Collapsar and Magnetar Models
for
Long-Duration Gamma-Ray Bursts

YITP YUKAWA INSTITUTE FOR THEORETICAL PHYSICS

Shigehiro Nagataki

Gamma-Ray Bursts 2012 Conference
7-11 May 2012, Munich, Germany

§ Introduction

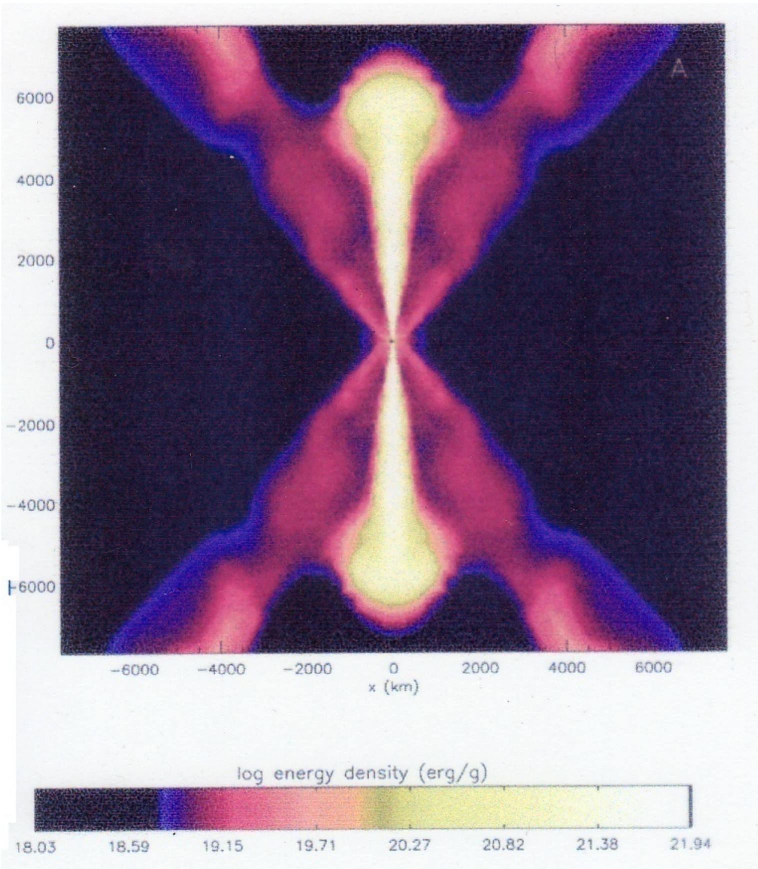
History of the Numerical Study on the Central Engine of Long-GRBs.

- First report on the association of a GRB with a hypernova was done in 1998.

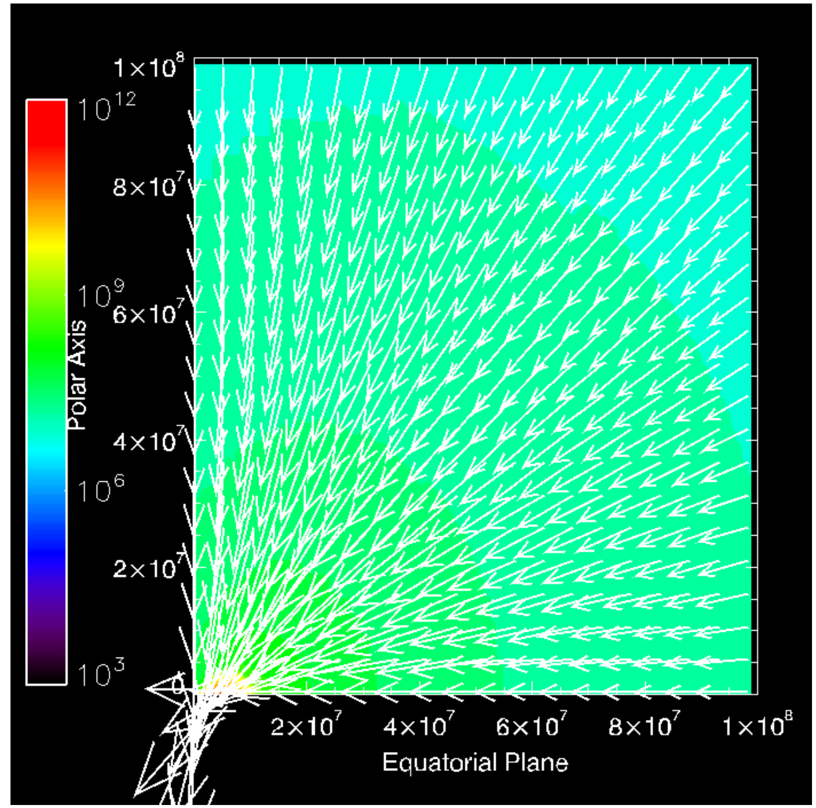
Outline of Explosion Mechanism is still under debate.
BH (Collapsar) or NS (Magnetar)?
Neutrino or B-Field?

- Rotating Black Hole with Neutrino Heating?
- Rotating Black Hole with Strong B-Fields ?
- Rotating Magnetars?

Black Hole with Neutrino Heating

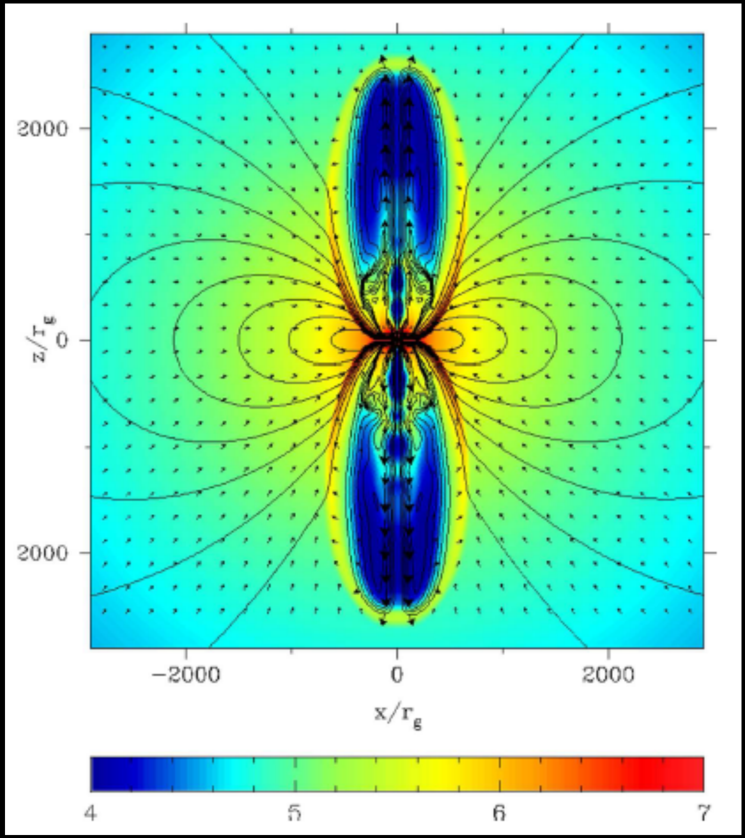


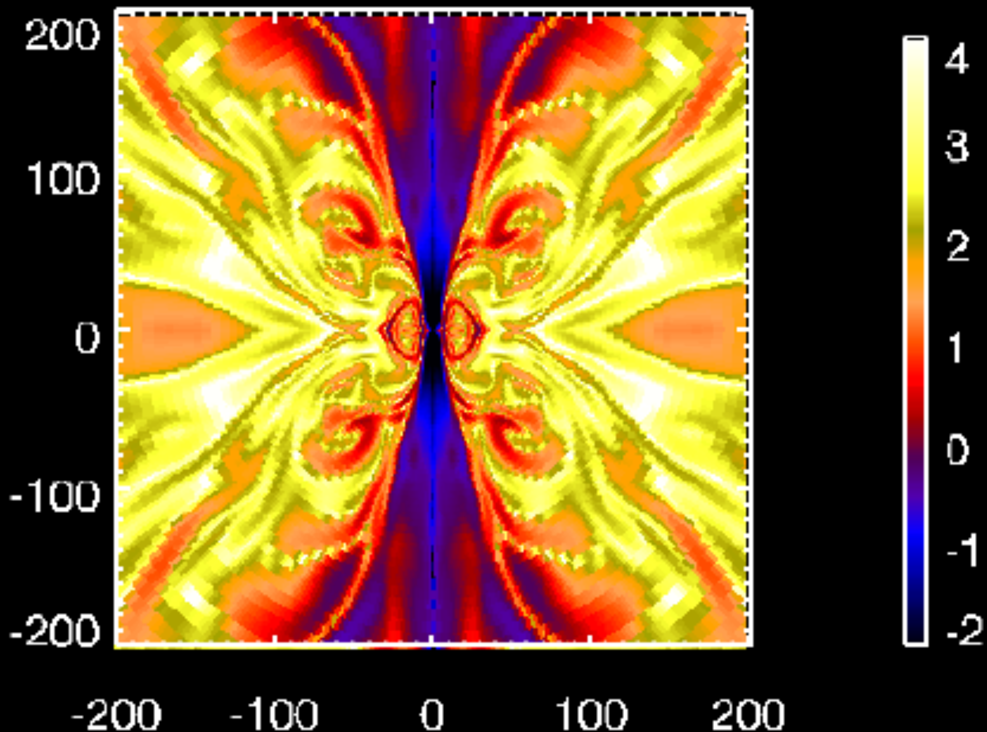
MacFadyen and Woosley 99
Newtonian
Without Neutrino physics



S.N.+07
Newtonian
With some Neutrino physics.

Black Hole with Strong B-Fields

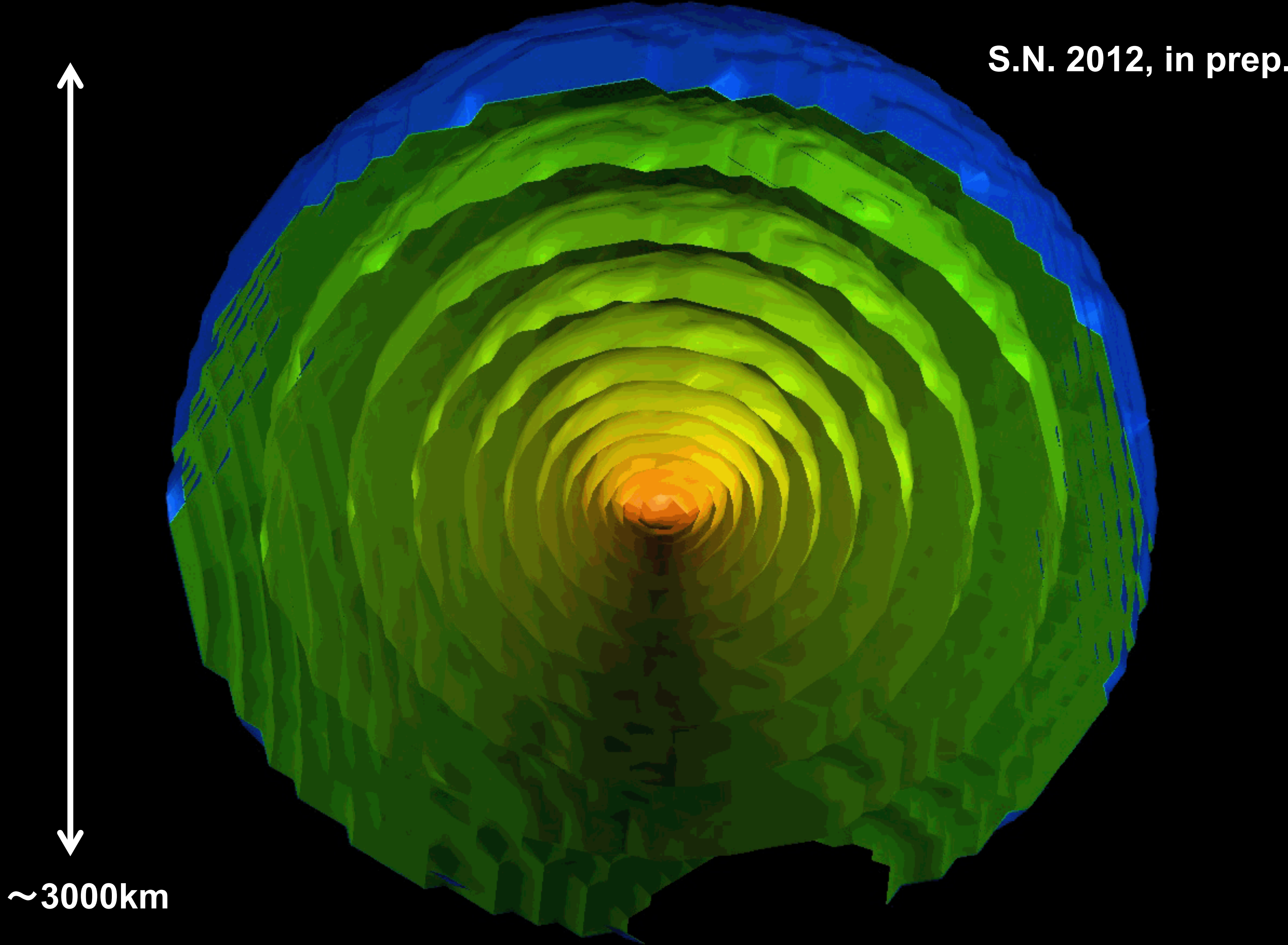




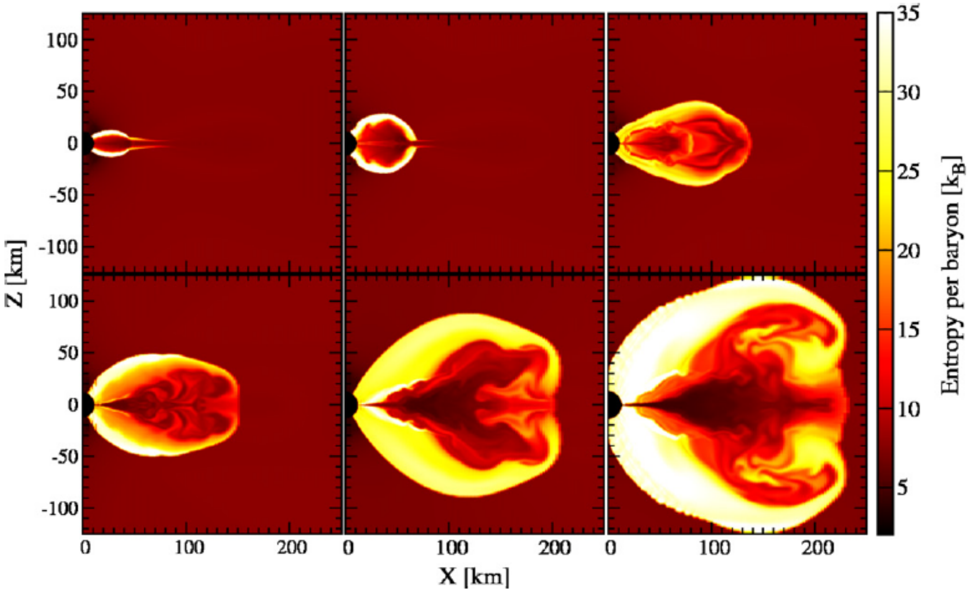
Barkov and Komissarov 08
2D-GRMHD, a=0.9
With Some Microphysics
Γ< a few. Density Contour.

S.N. 09
2D-GRMHD, a=0.5
Without Microphysics.
Γ< a few. Plasma beta.

3D-GRMHD Simulation



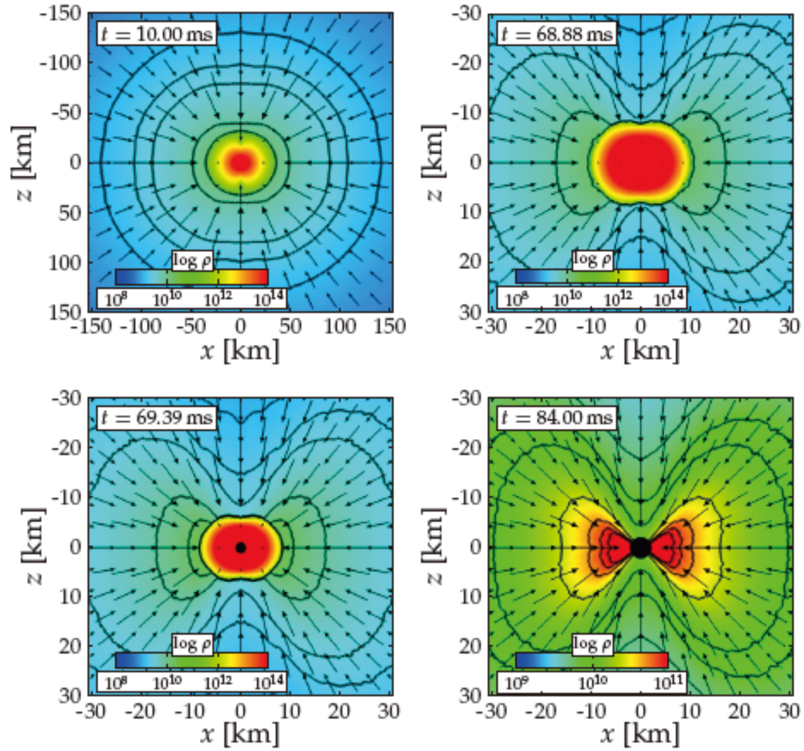
Black Hole Formation



. Contours of entropy per baryon

Full 2D-GRHD with Microphysics

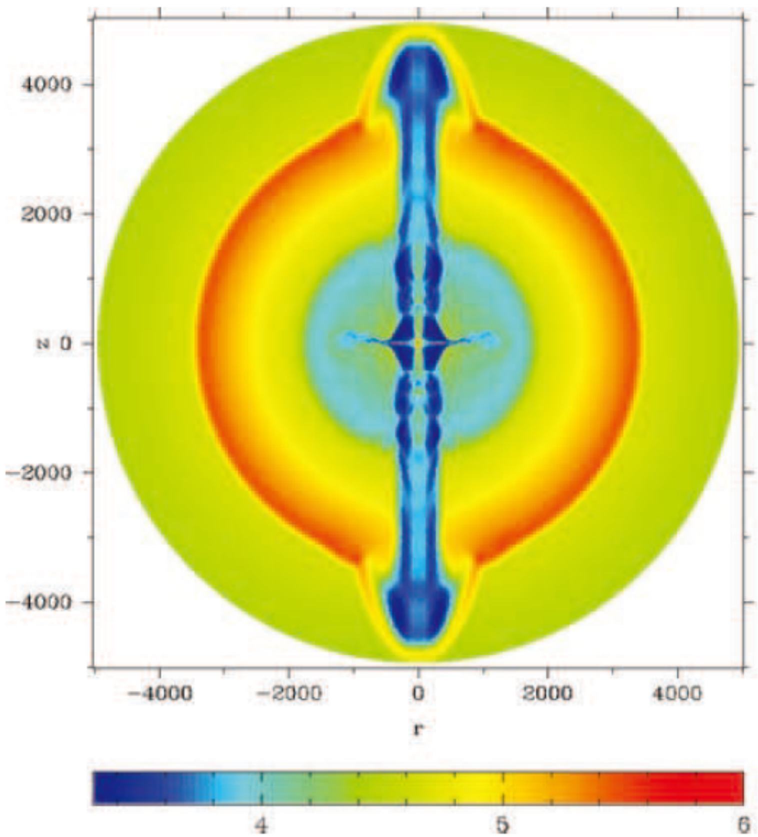
Sekiguchi and Shibata 11



Full 3D-GRHD without Microphysics

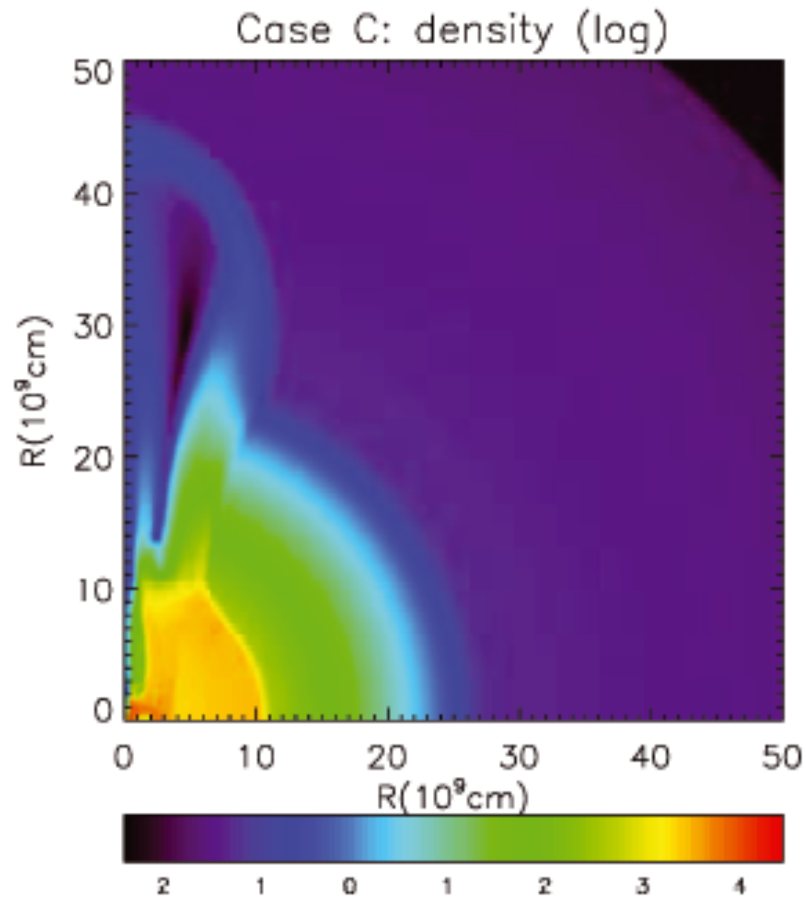
Ott+11

Magnetar Scenario



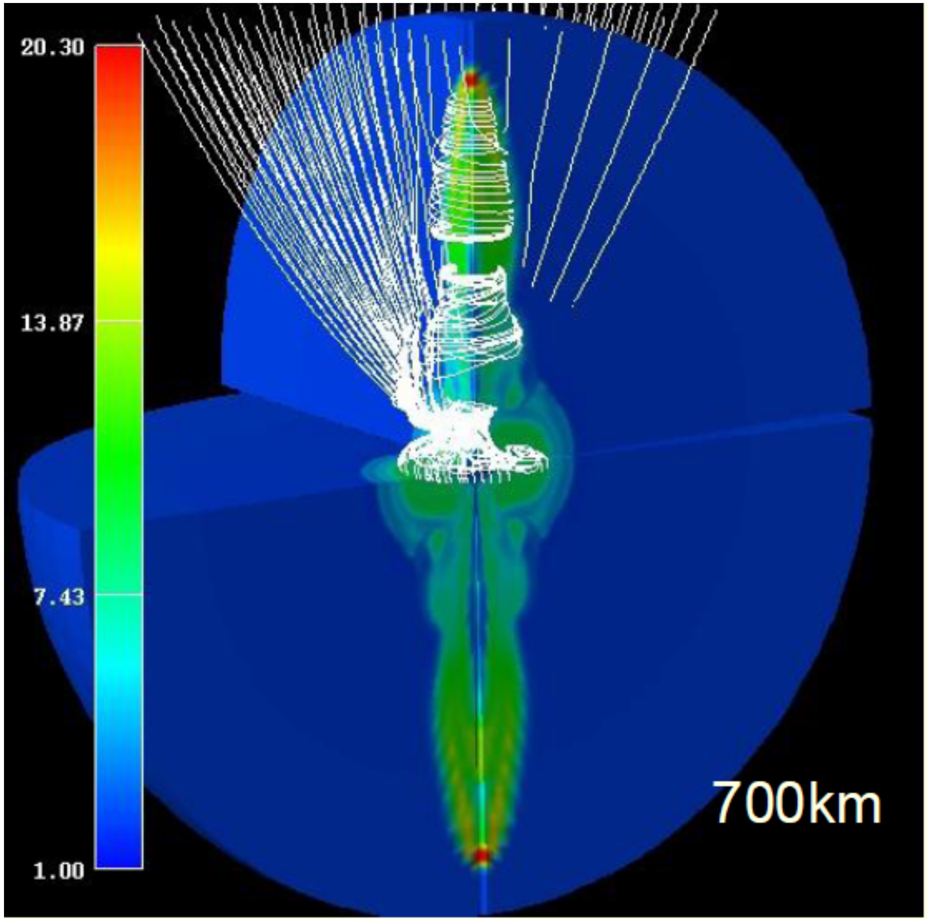
Komissarov and Barkov 07
2D-GRMHD with some Microphysics

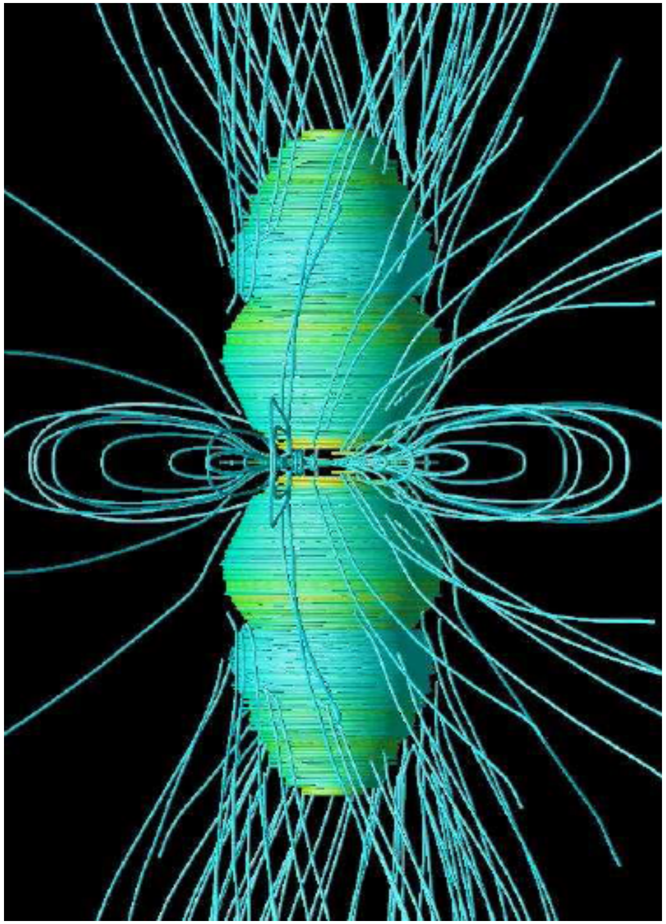
v^r / c ~0.5.



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

Magnetar Formation





Takiwaki et al. 09
SRMHD, Neutrino Physics,
Realistic EOS. Upto 100ms. Γ< a few.
See also Takiwaki,Kotake,S.N.,Sato 04.

Burrows et al. 07
Newtonian-MHD, Neutrino
Physics&EOS. Upto 0.5-0.6sec.

§ Study on a Rotating Black Hole with Strong B-Fields by a General Relativistic Magneto-Hydrodynamic (GRMHD) code

2D/3D GRMHD Codes with MPI.
2D/3D SRMHD with AMR & MPI.

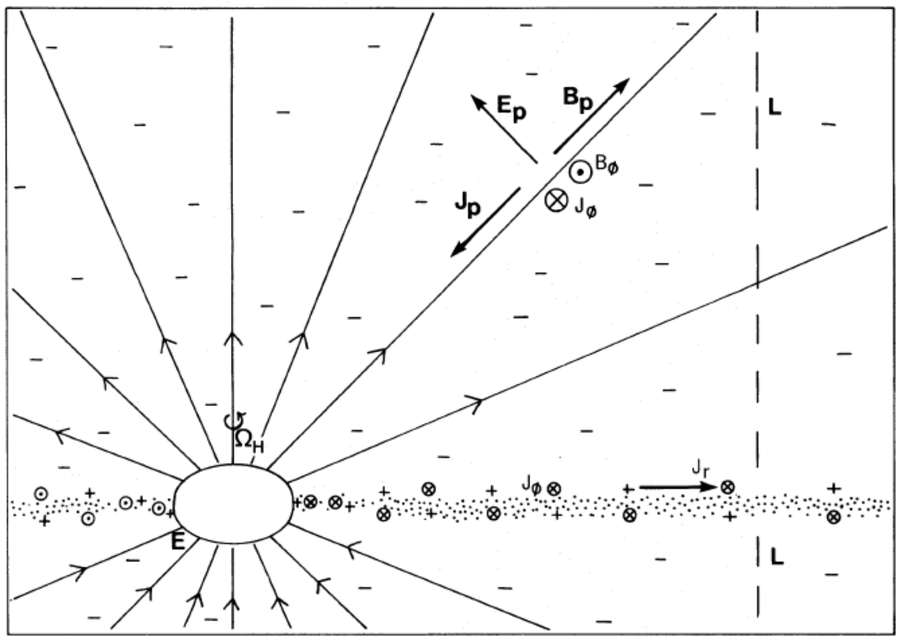
S.N. ApJ (2009).
S.N. PASJ (2011).
S.N. 2012, in prep.

Yuk**A**wa institute's **MA**gne**TO**-hydro (**YAMATO**) code
YAMATO (大和) =Old Name of Japan

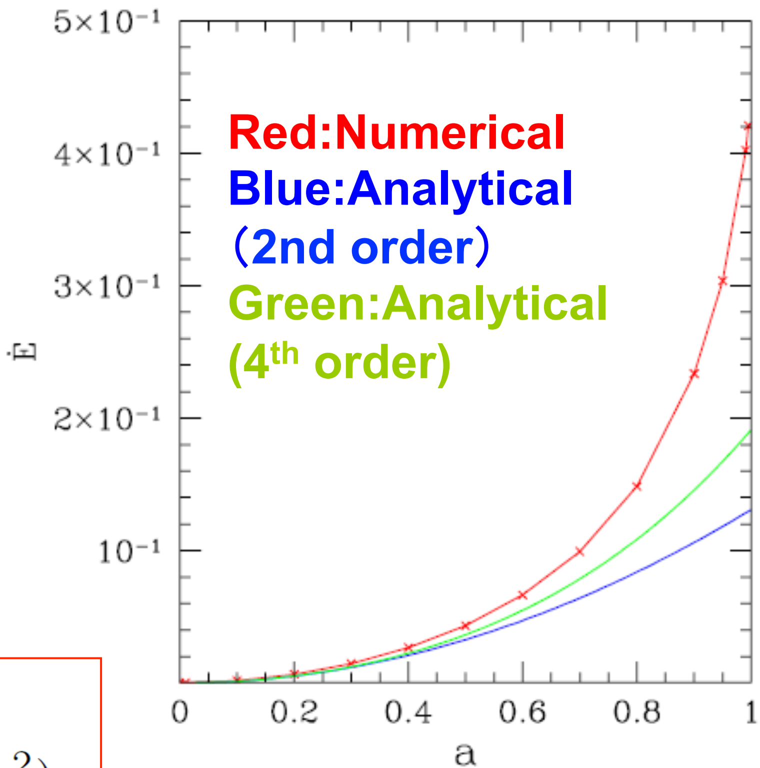
GRMHD Code is necessary to see Blandford-Znajek Process.

Blandford-Znajek Process can be seen Numerically Now

Blandford and Znajek 1977
Tanabe and S.N. PRD 2008



(Split-) Monopole Solution.



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

C:Amplitude of B-Field. a: Kerr-Parameter.

This solution can be used to check the validity of numerical codes.
Numerical Simulation is necessary for large a and different B-fields.

Initial Condition for GRB Simulations

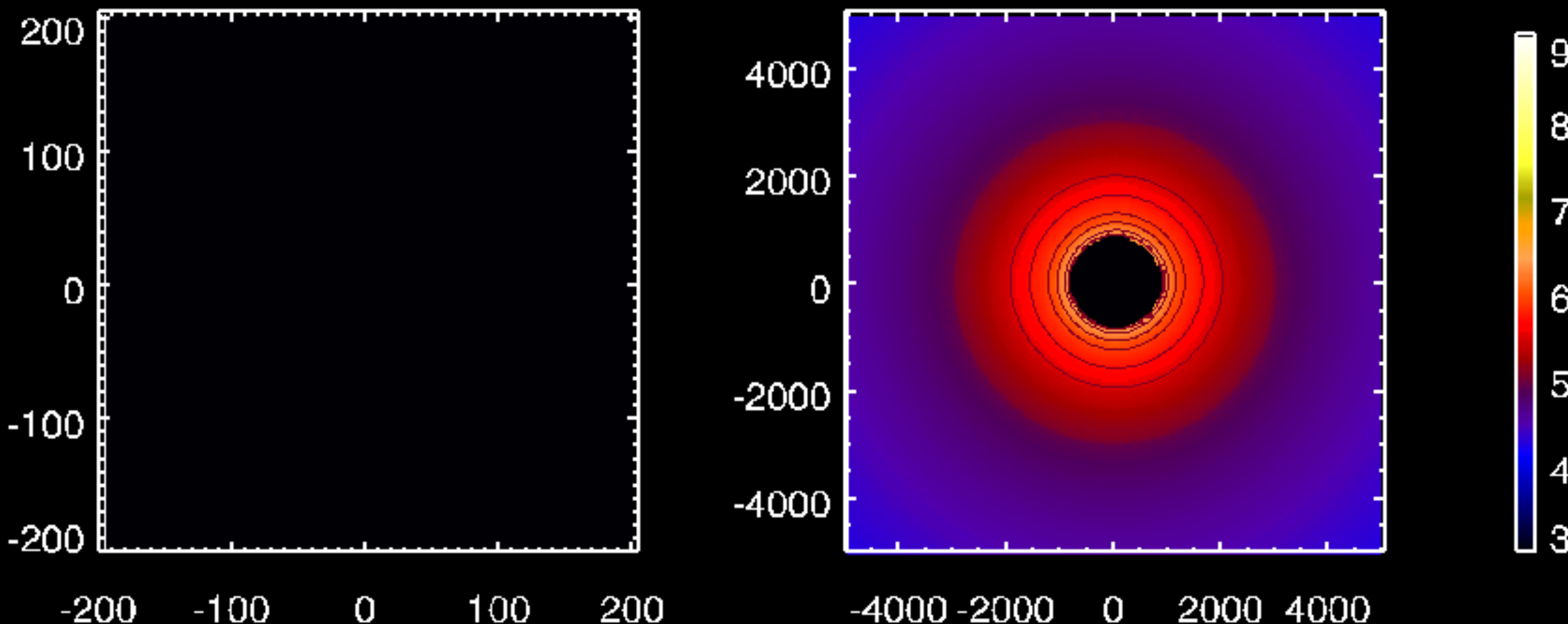
S. N. 09

- Fastly Rotating Massive Stellar Model (12TJ) by Woosley and Heger 2006.
- Fe core (1.82Msolar) 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

C=G=M=1 Unit



～600km

R<200

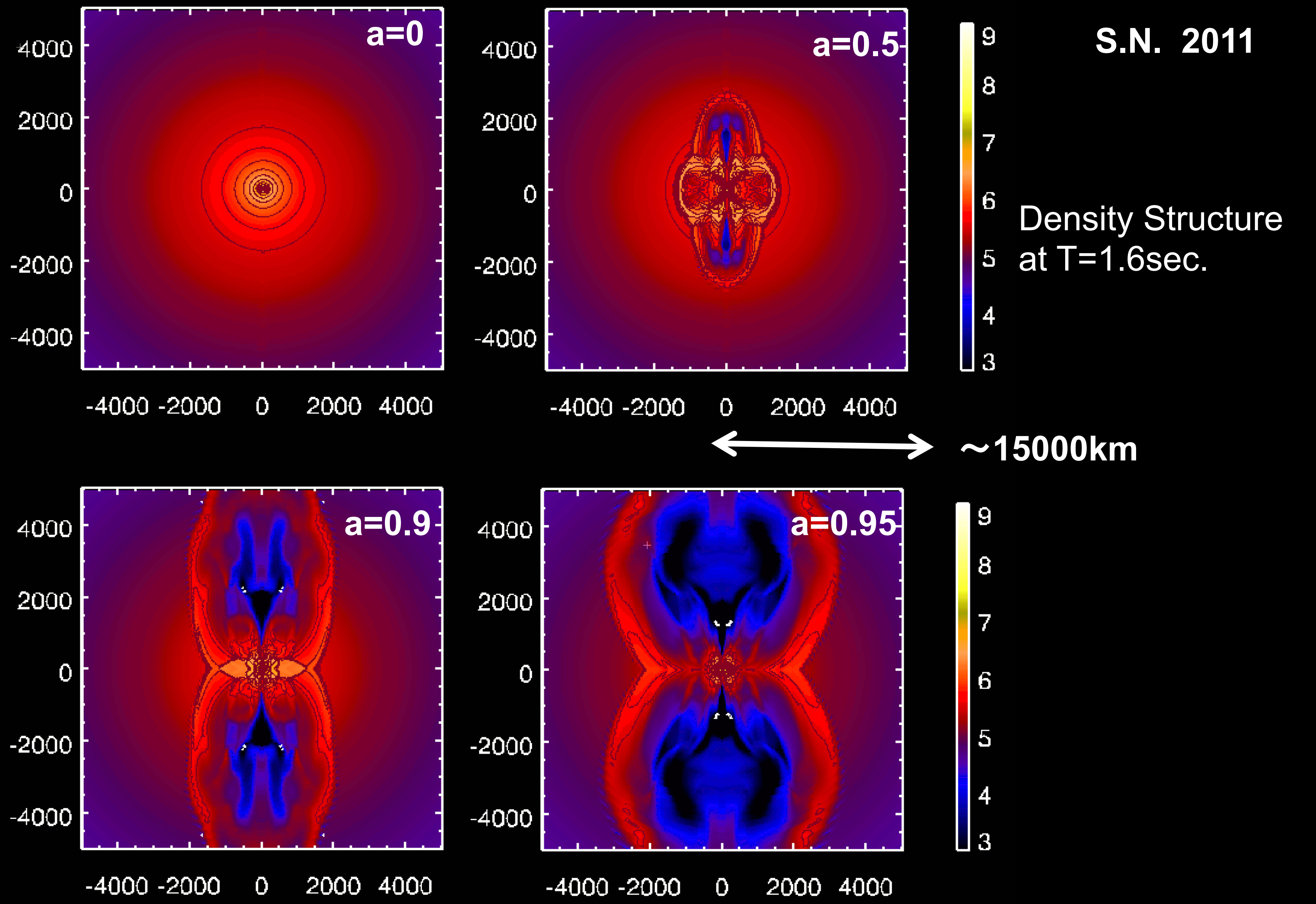
～15000km

R<5000

Density contour in logarithmic scale (g/cc)

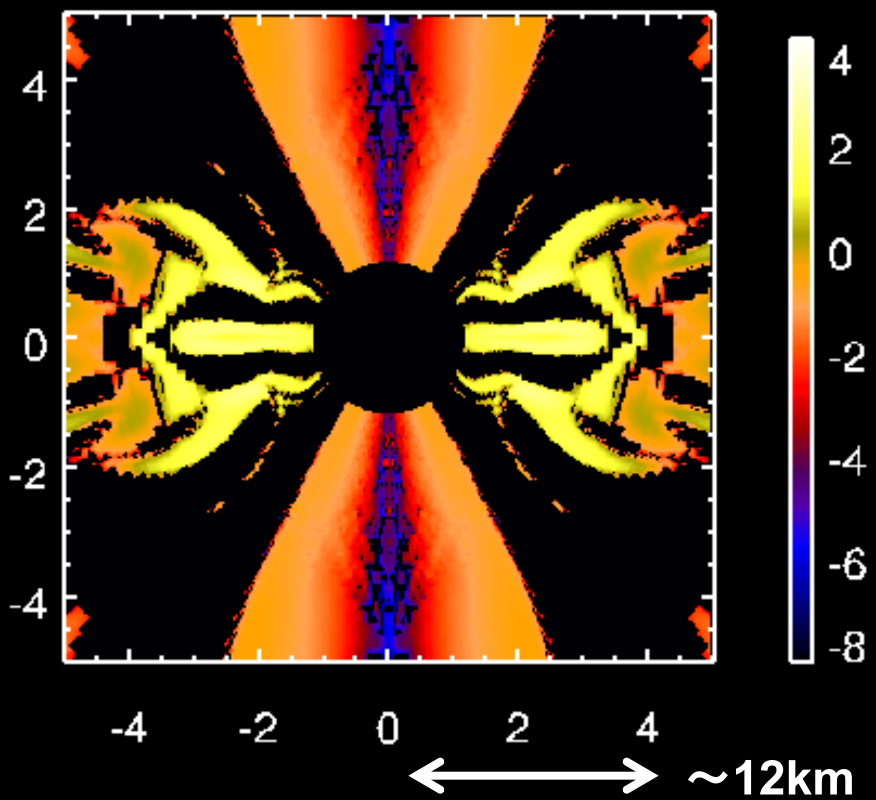
Dynamics is followed up to 1.77sec from the collapse.

Dependence of Dynamics on Rotating Black Hole

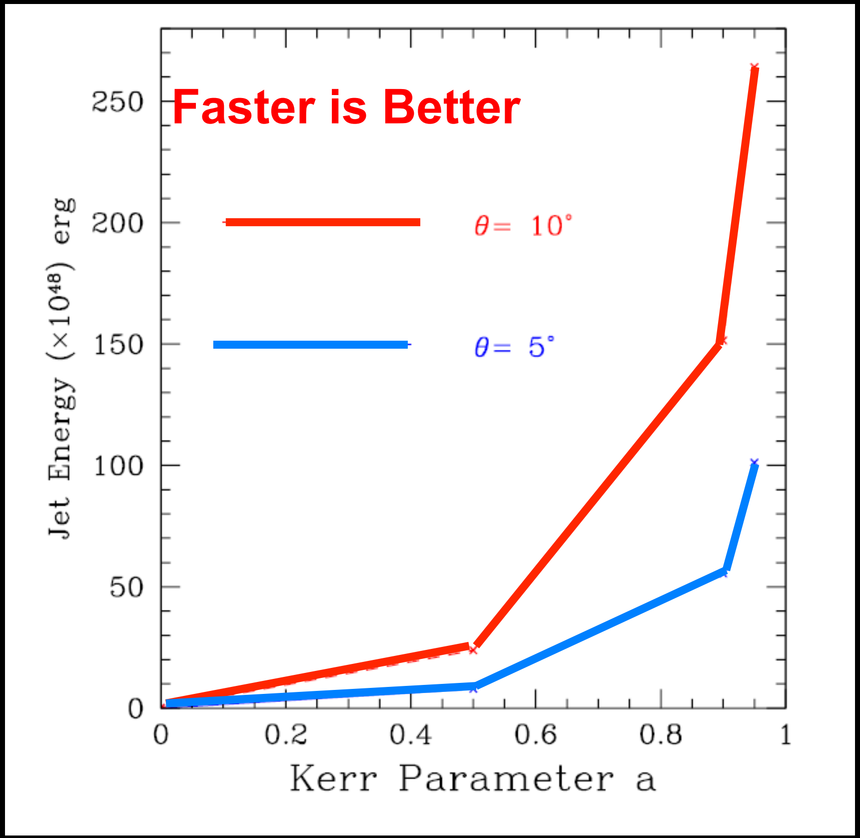


Blandford-Znajek Flux and Jet Energy

S.N. 2011



BZ (outgoing poynting)-Flux In unit of 10^50 erg/s/Sr at T=1.5760sec. Kerr Parameter, a=0.95.

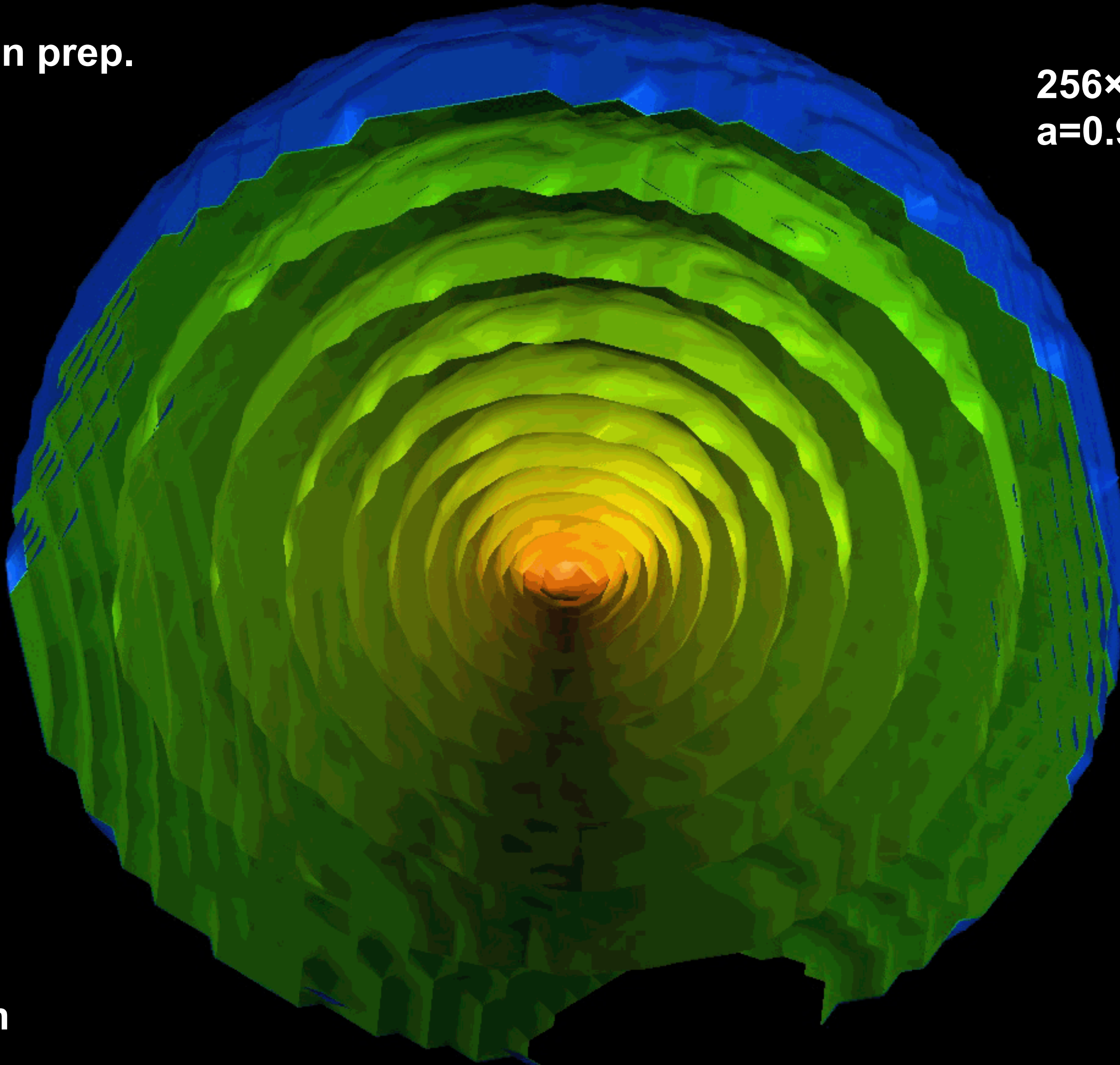


Jet Energy at t=1.5750 sec for a=0, 0.5, 0.9, 0.95 (Solid Curves).

3D-GRMHD Simulation of GRBs

S.N. 2012, in prep.

256×256×32
a=0.9



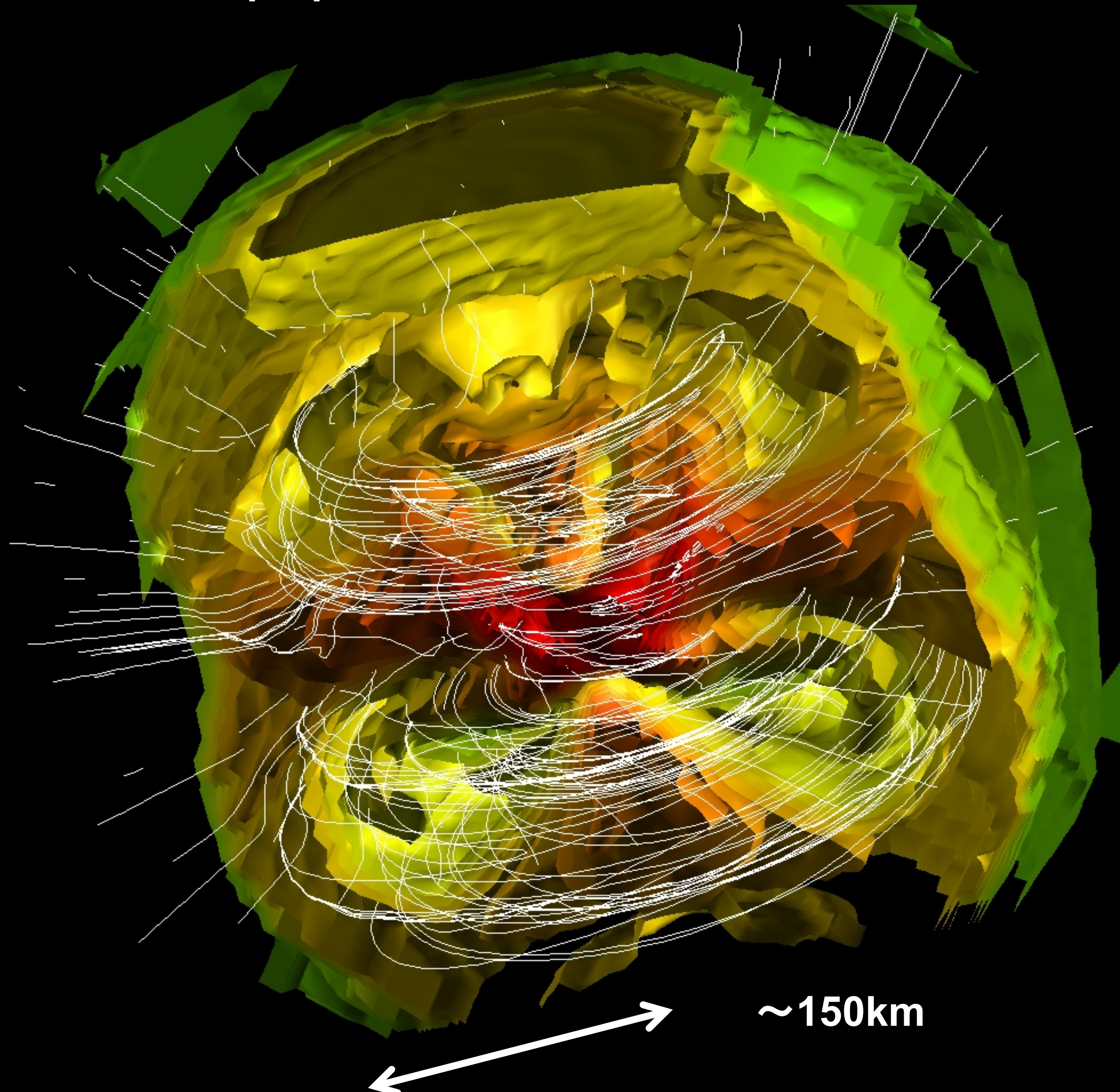
～3000km

S.N. 2012, in prep.

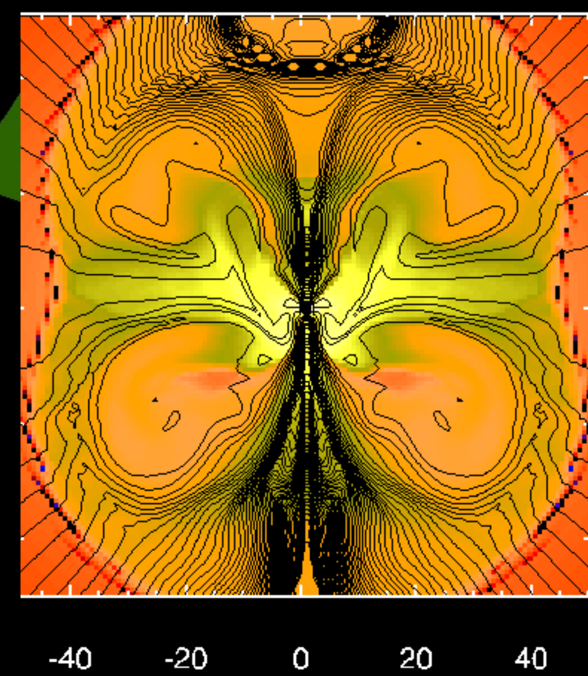
a=0.9
T～0.85sec

Same Simulations.
Left: 3D Image.
Density+B-fields.

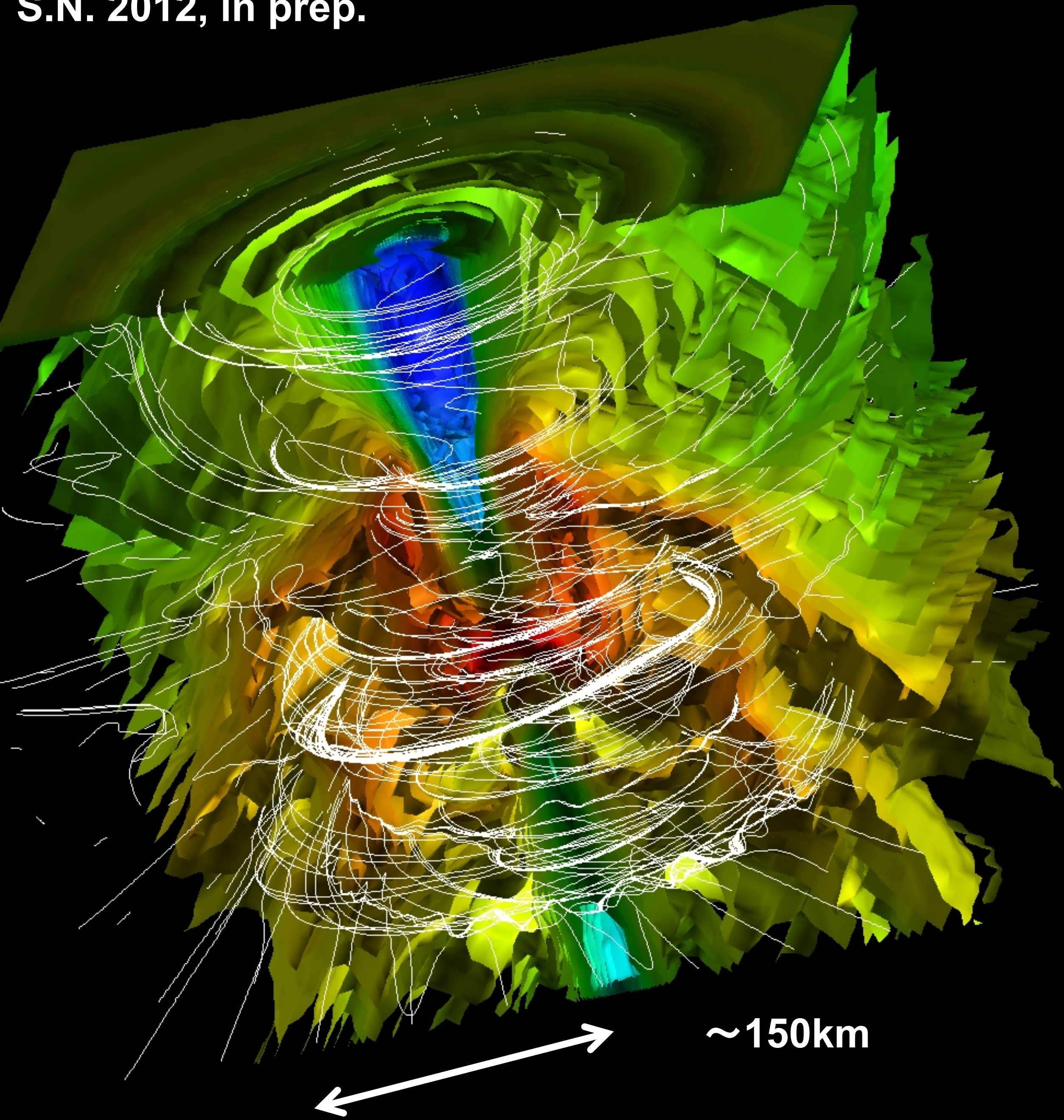
Bottom: 2D Slice
Density+Poloidal
B-Fields



～150km



S.N. 2012, in prep.

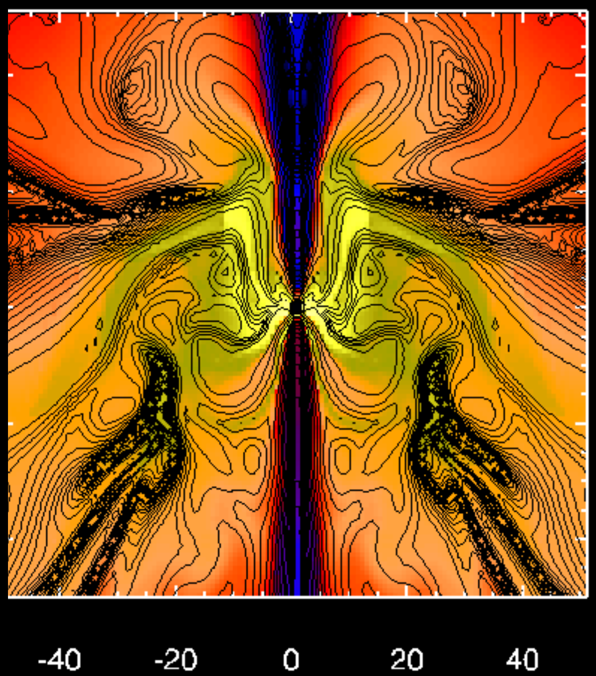


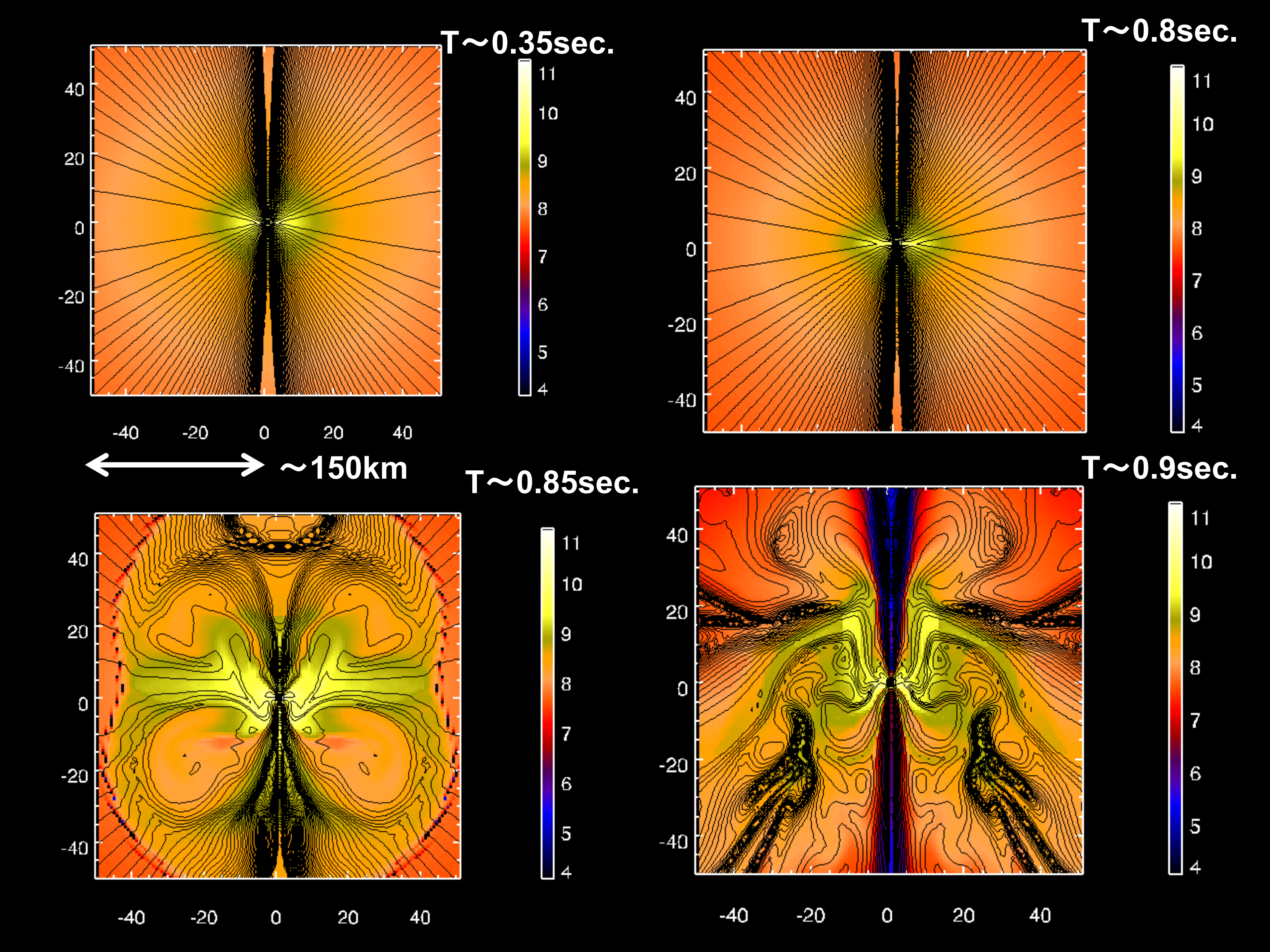
a=0.9
T∼0.9sec.

Same Simulations.
Left: 3D Image.
Density+B-fields.

Bottom: 2D Slice
Density+Poloidal
B-Fields

∼150km

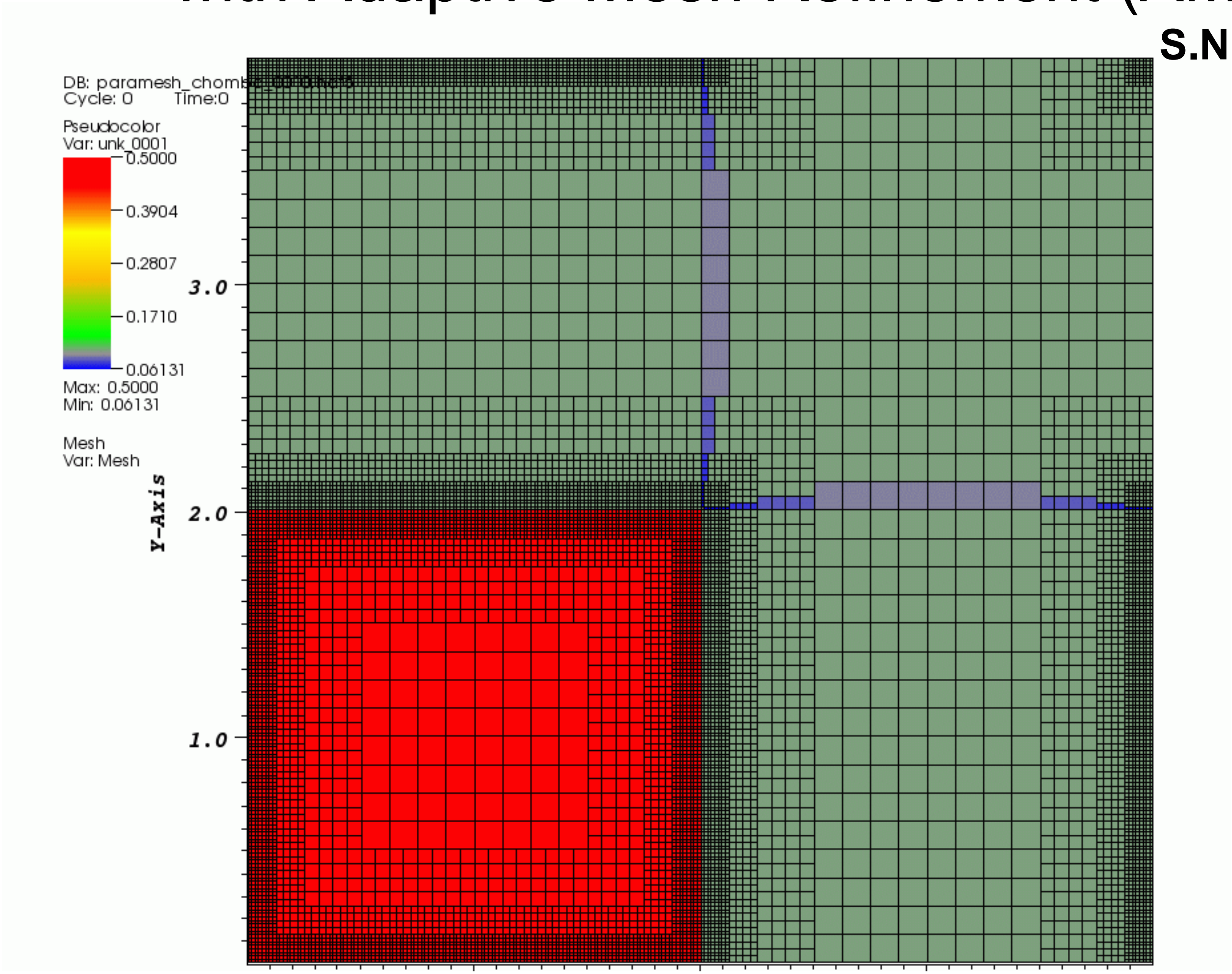




T~0.35sec.
T~0.8sec.
~150km
T~0.85sec.
T~0.9sec.

For Fine Resolution Simulations: SRMHD Code with Adaptive Mesh Refinement (AMR)

S.N. 2012, in prep.



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

K(京:10Peta-Flops) Computer is Coming Soon (2012-).

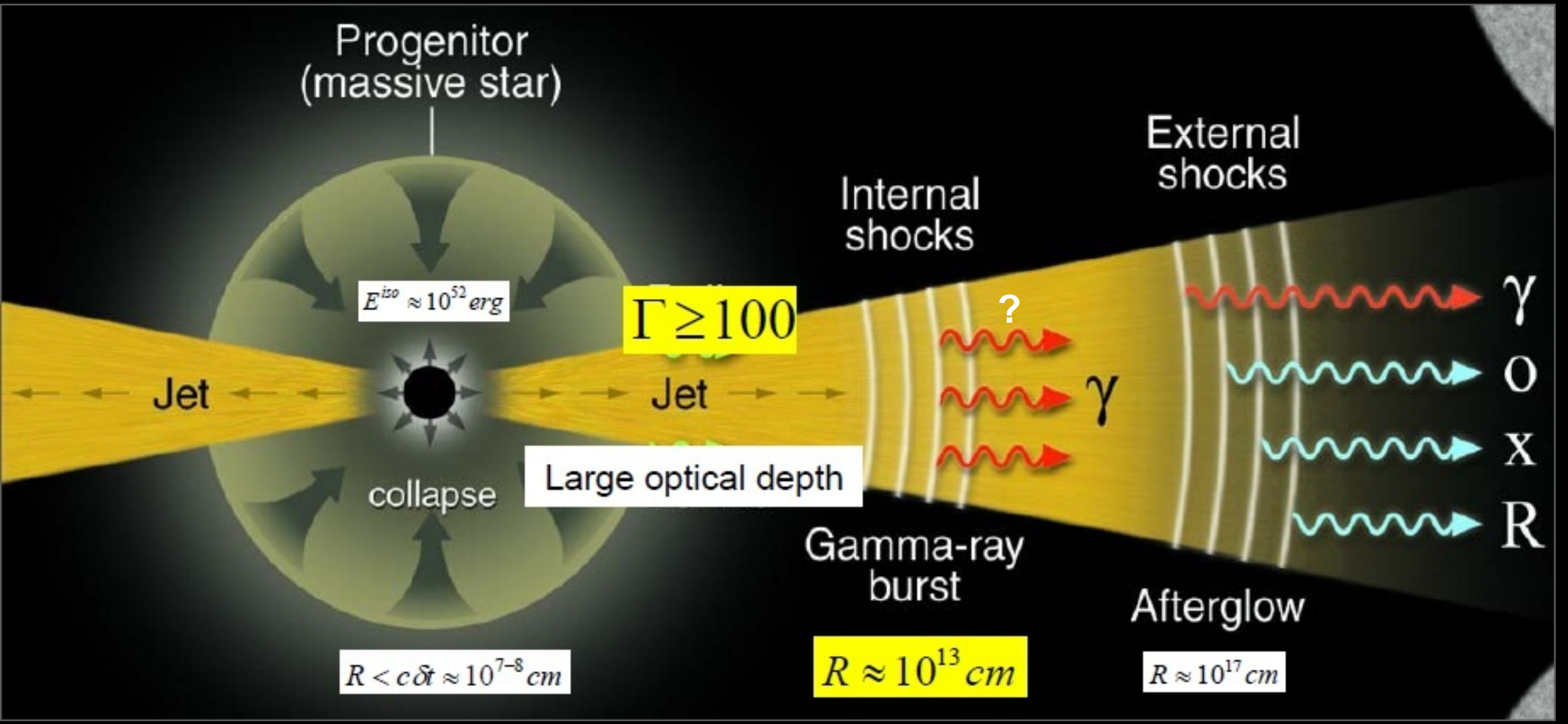
548,352Cores
Memory 8GB per 1Core
100GB/s.

Summary on the Central Engine of LGRBs

- Outline of Explosion Mechanism of LGRBs is still under debate. Lots of things to do.
- Rotation Energy of a Black Hole can be extracted with a help of Magnetic Fields (Blandford-Znajek Effect).
- Faster is better: Rapidly rotating Black Hole can drive an energetic GRB jet.
- GRB simulations by 3D GRMHD code are being done. AMR will be attached. 10-Peta Flops Computer will be open very soon.

§Slide Show of Our Studies

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



Nucleosynthesis
Central Engine

Photospheric
Emission?

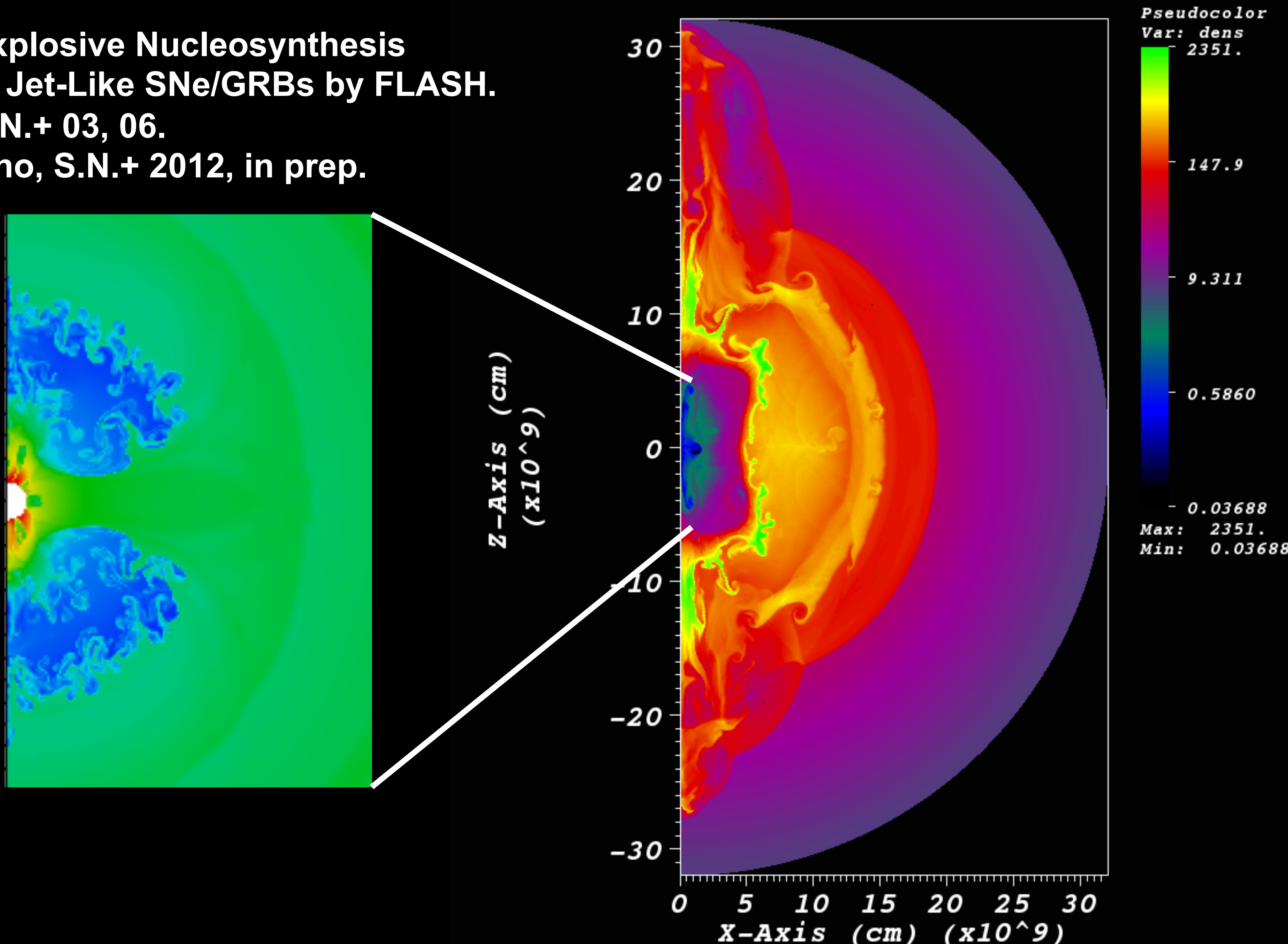
UHECRs?
Neutrinos?

GRB/SN
Remnants?

GRB Cosmology?

Figure from P. Meszaros

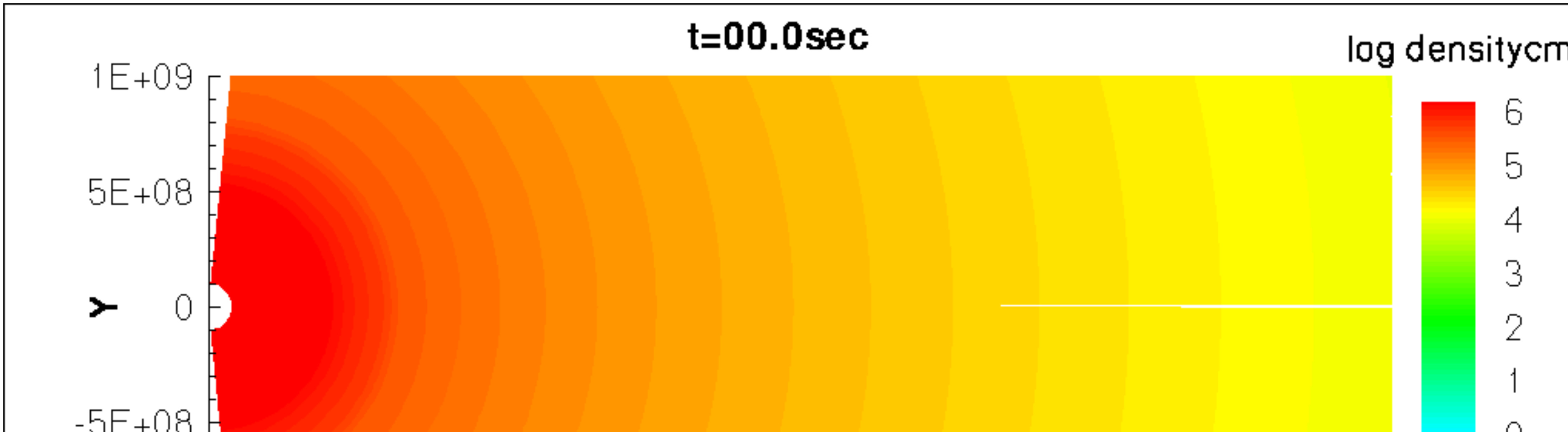
Explosive Nucleosynthesis in Jet-Like SNe/GRBs by FLASH.
S.N.+ 03, 06.
Ono, S.N.+ 2012, in prep.

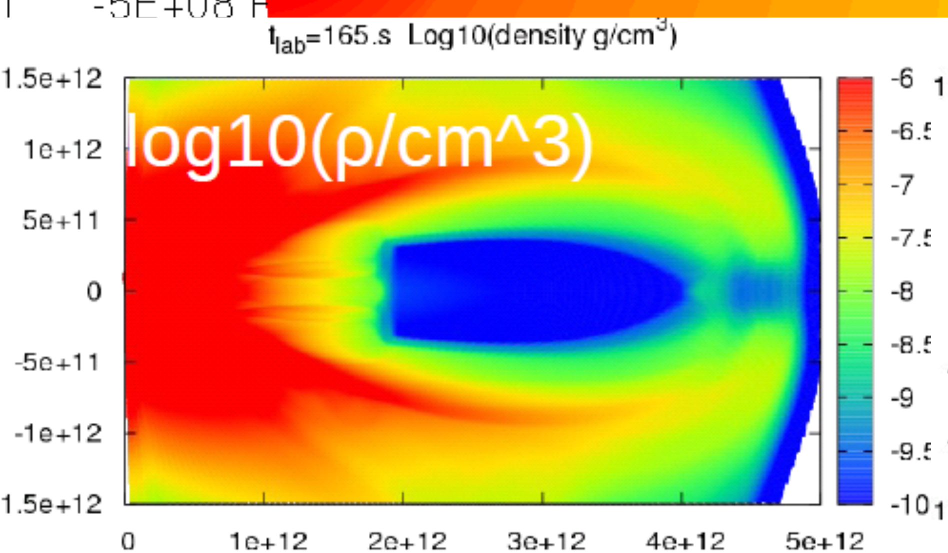


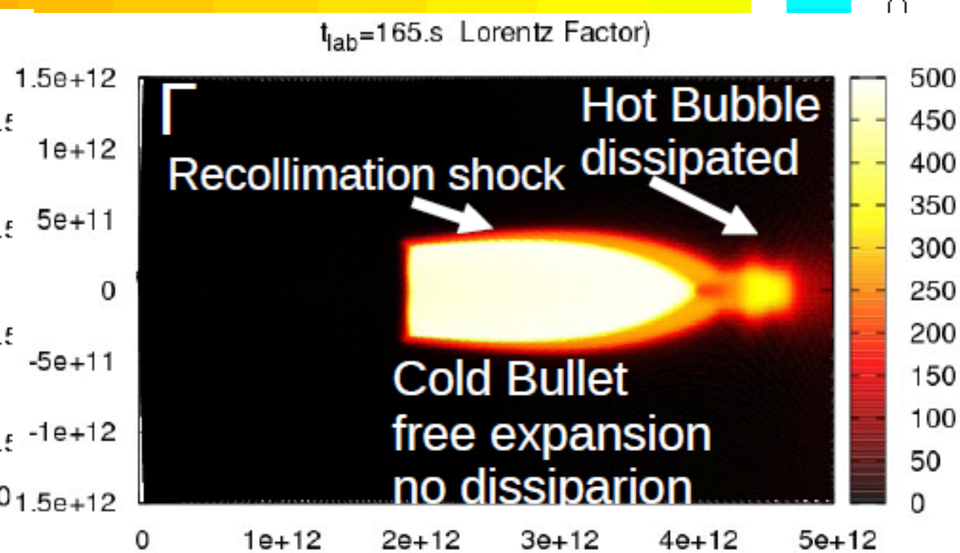
Simulations for the Photospheric Model

Mizuta, S.N., Aoi 2010
Mizuta, S.N., et al. 2012, in prep.

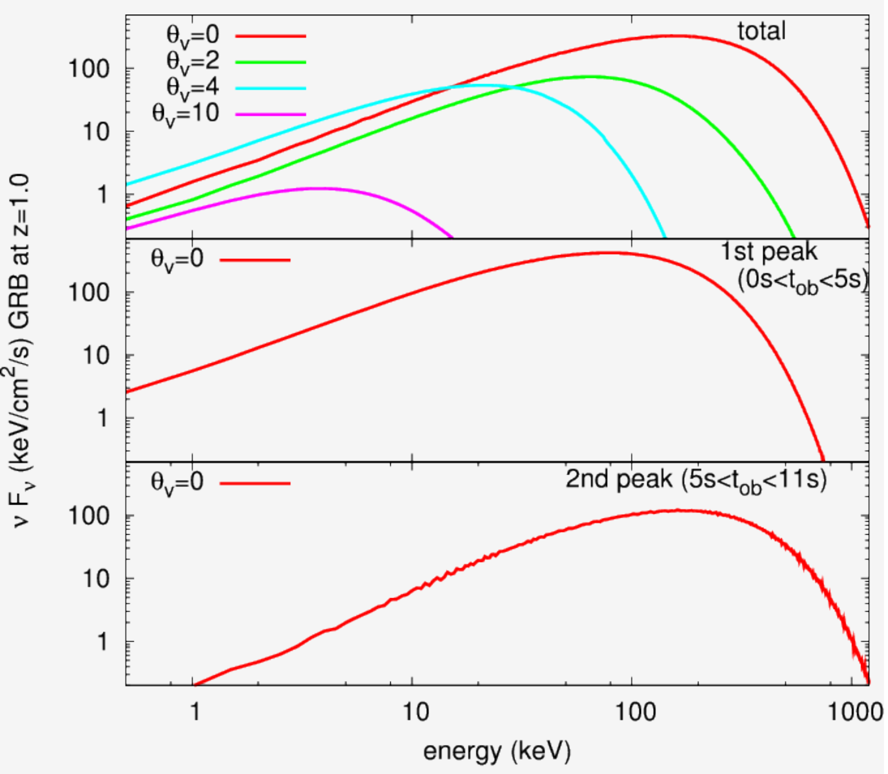
(Also, F.Ryde's talk and D.Lazzati's talk)

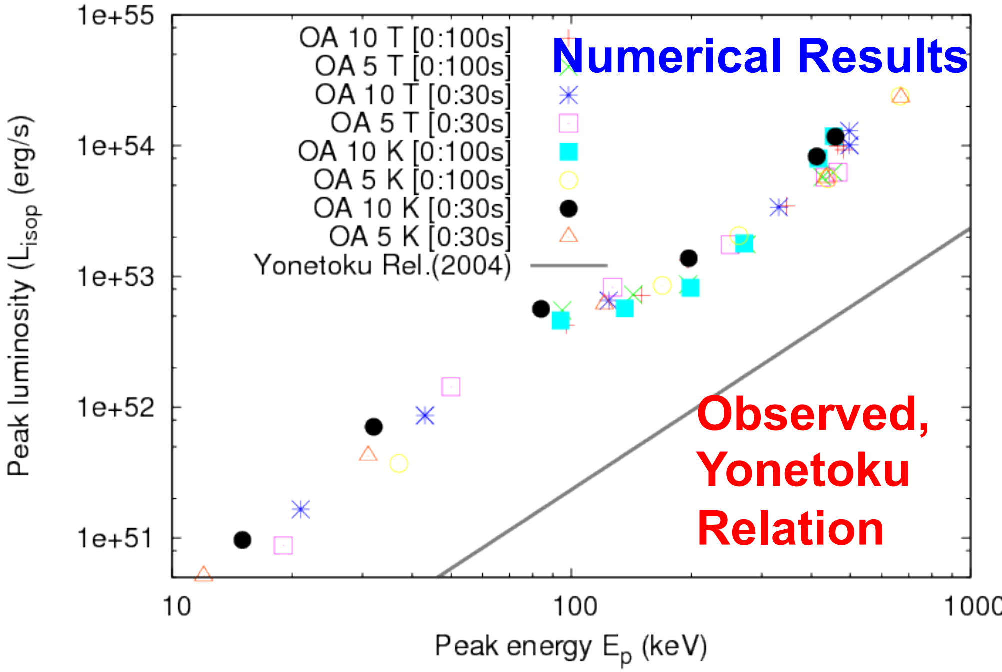






Spectrum, E_peak, and L_peak

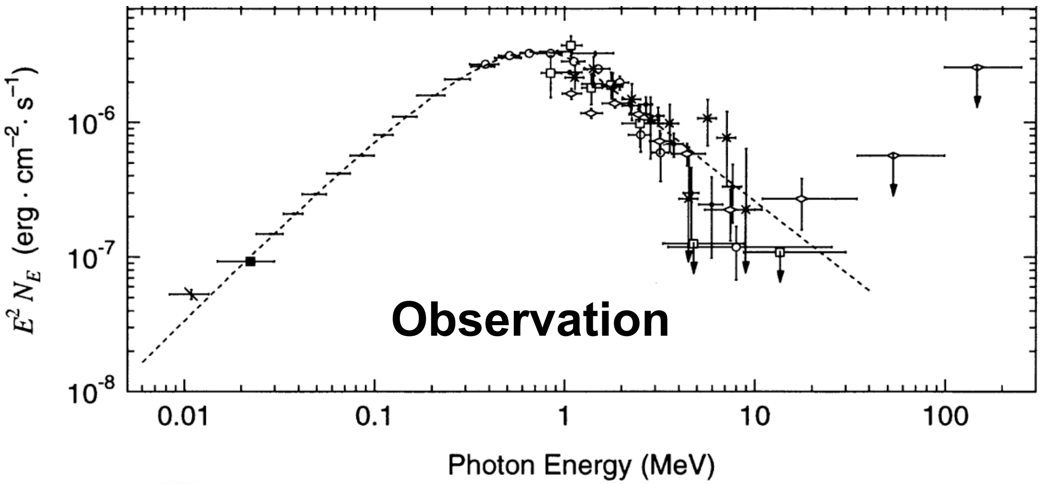




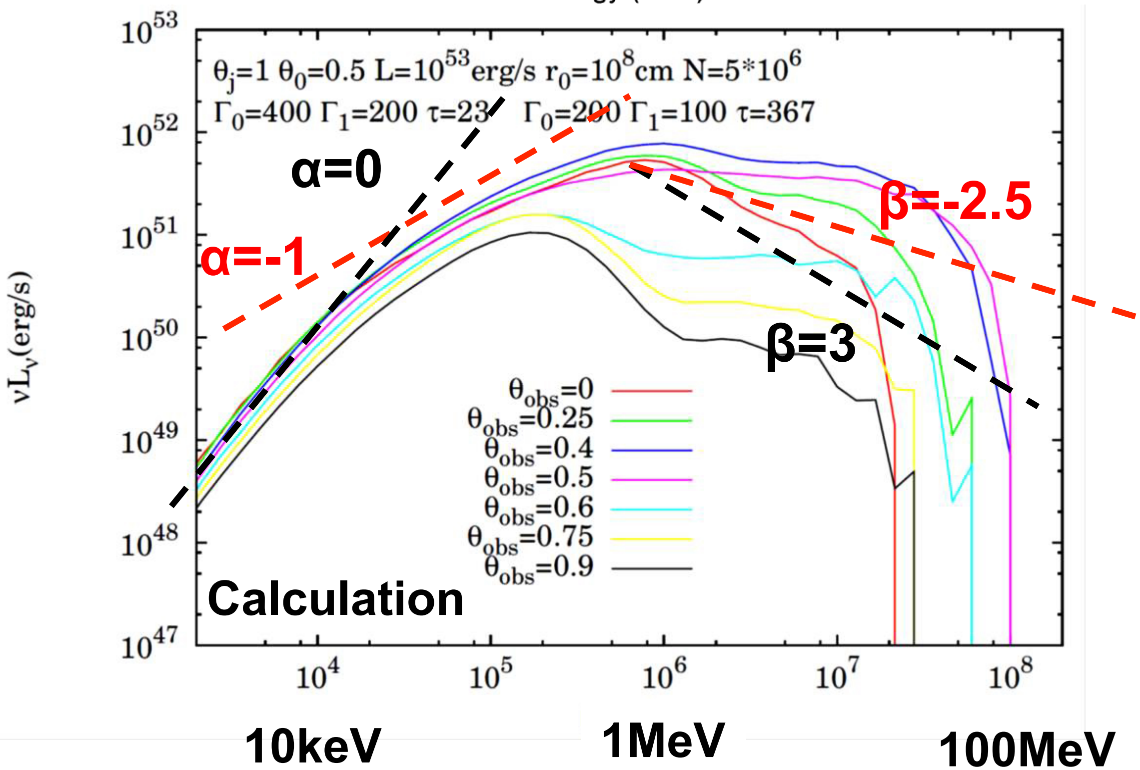
- Superposition of BB spectrum makes the spectrum at low-energy side a little bit softer, although it is not enough to explain alpha.
- Yonetoku (and Amati) Relation is almost reproduced except for some systematic difference.

Monte-Carlo Simulations for the Band-Function

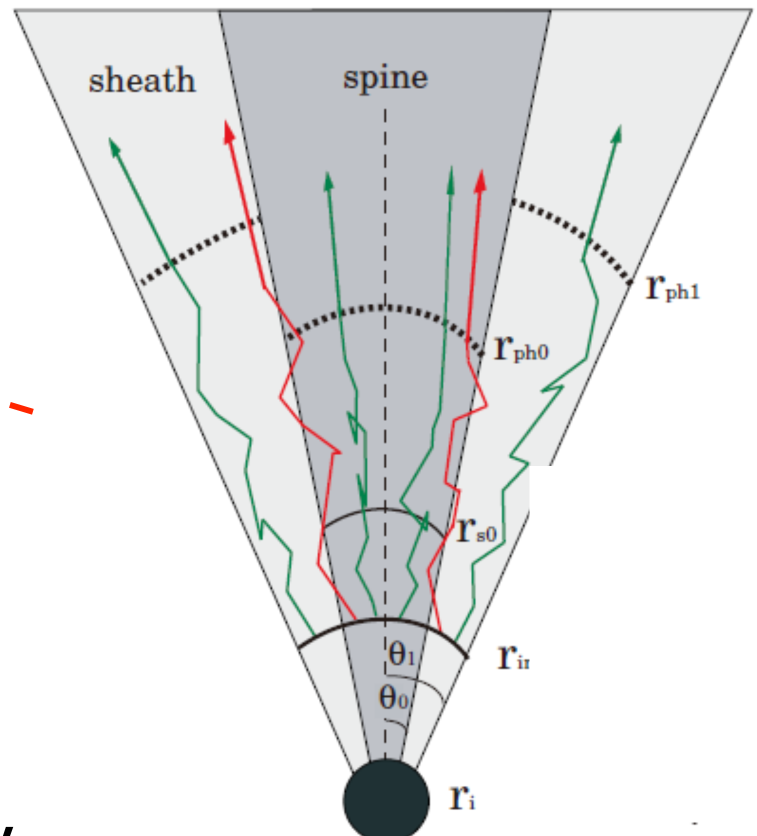
Ito, S.N. et al. 2012, in prep



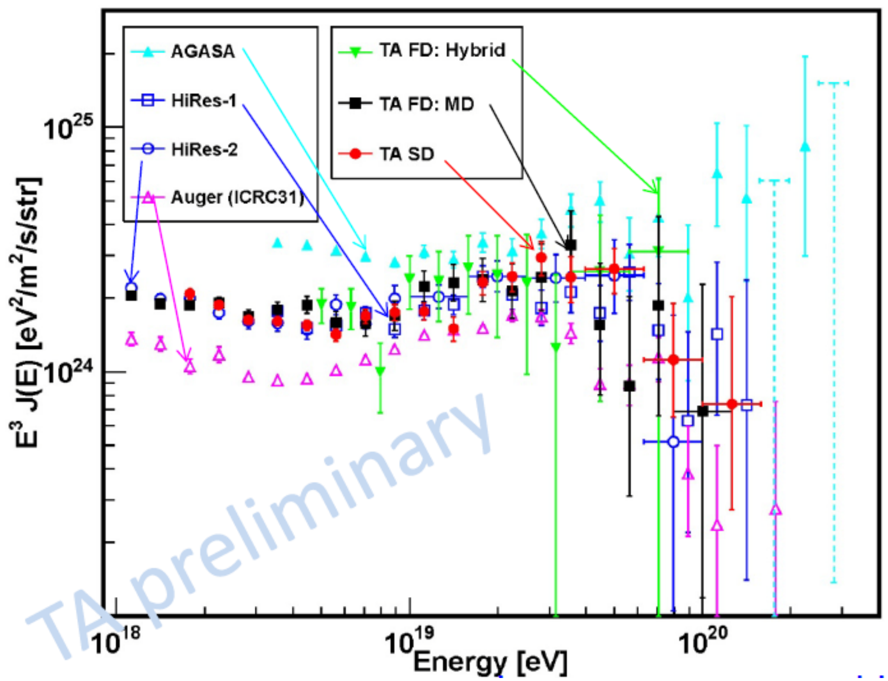
Band-Function can be reproduced By structured photospheric model.

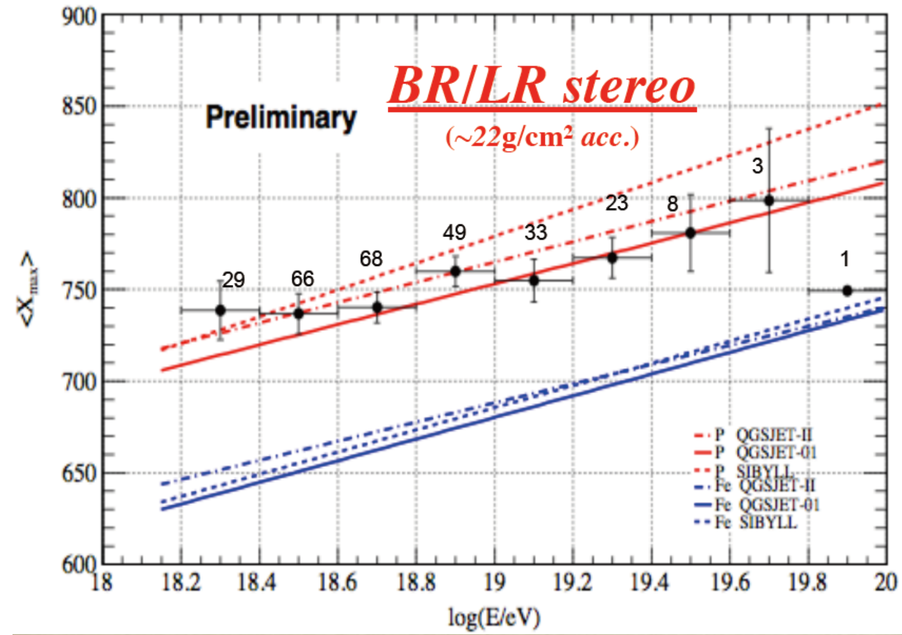


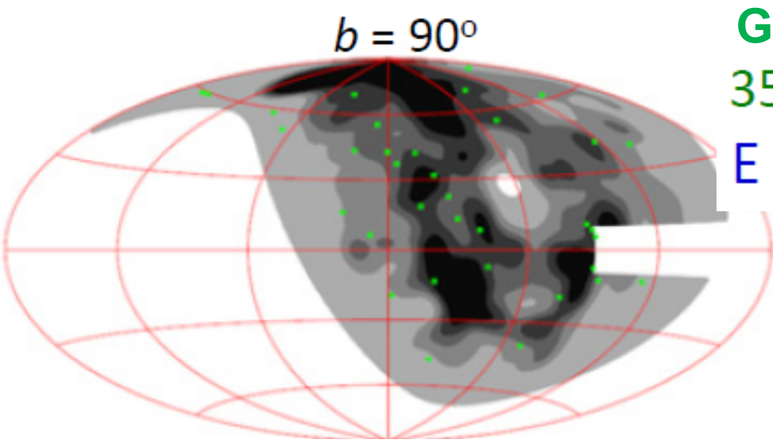
Numerical Set-Up & Monte-Carlo Calculations



First Results of Telescope Array are Open Now





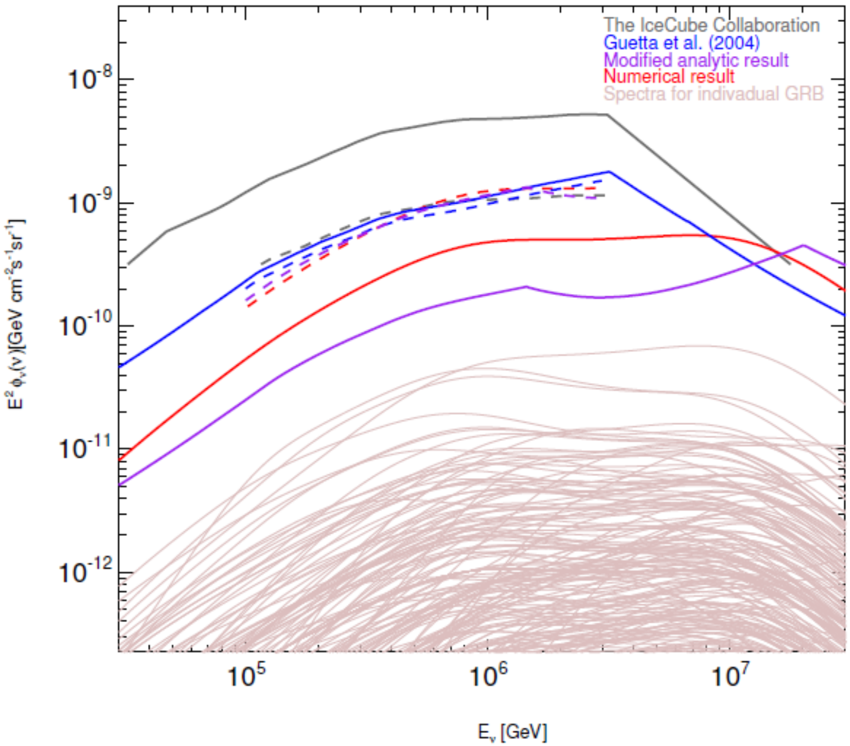


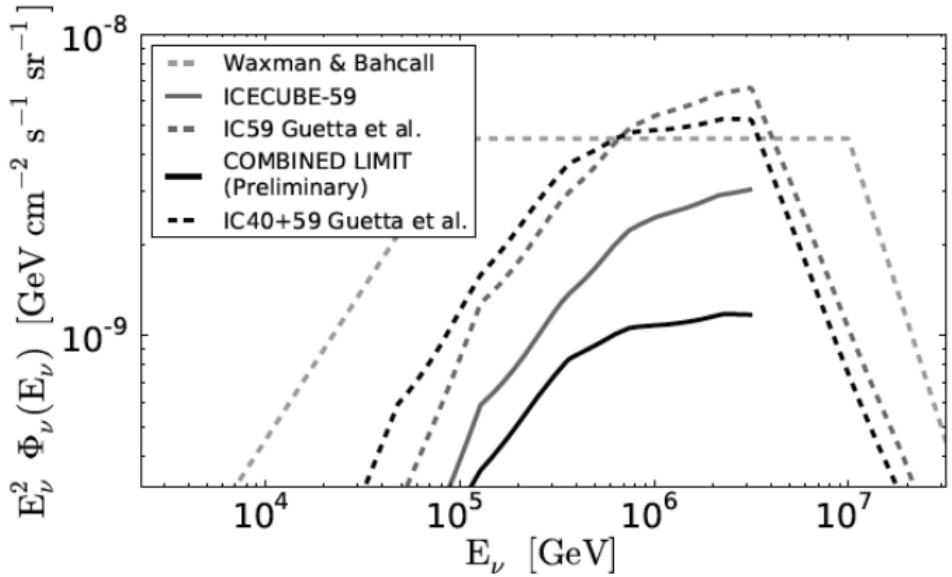
Green:
35 events
E > 40 EeV

Black: LSS model (smearing angle = 6°)

Re-analysis of 215 GRBs' Neutrinos

He, Liu, Wang, S.N.+ 12





the IceCube collaboration 2011

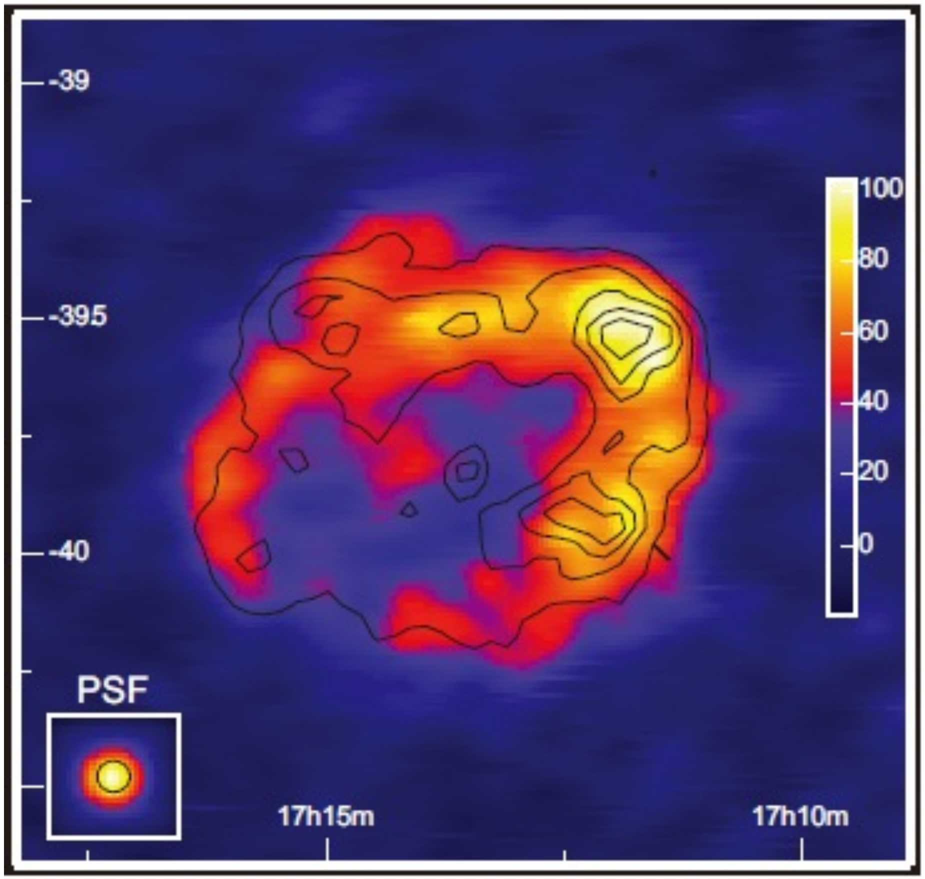
Expected Neutrino Flux from 215 GRBs.

See also Li 12, Hummer +12
Murase and S.N. 06a, 06b

$\alpha = 1$, $\beta = 2$, fluence $F_\gamma^{ob} = 10^{-5}\mathrm{erg\,cm^{-2}}$ (in 10keV to 1MeV), $z = 2.15$, $\epsilon_{\gamma,b}^{ob} = 200\mathrm{keV}$

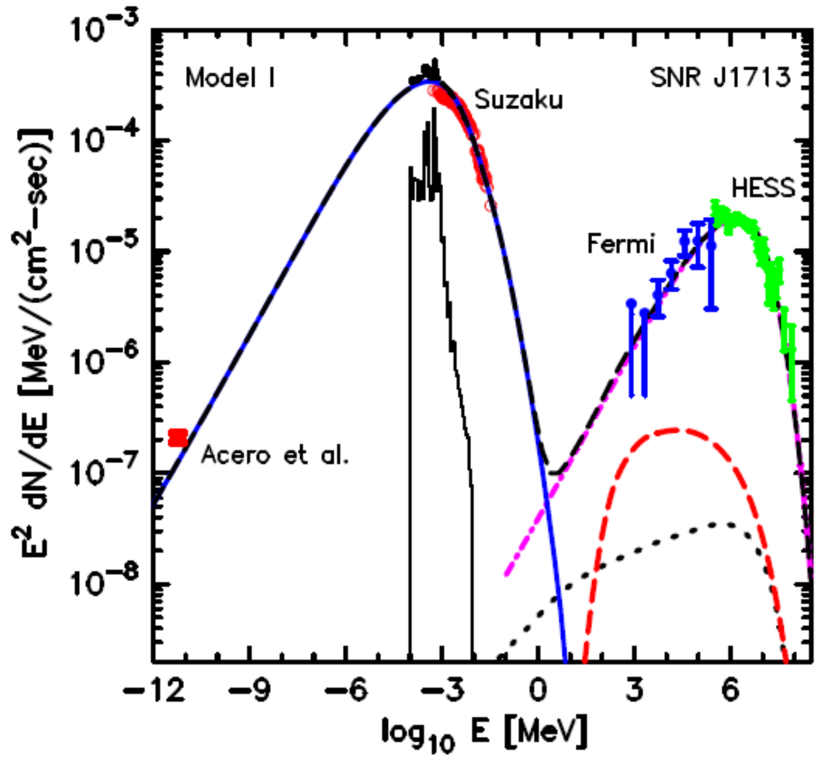
$L_\gamma = 10^{52}\mathrm{erg\,s^{-1}}$, bulk Lorentz factor $\Gamma = 10^{2.5}$, the observed variability timescale $t_v^{ob} = 0.01\mathrm{s}$ and the baryon ratio $\eta_p = 10$.

Study on Supernova Remnant RXJ1713.7-3946 with CR-Hydro-NEI Code



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

Lee, Ellison, S.N. 2012
Ellison+ 2010 and References there in.

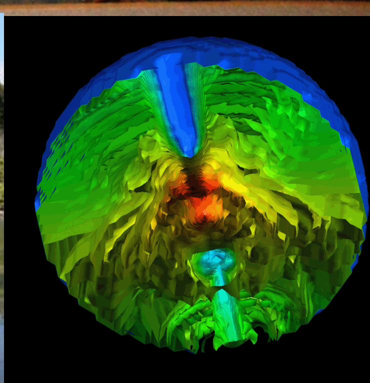


Supernovae and Gamma-Ray Bursts in Kyoto, 2013

- **Oct.-Nov. in 2013.**
- **2weeks for Conferences (SN and GRB)**
- **3weeks for Workshops (Seminars & Discussions).**

Photo from GRB2010, Kyoto In April.

YITP
YUKAWA INSTITUTE FOR THEORETICAL PHYSICS



You can Stay More in Kyoto.

- Program for Ph.D Students or Postdocs

Period: 1-3 Months.

Flight fee & accommodation fee are covered, at least.

- Some Programs for Visiting Staffs.

- Some Postdoc Positions will be open (YITP, Kyoto Univ. and JSPS).


Kyoto in Spring

Kyoto in Summer


Kyoto in Autumn

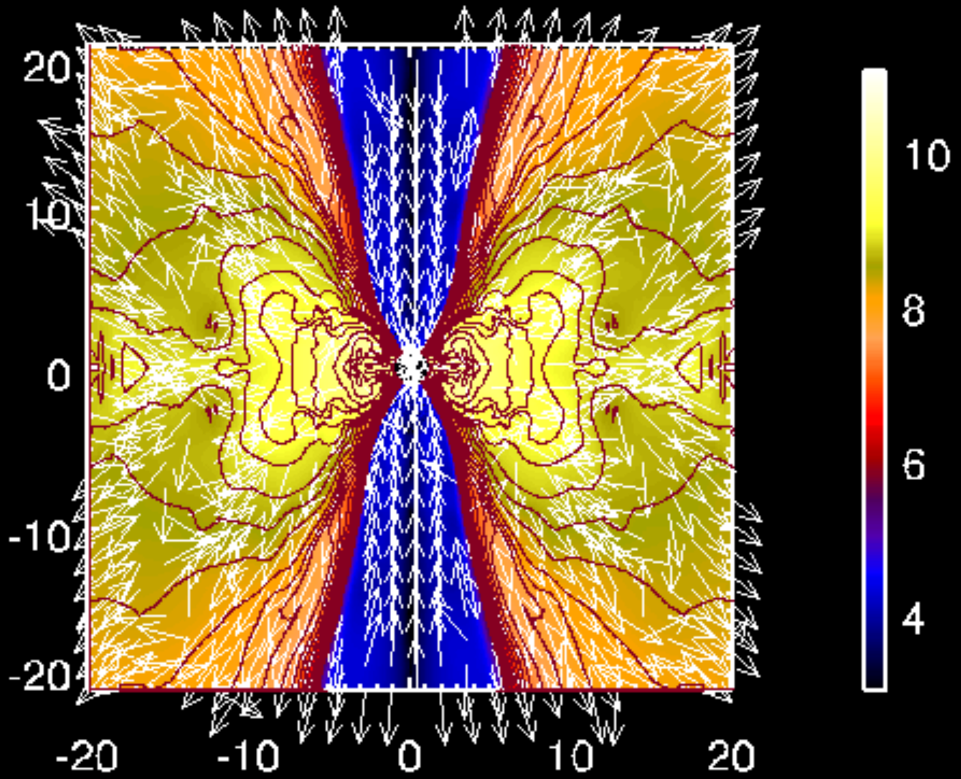
Kyoto in Winter

Summary

- Outline of Explosion Mechanism of LGRBs is still under debate.
- Rotation Energy of a Black Hole can be extracted with a help of Magnetic Fields (Blandford-Znajek Effect).
- Faster is better: Rapidly rotating Black Hole can drive an energetic GRB jet.
- GRB simulations by 3D GRMHD code are being done. AMR will be attached. 10-Peta Flops Computer will be open very soon.
- Explosive Nucleosynthesis is being studied by Flash code.
- Photosperic Models are studied by numerical simulations and Monte-Carlo calculations.
- UHECRs, VHE-Neutrinos, SNRs are being studied.
- 5 Week Conferences and Workshoos on SNe and GRBs will be held in Kyoto, 2013, Oct.-Nov.
- Programs for Visitors and Postdocs.

Stagnation Region

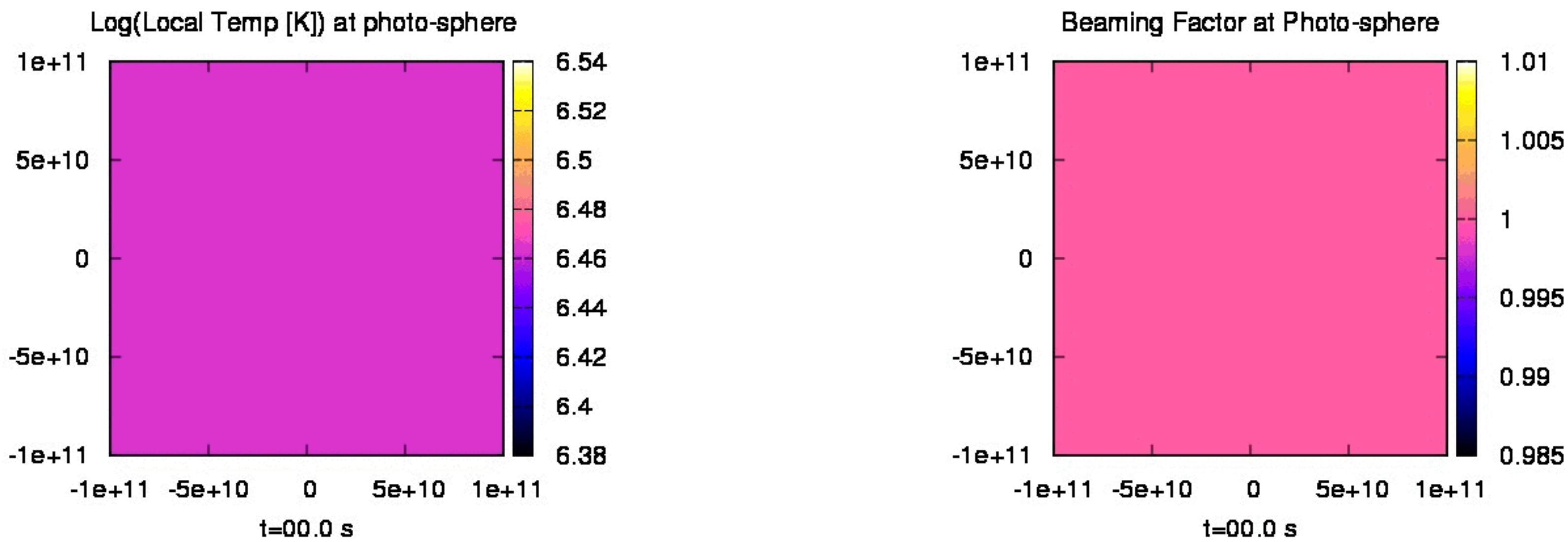
S.N. (2011)



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

Time evolution of the Photo-sphere and Thermal Emission



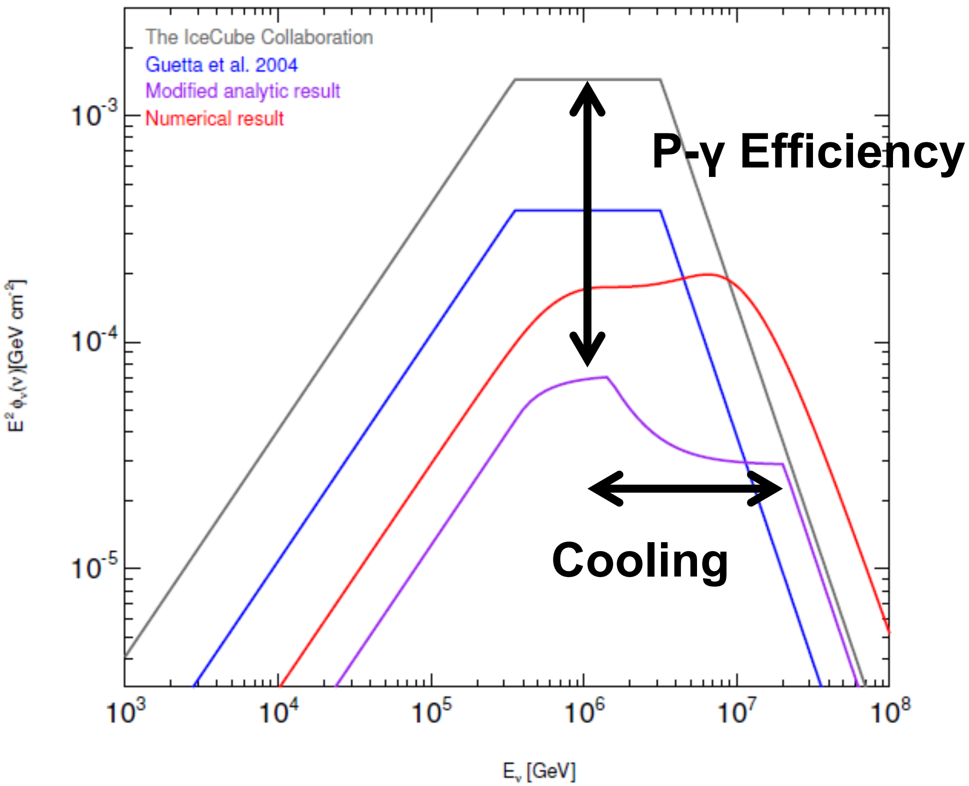
Left: Evolution of the temperature at the photo-sphere viewed from the jet axis.

Right: Beaming factor at the photo-sphere.

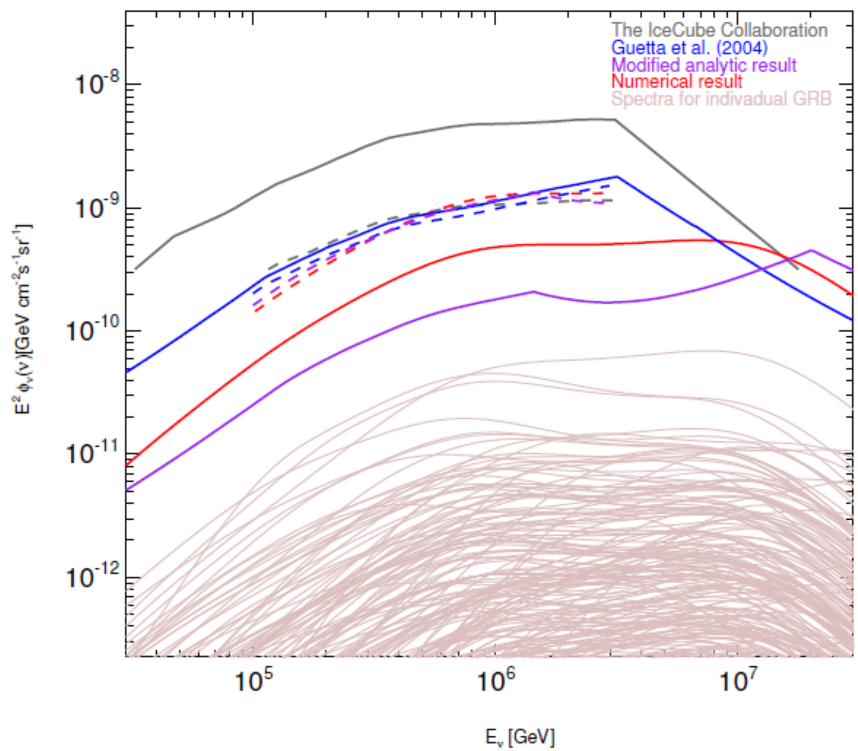
Superposition of thermal emissions from each area of the photosphere is observed.

Re-analysis of 215 GRBs' Neutrinos

He, Liu, Wang, S.N.+ 12



Expected Neutrino Flux from a single GRB



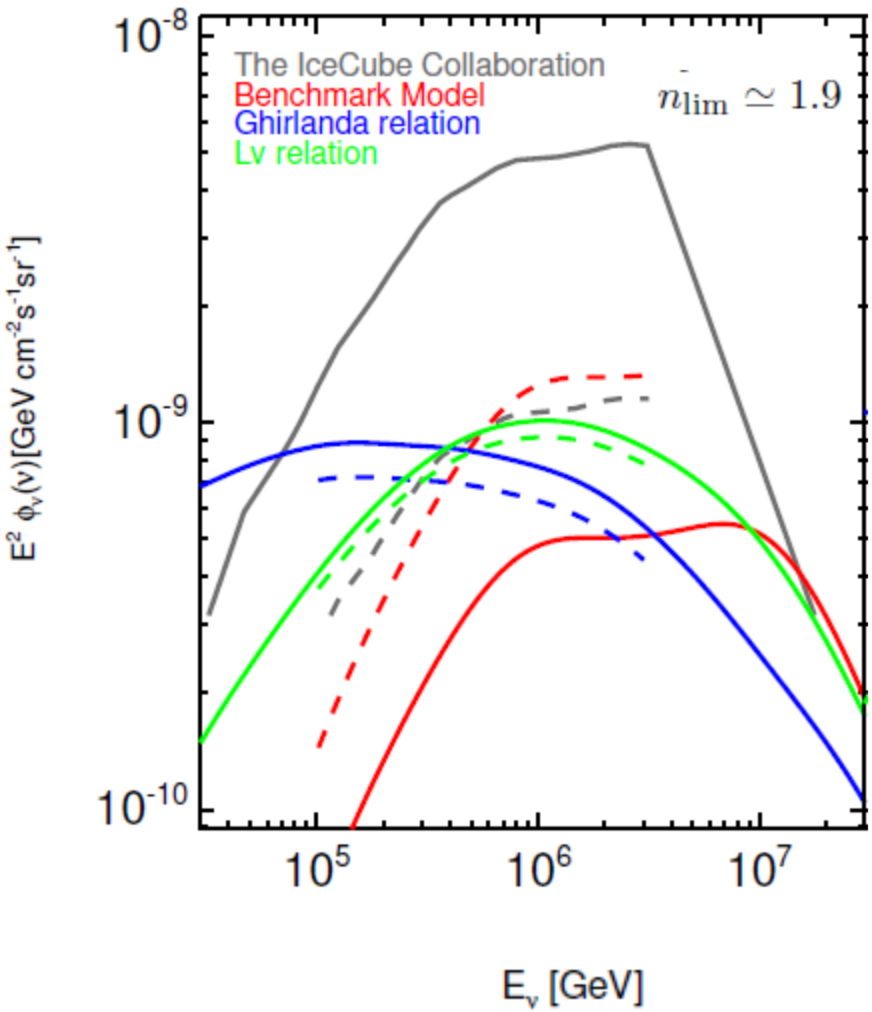
Expected Neutrino Flux from 215 GRBs.

$\alpha = 1$, $\beta = 2$, fluence $F_\gamma^{ob} = 10^{-5}\mathrm{erg\,cm^{-2}}$ (in 10keV to 1MeV), $z = 2.15$, $\epsilon_{\gamma,b}^{ob} = 200$keV

$L_\gamma = 10^{52}\mathrm{erg\,s^{-1}}$, bulk Lorentz factor $\Gamma = 10^{2.5}$, the observed variability timescale $t_v^{ob} = 0.01$s and the baryon ratio $\eta_p = 10$.

IC40/59 can draw a constraint on GRB-Neutrino scenarios with a help of some Empirical Relations

215 GRBs' Neutrinos



He, Liu, Wang, S.N.+ 12.

Gray: All GRBs are assumed to be same (IceCube Collaboration).

Red: Same with ICC, but for Numerical Model.

Green: Numerical Model with Lv relation (2011)

$$\Gamma_L = 118 E_{\rm iso,52}^{0.26}.$$

$$L_{\gamma G,52} = 7.54\left[\epsilon^{\rm ob}_{\gamma {\rm b,MeV}}(1+z)\right]^{1.75}$$

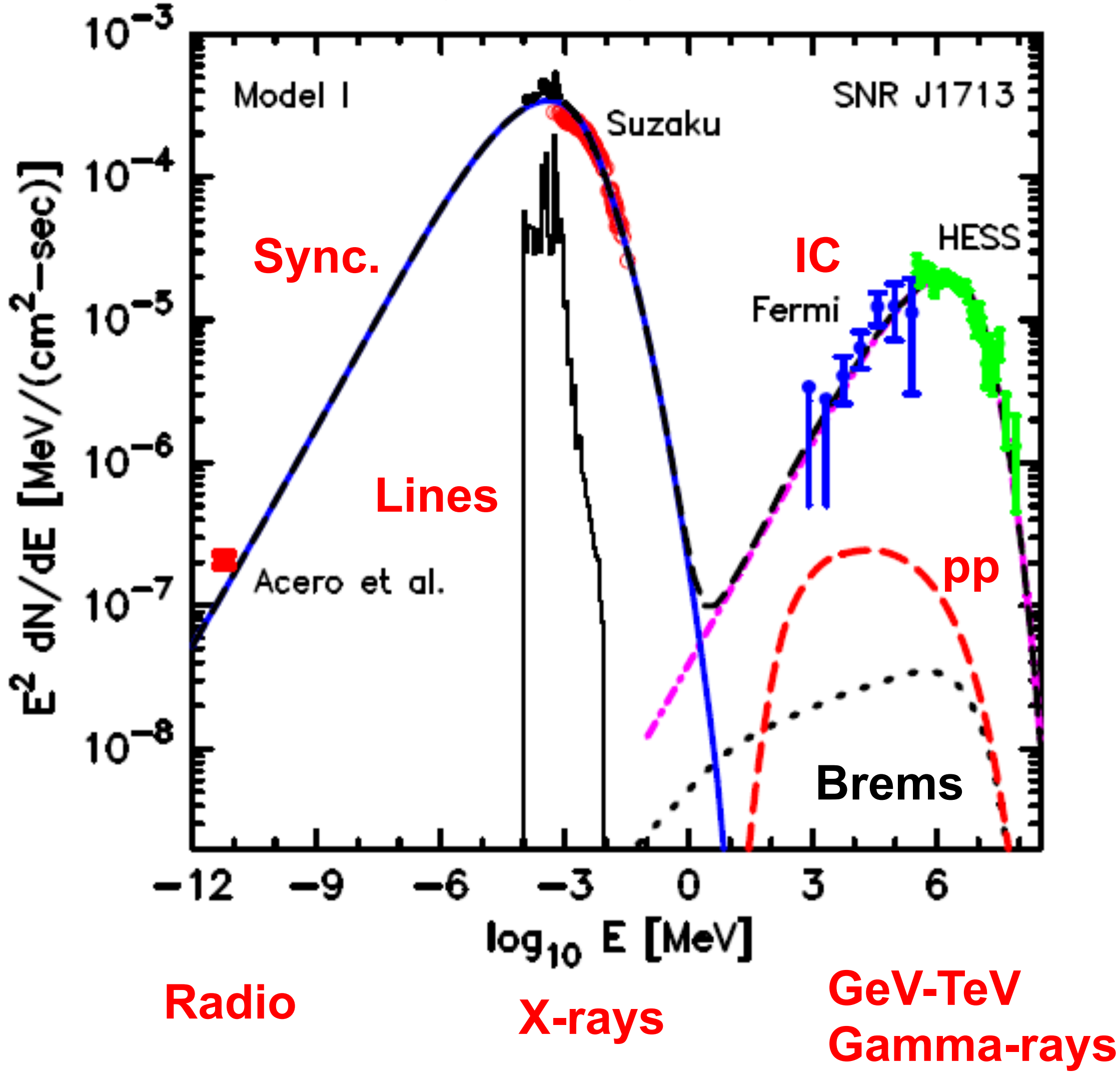
Blue: Numerical Model with Ghirlanda relation (2011)

$$\Gamma_G = 29.8 E_{\rm iso,52}^{0.51}.$$

$$L_{\gamma G,52} = 7.54\left[\epsilon^{\rm ob}_{\gamma {\rm b,MeV}}(1+z)\right]^{1.75}$$

Gamma-Rays look Leptonic Origin for RXJ1713. 7-3946

Lee, Ellison, S.N. 2012



Ellison+ 2010