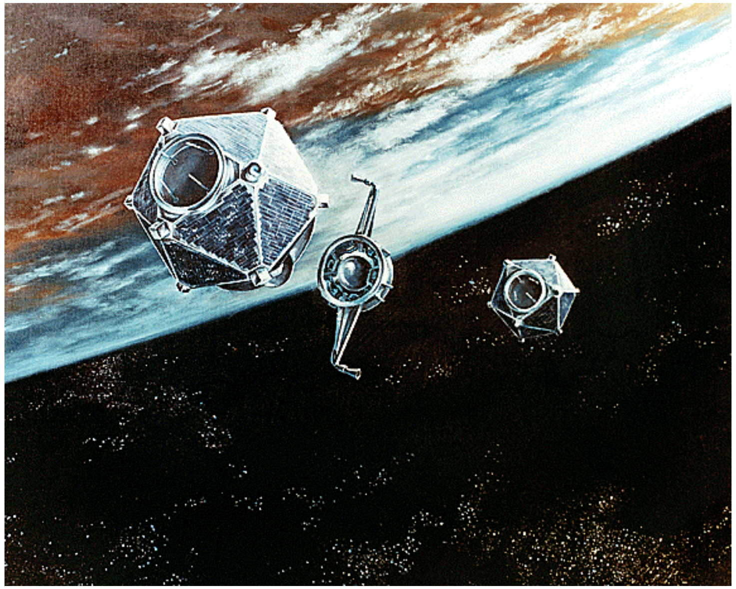
GRB history

Discovered 1967 Vela satellites

classified!

Published 1973!

Ruderman 1974 Texas: More theories
than bursts!



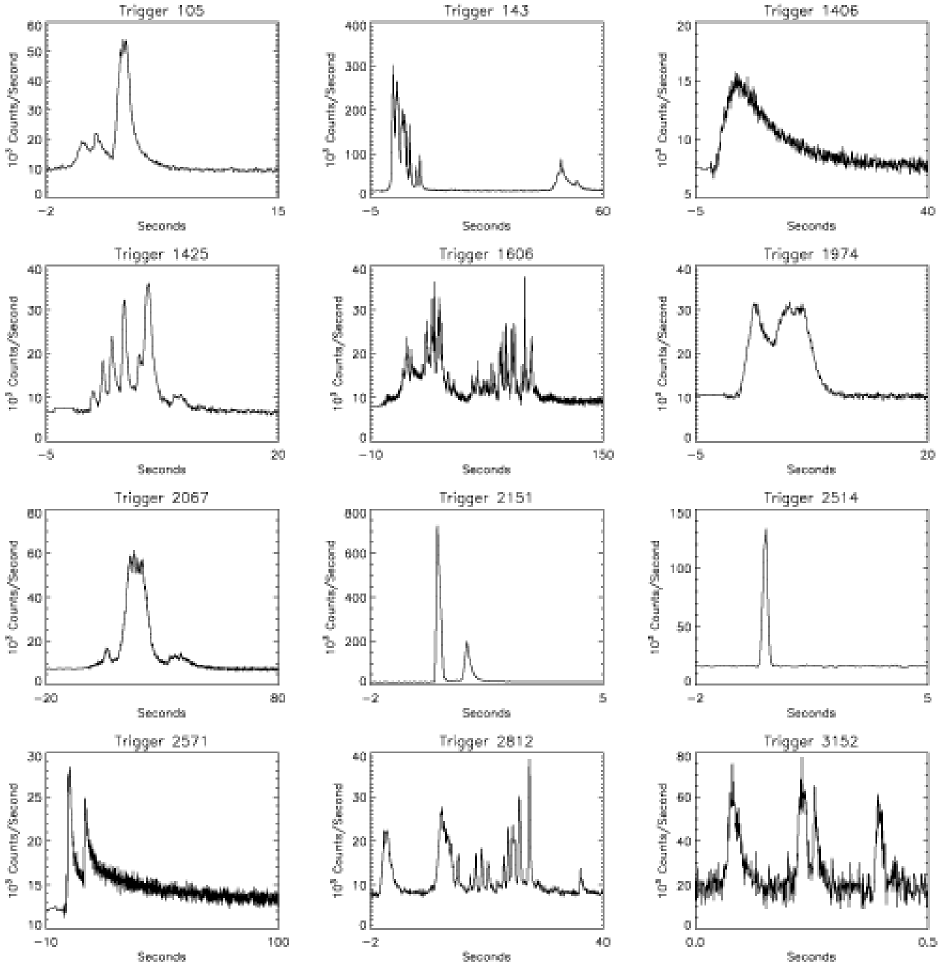
Burst diversity

E_{peak} ~ 300 keV

Non-thermal spectrum

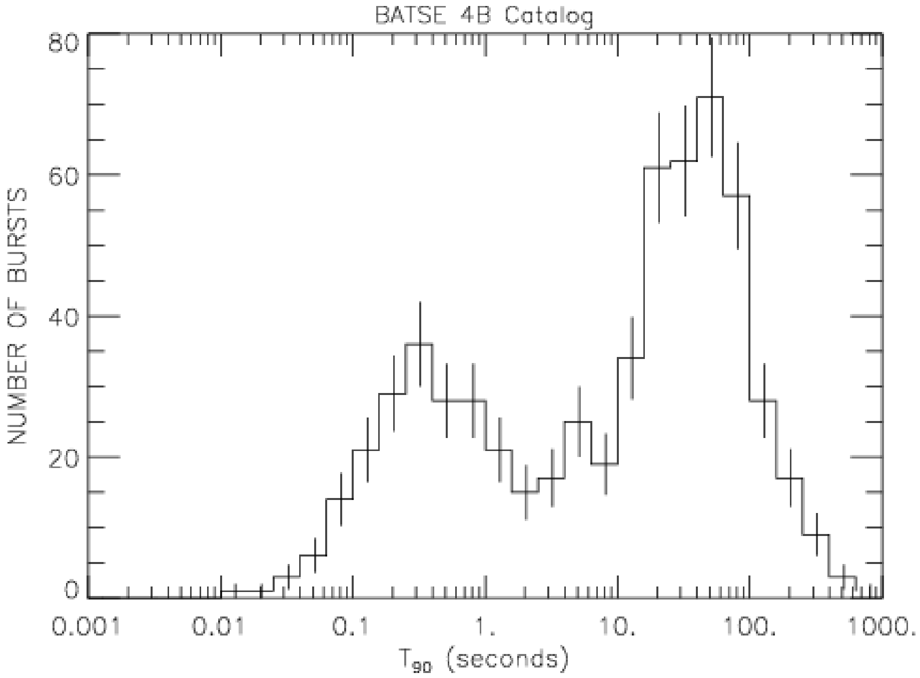
In some thermal contrib.

Short time variability down to ms



Duration: $10^{-2} – 10^{3}$ s   Often substructure

Bimodal distribution



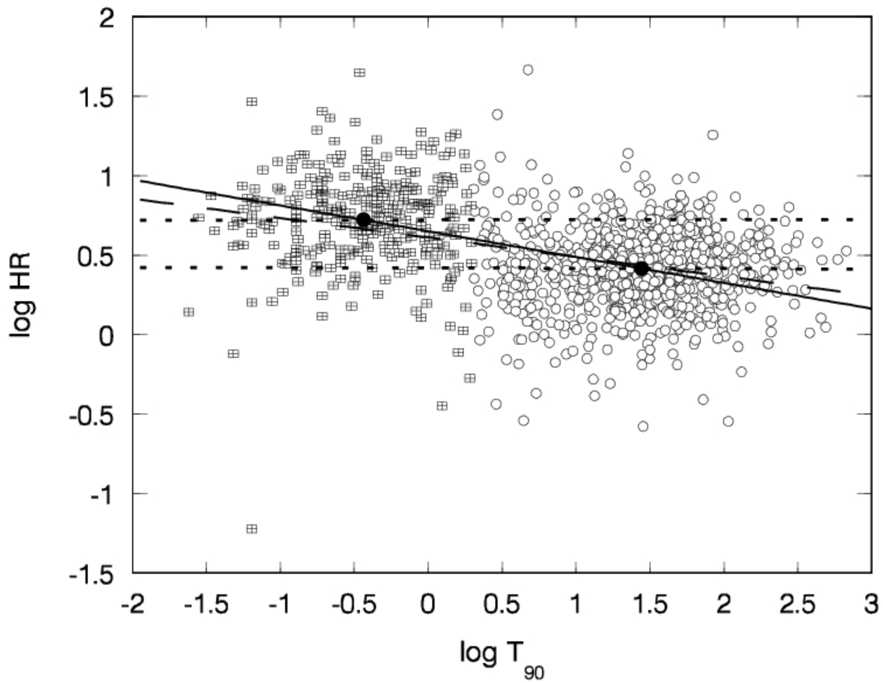
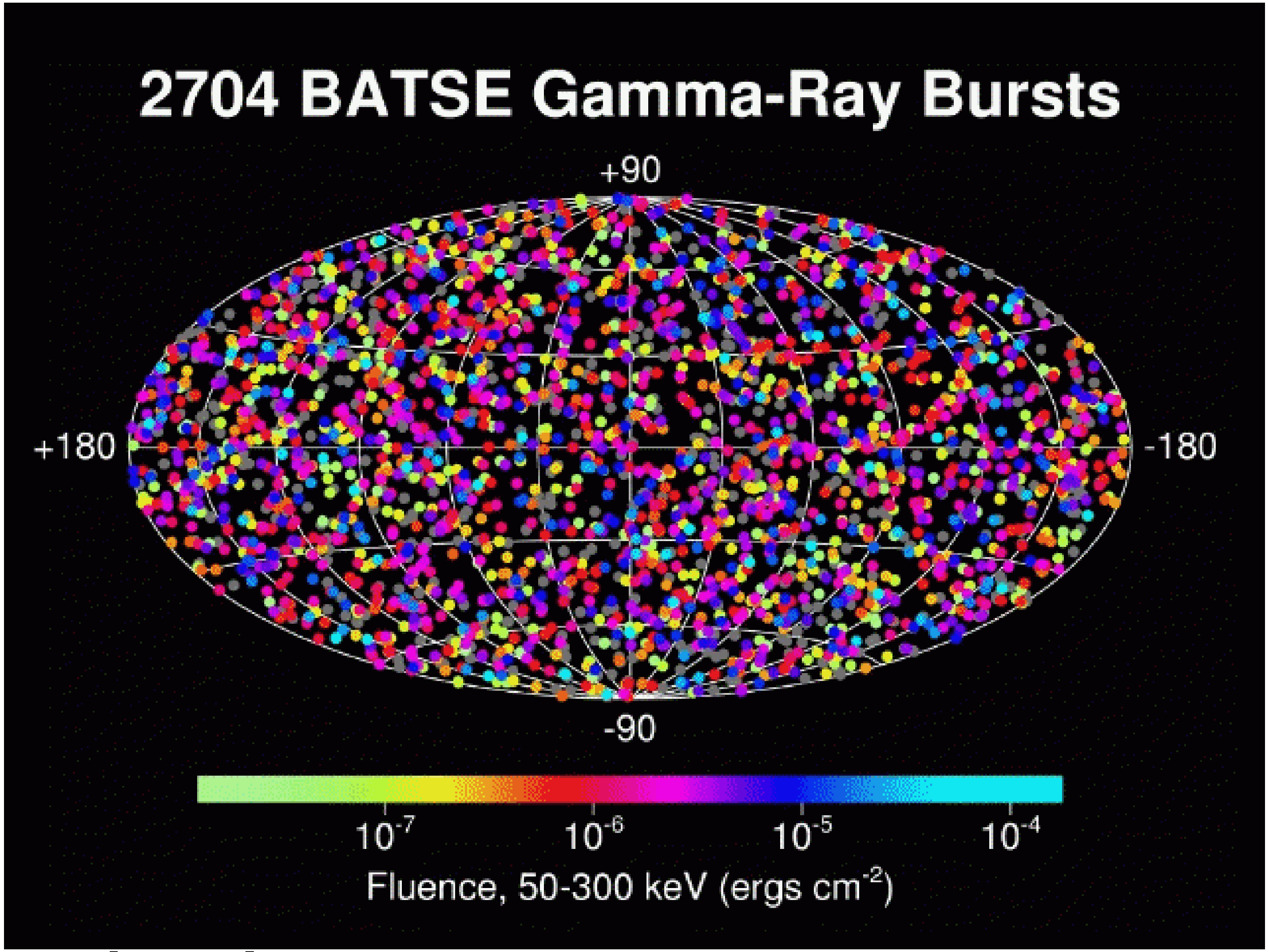


Fig. 1

Short: t < 2 s t_{mean} ~ 0.2 s ¼ Hard

Long: t > 2s t_{mean} ~ 35 s ¾ Soft

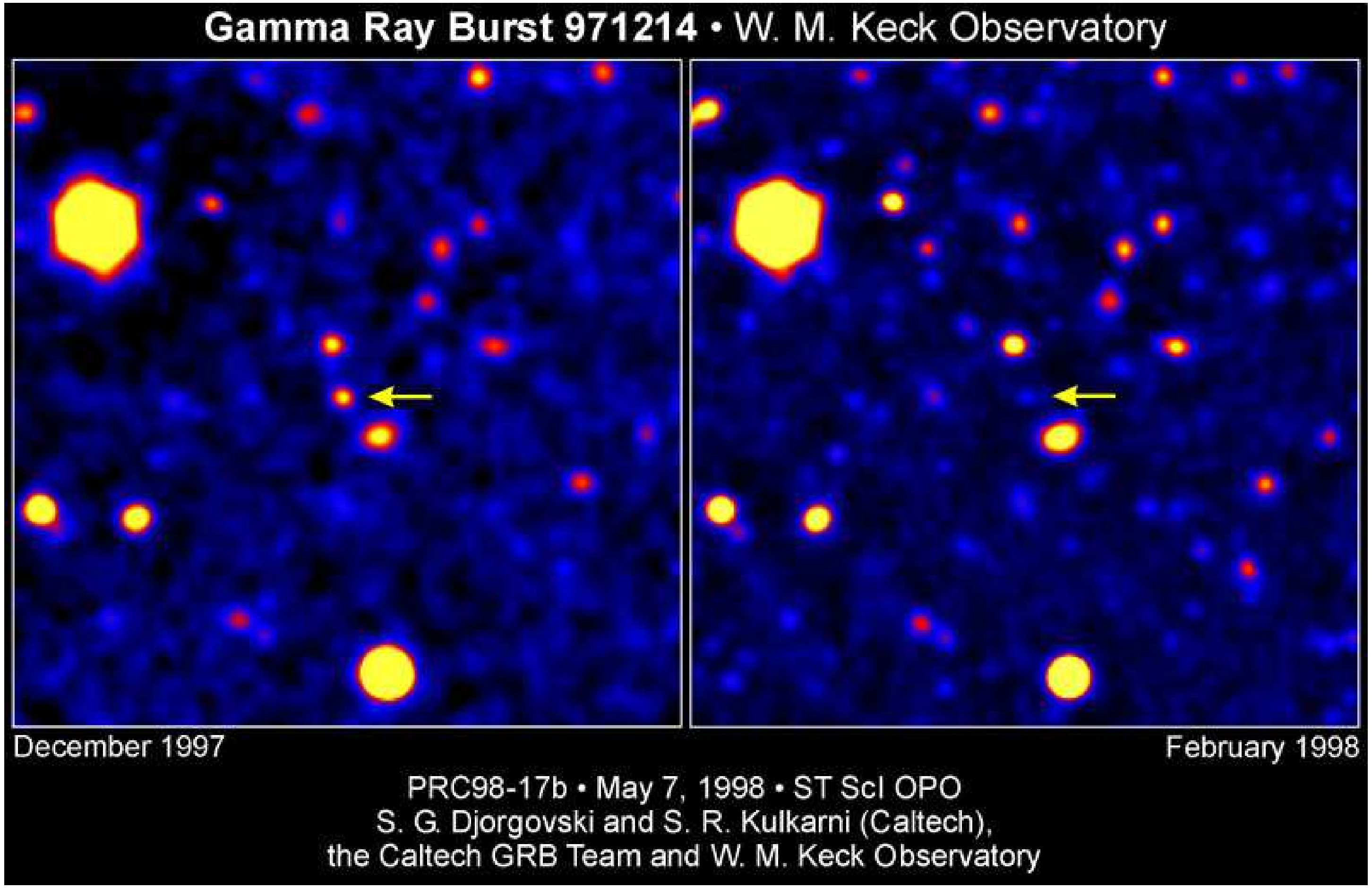


~ 1 burst/day

Isotropic distribution: 1. Cosmolgical

2. Distant halo contribution > 100 kpc

Beppo/SAX satellite



First GRB afterlow: GRB970228

First with redshift: GRB970508
z=0.835 from absorption lines

GRBs are cosmological!!

Energies 10^{50}-10^{54} erg/s if isotropic

Prompt phase

t ~ 10 -1000 s

rapid variability milli sec – sec

Gamma-rays

Both short and long bursts

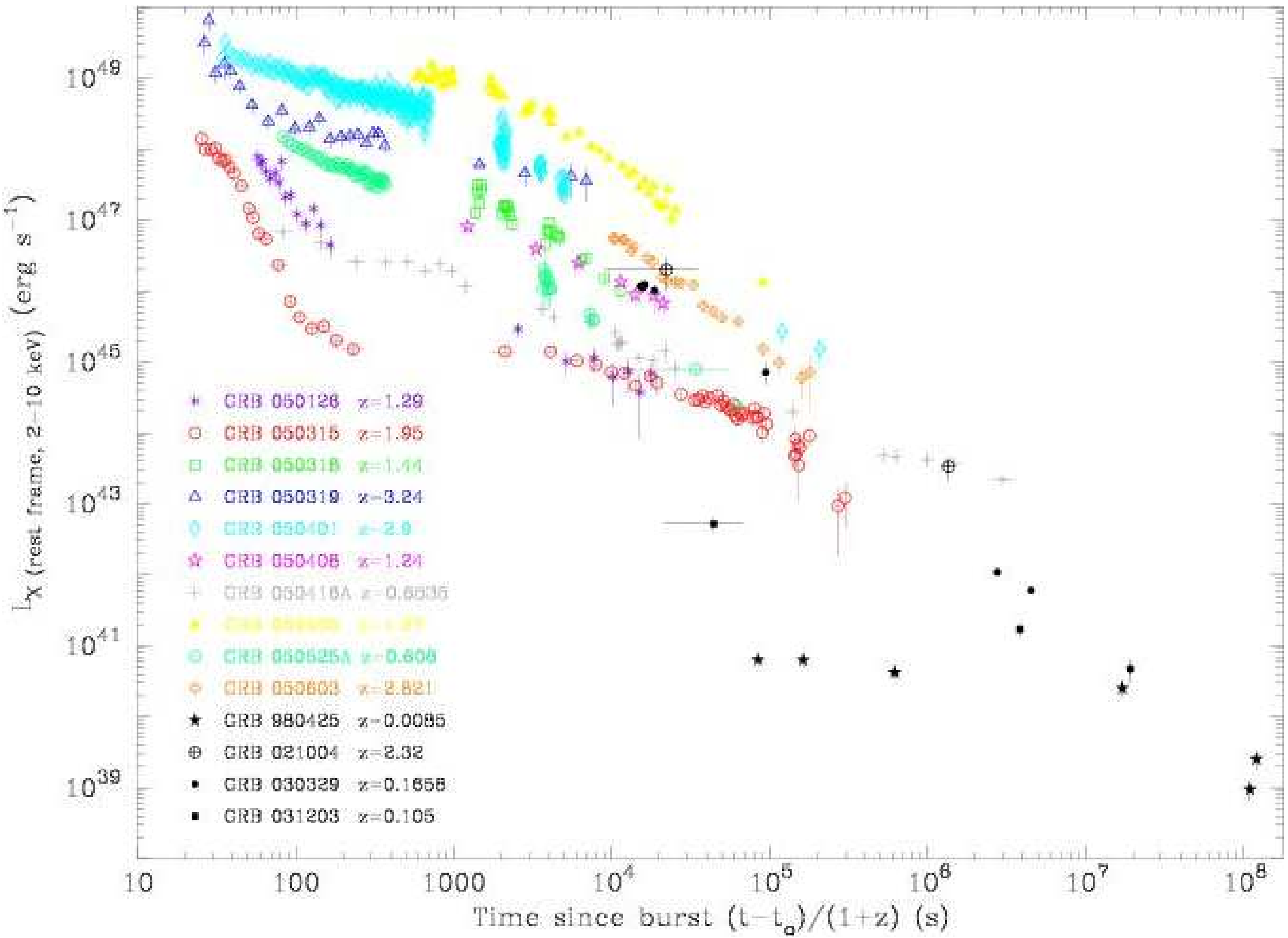
Afterglow

t ~ 100 s – years

X-rays, optical, radio

smooth evolution, often power law decay

Until SWIFT only long, now also short



L_X (rest frame, 2–10 keV) (erg s^{-1})
10^{49}
10^{47}
10^{45}
10^{43}
10^{41}
10^{39}
10
100
1000
10^4
10^5
10^6
10^7
10^8
Time since burst $(t-t_o)/(1+z)$ (s)
GRB 050126 z=1.29
GRB 050315 z=1.95
GRB 050318 z=1.44
GRB 050319 z=3.24
GRB 050401 z=2.9
GRB 050406 z=1.24
GRB 050416A z=0.6535
GRB 050525A z=0.606
GRB 050603 z=2.821
GRB 980425 z=0.0085
GRB 021004 z=2.32
GRB 030329 z=0.1658
GRB 031203 z=0.105

t (s)

Relativistic expansion?

Photon-photon pair production

$$\gamma + \gamma \rightarrow e^+ + e^- \qquad h\nu > 2 m_e c^2$$

$$\tau_{\gamma\gamma} \approx \sigma_T n_\gamma R \approx \sigma_T f_p \frac{L}{4\pi R^2 c m_e c^2} R$$

$$R \approx c\,\Delta t \qquad L = 4\pi D^2 F / \Delta t$$

$$\tau_{\gamma\gamma} \approx \frac{\sigma_T f_p F D^2}{(\Delta t\, c)^2 m_e c^2} \approx 3 \times 10^{14} f_p \frac{F}{10^{-6}} \left(\frac{\Delta t}{10^{-2} s} \right)$$

$$\tau_{\gamma\gamma} \gg 1$$ thermalisation: black-body!

Consequences of relativistic expansion

If relativistic, i.e., $\Gamma \gg 1$

$$\nu_{obs} \approx \Gamma \nu_{em}$$

Observed MeV photons become X-rays in rest frame: No pair production

$$f_p \propto \Gamma^{-2\alpha} \ll 1$$

Consequences of relativistic expansion II

$$t_1^{obs} = t_1^{em} + (D - r_1)/c$$

$$t_2^{obs} = t_2^{em} + (D - r_2)/c$$

$$dt^{obs} = dt^{em} - dr/c = dt^{em} - V\,dt^{em}/c = dt^{em}(1 - V/c)$$

$$dt^{obs} = dt^{em}(1 - \beta)$$

$$\Gamma^2 = \frac{1}{(1-\beta^2)} = \frac{1}{(1+\beta)(1-\beta)} \approx \frac{1}{2(1-\beta)} \qquad if\ \beta \approx 1$$

Consequences of relativistic expansion III

$$dt^{obs} = \frac{dt^{em}}{2\,\Gamma^2}$$

1. Observer sees everything slower compared to comoving frame

$$dt^{em} = 2\,\Gamma^2\,dt^{obs}$$

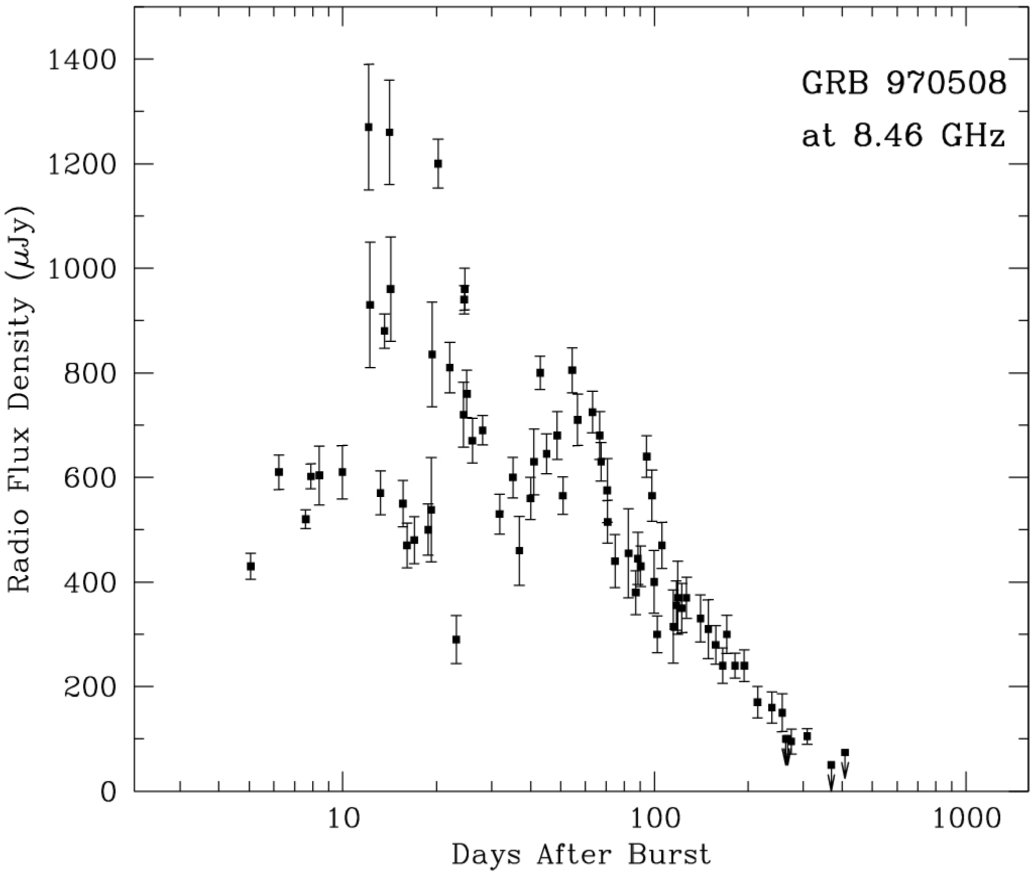
2. Size of object is NOT $c\,t^{obs}$ but $c\,t^{em} = 2\,c\,t^{obs}\,\Gamma^2$

3. Solves compactness problem!

$$\tau_{\gamma\gamma} \propto \Gamma^{-2(\alpha+1)}$$

$$\alpha \approx 2 \quad \Rightarrow \quad \tau_{\gamma\gamma} \propto \Gamma^{-6}$$

Interstellar scintillations



Size larger than scintillating elements $> 10^{17}$ cm

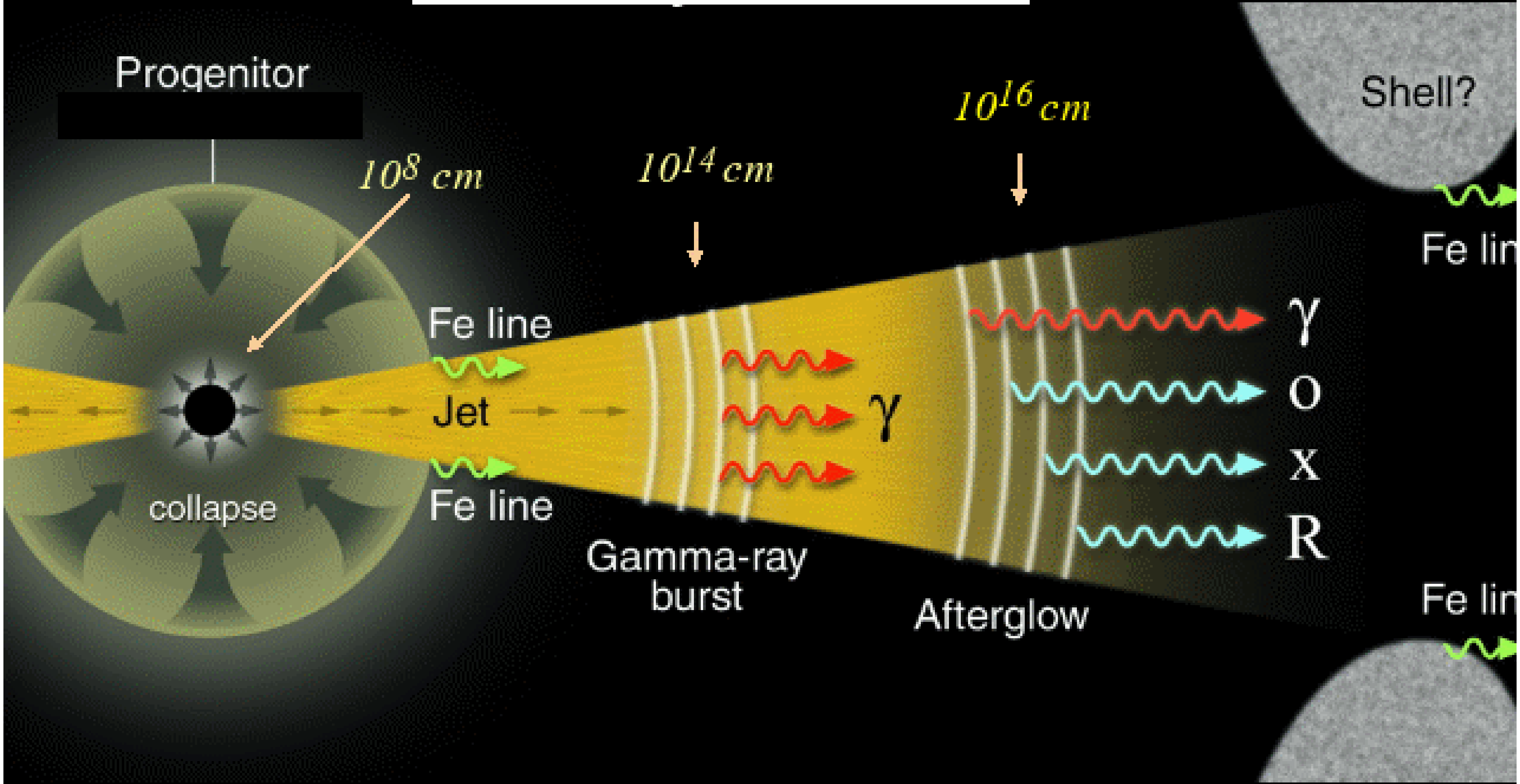
Needs relativistic expansion

Baryon loading

$$E = \Gamma M c^2$$

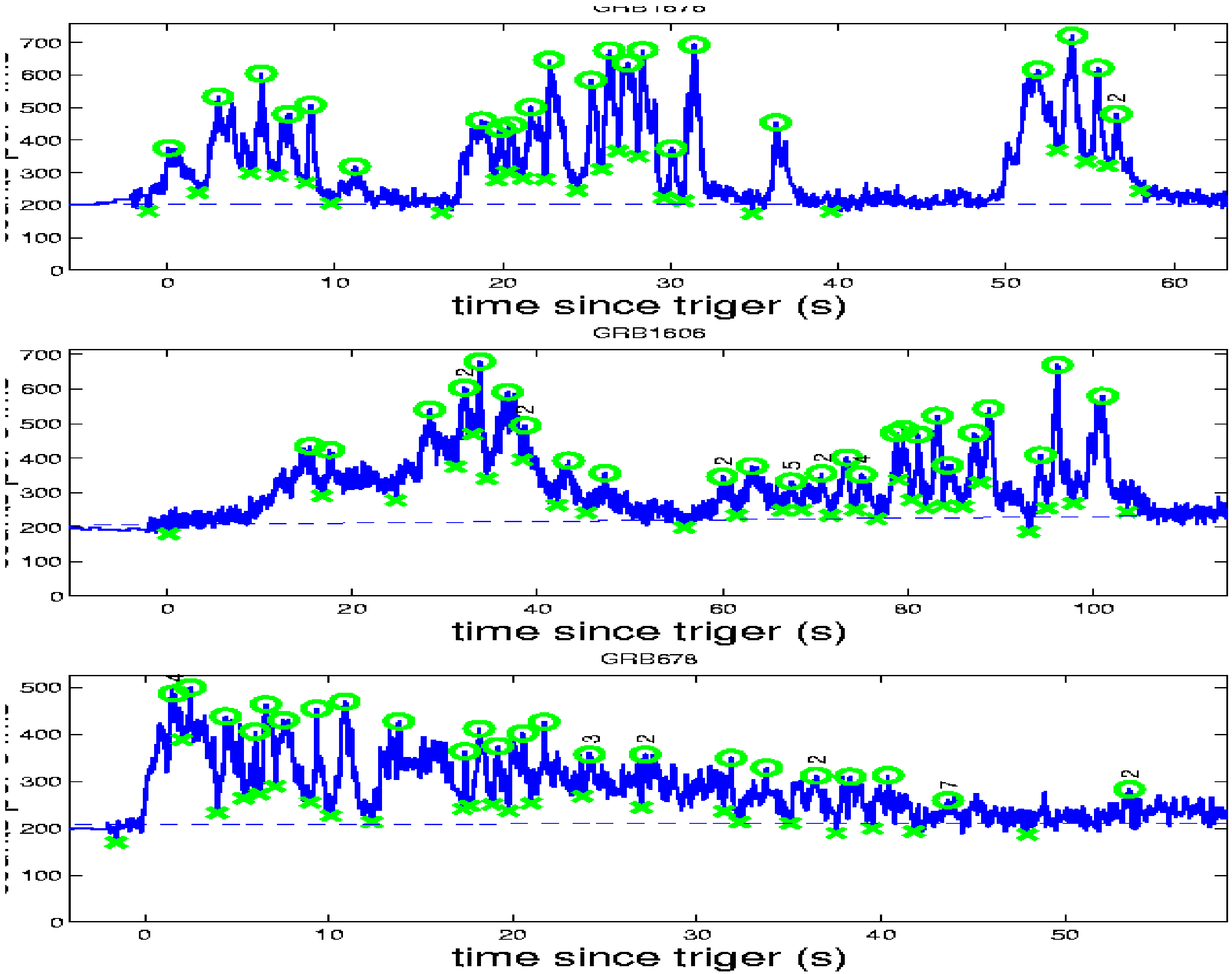
$$M \approx 5 \times 10^{-6} \left(\frac{\Gamma}{10^3} \right)^{-1} \left(\frac{E}{10^{52} erg\, s^{-1}} \right)^{-1} \quad M_O$$

Anatomy of a GRB



See Piran 1999; Mészáros 2002 (ARAA) for reviews

Temporal Variability

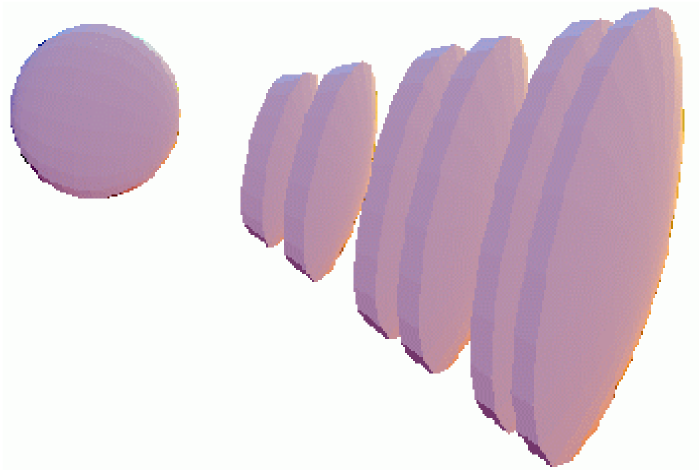


Prompt burst scenarios

- **Internal Shocks**

↓

many colliding shells

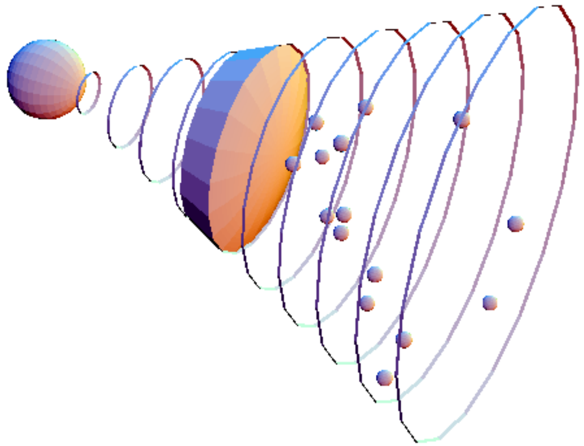


- Complex, Long Lasting Engine

- **External Shocks**

↓

irregular surrounding



- Simple “Explosive” Engine

Sari

Blast wave hydrodynamics

Relativistic version of the Sedov solution

Parameters: Total energy E, surrounding density (constant or wind)

$$\Gamma_2 \approx \left(9 \frac{E}{16 \pi n_1 m_u c^2} \right)^{1/2} R^{-3/2}$$

$$R = 8 \Gamma_2^2 c \, t_{obs}$$

$$\Gamma_2 \approx 0.4 \left(\frac{E}{n_1 m_u c^5} \right)^{1/8} t_{obs}^{-3/8}$$

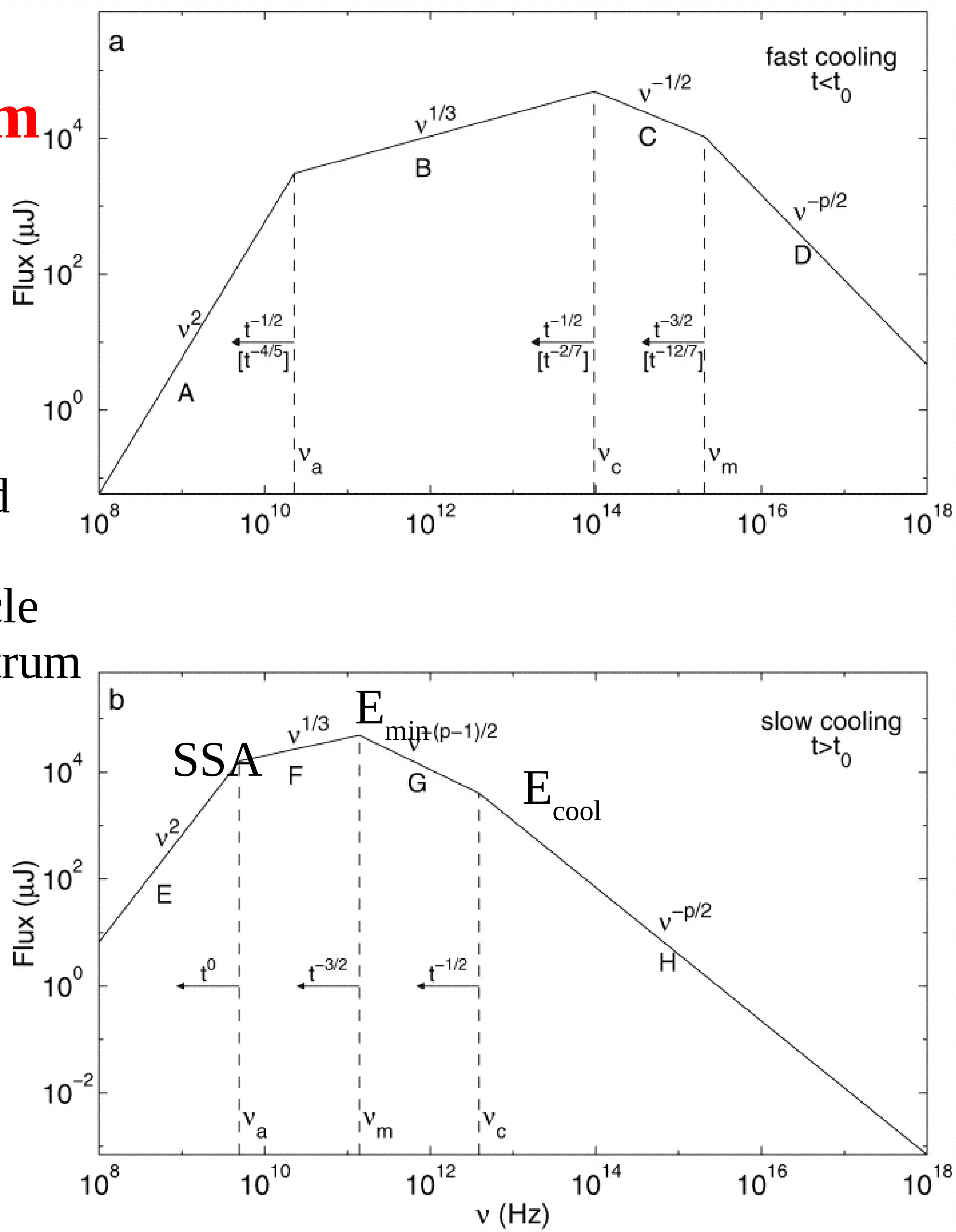
$$\Gamma_2 \approx 4.4 \left(\frac{E}{10^{52} \;\; ergs} \right)^{1/8} \left(\frac{n_1}{1 \;\; cm^{-3}} \right)^{-1/8} \left(\frac{t_{obs}}{days} \right)^{-3/8}$$

$$R \approx 4 \times 10^{17} \left(\frac{E}{10^{52} \;\; ergs} \right)^{1/8} \left(\frac{n_1}{1 \;\; cm^{-3}} \right)^{-1/8} \left(\frac{t_{obs}}{days} \right)^{1/4} \quad cm.$$

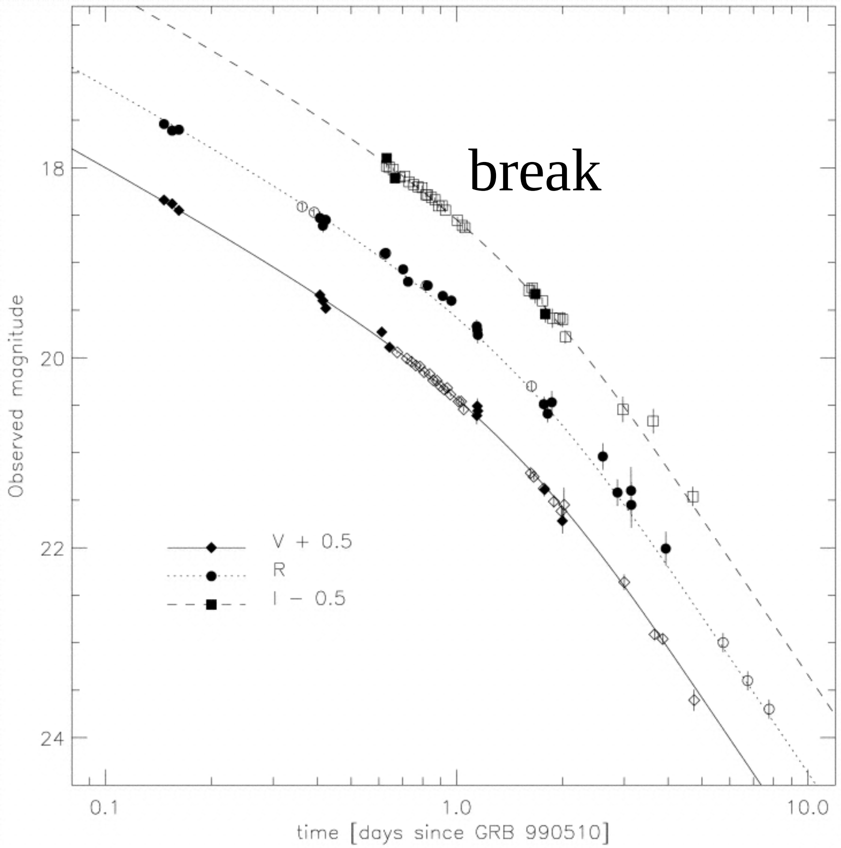
Blandford-McKee solution

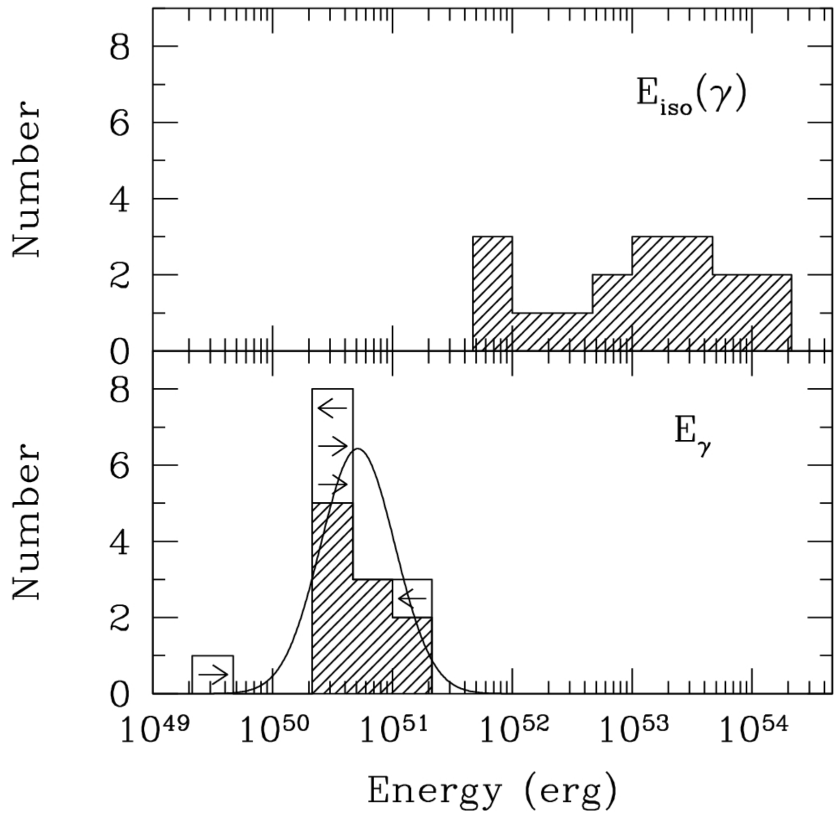
Synchrotron spectrum

Spectral fits of synchrotron-self absorption, minimum energy, and cooling breaks give total energy, magnetic field, non-hermal particle energy density, and particle spectrum



Jet steepening





Relativistic abberation

$$\cos\theta = \frac{\cos\theta' + \beta}{1+\beta\cos\theta'} \quad \Rightarrow \quad \theta \approx \frac{1}{\Gamma}$$

Correct for opening angle gives total energy. Nearly constant ~ 10^{51} ergs

Close to 'normal' supernova energy! θ ~ 5-10 degrees

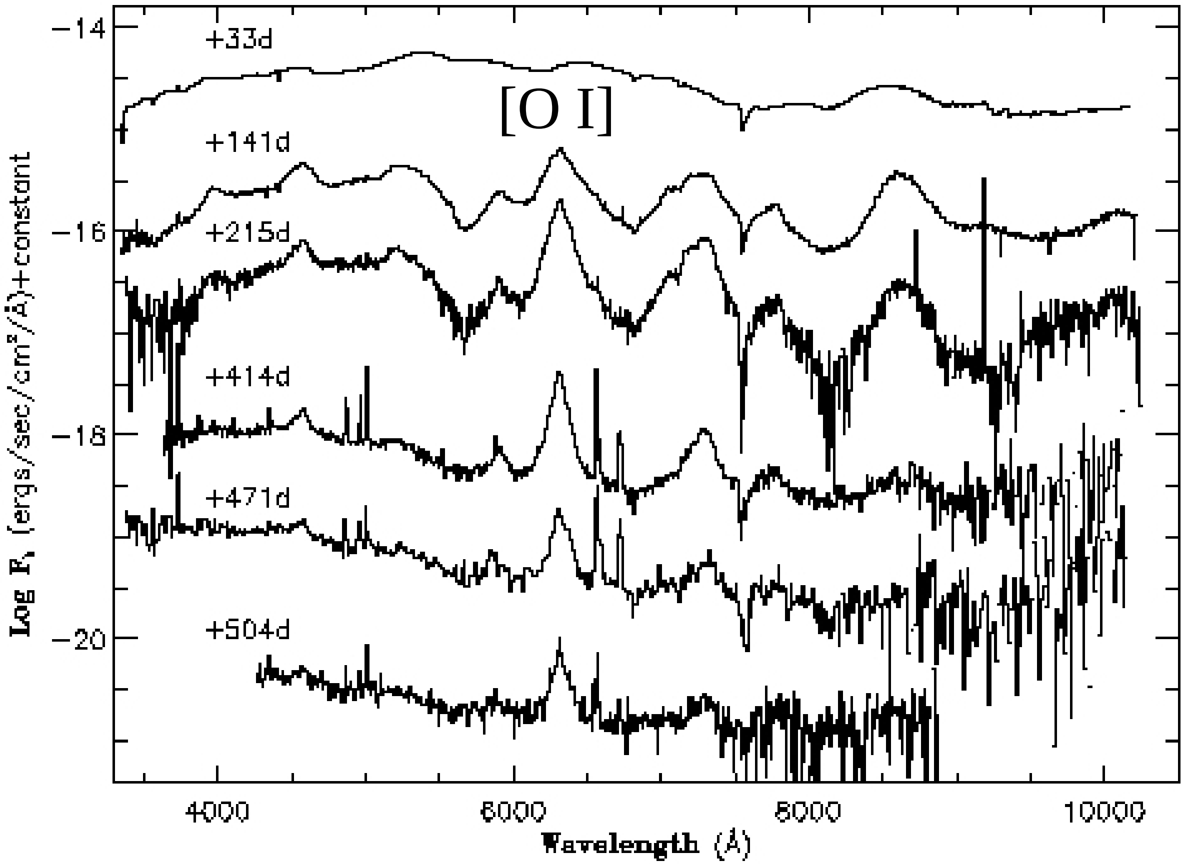
Beaming $\Delta\Omega \sim 0.03$. Only one of 100-500 GRBs seen by us

1-3 GRBs observed per day. Total rate 100-1000 per day

1 GRB per 10^5 - 10^6 years per galaxy

Compare 1-2 SNe per galaxy per 100 years, i.e. 1 GRB / 10^3 – 10^4 SNe

SN 1998bw = GRB 980425



Sollerman et al

Type Ic supernova   z=0.0085   in ESO 184-G82   Radio: Γ~ 2

Optical: Expansion velocity ~ 60,000 km/s   M(^{56}Ni) ~ 0.7 M_O

E ~ 10^{48} erg/s,   low compared to 'normal' GRBs

No H or He in spectrum. Exploding Wolf-Rayet star

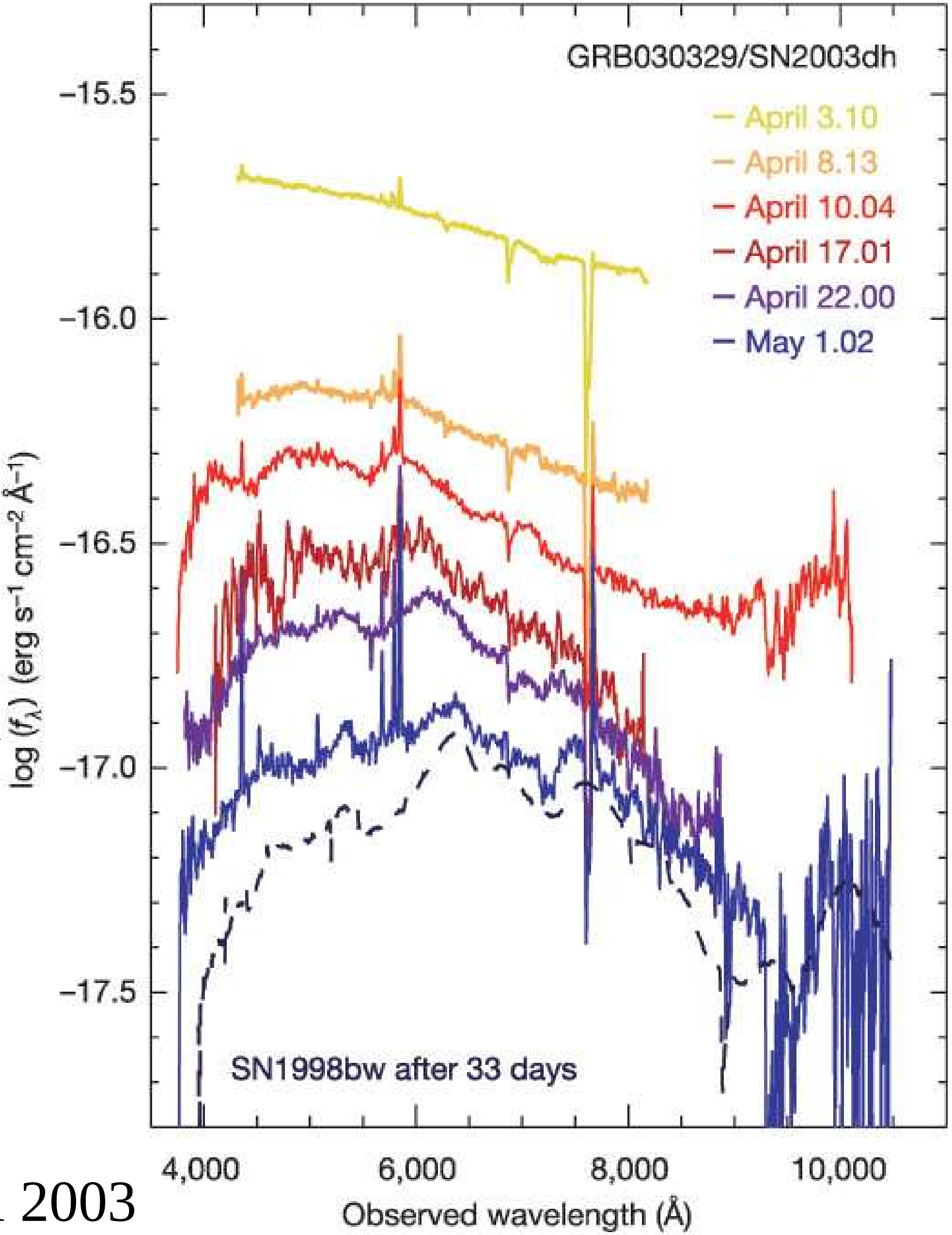
GRB 030329 = SN 2003dh

z = 0.17 . Starforming dwarf galaxy

'Normal' gamma-ray burst energy

Type Ic spectrum after ~ 1 month

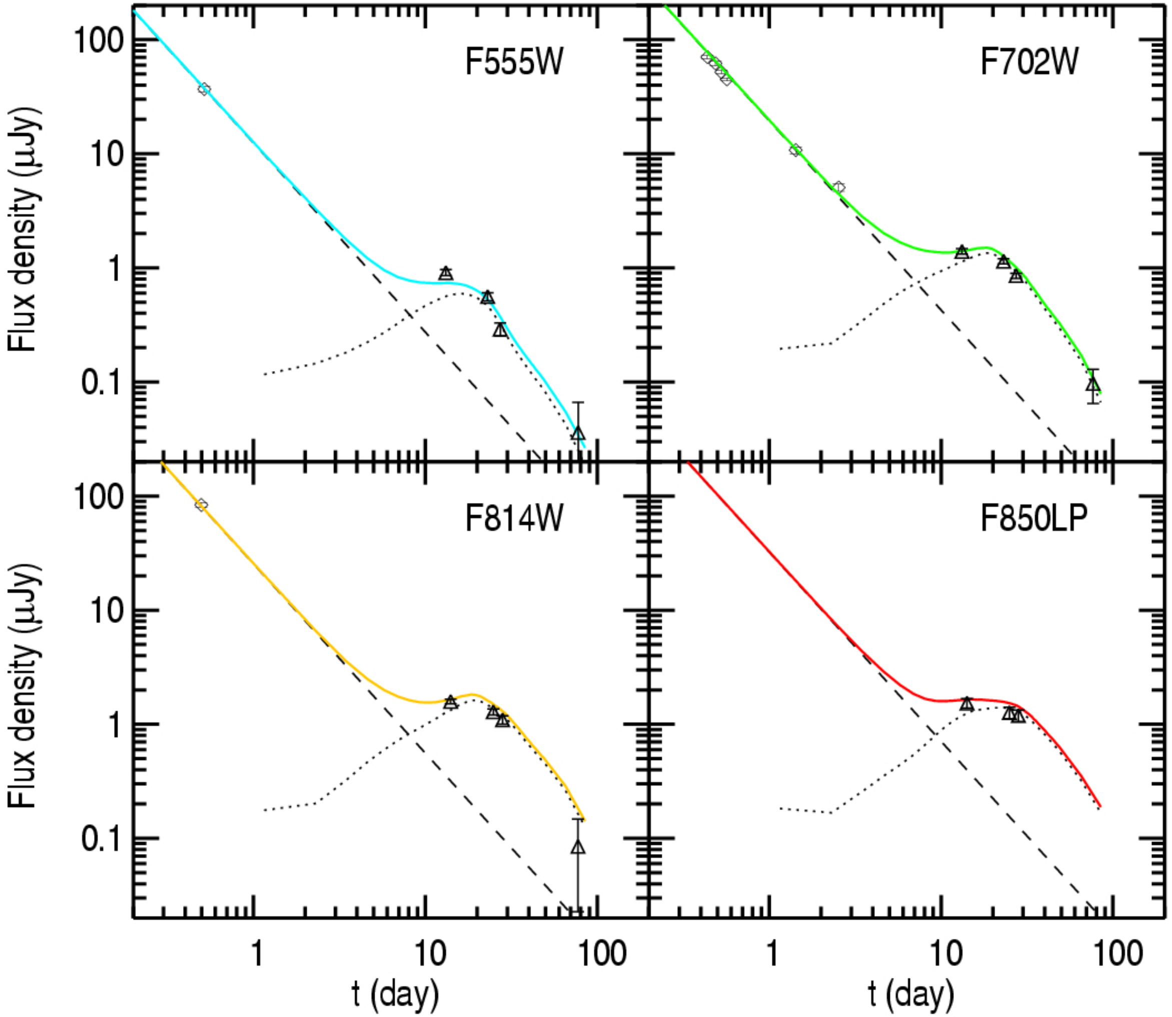
Spectrum identical to SN 1998bw



Hjorth et al 2003

Bump in light curves

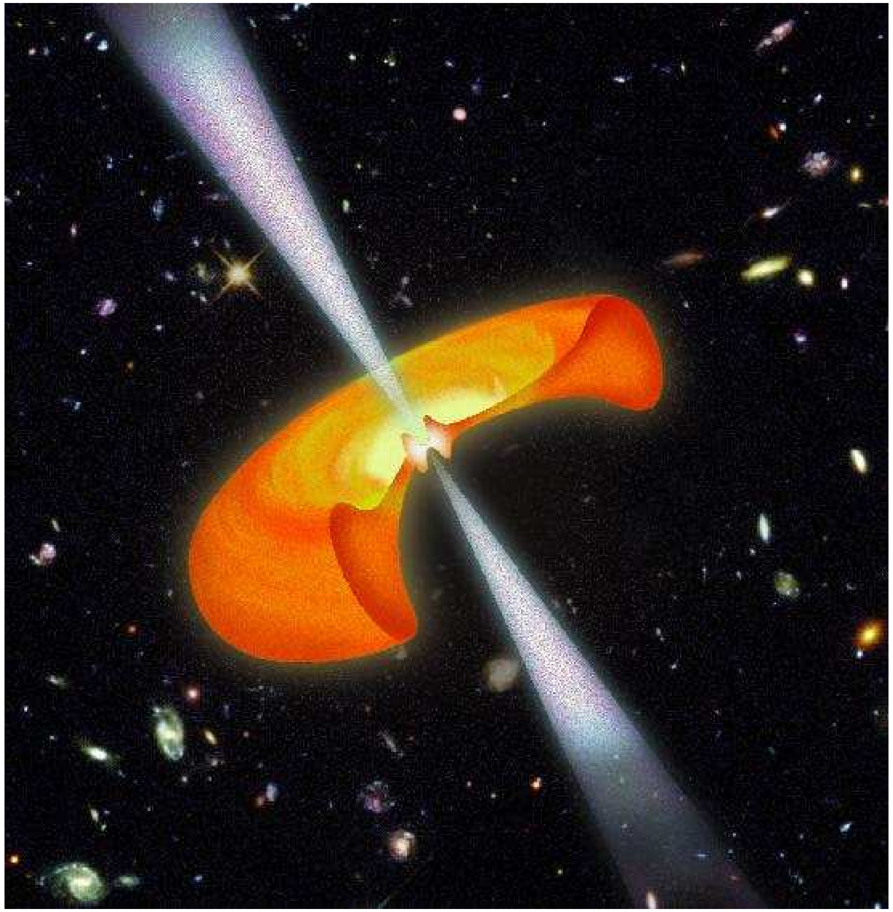
GRB 011121



Bloom et al

Bump at ~ 1 month well fitted with SN 1998bw supernova light curve

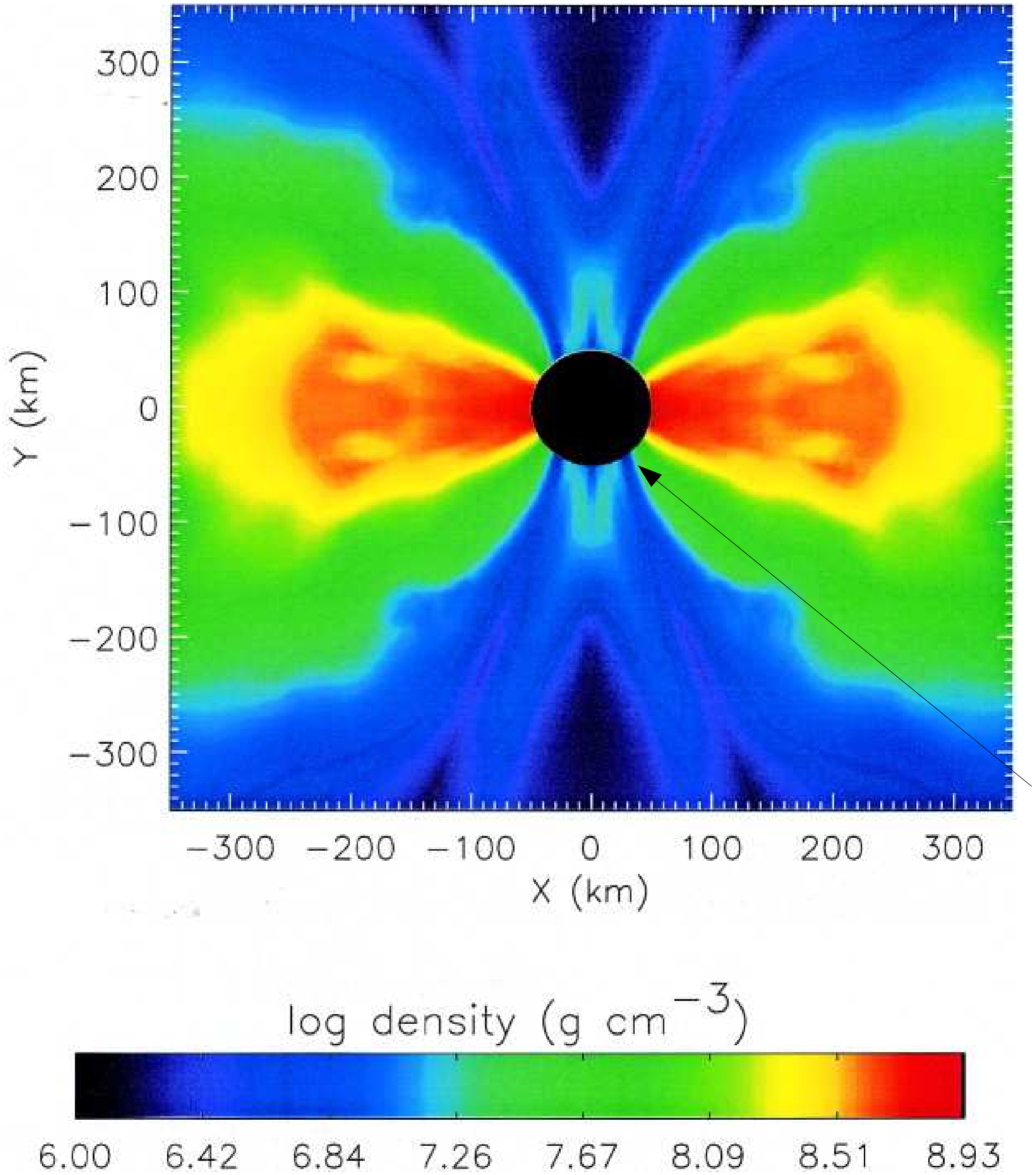
Collapsar model



Collapse of a very massive star (M > 30 MO).
Needs compact progenitor, i.e., no H envelope = Wolf-Rayet star
Fast rotation gives accretion disk + jets.
Electromagnetic energy extraction ?

Collapsar model II

jet

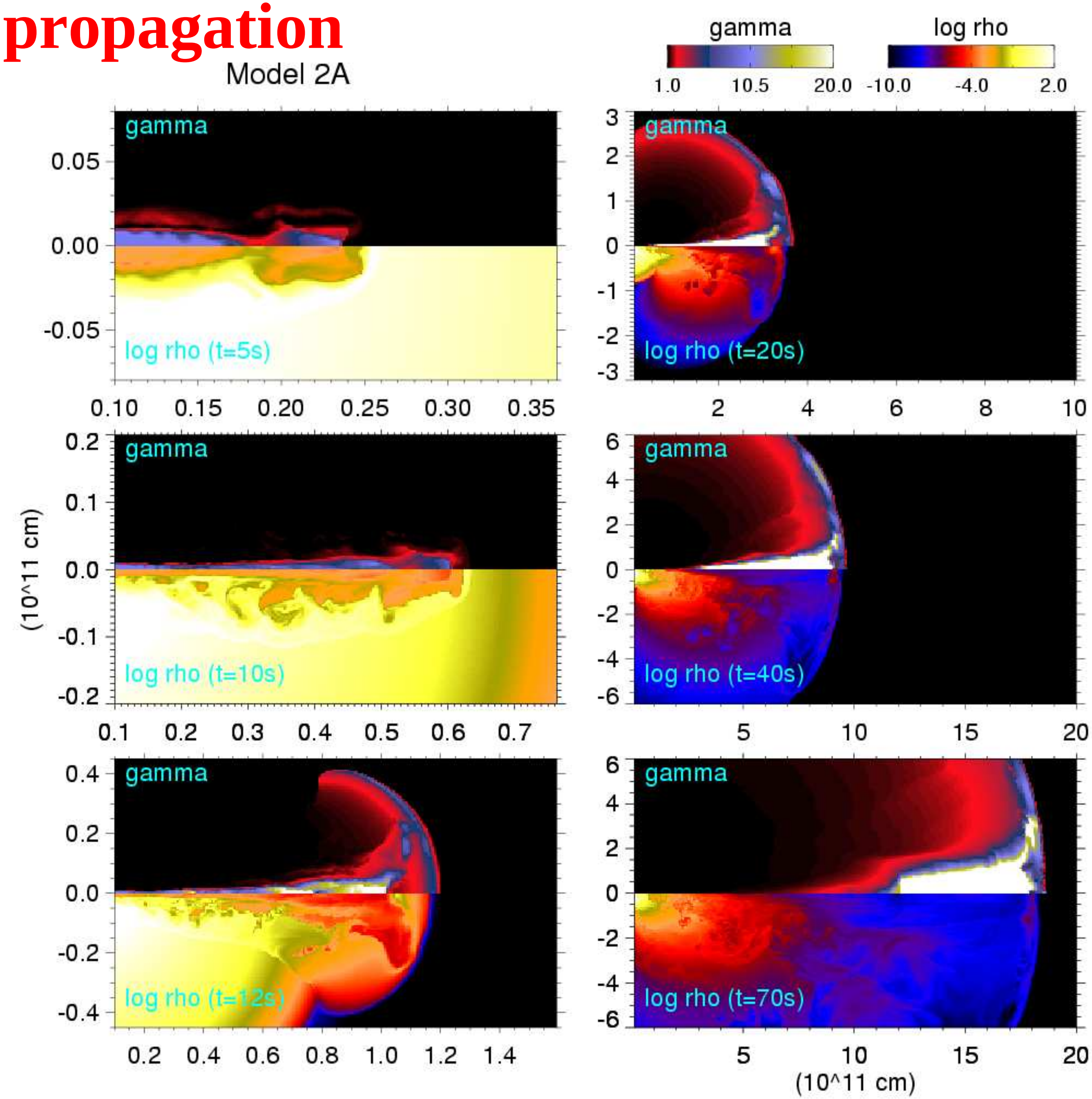


accretion disk

black hole

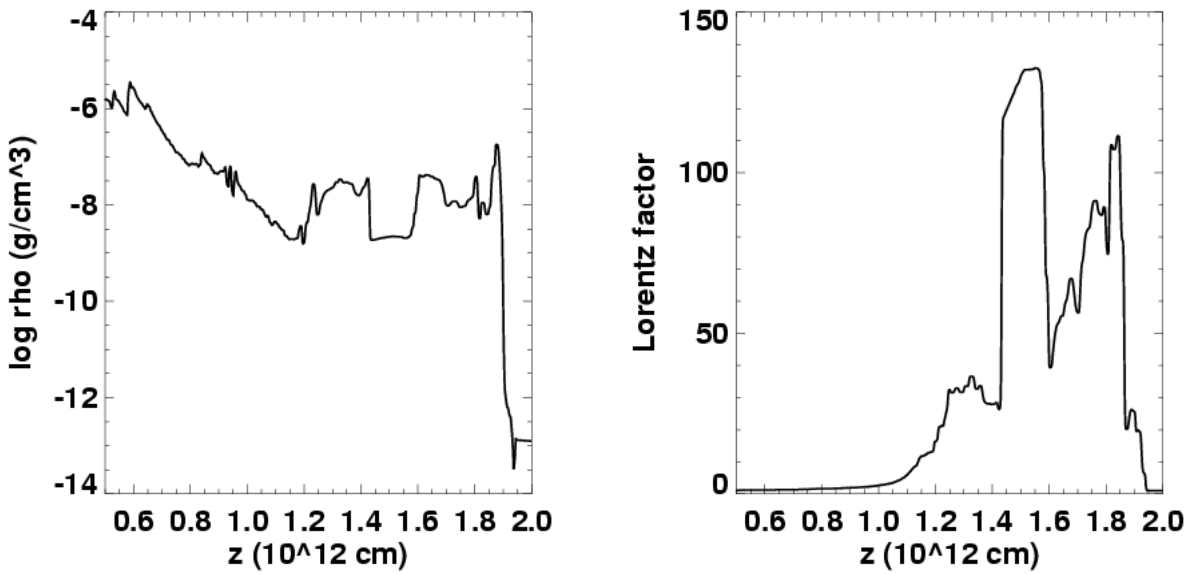
MacFadyen & Woosley

Jet propagation

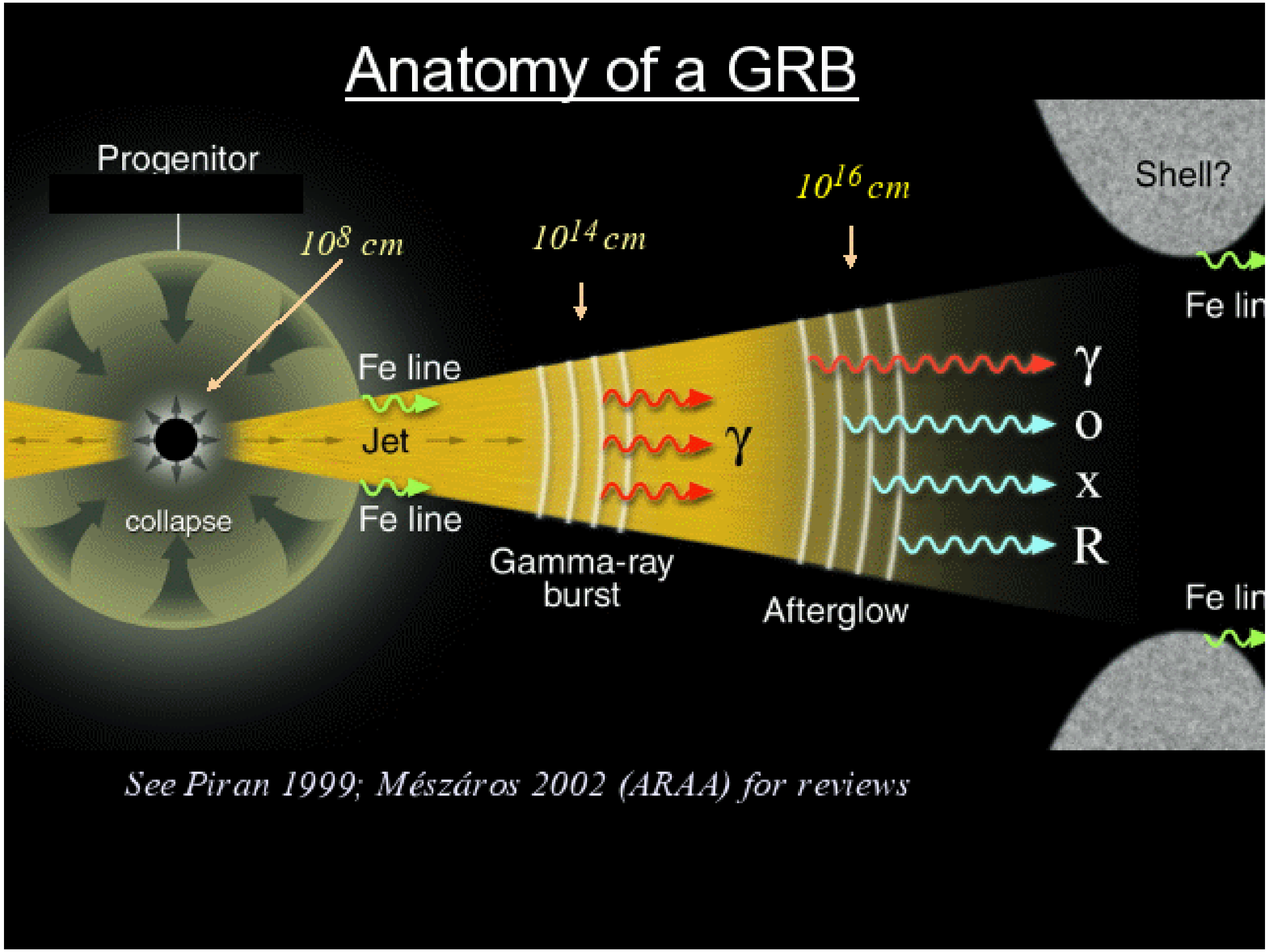


Stellar radius ~ 10^{11} cm, V ~ 50,000 km/s t ~ 20 s

Highly variable Lorentz factor source for internal shocks for the prompt burst

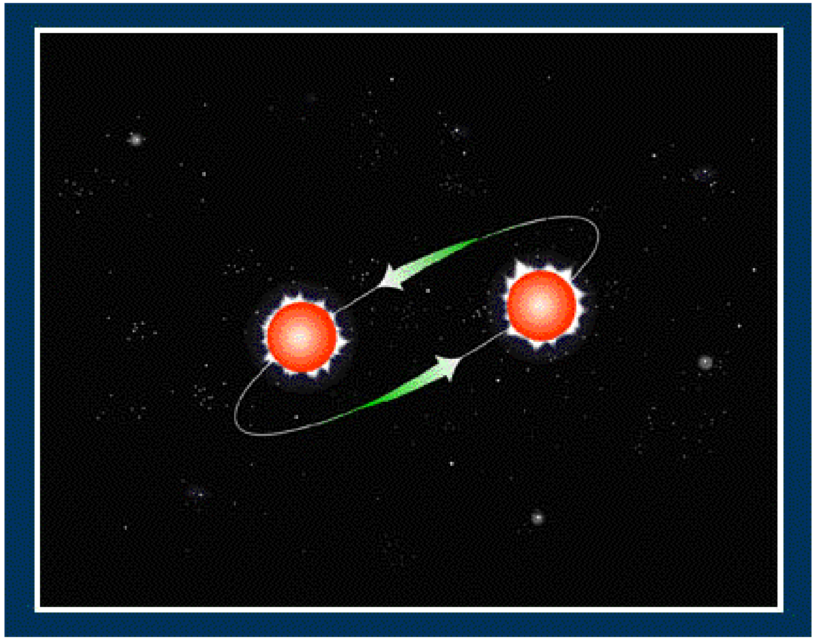


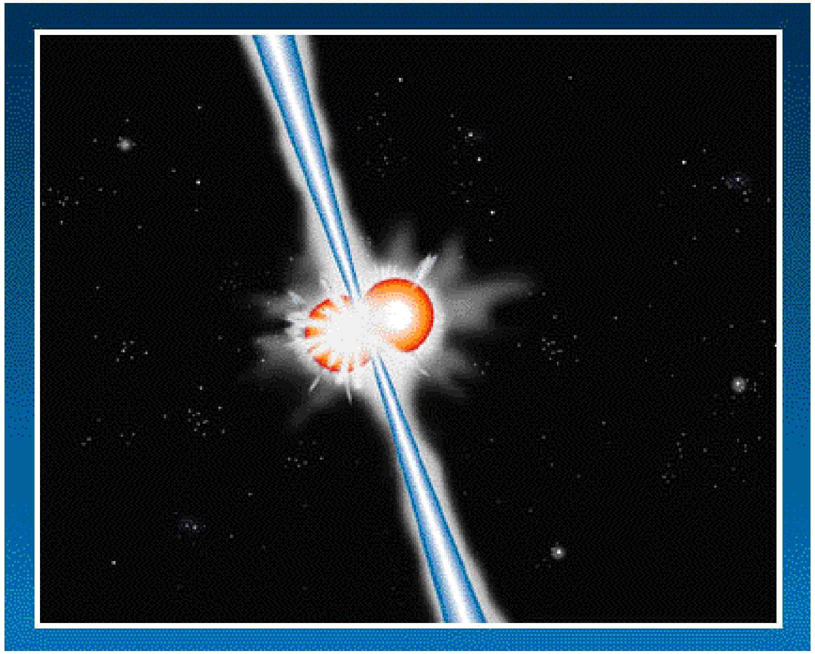
Difficult to get millisecond bursts Main candidate: Long bursts



Jet expansion in circumstellar medium gives afterglow

Neutron star merger





Progenitor: Close binary neutron star system. Energy loss by gravitational waves give spiral-in and merger within ~ 10^8 years
Final merger within ~ millisecond

Merger sequence

Merger → accretion disk

T ~ 10^{10} K

energy loss by neutrinos

Energy conversion by

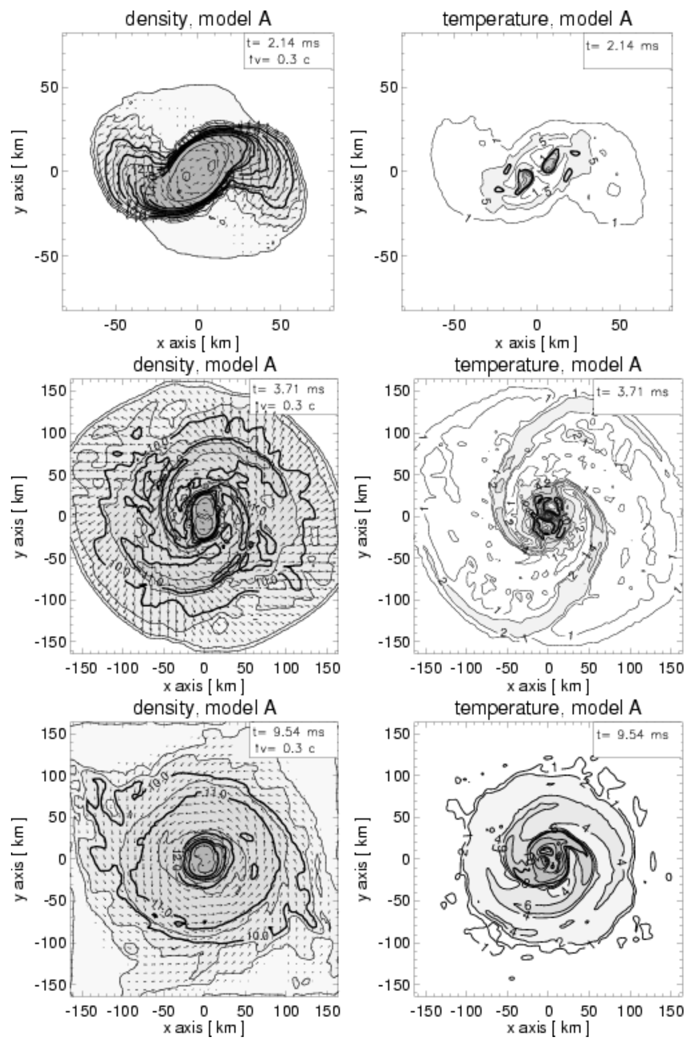
$$\nu + \bar{\nu}_e \rightarrow e^- + e^+$$

Pair plasma expands into ISM

All in milliseconds

No supernova in afterglow expected

Excellent candidate for short bursts



Short bursts with SWIFT

GRB 050509B, 050709, 050724

all short

X-ray afterglows!!

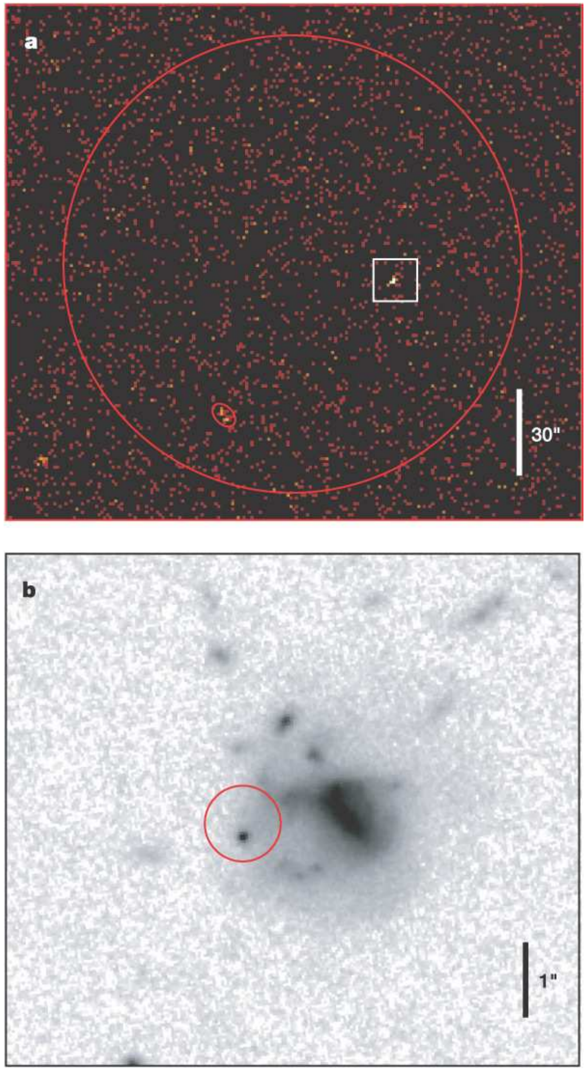
GRB 050709, 050724 also
optical afterglows

z = 0.16 – 0.25

E ~ 10^{50} ergs << Long

Two in ellipticals, one in a starforming galaxy

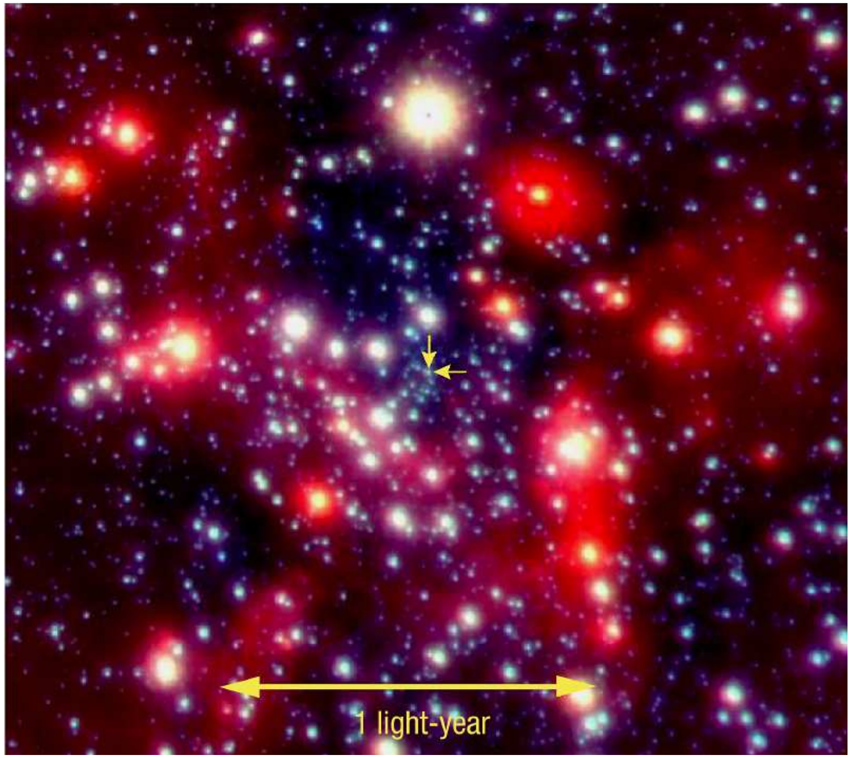
No supernova signature

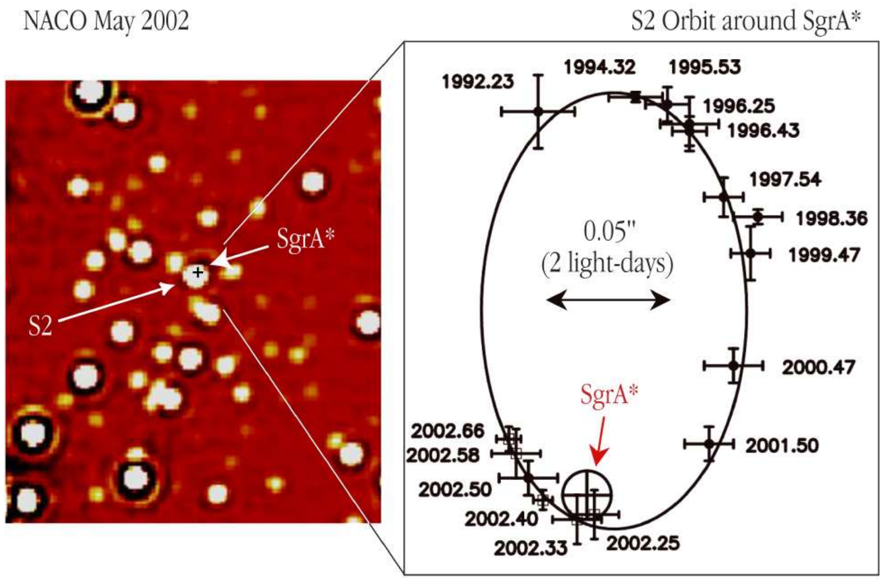


All consistent with merging neutron star system. Could also be NS + BH

SUPERMASSIVE BLACK HOLES
and
ACTIVE GALACTIC NUCLEI

Galactic Center Black Hole

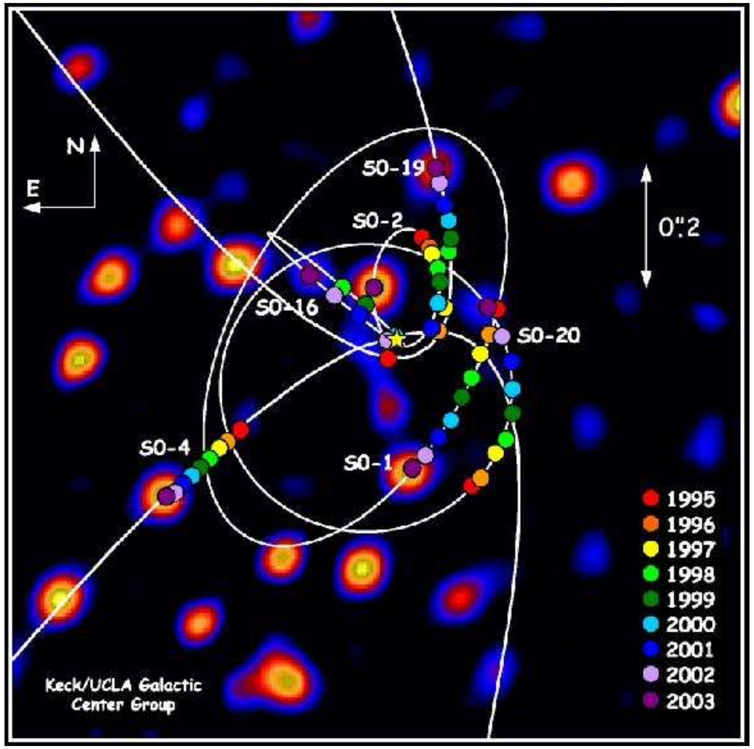




Radio souce Sagittarius A

Infrared observations penetrate the dust

Mass of Black Hole



Gaez et al

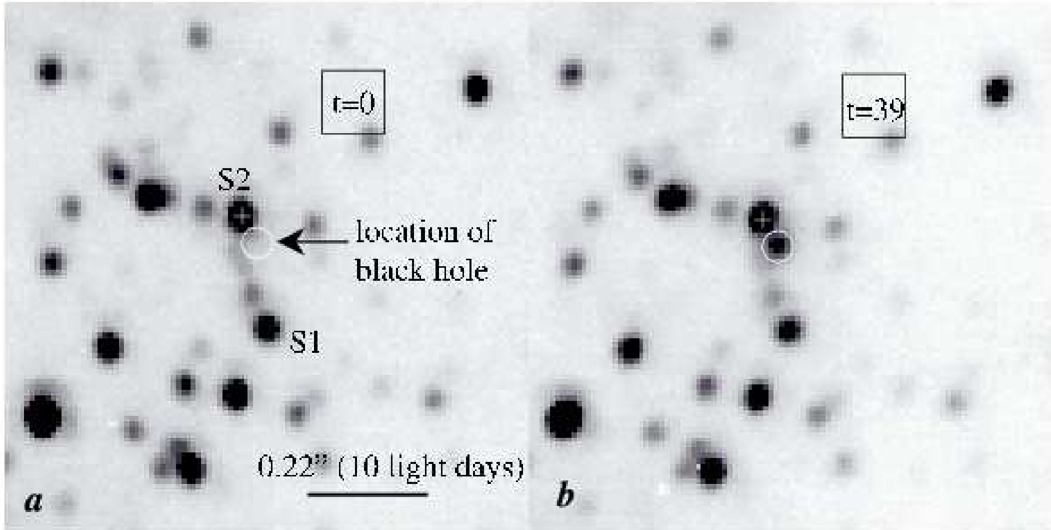
Stellar orbits around Sgr A give enclosed total mass within the orbit

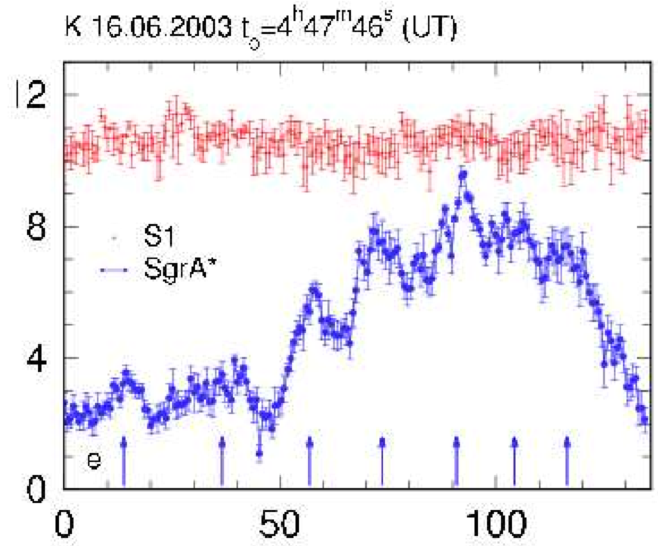
Star S 2 period 15.2 years

Closest approach (pericentre) ~ 17 light hours

Total mass 3.7 (±1.5) x 10^6 $M_\odot$. Must be a black hole!!

Galactic Center Flares



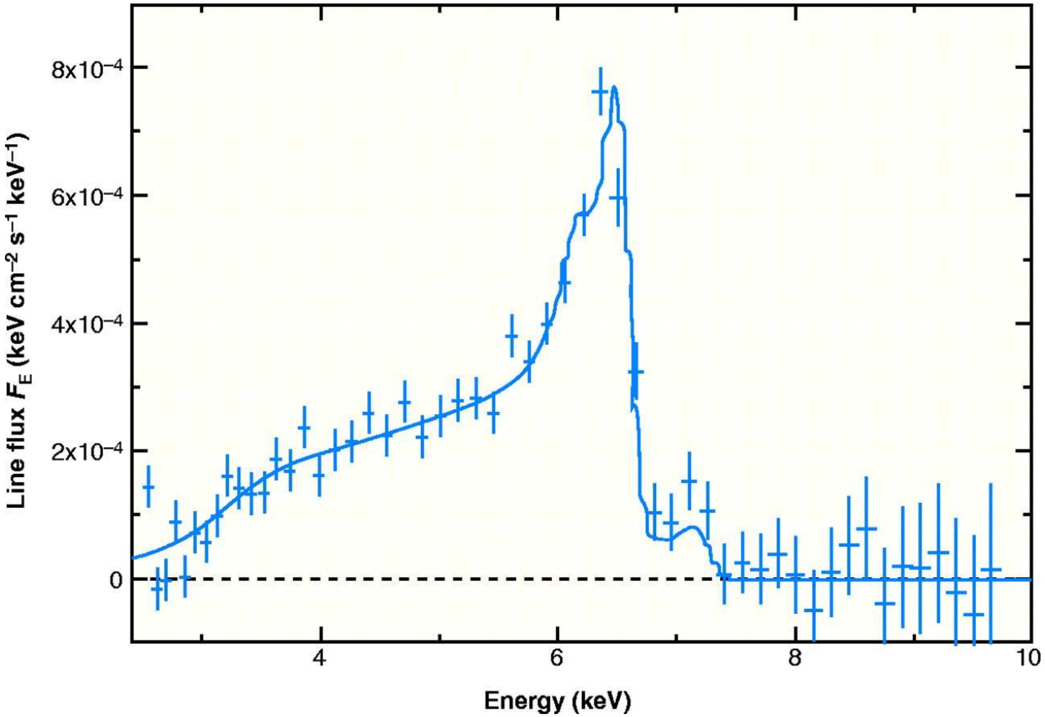


IR and X-ray flares with L ~ 6x10^{33} erg/s <<< L_{Edd}
Duration ~ 1 hour

Time scale shorter than last stable orbit from Schwarzshild BH $\Rightarrow$ Kerr BH (?)

Infalling matter (?)

Fe K emission



XMM, Fabian et al

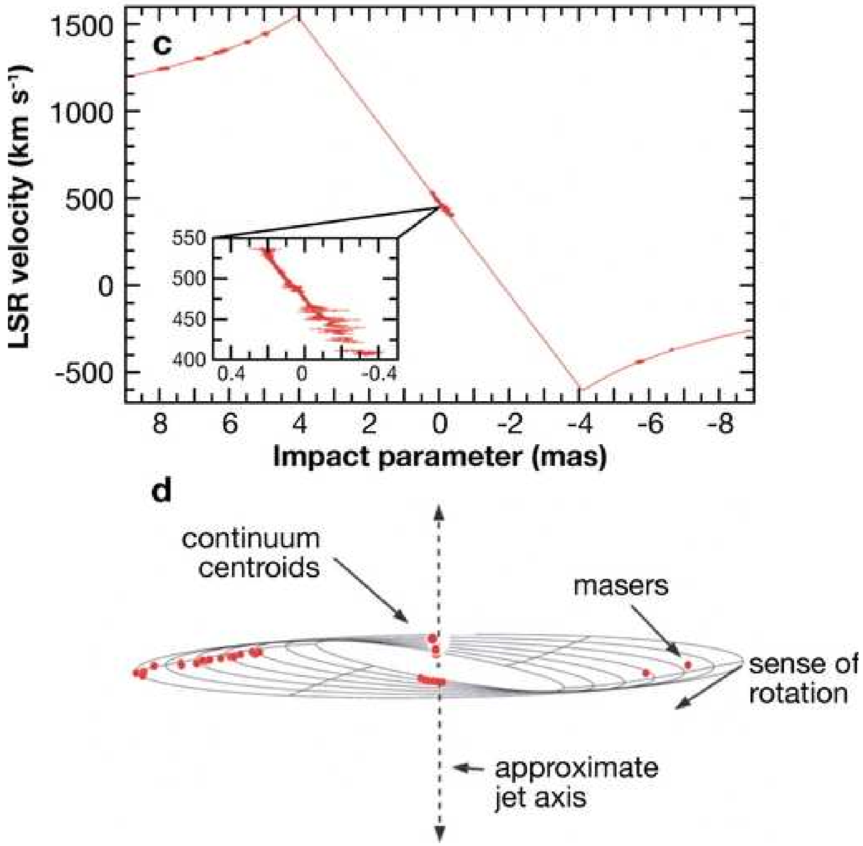
MCG-6-30-15 Seyfert 1 galaxy

M(BH) 10^6 - $2\text{x}10^7$

Asymmetric Fe K line. Must come from very close to BH horizon

To explain red extension material from inside the last stable orbit is needed if Schwarzshild BH, or a BH rotating at the maximum velocity.

Maser Emission from Active Galactic Nuclei



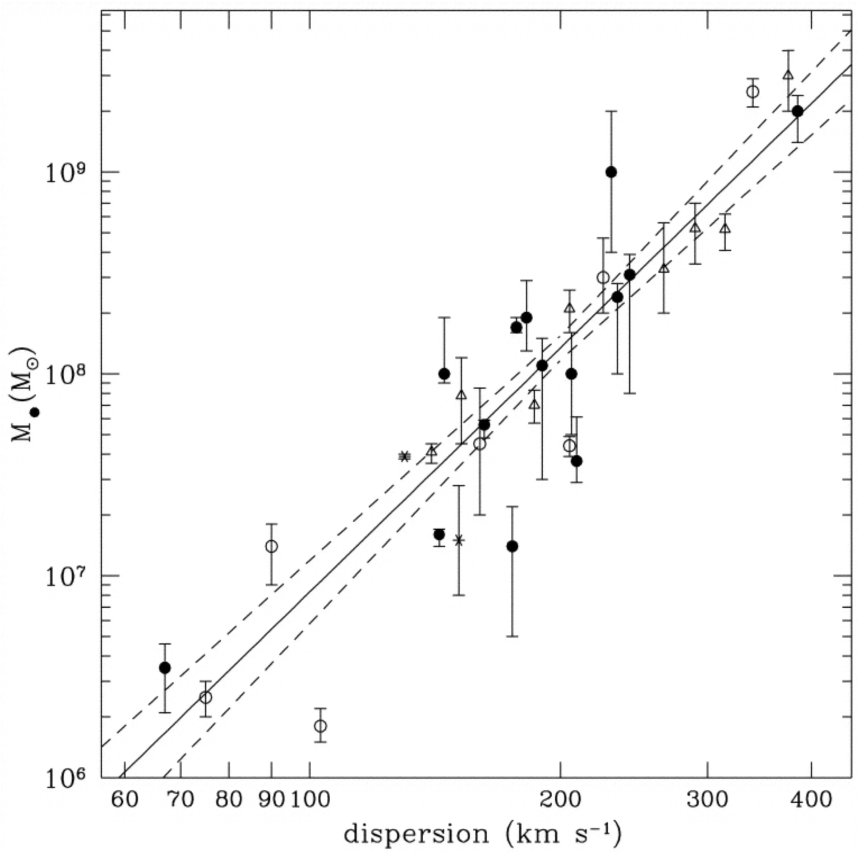
Lo 2005

VLBA observations of maser emission from NGC 4258

Maser emission from disk gives dynamics. Rotation curve well fitted by Kepler rotation around point mass.

~ 3.7×10^{7} M_{O} within 0.13 pc = 150 light days

Supermassive Black Holes



Tremaine et al 2002

Most galaxies have a BH in the center. Most of these are in a quiesent state. 'Starved' or very inefficient accretion flow.

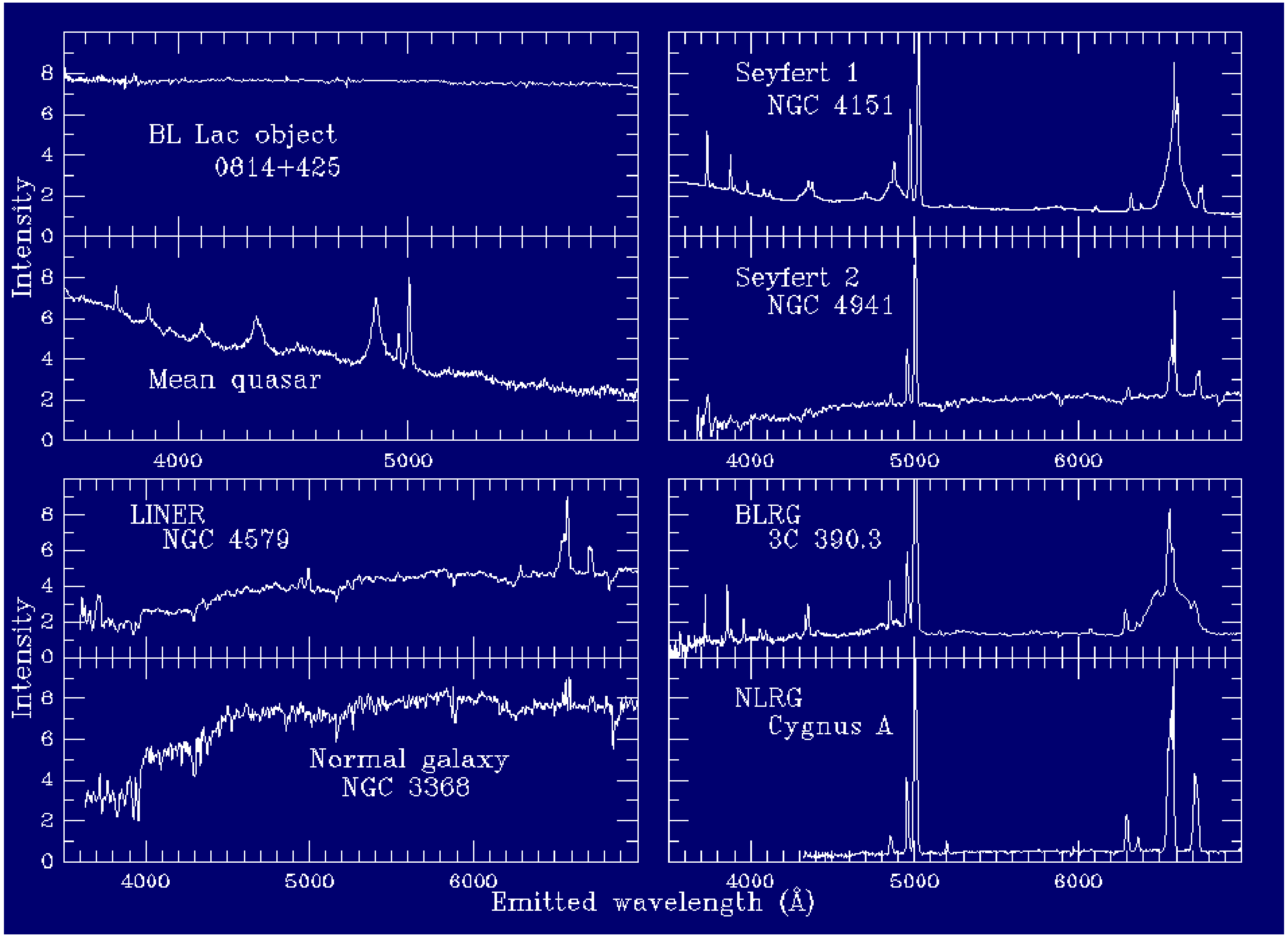
For ellipticals and spiral bulges there is a strong correlation between BH mass and velocity dispersion of the bulge component.

Types of Active Galactic Nuclei

	Narrow em. lines	Broad em. lines	No lines
	few x 100 km/s	10-30,000 km/s	
Radio quiet	Seyfert I	Seyfert II	
		Quasars	
Radio loud	NL radio gal.	BL radio gal.	Blazars

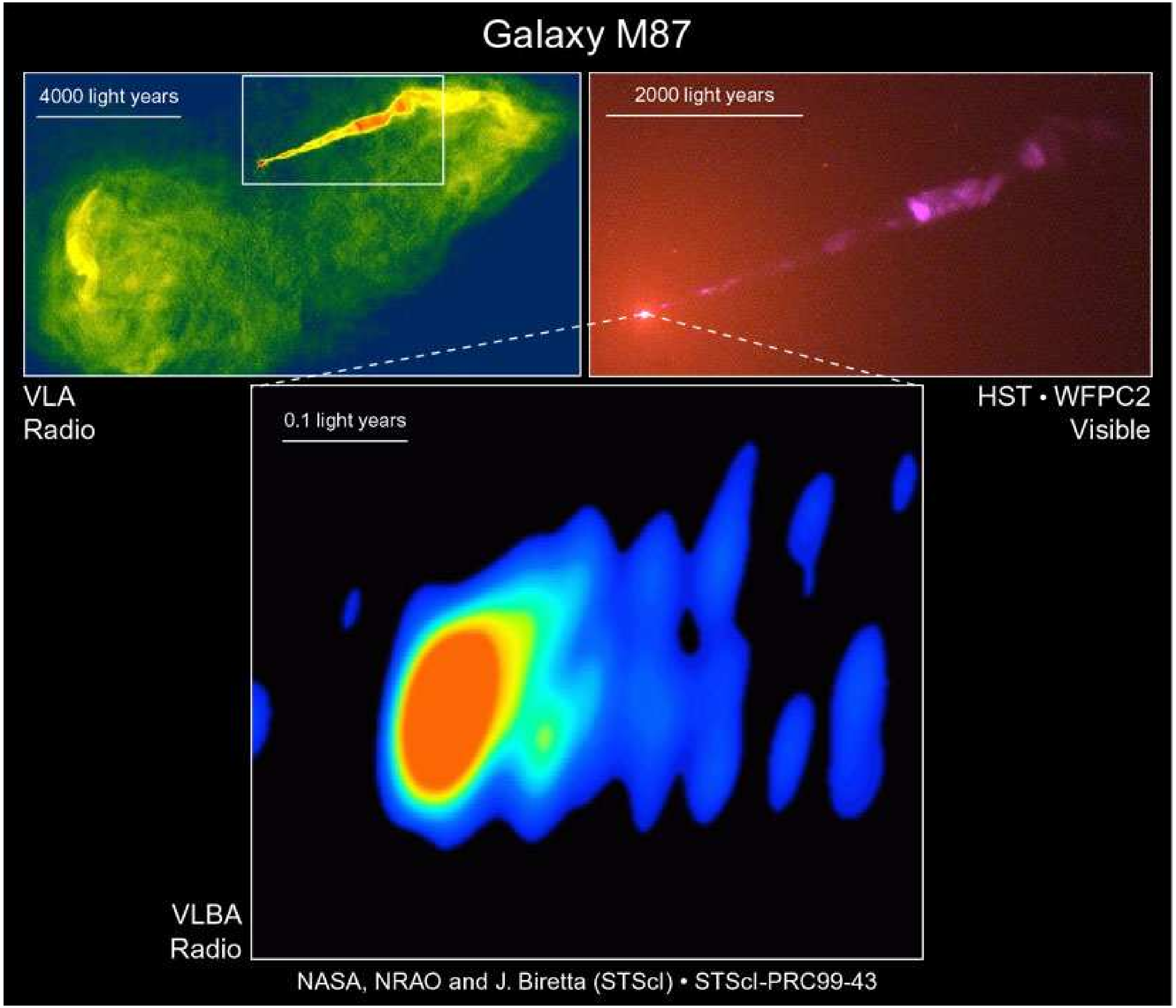
Optical spectrum: Seyfert I, QSOs: Broad, highly ionized emission lines non-thermal continuum. V ~ $(1\text{-}3)\times10^4$ km/s.

Seyfert 2, NLRG, Liners: High ionization, narrow lines

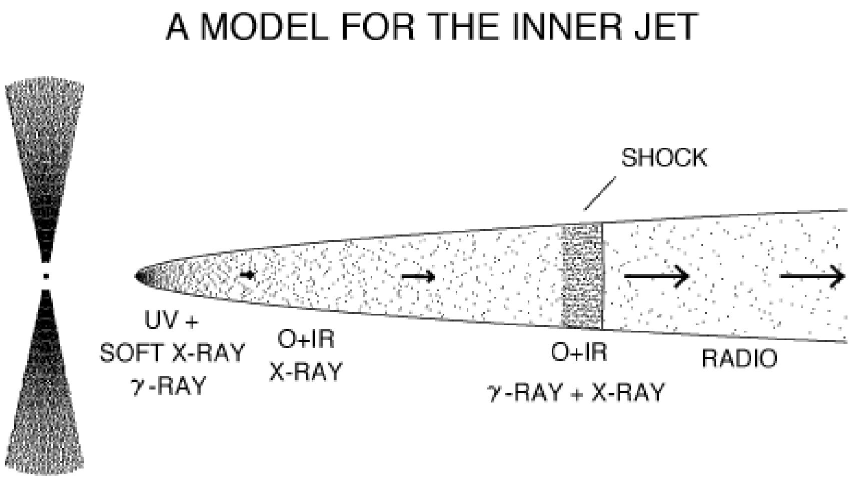


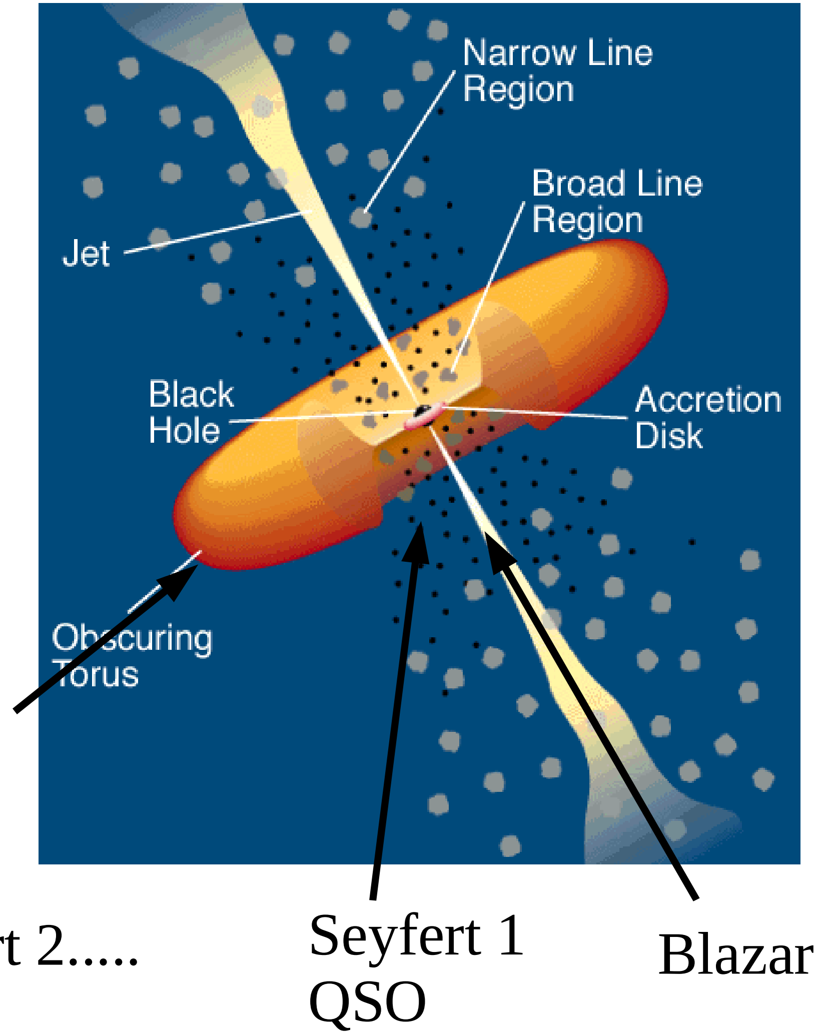
Jets

radio, optical synchrotron emission



Unified picture of AGNs





Type of AGN depends on viewing angle.

In disk (torus) plane, no broad lines ⇒ Seyfert 2.....

Large inclination: Disk + broad lines ⇒ Seyfert 1, QSO...

In jet direction: Only continuum synchrotron ⇒ blazar