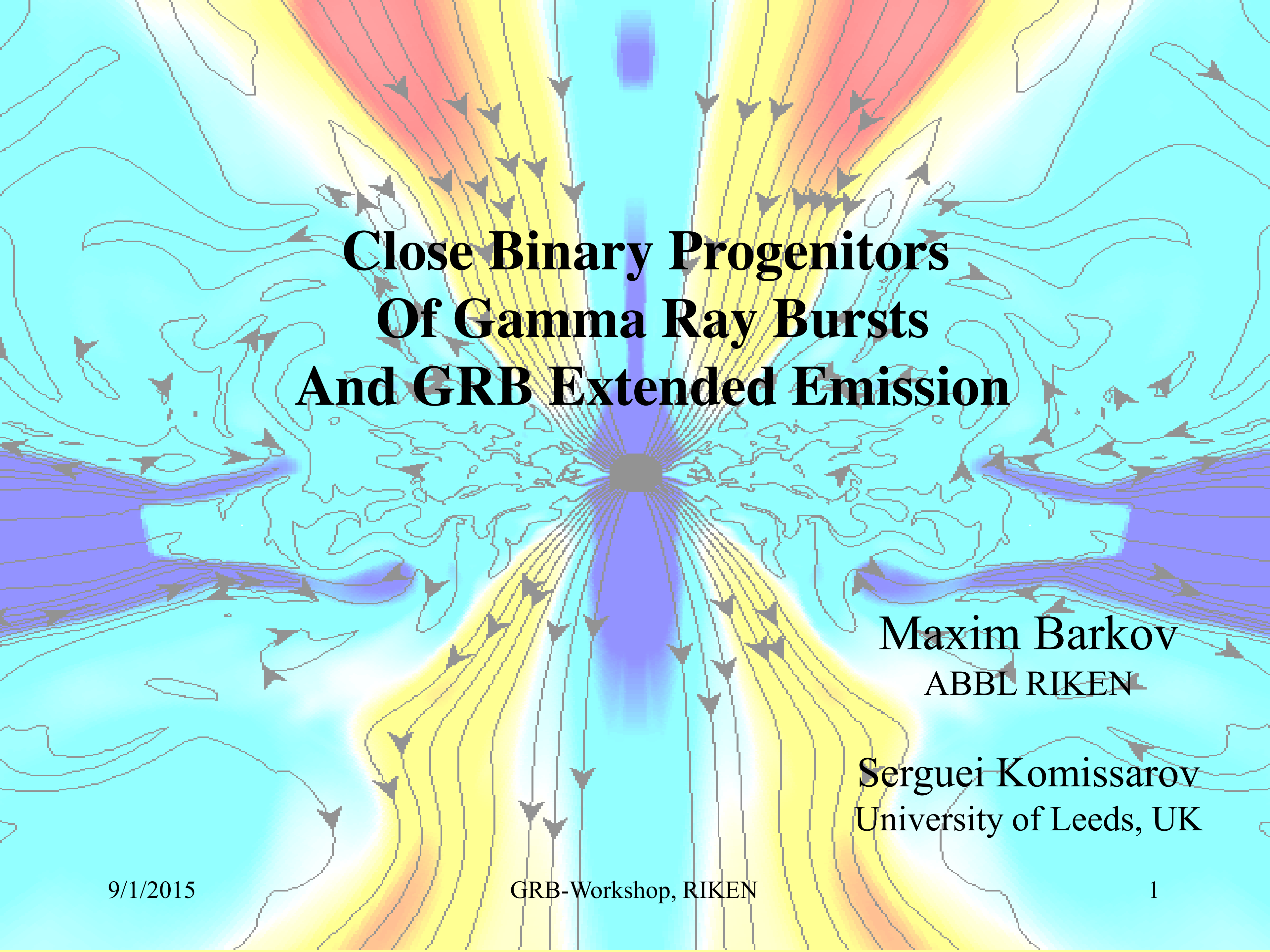

Close Binary Progenitors Of Gamma Ray Bursts And GRB Extended Emission

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ABBL RIKEN

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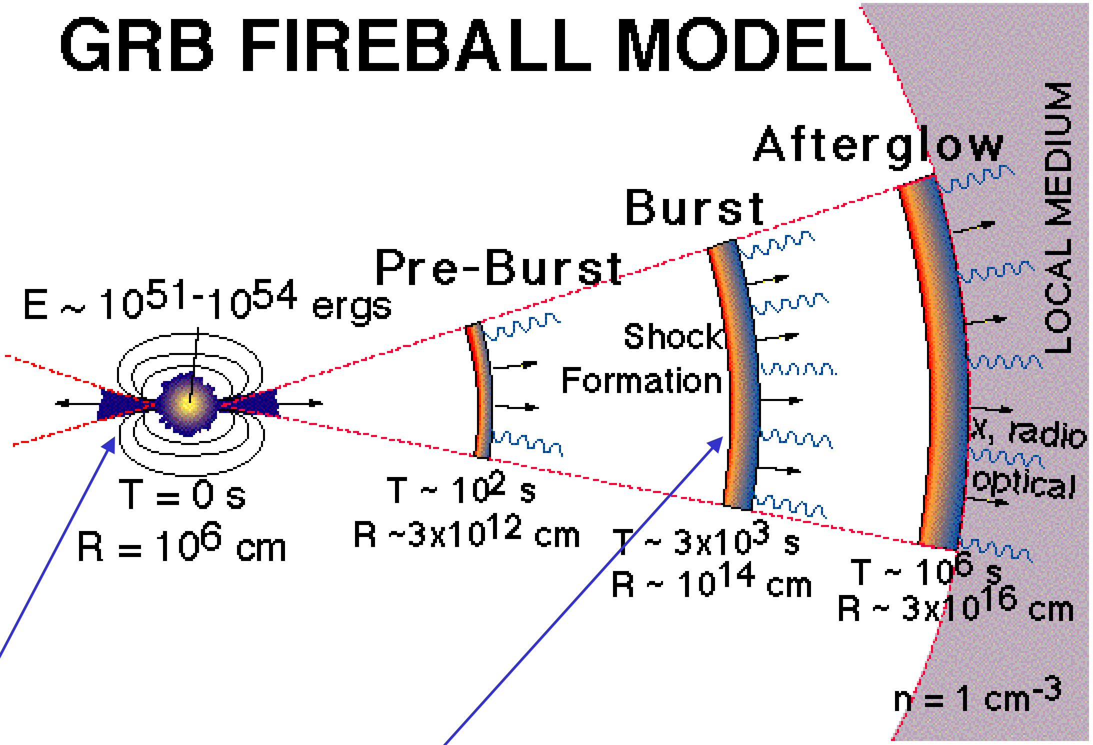
Plan of this talk

- *Models of Central Engines,*
- *Magnetic Unloading,*
- *Realistic initial conditions,*
- *Numerical simulations II: Collapsar model,*
- *Common Envelop and X-Ray flares,*
- *Extended emission of short GRBs,*
- *Conclusions*

II. *Relativistic jet/pancake model of GRBs and afterglows:*



jet at birth
(we are here)

pancake later

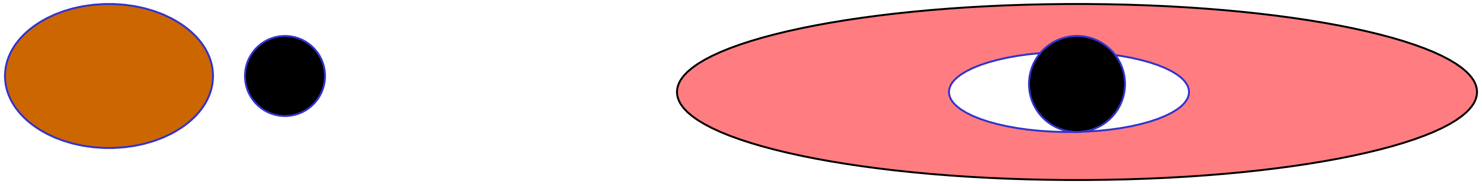
Merge of compact stars – origin of short duration GRBs?

Blinnikov (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:

$$E_d \lesssim 8 \times 10^{52} \div 8 \times 10^{53} \text{erg}$$

Fast Rotating 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 →

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

(ii) non-relativistic →

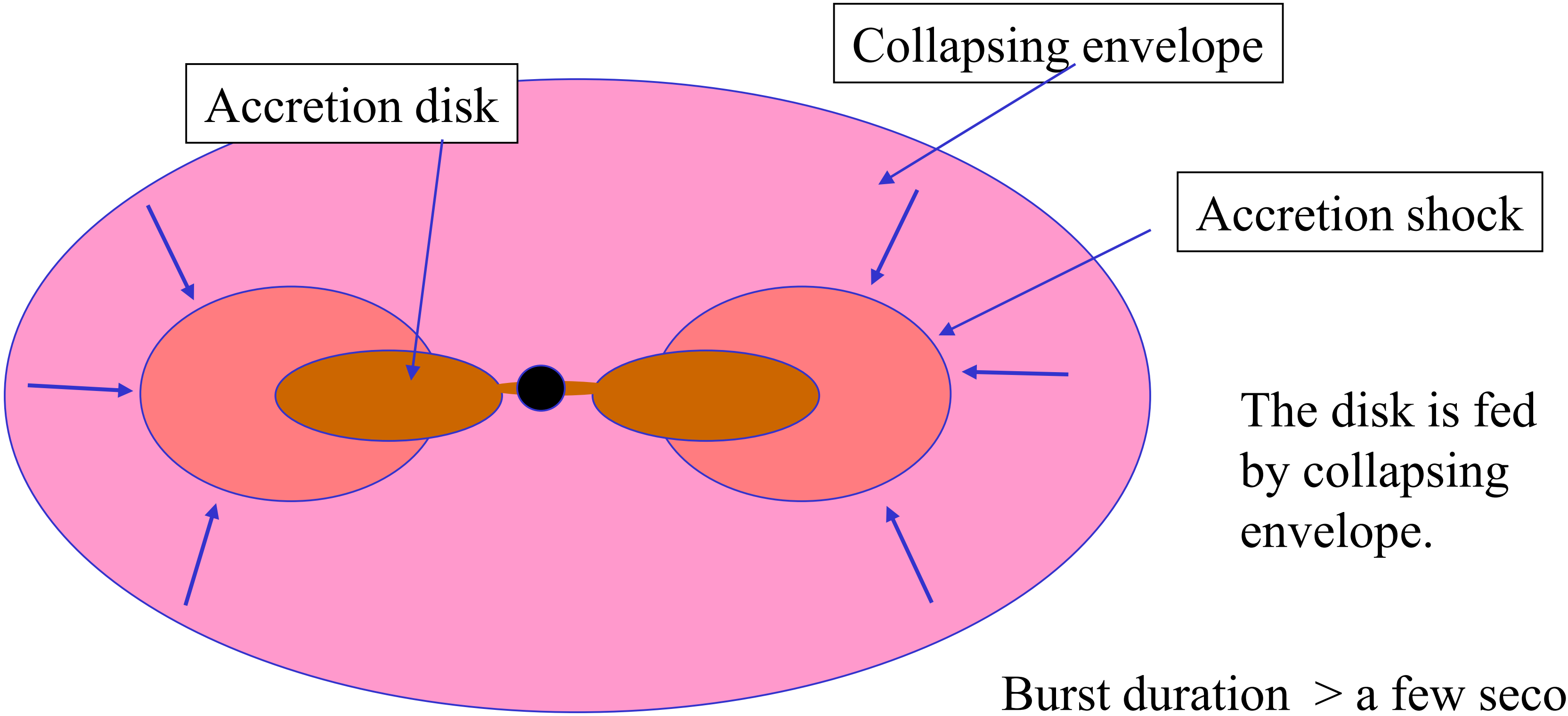
$$L\simeq 4\times10^{51} \left(\frac{B}{10^{15}\text{G}}\right)^2 \left(\frac{R}{10km}\right)^4 \left(\frac{P}{1ms}\right)^{-5/3} \text{erg/s}$$

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)

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)



Collapsing envelope

Accretion disk

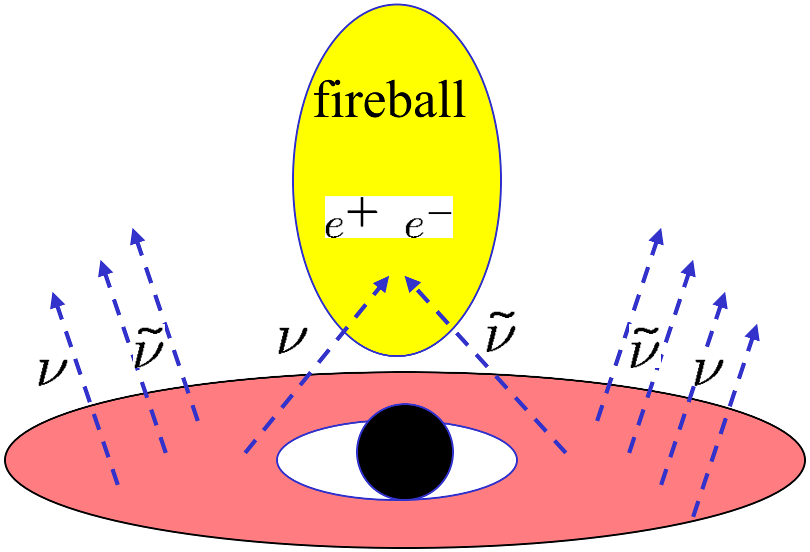
Accretion shock

The disk is fed by collapsing envelope.

Burst duration > a few seconds

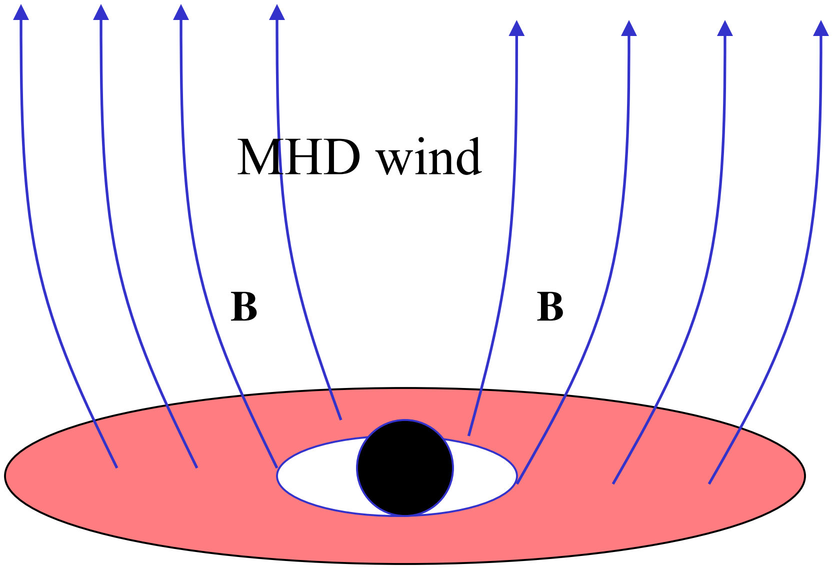
Mechanisms for tapping the disk energy

Neutrino heating



Eichler et al.(1989),
MacFadyen&Woosley (1999), Aloy et al.(2000)
Nagataki et al.(2006), Birkl et al (2007)
Zalamea & Beloborodov (2008,2011)

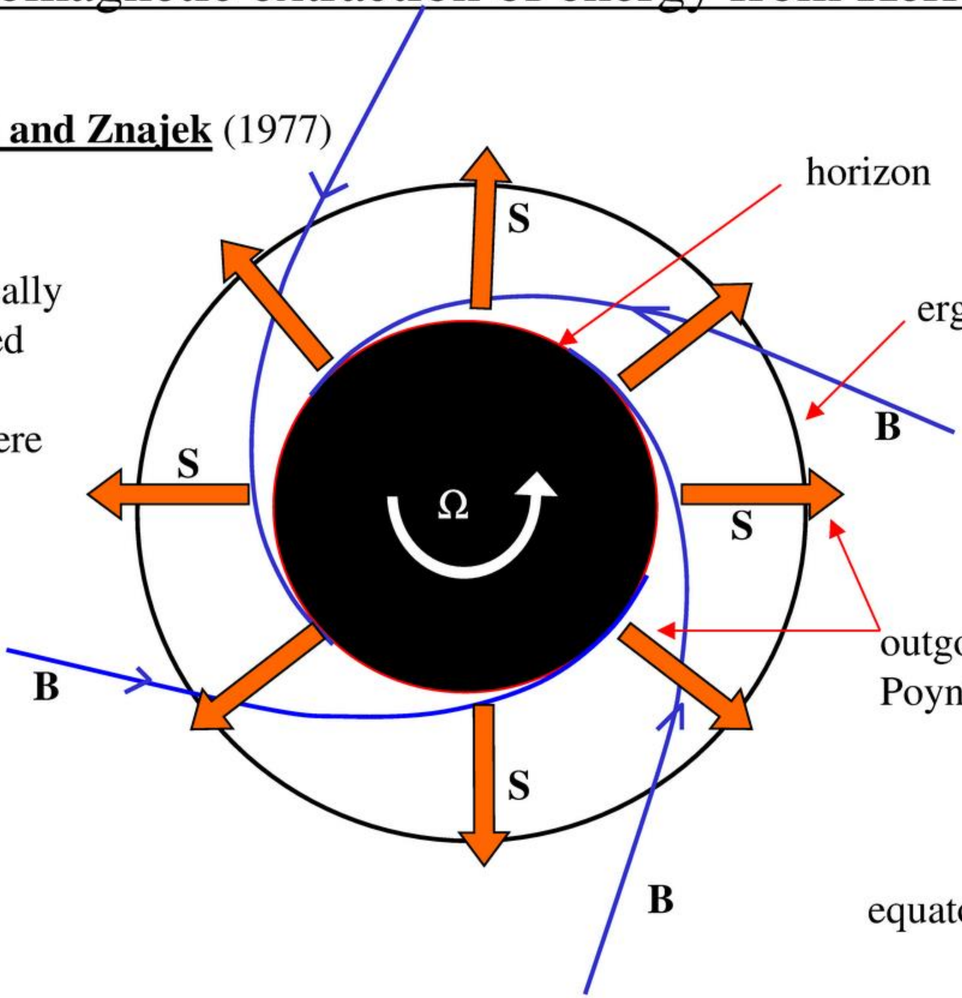
Magnetic braking



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)



magnetically
dominated
plasma
everywhere

horizon

ergosphere

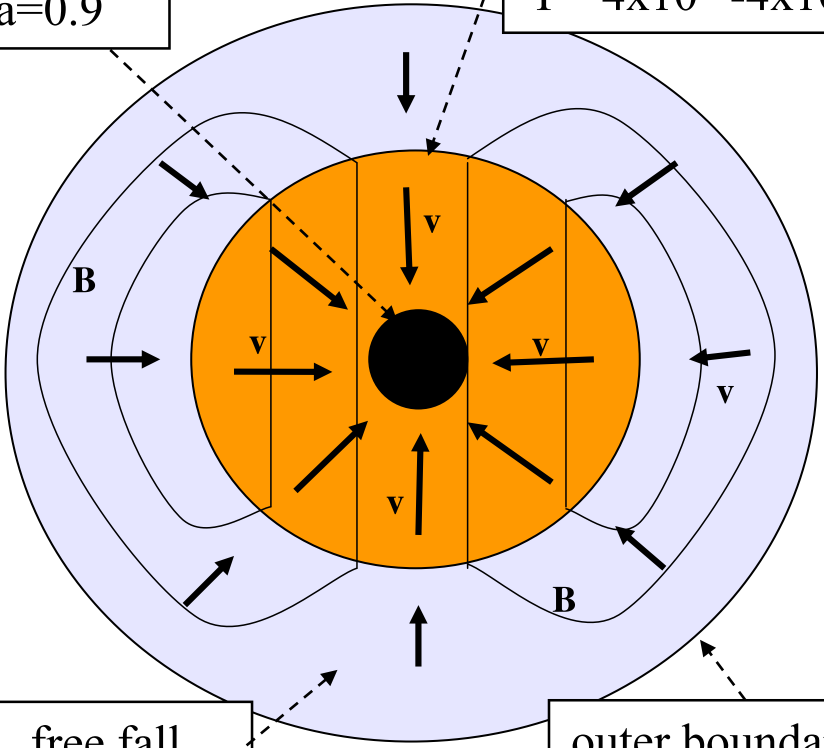
outgoing
Poynting flux

equatorial plane

Numerical simulations

Setup

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



black hole
$M=3M_{sun}$
$a=0.9$

Uniform magnetization
R=4500km
$\Psi = 4\times10^{27}$-$4\times10^{28}\,\mathrm{G\,cm^{-2}}$

free fall
accretion
(Bethe 1990)

outer boundary,
$R = 2.5\times10^{4}$ km

Rotation:

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

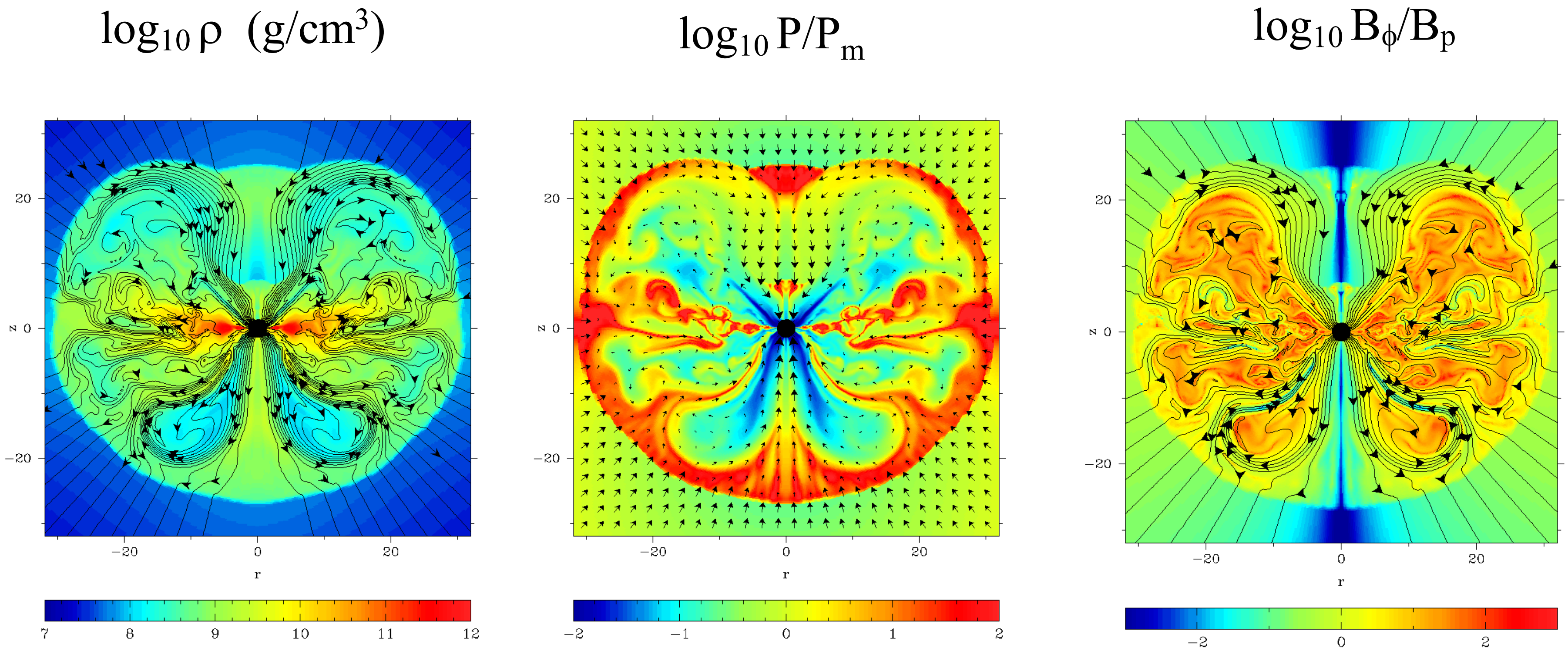
$r_c = 6.3\times10^{3}$km
$l_0 = 10^{17}\ \mathrm{cm^2\ s^{-1}}$

- 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

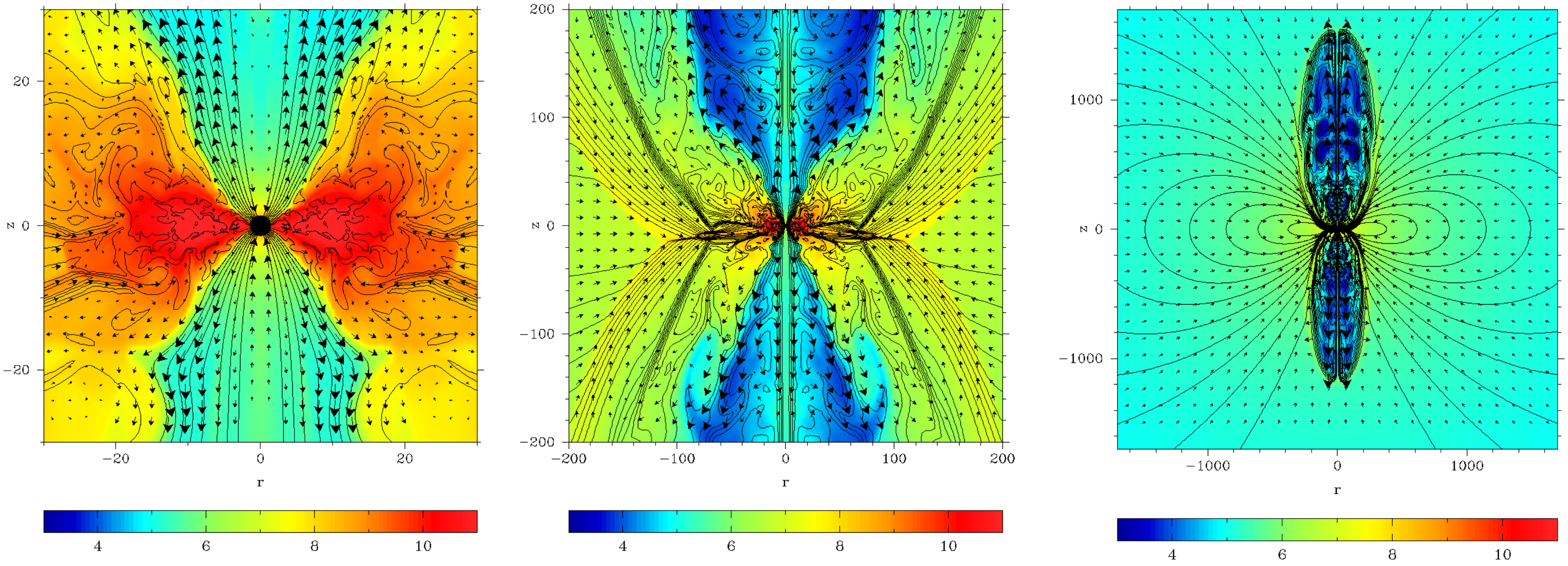
Model:A

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

unit length=4.5km

t=0.31s

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



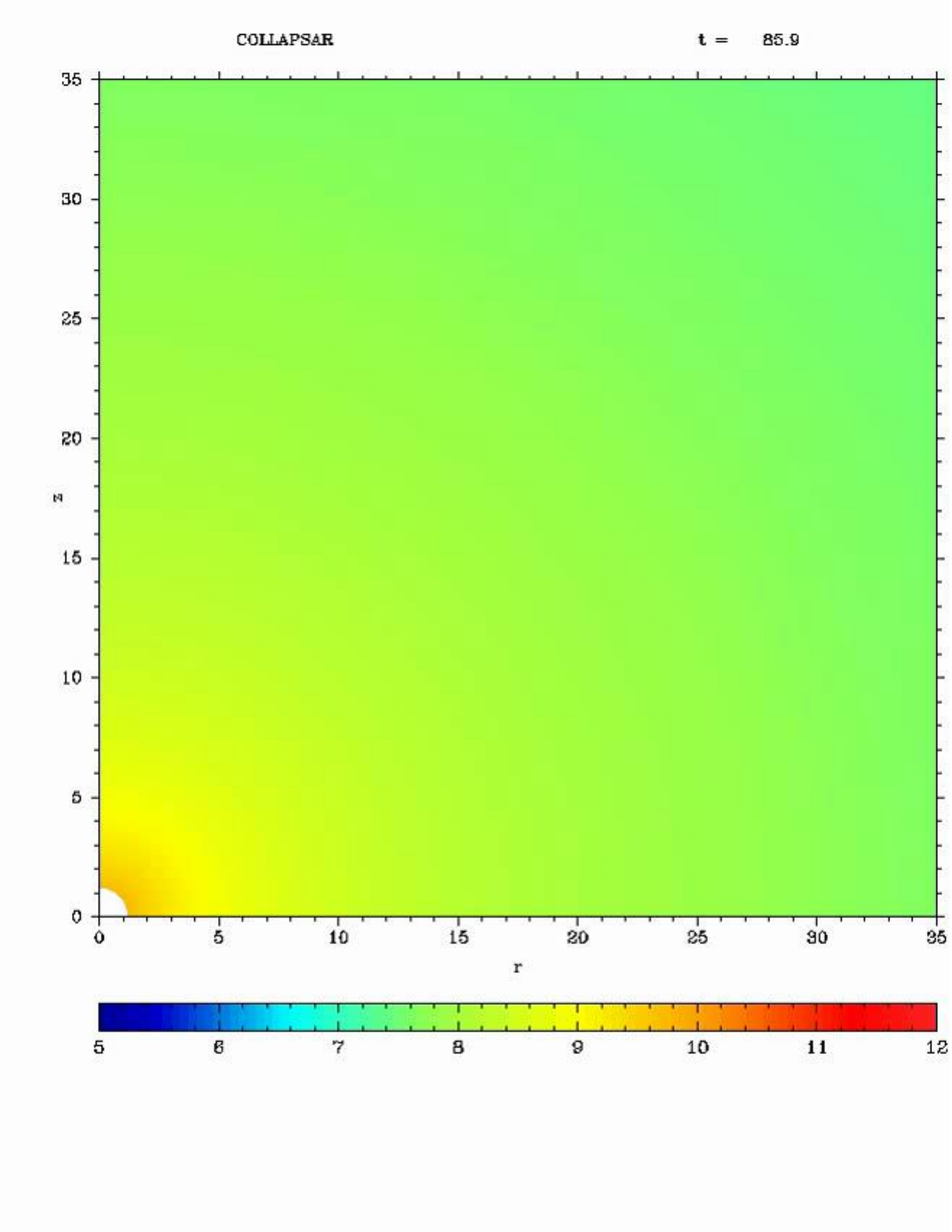
magnetic field lines, and velocity vectors

Model:A

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

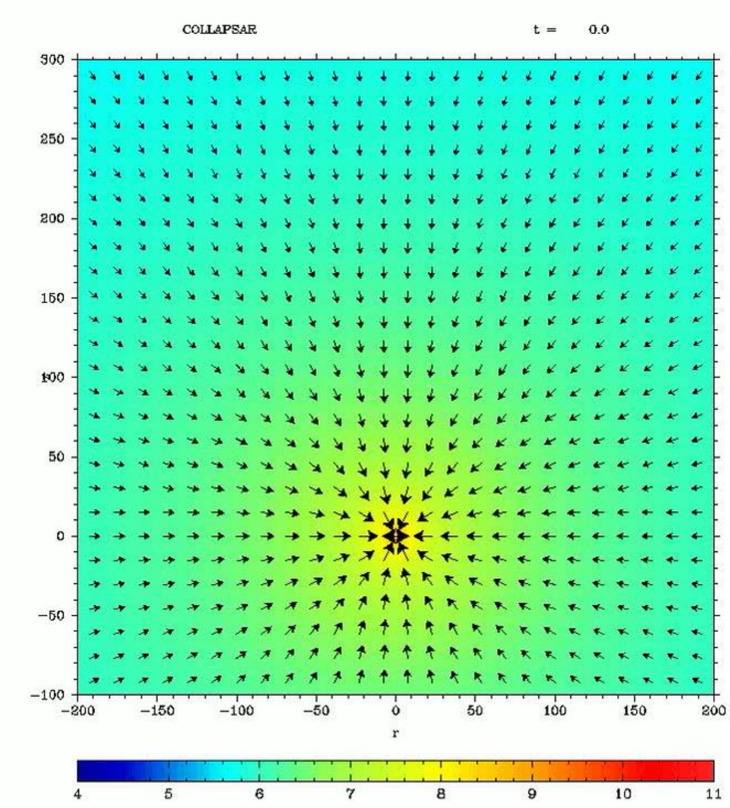
$\log_{10}\rho$ (g/cm^3)

magnetic field lines

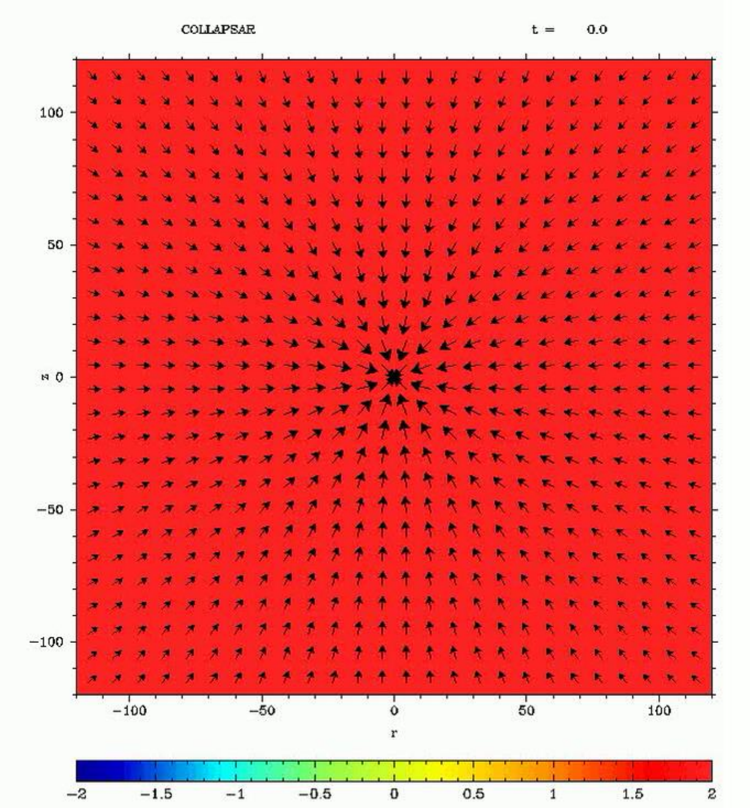


$\dot{M} = 0.15\, M_{SUN}\, s^{-1} \quad (C_1 = 3)$ $\quad l_0 = 10^{17}\ cm^2\, s^{-1}$

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



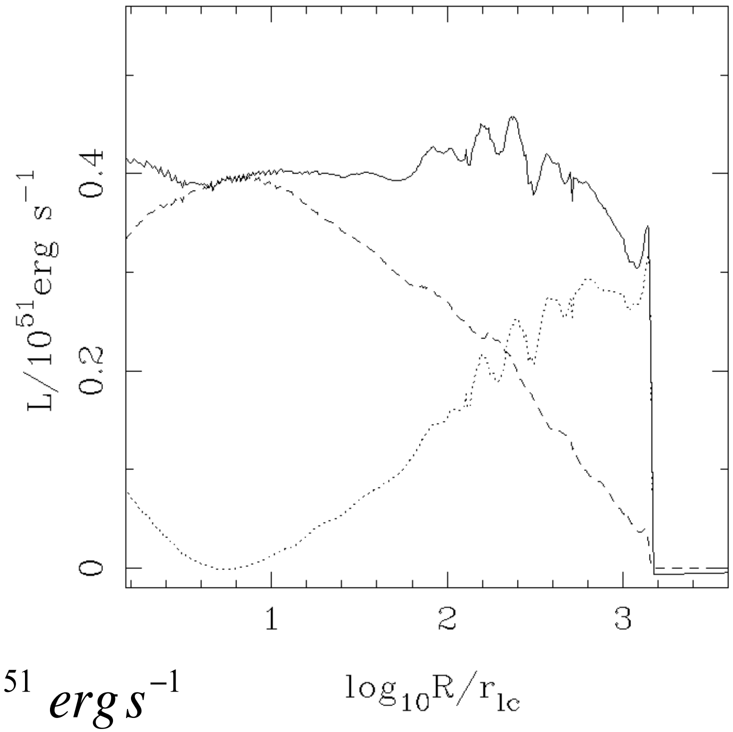
$\log_{10}(\rho)$



$\log_{10}\left({}^{P_g}\!\big/_{P_m} \right)$

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:

$$\dot{E}_{BZ} = 3.6\times10^{50} f(a)\Psi_{27}^{2} M_{3}^{-2} = 0.48\times10^{51}\ erg\, s^{-1}$$

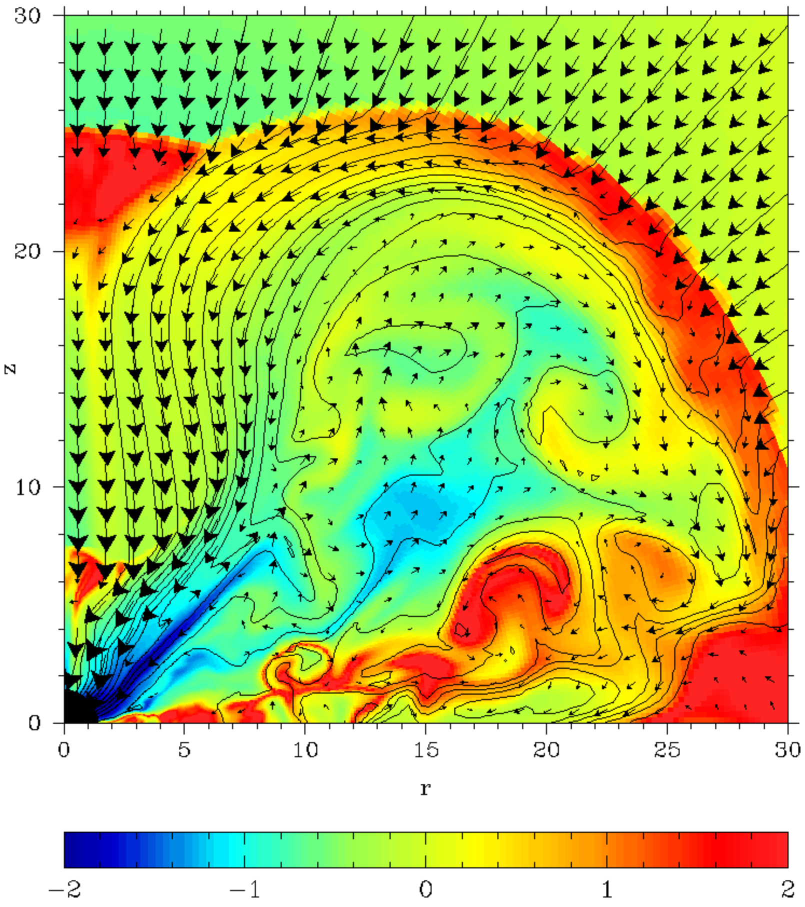
Magnetic Unloading

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 $\boxed{B^2/4\pi\rho c^2 > 1}$

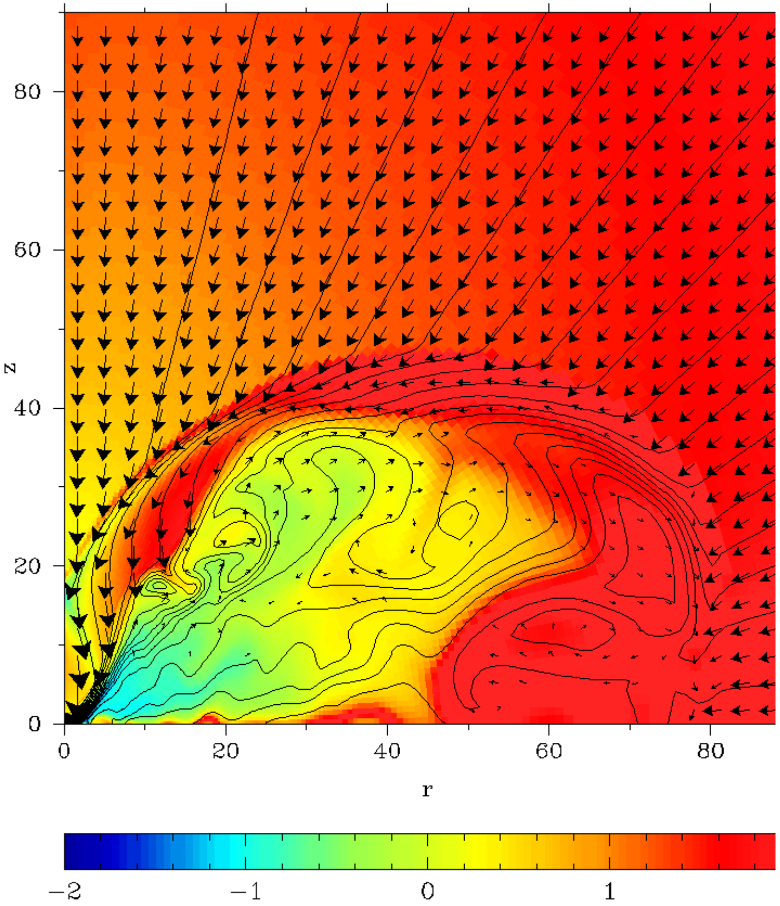
2) The torque of magnetic lines from BH should be sufficient to stop accretion
(Barkov & Komissarov 2008b)
(Komissarov & Barkov 2009)

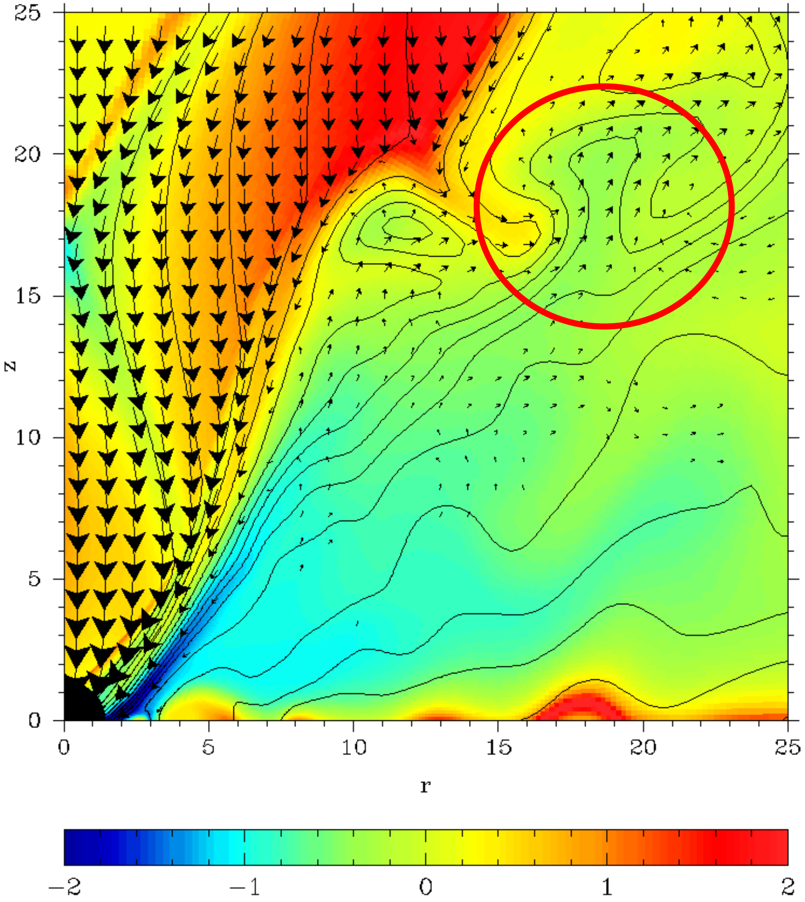


$$\dot{E}_{BZ} / \dot{M}c^2 = \kappa > 1\,(???)$$

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

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





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

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

Neutrino heating vs Magnetic jets

$$\dot{E}_{\nu\bar{\nu}} \approx 1.1 \times 10^{52}\, x_{\rm ms}^{-4.8} \left(\frac{M}{3\,{\rm M}_\odot}\right)^{-3/2} \times \left\{ \begin{array}{ll} 0 & \dot{M} < \dot{M}_{\rm ign} \\ \dot{m}^{9/4} & \dot{M}_{\rm ign} < \dot{M} < \dot{M}_{\rm trap} \\ \dot{m}_{\rm trap}^{9/4} & \dot{M} > \dot{M}_{\rm trap} \end{array} \right\} \,{\rm erg\,s^{-1}}$$

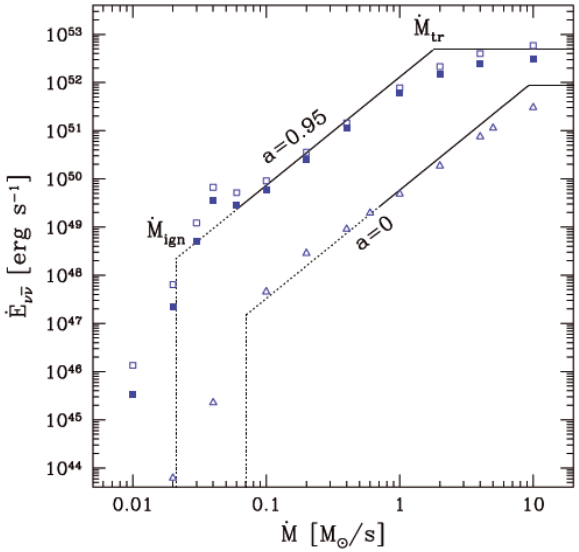
Zalamea & Beloborodov (2011)

$$\dot{E}_{BZ} = C(a)\beta\dot{m}c^2$$

$$C(a) = 2 * 10^{54} f(a)\ \text{ergs/s}$$

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

Komissarov & BMV (2011)



Magnetically driven jets can last much longer compare to neutrino heating jets.

Discussion

Magnetically-driven stellar explosions require combination of
(i) fast rotation of stellar cores and **(ii) strong magnetic fields**.

Can this be achieved?

- Evolutionary models of solitary massive stars show that even much weaker magnetic fields (Taylor-Spruit dynamo) result in rotation being too slow for the collapsar model (Heger et al. 2005)

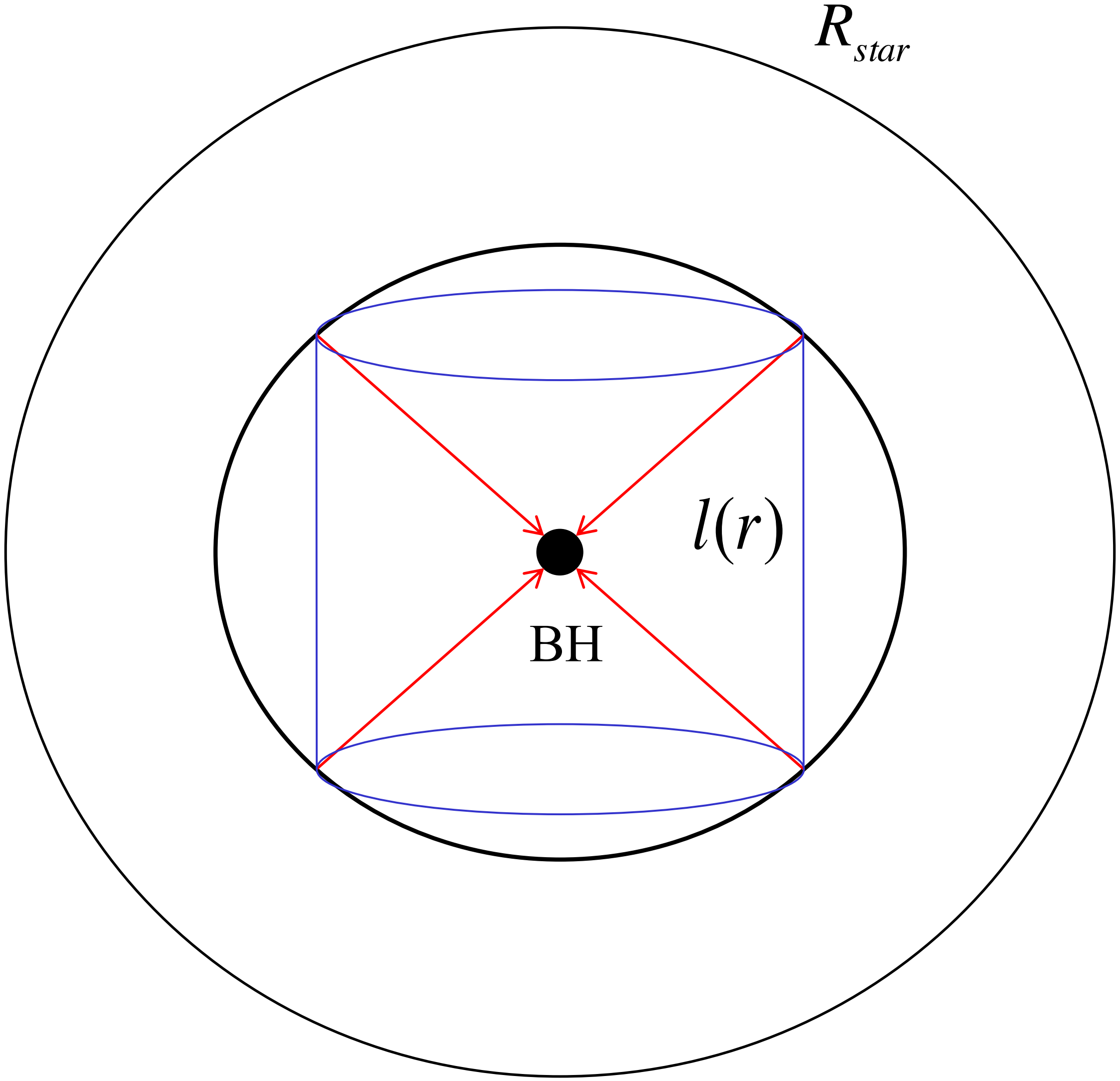
- Low metallicity may save the collapsar model with neutrino mechanism (Woosley & Heger 2006) but magnetic mechanism needs much stronger magnetic field.

- Solitary magnetic stars (Ap and WD) are slow rotators (solid body rotation).

- **We need strongly magnetized star in close binary system!**

Simple model:

Barkov & Komissarov (2010)



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

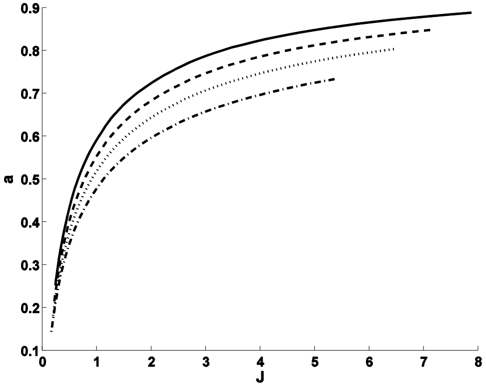
If $l(r)>l_{cr}$ then matter goes to disk and after that to BH

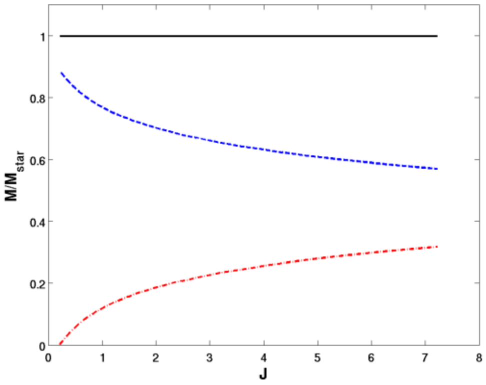
Agreement with model Shibata&Shapiro (2002) on level 1%

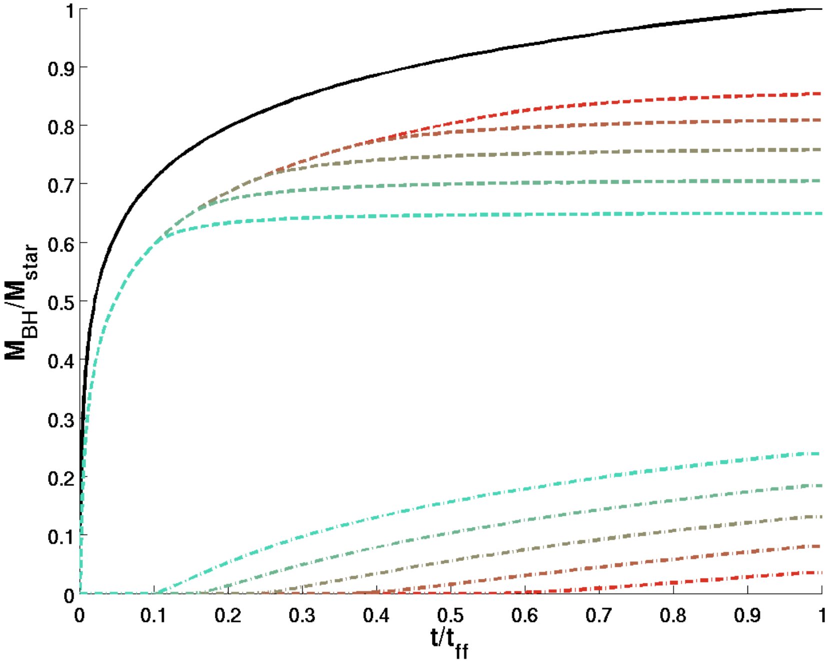
Power low density distribution model

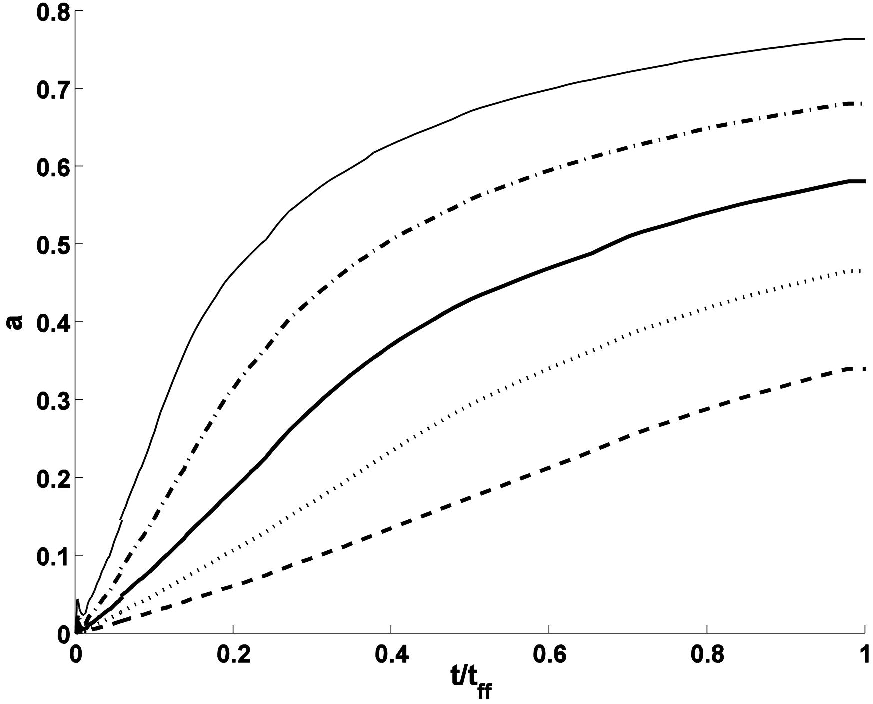
$$\rho \propto r^{-3}$$

$$J = \frac{J_s c}{G M_s^2}$$





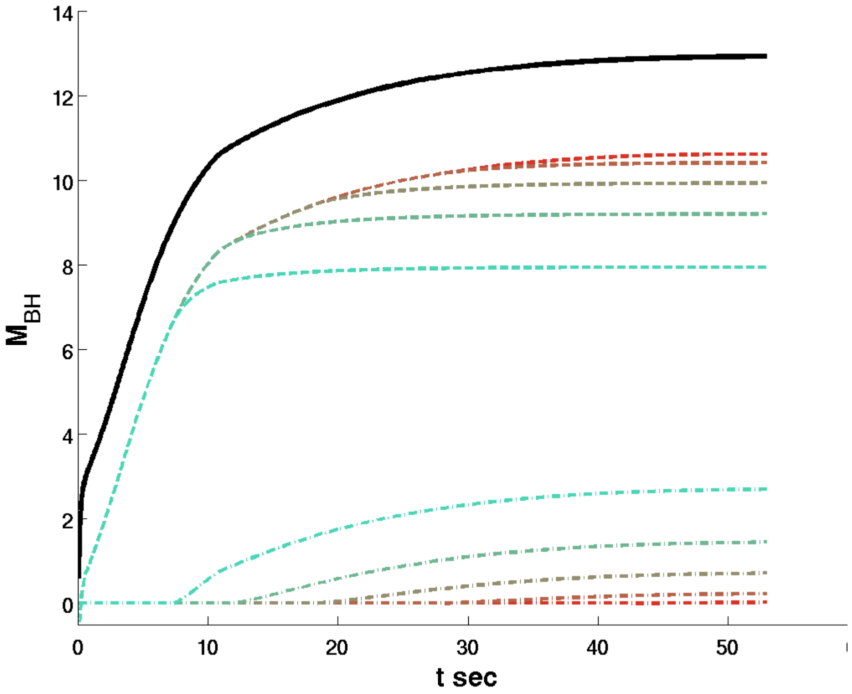


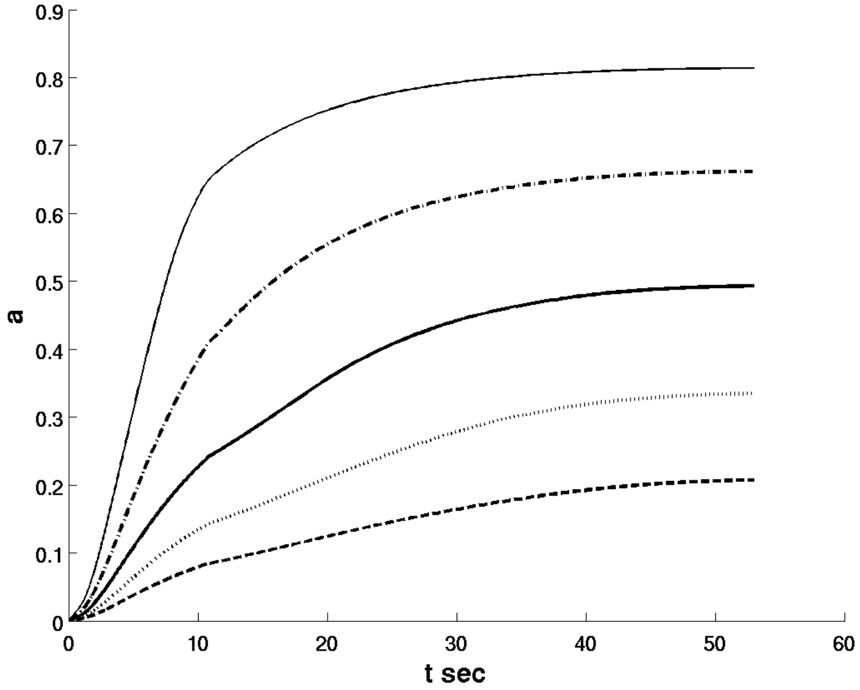


Realistic model

Heger at el (2004)

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



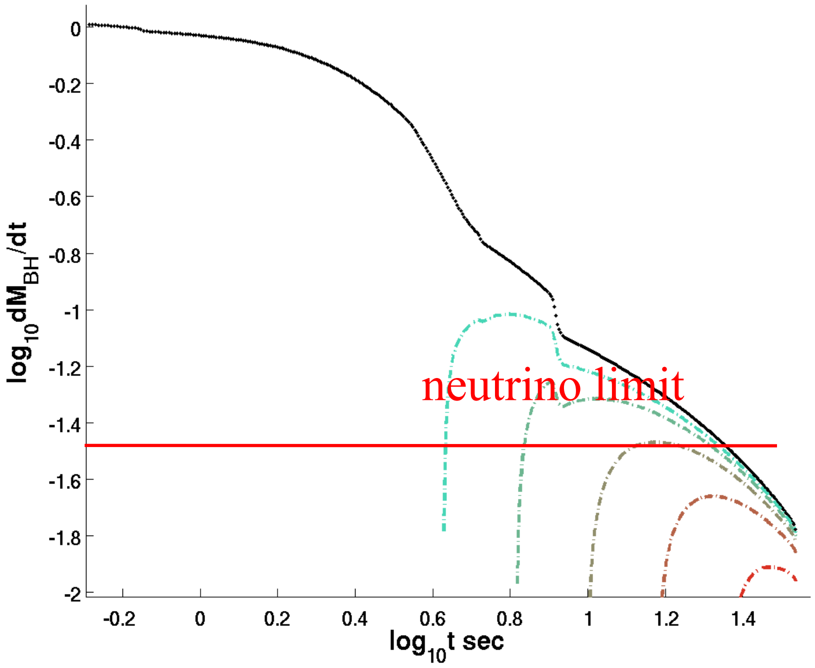


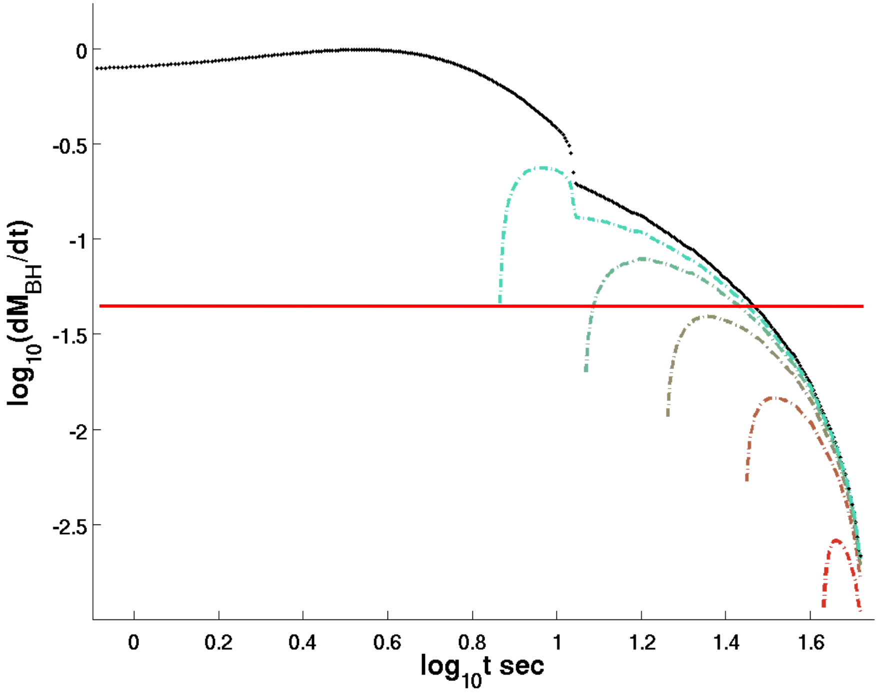
Realistic model

Heger at el (2004)

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

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



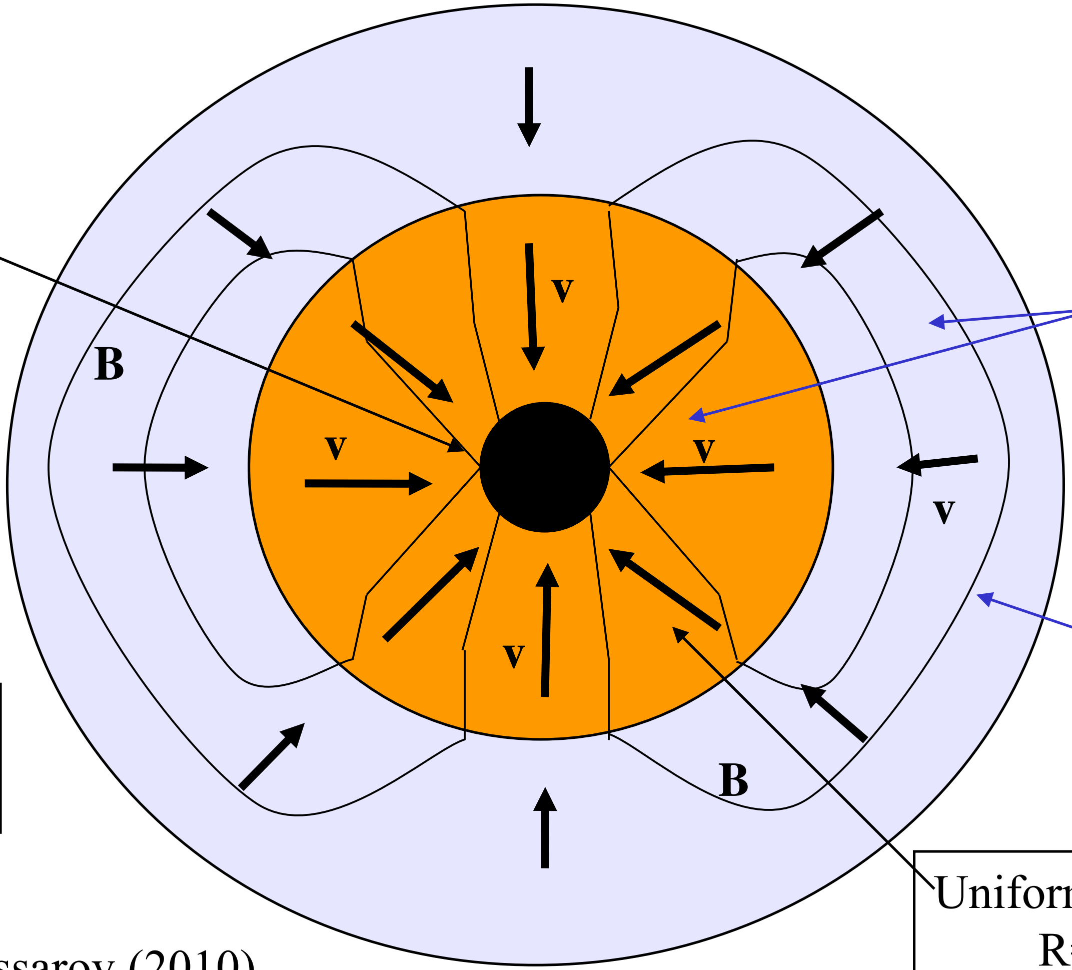


BZ limit

Numerical simulations II: Collapsar model

Setup

GR MHD
2D



black hole
M=10 M_{sun}
a=0.45-0.6

Bethe’s
free fall model,
T=17 s, C_1=23

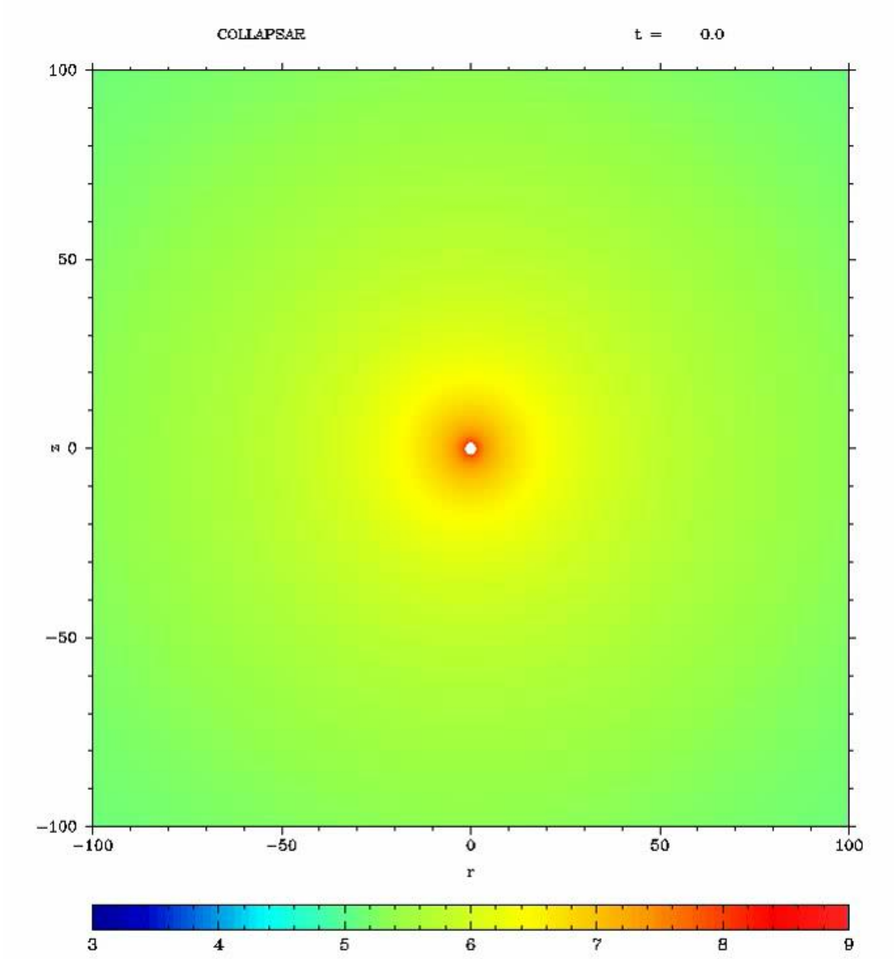
Dipolar
magnetic field

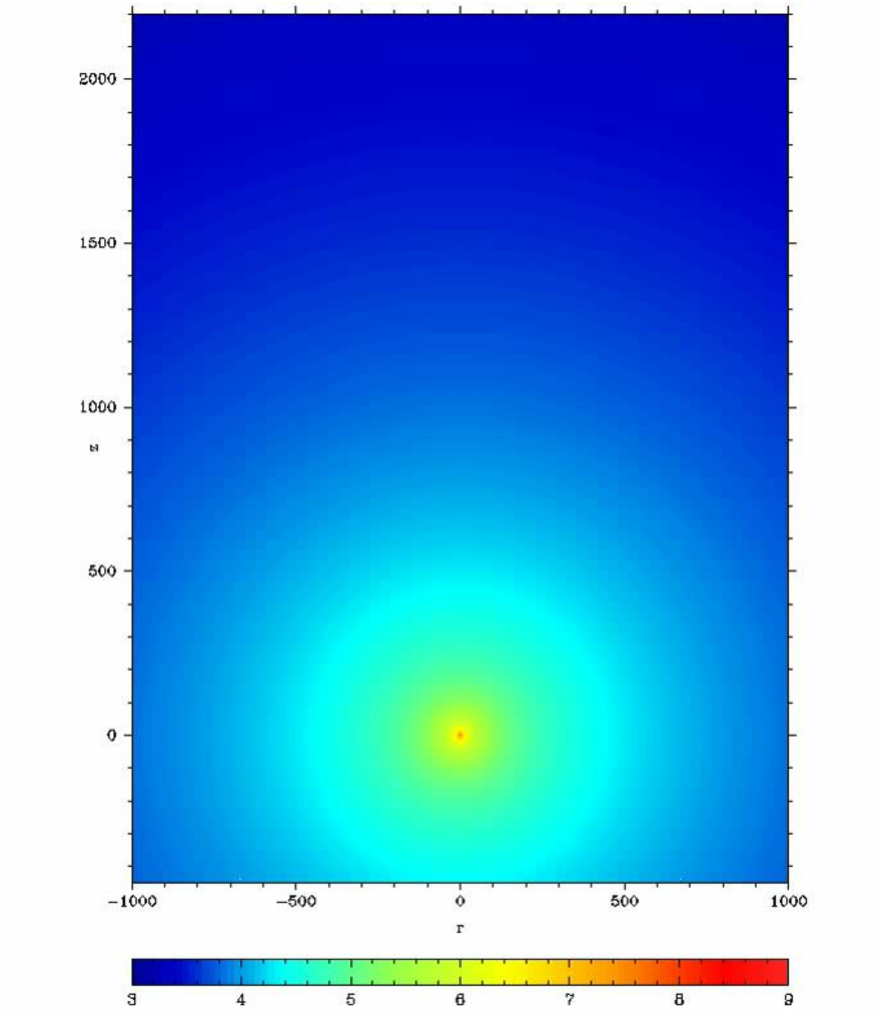
Initially solid
body rotation

Uniform magnetization
R=150000km
B_0= 1.4x10^7-8x10^7G

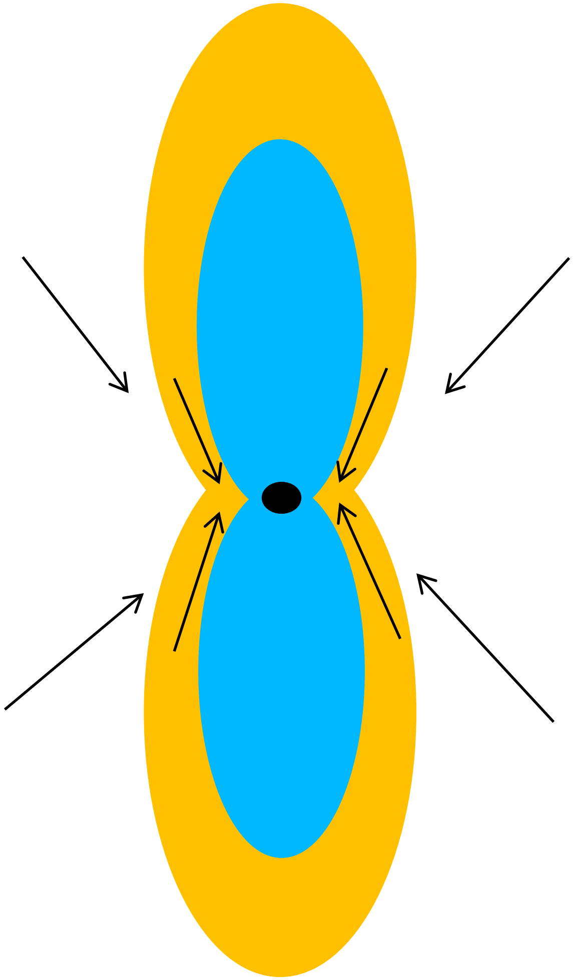
Barkov & Komissarov (2010)

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

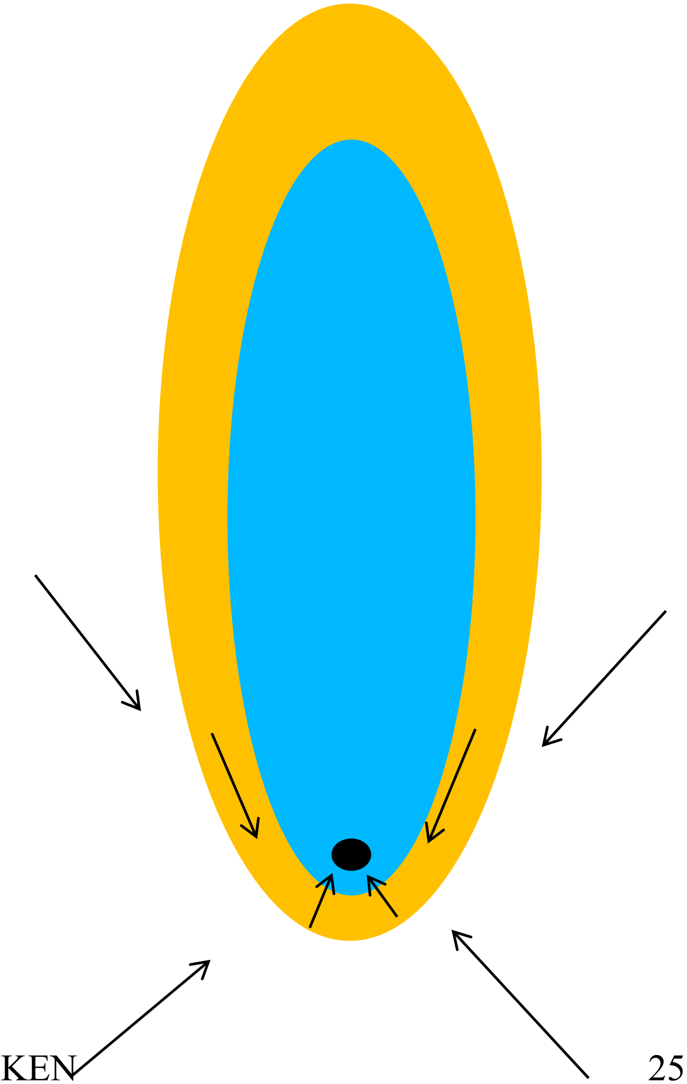




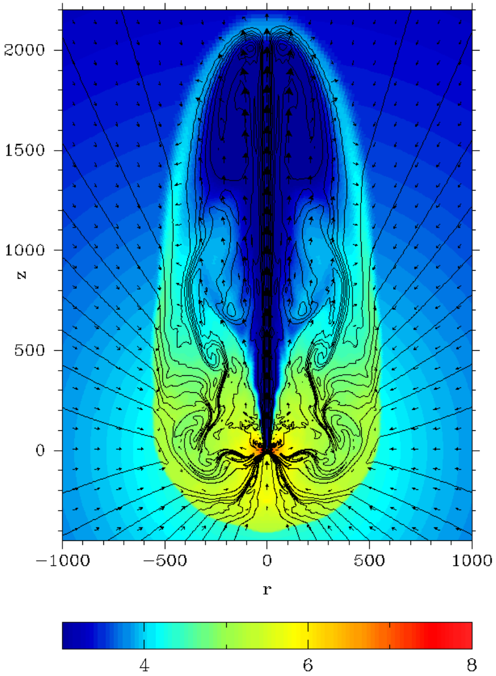
2 Side jets

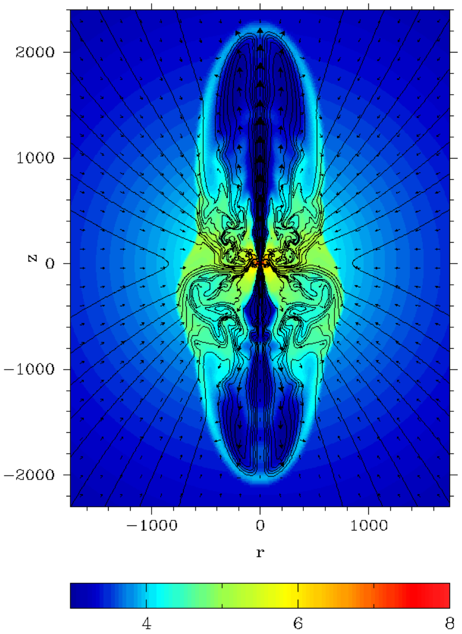


1 Side jet



a=0.6 Ψ=3x10^{28} a=0.45 Ψ=6x10^{28}





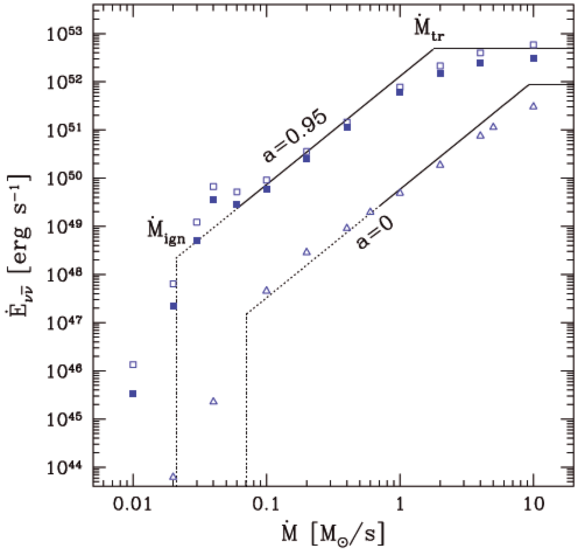
$$V_{kick} \leq 170\left(\frac{E}{10^{52}\,ergs}\right)\left(\frac{10\,M_{sun}}{M_{bh}}\right) km\,s^{-1}$$

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

Neutrino heating vs Magnetic jets

$$\dot{E}_{\nu\bar{\nu}} \approx 1.1 \times 10^{52}\, x_{\rm ms}^{-4.8} \left(\frac{M}{3\,{\rm M}_\odot}\right)^{-3/2} \times \left\{ \begin{array}{ll} 0 & \dot{M} < \dot{M}_{\rm ign} \\ \dot{m}^{9/4} & \dot{M}_{\rm ign} < \dot{M} < \dot{M}_{\rm trap} \\ \dot{m}_{\rm trap}^{9/4} & \dot{M} > \dot{M}_{\rm trap} \end{array} \right\} {\rm erg\ s^{-1}}$$

Zalamea & Beloborodov (2011)



$$\dot{E}_{BZ} = C(a)\beta\dot{m}c^2$$

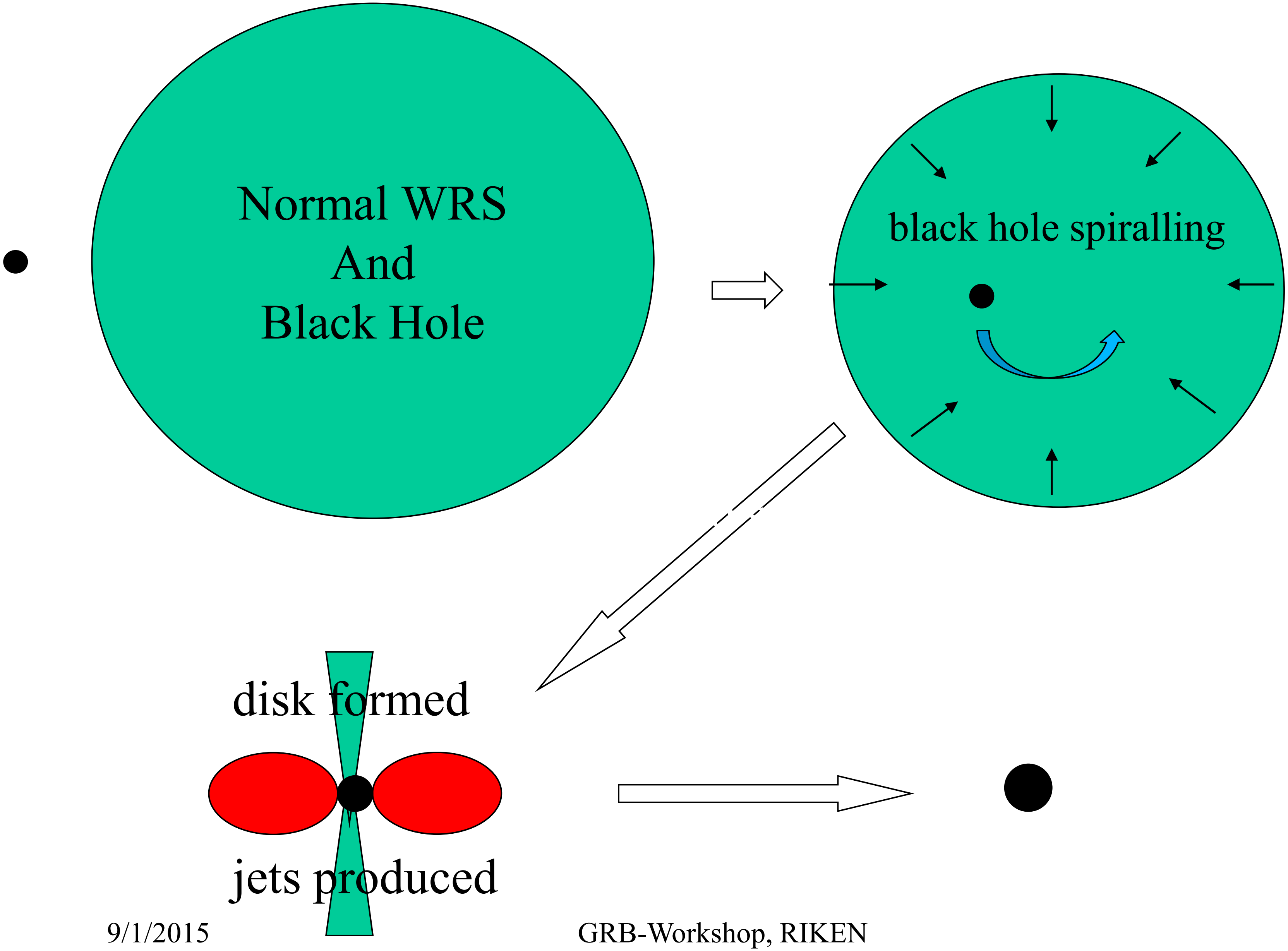
$$C(a) = 2 * 10^{54} f(a)\ \text{ergs/s}$$

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

Komissarov & BMV (2011)

Magnetically driven jets can last much longer compare to neutrino heating jets.

Common Envelop (CE):

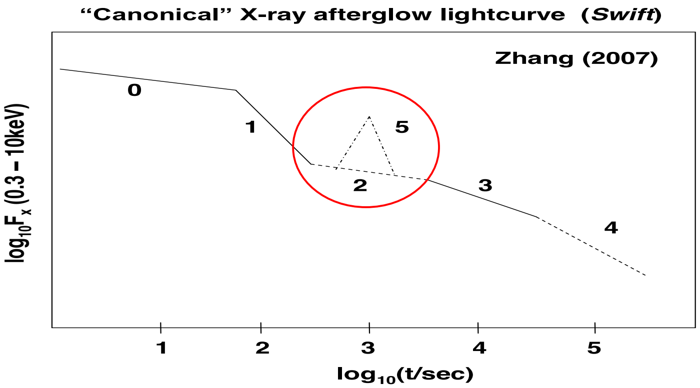


Normal WRS
And
Black Hole

black hole spiralling

disk formed

jets produced

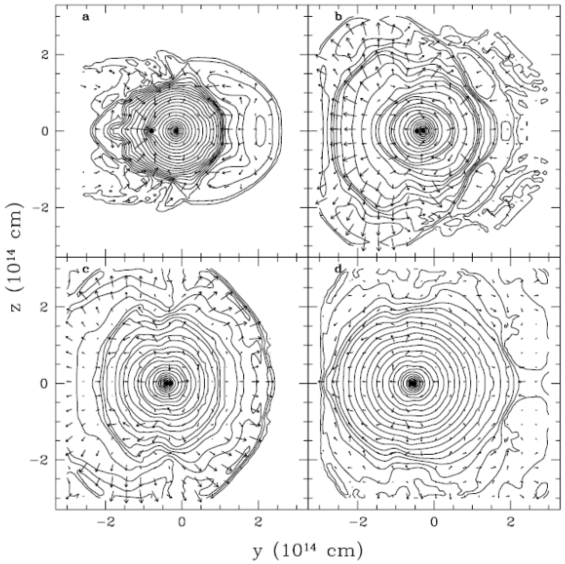


- During CE stage a lot of angular momentum is transferred to the envelop of normal star.

- Accretion of the stellar core can give the main gamma ray burst driven by neutrino heating.

- BZ could work effectively much longer with low accretion rates.

- Long accretion disk phase could be as long as 10^4 s, i.e. a feasible explanation for X-Ray plateau phase.



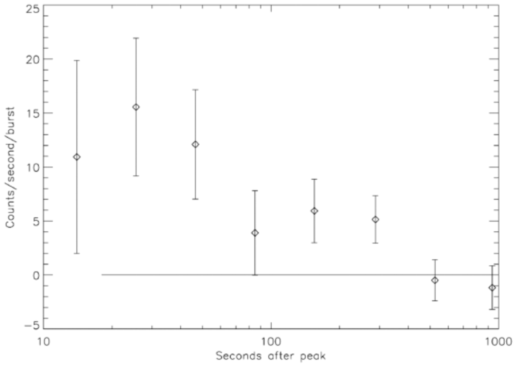
see for review
(Taam & Sandquist 2000)

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

$$t_d \approx 8000\,s$$

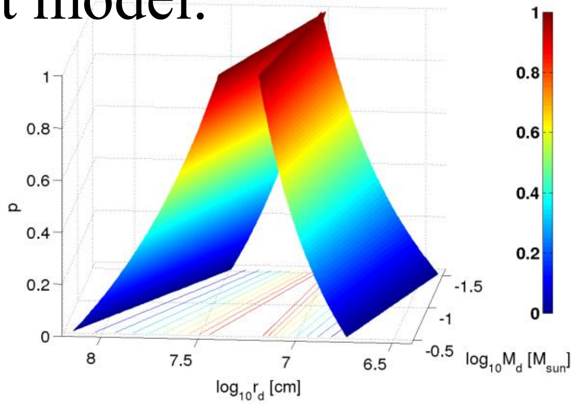
(Barkov & Komissarov 2010)

Extended emission of short GRBs

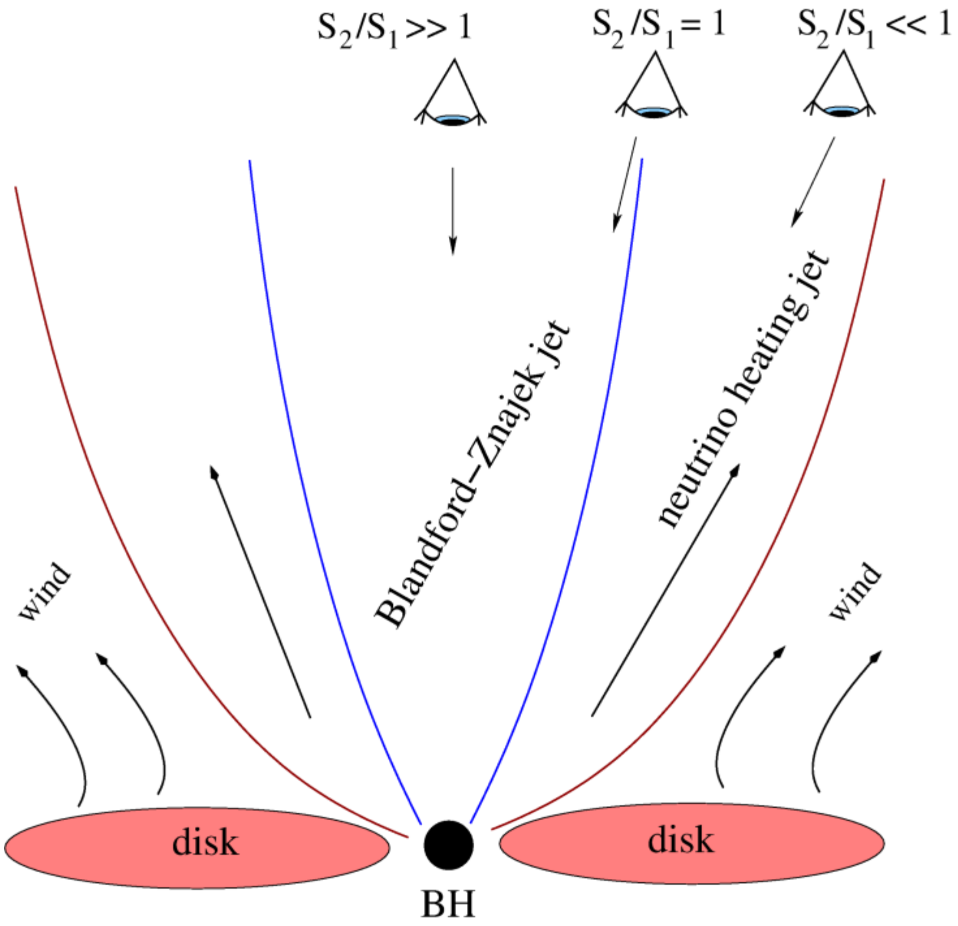


Short GRBs have extended Emission up to 100 s.

We suggest a two component Jet model.



BMV & Pozanenko 2011



Conclusions

- The Collapsar is a promising model for the central engine of long 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;

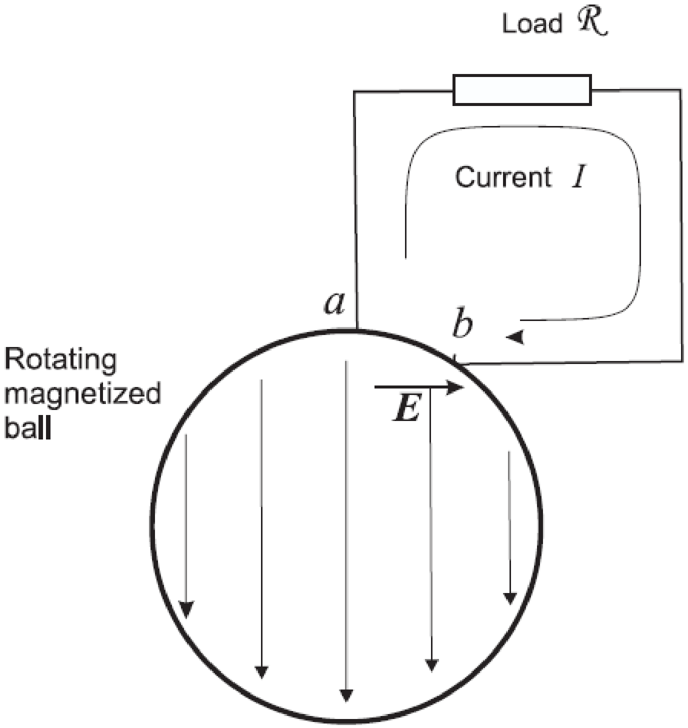
  + Blandford-Znajek mechanism of GRB has much lower limit on accretion rate to BH then neutrino driven one (excellent for very long GRBs >100s);

  + 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.

Neutrino driven jet and magnetically driven jet can be in operation in the same event.
Magnetically driven jet can be feasible explanation for extended emission.

Unipolar inductor



$$W_{\rm tot} = I\delta U$$

$$\delta U \sim E R_0 \sim \frac{\Omega R_0^2}{c} B$$

$$j_{\rm GJ} = \rho_{\rm GJ} c$$

$$\rho_{\rm GJ} = -\frac{\mathbf{\Omega}\cdot\mathbf{B}}{2\pi c}$$

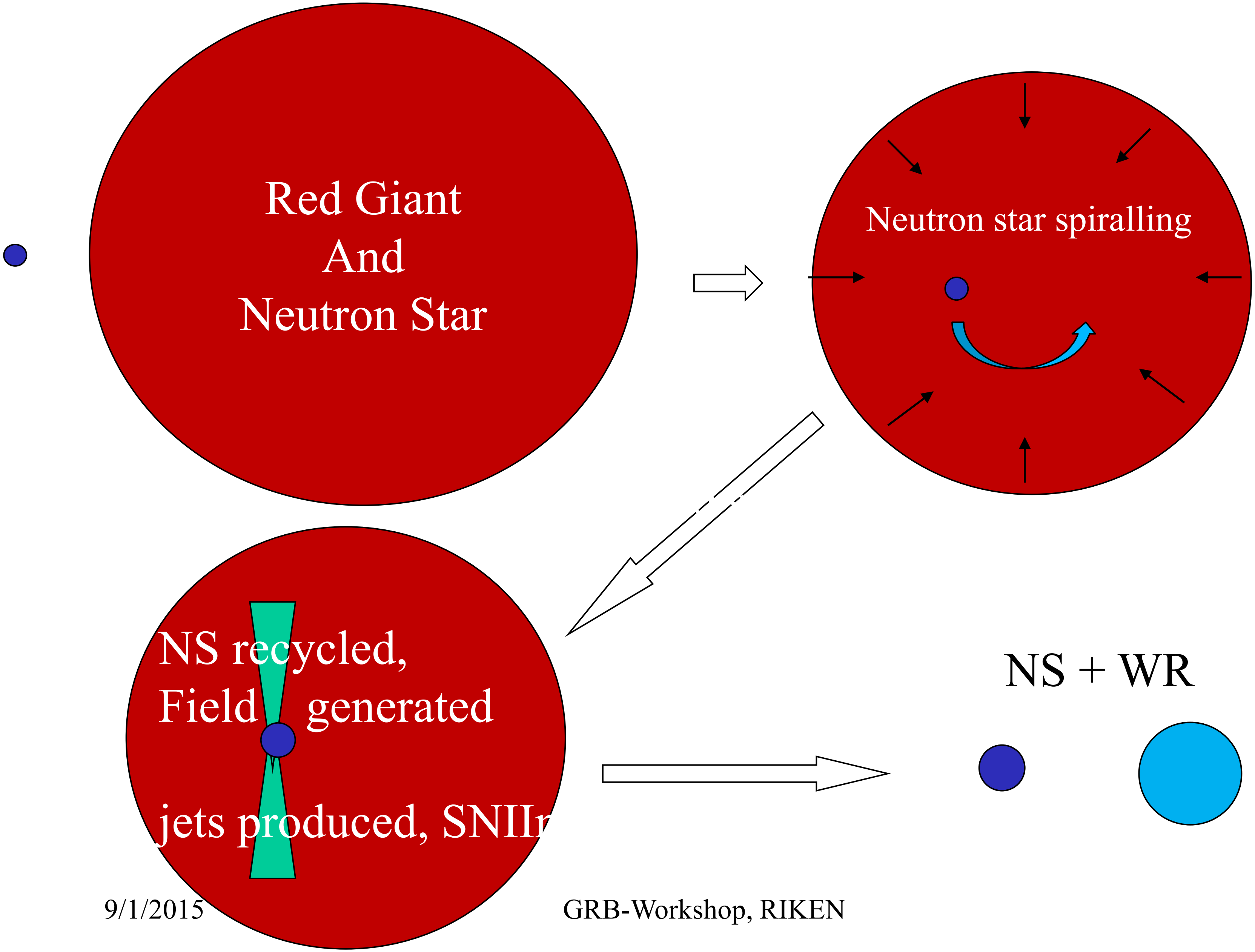
$$I_{\rm GJ} = \pi R_0^2 c \rho_{\rm GJ}$$

$$W_{\rm tot} \approx \left(\frac{\Omega R_0}{c}\right)^2 B_0^2 R_0^2 c.$$

Beskin 2010

$$W_{tot} \propto f(a)\, \Psi^2 M_{BH}^{-2}$$

NS in Common Envelop:



Red Giant
And
Neutron Star

Neutron star spiralling

NS recycled,
Field generated

jets produced, SNIIr

NS + WR

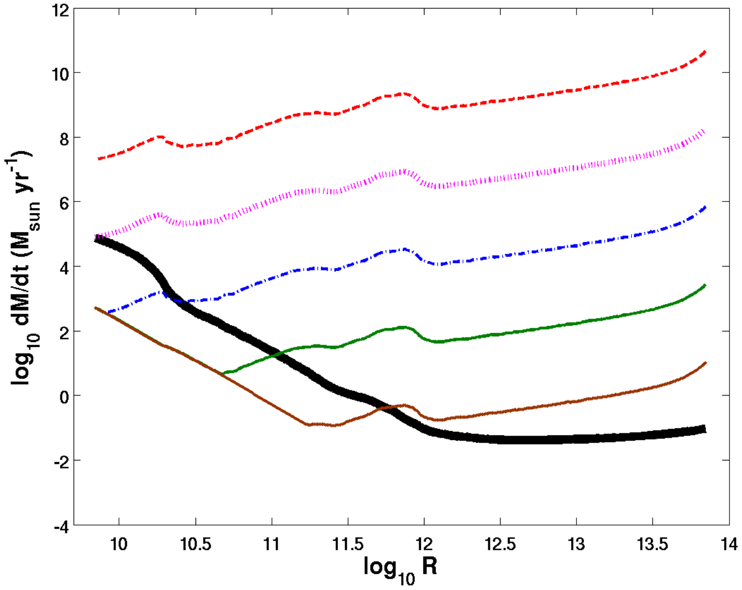
The accretion to NS: the sensitivity to parameters.

$$R_{\rm A} \approx 2\beta \frac{aM_{\rm NS}}{M_*}$$

Barkov & Komissarov (2011)

$$\langle j_{\rm A}\rangle = \frac{\eta}{4}\Omega R_{\rm A}^2$$

$$R_{\rm c} = \frac{\langle j_{\rm A}\rangle^2}{GM_{\rm NS}} \approx a\eta^2\beta^4\left(\frac{M_{\rm NS}}{M_*}\right)^3$$



$$R_{\rm sh} \approx 3\times 10^9 R_{\rm c,6}^{1.48}\dot{M}_0^{-0.37}\ {\rm cm}$$

$$\dot{M}_{\rm cn1} \approx 1.1\times 10^{-3} R_{\rm c,6}^{1.08} M_\odot\ {\rm yr}^{-1}$$

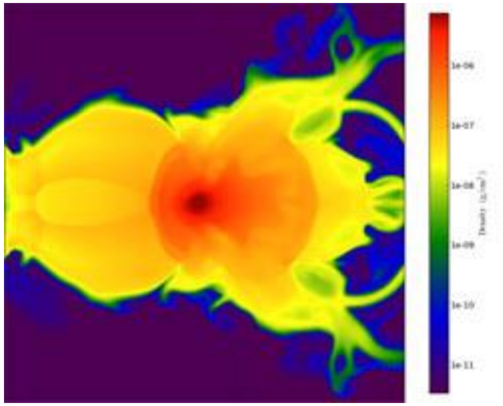
$$\dot{M}_{\rm cn2} \approx 10^4 R_{\rm acc,8}^{-2.7} R_{\rm c,6}^4 M_\odot\,{\rm yr}^{-1}$$

$\dot{M}_{\rm cn1} \propto \eta^{2.16}$ and $\dot{M}_{\rm cn2} \propto \eta^8$

Chevalier (1996)

De Marco et al (2011)

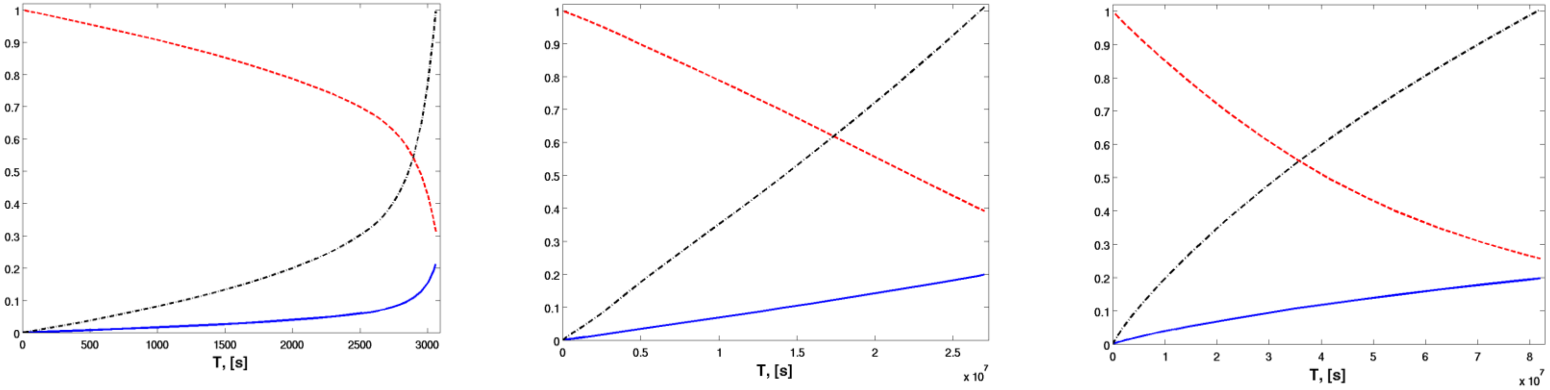
The NS penetration to the envelop of RG



$$\Delta M \simeq \frac{\Omega I}{j_{\rm K}} \simeq 0.18\, M_0 R_{\rm NS,6}^2 P_{\text{-}3}\, M_\odot$$

$$\frac{\dot{a}}{a} = -\frac{4\pi G^2 M \rho}{v^3}\left[\frac{M}{M_*(1+\mathcal{M}^{-2})^{3/2}} + \zeta C_D\right]\left(\zeta + 3\frac{\rho}{\bar{\rho}}\right)^{-1}$$

Chevalier (1996)



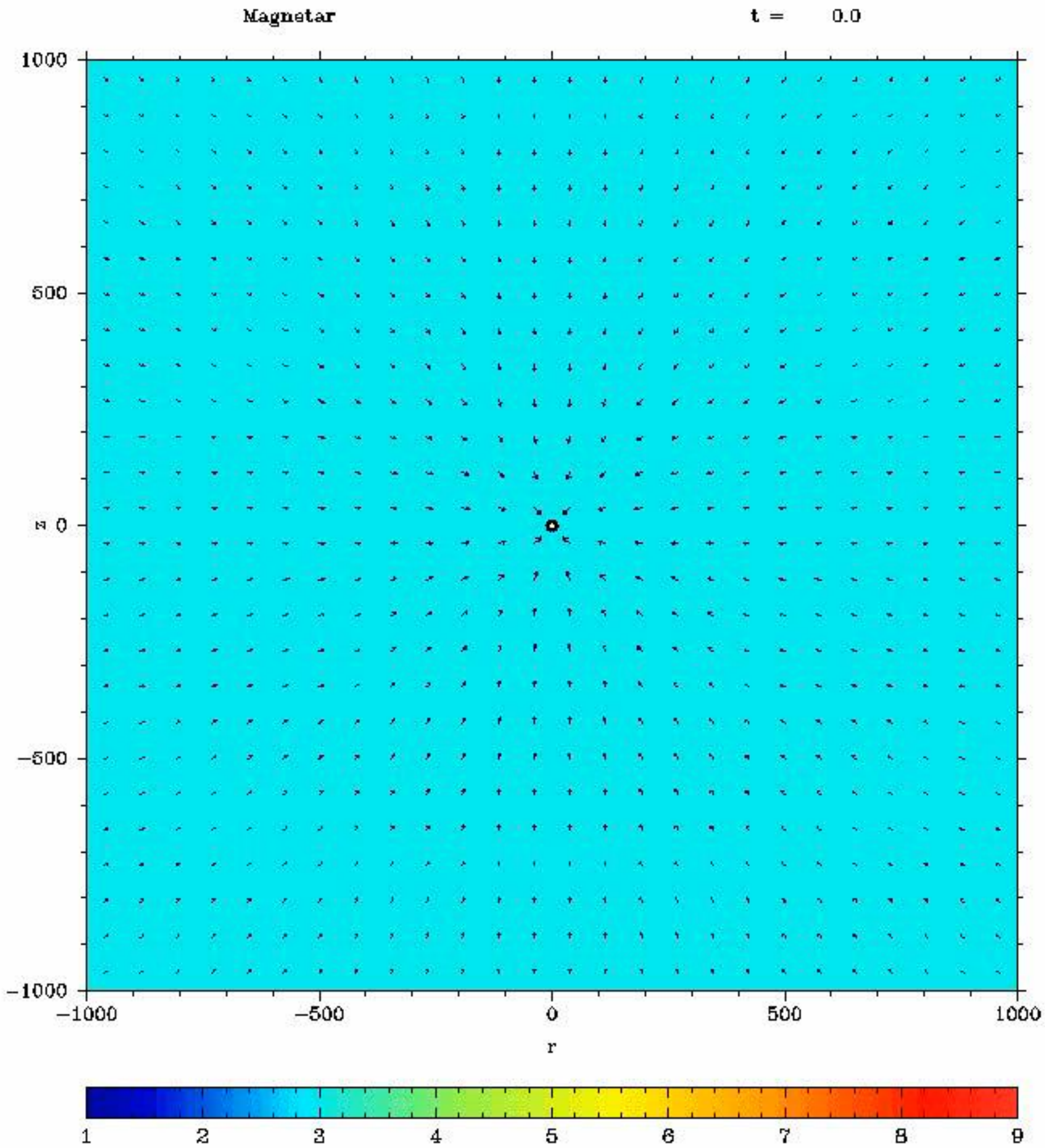
NS with dipole field:

P=4 ms

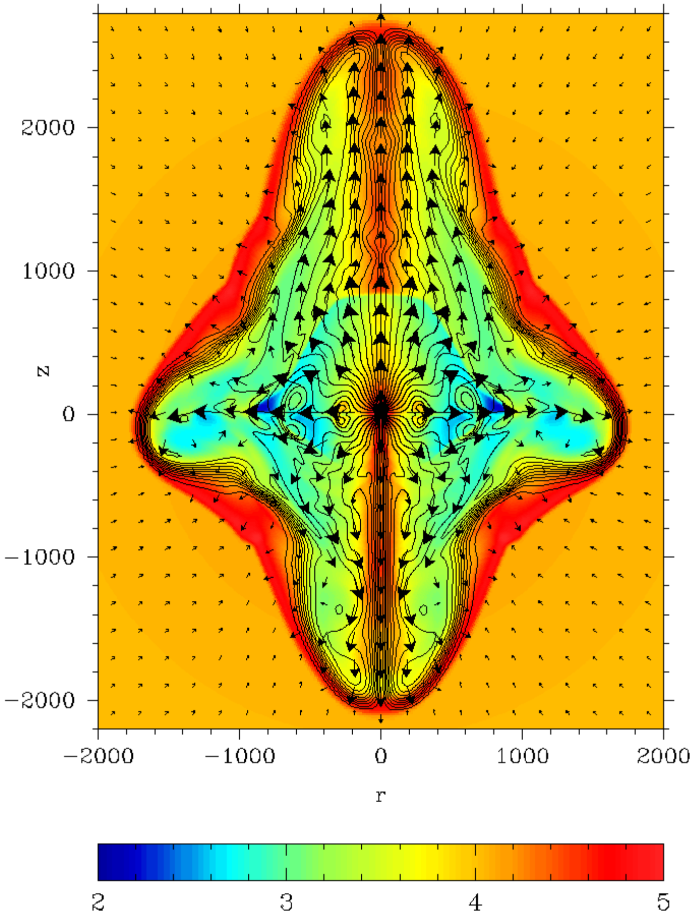
B=10^{15} G

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

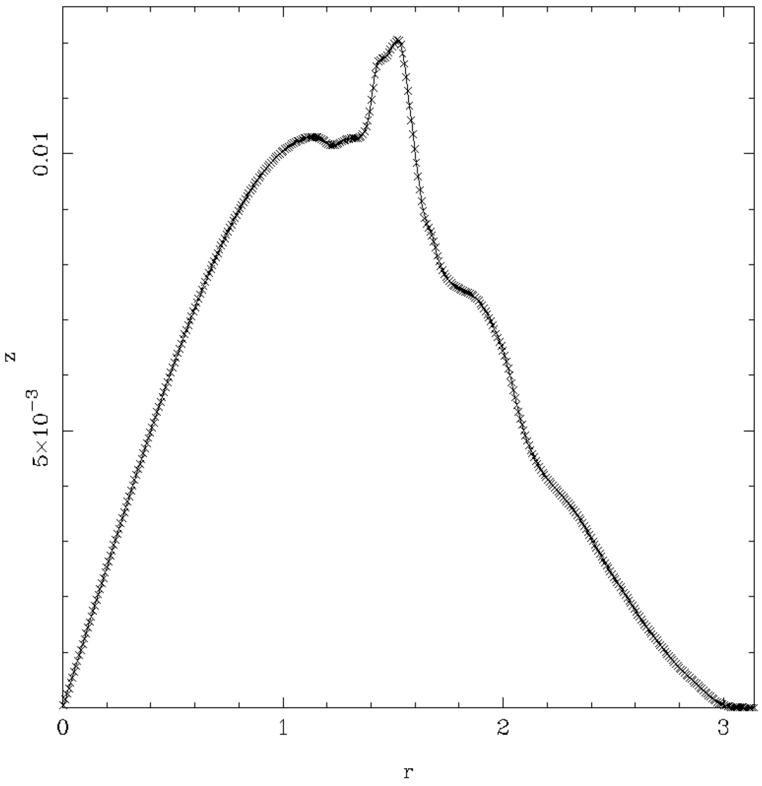
The intensive accretion to NS of matter with accretion rate of 10^3 M_{sun}/yr can lead to the generation of strong magnetic field.



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



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

The NS activity after the explosion:

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

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

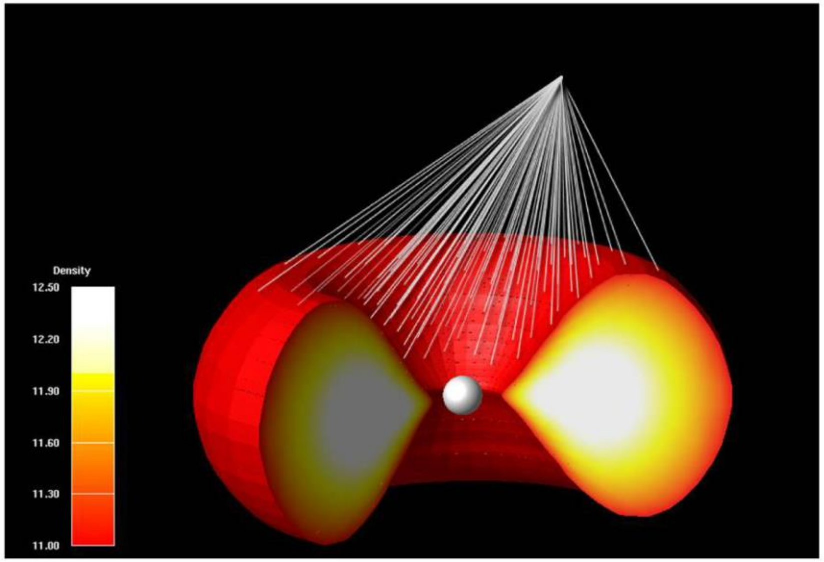
$$E_{\rm e}^{\rm max} \simeq 100\, t_7 B_{\rm NS,15}^{1/2} v_{\rm ej,9}^{1/2}\ {\rm TeV}$$

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

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

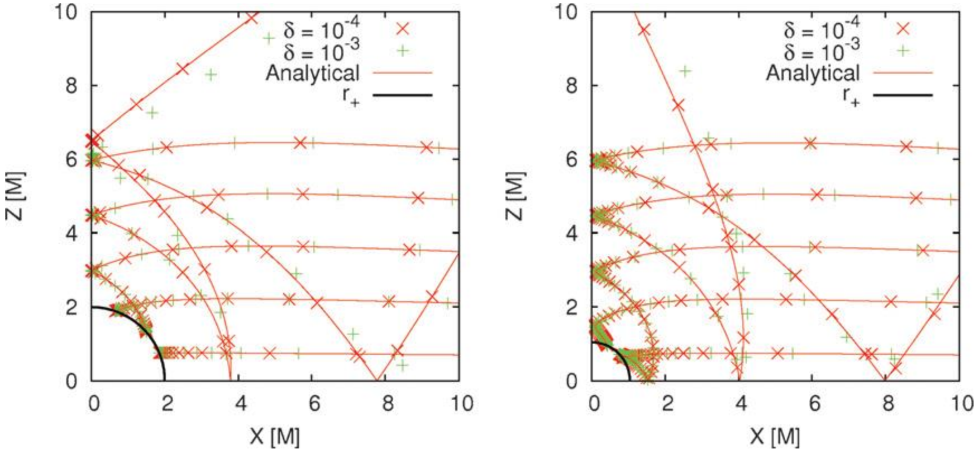
Such an emission can be detected at distances about 10 Mpc.

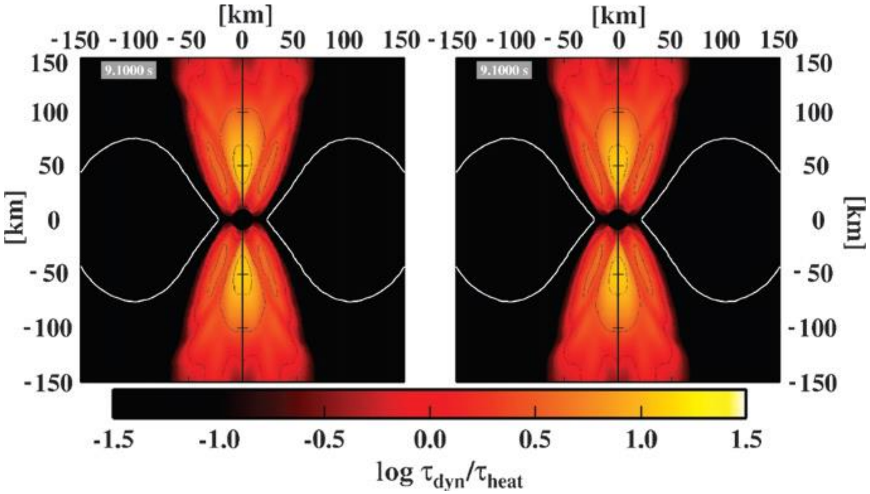
Neutrino heating



$$\nu + \bar{\nu} \rightarrow e^- + e^+$$

$$Q^{\mathrm{L}}_{\mu}(\boldsymbol{r}) = 2KG_{\mathrm{F}}^2 \int d^3\boldsymbol{p}^{\mathrm{L}}_{\nu} d^3\boldsymbol{p}^{\mathrm{L}}_{\bar{\nu}} \times (\epsilon^{\mathrm{L}}_{\nu}\epsilon^{\mathrm{L}}_{\bar{\nu}})(\boldsymbol{p}^{\mathrm{L}}_{\nu} + \boldsymbol{p}^{\mathrm{L}}_{\bar{\nu}})_{\mu} f^{\mathrm{L}}_{\nu}(\boldsymbol{p}^{\mathrm{L}}_{\nu}, \boldsymbol{r}) f^{\mathrm{L}}_{\bar{\nu}}(\boldsymbol{p}^{\mathrm{L}}_{\bar{\nu}}, \boldsymbol{r}) \times [1 - \sin\theta_{\nu}\sin\theta_{\bar{\nu}}\cos(\varphi_{\nu} - \varphi_{\bar{\nu}}) - \cos\theta_{\nu}\cos\theta_{\bar{\nu}}]^2$$





Harikae et al 2010

Free fall model of collapsing star (Bethe, 1990)

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

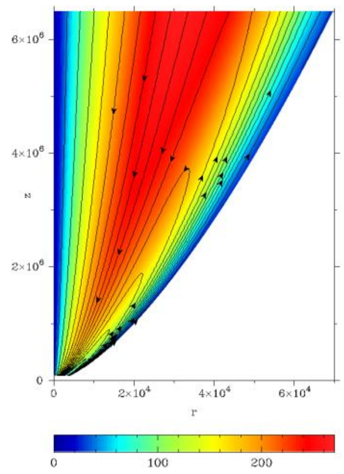
mass density: $\rho = C_1 \times 10^7 \left(\frac{t}{1s}\right)^{-1} \left(\frac{r}{100km}\right)^{-3/2} \mathrm{g/cm}^3$

accretion rate: $\dot{M} = 0.1C_1\left(\frac{t}{1s}\right)^{-1}\left(\frac{M}{10M_{sun}}\right)^{1/2} M_{sun}s^{-1}$

Gravity: gravitational field of Black Hole only (Kerr metric);
no self-gravity;

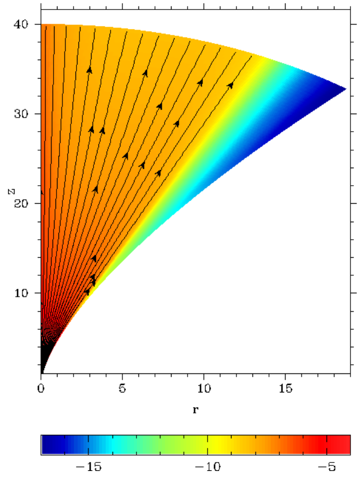
Microphysics: neutrino cooling ;
realistic equation of state, (HELM, Timmes & Swesty, 2000);
dissociation of nuclei (Ardeljan et al., 2005);
Ideal Relativistic MHD - no physical resistivity (only numerical);

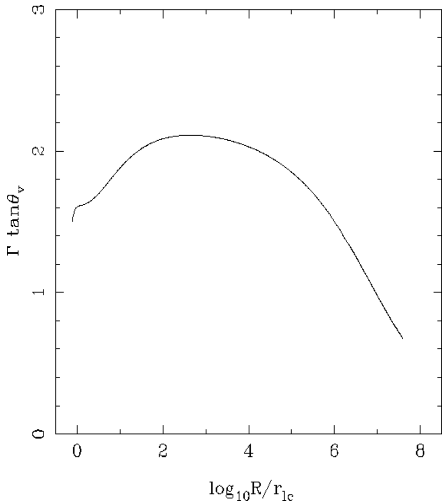
GRBs Jet magnetic acceleration:

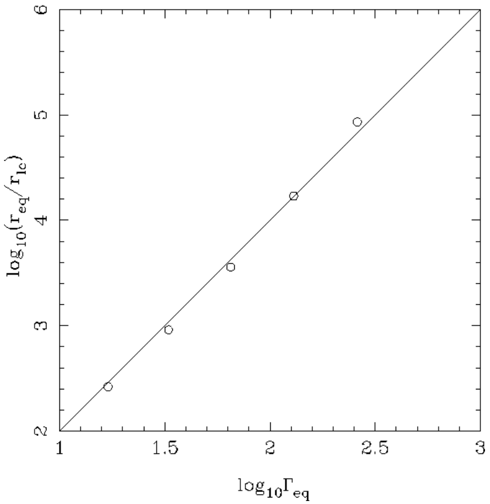


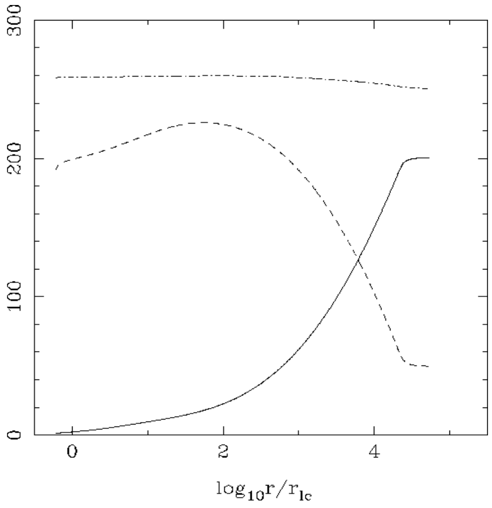
- We get MHD acceleration of relativistic jet up to $\Gamma \approx 300$
- Conversion of magnetic energy to kinetic one more than 50%
- Acceleration have place on long distance $r_{eq} \approx \Gamma^2 r_{lc}$
- The main part of the jet is very narrow $\Gamma\theta < 2$

(Komissarov et al 2009)









Summary:

- Jets are formed when BH accumulates sufficient magnetic flux.
- Jets power $0.4 \div 13 \times 10^{51}\, erg\; s^{-1}$
- Total energy of BH $\simeq 8 \times 10^{53}\text{erg}$
- Expected burst duration $> 1\text{s}$ (?)
- Jet advance speed $V_s \approx 0.1 \div 0.5\, c$
- Expected jet break out time $\simeq 4\text{s}\ (r_* \simeq 2 \times 10^5\text{km})$
- Jet flow speed $\Gamma_j \lesssim 3$ (method limitation)
- Jets are powered by the Blandford-Znajek mechanism

Good news for the collapsar model of long duration GRBs !