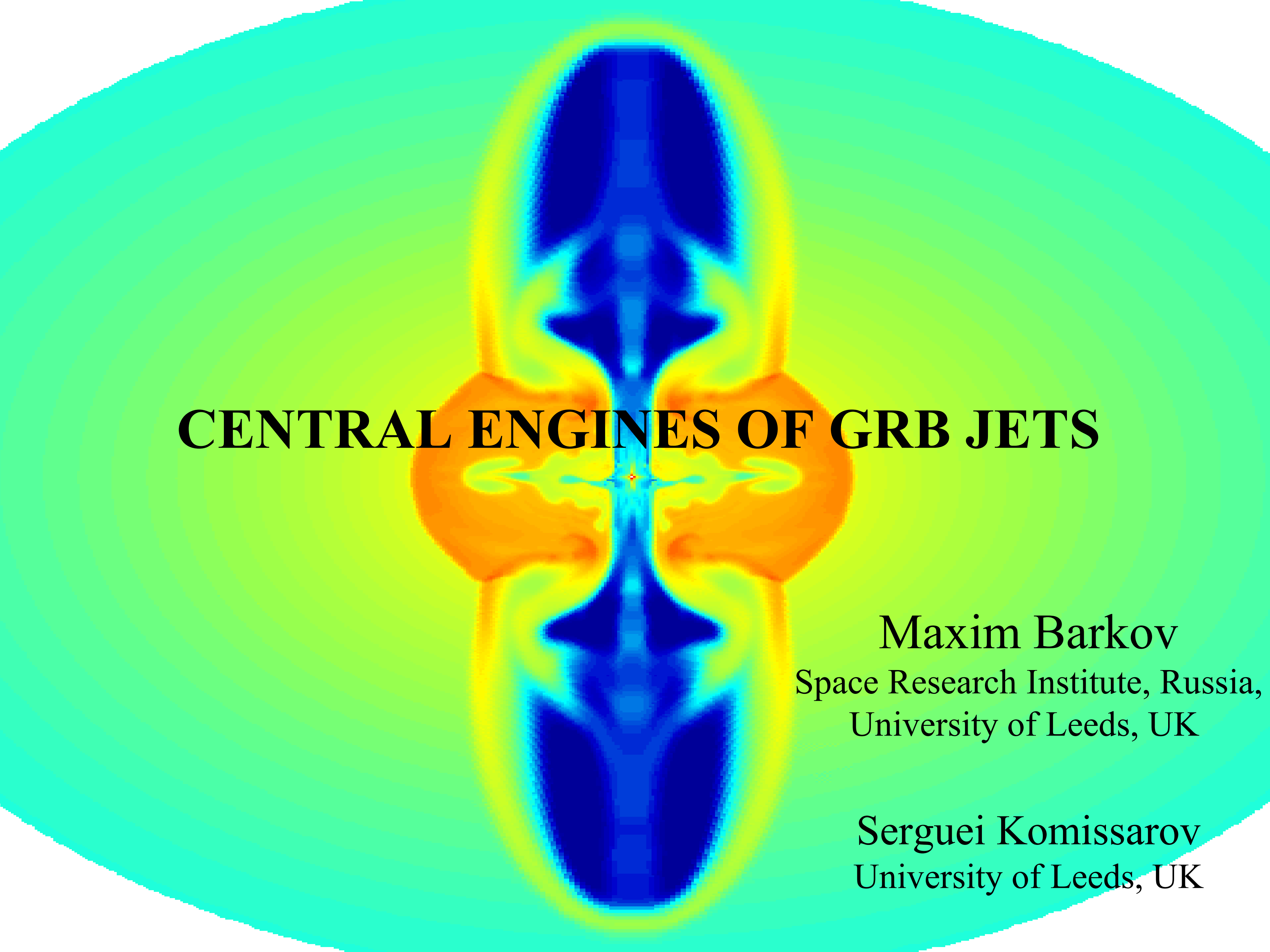

CENTRAL ENGINES OF GRB JETS

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Plan of this talk

- *Gamma-Ray-Bursts – very brief review,*
- *Models of Central Engines,*
- *Numerical simulations I: Magnetar model,*
- *Numerical simulations II: Collapsar model,*
- *Conclusions*

I. Gamma-Ray-Bursts

Discovery: Vela satellite (Klebesadel et al.1973);

Konus satellite (Mazets et al. 1974);

Cosmological origin:

2. Beppo-SAX satellite – X-ray afterglows (arc-minute resolution) , optical afterglows – redshift measurements – identification of host galaxies (Kulkarni et al. 1996, Metzger et al. 1997, etc)
1. Compton observatory – isotropic distribution (Meegan et al. 1992);

Supernova connection of long duration GRBs:

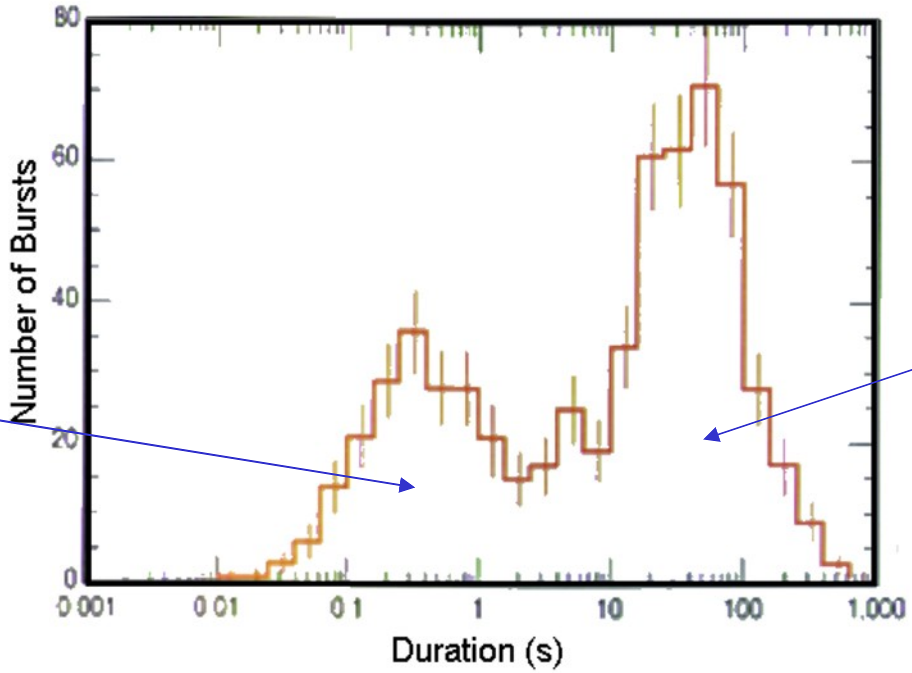
1. Association with star-forming galaxies/regions of galaxies;
2. Few solid identifications with supernovae, SN 1998bw, SN 2003dh and others...
3. SN bumps in light curves of optical afterglows.
4. High-velocity supernovae (30,000km/s) or hypernovae (10^{52}erg).

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?):

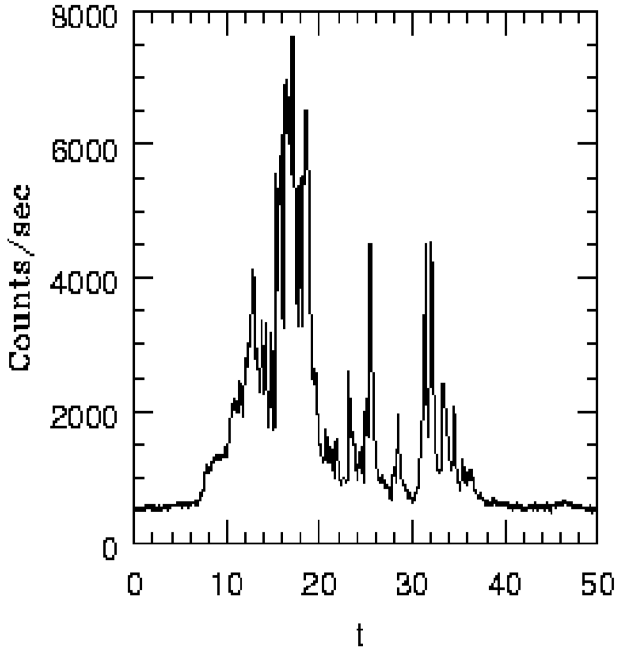


short duration GRBs

long duration GRBs

Variability:

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



Total power:

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

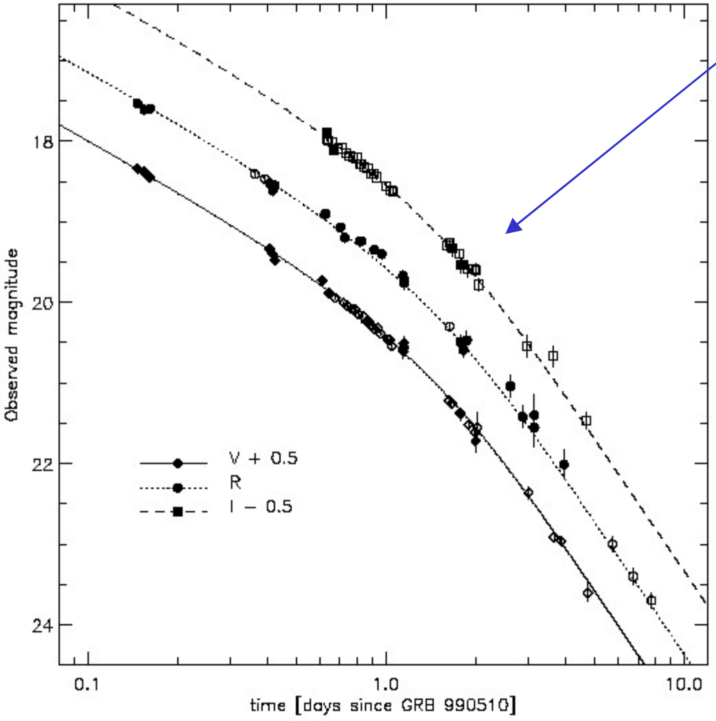
assumption of isotropic emission

Inferred high speed:

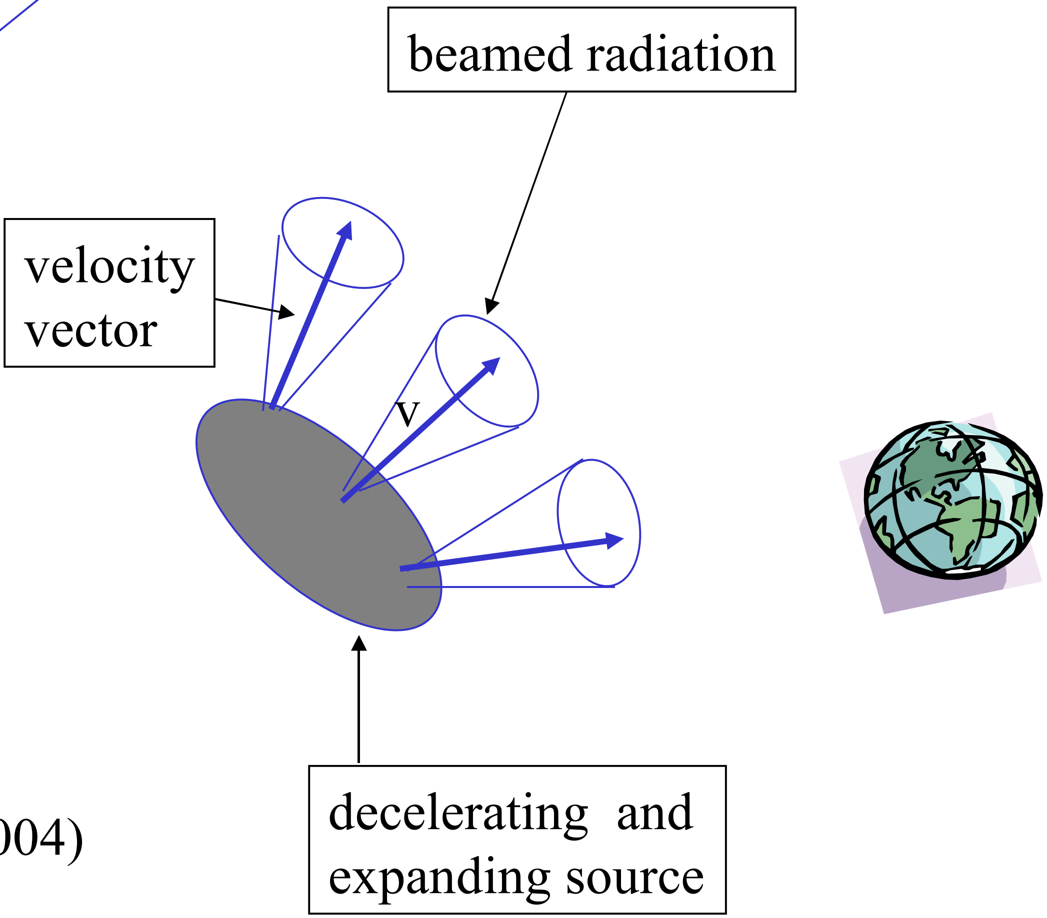
Too high opacity to $\gamma\gamma \rightarrow e^{\pm}$ unless Lorentz factor > 100

Inferred collimation:

afterglow light curve with achromatic break



$1^o < \theta_{jet} < 20^o$ (Piran, 2004)

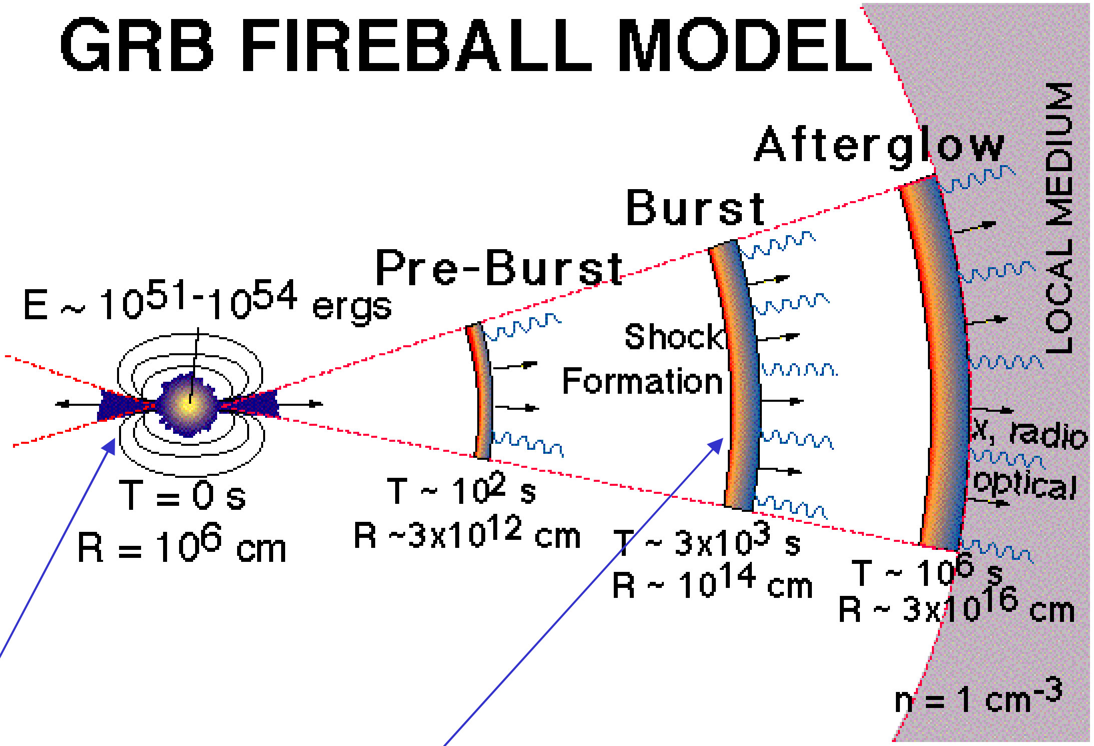


beamed radiation

velocity vector

decelerating and expanding source

Relativistic jet/pancake model of GRBs and afterglows:



jet at birth

pancake later

II. Models of central engines

(1) Potential of disk accretion onto stellar mass black holes:

disk binding energy:

$$E_d < 0.42 M_d c^2 \simeq 8 \times 10^{53} \left(\frac{M_d}{M_\odot}\right) \mathrm{erg}$$

thin disk life time:

$$t_{acc} \simeq 0.1 \left(\frac{\alpha}{0.1}\right)^{-6/5} \left(\frac{M_b}{M_\odot}\right)^{6/5} \left(\frac{R_d}{10 R_g}\right)^{4/5} \mathrm{s}$$

Ultra-dense Hyper-Eddington neutrino cooled disks !!!

M_d - accreted mass

R_d - disk outer radius

R_g - gravitational radius

α – Shakura–Sunyaev parameter

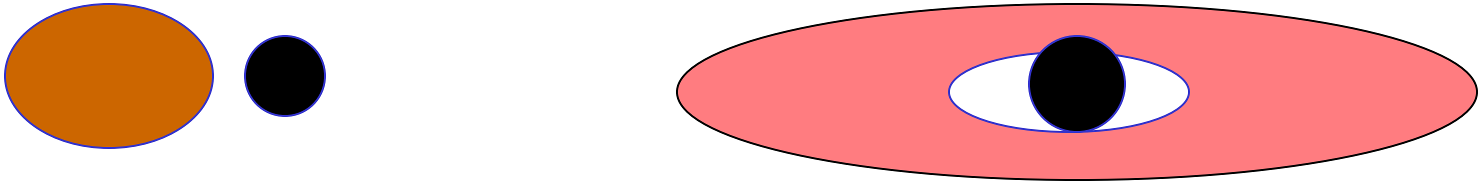
(1.1) Merger of compact stars – origin of short duration GRBs?

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

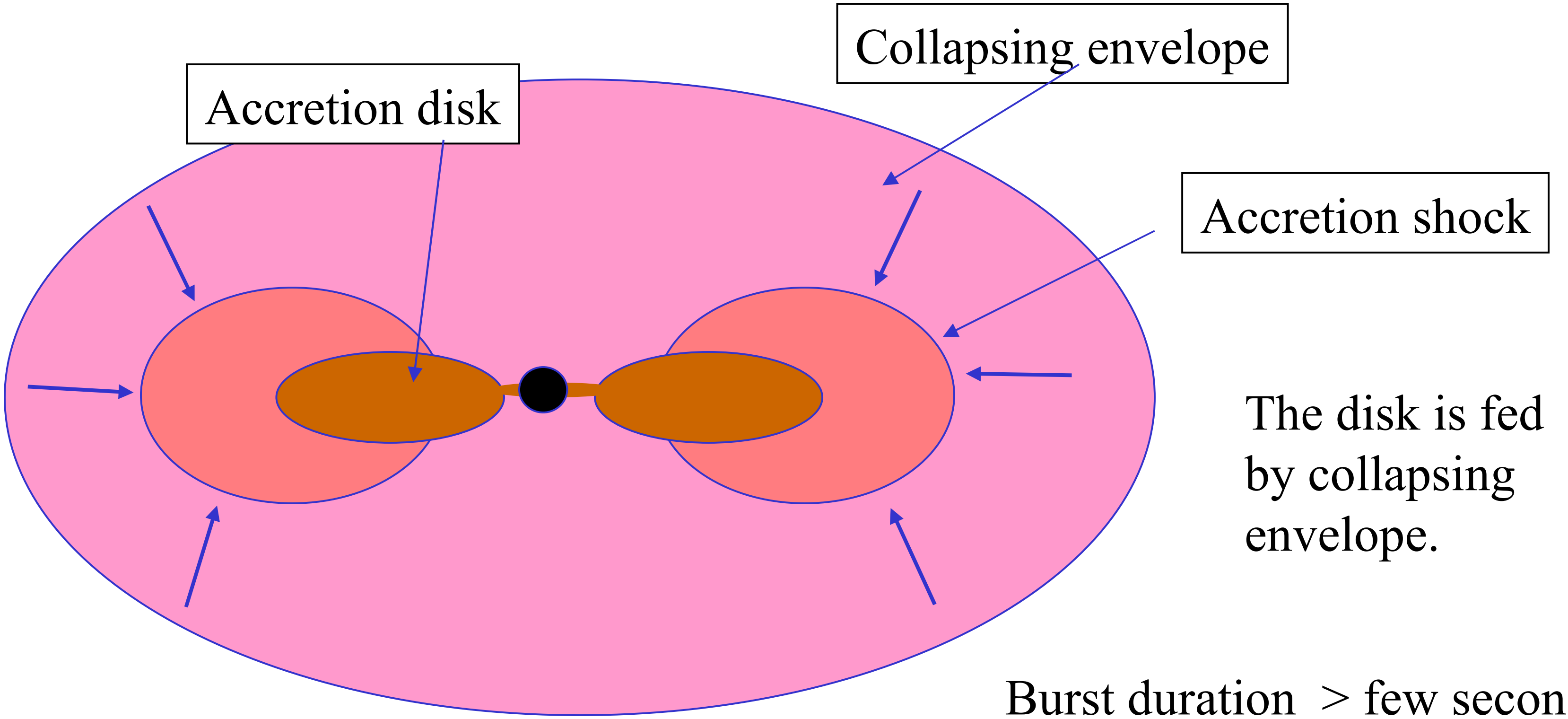
Released binding energy:

$$E_d \leq 8 \times 10^{52} \div 8 \times 10^{53} \mathrm{erg}$$

(1.2) 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)



Accretion disk

Collapsing envelope

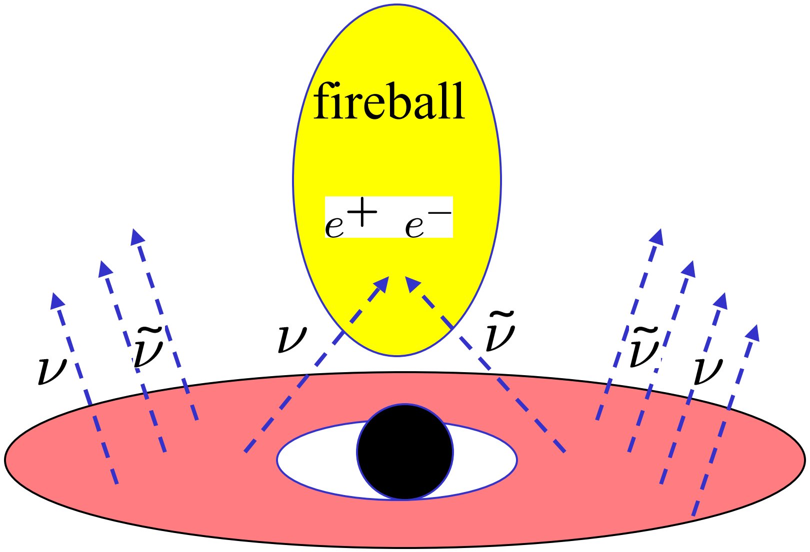
Accretion shock

The disk is fed
by collapsing
envelope.

Burst duration > few seconds

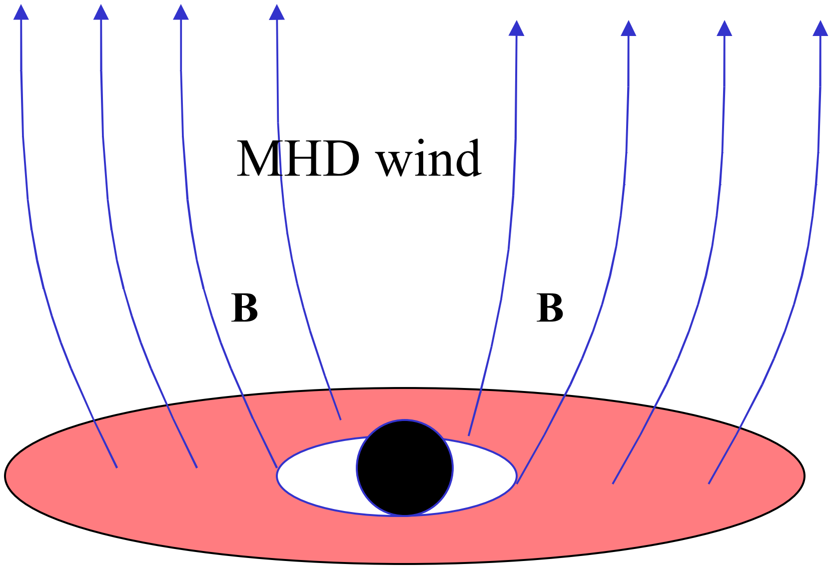
(1.3) Mechanisms for tapping the disk energy

Neutrino heating



Eichler et al.(1989), Aloy et al.(2000)
MacFadyen & Woosley (1999)
Nagataki et al.(2006) → (???)

Magnetic braking



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

(2) Potential of a neutron star (millisecond magnetar):

Usov(1992), Thompson(1994), Thompson(2005),
Bucciantini et al.(2006,2007)

Rotational energy:

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

Wind Power:

(i) ultra-relativistic →

$$L\simeq 6\times10^{49}\left(\frac{B}{10^{15}\mathrm{G}}\right)^2\left(\frac{R}{10km}\right)^6\left(\frac{P}{1ms}\right)^{-4}\mathrm{erg/s}$$

(ii) non-relativistic →

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

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)

(3) Potential of black hole rotation:

Blandford & Znajek (1977), Meszaros & Rees (1997)

Black hole rotational energy:

$$E_b < 0.29 M_b c^2 \simeq 1.5 \times 10^{54} \left(\frac{M_b}{3M_\odot}\right) \text{erg}$$

Power of the Blandford-Znajek mechanism:

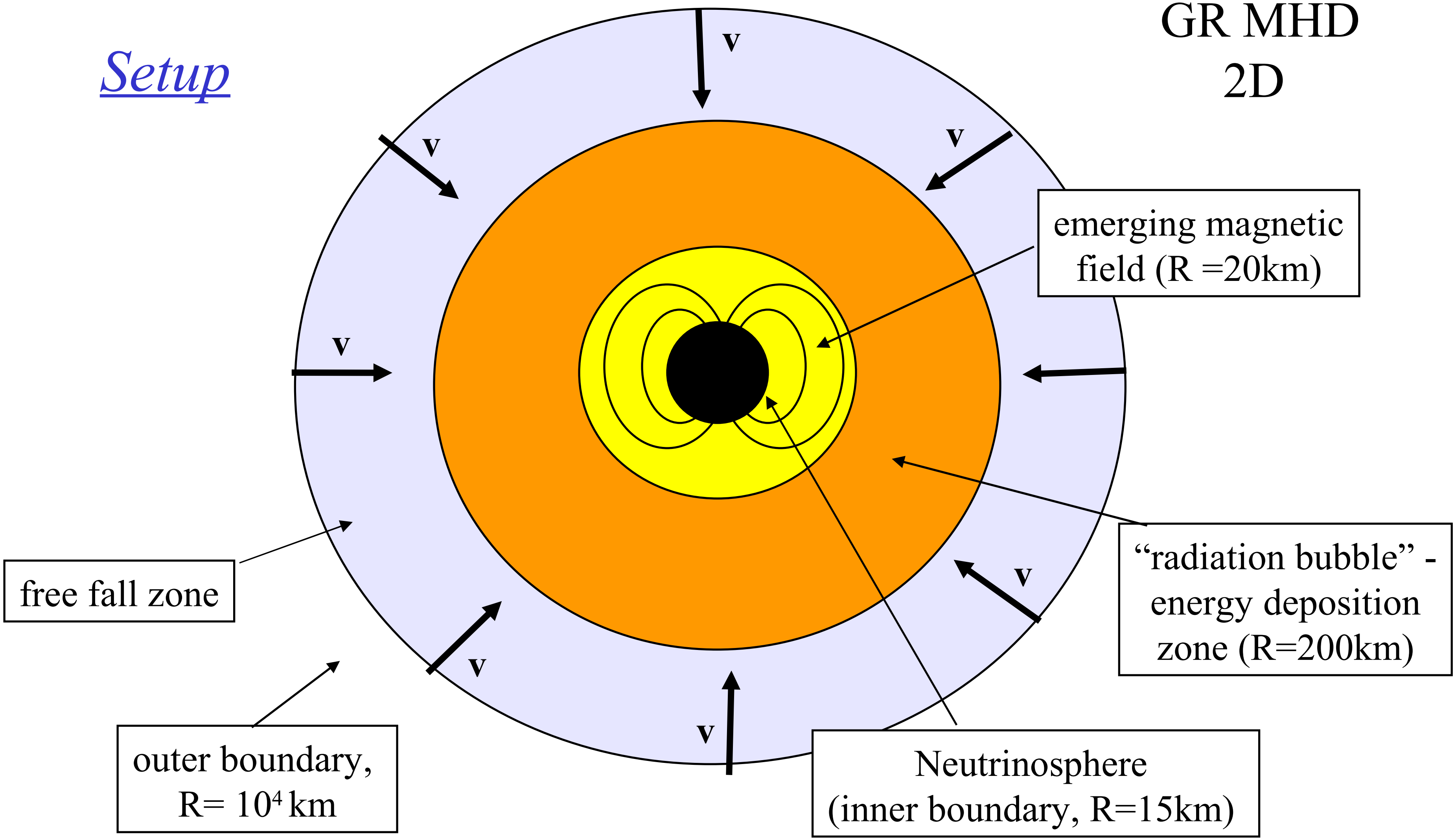
$$L_{BZ} \simeq 2.2 \times 10^{51} \left(\frac{M_b}{3M_\odot}\right)^2 \left(\frac{B_p}{3 \times 10^{15} G}\right)^2 \text{erg/s}$$

B_p - poloidal magnetic field near the BH horizon

III. Computer simulations: Magnetar model

Setup

GR MHD
2D



emerging magnetic field (R =20km)

"radiation bubble" - energy deposition zone (R=200km)

free fall zone

outer boundary, R= 10^4 km

Neutrinosphere (inner boundary, R=15km)

Free fall model of collapsing star (Bethe, 1990)

radial velocity: $v^{\hat{r}} = -(2GM/r)^{1/2}$

mass density: $\rho = C_1 \times 10^7 \left(\frac{t}{1s}\right)^{-1} \left(\frac{r}{100km}\right)^{-3/2} \mathrm{g/cm^3}$

accretion rate: $\dot{M} = 0.038 C_1 \left(\frac{t}{1s}\right)^{-1} \left(\frac{M}{1.4 M_\odot}\right)^{1/2} M_\odot \mathrm{s}^{-1}$

(Delayed explosion, t=1s.) $C_1 = 1 \div 10$

\+ specific angular momentum: $l = 10^{16} \sin\theta$ cm^2/s

Energy of radiation bubble (heat): $C_2 \times 10^{51} \mathrm{erg}$

Inner boundary (R=15km):

Rotation period: $P=2\,\mathrm{ms}$; poloidal velocity: $v_p=0$

Mass density: $\rho=3\times10^9\,\mathrm{g/cm^3}$; gas temperature: $T=4$ Mev (Thompson et al.,2001);

Neutrino luminosity: $L(R,T)=6.5\times10^{51}$ erg/s in each flavour;

Neutrino energy: $E_\nu=3.15T=12.6$ Mev in each flavour;

Magnetic field: "squashed" dipole, $B_0=10^{15}$ G;

Gravity: gravitational field of magnetar only (Schwarzschild metric);

no self-gravity;

Microphysics: neutrino transport – optically thin regime;

neutrino cooling and heating (Thompson et al.,2001);

realistic equation of state, (HELM, Timmes & Swesty, 2000);

dissociation of nuclei (Ardeljan et al., 2005);

Ideal Relativistic MHD - no physical resistivity (only numerical);

results

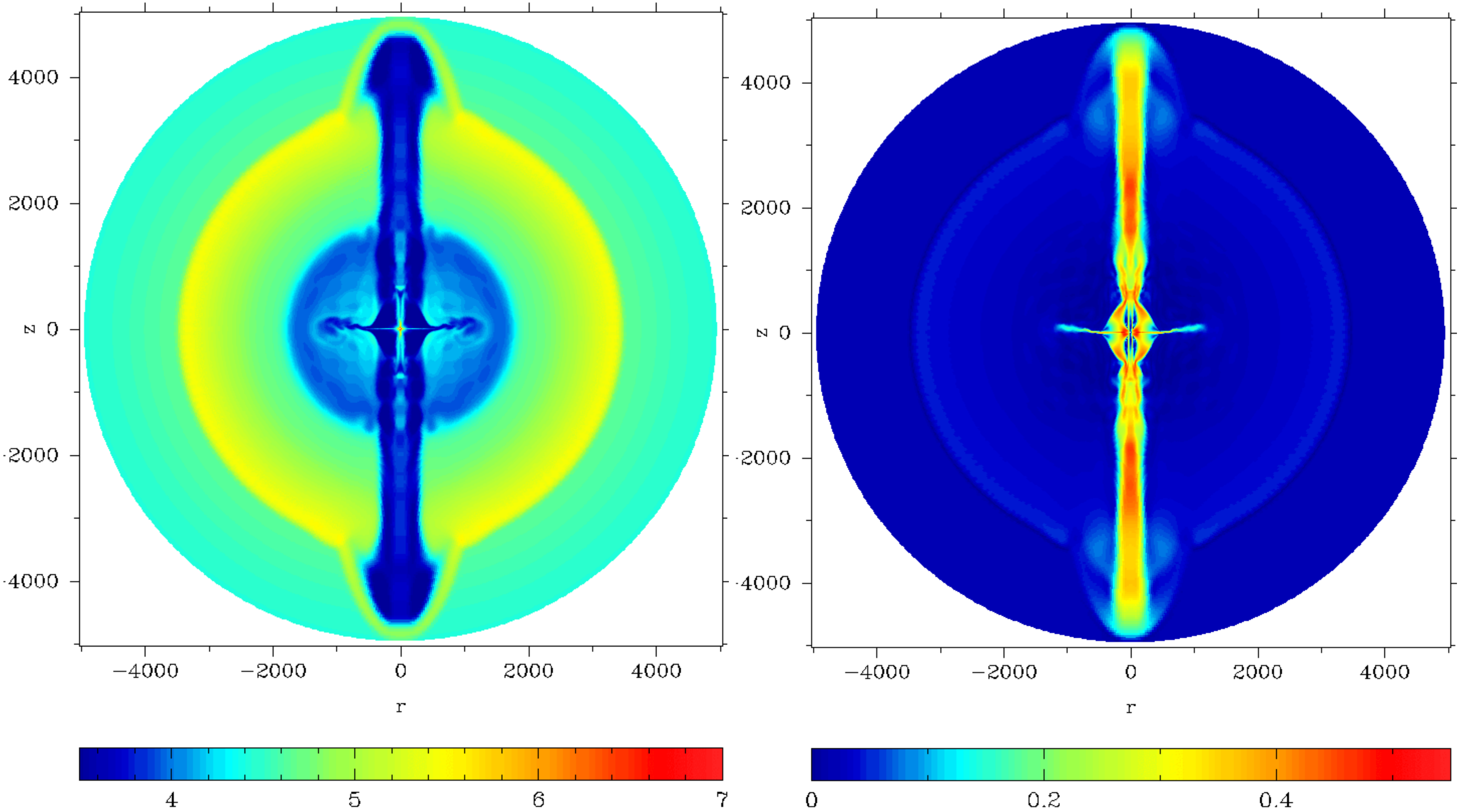
	Model	A	B	C	D
Mass accretion rate	C_1	3	3	9	9
Delayed explosion power	C_2	1	0.1	1	0.1

movie 1: Model A: inner region , R<1000 km radius;
colour image - log(ρ), g/cm^3

movie 2: Model A: inner region, R<1000 km radius;
lines and colour – poloidal magnetic field lines

Model A, t=0.2s

unit length=2km



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

v_p/c

Summary or results:

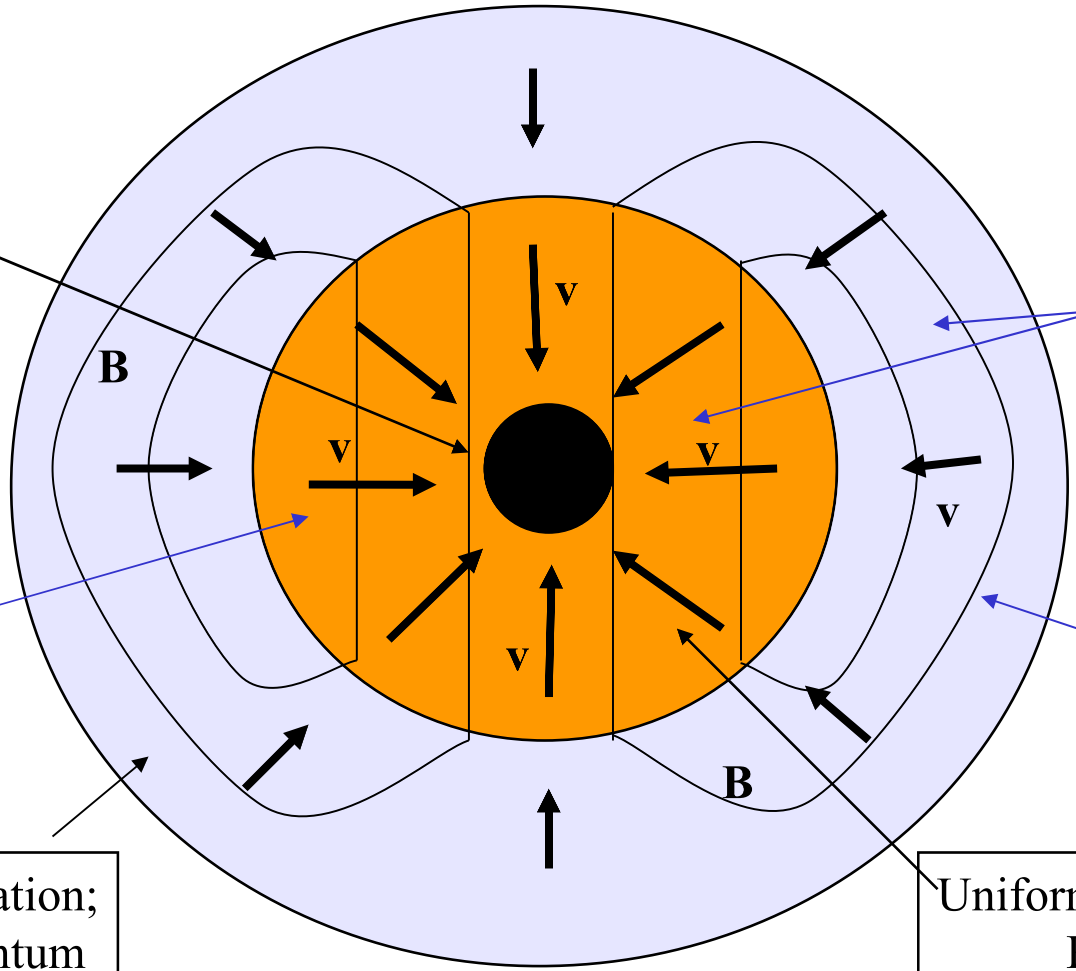
- Jets are formed immediately after the supernova explosion.
- Jets power $\simeq 3 \times 10^{50}\mathrm{erg/s}$
- Total energy of magnetar $\simeq 10^{52}\mathrm{erg}$
- Expected burst duration (spin-down time) $30 \div 40\mathrm{s}$
- Jet advance speed $v_a \simeq 0.17c$
- Expected break out time $\simeq 4\mathrm{s}$ $(r_* \simeq 2 \times 10^5\mathrm{km})$
- Jet flow speed $v_j \simeq 0.5c$

Good news for the magnetar model of long duration GRBs !

IV. Computer simulations: Collapsar model

Setup

GR MHD
2D



black hole
$M=3M_3$
$a=0.9$

Bethe's
free fall model

Solid body
rotation

Dipolar
magnetic field

differential rotation;
angular momentum
$l=10^{17}\sin\theta\ \mathrm{cm^2/s}$

Uniform magnetization
R=4500km
$B_0= 3\times10^{9}-3\times10^{10}$G

Same microphysics as in magnetar simulations (no neutrino heating)

results

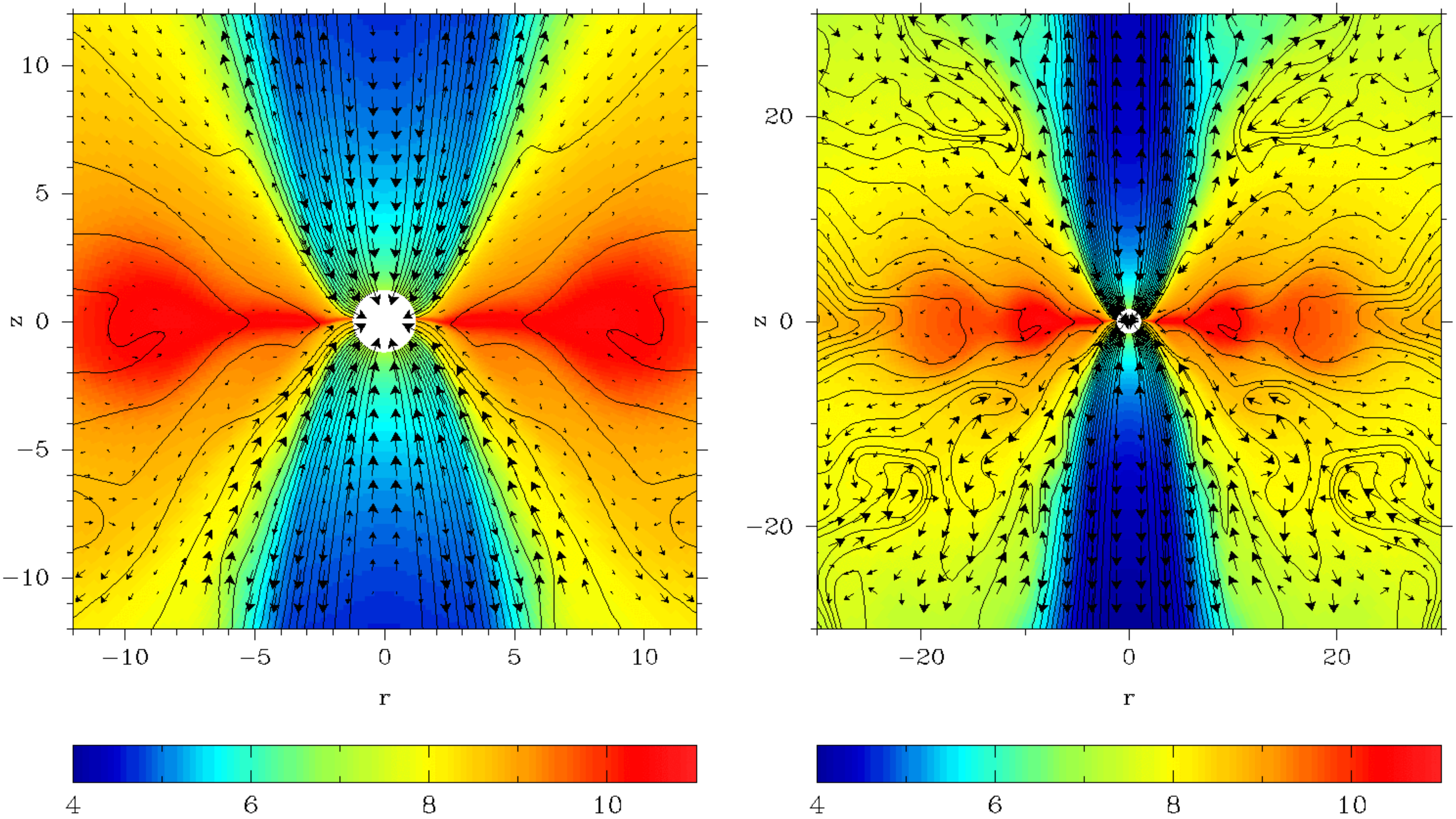
Model parameters: (1) Bethe's C1=3, 9
(2) Magnetic field $B_0=10^{10}$G, $3\text{x}10^{10}$G
(3) Black hole hole rotation parameter, a=0, 0.9

movie 1: $B_0=10^{10}$G, C1=9, a=0.9
inner region - 800 km radius;
colour image - log(ρ), g/cm^3

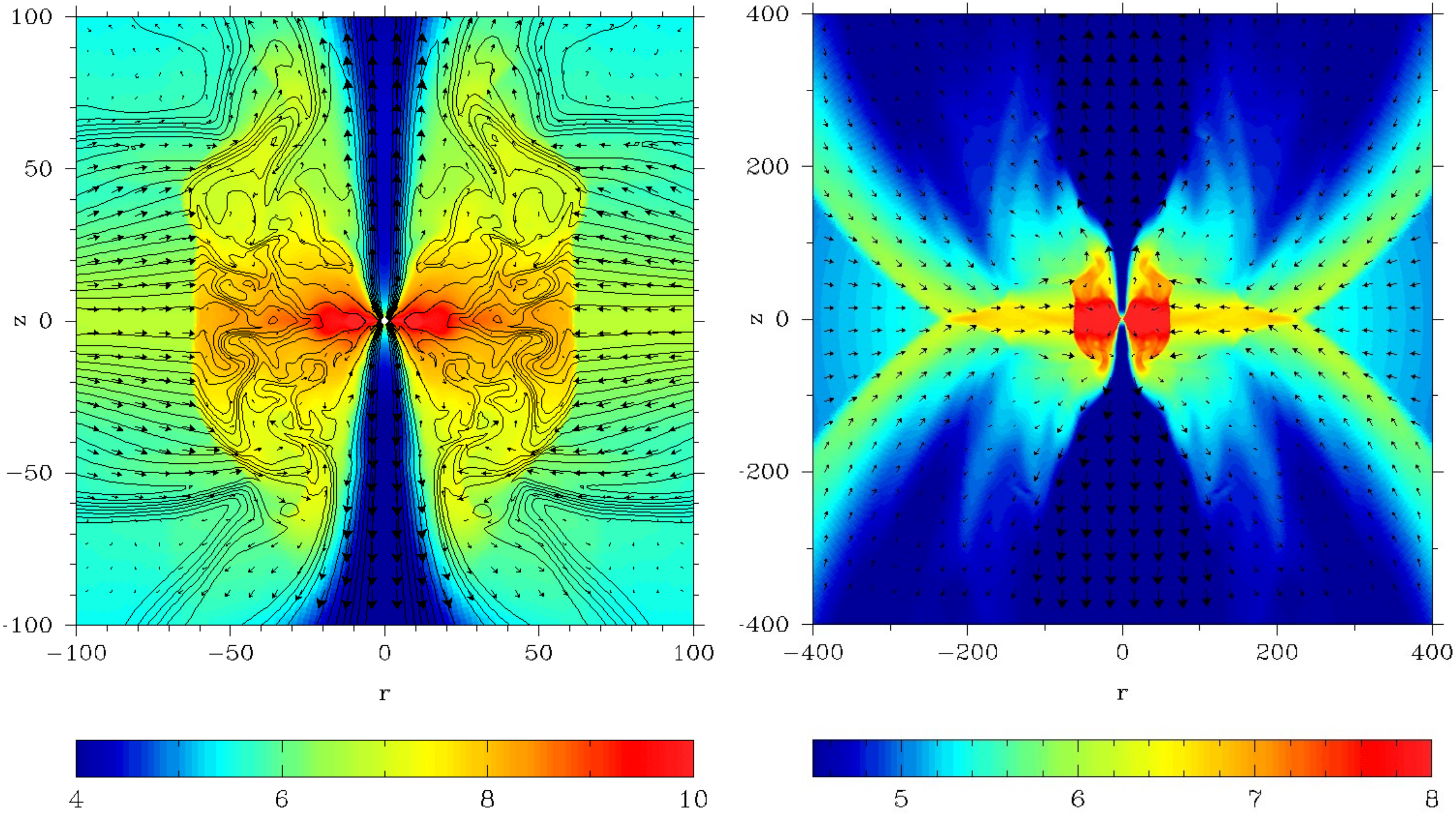
movie 2: $B_0=3 10^{10}$G, C1=9, a=0.9
inner region - 800 km radius;
colour image - log(ρ), g/cm^3

movie 3: $B_0=3 10^{10}$G, C1=9, a=0.9
inner region - 16000 km radius;
colour image - log(P/P_m),

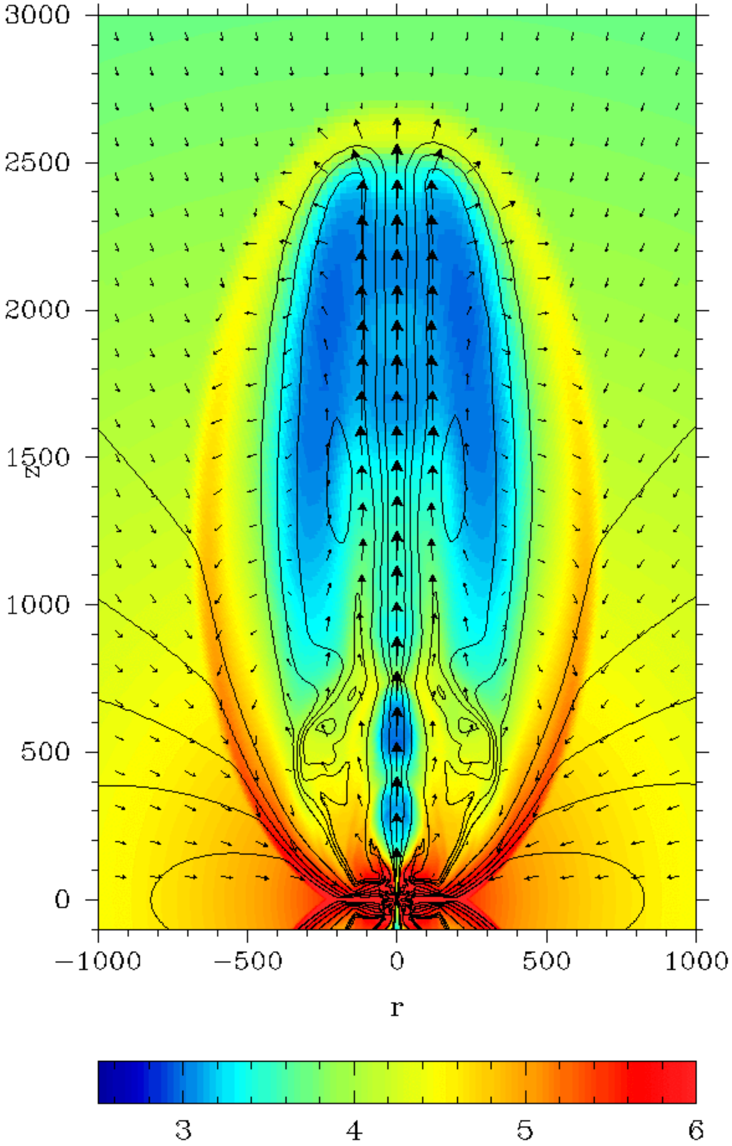
unit length=4km
t=0.4s



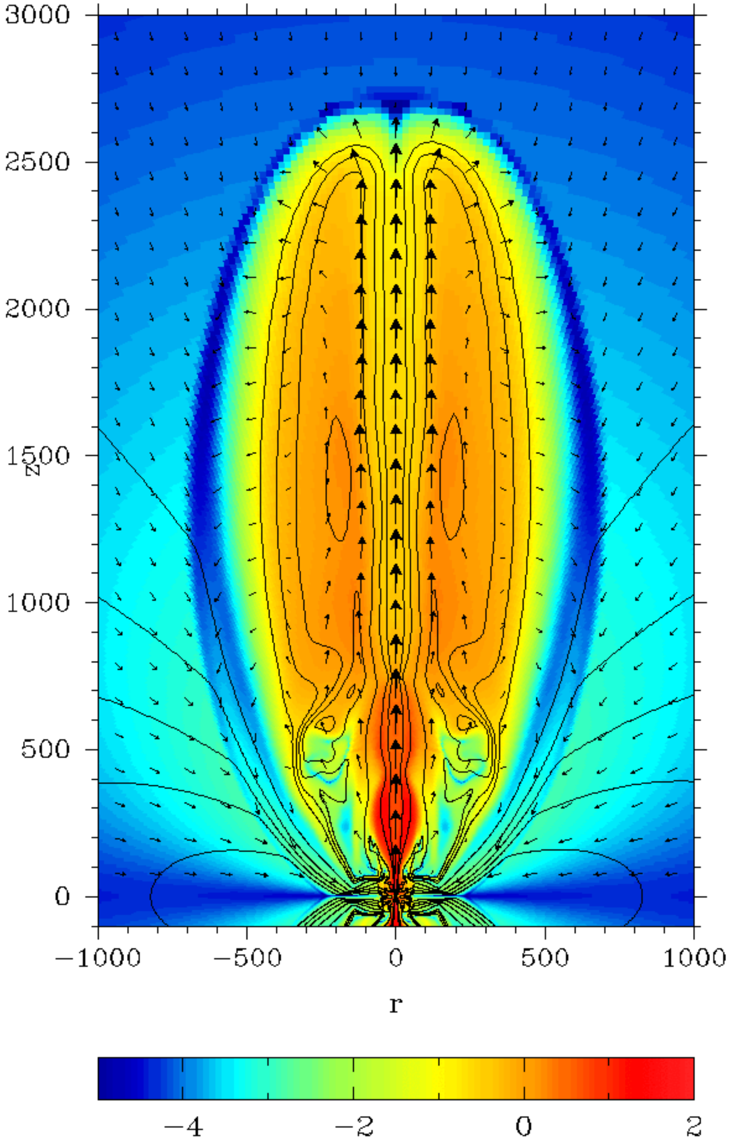
$\log_{10}\rho$ (g/cm^3), magnetic field lines, and velocity vectors



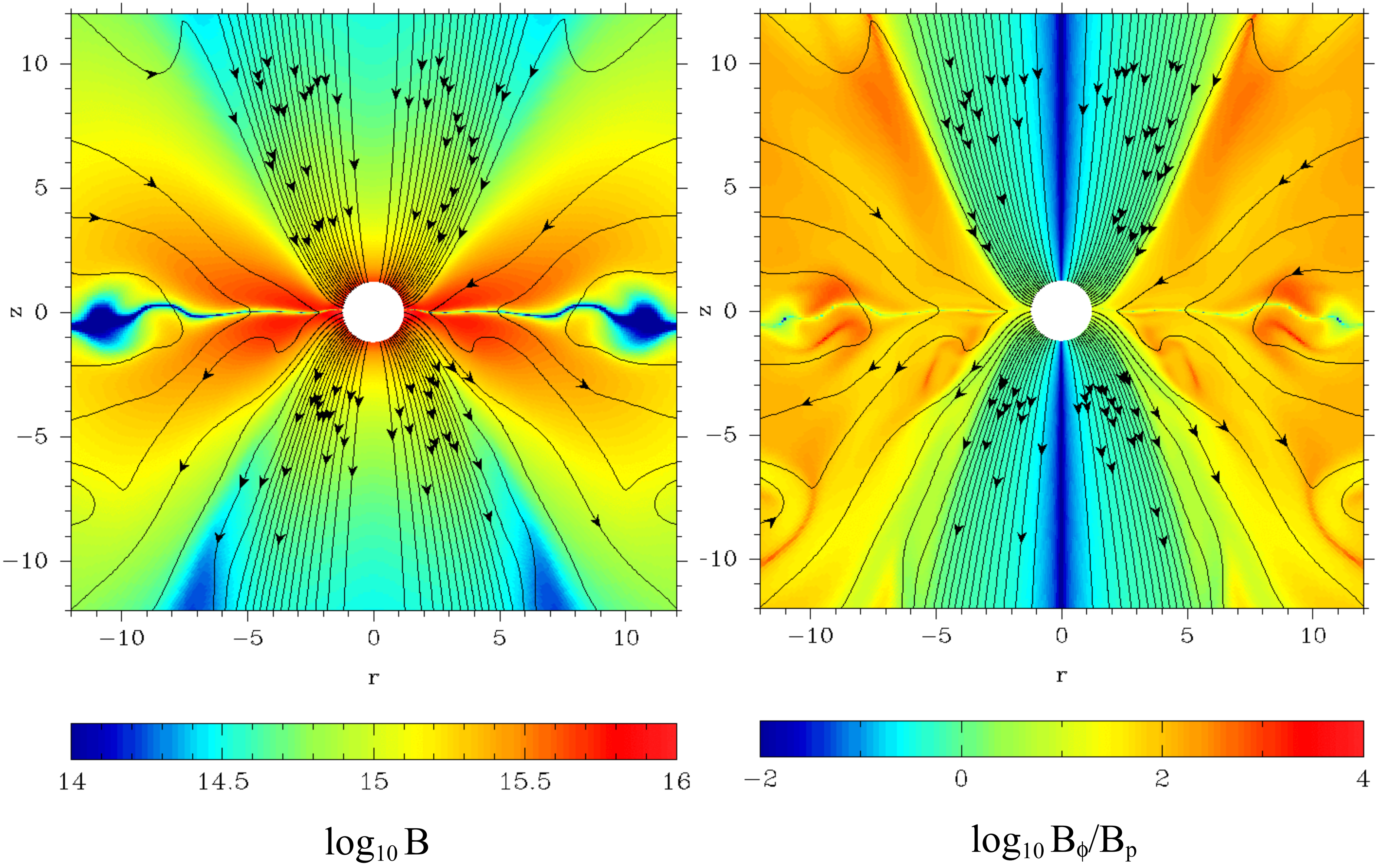
$\log_{10}\rho$ (g/cm^3), magnetic field lines, and velocity vectors



$\log_{10}\rho$



$\log_{10} P_m/P$

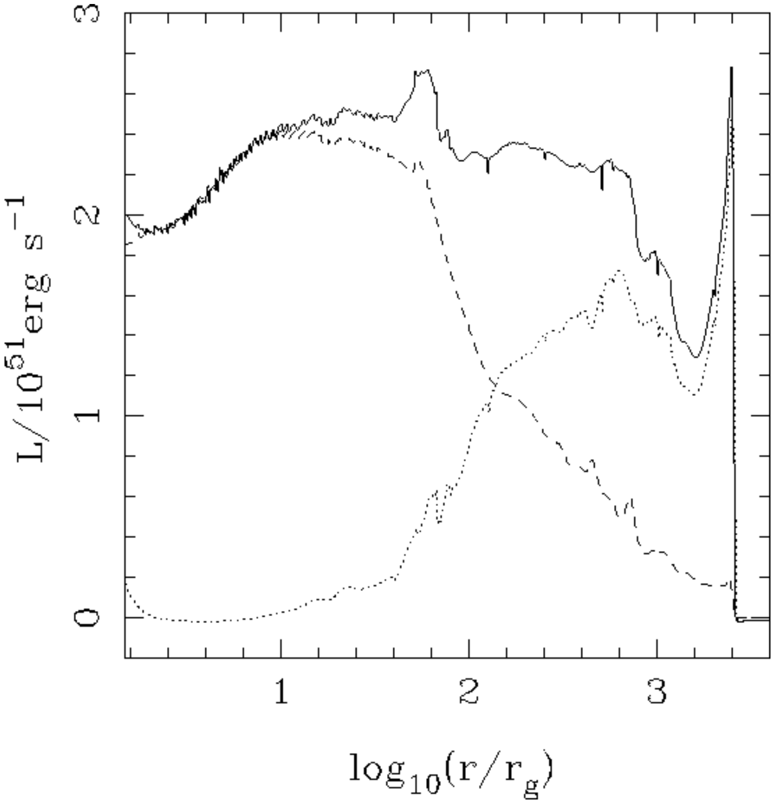


10
5
z 0
−5
−10
−10
−5
0
5
10
r
14
14.5
15
15.5
16
$\log_{10} B$
−2
0
2
4
$\log_{10} B_\phi/B_p$

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

- No explosion if a=0;
- Jets originate from
  the black hole;
- ~70% of total magnetic flux
  is accumulated by the black
  hole;
- Energy flux in the ouflow ~
  energy flux through the horizon
  (disk contribution < 20%);
- Theoretical BZ power:

$$L_{BZ} \simeq \frac{1}{6c}\left(\frac{\Omega_b \Psi}{4\pi}\right)^2 \simeq 2.6 \times 10^{51}\mathrm{erg/s}$$



Summary or results:

- Jets are formed when BH accumulates sufficient magnetic flux.
- Jets power $\simeq 2 \times 10^{51}\mathrm{erg/s}$
- Total energy of BH $\simeq 8 \times 10^{53}\mathrm{erg}$
- Expected burst duration $> 1\mathrm{s}$ (?)
- Jet advance speed $v_a \simeq 0.18c$
- Expected jet break out time $\simeq 4\mathrm{s}\ (r_* \simeq 2 \times 10^5\mathrm{km})$
- Jet flow speed $\Gamma_j \leq 3$ (method limitation)
- Jets are powered by the Blandford-Znajek mechanism

Good news for the collapsar model of long duration GRBs !

V. Conclusions

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

1) Millisecond magnetars can indeed drive long duration GRB jets of medium power (up to few $\times 10^{52}$ erg/s). These jets can be produced at very early stages of successful supernova explosions;
2) Black holes of failed supernovae can drive very powerful GRB jets via Blandford-Znajek mechanism if the progenitor star has strong poloidal magnetic field $B_0 > 10^9$G;