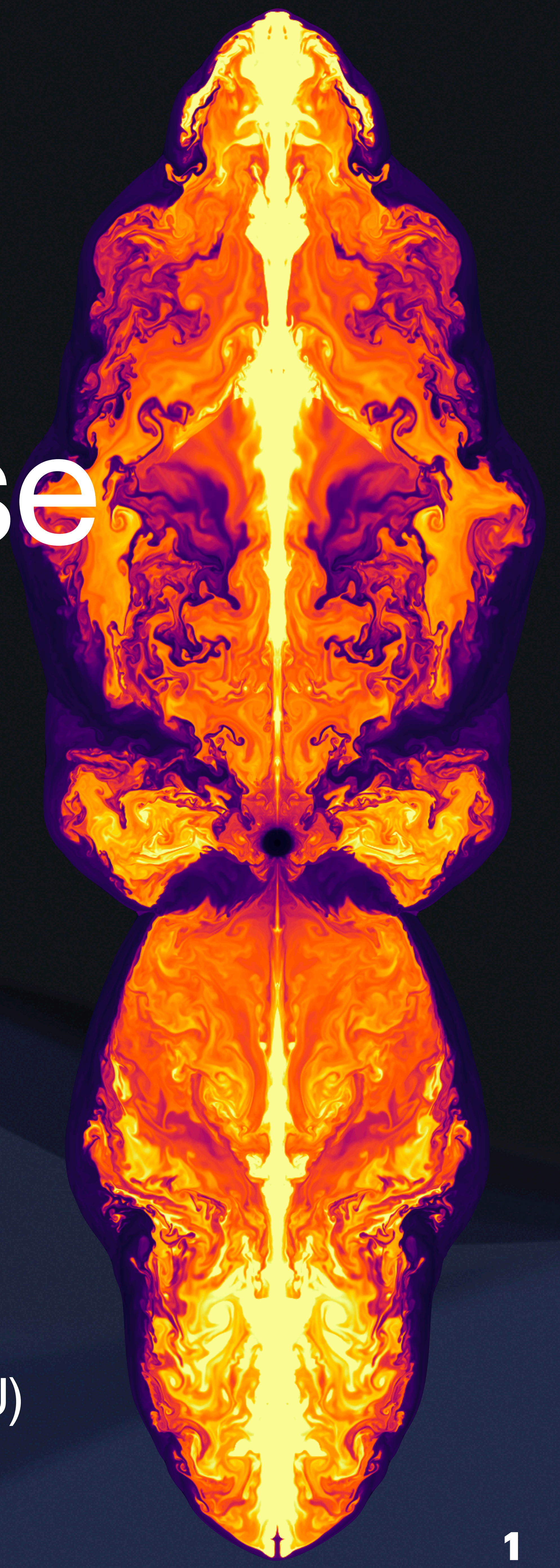
Gravitational Wave Emissions from Magnetized Core-Collapse Supernovae

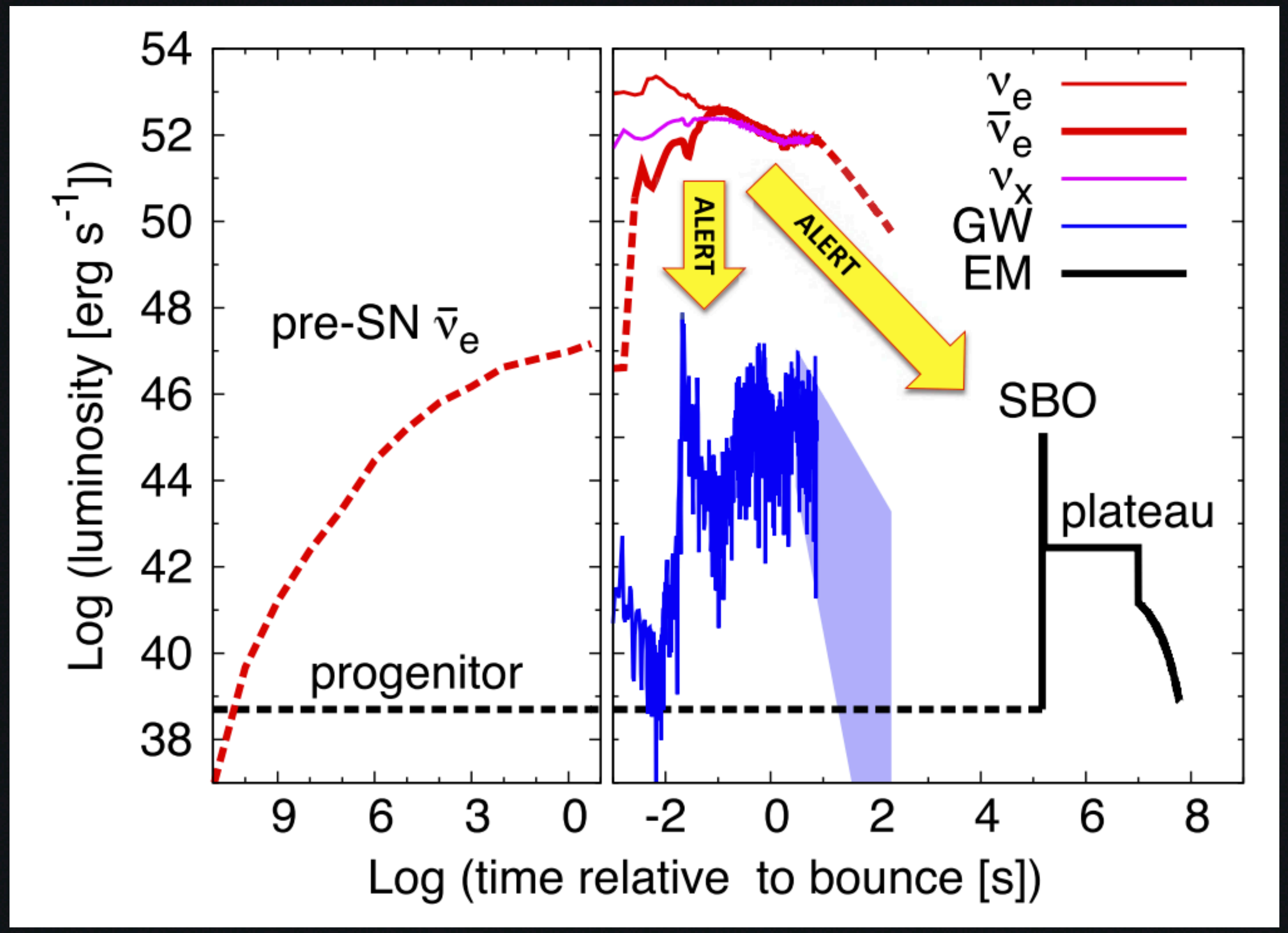


Kuo-Chuan Pan (潘國全)
Department of Physics & Institute of Astronomy
National Tsing Hua University, Hsinchu, Taiwan

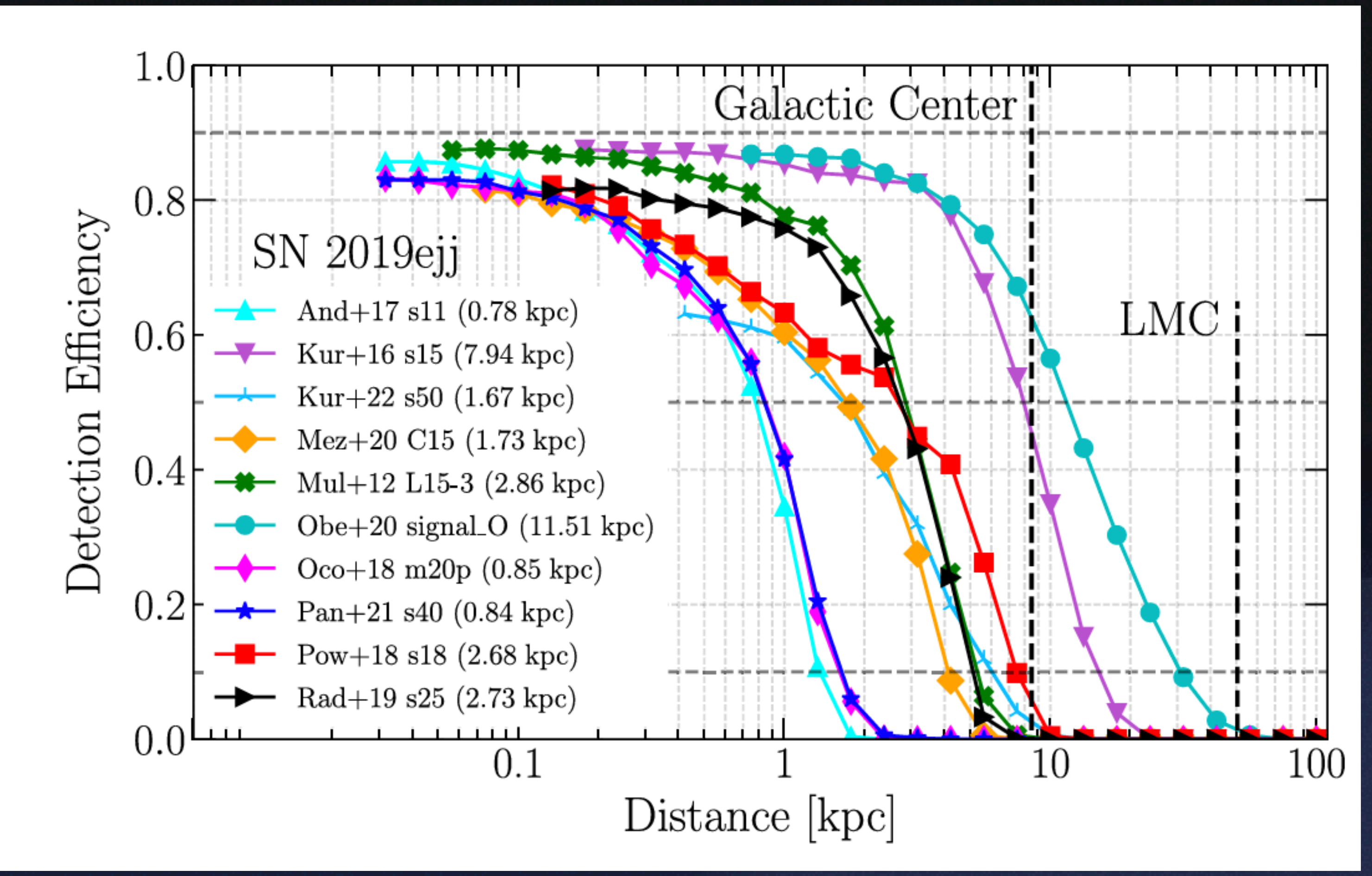
Collaborators:
Yi-Fang Li (NTHU), Inhyeok Song (NTHU), He-Feng Hsieh (NTHU/NTU), Hsi-Yu Schive (NTU)

Introduction & Motivations

- Detection of GWs from a CCSN will be the next milestone in gravitational wave physics and multi-messenger astrophysics.
- Recent analyses suggest that GWs from normal CCSNe can only be detected during galactic events.
- Extreme CCSNe such fast-rotating or strongly magnetized CCSNe, may have better chances being detected in extragalactic events (but rare).
- These extreme events are associated with long gamma-ray busrts, hypernovae, or magnetars, which are excellent targets for multi-messenger astrophysics.



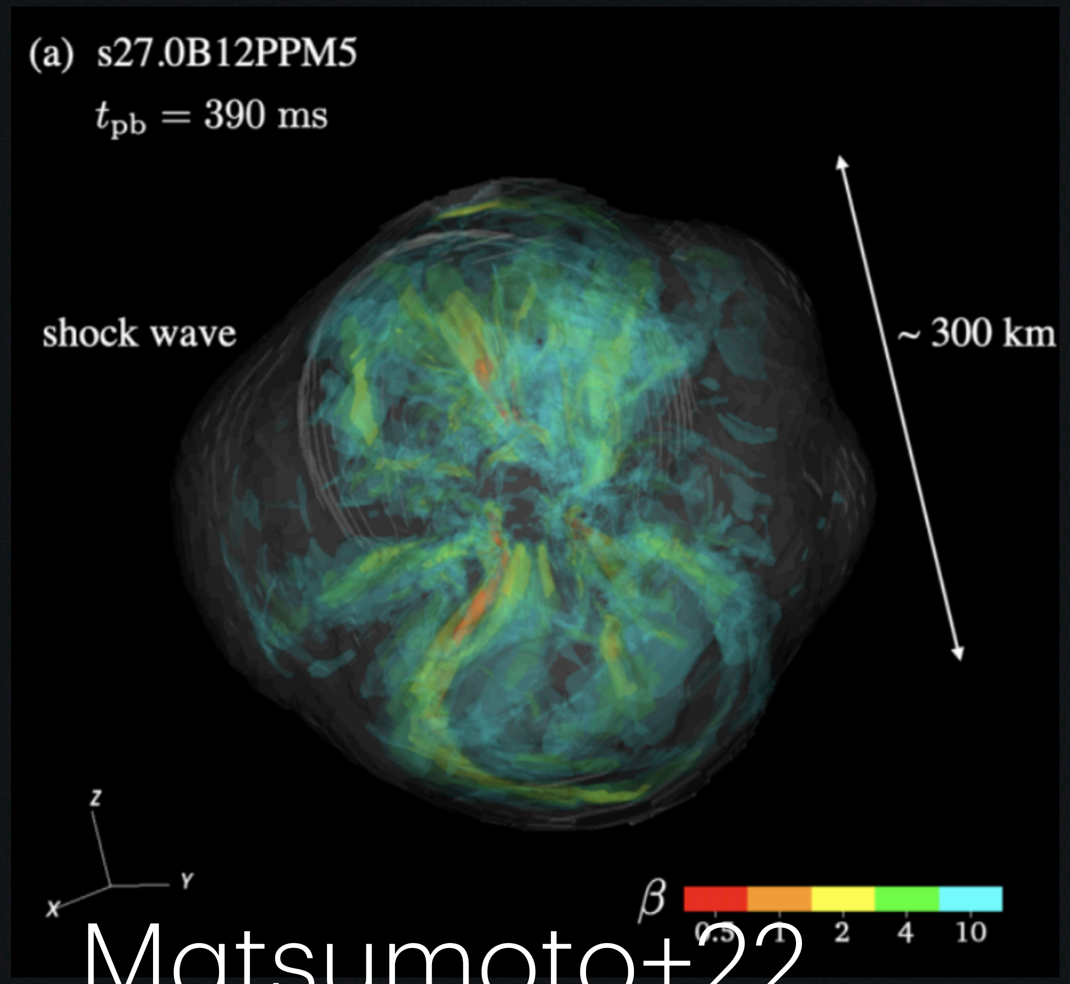
Kharusi et al. (2021)



Szczepańczyk et al. (2024)

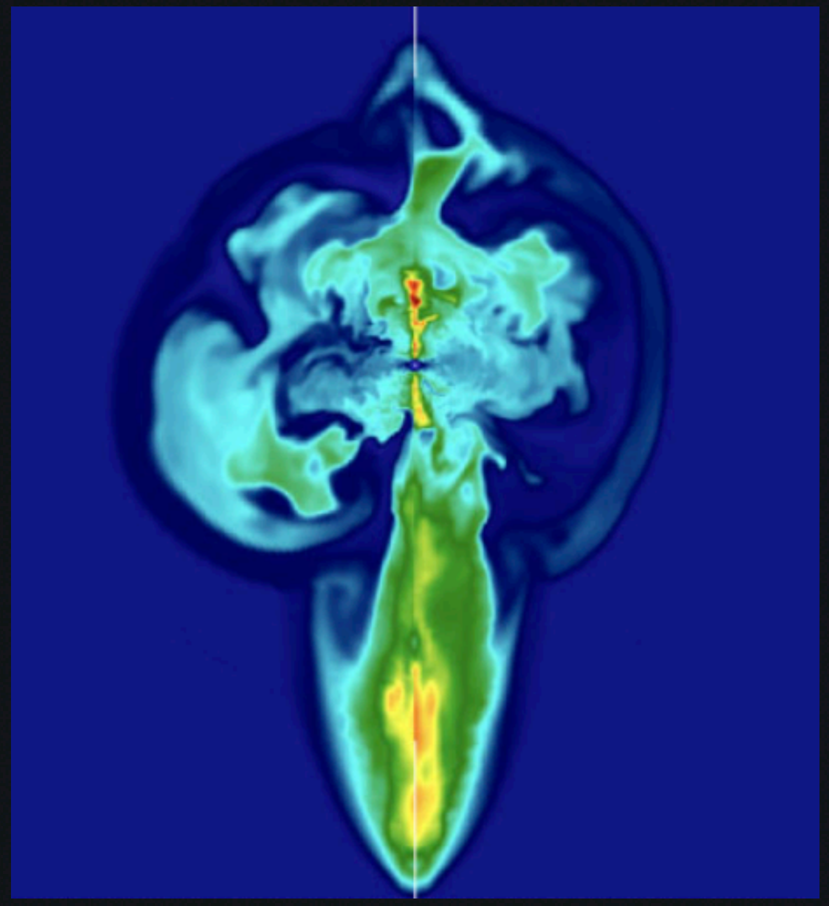
Also see Andy Chen's poster

CCSN Zoo: Diverse explosion morphologies



Matsumoto+22

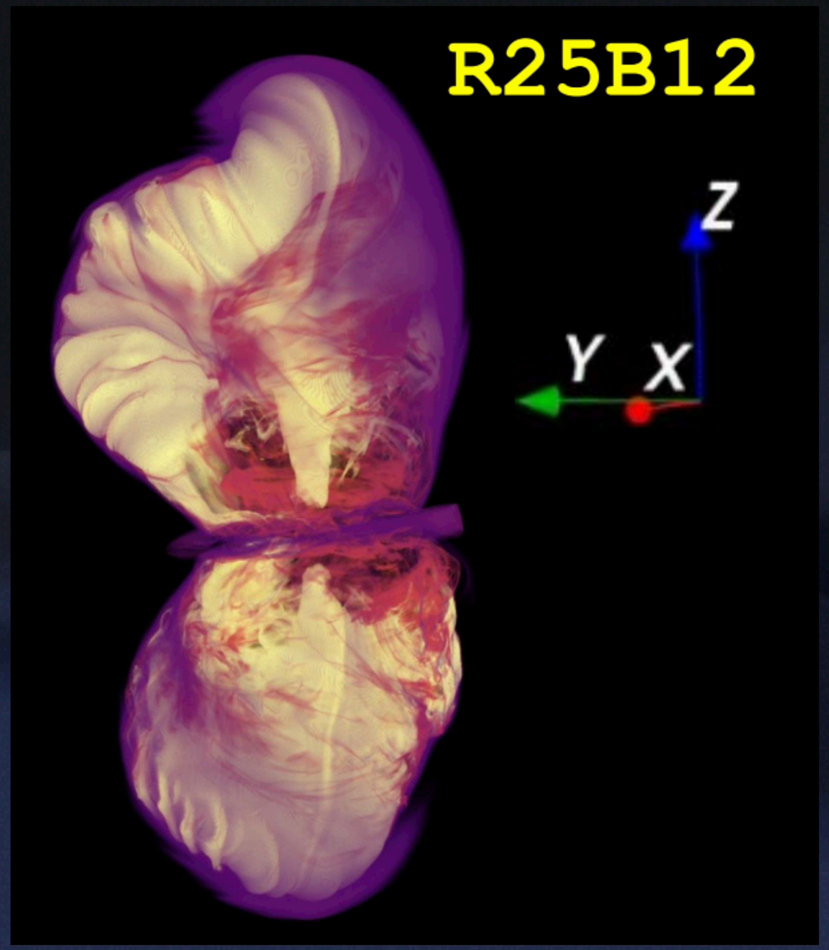
Endeve+10 (w rot.), Muller+20, Matsumoto+22, Nakamura+25, ...



Powell+23

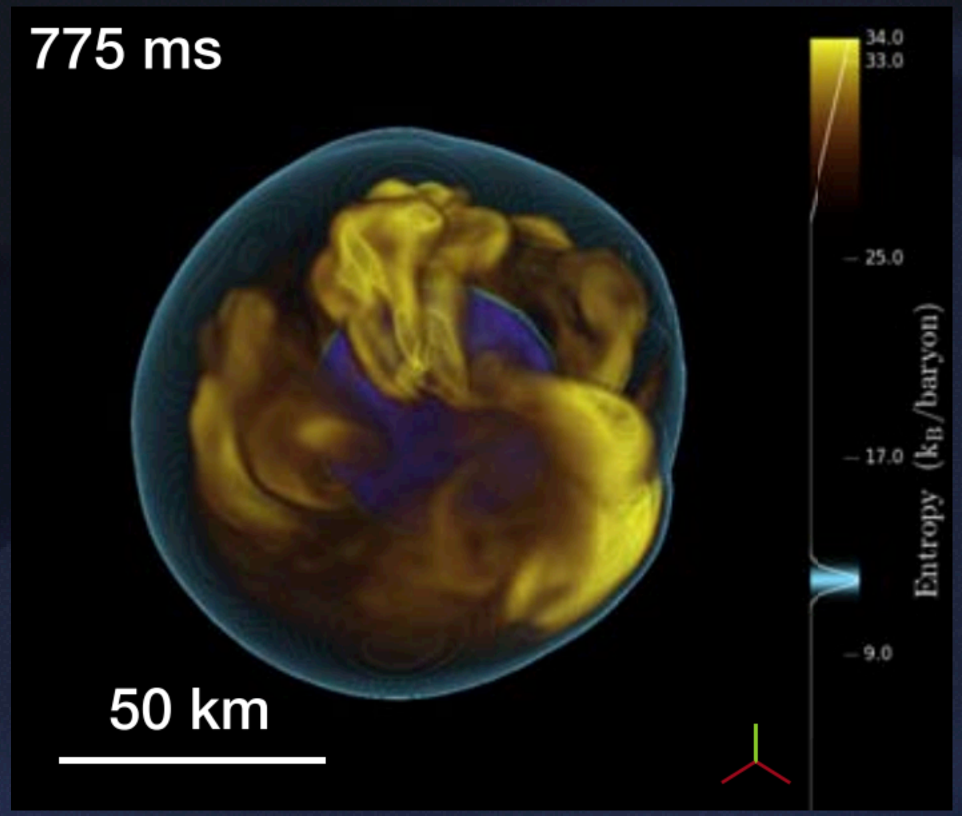
Powell+23, Obergaulinger+17 (2D), Burrows+23 (no-B), Kuroda+20, ...

But these are done with different progenitors, EoS, field strength, rotation, ...



Shankar+25

Mosta+14, Bugli+20, Kuroda+20, Obergaulinger+21, Powell+23, Shibagaki+24, Shankar+25, ...

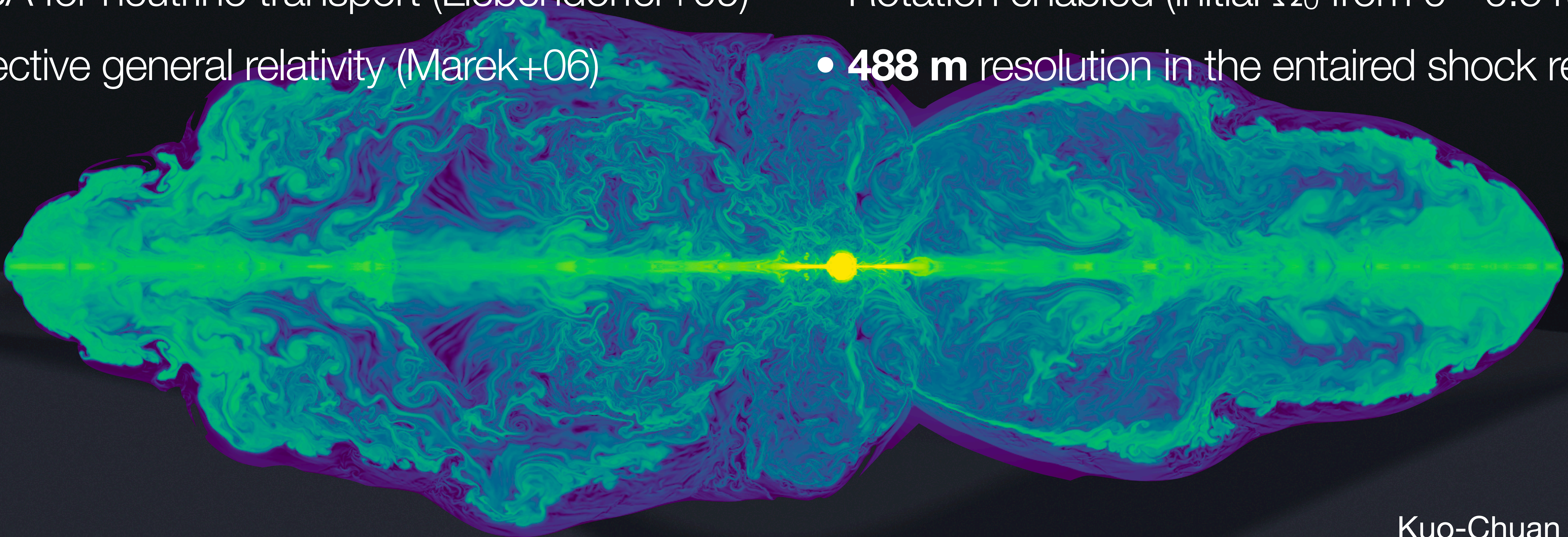


Pan+21

Kuroda+18,24, Pan+21, Powell+25, Halevi+25, ...

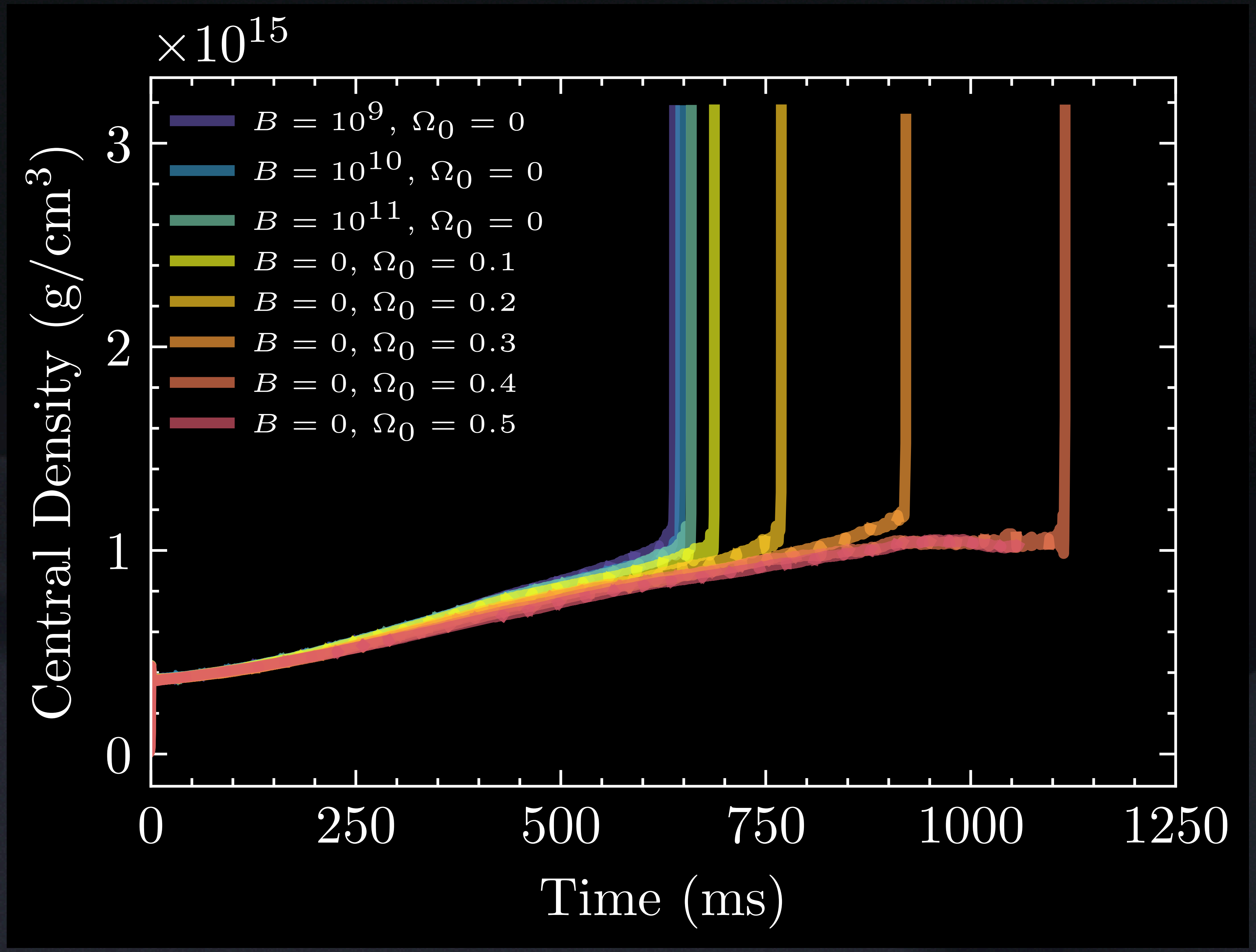
FLASH-IDSA simulations

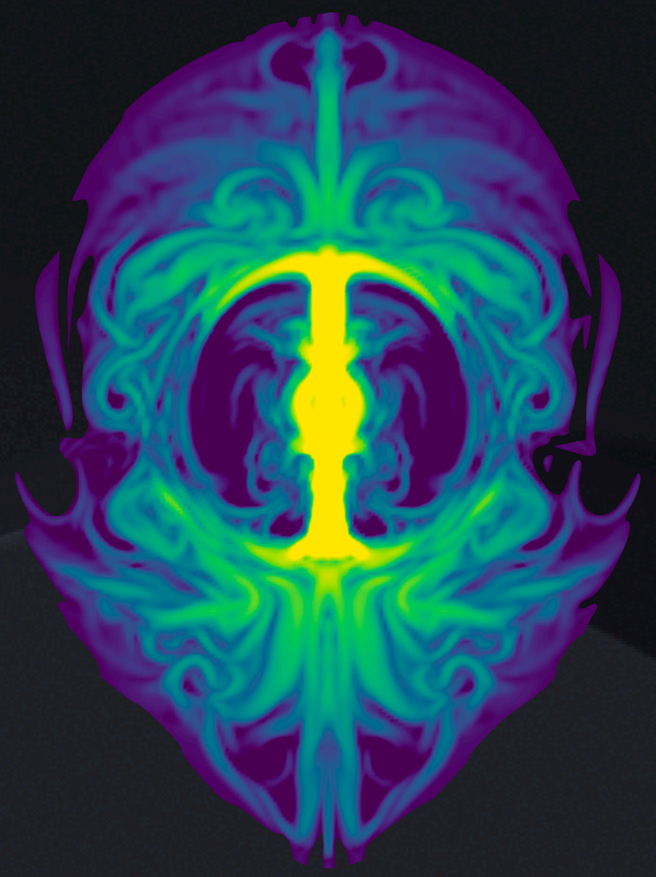
- > 36 magnetized CCSN simulations
- FLASH Code (**2D** in cylindircal coordinates)
- Unsplit MHD solver (usm)
- IDSA for neutrino transport (Liebendorfer+09)
- Effective general relativity (Marek+06)
- The **s40** progenitor (Woosley & Heger 2007)
- **SFHo** EoS
- MHD enabled (B_0 = 0, 10^9, 10^{10}, 10^{11}, 10^{12} G)
- Rotation enabled (initial Ω_0 from 0 - 0.5 rad/s)
- **488 m** resolution in the entaired shock region



Case A: Failed Supernova

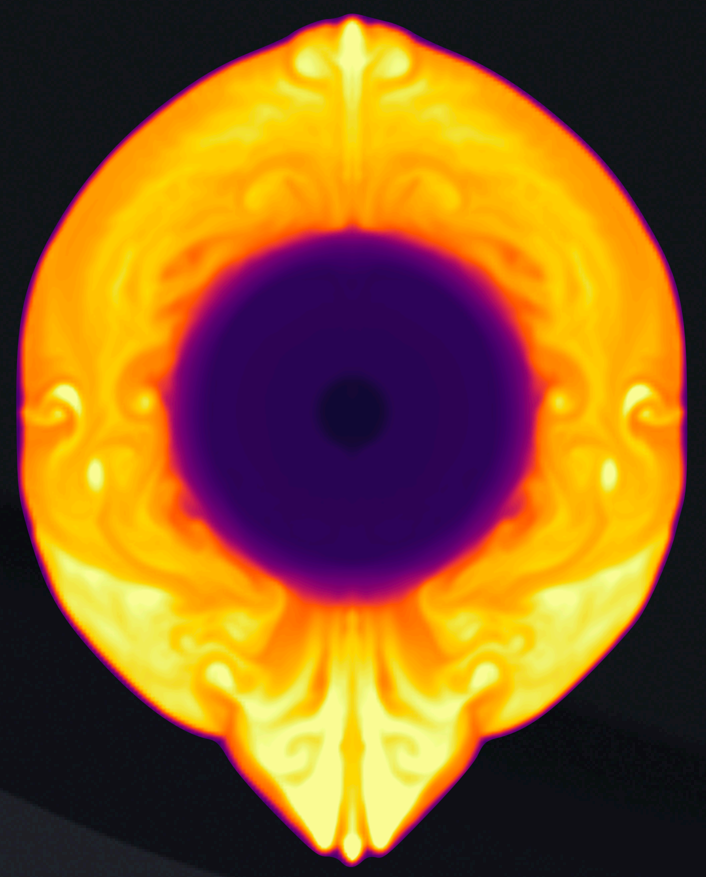
- Shock stalled. Failed supernova
- Strong SASI
- Magnetic field and rotation (2D) delay the BH formation





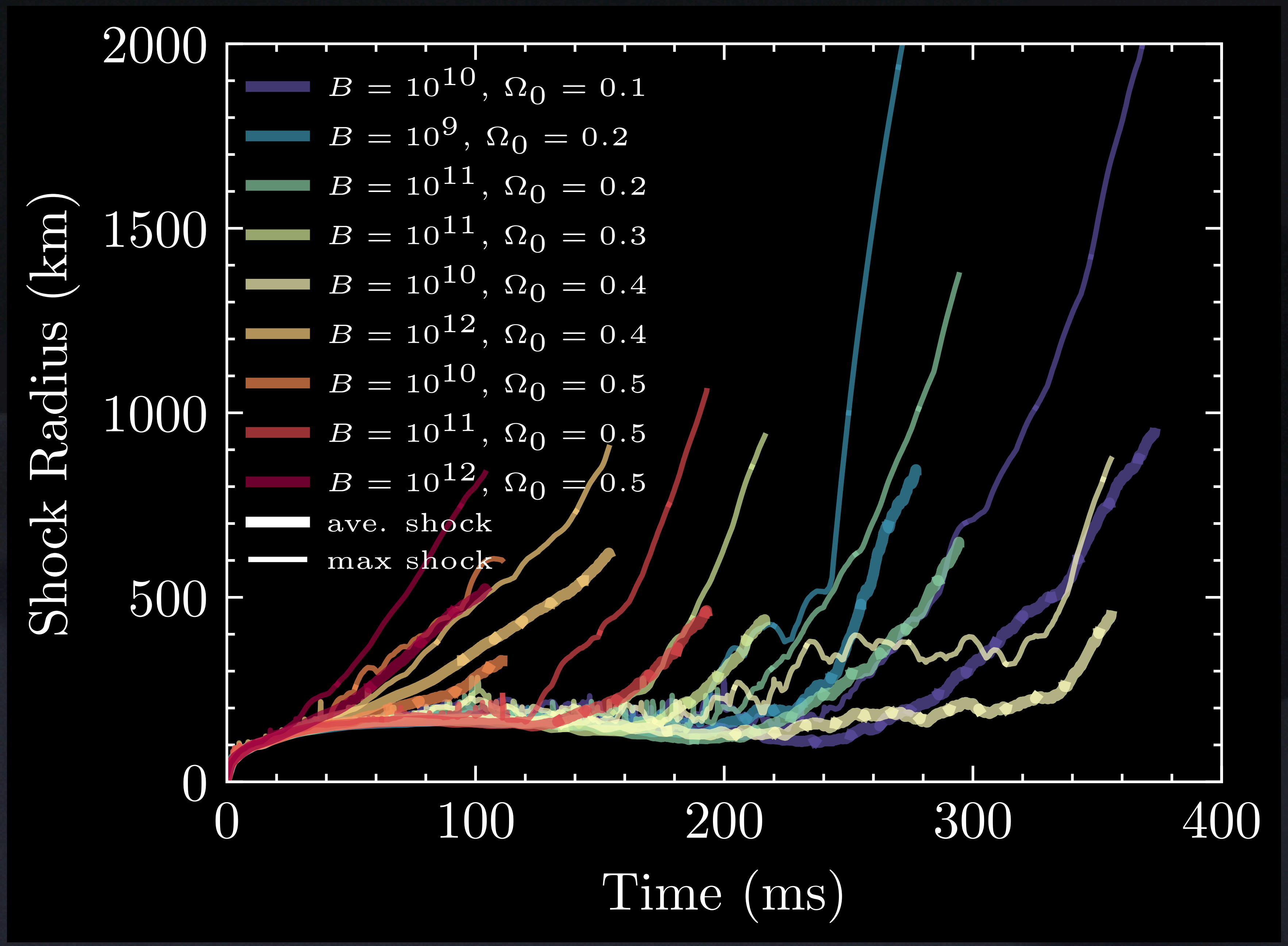
Magnetic pressure

Entropy

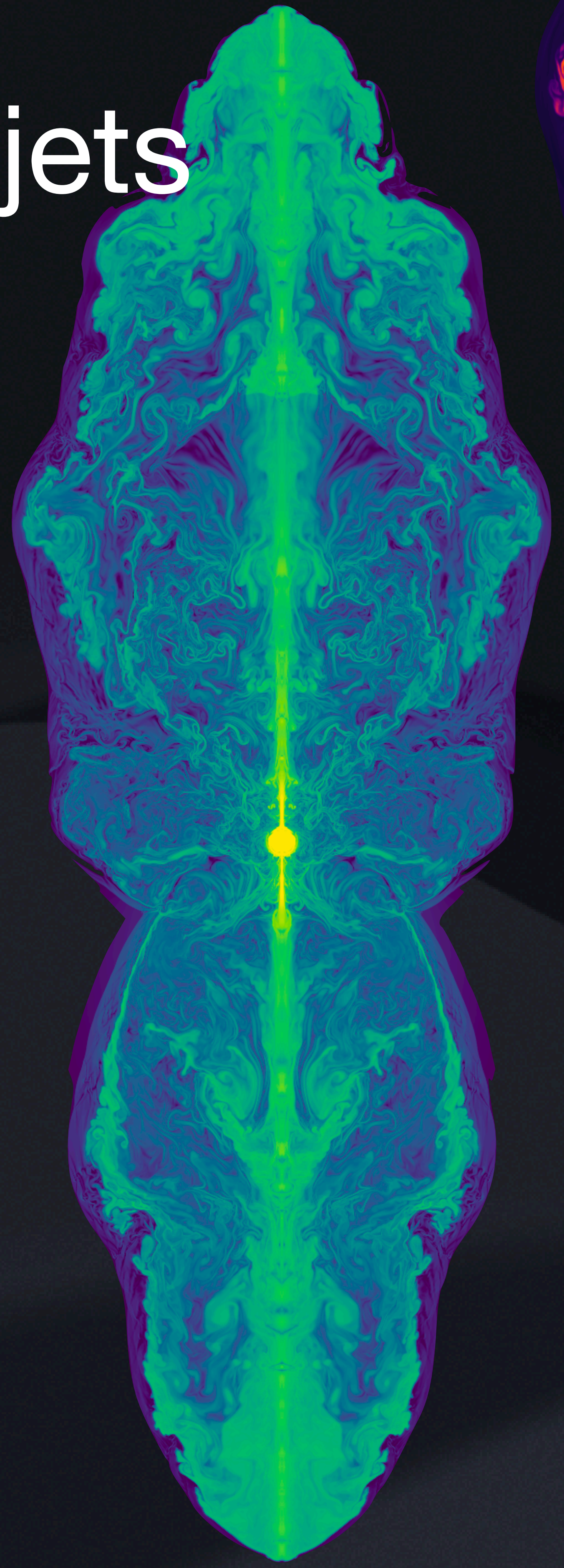


Case B: Bipolar Jet

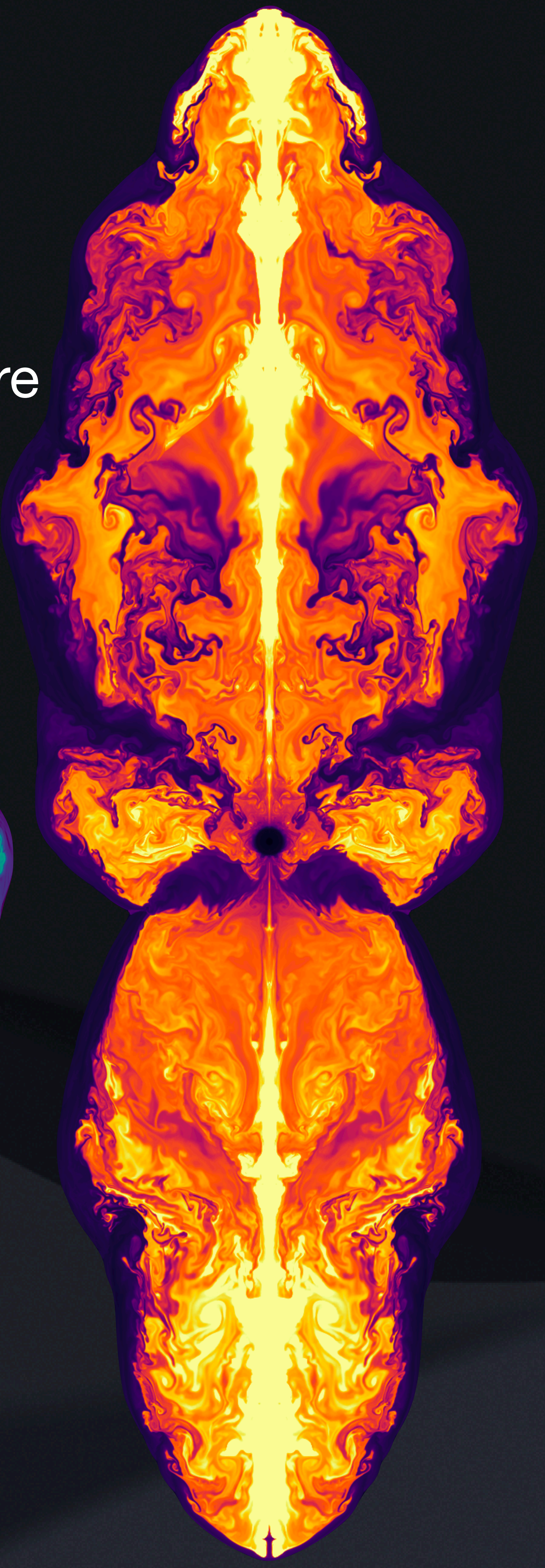
- Jet-driven explosion
- Explosion time depends on the roation
- Strong shearing and turbulence triggered by the jets



Magnetic pressure

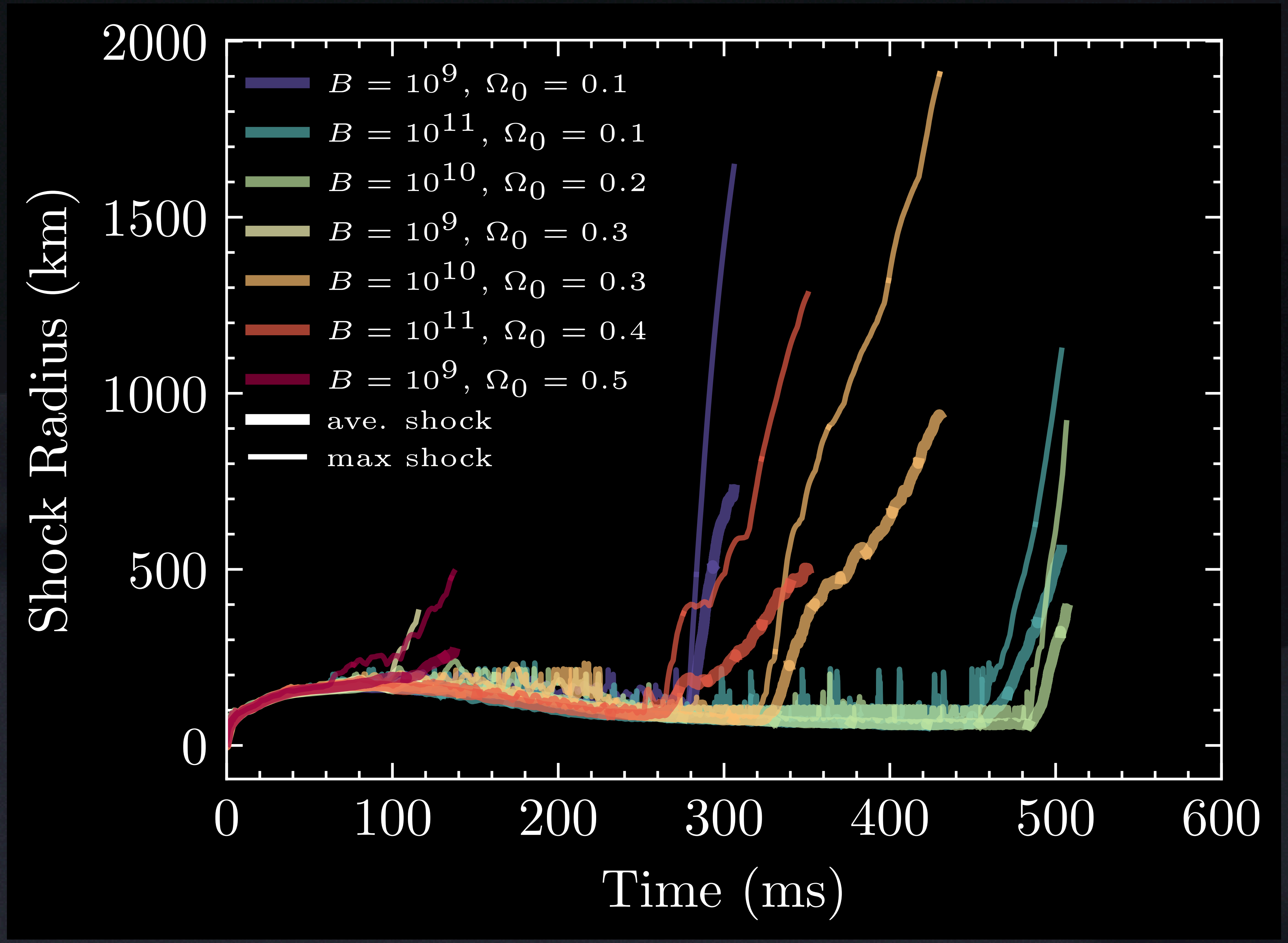


Entropy

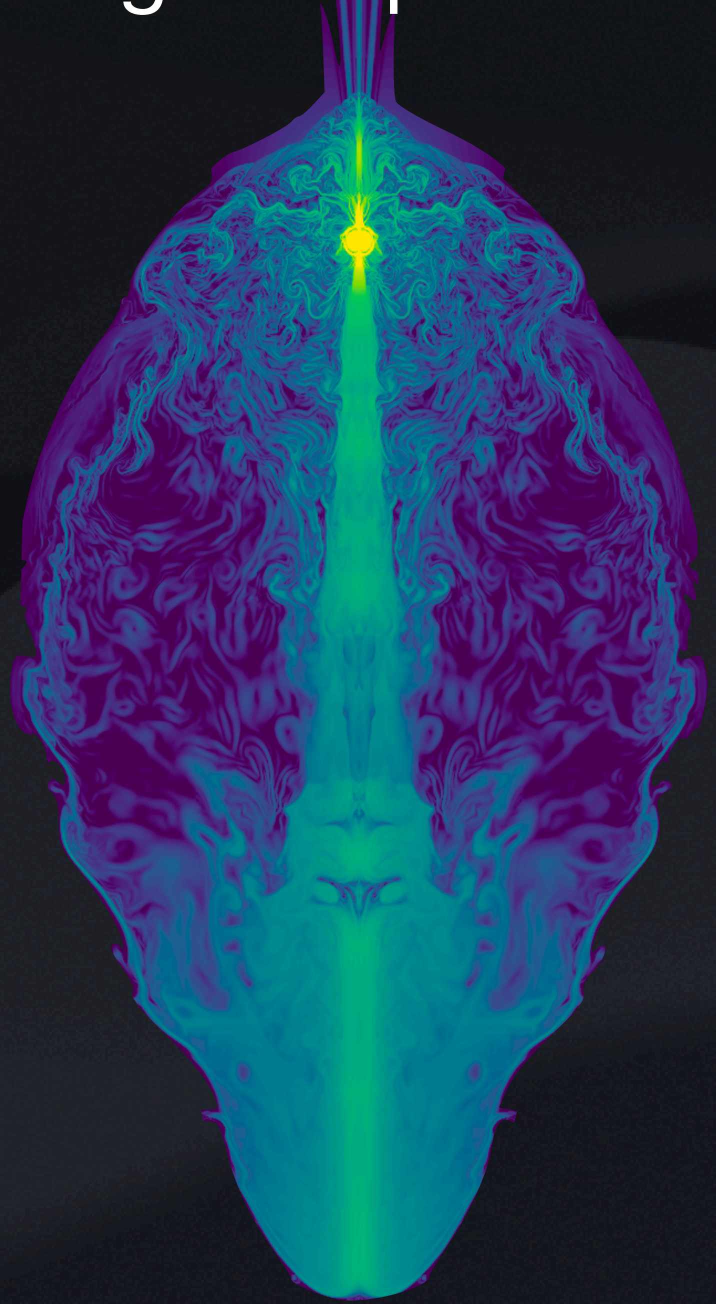


Case C: Monopolar Jet

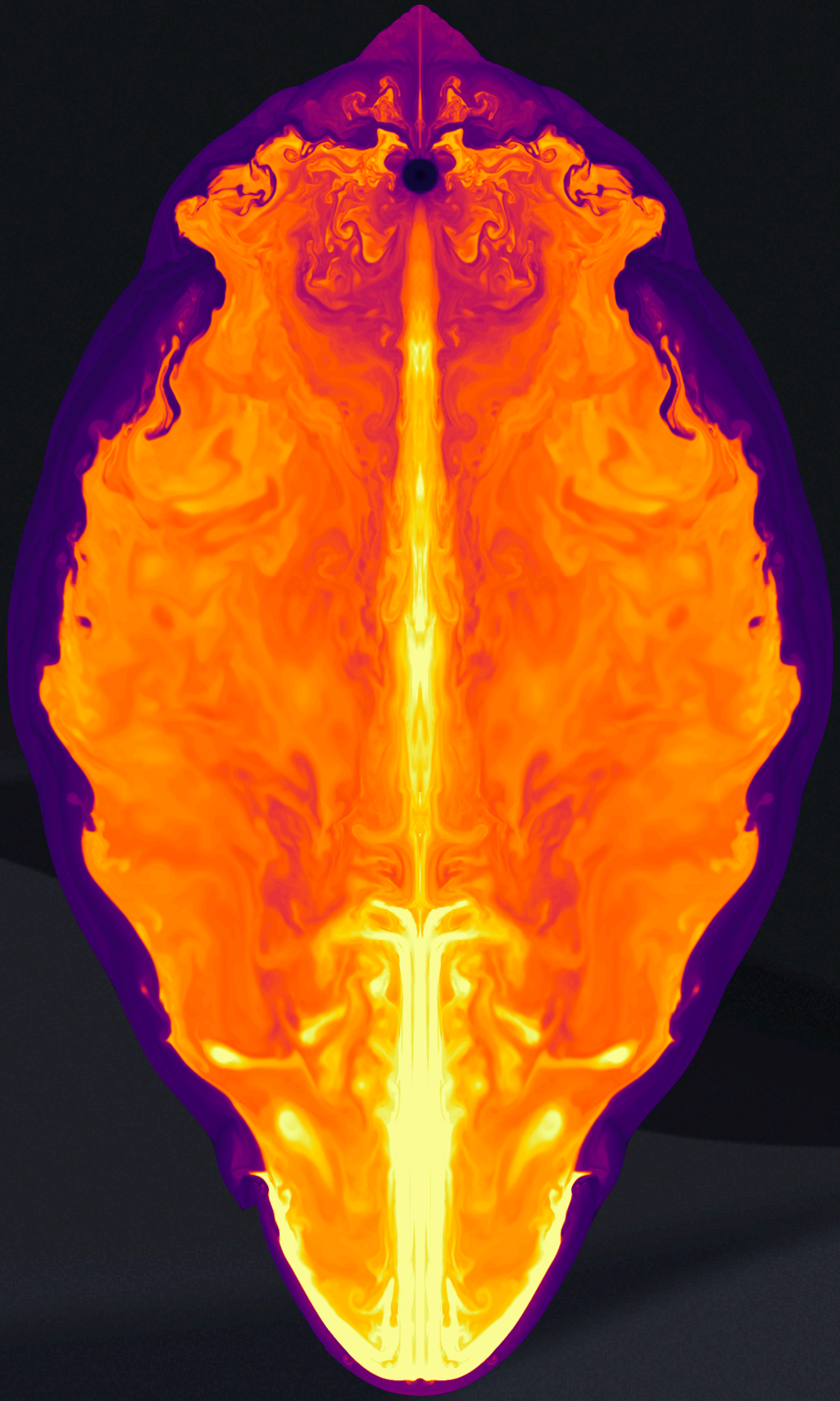
- Delayed explosion
- Evolution was similar to a failed supernova at the early stage but exploded later.
- Fast shock expansion once exploded



Magnetic pressure

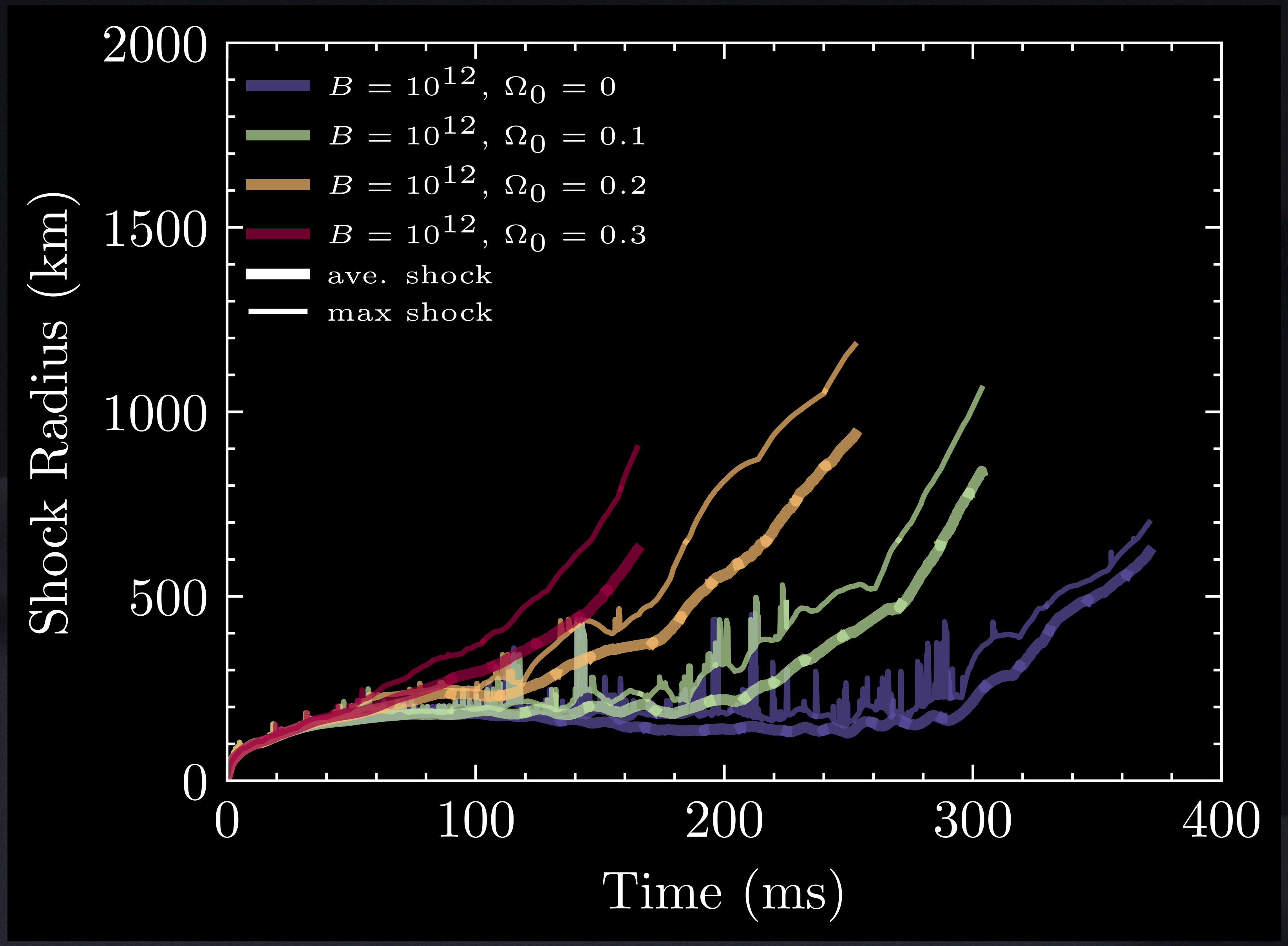


Entropy

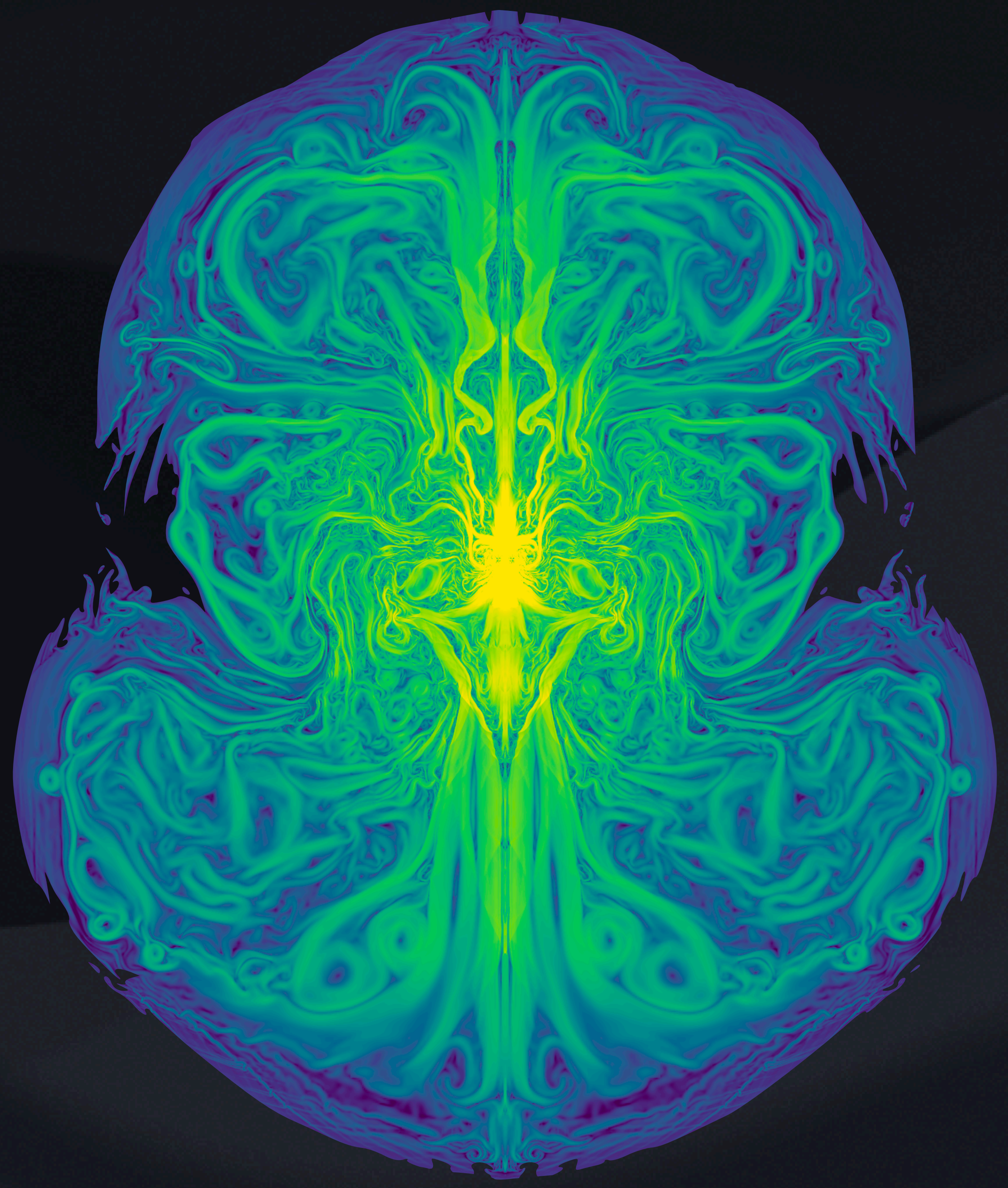


Case D: Neutrino-driven explosion

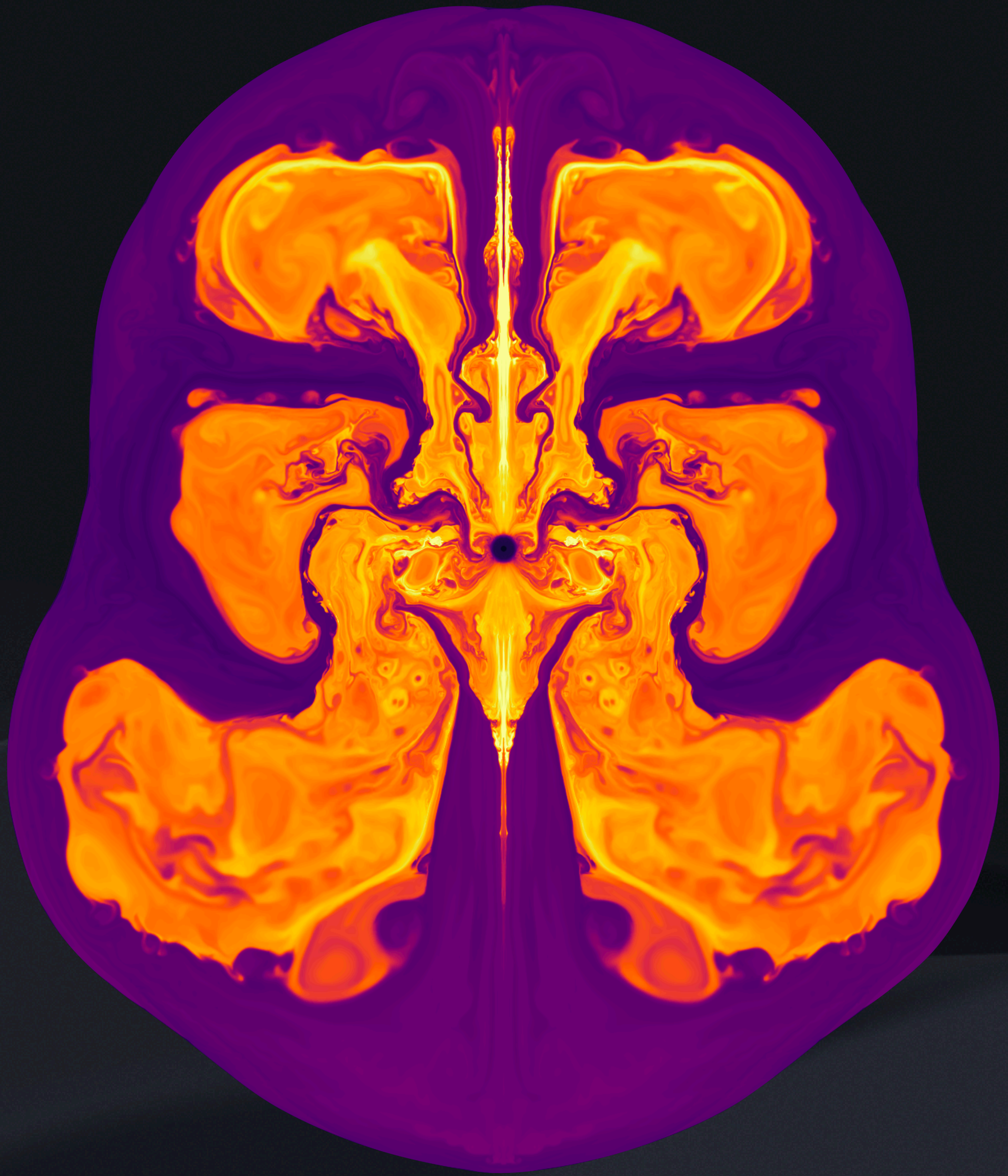
- Exploded due to neutrino-driven explosion
- Butterfly pattern
- Exist cool accretion funnels



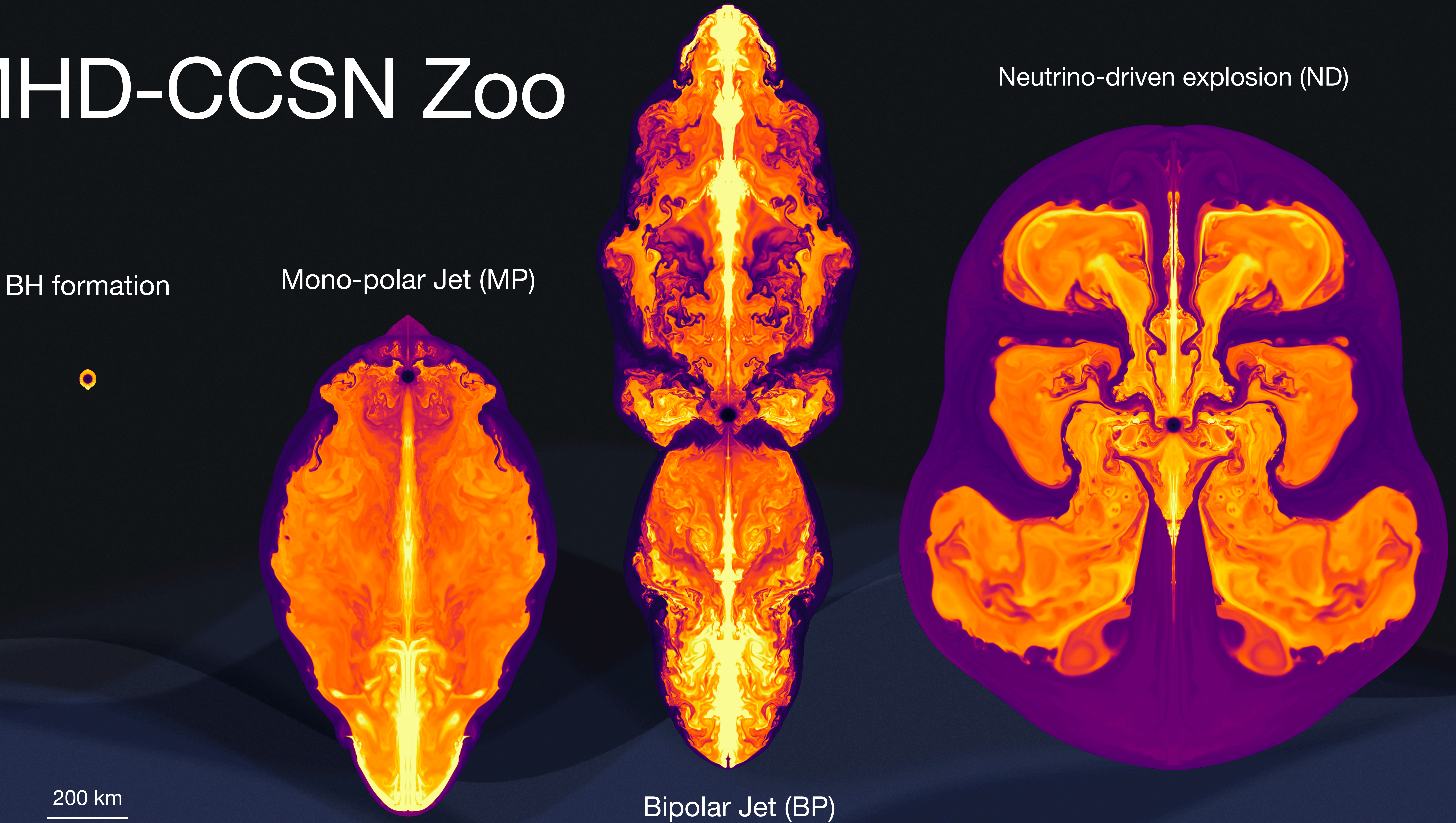
Magnetic pressure



Entropy

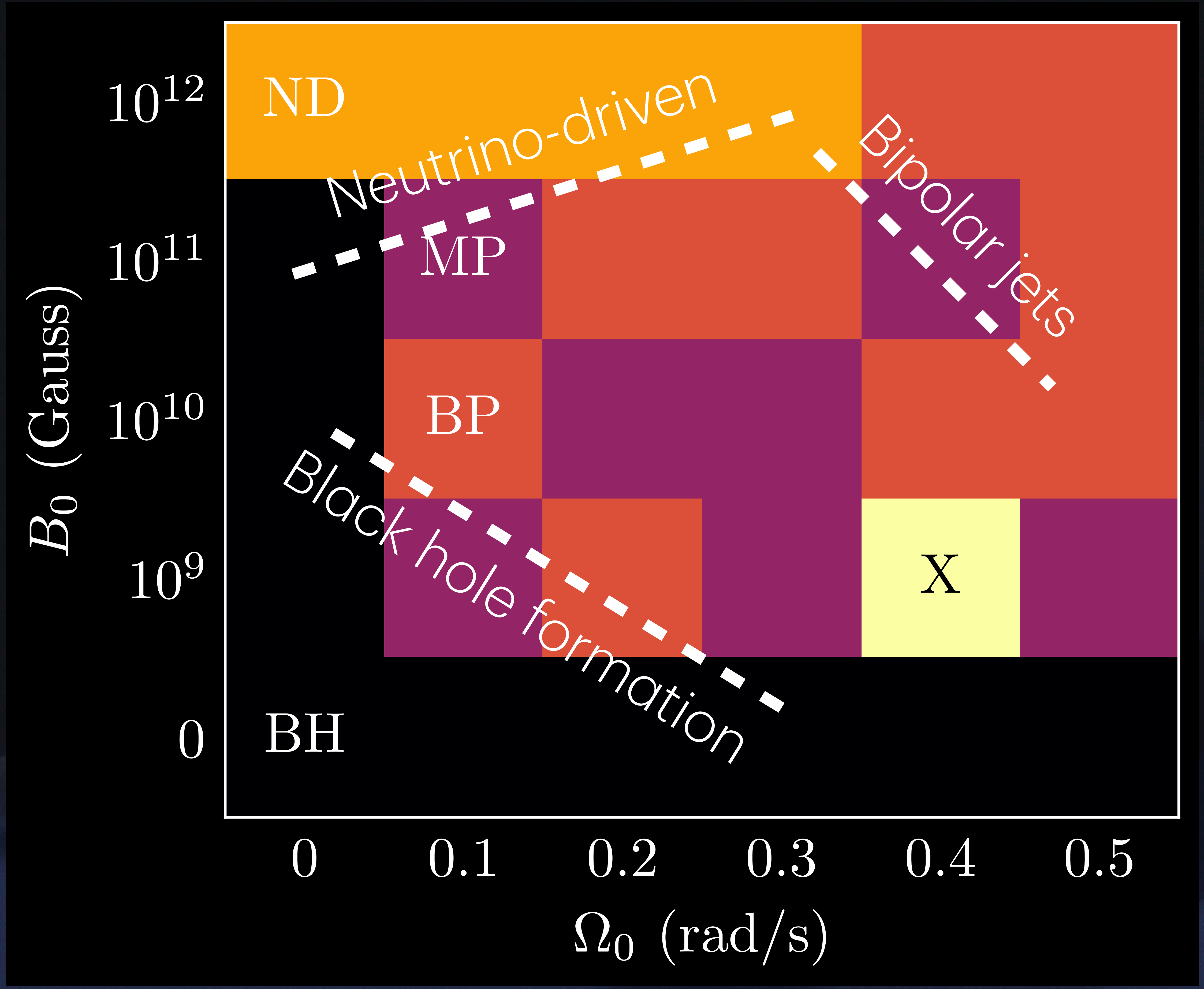


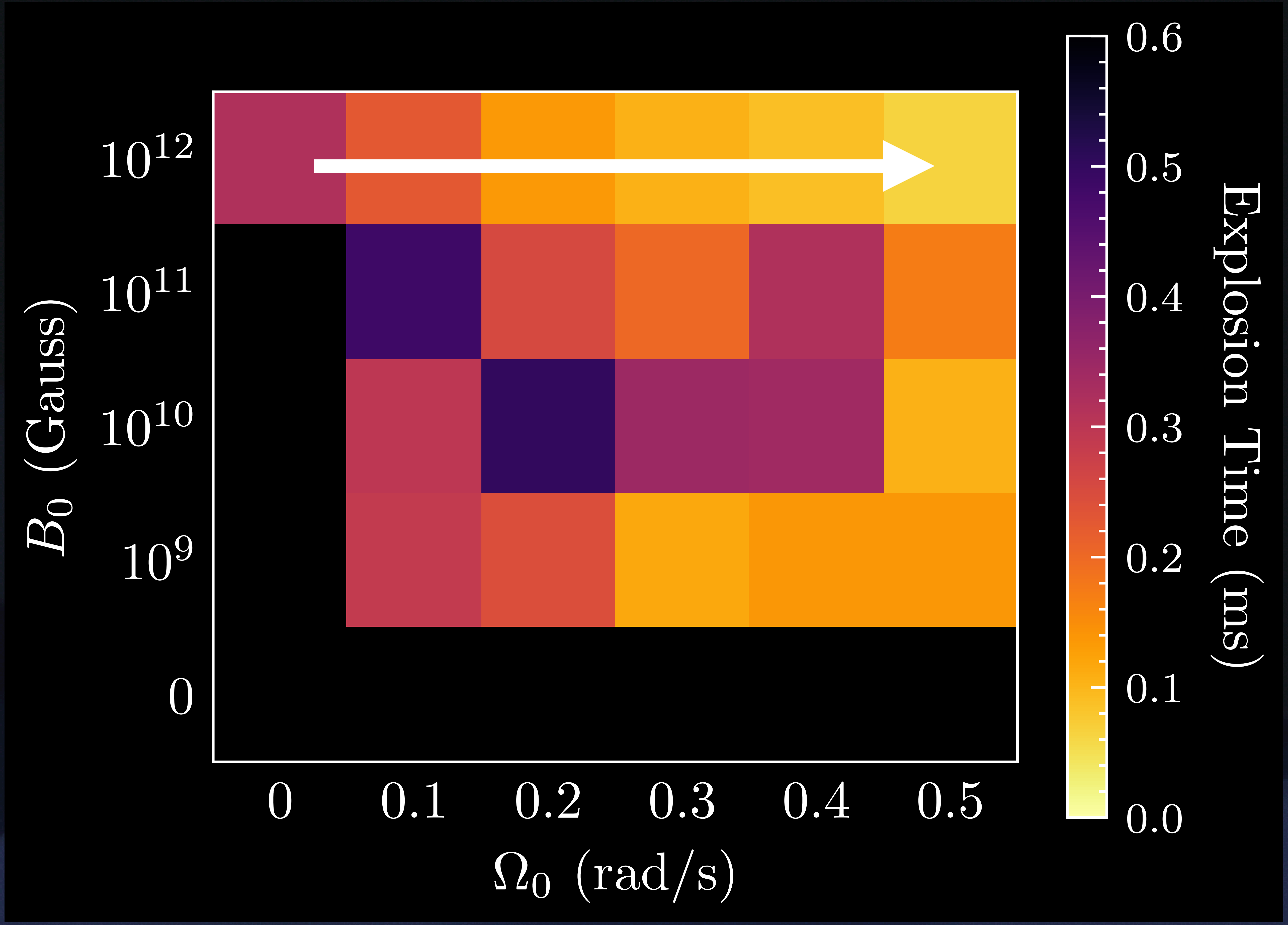
MHD-CCSN Zoo


BH formation
Mono-polar Jet (MP)
Bipolar Jet (BP)
Neutrino-driven explosion (ND)
200 km

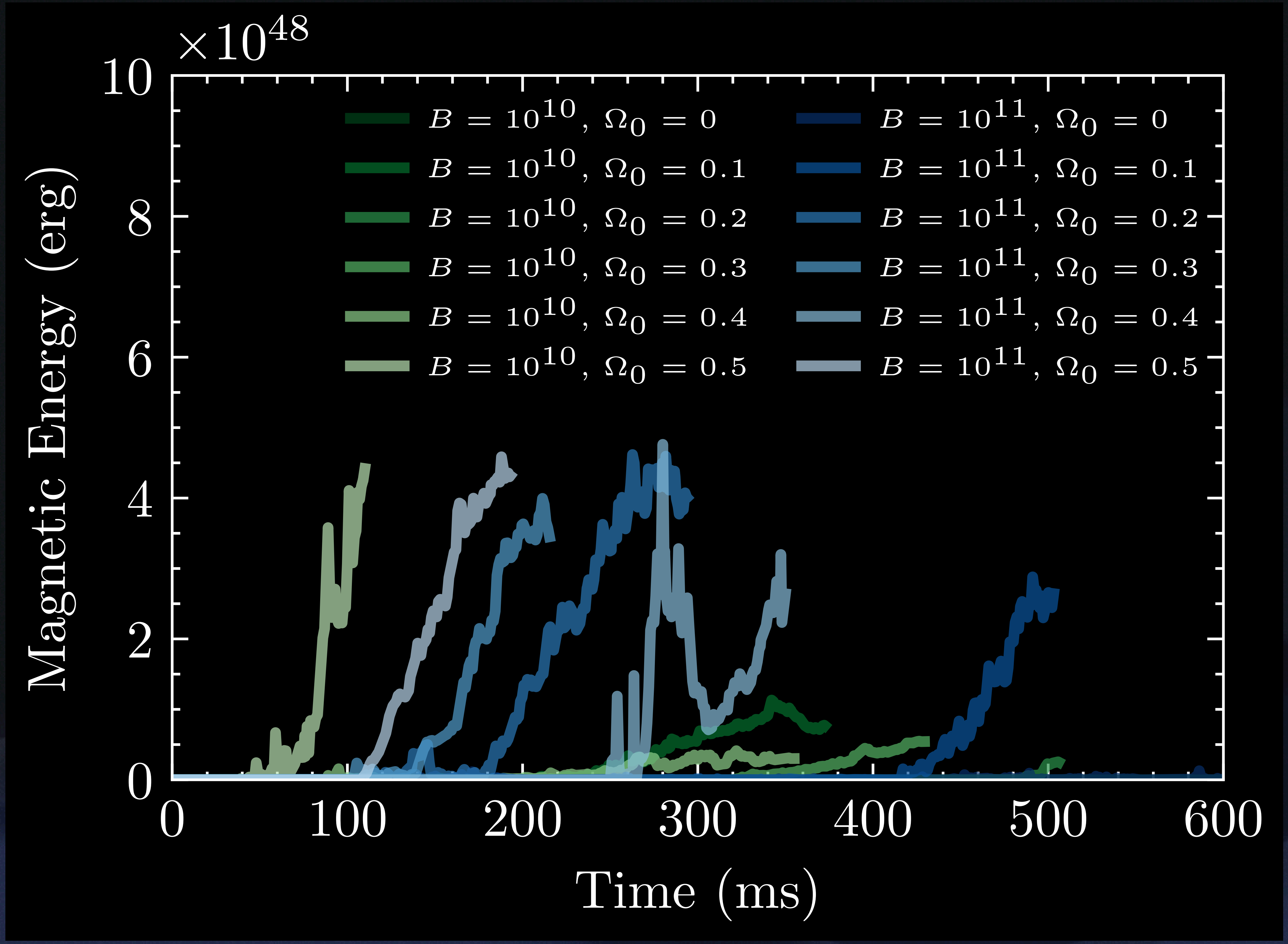
Overview of results

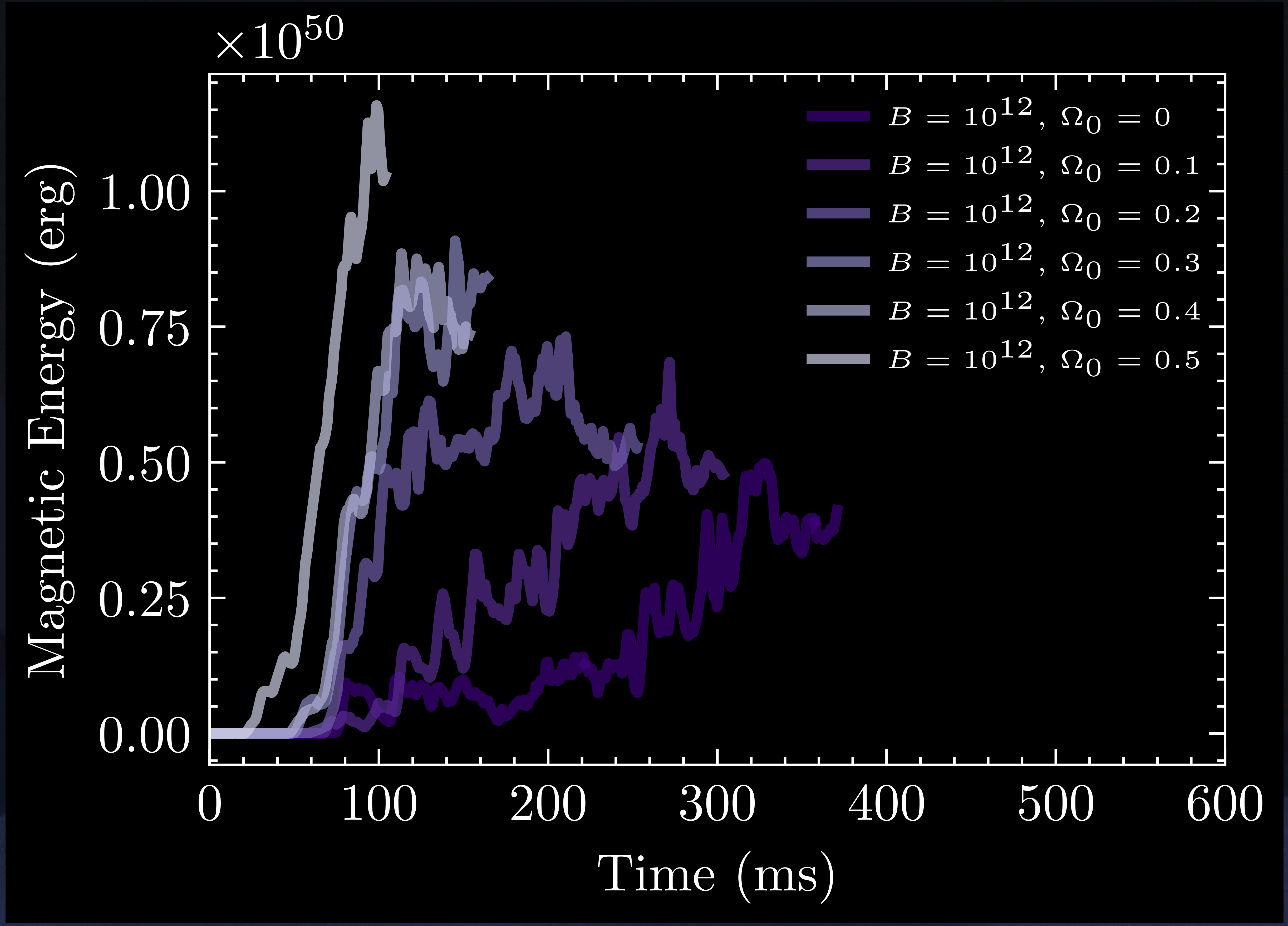
Preliminary results



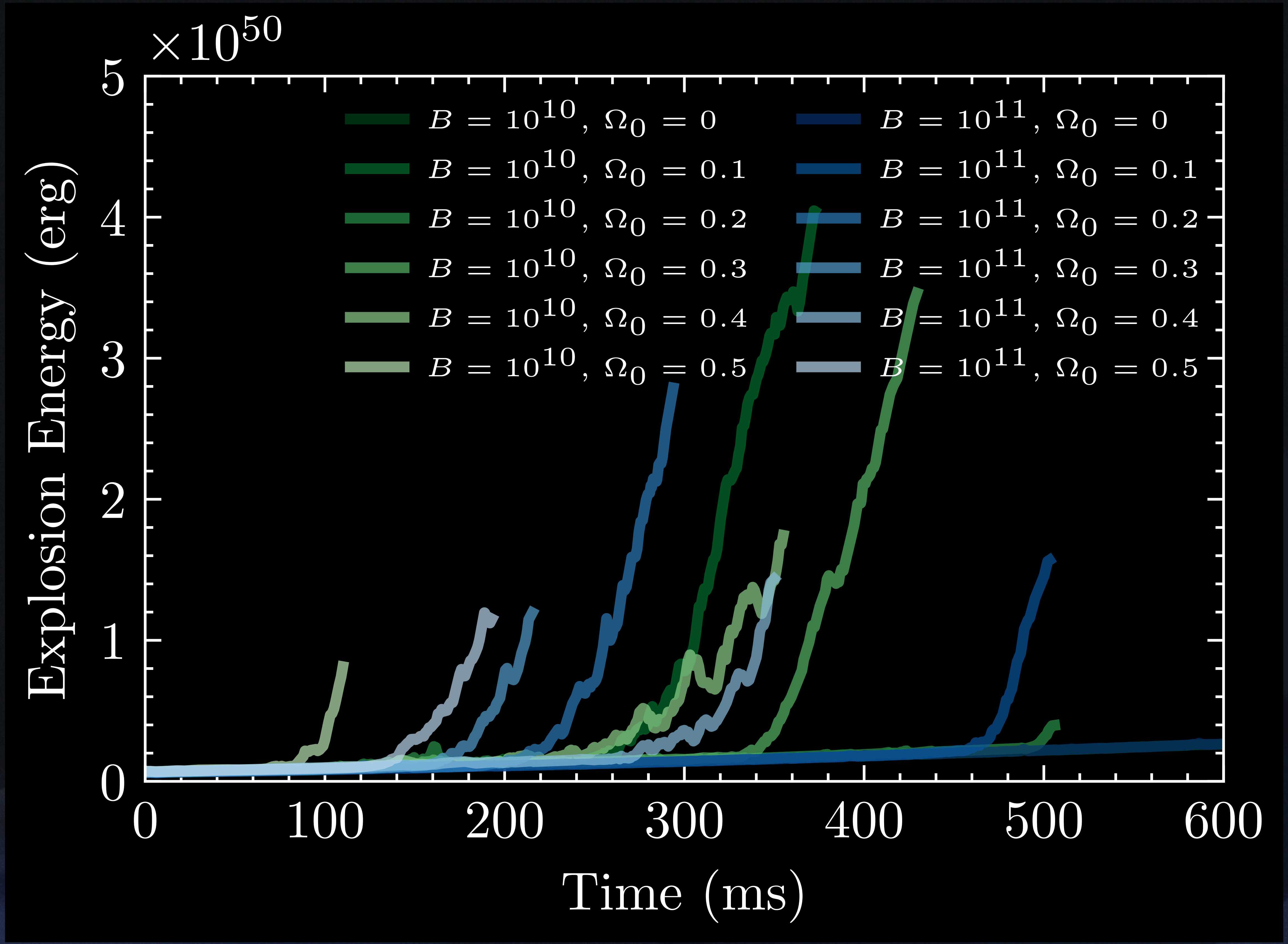


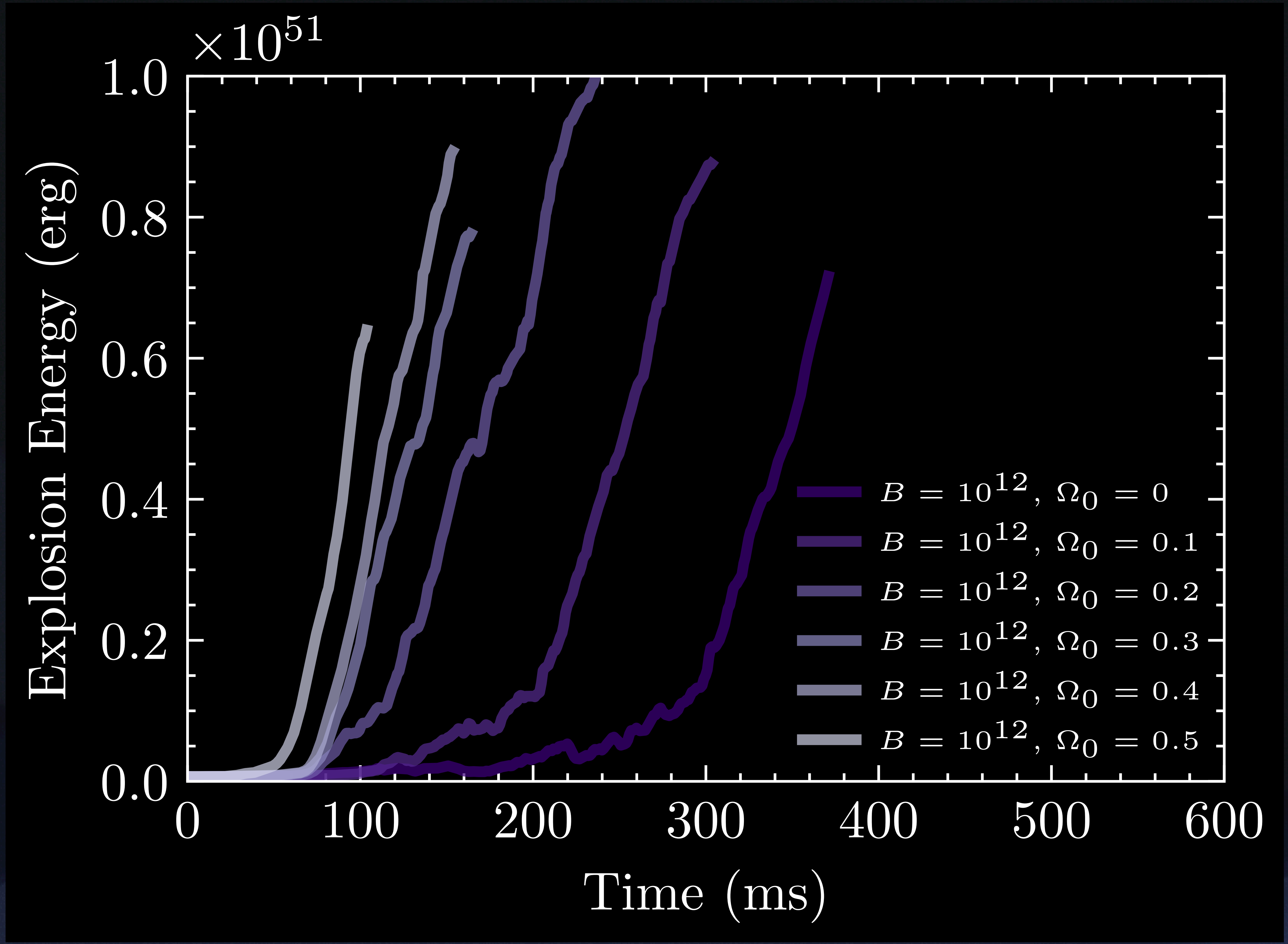
Magnetic Energies





Explosion Energies





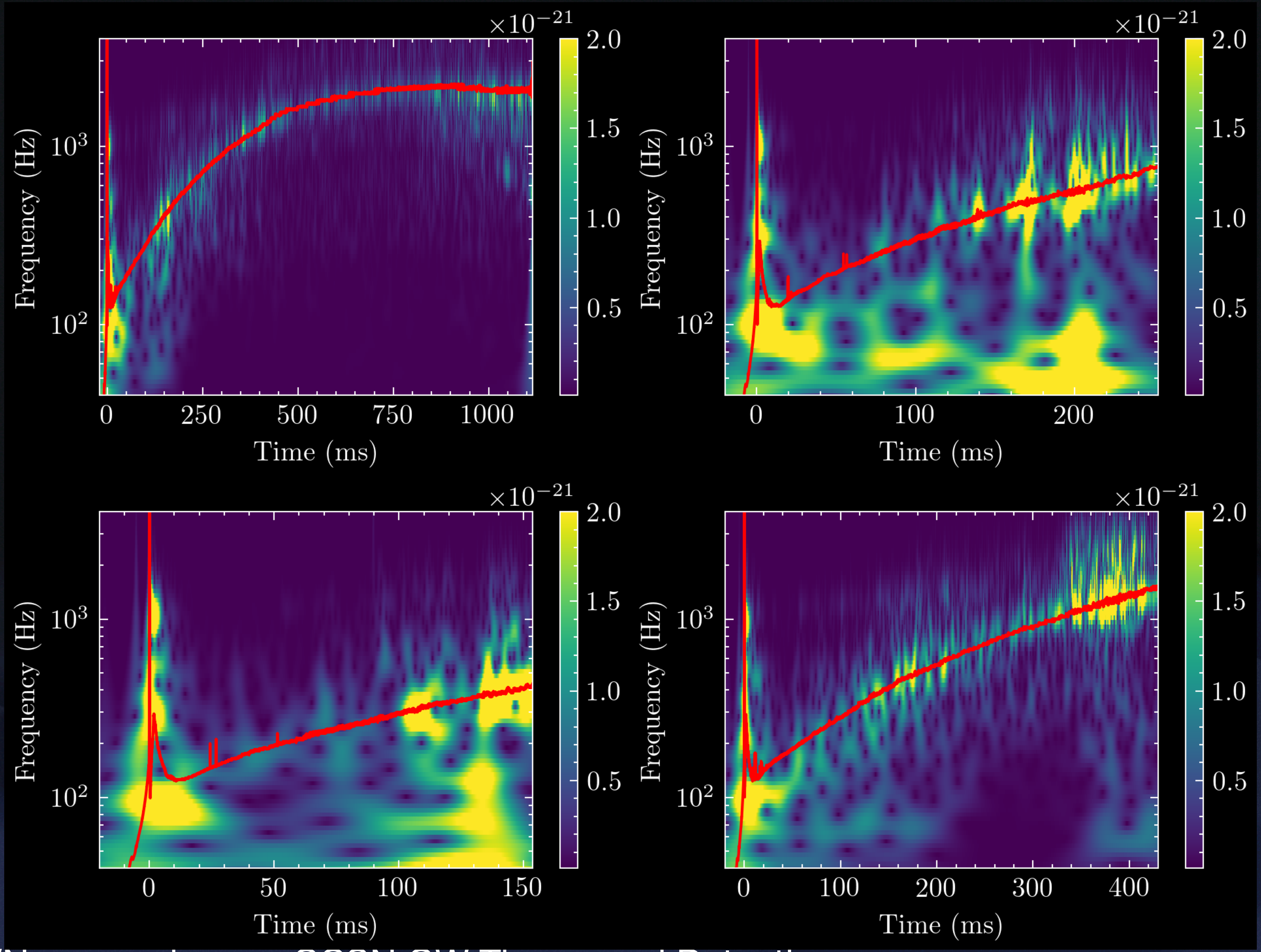
Gravitational Waves

Failed Supernova

Neutrino-driven

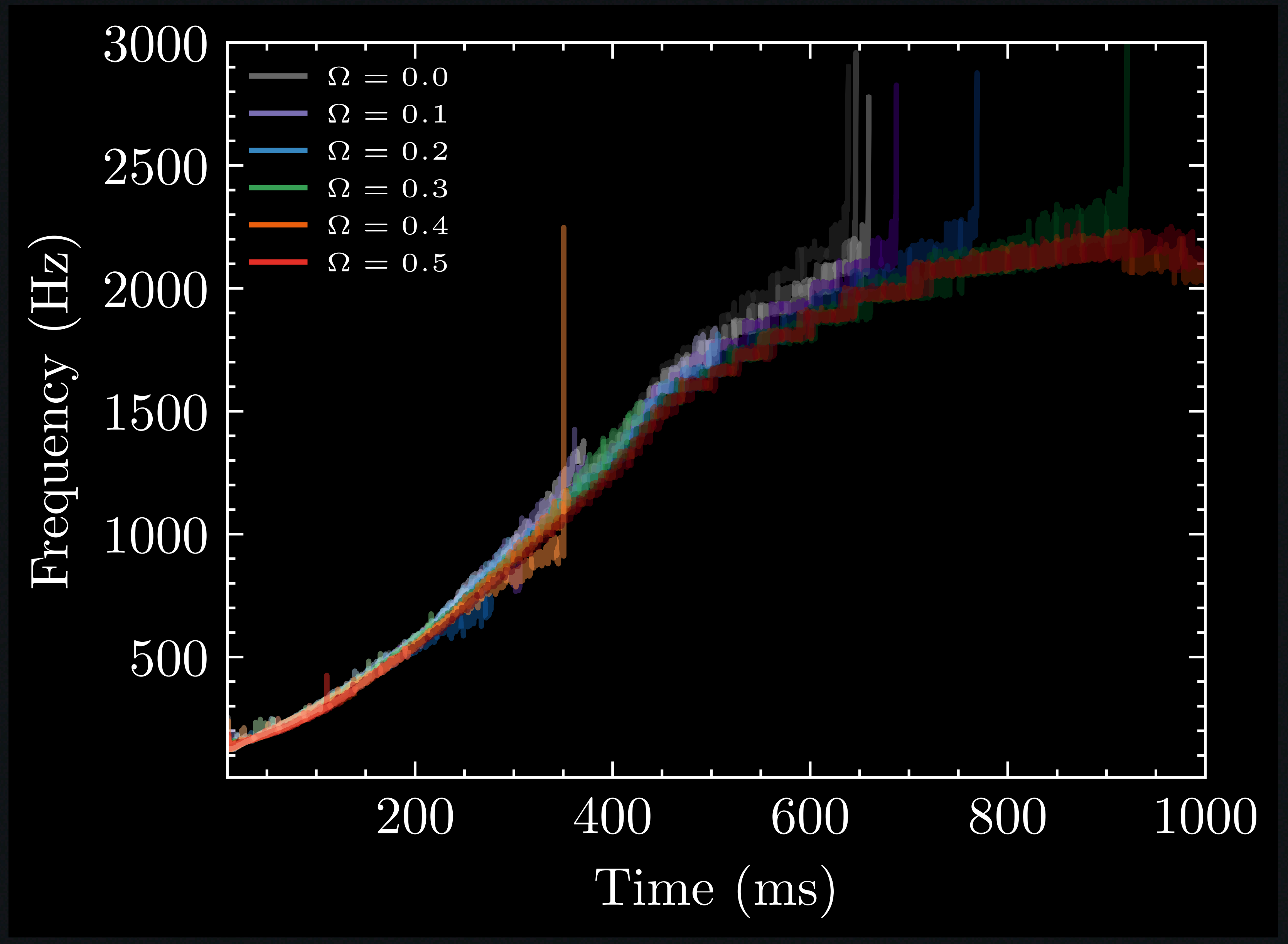
Bipolar Jets

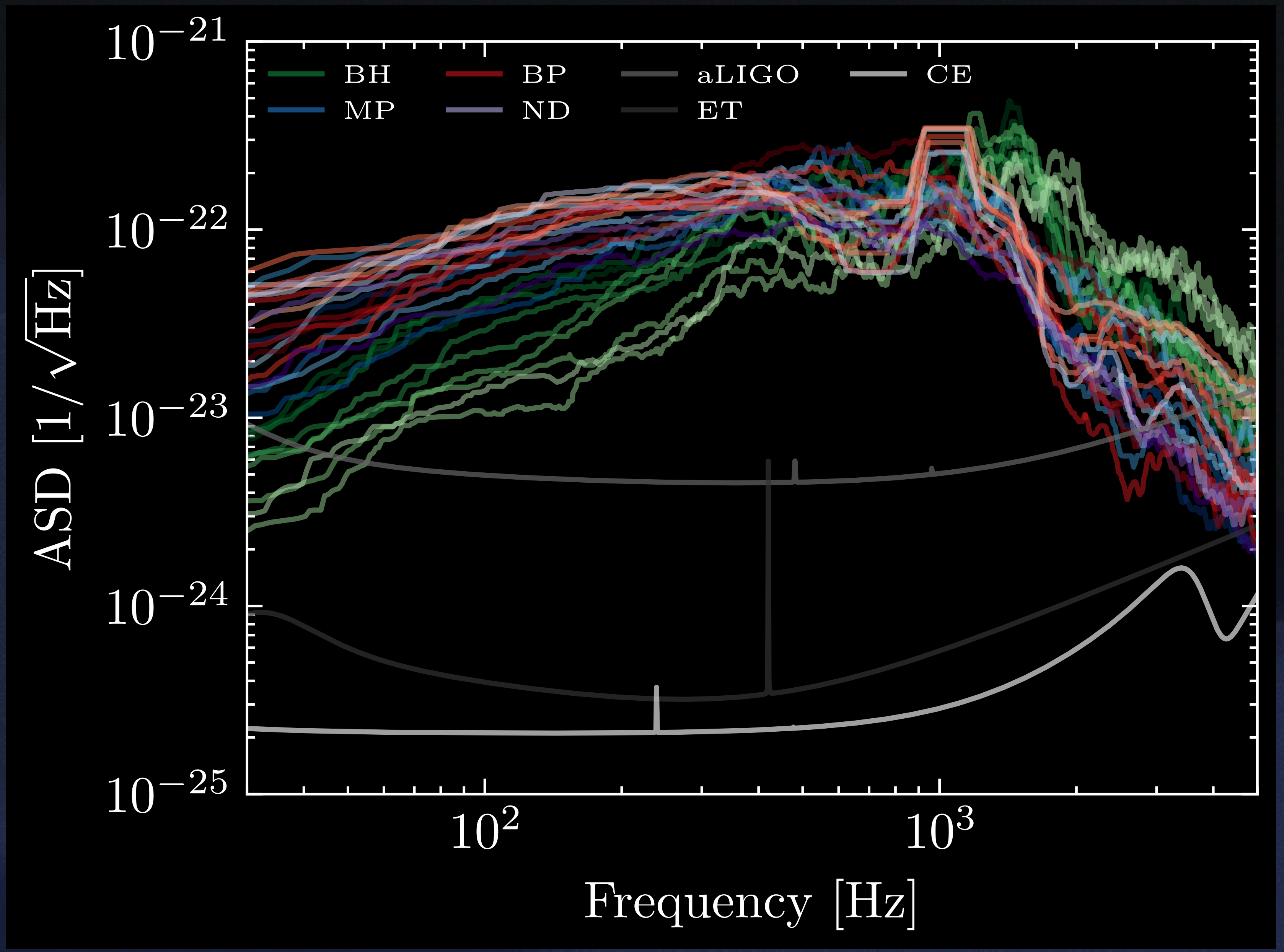
Monopolar Jet



Gravitational Wave

- The GW “peak” frequency mainly depends on the rotational speed, but weakly depends on the magnetic fields.
- Explosion time and the GW amplitudes highly depends on the rotation and B-fields.
- Each type of morphologies show unique GW sub-features.

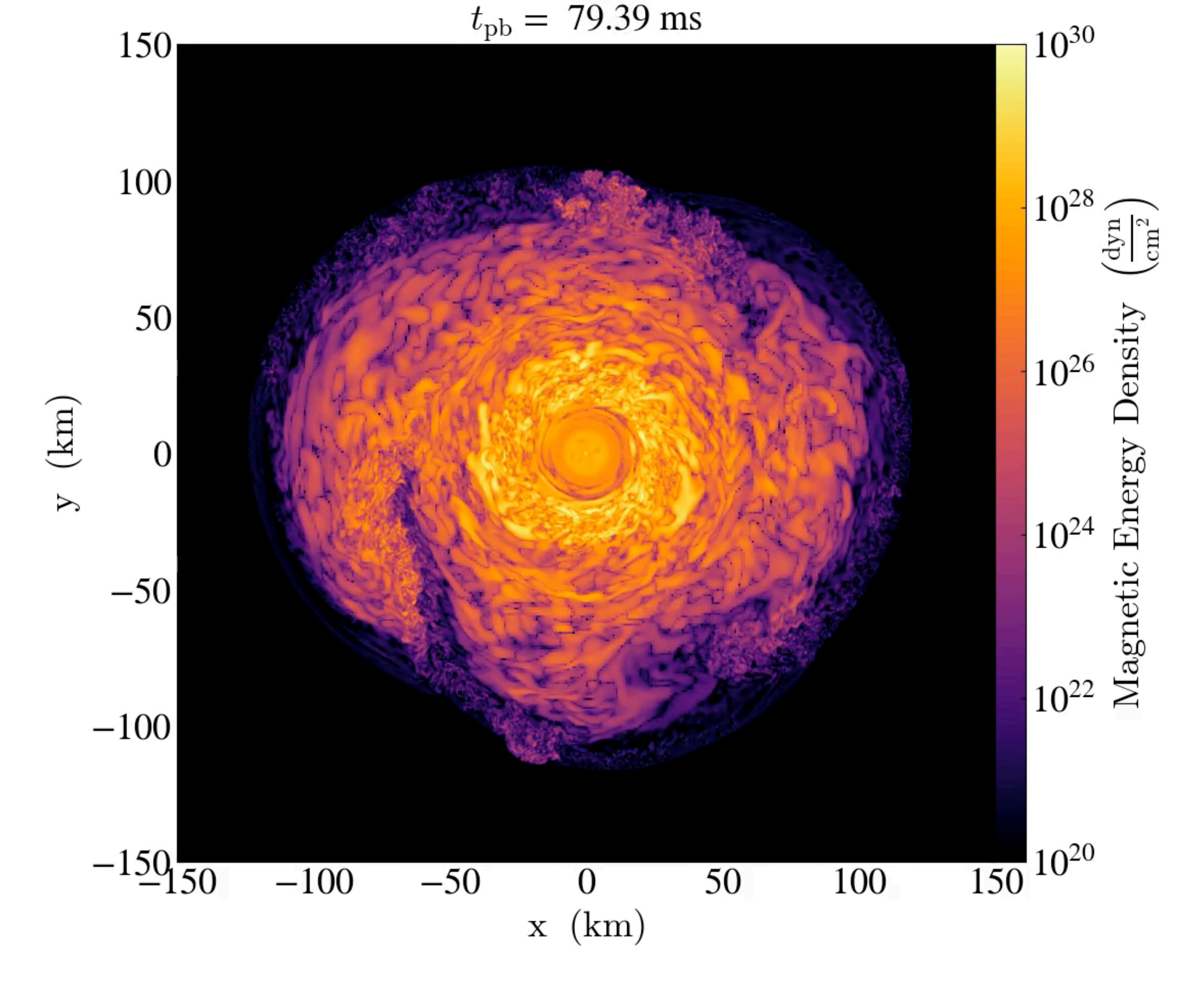




Magneto-rotational Instability

- Note that the third dimension allows additional degree of freedom for magneto-hydrdodynamics instabilities.
- High-resolution 3D simulations are expensive but necessary
- 3D GAMER simulation with **250 m** resolution in shocked region (no “angular” resolution).

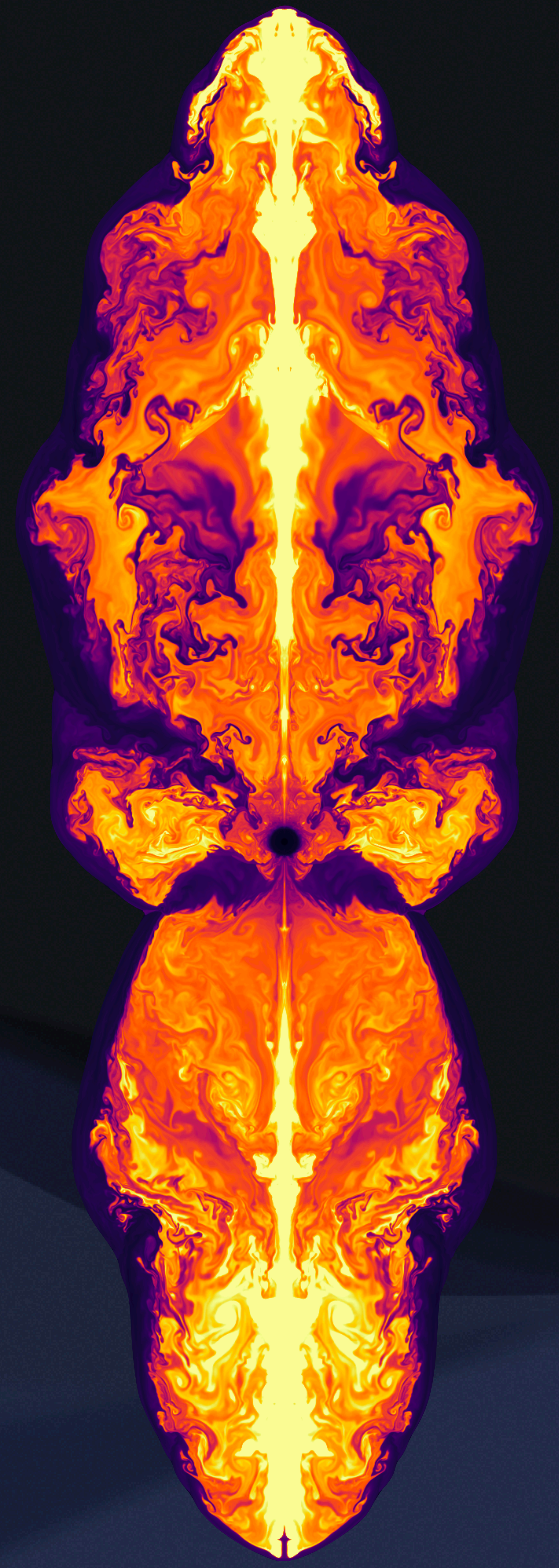
3D CCSN-MHD with GPU, GAMER
(effective-GR + neutrino leakage)



Hsieh et al. in prep.

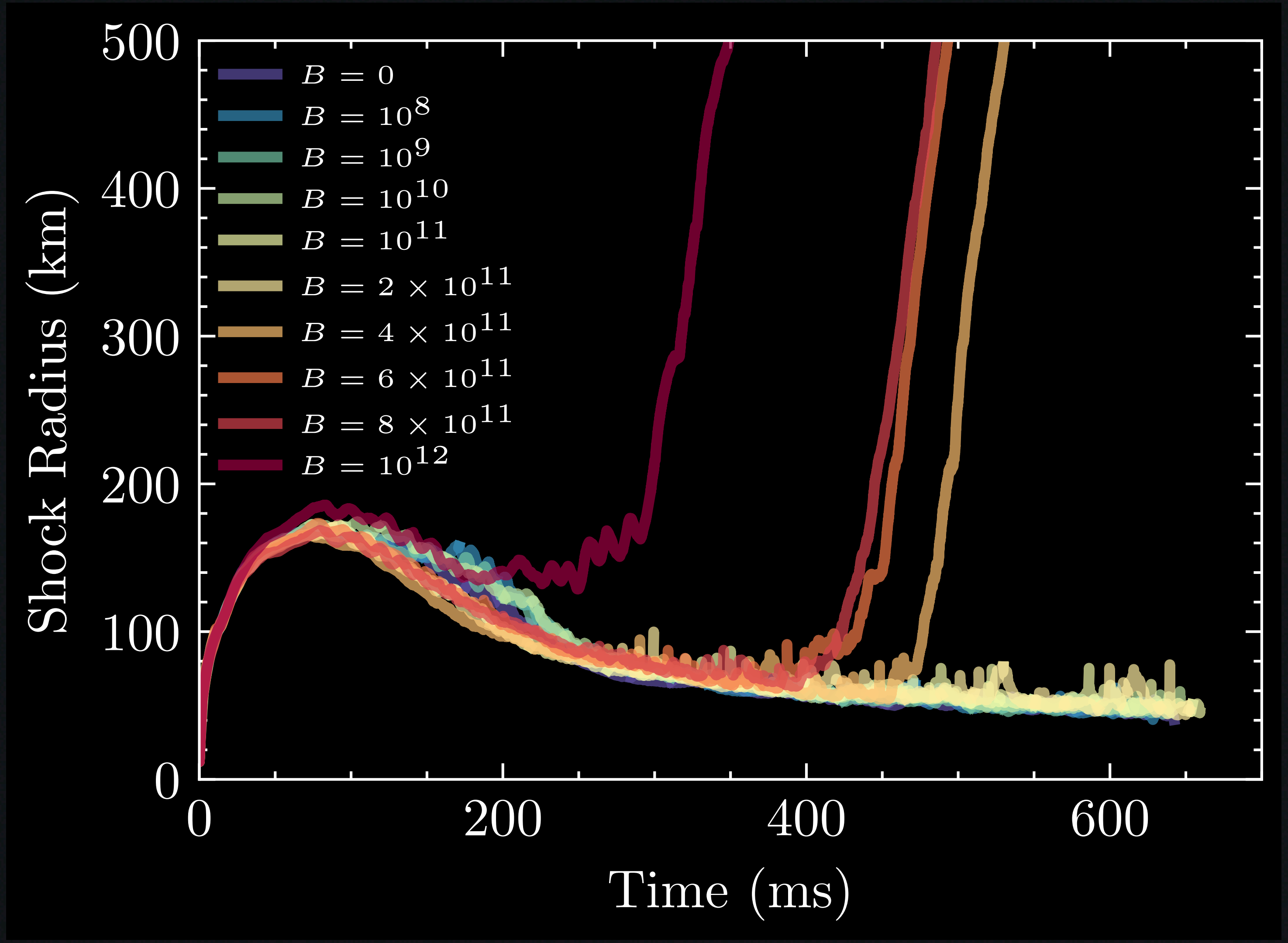
Summary & Conclusions

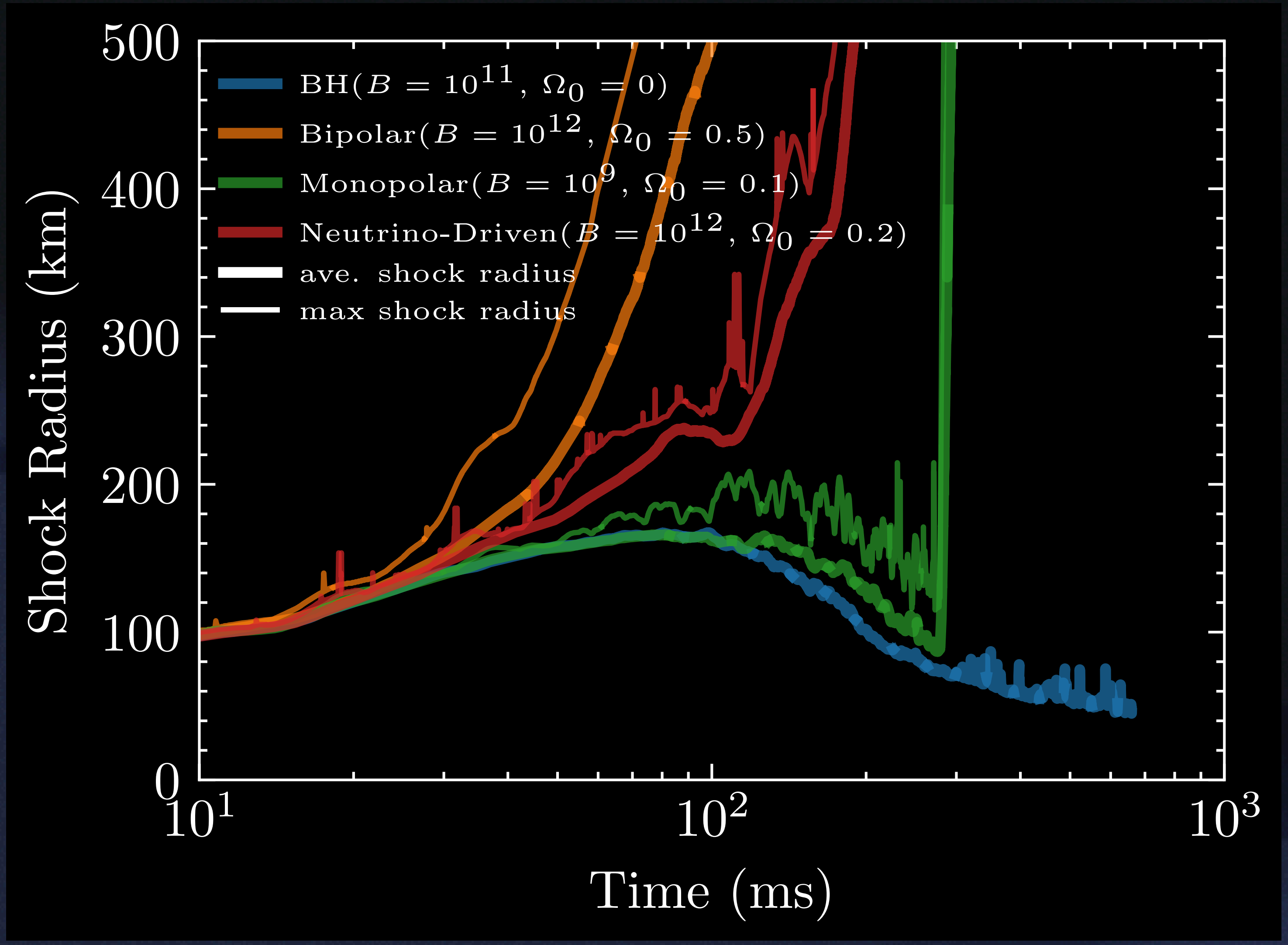
- MHD-driven CCSNe are the possible origins of hypernovae, magnetars, and long gamma-ray bursts.
- Magnetized CCSN show a wide range of morphologies. Each of them shows unique dynamics and GW features.
- The peak GW frequencies mainly depend on the rotational speed and weakly depends on the fields.
- Additional analysis on MRI and 3D effects are necessary.
- Future GW and MMA observations of a nearby CCSN are important to examin the CCSN physics.



Shock dynamics

- Non-magnetized models and weak fields models form BH at the end of simulations
- Magnetic fields assist in explosion (Muller+20)
- Without B, rotation tends to suppress explosion in 2D (Pajkos+19)
- If B exists, rotation could assist in the explosion
- Once a model explodes, BH formation will be delayed or not happen due to less accretion

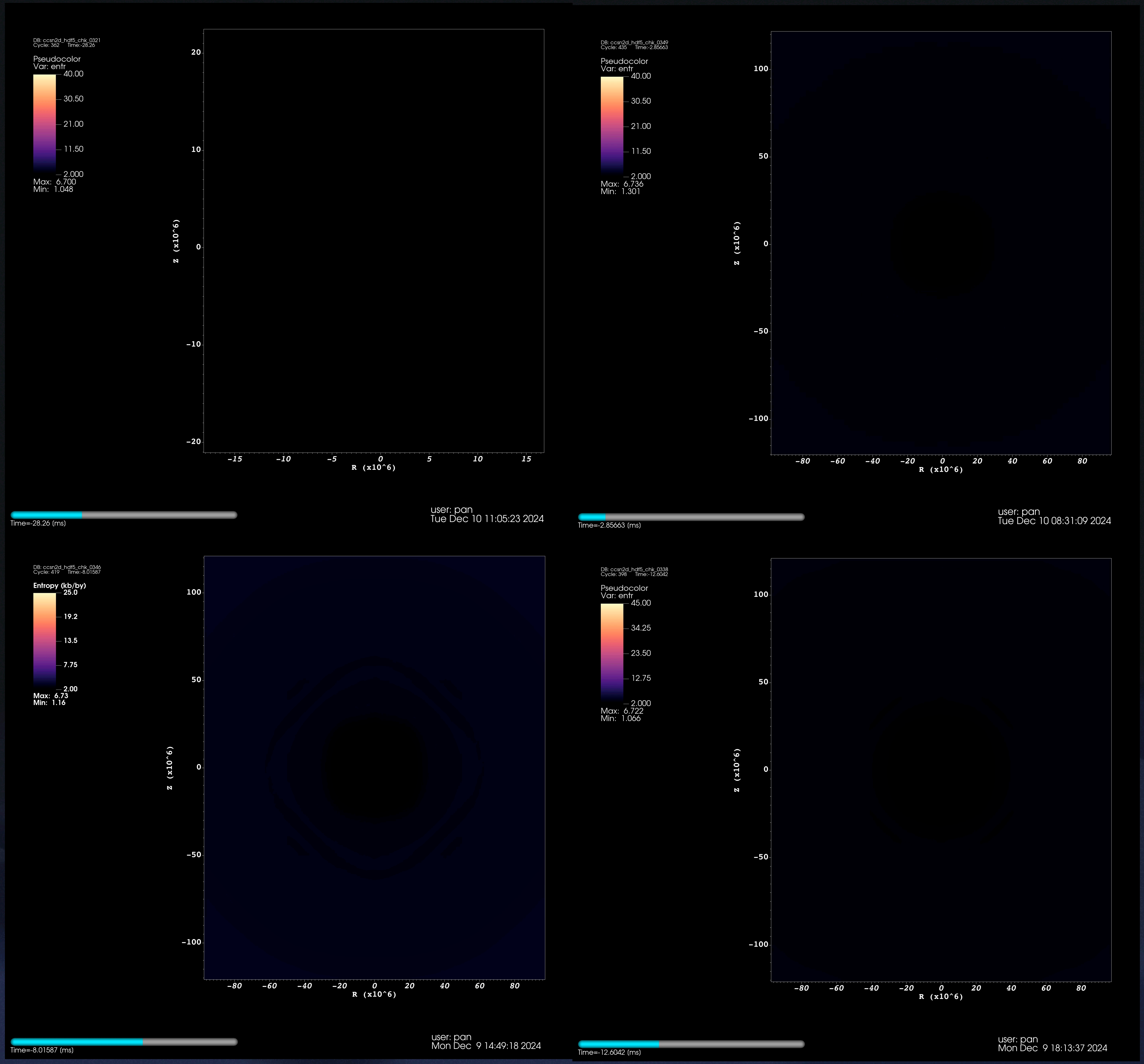




Preliminary results

Failed Supernova

Neutrino-driven



Bipolar Jets

Monopolar Jet