Gamma-Ray Bursts and Magnetic Fields

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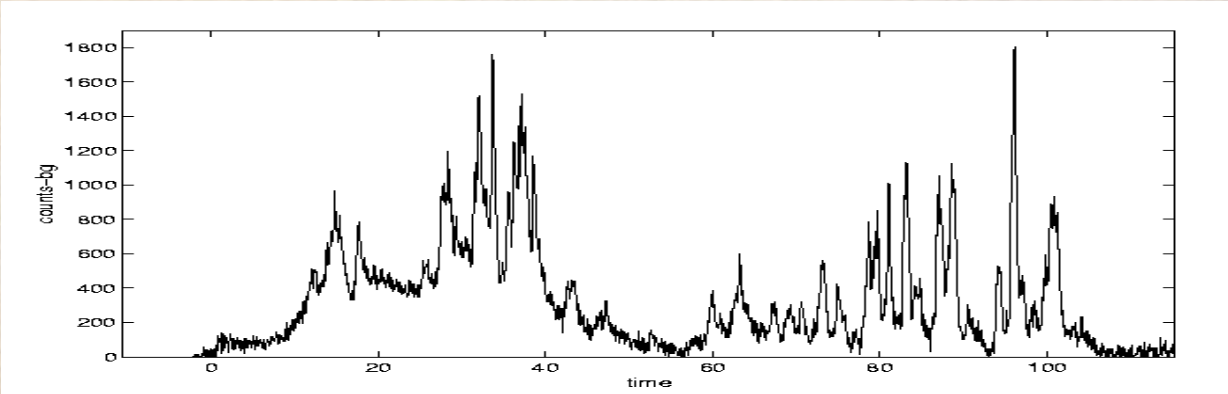
Outline

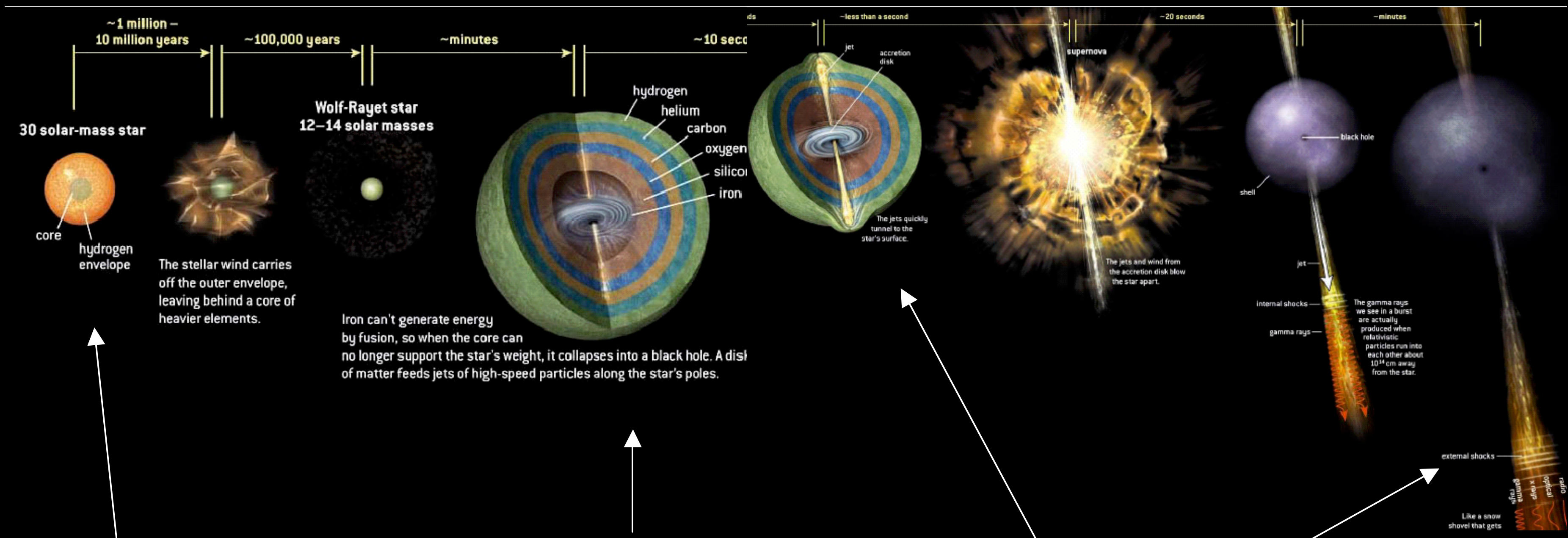
- Gamma-Ray Bursts (GRBs)
  - GRBs and Afterglows
- Synchrotron Shock Model
  - Open Issues
- Magnetized Fireballs
- Polarization
  - Liverpool Telescope Results
  - Fireball Dynamics
  - GRB Jet Structure

Gamma-ray bursts (GRBs)

- Intense flashes of 0.1-1MeV photons
  - Arriving from random directions in the sky
  - A few events per day
  - Light curves: highly variable



Collapsar



Core collapse

Massive Star >30Msun

relativistic jet powered
by BH accretion disk system

Why interesting?

- Extreme Objects
  - Relativistic motion $\Gamma > 100$
  - Brightest Objects

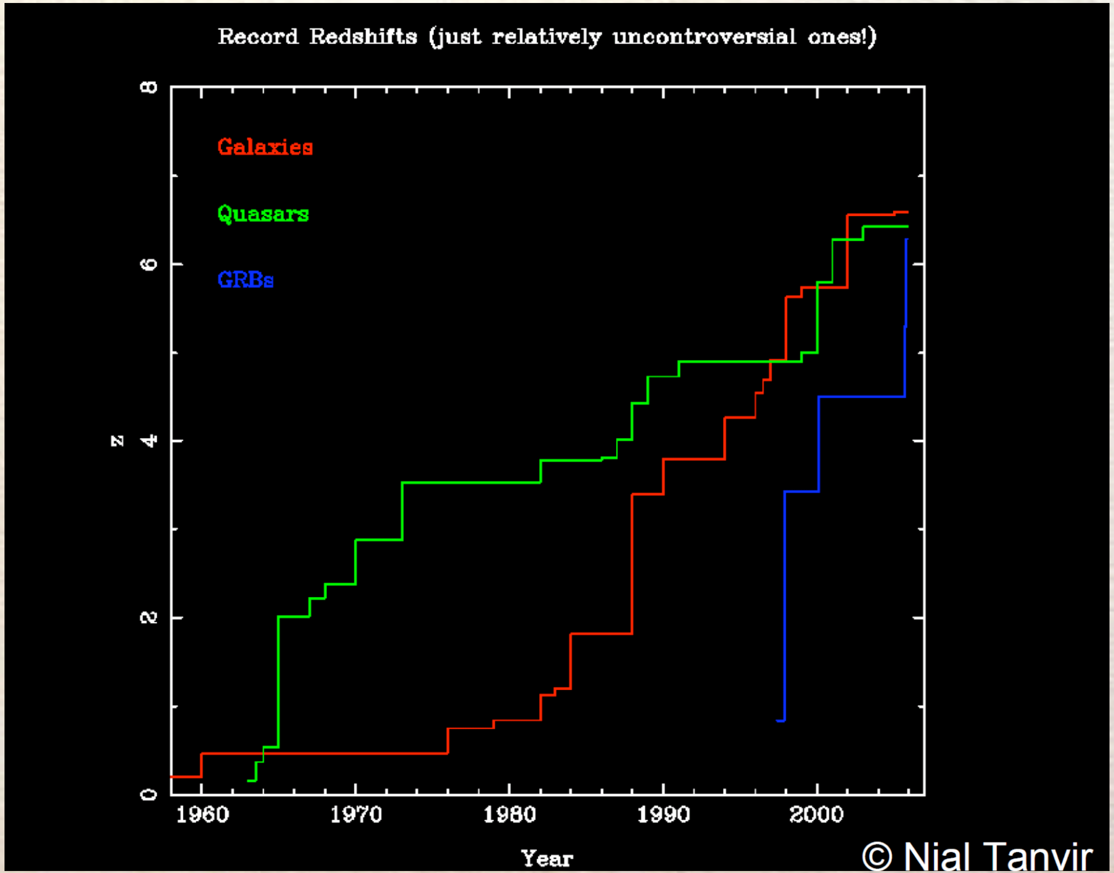
    Lgrb~10^52erg/s
    Lgalaxy~10^44erg/s within the horizon 10^8 galaxies

- Cosmological Probe
  - The First Stars
  - Star formation, reionization history

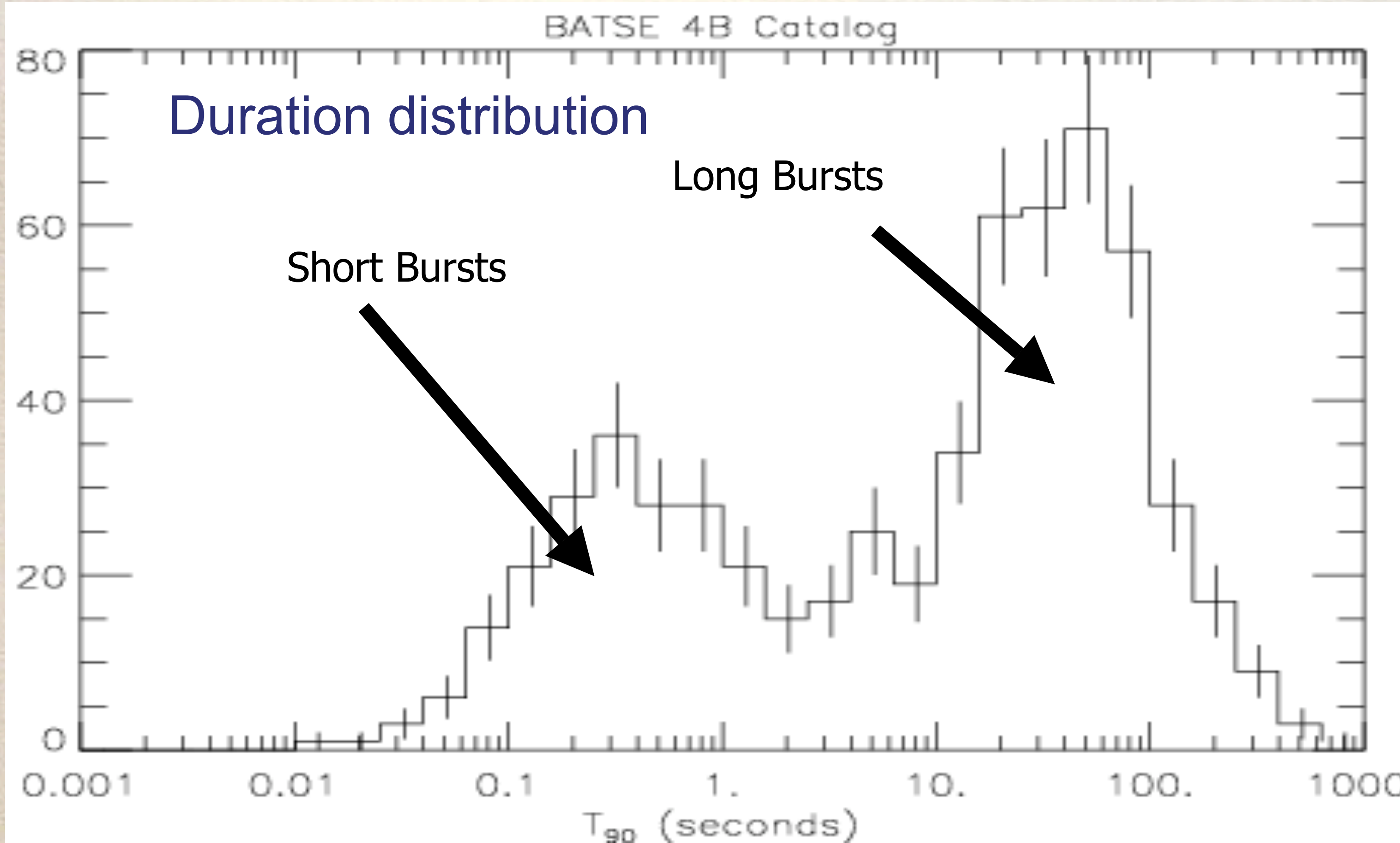
- Gravitational Wave, neutrino, UHECR Sources
  - BH formation, compact stellar mergers

GRBs could replace quasars as the preferred probe of the star formation history and reionization in the early Universe.

- GRB 050904: z~6.3



Long and Short bursts



- Long Bursts: T> a few sec

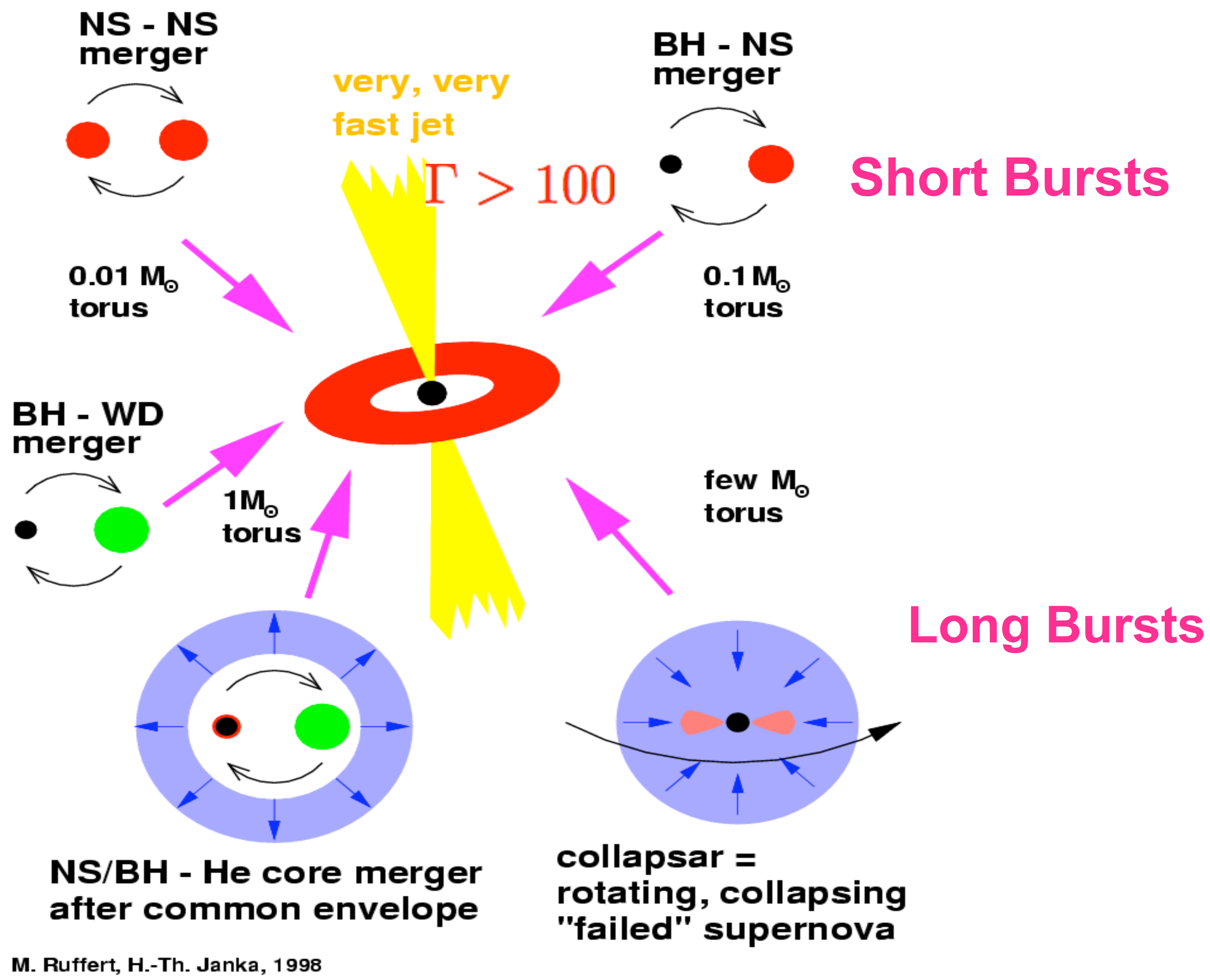
$$E_{iso} \approx 10^{52-54} ergs$$

HOST: Star forming galaxies (no elliptical host)
SN association (at least some bursts) ← Nearby long bursts: GRB 060505/060614 No SN association
Typical z~1 and events follow the star formation rate
Massive stellar Collapse

- Short Bursts: T< a few sec

Less energetic $E_{iso} \approx 10^{49-51} ergs$
HOST: non-star-forming-elliptic, star-formation
No SN association
Lower redshift
Old stellar population: DNS or BH-NS?

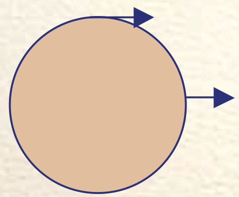
Hyperaccreting Black Holes



Relativistic Motion is essential in GRB models

- Observations: optically thin source
  - Non-thermal spectrum with a high energy tail
- Simple estimates: optically thick source
  - the number of photons above 500keV
  - The source size (variability time $\delta t = R/c$)
- Relativistic effects
  - less photon above 500keV in source frame
  - source size estimate $\delta t = R/c\Gamma^2$

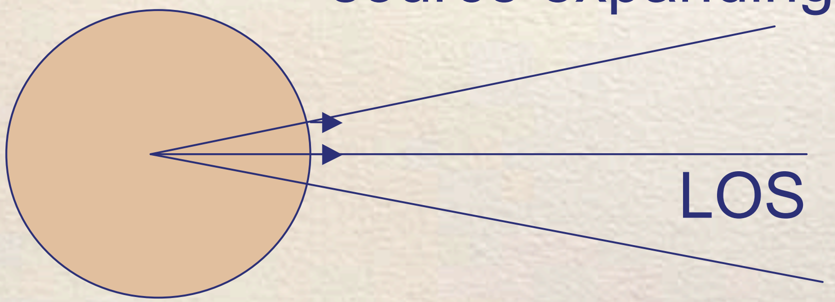
Relativistic Effect



source at rest

$$\delta t \approx R / c$$

source expanding with relativistic speed

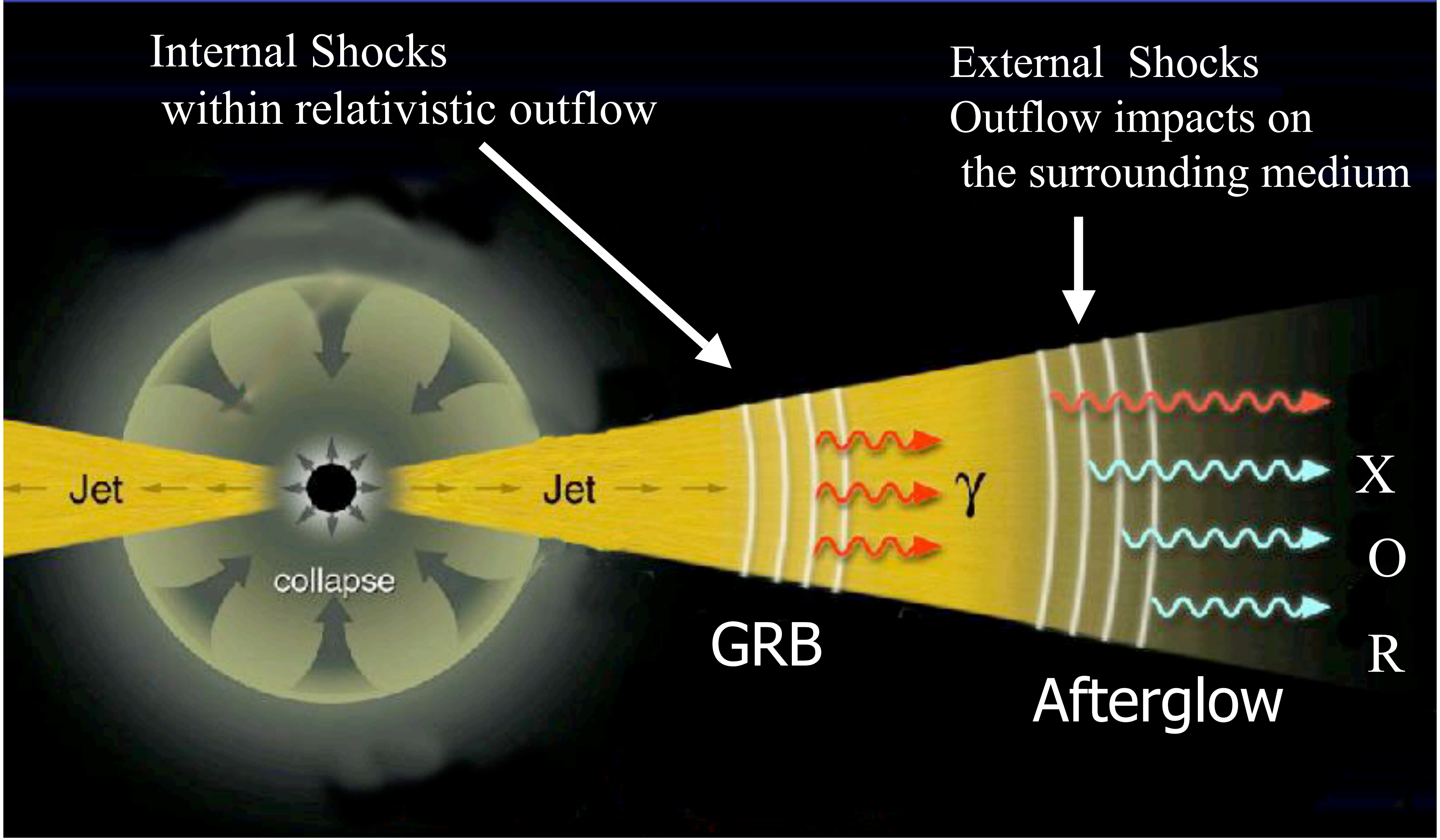


$$\theta \approx 1/\Gamma$$

$$\delta t \approx R / c\Gamma^2$$

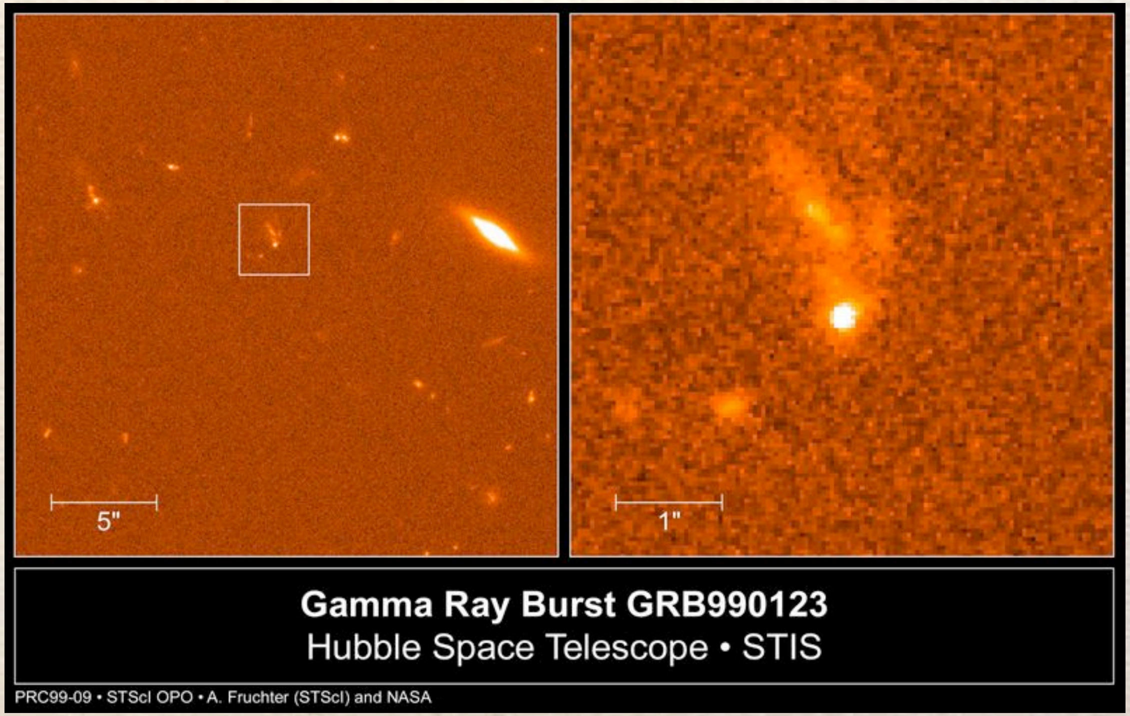
relativistic beaming effect

Synchrotron shock model



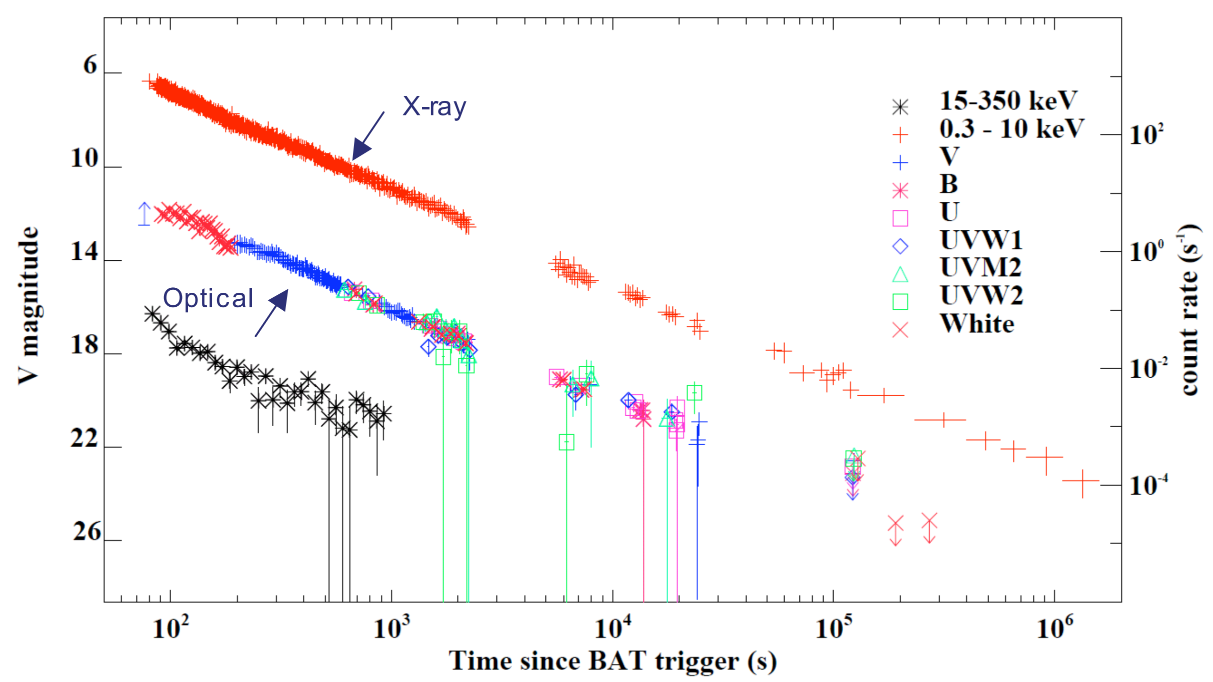
Afterglow

Long-lived low energy emission
following the prompt burst of gamma-rays



Power-Law decay

- Radio, optical, X-ray bands



GRB 061007: Schady et al.(2007)

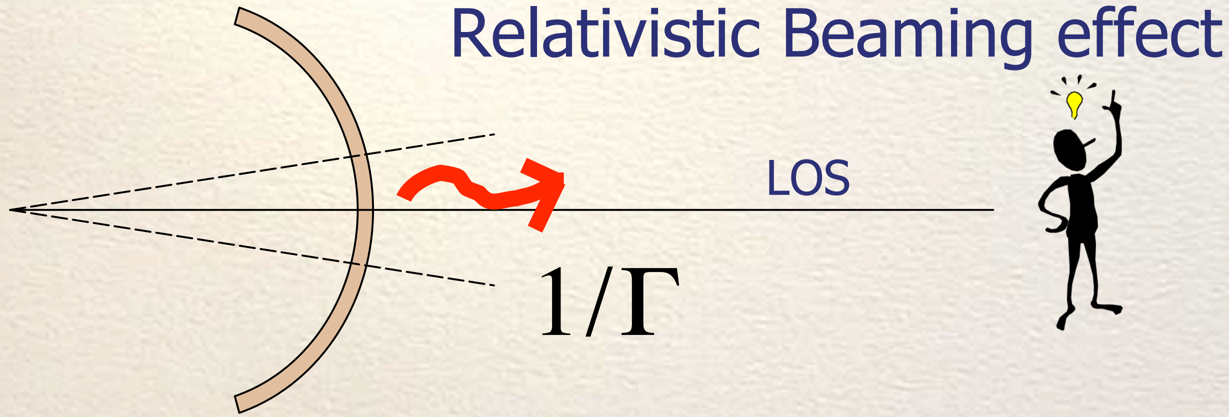
Afterglow: Power Law Light Curve

- Synchrotron emission from a blast wave
- Deceleration of Blast wave
  - power law decay of gamma

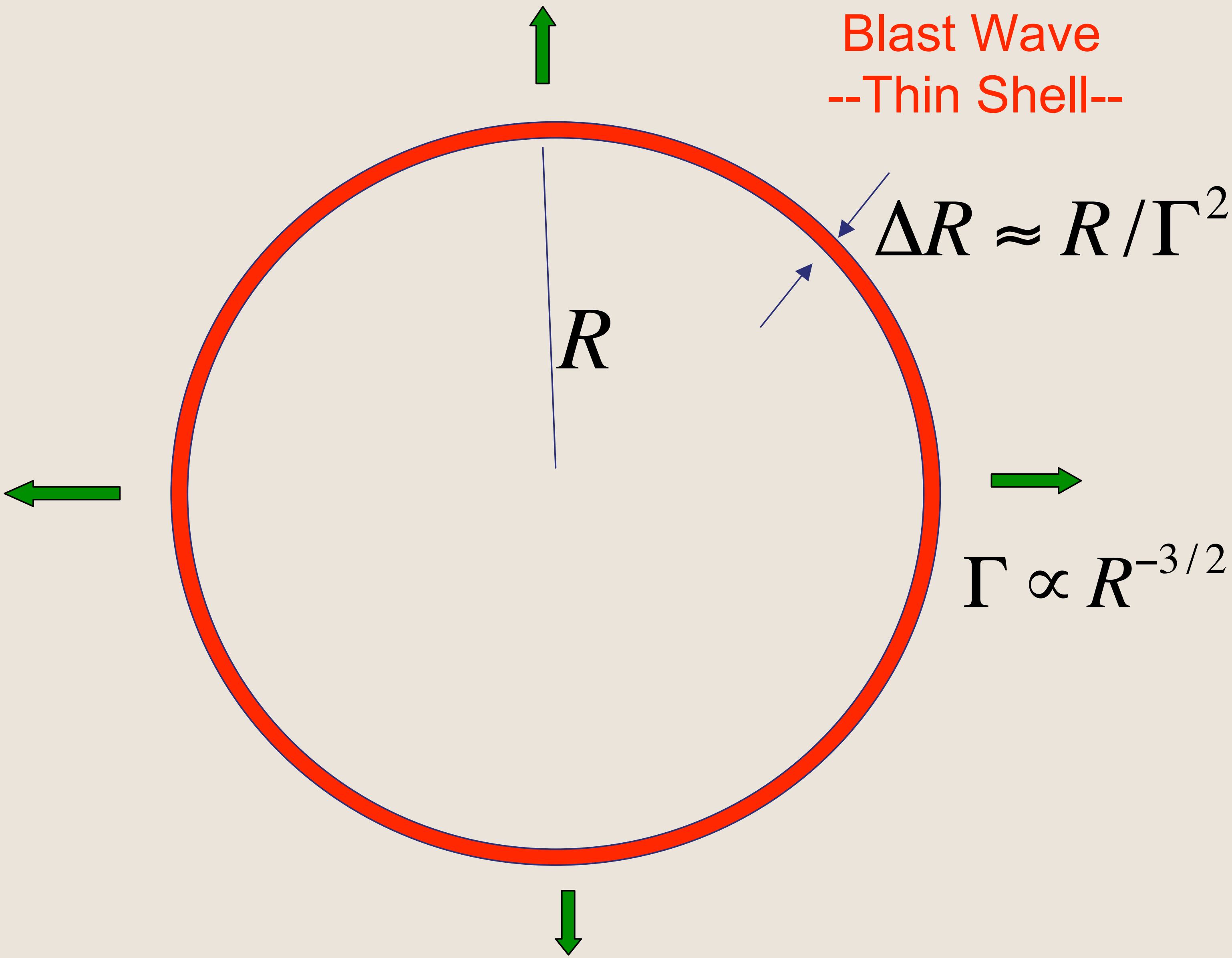
$$E \approx (m_p n R^3 \Gamma_{random}) c^2 \Gamma \propto R^3 \Gamma^2 \Rightarrow \quad \Gamma \propto R^{-3/2}$$

- Shock acceleration: electrons
  - power-law energy distribution

Fireball model for Jets

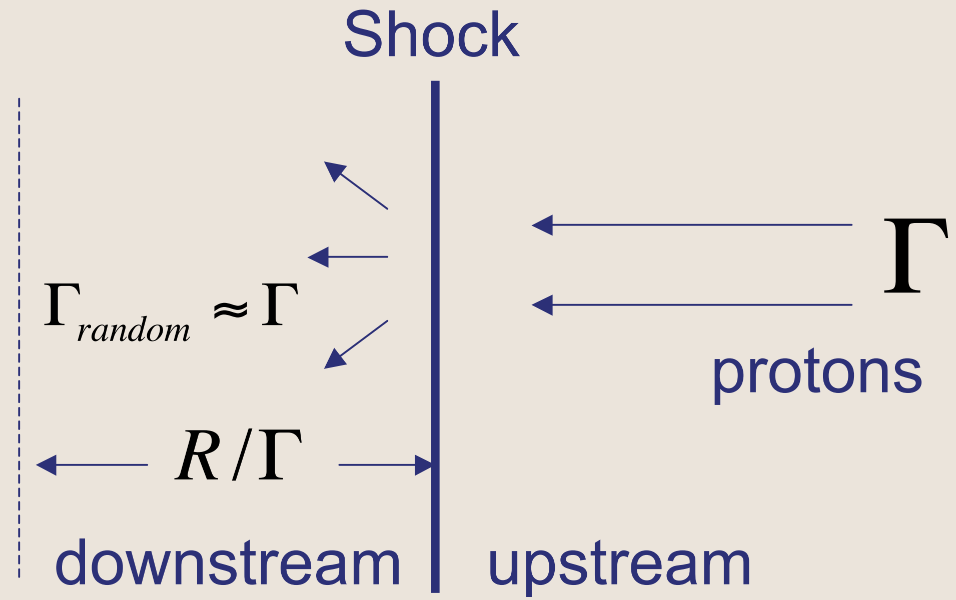


Only a small part is observable.
Spherical or collimated: No difference for observer



Blast Wave
--Thin Shell--
$\Delta R \approx R/\Gamma^2$
R
$\Gamma \propto R^{-3/2}$

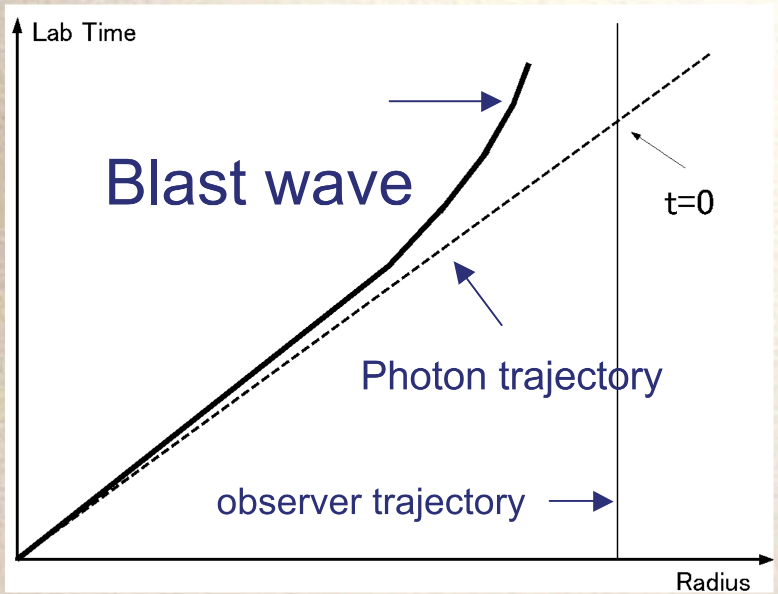
- Shock expands with relativistic velocity, reaches radius R at R/c (lab frame), at $R/c\Gamma$ (shock frame).



- Plasma flows away from the shock at relativistic velocity ~ c

- Thickness of the downstream region(shocked ISM)
  - R/Γ (shock frame), R/Γ^2 (lab frame).

Observed Time



Space-time diagram

- Fireball expanding with almost speed of light, propagating right behind photons emitted at smaller radii.
- Photons emitted from a shock at R are delayed compared to that emitted at R=0 by $t \approx R/2\Gamma^2 c \propto R^4$

gamma: a few hundred

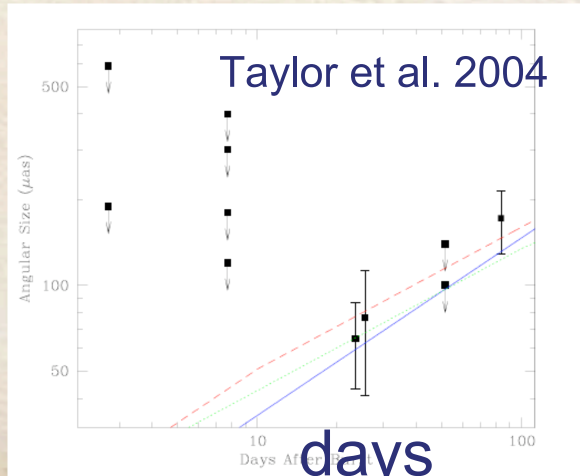
1day --> 1sec

Superluminal Motion

indication of relativistic expansion

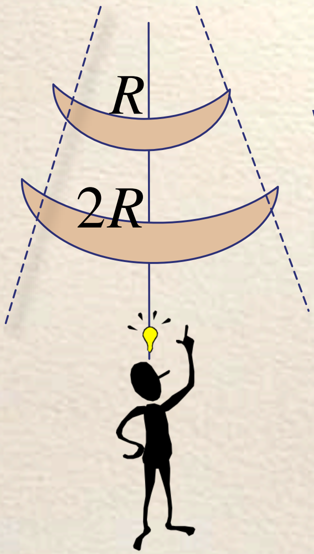
- **V**ery **L**arge **B**aseline **I**nterferometry
  - Afterglow images resolved

    25 and 83 days after GRB
- The observed expansion velocity: 3c-5c



GRB 030329 (bright, nearby event)

Superluminal motion



Apparent size of a blast wave at R

$$r_\perp \approx R/\Gamma \quad \text{(relativistic beaming)}$$

When the blast wave expands from a radius R to 2R,

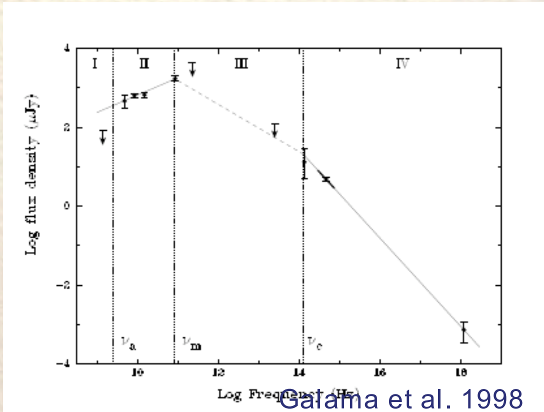
$$\Delta r_\perp \approx R/\Gamma$$

$$\Delta t \approx R/\Gamma^2 c$$

Observed velocity $$\mathrm{v} \approx \frac{\Delta r_\perp}{\Delta t} \approx \Gamma c > c$$

Synchrotron Shock model can explain afterglows well.

Light curves in radio, optical and X-ray bands
Wide Band Spectrum



Galama et al. 1998

In the Swift era, it is not so easy to explain early afterglows, though.

Some of open Issues

- How to accelerate jets?
  - gamma>100, E=10^52 ergs
- Origin of Magnetic fields
  - synchrotron emission
- How to produce prompt gamma-rays
  - internal shocks/efficiency issue
- Lack of reverse shock emission
  - observed only for several events

Magnetic field issue

- GRBs/Afterglow : Synchrotron emission
- Luminosity & spectrum depend on
  - the strength of Magnetic field in Blast wave
- The lack of first principle theories
  - Phenomenological approach
  - Free parameter $U_B = \varepsilon_B U_{\mathrm{shock}}$

- Afterglow modeling (Radio, Optical, X)
  - Values Inferred from observations

$$\varepsilon_B \approx 0.001 - 0.1$$

Significant fraction of shock energy

Wijers & Galama 1998; Panaitescu & Kumar 2001; Frail et al 2001; Freedman & Waxman 2001

- Post-shock Magnetic field: close to equipartition
  - Prompt emission: B~10^6 G
  - Afterglow: B~1 G

- Shock compression can not account for the large value.
  - Intergalactic: B~10^-6 G

- Produced by electromagnetic (e.g. Weibel) instabilities at shocks?

(e.g. Medvedev & Loeb 1999)

- Magnetic field decays rapidly?
  - within a few skin depth from the shock transition?

	R	B	R_L	Δ	δ	Δ/δ
Internal Shocks	$10^{13}-10^{15}$cm	10^{6}G	1 cm	10^{11}cm	100 cm	10^{9}
Afterglow	$10^{16}-10^{18}$cm	1G	10^{6}cm	10^{16}cm	10^{6}cm	10^{9}

Width of emitting region (↑ Δ)

Skin depth (↑ δ)

$$c/\omega_p \approx c(4\pi ne^2/m_p)^{-1/2}$$

Efficiency issue

Internal Shocks: Leading model for production of prompt emission

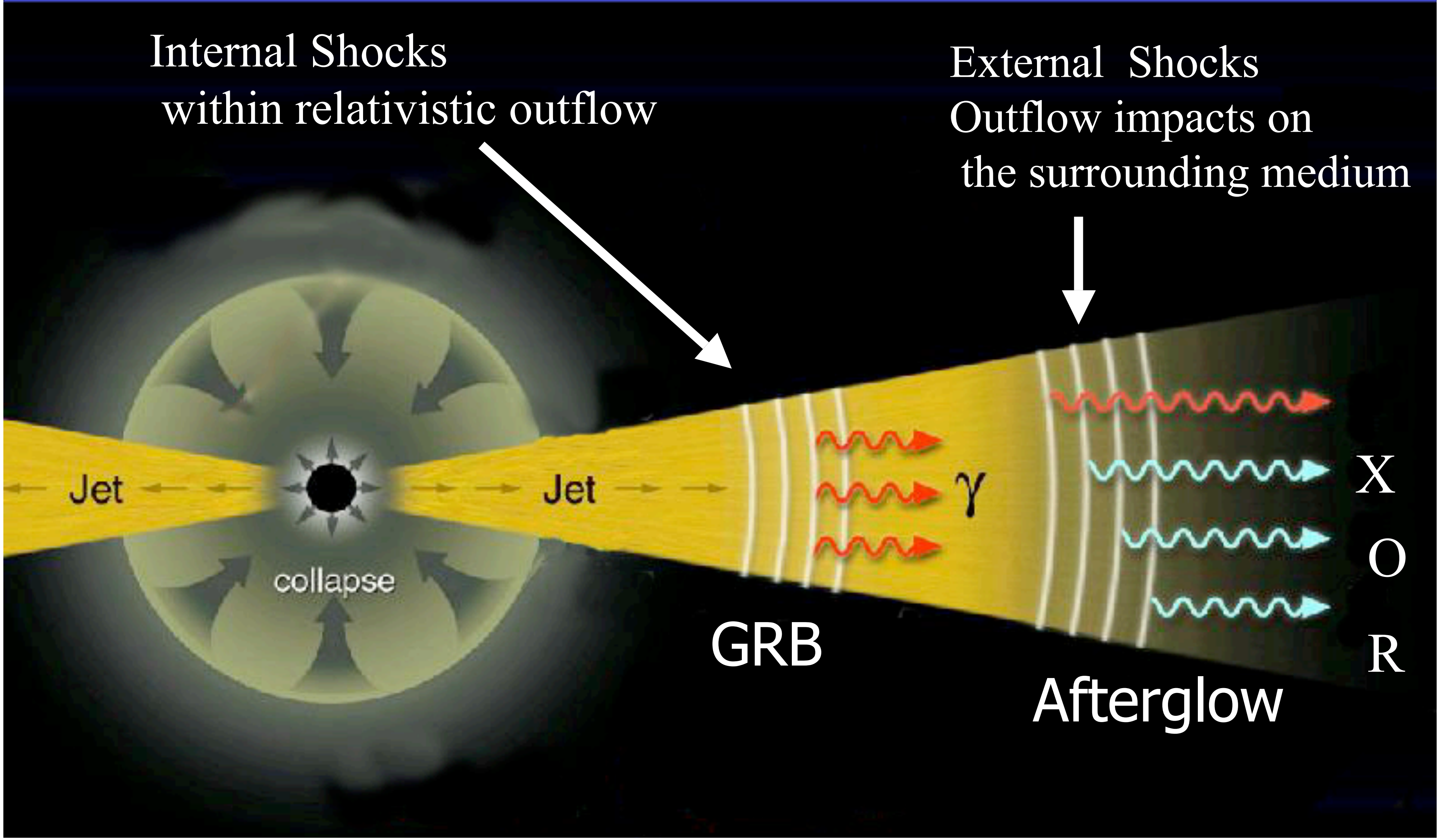
Shocks within relativistic outflow due to the inhomogeneity of the velocity distribution

Inefficient: conversion efficiency < 20-30 %

Most explosion energy should be radiated in afterglow

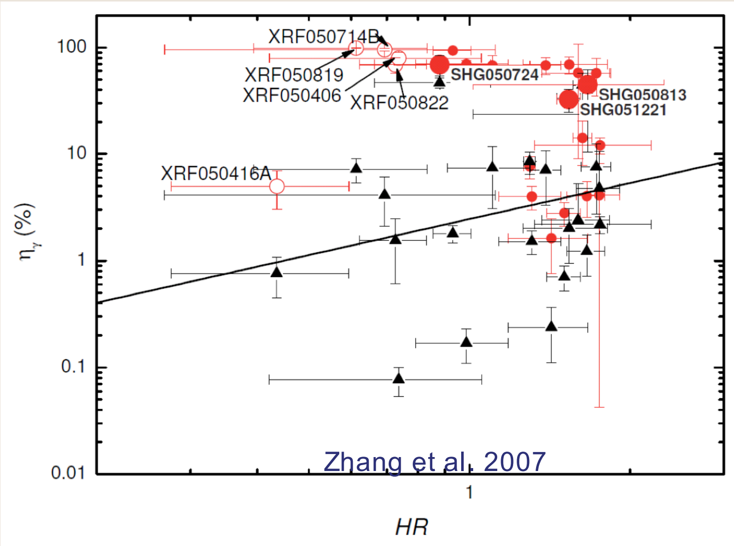
(SK,Piran&Sari1997; Beloborodov 2000; SK&Sari 2001)

Synchrotron shock model

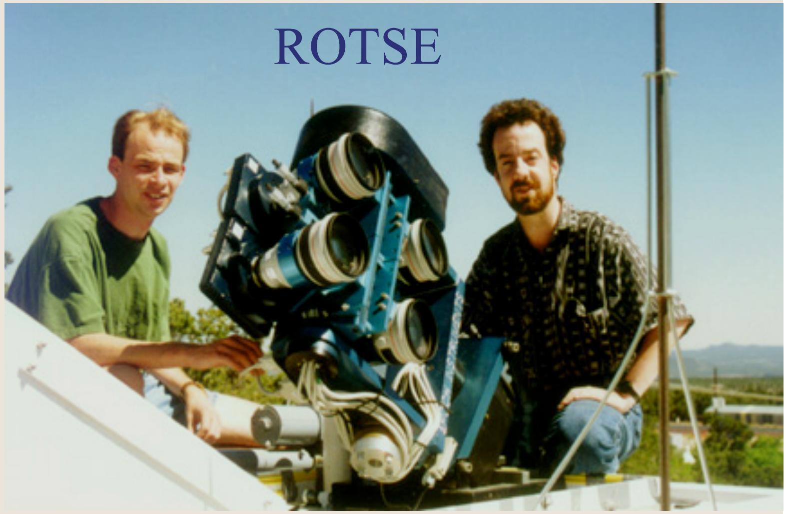


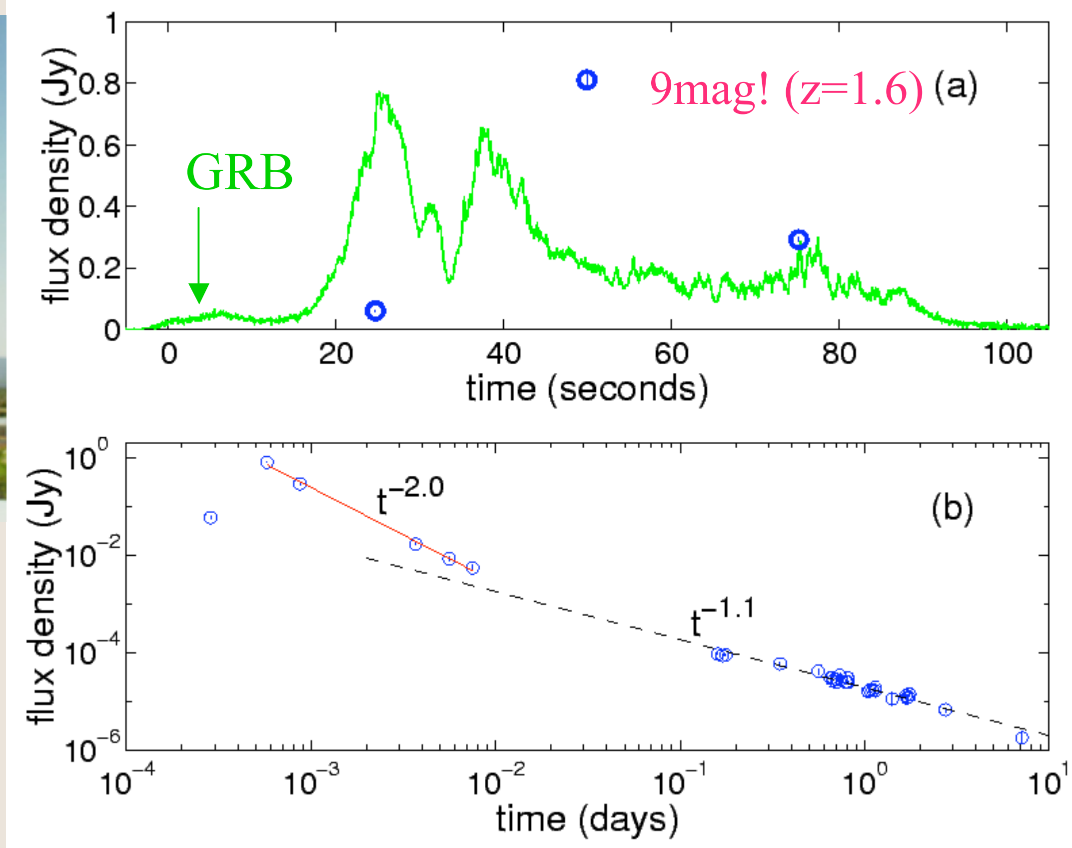
- Prompt emission flux
- Afterglow modeling

Prompt emission energy >> blast wave energy

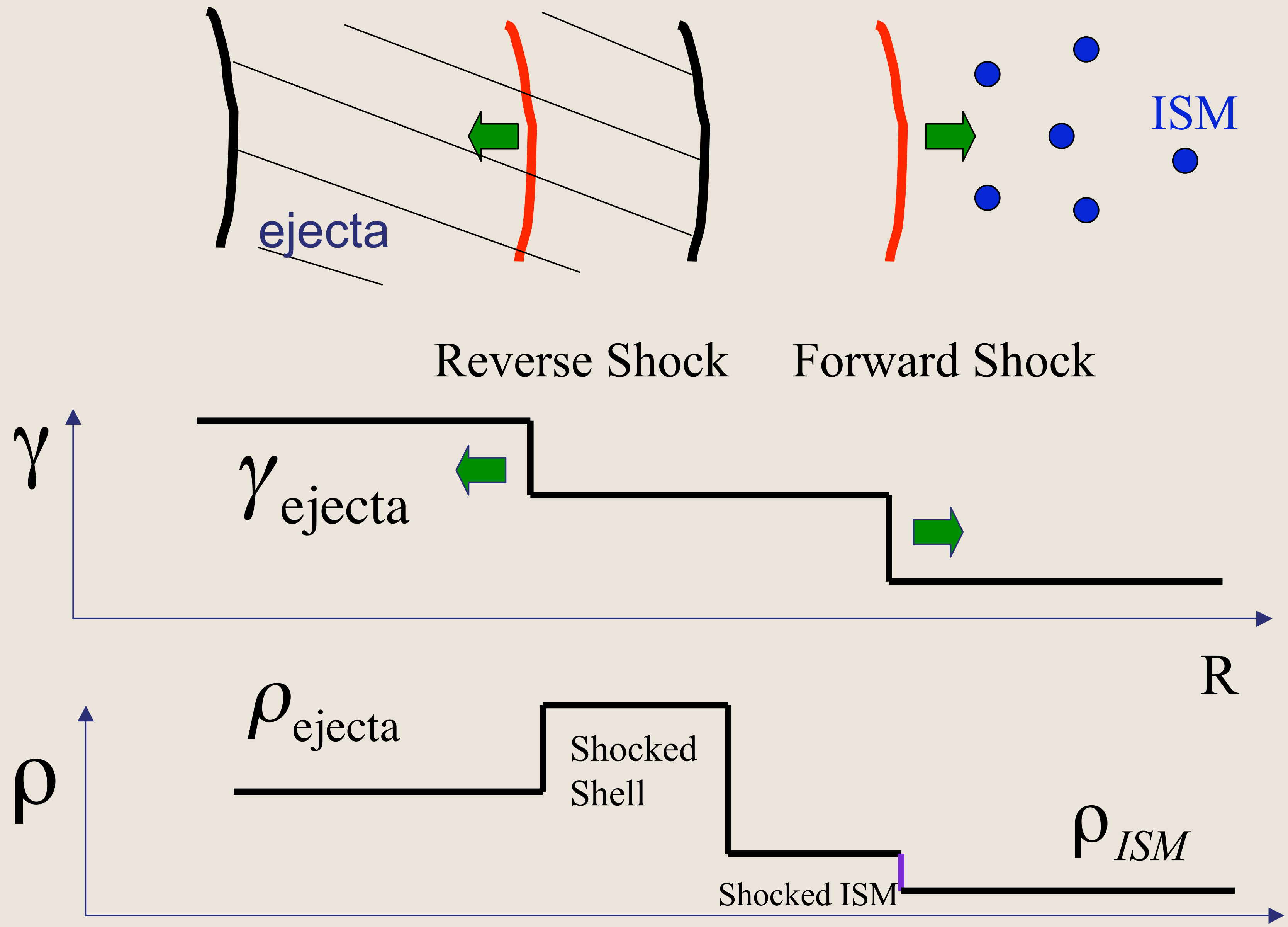


Optical Flash Issue





(Akerlof et al. 1999; Meszaros&Rees; Sari & Piran 1999; S.K. 2000)


ejecta
ISM
Reverse Shock
Forward Shock
γ
γ_{ejecta}
R
ρ
ρ_{ejecta}
Shocked
Shell
Shocked ISM
ρ_{ISM}

GRB jet might be highly magnetized?

- How to accelerate jets?
  - Low baryon loading : high velocity
  - collimation
- Origin of Magnetic fields
  - from a central engine
- How to produce prompt gamma-rays
  - reconnection?
  - overcome efficiency issue?
- Lack of reverse shock emission
  - magnetic pressure suppress

Polarization

- Synchrotron emission is intrinsically polarized
  - random magnetic fields: no polarization (net)

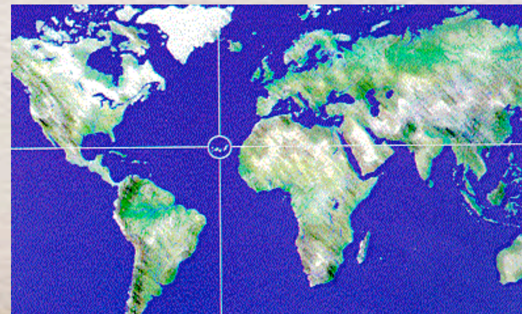
- Magnetized fireball
  - Field created at central engine
  - Large scale (ordered) fields
  - Emission could be highly polarized?

- Strong (80%) polarization from the prompt emission (Coburn and Boggs 2003)
  - However, independent groups reanalyzed the same data, and found no statistical significance.

Early polarization measurements

- Polarimeter on 2m robotic telescope
- ~100 sec after GRBs
- 12mag (100sec exp)

Liverpool Telescope@Canary Islands

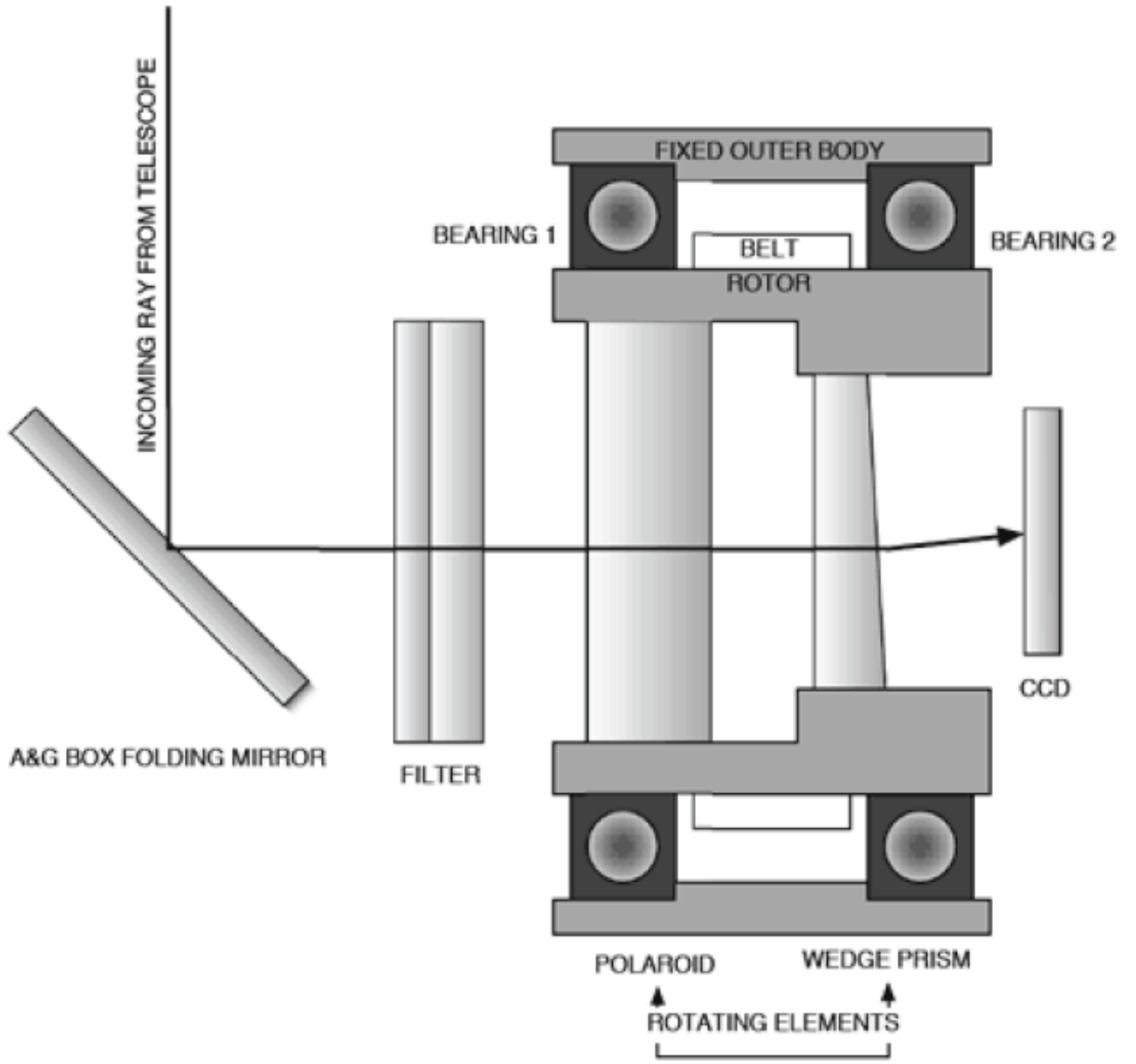


GRB 060418

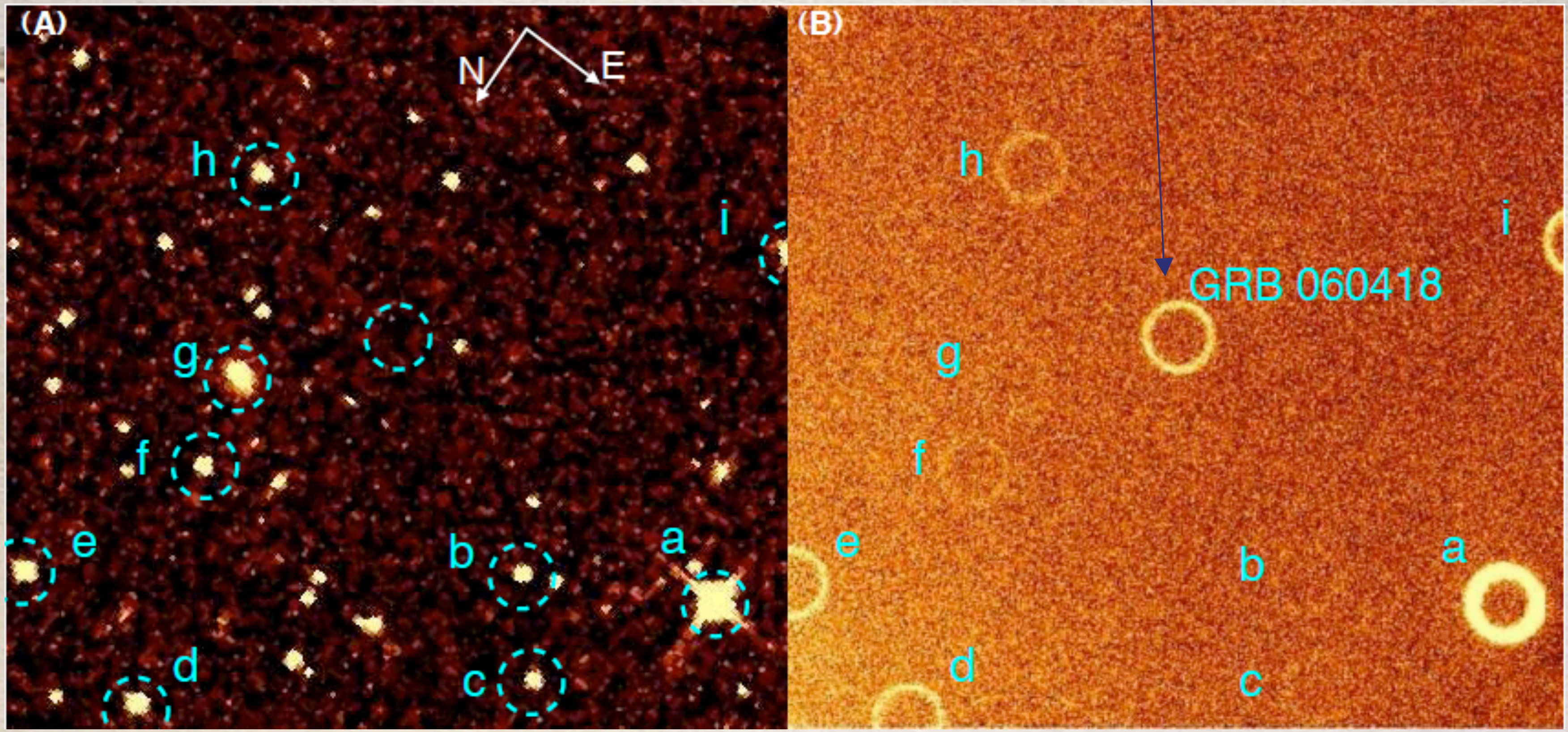
- Afterglow polarization measurement
  - 200 sec after the start of prompt gamma-ray
  - At the onset of the afterglow
  - Polarization: 8% upper limit

Mundell et al. 2007

RINGO: using a rotating Polaroid to modulate any polarized flux, each star image is recorded on CCD chip as a circular pattern.



Polarization signal mapped out around the circumference

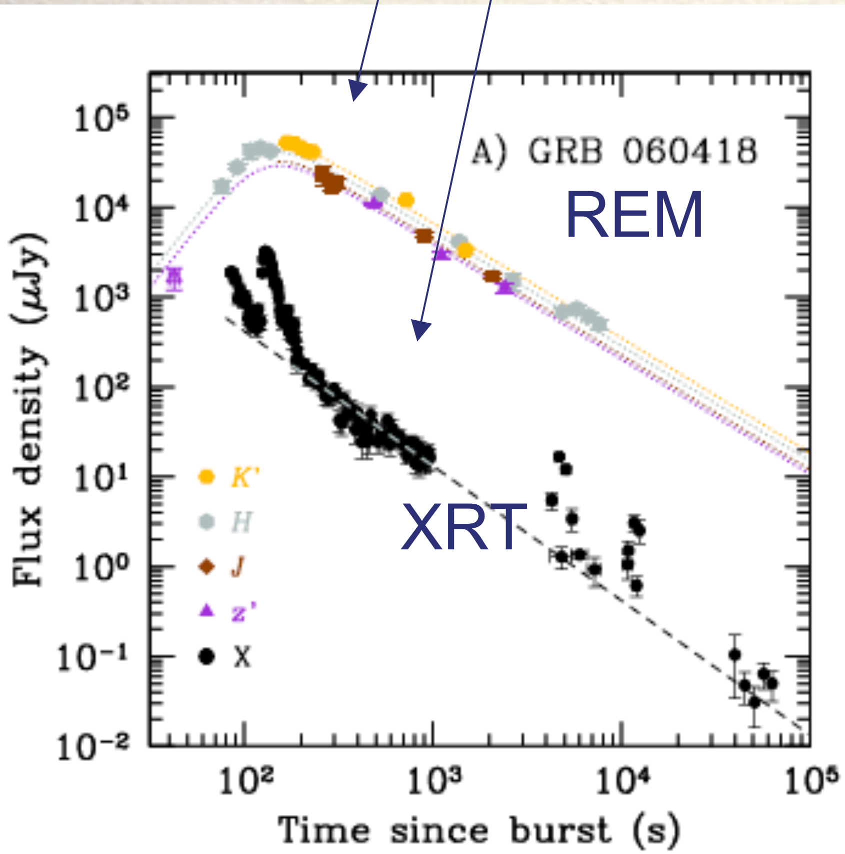


Digital Sky Survey:
the sky before the GRB.
R-band

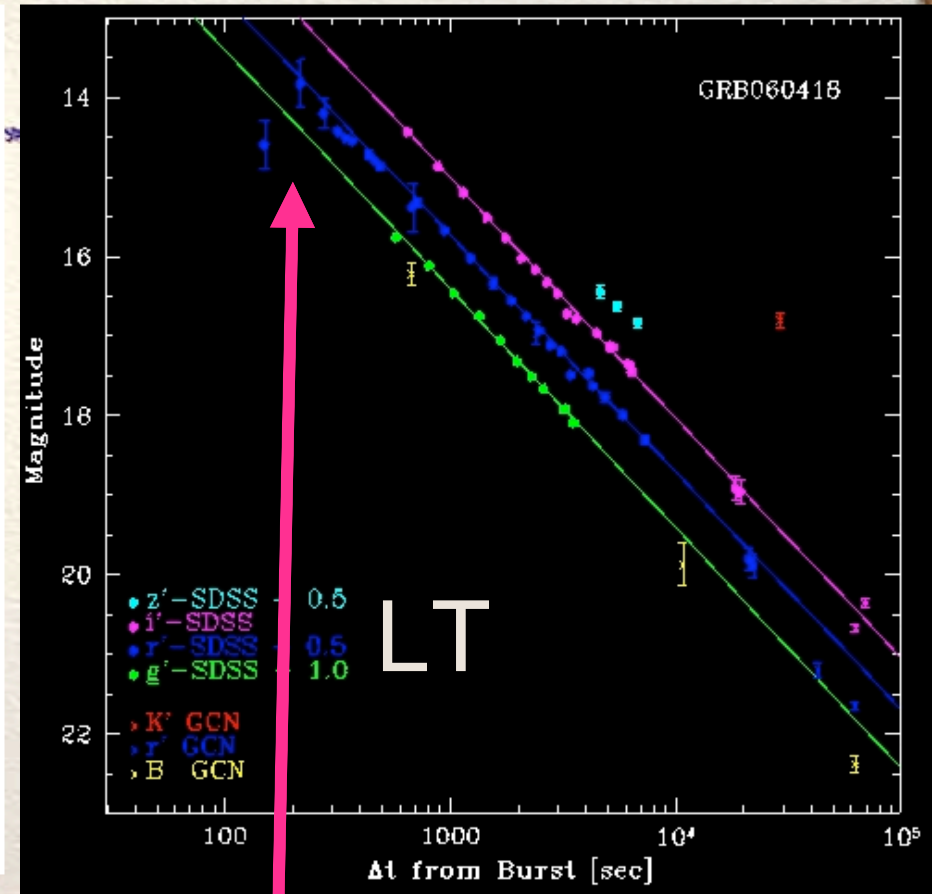
RINGO image
GRB 060418(afterglow)
and other bright sources
in the field.

IR, X

Optical



Molinari et al. 2006



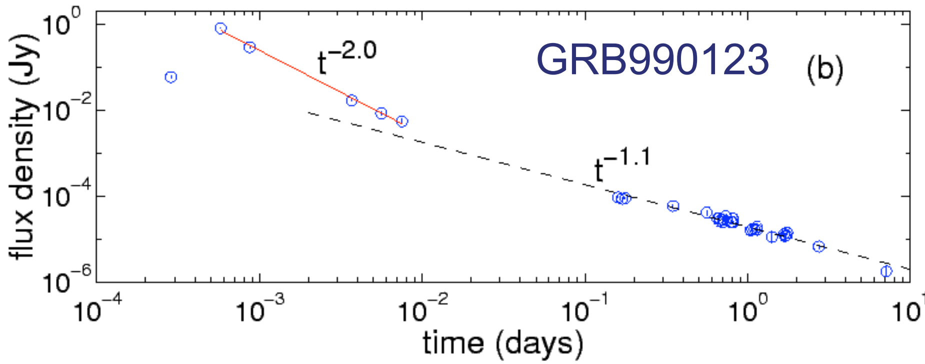
Polarization measurement: ~200sec

- Single peak in light curves
  - Single power-law light curves (IR/Opitcal) after the peak

$$\nu_{m,fs} < \text{ IR band}$$

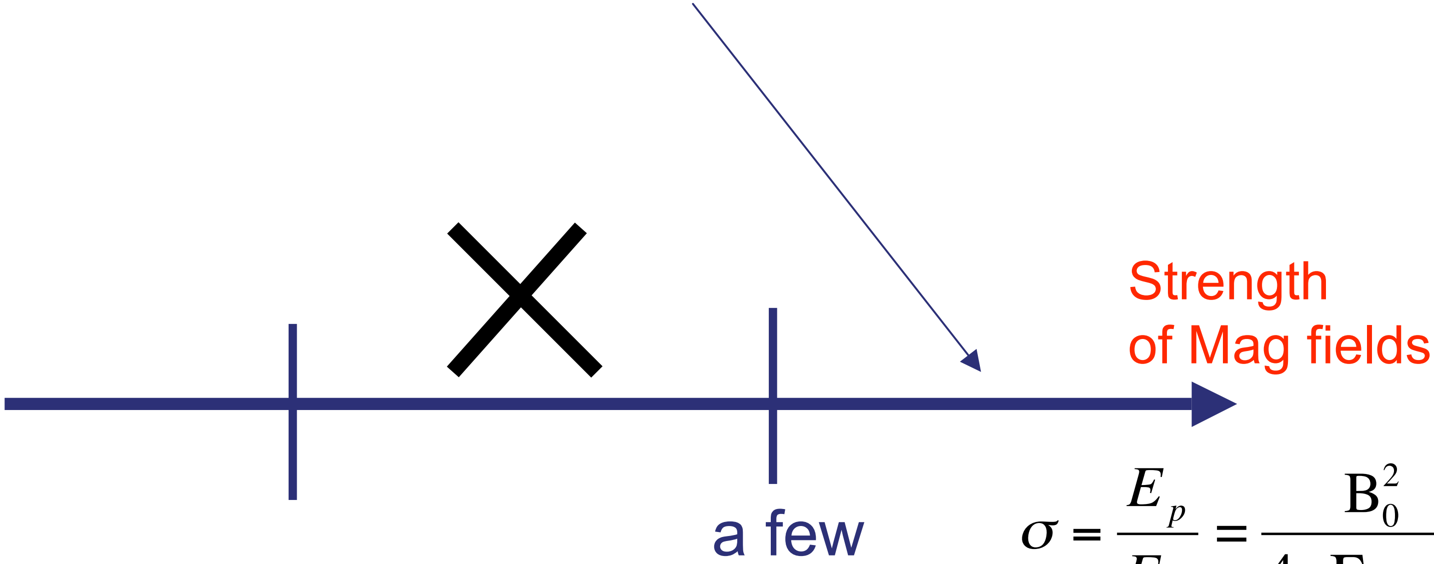
  - The lack of RS emission in the form of “Optical Flash” is consistent with the onset interpretation.
- More than 50% photons coming from reverse shock region.

- Our results rule out the presence of a large-scale ordered field in “the emitting regions ” at the onset of afterglow.



- Our results exclude fireball with ordered Magnetic fields
  - moderate strength

- Poynting flux dominated fireball
  - No reverse shock
  - No reverse shock emission



$$\sigma = \frac{E_p}{E_K} = \frac{B_0^2}{4\pi\Gamma_0\rho_0 c^2}$$

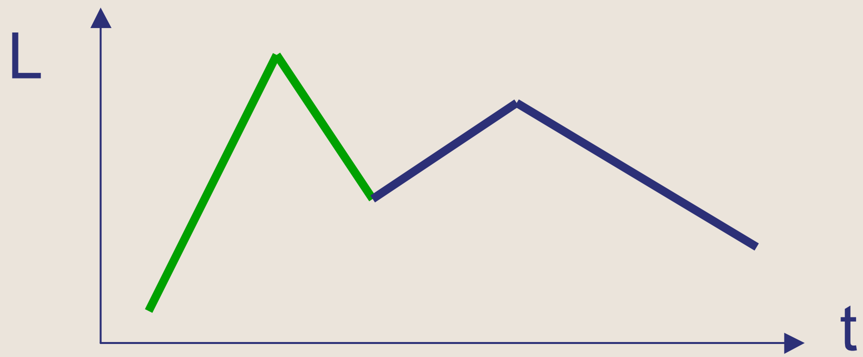
Zhang&KS05;Giannios et al.07

- High magnetic pressure suppresses a reverse shock
  - magnetosonic wave is faster for high magnetization.
  - motion in ejecta: subsonic

$$\Gamma_A = \sqrt{1+\sigma_0}$$

- Poynting-flux dominated jet
  - no reverse shock ---> no electron acceleration?
  - Reconnection process accelerates electrons?
  - Stability of the contact discontinuity
  - How magnetic energy is transferred to shocked ambient medium eventually?

- There are several optical flash detections.
  - At least in some cases, reverse shocks formed in fireball ejecta
  - variation in magnetization degree of fireball?



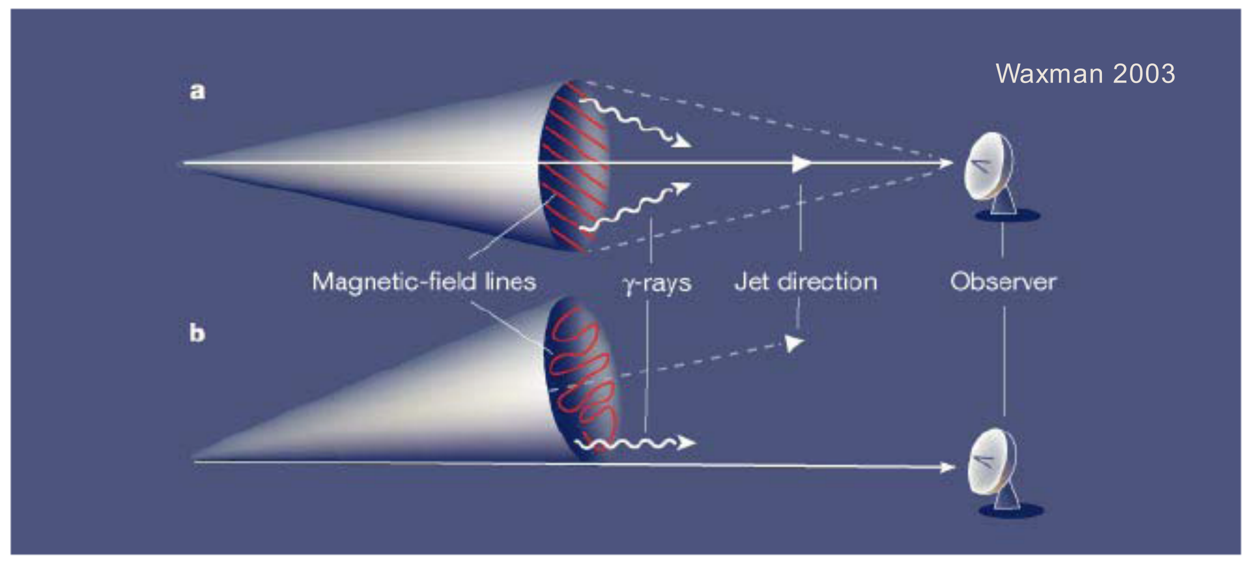
Jet Structure and Polarization

- If we detect high polarization in early early afterglow…
  - Magnetized fireball?
  - How fireball jet structure affects the conclusion?

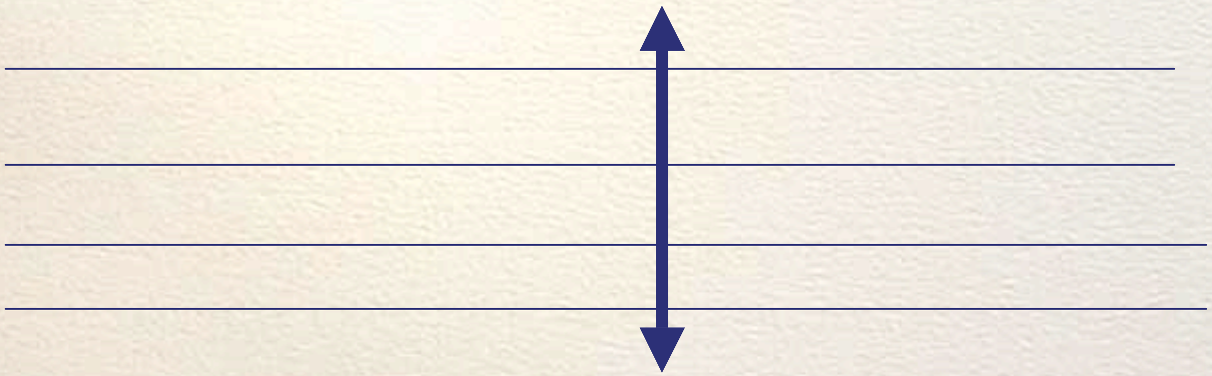
Large Polarization

a) Magnetic field is ordered.
b) Specific viewing angle: random Magnetic field

The line-of-sight to GRB runs along the edge of a jet cone.

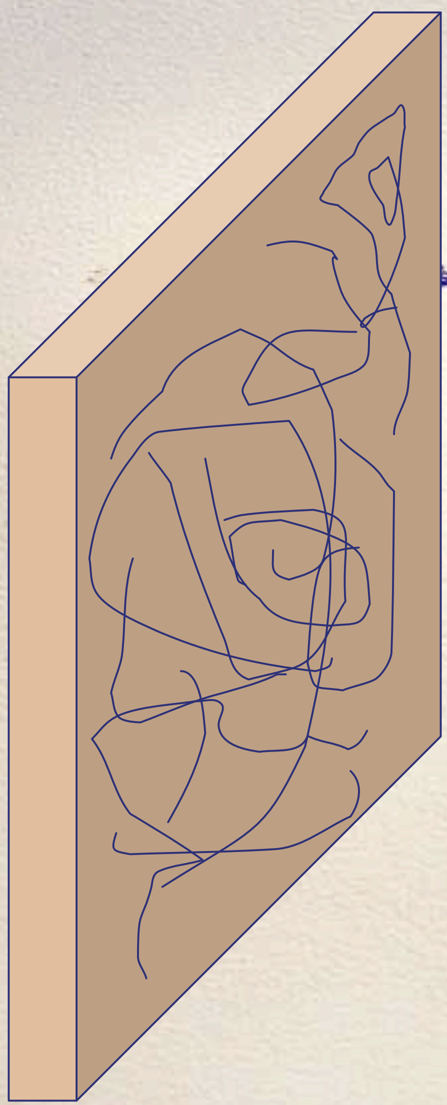


Emission due to Uniform Magnetic fields



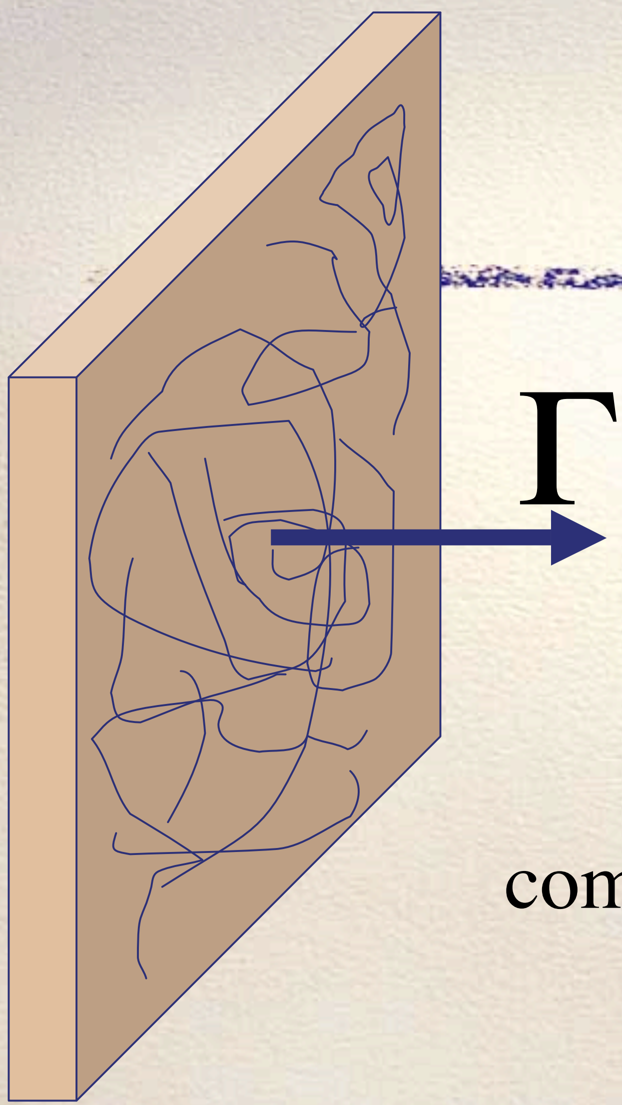
Synchrotron Emission: P ~ 70%

Random Magnetic fields



Thin slab: (shock region is thin)
Some degree of alignment if observed edge-on

If the slab is observed edge-on,
the radiation is polarized!



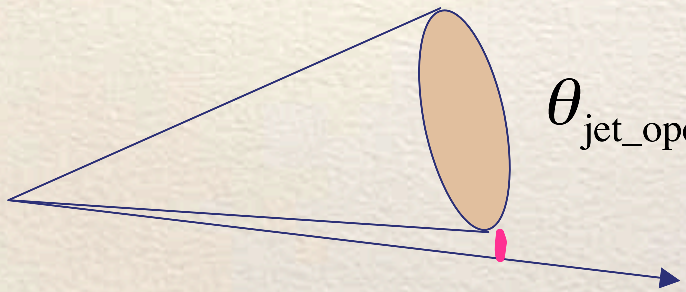
If the emitting slab moves with
a relativistic velocity,

we have to take into account the
relativistic aberration of photons.

$$\text{comoving } \theta' = \pi/2 \Rightarrow \text{ lab } \theta = 1/\Gamma$$

It the line-of-sight to GRB runs along the edge of the jet cone, we might observe large polarization.

but it is rather rare to see GRB from the preferable angle by chance.



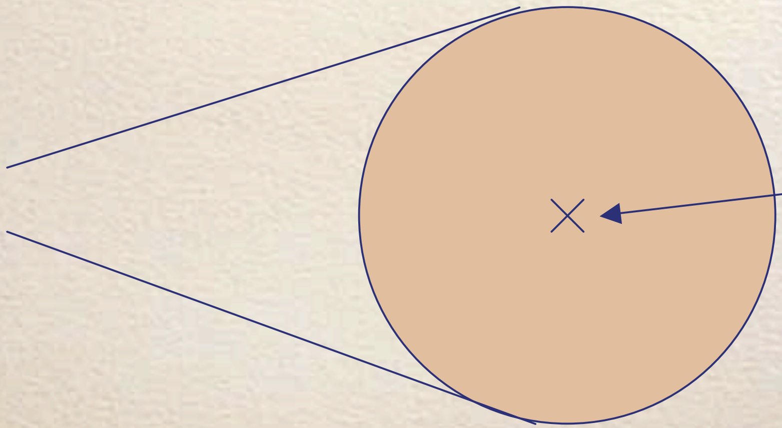
$$\theta_{\text{jet\_opening}} \approx 10^{-1}$$

$$\theta \approx 1/\Gamma \approx 10^{-3} - 10^{-2}$$

Jets should be structured!

Higher velocity at the center

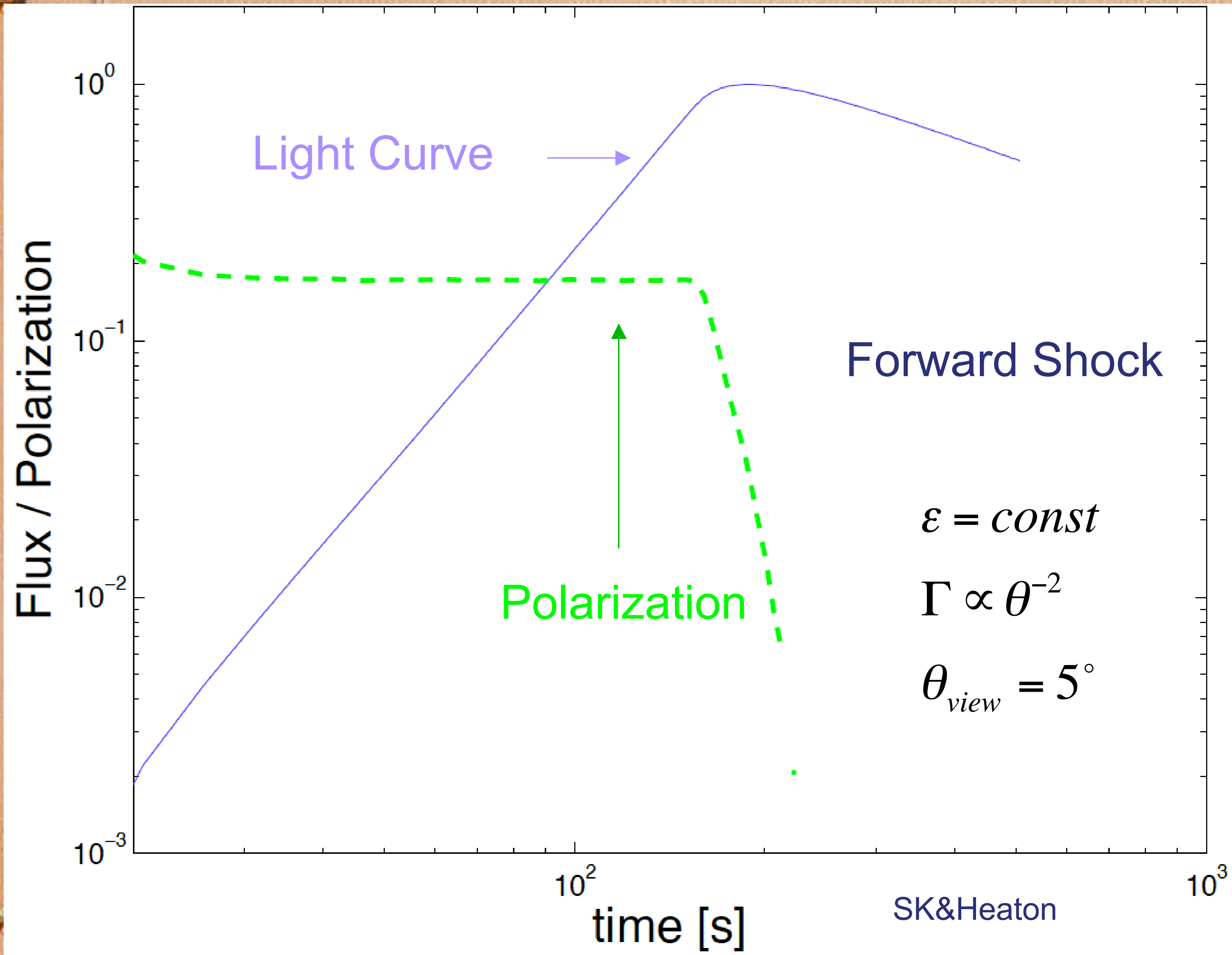
- Jet could decelerates first around the center
- Deceleration radius is a function of viewing angle.
- Deceleration = the onset of afterglow
- At the onset of Afterglow, the line-of-sight runs along the edge of the emitting jet cone



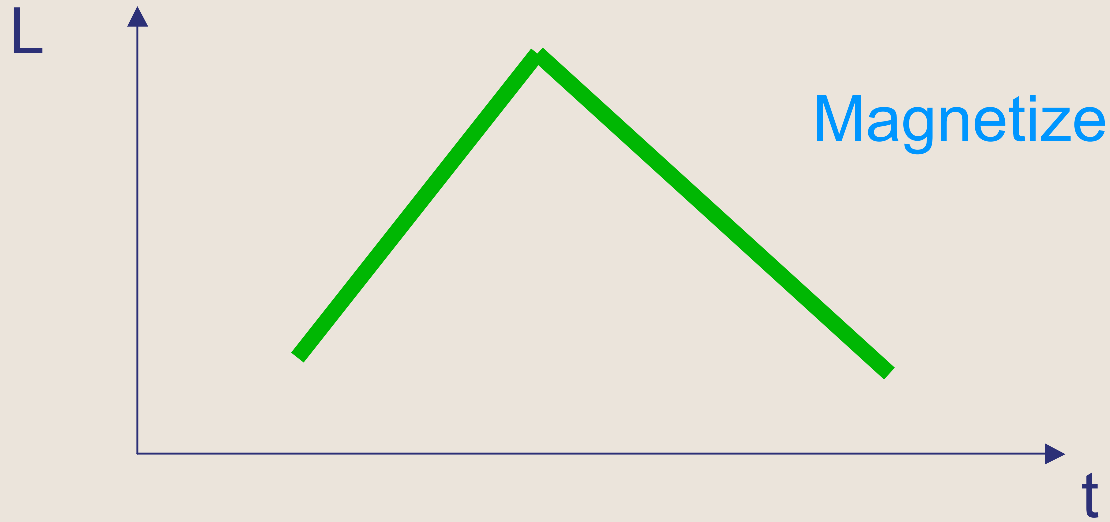
Jet decelerates around the center first.

$$8g - k > 0$$

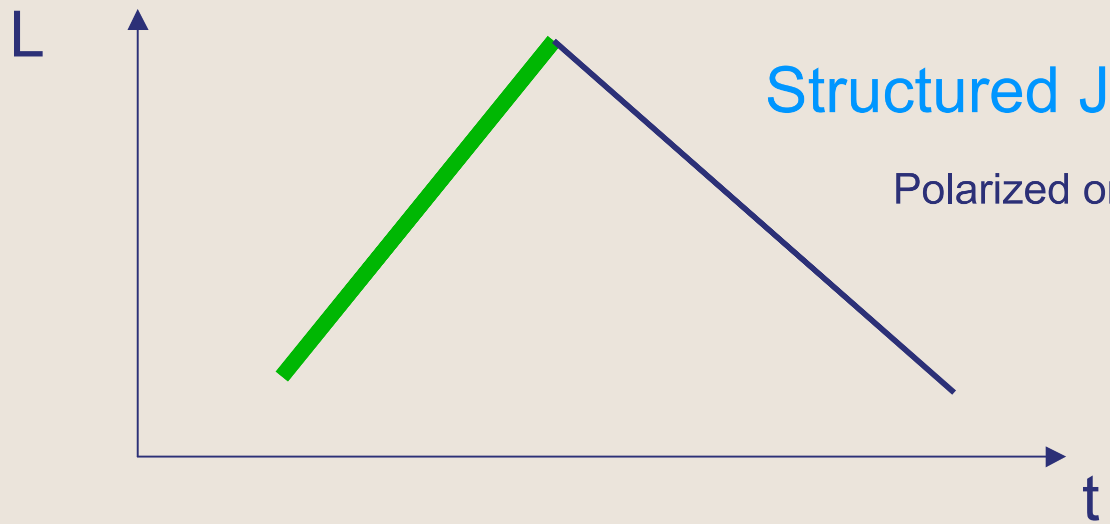
$$\varepsilon \propto \theta^{-k}, \;\; \Gamma \propto \theta^{-g}$$



Flux / Polarization
10^0
10^{-1}
10^{-2}
10^{-3}
10^2
10^3
time [s]
Light Curve
Polarization
Forward Shock
$\varepsilon = const$
$\Gamma \propto \theta^{-2}$
$\theta_{view} = 5^\circ$
SK&Heaton



Magnetized Jet



Structured Jet (baryonic)

Polarized only in the rising phase

Summary

- GRBs
  - What, How (the standard fireball model)
- Magnetized fireball
  - jet acceleration, origin of B-field, efficiency problem, no reverse shock
- Polarization
  - Liverpool Telescope observations
  - Jet Structure