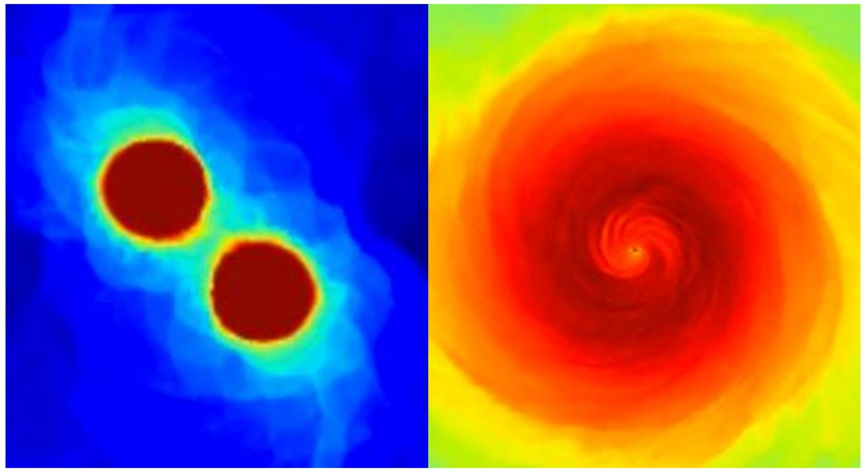
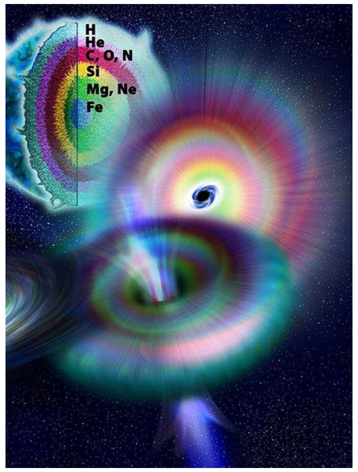
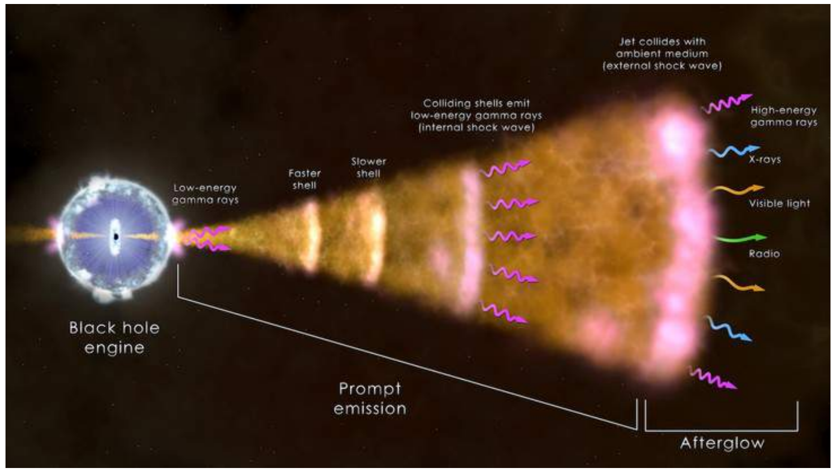
COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

# ICTP school: GRB central engine slides



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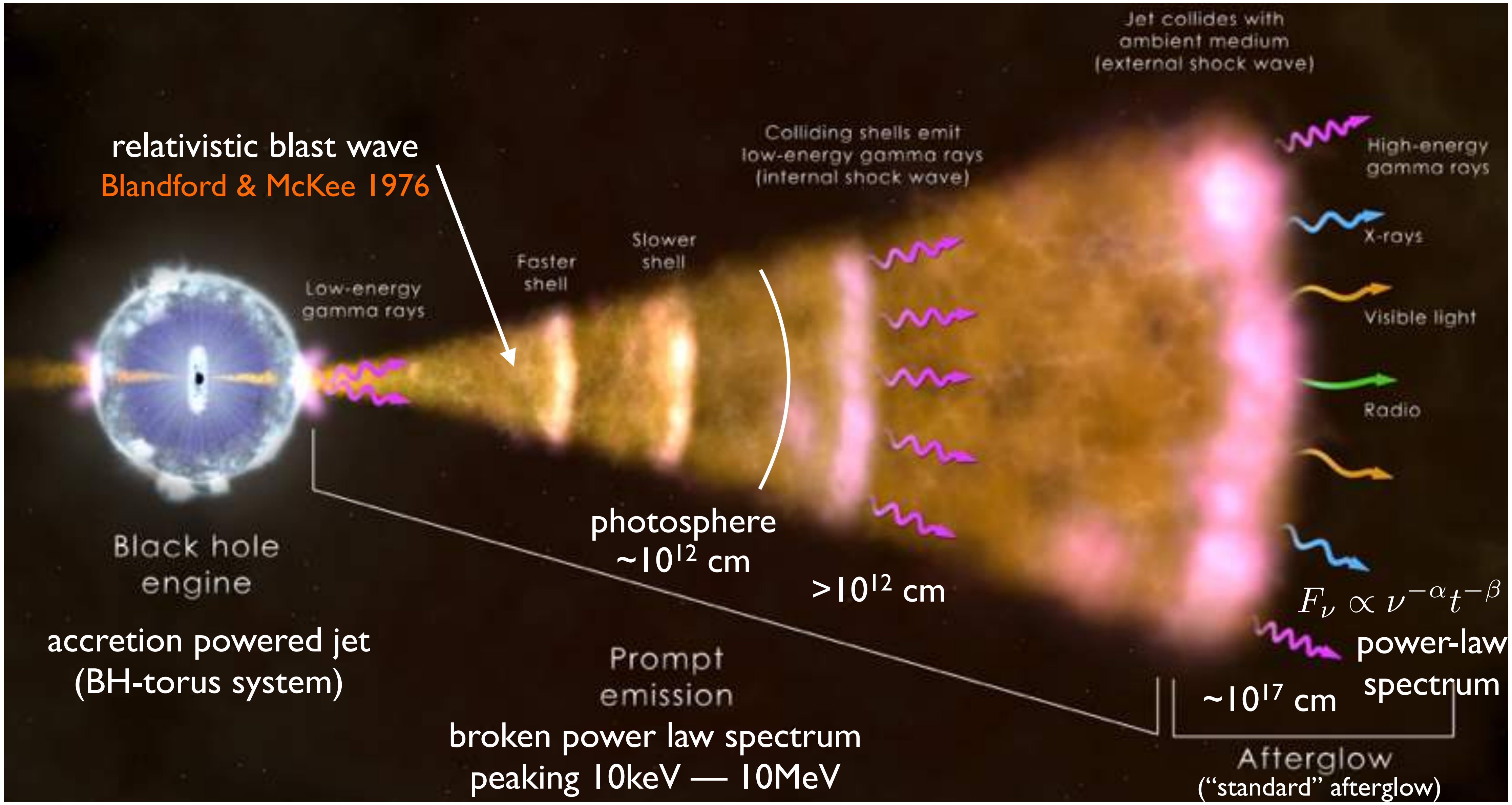
ICTP school *The Sound of Space-time: The Dawn of Gravitational Wave Science*,
Sao Paulo, Dec 10-14, 2018

# The canonical GRB picture



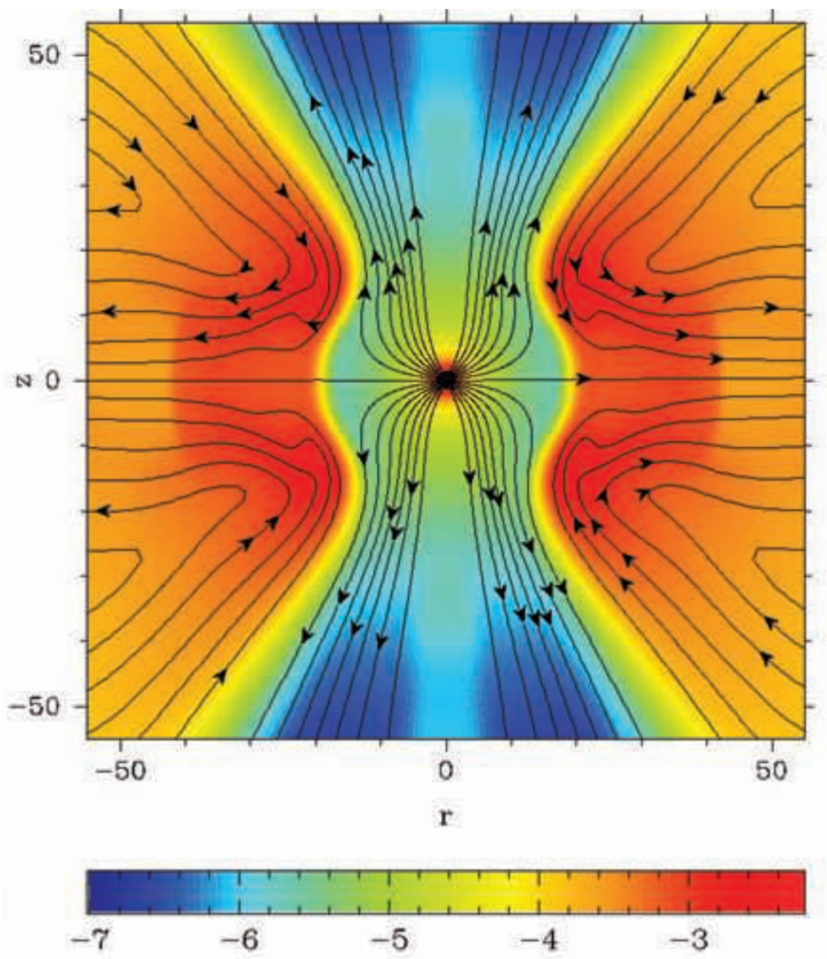

What actually powers these explosions?
Where does the energy come from?

# Preliminaries

# What is the central engine of GRBs?

Rapidly rotating black hole?

Blandford-Znajek mechanism

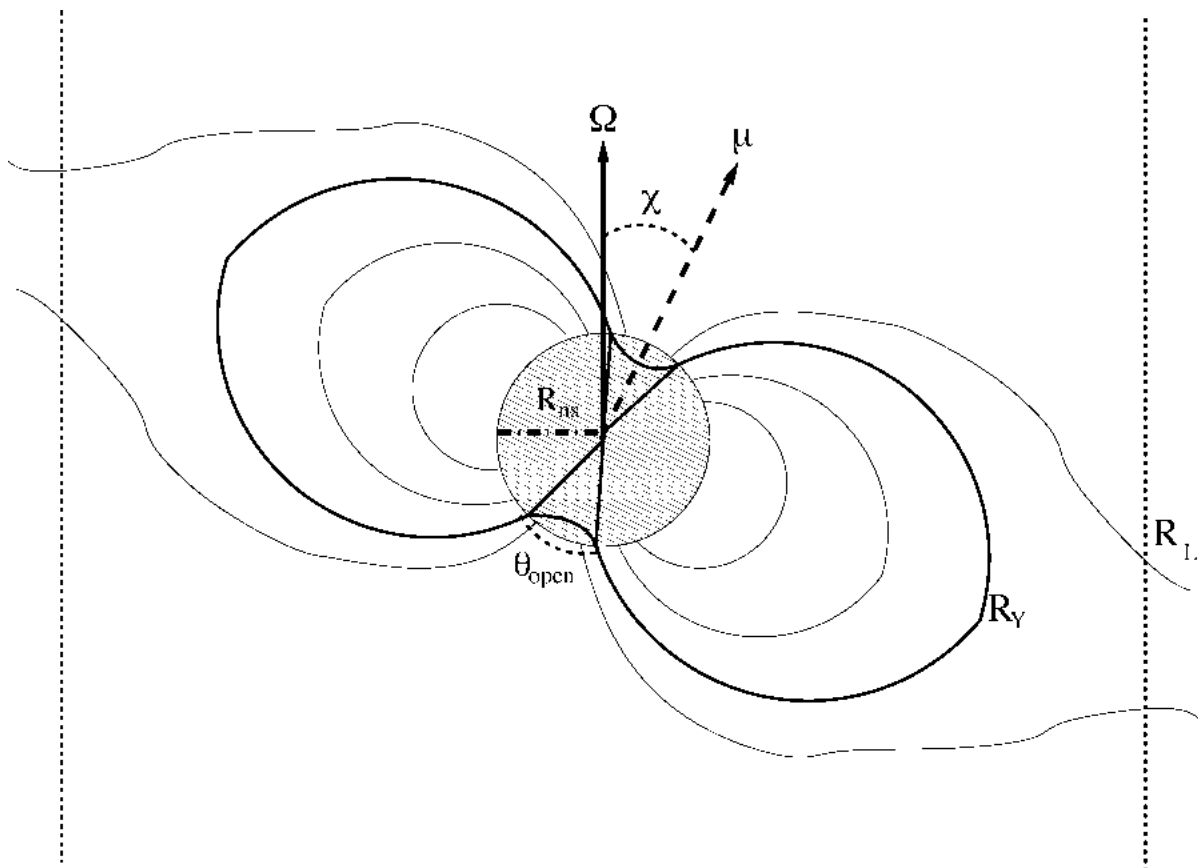



Komissarov & Barkov 2009

$$E_{\rm rot} = 10^{54} f \left(\frac{a}{0.9}\right)\left(\frac{M_{\rm BH}}{4M_\odot}\right) \text{erg}$$

Rapidly rotating, highly magnetized neutron stars (ms-magentars?)

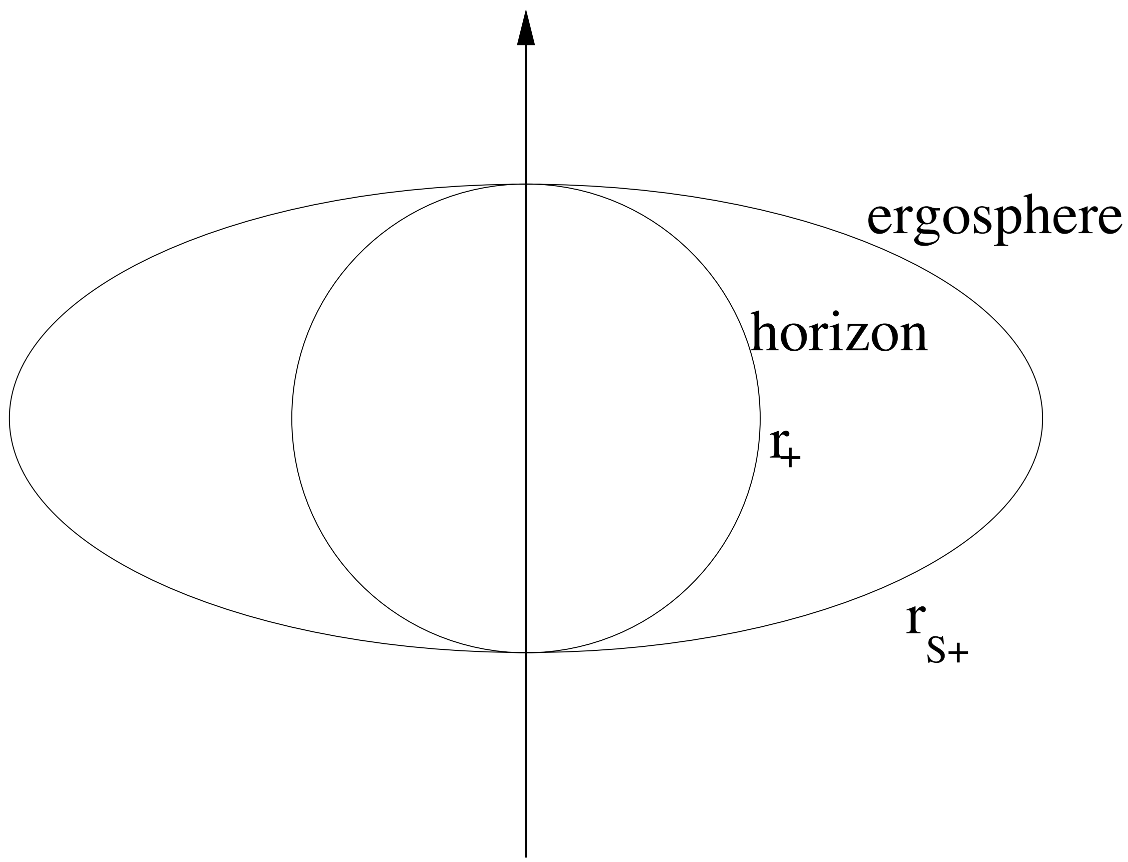
Magnetar model for GRBs




Metzger+ 2011

$$E_{\rm rot} \approx 3\times 10^{52}\,\text{erg}\left(\frac{M_{\rm ns}}{1.4\,{\rm M}_\odot}\right)\left(\frac{R_{\rm ns}}{12\,{\rm km}}\right)^{2}\left(\frac{P}{\rm ms}\right)^{-2}$$

# Basic Kerr-BH anatomy




**Boyer-Lindquist coordinates:**

$$ds^2 = g_{tt}\mathrm{d}t^2 + 2g_{t\phi}\mathrm{d}t\mathrm{d}\phi + \gamma_{rr}\mathrm{d}r^2\gamma_{\phi\phi}\mathrm{d}\phi^2 + \gamma_{\theta\theta}\mathrm{d}\theta^2$$

$$\begin{aligned} g_{tt} &= (2Mr/\Sigma) - 1, \\ g_{t\phi} &= -2aMr\sin^2\theta/\Sigma, \\ \gamma_{rr} &= \Sigma/\Delta, \\ \gamma_{\phi\phi} &= A\sin^2\theta/\Sigma, \\ \gamma_{\theta\theta} &= \Sigma, \end{aligned} \qquad \begin{aligned} \Sigma &= r^2 + a^2\cos^2\theta, \\ \Delta &= r^2 - 2Mr + a^2, \\ A &= (r^2+a^2)^2 - a^2\Delta\sin^2\theta, \\ a &= J/M, \quad -1 < a/M < +1. \end{aligned}$$

**Writing as a 3+1 split (remember from NR lecture):**

$$ds^2 = -(\alpha^2 - \beta^2)\mathrm{d}t^2 + 2\beta_i\mathrm{d}x^i\mathrm{d}t + \gamma_{ij}\mathrm{d}x^i\mathrm{d}x^j$$

$$\begin{aligned} \alpha^2 &= -1/g^{tt} = \Delta\Sigma/A, \\ \beta^2 &= \alpha^2 + g_{tt} = 4a^2r^2\sin^2\theta/A, \\ \beta^\phi &= \alpha^2 g^{t\phi} = -2aMr/A, \quad \beta^r = \beta^\theta = 0. \end{aligned}$$

Identify using general form of metric components:

$$g_{\mu\nu} = \begin{pmatrix} -\alpha^2 + \beta_k\beta^k & \beta_i \\ \beta_j & \gamma_{ij} \end{pmatrix}, \quad g^{\mu\nu} = \begin{pmatrix} -\alpha^{-2} & \alpha^{-2}\beta^i \\ \alpha^{-2}\beta^i & \gamma^{ij} - \alpha^{-2}\beta^i\beta^j \end{pmatrix}$$

**Horizon location:** $\Delta = 0$

$$r_\pm = M \pm \sqrt{M^2 - a^2}.$$

**Ergosphere:** $g_{tt} = \beta^2 - \alpha^2 = 0$

$$r_{S\pm} = M \pm \sqrt{M^2 - a^2\cos^2\theta}.$$

Inside, the killing vector $t^\alpha = \partial_t$ not timeline anymore:

$$g_{\mu\nu}t^\mu t^\nu = g(t^\mu, t^\nu) = g_{tt} > 0$$

# Black hole electrodynamics

Covariant Maxwell equations:

Faraday tensor

$$
\begin{aligned}
\nabla_\nu F^{*\mu\nu} &= 0, \\
\nabla_\nu F^{\mu\nu} &= I^\mu
\end{aligned}
$$

Maxwell tensor

Define electric and magnetic field as seen by normal (Eulerian) observer in 3+1 split:

$$
\begin{aligned}
D^\mu &= -F^{\mu\nu} n_\nu, \\
B^\mu &= -F^{*\mu\nu} n_\nu
\end{aligned}
$$

Define auxiliary fields (only physical meaning at infinity):

$$
\begin{aligned}
E^\mu &= -\frac{1}{2}\gamma^{\mu\nu}\eta_{\nu\alpha\beta\gamma}k^\alpha F^{*\beta\gamma}, \\
H^\mu &= -\frac{1}{2}\gamma^{\mu\nu}\eta_{\nu\alpha\beta\gamma}k^\alpha F^{\beta\gamma}, \\
J^\mu &= 2I^{[\nu}k^{\mu]}n_\nu, \\
\rho_q &= -I^\nu n_\nu.
\end{aligned}
$$

electric current → $J^\mu$

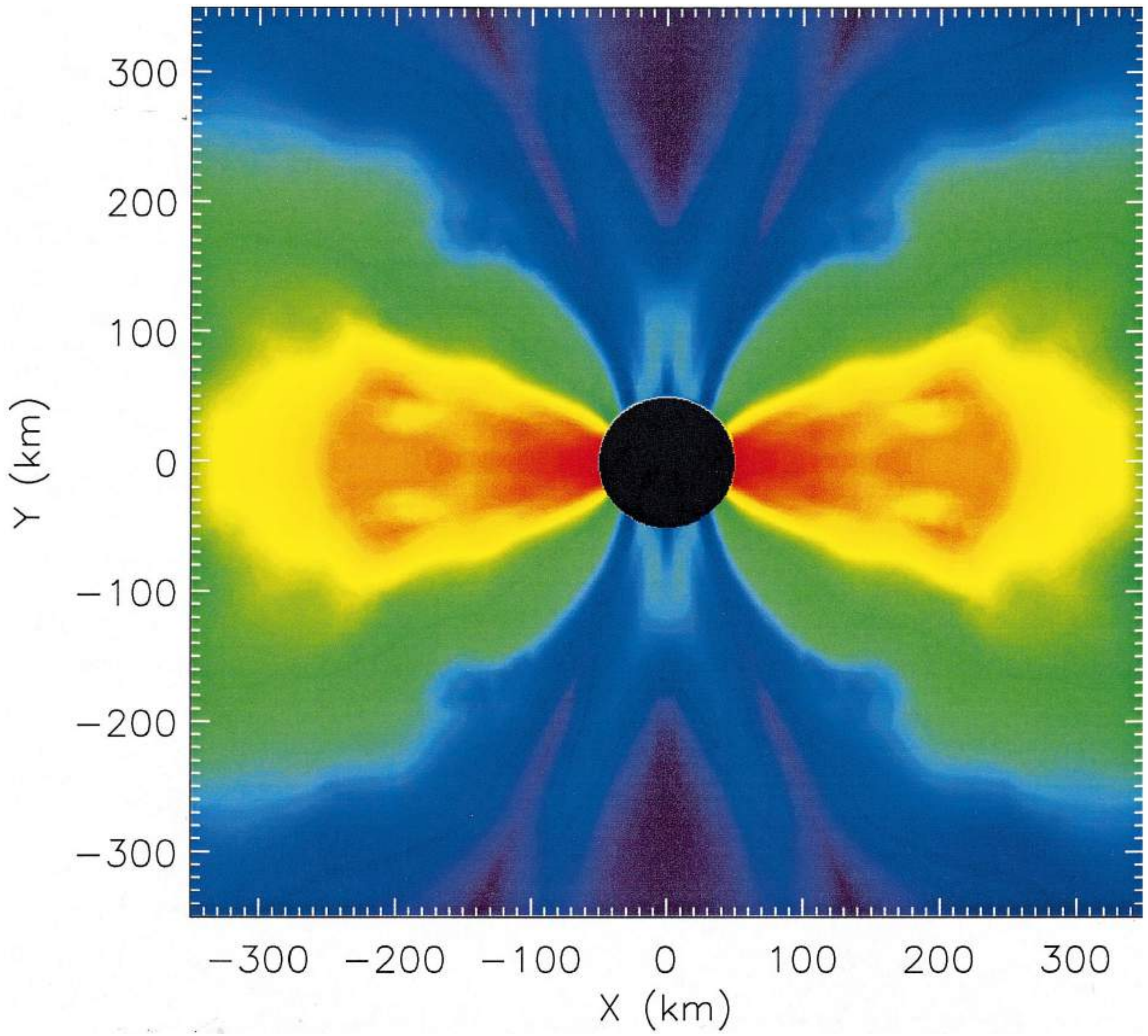
electric charge → $\rho_q$

Exercise: all these fields are purely spatial: $X^\mu n_\mu = 0$

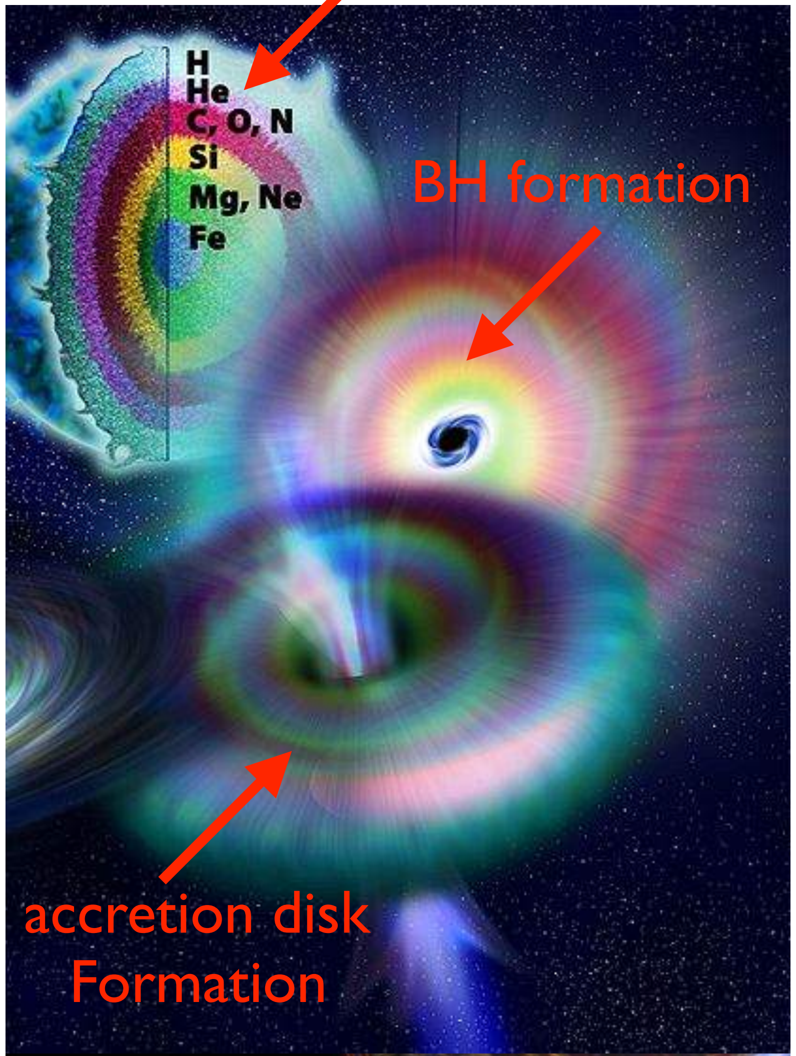
(i.e., they live on the spatial hyper-surfaces of the 3+1 split)

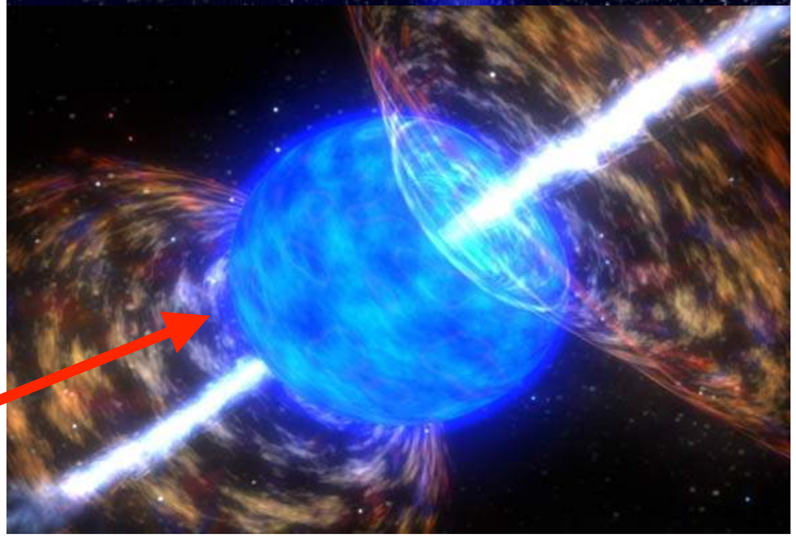
# Activation of the BZ mechanism

# Long GRBs: collapsars




MacFadyen & Woosley 1999

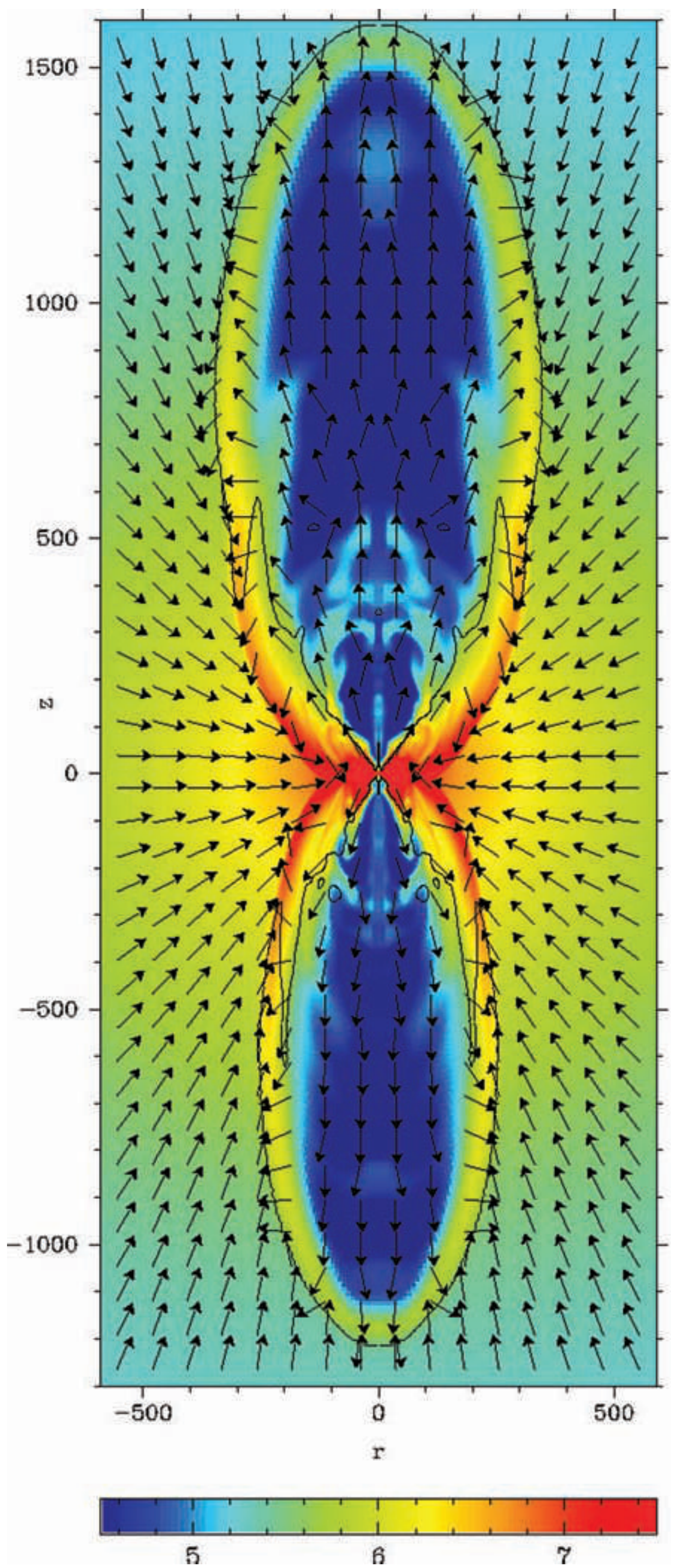


BH-accretion disk from collapse of *rapidly* rotating massive stars ($M > 20\ M_{sun}$)

jet punches through infalling material, generates GRB

# Long GRBs: collapsars




Komissarov & Barkov 2009

- Initial conditions: free-fall material with angular momentum, roughly approximating collapse of massive, rapidly rotating star
- Initial dipole B-field superimposed on infalling material
- Find that accretion onto BH predominantly occurs through accretion disk
- Find activation of BZ mechanism if

$$\beta_\rho = \frac{4\pi\rho c^2}{B^2} < 1$$

develops in polar region near BH horizon

# Short GRBs: binary neutron star mergers

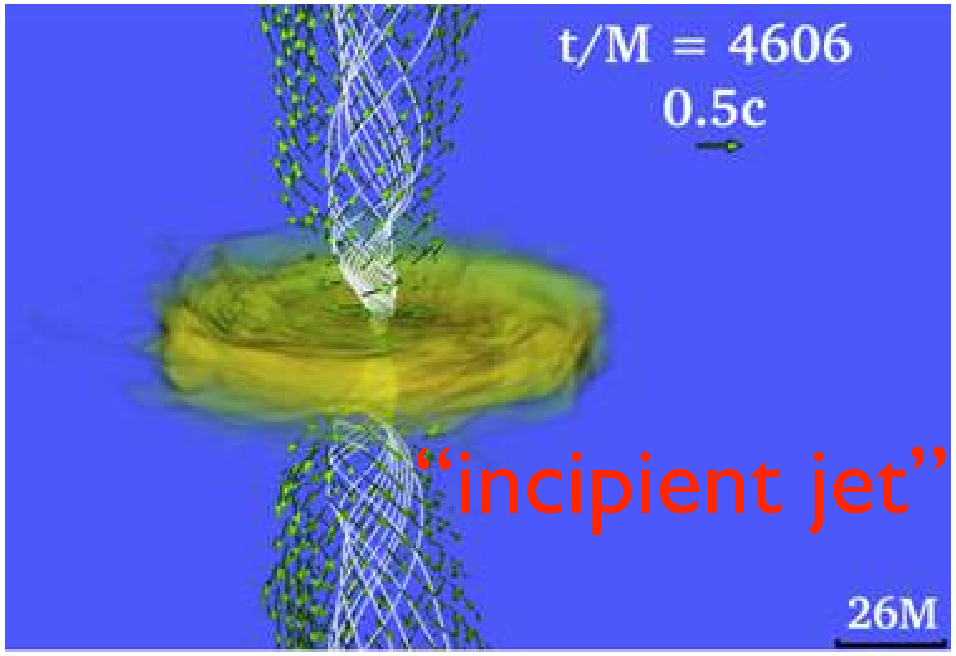



Fig.: Magnetic funnel (“incipient jet”) emerging from a BH-torus system (BNS merger)

Ruiz+ 2016
Paschalidis et al. 2015

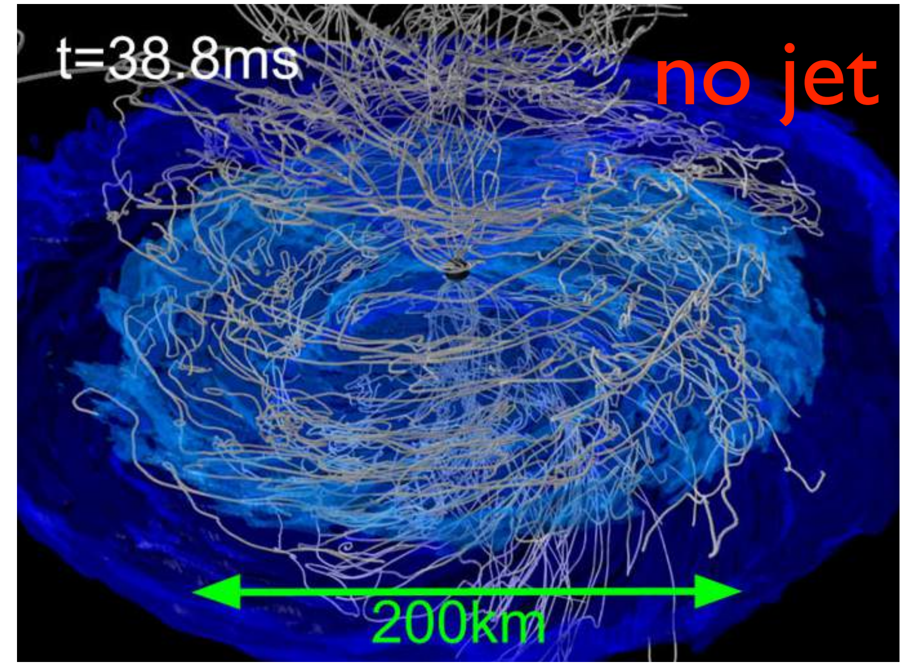



Fig.: Magnetic configuration from the highest resolution BNS simulations: no jet

Kiuchi+ 2017

- jet formation in NS mergers not understood yet
- successful case only for prompt collapse

no jet

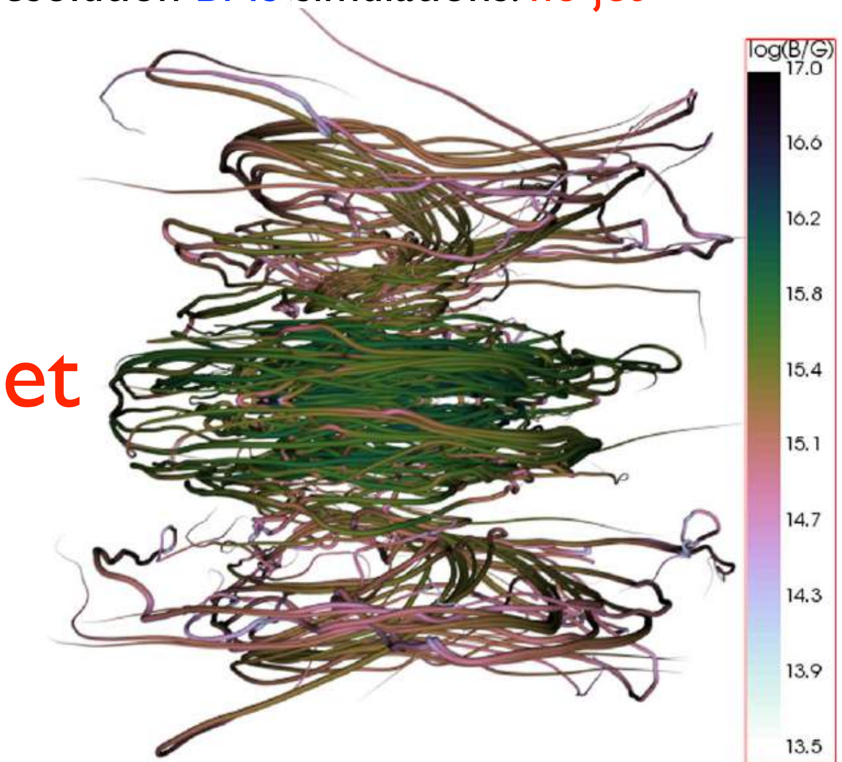
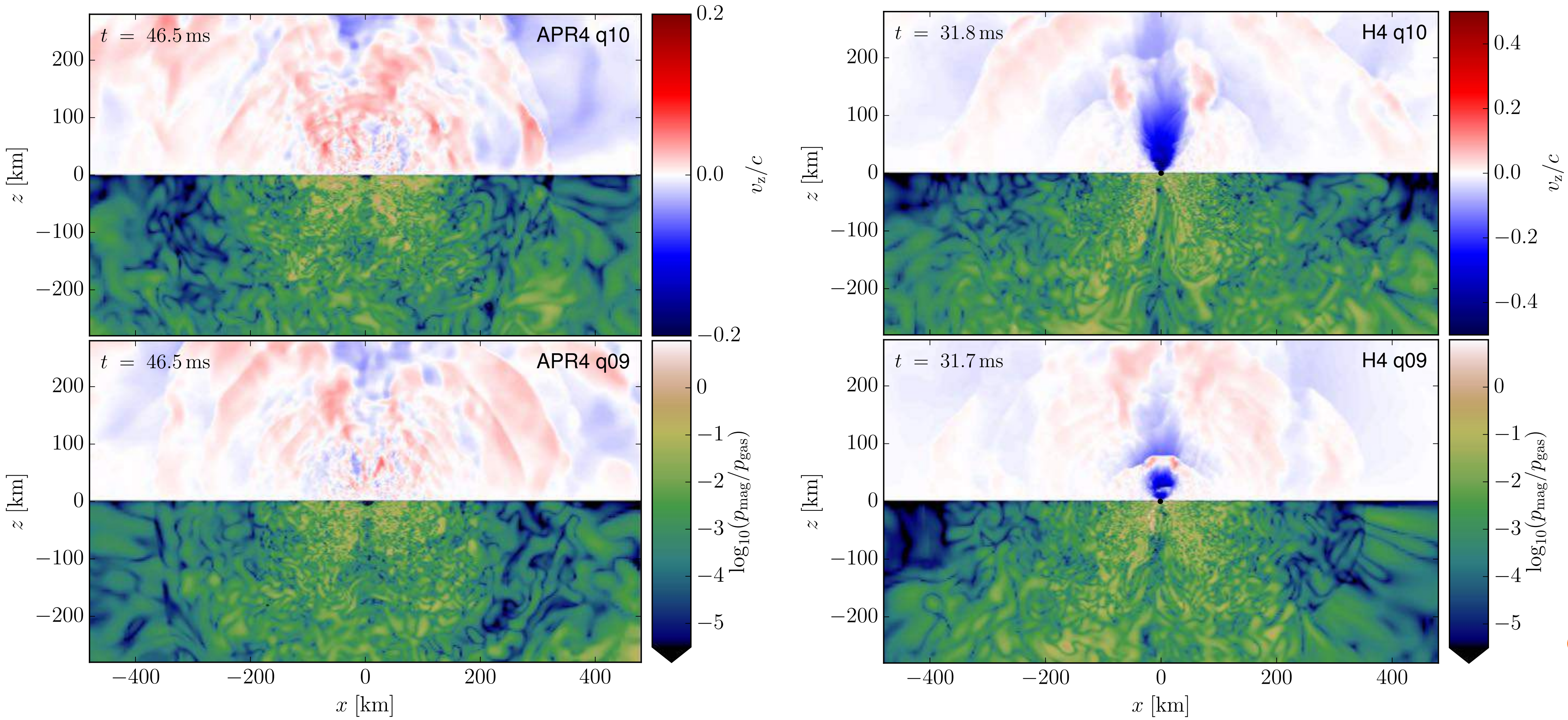



Fig.: Magnetic configuration from the latest BNS simulations: no jet

Ciolfi, Siegel+ 2017

# Baryon pollution in BNS mergers




Ciolfi+ 2017

BNS ⟶ NS
isotropic baryon pollution

BNS ⟶ BH
low-density polar funnel

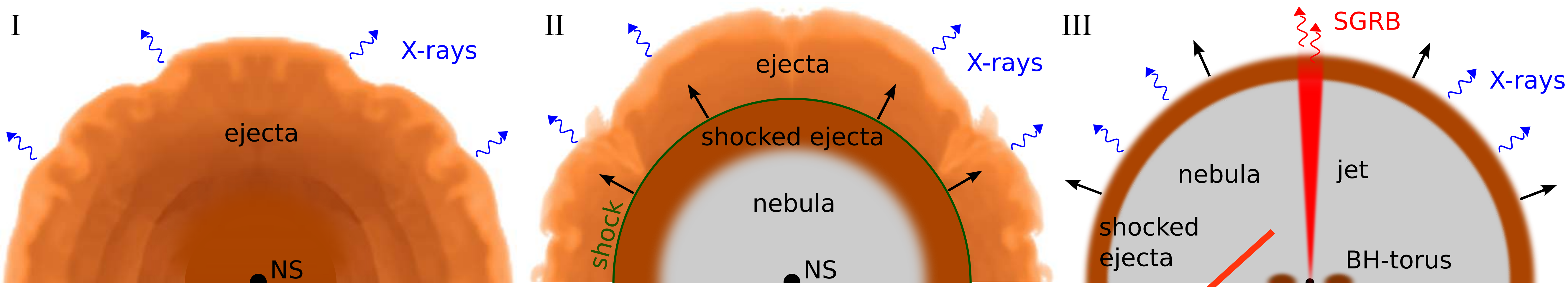
relativistic outflows likely choked
or prevented to form

Murguia-Berthier+ 2015,2016
Nagakura+ 2014
Just+ 2016

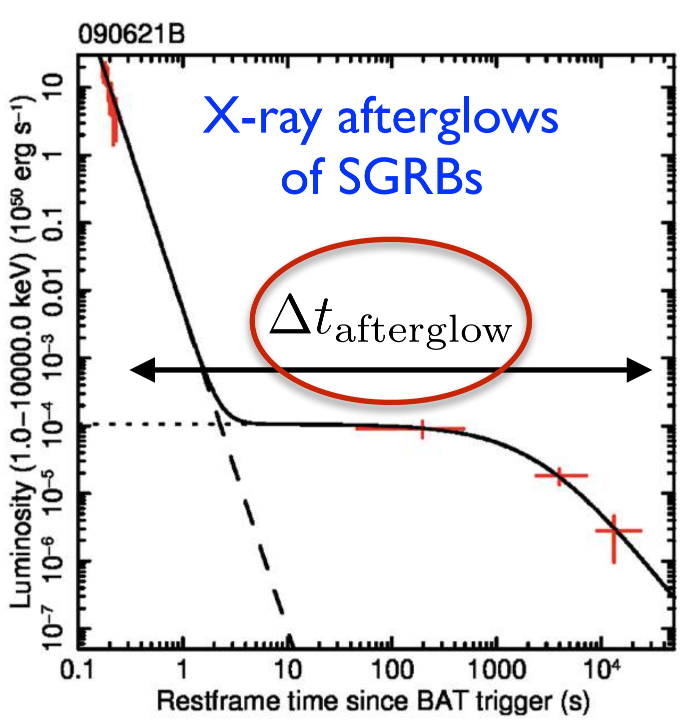
⟶ how can GRB jets be produced at all in BNS⟶NS events?

# How to avoid baryon pollution?

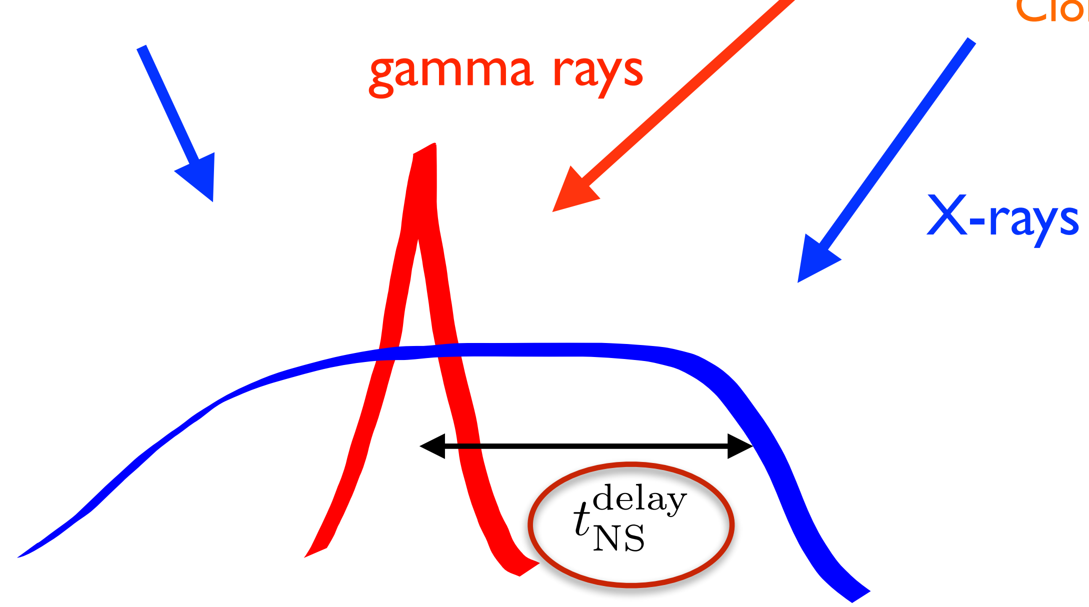
# Time-reversal scenario
Ciolfi & Siegel 2015a,b




Ciolfi & Siegel 2015a,b

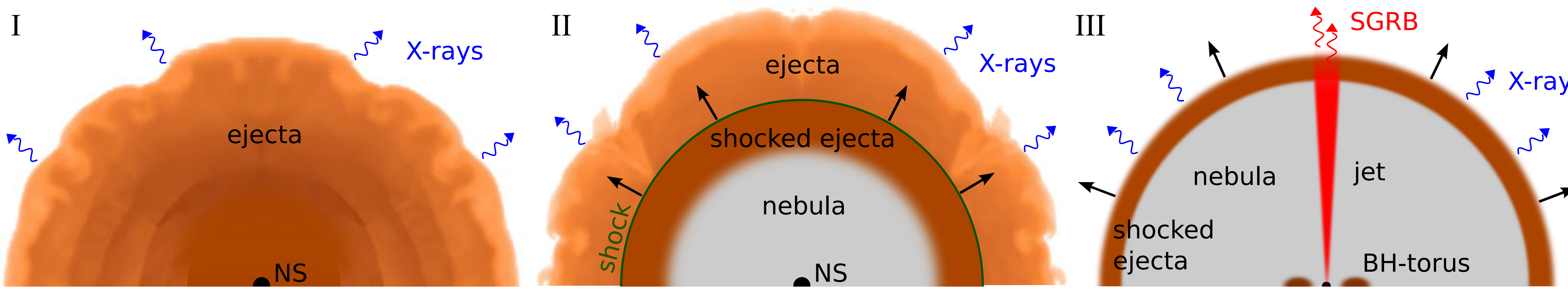



Rowlinson+2013

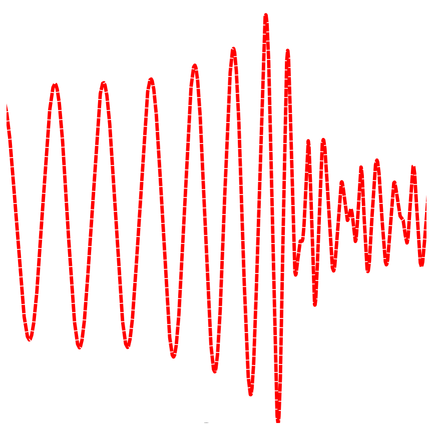



→ SGRB at time of NS collapse
X-ray precursor and afterglow

# Time-reversal scenario Ciolfi & Siegel 2015a,b



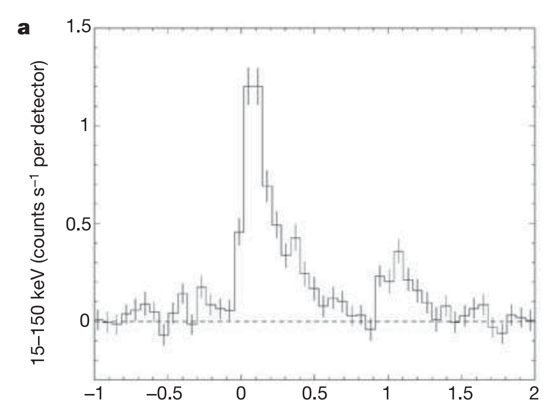

Ciolfi & DMS 2015a,b



peak amplitude GW signal

$$t_{\rm coll} \sim t_{\rm sd} \sim 10^3\,{\rm s}$$

lifetime of the NS




EM SGRB signal

→ GW-EM multimessenger observations ideal to reveal the central engine