Exploring collapsar scenarios in numerical relativity

Masaru Shibata

YUKAWA INSTITUTE FOR THEORETICAL PHYSICS

Max Planck Institute for Gravitational Physics at Potsdam
& Yukawa Institute for Theoretical Physics, Kyoto U.

Collaborators: S. Fujibayashi, Alan T.L Lam, Y. Sekiguchi, K. Ioka

Based on arXiv:2212.03958, 2309.02161, 2309.12086

12.05.2024 @Dream field, China

Numerical relativity 2020s

$$G_{\mu\nu} = 8\pi \frac{G}{c^4} T_{\mu\nu}$$

- Einstein's equation: Established

$$\begin{Bmatrix} \nabla_\mu T^\mu_\nu = 0 \\ \nabla_\mu\left(\rho u^\mu\right) = 0 \end{Bmatrix}$$

- Hydrodynamics/Magntohydrodynamcis/ Radiation hydrod/viscous hydro: Many good codes
- Maxwell's equation; Ideal MHD → induction equation: Many good codes (as well as poor ones)

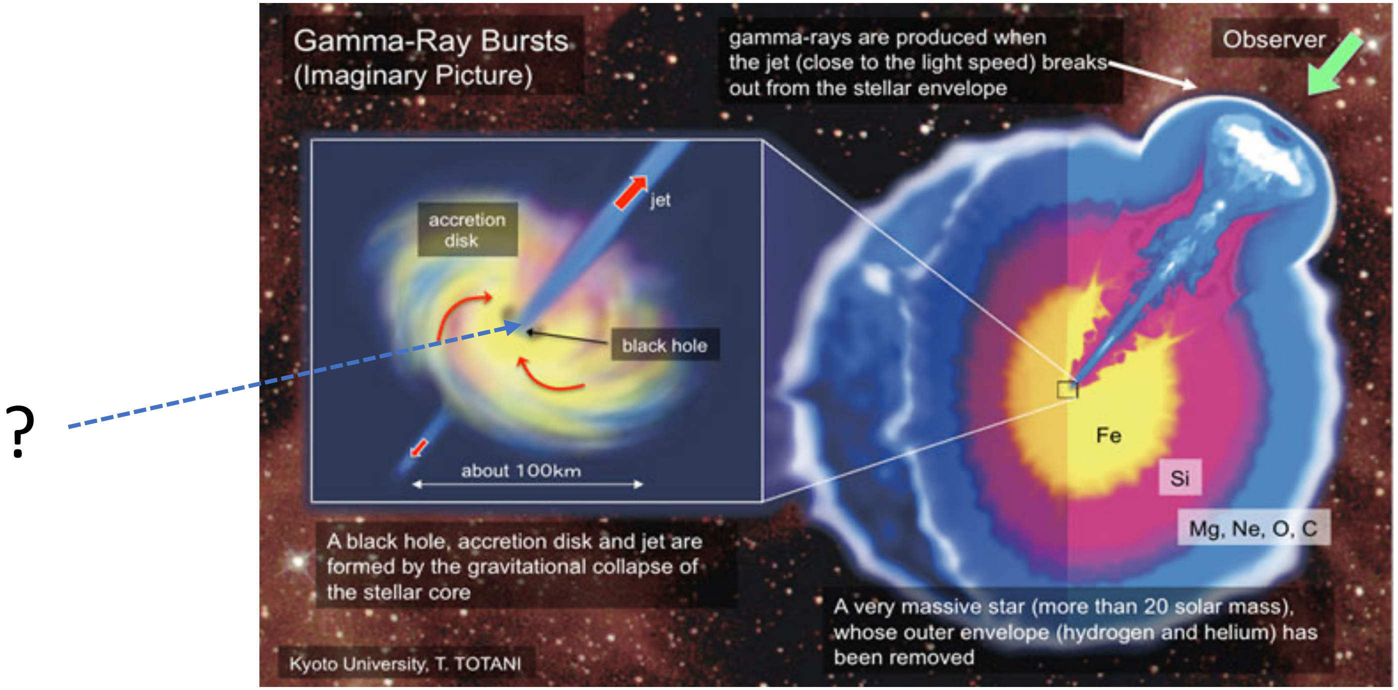
$$\begin{pmatrix} \nabla_\mu F^{\mu\nu} = -4\pi j^\nu \\ \nabla_{[\mu} F_{\nu\lambda]} = 0 \\ \text{Radiation} \quad ..... \end{pmatrix}$$

- Neutrino radiation transfer: Last frontier but several approximate solvers, e.g., M1 scheme, are available

+ powerful HPC (>10 PFlops): available

Now we can now apply NR to a variety of high-energy astrophysical phenomena

I **Introduction**: long gamma-ray bursts



?

Credit: Totani

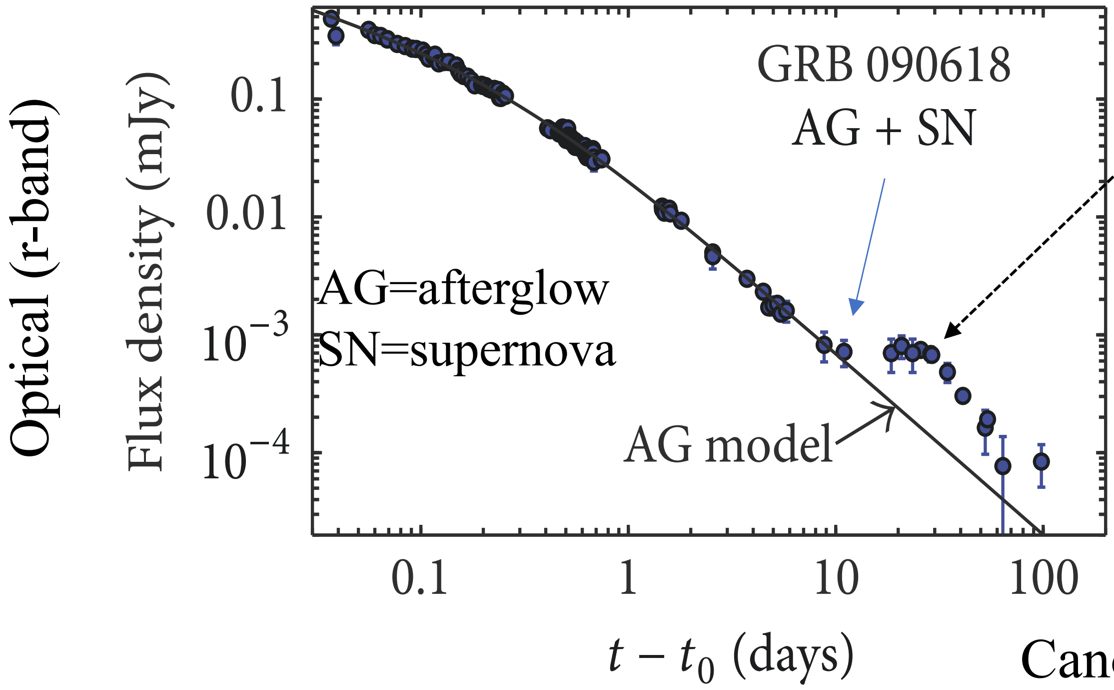
- Real Energy ~ $10^{51\pm1}$ erg (isotropic ~ $10^{53\pm1}$ erg)
- Duration ~ a few—100 sec; luminosity ~ $10^{49—51}$ erg/s
  → Relativistic phenomena

cf $L_{\mathrm{sun}}=4*10^{33}$ erg/s

- Event rate ~ 10^{-4} of ordinary supernovae

I **Introduction**: long gamma-ray bursts

- Some of them are associated with high-energy SNe



Significant ^{56}Ni production, with >0.1 solar mass, and radio active heating

$^{56}\mathrm{Ni} \rightarrow {}^{56}\mathrm{Co} \rightarrow {}^{56}\mathrm{Fe}$

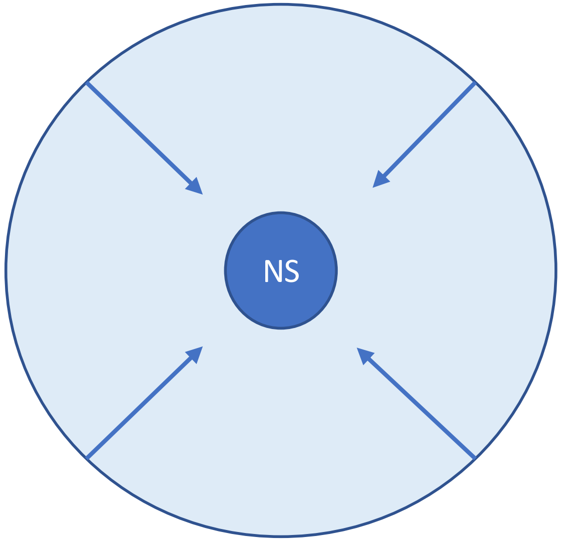
Cano et al. 2017

- Promising engine = Collapsar ~ rotating stellar core collapse to a BH + jet (Woosley 1993)
- However, detailed mechanism is still uncertain

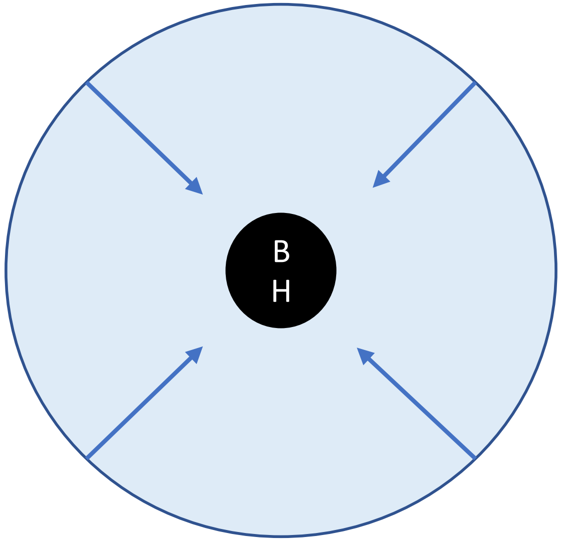
Rotating black hole formation & explosion

Naïve qualitative scenario is

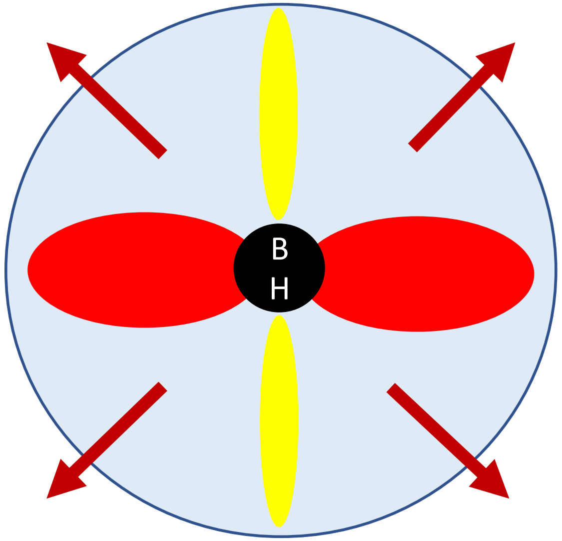
1. Collapse of a massive rotating progenitor
2. Proto neutron star formation
3. Further infall → black hole formation
4. Accretion onto black hole + formation of disk
5. Jet from vicinity of the black hole + explosion



$t <$ a few 100ms



$t \sim 1$ s

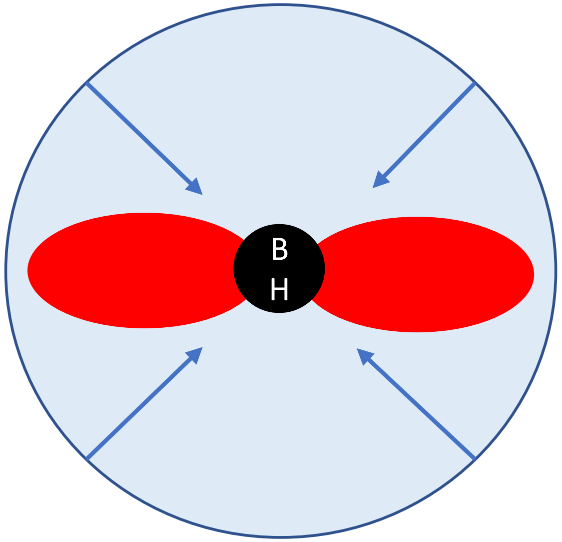


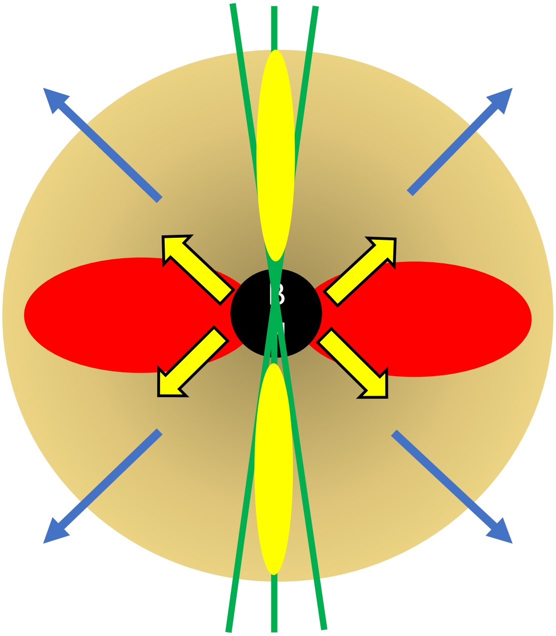
$t > 1$ s

How to produce a GRB + supernova?

- There are three major questions:

1. Is the system of a BH + disk formed? Sec. II
2. What produces a supernova-like explosion? Sec. II
3. How a jet is launched? Sec. III—V





II Supernova-like explosion from a torus around a black hole in viscous hydro

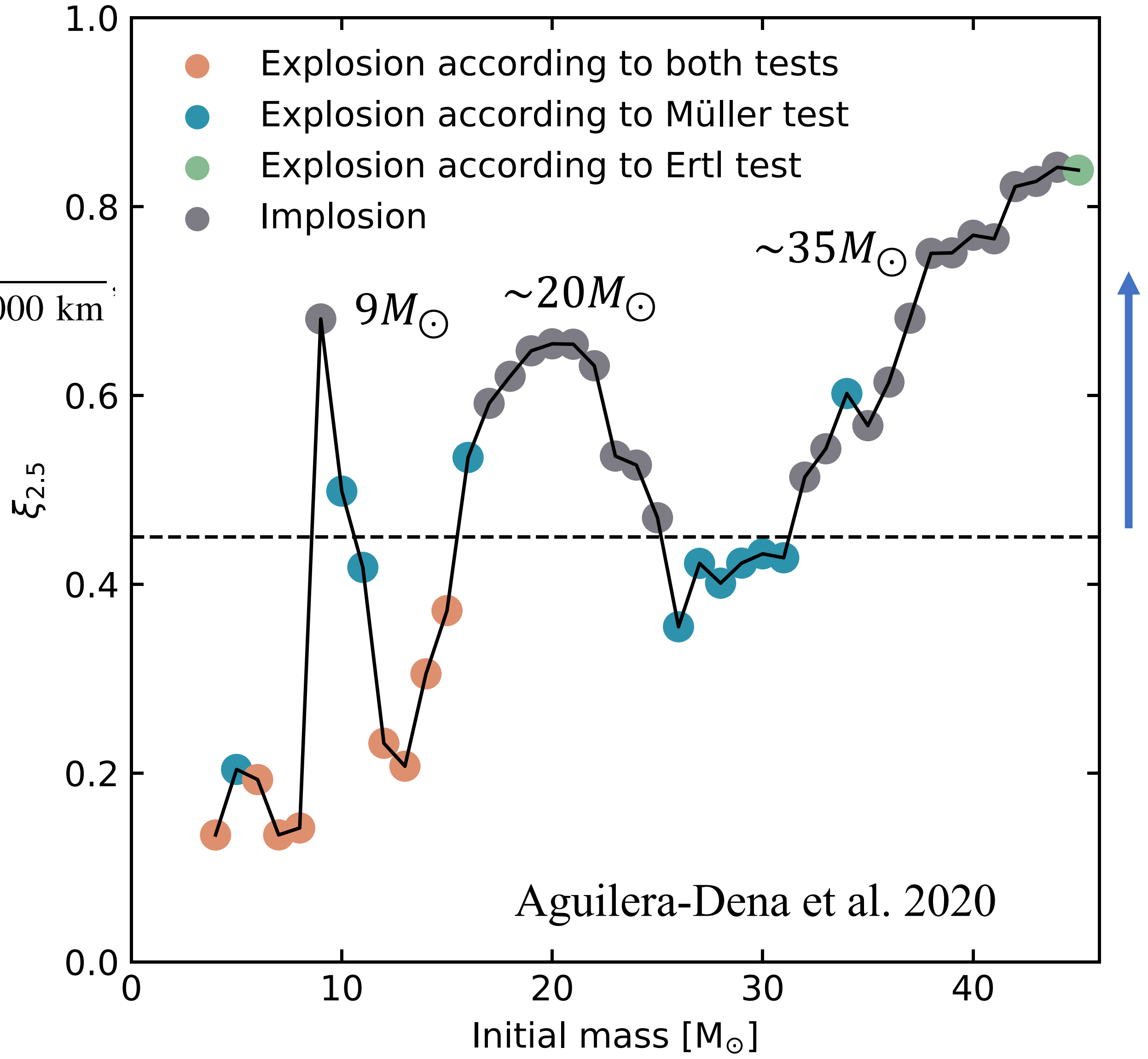
Fujibayashi et al. ApJ 2023, 956 (2309:02161)

- We can accept formation of a black hole and torus, *if* a progenitor star is compact and rapidly rotating
- Stellar evolution researchers have shown it possible to have rapidly rotating massive progenitors;
  E.g., Wooley & Heger 2005; Aguilera-Dena et al. 2018, 2020

O’Conner-Ott compactness parameter for Aguilera-Dena (ApJ 2020) models

$$\xi_M = \frac{M/\,M_\odot}{R(M_{\rm bary} = M)/1000\ {\rm km}}$$

M=2.5 solar mass

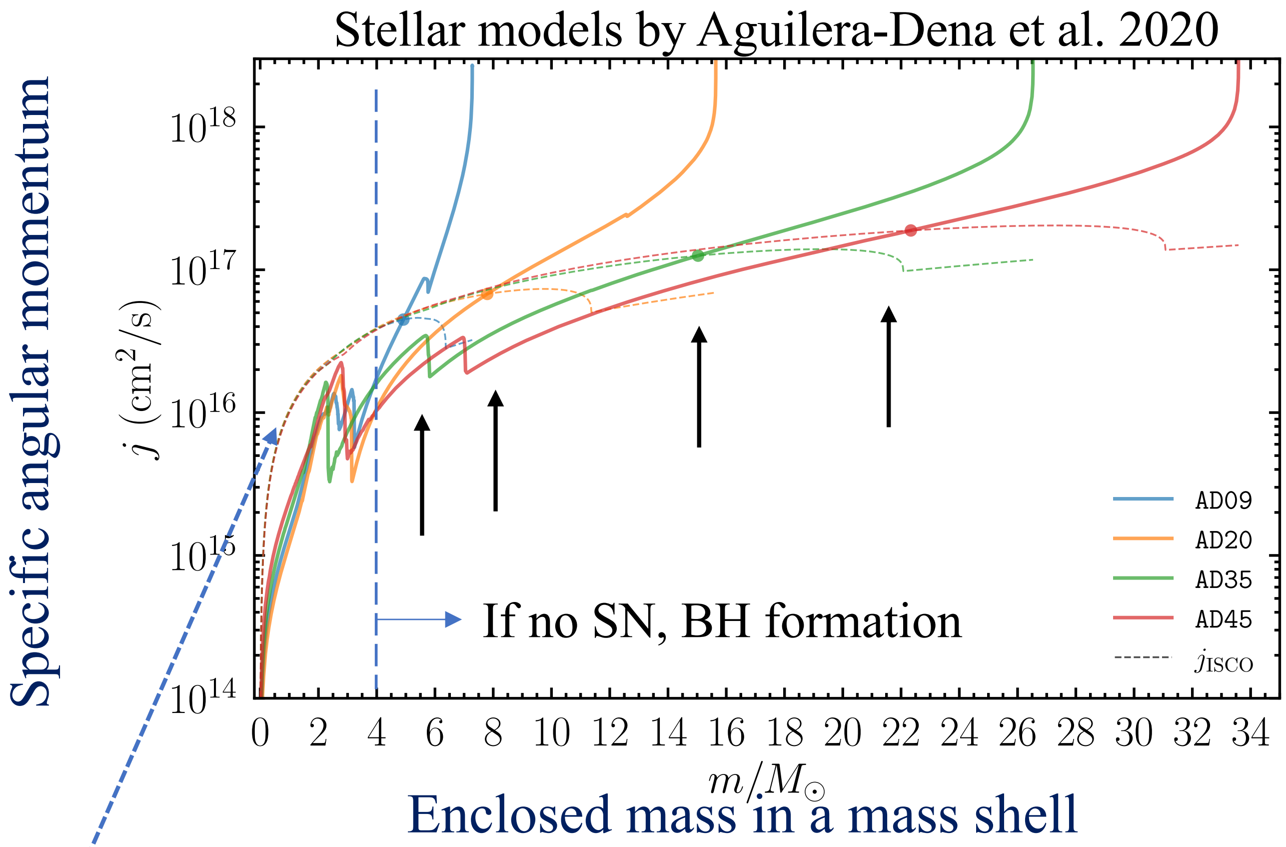


Black hole formation is likely

Metallicity = 0.02 solar abundance, Rotation=600km/s

→ Chemically homogeneous model

Specific angular momentum wrt enclosed mass


Stellar models by Aguilera-Dena et al. 2020

Specific angular momentum

If no SN, BH formation

Enclosed mass in a mass shell

Inner region:
Slow rotation
Outer region:
Rapider

- Dashed curves: Specific angular momentum of innermost stable circular orbit of BH for given mass *m* and spin $J = \int j dm$
- Filled circles show the parameter at the formation of a disk
- **Massive BH + disk is a natural outcome** (in the absence of earlier SN explosion) in their stellar models

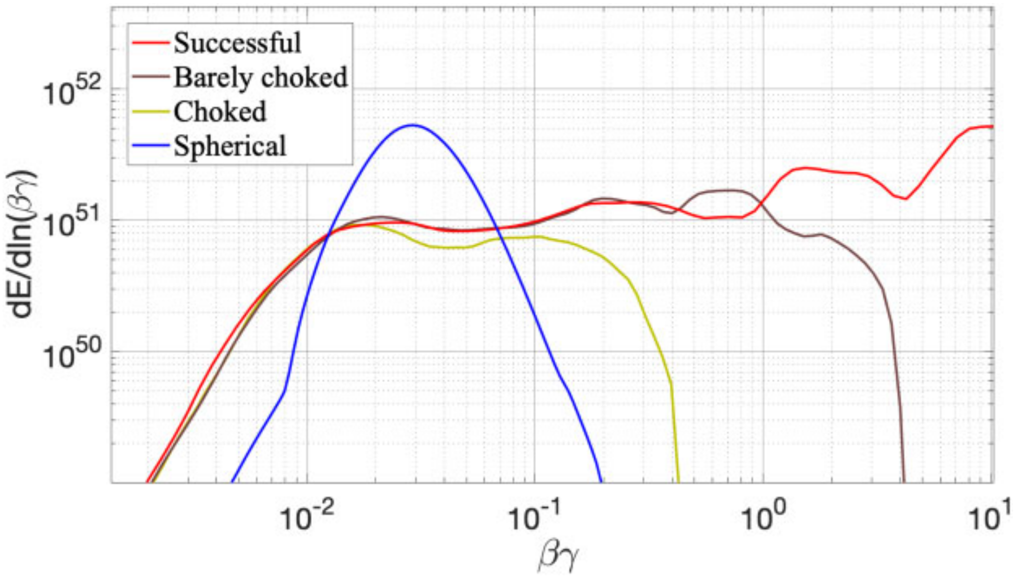
Supernova-like explosion from a torus around a black hole in viscous hydro

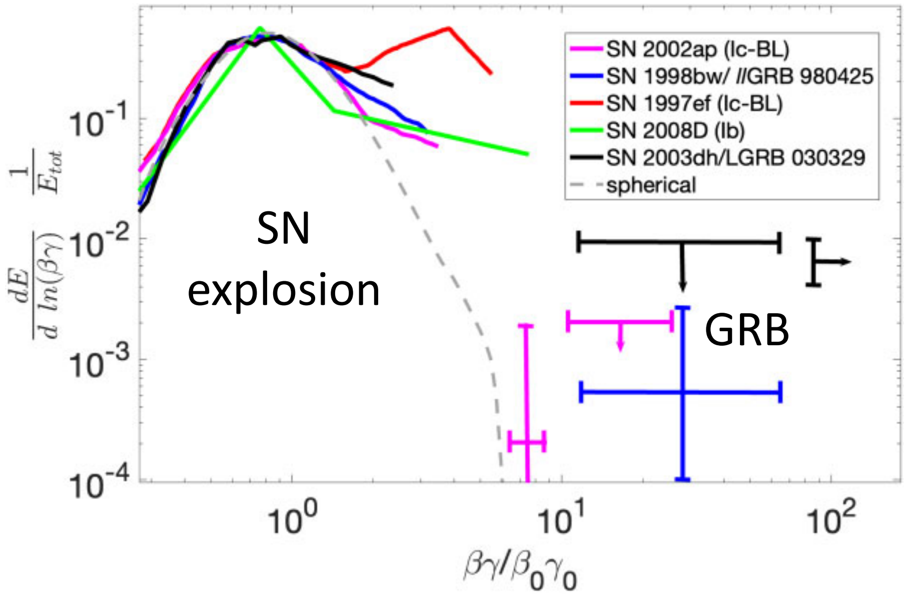
Fujibayashi et al. ApJ 2023, 956 (2309:02161)

- We can accept formation of a black hole and torus, *if* a progenitor star is compact and rapidly rotating
- Stellar evolution researchers have shown it possible to have rapidly rotating massive progenitors;
  E.g., Wooley & Heger 2005; Aguilera-Dena et al. 2018, 2020
- Another hint: Stellar explosion is not likely to be driven by a jet of gamma-ray bursts;
  E.g., Eisenberg, Gottlieb, & Nakar, MNRAS **517** (2022) ;
  dE/dv (v) distribution cannot be reproduced by jets
  → We need a mechanism for the "explosion"

Another hint

Eisenberg, Gottlieb, & Nakar, MNRAS **517** (2022)





Simulation results **vs** **Observational facts:**

Looks two components

Engine of supernova explosion is not likely to be GRB jet

Viscous heating rate in a disk around BH

- Suppose BH mass ~ 10 $M_{\rm sun}$ and disk mass ~ 1 $M_{\rm sun}$
- A torus/disk is magnetized and turbulence is induced by *magnetorotational instability* → viscosity is induced
- Viscous heating rate of tori/disks:

$$\dot{E}_\nu \sim \underline{4\times10^{52}\,{\rm erg/s}}\left(\frac{\alpha_\nu}{0.03}\right)\left(\frac{M_{\rm torus}}{M_\odot}\right) \times\left(\frac{c_{\rm s}}{10^9\,{\rm cm/s}}\right)^2\left(\frac{M_{\rm BH}}{10M_\odot}\right)^{-1/2}\left(\frac{R}{10M_{\rm BH}}\right)^{-3/2}$$

Very large!

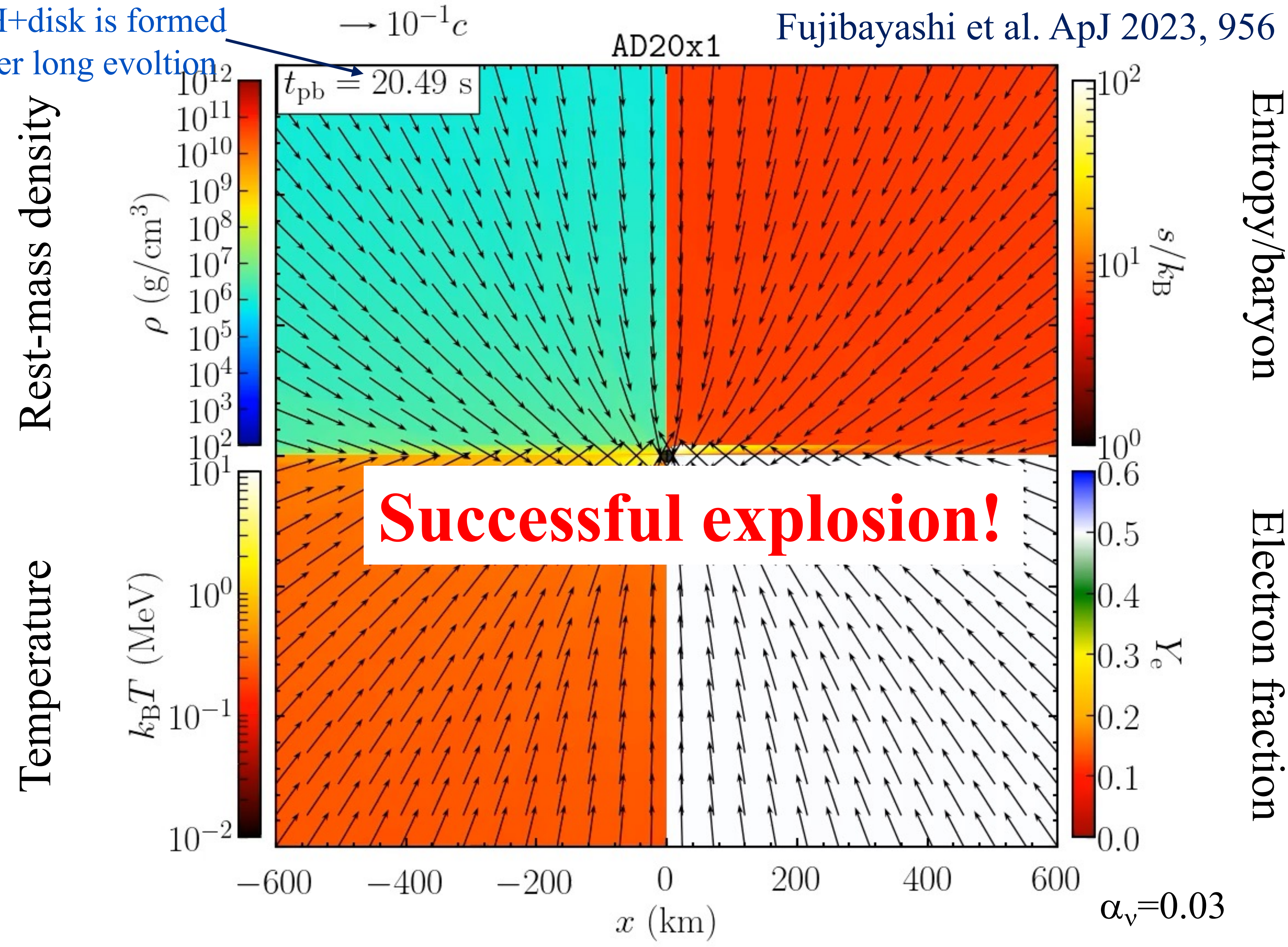
Alpha disk model with $\nu = \alpha_\nu c_s^2 \Omega^{-1}$; $\Omega = \sqrt{\frac{GM_{BH}}{R^3}}$, $\alpha_\nu = O(0.01)$

- If viscous heating power can be injected efficiently to the infalling matter, (luminous) explosion may occur → Investigate in numerical simulation!

20 solar mass model; α_ν=0.03 viscous + neutrino rad-hydro

BH+disk is formed after long evoltion

Fujibayashi et al. ApJ 2023, 956



Successful explosion!

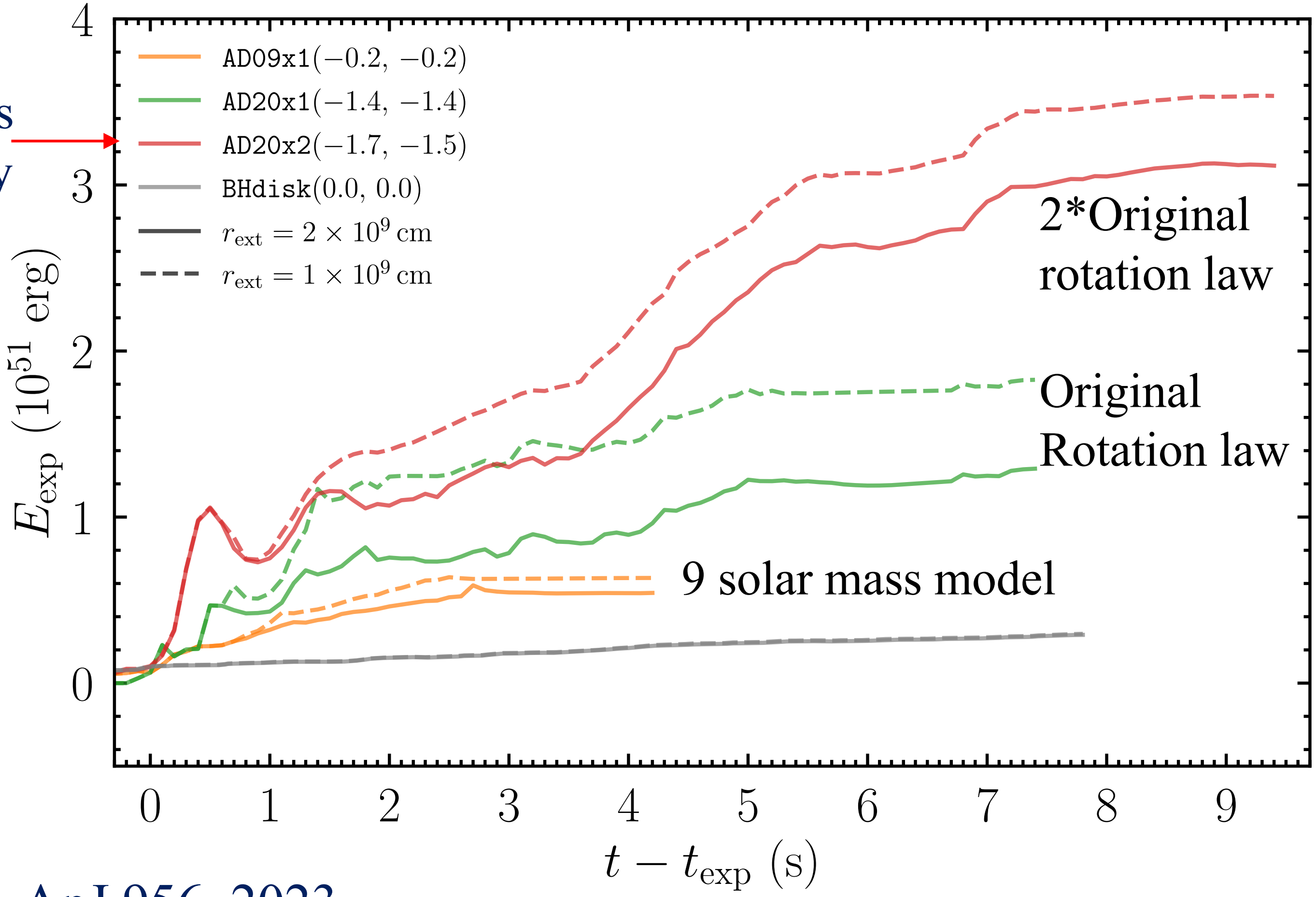
α_ν=0.03

Explosion energy for 9 and 20 solar-mass models

- Typical explosion energy ~ 10^{51} erg, comparable to the typical supernovae energy

→ We may expect SN-like explosions but not high-energy

Angular velocity is doubled artificially



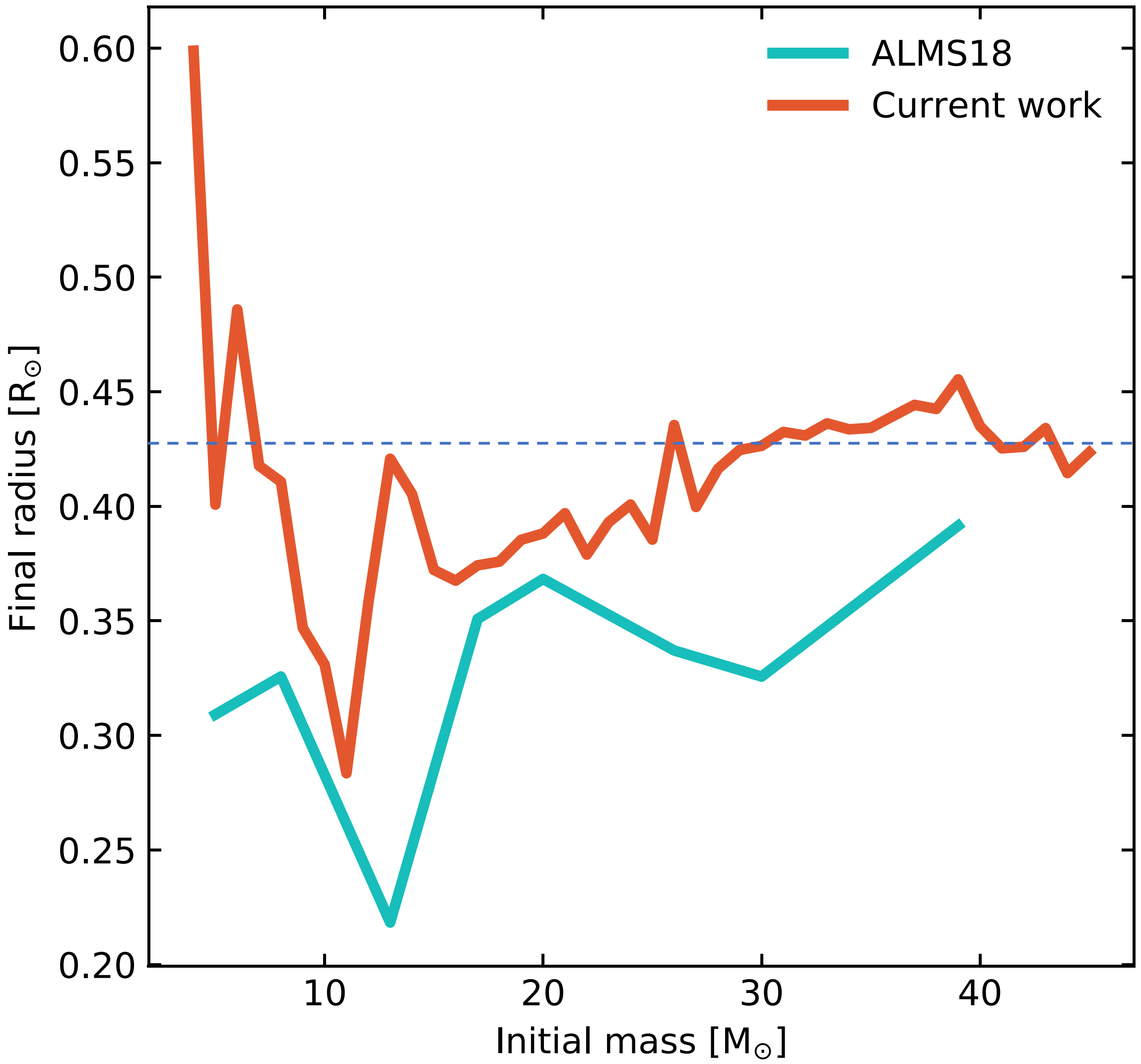
Fujibayashi et al. ApJ 956, 2023

Exploring larger-mass models

- Numerical simulation for larger-mass models is expensive (longer timescale for BH growth)
- BH formation and early evolution may be skipped, because matter simply collapses to a BH and free-falls into the BH until disk formation
- Start from **a BH + infalling matter with free fall** from the original progenitor models

Fujibayashi et al. arXiv: 2309:02161; PRD 109 (2024)

Final stellar radius depends only weakly on the initial mass: $R_* \sim$ 300,000 km, i.e., compact (=good for jet penetration)



300,000 km

Final radius

Initial mass

Why high-mass has advantage for high energy?

- Compactness of progenitor stars

$$C_* \equiv \frac{M_*}{R_*} \quad M_*\text{: Stellar mass, } R_*\text{: Radius}$$

- Mass accretion rate $\dot{M}_* \propto \frac{M_*}{t_{\mathrm{ff}}} \propto \left(\frac{M_*}{R_*}\right)^{3/2} = C_*^{\frac{3}{2}}$

$$t_{\mathrm{ff}} = \sqrt{\frac{R_*^3}{GM_*}} : \text{ free fall timescale}$$

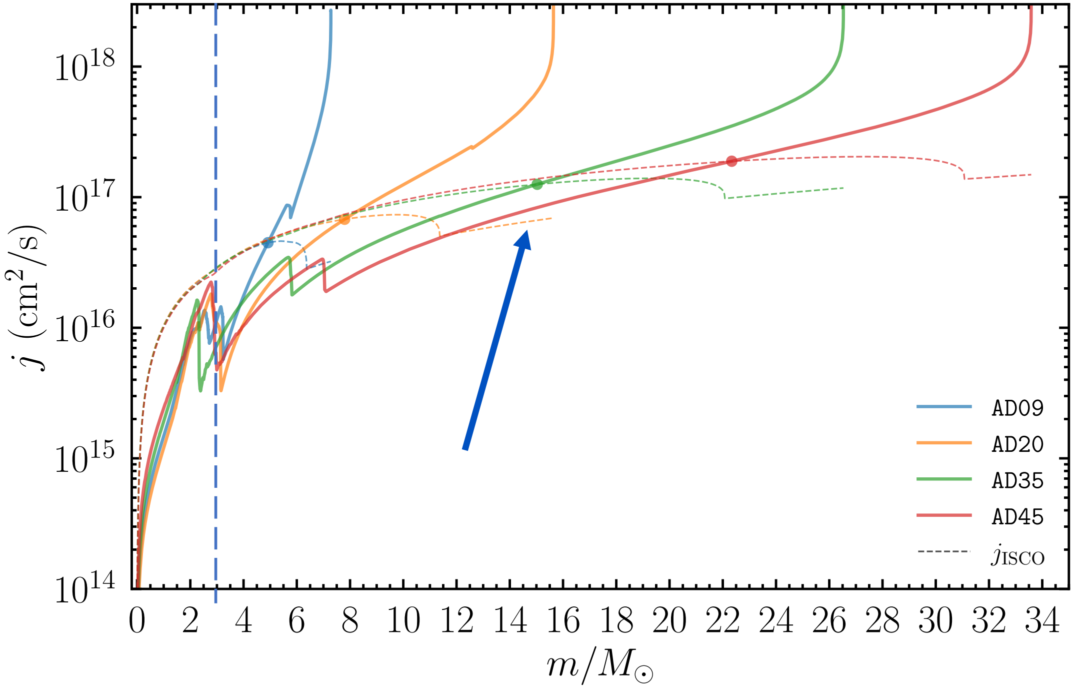
- Progenitor models: $R_* \approx 300{,}000$ km irrespective of the stellar mass

→ Higher mass models result in higher mass accretion rate

→ High efficiency in viscous energy generation

Exploring larger-mass models

Stellar models by Aguilera-Dena et al



Specific angular momentum

Enclosed mass in a mass shell

35 solar mass progenitor model = 15 solar mass, spin 0.66 BH + 12 matter infalling (+ mass loss)

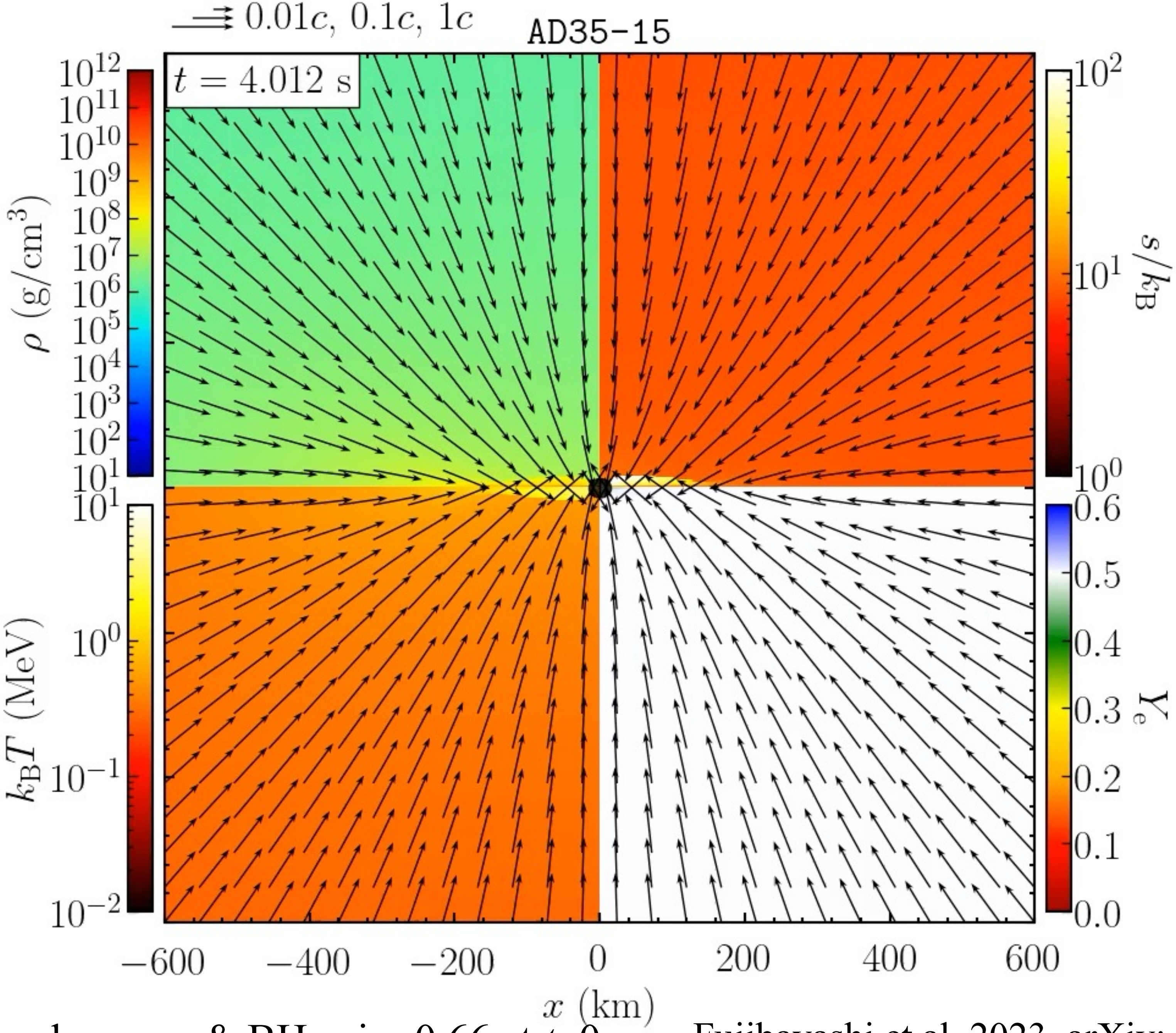
35 solar mass model; α_ν=0.03 + neutrino hydro

Rest-mass density

Temperature

Entropy/baryon

Electron fraction

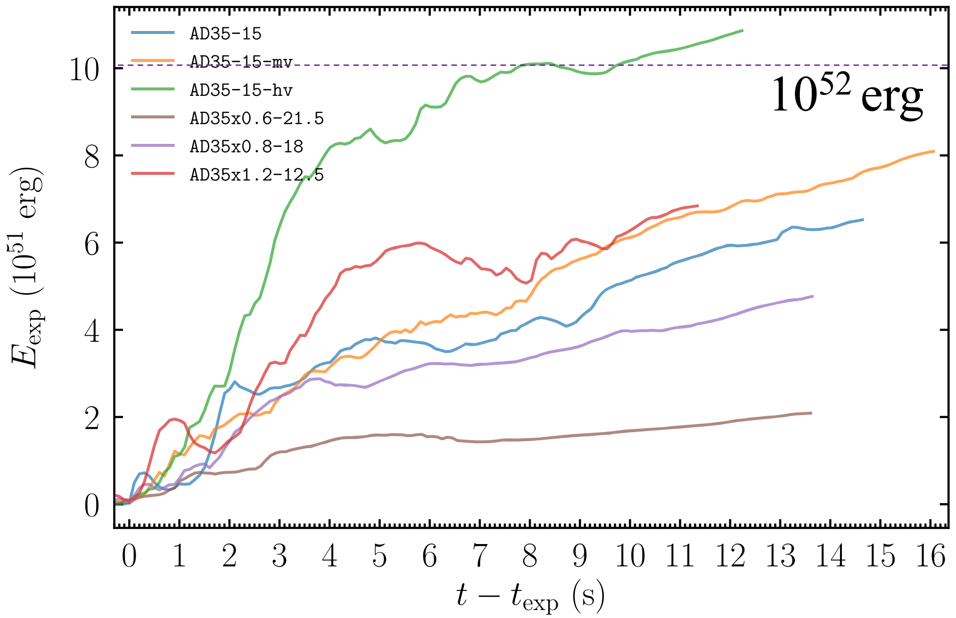


M_{BH}=15 solar mass & BH spin=0.66 at *t*=0

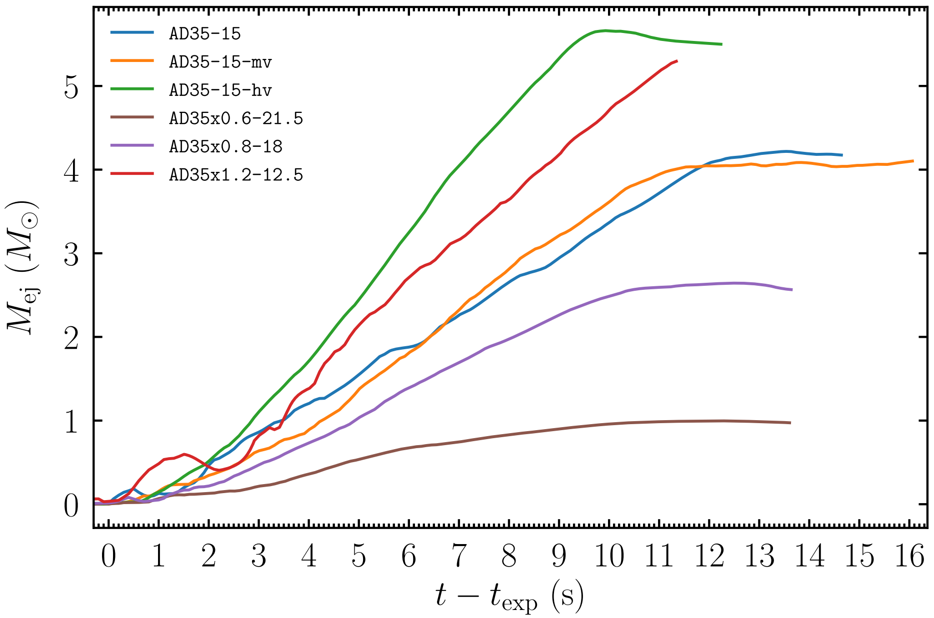
Fujibayashi et al. 2023, arXiv: 2309:02161

High explosion energy and ejecta mass!

Explosion energy in units of 10^{51} erg



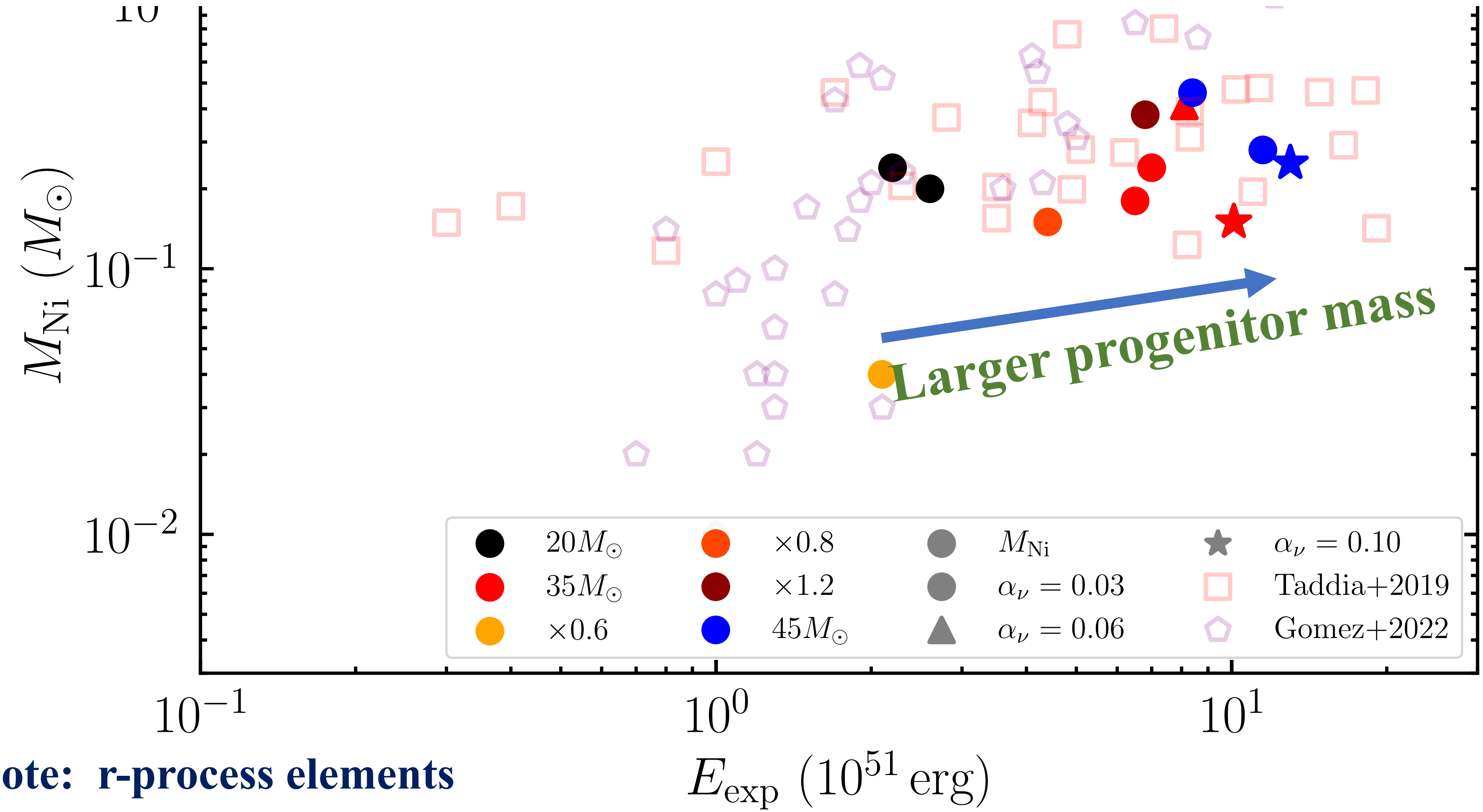
Ejecta mass



- **Explosion energy ~ 10^{52} erg >> 10^{51} erg**
- **Ejecta mass ~ 4—5 solar mass**
- **^{56}Ni mass (radio active source) > 0.15 solar mass**

→ Large enough for Hypernovae!

BH + massive disk can be the central engine of stellar explosion



Note: r-process elements

Observational data: Taddis et al., A & A 621 A71 (2019); Gomez et al., ApJ 941, 107 (2022)

III GRMHD (+ neutrino) simulations: jets

Shibata et al. 2023, arXiv: 2309.12086; PRD 109, 2024

✓GRB jets *cannot* be driven by viscous hydrodynamics

✓Viscous effects come from magnetohydrodynamical (MHD) effects in reality

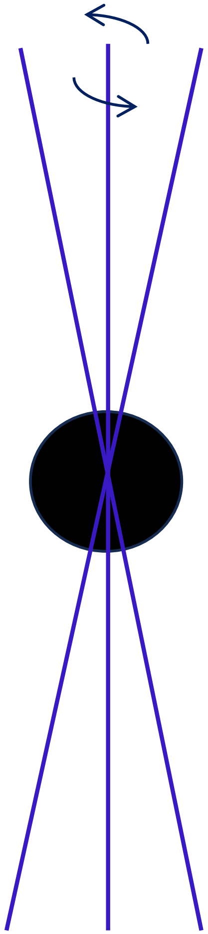
→Viscous hydrodynamics should be replaced by MHD

→Perform MHD simulation with the same initial condition: BH + infalling matter!

- Axisymmetric simulation, to perform a simulation for >10 sec (as a first step; 3D is necessary ultimately)
- Initial magnetic field?? Broadly, two possibilities

1. Fossil poloidal field (easy to do, often done)
2. Poloidal field developed in the disk through MRI (more realistic, but super expensive)

Promising generation mechanism of GRB jets = Blandford-Znajek mechanism (1977)



- Suppose the presence of a spinning black hole penetrated by magnetic fields
- Rotational kinetic energy of BH is extracted by the magnetic field
- Luminosity ($f = \omega/\Omega_H$, χ=BH spin)

$$\frac{dM_{\rm BH}}{dt} \approx -\frac{f(1-f)}{3}\left(B^r M_{\rm BH}\chi\right)^2\left(\hat{r}_+ + 2\right)$$

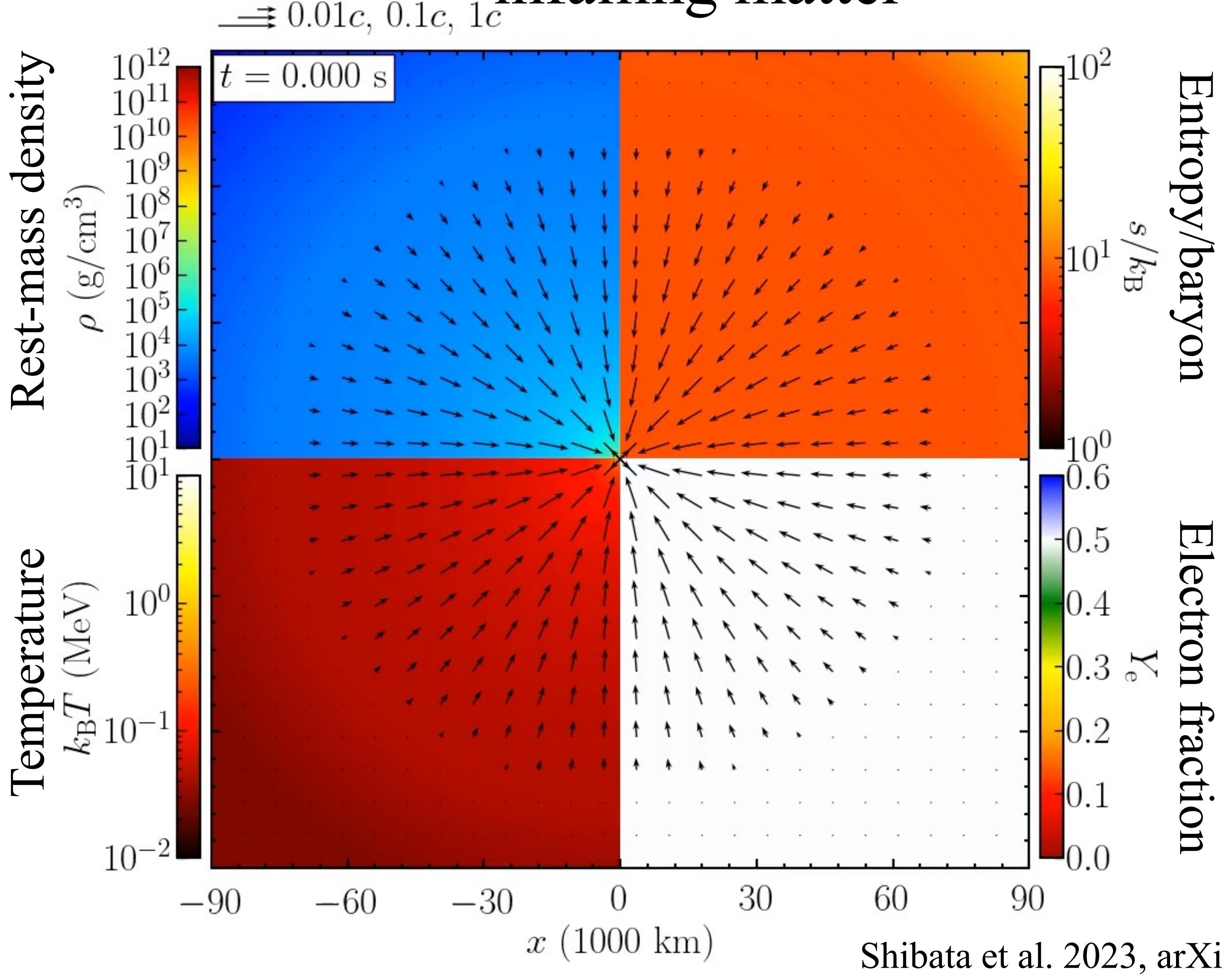
$$\approx \underline{-1.1\times 10^{50}}\, f_{1/2}\frac{1-f}{1/2}\left(\frac{M_{\rm BH}}{10M_\odot}\right)^2 \times \underline{\left(\frac{B^r}{10^{14}\,{\rm G}}\right)^2}\,\underline{\left(\frac{\chi}{0.7}\right)^2}\left(\frac{\hat{r}_+ + 2}{4}\right)\ {\rm erg/s}$$

E.g., McKinney & Gammie ApJ (2004)

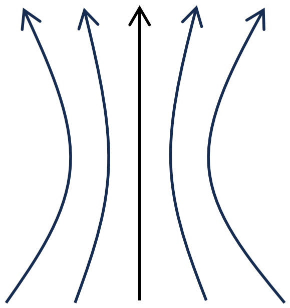
$$\hat{r}_+ = 1 + \sqrt{1-\chi^2}$$

Typical gamma-ray *luminosity* of GRBs could be produced

15 solar mass, spin=0.66 BH + 10.5 solar mass infalling matter

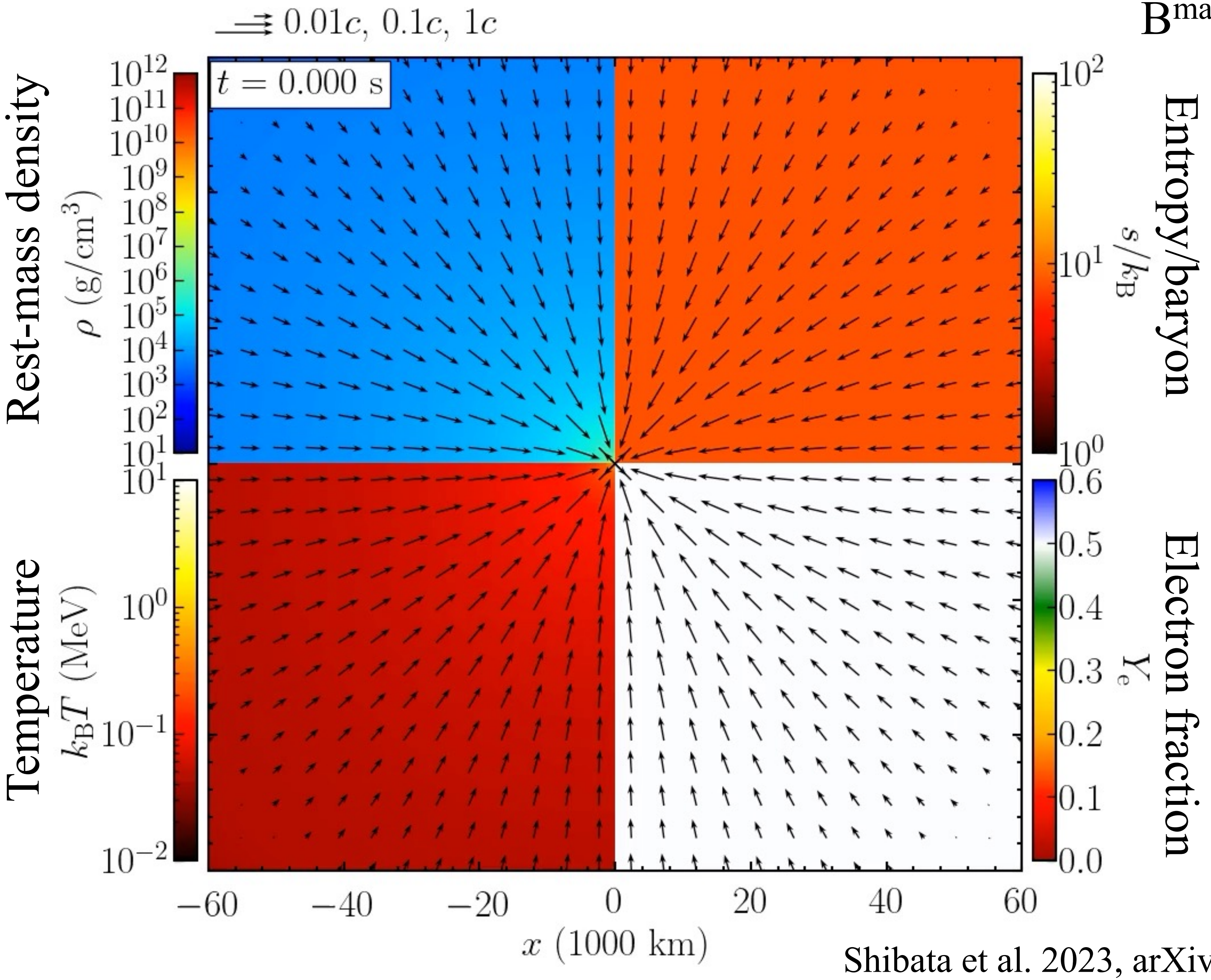


$B^{max}=10^{11}$ G

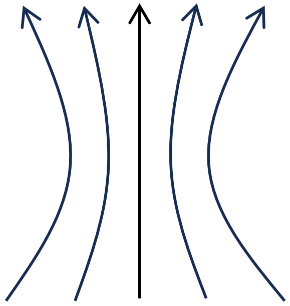


Shibata et al. 2023, arXiv: 2309.12086

Weaker magnetic field case: no jets in 15s but later yes



$B^{max}=10^{10.5}$ G



Shibata et al. 2023, arXiv: 2309.12086

GRMHD results with *initially poloial* field

- In the presence of *poloidal* magnetic fields, the field strength is amplified by winding associated with BH spin, and a jet is driven by the Blandford-Znajek effect when magnetic pressure overcomes the ram pressure, i.e.,

$$\boxed{\frac{B^2}{8\pi} > \rho_{\rm infall} v_{\rm infall}^2 \qquad (*)}$$

- **Then *B* on the horizon is approximately fixed:**

$$B \sim 7.5\times10^{13}\,{\rm G}\left(\frac{\rho_{\rm infall}}{10^6\,{\rm g/cm^3}}\right)^{1/2}\left(\frac{v_{infall}}{c/2}\right)$$

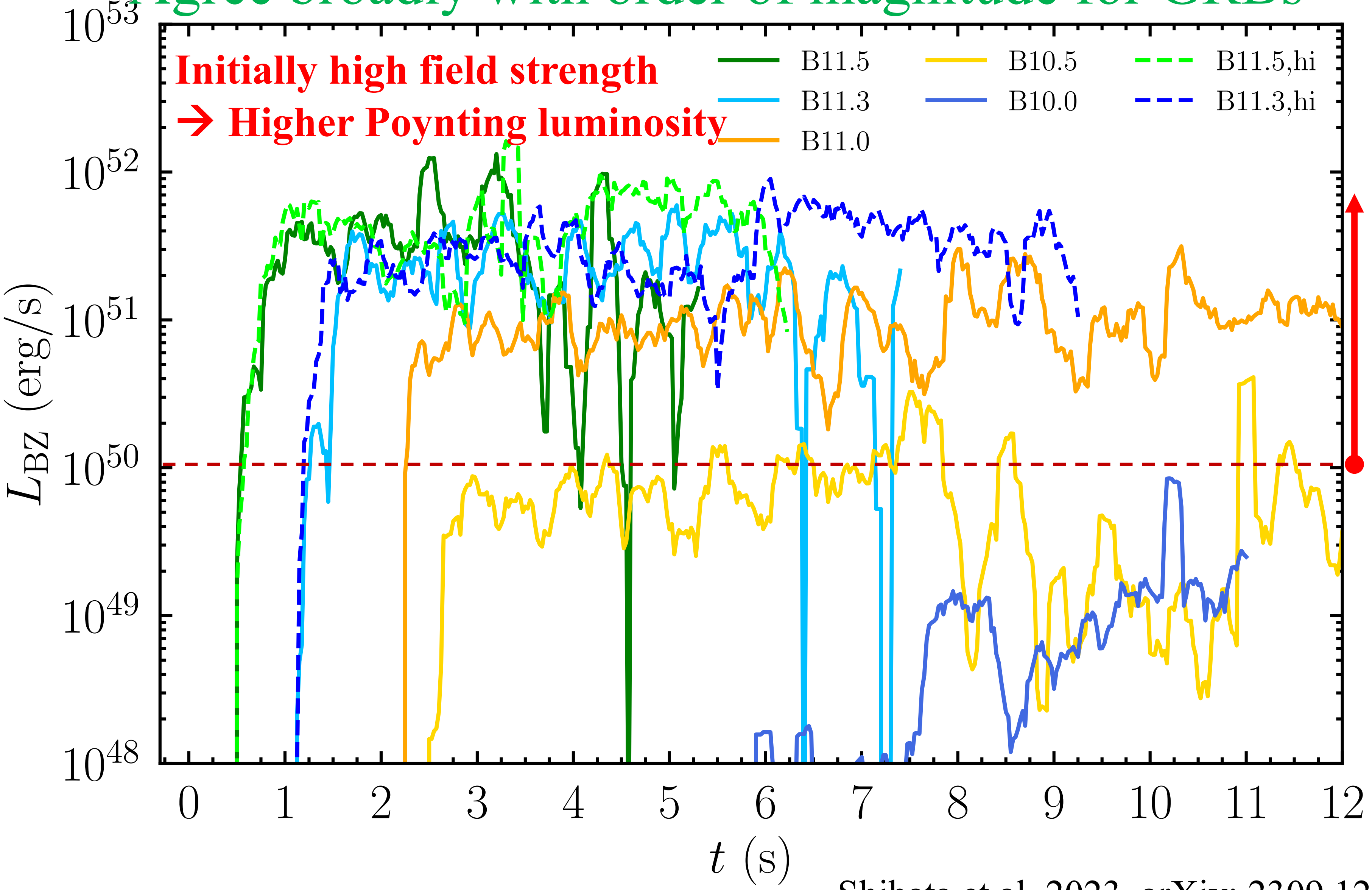
- Poynting luminosity is higher for stronger initial field because of Eq. (*); $\rho_{\rm infall}$ is higher in earlier phase

- Stellar explosion often accompanies with the explosion energy of order 10^{52} erg or more in this setting

Poynting luminosity

Jet launch cases → $L_{\rm BZ}$ ~10^{50}—10^{52} erg/s:

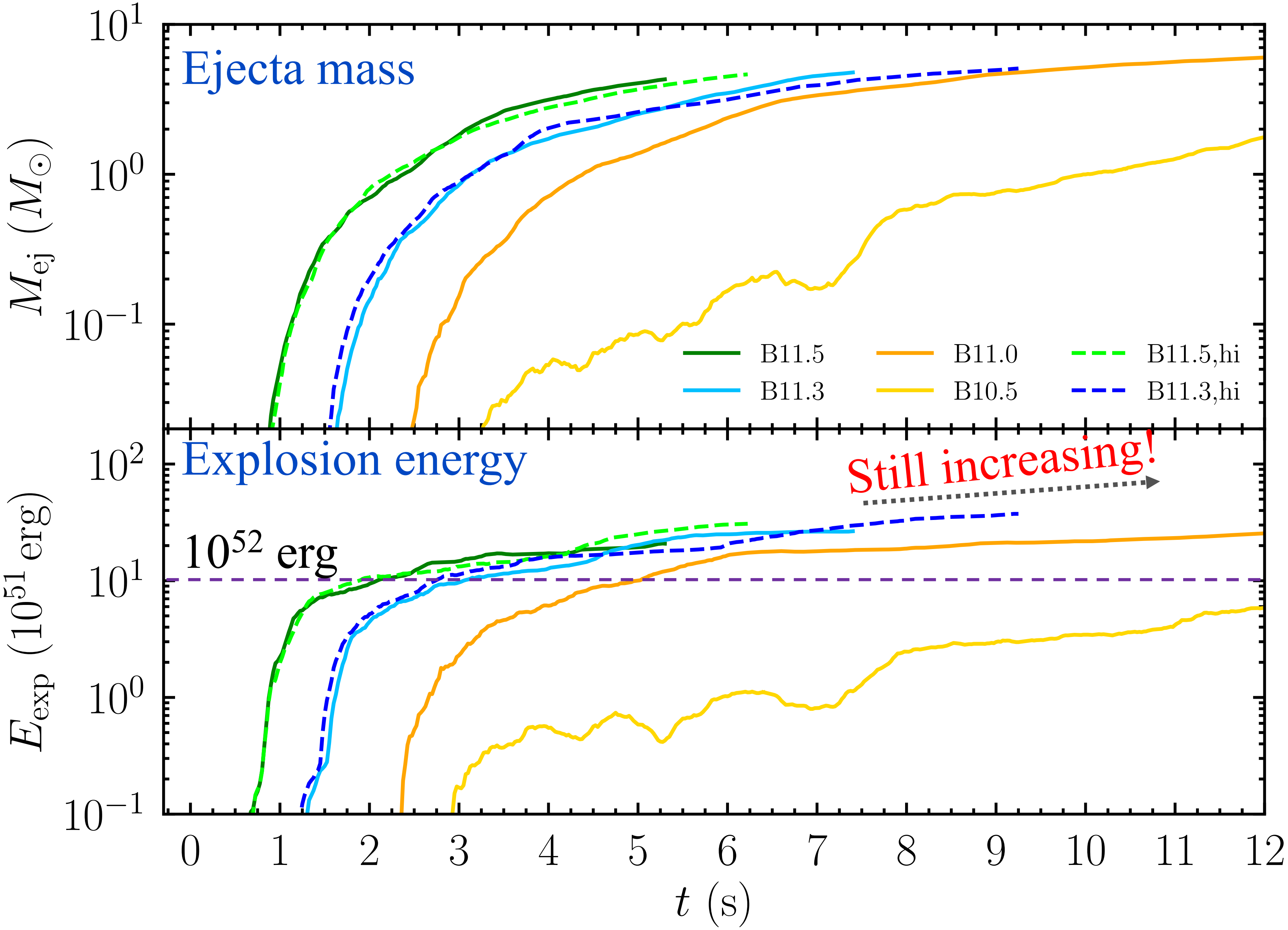
Agree broadly with order of magnitude for GRBs



Initially high field strength
→ Higher Poynting luminosity

Shibata et al. 2023, arXiv: 2309.12086

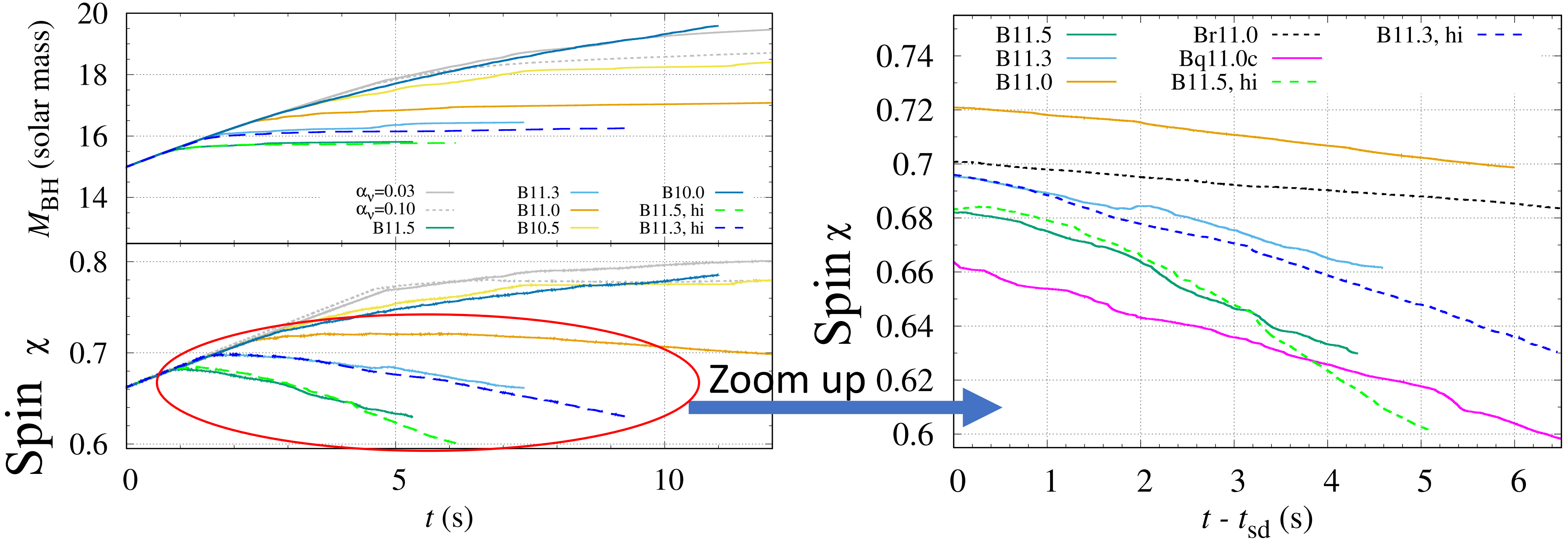
Ejecta mass and outflow (jet) energy



Outflow energy can be > 10^{52} erg; still increasing

Evolution of black holes: **spin down in MAD state**

In numerical relativity, this is directly obtained from BH!



- Spin-down timescale = 30—300 s for strong jet models
  → **Rotational kinetic energy is the source of jets**
- Spin-down timescale is shorter for stronger initial field

Problem: Huge total Poynting energy problem

- $E_{\rm BZ} = L_{\rm BZ} \times$ (spin-down timescale)
- For strong poloidal field models, $E_{\rm BZ} > 10^{53}$ **erg**: **Larger than GRB + afterglow + SN energy!?**
- This cannot be accepted
- The spin-down timescale should be much longer than GRB timescale ~ 10—100 s! And later, magnetic field should be dissipated

→**Fossil poloidal fields *must not* be very strong**

⬇

Magnetic field lines that penetrate BH should be developed in a later stage

IV How to get poloidal magnetic fields that penetrate black hole?

- Many numerical simulations assume aligned poloidal magnetic fields that penetrate black hole *initially*
  → Jet is launched as we show in this talk
- However, this is the “**assumption=result**” simulation
- The most important question (for me) is **“how and when such magnetic field is established”**
- Our belief: **In the torus/disk surrounding the BH, magnetic fields are amplified, and due to the matter accretion (together with the magnetic fields), a magnetic field that penetrates the BH is formed.**
- We need to resolve MHD instability in the disk; it is super expensive but necessary

Phenomenological approach: Add dynamo term

$$j^\mu = \tilde{\rho}_{\mathrm{e}} u^\mu + \sigma_{\mathrm{c}}\left(F^{\mu\nu}u_\nu + \alpha_{\mathrm{d}}\,{}^{*}F^{\mu\nu}u_\nu\right)$$

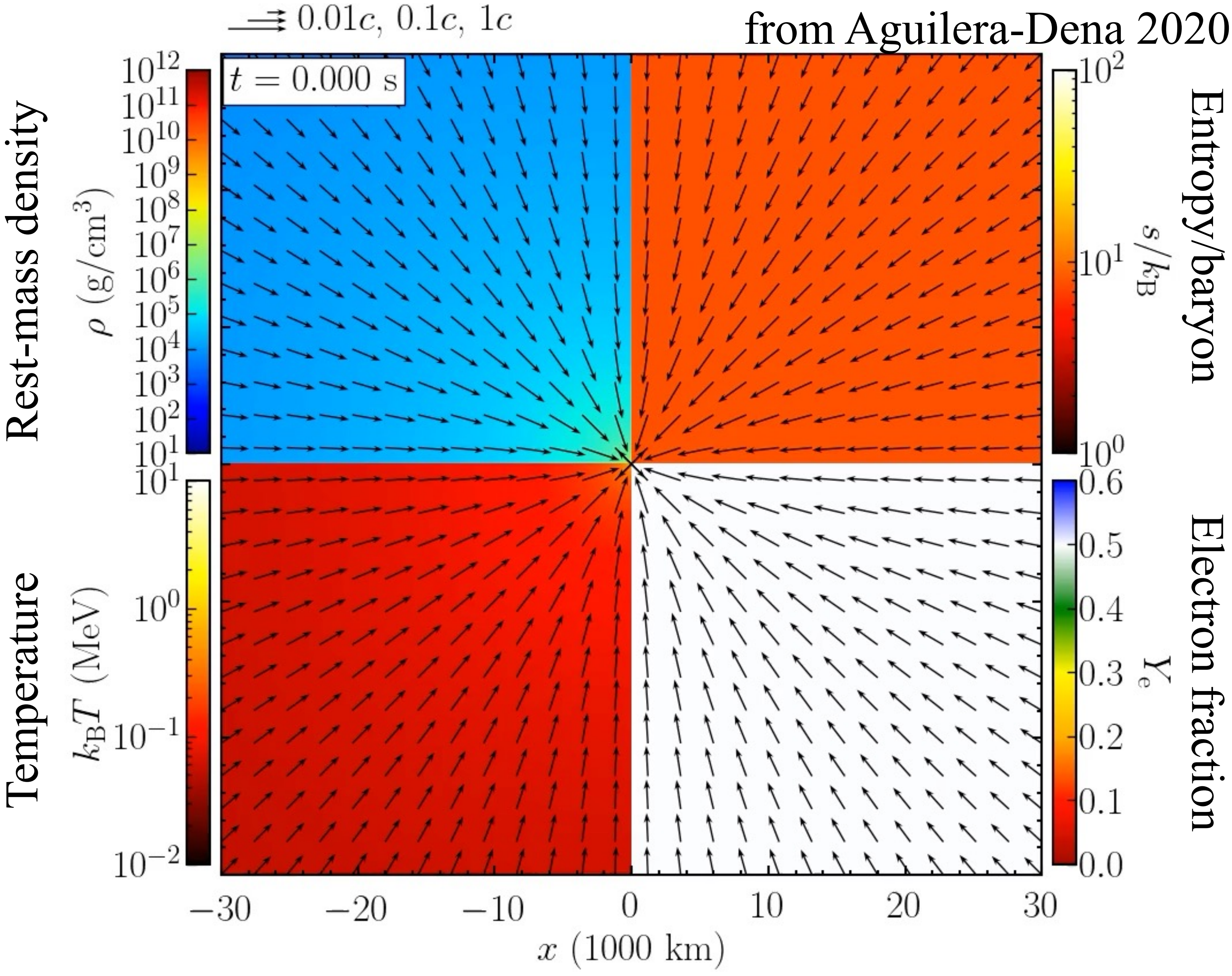
conductivity

- The dimensionless coefficient α_{d} is related to dynamo for *hypothetical amplification* of fields. $J^i \propto \alpha_d B^i$
- Magnetic field is amplified exponentially until the saturation is reached : $\propto \exp(\omega_{\max} t)$

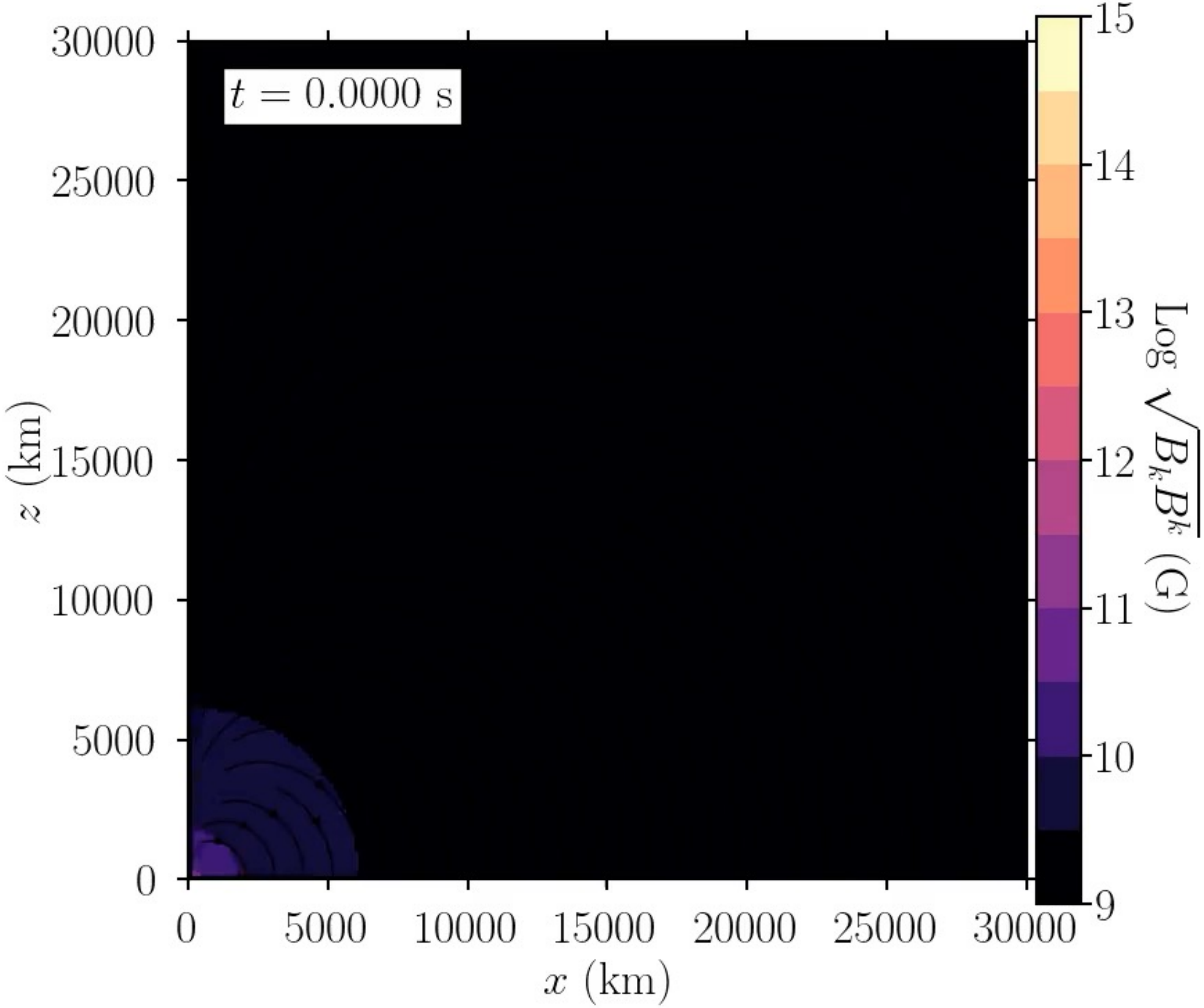
$$\omega_{\max} = \frac{3}{4}\left(\frac{\pi\alpha_{\mathrm{d}}^2\sigma_{\mathrm{c}}S_\Omega^2}{4}\right)^{1/3} = 46\ \mathrm{s}^{-1}\left(\frac{|\alpha_{\mathrm{d}}|}{10^{-4}}\right)^{2/3} \times\left(\frac{\sigma_{\mathrm{c}}}{3\times10^{7}\ \mathrm{s}^{-1}}\right)^{1/3}\left(\frac{|S_\Omega|}{10^{3}\ \mathrm{rad/s}}\right)^{2/3}.$$

S_Ω: degree of differential rotation

Start from 16 solar mass BH + infalling matter + toroidal field; from Aguilera-Dena 2020



Magnetic field strength



Order of Timescales inferred

1. Collapse to a proto neutron star ~ 0.1 s
2. Black hole formation ~ O(1) s
3. Subsequent disk formation around black hole ~ 10 s
4. Amplification of magnetic field in the disk ~10 s
   → Magnetic fields that penetrate the BH are formed
5. Jet & stellar explosion > 10 s

- GRB & stellar explosion may be launched at > 10 s after stellar collapse; different from ordinary supernovae

- It is not easy to prove it observationally…
- $L_\nu > 10^{52}$ erg/s is continued for > 10 s

V Summary

- Rapidly rotating massive stars have potential for powerful explosion of $E_{\mathrm{exp}} \sim 10^{52}$ erg by viscous effect (that should result from MHD turbulence)
- Explosion energy, ejecta mass, and ^{56}Ni production are good for reproducing type Ib/Ic/Ic-BL SNe
  → The engine for some of type Ib/Ic/Ic-BL SNe may be a black hole + a torus
- If a poloidal magnetic-field penetrating the black hole is present, a jet is likely to be produced as well
  → GRB-SN association may be explained
- However, the explosion energy can be *too high* in the presence of initially strong poloidal field
  → Magnetic field on the BH is likely to be developed from the MHD instability of the torus

Thank you for your attention!