2D Numerical Calculation of a Collapsar

with Realistic Equation of State, Rotation, Self-gravity, Photo-disintegration, and Neutrino Cooling, (+Neutrino Heating, Magnetic Field)

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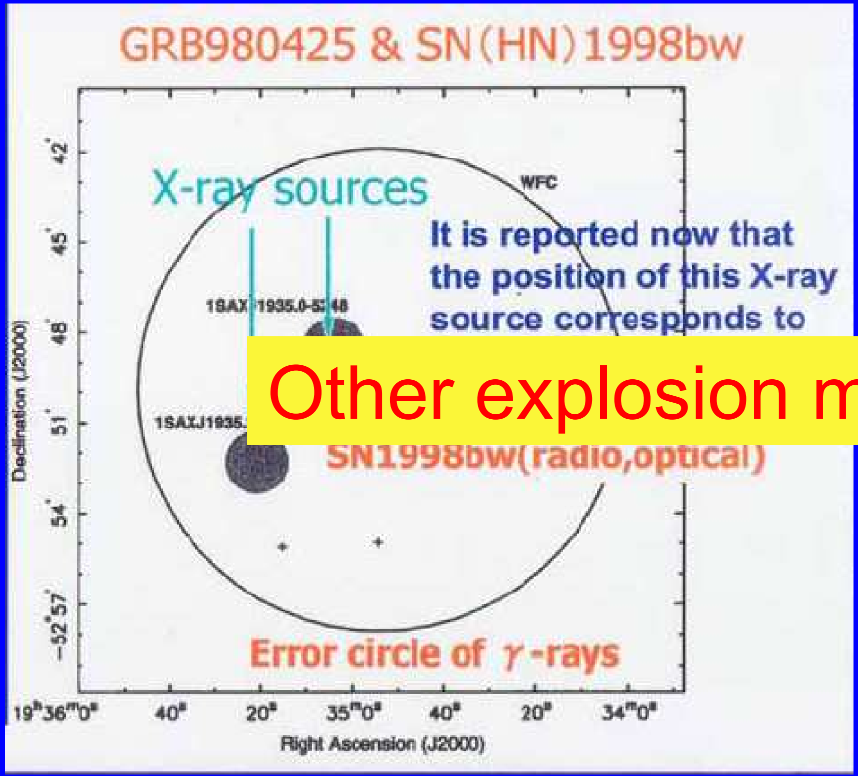
- Introduction

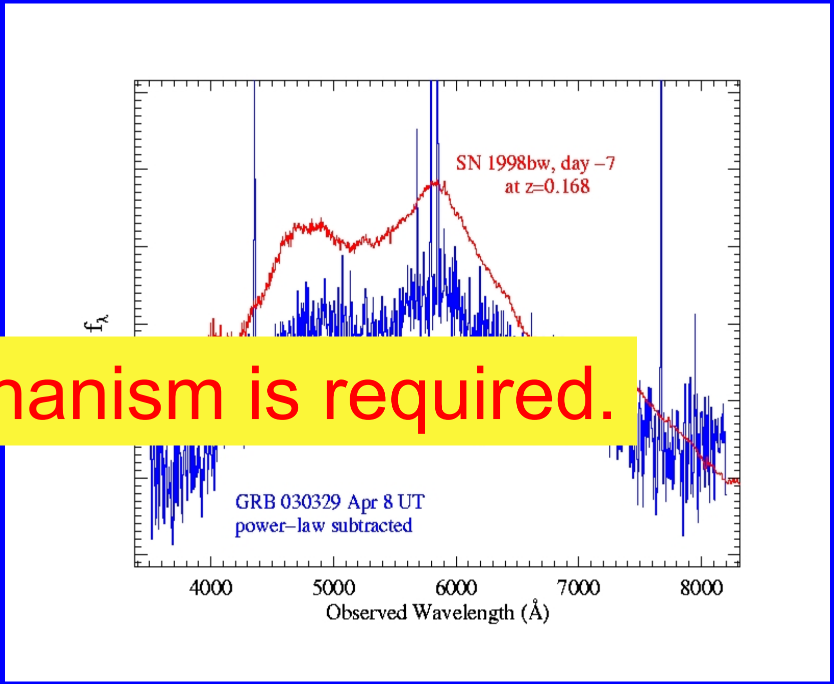
Some GRBs are Accompanied by Hypernovae



It is reported now that the position of this X-ray source corresponds to

SN1998bw(radio,optical)

GRB980425/SN1998bw



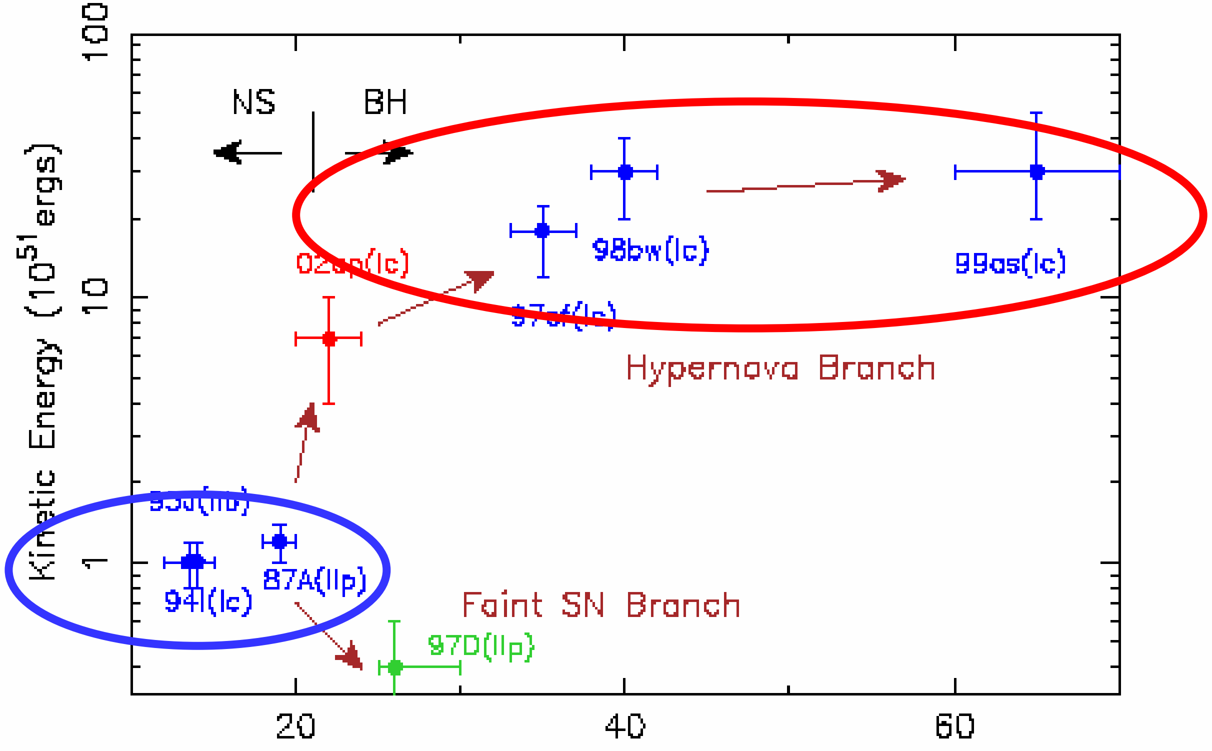
GRB030329/SN2003dh

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.

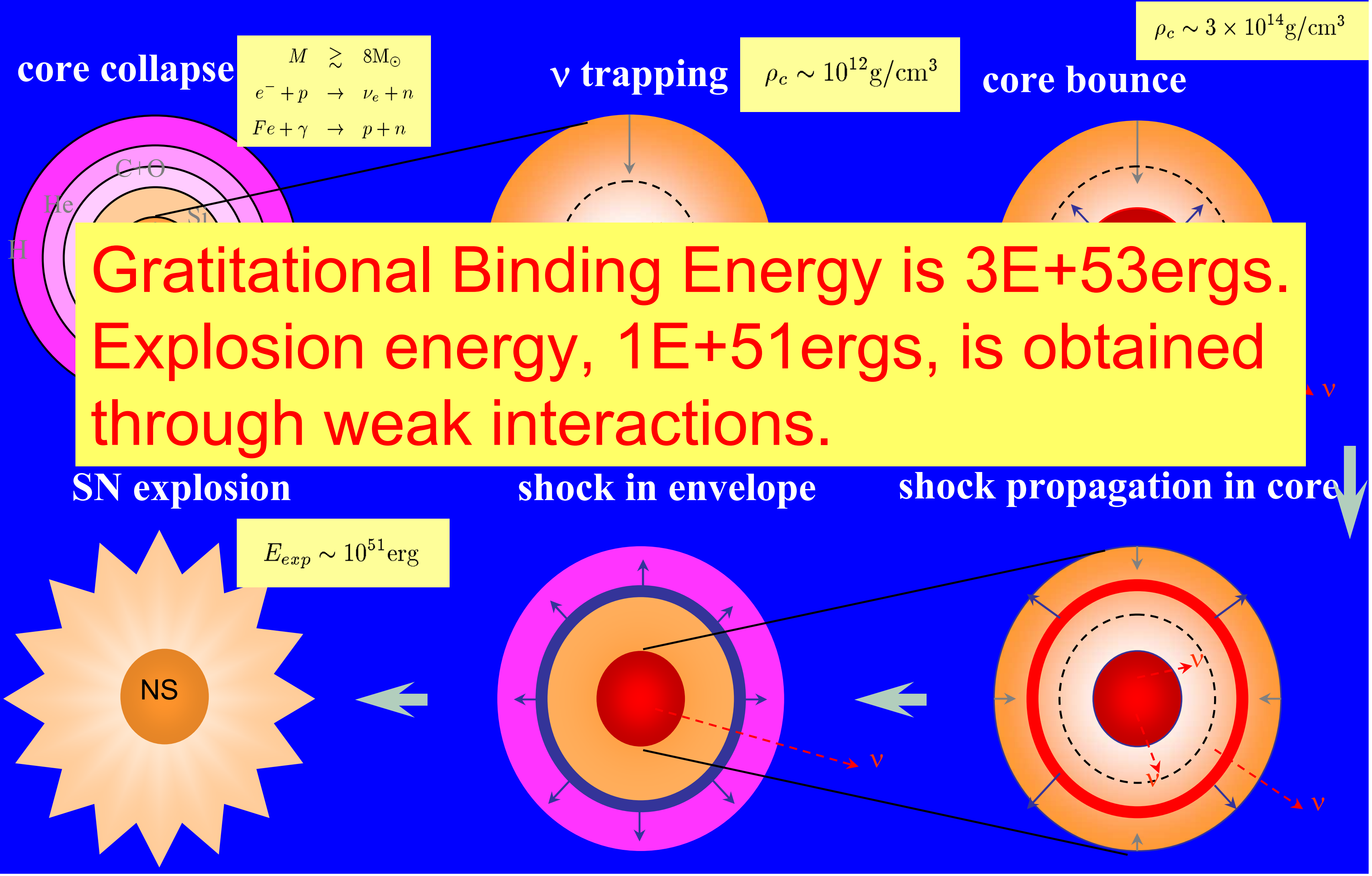
What determines the explosion energy of hypernovae?

Is there an energy scale/upper-limit
For explosion energy of hypernovae?



Nomoto et al. ’02

Scenario of Normal Collapse-driven Supernovae



core collapse

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

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

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

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

shock propagation in core

shock in envelope

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

Some possible energy scales

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

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

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

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

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

$$a = \frac{J C}{G M^2} \leq 1$$

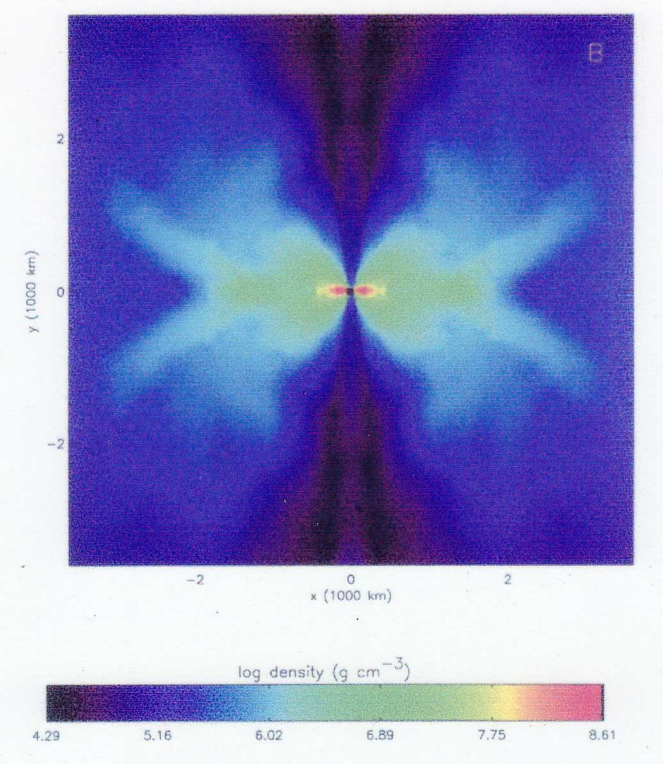
(a) Gravitational Potential Energy of Accreted Matter.
Duration is ～10sec.
Collapsar Model

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

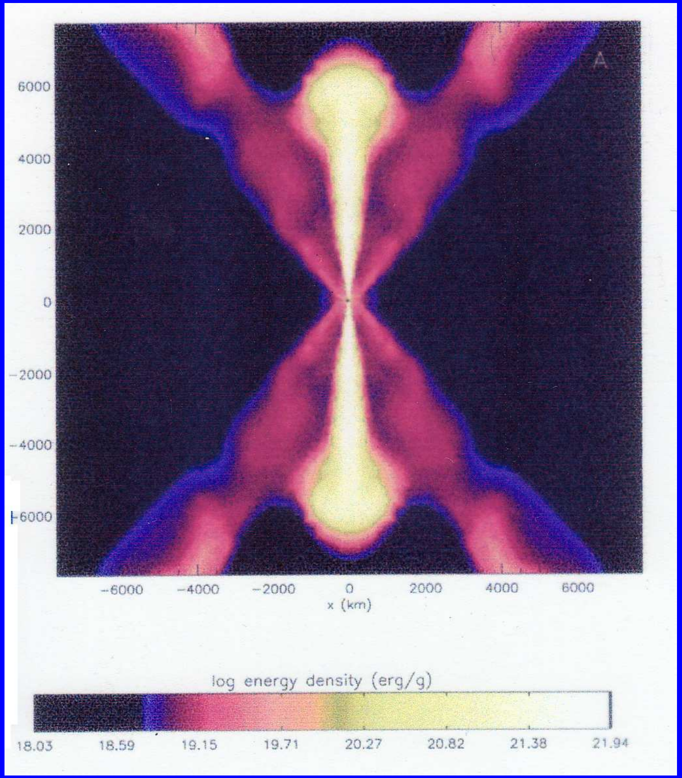
(a) Gravitational Potential Energy Model

MacFadyen and Woosley (1998)

Jet off



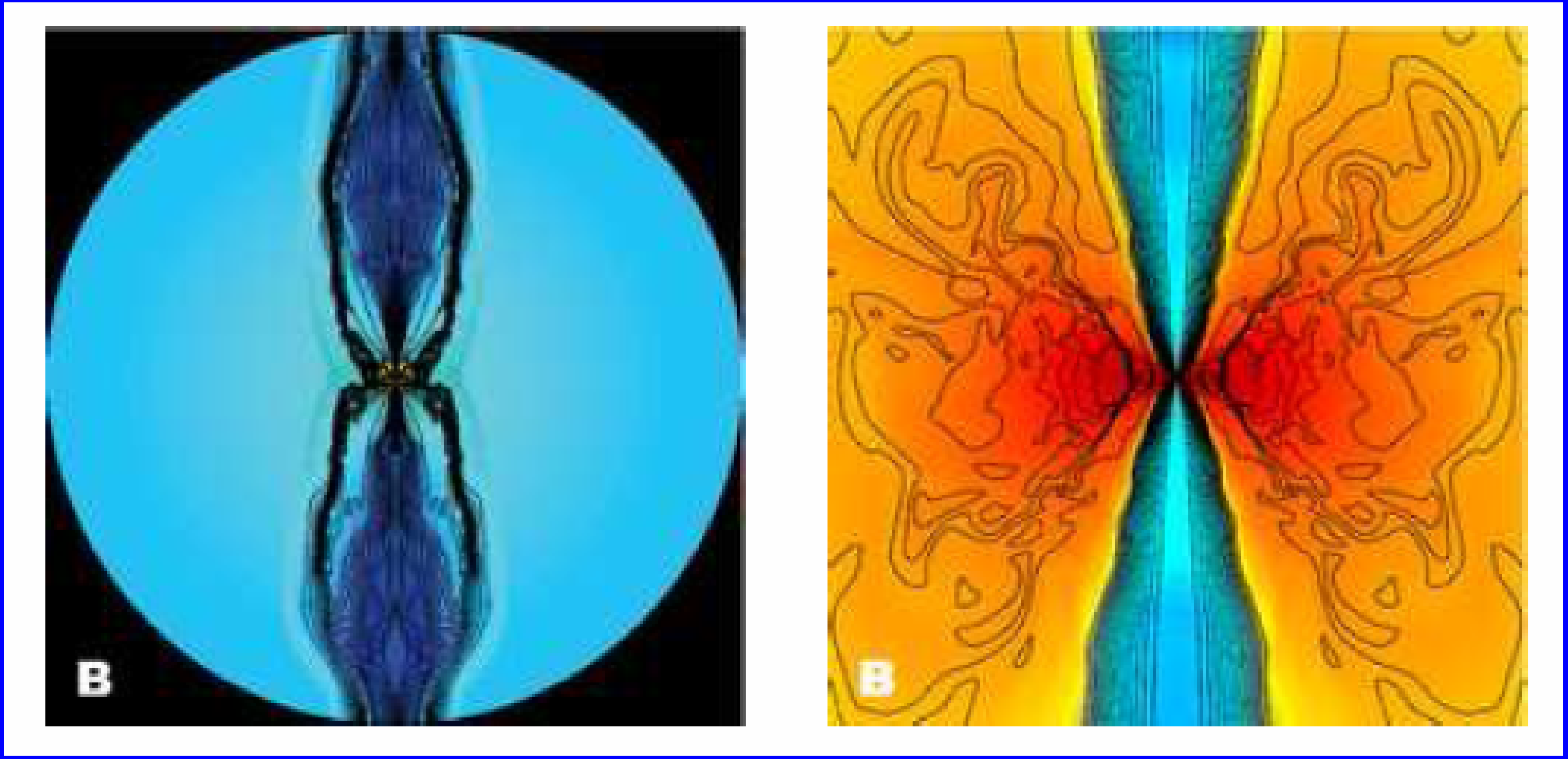
Jet on



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 Model

McKinney 05



Blandford-Znajek Process can be seen in numerical simulations.

§ Method of Calculation

Input Physics

- Progenitor: Model E25 in Heger et al. (2000).
- 2-D Ideal MHD with Rotation $(r,\theta)=(150,30)$.
- Inner boundary is set to be 10km.
- Realistic EOS (Blinnikov et al. 1996).
- Nuclear Reaction (N, P, He, O, Fe).
- Newton Gravity （Including self gravity; $M_{BH}=2.2M_o$）.
- Neutrino Cooling.
- Neutrino Heating （ON･OFF）.
- Magnetic Field （ON･OFF）.

Neutrino Processes (1)

Cooling Process

Locally Determined

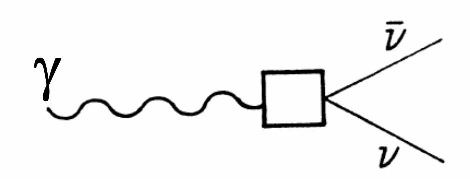
Electron and positron Capture on free nucleons
(Epstein and Pethick 1981)

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

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

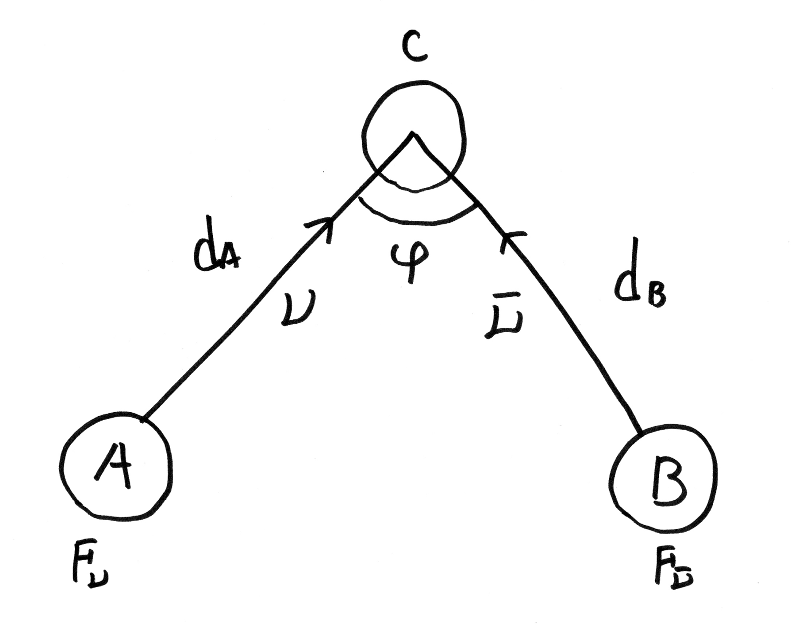
$F_{\nu,\bar{\nu}}$ are energy spectrum [cm^{-3} s^{-1} GeV^{-1}] of (anti-)neutrinos

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

8 dimensional integration!

We approximated as $(1-\cos\psi)^2 \sim 1$

This approximation sets upper limit for the Effects of neutrino heating through neutrino Pair annihilation.



Magnetic Fields

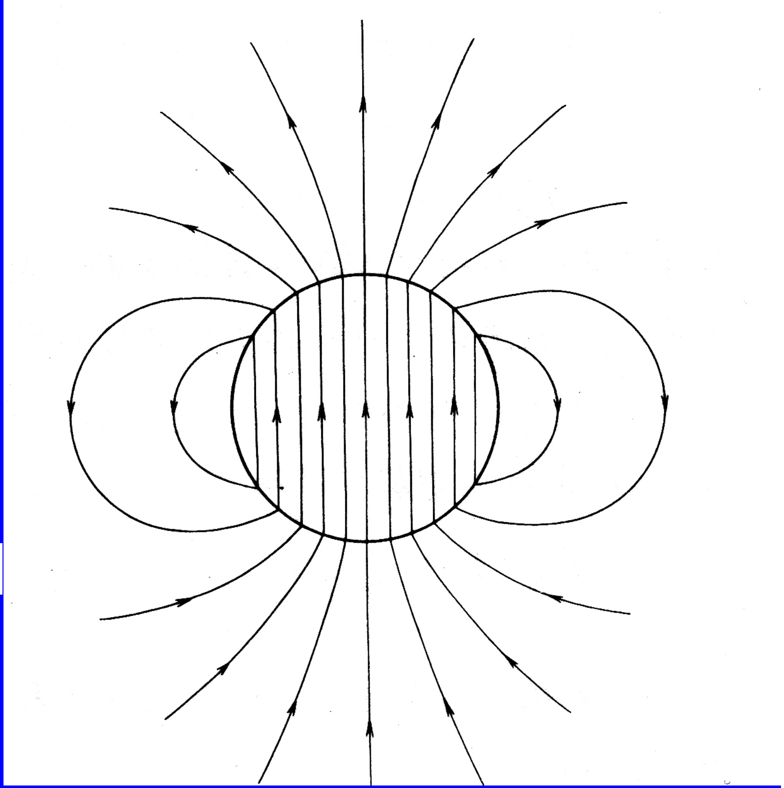
Initial Condition

$$\begin{aligned}\vec{B}(\vec{r}) &= \frac{1}{3}B_0\left(\frac{r_0}{r}\right)^3(2\cos\theta\vec{e_r}+\sin\theta\vec{e_\theta}) \quad \text{for r} \geq \text{r}_0 \\ &= \frac{2}{3}B_0(\cos\theta\vec{e_r}-\sin\theta\vec{e_\theta}) \quad \text{for r} < \text{r}_0.\end{aligned}$$

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.

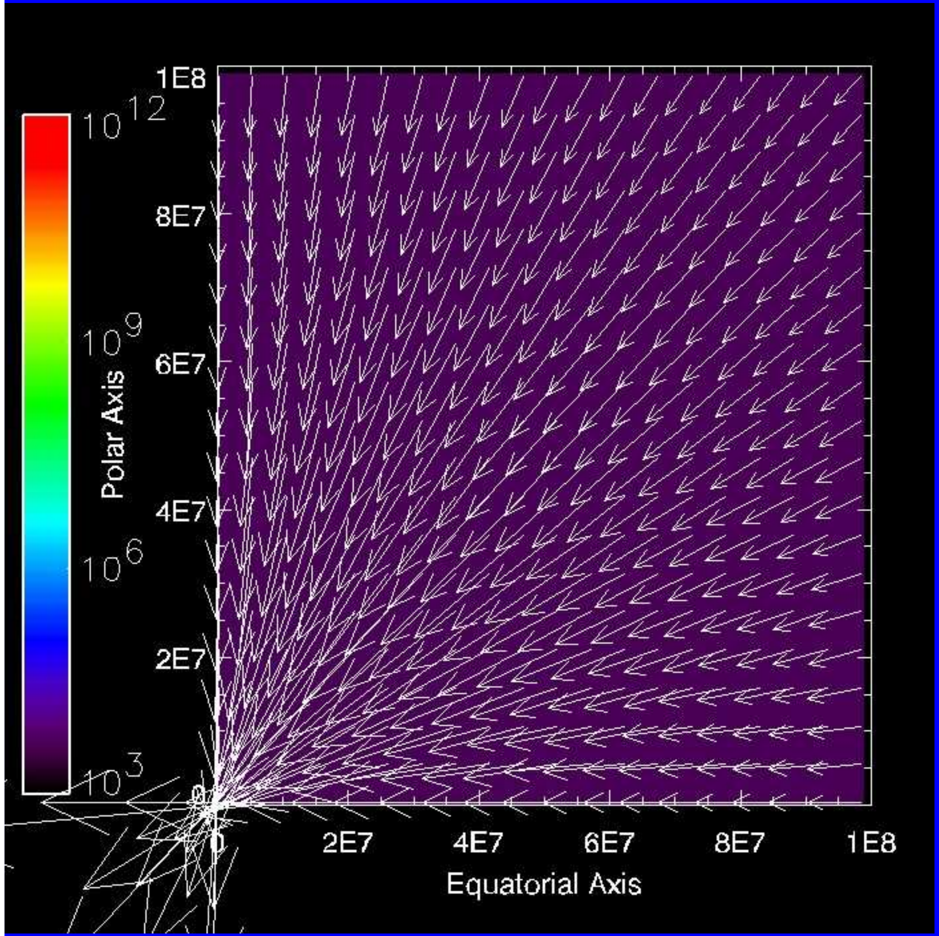
B_0 to be 0, 10^8G, 10^9G, and 10^{10}G.

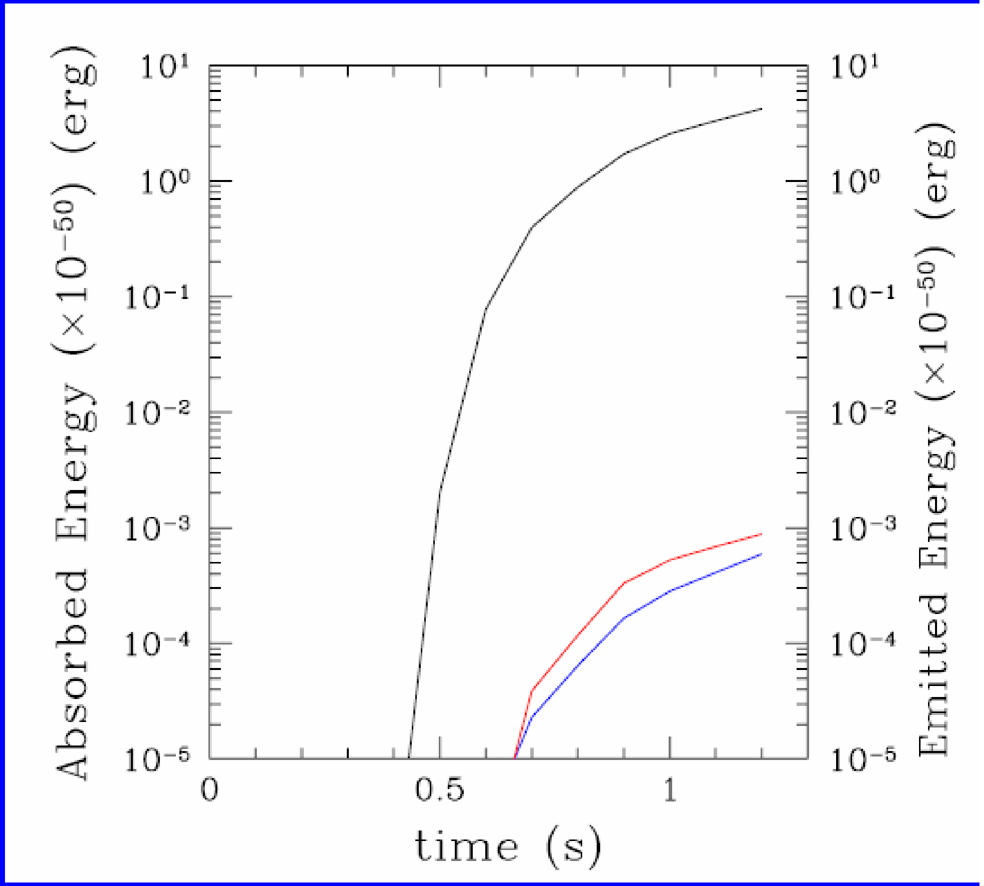


Initial |Em/W| are 0, 5E-8, 5E-6, 5E-4.
Initial |T/W| is 8E-3.

- **Results**

Case of Neutrino Heating (no B-Field)





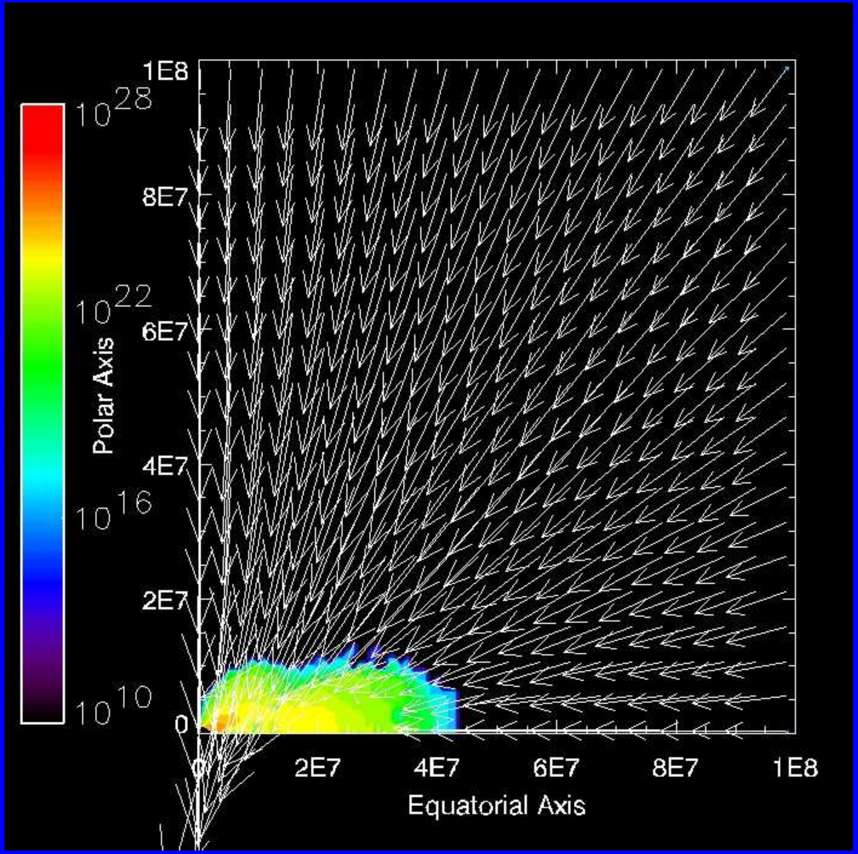
Density contour, Final time is 1.3sec.

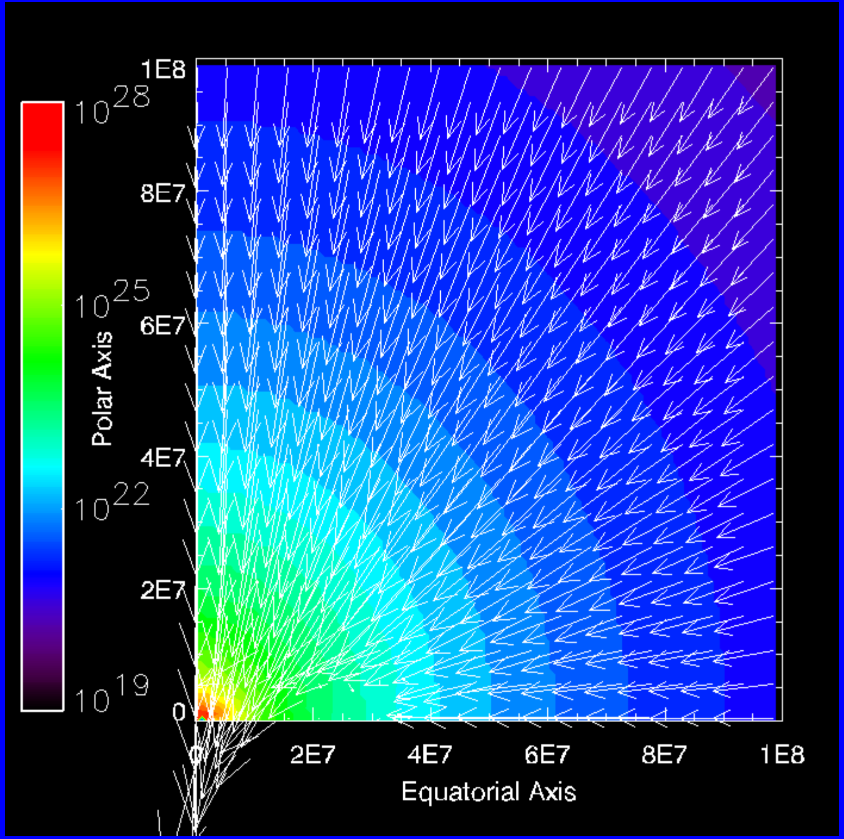
Black: Neutrino Cooling
Red: Neutrino Pair Annihilation
Blue: Neutrino Absorption

Case of Neutrino Heating (no B-Field)

Local, High Energy Deposition Rate

Global, Low Energy Deposition Rate

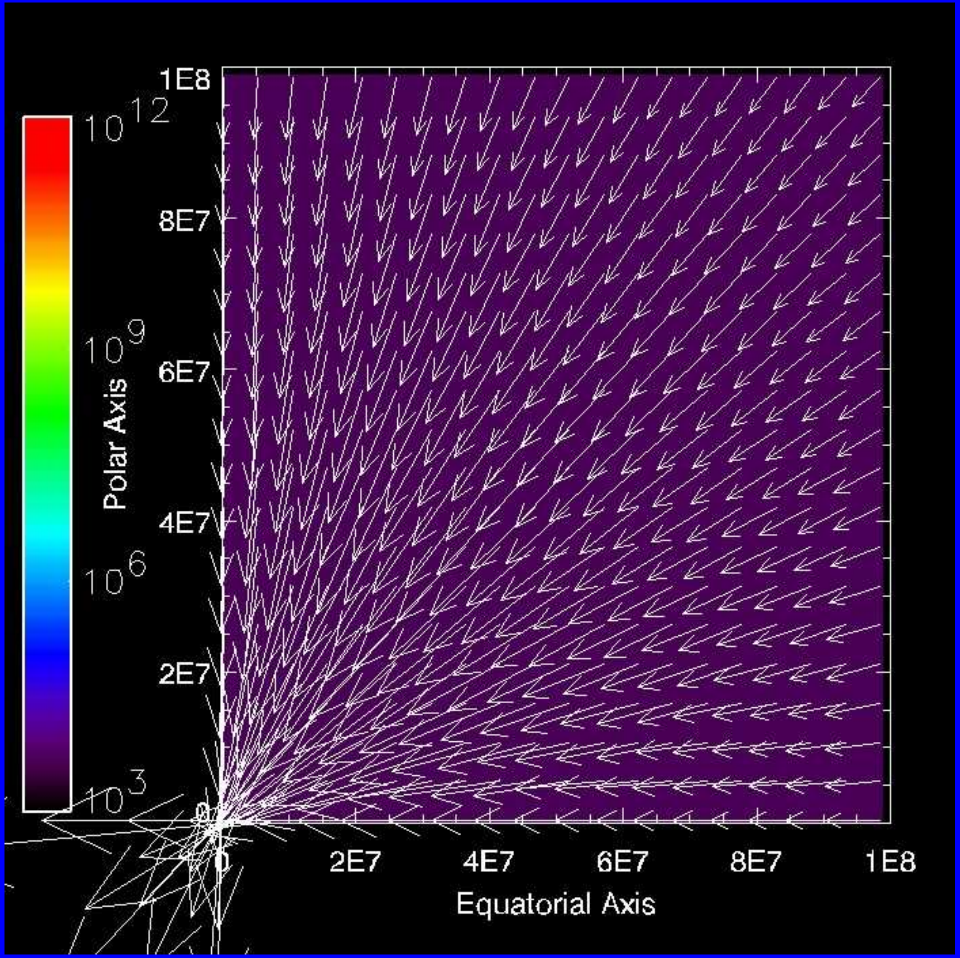




Energy Deposition Rate [erg/s/cc]
By neutrino absorption on free nucleons
At t = 1.3 sec.

Energy Deposition Rate [erg/s/cc]
By neutrino pair annihilation
at t = 1.3 sec.

Case of B=10^9G (no neutrino heating)



Jet energy at t=1.63sec is 1E+47 erg.
Def: Total energy (Kin+th+mag-Grav)
For $\theta < 10$ degree.
Mass of Jet is 2E+28 g.

↓

This jet is non-relativistic jet at Present.

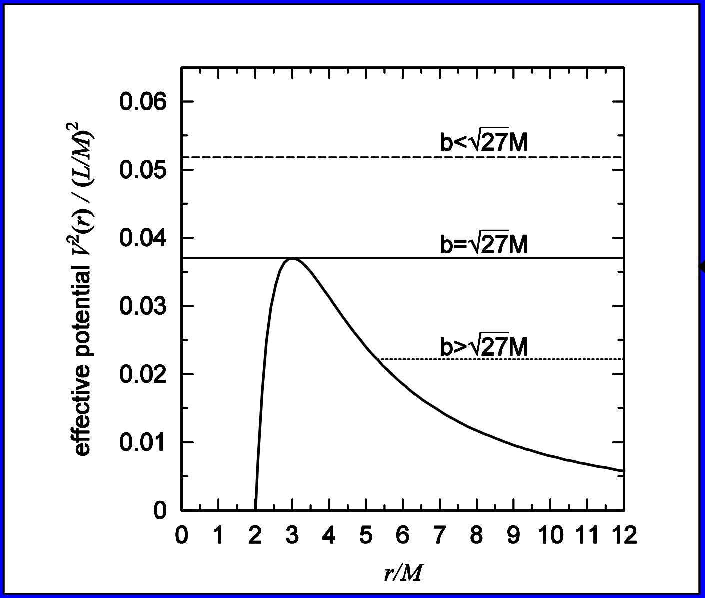
Density contour, Final time is 1.63sec.

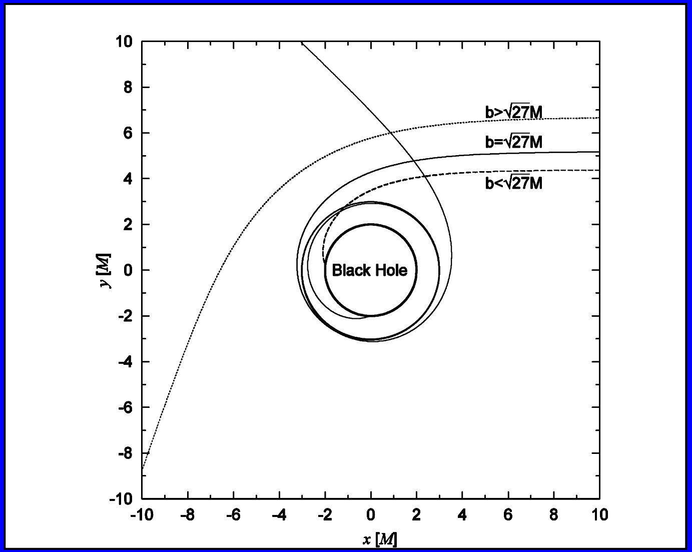
§ Discussion

Effects of Neutrino Pair Annihilation with General Relativity

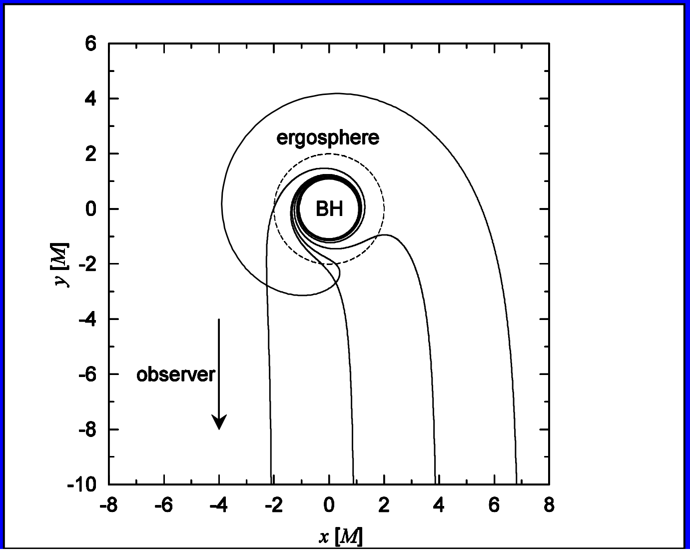
Takahashi and Nagataki in prep.

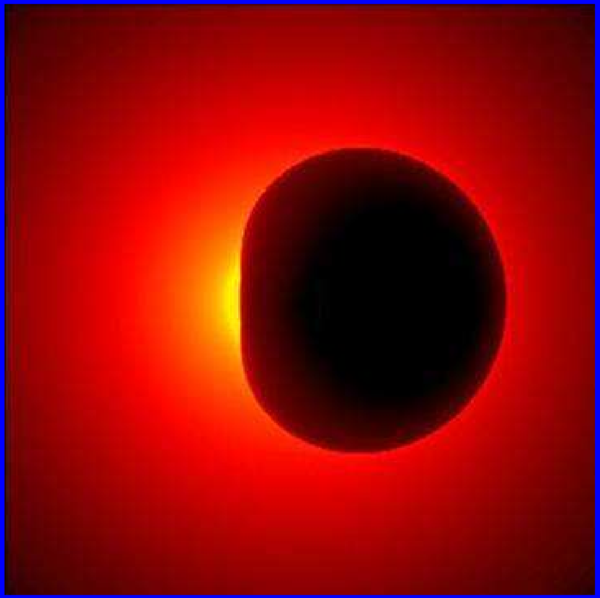
Effective Potential





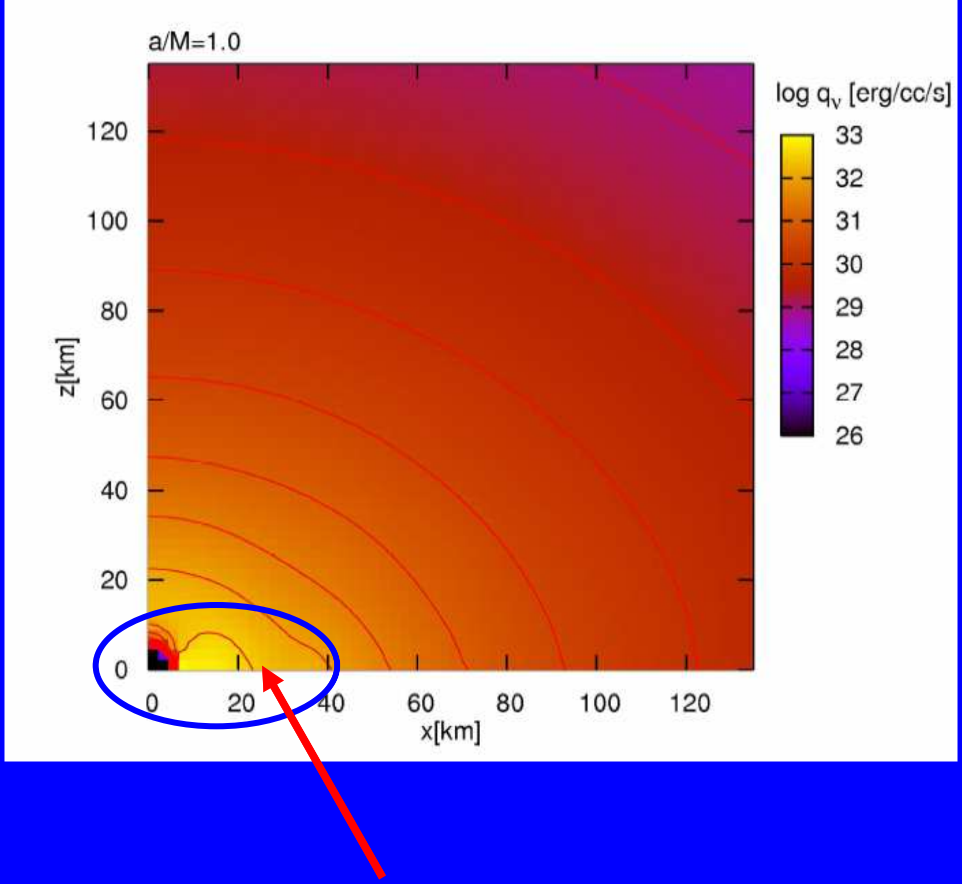
Geodesic of Neutrinos



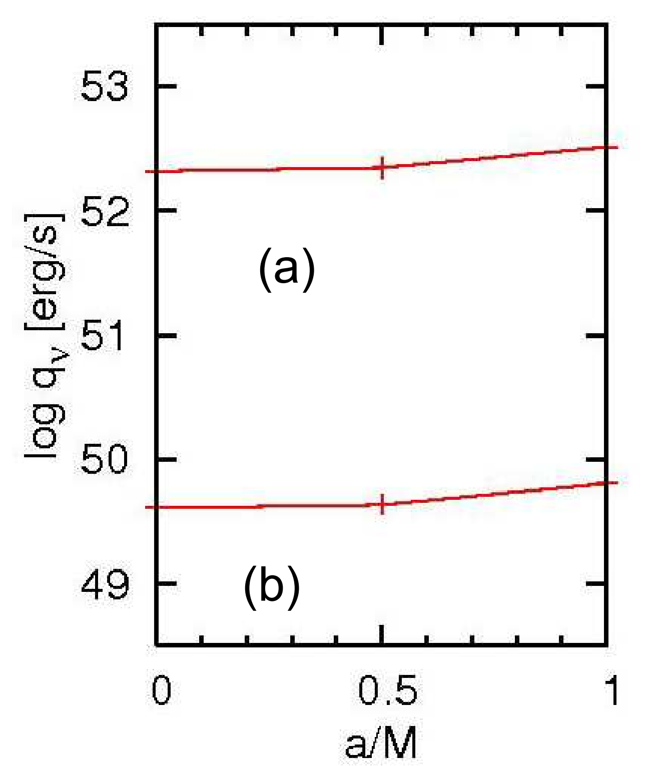


Preliminary results of Takahashi and Nagataki

Energy deposition rate due to neutrino
Pair annihilation



Energy deposition rate is enhanced because
neutrinos are trapped in the Gravitational
potential well.



Curve (a): Total energy depositon rate.
Curve (b): The same with curve (a),
But temperature of the accretion disk is
Artifitially set to be lower by a factor of 2.

BZ process should be also important.

§ Summary

Summary and Future Work

- Neutrino heating processes and magnetic fields are 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.
- Effects of general relativity should be important for the formation of relativistic jet (Efficiency of neutrino heating, Blandford-Znajek effect), which we are planning to include in the near future.