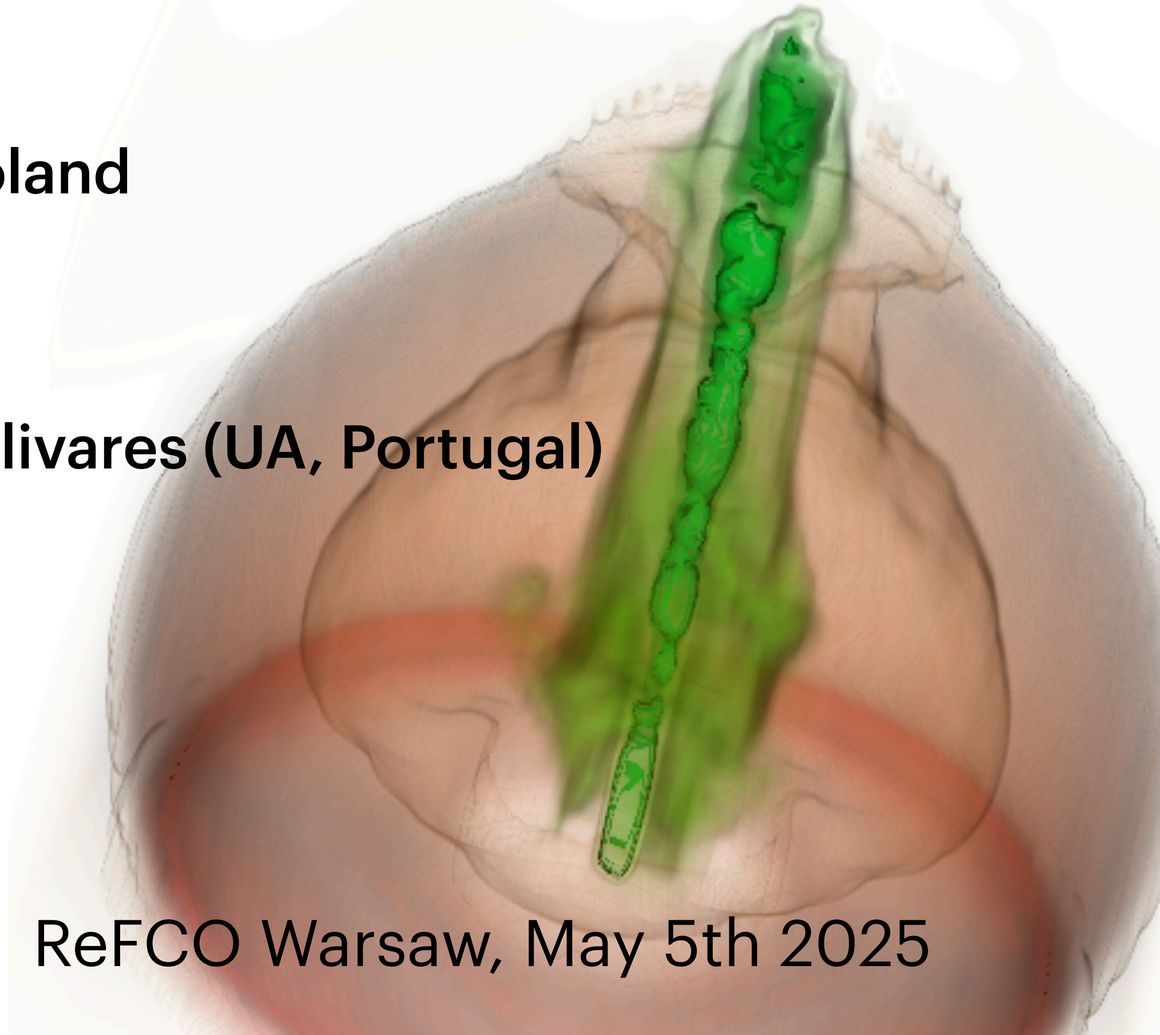
Numerical simulations of GRB jets from the BH horizon to post-breakout in collapsing stars

Gerardo Urrutia
Center for Theoretical Physics, Warsaw, Poland
gurrutia@cft.edu.pl

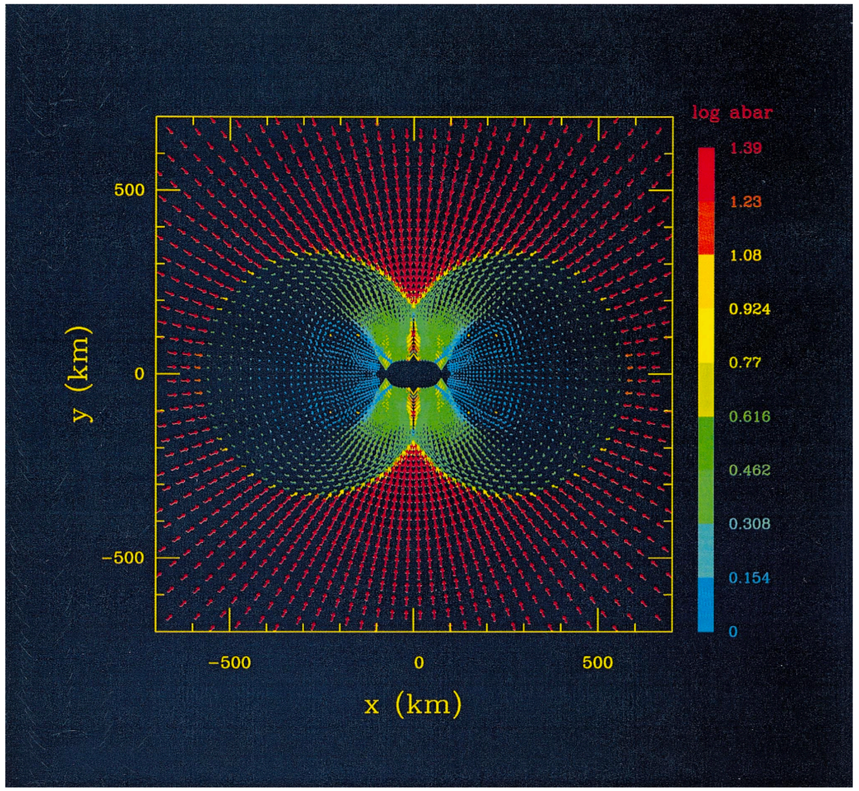
Agnieszka Janiuk (CFT, Poland) & Héctor Olivares (UA, Portugal)



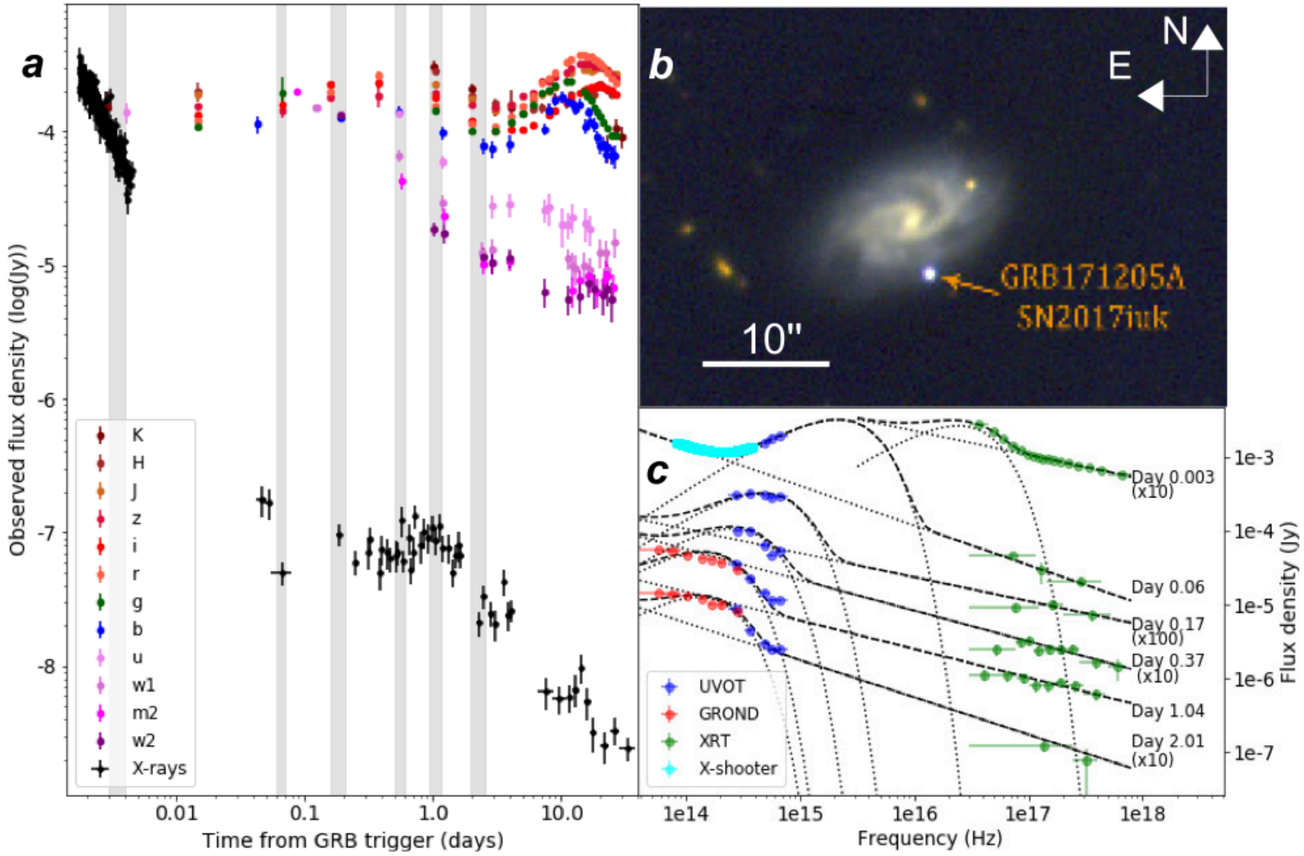
ReFCO Warsaw, May 5th 2025

GRBs from collapsars

McFadyen & Woosley 1999



Izzo et al. 2019



Long GRB Jet is a multi-scale problem

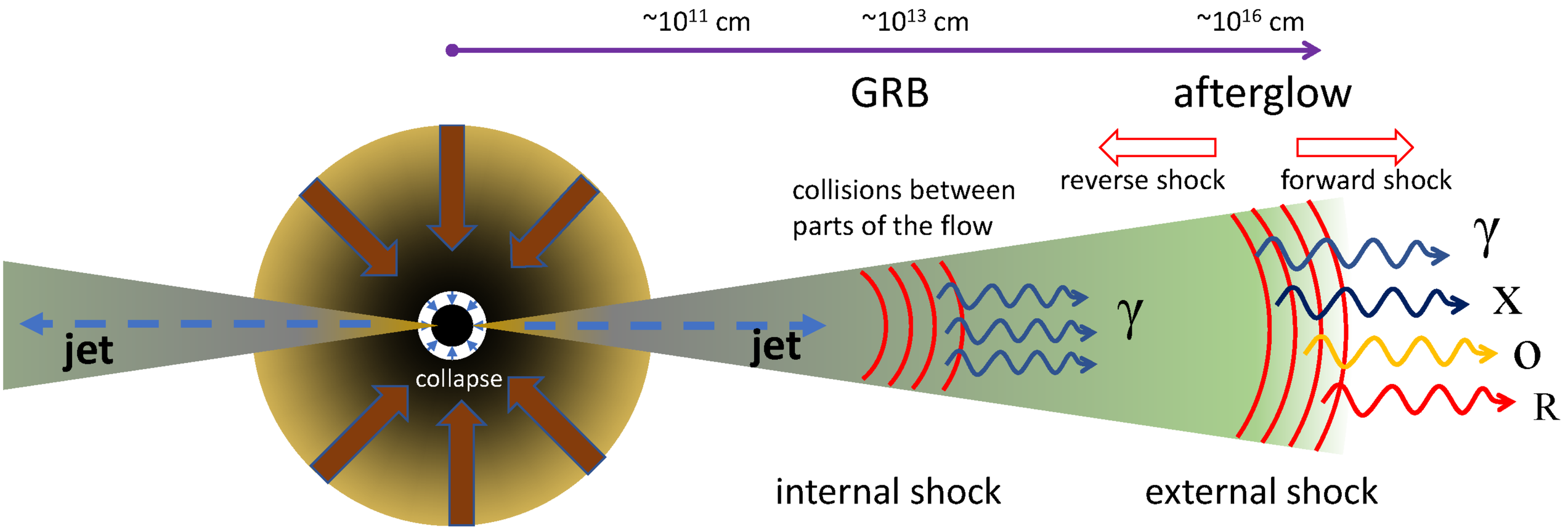


Figure Credits: Dado et al. 2022

Long GRB Jet is a multi-scale problem

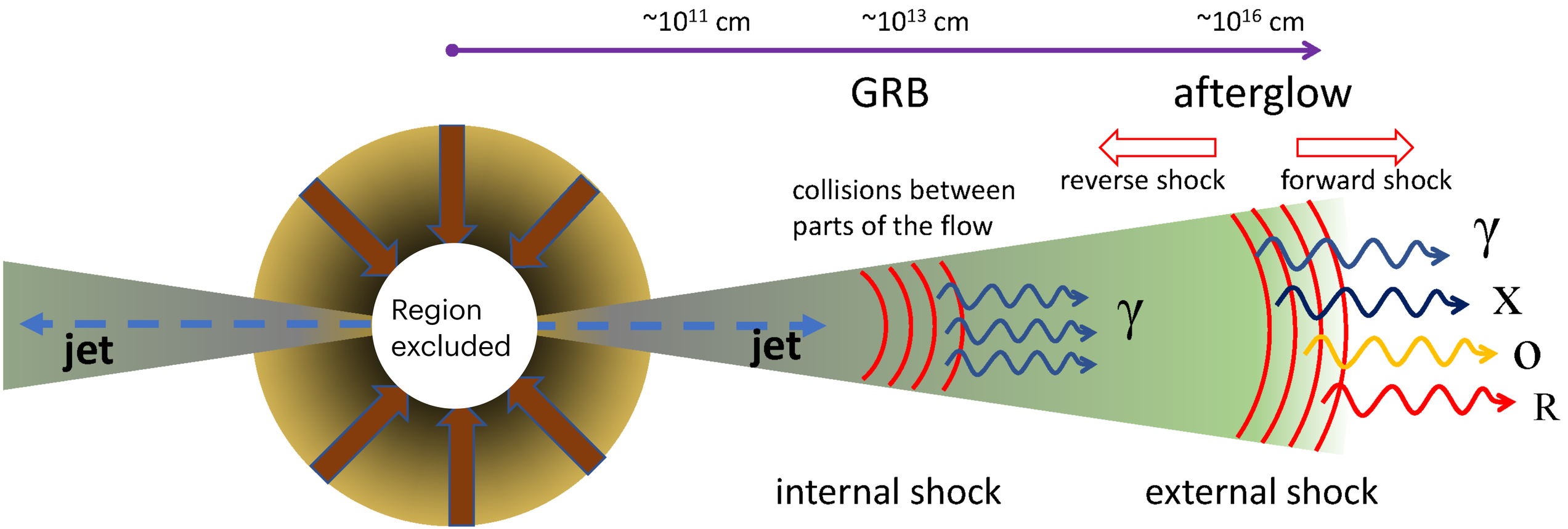
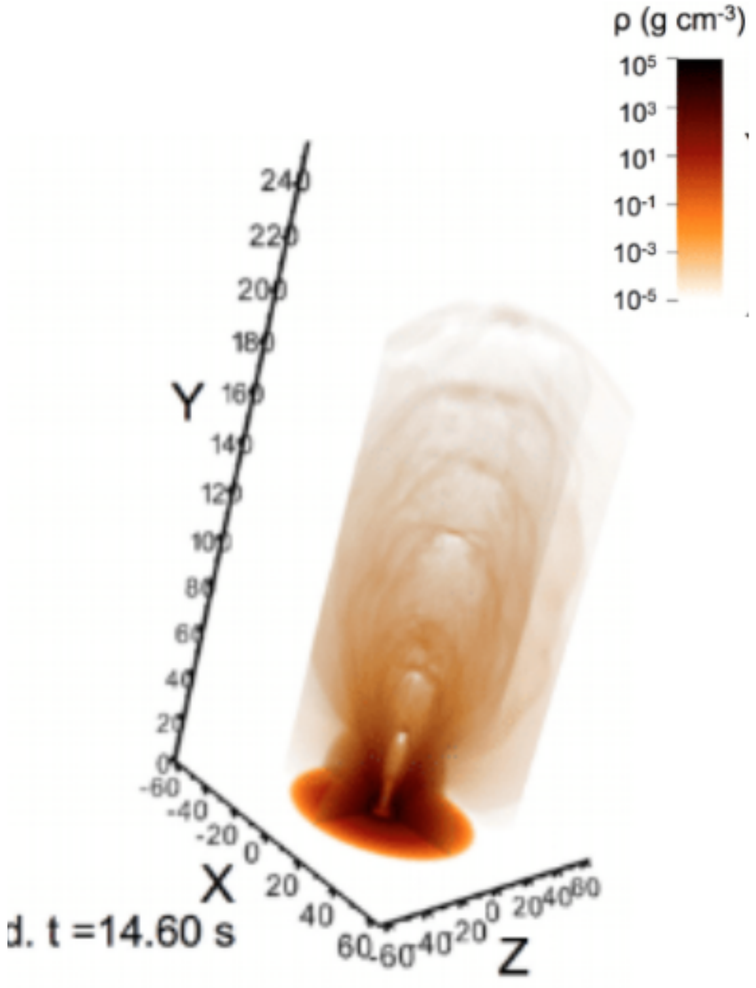


Figure Credits: Dado et al. 2022

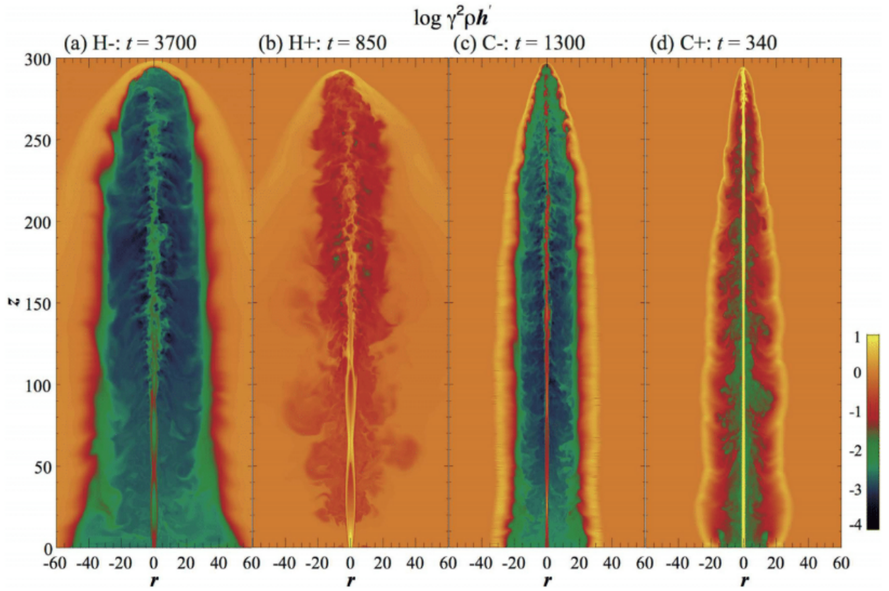
Jets launched beyond the iron core

Non symmetric Top-hat jet (variable source)



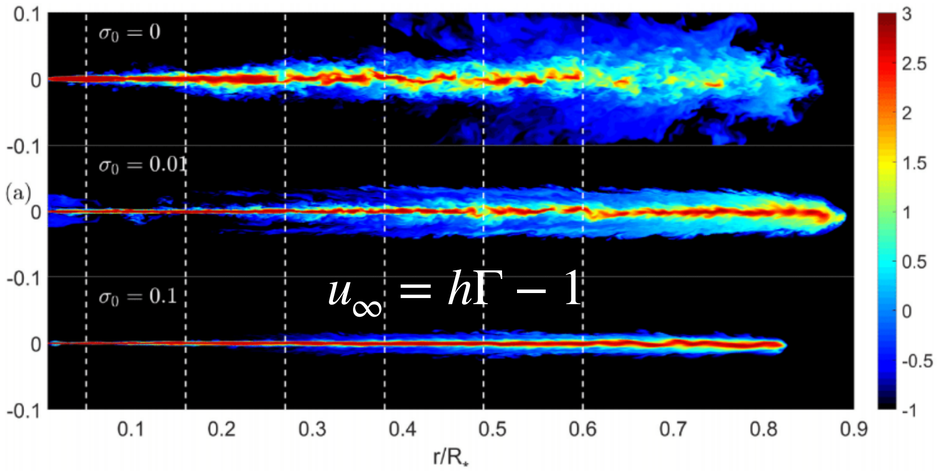
Lopez-Camara et al. 2016

Cold and pressure dominated jets



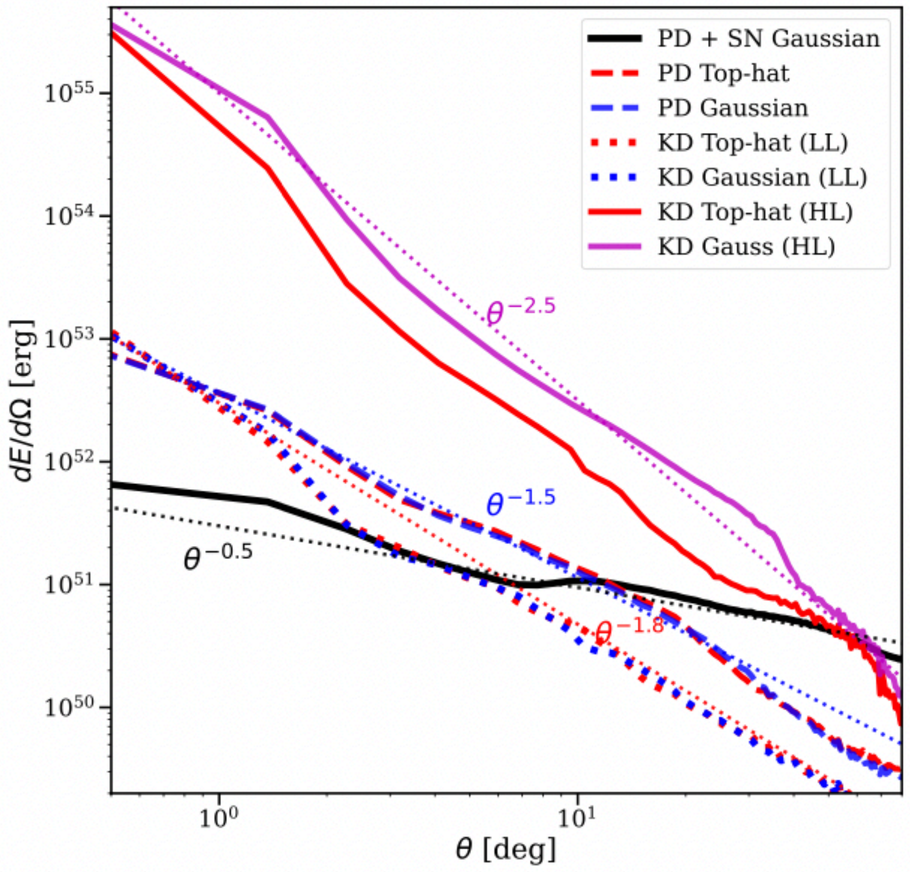
Matsumoto et al. 2019

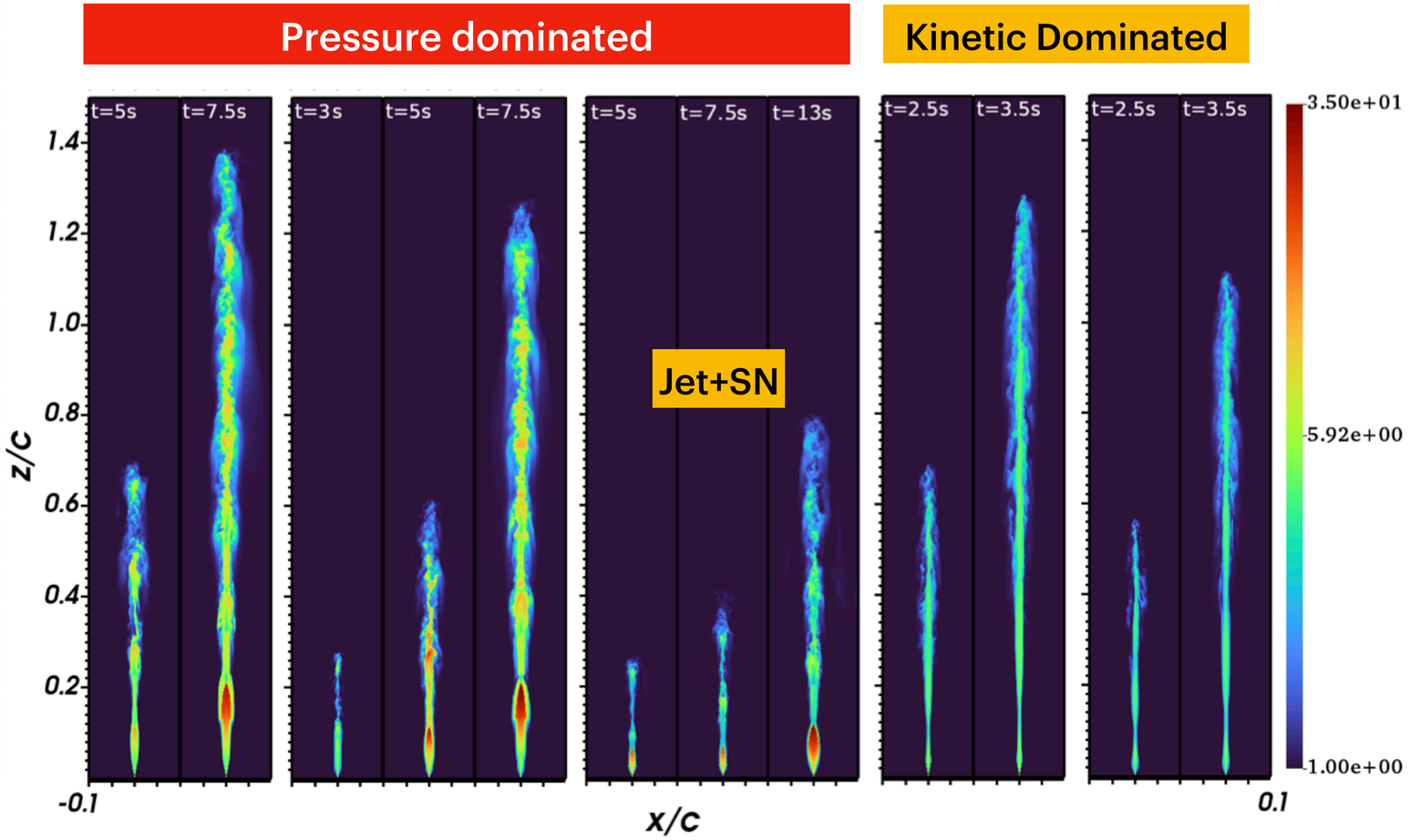
Weakly magnetized jet + variable source



Gottlieb et al. 2020

Jets beyond the iron core: jets initially structured

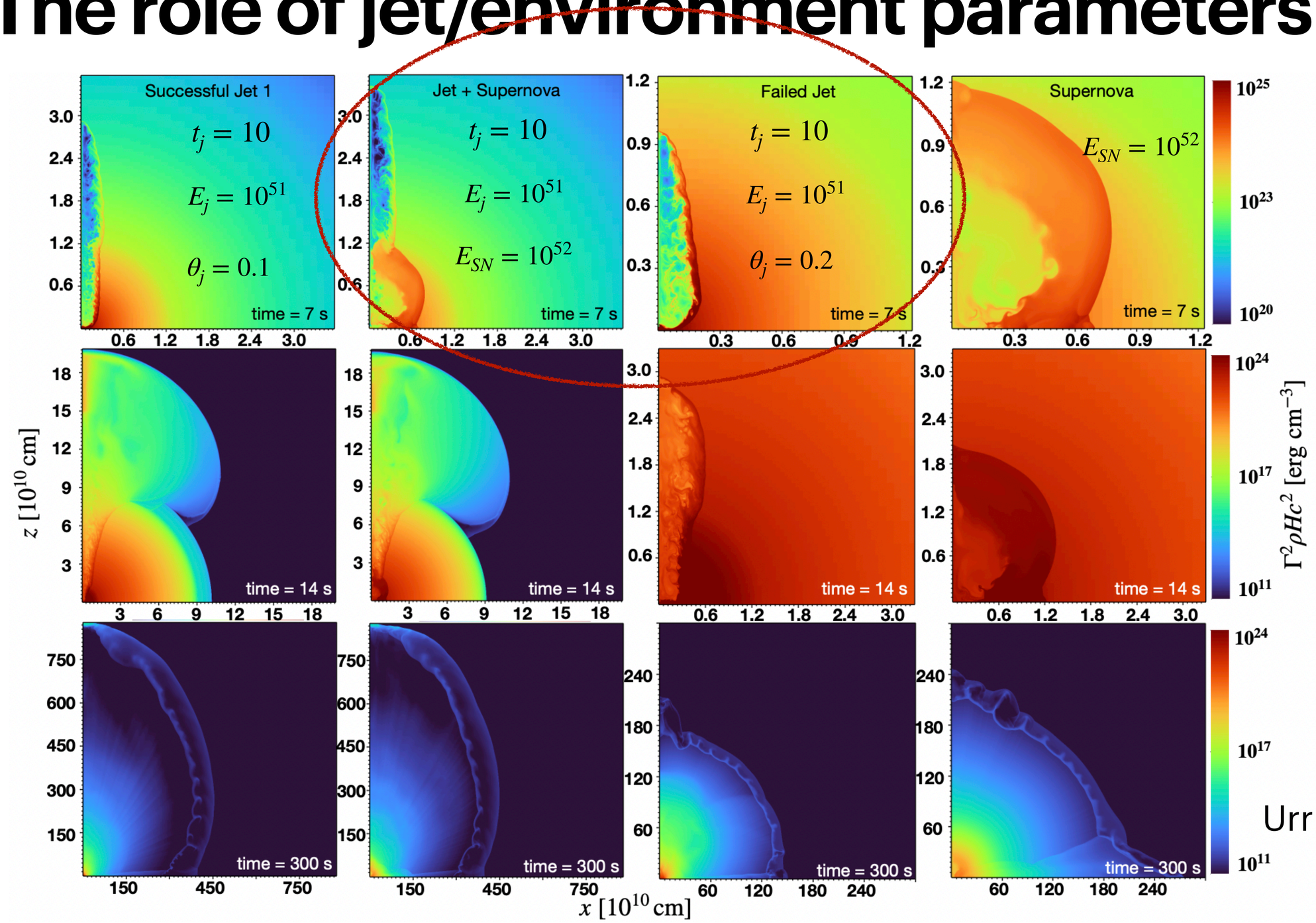




Urrutia, De Colle & Lopez-Camara 2023

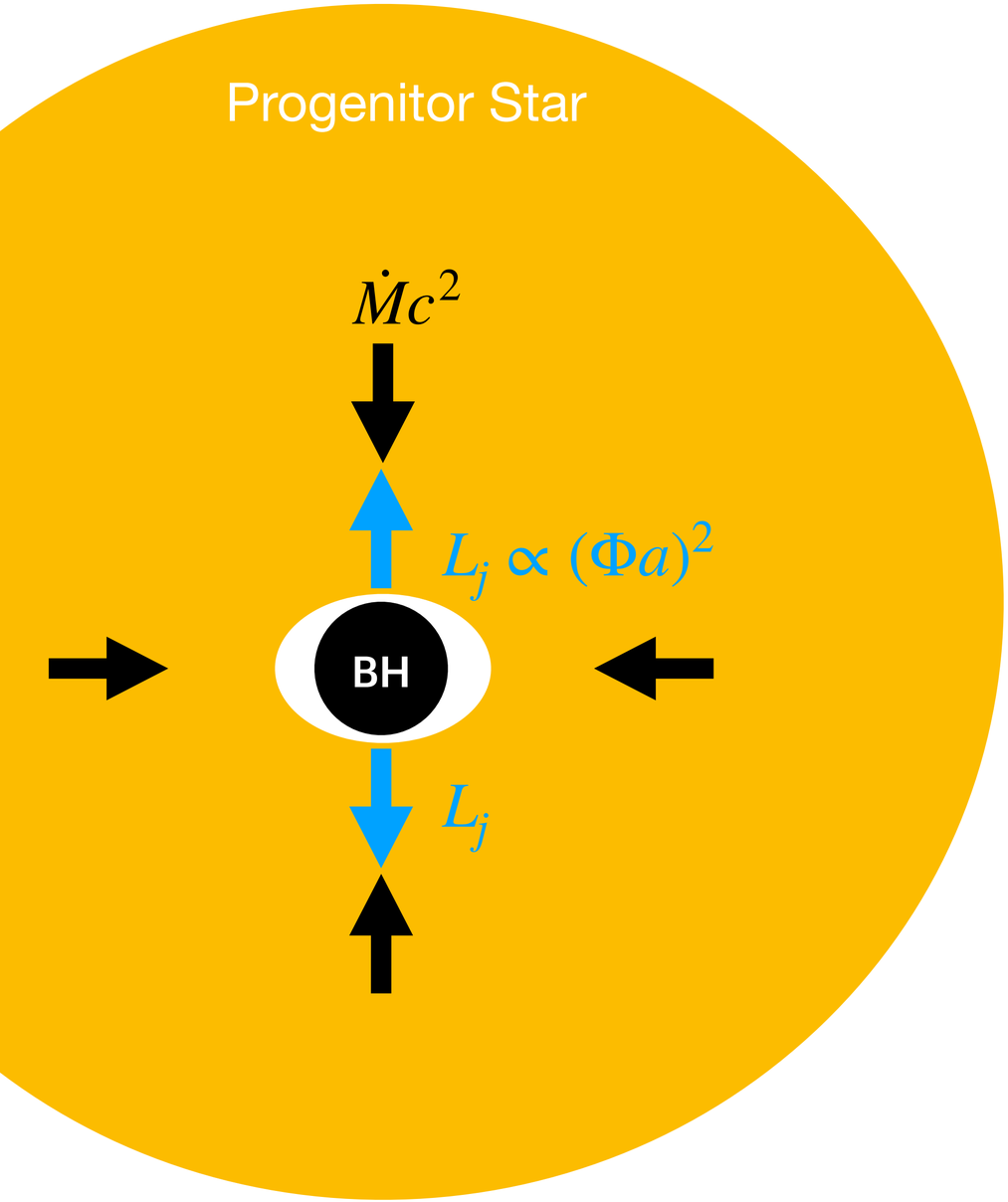
Time=0

The role of jet/environment parameters



Urrutia + 2023

Jet launching from the center



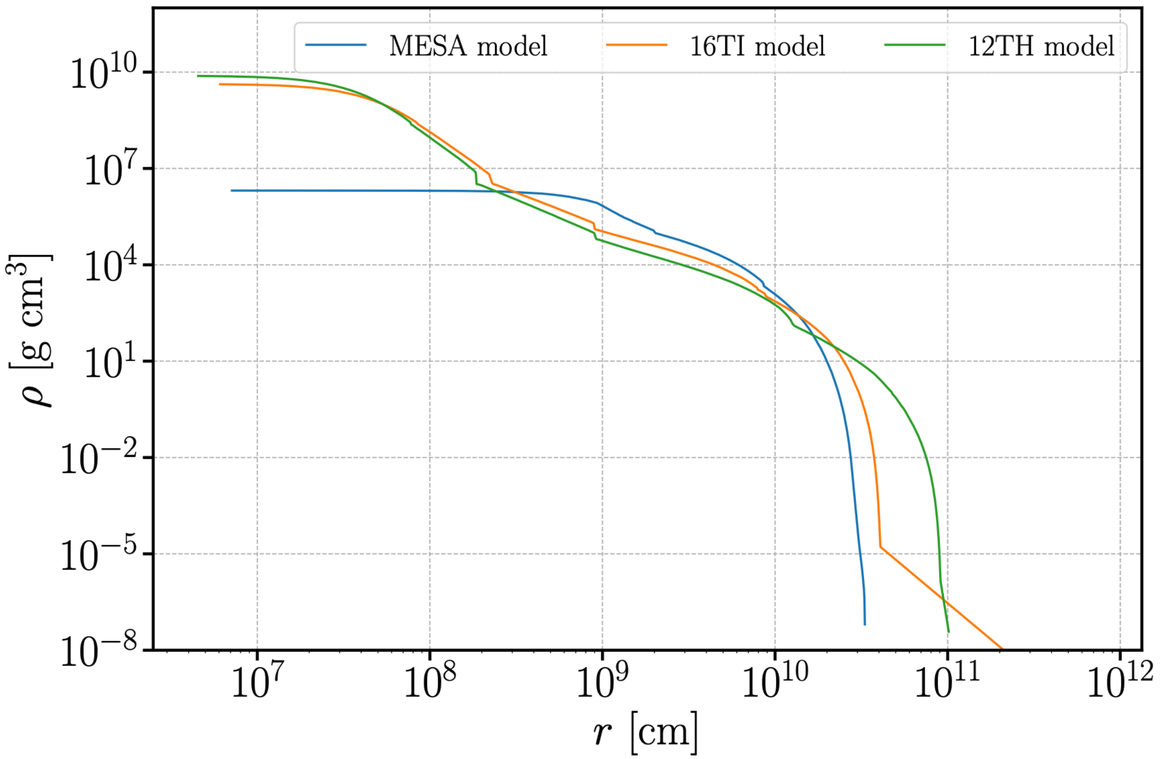
- Fast spinning BH (MacFadyen & Woosley 1999)
  - Angular moment distribution
    - Funnel

$$t_{\rm dyn} \sim 10\,{\rm s} \qquad \dot{M} \sim 0.1\,M_\odot {\rm s}^{-1}$$

- Magneto rotational core collapse (Mösta 2014; 2015; Obergaulinger & Aloy 2020; Gottlieb 2022)

$$B_0 \sim 10^{14} - 10^{15}\,{\rm G}$$

Initial conditions



Rotation

$$\epsilon_{\rm isco} = -u_{t,\rm isco} = \frac{1 - 2/r_{\rm isco} + a/r_{\rm isco}^{3/2}}{\sqrt{1 - 3/r_{\rm isco} + 2a/r_{\rm isco}^{3/2}}}$$

$$l_{\rm isco} = u_{\phi,\rm isco} = \frac{r_{\rm isco}^{1/2} - 2a/r_{\rm isco} + a^2/r_{\rm isco}^{3/2}}{\sqrt{1 - 3/r_{\rm isco} + 2a/r_{\rm isco}^{3/2}}}$$

$$u^{\phi} = C \sin^2\theta \left(-g^{t\phi}\epsilon_{\rm isco} + g^{\phi\phi} l_{\rm isco}\right)$$

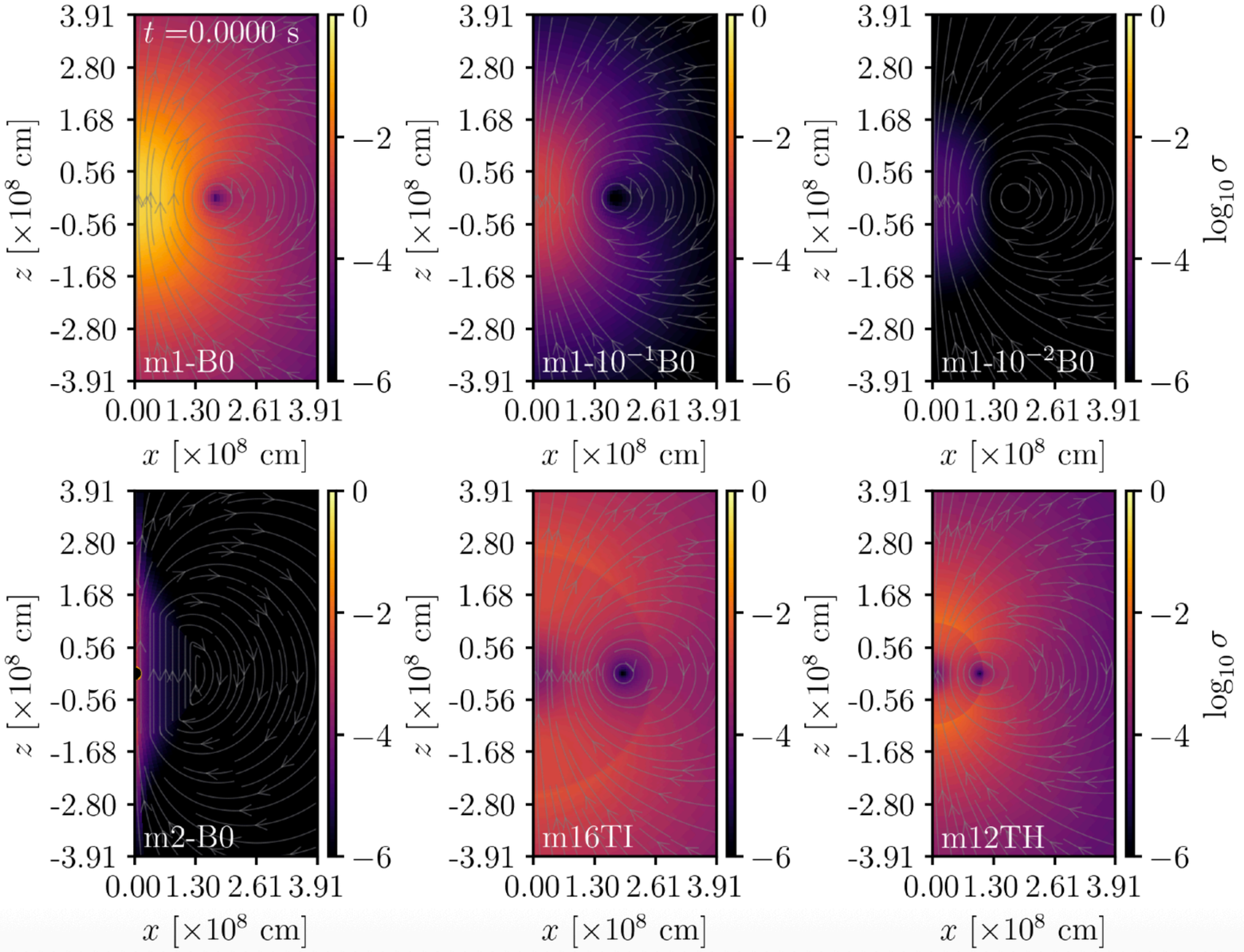
Magnetic Field Potential

$$A_{\phi} = \frac{B_0 r_c^3}{r^3 + r_0^3} \sin\theta \qquad B_0 = 10^{14}$$

We are remapping the stelar profile in BHAC code (Porth + 2017; Olivares + 2019)

Initial conditions

Model	Star Progenitor	$\rho^{\star}_{\rm max}$ [g cm^{-3}]	M_{BH}	B_0 [G]
m1-B0	MESA	2×10^6	$5M_\odot$	10^{14}
m1-10^{-1}B0				10^{13}
m1-10^{-2}B0				10^{12}
m2-B0	MESA	2×10^6	$5M_\odot$	B_0
m16TI	16TI	4×10^9	$3M_\odot$	10^{14}
m12TH	12TH	8×10^9		10^{14}
m1-zero	MESA	2×10^6	$5M_\odot$	Zero



Jet evolution

Model	Star Progenitor	$\rho^{\star}_{\rm max}$ [g cm^{-3}]	M_{BH}	B_0 [G]
m1-B0	MESA	2×10^6	$5M_\odot$	10^{14}
m1-10^{-1}B0				10^{13}
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m2-B0	MESA	2×10^6	$5M_\odot$	B_0
m16TI	16TI	4×10^9	$3M_\odot$	10^{14}
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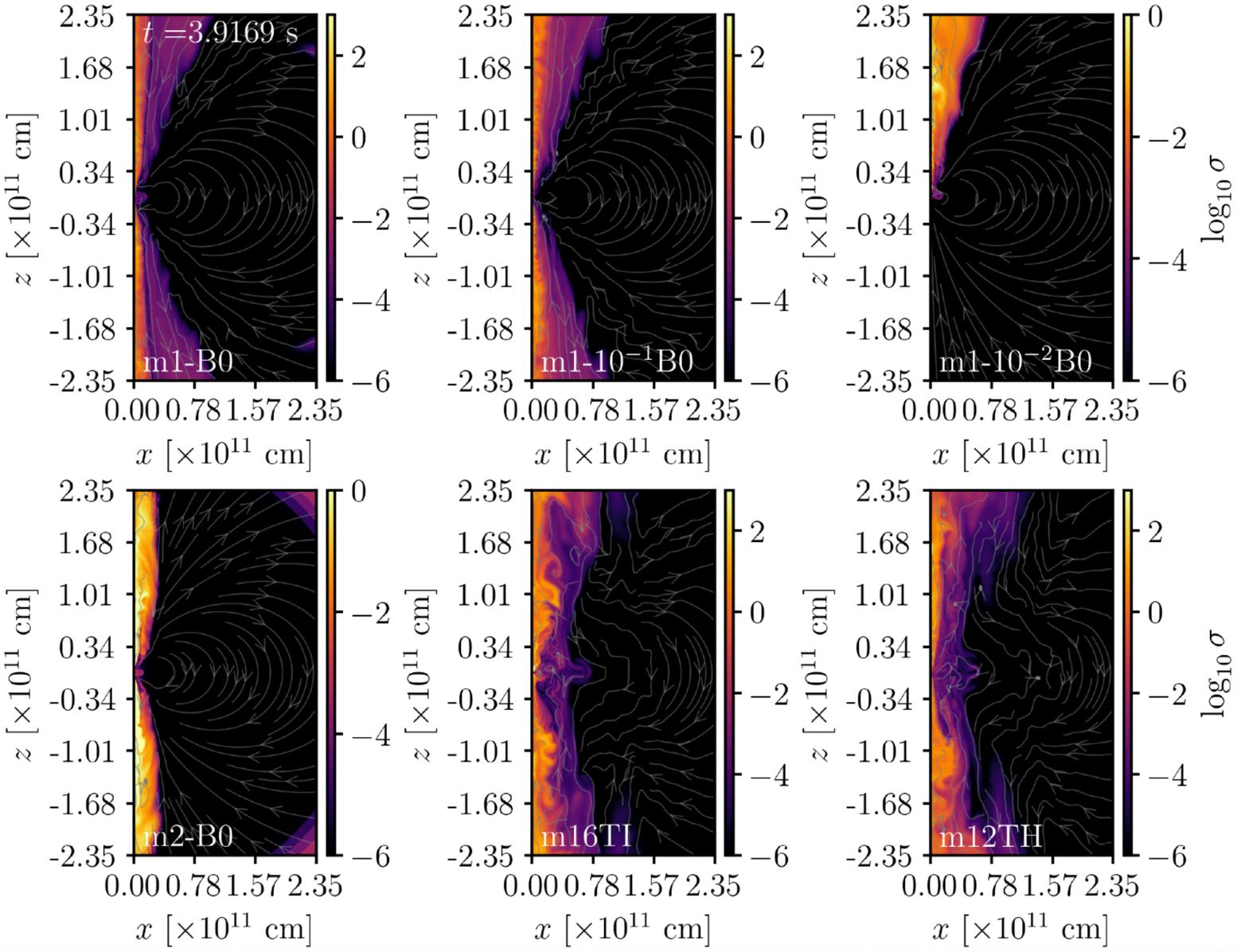
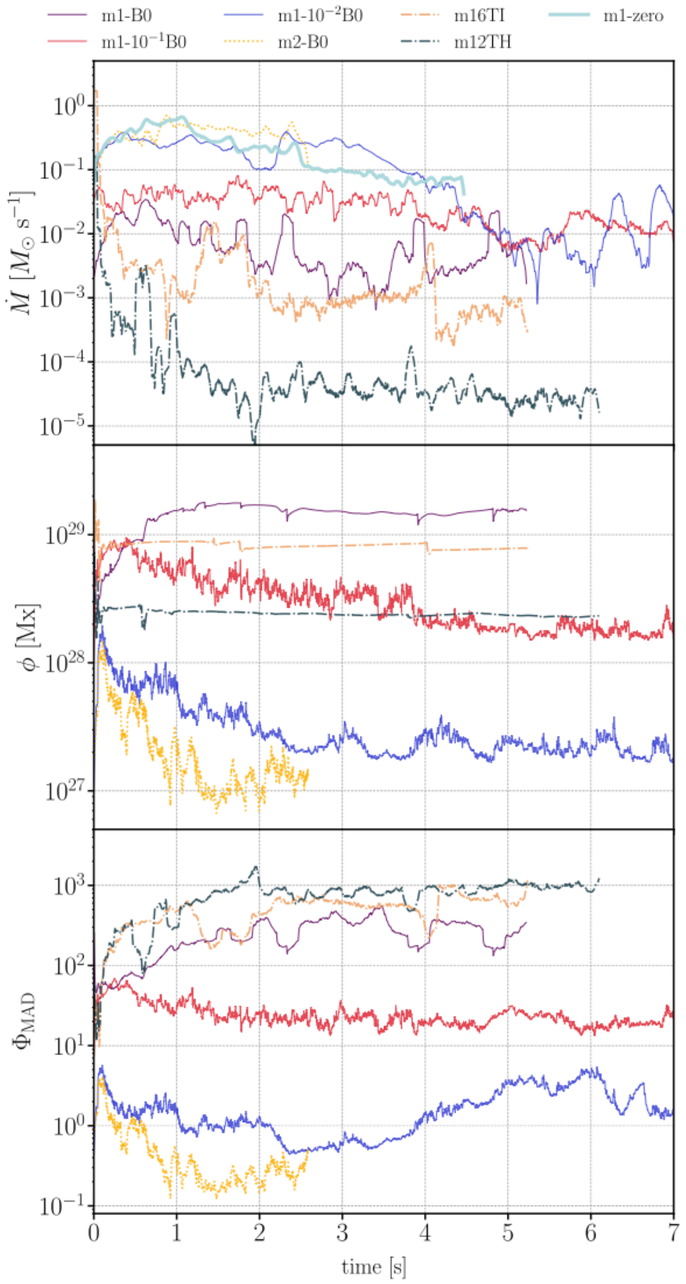
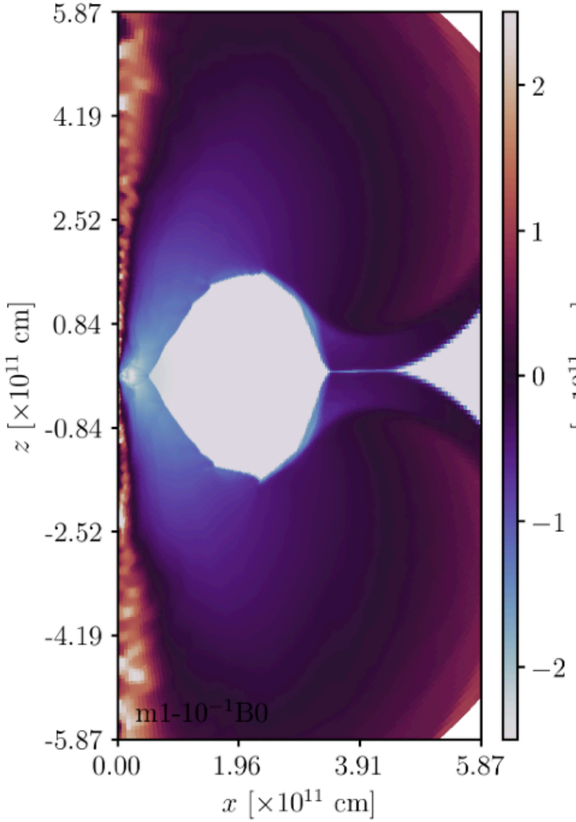


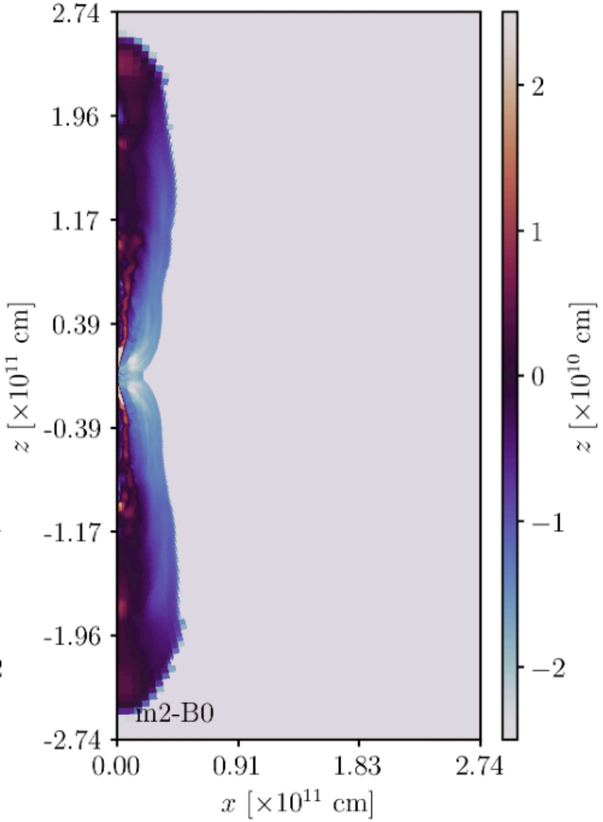
Jet evolution



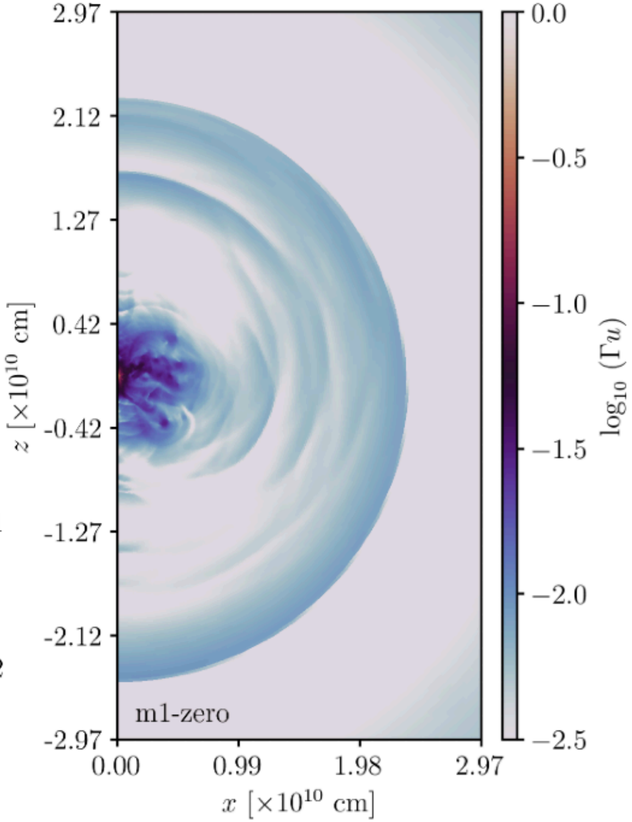
High magnetized

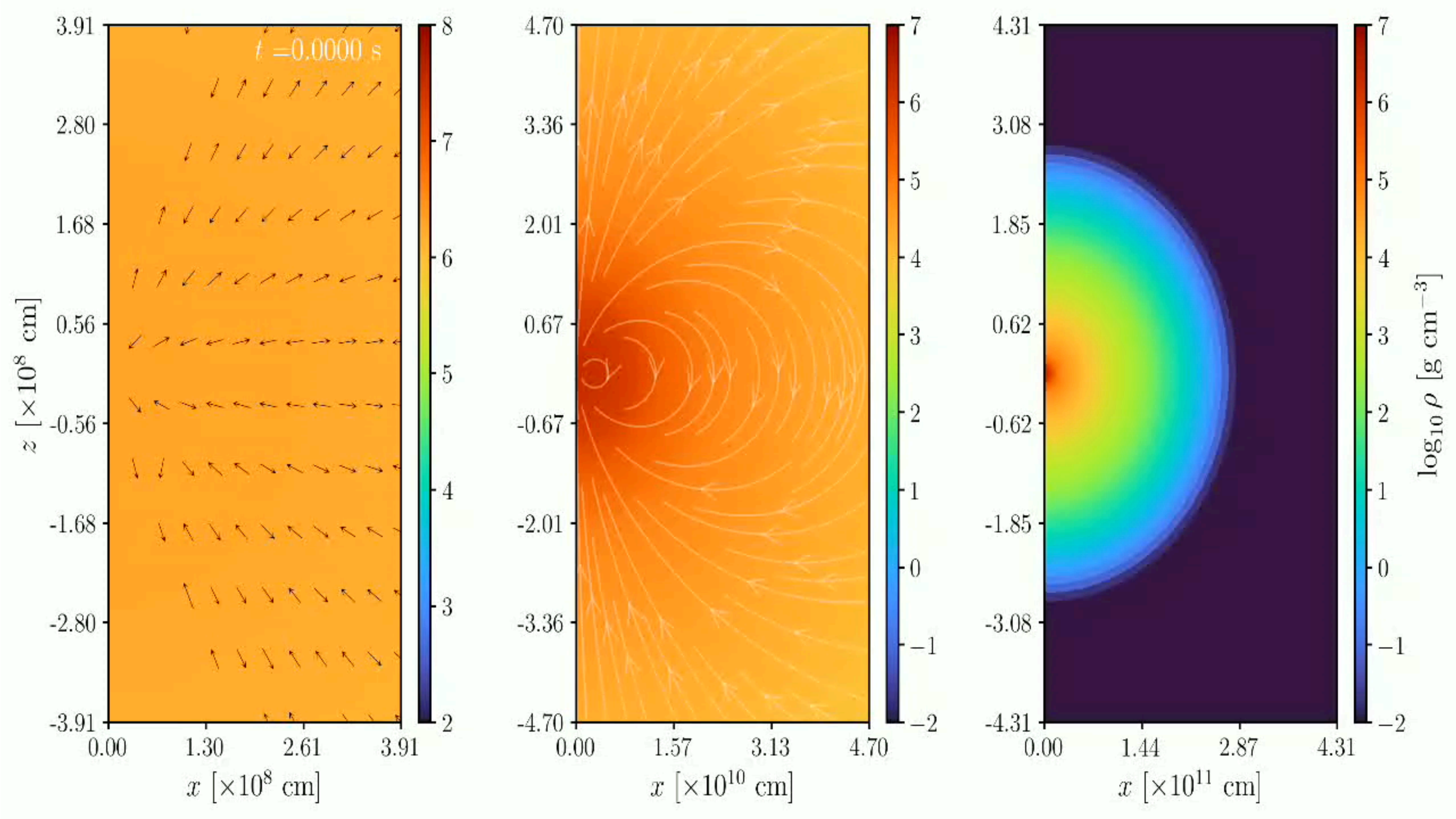


Weakly magnetized

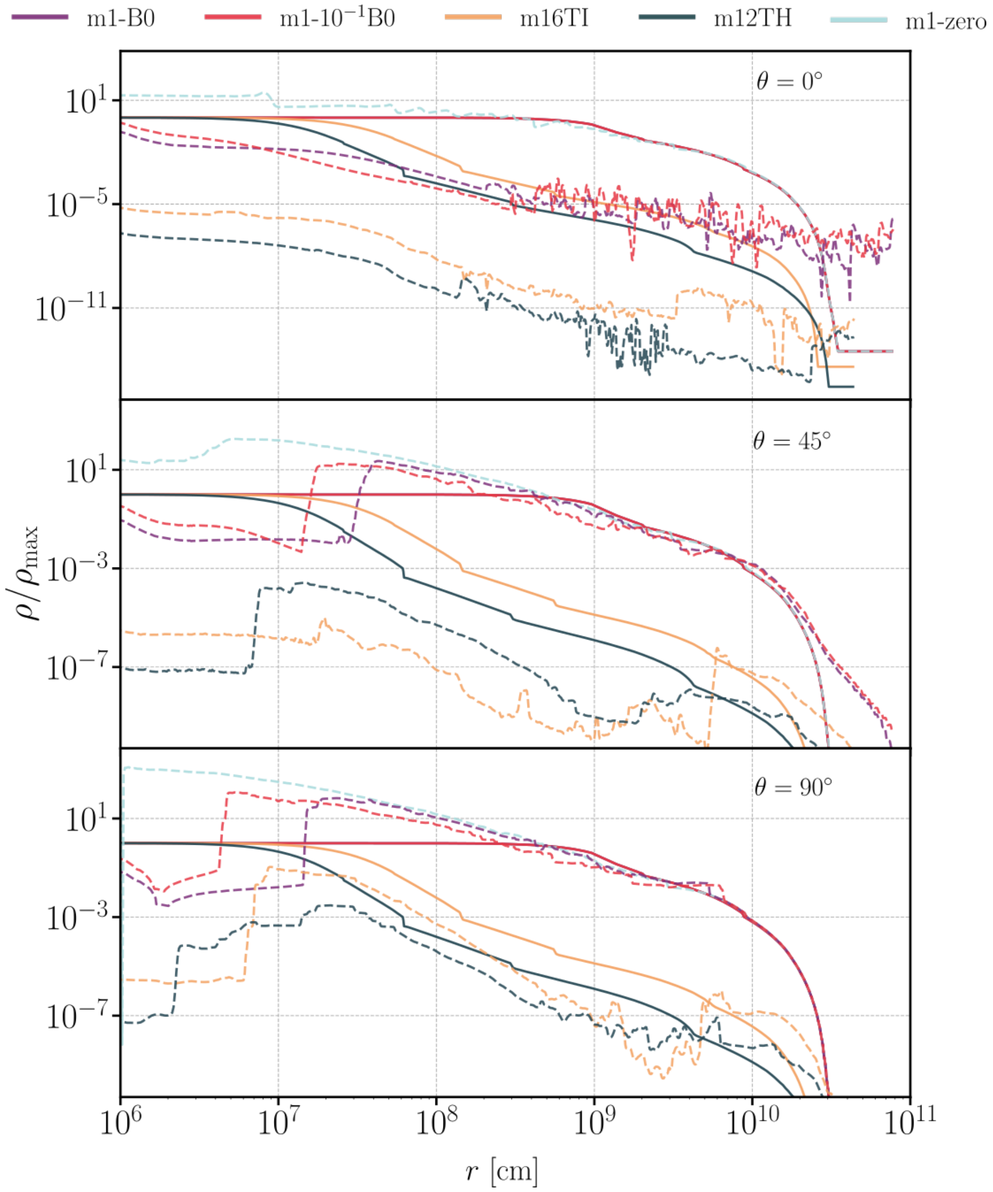


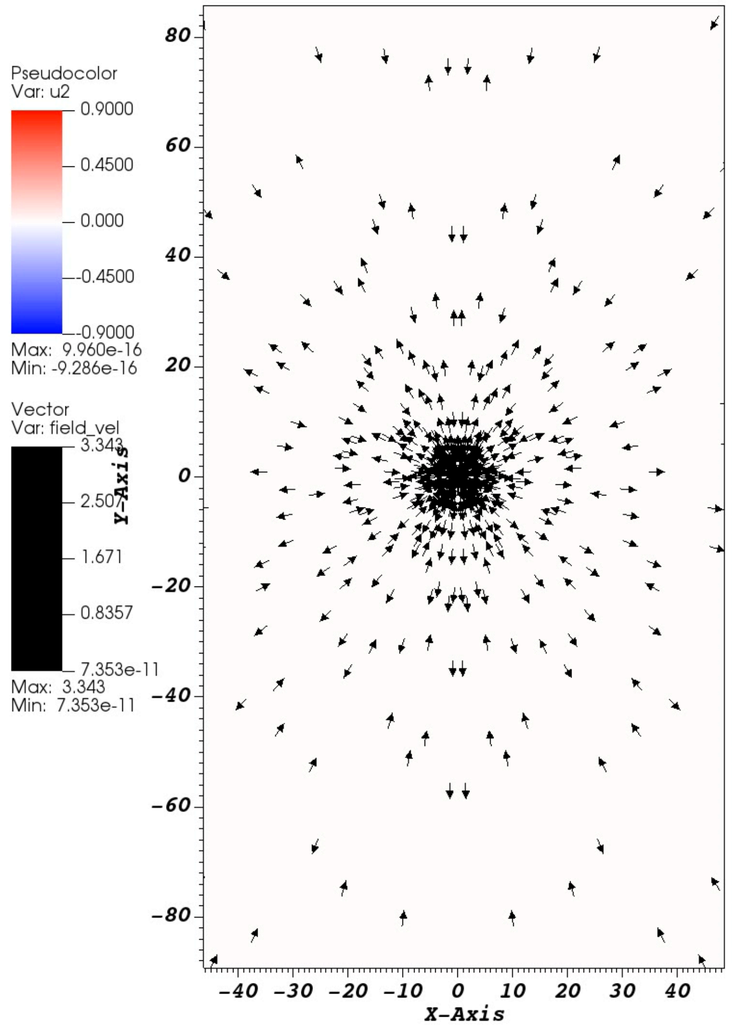
Non magnetized




t =0.0000 s
3.91
2.80
1.68
0.56
-0.56
-1.68
-2.80
-3.91
z [×10^8 cm]
0.00
1.30
2.61
3.91
x [×10^8 cm]
8
7
6
5
4
3
2
4.70
3.36
2.01
0.67
-0.67
-2.01
-3.36
-4.70
0.00
1.57
3.13
4.70
x [×10^10 cm]
7
6
5
4
3
2
1
0
−1
−2
4.31
3.08
1.85
0.62
-0.62
-1.85
-3.08
-4.31
0.00
1.44
2.87
4.31
x [×10^11 cm]
7
6
5
4
3
2
1
0
−1
−2
log10 ρ [g cm^−3]

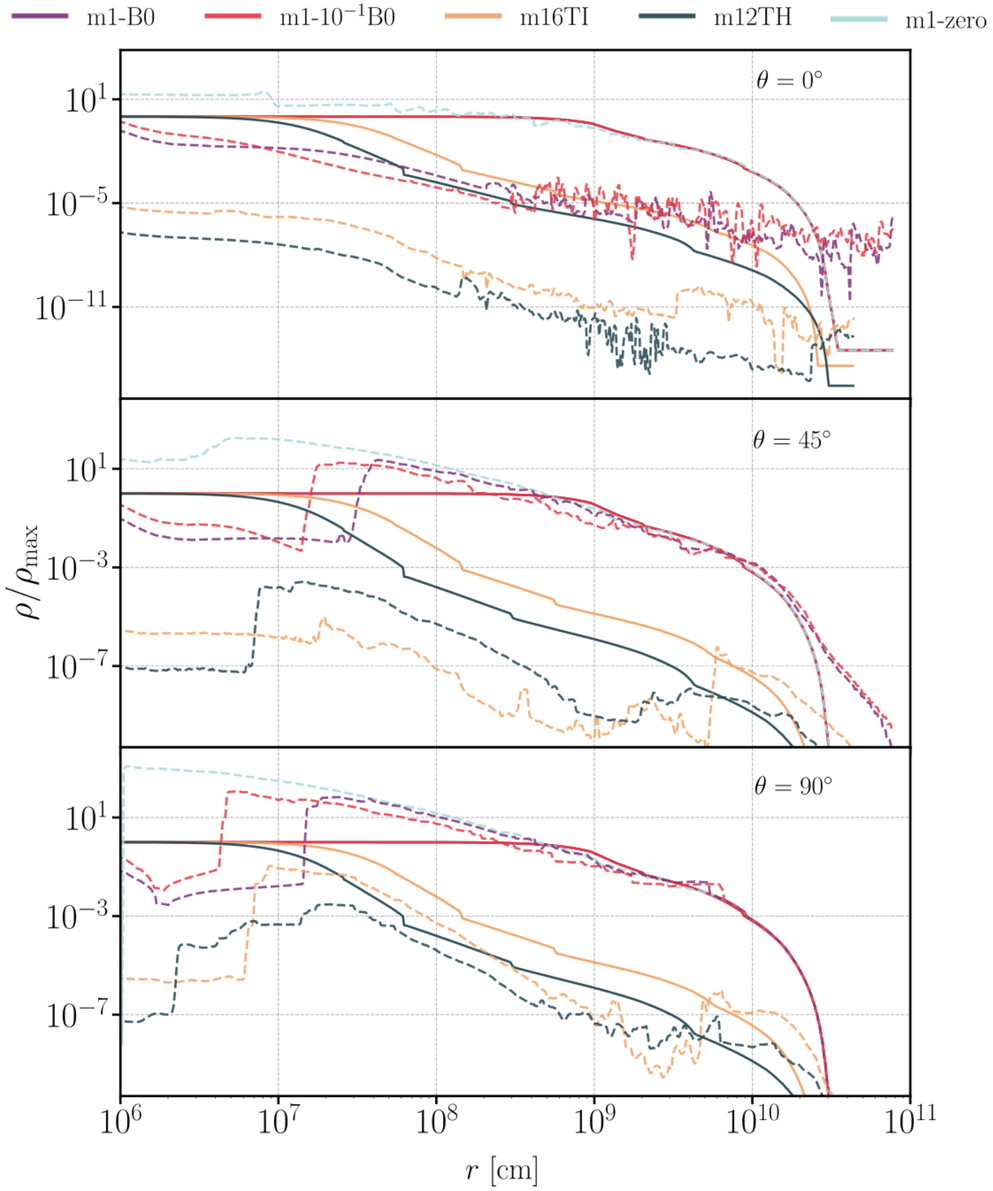
Evolution of the progenitor structure

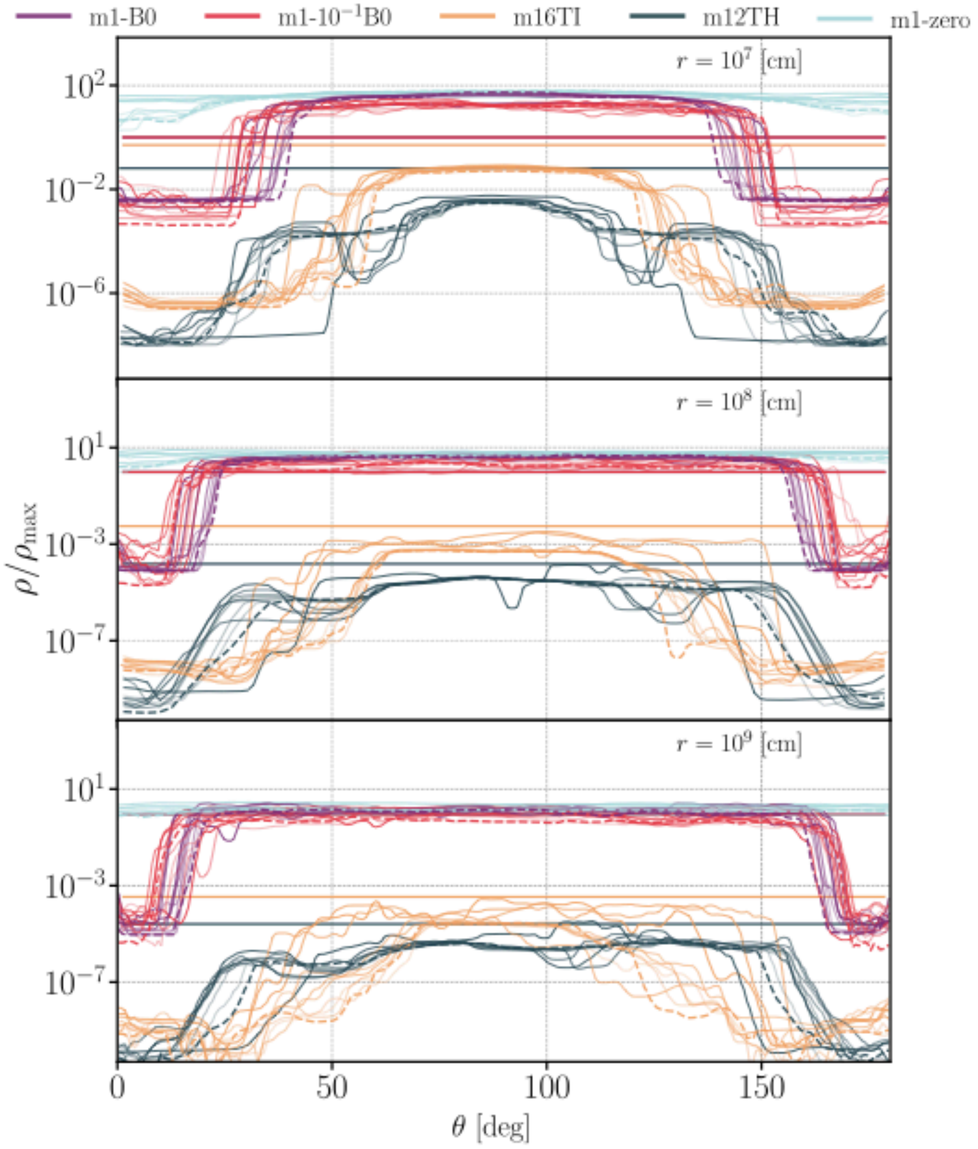




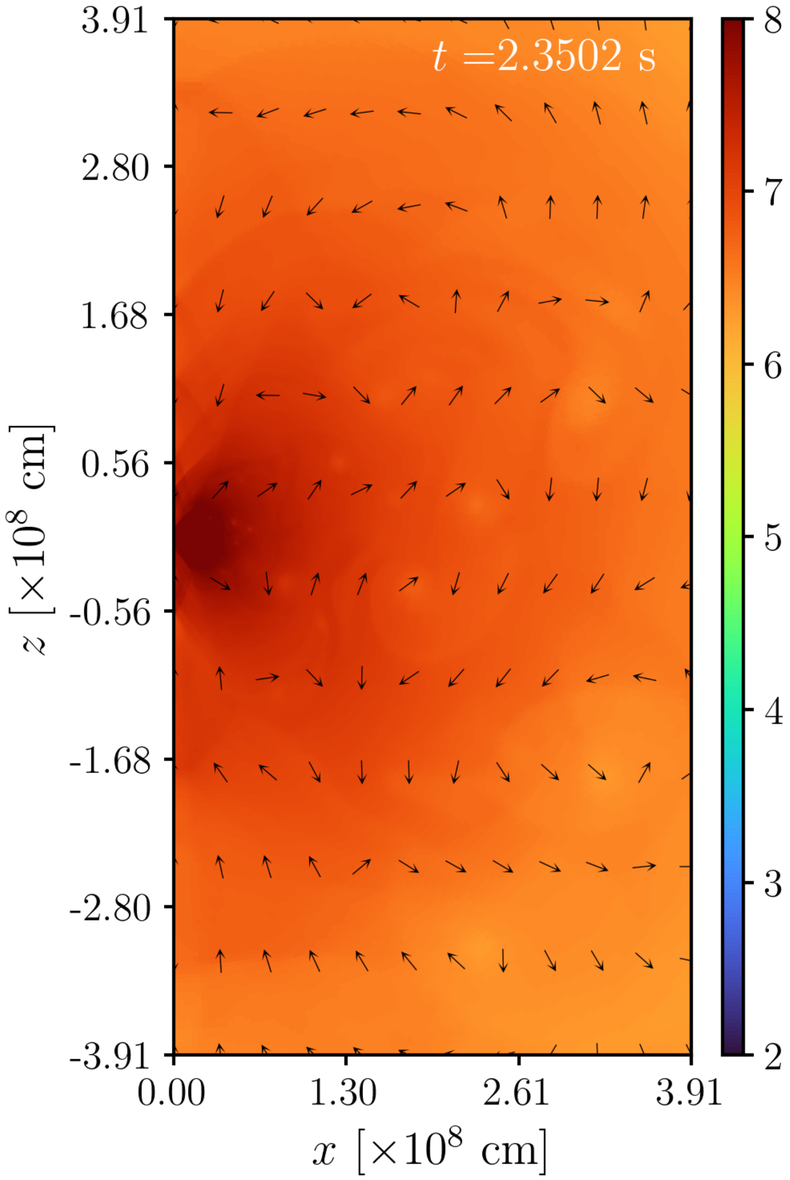
Time=0

Evolution of the progenitor structure

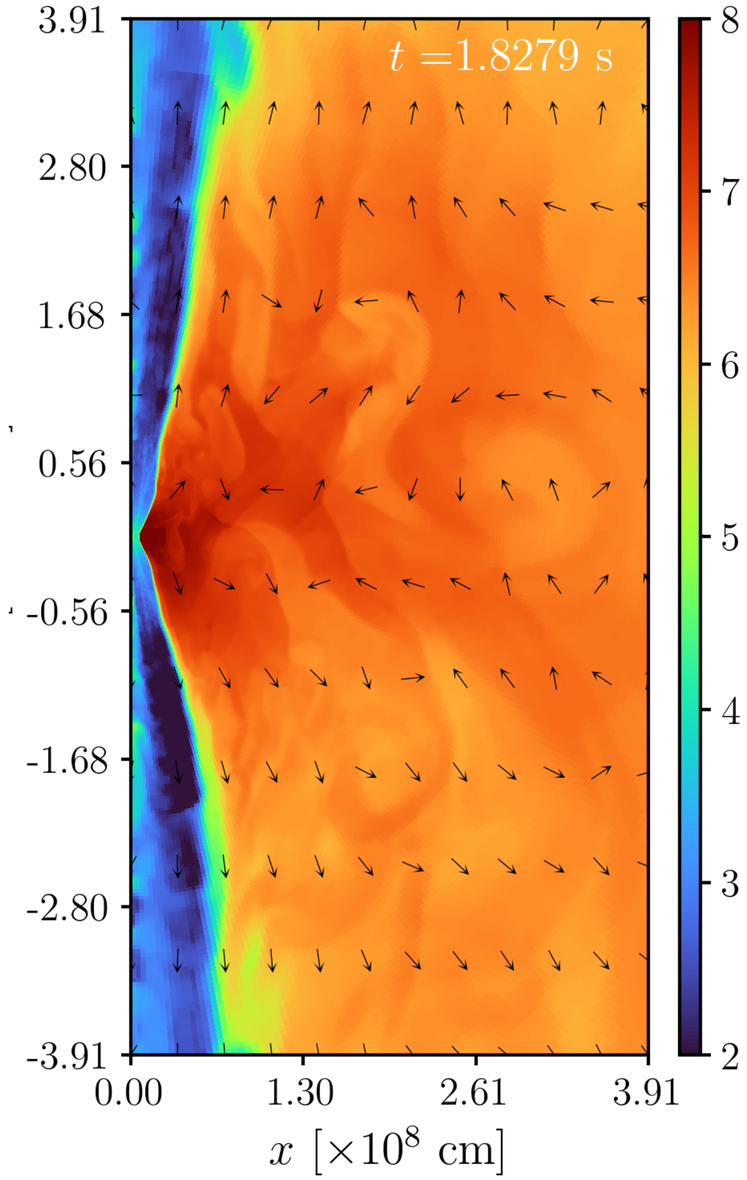




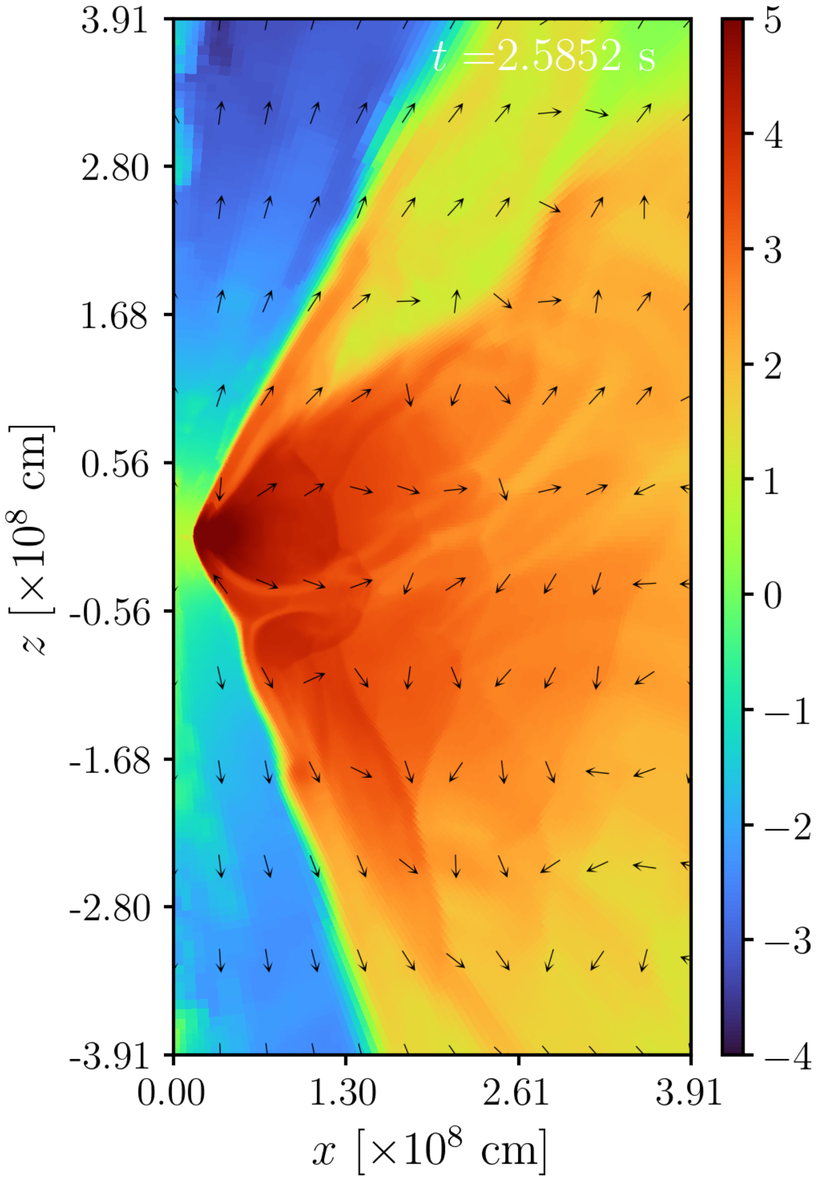
No B field



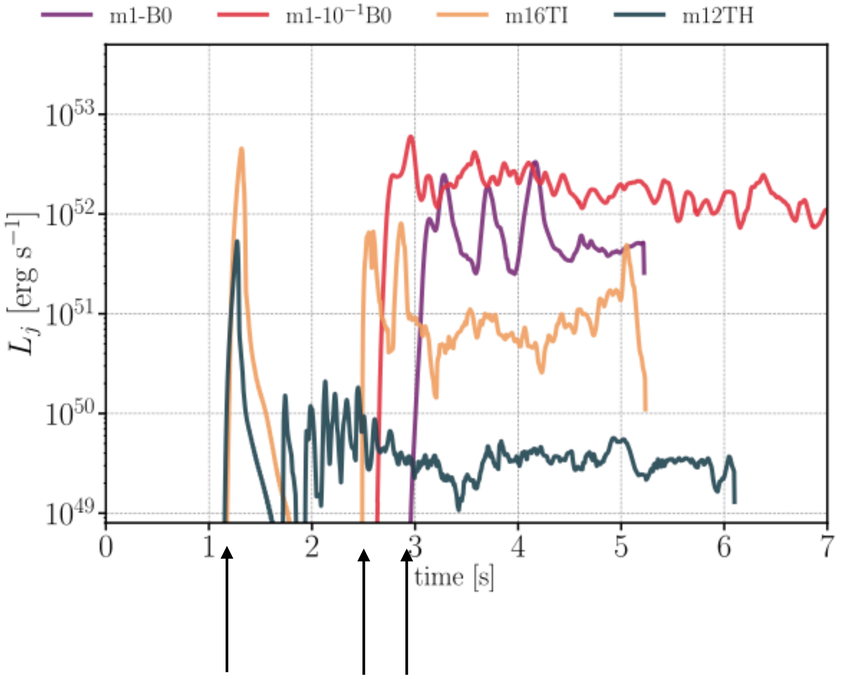
Mesa progenitor



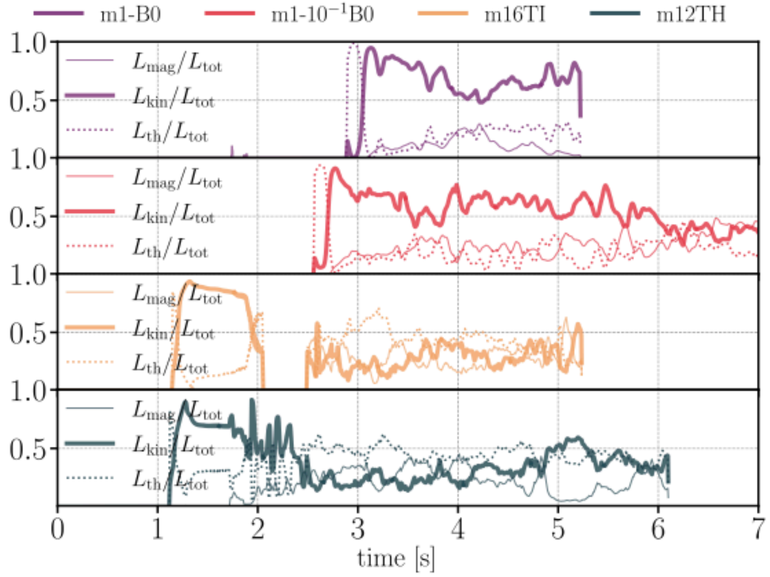
16TI progenitor

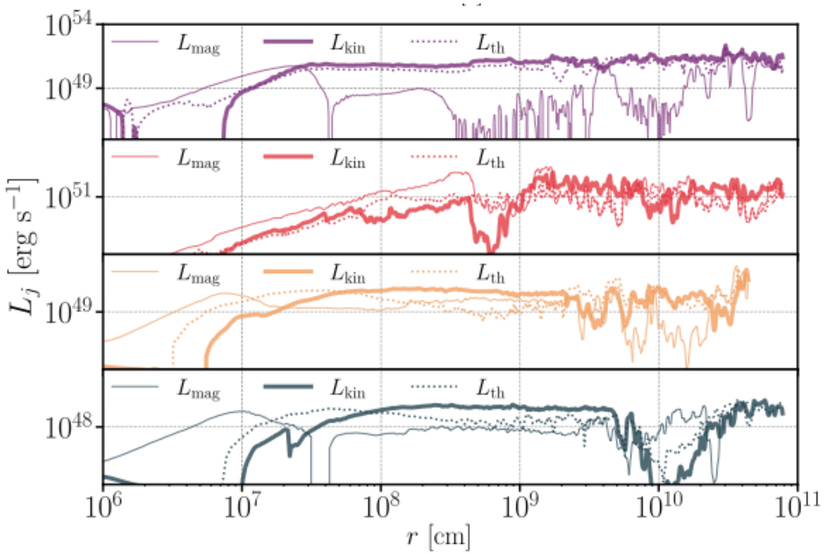


Energy components



Breakout time

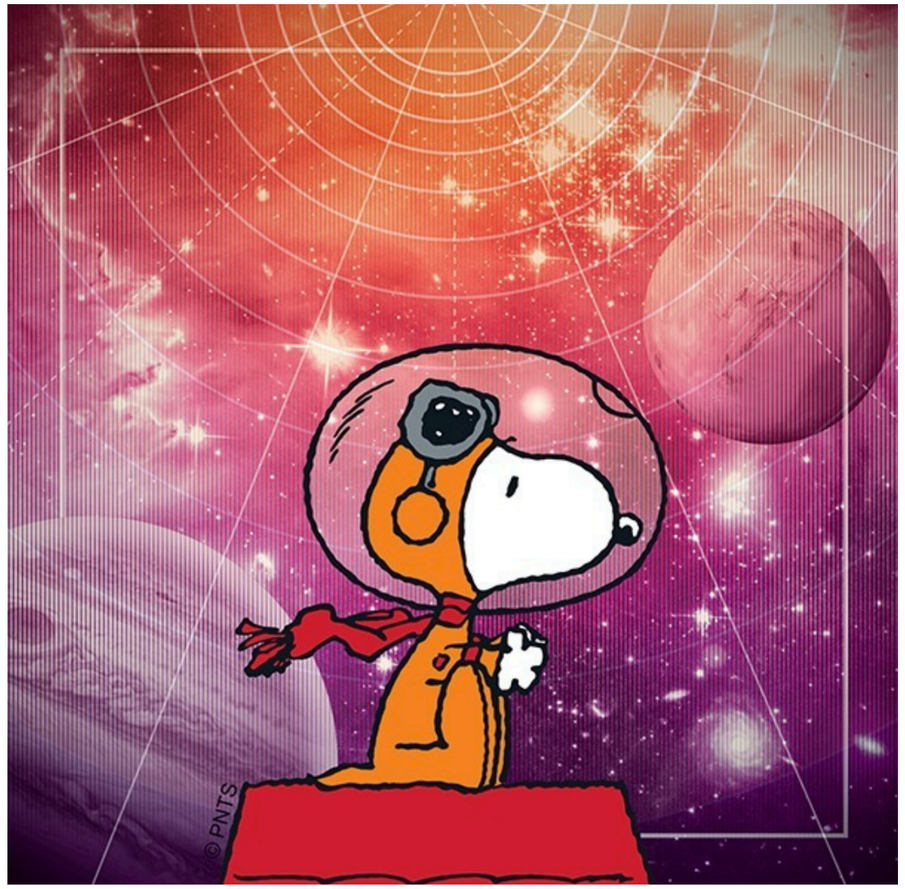




Summary

- The structure of the progenitor affects: magnetization and properties of the central engine such as, history luminosity and jet funnel.
- Luminosities and accretion rates were affected by the magnetic field strength.
- For jet collimation the magnetization of the jet plays an important role to drilling the inner higher density. The Kinetic jets were not found on this study.
- We obtain very short jet-breakout times because the magnetization increase the acceleration of the jet head.

Dziękuję - Thank you! - ¡Gracias!



Gerardo Urrutia

gurrutia@cft.edu.pl

gerardourrutia.com

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