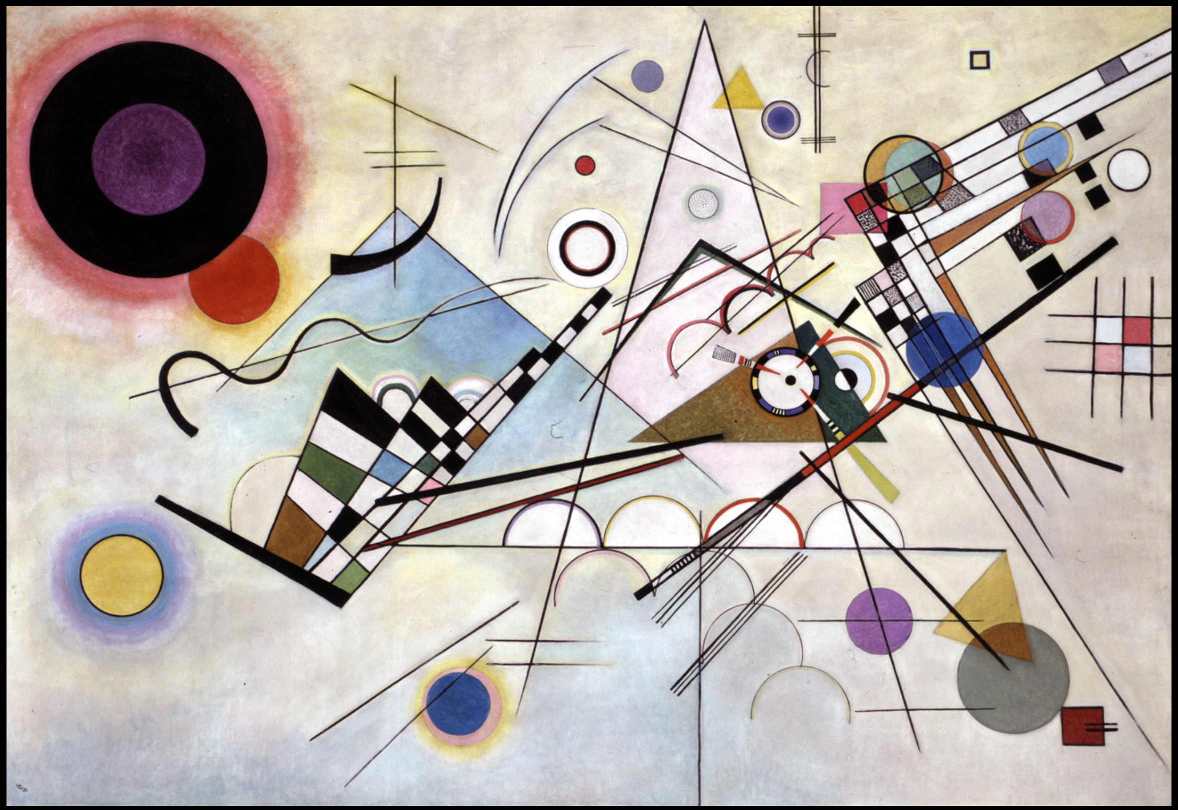
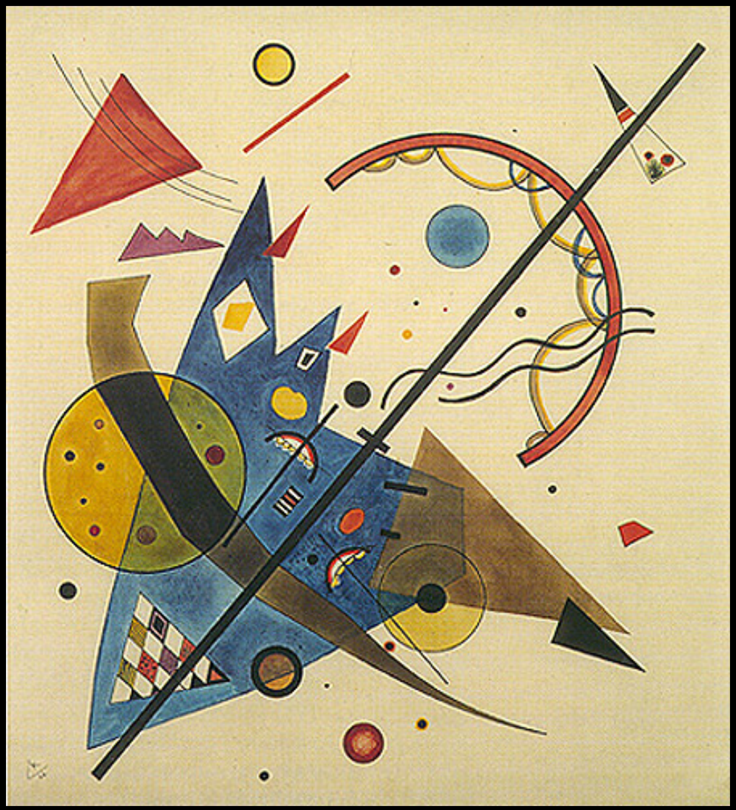
Physics & Astrophysics of Gamma-Ray Bursts

Frédéric Daigne (Institut d’Astrophysique de Paris - Sorbonne University)



Kandinksy – Composition 8- 1923



Kandinksy – Curves and sharp angles - 1923

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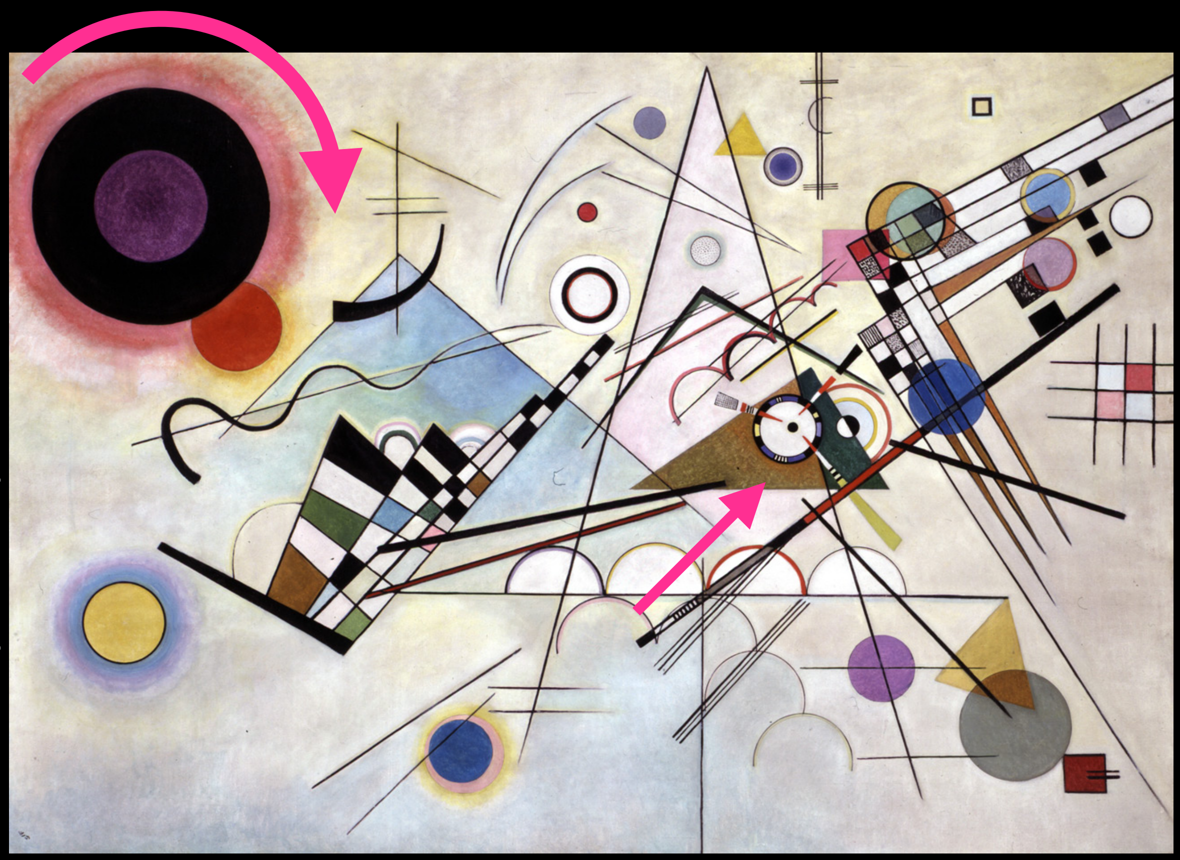
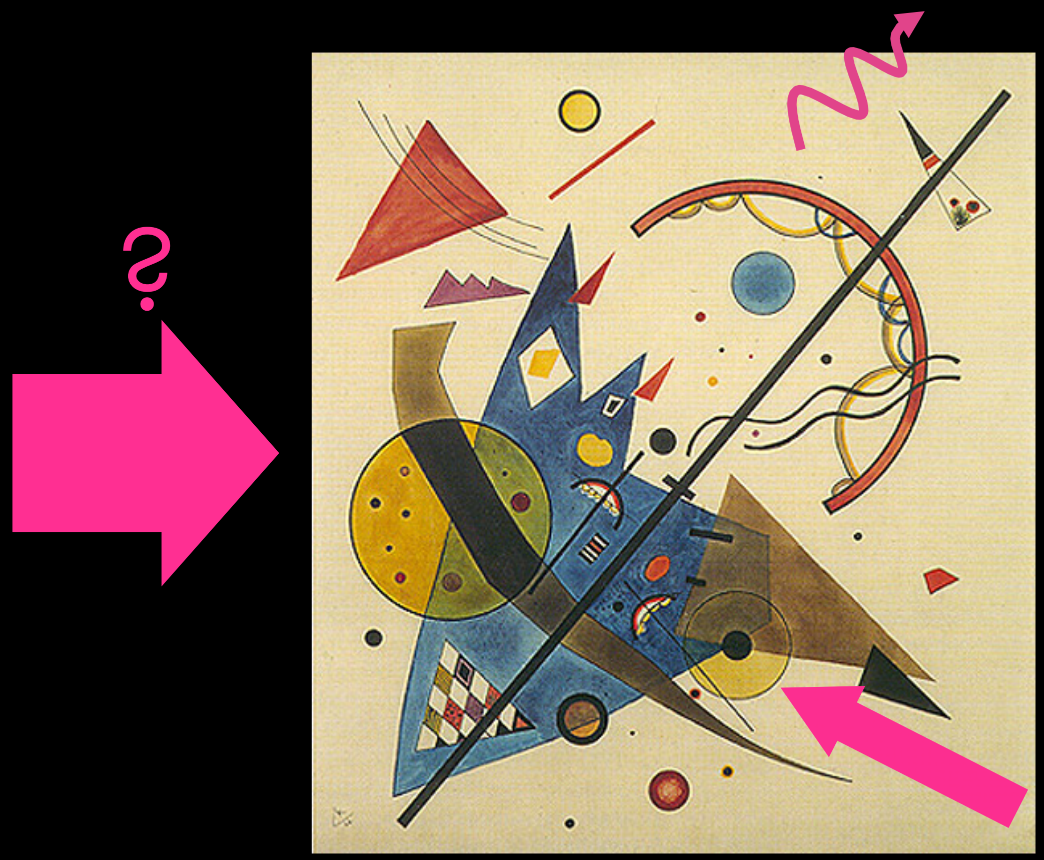


Kandinksy – Composition 8- 1923



Kandinksy – Curves and sharp angles - 1923

Physics & Astrophysics of Gamma-Ray Bursts

Introduction

- A brief history
- Observational Facts
- Basic Constraints on any GRB model: compact source + relativistic ejecta

Theory

- Progenitor - Central Engine - Relativistic Ejection
- Prompt Emission: internal dissipation in a relativistic ejecta
- Afterglow: interaction of a relativistic ejecta with its environment

Focus on short GRBs: the binary neutron star merger connection - 170817

- Afterglow: Constraints on the geometry of the relativistic ejecta
- Origin of the prompt emission
- Prospects for future associations

Gamma-ray bursts: discovery

Gamma-ray bursts: historical remarks

- the US military VELA program

Treaty Banning Nuclear Weapon Tests in the Atmosphere, in Outer Space and under Water
Signed by the Original Parties, the Union of Soviet Socialist Republics, the United Kingdom of Great Britain and Northern Ireland and the United States of America at Moscow : 5 August 1963

The Governments of the United States of America, the United Kingdom of Great Britain and Northern Ireland, and the Union of Soviet Socialist Republics, hereinafter referred to as the « Original Parties, »

Proclaiming as their principal aim the speediest possible achievement of an agreement on general and complete disarmament under strict international control in accordance with the objectives of the United Nations which would put an end to the armaments race and eliminate the incentive to the production and testing of all kinds of weapons, including nuclear weapons,

Seeking to achieve the discontinuance of all test explosions of nuclear weapons for all time, determined to continue negotiations to this end, and desiring to put an end to the contamination of man's environment by radioactive substances,

Have agreed as follows :

Article I

1. Each of the Parties to this Treaty undertakes to prohibit, to prevent, and not to carry out any nuclear weapon test explosion, or any other nuclear explosion, at any place under its jurisdiction or control :

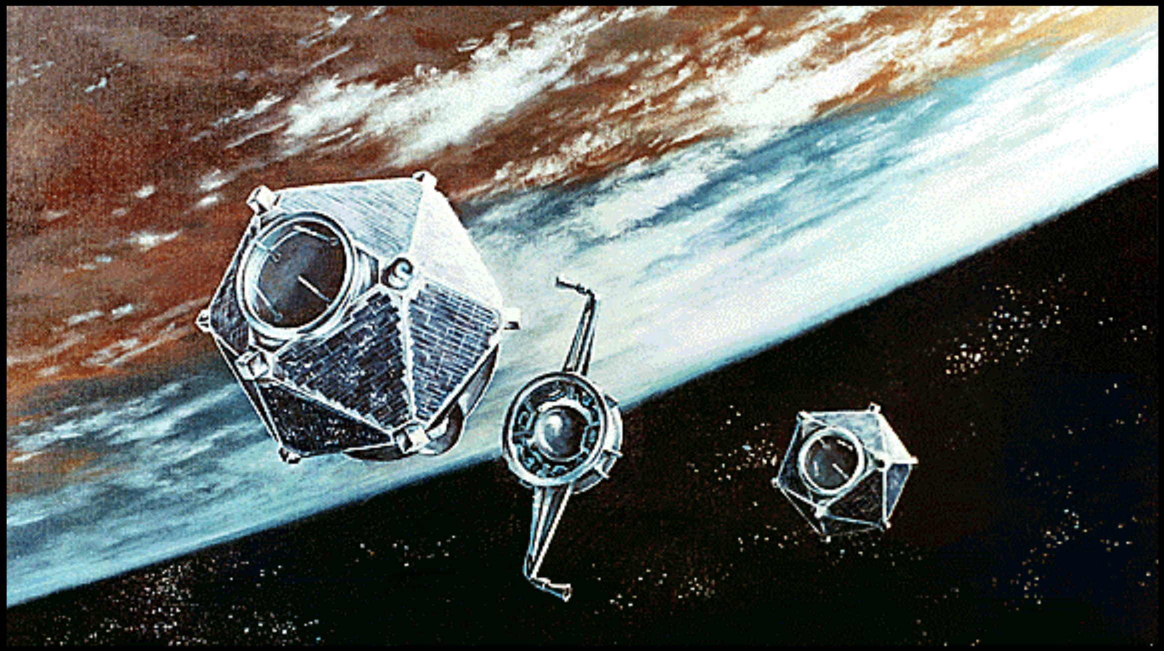
   (a) in the atmosphere ; beyond its limits, including outer space ; or under water, including territorial waters or high seas ; or

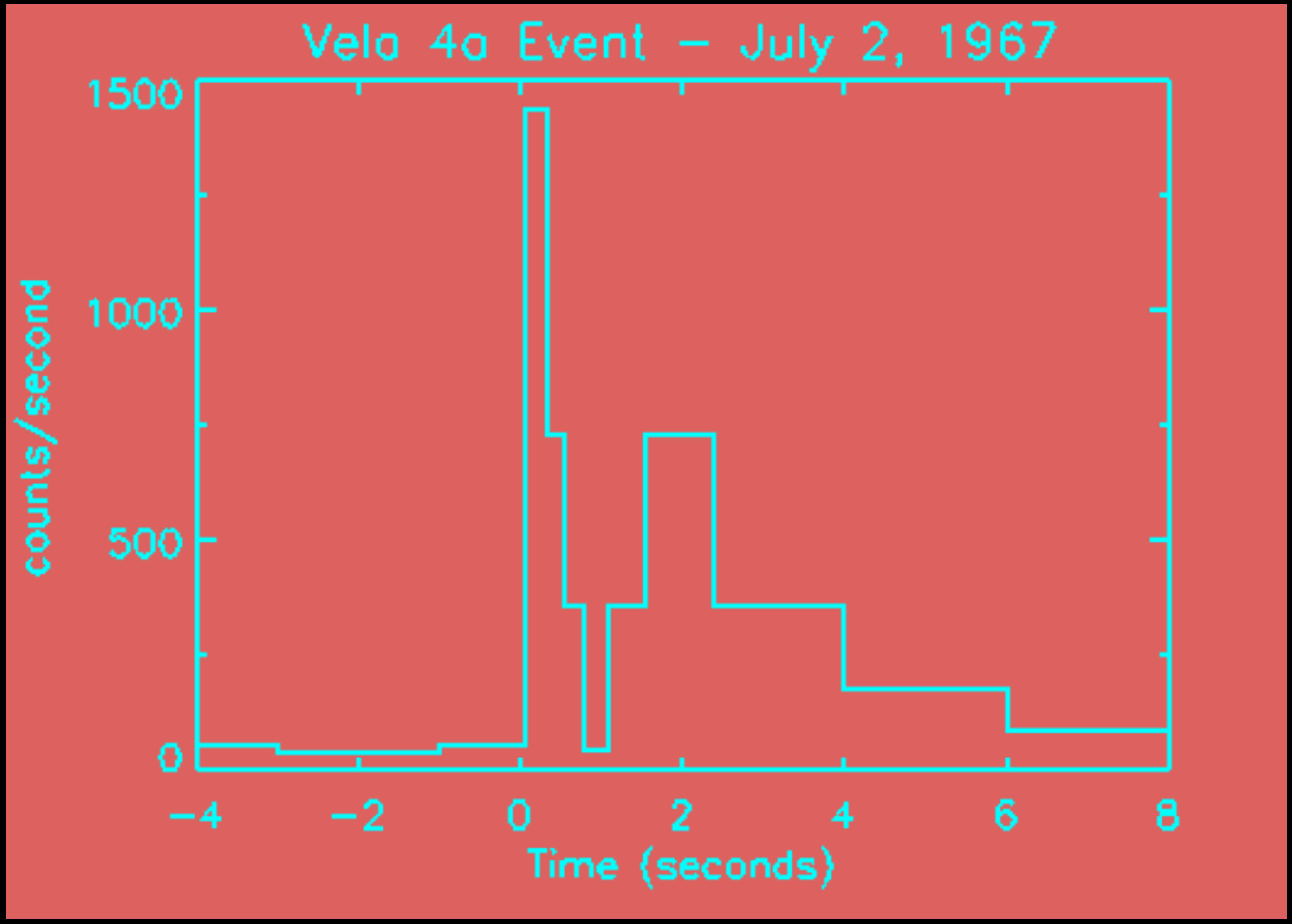
   (b) in any other environment if such explosion causes radioactive debris to be present outside the territorial limits of the State under whose jurisdiction or control such explosion is conducted. It is understood in this connection that the provisions of this subparagraph are without prejudice to the conclusion of a Treaty resulting in the permanent banning of all nuclear test explosions, including all such explosions underground, the conclusion of which, as the Parties have stated in the Preamble to this Treaty, they seek to achieve.

2. Each of the Parties to this Treaty undertakes furthermore to refrain from causing, encouraging, or in any way participating in, the carrying out of any nuclear weapon test explosion, or any other nuclear explosion, anywhere which would take place in any of the environments described, or have the effect referred to, in paragraph 1 of this Article.

Gamma-ray bursts: historical remarks

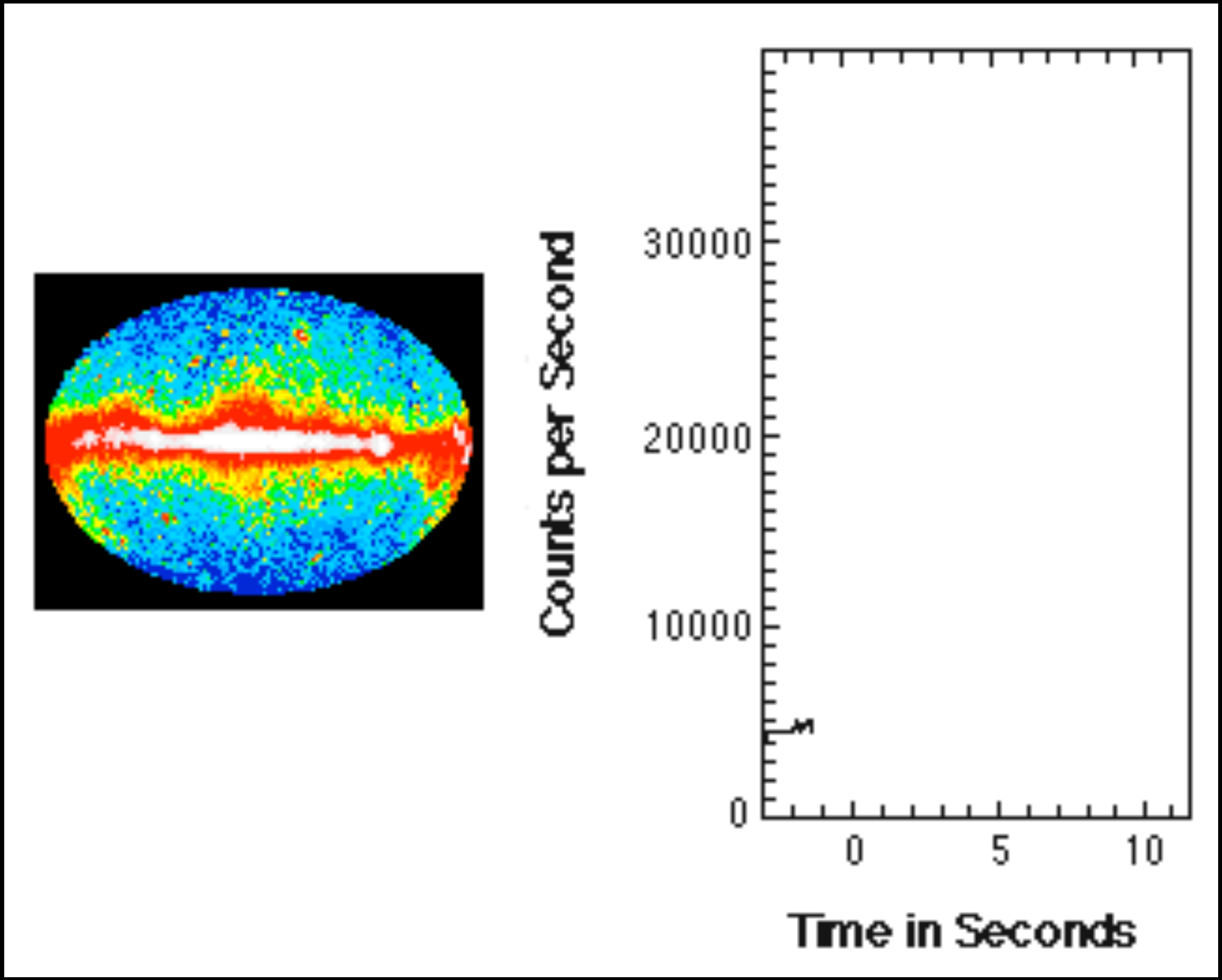
- the US military VELA program
(3 pairs of satellites: 1963, 64 and 65)
- 1973: discovery paper (Klebesadel et al.)
- 1970-1980: more studies with scientific satellites





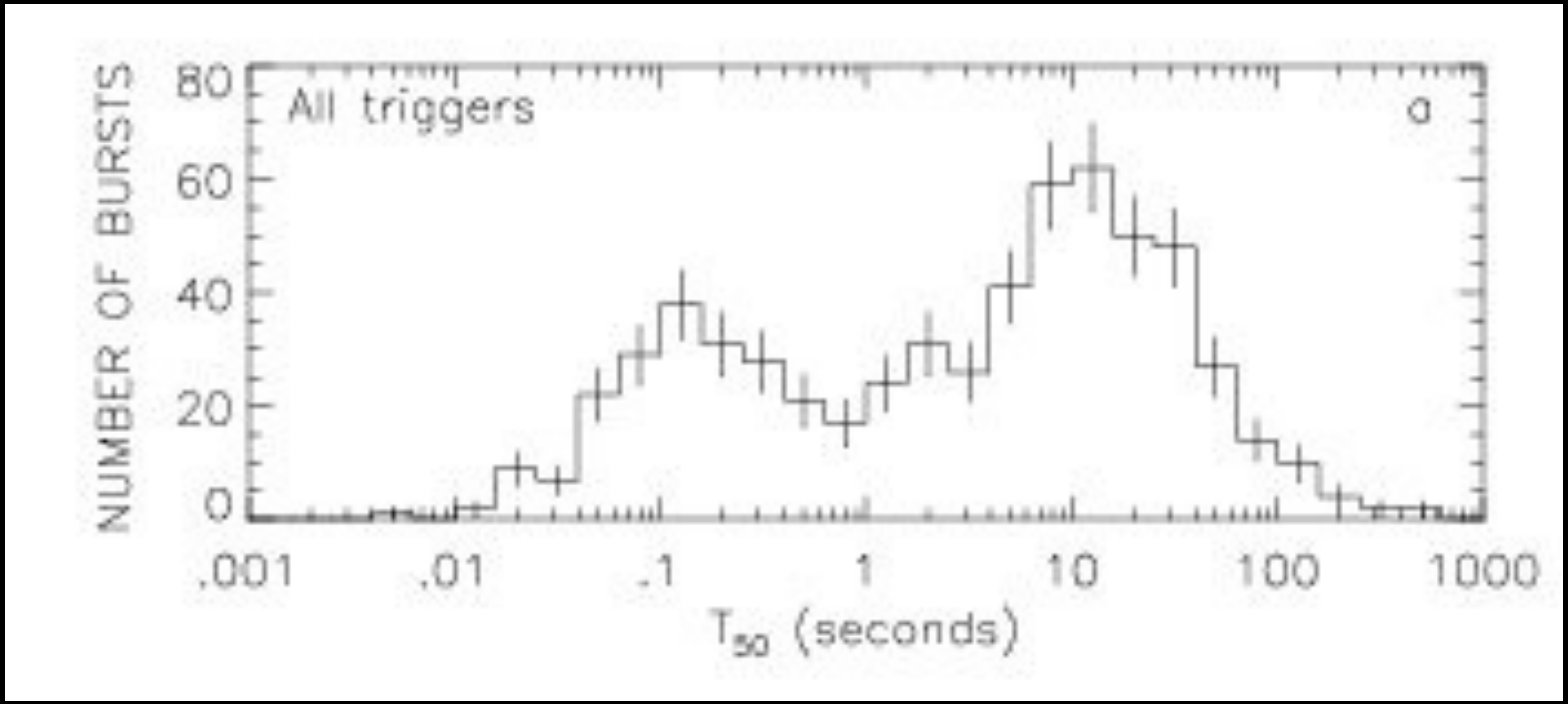
Introduction:
observational facts (1) prompt emission

What is a gamma-ray burst?



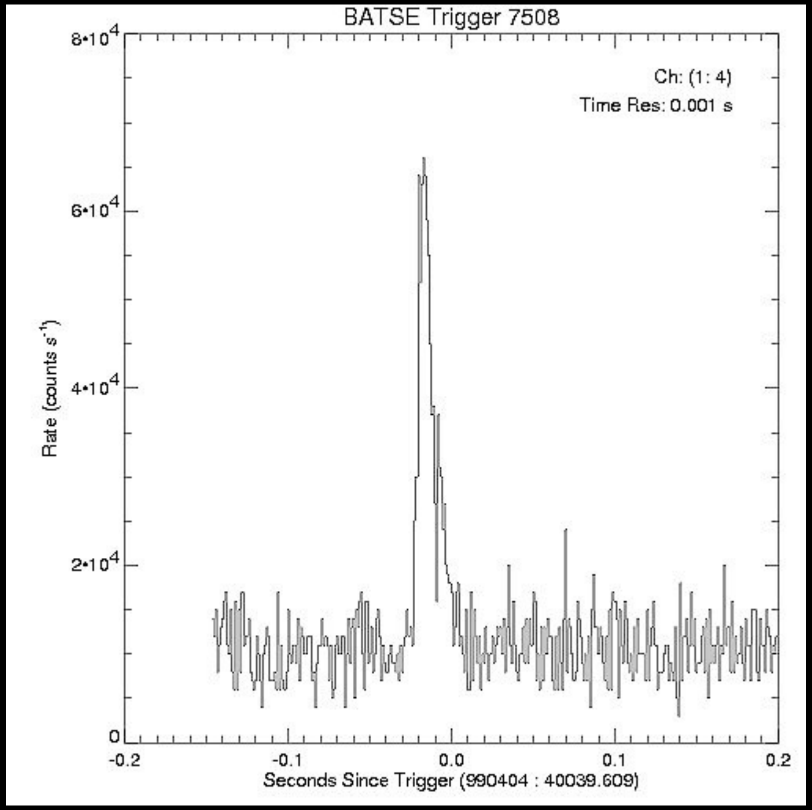
Long & short gamma-ray bursts

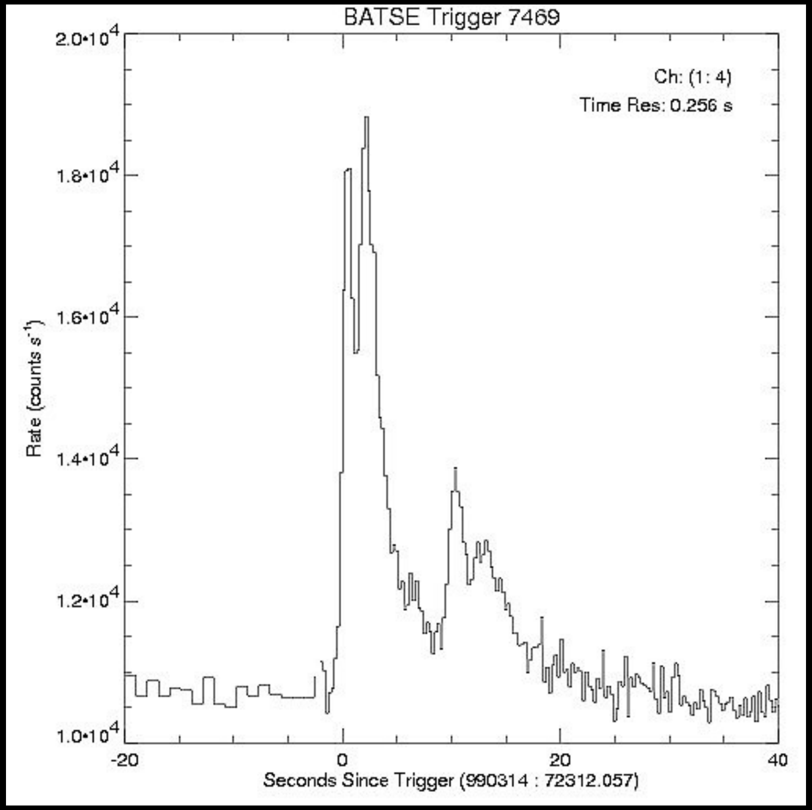
Distribution of the duration:

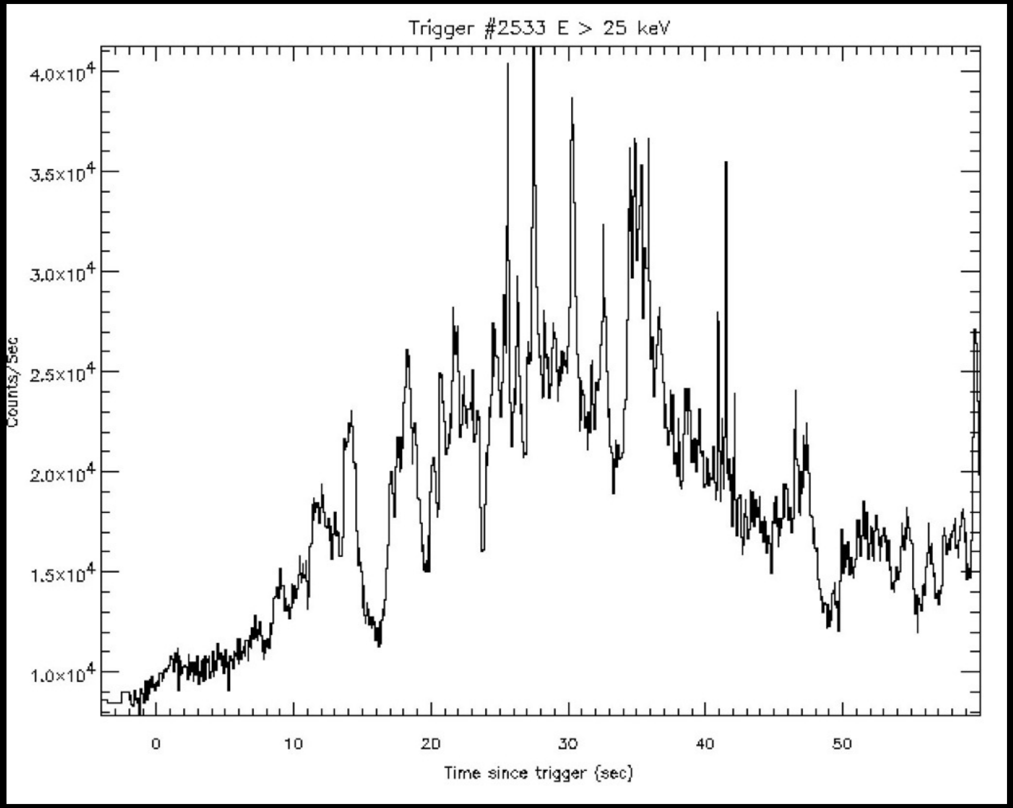


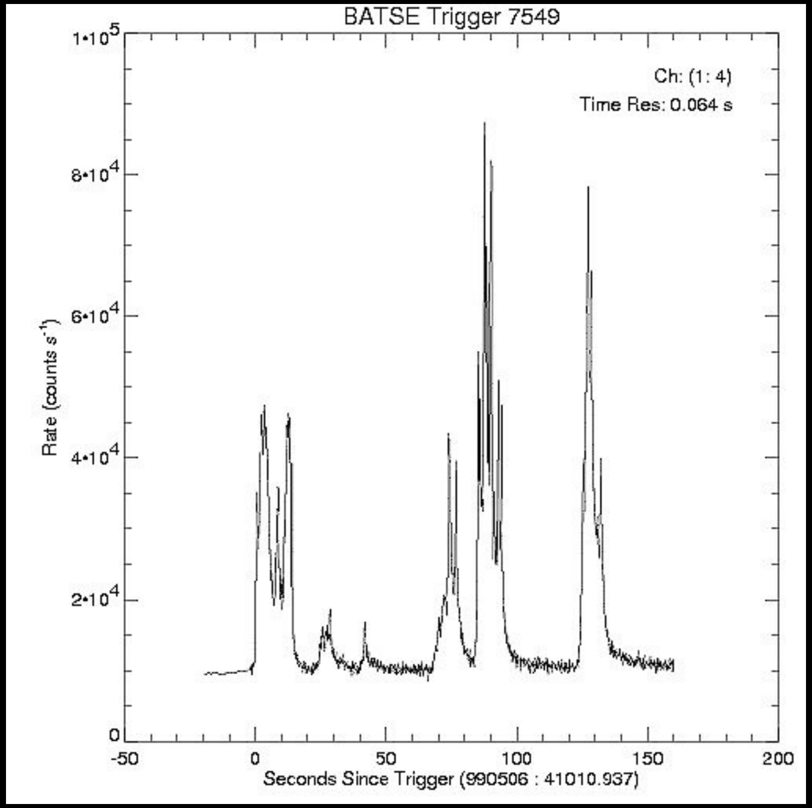
(BATSE catalog)

Lightcurves: diversity and variability



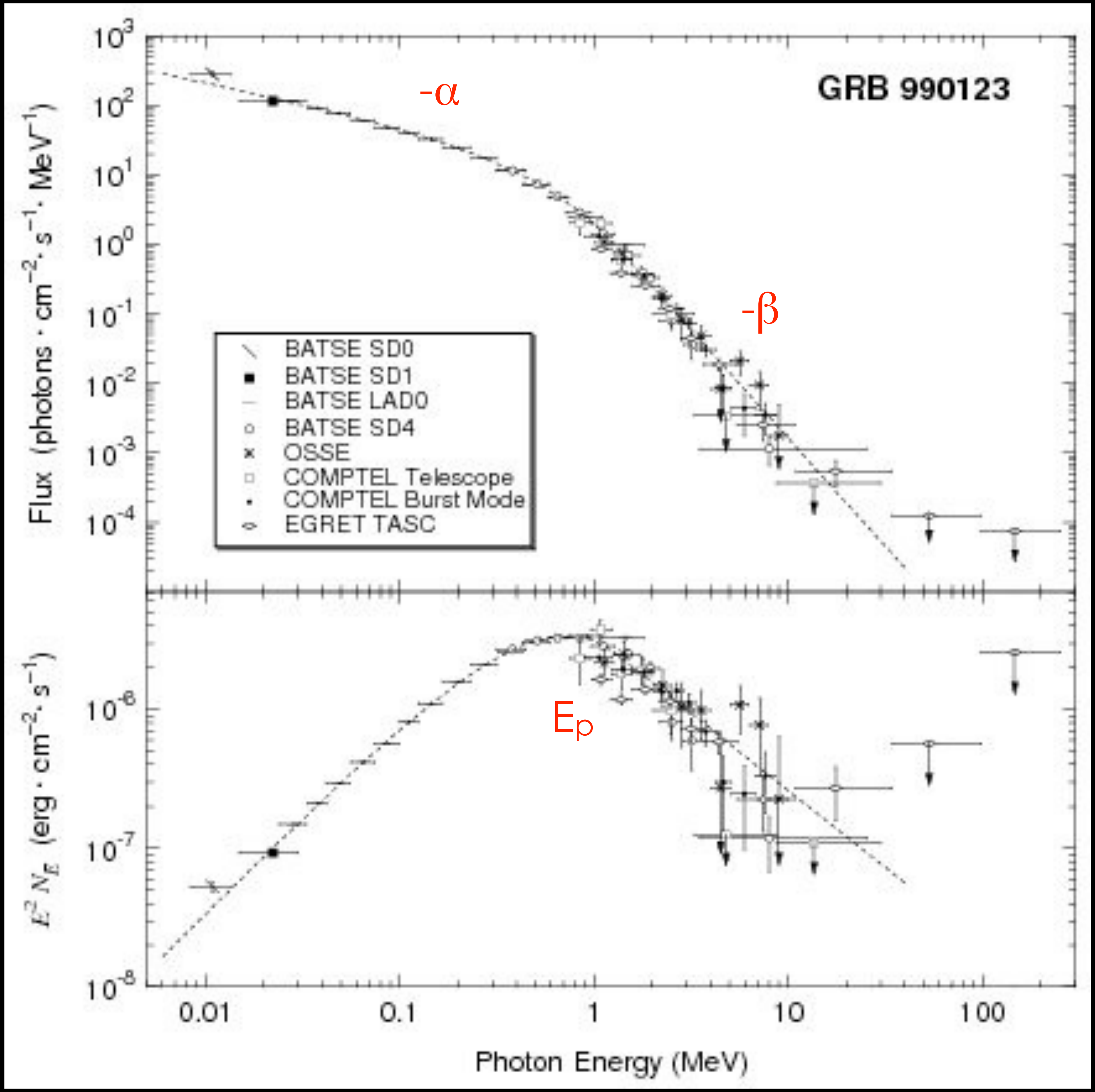






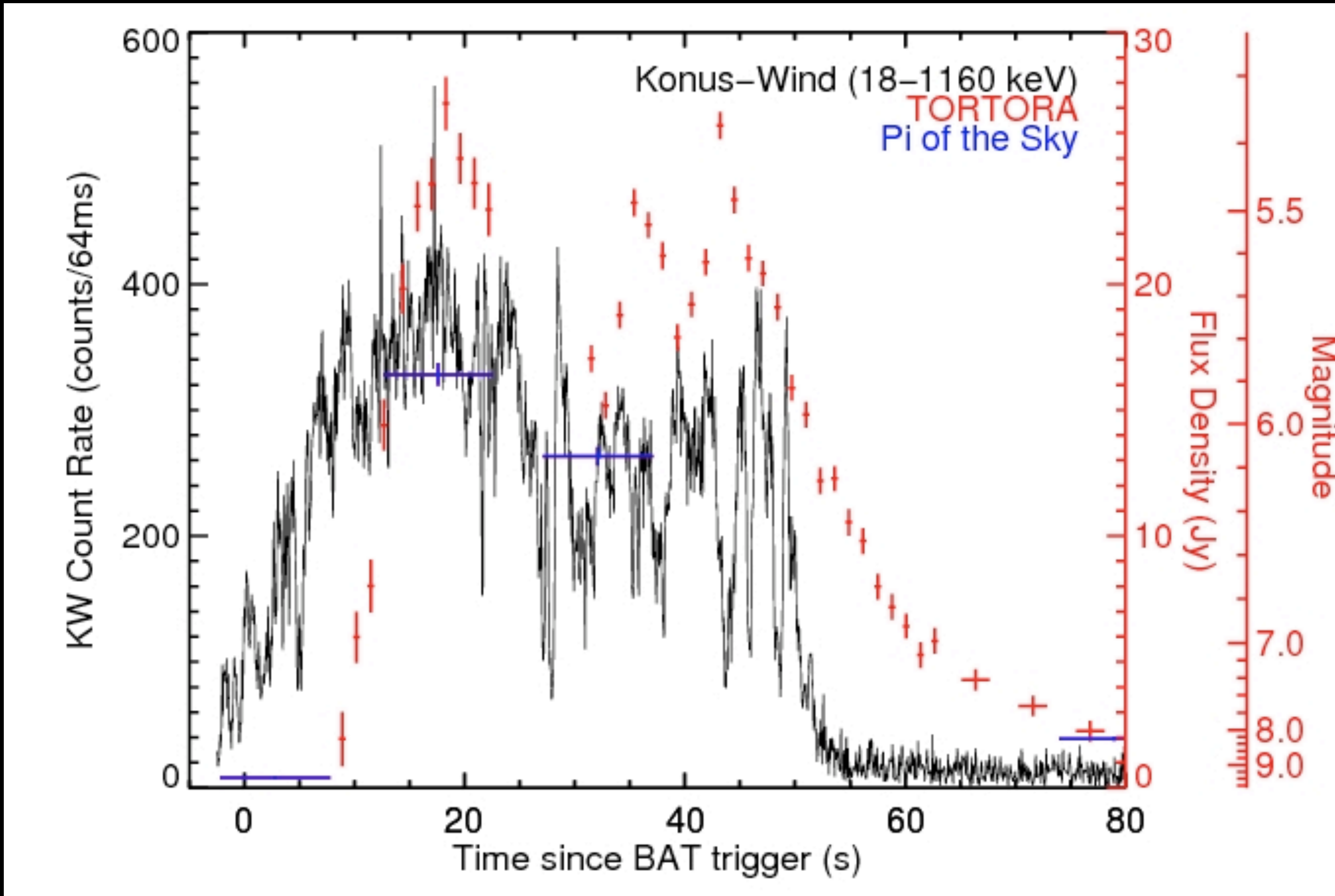
(BATSE catalog)

Non-thermal spectrum



(BATSE catalog)

The optical prompt emission

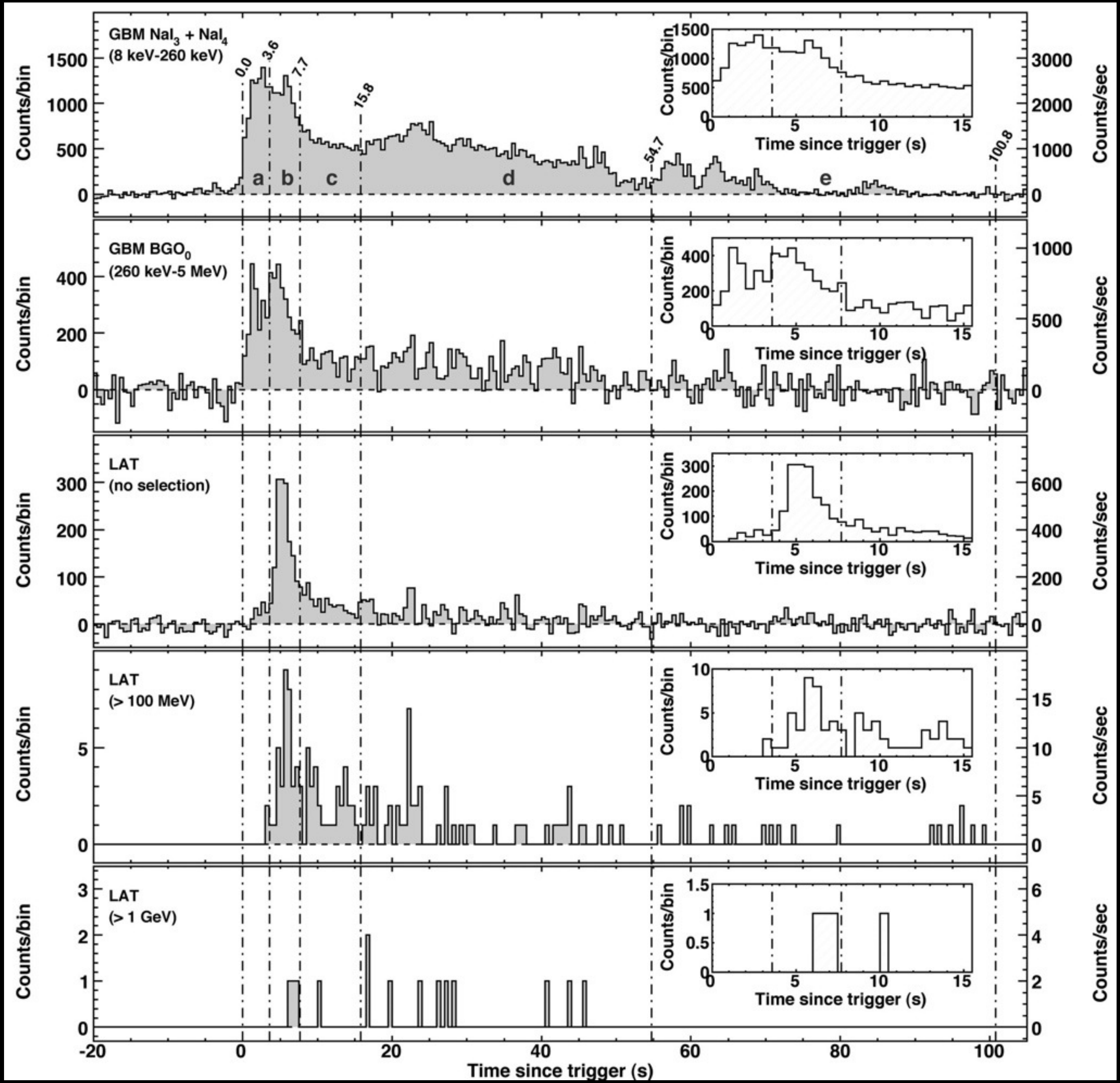


Naked eye burst (Racusin et al. 2008): an extreme case

Great diversity: optical emission can be above or below the extrapolation of the soft gamma-ray spectrum

The GeV prompt emission

Detection at high energy by *Fermi*



GRB 080916C (Abdo et al. 2009)

Location, location, location!

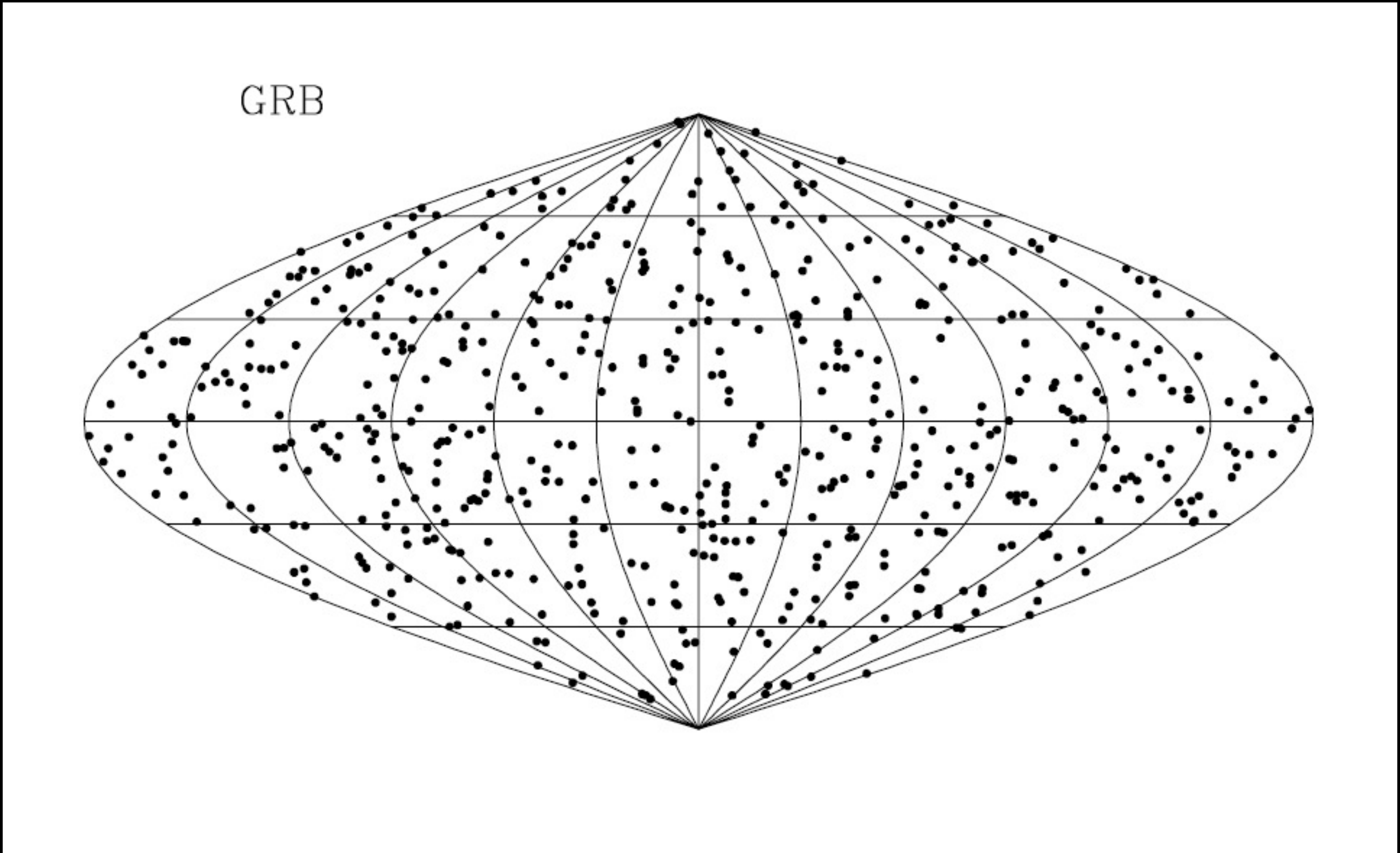
Gamma-ray bursts: historical remarks

- the US military VELA program
(3 pairs of satellites: 1963, 64 and 65)
- 1973: discovery paper (Klebesadel et al.)
- 1970-1980: more studies with scientific satellites
- 1973-1997: distance scale ? Galactic models
- 1994: the Great Debate

Main problem = poor localisation
BATSE: ~ 10 degrees
IPN: ~arcmin, but with a delay of several days

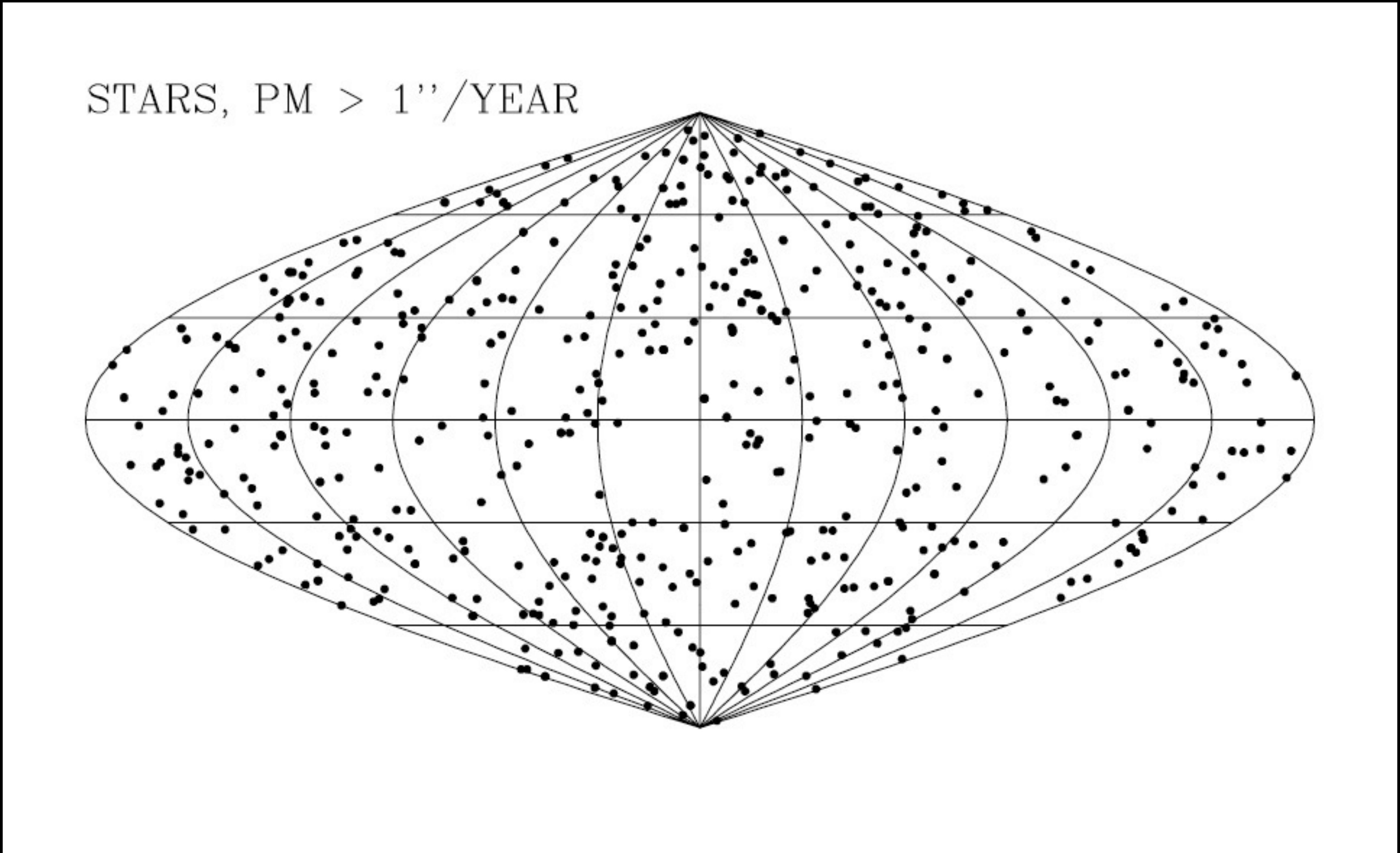
GRB distance scale?

GRB sky map (CGRO/BATSE, 1994)



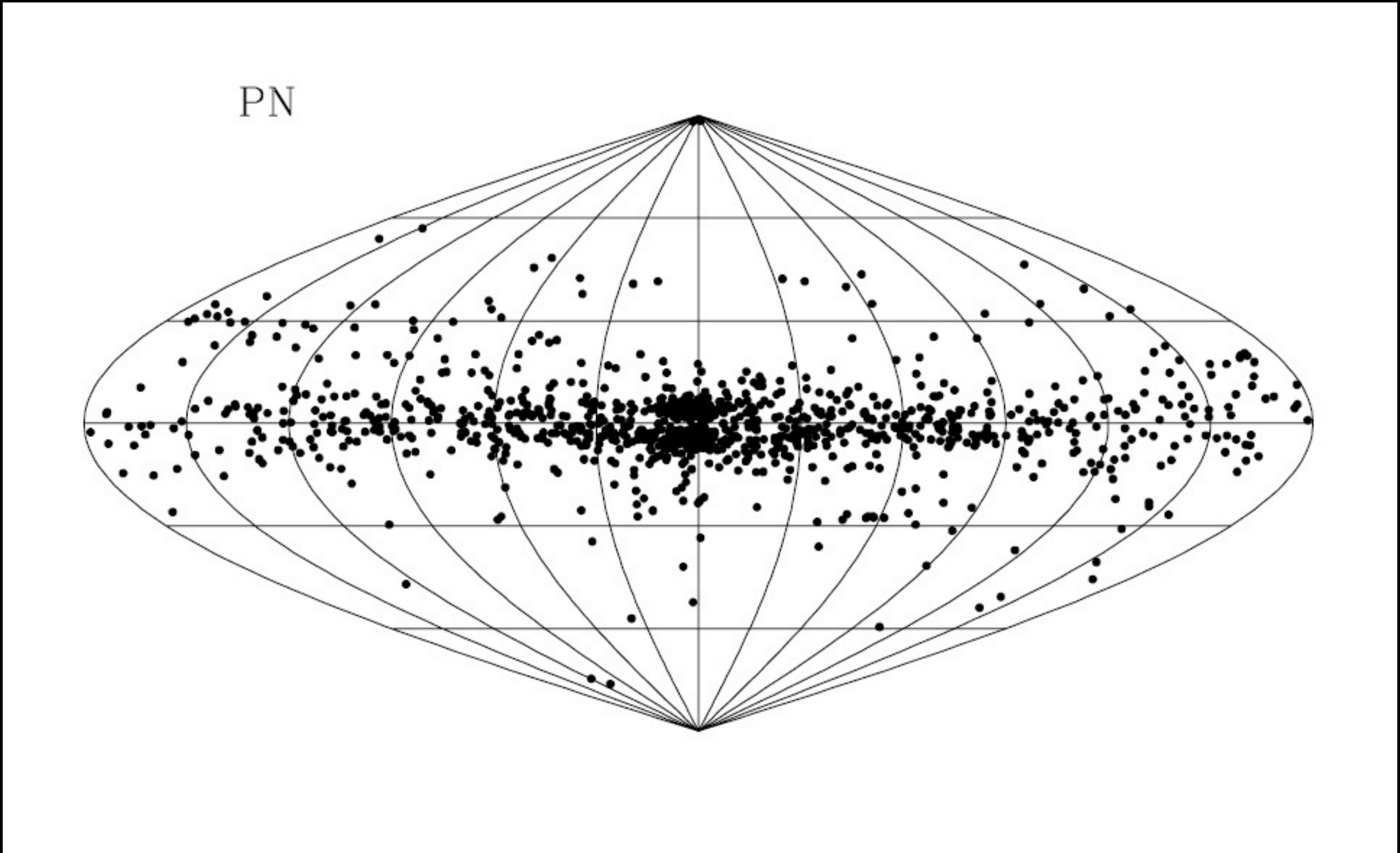
GRB distance scale?

Nearby stars (isotropy and proper motion)



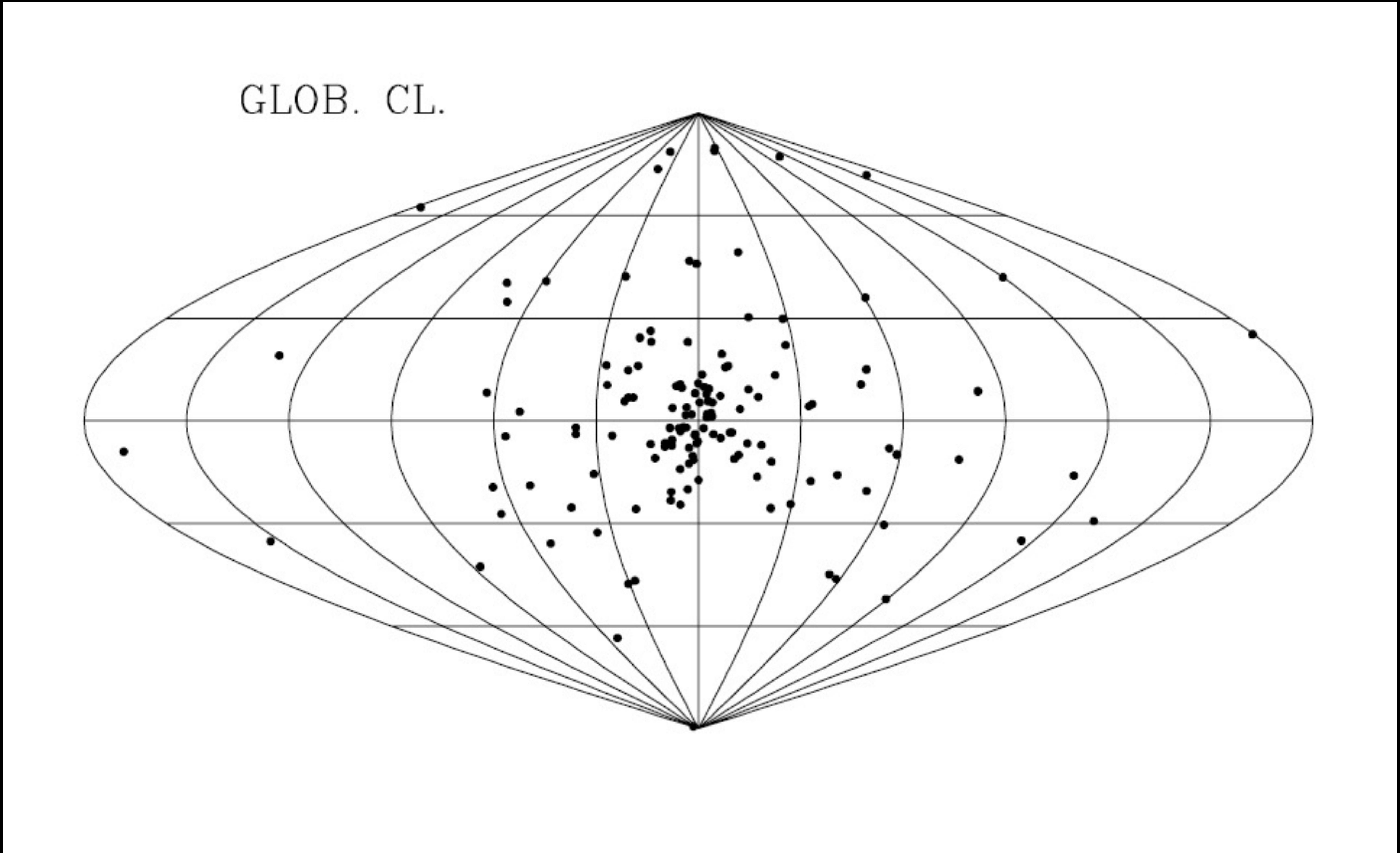
GRB distance scale?

Planetary nebulae (Galactic disk)



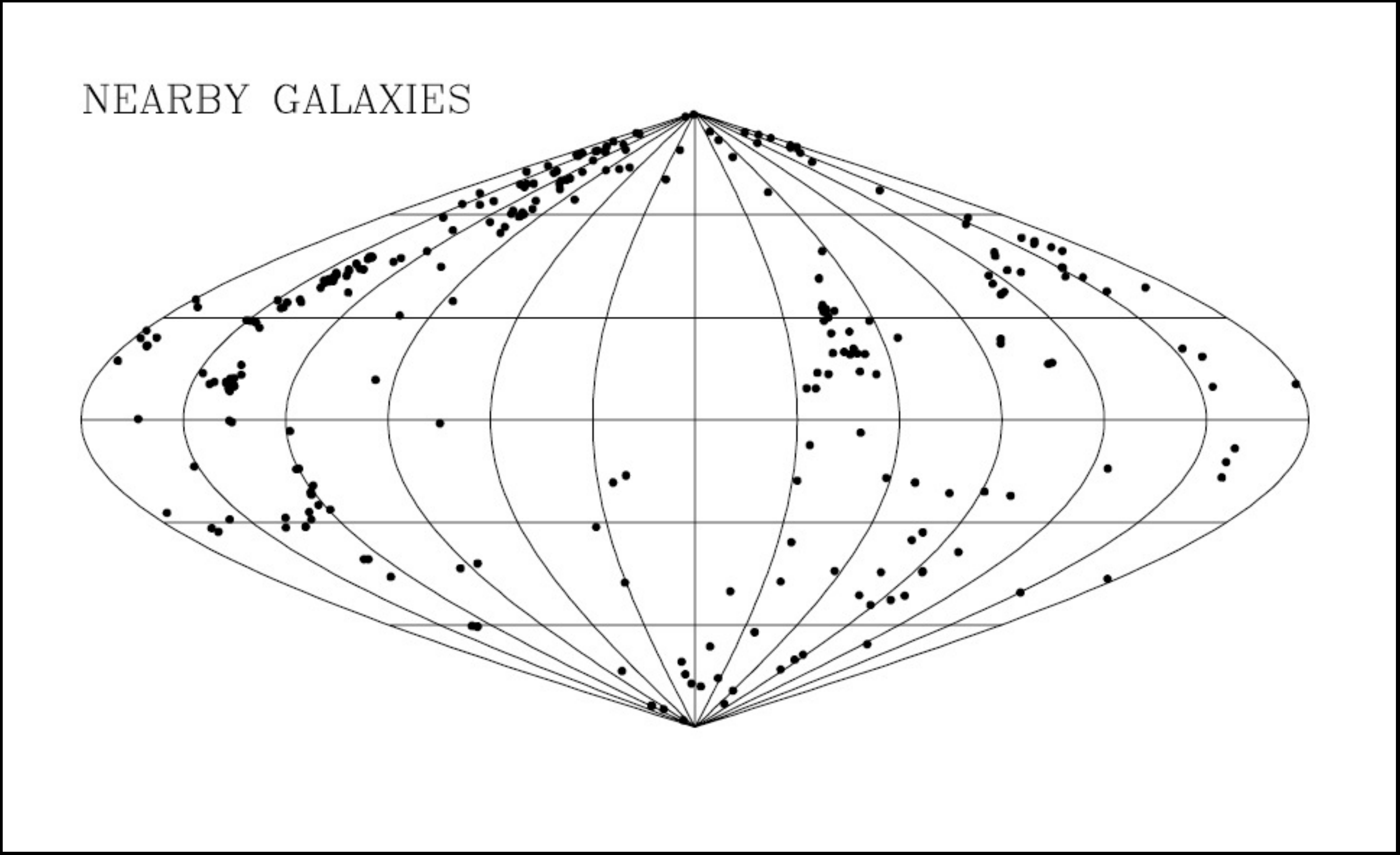
GRB distance scale?

Globular clusters (~spherical halo, Sun is not at the center)



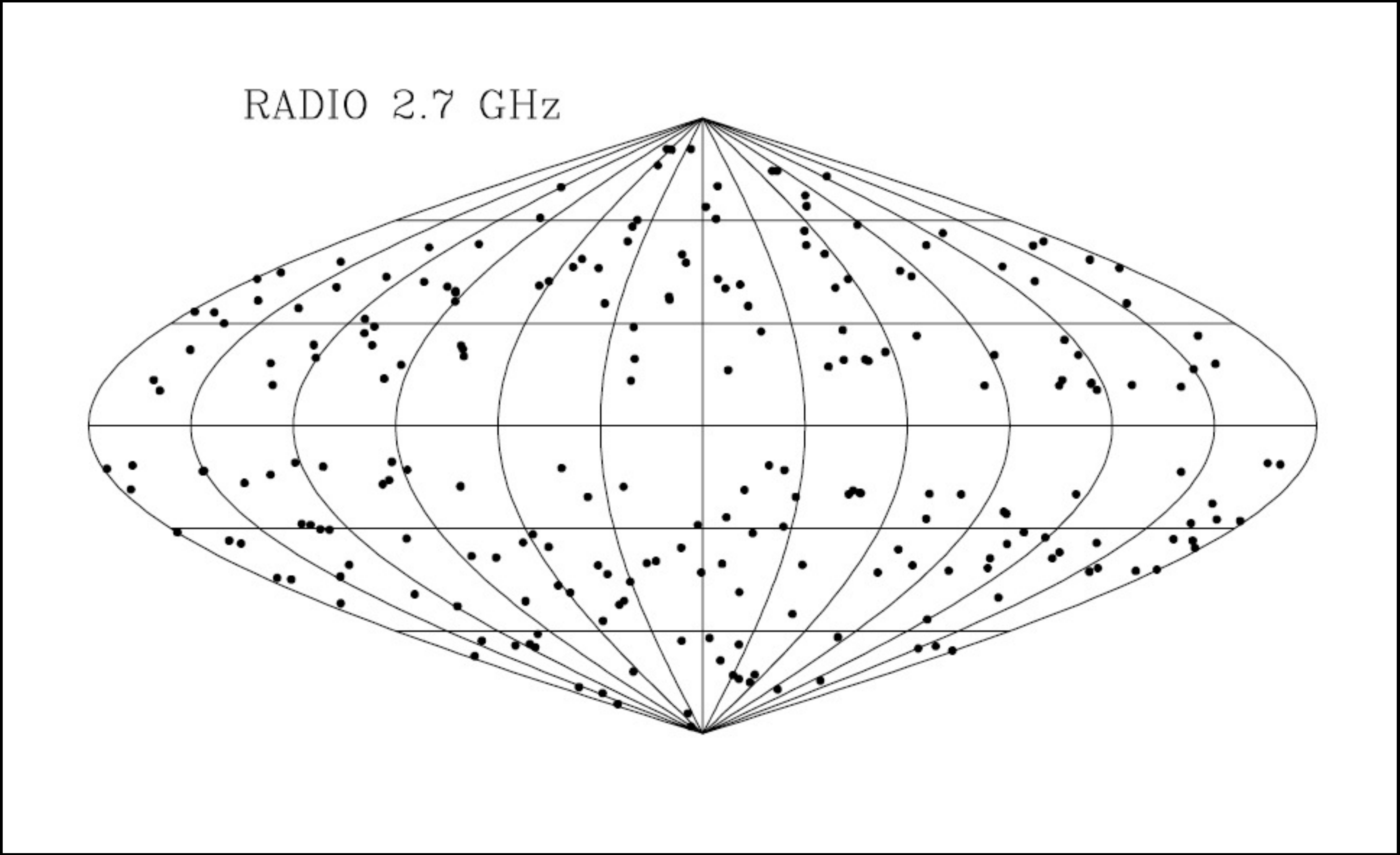
GRB distance scale?

Nearby galaxies (large structures)



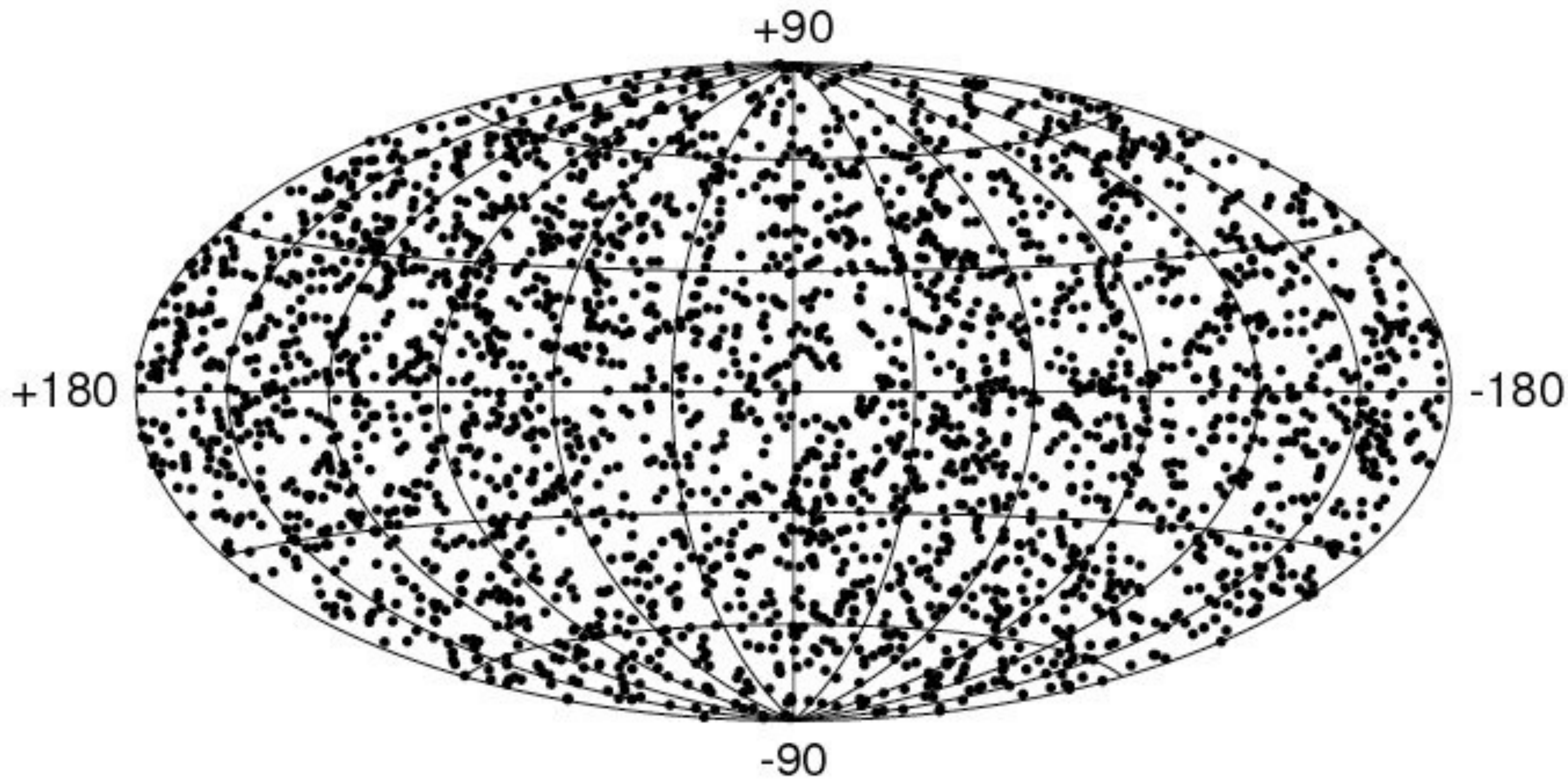
GRB distance scale?

Radio-galaxies (isotropy)



GRB distance scale?

Gamma-ray bursts (final BATSE catalog)

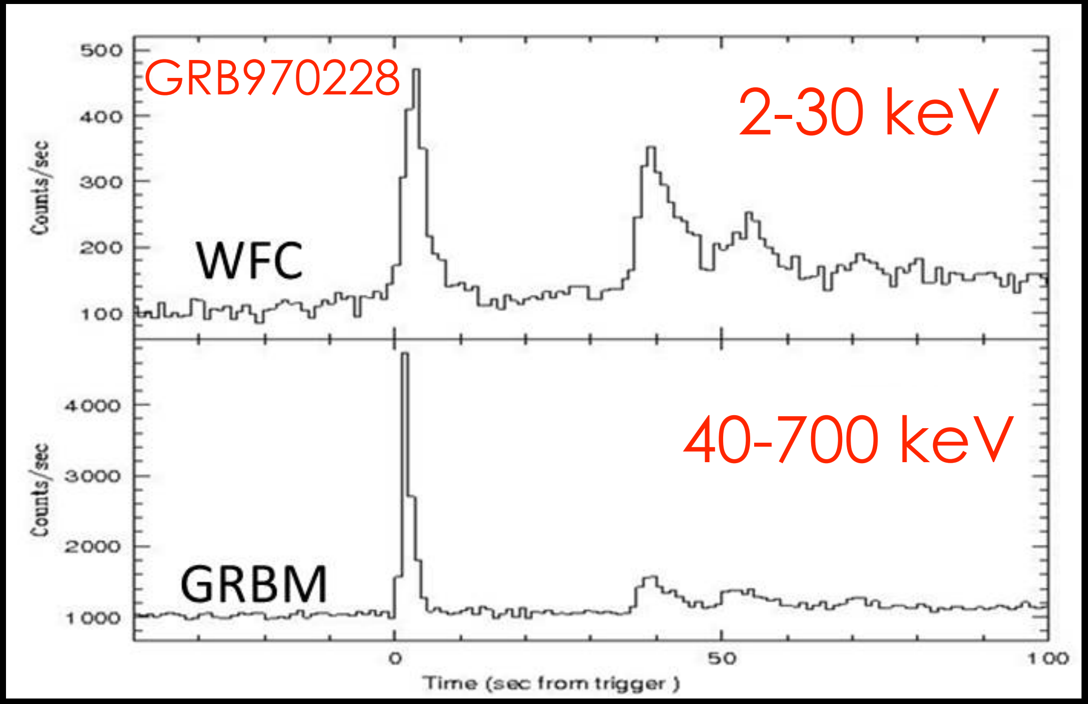


The discovery of afterglows: Gamma-ray bursts occur at cosmological distance!

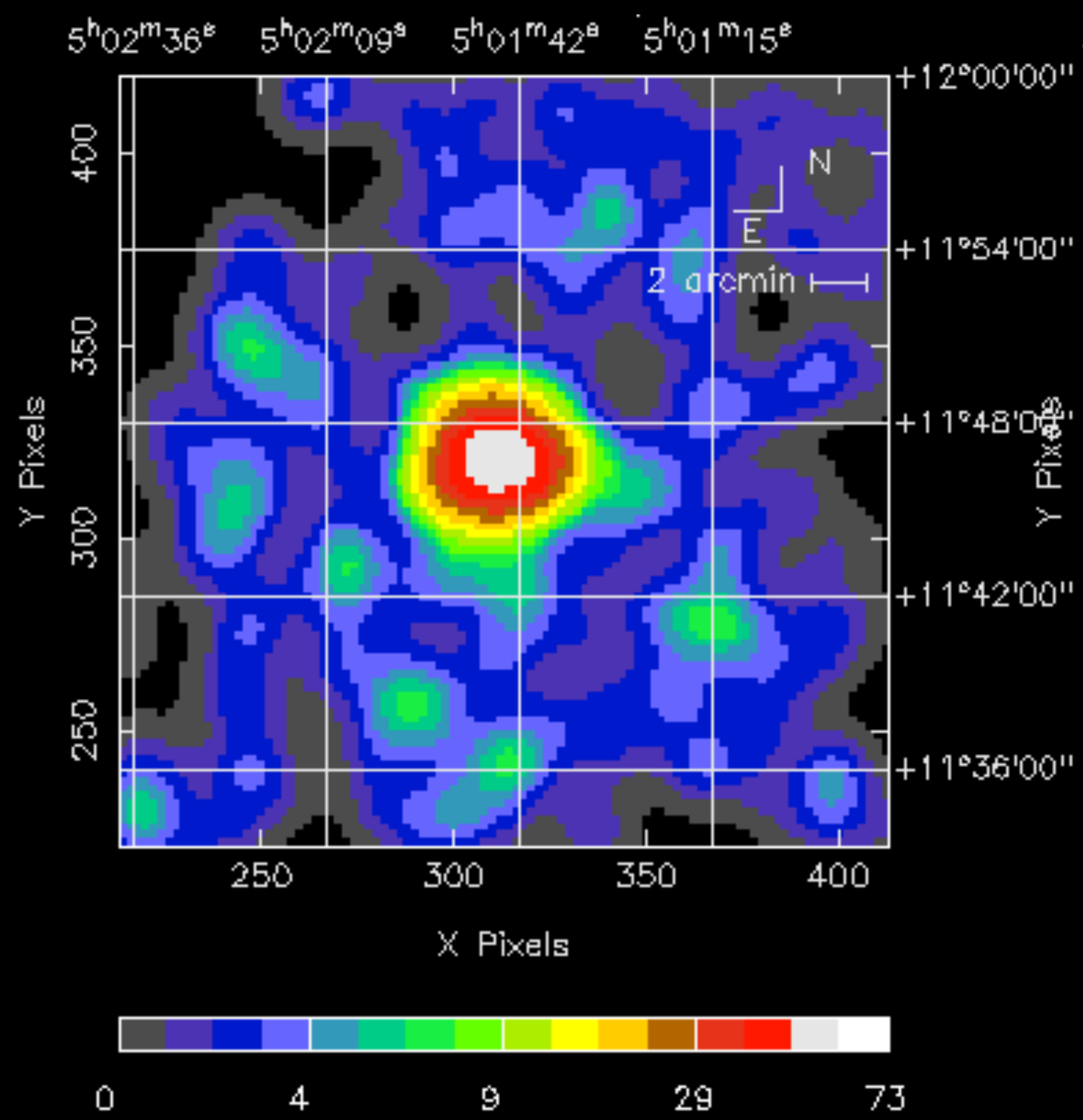
(Beppo-SAX, van Paradijs et al., 1997)

Afterglows

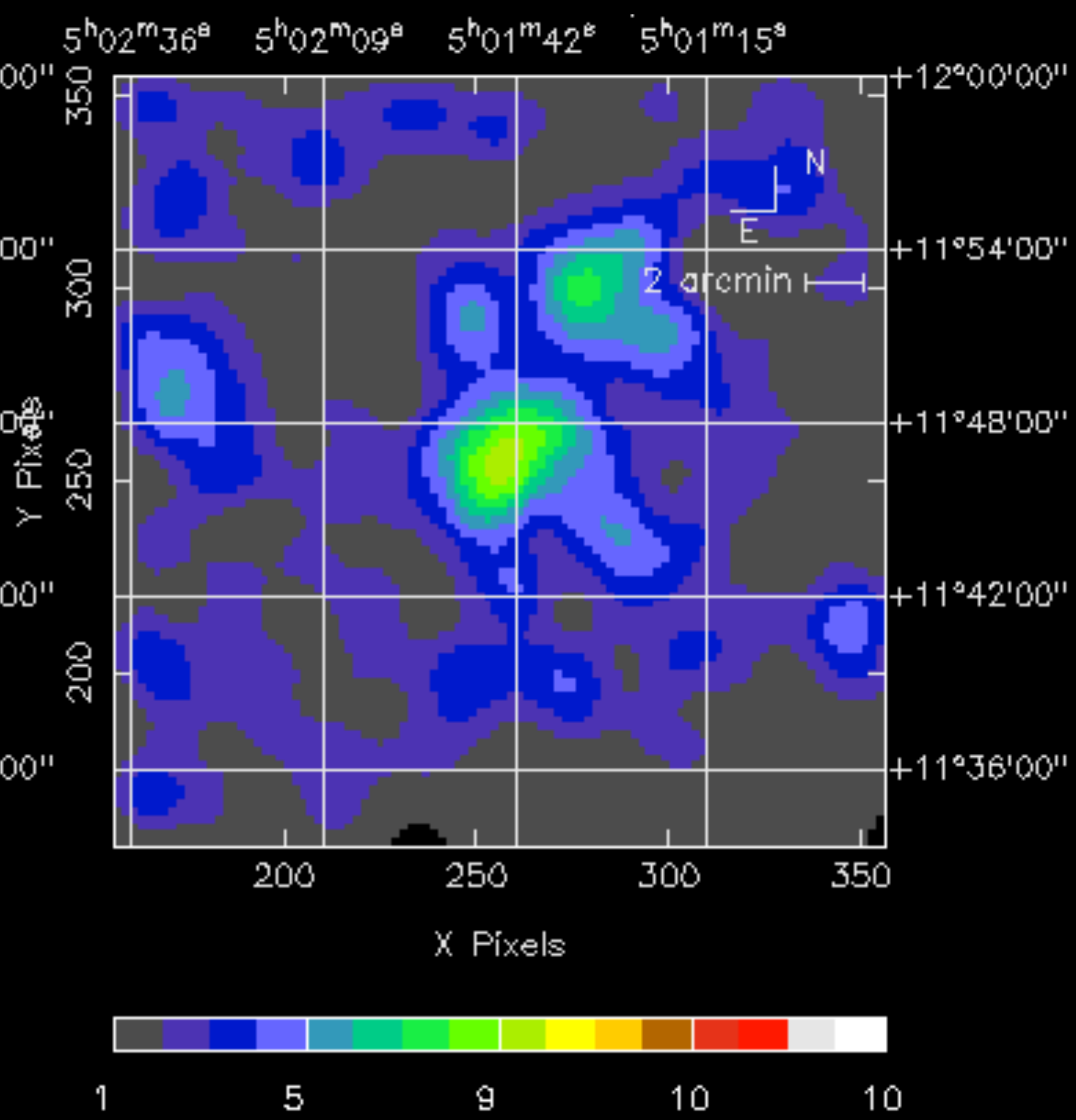
The first X-ray afterglow (GRB 970228):
Beppo-SAX



1997 Feb 28

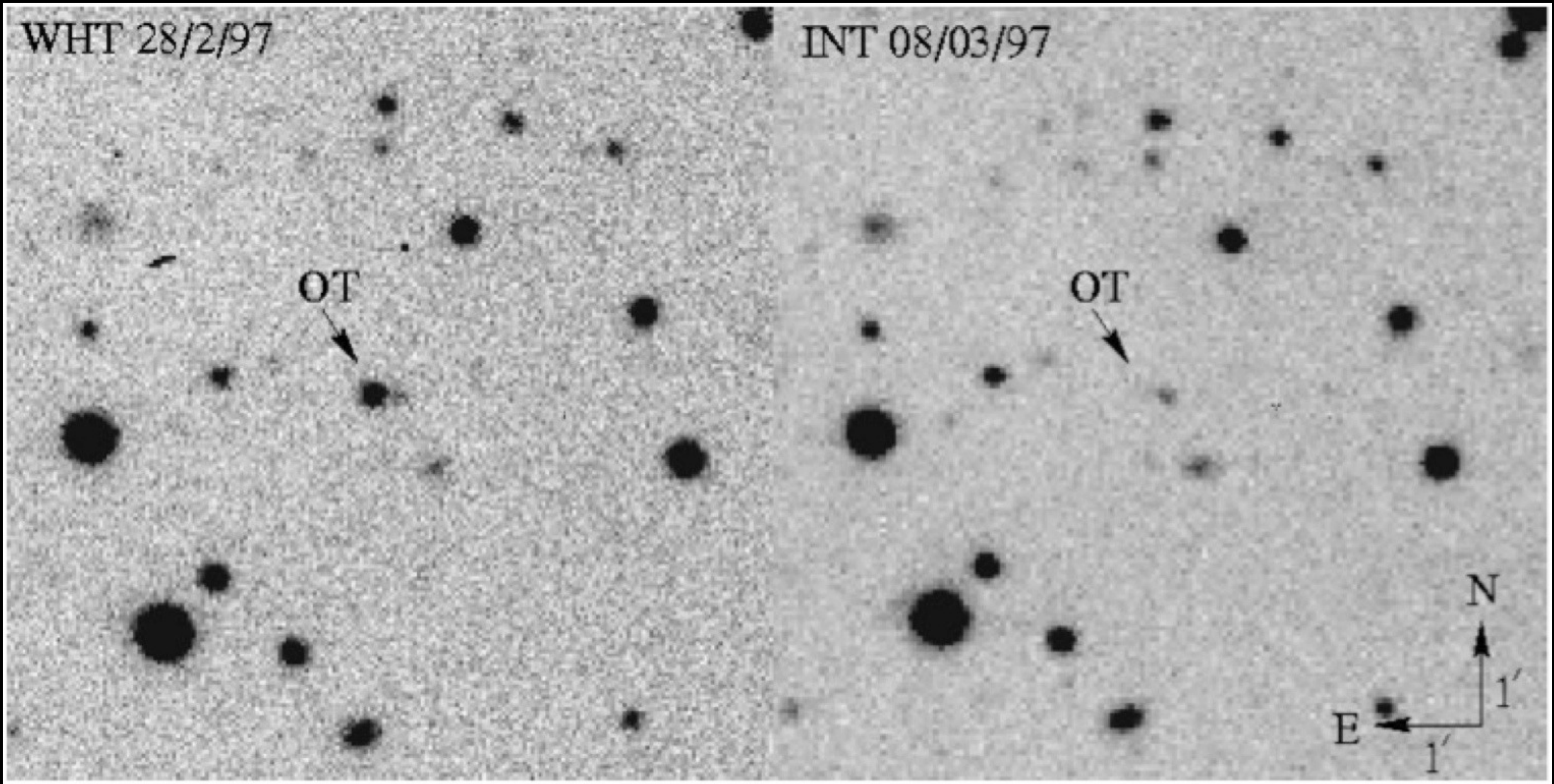


1997 Mar 3



Afterglows

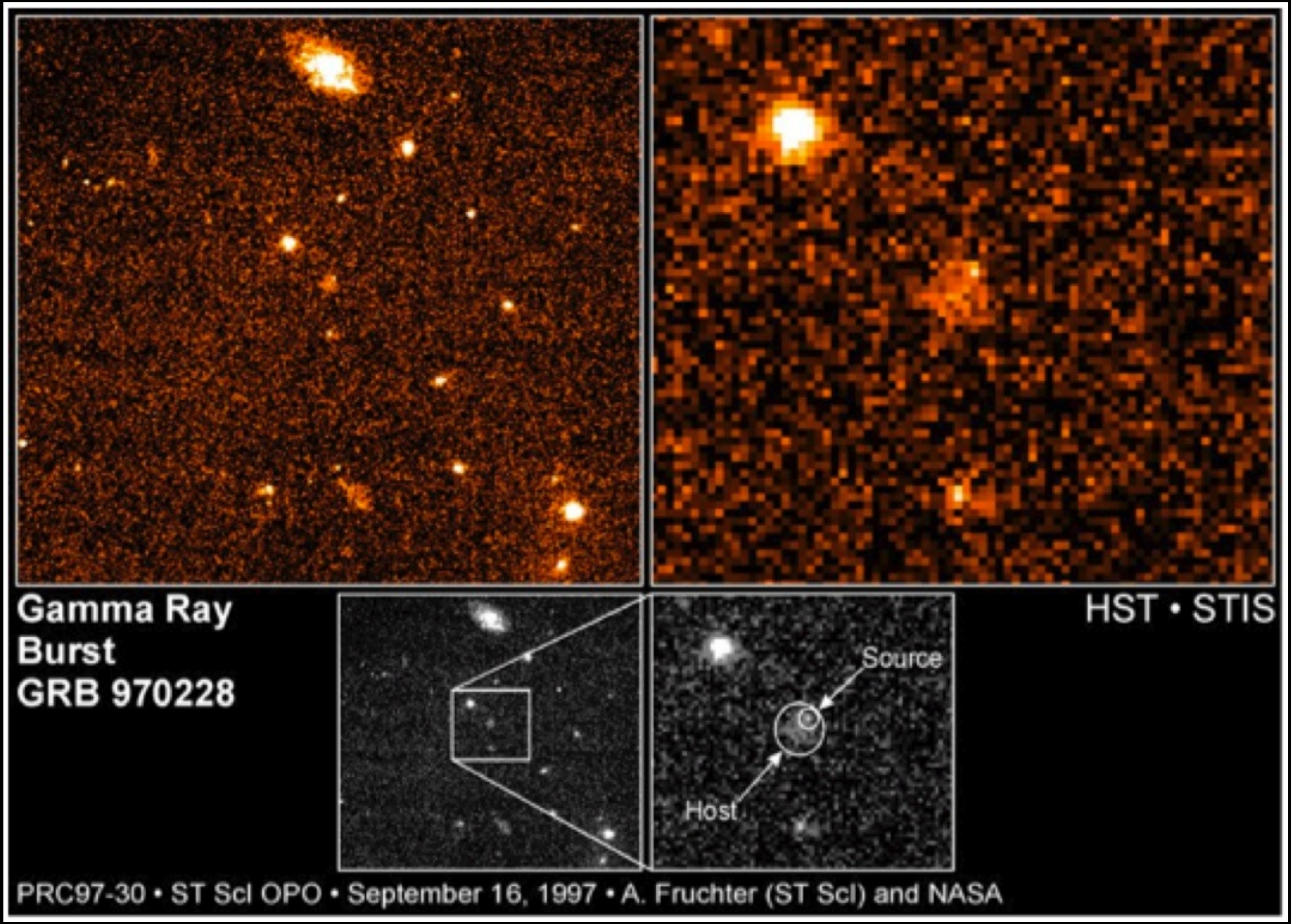
The first optical afterglow (GRB 970228)



van Paradijs et al. 1997

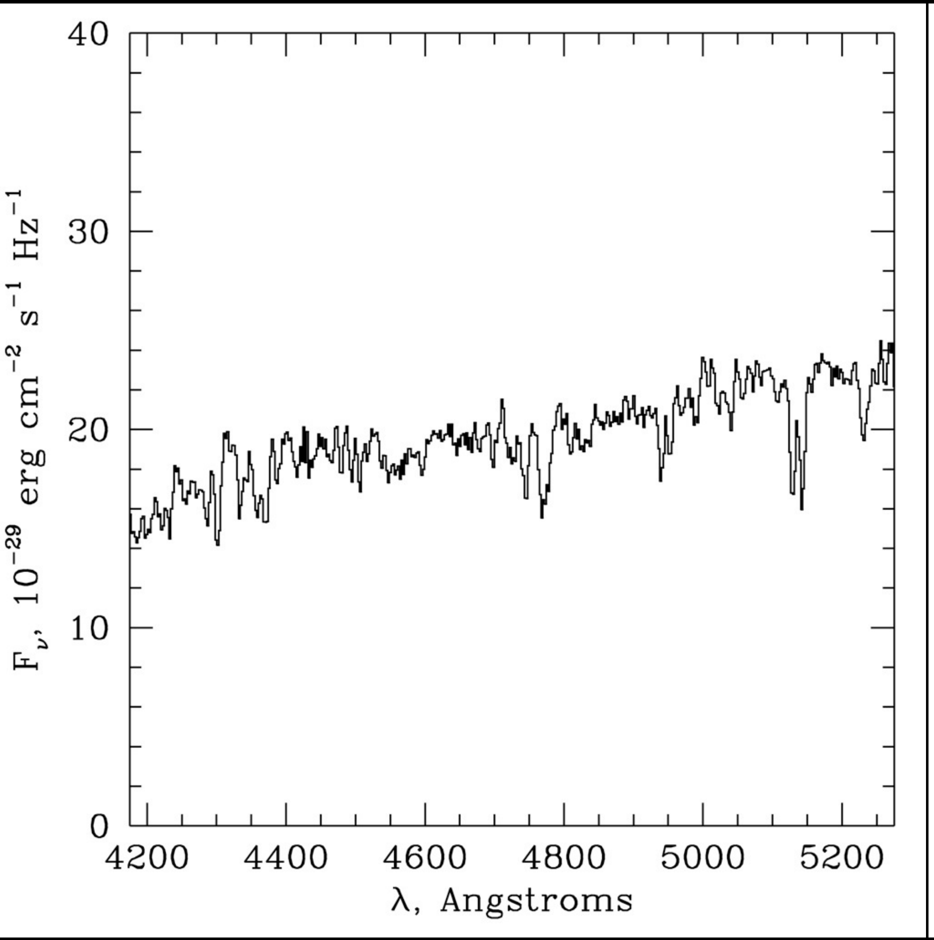
Afterglows

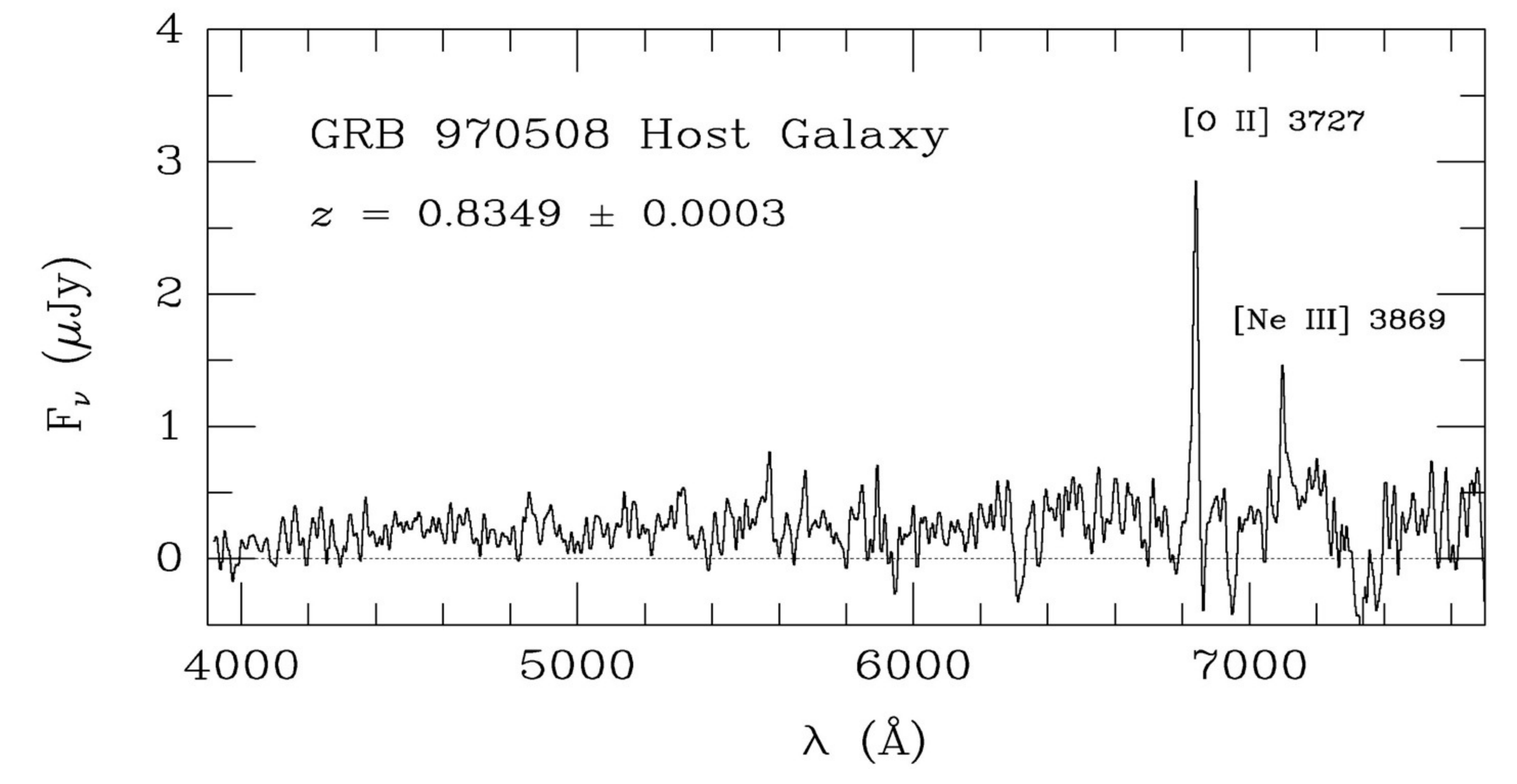
The first optical afterglow (GRB 970228): host galaxy



Afterglows

Optical spectrum of the afterglow of GRB 070508 and its host galaxy : z = 0.835

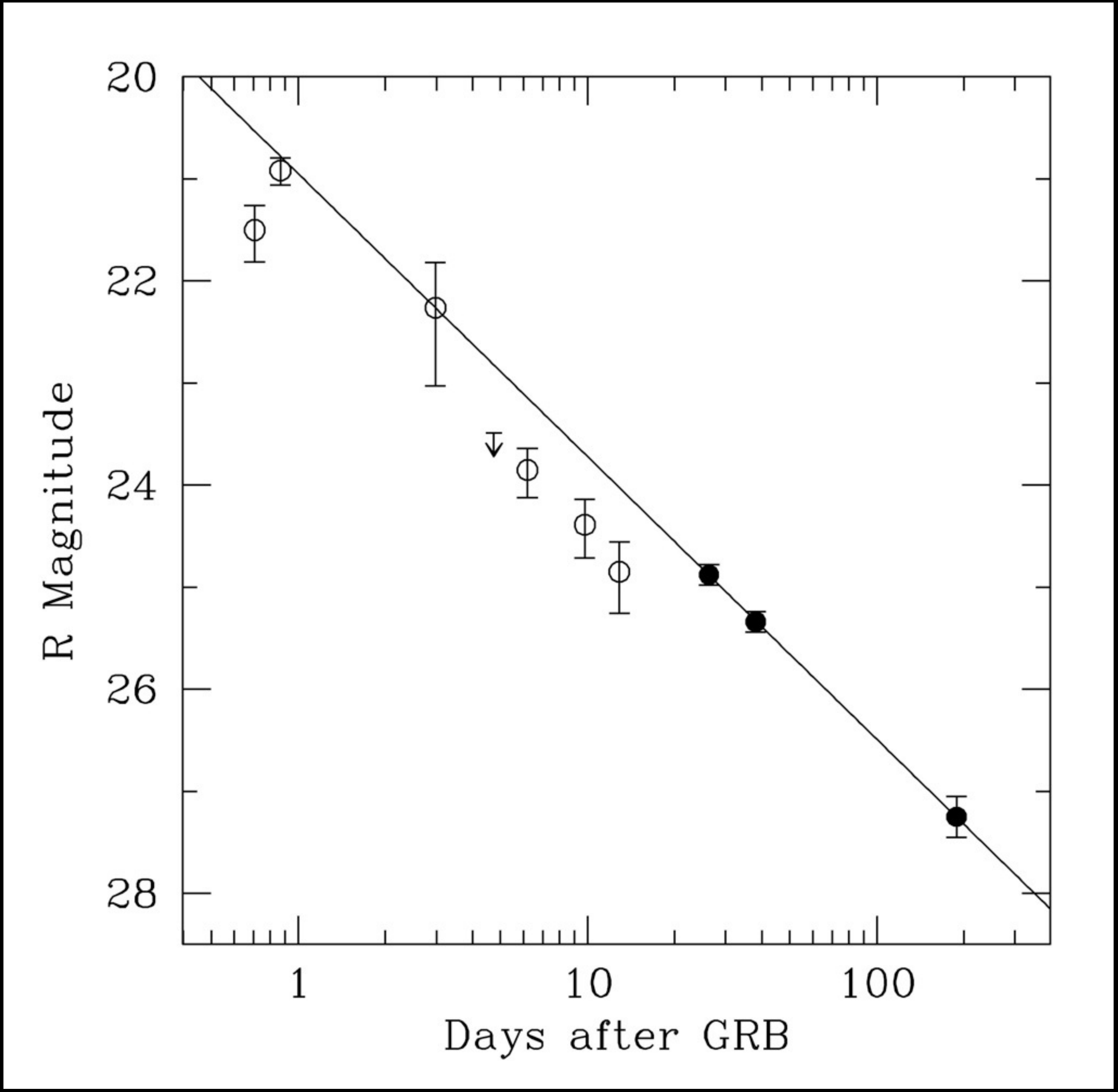




Metzger et al. 1997

Afterglows: lightcurves

First optical afterglow (GRB 970228)



Sorting out models…

Table 1

#	Author	Year Pub	Reference	Main Body	2nd Body	Place	Description
1.	Colgate	1968	CJPhys, 46, S476	ST		COS	SN shocks stellar surface in distant galaxy
2.	Colgate	1974	ApJ, 187, 333	ST		COS	Type II SN shock brem, inv Comp scat at stellar surface
3.	Stecker et al.	1973	Nature, 245, PS70	ST		DISK	Stellar superflare from nearby star
4.	Stecker et al.	1973	Nature, 245, PS70	WD		DISK	Superflare from nearby WD
5.	Harwit et al.	1973	ApJ, 186, L37	NS	COM	DISK	Relic comet perturbed to collide with old galactic NS
6.	Lamb et al.	1973	Nature, 246, PS52	WD	ST	DISK	Accretion onto WD from flare in companion
7.	Lamb et al.	1973	Nature, 246, PS52	NS	ST	DISK	Accretion onto NS from flare in companion
8.	Lamb et al.	1973	Nature, 246, PS52	BH	ST	DISK	Accretion onto BH from flare in companion
9.	Zwicky	1974	Ap & SS, 28, 111	NS		HALO	NS chunk contained by external pressure escapes, explodes
10.	Grindlay et al.	1974	ApJ, 187, L93	DG		SOL	Relativistic iron dust grain up-scatters solar radiation
11.	Brecher et al.	1974	ApJ, 187, L97	ST		DISK	Directed stellar flare on nearby star
12.	Schlovskii	1974	SovAstron, 18, 390	WD	COM	DISK	Comet from system's cloud strikes WD
13.	Schlovskii	1974	SovAstron, 18, 390	NS	COM	DISK	Comet from system's cloud strikes NS
14.	Bisnovatyi- et al.	1975	Ap & SS, 35, 23	ST		COS	Absorption of neutrino emission from SN in stellar envelope
15.	Bisnovatyi- et al.	1975	Ap & SS, 35, 23	ST	SN	COS	Thermal emission when small star heated by SN shock wave
16.	Bisnovatyi- et al.	1975	Ap & SS, 35, 23	NS		COS	Ejected matter from NS explodes
17.	Pacini et al.	1974	Nature, 251, 399	NS		DISK	NS crustal starquake glitch; should time coincide with GRB
18.	Narlikar et al.	1974	Nature, 251, 590	WH		COS	White hole emits spectrum that softens with time
19.	Tsygan	1975	A&A, 44, 21	NS		HALO	NS corequake excites vibrations, changing E & B fields
20.	Chanmugam	1974	ApJ, 193, L75	WD		DISK	Convection inside WD with high B field produces flare
21.	Prilutski et al.	1975	Ap & SS, 34, 395	AGN	ST	COS	Collapse of supermassive body in nucleus of active galaxy
22.	Narlikar et al.	1975	Ap & SS, 35, 321	WH		COS	WH excites synchrotron emission, inverse Compton scattering
23.	Piran et al.	1975	Nature, 256, 112	BH		DISK	Inv Comp scat deep in ergosphere of fast rotating, accreting BH
24.	Fabian et al.	1976	Ap & SS, 42, 77	NS		DISK	NS crustquake shocks NS surface
25.	Chanmugam	1976	Ap & SS, 42, 83	WD		DISK	Magnetic WD suffers MHD instabilities, flares
26.	Mullan	1976	ApJ, 208, 199	WD		DISK	Thermal radiation from flare near magnetic WD
27.	Woosley et al.	1976	Nature, 263, 101	NS		DISK	Carbon detonation from accreted matter onto NS
28.	Lamb et al.	1977	ApJ, 217, 197	NS		DISK	Mag grating of accret disk around NS causes sudden accretion
29.	Piran et al.	1977	ApJ, 214, 268	BH		DISK	Instability in accretion onto rapidly rotating BH
30.	Dasgupta	1979	Ap & SS, 63, 517	DG		SOL	Charged intergal rel dust grain enters sol sys, breaks up
31.	Tsygan	1980	A&A, 87, 224	WD		DISK	WD surface nuclear burst causes chromospheric flares
32.	Tsygan	1980	A&A, 87, 224	NS		DISK	NS surface nuclear burst causes chromospheric flares
33.	Ramaty et al.	1981	Ap & SS, 75, 193	NS		DISK	NS vibrations heat atm to pair produce, annihilate, synch cool
34.	Newman et al.	1980	ApJ, 242, 319	NS	AST	DISK	Asteroid from interstellar medium hits NS
35.	Ramaty et al.	1980	Nature, 287, 122	NS		HALO	NS core quake caused by phase transition, vibrations
36.	Howard et al.	1981	ApJ, 249, 302	NS	AST	DISK	Asteroid hits NS, B-field confines mass, creates high temp
37.	Mitrofanov et al.	1981	Ap & SS, 77, 469	NS		DISK	Helium flash cooled by MHD waves in NS outer layers
38.	Colgate et al.	1981	ApJ, 248, 771	NS	AST	DISK	Asteroid hits NS, tidally disrupts, heated, expelled along B lines
39.	van Buren	1981	ApJ, 249, 297	NS	AST	DISK	Asteroid enters NS B field, dragged to surface collision
40.	Kuznetsov	1982	CosRes, 20, 72	MG		SOL	Magnetic reconnection at heliopause
41.	Katz	1982	ApJ, 260, 371	NS		DISK	NS flares from pair plasma confined in NS magnetosphere
42.	Woosley et al.	1982	ApJ, 258, 716	NS		DISK	Magnetic reconnection after NS surface He flash
43.	Fryxell et al.	1982	ApJ, 258, 733	NS		DISK	He fusion runaway on NS B-pole helium lake
44.	Hameury et al.	1982	A&A, 111, 242	NS		DISK	e- capture triggers H flash triggers He flash on NS surface
45.	Mitrofanov et al	1982	MNRAS, 200, 1033	NS		DISK	B induced cyclo res in rad absorp giving rel e-s, inv C scat
46.	Fenimore et al.	1982	Nature, 297, 665	NS		DISK	BB X-rays inv Comp scat by hotter overlying plasma
47.	Lipunov et al.	1982	Ap & SS, 85, 459	NS	ISM	DISK	ISM matter accum at NS magnetopause then suddenly accretes
48.	Baan	1982	ApJ, 261, L71	WD		HALO	Nonexplosive collapse of WD into rotating, cooling NS
49.	Ventura et al.	1983	Nature, 301, 491	NS	ST	DISK	NS accretion from low mass binary companion
50.	Bisnovatyi- et al.	1983	Ap & SS, 89, 447	NS		DISK	Neutron rich elements to NS surface with quake, undergo fission
51.	Bisnovatyi- et al.	1984	SovAstron, 28, 62	NS		DISK	Thermonuclear explosion beneath NS surface
52.	Ellison et al.	1983	A&A, 128, 102	NS		HALO	NS corequake + uneven heating yield SGR pulsations
53.	Hameury et al.	1983	A&A, 128, 369	NS		DISK	B field contains matter on NS cap allowing fusion
54.	Bonazzola et al.	1984	A&A, 136, 89	NS		DISK	NS surface nuc explosion causes small scale B reconnection
55.	Michel	1985	ApJ, 290, 721	NS		DISK	Remnant disk ionization instability causes sudden accretion
56.	Liang	1984	ApJ, 283, L21	NS		DISK	Resonant EM absorp during magnetic flare gives hot sync e-s
57.	Liang et al.	1984	Nature, 310, 121	NS		DISK	NS magnetic fields get twisted, recombine, create flare
58.	Mitrofanov	1984	Ap & SS, 105, 245	NS		DISK	NS magnetosphere excited by starquake
59.	Epstein	1985	ApJ, 291, 822	NS		DISK	Accretion instability between NS and disk
60.	Schlovskii et al.	1985	MNRAS, 212, 545	NS		HALO	Old NS in Galactic halo undergoes starquake
61.	Tsygan	1984	Ap & SS, 106, 199	NS		DISK	Weak B field NS spherically accretes, Comptonizes X-rays
62.	Usov	1984	Ap & SS, 107, 191	NS		DISK	NS flares result of magnetic convective-oscillation instability
63.	Hameury et al.	1985	ApJ, 293, 56	NS		DISK	High Landau e-s beamed along B lines in cold atm of NS
64.	Rappaport et al.	1985	Nature, 314, 242	NS		DISK	NS + low mass stellar companion gives GRB + optical flash
65.	Tremaine et al.	1986	ApJ, 301, 155	NS	COM	DISK	NS tides disrupt comet, debris hits NS next pass
66.	Muslimov et al.	1986	Ap & SS, 120, 27	NS		HALO	Radially oscillating NS
67.	Sturrock	1986	Nature, 321, 47	NS		DISK	Flare in the magnetosphere of NS accelerates e-s along B-field
68.	Paczynski	1986	ApJ, 308, L43	NS		COS	Cosmo GRBs: rel e- e+ opt thk plasma outflow indicated
69.	Bisnovatyi- et al	1986	SovAstron, 30, 582	NS		DISK	Chain fission of superheavy nuclei below NS surface during SN
70.	Alcock et al.	1986	PRL, 57, 2088	SS	SS	DISK	SN ejects strange mat lump craters rotating SS companion
71.	Vahia et al.	1988	A&A, 207, 55	ST		DISK	Magnetically active stellar system gives stellar flare
72.	Babul et al.	1987	ApJ, 316, L49	CS		COS	GRB result of energy released from cusp of cosmic string
73.	Livio et al.	1987	Nature, 327, 398	NS	COM	DISK	Oort cloud around NS can explain soft gamma-repeaters
74.	McBreen et al.	1988	Nature, 332, 234	GAL	AGN	COS	G-wave bkgrd makes BL Lac wiggle across galaxy lens caustic
75.	Curtis	1988	ApJ, 327, L81	WD		COS	WD collapses, burns to form new class of stable particles
76.	Melia	1988	ApJ, 335, 965	NS		DISK	Be/X-ray binary sys evolves to NS accretion GRB with recurrence
77.	Ruderman et al.	1988	ApJ, 335, 306	NS		DISK	e+ e- cascades by aligned pulsar outer-mag-sphere reignition
78.	Paczynski	1988	ApJ, 335, 525	CS		COS	Energy released from cusp of cosmic string (revised)
79.	Murikami et al.	1988	Nature, 335, 234	NS		DISK	Absorption features suggest separate colder region near NS
80.	Melia	1988	Nature, 336, 658	NS		DISK	NS + accretion disk reflection explains GRB spectra
81.	Blaes et al.	1989	ApJ, 343, 839	NS		DISK	NS seismic waves couple to magnetospheric Alfen waves
82.	Trofimenko et al.	1989	Ap & SS, 152, 105	WH		COS	Kerr-Newman white holes
83.	Sturrock et al.	1989	ApJ, 346, 950	NS		DISK	NS E-field accelerates electrons which then pair cascade
84.	Fenimore et al.	1988	ApJ, 335, L71	NS		DISK	Narrow absorption features indicate small cold area on NS
85.	Rodrigues	1989	AJ, 98, 2280	WD	WD	DISK	Binary member loses part of crust, through L1, hits primary
86.	Pineault et al.	1989	ApJ, 347, 1141	NS	COM	DISK	Fast NS wanders though Oort clouds, fast WD bursts only optical
87.	Melia et al.	1989	ApJ, 346, 378	NS		DISK	Episodic electrostatic accel and Comp scat from rot high-B NS
88.	Trofimenko	1989	Ap & SS, 159, 301	WH		COS	Different types of white, "grey" holes can emit GRBs
89.	Eichler et al.	1989	Nature, 340, 126	NS	NS	COS	NS - NS binary members collide, coalesce
90.	Wang et al.	1989	PRL, 63, 1550	NS		DISK	Cyclo res & Raman scat fits 20, 40 keV dips, magnetized NS
91.	Alexander et al.	1989	ApJ, 344, L1	NS		DISK	QED mag resonant opacity in NS atmosphere
92.	Melia	1990	ApJ, 351, 601	NS		DISK	NS magnetospheric plasma oscillations
93.	Ho et al.	1990	ApJ, 348, L25	NS		DISK	Beaming of radiation necessary from magnetized neutron stars
94.	Mitrofanov et al.	1990	Ap & SS, 165, 137	NS	COM	DISK	Interstellar comets pass through dead pulsar's magnetosphere
95.	Dermer	1990	ApJ, 360, 197	NS		DISK	Compton scattering in strong NS magnetic field
96.	Blaes et al.	1990	ApJ, 363, 612	NS	ISM	DISK	Old NS accretes from ISM, surface goes nuclear
97.	Paczynski	1990	ApJ, 363, 218	NS	NS	COS	NS-NS collision causes neutrino collisions, drives super-Ed wind
98.	Zdziarski et al.	1991	ApJ, 366, 343	RE	MBR	COS	Scattering of microwave background photons by rel e-s
99.	Pineault	1990	Nature, 345, 233	NS	COM	DISK	Young NS drifts through its own Oort cloud
100.	Trofimenko et al.	1991	Ap & SS, 178, 217	WH		HALO	White hole supernova gave simultaneous burst of g-waves from 1987A
101.	Melia et al.	1991	ApJ, 373, 198	NS		DISK	NS B-field undergoes resistive tearing, accelerates plasma
102.	Holcomb et al.	1991	ApJ, 378, 682	NS		DISK	Alfen waves in non-uniform NS atmosphere accelerate particles
103.	Haensel et al.	1991	ApJ, 375, 209	SS	SS	COS	Strange stars emit binding energy in grav rad and collide
104.	Blaes et al.	1991	ApJ, 381, 210	NS	ISM	DISK	Slow interstellar accretion onto NS, e- capture starquakes result
105.	Frank et al.	1992	ApJ, 385, L45	NS		DISK	Low mass X-ray binary evolve into GRB sites
106.	Woosley et al.	1992	ApJ, 391, 228	NS		HALO	Accreting WD collapsed to NS
107.	Dar et al.	1992	ApJ, 388, 164	WD		COS	WD accretes to form naked NS, GRB, cosmic rays
108.	Hanami	1992	ApJ, 389, L71	NS	PLAN	COS	NS - planet magnetospheric interaction unstable
109.	Meszaros et al.	1992	ApJ, 397, 570	NS	NS	COS	NS - NS collision produces anisotropic fireball
110.	Carter	1992	ApJ, 391, L67	BH	ST	COS	Normal stars tidally disrupted by galactic nucleus BH
111.	Usov	1992	Nature, 357, 472	NS		COS	WD collapses to form NS, B-field brakes NS rotation instantly
112.	Narayan et al.	1992	ApJ, 395, L83	NS	NS	COS	NS - NS merger gives optically thick fireball
113.	Narayan et al.	1992	ApJ, 395, L83	BH	NS	COS	BH - NS merger gives optically thick fireball
114.	Brainerd	1992	ApJ, 394, L33	AGN	JET	COS	Synchrotron emission from AGN jets
115.	Meszaros et al.	1992	MNRAS, 257, 29P	BH	NS	COS	BH-NS have neutrinos collide to gammas in clean fireball
116.	Meszaros et al.	1992	MNRAS, 257, 29P	NS	NS	COS	NS-NS have neutrinos collide to gammas in clean fireball
117.	Cline et al.	1992	ApJ, 401, L57	BH		DISK	Primordial BHs evaporating could account for short hard GRBs
118.	Rees et al.	1992	MNRAS, 258, 41P	NS	ISM	COS	Relativistic fireball reconverted to radiation when hits ISM

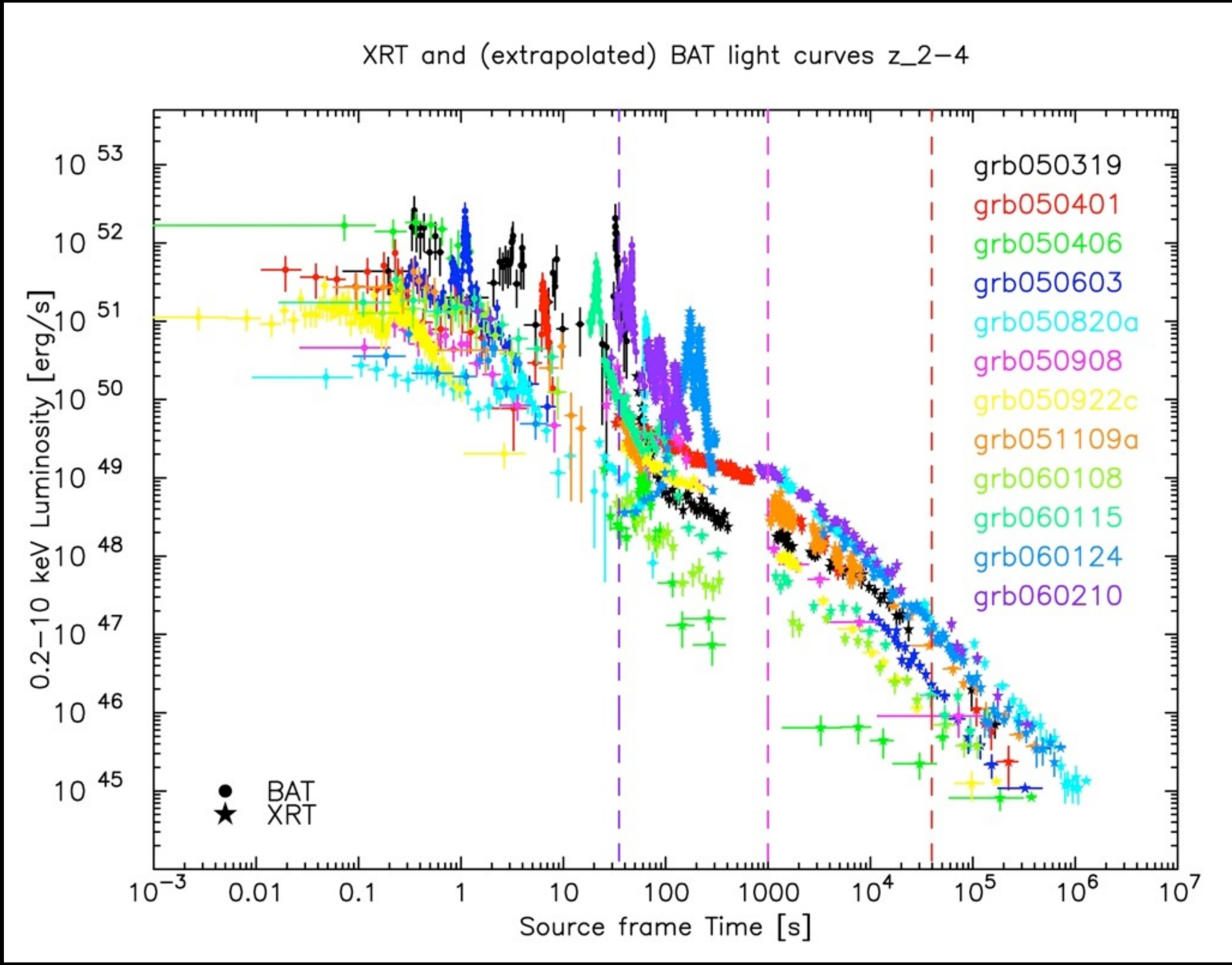
Table from: Nemiroff, R. J. 1993, Comments on Astrophysics, 17, No. 4, in press

Nemiroff 1993

Introduction:
observational facts (2) afterglow

Afterglows: lightcurves

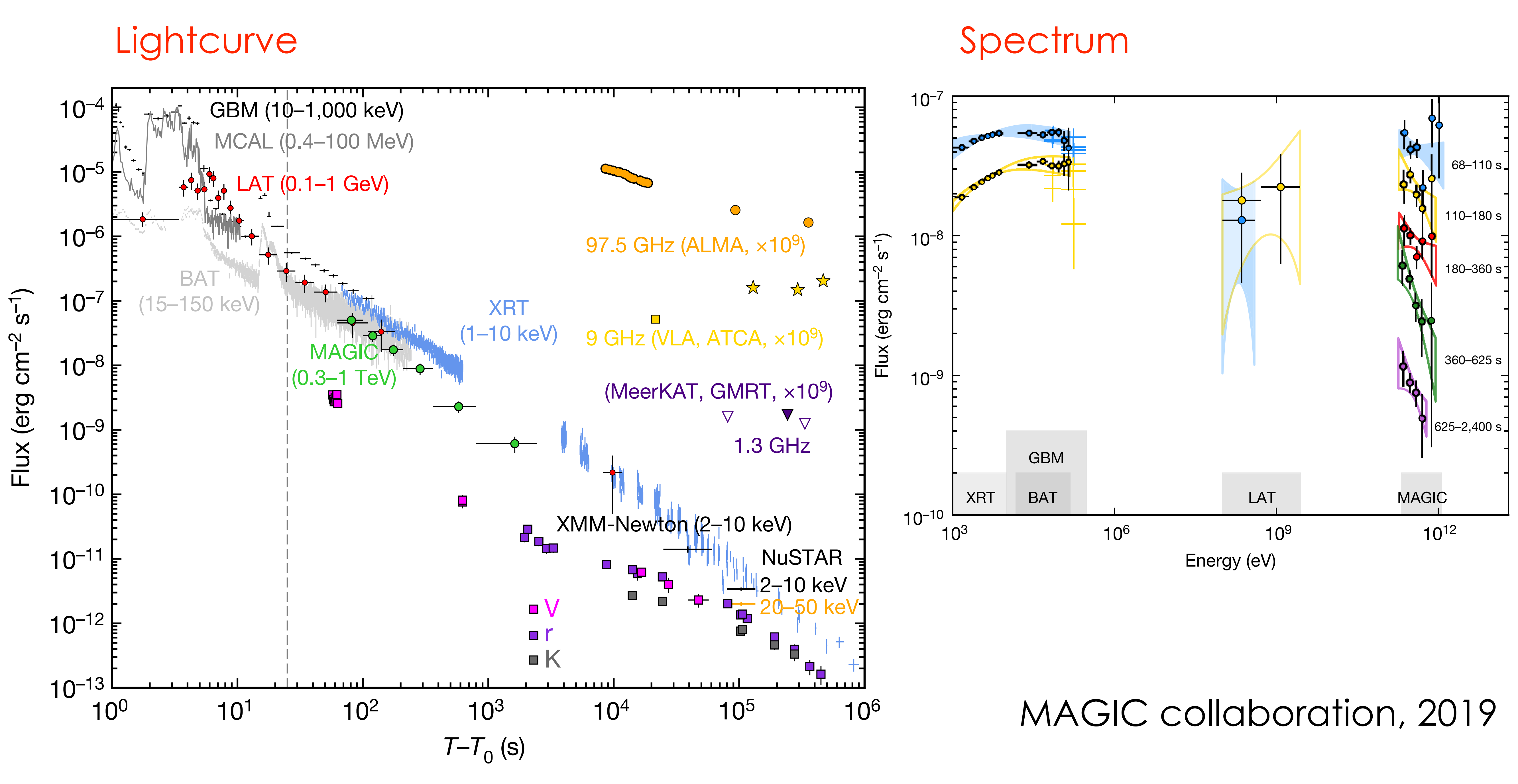
Complexity of the X-ray light curve (*Swift*)



[non-thermal spectrum: synchrotron?]

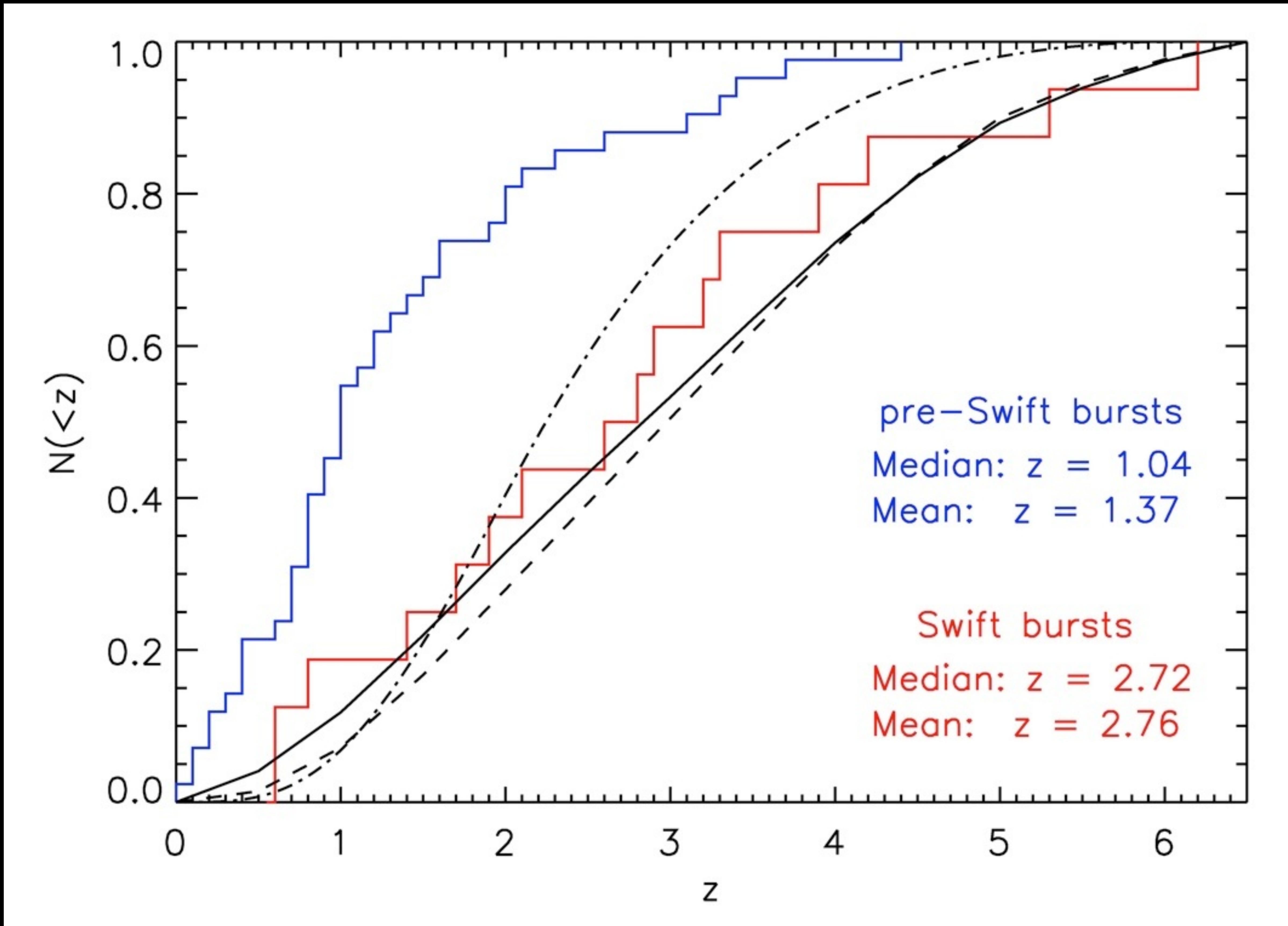
Spectrum: afterglow

Non-thermal spectrum
Several components? see recent observation of 190114C above 100 GeV



MAGIC collaboration, 2019

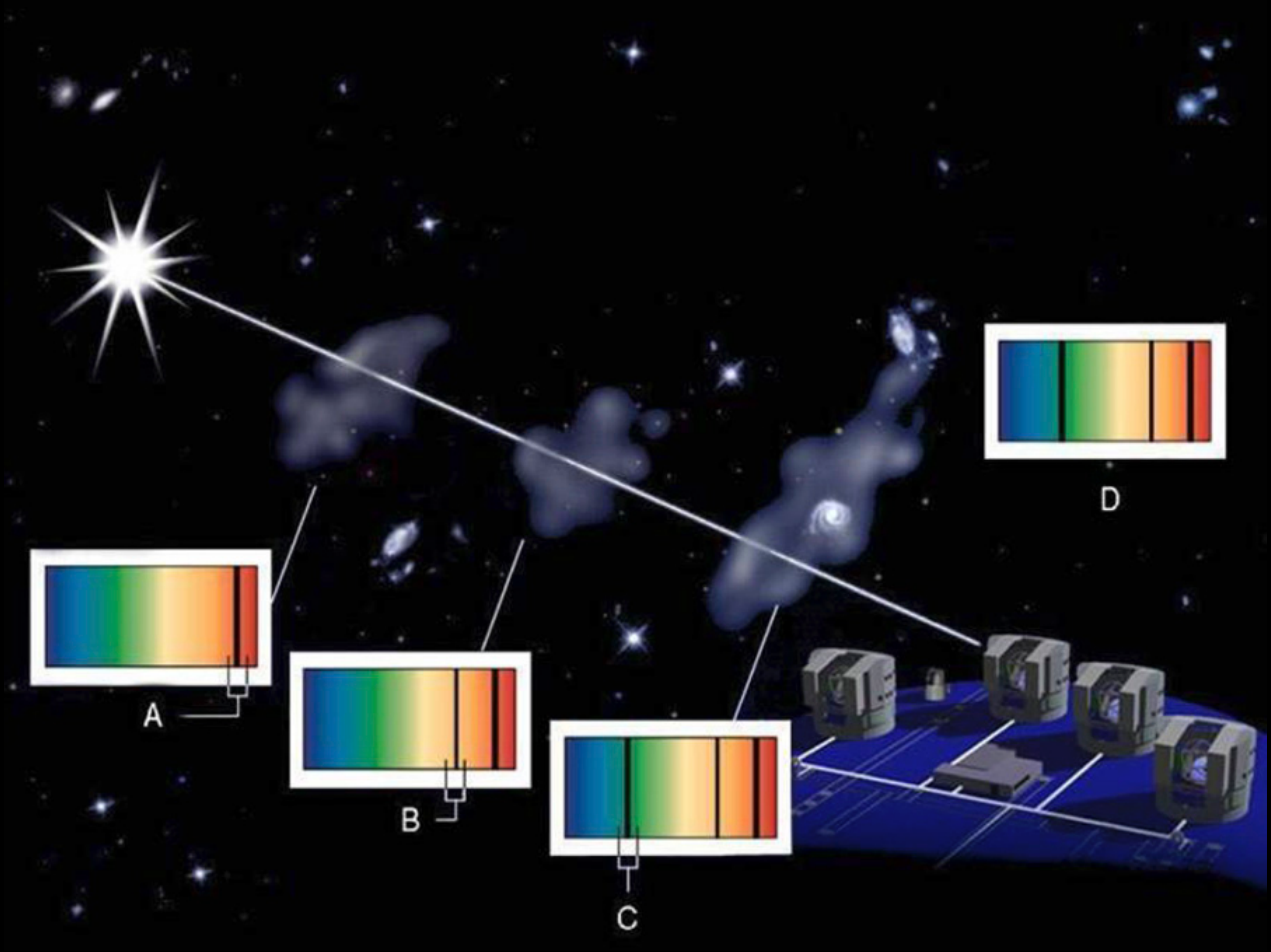
Distance: redshift distribution



Jakobsson et al. 2006

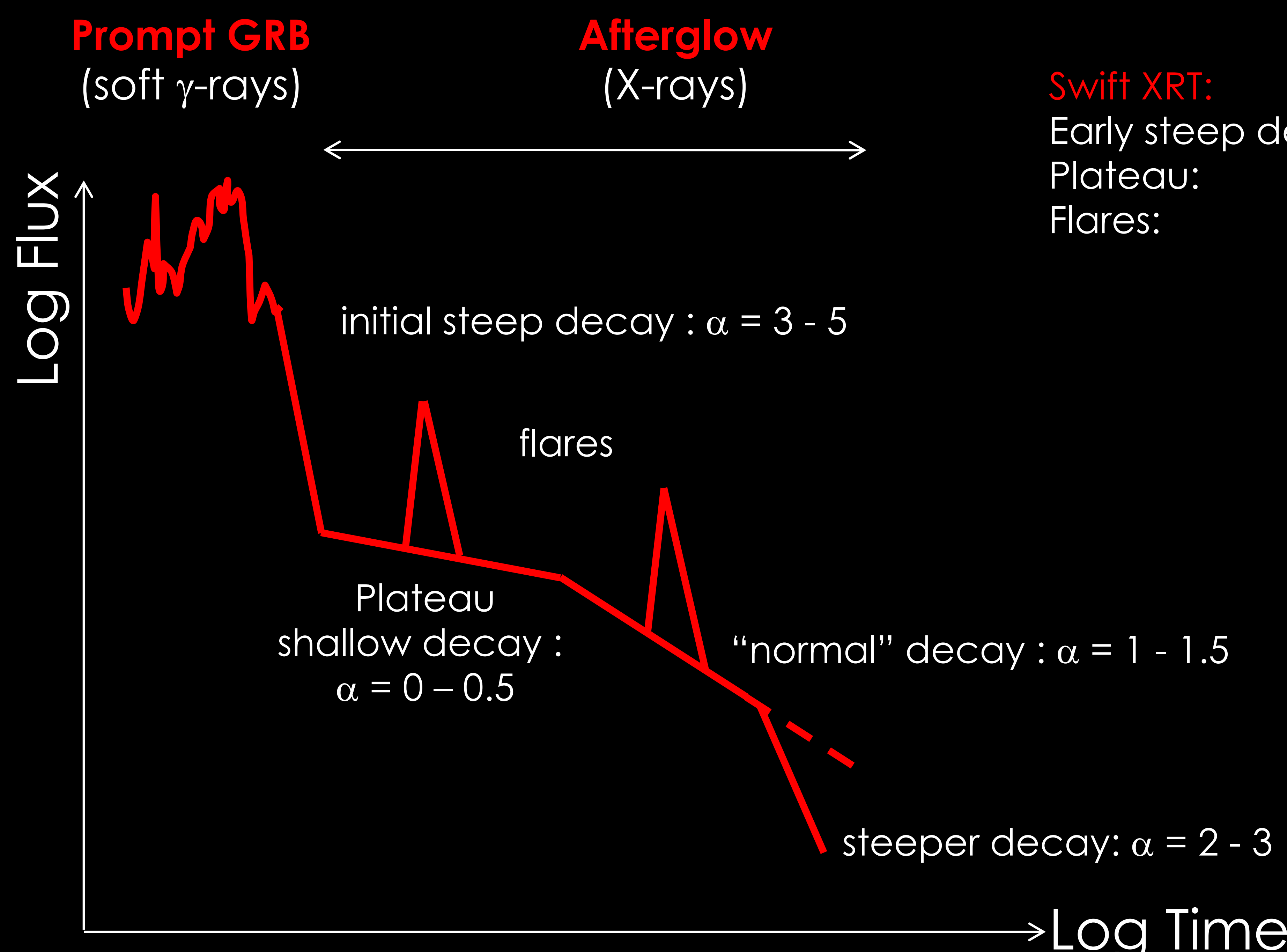
090423: z=8.2 (spectro-z) ; 090429B: z=9.4 (photo-z)

Gamma-ray bursts and cosmology



Introduction:
observational facts
(3) prompt+afterglow summary

Lightcurve: prompt to afterglow



Swift XRT:

Early steep decay:	>90%
Plateau:	~60%
Flares:	~30%

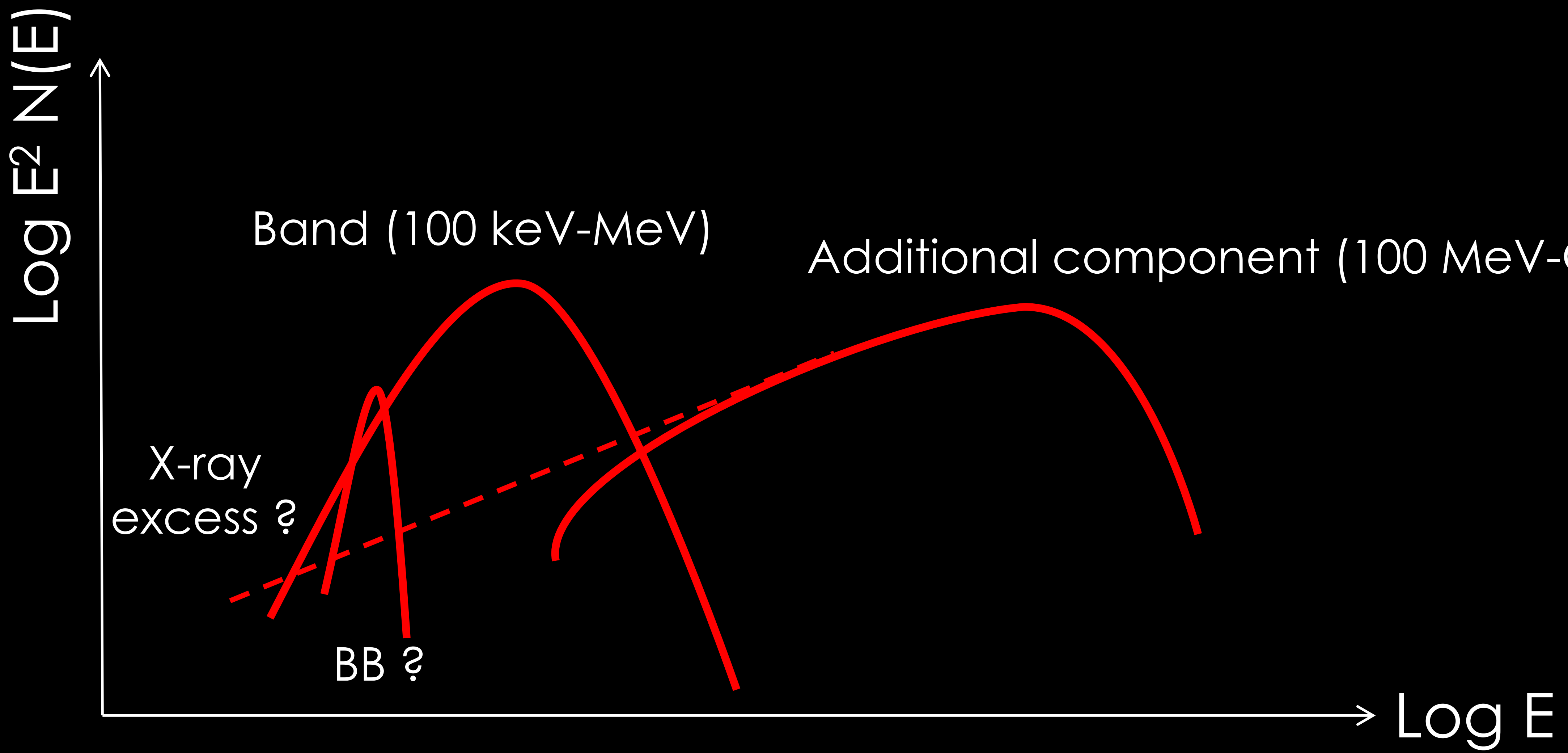
Also: prompt optical, GeV

Also: optical, radio afterglow
long-lasting Fermi/LAT emission
+ GRB 190114C (MAGIC)

Spectrum: prompt

Fermi/GBM:
BB looked for in bright cases
& found in many cases

Fermi/LAT: 1st catalog
extra-component in 4/28



Spectrum: afterglow

-non-thermal
-multi-component? probably (see GRB190114C, MAGIC)

Introduction:
Basic Constraints on any GRB Model

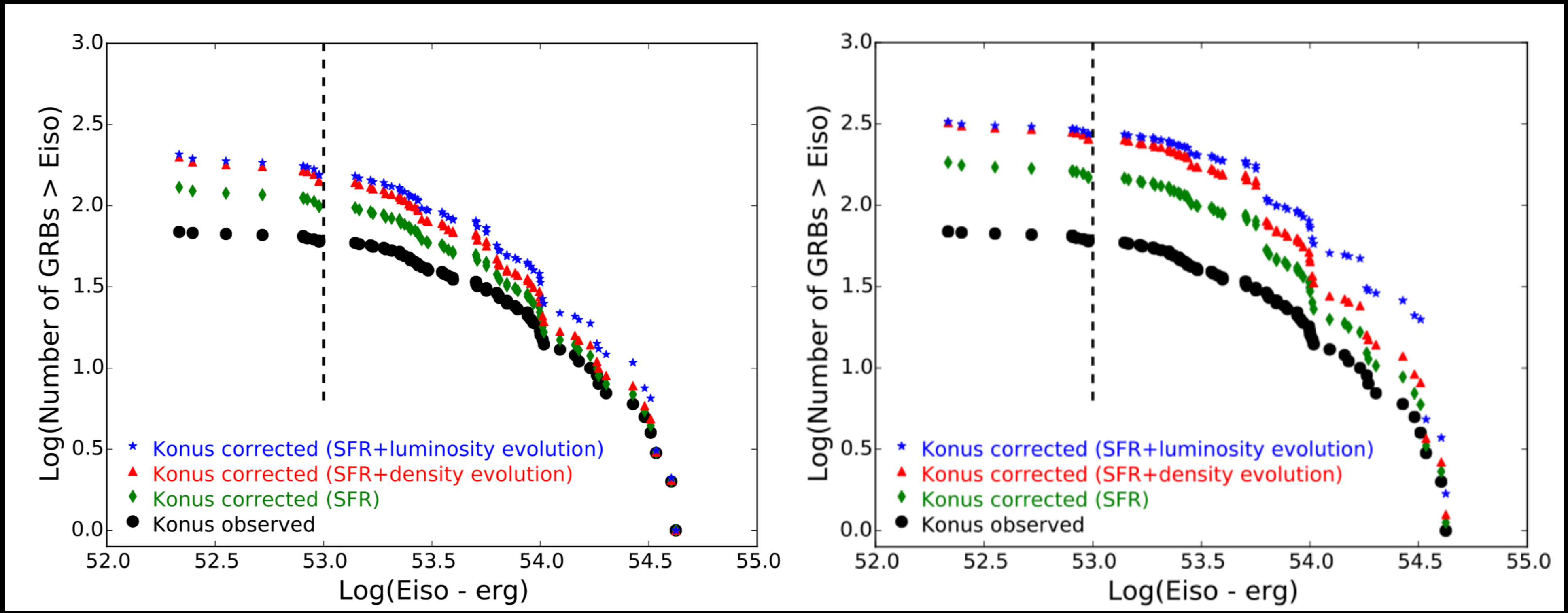
GRB Physics: basic constraints

- Cosmological distance: huge gamma-ray isotropic energy/luminosity

$$\mathcal{E}_{\gamma,\mathrm{iso}} \simeq 10^{50} - 10^{54}\,\mathrm{erg}$$

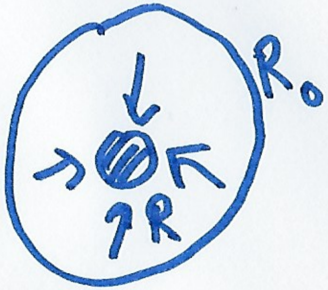
$$M_{\odot}c^2 \simeq 2\,10^{54}\,\mathrm{erg}$$

Maximum?
Atteia+ 2017



- Huge radiated energy on a short timescale:
  gravitational collapse & formation of a compact object (NS, BH)

- Short timescale variability: compact source (NS, BH)



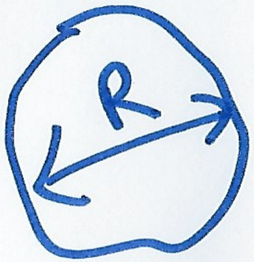
$$\Delta E \sim \Delta E_{grav}$$

$$\sim -E_{grav}(\text{final})$$

$$\simeq \alpha \frac{GM^2}{R} \simeq \alpha \underbrace{\frac{GM}{Rc^2}}_{\gtrsim 0.1} \underbrace{Mc^2}_{2\times10^{54}\,\text{erg}\,\frac{M}{M_\odot}}$$

$\gtrsim 0.1$ NS, BH

emission region



$$R \lesssim c\, t_{var}$$

GRB Physics: basic constraints

- Cosmological distance: huge gamma-ray isotropic energy/luminosity

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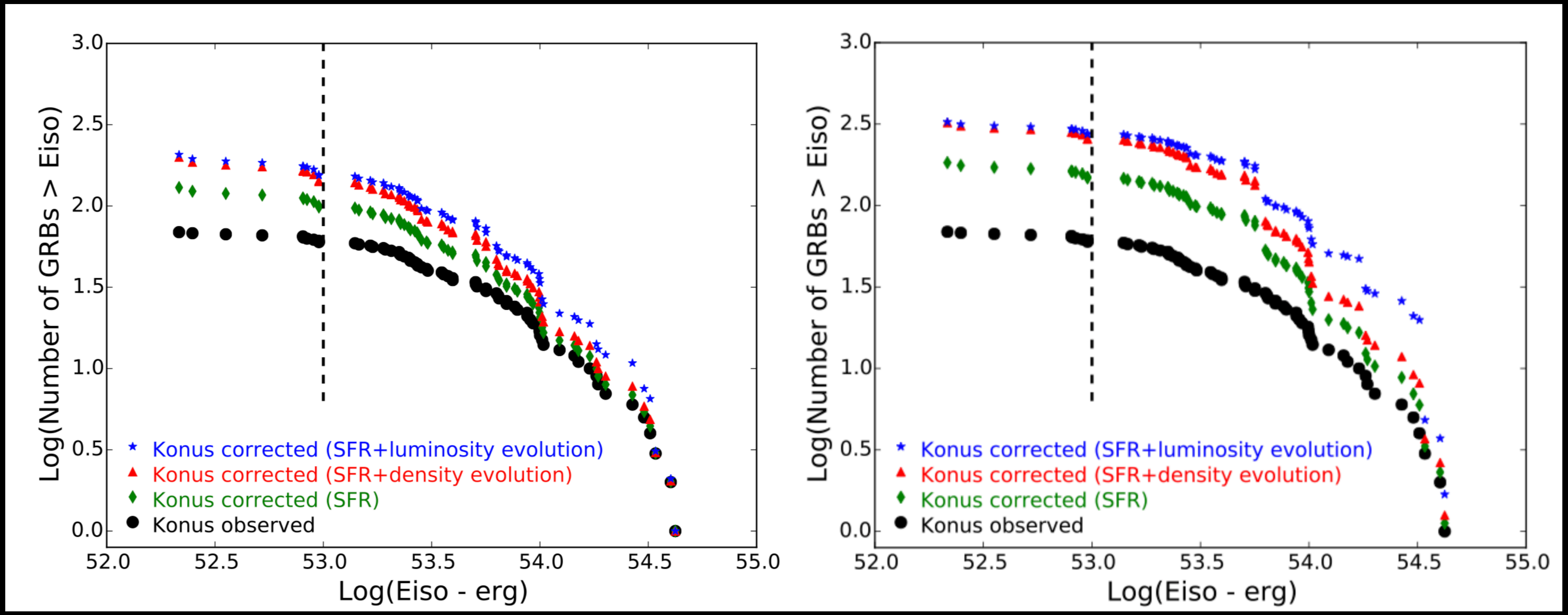


- Huge radiated energy on a short timescale:
gravitational collapse & formation of a compact object (NS, BH)

$$\Delta\mathcal{E}_{\mathrm{collapse}} \simeq \alpha\frac{GM^2}{E} \simeq 2\alpha\,10^{53}\,\mathrm{erg}\left(\frac{GM/Rc^2}{0.1}\right)\left(\frac{M}{M_{\odot}}\right)$$

- Short timescale variability: compact source (NS, BH)

$$R \lesssim c t_{\mathrm{var}} \simeq 3000\,\mathrm{km}\left(\frac{t_{\mathrm{var}}}{10\,\mathrm{ms}}\right)$$

(causality)

GRB Physics: basic constraints

- Huge radiated energy + short timescale variability: cataclysmic event leading to the formation of a compact source (NS, BH)

GRB Physics: basic constraints

- Huge radiated energy + short timescale variability: cataclysmic event leading to the formation of a compact source (NS, BH)

- Non-thermal gamma-ray spectrum: relativistic ejection (prompt emission is produced at large distance from the source)

Pair production:
$\gamma\gamma \to \mathrm{e}^+\mathrm{e}^-$

Threshold: $$\left(\frac{E_{\rm LE}}{m_{\rm e}c^2}\right)\left(\frac{E_{\rm HE}}{m_{\rm e}c^2}\right) \geq \frac{2}{1-\cos\theta}$$

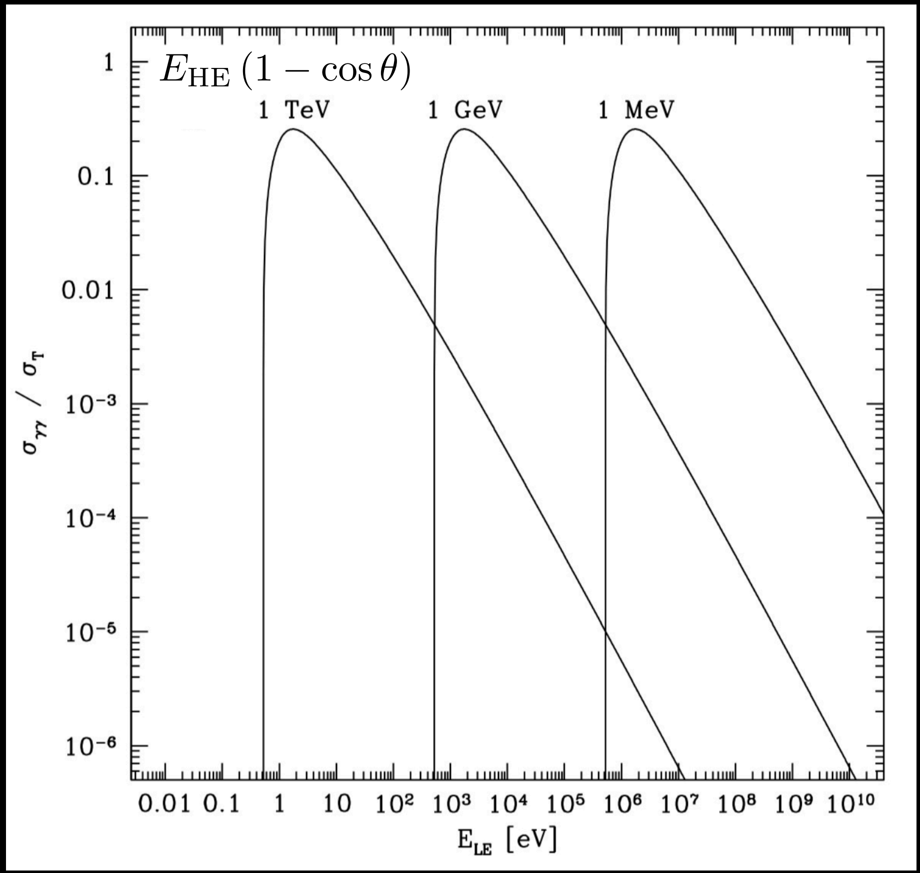
Cross section: $$\sigma_{\gamma\gamma}\left(E_{\rm LE}\,;E_{\rm HE},\theta\right) \simeq \sigma_{\rm T}\,\delta\left(1-\frac{E_{\rm LE}}{2E_{\rm th}(E_{\rm HE},\theta)}\right)$$

Observed soft-gamma ray spectrum (HE):

$$\frac{\mathrm{d}N}{\mathrm{d}E_{\rm obs}} \simeq (\beta-2)\,\frac{\mathcal{E}_{\gamma,\rm iso,HE}}{E_{\rm p,obs}^2}\left(\frac{E_{\rm obs}}{E_{\rm p,obs}}\right)^{-\beta}$$

with $\beta \simeq 2.3$ $\quad E_{\rm p,obs} \simeq 150\,\mathrm{keV}$

$E_{\rm max,obs} \gtrsim 1\,\mathrm{MeV}$



GRB Physics: basic constraints

- Huge radiated energy + short timescale variability: cataclysmic event leading to the formation of a compact source (NS, BH)

- Non-thermal gamma-ray spectrum: relativistic ejection (prompt emission is produced at large distance from the source)

$$\tau_{\gamma\gamma}(E_{\rm HE}) \simeq 2^{2-\beta}\frac{\beta-2}{\beta+1}\left(\frac{\ell}{V}\right)\frac{\mathcal{E}_{\gamma,{\rm iso,HE}}\sigma_{\rm T}}{E_{\rm p,obs}}\left(\frac{(m_{\rm e}c^2)^2}{E_{\rm p}E_{\rm HE}}\right)^{1-\beta}$$

Static case: $R \simeq c t_{\rm var}$ $\quad \ell \simeq R$ $\quad V \simeq \frac{4\pi}{3}R^3$ $\quad E_{\rm p} = E_{\rm p,obs}$ $\quad E_{\rm HE} = E_{\rm max,obs}$

$$\tau_{\gamma\gamma}(E_{\rm HE}) \simeq 6\,10^{15}\left(\frac{t_{\rm var}}{10\,{\rm ms}}\right)^{-2}\left(\frac{\mathcal{E}_{\gamma,{\rm iso,HE}}}{10^{52}\,{\rm erg}}\right)\left(\frac{E_{\rm p,obs}}{150\,{\rm keV}}\right)^{0.3}\left(\frac{E_{\rm max,obs}}{1\,{\rm MeV}}\right)^{1.3}$$

gamma-ray photons cannot escape from the source!

GRB Physics: basic constraints

- Huge radiated energy + short timescale variability: cataclysmic event leading to the formation of a compact source (NS, BH)

- Non-thermal gamma-ray spectrum: relativistic ejection (prompt emission is produced at large distance from the source)

$$\tau_{\gamma\gamma}(E_{\mathrm{HE}}) \simeq 2^{2-\beta}\frac{\beta-2}{\beta+1}\left(\frac{\ell}{V}\right)\frac{\mathcal{E}_{\gamma,\mathrm{iso,HE}}\sigma_{\mathrm{T}}}{E_{\mathrm{p,obs}}}\left(\frac{(m_{\mathrm{e}}c^2)^2}{E_{\mathrm{p}}E_{\mathrm{HE}}}\right)^{1-\beta}$$

Relativistic case:

GRB Physics: basic constraints

- Huge radiated energy + short timescale variability: cataclysmic event leading to the formation of a compact source (NS, BH)

- Non-thermal gamma-ray spectrum: relativistic ejection (prompt emission is produced at large distance from the source)

$$\tau_{\gamma\gamma}(E_{\mathrm{HE}}) \simeq 2^{2-\beta}\frac{\beta-2}{\beta+1}\left(\frac{\ell}{V}\right)\frac{\mathcal{E}_{\gamma,\mathrm{iso,HE}}\sigma_{\mathrm{T}}}{E_{\mathrm{p,obs}}}\left(\frac{(m_{\mathrm{e}}c^2)^2}{E_{\mathrm{p}}E_{\mathrm{HE}}}\right)^{1-\beta}$$

Relativistic case: comoving frame

$$R \simeq 2\Gamma^2 c t_{\mathrm{var}} \qquad \ell \simeq \frac{R}{\Gamma} \qquad V = 4\pi R^2 \ell \qquad E_{\mathrm{p}} = \frac{E_{\mathrm{p,obs}}}{\Gamma} \qquad E_{\mathrm{HE}} = \frac{E_{\mathrm{max,obs}}}{\Gamma}$$

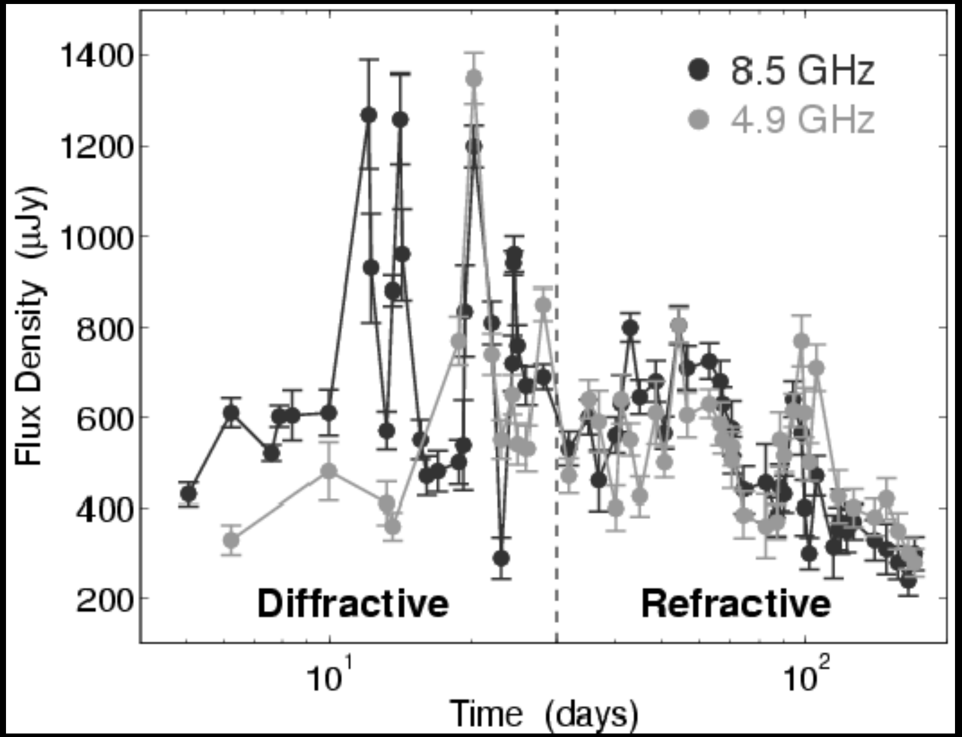
$$\tau_{\gamma\gamma}(E_{\mathrm{HE}}) \simeq 3\left(\frac{\Gamma}{100}\right)^{-6.6}\left(\frac{t_{\mathrm{var}}}{10\,\mathrm{ms}}\right)^{-2}\left(\frac{\mathcal{E}_{\gamma,\mathrm{iso,HE}}}{10^{52}\,\mathrm{erg}}\right)\left(\frac{E_{\mathrm{p,obs}}}{150\,\mathrm{keV}}\right)^{0.3}\left(\frac{E_{\mathrm{max,obs}}}{1\,\mathrm{MeV}}\right)^{1.3}$$

gamma-ray photons can escape if they are produced at large distance in a relativistic ejecta

Relativistic motion: direct evidence

Method 1 :
Radio scintillation quenches as the source increases
Transition diffractive / refractive : estimate of the size

From the size, the apparent velocity is deduced :
superluminic apparent motion: relativistic motion

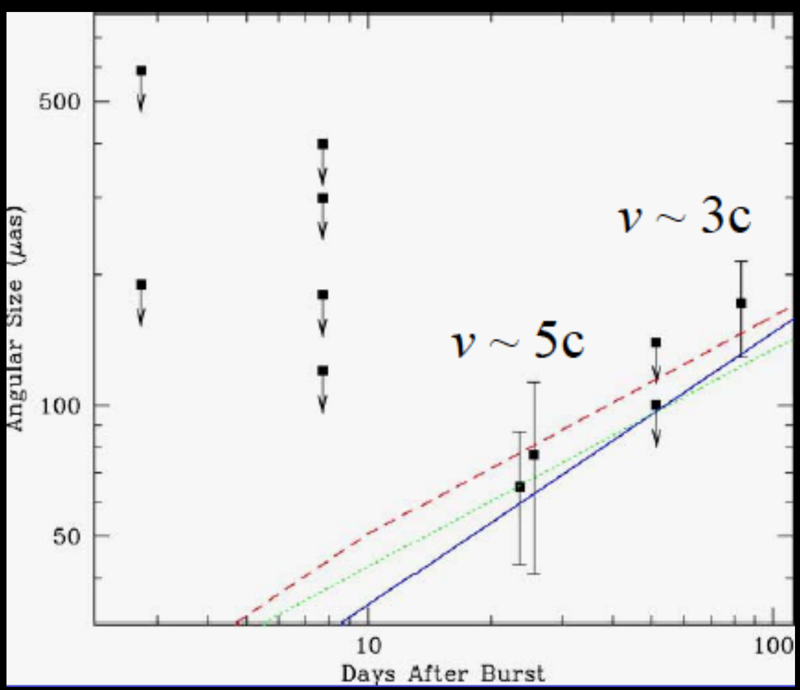


5 μas (2 10^{17} cm)

Relativistic motion: direct evidence

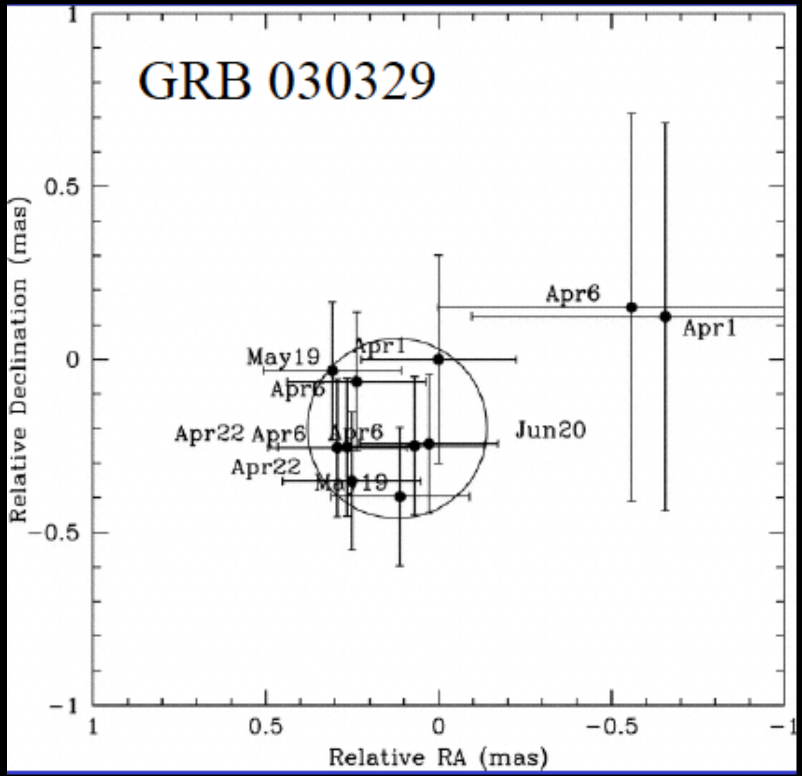
Method 2 :
VLBI allows to resolve the late afterglow for nearby bursts

From the size, the apparent velocity is deduced : superluminic apparent motion: relativistic motion



After 25 days:
65 μas (5.7 10^{17} cm)

Proper motion:
0.1 mas in 80 days



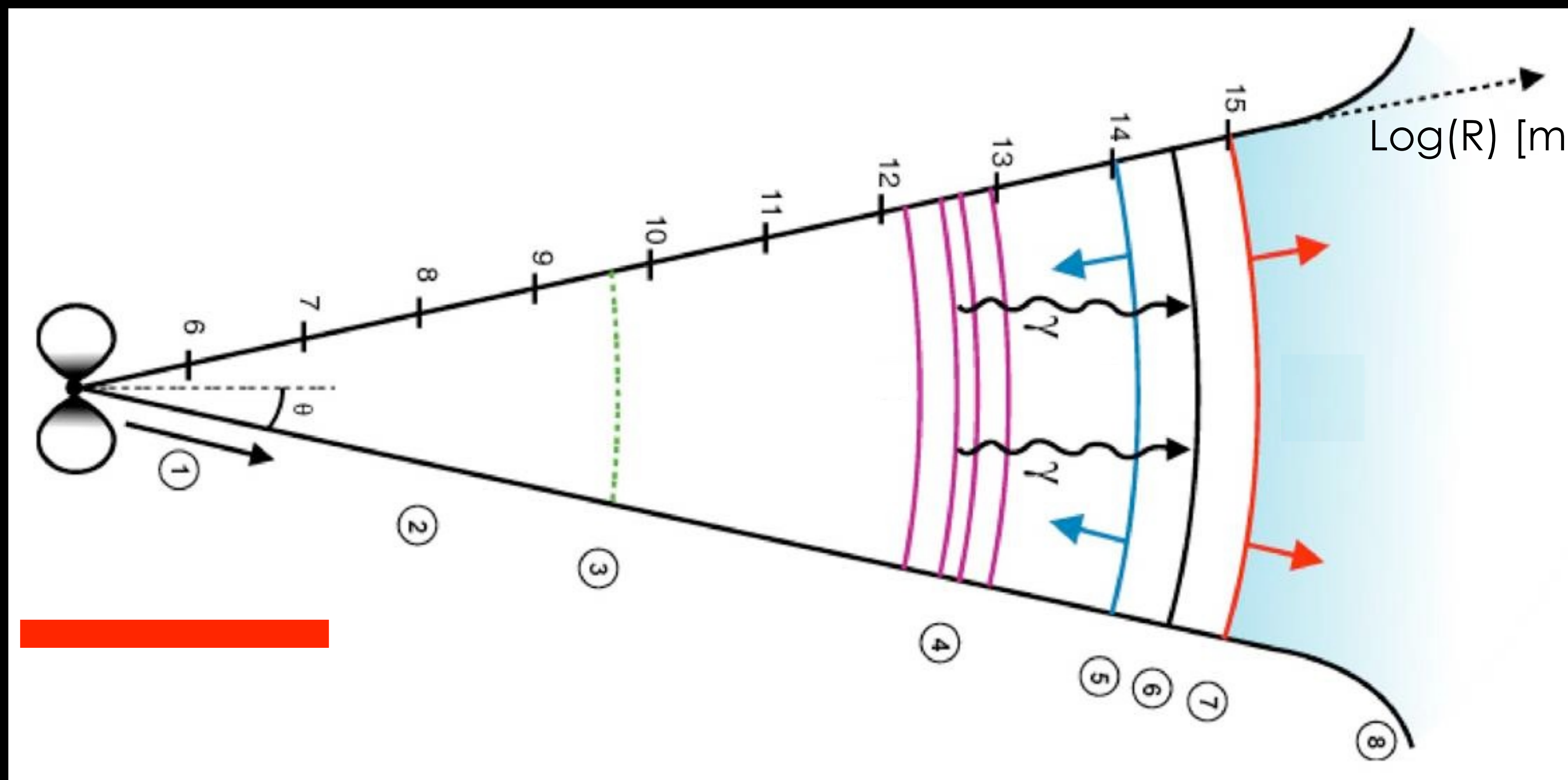
Taylor et al. 2004

A recent spectacular application: 170817's afterglow (see lecture #3)

GRB Physics: standard scenario & characteristic radii

GRB Physics: initial event & central engine

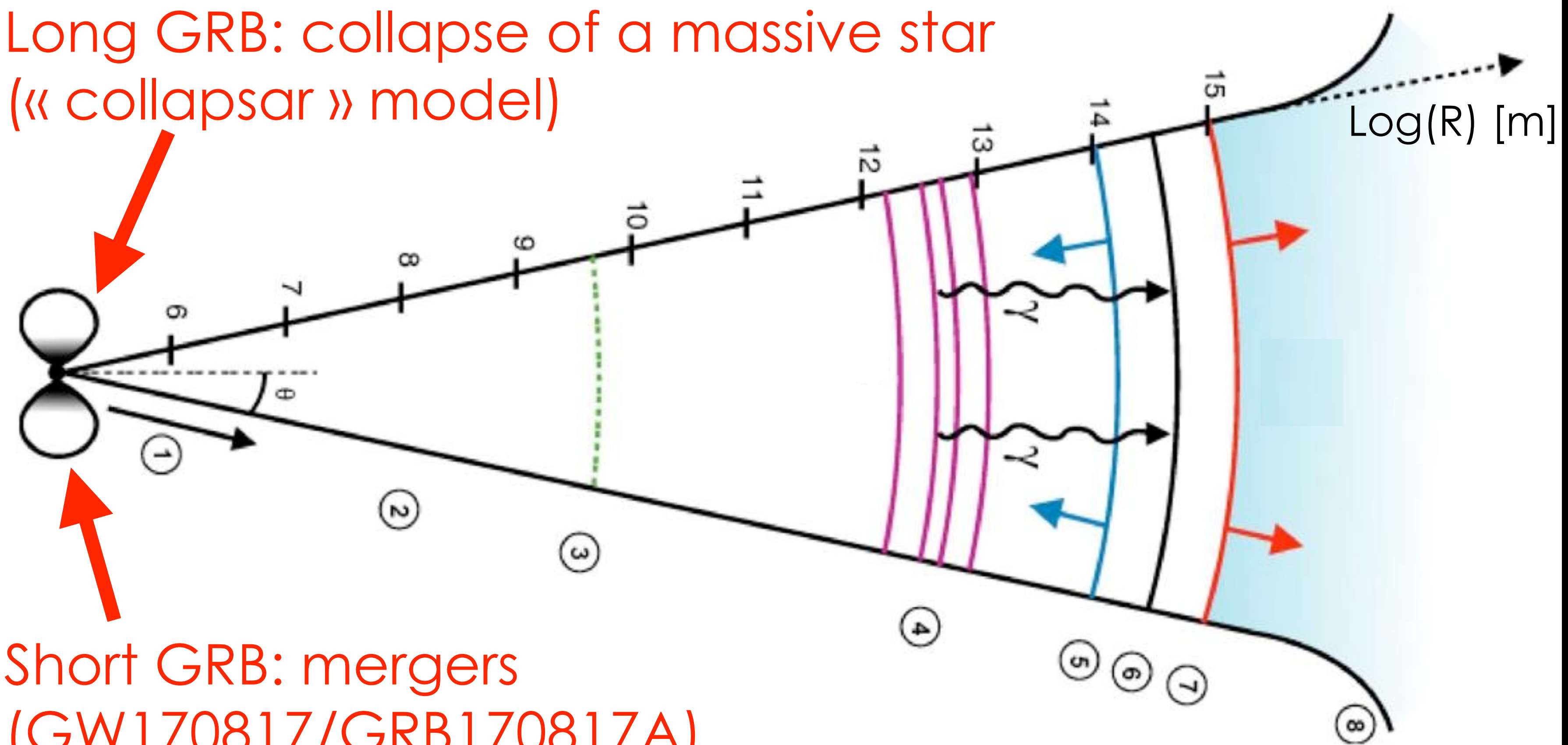
- Huge radiated energy ($E_{iso,\gamma}$~10^{50}-10^{55} erg) + short time scale variability (<100 ms): cataclysmic event leading to the formation of a stellar-mass compact object (accreting BH, magnetar)



GRB Physics: initial event & central engine

- Huge radiated energy ($E_{iso,\gamma} \sim 10^{50}$-$10^{55}$ erg) + short time scale variability (<100 ms): cataclysmic event leading to the formation of a stellar-mass compact object (accreting BH, magnetar)

Long GRB: collapse of a massive star
(« collapsar » model)



Short GRB: mergers
(GW170817/GRB170817A)