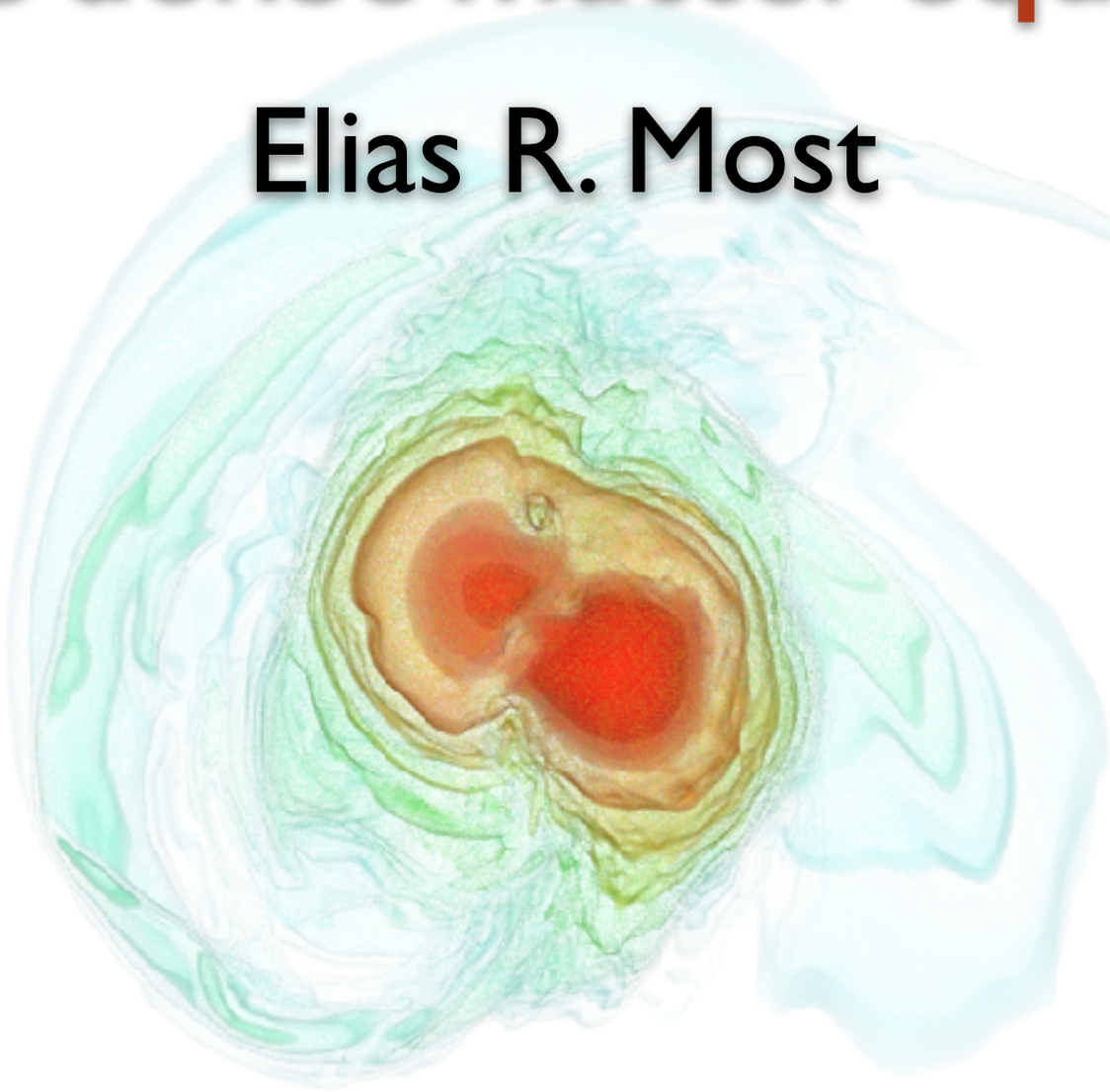
The crack, the whisk and the spark:
Neutron star mergers beyond the dense matter equation state

Elias R. Most



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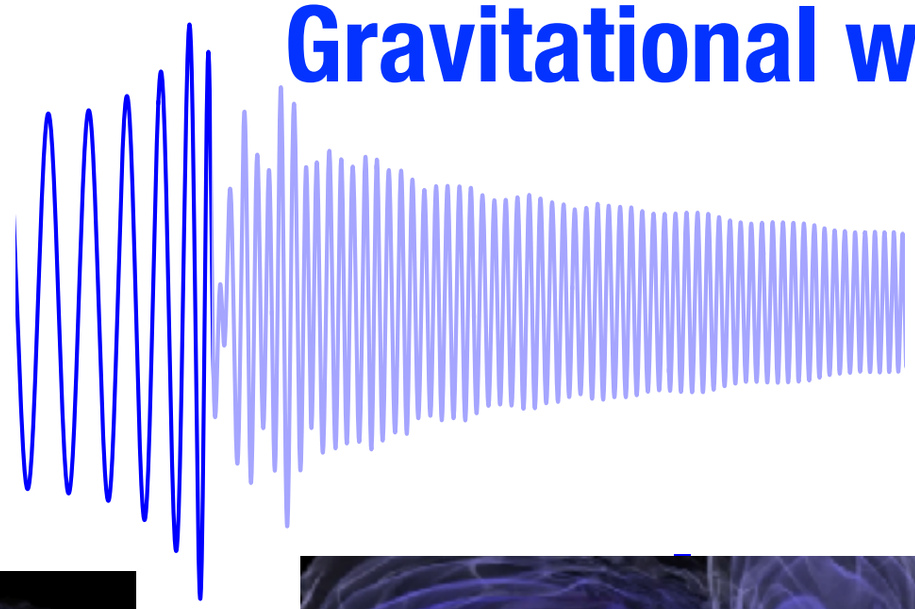
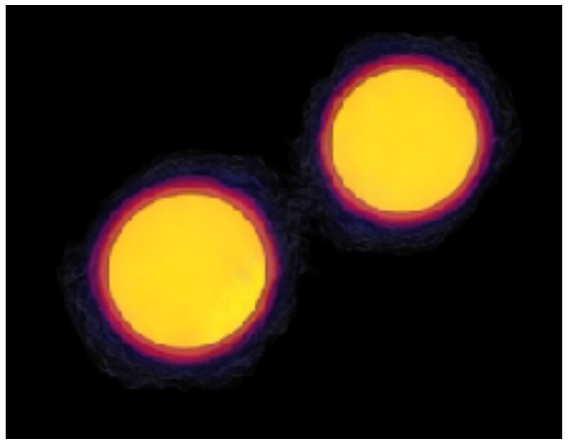
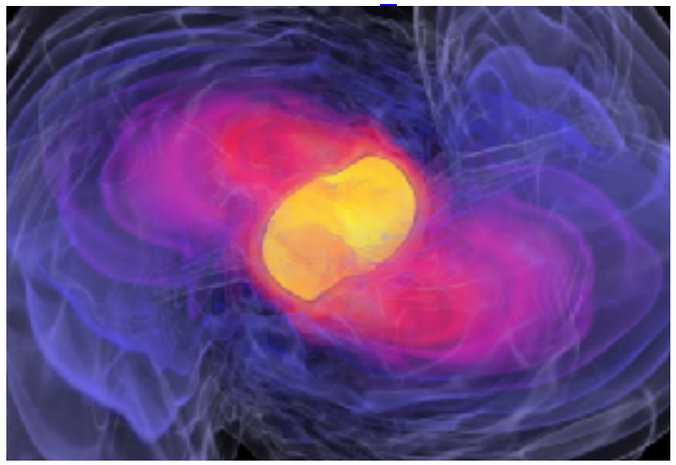
The final fate of a neutron star binary

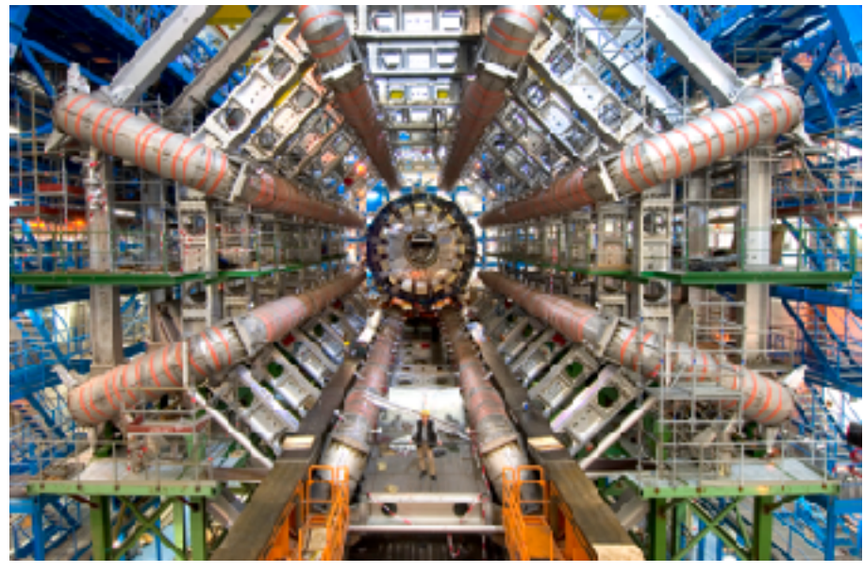
Gravitational waves



Neutron star mergers as cosmic colliders?



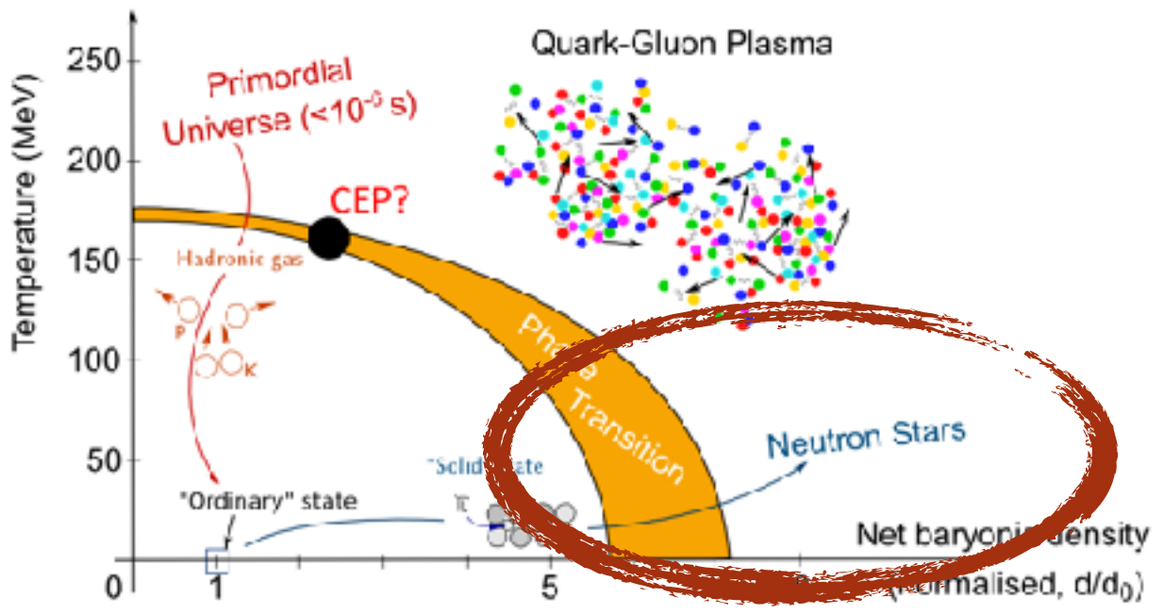




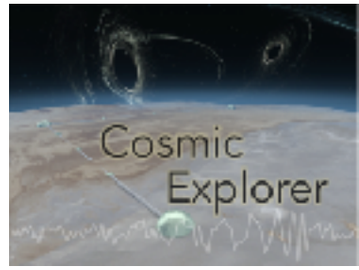
Can these events reveal extreme states of matter?

e.g. **ERM**+ (PRL 2019); **ERM**+ (EPJA 2020); **ERM** & Raithel (2021); **ERM**+ (PRD 2023)

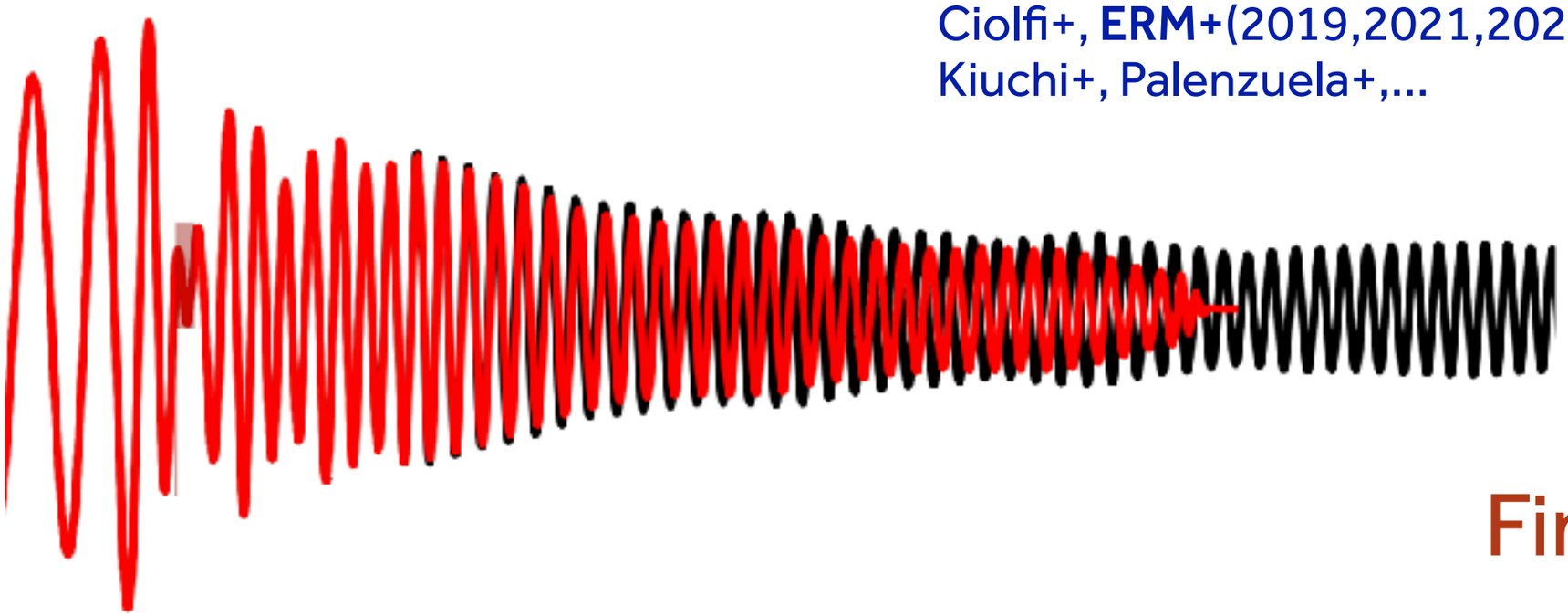
see also Bauswein+, Blacker+, Prakash+, Huang+, Ujevic+, Radice+, Shibata, Oechslin+, ...



A true multi-physics problem

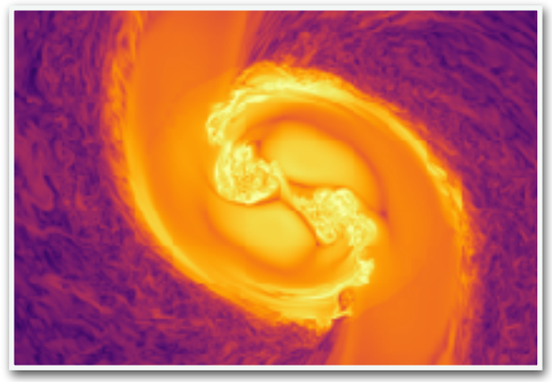


Post-merger gravitational wave emission probes new regimes of physics!



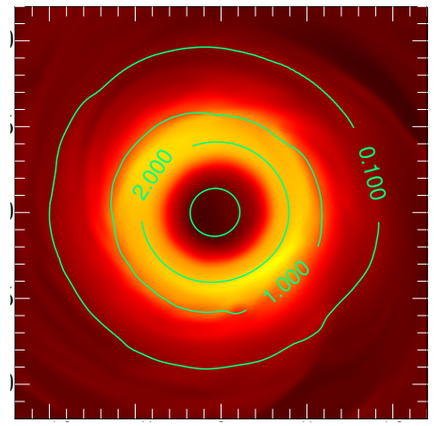
Magnetic fields?

Ciolfi+, **ERM+**(2019,2021,2023ab,2024,2025), Giacomazzo+, Kiuchi+, Palenzuela+,...



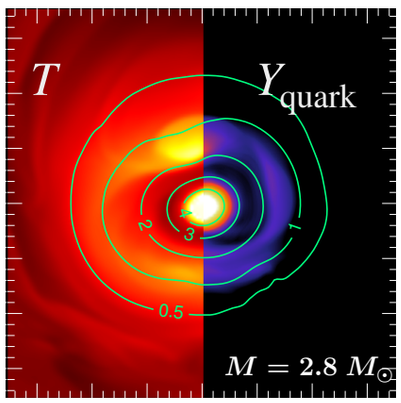
Finite-temperature and composition?

Bauswein+, **ERM+**(2021), Figura+, Hanauske+,Perego+,Raithel+...



Exotic degrees of freedom (incl. DM)?

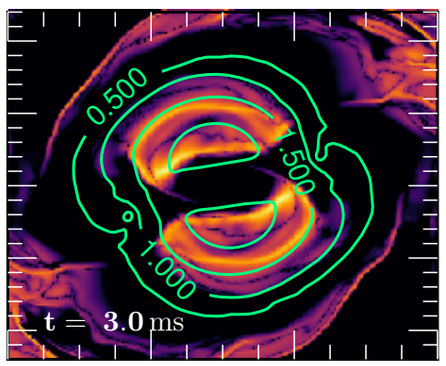
Bauswein+, Huang+, **ERM**+(2019,2020,2023),Prakash+, Radice+,Sekiguchi+,Weih+... (+ many more for EoS uncertainty!)



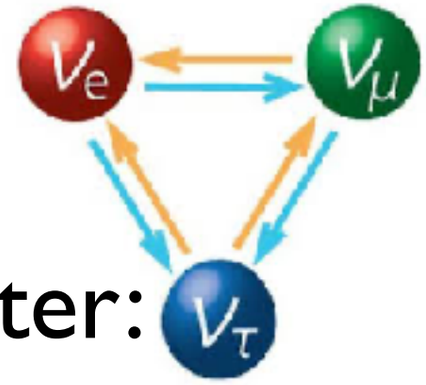
Neutrino effects?

(in dense matter)

Alford+, Camelio+, Foucart+, Hammond+, **ERM**+(2022,2024), Pajkos & **ERM** (2025), Radice+, Shibata+,...



Beyond the equation of state!



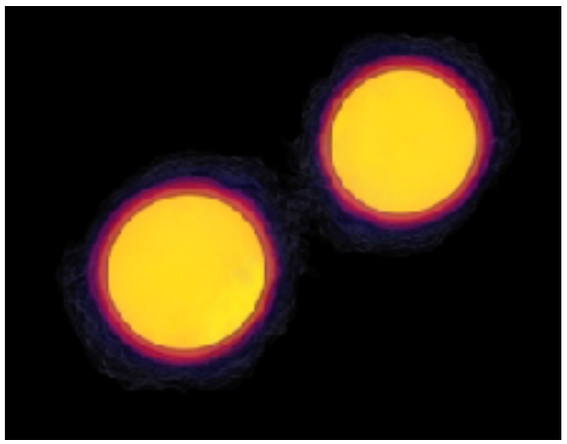
Weak interactions are crucial for neutron star matter:

$$n \rightarrow p + e^- + \bar{\nu}_e$$

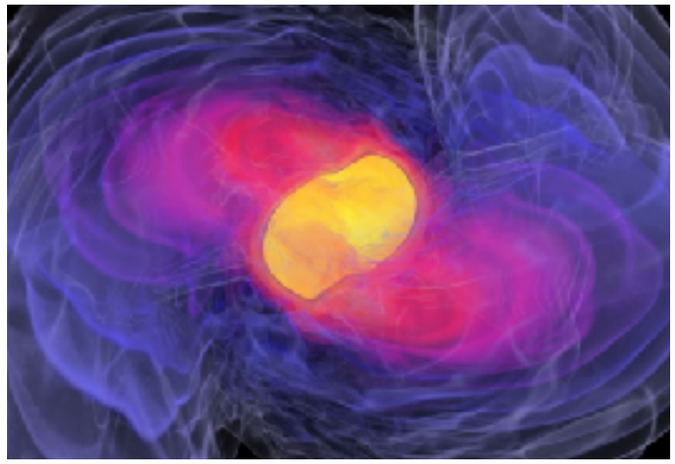
$$p + e^- \rightarrow n + \nu_e$$

Equilibrium
(reactions balance)

Out-of-equilibrium
(reactions do NOT balance)

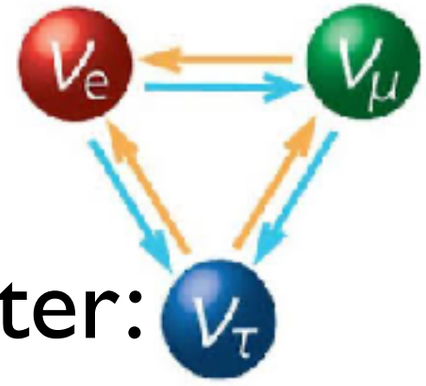


merger



see Haber overview talk, and Tue talks

Beyond the equation of state!



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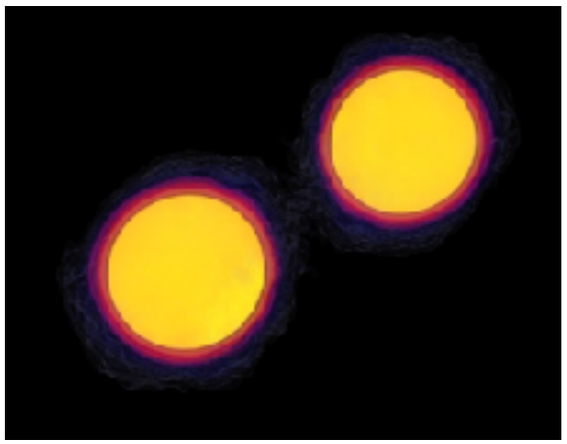
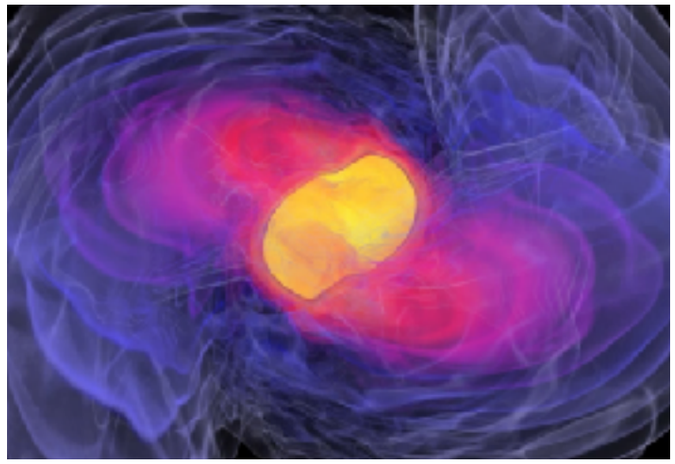


merger



$$\delta\mu \approx 0$$

$$\delta\mu \neq 0$$

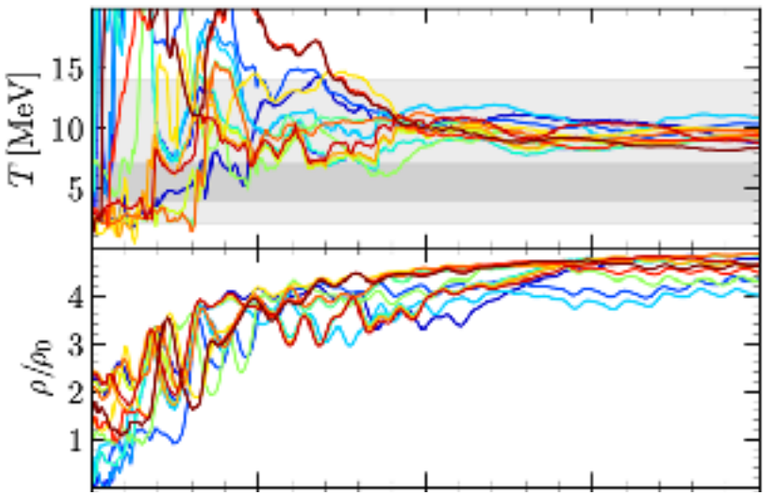
Effective chemical potential imbalance

$$\delta\mu = \mu_n - \mu_p - \mu_e - \mu_\nu$$

(in case of neutrino trapping)

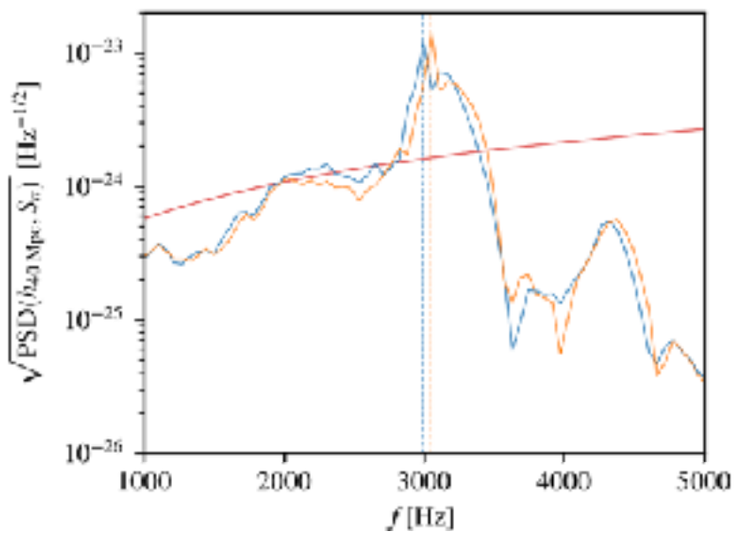
How out-of-equilibrium is the post-merger?

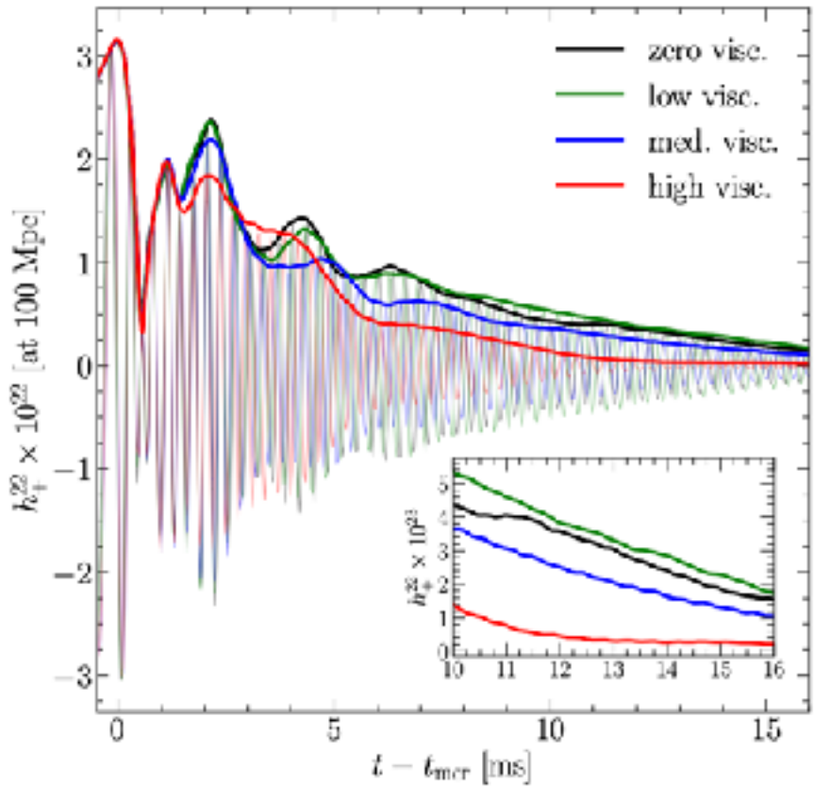
Beyond the equation of state



Alford+(2018)

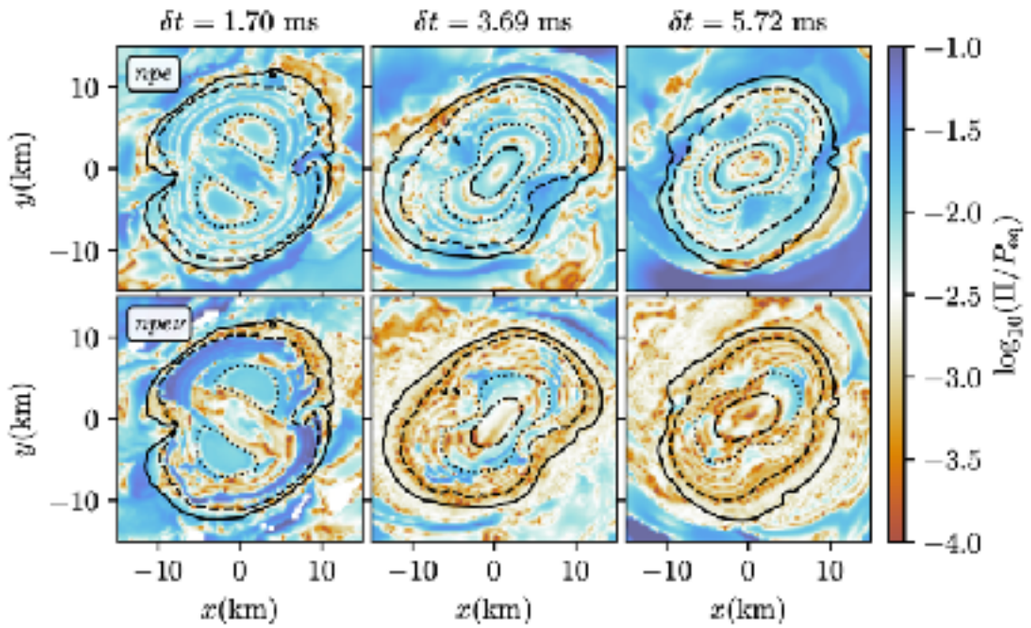
Hammond+(2023,2022)
see also Celora+





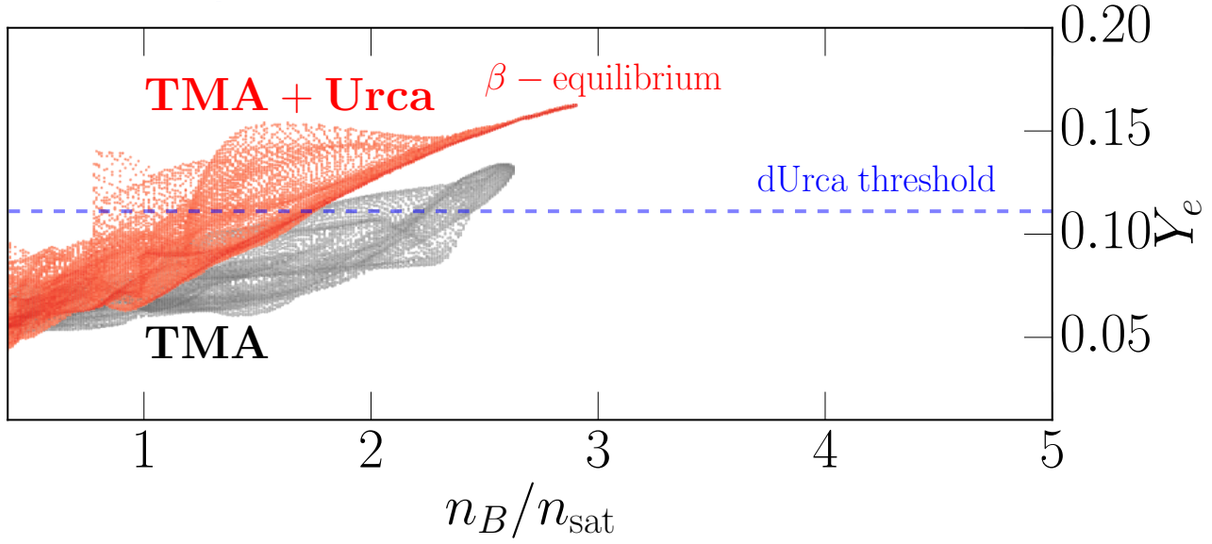
Chabanov & Rezzolla (2023)
see also Camelio+, Pandya+

Neutrinos, reactions, viscosity?



Espino+ (PRL 2023), see also Zappa+, Radice+

ERM+ (ApJL 2024, MNRAS 2022)



The physics of chemical equilibration

Gavassino+, Celora+

$$\nabla_\alpha T^{\alpha\beta} = -Q^\beta_\nu$$

see Andersson talk

$$P = P\left(n_B, T, Y_e\right)$$

$$u^\alpha \nabla_\alpha Y_e = \Gamma_\nu\left(\delta\mu, \ldots\right)$$

- This system models a two species chemical system with ($\beta-$equilibrium relaxation)
- Coupling happens through equation of state
- This system implies the following (exact!) evolution equation

$$u^\alpha \nabla_\alpha \delta\mu = -\frac{1}{\tau}\delta\mu + B\,\nabla_\beta u^\beta$$

Gavassino+, Celora+

- Choice of rates and neutrino transport enters through τ and B

Equilibration leads to bulk viscosity

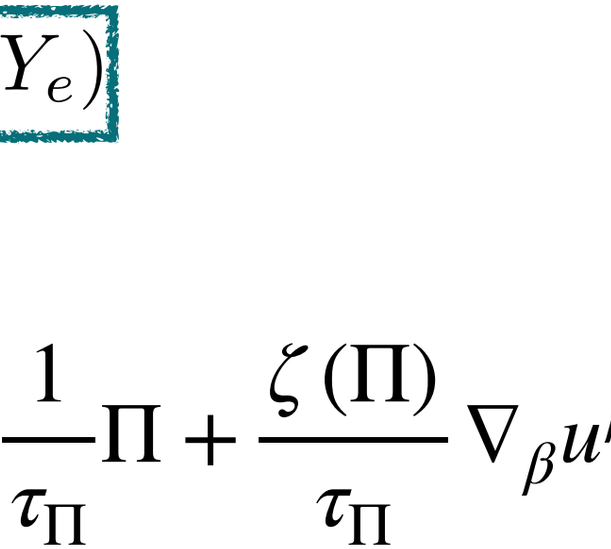
beta-eq. pressure dynamic pressure

$$P\left(n_B, T, Y_e\right) = P^{\rm eq}\left(n_B, T\right) + \Pi\left(n_B, T, Y_e\right)$$

$$u^\alpha \nabla_\alpha \delta\mu = -\frac{1}{\tau}\delta\mu + B\nabla_\beta u^\beta \quad \Longleftrightarrow \quad u^\alpha \nabla_\alpha \Pi = -\frac{1}{\tau_\Pi}\Pi + \frac{\zeta\left(\Pi\right)}{\tau_\Pi}\nabla_\beta u^\beta$$

Gavassino & Noronha (2023)

- This correspondence is exact (no truncation!)
- Bulk viscosity follows Israel-Stewart-like equations
  - ➡ Allows for resonances Alford, Harris, Haber,+
  - ➡ Far-from-equilibrium dynamics Gavassino & Noronha



ERM+ (MNRAS 2022)

How bulk viscosity in mergers works

Weak interaction driven decay

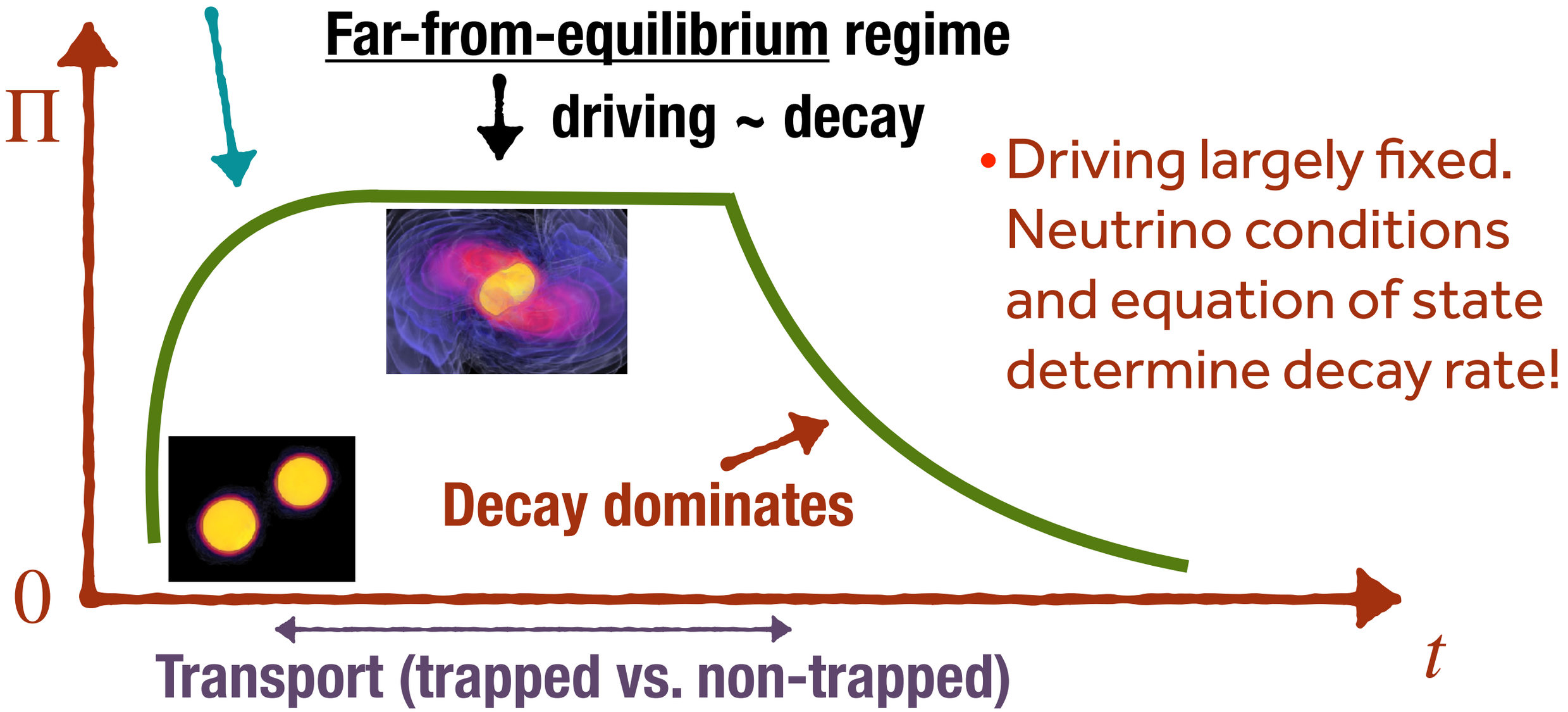
$$u^\alpha \nabla_\alpha \Pi = -\frac{1}{\tau_\Pi}\Pi + \frac{\zeta(\Pi)}{\tau_\Pi}\nabla_\beta u^\beta$$

Out-of-eq. driving term

Driving dominates

Far-from-equilibrium regime

driving ~ decay



- Driving largely fixed. Neutrino conditions and equation of state determine decay rate!

Neutrino transparent regime

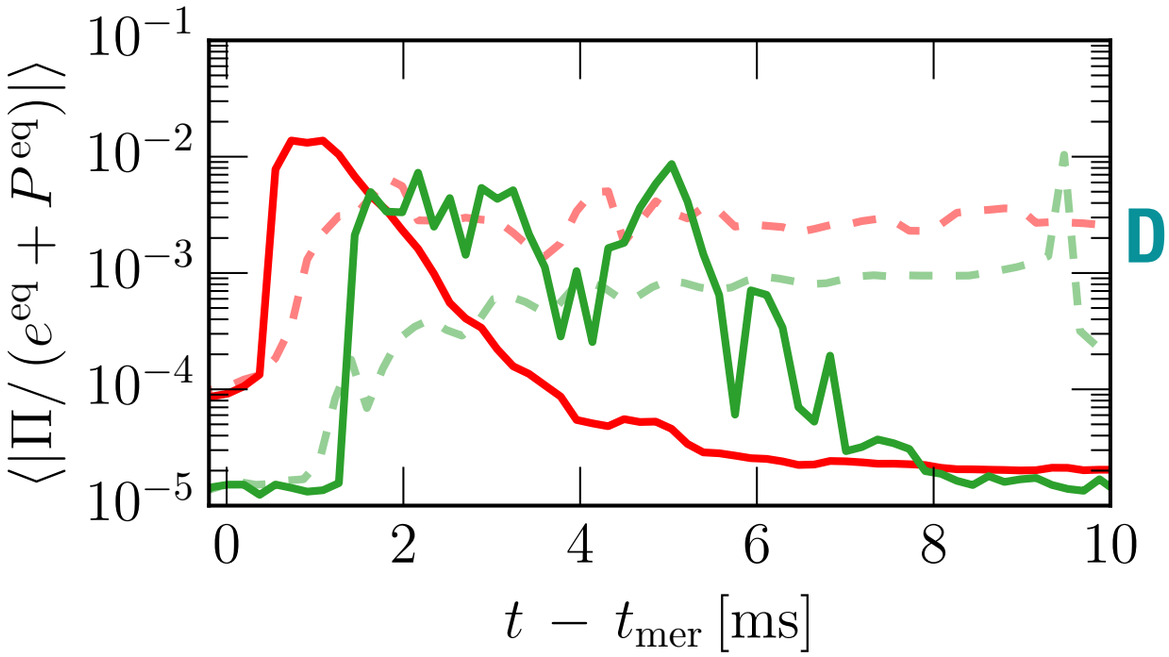
- Simulate direct and <u>modified</u> <u>URCA</u> process in merger assuming neutrinos free-stream (a bit simplistic)

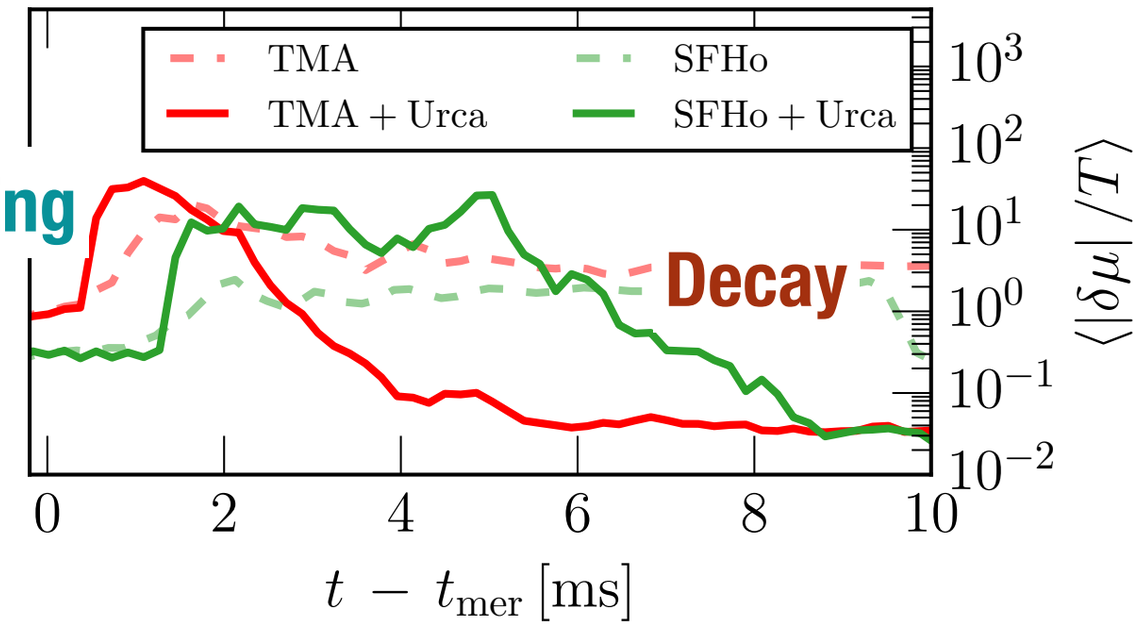
$$x + n \rightarrow p + e^- + \bar{\nu}_e + x$$

$$x + p + e^- \rightarrow n + \nu_e + x$$

ERM, Haber, Harris,Zhang, Alford, Noronha (ApJL 2024)

Simulation confirms far-from-equilibrium picture!





- Because of mathematical duality, will look the same also for trapped regime, but decay can be (significantly) faster.

M1 simulation with trapping (Espino+2023): decay sets in almost directly, effect suppressed

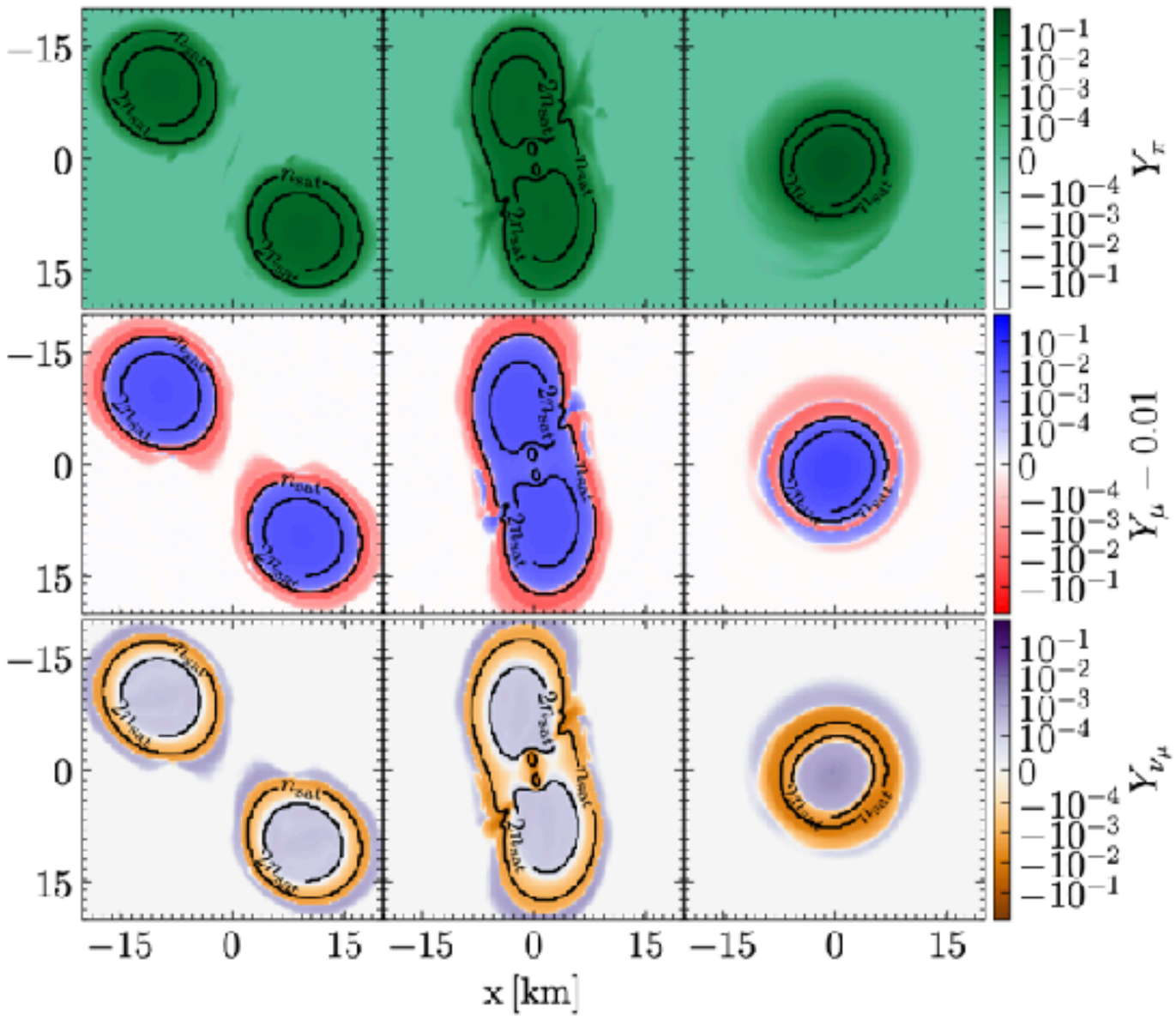
Systematic chemistry explorations

Include pions and muons as next step (only trapped equil.)

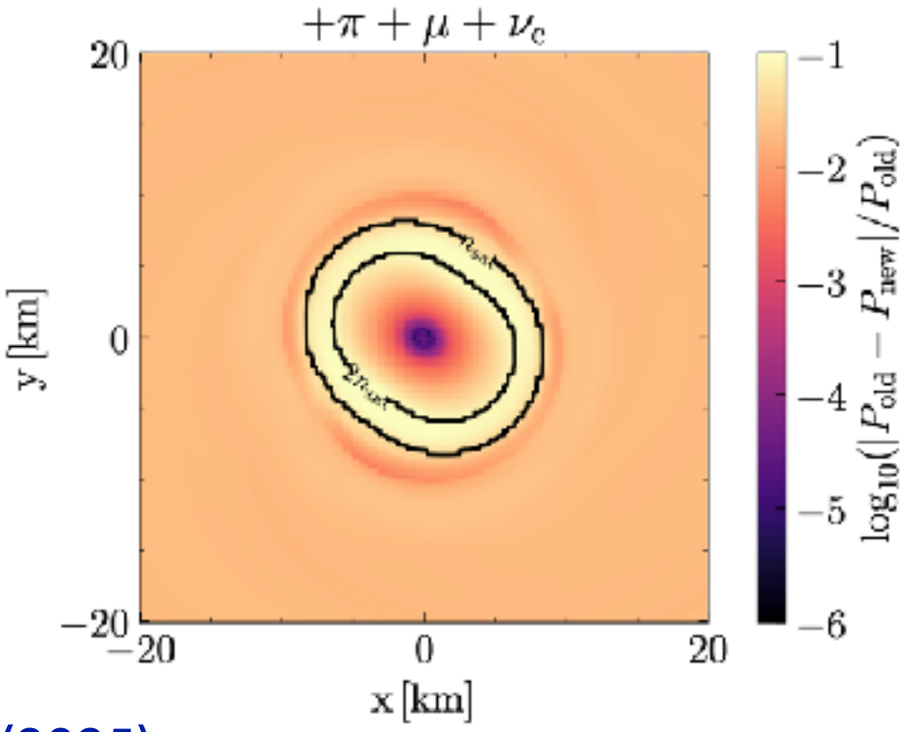
In the merger context, see also Vijayan+ (pions, 2023), Loffredo+ (muons, 2023)

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu \qquad \mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$$

Mike Pajkos (Caltech)



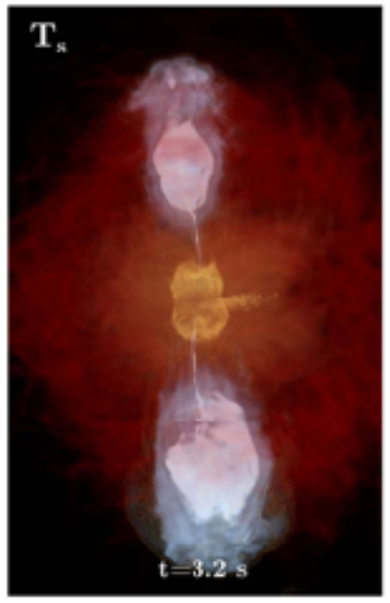
- Pressure corrections of similar order to viscous correction.



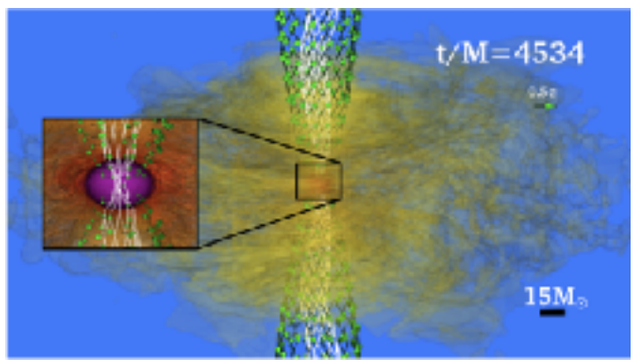
Pajkos & **ERM** (2025)

Gamma-ray bursts from stellar remnants?

Not a magnetar, but strong constraints on BH-disk engine

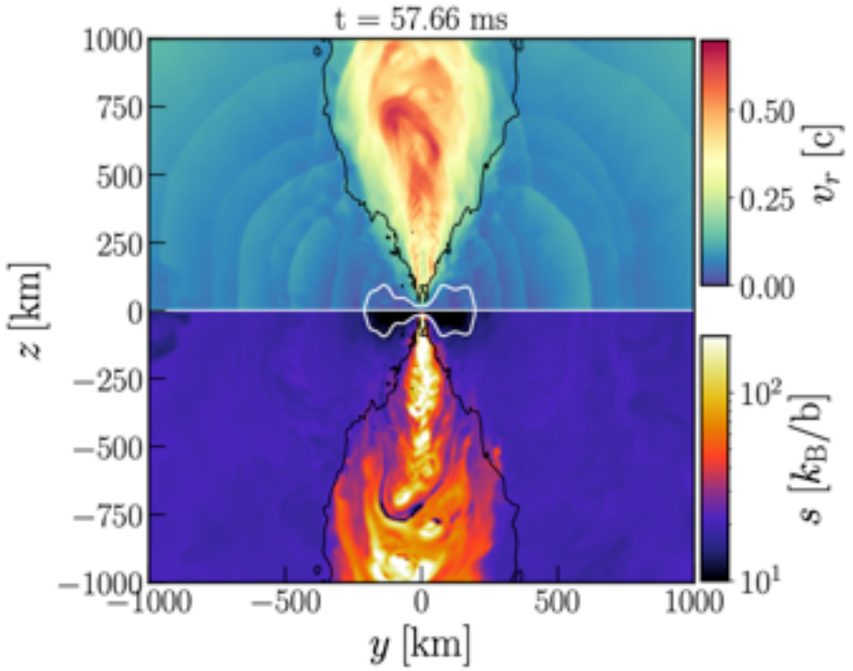


Gottlieb+2023



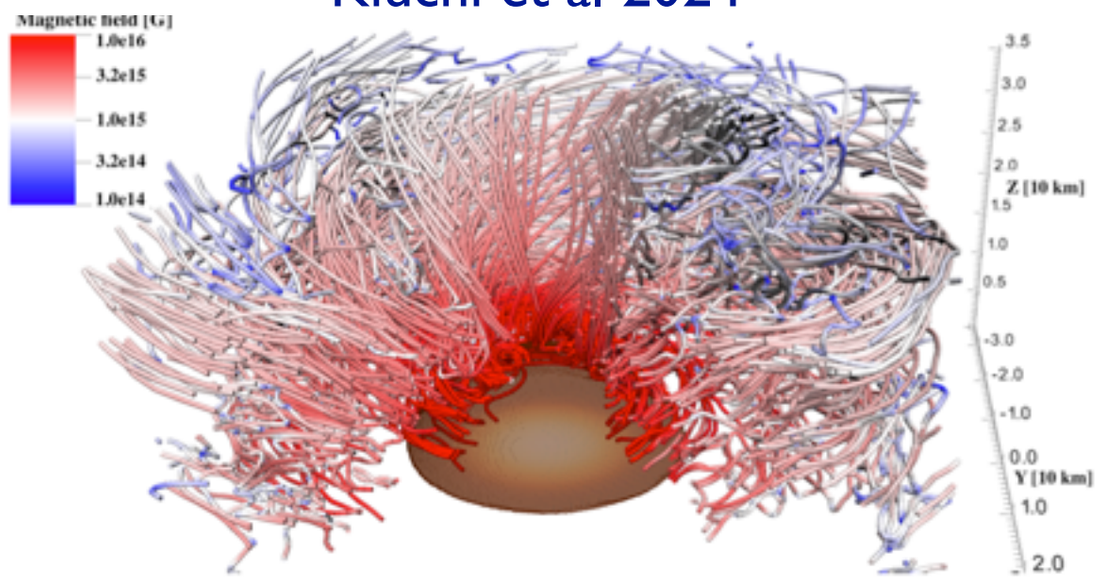
Bamber+2024

Combi & Siegel 2023



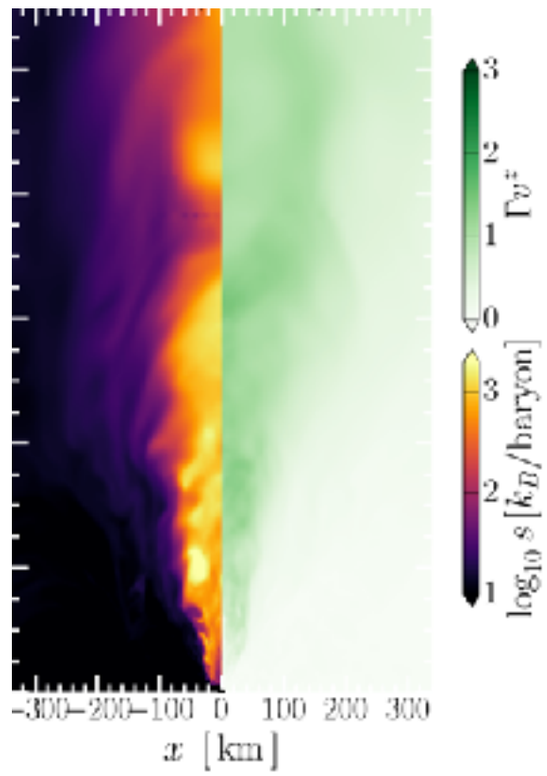
see Kiuchi talk

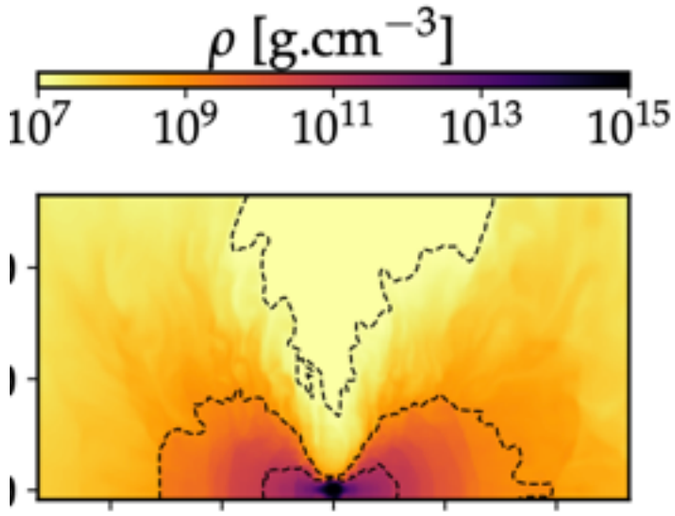
Kiuchi et al 2024



ERM & Quataert 2023

ERM 2023





Curtis+ 2023; de Haas+2023

Major developments in numerical relativity in past years!

The final fate of a neutron star binary

Magnetic dynamos are one of the key ingredients in the merger!

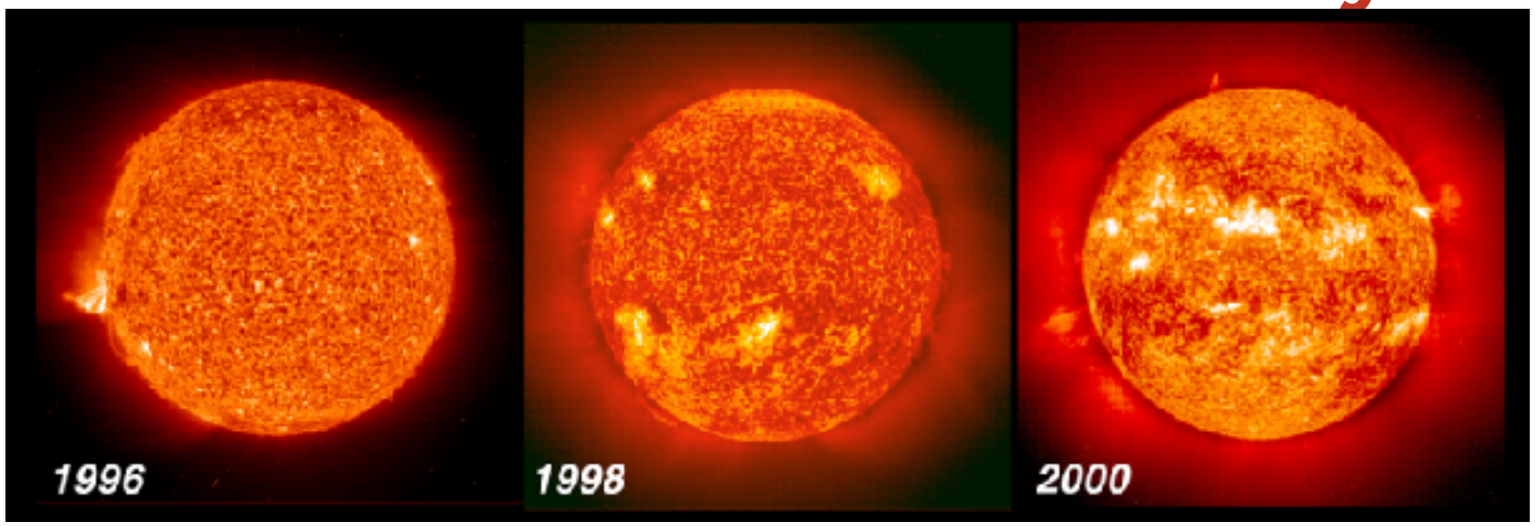
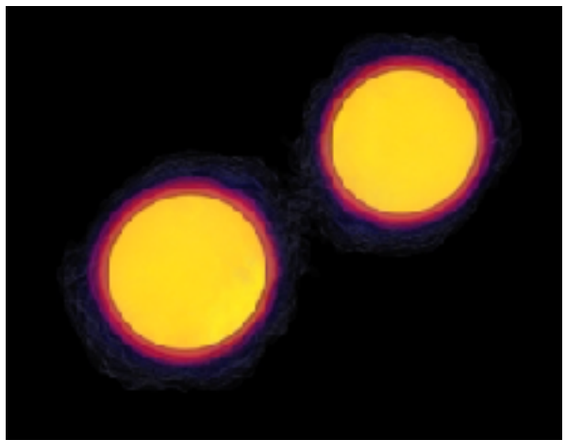
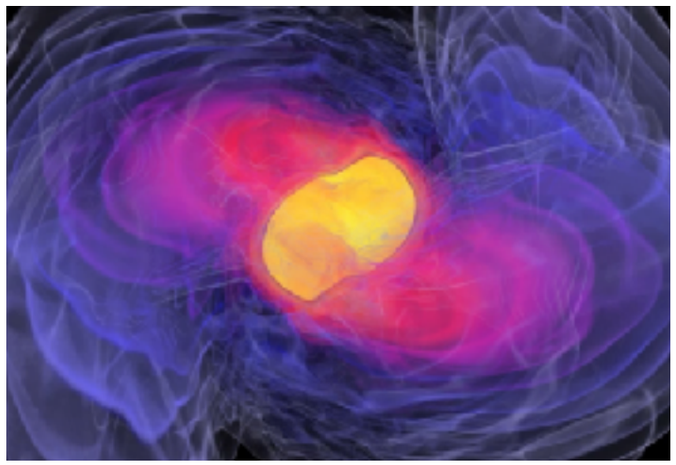
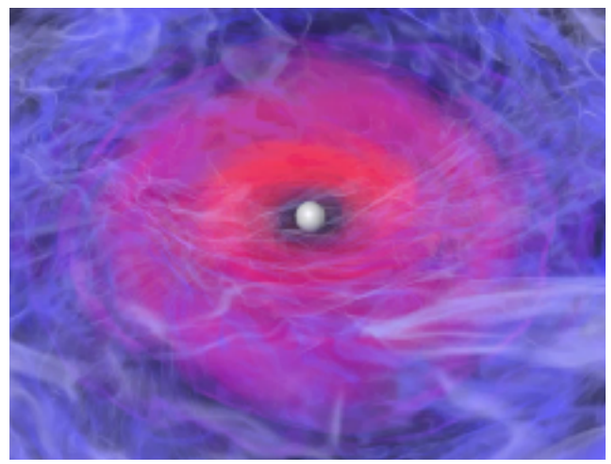


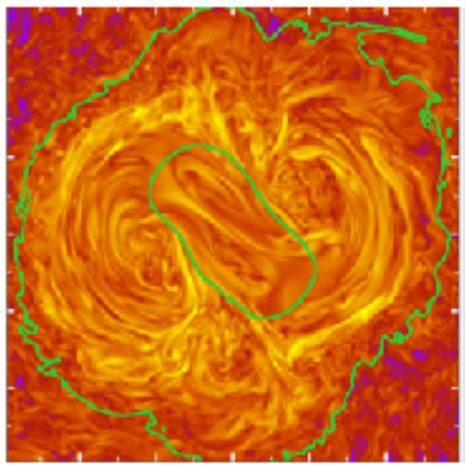
Image credit: NASA



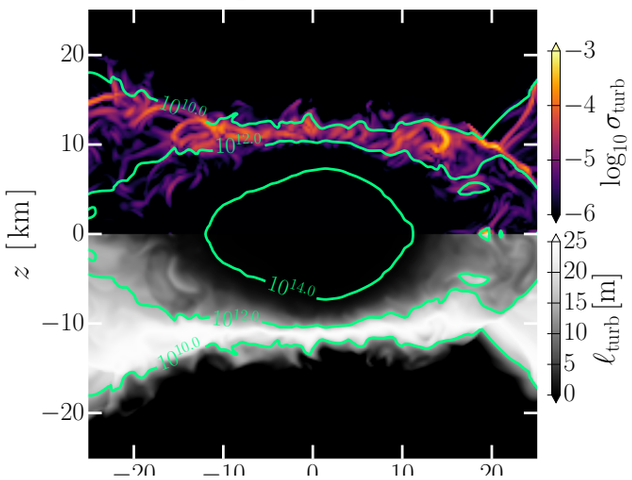




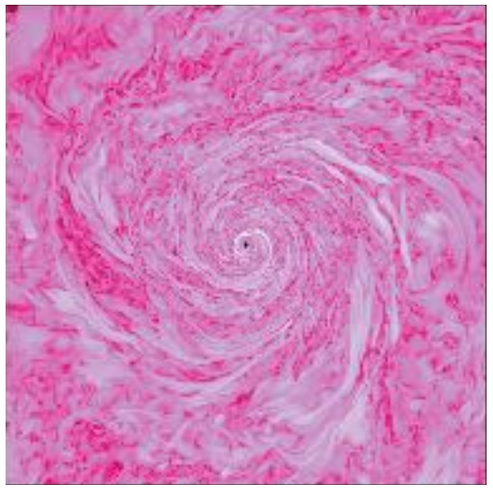
Small scale



Large scale



Disk dynamo

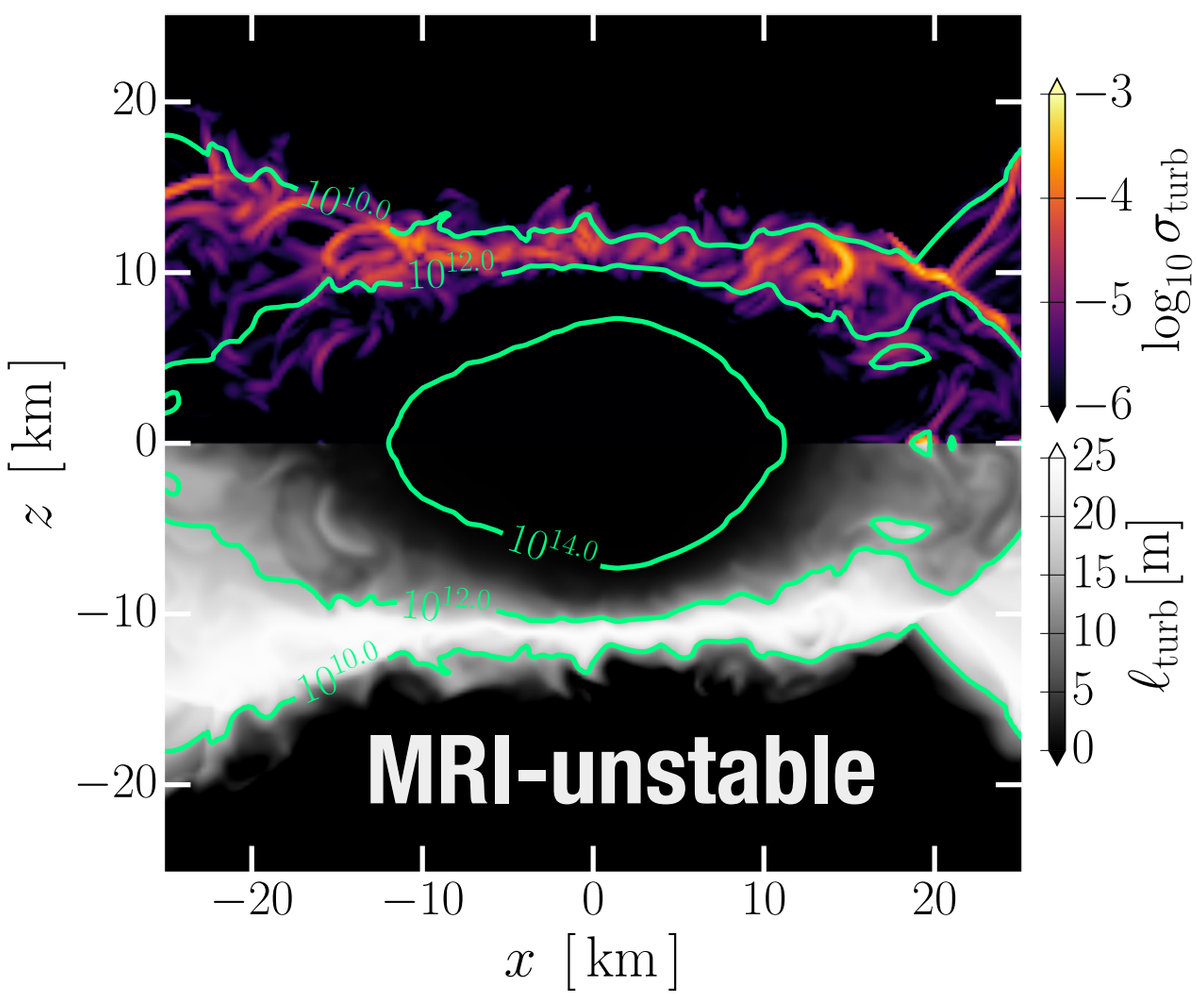


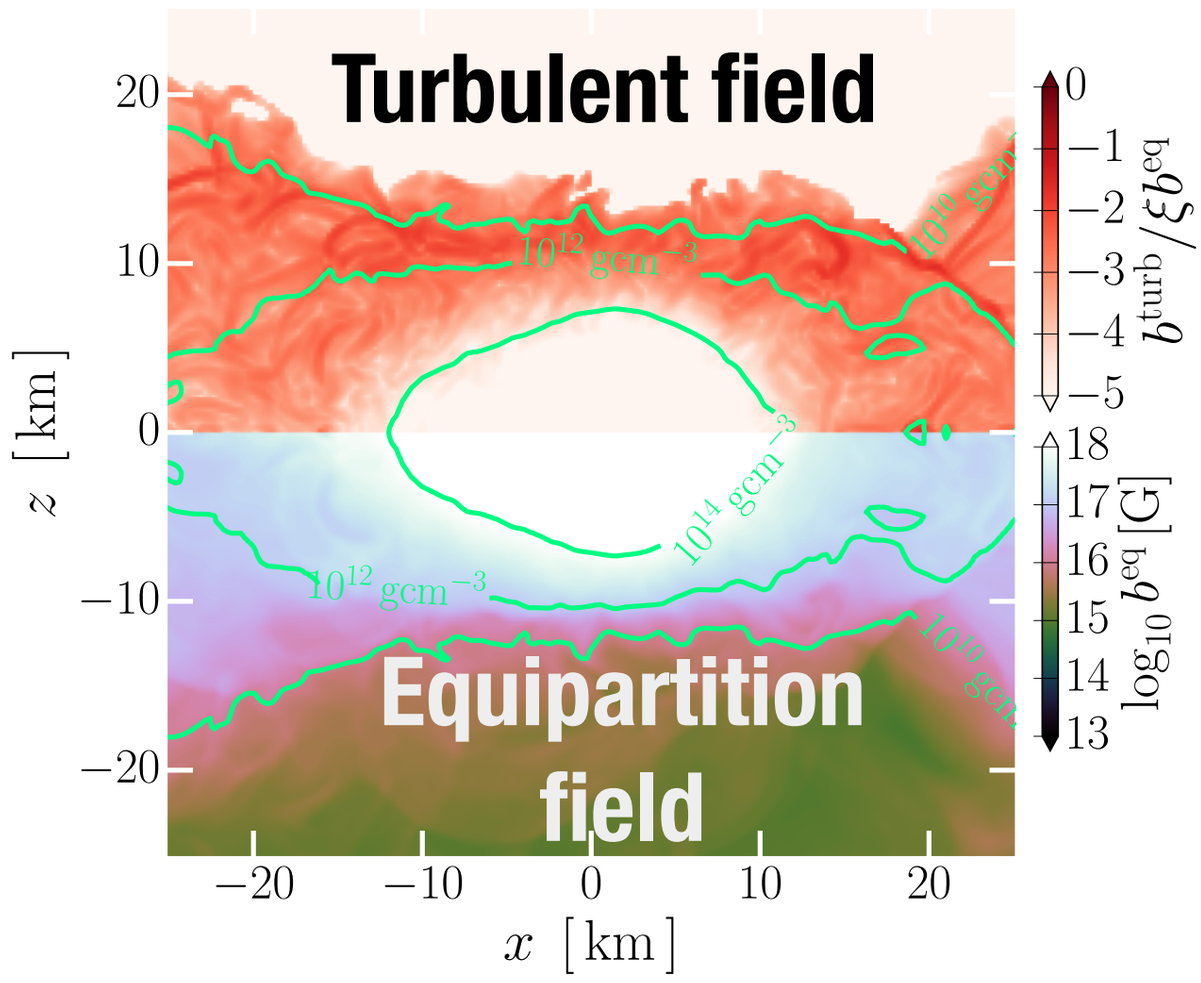
Price+,Kiuchi+,Palenzuela+, Aguilera-Miret+, Chabanov+, Liska+, Christie+, Jacquemin-Ide+, Hogg+, Musoke+, Galishnikova+, others

Magnetorotational instability dynamo!

New subgrid model!

ERM (PRD 2023)





Outer layers of the star subject to strong dynamo amplification (Kiuchi+2023).

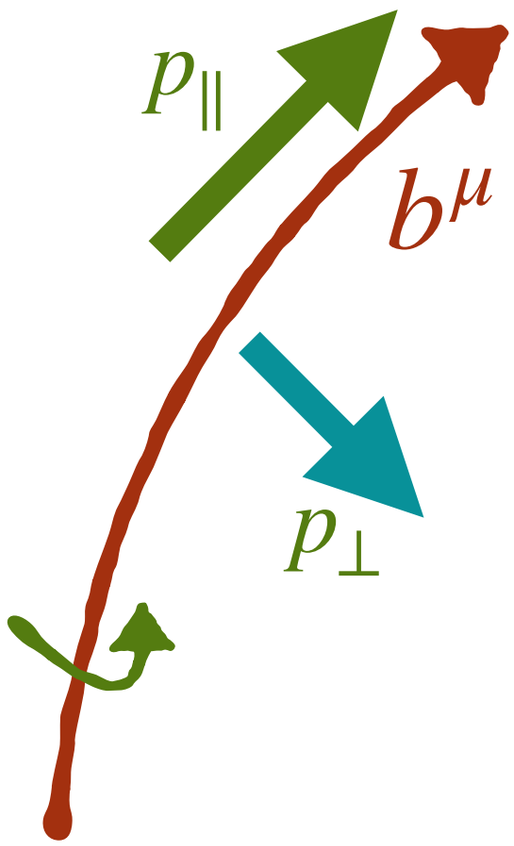
Reach near equipartition field strength there.

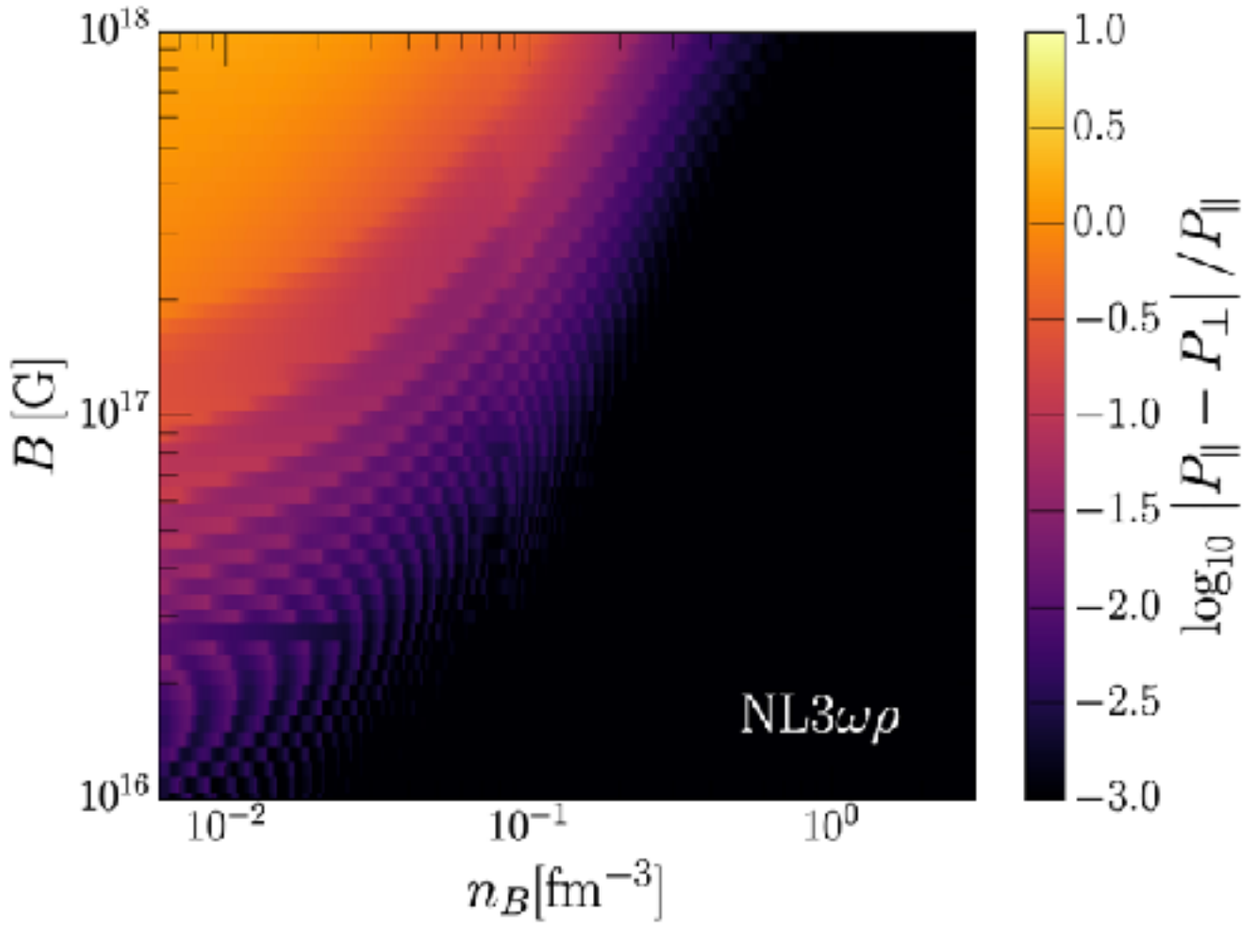
Pressure anisotropies in the crust?

At near equipartition field strengths could have feedback on equation of state (Landau level quantization)

Pressure anisotropy can be same order as viscosities or thermal effects.

$$\Pi = \frac{1}{2}\left(P_{\parallel} - P_{\perp}\right)$$





Based on Pais & Providencia (2016)

GRMHD with polarization

Adding a polarization tensor to nuclear matter amounts to the following

Bulk pressure

$$\Pi = -\frac{2}{3}\mu b^2$$

Braginskii-like shear

$$\pi^{\mu\nu} = \mu\left(b^\mu b^\nu - \frac{1}{3}\Delta^{\mu\nu}b^2\right)$$

Chatterjee et al. (2015)

On the technical side, can come up with a hydrodynamical frame transformation

Susceptibility

$$\mu b^2 = \left(P_\perp - P_\parallel\right)$$

ERM, Peterson, Scurto, Pais, Dexheimer (ApJL2025)

$$\tilde{b}^\mu = \sqrt{1-\mu}\, b^\mu\,,$$

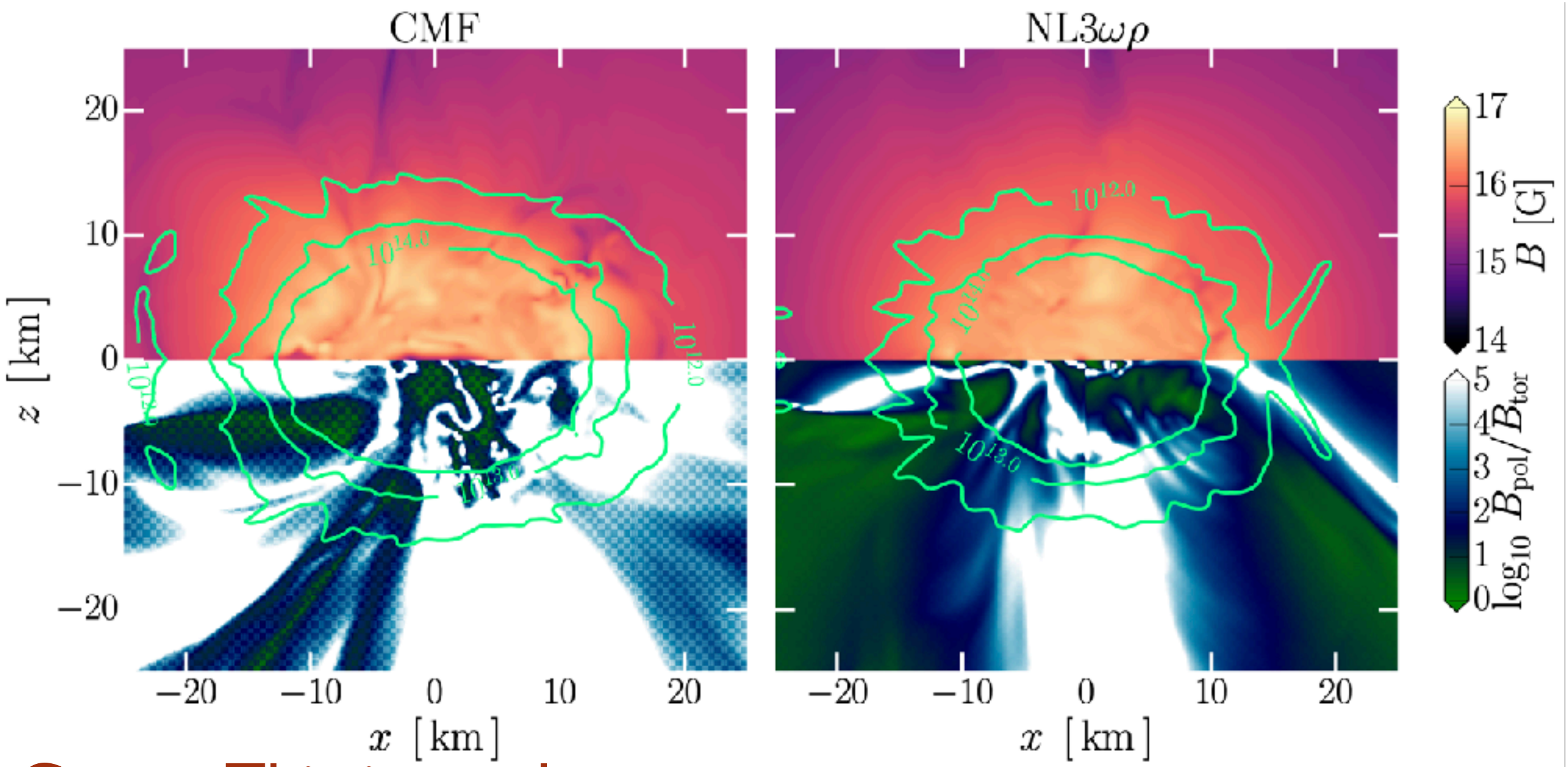
$$\tilde{e} = e - \frac{\mu}{2\,(1-\mu)}\tilde{b}^2 = e - \frac{P_\perp - P_\parallel}{2}\,,$$

$$\tilde{P} = P_\parallel - \frac{\mu}{2\,(1-\mu)}\tilde{b}^2 = \frac{3}{2}P_\parallel - \frac{1}{2}P_\perp\,.$$

The resulting equations look like ideal GRMHD!

Magnetic field configuration

Background magnetic field for polarization exploration



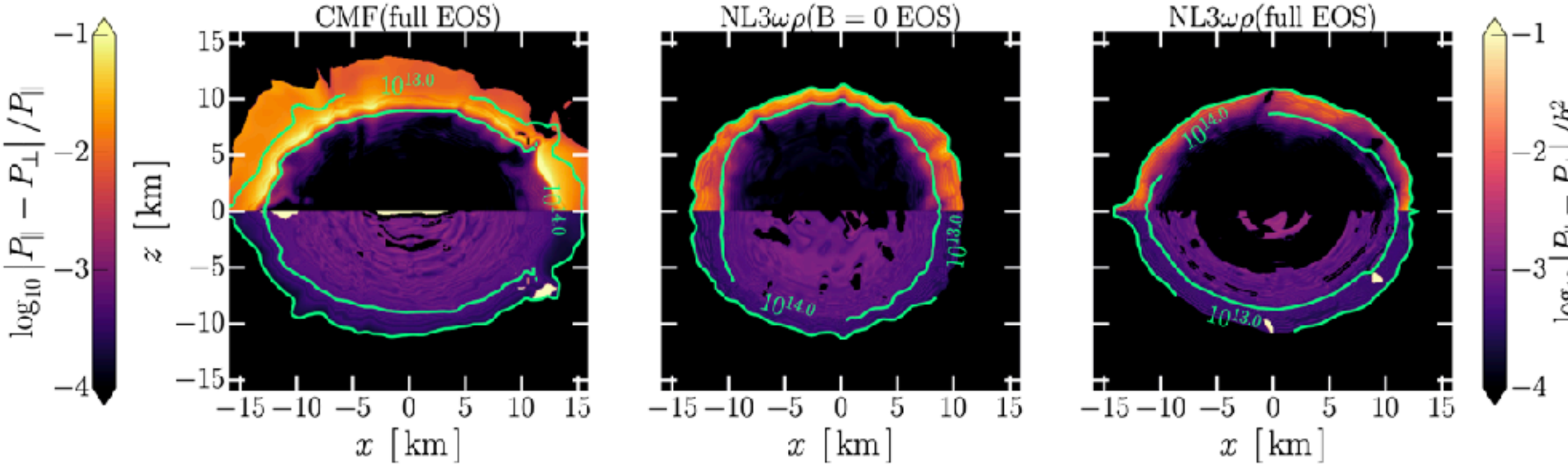
Caveat: This is on the extreme end of things

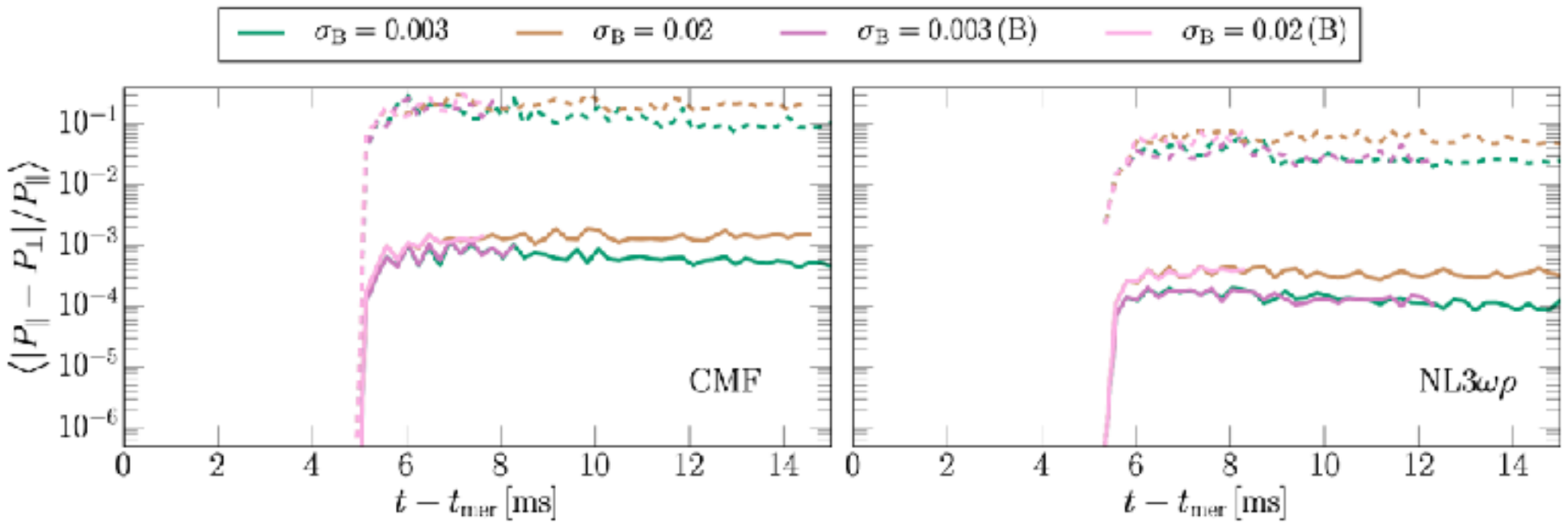
ERM, Peterson, Scurto, Pais, Dexheimer (ApJL 2025)

Pressure anisotropies in the crust?

First upper bounds on pressure anisotropy in mergers (largely crust region).

ERM, Peterson, Scurto, Pais, Dexheimer (ApJL 2025)

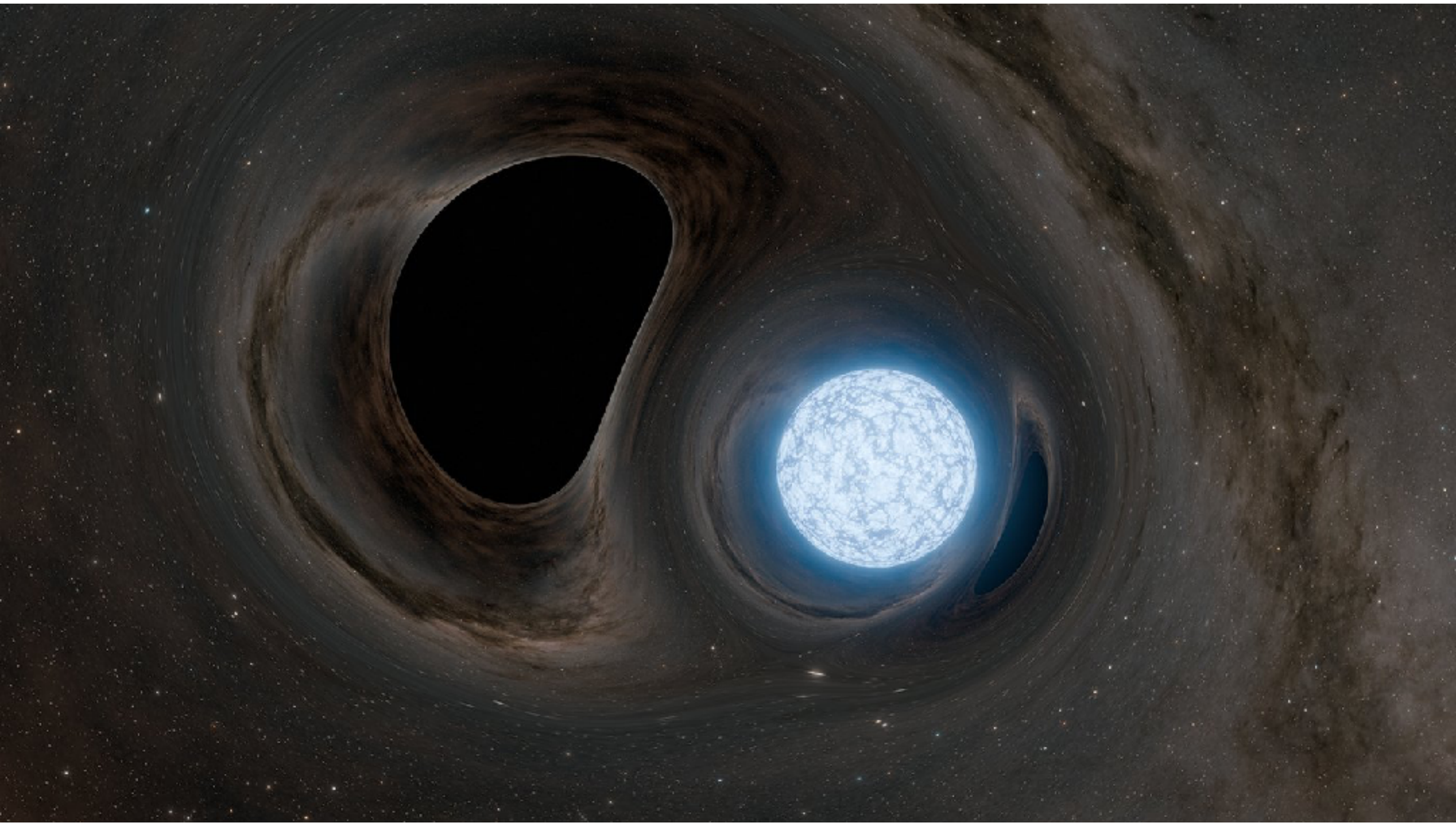




Up to 10% in crust

<0.1% in core

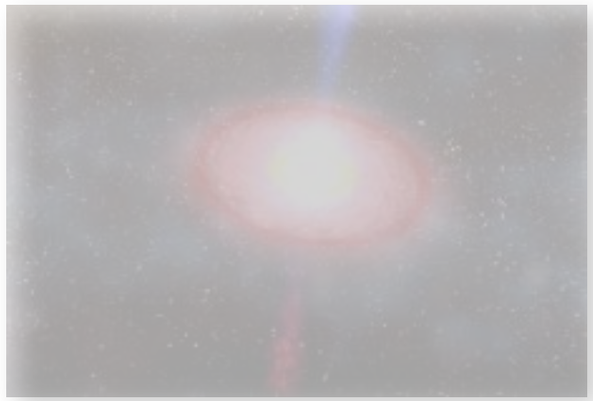
What about neutron star black hole mergers?

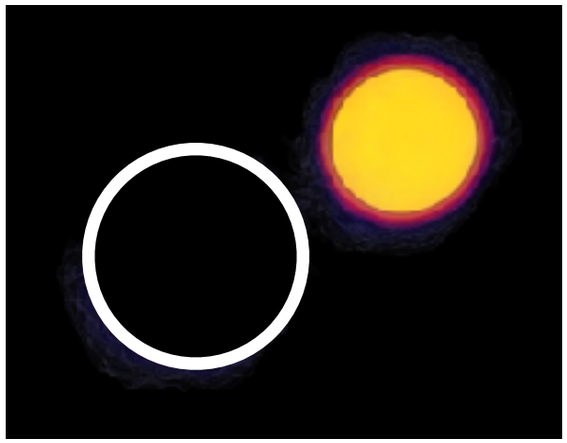


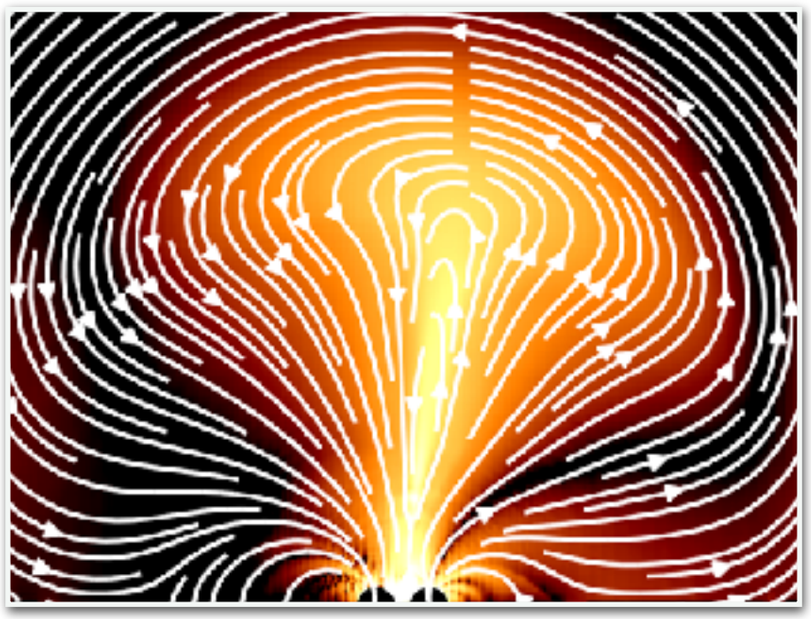
In most cases, neutron star will be swallowed whole…

The likely fate of a black hole neutron star binary

Gravitational waves

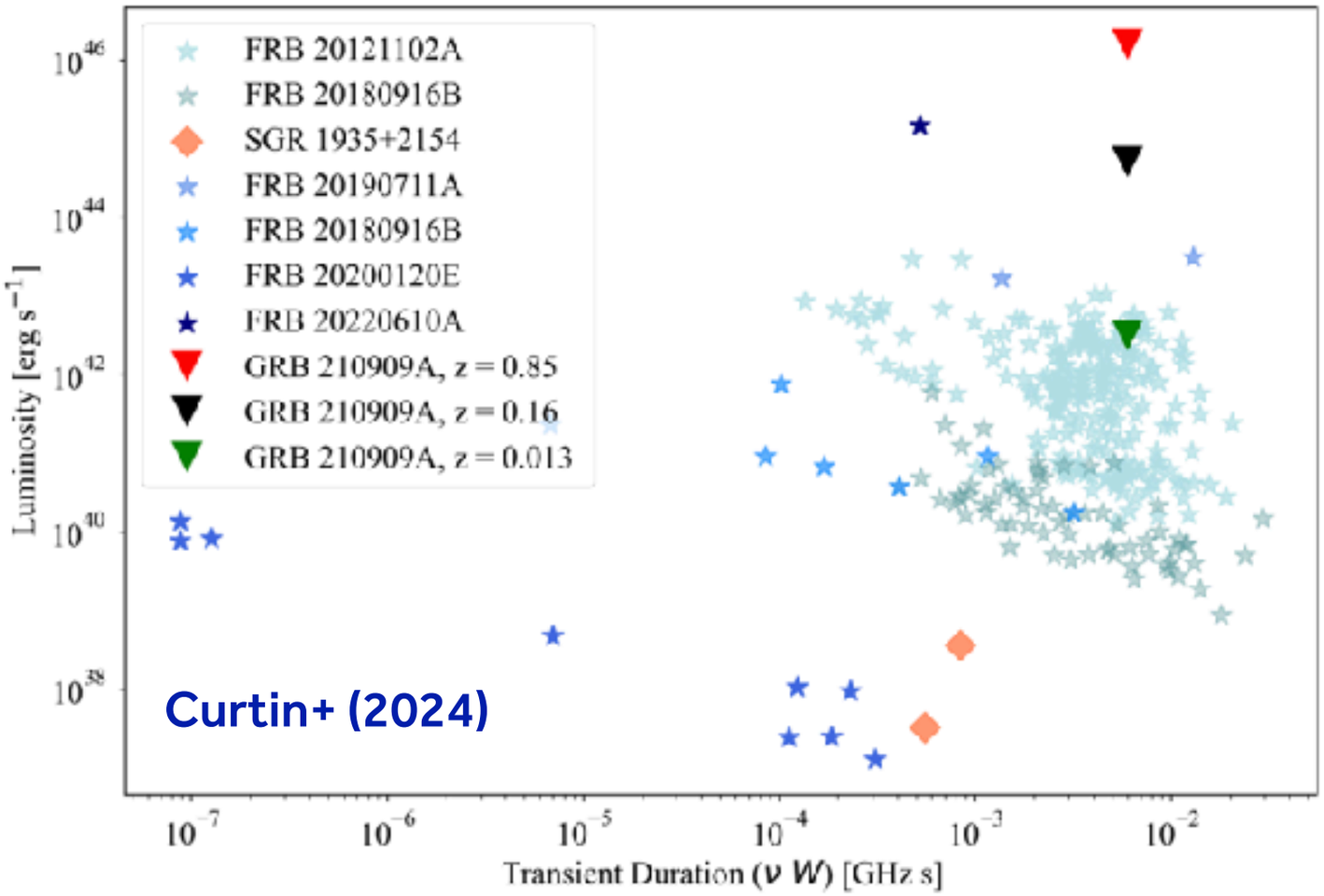






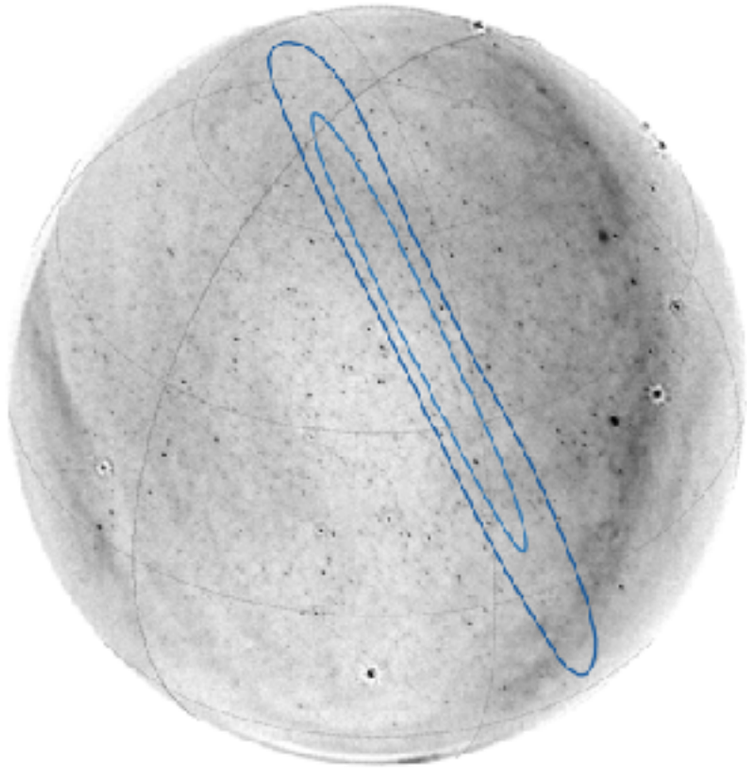
Precursor Emission?

Observational prospects



Curtin+ (2024)

Callister+ (2019)



CHIME-GRB correlation study

Radio search for GW170104

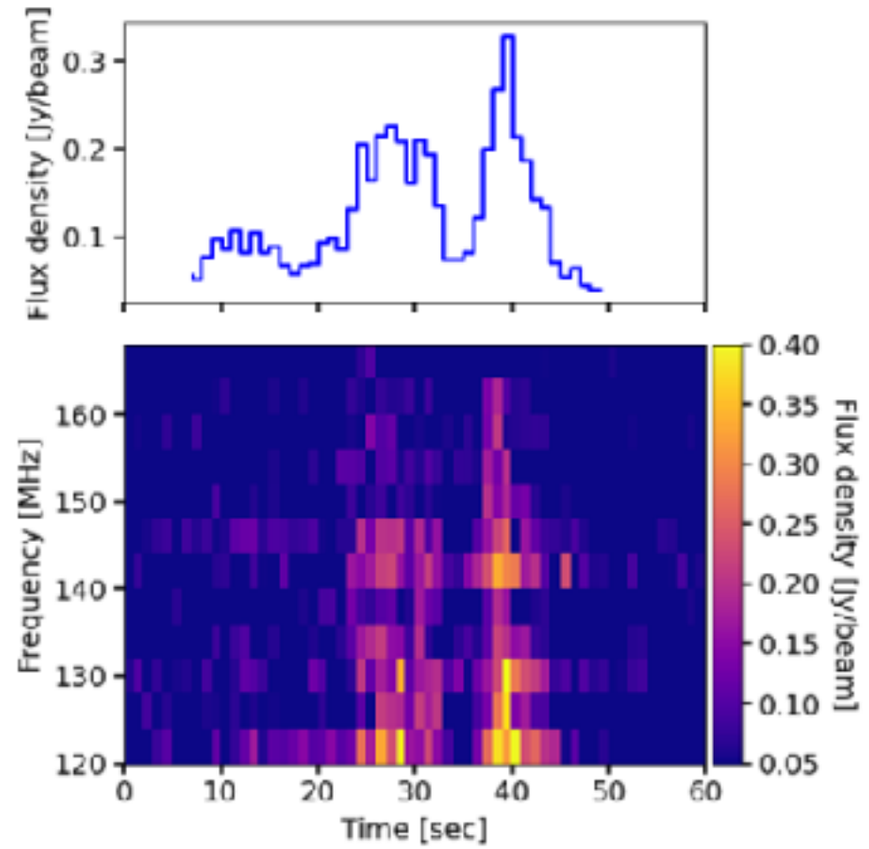
Interacting White Dwarf binaries

Recently reported discovery of short radio pulses (<1min) in galactic white-dwarf — M-dwarf binaries with LOFAR. De Ruiter+ (2025)

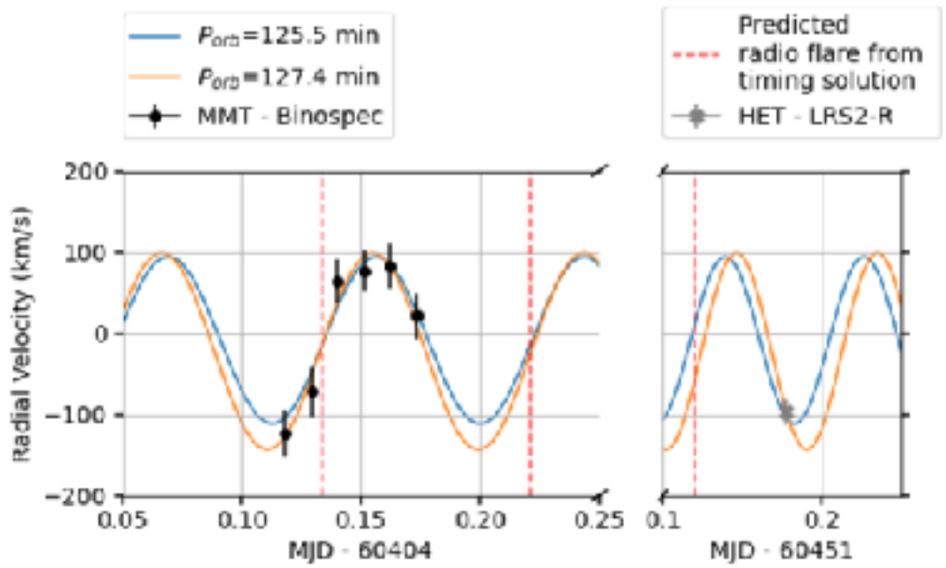
Similar system also found with MeerKAT Hurley-Walker+ (2025)

Radio emission potentially magnetospheric
(luminosity, polarization)

Some similarities to proposed neutron star binary precursors



De Ruiter+ (2025)

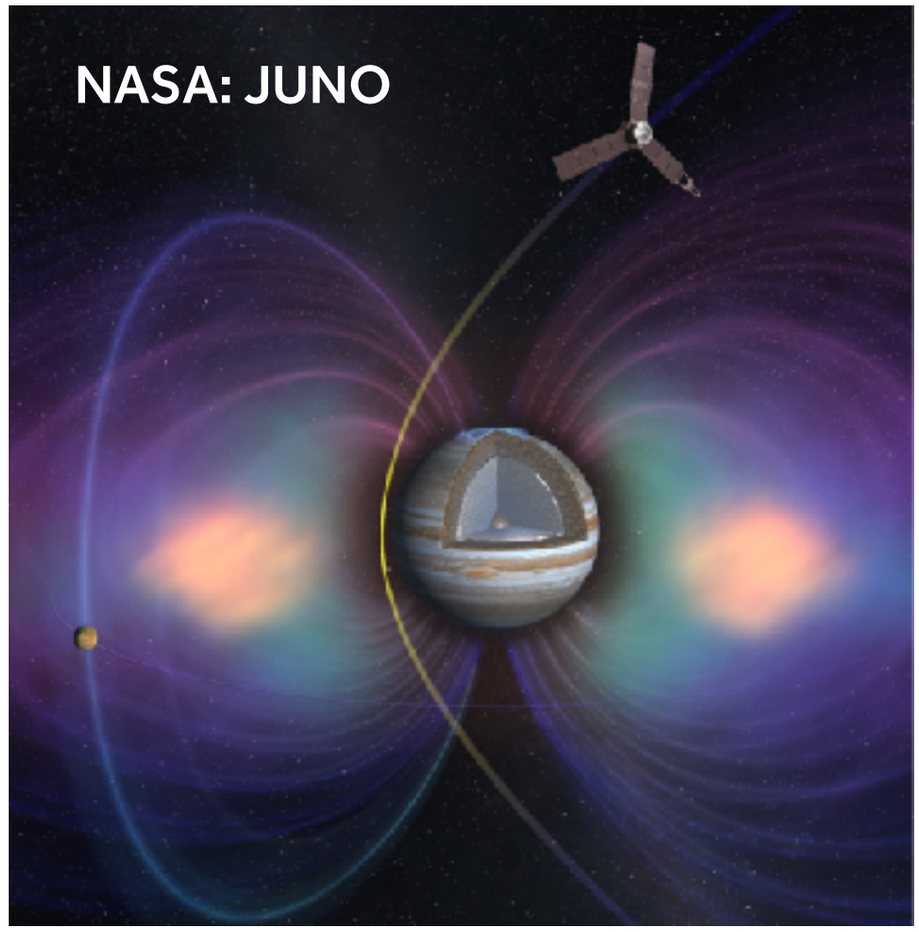


Radio emission from white dwarfs??

First kinetic simulations of relativistic electron-cyclotron maser under WDMD conditions supports a Jupiter-Io-like emission scenario

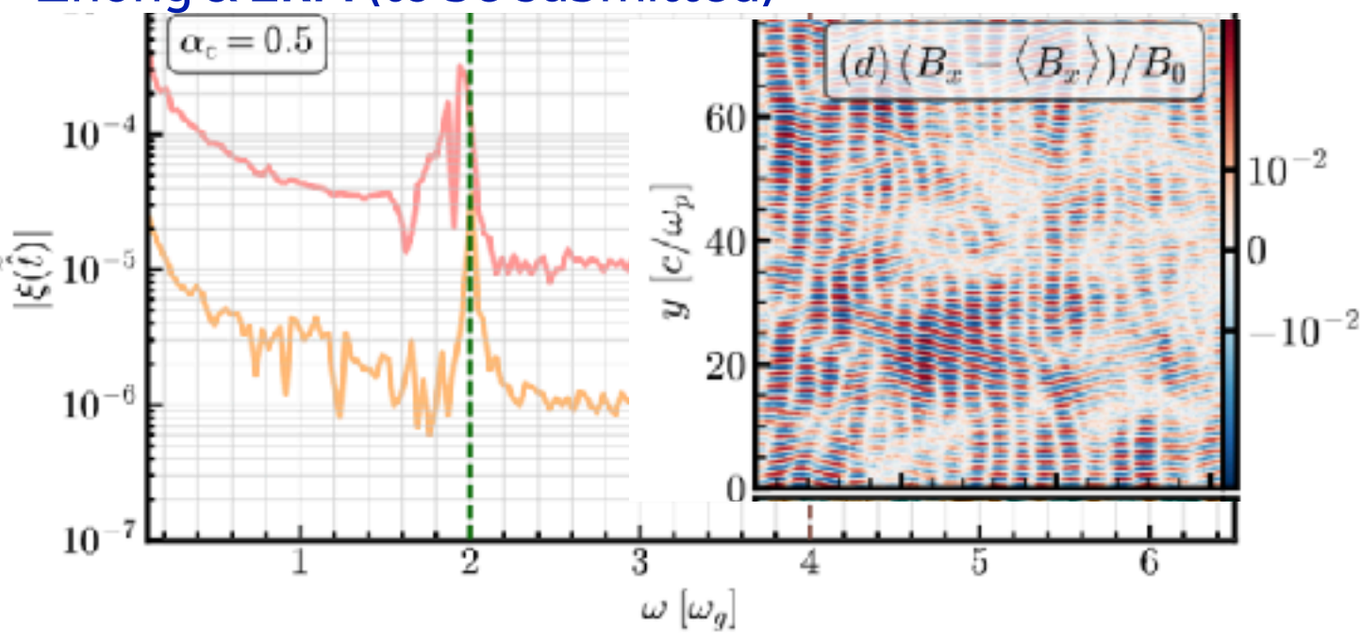
Zhong & **ERM** (to be submitted)

Also Goldreich&Lynden-Bell (1968)
Qu & Zhang (2025)

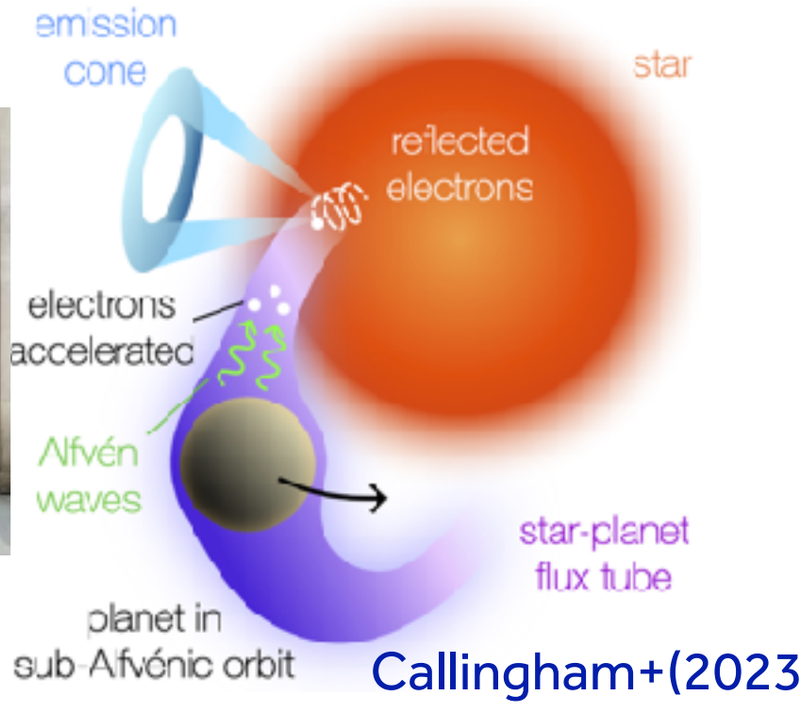


Spectral width and polarization consistent (though with caveats)

Zhong & **ERM** (to be submitted)



Yici Zhong
(Caltech)

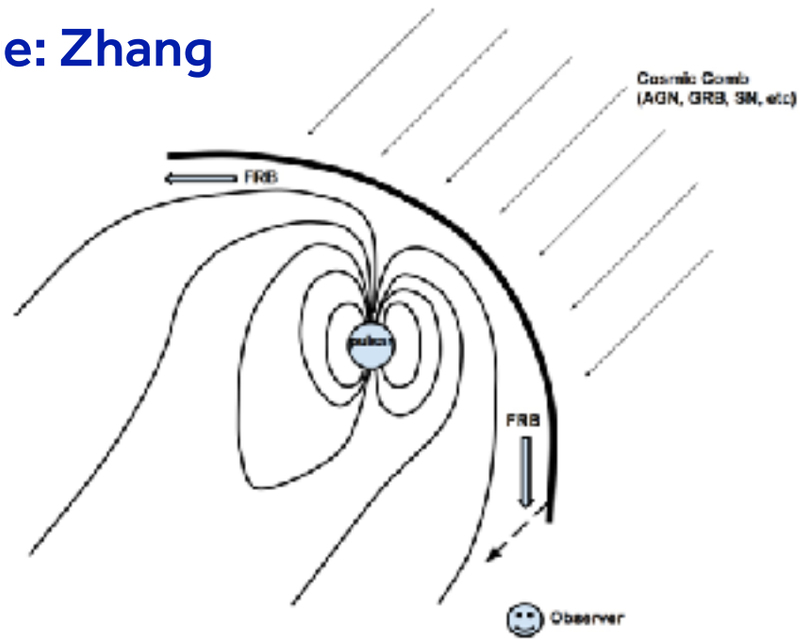


Callingham+(2023)

Pre-merger transients

Wind interactions

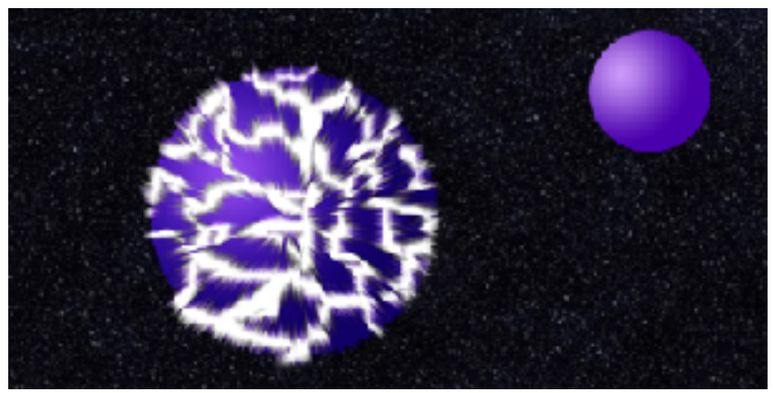
Image: Zhang



Zhang+, Ioka+; Sridhar+

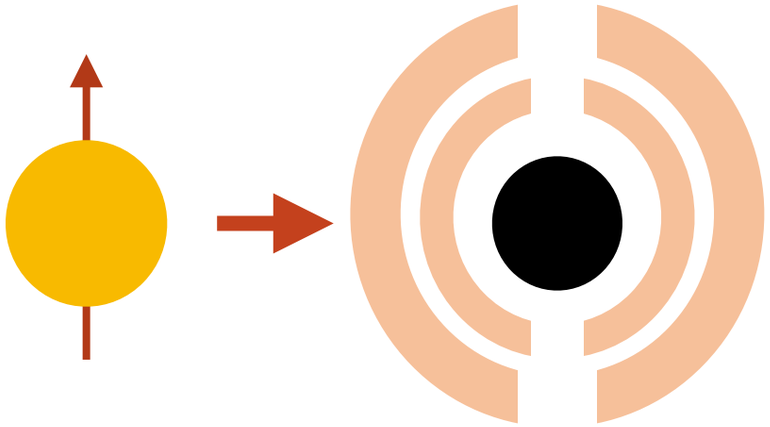
Tidal interactions

Image: APS



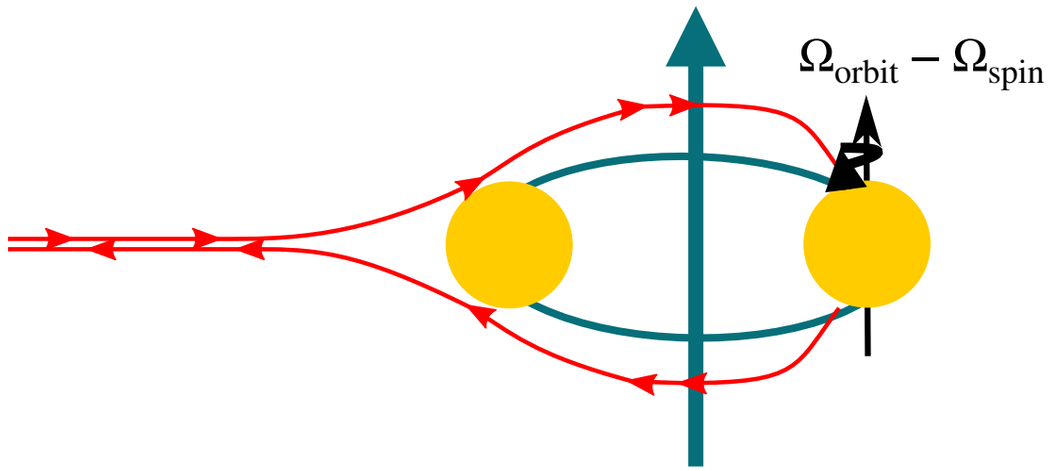
Tsang+, Blaes+

Merger transients (collapse-like)



Falcke & Rezzolla, Zhang+, Mingarelli+, Levin

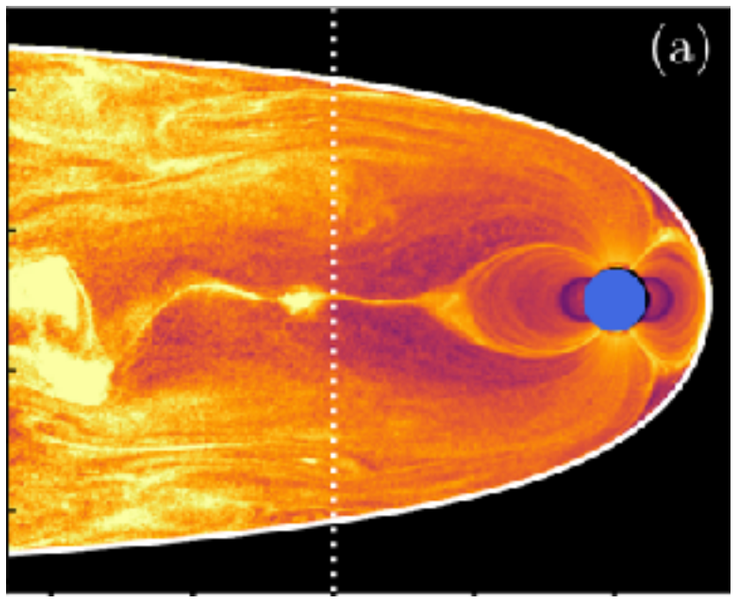
Orbital motion / binary interaction



Hansen & Lyutikov, Zhang, Cooper+, Piro, Lai, Totani, Lyutikov+, Wang+

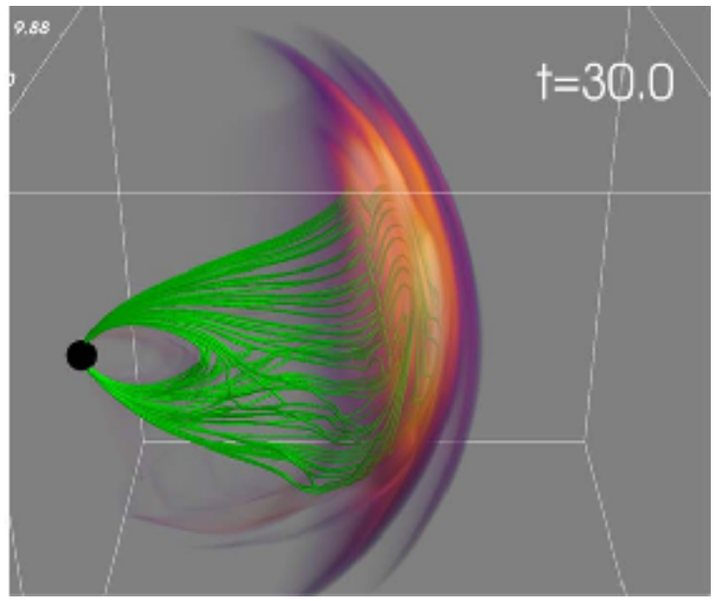
Computational breakthroughs

Wind interaction



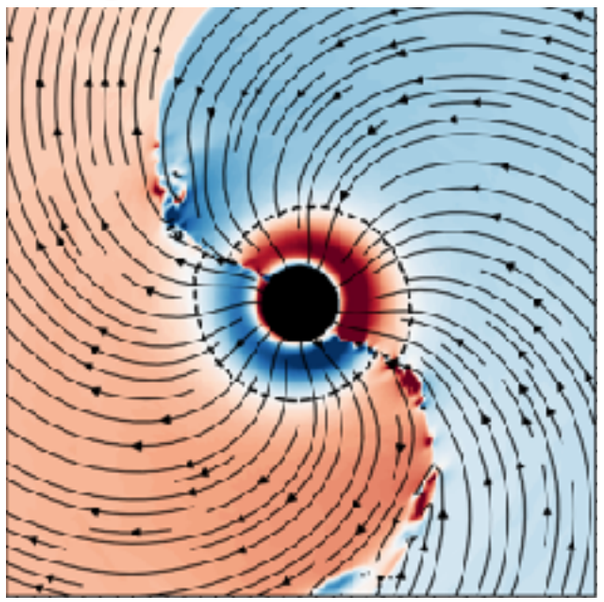
Zhong+(2024), Cortes+(2023), Sirdhar+(2021)

(Non-linear) Alfven waves



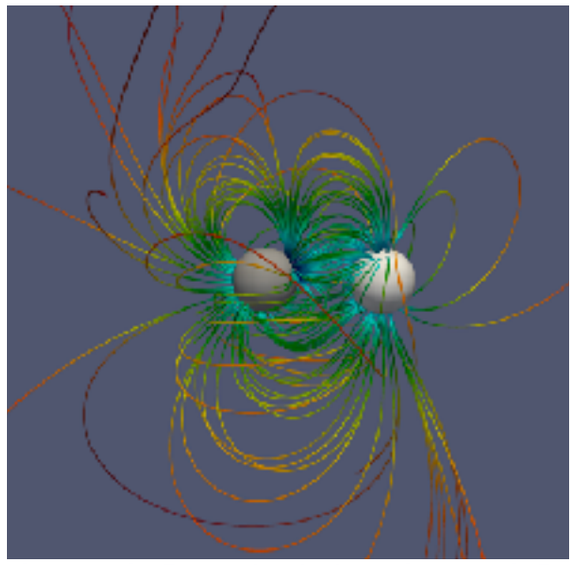
Yuan+(2020, 2022), **ERM**+(ApJL 2024)

Balding transients/shocks



ERM+(2018); Nathanail, **ERM**+(2017), East+(2020)
Kim, **ERM**+(ApJL 2025)

Binary interactions



Palenzuela+(2013), Paschalidis+(2013),Ponce+(2014),
Carrasco & Shibata(2020,2022),
ERM & Philippov (ApJL 2020,2022, PRL 2023, ApJL 2023),
Mahlmann & Beloborodov (2025)

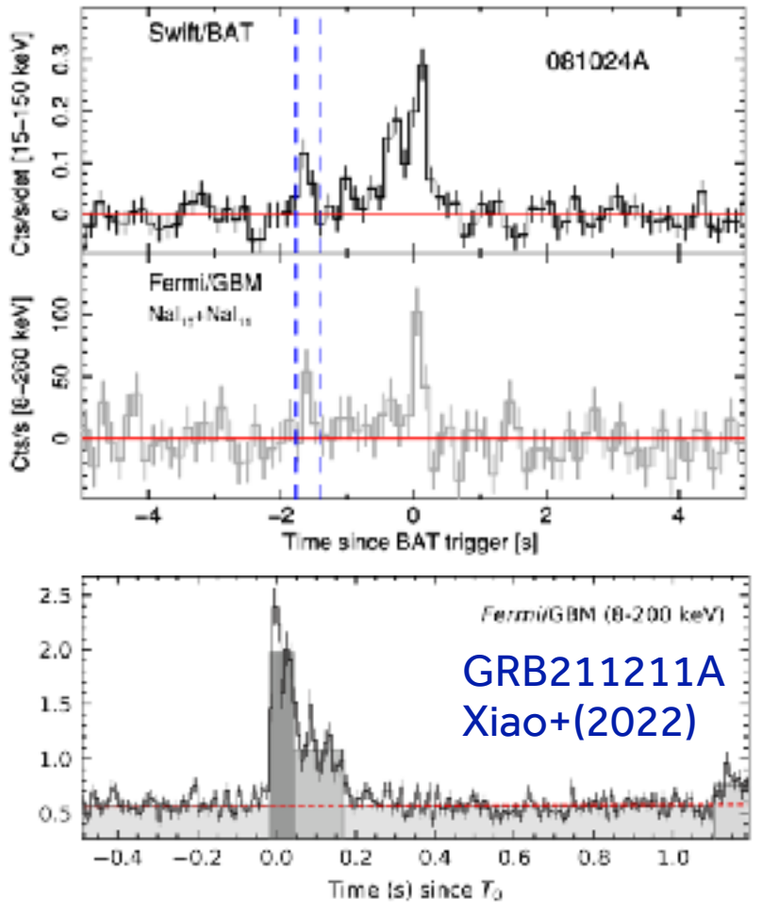
Gamma-Ray Burst Precursors?

Small number of gamma-ray bursts feature precursors seconds before the main event.

Several explanations possible, including resonant shattering of the neutron star crust prior to merger.

Tsang+(2012;2013), Penner+(2013), Neill+

Gamma-ray bursts precursor Troja+(2010)



Main questions:

- How does the crust fracture?
- ➡ What type of emission is possible?
- Constraints on nuclear physics?

see Tsang talk

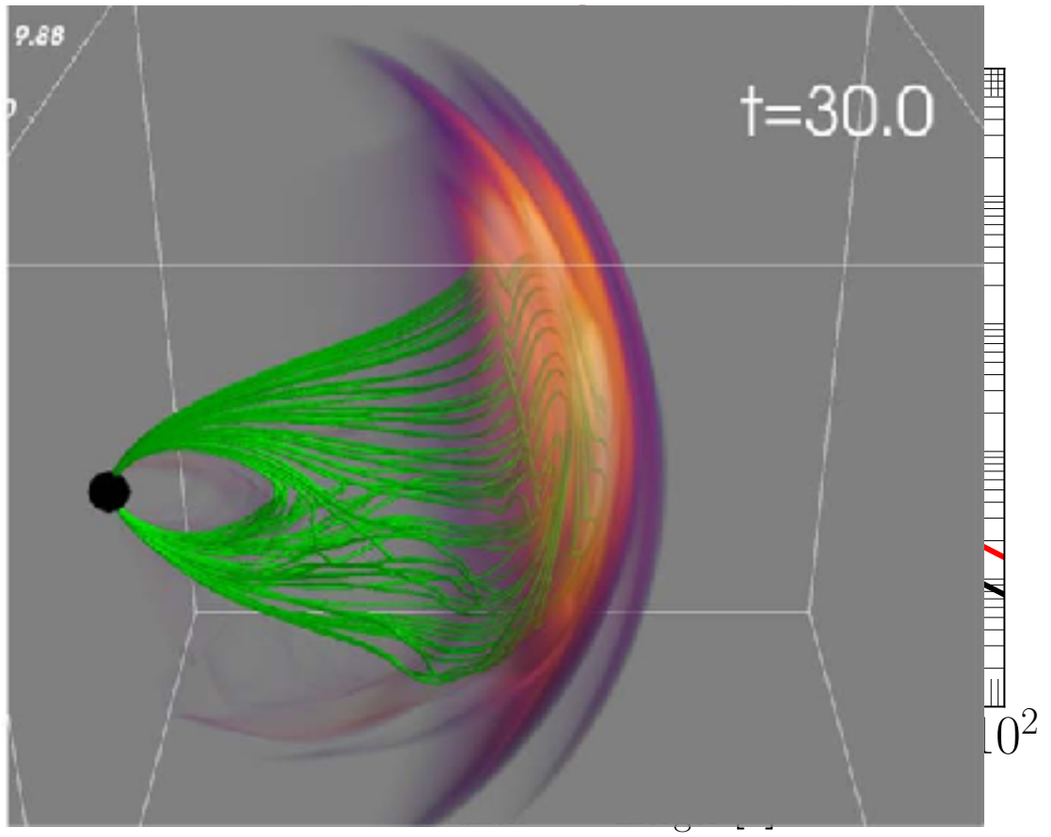
Alfven wave dynamics

In a dipole background Alfven waves steepen with distance, $\delta B/B \sim r^{3/2}$

Non-linear dynamics sets in once $\delta B \gg B$ Original idea goes back to Blaes+ (1989)

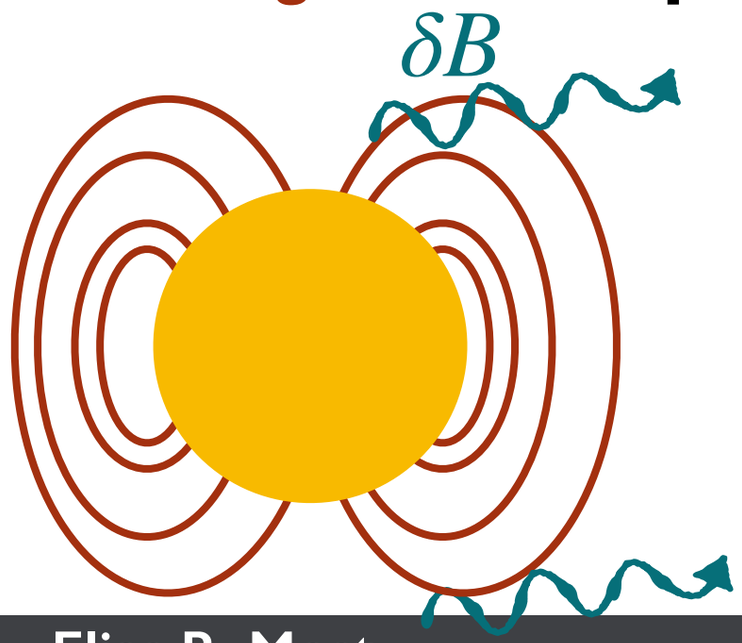
Non-linear dynamics leads to flare/blast wave Yuan+(2021,2022)

Yuan+(2022)



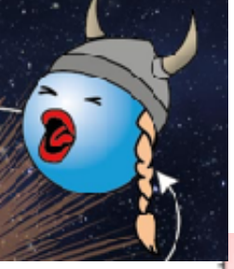
ERM, Chatziioannou, Kim, Legred (ApJL 2024)

Challenge: Scale separation between compact object and flaring radius!



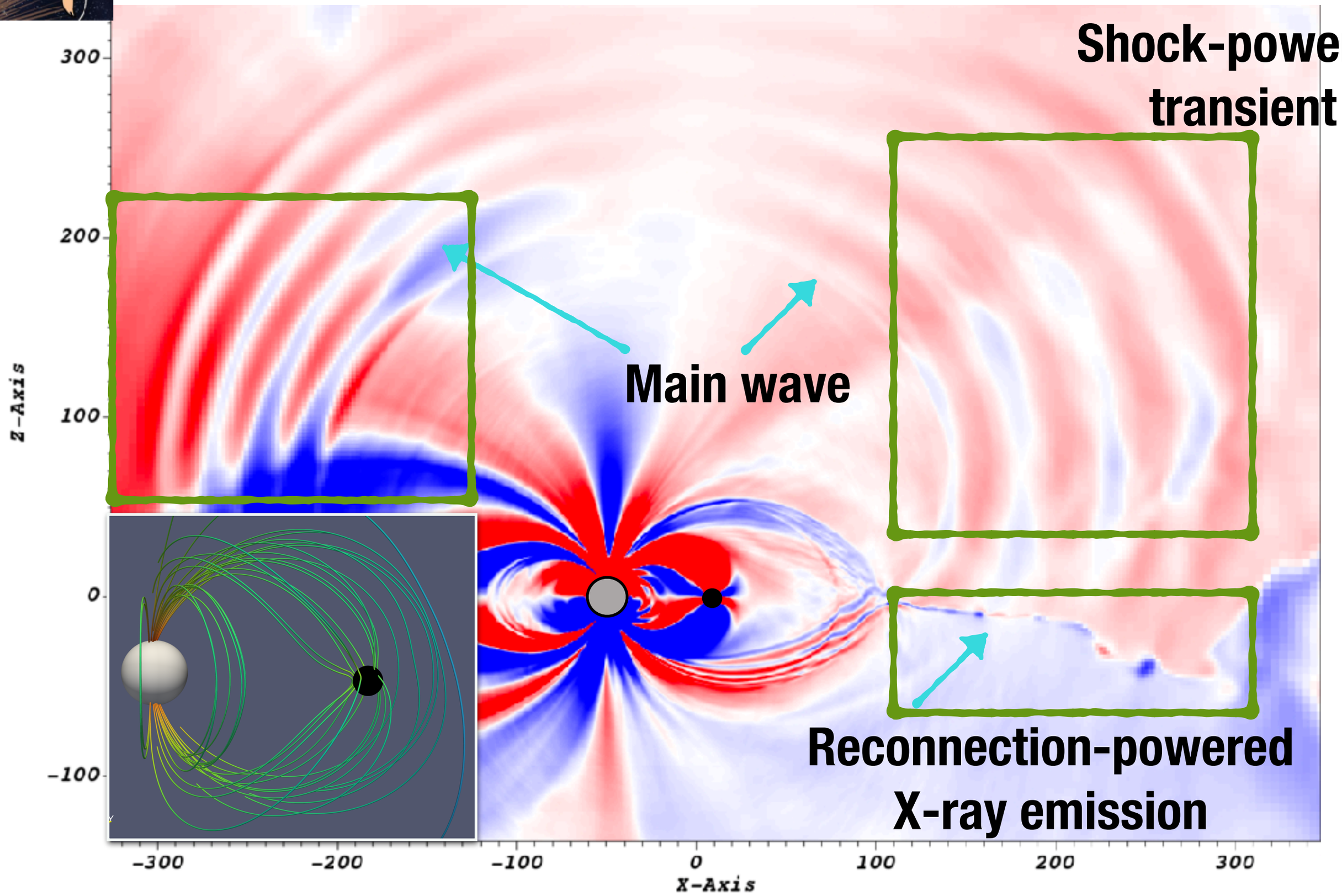
Even small perturbations have enough time to steepen!

$$\left(\frac{\delta B}{B}\right)_{\min} = \frac{{r_{\rm NS}}^{3/2}}{\left[a\left(\sqrt{\frac{a}{GM}} + \frac{Q}{1+Q}\right)\right]^{3/2}} \approx \frac{(GM)^{3/4}\, r_{\rm NS}^{3/2}}{a^{9/4}}$$

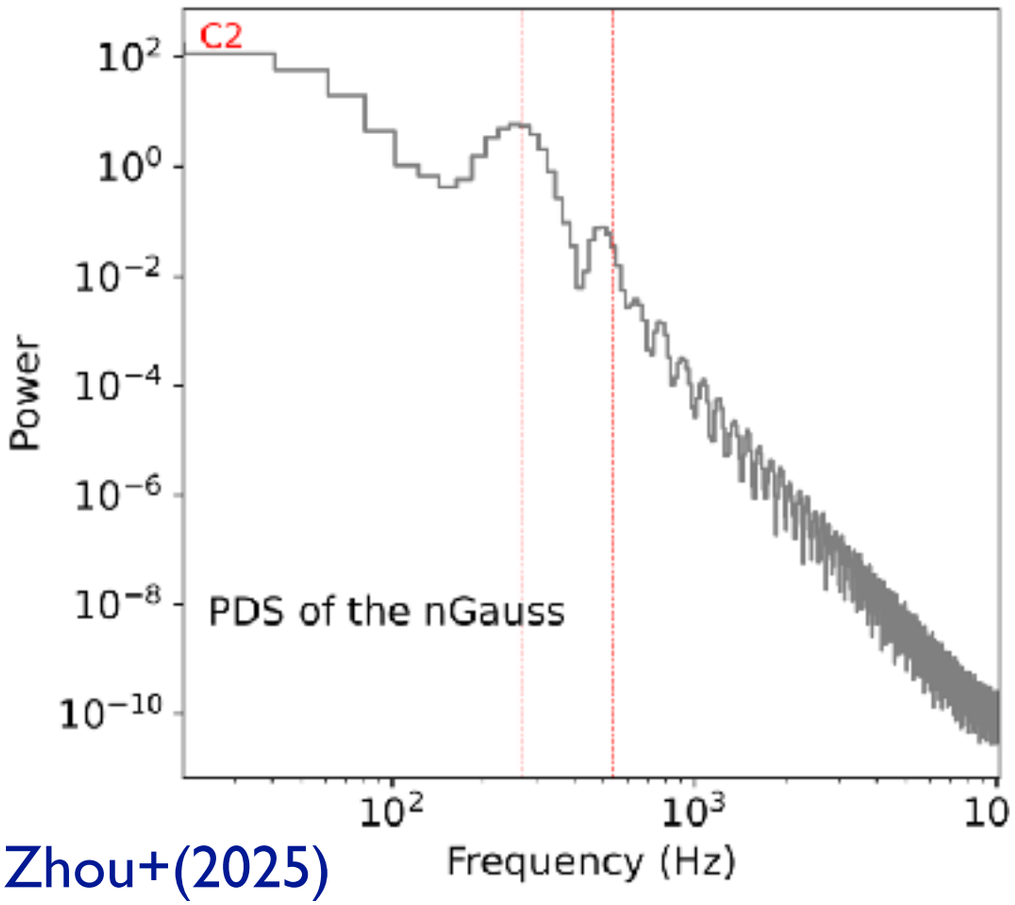


Alfven wave-powered precursors!

ERM, Kim, Chatziiouannou, Legred (ApJL 2024)



Crustal physics from hyperactive FRBs?



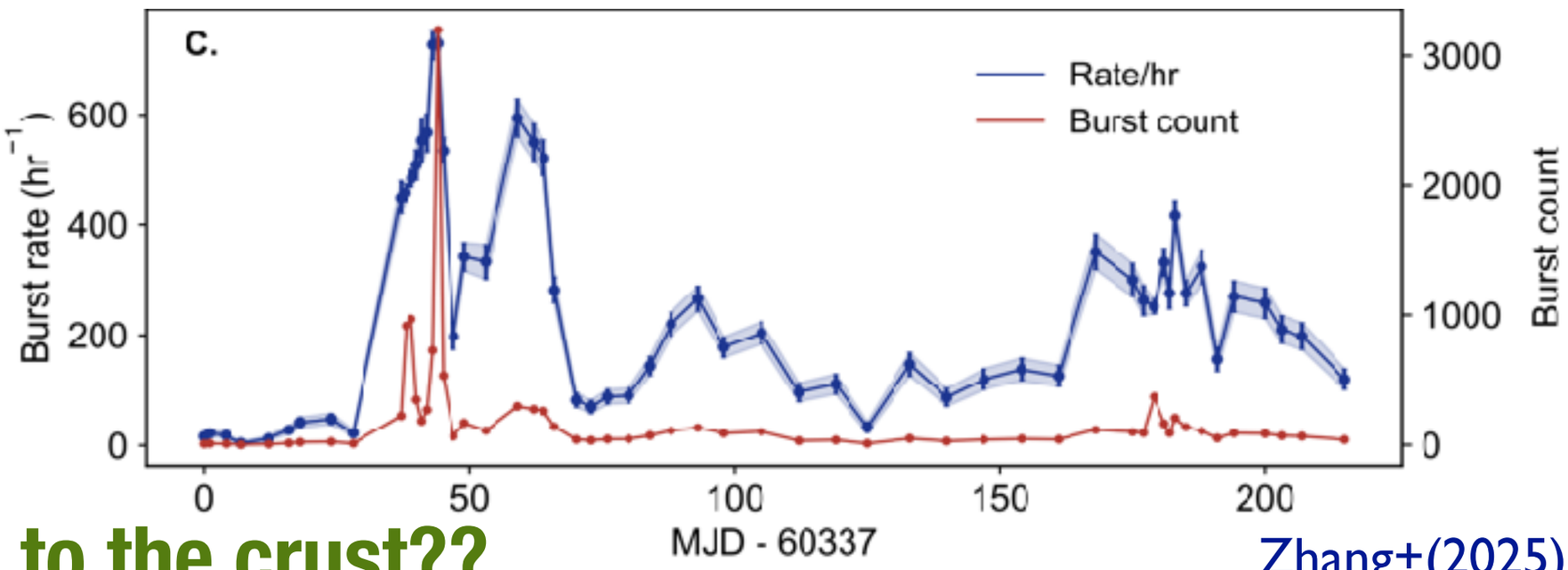
Zhou+(2025)

Recent discovery of hyperactive Fast Radio Burst with more than 11,000(!) bursts with FAST.

Individual burst episodes of up to 700 bursts per hour.

Potential energy constraints on FRB emission mechanism and magnetar engine (with many caveats...)

Clear imprints of 500 Hz periodicity in the signal.

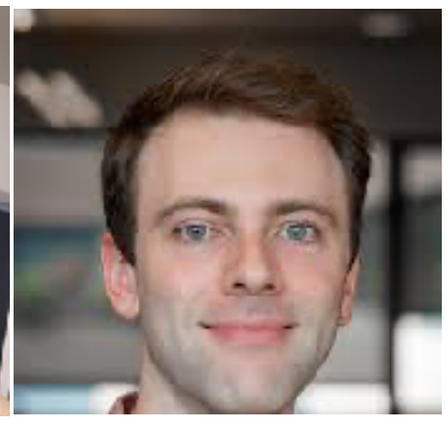


Zhang+(2025)

Could this be related to the crust??

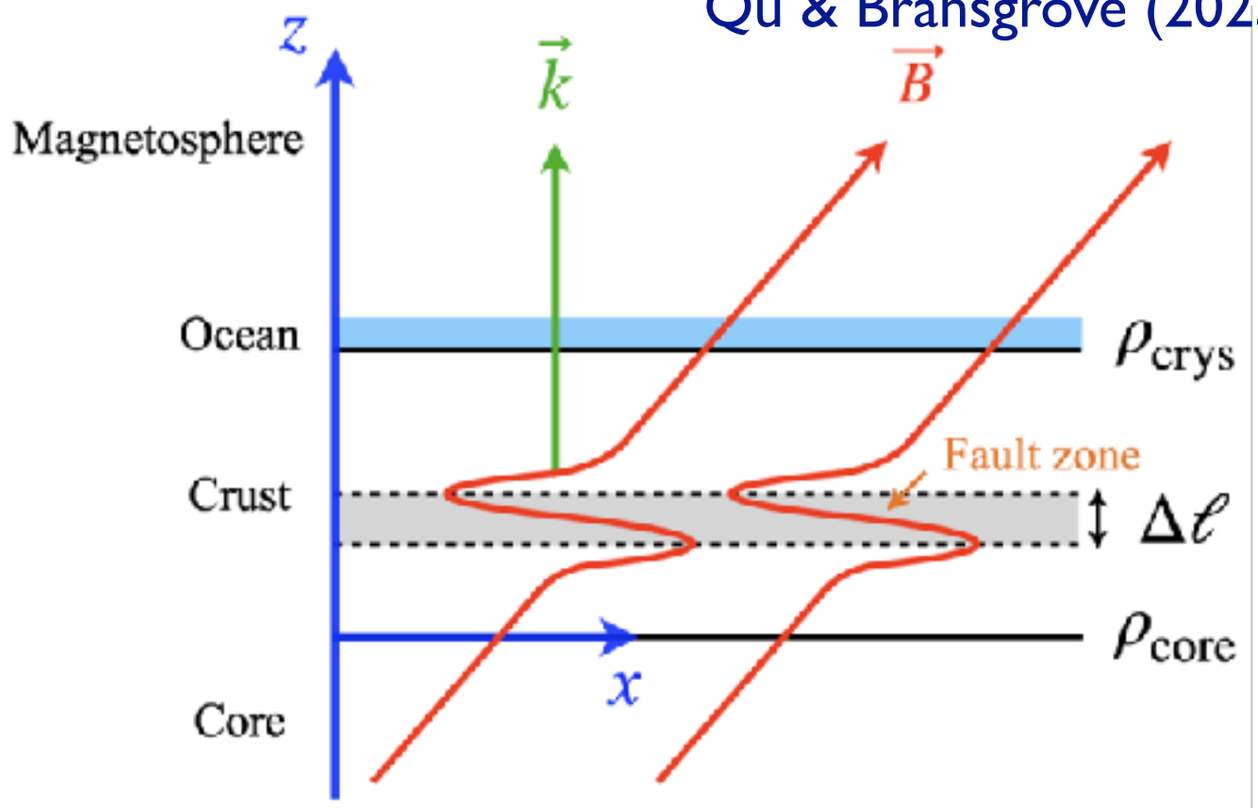
Realistic magnetar quakes!

L. Burnaz
(Caltech/Lyon)



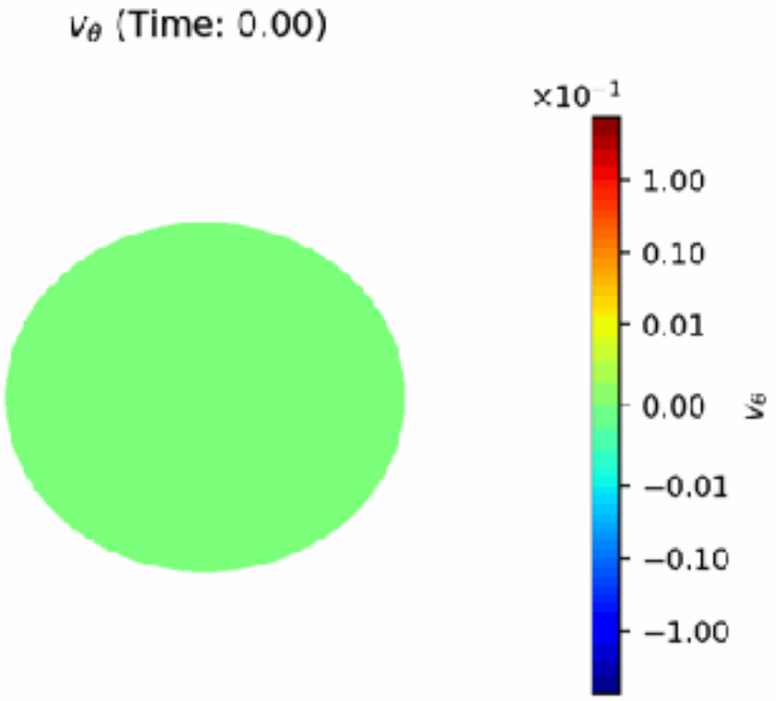
A.Bransgrove
(Princeton)

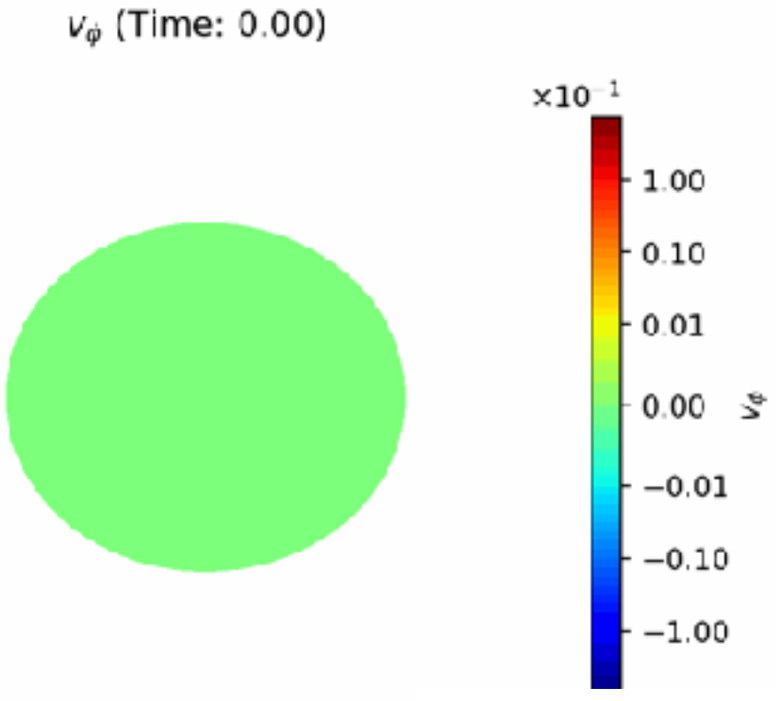
Qu & Bransgrove (2025)



Couple full crust model to magnetosphere

Bransgrove+ (2020), Qu & Bransgrove (2025)



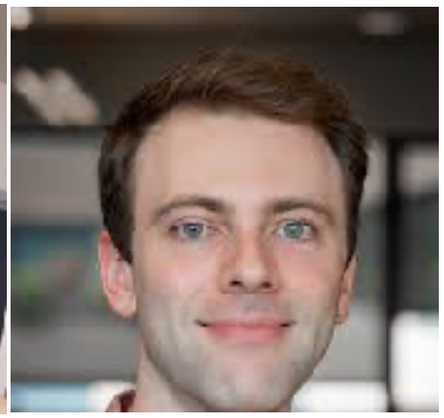


Surface motion of crust oscillation

Burnaz, ERM, Bransgrove (arXiv 2025)

Quakes spark blasts!

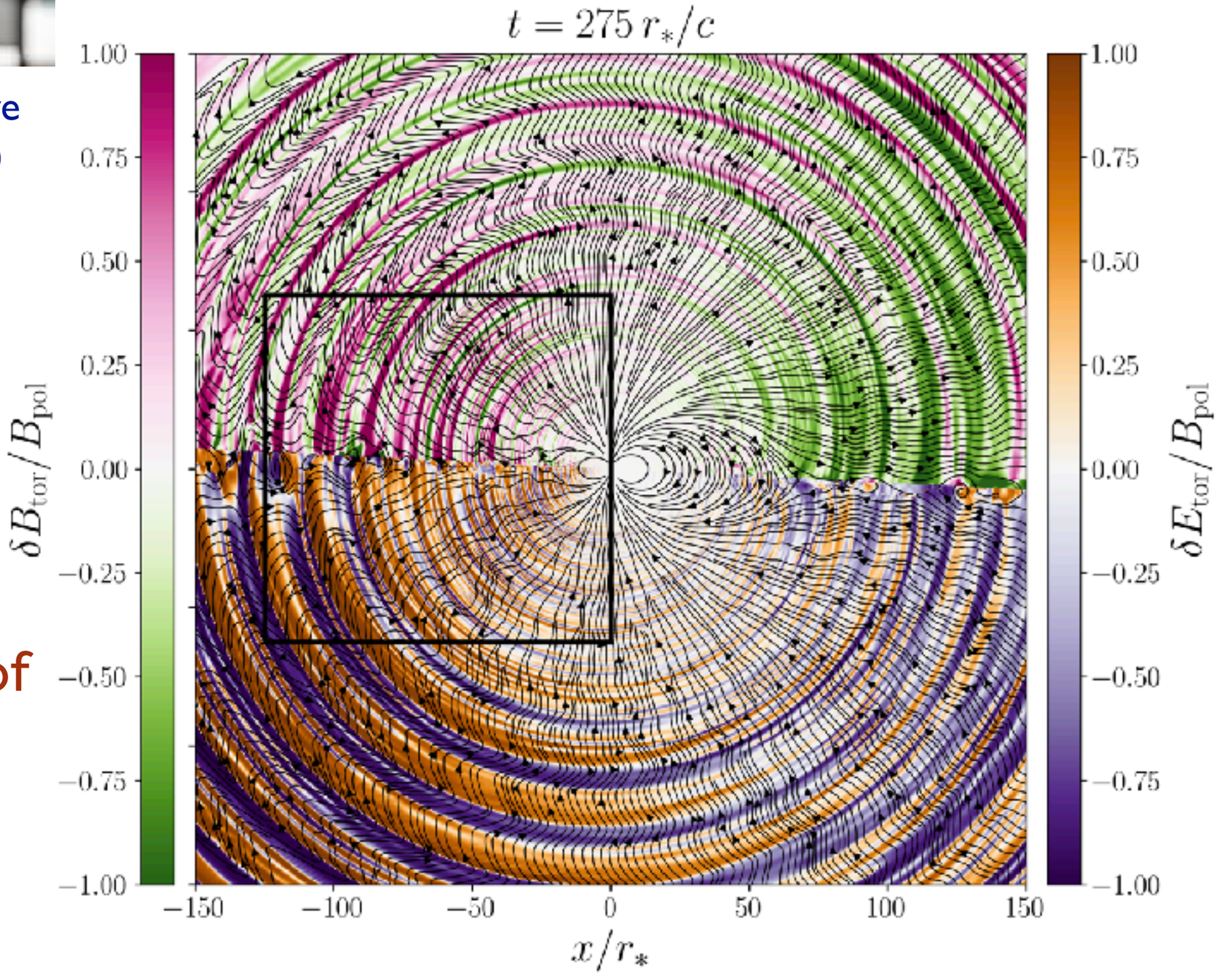
L. Burnaz
(Caltech/Lyon)



A.Bransgrove
(Princeton)

Series of fast magnetosonic and Alfven waves launched in the magnetosphere

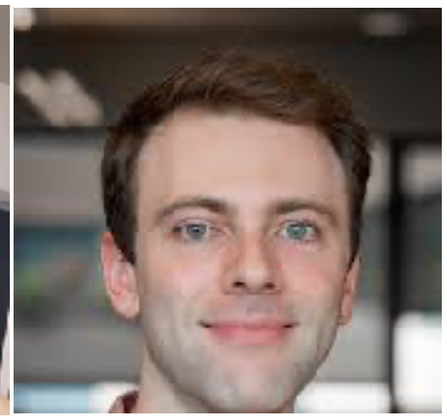
Cosmic symphony of monster shocks, nonlinear Alfven wave ejecta, reconnection



Burnaz, ERM, Bransgrove (arXiv 2025)

Oscillation imprints!

L. Burnaz
(Caltech/Lyon)



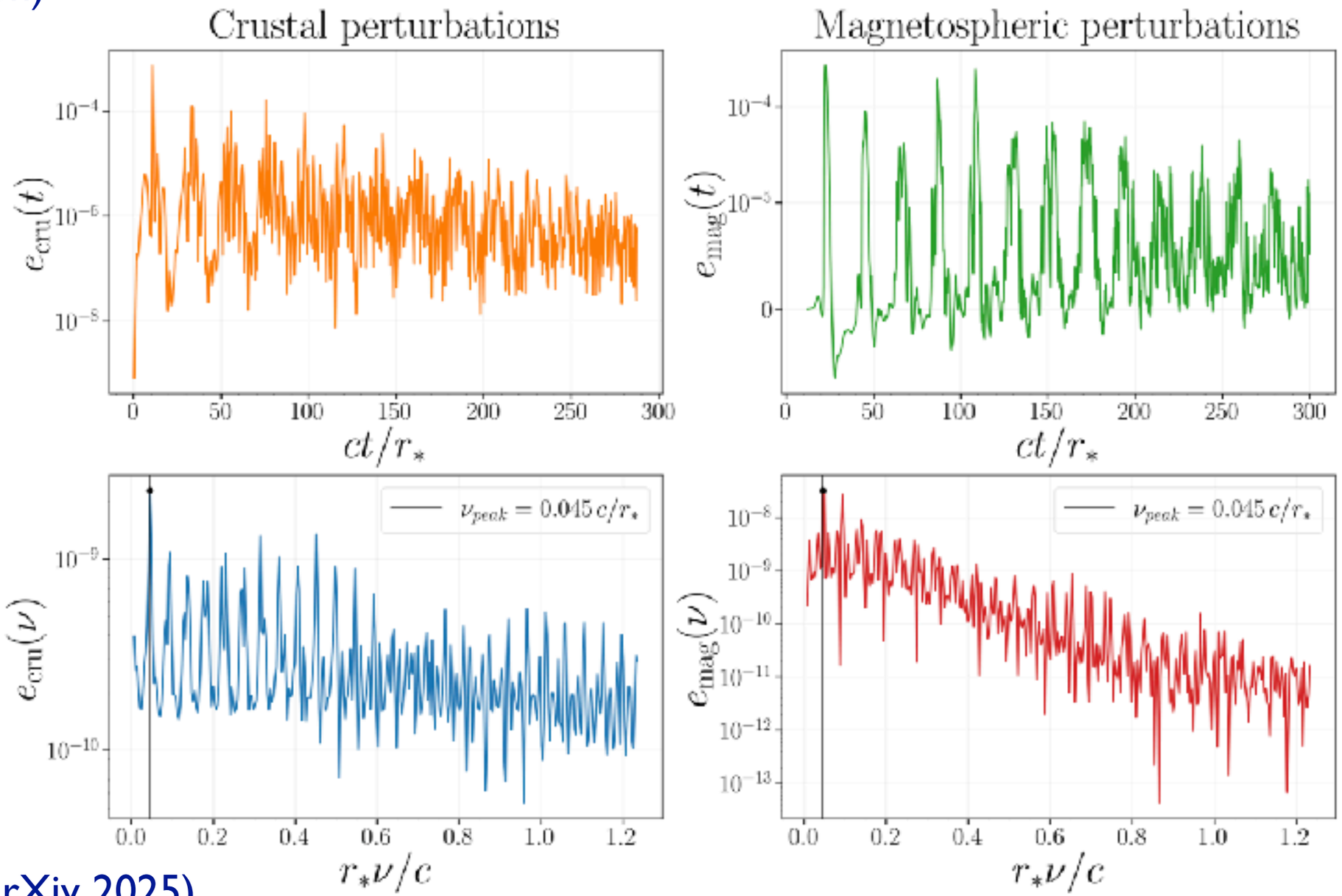
A.Bransgrove
(Princeton)

500 Hz signal consistent with crossing of crustal thickness for low mass magnetar!

Crust crossing time probes a combination of thickness and crustal velocity

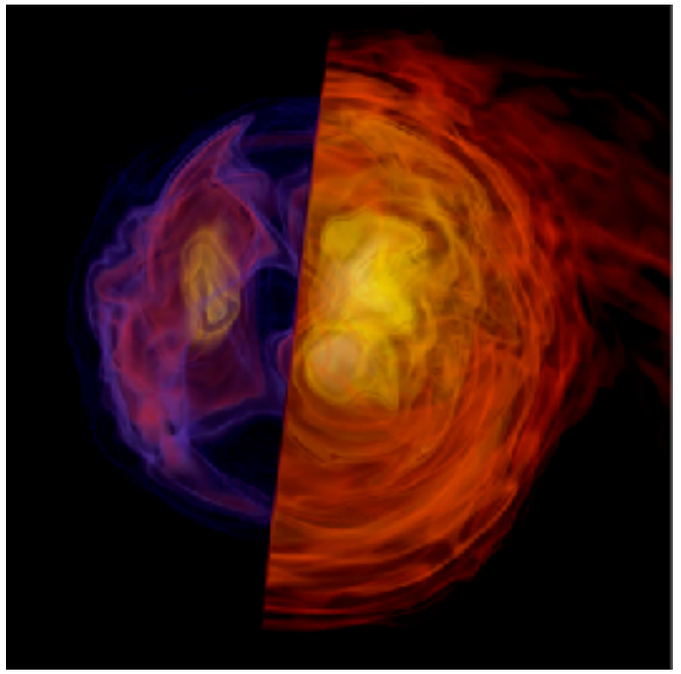
$$t_{\rm el} \simeq H/v_{\rm el}$$

$$\nu \simeq 1/2t_{\rm el}$$

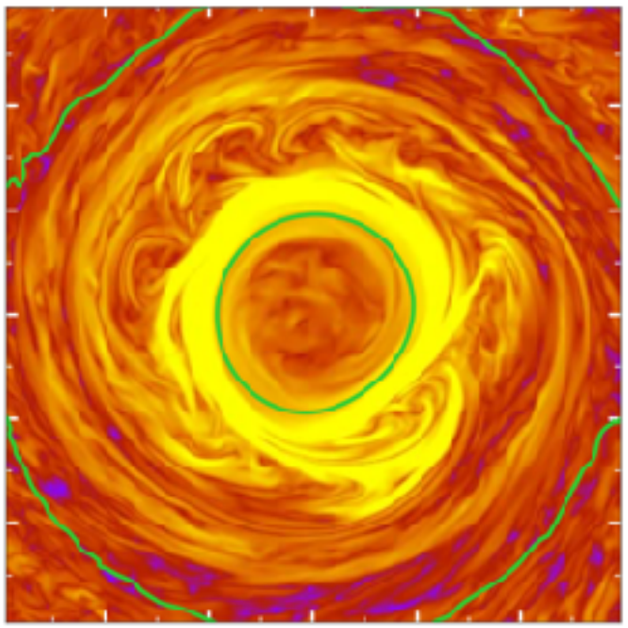


Burnaz, ERM, Bransgrove (arXiv 2025)

Key points

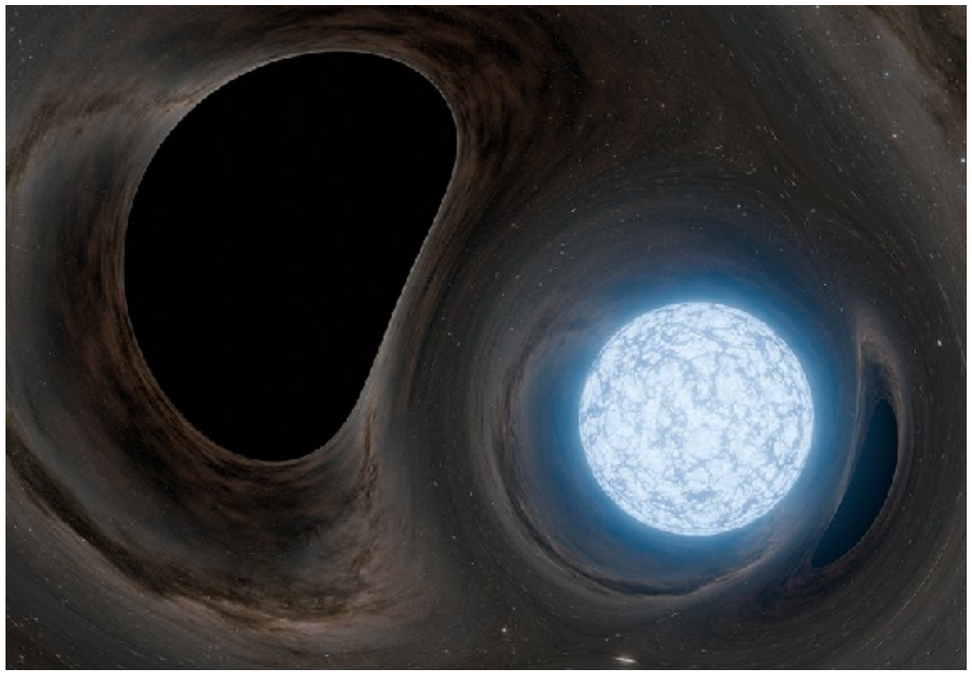


Neutron star mergers are exciting probes of hot and dense matter, even beyond the equation of state!

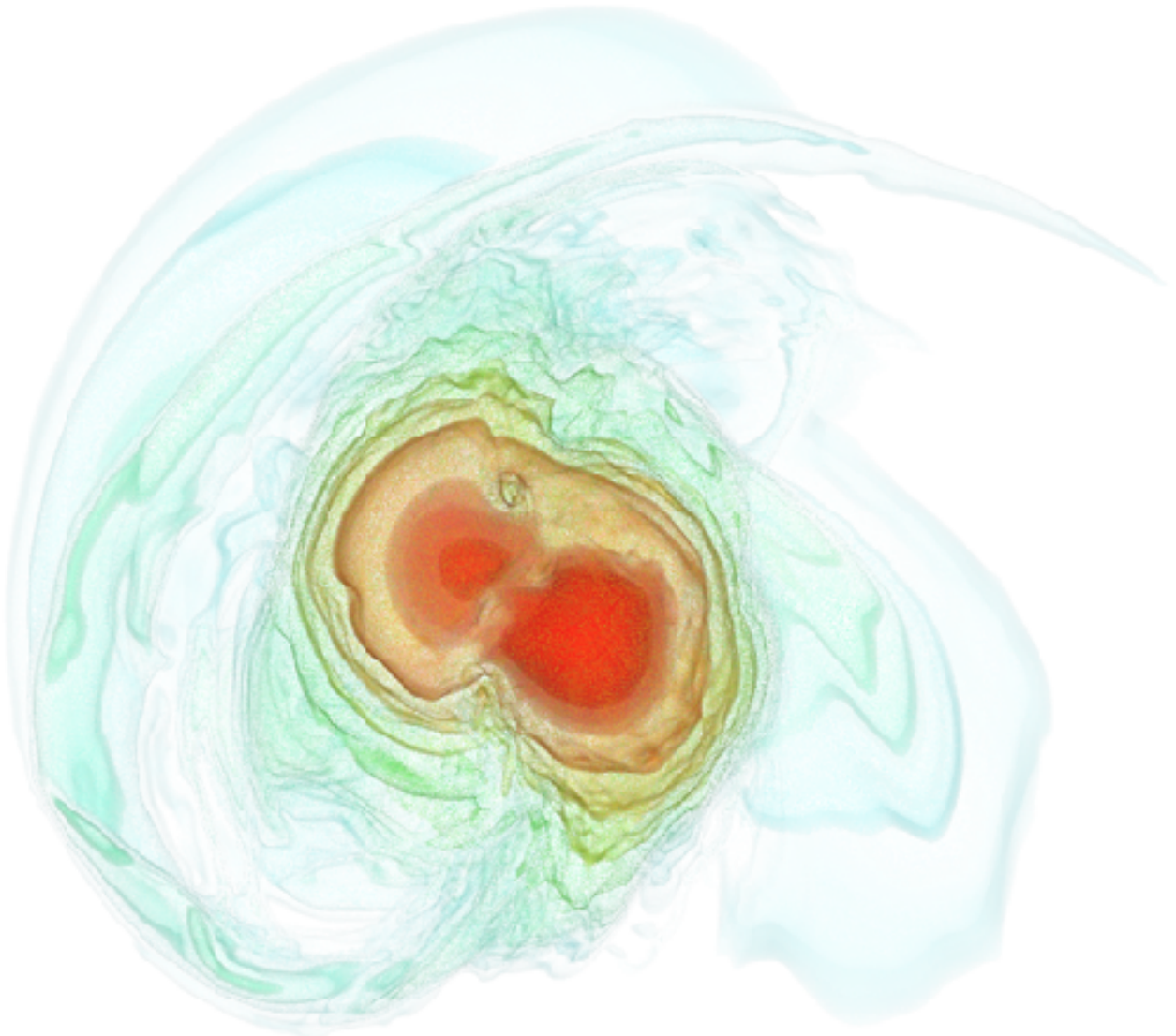


Magnetic field and plasma physics critical for understanding the secular evolution of the remnant, outflows and jets!

Radio and gamma-ray probes are promising future avenues to potentially constrain crustal physics relevant for the merger, and beyond.



Thank you!



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