The **astrophysics** of binary neutron star mergers

Lecture III

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57th Karpacz Winter School of Theoretical Physics
13-19 June 2021, Karpacz

Plan of the lectures

- ✴Lecture I: the **math** of neutron-star mergers
- ✴Lecture II: the **physics** of neutron-star mergers
- ✴Lecture III: the **astrophysics** of neutron-star mergers

- ✴**L. Baiotti and L. Rezzolla, Rep. Prog. Phys. 80, 096901, 2017**
- ✴V. Paschalidis, Classical Quantum Gravity 34, 084002 2017
- ✴Rezzolla and Zanotti, *"Relativistic Hydrodynamics"*, Oxford University Press, 2013

Answering yesterday's question

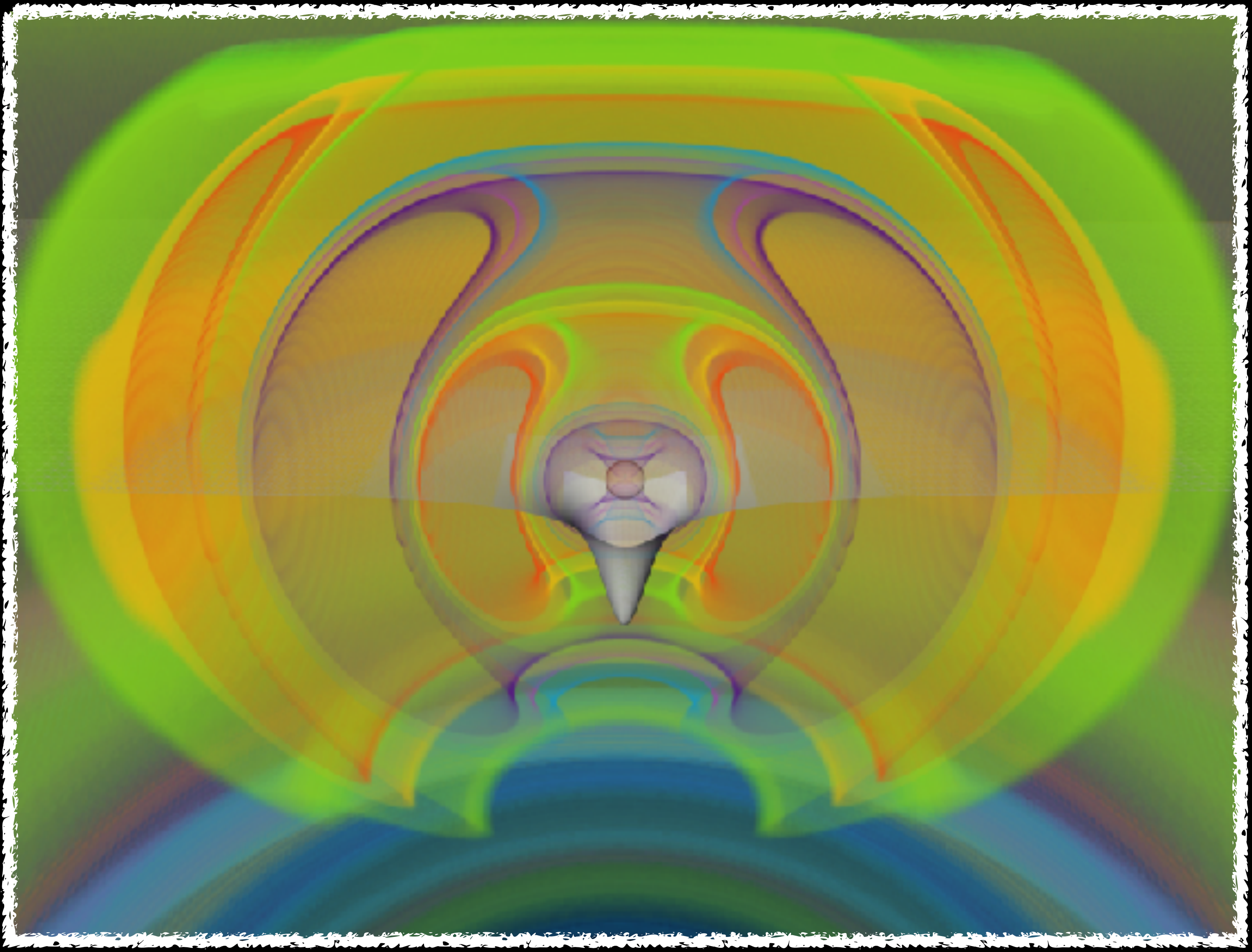
- What are the 10 parameters used to model the maximum-mass investigation?

$$\chi,\ \xi,\ \eta,\ M_{\rm GW}^{\rm insp},\ M_{\rm ej}^{\rm blue},\ M_{\rm ej}^{\rm dyn},\ M_{\rm TOV},\ \nu,\ f_{\rm disk},\ \text{and}\ f_B$$

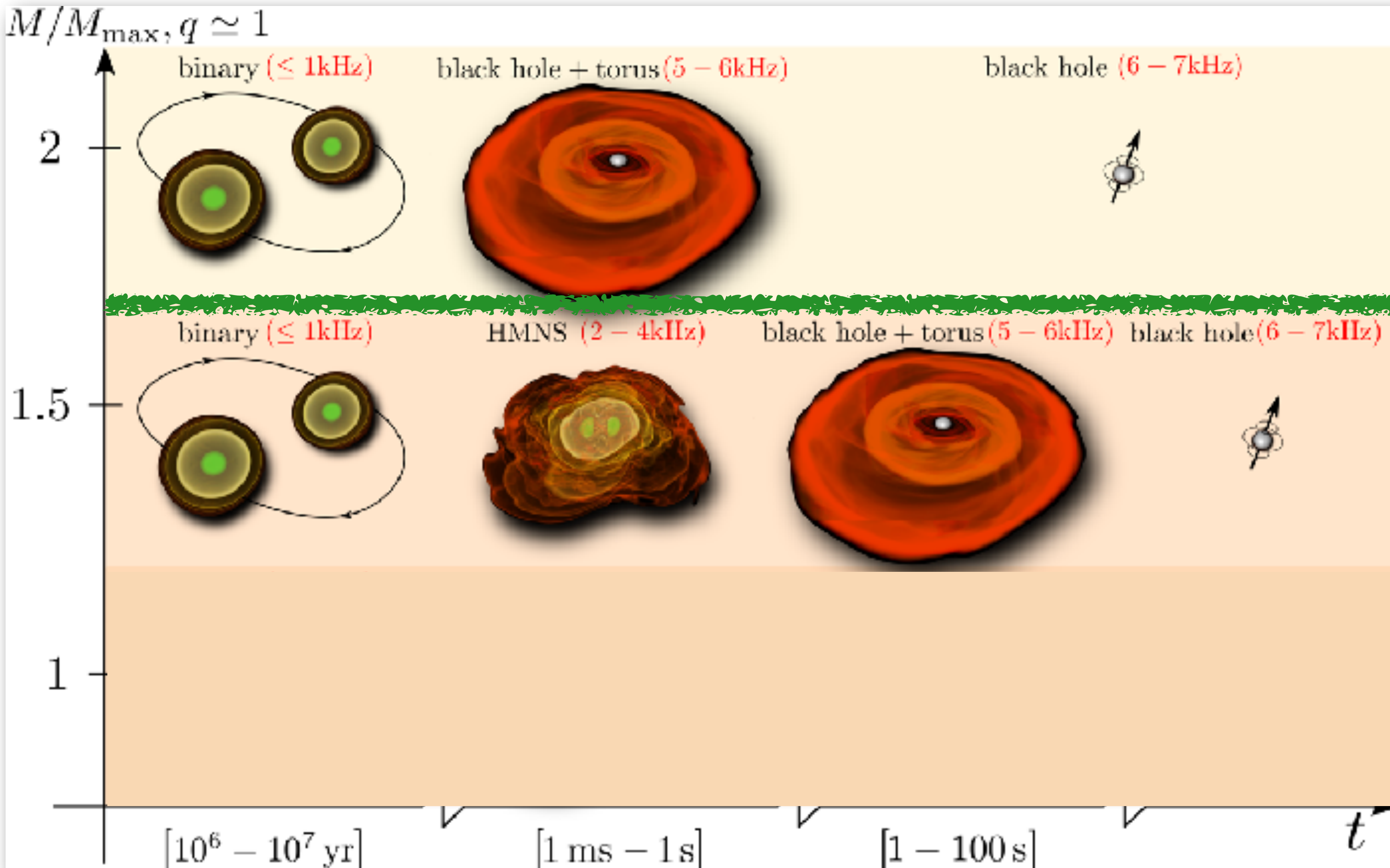
ratio of masses along critical line; fraction of the HMNS rest-mass contained in the uniformly rotating core; ratio between baryon and gravitational mass; mass lost in GWs in the inspiral; mass ejected leading to blue kilonova; mass ejected leading to red kilonova; maximum mass; symmetric mass ratio; fraction of the disk baryon mass leading to a red kilonova; fraction of HMNS angular momentum not contained in the formed BH.

Nathanail, Most, LR (ApJL 908, 2, 2021)

Threshold Mass to prompt collapse



Remember this diagram?



- If mass sufficiently large, no HMNS and the merger "**promptly**" leads to a black-hole formation.
- The **threshold mass** marks the separation from the two scenarios.

Some things to ponder about "prompt" collapse

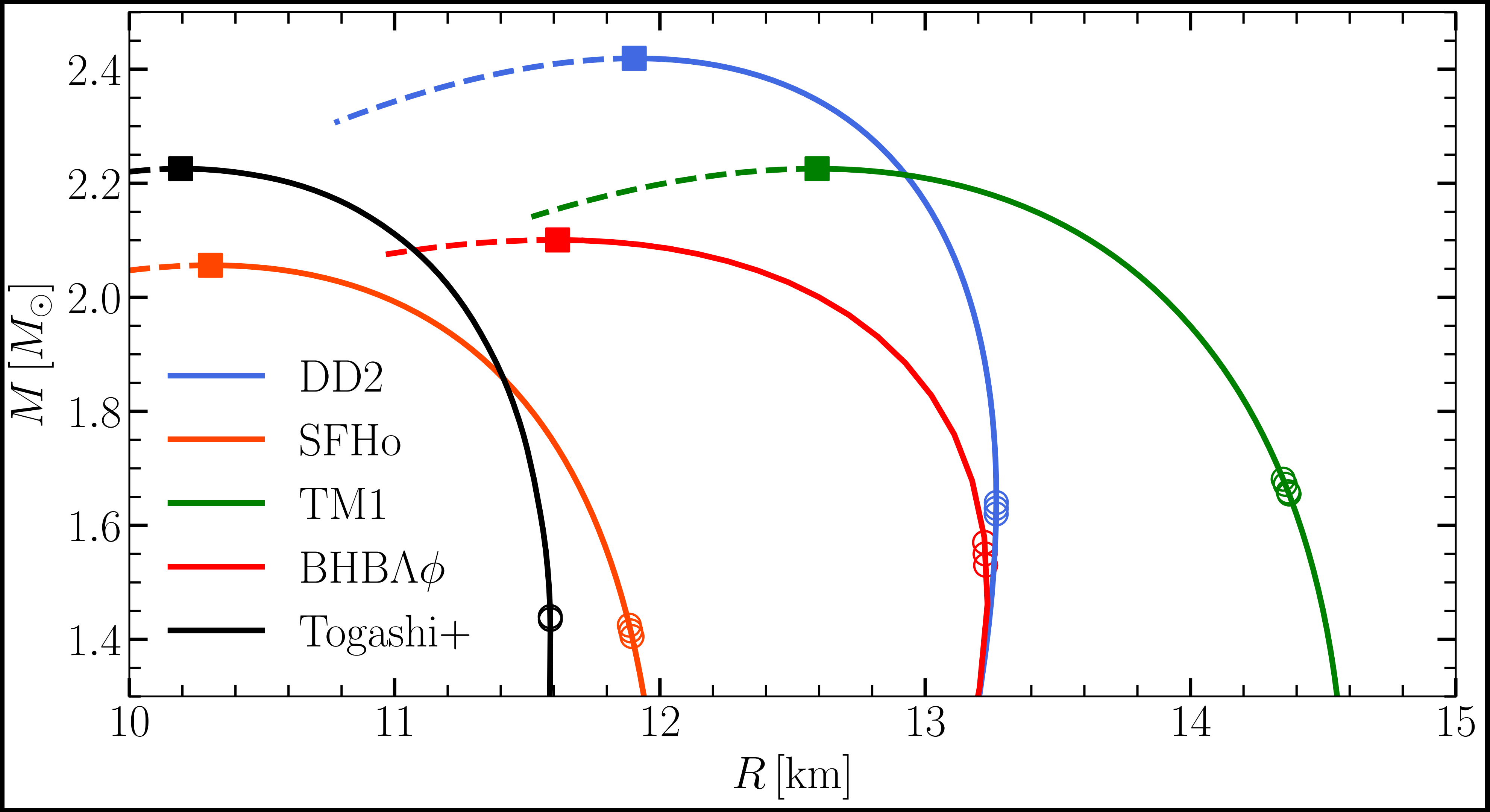
- ✳ The problem is less simple than it may appear at first sight; definition of "prompt" collapse can be rather vague.
- ✳ **Generic collapse** depends on **angular momentum** of the star, e.g. rotating or nonrotating.
- ✳ **Generic collapse** depends on **EOS.**
- ✳ **Prompt collapse** is essentially insensitive: gravity prevails!

If rigorous definitions are made (not everybody does!), possible to obtain **quasi-universal behaviour**.

What to expect is clear: the HMNS will survive less and less as the threshold is reached

$$\tau_{\rm HMNS} \to 0 \quad \text{for} \quad M \to M_{\rm th}$$

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



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

Define $t_{\rm coll}$ as the time between the merger and the appearance of a black hole. $t_{\rm coll} := t_{\rm BH} - t_{\rm merg}$

$$t_{\rm merg}: \quad \min(\alpha) = \alpha_{\rm merg} := 0.35\,,$$
$$t_{\rm BH}: \quad \min(\alpha) = \alpha_{\rm BH} := 0.2\,.$$

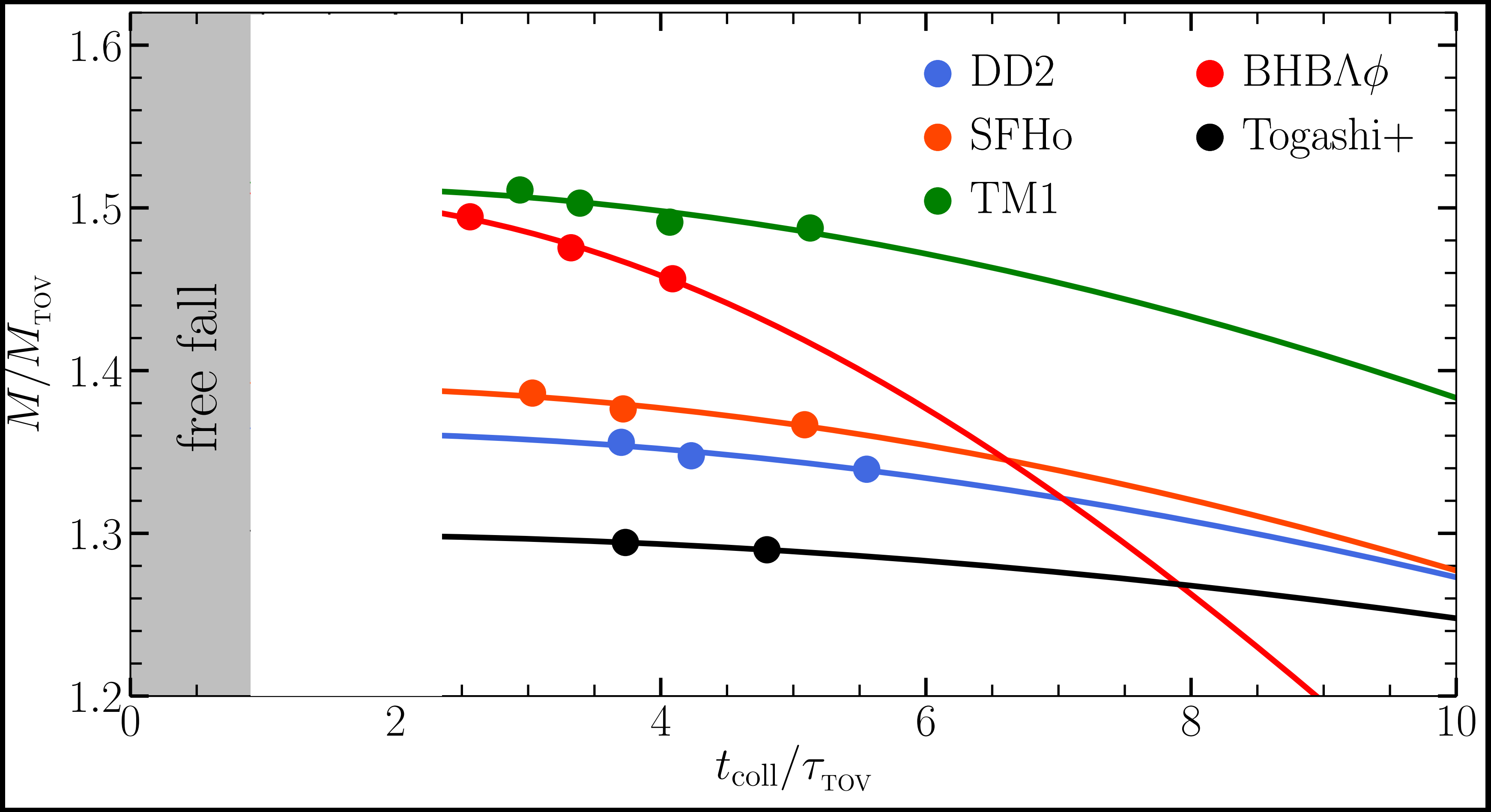
extremely robust and EOS independent

Compare $t_{\rm coll}$ with the free-fall timescale

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

free-fall timescale in Oppenheimer-Snyder collapse (no EOS!)

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

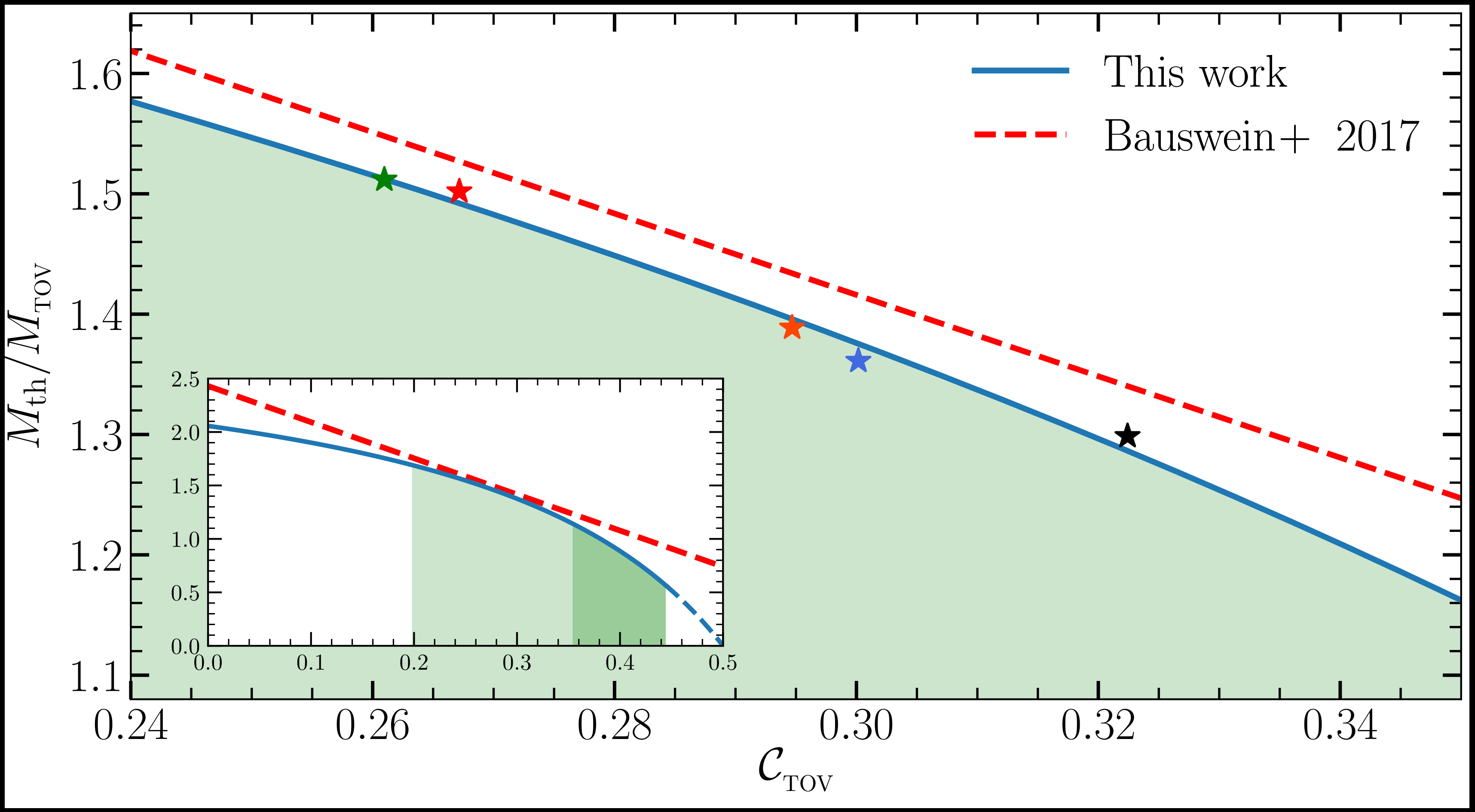


$$\frac{M_{\rm th}}{M_{\rm TOV}} \approx 1.415$$

first rough estimate

Fit behaviour and extrapolate to the limit of free-fall

4. Seek universal behaviour in terms of maximum compactness $\mathcal{C}_{\rm TOV} := (M/R)_{\rm TOV}$



requiring that

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

for

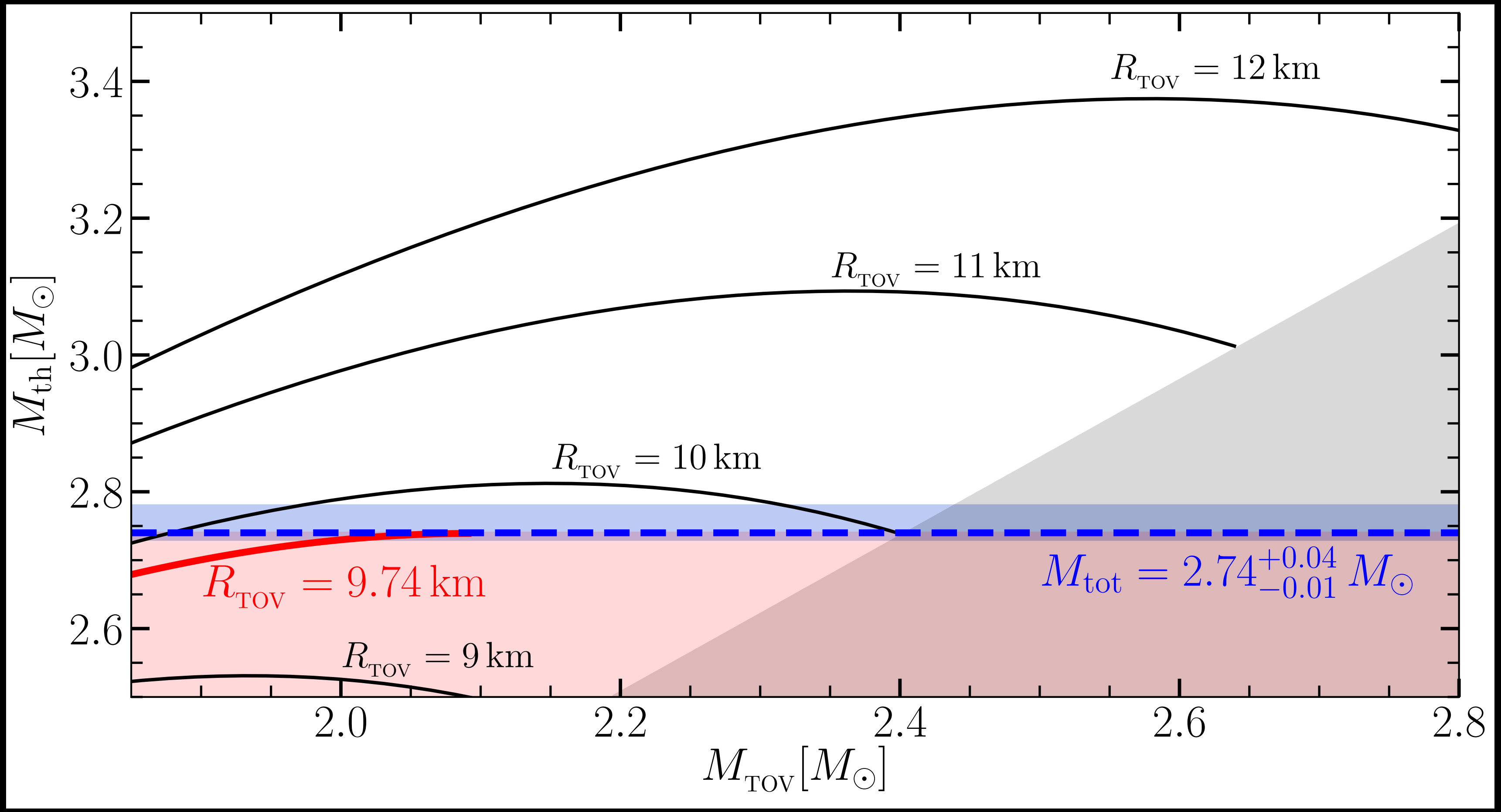
$$\mathcal{C}_{\rm TOV} \to 1/2$$

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

Overall, given reasonable values for the compactness, the threshold mass is $M_{\rm th}/M_{\rm TOV} \simeq 1.3 - 1.5$

5. Since $M_{\rm th} = M_{\rm th}(R_{\rm TOV}, M_{\rm TOV})$, for any value of $M_{\rm TOV}$ and $M_{\rm th}$ there and will be a corresponding value of $R_{\rm TOV}$

Since mass of GW170817 is known and did not lead to a prompt collapse: constraint on $R_{\rm TOV}$ from below



GW170817

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

so that

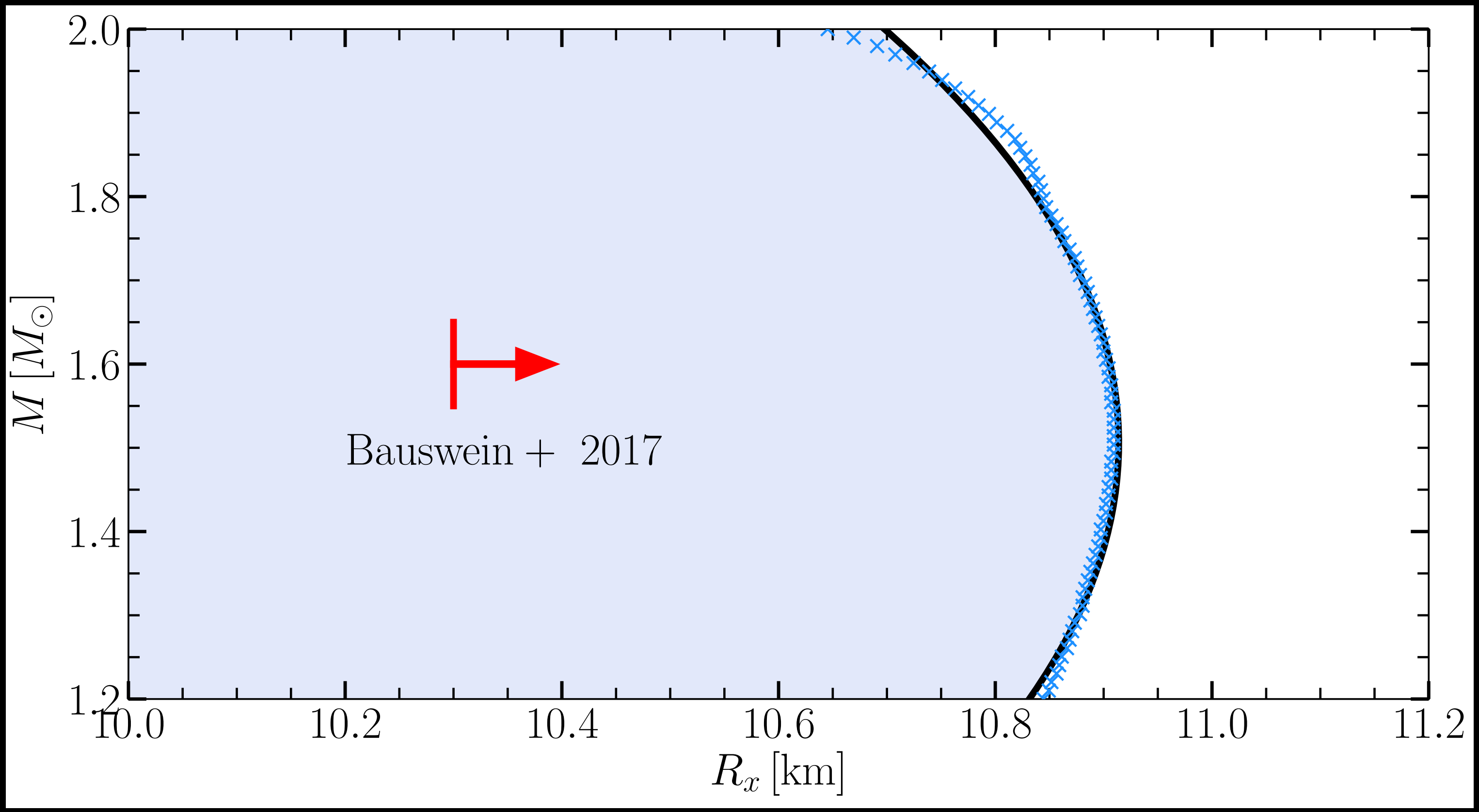
$$R_{\rm TOV} \geq 9.74^{+0.14}_{-0.04}\,{\rm km}$$

Tighter constraint than Bauswein+ 2017: $R_{\rm TOV} \geq 9.26^{+0.17}_{-0.03}\,{\rm km}$

6. The same logic can be applied for any compactness, i.e., $\mathcal{C}_{\rm TOV} \to \mathcal{C}_x$ and obtain a minimum radius as a function of the mass

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

This generalises the estimate by Bauswein+ 2017 relative to $1.6\,M_\odot$

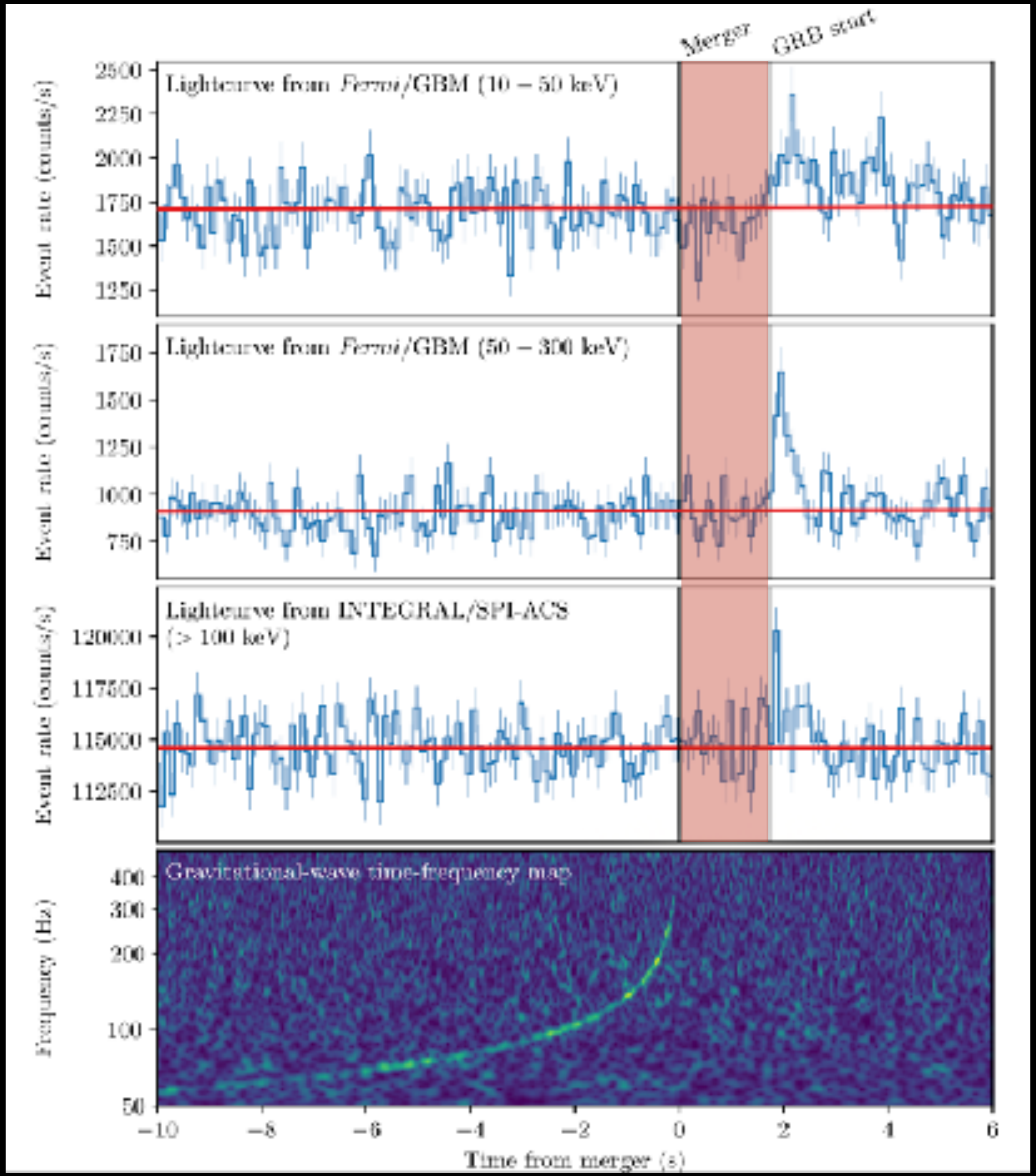


Example: $R_{1.4} \geq 10.92\,\mathrm{km}$ $\quad R_{1.6} \geq 10.90\,\mathrm{km}$

$R_{1.6} \geq 10.30\,\mathrm{km}$

When did the merger of GW170817 collapse to a BH?

Gill, Nathanail, LR (2019)

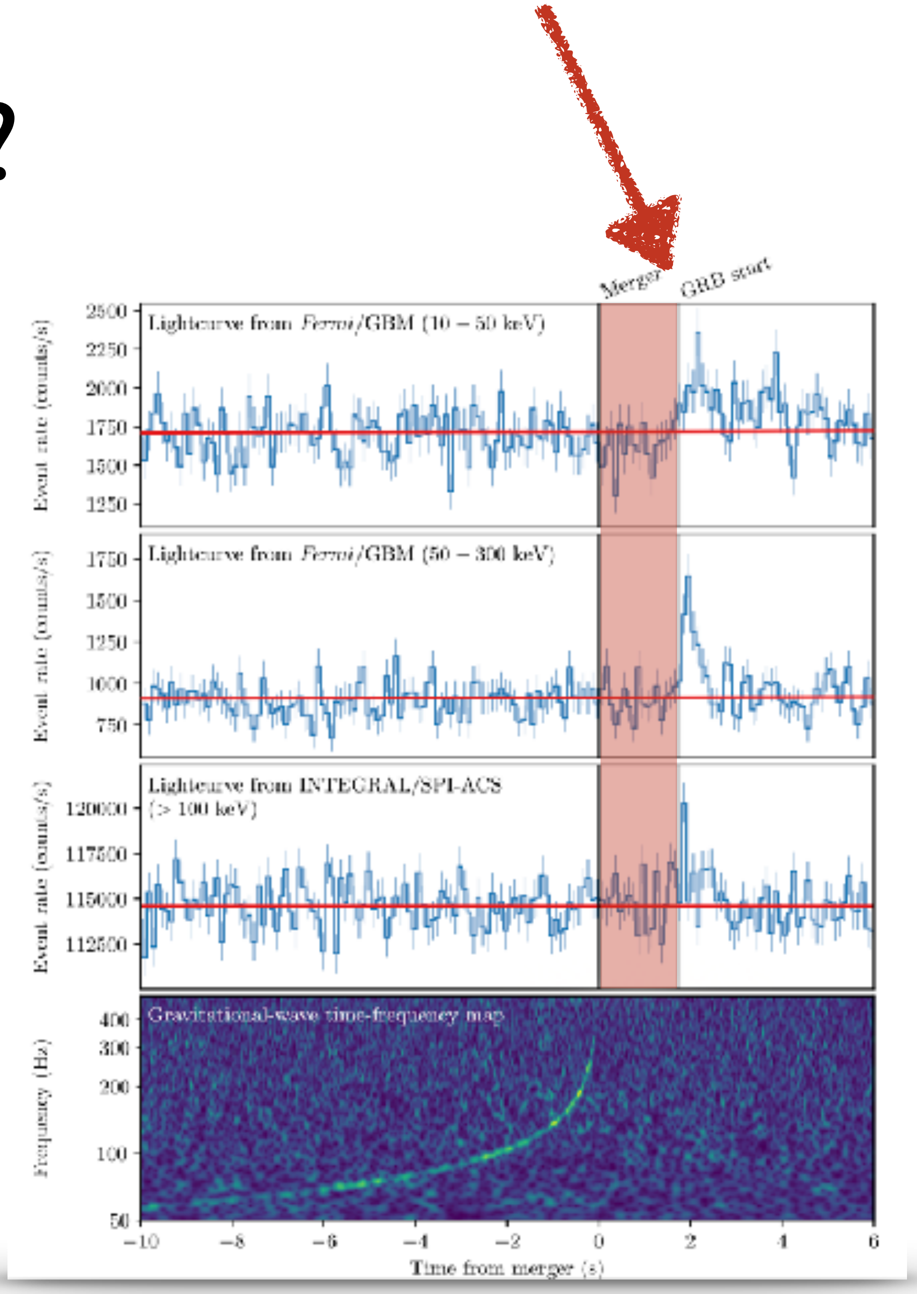


Why is this important?

Conservative assumption: the remnant of GW170817 collapsed to a BH. GRB observed at $t_{\rm del} = 1.74 \pm 0.05\,{\rm s}$

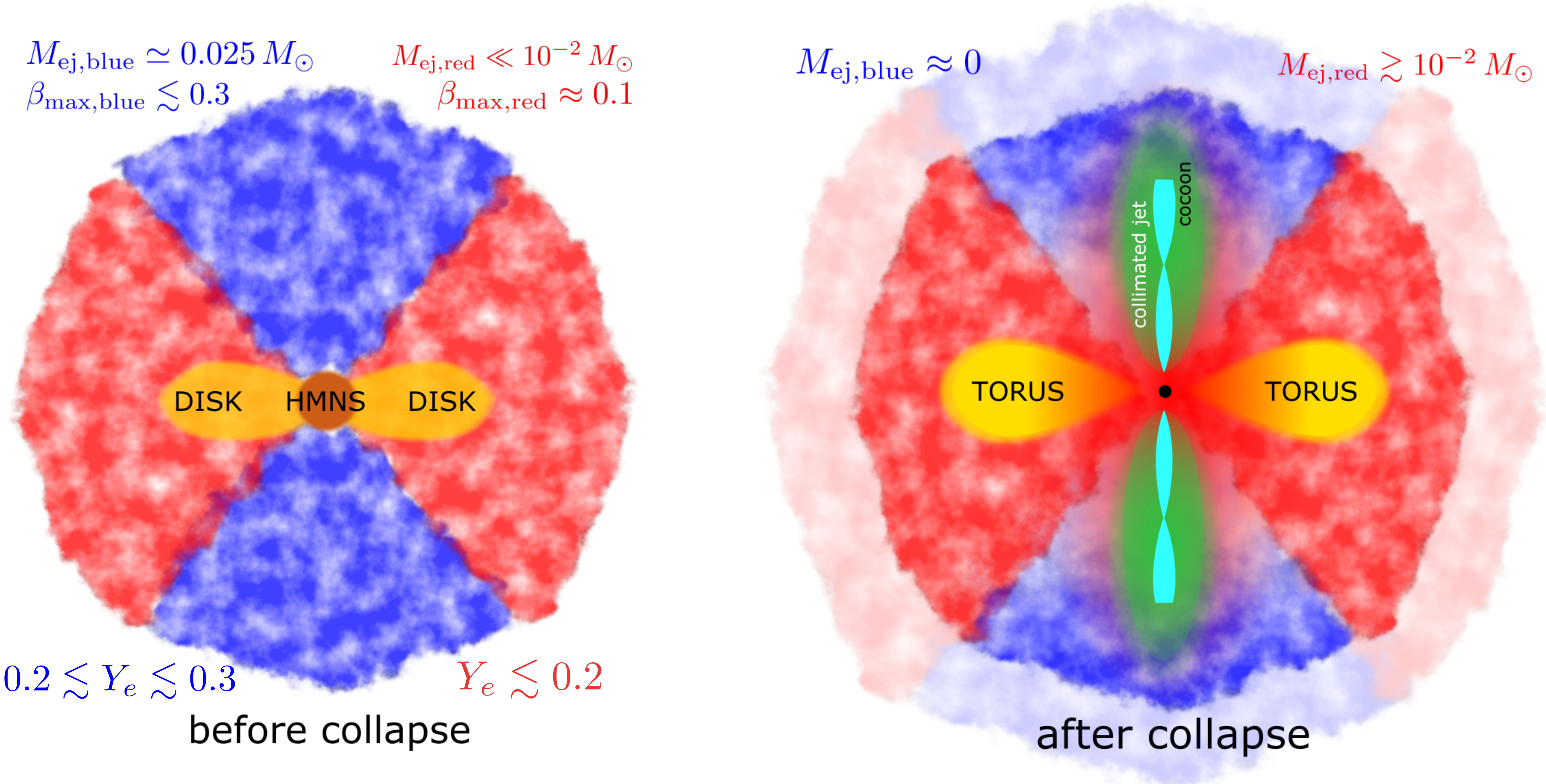
However, when did it actually collapse?

- If it collapsed **too early** it would have not **ejected** the matter that we can deduce from the kilonova emission.
- If it collapsed **too late** it would have not produced the delay we have observed of.
- The more the mass ejected, the longer for the jet to bore its way and **breakout**.

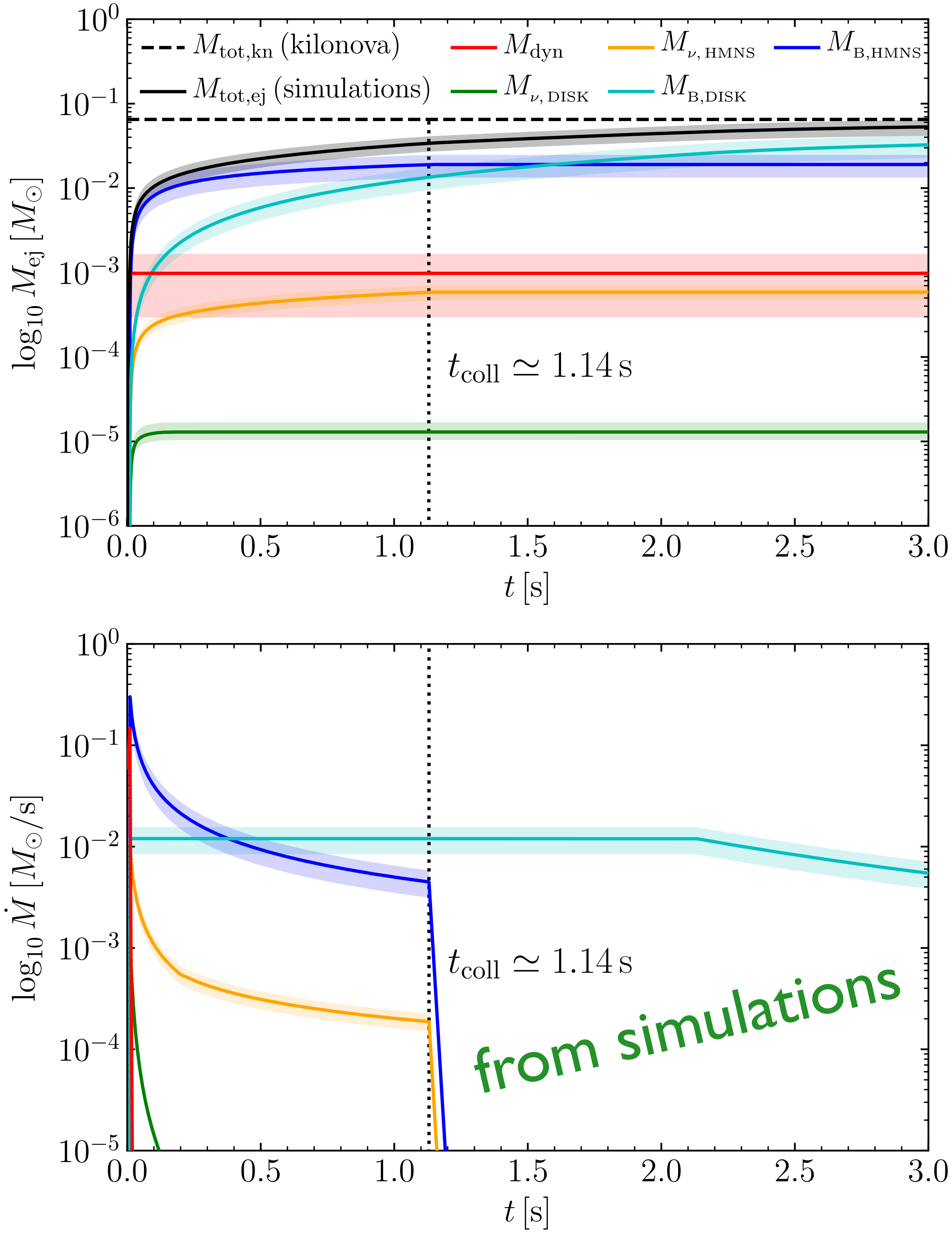


Ejection of mass

- After merger mass is lost in many different **channels** (shock heating, neutrino or magnetic-driven winds) and on very different **timescales** (dynamical and secular).



Ejection of mass

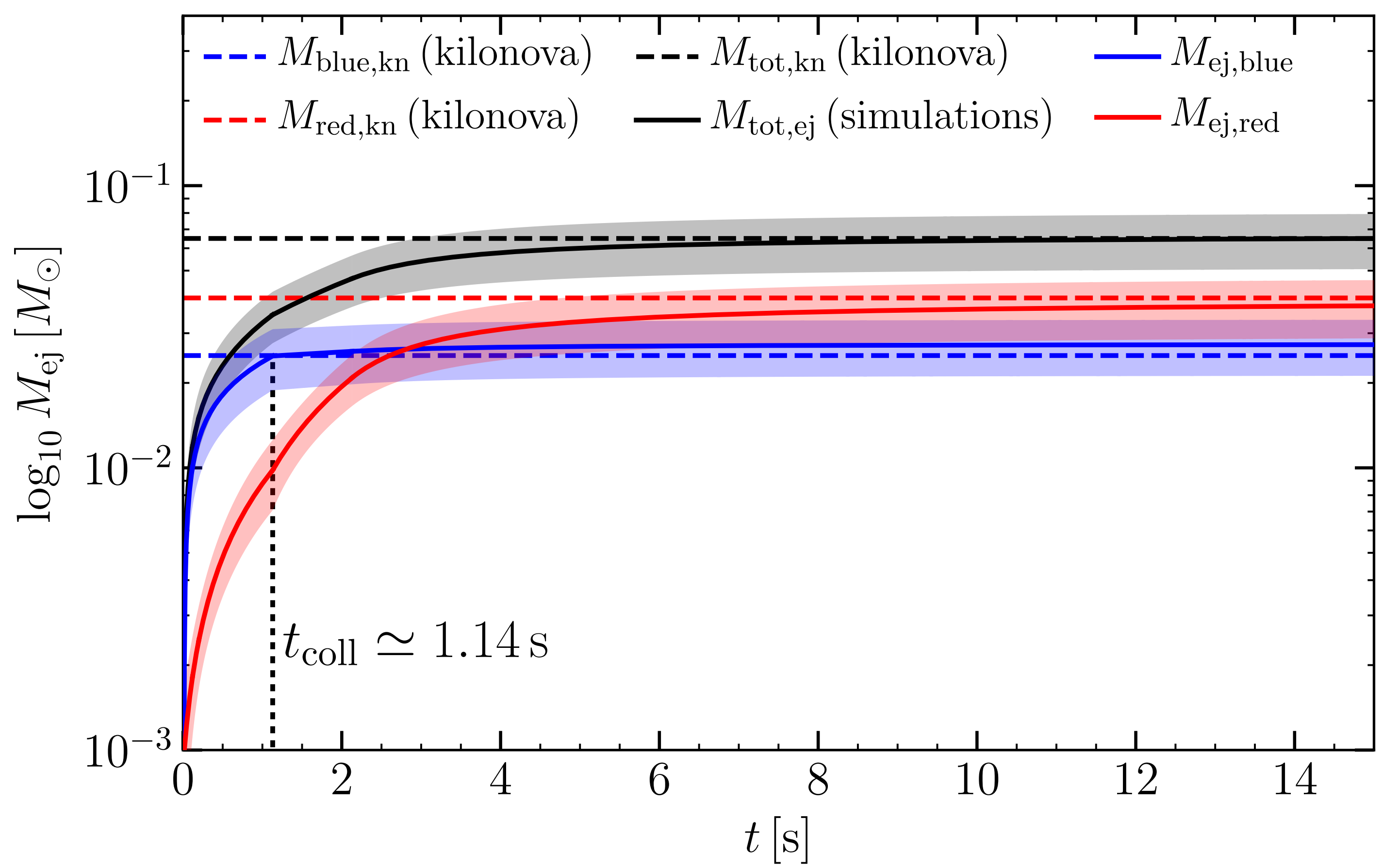


- Shown are the mass-ejection rates deduced from numerical simulations.
- $M_{\rm dyn}$: matter ejected dynamically
- M_ν : matter ejected via neutrino-driven winds
- $M_{\rm B}$: matter ejected via magnetically driven winds

All channels have contribution from the central object and the disk.

All channels provide both **blue** or **red** ejecta in different amounts

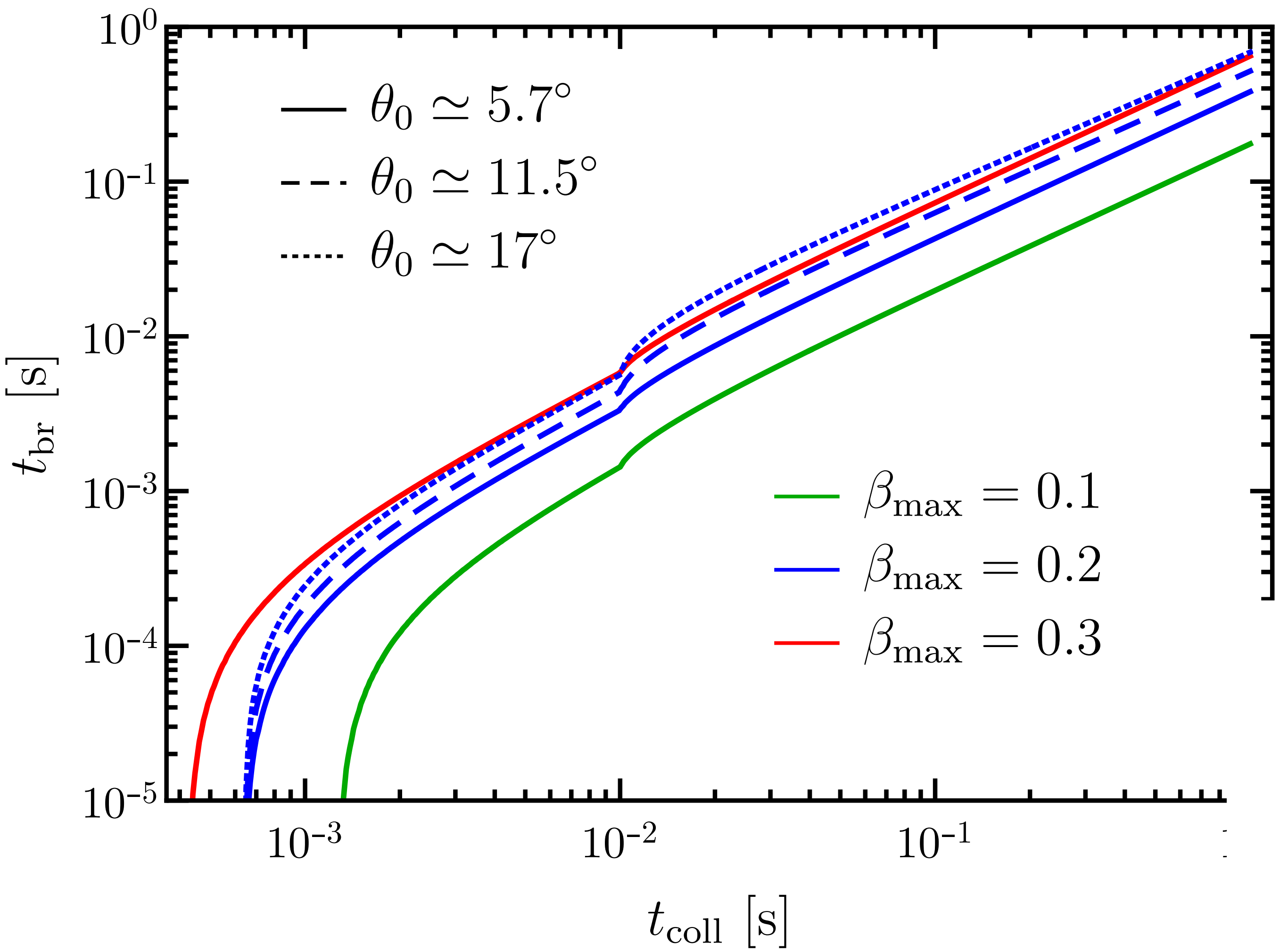
Constraints from mass ejection



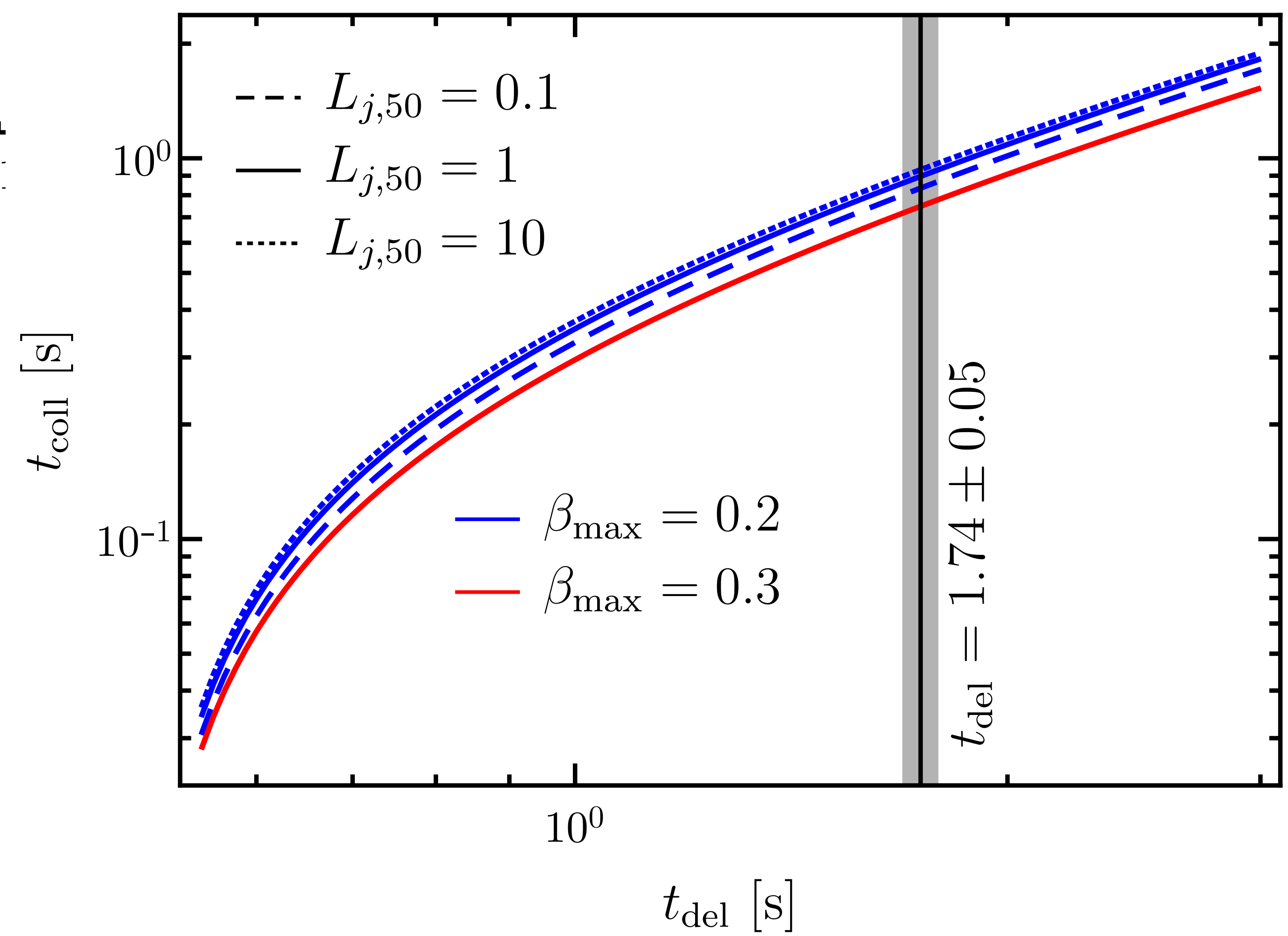
- Shown are the mass contributions (blue/red) on "long" timescales.
- Blue ejecta essentially stops after collapse and constraints collapse time **from mass ejection** to be

$$t_{\rm coll} = 1.14^{+0.60}_{-0.50}\ {\rm s}$$

Constraints from breakout



- Breakout time depends on collapse time, speed of ejecta jet opening angle, and energy injected (more and faster ejecta, longer to escape).



- Given measured $t_{\rm del}$ we can constrain collapse time **from breakout** to be

$$t_{\rm coll} = 0.82 \pm 0.15 \ \text{ s}$$

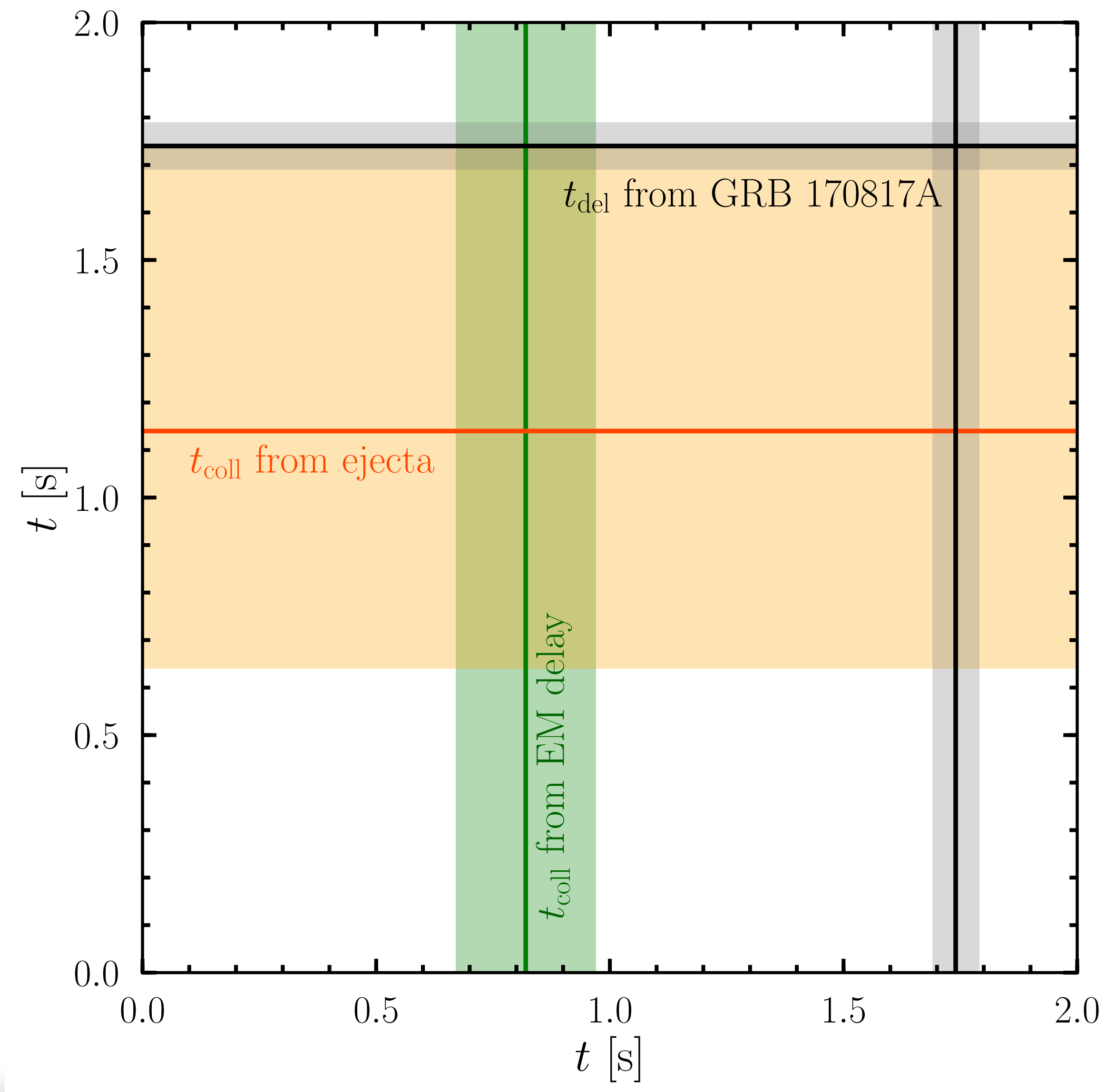
$t_{\rm del} = 1.74 \pm 0.05\,\text{s} = t_{\rm coll} + t_{\rm br}(t_{\rm coll}) + t_R$

Putting things together

- Can combine two constraints and their uncertainties to obtain a single estimate

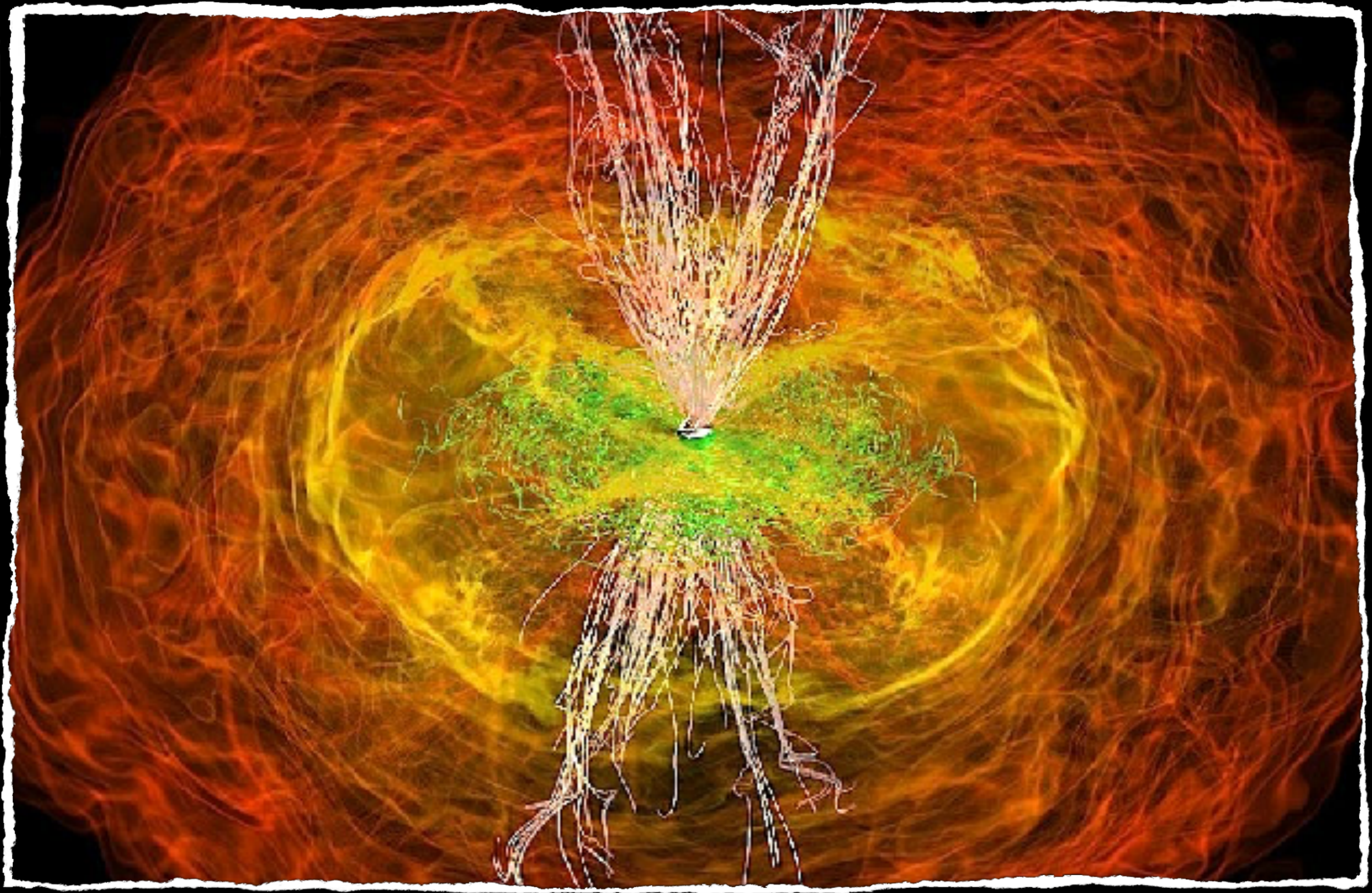
$$t_{\rm coll} = 0.98^{+0.31}_{-0.26}\ {\rm s}$$

- What are the **implications?**
  - ✳correlates $M_{\rm ej,blue}$ and $t_{\rm coll}$: to be tested new detections
  - ✳much longer than what can be simulated accurately (~0.1 s)



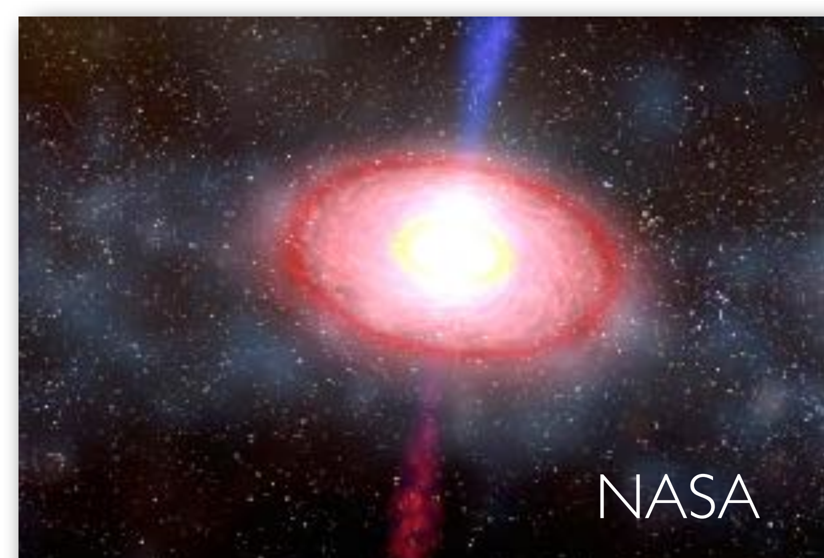
  - ✳mechanisms other than GWs for loss of angular momentum: spin down due to dipolar EM radiation appears reasonable
  - ✳this implies $B \gtrsim 10^{16}\,{\rm G}$ need to be produced **after** merger.

Electromagnetic counterparts



Electromagnetic counterparts

- Since 70's we have observed flashes of gamma rays with enormous energies 10^{50-53} erg: **gamma-ray bursts**.
- There are two families of bursts: "**long**" and "**short**".
- The first ones last **tens** or more of **seconds** and could to be due to the collapse of very massive stars.
- The second ones last **less** than a **second**.
- Merging neutron stars most reasonable explanation but how do you produce a **jet**?



Electromagnetic counterparts (B-field)

B-fields essential for EMCs. Most simulations use **ideal MHD**: (infinite conductivity, B-field advected). Simple questions:

- can B-fields be measured during the inspiral?
- is EMC produced before merger?
- do B-fields grow after merger and yield EMC?
- does jet appear after BH formation and yield EMC?

Last two questions are **incredibly hard** to answer; may require far more sophisticated numerics and microphysics

Electromagnetic counterpart (EMC)

B-fields essential for EMCs. Most simulations use **ideal MHD**: (infinite conductivity, B-field advected). Simple questions to ask:

- can B-fields be measured during the inspiral? ✅

  NO!

- is EMC produced before merger? ❓

  Maybe. Luminosity is however low.

- do B-fields grow after merger and yield EMC? ❗❓

  Certainly but unclear how much: 20-10^3 amplification?

- does jet appear after BH formation and yield EMC? ‼❓

  YES (jet structure and outflow). Unclear how to produce ultrarelativistic outflow.

Presence of a jet immediately implies presence of large-scale magnetic fields

What happens when magnetised stars collide?

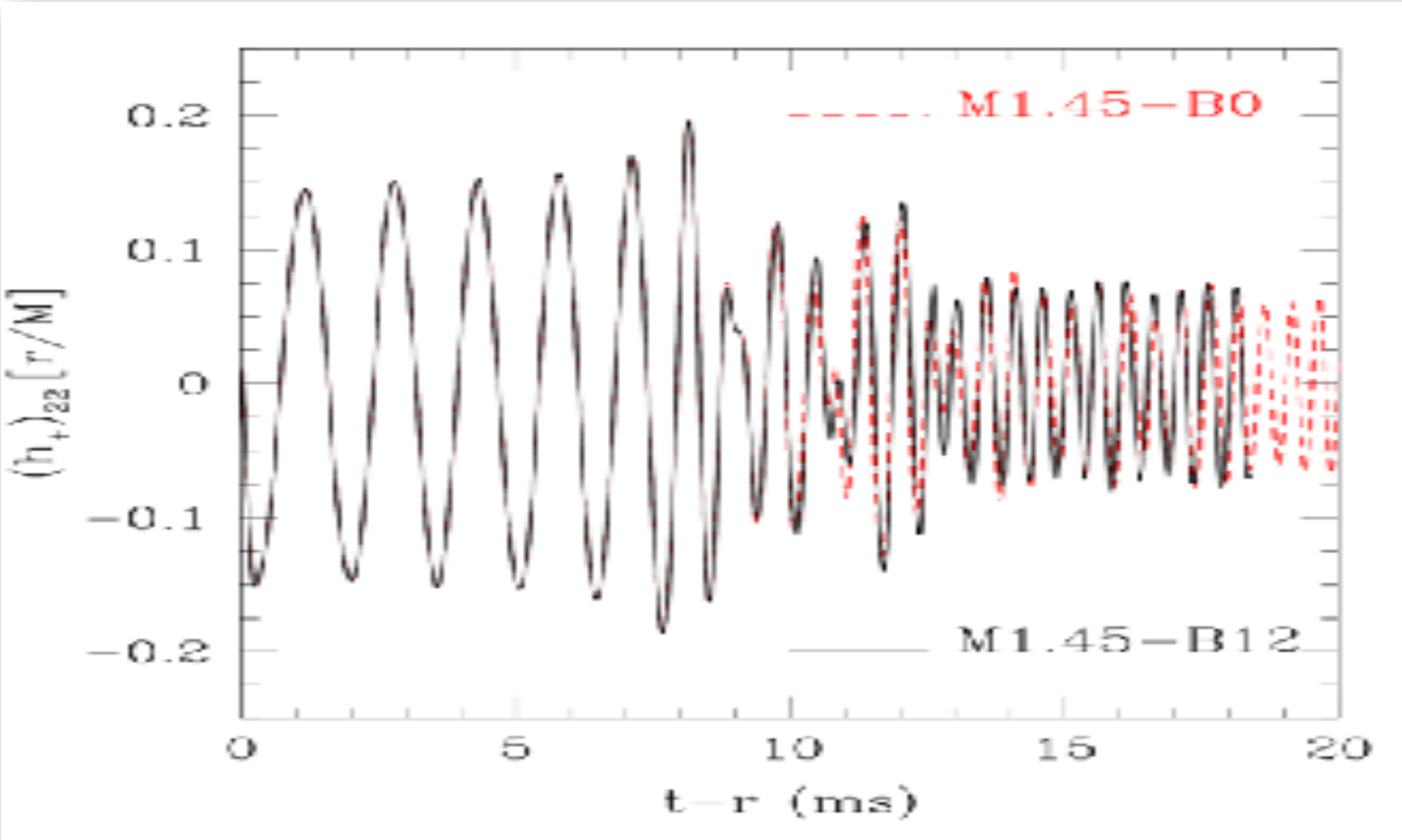
Need to solve equations of magnetohydrodynamics in addition to the Einstein equations

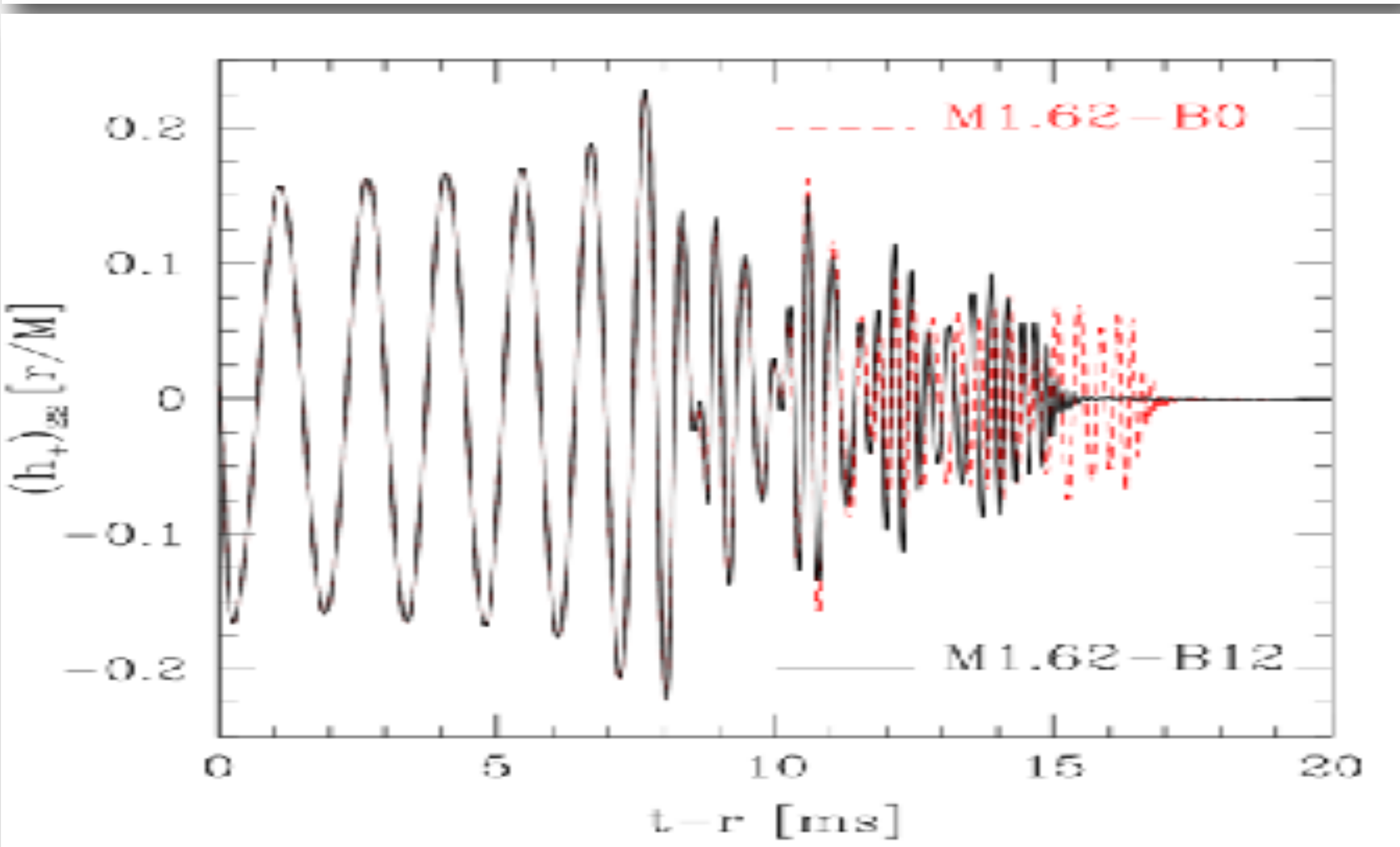
$$T_{\mu\nu} = (e+p)\, u_\mu u_\nu + p g_{\mu\nu} + F_\mu{}^\lambda F_{\nu\lambda} - \frac{1}{4} g_{\mu\nu}\, F^{\lambda\alpha} F_{\lambda\alpha},$$

$$\nabla^\nu T_{\mu\nu} = 0$$

$$\nabla_\nu (F^{\mu\nu} + g^{\mu\nu}\psi) = I^\mu - \kappa n^\mu \psi, \quad \nabla_\nu ({}^*F^{\mu\nu} + g^{\mu\nu}\phi) = -\kappa n^\mu \phi,$$

Can we detect B-fields in the inspiral?





Compare B/no-B field:

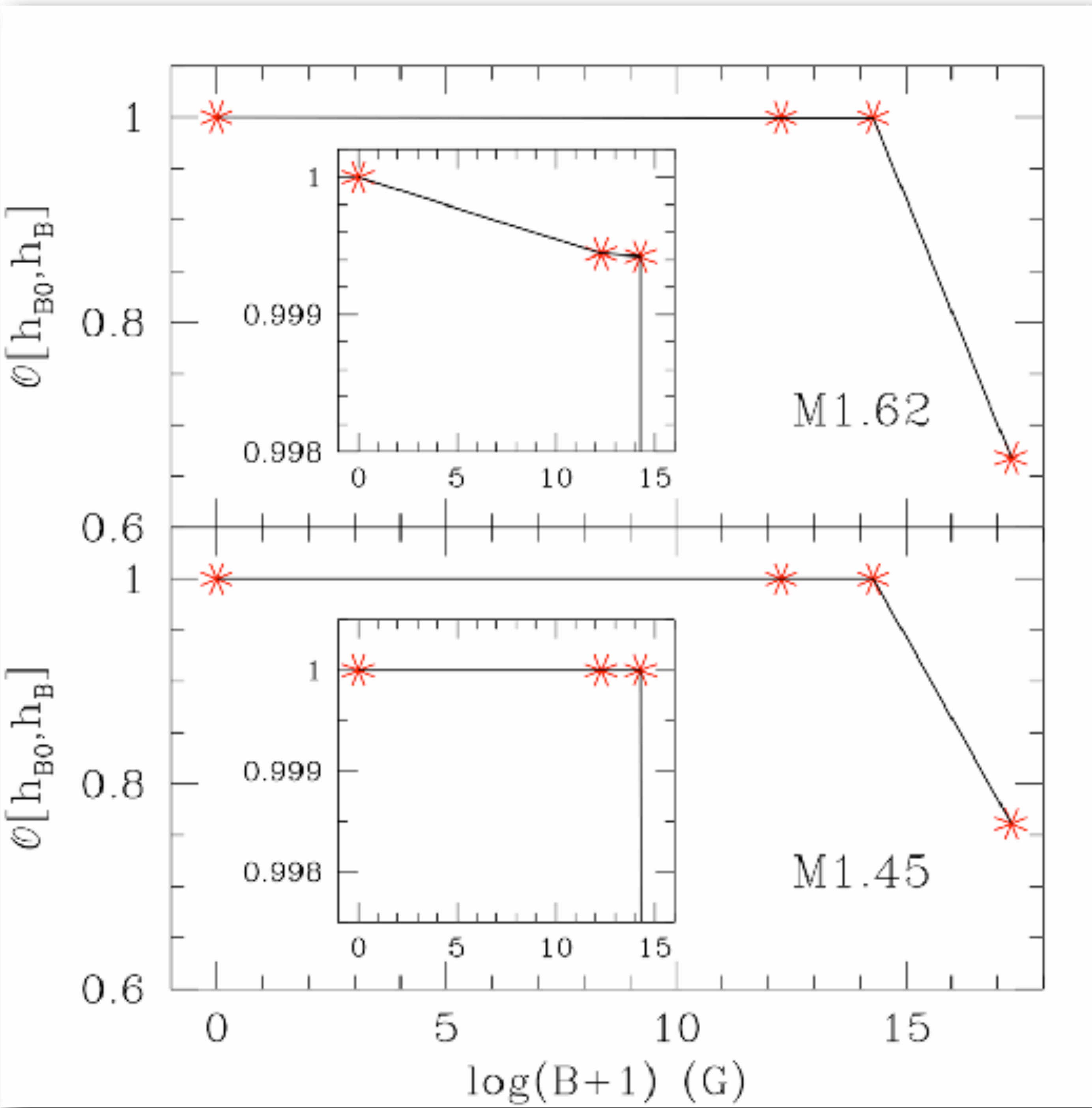
- **inspiral** waveform is different but for unrealistic B-fields (i.e. B~10^{17} G).

- **post-merger** waveform is different for all masses; strong B-fields delay the collapse to BH

Influence of B-fields on inspiral is **unlikely to be detected** for realistic fields

Can we detect B-fields in the inspiral?

To quantify the differences and determine whether detectors will see a difference in the inspiral, we calculate the overlap



$$\mathcal{O}[h_{\rm B1},h_{\rm B2}] \equiv \frac{\langle h_{\rm B1}|h_{\rm B2}\rangle}{\sqrt{\langle h_{\rm B1}|h_{\rm B1}\rangle\langle h_{\rm B2}|h_{\rm B2}\rangle}}$$

where the scalar product is

$$\langle h_{\rm B1}|h_{\rm B2}\rangle \equiv 4\Re\int_0^\infty df\,\frac{\tilde{h}_{\rm B1}(f)\tilde{h}^*_{\rm B2}(f)}{S_h(f)}$$

In essence, at these res:

$$\mathcal{O}[h_{\rm B0},h_{\rm B}] \gtrsim 0.999$$

for $\rm B \lesssim 10^{17}\ G$

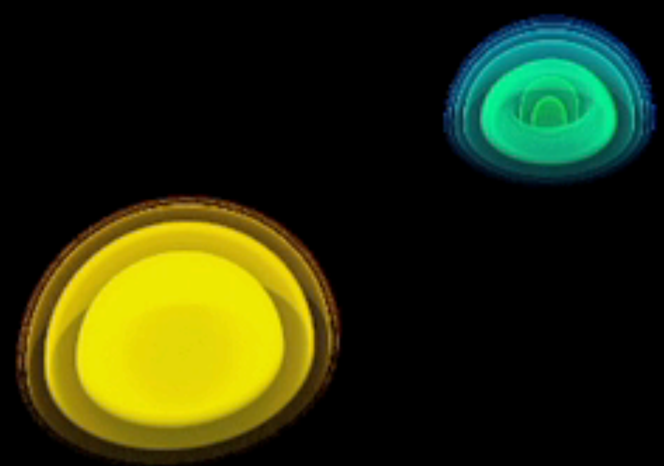
Influence of B-fields on inspiral is **unlikely to be detected**

Presence of a jet immediately implies presence of large-scale magnetic fields

What happens when magnetised stars collide?

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

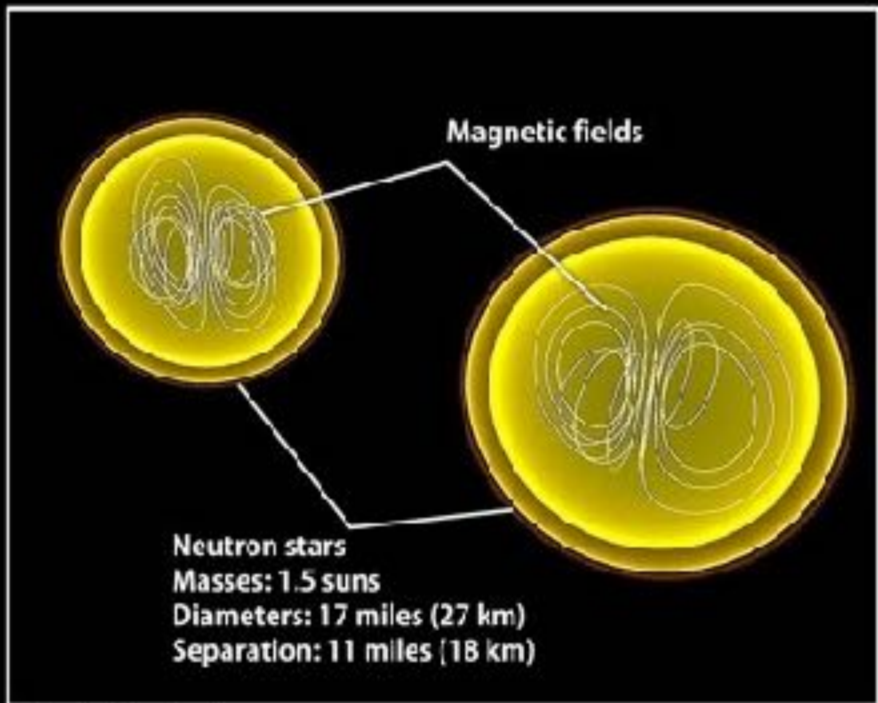
If magnetic fields cannot be measured in the inspiral, what happens after merger?



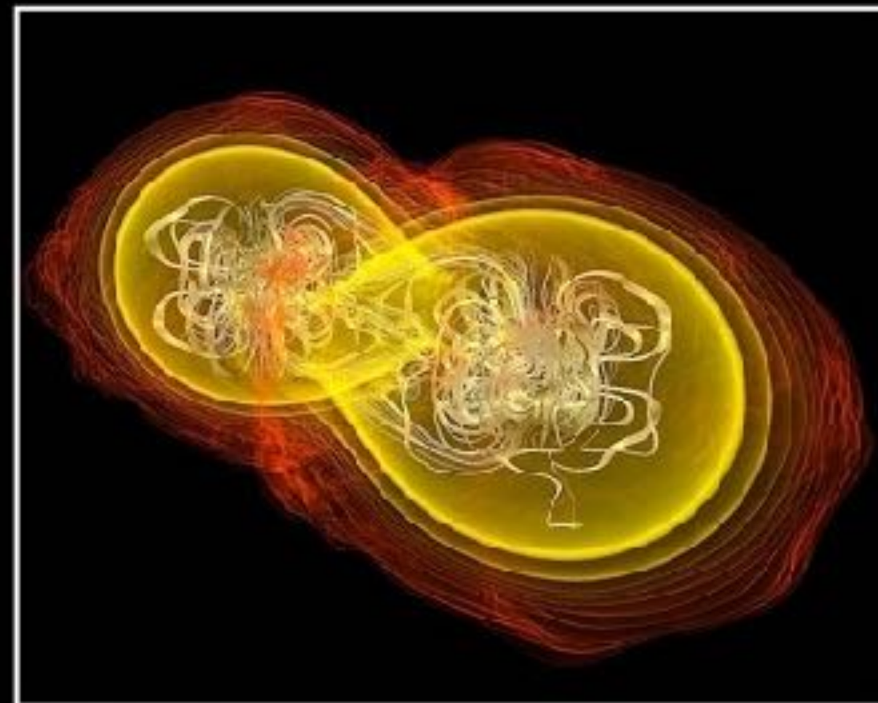
$$M = 1.5\, M_\odot,\, B_0 = 10^{12}\, \mathrm{G}$$

Animations:, LR, Koppitz

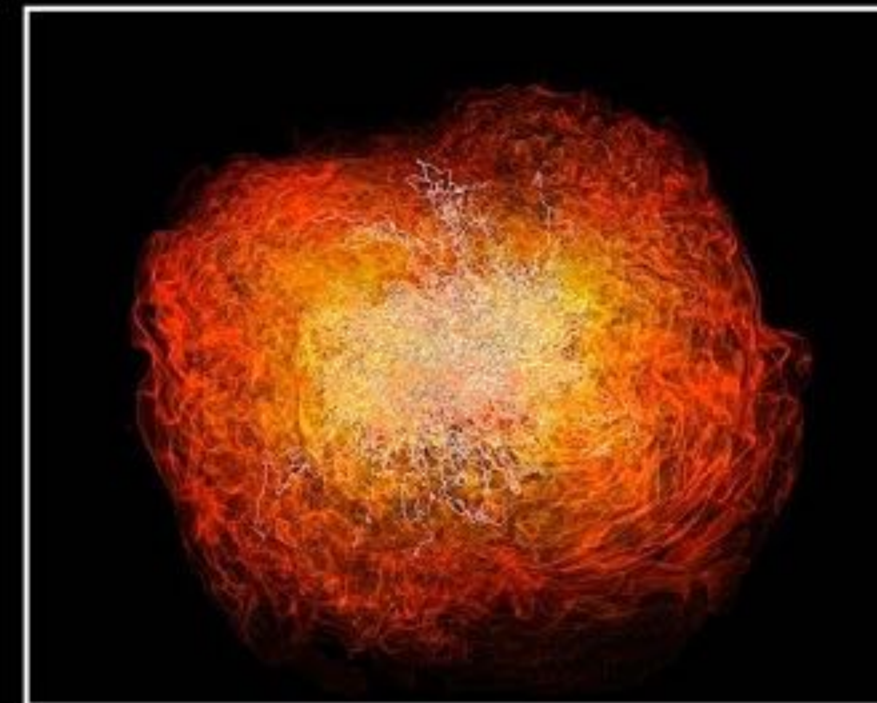
What happens when magnetised stars collide?



Simulation begins

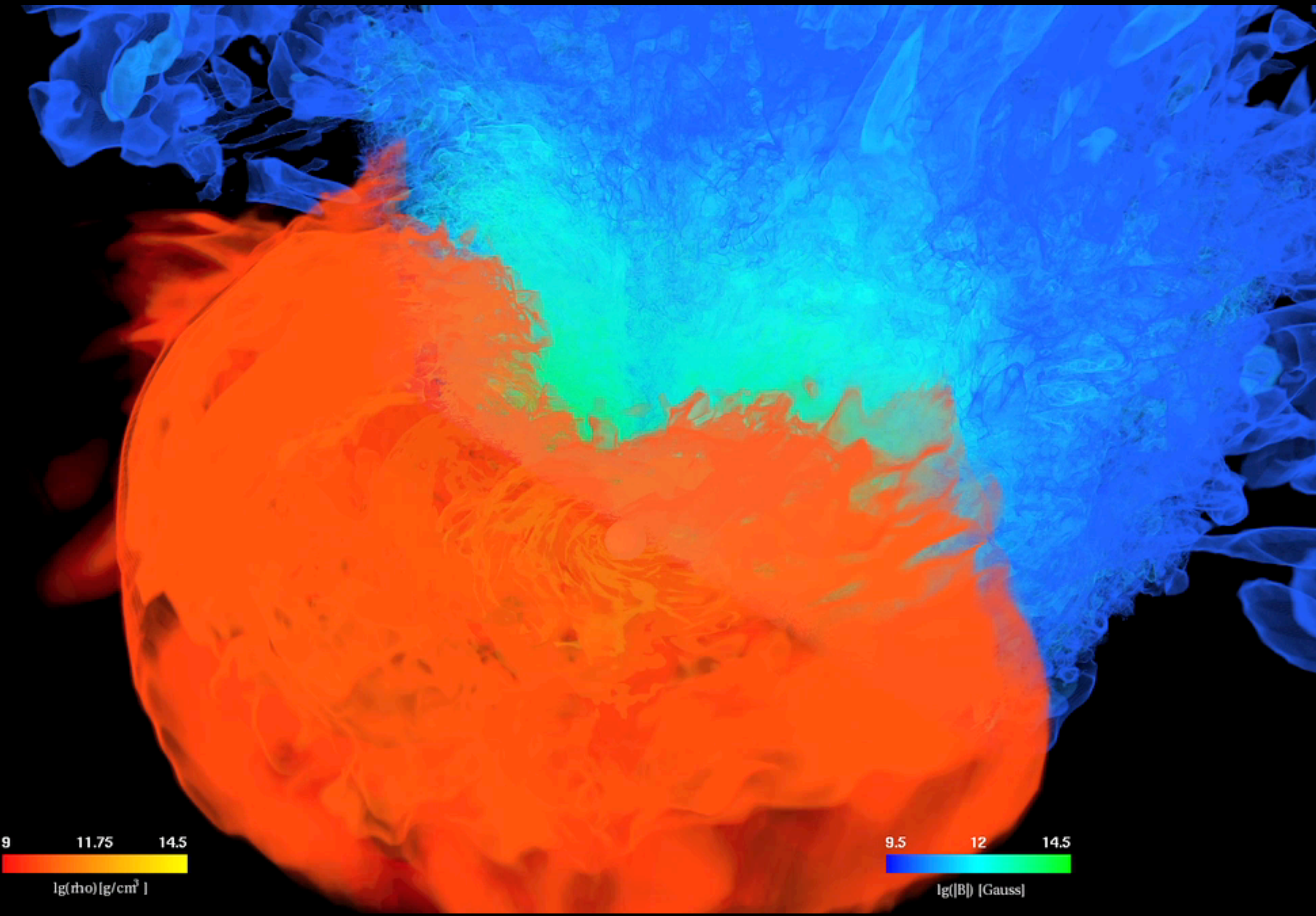


7.4 milliseconds

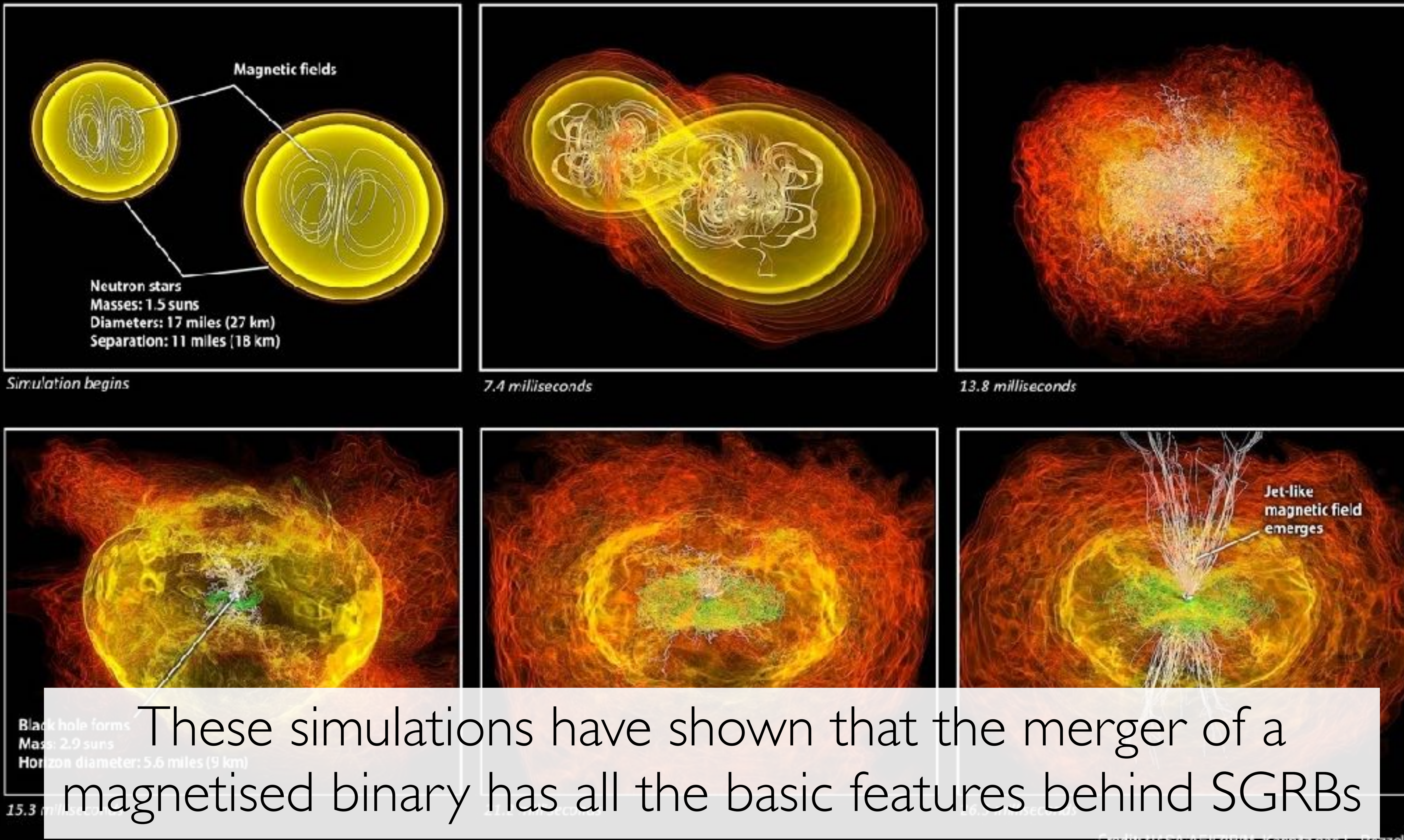


13.8 milliseconds

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

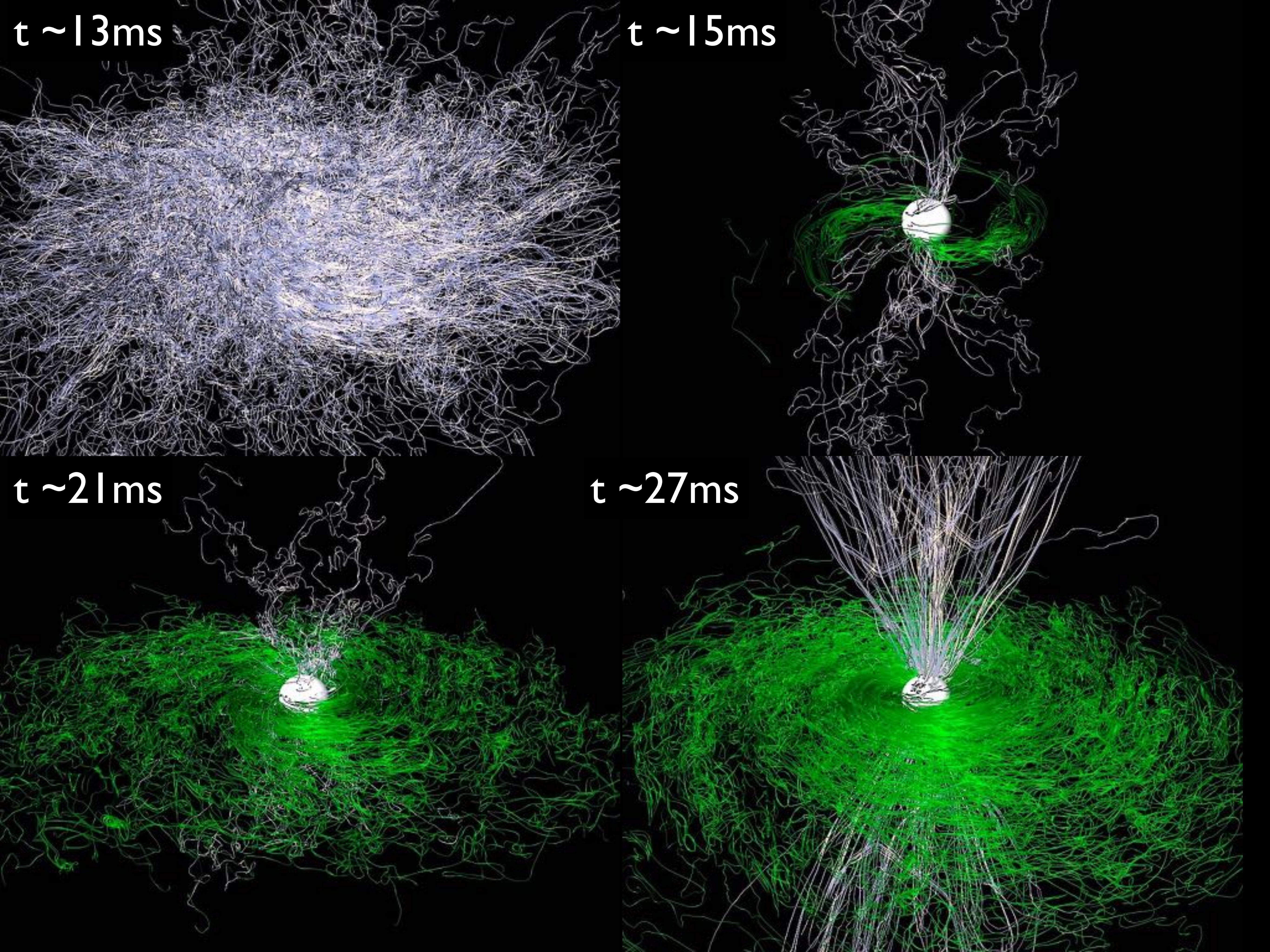

9
11.75
14.5
lg(rho) [g/cm³]
9.5
12
14.5
lg(|B|) [Gauss]

LR+ 2011

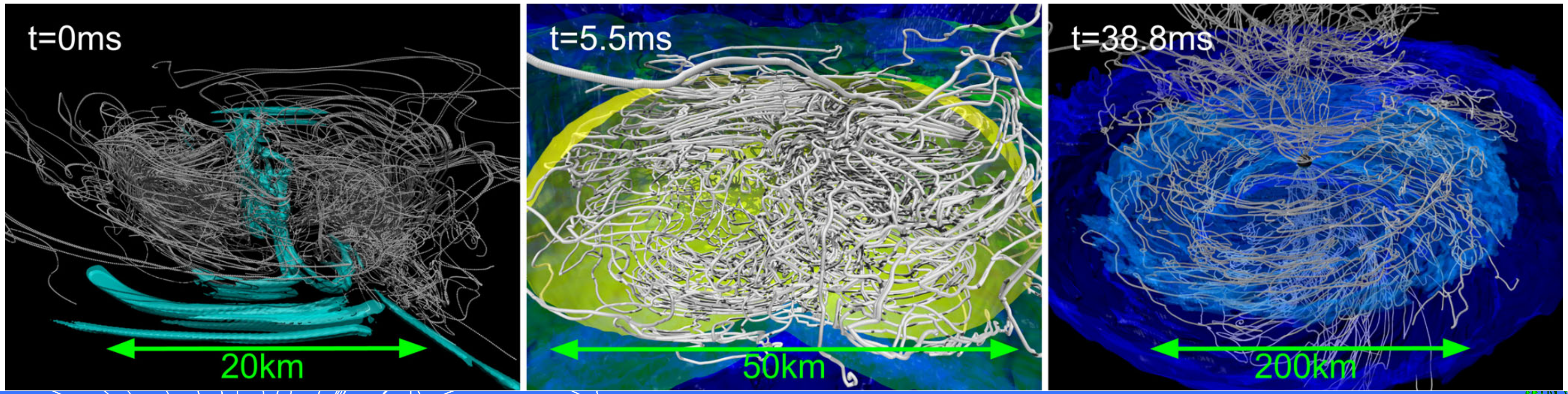


These simulations have shown that the merger of a magnetised binary has all the basic features behind SGRBs

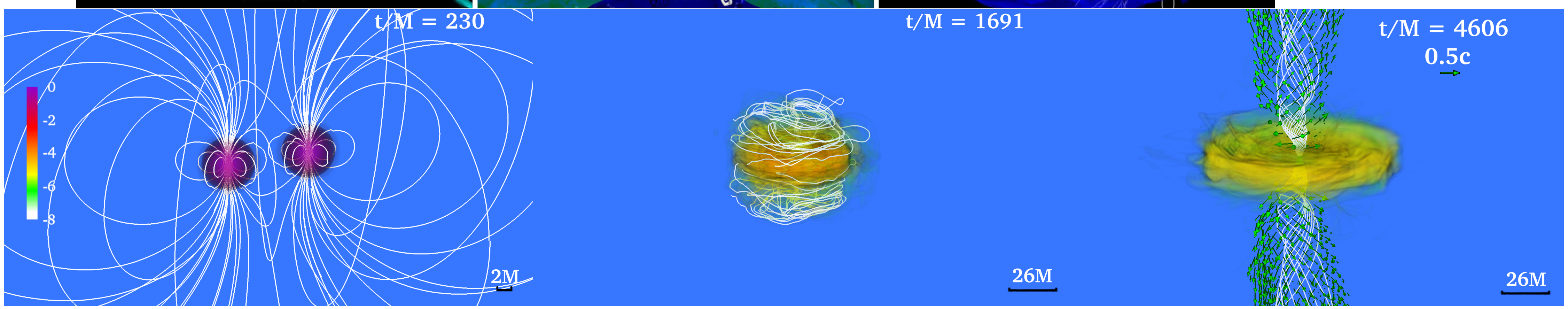
$J/M^2 = 0.83$ $\mathrm{M_{tor}} = 0.063 M_\odot$ $\mathrm{t_{accr}} \simeq M_{\mathrm{tor}}/\dot{M} \simeq 0.3\ \mathrm{s}$


t ~13ms
t ~15ms
t ~21ms
t ~27ms

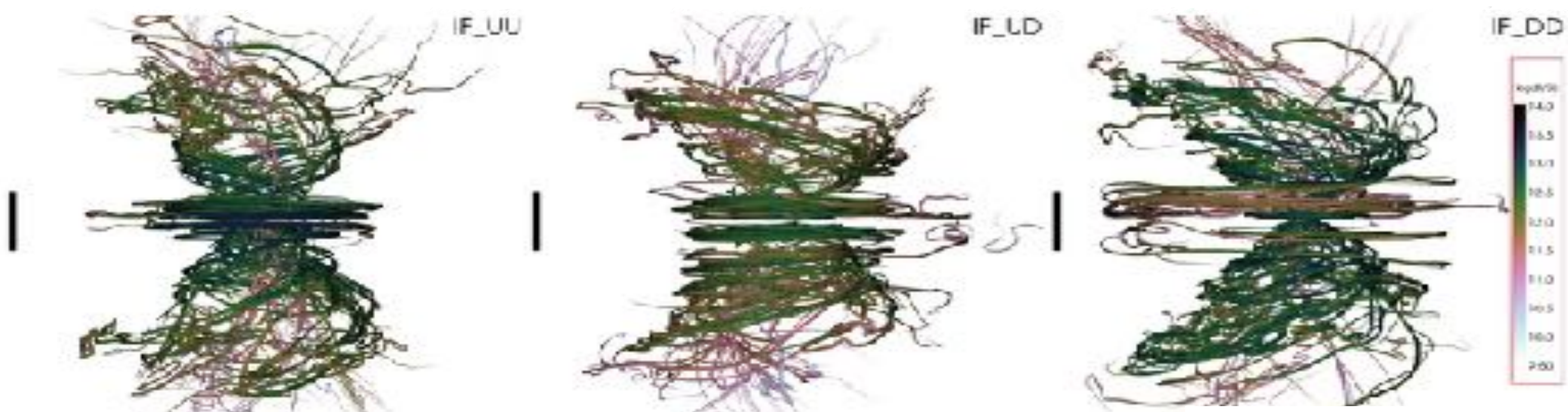
With due differences, other groups confirm this picture



Kiuchi+ 2014

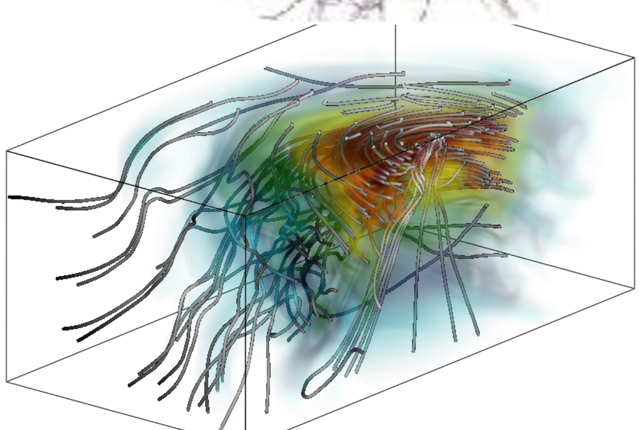


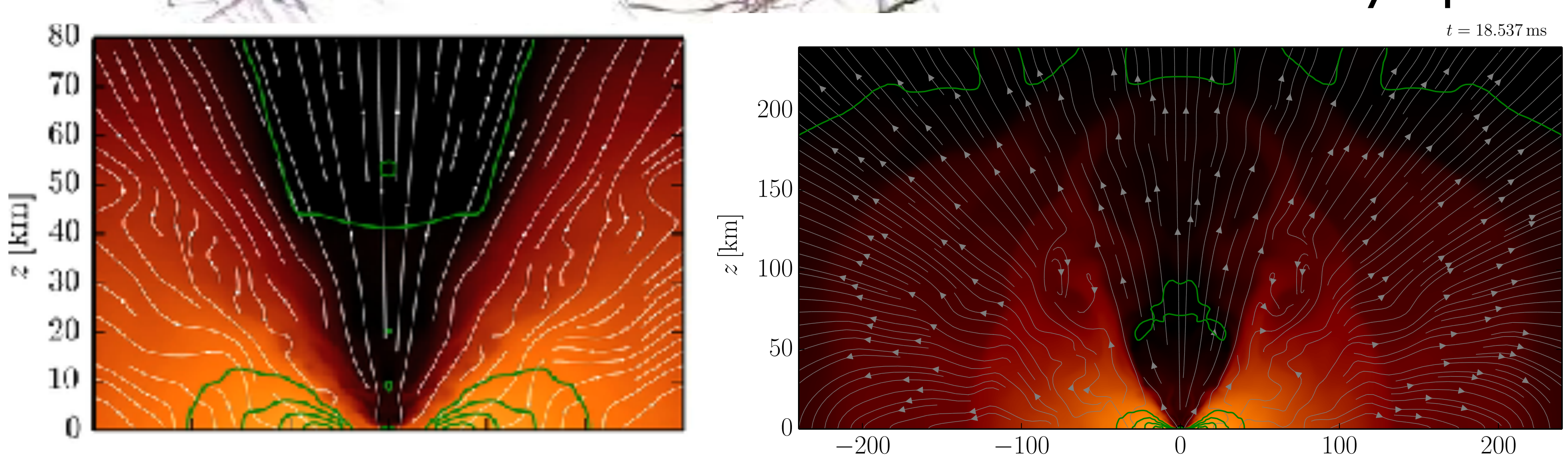
Ruiz+ 2016



Kawamura+2016

Dionysopoulou+ 2015





RMHD

Beyond IMHD: Resistive Magnetohydrodynamics

Dionysopoulou, Alic, LR (2015)

- Ideal MHD is a good approximation in the inspiral, but not after the merger; match to **electro-vacuum** not possible.
- Main difference in resistive regime is the current, which is dictated by Ohm's law but microphysics is **poorly** known.
- We know conductivity σ is a **tensor** but hardly know it as a scalar (prop. to density and inversely prop. to temperature).
- A simple prescription with scalar (isotropic) conductivity:

$$J^i = qv^i + W\sigma[E^i + \epsilon^{ijk}v_j B_k - (v_k E^k)v^i] \, ,$$

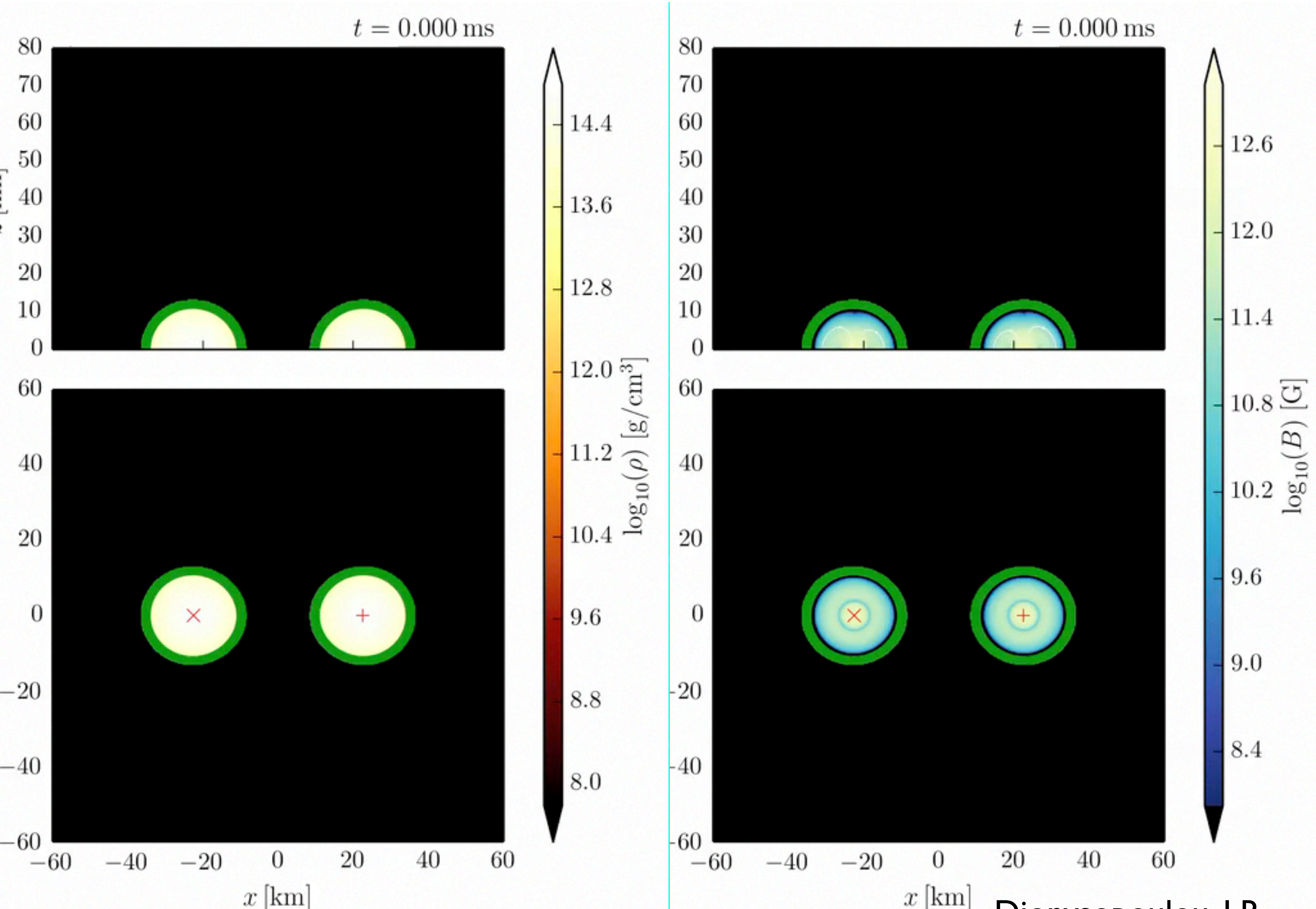
$\sigma \to \infty$ ideal-MHD (IMHD)

$\sigma \neq 0$ resistive-MHD (RMHD)

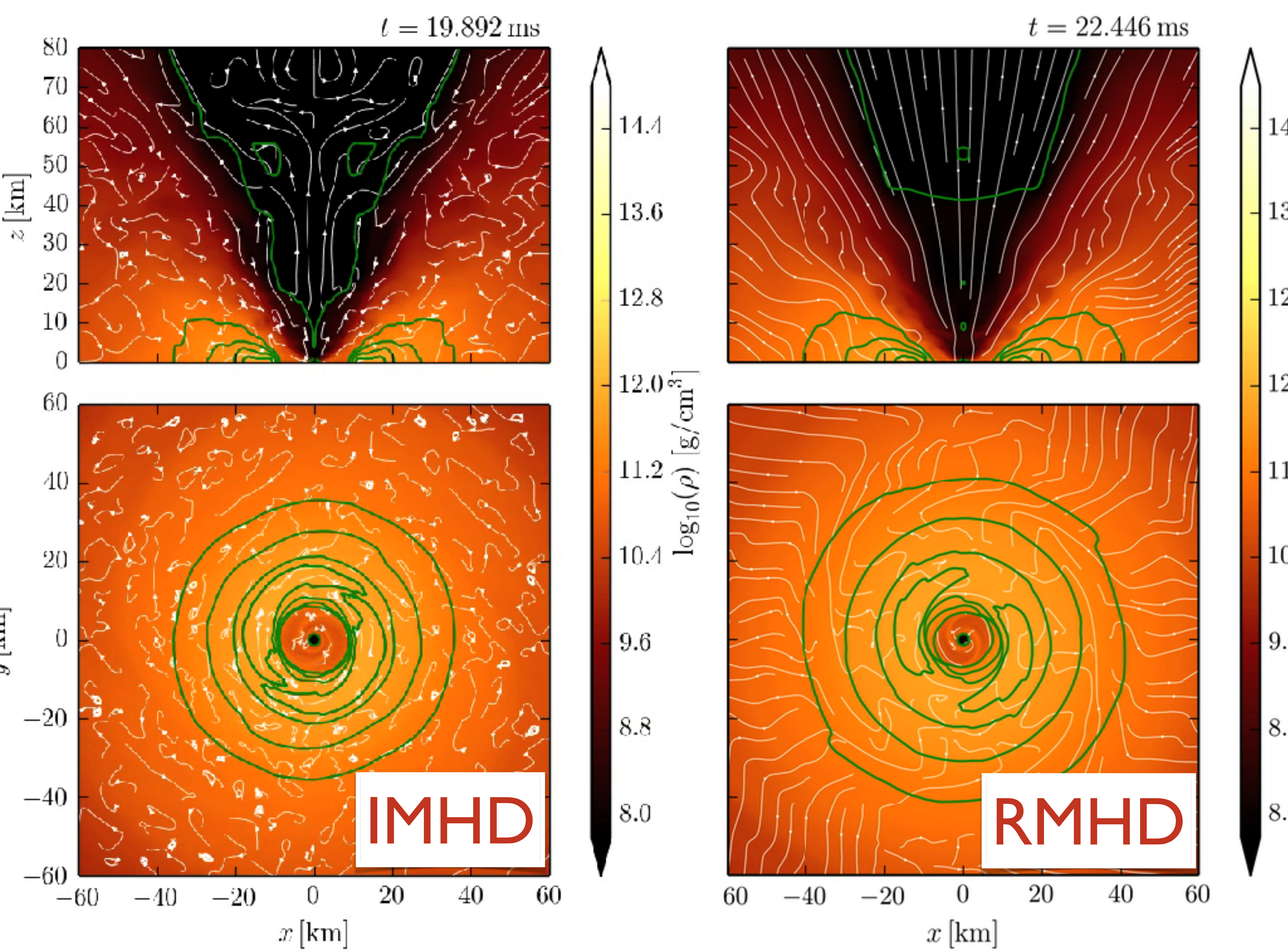
$\sigma \to 0$ electrovacuum

$$\sigma = f(\rho, \rho_{\min})$$

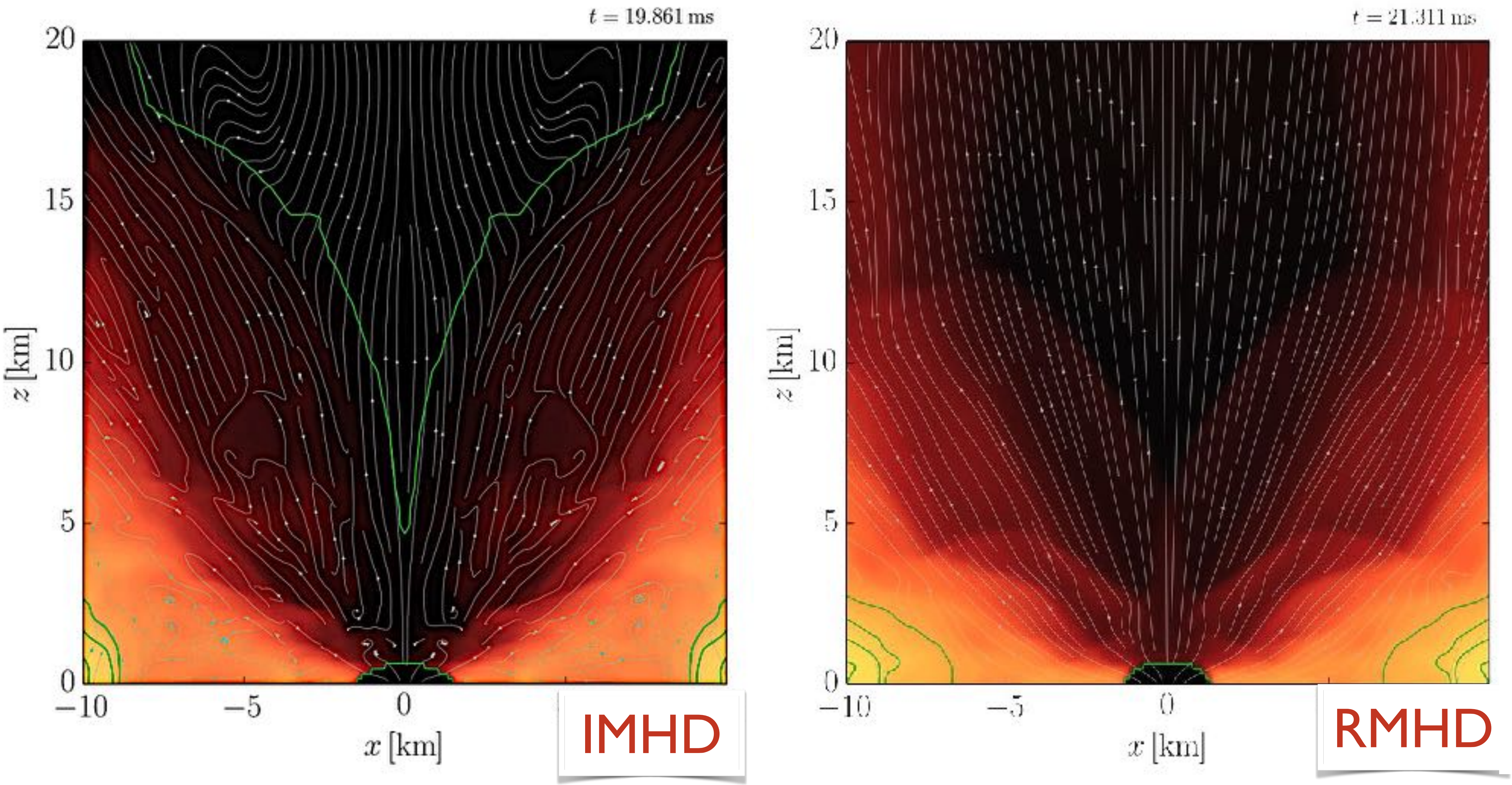
phenomenological prescription



Dionysopoulou, LR



t = 19.892 ms
t = 22.446 ms
z [km]
y [km]
x [km]
x [km]
log10(ρ) [g/cm^3]
14.4
13.6
12.8
12.0
11.2
10.4
9.6
8.8
8.0
IMHD
RMHD

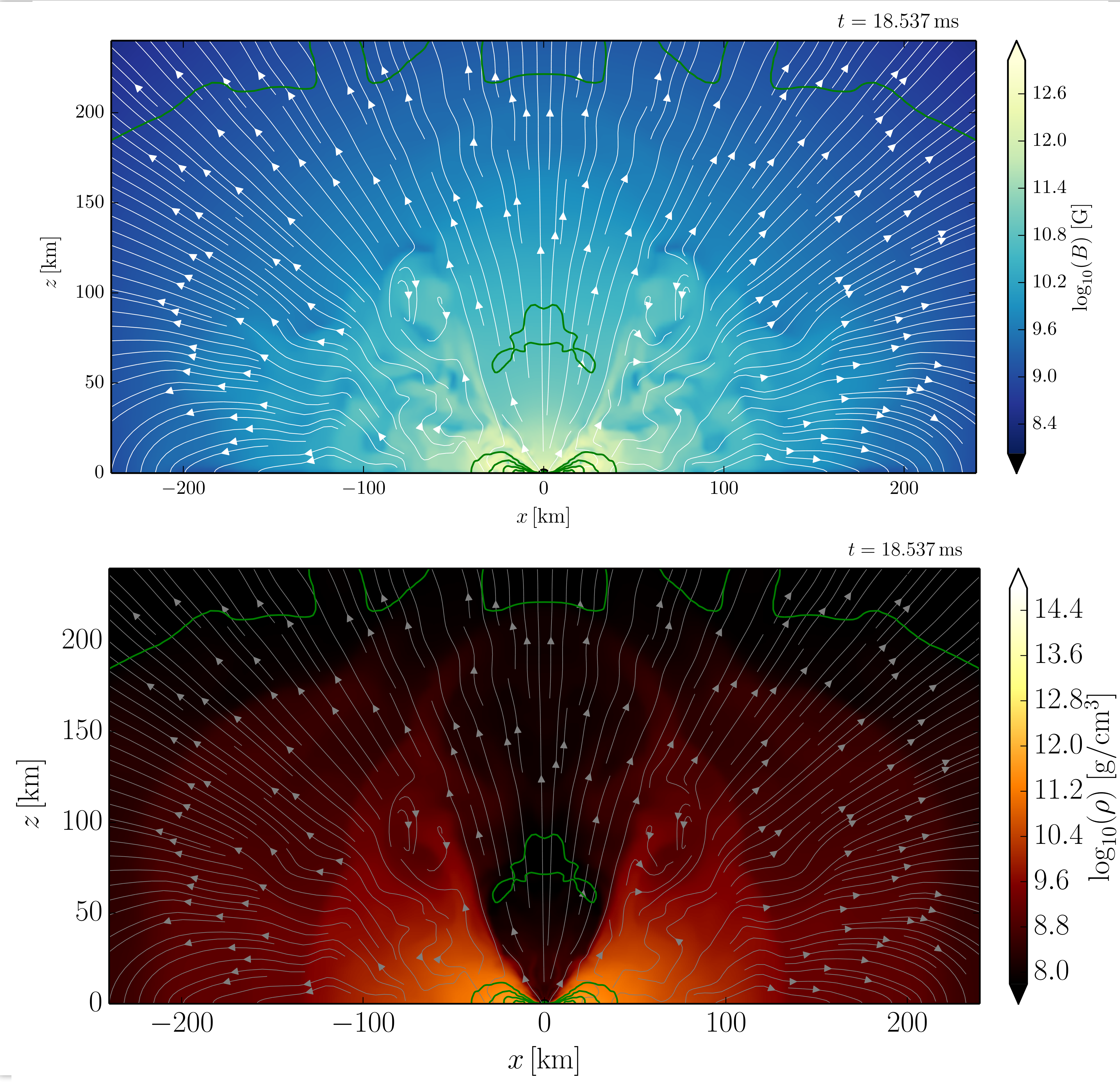


NOTE: the **magnetic jet structure** is **not** an **outflow**. It's a plasma-confining structure.

In IMHD the magnetic jet structure is present but less regular.

In RMHD it is more regular at all scales.

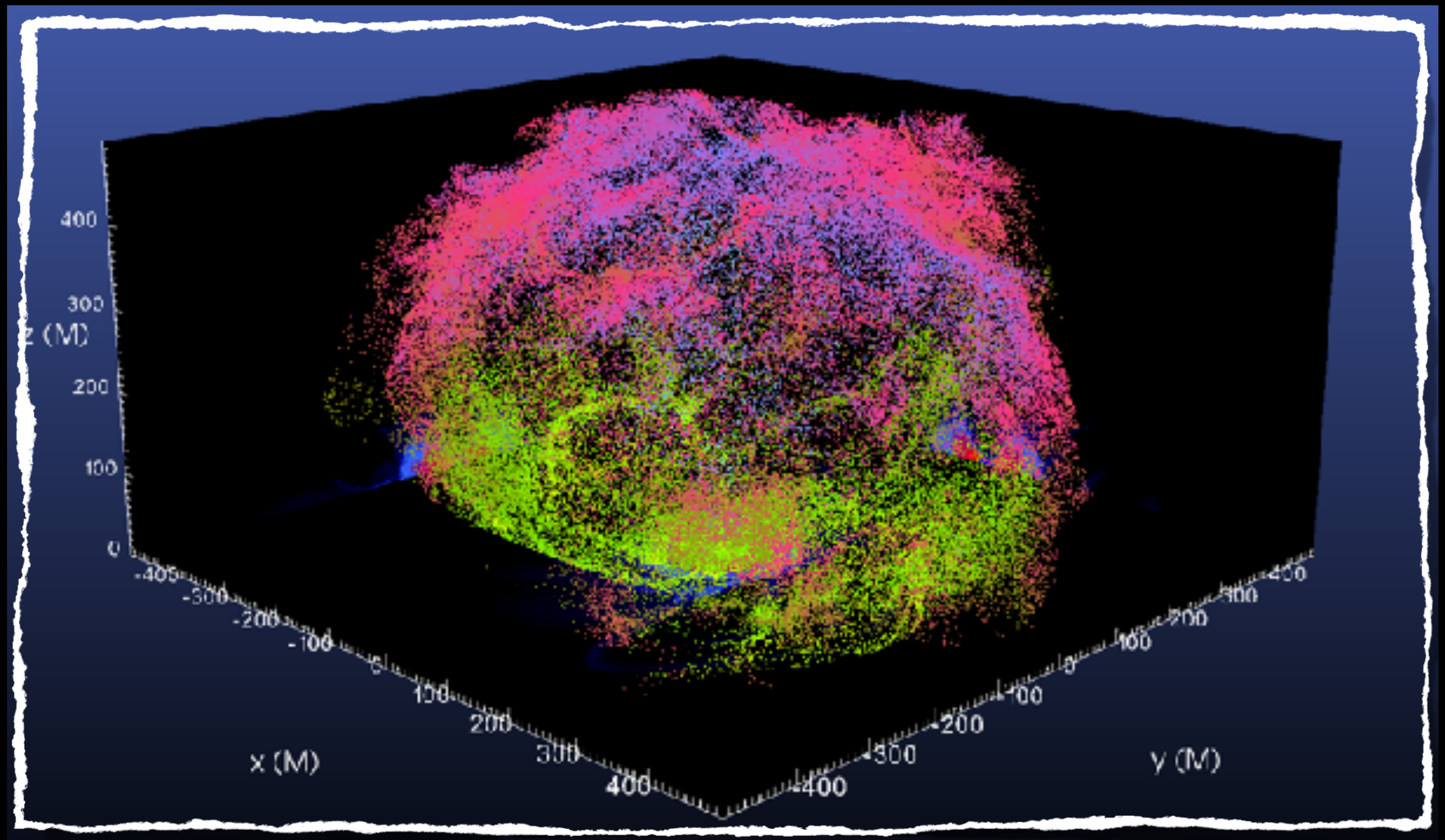
The magnetic jet structure maintains its coherence up to the largest scale of the system.



RMHD

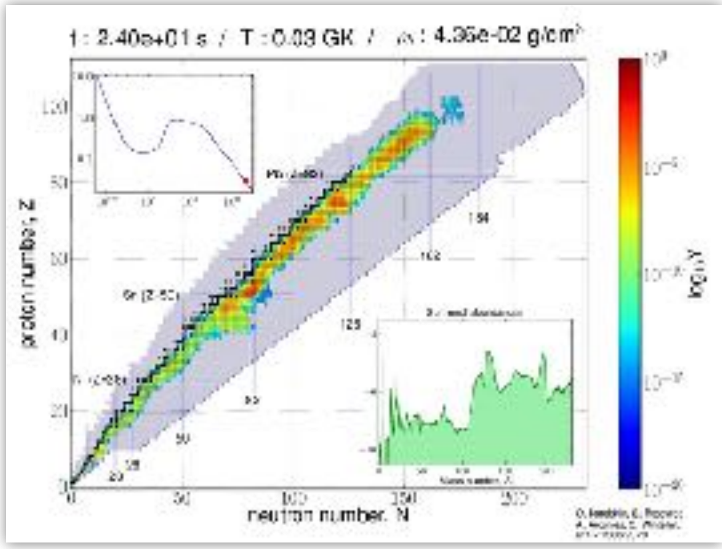
Ejected matter and nucleosynthesis

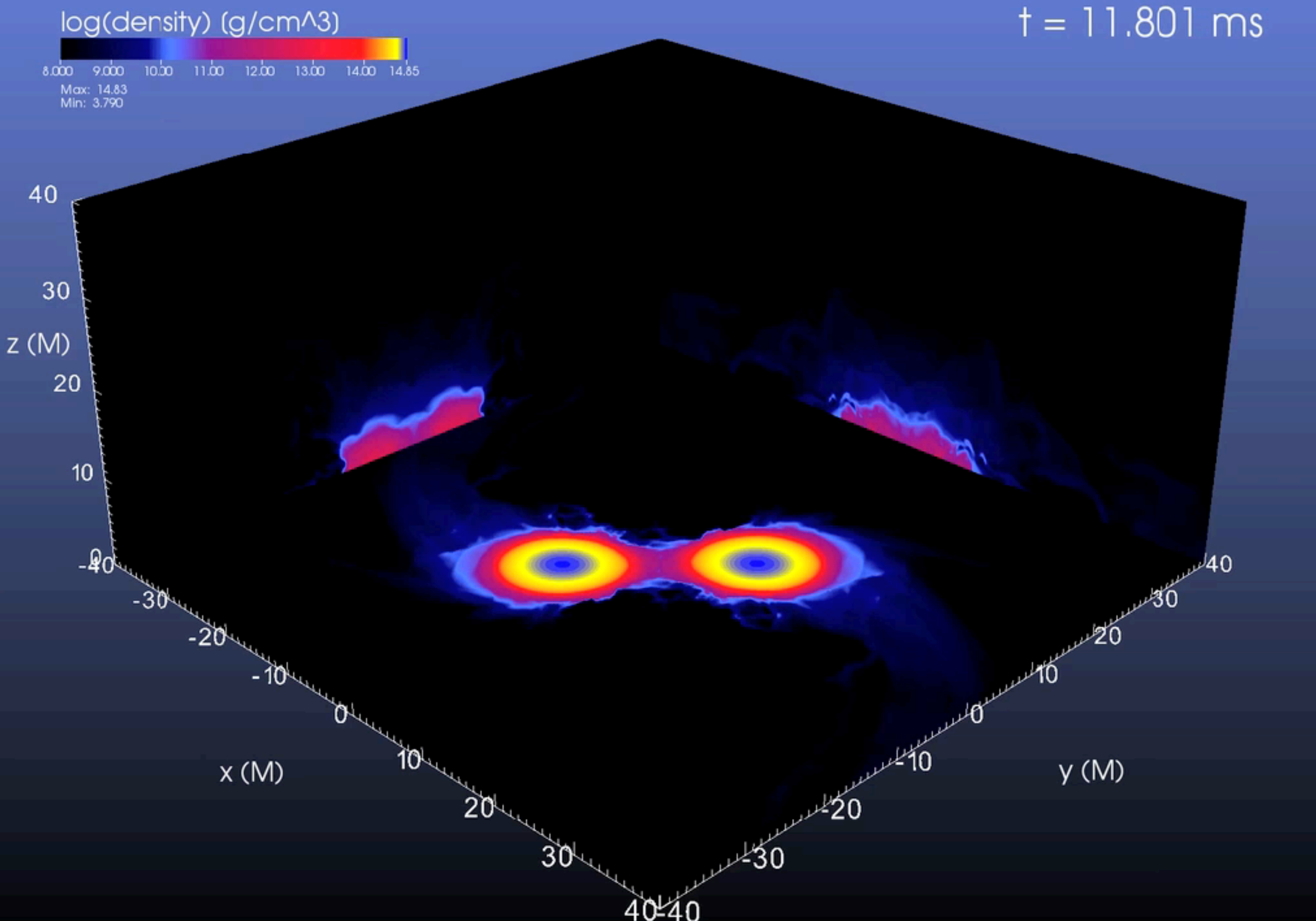
Bovard+ (2017)



Nucleosynthesis

- Already in the 50's, nuclear physicists had tracked the production of elements in stars via nuclear fusion.
- **Heavy elements** $(A \gtrsim 56)$ 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** $(A \gtrsim 120)$.
- To produce such elements very high temperatures and "**neutron-rich**" material is needed.
- **Neutron-star mergers** seem perfect candidates for this process!

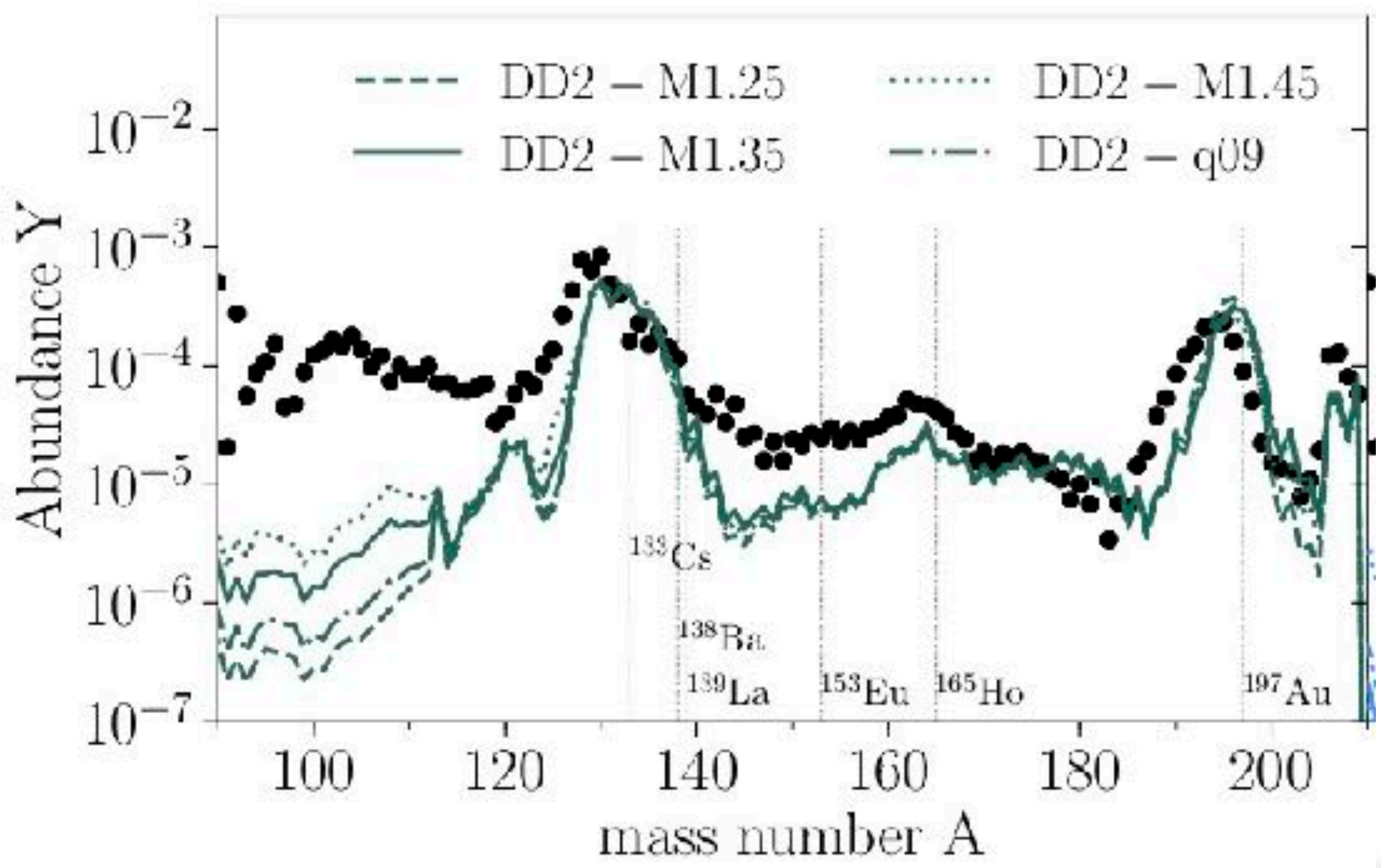



log(density) (g/cm^3)
8.000 9.000 10.00 11.00 12.00 13.00 14.00 14.85
Max: 14.83
Min: 3.790
t = 11.801 ms
z (M)
40
30
20
10
0
x (M)
-40 -30 -20 -10 0 10 20 30 40
y (M)
-40 -30 -20 -10 0 10 20 30 40

L. Bovard, LR

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, masses, nuclear reactions and merger type**



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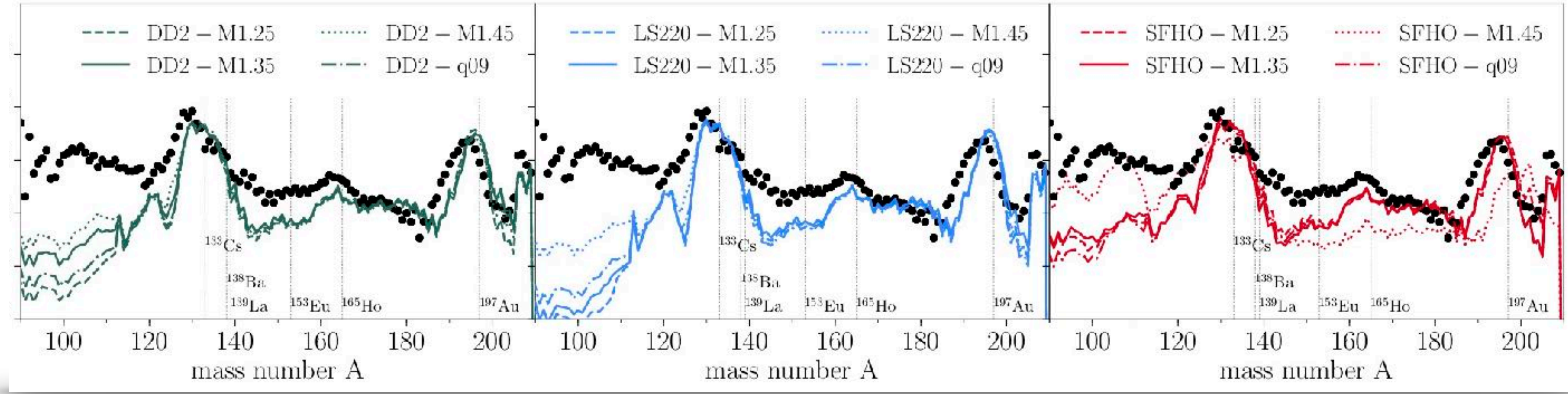

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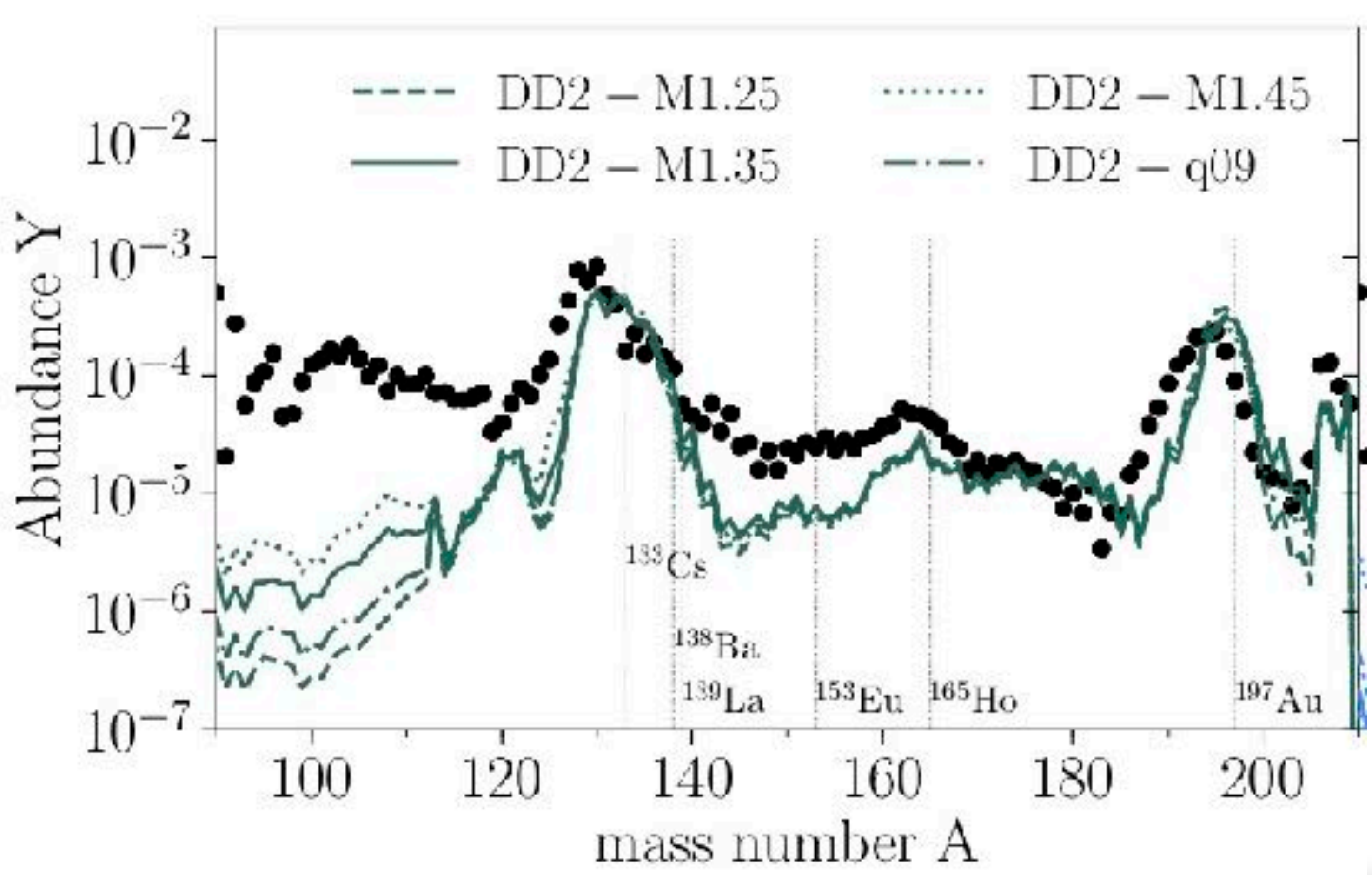
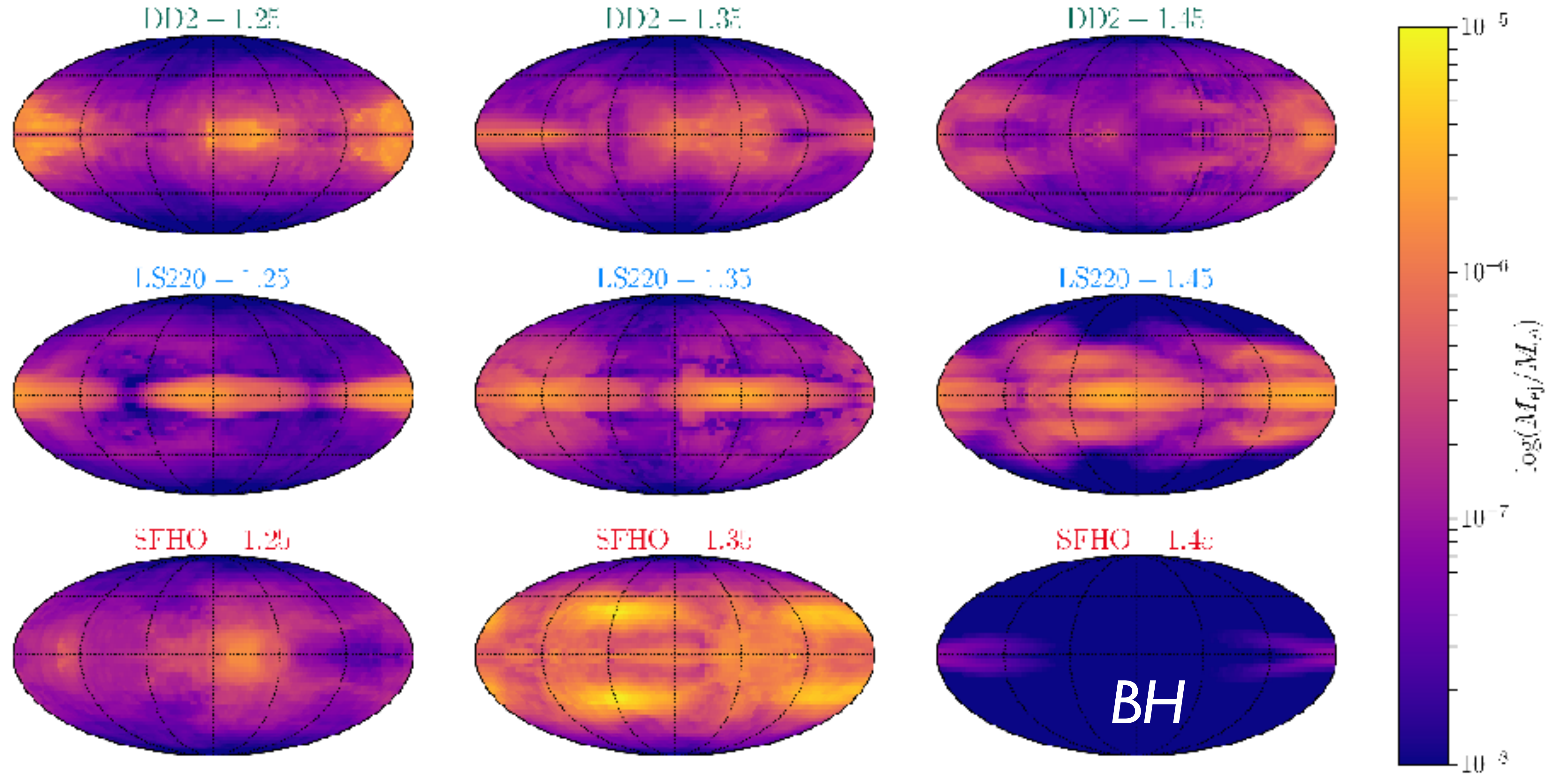


- GW170817 produced total of **16,000** times the mass of the Earth in heavy elements (**10** Earth masses in **gold/platinum**)
- We are not only **stellar dust** but also **neutron-star dust!**

Spatial distributions: M_{ej} Bovard+ 17

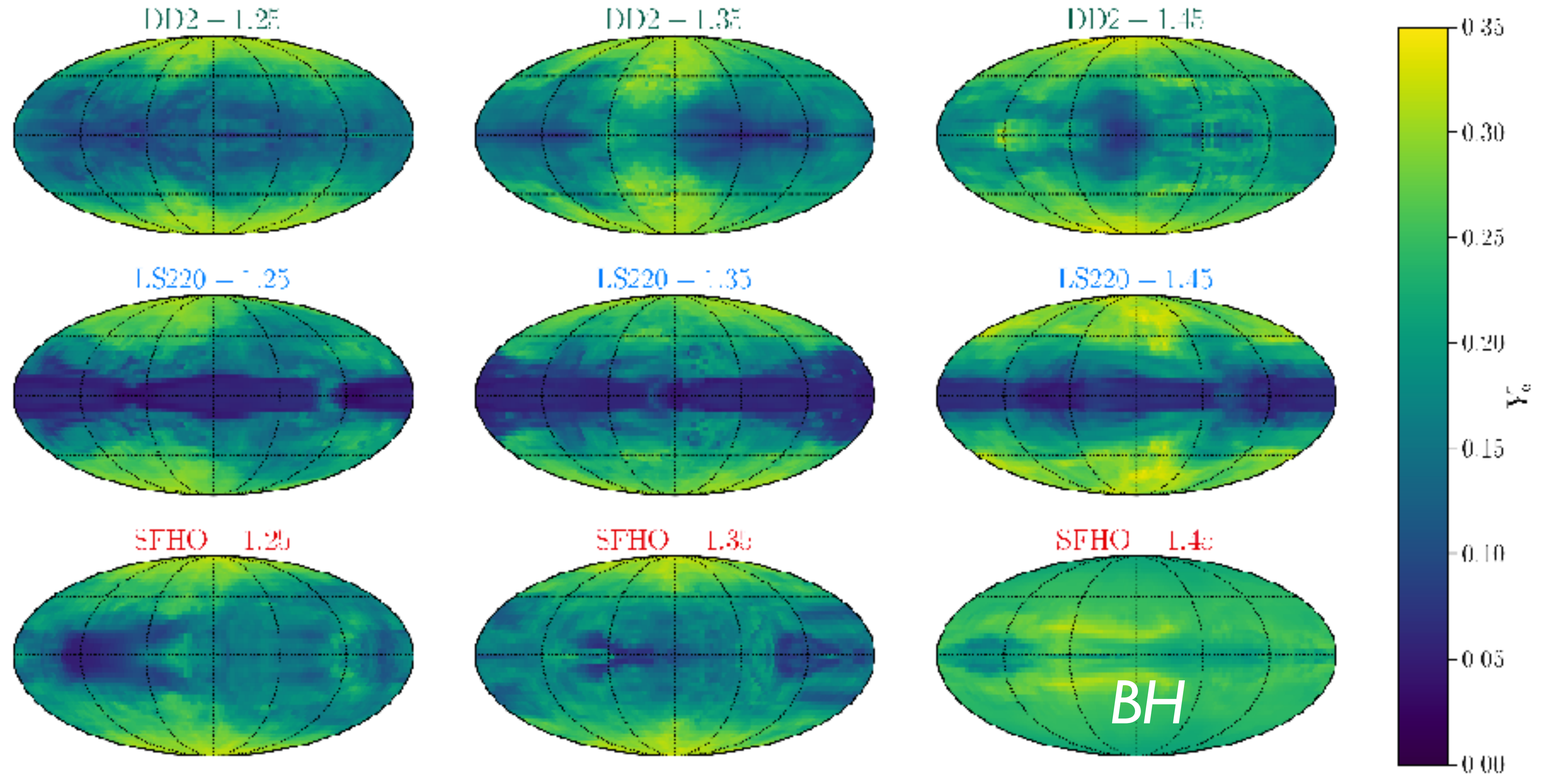


Spatial distribution of M_{ej} impacts detectability of EM counterpart:

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

Spatial distributions: Y_e

Bovard+ 17

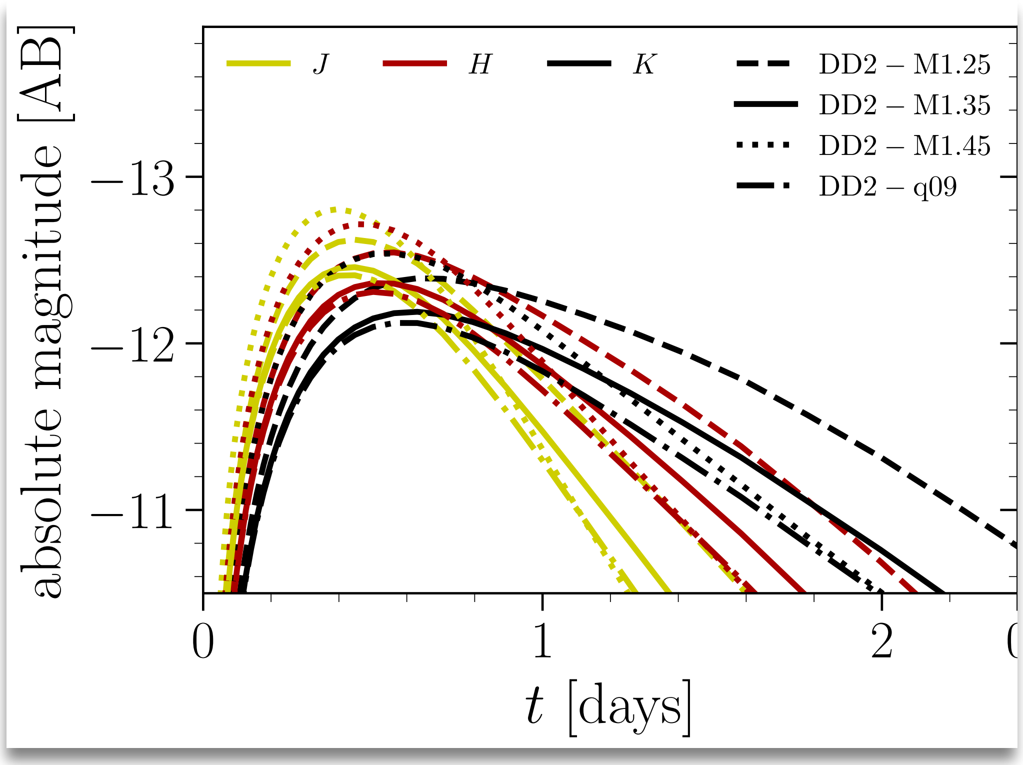


Spatial distribution of Y_e impacts detectability of EM counterpart:

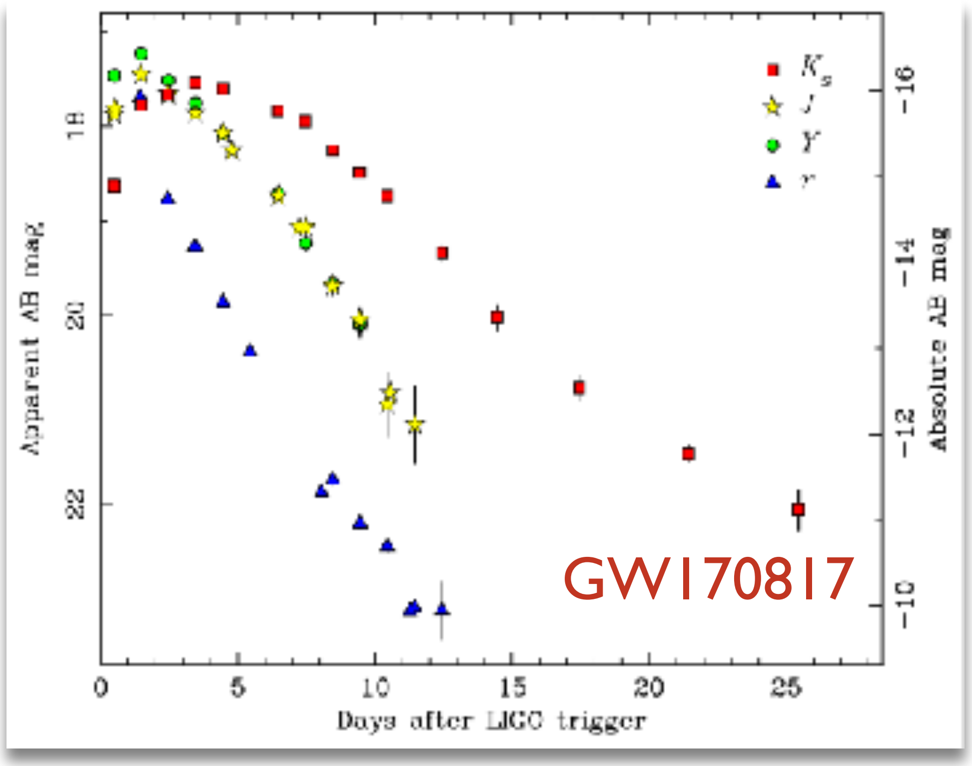
- ★ **high** Y_e in **polar** regions: **blue** (optical) macronova
- ★ **low** Y_e in **equatorial** regions: **red** (FIR) macronova

Kilonova emission

- Ejected matter undergoes **nucleosynthesis** as expands and cools.
- When critical densities and temperatures are reached, matter undergoes radioactive decay emitting light (optical/infrared): kilonova/macronova (Li & Paczynski '98).



simulations



observations (Tanvir+2017)

- Astronomical observations of GW170817 show **kilonova emission**: evidence connection GRBs and binary neutron stars!

Recap

- ☑ **Mergers** lead naturally to EM counterparts (GRB, kilonova).
- ☑ Magnetic fields unlikely to be detected during the inspiral but **important** after the merger: instabilities and EM counterparts.
- ☑ **Electromagnetic counterparts** and a **jet** are **likely** to be produced but the details of this picture are still **far from clear**.
- ☑ **Mergers** lead to tiny but important ejected matter and macronova emission.
- ☑ "high-*A*" nucleosynthesis very robust (little dependence on EOS and mass ratio) and good agreement with solar abundances.
- ☑ First constraints on lifetime of **GW170817** remnant

$$t_{\rm coll} = 0.98^{+0.31}_{-0.26}\ {\rm s}$$