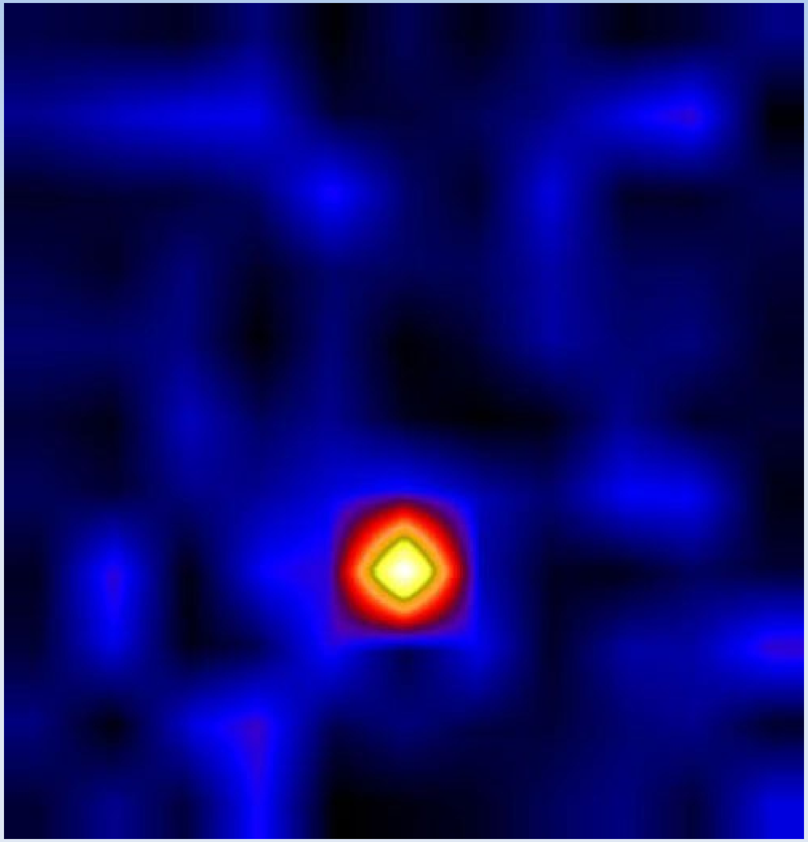
Compact Stars

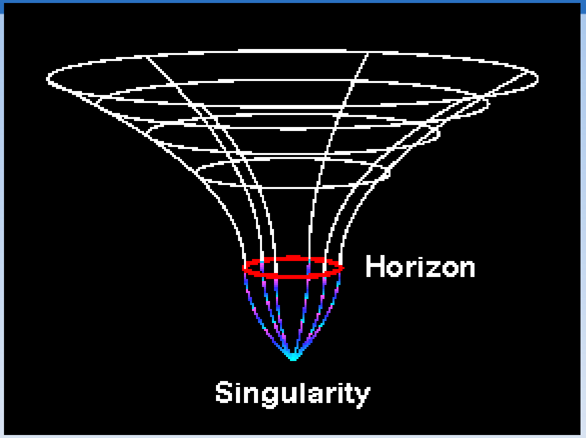


Lecture 8

Summary of the previous lecture

- I talked about active galaxies and their emission lines properties. The Unification Scheme applies to AGN of Sy1 and Sy2 type, as well as to Blazars and QSOs, and is based on orientation of the observer.
- I talked about jets content and morphology, as observed from active galaxies.
- The Inverse Compton process was introduced, as supplementary to the Synchrotron process, and responsible for jet's radiation.
- I discussed the phenomenological constraints for disk-jet connection scenarios.
- I presented the spin paradigm for power of the BH jets

Reminder: Schwarzschild black holes



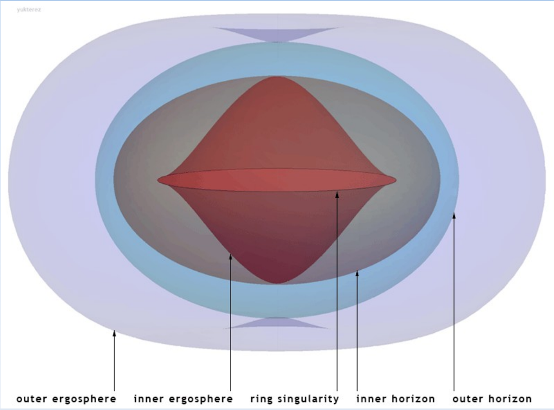
- Schwarzschild metric gives a complete solution for gravitational field around a spherical non-rotating, charge-free BH

- Symmetry breaks down at horizon, r=2M. No static observers can exist below.

- Energy at infinity is conserved due to spherical symmetry. Local energy is released at emitting points, changed by the gravitational redshift
- Proper time is dilated w.r.t time measured at infinity. Proper length is stretched
- Last photon orbit is located at 3M. Marginally stable orbit for particles is at 6M. Binding energy per unit mass at this orbit is 0.057.

and Kerr

- Gravitational field around rotating black hole, axially symetric.
- Metric contains mixed term with time and azimuthal angle components. Hence dragging effect, particle has to move in direction of BH rotation.



➔ Inner and outer horizons are surfaces where the metric breaks down. Their locations depend on BH spin, a=J/M, and vary from 1M to 2M.

➔ Ergosphere is region where no stationary observers exist

➔ Marginally stable circular orbits (ISCO) are different for prograde and retrograde motions. We obtain them by solving Euler-Lagrange equation of motion.

➔ At equatorial plane, ISCO radius is between 1M and 9M. Maximum particle binding energy for prograde orbit is about 0.42.

Reminder: BH spin from Iron line profile

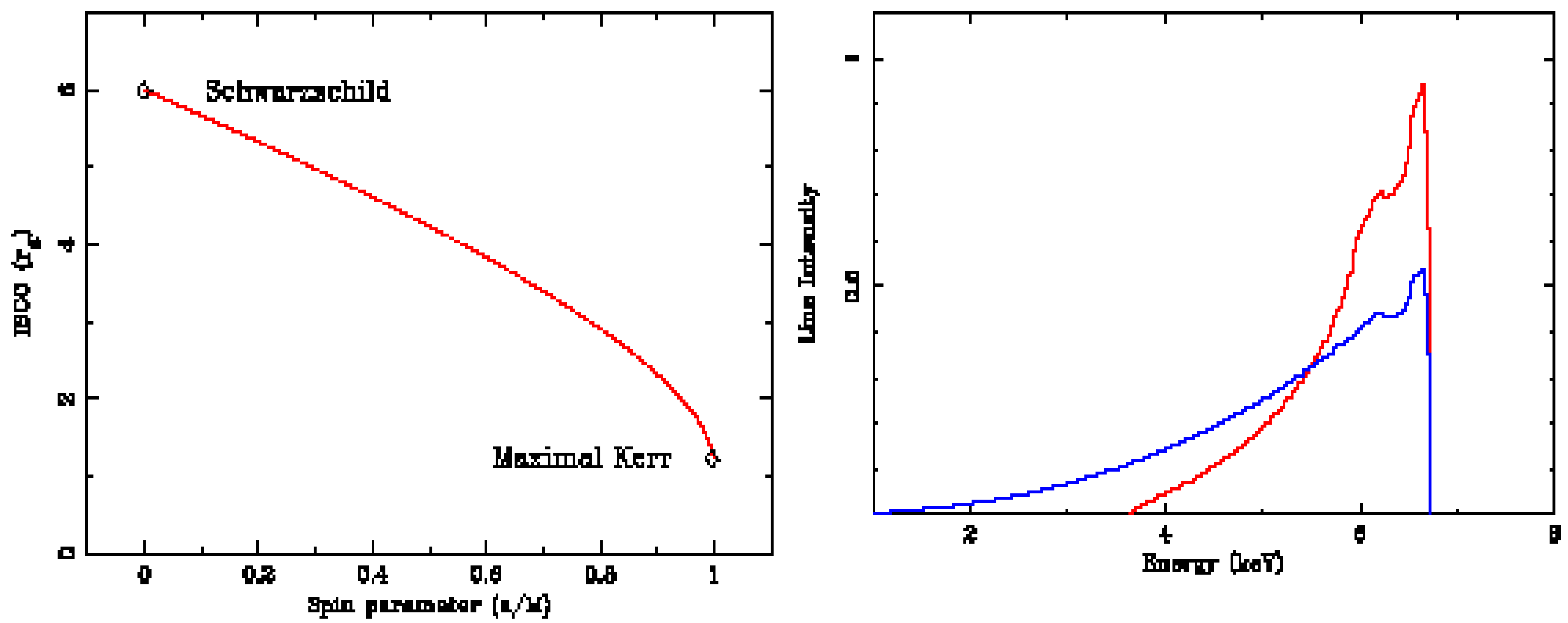
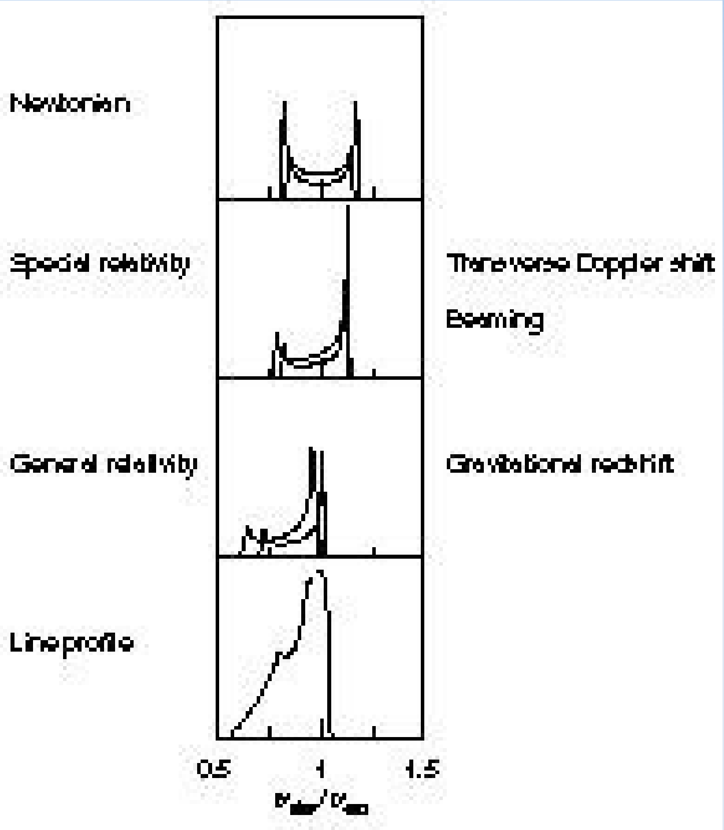


Figure 1: *Left*: The dependence of the innermost stable circular orbit (ISCO) on the black hole spin parameter is shown here, from Schwarzschild ($a = 0$) to maximal Kerr ($a = 0.998$) solutions. *Right*: The line profiles predicted in the case of Schwarzschild (red) and maximal Kerr (blue) black holes are shown here. It is the extent of the red wing and its importance relative to the blue wing that allow black hole spin to be determined with disk lines. (Adapted from Fabian & Miniutti 2006).

Relativistic effects on Iron line profile

- Gravitational redshift: centroid energy shifts from E_0 to E_1
- Doppler effect: line is broadened symmetrically
- Doppler boosting: approaching wing is brighter



Profiles from subsequent rings are added and line profile smeares.
Full calculation accounts numerically for radiation transport and light bending effect

Today: GRBs

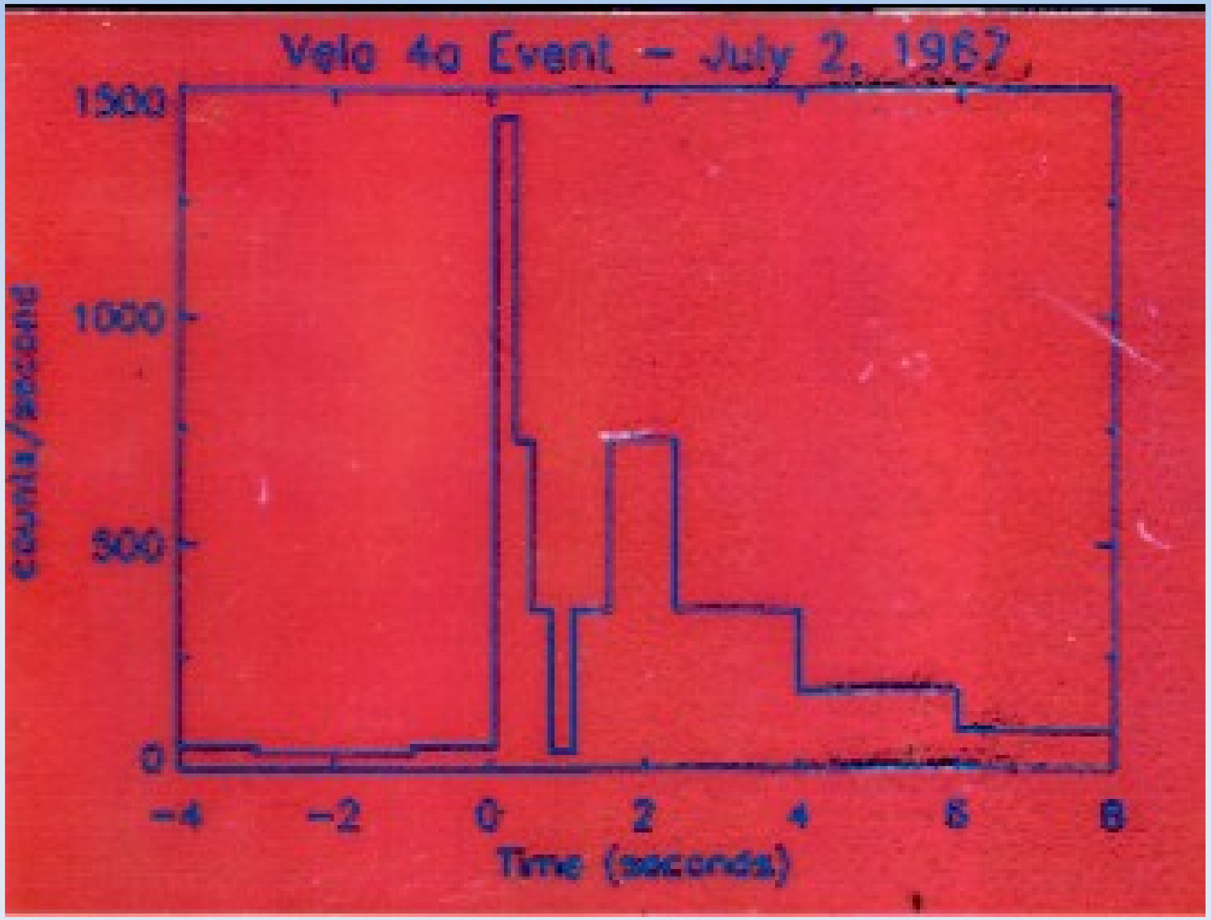
- I will now talk about a special type of events related to accreting black holes with ultrarelativistic fast jets, the gamma ray bursts.
- I will also introduce more about the process of launching jets and present some results of numerical GR MHD simulations

Gamma Ray Bursts

- Observed from 1960's, firs discovered by Vela sattelite
- These short, transient events (dt~0.001 – 1000 s) are seen isotropically on the sky in gamma rays (10 keV – 20 MeV)
- They occur roughly every couple days, and are not recurrent.
- They may be accompanied by a prompt, optical flash and afterglow emission in lower energies, lasting up to a few months

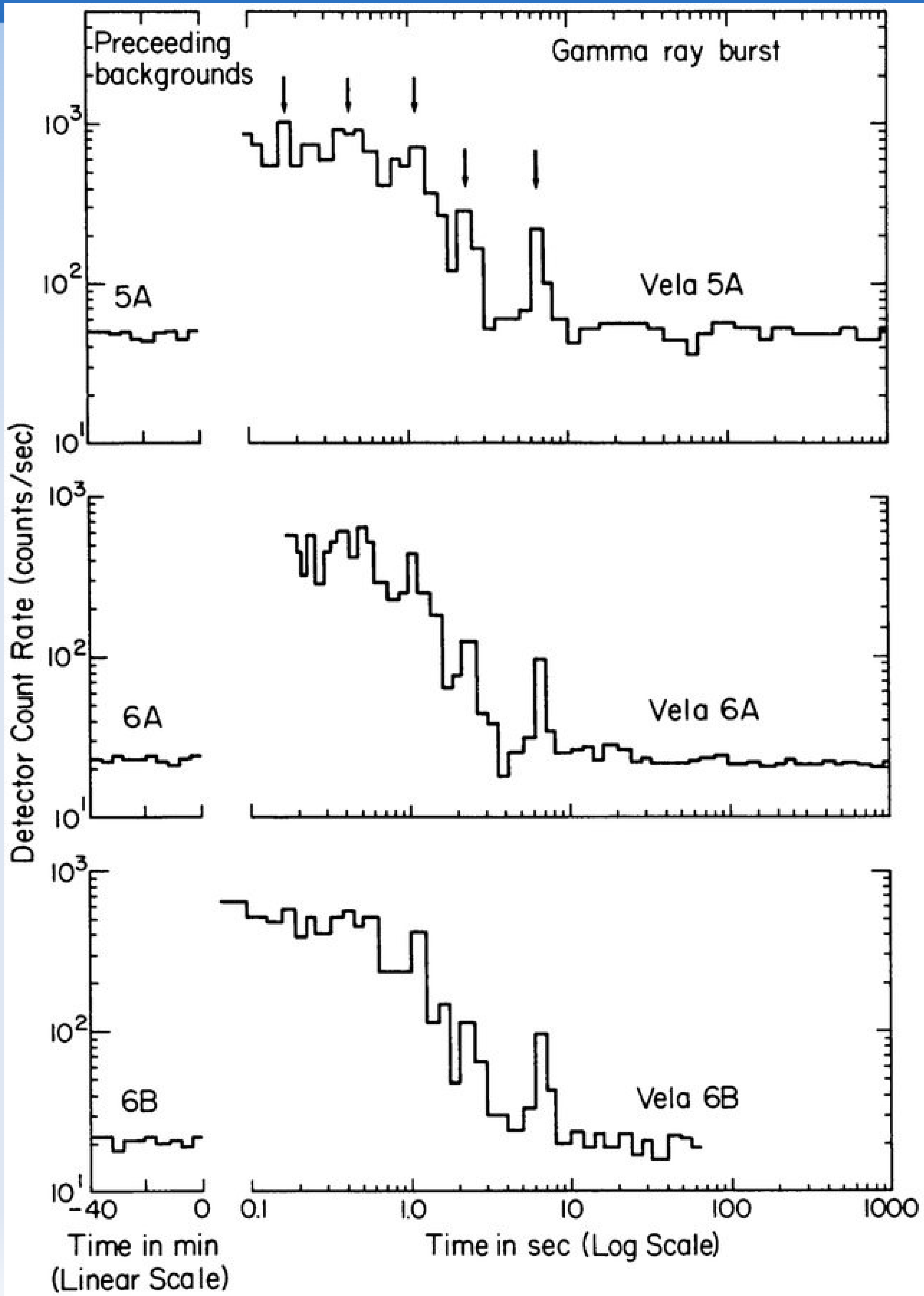
Historical GRB observation

- First detected GRBs: Vela sattelite
- Scintillation X-ray detectors, sensitive in 3-12 keV
- CsI detectors, sensitive in 150-750 keV



GRBs have cosmic origin

- Klebesadel, Strong & Olsen (1973, Astrophysical Journal) analyzed 16 events detected between ’69 and ’72
- Deduced the directions to the events with sufficient accuracy to rule out the sun and earth as sources.

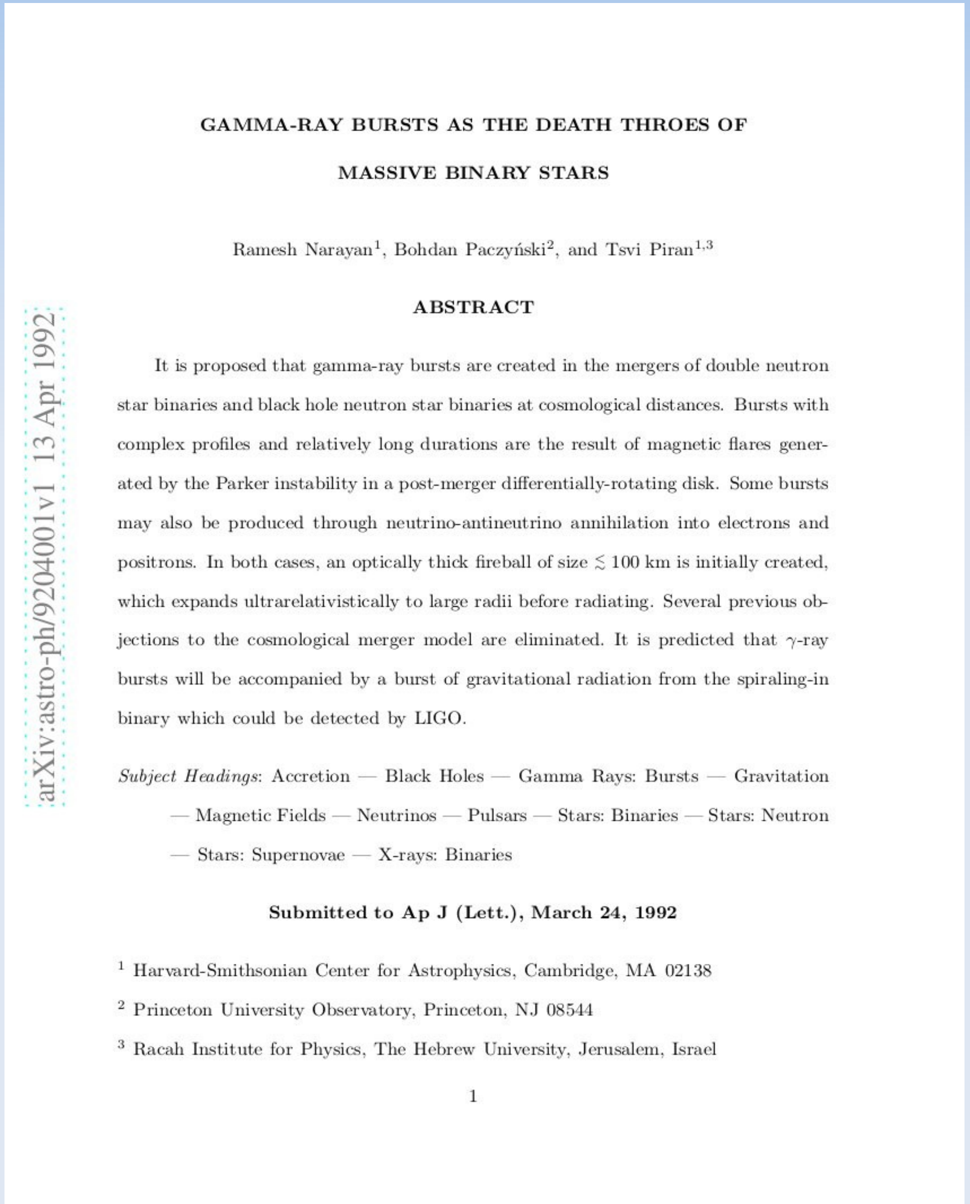


Historical models

- By 1992, about 100 models for GRBs origin were proposed
- They were based on location: Solar system, our Galaxy, Extragalactic
- Energy is given by the observed flux x $distance^2$, and they differ by 20 orders of magnitude
- Some examples: lightning in the athmospheere, magnetic reconnection in Heliopause, accretion onto comets, neutron star quakes, white holes, cosmic strings...

First arXiV preprint

- Astro-ph/9204001
- Ramesh Narayan, Bohdan Paczyński, Tsvi Piran
- ”Gamma Ray Bursts as the death throes of massive stars”



arXiv:astro-ph/9204001v1 13 Apr 1992

GAMMA-RAY BURSTS AS THE DEATH THROES OF MASSIVE BINARY STARS

Ramesh Narayan[1], Bohdan Paczyński[2], and Tsvi Piran[1,3]

ABSTRACT

It is proposed that gamma-ray bursts are created in the mergers of double neutron star binaries and black hole neutron star binaries at cosmological distances. Bursts with complex profiles and relatively long durations are the result of magnetic flares generated by the Parker instability in a post-merger differentially-rotating disk. Some bursts may also be produced through neutrino-antineutrino annihilation into electrons and positrons. In both cases, an optically thick fireball of size $\lesssim 100$ km is initially created, which expands ultrarelativistically to large radii before radiating. Several previous objections to the cosmological merger model are eliminated. It is predicted that γ-ray bursts will be accompanied by a burst of gravitational radiation from the spiraling-in binary which could be detected by LIGO.

Subject Headings: Accretion — Black Holes — Gamma Rays: Bursts — Gravitation — Magnetic Fields — Neutrinos — Pulsars — Stars: Binaries — Stars: Neutron — Stars: Supernovae — X-rays: Binaries

Submitted to Ap J (Lett.), March 24, 1992

[1] Harvard-Smithsonian Center for Astrophysics, Cambridge, MA 02138

[2] Princeton University Observatory, Princeton, NJ 08544

[3] Racah Institute for Physics, The Hebrew University, Jerusalem, Israel

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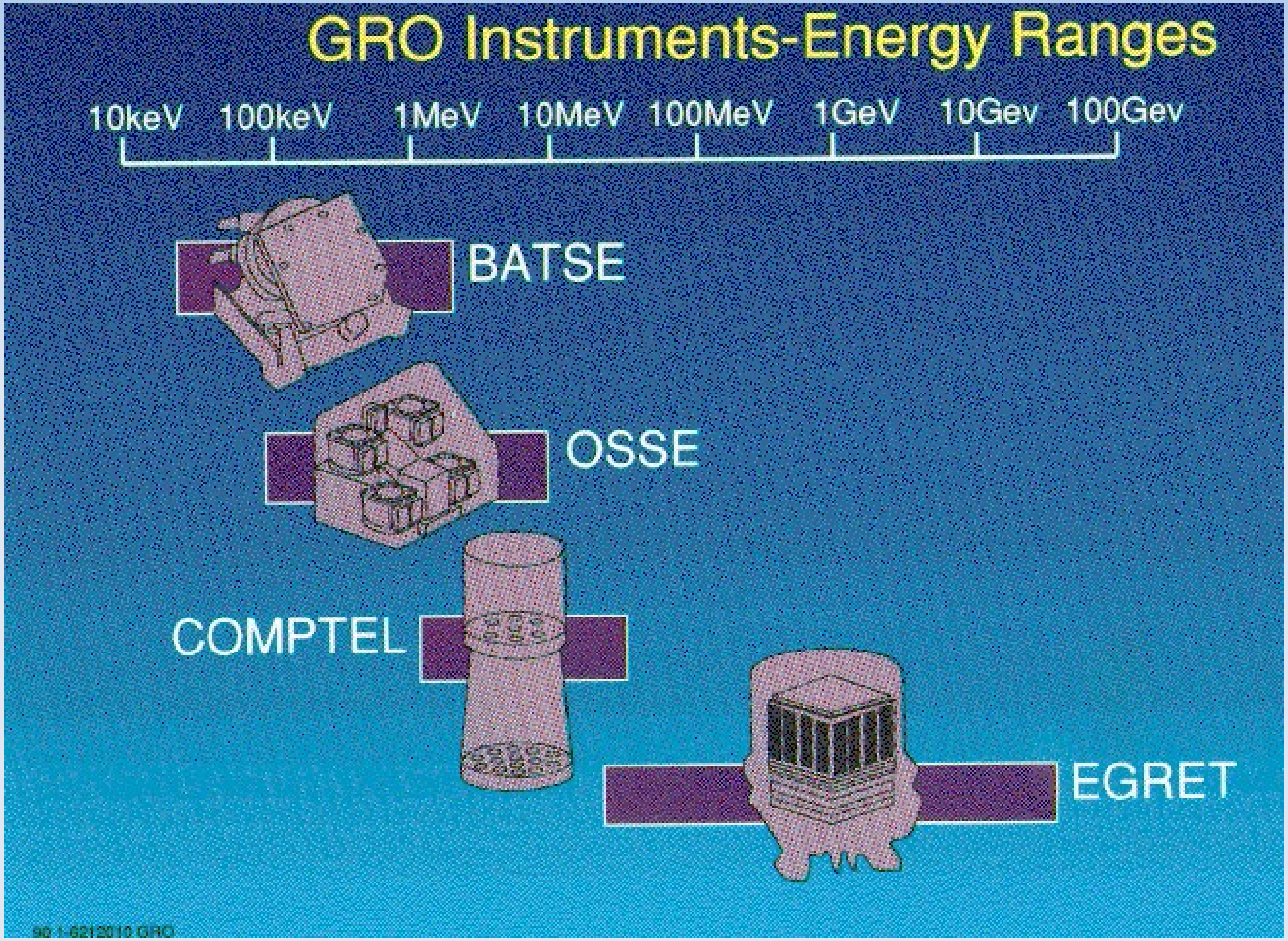
Oxford debate

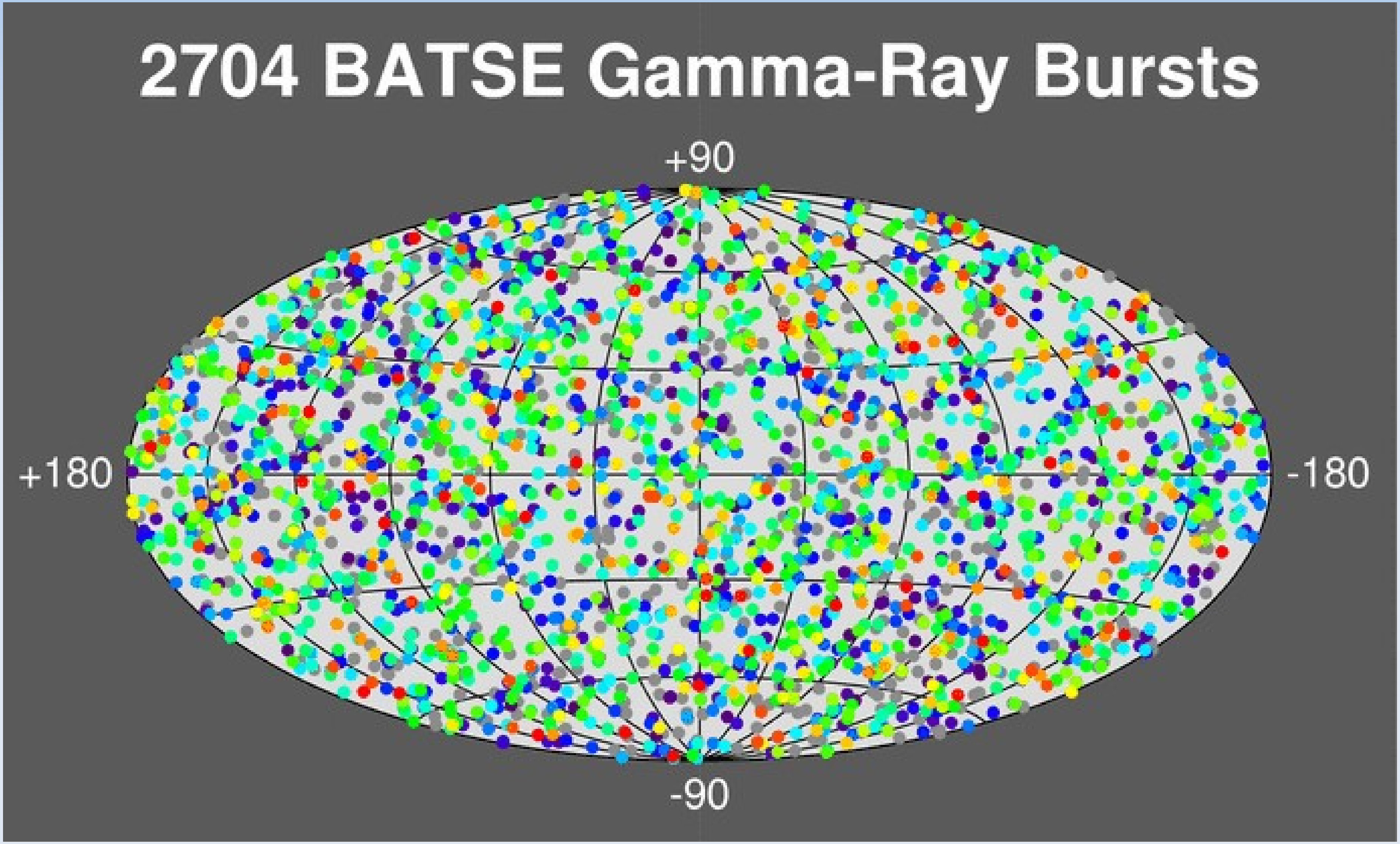
- Debate between B. Paczyński and D. Lamb on the distance scale to Gamma Ray Bursts
- Organized in April 1995, at anniversary of denate between Curtis and Shapley on the nature of spiral nebulae
- Lamb and Paczynski publicly disagreed, and each displayed evidence and reasoning on why one distance scale should be preferred over the other.

Compton Gamma Ray Observatory

- 1991-2000
- Covered range of wavelengths
- BATSE spectrometer 20-600 keV
- Made all sky map of GRBs



Galactic or Extragalactic?



GRBs are extragalactic

- BATSE map: GRBs are distributed isotropically, not localized in our Galaxy plane
- First redshift detected for GRB970508: z>~0.8 (Metzger et al. 1997). Swift data: z~8 (Salvaterra 2009).
- HST observations: first identificaltions of host galaxies of GRBs.
- Typically the redshift distribution of the long GRBs follows the star formation rate in the Universe (Porciani & Madau 2001).
- Volume distribution V/V_{max} estimated to be 0.39 and 0.28 for short and long GRBs (Piran 2004). This indicates non-Euclidean space, otherwise 0.5.

GRB970805

- Firm detection of redshift. Z=0.835, distance is estimated from the observations of radio scintillation due to the interstellar medium
- Proved that bursts are cosmological

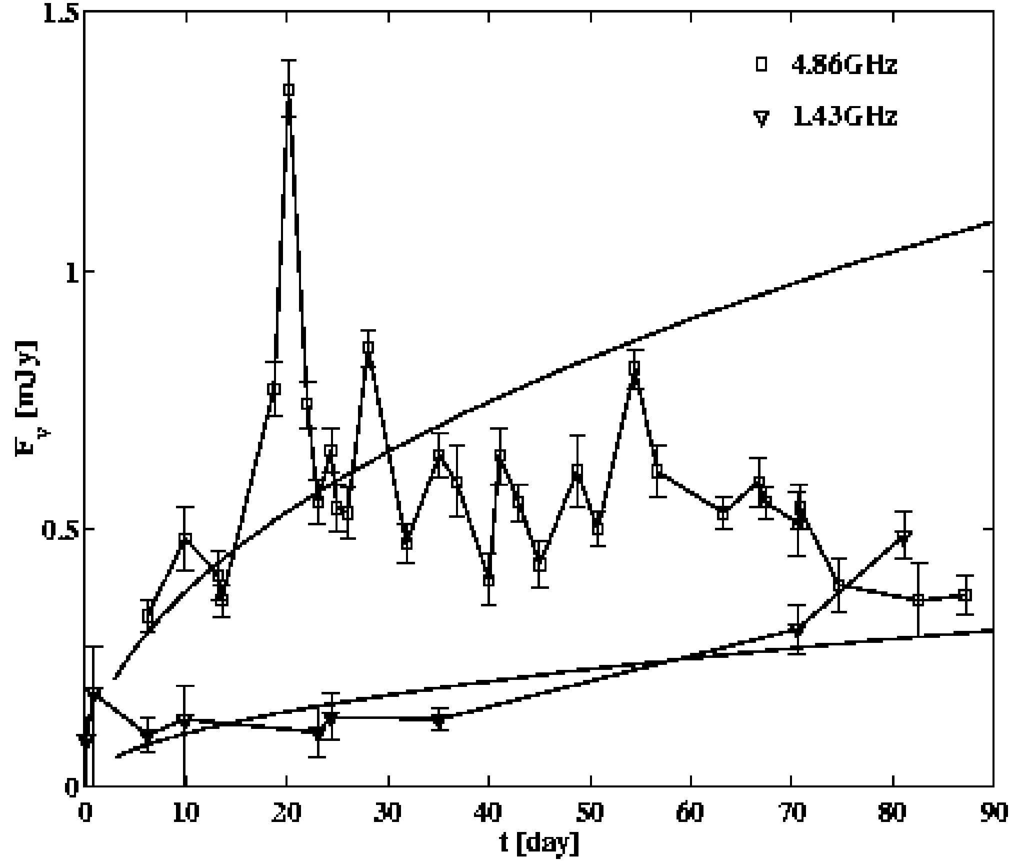
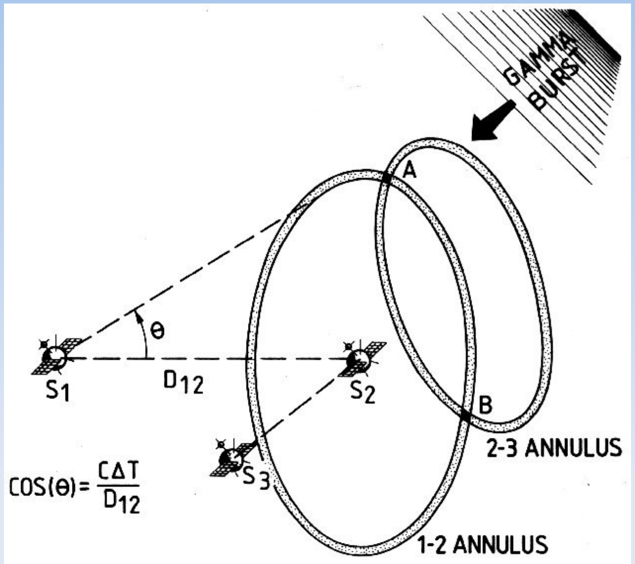


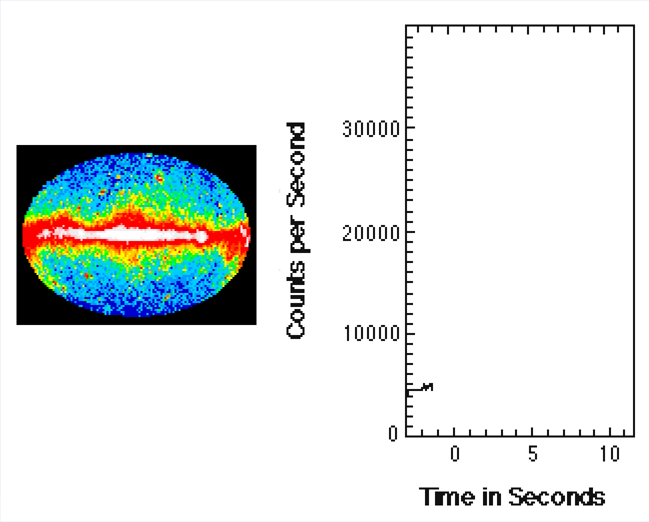
Fig. 1a.— Light curves of the radio afterglow of GRB970508 at 4.86GHz and 1.43GHz, compared with the predictions of the adiabatic fireball model (Waxman 1997b).

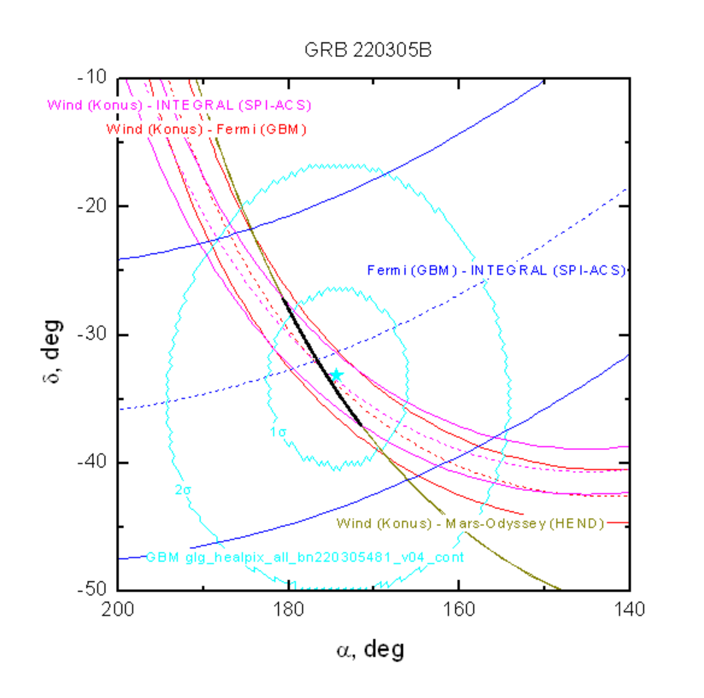
Waxman et al. (1997)

Localisation

- Three satellites are needed
- Triangulation map is made based on signal time-delays

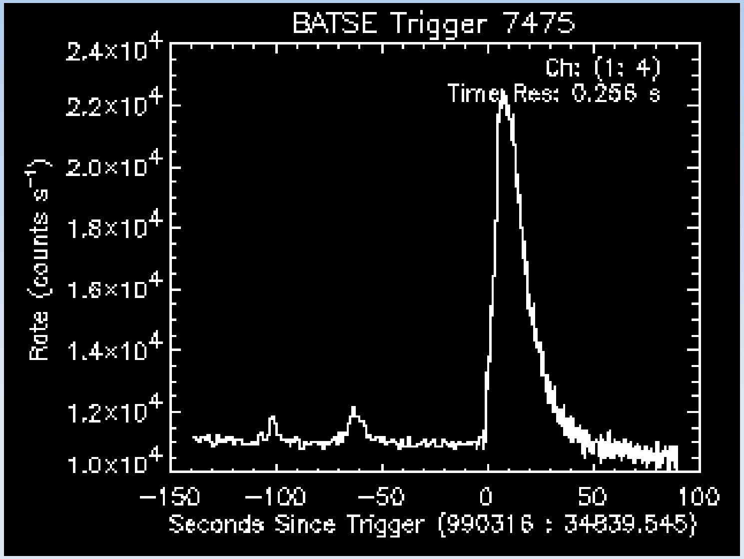




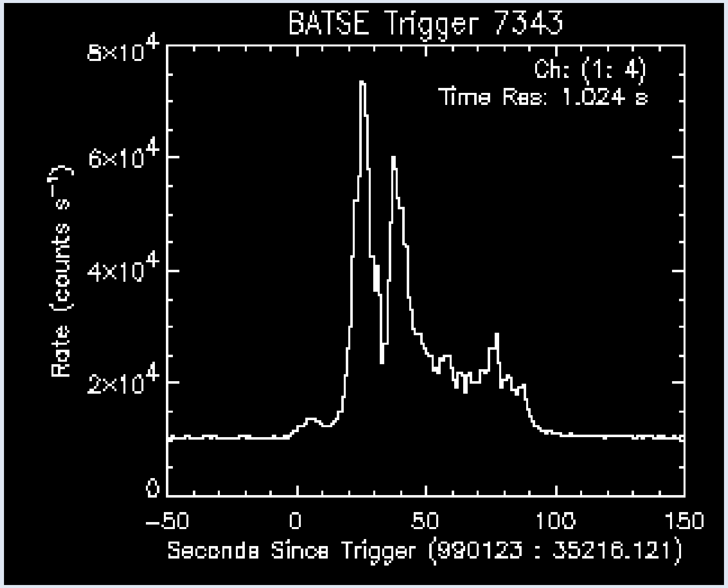


Lightcurves

GRB990316



- FRED profile (fast rise, exponential decay)
- Substructure, multiple peaks
- Durations from 0.001 to >1000 sec (28 min was the ”Christmas burst” in 2010)

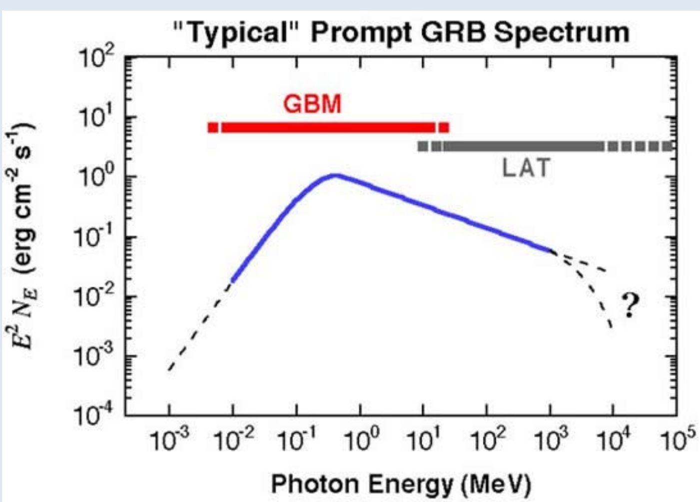


GRB990123

Spectra

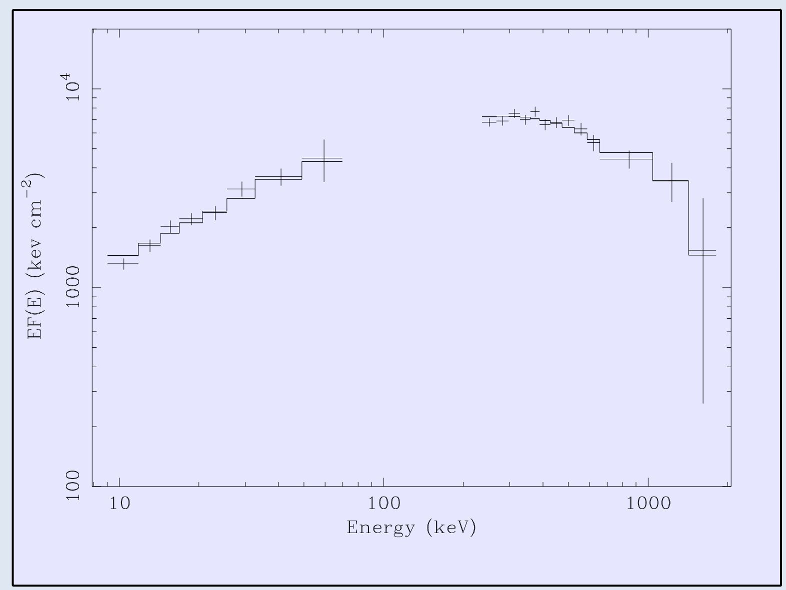
- Fitted with broken power-law
- Function called ”Band spectrum” Band et al. 1993)

$$N(\nu) = N_0 (h\nu)^{\alpha} \exp(-h\nu/E_0) \qquad h\nu<(\alpha-\beta)E_0$$
$$= N_0 [(\alpha-\beta)E_0]^{(\alpha-\beta)}(h\nu)^{\beta}\exp(\beta-\alpha) \qquad h\nu>(\alpha-\beta)E_0$$



D. Band,
slac.stanford.edu

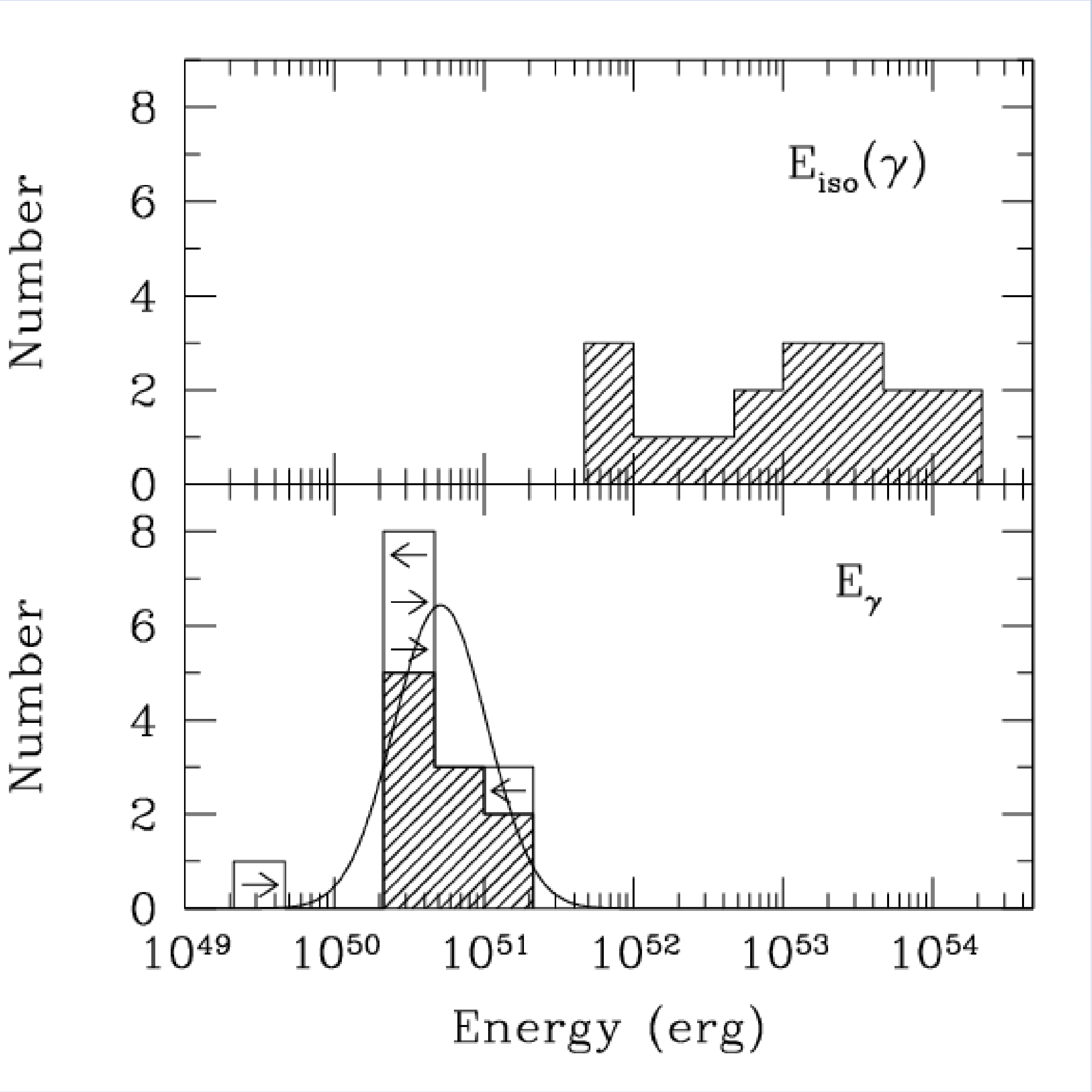
GRB 990510



Energetics of GRBs

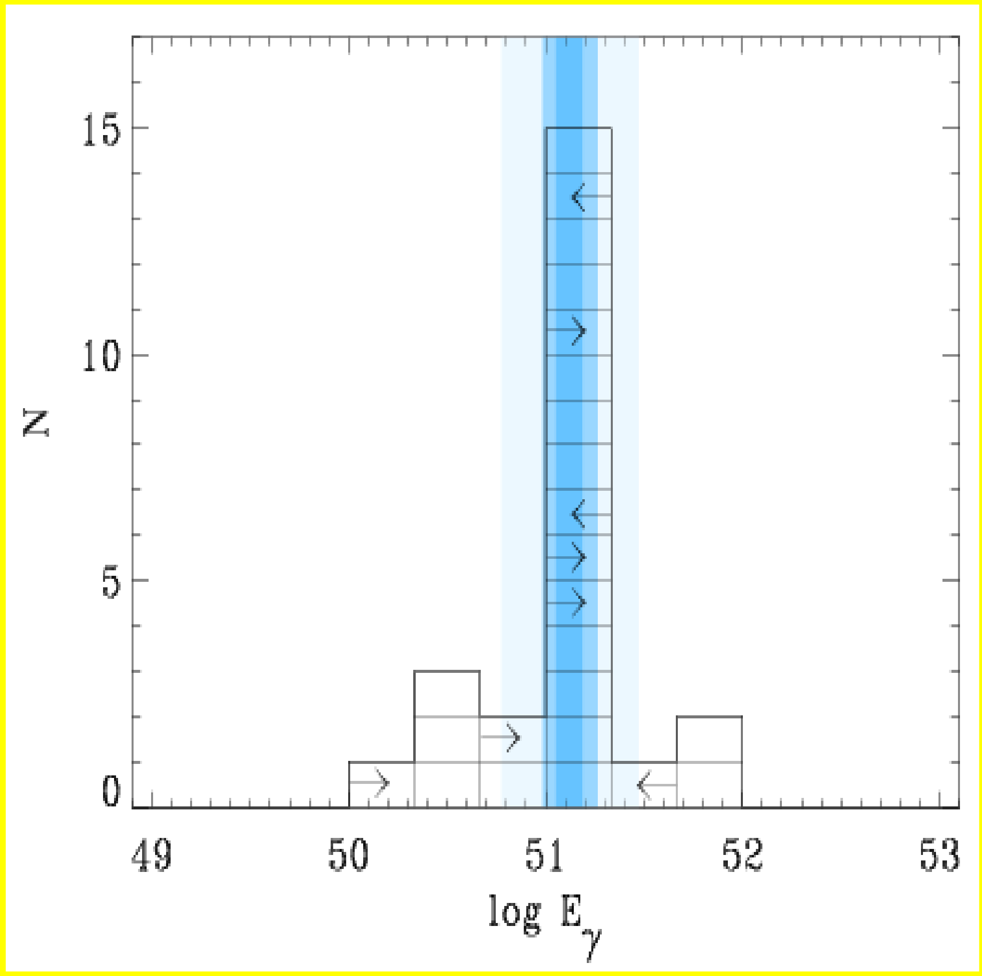
- Isotropic energy in gamma rays would be huge
- If we account for beaming of radiation into a narrow cone, the energies are lower
- $E_\gamma = f_b E_{\gamma,iso}$

  $= \theta^2/2 \, E_{\gamma,iso}$



Beaming correction

- Mean opening angle is about 4 degrees, with some dispersion
- This gives the beaming factor of 1/500 and corrected energies



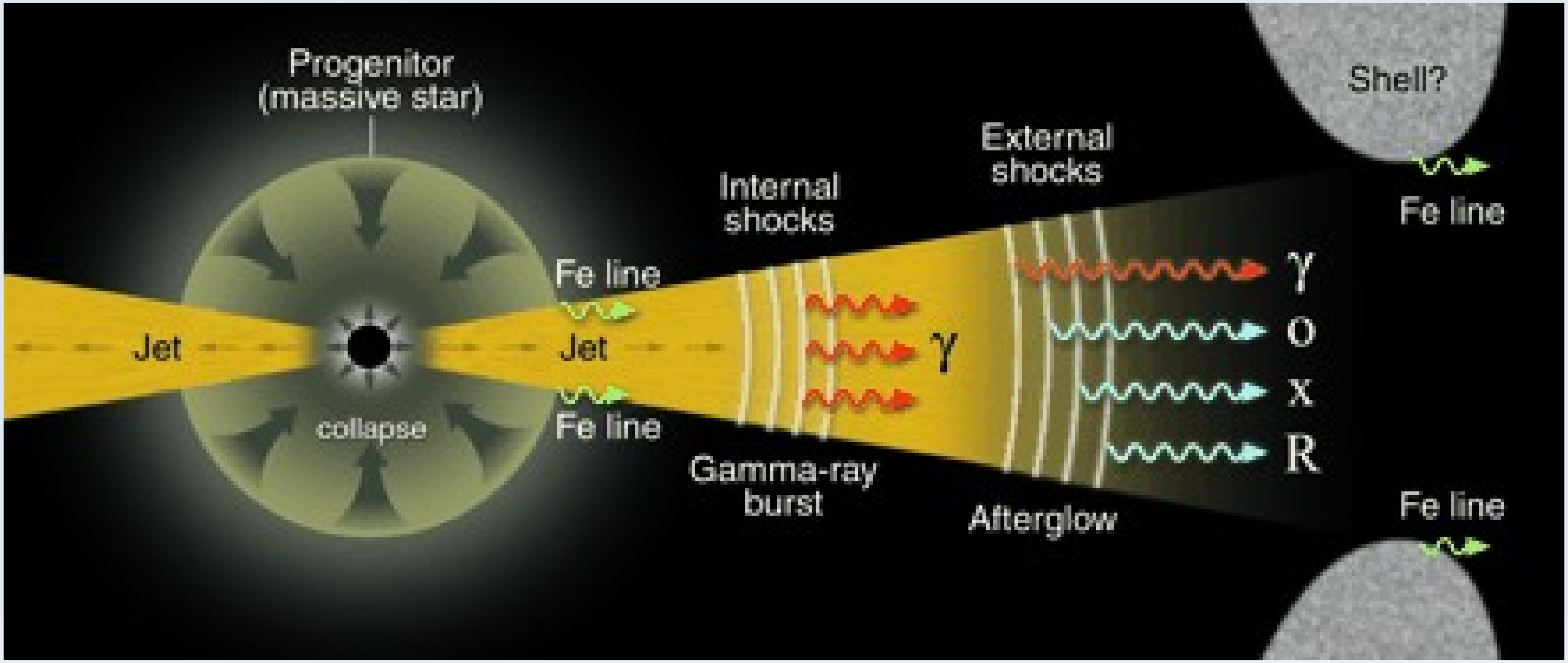
Bloom, Frail & Kulkarni (2003)

Model requirementss

- Energetics of explosion: after beaming and jet efficiency corrections, we need to have about 10^{52} ergs to be released. This is a binding energy of a compact star, $E = G M^2/R$ ($M = 10\ M_{Sun}$, $R = 10$ km).
- Most efficient energy extraction mechanism is accretion onto a compact star.
- Duration of event: rotation period (at the surface of star), $P = 2\pi r^{3/2}/G^{1/2}M^{1/2} = 0.3$ ms, divided by viscosity. For small disks and alpha~0.1 this gives about 300 ms.
- Short events may be powered by accretion of remnant matter after a merger, onto a black hole/neutron star.
- Long events require large disks, fallback supply of matter from part of extended envelope, and long-term existence of rotationally supported disks

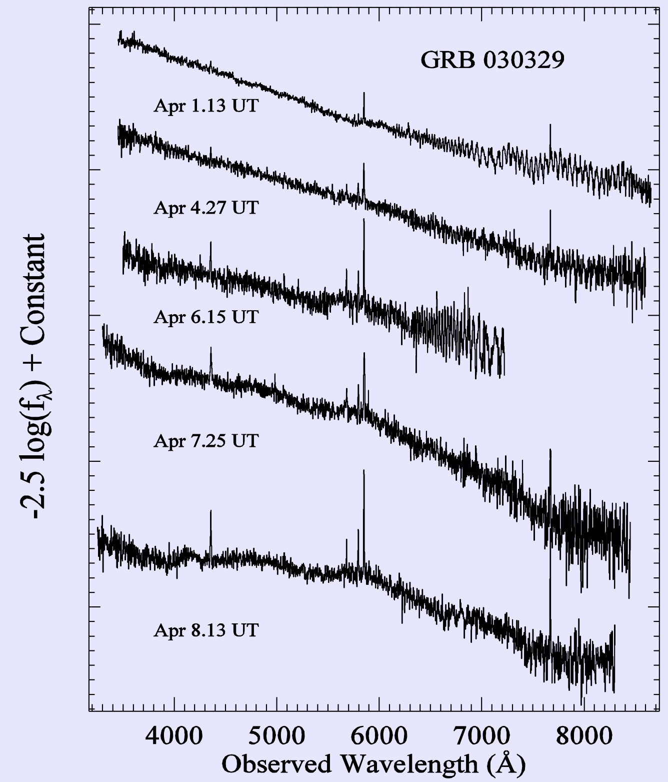
Massive star collapse

- Collapse of a rotating massive star into black hole
- Predicted is beamed explosion, accompanied by a supernova-like ejection



Supernova signatures

- Red bump in the GRB afterglow lightcurve
- Underlying spectrum shows emission lines characteristic for supernova

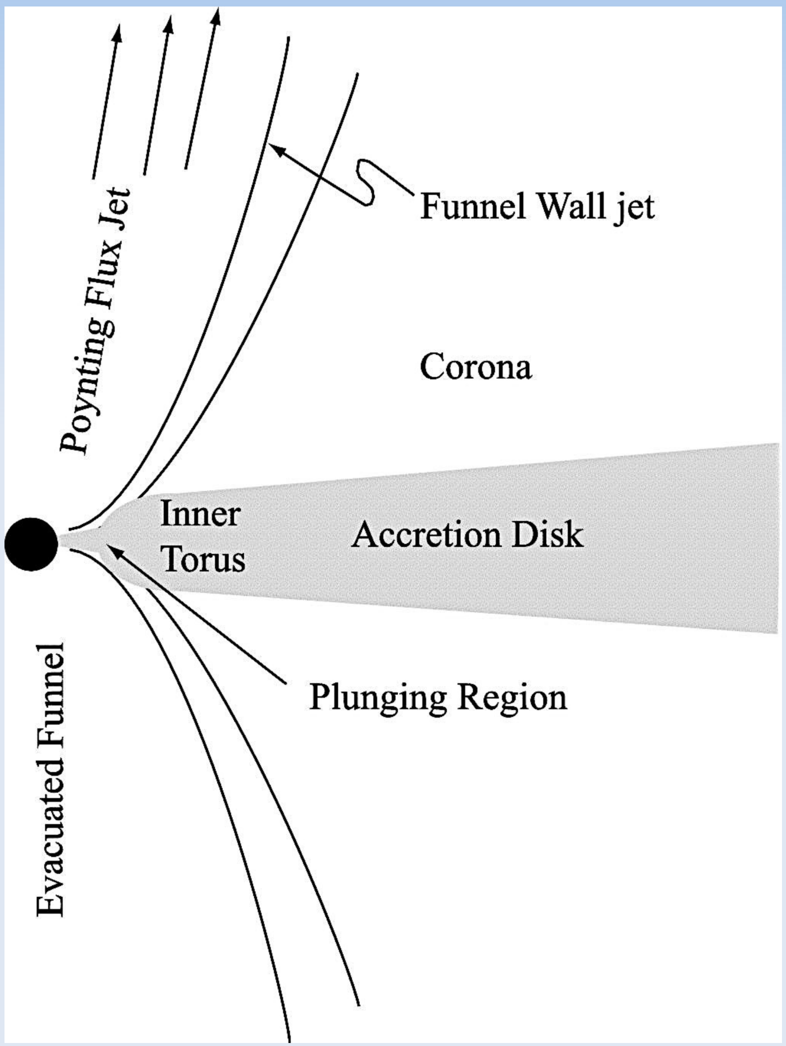


Stanek et al. (2003)

Break

Jet power

- Three mechanisms proposed for jet acceleration: thermal expansion, radiation pressure, magnetic field and rotation
- In GRBs, also neutrinos may be important (anihillation)
- Collimation mechanisms: thick disk or corona, pressure gradient in surrounding wall, external (matter dominated) jet, toroidal magnetic field



C. Fragile, 2008 (arXiv:0810.0526)

Magnetic dynamo

Hoover Dam – Arizona/Nevada

Magnetic dynamo

- Gravitation potential energy: accelerates waterfall. Water moves the rotating magnets and electric current is produced.
- With this analogy, accretion process releases gravitational potential energy and magnetic field is coupled with rotation. The magnetic field lines are frozen into the disk plasma and rotate, acting as a dynamo.
- The black hole also rotates. Open field lines are formed along the rotation axis; along these lines jets are launched.

GR MHD

General Relativistic Magneto-Hydrodynamics

- Continuity Equation

$$\nabla_\mu (n u^\mu) = 0$$

- Energy-Momentum Equation

$$\nabla_\mu T^{\mu\nu} = 0$$

- Maxwell Equation

$$\nabla_\mu^* F^{\mu\nu} = 0$$

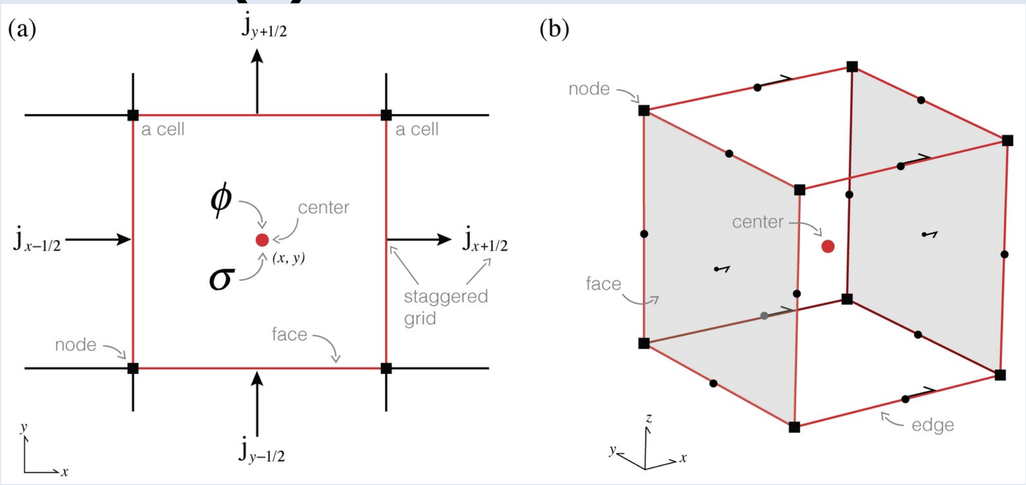
- These equations are supplemented by equation of state, and perfect conductivity condition.
- Stress-energy tensor contains the matter and electromagnetic parts

Numerical simulations

- GR MHD equations can be written in form

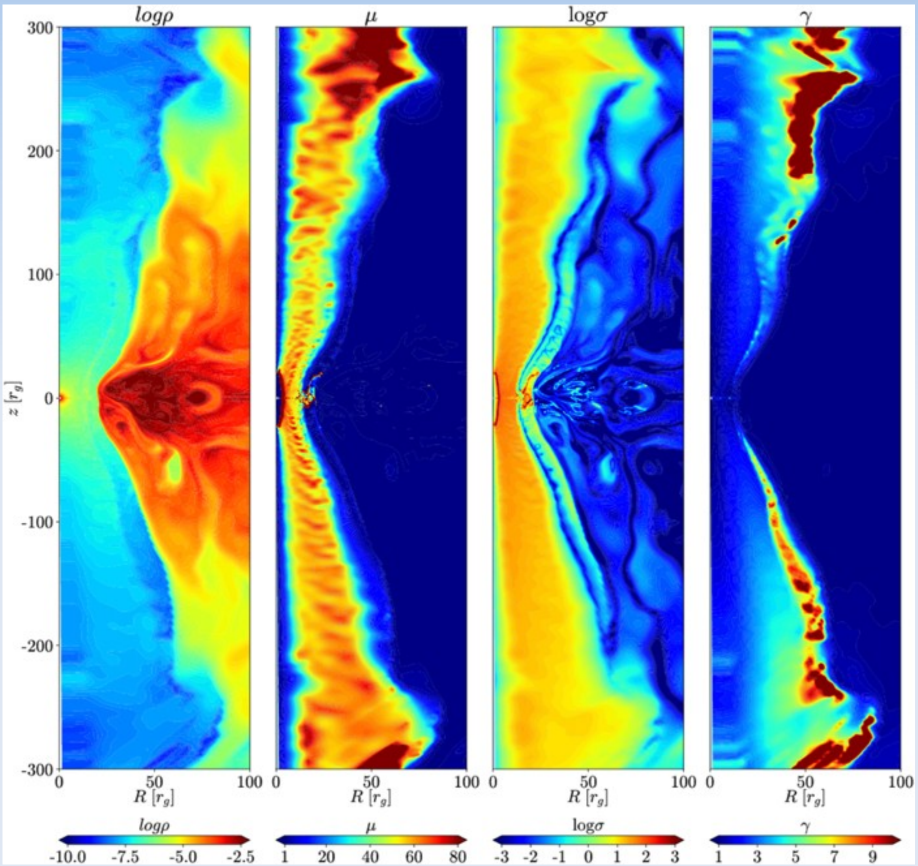
$$\partial_t \mathbf{U(P)} = -\partial_i \mathbf{F^i (P)} + \mathbf{S(P)}$$

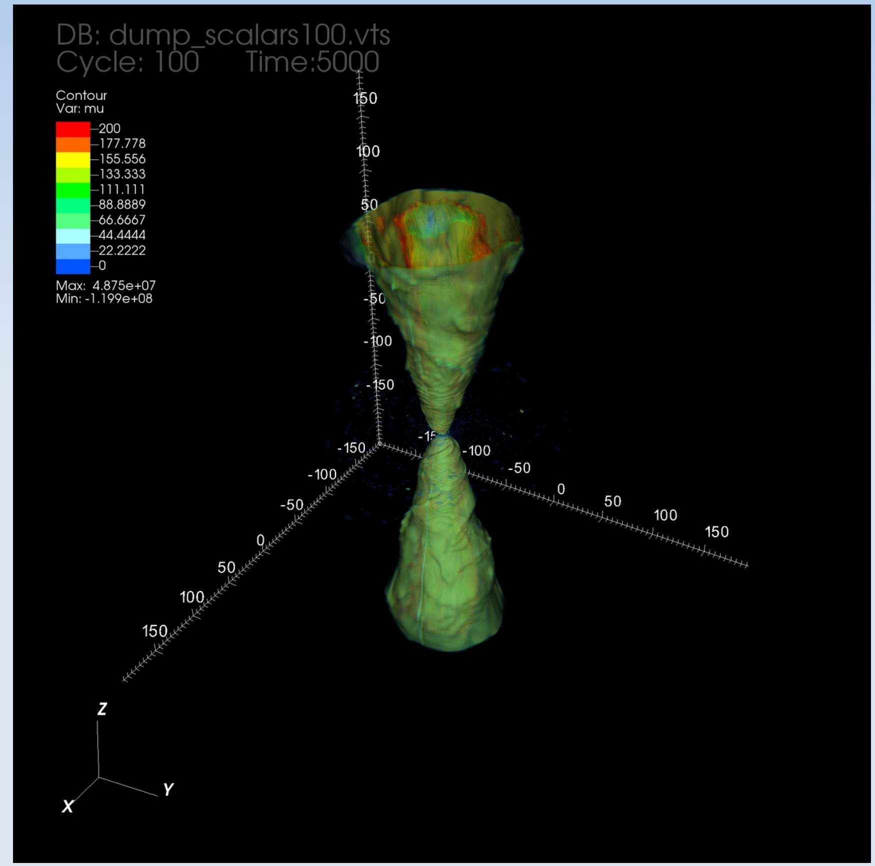
- where **U** is vector of conserved variables (total energy, momentum, comoving density), and **P** are primitive variables, that have physical interpretation (rest mass density, internal energy, 3-velocity, and 3-B field components). **F(P)** are fluxes and **S(P)** are source terms.



- Code advances conserved variables in time, by finite volume numerical scheme on a fixed grid
- Inversion **P(U)** is done in every time step, by solving set of nonlinear differential equations

Numerical simulations



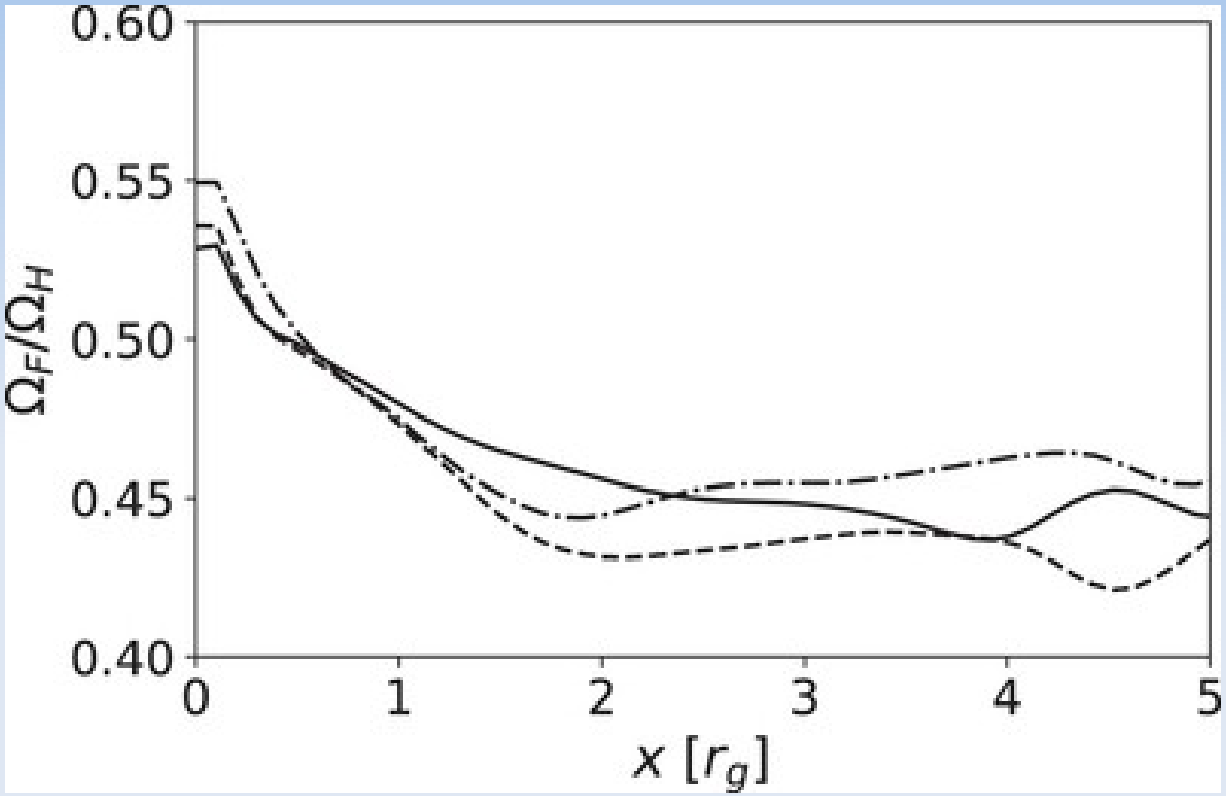


Profiles of density, total energy (Poynting and thermal), magnetisation, Lorentz factor, in the jet launched from accreting black hole.
Evolved state of a 2-dimensional simulation, Sapoutzis & Janiuk (2019, ApJ)

Profile of jet energetics in a 3-dimensional simulation

James, Janiuk & Nouri (2022, ApJ)

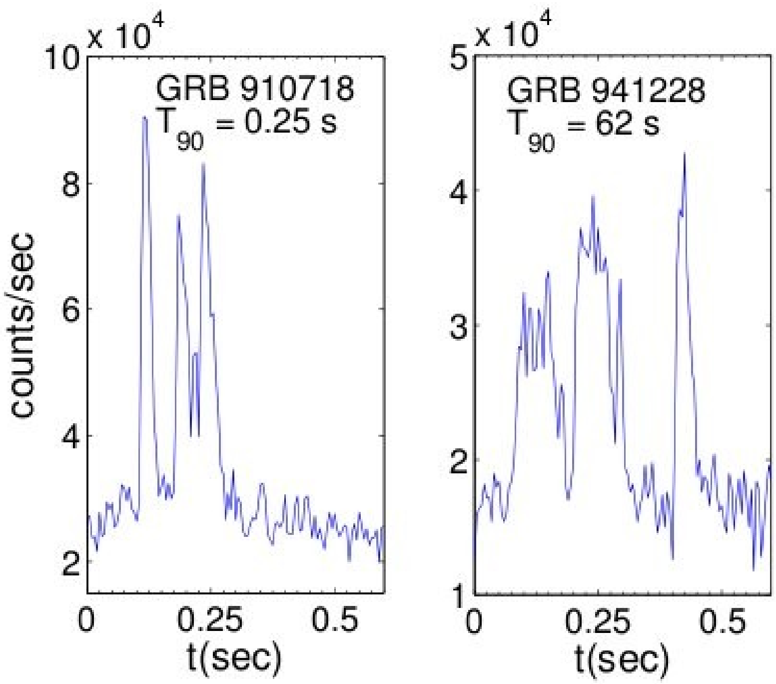
Extraction of BH rotational energy

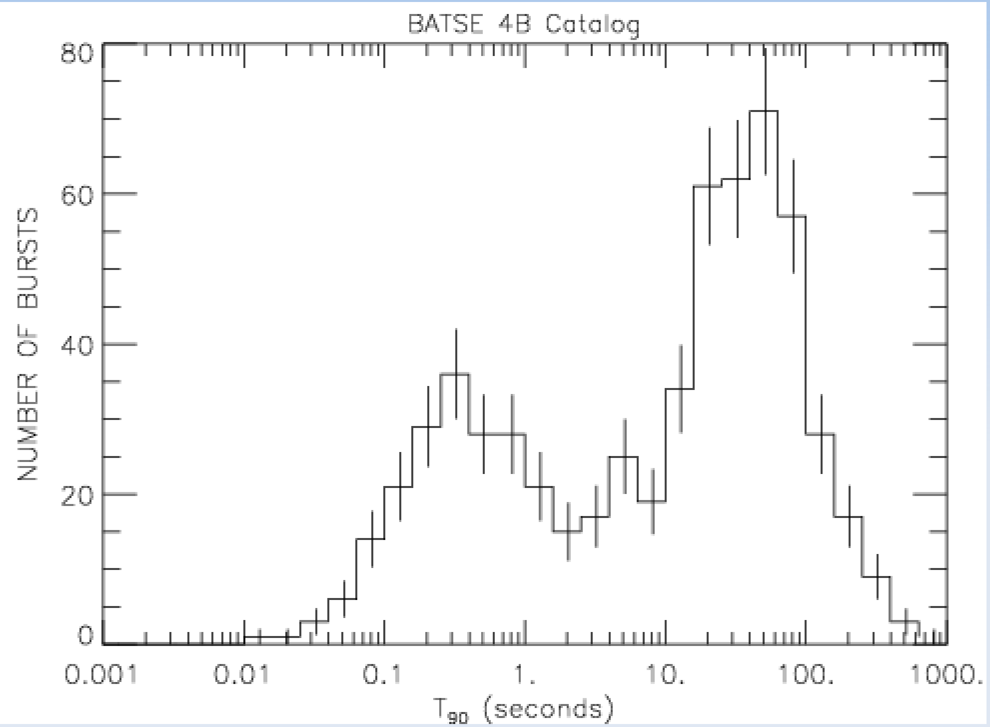


- Sapountzis & Janiuk (2019) showed that rotational velocity of magnetic fields is larger than angular velocity of the Kerr black hole, at the base of the jet
- Plot is made at hight z=7 r_g, for a=0.9 and three different sizes of the accretion disk. Evolved state of disk is shown (t=3000 tg)

Two classes of GRBs

- Distribution of durations of GRBs forms two distinct peaks
- GRBs with T_{90} < 2 sec are called 'short'

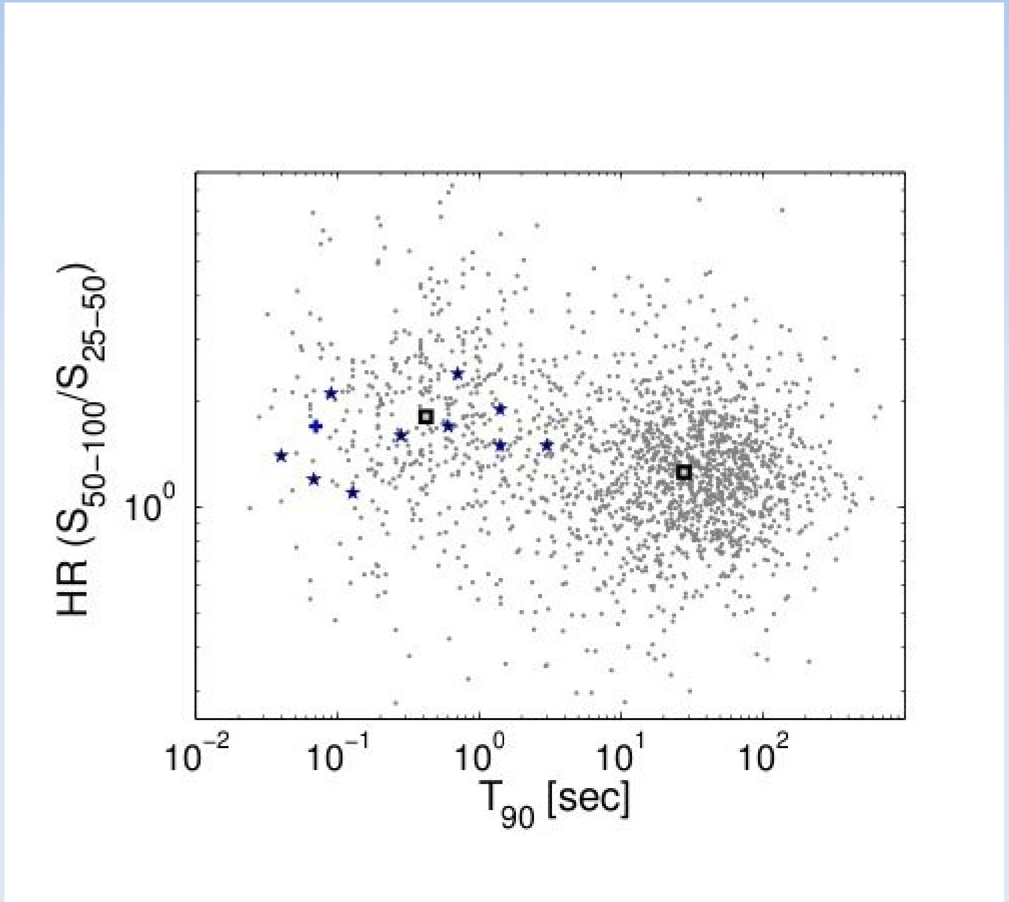




Kouvelietou et al. (1992)

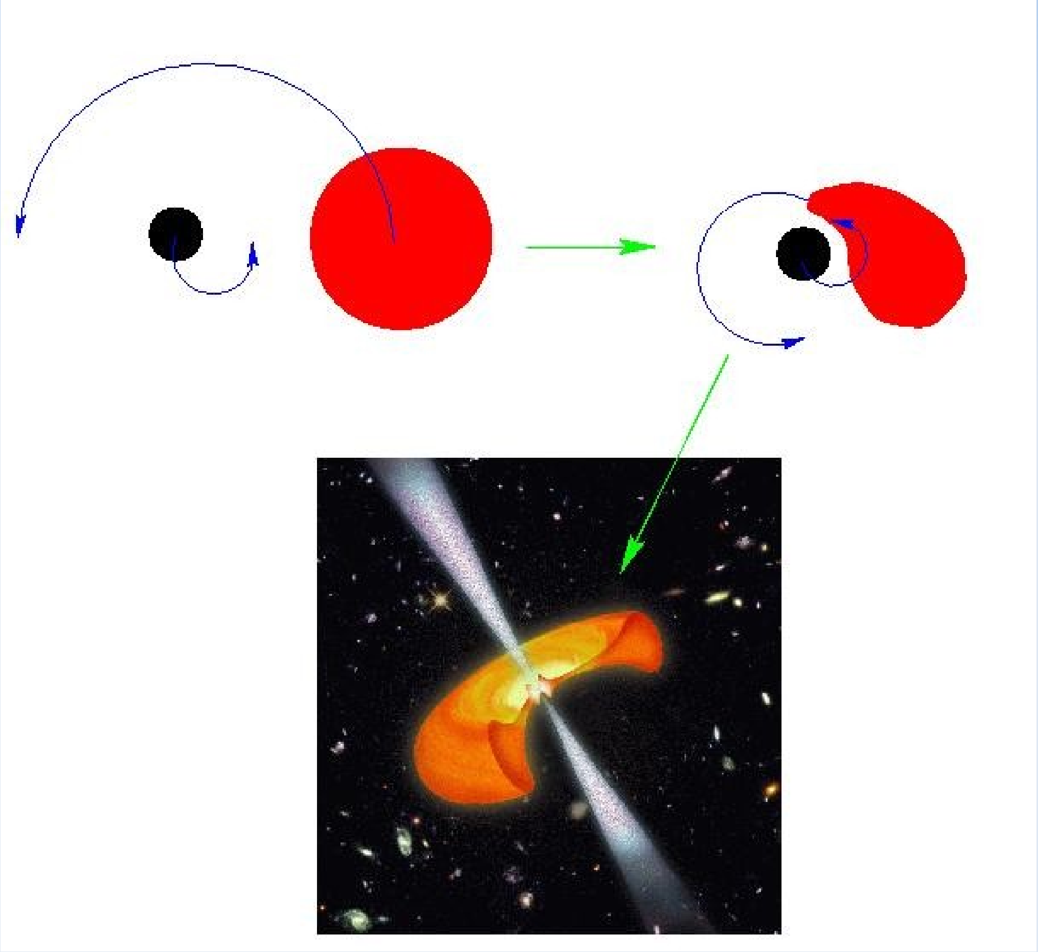
Two classes of GRBs

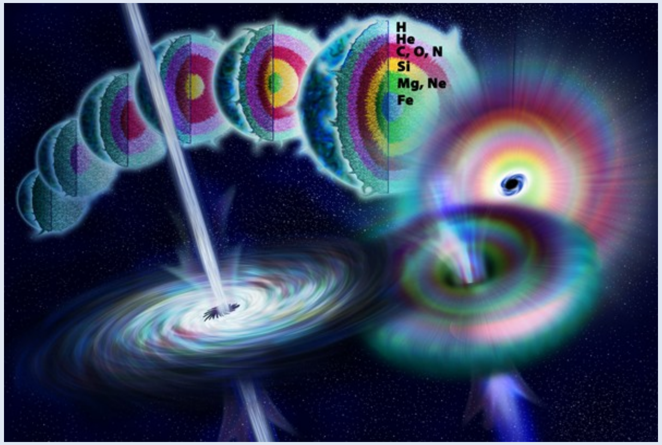
- Short GRBs have hard spectra
- Long GRBs are soft



Model requirements: disk size

- Variability of event: size vs. speed of light.
- $Dt = 2\pi r / c = 0.6$ ms at the inner radius of a disk



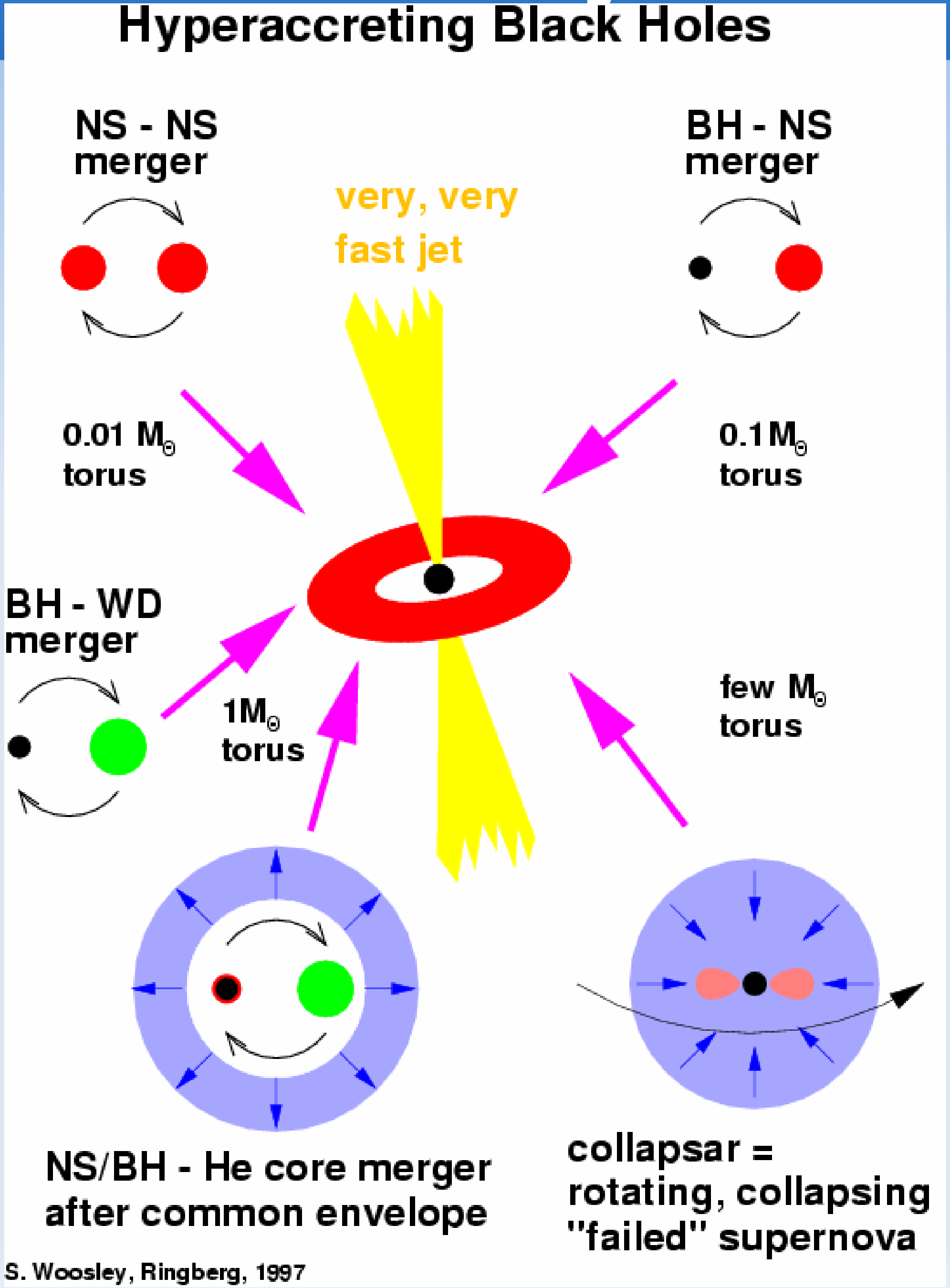


Progenitors

- Progenitors range from mergers of compact stars to collapse of massive stars
- Massive star must form a black hole: 10% of all collapsing stars.
- The star must have enough rotation in its envelope to form a disk: another 10%. GRBs (due to collapsars) may therefore occur in about 1% of all core-collapse supernovae (Type I b/c)
- Models must account for the energy of explosion, collimation, rapid variability, range of durations, statistics

Types of models for GRB jets

- Most popular models of GRBs invoked accretion onto a compact star
- The hyper-accretion flow drives the production of very fast, relativistic jet
- This jet is a source of gamma ray radiation



Some scenarios

TABLE 1

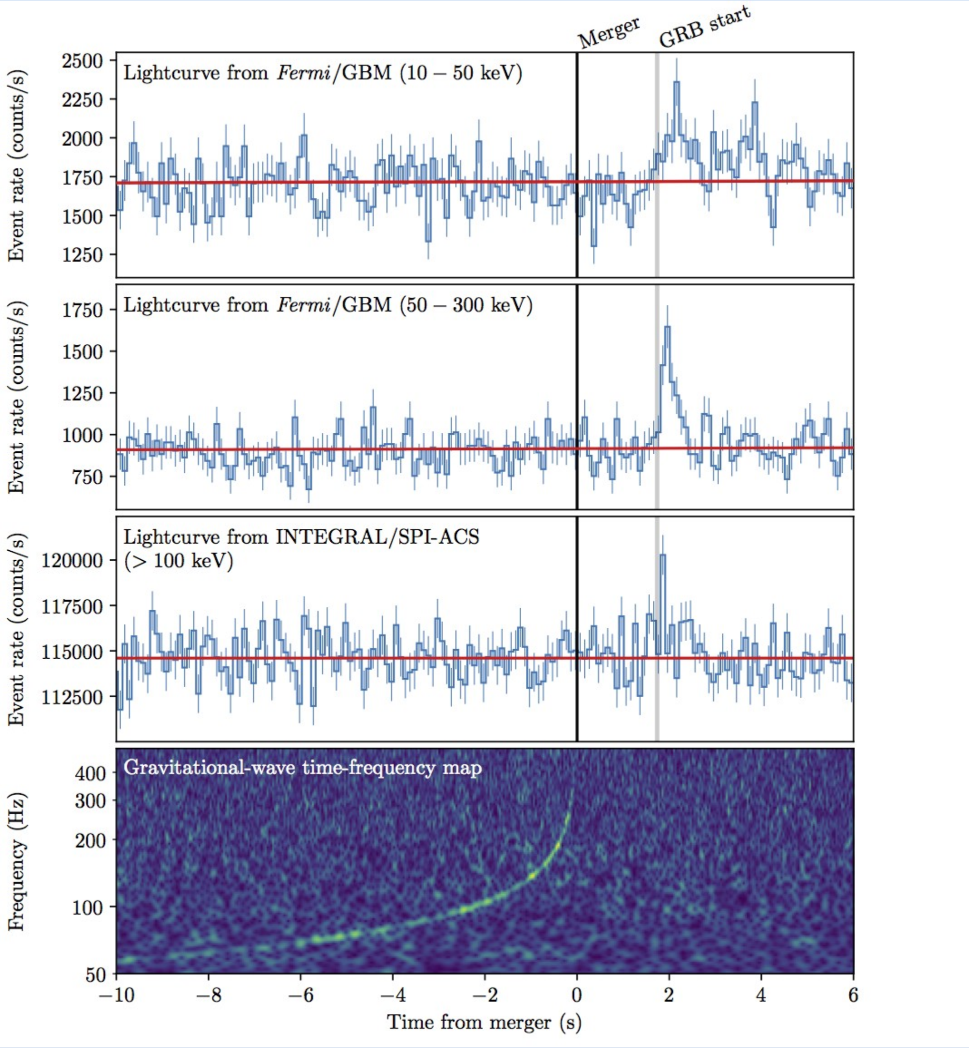
CHARACTERISTIC QUANTITIES FOR VARIOUS EVOLUTIONARY SCENARIOS

Model	$M_{accrete}$[a] ($M_\odot$)	Radius (km)	$\dot{M}$ ($M_\odot$ s^{-1})	j (10^{16} cm^2 s^{-1})	Duration (s)	Gravity Waves
NS + NS	0.1	50	1	4	0.1	Yes
NS + BH	0.5	50	5	4	0.1	Yes
Collapsar	2	50–250	0.1	5–10	10–20	No
BH + WD	1	$(1–5) \times 10^4$	0.01–0.07	50–150	15–150	No
BH + He core......	2	$(1–10) \times 10^4$	0.01–0.1	50–200	15–500	No

[a] Masses are for accretion through a disk. The total accretion rate, e.g., in the collapsar and He core models, is greater because of mass infall along the poles. The assumed mass of the black hole is 3 $M_\odot$ in all cases, and the disk viscosity is $\alpha = 0.1$.

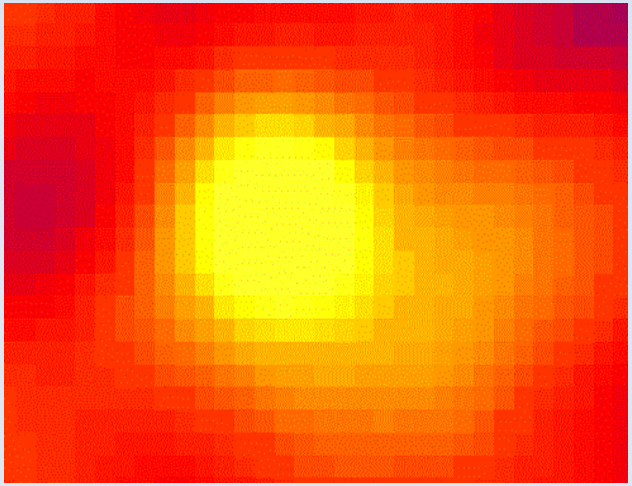
First confirmed short GRB progenitor

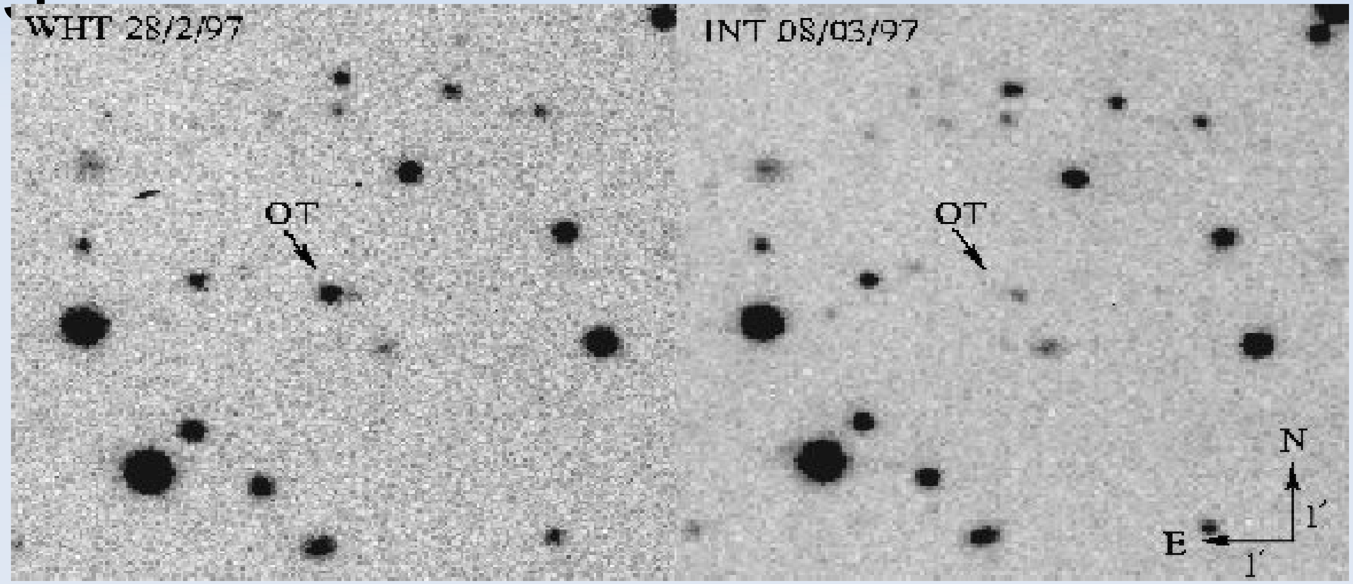
- GRB 170817
- Detected 1.7 seconds after gravitational wave
- Source of the wave is binary neutron star merger



Localisations in host galaxy

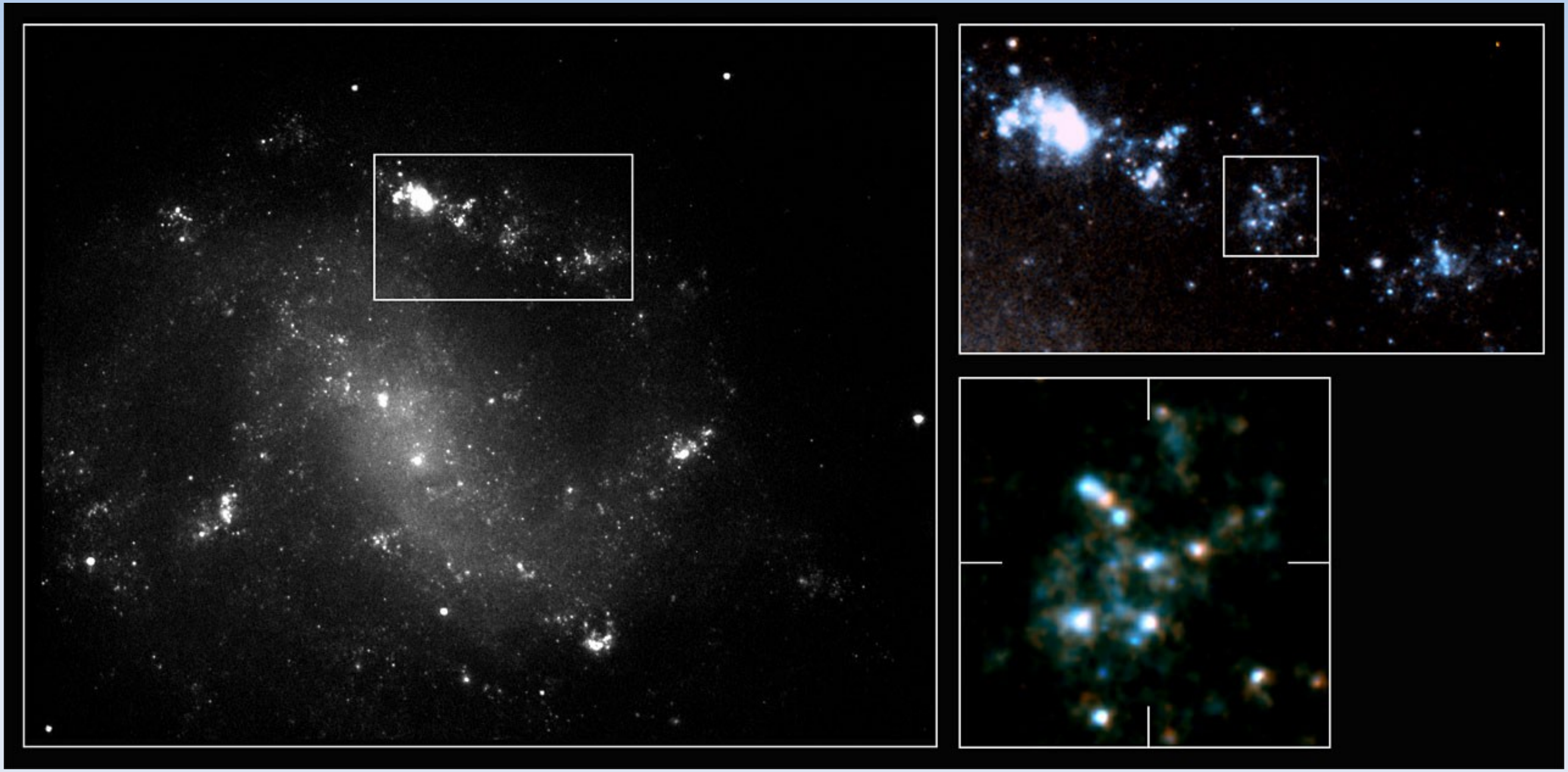
- First localisation, GRB970228. Optical counterpart discovered. Host galaxy with redshift z=0.695





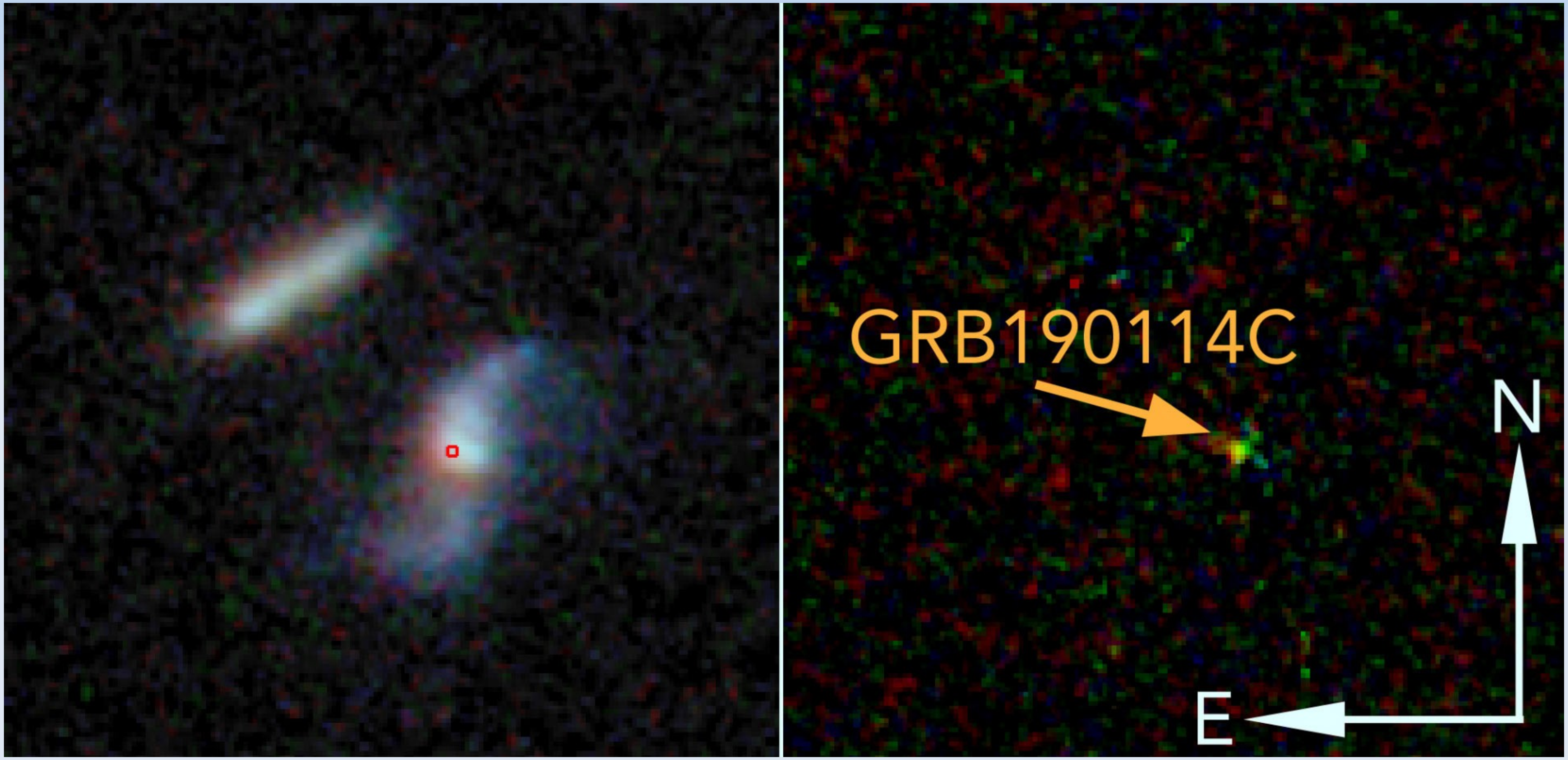
- Beppo SAX started the afterglow observations. Limited to long GRBs

GRB980425



Galaxy ESO- 184-G82, (Holland et al. 2000). Spiral Galaxy with loose arms, signatures of ionised hydrogen emission, strog star formation activity

Host of GRB190114



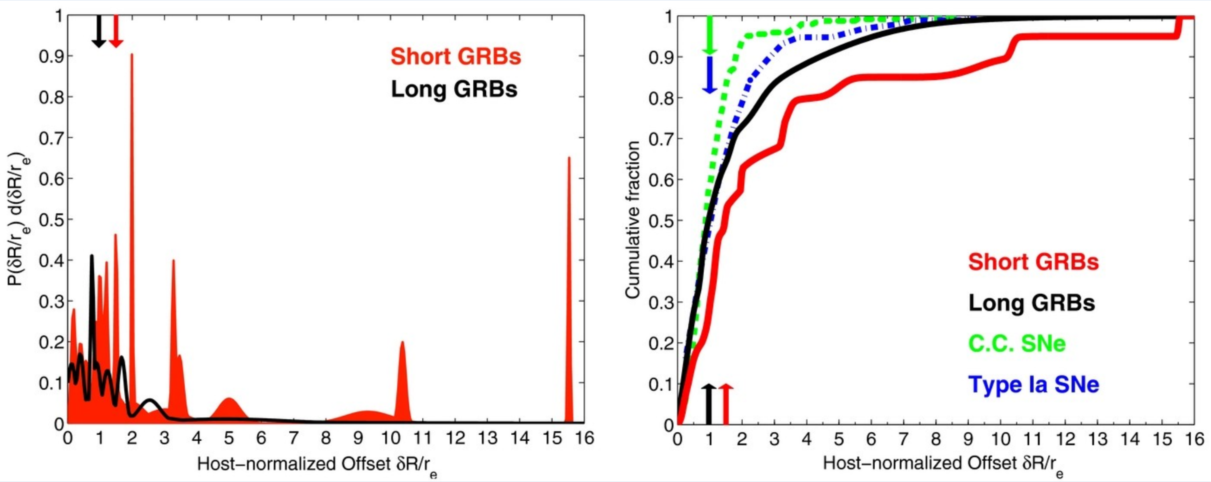
GRB 190114C: the left panel shows a close pair of interacting galaxies, which is a host system of GRB 190114C; the location of GRB 190114C is indicated with a red circle; the right panel shows the optical counterpart of GRB 190114C.

Image credit: de Ugarte Postigo et al, arXiv: 1911.07876.

Localisations of short and long GRBs

Long GRBs appear in star-forming galaxies, and their distribution is consistent with that of massive stars.

Short GRBs do not occur in regions of star formation or even stellar mass. This demonstrates that the progenitor systems of short GRBs must migrate from their birth sites to their eventual explosion sites, a signature of kicks in compact object binary systems.

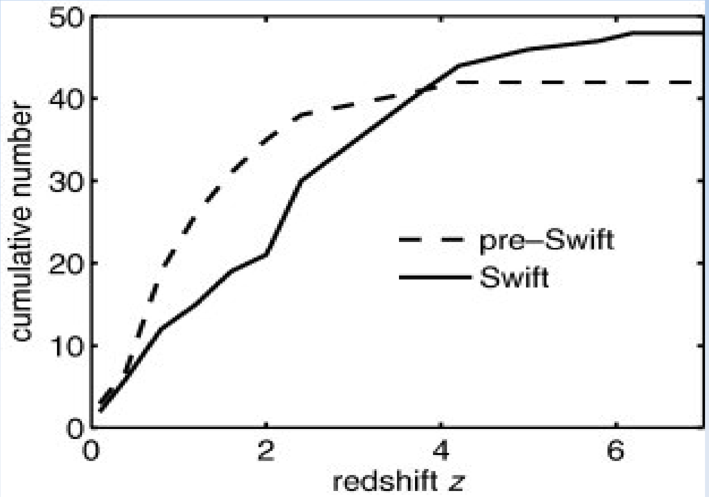


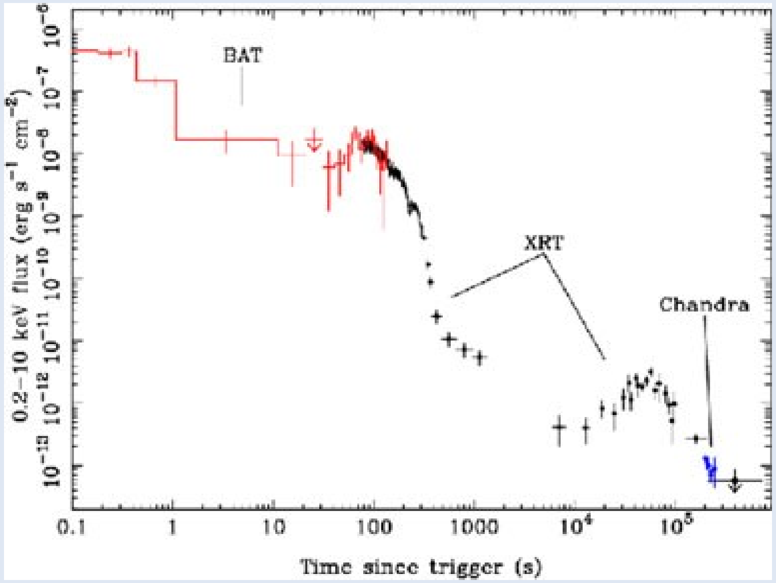
Fong & Berger 2013

Left: differential distributions of host-normalized offsets in units of effective radius, re, accounting for the uncertainty in each offset measurement, for short GRBs (red shaded region) and long GRBs (black line). Right: cumulative host-normalized offset distributions for short GRBs (red) and long GRBs (black). Also shown are the distributions for core-collapse supernovae and Type Ia supernovae

Swift GRBs

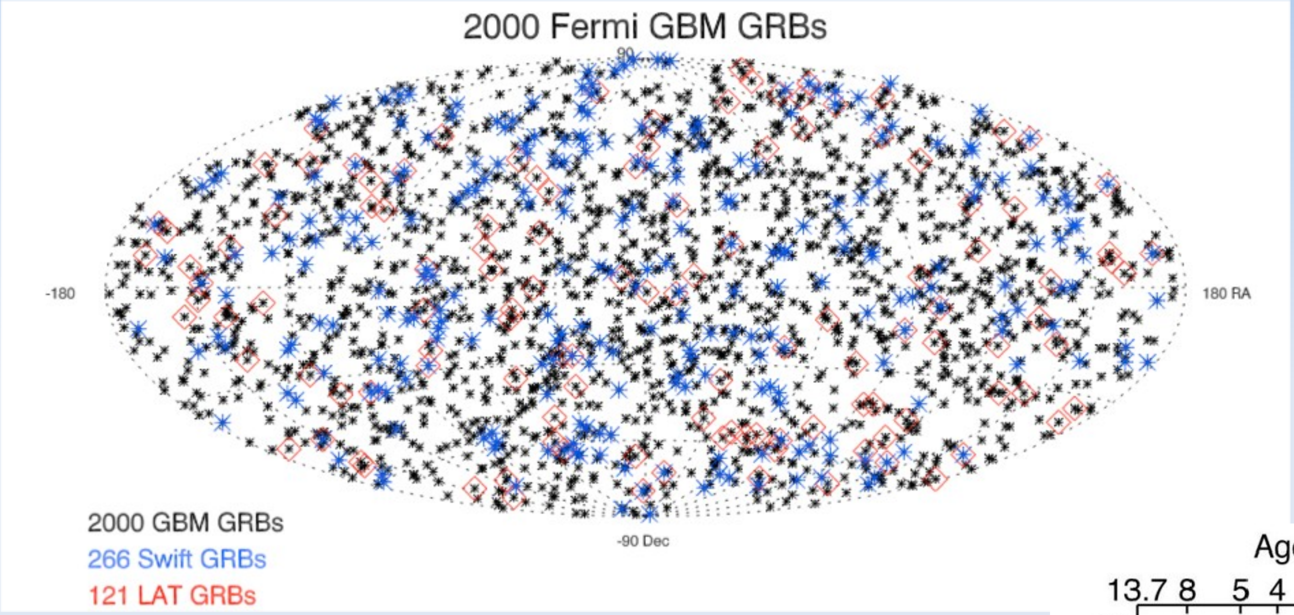
- Detector operates since 2004
- Observed the first afterglow for a short burst, GRB050509B

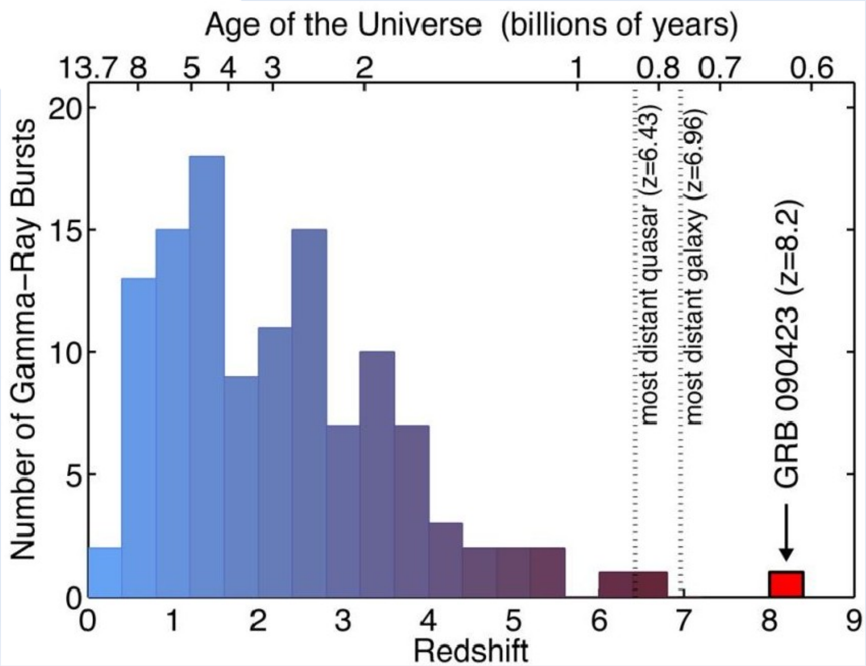




GRB 050724 (Barthelmy et al. 2005)

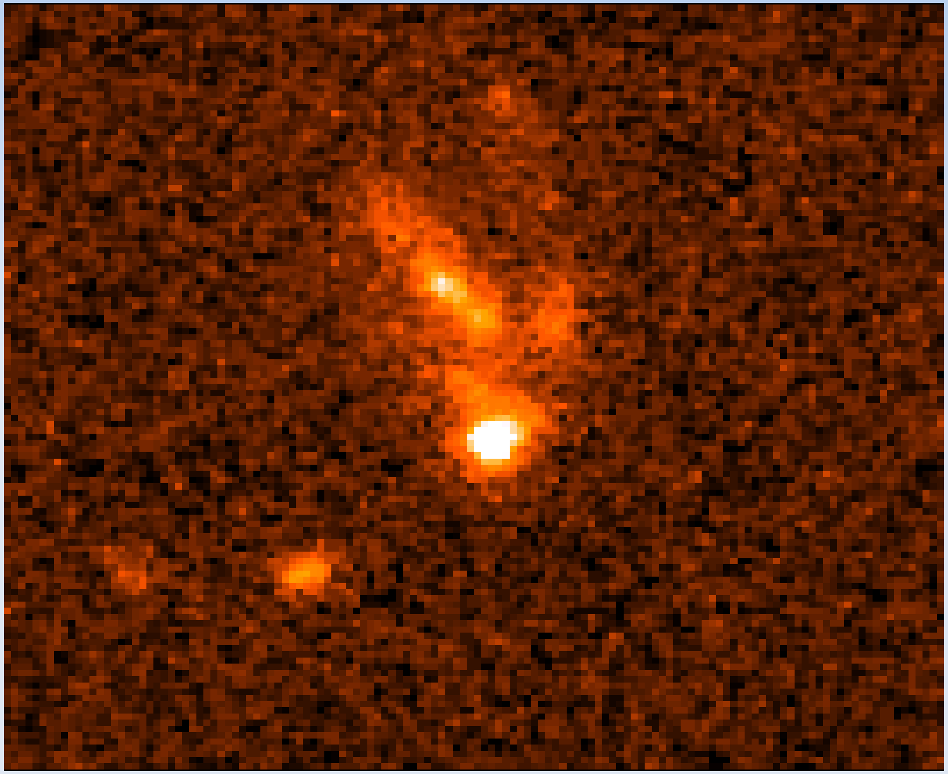
Fermi GRBs


2000 Fermi GBM GRBs
90
-180
180 RA
-90 Dec
2000 GBM GRBs
266 Swift GRBs
121 LAT GRBs


Age of the Universe (billions of years)
13.7 8 5 4 3 2 1 0.8 0.7 0.6
Number of Gamma-Ray Bursts
0
5
10
15
20
most distant quasar (z=6.43)
most distant galaxy (z=6.96)
GRB 090423 (z=8.2)
0 1 2 3 4 5 6 7 8 9
Redshift

Afterglows

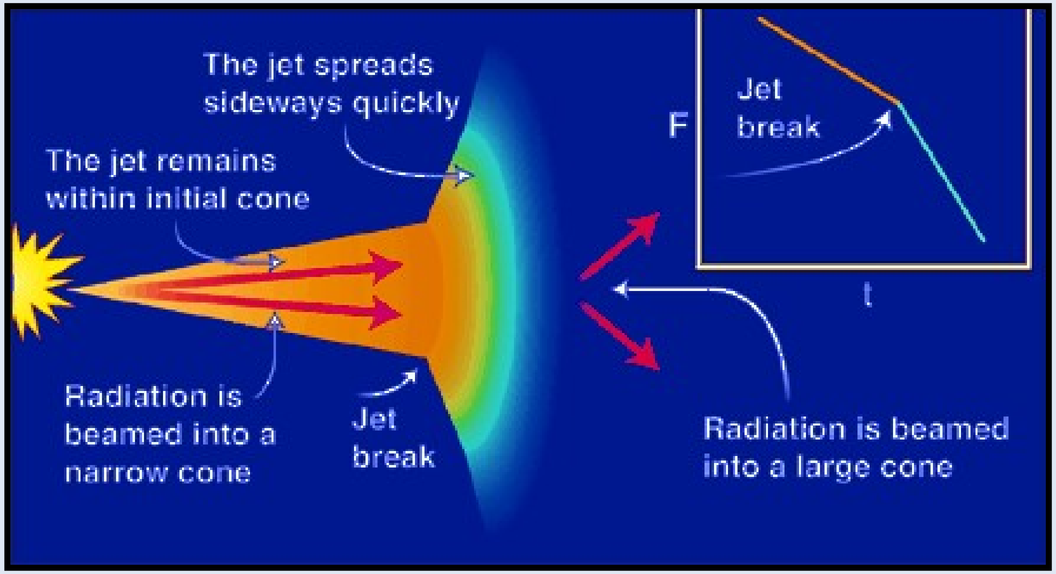
- Lightcurves show power law decay: support for relativistic blast wave explosion models
- After the optical afterglow fades, the host galaxy can be studied
- The hosts of long GRBs are in star forming regions, which have higher gas densities and metalicities (Holland 2001; Chevalier 2003)



Fading optical afterglow of GRB 990123 was observed by HST to 380 days after the burst.

Jet signatures

- The break in the afterglow lightcurve occurs when the jet expands sideways very quickly
- This allows to estimate the jet opening angle (Piran 2002)



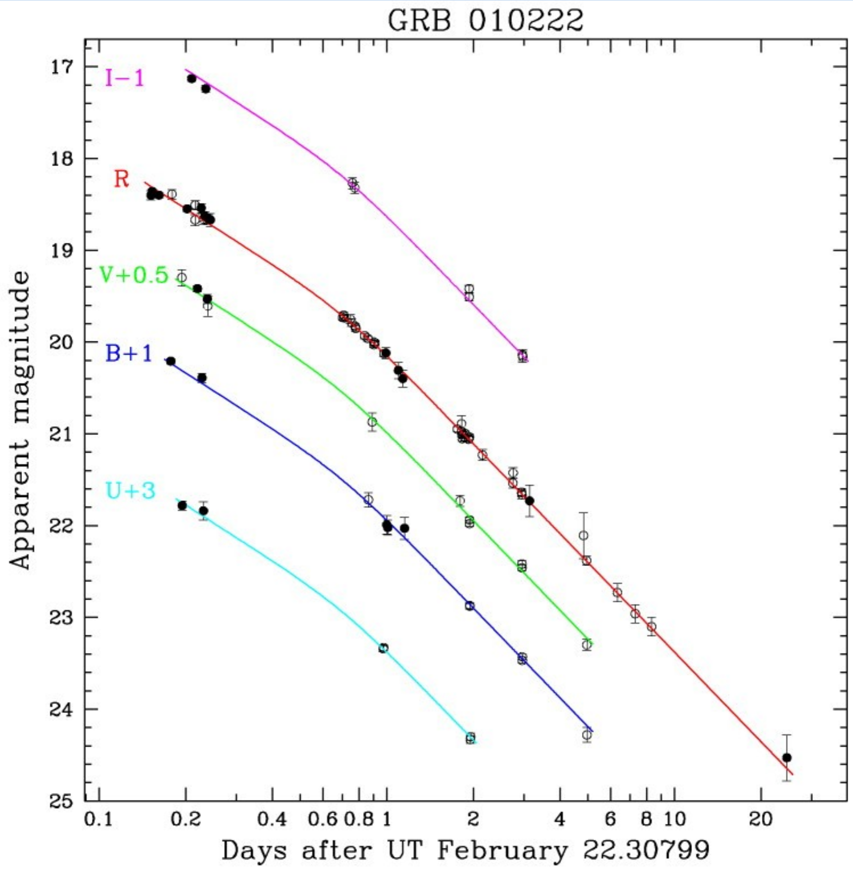
Opening angle

$$\theta_b \propto \left[\frac{n_o \eta_\gamma}{E_{\gamma,iso}}\right]^{1/8} \left[\frac{t_{break}}{1+z}\right]^{3/8}$$

$$E_\gamma = (1-\cos\theta_b) E_{\gamma,iso}$$

$$f_b = (1-\cos\theta_b) \approx \theta_b^{\,2}/2$$

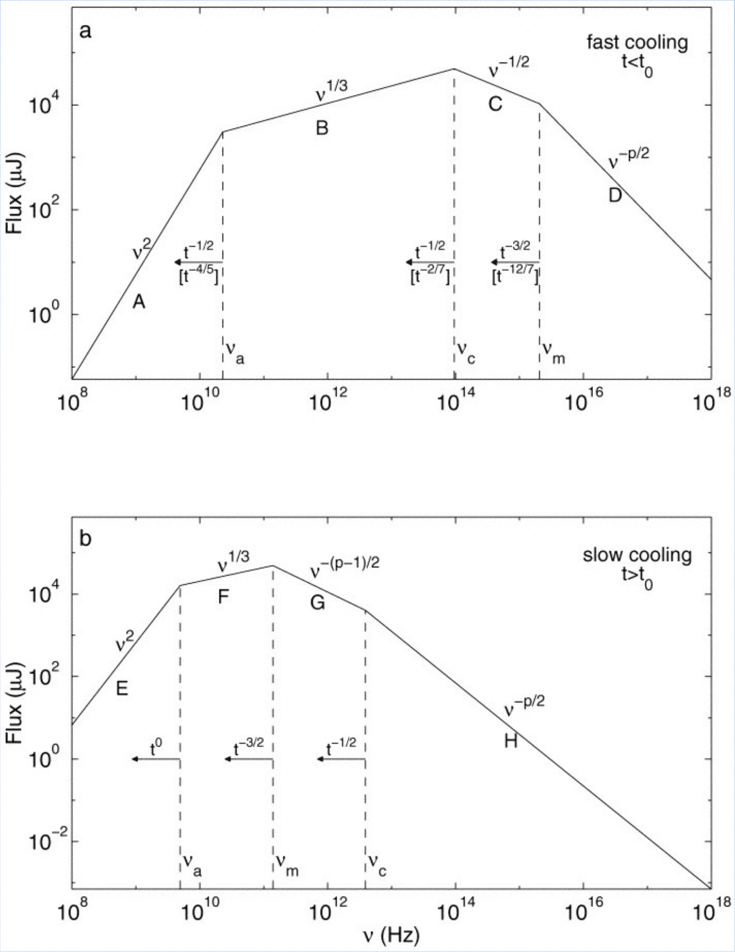
- Measured densities: on the order of 0.1 cm^{-3}
- Radiative efficiency of shocks: ~0.1

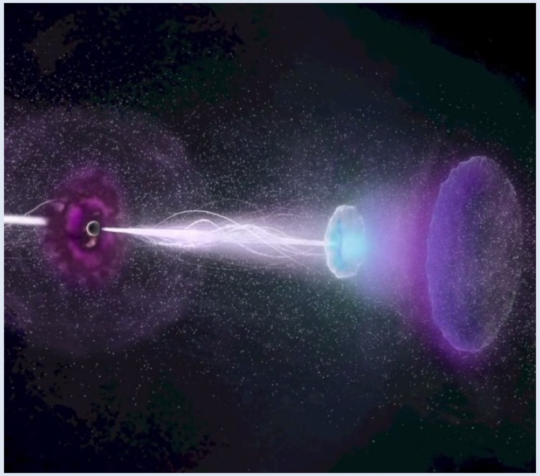


(Stanek et al. 2001)

Fireball model

- Relativistic shocks with Synchrotron and Inverse Compton emission produce prompt radiation in gamma rays and optical flash
- External shocks produce afterglow emission





Sari & Piran 1999

Next week

- More about gamma ray bursts, Magnetar model
- Central engines, nuclear reactions
- Neutrino cooling
- Kilonova

Further reading suggested:

- T. Piran,”The Beaming Factor and Other Open Issues in GRB Jets”, astro-ph/0502473
- Thorne, Price & McDonald, ”Black Hole: The membrane paradigm”, (1986, Yale Univ. Press)
- P. Kumar & B. Zhang, ”The physics of gamma-ray bursts and relativistic jets”, 2015, Physics Reports, v. 561, p. 1-109