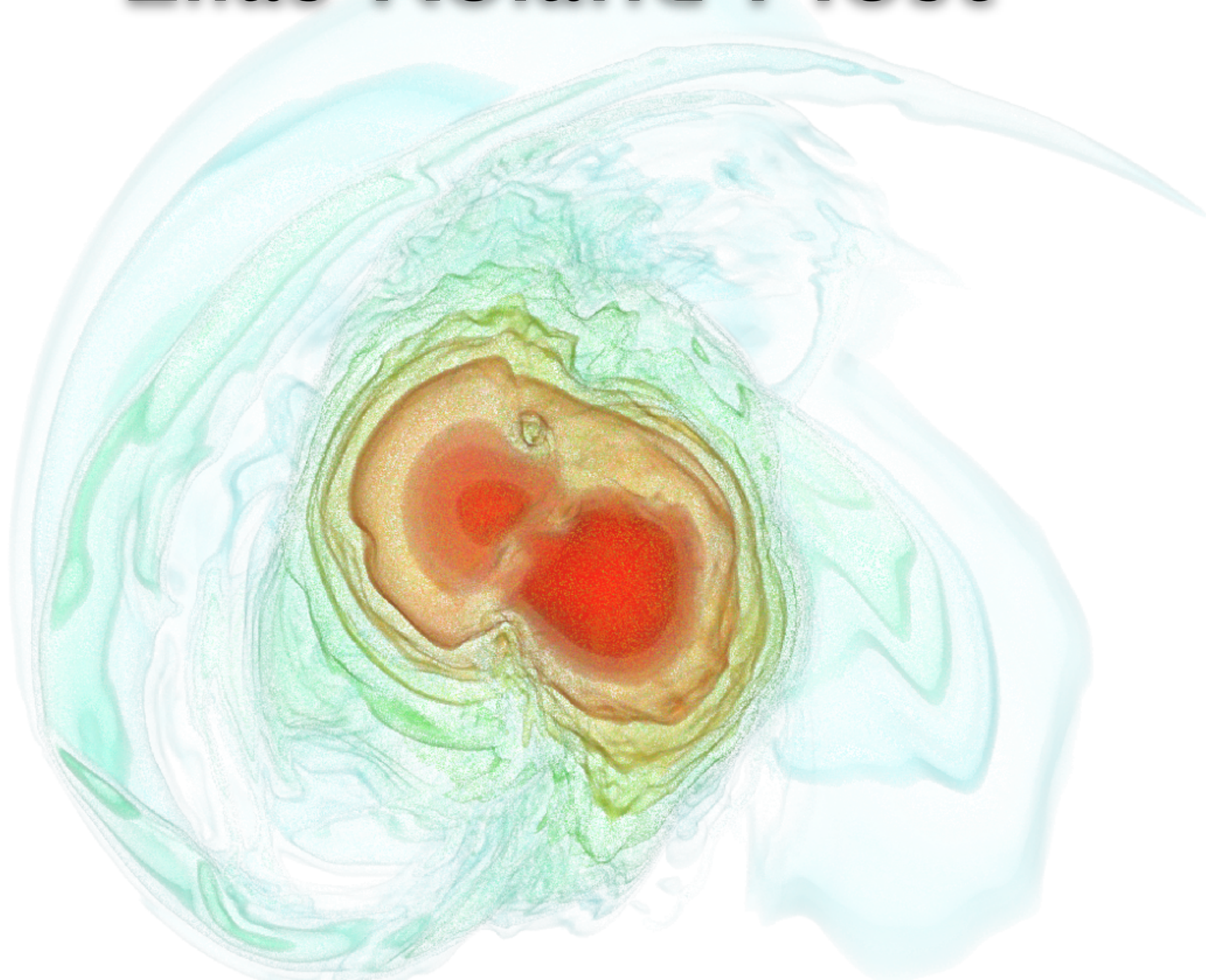
# Kilohertz QPOs in short gamma-ray bursts: A hypermassive neutron star origin?

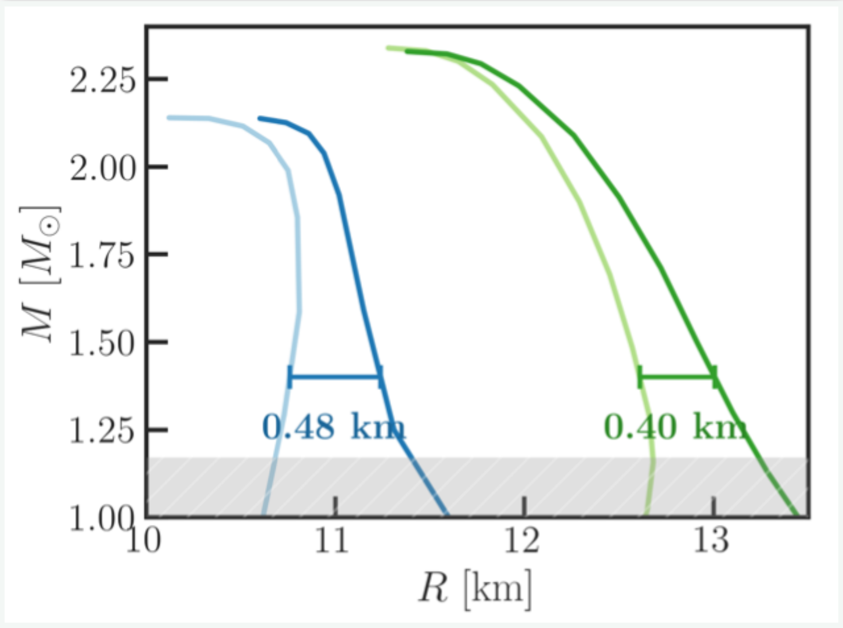
Elias Roland Most



Caltech

TAPIR

# Outline




## Tidal deformability doppelgängers

Raithel & **ERM** (PRL 2023; PRD 2023)

*see also talks by Legred and Read*

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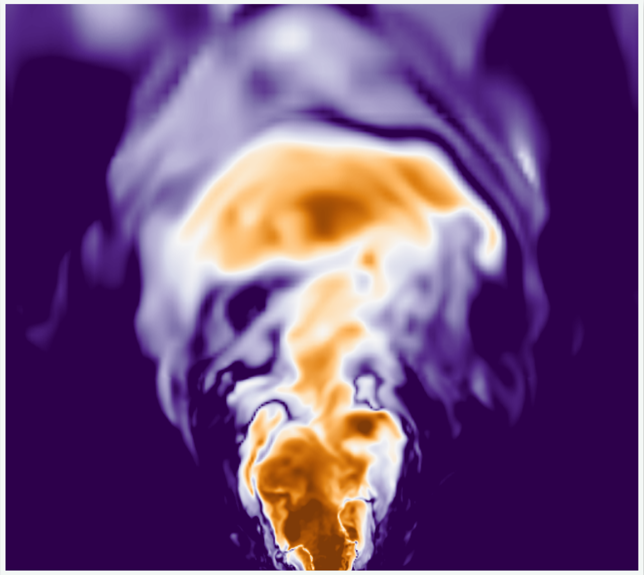
**ERM** & Quataert (ApJL 2023)



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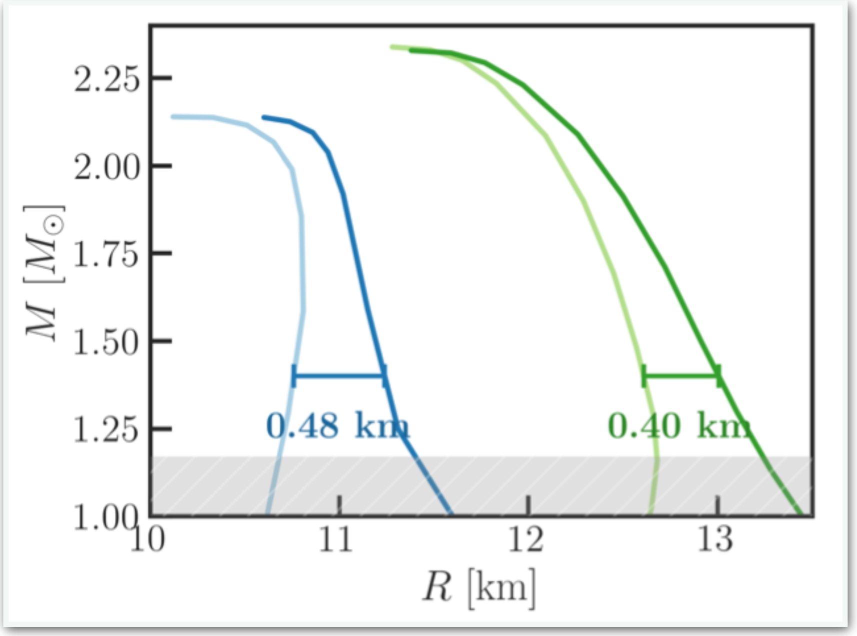


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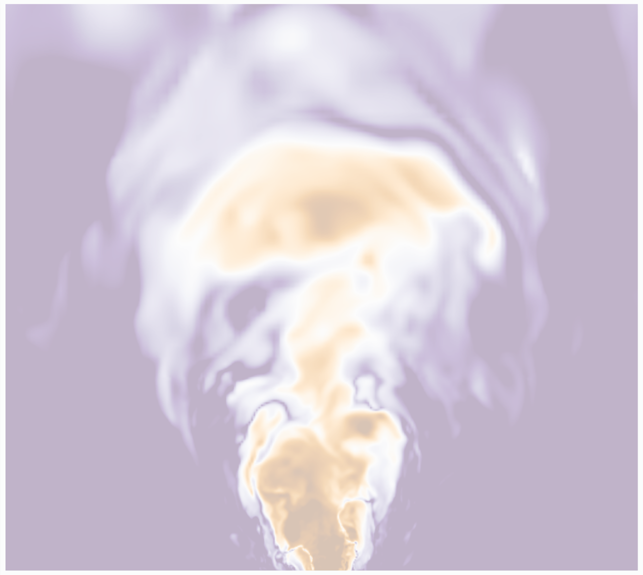
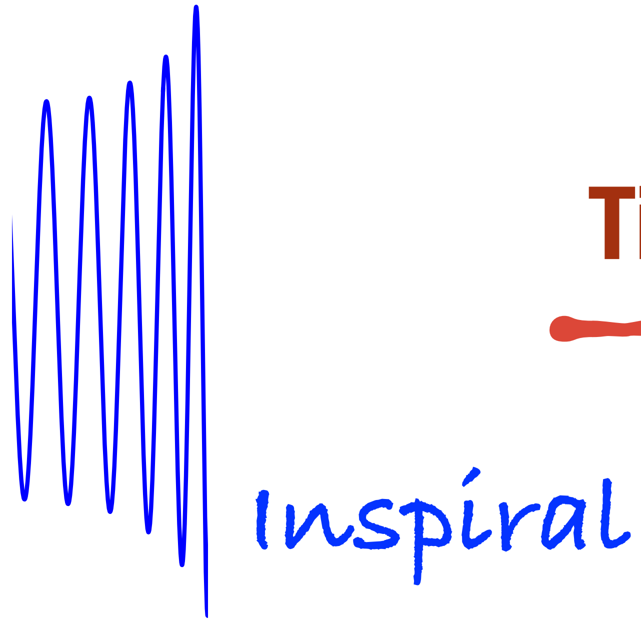
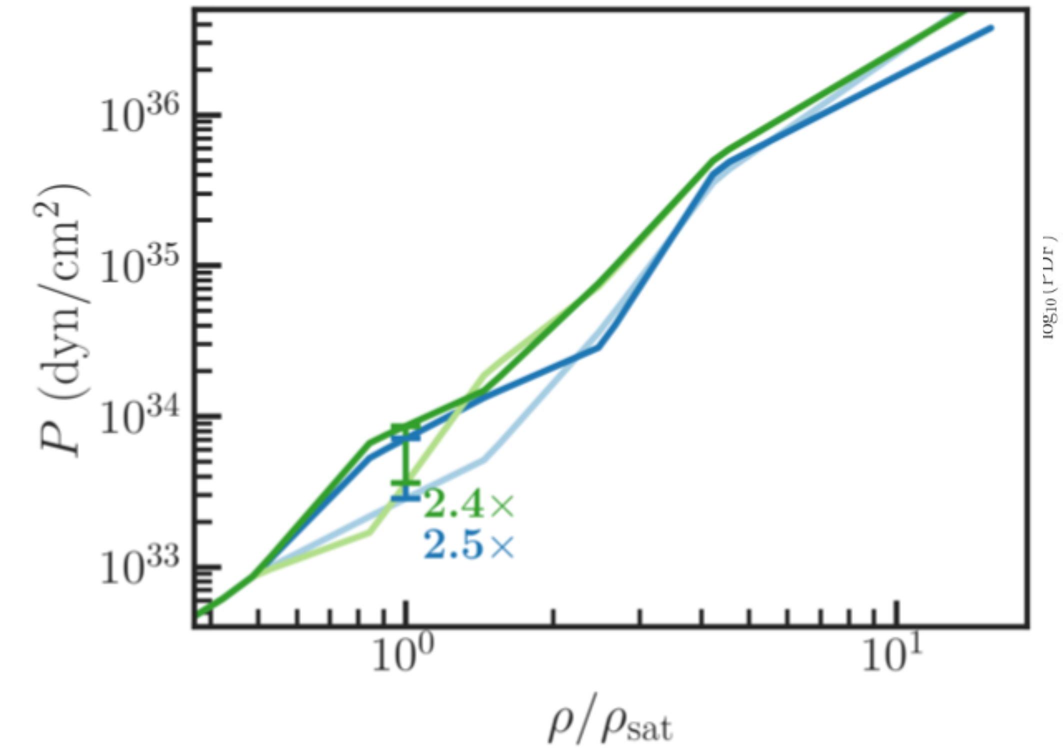


# Gravitational waves




Tidal deformability $\tilde{\Lambda}$

# Equation of state




Raithel & ERM (PRL 2023)

# Gravitational waves

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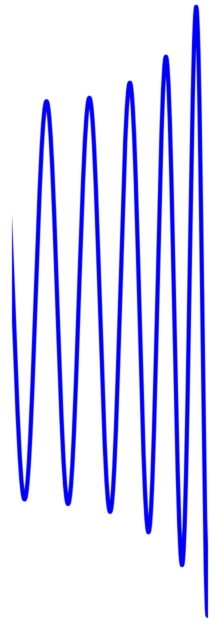
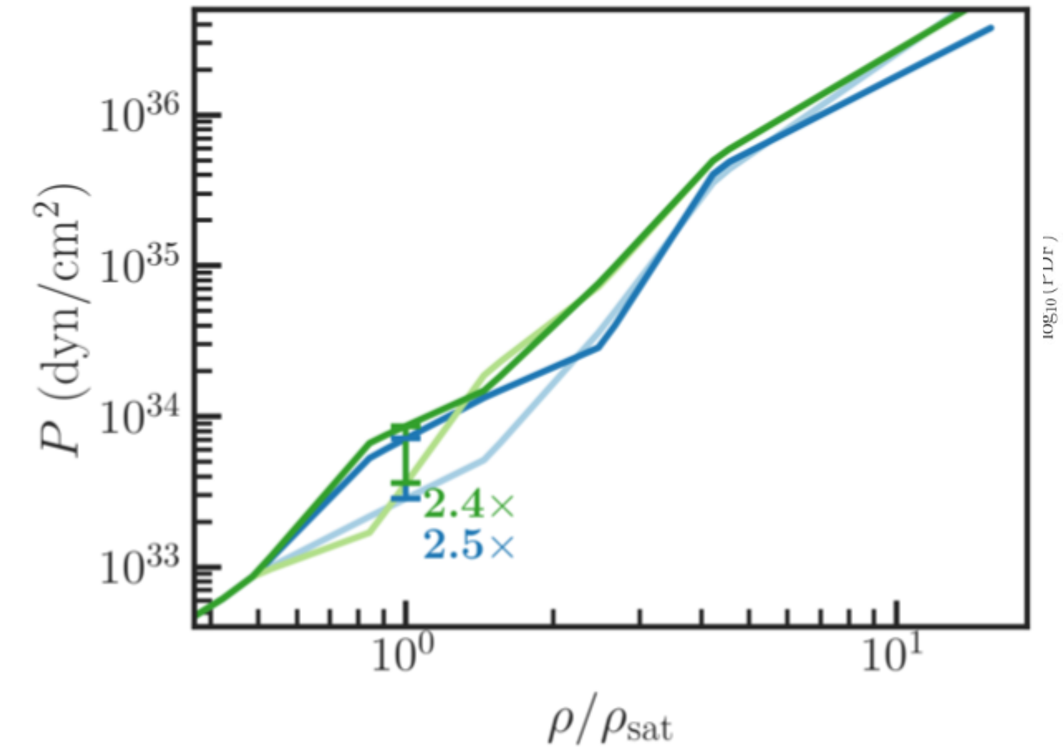
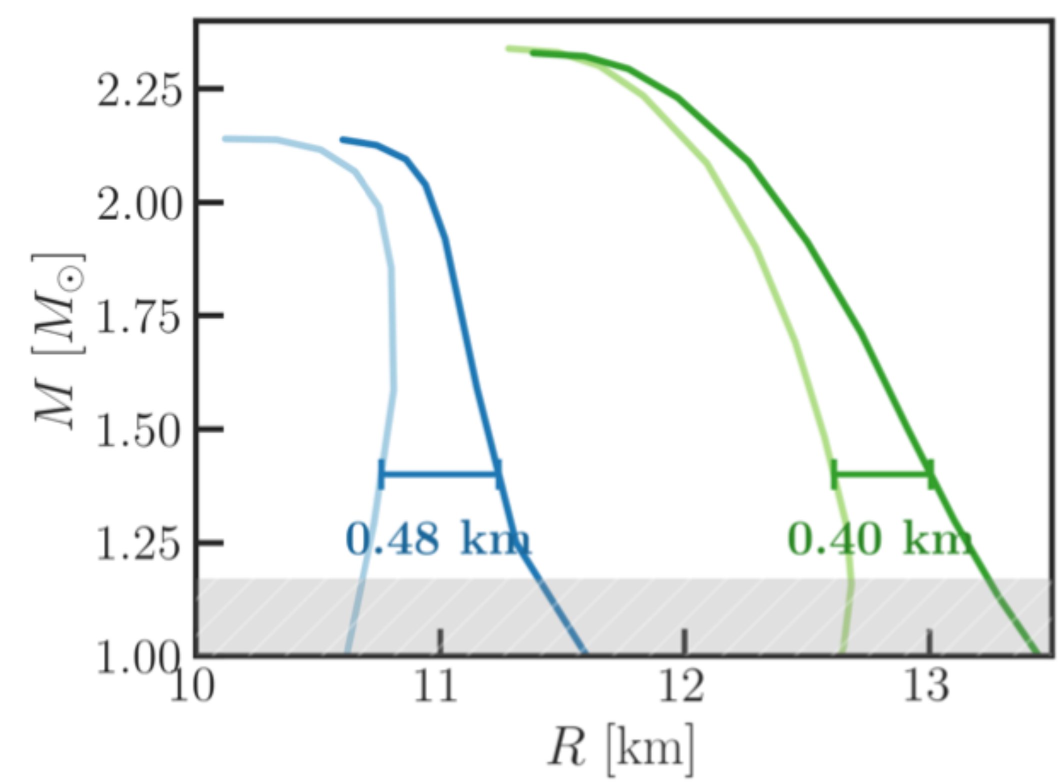


Inspiral

**Tidal deformability $\tilde{\Lambda}$**




Raithel & ERM (PRL 2023)

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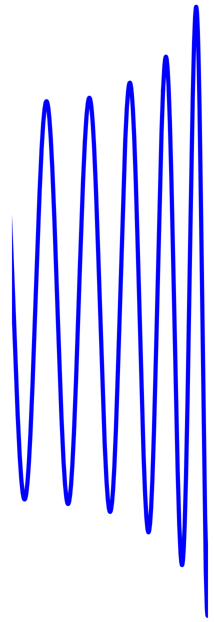

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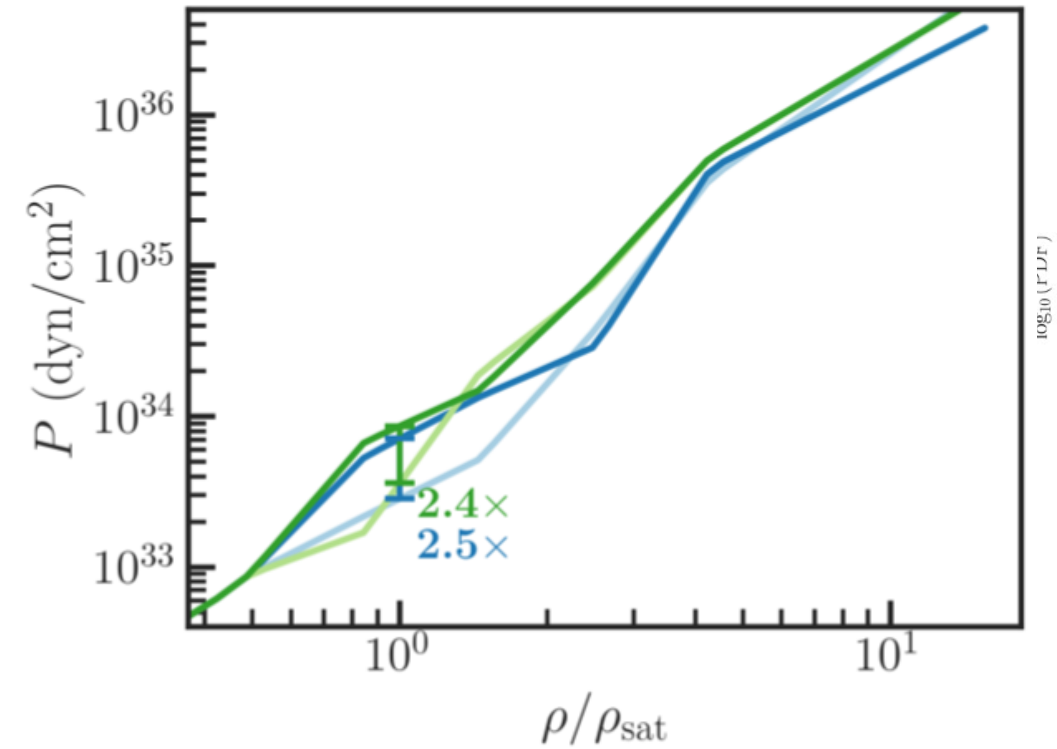
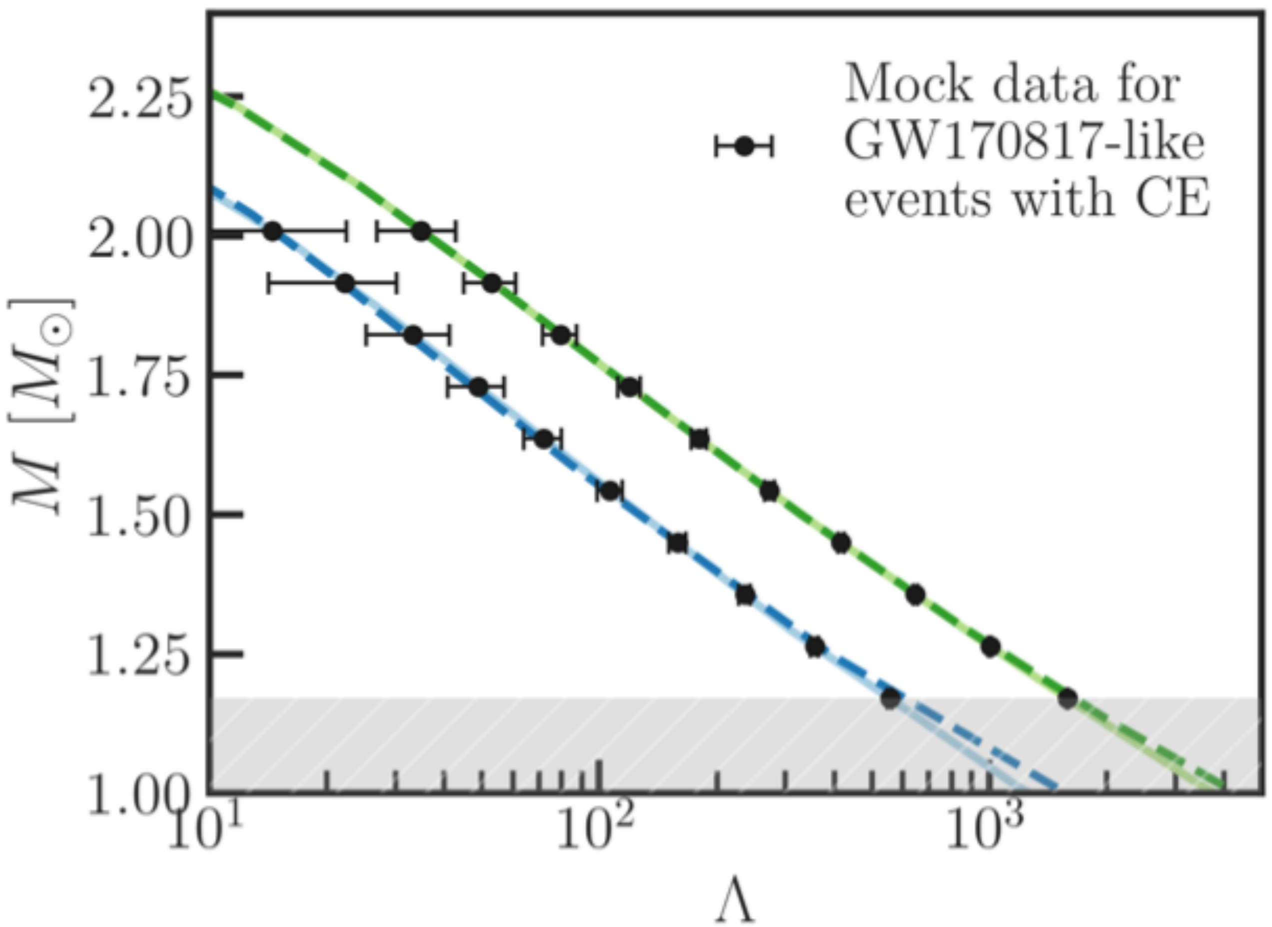
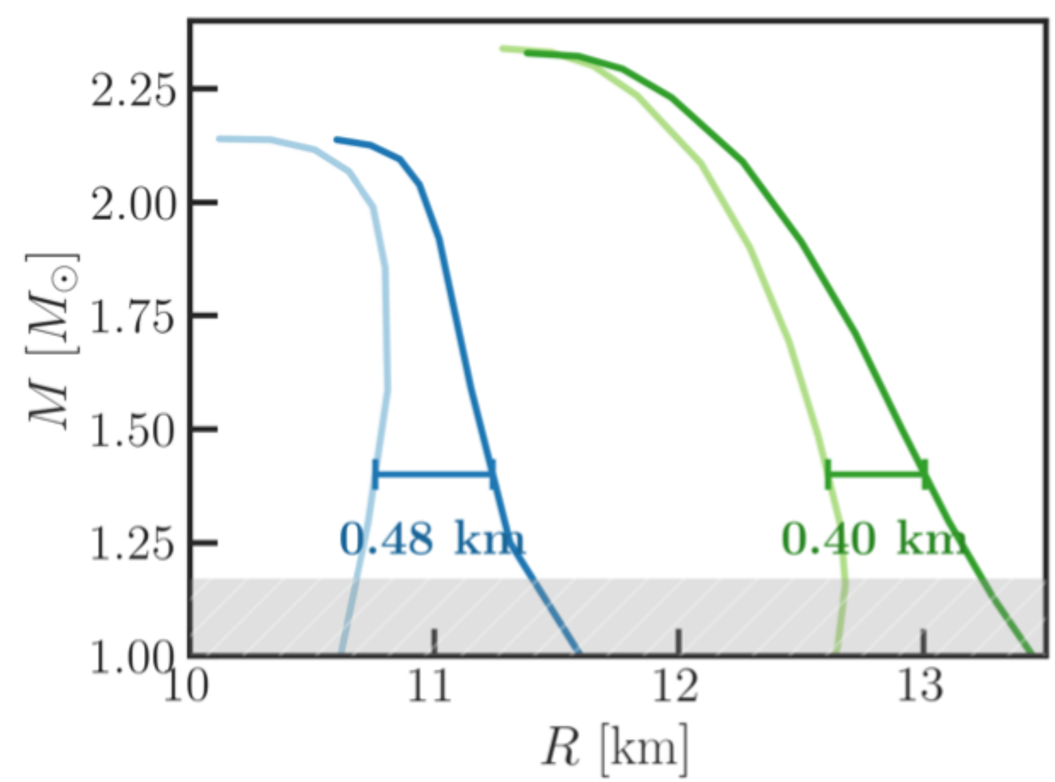



What a gravitational wave detector sees...




Raithel & ERM (PRL 2023)

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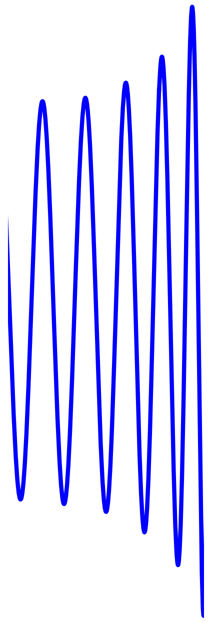

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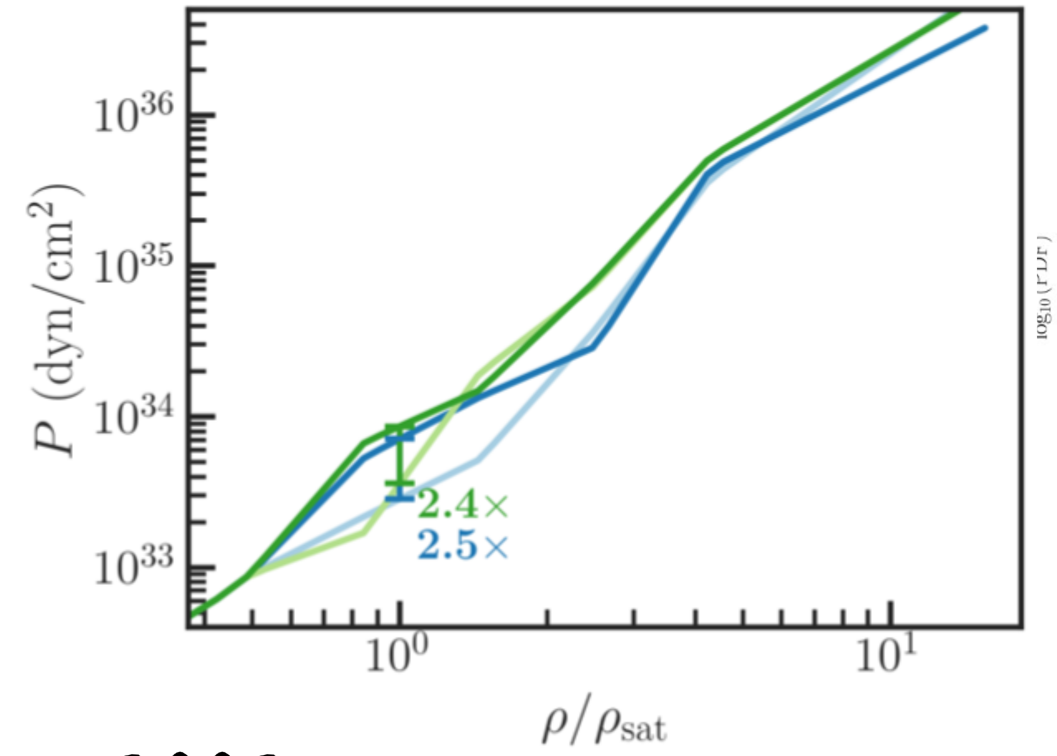


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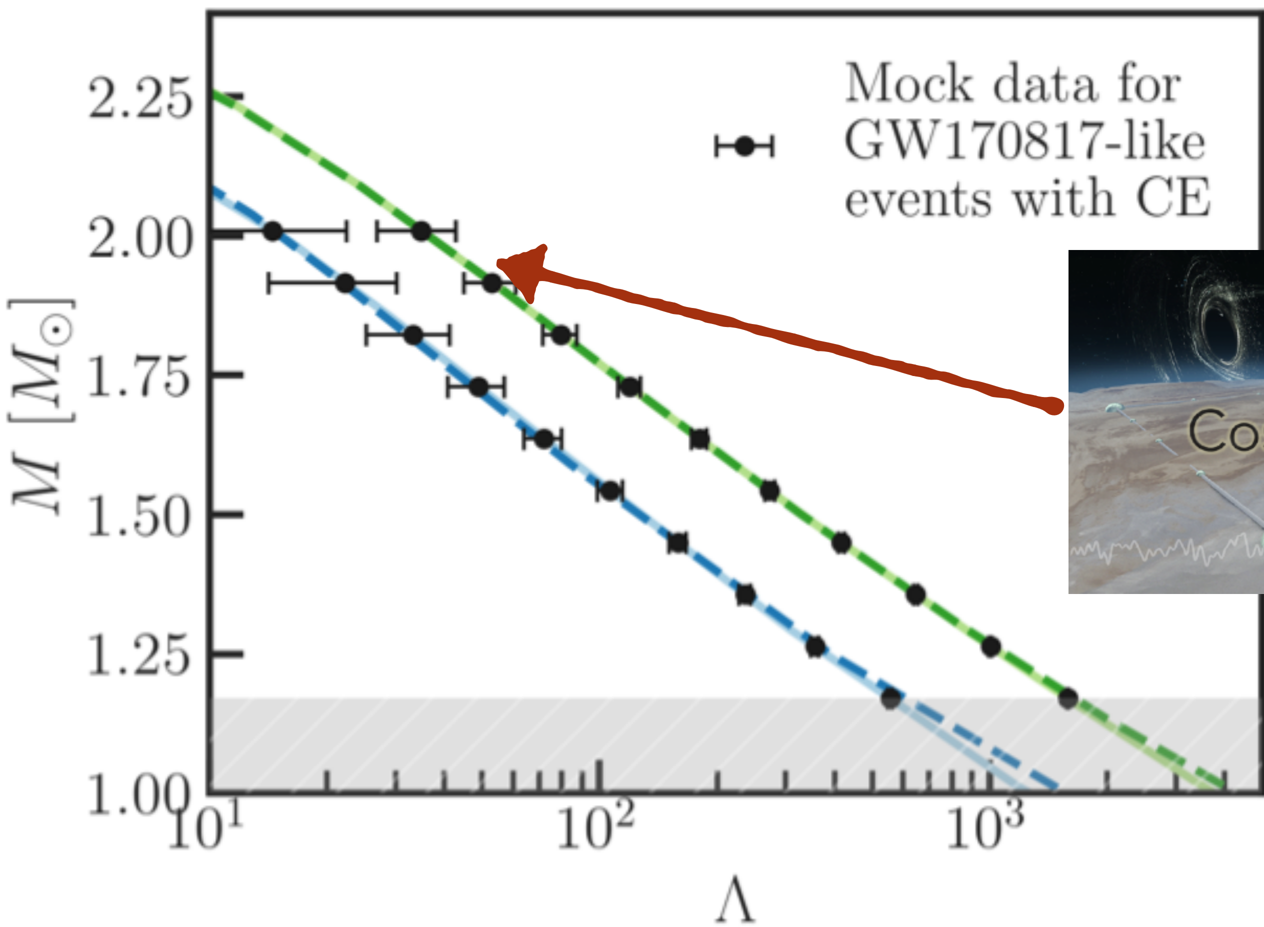
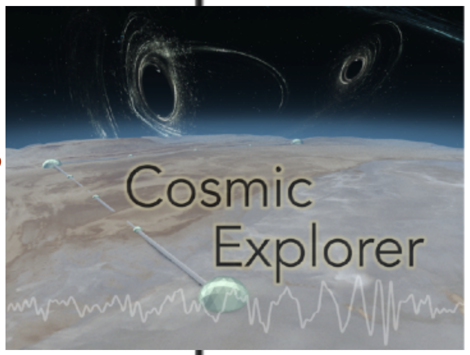
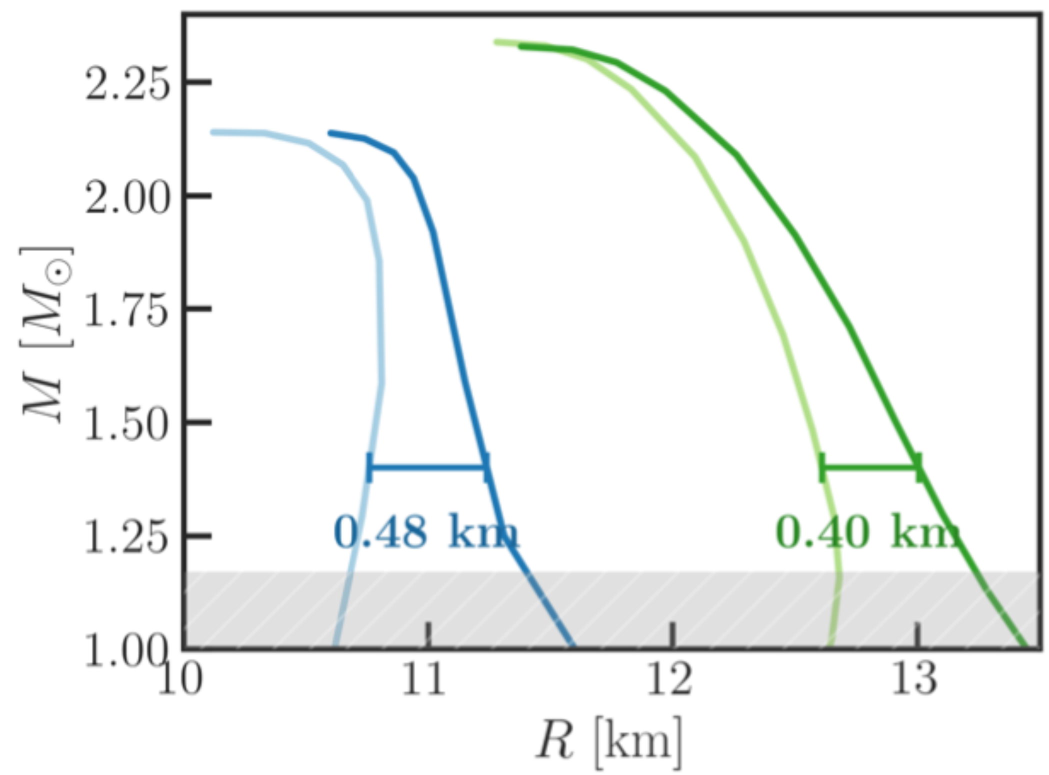
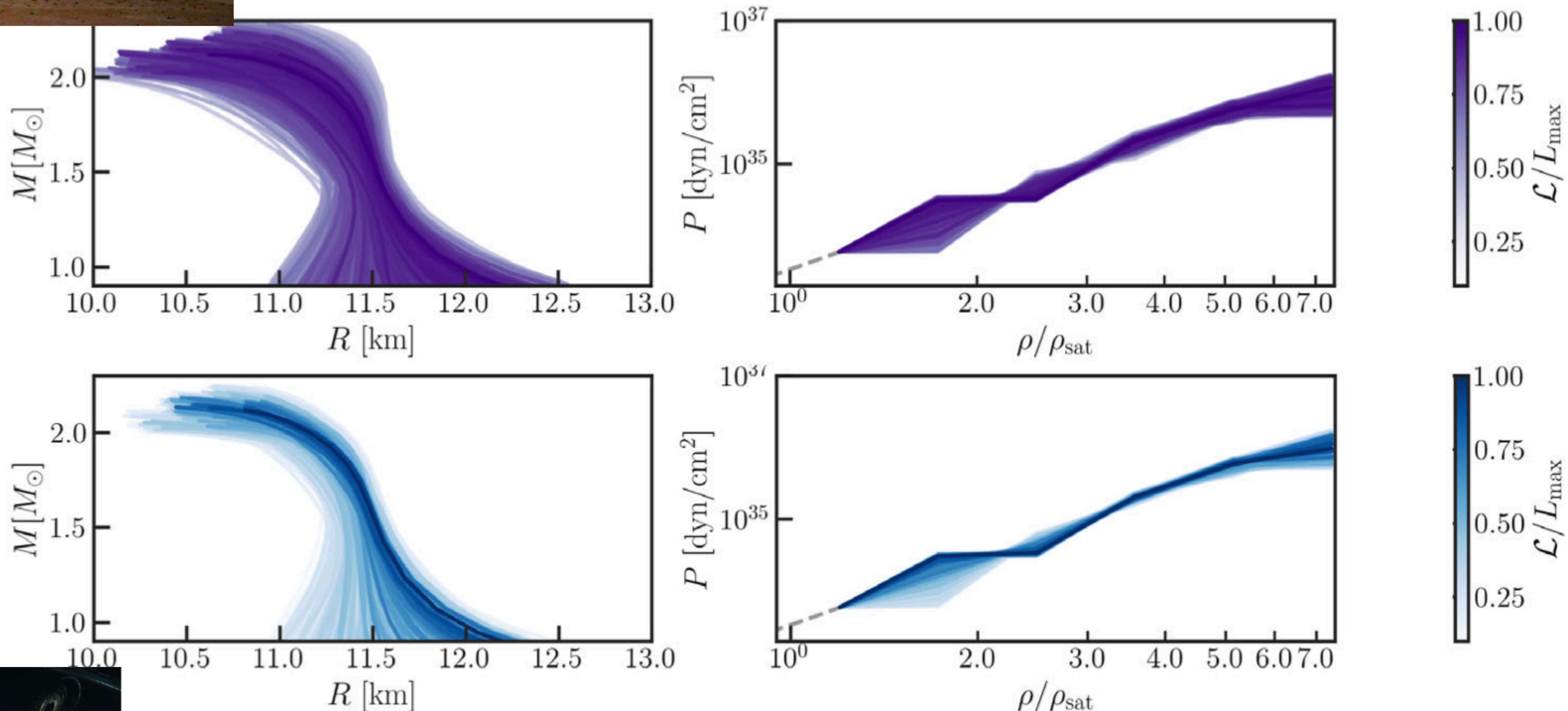


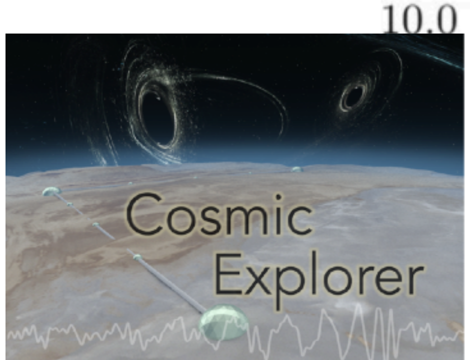




Raithel & ERM (PRL 2023)

# What effect can this have?

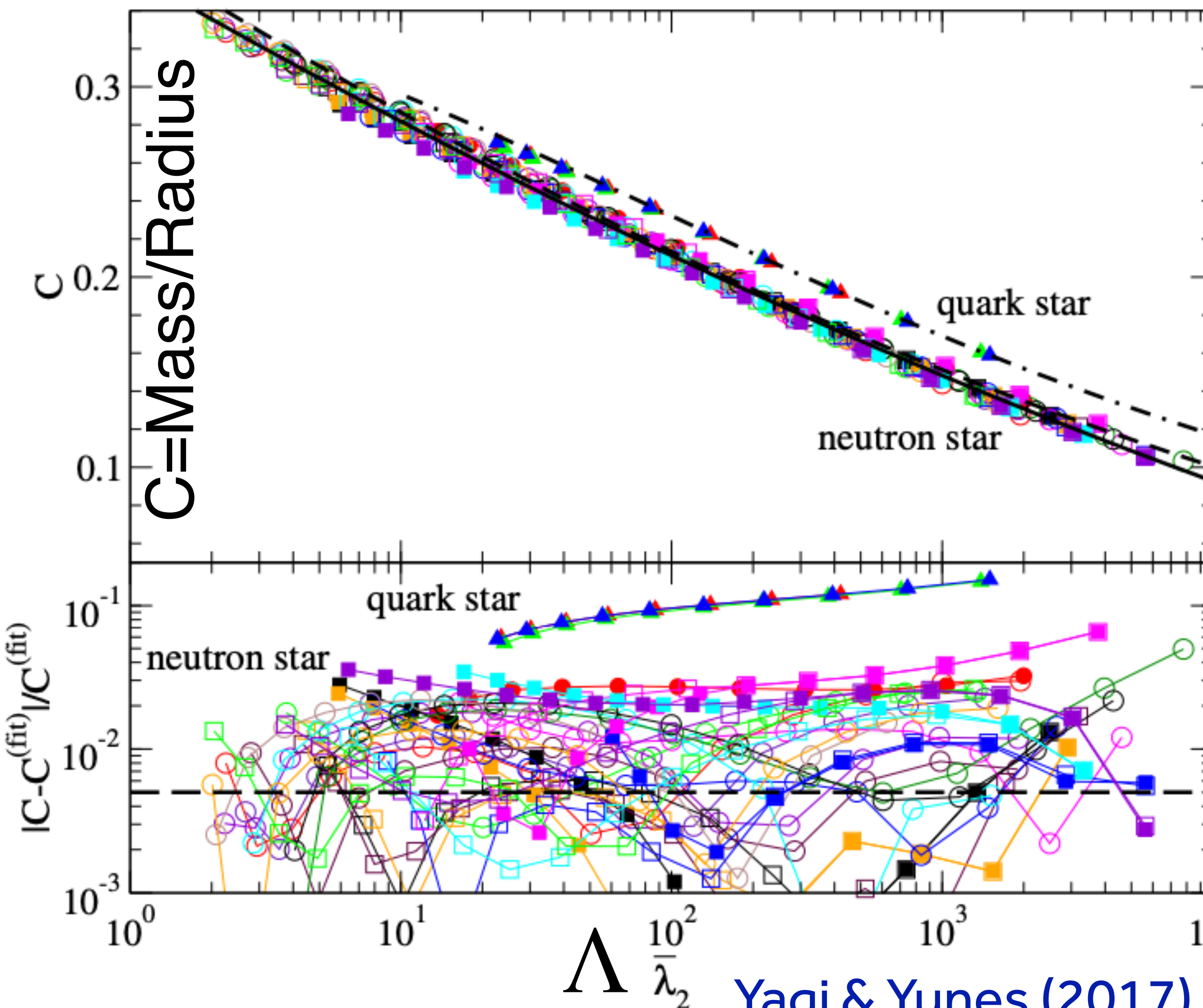




Raithel & ERM (PRL 2023)

# Tidal deformability

Putting this into context:

Relating tidal deformabilities, $\Lambda$, to neutron star compactness, $C = M/R$, is only quasi-universal!




Yagi & Yunes (2017)
see also Maselli+(2013)

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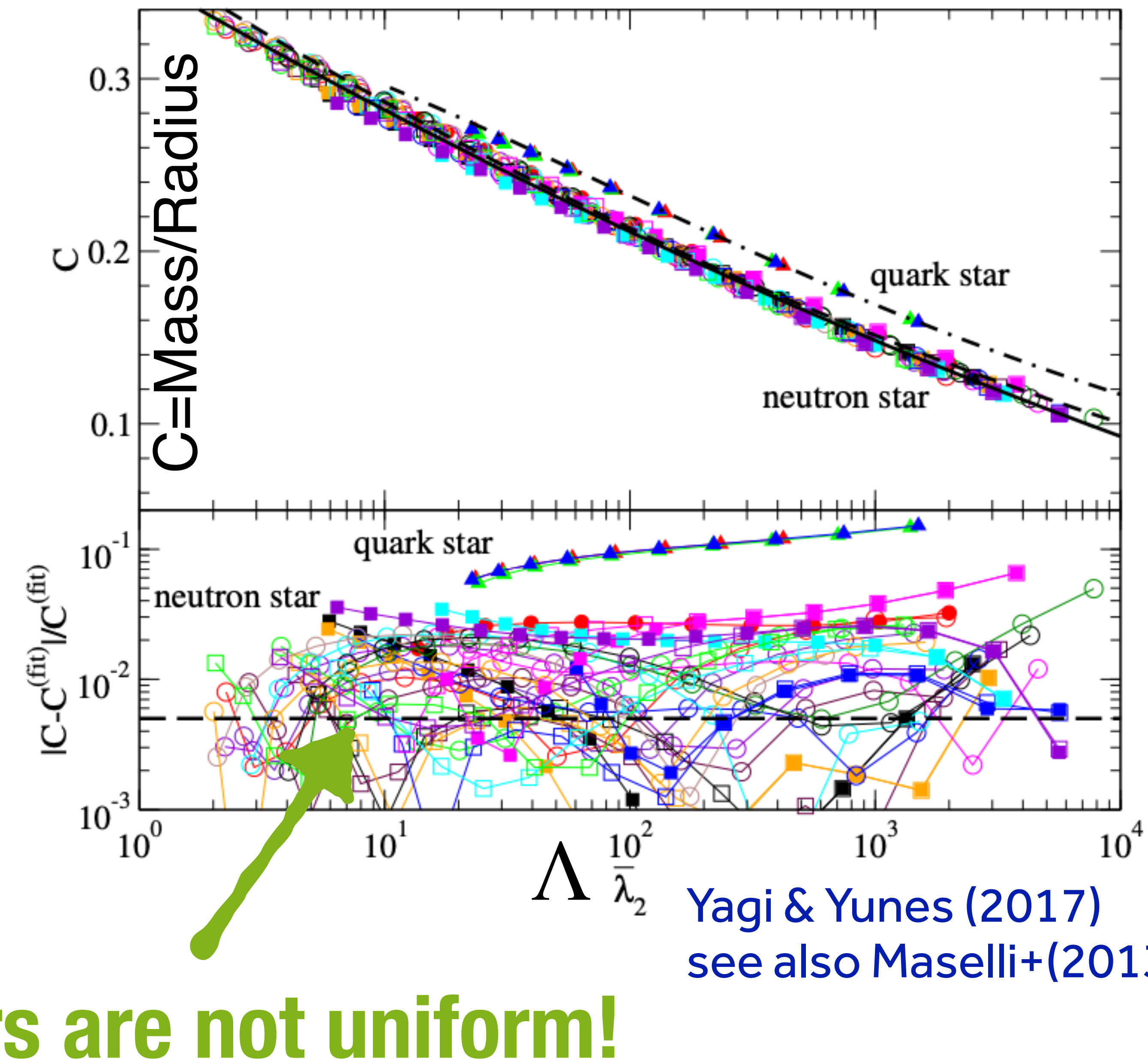


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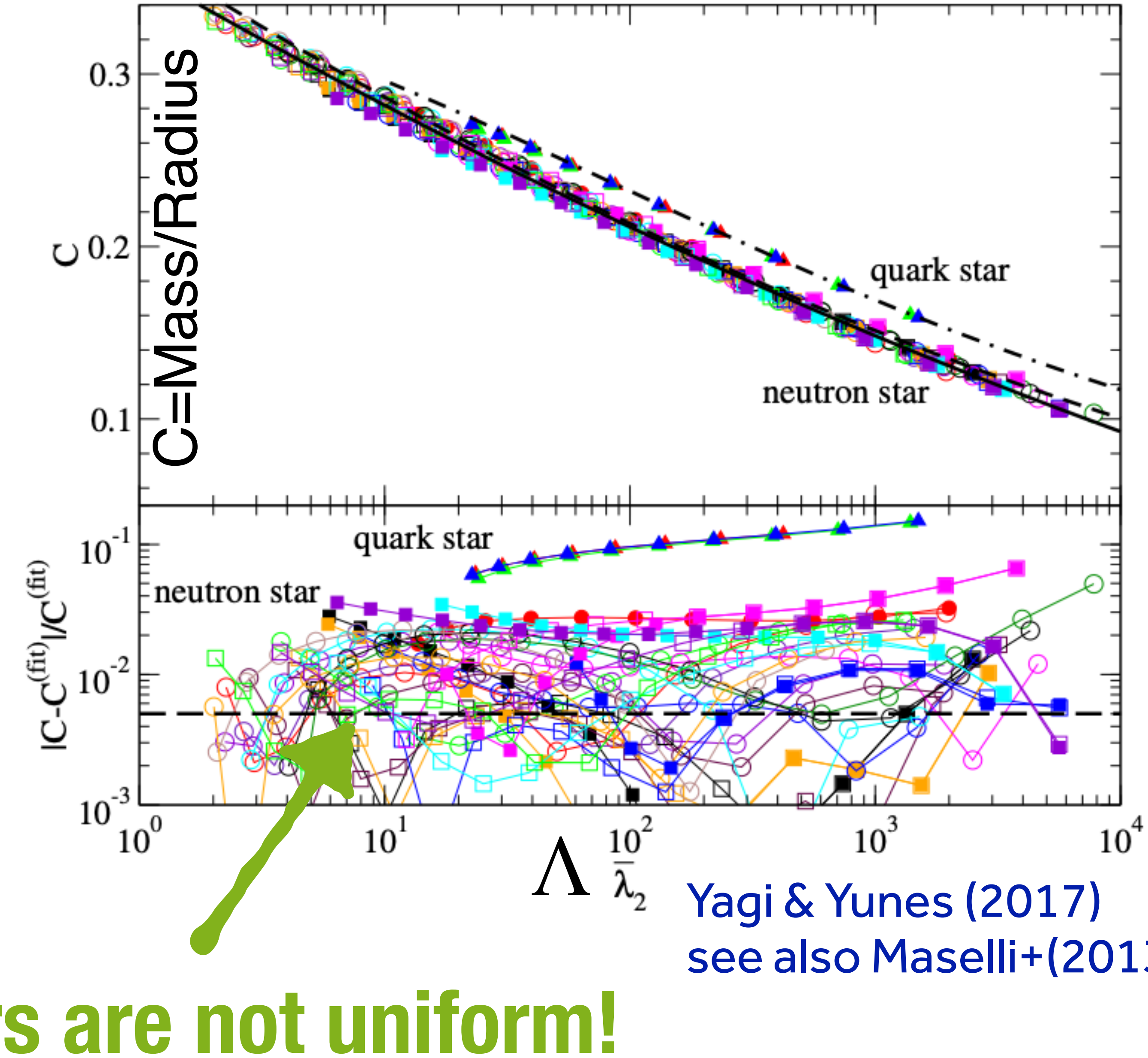



Yagi & Yunes (2017)
see also Maselli+(2013)

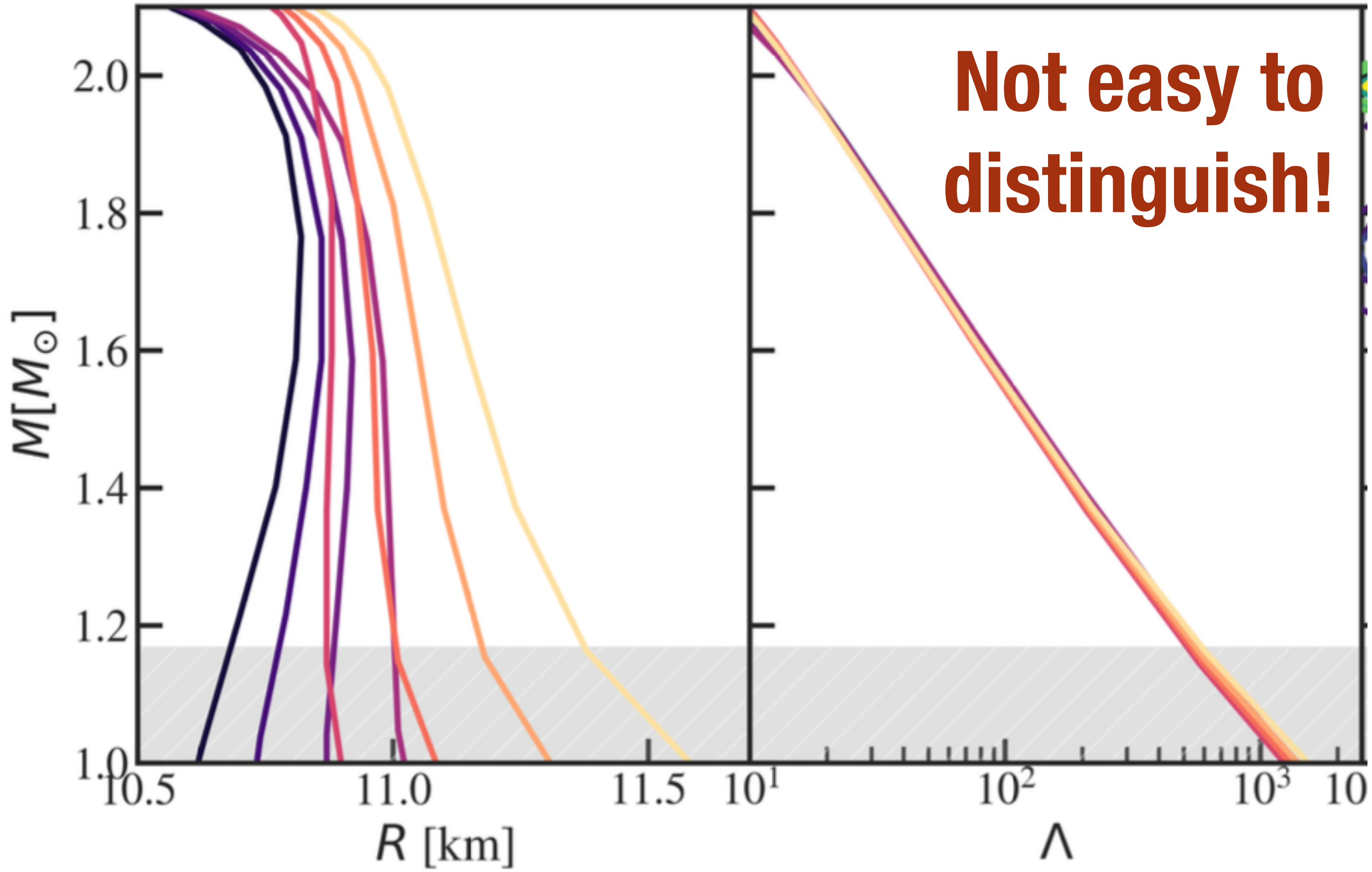
**How does the family of EoS look like that maximizes the difference in $C$, while being nearly identical in $\Lambda$?**

# Tidal deformability

What is a doppelgänger?

Image credit: Guardian

**Tidal deformability dopplergängers**




Raithel & ERM (PRD 2023)

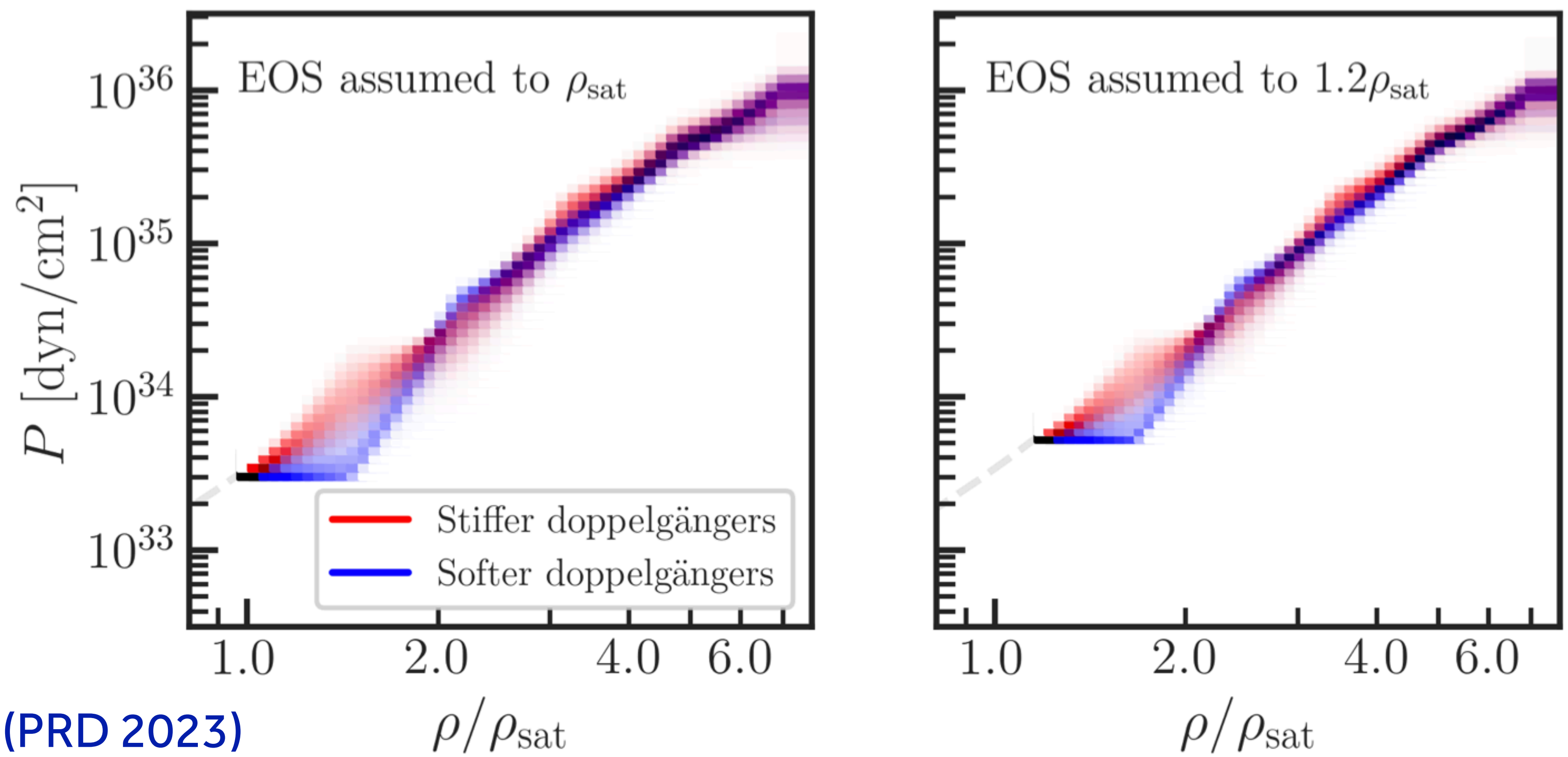
**How does the family of EoS look like that maximizes the difference in $C$, while being nearly identical in $\Lambda$?**

# Low-density phase transitions

What produces Doppelgängers?

Studied a large sample drawn from > 1 Mio EoS models!

Pressure



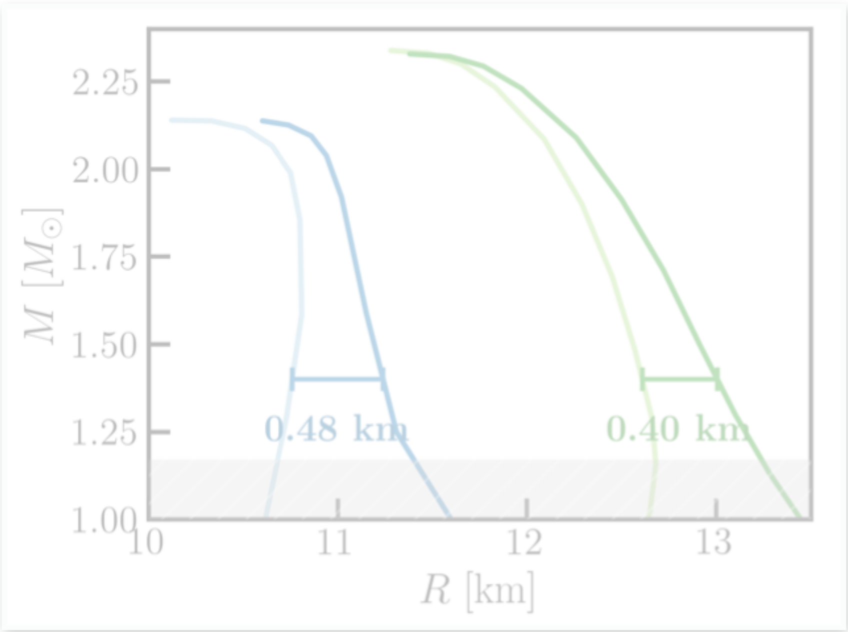

Raithel & ERM (PRD 2023)

Density Density

**Dopplergängers are the result of low density phase transitions!**

Check out Raithel & ERM (PRL2023; PRD 2023) for more details.

# Outline




## Tidal deformability doppelgängers

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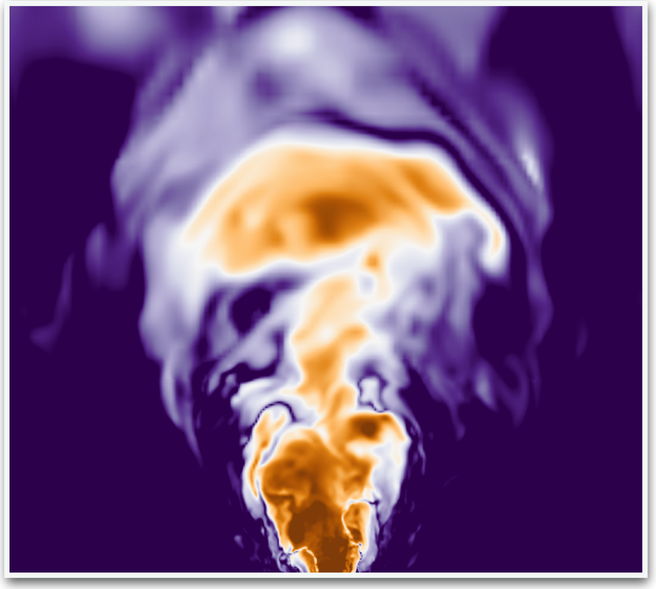
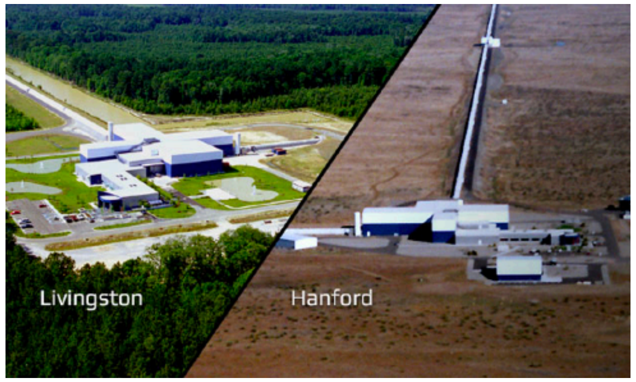
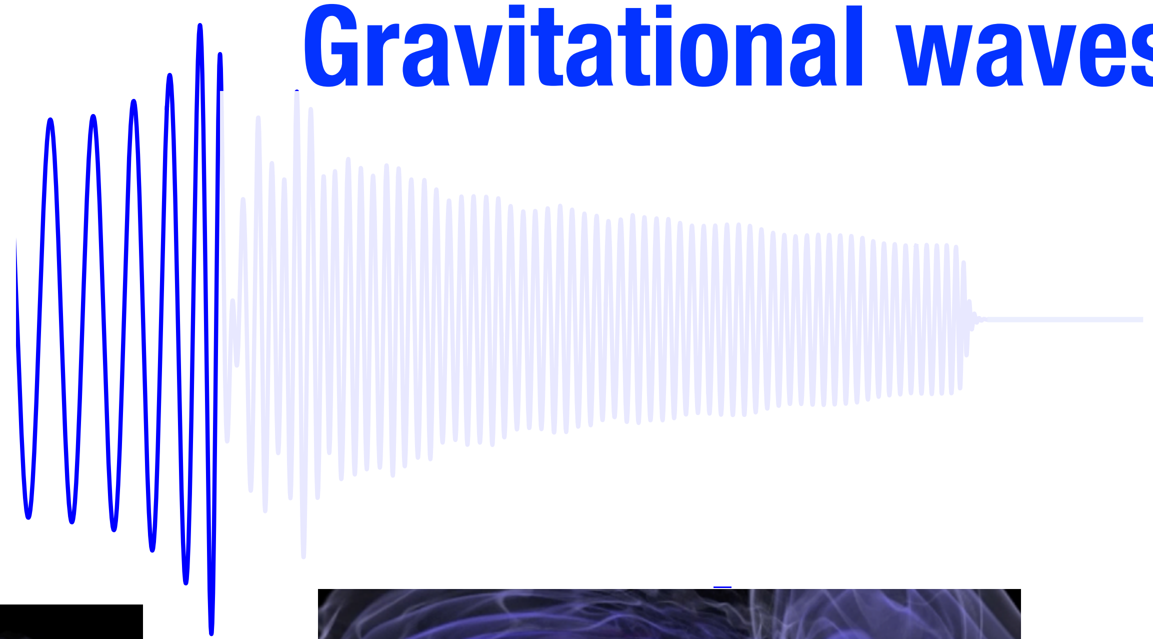


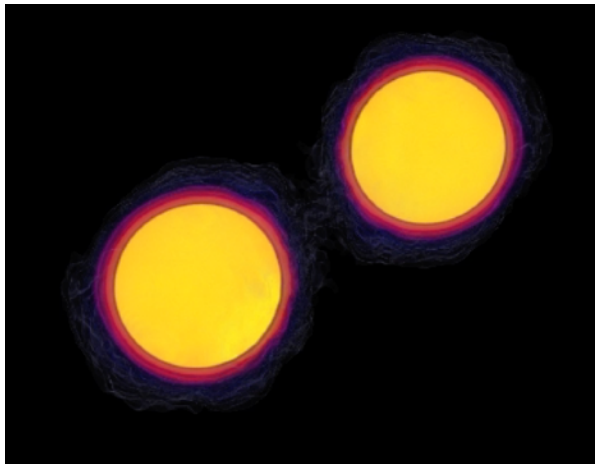
# The final fate of a neutron star binary

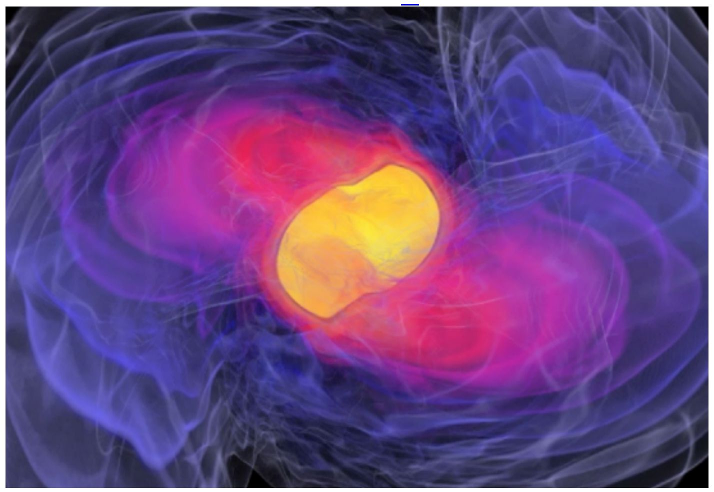
## Gravitational waves

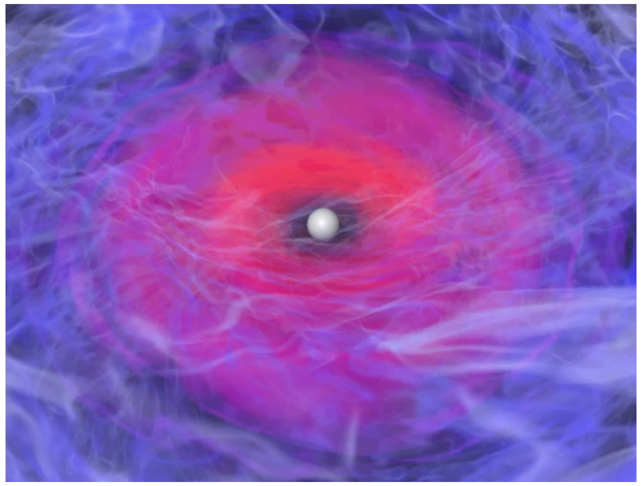


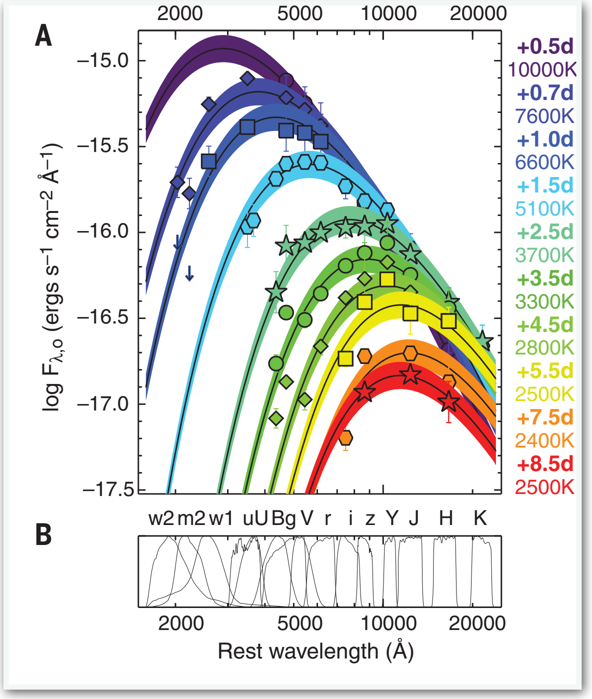



## short GRB



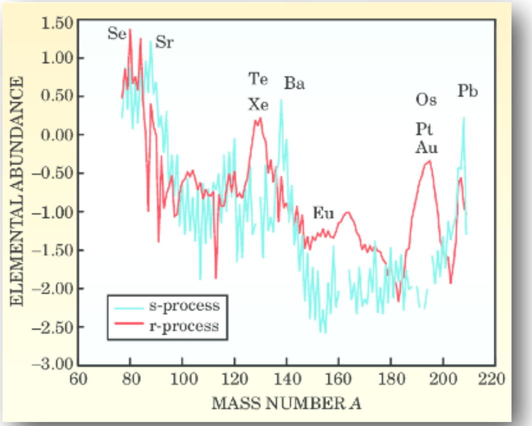







## Kilonova

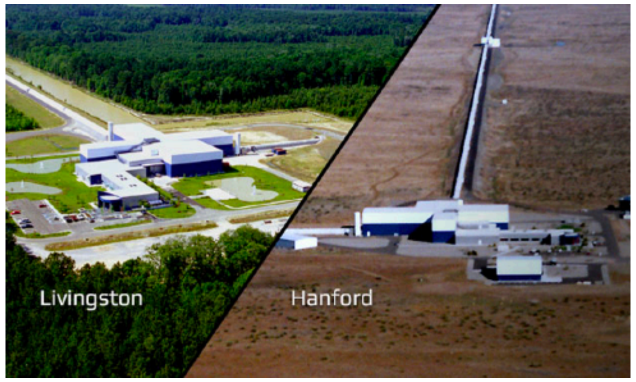
## Afterglow

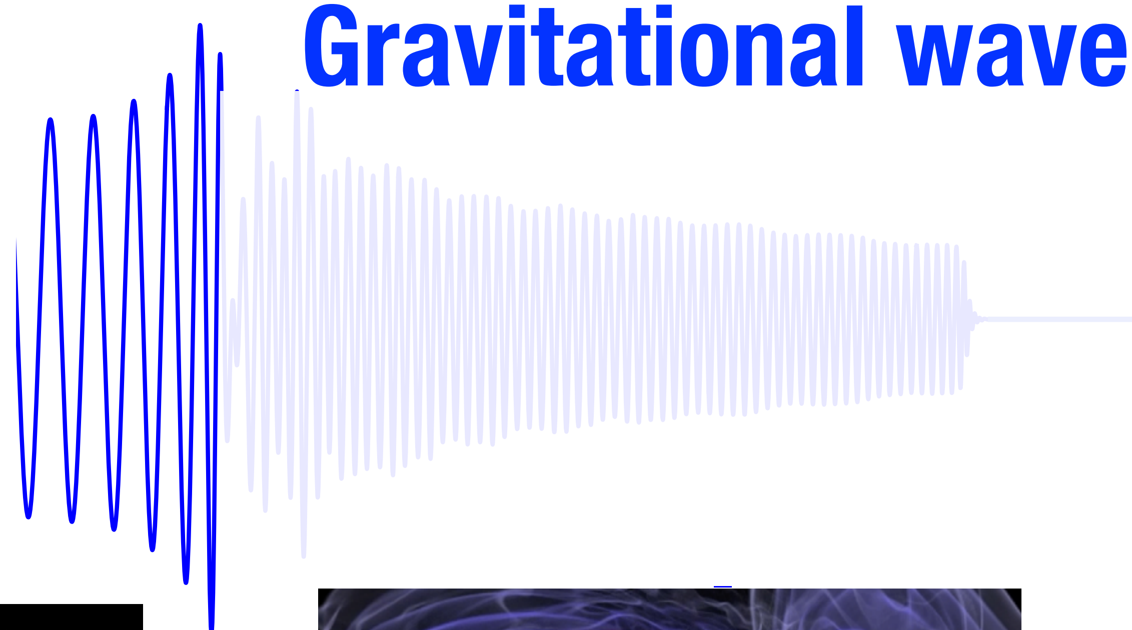


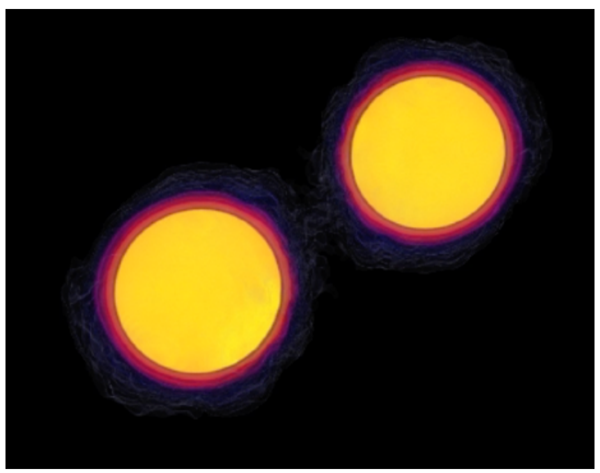
# The final fate of a neutron star binary

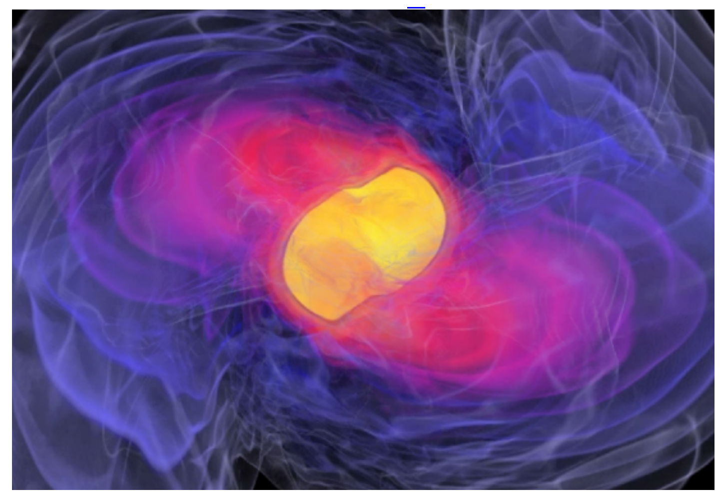
**Gravitational waves**

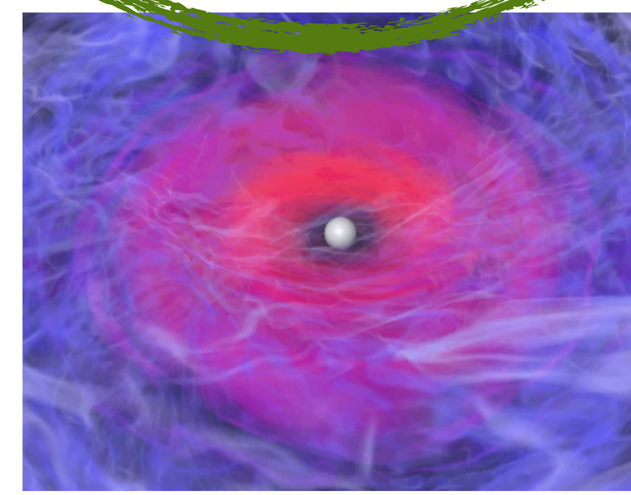
**short GRB**

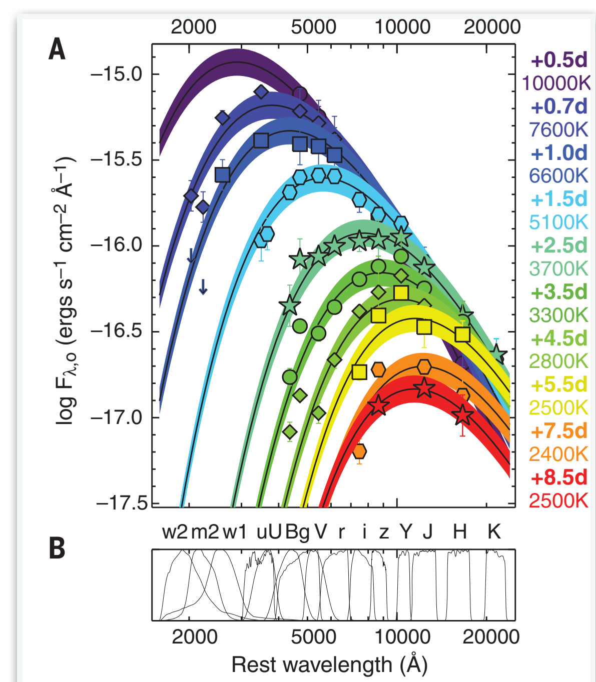




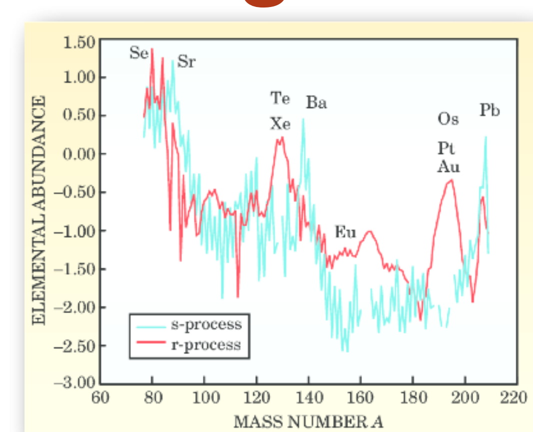







**Kilonova**

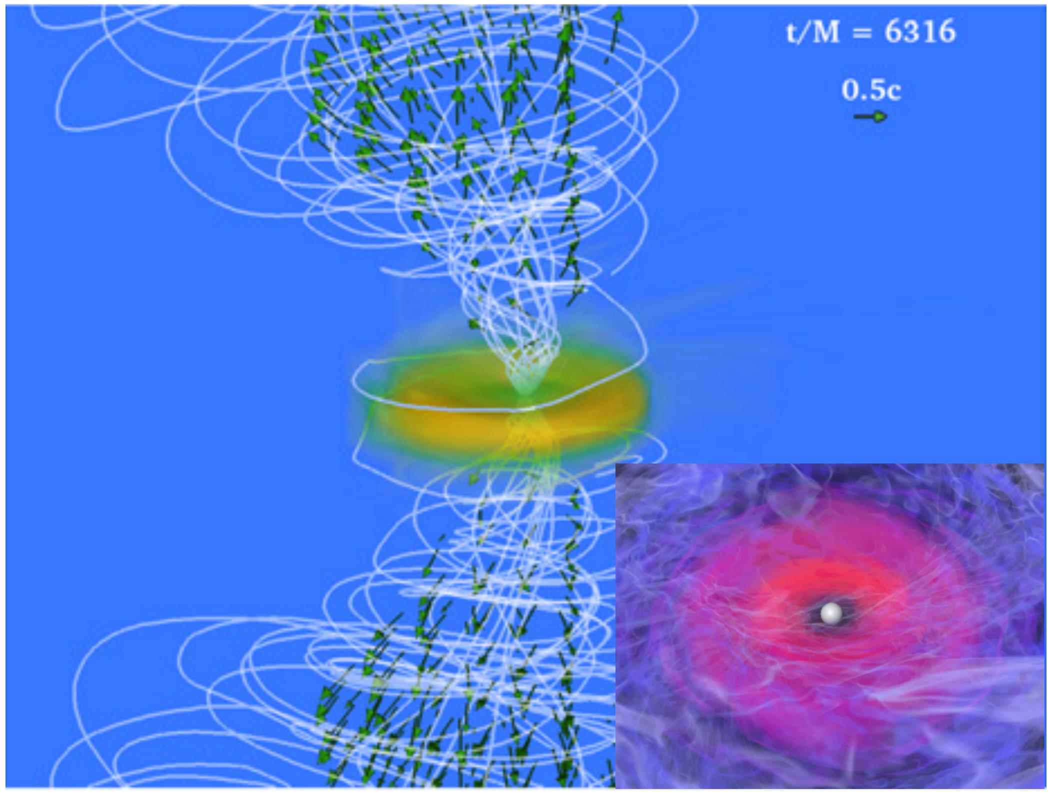
**Afterglow**



# Sourcing sGRBs in neutron star mergers

## What's the engine behind sGRBs?

**Black hole!**




Paschalidis et al 2015; **Ruiz** et al.

# Sourcing sGRBs in neutron star mergers

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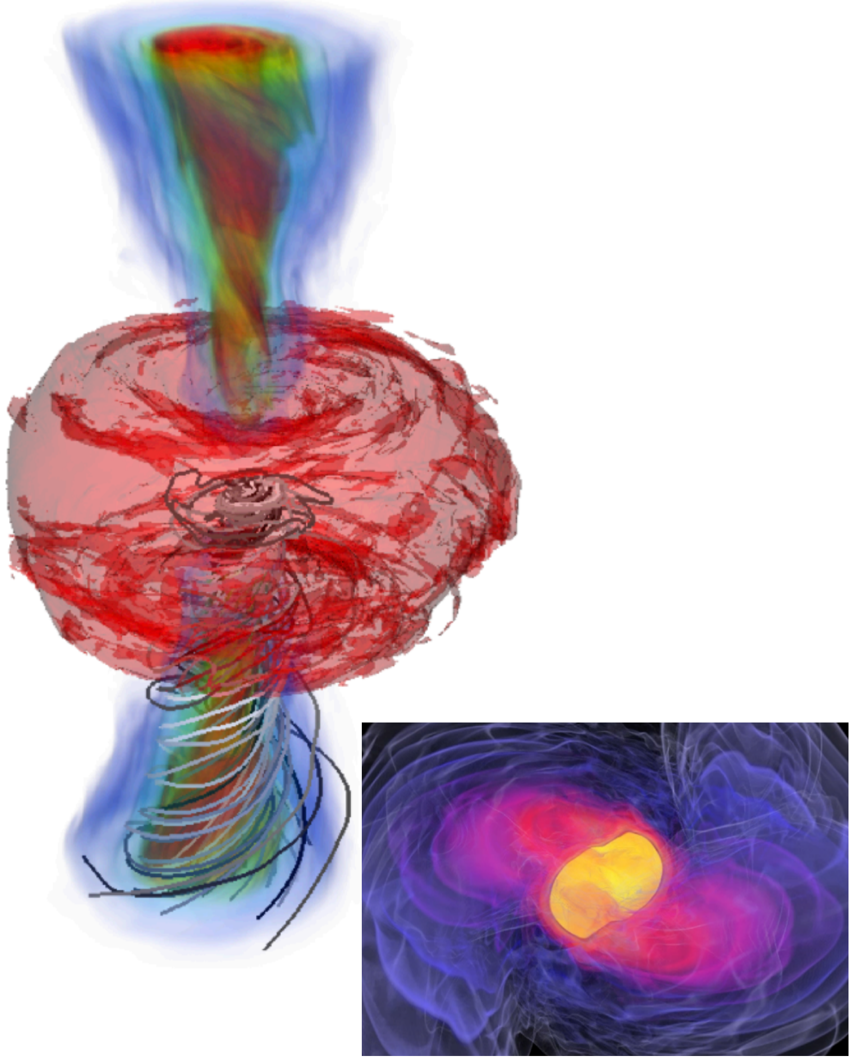
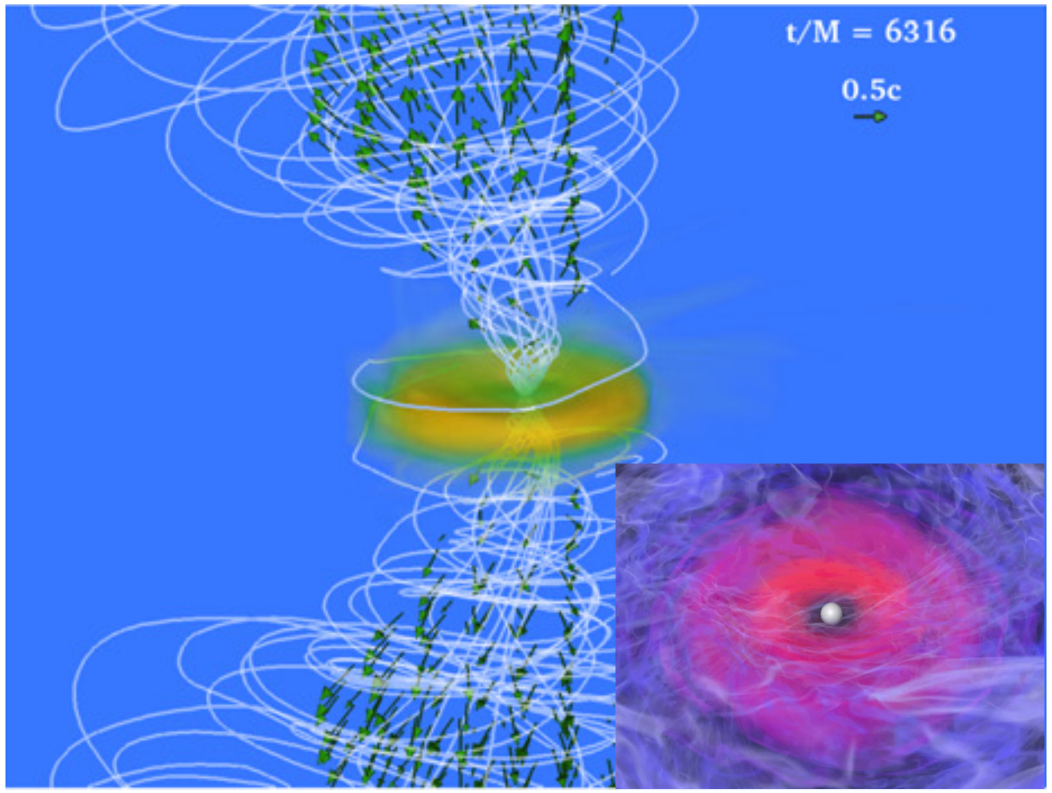
Mösta et al 2020





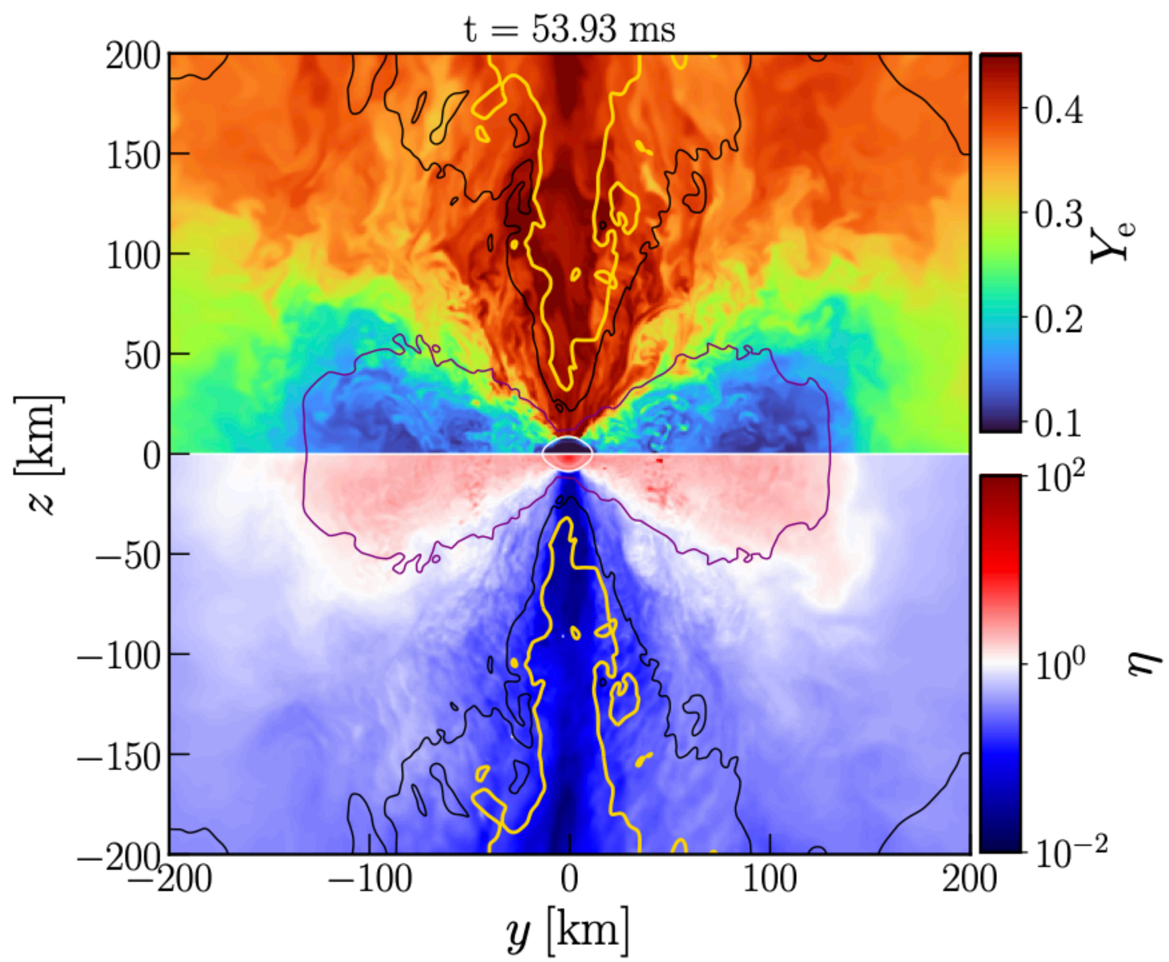

Paschalidis et al 2015; **Ruiz** et al.

**Hypermassive neutron star?**

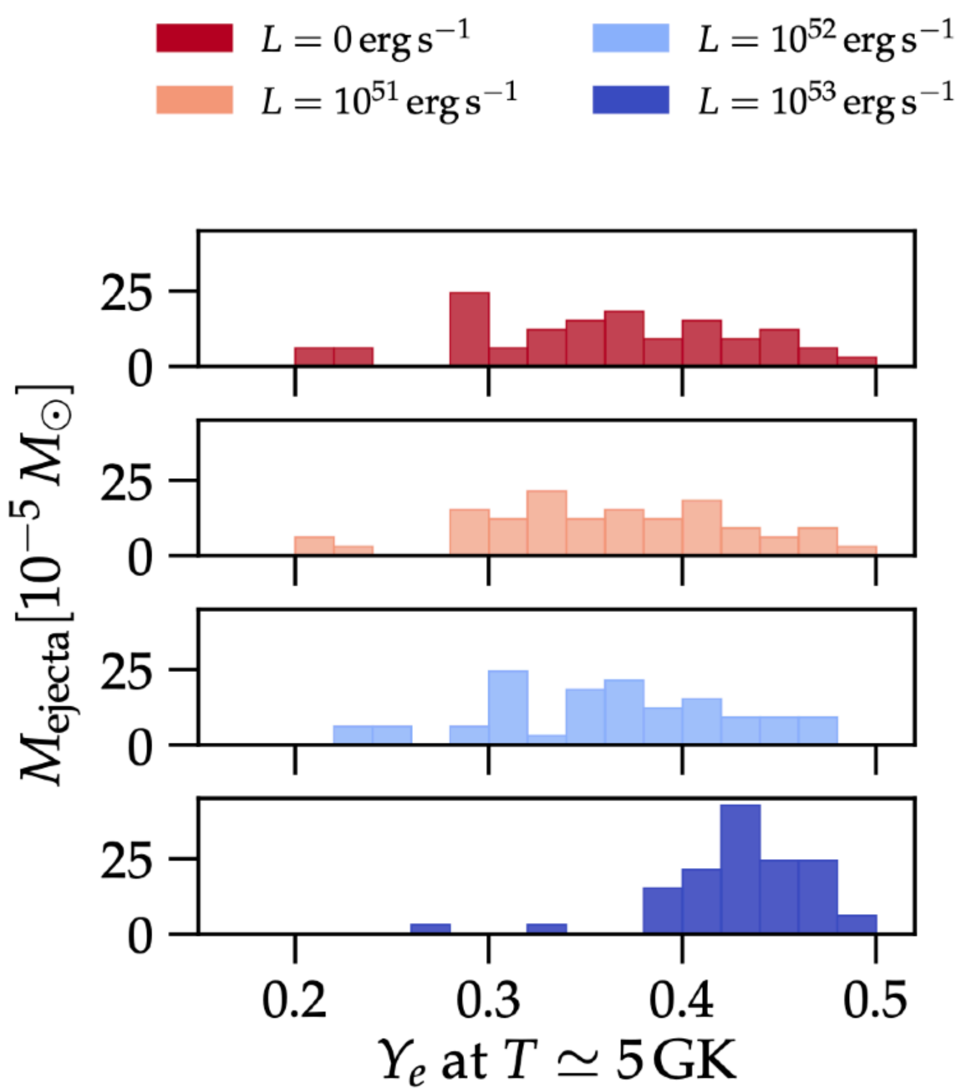
**Can we also get sGRBs from neutron stars? What's the expected fraction?**

# Blue kilonova from jet-like outflows?

**Stellar jet-like outflows might contribute to blue kilonova component of mergers**



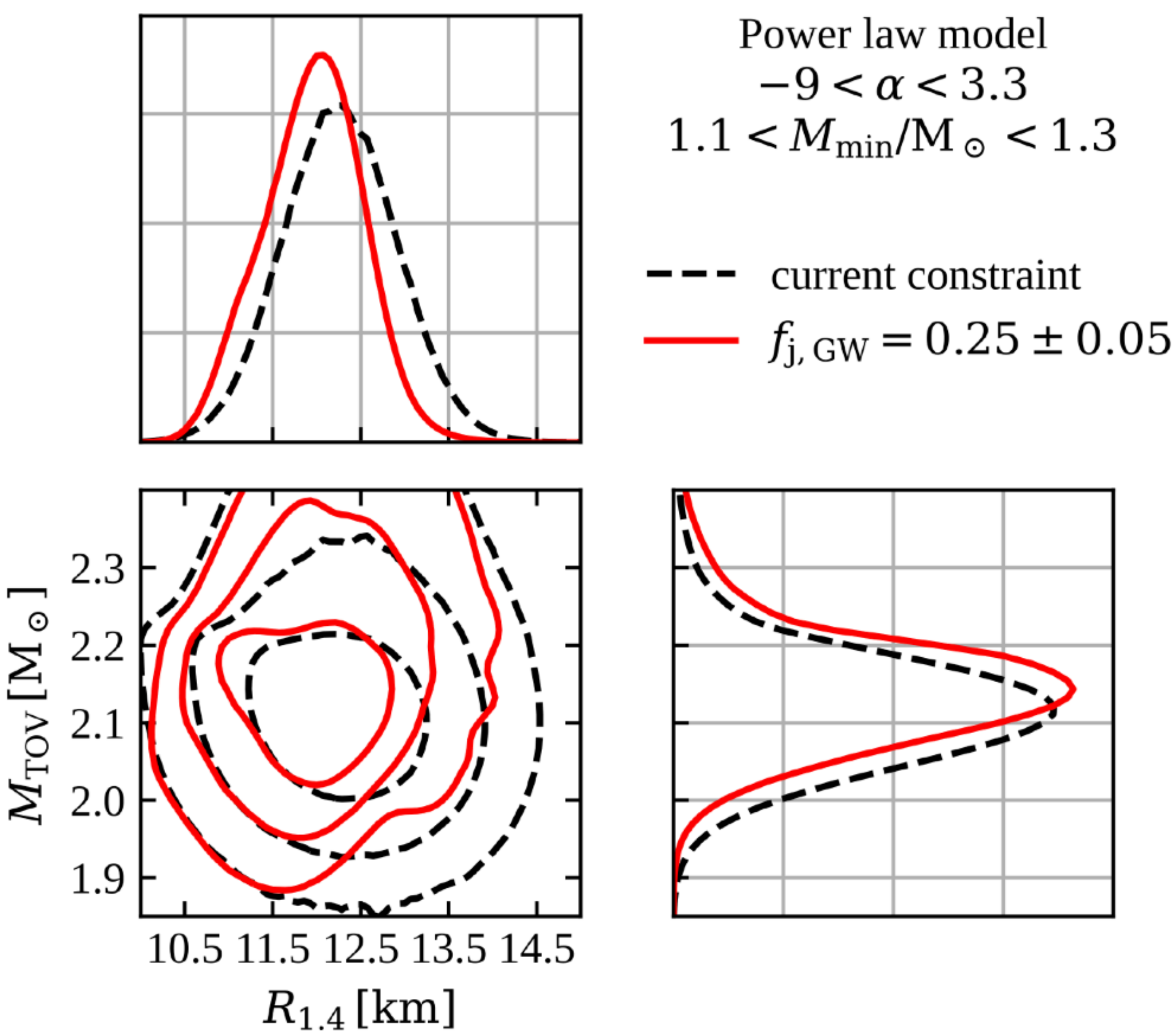

Combi+2023

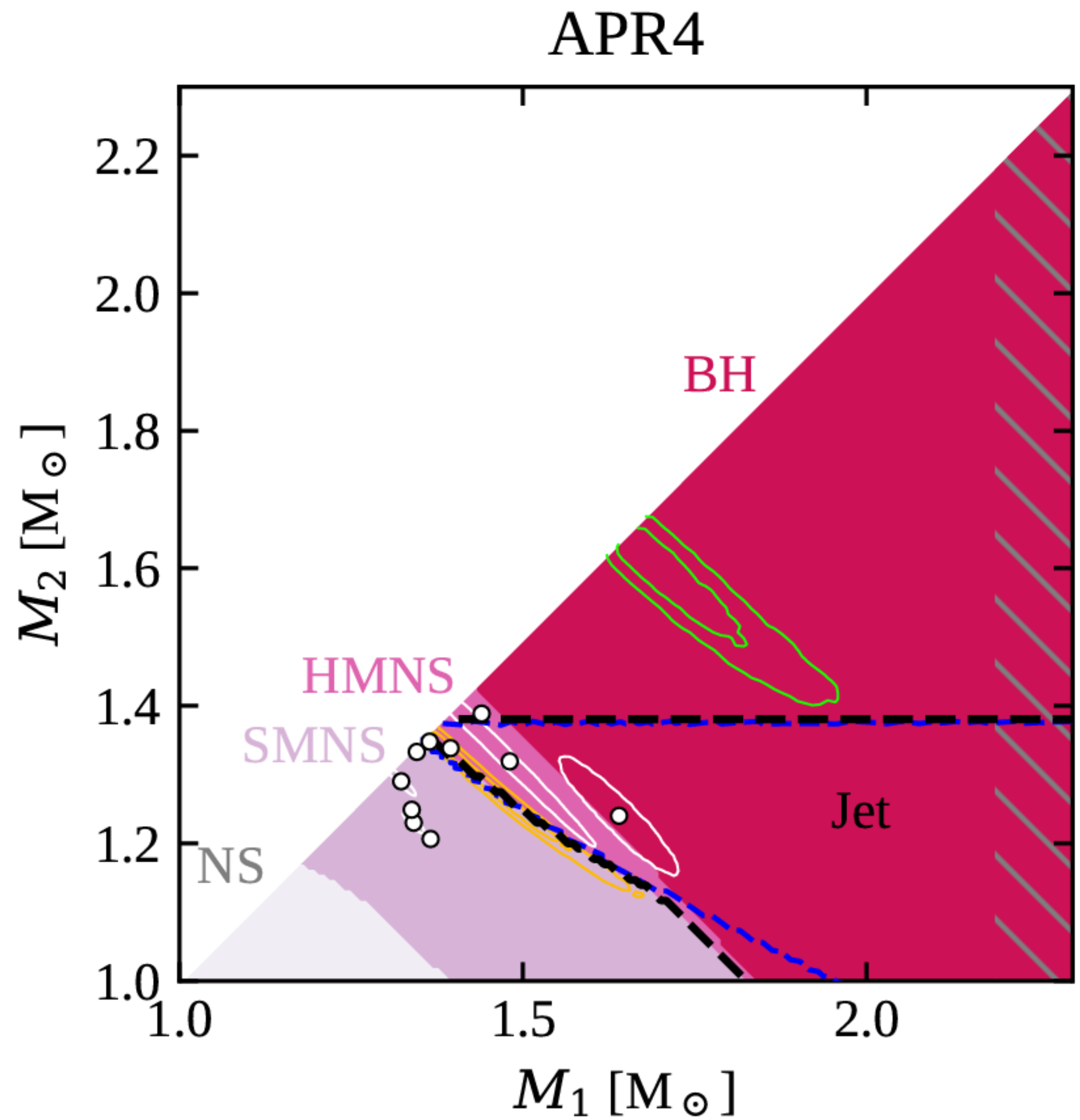



Curtis+2023

# Constraining the sGRB population

**Potential constraints from the sGRB population require reliable engine models**



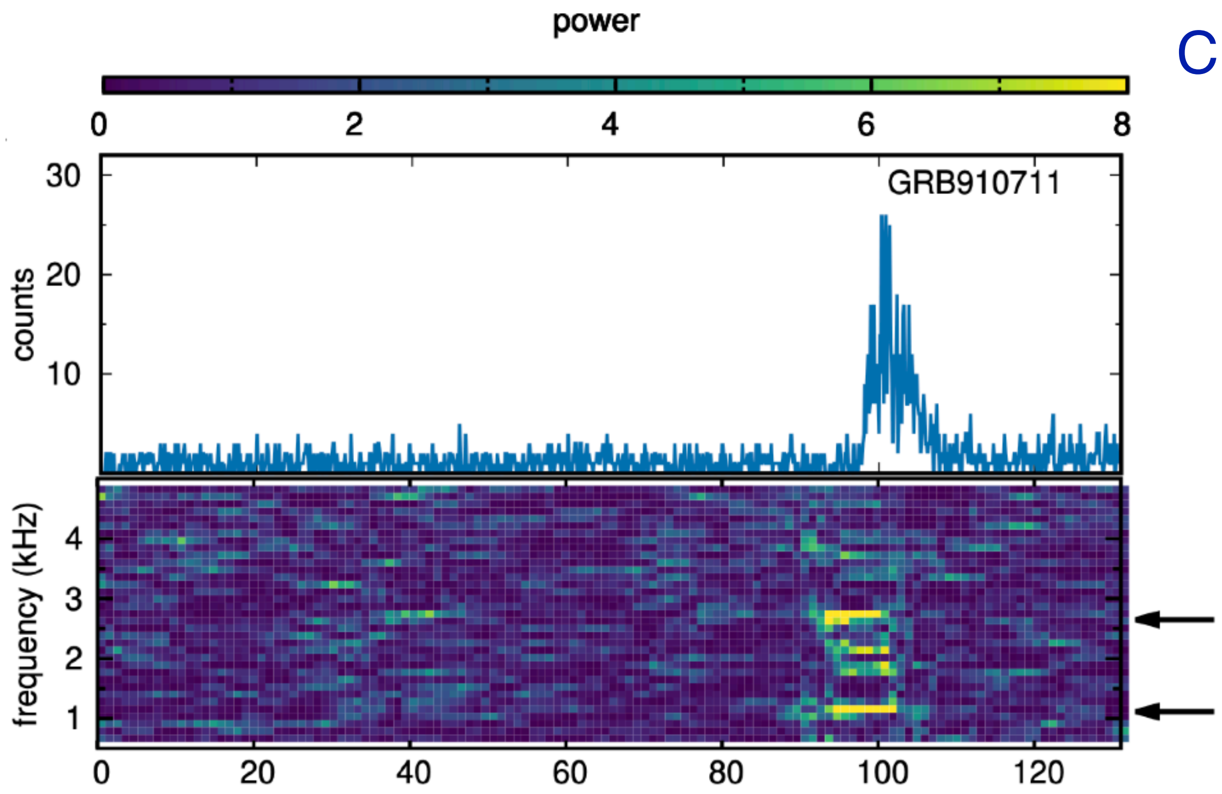




Salafia+ 2022
see also Sarin+ 2022

**See Margalit & Metzger; Rezzolla, ERM+; Ruiz+; Shibata+;… for constraints from GW170817**

# Kilohertz QPOs in neutron star mergers?

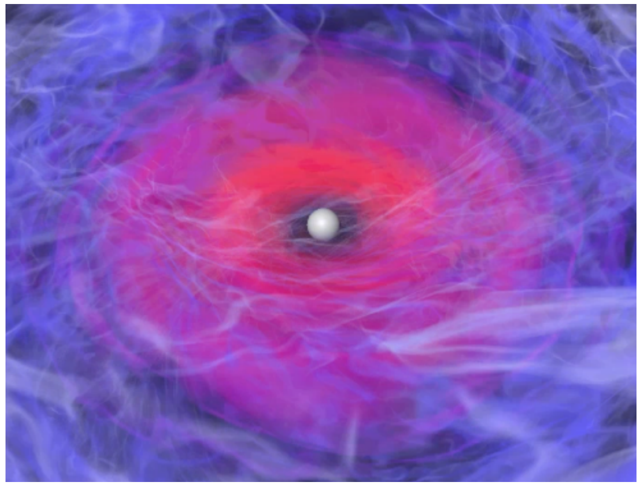
Small fraction of GRB recently reported to have quasi-periodic oscillations!




Chirenti+(Nature 2023)

2.6 kHz

sGRB



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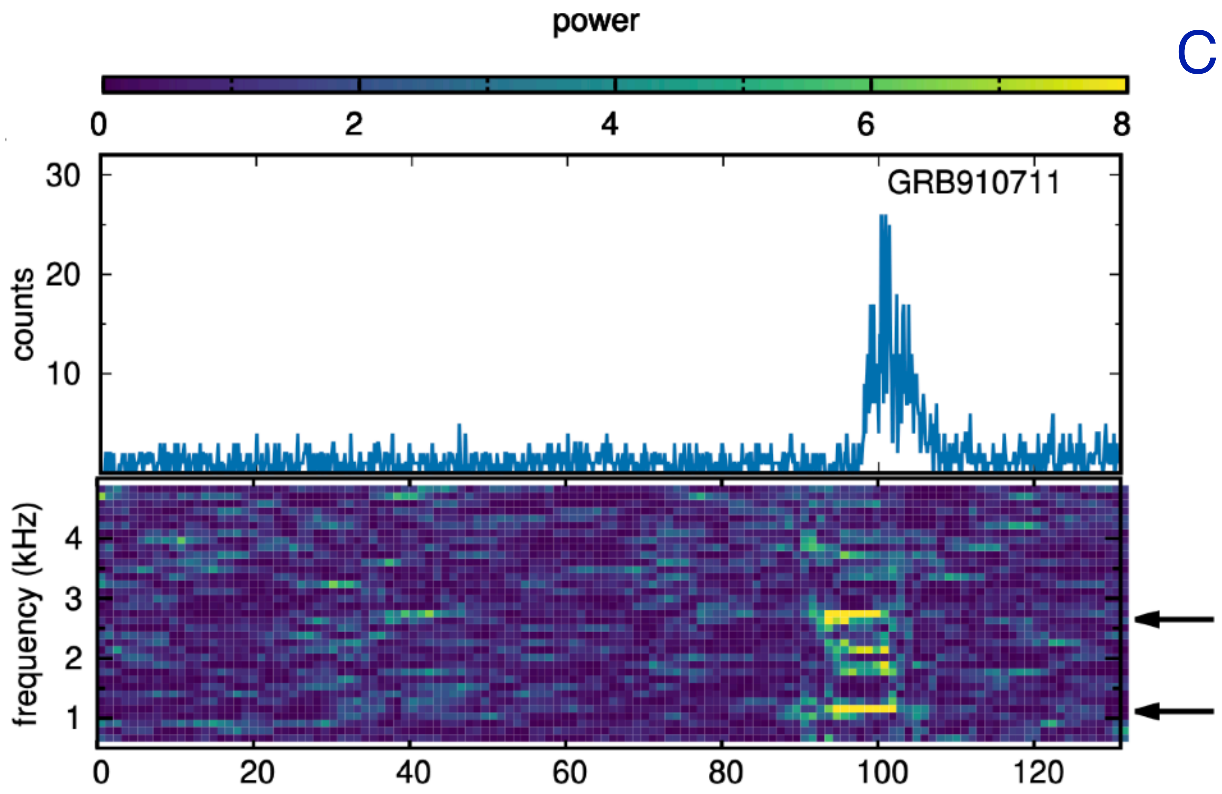
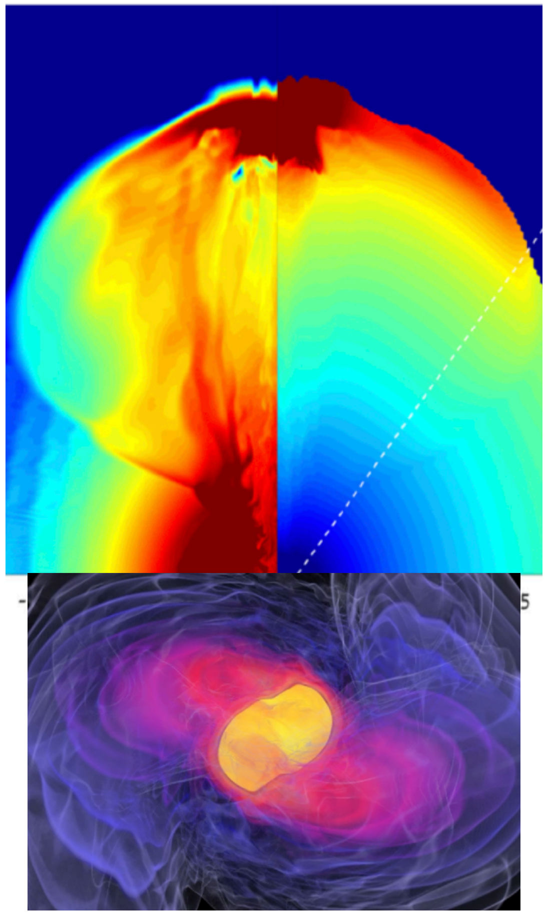



2.6 kHz

sGRB



HMNS has kHz QPOs!

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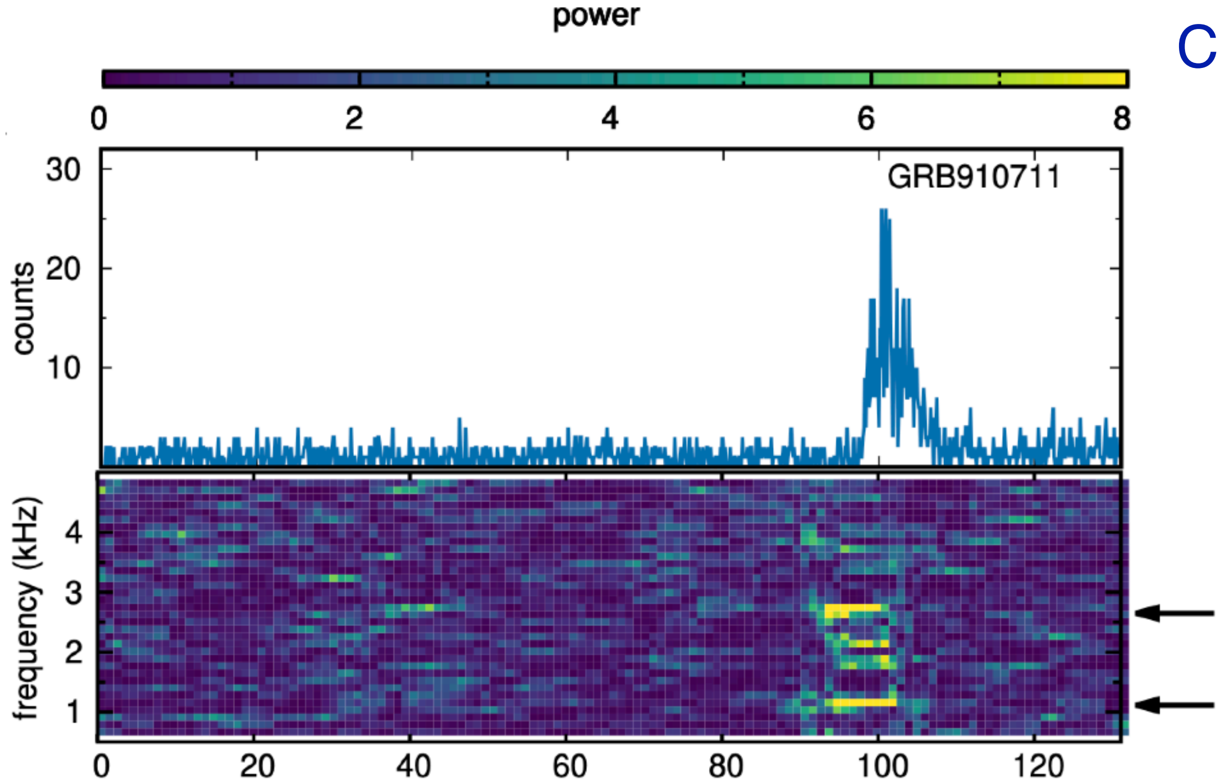


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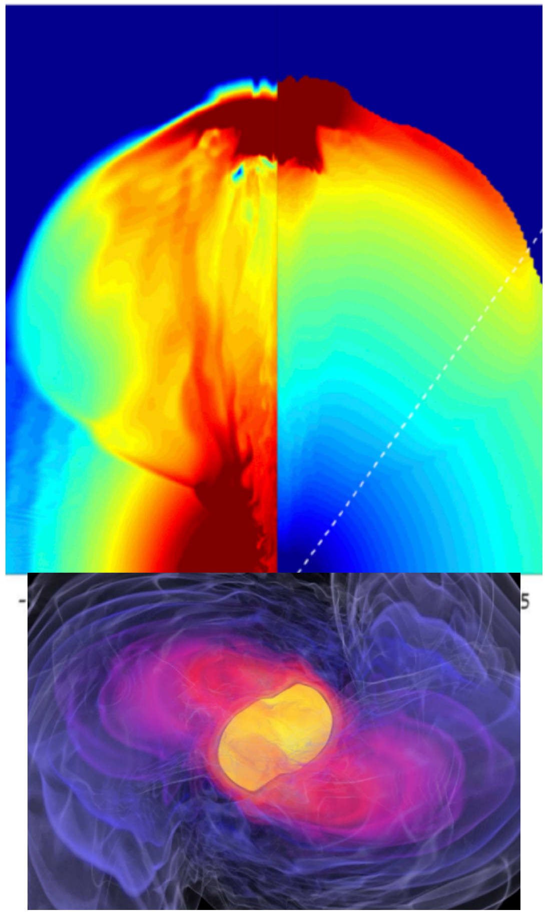
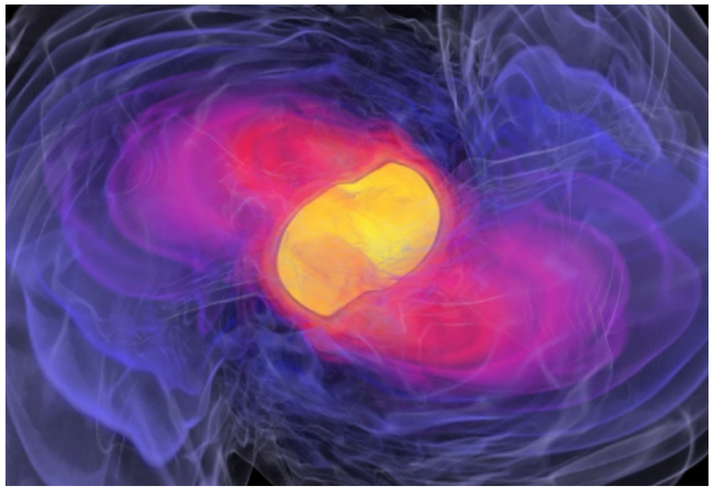


Could these QPOs be coming from a neutron star? Chirenti+(2019)

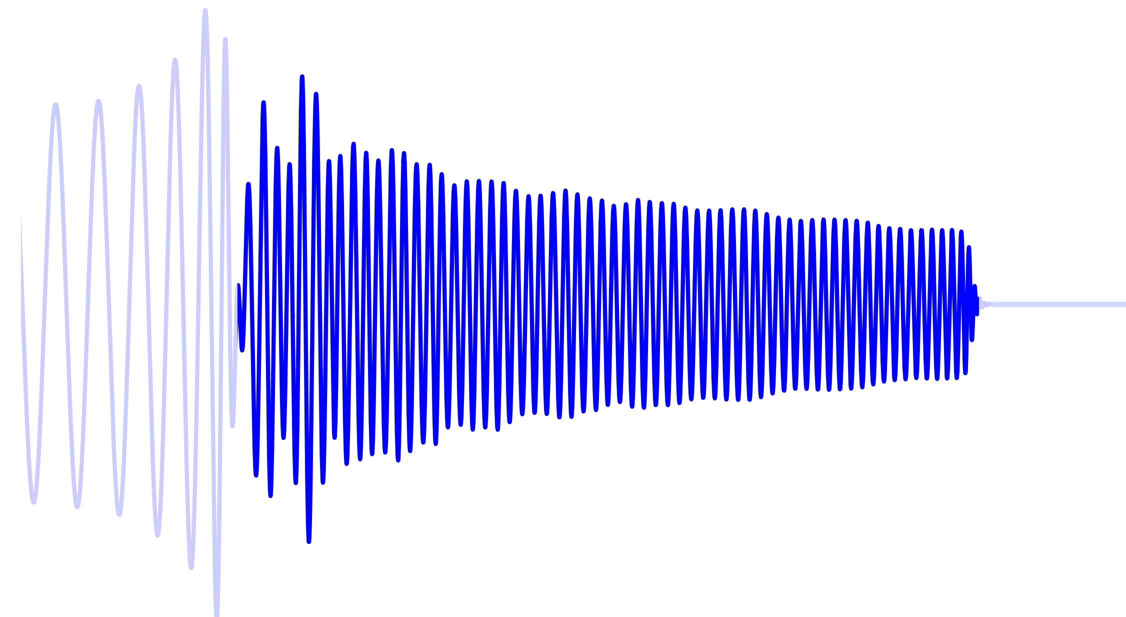
HMNS has kHz QPOs!

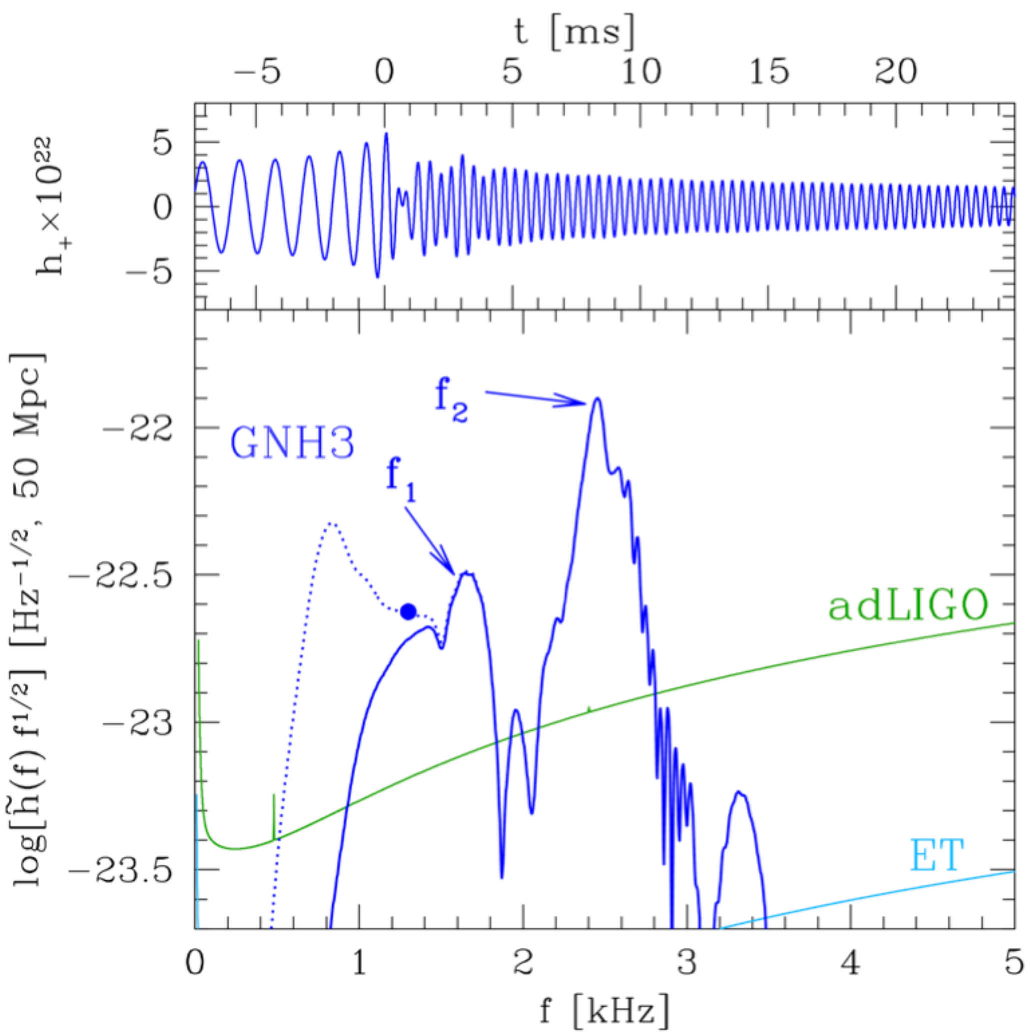
# Implications for nuclear physics?



oscillations

**Gravitational waves**






Takami+ (2014, 2015)

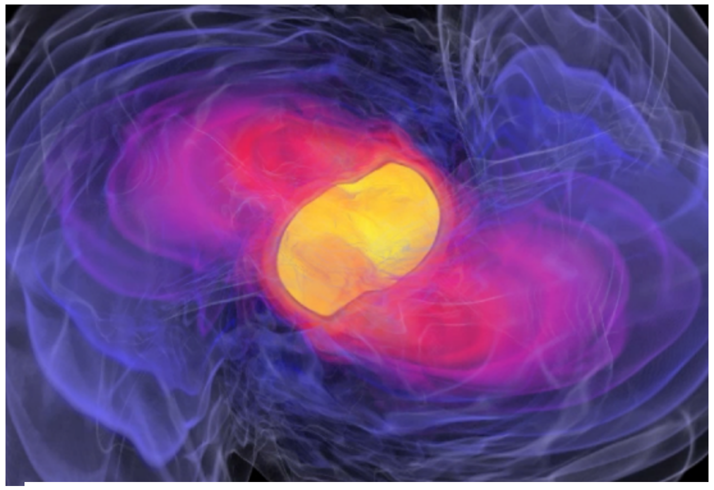
Different dense matter models give rise to different frequency spectra.

Bauswein+ 2011, 2012, Stergioulas+ 2011, Bernuzzi+ 2015, Raithel & ERM 2022,...

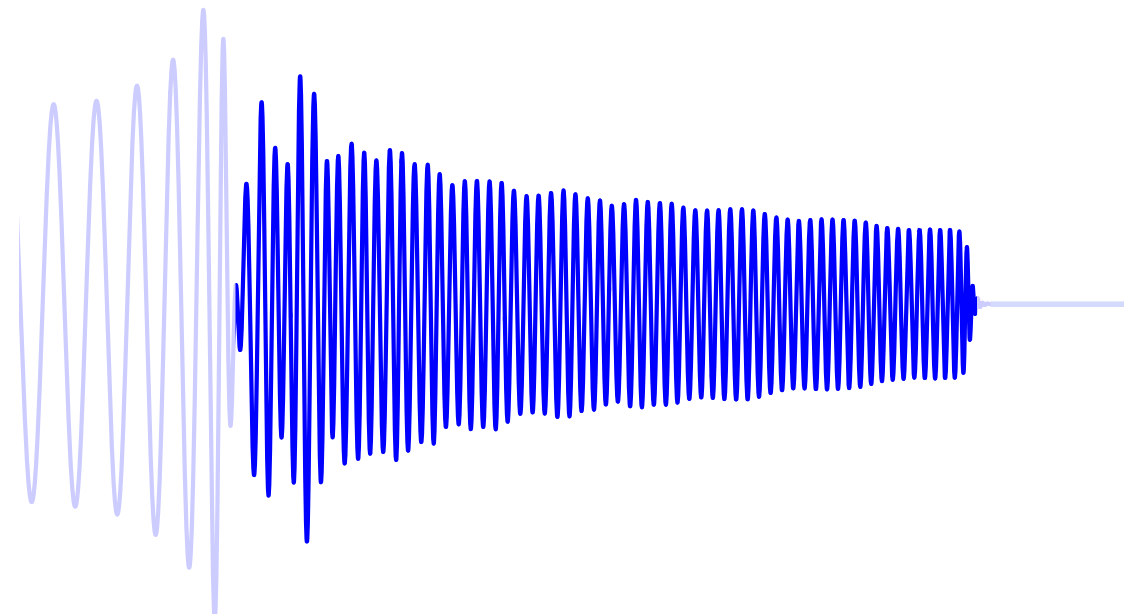
**Probing hot and dense matter!**

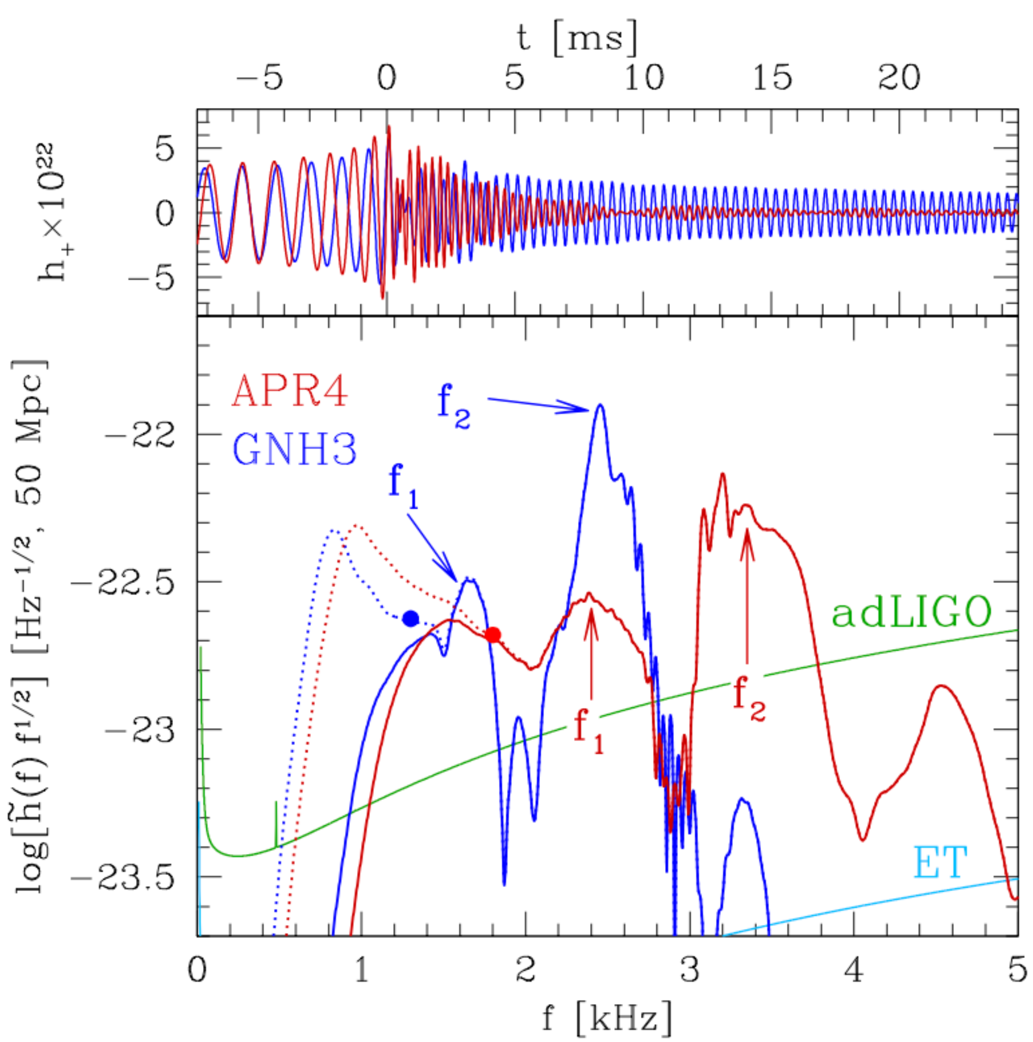
# Implications for nuclear physics?

**Gravitational waves**



**oscillations**



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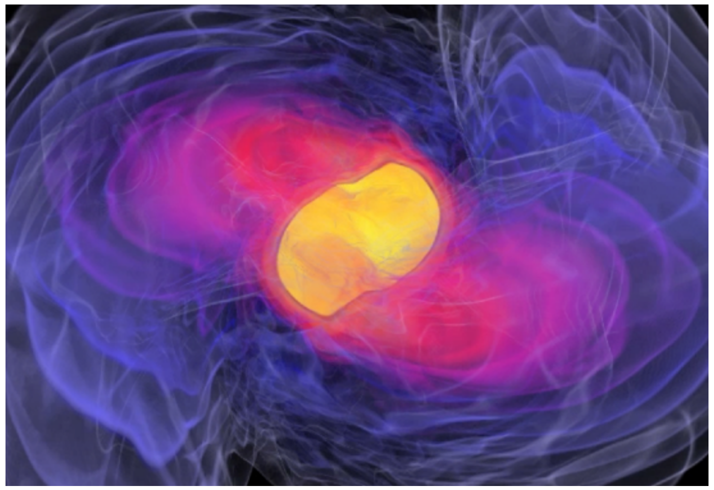

oscillations

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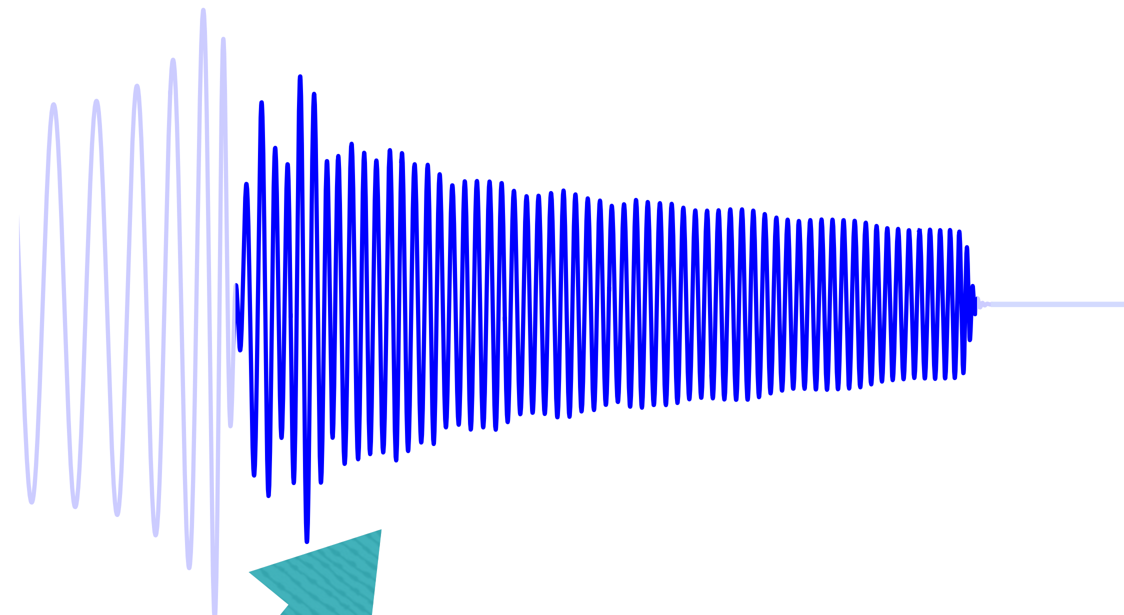
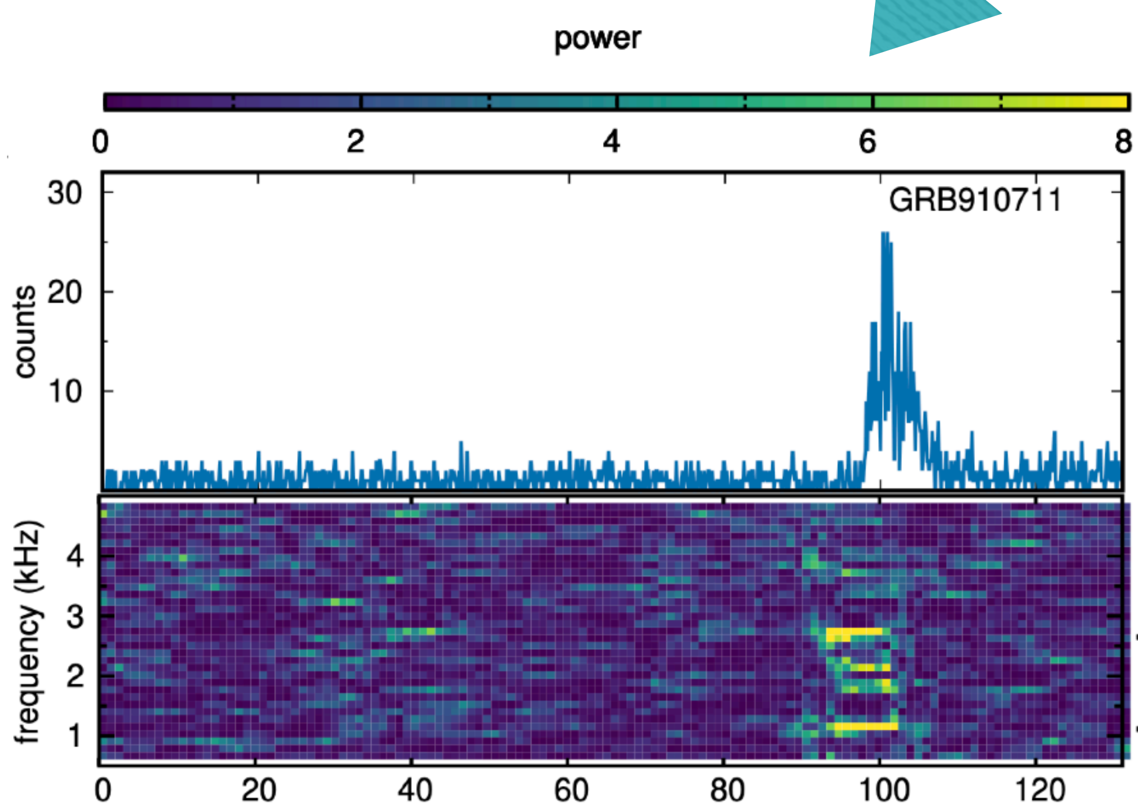


??

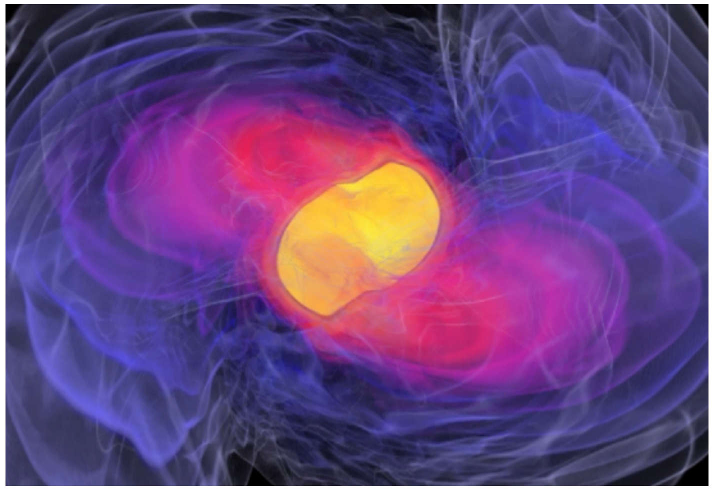
**Can gamma-ray burst QPOs provide additional constraints?**



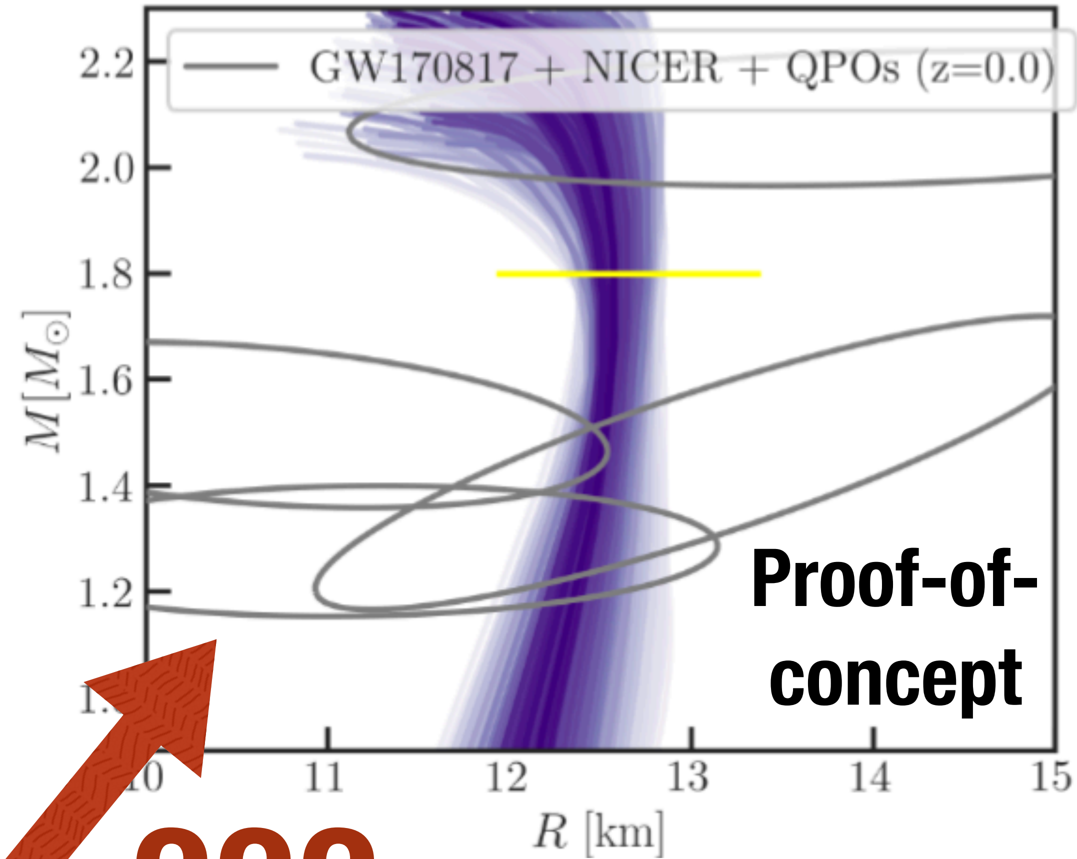

2.6 kHz

Chirenti+(Nature 2023)

# Implications for nuclear physics?



oscillations



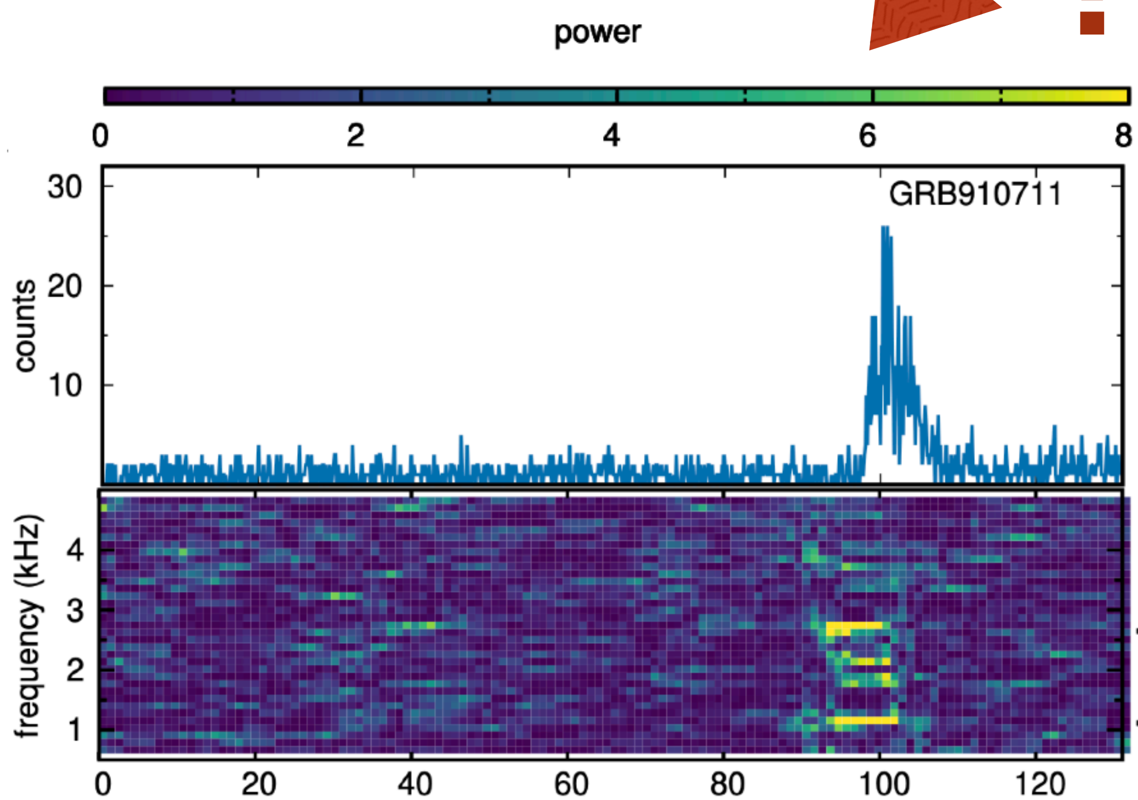

**Proof-of-concept**

**Challenge:**
**Redshift unknown…**

???

Raithel & ERM (in prep)

**Can gamma-ray burst QPOs provide additional constraints?**

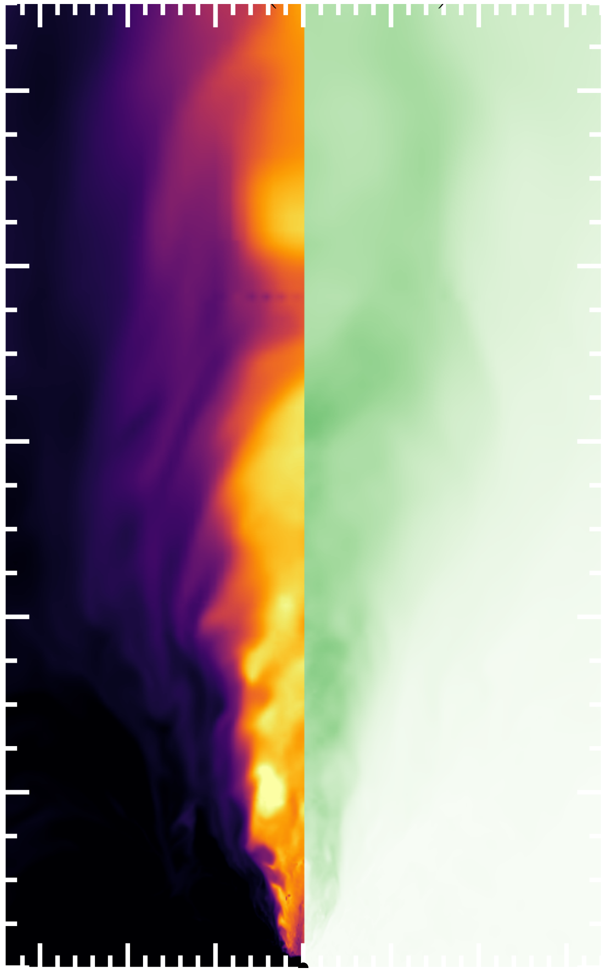



2.6 kHz

Chirenti+(Nature 2023)

# Thinking about a model

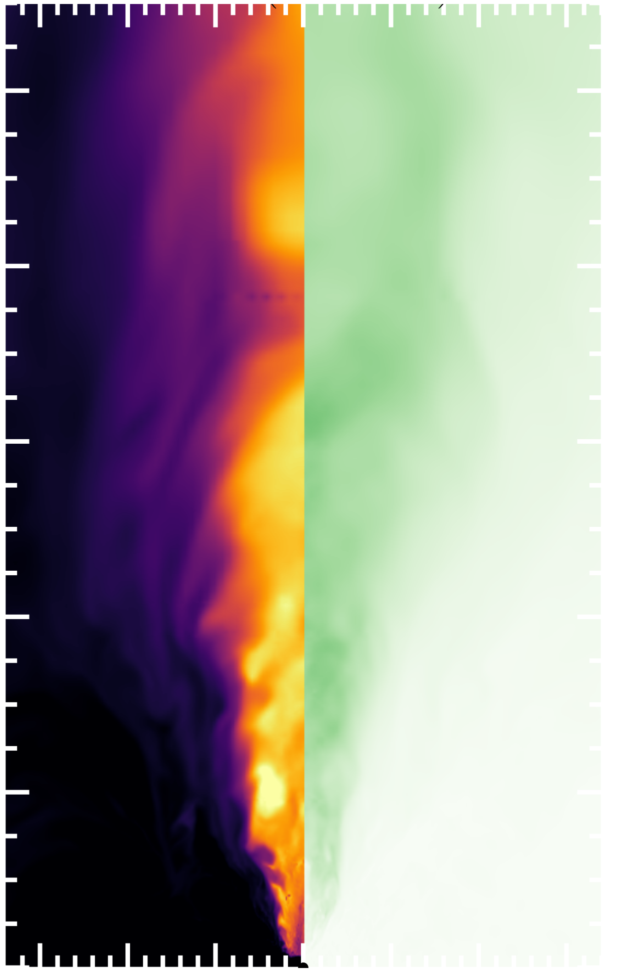
Question: Can a hypermassive neutron star inject kHz variability into a jet-like outflow?



# Thinking about a model

Question: Can a hypermassive neutron star inject kHz variability into a jet-like outflow?

- Post-merger oscillations strongest during and shortly after merger
- Likely requires production of ultra-strong magnetic fields during merger
- Variability may correlate with equation of state, but also with magnetic field topology



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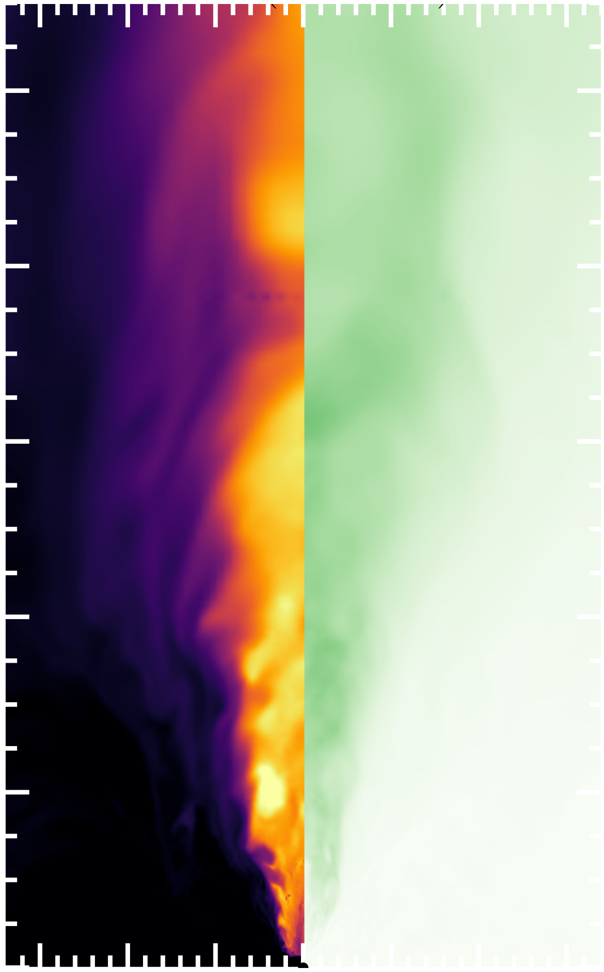
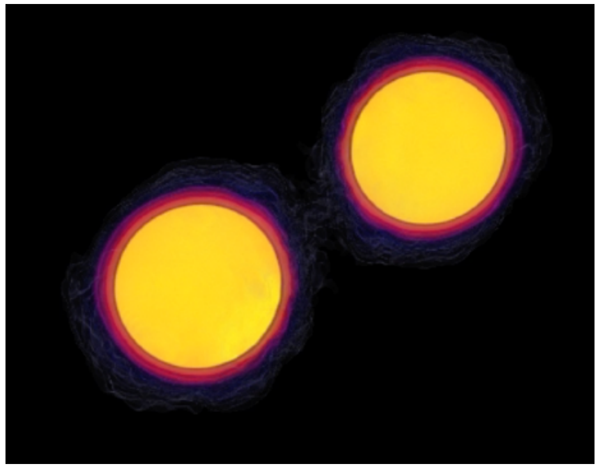


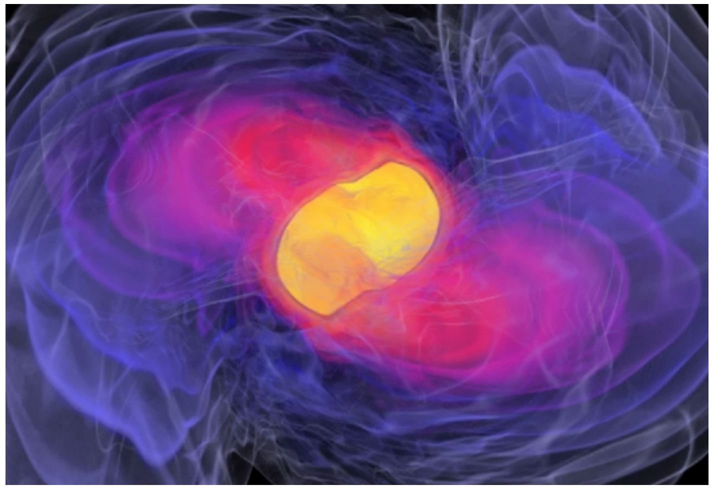
# Why magnetic fields pose a challenge

**Inspiral**



$B < 10^{13}$ G

**merger**



$B \gg 10^{16}$ G

$\sigma \gg 10^{-4}$

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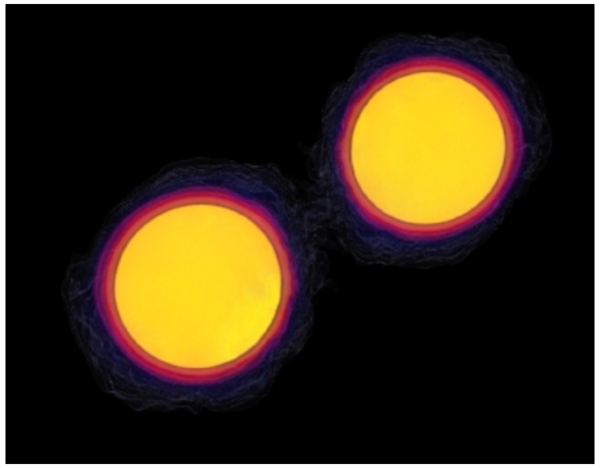

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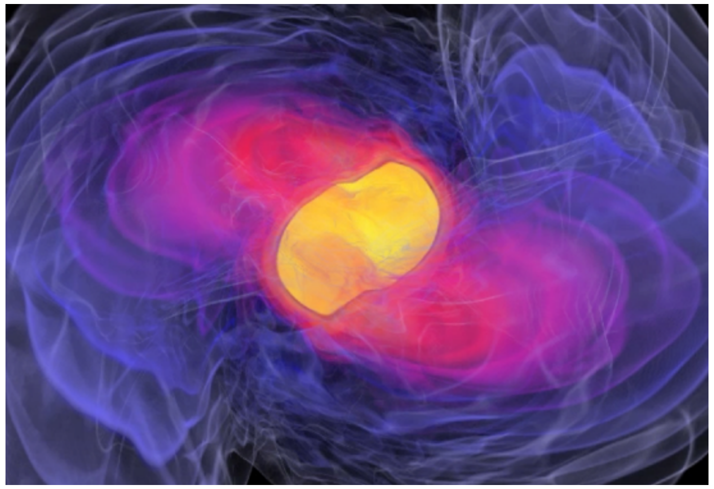

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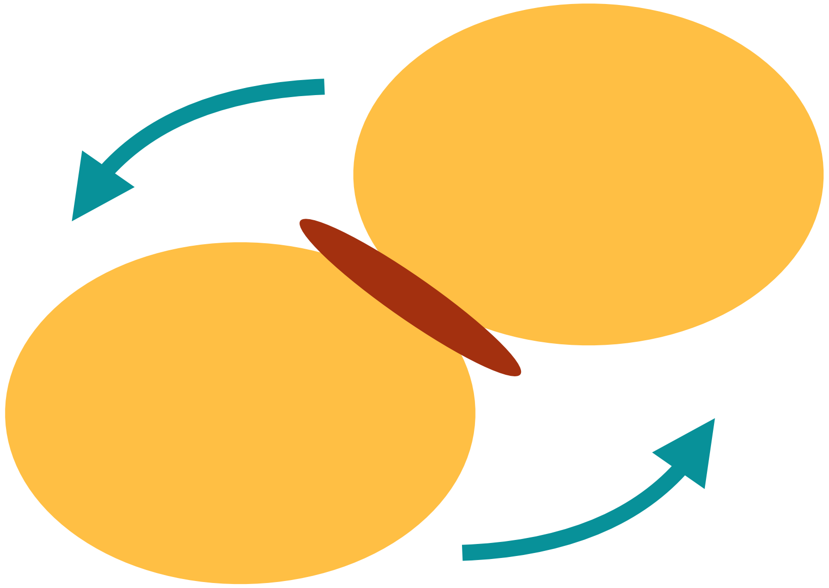
**shear layer**



**during merger**

Price&Rosswog (2006), Kiuchi+(2015,17), Palenzuela+(2021)

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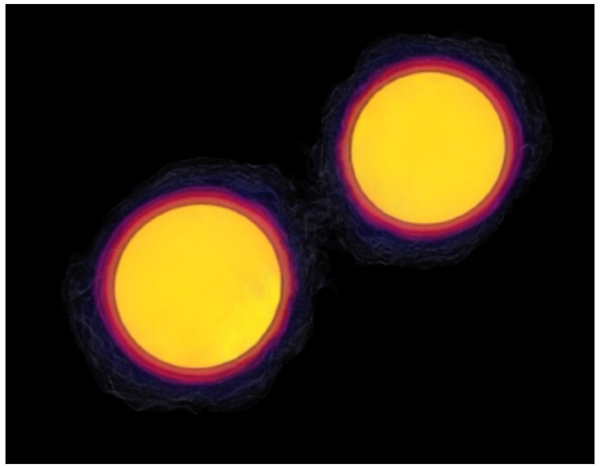

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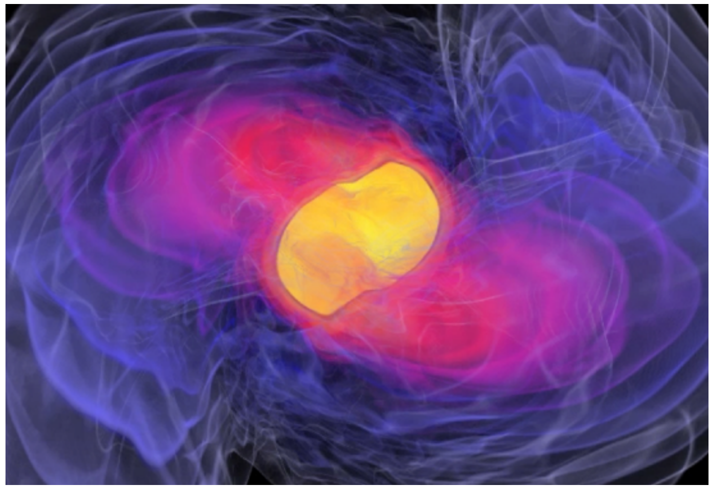

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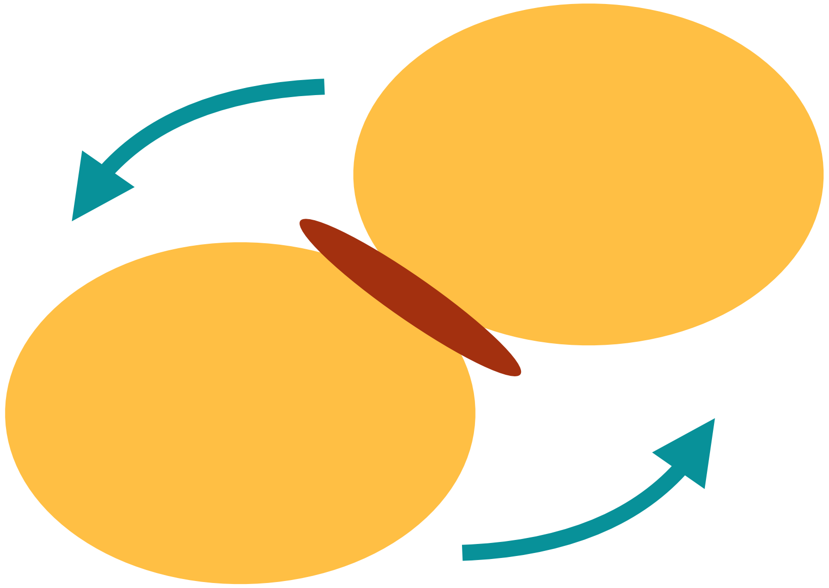

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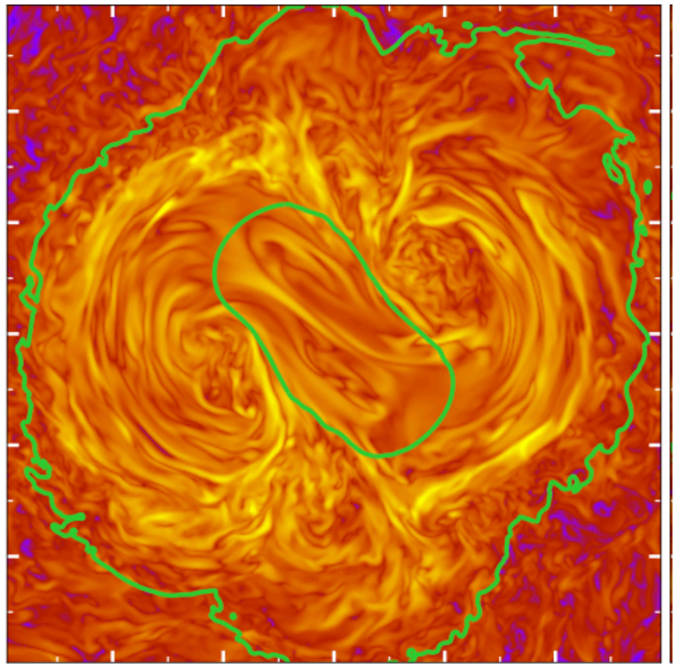
- Ampflication of magnetic field due to small scale turbulence in the merger
- Initial magnetic field topology seems to get washed out Aguilera-Miret+(2021)



Chabanov+(incl. ERM, ApJL '23)

# Why magnetic fields pose a challenge

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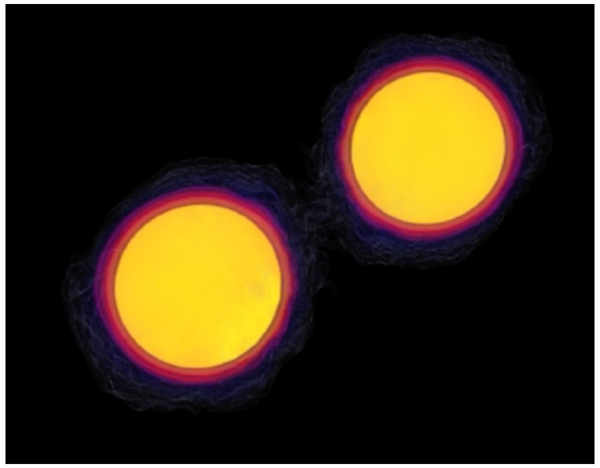

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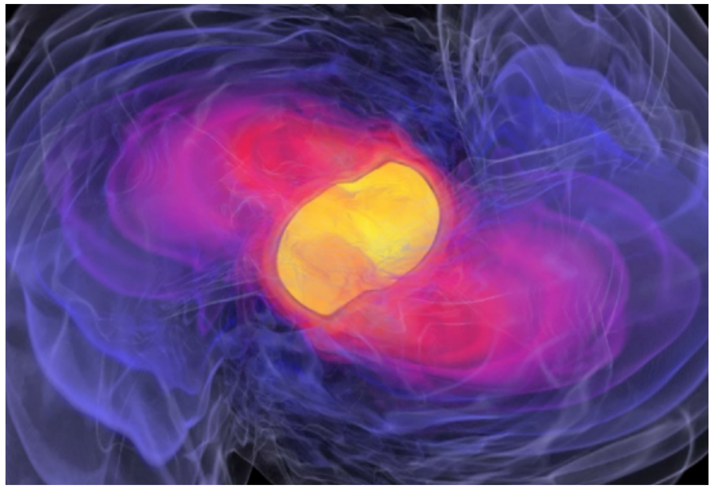

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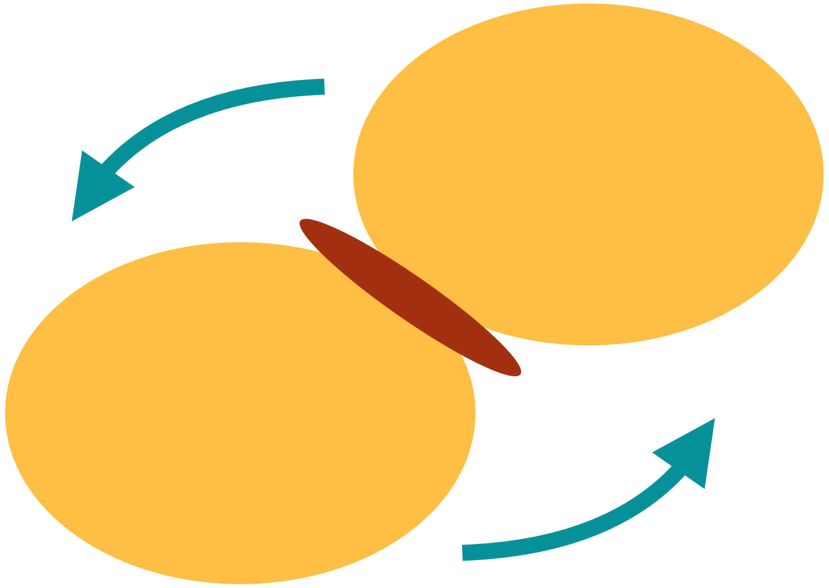

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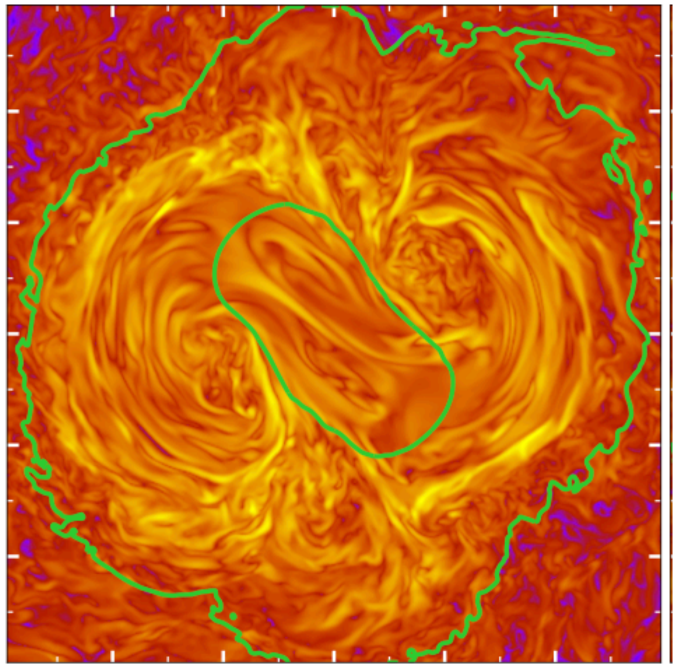
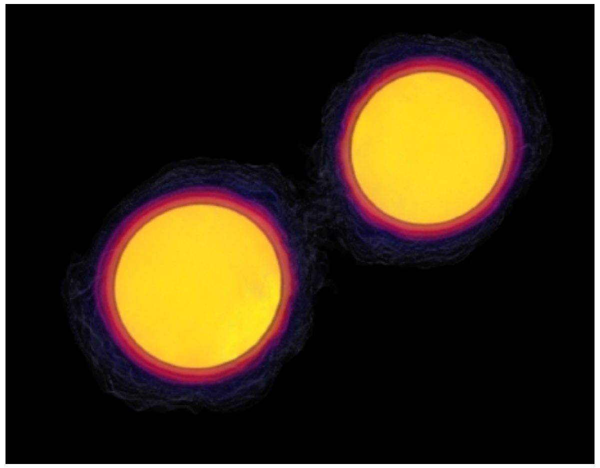


Chabanov+(incl. ERM, ApJL ’23)

**Magnetic field configuration after merger remains uncertain…**

# Why magnetic fields pose a challenge

## Inspiral



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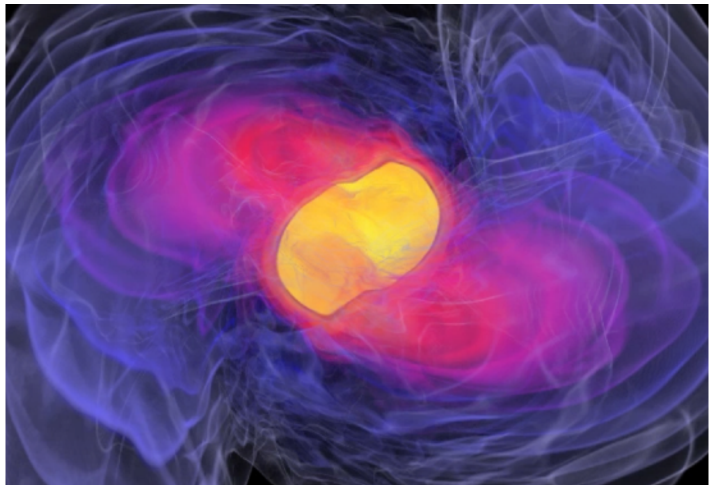

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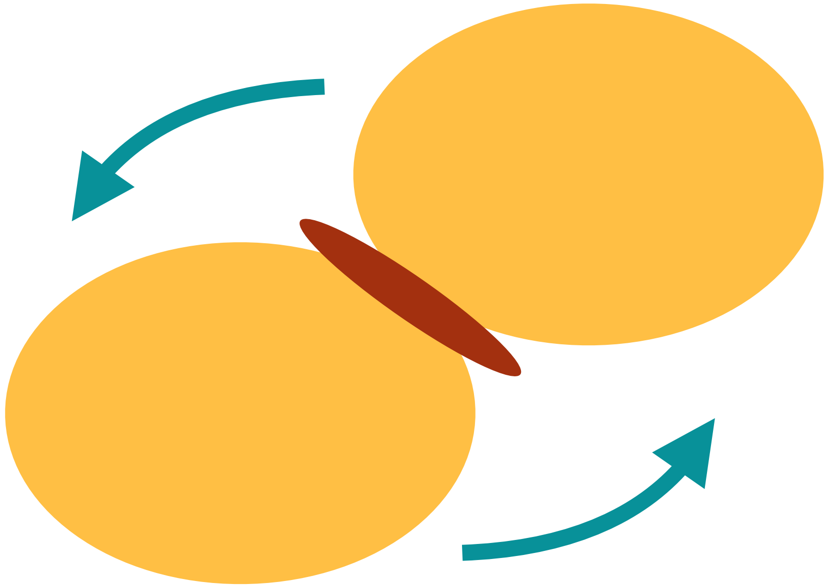
## shear layer

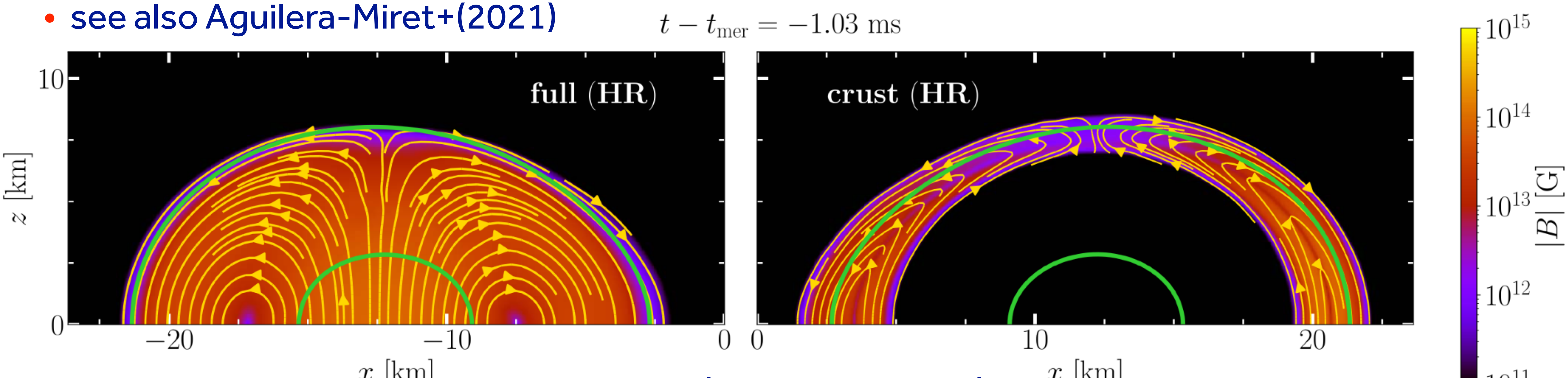


**during merger**

Price&Rosswog (2006), Kiuchi+(2015,17), Palenzuela+(2021)

## What's the impact of different initial fields?

- see also Aguilera-Miret+(2021)




Chabanov+(incl. ERM, ApJL '23)

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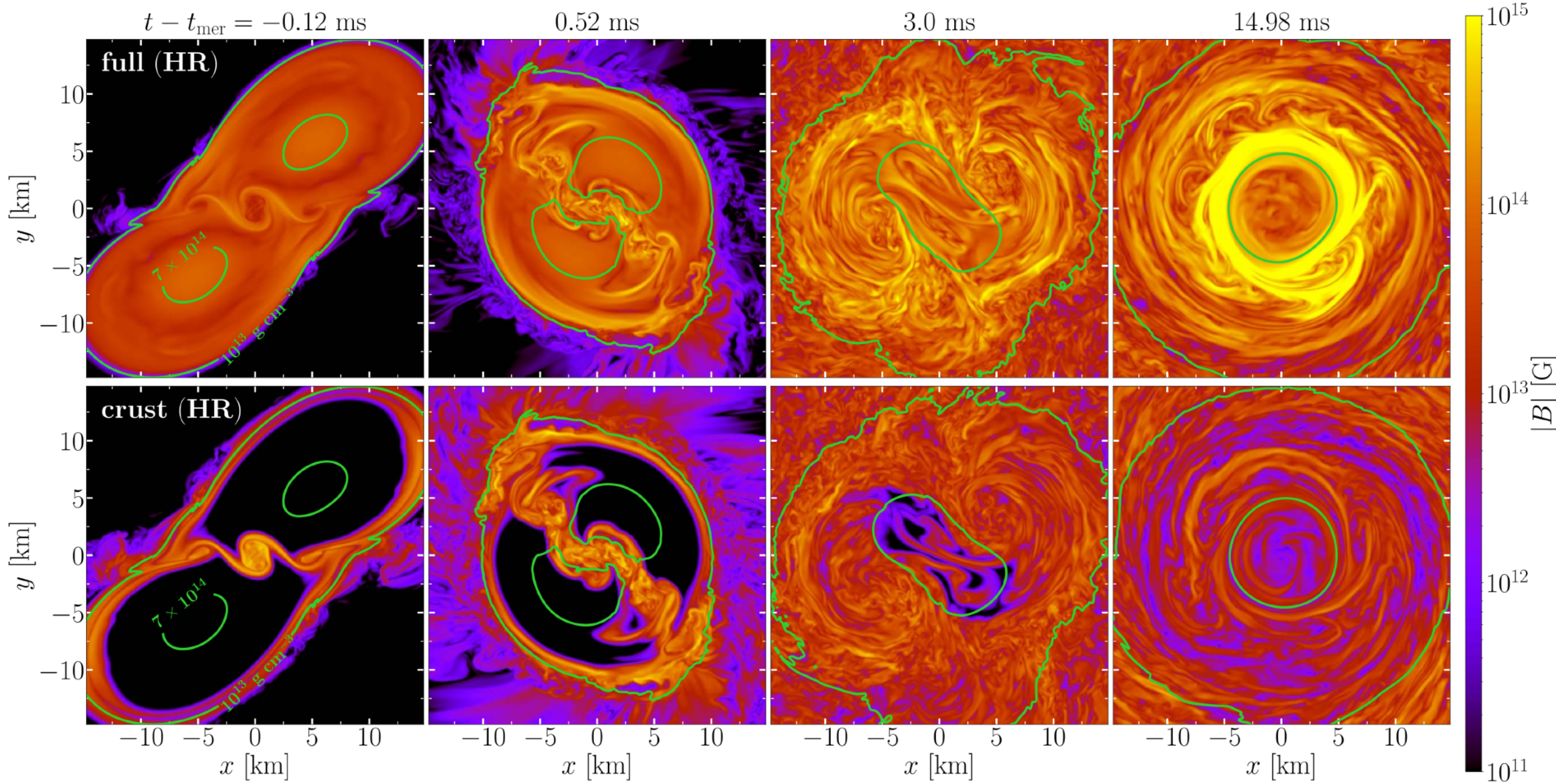


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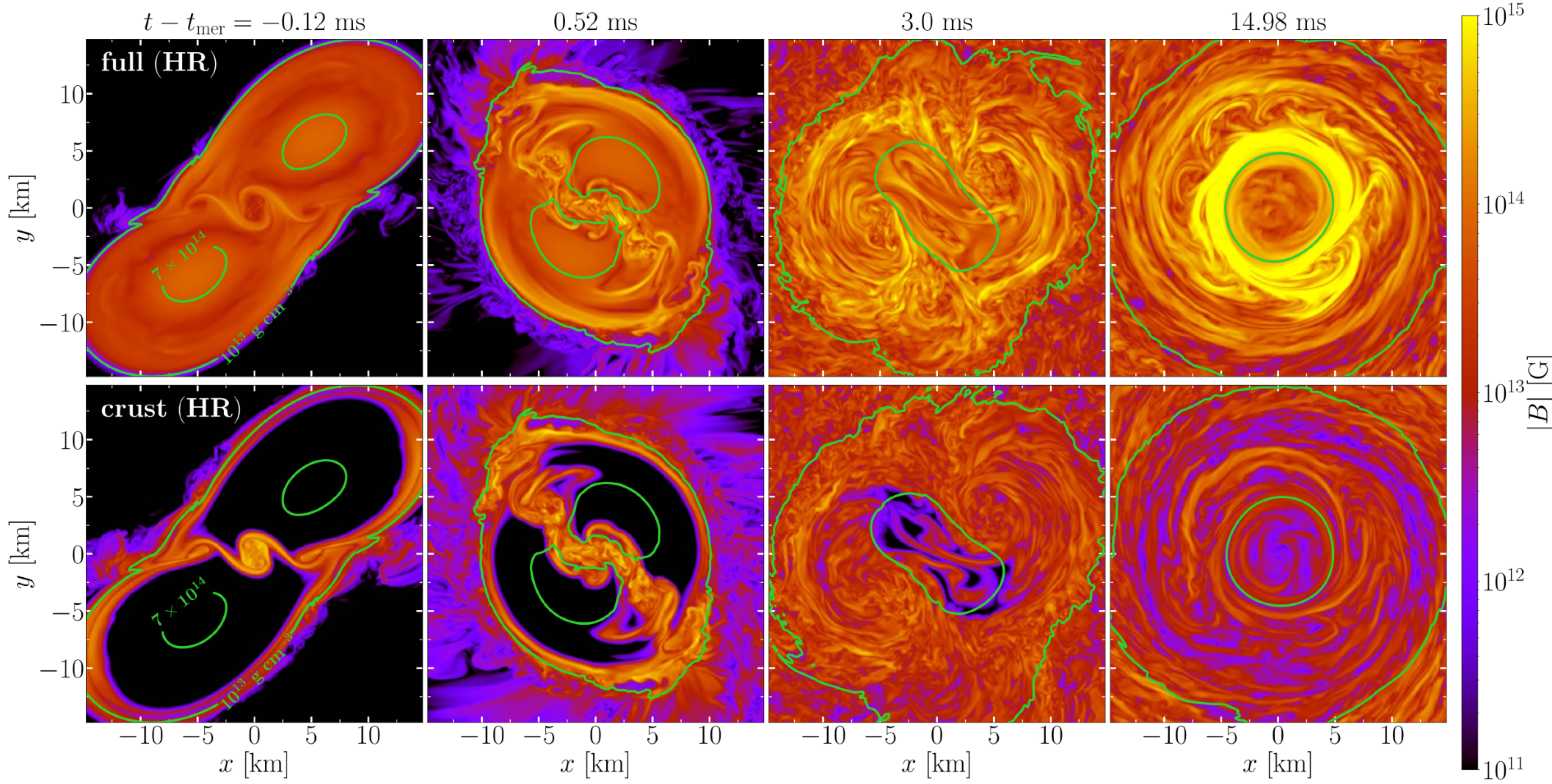


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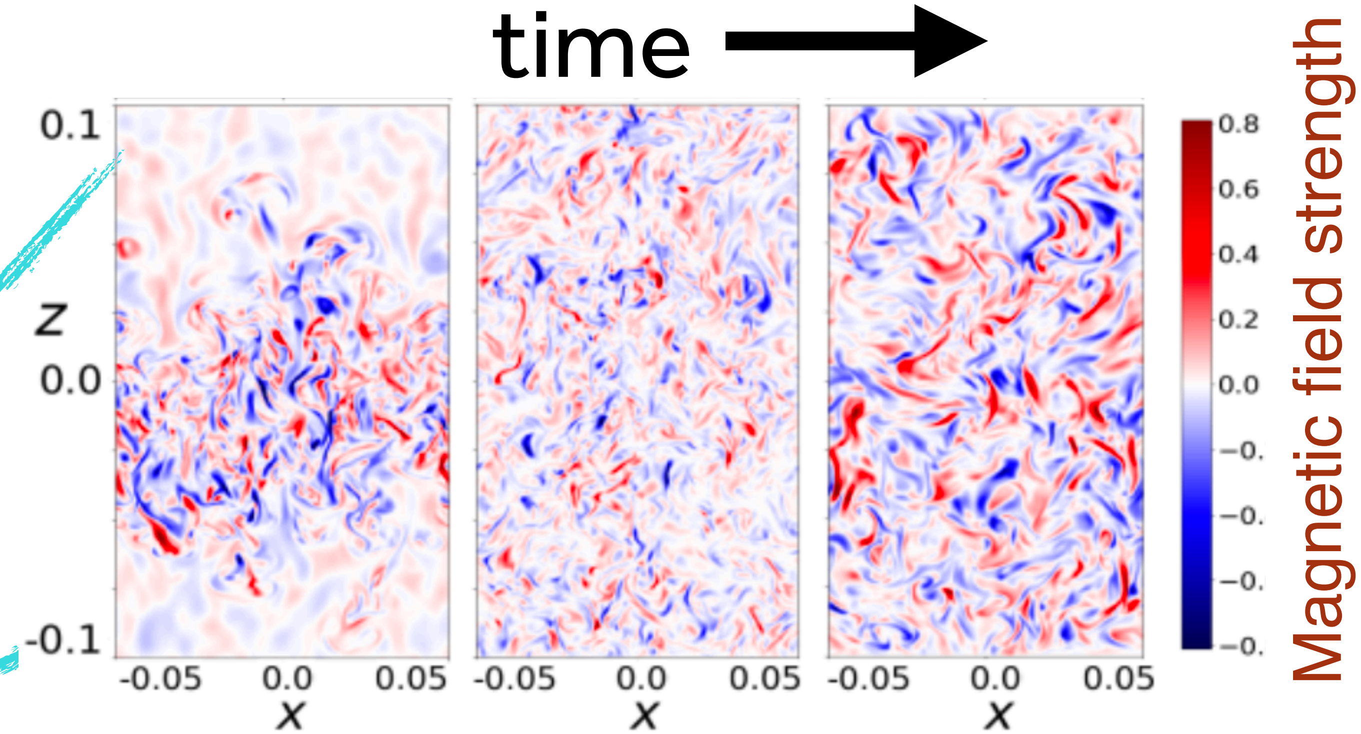
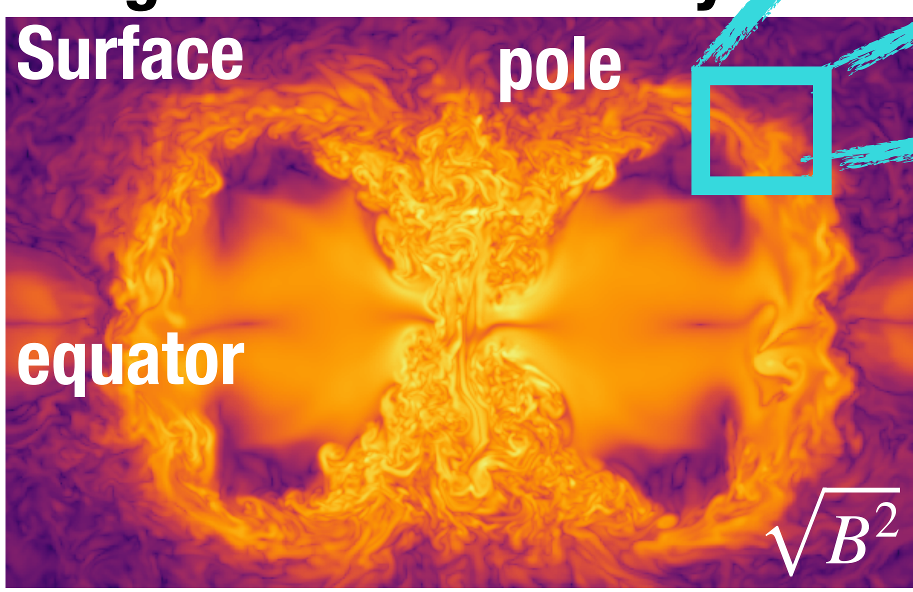
# Small-scale effects?

Understand the local problem, and the the scales involved ( e.g. viscous, resistive scales)




Skoutnev, ERM+ (2021)

**Merger remnant at early times**




**Meridional view of the remnant**

What small-scale dynamo processes operate during the merger? Rayleigh-Taylor dynamo?

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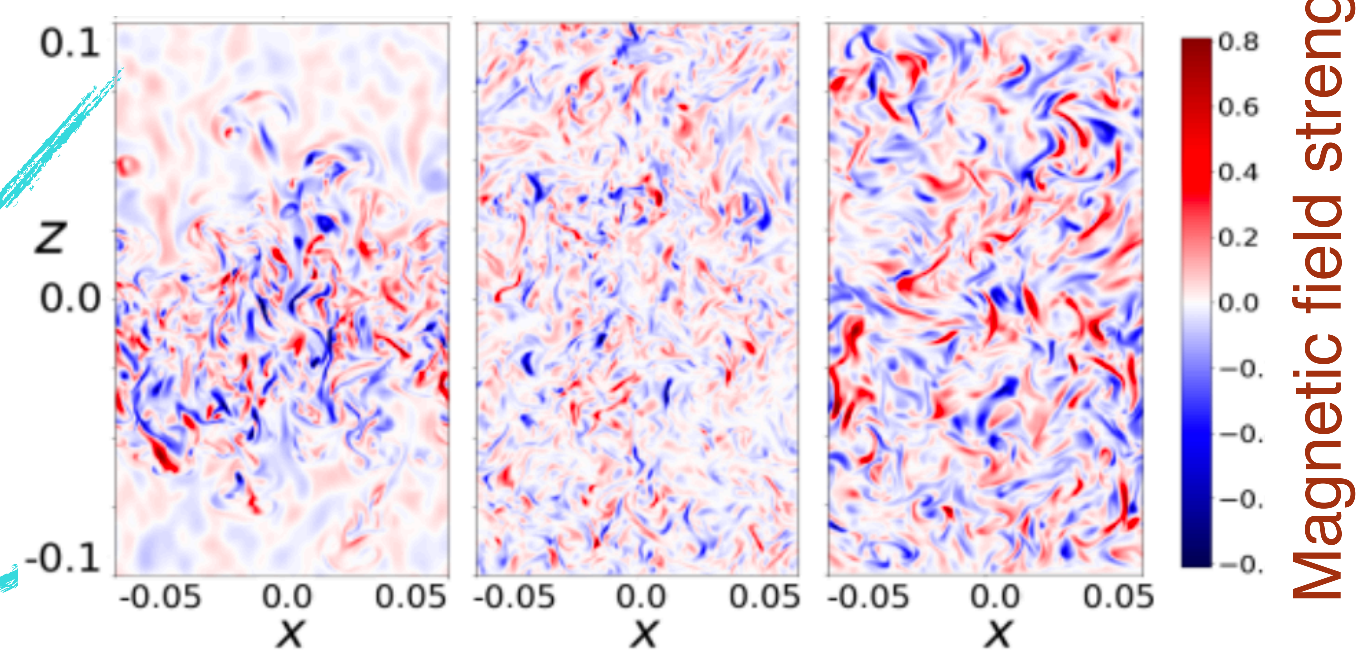
time →

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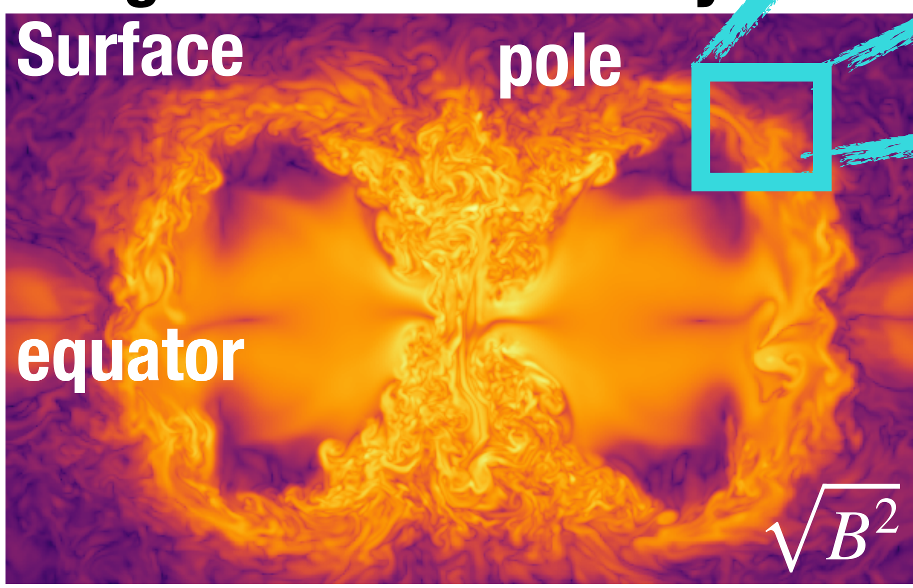


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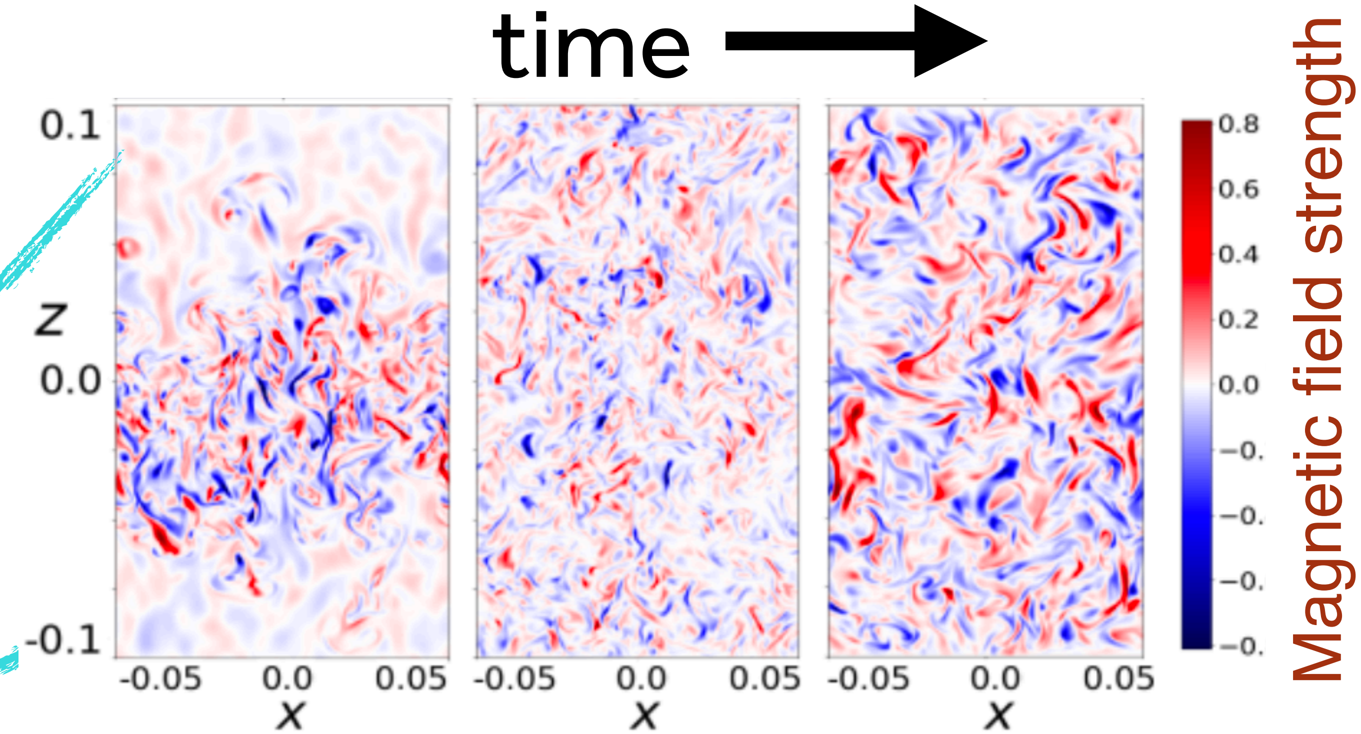


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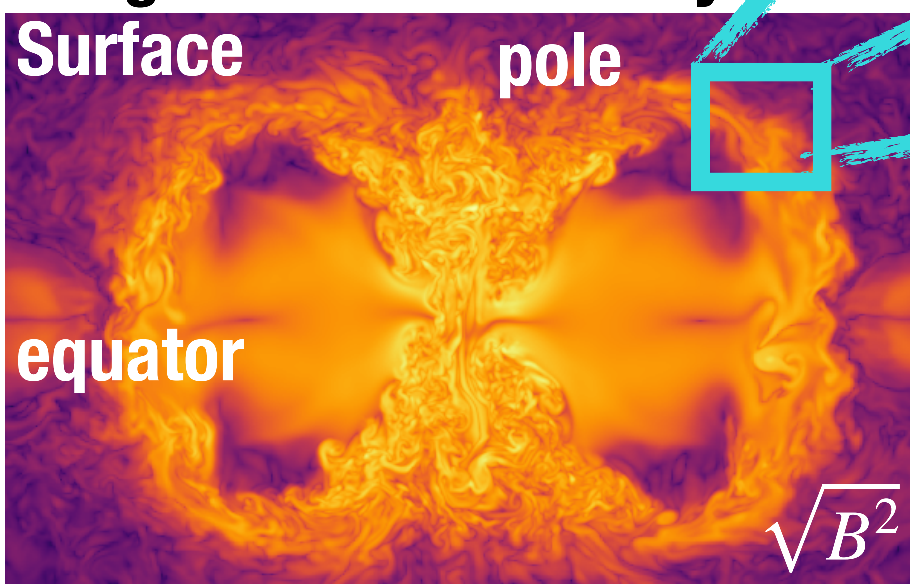


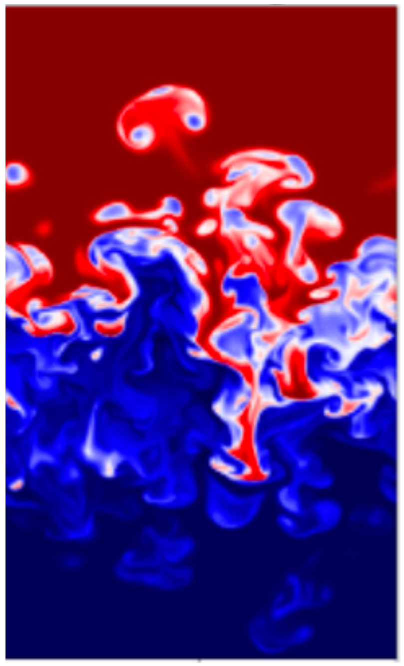

**Meridional view of the remnant**

What small-scale dynamo processes operate during the merger? Rayleigh-Taylor dynamo?

**Need a <u>effective</u> framework to model dynamo effects in global merger simulations!**

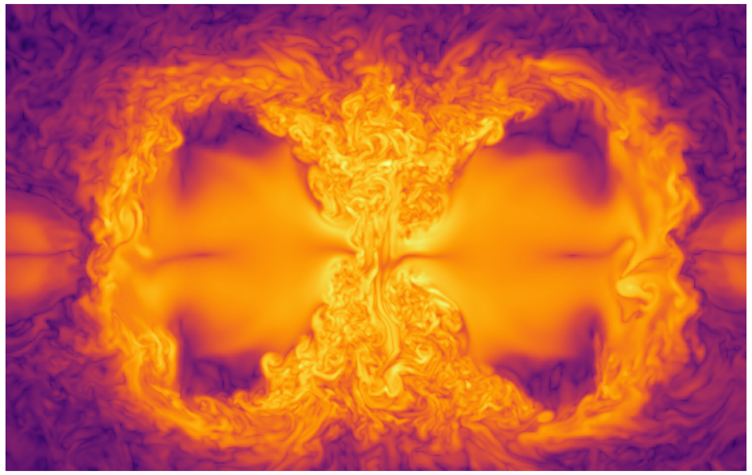
# Vastly different scales

$\ll 10^{-4}\,\mathrm{m}$



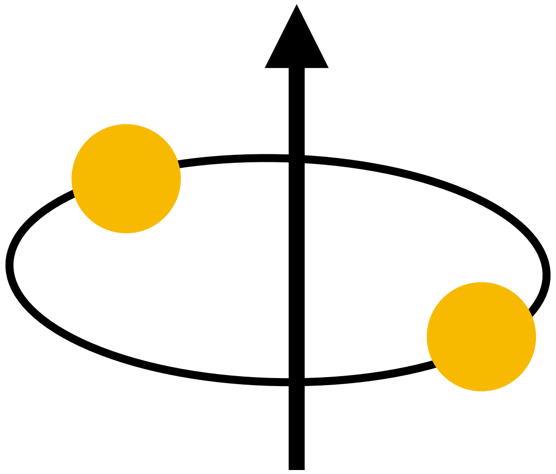
**Small-scales**

$\sim 100\,\mathrm{m}$



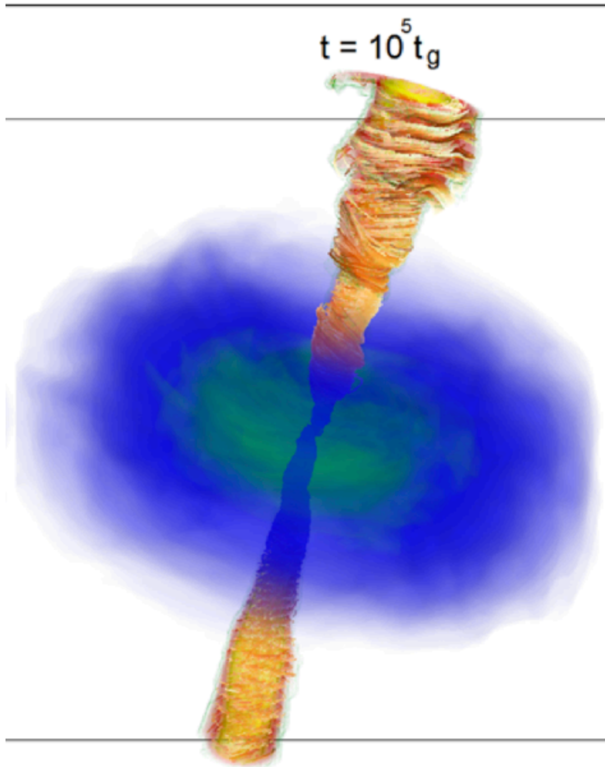
**Shear layer**

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



**Binary**

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




**Jet**

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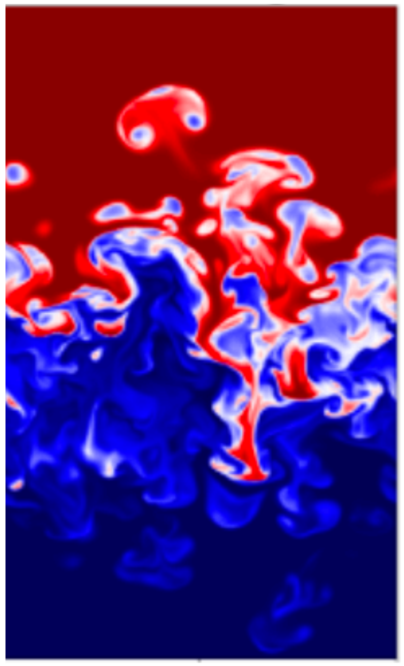

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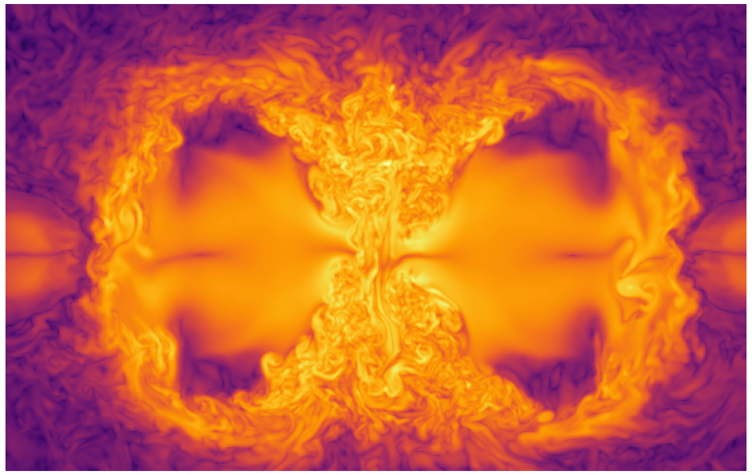

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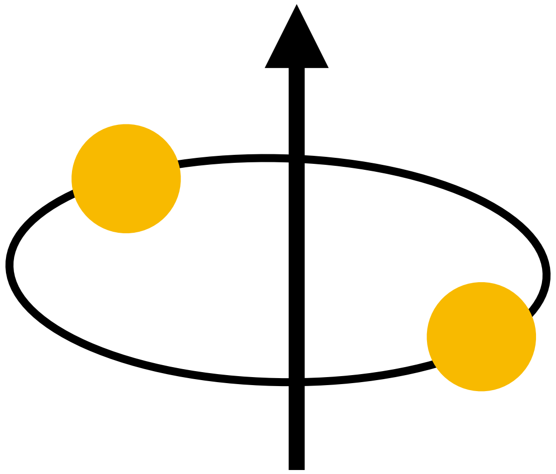

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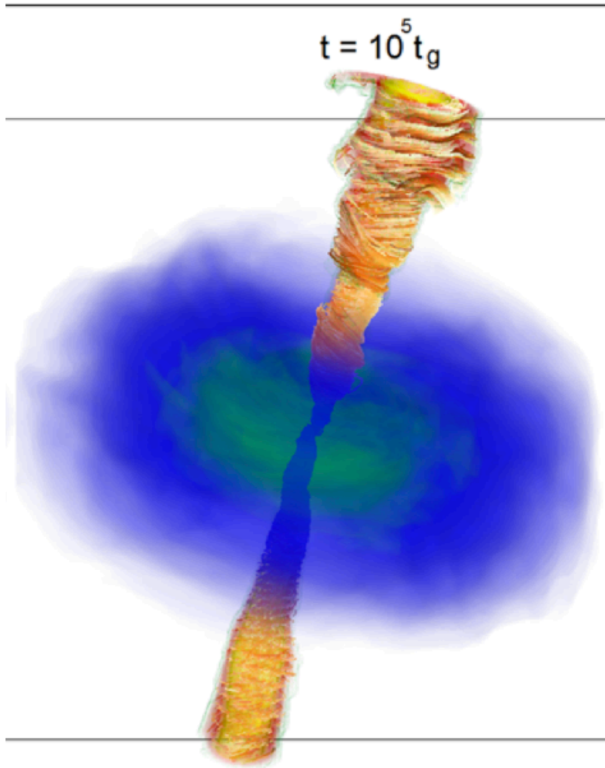


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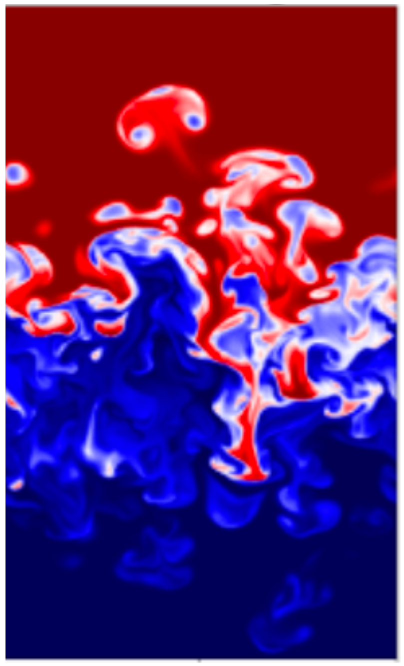

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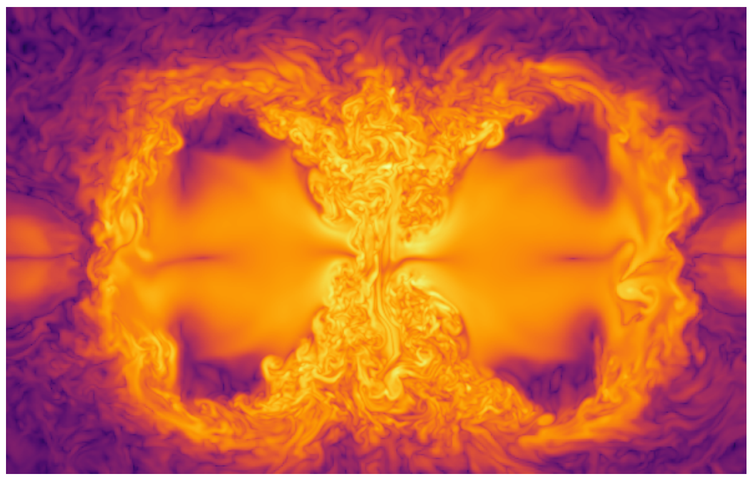

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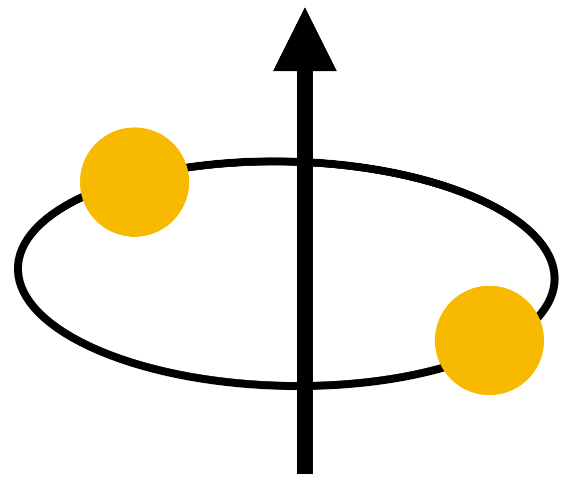

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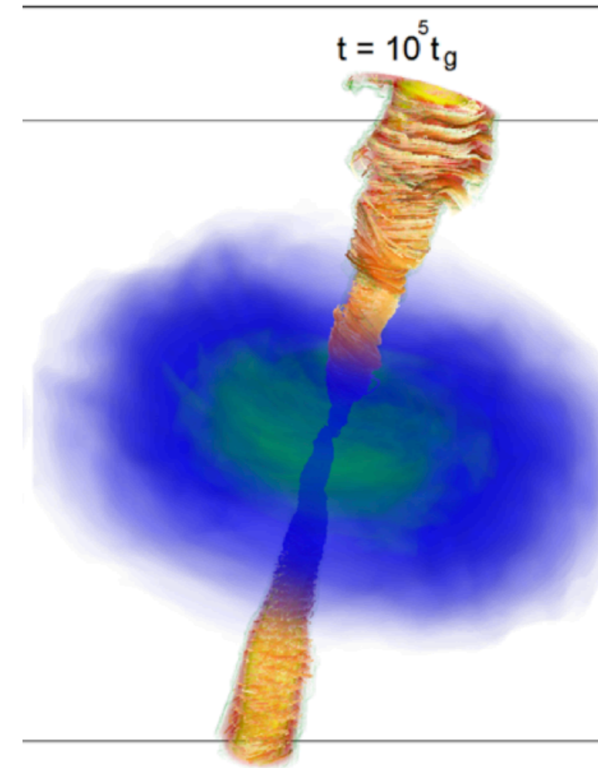


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**? Ab-initio modeling ?**

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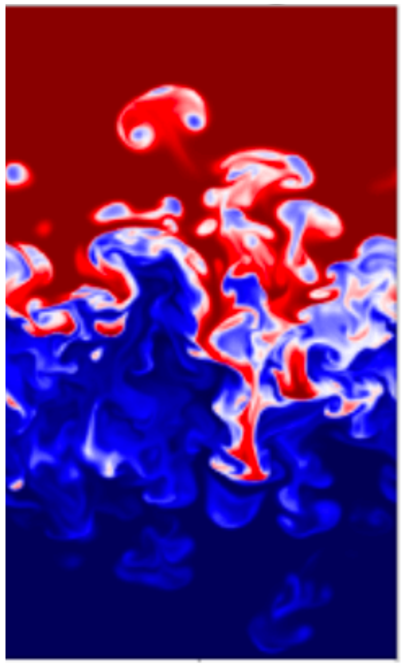

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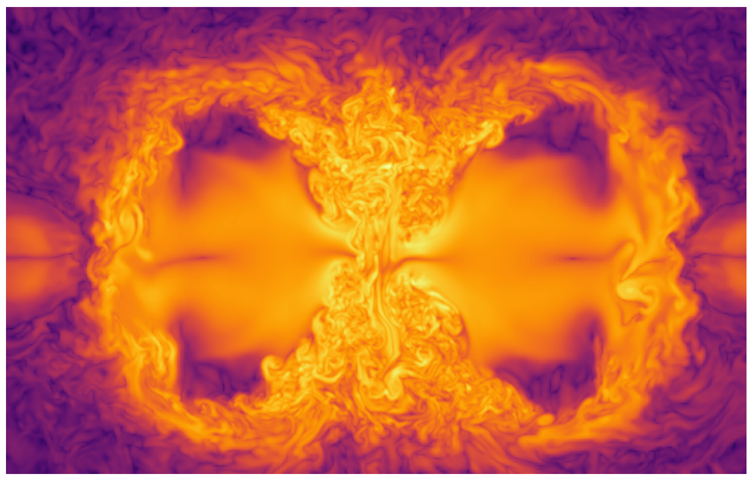

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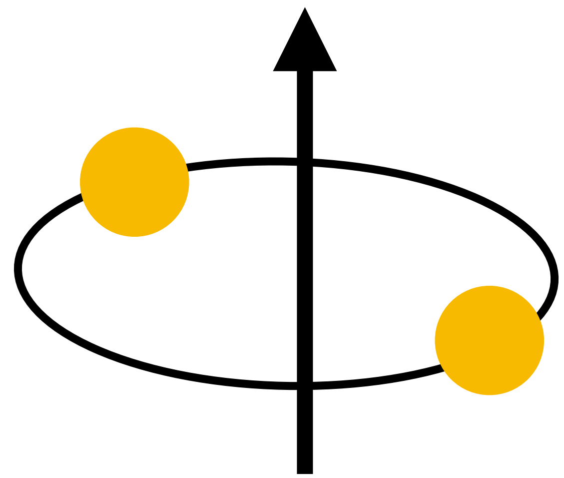

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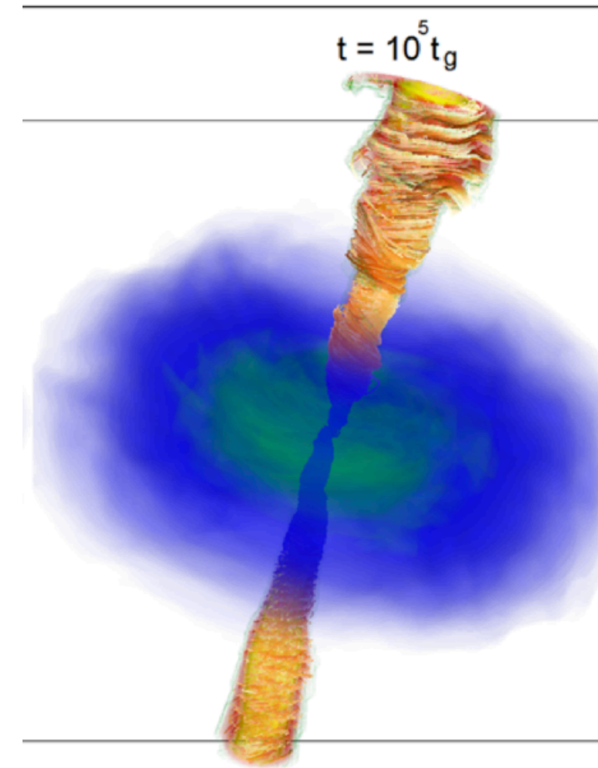


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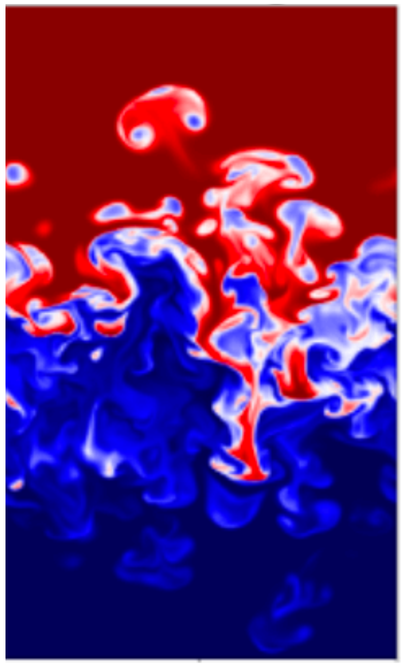

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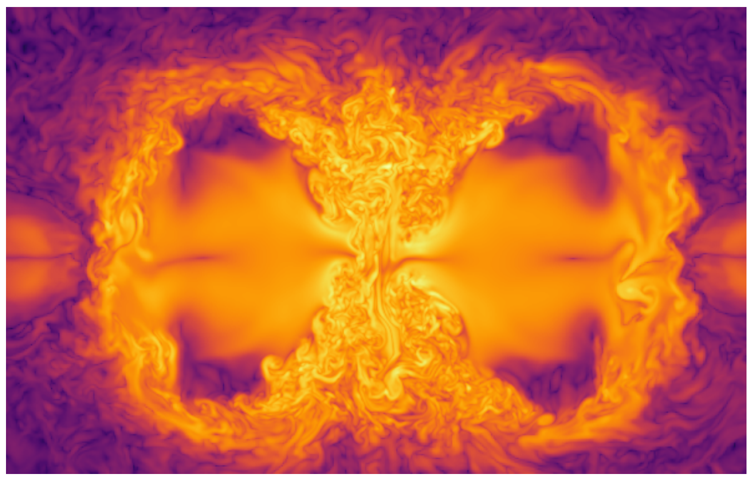

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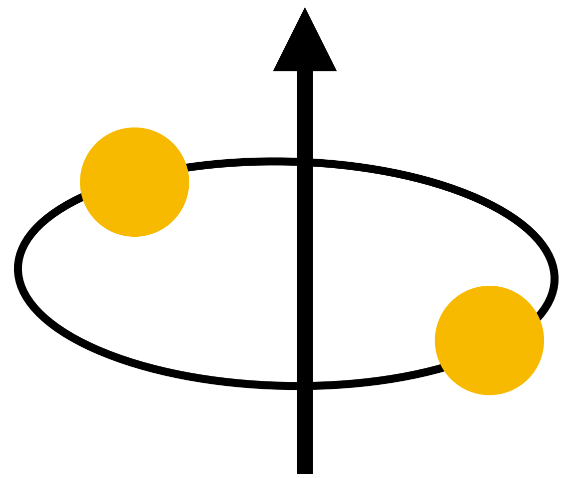

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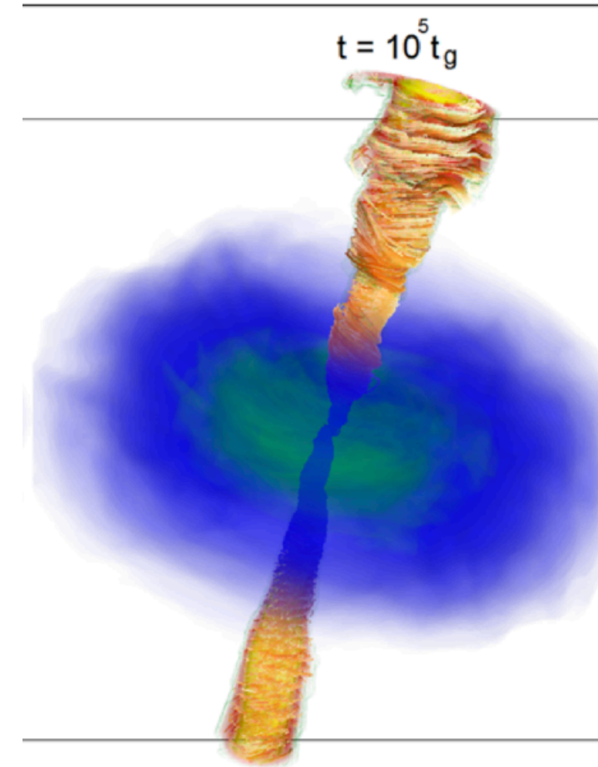



**Jet**

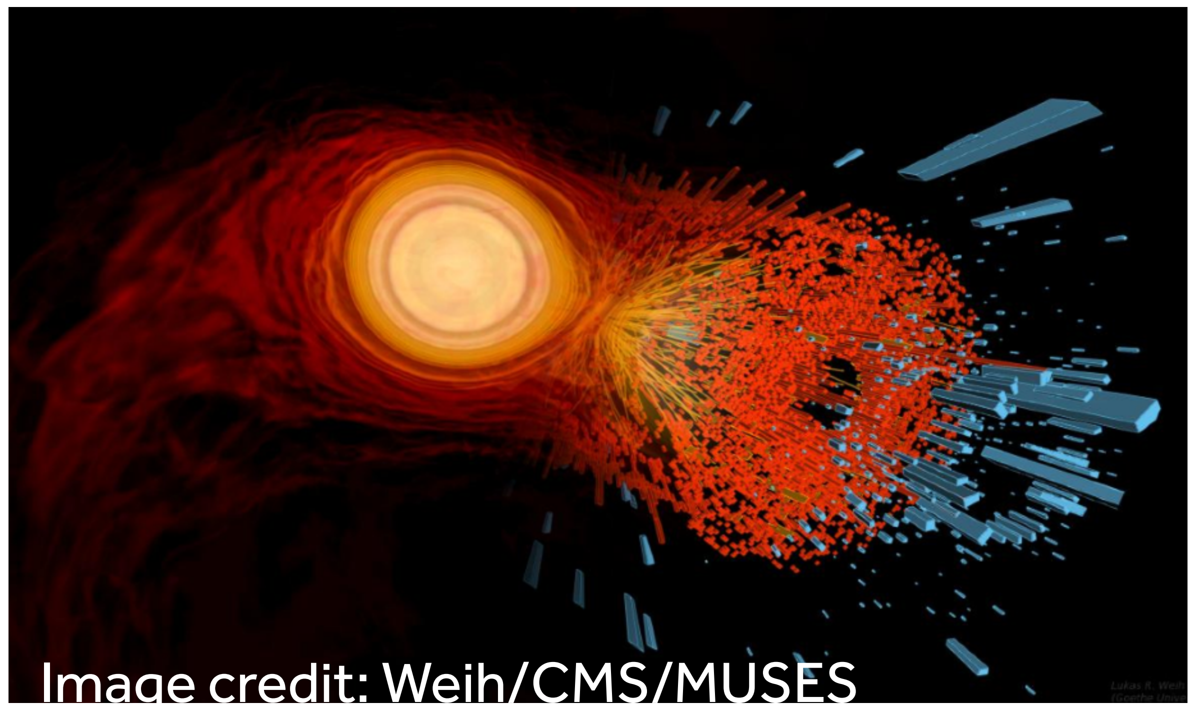
**Need a multi-scale approach to capture (effects of) all scales!**

**?** **Ab-initio modeling ?**

**✓** **Effective models ?**

# Inspiration from nuclear physics

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



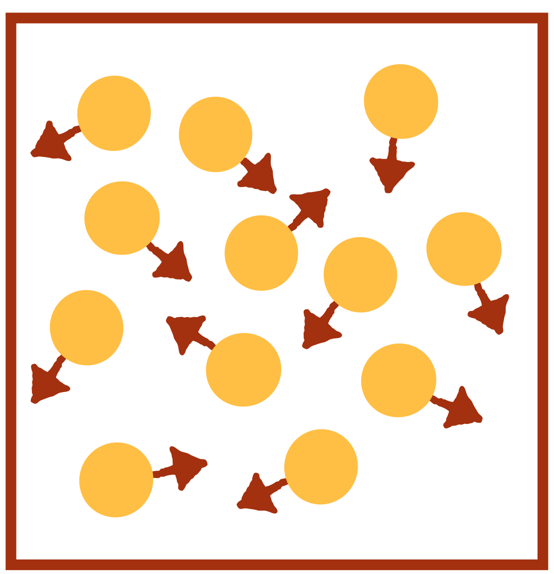

e.g., Romatschke+(2008),
Denicol+(2012,2018,2019), Kovtun+(2019),
Bemfica+(2017,2022), and many others

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

# Hydrodynamics as an effective theory

**Hydrodynamics**

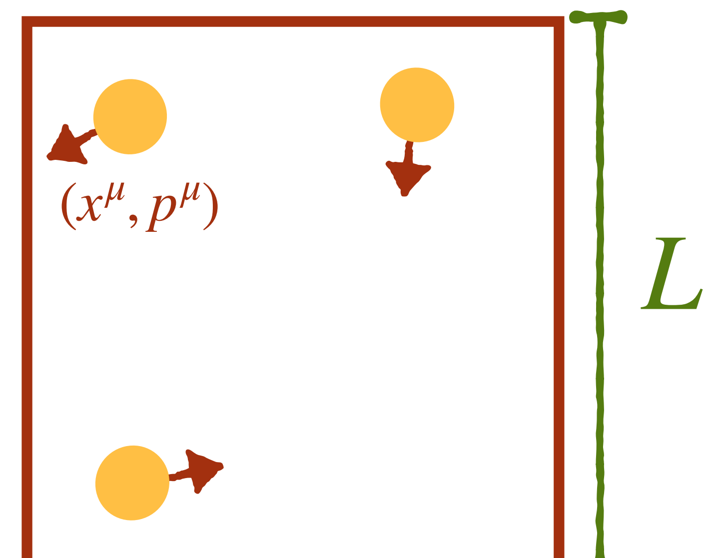
$$\nabla_\mu T^{\mu\nu}_{\rm hydro} = 0$$



**Collisional** $(\lambda \simeq 0)$

**Kinetic theory**

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




**Collisionless** $(\lambda \simeq L)$

. . .

**mean free path** $\lambda$ →

# 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**

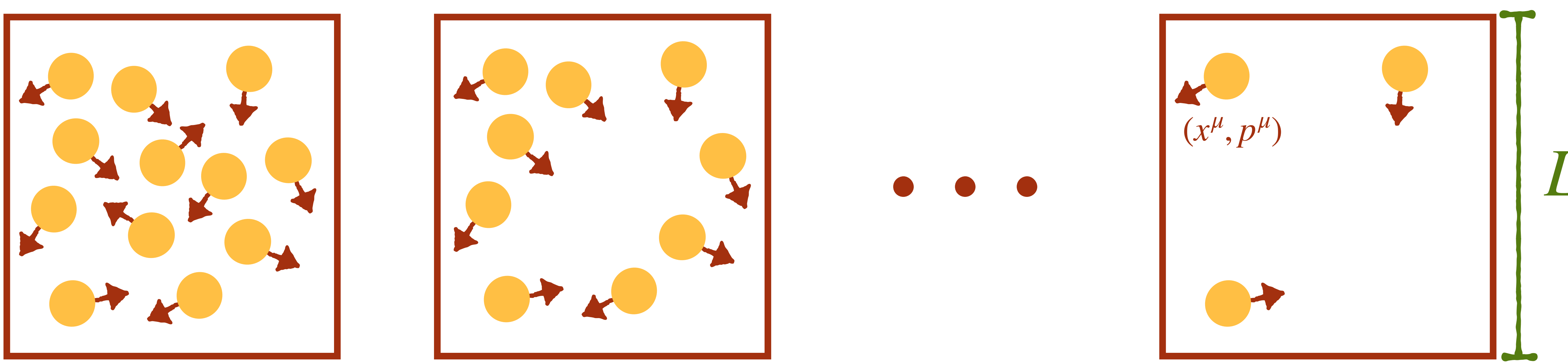
$$\nabla_\mu T^{\mu\nu}_{\rm hydro} = 0$$

**Dissipative Hydrodynamics**

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

**Kinetic theory**

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



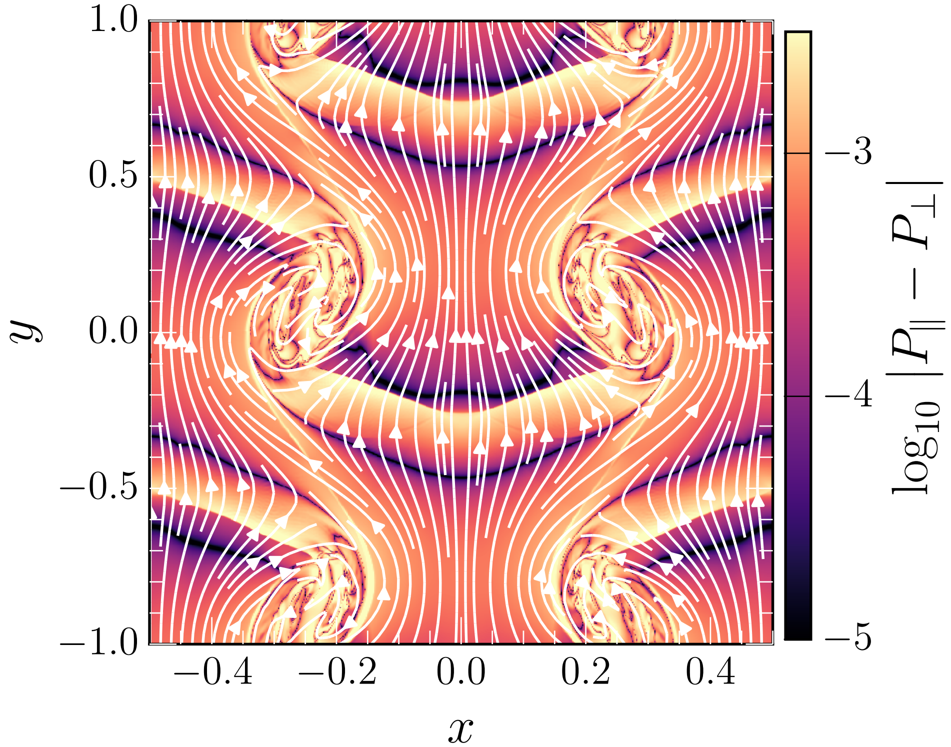

**Collisional** $(\lambda \simeq 0)$ — **mean free path** $\lambda$ → **Collisionless** $(\lambda \simeq L)$

# Dissipative Magnetohydrodynamics

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

**ERM** & Noronha (PRD 2021)

**Pressure anisotropy**

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# Dissipative Magnetohydrodynamics

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

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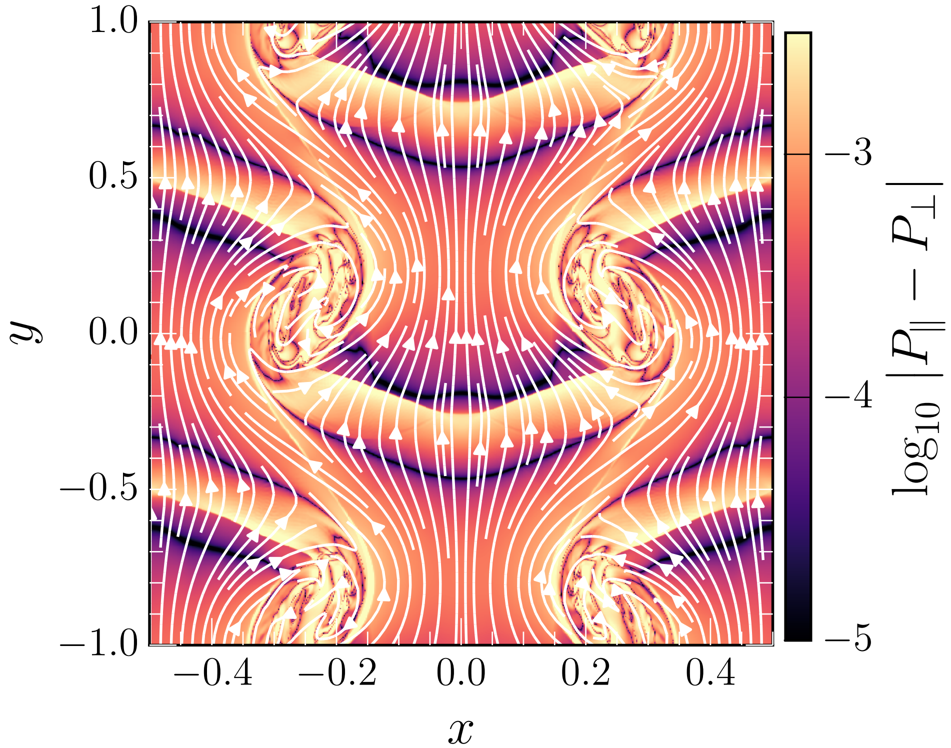


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Novel fully flux conservative approach with stiff relaxation.

**Well suited to handle highly turbulent astrophysical flows!**

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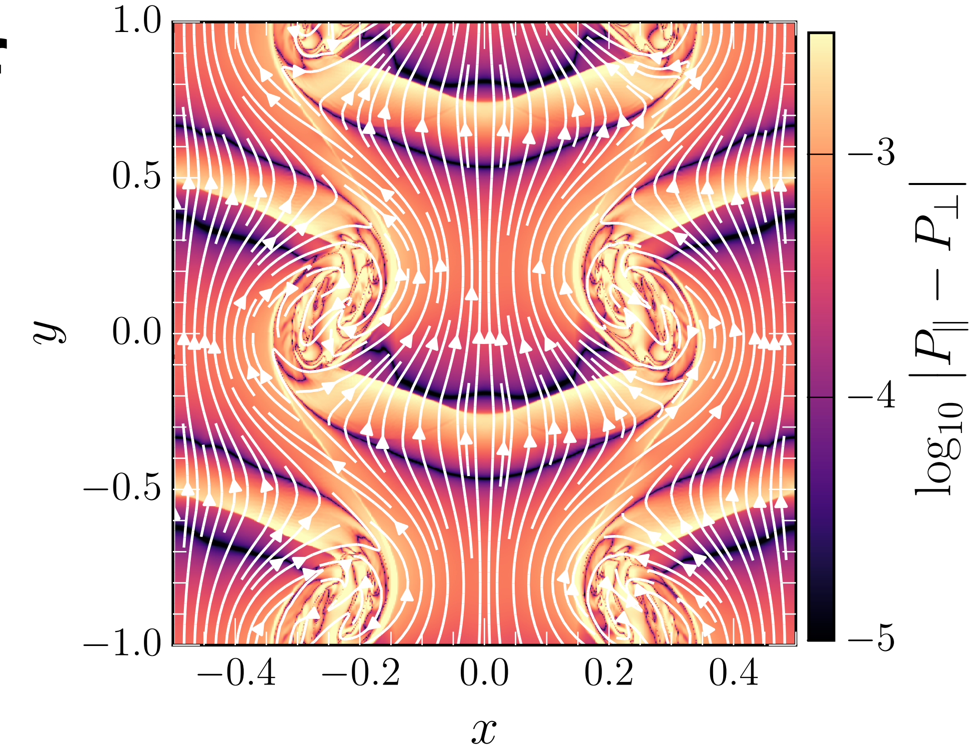


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# Applications to dynamo physics

Can use same philosophy to think about mean-field dynamo theory.

Common in other contexts:

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Supernova (White, Burrows+,…)

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For now, try a simple $\alpha\Omega$ – dynamo in the near ideal GRMHD regime.

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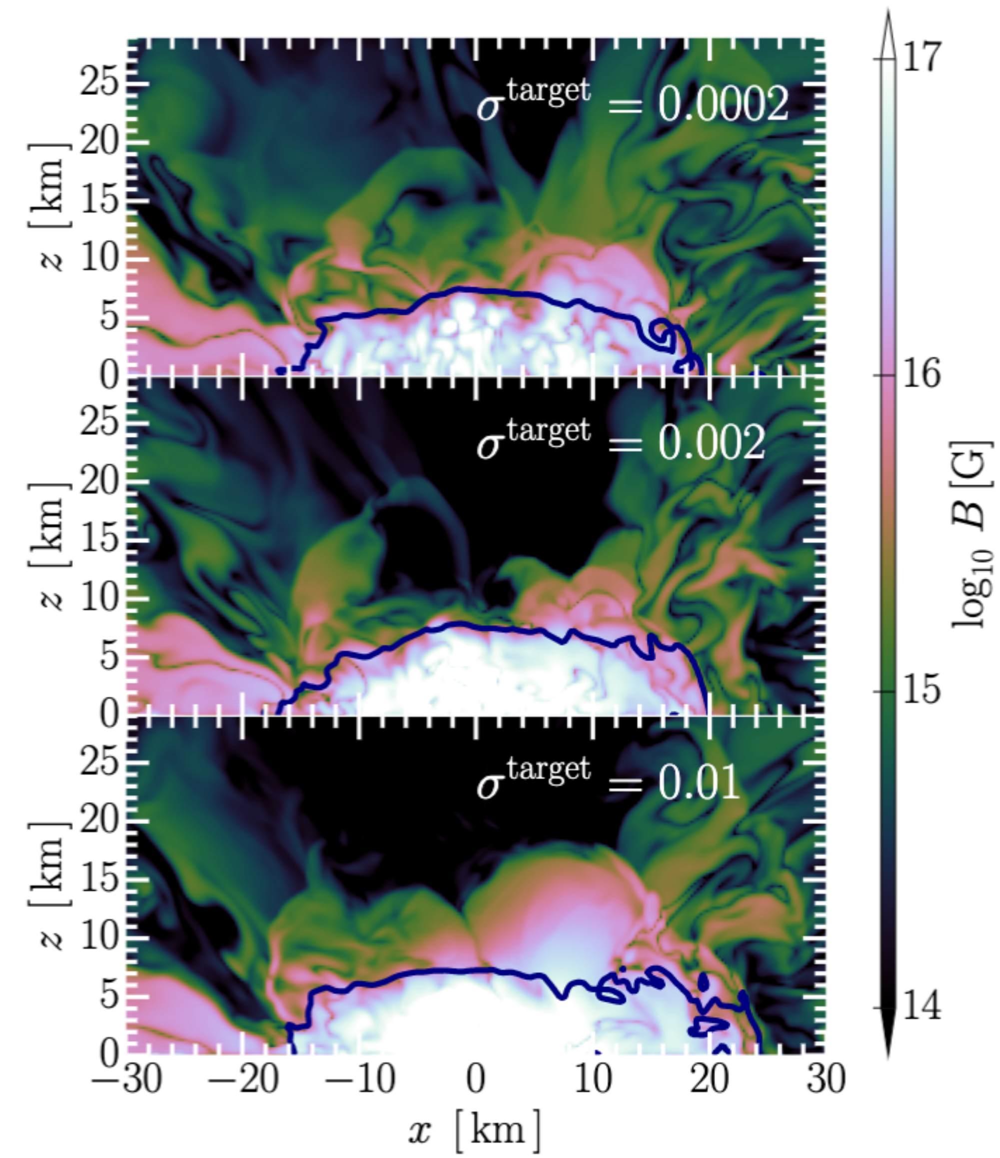
**Amplification during merger**




ERM+ (in prep)

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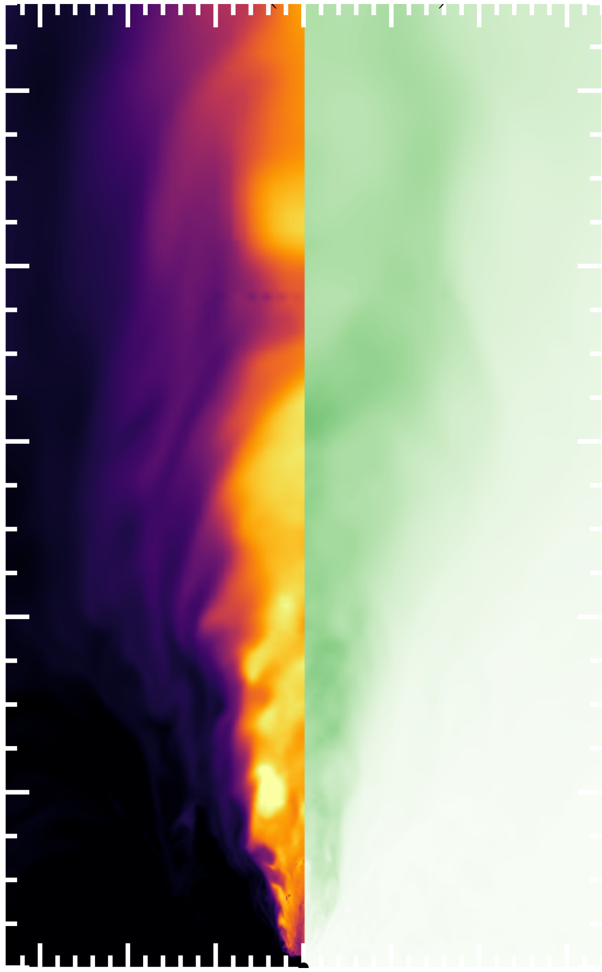
$$\vec{E} = -\vec{v} \times \vec{B} + \alpha \vec{B} + \beta \vec{J} \times \vec{B}$$

# Thinking about a model

Question: Can a hypermassive neutron star inject kHz variability into a jet-like outflow?

- Post-merger oscillations strongest during and shortly after merger
- Likely requires production of ultra-strong magnetic fields during merger
- Variability may correlate with equation of state, but also with magnetic field topology



# Simulation setup

ERM & Quataert (ApJL 2023)

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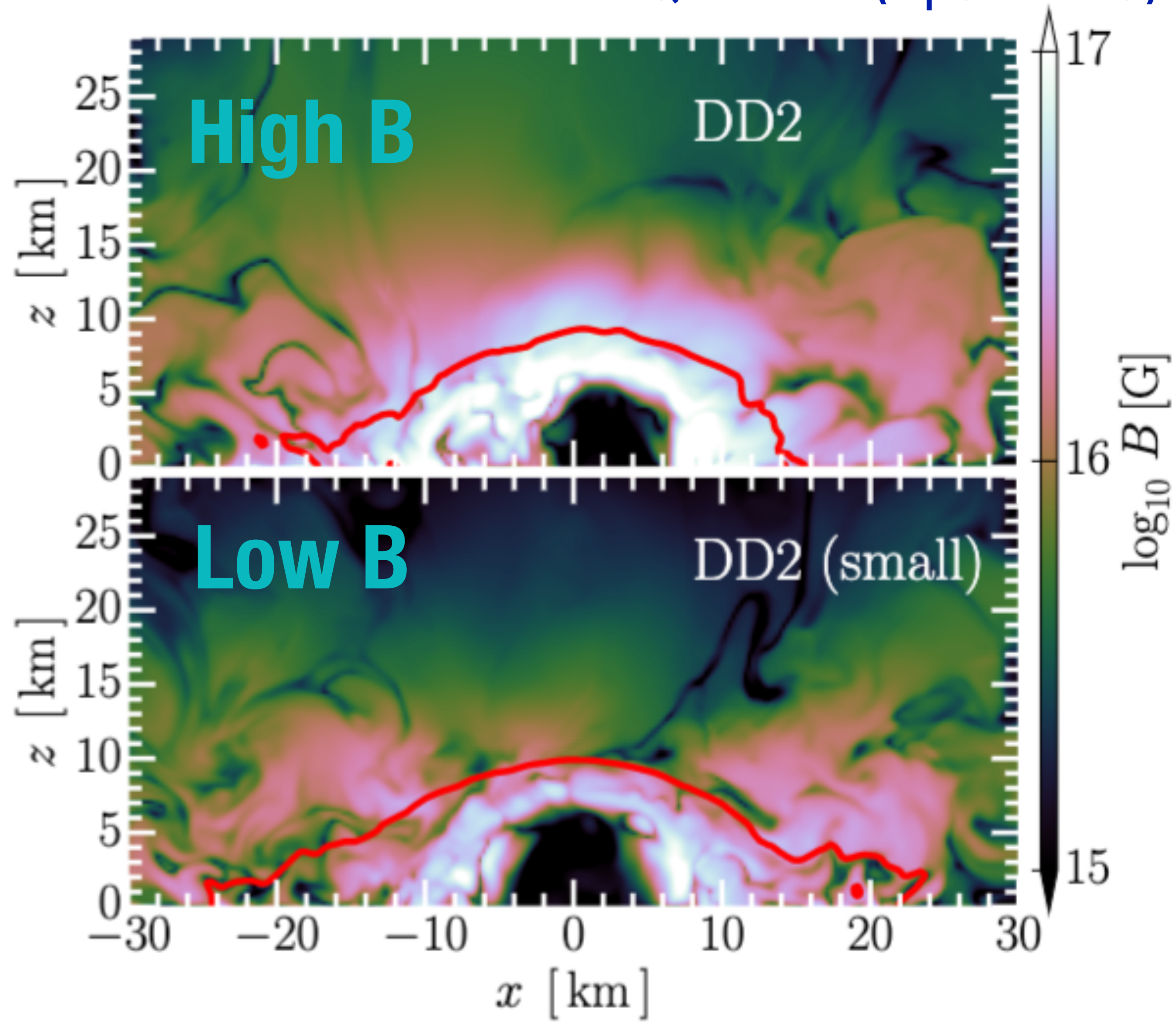
- Study two magnetic field configurations, leading to magnetization $\sigma = 0.01;\ 0.001$ close to the surface.

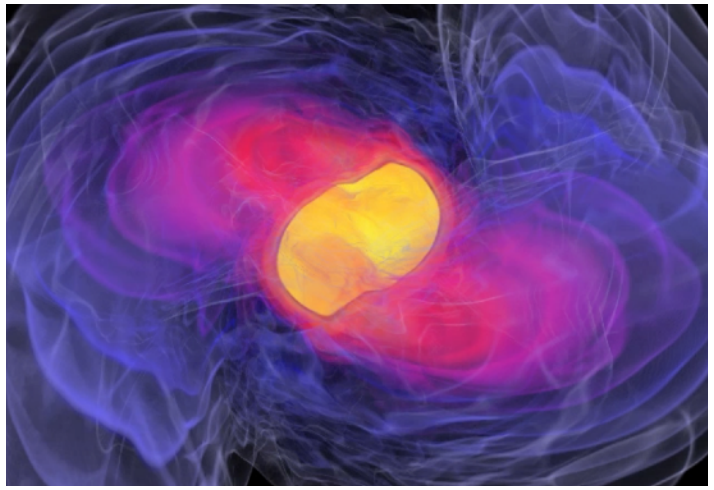


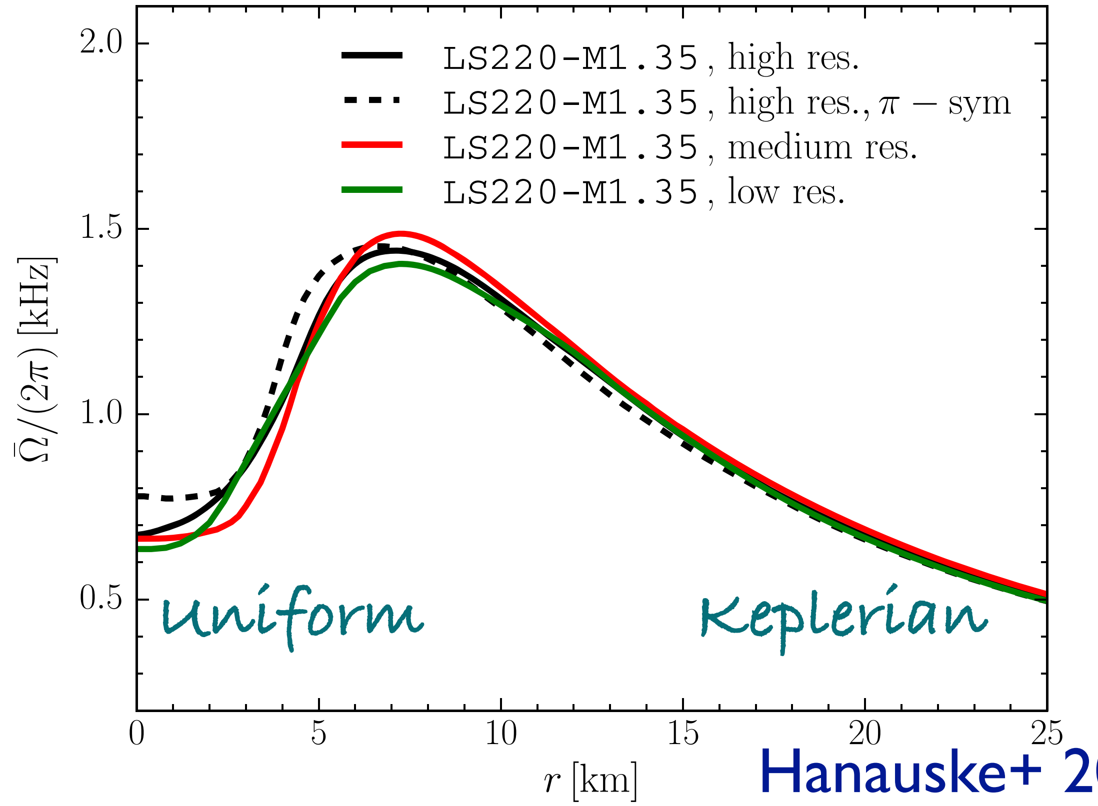

GW170817-like binary

- Initial field amplification due to $\alpha$-dynamo, then self-consistent evolution

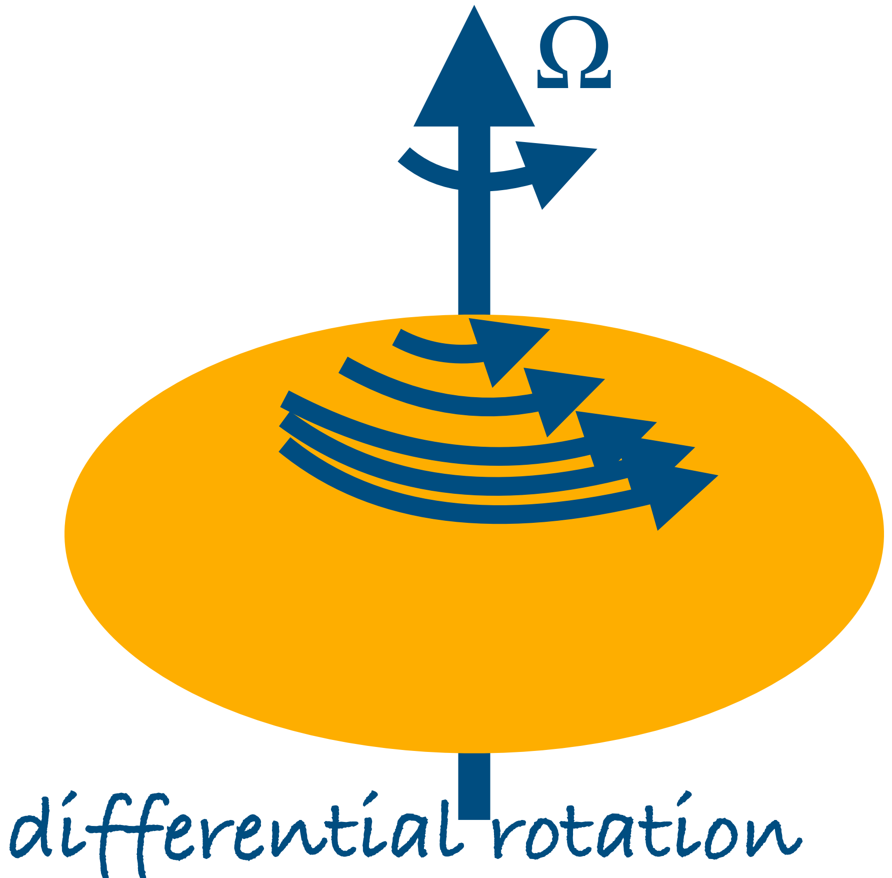
# Flares from hypermassive neutron stars

ERM & Quataert (ApJL 2023)






Hanauske+ 2016



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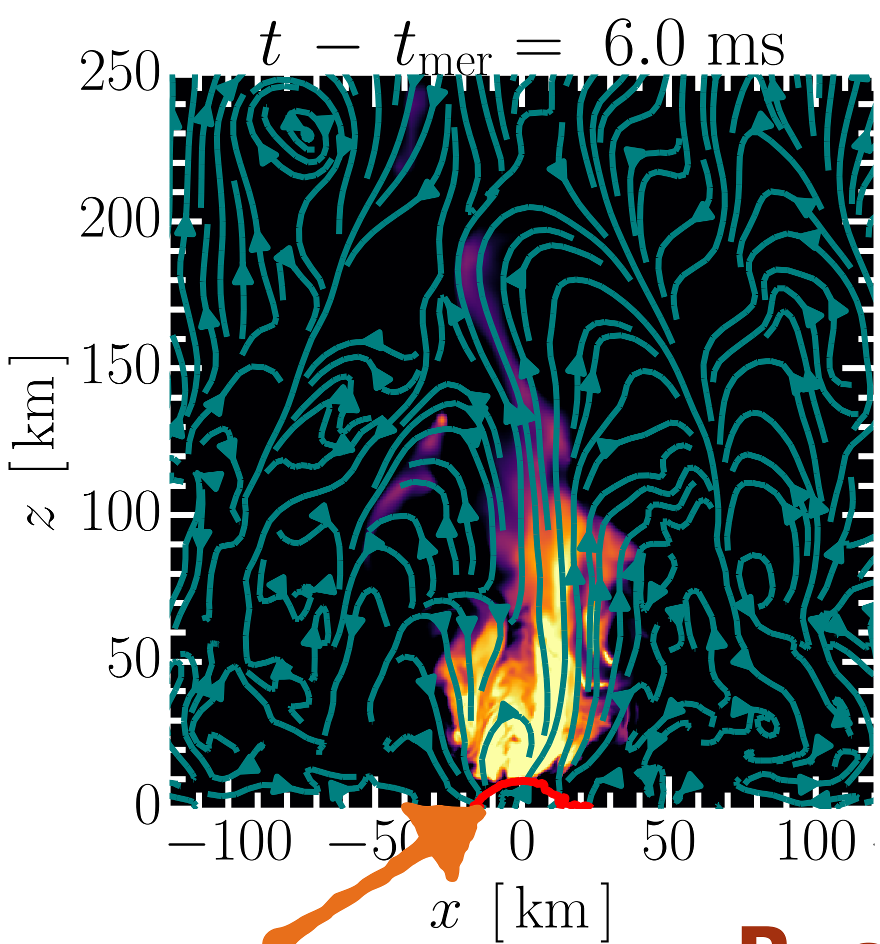


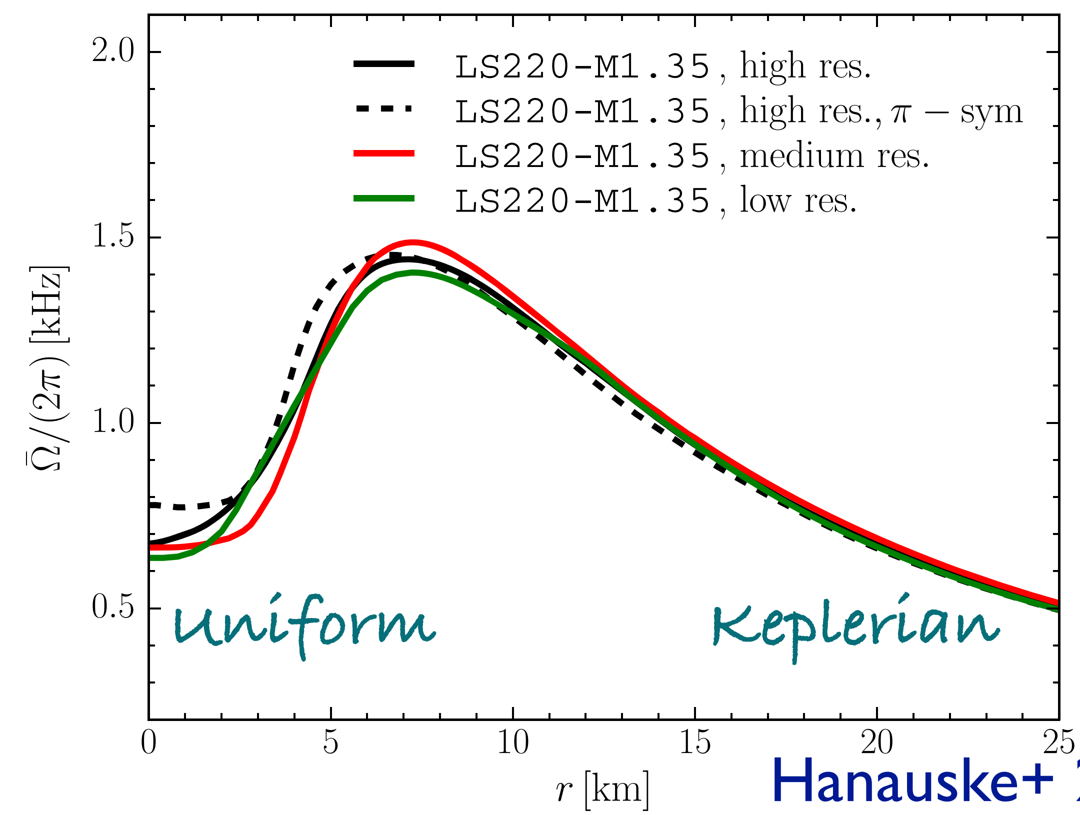


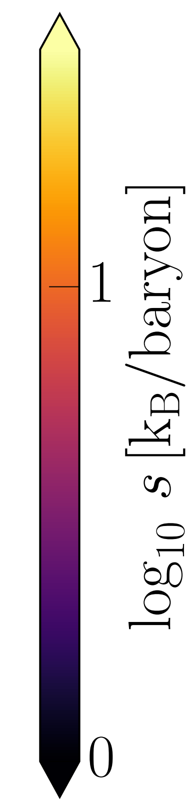


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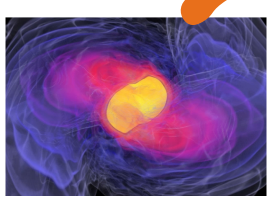
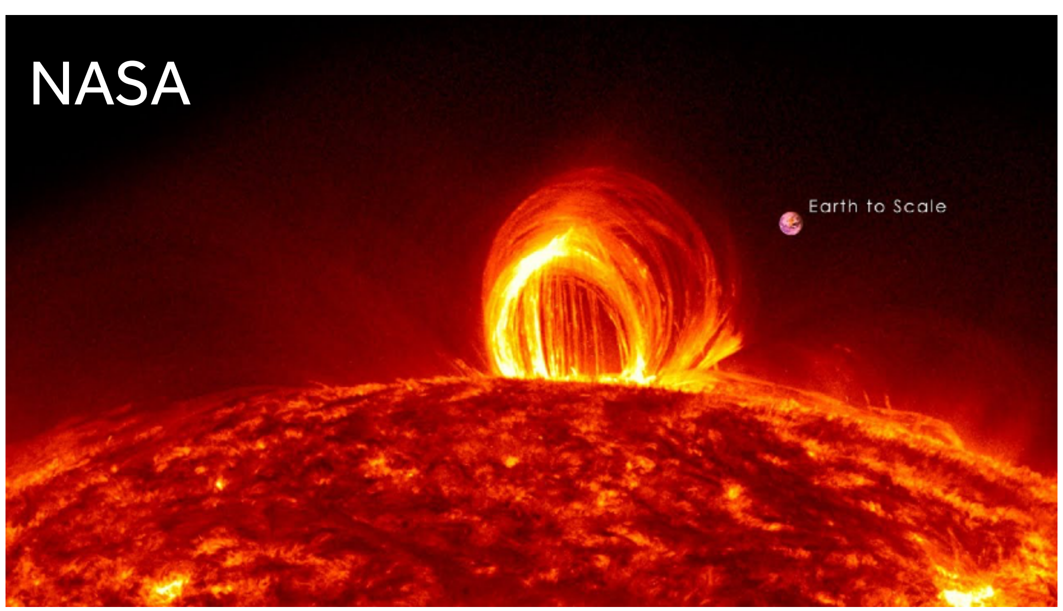


**Buoyant instabilities cause magnetic loops to rise up!**

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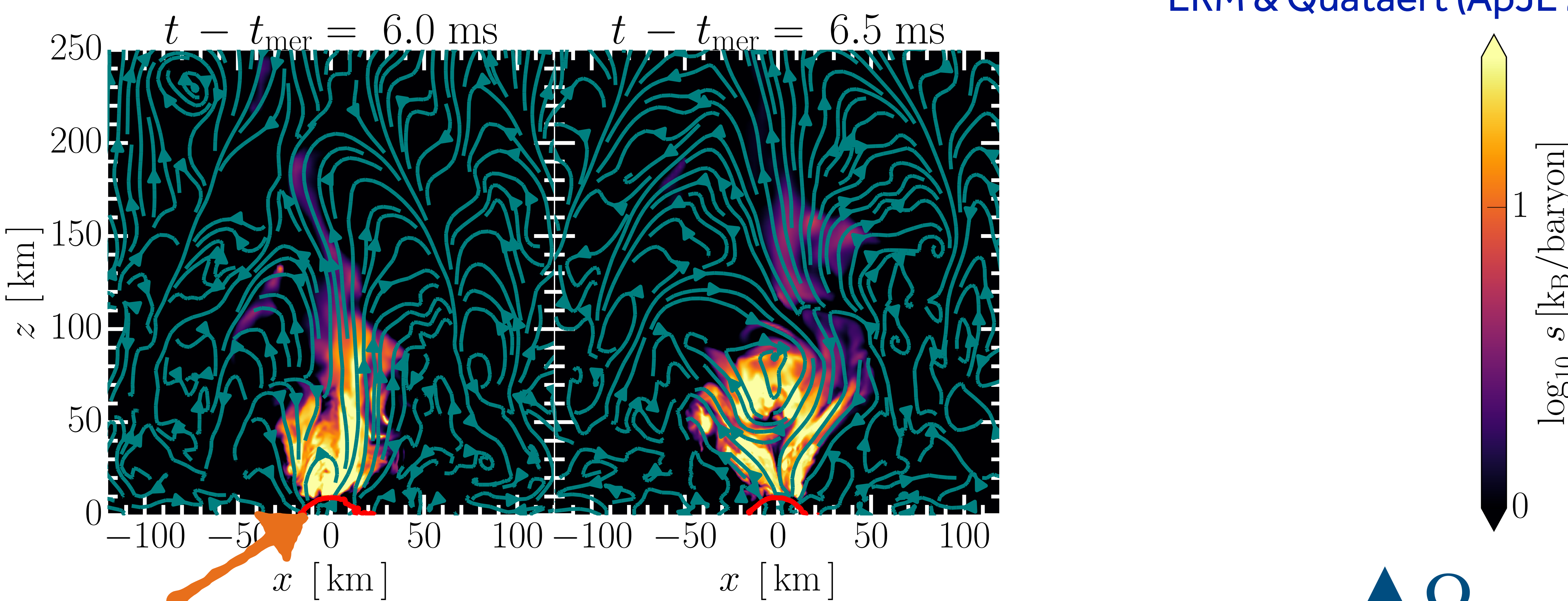
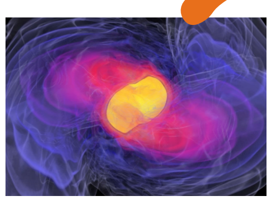
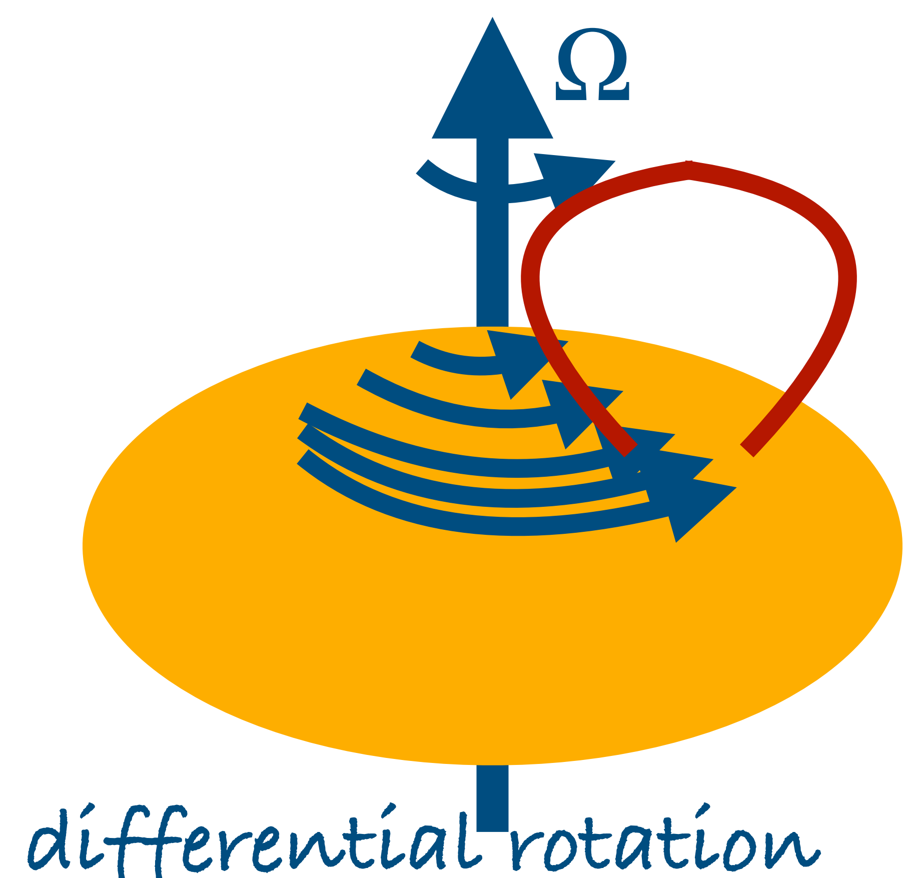


**Differential rotation twists the loop, causing it to inflate.**



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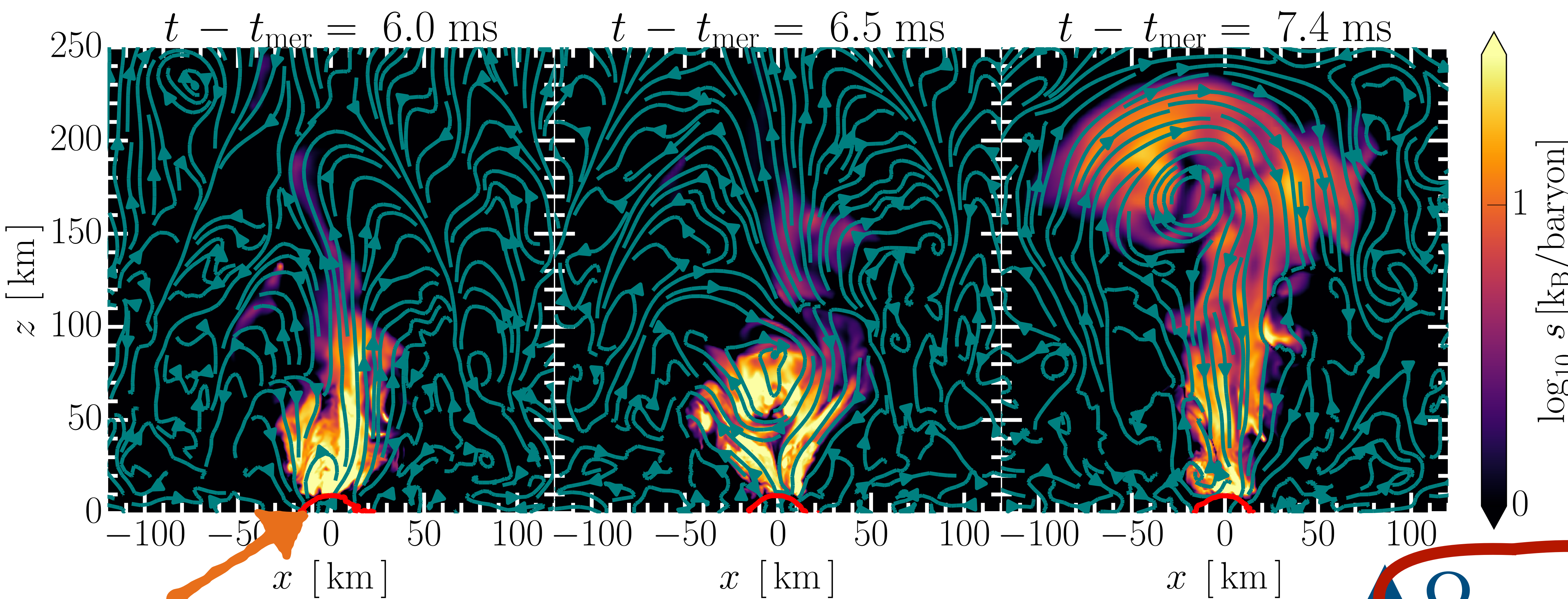
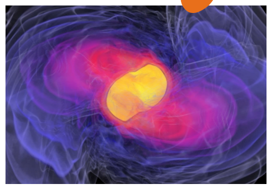
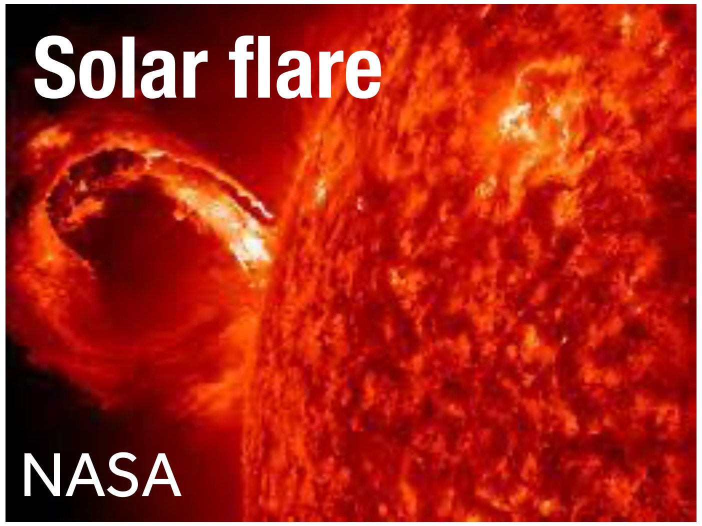
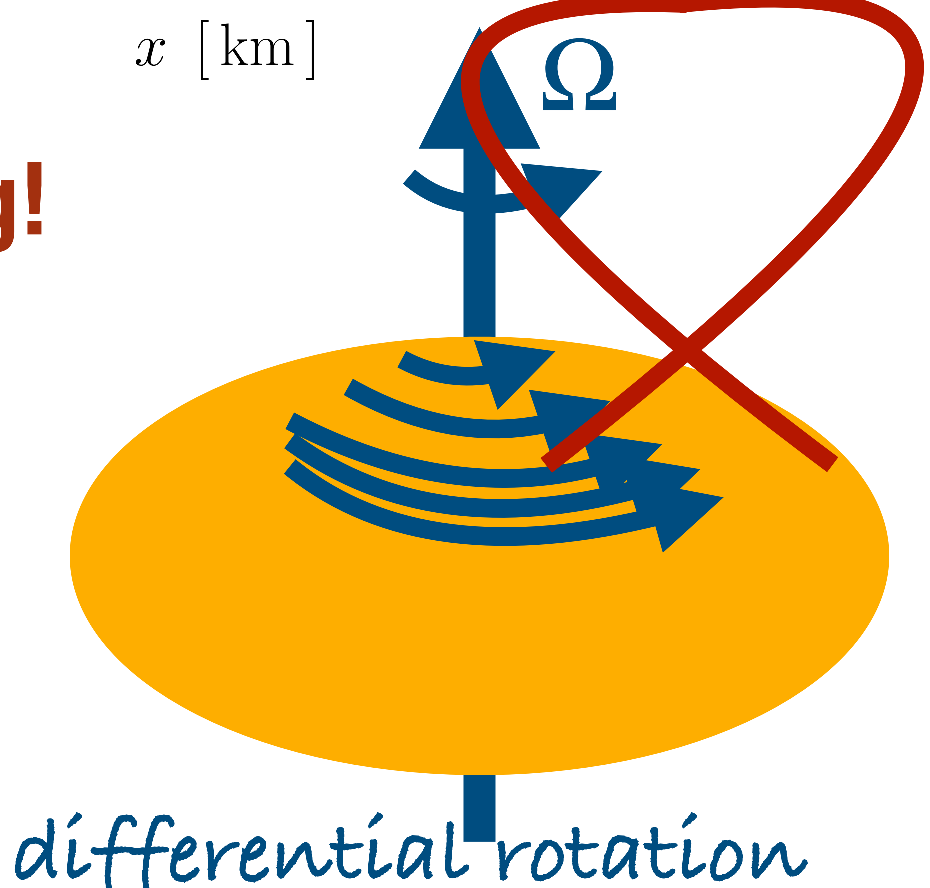


**Reconnection triggers flaring!**



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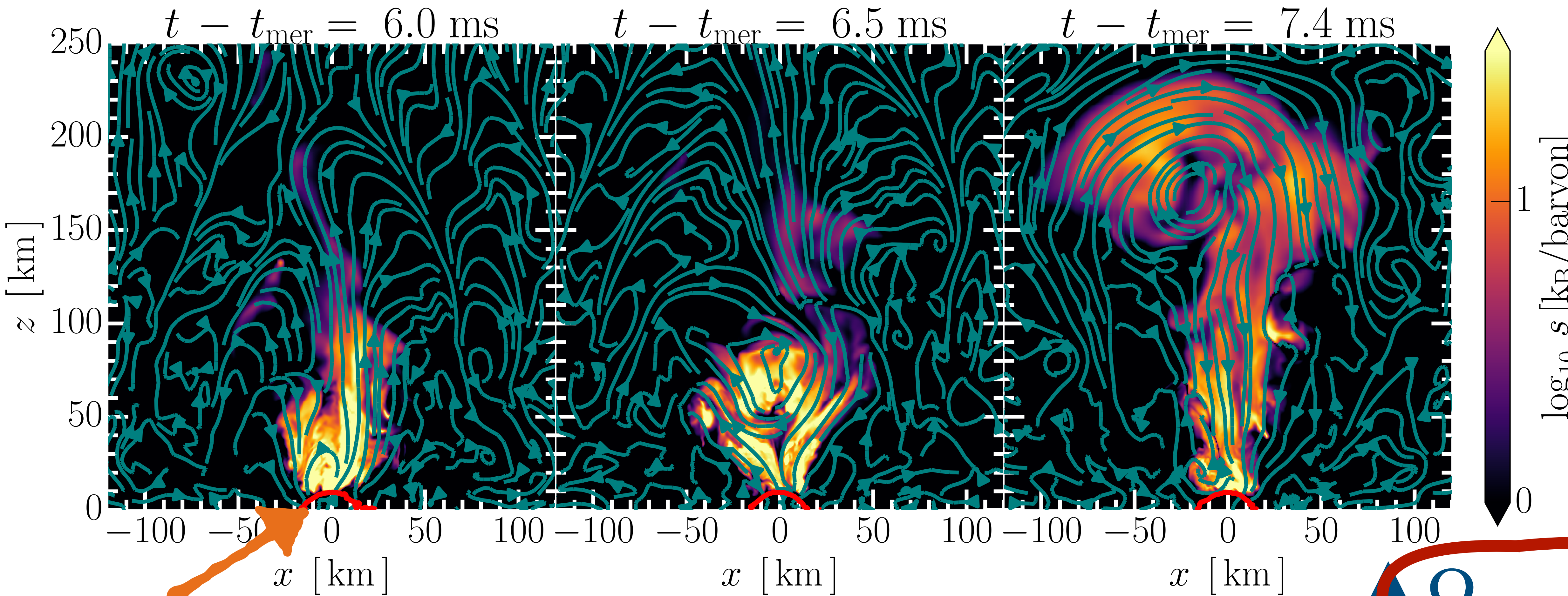


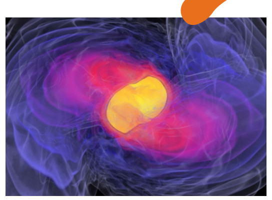

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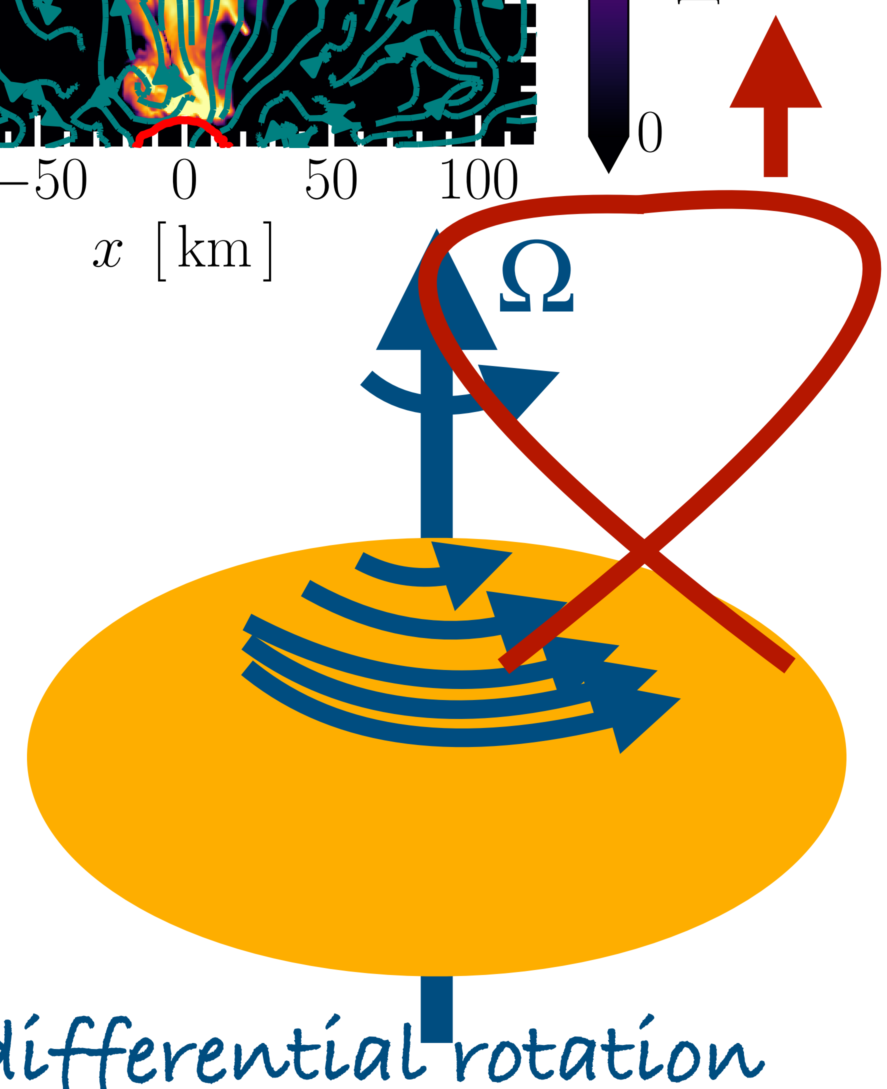
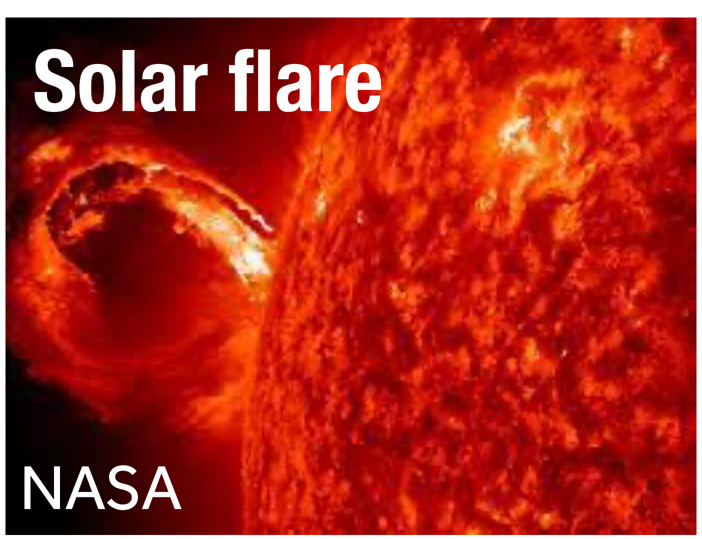
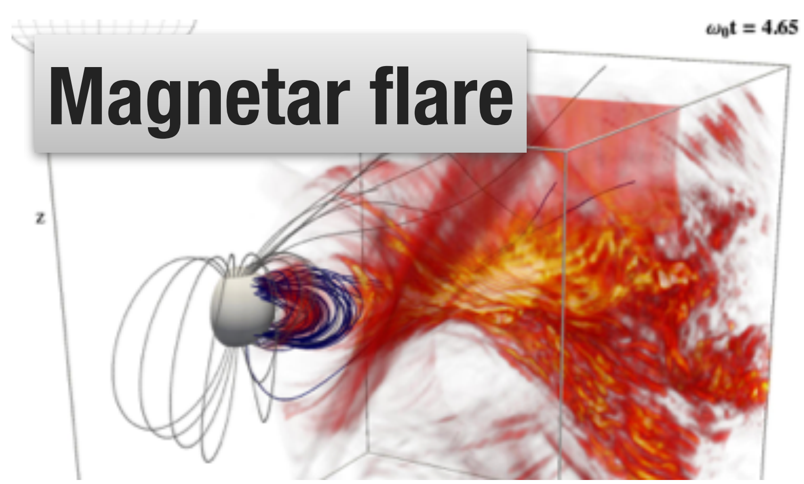


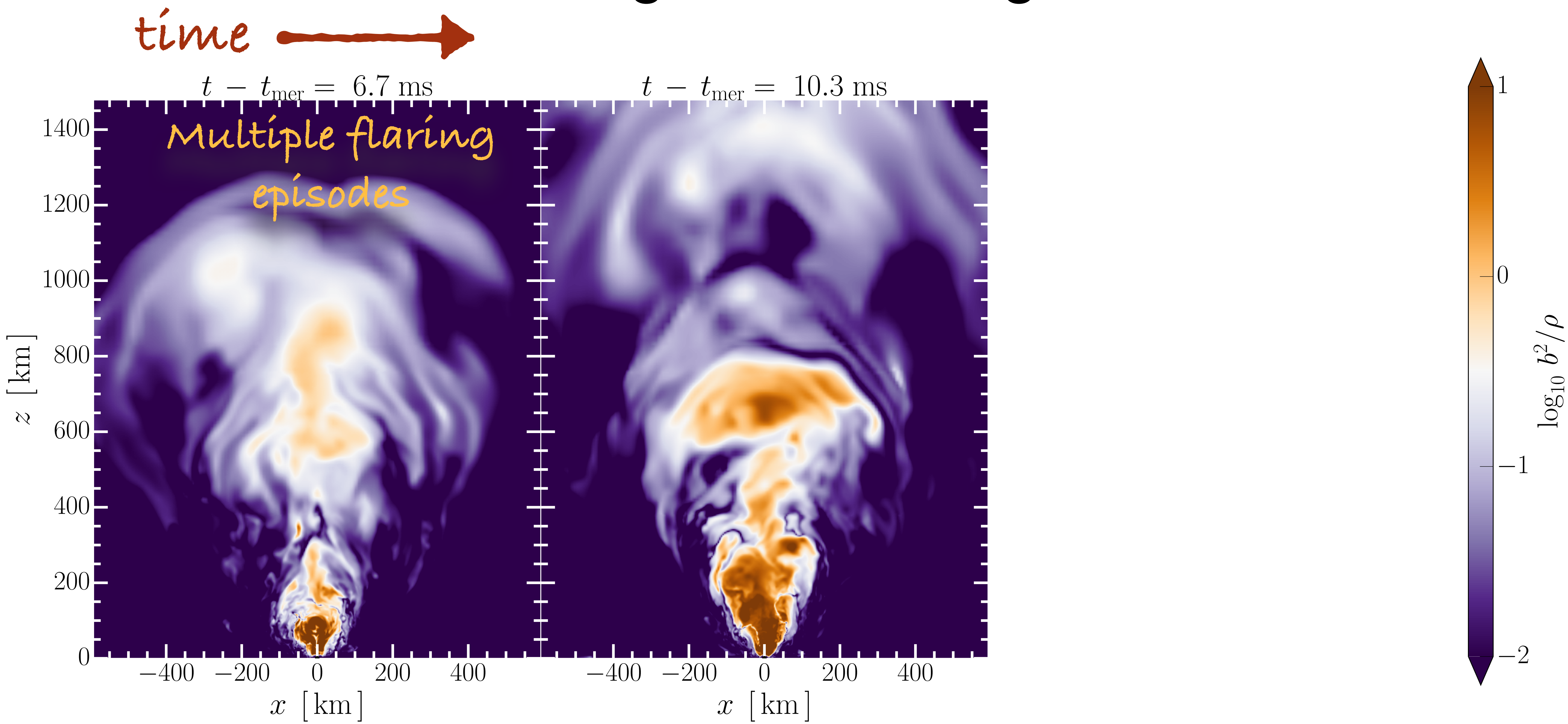




Mahlmann+(ApJL 2023, incl. ERM)

# Magnetically driven outbursts

ERM & Quataert (ApJL 2023)

Flares and quasi-periodic outbursts can be driven from ultra-magnetized mergers!




**Potential source of sGRBs or sGRB precursors**

See also Kluzniak & Ruderman (1998); Beloborodov (2014)

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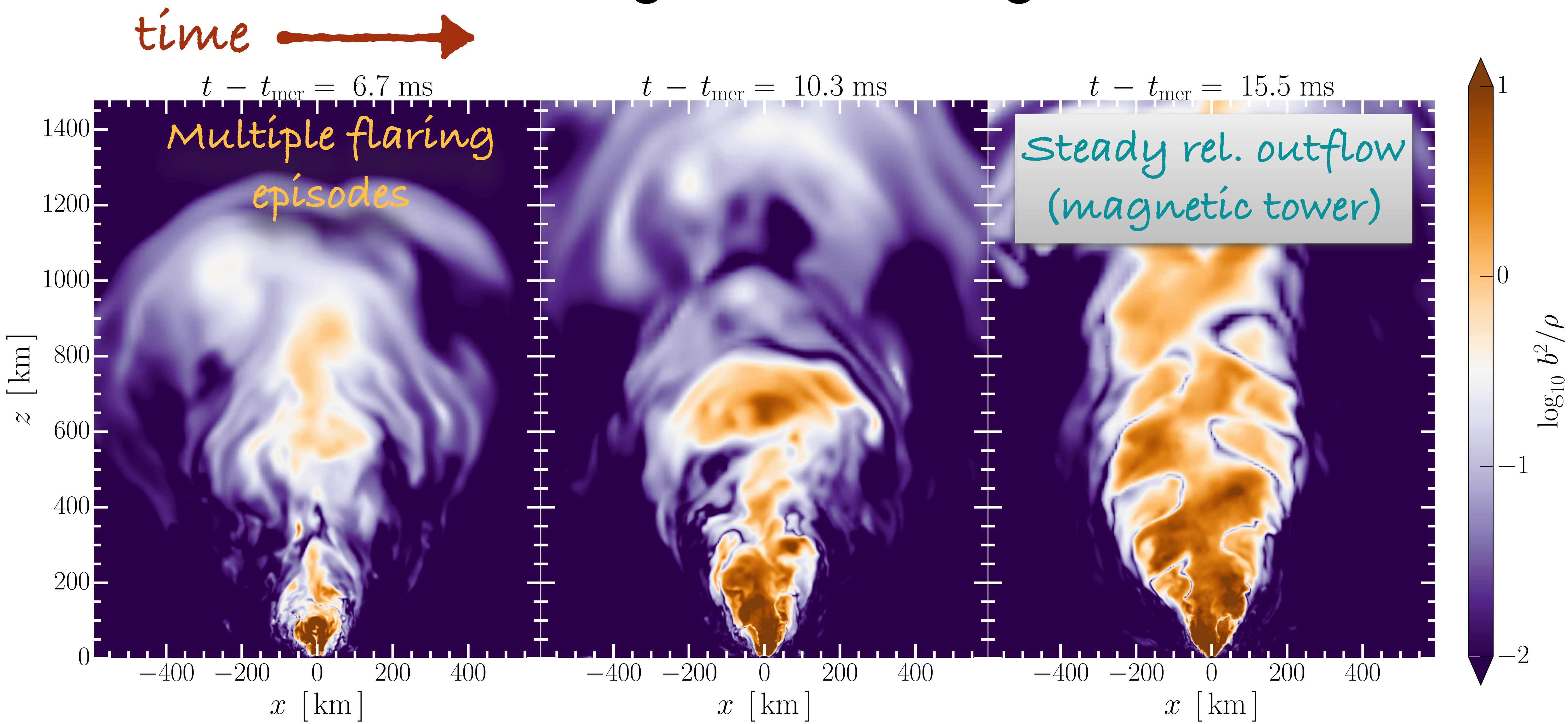


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# Properties of flares and outbursts

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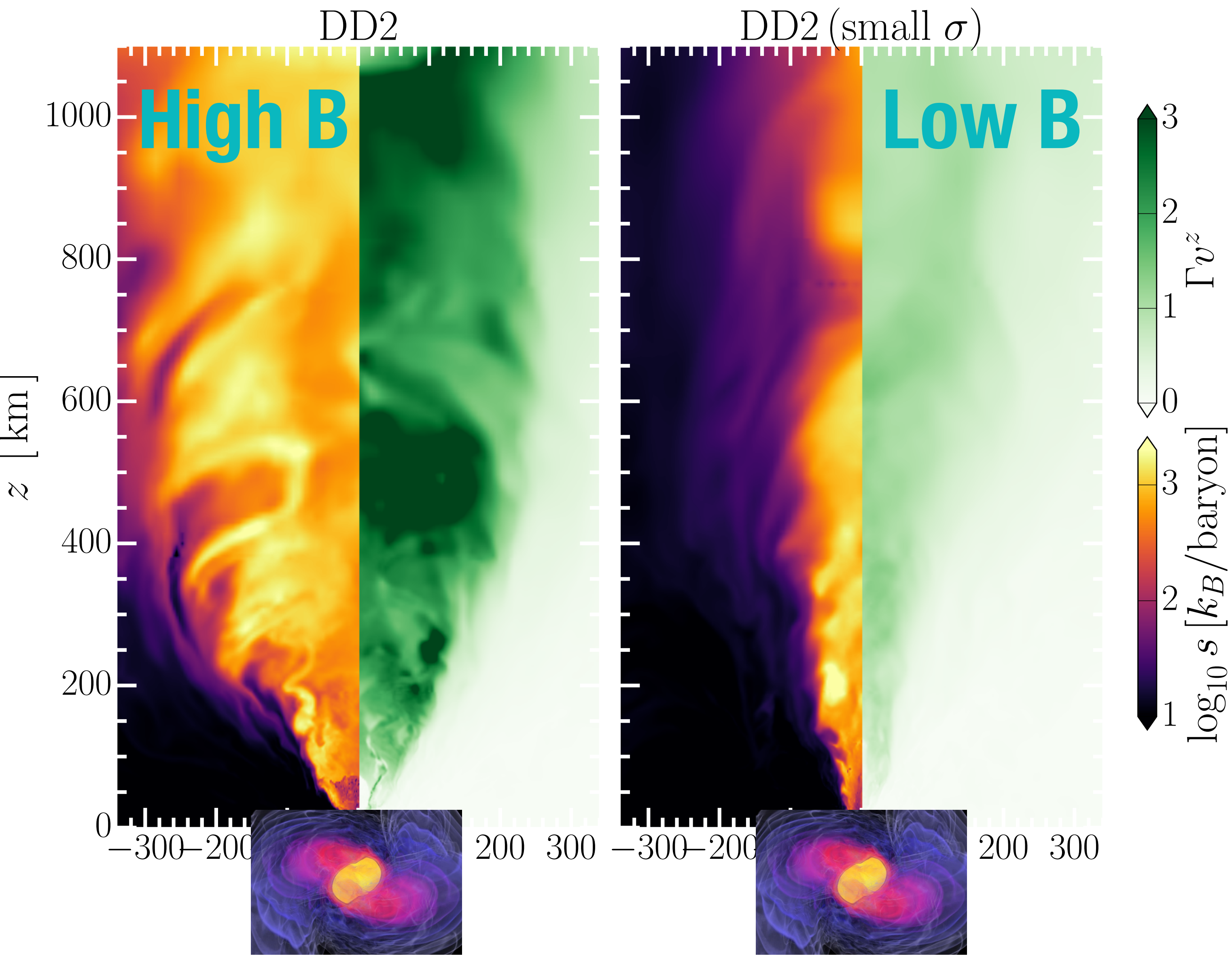


- Outflow is mildly relativistic
- Strong dependence on the dynamo amplification

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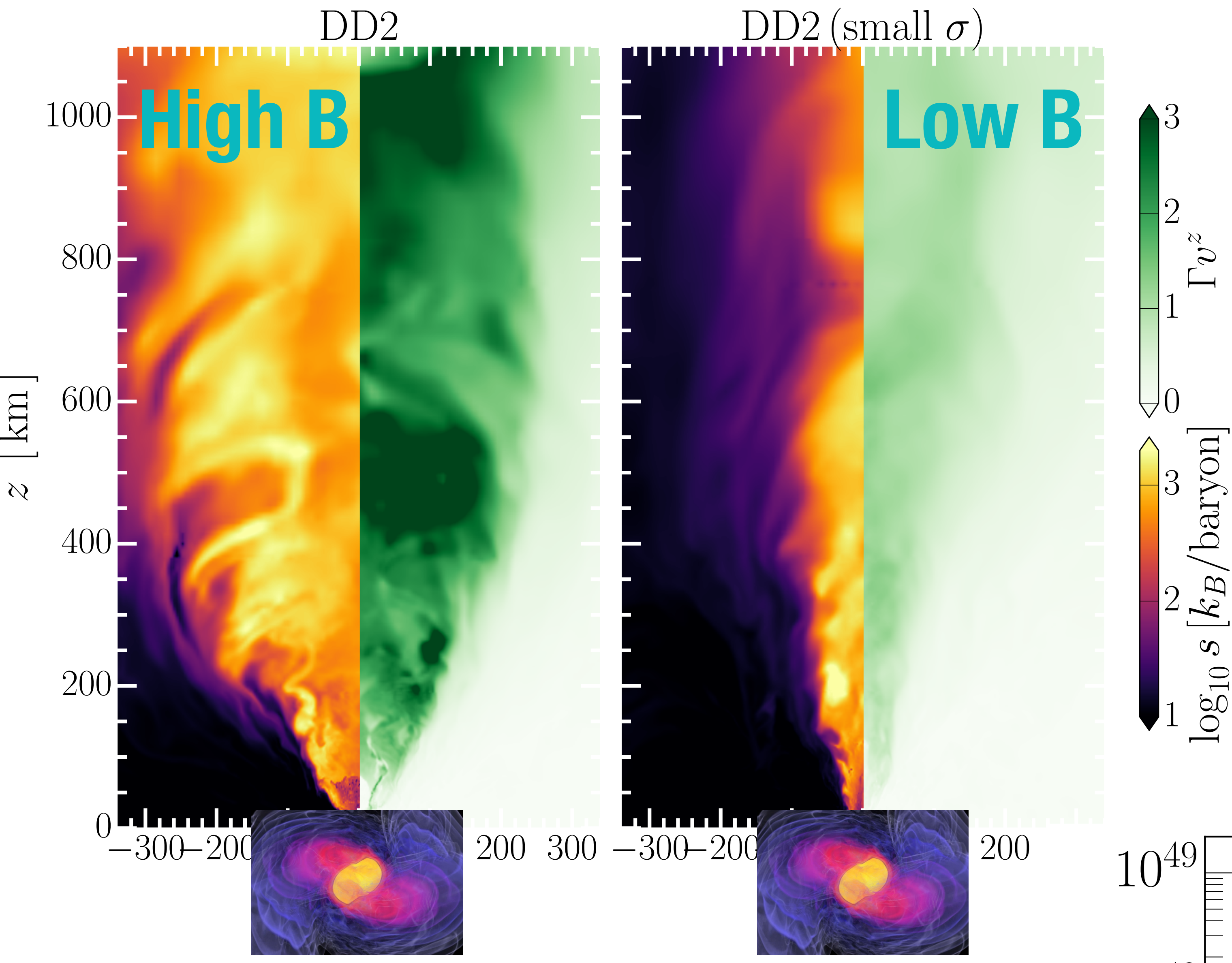


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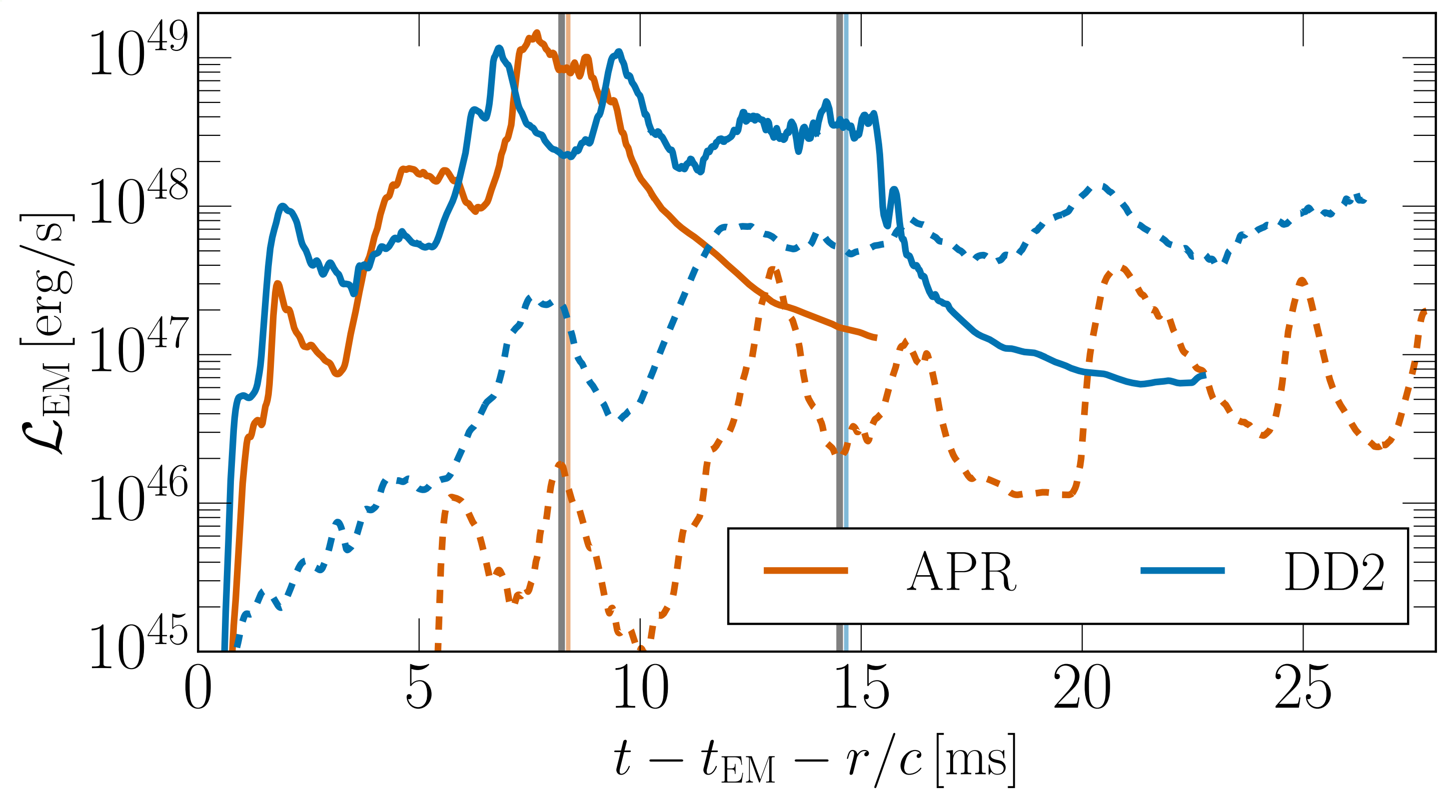
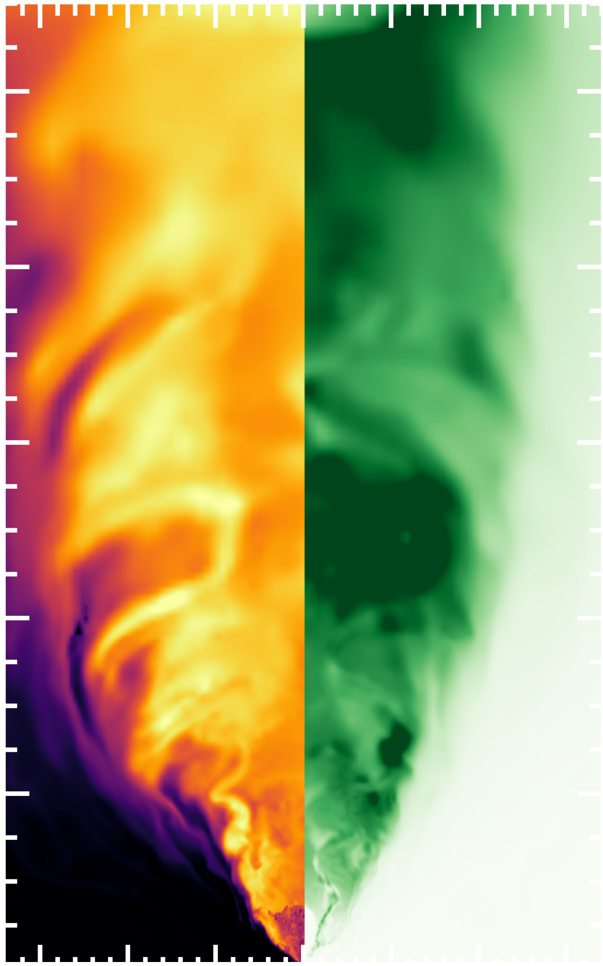
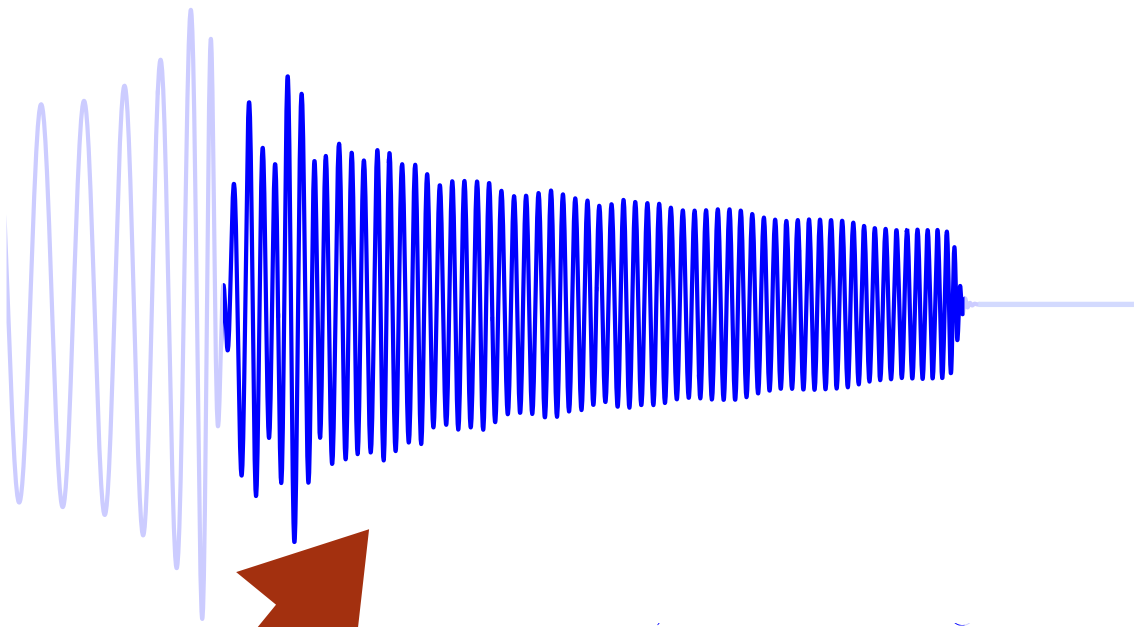
Strong dependence on the dynamo amplification

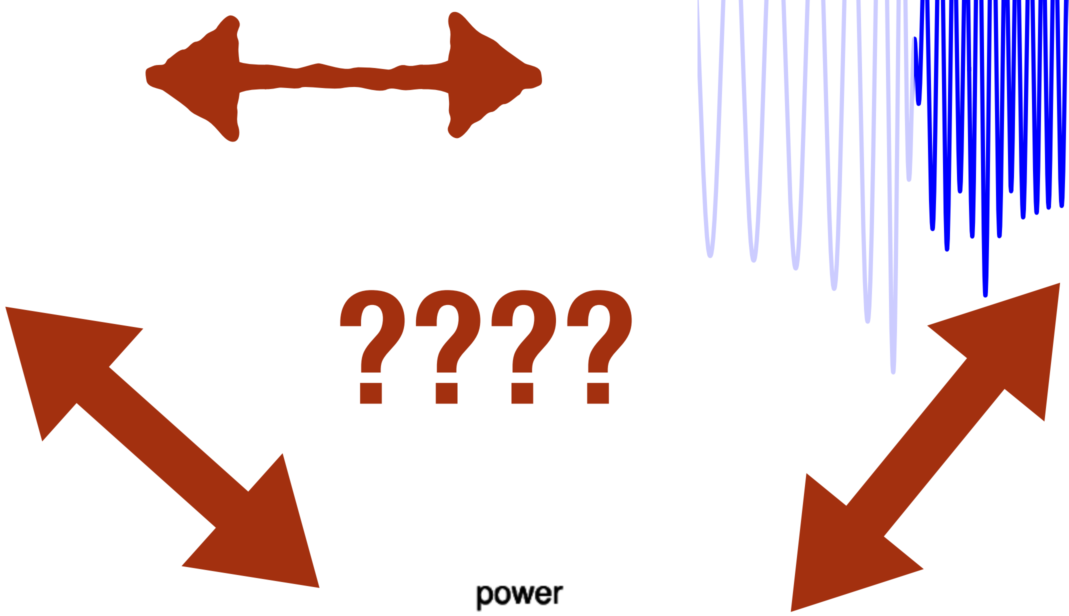
**Luminosity contains discrete frequency spectrum (incl. kHz)!**

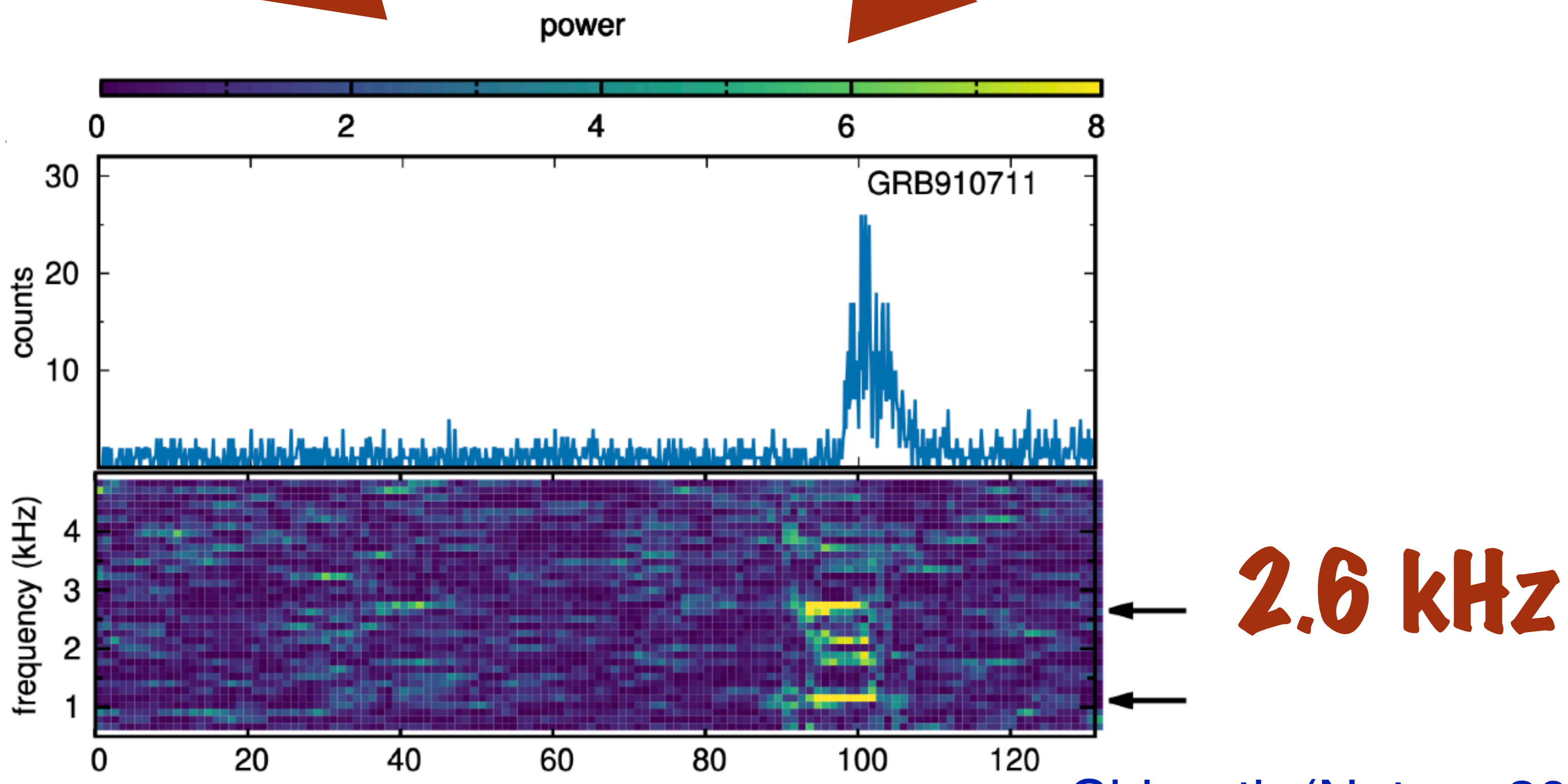


# Implications for nuclear physics?





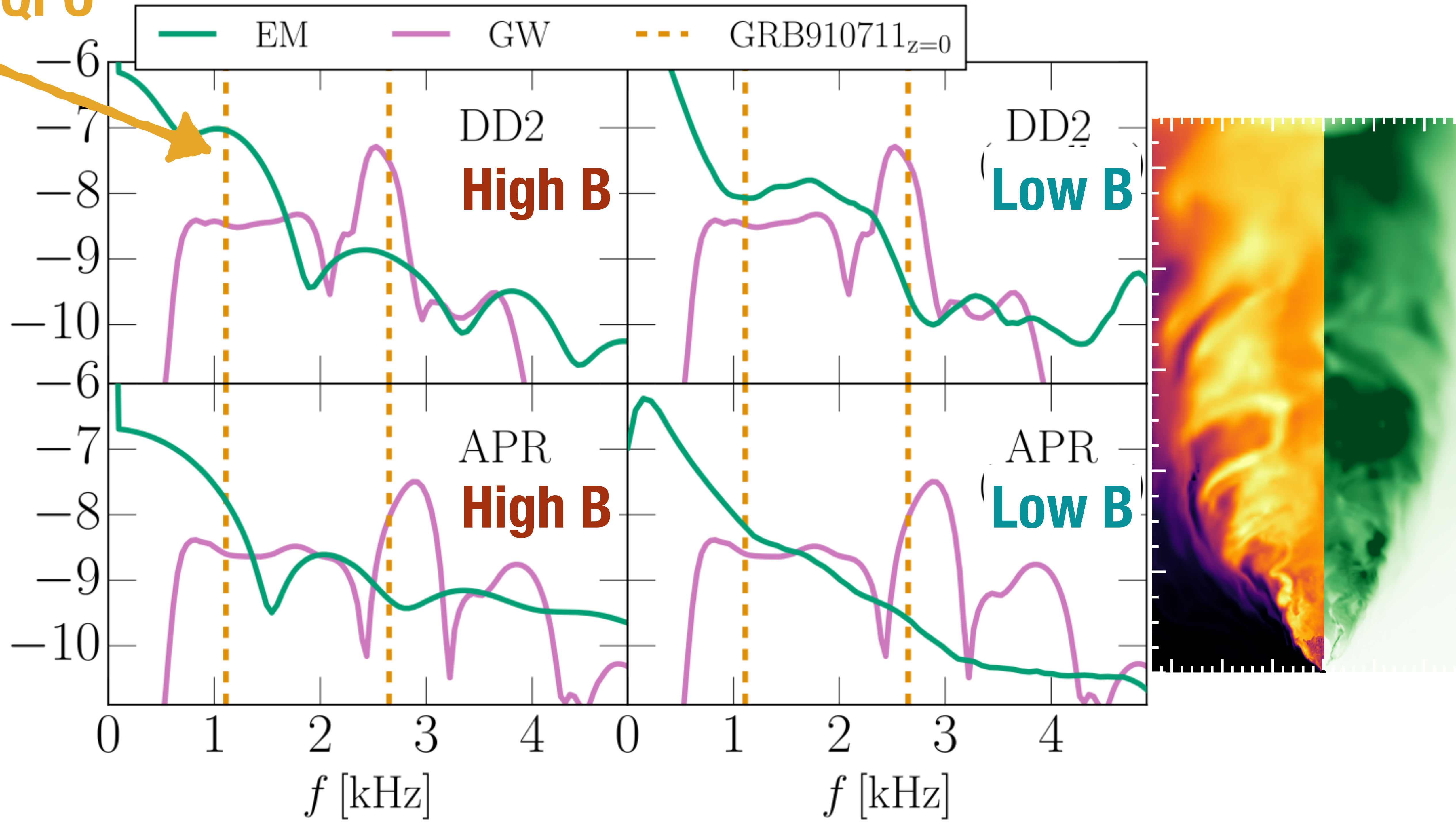




Chirenti+(Nature 2023)

# Using GRBs to learn about dense matter?

ERM & Quataert (ApJL 2023)

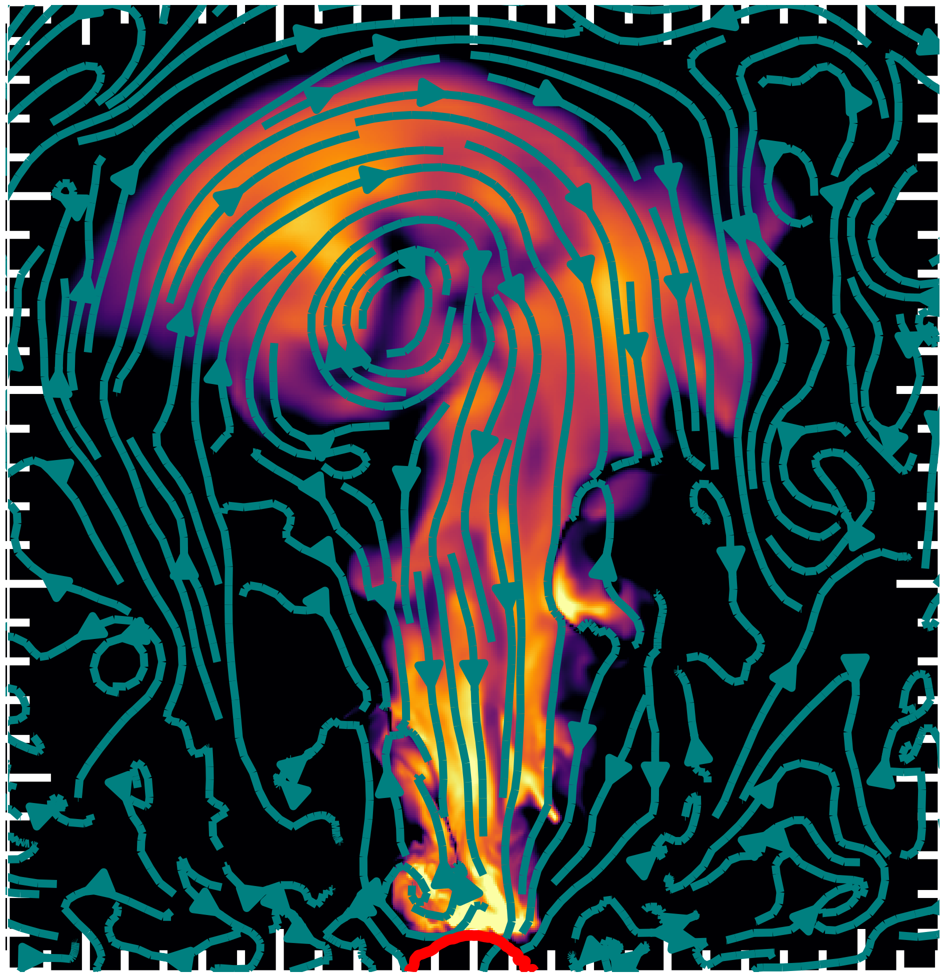
GRB QPO




**Association of frequencies depends on field strength, EOS,…**

# Summary

Ultra-strong magnetic fields produced in the collision of two neutron stars can give rise to flaring, quasi-periodic outbursts and jets.



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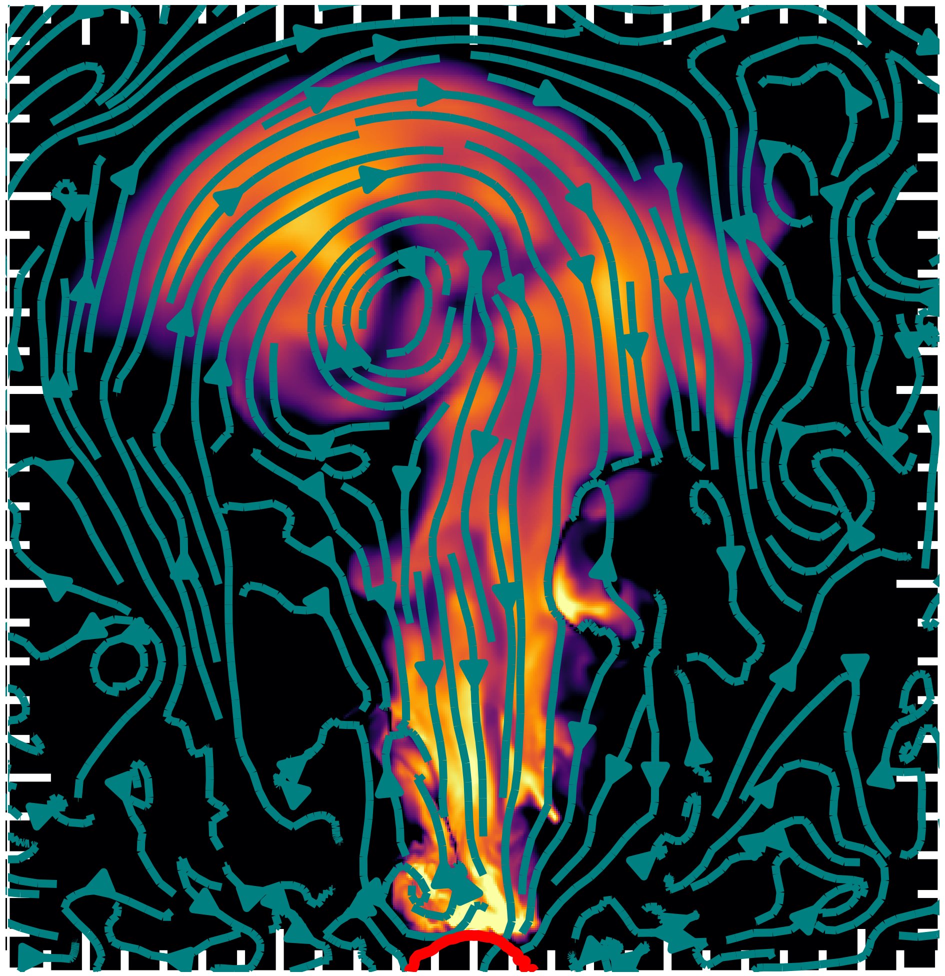

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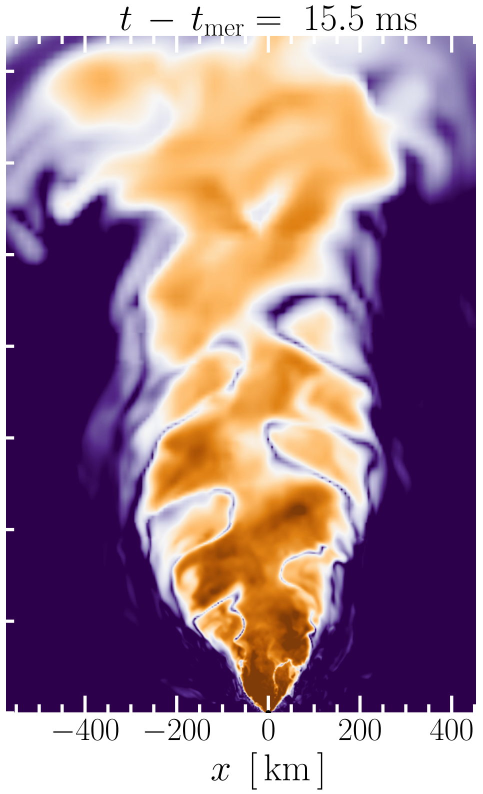


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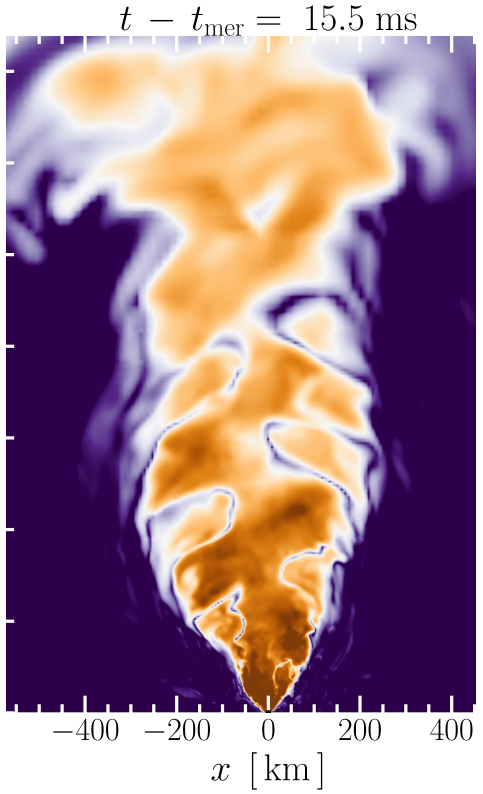


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