Banff State
Dept of Ultrarelativistic Jets
GRBs 101

Practice Final Exam

Time 1hr

Collaboration Allowed

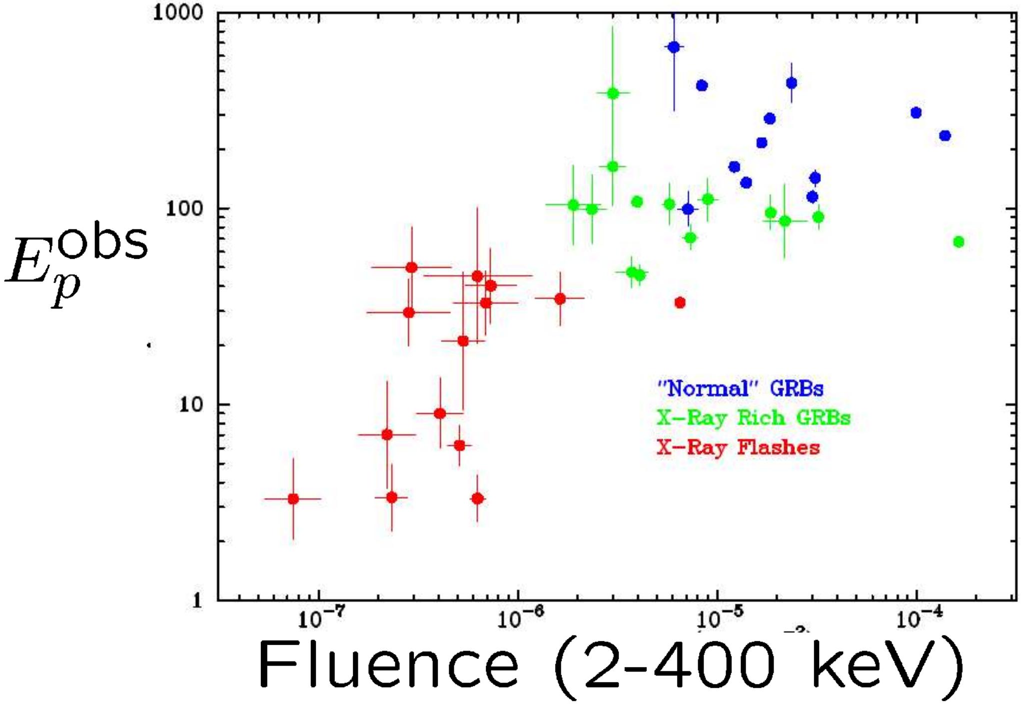
Sample Questions

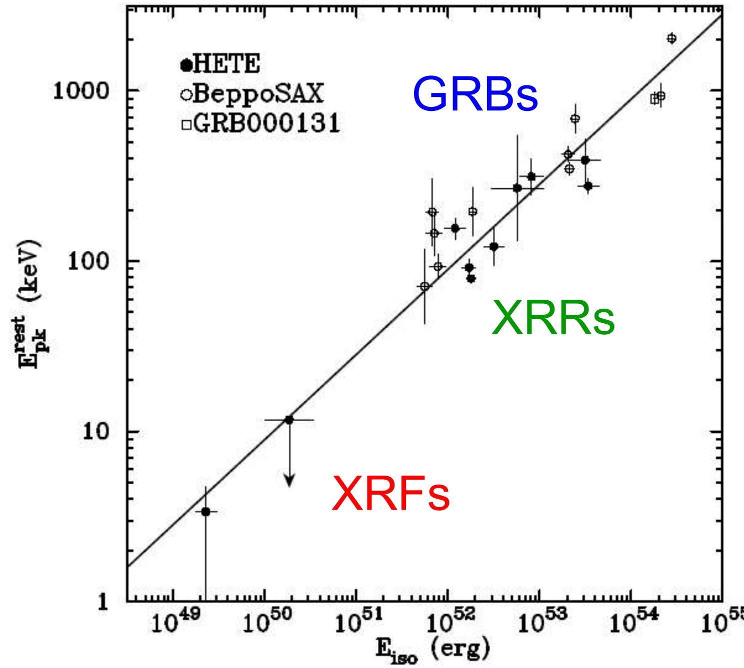
- What have GRB observers done for us lately?
- Compare and contrast: GRB, AGN, PWN, GSL, SGR,YSO
- Distinguish temporally short and long bursts
- Define thoughtfully: jet, pancake?
- Why are jets thought to be fluid dynamical?
- How do black holes work?
- Why has it taken so long to develop GRMHD codes?
- Describe carefully the chain of events that leads to a magnetar explosion
- Discuss prophetically what we will learn in the future about GRB

What have GRB observers done for us lately?

- HETE, Integral, Swift
- Short - 050509b XRF, z=0.22
- Afterglow >=Burst, E> 10^{49}erg
- Amati: $E_{iso} \sim E_p^2$ may be selection effect
- 3 x 10^{-6} yr^{-1} G^{-1}; 3 x 10^{-4} SN
- SN1c w/o GRB
- Long bursts w/o SN!

(Lamb et al. 2003)



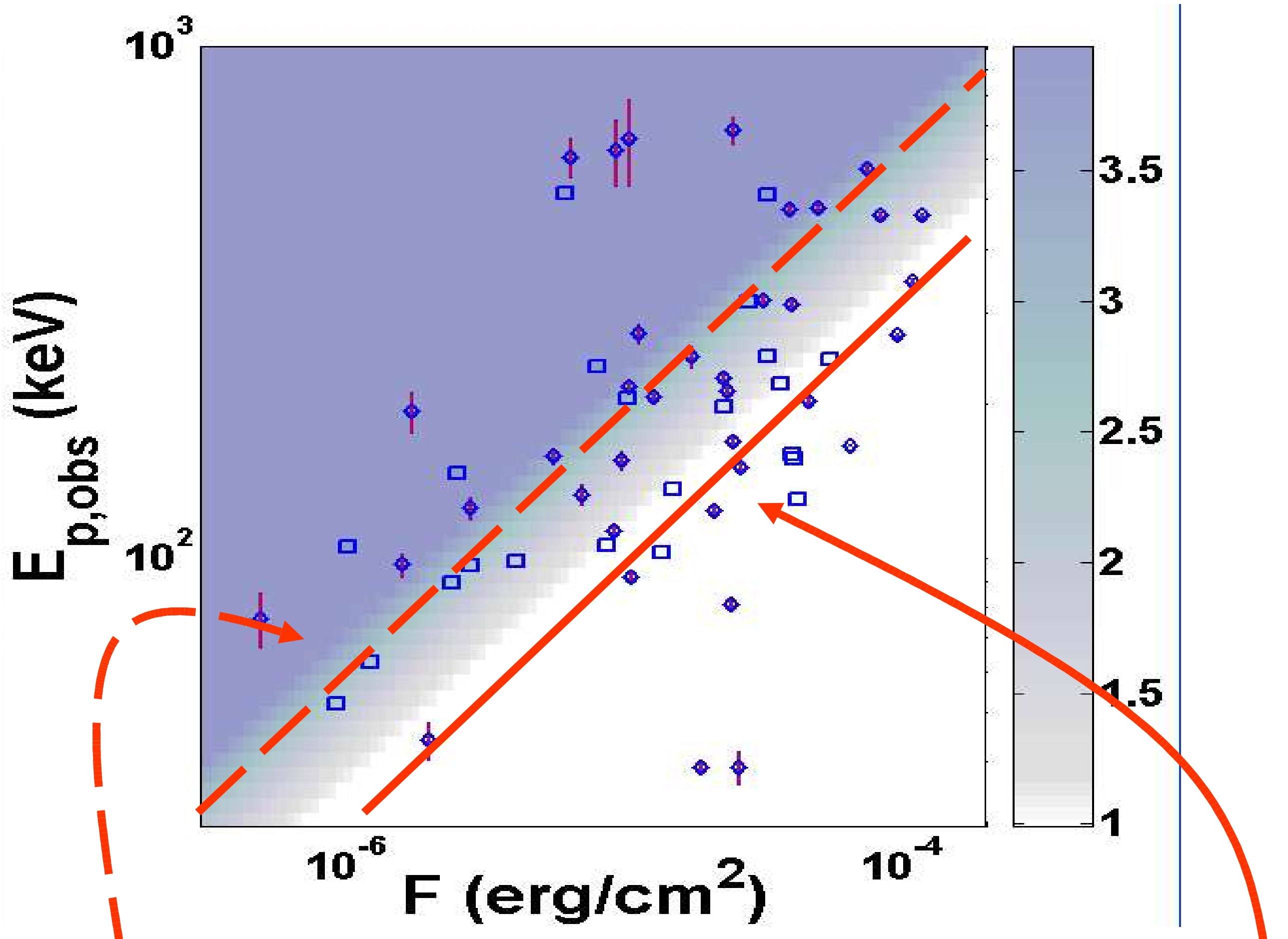


$$E_p \propto (E_{iso})^{0.5}$$

HETE-2 observations confirmed that softer and dimmer (long) GRBs smoothly extend to XRFs through an intermediate class, X-Ray Rich GRB (XRR).

⇨ Origins of XRFs & XRRs are the same as (long) GRBs.

Ghirlanda Ghiselline and Firmani 05:



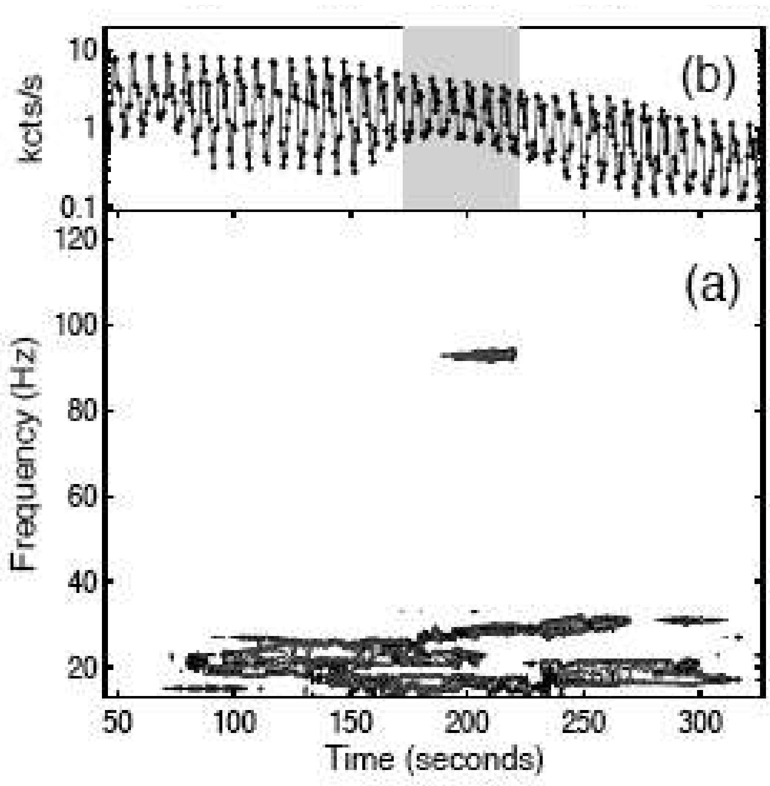
Amati relation II for BATSE bursts

Amati relation I for BeppoSAX & HETE bursts

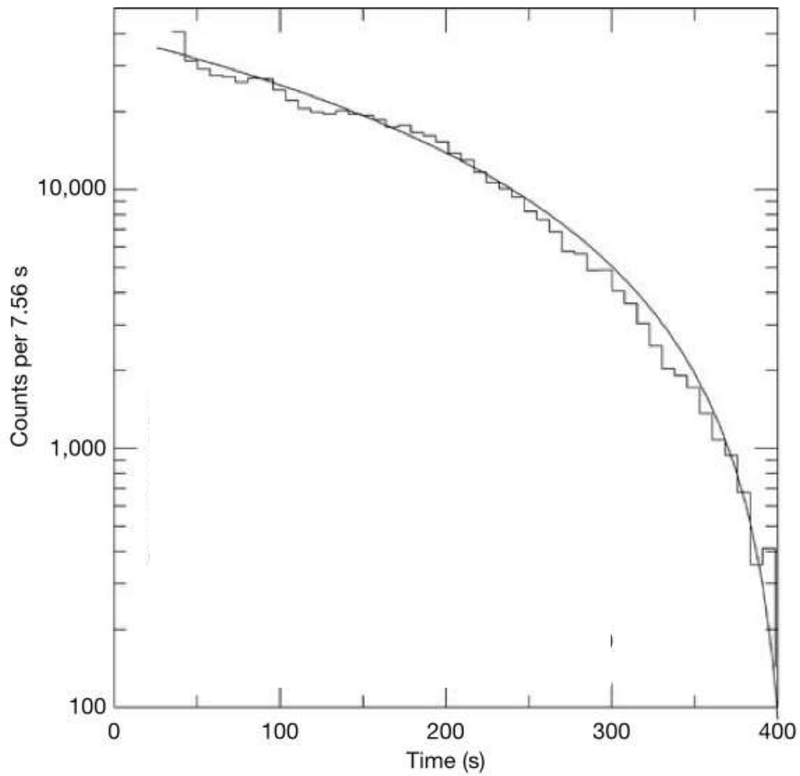
The Tail

• Quasi-periodic oscillations at 18, 30.4, 92.5 Hz (Israel et al. 2005)
  - possibly represent seismic modes on neutron star surface, coupled to magnetosphere (30, 92 Hz) and to 7 x 10^{15} G interior field (18 Hz)

• Unpulsed component of tail good fit to trapped fireball model (Hurley et al. 2005)



Israel et al. (2005)



Hurley et al. (2005)

Compare and contrast: GRB, AGN, PWN, GSL, SGR,YSO

- All make high M (aka Γ) jets possess disks and have spinning central stars
- GRB outflows, which have the highest M, generally supposed to gas dynamical
- Remainder MHD!

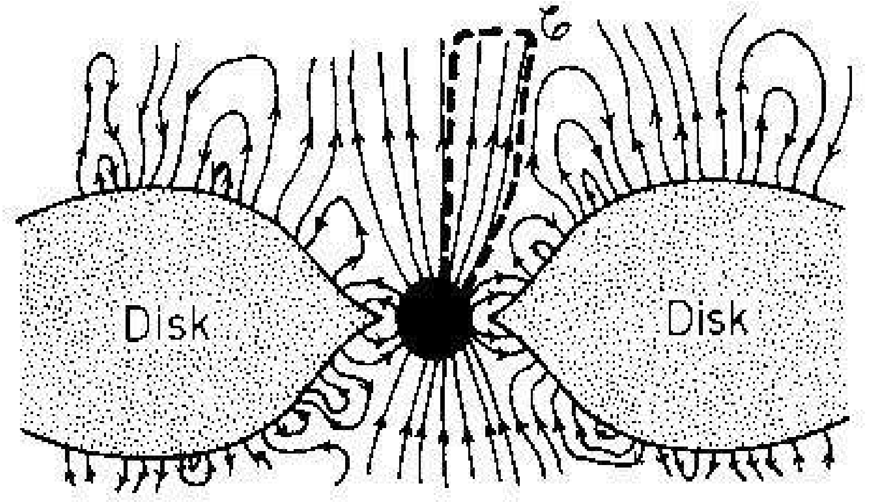
Some Questions

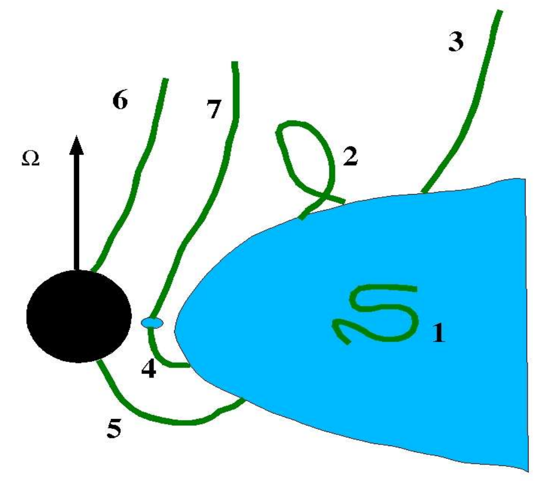
- How is the fireball entropy created?
- How do you sustain ultrasonic jets?
- Why do the baryons remain and not the field?
- Where are there no thermal precursors?
- Why aren't afterglow shocks "universal"
  - How are particles accelerated and field amplified?
- What determines the jet opening angle?
- What are X-ray flashes?
- Where are the orphan afterglows?

Unipolar Inductio

- Rules of thumb:
- $\Phi \sim B R^2$; $V \sim \Omega \Phi$
- $I \sim V / Z_0$; $P \sim V I$

	PWN	AGN	GRB
B	100 MT	1 T	1 TT
ν	10 Hz	10 μ Hz	1 kHz
R	10 km	10 Tm	10 km
V	3 PV	300 EV	30 ZV
I	300 TA	3 EA	300 EA
P	100 XW	1 TXW	10 PXW





UHECR!

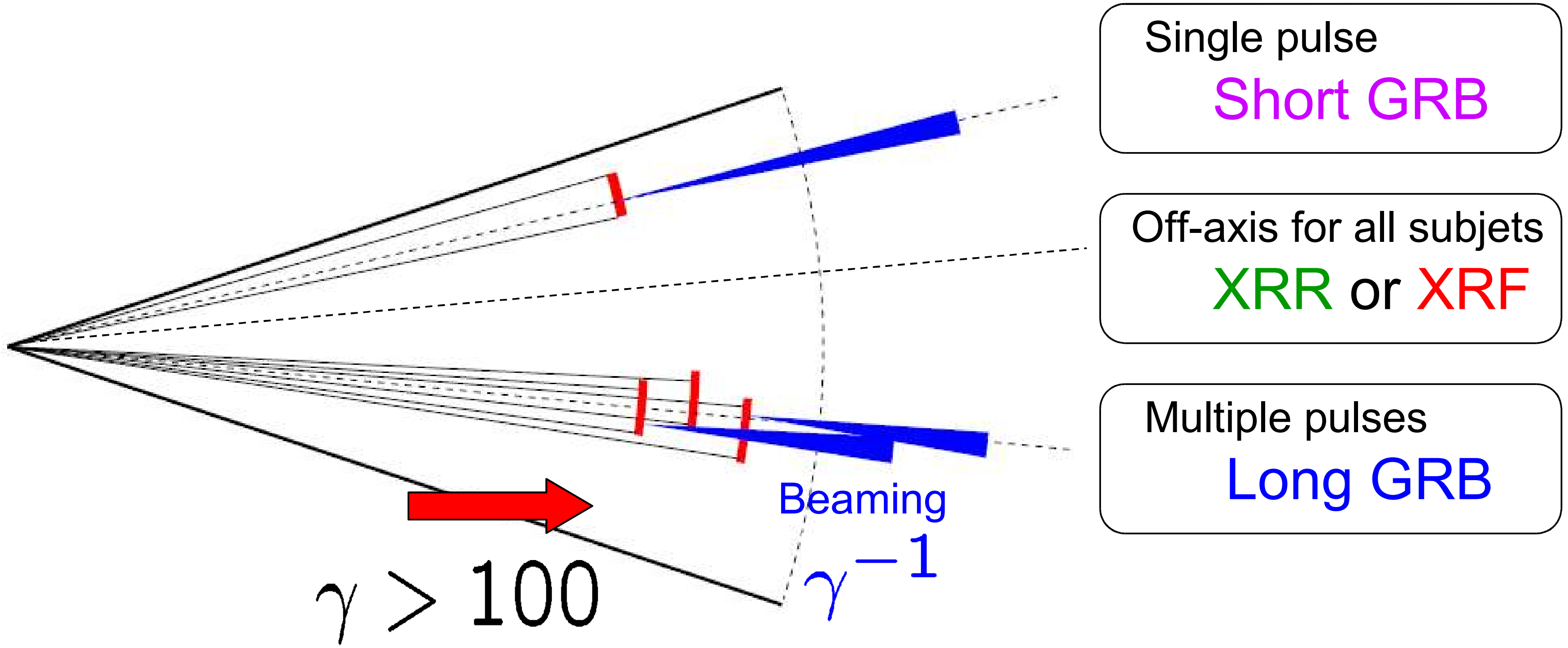
Distinguish temporally short and long bursts

- May be essentially similar
  - Orientation
  - Inhomogensity
- Short bursts could be
  - Millisecond magnetars
  - NS binaries
  - ….
- Swift!

A Unified Model: Concept

We assume that a GRB jet consists of multiple subjets.

(Nakamura 00, Kumar & Piran 00)

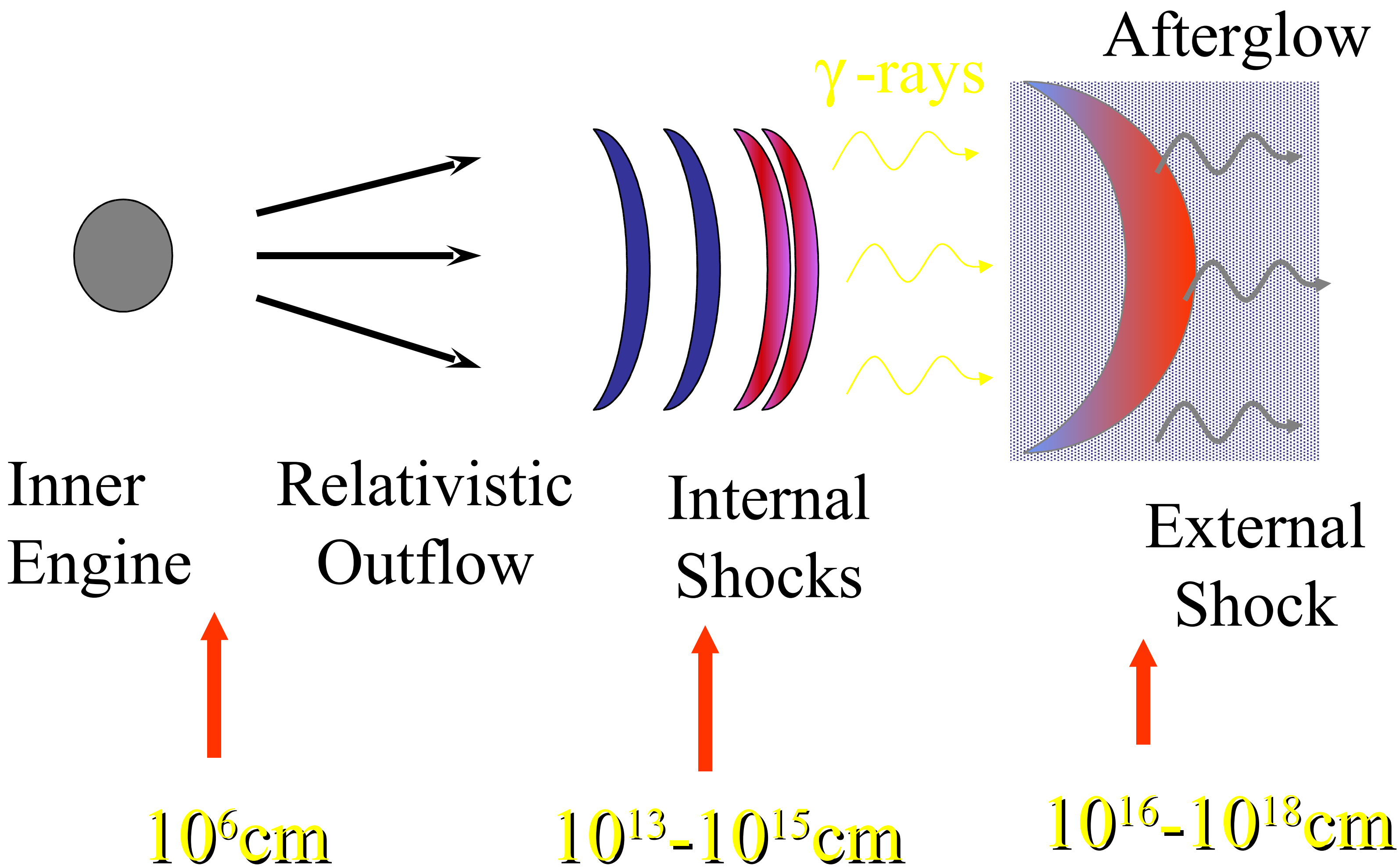


Viewing angle effects cause diversity of phenomena.

Define carefully jet, pancake?

- Jets are 4 time longer than they are wide in the rest frame (Bridle)

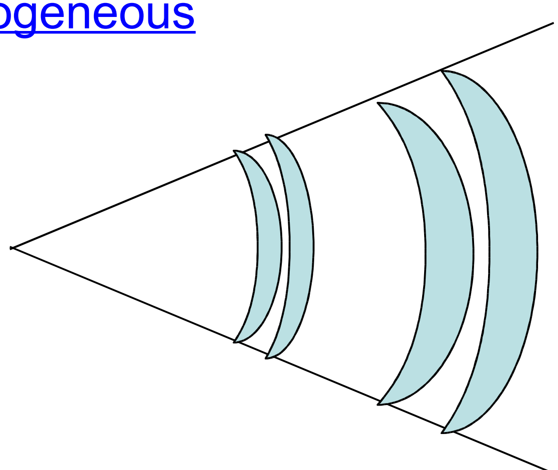
The Internal-External Fireball Model



What is subjet?

Multiple subjet model = *Inhomogeneous jet model*

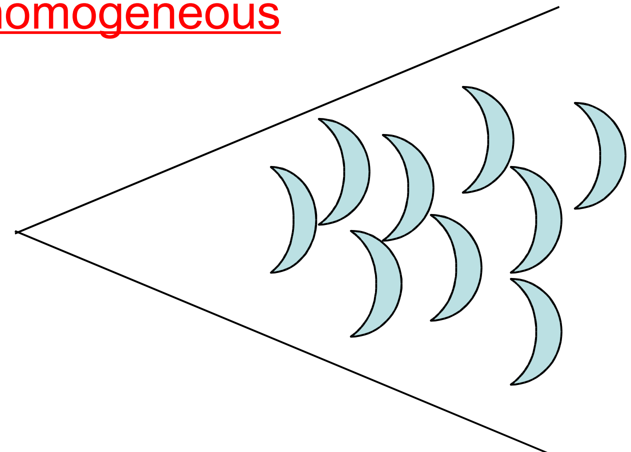
Homogeneous



Radial fluctuation

Continuous emission

Inhomogeneous

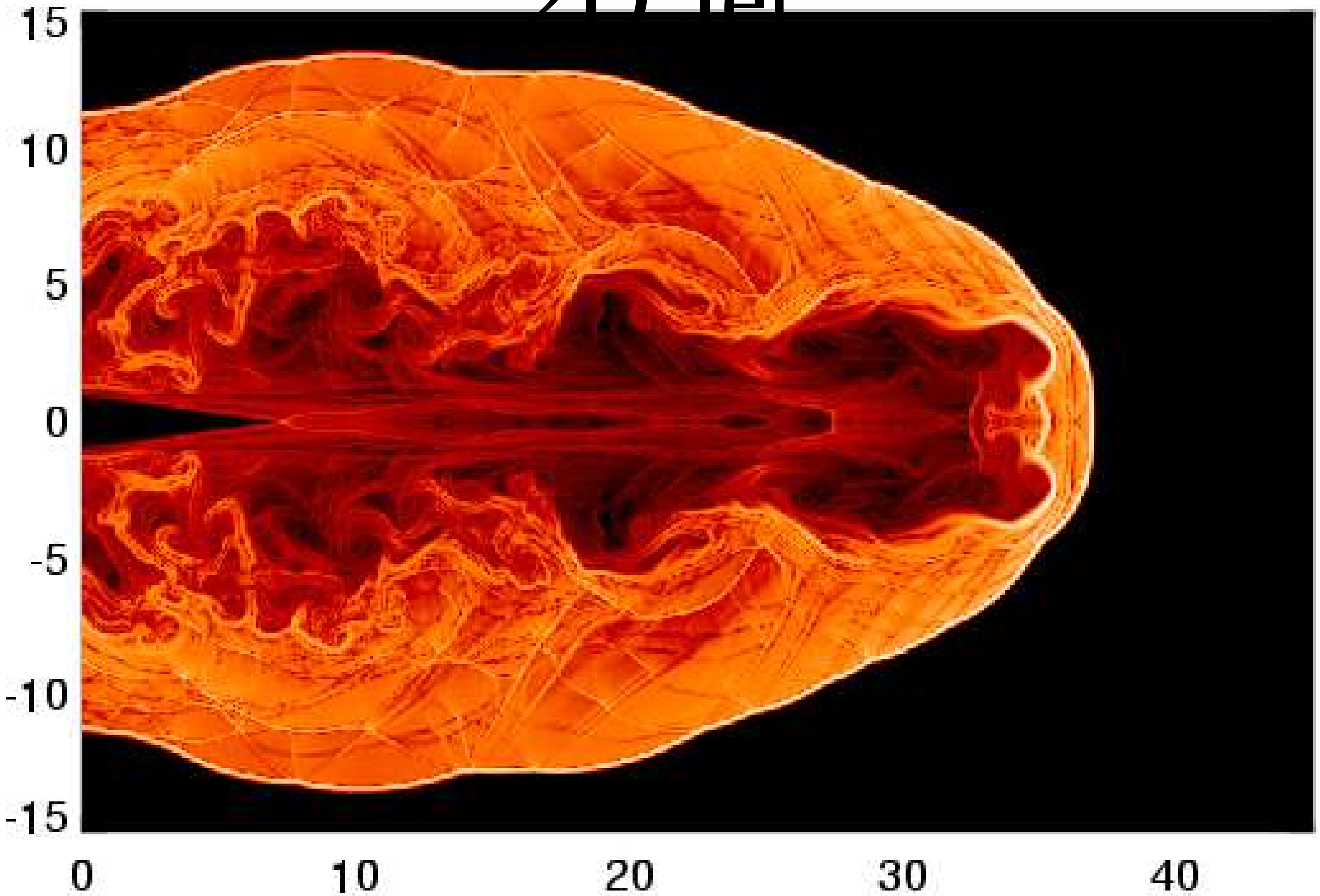


Radial + angular fluctuations

Discrete emission patches

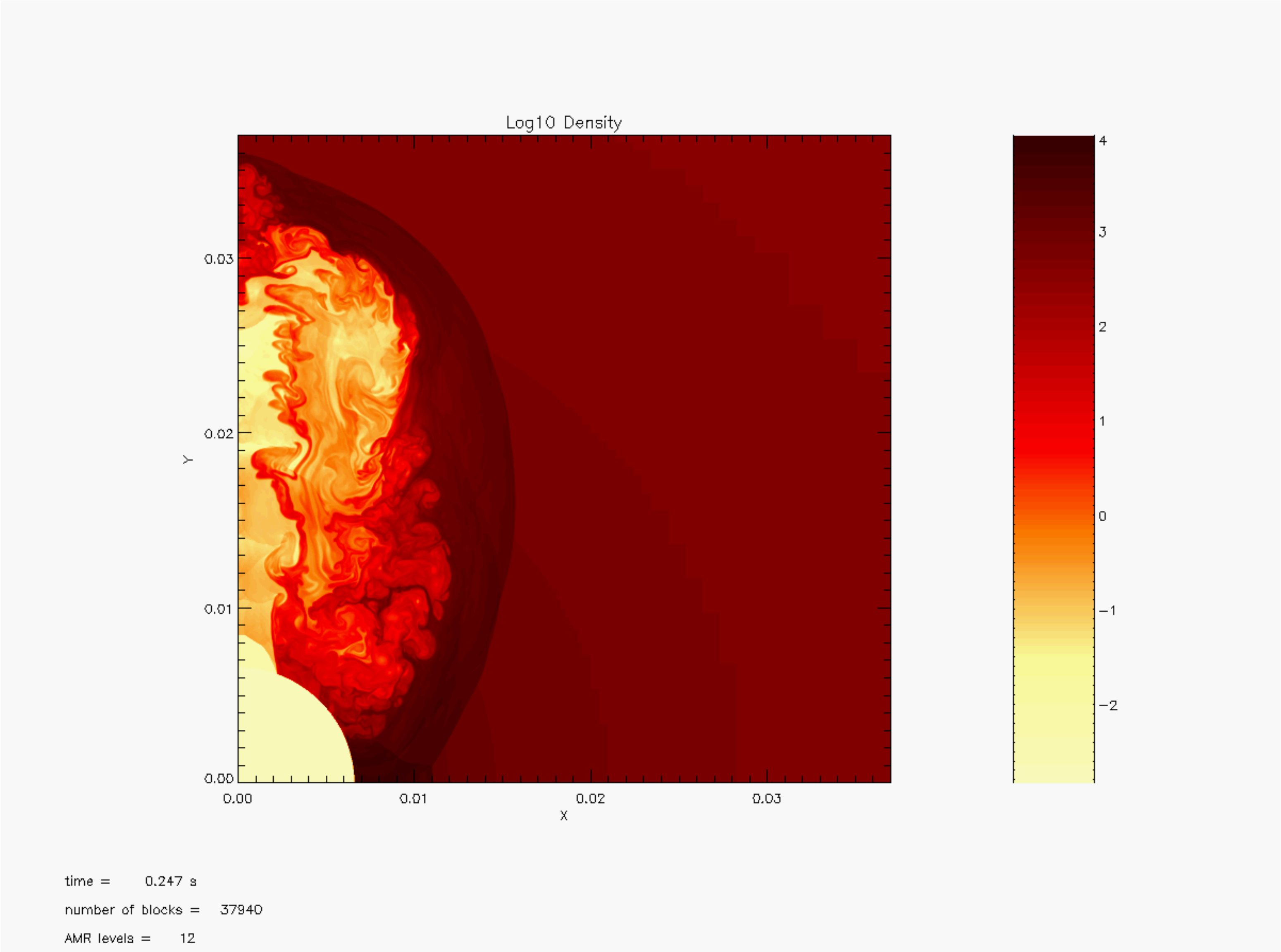
But we do not calculate the detailed process of each internal shock.

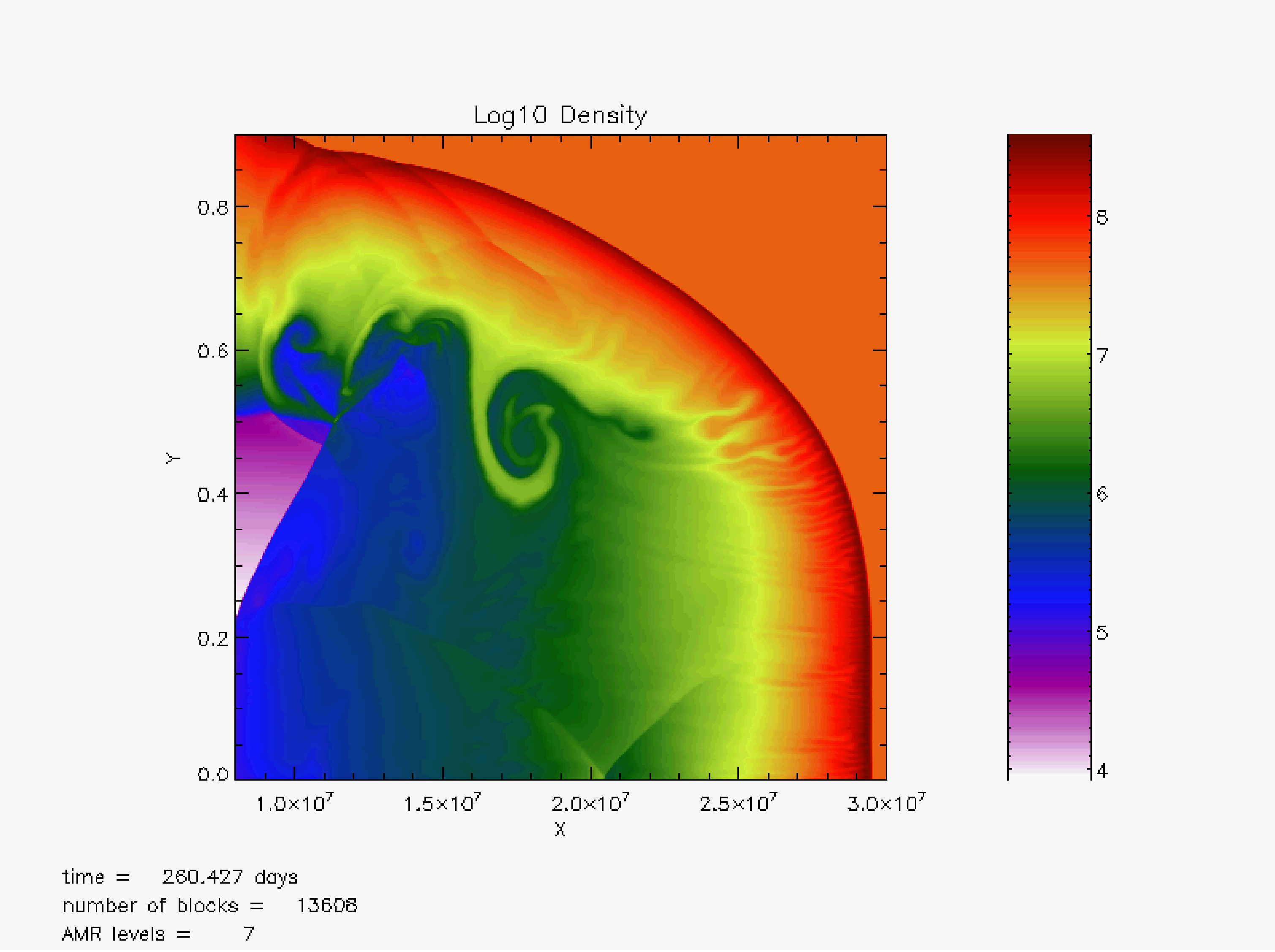
2D Jet



EOS in weak shocks

Relativistic Jet Simulations with RAM (2004)




Log10 Density
0.8
0.6
0.4
0.2
0.0
Y
1.0×10^7
1.5×10^7
2.0×10^7
2.5×10^7
3.0×10^7
X
8
7
6
5
4
time = 260.427 days
number of blocks = 13608
AMR levels = 7

Why are jets thought to be fluid dynamical?

- Occam!
- FD much easier than MHD/EM
  - Plenty hard enough - RAM
- Ignorance
- May be right

Early optical emission ($\propto t^{-2}$) + radio flare:

- **1 bursts**

Early optical emission ($\propto t^{-2}$) - no radio detection:

- **2 bursts**

Early radio flare - no early optical observations:

- **2 bursts**

Early optical emission that do not decay as t^{-2}

- **4 bursts**

Tight upper limits (R>17mag) on any early (t<100sec) optical emission:

- **6 bursts (all are faint; fluence $\leq 10^{-6}$ erg/cm^2)**

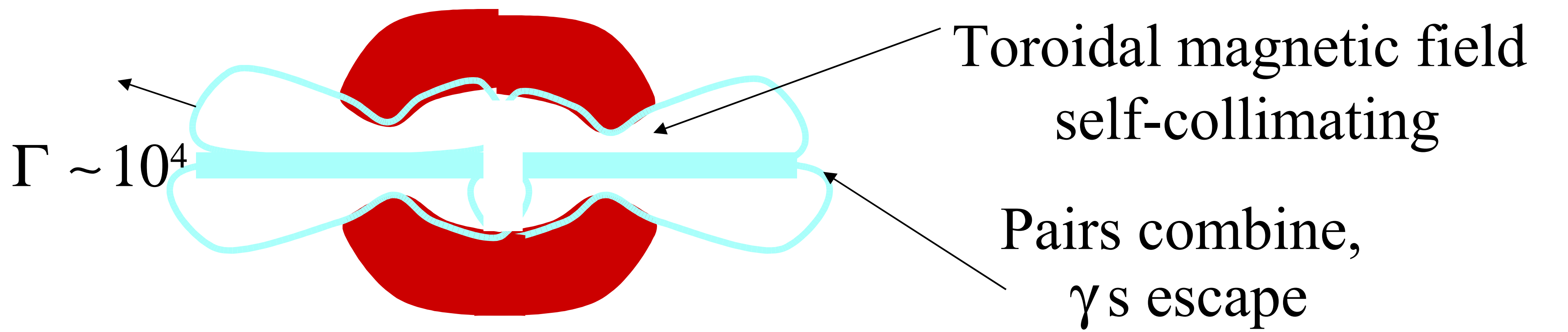
Electromagnetic GRB Model

RB + Lyutikov

- Gravitational binding energy=>EM energy flux
  - **Organized** Poynting flux (disorganized also possible)
  - V_{EM}=E/B ~ c
- Electromagnetic acceleration -> Γ~100, M < 1
- Pairs combine, gammas escape, E,B dominate
- Poynting flux catches shocked circumstellar medium at ~ 10^{16}cm
  - Form regions with E>B; pairs accelerated
  - Relativistic internal motions
  - GRB
- Sweep up ISM at ~ 10^{17}cm
  - Field incorporated from magnetic piston, shock acceleration
  - Anisotropic afterglow

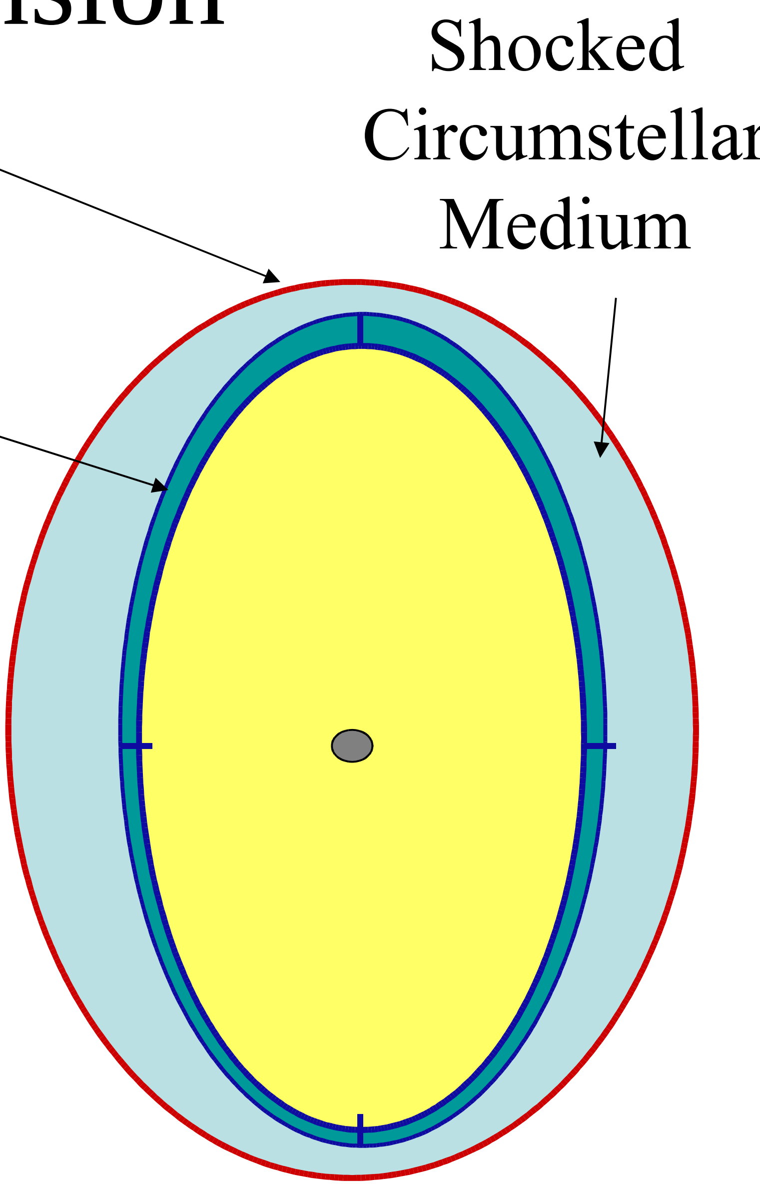
II Bubble Inflation

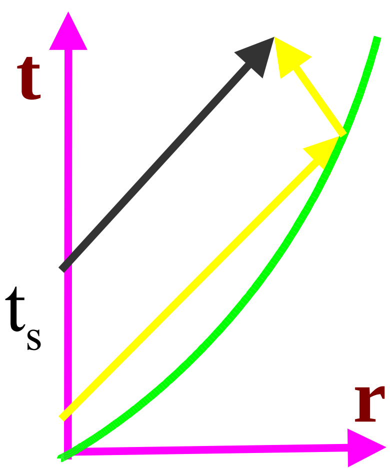
- Collapsar/hypernova within stripped star, $R \sim 10^{11}$cm
- Surface return current, surface stress $\sim (I/R\sin\theta)^2$
  - Anisotropric expansion in absence of rotation
- Dissipation inevitable if $V<c/\ln(\theta_{max}/\theta_{min})\sim 0.1c$; otherwise not
  - cf PWN
  - Rationale for fireball model?
- Compute evolution given envelope dynamics; $t_{breakout}\sim 10$s
- Biconical expansion outside star dictated by CSM
- Shell forms when $r>ct_s\sim 3 \times 10^{12}$cm; ultrarelativistic expansion
- Thermal precursor measure of dissipation?

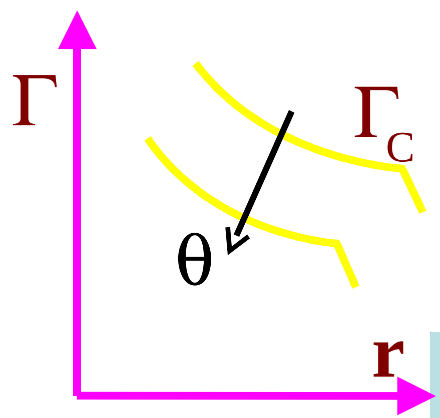


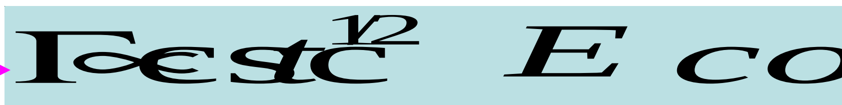
III Shell Expansion

- $r_{GRB} \sim \Gamma^2 c t_s \sim (L t_s^2/\rho c^2)^{1/4} \sim 10^{16}$cm
- $V = \mathbf{E} \mathrm{x} \mathbf{B}/B^2$; $\Gamma \sim 100$
- Piston thickness $ct_s \sim 3\mathrm{x}10^{12}$cm
  - Instability=>variable γ-ray emission
  - Facilitates escape of hardest γ-rays



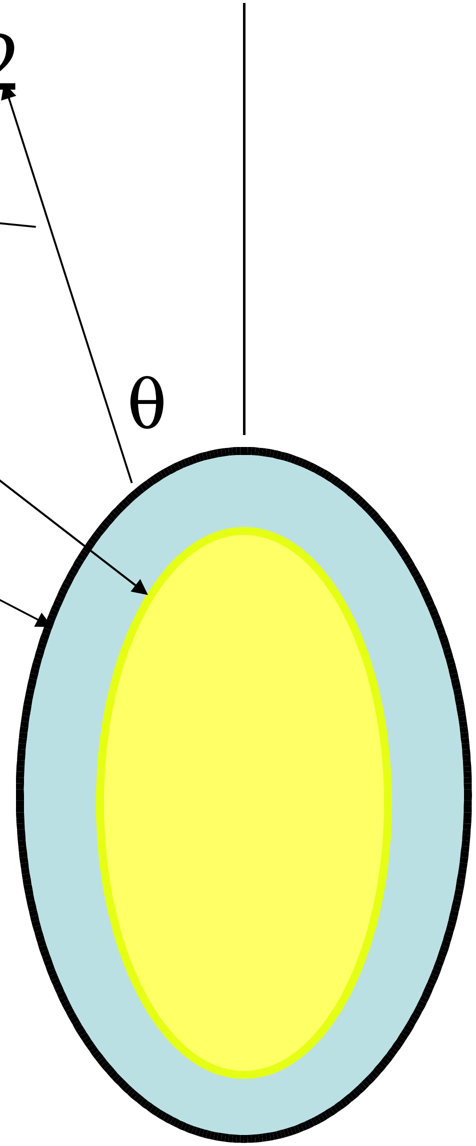






IV Blast Wave

- $r_{GRB} < r < r_{NR} \sim (Lt_s/\rho c^2)^{1/3} \sim 10^{18}$cm; $\Gamma \sim 100\text{-}2$
- Achromatic break when $\Gamma \sim \theta^{-1}$
- Magnetic field mixed in from CD?
- Particles accelerated at shock?
- Energy per sterad constant
- Standard qualitative interpretation of afterglow spectra
  - More variation than in shock models
  - θ is important parameter
- Axial currents->short bursts?
- Becomes more spherical when $r > r_{NR}$

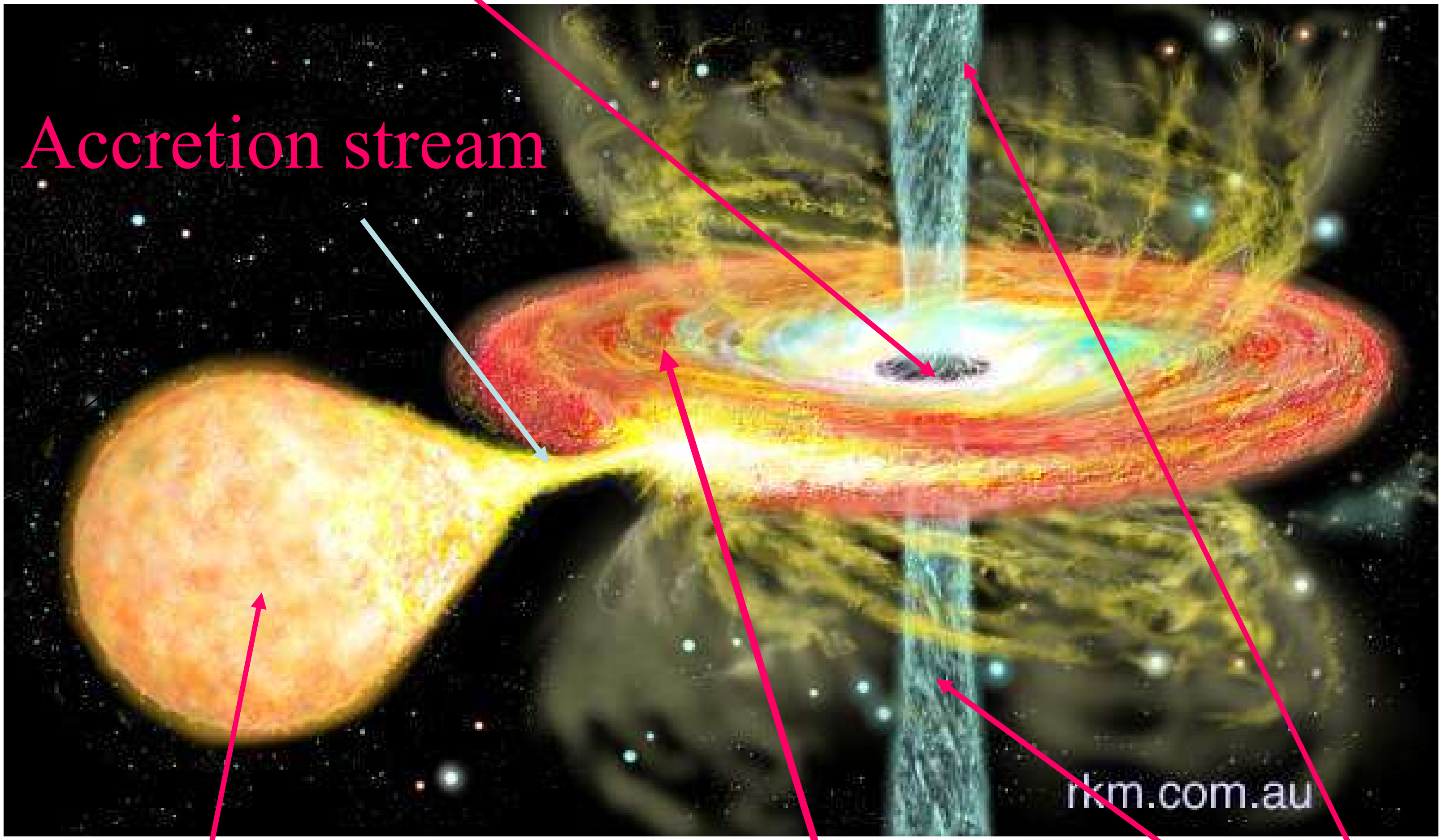


How do black holes work?

- Background geometry for disk dynamics
- Modify EM => Energy extraction from spacetime as well as gas
- Create anisotropic Maxwell tensor

Jets from binary stars

(Schematic figure)



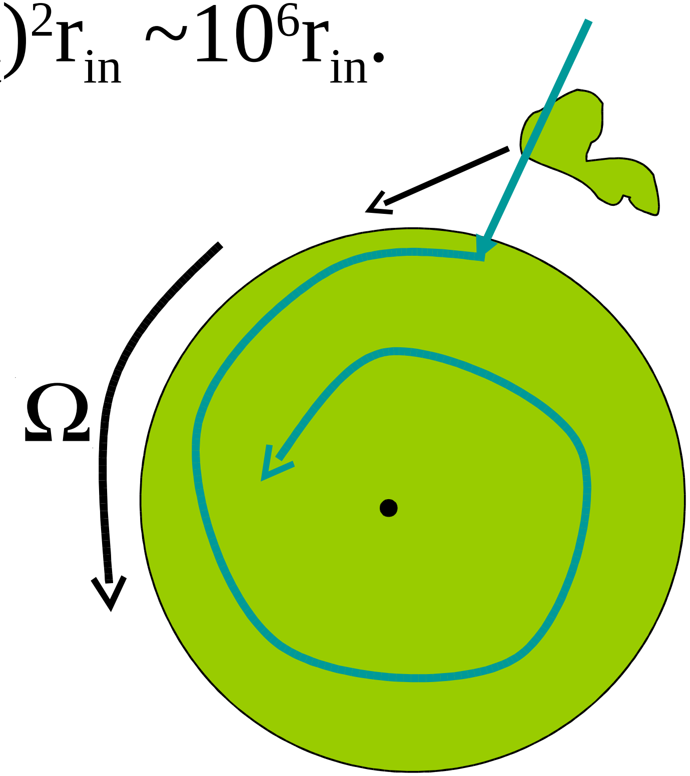
Archimedean Disks

- $r_{out} \sim (c/v_{out})^2 r_{in} \sim 10^6 r_{in}$.

$$B_r \quad r^{2}$$

$$P_{mag} \quad r^{4}$$

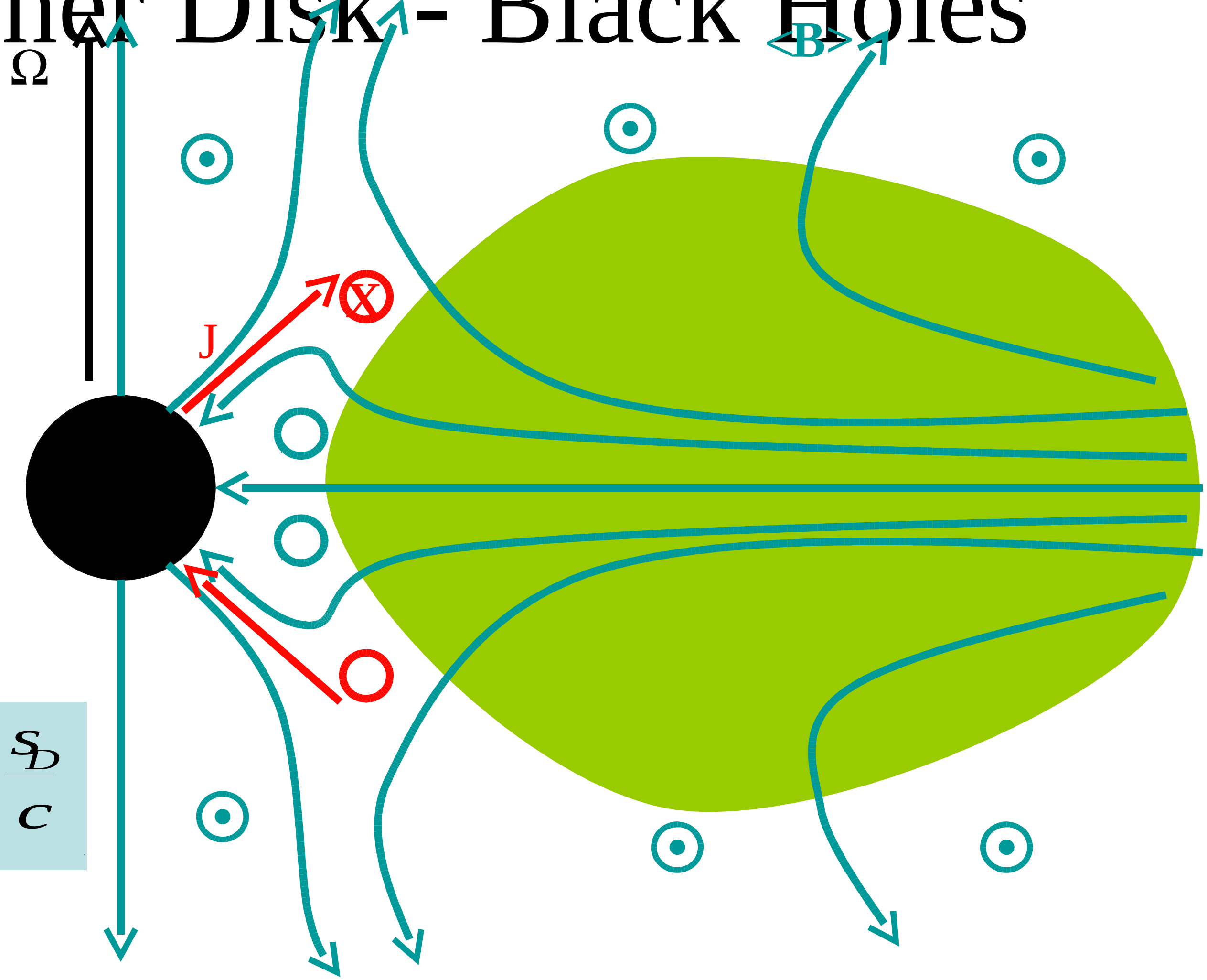
$$P_{gas} \quad r^{5/2}$$



Net radial field
Conservative disk
Ignore irradiation,
self-gravitation etc

Magnetic pressure dominates and field lines escape

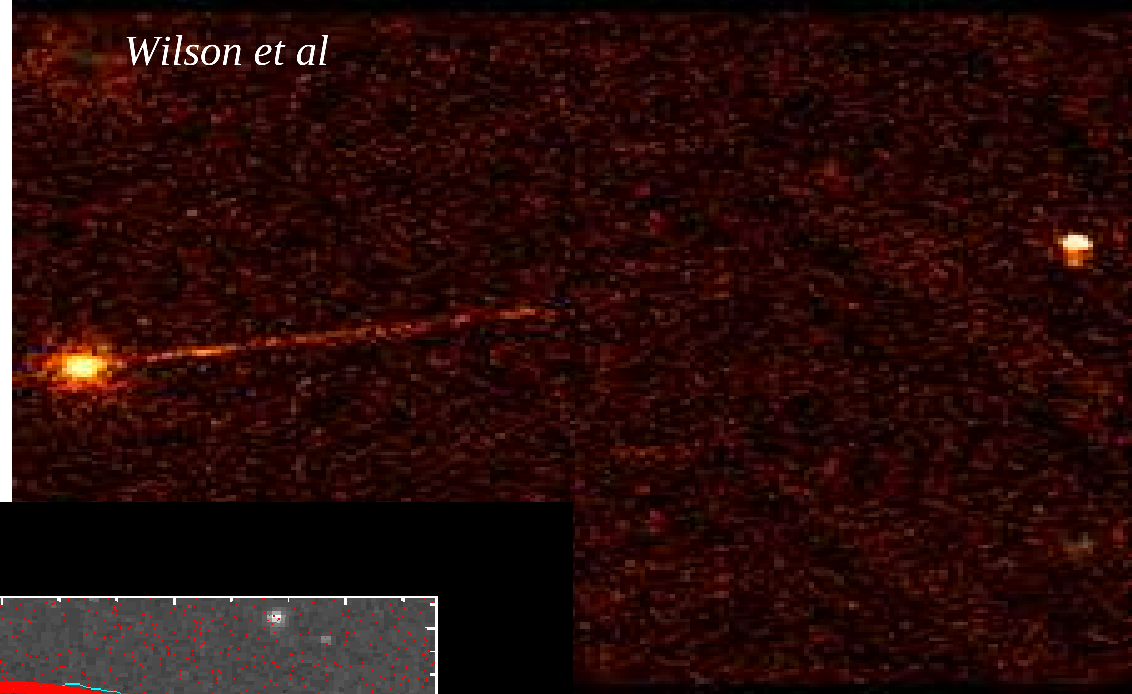
Inner Disk - Black Holes

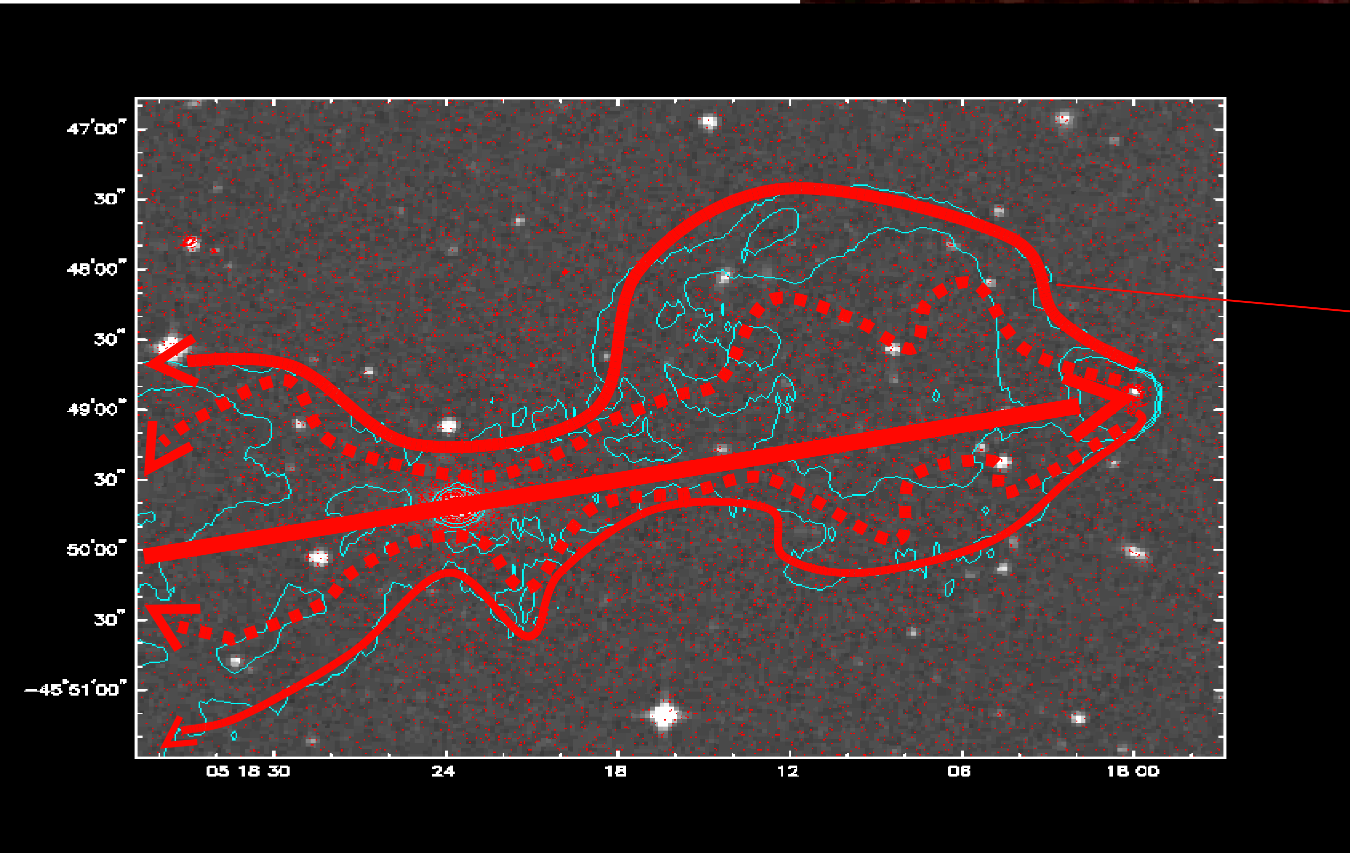


$$\frac{L_H}{L_D} \sim \frac{1}{\ _D\ _D}\ \frac{\ _H}{\ _D}^{2}\ \frac{S_D}{c}$$

Pictor A

Electromagnetic Transport
10^{18} not 10^{17} A
DC not AC
No internal shocks
New particle acceleration mechanisms





Current Flow

Nonthermal emission is ohmic dissipation of current flow?

Pinch stabilized by velocity gradient

Equipartition in core

Why has it taken so long to develop GRMHD codes?

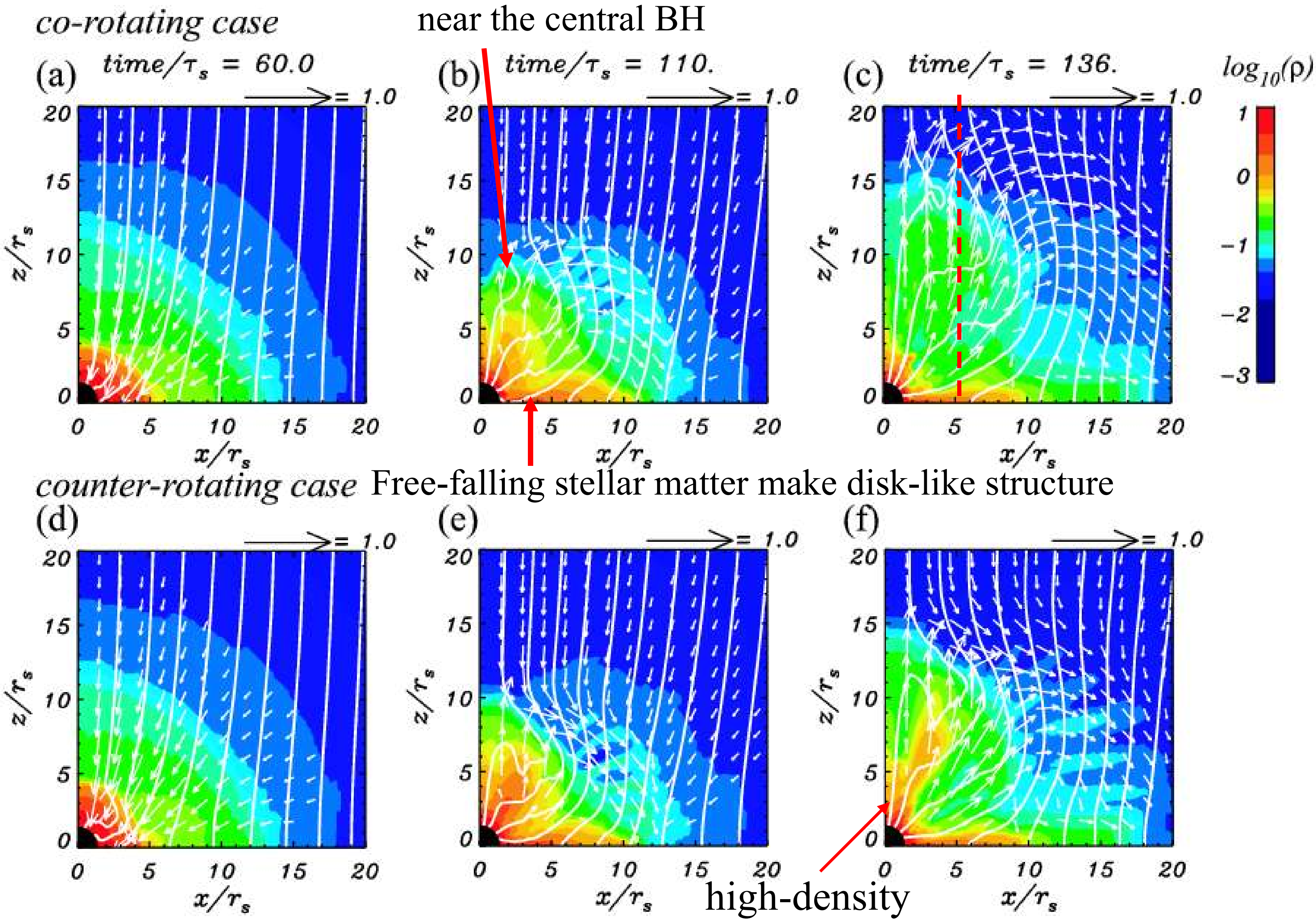
- It’s hard

Snapshot of density

Mizuno

color density

line magnetic field lines

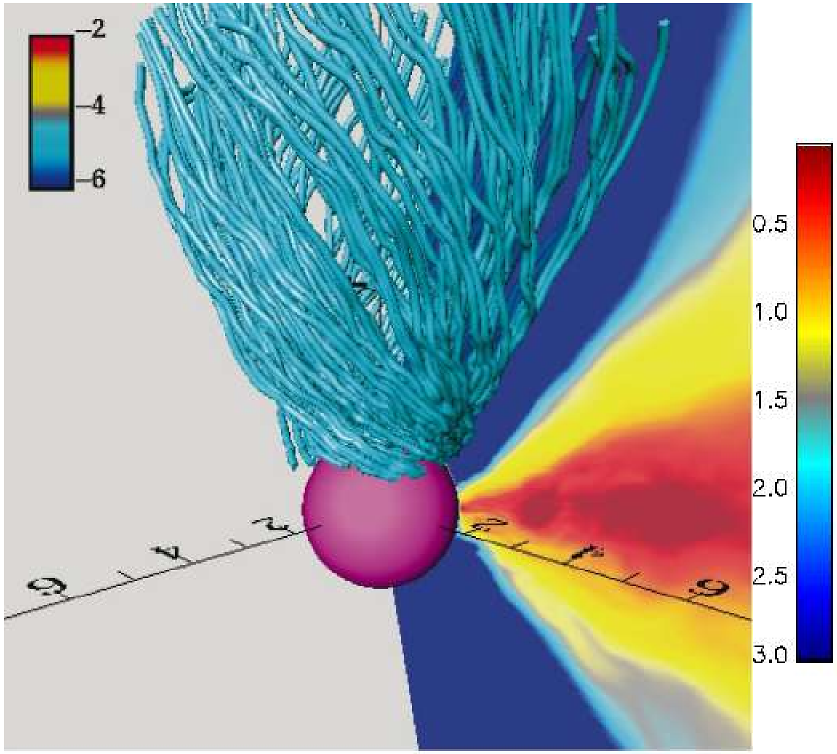


Simulating Accretion Disks

- 3D GRMHD:
  - Explicit 3+1 FD code, Kerr background (BL)
  - Equations of motion from conservation laws
  - Induction equation using Constrained Transport
- Initial Conditions:
  - Torus + seed magnetic field (MRI)
  - Ambient medium: dust + external field

Kerr BH with an initial weak poloidal magnetic fields

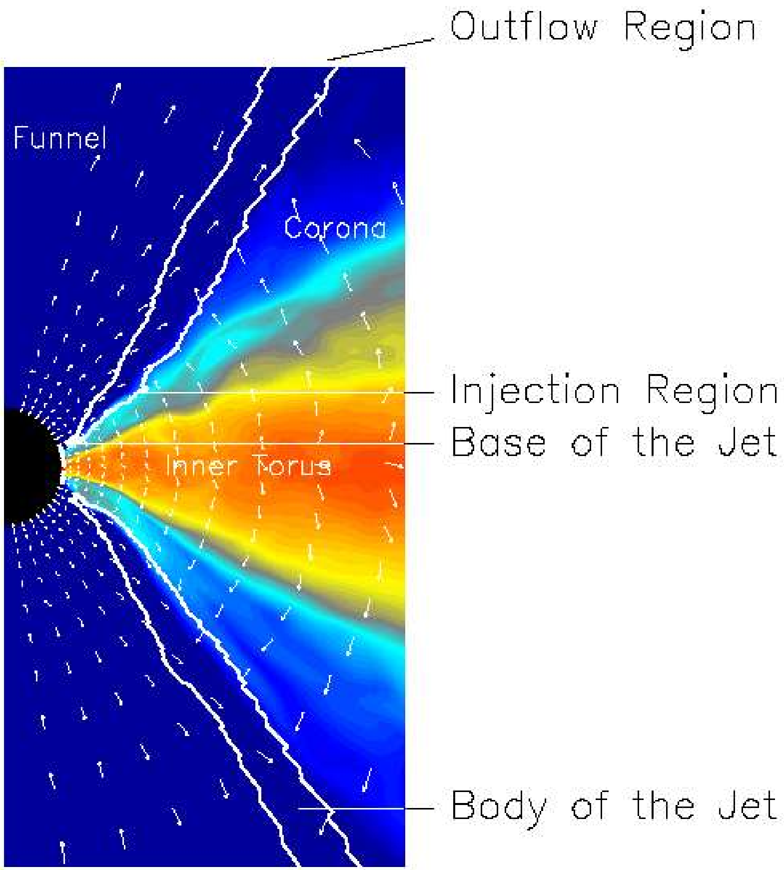
a/M =0.9, t= 7760, 0.1π<θ< 0.2π



log(ρ)

(Hirose et al. 2004)

gas density (log(ρ))



(De Villiers et al. 2005)

Nishikawa

Describe carefully the chain of events that leads to a magnetar explosion

- Release of magnetic energy into magnetosphere
- Dissipation
- Relativistic Outflow
- Blast Wave
- Afterglow

Magnetars

- **Soft Gamma Repeaters (SGRs) and Anomalous X-ray Pulsars (AXPs)**
  - occasional X-ray/γ-ray bursts
  - very rare giant γ-ray flares
  - slow X-ray periods (P ~ 5–12 sec)
  - rapid spin-down, sudden changes in torque
  - low Galactic latitude, some in SNRs
  - not seen in radio, no companions

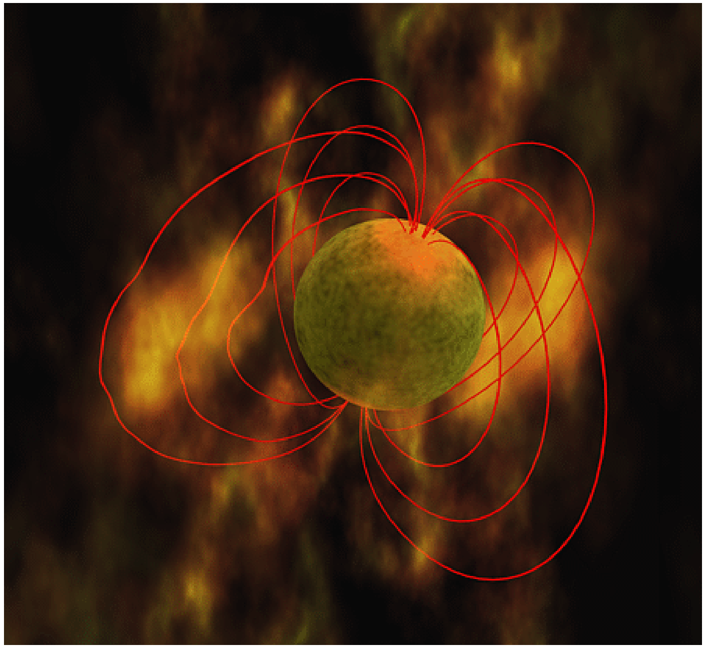
→ young neutron stars, but not ordinary pulsars, not accreting binaries

⇒ *"magnetars"*, isolated neutron stars with $B_{surface} \sim 10^{14}$–10^{15} G

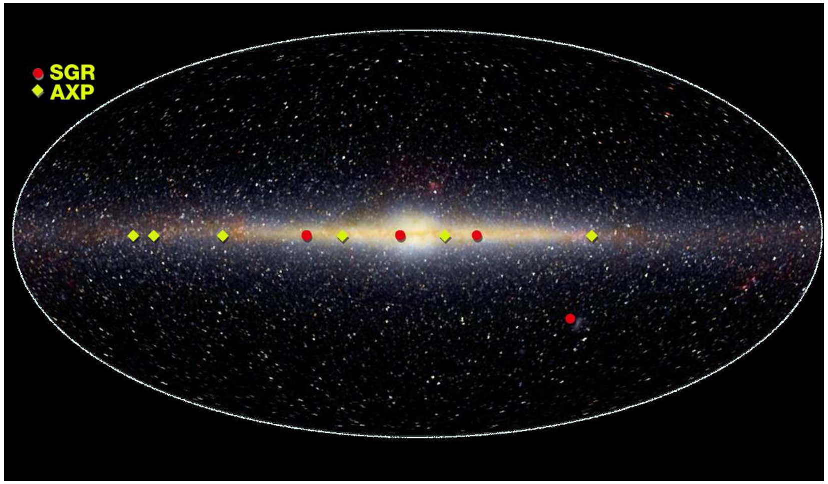
(Duncan & Thompson 1992; Kouveliotou et al 1998)

- Rare objects: only ~12 magnetars known
  - active lifetimes ~10 kyr
  - ~10% of neutron star population?

(Kouveliotou et al. 1994; Gaensler et al. 2001, 2005)



Robert S. Mallozzi, UAH / NASA MSFC



E. L. Wright (UCLA), COBE Project, Courtesy MSFC, NASA

Further Considerations

• Pre-existing shell

- bow shock? (Gaensler et al. 2005)
- shock driven by flare? (Granot et al. 2005)
- data at $t < 7$ days are needed! (Fan et al. 2005)

• Motion of centroid implies outflow was anisotropic (Taylor et al. 2005; Granot et al. 2005)

- hemispherical outflow? wide jet?
- for outer edge of source expanding at β,

$$\Gamma\beta = \beta_{apparent} \approx 1.0 \rightarrow \beta \approx 0.7$$

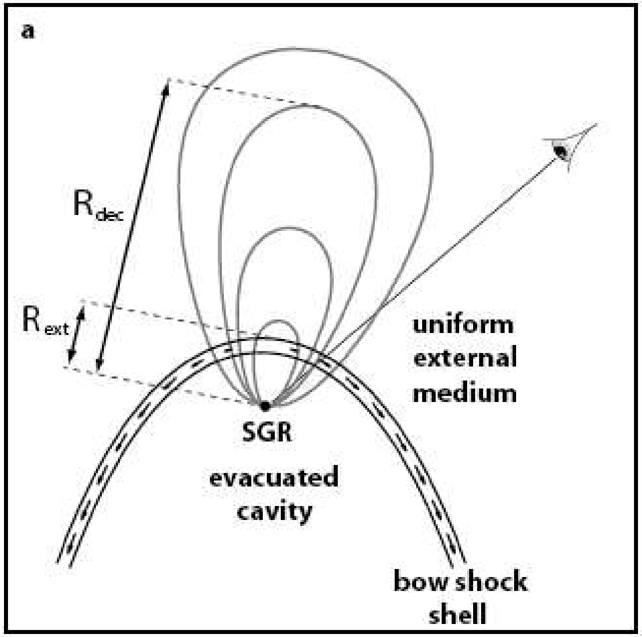
$$\rightarrow M_{ejected} \approx 9 \times 10^{24}\ \text{g}\ ,\ E_{kinetic} \approx 7 \times 10^{44}\ \text{ergs}$$

• Compactness (Gelfand et al. 2005; Granot et al. 2005)

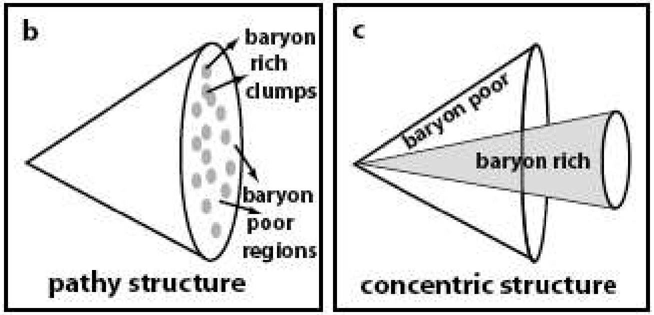
- patchy ejecta, or concentric structures
- low baryon content along line of sight

• Late time features in light curve

- continued activity from SGR 1806-20?



Granot et al. (2005)

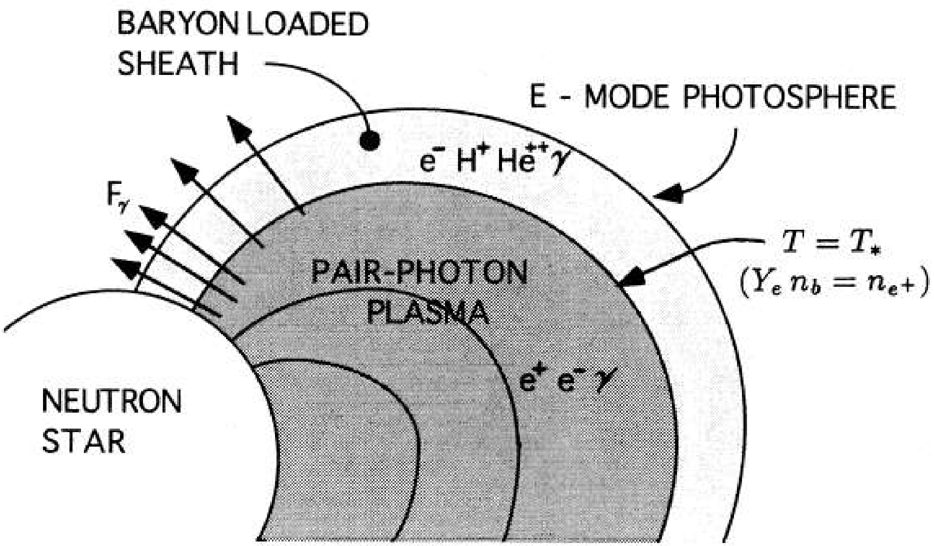


Granot et al. (2005)

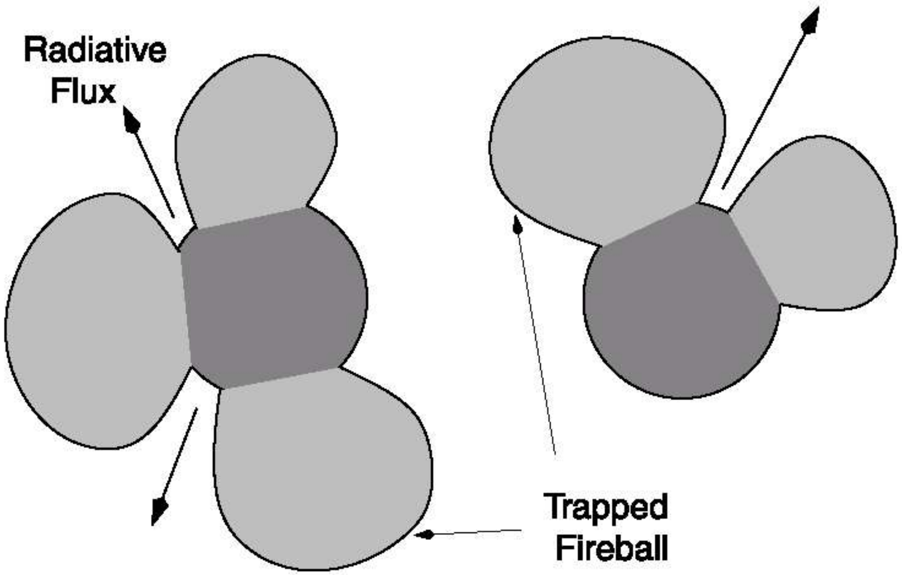
Weakly collimated pulsating tail

$\Delta\theta_{tail}$ 1 rad is possible in magneter model.

(but collimation degree highly depends on B-field configuration.)



Thompson & Duncan (1995)



Thompson & Duncan (2001)

Nakar

Relativistic Spheromak Interpretation

- Magnetic flux loop escape from neutron star
  - Thermomagnetic dynamo?
- Inductive electric field accelerates optically thick pair plasma in rough thermal equilibrium
- “Spheromak” expelled by magnetosphere with speed ~ c
- Anisotropic ultrarelativistic expansion in moving frame
  - Quickly expand to Γ~10, pairs annihilate and gamma rays escape
- anisotropic expansion $\beta_{ob} \sim \cot\theta/2$, $D \sim (1+\beta_{ob}^{2})/2\Gamma$
- Deceleration by circumstellar medium

Discuss prophetically what we will learn in the future about GRB

- Next 1806 superburst
- High redshift universe
- VLBI
- GLAST/ HESS
- Neutrinos
- LIGO
- Numerical simulations