ガンマ線バースト・極超新星に於ける爆発的元素合成
Explosive Nucleosynthesis in Gamma-Ray Bursts and Hypernovae

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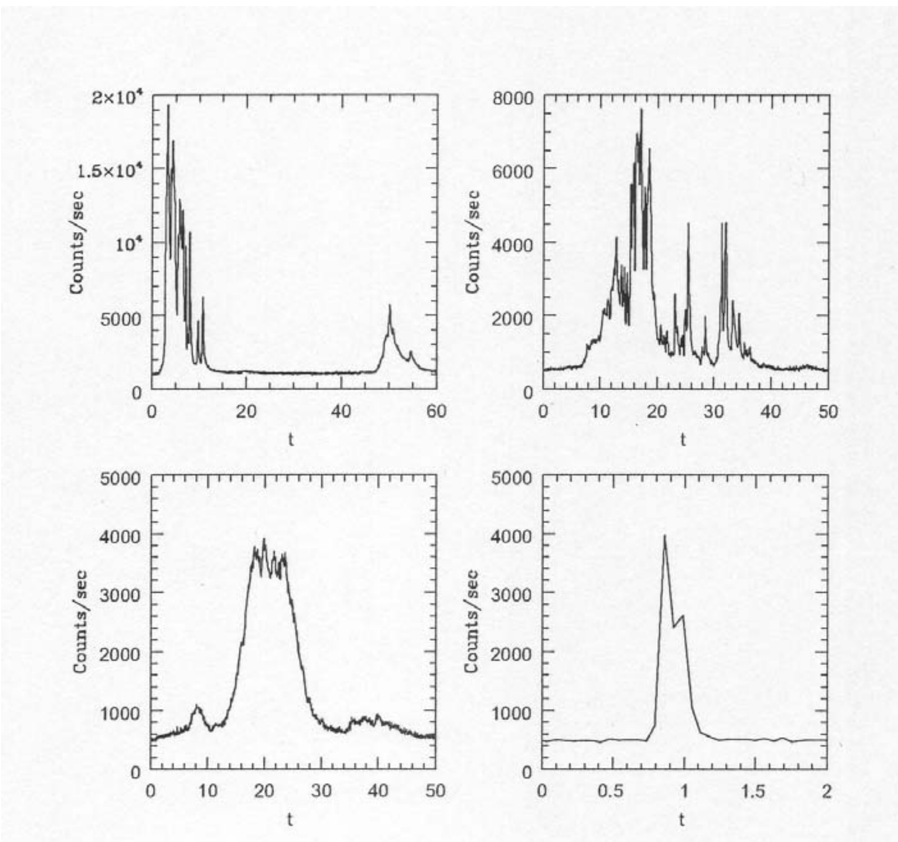
§ Introduction

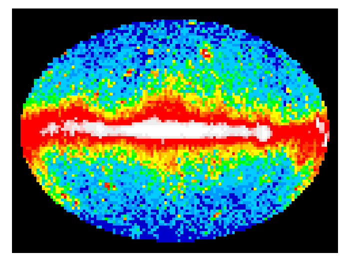
Gamma-Ray Bursts (GRBs): the Most Powerful Explosion in the Universe

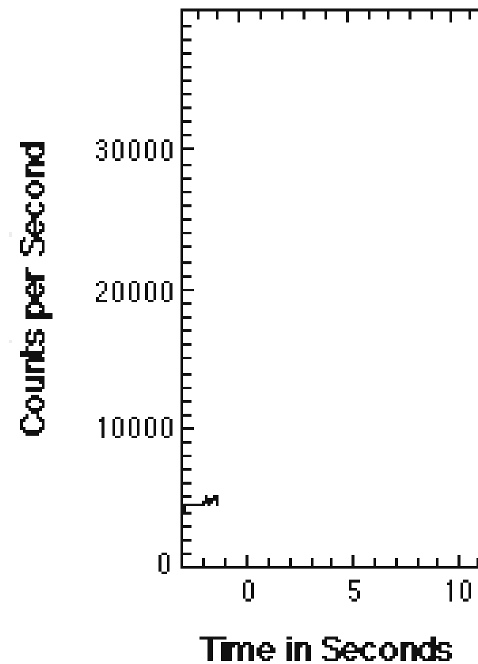
Some GRBs are found to be associated with peculiar supernovae (hypernovae) whose explosion energy is 10 times greater than normal core-collapse supernovae. Only small fraction of supernovae can have GRBs.

Counts/s



Time (sec





A GRB by CGRO

Movie of a Long GRB (Imagination)

From NASA's HP.

Short History of the Central Engine of GRBs.

- First report on the association of a GRB with a hypernova was done in 1998.
- Black Hole with Neutrino Heating?
  E.g. MacFadyen and Woosley 1999; S.N. + 2007
- Black Hole with Strong B-Fields?
  E.g. S.N. 2009, 2011.
- Neutron Star with Strong B-Fields (Magnetar)?
  E.g. Takiwaki, Kotake, S.N., Sato 2004.

BH or NS?
Neutrino or B-Field?
Outline of Explosion is still under debate.

§ Numerical Simulation of a GRB engine by a General Relativistic Magneto-Hydrodynamic (GRMHD) code.

2D/3D GRMHD Codes written by MPI.
SRHD with AMR written by MPI.

S.N. ApJ (2009).
S.N. PASJ (2011).
S.N. 2012, in prep.

General Relativistic Numerical Code is necessary to see general relativistic effects.

Energy extraction from a Black Hole (Blandford-Znajek Process) is one of them.

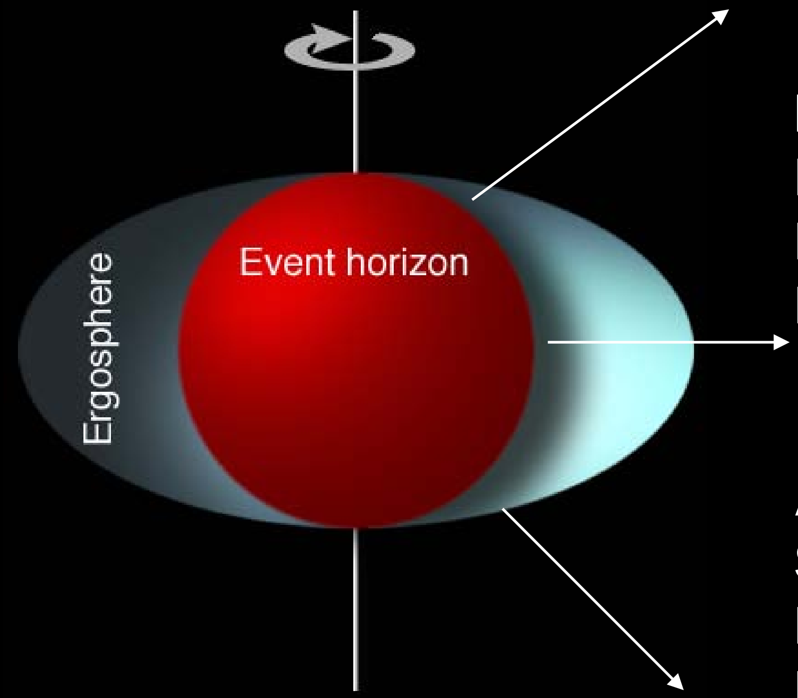
This effect may be the key process of the GRB engine.

What is Blandford-Znajek Process?

Blandford and Znajek 1977

Tanabe and S.N. PRD 2008

Energy extraction from a rotating BH: General Relativistic Effect



**In principle,
Rotation Energy of a BH can be
Extracted when particles with negative
Energy are absorbed into the BH.**

**Analytical solution (only mono-pole
Solution!) was introduced by BZ.
Nowadays, this effect can be seen
Numerically with a GRMHD code.**

Basic Equations

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

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

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

Additional Equations

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

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

Solver

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

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

↓ Newton-Raphson Method

$$P = (\rho, u, v^i, B^i)$$ Primitive Variables

Flux term (HLL Method)

$$F = \frac{c_{\min}F_R + c_{\max}F_L - c_{\max}c_{\min}(U_R - U_L)}{c_{\max} + c_{\min}}$$

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

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

Slope (2nd order in Space, 3rd in time)
Mimmod or Monotonized Center
TVD Runge-Kutta

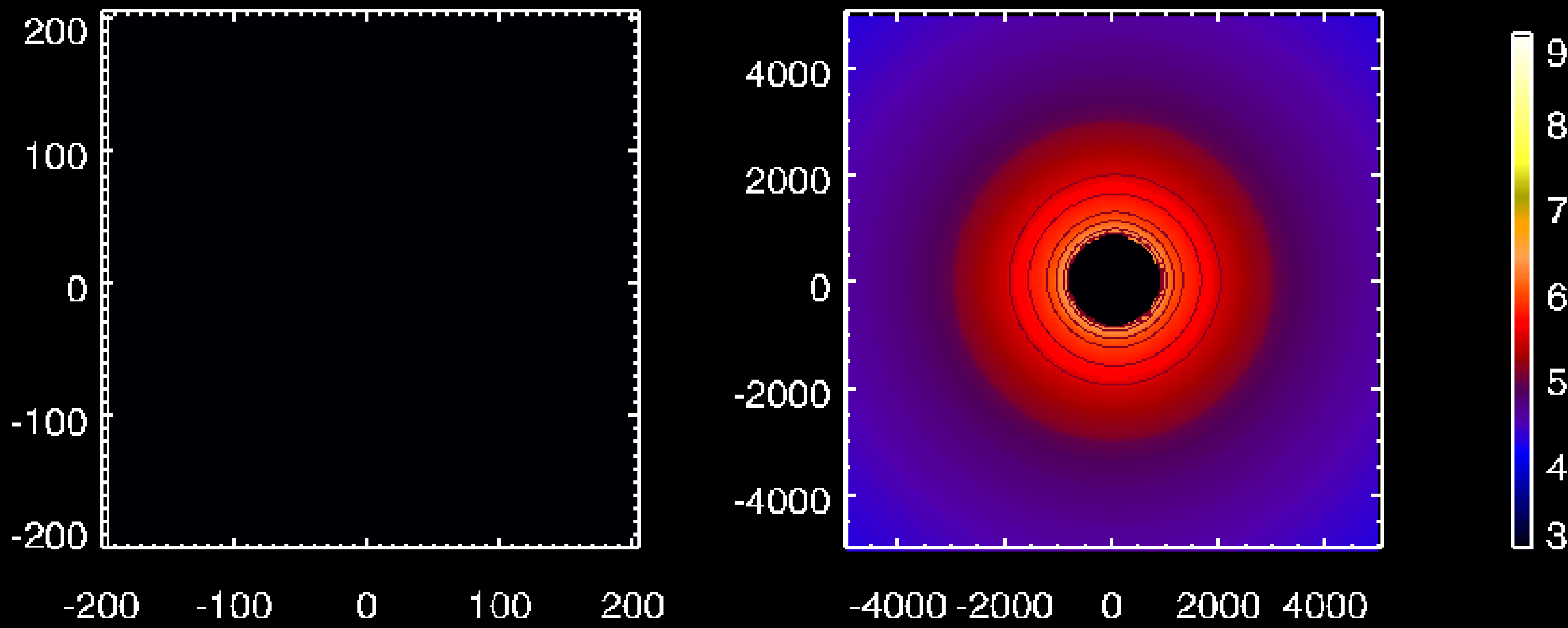
Initial Condition for GRB Simulations

S. N. 09

- Rotating Massive Stellar Model by Woosley and Heger 2006.
- Fe core is extracted and a rotating black hole is put instead.
- M_{BH}=2Msolar, a=0.5 (Fixed Kerr Metric).
- $\Gamma = 4/3$
- $A_\phi \propto \max(\rho/\rho_{\rm max} - 0.2, 0) \sin^4\theta$
- Minimum value of $p_{\rm gas}/p_{\rm mag} = 10^2$

Simulation of a Collapsar

S.N. 2009



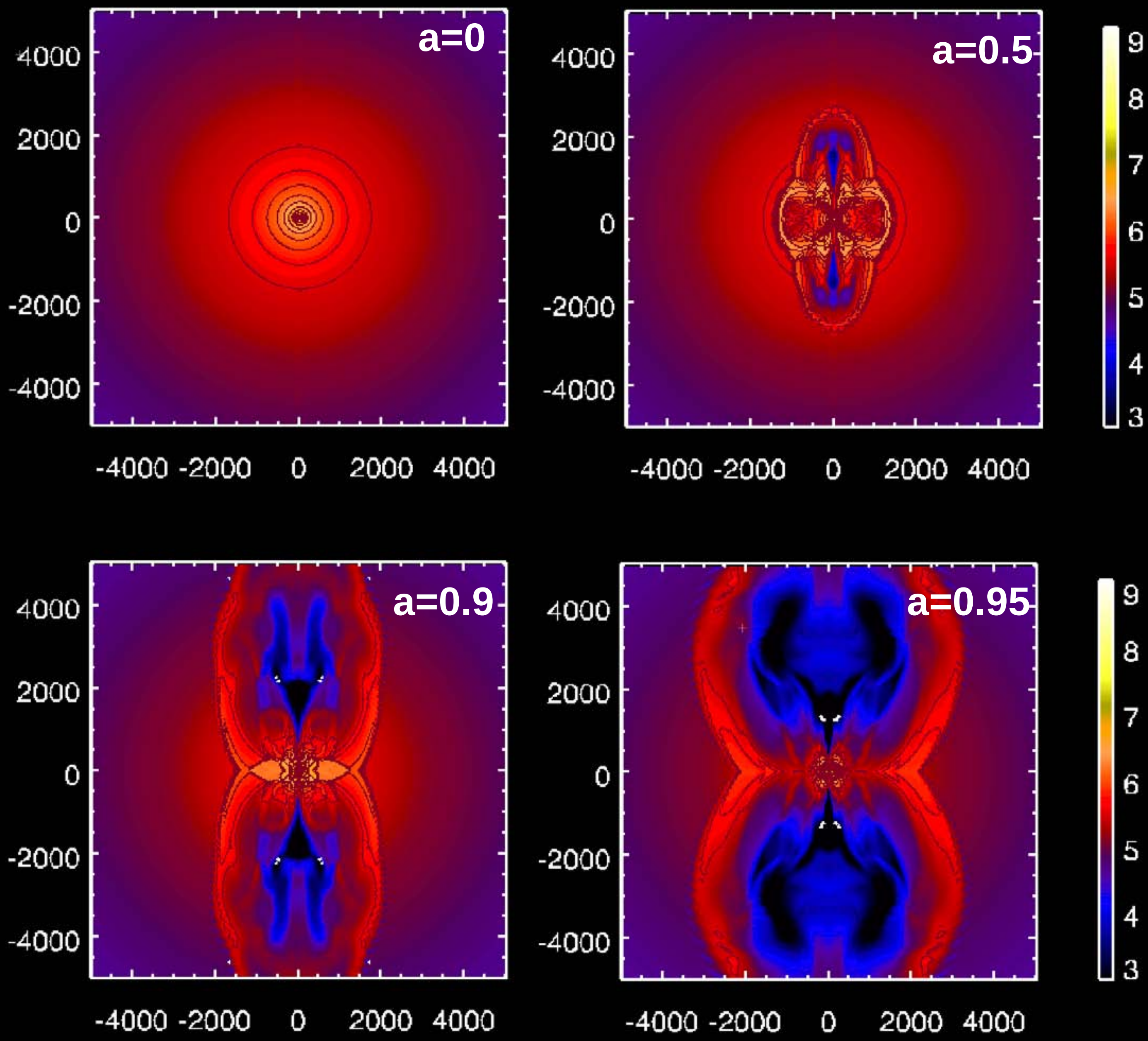
R<200

R<5000

Density contour in logarithmic scale (g/cc)

Final time corresponds to 1.77sec. R=200 corresponds to 600km.

Dependence of Dynamics on Rotating Black Hole



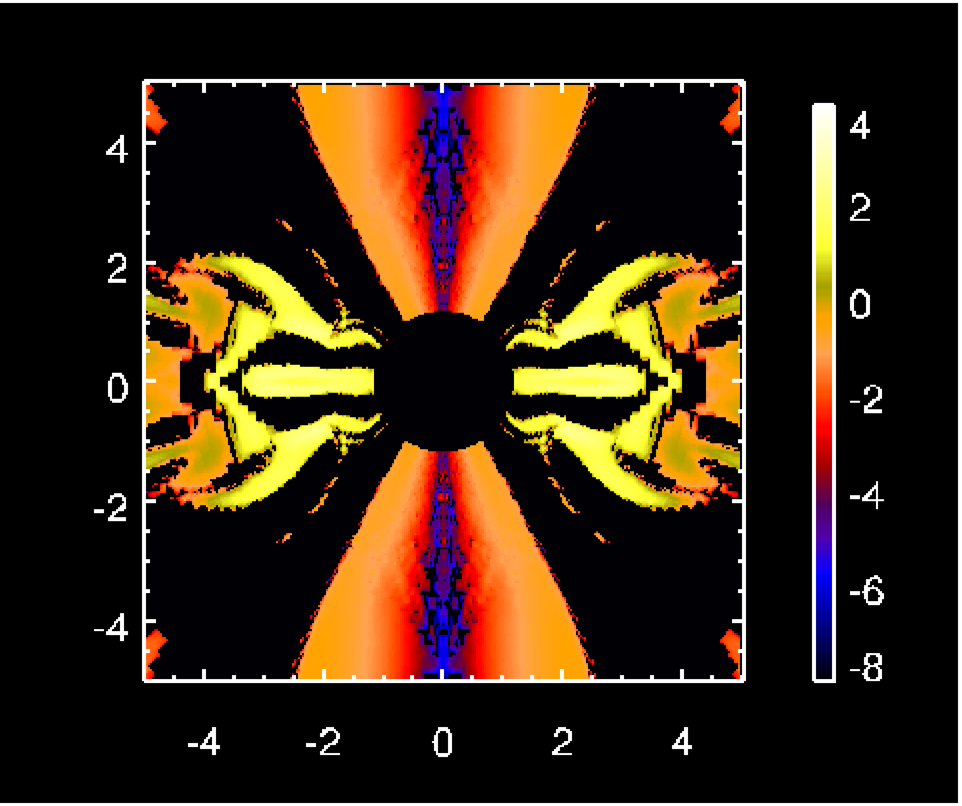
S.N. 2011

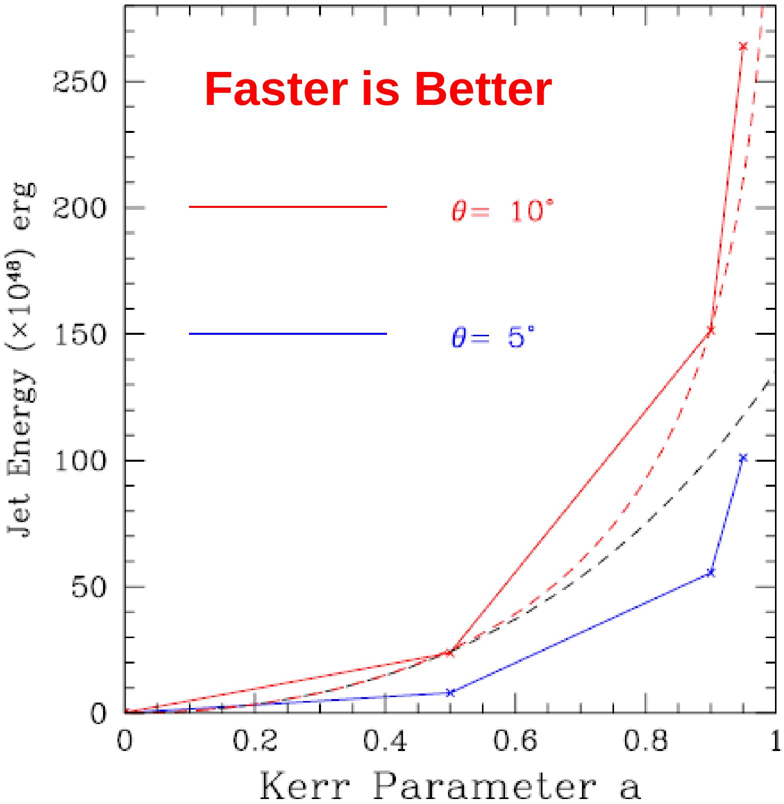
Density Structure
at T=1.6sec.

Not the Time
Sequence, but
For Different Models
With different Kerr
parameters.

Blandford-Znajek Flux and Jet Energy

S.N. 2011



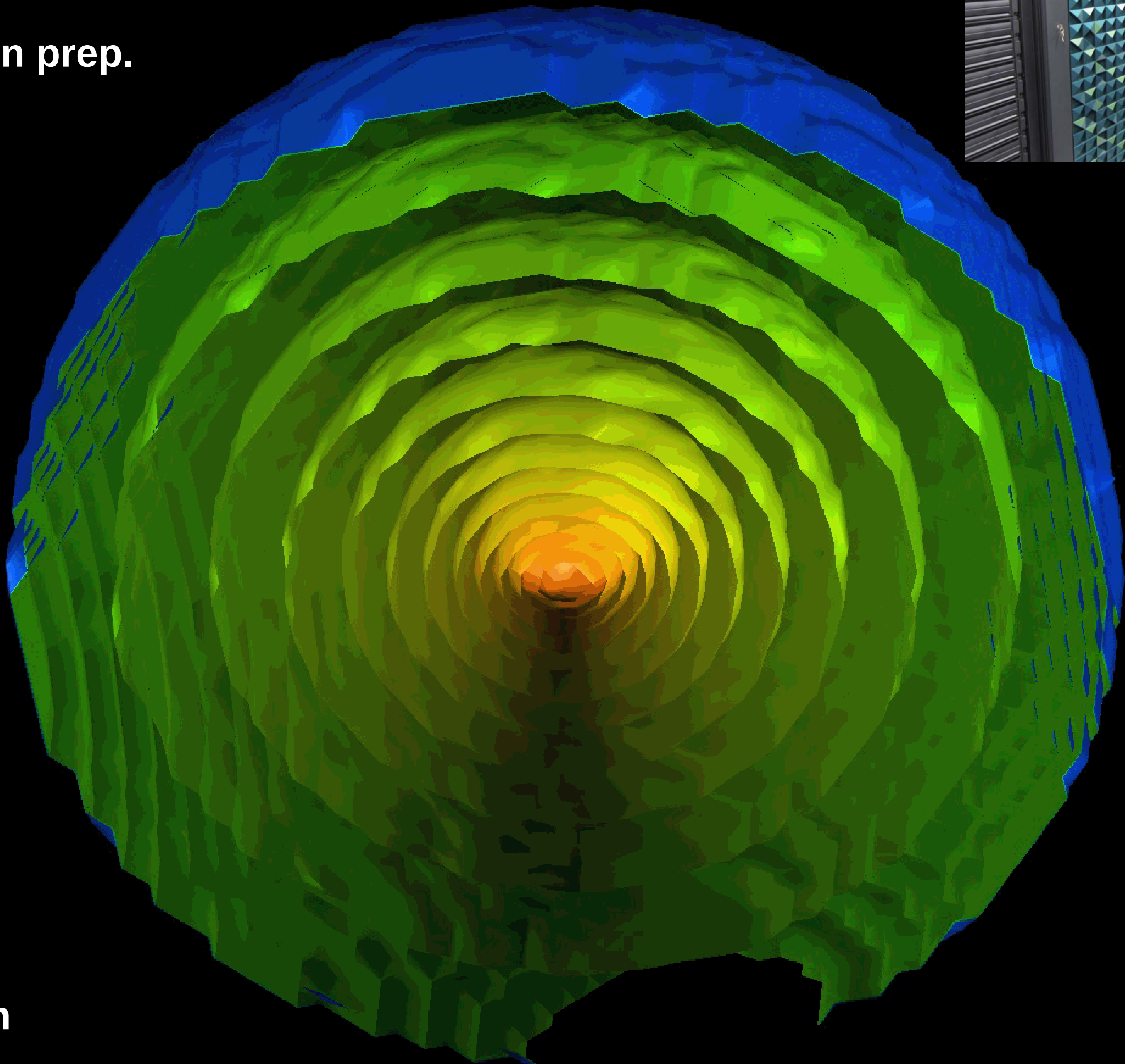


BZ (outgoing poynting)-Flux
In unit of 10^50 erg/s/Sr at
T=160000 (1.5760sec).
Kerr Parameter, a=0.95.
Time variability is also triggered by the BH?

Jet Energy at t=1.5750 sec for a=0, 0.5, 0.9, 0.95 (Solid Curves).
Dotted Curves represents analytical Solution by Tanabe
And S.N. (2008) and Tchekhovskoy et al. (2010) with B=5*10^14G.

3D-GRMHD Simulation of GRBs

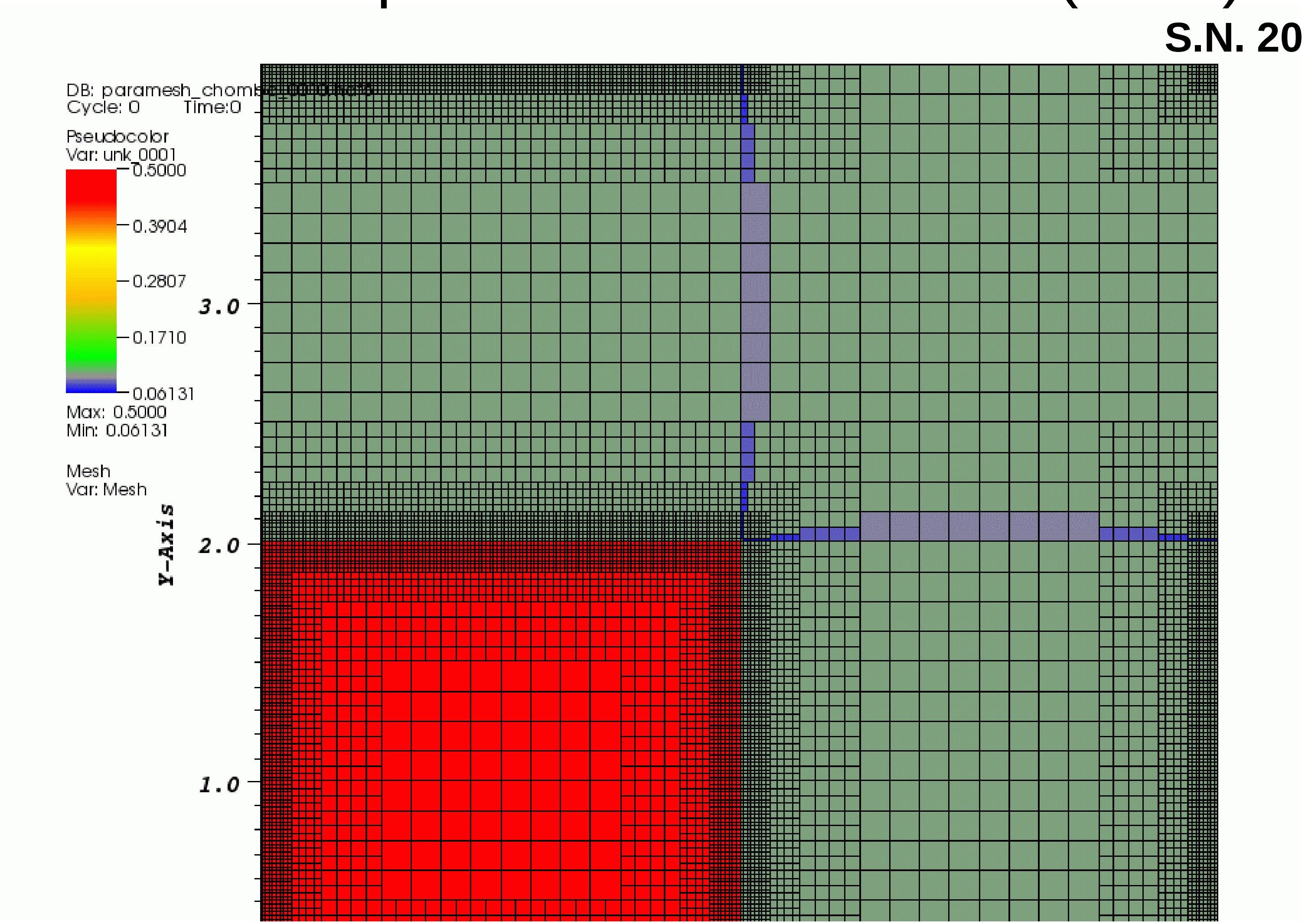
S.N. 2012, in prep.



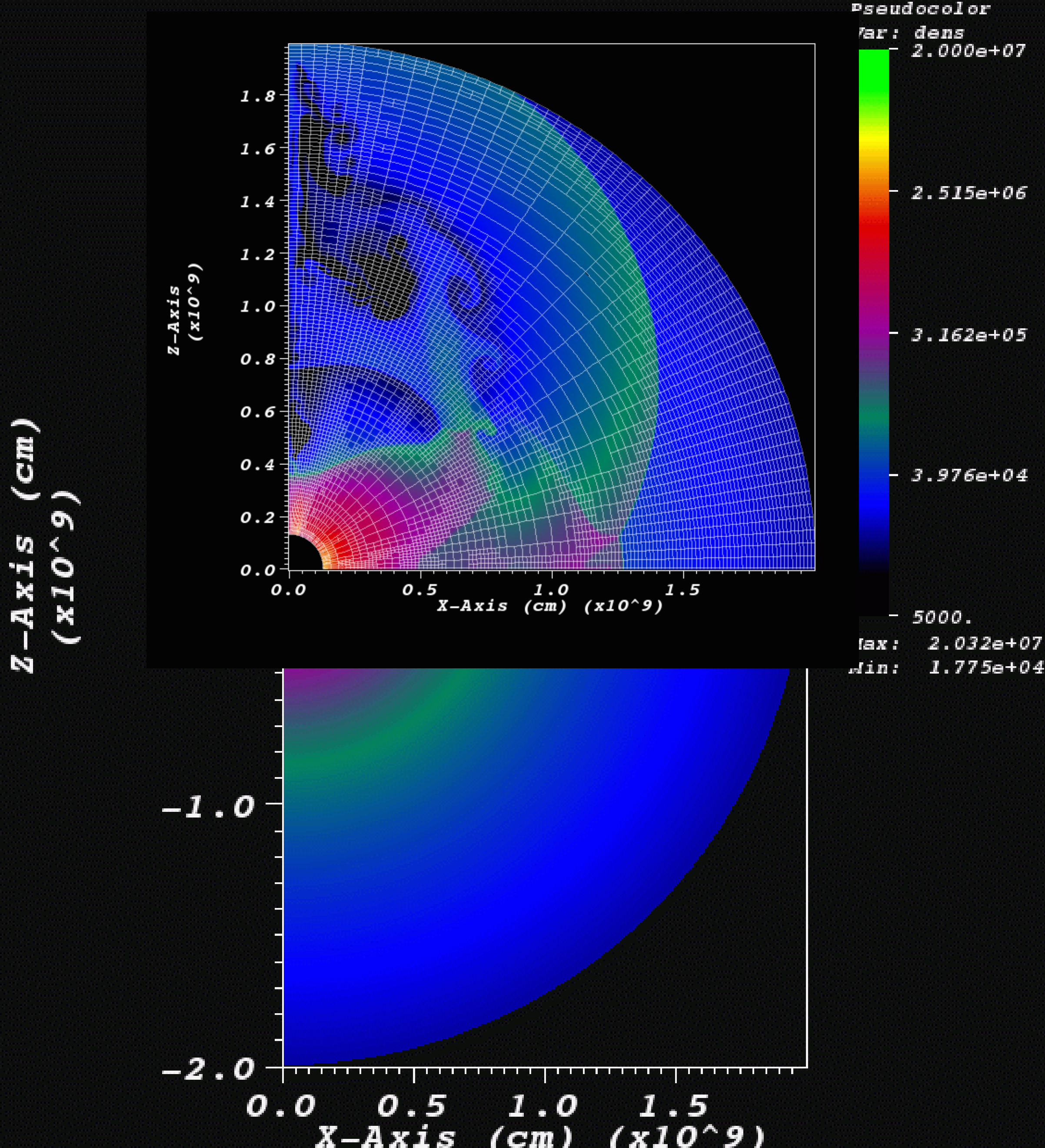
～3000km

Combining SRHD Code with Adaptive Mesh Refinement (AMR)

S.N. 2012, in prep.



Paramesh:
http://www.physics.drexel.edu/~olson/paramesh-doc/Users_manual/amr.html



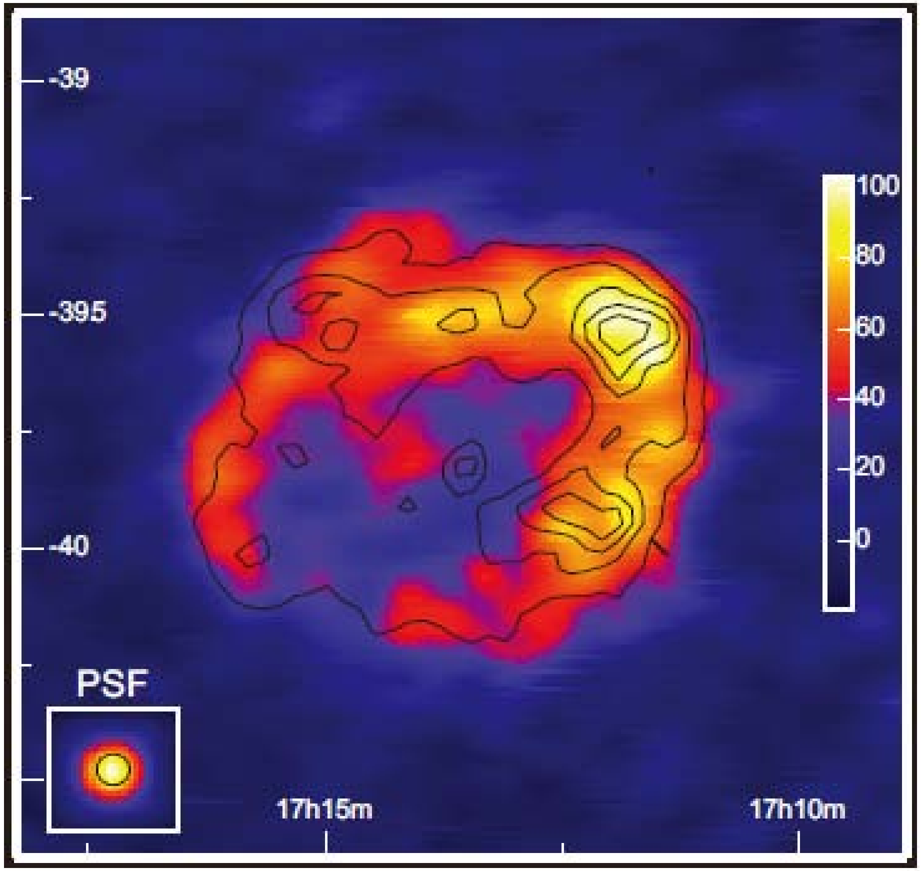
Explosive Nucleosynthesis
In Jet-Like Sne/GRBs.
Ono and S.N. 2011, in prep.

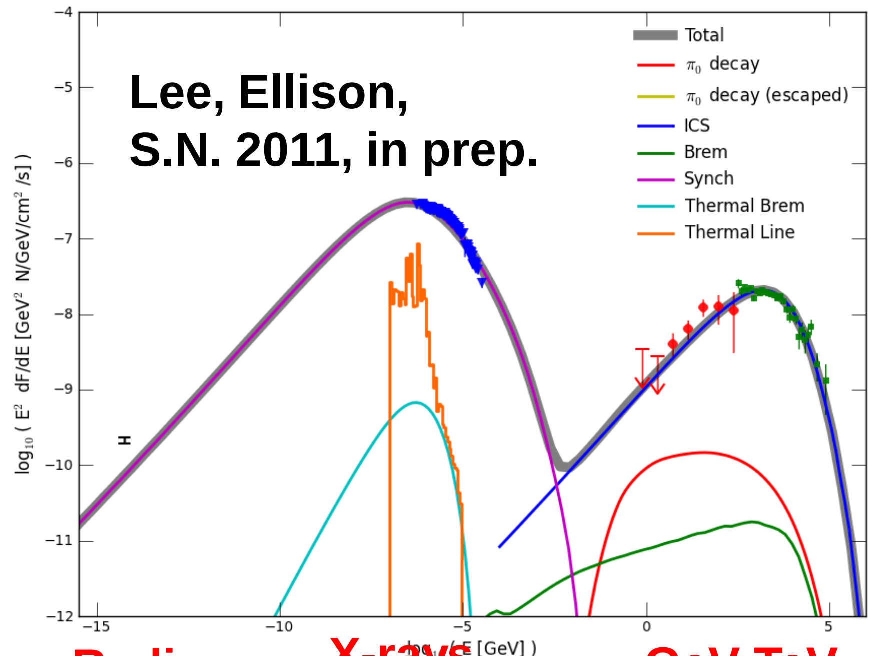
Flash code with some
Micro-physics is used
Currently.

We are planning to couple
My GRMHD code with
Micro-physics in Flash
Such as Nuclear-Reactions
To discuss 56Ni production.

Dr. Ono at YITP (2011-)

Supernova Remnant Phase





Radio

X-rays

GeV-TeV Gamma-rays

Shiu-Hang (Herman) Lee at YITP (2011-)

RXJ1713 in TeV-Gamma (color, HESS)
And X-rays (contour, ASCA)
Age is about 1600yrs.

Supernovae and Gamma-Ray Bursts in Kyoto, 2013

- Oct.-Nov. in 2013 (preliminary).
- 1 month workshop at YITP.

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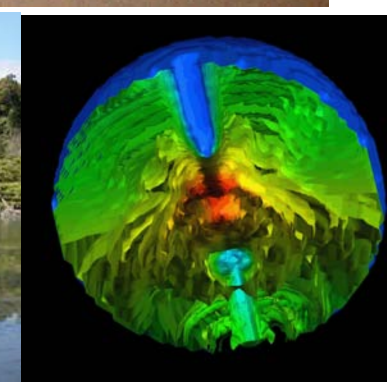

§ **Summary**

Summary

- General Relativistic Magneto-Hydrodynamic (GRMHD) Code has been developed from scratch.
- Fast-rotating Black Hole is better to produce an energetic GRB jet (Faster is Better) due to Blandford-Znajek process.
- GRB simulations by 3D GRMHD code are being done.
- Adaptive Mesh Refinement has been attached to SRHD code.
- Explosive Nucleosynthesis (56Ni production) is being studied by Flash code using nuclear reaction network.
- Supernova remnants are being studied taking account of particle acceleration and emission mechanisms including line emissions from heavy nuclei in SNRs.
- One month Conference on SNe and GRBs will be held in Kyoto, 2013.