GAMMA-RAY BURSTS

Frédéric Daigne
(Institut d'Astrophysique de Paris; Sorbonne University)

Introduction	A brief history Observational Facts Basic Constraints on any GRB model: compact source + relativistic ejecta
Theory: Basic Elements	Progenitor / Central Engine / Relativistic Ejection Prompt GRB Emission: internal dissipation in a relativistic ejecta Afterglow: interaction Ejecta / External Medium (deceleration)

+ a selection of Modern Topics

The Transient Universe 2023 - Cargèse - June 5, 2023

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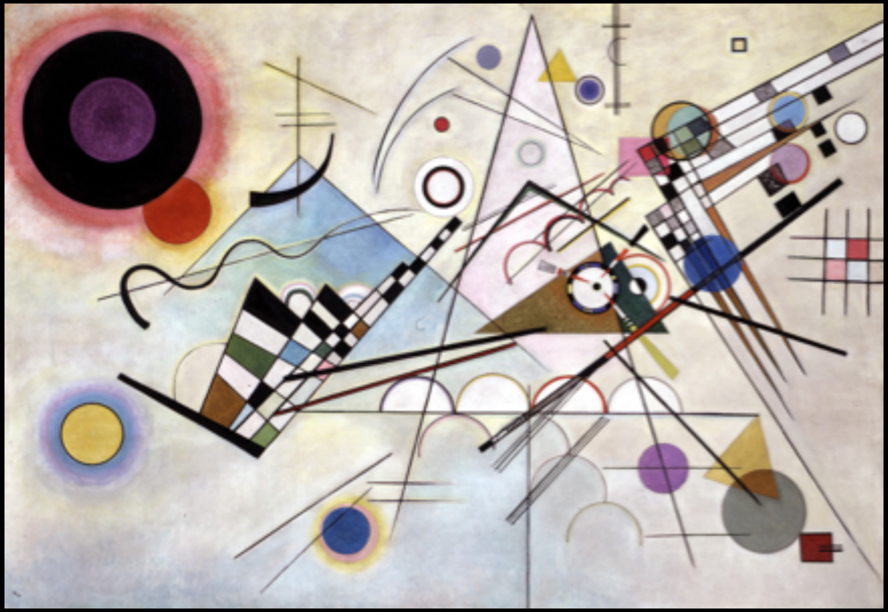

Kandinksy - Composition 8- 1923
Guggenheim Museum, New-York

Kandinksy - Curves and sharp angles - 1923
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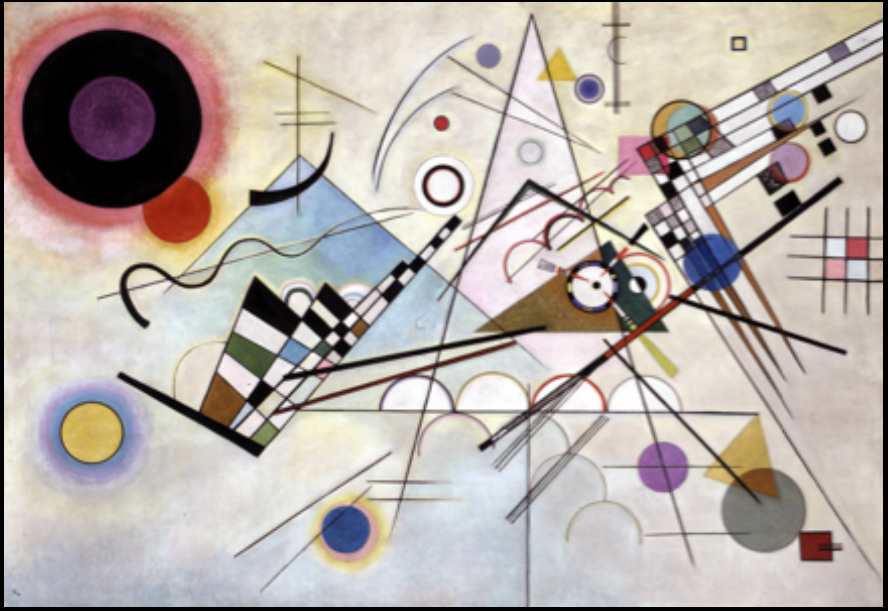

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**Relat.
Ejecta
&
Emission
γ
CR,ν?**

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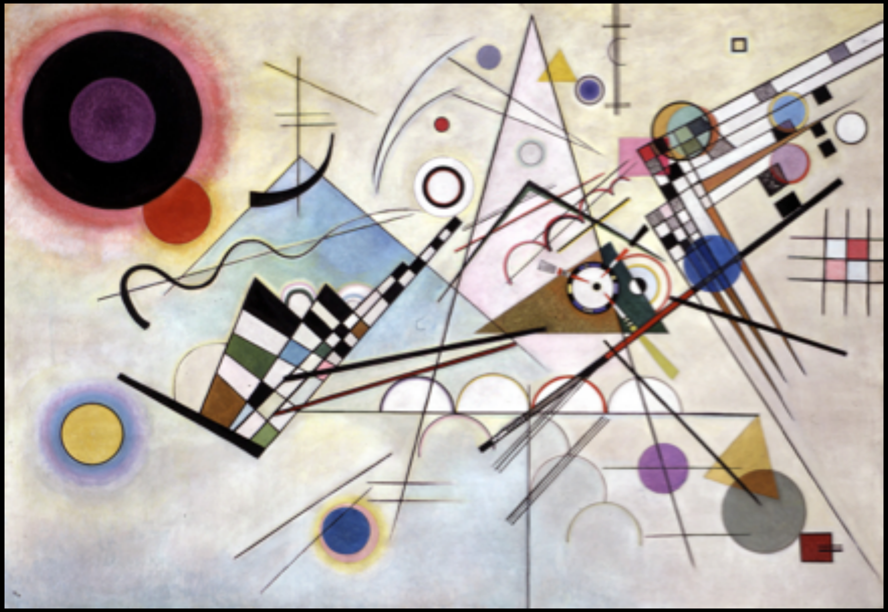

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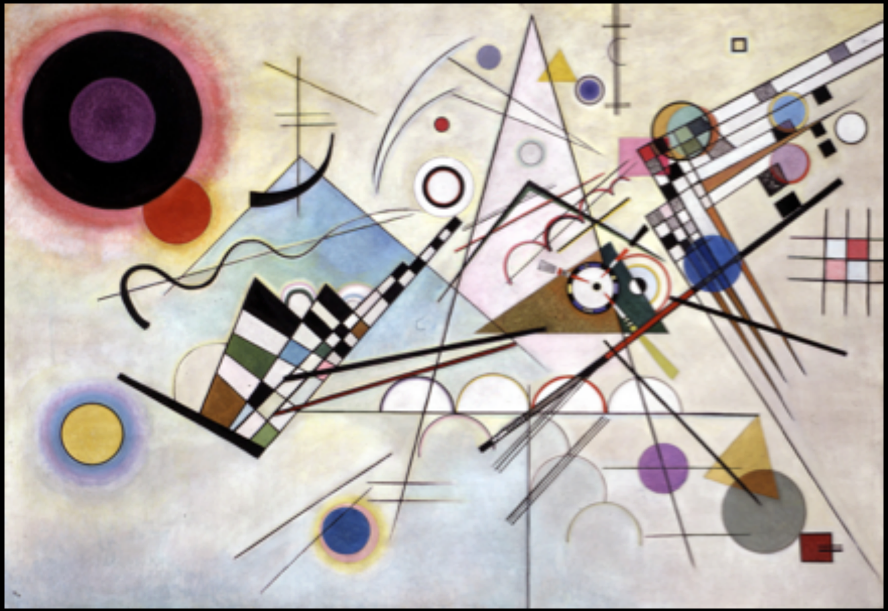

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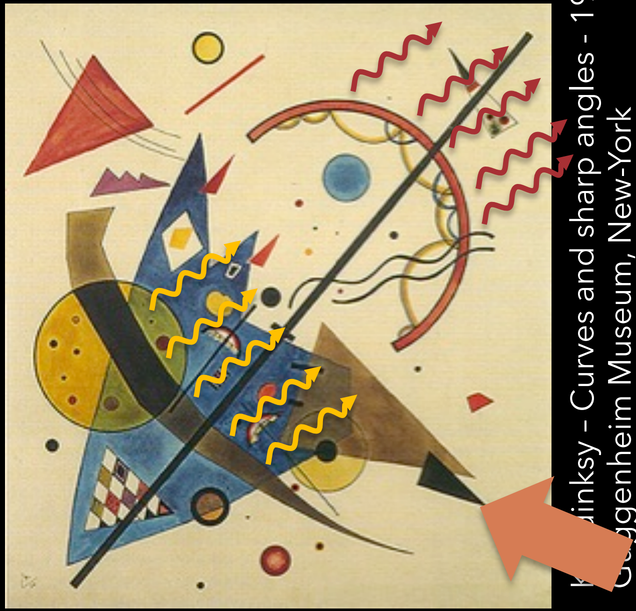

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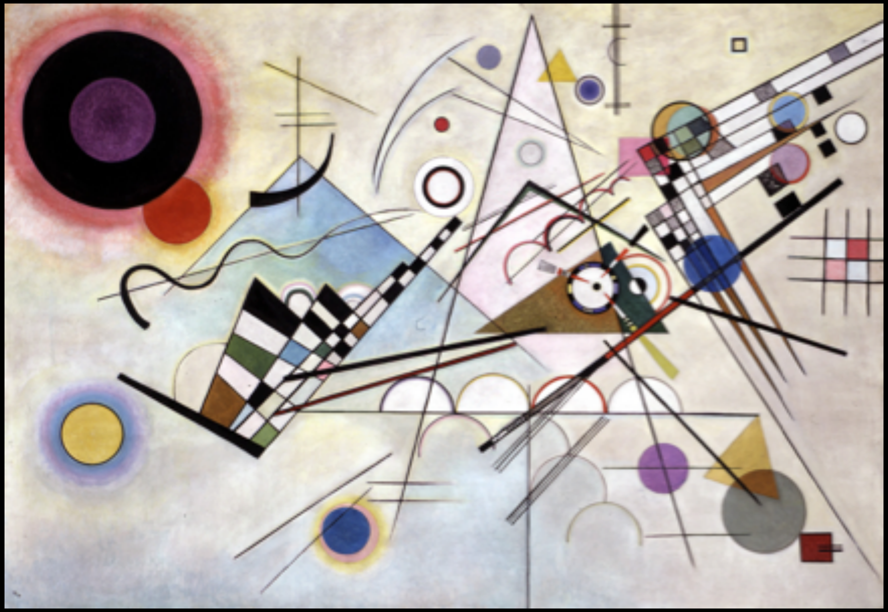

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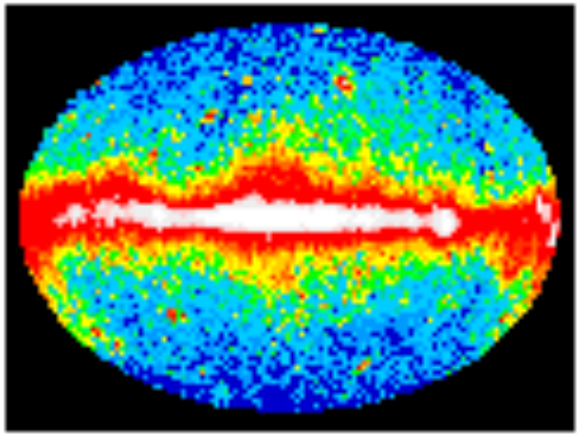
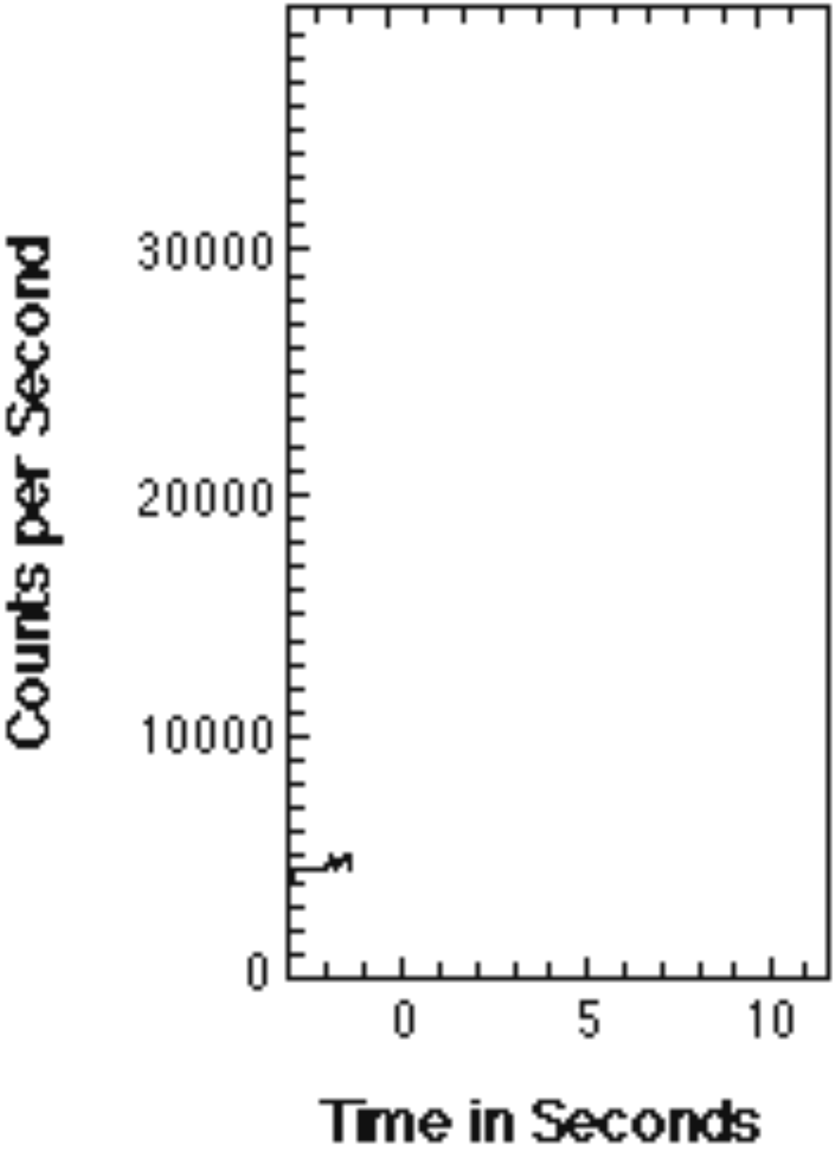
The Transient Universe 2023 - Cargèse - June 5, 2023

Introduction

What is a Gamma-Ray Burst?

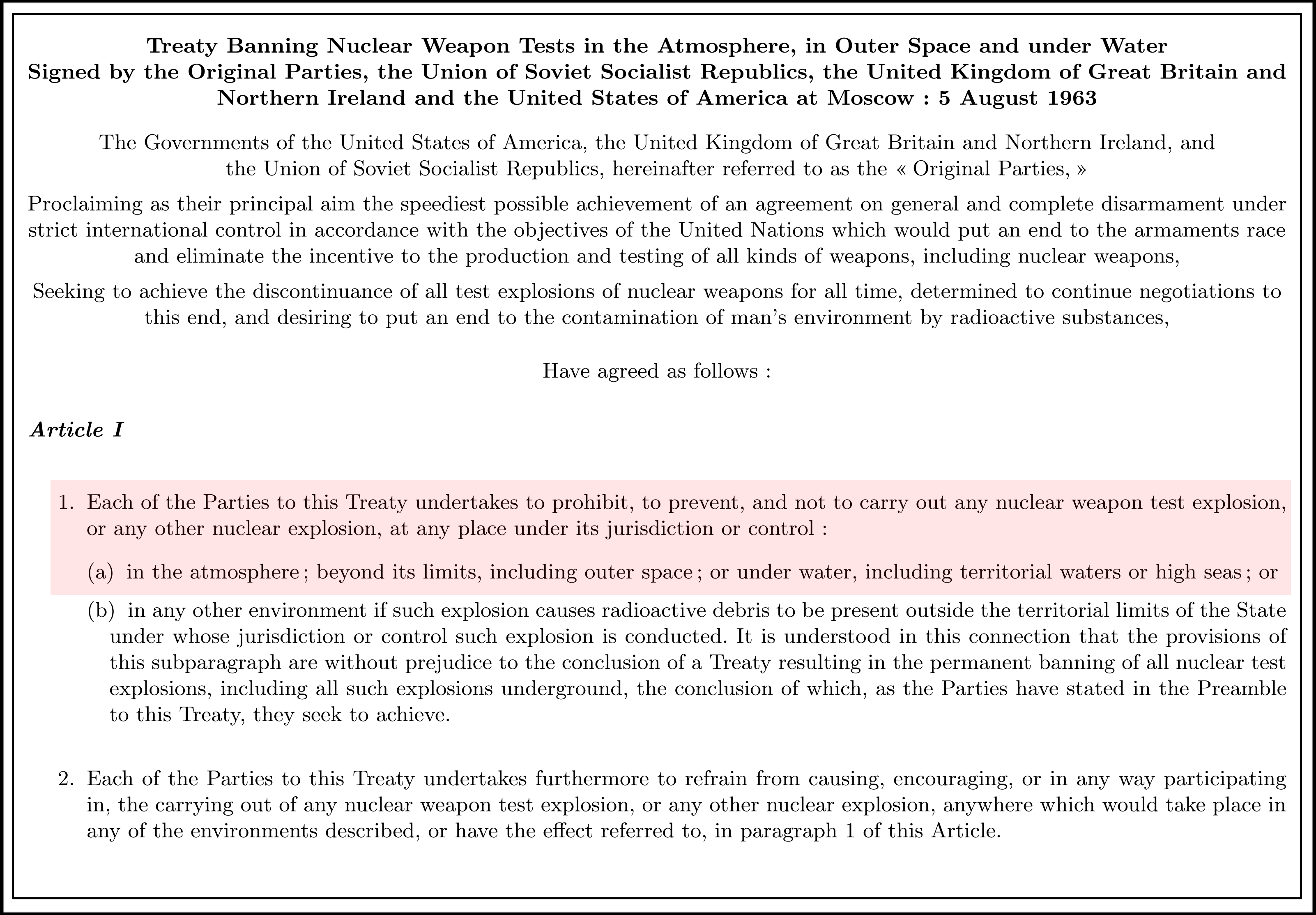



Counts per Second
30000
20000
10000
0
0
5
10
Time in Seconds

Introduction

Gamma-Ray Bursts: The discovery

Cuban Missile Crisis (October-November 1962)
Partial Nuclear Test Ban Treaty (5 August 1963)



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,

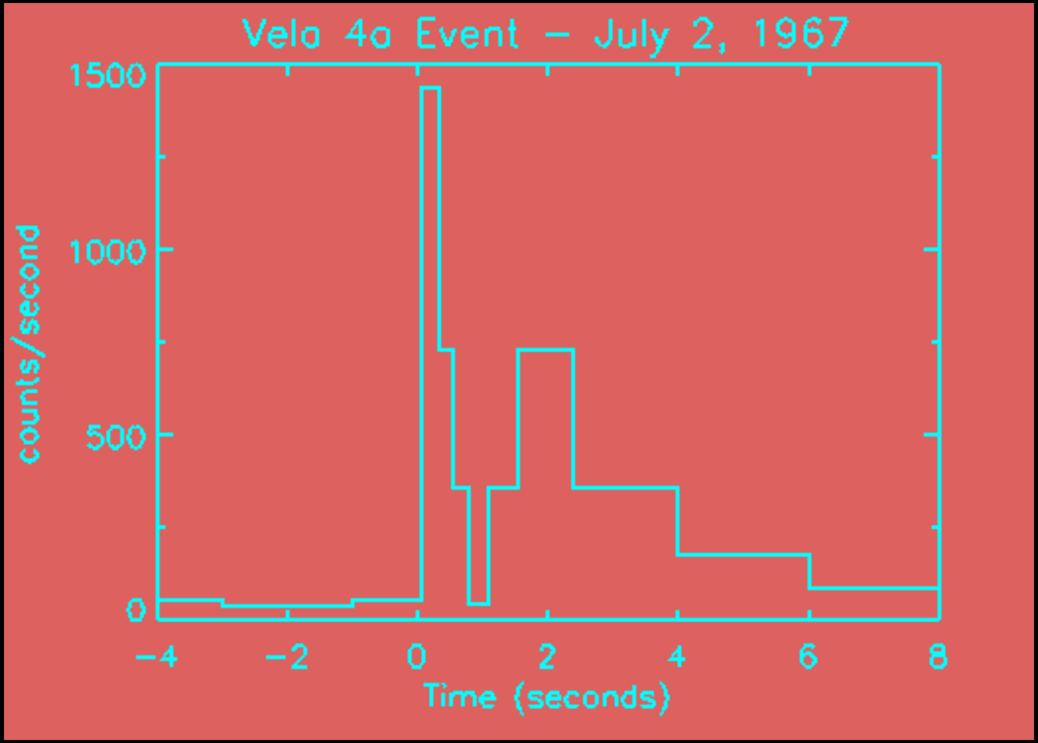
Seeking to achieve the discontinuance of all test explosions of nuclear weapons for all time, determined to continue negotiations to this end, and desiring to put an end to the contamination of man's environment by radioactive substances,

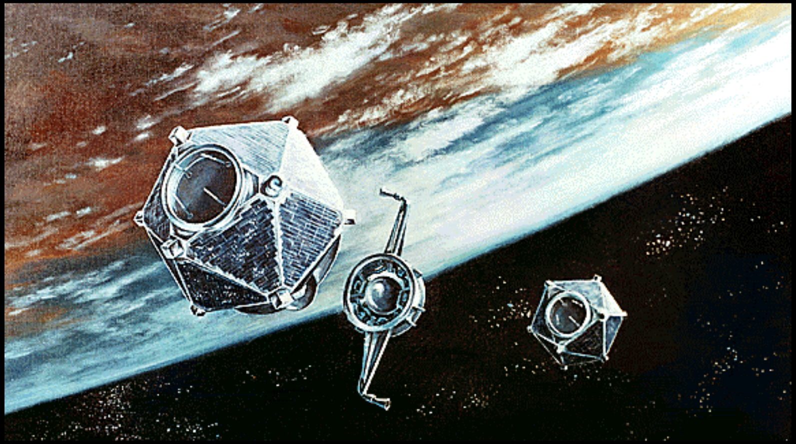
Have agreed as follows :

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.

US military VELA program
(3 pairs of satellites: 1963, 64 and 65)





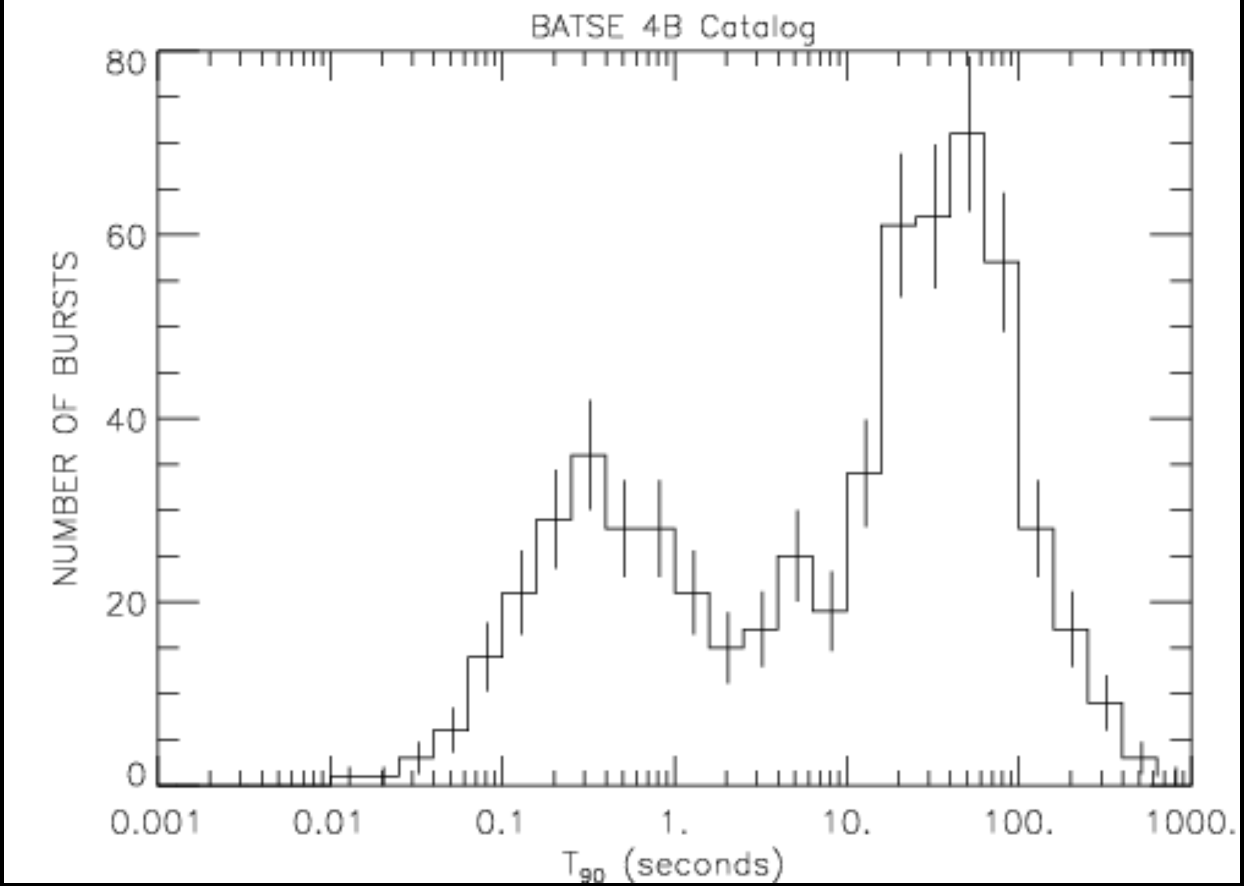
Gamma-Ray Burst are discovered in 1967.

Discovery paper: Klebesadel et al. 1973

Introduction

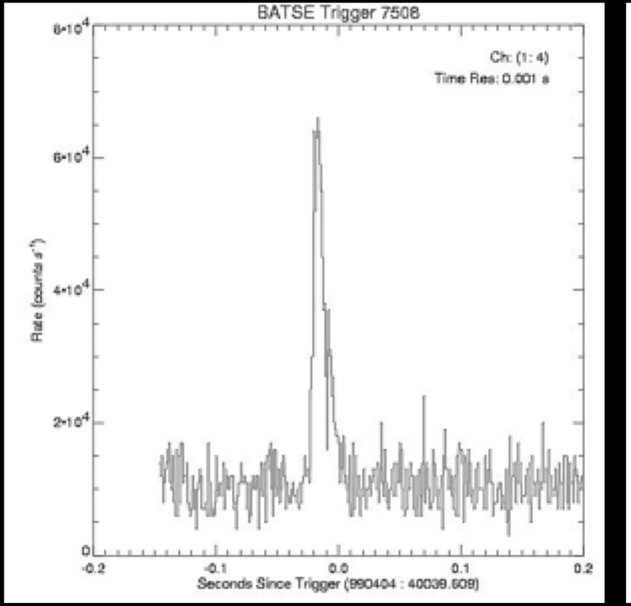
Observational Facts (1) The GRB Prompt Emission

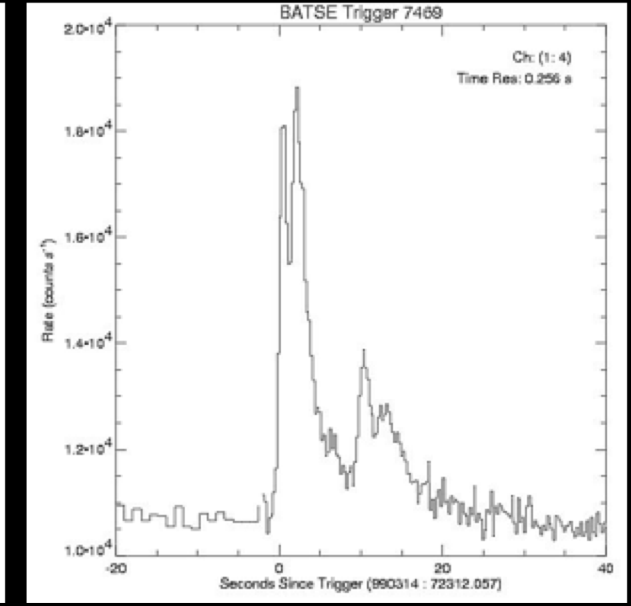
GRB Durations: Two Classes

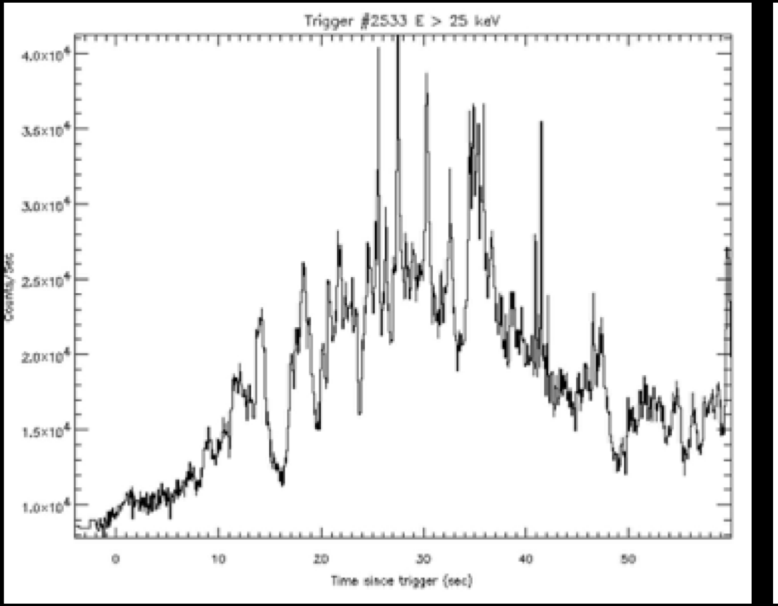


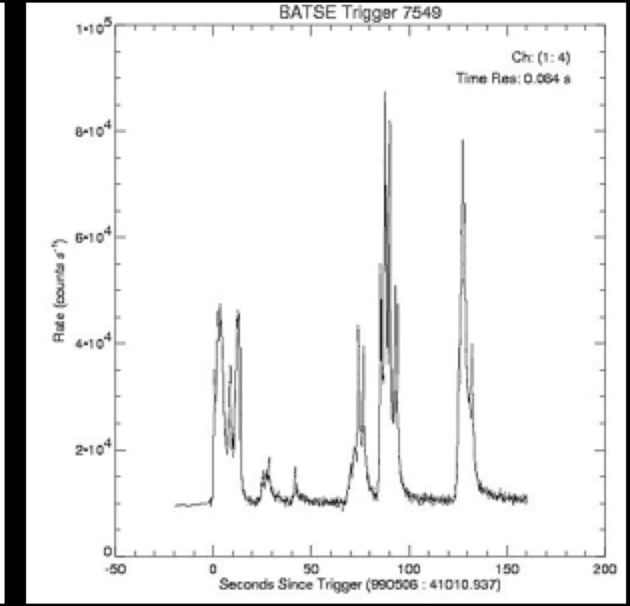
(CGRO/BATSE Catalog)

GRB Lightcurves: Diversity & Variability



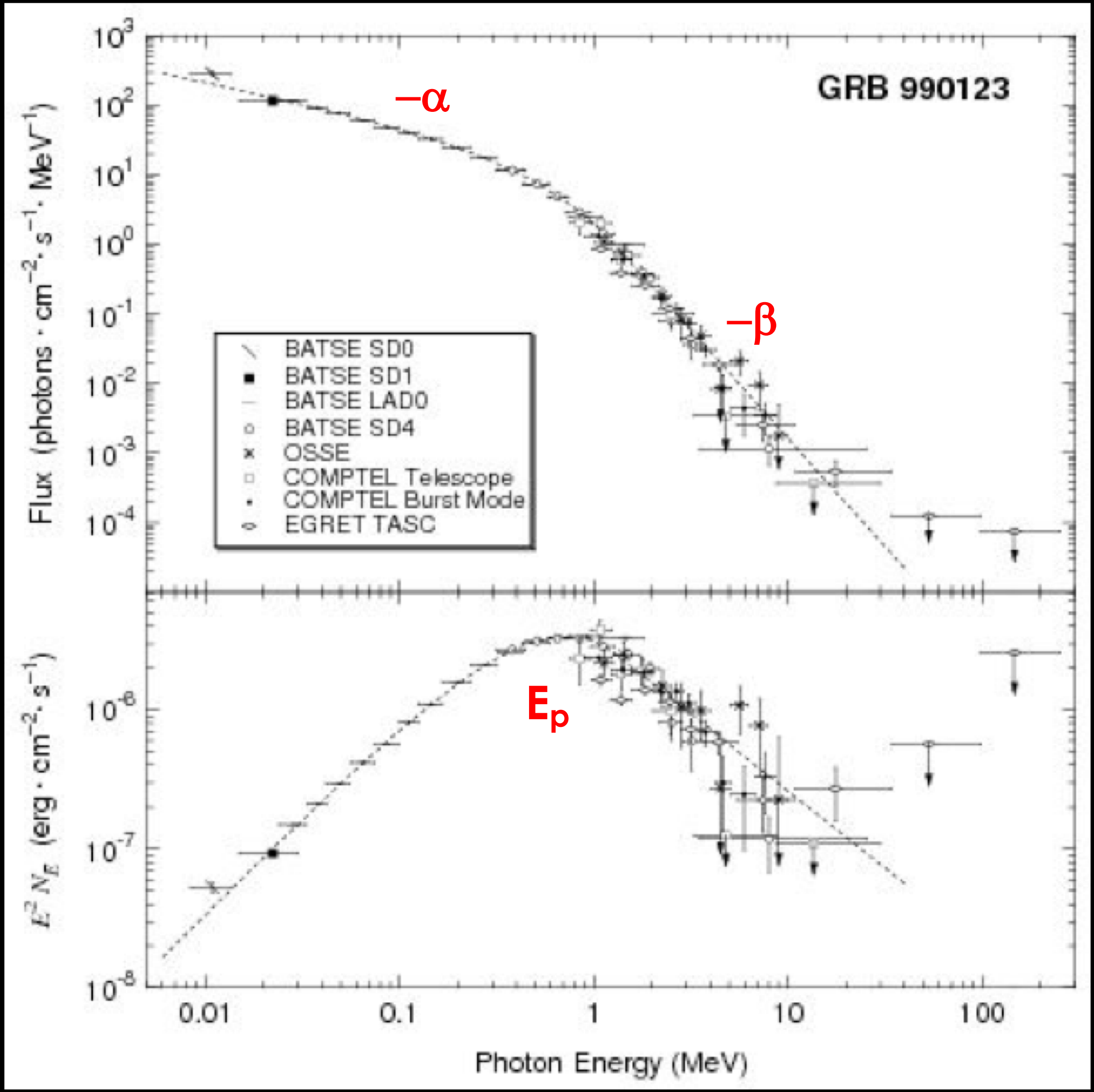






(CGRO/BATSE Catalog)

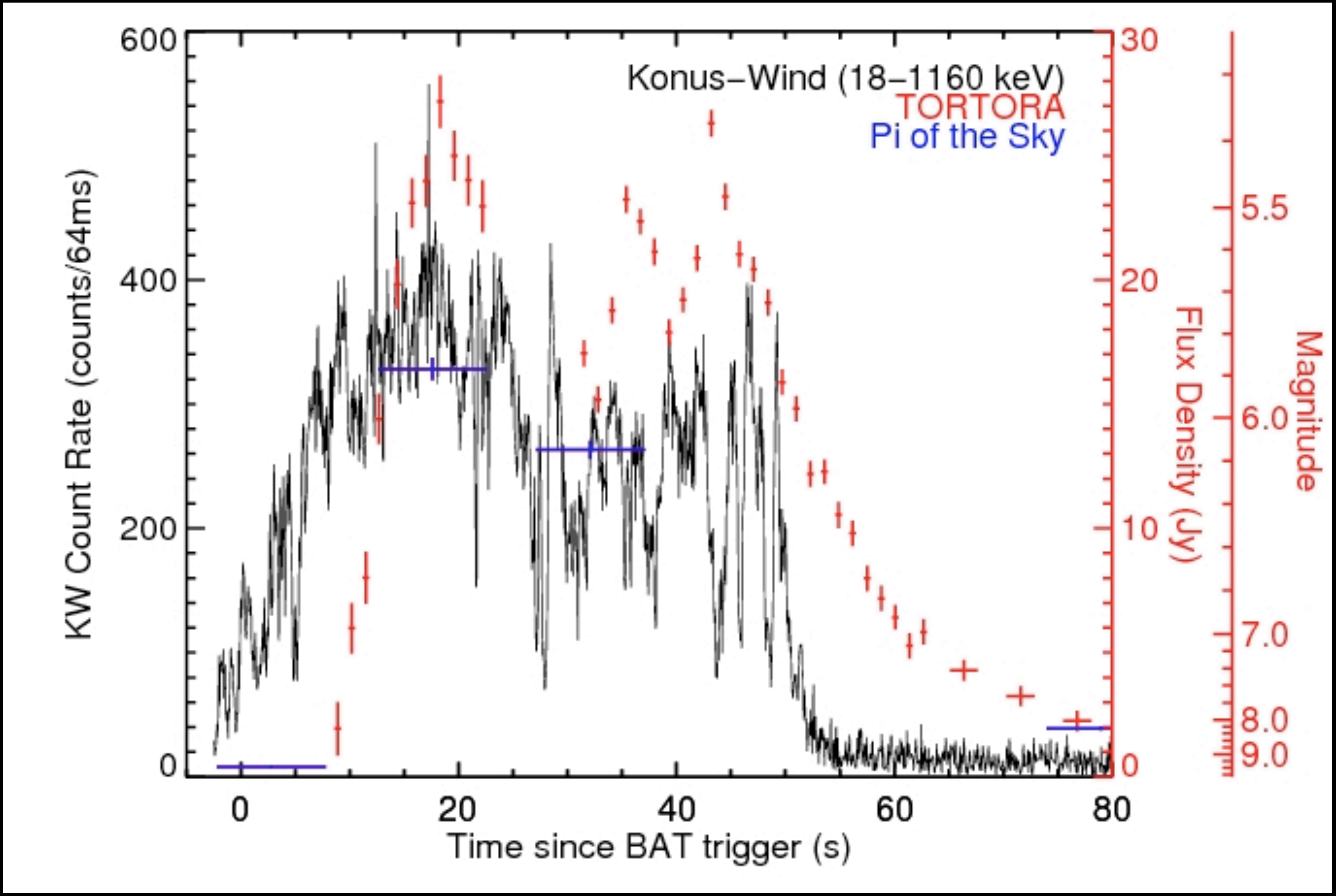
GRB Spectra: Non-Thermal!



(CGRO/BATSE Catalog)

The peak energy typicaly ranges from 10 keV to 10 MeV
The low energy photon index is typically ~ -1 but ranges from -1.5 to -0.5

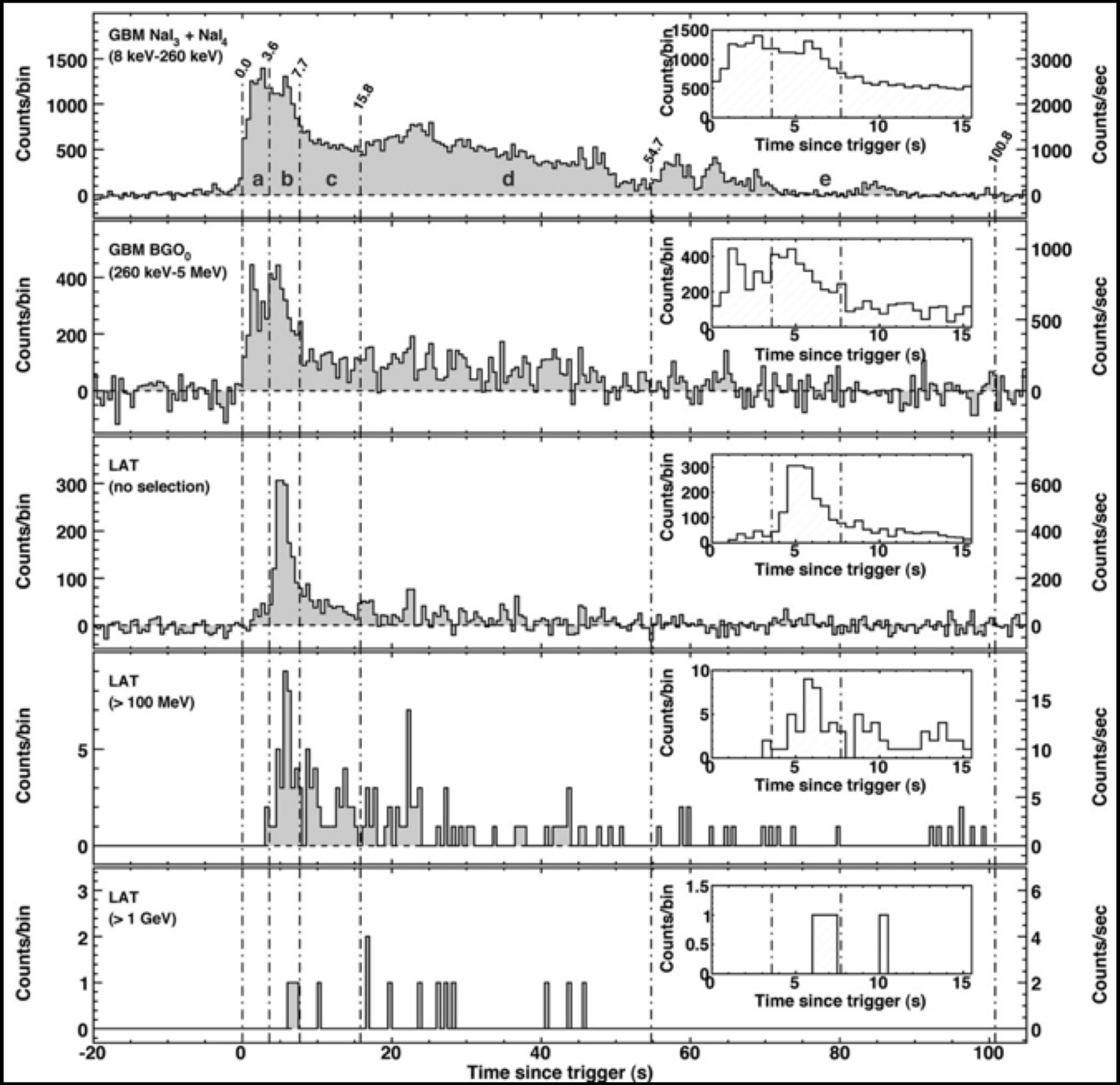
Optical Prompt Emission (rare observations)



The Naked Eye Burst: an extreme case (Racusin et al. 2008)

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

The High-Energy Gamma-Ray Emission (Fermi/LAT)



GRB 080916C (Abdo et al. 2009)

Introduction

Location ! Location ! Location !

Gamma-Rays are difficult to localize: it looks 30 years to measure the distance of gamma-ray bursts.

Discussions in the 80s about the distance scale:
- Galactic GRBs: the most discussed scenario
- Extragalactic GRBs: an extreme scenario proposed by Paczynski (1986)

The Great Debate (1995): The Distance Scale to GRBs

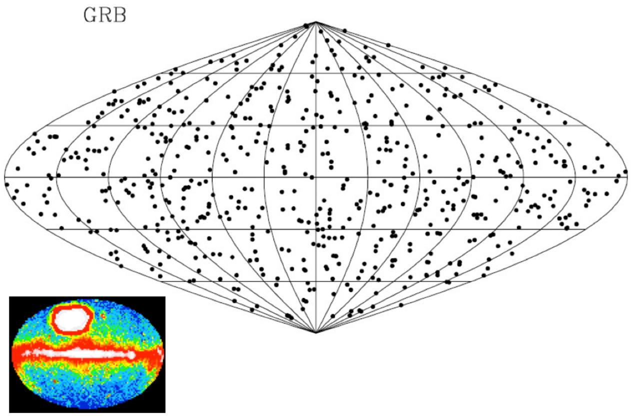
GRB Localization accuracy at that time:

- BATSE: ~ 10 degrees
- IPN: ~arcmin, but with a delay of several days

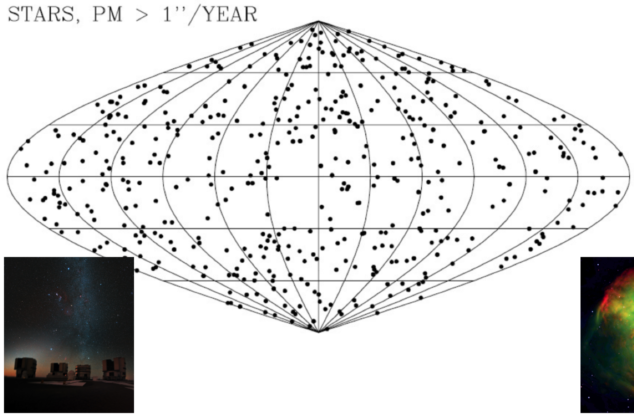
B. Paczynski (Extragalactic)
M. Rees (Moderator)
D. Lamb (Galactic)

The Great Debate (1995): The Distance Scale to GRBs

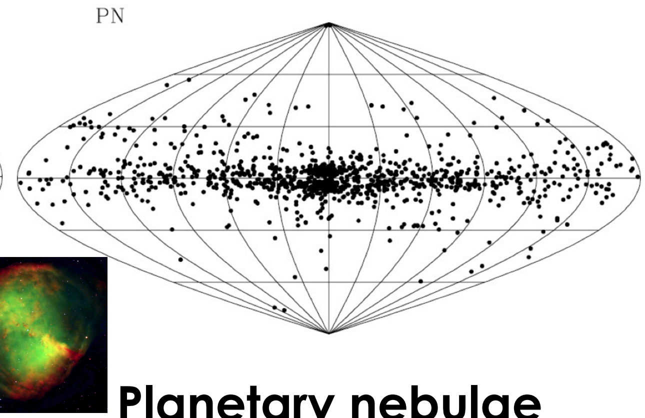
Figures taken from B. Paczynski's presentation at the Great Debate



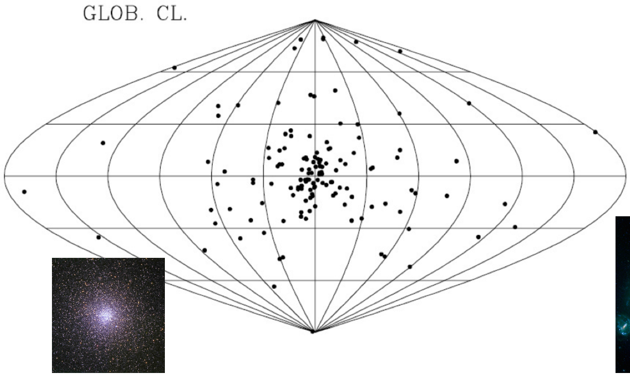
GRB sky map
(CGRO/BATSE, 1994)



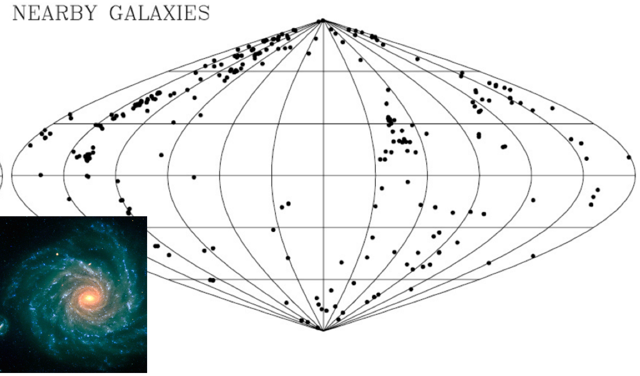
Nearby stars
(isotropy but proper motion, counterparts)



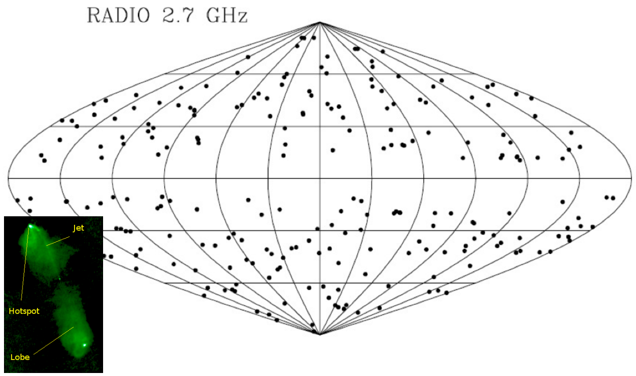
Planetary nebulae
(Galactic disk)
= Remnant of solar type stars



Globular clusters
(Galactic halo, ⊙ not at the center)
= groups of old stars



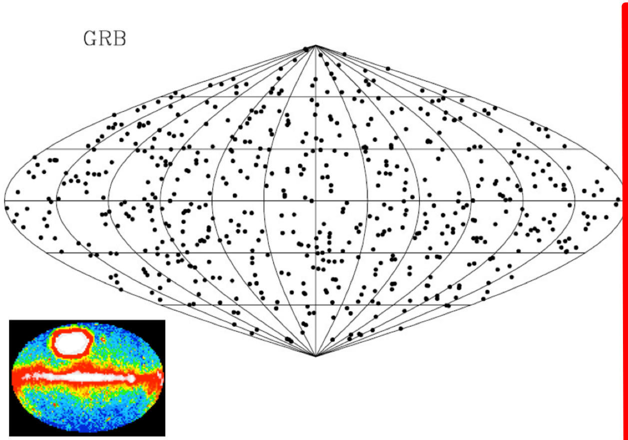
Nearby Galaxies
(anisotropic:
large scale structures)



Radio-Galaxies
(isotropy)
= Distant Active Galaxies

The Great Debate (1995): The Distance Scale to GRBs

Figures taken from B. Paczynski's presentation at the Great Debate



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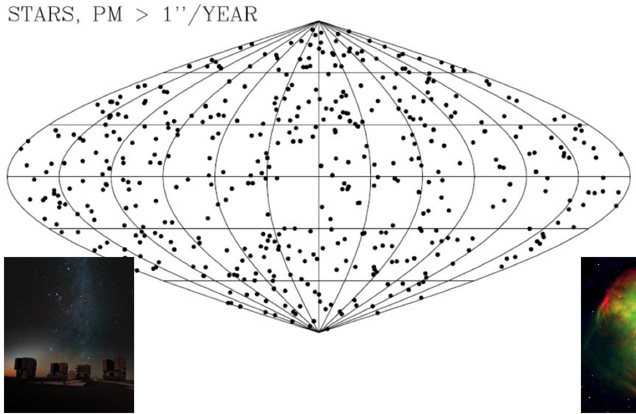

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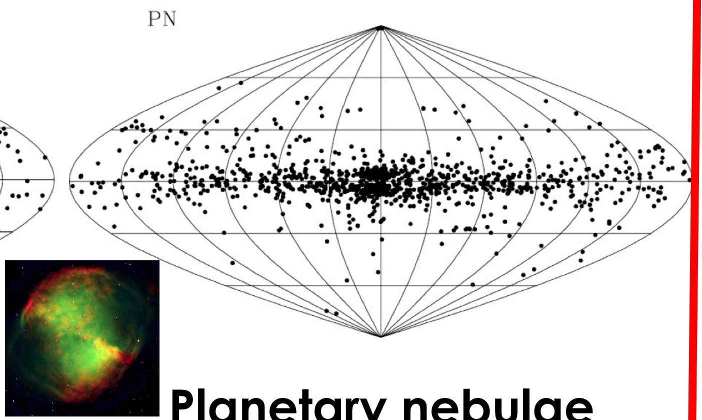

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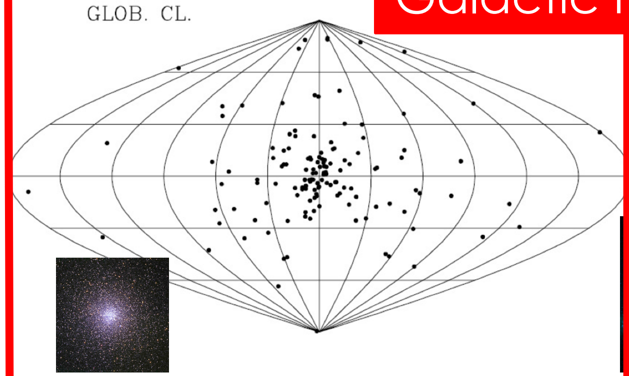
Galactic Populations



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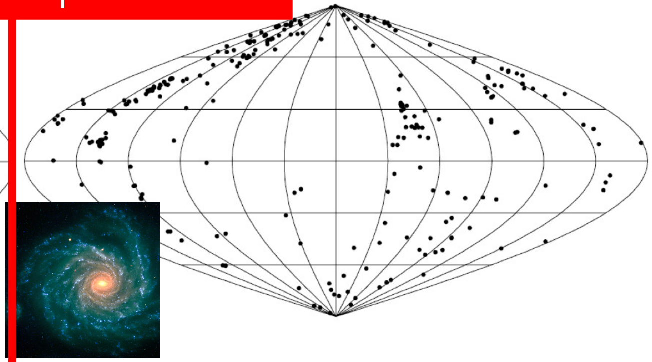

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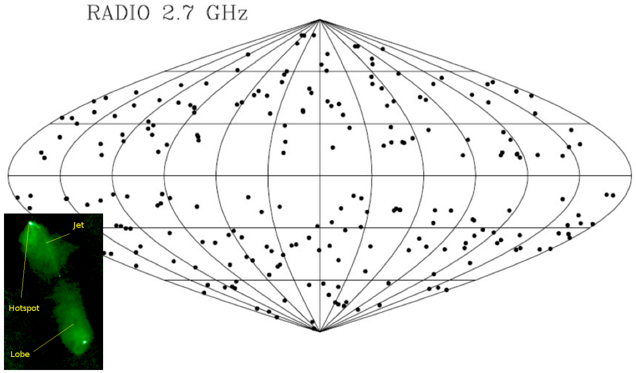

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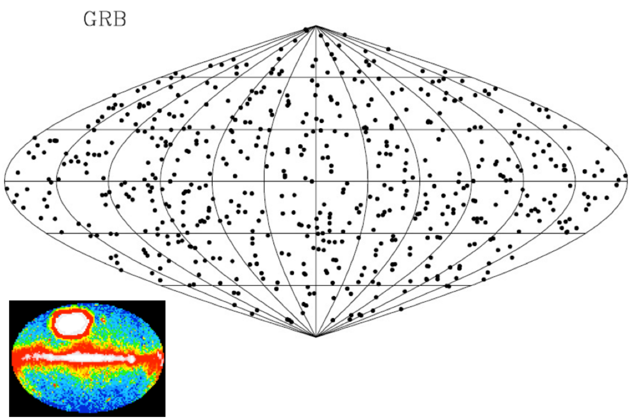

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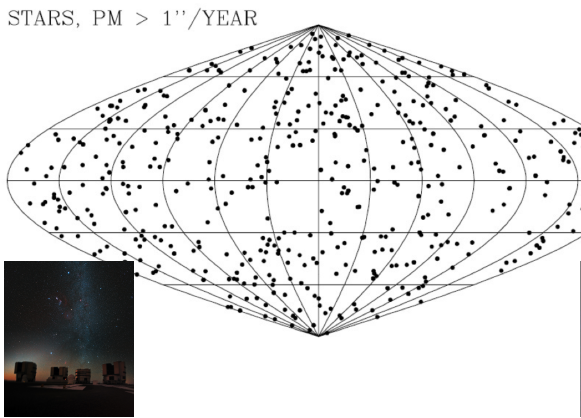
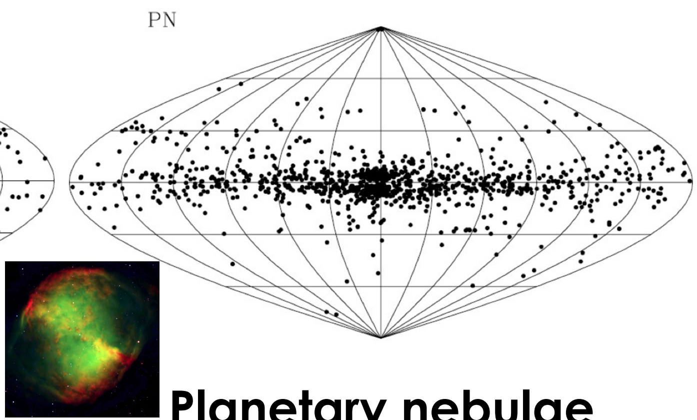


Nearby stars
(isotropy but proper
motion, c



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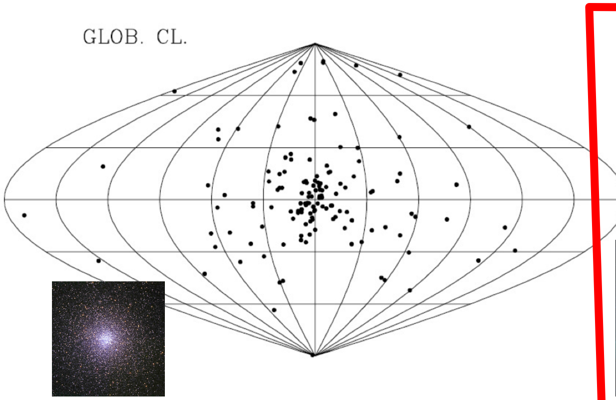
Extragalactic Populations



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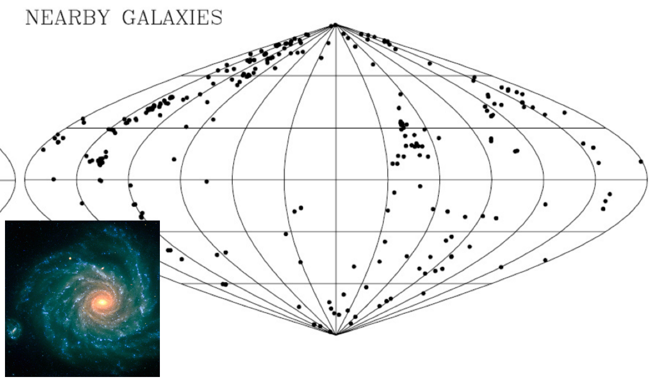

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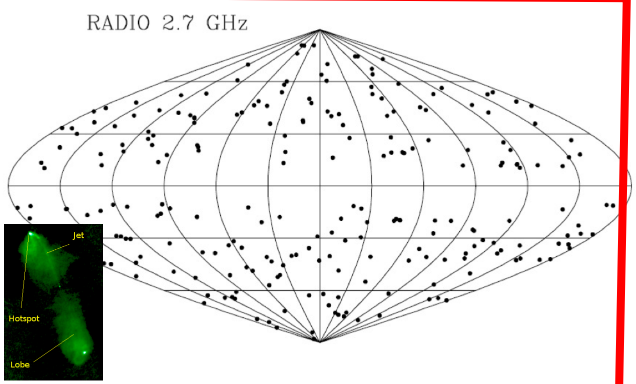

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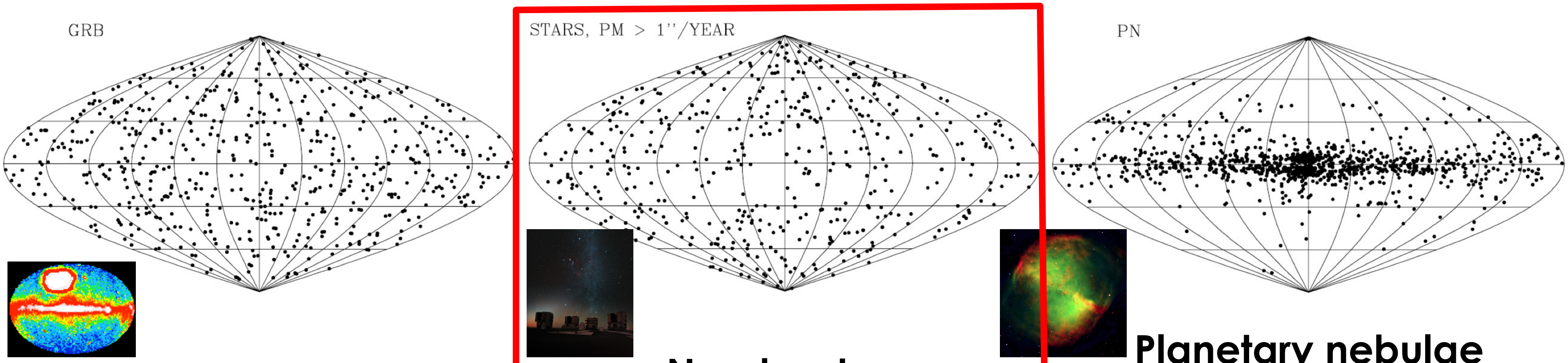

GRB sky map
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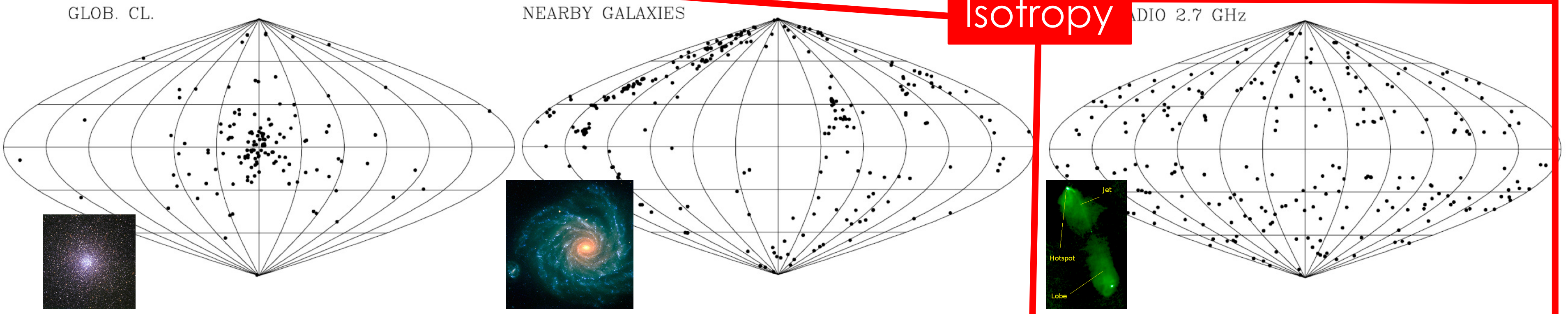
Isotropy



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Radio-Galaxies
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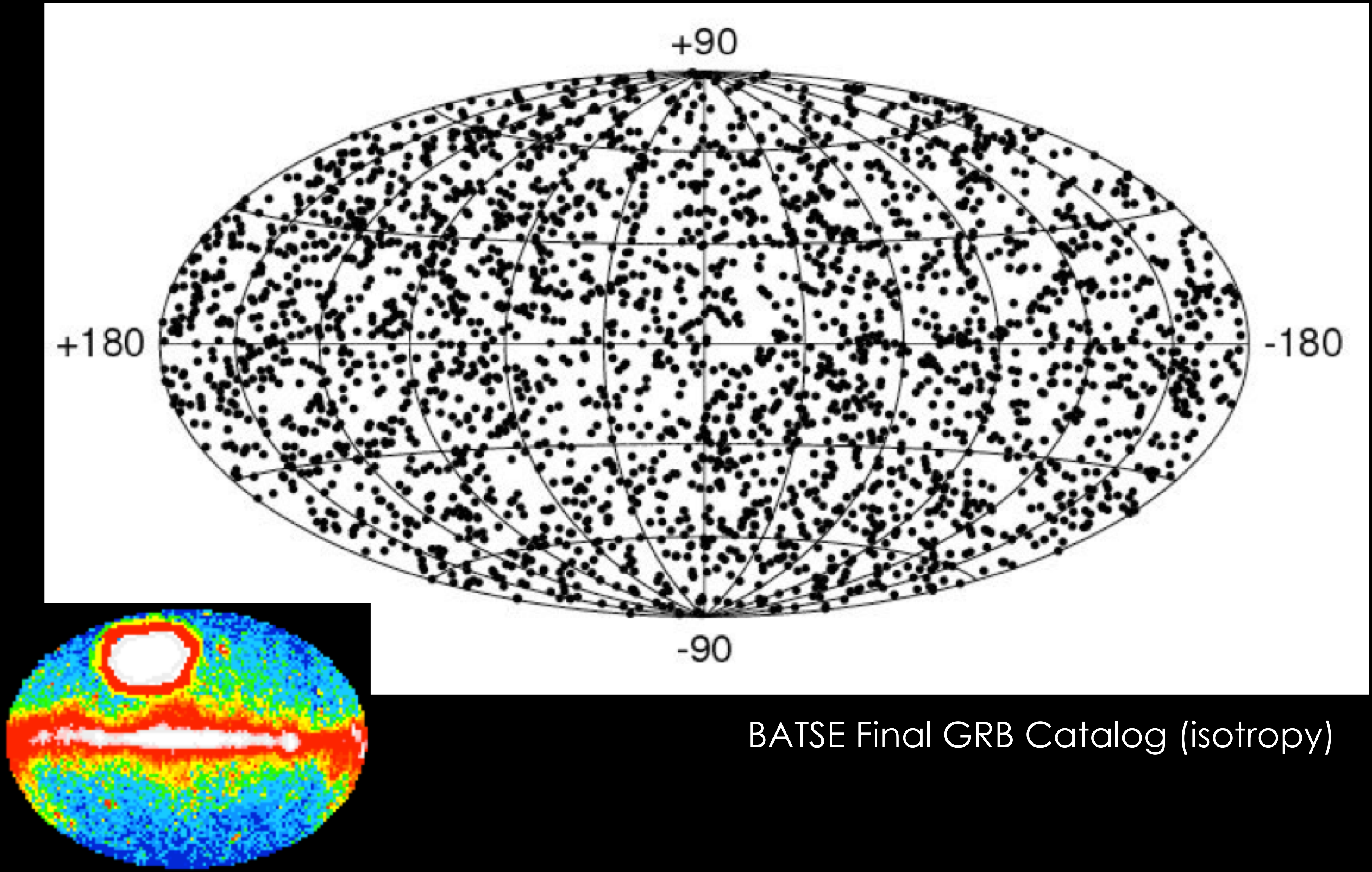
The Distance Scale to GRBs?



BATSE Final GRB Catalog (isotropy)

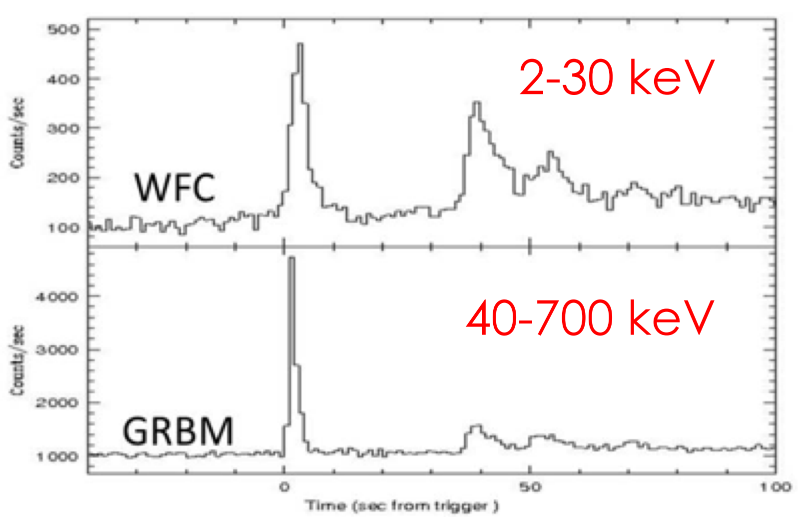
Introduction

The Discovery of Afterglows: GRBs occur at cosmological distance (Gpc) !

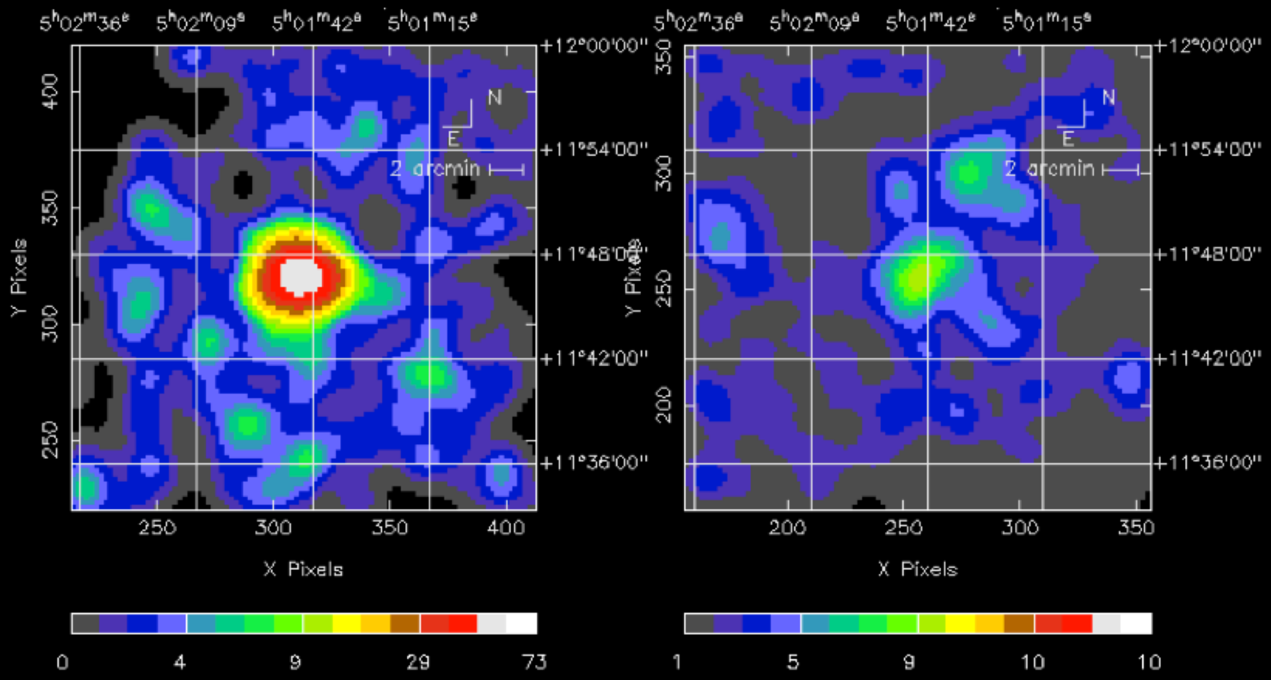
(Beppo-SAX, van Paradijs et al., 1997)

The First Afterglow: 970228

Beppo-SAX: γ-rays **+ X-rays**
= better localization in case of
a double detection



GRB970228: prompt GRB



28 Feb. 1997

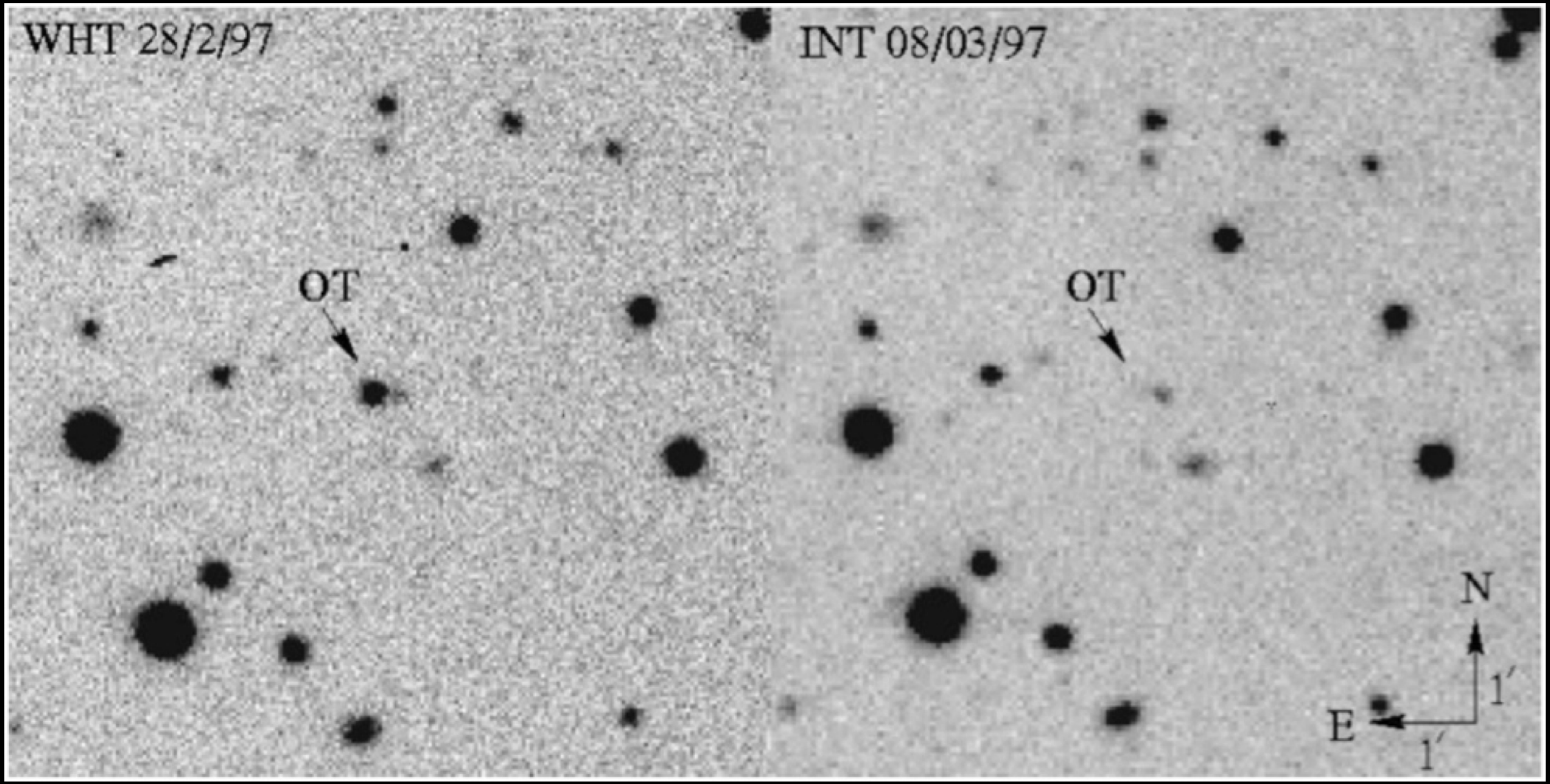
3 Mars 1997

X-ray afterglow

Localization
within 6 arcmin
after 8 hours

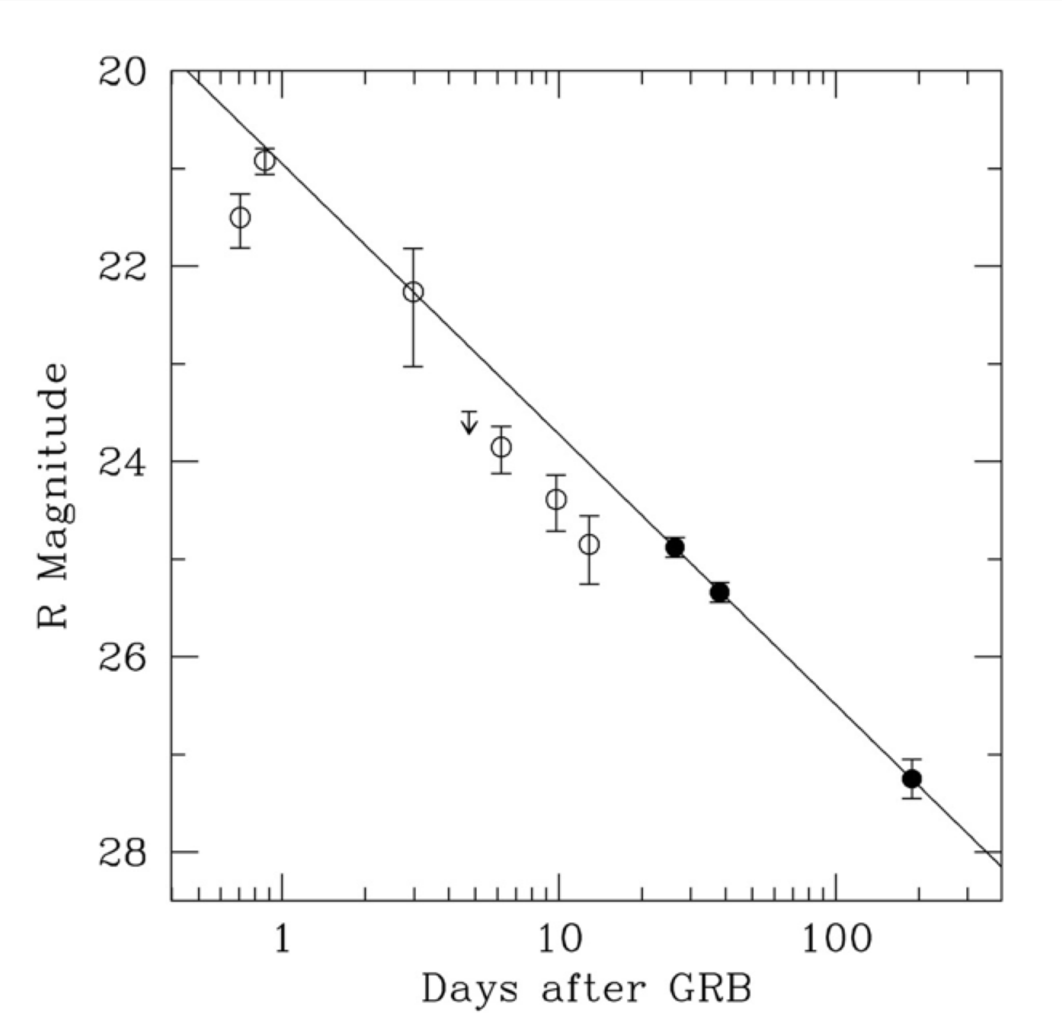
The First Afterglow: 970228

The accuracy of the localization of the X-ray afterglow allows an efficient follow-up with visible telescopes.
If the visible afterglow is detected: sub-arcsec localization.



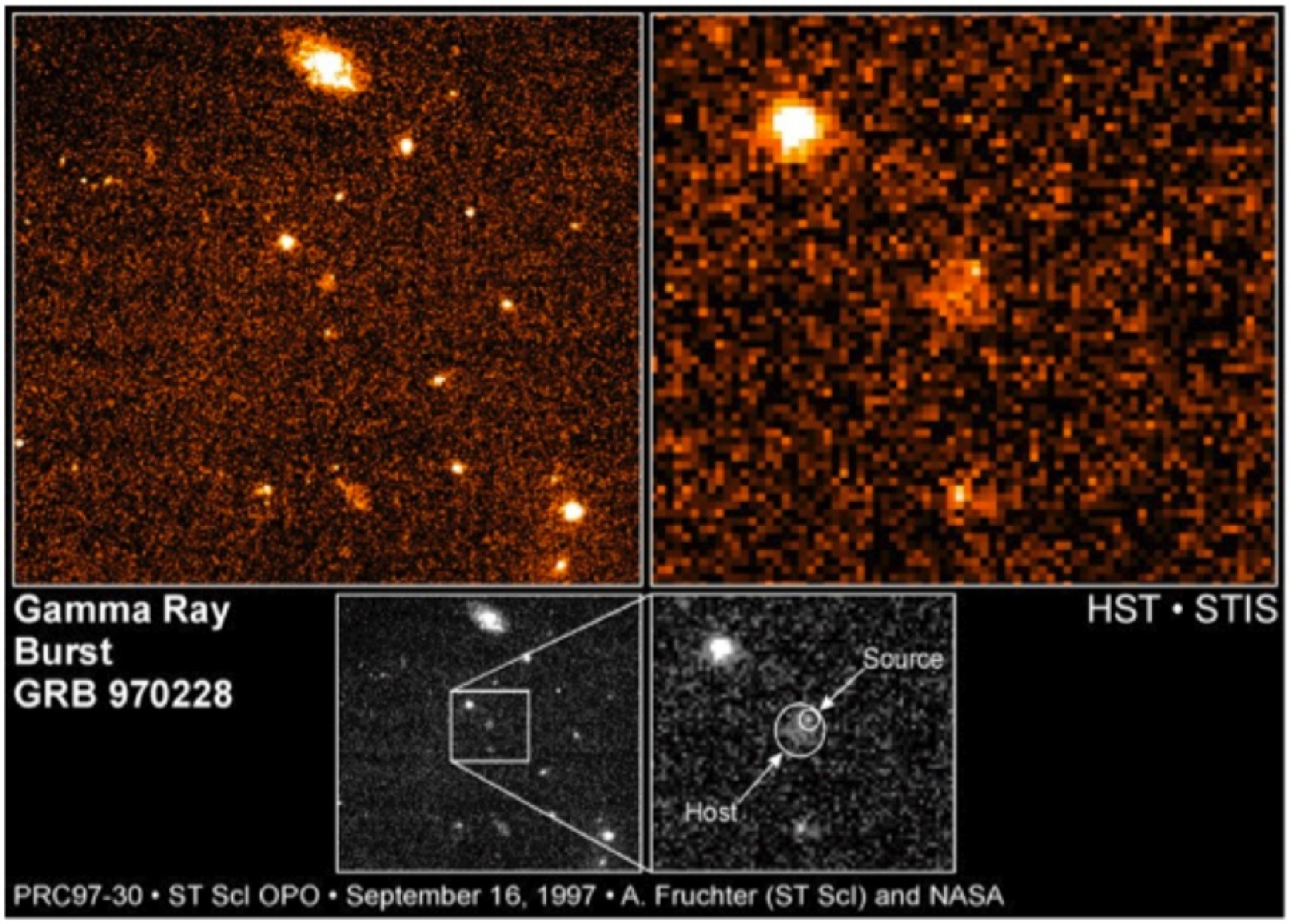
The optical afterglow of GRB970228 (van Paradijs et al. 97)

The First Afterglow: 970228



Lightcurve of the visible afterglow of GRB970228
Fast decay (flux ~t^{-1})

The First Host Galaxy: GRB970228

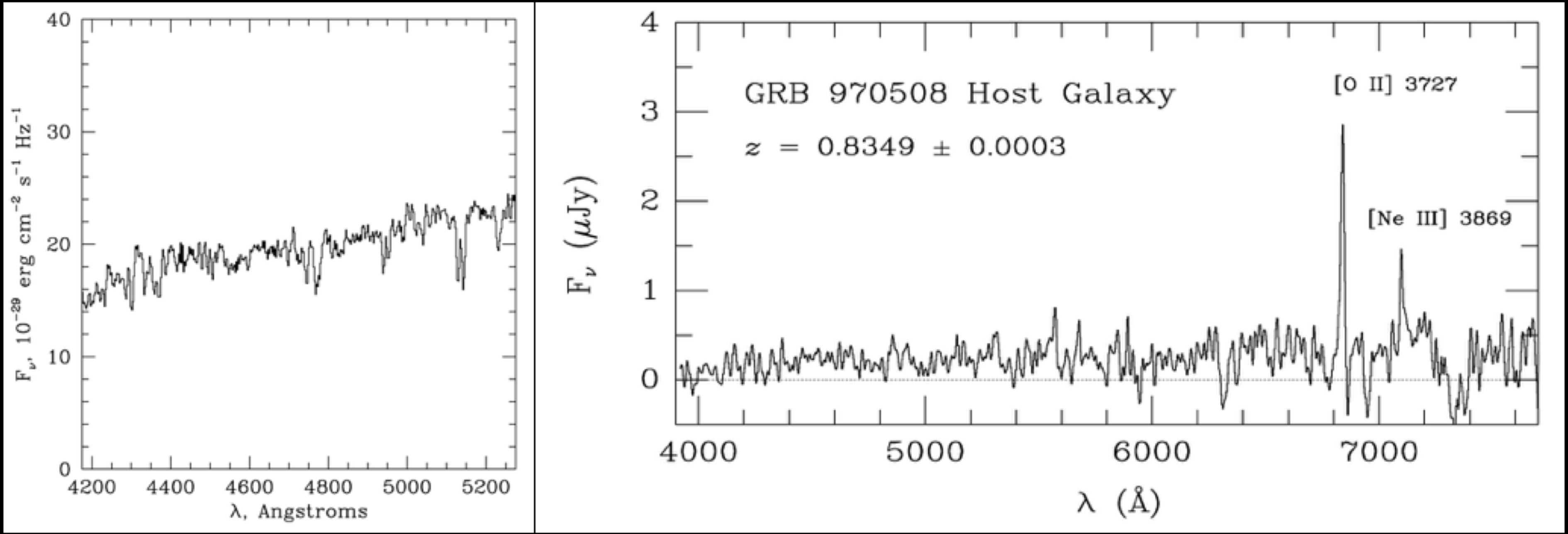


Fruchter et al. 1997

The First Redshift: GRB970508

Afterglow:
absorption lines at z = 0.835

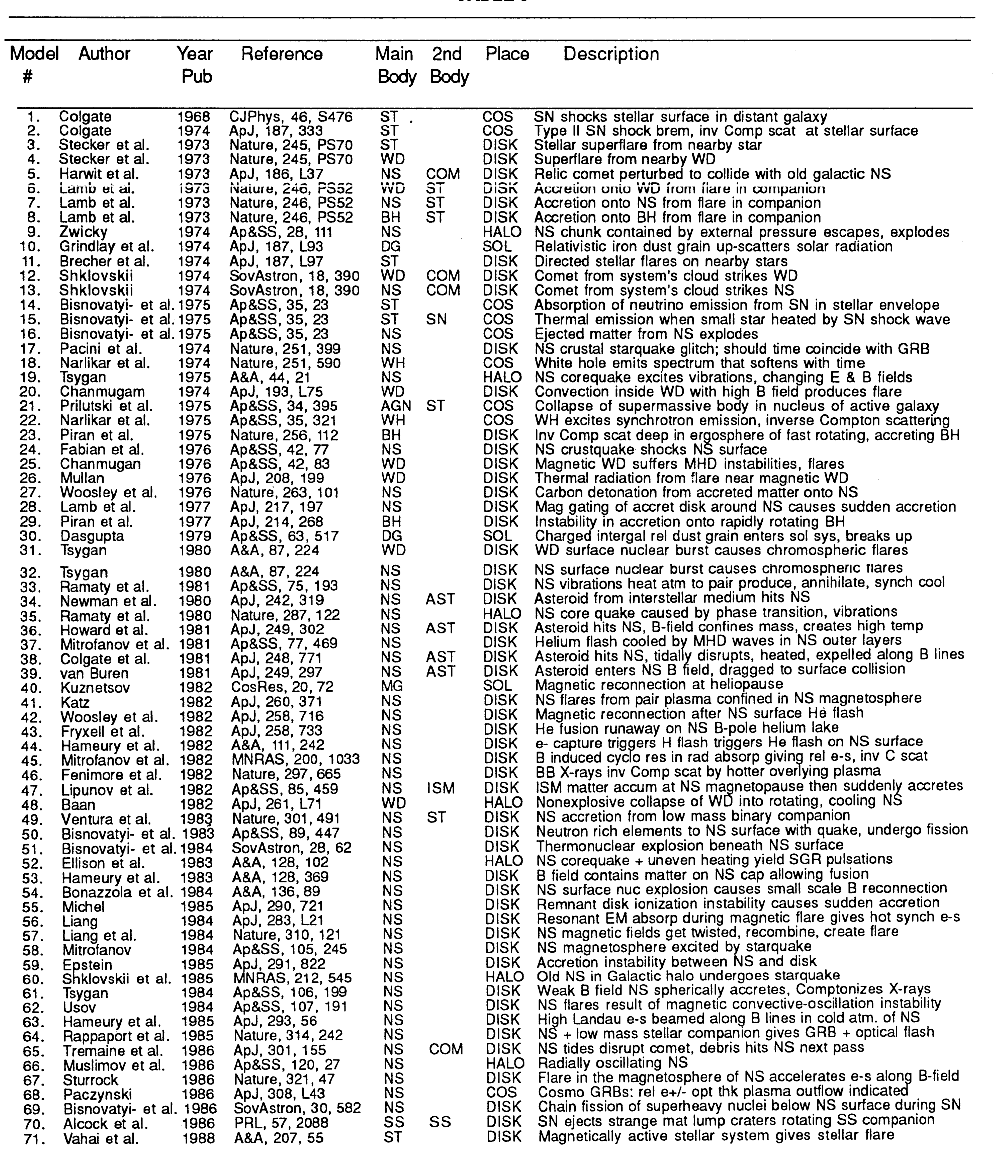
Host galaxy:
emission lines at z = 0.835



Metzger et al. 1997

Gamma-ray Bursts occur at cosmological distance (Gpc)!
They are intrinsically extremely bright ($E_{iso,\gamma} \sim 10^{51-54}$ erg)

Sorting out models…



Model #	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 flares on nearby stars
12.	Shklovskii	1974	SovAstron, 18, 390	WD	COM	DISK	Comet from system's cloud strikes WD
13.	Shklovskii	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.	Chanmugan	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 gating 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
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32.	Tsygan	1980	A&A, 87, 224	NS		DISK	NS surface nuclear burst causes chromospheric flares
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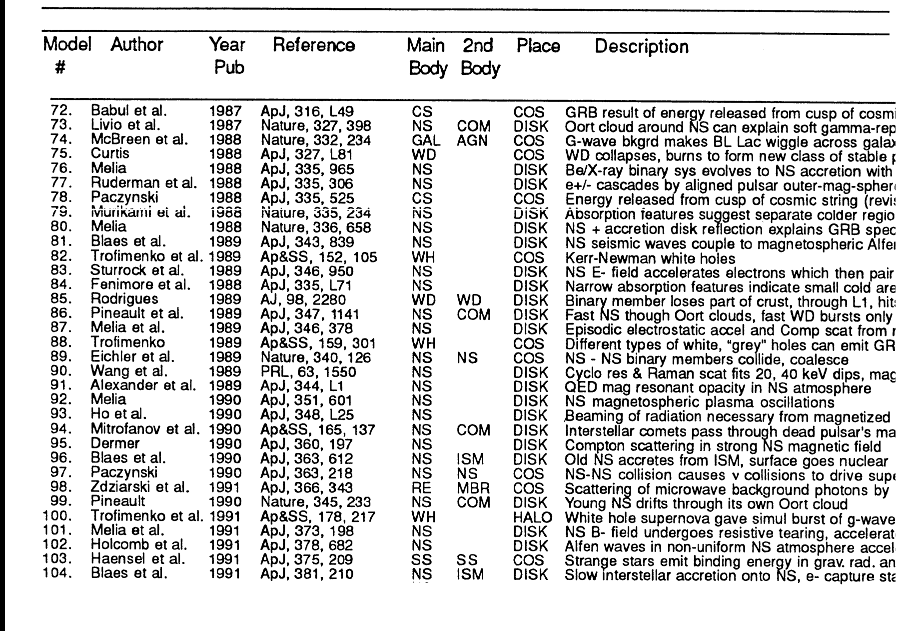
34.	Newman et al.	1980	ApJ, 242, 319	NS	AST	DISK	Asteroid from interstellar medium hits NS
35.	Ramaty et al.	1980	Nature, 287, 122	NS		HALO	NS core quake caused by phase transition, vibrations
36.	Howard et al.	1981	ApJ, 249, 302	NS	AST	DISK	Asteroid hits NS, B-field confines mass, creates high temp
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 synch 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.	Shklovskii 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+/- 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.	Vahai et al.	1988	A&A, 207, 55	ST		DISK	Magnetically active stellar system gives stellar flare



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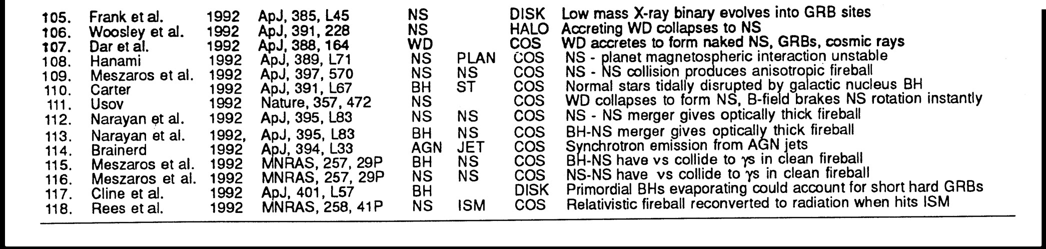
72.	Babul et al.	1987	ApJ, 316, L49	CS		COS	GRB result of energy released from cusp of cosmi
73.	Livio et al.	1987	Nature, 327, 398	NS	COM	DISK	Oort cloud around NS can explain soft gamma-rep
74.	McBreen et al.	1988	Nature, 332, 234	GAL	AGN	COS	G-wave bkgrd makes BL Lac wiggle across gala
75.	Curtis	1988	ApJ, 327, L81	WD		COS	WD collapses, burns to form new class of stable
76.	Melia	1988	ApJ, 335, 965	NS		DISK	Be/X-ray binary sys evolves to NS accretion with
77.	Ruderman et al.	1988	ApJ, 335, 306	NS		DISK	e+/- cascades by aligned pulsar outer-mag-spher
78.	Paczynski	1988	ApJ, 335, 525	CS		COS	Energy released from cusp of cosmic string (revi
79.	Murikami et al.	1988	Nature, 335, 234	NS		DISK	Absorption features suggest separate colder regio
80.	Melia	1988	Nature, 336, 658	NS		DISK	NS + accretion disk reflection explains GRB spec
81.	Blaes et al.	1989	ApJ, 343, 839	NS		DISK	NS seismic waves couple to magnetospheric Alfe
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
84.	Fenimore et al.	1988	ApJ, 335, L71	NS		DISK	Narrow absorption features indicate small cold are
85.	Rodrigues	1989	AJ, 98, 2280	WD	WD	DISK	Binary member loses part of crust, through L1, hit
86.	Pineault et al.	1989	ApJ, 347, 1141	NS	COM	DISK	Fast NS though Oort clouds, fast WD bursts only
87.	Melia et al.	1989	ApJ, 346, 378	NS		DISK	Episodic electrostatic accel and Comp scat from
88.	Trofimenko	1989	Ap&SS, 159, 301	WH		COS	Different types of white, "grey" holes can emit GR
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, ma
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
94.	Mitrofanov et al.	1990	Ap&SS, 165, 137	NS	COM	DISK	Interstellar comets pass through dead pulsar's ma
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 ν collisions to drive sup
98.	Zdziarski et al.	1991	ApJ, 366, 343	RE	MBR	COS	Scattering of microwave background photons by
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 simul burst of g-wave
101.	Melia et al.	1991	ApJ, 373, 198	NS		DISK	NS B- field undergoes resistive tearing, accelera
102.	Holcomb et al.	1991	ApJ, 378, 682	NS		DISK	Alfen waves in non-uniform NS atmosphere accel
103.	Haensel et al.	1991	ApJ, 375, 209	SS	SS	COS	Strange stars emit binding energy in grav. rad. an
104.	Blaes et al.	1991	ApJ, 381, 210	NS	ISM	DISK	Slow interstellar accretion onto NS, e- capture st



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105.	Frank et al.	1992	ApJ, 385, L45	NS		DISK	Low mass X-ray binary evolves into GRB sites
106.	Woosley et al.	1992	ApJ, 391, 228	NS		HALO	Accreting WD collapses to NS
107.	Dar et al.	1992	ApJ, 388, 164	WD		COS	WD accretes to form naked NS, GRBs, 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 νs collide to γs in clean fireball
116.	Meszaros et al.	1992	MNRAS, 257, 29P	NS	NS	COS	NS-NS have νs collide to γs 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

(Nemiroff 1994)

Sorting out models…

Model #	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 flares on nearby stars
12.	Shklovskii	1974	SovAstron, 18, 390	WD	COM	DISK	Comet from system's cloud strikes WD
13.	Shklovskii	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
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26.	Mullan	1976	ApJ, 208, 199	WD		DISK	Thermal radiation from flare near magnetic WD
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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
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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
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36.	Howard et al.	1981	ApJ, 249, 302	NS	AST	DISK	Asteroid hits NS, B-field confines mass, creates high temp
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38.	Colgate et al.	1981	ApJ, 248, 771	NS	AST	DISK	Asteroid hits NS, tidally disrupts, heated, expelled along B lines
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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
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44.	Hameury et al.	1982	A&A, 111, 242	NS		DISK	e- capture triggers H flash triggers He flash on NS surface
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49.	Ventura et al.	1983	Nature, 301, 491	NS	ST	DISK	NS accretion from low mass binary companion
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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 synch e-s
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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
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63.	Hameury et al.	1985	ApJ, 293, 56	NS		DISK	High Landau e-s beamed along B lines in cold atm. of NS
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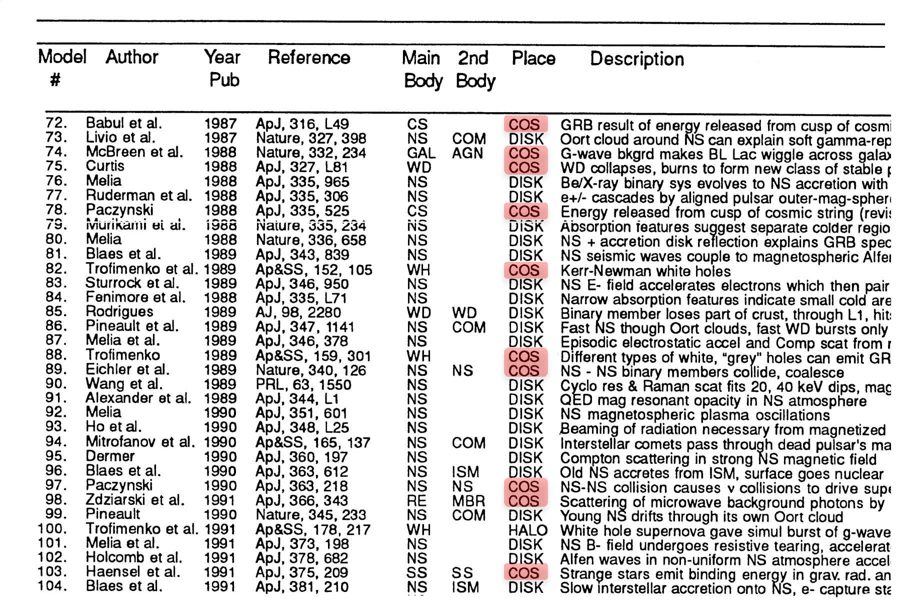
71.	Vahai et al.	1988	A&A, 207, 55	ST		DISK	Magnetically active stellar system gives stellar flare



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73.	Livio et al.	1987	Nature, 327, 398	NS	COM	DISK	Oort cloud around NS can explain soft gamma-rep
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79.	Murikami et al.	1988	Nature, 335, 234	NS		DISK	Absorption features suggest separate colder regio
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83.	Sturrock et al.	1989	ApJ, 346, 950	NS		DISK	NS E- field accelerates electrons which then pair
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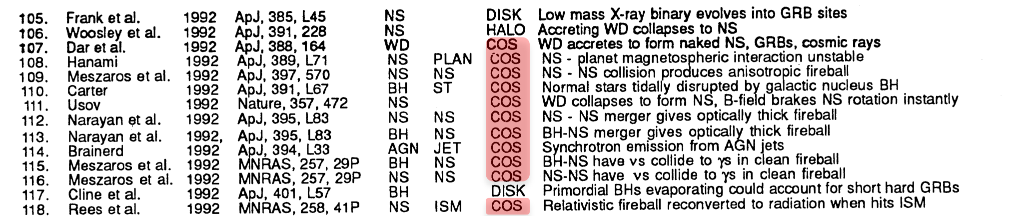
88.	Trofimenko	1989	Ap&SS, 159, 301	WH		COS	Different types of white, “grey" holes can emit GR
89.	Eichler et al.	1989	Nature, 340, 126	NS	NS	COS	NS - NS binary members collide, coalesce
90.	Wang et al.	1989	PRL, 63, 1550	NS		DISK	Cyclo res & Raman scat fits 20, 40 keV dips, ma
91.	Alexander et al.	1989	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
94.	Mitrofanov et al.	1990	Ap&SS, 165, 137	NS	COM	DISK	Interstellar comets pass through dead pulsar's ma
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 ν collisions to drive sup
98.	Zdziarski et al.	1991	ApJ, 366, 343	RE	MBR	COS	Scattering of microwave background photons by
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 simul burst of g-wave
101.	Melia et al.	1991	ApJ, 373, 198	NS		DISK	NS B- field undergoes resistive tearing, accelera
102.	Holcomb et al.	1991	ApJ, 378, 682	NS		DISK	Alfen waves in non-uniform NS atmosphere acce
103.	Haensel et al.	1991	ApJ, 375, 209	SS	SS	COS	Strange stars emit binding energy in grav. rad. an
104.	Blaes et al.	1991	ApJ, 381, 210	NS	ISM	DISK	Slow interstellar accretion onto NS, e- capture st

→ End of 1991: firstt BATSE results



Model #	Author	Year Pub	Reference	Main Body	2nd Body	Place	Description
105.	Frank et al.	1992	ApJ, 385, L45	NS		DISK	Low mass X-ray binary evolves into GRB sites
106.	Woosley et al.	1992	ApJ, 391, 228	NS		HALO	Accreting WD collapses to NS
107.	Dar et al.	1992	ApJ, 388, 164	WD		COS	WD accretes to form naked NS, GRBs, 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 νs collide to γs in clean fireball
116.	Meszaros et al.	1992	MNRAS, 257, 29P	NS	NS	COS	NS-NS have νs collide to γs 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

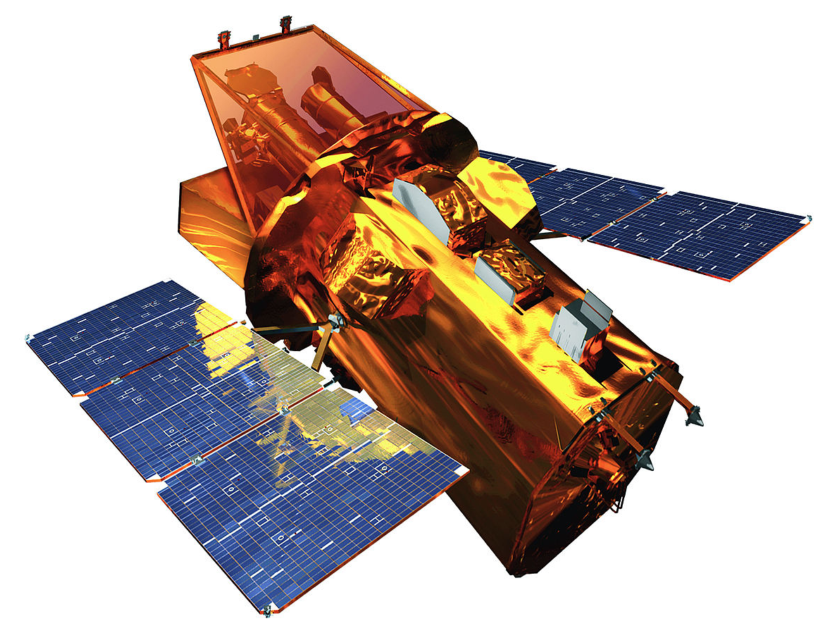
Paczynski 1986

(Nemiroff 1994)

Introduction

Observational Facts (2)
The Afterglow Emission

Neils Gehrels Swift Observatory



The mask of BAT

Three instruments to observe gamma-ray bursts:

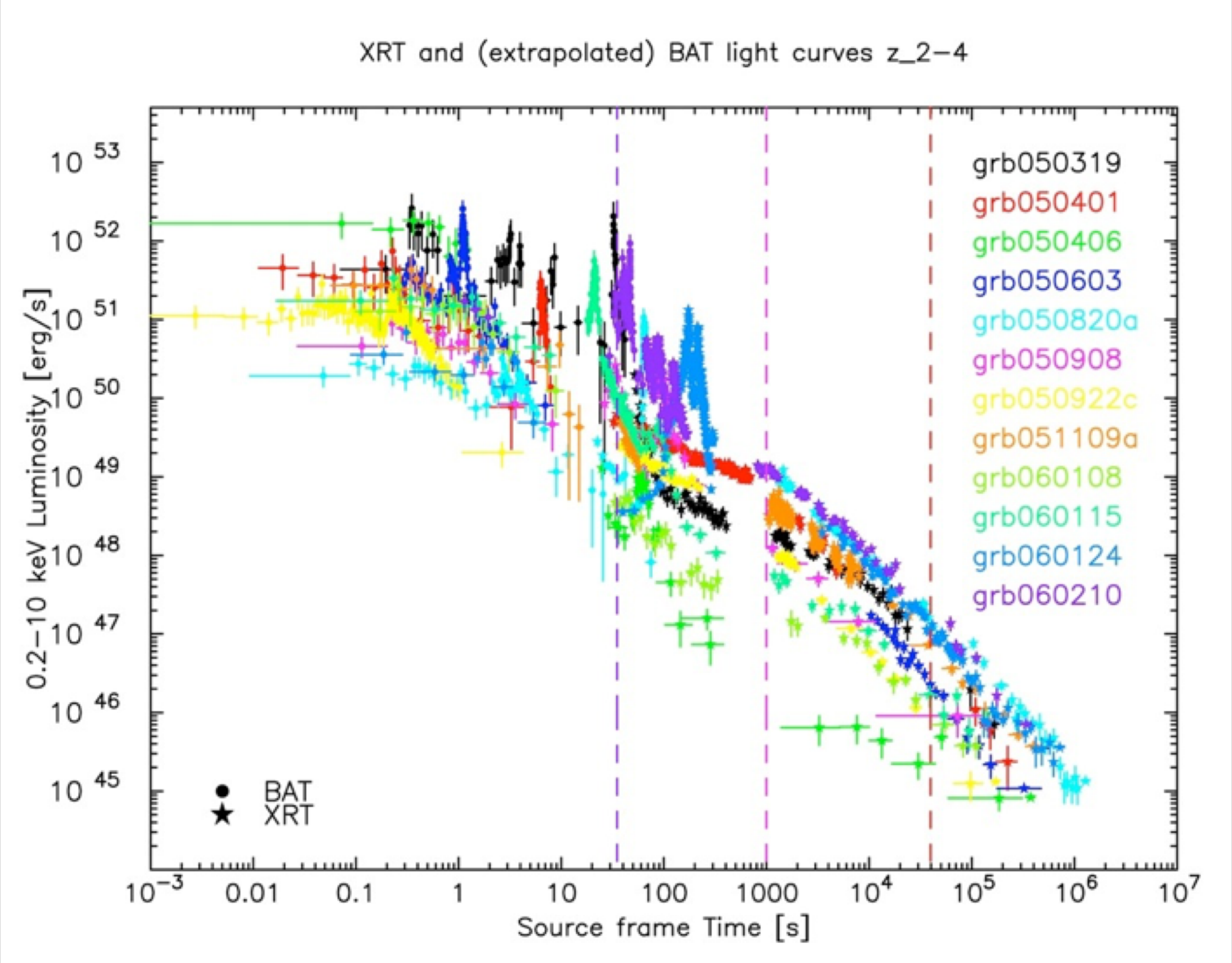
(1) Prompt Emission:

- BAT: coded mask telescope (15-150 keV), large field of view
  = trigger + on-board localization (~arcmin) in real time

(2) Afterglow (after a satellite slew within ~1 min)

- XRT: X-ray Telescope
- UVOT: Visible Telescope

Complexity of Afterglow Lightcurves

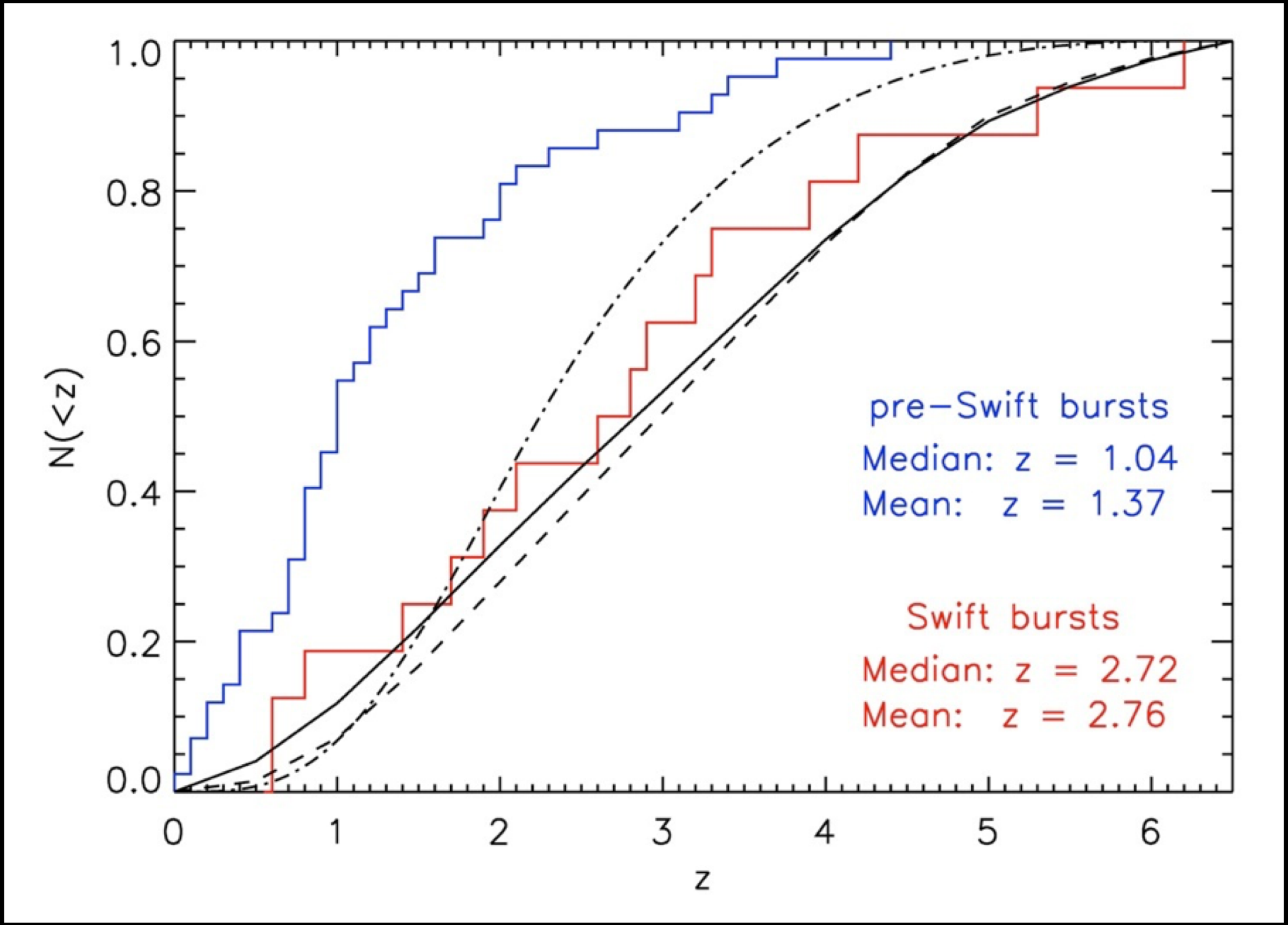


Swift XRT

Plateaus, flares, bumps, etc.

Non-thermal spectrum

Redshift distribution



Jakobsson et al. 2006

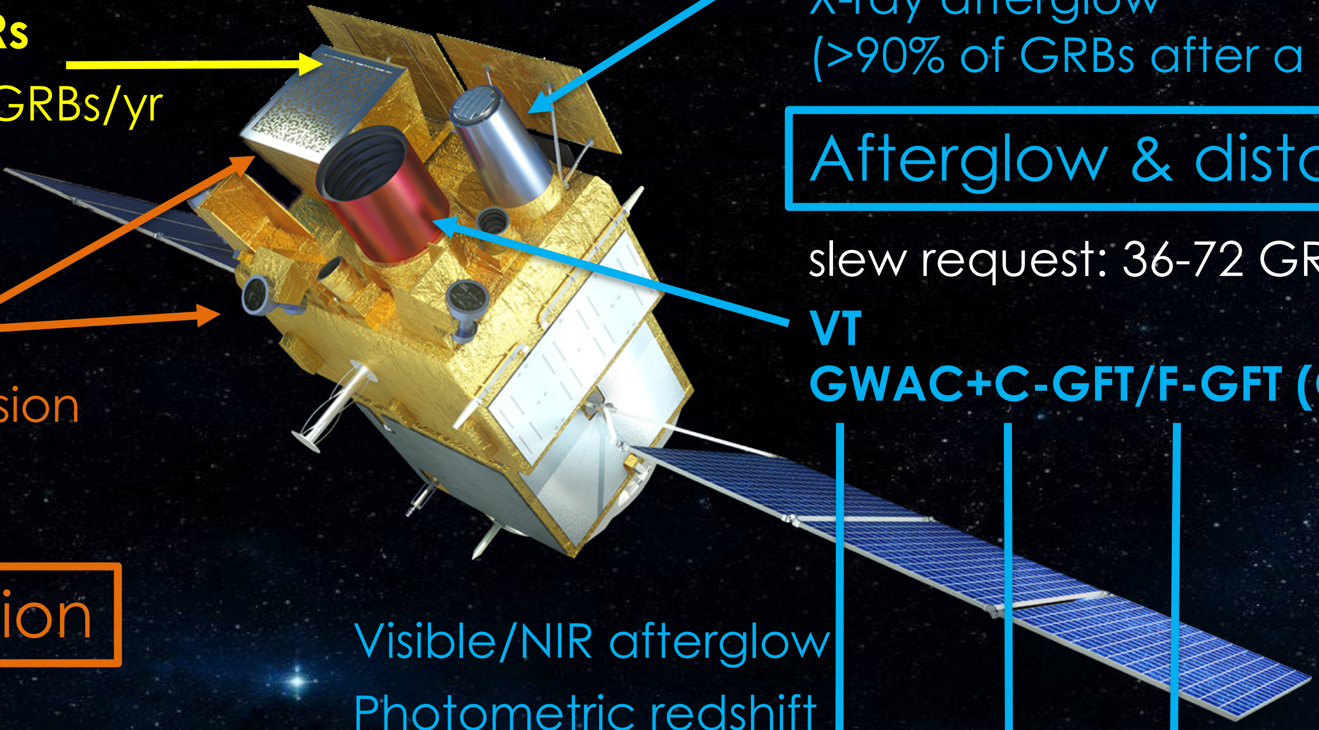
Maximum redshift:
090423: z=8.2 (spectro-z) ; 090429B: z=9.4 (photo-z)

Observational Strategy: many challenges

To study GRBs (and possibly use them for someting else: cosmology, …), you want ideally:

- **To characterize properly the prompt GRB emission (lightcurve+spectrum)**
  γ-rays: **Fermi-GBM+LAT (8 keV-10 GeV)** ; Swift-BAT (15-150 keV)
  optical: robotic telescopes ; radio ? ; VHE γ-rays: CTA ?
- **To localize accurately and in near real time the prompt GRB** (~a few arcmin)
  Best current method: coded-mask telescope = **Swift-BAT**
- **To make a very rapid multi-wavelength follow-up**
  X-rays: slewing satelite **Swift-XRT**
  Optical: slewing satelite **Swift-UVOT** / **robotic telescopes**
  Other wavelengths: rapid/robotic mode or very large fov
- **To make the long-term photometric follow-up of the afterglow**
  = large instruments
- **To obtain the UV-optical-IR spectrum of the afterglow**
  = (very) large instruments at early times, e.g. VLT/XSHOOTER
- **To identify and characterize the host galaxy**
  = (very) large instruments
- **To measure the redshift: photo-z (afterglow) or spectro-z (afterglow/host)**
- **Etc.**

SVOM (to be launched next year)



GRB trigger

ECLAIRs

42-80 GRBs/yr

ECLAIRs+GRM

Prompt GRB emission
over 3 decades
(4 keV-5.5 MeV)

Prompt emission

GWAC

prompt visible emission
in ~16% of cases

MXT

X-ray afterglow
(>90% of GRBs after a slew)

Afterglow & distance

slew request: 36-72 GRB/yr

VT

GWAC+C-GFT/F-GFT (Colibri)

Visible/NIR afterglow

Photometric redshift

Follow-Up by other instruments (including very large telescopes)
Redshift for 2/3 of the sample

SVOM (to be launched next year)

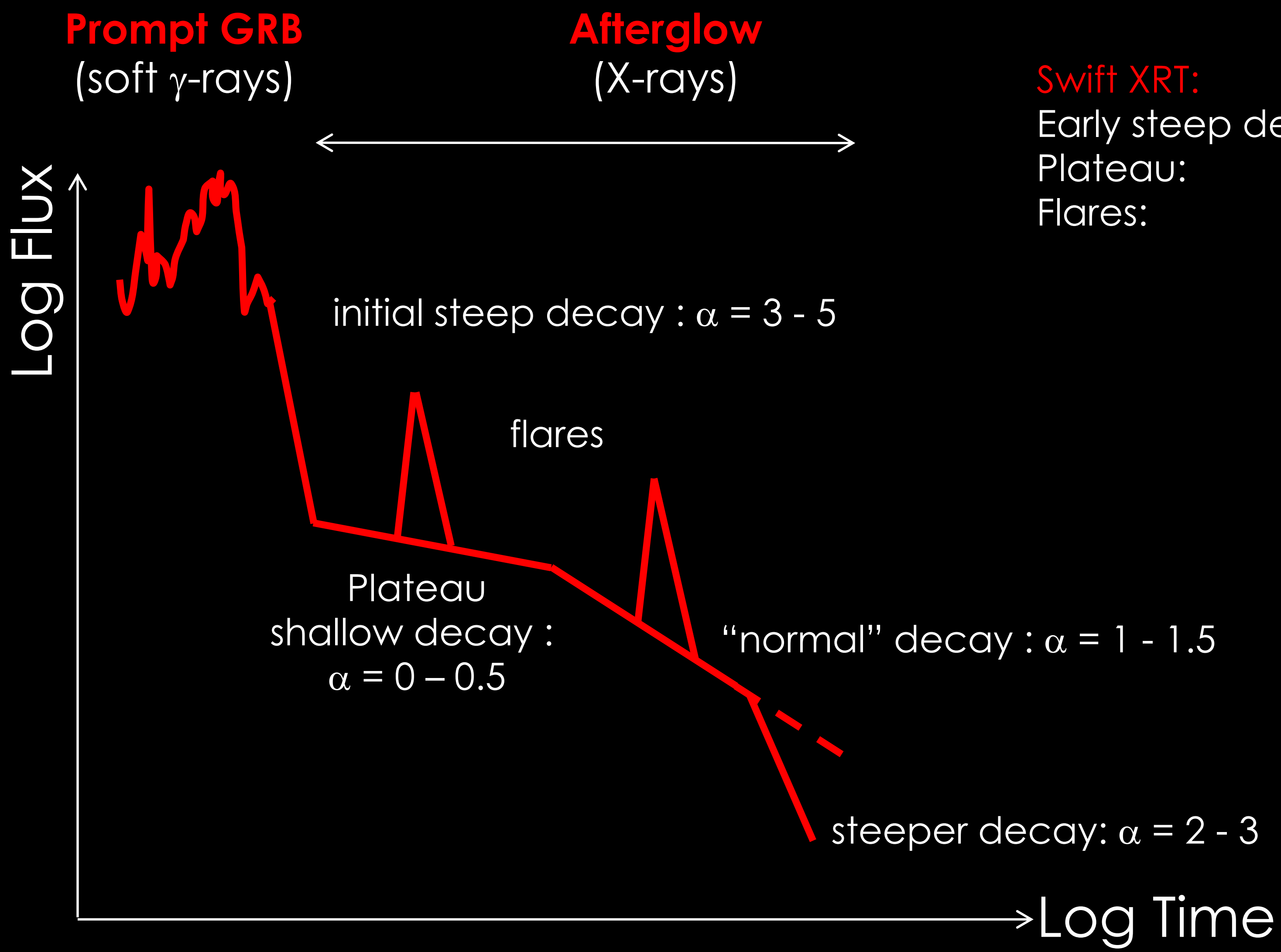
Tuesday's lectures:

- **S. Schanne: observation of the prompt emission**
- **S. Vergani & D. Götz: follow-up and observation of the afterglow and host**

Introduction

Observational Facts (3)
Prompt + Afterglow Summary

GRB Lightcurves: prompt to afterglow



Prompt GRB
(soft γ-rays)

Afterglow
(X-rays)

Log Flux

initial steep decay : α = 3 - 5

flares

Plateau
shallow decay :
α = 0 – 0.5

“normal” decay : α = 1 - 1.5

steeper decay: α = 2 - 3

Log Time

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

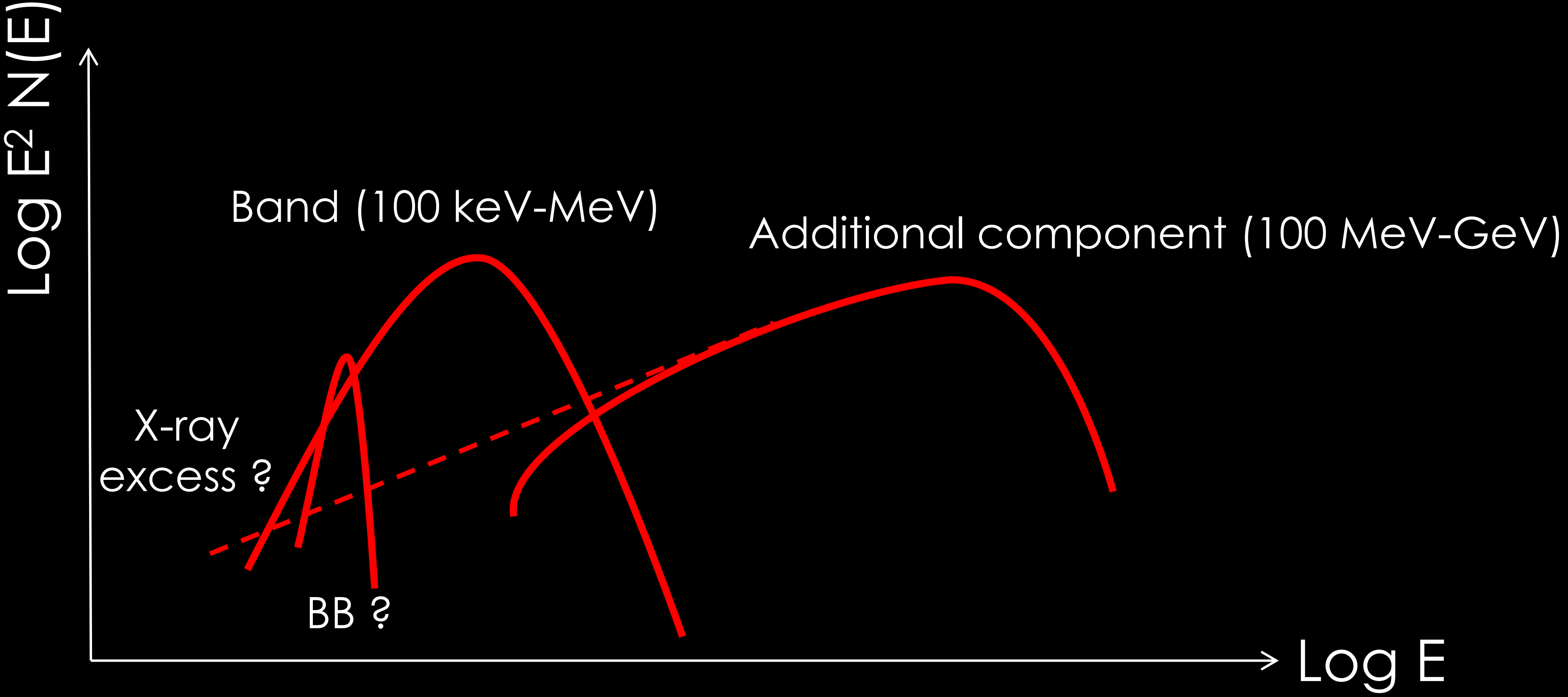
Also: prompt
optical, GeV

Also: optical, radio afterglow
long-lasting Fermi/LAT emission

\+ VHE gamma-rays in a few cases (MAGIC, HESS, LHASSO)

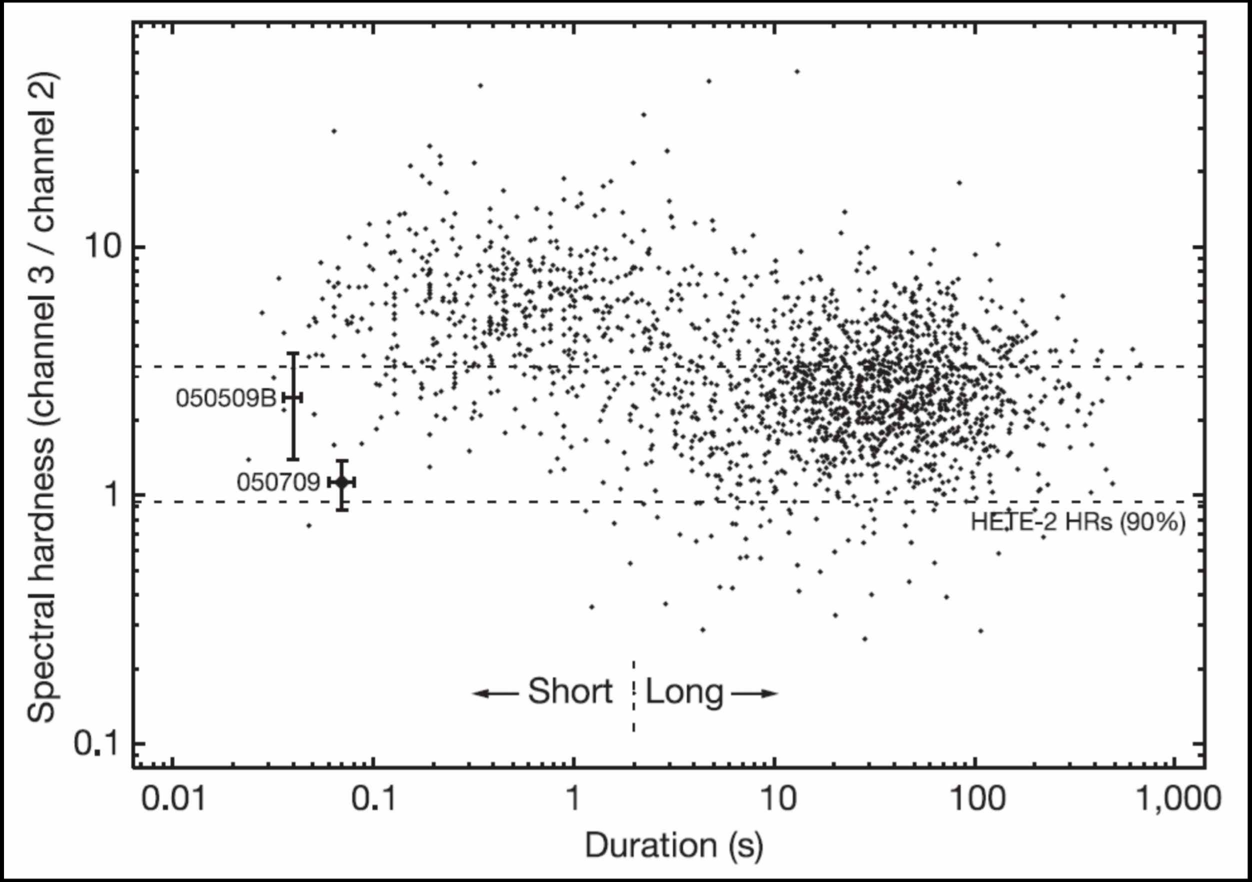
GRB Spectrum: Prompt

Fermi/GBM:
BB looked for in bright cases
& possibly found in some cases
Fermi/LAT: 1st catalog
extra-component in 4/28



GRB Spectrum: Afterglow = non-thermal, probably 2 components

GRB diversity: XRR, XRFs, Low-L GRBs, etc.

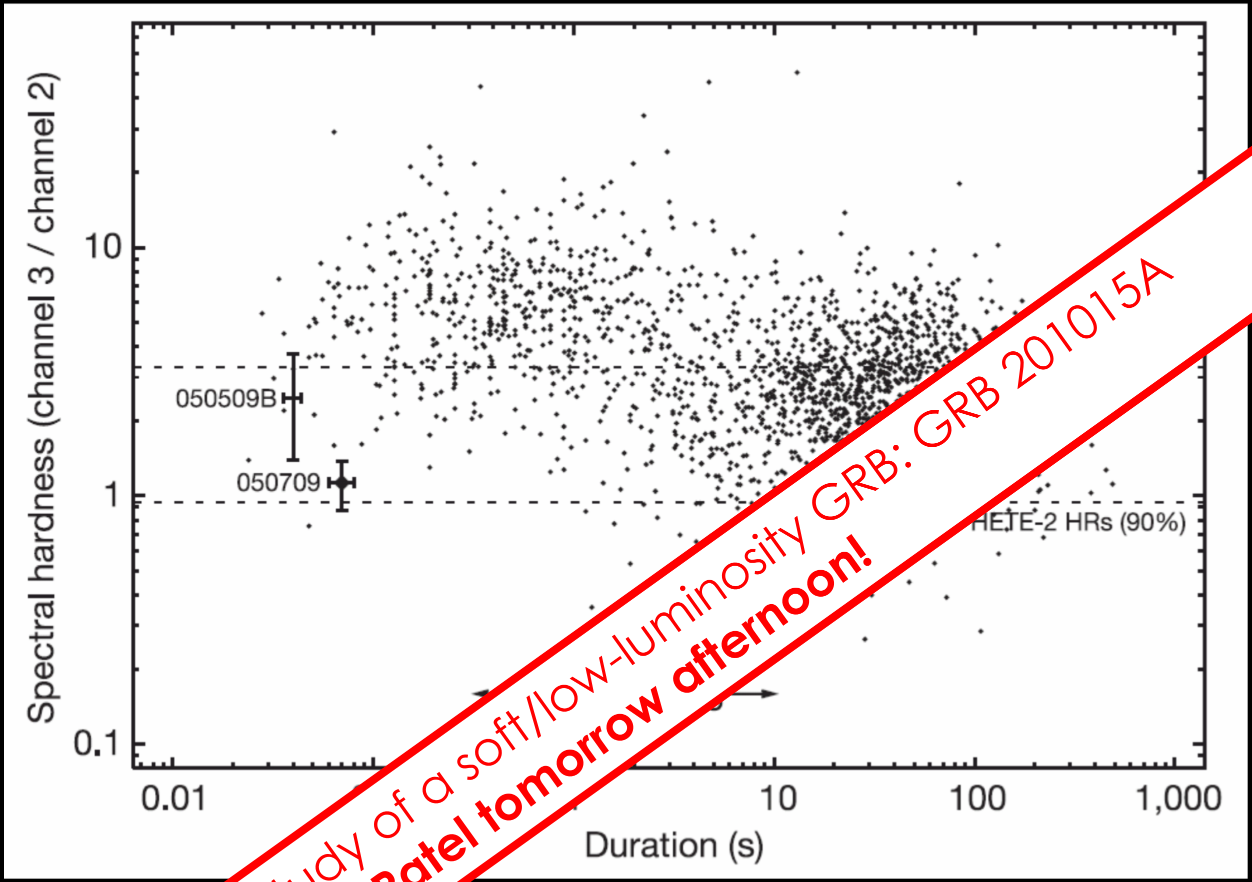


Hjorth et al. 2005

- **Short GRBs tend to be harder**, with some exceptions

- Long GRBs show a lot of diversity, with soft or very soft events, usually also weaker:
  X-ray Rich Bursts, X-Ray Flashes, Low-Luminosity Bursts, etc.
  Same physics/progenitors ?

GRB diversity: XRR, XRFs, Low-L GRBs, etc.



Hjorth et al. 2005

A detailed study of a soft/low-luminosity GRB: GRB 201015A

see talk by Miti Patel tomorrow afternoon!

- **Short GRBs te arder**, with some exceptions

- Long GRBs a lot of diversity, with soft or very soft events, usually also weaker:
  X-ray Rich Bursts, X-Ray Flashes, Low-Luminosity Bursts, etc.
  Same physics/progenitors ?

Lightcurves, Spectra, what about polarization?

Not discussed in this course.

Polarization offers interesting complementary diagnostics on

- **The geometry of the source**
- **The structure of the magnetic field in the emitting region**
- **The nature of the radiation mechanisms**

Prompt emission: **polarization in the gamma-ray range remains difficult**

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Polarization offers interesting complementary diag
- **The geometry of the source**
- **The structure of the magnetic field in the e**
- **The nature of the radiation mechanism**

Prompt emission: **polarization in th** **ns difficult**

Interested to know more on prompt GRB polarization measurements?
Ask Diego Götz!

Interested to learn more on the possibility to perform more accurate measurements using a CubeSat mission?
See talk by Nathan Franel this afternoon!

Lightcurves, Spectra, what about polarization?

Not discussed in this course.

Polarization offers interesting complementary diagnostics on

- **The geometry of the source**
- **The structure of the magnetic field in the emitting region**
- **The nature of the radiation mechanisms**

Prompt emission: polarization in the gamma-ray range remains difficult

Afterglow: some measurements in optical or radio

Example: afterglow of 170817

Lightcurves, Spectra, what about polarization?

Not discussed in this course.

Polarization offers interesting complementary diagnostics o

- **The geometry of the source**
- **The structure of the magnetic field in the emitting**
- **The nature of the radiation mechanisms**

Prompt emission: polarization in the gamm emains difficult

Afterglow: some measurements in o

Example: afterglow

An example of polarization measurements in an optical afterglow (GRB080928)
and associated diagnostics:
See talk by Riccardo Brivio this afternoon!

Introduction

Basic Constraints on any GRB Model

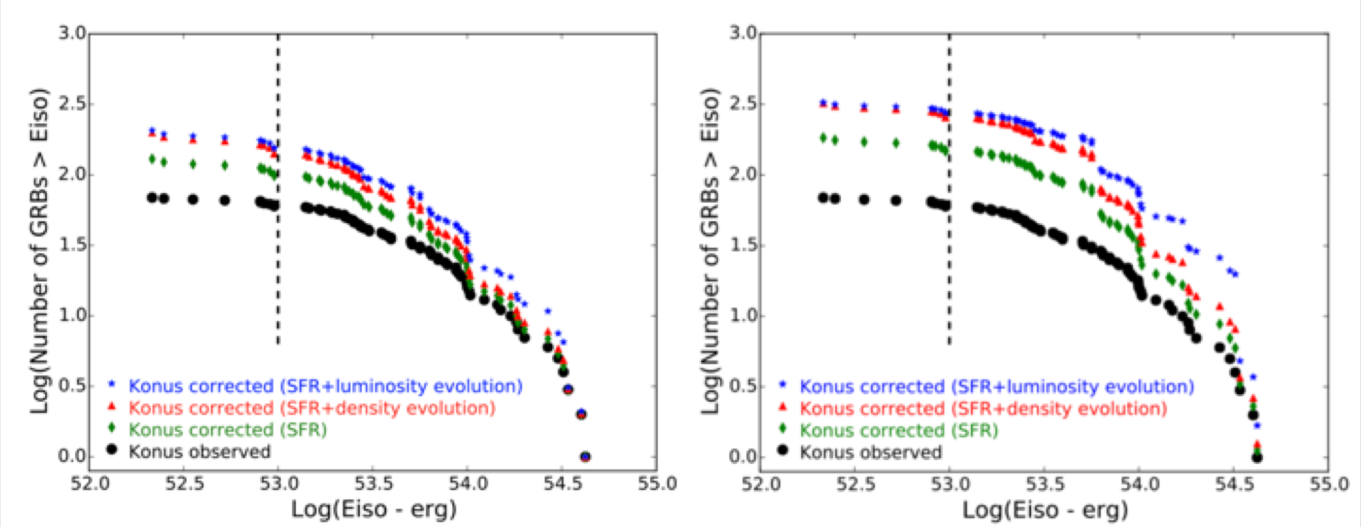
GRB Theory: Basic Constraints (1)

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



GRB 221009A (the BOAT): $E_{\gamma,\mathrm{iso}} \gtrsim 10^{55}$ erg

GRB 221009A: The Brightest burst Of All Times (the BOAT)

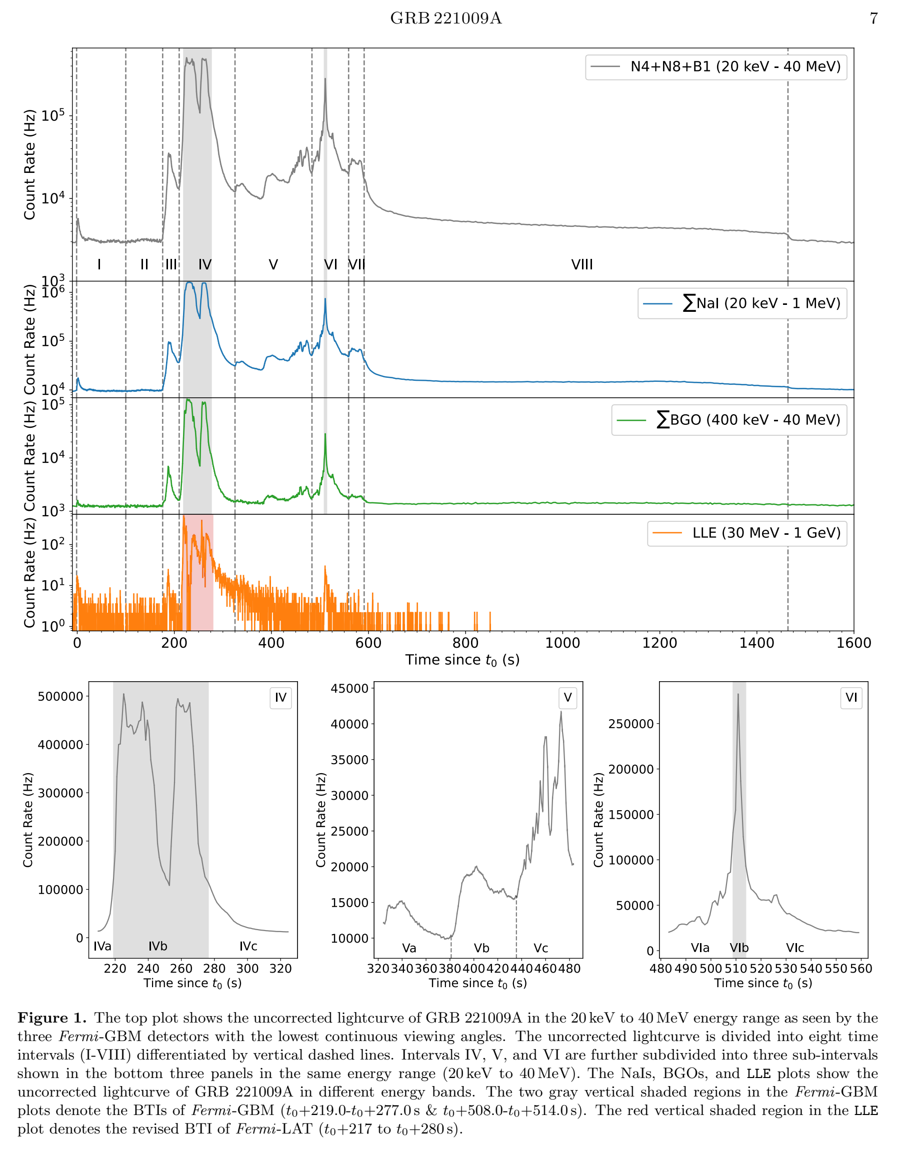
GRB 221009A (the BOAT): $E_{\gamma,iso} \gtrsim 10^{55}$ erg (x10 the second brightest GRB)
+ z = 0.15
= very very bright!

Impressive follow-up, from radio to TeV

Fermi detectors are over-saturated…

Impact on Earth's atmosphere
(as a solar flare would, except that the event occured at 2.3 Gly…

VHE detection by LHASSO
No HE ν detection by IceCube



GRB 221009A 7

Figure 1. The top plot shows the uncorrected lightcurve of GRB 221009A in the 20 keV to 40 MeV energy range as seen by the three *Fermi*-GBM detectors with the lowest continuous viewing angles. The uncorrected lightcurve is divided into eight time intervals (I-VIII) differentiated by vertical dashed lines. Intervals IV, V, and VI are further subdivided into three sub-intervals shown in the bottom three panels in the same energy range (20 keV to 40 MeV). The NaIs, BGOs, and `LLE` plots show the uncorrected lightcurve of GRB 221009A in different energy bands. The two gray vertical shaded regions in the *Fermi*-GBM plots denote the BTIs of *Fermi*-GBM (t_0+219.0-t_0+277.0 s & t_0+508.0-t_0+514.0 s). The red vertical shaded region in the `LLE` plot denotes the revised BTI of *Fermi*-LAT (t_0+217 to t_0+280 s).

Fermi GBM lightcurve (Lesage +23)

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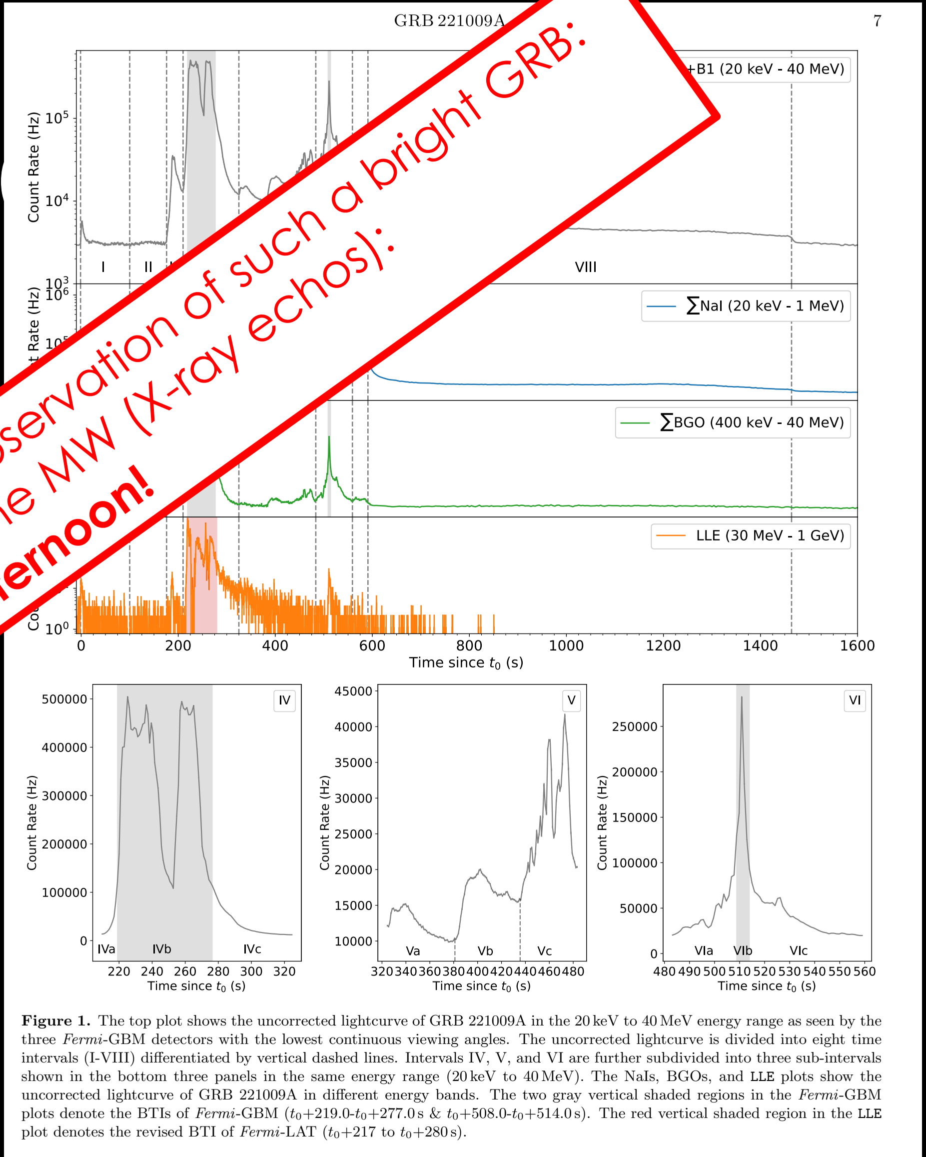
Fermi detectors are over-saturated…

Impact on Earth's atmosphere
(as a solar flare would, except that t
event occured at 2.3 Gly…

VHE detection by LHA
No HE ν detection

An impressive application of the observation of such a bright GRB:
mapping the dust distribution in the MW (X-ray echos):
see talk by Beatrice Vaia this afternoon!

Fermi GBM lightcurve (Lesage +23)



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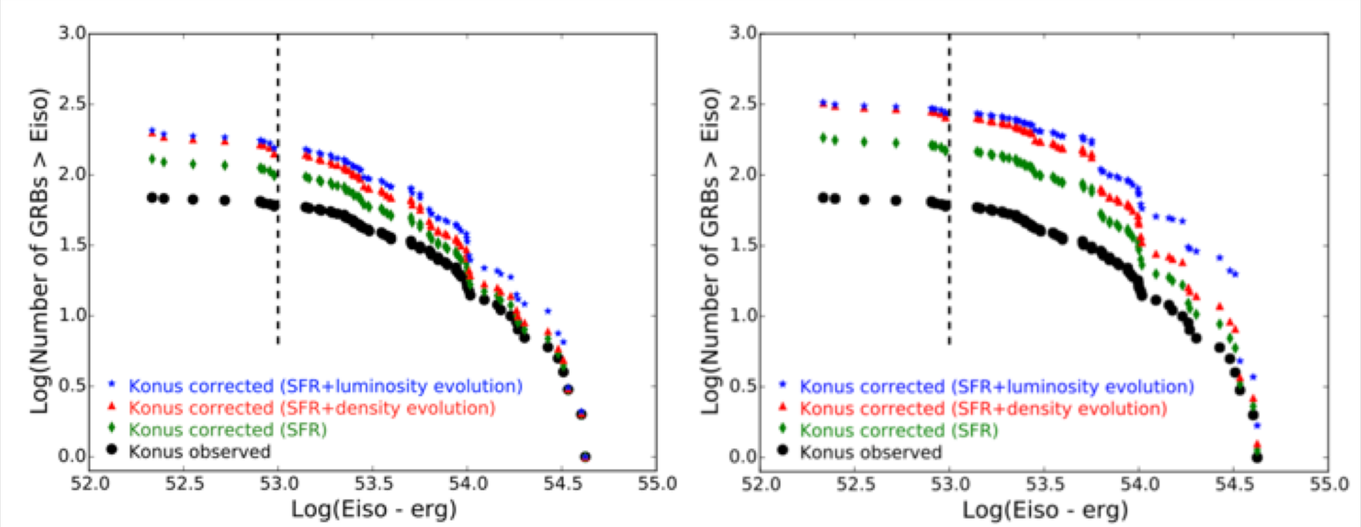
Atteia+ 2017



GRB 221009 (the BOAT): $E_{\gamma,\mathrm{iso}} \gtrsim 10^{55}$ erg

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

Short timescale variability:
compact source (NS, BH)

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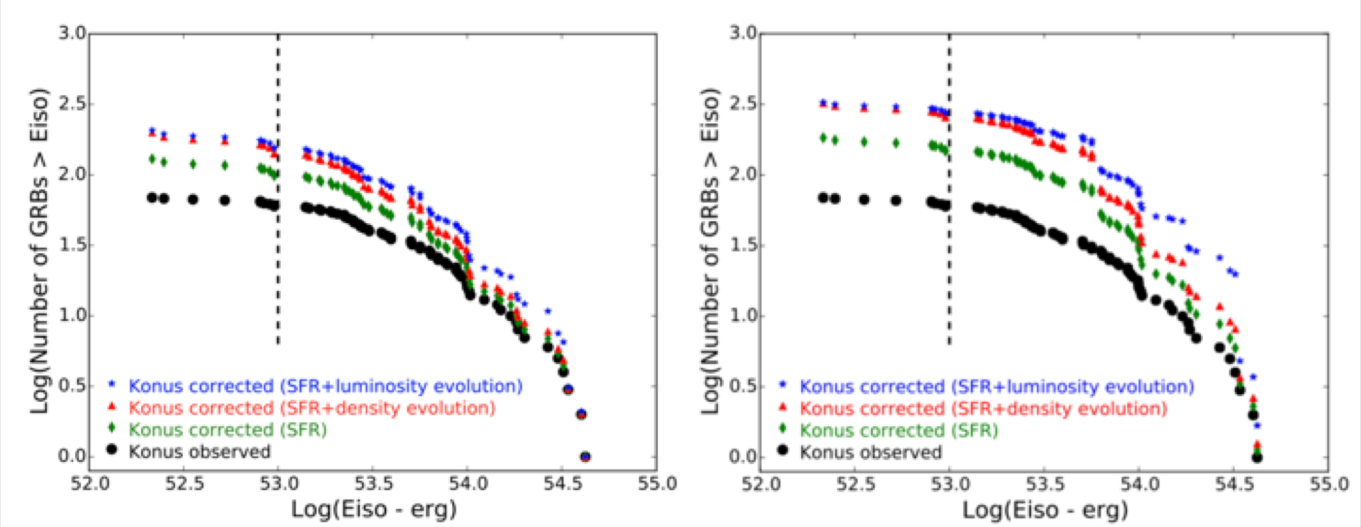
Atteia+ 2017



GRB 221009 (the BOAT): $E_{\gamma,\mathrm{iso}} \gtrsim 10^{55}$ erg

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 Theory: Basic Constraints (2)

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

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

See R. Belmont's Lecture

Pair production

$$\gamma\gamma \rightarrow \mathrm{e}^{+}\mathrm{e}^{-}$$

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

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

Observed γ-ray spectrum:
(ph/keV)

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

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

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

Assume there is a frame where the radiation field is isotropic:

Photon density:
(ph/keV/sr)

$$\frac{\mathrm{d}^2n}{\mathrm{d}E\,\mathrm{d}\Omega} = \frac{1}{4\pi}\,\frac{1}{V} \times (\beta-2)\,\frac{\mathcal{E}_{\mathrm{iso,HE}}}{E_{\mathrm{p,obs}}E_{\mathrm{p}}}\left(\frac{E}{E_{\mathrm{p}}}\right)^{-\beta}$$

Mean free path of the most energetic gamma-ray photons?

GRB Theory: Basic Constraints (2)

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

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

Mean free path of the most energetic gamma-ray photons?

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

GRB Theory: Basic Constraints (2)

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

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

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

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

Gamma-ray photons cannot escape from the source!

GRB Theory: Basic Constraints (2)

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

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Relativistic source:

GRB Theory: Basic Constraints (2)

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

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

Mean free path of the most energetic gamma-ray photons?

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

Relativistic source:

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

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

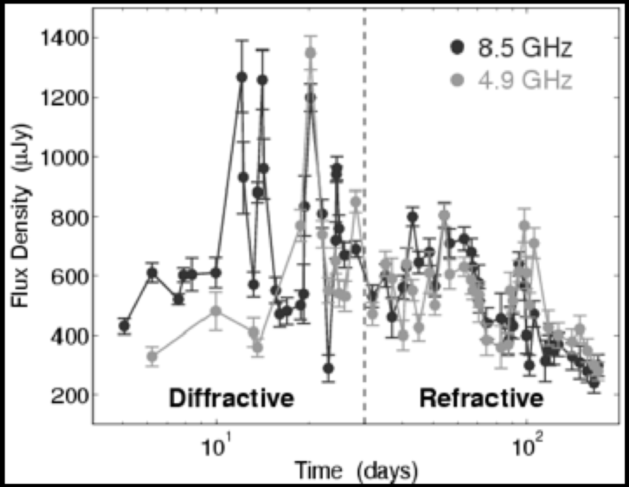
Gamma-rays can escape the source if they are produced at large distance in an ultra-relativistic ejecta (Lorentz factor > 100).

Relativistic motion: direct evidence = apparent superluminic motion (rare)

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

GRB030329 (HETE-2)

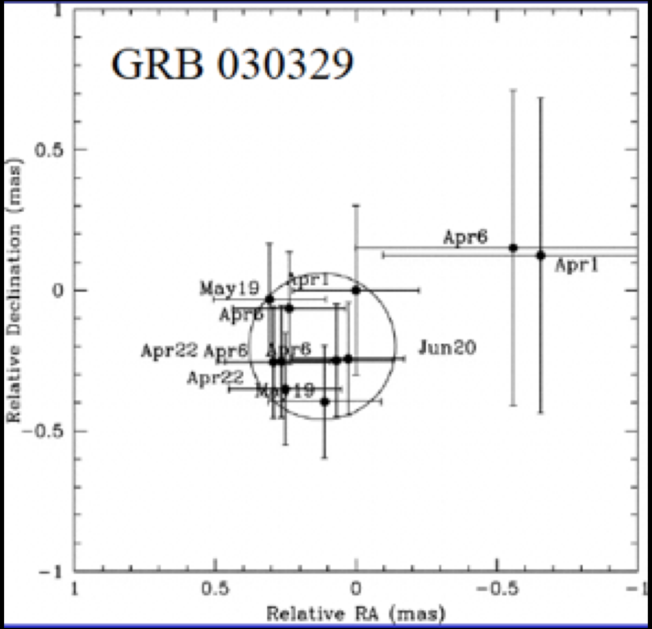


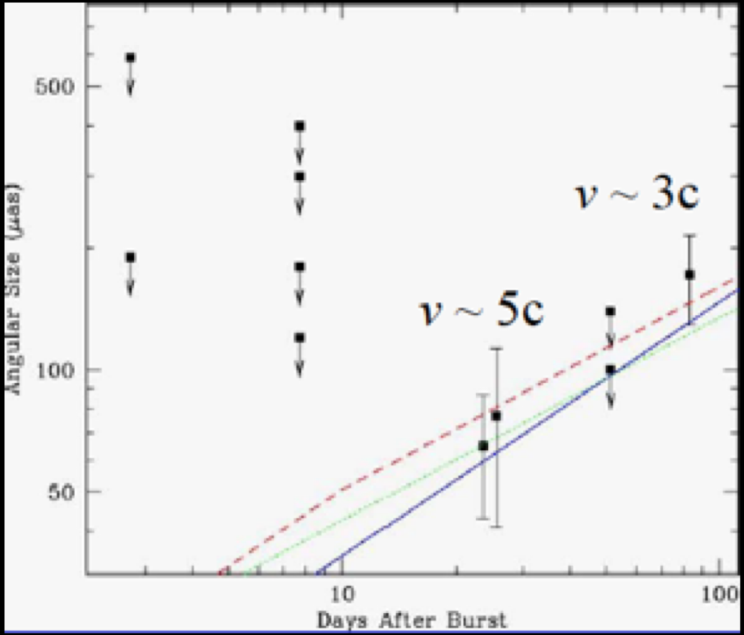
5 μas (2 10^{17} cm)

Relativistic motion: direct evidence = apparent superluminic motion (rare)

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



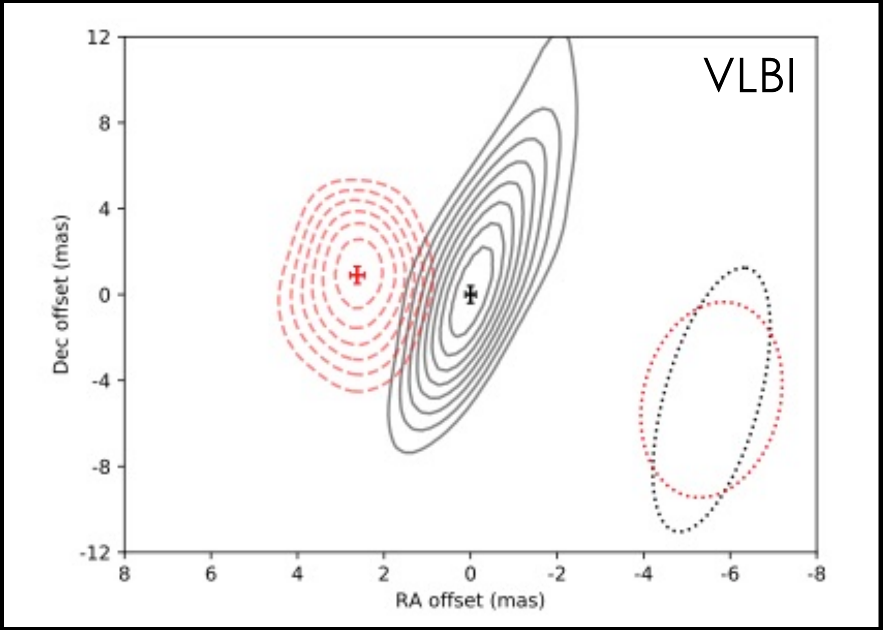


Taylor et al. 2004

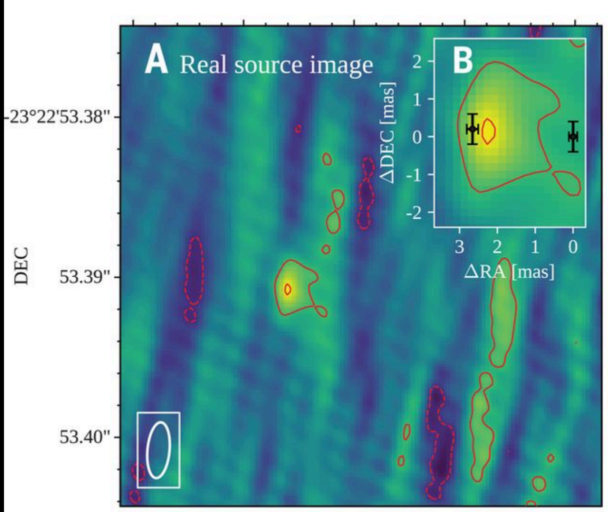
After 25 days:
65 μas (5.7 10^{17} cm)

Proper motion:
0.1 mas in 80 days

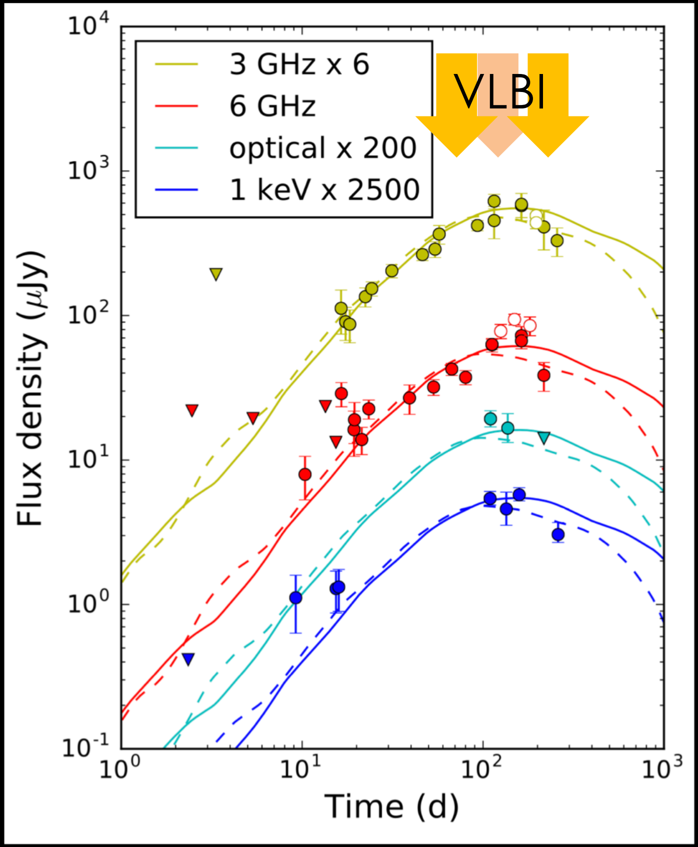
Relativistic motion: direct evidence
= apparent superluminic motion (rare)



Mooley et al. 2018



Ghirlanda et al. 2019

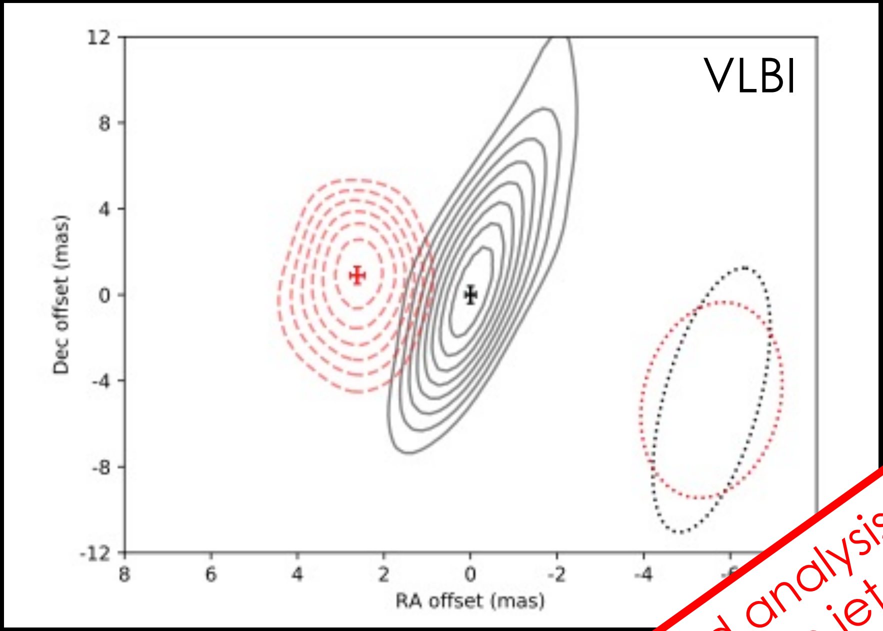


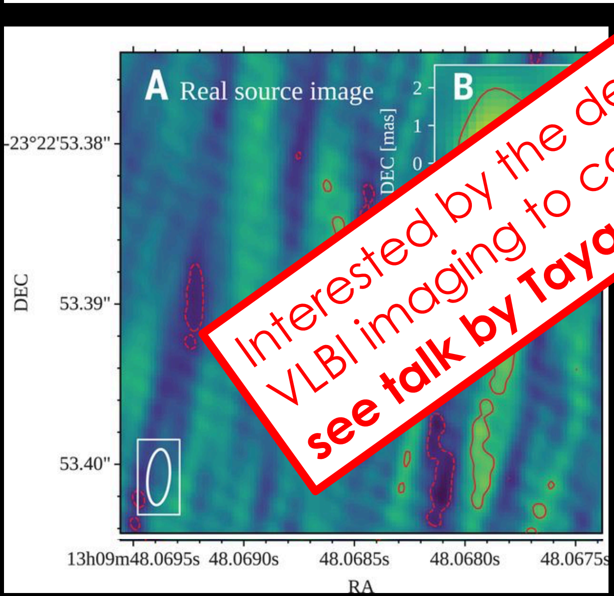
Alexander et al. 2018

A recent spectacular case: 170817
(Saturday's Lecture by Marica Branchesi)

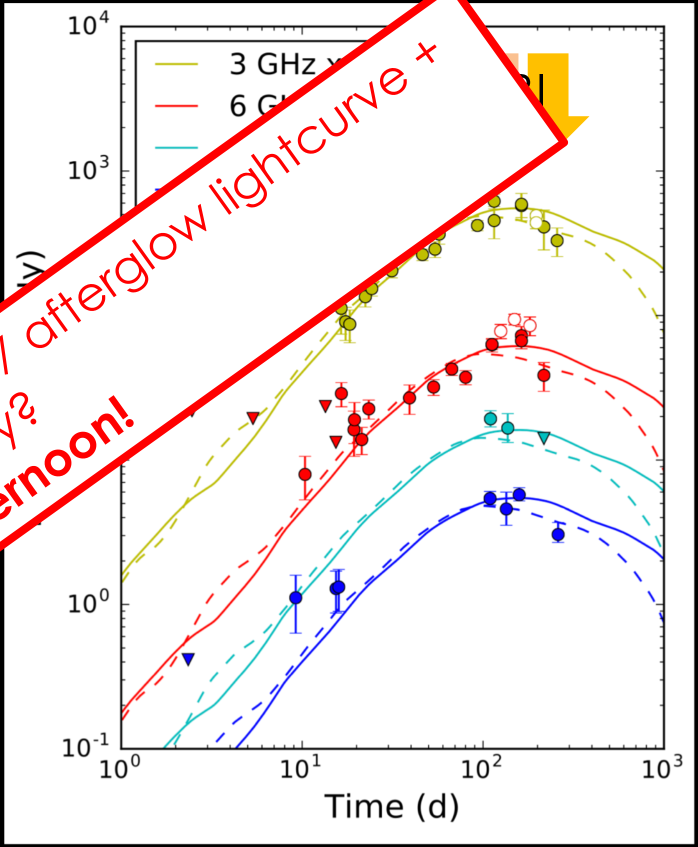
Direct evidence for relativistic motion + constraints on jet geometry/viewing angle

Relativistic motion: direct evidence = apparent superluminic motion (rare)





Ghirlanda … et al. 2018



Alexander et al. 2018

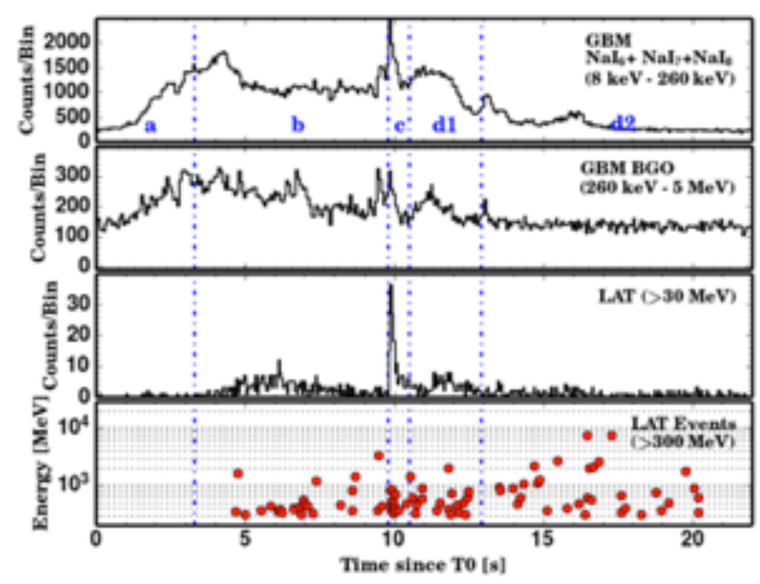
Interested by the detailed analysis of 170817 afterglow lightcurve + VLBI imaging to constrain the jet geometry?
see talk by Taya Govreen-Segal this afternoon!

A recent spectacular case: 170817 (Saturday's Lecture by Marica Branchesi)

Direct evidence for relativistic motion + constraints on jet geometry/viewing angle

$\gamma\gamma$ cutoff in the HE spectrum?

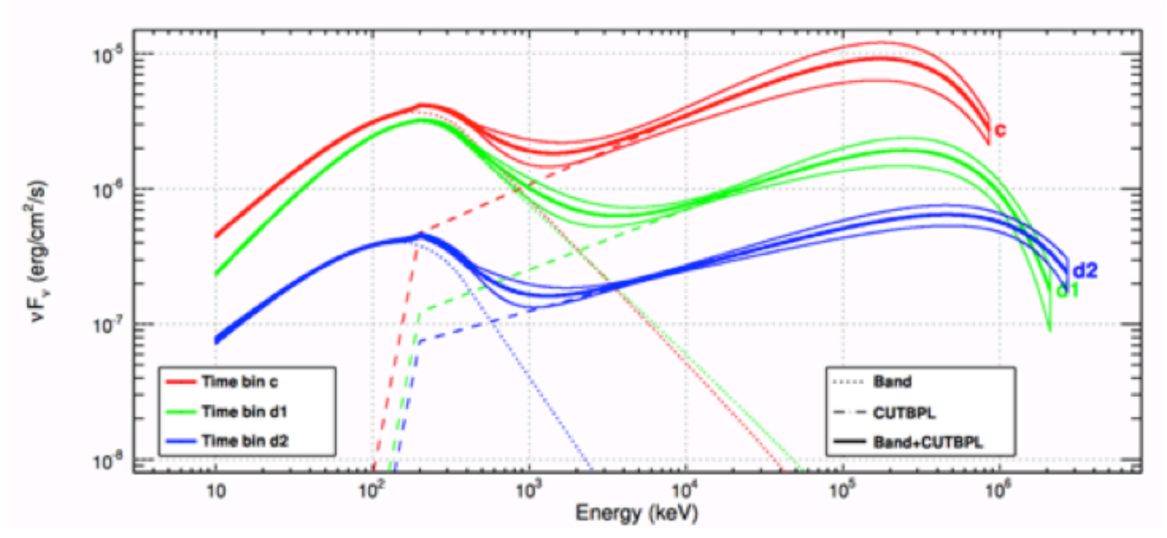
GRB 090926A (Fermi-LAT): first observed cutoff at high-energy (Ackermann et al. 2011)



New analysis and interpretation:

Path 8: 447 → 1088 evts in LAT (× 2.4)

cutoff is better detected, in several time bins



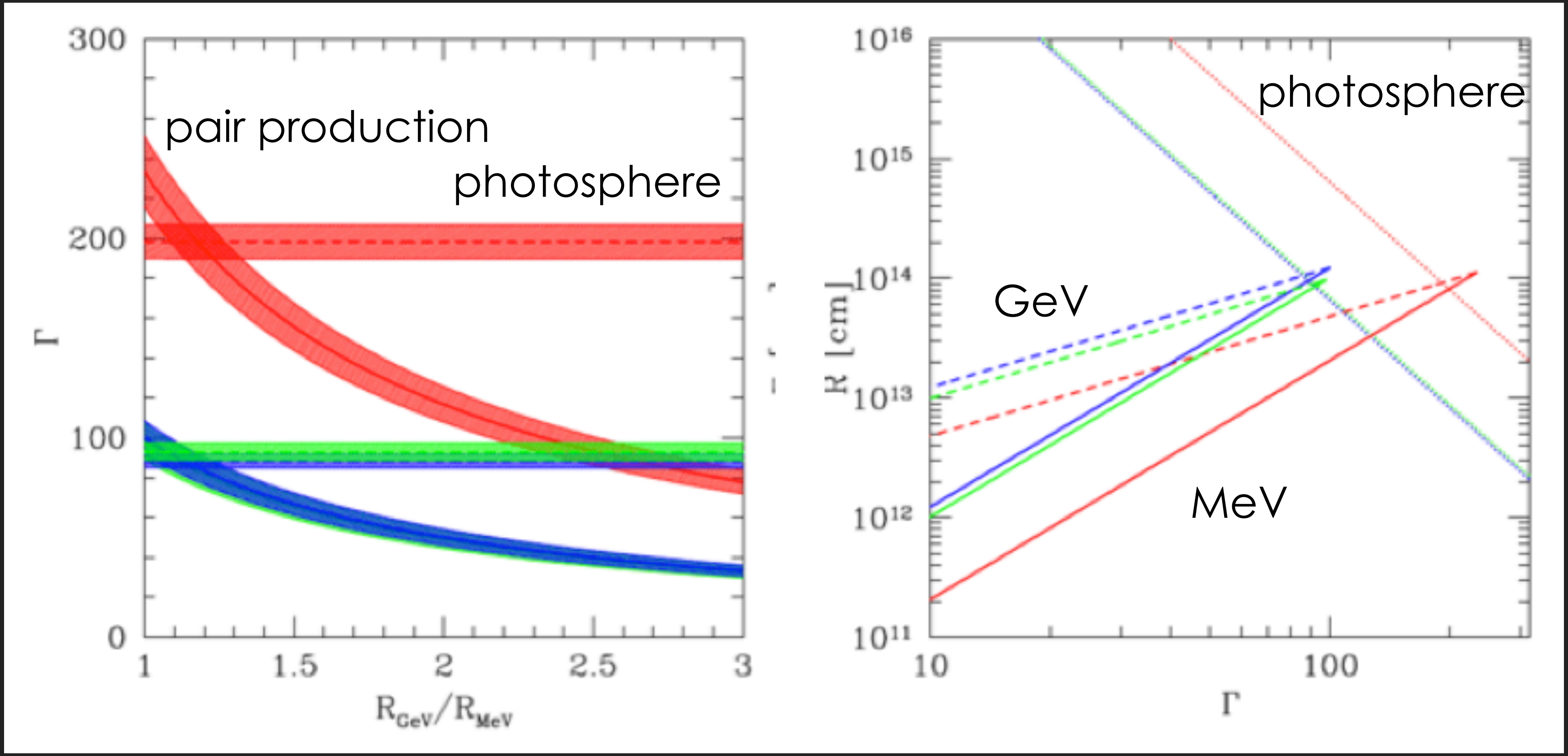
Yassine, Piron, Mochkovitch & Daigne 2017

$\gamma\gamma$ cutoff in the HE spectrum?

Strong constraint on **Lorentz factor** and emission radius

- Lorentz factor ~ 230 to 100
- Emission radius ~ 10^{14} cm
- Photospheric radius ~5 10^{13} cm

**Compatible with « standard scenario »
(shocks/reconnection above photosphere)**



Yassine, Piron, Mochkovitch & Daigne 2017

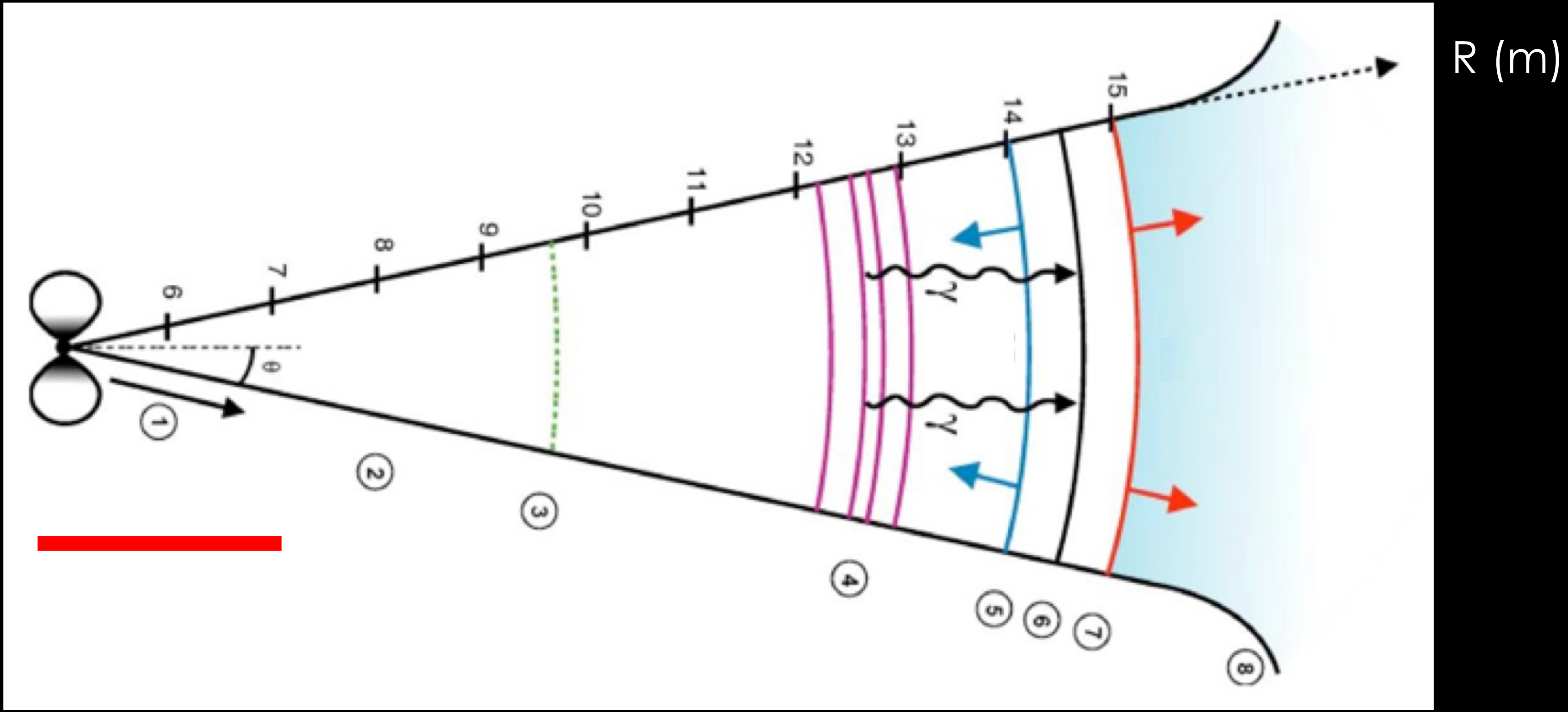
GRB Physics

« Standard » Scenario & Characteristic Radii

With a long list of open questions…

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 ?)



Progenitors:

- **Long GRBs: core-collapse of massive star (collapsar model)**
  Some supernova associations
- **Short GRBs: merger of binary neutron star system (or NSBH)**
  Some kilonova associations – one GW/GRB association (170817)

Initial event & central engine

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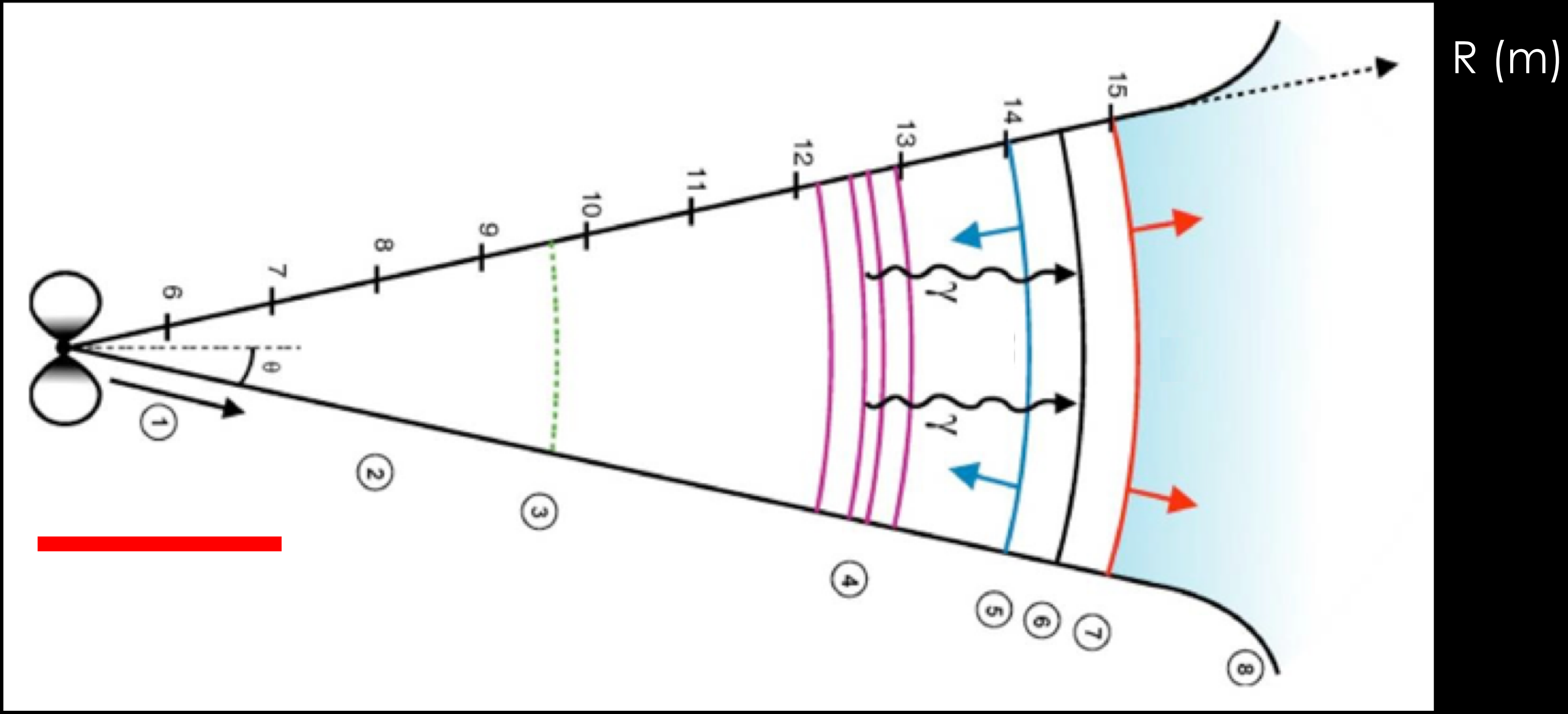
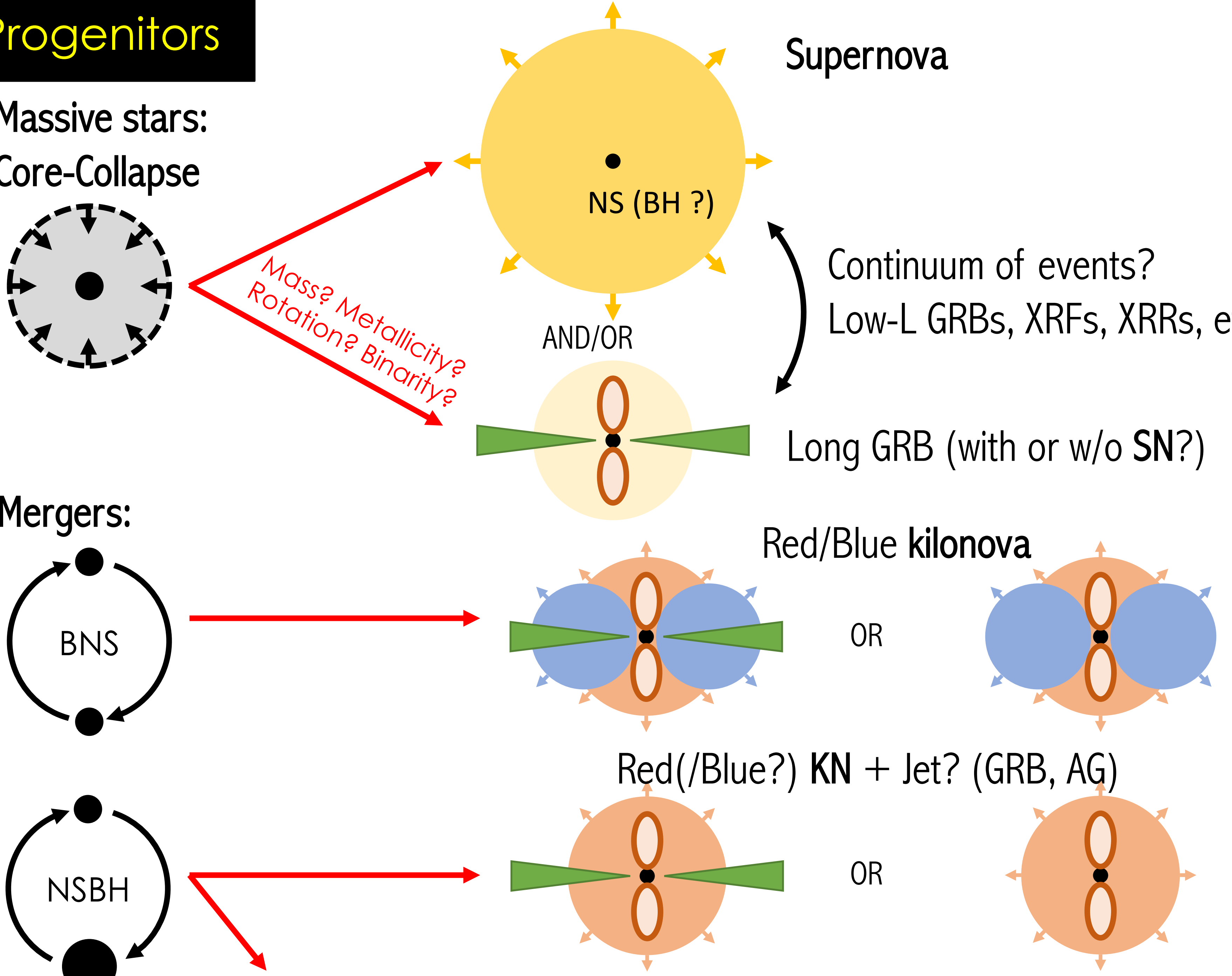


Progenitors:

- **Long GRBs: core-collapse of massive star (collapsar model)**
- **Short GRBs: merger of binary neutron star system (or NSBH)**

Other observational evidences: see Susanna Vergani's lecture tomorrow.

Progenitors



Massive stars:

Core-Collapse

Mass? Metallicity?
Rotation? Binarity?

Supernova

NS (BH ?)

AND/OR

Continuum of events?
Low-L GRBs, XRFs, XRRs, etc.

Long GRB (with or w/o **SN**?)

Mergers:

BNS

Red/Blue **kilonova**

OR

NSBH

Red(/Blue?) **KN** + Jet? (GRB, AG)

OR

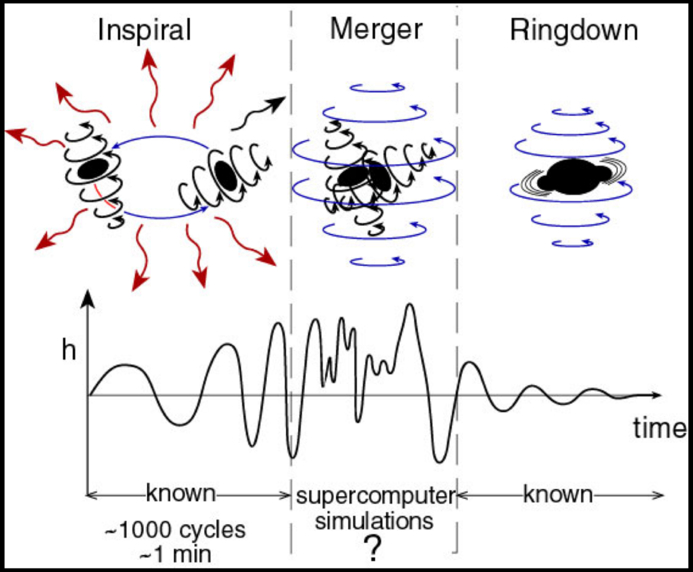
Or nothing for a large mass ratio… (« just GW »)

Central engine: a long list of difficult questions

No direct information:

- The central region is very opaque: no electromagnetic signal

- Gravitational waves:
  Short GRBs: the post-merger GW signal contains a direct information on the nature of the final central object but cannot be detected with current detectors.



Long GRBs: GW signal of a core-collapse can be detected only at short distance (Milky Way+satellites).

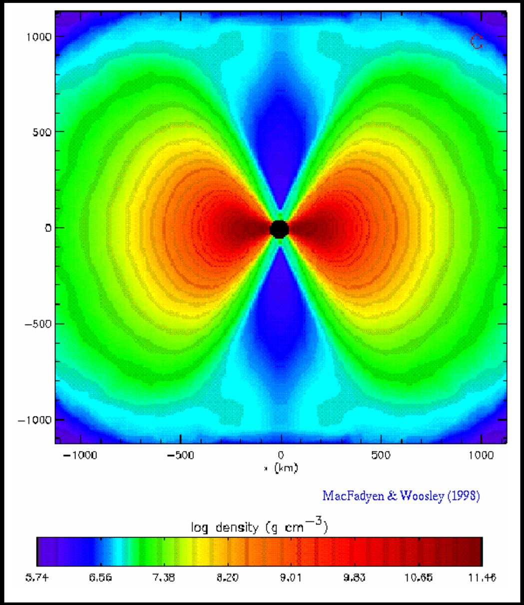
GW signal & diagnostics: see Irina Dvorkin & Marica Branchesi's Lectures.

- Neutrinos?
  Collapse: MeV neutrinos, cannot be detected at extragalactic distance
  HE neutrinos: rather expected in the next phase (early jet propagation)

Central engine: a long list of difficult questions

Questions:

- Nature of the central object? (BH, magnetar, magnetar → BH ?)
- Lifetime? (different episods of accretion: direct / fallback ?)
- Energy reservoirs? (BH/NS rotational energy, magnetic energy ?)
- Etc.



MacFadyen & Woosley (1998)

The most standard scenario in the collapsar model: a stellar-mass black hole + a thick accretion disk (torus)

Ejection = Blandford-Znajek
(energy reservoir: rotational energy of the BH)
Lifetime = lifetime of the torus

Pioneering work by Woosley & McFadyen, still a very active topic of research.

Central engine: a long list of difficult questions

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- Nature of the central object? (BH, magnetar, magnetar → BH ?)
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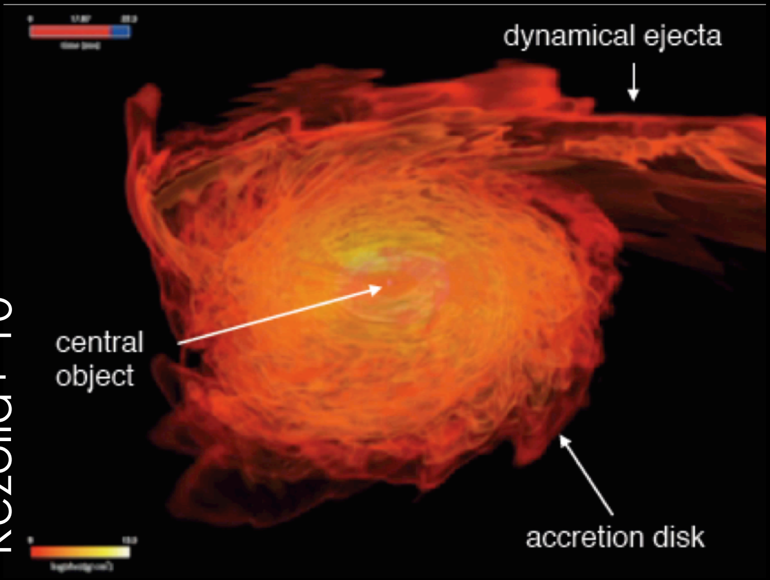


Rezolla+ 10

The most standard scenario in the merger model: again BH + torus, but:

- BH mass is smaller (BH spin is higher?)
- torus mass is much smaller: lifetime is much shorter
- fallback accretion is expected (tidal arms)
- depending on the NS equation of state: an intermediate hypermassive NS stage is possible (lifetime ?): see discussion later on the GW-GRB delay in 170817

Central engine: a long list of difficult questions

Questions:

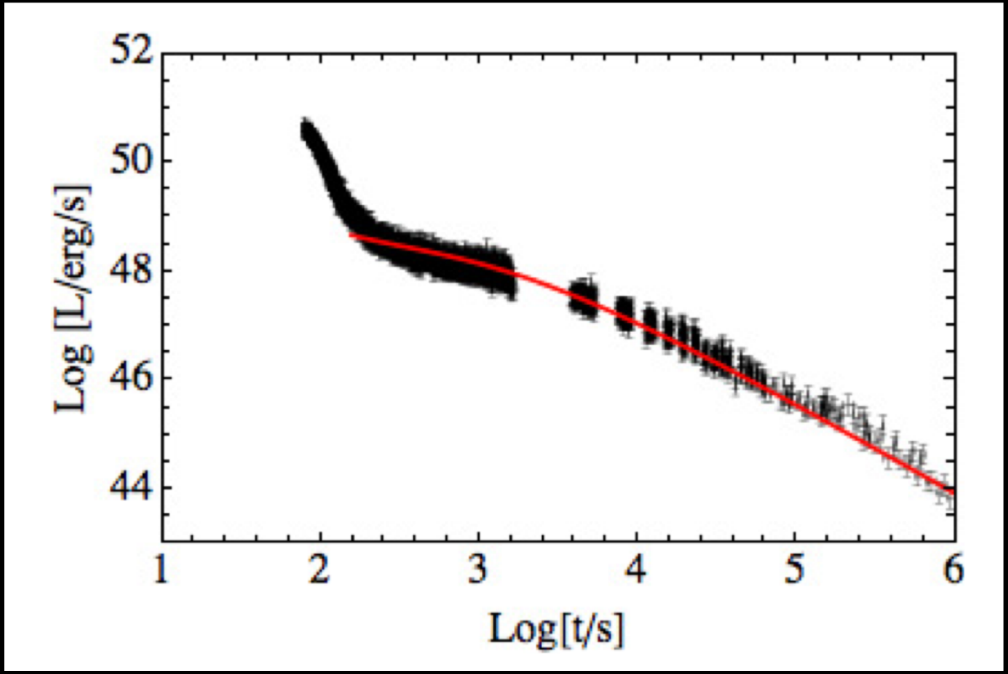
- Nature of the central object? (BH, magnetar, magnetar → BH ?)
- Lifetime? (different episods of accretion: direct / fallback ?)
- Energy reservoirs? (BH/NS rotational energy, magnetic energy ?)
- Etc.

Observational constraints?

- In most prompt emission models: GRB duration ≥ lifetime of the central engine
- Interpretation of the plateaus in the early X-ray afterglow?
  Late energy injection? (strong constraint on the central engine)
  Magnetar activity?
- Interpretation of X-ray flares?
  Late ejection? (strong constraint on the central engin)
- Interpretation of the soft X-ray extended emission found in some short GRBs?
  Late fallback of ejected material during the merger?

Etc.

Central engine: a long list of difficult questions



Bernardini 2012

X-ray afterglow of GRB090618 (Swift XRT)

Red curve: best-fit for energy injection from a ms magnetar

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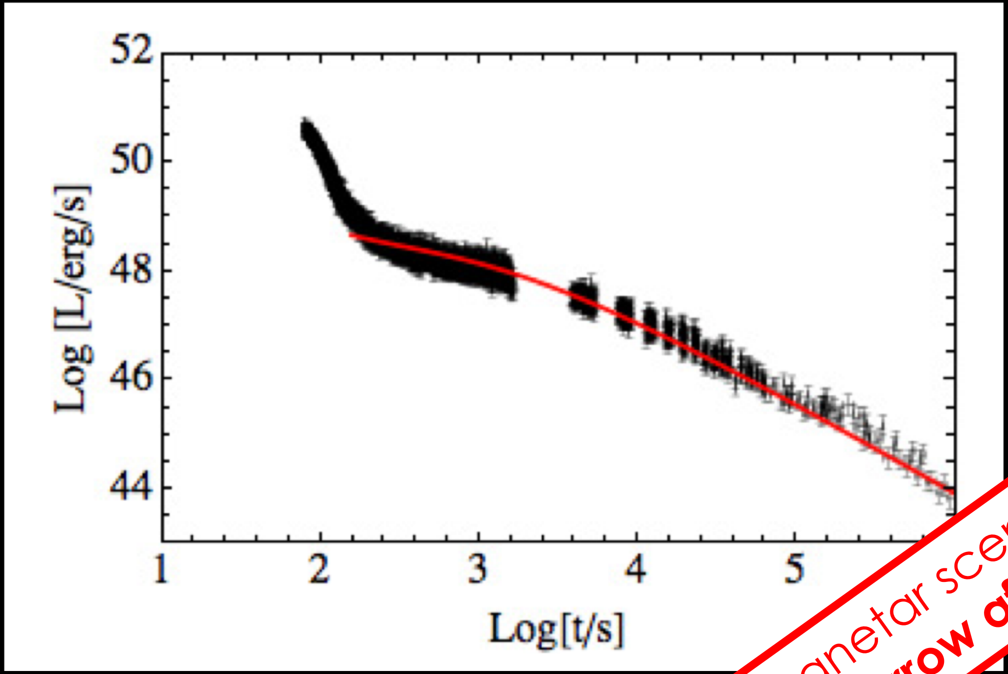
Central engine: a long list of difficult questions



Be i 2012

X-ray afterglov B090618
(Swift XRT)

Red est-fit for energy
i om a ms magnetar

How to explore the ms-magnetar scenario for short GRBs?
see talk by Clara Plasse tomorrow afternoon!

Observational constraints?

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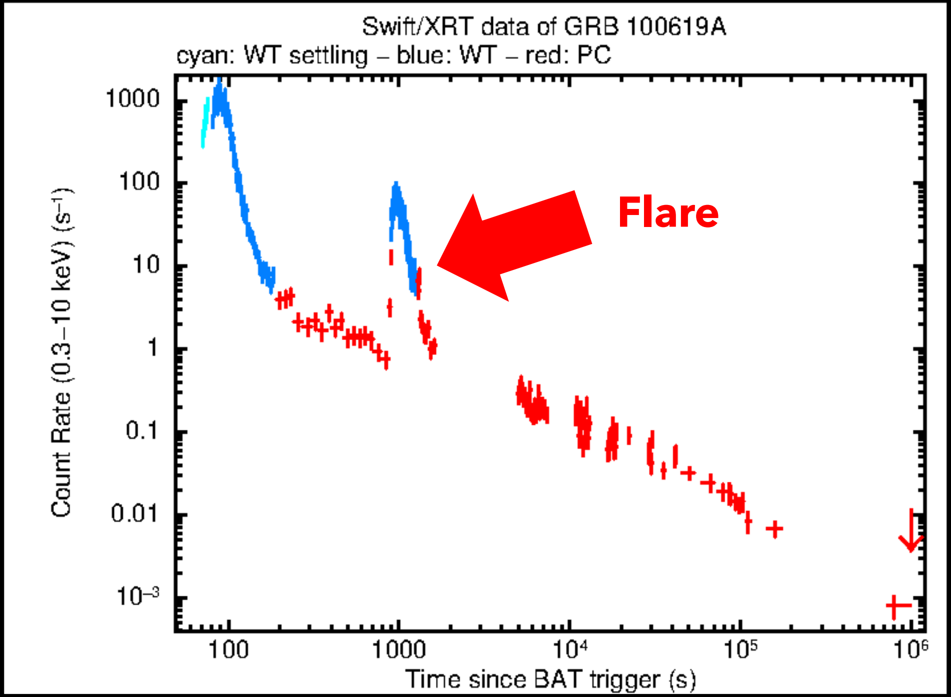
Etc.

Central engine: a long list of difficult questions



X-ray flares in the early afterglow

Observational constraints?

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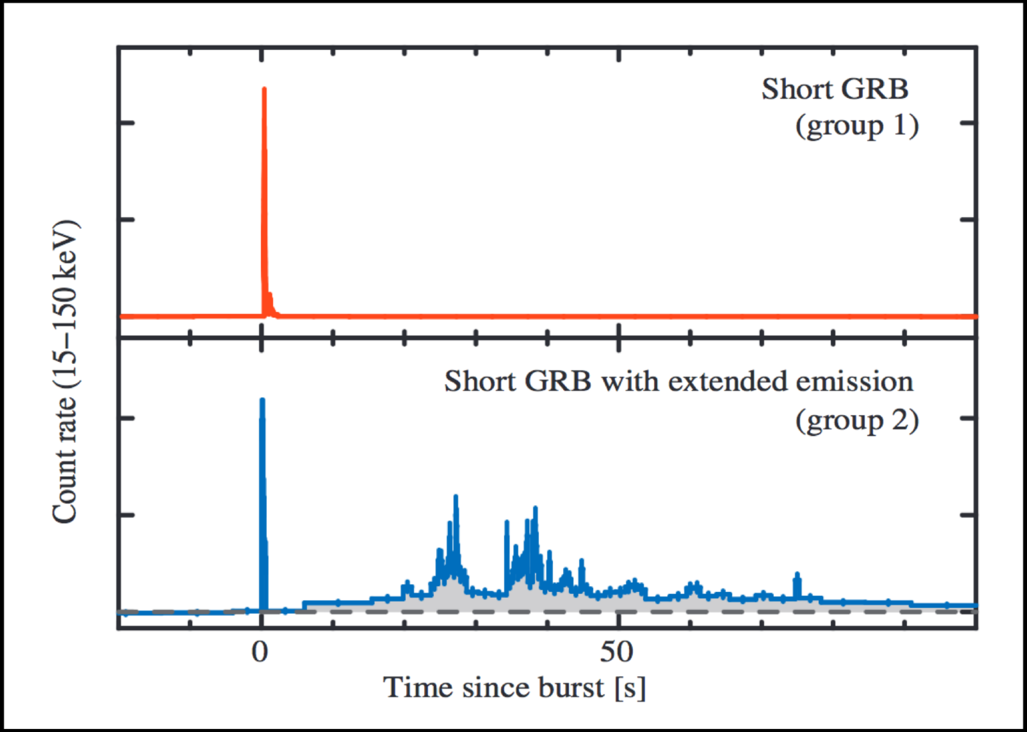

Troja 2013

Swift lightcurves of short GRBs

~15-20% of Swift short GRBs show a soft tail

Observational constraints?

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Etc.

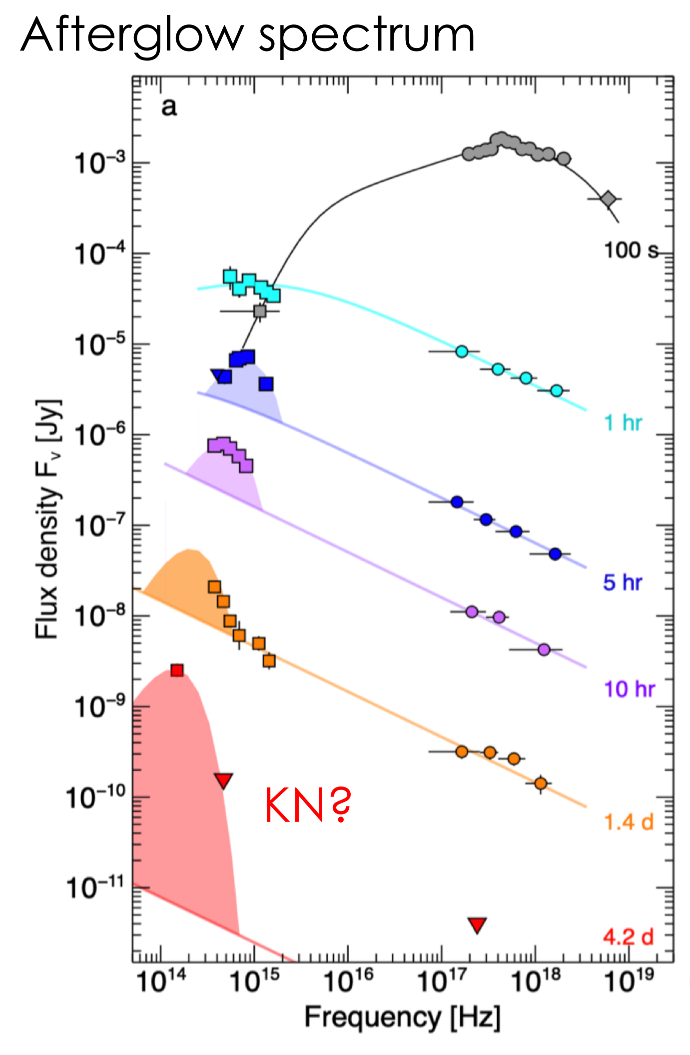
The puzzling case of GRB211211A: long GRB + kilonova?

Several evidence for a merger progenitor…

-Offset

-No association with a star forming region

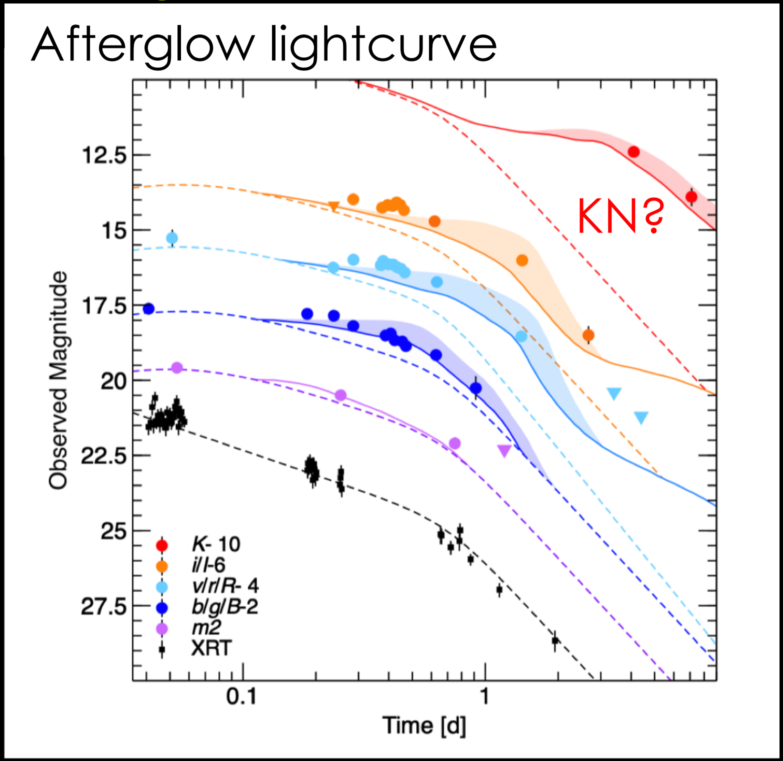
-Associated kilonova?



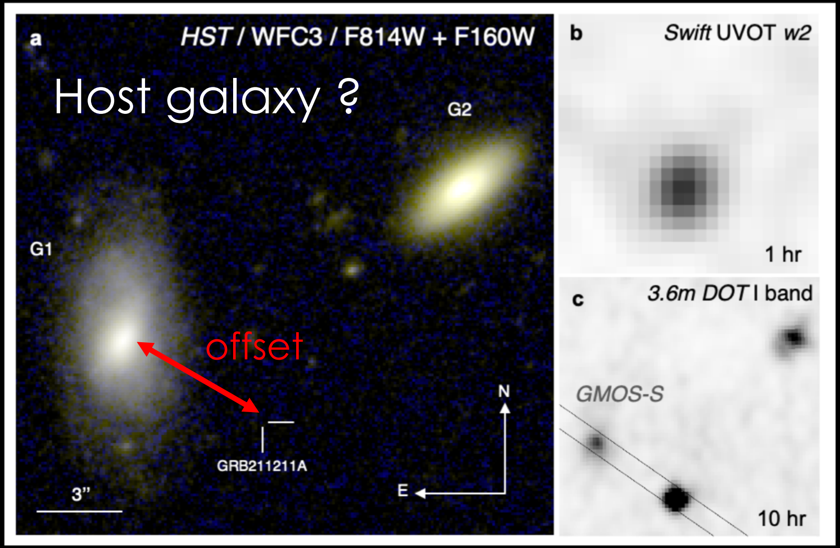
Afterglow spectrum

Figures taken from Troja et al. 2022

D ~350 Mpc



Afterglow lightcurve



Host galaxy ?

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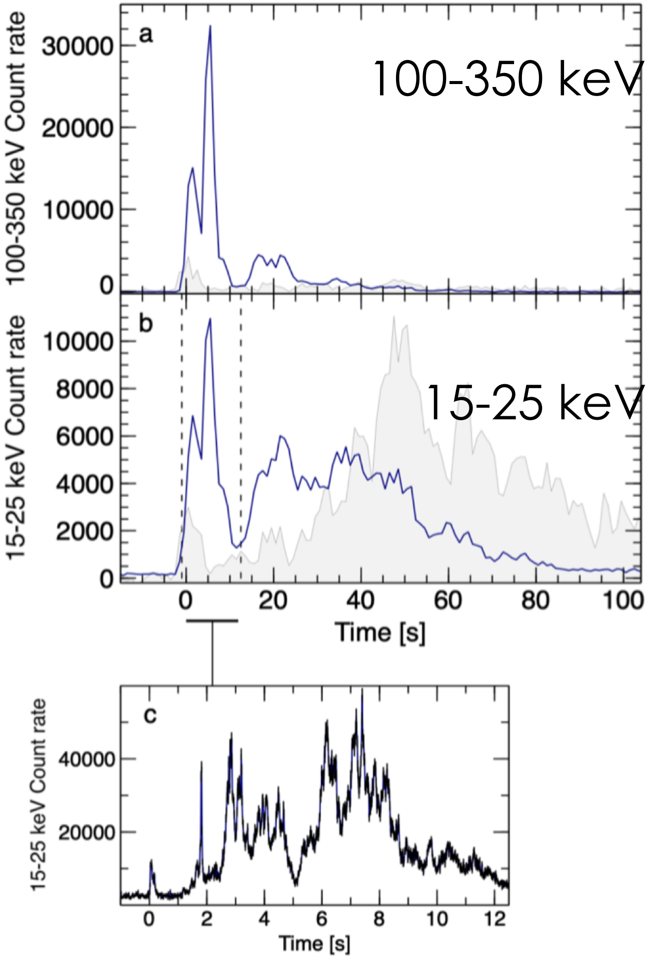
GRB lightcurve:



Figures taken from Troja et al. 2022

… but a long duration

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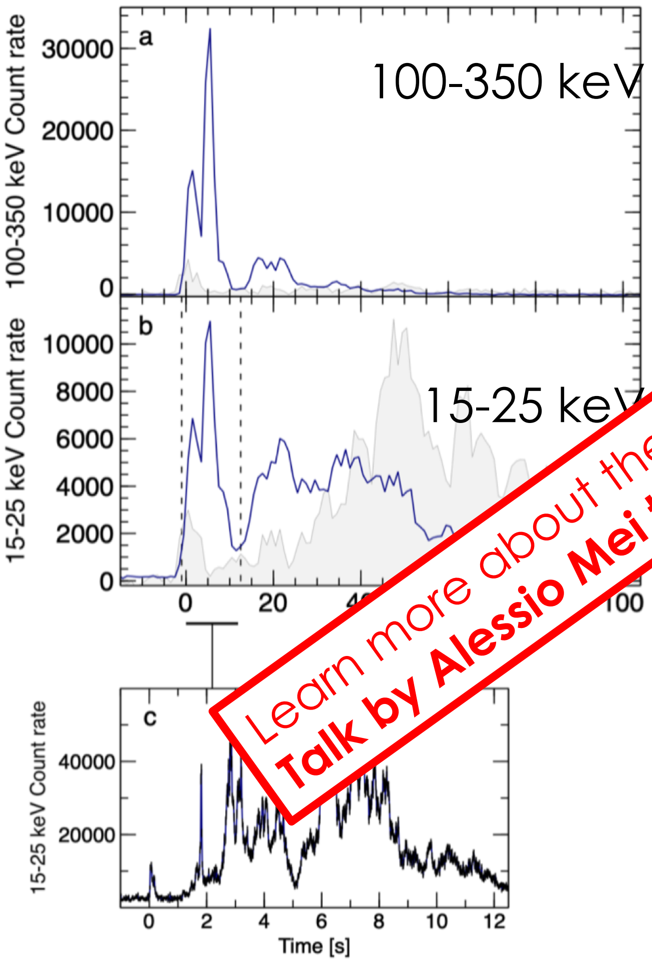


. but a long duration

Figures taken fro

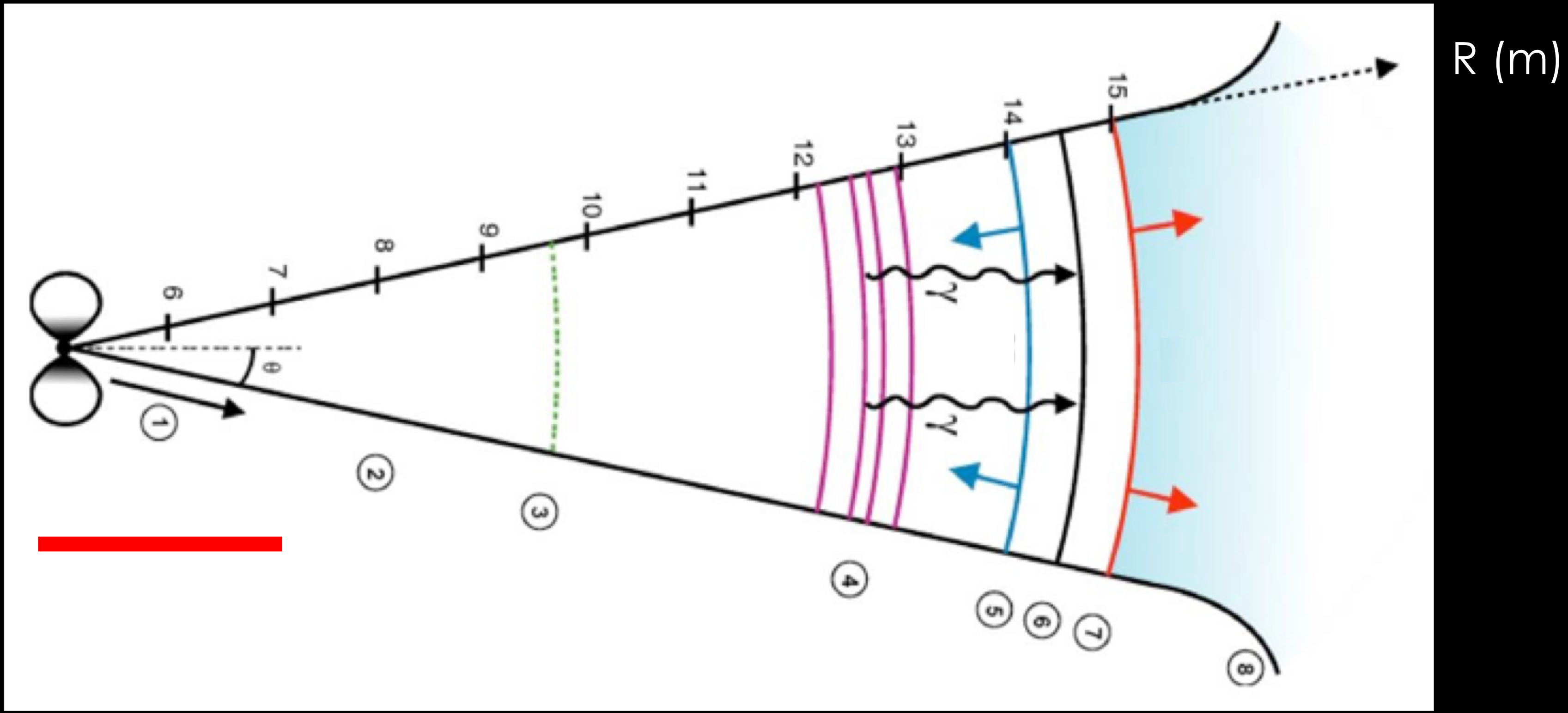
et al. 2022

Learn more about the afterglow at high energy of this event?

Talk by Alessio Mei this afternoon!

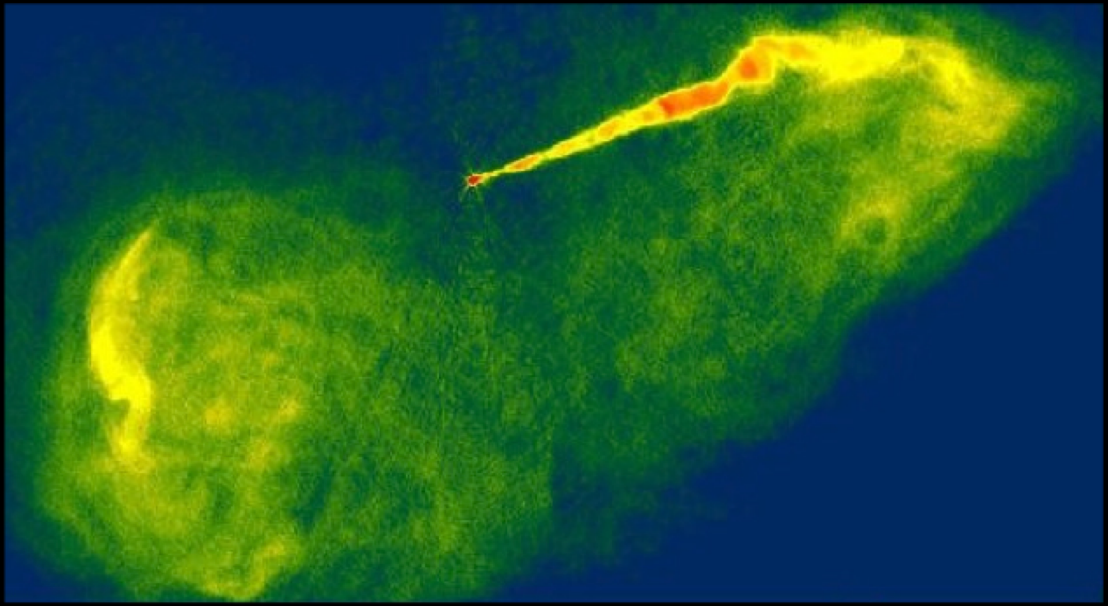
Relativistic ejection

The GRB prompt emission has to be produced at large distance in a relativistic ejecta.



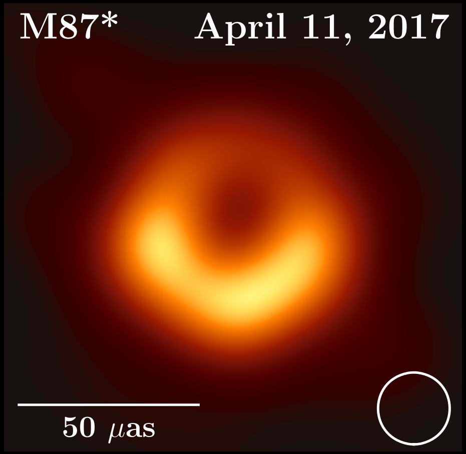
« Relativistic flying pancakes » (Piran)

As the ejection is short-lived, most of the energy is contained in a thin layer (width << radius). This is significantly different from AGN jets.

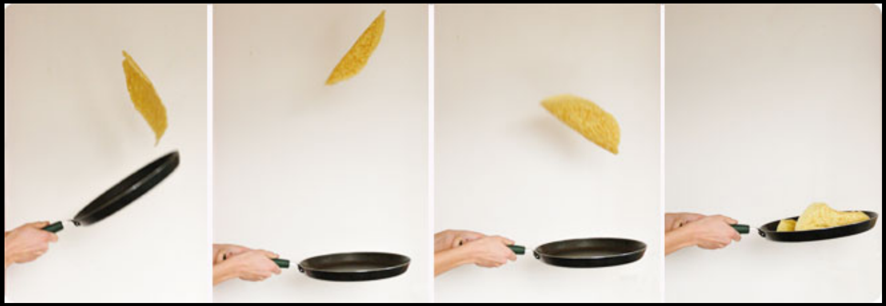


Relativistic jet in M87 (VLA)

Central engine:
accreting SMBH



EHT image of M87*



A non-relativistic, gravitationally bound, flying pancake.

Relativistic ejection

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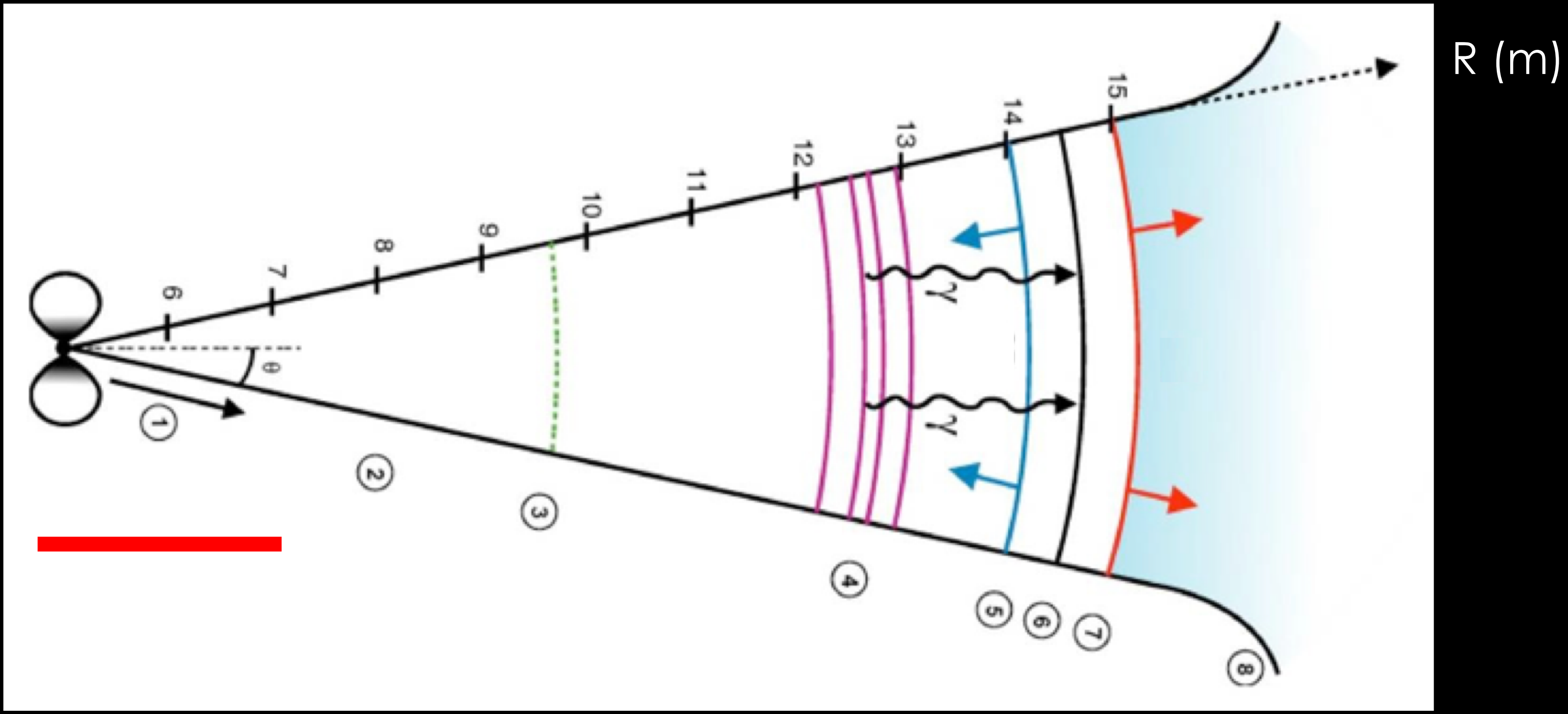


Relativistic ejection:
- Mechanism?
- Properties of the ejecta: Lorentz factor, geometry, magnetization, etc.

Relativistic ejection: again a long list of difficult questions

No direct information?

- The jet is opaque to its own radiation during the acceleration/early propagation phase.
- Early high-energy neutrinos may be produced during the early propagation

Early propagation: the jet has to propagate through

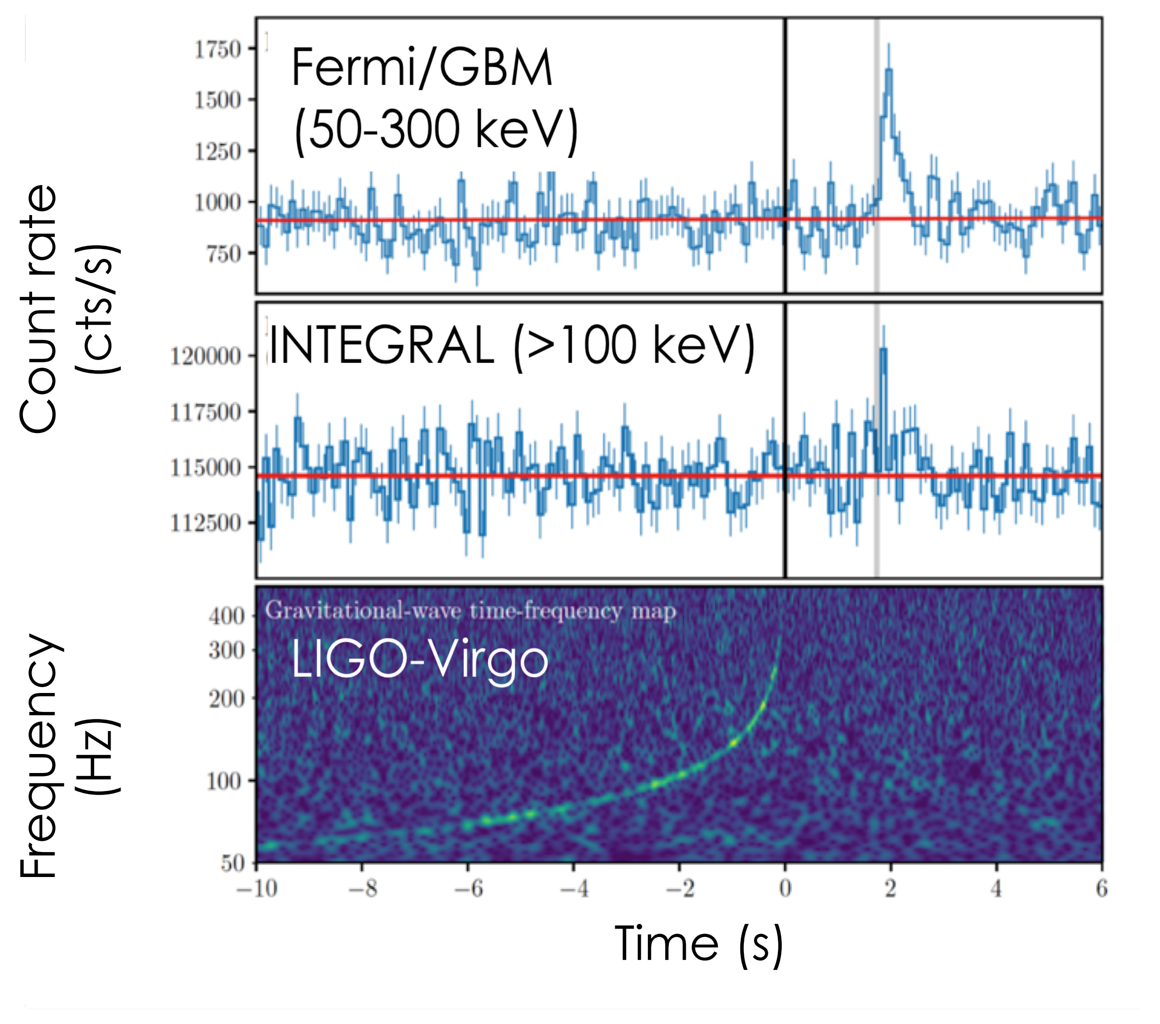
- Collapsar: the collapsing progenitor envelope
- Mergers: the expanding kilonova ejecta (especially if their is a polar ejection: cf. blue kilonova in 170817, see M. Branchesi's lecture)

Consequences:

- Possibility of choked jets: fraction of successful jets in collapsars/mergers?
- GRB duration (~width of the ejecta/c)
  ~lifetime of the relativistic ejection – time needed for the early ejecta to drill a way through the stellar envelope/kilonova ejecta
  (Bromberg et al. 2012)
- Successful jets: shock-breakout emission
  - Some Weak/low-luminosity bursts?
  - The case of GRB170817A

GW170817/GRB170817A

- GRB: E_p > 100 keV but very weak
- Pair production argument: observed GRB is probably not produced in an ultra-relativistic core jet like in cosmic GRBs (Matsumoto et al. 2019a,b)



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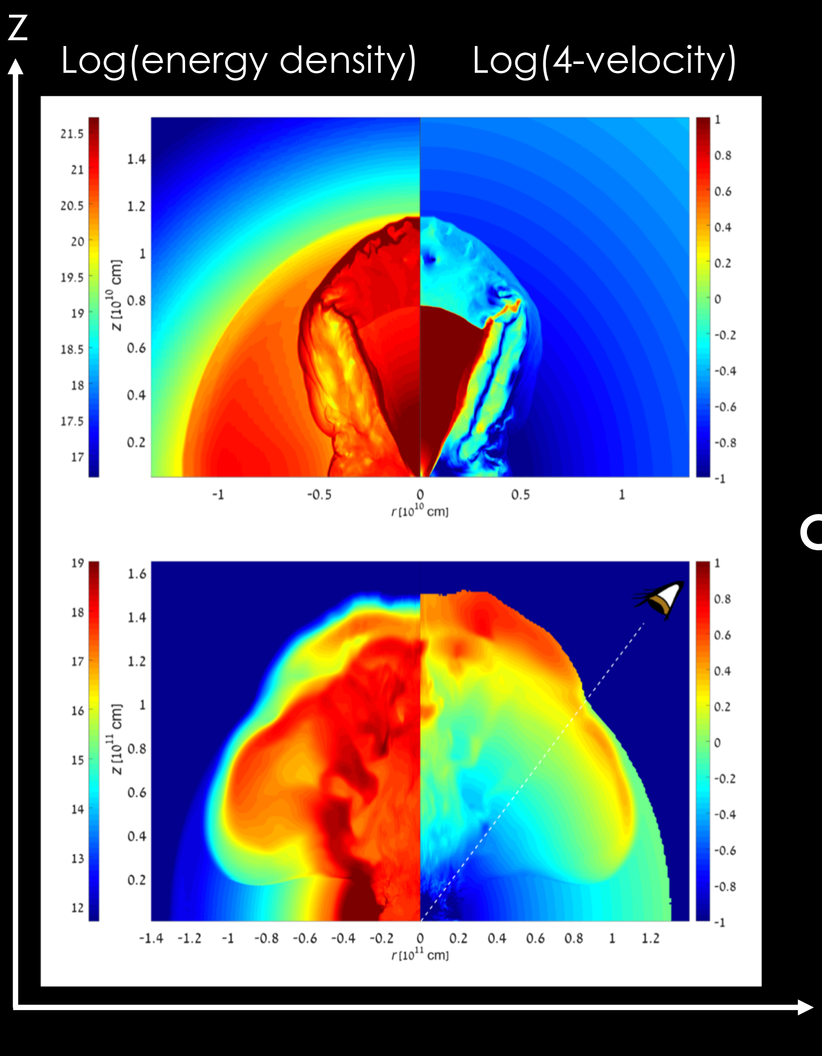
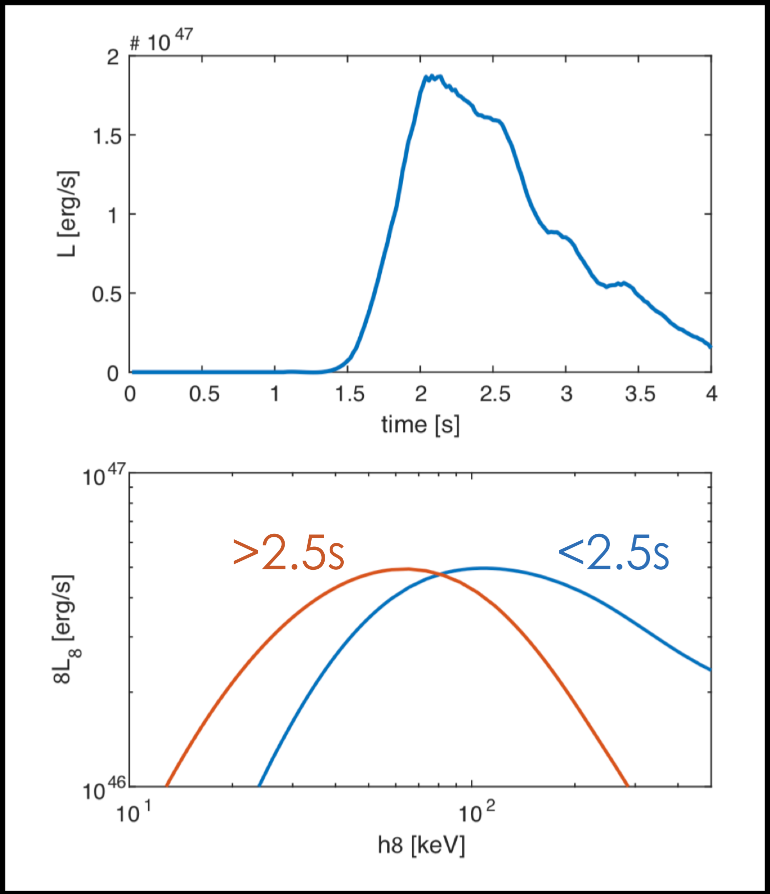
- **Shock breakout? (interaction relativistic jet + KN ejecta)**



Choked jet

Shock breakout:
lightcurve & spectrum @ 0.7 rad



Gottlieb et al. 2017

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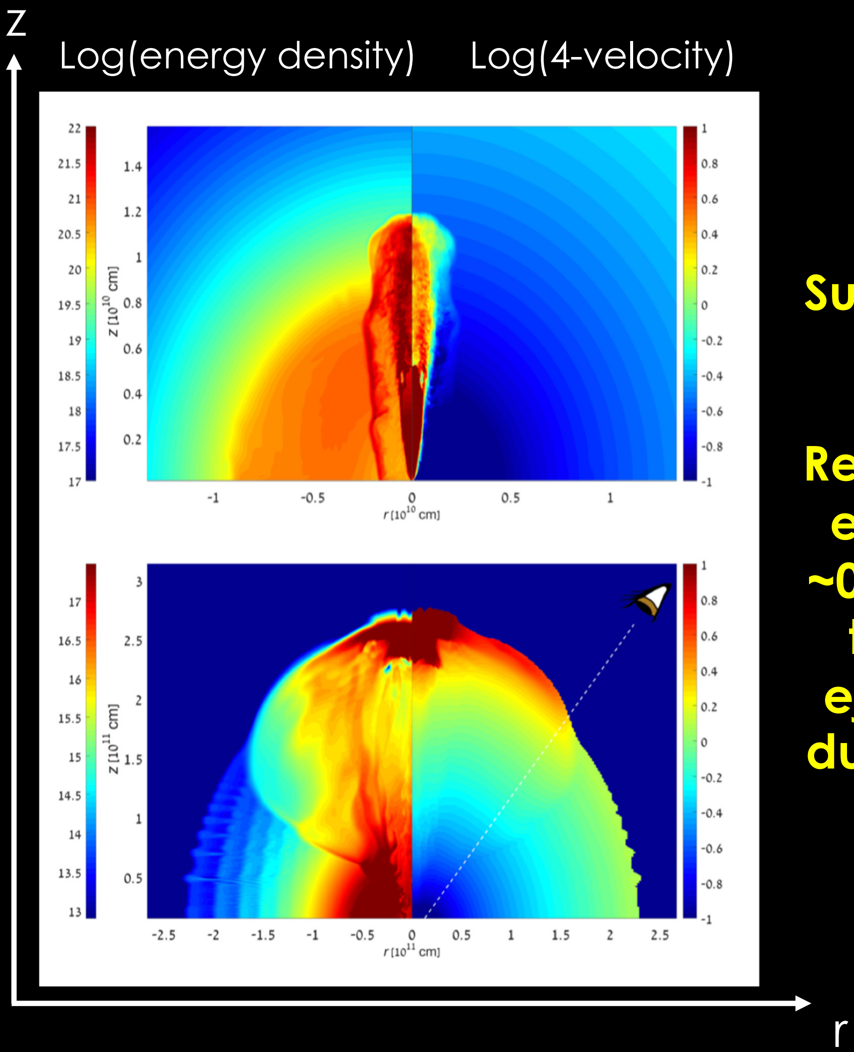
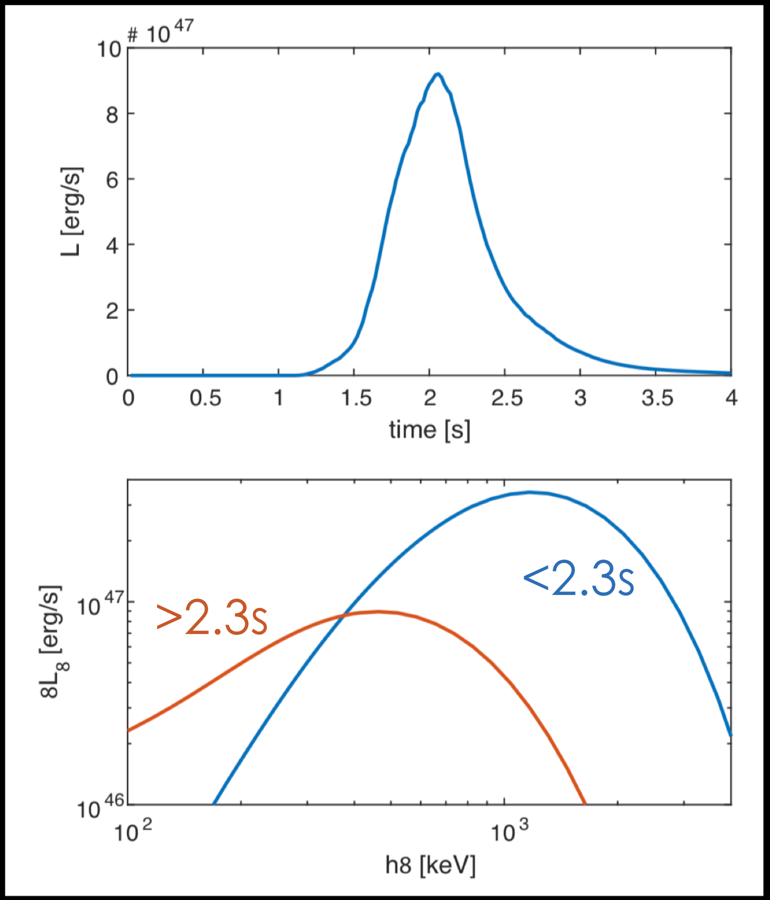


Successful jet

Relativistic ejection ~0.8s after the KN ejection, during ~1s

Shock breakout:
lightcurve & spectrum @ 0.7 rad



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Gottlieb et al. 2017, see also Bromberg et al. 2017 (magnetized jet)

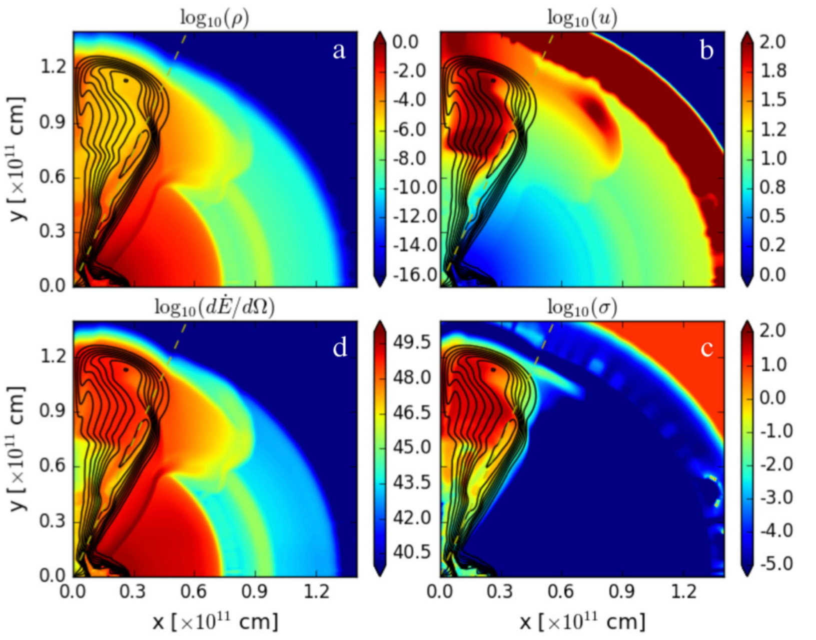

Figure 3. The properties of the jet at breakout; panels show (clockwise) the density (a), the 4-velocity (b), the magnetization (c), and total energy flux per solid angle (d). The black contours depict the poloidal field lines that thread the jet and the inner cocoon. The yellow dashed line marks an opening angle of 20°, which roughly demarcates the boundary between the jet and the cocoon.

Bromberg et al. 2017

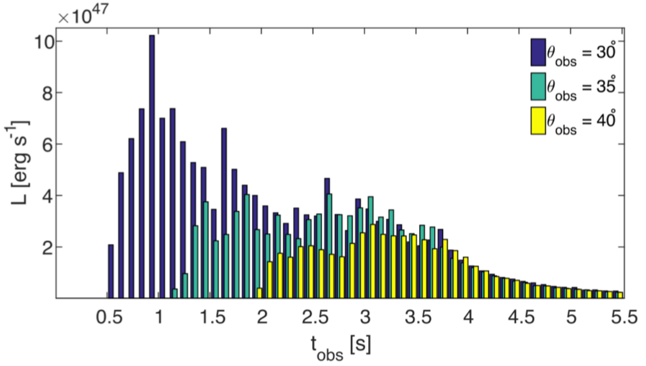

Figure 5. The bolometric luminosity of the shock breakout seeing by viewers at various angles from the jet axis.

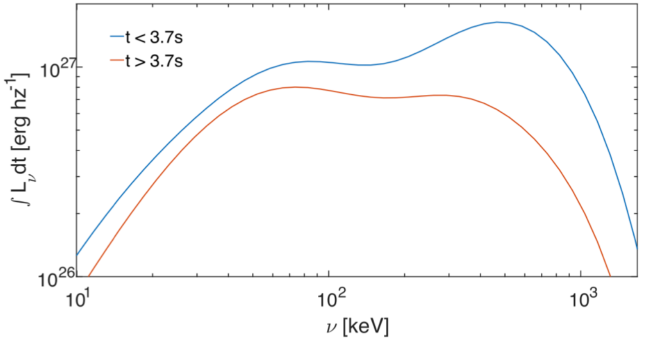

Figure 6. The spectrum of the breakout emission, seen by an observer at 40° from the jet axis.