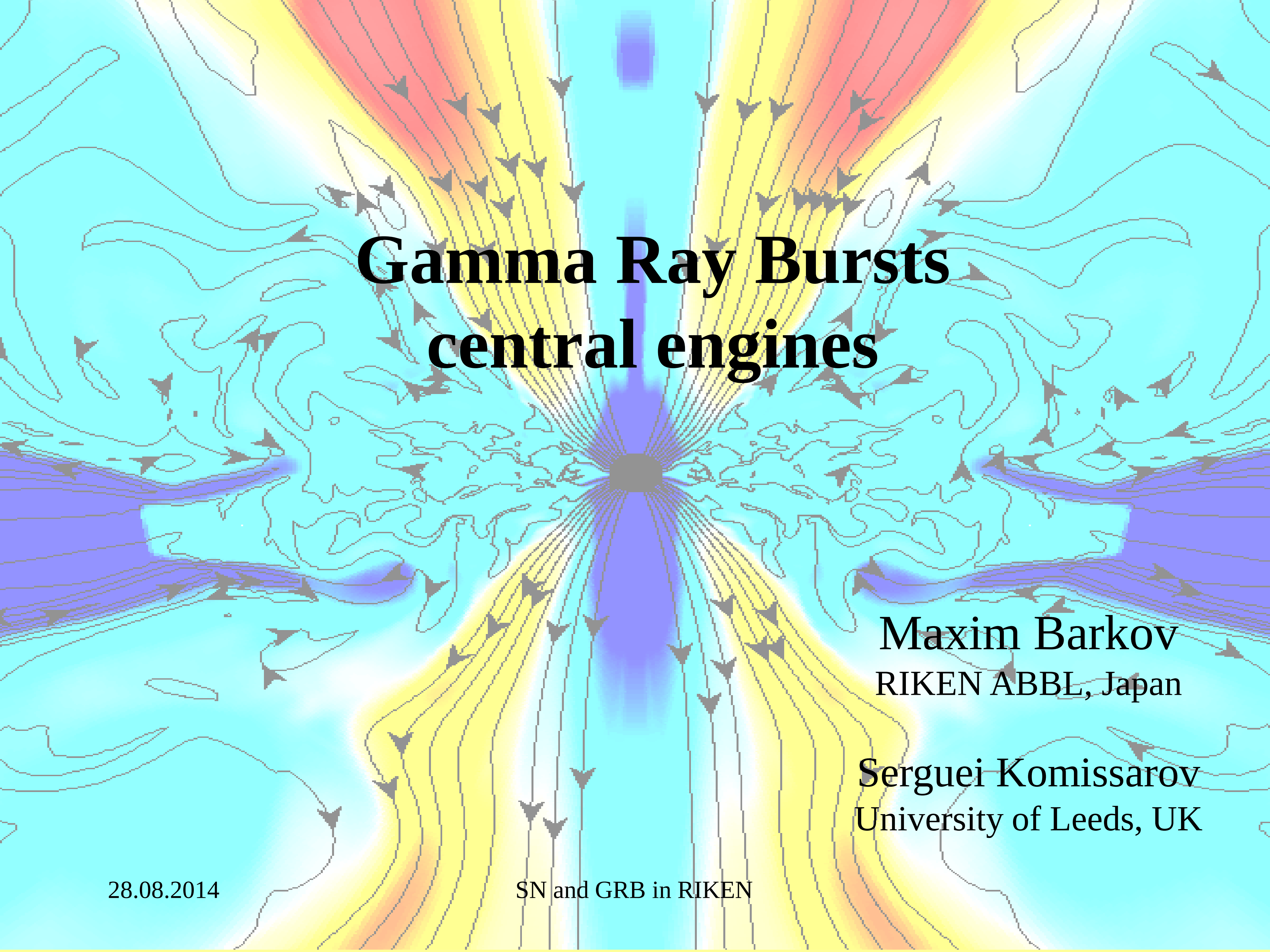


Gamma Ray Bursts central engines

Maxim Barkov
RIKEN ABBL, Japan

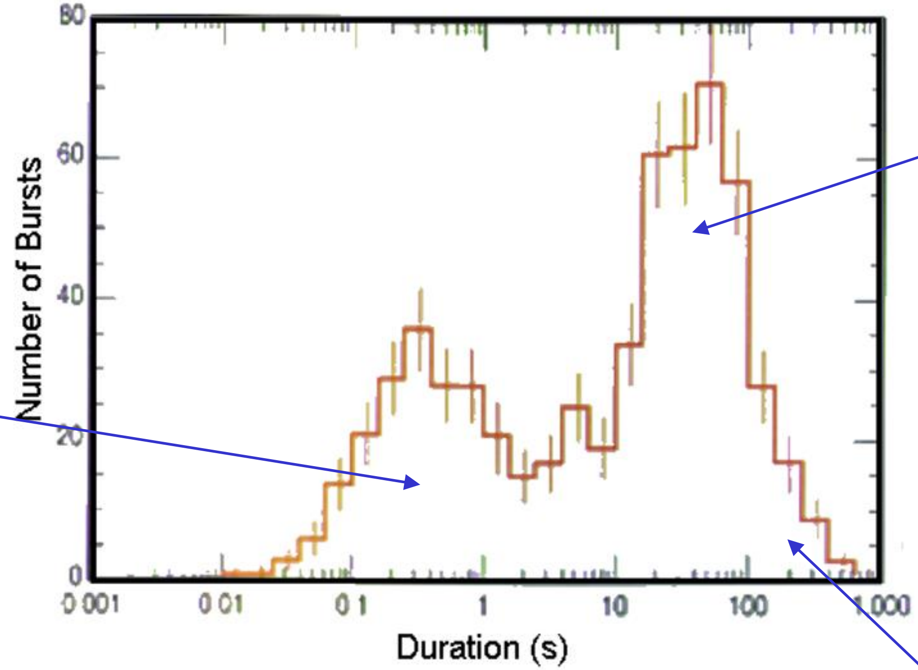
Serguei Komissarov
University of Leeds, UK

Spectral properties:

Non-thermal spectrum from 0.1MeV to GeV:

$$N(E) \propto E^{-\alpha}, \;\; \alpha = 1 \div 2$$

Bimodal distribution (two types of GRBs?):



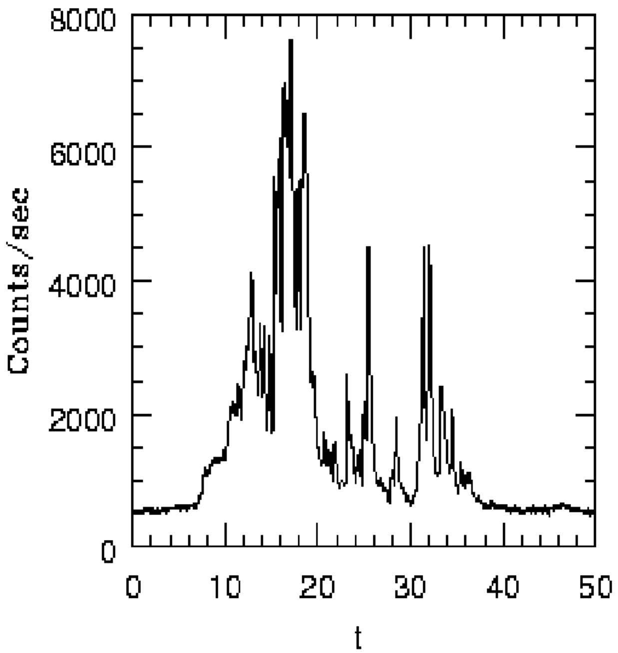
long duration GRBs

short duration GRBs

very long duration GRBs

Variability:

- smooth fast rise + decay;
- several peaks;
- numerous peaks with substructure down to milliseconds



Total power:

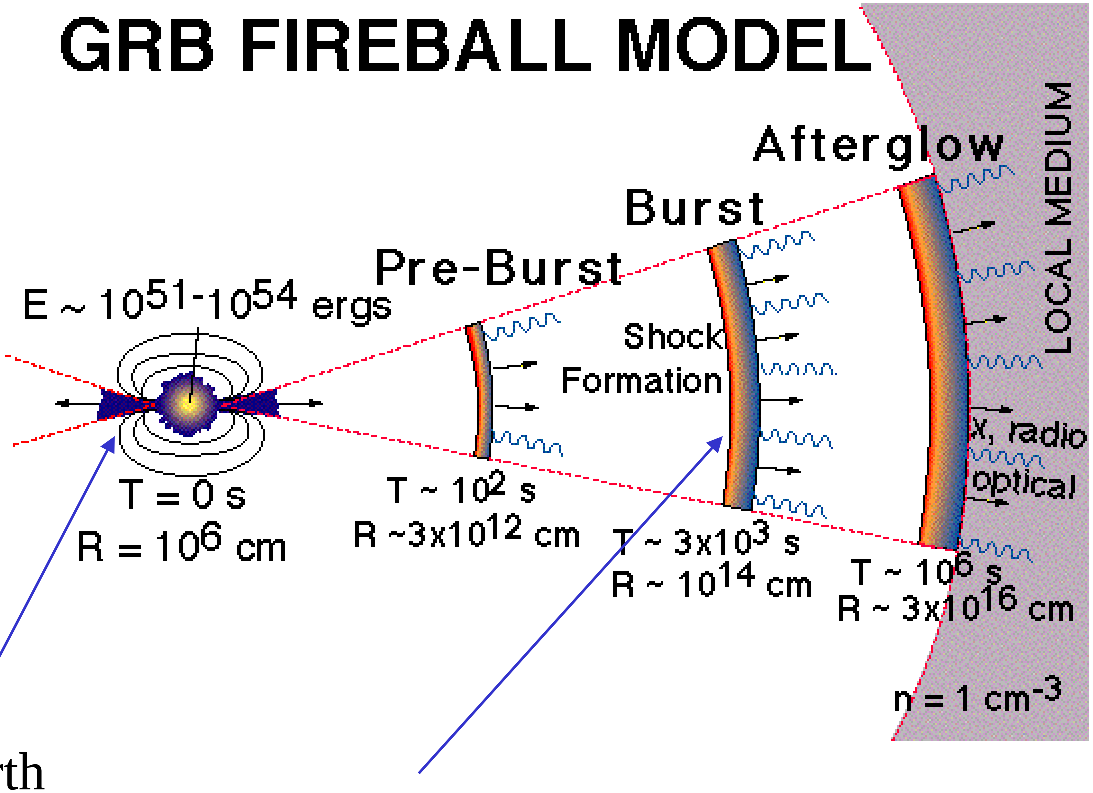
$$E_{tot} = 10^{51} - 10^{54} erg$$

assumption of isotropic emission

Inferred high speed:

Too high opacity to $\gamma\gamma \longrightarrow e^{\pm}$ unless Lorentz factor > 100

Relativistic jet/pancake model of GRBs and afterglows:



jet at birth

(we are here)

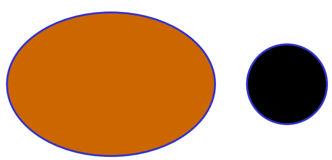
pancake later

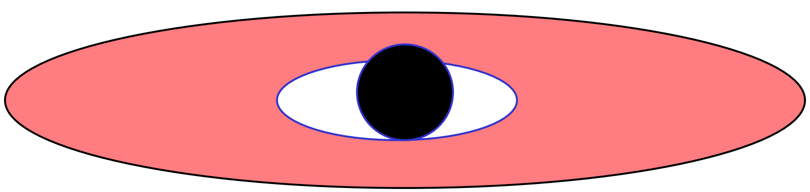
Merge of compact stars – origin of short duration GRBs?

Blinnikov et al (1984);
Paczynsky (1986);
Goodman (1986);
Eichler et al.(1989);

Neutron star + Neutron star
Neutron star + Black hole
White dwarf + Black hole

→ Black hole + compact disk





$M_d \simeq 0.1 - 1 M_\odot$
$R_d \simeq 10 - 100 R_g$

→

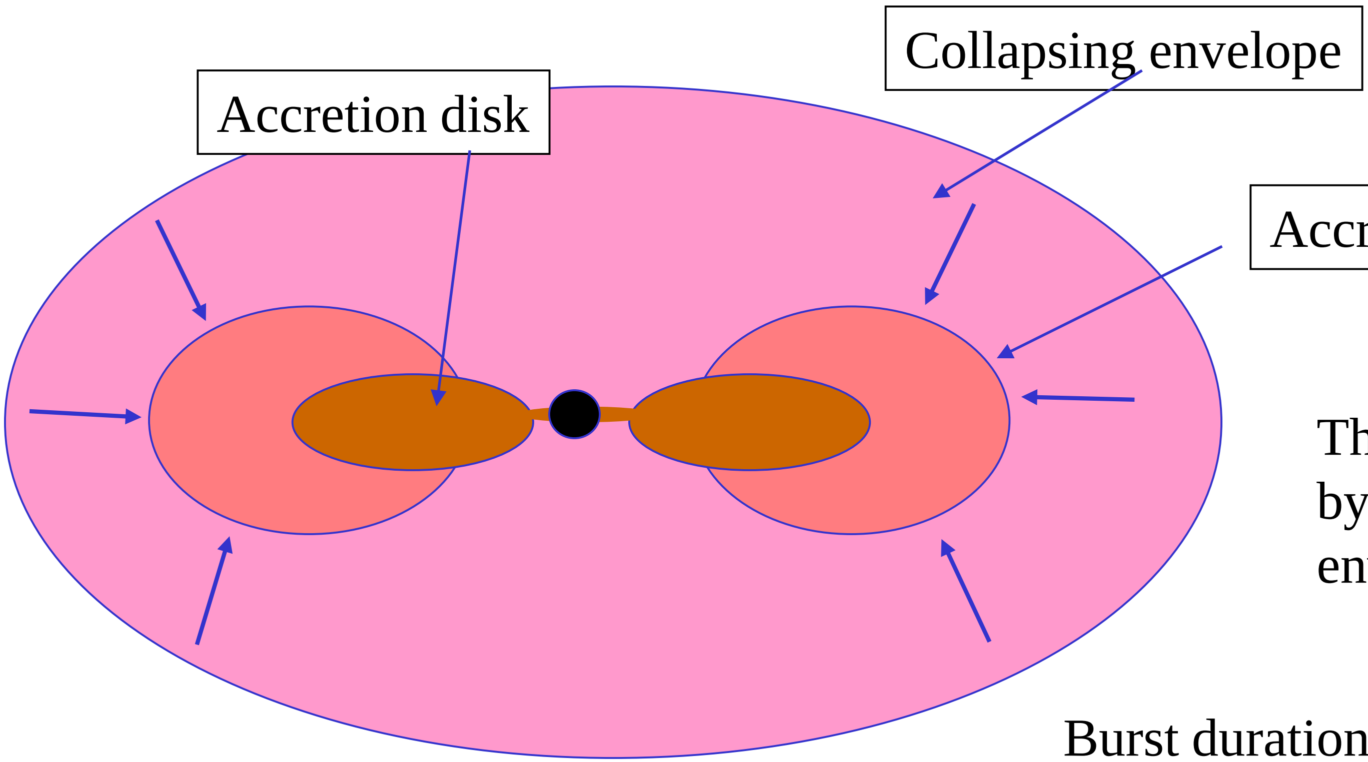
Burst duration: 0.1s – 1.0s

Released binding energy:
$E_d \leq 8 \times 10^{52} \div 8 \times 10^{53} \mathrm{erg}$

Collapsars– origin of long duration GRBs?

Iron core collapses into a black hole: “failed supernova”. Rotating envelope forms hyper-accreting disk

Woosley (1993)
MacFadyen & Woosley (1999)

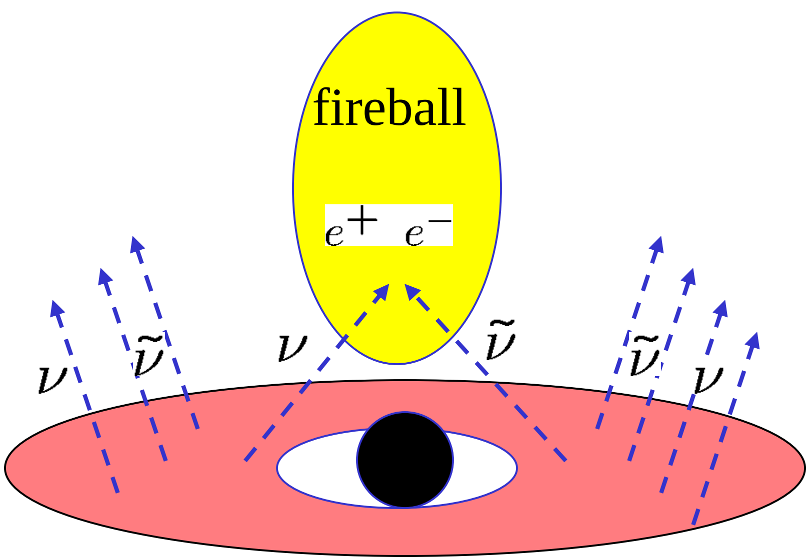


The disk is fed by collapsing envelope.

Burst duration > a few seconds

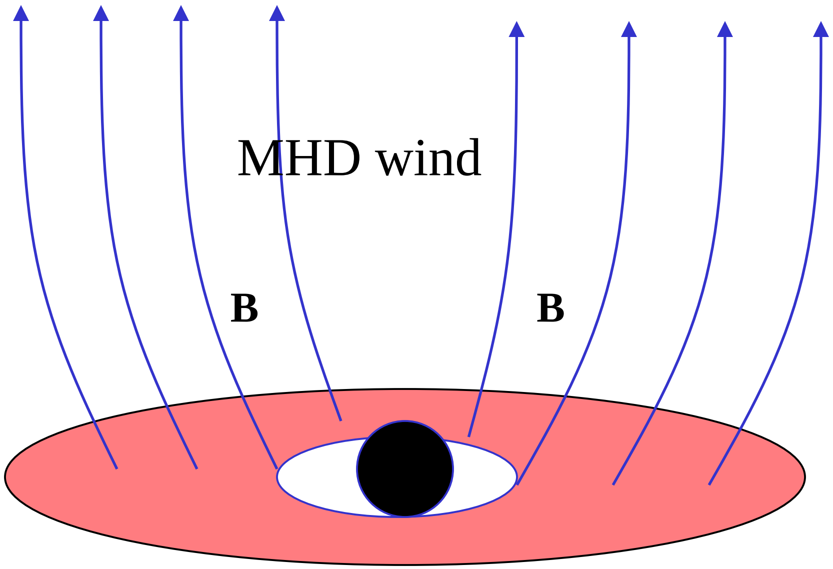
Mechanisms for tapping the disk energy

Neutrino heating



Eichler et al.(1989), Aloy et al.(2000)
MacFadyen & Woosley (1999)
Nagataki et al.(2006), Birkl et al (2007)
Zalamea & Beloborodov (2008,2010)

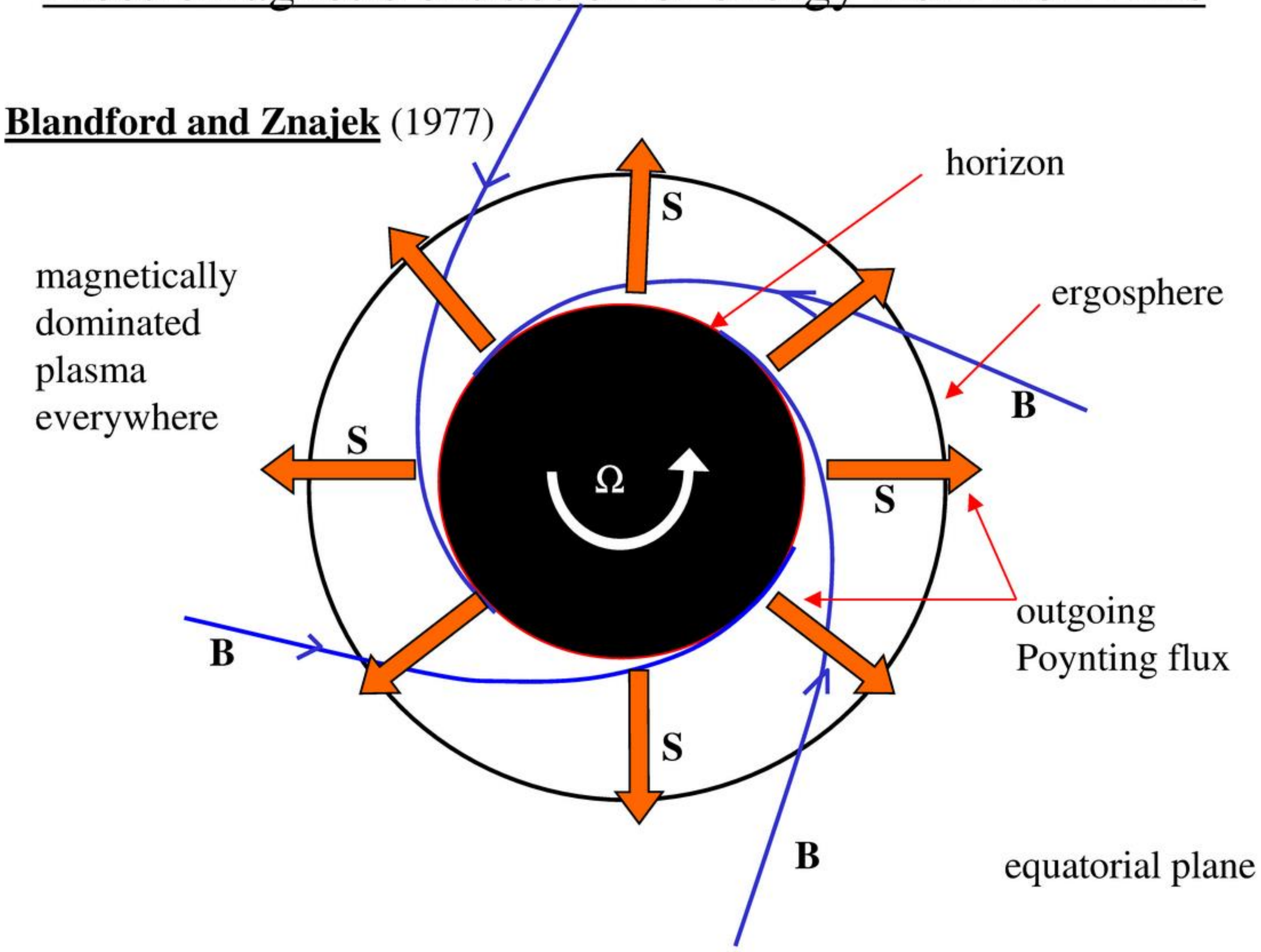
Magnetic braking



Blandford & Payne (1982)
Proga et al. (2003)
Fujimoto et al.(2006)
Mizuno et al.(2004)

Electromagnetic extraction of energy from Kerr BHs

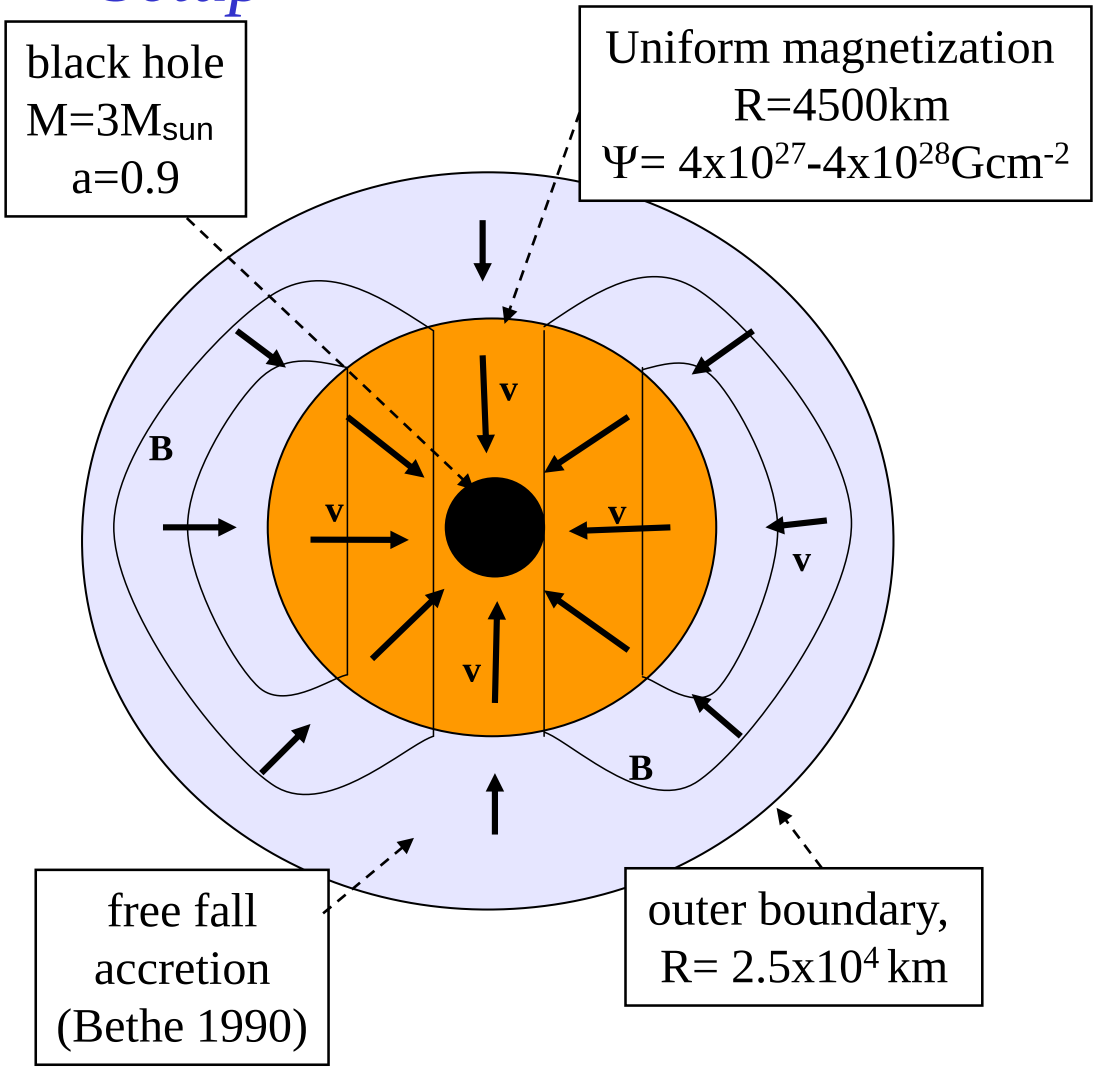
Blandford and Znajek (1977)



Numerical simulations: I

Setup

(Barkov & Komissarov 2008a,b)
(Komissarov & Barkov 2009)



Rotation:

$$l = l_0 \sin^3\theta \min(r/r_c, 1)^2$$

$r_c = 6.3\times10^3$ km
$l_0 = 10^{17}$ cm^2 s^{-1}

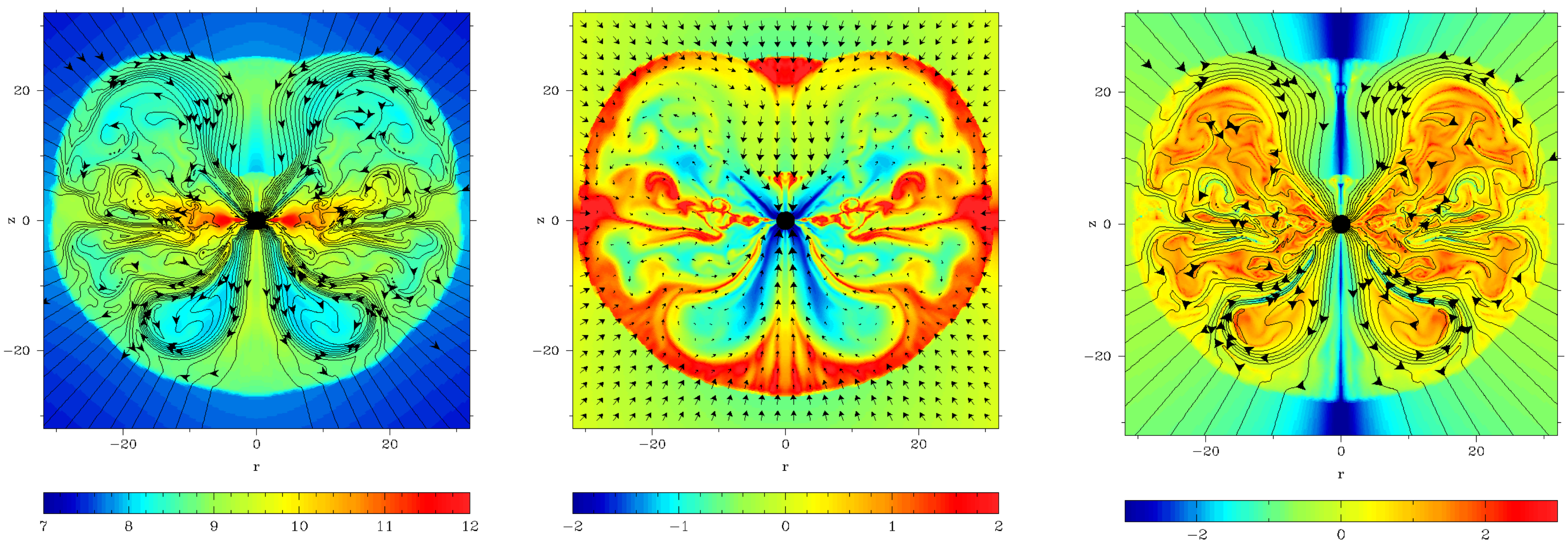
- 2D axisymmetric GRMHD;
- Kerr-Schild metric;
- Realistic EOS;
- Neutrino cooling;
- Starts at 1s from collapse onset. Lasts for < 1s

Model:A

$C_1=9$; $B_p=3x10^{10}$ G

unit length=4.5km
t=0.24s

$\log_{10}\rho$ (g/cm^3) $\log_{10} P/P_m$ $\log_{10} B_\phi/B_p$



magnetic field lines, and velocity vectors

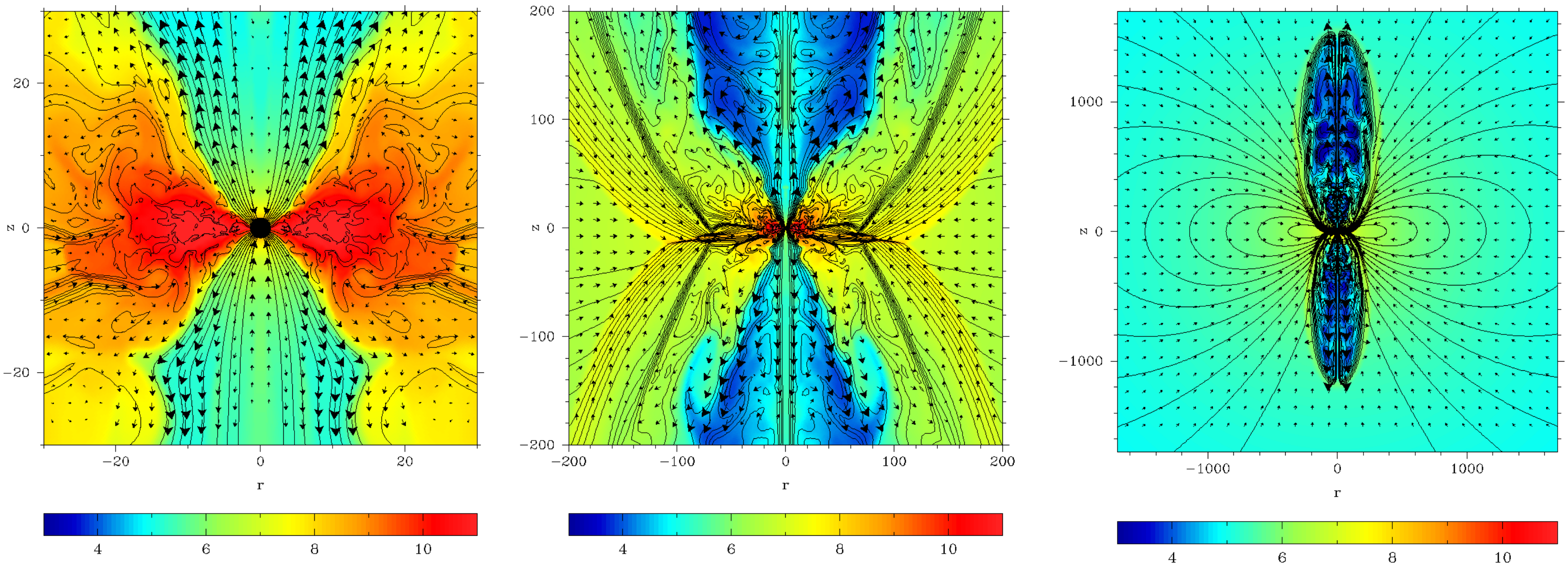
Model:A

$C_1=9$; $B_p=3\times10^{10}$ G

unit length=4.5km

t=0.31s

$\log_{10} \rho$ (g/cm^3)



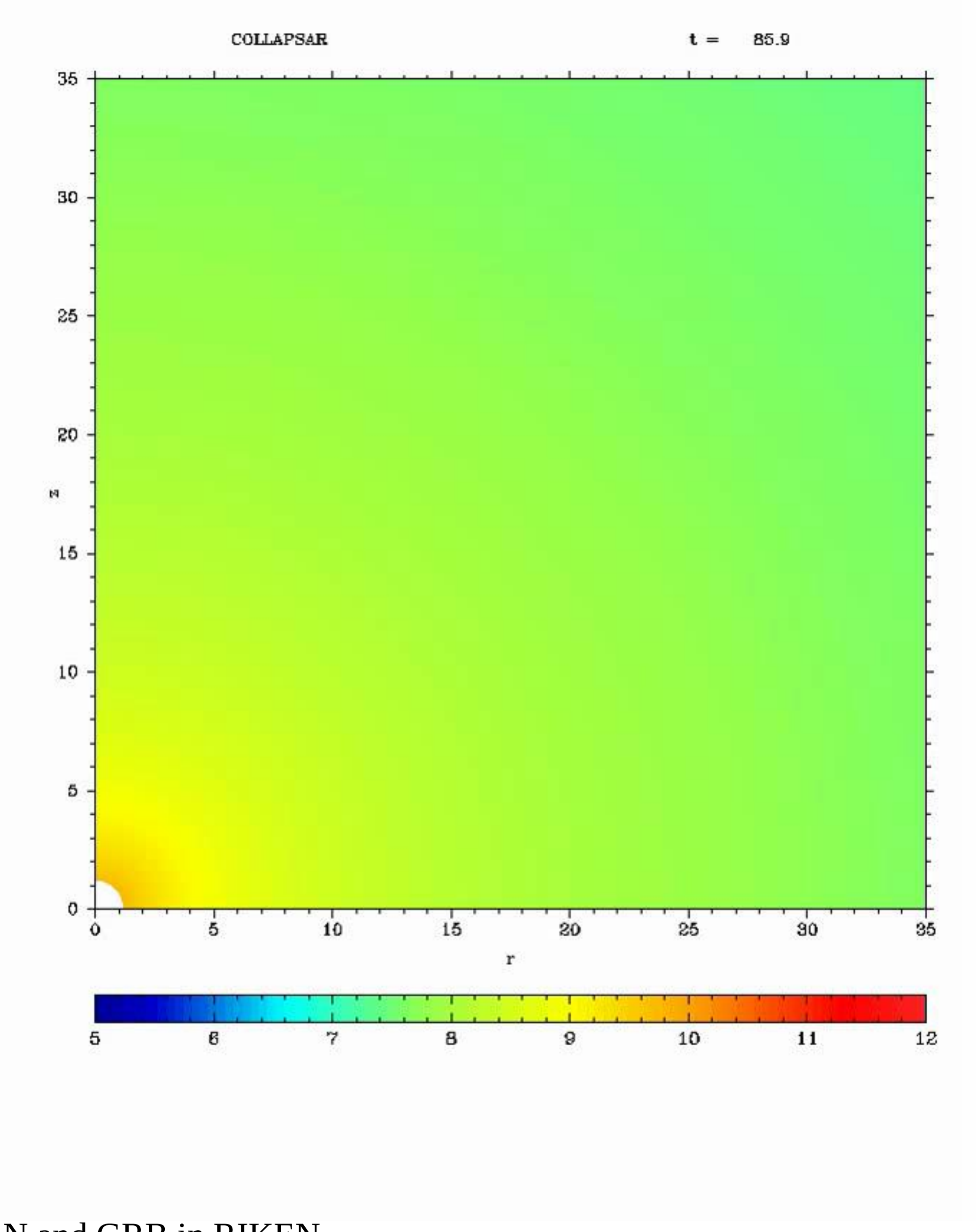
magnetic field lines, and velocity vectors

Model:A

C_1=9; B_p=3x10^{10} G

$\log_{10} \rho$ (g/cm^3)

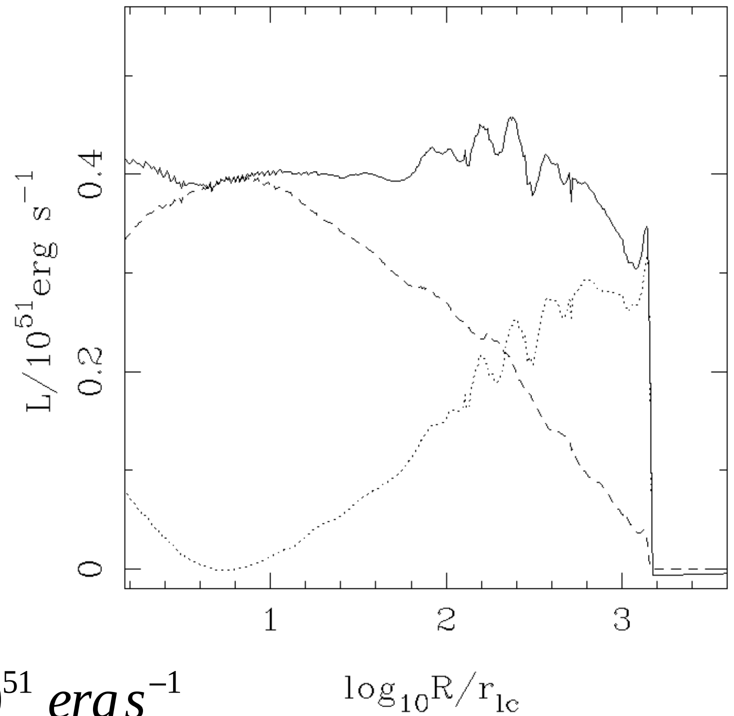
magnetic field lines



Jets are powered mainly by the black hole via the Blandford-Znajek mechanism !!

Model: C

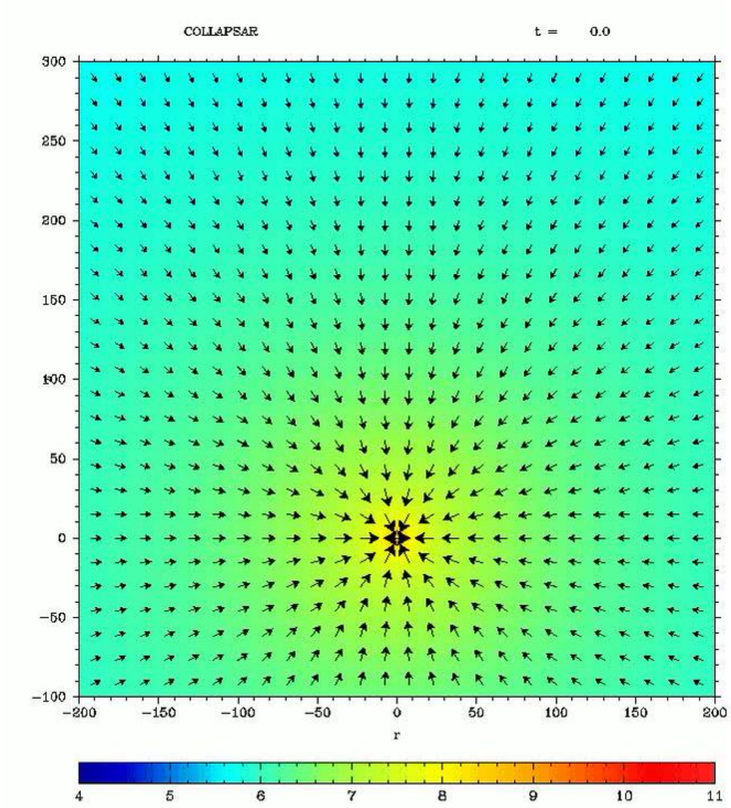
- No explosion if a=0;
- Jets originate from the black hole;
- ~90% of total magnetic flux is accumulated by the black hole;
- Energy flux in the ouflow ~ energy flux through the horizon (disk contribution < 10%);
- Theoretical BZ power:



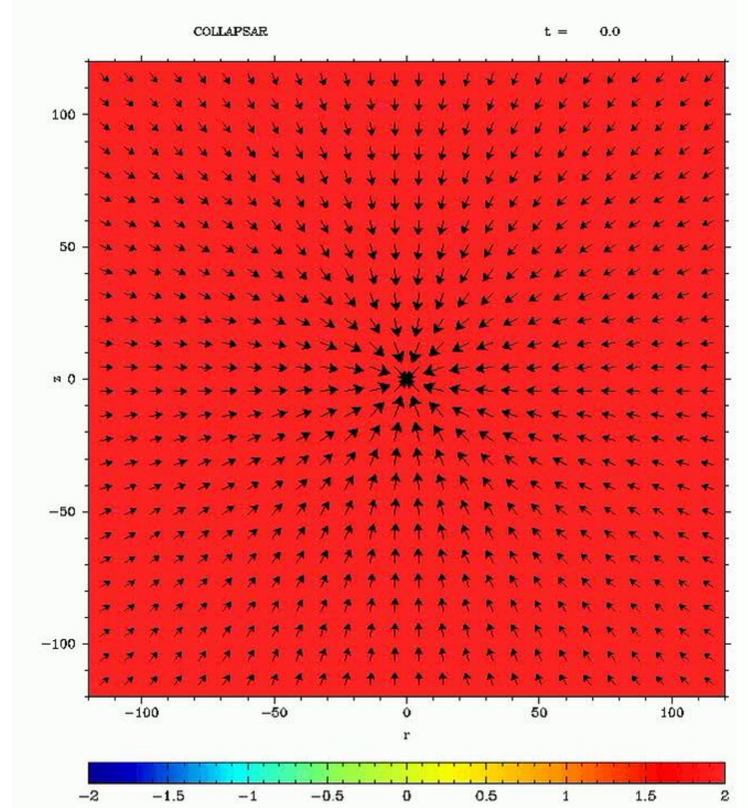
$$\dot{E}_{BZ} = 3.6\times10^{50} f(a)\Psi_{27}^{2} M_{2}^{-2} = 0.48\times10^{51}\, erg\, s^{-1}$$

$\dot{M} = 0.15\, M_{SUN}\, s^{-1} \quad (C_1 = 3) \qquad l_0 = 10^{17}\ cm^2 s^{-1}$

$B = 0.3 \times 10^{10} G \qquad a = 0.9$



$$\log_{10}(\rho)$$



$$\log_{10}\left(P_g / P_m\right)$$

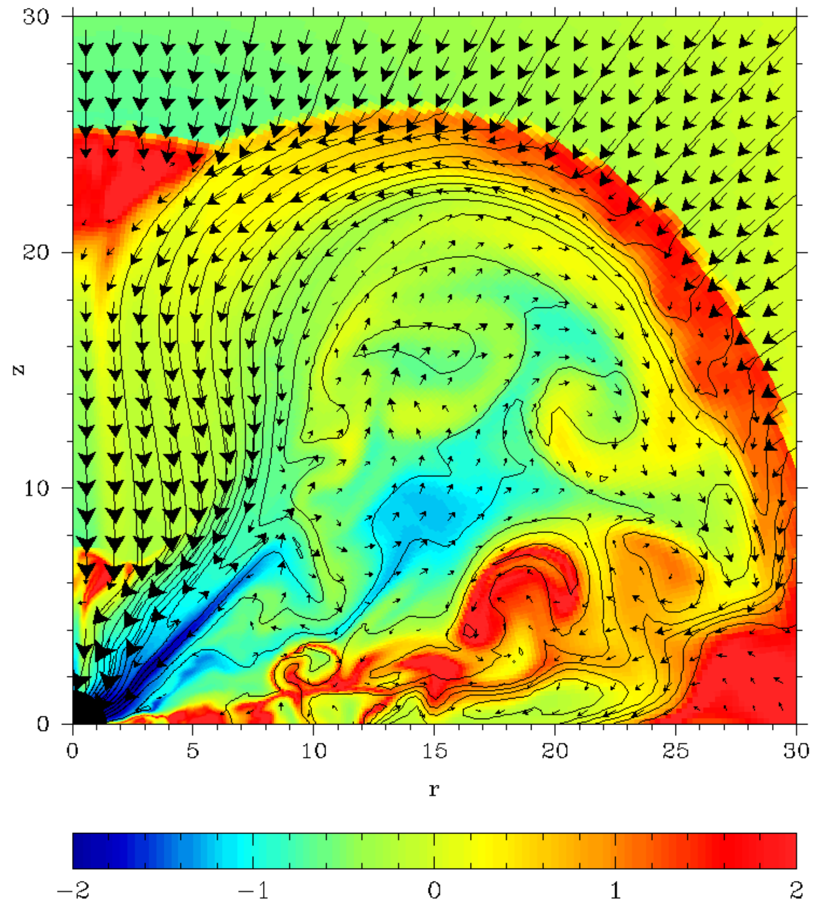
Magnetic Unloading

What is the condition for activation of the BZ-mechanism ?

1) MHD waves must be able to escape from the black hole ergosphere to infinity for the BZ-mechanism to operate, otherwise accretion is expected.

or $B^2/4\pi\rho c^2 > 1$

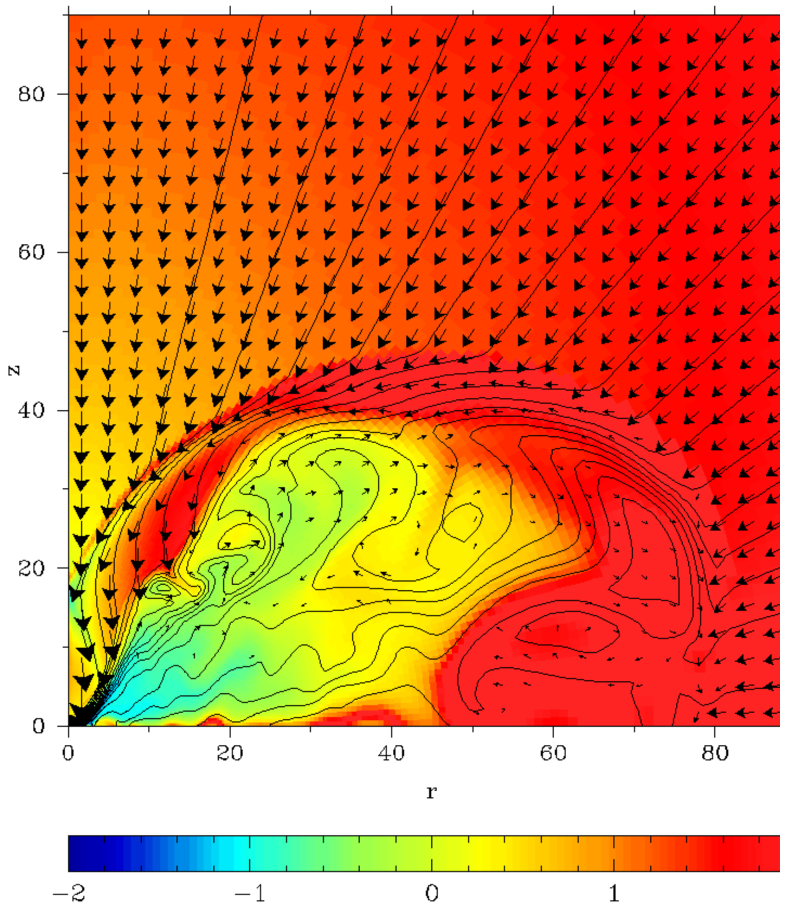
2) The torque of magnetic lines from BH should be sufficient to stop accretion
(Barkov & Komissarov 2008b)
(Komissarov & Barkov 2009)

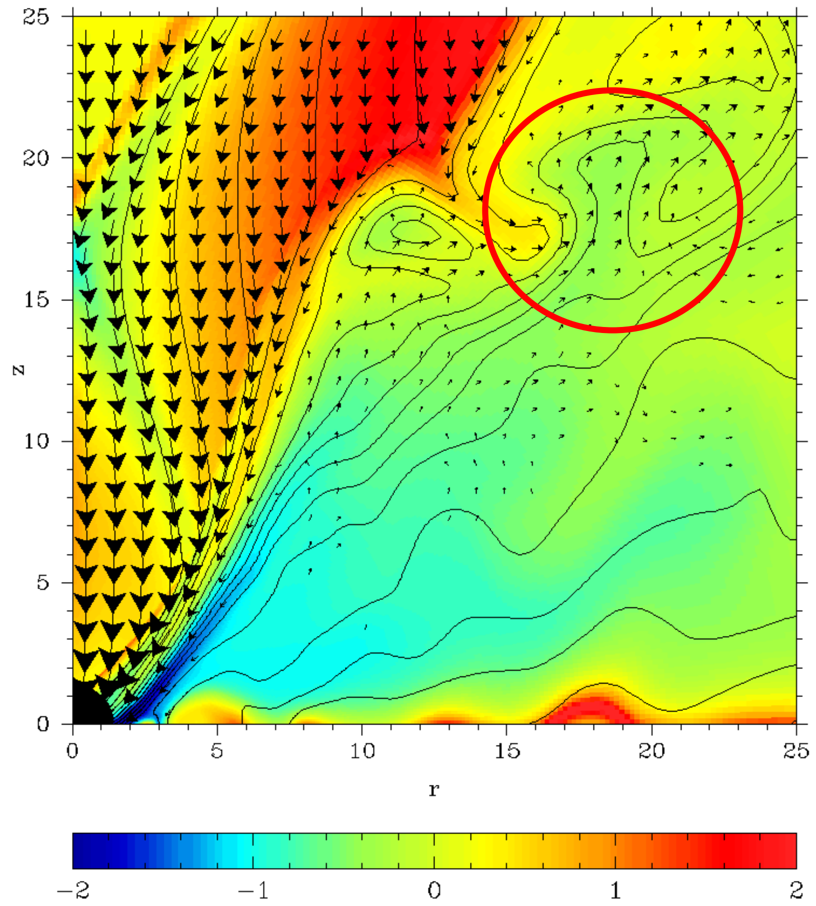


$$\dot{E}_{BZ} / \dot{M}c^2 = \kappa > 1 \,(???)$$

$$\dot{E}_{BZ} = 3.6\times10^{50} f(a)\Psi_{27}^2 M_2^{-2}$$

$$f(a) = \frac{a^2}{\left(1+\sqrt{1-a^2}\right)^2}$$





The disk accretion relaxes the explosion conditions. The MF lines' shape reduces the local accretion rate.

$$\dot{E}_{BZ} / \dot{M}c^2 = \kappa > 1/10$$

Realistic initial conditions

- Strong magnetic field suppresses the differential rotation in the star (Spruit et. al., 2006).

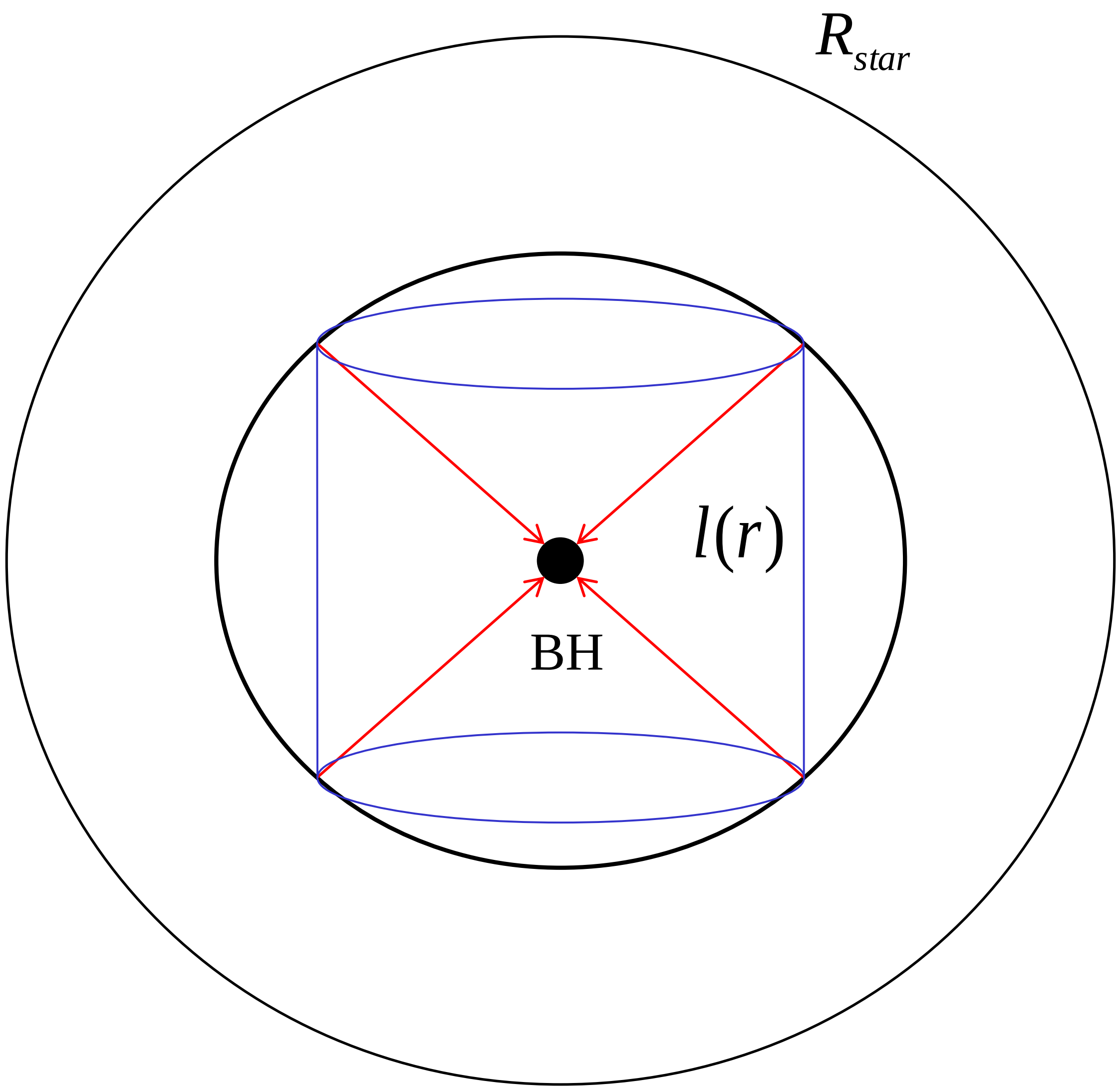
- Magnetic dynamo can’t generate a large magnetic flux, a relict magnetic field is necessary. (see observational evidences in Bychkov et al. 2009)

- In close binary systems we could expect fast solid body rotation.

- The most promising candidate for long GRBs is Wolf-Rayet stars.

Simple model:

Barkov & Komissarov (2010)



If l(r)<l_{cr} then matter falling to BH directly

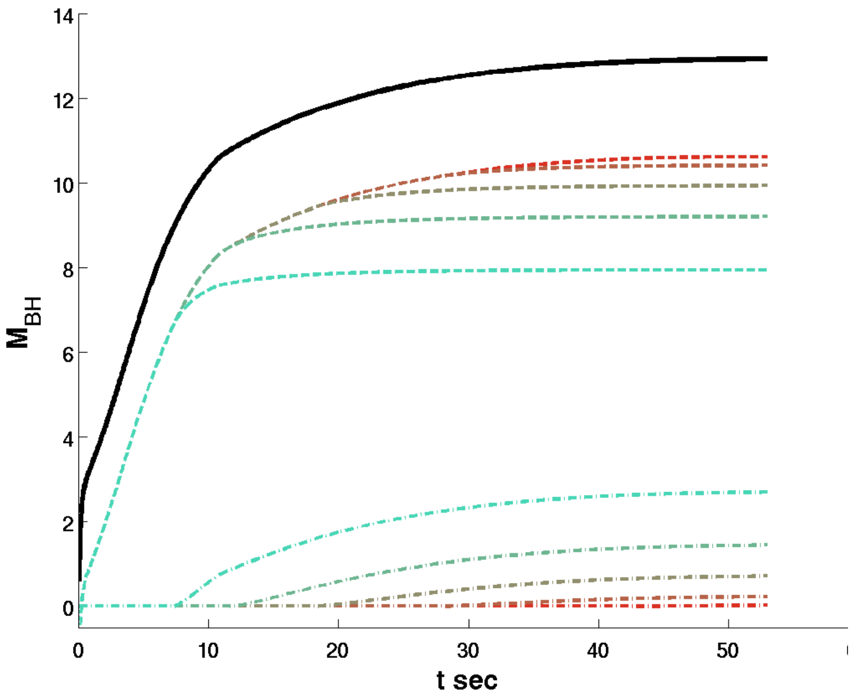
If l(r)>l_{cr} then matter goes to disk and after that to BH

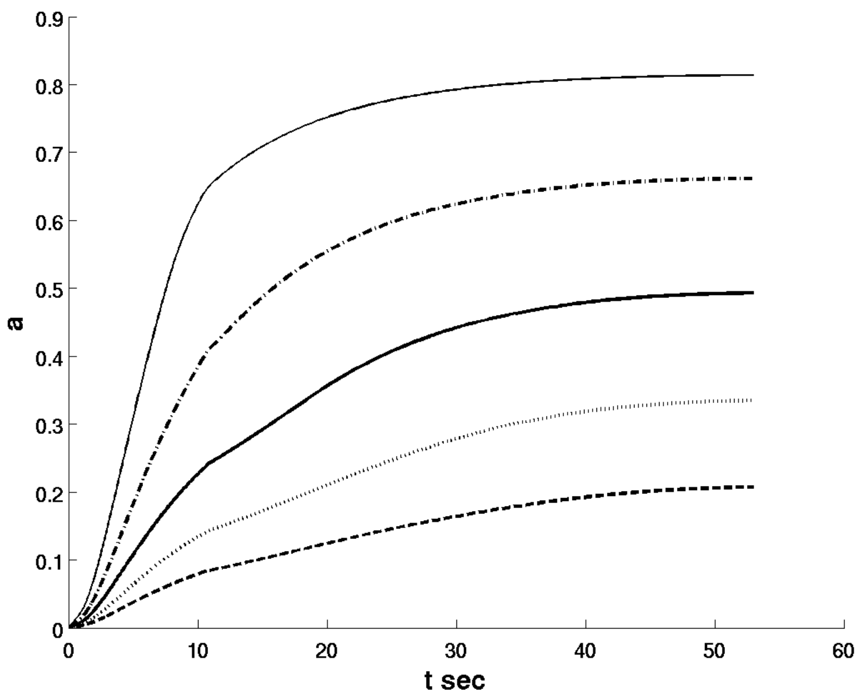
Agreement with model Shibata&Shapiro (2002) on level 1%

Realistic model

Heger at el (2004)

$M=35\ M_{sun},\ \ M_{WR}=13\ M_{sun}$



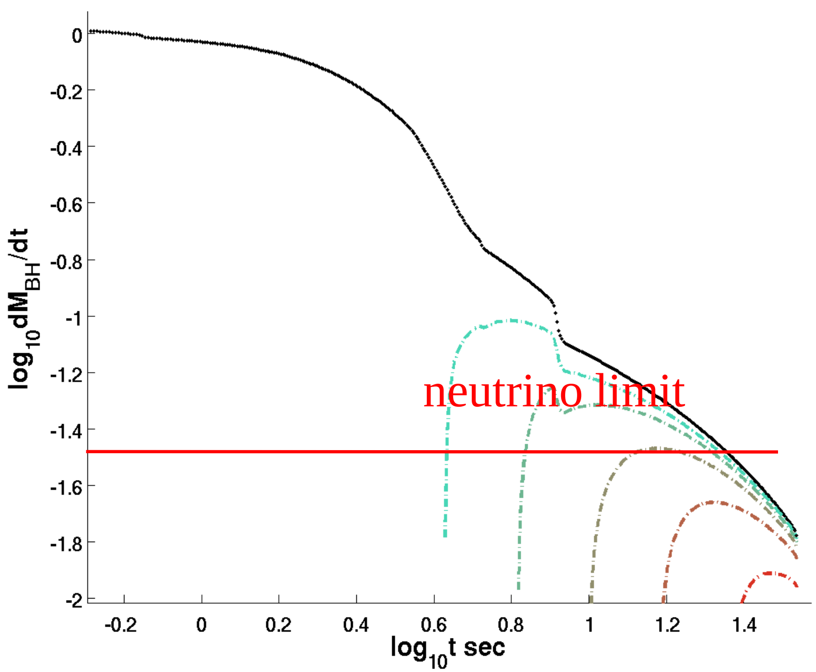


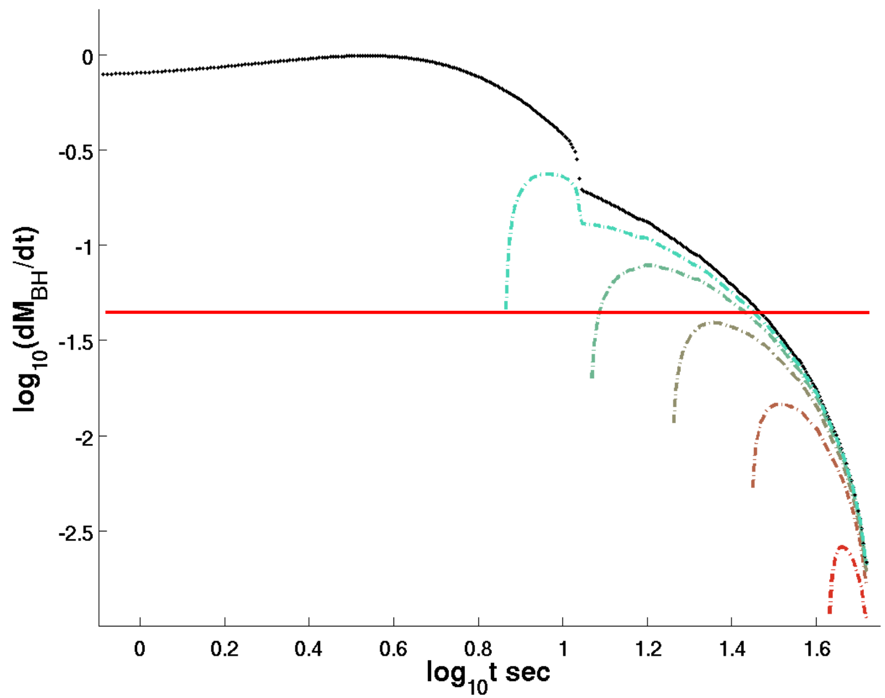
Realistic model

Heger at el (2004)

$M=20\ M_{sun}$, $M_{WR}=7\ M_{sun}$

$M=35\ M_{sun}$, $M_{WR}=13\ M_{sun}$



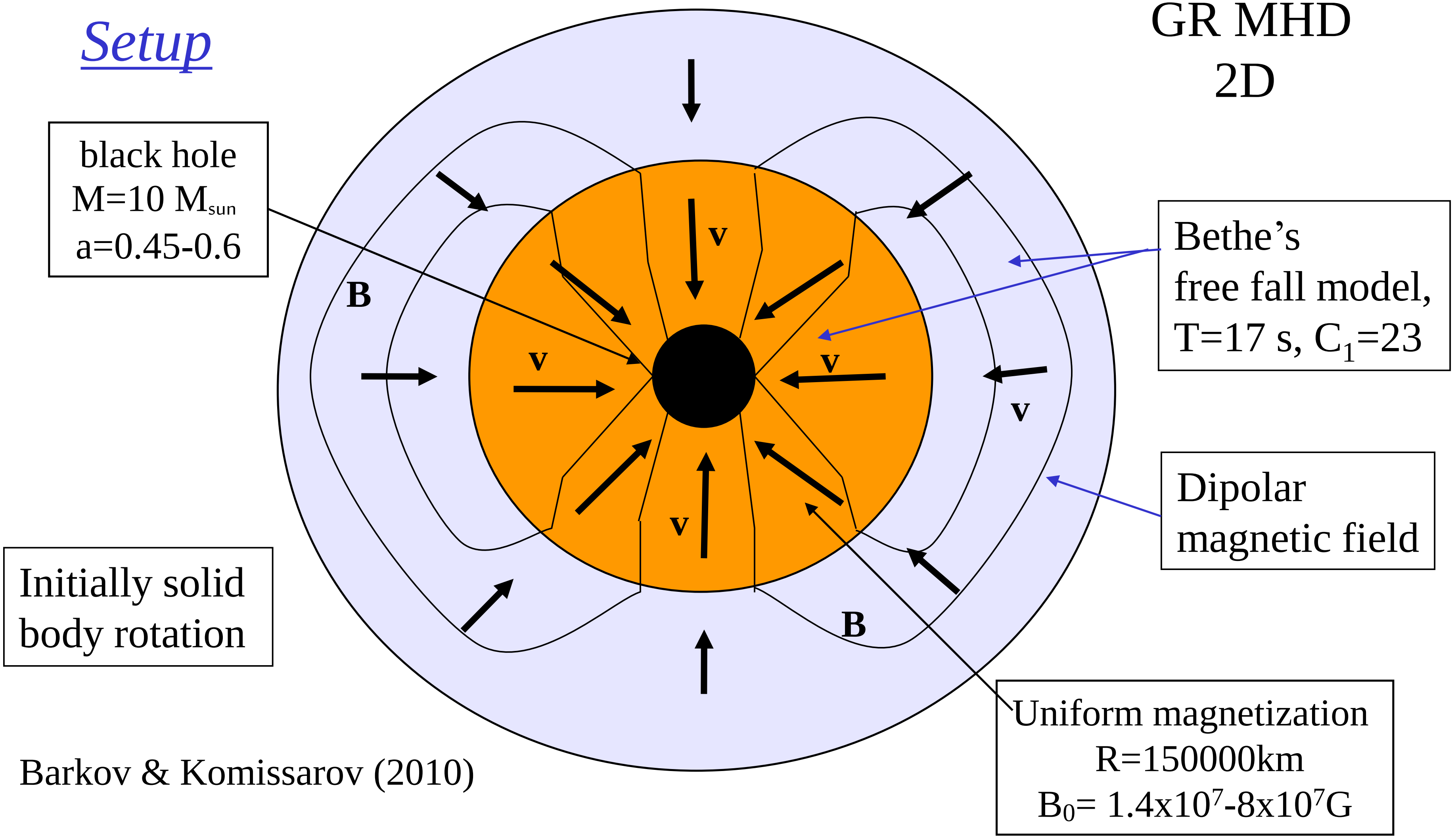


BZ limit

Numerical simulations II: Collapsar model

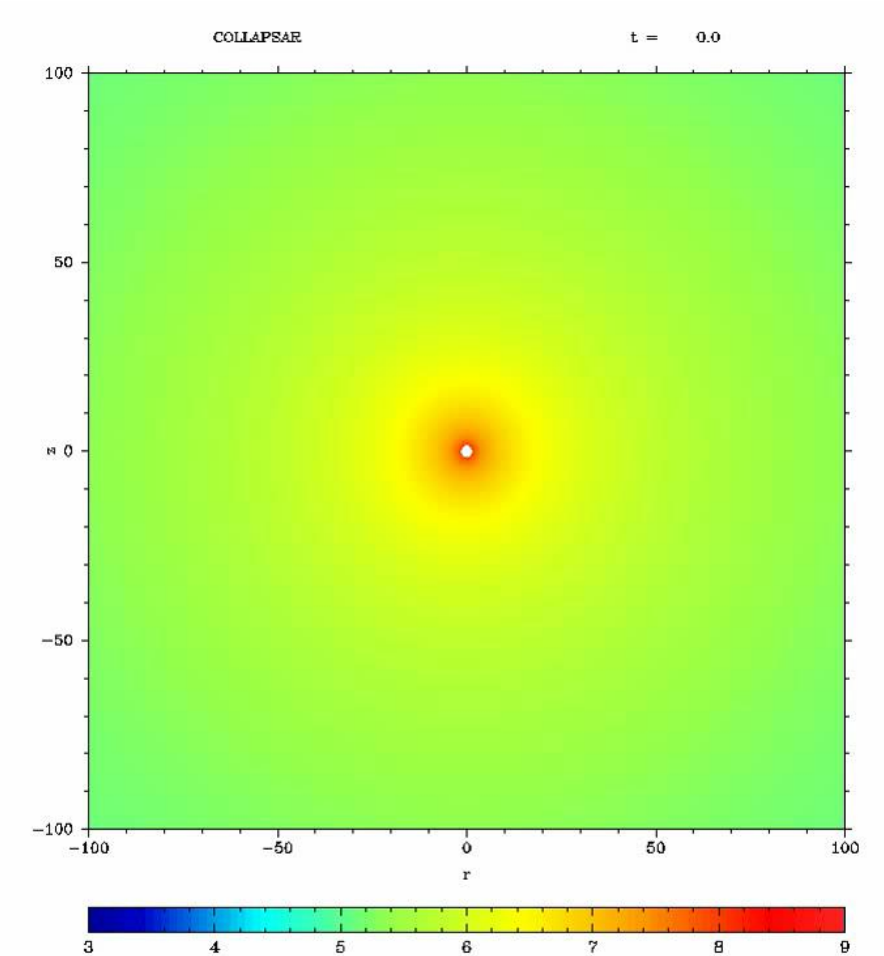
GR MHD
2D

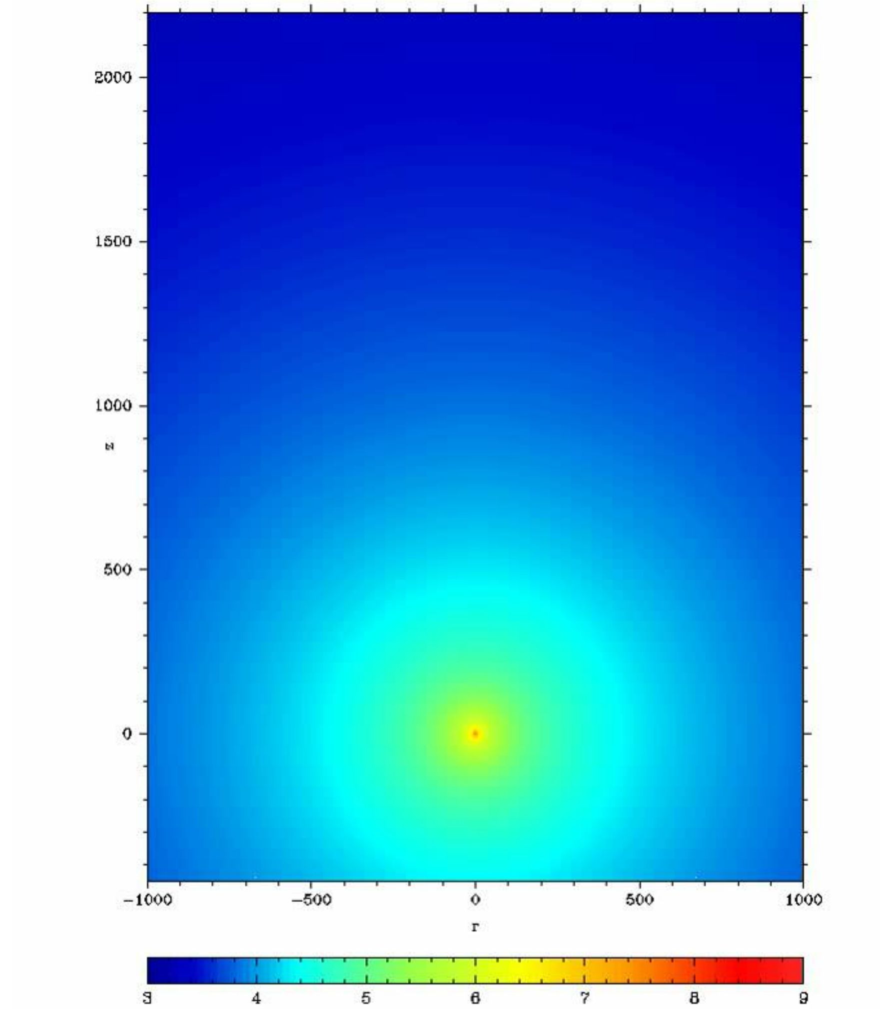
Setup

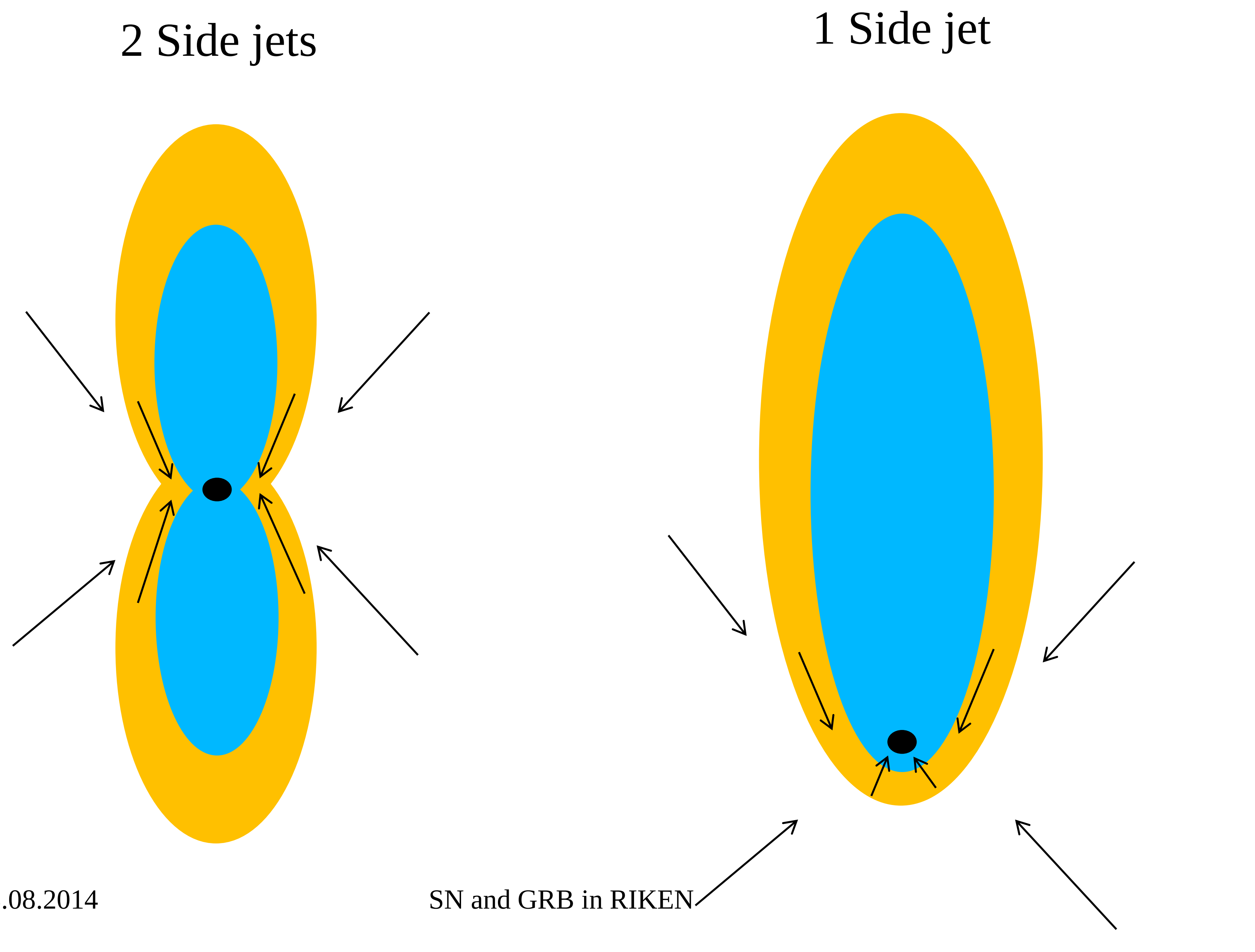


Barkov & Komissarov (2010)

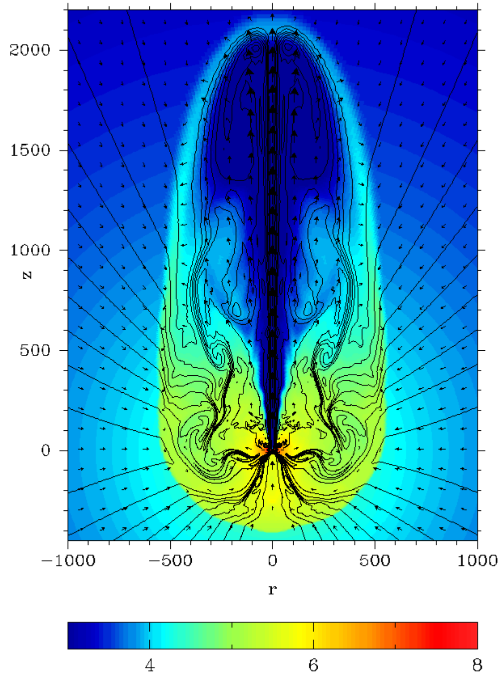
In some cases (30%) one side jets are formed.



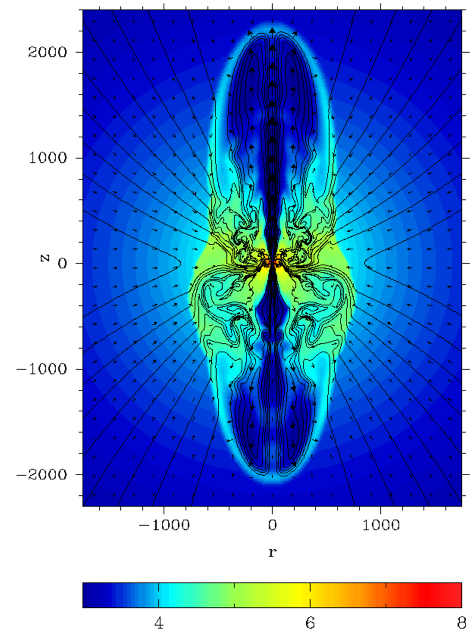



2 Side jets
1 Side jet

a=0.6 $\Psi=3x10^{28}$



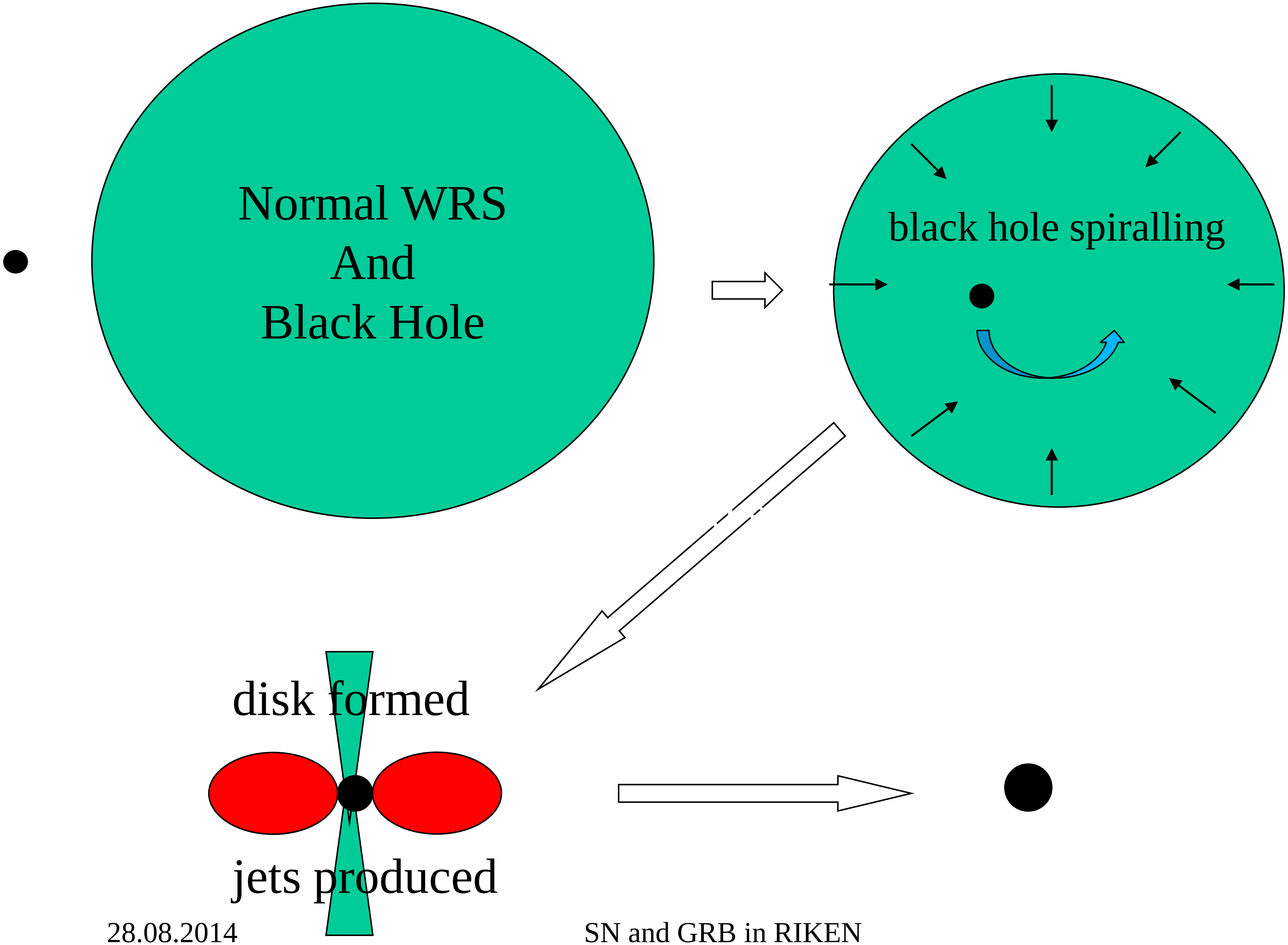
a=0.45 $\Psi=6x10^{28}$

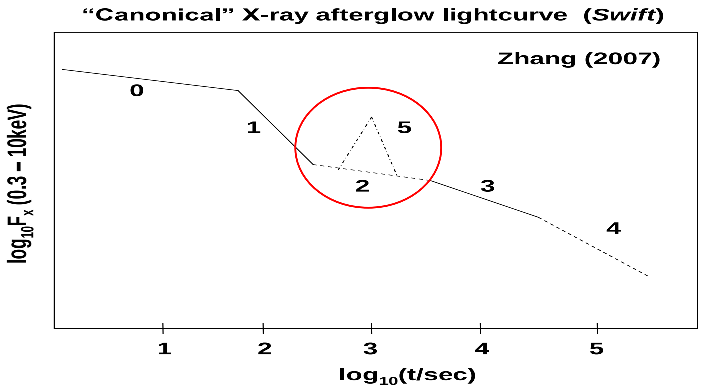


$$V_{kick} \leq 170 \left(\frac{E}{10^{52} ergs} \right) \left(\frac{10 M_{sun}}{M_{bh}} \right) km\, s^{-1}$$

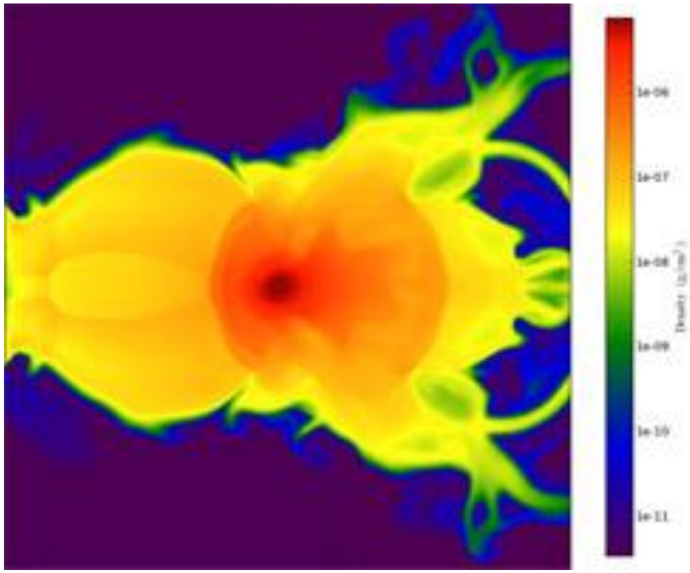
Model	a	Ψ_{28}	$B_{0,7}$	L_{51}	dM_{BH}/dt	η
A	0.6	1	1.4	-	-	-
B	0.6	3	4.2	0.44	0.017	0.0144
C	0.45	6	8.4	1.04	0.012	0.049

Common Envelop (CE):





De Marco et al (2011)



- During CE stage a lot of angular momentum is transferred to the envelop of normal star.

- Accretion of the stellar core can give the main gamma ray burst.

- BZ could work effectively with low accretion rates.

- Long accretion disk phase could be as long as 10^4 s, i.e. a feasible explanation for X-Ray flashes and/or shallow decay phase.

$$\dot{M} \approx 1.4\left(\frac{M}{10M_{sun}}\right)\frac{1}{t}M_{sun}s^{-1}$$

$$t_d \approx 8000\, s$$

(Barkov & Komissarov 2010)

Fast Recycling of Neutron Star as Hypernova engine:

Usov(1992), Thompson(1994), Thompson(2005),
Bucciantini et al.(2006,2007,2008),
Komissarov & Barkov (2007), Barkov & Komissarov (2011)

Rotational energy:

$$E_{rot} \simeq 2\times10^{52} \left(\frac{M}{1.4M_\odot}\right) \left(\frac{R}{10km}\right)^2 \left(\frac{P}{1ms}\right)^{-2} \text{erg}$$

Wind Power:

(i) ultra-relativistic

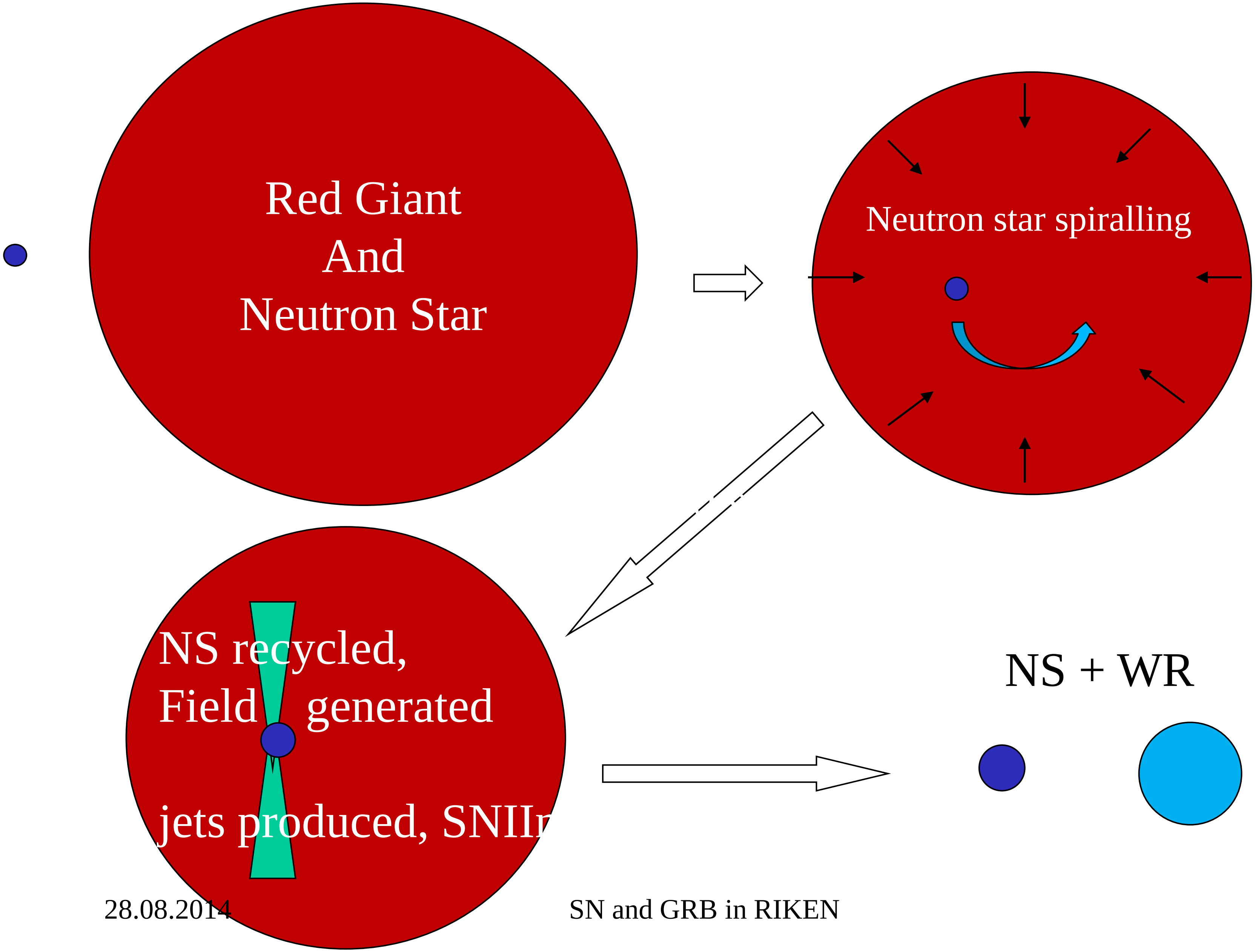
$$L \simeq 6 \times 10^{49} \left(\frac{B}{10^{15}\text{G}}\right)^2 \left(\frac{R}{10km}\right)^6 \left(\frac{P}{1ms}\right)^{-4} \text{erg/s}$$

(ii) non-relativistic

$$L \simeq 4\times10^{51} \left(\frac{B}{10^{15}\text{G}}\right)^2 \left(\frac{R}{10km}\right)^4 \left(\frac{P}{1ms}\right)^{-5/3} \text{erg/s}$$

Gamma-Ray-Repeaters and Anomalous X-ray pulsars - isolated neutron stars with dipolar(?) magnetic field of 10^{14}- 10^{15} G (*magnetars*); (Woods & Thompson, 2004)

NS in Common Envelop:



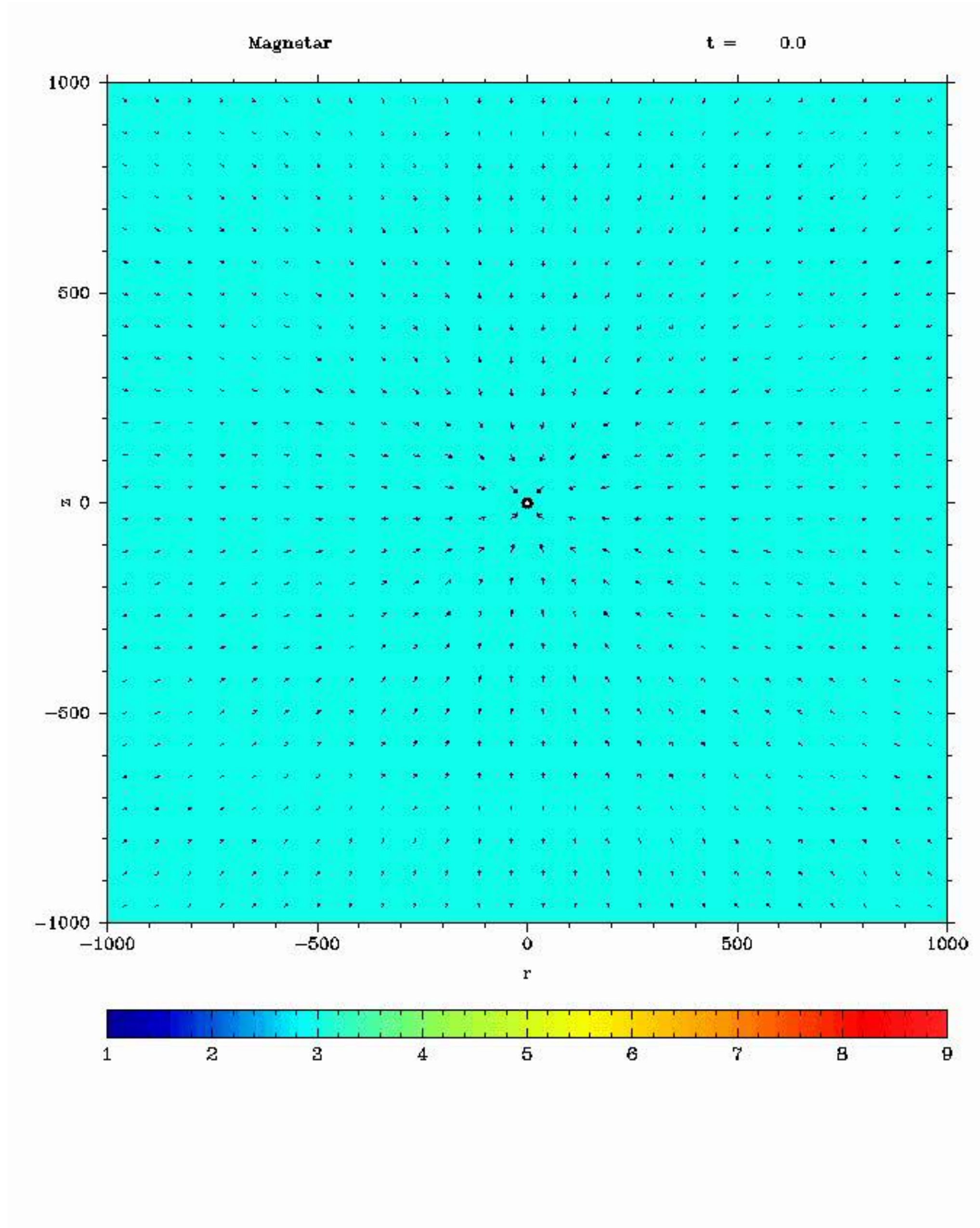
NS with dipole field:

P=4 ms

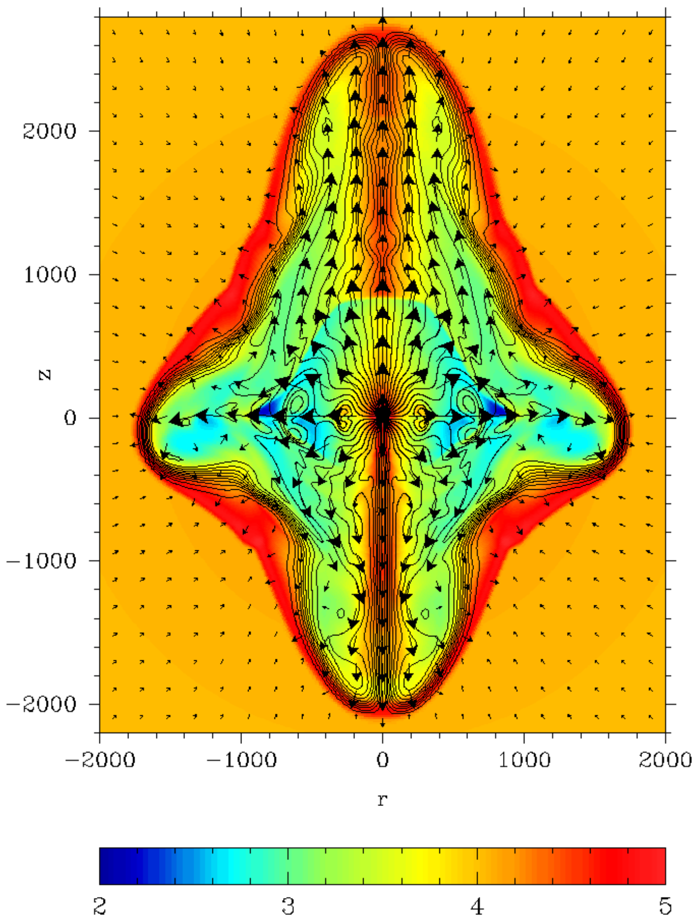
B=10^{15} G

$L = 3.7 \times 10^{49}$ erg/s

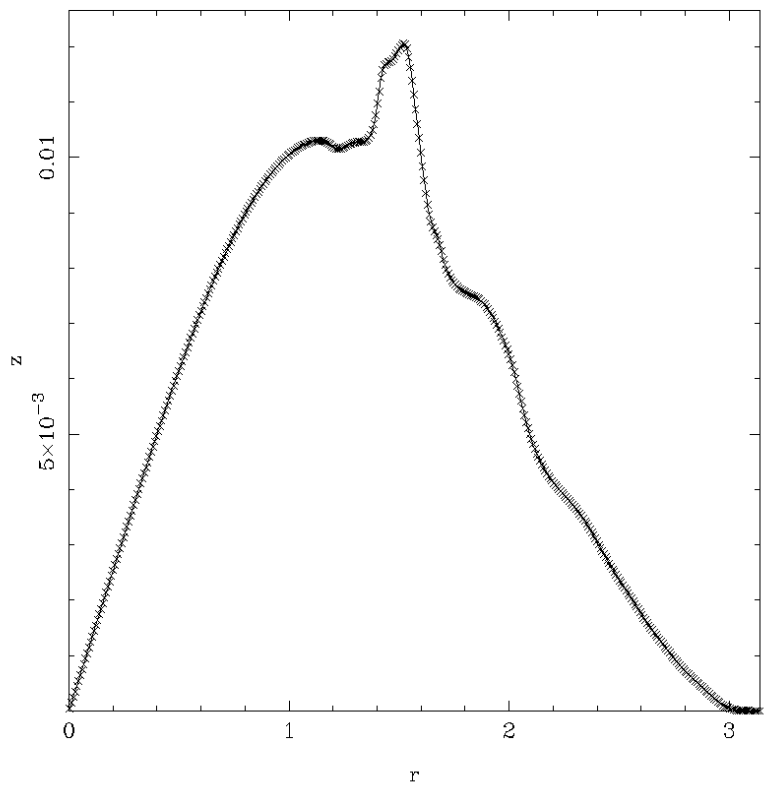
The intensive accretion to NS of matter with accretion rate of 10^3 M_{sun}/yr can lead to the generation of strong magnetic field.



The complex topology of the NS magnetic field can lead to asymmetric explosion. Here is presented the explosion driven by NS with magnetosphere containing both dipole and quadruple harmonics (see also Lovelace et al. 2010)



Energy flux depends on polar angle



$$v_{kick} \leq \frac{E_{tot}}{3M_{NSc}} \approx 370 E_{tot,52}\ km\ s^{-1}$$

The NS activity after the explosion:

$$v_{\rm ej} = 10^9 M_{\rm ej,1}^{-1/2} \frac{\rm cm}{\rm s}$$

$$L_{\rm w} = \frac{1}{4}\frac{I^2 c^3}{\mu^2 t^2} \simeq 10^{41}\, B_{\rm NS,15}^{-2} t_7^{-2} \frac{\rm erg}{\rm s}$$

$$E_{\rm e}^{\rm max} \simeq 100\, t_7 B_{\rm NS,15}^{1/2} v_{\rm ej,9}^{1/2}\, {\rm TeV}$$

$$\tau_{\gamma\gamma} \simeq \frac{\sigma_{\rm T}}{5}\frac{L_{\rm soft}}{4\pi(v_{\rm ej}t)cE_{\rm soft}} \simeq 2L_{\rm soft,41} v_{\rm ej,9}^{-1} t_7^{-1}$$

1 year after the beginning of the explosion we expect TeV and GeV photons with total luminosity of 10^{40} erg/s

Such an emission can be detected at distances up to 10 Mpc.

Conclusions

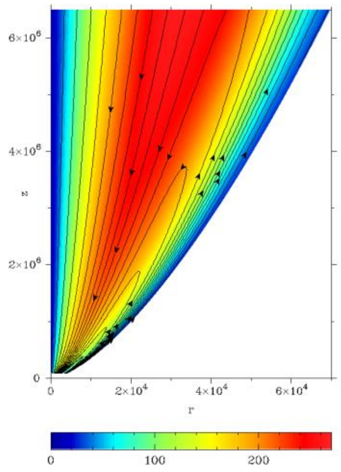
- The Collapsar is a promising model for the central engine of GRBs.
- Theoretical models are sketchy and numerical simulations are only now beginning to explore them.
- Our results suggest that:

+ Black holes of failed supernovae can drive very powerful GRB jets via Blandford-Znajek mechanism if the progenitor star has strong poloidal magnetic field;
+ Blandford-Znajek mechanism of GRB has much lower limit on accretion rate to BH then neutrino driven one (excellent for very long GRBs >100s);
+ One side jet can be formed (kick velocity order of V=200 km/s).

All Collapsar and NS based models need high angular momentum, the common envelop stage could help.

Magnetar driven explosion on the common envelop stage can lead not only to SN IIn with long plateau phase, but also to one year long TeV and GeV transient. Such a transient can be detected with Cherenkov telescopes from distance ~10 Mpc.

GRBs Jet magnetic acceleration:



- We get MHD acceleration of relativistic jet up to $\Gamma \approx 300$
- Conversion of magnetic energy to kinetic one more than 50%
- Acceleration have place on long distance $r_{eq} \approx \Gamma^2 r_{lc}$
- The main part of the jet is very narrow $\Gamma\theta < 2$

(Komissarov et al 2009)