Toward Understanding the Central Engine of Long GRBs

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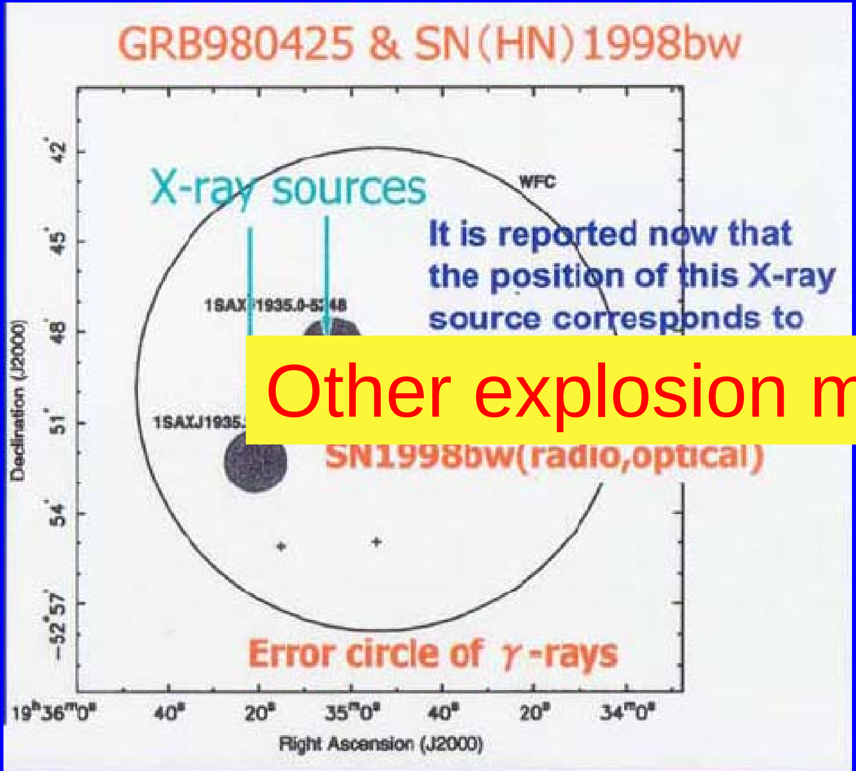
§ Introduction

Some GRBs are Accompanied by Hypernovae



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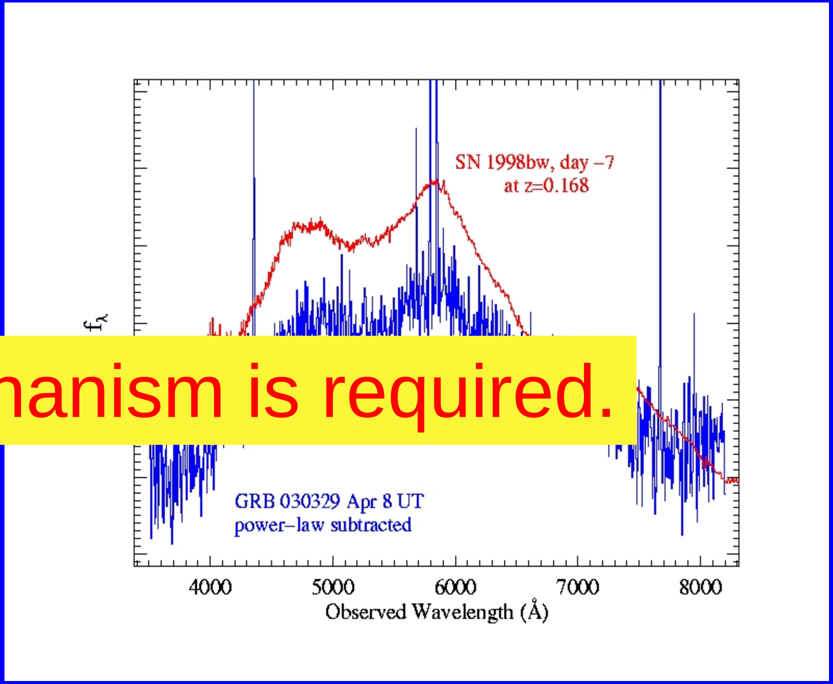


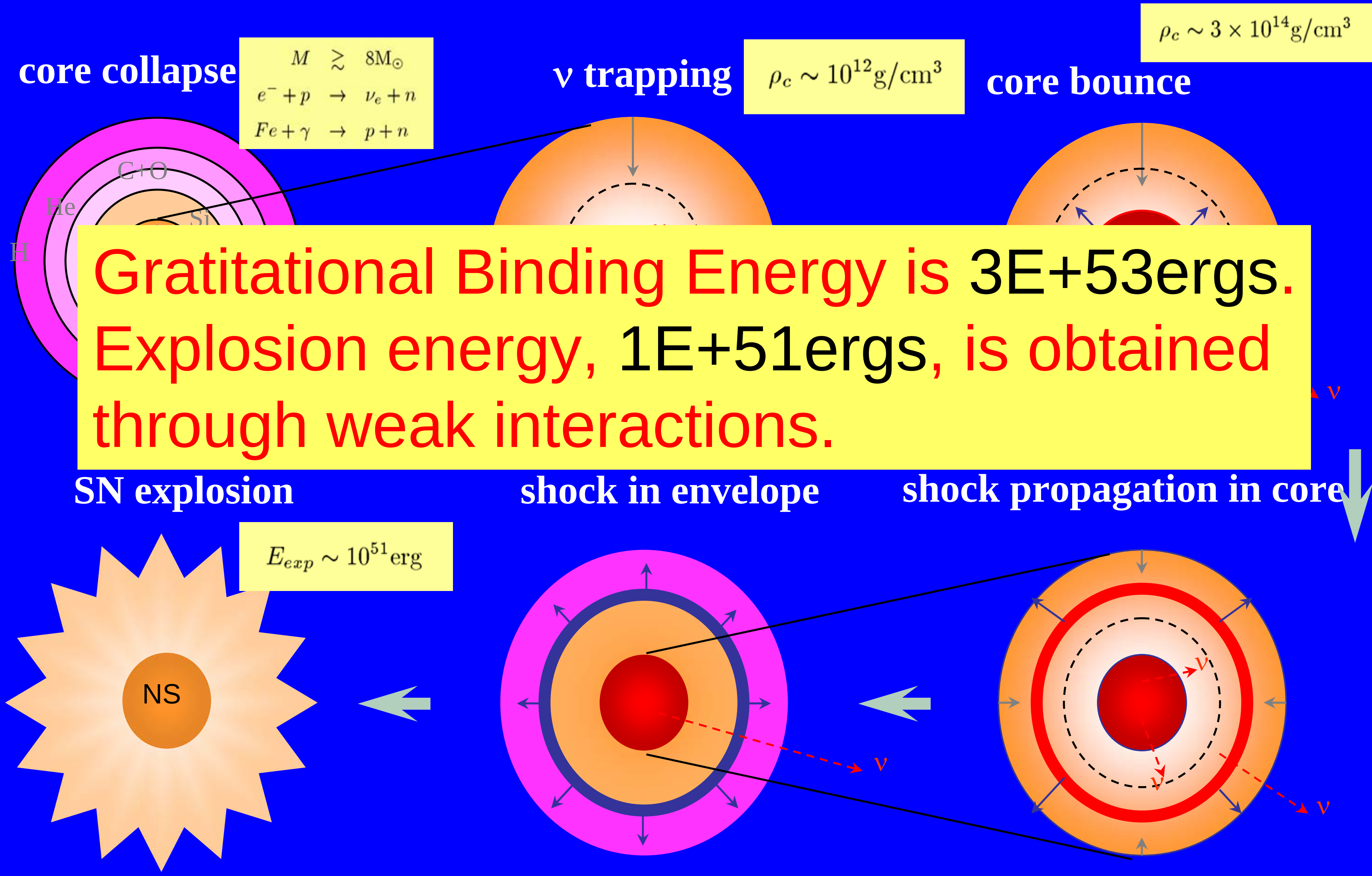
GRB030329/SN2003dh

Other explosion mechanism is required.

Explosion energy of a hypernova is estimated to be ~1E+52ergs, which cannot be explained by the standard scenario of a normal collapse-driven supernova.

Scenario of Normal Collapse-driven Supernovae

Figure: S.Yamada



core collapse

$$\begin{aligned} M &\gtrsim 8\mathrm{M}_\odot \\ e^- + p &\rightarrow \nu_e + n \\ Fe + \gamma &\rightarrow p + n \end{aligned}$$

ν trapping

$\rho_c \sim 10^{12}\mathrm{g/cm^3}$

core bounce

$\rho_c \sim 3 \times 10^{14}\mathrm{g/cm^3}$

SN explosion

$E_{exp} \sim 10^{51}\mathrm{erg}$

shock in envelope

shock propagation in core

Gratitational Binding Energy is 3E+53ergs. Explosion energy, 1E+51ergs, is obtained through weak interactions.

Promising candidates for the energy scales

$$E_{pot} \sim \frac{G M_{BH} M_{acc}}{r_H} \sim \frac{G M_{BH} M_{acc}}{\frac{G M_{BH}}{c^2}}$$

$$\sim M_{acc} c^2 = 2 \times 10^{54} \left(\frac{M_{acc}}{1 M_\odot} \right) [\mathrm{erg}]$$

(a) Gravitational Binding Energy of Accreted Matter onto a central BH. Duration is ~ 10sec.

MacFadyen and Woosley (1999)

$$E_{rot} = f(a) M_{BH} c^2 \le f(a=1) M_{BH} c^2$$

$$= 1.6 \times 10^{54} \left(\frac{M_{BH}}{3 M_\odot} \right) [\mathrm{erg}]$$

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

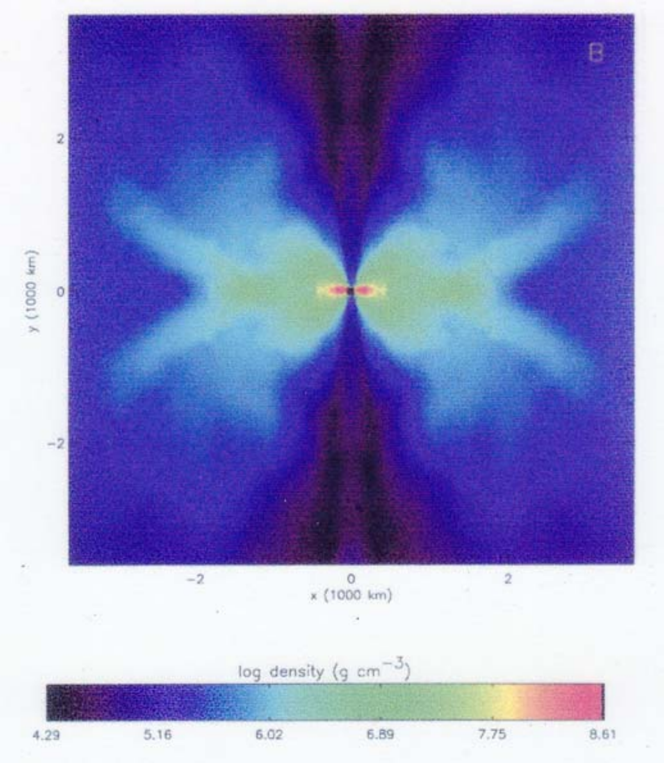
$$a = \frac{Jc}{GM^2} \le 1$$

(b) Rotation Energy of a central BH (magnetar). Duration is ~ (1-10) sec? Blandford-Znajek Process

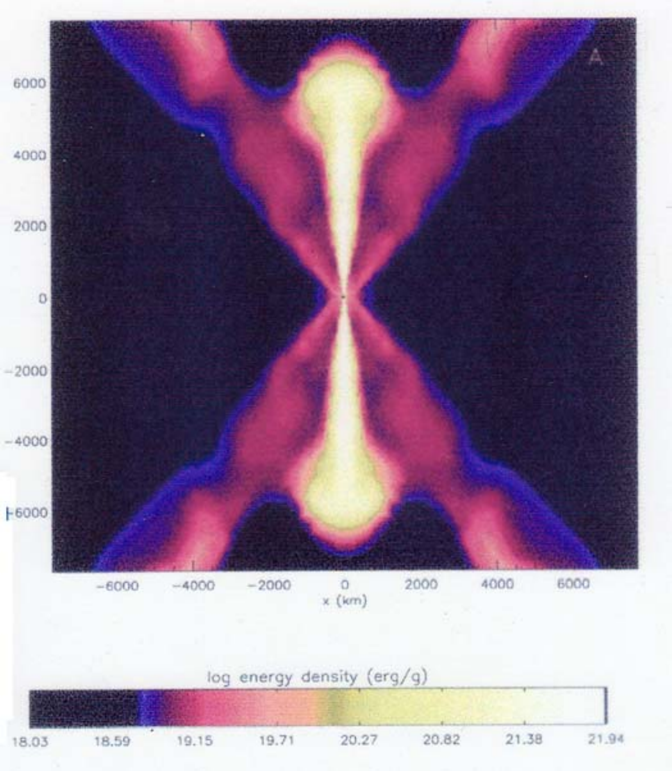
(a) Gravitational Potential Energy

MacFadyen and Woosley (1998)

Jet off



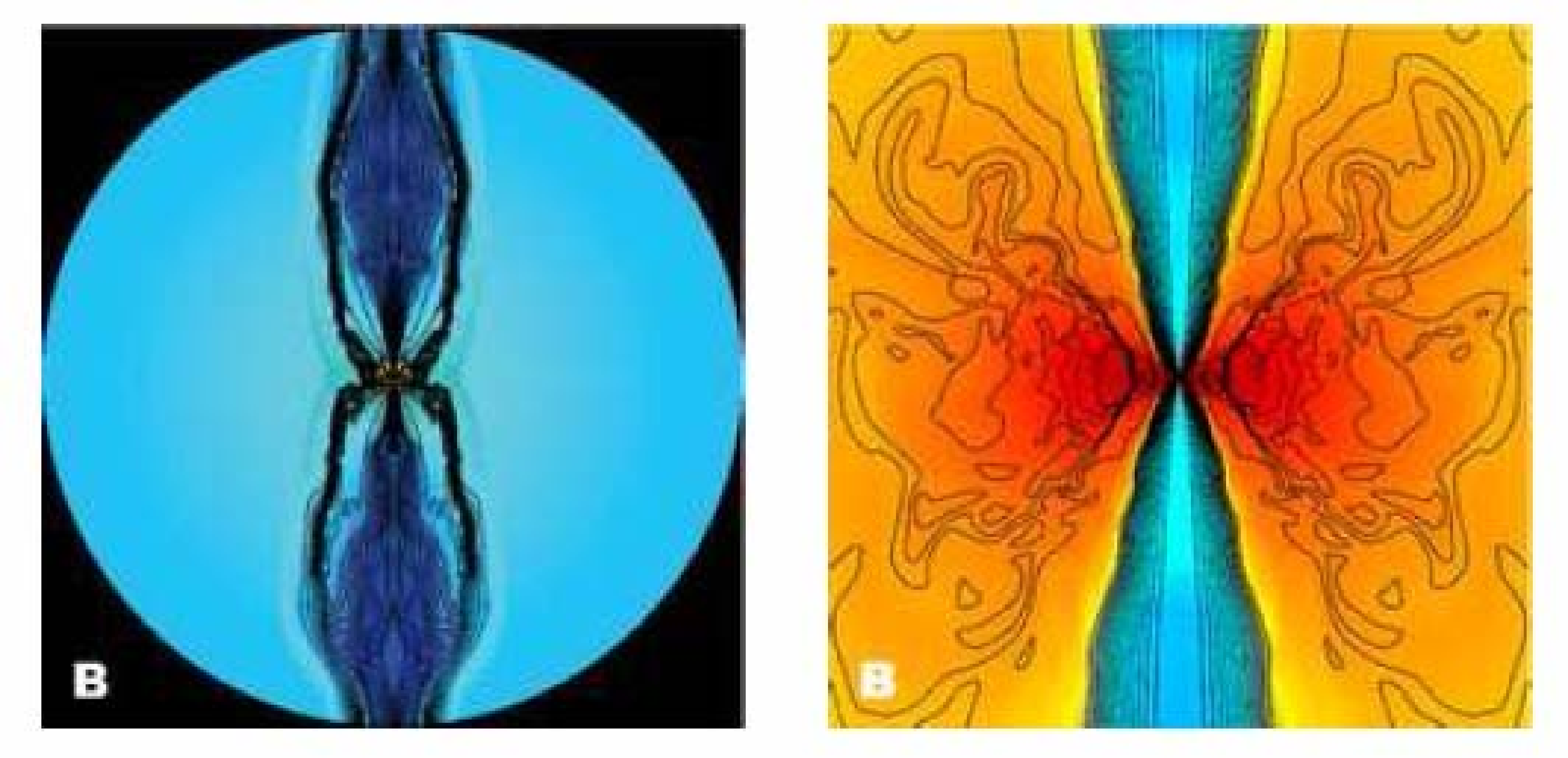
Jet on



BH with 3solar mass is put at the center as an initial condition.
Rotation is introduced so that the model mimics Heger et al. (00).
Thermal energy is deposited at the inner most region, which might be realized when effect of neutrino annihilation is included. Newtonian gravity.
Magnetic Fields are not included. Inner most boundary is set to be 50km.

(b) Rotation Energy of a Central BH

McKinney 05



Blandford-Znajek Process can be seen in numerical simulations.

§ (a) Gravitational Binding Energy (collapsar model)

Input Physics

- Progenitor: Model E25 in Heger et al. (2000) that is modified so that inner most core has collapsed to form a BH with 1.7Mo.
- 2-D Ideal MHD $(r,\theta)=(150,30)$ is solved by ZEUS code.
- Initial rotation is same with MacFadyen and Woosley (1999).
- Realistic EOS (Blinnikov et al. 1996).
- Photo-disintegration (N, P, He, O, Ni).
- Newton Gravity （Including self gravity; MBH =1.7Mo）.
- Neutrino Cooling (Leakage scheme).
- Neutrino Heating (optically-thin limit).
- Magnetic Field （Vertical + Dipole field: ON・ OFF）.

Neutrino Processes (1)

Cooling Process

Locally Determined

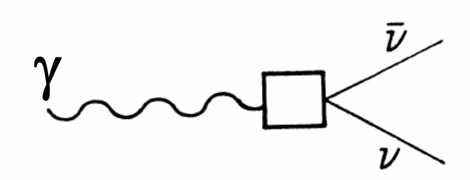
Electron and positron Capture on free nucleons
(Epstein and Pethick 1981)

$$\begin{cases} p + e^- \rightarrow n + \nu_e \\ n + e^+ \rightarrow p + \bar{\nu}_e \end{cases}$$

Pair annihilations
(Itoh et al. 1999)

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

Plasmon decays
(Itoh et al. 1989)



Heating Process

Globally Determined

Electron-type neutrino capture on free nucleons
(Epstein and Pethick 1981)

$$\begin{cases} n + \nu_e \rightarrow p + e^- \\ p + \bar{\nu}_e \rightarrow n + e^+ \end{cases}$$

Neutrino pair annihilations
(Goodman et al. 1987)

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

Neutrino Processes (2)

Example of Heating Processes: Neutrino Pair Annihilation

$$\dot{Q}(C) = \frac{KG_F^2}{2\pi c}\int\int dx_A^3 dx_B^3 \frac{(1-\cos\psi)^2}{d_A^2 d_B^2}\int\int d\epsilon_\nu d\epsilon_{\bar{\nu}}\epsilon_\nu\epsilon_{\bar{\nu}}(\epsilon_\nu+\epsilon_{\bar{\nu}})F_\nu F_{\bar{\nu}}(1-f_e^-)(1-f_e^+)$$

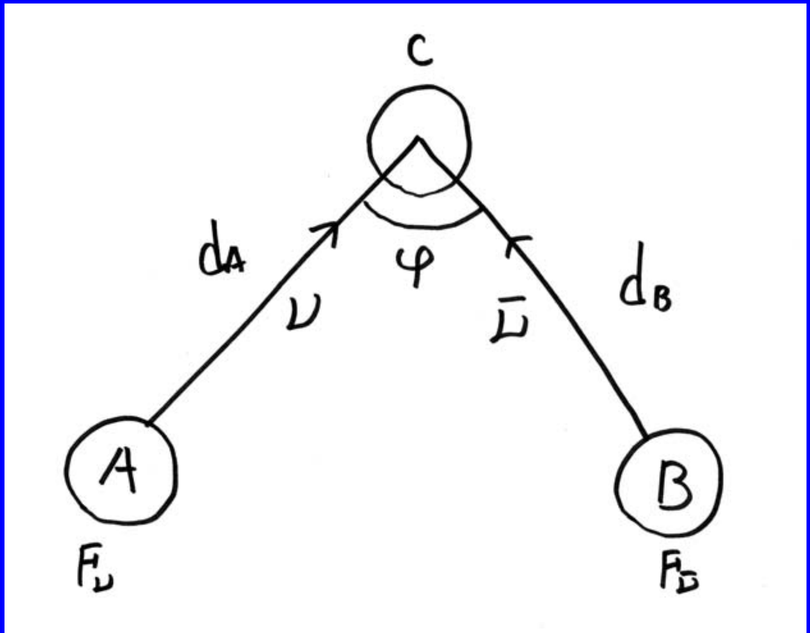
[erg/cc/s]

K is $(1-4\sin^2\theta_W+8\sin^4\theta_W)/(6\pi)$ for $\nu_\mu\nu_{\bar{\mu}}$ and $\nu_\tau\nu_{\bar{\tau}}$ annihilations

$(1+4\sin^2\theta_W+8\sin^4\theta_W)/(6\pi)$ for $\nu_e\nu_{\bar{e}}$ annihilation

$F_{\nu,\bar{\nu}}$ are energy spectrum [cm^{-3} s^{-1} GeV^{-1}] of (anti-)neutrinos

$f_e^\pm$ are fermi bloking factors of electrons/positrons at point C.



8 dimensional integration!

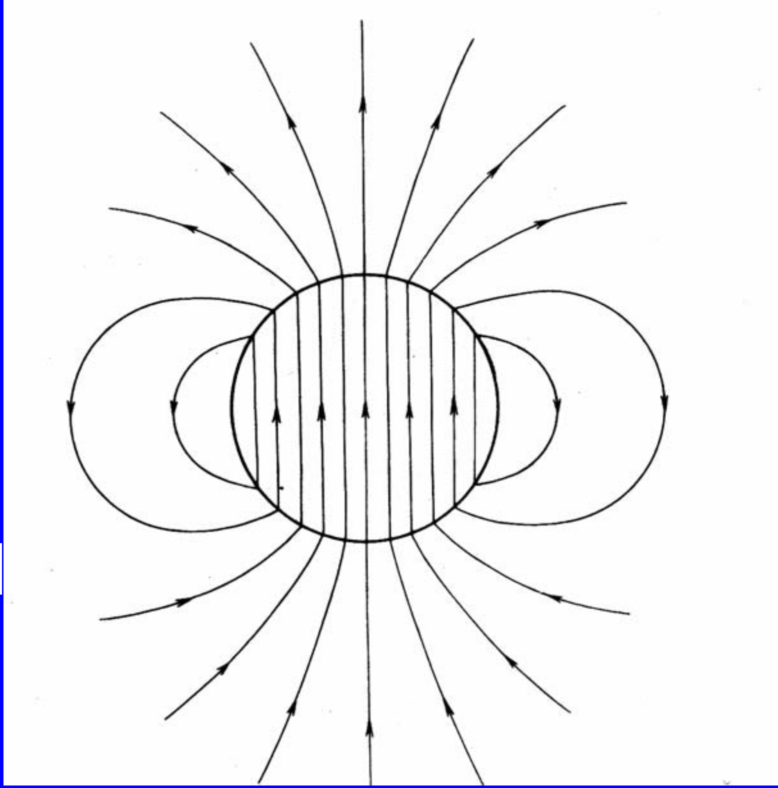
↓

Energies of neutrinos are represented by typical ones for each process (Rosswog et al., Itoh et al.).
Heating rates are updated every 100 time Steps (cf. total timestep is ~1E+6 steps).

Magnetic Fields

Initial Condition

$$\vec{B}(\vec{r}) = \frac{1}{3}B_0\left(\frac{r_0}{r}\right)^3(2\cos\theta\vec{e_r} + \sin\theta\vec{e_\theta}) \quad \text{for } \mathrm{r} \geq \mathrm{r_0}$$
$$= \frac{2}{3}B_0(\cos\theta\vec{e_r} - \sin\theta\vec{e_\theta}) \quad \text{for } \mathrm{r} < \mathrm{r_0}.$$



We set r_0 to be the boundary between CO core/He layer ($= 3.6 \times 10^9$ cm)

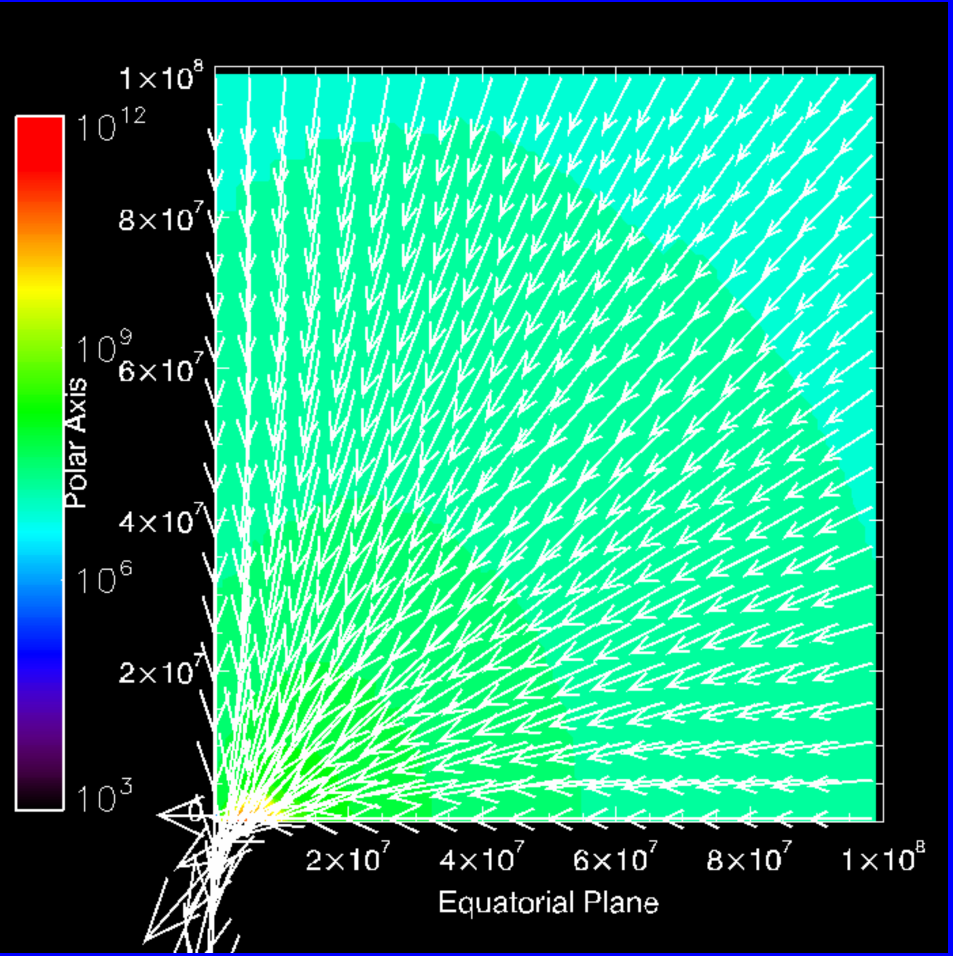
B_0 corresponds to the strength of the magnetic field in the sphere.

We set B0 to be 0, 1E+8, 1E+9, 1E+10, 1E+11, and 1E+12G

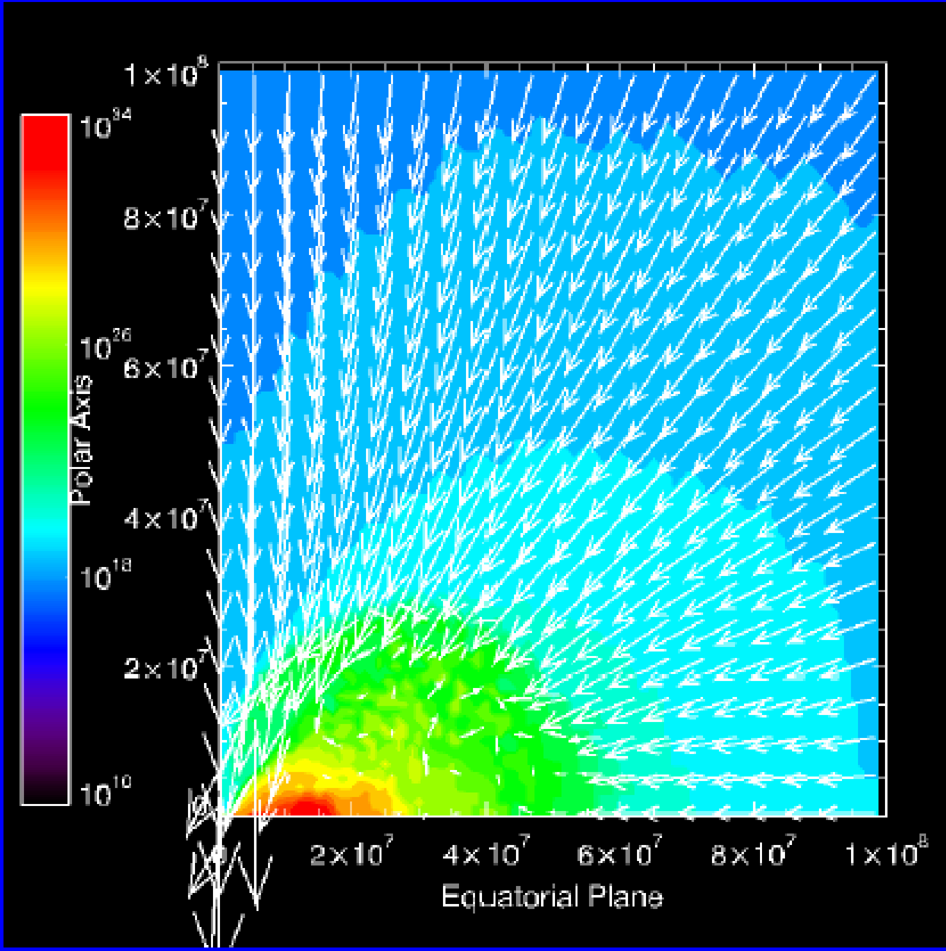
Initial |Em/W| are 0, 1.1E-8, 1.1E-6, 1.1E-4, 1.1E-2, and 1.1.
Initial |T/W| is 1.3E-2.

§ Result s of collapsar model

Simulation with no B-Field



Density contour with velocity fields, Final time is 4.8sec.

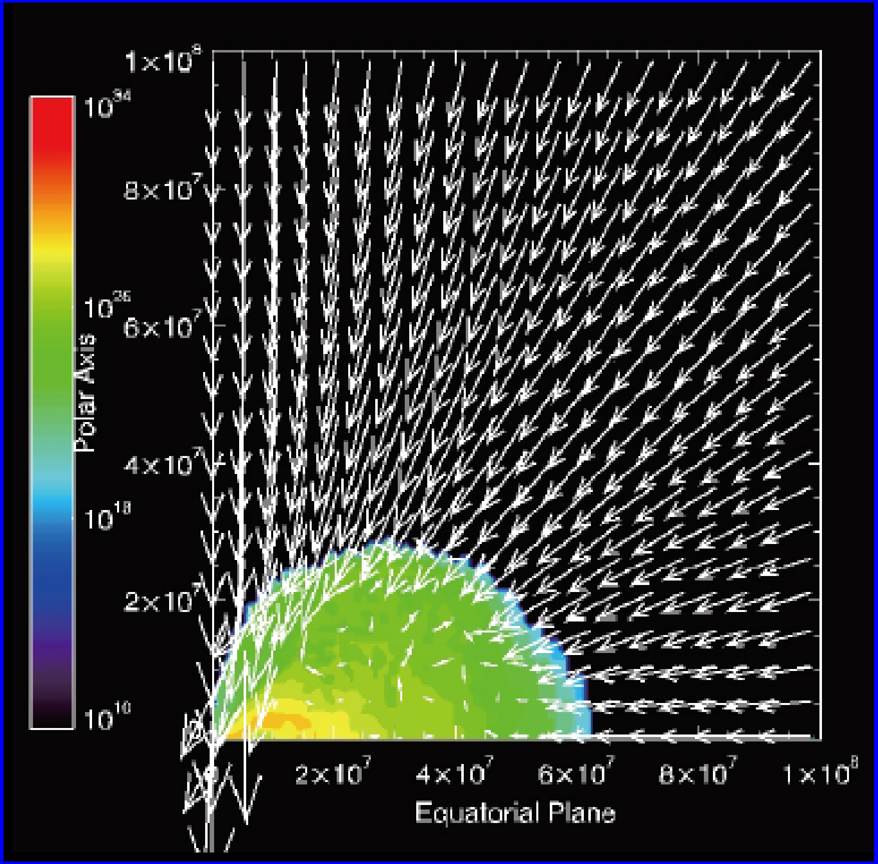


Neutrino cooling Rate [erg/s/cc] at t = 2.2 sec. The rate correlates with Nucleon density.

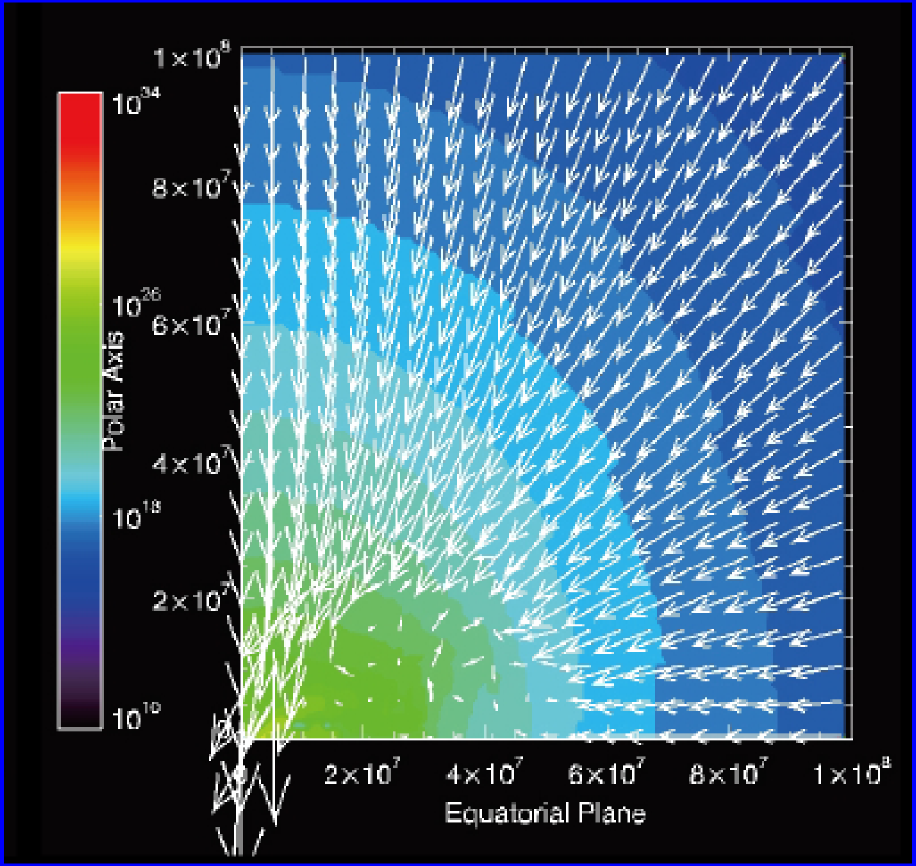
Neutrino Heating Processes

Energy is absorbed at the accretion disk

Energy is deposited globally, but
With low efficiency

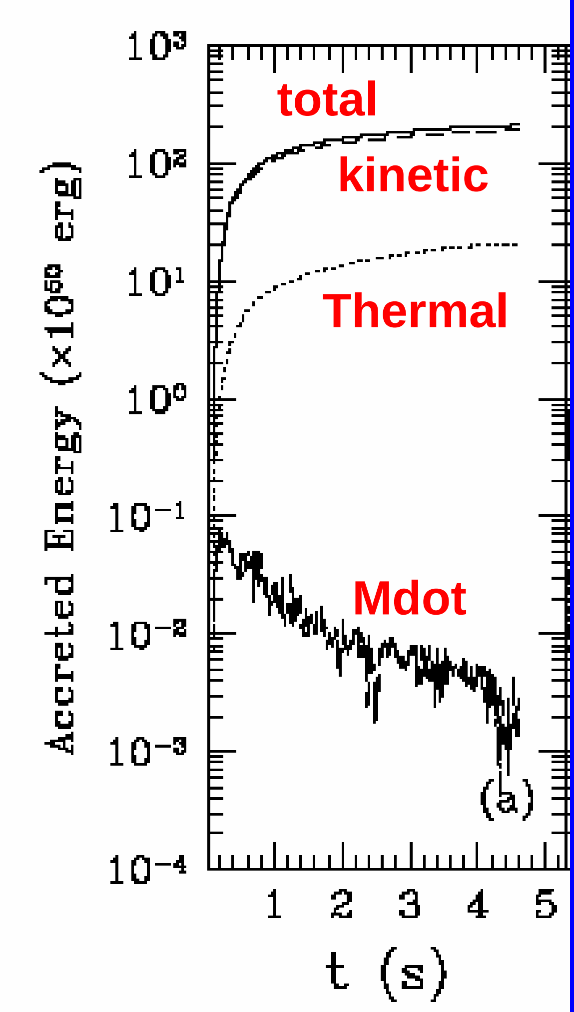


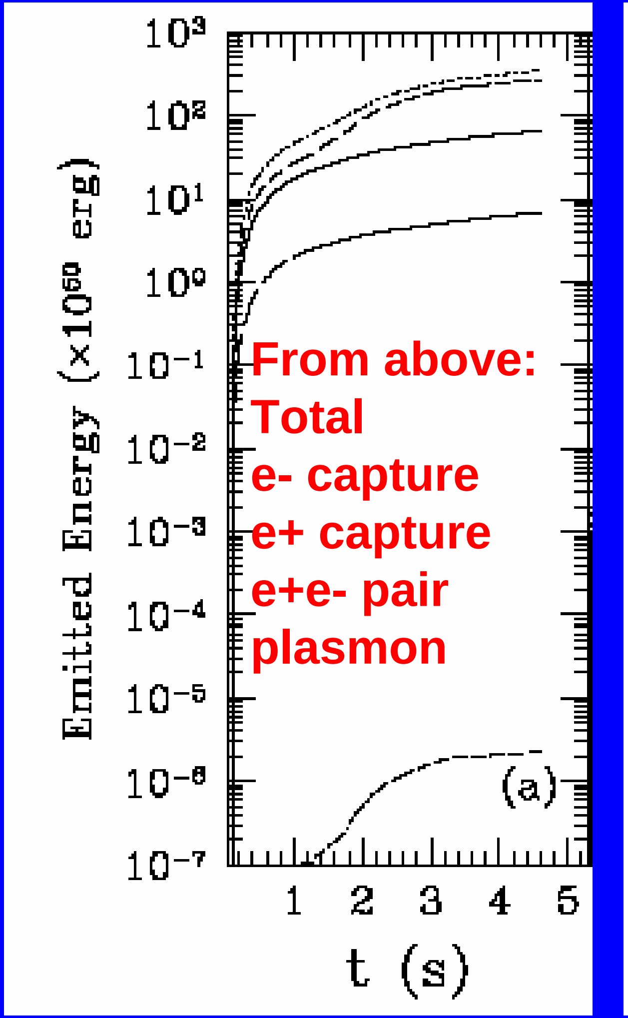
Energy Deposition Rate [erg/s/cc]
By neutrino absorption on free nucleons
At t = 2.2 sec. The rate correlates with
Nucleon density.

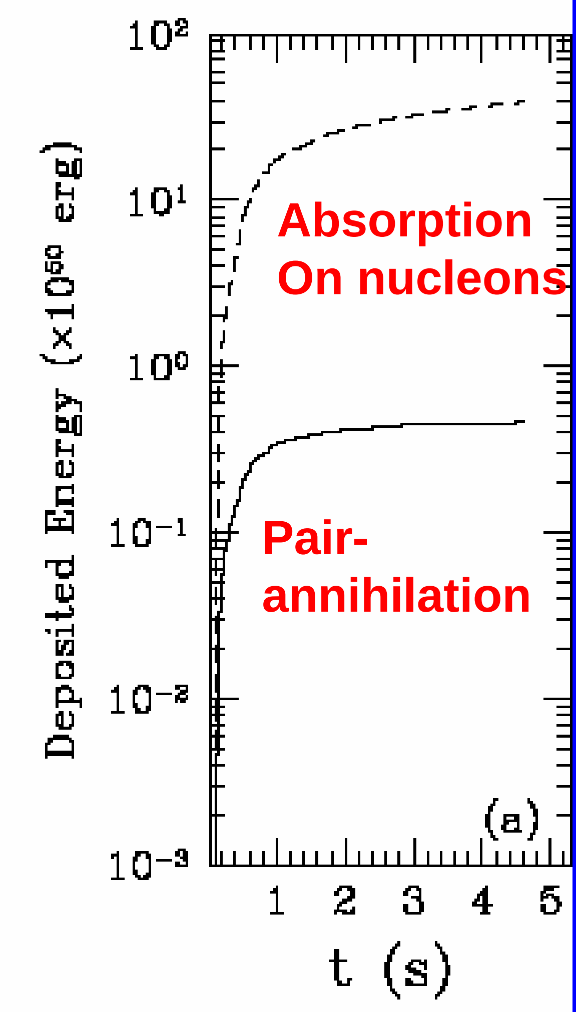


Energy Deposition Rate [erg/s/cc]
By neutrino pair annihilation
at t = 2.2 sec.

Energetics



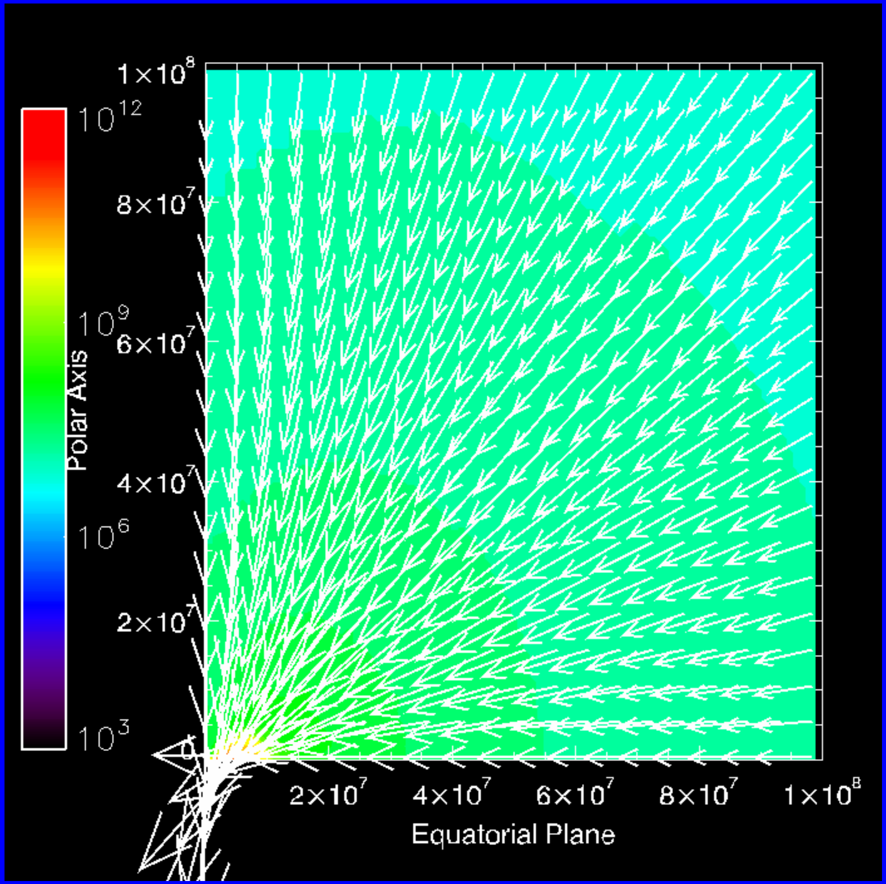


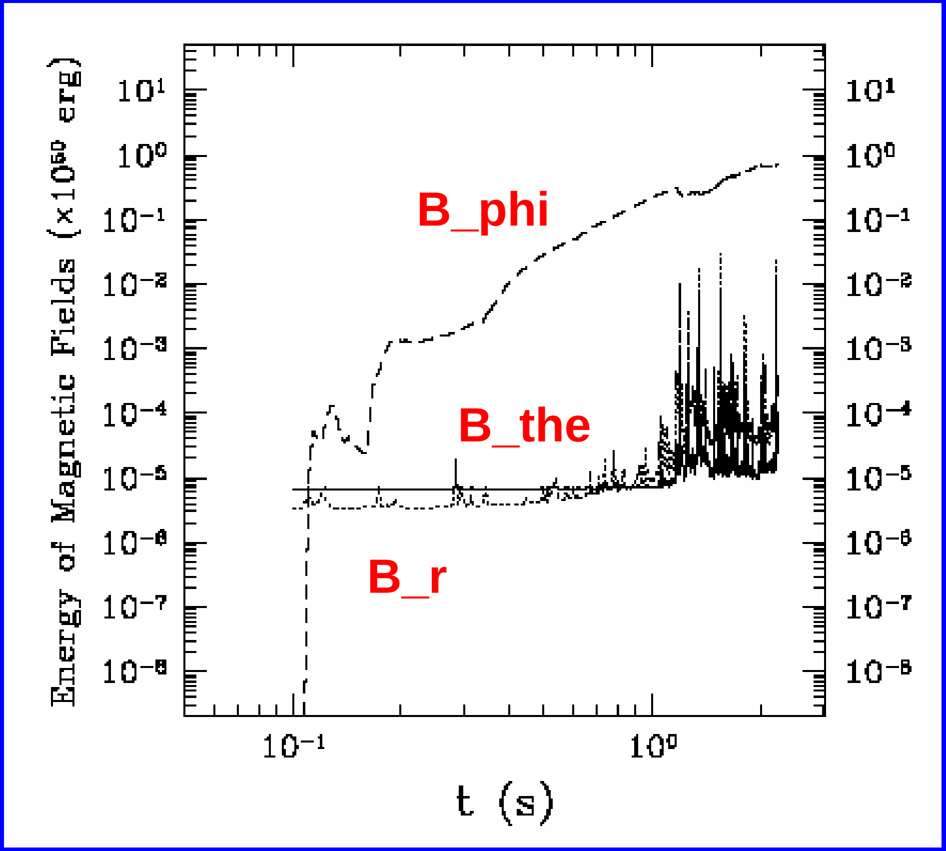


After the shock passage, the released energy was shared by kinetic and thermal Energy almost equally (～1E+52erg). Most of thermal energy was lost by neutrino Cooling. About 10% was absorbed at the accretion disk (～1E+51erg). Efficiency Of neutrino pair annihilarion is as low as 0.1% (～1E+49erg).

Simulations with Magnetic Fields

Initial B=10^9 G





Density contour
Final time is 2.2sec.

Jet is launched by B_phi, which is amplified by winding-up effect.

Can the Jet be a GRB?

Mass, total energy, and terminal bulk lorentz factor of the jet (within 10 degrees, positive total energy, and high velocity(=5E+9cm/s)) as a function of the initial amplitude of magnetic fields.

Initial B	B=1E+10G	B=1E+11 G	B=1E+12G
Mass	2.1E-8Msolar	1.2E-5Msolar	1.5E-4Msolar
Total Energy **(without rest mass)**	9.1E+45erg	1.2E+48erg	1.8E+49erg
Lorentz Factor	1.08	1.05	1.07

These jets can not be GRB jets.

M_J seems to increase with B_0, since the jet is launched earlier for larger Bo.

Simulation for longer physical time is required?

→ At least, special relativistic MHD is required.

§ (b) Rotation Energy of a Central BH (BZ-Process Model)

§ Formulation of General Relativistic Magneto-Hydrodynamic Code

(GRMHD Code)

Gammie, McKinney, Toth 03

Basic Equations

$$\frac{1}{\sqrt{-g}}\partial_\mu\left(\sqrt{-g}\,\rho u^\mu\right) = 0$$

$$\partial_t\left(\sqrt{-g}\,T^t_\nu\right) = -\partial_i\left(\sqrt{-g}\,T^i_\nu\right) + \sqrt{-g}\,T^\kappa_\lambda \Gamma^\lambda{}_{\nu\kappa},$$

$$\partial_t\left(\sqrt{-g}\,B^i\right) = -\partial_j\left[\sqrt{-g}\left(b^j u^i - b^i u^j\right)\right]$$

Additional Equations

$$\frac{1}{\sqrt{-g}}\partial_i\left(\sqrt{-g}\,B^i\right) = 0\,,$$

(Constrained Transport)

$$p = (\gamma - 1)u.$$

Solver

$$\partial_t \boldsymbol{U}(\boldsymbol{P}) = -\partial_i \boldsymbol{F}^i(\boldsymbol{P}) + \boldsymbol{S}(\boldsymbol{P}),$$

$$\boldsymbol{U} \equiv \sqrt{-g}\left(\rho u^t, T^t_t, T^t_i, B^i\right)$$

Conserved Variables

↓ Newton-Raphson Method

$$\boldsymbol{P} = \left(\rho, u, v^i, B^i\right)$$

Primitive Variables

Flux term (HLL Method)

$$\boldsymbol{F} = \frac{c_{\min}\boldsymbol{F}_R + c_{\max}\boldsymbol{F}_L - c_{\max}c_{\min}(\boldsymbol{U}_R - \boldsymbol{U}_L)}{c_{\max} + c_{\min}}$$

$$c_{\max} \equiv \max(0,\ c_{+,R}, c_{+,L})$$

$$c_{\min} \equiv -\min(0,\ c_{-,R}, c_{-,L})$$

Slope (2nd order in Space, 3rd in time)

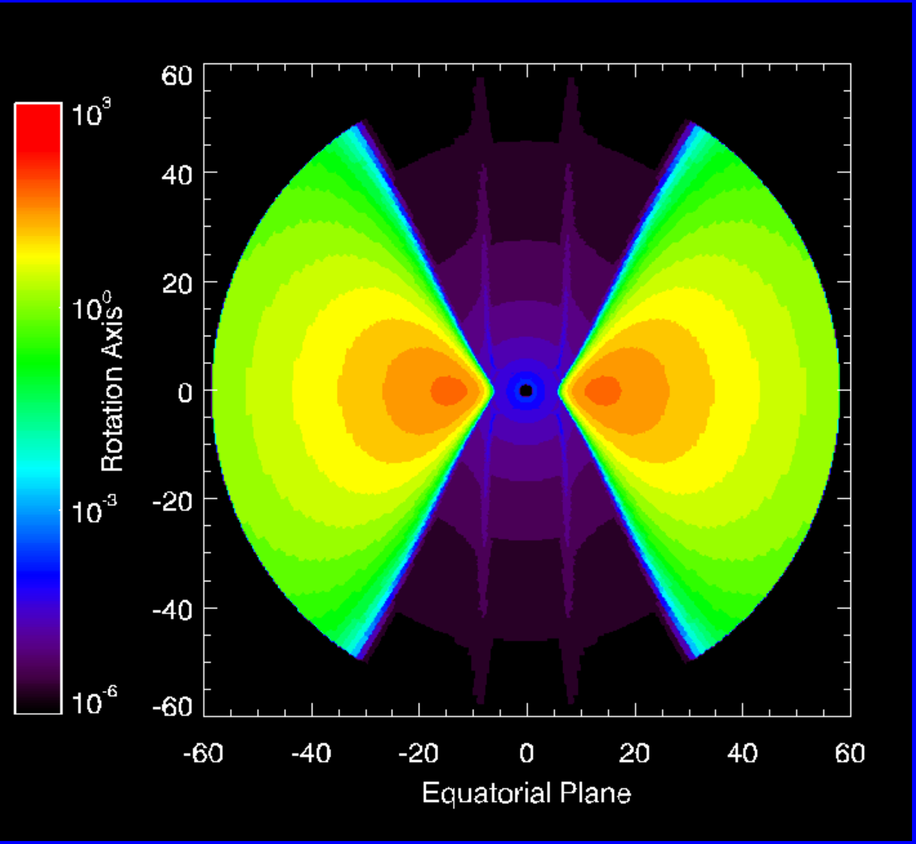
Mimmod or Monotonized Center

TVD Runge-Kutta

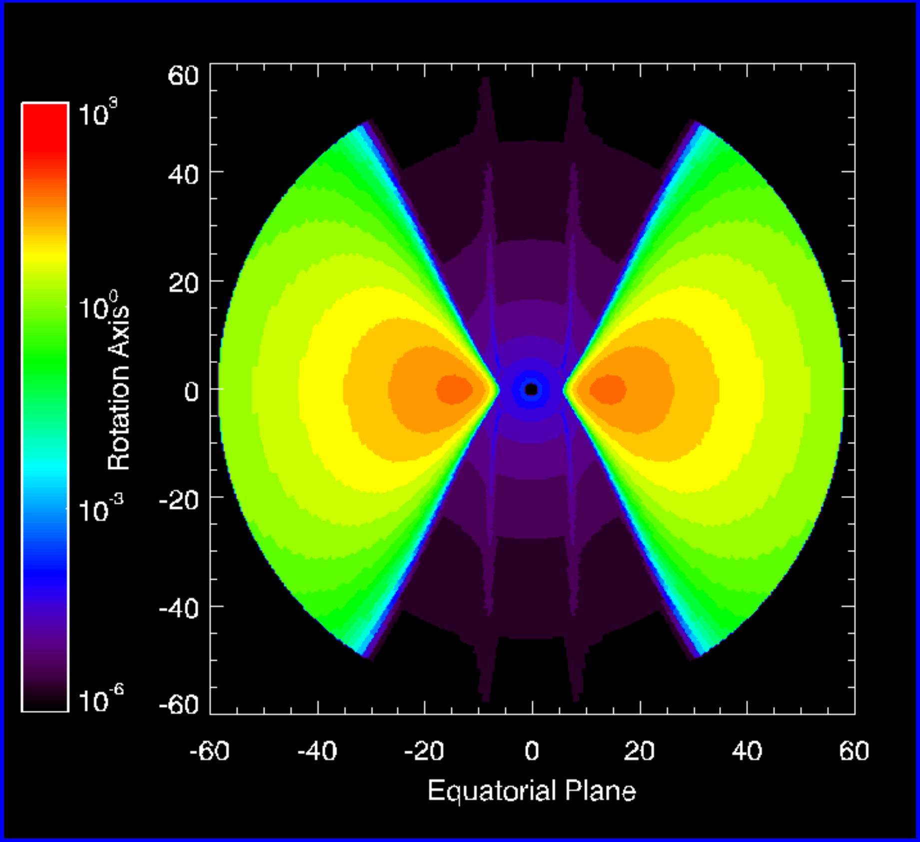
§ Results of GRMHD Simulation

Fishbone and Moncrief's Problem

$u_\varphi u^t \ (= l)$ constant a=0.938, no-magnetic field N×N=150×150



T = 0



T = 1200

G=c=M=1

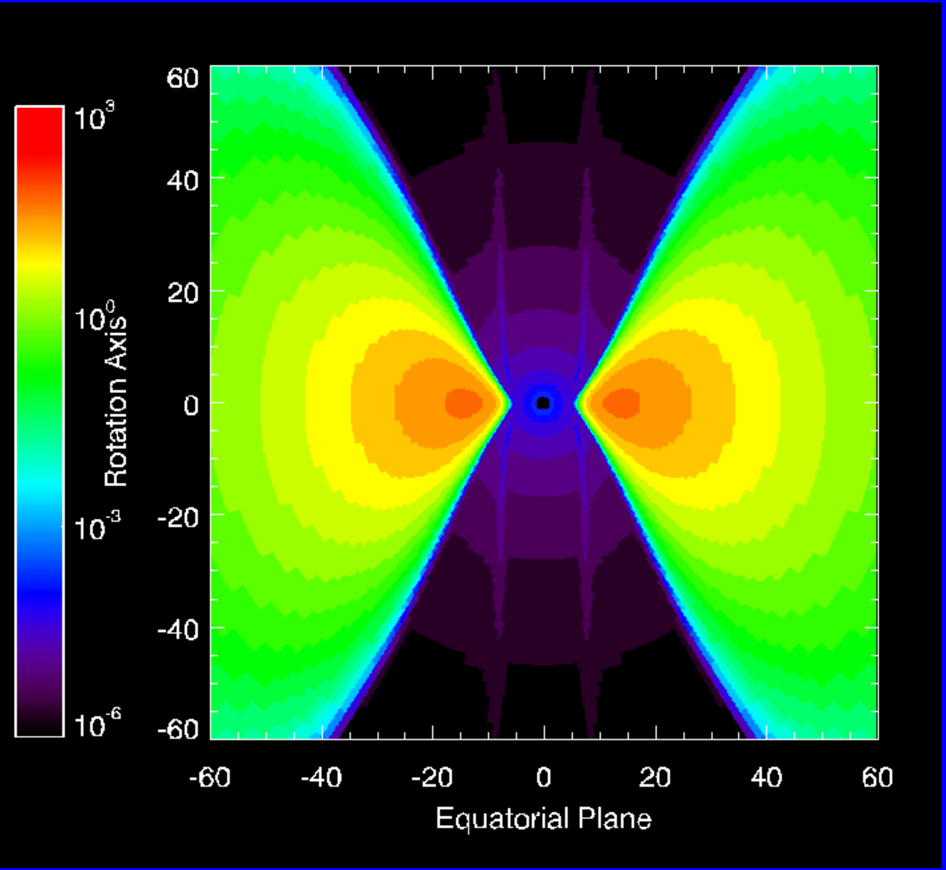
c.f. e.g. McKinney and Gammie 2004, McKinney 2006

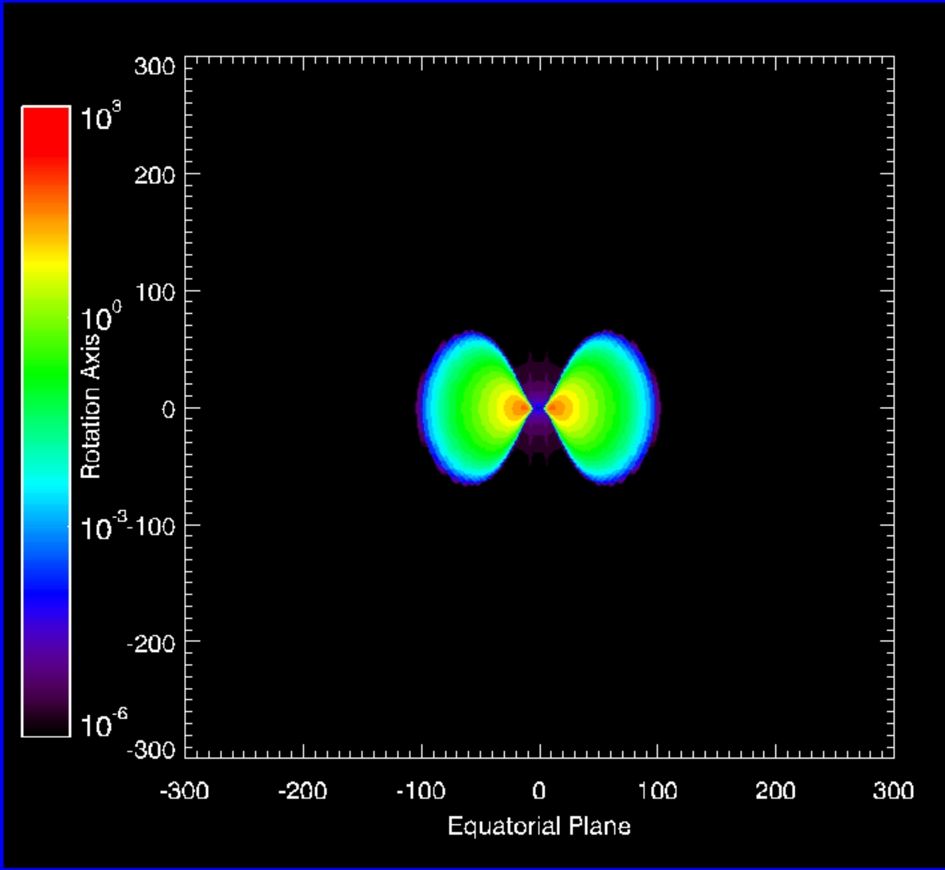
Fishbone and Moncrief's Problem (cont'd)

Beta_min=100

a=0.938, with-magnetic field $A_\phi \propto \max(\rho/\rho_{\max} - 0.2,\ 0)$

N×N=150×150





R < 60

T=1200

R < 300

G=c=M=1

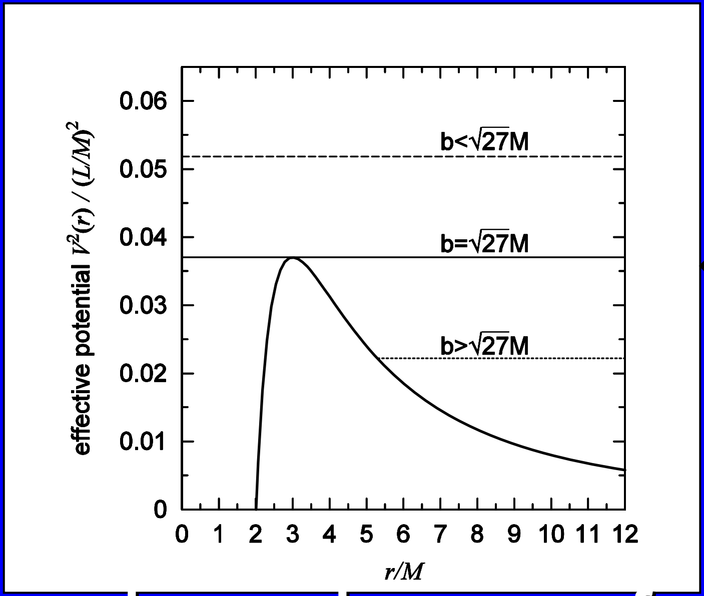
c.f. e.g. McKinney and Gammie 2004, McKinney 2006

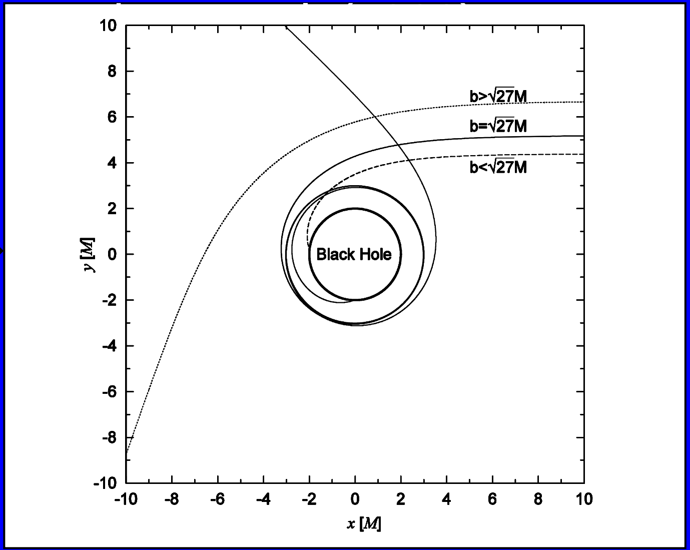
- **Discussion**

Effects of Neutrino Pair Annihilation with **General Relativity**

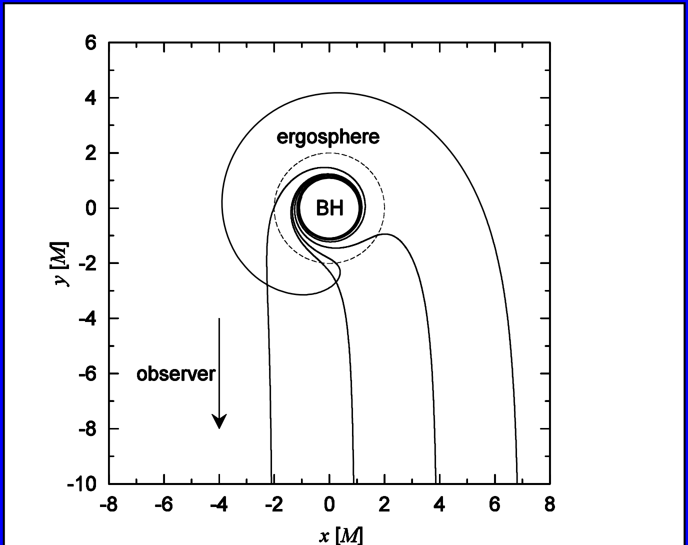
R. Takahashi and S.N. (200 7) in prep.
c.f. e.g

Effective Poten





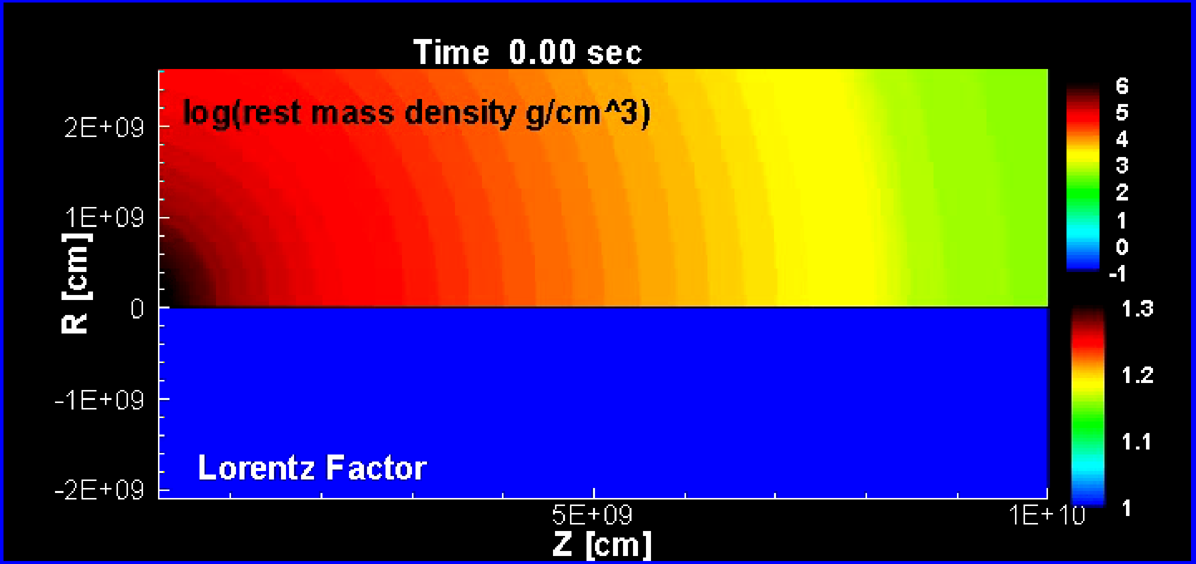
Geodesic of Neutrinos



Disk structure is also changed.

Properties of the Central Engine will be constrained by simulations of propagation of the Jet.

Mizuta, Yamasaki, S.N., Mineshige ApJ 651 960 (2006)

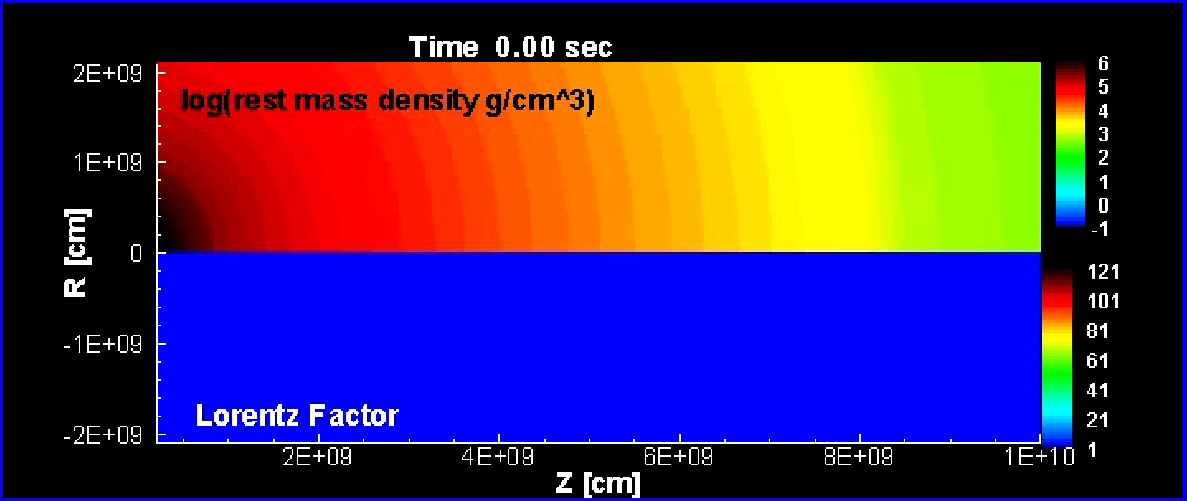


$\Gamma_0 = 1.15$

$\varepsilon_0/c^2=0.1$

Mildly Relativistic Jet

Related with X-ray flash?



$\Gamma_0 = 5$

$\varepsilon_0/c^2=30$

Highly relativistic Jet. Related with GRB?

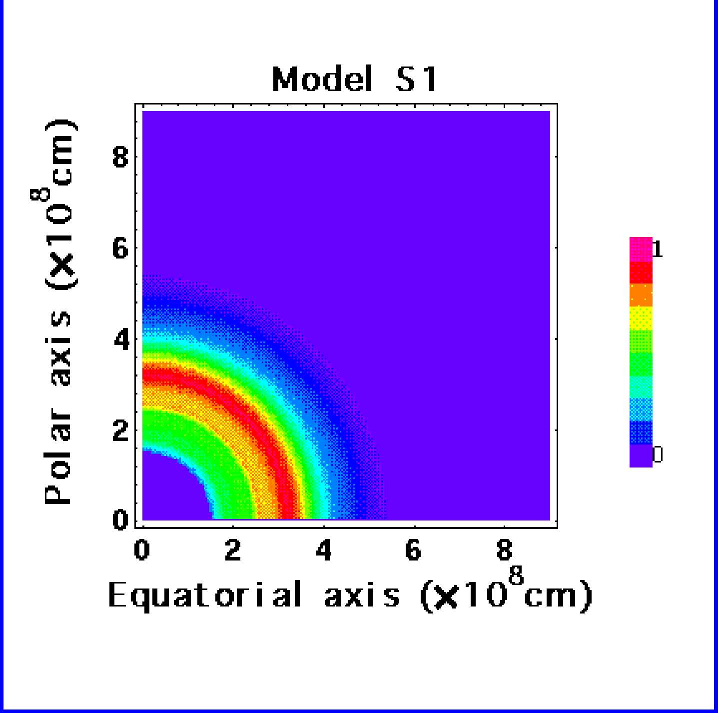
§ Brief Comments on Explosive Nucleosynthesis in a GRB (Hypernova)

Results of Explosive Nucleosynthesis including effects of Bi-polar explosion applied for SN1987A

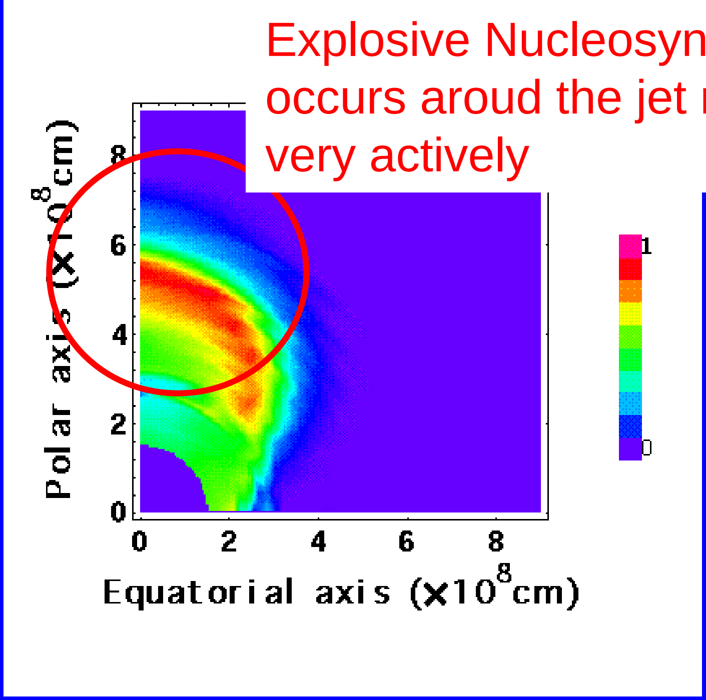
Mass Fraction of ^{56}Ni

S.N. et al. 97, S.N. 00

Spherical Explosion



Jet like Explosion



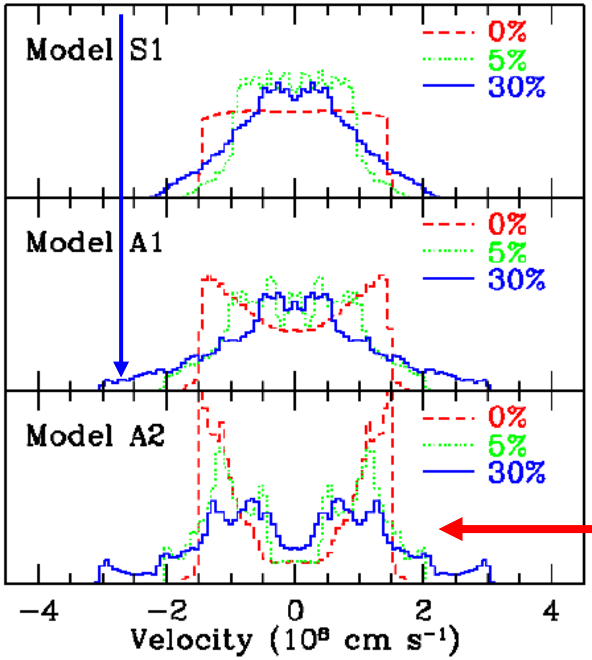
Explosive Nucleosyntheis occurs aroud the jet region very actively

2D Simulation, 6Msolar He Core
Explosion energy is fixed to be 1 times10^{51} erg
Nuclear Reaction Network contains 250 nuclei
Explosion Energy is injected at the inner boundary with asymmetric injection rate so that jet like explosion occurs.

Model S1: Spherical Model
Model A1: Vp/Ve = 2:1
Model A2: Vp/Ve = 4:1
Model A3: Vp/Ve = 8:1

One of Our Predictions on GRBs in 2000.

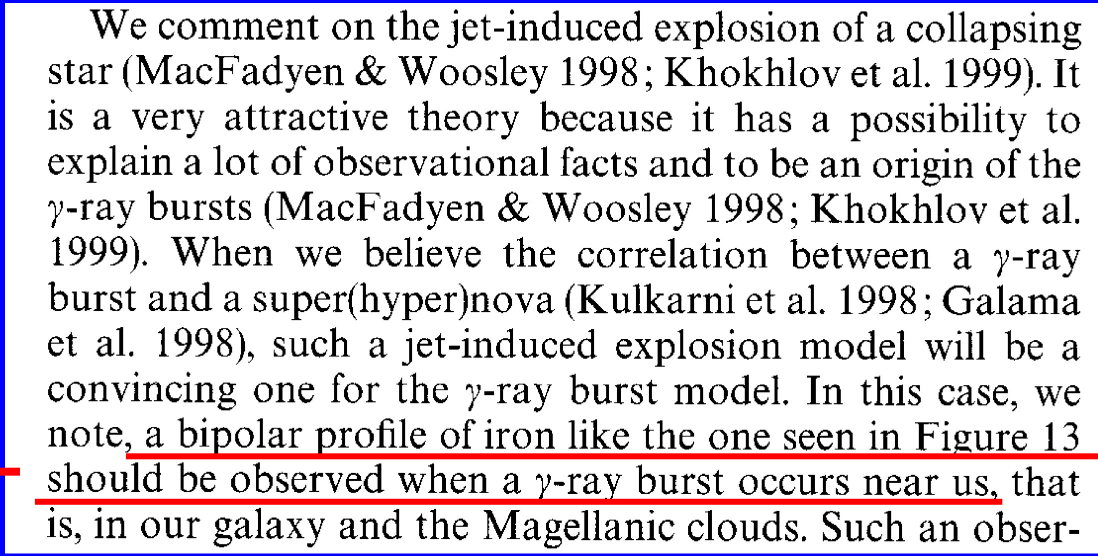
Mildly bi-polar Explosion is favored for SN1987A



Model S1: Spherical Model
Model A1: Vp/Ve = 2:1
Model A2: Vp/Ve = 4:1

S.N. et al. 1998, S.N. 2000

Velocity Distribution of Iron



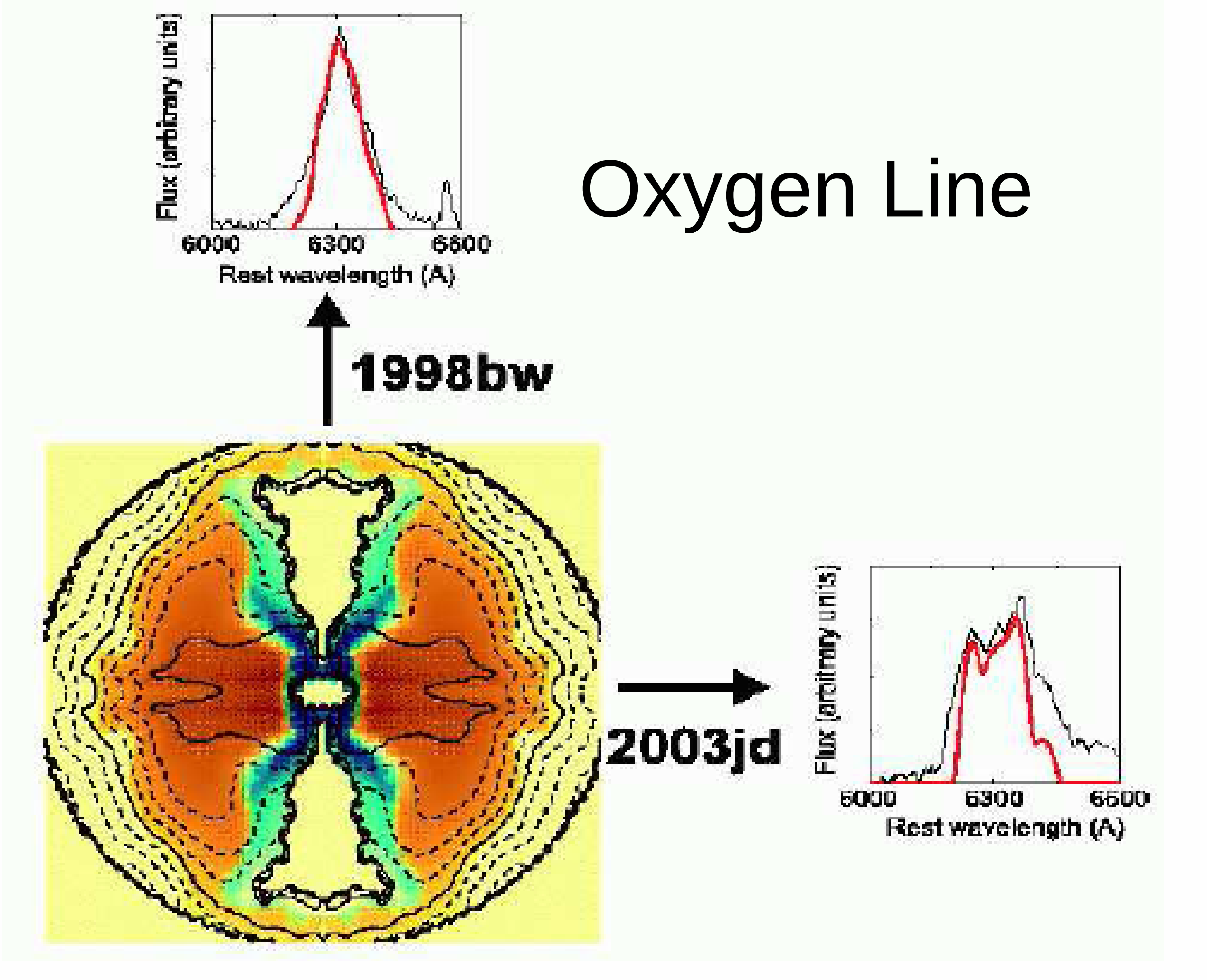
We comment on the jet-induced explosion of a collapsing star (MacFadyen & Woosley 1998; Khokhlov et al. 1999). It is a very attractive theory because it has a possibility to explain a lot of observational facts and to be an origin of the γ-ray bursts (MacFadyen & Woosley 1998; Khokhlov et al. 1999). When we believe the correlation between a γ-ray burst and a super(hyper)nova (Kulkarni et al. 1998; Galama et al. 1998), such a jet-induced explosion model will be a convincing one for the γ-ray burst model. In this case, we note, a bipolar profile of iron like the one seen in Figure 13 should be observed when a γ-ray burst occurs near us, that is, in our galaxy and the Magellanic clouds. Such an obser-

S.N. ApJS 127 (2000) 141-157

c.f. Maeda et al. 2002, 2005

Observations of Line Profiles of Hypernovae

Mazzali et al. 05

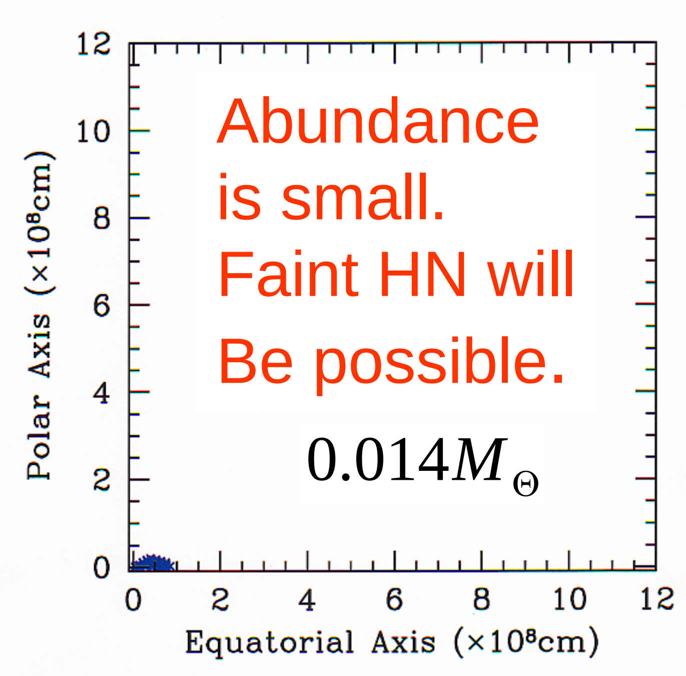


Oxygen Line

Where is ^{56}Ni synthesized?

S.N. et al. ApJ 2003
S.N. et al. ApJ 2006
c.f. Tominaga et al. 2007

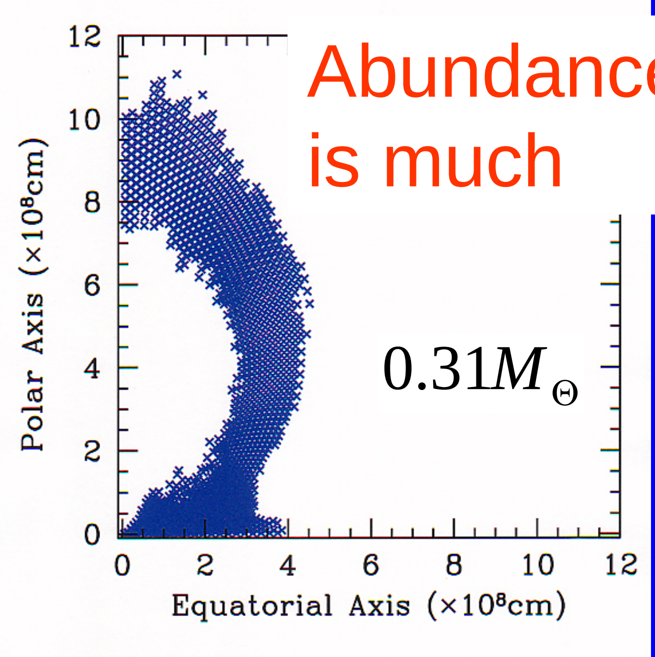
Duration of Explosion is set to be10sec.



Abundance is small.
Faint HN will
Be possible.

$0.014M_\Theta$

All explosion energy is Deposited Initially.



Abundance is much

$0.31M_\Theta$

(i) Origin of ^{56}Ni in a hynernova is not unknown.
Another possibility: Ejection from the accretion flow.
(e.g.MacFadyen and Woosley 99)

(ii) Amount of ^{56}Ni synthesized in the jet depends on the duration of the jet, if ^{56}Ni is synthesized in the Jet.

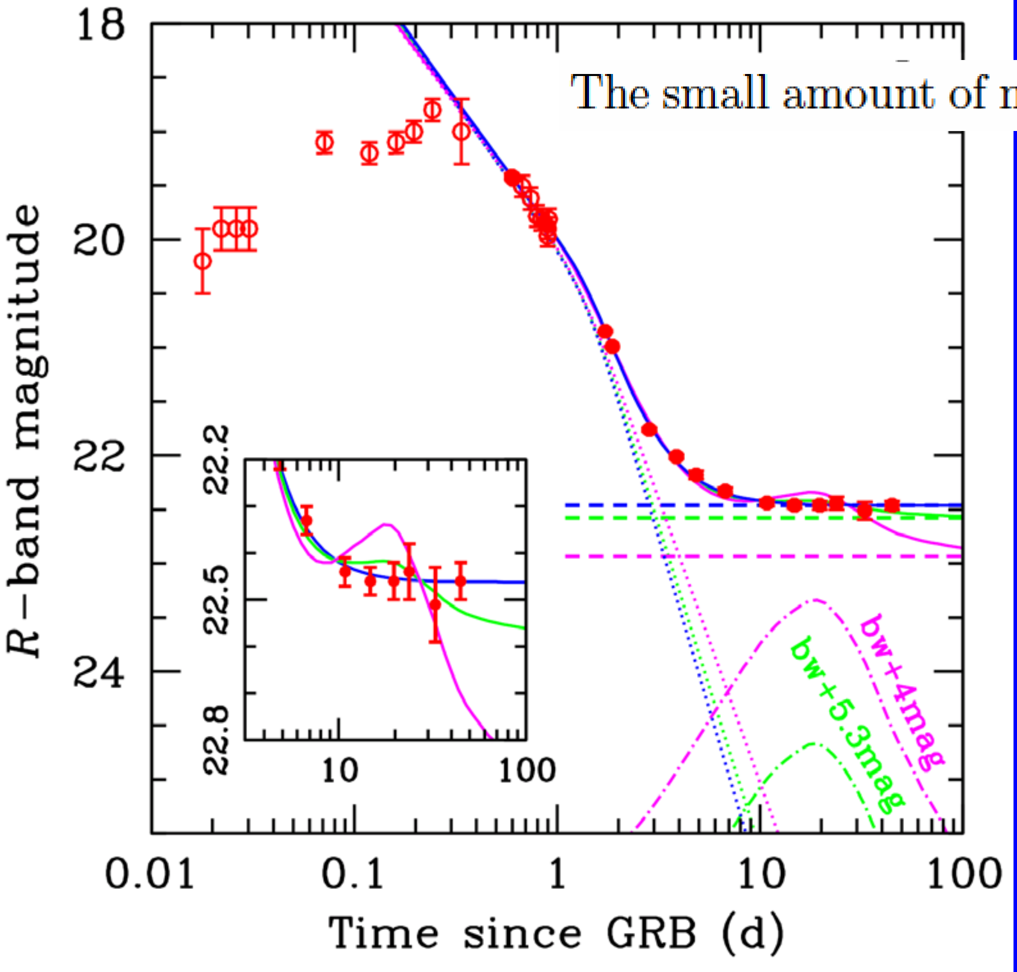
Faint Hypernova?

GRB060614

Gehrels et al. Nature 2006
Gal-Yam et al. Nature 2006

S.N. et al. ApJ 2003
S.N. et al. ApJ 2006
c.f. Tominaga et al. 2007

GRB060505



The small amount of nickel ($< 10^{-3} M_\odot$)

Is preferred.

Della Valle et al. 2006

Duration?

Small ejection
From the accretion
Disk?

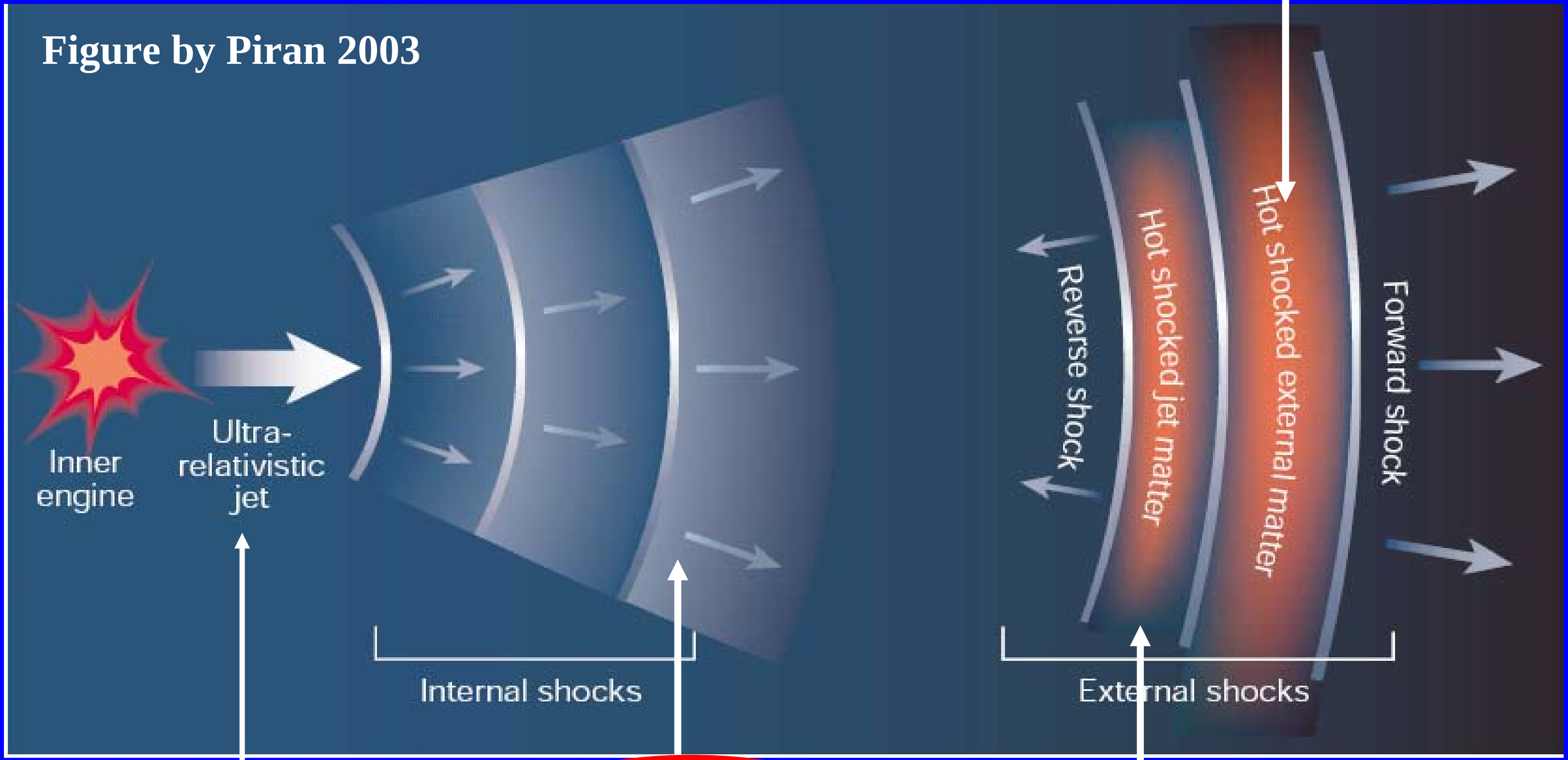
Short GRB?

§Particle Acceleration and High Energy Phenomena in GRB s

Where are very high-energy neutrinos produced?

10^13 – 10^15 cm

Dermer 02 TeV-PeV Neutrinos



Waxman and Bahcall 97

Murase and S.N. 06

TeV-PeV Neutrinos

Bahcall and Meszaros 00

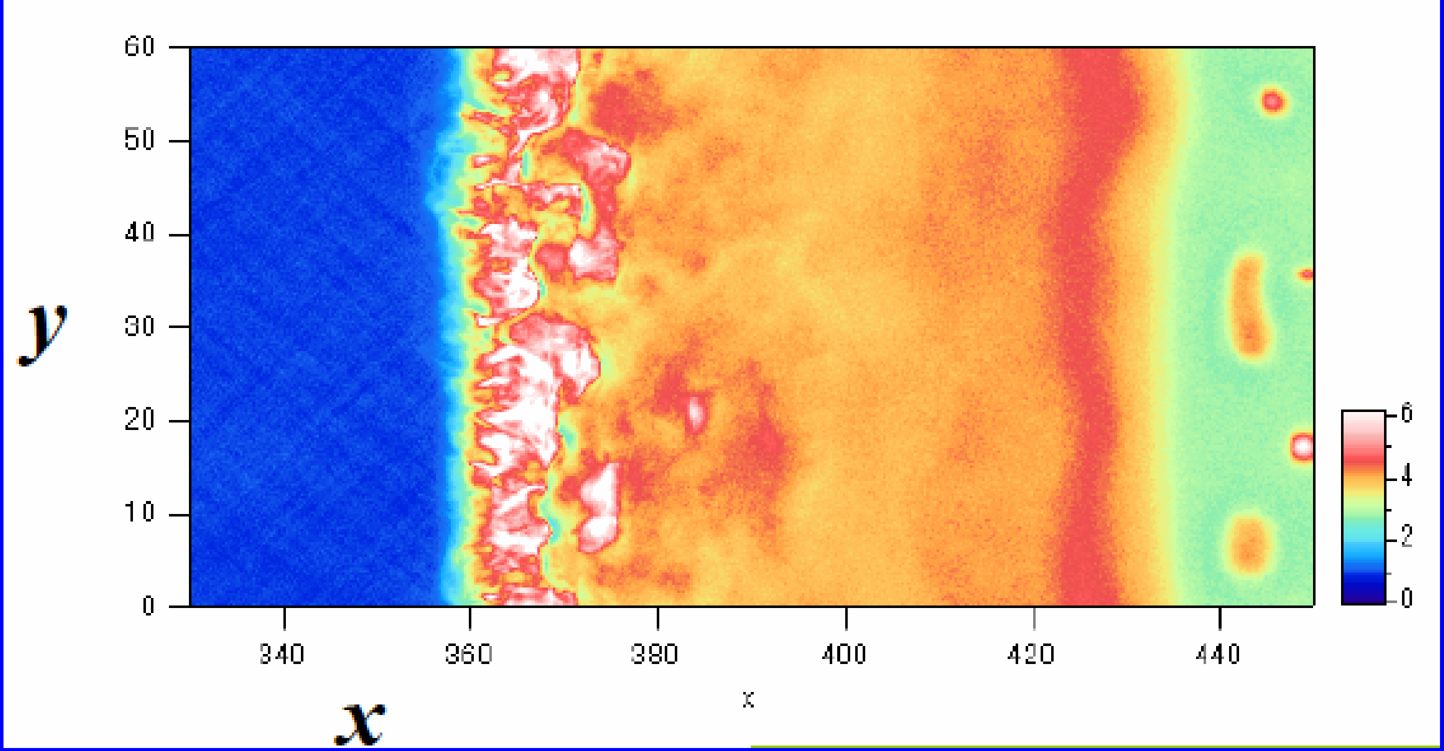
GeV Neutrinos

Waxman and Bahcall 01

TeV-PeV Neutrinos

Particle in Cell Simulation

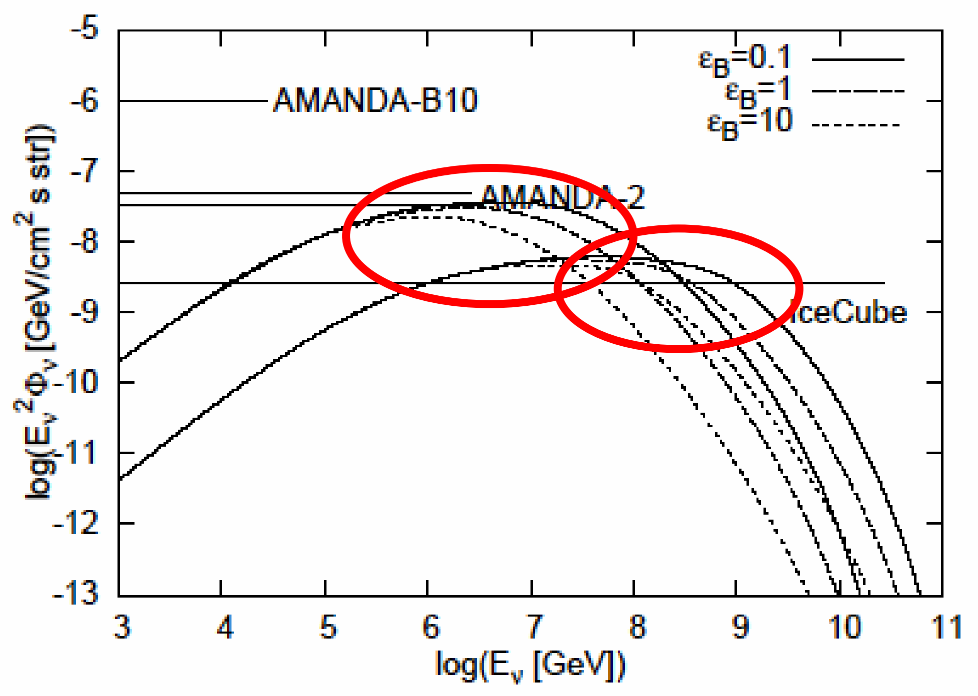
Kato and S.N. 2007 in prep



Formation of a Collision-less shock with magnetic Fields In the Up-stream

High Energy Neutrino Emission from Gamma-Ray Burst

K. Murase and S. N. PRD, 73, 063002 (2006)



Spectra of Neutrino Background with
Detection limits of AMANDA and IceCube
Our model is now being used a template
Of GRB neutrino by IceCube project.

High energy neutrino background is estimated by using GEANT4.

GRB rate was assumed to be proportional to SFR.

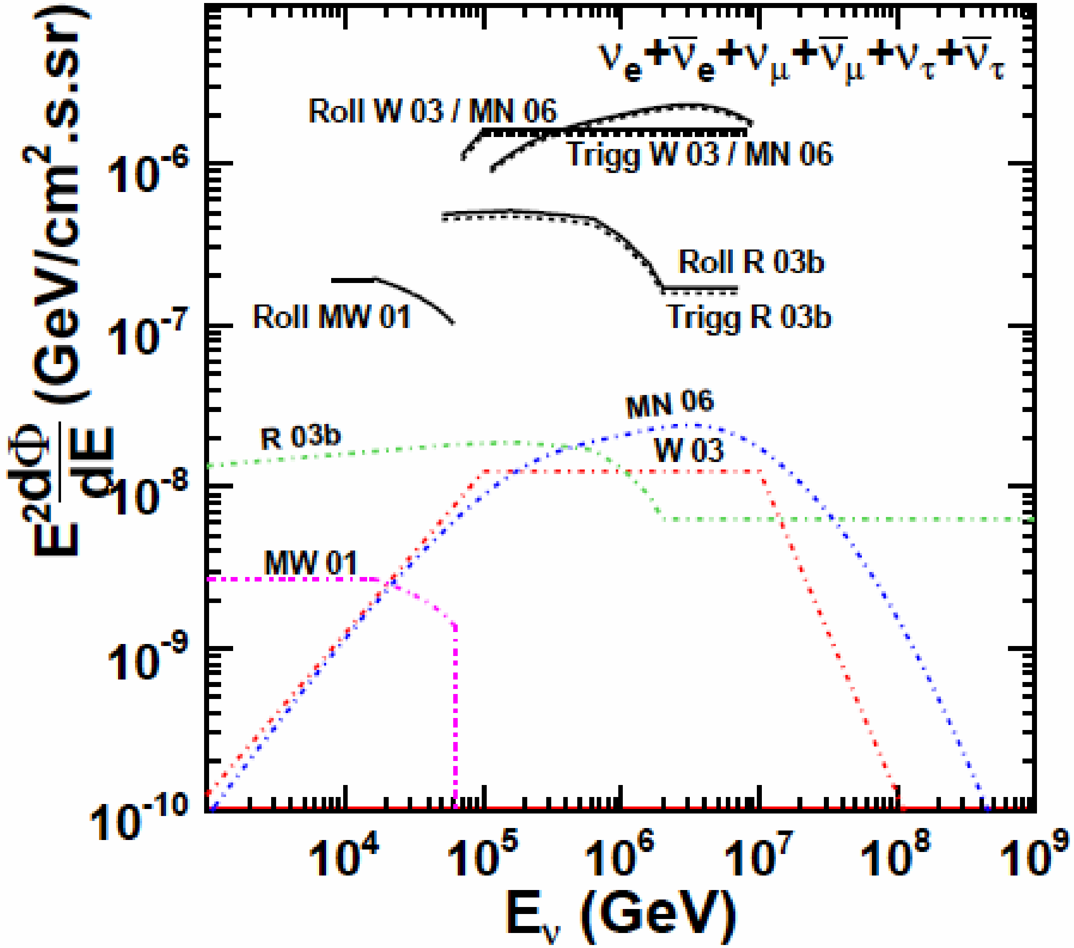
Much neutrinos are produced when photo-pion production is so effective That Internal shocks are optically thick Against ultra high energy protons.

UHECRs may also be explained if internal shocks are optically thin against ultra high energy protons.

Cf. Waxman and Bahcall (1997)
Rachen and Meszaros (1998)

Template of GRB Neutrinos in IceCube Collaboration

Achterberg et al. astro-ph/0702265



**Due to the effect
Of multi-pion production,
Our model predicts higher
Flux of neutrinos at high
Energy region.**

**GRB neutrinos should be
Correlated with GRBs.
Thus they can be distinguished
From other type of high energy
Neutrinos.**

§ Summary

Summary on the central engine of Long GRBs

Neutrino heating processes have been included in the collapsar model.

It is found that neutrino heating processes are insufficient to launch a jet in this study.

A Jet is launched by magnetic fields, although this jet is non-relativistic at present.

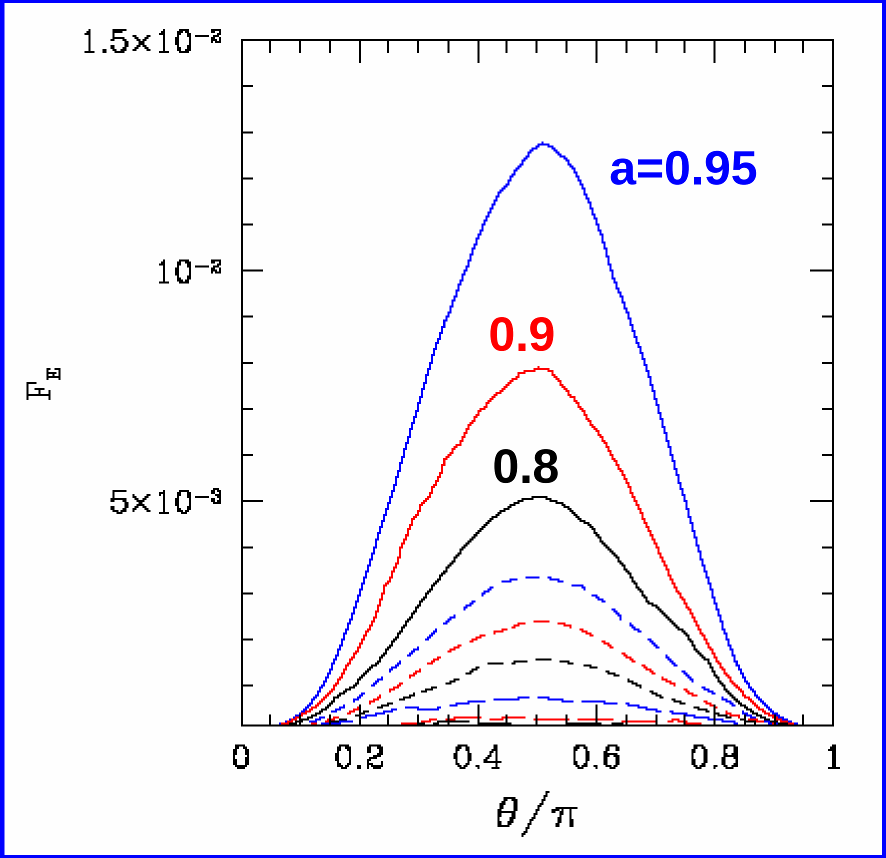
Simulations of the order of 10sec may be required to generate a powerful jet by special (general) relativistic MHD code.

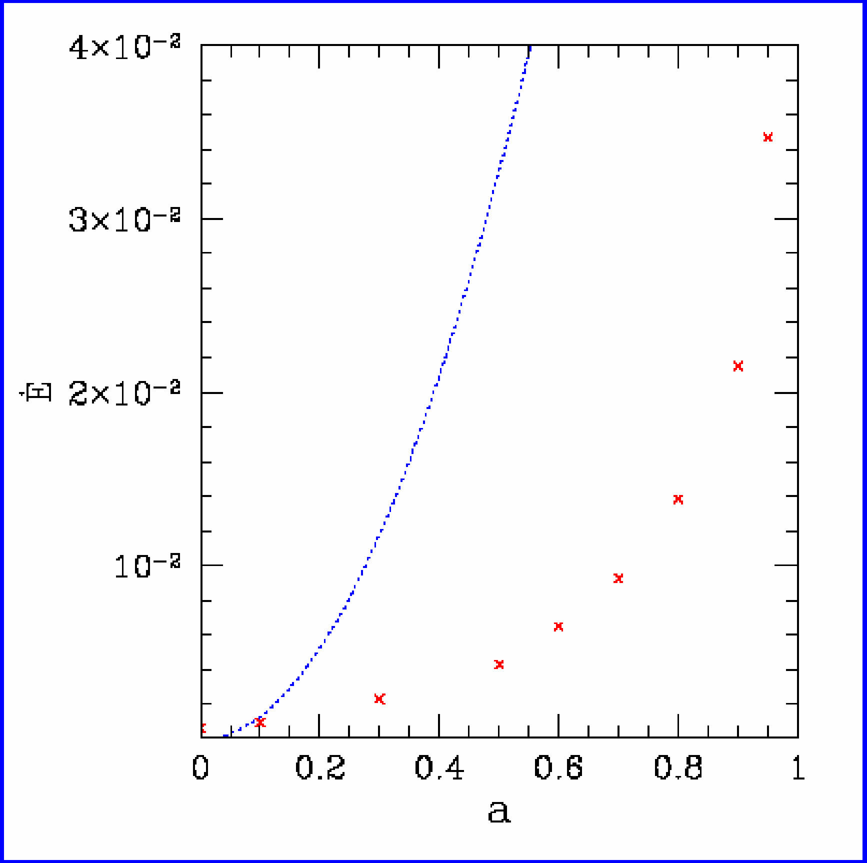
Effects of general relativity should be important for the formation of relativistic jet (BZ-process, Neutrino Heating), which we are planning to study using our GRMHD code with microphysics.

Numerical simulation of Blandford-Znajek Process

T=60, c=G=M=1

c.f. Komissarov 2001, 2006; McKinney 2006





$$\dot{E} = 2\pi\int_0^\pi d\theta\sqrt{-g}(-\ T^r{}_t)$$

=

$$\frac{C^2\pi}{32}a^2\int_0^\pi d\theta\sin^3\theta$$

$*F^{tr} = C/(r^2 + a^2\cos^2\theta) = C\sin\theta/\sqrt{-g}$ in KS

Monopole solution

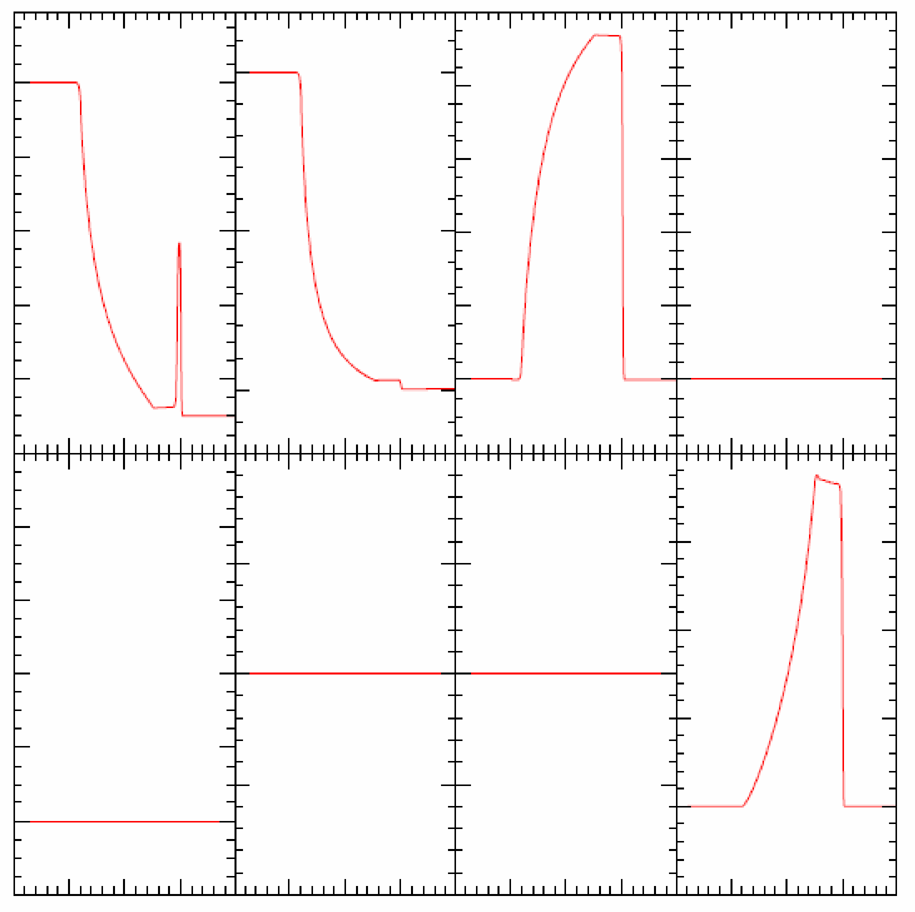
$$\dot{E} = \frac{\pi}{24}C^2a^2 \propto a^2$$

For a << 1

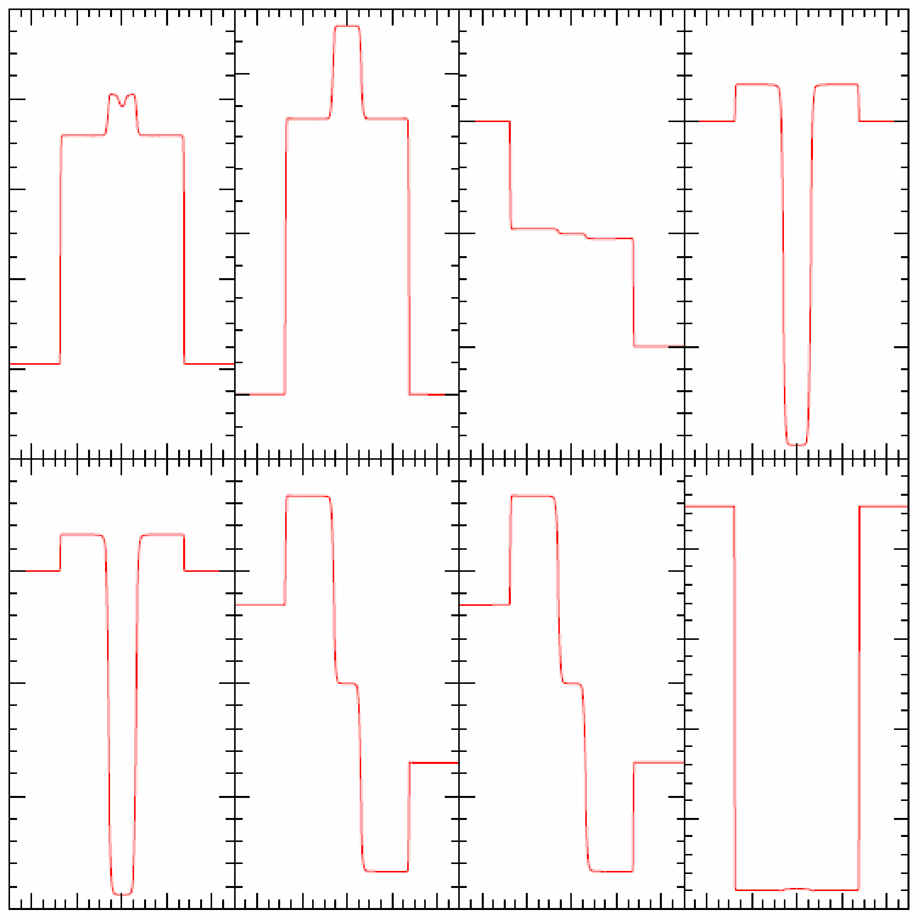
Blandford and Znajek (1997)

1-D Shock Tube Problems

density p vx vy



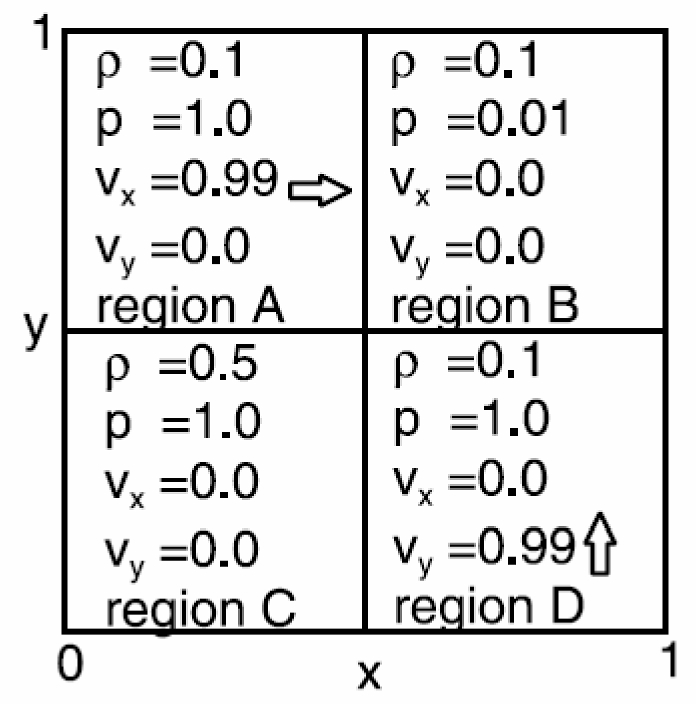
vz By Bz gamma



	ρ	p	v^x	v^y	v^z	B^x	B^y	B^z
left state	1.0	1000.0	0.0	0.0	0.0	1.0	0.0	0.0
right state	0.1	1.0	0.0	0.0	0.0	1.0	0.0	0.0

	ρ	p	v^x	v^y	v^z	B^x	B^y	B^z
left state	1.0	0.1	0.999	0.0	0.0	10.0	7.0	7.0
right state	1.0	0.1	-0.999	0.0	0.0	10.0	-7.0	-7.0

2-D Shock Tube problem



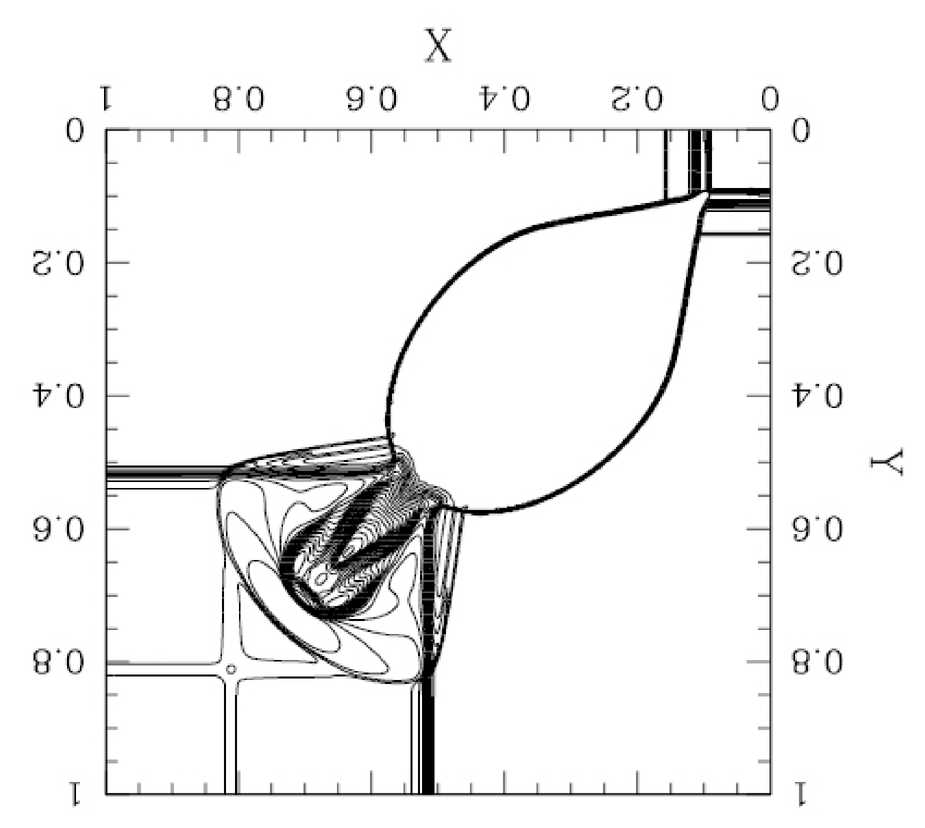
region A: ρ =0.1, p =1.0, v_x =0.99 ⇨, v_y =0.0

region B: ρ =0.1, p =0.01, v_x =0.0, v_y =0.0

region C: ρ =0.5, p =1.0, v_x =0.0, v_y =0.0

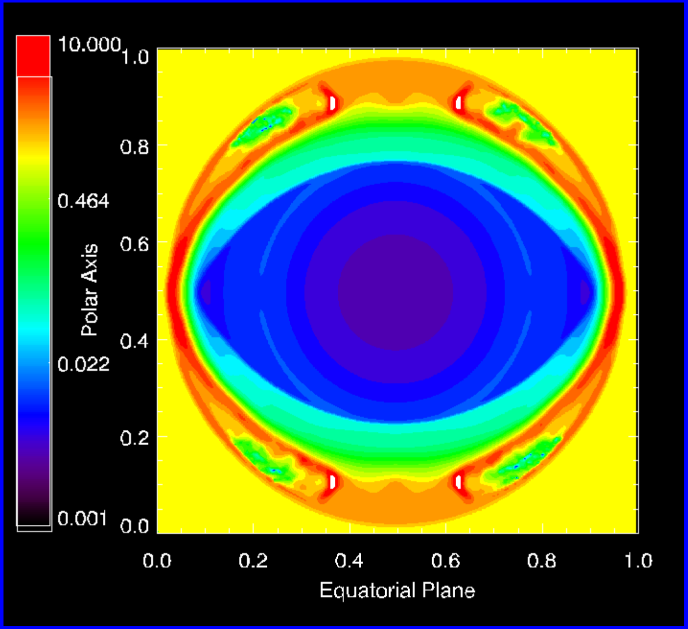
region D: ρ =0.1, p =1.0, v_x =0.0, v_y =0.99 ⇧

N×N=400×400

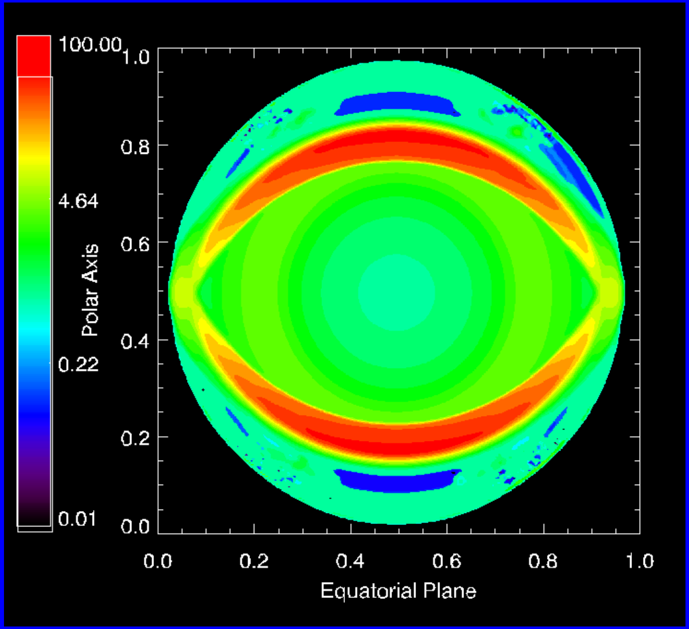


Cylindrical explosion problem

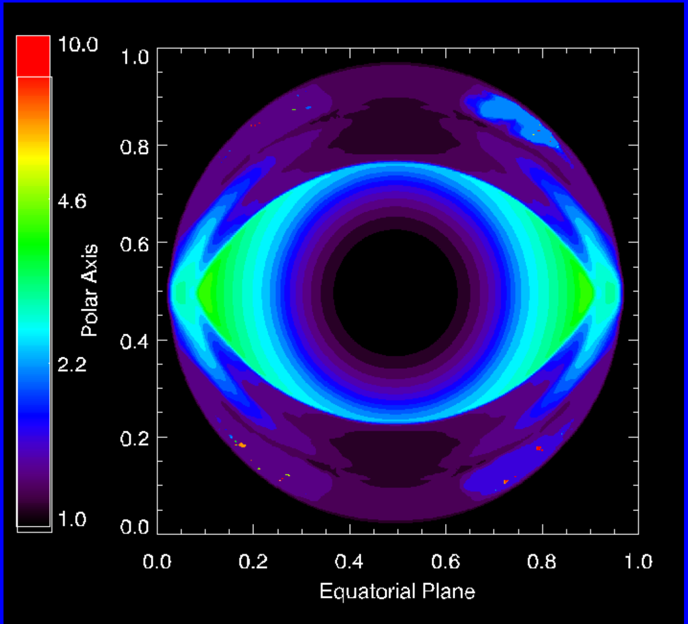
density



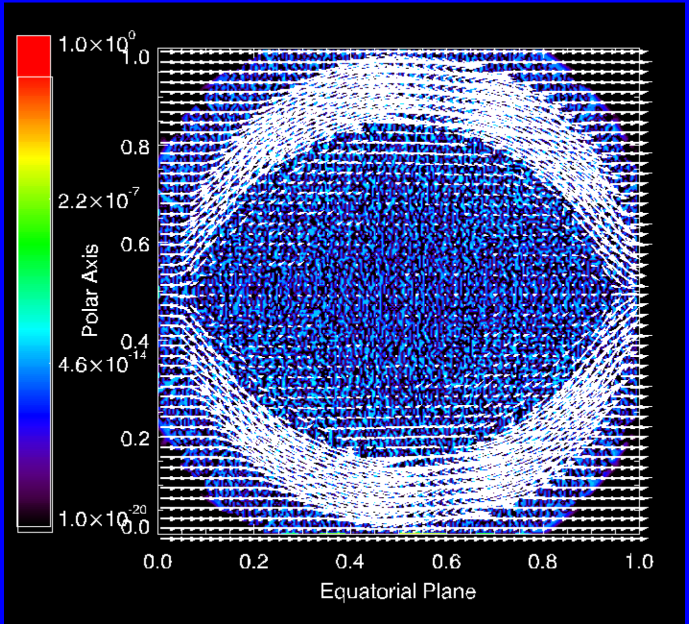
pressure



gamma



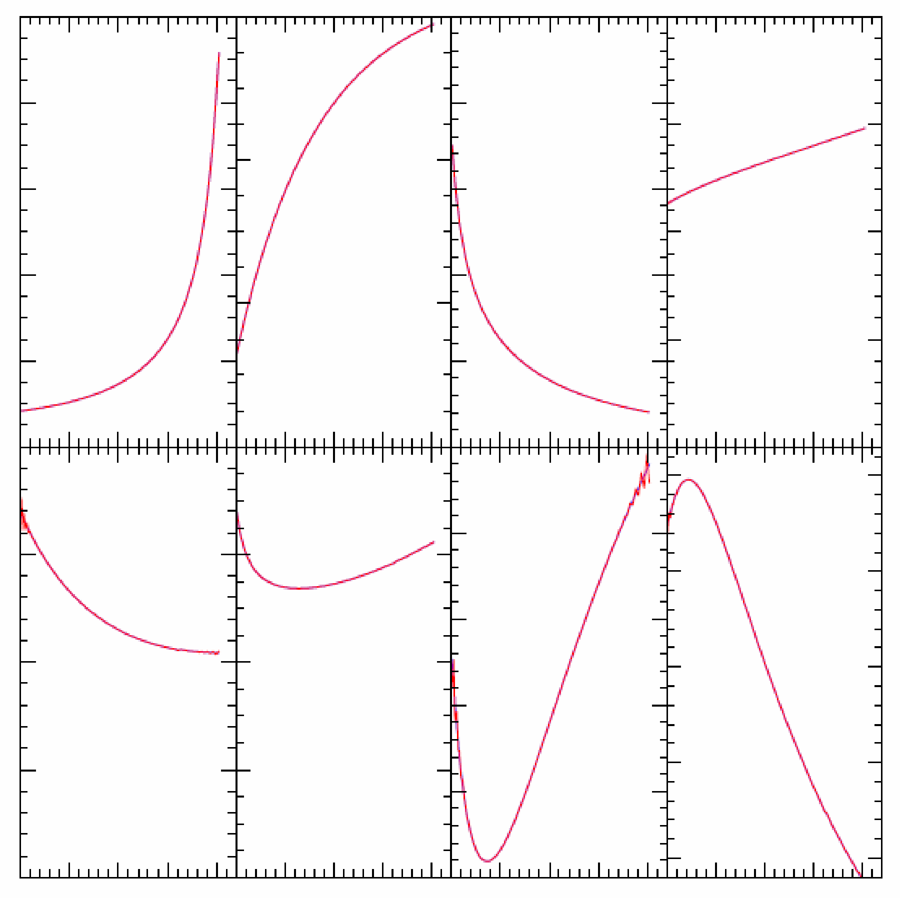
Div B



Gammie’s Inflow Problem

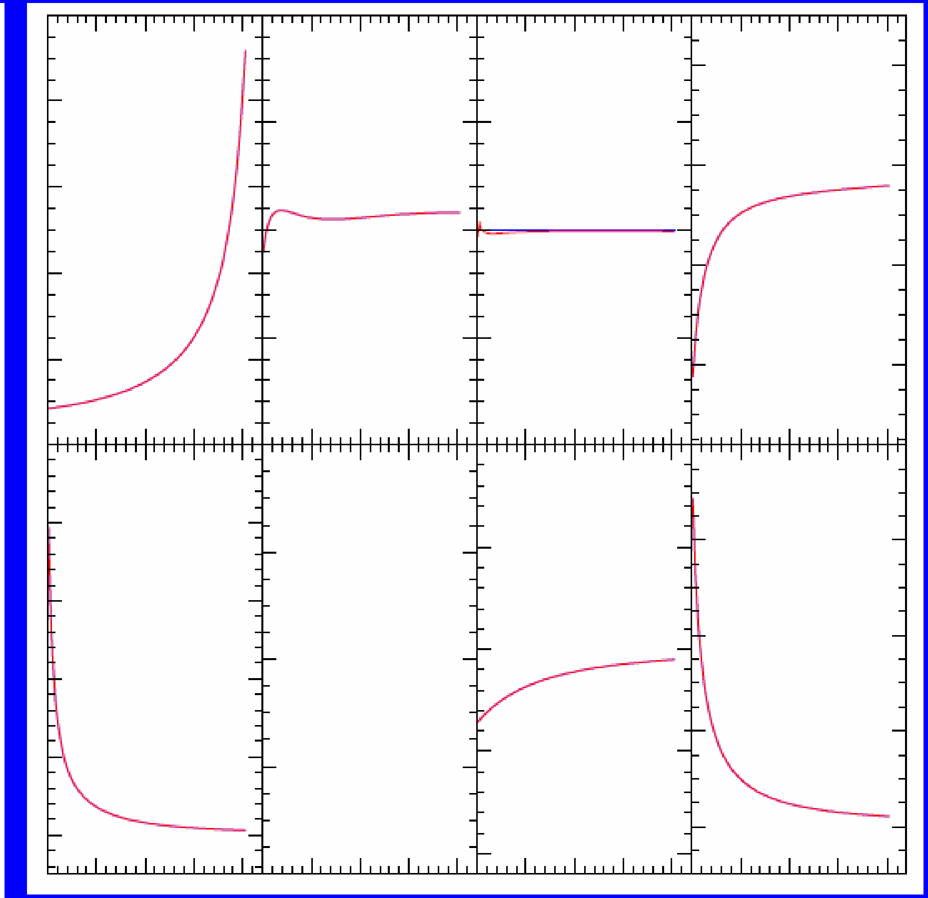
a=0.5, T=1(GM/c^3)

density u^r U^phi U_phi



B^2 B^phi V^r V^phi

BL-Coordinate



KS-Coordinate