta present in all cases.
- Potentially interesting in the context of late X-ray aferglows.



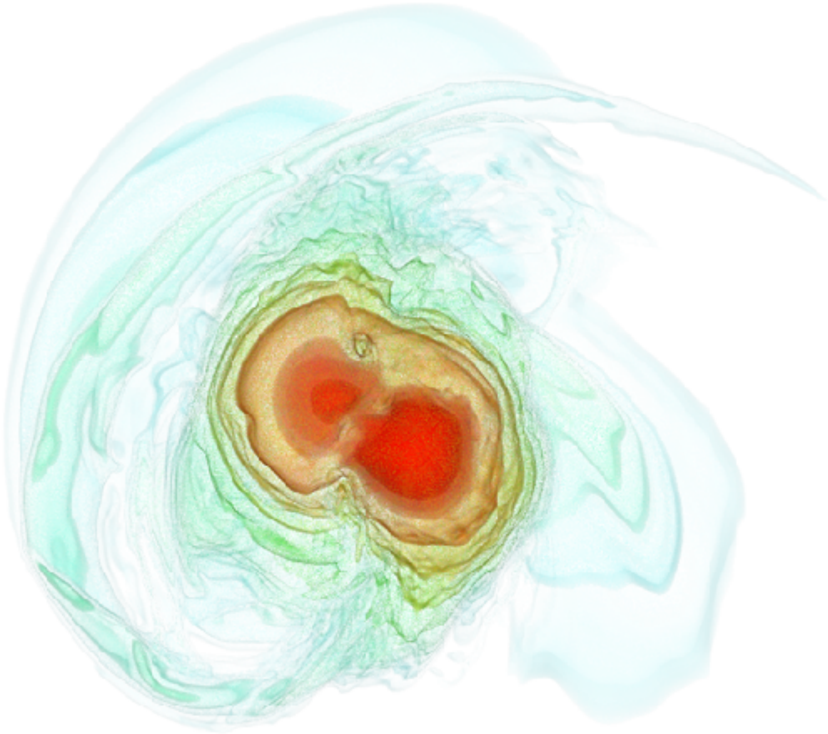
For fallback scenarios see:
Metzger & Fernandez , Ishizaki+, and others

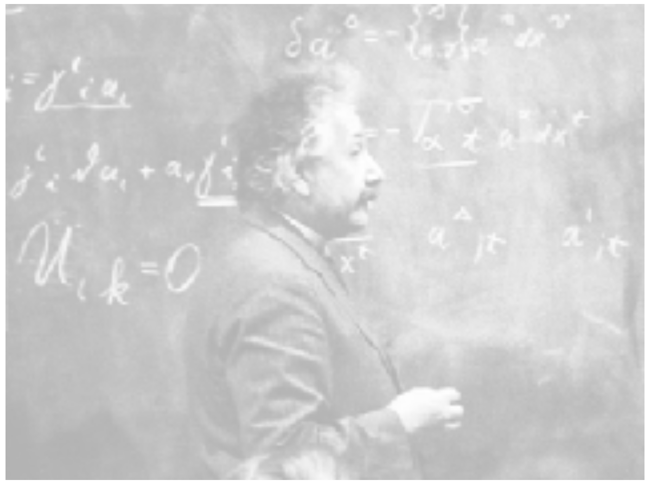
GW170817 follow-up Hajela+ (2022)

The many faces of neutron star mergers

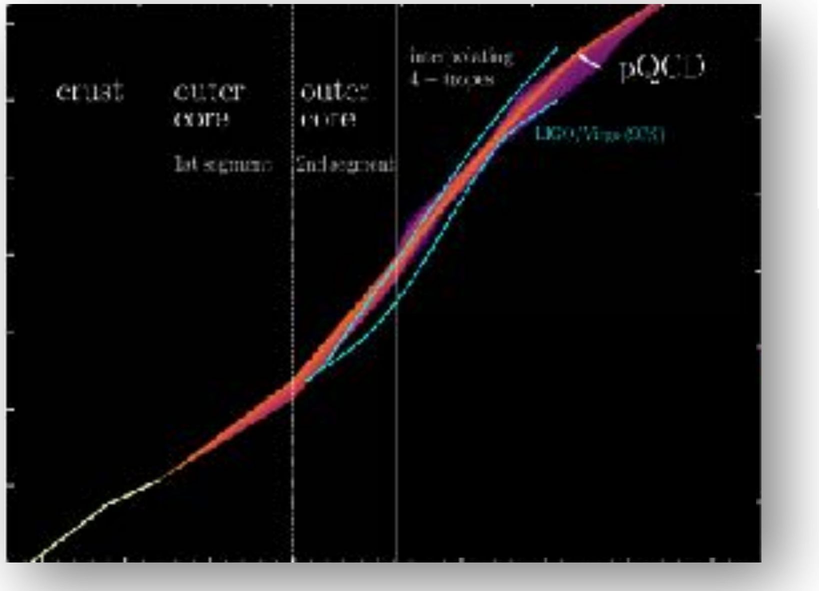


Neutrino physics

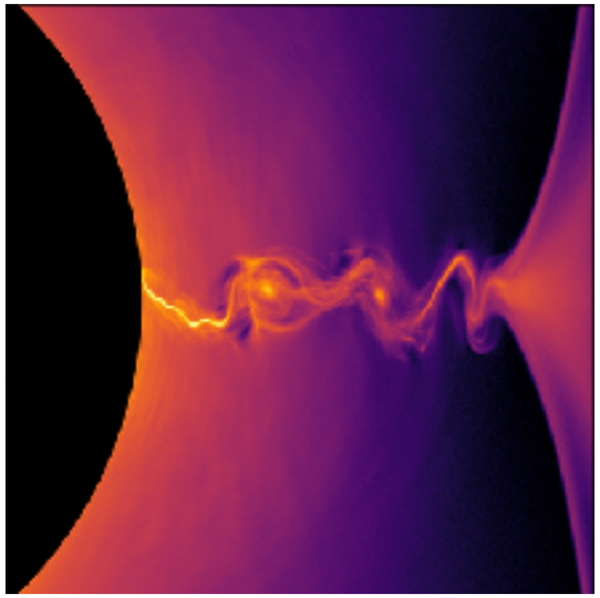




Gravitational physics



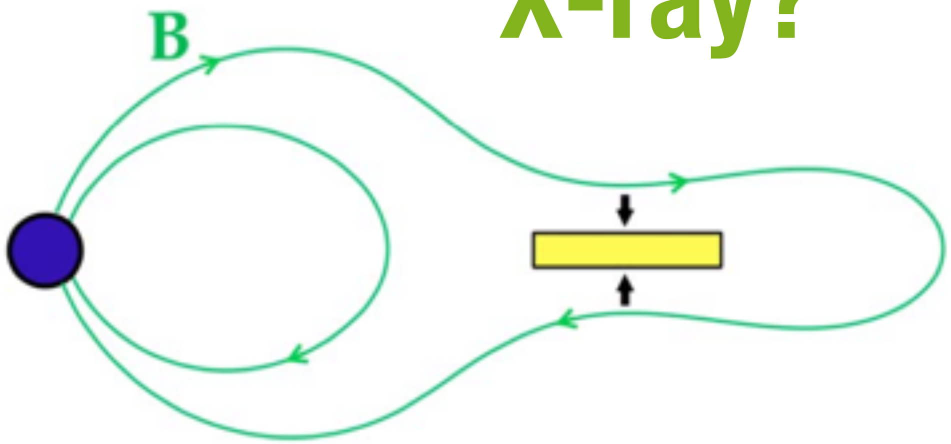
Nuclear physics



Plasma physics

Different precursor transients

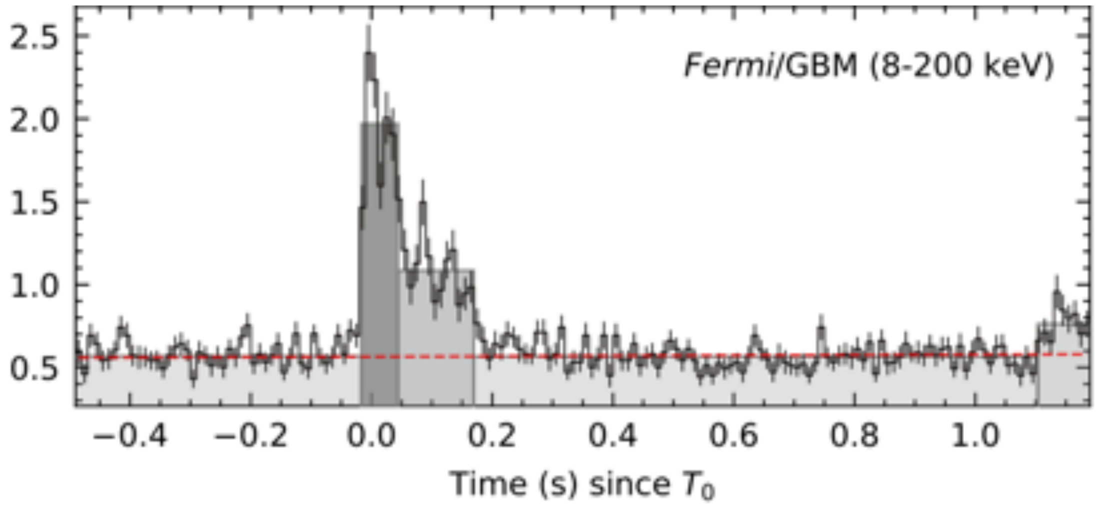
X-ray?



Tsang+(2012), Neill+(2021)

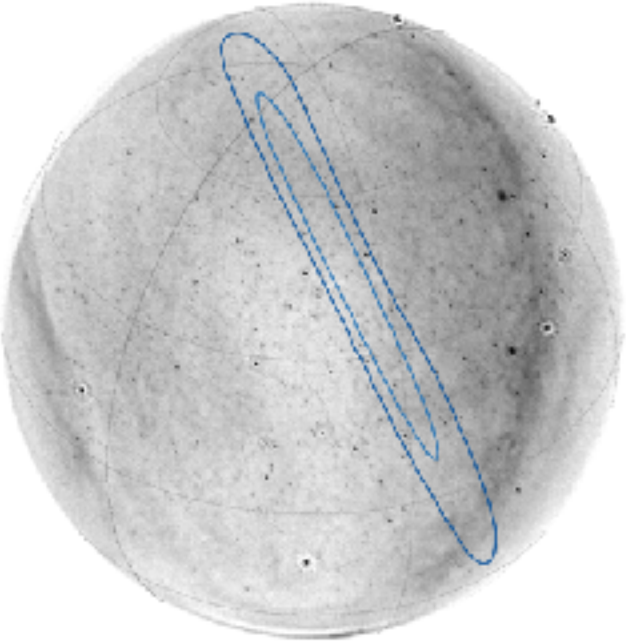
Beloborodov(2020)

Gamma-rays?



Xiao+ (2022)

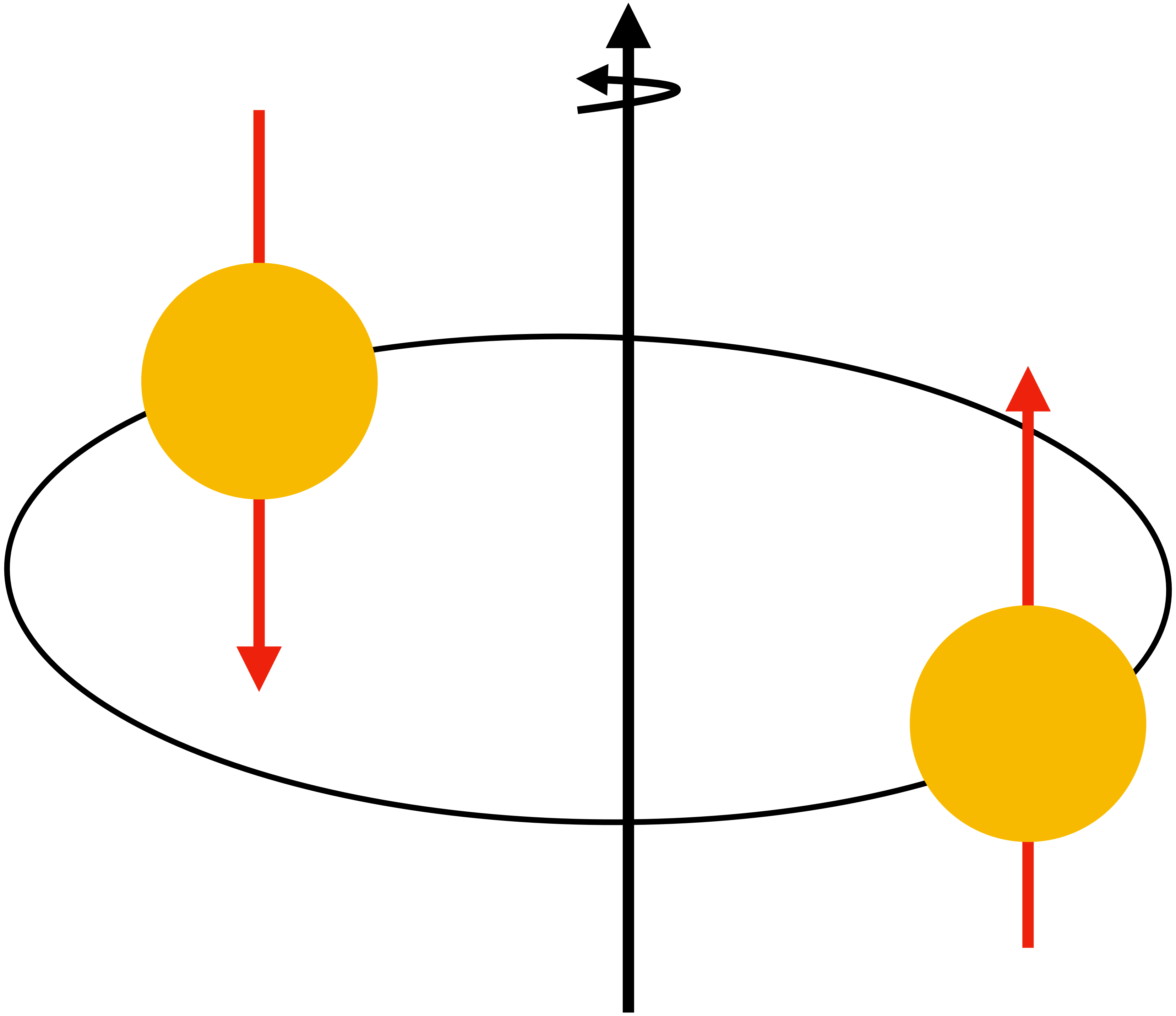
Radio search for GW170817



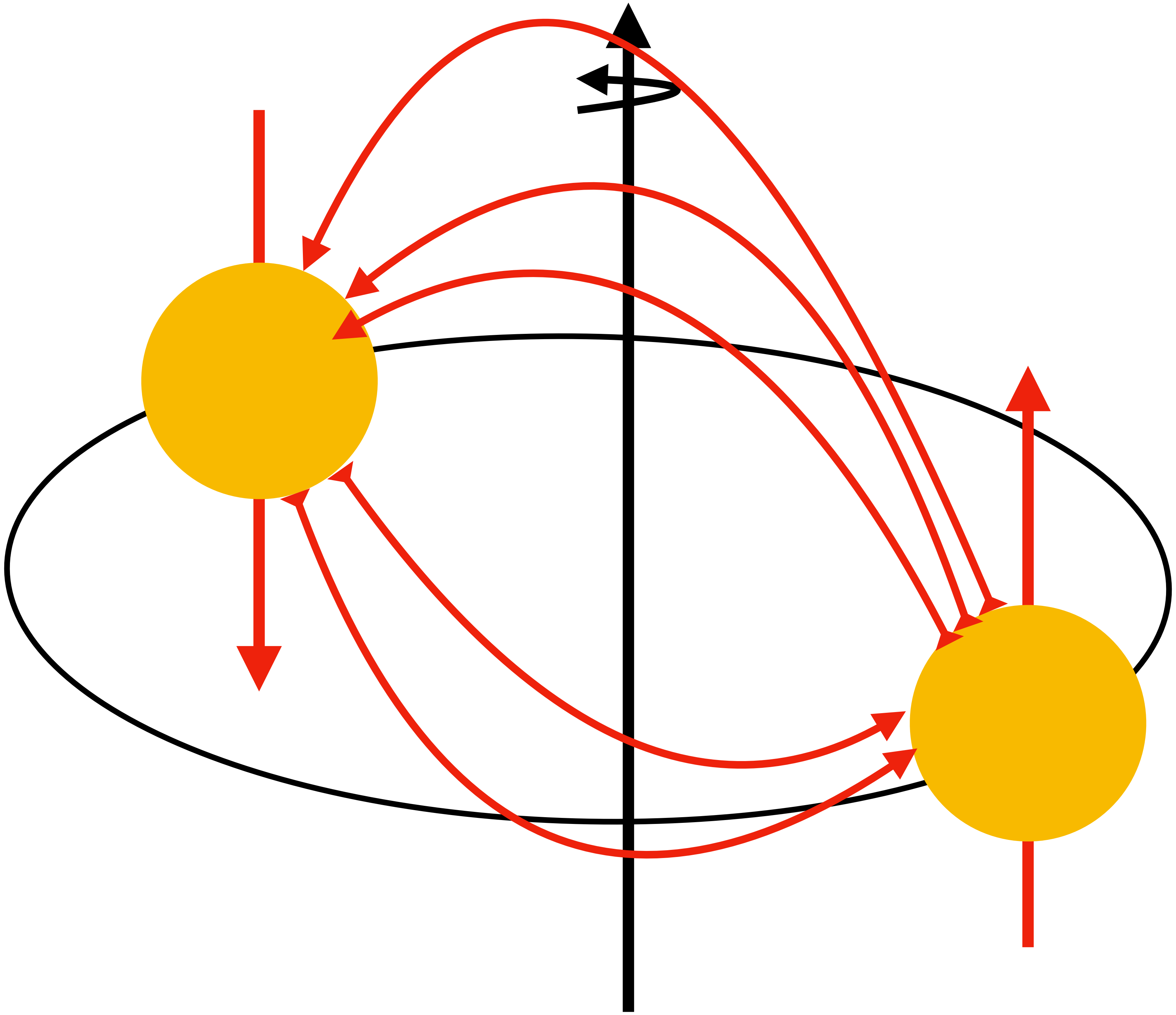
Callister+ (2019)

See also Palenzuela+; Carrasco & Shibata; East+

Electromagnetic precursors

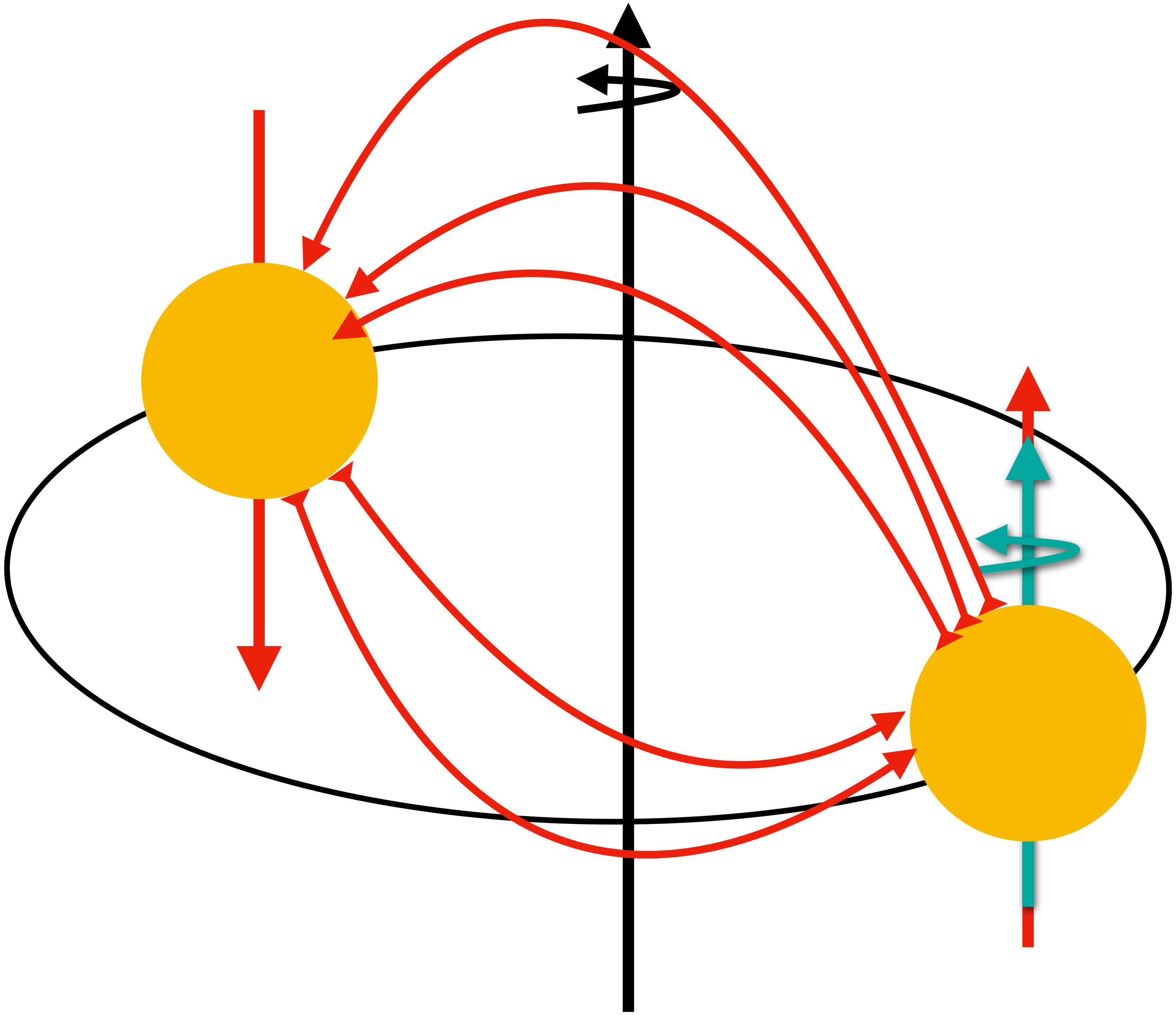


Electromagnetic precursors



Electromagnetic precursors

Adding the right twist



Electromagnetic precursors

Adding the right twist

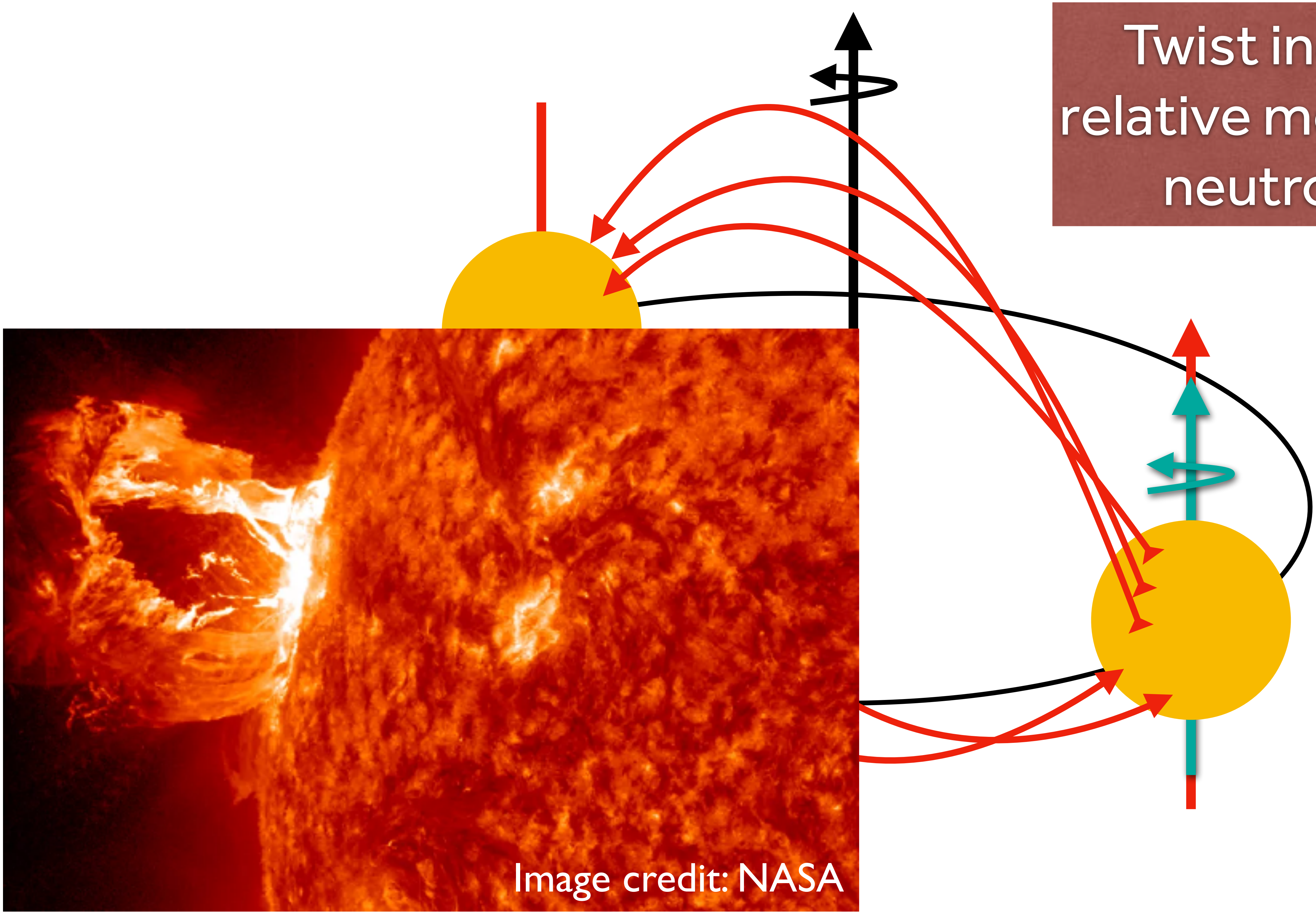
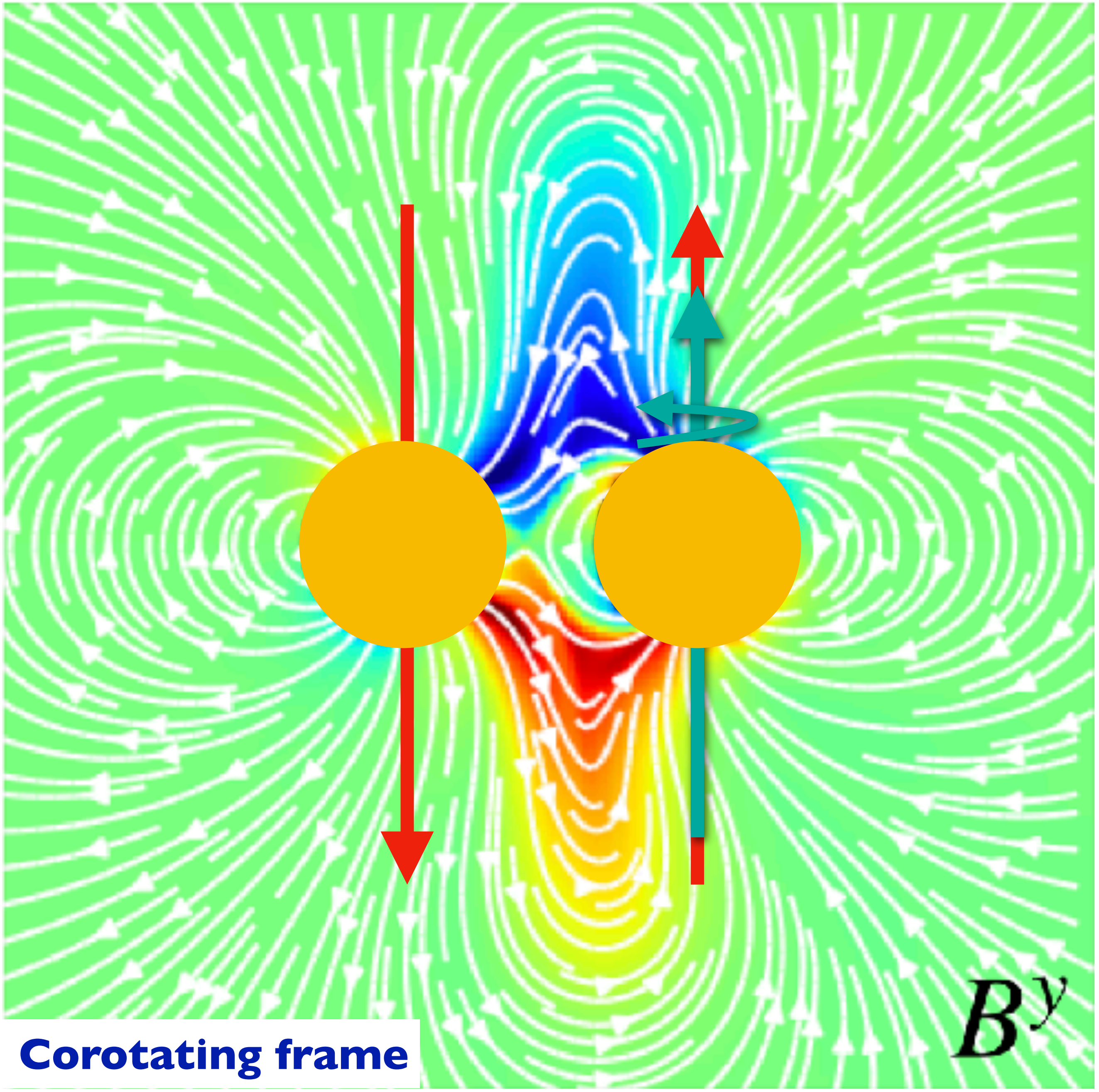


Image credit: NASA

Twist induced by relative motion of the neutron stars

Electromagnetic precursors

Adding the right twist



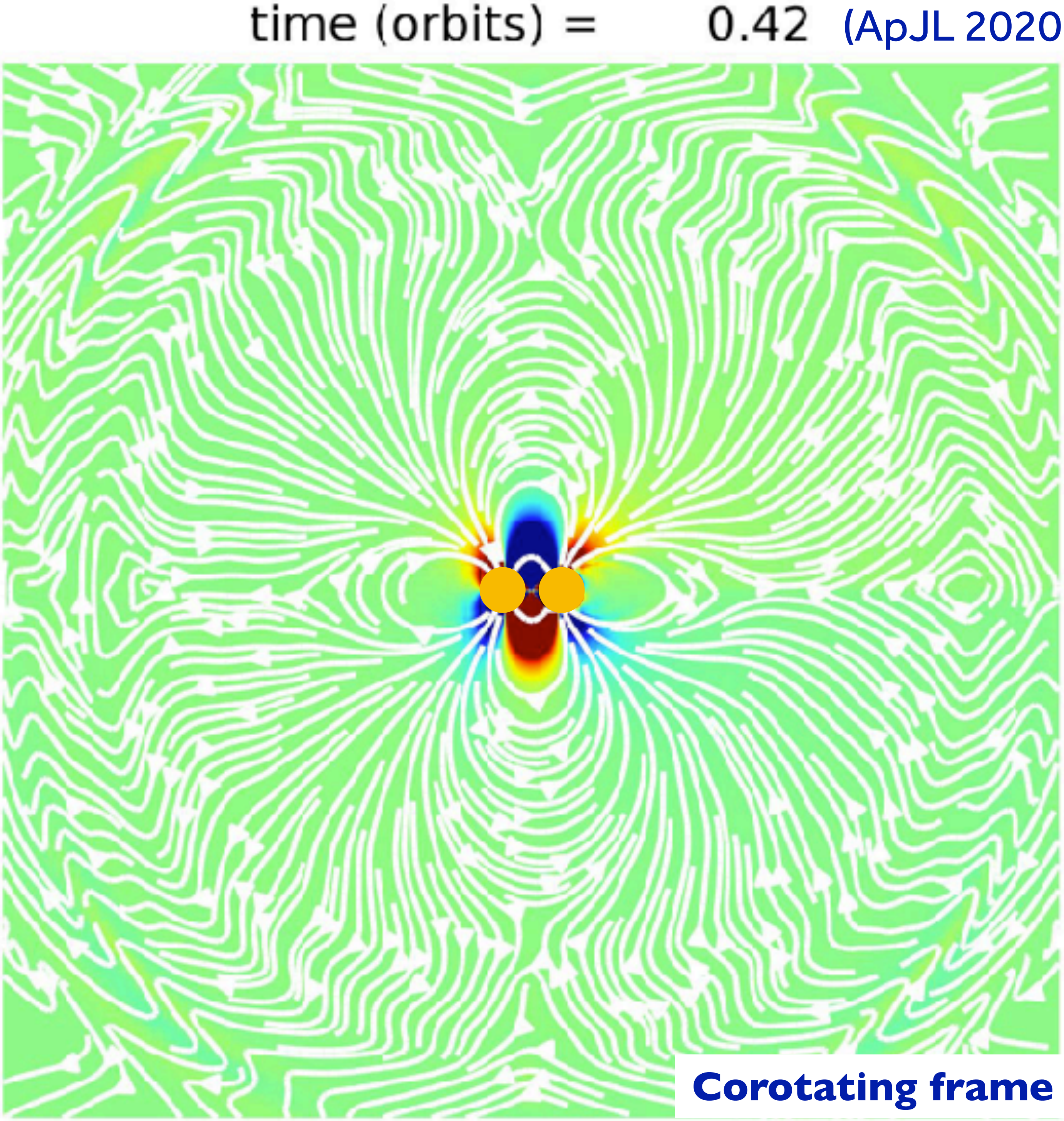
ERM & Philippov
(ApJL 2020)

A new radio transient?

Differential motion leads to the emission of strong electromagnetic flares.

Relativistic force-free electrodynamics simulations in corotating frame

ERM,Philippov (ApJL 2020)

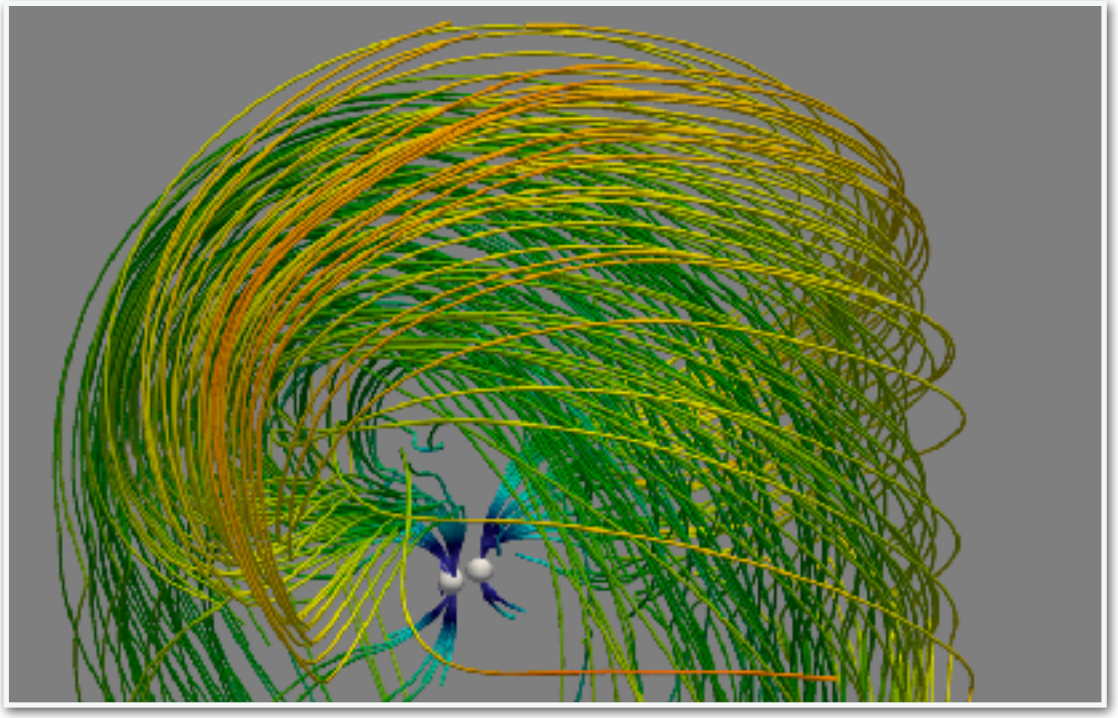


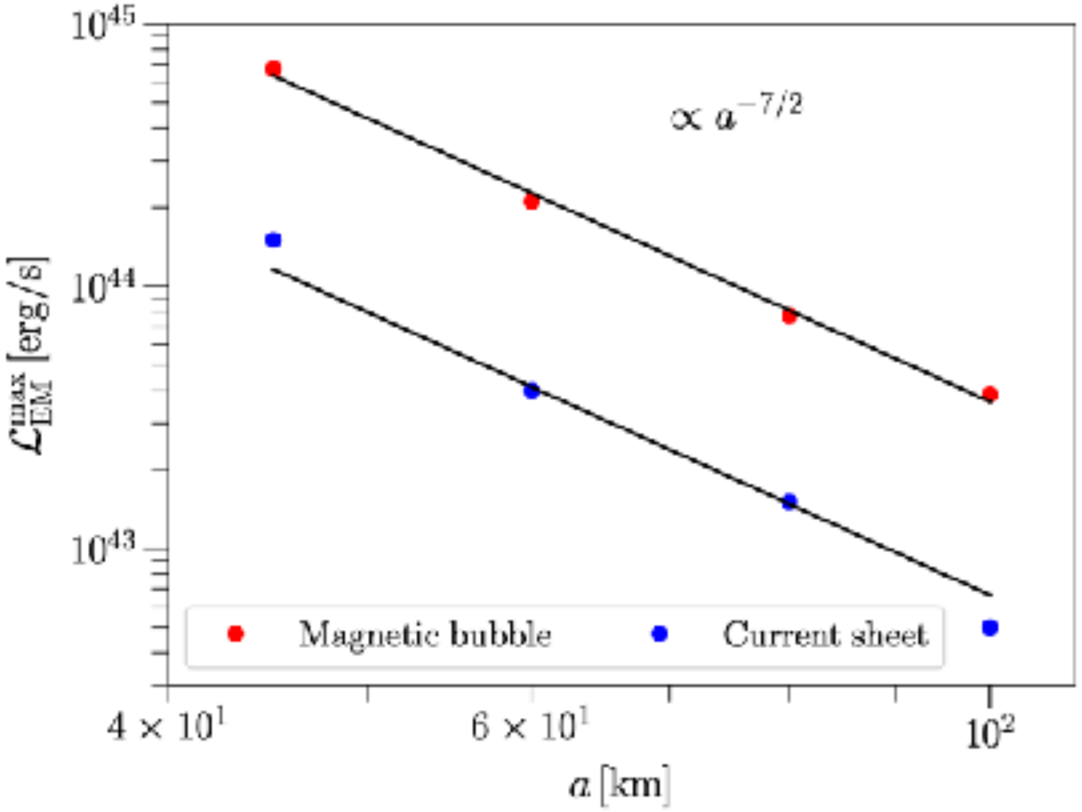
A new radio transient?

Prior to merger, potentially up to 20* sufficiently strong flares could be emitted

(*: for $B \simeq 10^{11}$ G).

ERM,Philippov (MNRAS 2022)

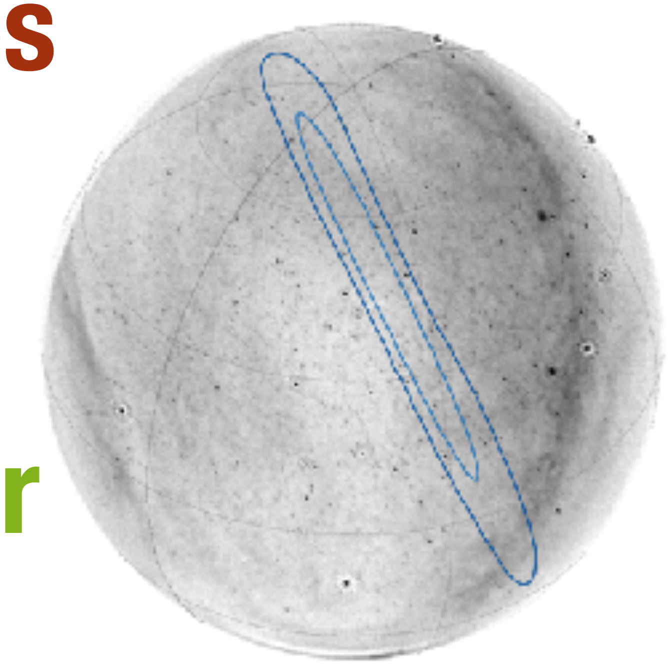




ERM,Philippov (ApJL2020)

Are these flares observable?

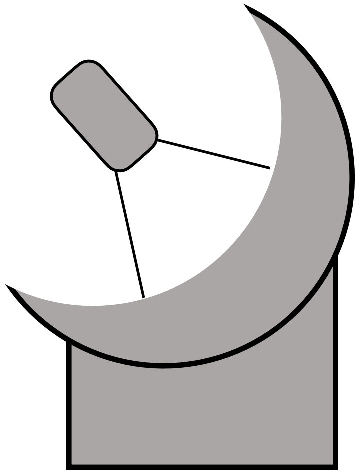
Radio search for GW170817

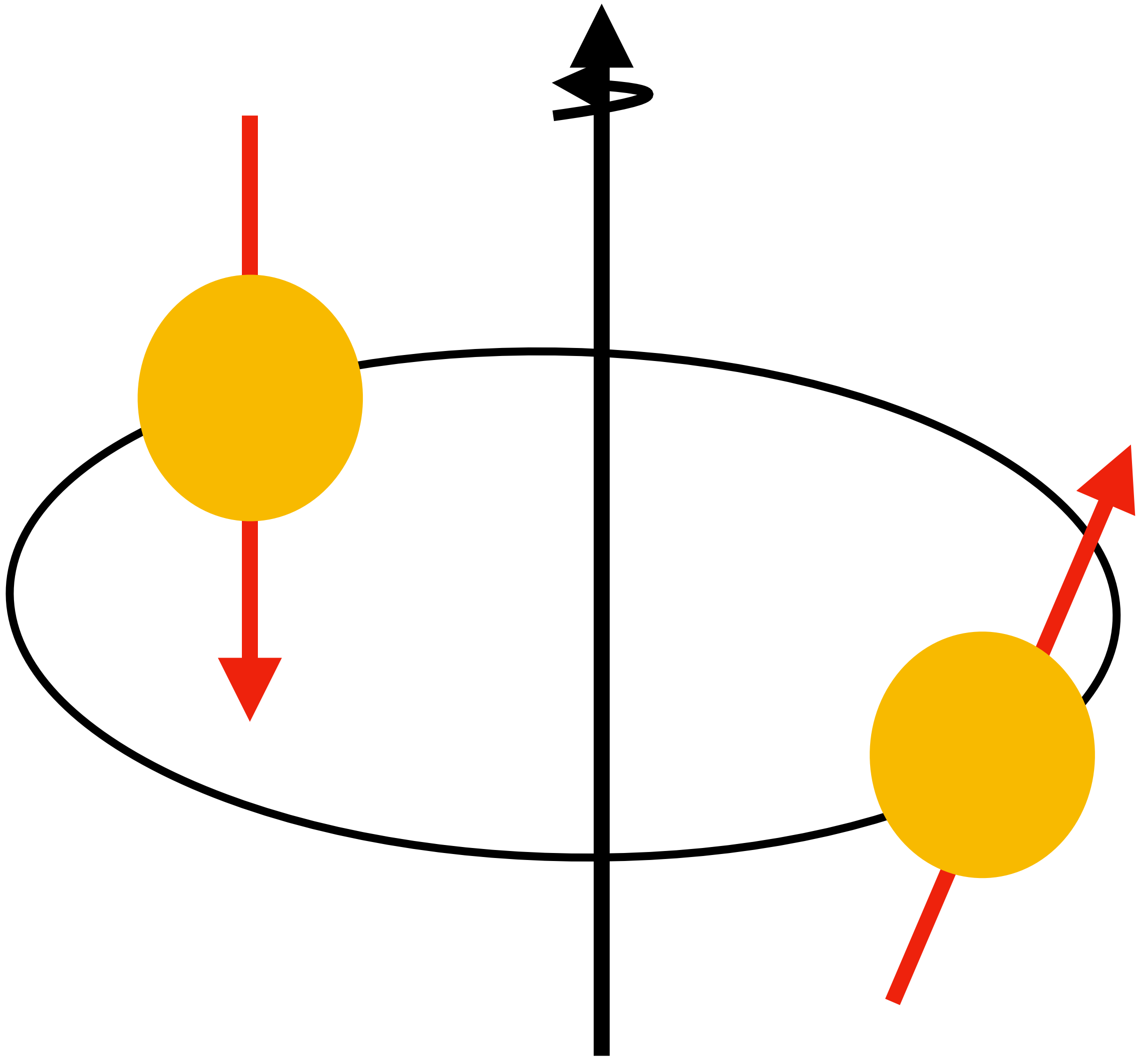


Callister+ (2019)

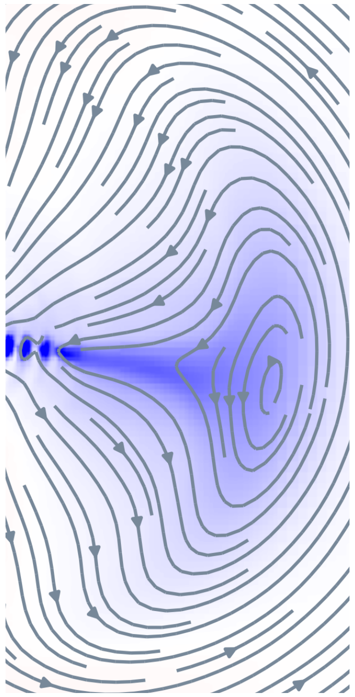
Emission mechanism

- Need to convert the emitted electromagnetic energy into observable signals!

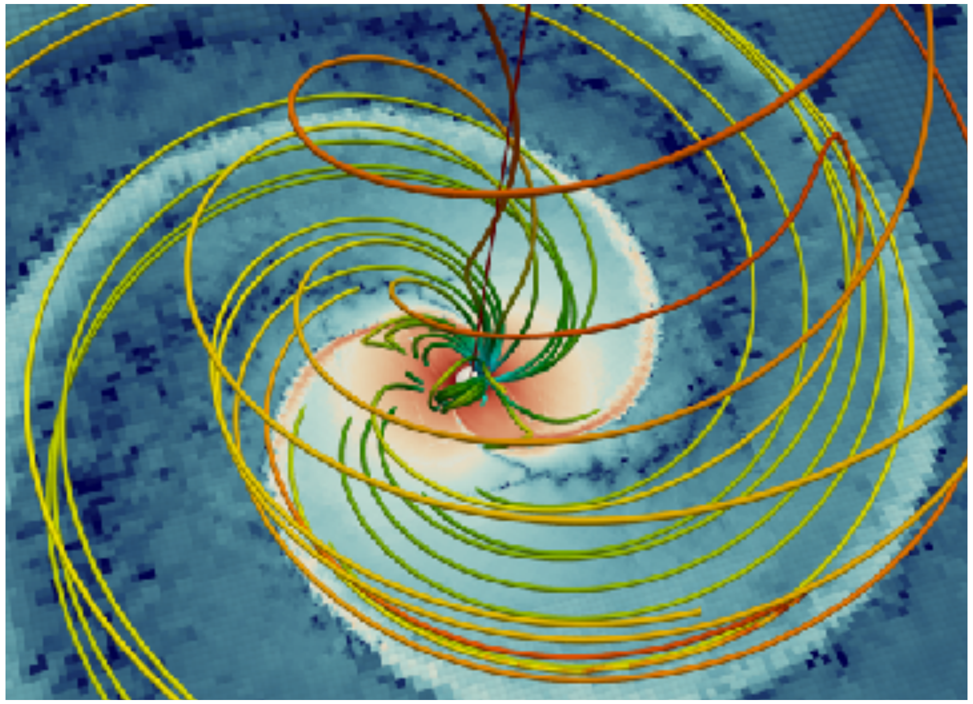




flare



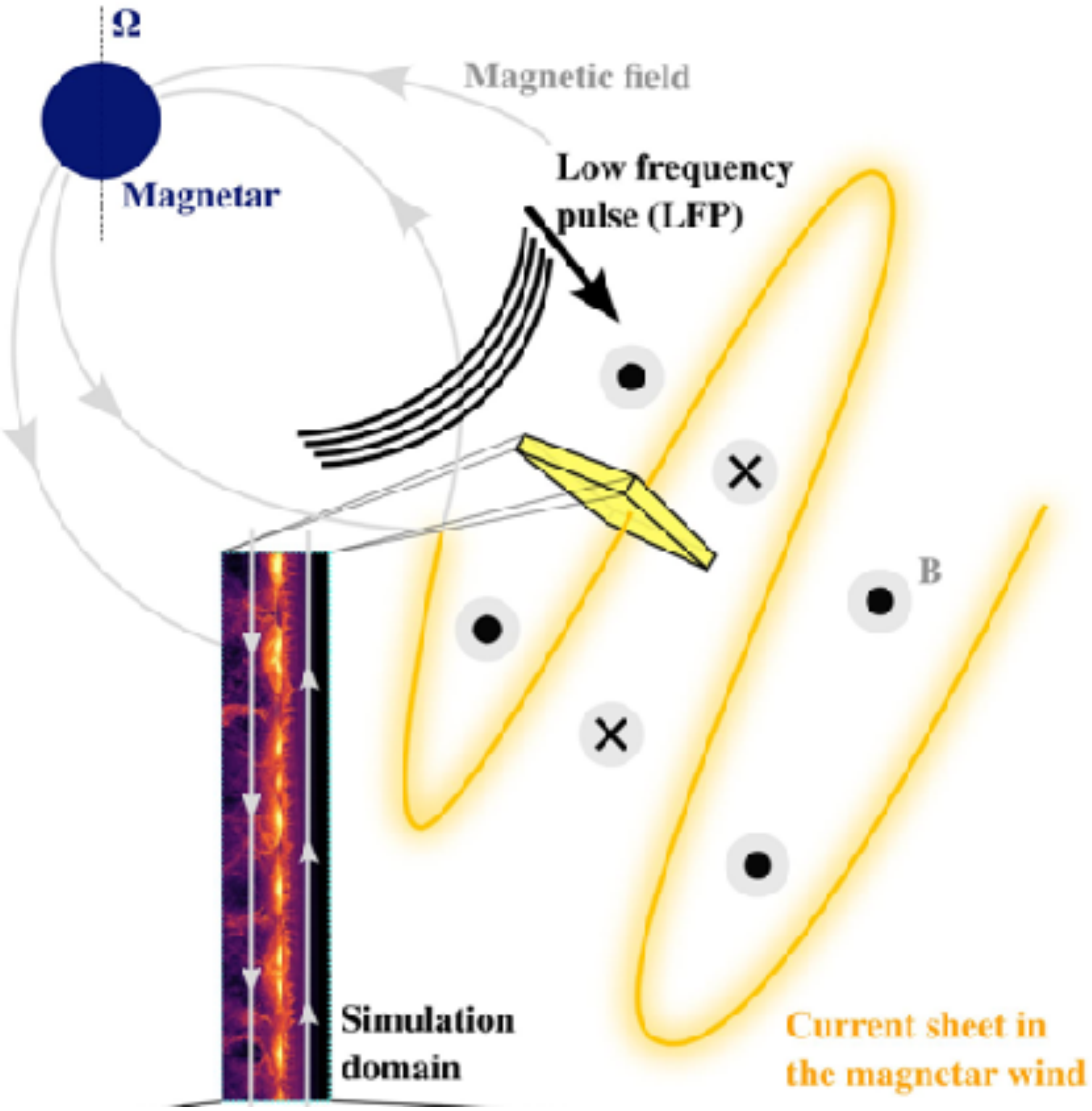
Plasmoids!

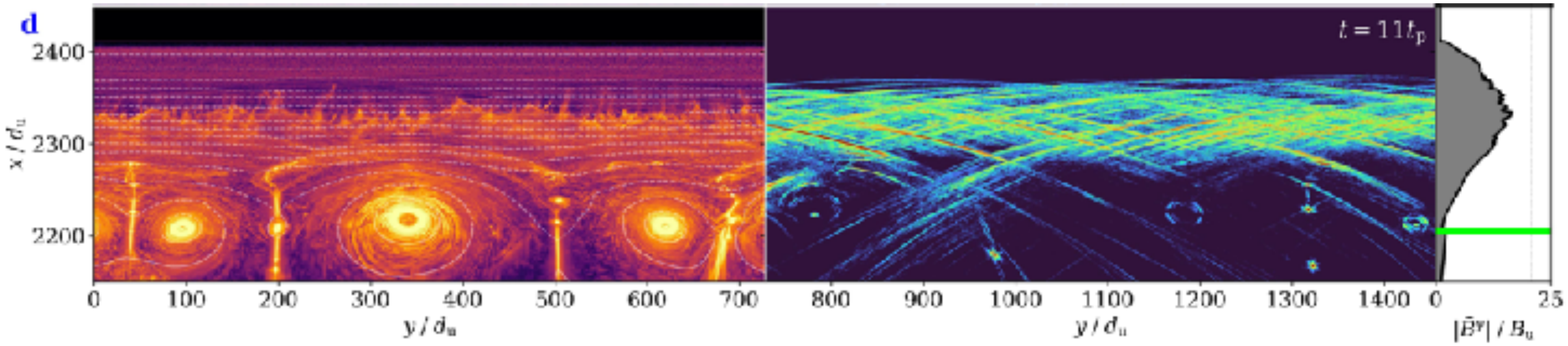


Orbital current sheet

Emission mechanism

- Need to convert the emitted electromagnetic energy into coherent radiation !
- Borrow idea from magnetar Fast radio burst model : Flare -current sheet interaction Lyubarsky (2020)





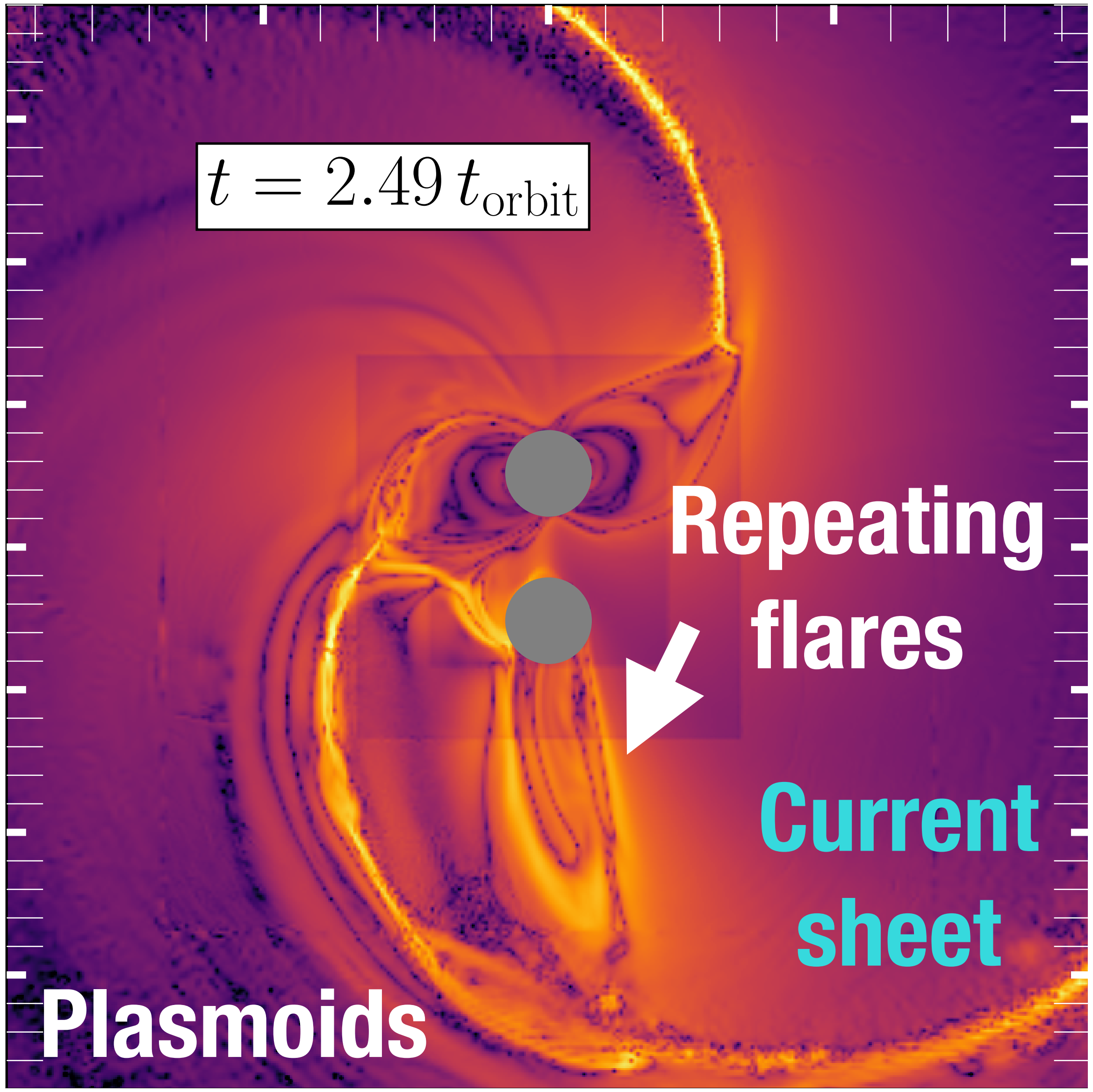
Mahlmann+ (2022)

Emission mechanism

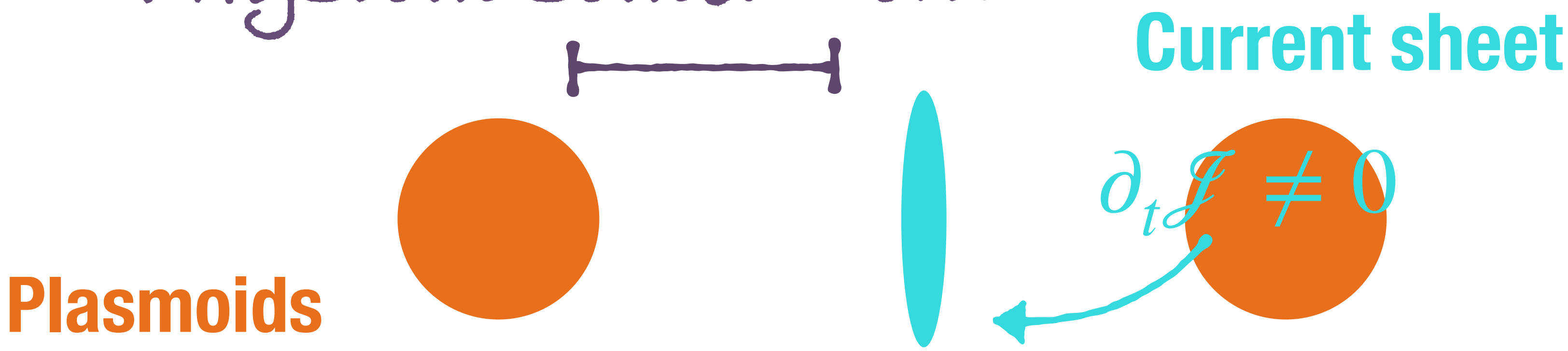
ERM & Philippov
(in prep)

- Flare -(orbital) current sheet interaction triggers reconnection. Lyubarsky (2020)

- Depending on the field strength, plasmoid mergers will lead to the emission of a radio or X-ray transient. Philippov+(2019)



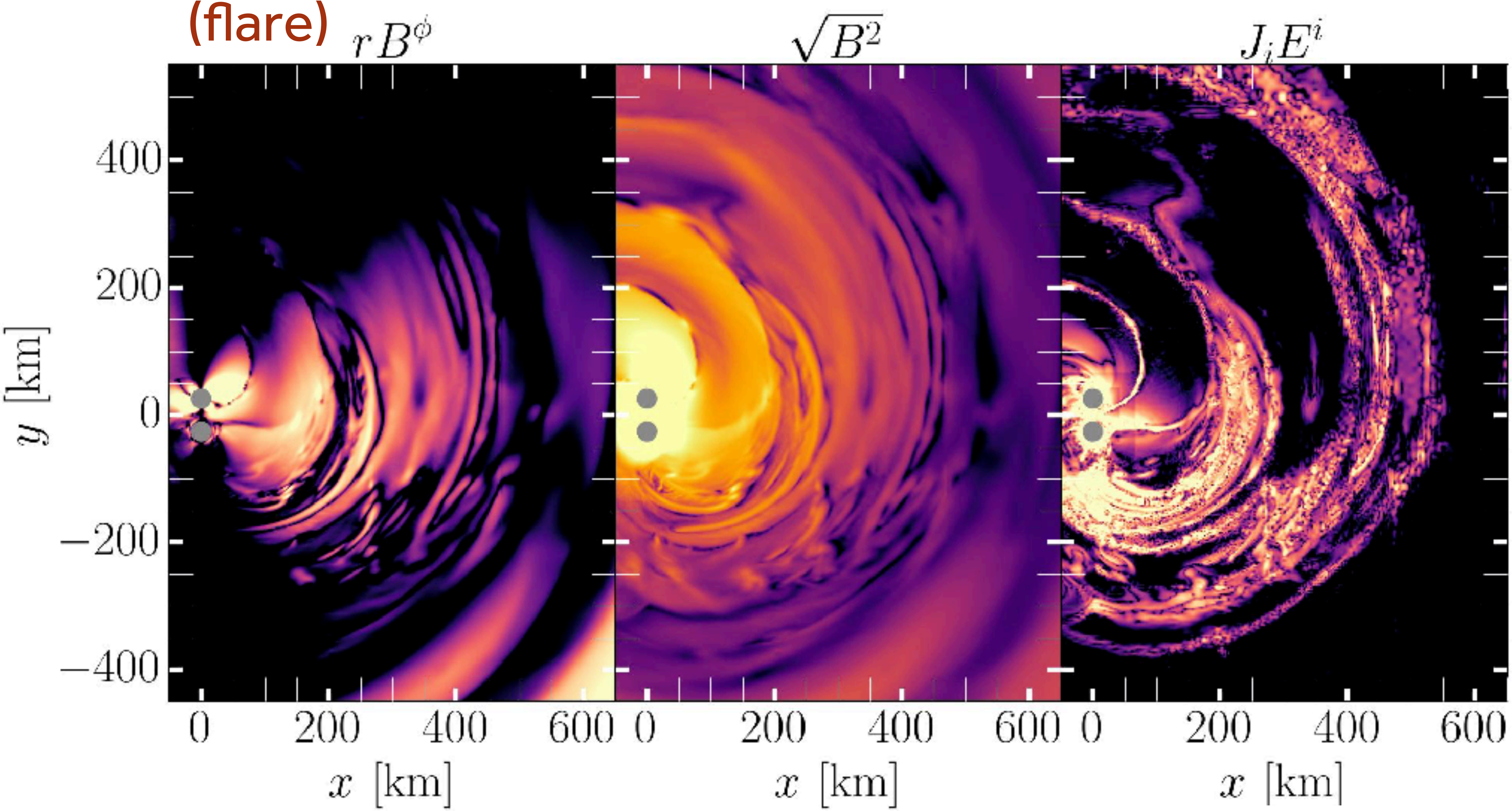
Physical scale: ~cm



Flare-current sheet interaction

Toroidal field (flare)

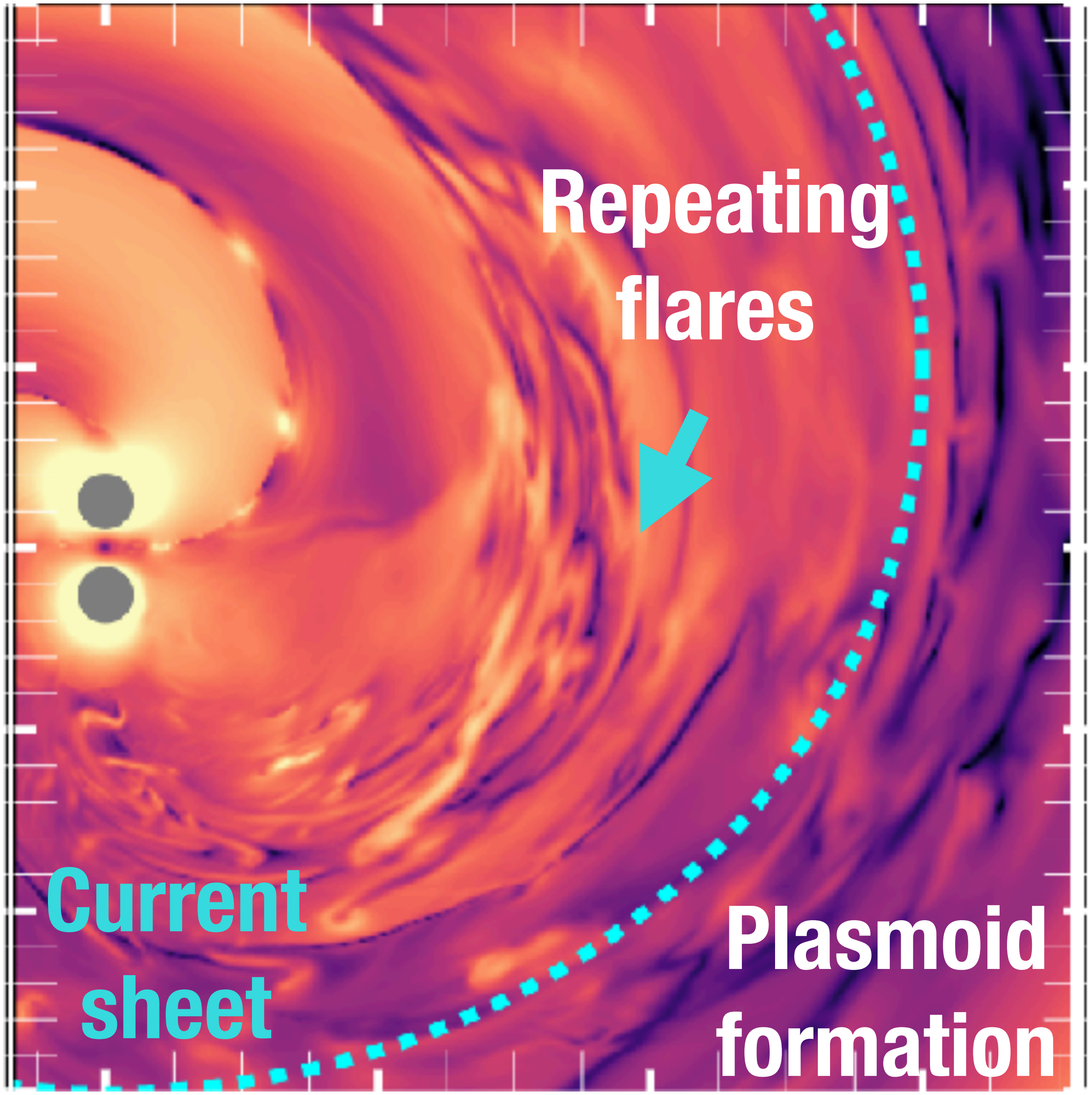
Dissipation rate



ERM & Philippov (arXiv:2022)

Emission mechanism

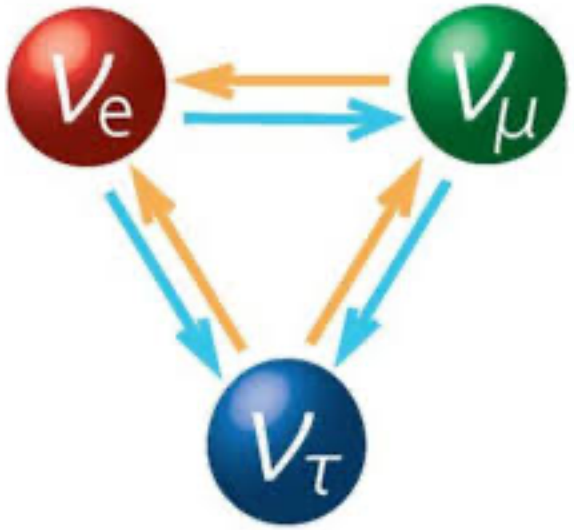
- Need to convert the emitted electromagnetic energy into coherent emission!
  - Flare -(orbital) current sheet interaction triggers reconnection. Lyubarsky (2020)
  - Depending on the field strength, plasmoid mergers will lead to the emission of a radio or X-ray transient. Philippov+(2019)



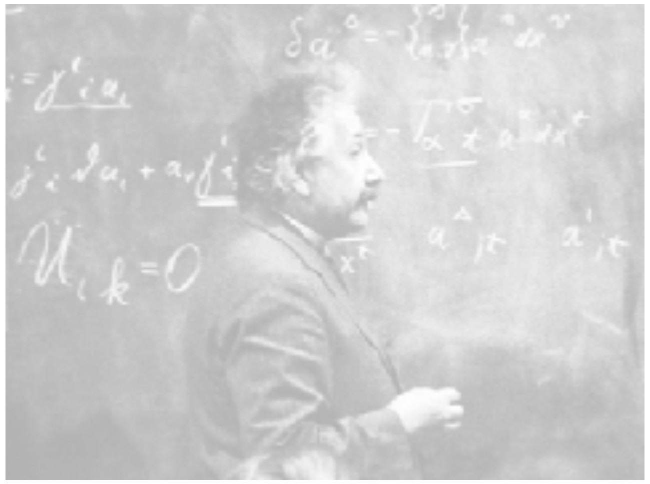
Fast Radio Burst-like transients ($\nu \simeq 10 - 20$ GHz)

ERM & Philippov (arXiv:2022)

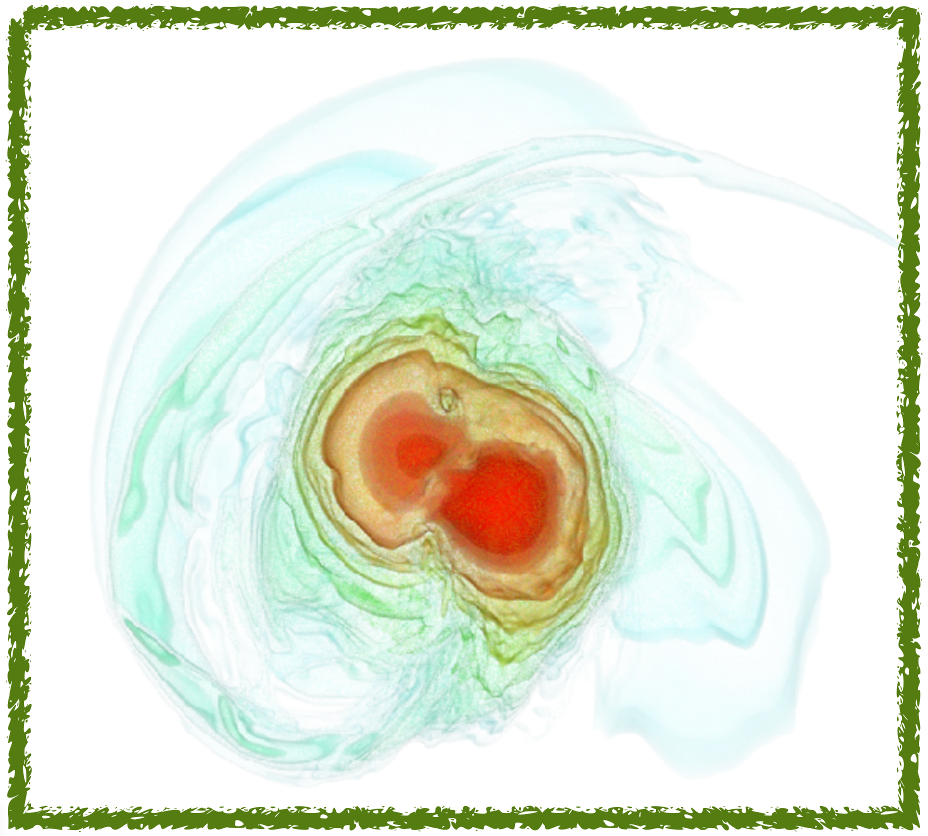
The many faces of neutron star mergers

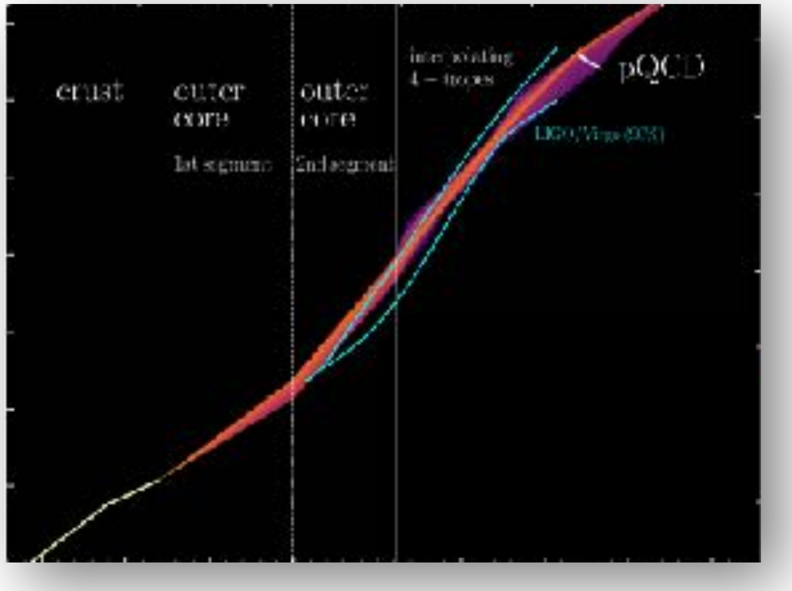


Neutrino physics

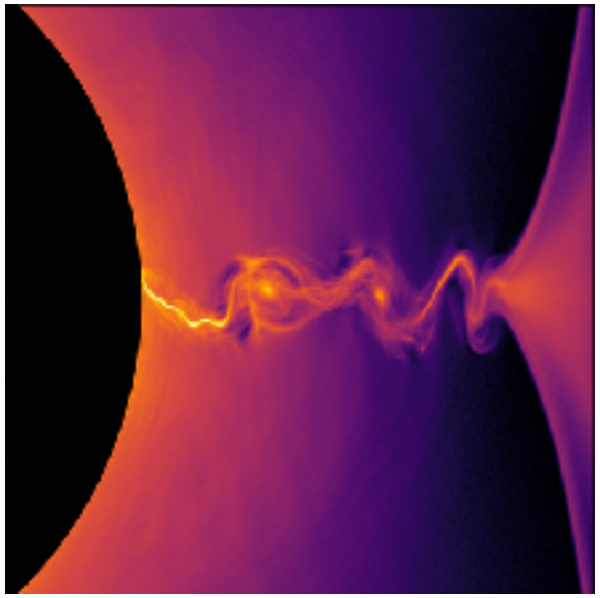


Gravitational physics





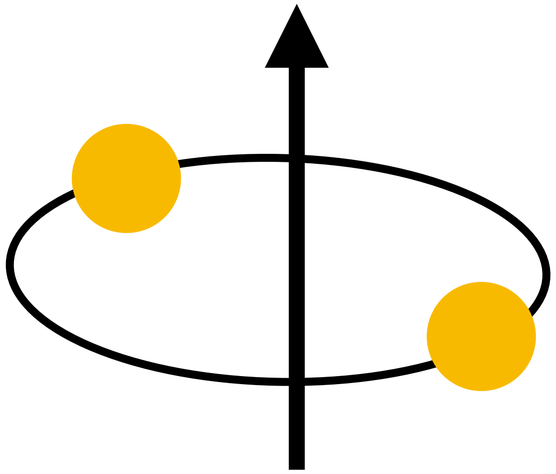
Nuclear physics



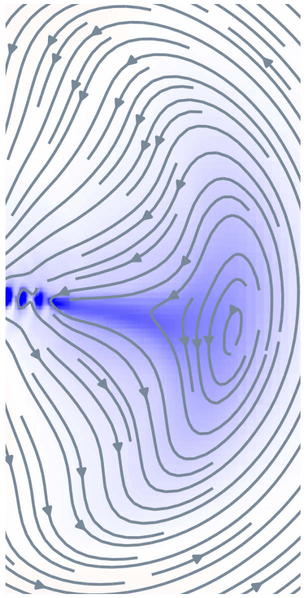
Plasma physics

Vastly different scales

$\sim 50\,\mathrm{km}$

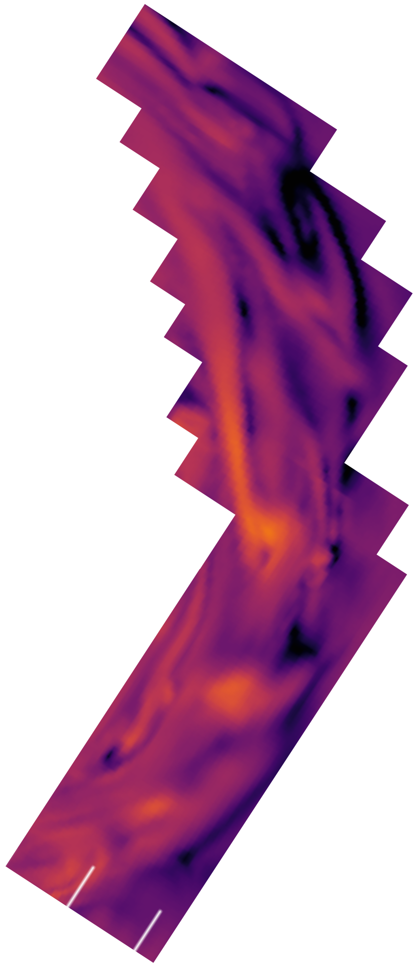


$\sim 200\,\mathrm{km}$



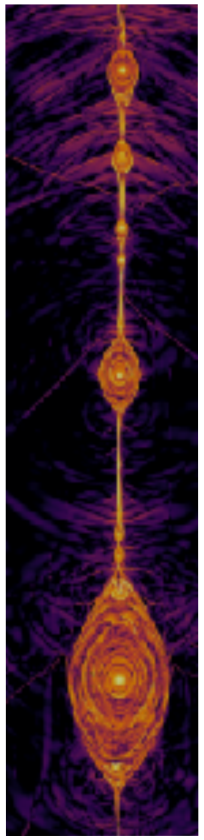
flare

$\sim 1000\,\mathrm{km}$



current sheet

$\sim 10^{-5}\,\mathrm{km}$



reconnection

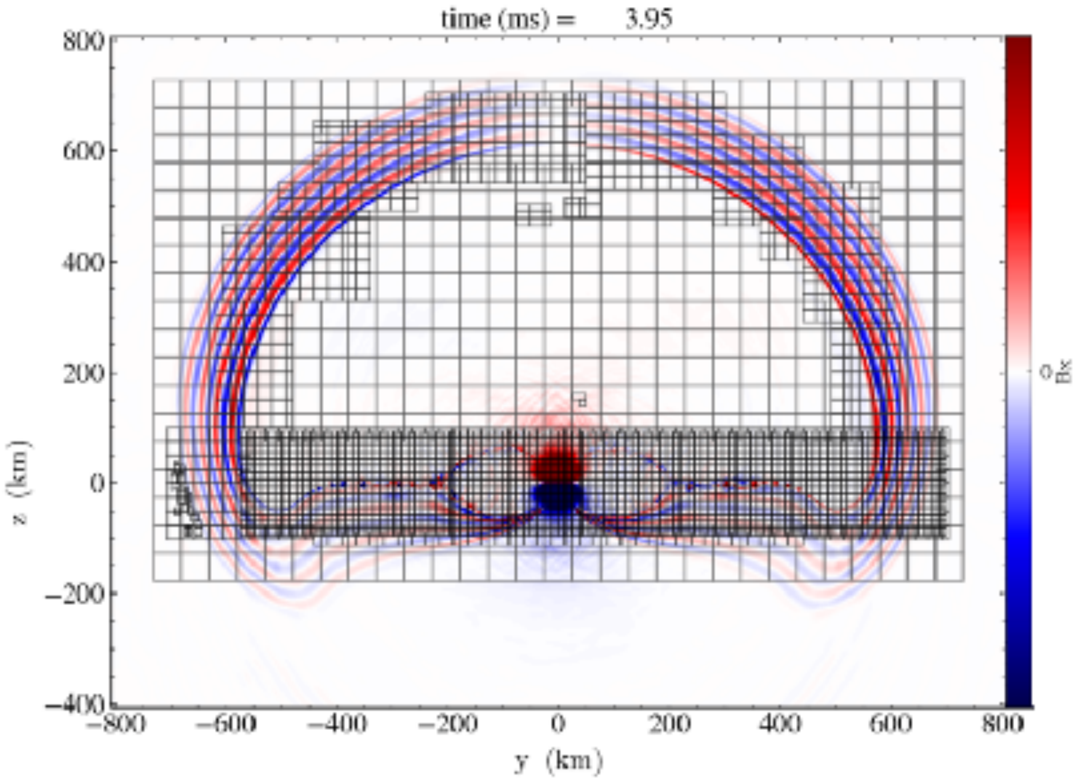
Need a multi-scale approach to capture (effects of) all scales!

✗ **Ab-initio modeling** *(e.g.,particle-in-cell)***?**

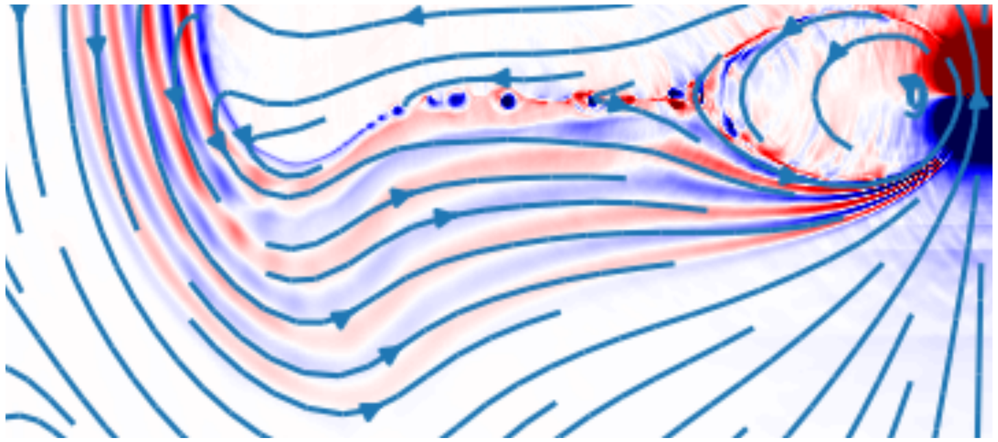
✓ **Effective models** *(e.g.,moment methods)***?**

Model local AND global scales

While accounting for microphysics on small scales, we want to capture global dynamics within the same simulation.



Adopting a fluid-like* description, allows to implicitly overstep scales, and to use mesh-refinement techniques.



ERM+ (in prep)

* Caveat:

Single-velocity description

ERM & Noronha (PRD 2021)

Inspiration from nuclear physics

Non-equilibrium transport is critical to understand momentum anisotropies in heavy-ion collisions.

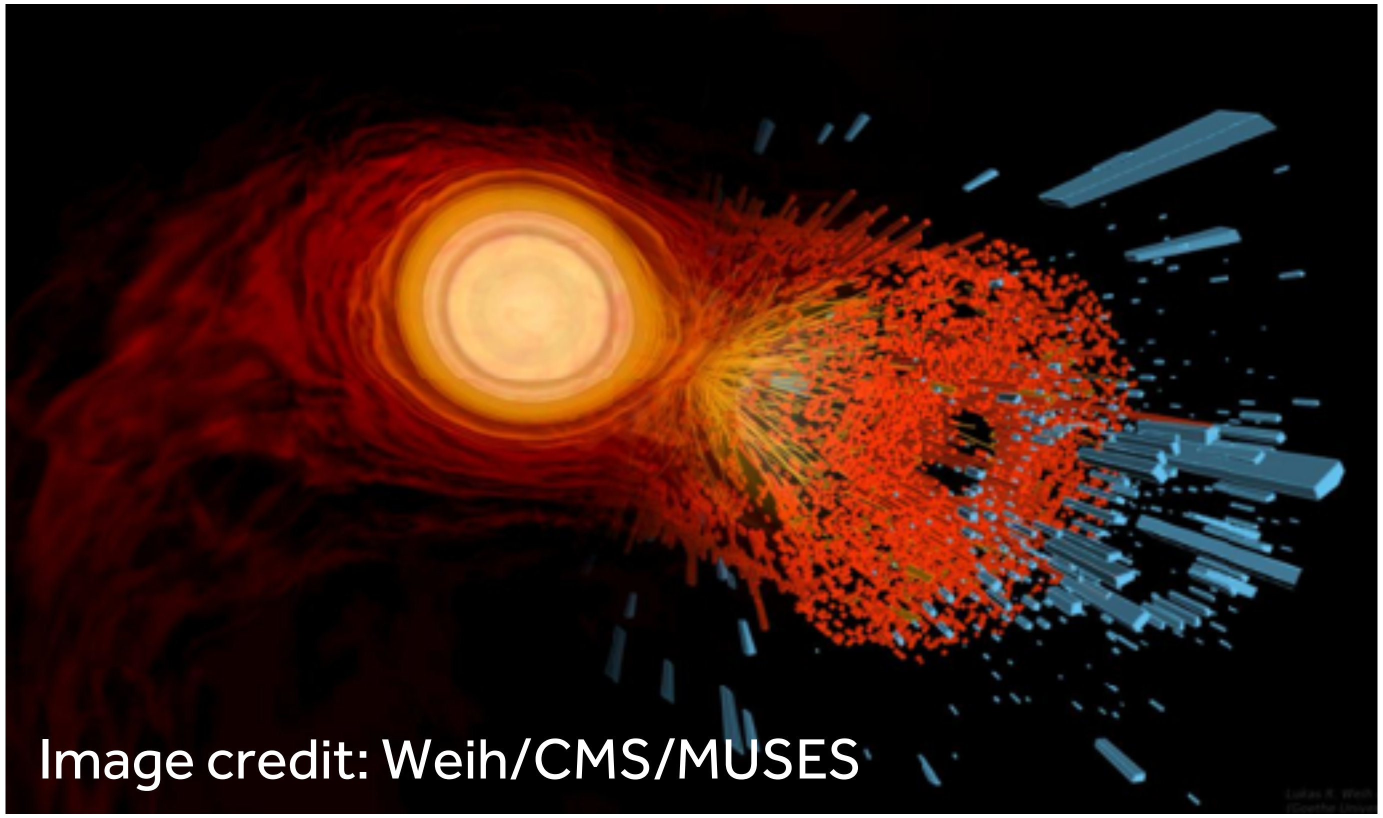


Image credit: Weih/CMS/MUSES

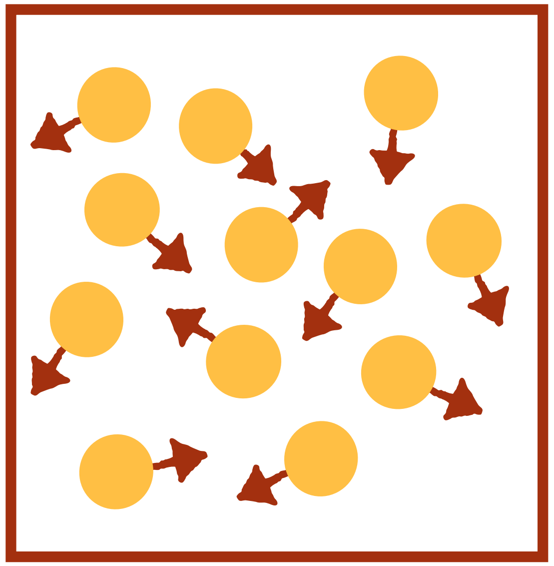
e.g., Romatschke+(2008), Denicol+(2012,2018,2019), Kovtun+(2017), Bemfica+(2017,2022), and many others

Leverage advances made by the nuclear physics community to study astrophysical systems!

Hydrodynamics as an effective theory

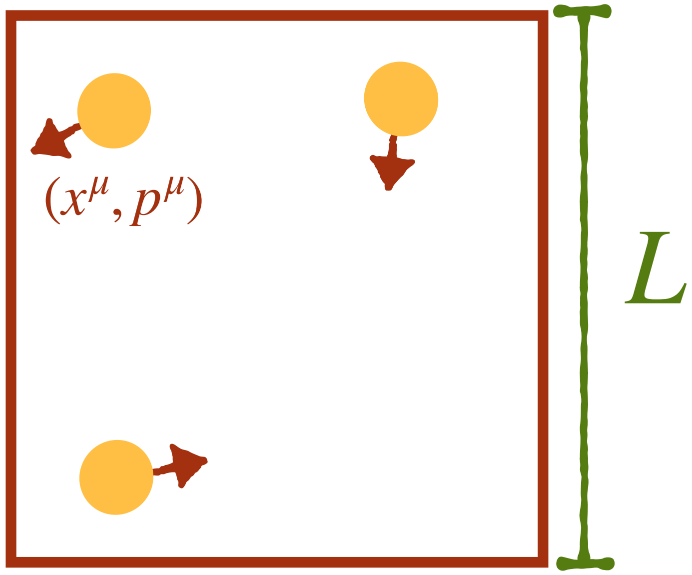
Hydrodynamics

$$\nabla_\mu T^{\mu\nu}_{\text{hydro}} = 0$$



Kinetic theory

$$p^\mu \partial_\mu f = \mathscr{C}\left[f\right]$$



$\cdots$

Collisional $(\lambda \simeq 0)$ **mean free path** λ → **Collisionless** $(\lambda \simeq L)$

Hydrodynamics as an effective theory

Perturbatively include corrections to hydrodynamics

$$T^{\mu\nu} = \boxed{T^{\mu\nu}_{\rm hydro}} + \boxed{\epsilon T^{\mu\nu}_{(1)} + \epsilon^2 T^{\mu\nu}_{(2)}} + \dots \qquad \epsilon \sim \frac{\lambda}{L} \ll 1$$

Hydrodynamics

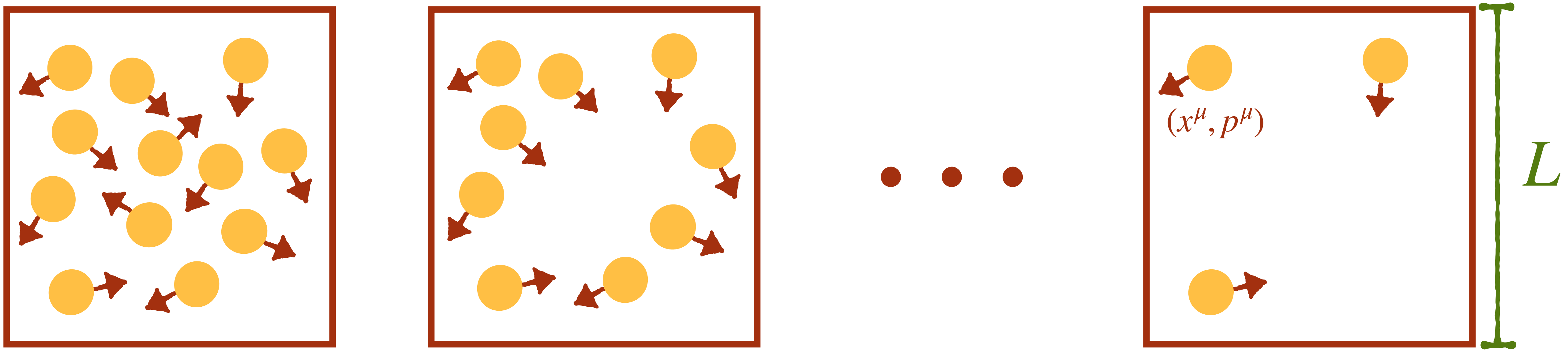
$$\nabla_\mu T^{\mu\nu}_{\rm hydro} = 0$$

Dissipative Hydrodynamics

$$\nabla_\mu T^{\mu\nu} = 0$$

Kinetic theory

$$p^\mu \partial_\mu f = \mathscr{C}\left[f\right]$$



Collisional $(\lambda \simeq 0)$ **mean free path** λ → **Collisionless** $(\lambda \simeq L)$

See also Shibata talk

Dissipative fluid dynamics

Hydrodynamics **Dissipative corrections**

$$T^{\mu\nu} = \boxed{e u^\mu u^\nu + P\Delta^{\mu\nu}} + \boxed{\boxed{\Pi}\Delta^{\mu\nu} + \boxed{q^\mu} u^\nu + \boxed{q^\nu} u^\mu + \boxed{\pi^{\mu\nu}}}$$

Bulk pressure

Energy diffusion/ heat flux

Anisotropic pressure

14-moment evolution equation

bulk viscosity

$$u^\alpha \nabla_\alpha \Pi = -\zeta \nabla_\beta u^\beta + \dots$$

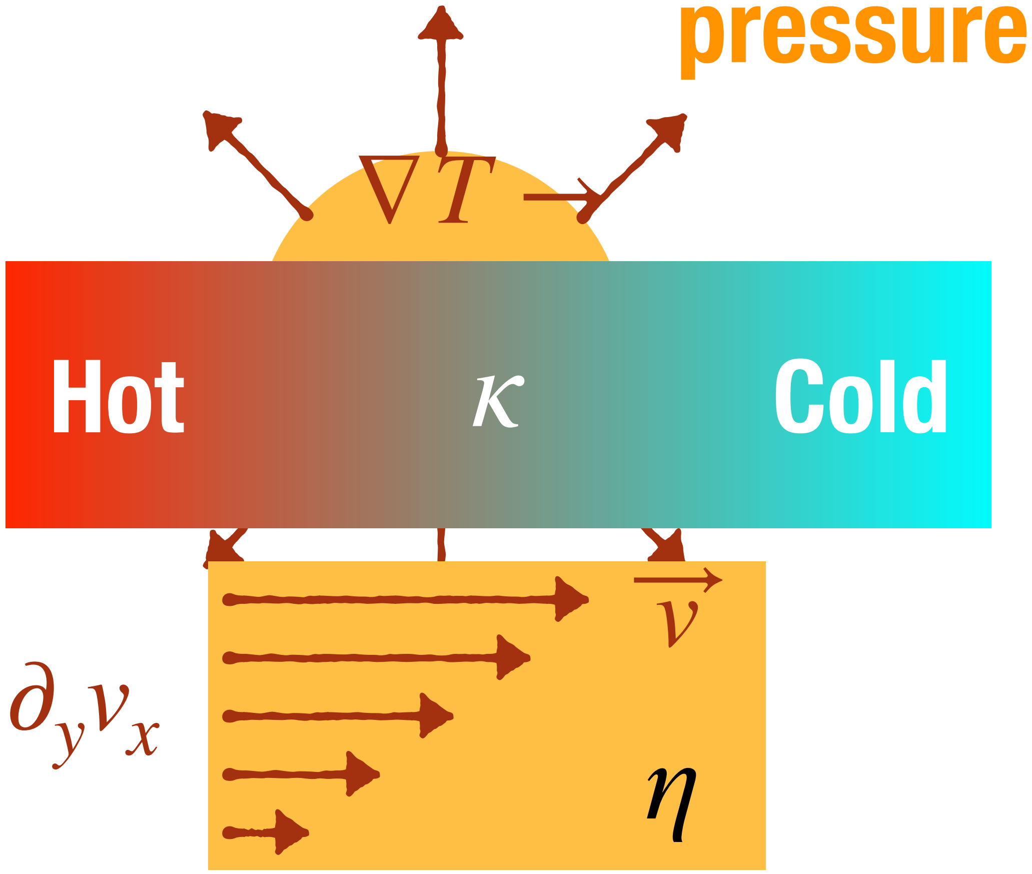
heat conductivity

$$u^\alpha \nabla_\alpha q^\mu = -\kappa \nabla^\mu T - \tau^{-1} q^\mu + \dots$$

shear viscosity

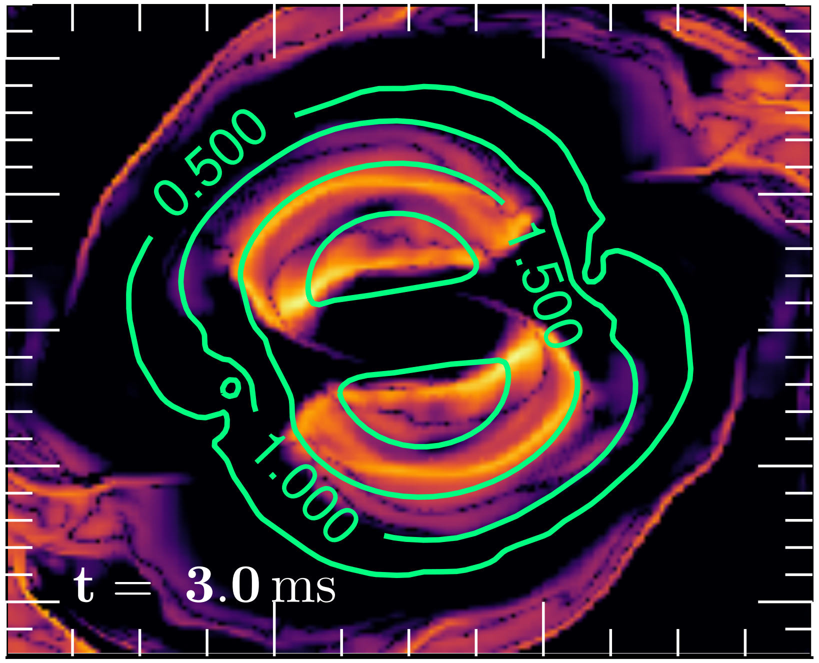
$$u^\alpha \nabla_\alpha \pi^{\mu\nu} = -\eta \sigma^{\mu\nu} - \tau^{-1} \pi^{\mu\nu} + \dots$$

see also Israel & Stewart (1979)



New Physics at every order!

$$T^{\mu\nu} = T^{\mu\nu}_{\text{hydro}} + \boxed{\epsilon T^{\mu\nu}_{(1)}}$$



Bulk viscosity in neutron star mergers

See also Alford+, Celora+, Hammond+, Camelio+

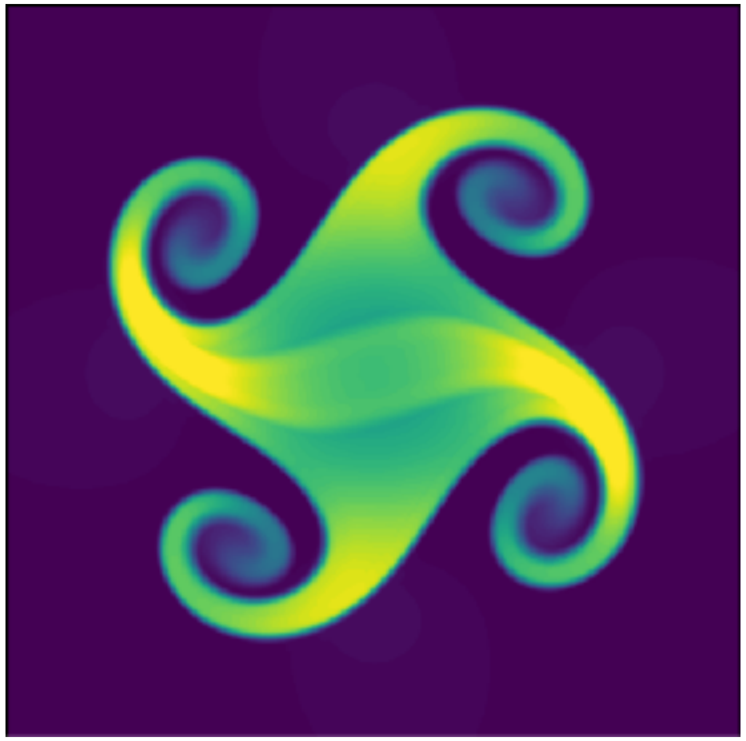
ERM+ (MNRAS 2022; arXiv 2022)

PU Grad. Student

Alex Pandya

Novel approaches to simulations of first-order relativistic hydrodynamics

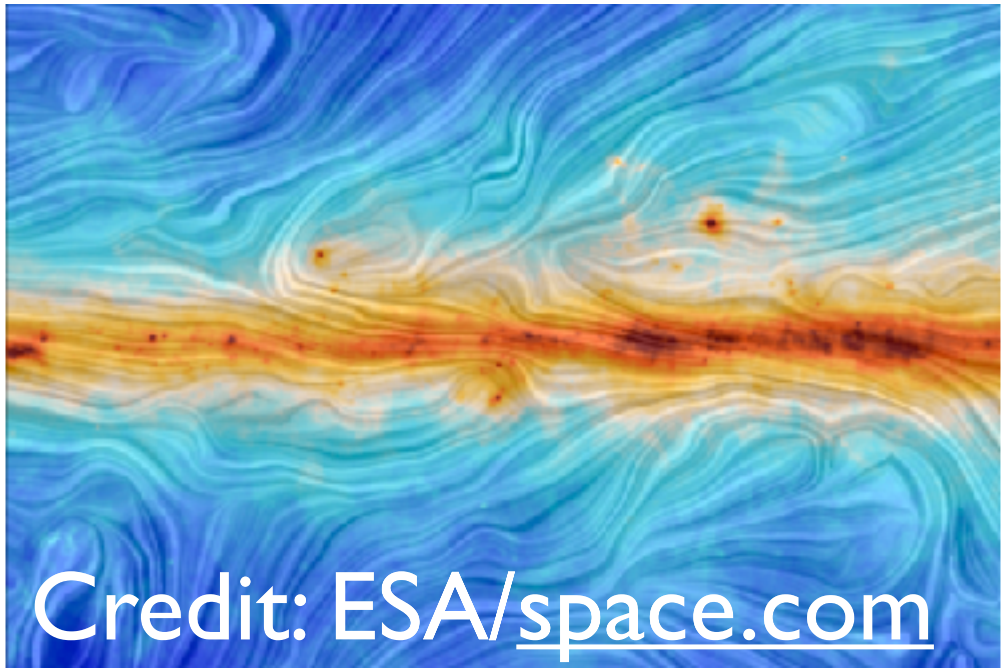
Mathematical formulation based on:
Bemfica+(2017,2022), Kovtun+(2017)



Pandya, **ERM**, Pretorius (PRD 2022; arXiv:2022)

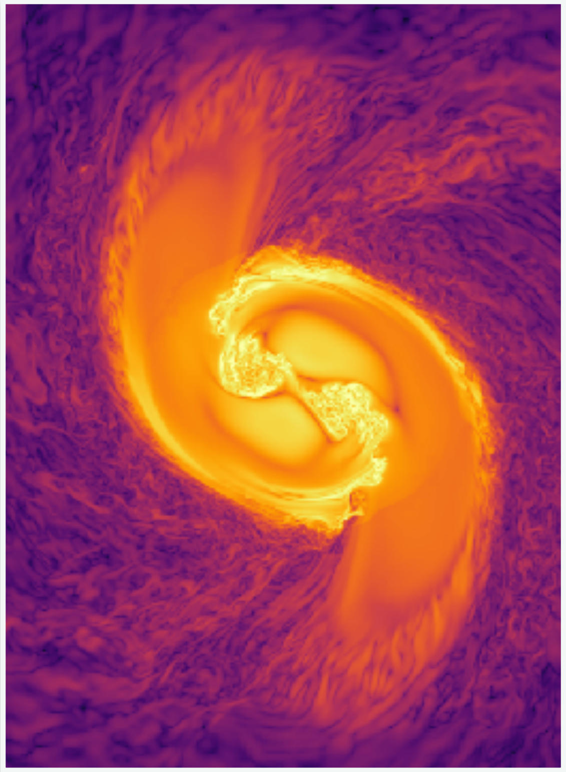
New Physics at every order!

$$T^{\mu\nu} = T^{\mu\nu}_{\text{hydro}} + \boxed{\epsilon T^{\mu\nu}_{(1)}}$$


Credit: ESA/space.com

"Magnetic fields are the Unsung Workhorses of Astrophysics" P.Sutter (space.com)

Dynamos and resistive effects in neutron star mergers


ERM+ (in prep)

➡Dissipative Magnetohydrodynamics

ERM & Noronha (PRD 2021); **ERM**, Noronha & Philippov (2022)

Novel numerical scheme to simulate this!

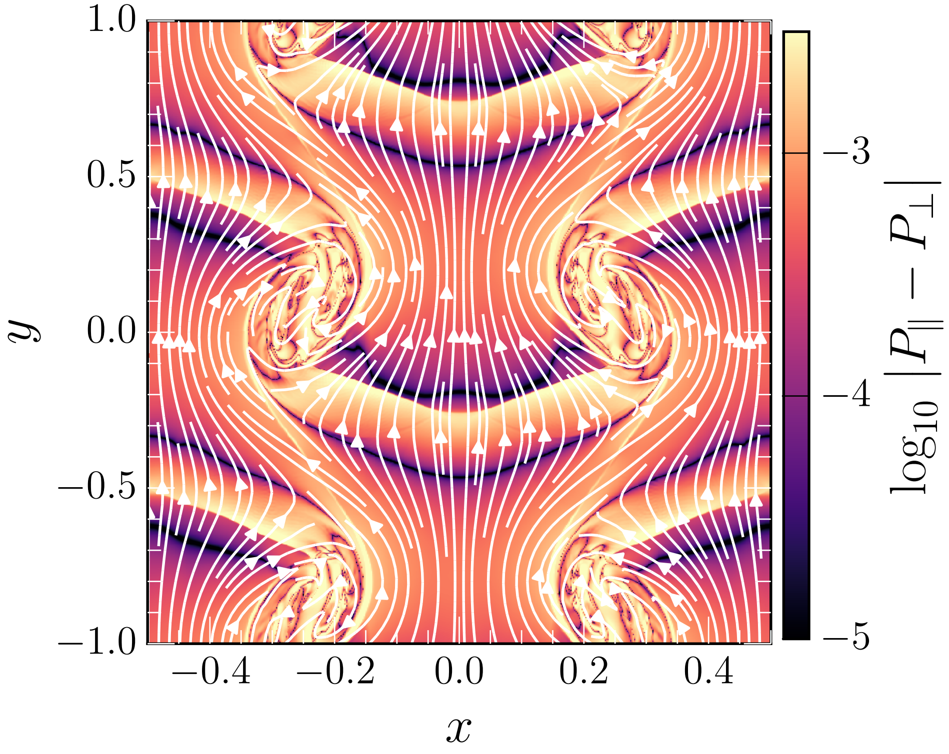
Alternative formulations:
Andersson+, Chandra+, Dommes+, Gusakov+, Rau & Wasserman,...

Dissipative Magnetohydrodynamics

First numerical scheme to handle general viscosities in the presence of magnetic fields for relativistic fluids.

ERM & Noronha (PRD 2021)

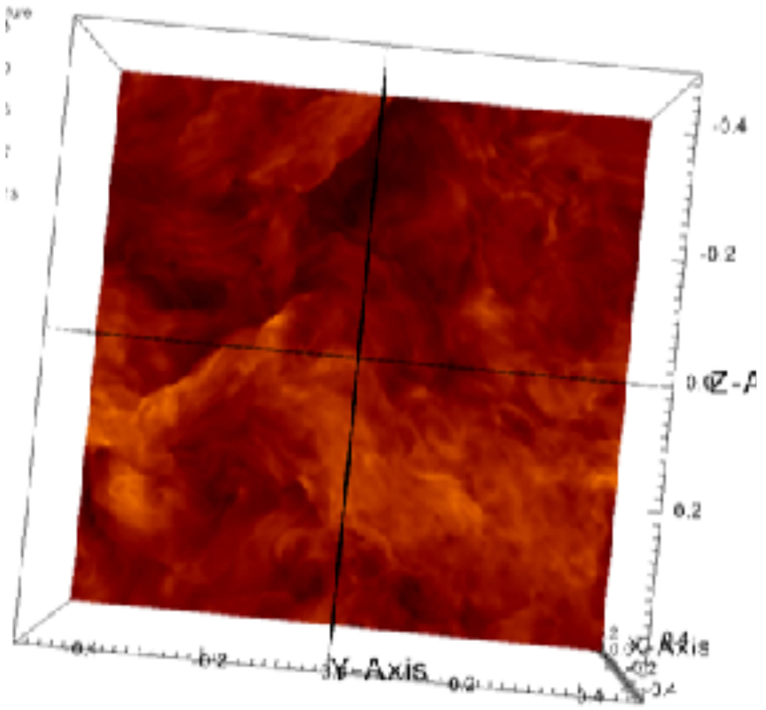
Pressure anisotropy



ERM & Noronha (PRD 2021)

Leverages a 14-moment closure derived from kinetic theory by the nuclear physics community.

Denicol+(2018,2019)



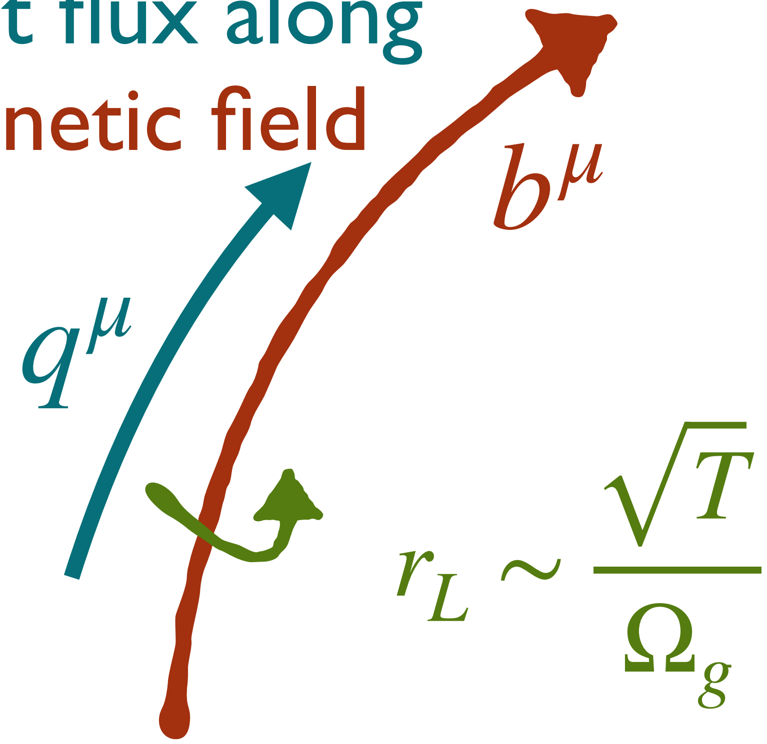
ERM+ (in prep)

Novel fully flux conservative approach with stiff relaxation.

Well suited to handle highly turbulent astrophysical flows!

Dissipative Magnetohydrodynamics

The scheme fully accounts for anisotropies induced by the presence of magnetic fields (gyrofrequency Ω_g). See also Chandra+, Foucart+



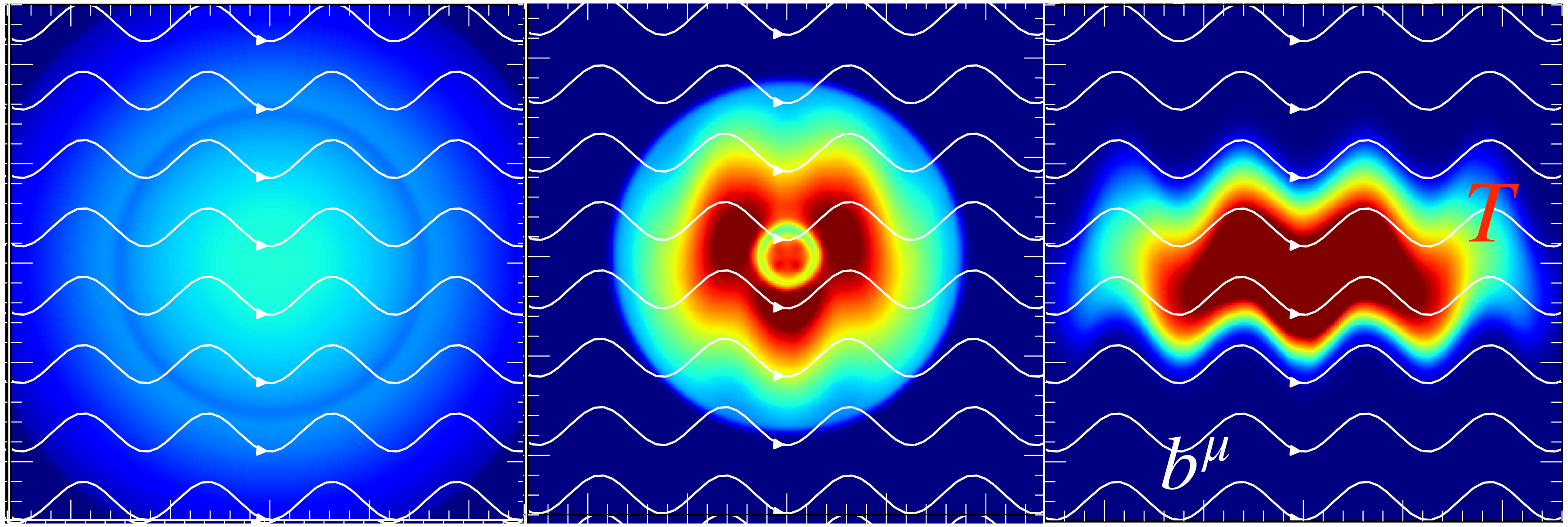
Heat flux along magnetic field

$r_L \sim \frac{\sqrt{T}}{\Omega_g}$

Larmor radius

Isotropic heat conduction

Anisotropic heat conduction



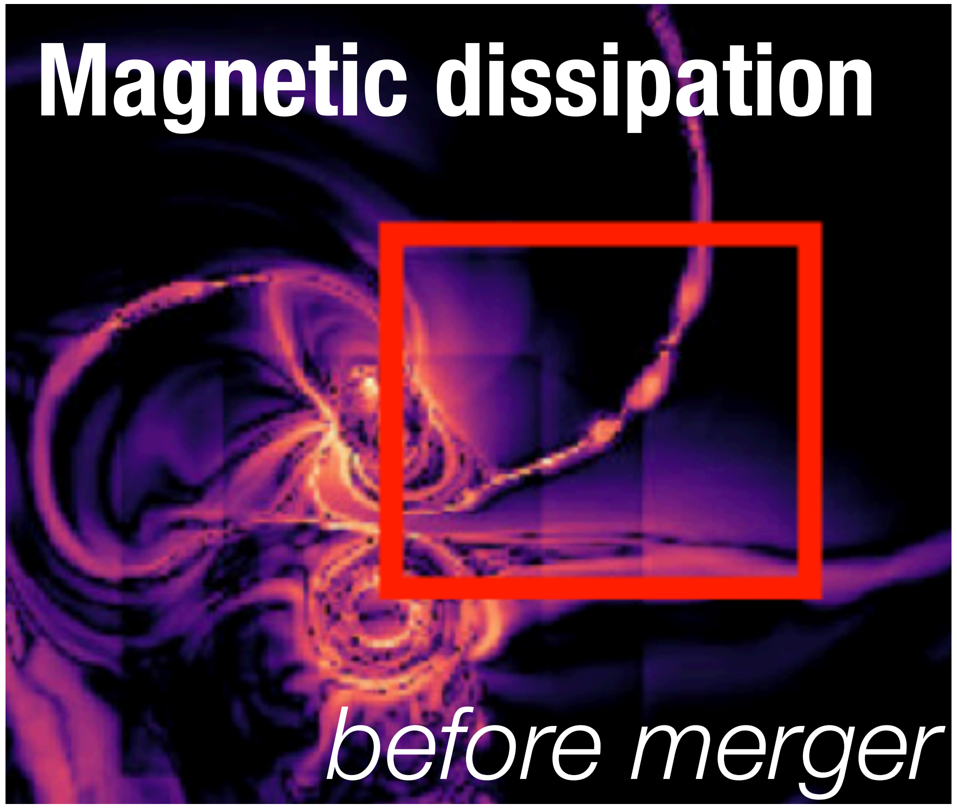
Implicit integration allows to overstep small scales!

ERM & Noronha (PRD 2021)

New Physics at every order!

$$T^{\mu\nu} = T^{\mu\nu}_{\rm hydro} + \epsilon T^{\mu\nu}_{(1)} + \boxed{\epsilon^2 T^{\mu\nu}_{(2)}}$$

ERM & Philippov (in prep)



Reconnection powered transients

Current force-free electrodynamics simulation cannot capture reconnection physics correctly.

(timescale, dissipation rate, ...)

Need to model e^+e^- dynamics in global simulations.

Positrons

➡Dissipative Two-Fluid MHD

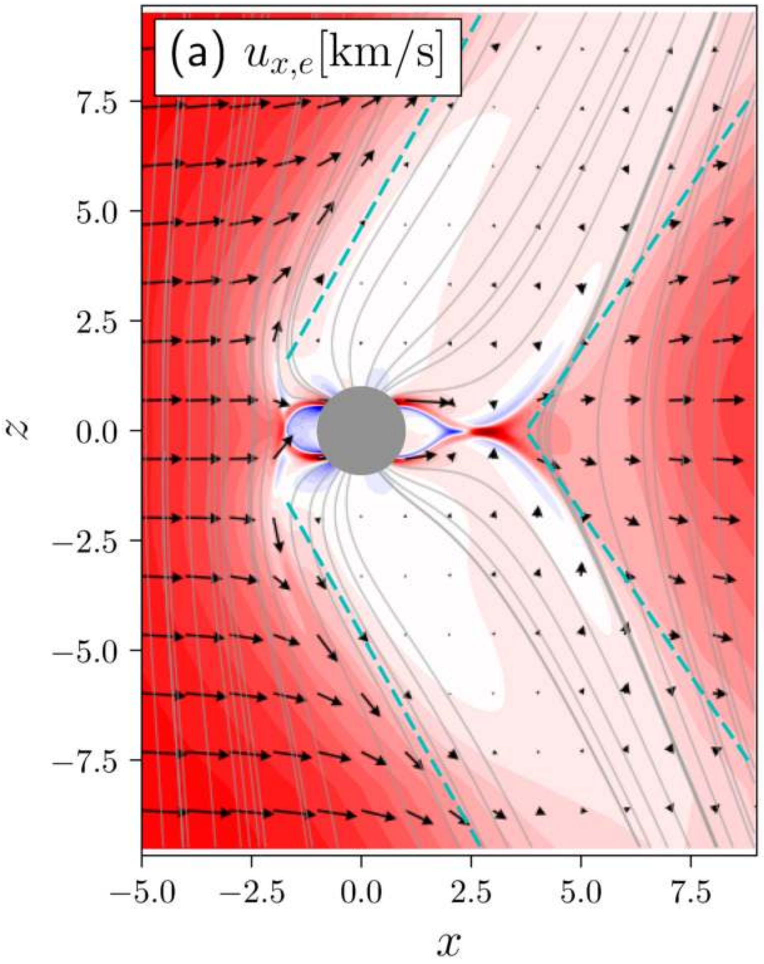
ERM, Noronha & Philippov (2022)

Electrons

Inspiration from space physics

$$\boxed{\epsilon^2 T^{\mu\nu}_{(2)}}$$

Ganymede



Wang+(2018)

Generalize 10-moment two-fluid approach from space physics to relativistic setting!

number density

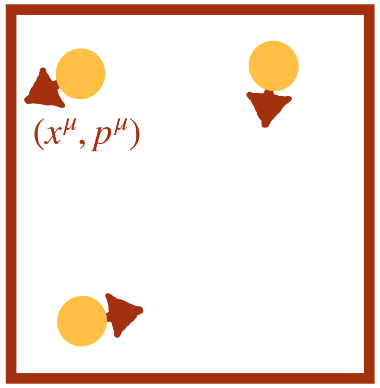
$$\frac{\partial\left(m_s n_s\right)}{\partial t} + \frac{\partial\left(m_s n_s u_{j,s}\right)}{\partial x_j} = 0,$$

momentum density

$$\frac{\partial\left(m_s n_s u_{j,s}\right)}{\partial t} + \frac{\partial \mathcal{P}_{ij,s}}{\partial x_j} = n_s q_s \left(E_i + \epsilon_{ijk} u_{j,s} B_k\right),$$

(an-)isotropic stresses

$$\frac{\partial \mathcal{P}_{ij,s}}{\partial t} + \frac{\partial \mathcal{Q}_{ijm,s}}{\partial x_m} = n_s q_s u_{[i,s} E_{j]} + \frac{q_s}{m_s} \epsilon_{[iml} \mathcal{P}_{mj],s} B_l.$$



Need generalized Ohm's law to model collisionless physics.

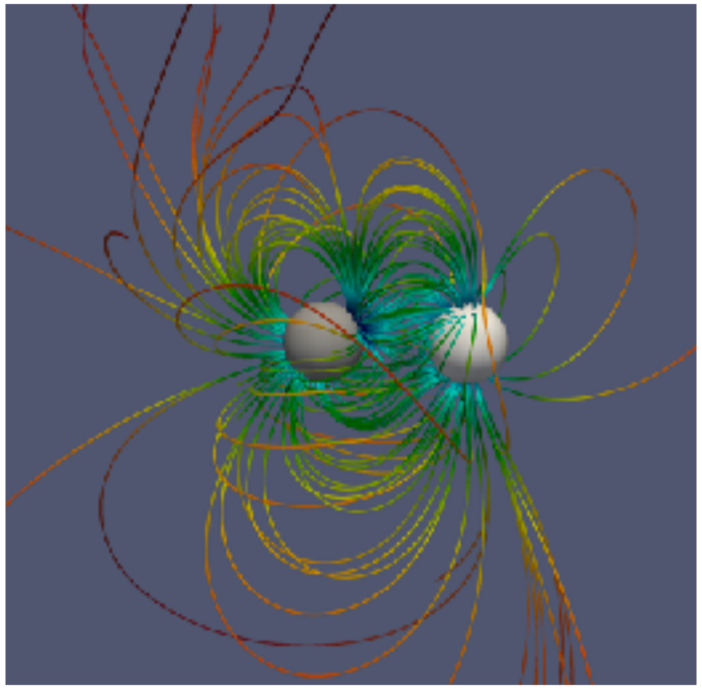
$$\vec{E} = -\underbrace{\vec{v} \times \vec{B}}_{\text{0th order}} + \underbrace{\eta \vec{J}}_{\text{1st order}} + \underbrace{\boxed{\vec{J}\,\mathrm{div}\, v + \mathrm{div}\, \overleftrightarrow{\mathscr{P}} + \dots}}_{\text{2nd order}}$$

Need 2nd order!

Bessho&Bhattarcharjee (2008)

Inspiration from space physics

$$\boxed{\epsilon^2 T^{\mu\nu}_{(2)}}$$



Generalize ~~10~~ 14-moment approach from space physics to **relativistic** setting!

number density

total energy-momentum

$$\nabla_\mu N_e^\mu = 0 \qquad \nabla_\mu N_p^\mu = 0 \qquad \nabla_\mu T^{\mu\nu} = 0$$

electron temperature

$$U^\mu \nabla_\mu e_e = \dots$$

electron current

$$U^\mu \nabla_\mu \mathcal{J}_e^{<\nu>} = \dots$$

anisotropic electron pressure

$$U^\mu \nabla_\mu \pi_e^{<\alpha\beta>} = \dots$$

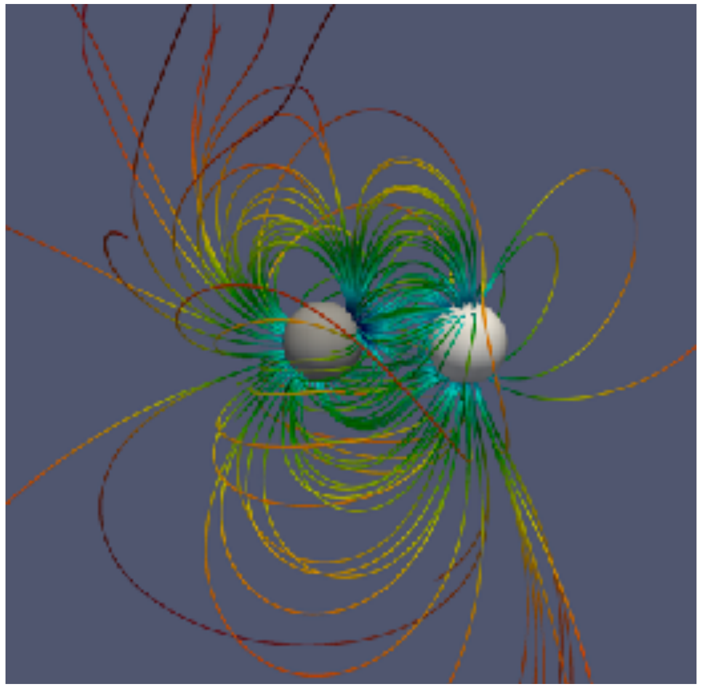
➡Dissipative Two-Fluid MHD

ERM, Noronha & Philippov (2022)

Need generalized Ohm's law to model collisionless physics.

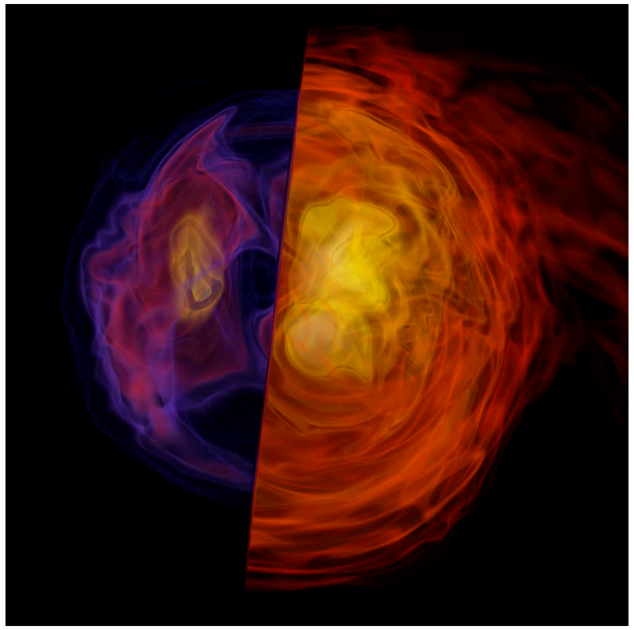
$$\underbrace{e^\mu}_{\text{0th order}} = \underbrace{\eta \mathcal{J}_e^{<\nu>}}_{\text{1st order}} \underbrace{\boxed{- \underbrace{\tau U^\mu \nabla_\mu \mathcal{J}_e^{<\nu>}}_{\text{dynamical part}} + \delta_J \mathcal{J}_e^{<\nu>} \nabla_\mu U^\mu + \delta_\pi \nabla_\mu \pi_e^{\mu\nu} + \dots}}_{\text{2nd order}}$$

Summary



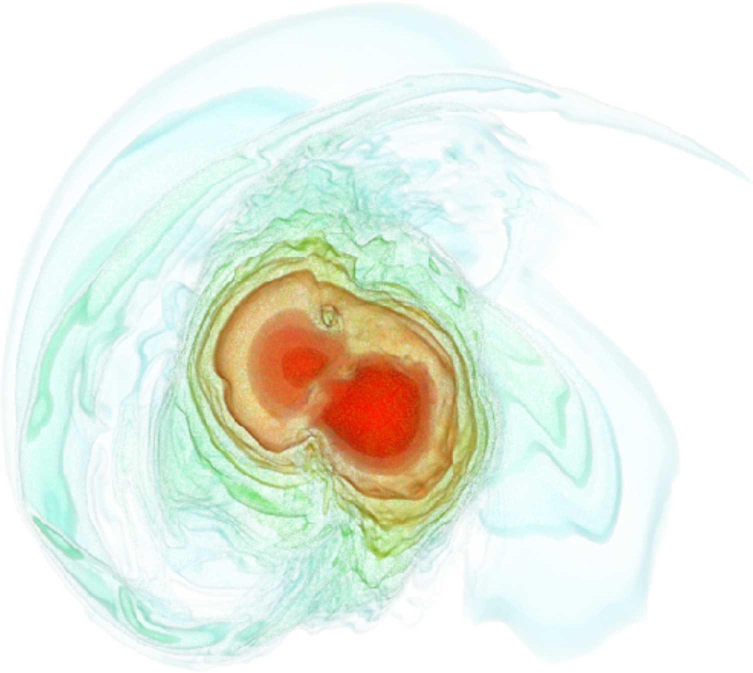
Improved nuclear physics

Systematic studies
needed to clarify imprints
of hot dense matter
in post-merger observables.



Precursors

Neutron star mergers
could be preceded by
Fast Radio Burst-like
transient at higher
frequencies (10-20 GHz)



Multi-scale modeling

New approaches
needed to captures
physics at different
scales.