Binary Neutron Stars II: multi-messenger emission

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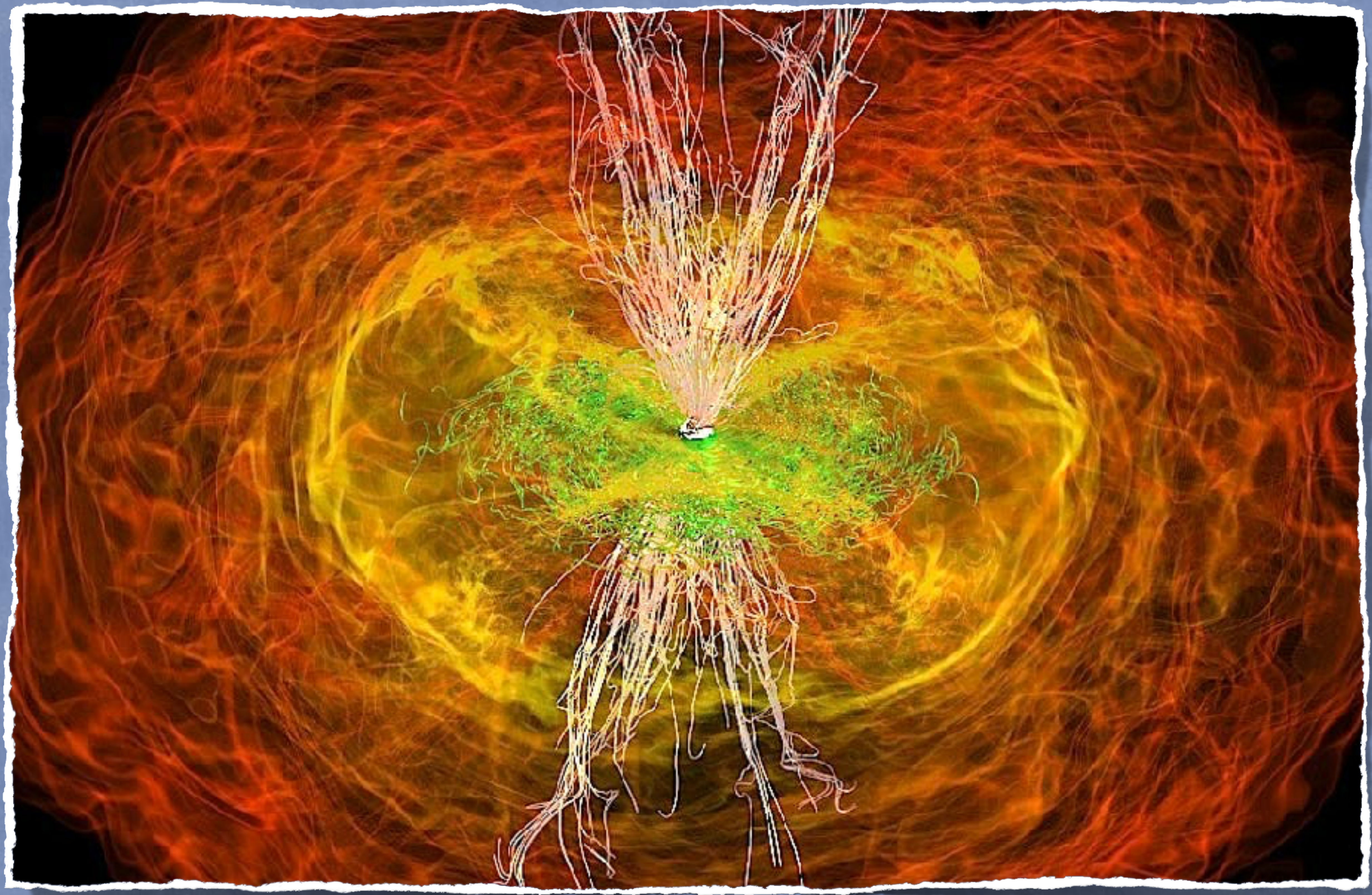
Blended Intensive Programme (BIP):

Relativistic Fluid Dynamics

Plan of the talk II

- Electromagnetic counterparts and jet formation
- Magnetic field amplification at merger KHI
- Role of B-field topology and NS spin
- Neutrino emission and magnetar jets
- *r*-process nucleosynthesis of heavy elements



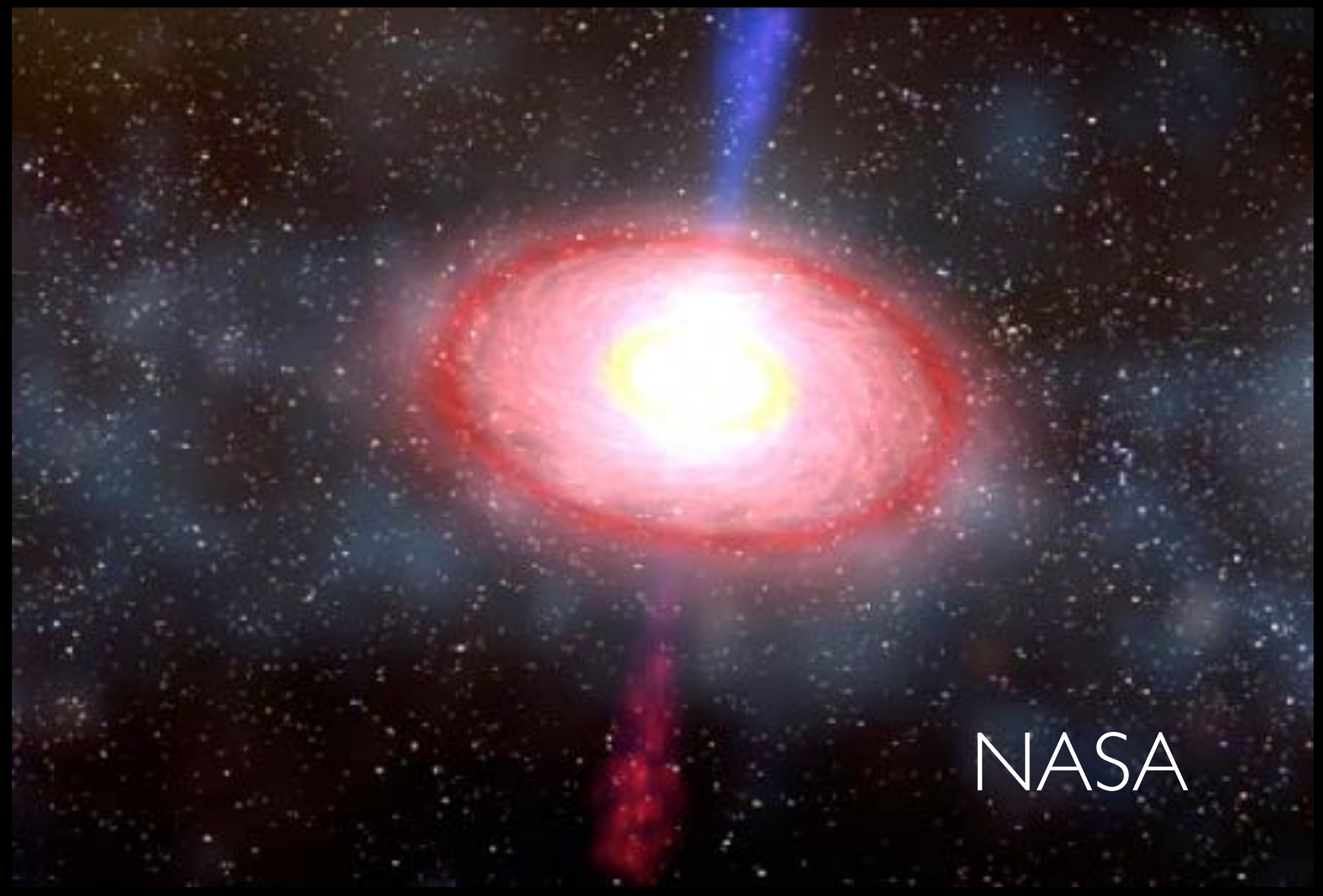
Electromagnetic counterparts and jet formation

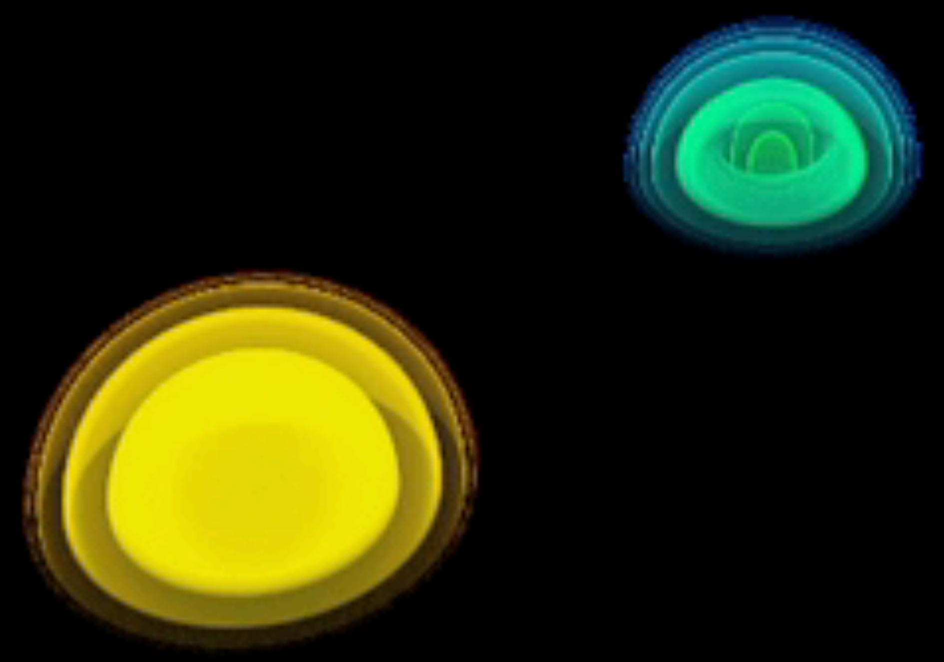
LR+(2011, 2022)

Electromagnetic counterparts

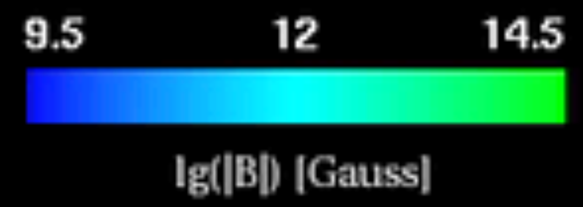
- Since 70's observed flashes of gamma rays observed with energies $10^{50\text{-}53}$ erg: **gamma-ray bursts (GRBs)**
- Two families of GRBs: **"long"**and **"short"**
- **Long:** last 10-100 s; likely due to the collapse of very massive stars.
  Short: last 1-10 s; we know they are due to NS mergers (GW170817)
- All GRBs show **jets** but how is a jet produced from a binary merger?

Need to solve equations of GRMHD in addition to the Einstein equations



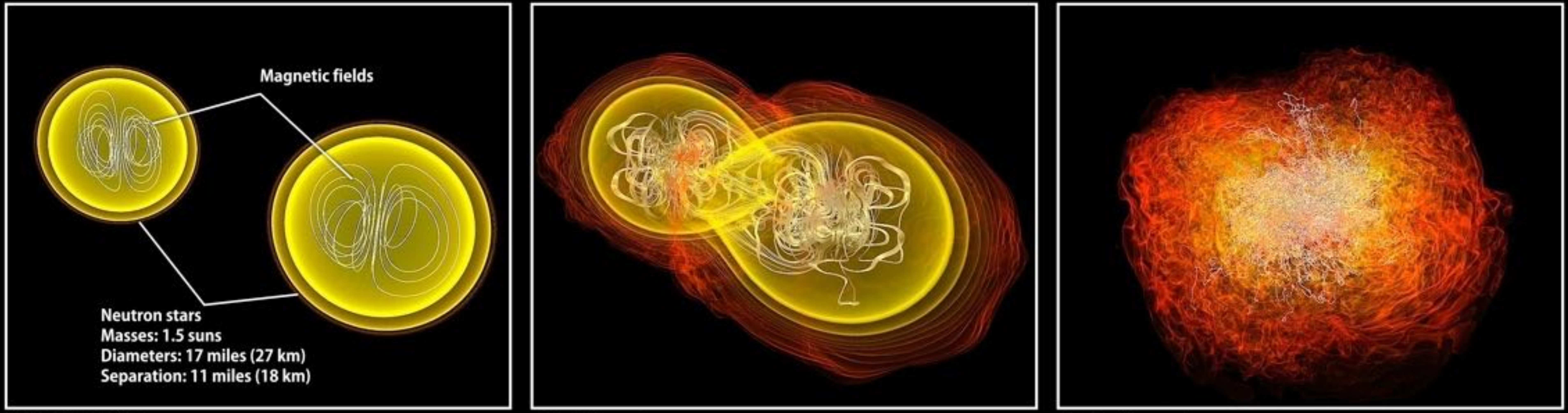


$$M = 1.5\, M_{\odot},\, B_0 = 10^{12}\,\mathrm{G}$$



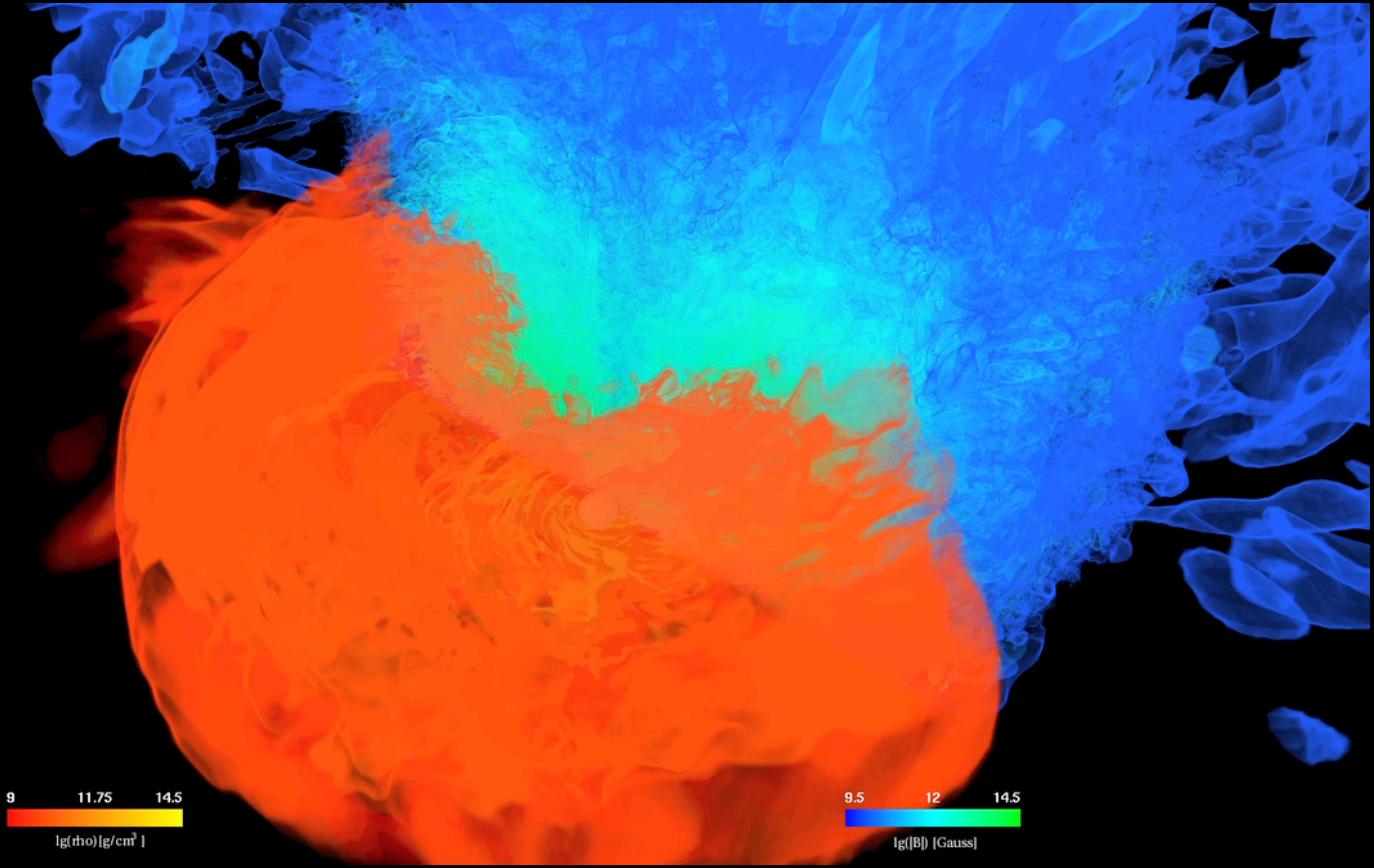
Animations:, LR, Koppitz

What happens when magnetised stars collide?



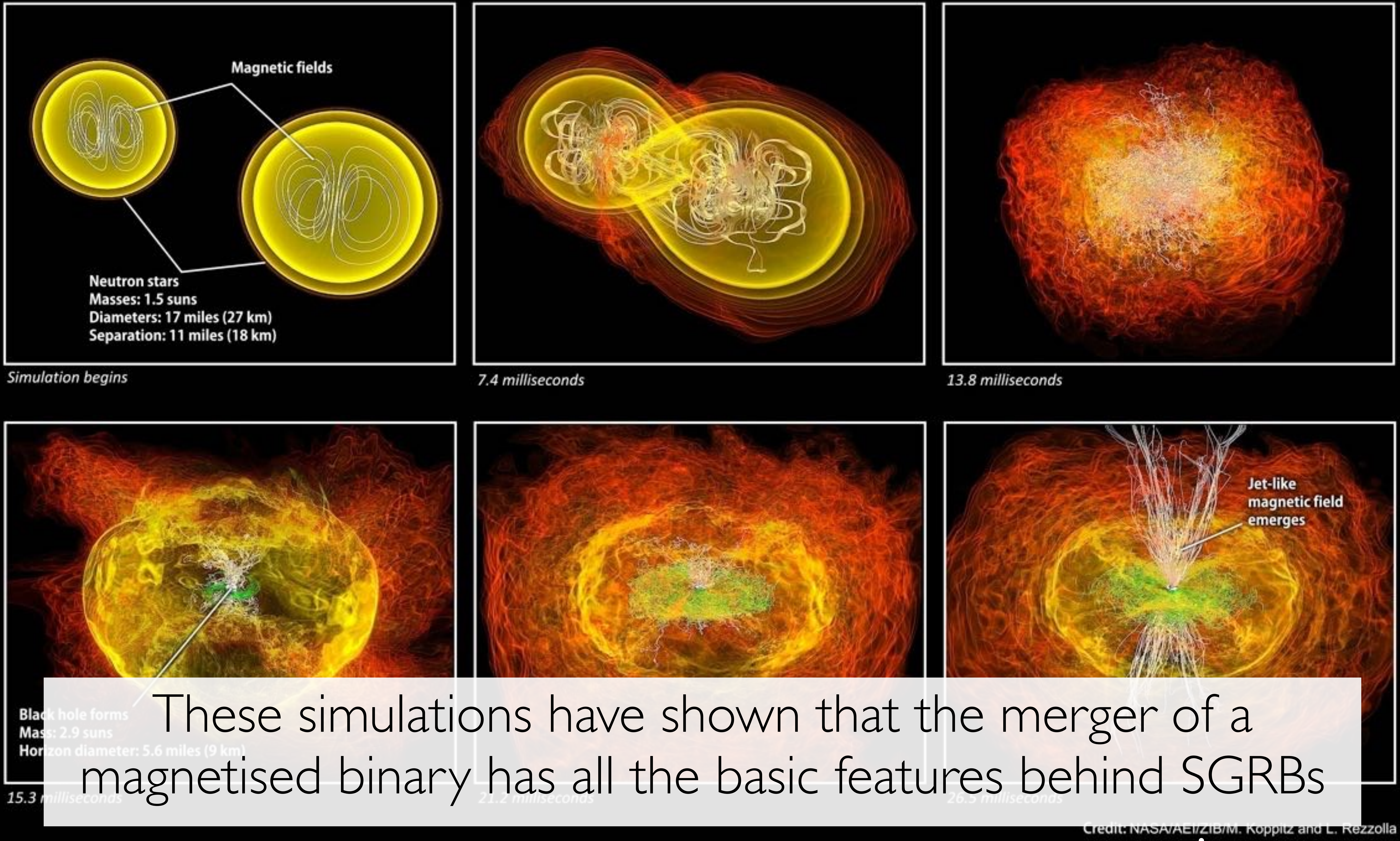
Simulation begins *7.4 milliseconds* *13.8 milliseconds*

Magnetic fields in the HMNS have complex topology: dipolar fields are destroyed.



9
11.75
14.5
lg(rho) [g/cm³]
9.5
12
14.5
lg(|B|) [Gauss]

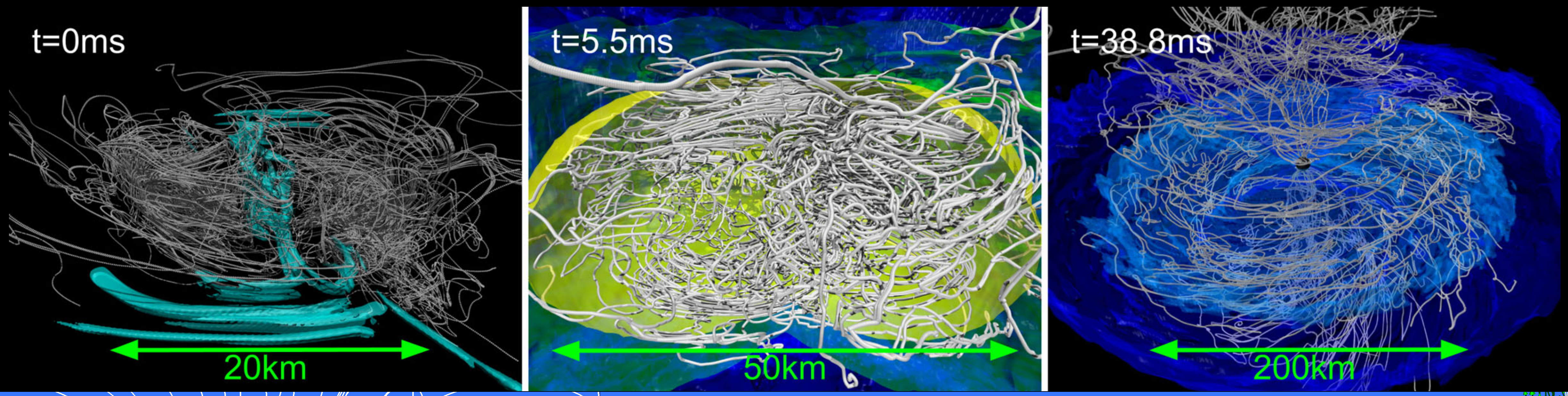
LR+ 2011



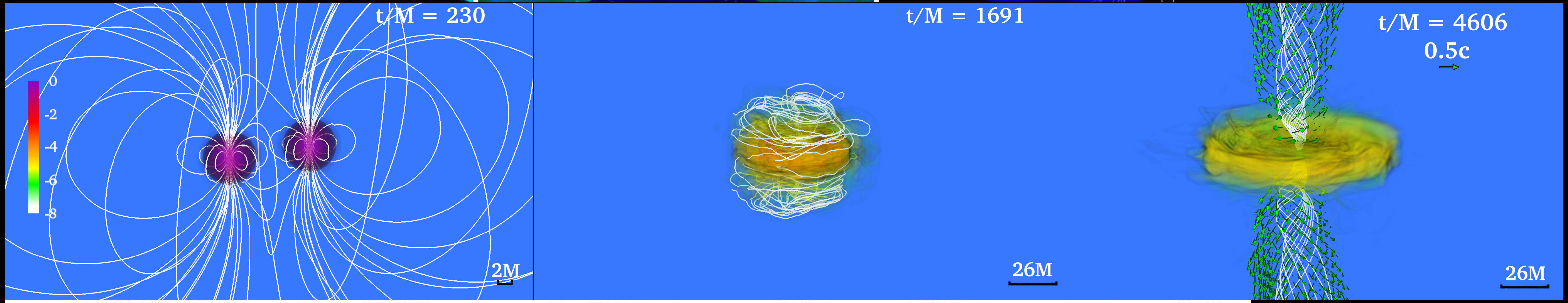
These simulations have shown that the merger of a magnetised binary has all the basic features behind SGRBs

$J/M^2 = 0.83$ $\quad$ $\mathrm{M_{tor}} = 0.063 M_\odot$ $\quad$ $\mathrm{t_{accr}} \simeq M_{\rm tor}/\dot{M} \simeq 0.3\ \mathrm{s}$

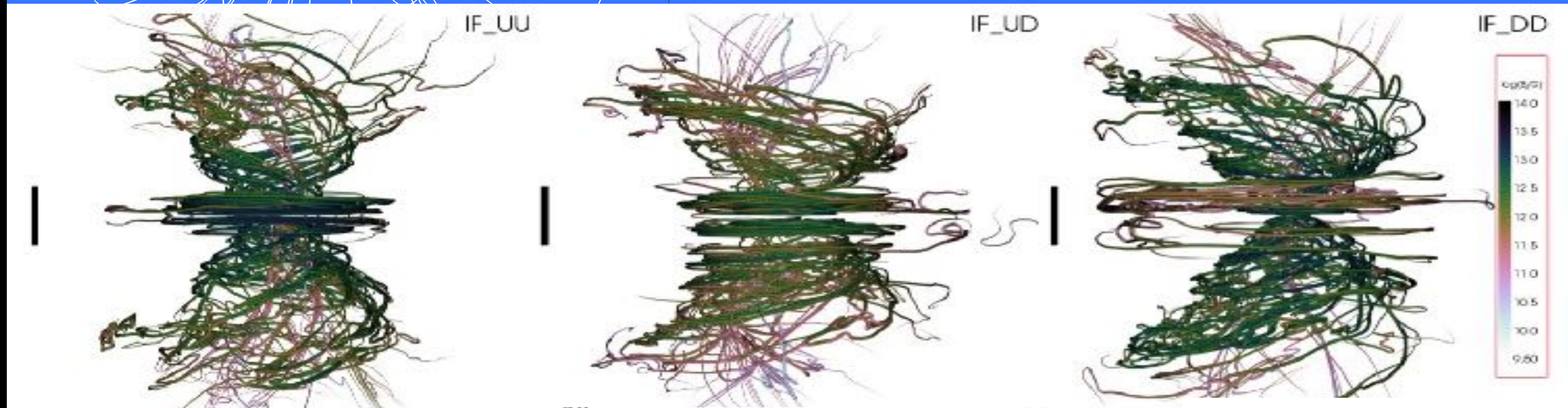
With due differences, other groups confirm this picture



Kiuchi+ 2014

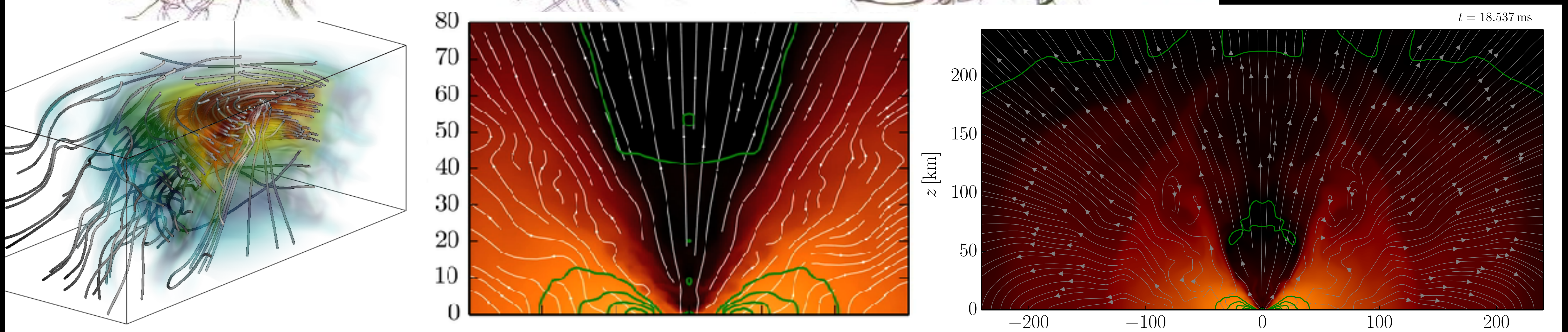


Ruiz+ 2016

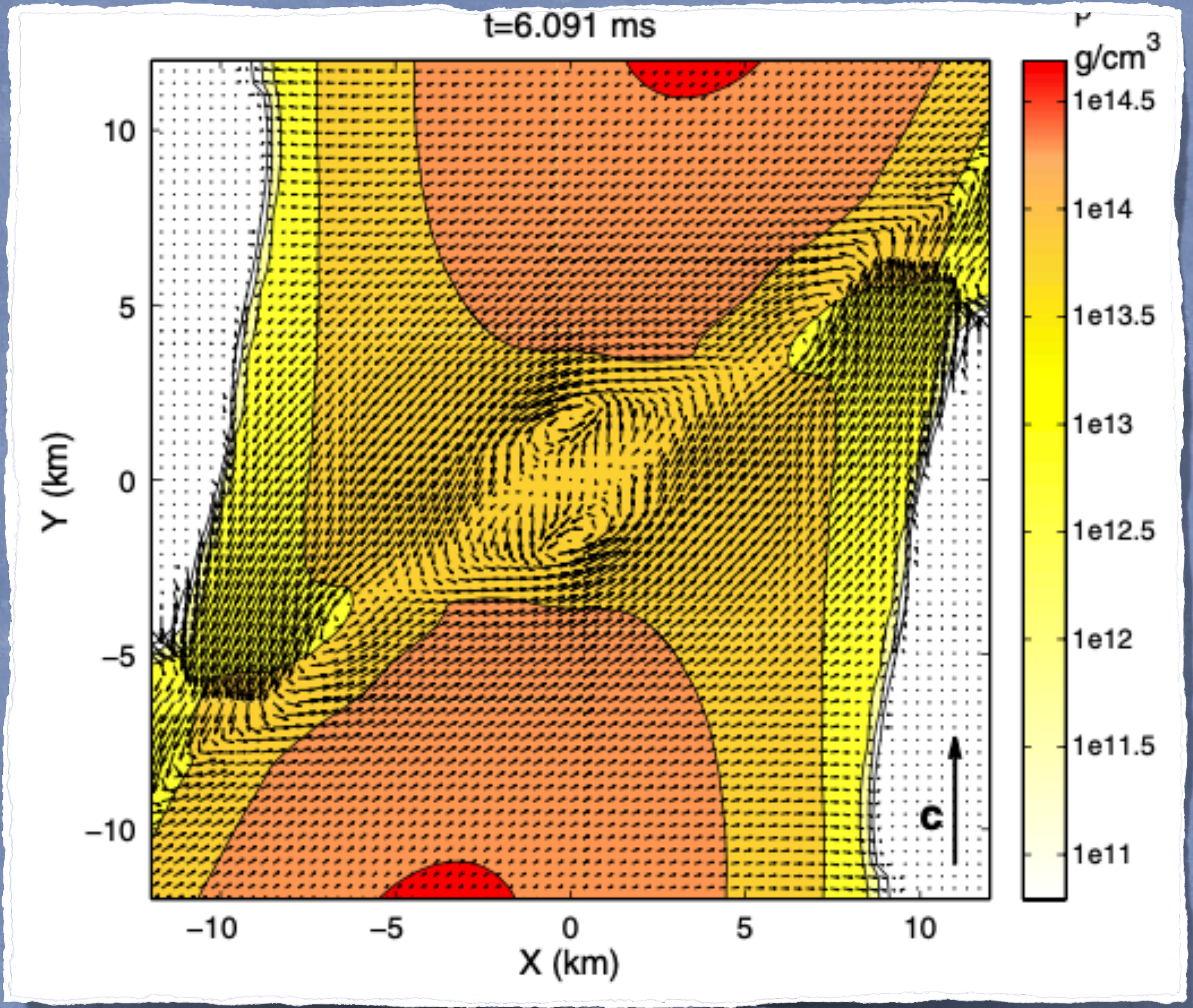


Kawamura+2016

Dionysopoulou+ 2015



RMHD

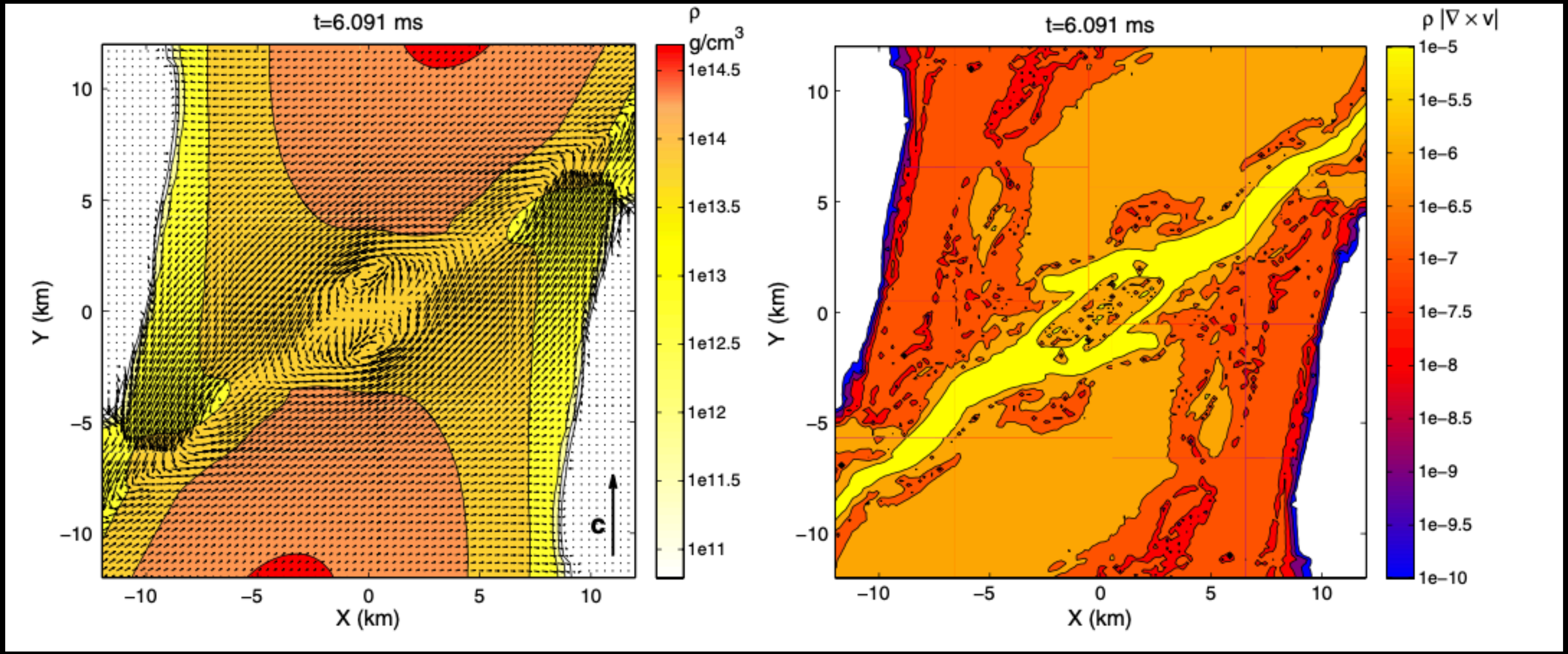


Magnetic-field amplification and crustal fields

Chabanov, Tootle, Most, LR (2022)

A very powerful instability

- at merger, a strong **tangential discontinuity** is produced by the shear between the stellar surfaces.



- this leads to **Kelvin-Helmholtz** instability (KHI) and large vorticity
- in turn this leads to exponential growth of toroidal magnetic field

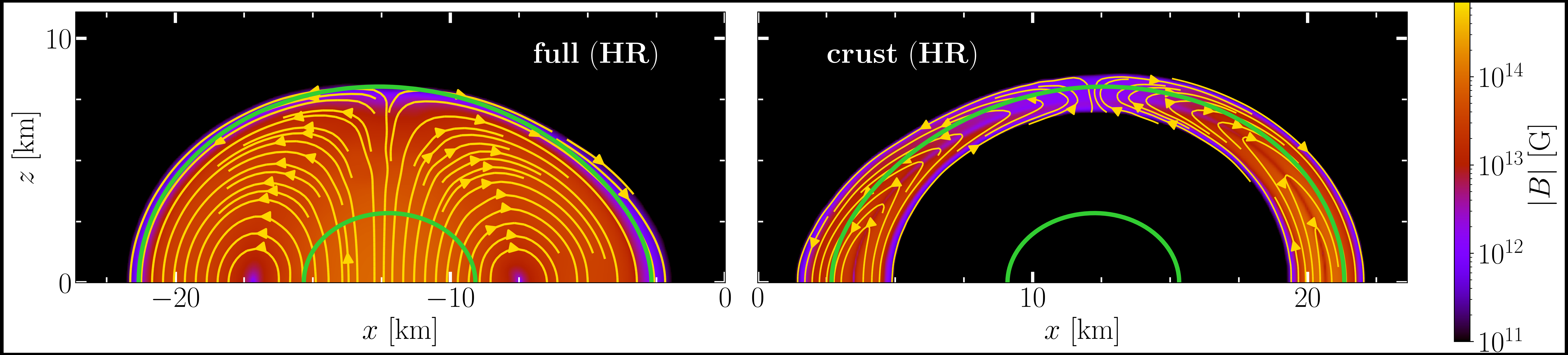
A very powerful instability

- in practice, we cannot model this process yet despite simulations at ultra-high resolution and enormous computational costs.
- this is because there is no minimum wavelength in the development of KHI
- all we know is that magnetic fields grow exponentially till equipartition with binding/kinetic energy in the system

$$10^{10}\,\mathrm{G} \to 10^{16}\,\mathrm{G}$$ in few ms!

- additional linear amplification of the B-field takes place later on because of a turbulent magnetorotational (shearing) instability (MRI)

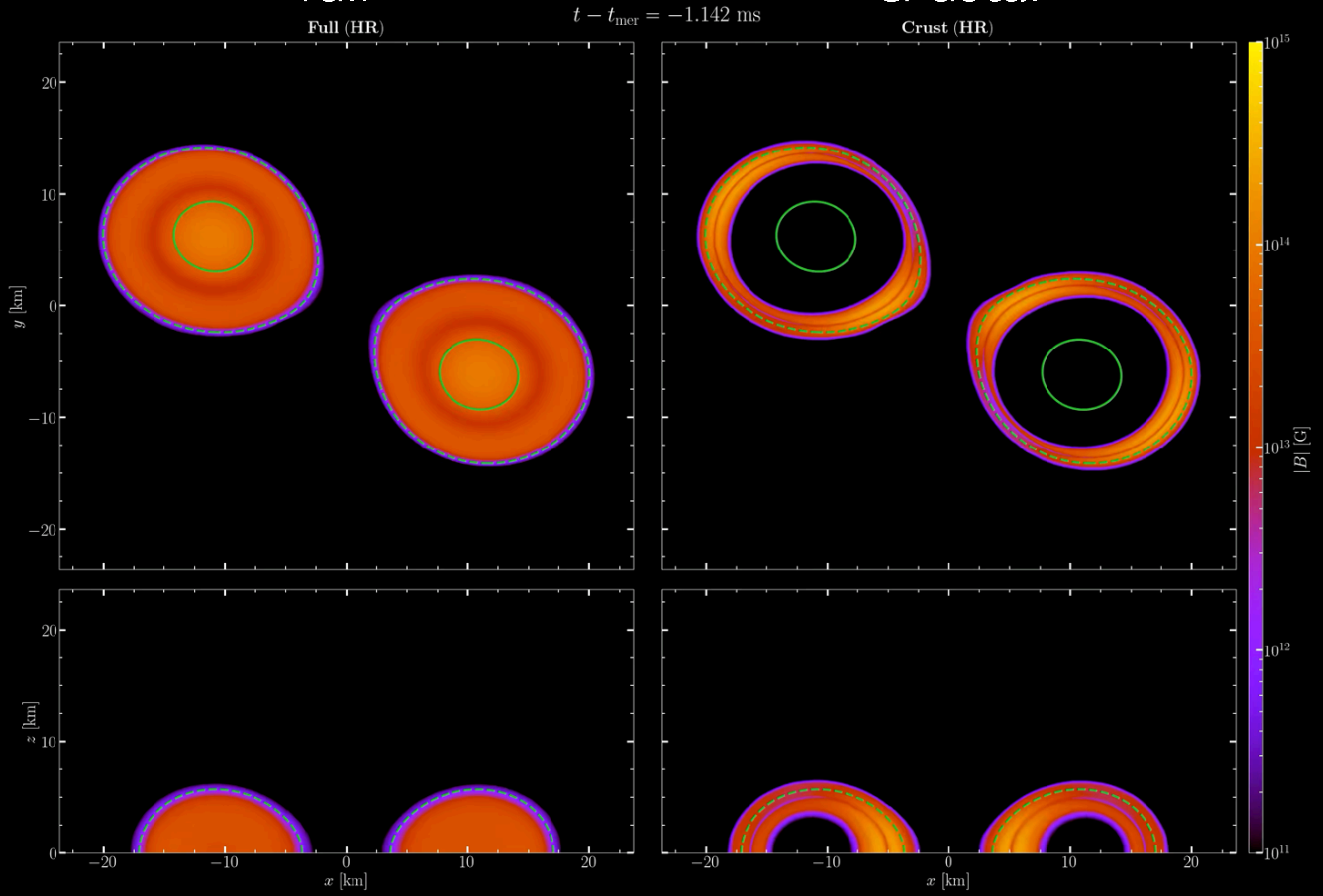
- simple question: does the amplification depend on the B-field topology?
- internal magnetic field in NSs is unknown
- a global poloidal field is the standard assumption but not only one
- a number of pulsar models postulate the existence of crustal fields only



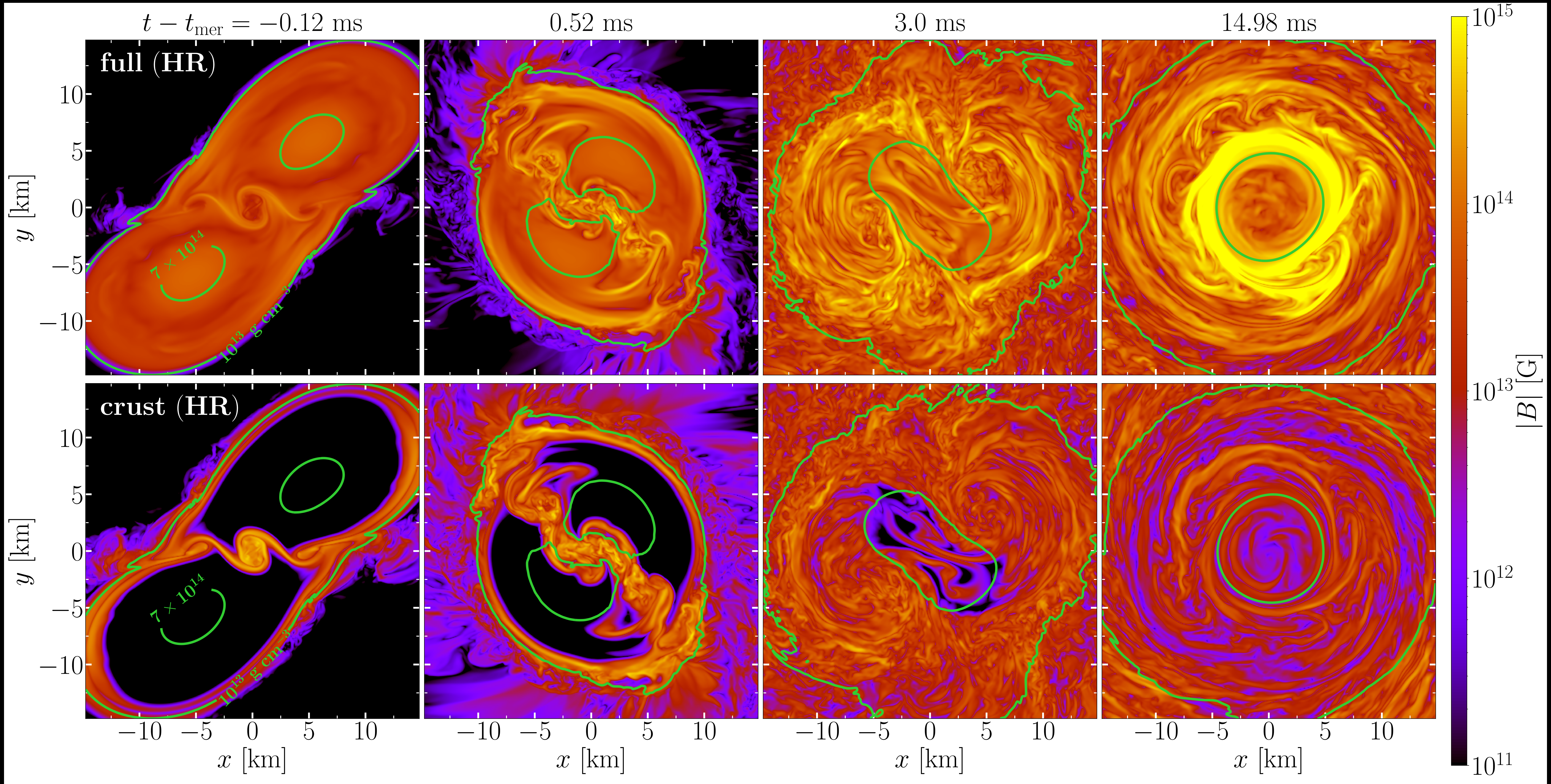
- assuming the same magnetic energy can we tell the difference via numerical simulations?

full

crustal

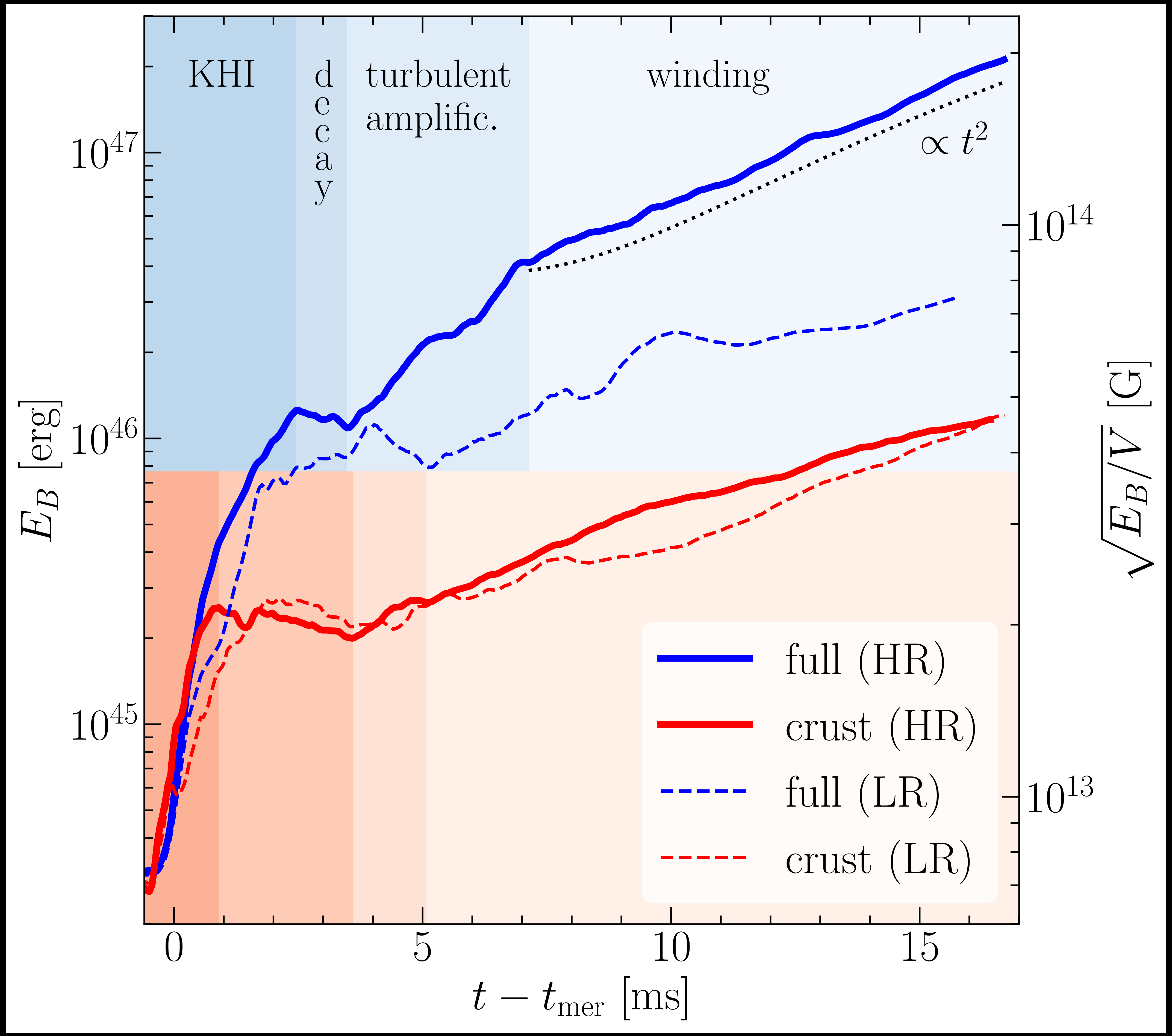


A closer comparison



- significant differences: crustal field is partly lost at the surface and not further amplified by interior turbulence

A more quantitative description



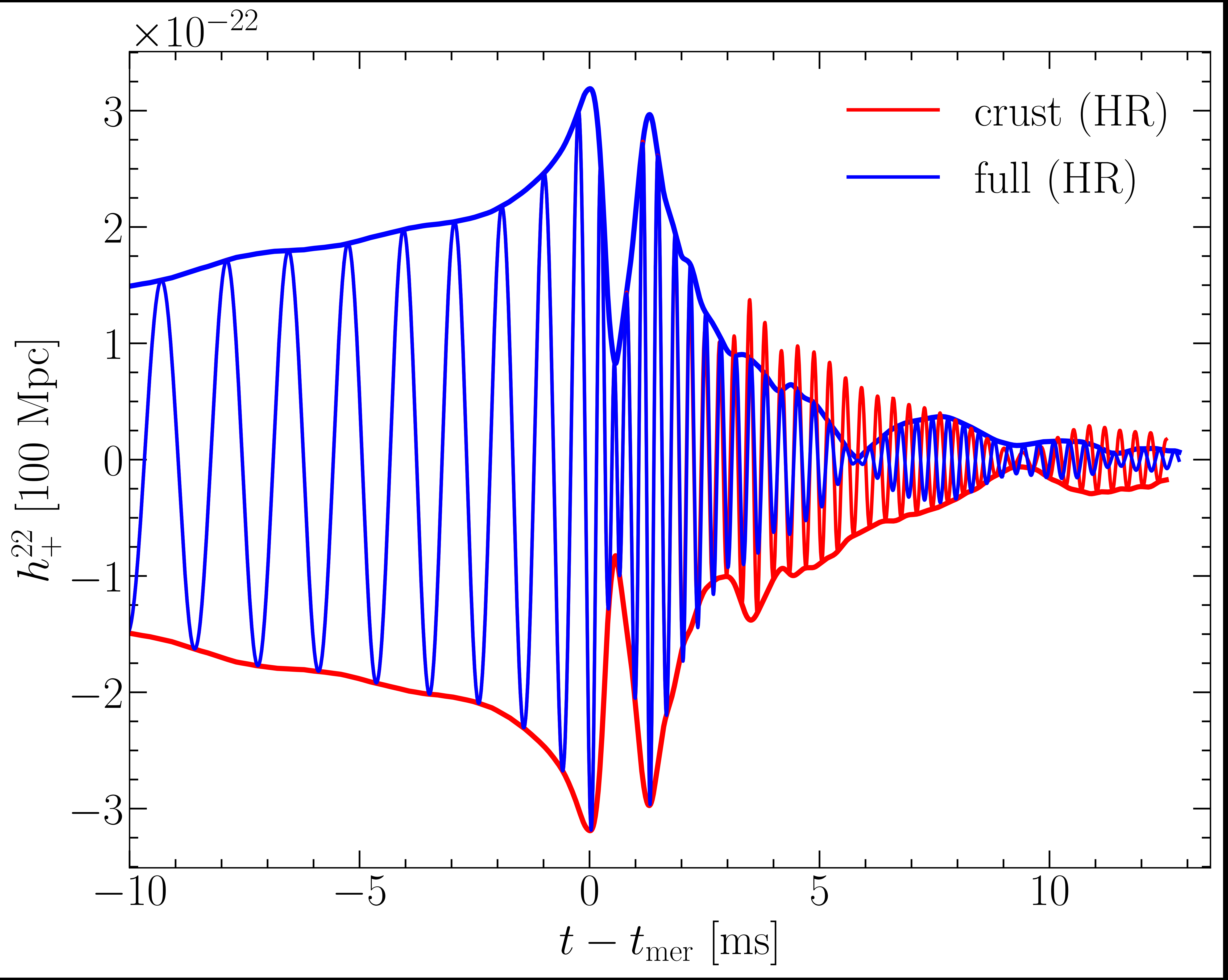
- crustal fields are initially more efficient in amplifying the B-field
- however, their amplification is quickly quenched because of mass loss not present in full fields
- when a shearing amplification is active, i.e., $t - t_{\rm mer} \gtrsim 5\,{\rm ms}$, crustal fields are one order of magnitude weaker

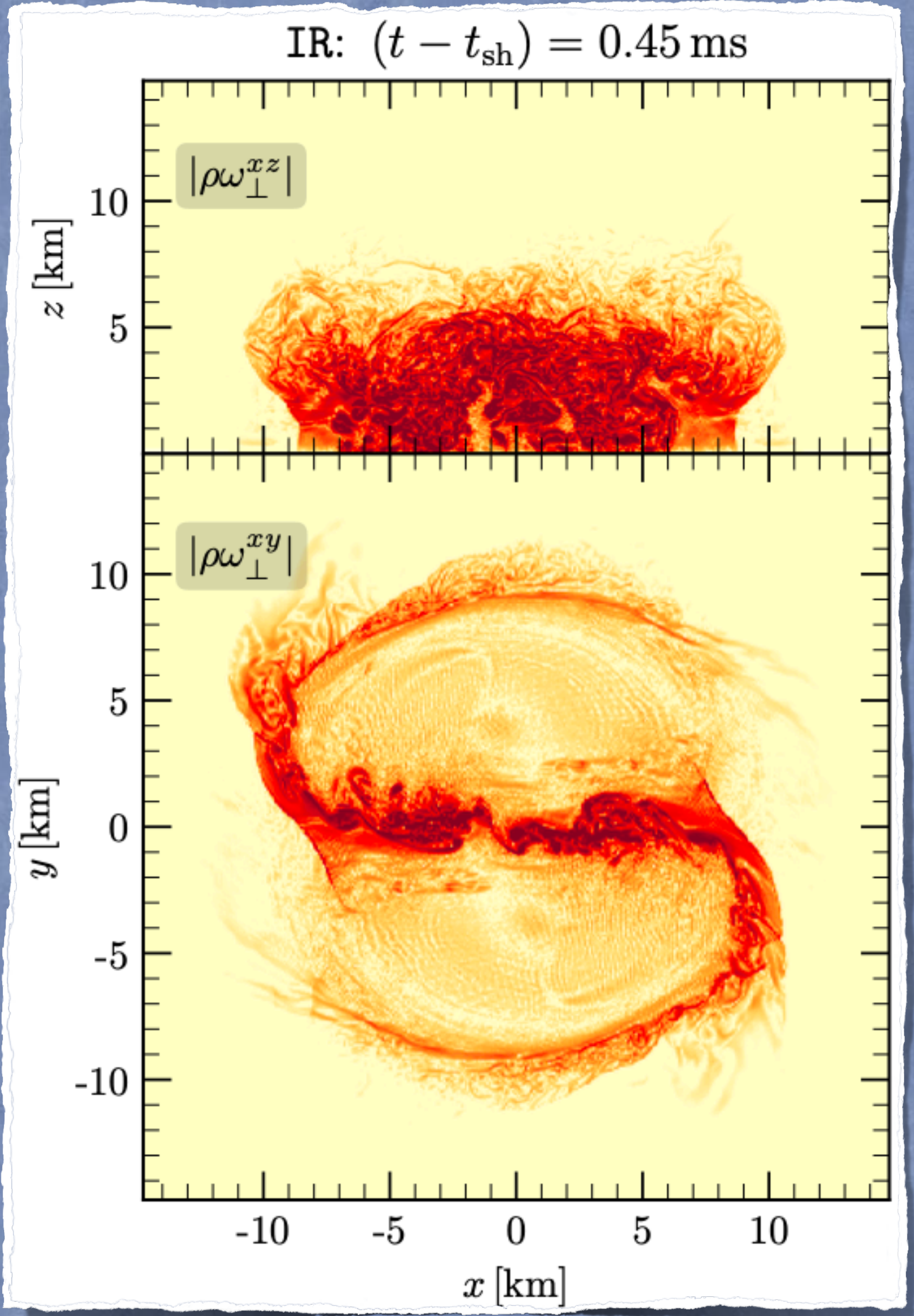
Bottom line: crustal magnetic fields do not lead to large magnetic-field amplifications in BNS mergers

How can we tell the difference?

- different magnetic fields in the remnant will lead to different (weaker) EM emission

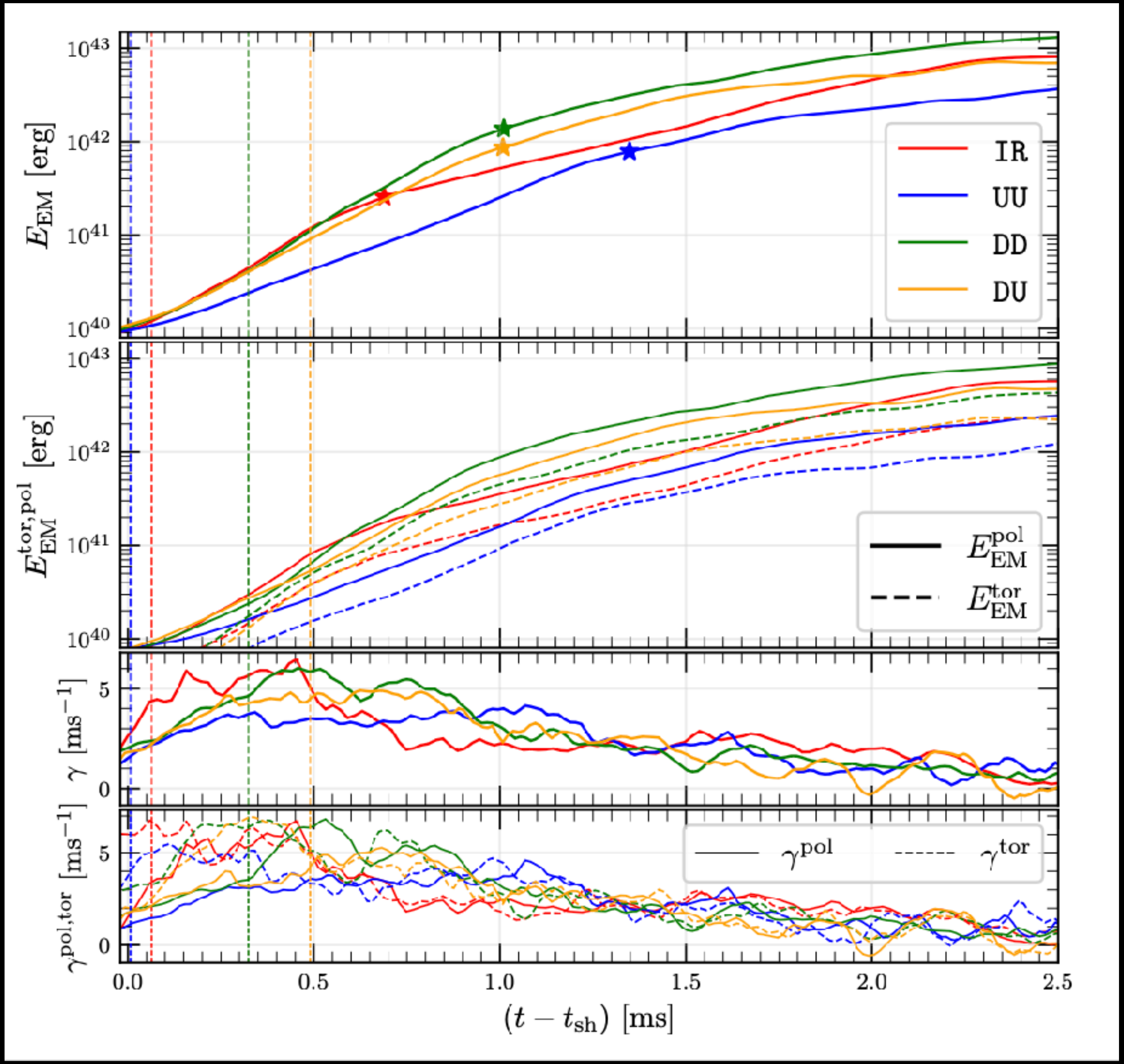
- GWs will also be different: weaker for full configuration (more energy into B-field) and smaller $l=2$, $m=2$ deformations (magnetic tension)





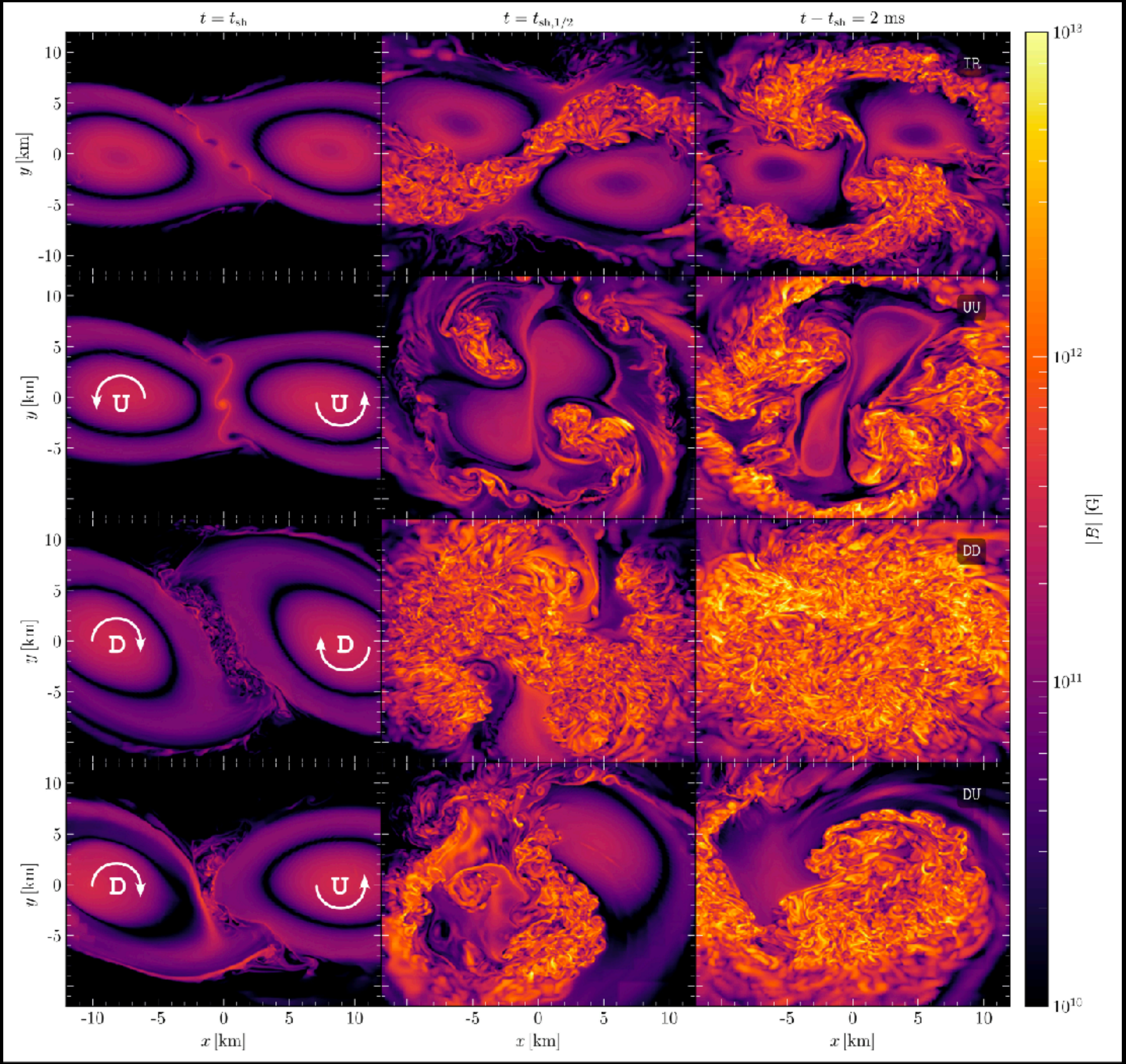
The role of stellar spin in the B-field amplification

Ng, Jiang, LR (2026)



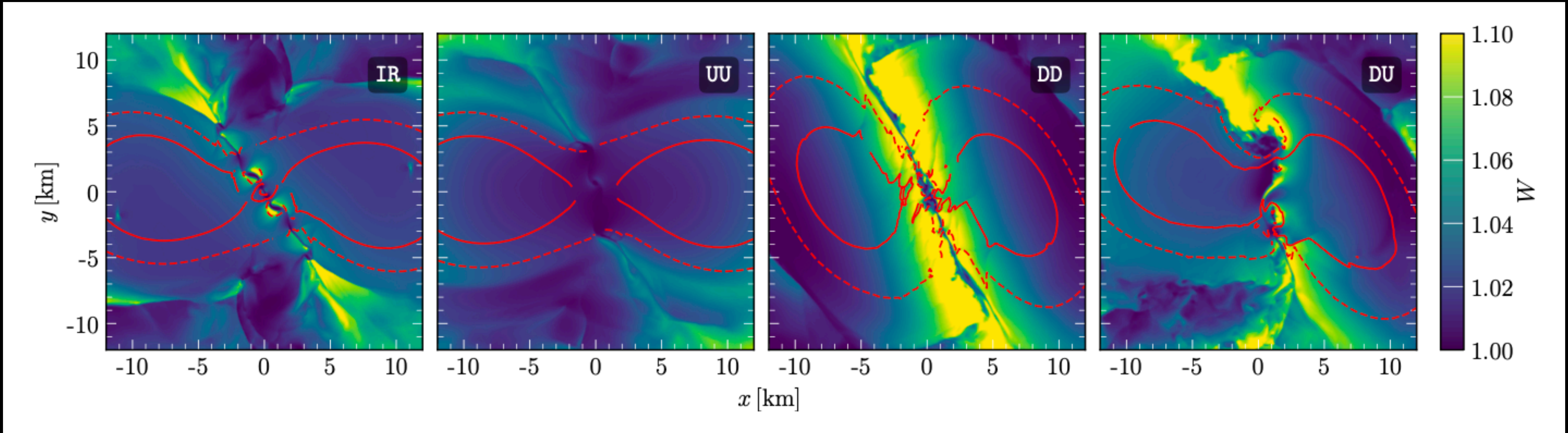
- NSs at merger not expected to have large spins if produced in a binary
- in globular clusters, dynamical capture is potential formation channel
- have considered rapidly spinning stars with aligned/misaliagned spins
  - ★ IR (irrot.), UU (↑↑), DD (↓↓), DU (↓↑)
- spin introduces changes also in the inspiral; tidal deformation is different
- Interestingly, both the B-field growth rates and the fields after KHI differ

performed ultra-high resolution simulations (35 m)

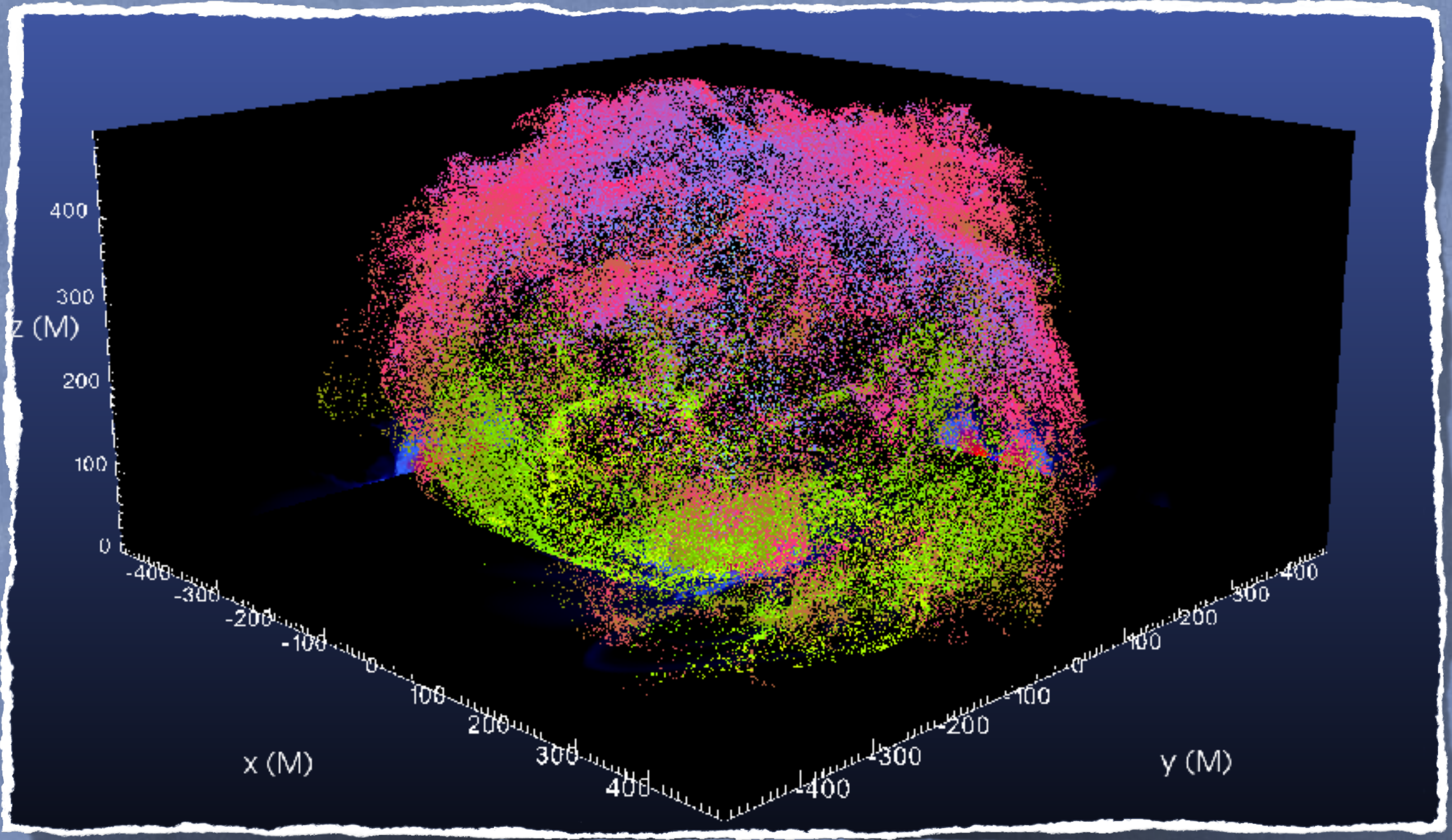


- IR binaries produce considerable vorticity but not the largerst
- UU produces smallest vorticity and smallest "final" B-field
- DD produces largest vorticity and largest "final" B-field
- DU produces vorticity only in Ns with misaligned spin

Why this different behaviour?



- intrinsic tangential discontinuity in UU is large but contrasted by orbital vorticity
- intrinsic tangential discontinuity in DD is also large but amplified by orbital vorticity
- UU merges with small radial velocity; DD merges with large radial velocity
- larger shocks allow the KHI to shear larger magnetic field with greater magnification

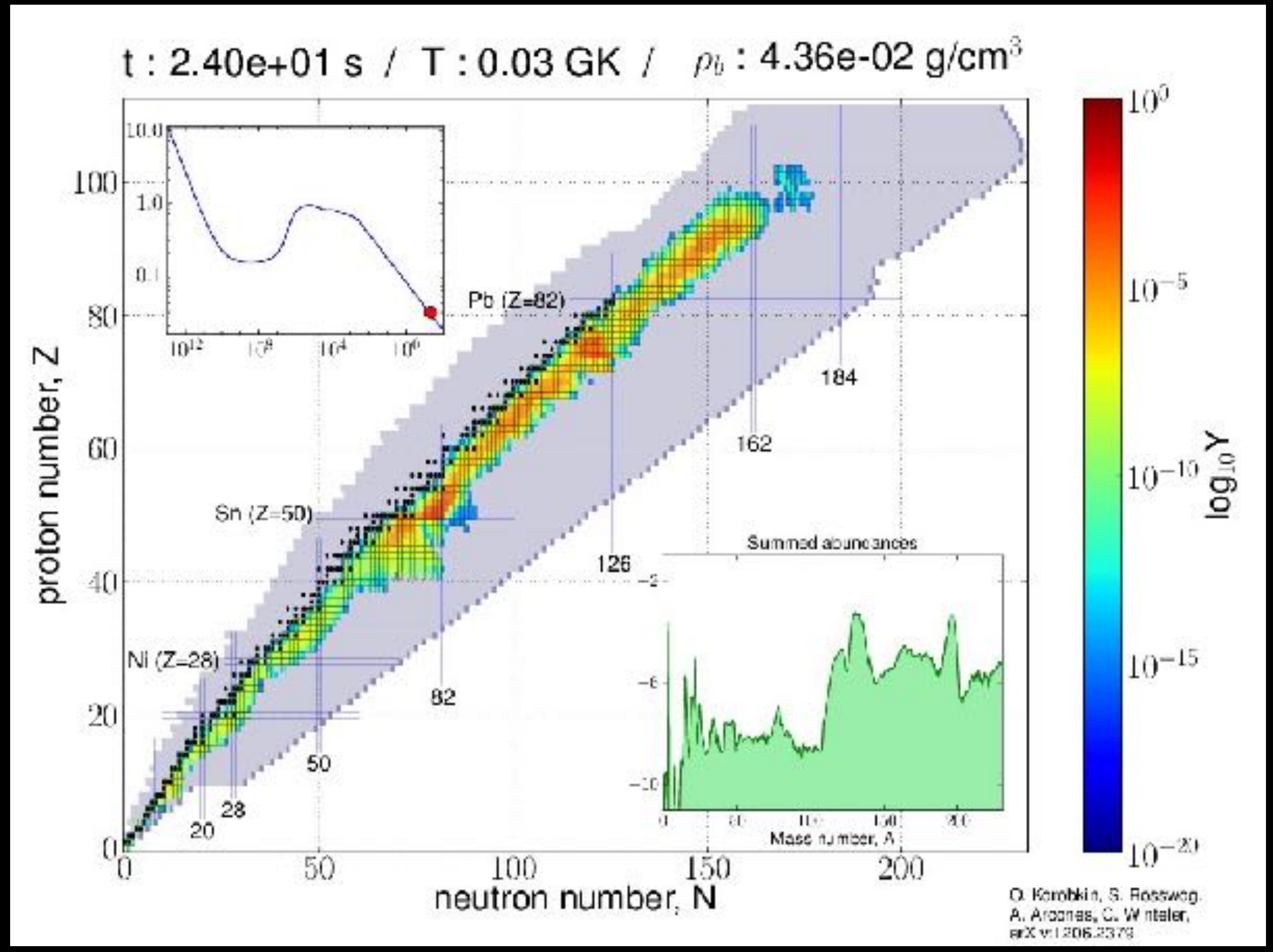


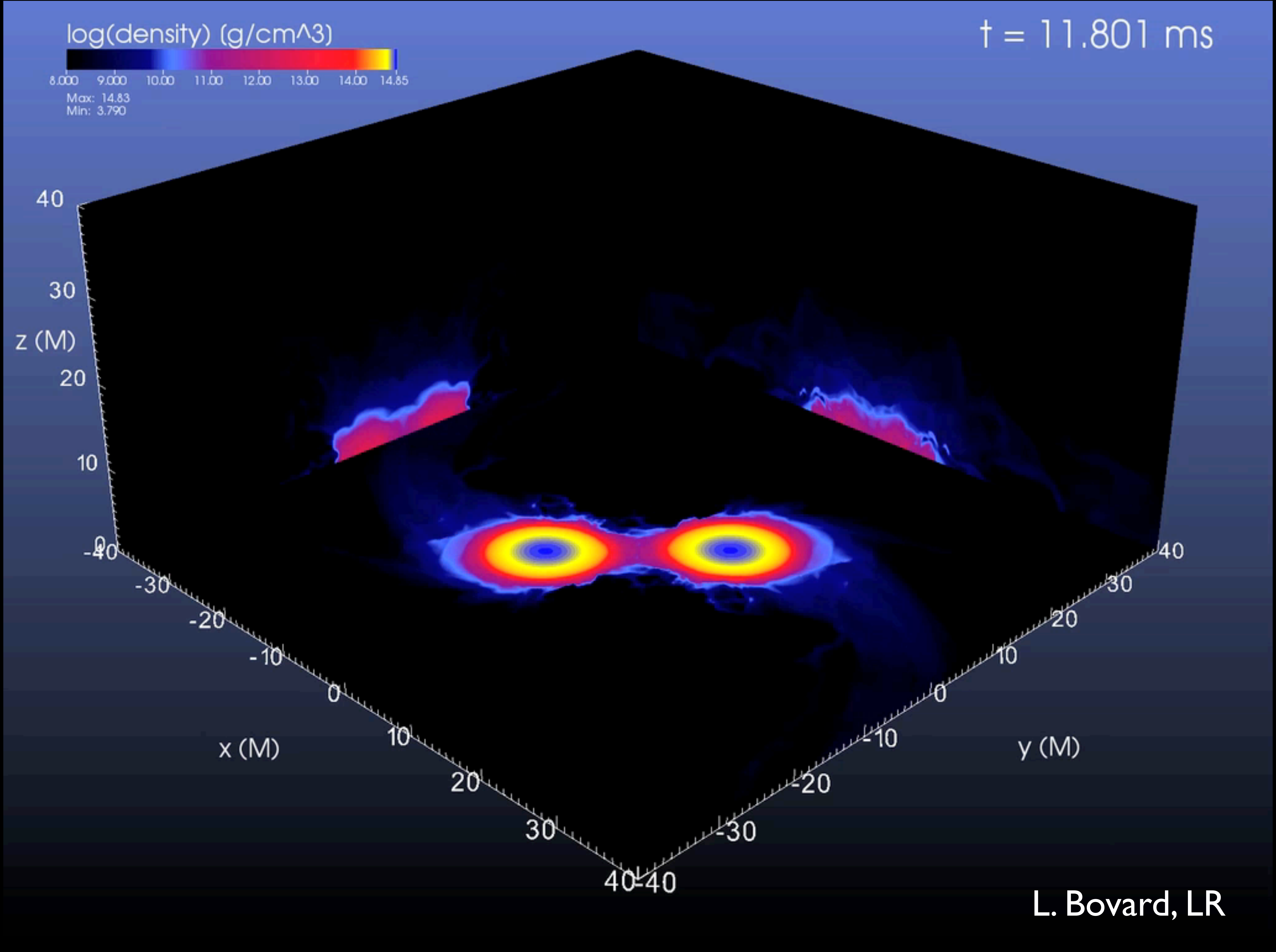
Ejected matter and r-process nucleosynthesis

Bovard+ (2017), Topolski+ (2026)

Heavy-elements nucleosynthesis

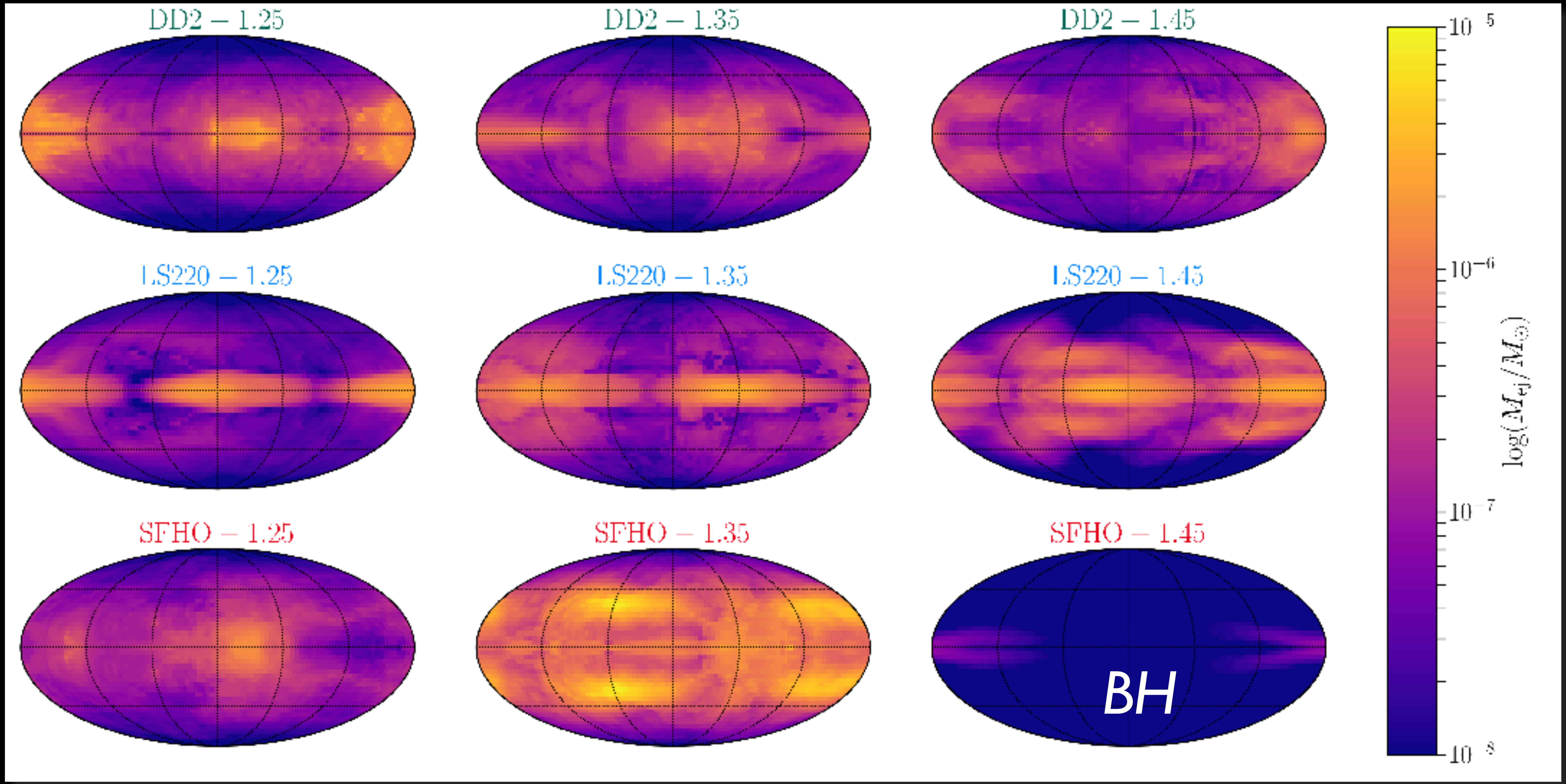
- Already in the 50's, nuclear physicists had tracked the production of elements in stars via nuclear fusion.
- **Heavy elements** (*A*>56) cannot be produced in stellar interiors but can be synthesised during a **supernova**.
- SN simulations have shown that temperatures/energies not enough to produce **"very heavy" elements** (*A*>120).
- To produce such elements very high temperatures and **"neutron-rich"** material is needed.
- Physical conditions in **neutron-star mergers** are perfect candidates for this process!





log(density) (g/cm^3)
8.000 9.000 10.00 11.00 12.00 13.00 14.00 14.85
Max: 14.83
Min: 3.790
t = 11.801 ms
z (M)
x (M)
y (M)
L. Bovard, LR

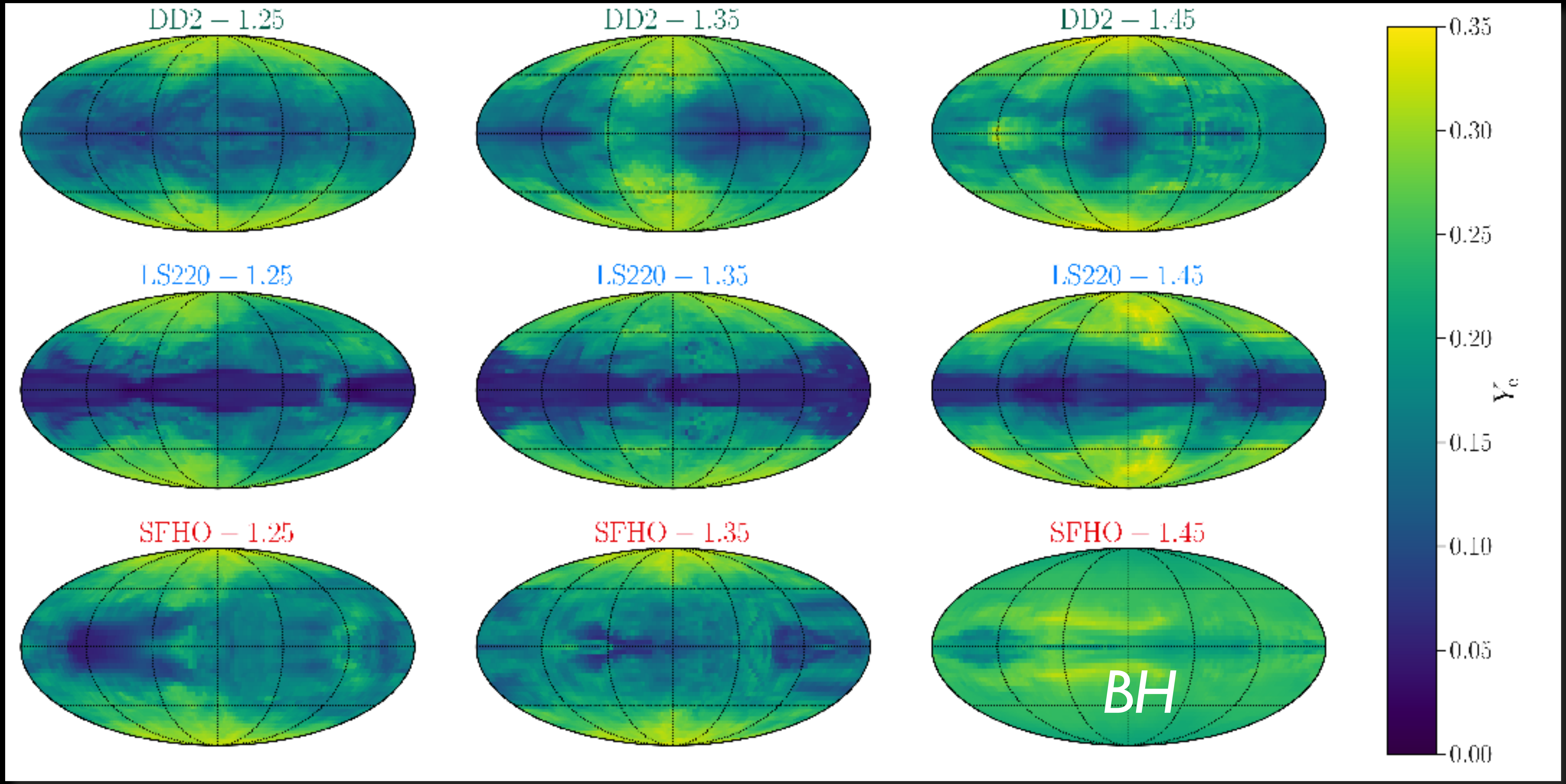
Spatial distributions: M_{ej}



Spatial distribution of M_{ej} impacts detectability of EM counterpart:

- ★ most of M_{ej} lost at low latitudes;
- ★ depending on EOS/mass, contamination also in polar regions

Spatial distributions: Y_e

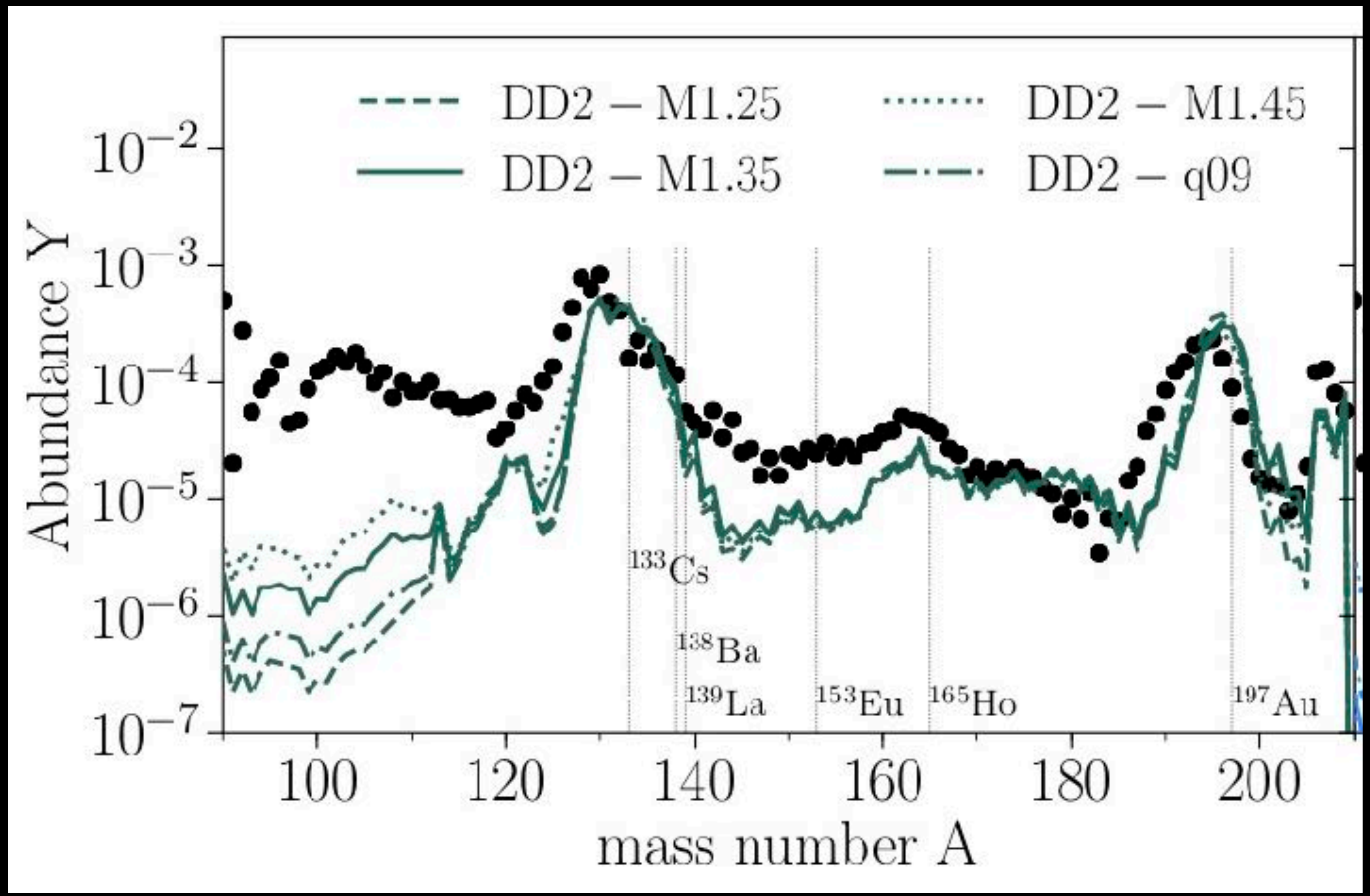


Spatial distribution of Y_e impacts detectability of EM counterpart:

- ★ **high** Y_e in **polar** regions: **blue** (optical) macronova
- ★ **low** Y_e in **equatorial** regions: **red** (FIR) macronova

Relative abundances

- Mass ejection can either be **dynamical** (shocks; 100 ms) or **secular** (magnetic or neutrino-driven winds; 1-10 s).
- Even **tiny amounts** of ejected matter (*0.01 M*$_\odot$) sufficient to explain observed abundances.
- Abundances for *A>120* good agreement with solar. **robust** for different **EOSs**, **NS masses,** **and** **mass ratios**



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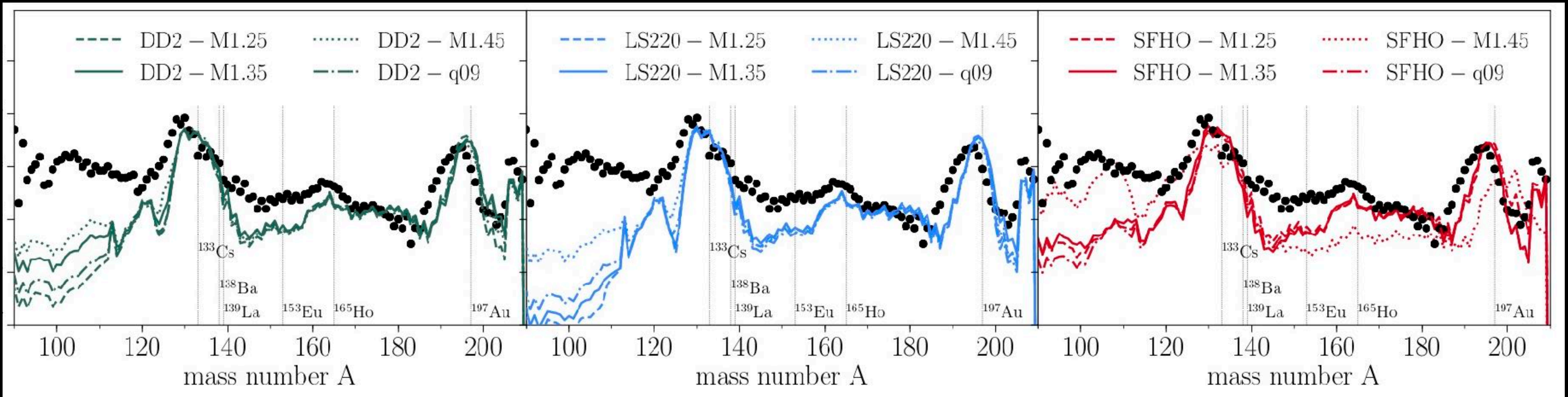

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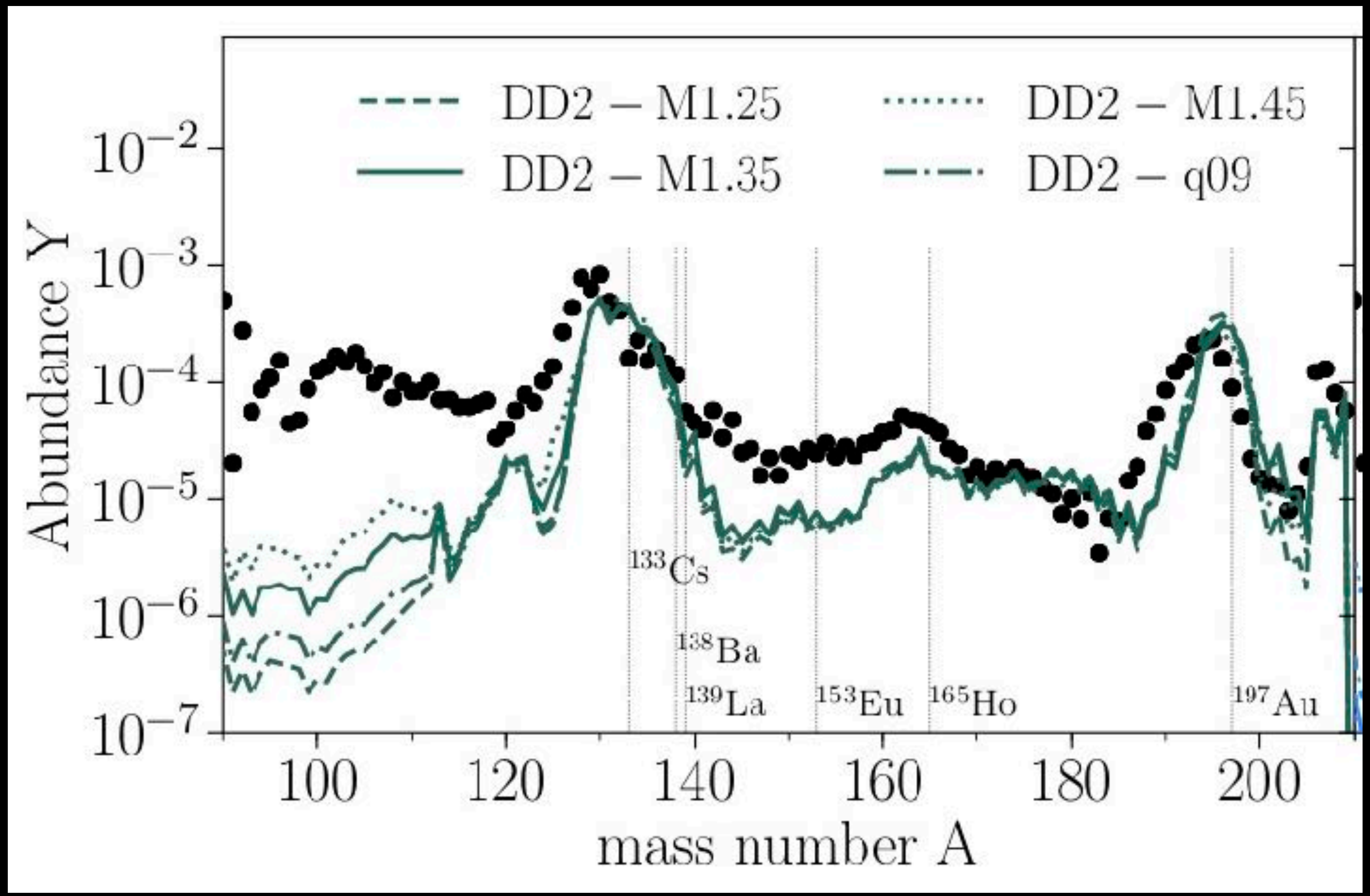
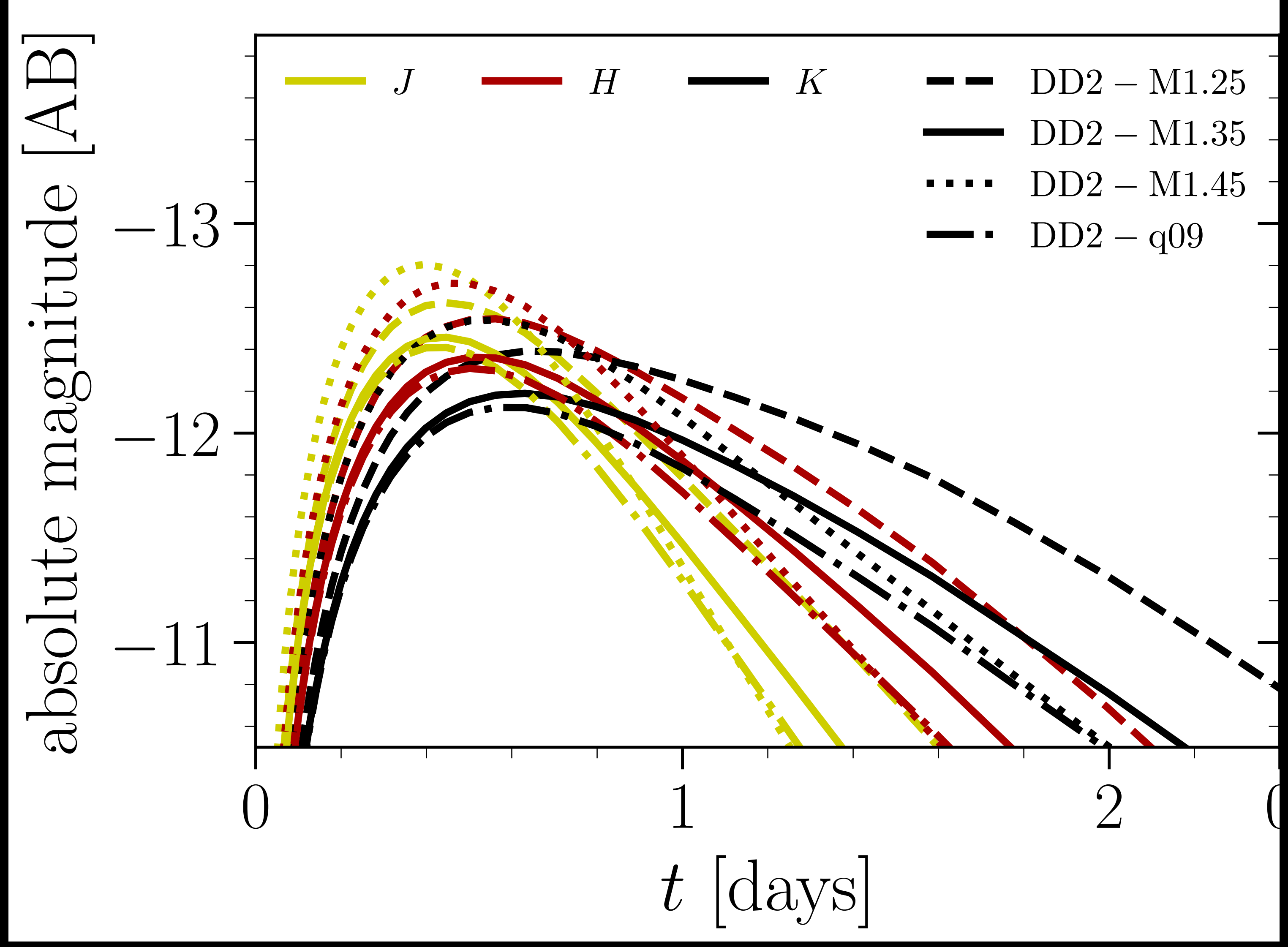


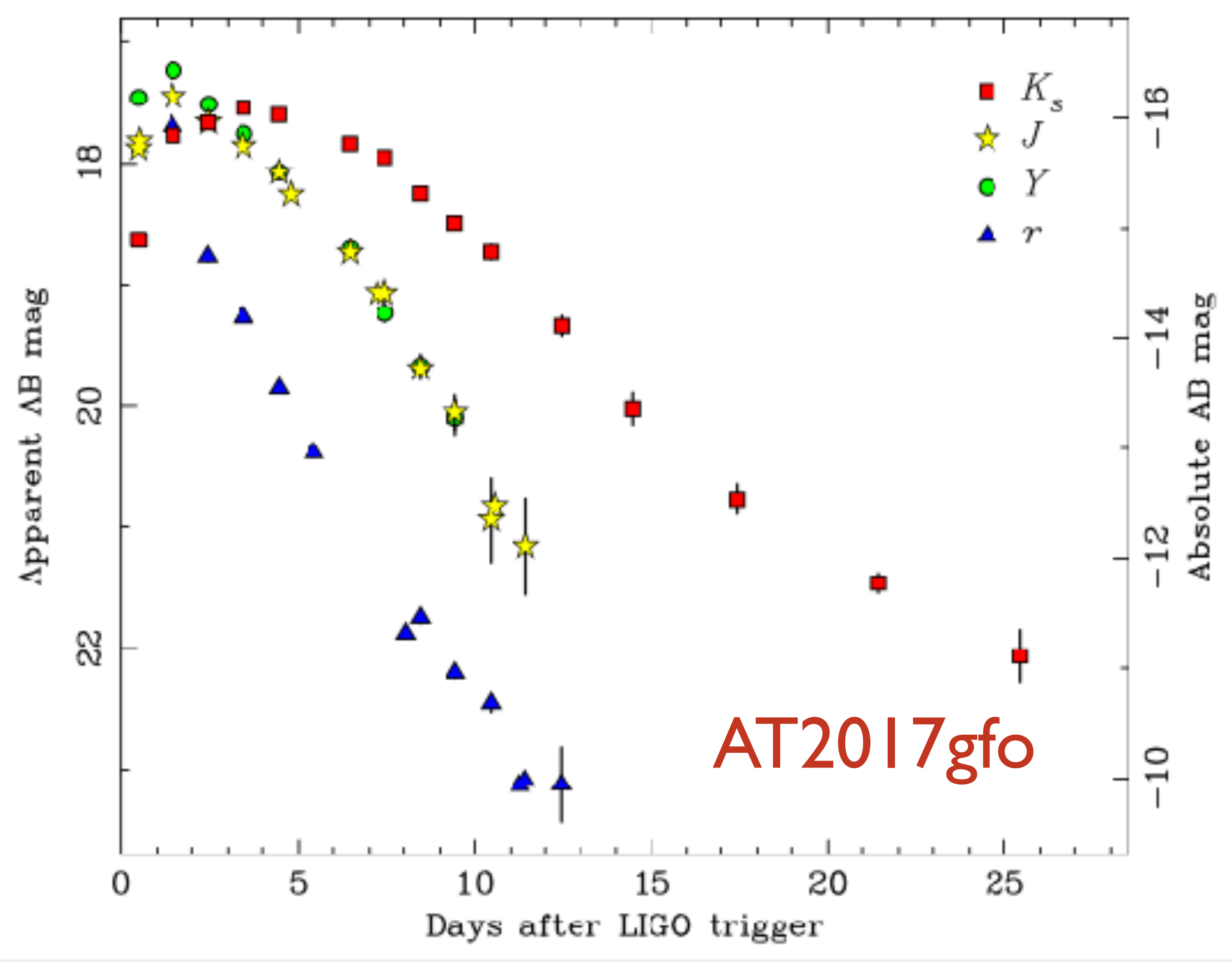
GW170817 produced total of **16,000** times the mass of the Earth in heavy elements (**10** Earth masses in **gold/platinum**)

Kilonova emission

- Besides nucleosynthesis, the ejected matter also provides important EM information.
- When critical densities and temperatures are reached, matter undergoes radioactive decay emitting light (optical/infrared): **kilonova/macronova** (Li & Paczynski '98).



simulations



observations (Tanvir+2017)

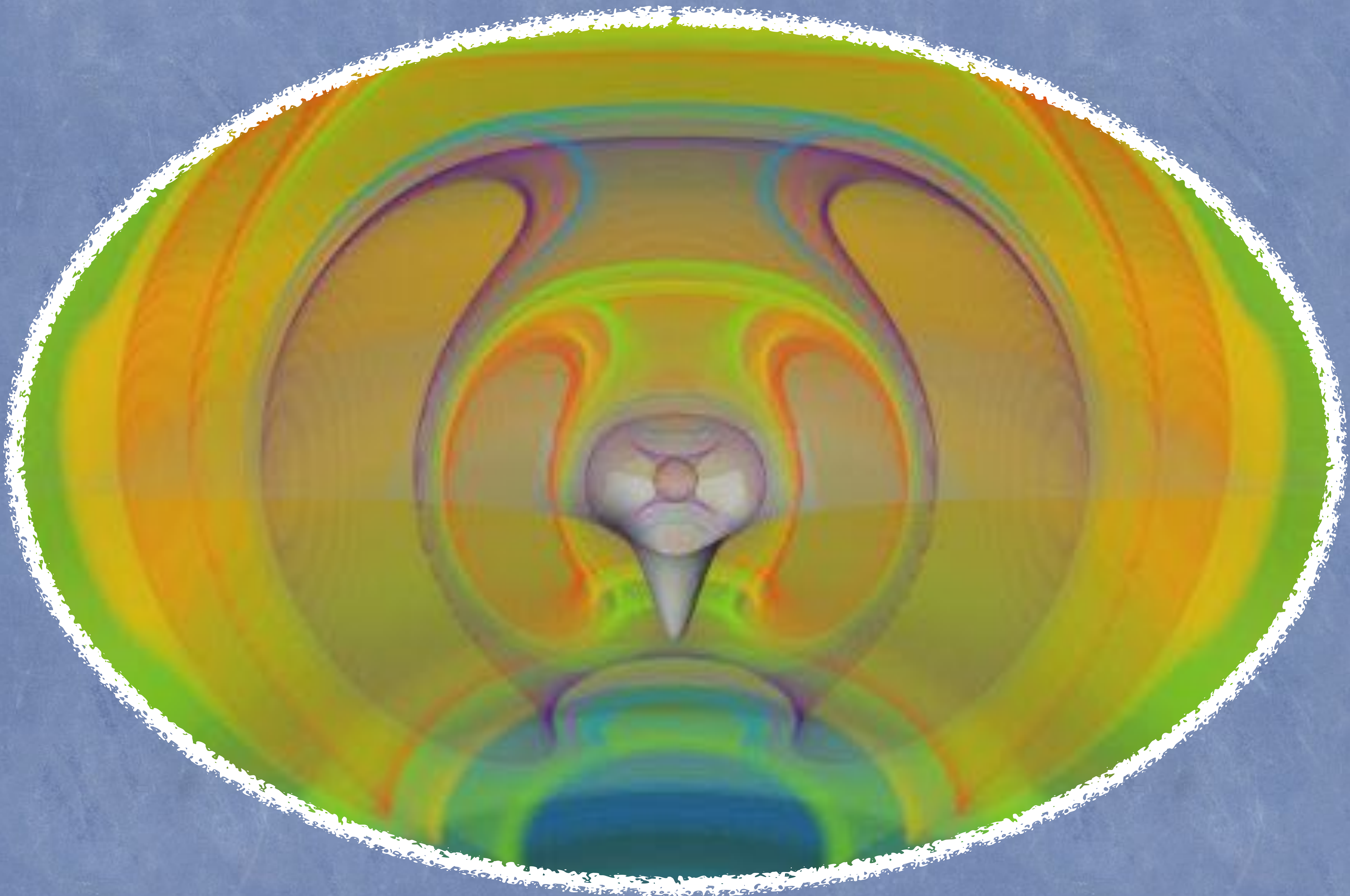
- AT2017gfo is kilonova measured with GW170817, showing it was a BNS merger.
- Using simulations, it is possible to reproduce qualitatively the AT2017gfo signal

Conclusions

- Inclusion of B-fields and the collapse to a BH, naturally leads to the formation of a large-scale jet structure; outflow only mildly relativistic
- KHI represents efficient way of amplifying B-fields from small pulsar-scale values $(10^{10}\,\mathrm{G})$ to magnetar values $(10^{15}\,\mathrm{G})$
- crustal magnetic fields do not lead to large amplification: precious B-field is ejected at merger
- spins impact KHI; larger B-fields amplifications for anti-aligned spins
- r-process nucleosynthesis is robust and matches well the observations

EXTRAS

On the maximum compactness



LR, Ecker(2023)

How compact can a **realistic** neutron star be?

This is a very old question and we have a very important limit in general relativity (Buchdahl Theorem)

$$\frac{M}{R} \leq \frac{4}{9} \simeq 0.444$$

We could ask this question for the 10^6 EOSs we have constructed

However, compactness can change as a function of mass and a criterion is needed to compare the maximum compactness

How compact can a **realistic** neutron star be?

To address this question we formulate the following conjecture

$$\mathscr{C}_{\rm max} = \mathscr{C}_{\rm TOV}$$

In other words the maximum compactness is attained by the star with the maximum mass.

This condition can be shown to be true for a large number of possible EOSs and a simple theorem can be proven.

More in general, however, it is hard to prove.

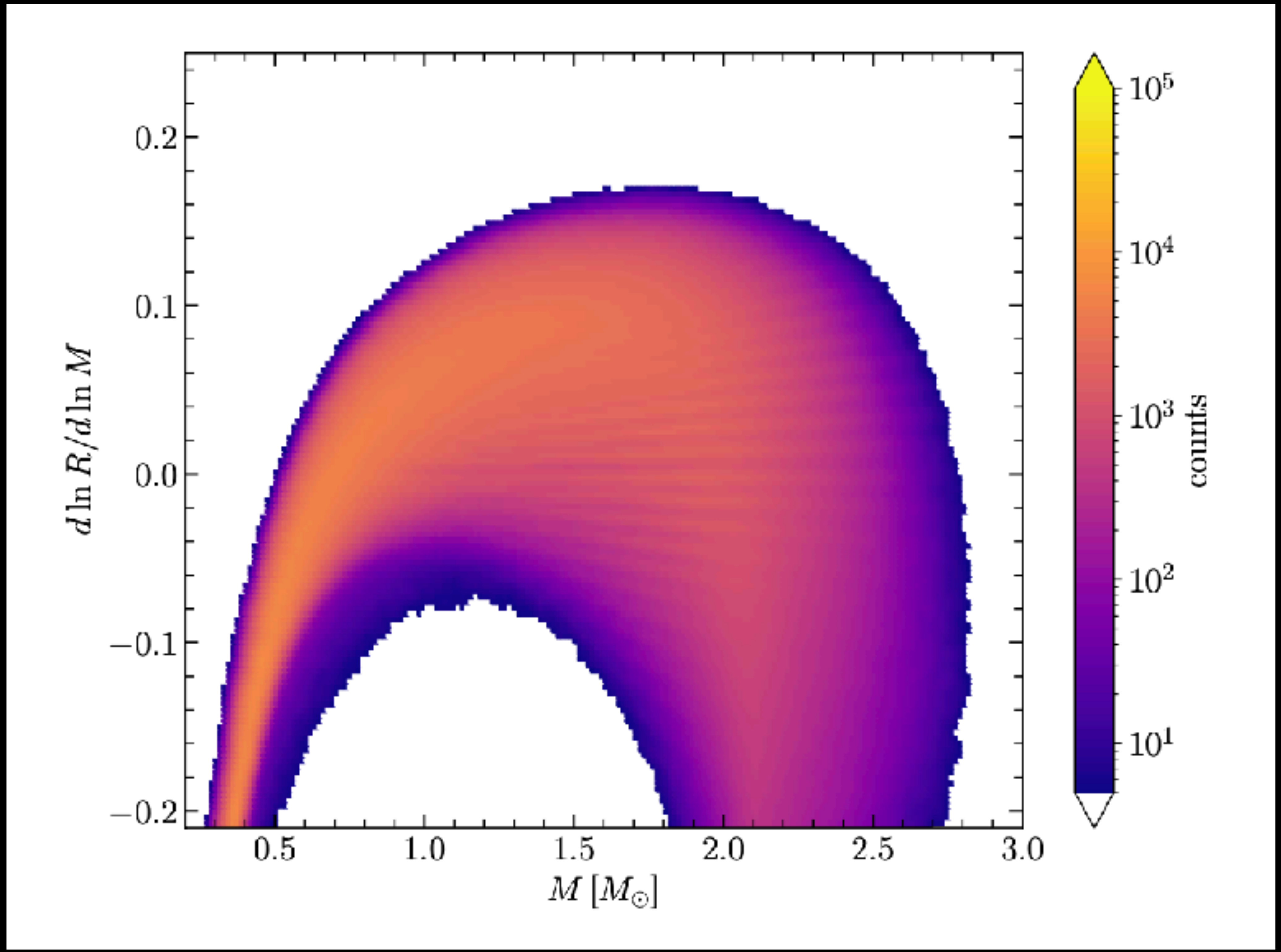
How compact can a **realistic** neutron star be?

Is the conjecture ctrue for realistic EOSs? The conjecture can be cast as

$$\mathscr{C}_{\rm max} = \mathscr{C}_{\rm TOV} \qquad \Leftrightarrow \qquad \frac{d\mathscr{C}(M)}{dM} = \frac{1}{R(M)}\left(1 - \frac{d\ln R}{d\ln M}\right) \geq 0\,.$$

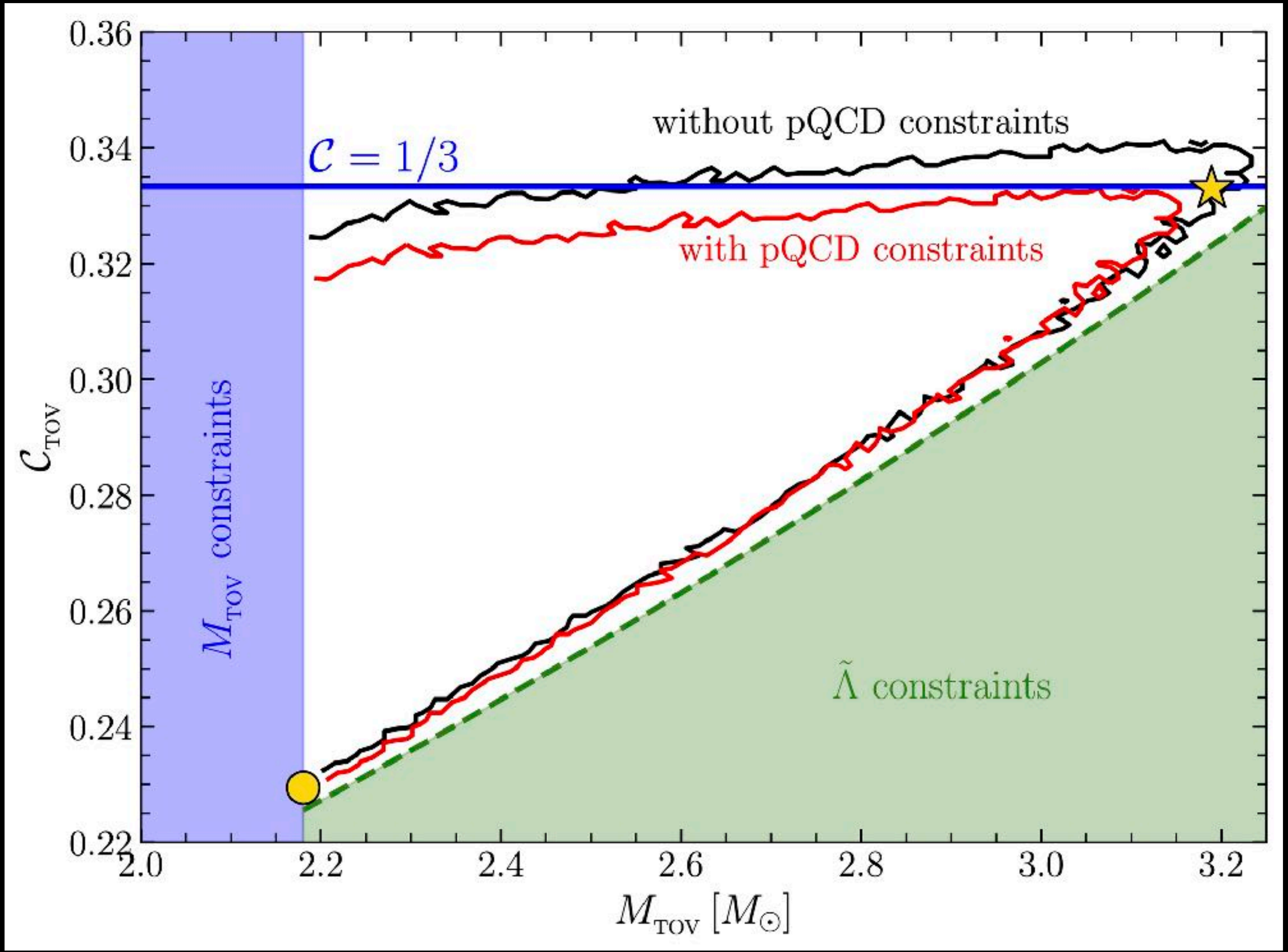
All we need to check is whether the term in the round brackets is validated by all our stellar models.

Hence, the conjecture is far more solid then a conjecture…



How compact can a **realistic** neutron star be?

We can finally answer the question

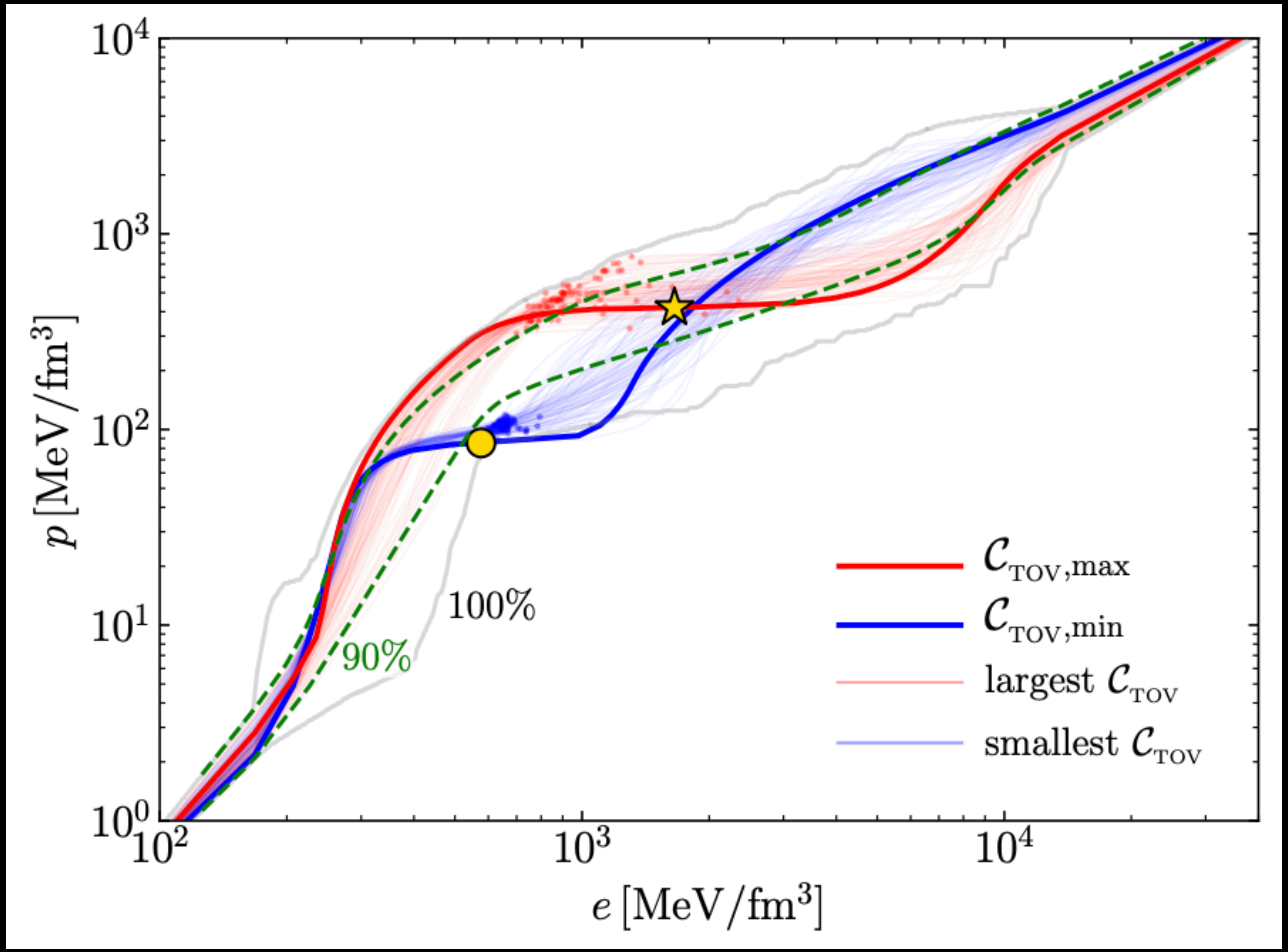


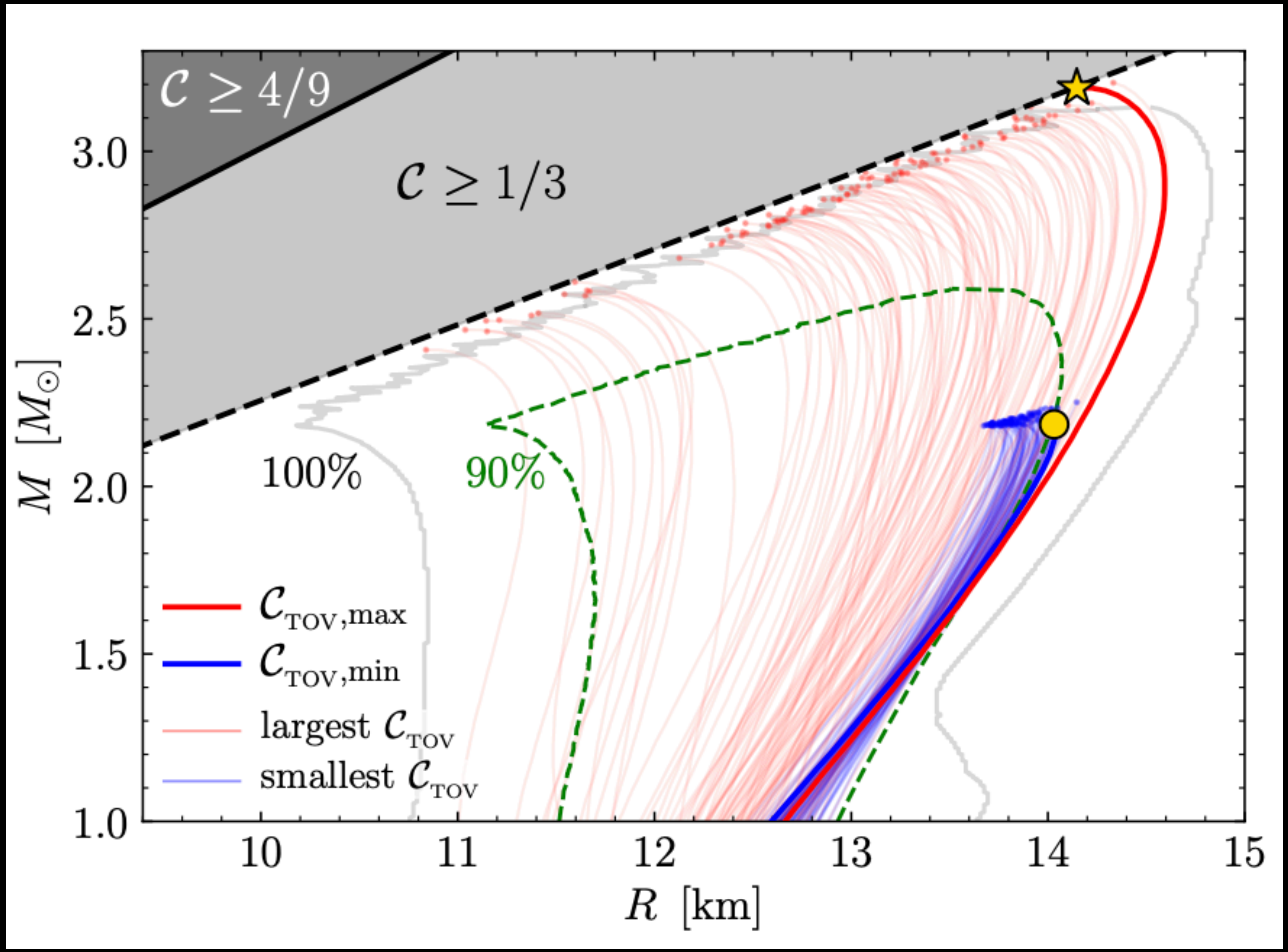
If the pQCD constraint is imposed, the evidence is that

$$\mathscr{C} \leq 1/3$$

Violation of this bound would provide important information: anomalous QCD behaviour at largest densities

How compact can a **realistic** neutron star be?

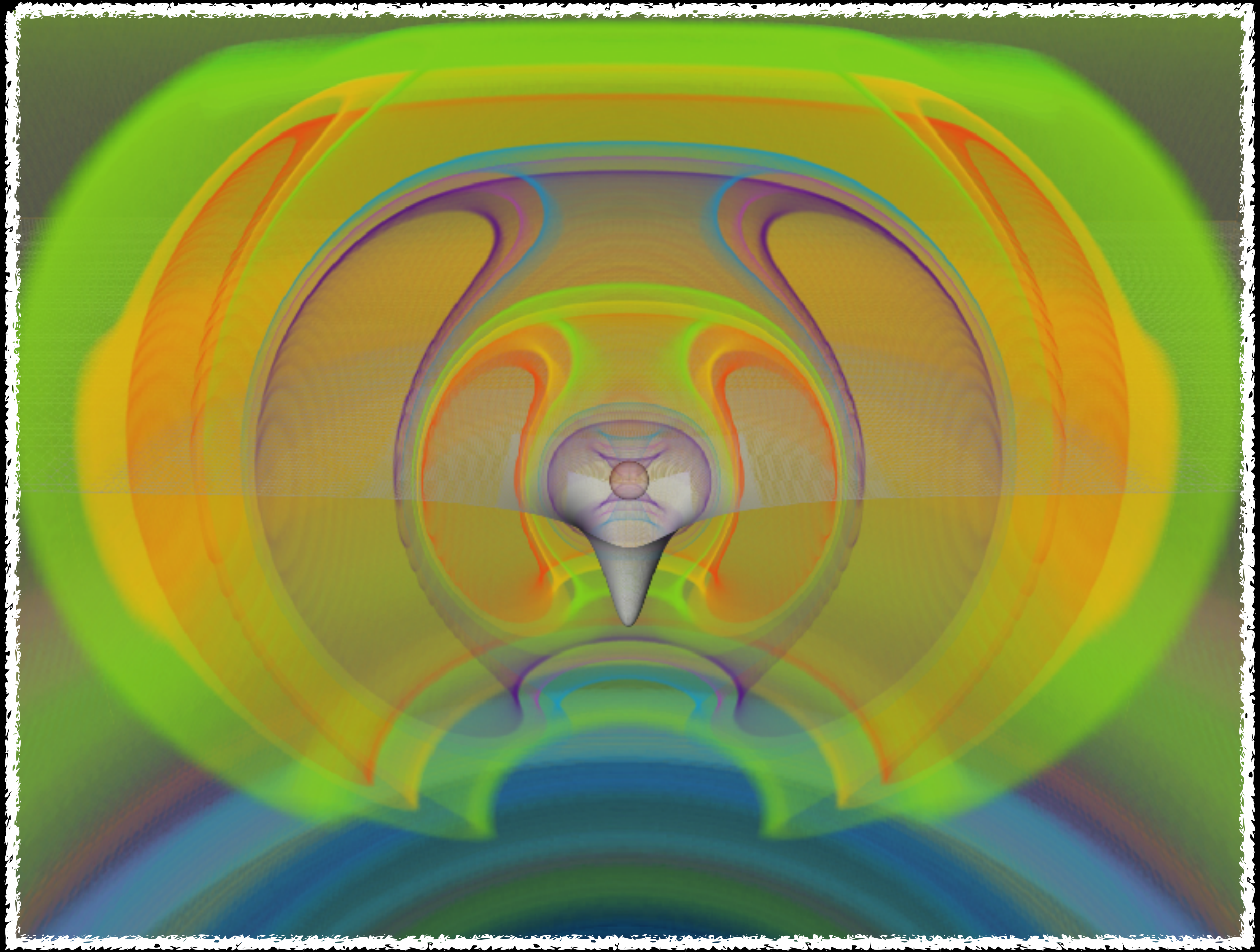




Conclusions

- Spectra of post-merger shows peaks, some "quasi-universal".
- When used together with tens of observations, they will set tight constraints on EOS: radius known with **~1 km** precision.
- A **phase transition** after a BNS merger leaves GW **signatures** and opens a gate to access quark matter beyond accelerators.
- The sound speed is likely to be super-conformal in a NS and its maximum value is reached at the centre/interior for light/heavy stars.
- Long ringdown, is **new tool** to constrain NS properties relating slope and EOS at highest densities and pressures.
- pQCD imprints intriguing upper bound on stellar compactness: $\mathscr{C} \leq 1/3$.

Threshold Mass to prompt collapse

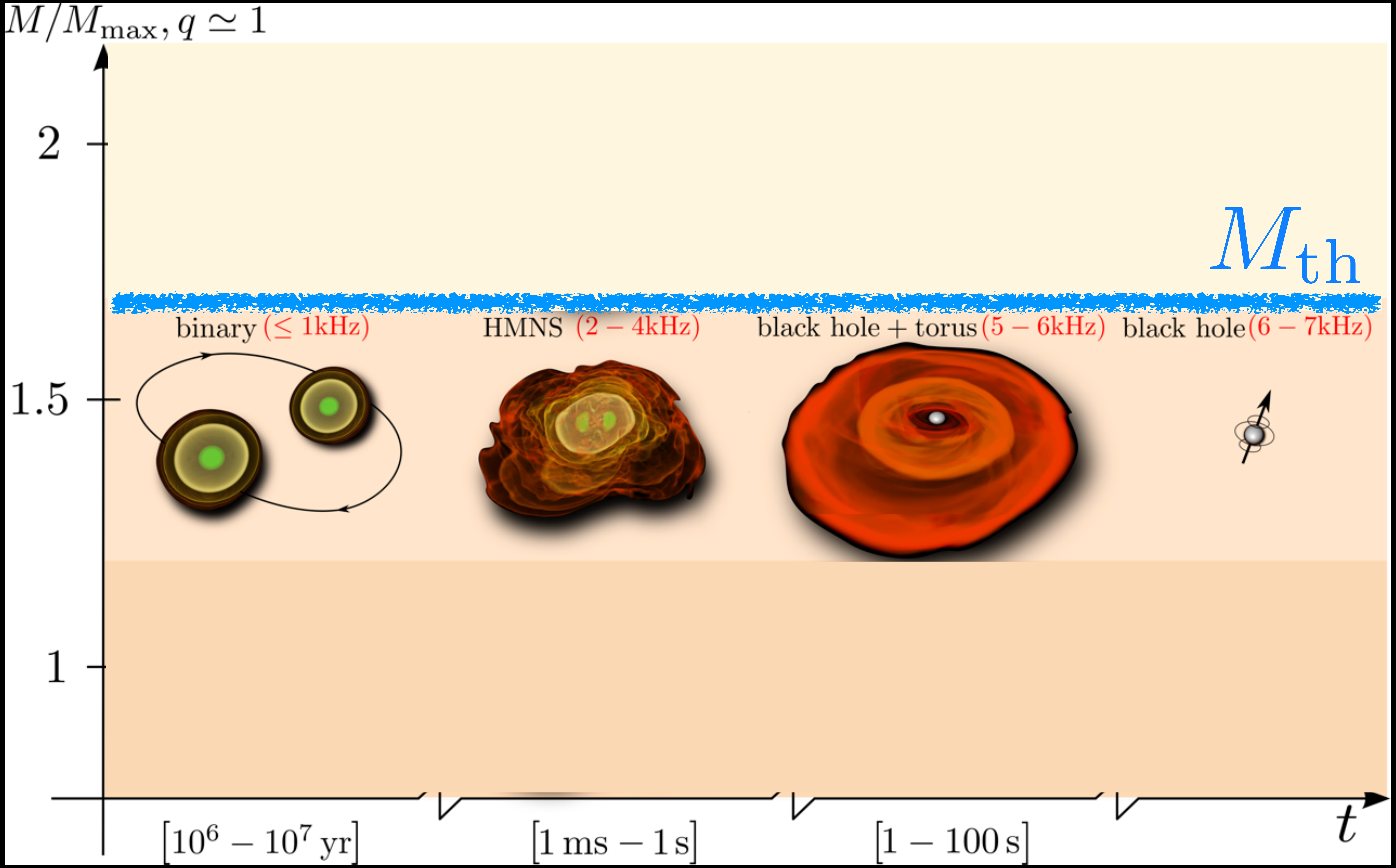


Köppel, Bovard, LR, ApJL (2019)
Tootle, Papenfort, Most, LR ApJL (2021)

A universal behaviour ?

- Given an EOS, a **threshold mass** exists that marks the prompt collapse. Is this **universal?**

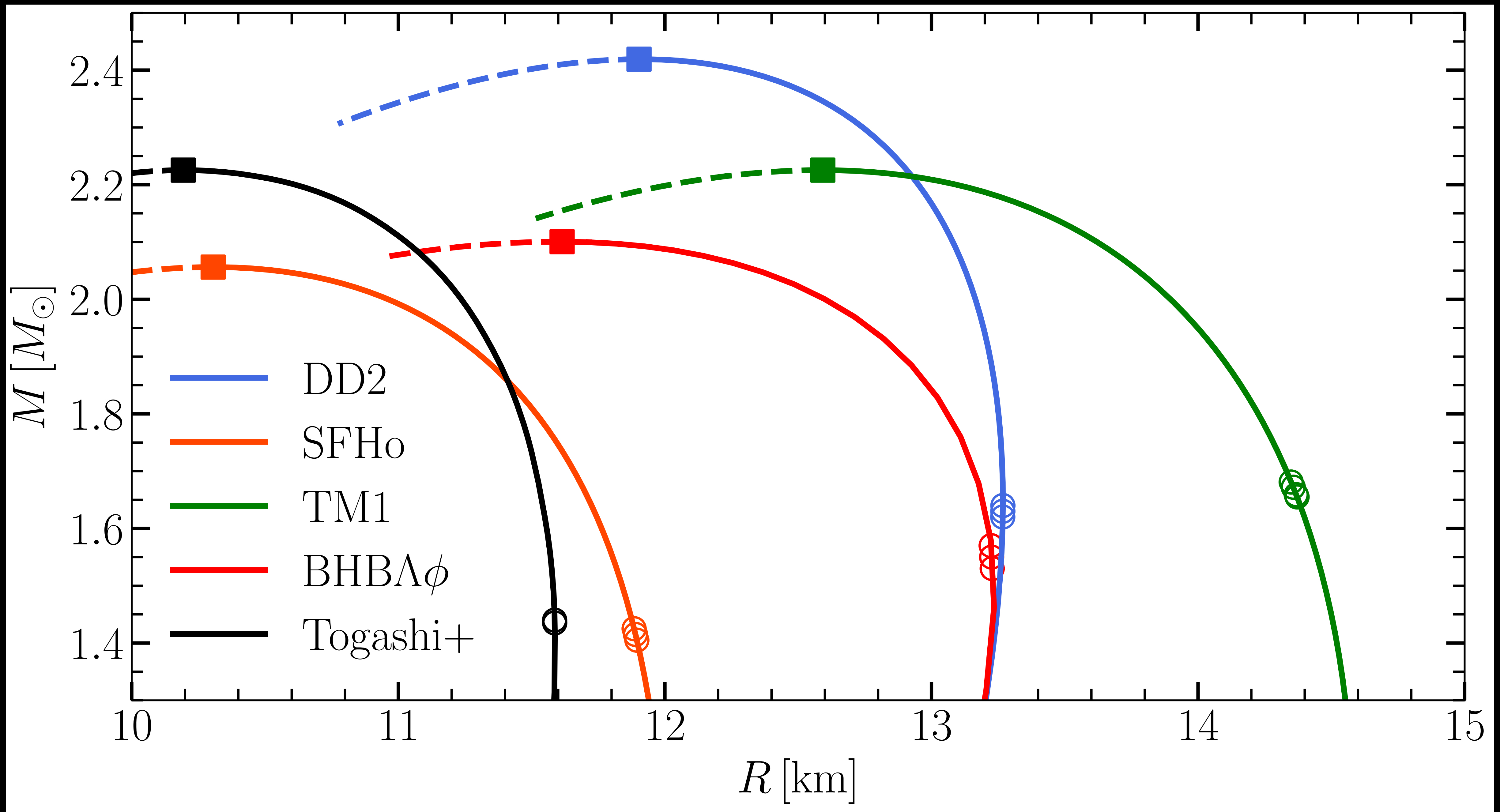
Threshold mass



A universal behaviour ?

- Given an EOS, a **threshold mass** exists that marks the prompt collapse. Is this **universal?**

1. Select useful EOSs that self-consistently incorporate ***finite-temperature effects.***



A universal behaviour ?

- Given an EOS, a **threshold mass** exists that marks the prompt collapse. Is this **universal?**

2. Determine rigorous definition of ***"prompt"*** collapse and produce dimensionless quantity

$$t_{\rm coll} := t_{\rm BH} - t_{\rm merg}$$

$$t_{\rm merg}: \quad \min(\alpha) = \alpha_{\rm merg} := 0.35\,,$$

$$t_{\rm BH}: \quad \min(\alpha) = \alpha_{\rm BH} := 0.2\,.$$

extremely robust and EOS independent

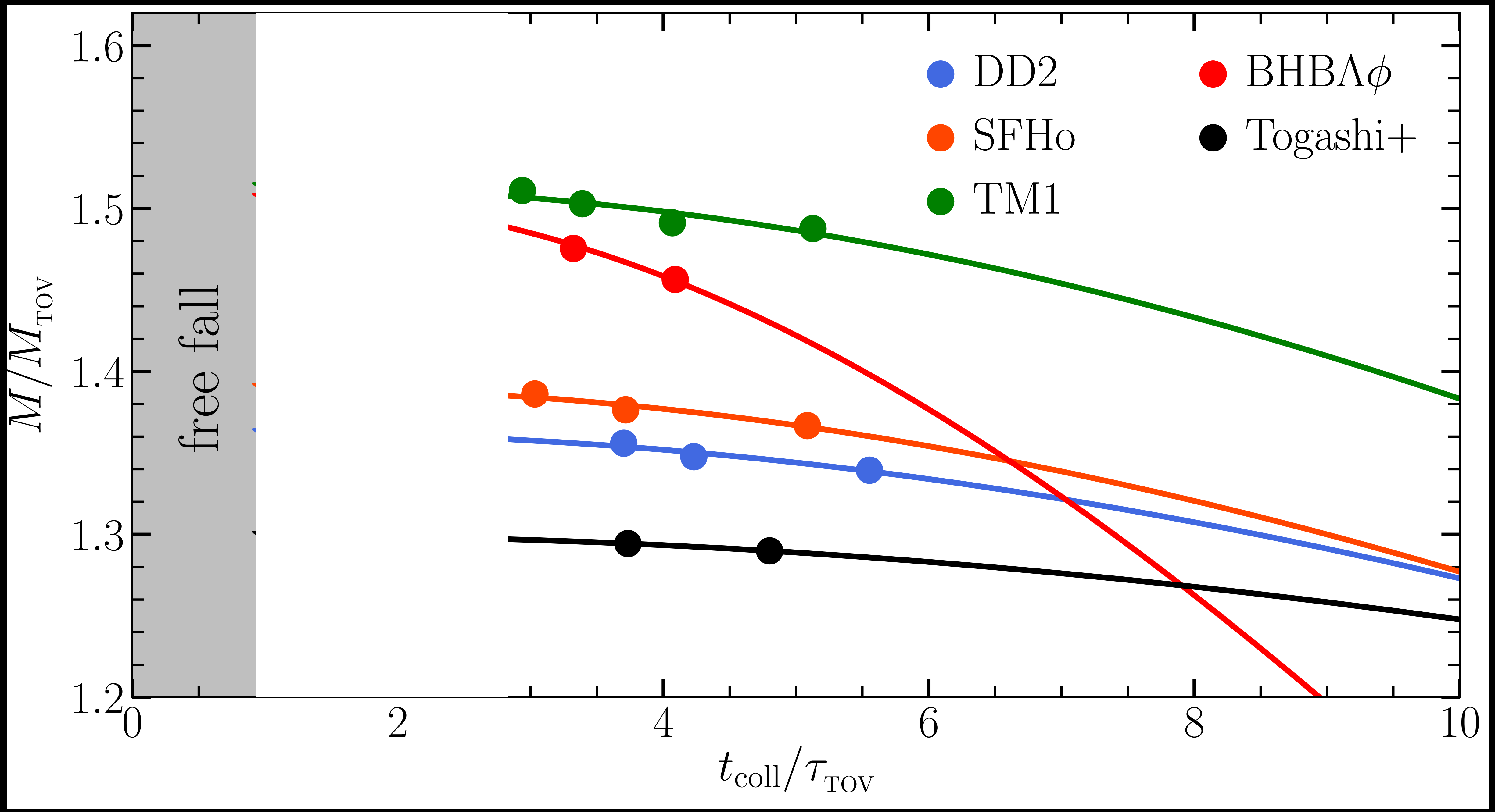
$$\tau_{\rm ff}(M,R) := \frac{\pi}{2}\sqrt{\frac{R^3}{2M}}\,.$$

free-fall timescale in Oppenheimer-Snyder collapse

A universal behaviour ?

- Given an EOS, a **threshold mass** exists that marks the prompt collapse. Is this **universal?**

3. Express measured values in terms of dimensionless collapse time.



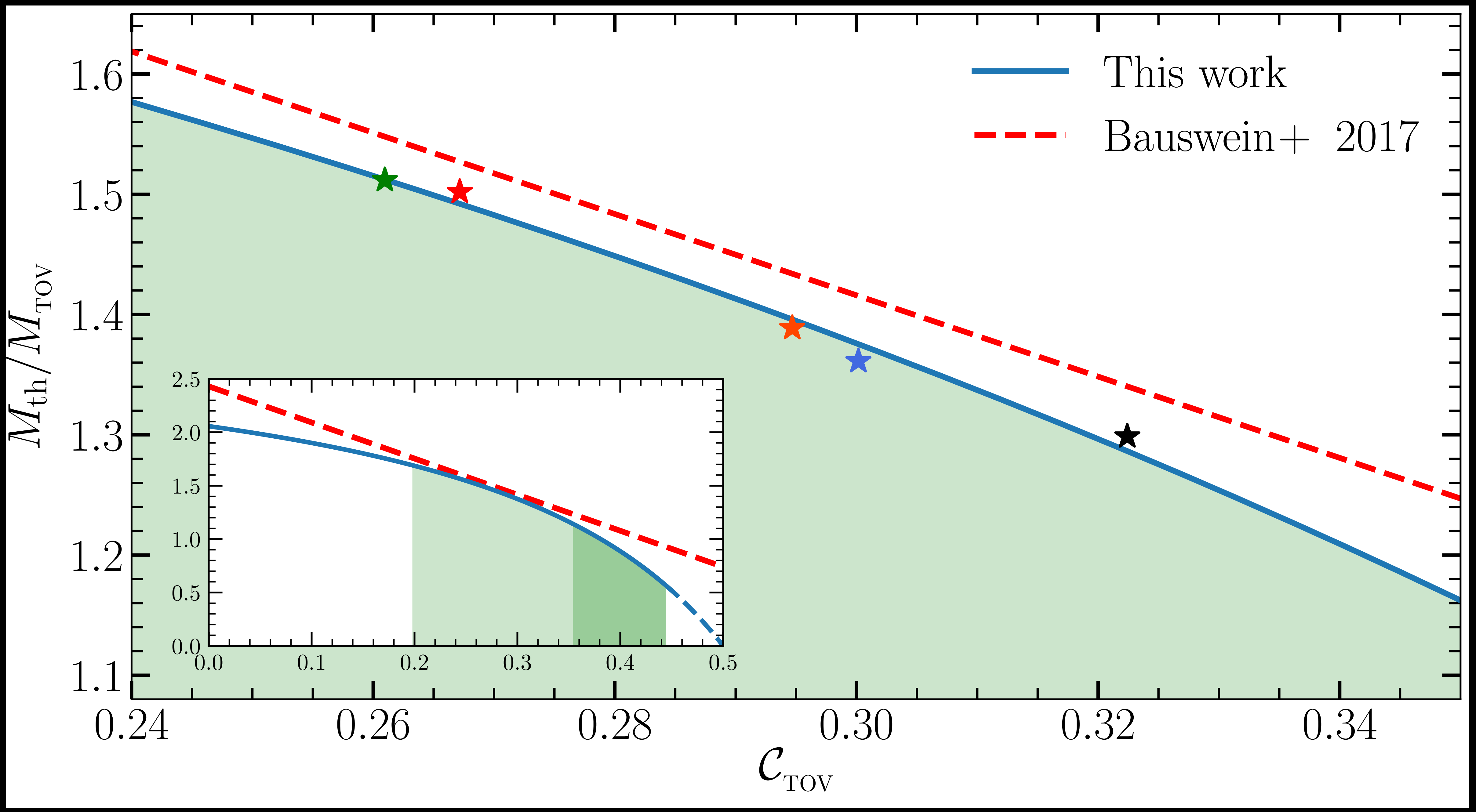
$$\frac{M_{\rm th}}{M_{\rm TOV}} \approx 1.415$$

first rough estimate

A universal behaviour ?

- Given an EOS, a **threshold mass** exists that marks the prompt collapse. Is this **universal?**

4. Seek universal behaviour via maximum compactness. $\mathcal{C}_{\rm TOV} := (M/R)_{\rm TOV}$. A **linear** fit is possible but not satisfactory. A **nonlinear** fit obtained by requiring that



$$M_{\rm th}/M_{\rm TOV} \to 0$$

for

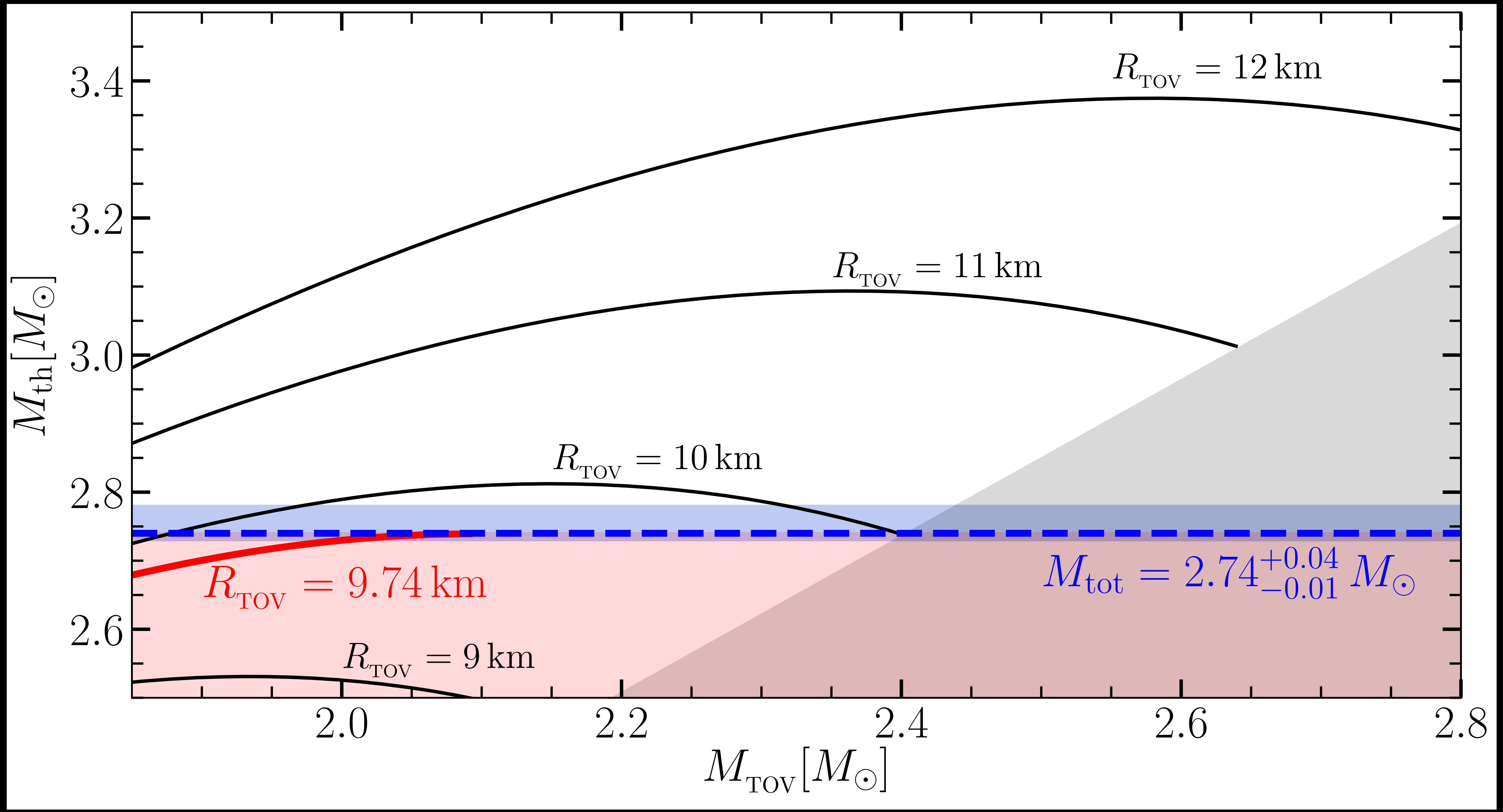
$$\mathcal{C}_{\rm TOV} \to 1/2$$

$$\frac{M_{\rm th}}{M_{\rm TOV}} = a - \frac{b}{1 - c\,\mathcal{C}_{\rm TOV}}$$

Another universal behaviour

- Given an EOS, a **threshold mass** exists that marks the prompt collapse. Is this **universal?**

5. The detection of a merger not leading to prompt collapse constraints the radius from below



GW170817

$$M_{\rm tot} = 2.74^{+0.04}_{-0.01}\,M_\odot$$

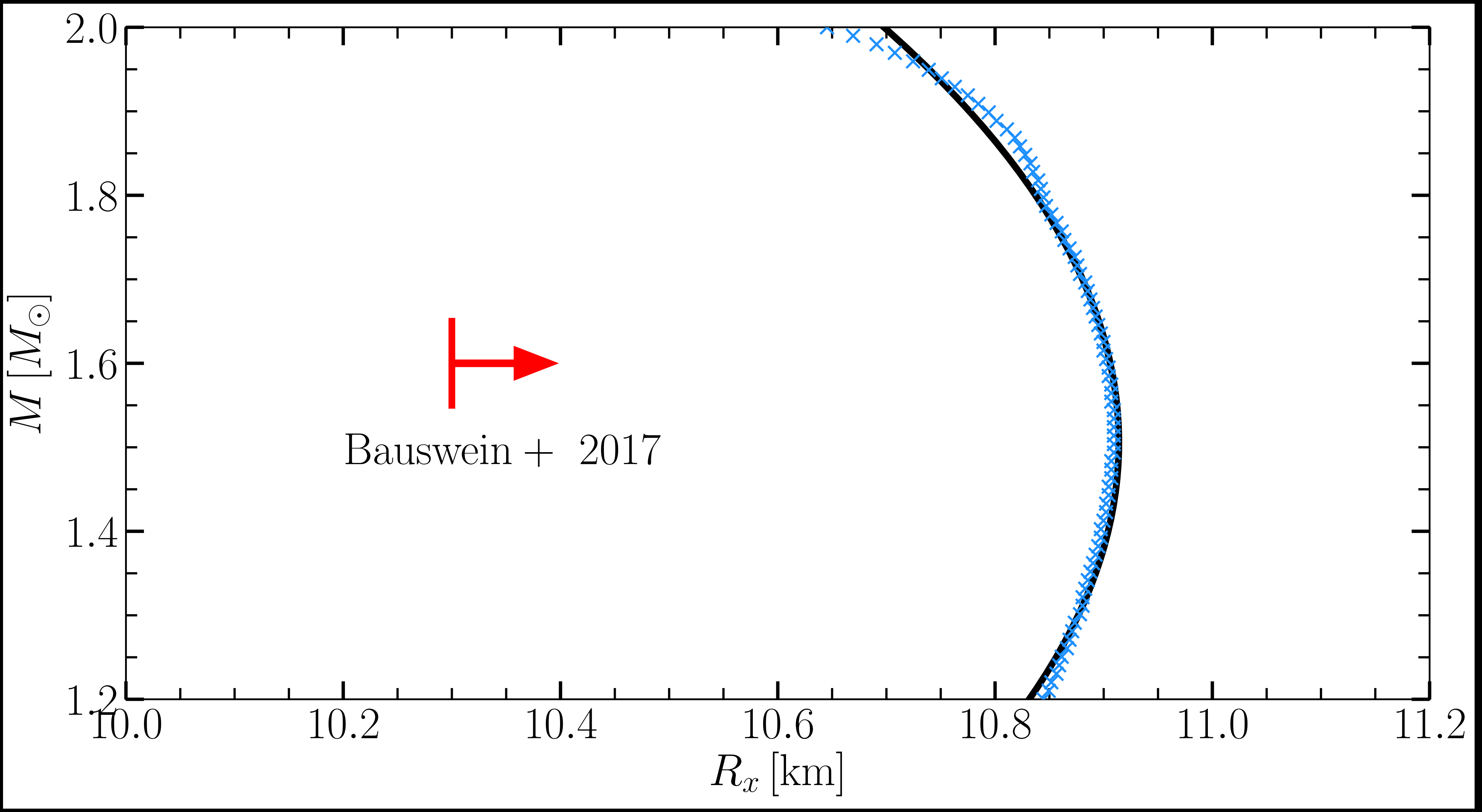
so that

$$R_{\rm TOV} \geq 9.74^{+0.14}_{-0.04}\,{\rm km}$$

Another universal behaviour

- Given an EOS, a **threshold mass** exists that marks the prompt collapse. Is this **universal?**

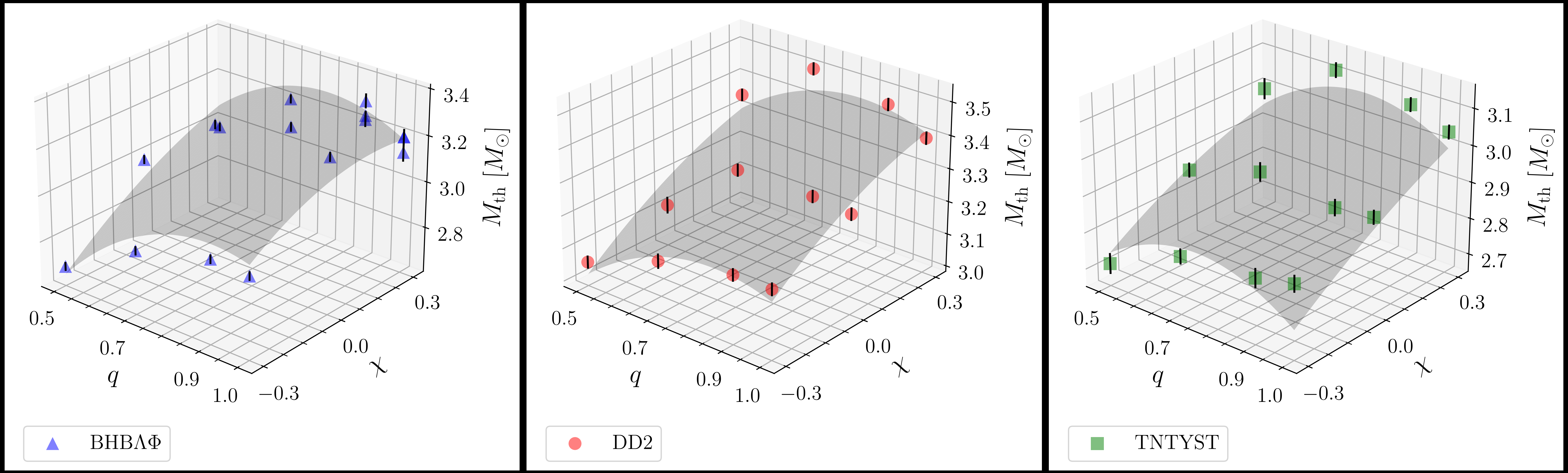
5. The detection of a merger not leading to prompt collapse constraints the radius from below



$$R_x = -0.88\, M^2 + 2.66\, M + 8.91$$

A more general behaviour

- All results so far true for **irrotational equal-mass** binaries
- $M_{\rm th}$ will depend also on **mass ratio** and **spin**
- Intuitively, $M_{\rm th}$ increases with **positive spin** and **mass ratio**
- We have considered **40** configurations, **360** simulations



Clearly, $M_{\rm th} = M_{\rm th}({\rm EOS}, q, \chi)$

A more general behaviour

Is this behaviour **universal?**

Assume separable ansatz

$$M_{\rm th} = M_{\rm th}({\rm EOS}, q, \chi) = \kappa({\rm EOS})\, f(q,\chi)$$

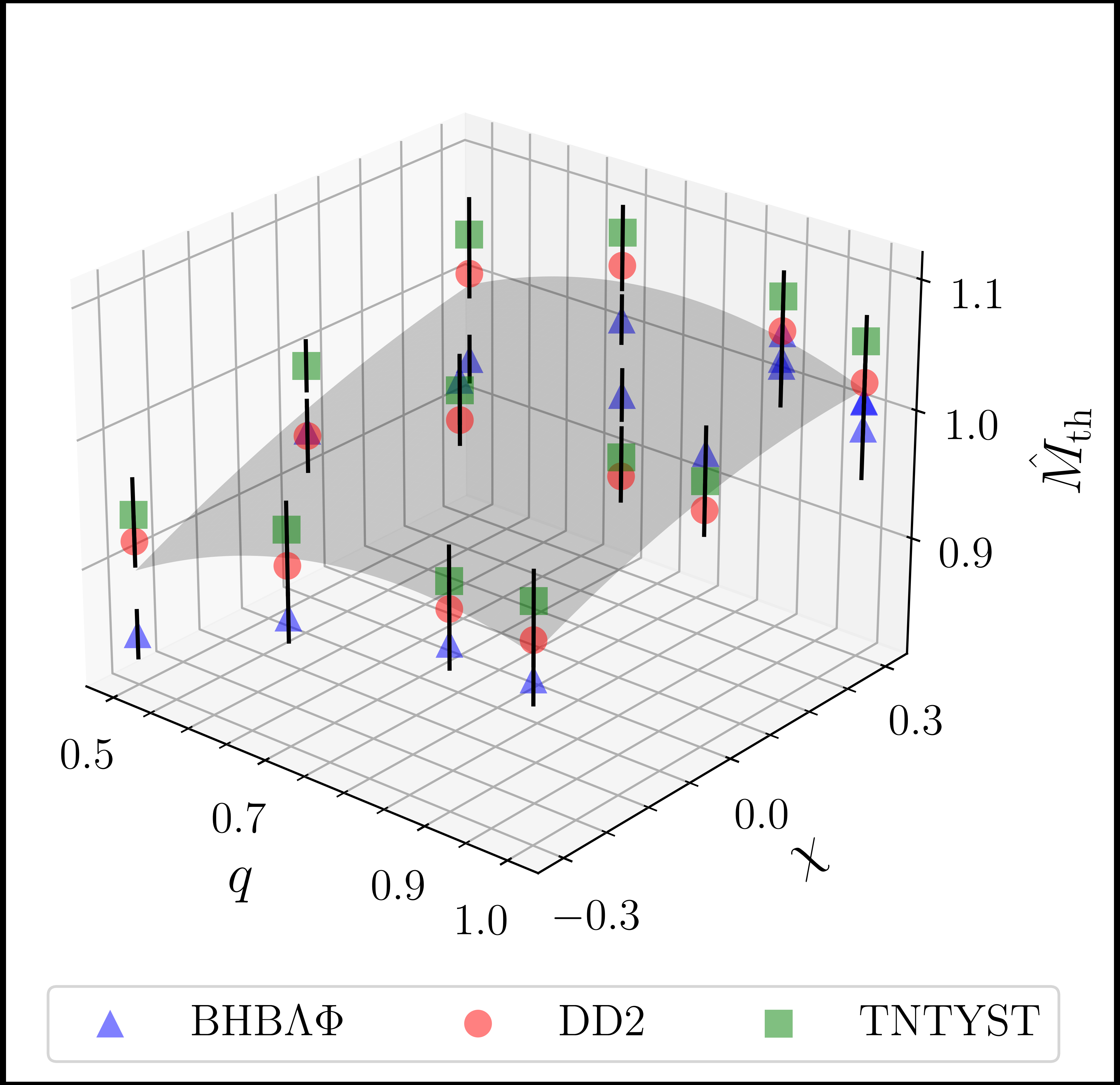
where $\kappa({\rm EOS})$ comes from $q = 1, \chi = 0$ (Köppel+ 2019)

$$\kappa({\rm EOS}) := \left(a - \frac{b}{1 - c\,\mathcal{C}_{\rm TOV}}\right) M_{\rm TOV}$$

and $f(q,\chi)$ is a quadratic function of q and χ

$$f(q,\chi) := a_1 + a_2(1-q) + a_3\chi + a_4(1-q)\chi + a_5(1-q)^2 + a_6\chi^2$$

Does this work?



Indeed a **universal relation** exists and yields:

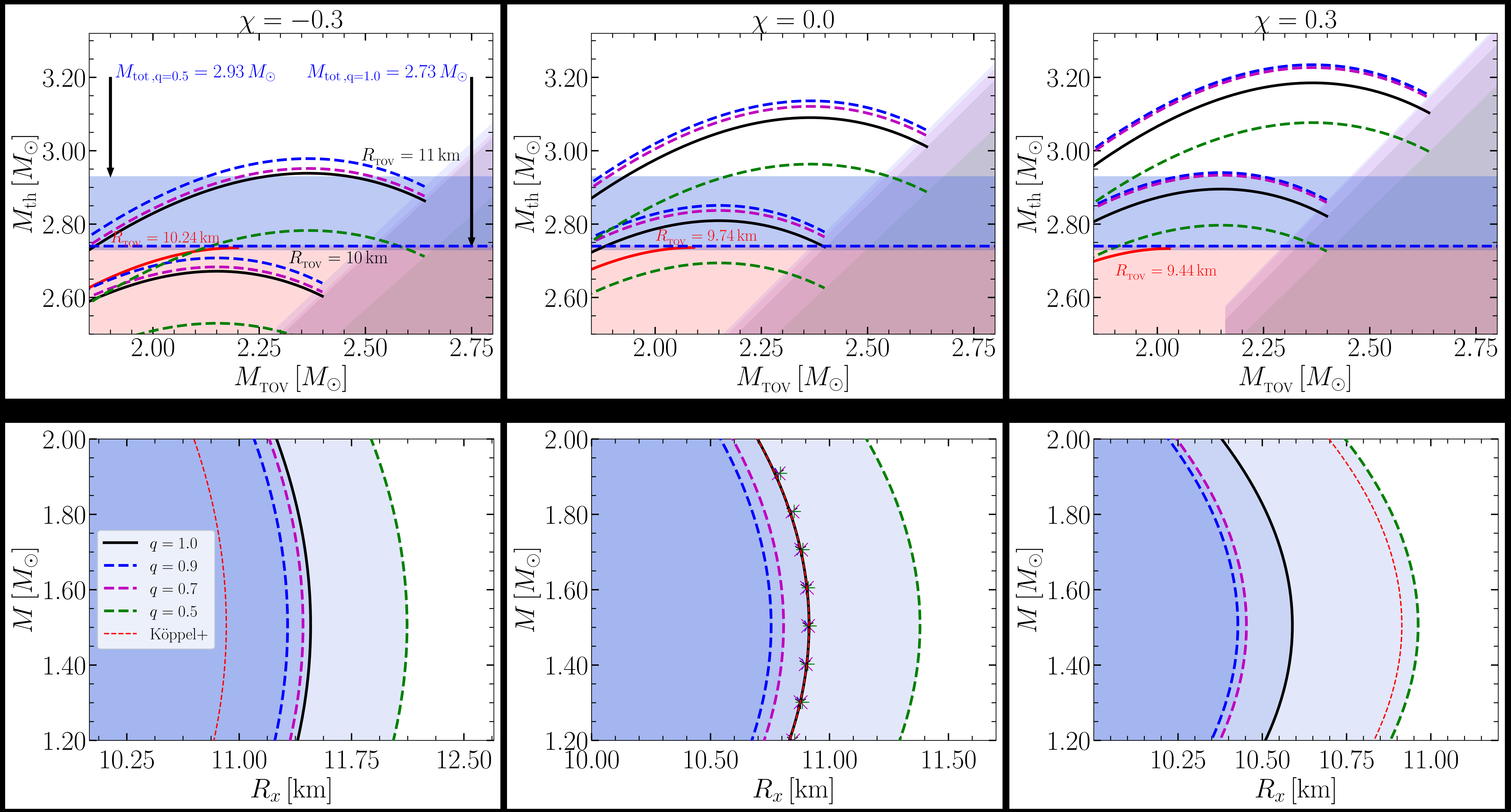
- **average deviation** from fit of ~2%, and **largest deviation** below ~6%.
- $M_{\rm th}$ **increases** by ~10% for **aligned** spins
- $M_{\rm th}$ **decreases** by ~5% for **antialigned** spins

Note: dependence on q **not monotonic:** balance between larger "discs" for small q and increased stability for large q yields **local maximum**

Possible to extend logic for lower limit on radius:

$$R_x(M, q, \chi) = \frac{R_x(M)}{f(q, \chi)}$$

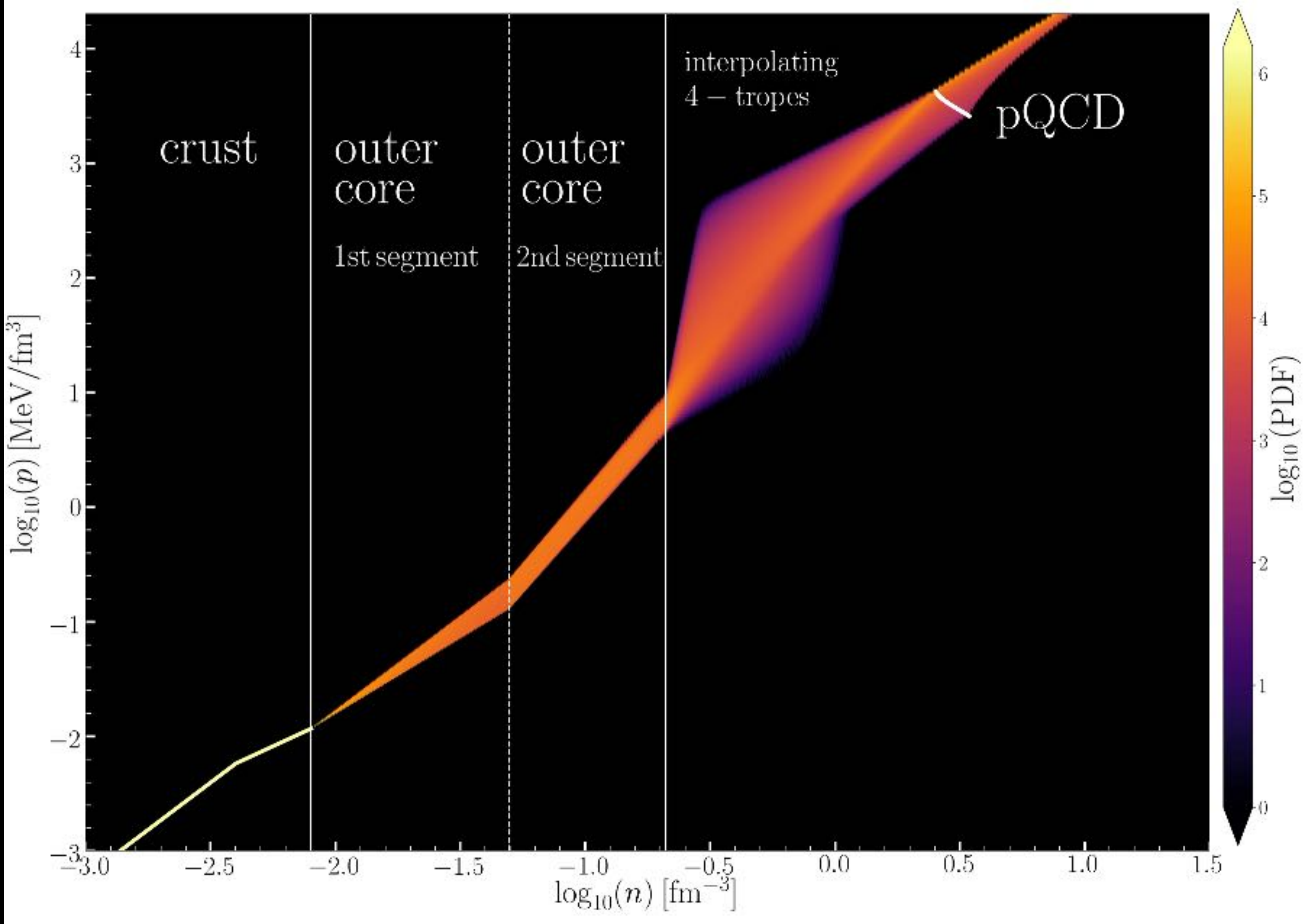
where $R_x(M)$ is from Köppel+ 2019
and $f(q, \chi)$ is the same as for $M_{\rm th}$



Antialigned binaries provide significantly tighter constraints:

$R_{\rm TOV} \geq 10.24\,{\rm km}$ for $\chi = -0.3$ **vs** $R_{\rm TOV} \geq 9.44\,{\rm km}$ for $\chi = 0.3$

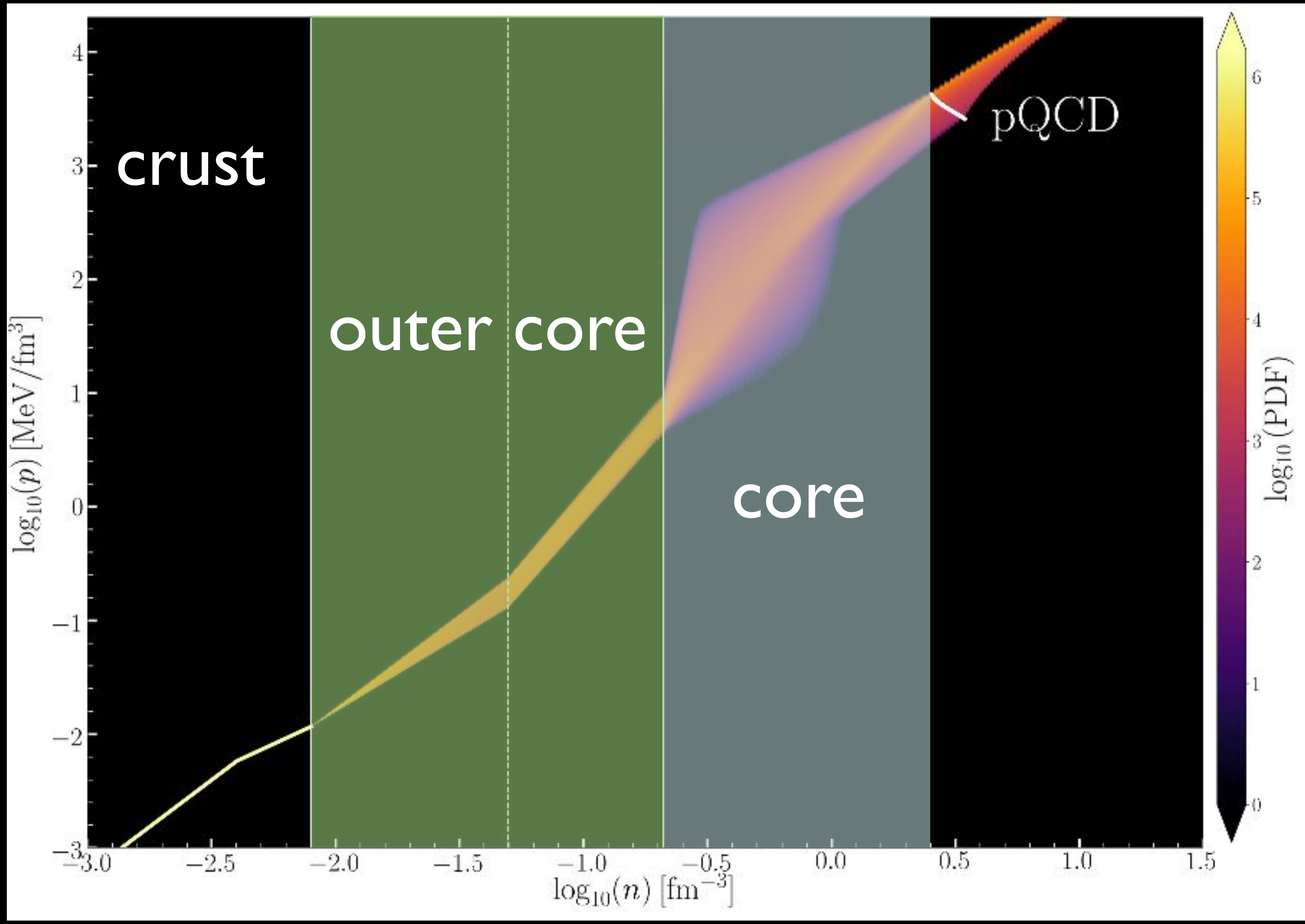
Limits on radii and deformabilities



Limits on radii and deformabilities

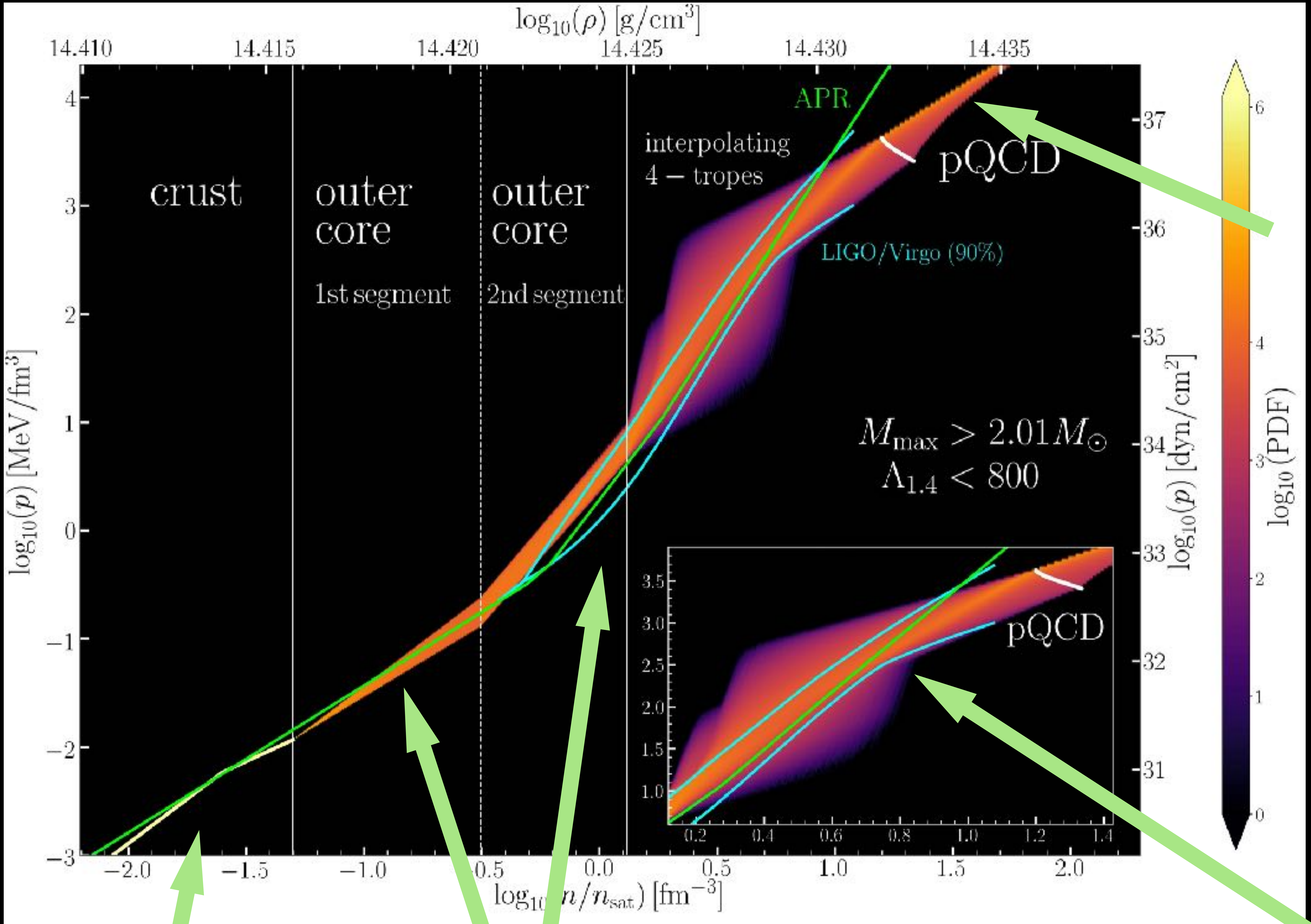
- Can new constraints be set on typical radius and tidal deformability by using GW170817?

- **Ignorance** can be parameterised and EOSs can be built arbitrarily as long as they satisfy specific **constraints** on **low** and **high** densities.



parametrising our ignorance

- Construct most generic family of NS-matter EOSs



from μ_b=2.6GeV
NNLO pQCD
Kurkela+ (2014)
Fraga+ (2014)

interpolation by matching 4 polytropes

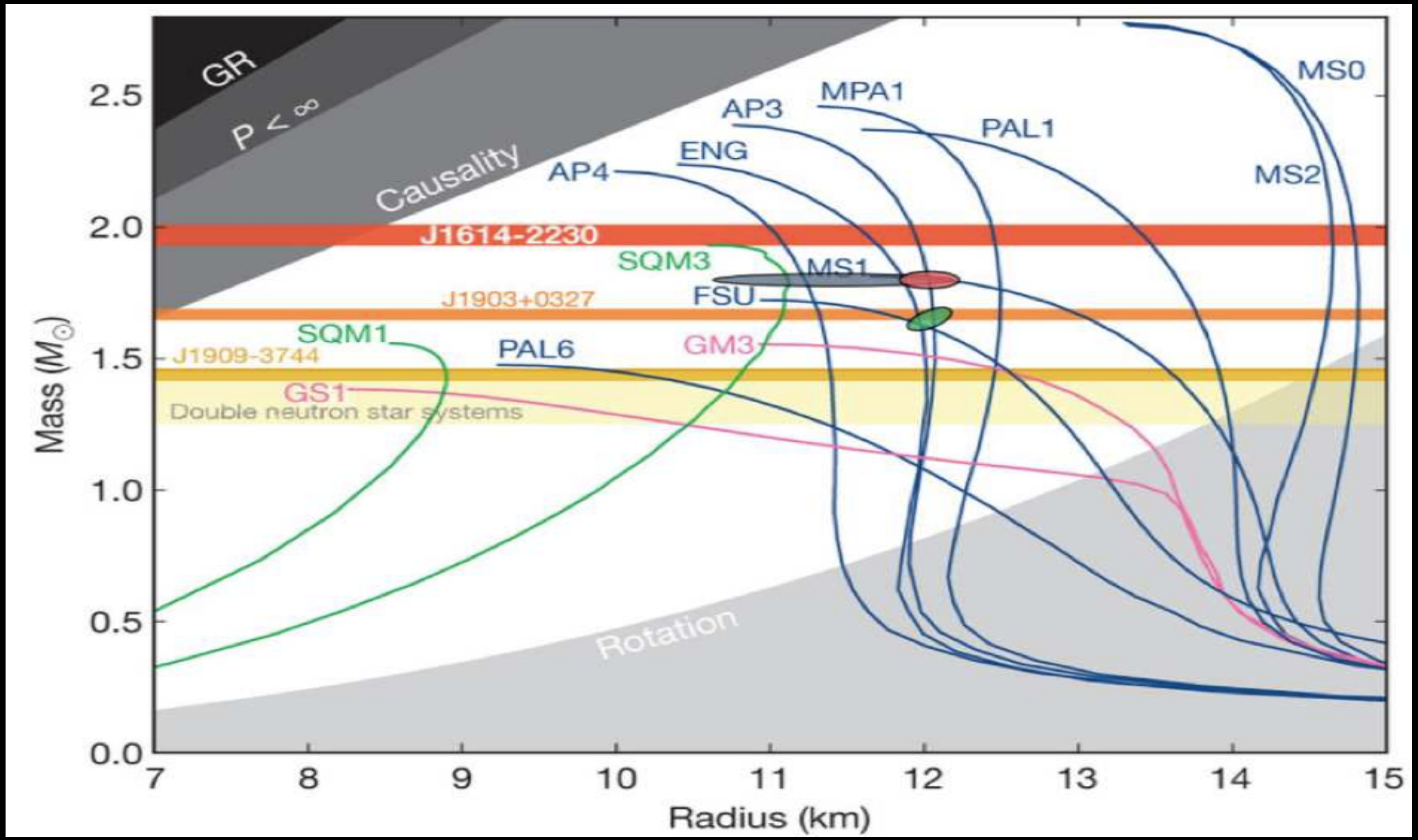
BPS

polytropic fit of Drischler+ (2016)
(large impact on results)

Mass-radius relations

- We have produced 10^6 **EOSs** with about 10^9 **stellar models.**

- Can impose differential constraints from the **maximum mass** and from the **tidal deformability** from GW170817



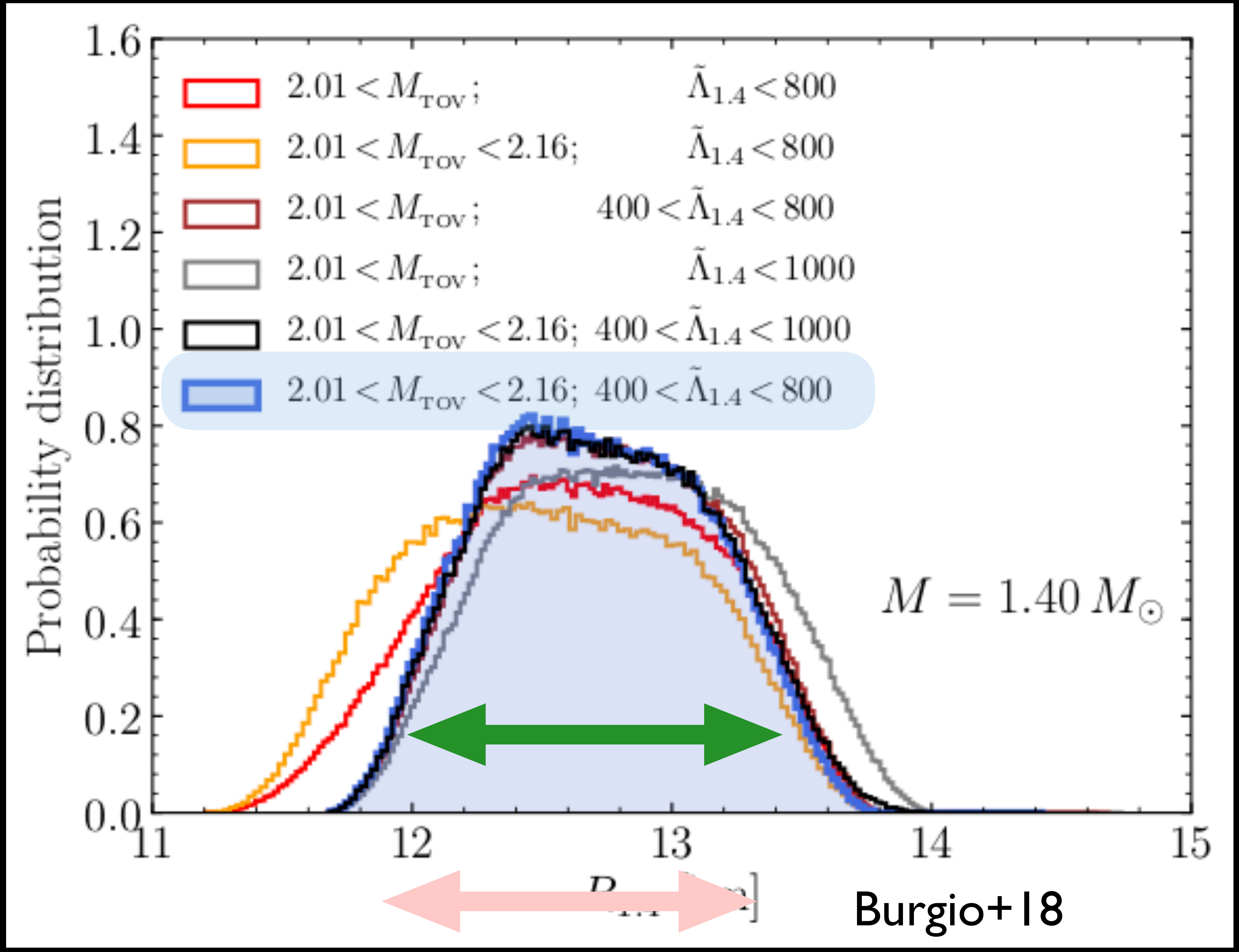
one-dimensional cuts

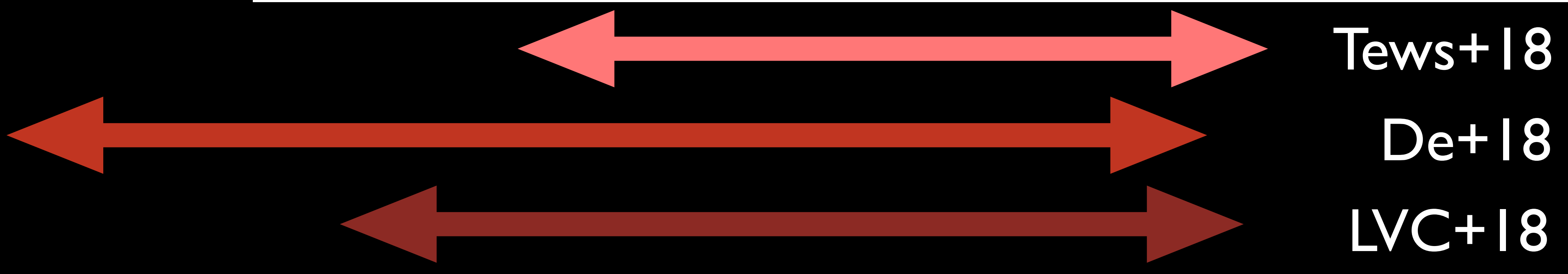
- Closer look at a mass of $M = 1.40\,M_\odot$

- Can play with different constraints on maximum mass and tidal deformability.

- Overall distribution is very robust

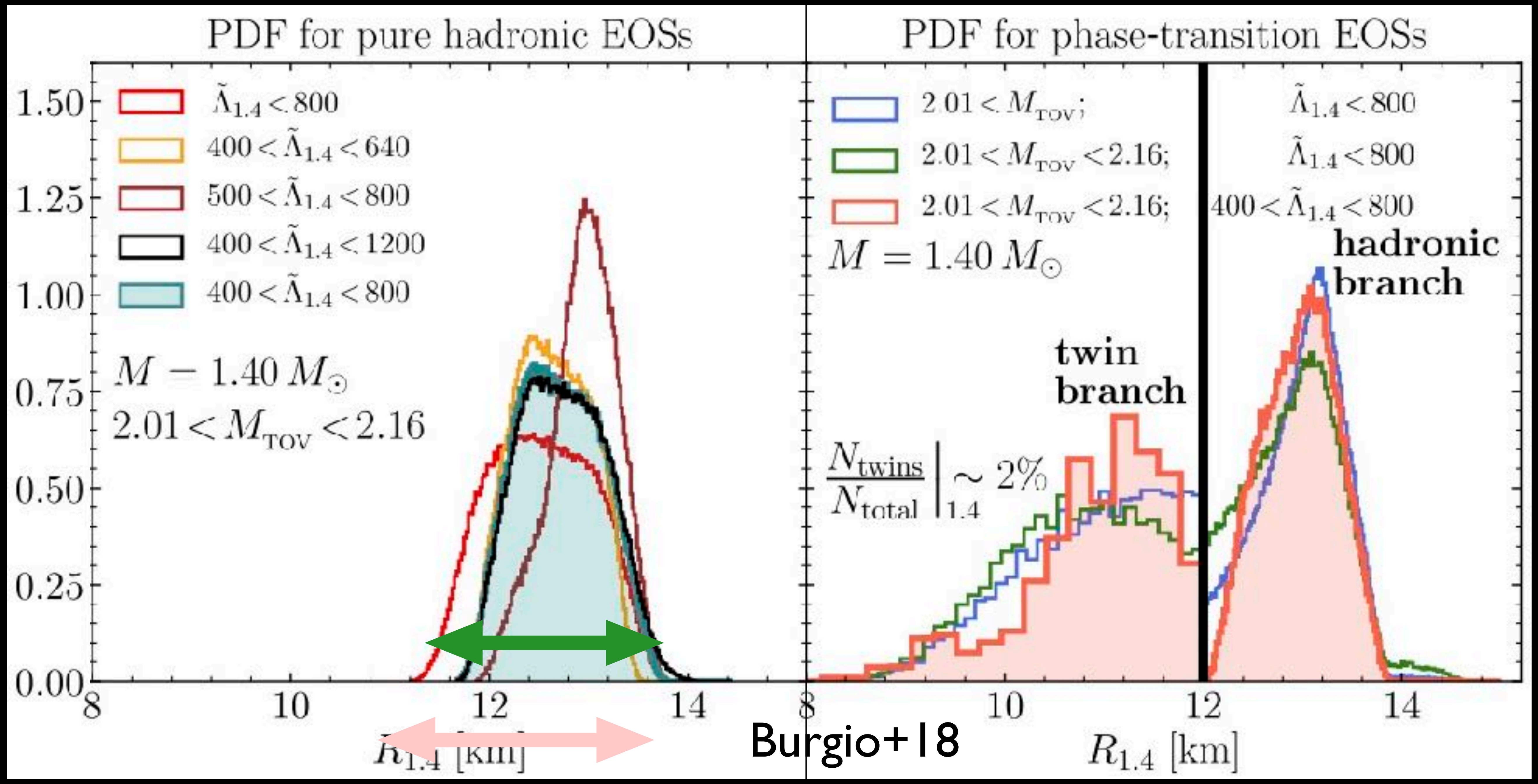
$$12.00 < R_{1.4}/\mathrm{km} < 13.45$$
$$\langle R_{1.4} \rangle = 12.45\,\mathrm{km}$$

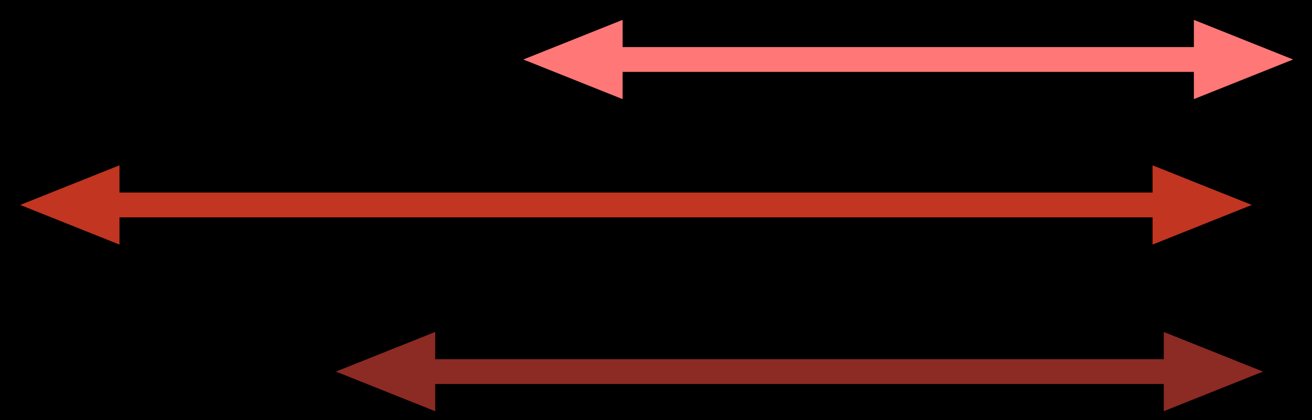




one-dimensional cuts

- Closer look at a mass of $M = 1.40\,M_\odot$
- Play with different constraints on M_{TOV} and tidal deformability
- Overall distribution is very robust





$$12.00 < R_{1.4}/\mathrm{km} < 13.45$$
$$\langle R_{1.4}\rangle = 12.45\,\mathrm{km}$$

Constraining tidal deformability

- Can explore statistics of all properties of our **10^9** models.
- In particular can study PDF of tidal deformability:

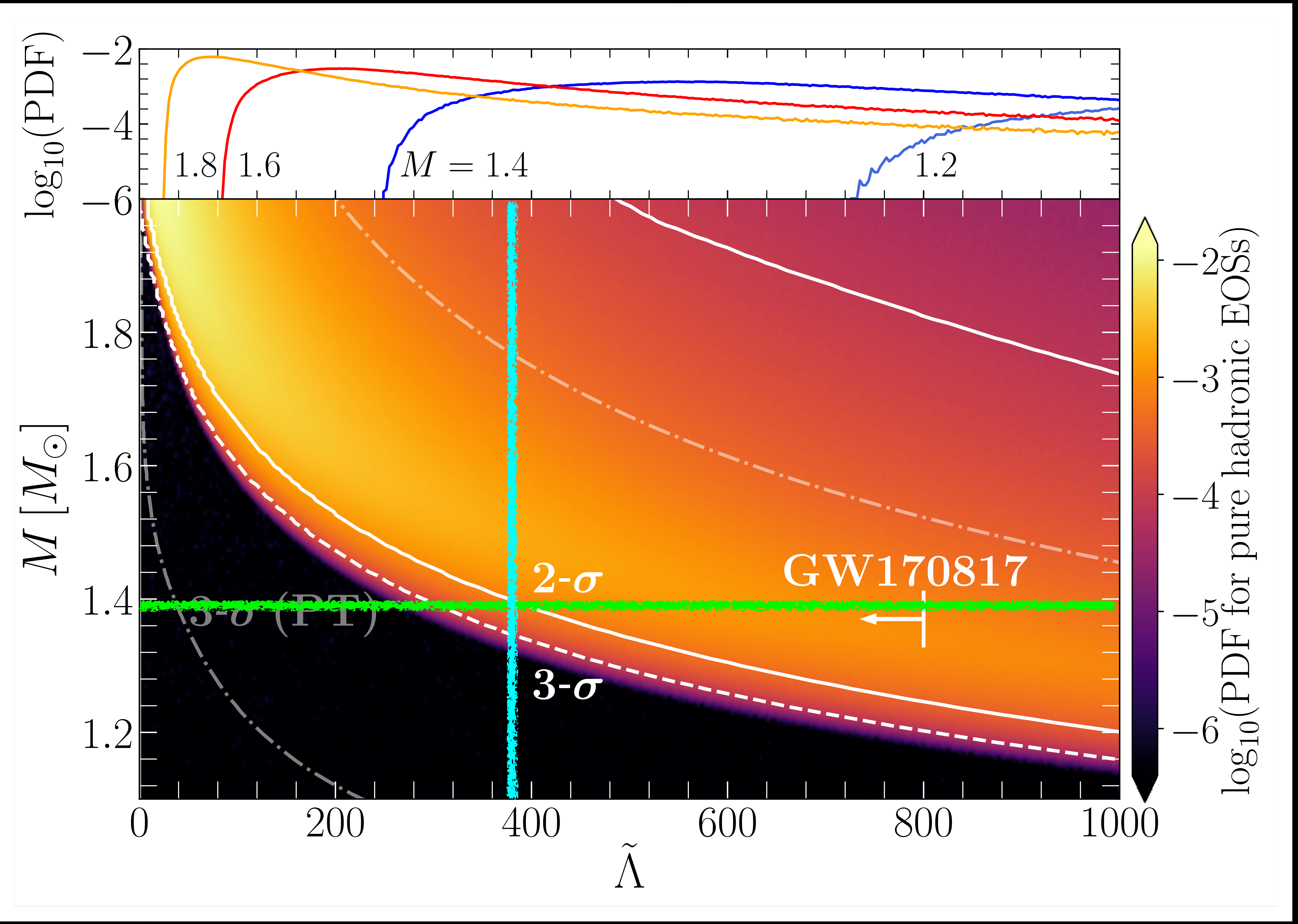
- LIGO has already set upper limit:

$$70 < \tilde{\Lambda}_{1.4} < 720$$

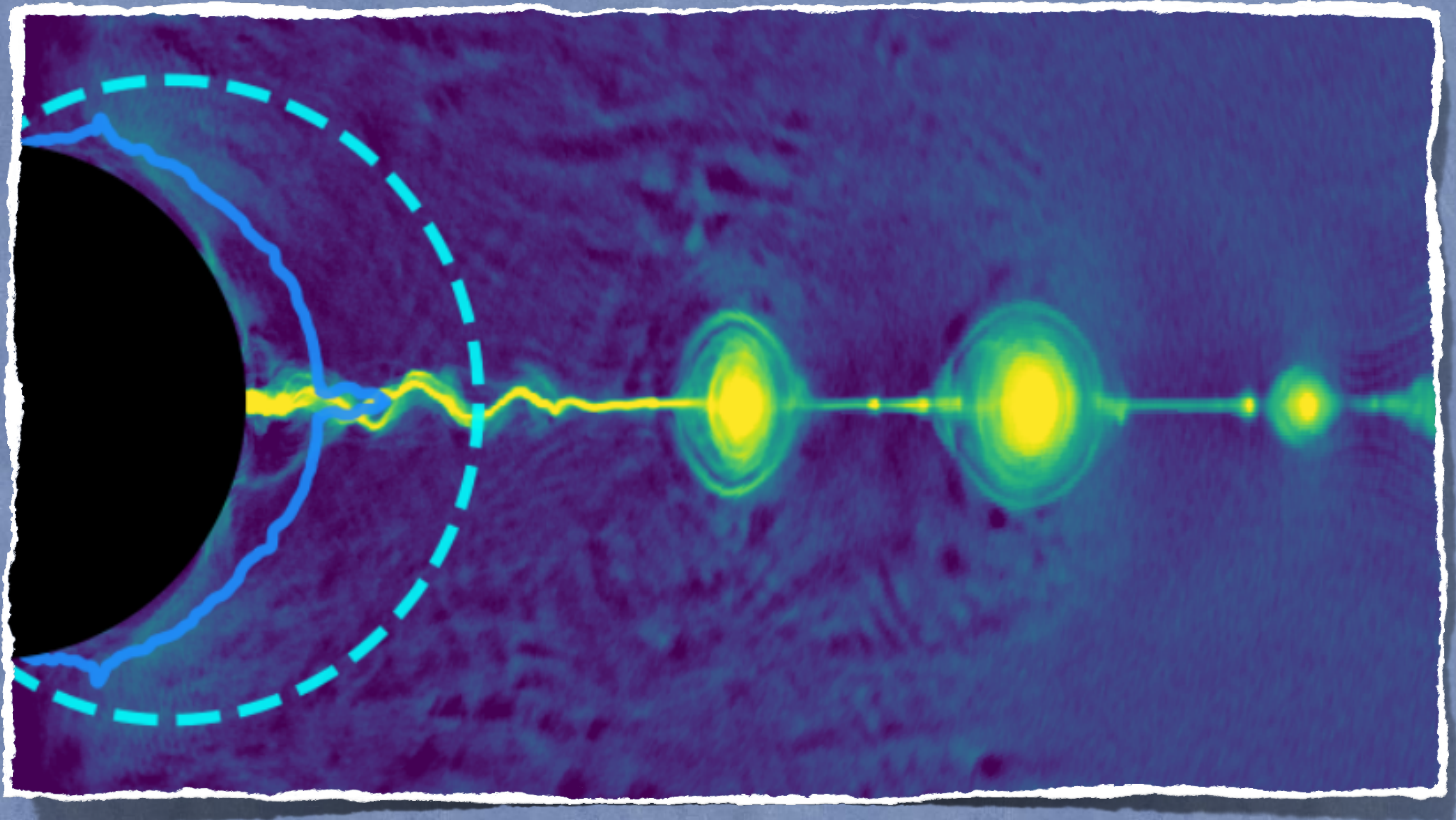
- Our sample sets a lower limit:

$$\tilde{\Lambda}_{1.4} > 375$$

the largest so far.



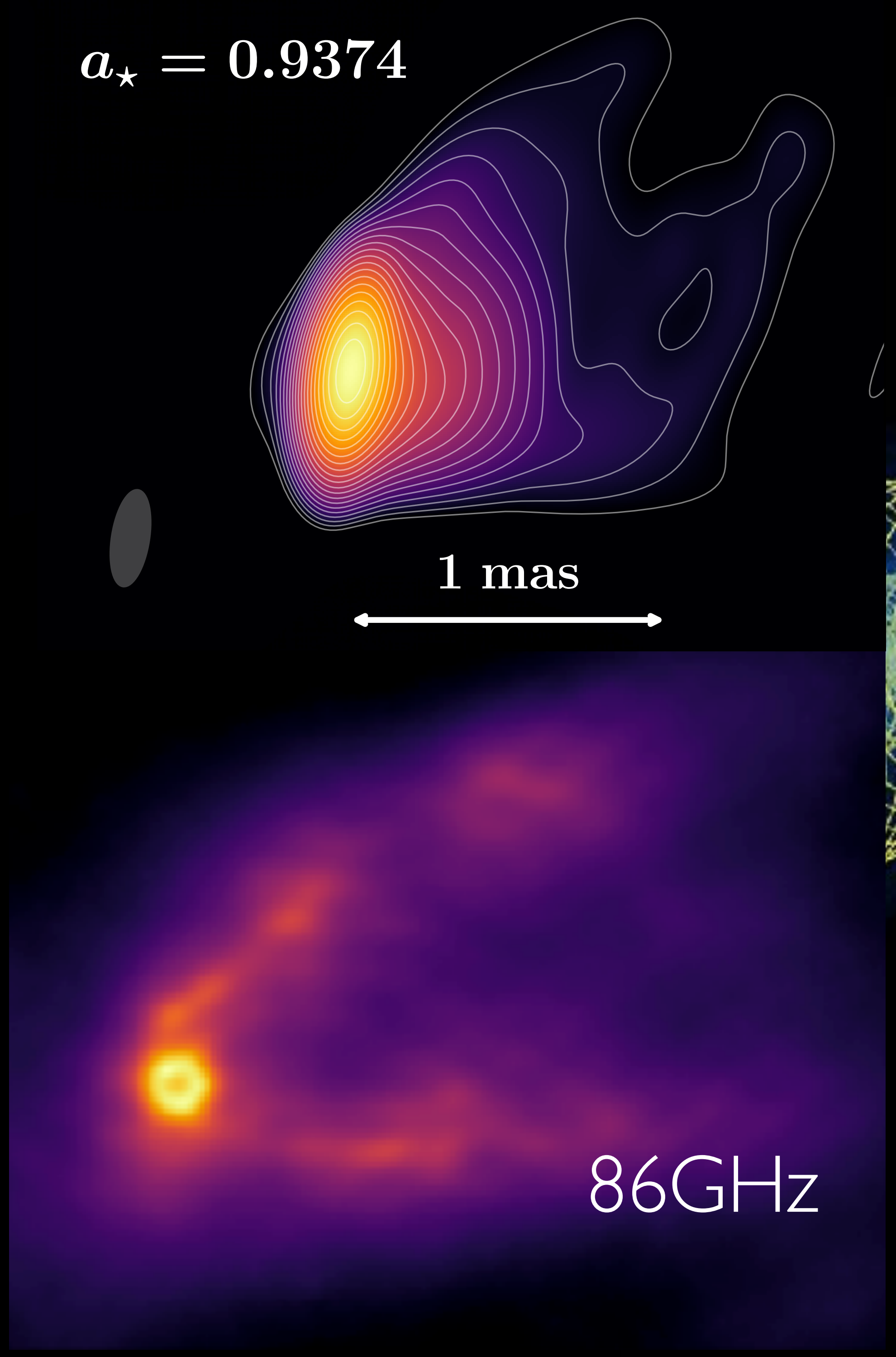
Energy extraction from rotating BHs



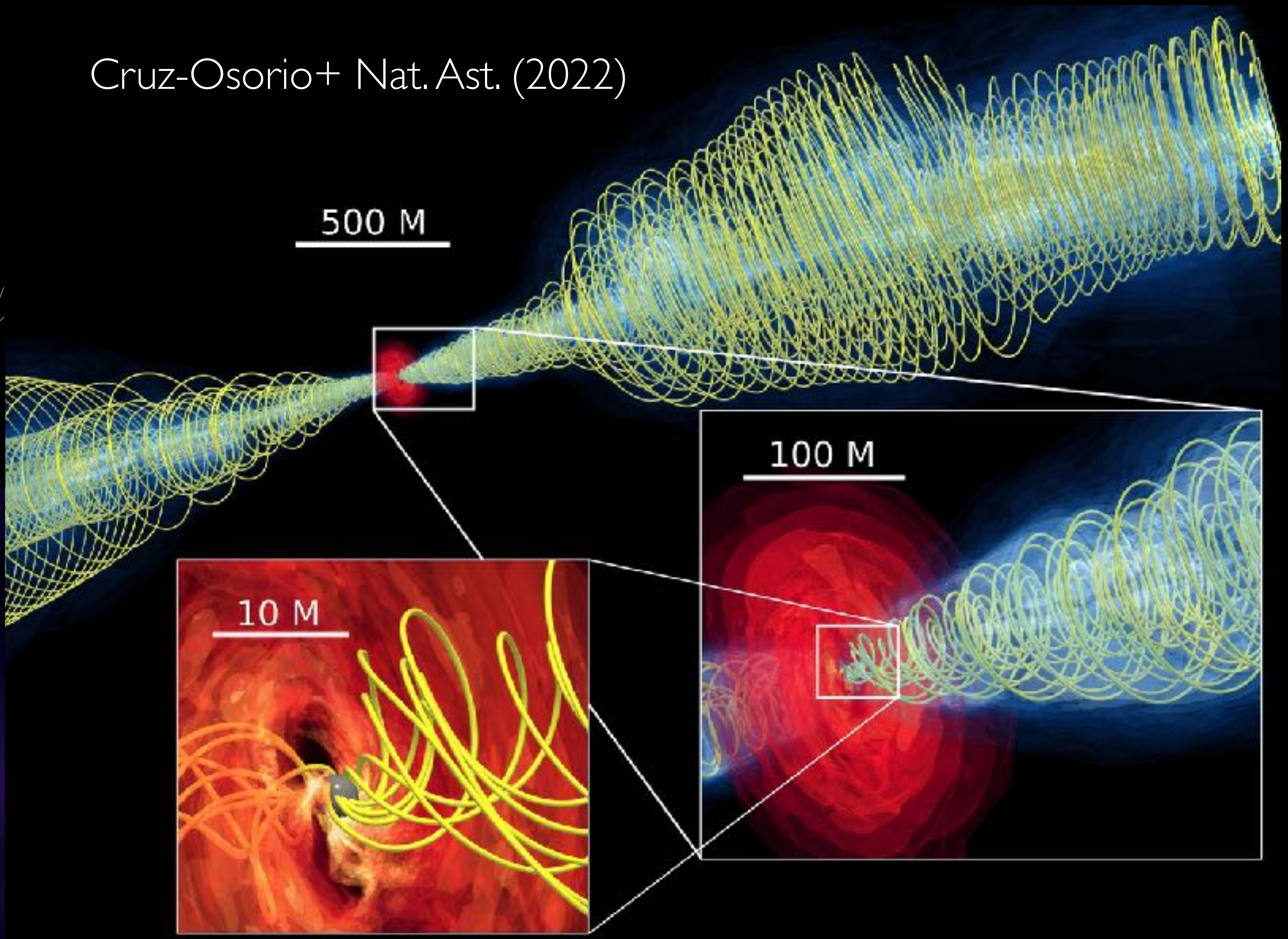
Meringolo+ 2507.08942 (2025)

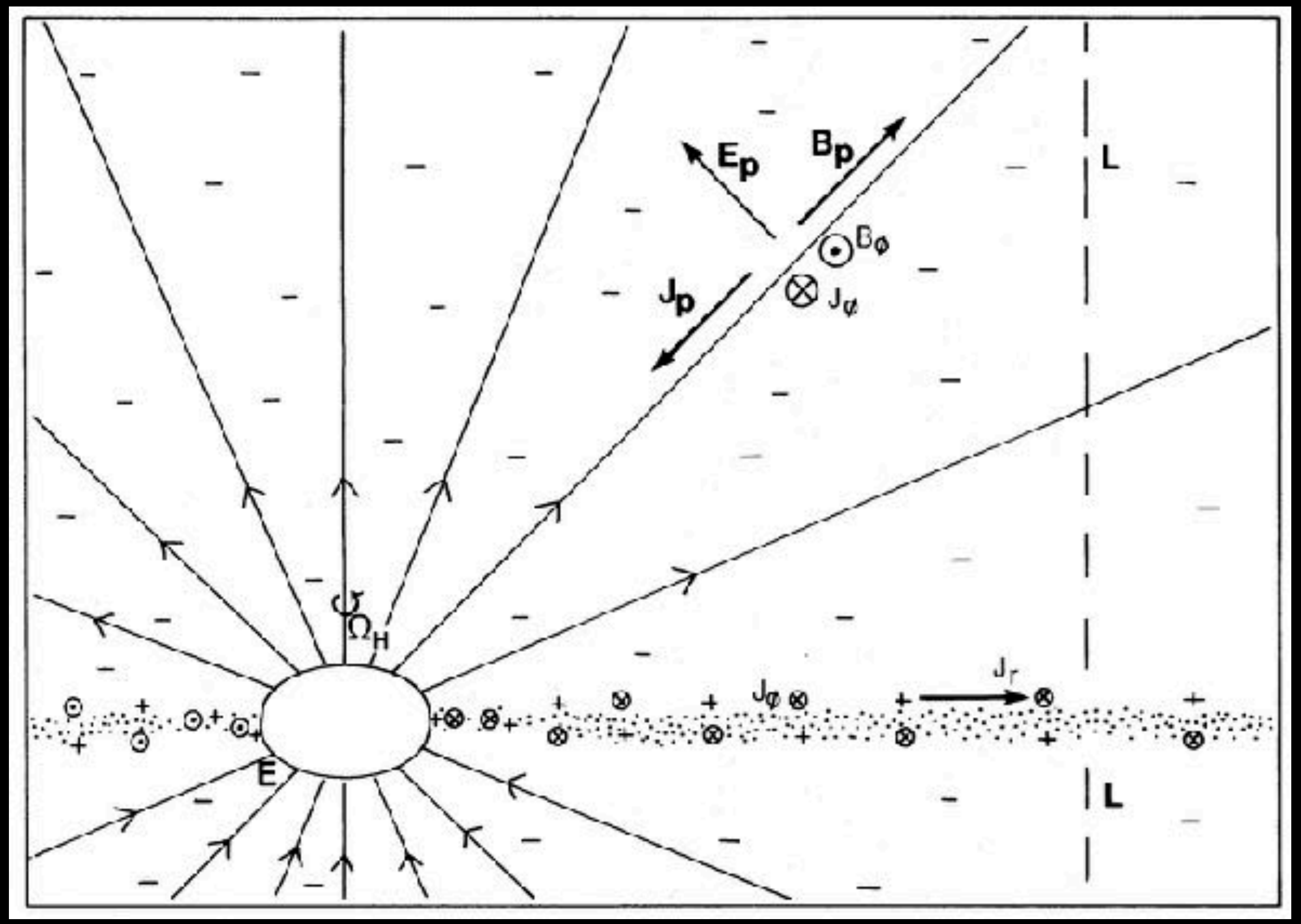
A collisional description on BH scales: GRMHD simulations

- GRMHD simulations of accretion onto supermassive BHs have reached high level of sophistication and are able to reproduce morphology and energy spectrum of M87 jet
- The Blandford-Znajek (BZ) mechanism offers most natural route to extract the rotational energy from rotating BHs and power relativistic jets. However, it assumes a FF regime



Cruz-Osorio+ Nat. Ast. (2022)

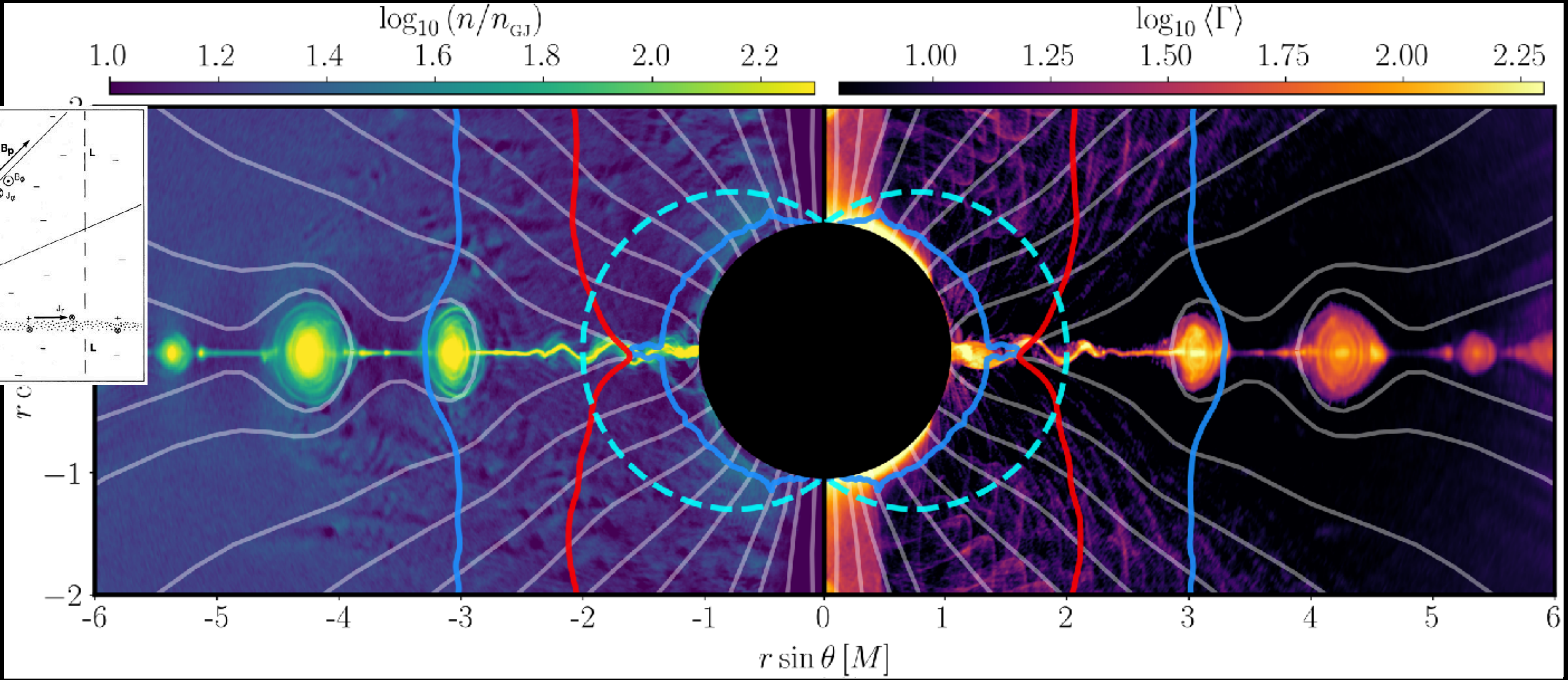


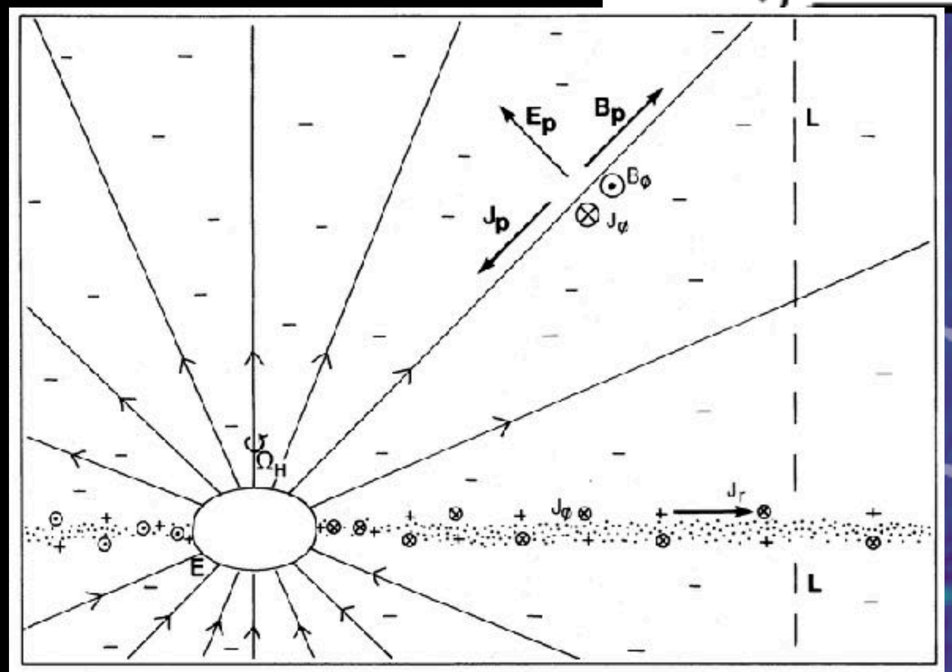


Blandford and Znajek MNRAS (1977)

A collisionless description on BH scales: PIC simulations

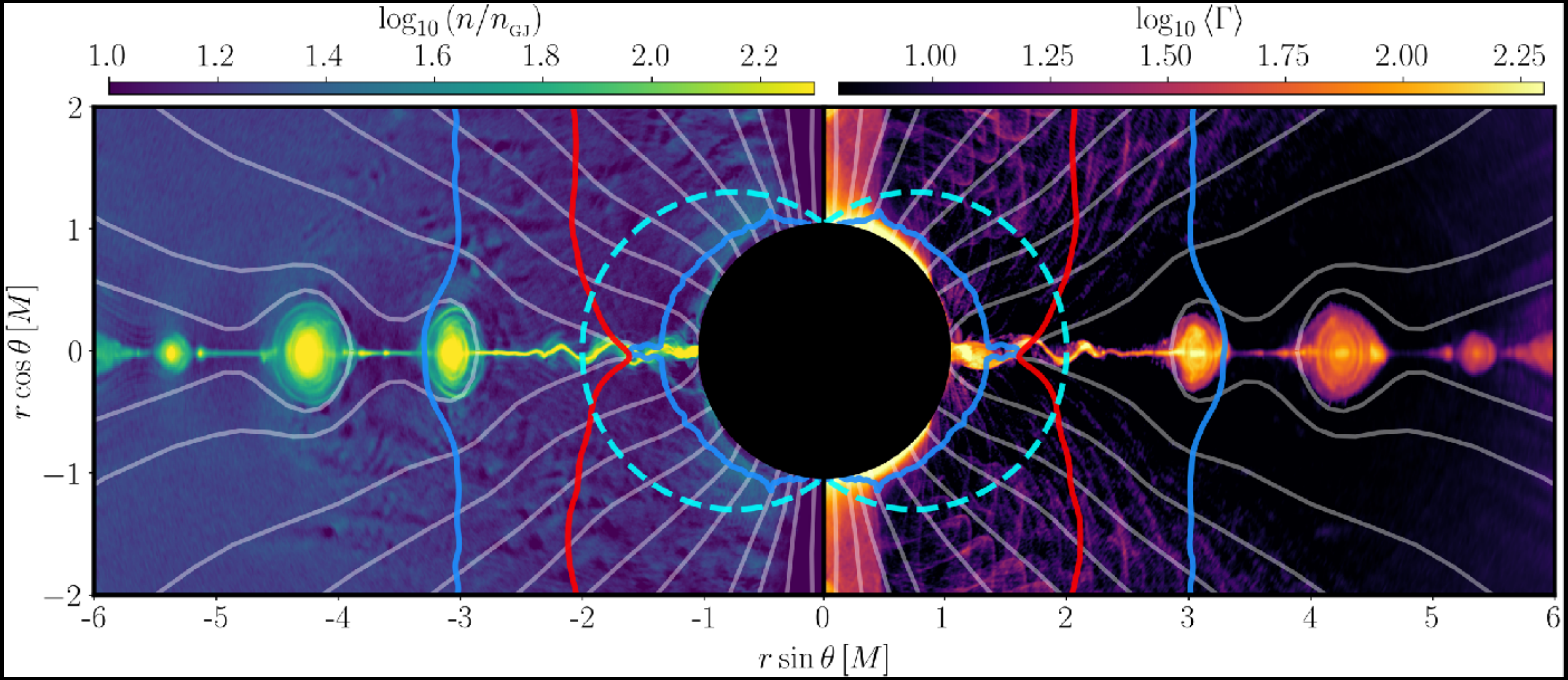
- Particle-in-cell simulations provide ab-initio description of FF conditions near BH
- Extension to GR not easy but provides first-principle dynamics near BHs
- Carried out extensive campaign of e_+/e_- pair plasma in 2D with new code **`FPIC`** and "classic" split-monopole of BZ solution





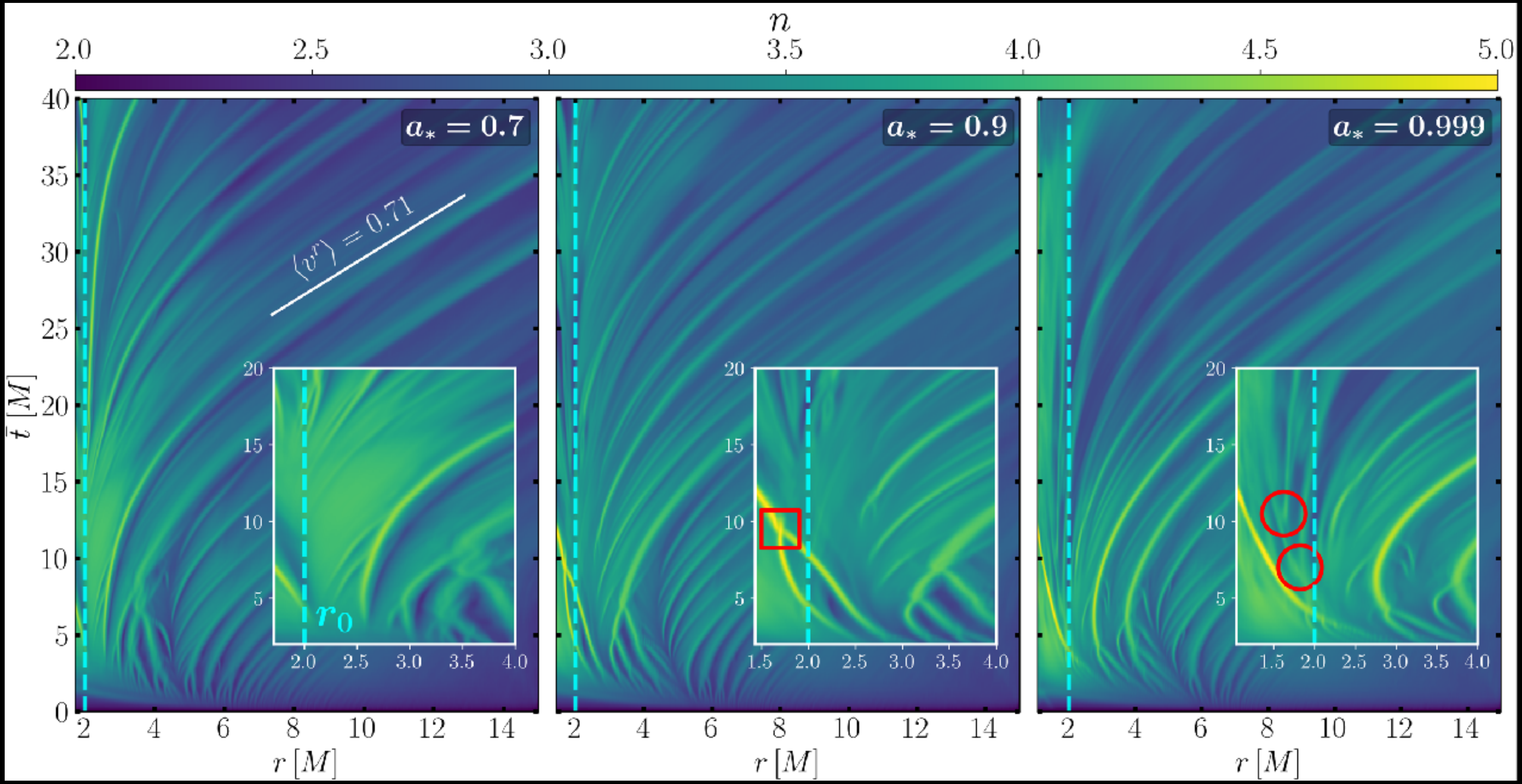
Microphysics on BH scales

- SR-PIC simulations provide important input for large-scale jet emission
- Extension to GR not easy but provides first-principle dynamics near BHs
- Carried out extensive campaign of e_+/e_- pair plasma in 2D with new code and "classic" split-monopole of Blandford-Znajek (BZ) solution



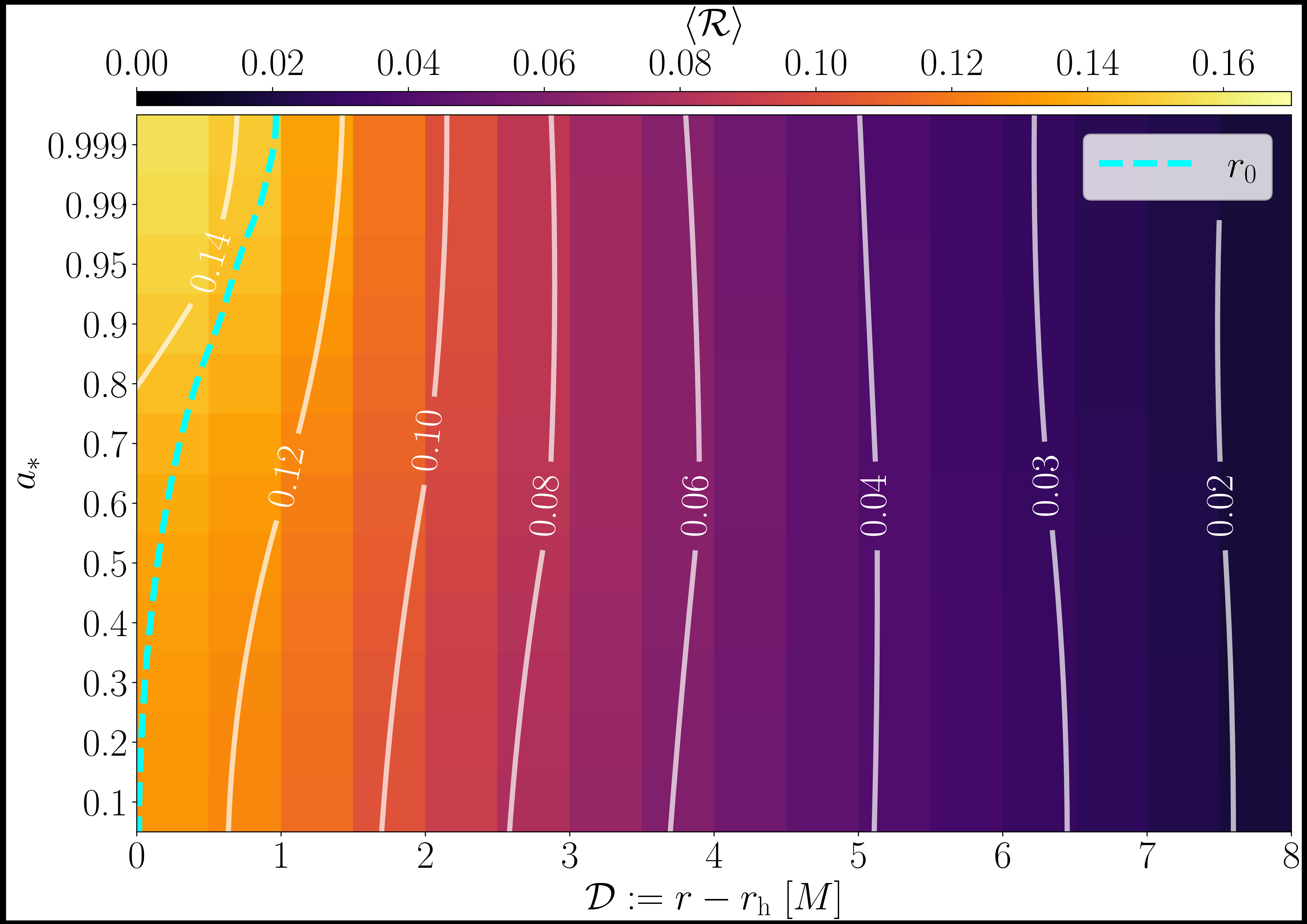
Among the new results…

- evidence plasmoids can collide and merge inside and outside ergosphere
- evidence plasmoids can also split inside ergosphere and reach infinity
- outgoing plasmoids have radial velocity $v \simeq 0.7$ independent of BH spin



Reconnection rate

- reconnection rate $\mathscr{R}$ essential for all considerations of EM emission
- simulations allow to compute $\mathscr{R} = \mathscr{R}(r, a_*)$
- reconnection grows with BH spin and reaches maximum $\mathscr{R} \simeq 0.14$ inside ergosphere of maximally rotating BH



Blandford-Znajek luminosity

The BZ luminosity can be expressed very generically as

$$P_{\rm BZ} = \frac{\kappa}{4\pi} \Phi_h^2 F(\Omega_h)$$

where (Camilloni+ JCAP 2022)

κ depends uniquely on the B-field topology ($\kappa_{sm} = 1/(6\pi)$ for split monopole)

Φ_h is the magnetic flux across the event horizon

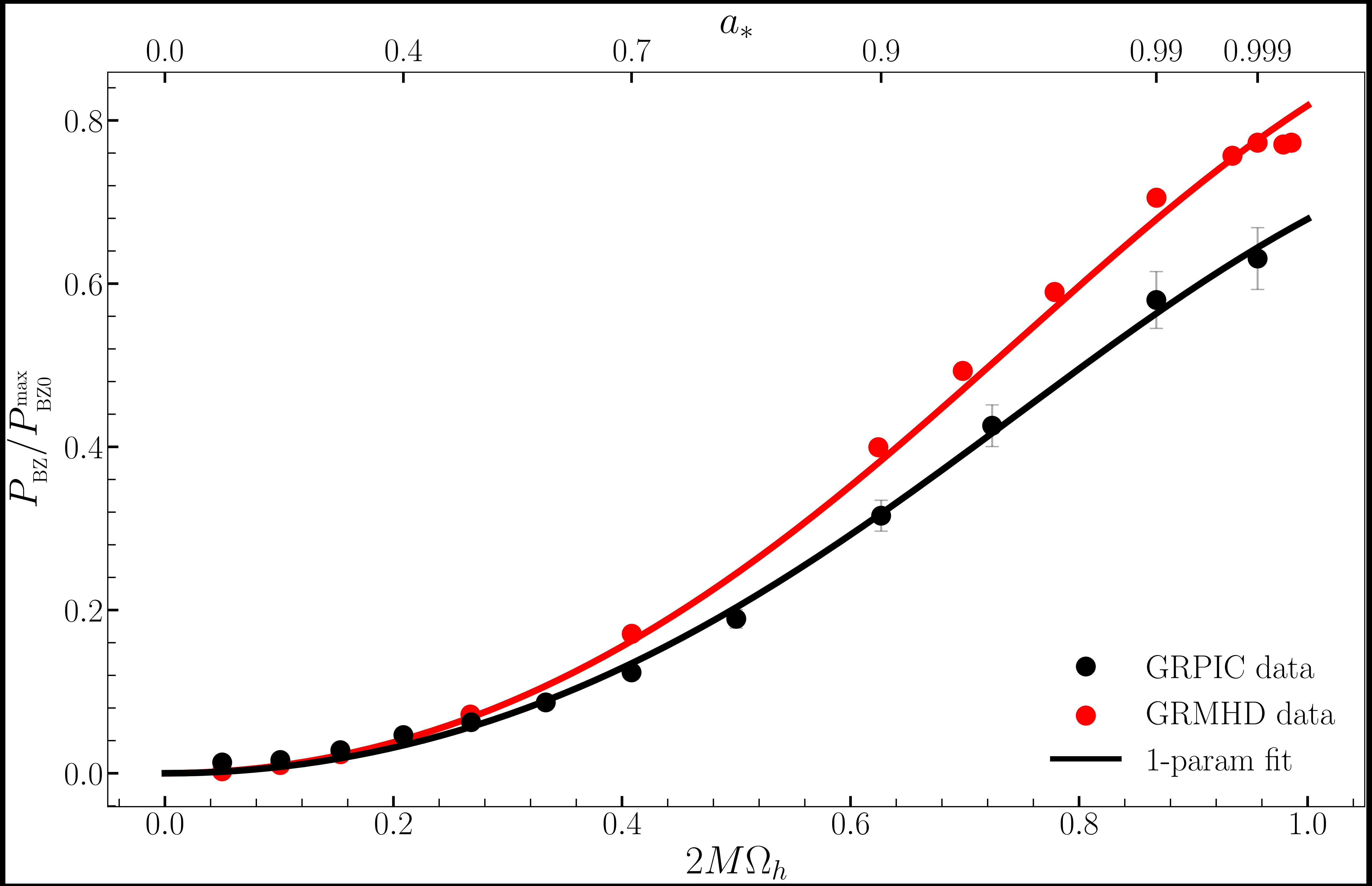
$F_{\rm an}(\Omega_h)$ is a nonlinear function of the event-horizon velocity Ω_h:

$$F_{\rm an}(\Omega_h) = \Omega_h^2 \left[1+\tilde{\alpha}(M\Omega_h)^2+\tilde{\beta}(M\Omega_h)^4+\tilde{\gamma}\,|M\Omega_h|^5+\left(\tilde{\delta}+\tilde{\epsilon}\log|M\Omega_h|\right)(M\Omega_h)^6\right]$$

Blandford-Znajek luminosity

The BZ can be measured from the simulations

$$P_{\rm BZ} = \frac{\kappa}{4\pi}\,\Phi_h^2\,F(\Omega_h)$$

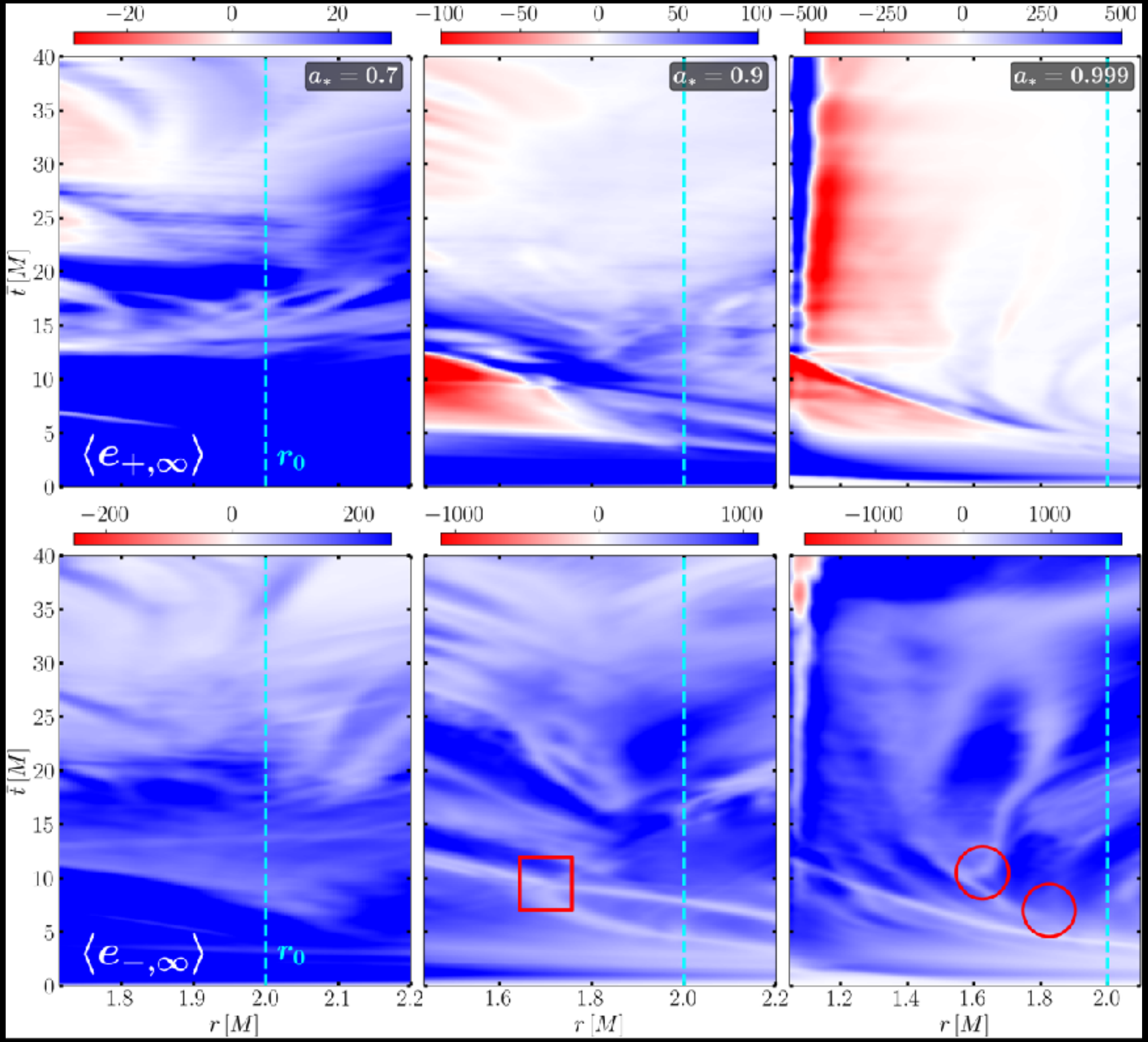


The measured BZ power matches very well analytic expression at $\mathcal{O}(\Omega_h^8)$

Good match is present also for GRMHD simulations; only difference is value of κ

Behaviour for extremal BHs can be captured with fit of quartic term

Evidence of Penrose process (PP)



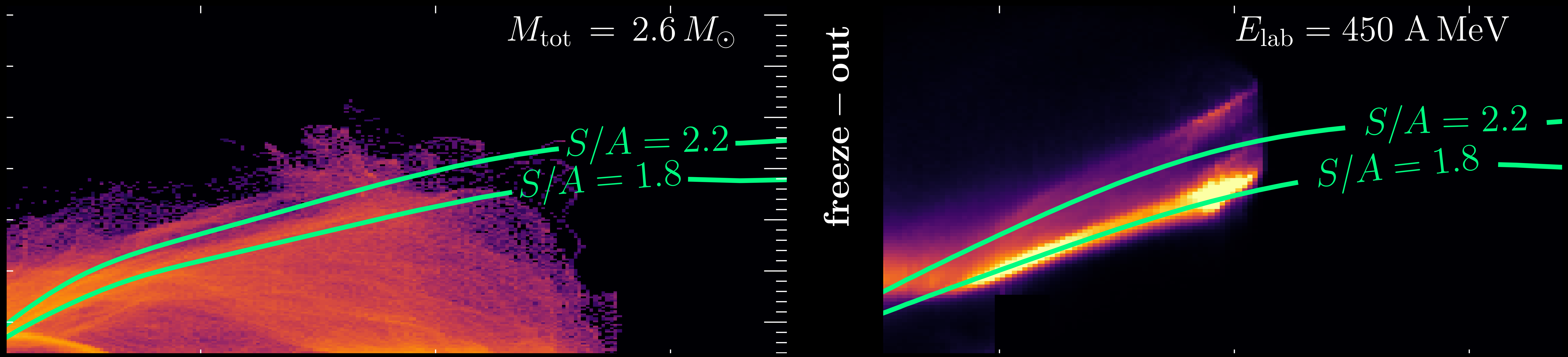
Evidence of negative-energy positrons inside ergosphere and accreting

Process is not steady and accretion rate increases with BH spin

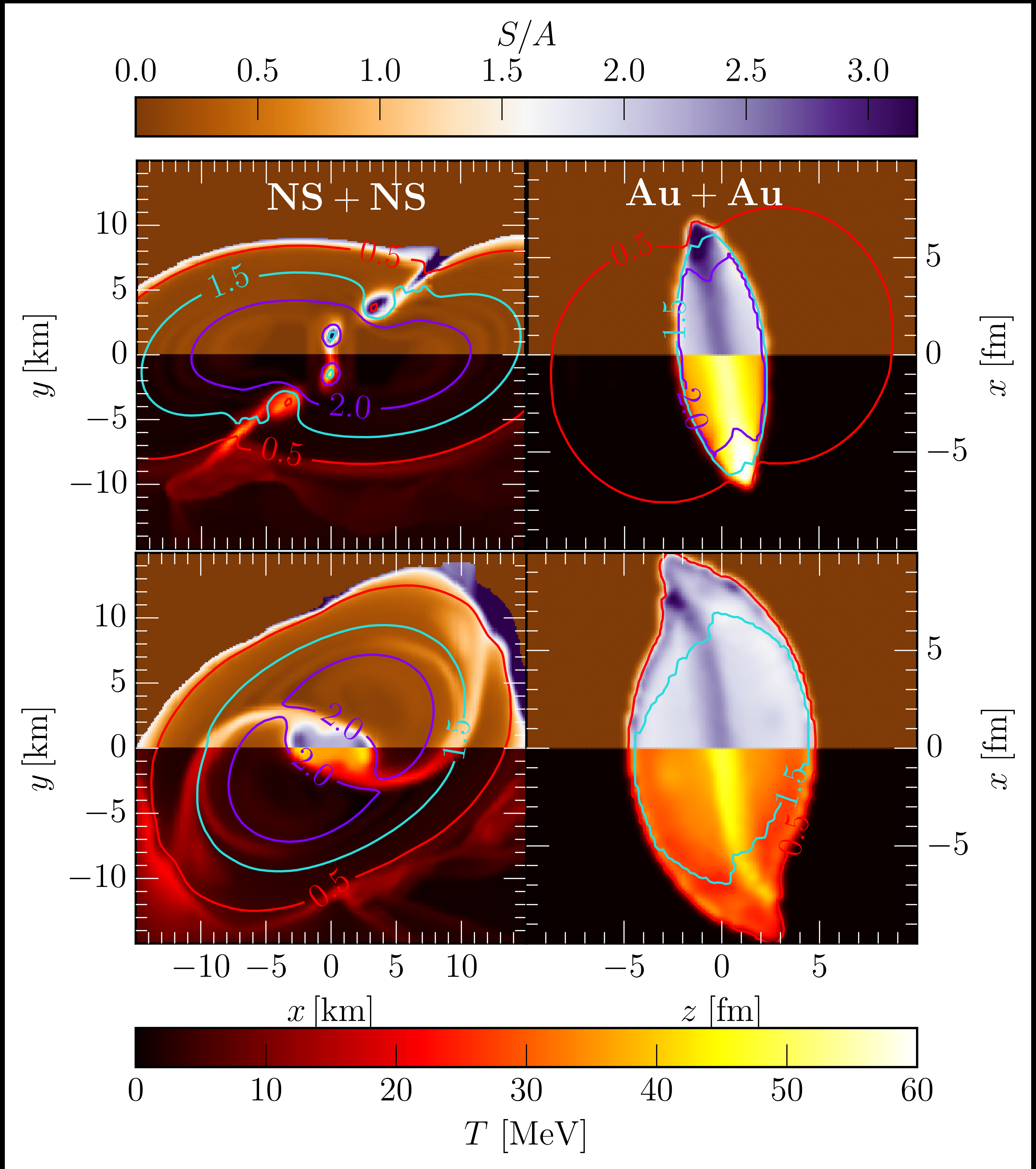
Accretion of negative-energy particles also for electrons but with smaller rates

Results suggest that both BZ and PP are present in force-free magnetospheres of rotating BHs: extraction is combination of effects.

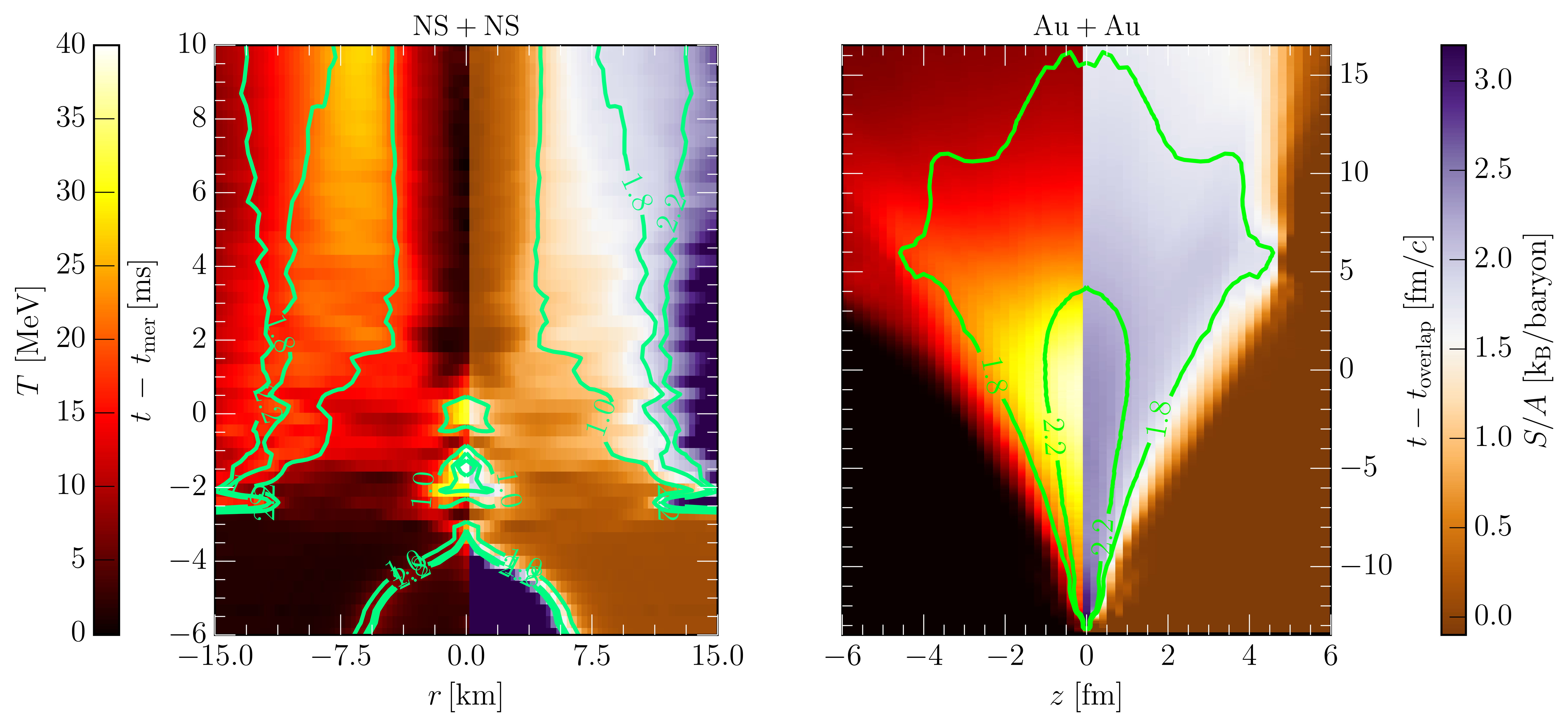
Probing neutron-star matter in the lab



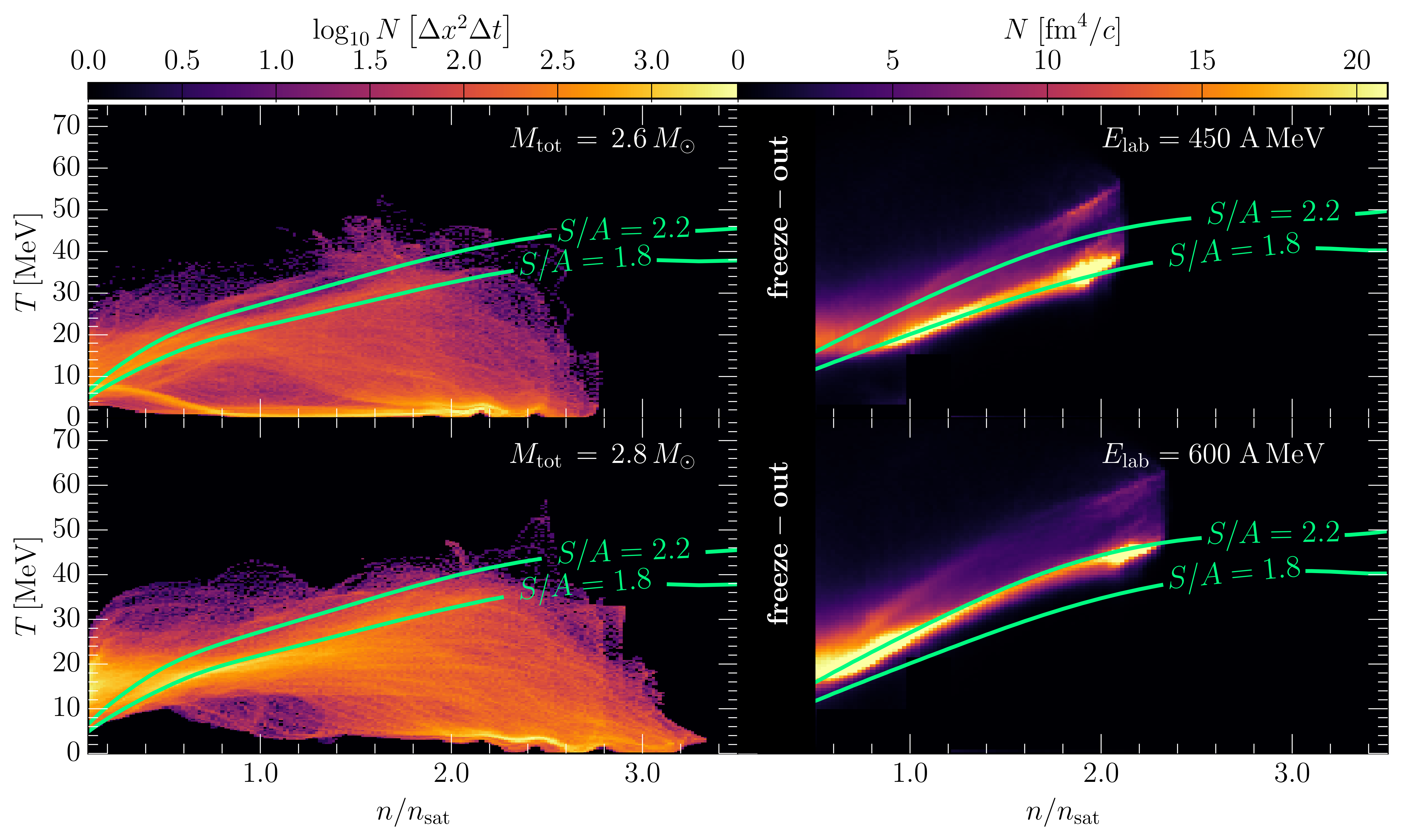
BNS mergers vs HICs



- We have explored the dynamics of BNS mergers and HIC using the same EOS.
- Chiral Mean Field model, based on the three-flavor chiral Lagrangian for hadronic matter.
- Crossover transition for deconfinement occurs at both, finite and zero temperature



- **BNSs**: core is hot and with high entropy; hot and high entropy ring is formed. Remnant is gravitationally bound.
- **HICs**: collision product is hot and with high entropy but expands rapidly cooling isentropically.



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