ガンマ線バースト中心エンジンに関する理論的・数値的研究

YUKAWA INSTITUTE FOR
THEORETICAL PHYSICS

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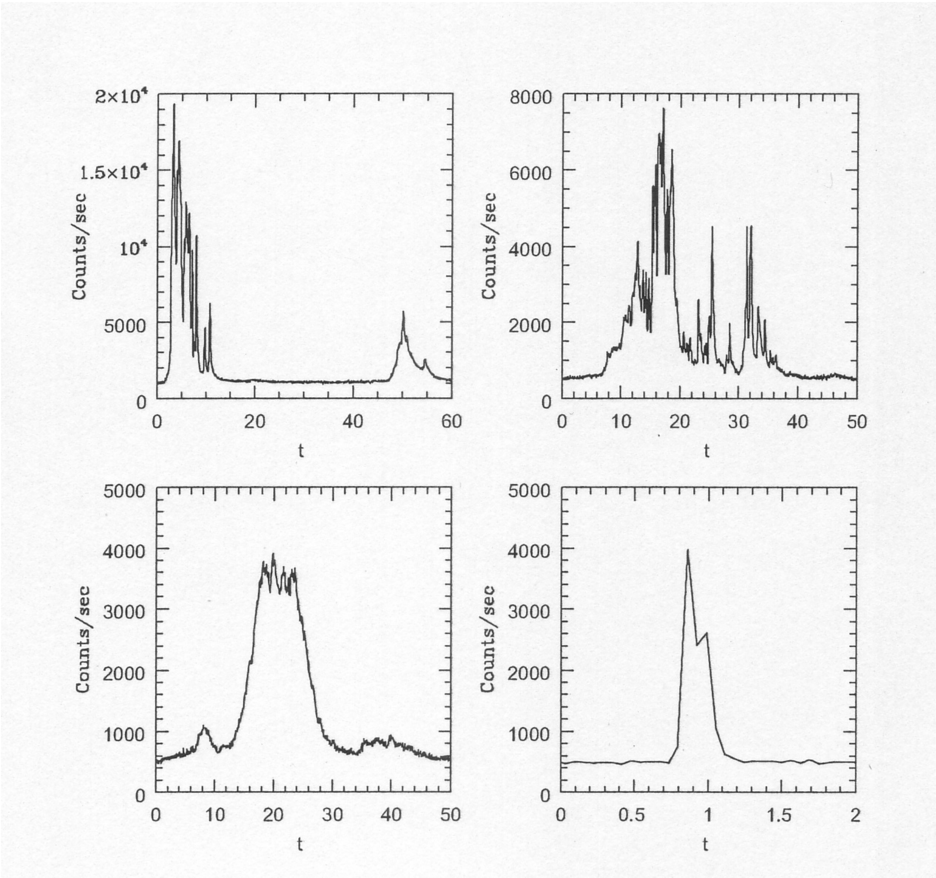
2011年12月28日
基研「超新星爆発と数値シミュレーション」

§ Introduction

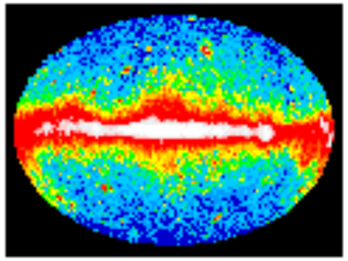
Gamma-Ray Bursts (GRBs): the Most Powerful Explosion in the Universe

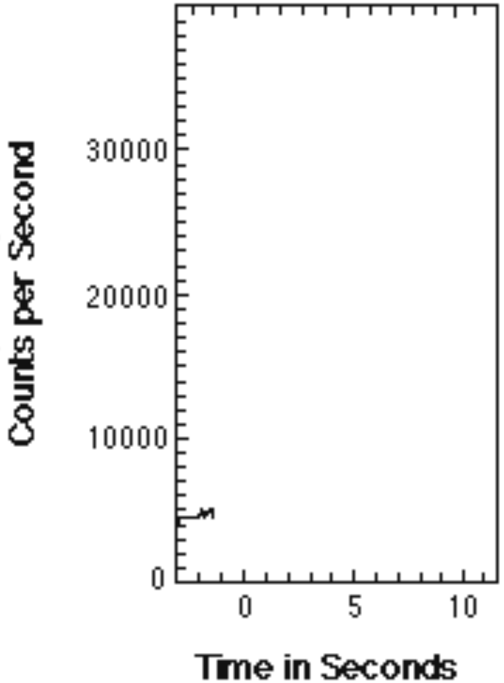
Some GRBs are found to be associated with peculiar supernovae (hypernovae) whose explosion energy is 10 times greater than normal core-collapse supernovae. Only small fraction of supernovae can have GRBs.

Counts/s



Time (sec





A GRB by CGRO

Movie of a Long GRB (Imagination)

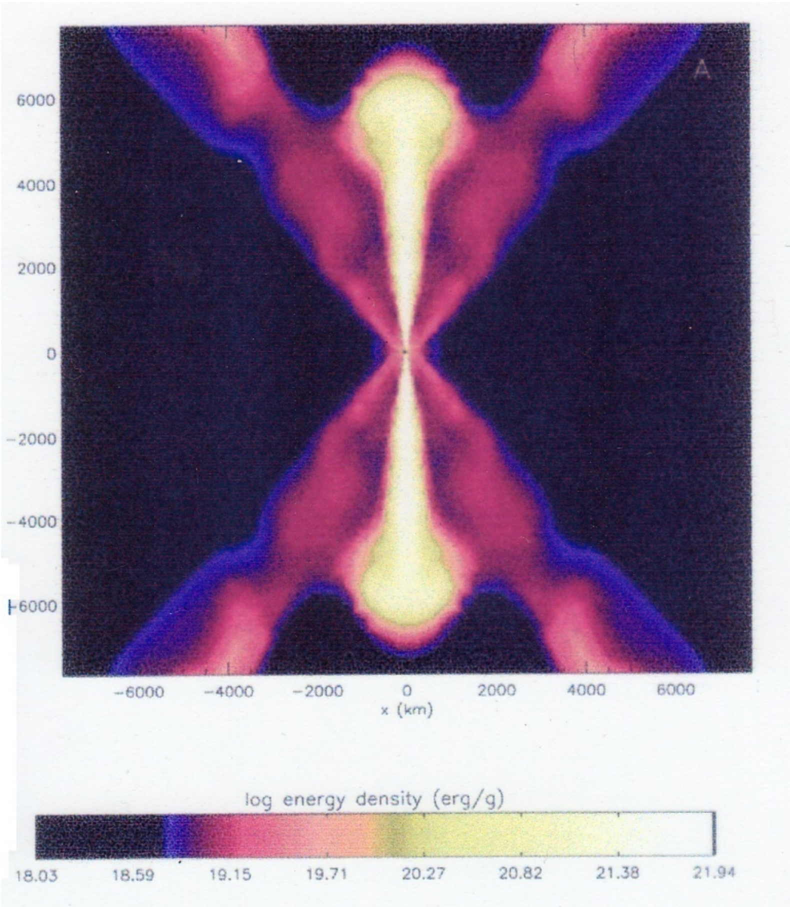
From NASA's HP.

Short History of the Central Engine of GRBs.

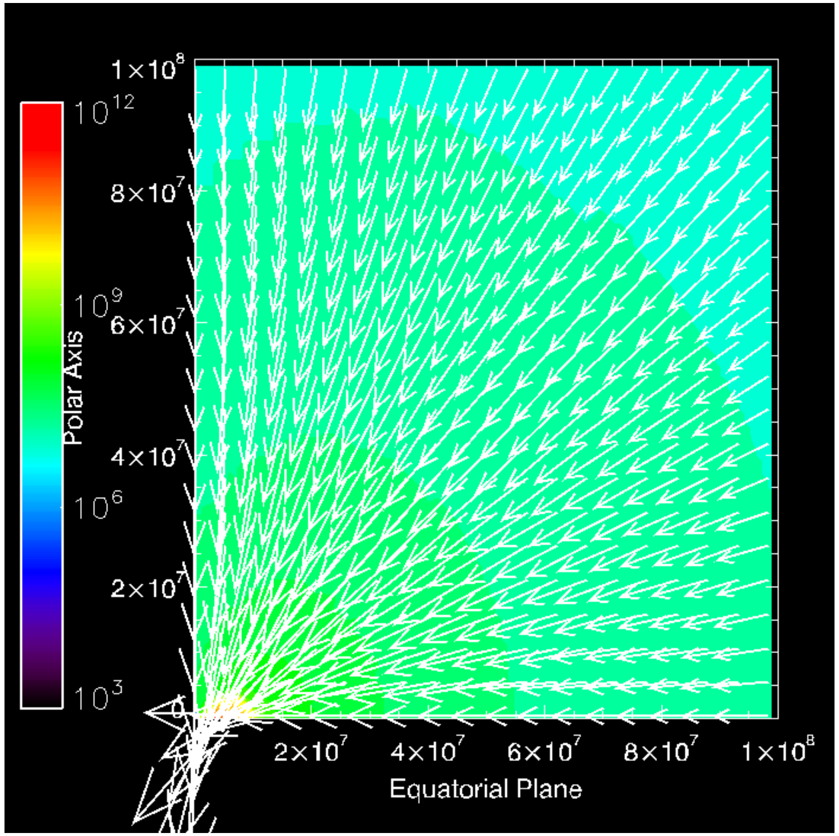
- First report on the association of a GRB with a hypernova was done in 1998.
- Black Hole with Neutrino Heating?
  E.g. MacFadyen and Woosley 1999; S.N. + 2007
- Black Hole with Strong B-Fields?
  E.g. S.N. 2009, 2011.
- Neutron Star with Strong B-Fields (Magnetar)?
  E.g. Takiwaki, Kotake, S.N., Sato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

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

Black Hole with Neutrino Heating



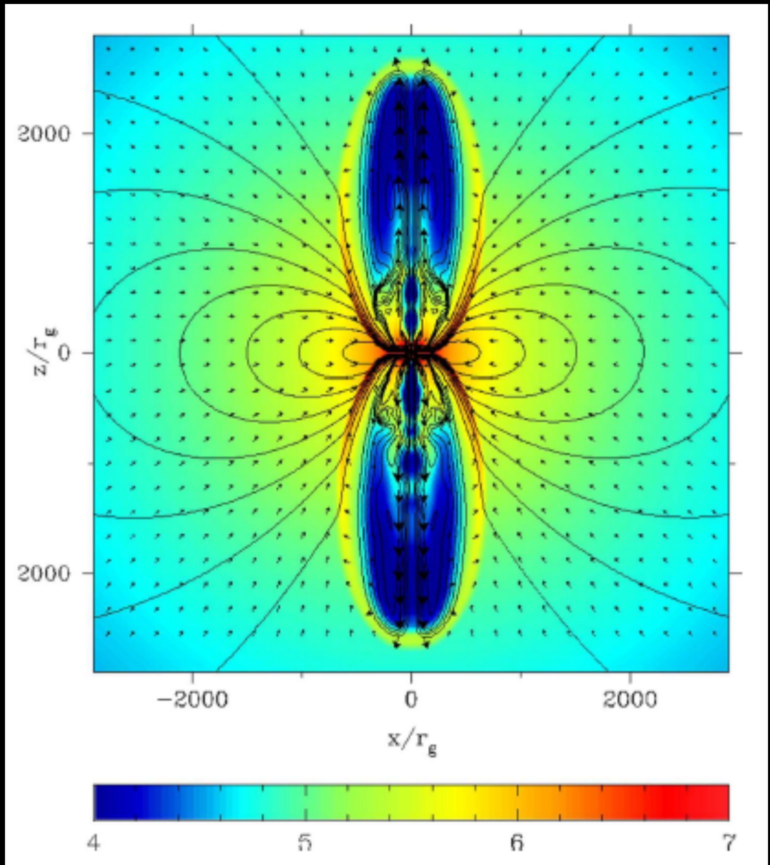
MacFadyen and Woosley 99
Newtonian, Neutrinoなし。

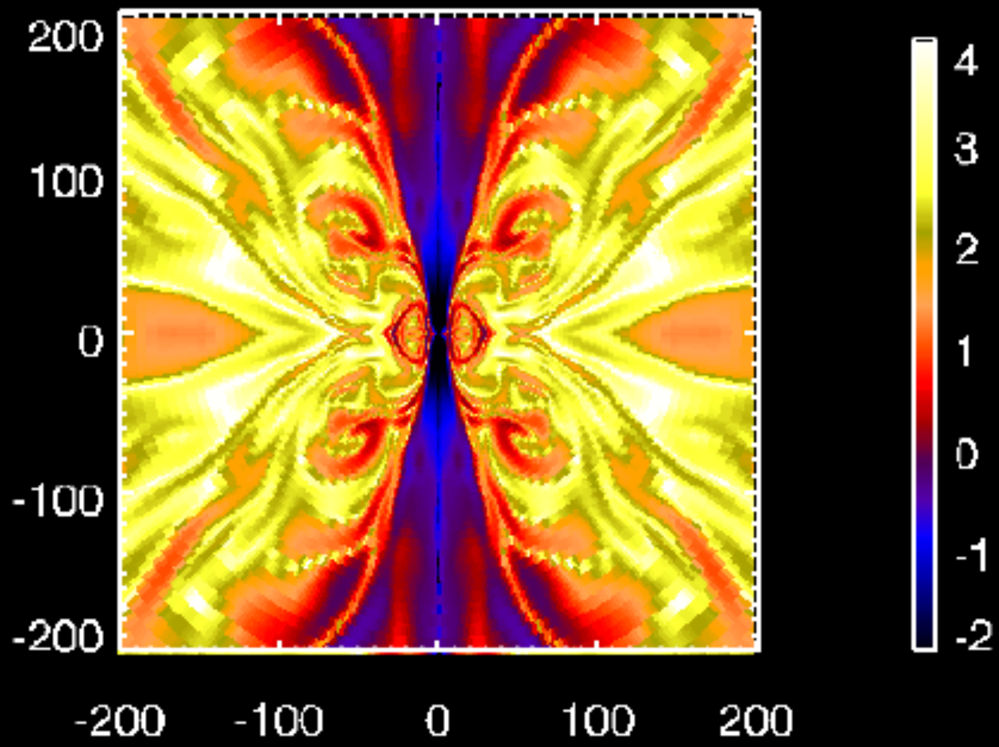


S.N.+07
Newtonian, Neutrinoあり。

But, Harikae+12, also Sekiguchi+12,…

Black Hole with Strong B-Fields



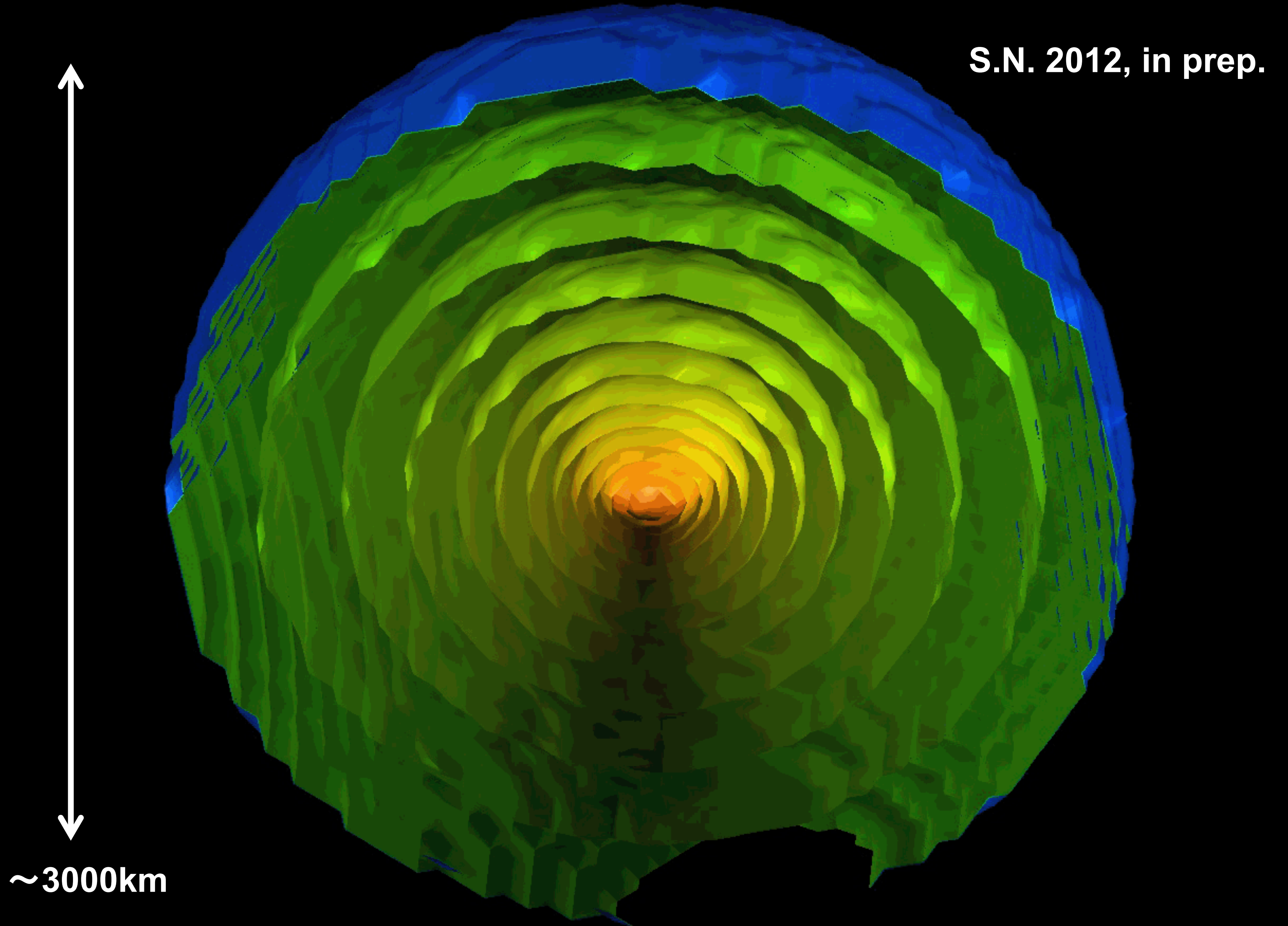


Barkov and Komissarov 08
2D-GRMHD, a=0.9
With Some Microphysics
Γ< a few.

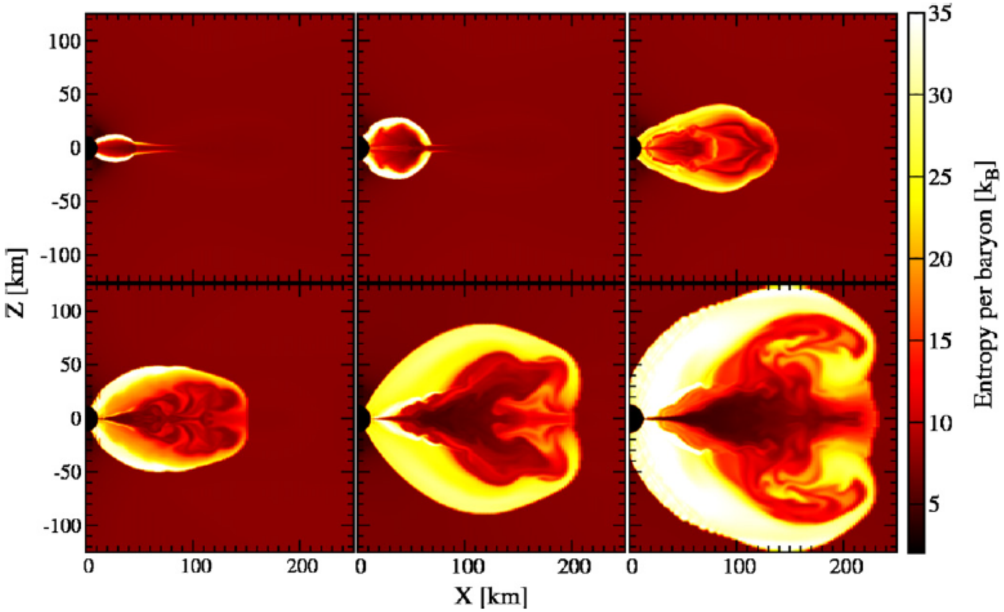
S.N. 09
2D-GRMHD, a=0.9
Without Microphysics.
Γ< a few.

See also Harikae+09.

3D-GRMHD Simulation of GRBs



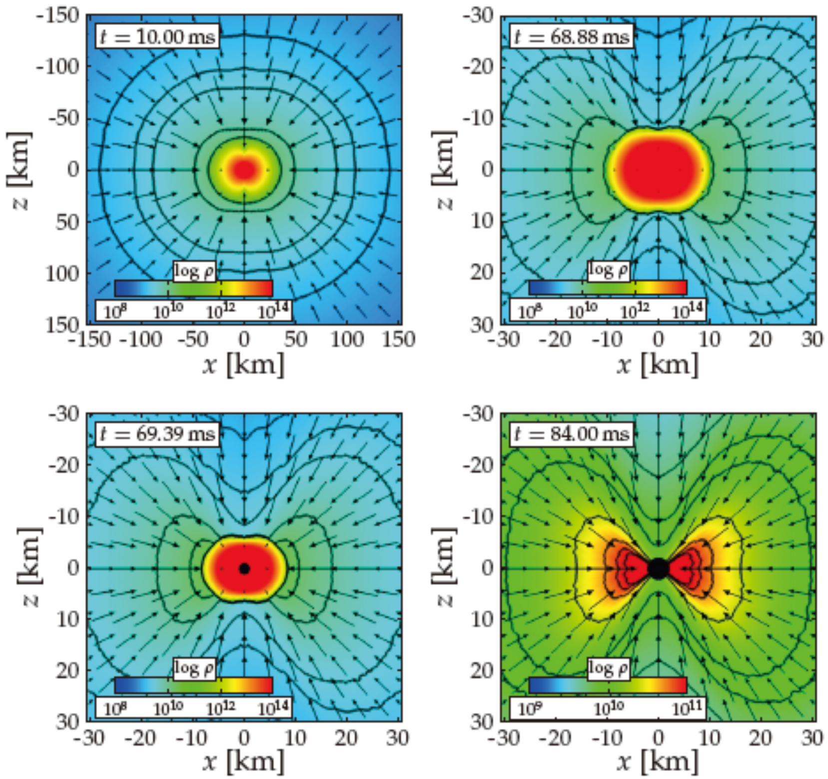
Black Hole Formation



Contours of entropy per baryon

Full 2D-GRHD with Microphysics

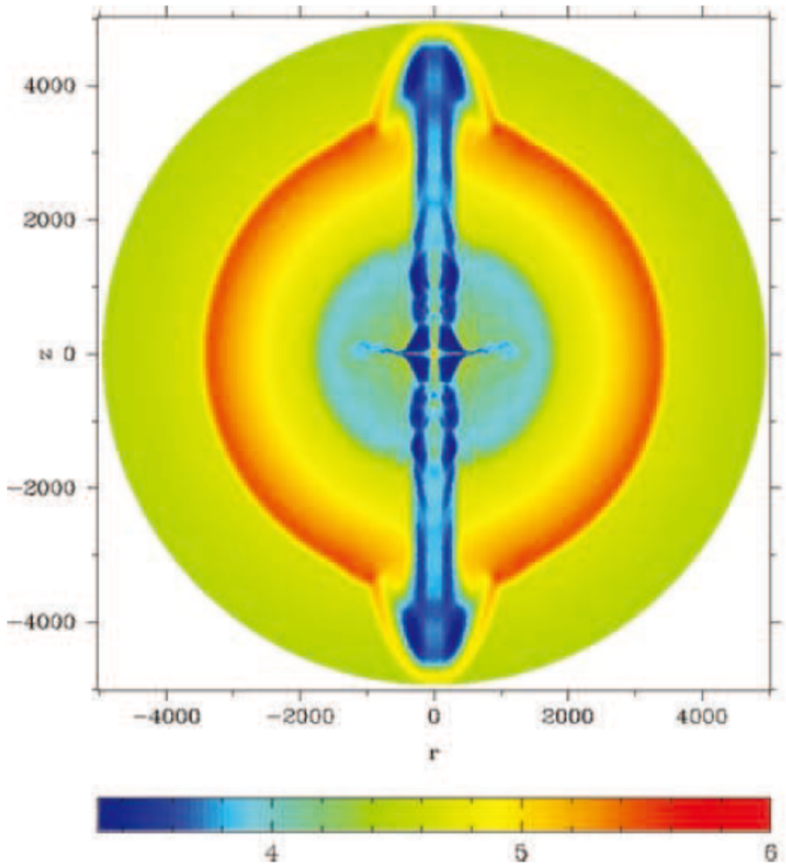
Sekiguchi and Shibata 11



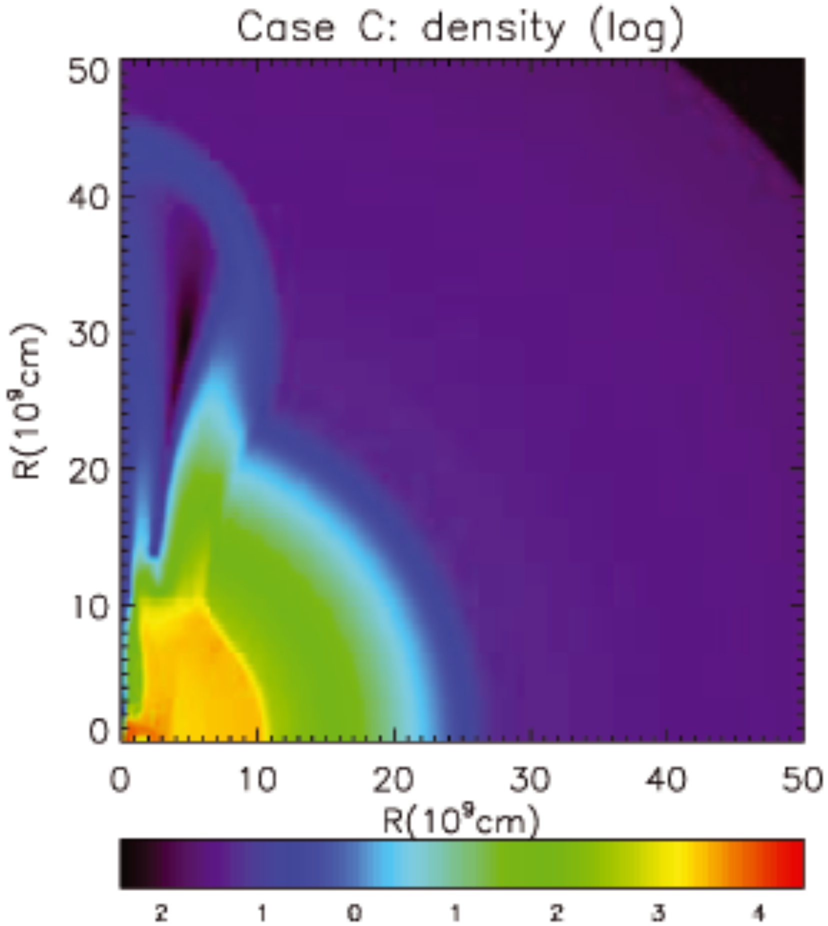
Full 3D-GRHD without Microphysics

Ott+11

Magnetar Scenario



Komissarov and Barkov 07
2D-GRMHD with some Microphysics
v^r/c. ~0.5. See also Takiwaki+09



Bucciantini+09
2D-SRMHD without Microphysics
Lorentz factor = 5-10

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

2D/3D GRMHD Codes written by MPI.

2D/3DSRMHD with AMR written by MPI.

（仮）**Y**uk**A**wa institute's **MA**gne**TO**-hydro (**YAMATO**) code

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.

Basic Equations

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

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

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

Solver

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

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

↓ Newton-Raphson Method

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

Additional Equations

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

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

Flux term (HLL Method)

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

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

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

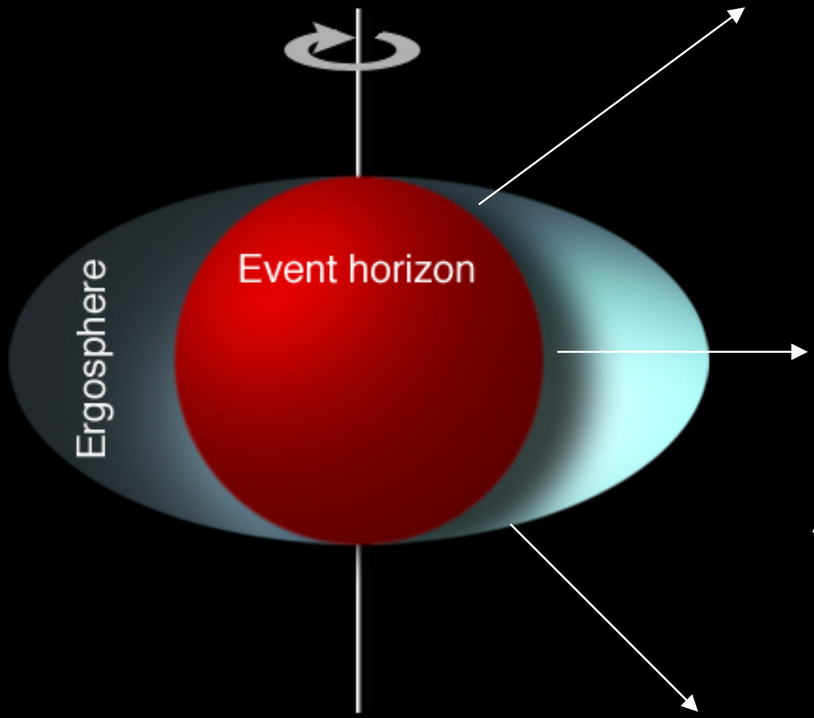
Slope (2nd order in Space, 3rd in time)
Mimmod or Monotonized Center
TVD Runge-Kutta

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!) is obtained only for a slowly rotating BH. There is no constraint For GRMHD simulations.

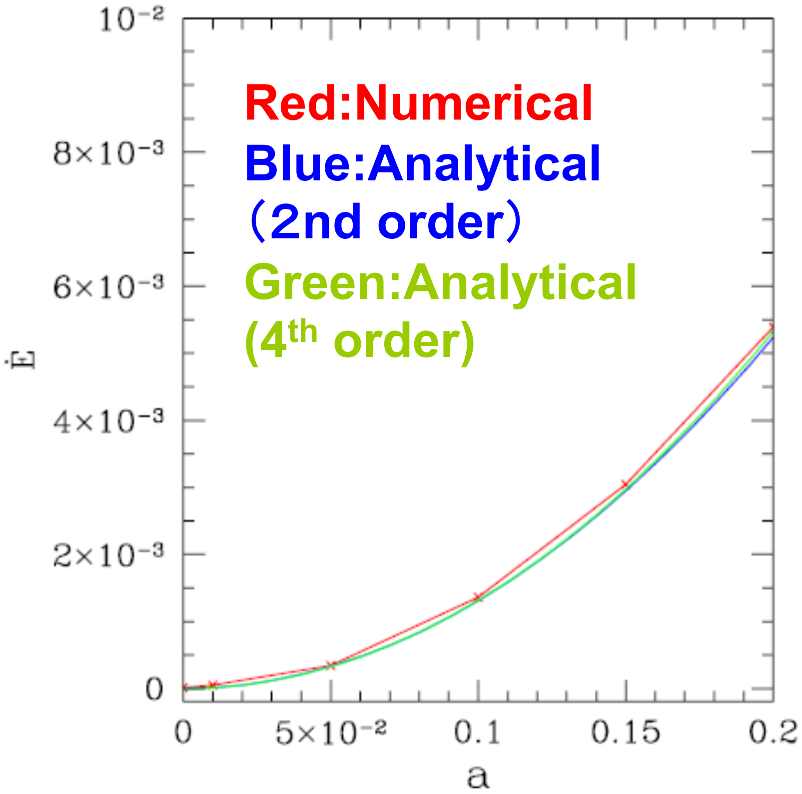
This solution can be used to check the validity of numerical codes.

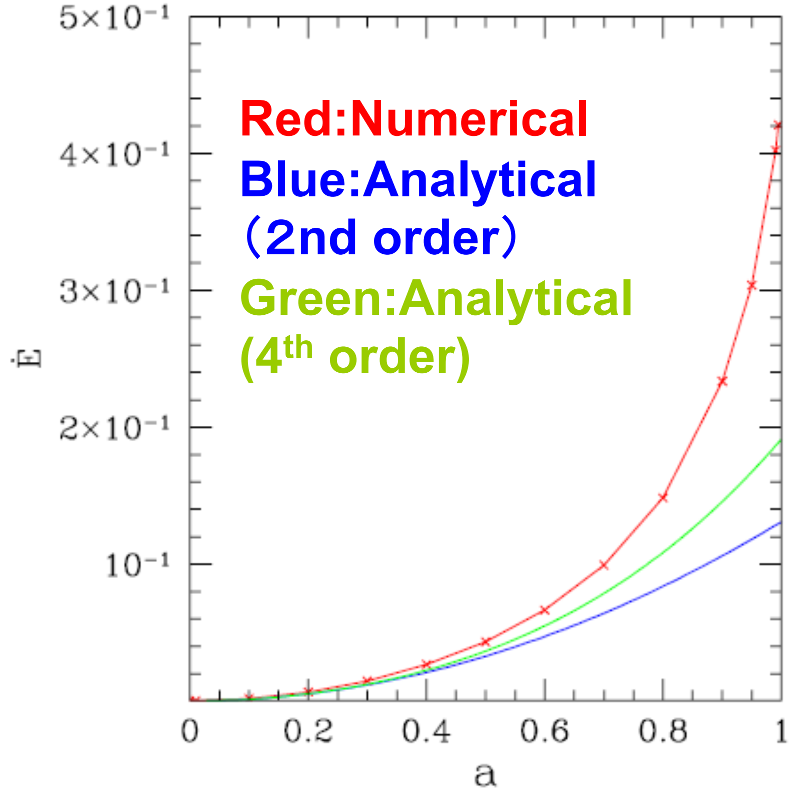
Higher Order Terms of BZ mono-pole Solution

Numerical results for the conserved Poyinting Flux.

Tanabe and S.N. (2008) PRD.

T=200, c=G=M=1





Analytical (for a<<1) :

$$\dot{E} = \frac{C^2\pi}{24}\frac{a^2}{M^2} + \frac{\pi C^2}{1080}\frac{a^4}{M^4}(56 - 3\pi^2)$$

c.f. Blandford and Znajek (1977)
Ruben (2004)

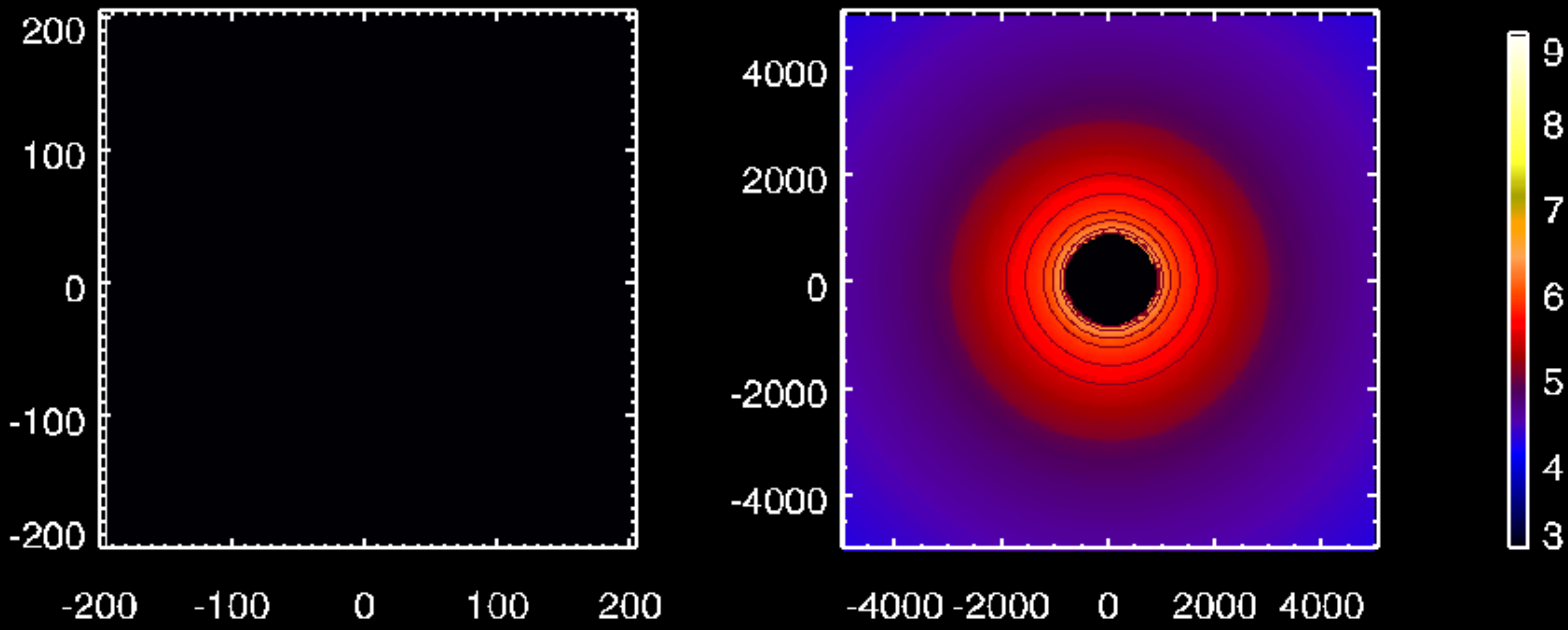
Initial Condition for GRB Simulations

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).
- $\Gamma = 4/3$
- $A_\phi \propto \max(\rho/\rho_{\max} - 0.2, 0)\sin^4\theta$
- Minimum value of $p_{\rm gas}/p_{\rm mag} = 10^2$

Simulation of a Collapsar

S.N. 2009



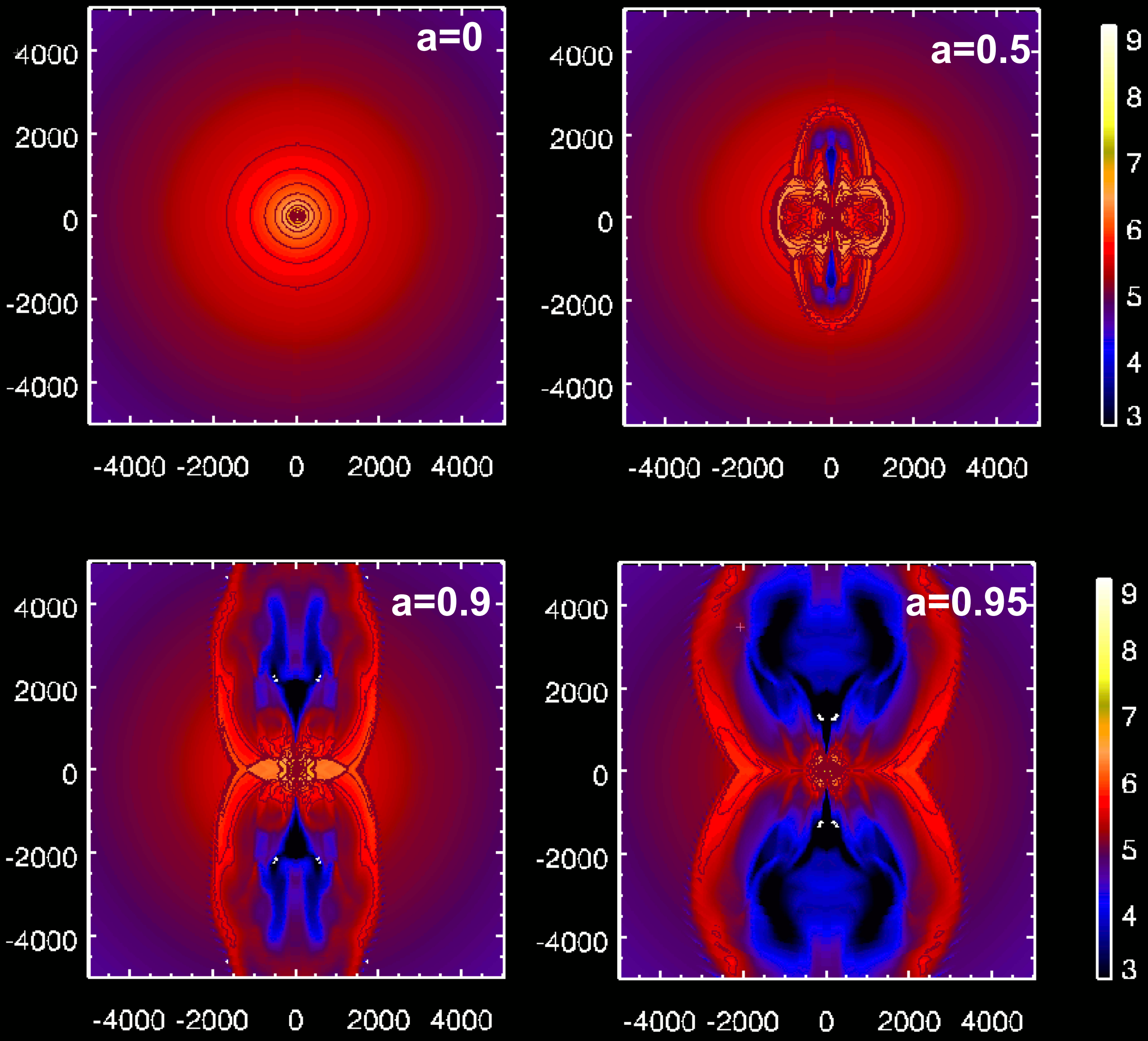
R<200

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



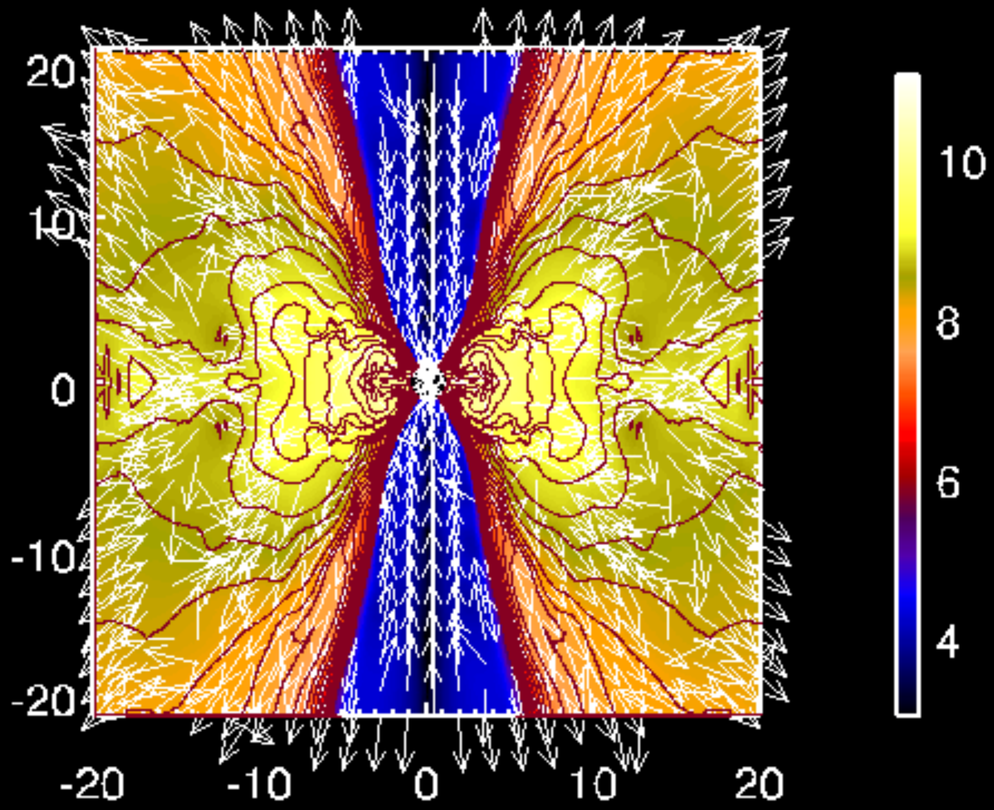
S.N. 2011

Density Structure
at T=1.6sec.

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

Stagnation Region

S.N. (2010)

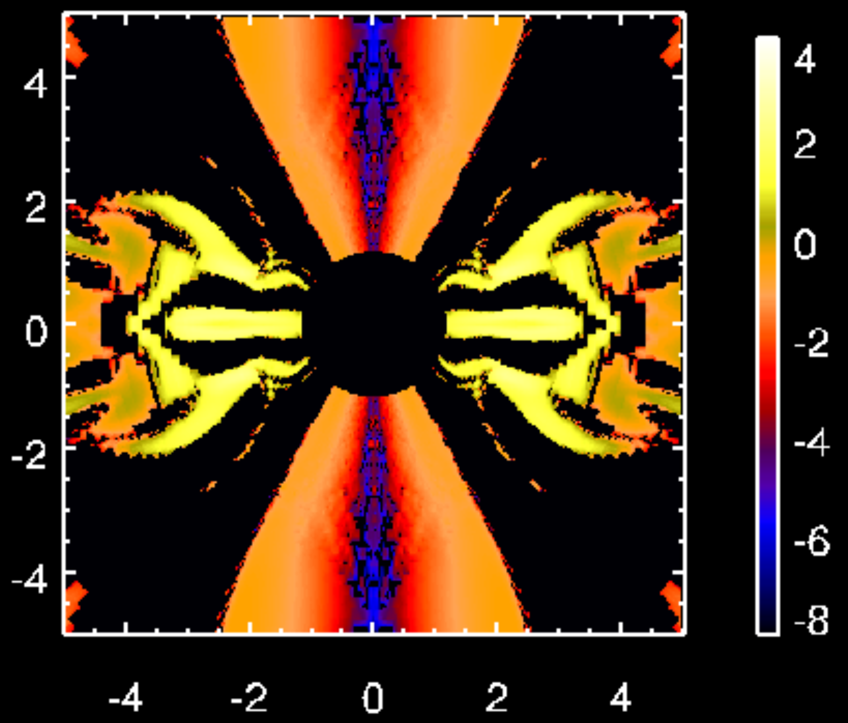


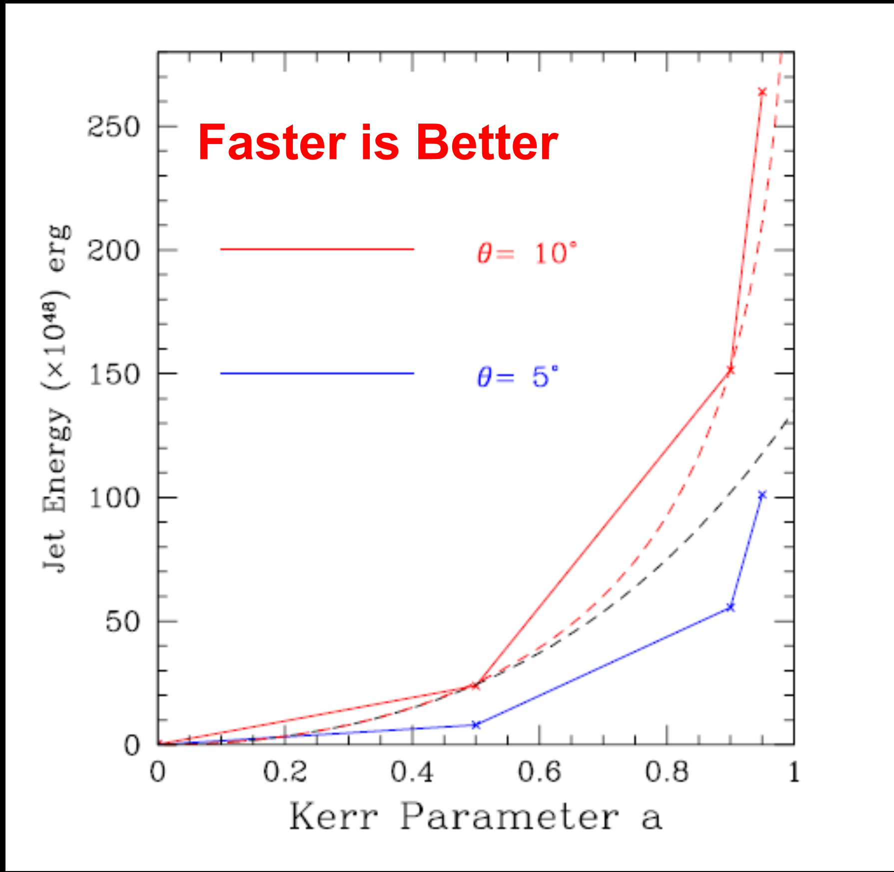
Kerr Parameter, a=0.95
T=160000 (=1.5760 sec).
Stagnation Region can be seen
At R=15 (=45km) in the Jet.

Density Contours in logarithmic scale (g/cc) with Velocity Fields

Blandford-Znajek Flux and Jet Energy

S.N. 2011



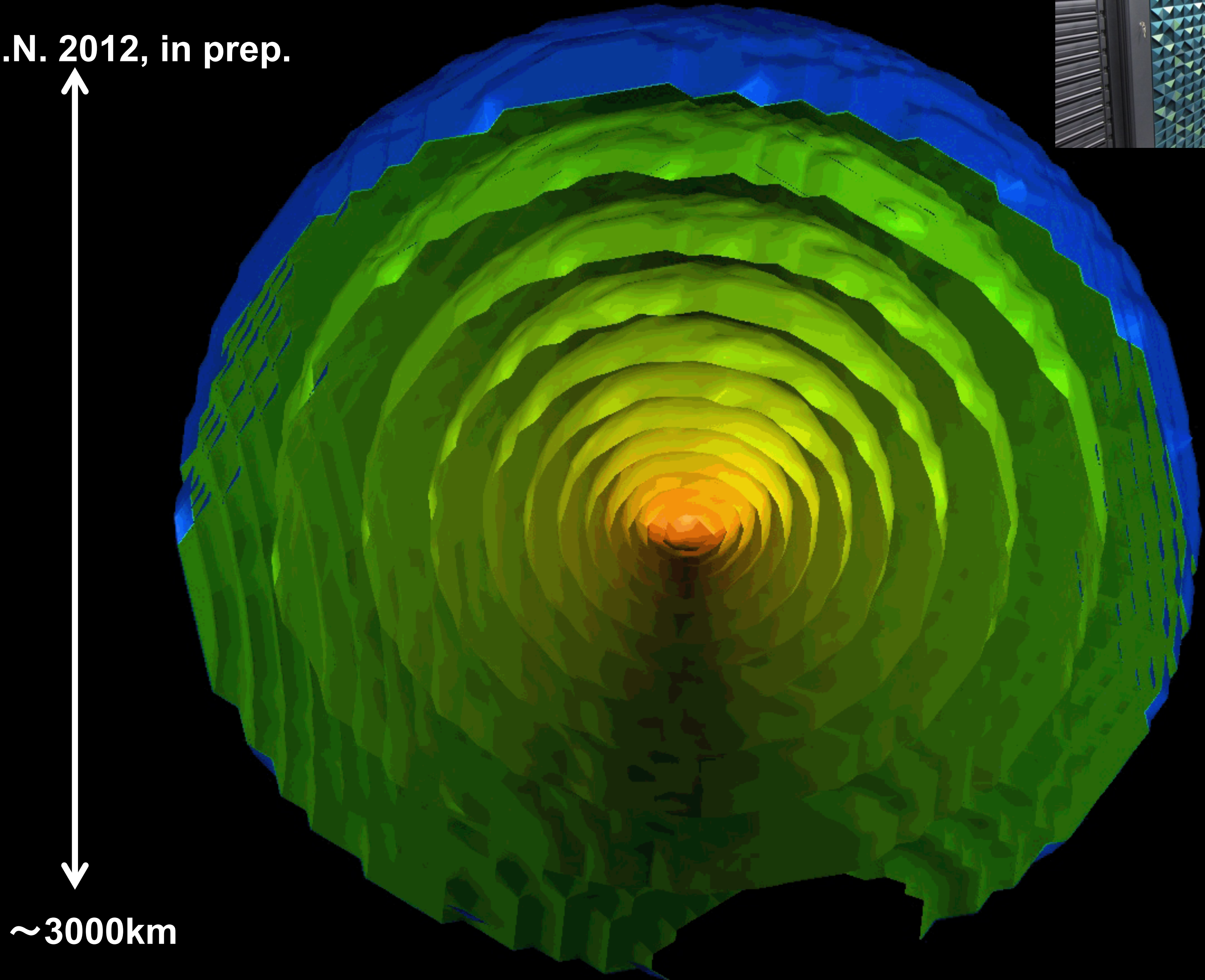


BZ (outgoing poynting)-Flux
In unit of 10^50 erg/s/Sr at
T=160000 (1.5760sec).
Kerr Parameter, a=0.95.
Time variability is also triggered by the BH?

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.

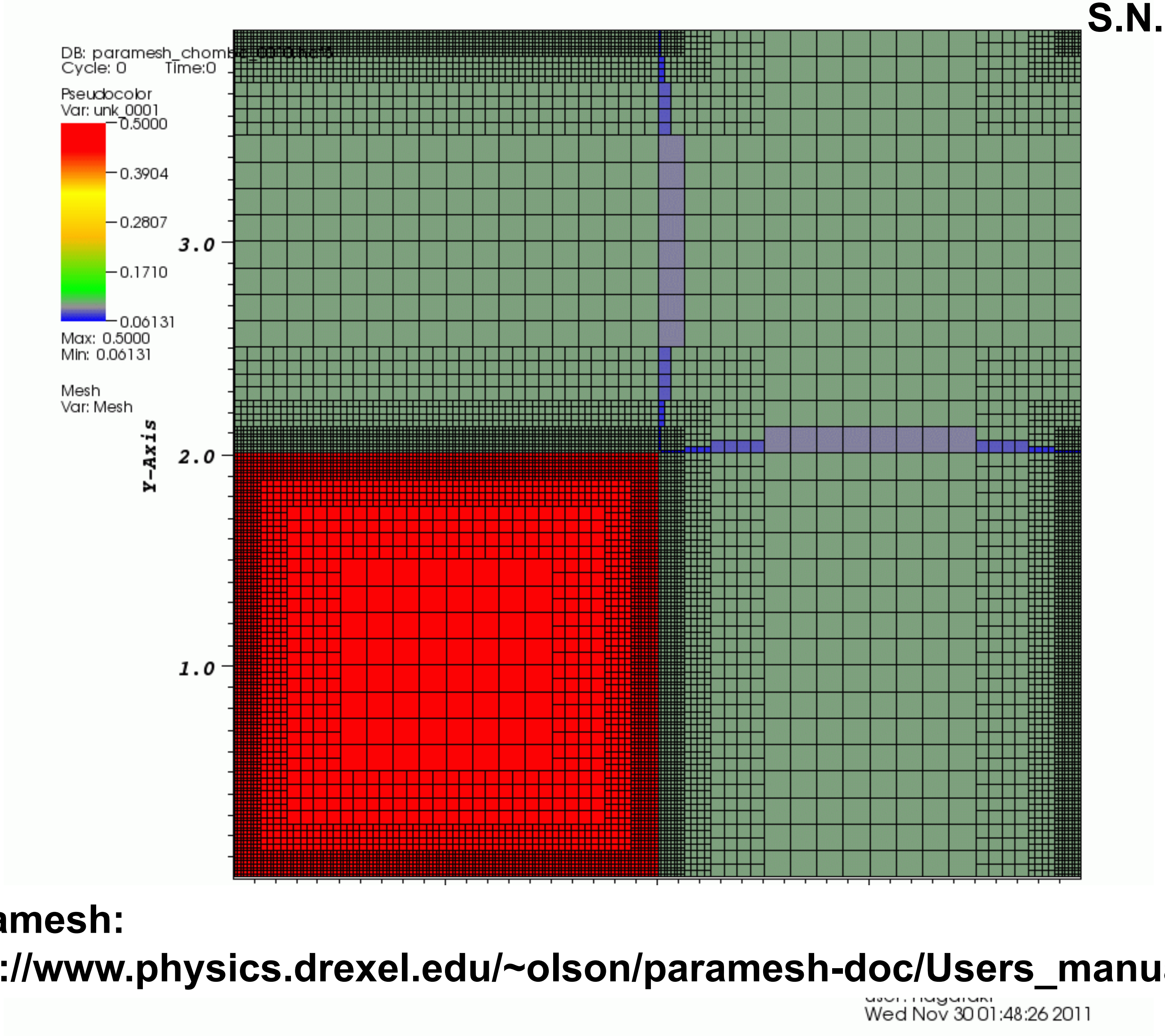
3D-GRMHD Simulation of GRBs

S.N. 2012, in prep.



Combining SRHD Code with Adaptive Mesh Refinement (AMR)

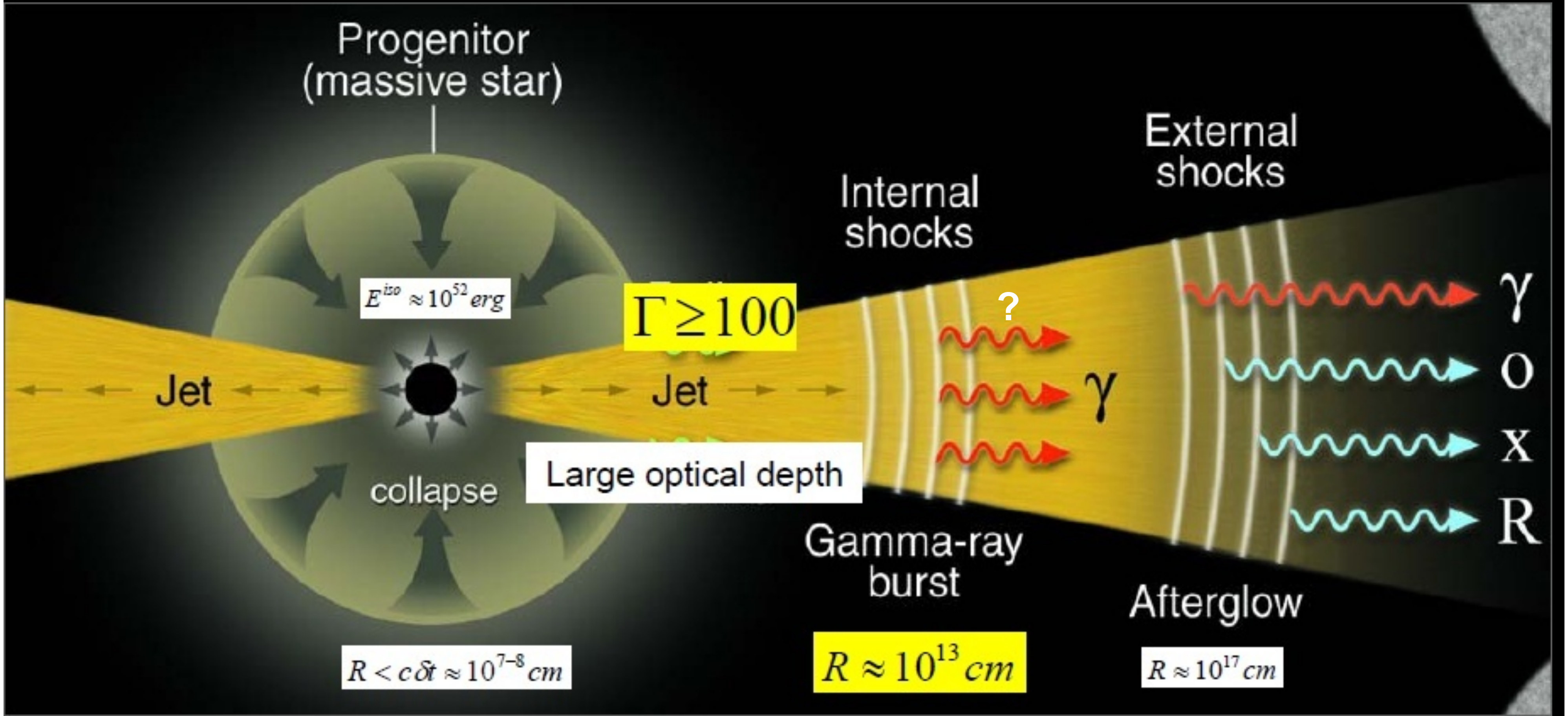
S.N. 2012, in prep.



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

§Other Topics (2011-)

Gamma-Ray Bursts as a Treasure Box of Physics & Mysteries



Nucleosynthesis Central Engine

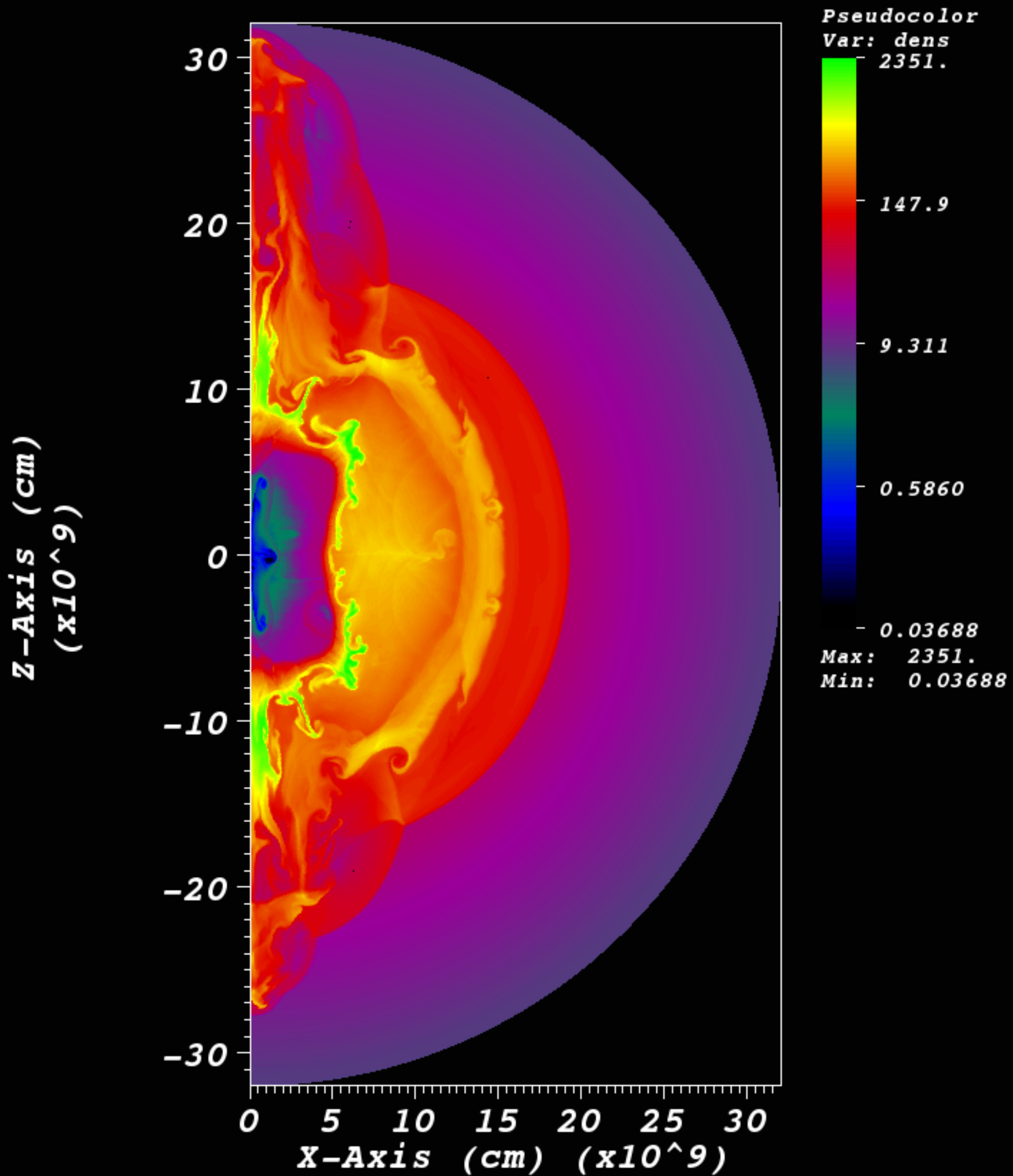
Photospheric Emission?

UHECRs? Neutrinos?

GRB/SN Remnants?

GRB Cosmology?

Figure from P. Meszaros



Explosive Nucleosynthesis
In Jet-Like SNe/GRBs.
Ono, S.N.+ 2012, in prep.

Flash code with some
Micro-physics is used
Currently. We will Extend it.

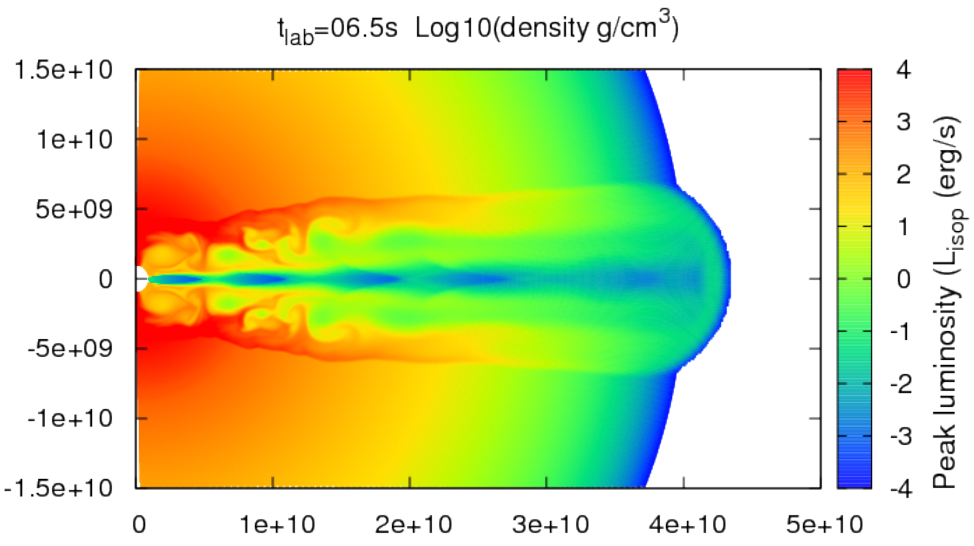
Spectral-Polarization by
Subaru with Dr.Tanaka (NAOJ)

Dr. Ono at YITP (2011-)

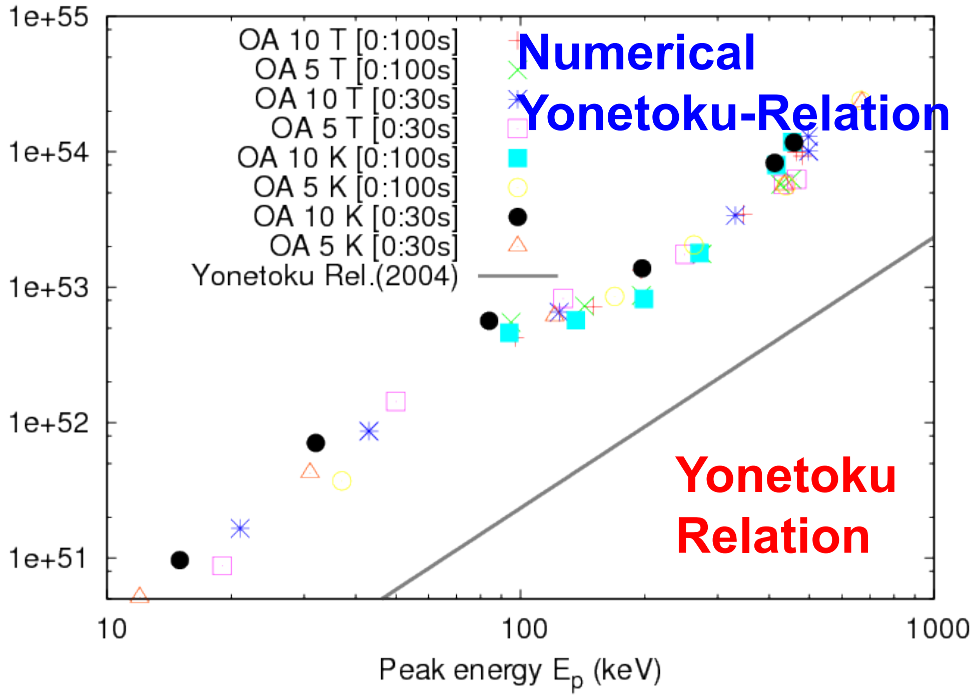
GRB-Cosmology

Photospheric Emission Model and Numerical Amati relation

Mizuta, S.N., Aoi 2010
Mizuta, S.N.+ 2012, in prep.



Special Relativistic Hydro Simulation by A. Mizuta

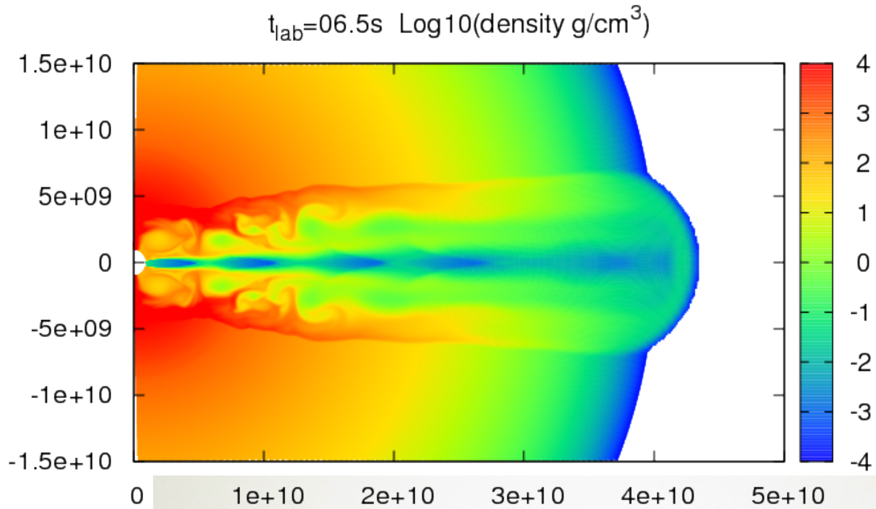


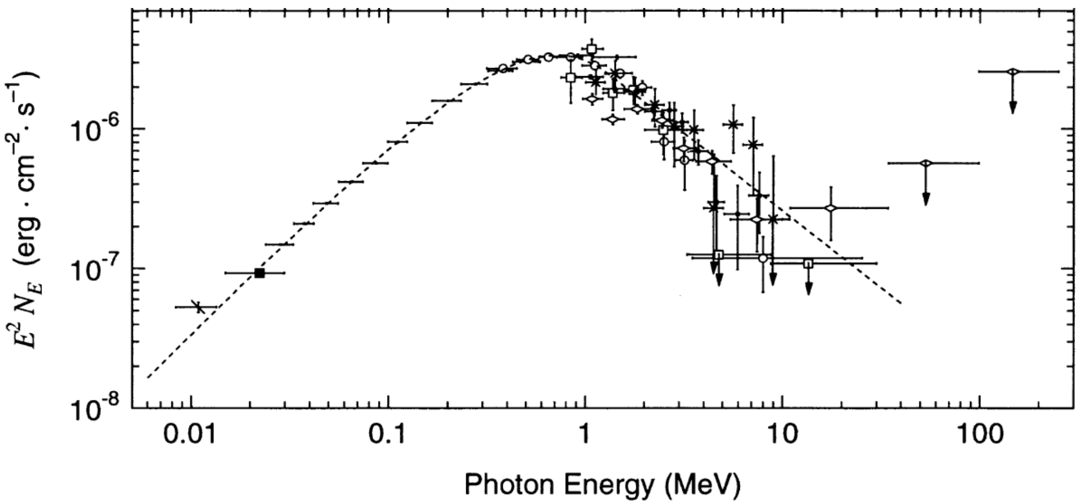
詳細は水田さんの講演

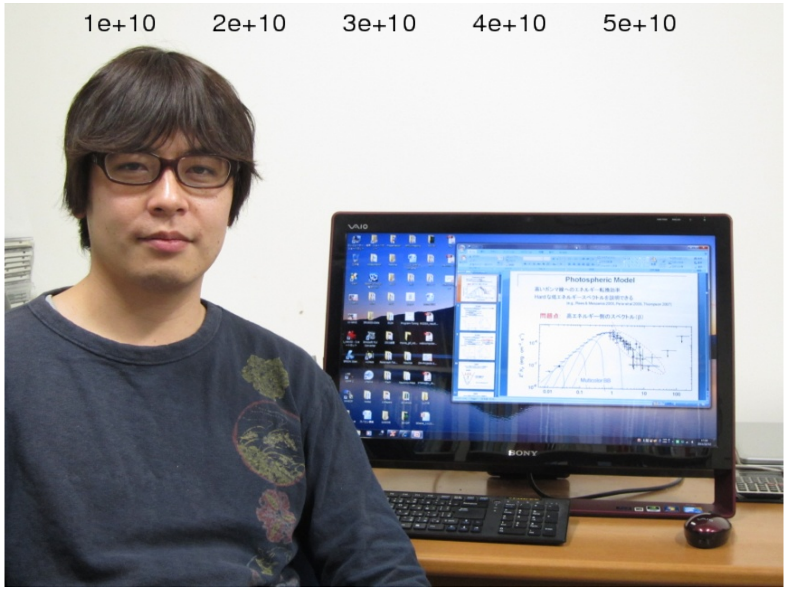
Monte-Carlo Simulations to Explain GRB Spectrum

フォトスフェリックモデルの下、
モンテカルロ計算でバンド関数を
再現する（Ito, S.N.,+ 2012, in prep）。

右図は水田氏によるシミュレーション。



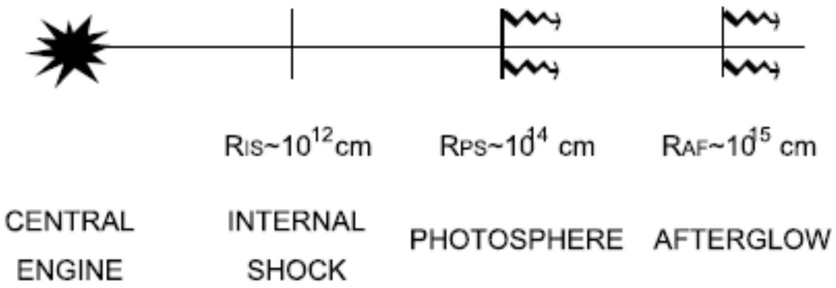


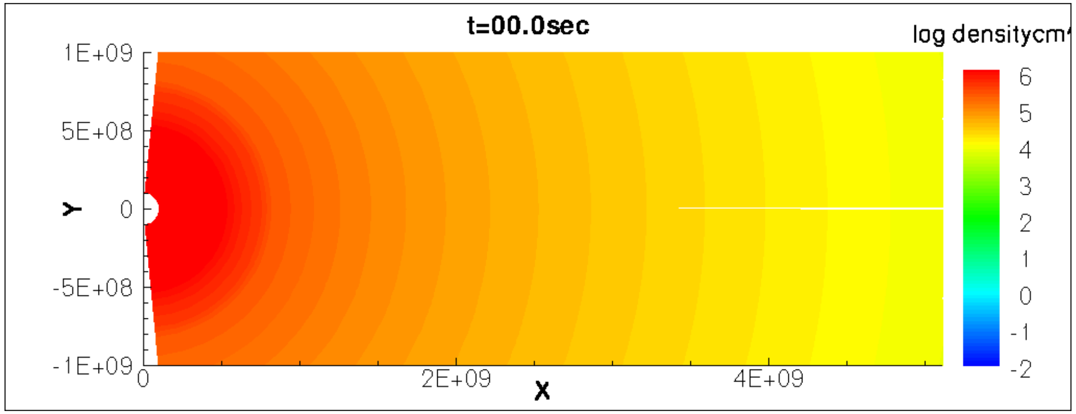


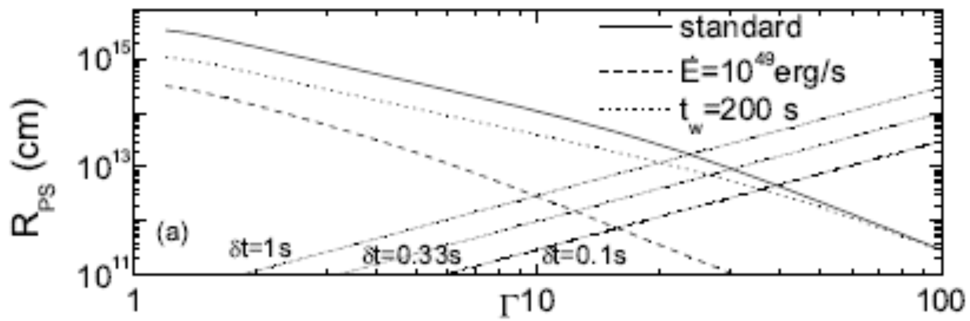
Dr. Ito at YITP (2011-)

UV/X-rays from Failed GRBs

Xu, S.N., Huang, Lee 2011 ApJ, accepted.



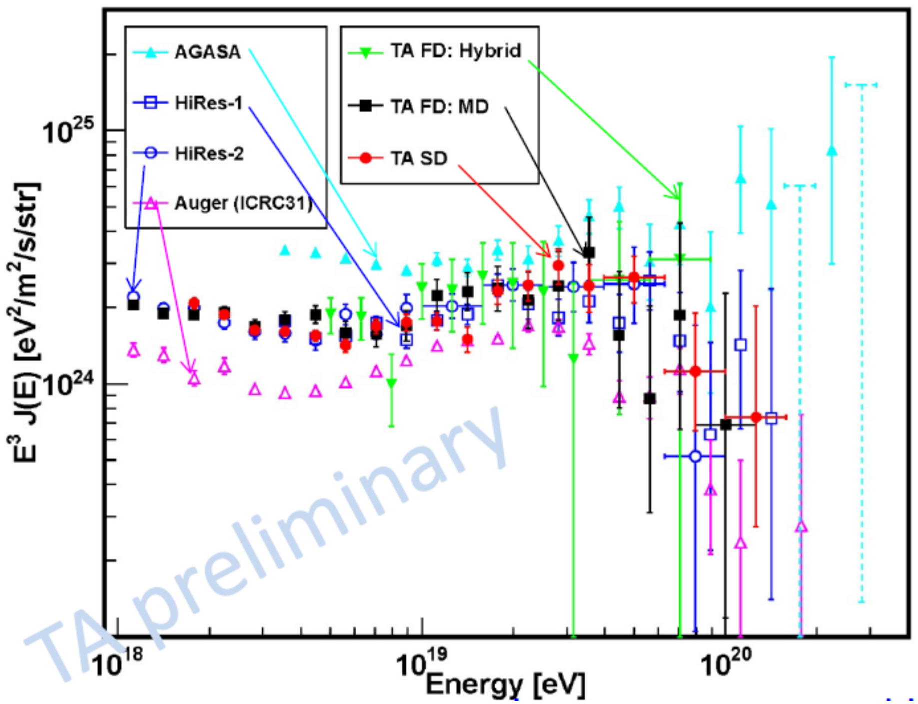


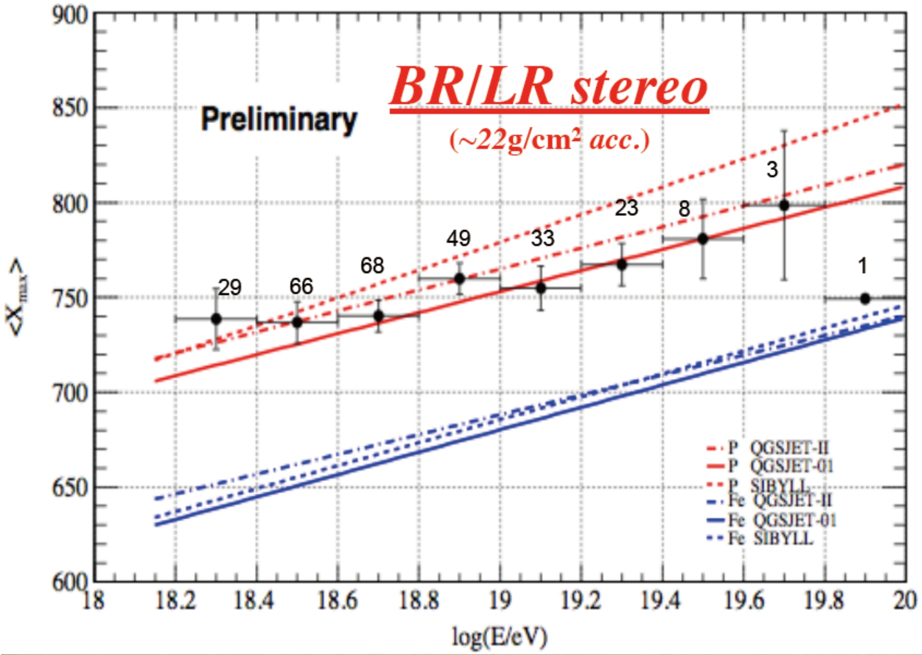


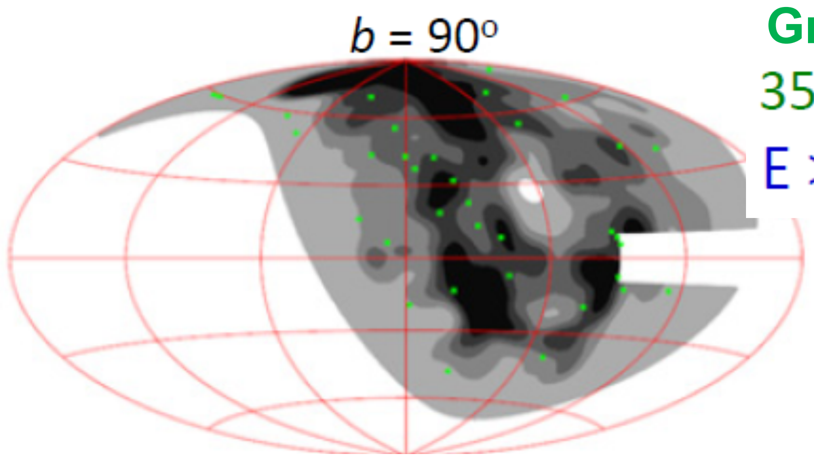
シミュレーションは水田氏による。
Mizuta, S.N. Aoi 2011 ApJ.
(Mizuta-san's Talk)

For sub-relativistic jet (Γ〜1-10), photo-sphere can be larger than Internal Shock Radius. -> Themal radiation (UV/X-rays) is followed by an afterglow.

First Results of Telescope Array are Open Now



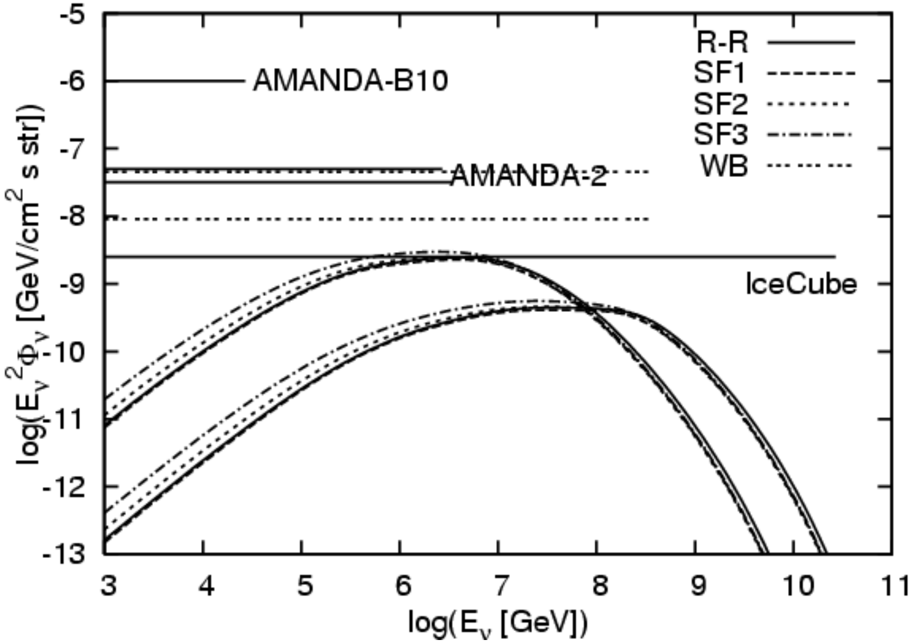




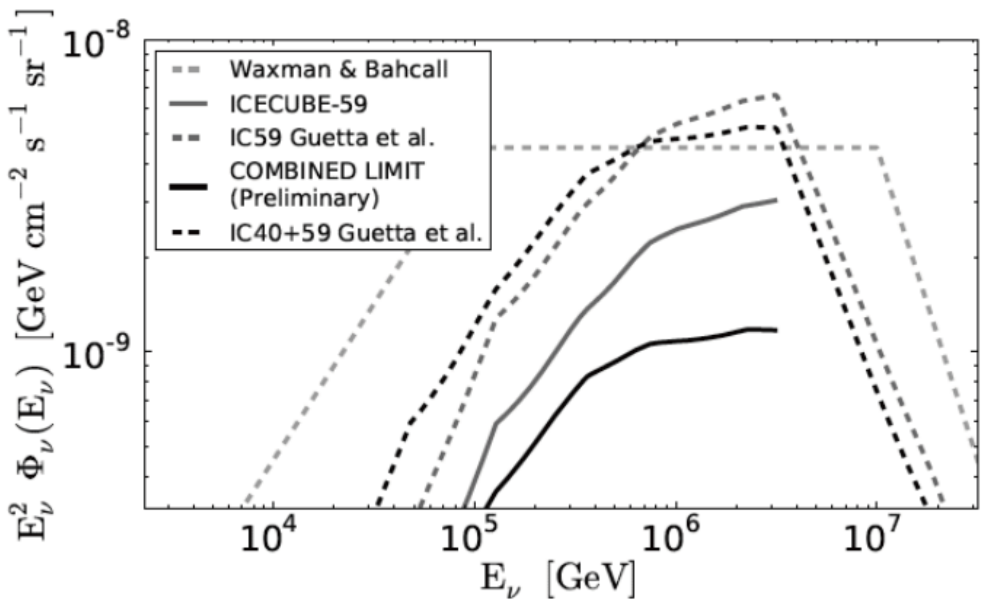
Green:
35 events
E > 40 EeV

Black: LSS model (smearing angle = 6°)

A Challenge for the GRB UHECR-Neutrino Scenario by IceCube, But… is that true?



Murase and S.N. 2006

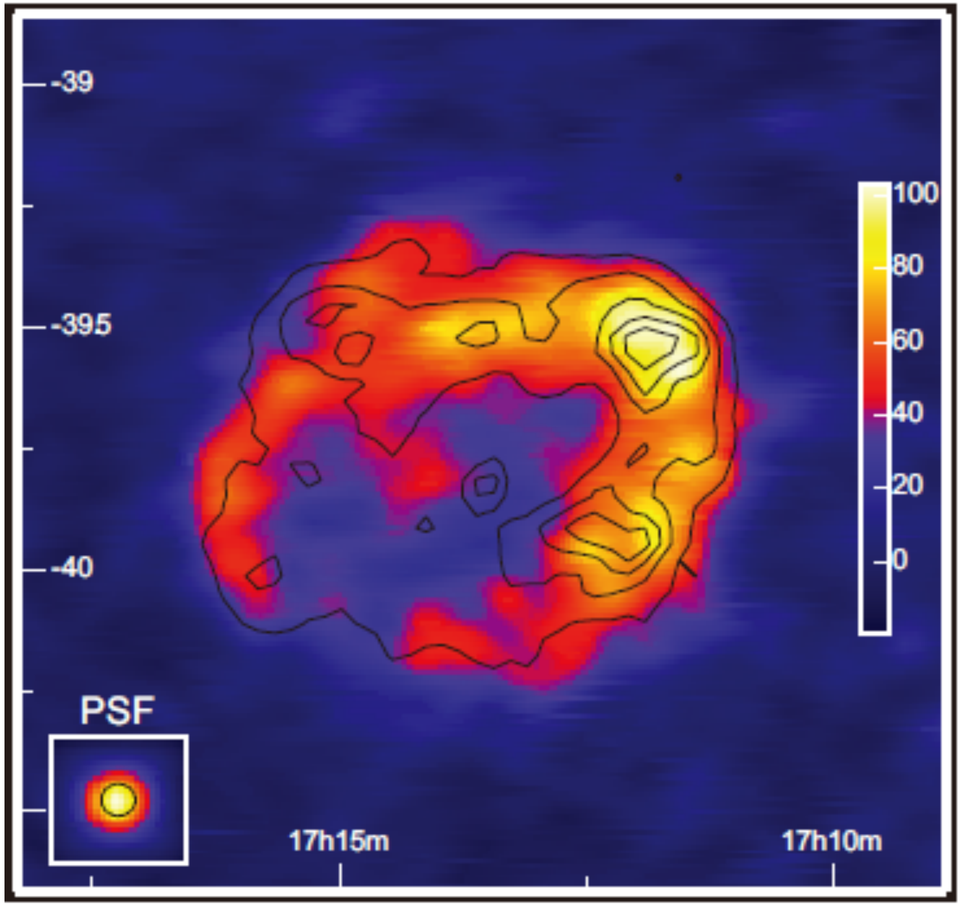


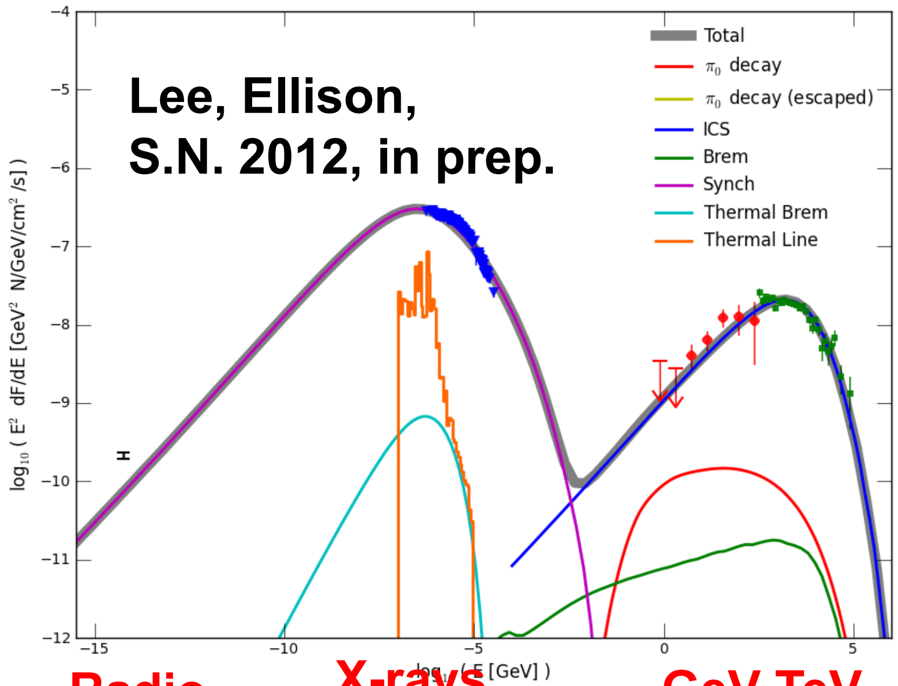
the IceCube collaboration 2011

But recently, it is pointed out that the analysis of IceCube looks to contain A serious mistake… (Hummer +arXiv:1112.1076, Li arXiv:1112.2240, He, Liu, Wang, S.N.+ 2011, in prep.)
The upper limit by IC40+59 will be not so severe as claimed by IceCube team.

Haoning He's Talk

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.

YITP

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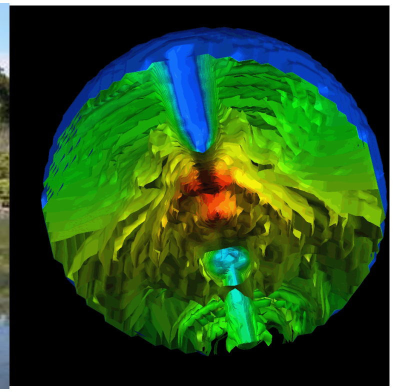
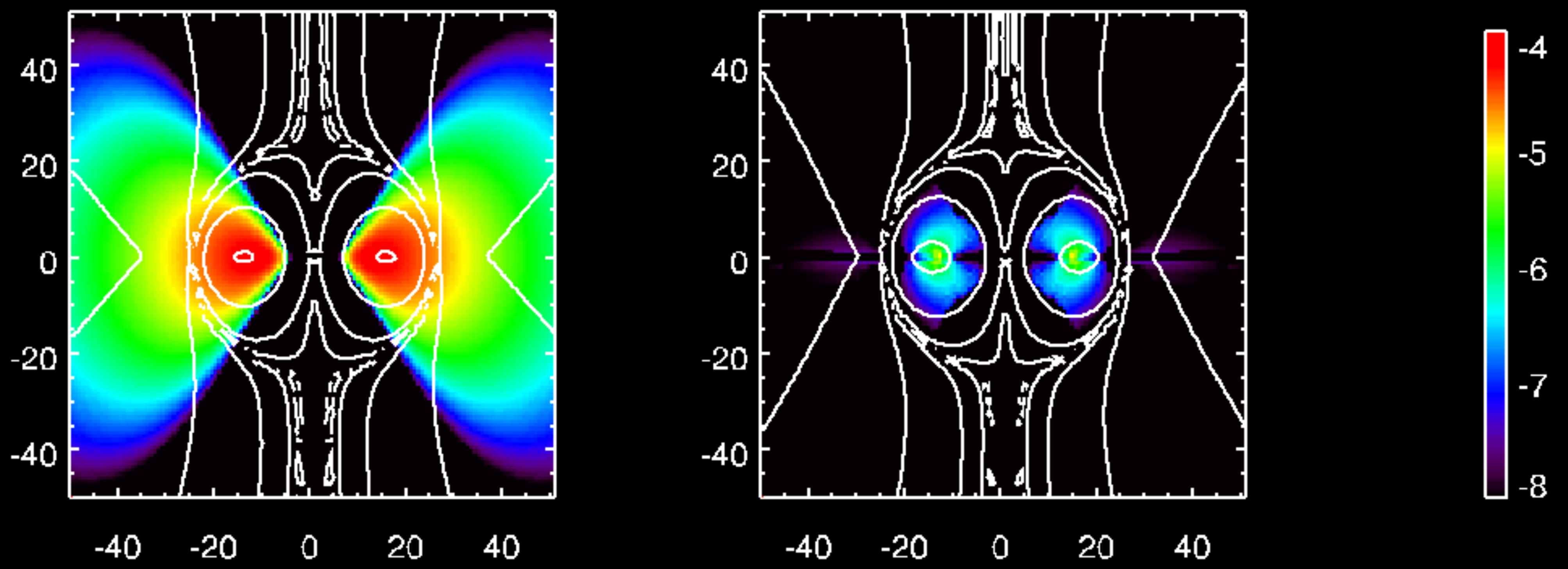


§Other Topics 2 (2011-)

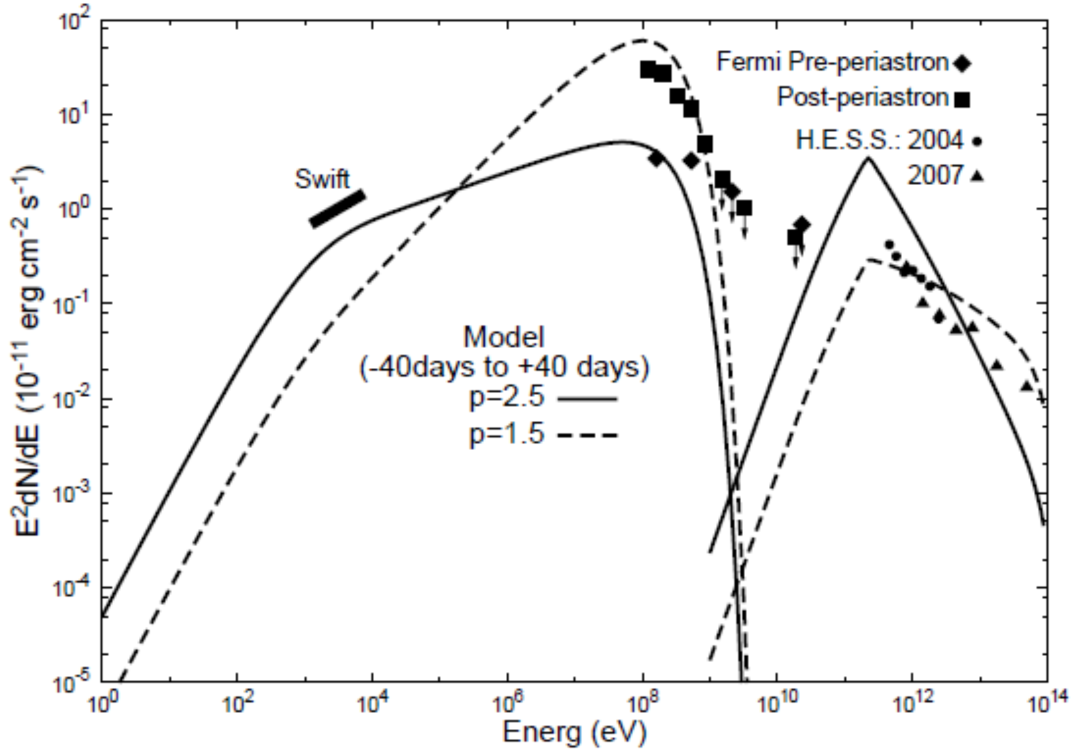
BZ機構の磁場形状依存性

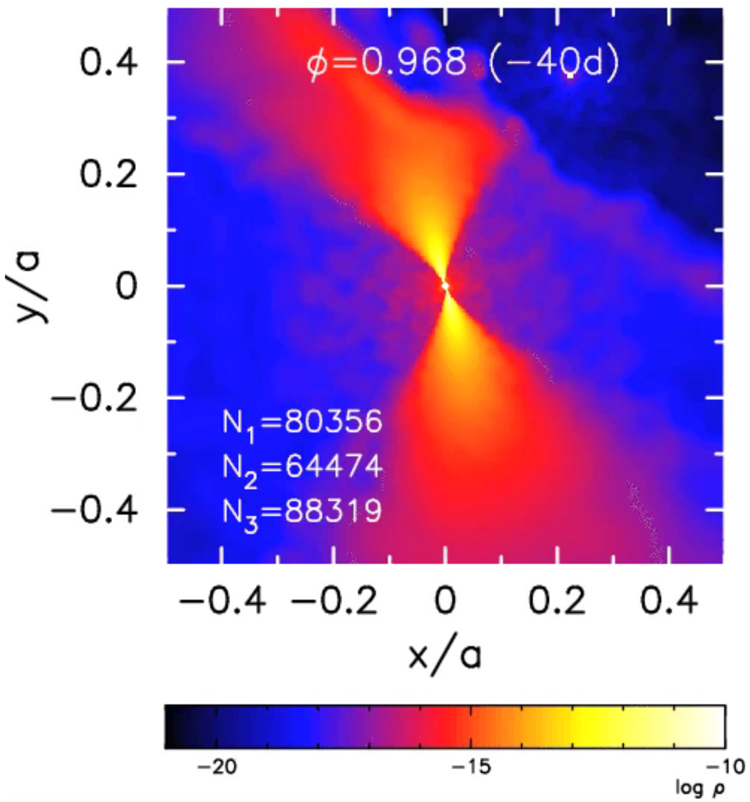
Maeda, S.N., Mineshige, Takahashi (2012), in prep.

冨松高橋解＋Fishbone-Moncrief解の時間発展 (このコンビネーションによるBZ数値シミュレーションは世界初)。a=0.9, t=3000GM/c^2まで(今後更に追う)。
左図：密度、右図：BZ-Flux。



PSR B1259-63/LS 2883の3次元流体シミュレーションとガンマ線放射





共同研究者： 岡崎敦男、高田順平、
内藤統也、河内明子、山口正輝、早崎公威、
Shiu-Hang Herman Lee, Stan.P. Owochi

銀河団に於けるSZ効果

Prokhorov, Dubois, S.N. A&A (2010)
Prokhorov, Colafrancesco, Akahori, Millon, S.N., Yoshikawa MNRAS (2011)
Prokhorov, Dubois, S.N., Akahori, Yoshikawa MNRAS (2011)

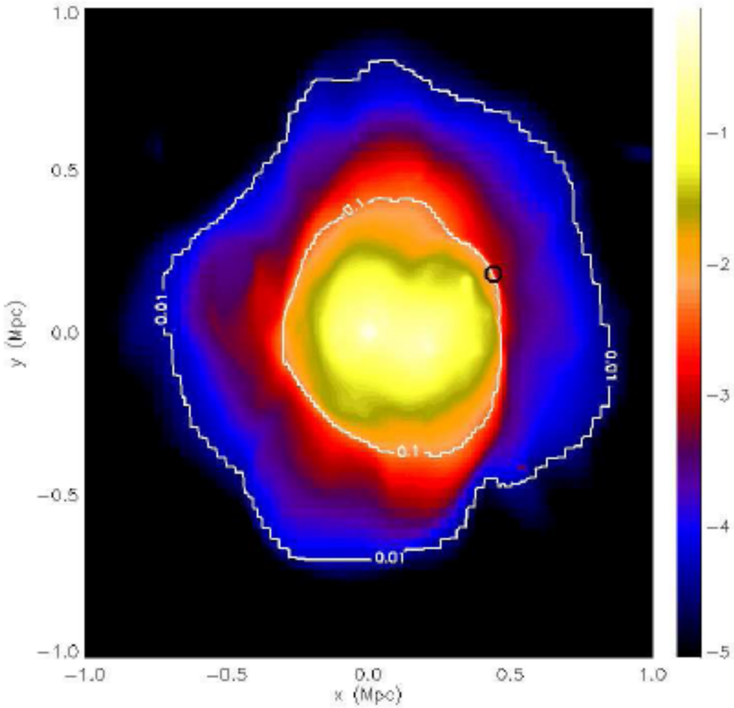


Fig. 6. The normalized X-ray surface brightness map of the simulated cluster in the [2.0-10.0 keV] band in logarithmic scale. The region corresponding to the highest temperature in Fig. 5 is shown by a black circle.

X線のSurface Brightness

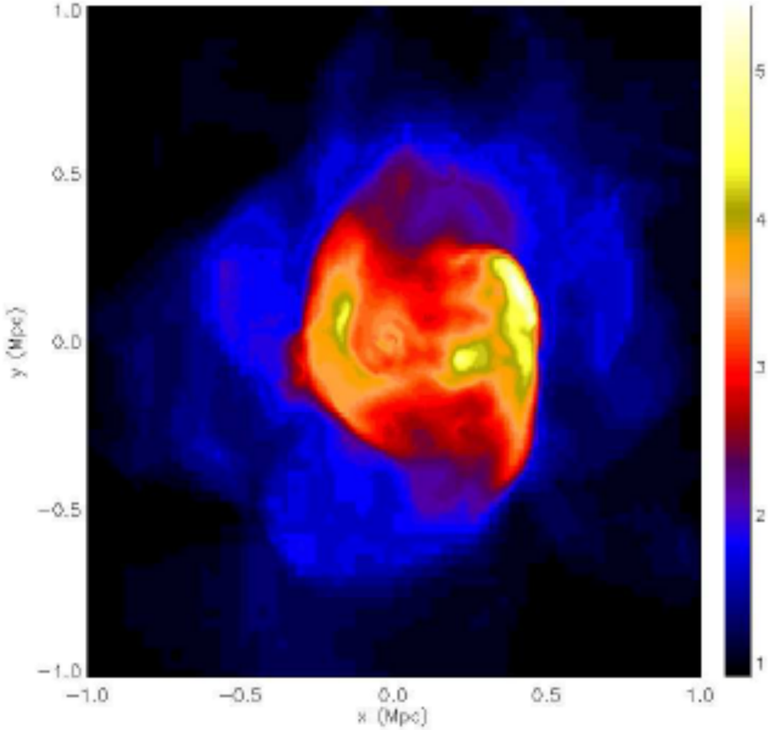


Fig. 5. Temperature (in keV) of the simulated cluster along the x direction at z=0.74 derived from the ratio of the SZ intensities.

SZ（Relativistic-Correction）で求めた電子温度分布

§ 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.
- Photospheric Model is studied using Monte-Carlo simulations to understand the Band Function.
- One month Conference on SNe and GRBs will be held in Kyoto, 2013.
- So on.