Title: Long-term impact of the magnetic-field strength on the evolution and electromagnetic emission by neutron-star merger remnants

Speakers: Michail Chabanov

Collection/Series: Magnetic Fields Around Compact Objects Workshop

Subject: Strong Gravity

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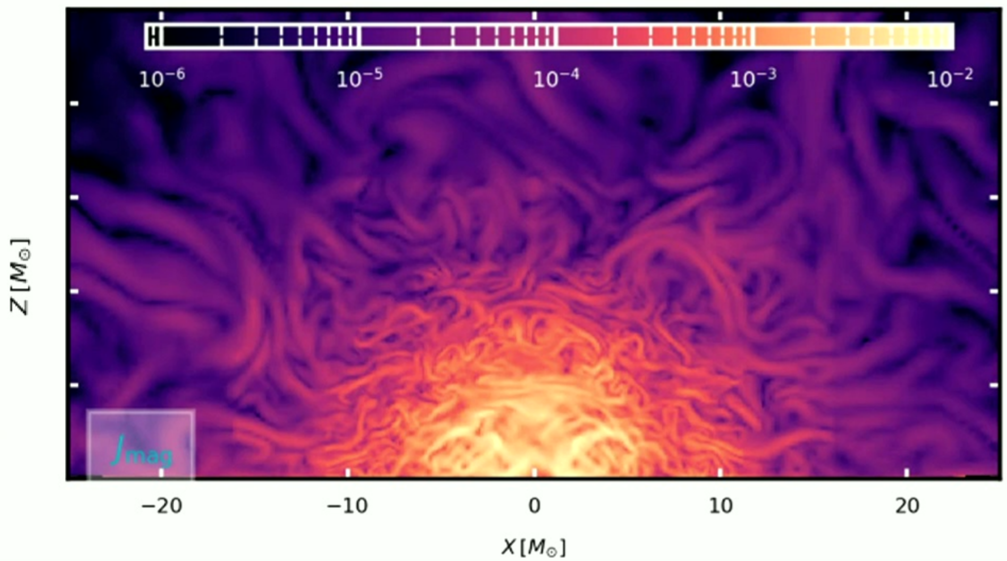
Abstract:

Numerical simulations are essential to understand the complex physics accompanying the merger of binary systems of neutron stars. However, these simulations become computationally challenging when they have to model the merger remnants on timescales over which secular phenomena, such as the launching of magnetically driven outflows, develop. To tackle these challenges, we have recently developed a hybrid approach that combines, via a hand-off transition, a fully general-relativistic code (FIL) with a more efficient code making use of the conformally flat approximation (BHAC+). We here report important additional developments of BHAC+ consisting of the inclusion of gravitational-wave radiation-reaction contributions and of higher-order formulations of the equations of general-relativistic magnetohydrodynamics. Both improvements have allowed us to explore scenarios that would have been computationally prohibitive otherwise. More specifically, we have investigated the impact of the magnetic-field strength on the long-term (i.e., ~ 200 ms) and high-resolution (i.e., 150 m) evolutions of the “magnetar” resulting from the merger of two neutron stars with a realistic equation of state. In this way, and for sufficiently large magnetic fields, we observe the loss of differential rotation and the generation of magnetic flares in the outer layers of the remnant. These flares, driven mostly by the Parker instability, are responsible for intense and collimated Poynting flux outbursts and low-latitude emissions. This novel phenomenology offers the possibility of seeking corresponding signatures from the observations of short gamma-ray bursts and hence revealing the existence of a long-lived strongly magnetized remnant.

Long-term impact of magnetic-field strength on the evolution of BNS merger remnants

arxiv: 2502.14962
Jin-Liang Jiang, Harry Ho-Yin Ng,
Michail Chabanov, Luciano Rezzolla

RIT
Rochester Institute of Technology



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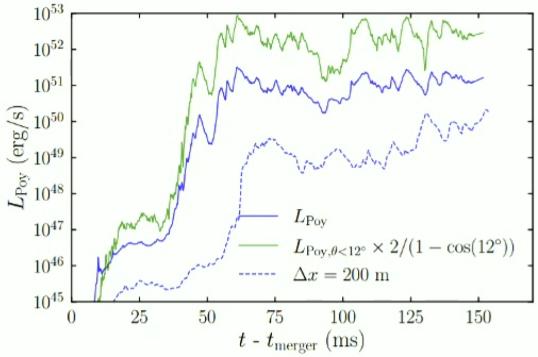
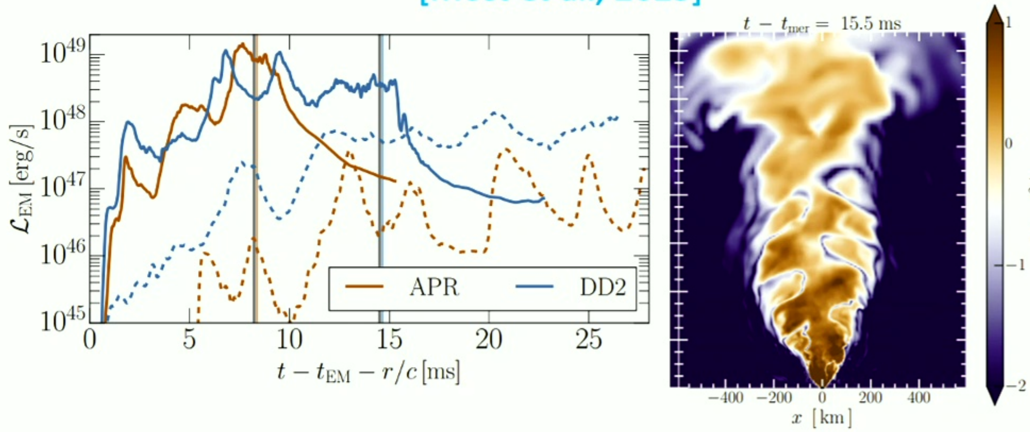
Magnetic polar outflows of BNS remnants

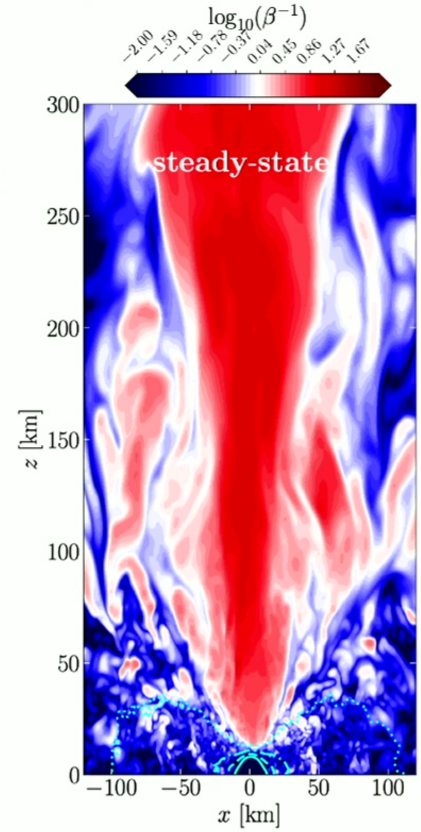
[Kiuchi et al., 2023]

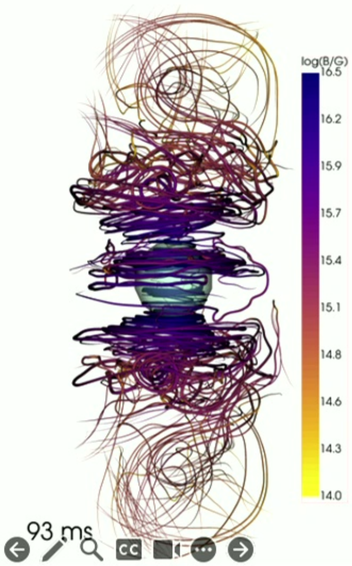


[Most et al., 2023]



[Musolino at al., 2024]





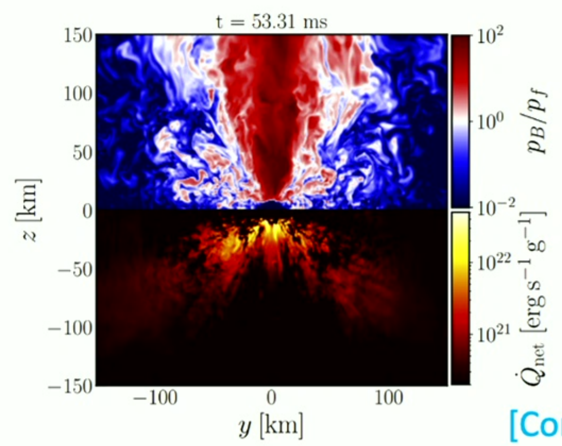
[Ruiz et al., 2016]

[Moesta et al., 2020]

[Curtis et al., 2023]

[Bamber et al., 2024]

[Ciolfi et al., 2020]



[Combi et al., 2023]

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Long-term and high-resolution simulations

Kelvin-Helmholtz Instability (KHI) $\quad \mathrm{Im}\,[\omega_+] = k\Delta V \frac{(\rho_+\rho_-)^{1/2}}{\rho_+ + \rho_-}$

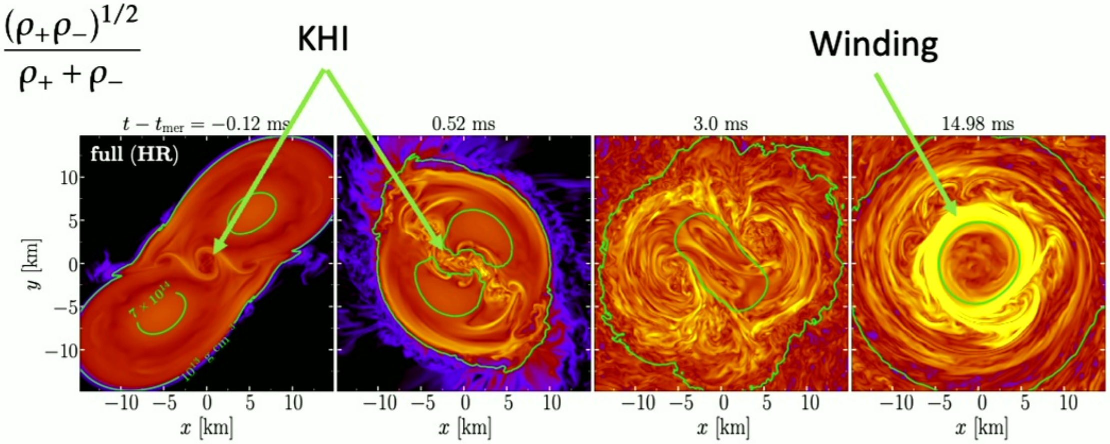
- Depends on NS models, e.g. EOS, mass, …
- Resolution might require $\approx$ 7 m grid spacing
- Saturation at $B \approx 10^{16} - 10^{17}\ G$

Magnetic winding and braking

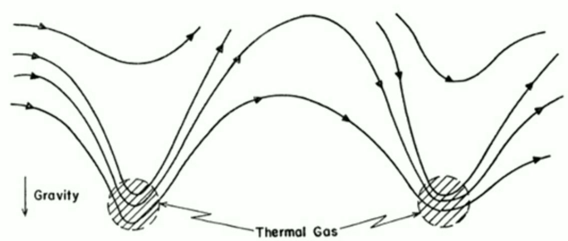
- Shearing poloidal and generation of toroidal field
- Eventually braking of differential rotation
- $t_{brake} \approx \mathcal{O}(0.1 - 1s)$

Parker instability

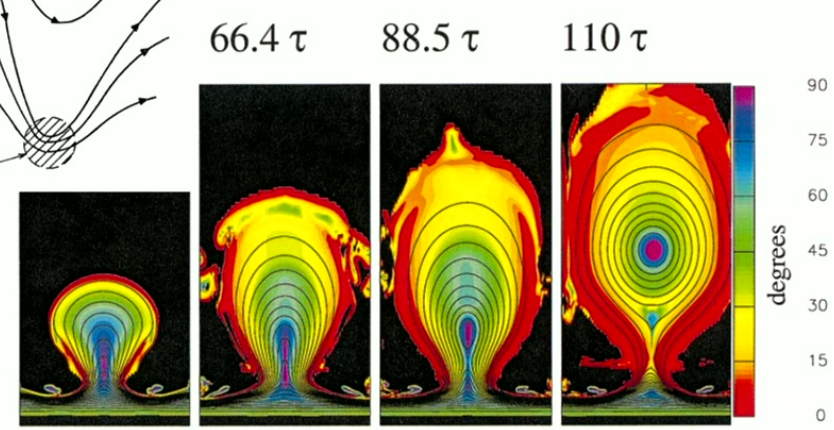
- Formation of discrete molecular clouds in galactic disks
- Buoyant magnetic fields lift up
- Mass accumulates in pockets suspended in the field



[MC et al., 2023]



[Parker, 1966]



[Manchester, 2001]

Methods: Hybrid approach with handoff

FIL (Frankfurt/IllinoisGRMHD)

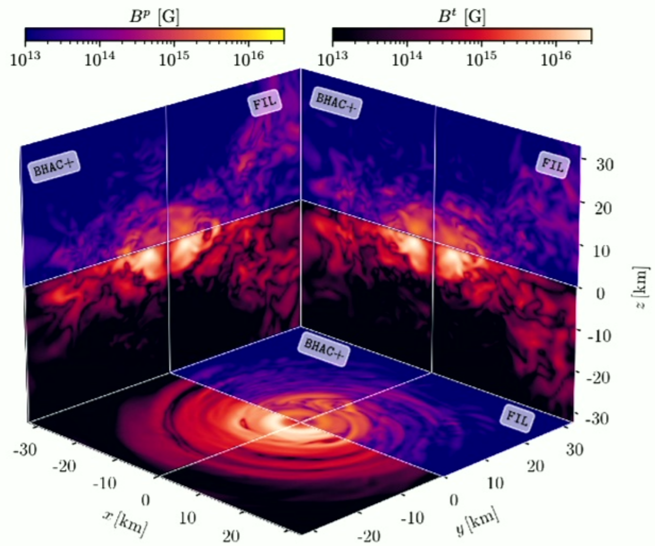
- **Inspiral and early postmerger**
- 4th-order GRMHD
- A-based UCT
- Fully dynamical spacetime: Z4c

Handoff

BHAC+ (Black Hole Accretion Code)

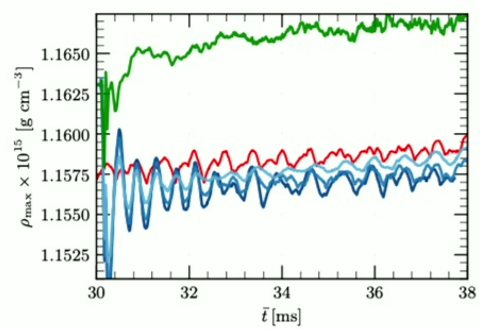
- **Late postmerger**
- 4th-order GRMHD
- B-based UCT
- **xCFC with RR**
  - Metric update every 20-40 fluid steps
  - Employ fluid-based speed in CFL condition

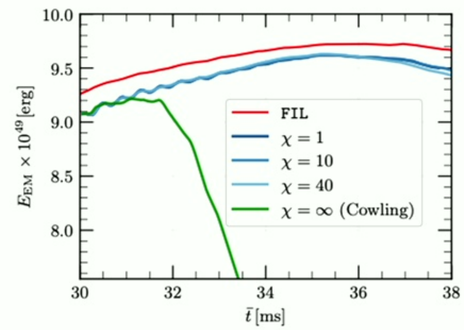
20 ms after handoff



Tests	$\Delta t_{\rm met}$ $[M_\odot]$	Cost for 1 ms [CPU hr ms^{-1}]
$\chi = 1$ (FIL)	1.3×10^{-2}	3117
$\chi = 1$ (BHAC+)	5.0×10^{-2}	1595
$\chi = 2$ (BHAC+)	1.0×10^{-1}	1222
$\chi = 10$ (BHAC+)	5.0×10^{-1}	1025
$\chi = 40$ (BHAC+)	2.0	944
$\chi = \infty$ (BHAC+/FIL)	∞	937/982

Factors 3 - 4 speed-up!





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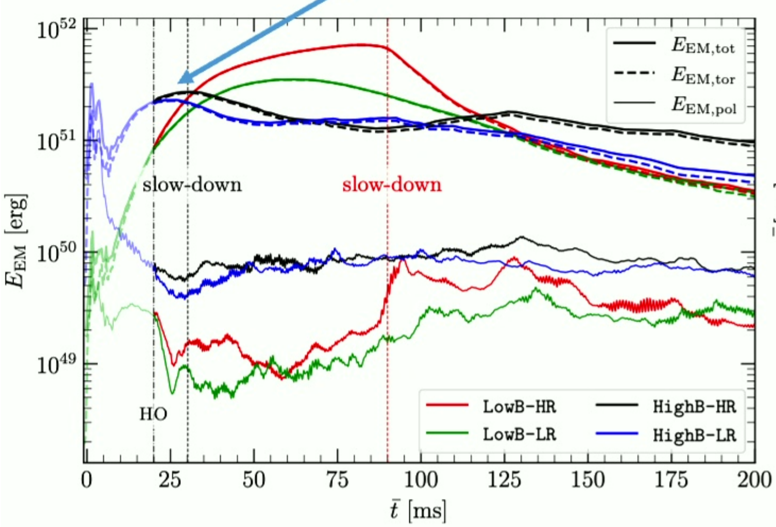
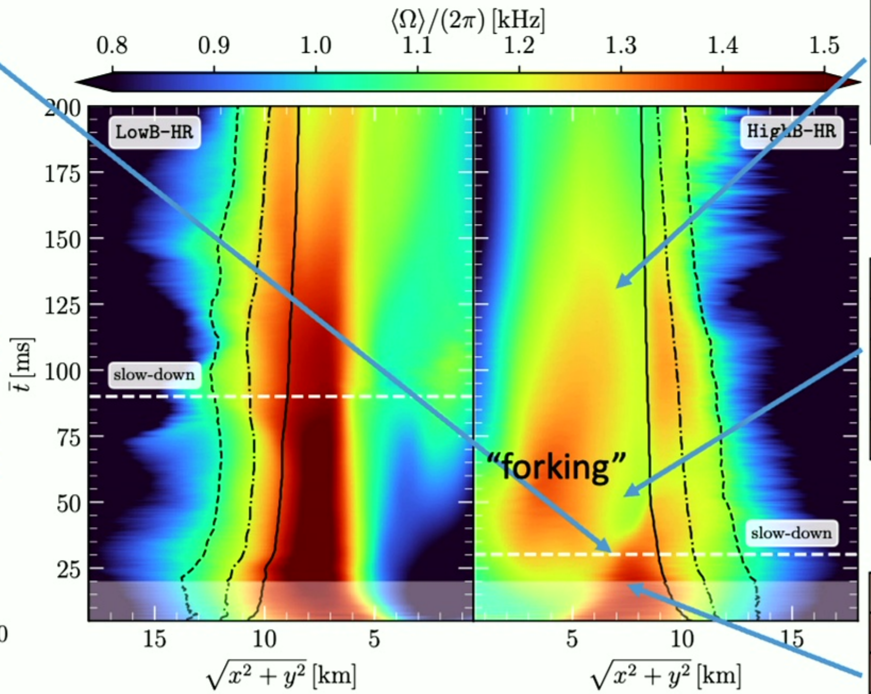
Magnetic winding and braking

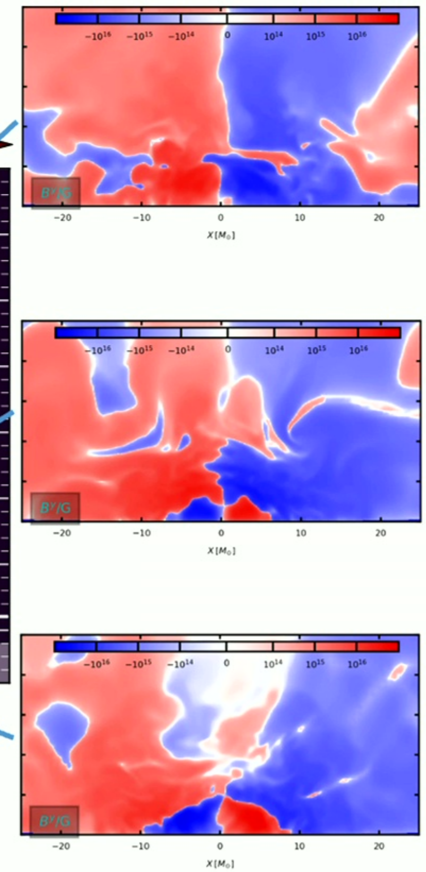
Toroidal field reversed after braking

B_T

Magnetic winding "slows down" → Magnetic braking begins







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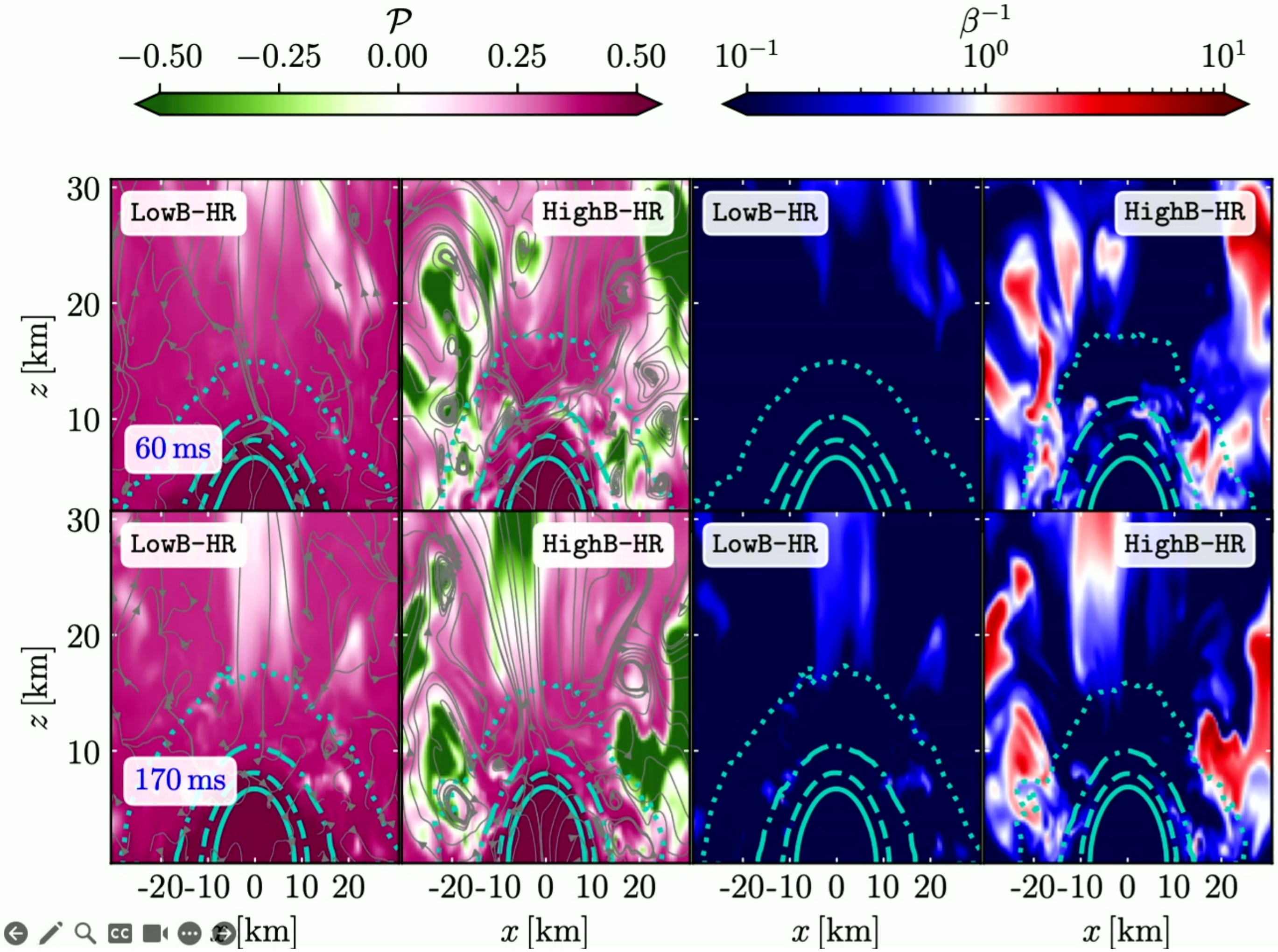
Parker instability and flares

$$\mathcal{P} := \frac{d\log p}{d\log \rho} - 1 - \frac{\beta^{-1}\left(1+2\beta^{-1}\right)}{2+3\beta^{-1}}$$



- Parker instability leads rising magnetic field loops
- Twisting loops breakout and erupt at the surface
- High magnetic fields lead to eruptions from much higher densities

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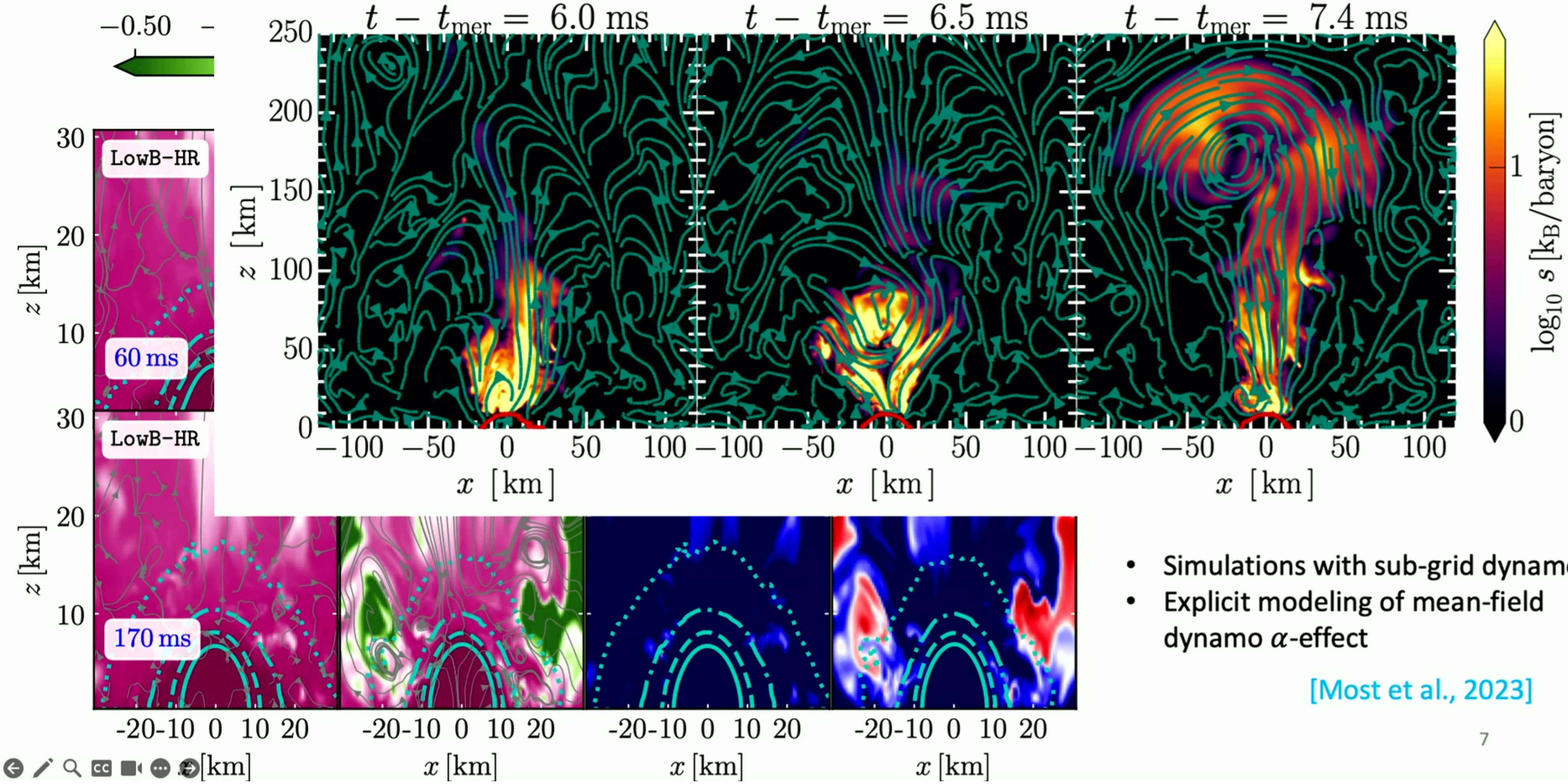
Parker instability and flares

$$\mathcal{P} := \frac{d\log p}{d\log \rho} - 1 - \frac{\beta^{-1}\left(1+2\beta^{-1}\right)}{2+3\beta^{-1}}$$



- Simulations with sub-grid dynamo
- Explicit modeling of mean-field dynamo α-effect

[Most et al., 2023]

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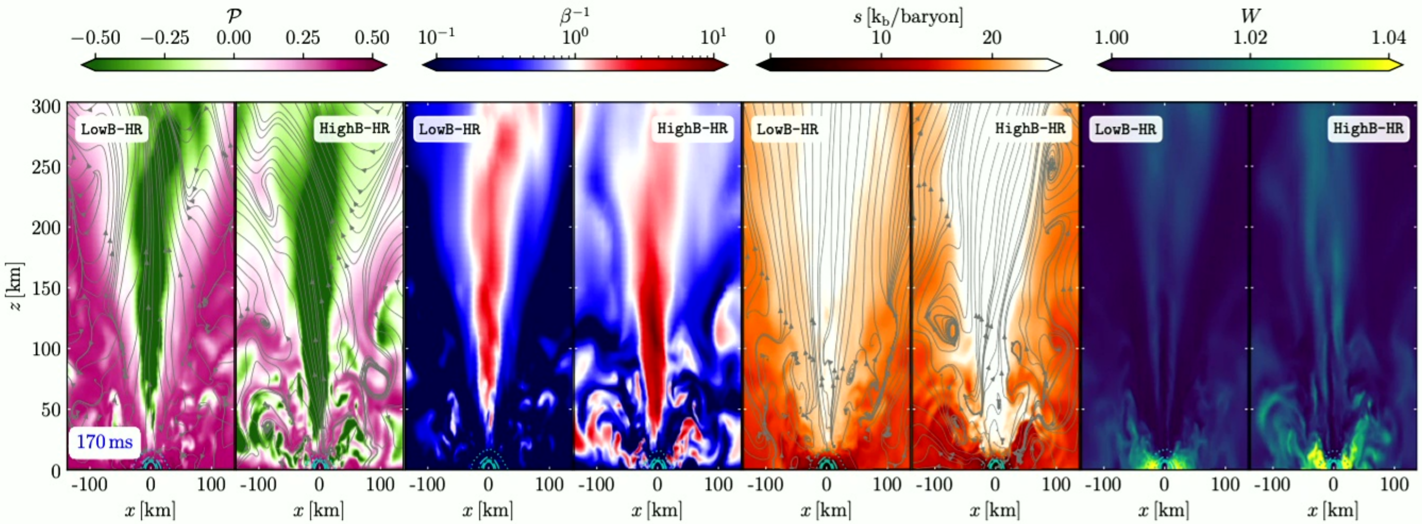
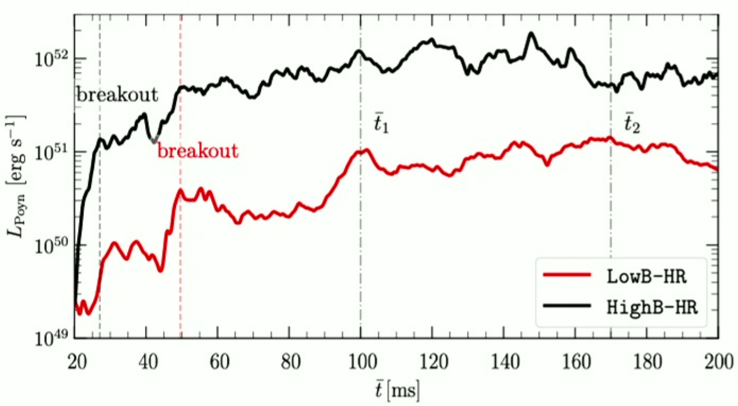
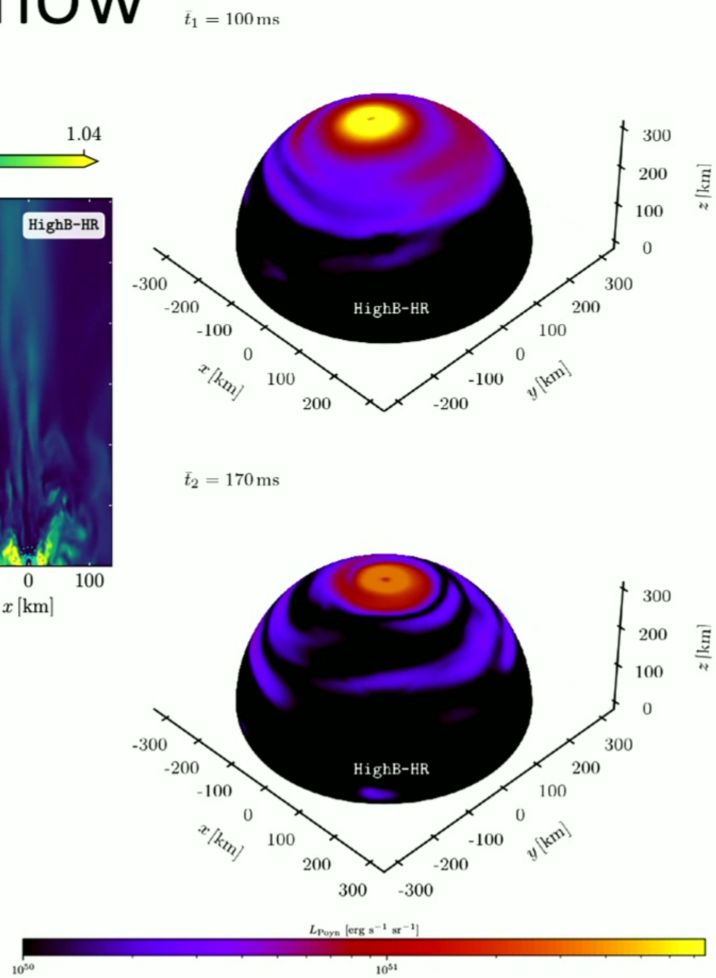
Large-scale magnetic field and outflow







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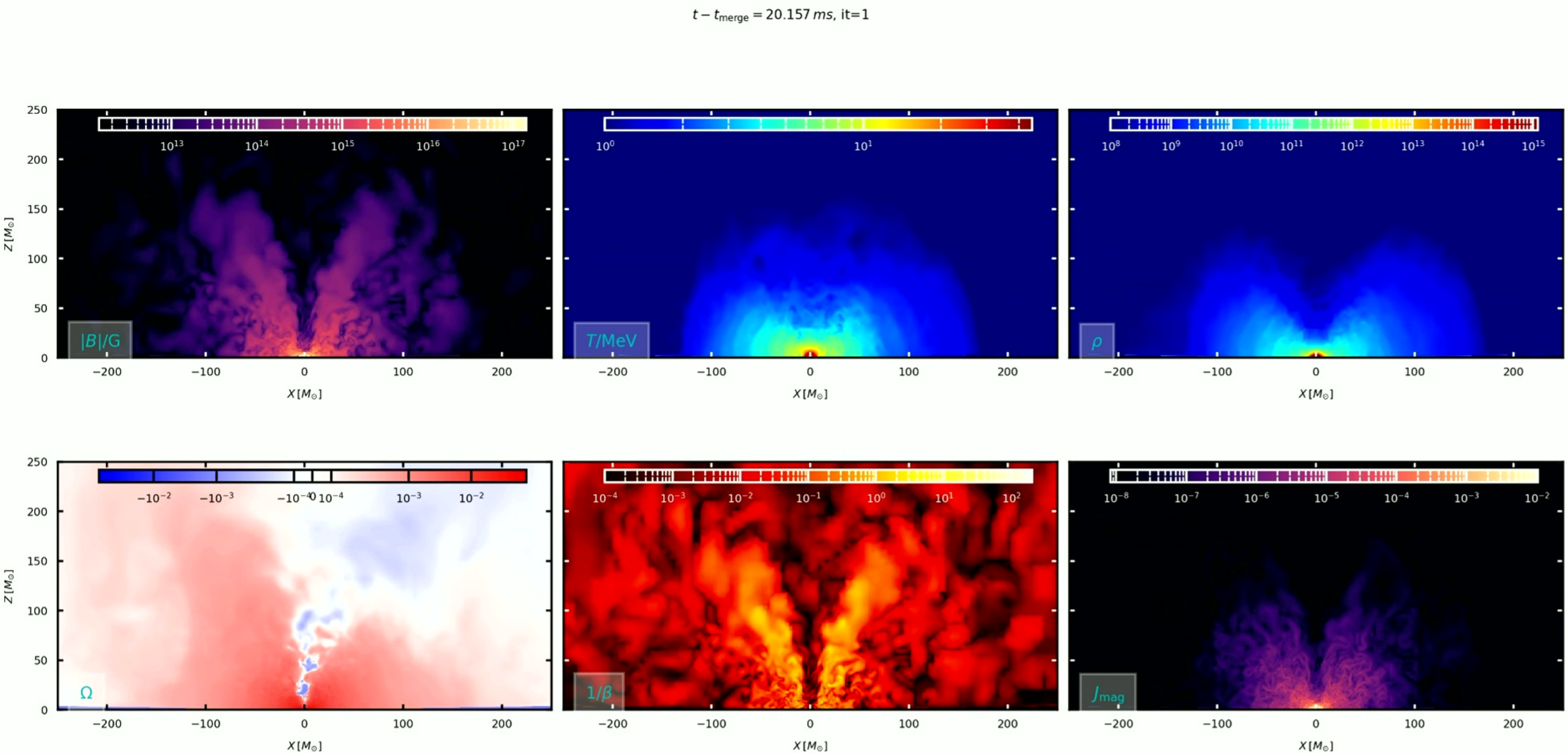
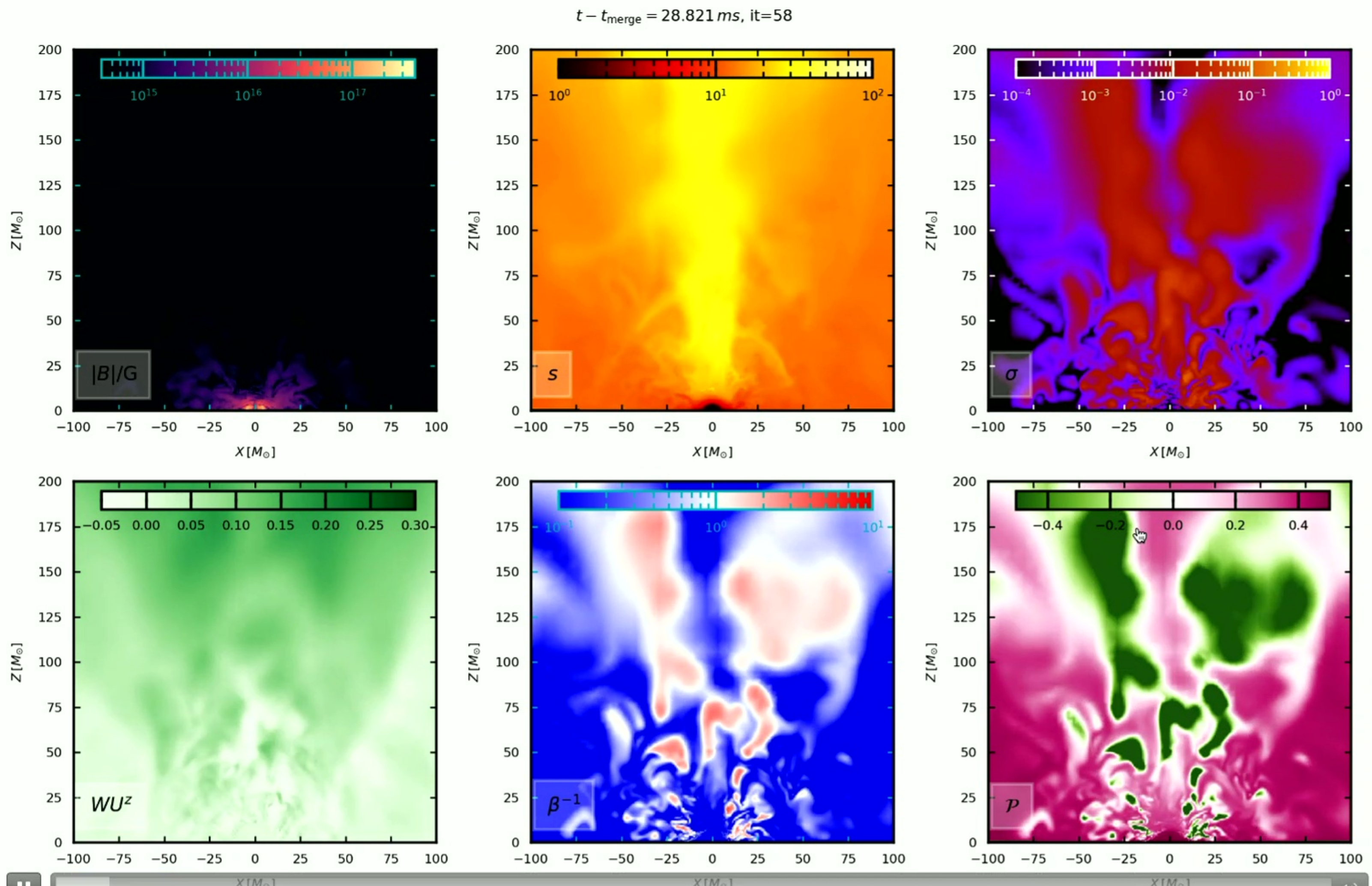


$t - t_{merge} = 20.157\ ms$, it=1
|B|/G
T/MeV
ρ
Ω
1/β
J_{mag}
X [M⊙]
Z [M⊙]


$t - t_{\rm merge} = 28.821\,ms$, it=58
$|B|/G$
s
σ
WU^z
β^{-1}
$\mathcal{P}$
$Z\,[M_\odot]$
$X\,[M_\odot]$

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Conclusion and summary

- Hybrid approach using the handoff method with a xCFC metric solver leads to factors 3-4 of speedup
- Explore the impact of magnetar magnetic-field strengths in long-term postmerger simulations
- Development of large-scale magnetic fields and collimated Poynting flux in both cases
- Earlier breakout, stronger flaring and larger luminosity for large fields but present in both cases
- Large fields lead to breakout and flaring in high-density regions