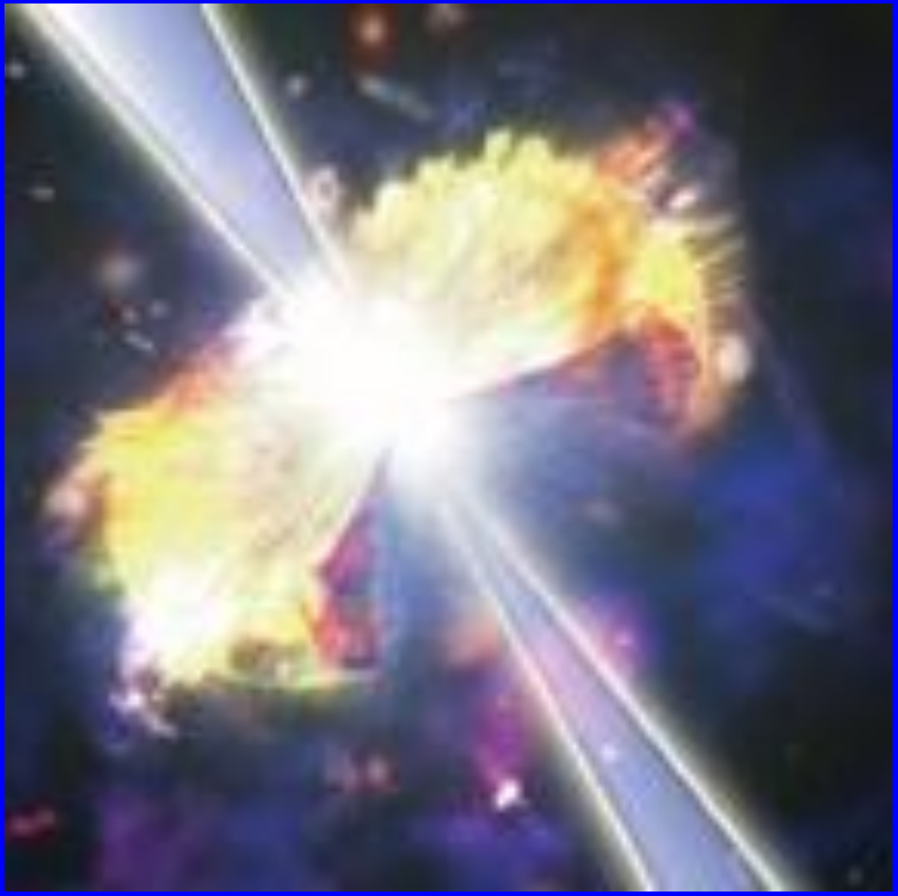
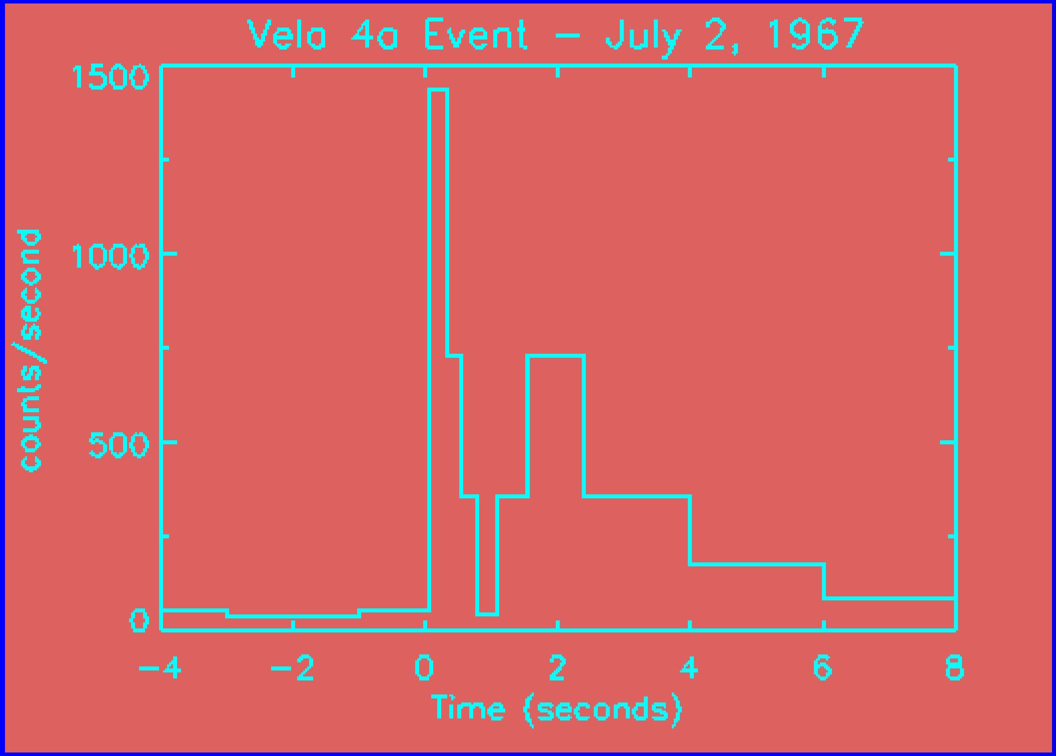
# Космические гамма-всплески

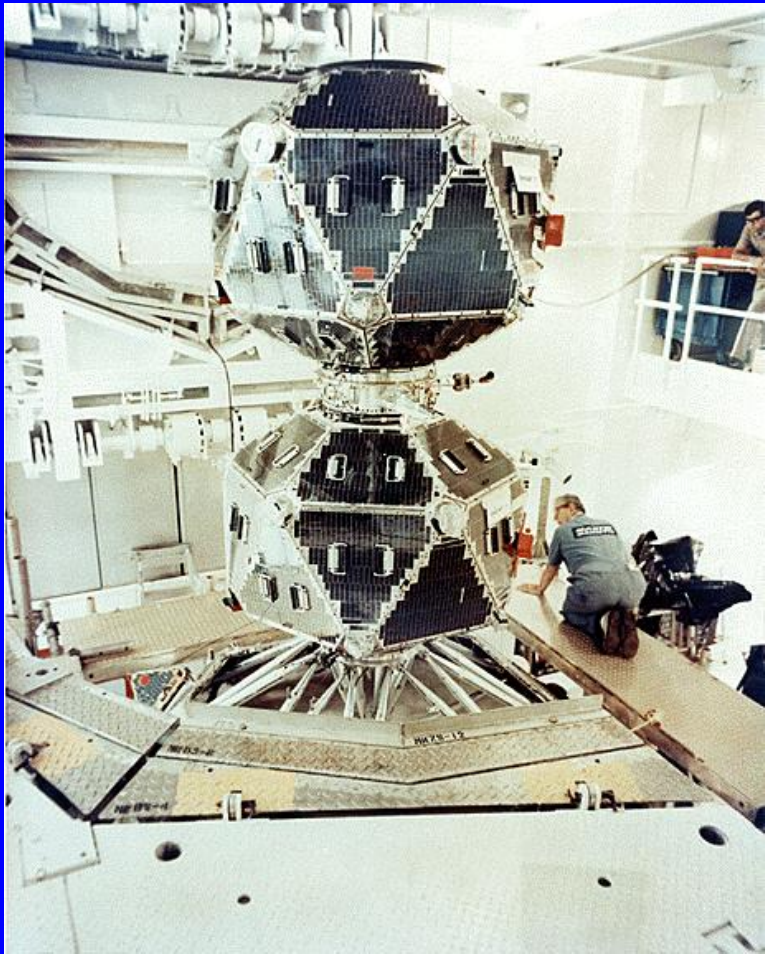
- Самые мощные взрывы во Вселенной!



# История

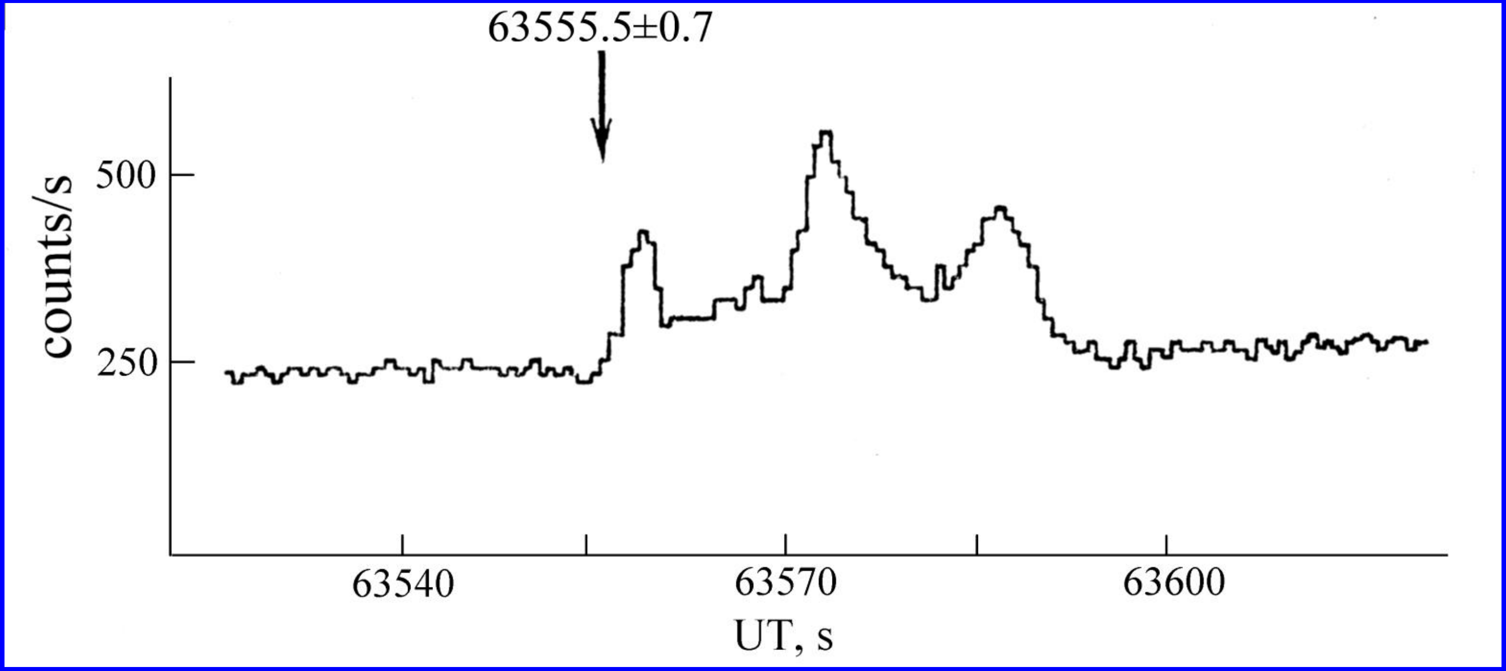
- Открыты в конце 60х
  на американских спутниках Vela (150 – 750 кэВ); первый всплеск – 2 июля 1967 г.
- Опубликовано в 73г (16 GRBs)



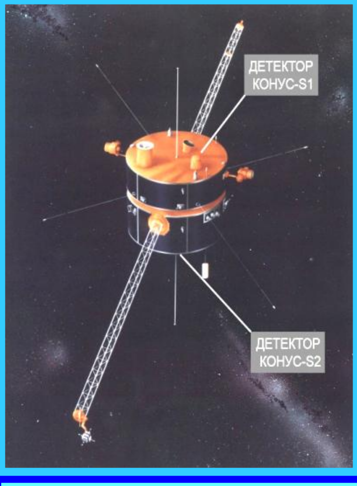



# Наблюдения гамма-всплеска GRB 720117 детектором спутника Космос 461

- Мазец, Голенецкий, Ильинский, Письма в ЖЭТФ 1974 – одно из первых независимых подтверждений открытия гамма-всплесков



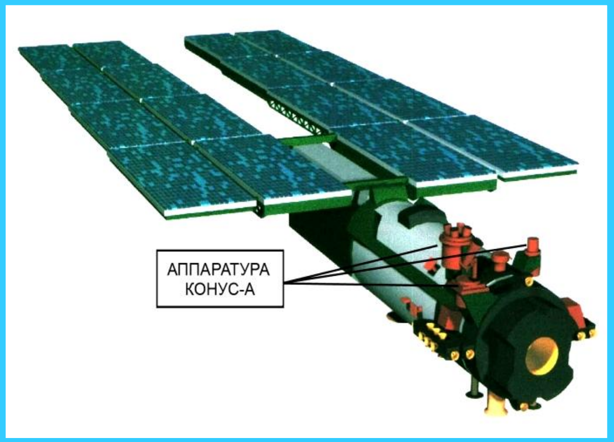
## Эксперименты ФТИ по исследованию нейтронных звезд со сверхсильными магнитными полями, солнечных вспышек и *самых мощных взрывов во Вселенной – космических гамма-всплесков*




Аппаратура «Конус» на КА НАСА «Винд»

Аппаратура «Конус-РФ» на КА «Коронас-Фотон»

Аппаратура «Геликон» на КА «Коронас-Ф»




Аппаратура «Конус-А» на КА серии «Космос»

В лаборатории «Экспериментальной астрофизики» успешно проводятся эксперименты по исследованию астрофизических источников гамма-излучения с 70-х годов XX века.

С 1994 года бесперебойно функционирует эксперимент «Конус» на американском космическом аппарате (КА) Винд

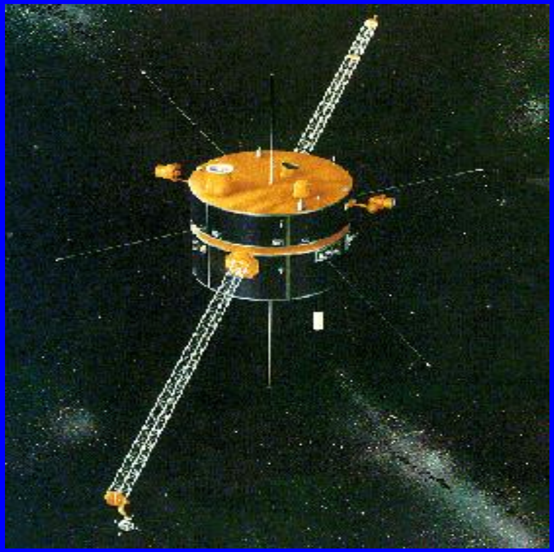
В 1995-2006 гг. проведены эксперименты Конус-А, Конус-А2, Конус-А3 на КА Космос-2326, 2367, 2421

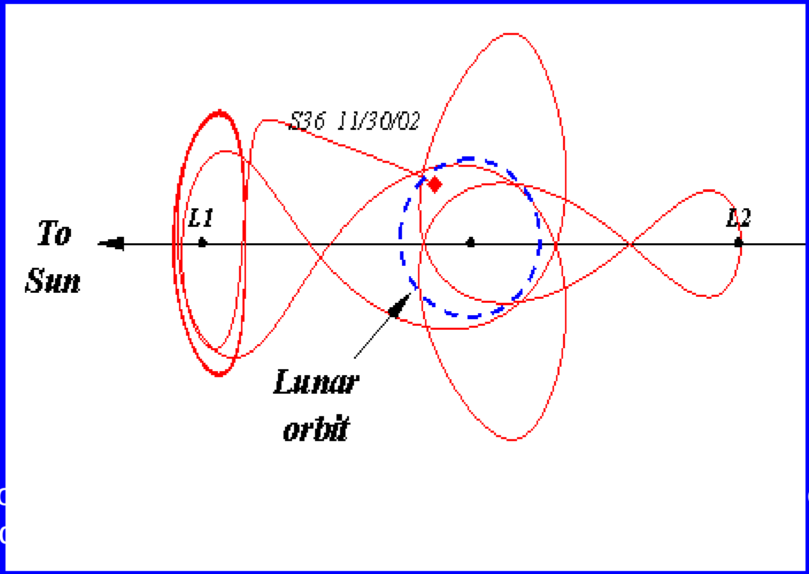
В 2001-2005 гг. проведен эксперимент «Геликон» на КА «Коронас-Ф»

В 2009 г. – эксперимент «Конус-РФ» на КА «Коронас-Фотон»

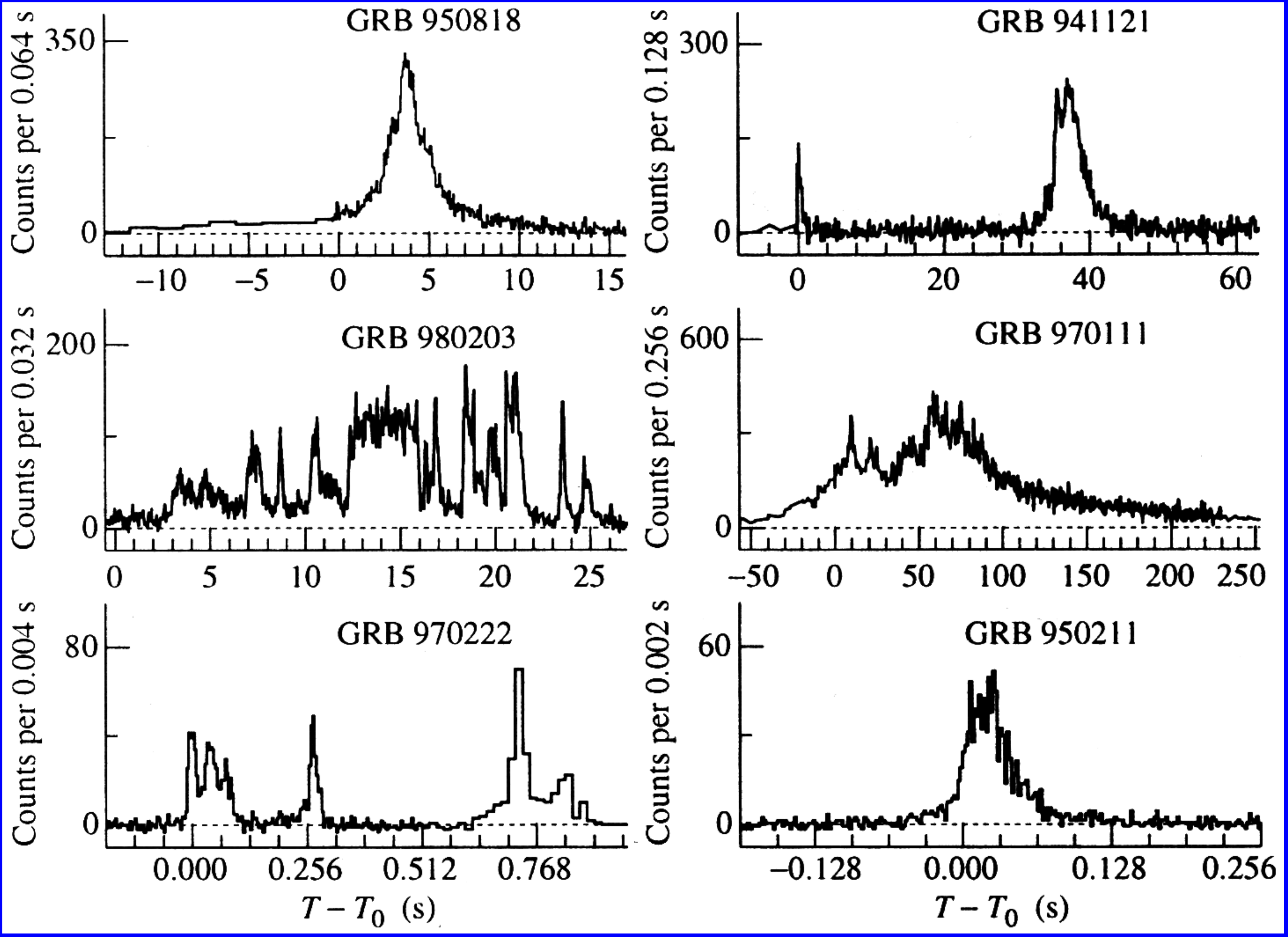
# Российско-американский эксперимент Конус-Винд (1994 -)

- *Два детектора S1 и S2:*
  NaI(Tl) 13 cm x 7.5 cm
- Постоянный обзор всей небесной сферы в диапазоне энергий ~20 кэВ – 15 МэВ
- Эфф. площадь ~100-160 cm$^2$
- Удаление от Земли ~1.5 млн. км



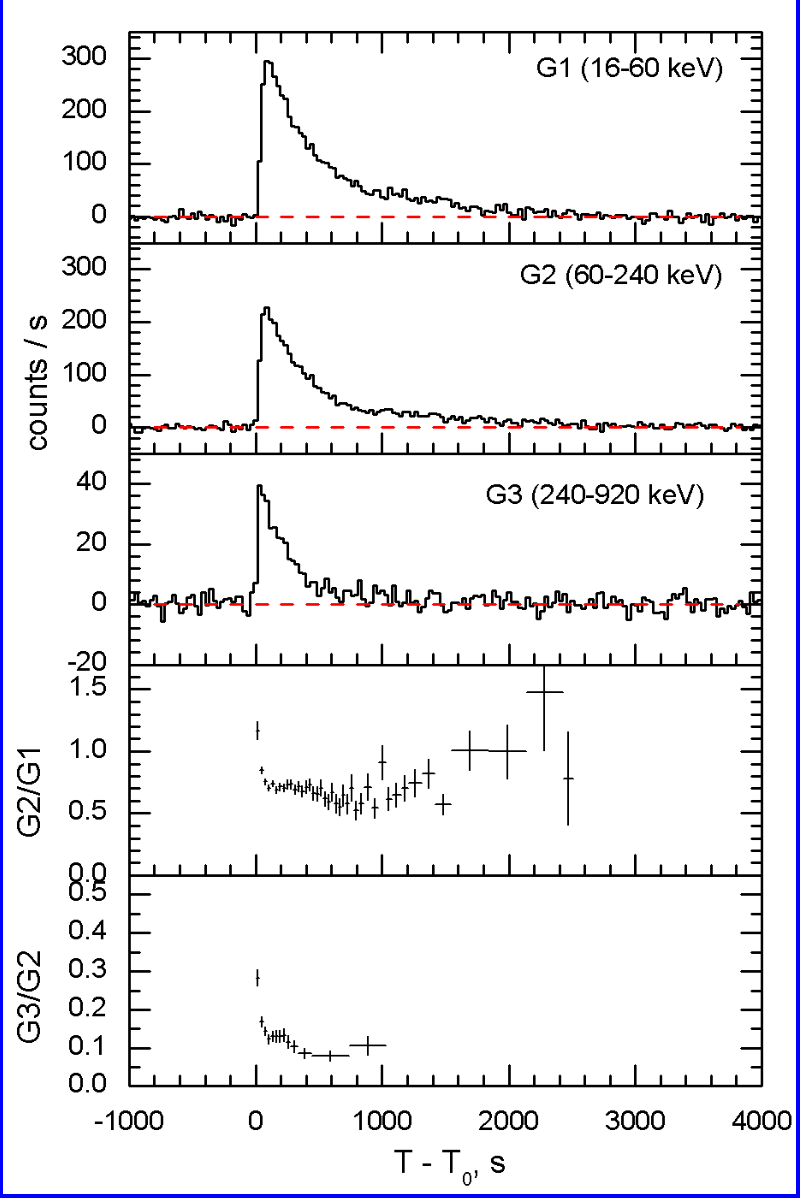


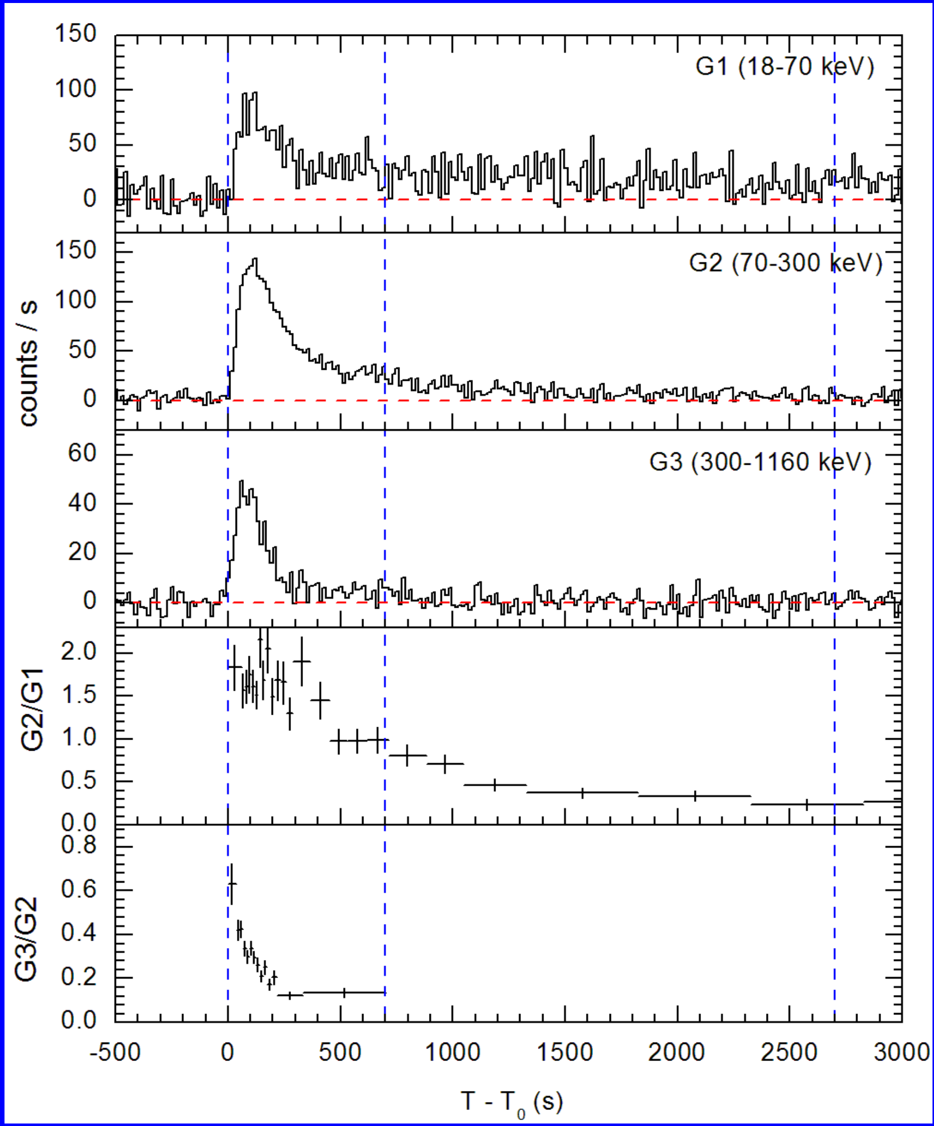

The orbit c ... e
Earth shac



GRB 950818
Counts per 0.064 s
350
0
−10
−5
0
5
10
15
GRB 941121
Counts per 0.128 s
300
0
0
20
40
60
GRB 980203
Counts per 0.032 s
200
0
0
5
10
15
20
25
GRB 970111
Counts per 0.256 s
600
0
−50
0
50
100
150
200
250
GRB 970222
Counts per 0.004 s
80
0
0.000
0.256
0.512
0.768
T − T0 (s)
GRB 950211
Counts per 0.002 s
60
0
−0.128
0.000
0.128
0.256
T − T0 (s)

# GRB 971208 , GRB 060814B - самые длинные гамма-всплески



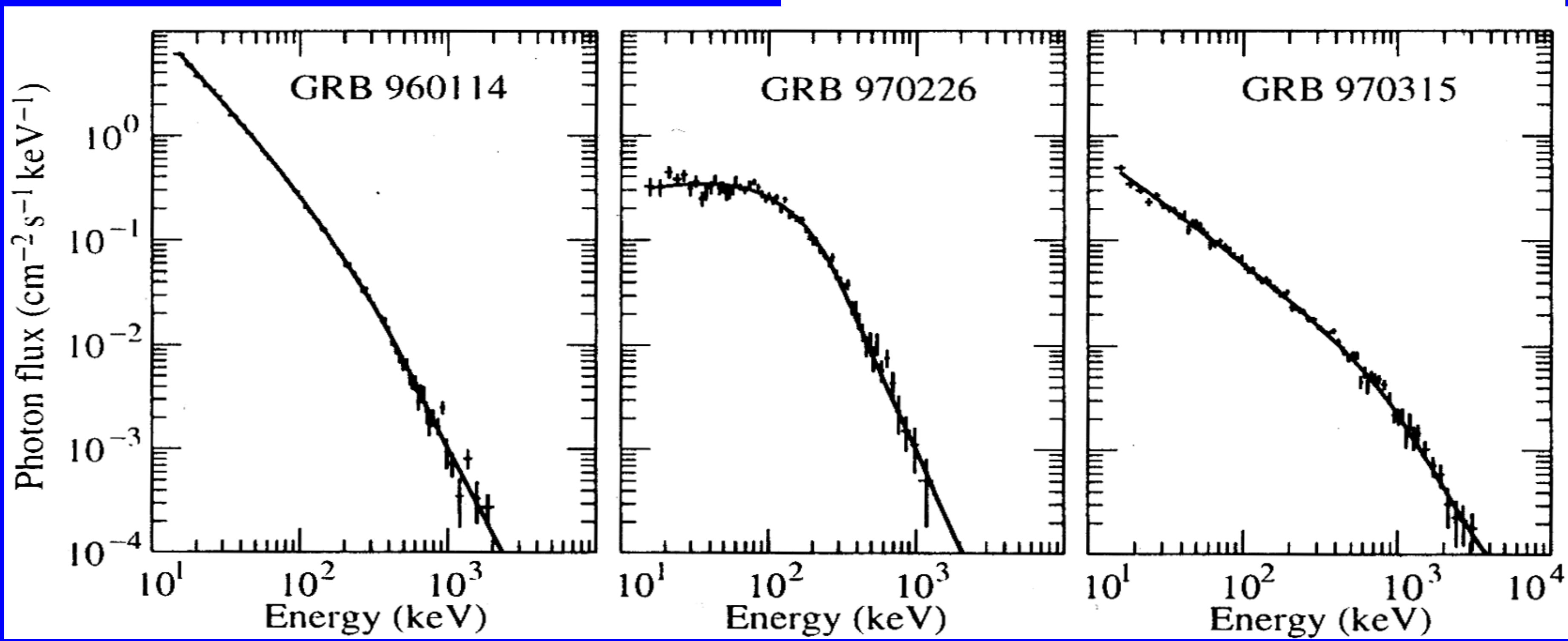



# Спектры гамма-всплесков

Хорошо описываются эмпирической моделью Банда: две степени, плавно соединенные экспонентой

$$N_E(E) = A\left(\frac{E}{100\ \mathrm{keV}}\right)^{\alpha} \exp\left(-\frac{E}{E_0}\right), \qquad (\alpha-\beta)E_0 \geq E$$

$$= A\left[\frac{(\alpha-\beta)E_0}{100\ \mathrm{keV}}\right]^{\alpha-\beta} \exp(\beta-\alpha)\left(\frac{E}{100\ \mathrm{keV}}\right)^{\beta}, \qquad (\alpha-\beta)E_0 \leq E$$

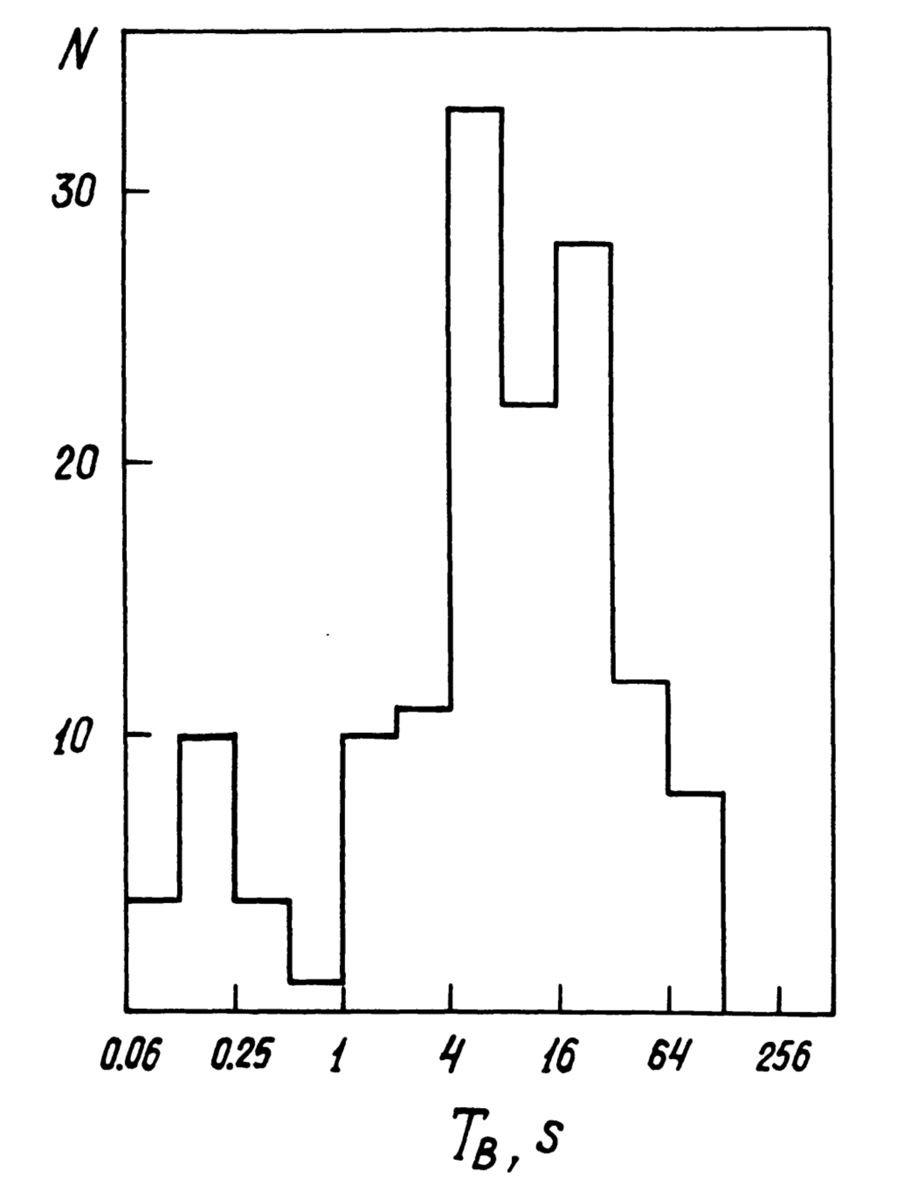


# Общие характеристики

- Длительности ~10 мсек – 1000 сек
- Характерные энергии ~100-1000 кэВ
- Характерные потоки ~$10^{-7}$-$10^{-5}$ эрг/см$^2$/сек (могут в сотни раз превосходить фон гамма-излучения)

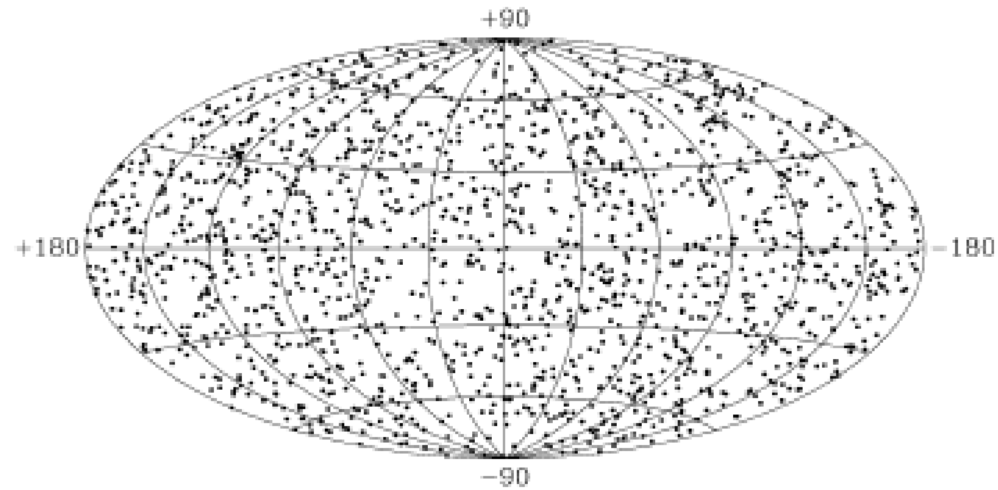
# Бимодальное распределение гамма-всплесков по длительностям

- Венера 11, 12 (1978-1980)
- Венера 13, 14 (1981-1983)
- Эксперимент Конус (30 кэВ – 2 МэВ)
- Первый каталог космических гамма-всплесков (Mazets et al., Ap&SS, 80, 3 (1981) – 143 GRBs



# Эксперимент BATSE (1991-2000)

- BATSE – burst and transient source experiment (CGRO)
- 20-1000 кэВ
- S = 8×2020 см$^2$
- Локализация с точностью несколько град.
- 1637 GRBs 4-ом каталоге
- Всего – 2072 GRBs



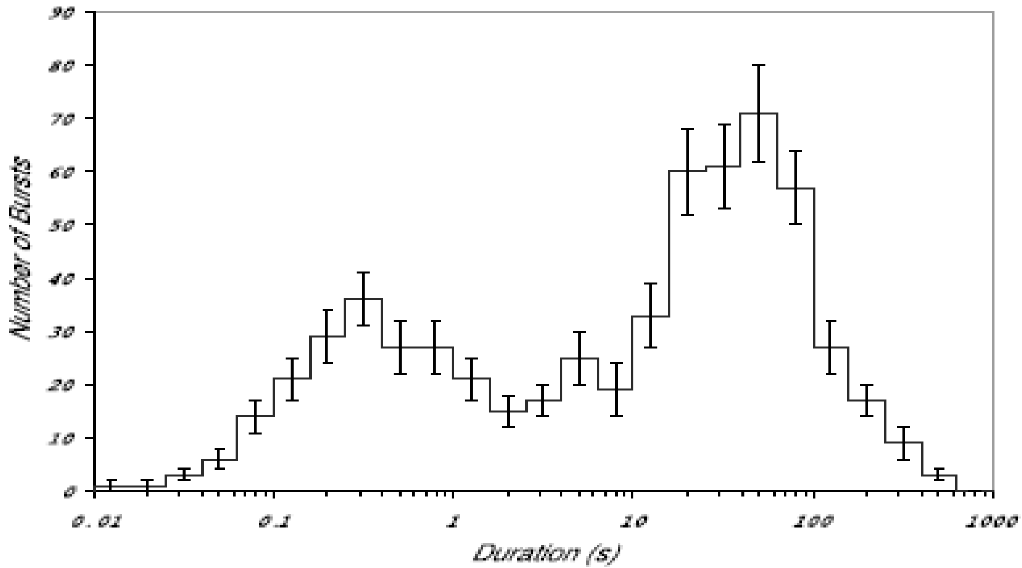
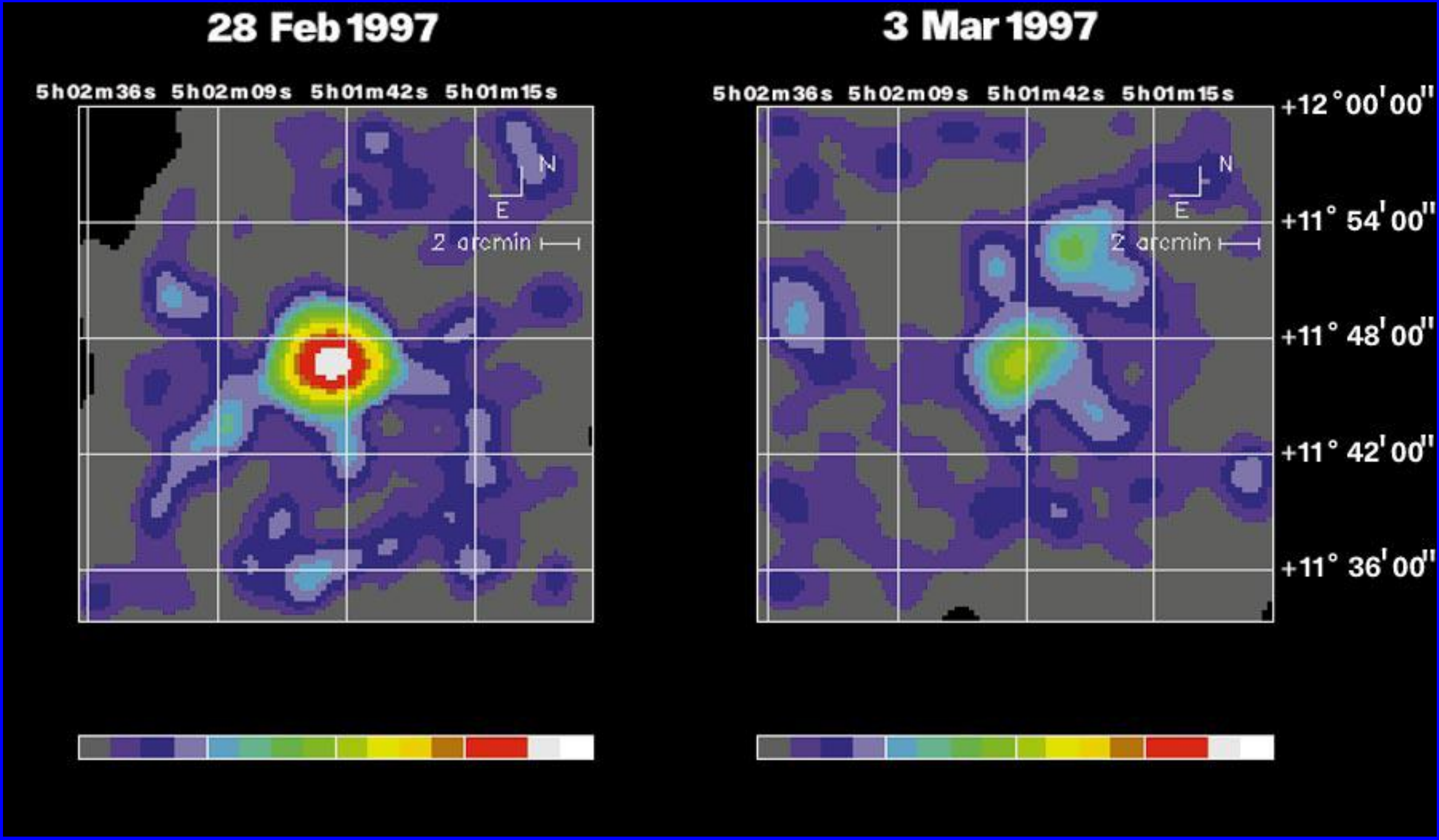




FIG. 1.—Burst duration vs. number of GRBs detected by BATSE. The two peaks occur at ~0.3 and ~30 s (based on Meegan et al. 1996).

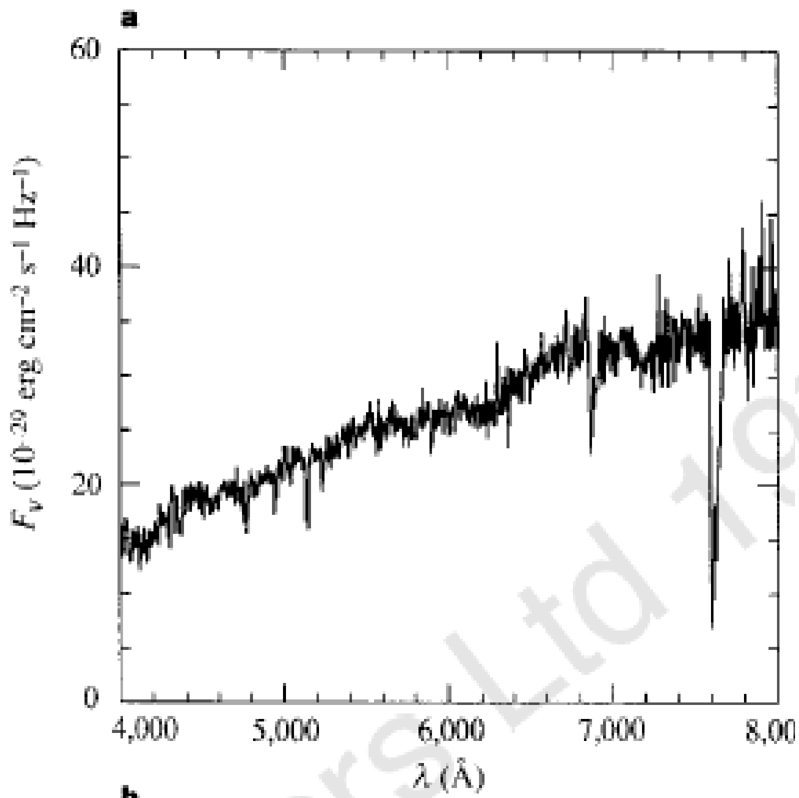
# Происхождение

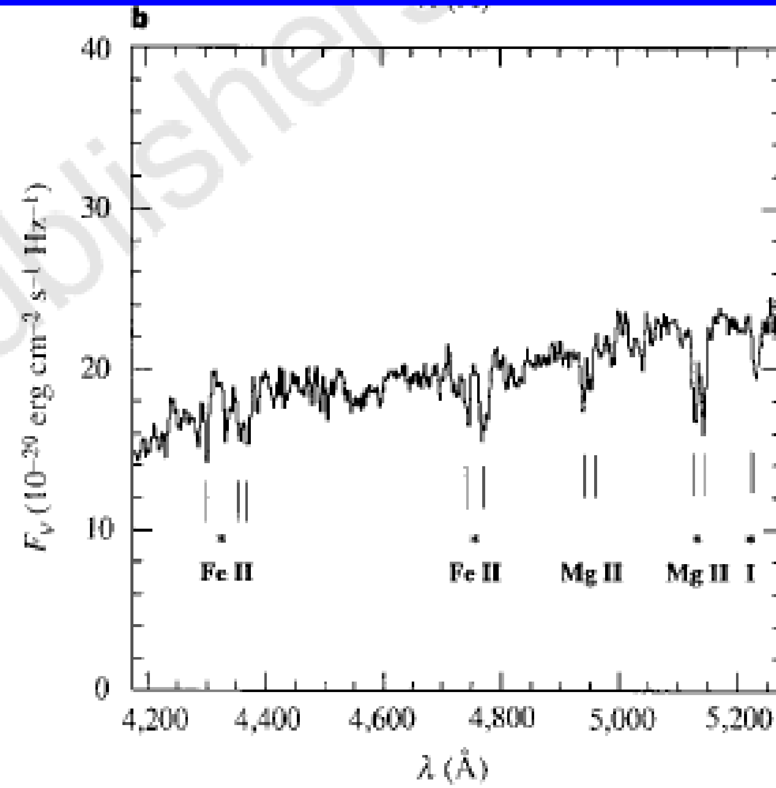
- Основной вопрос – галактические или космологические?
- Галактические – трудно объяснить изотропное распределение
- Галактические – трудно объяснить огромное энерговыделение, проблема компактности

# GRB 970228 - первый гамма-всплеск с рентгеновским послесвечением



# GRB 970508 - первое измерение красного смещения (z=0.835 ~7.5 млрд. лет назад)



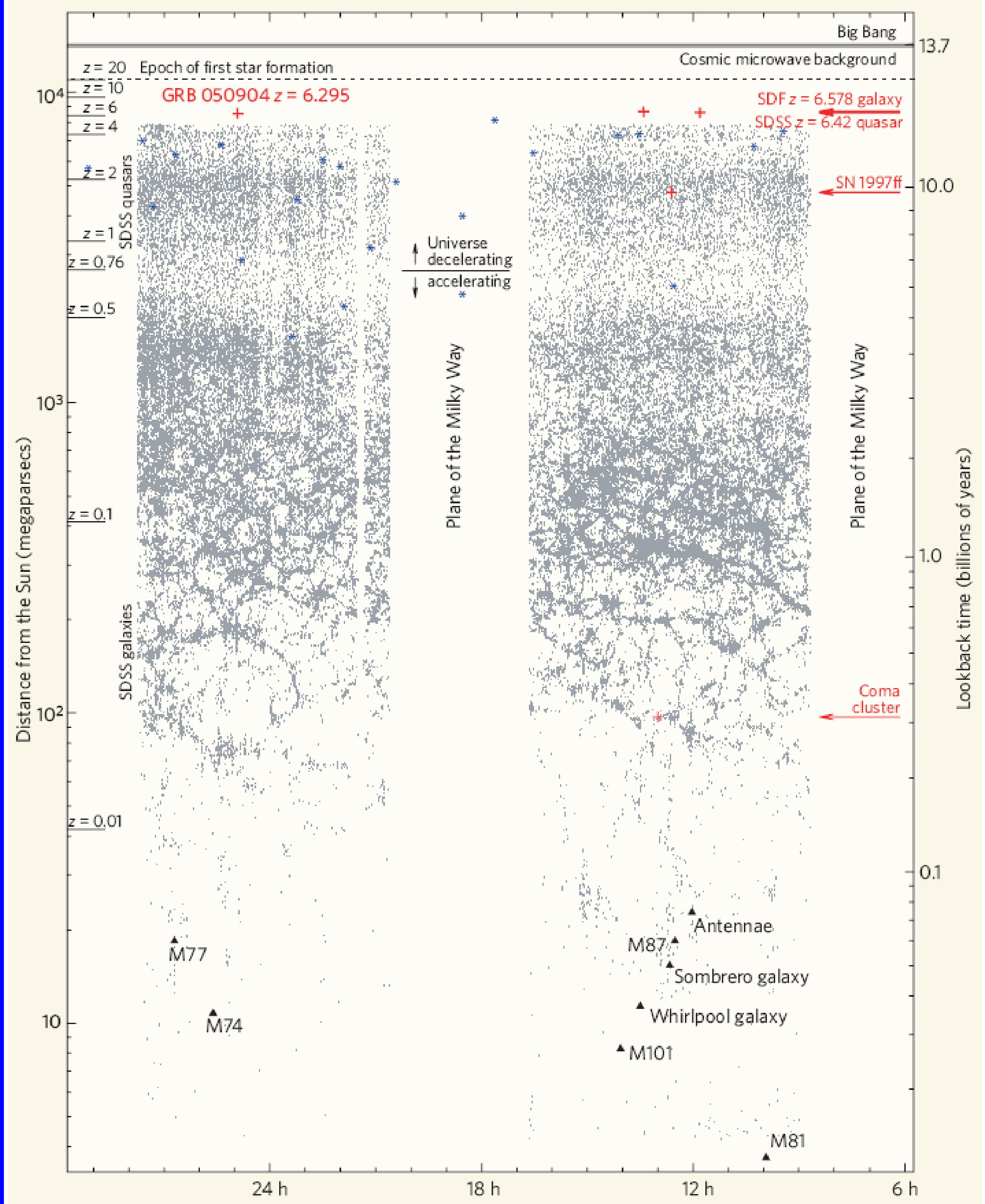

$$\lambda_{obs} = (1+z)\lambda_0$$

Z – космологическое красное смещение (redshift)

**Figure 1** The spectrum of the optical variable. **a**, Full spectrum; **b**, expansion of a limited region, with strong absorption lines and identifications indicated. The lines marked with an asterisk are identified with an absorption system at redshift $z = 0.835$, the others at $z = 0.767$. The spectrum has been smoothed with a three-pixel boxcar filter. A few additional weak features (not shown) have also been tentatively identified with the $z = 0.767$ system. $F_\nu$ is the flux density, and $\lambda$ is the wavelength in Å.

# Шкала расстояний

- 1AU = $1.5\times10^{13}$ см (150 млн. км)
- $D_{Galaxy} \cong 30$ кпк ($1$ пк $\cong 3$ св. года $\cong 3\times10^{18}$ см)
- Андромеда $\cong 780$ кпк



# The Shaw Prize in Astronomy (2011)

- Awarded in equal shares to **Dr Enrico Costa**, Director of Research at the Institute of Space Astrophysics and Cosmic Physics (Rome) of the National Institute of Astrophysics, Italy and **Dr Gerald J Fishman**, Chief Scientist at the NASA – Marshall Space Flight Center, USA for their leadership of space missions that enabled the demonstration of the cosmological origin of gamma ray bursts, the brightest sources known in the universe.

  Established under the auspices of Mr Run Run Shaw in November 2002, the Prize honours individuals, regardless of race, nationality, gender and religious belief, who have recently achieved significant breakthrough in academic and scientific research or applications and whose work has resulted in a positive and profound impact on mankind. The Shaw Prize consists of three annual prizes: Astronomy, Life Science and Medicine, and Mathematical Sciences, each bearing a monetary award of one million US dollars.

# Послесвечения

- У ~95% гамма-всплесков, зарегистрированных Swift-BAT регистрируется рентгеновское послесвечение; у ~60% - оптическое послесвечение

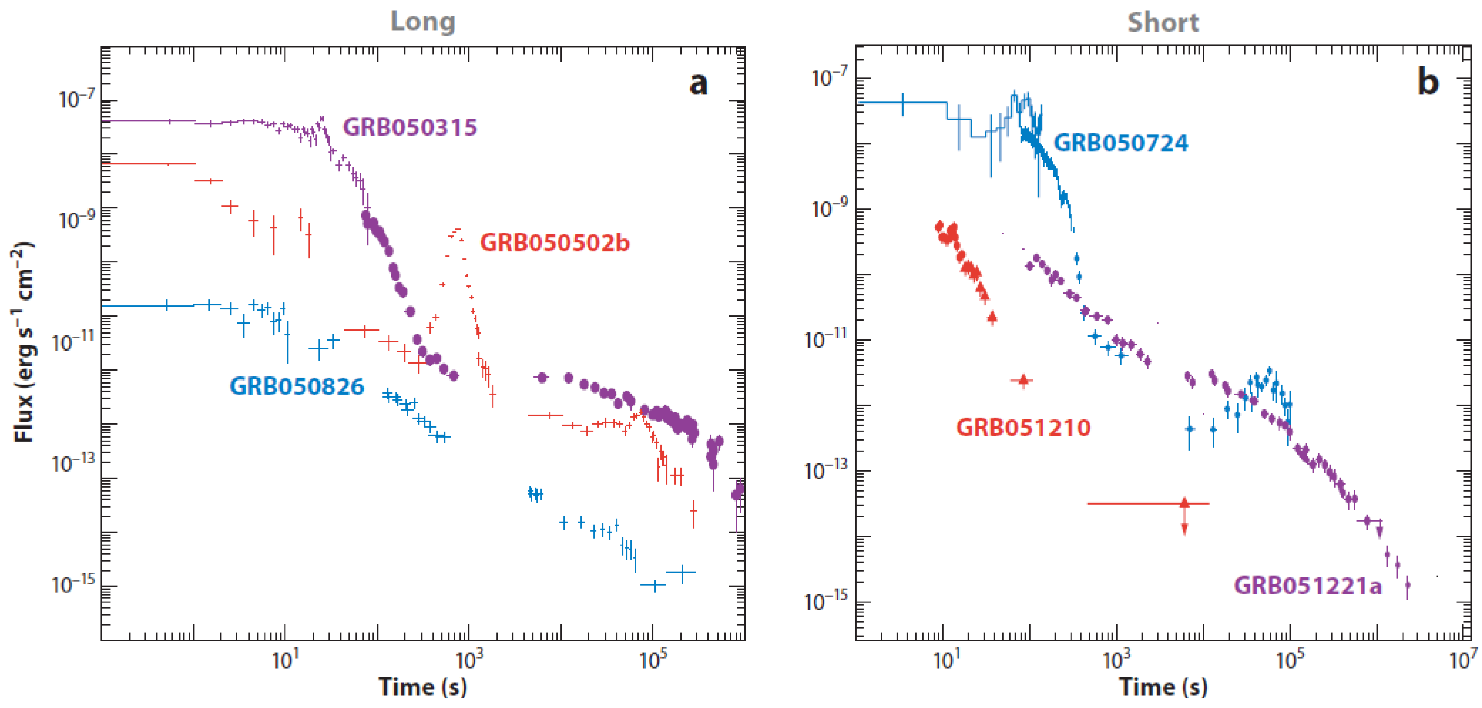



Figure 6

Representative examples of X-ray afterglows of (*a*) long and (*b*) short *Swift* events with steep-to-shallow transitions (GRB050315, 050724), large X-ray flares (GRB050502B, 050724), and rapidly declining (GRB051210) and gradually declining (GRB051221a, 050826; flux scale divided by 100 for clarity) afterglows.

- Быстрые и яркие рентгеновские вспышки (у ~50% послесвечений) – свидетельство продолжающейся активности центральной машины
- «Стандартный» трехстадийный вид рентгеновского послесвечения – различные фазы взаимодействия с окружающей средой Открытие рекордно далеких гамма-всплесков (z=6.29, 8.2, 9.4)
- Обрывы в кривой послесвечения (в рентгеновском и оптическом диапазонах) – возможность определения угла коллимации

# Энергетика гамма-всплесков

- $L_{max,\ iso}$ ~$10^{51}$ – $10^{54}$ эрг/сек
- $E_{rad,\ iso}$ $10^{48}$ – $10^{54}$ эрг (~$10^{-6}$ – 1 $M_{Sun}c^2$!!!)

$L_{sun}$ ~$4x10^{33}$ эрг/сек

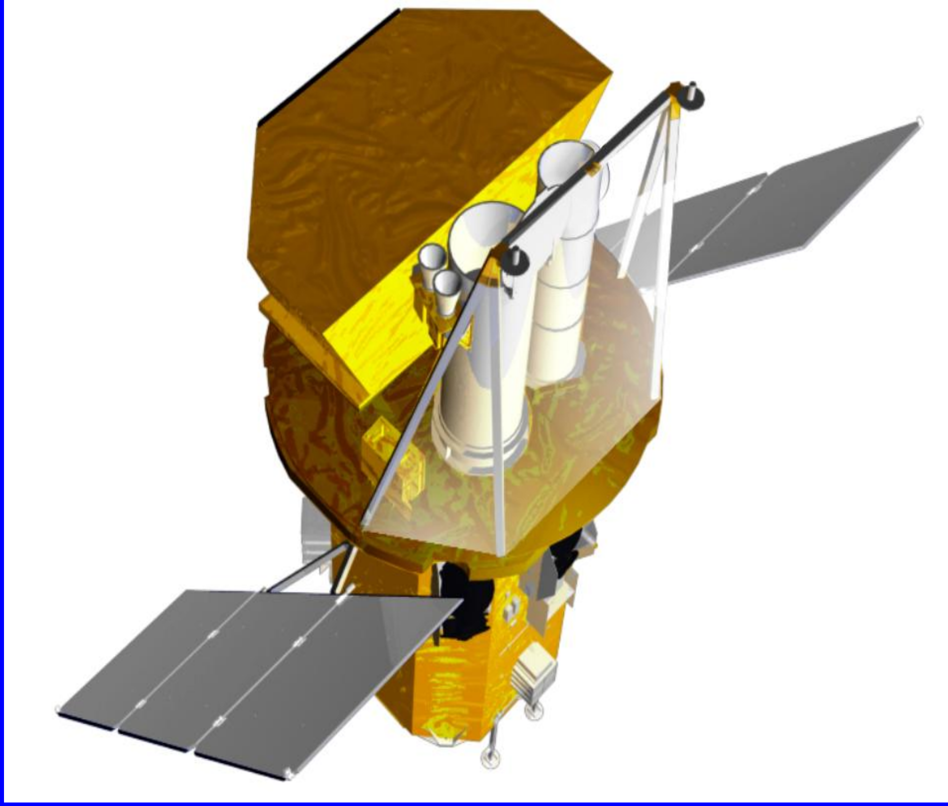
$L_{MW}$ ~$2x10^{44}$ эрг/сек

$L_{SNIa,\ max}$ ~$10^{43}$ эрг/сек

$L_{QSO}$ ~$10^{45}$ эрг/сек

# Космическая обсерватория Swift

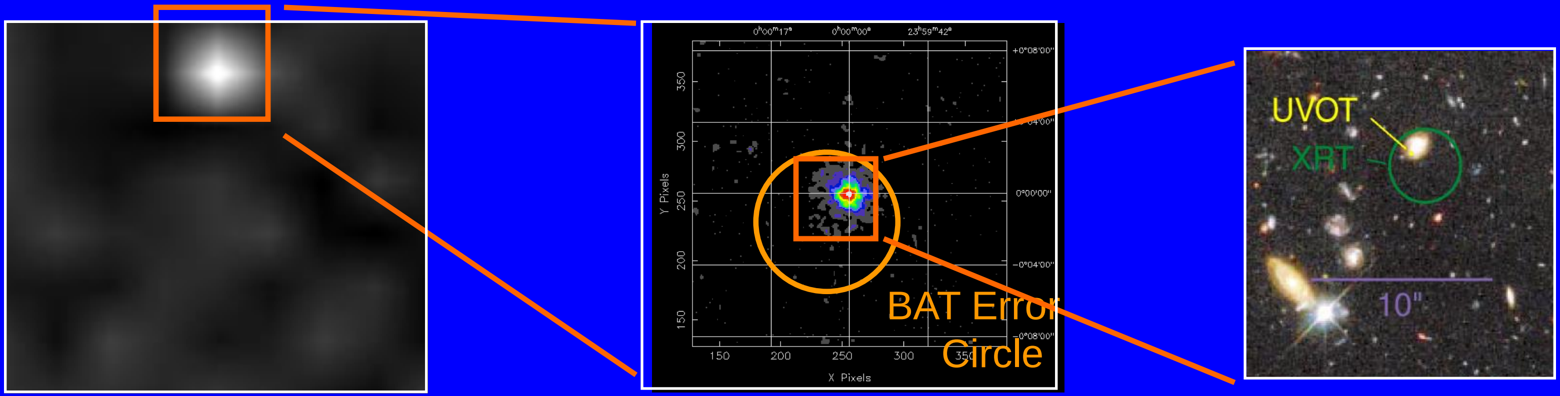
- Запущен на экваториальную орбиту 20 декабря 2004 г.
- Burst Alert Telescope (BAT) 15-150 keV
- X-ray Telescope (XRT) 0.2-10 keV
- Ultraviolet/Optical Telescope (UVOT) 170-600 нм



# Стратегия наблюдений

- BAT triggers on GRB, calculates position to < 4 arcmin
- Spacecraft autonomously slews to GRB position in 20-70 s
- XRT determines position to < 5 arcseconds
- UVOT images field, transmits finding chart to ground

**BAT Burst Image** | **XRT Image** | **UVOT Image**

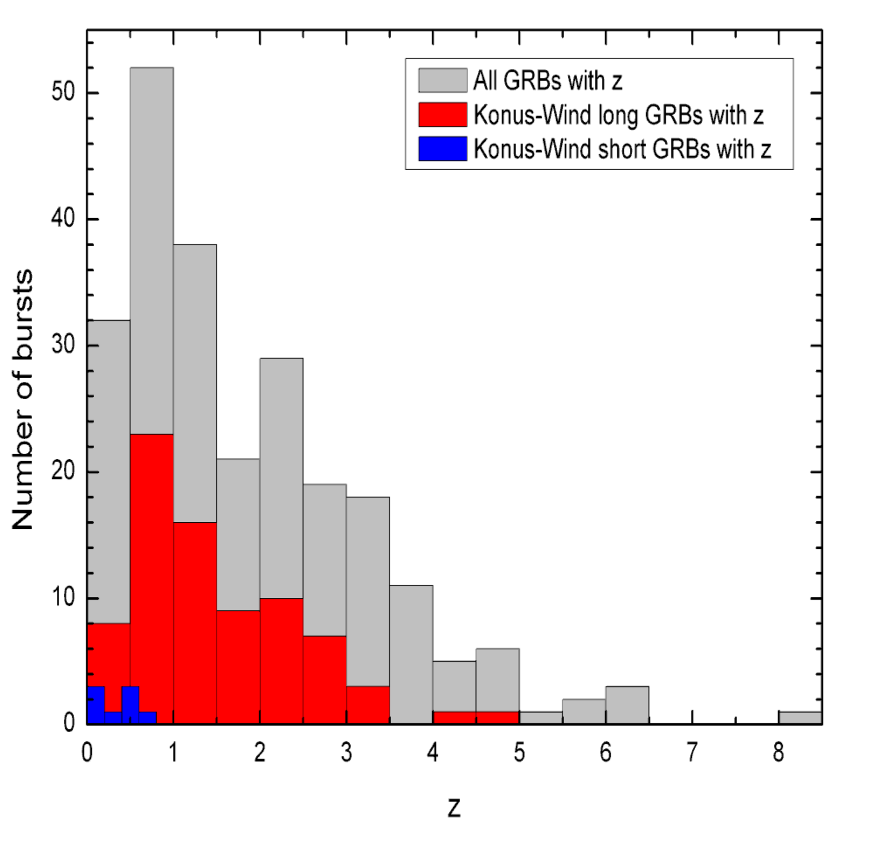


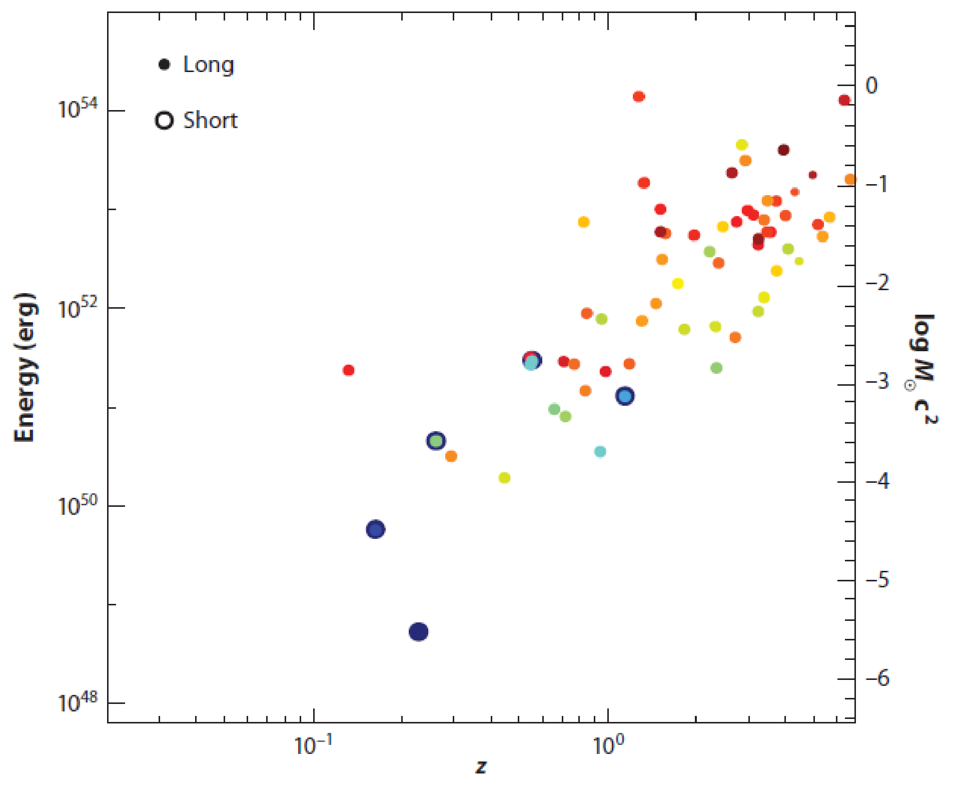

**T<10 sec** $\theta < 4'$

**T<100 sec** $\theta < 5''$

**T<300 sec**

# Гамма-всплески как инструмент для исследования Вселенной




Распределение по z 238 GRBs с известным красным смещением и 88 всплесков Konus-Wind (78 длинных и 10 коротких).

Изотропное энерговыделение гамма-всплесков

Mean redshift pre-Swift ~1.2

Mean redshift Swift ~2.5

# Гамма-всплески на больших красных смещениях

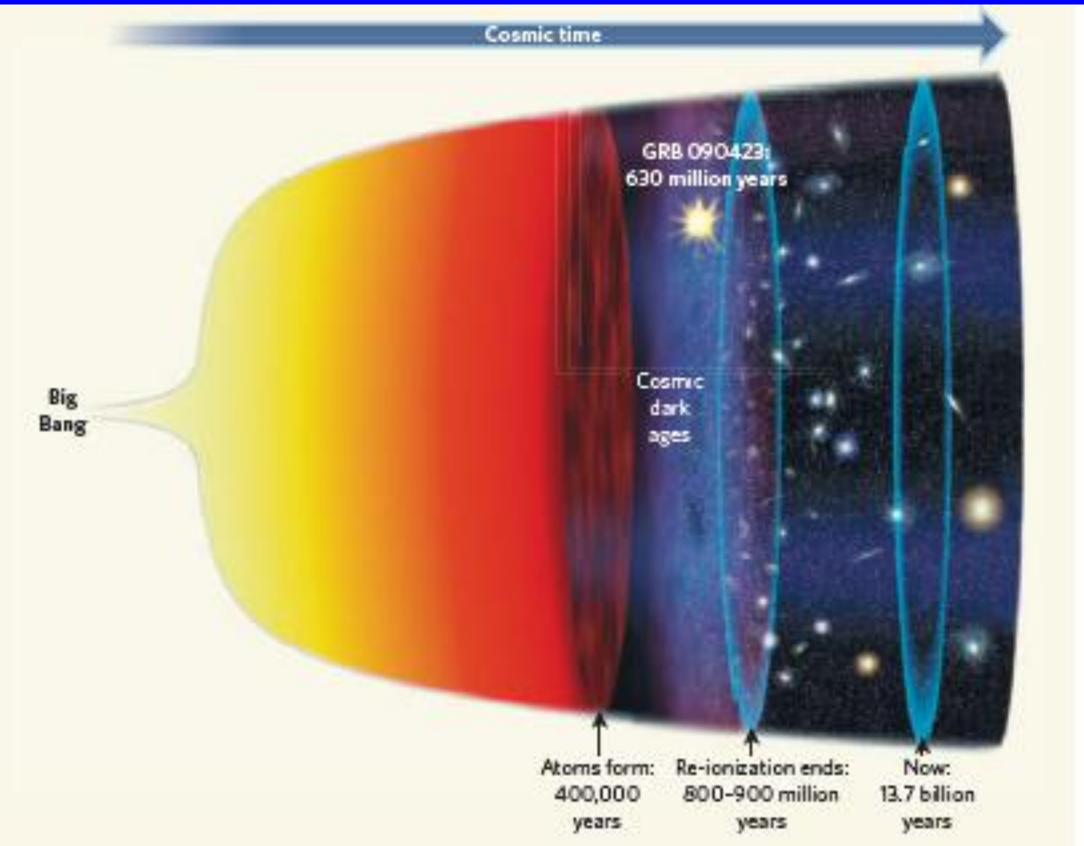



**Figure 2 | The cosmic dark ages and GRB 090423.** After the Big Bang, the Universe cools rapidly while expanding. About 400,000 years after this event, free electrons and protons combine to form neutral atoms, leaving a bath of background radiation that currently shines in the microwave part of the electromagnetic spectrum. Thereafter, the Universe remains neutral, until the first stars and galaxies light up at a later epoch. Photons emitted by these objects knock electrons out of atoms and 're-ionize' the Universe. Studies of the most distant galaxies and quasars suggest that the re-ionization process was completed around 800 million to 900 million years after the Big Bang, but no information is available about the cosmic 'dark ages'. Observations of γ-ray bursts such as GRB 090423 (refs 1, 2), which occurred about 630 million years after the Big Bang, offer a glimpse of the cosmic dark ages. (Adapted from ref. 15.)

GRB 090423 z=8.2 (~630 млн. лет после Большого Взрыва; современный возраст Вселенной ~13.7 млрд. лет)

GRB 090429B z ~9.4!

Эпоха реионизации: z ~10 (начало), z ~6 (конец)

- Предыдущий рекордсмен – галактика на z=6.96 (в 2010 была открыта галактика на z=8.55)

- Что нам дают гамма-всплески на больших z? (могут наблюдаться до z~20!)
  -Изучение первичных галактик
  -История звездообрзования
  -Элементный состав среды

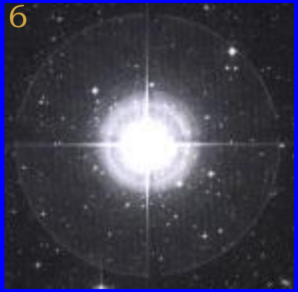
# GRBs: short versus long

| | *Short* | *Long* |
|---|---|---|
| Host galaxy | Low/high SFR | High SFR, associated with the brightest regions of galaxies |
| SN association | No | Yes (Ib/c) |
| z (median) | ~0.3 | ~1.8 |
| X-ray afterglow | Not always observed, ~10 time weaker, X-ray flares | Always observed, X-ray flares |
| Optical afterglow | Often not observed; weak when observed | Observed and bright for most bursts |
| Progenitor | NS-NS/NS-BH/? | Core collapse of massive star |
| | | |

# What causes Gamma Ray Bursts?

$M \gtrsim 25\ M_{Sun}$

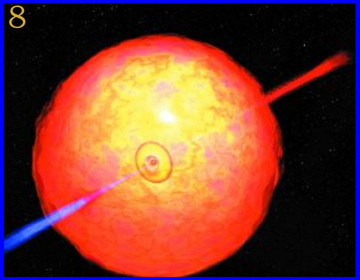
Лишь ~$10^{-3}$ дают гамма-всплески



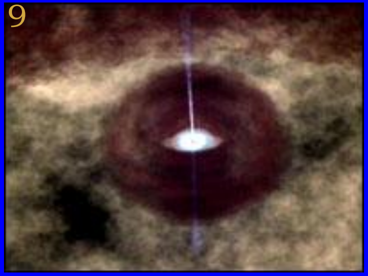

Typical massive star

(“Wolf-Rayet” Star)


Hypernova

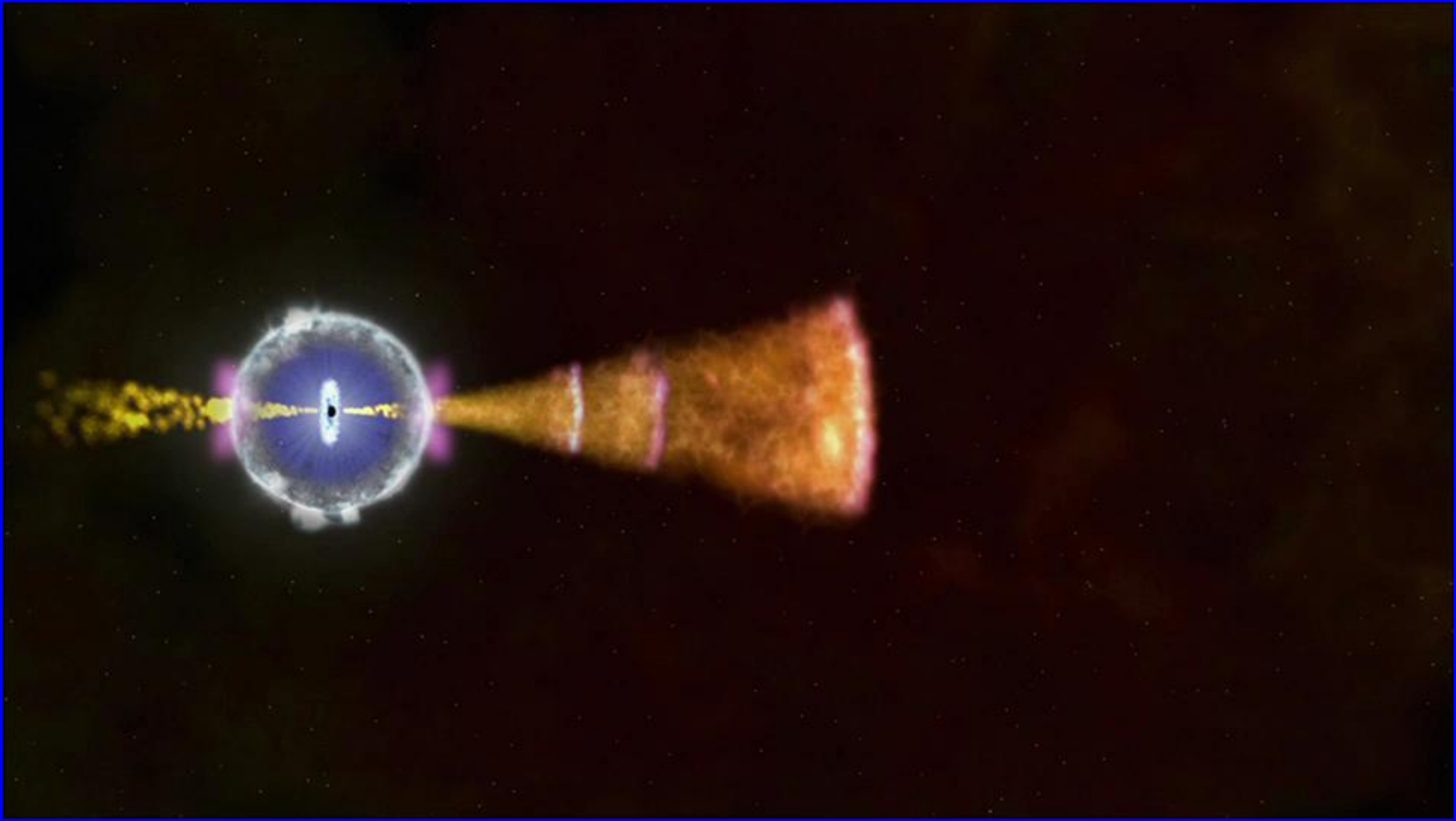


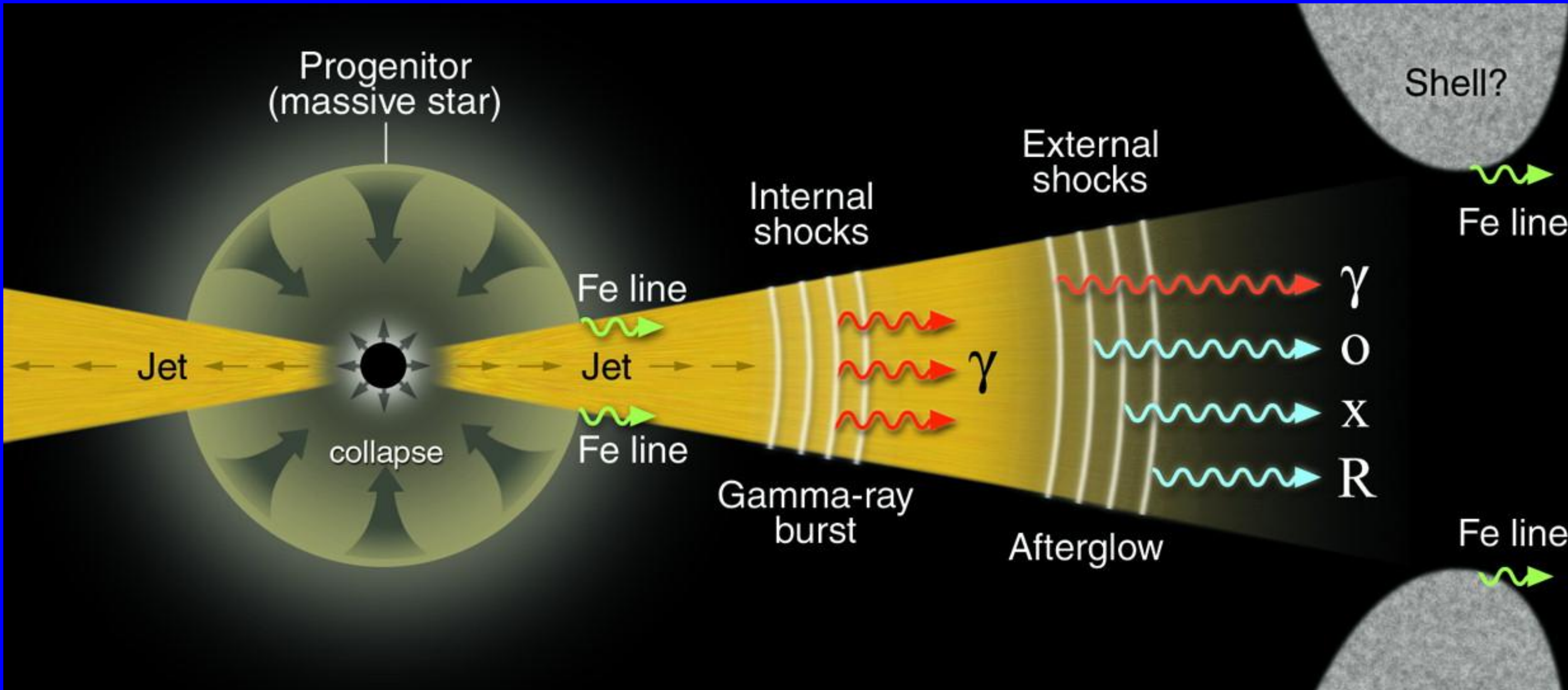

Gamma Ray Burst




Black Hole

(Chandra Image)

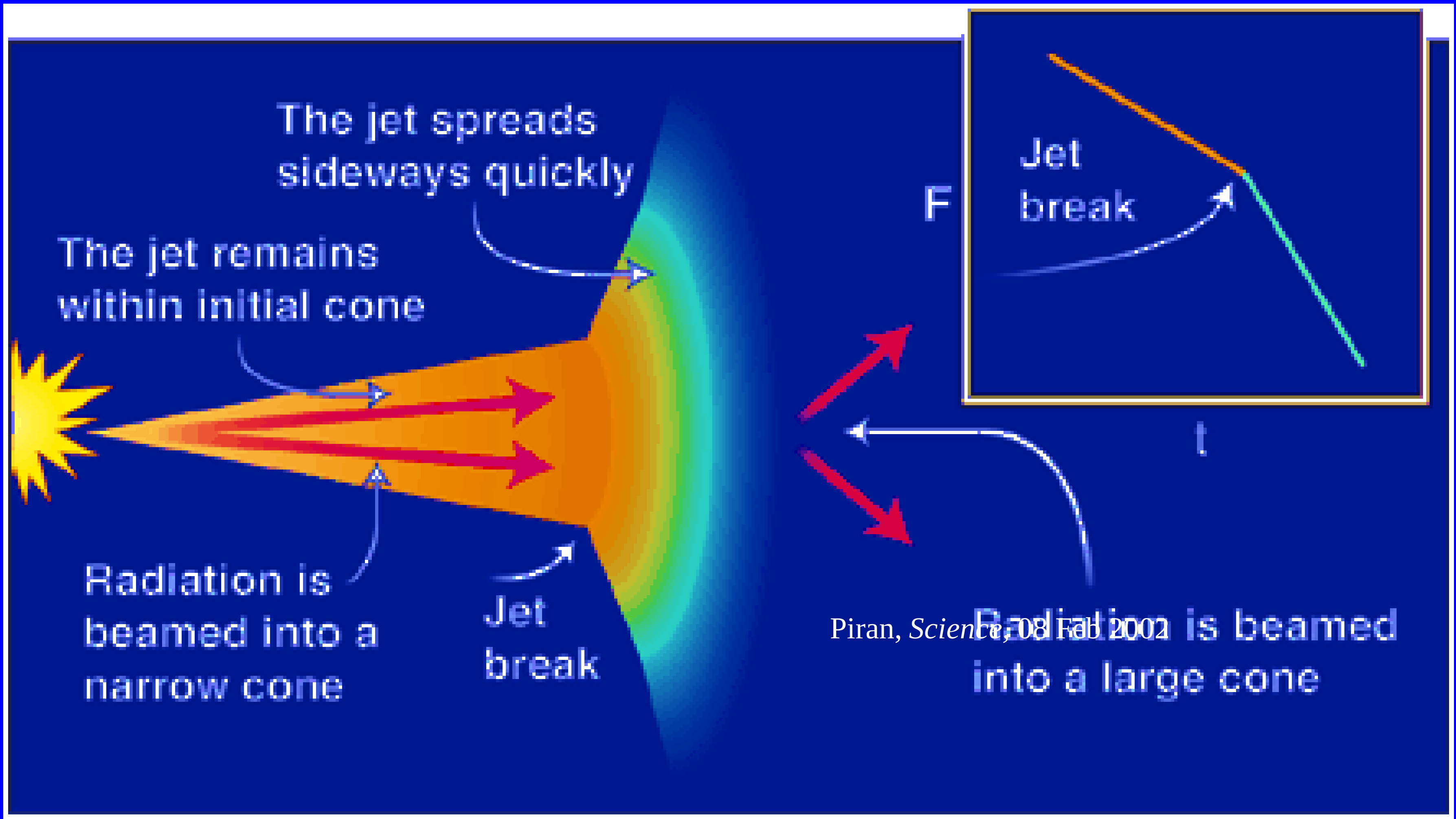





$\Gamma \approx 100$
$r \approx 10^{15}$ cm

$\Gamma \approx 10 \rightarrow 1$
$r \approx 10^{17}$ cm

# Jet Signatures: Optical/X-ray




Piran, *Science*, 08 Feb 2002

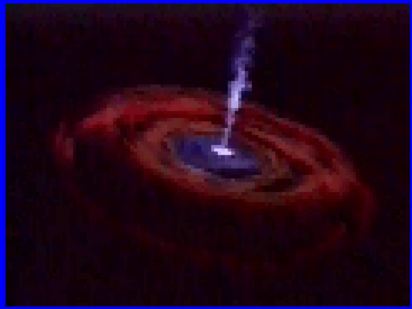
## The Resolution of the Energy Crisis

- $E_{tot}$ – полная выделившаяся энергия
- $E_{\gamma\ iso}$ - энергия в гамма-диапазоне (изотропный эквивалент)

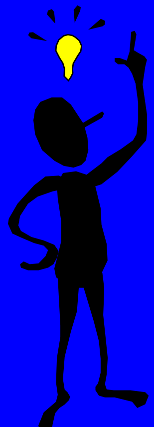
$$E_{tot} = \varepsilon_{\gamma}^{-1} E_{\gamma\, iso}$$

# Beaming:

- $E_{\gamma}$ - Actual γ–ray energy



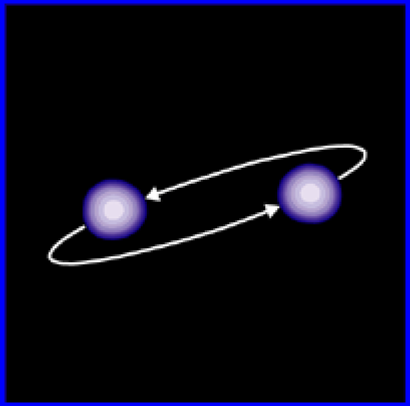
$$E_{tot} = \varepsilon_{\gamma}^{-1} E_{\gamma} = \varepsilon_{\gamma}^{-1} \frac{\theta^2}{2} E_{\gamma\, iso}$$

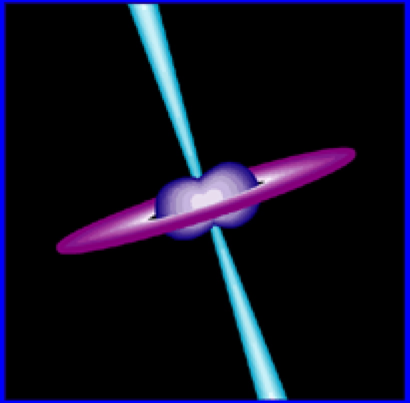


**θ ~ 1 градуса!** θ $^2/2 \sim 10^{-4}$

# Короткие гамма-всплески: общая картина

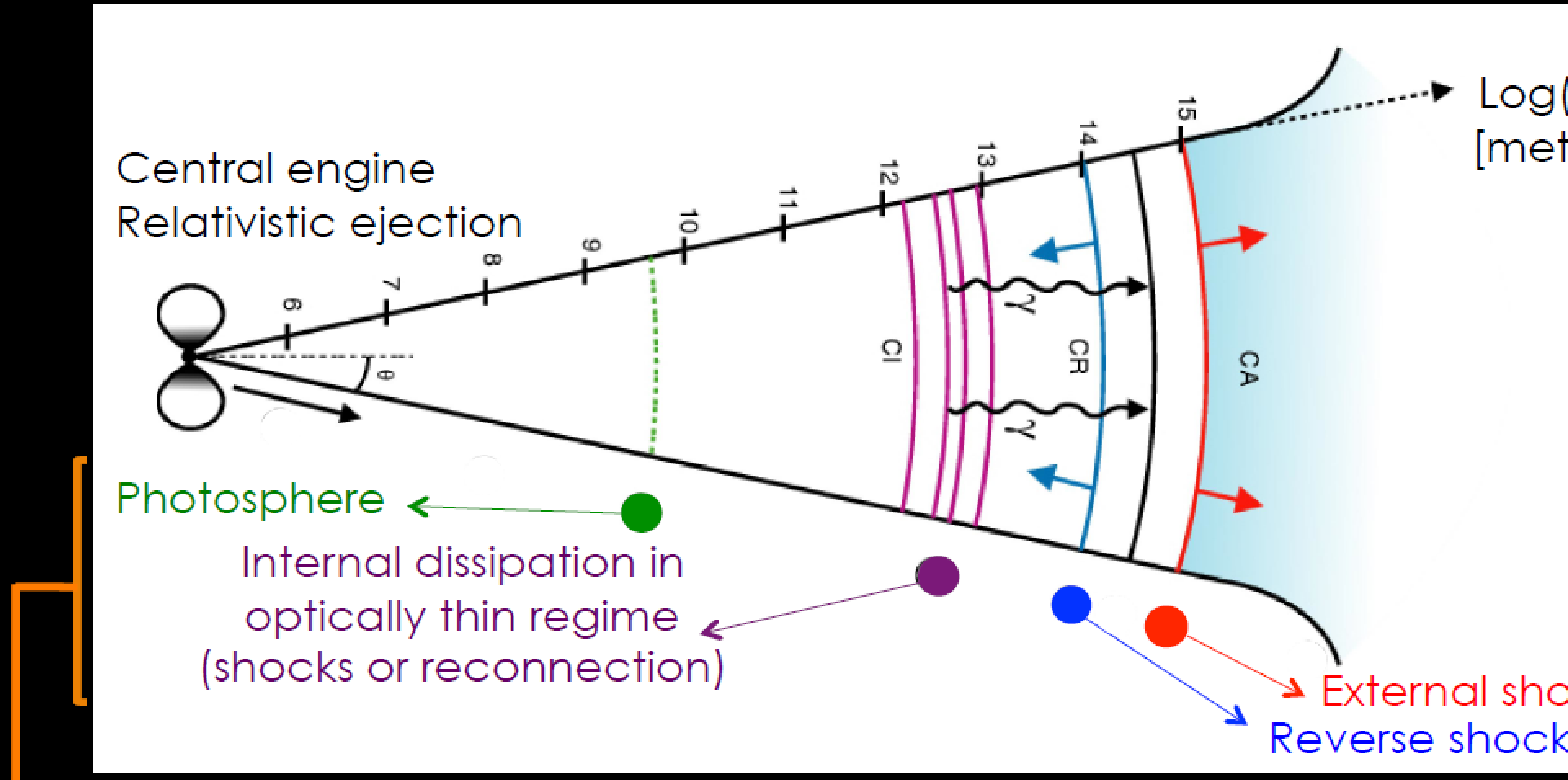
- Closely orbiting neutron stars (d ~< solar radius) lose energy from gravitational radiation.
- Systems known to exist (binary pulsars)
- Must eventually merge.
- Post-merger object quickly collapses to black hole
- Very high angular momentum of system : accretion disk forms; falls onto black hole.
- Gravitational binding energy:
- $GM^2/R \sim 10^{53}$ erg
- → Mpc/Gpc distances
- Timescale for collapse: <~1 second





# Слияние нейтронных звезд

# Possible emission sites in GRBs




Contribution of each region ?
Dissipation mechanism ?
Radiative process ?

# Internal dissipation (1) photosphere

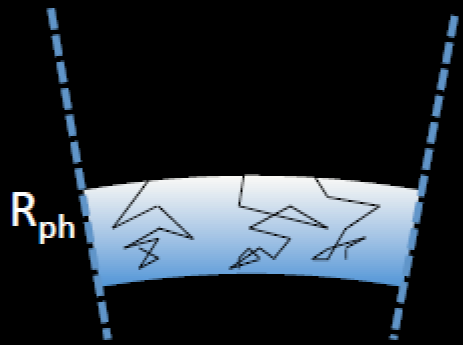
- PHOTOSPHERE:

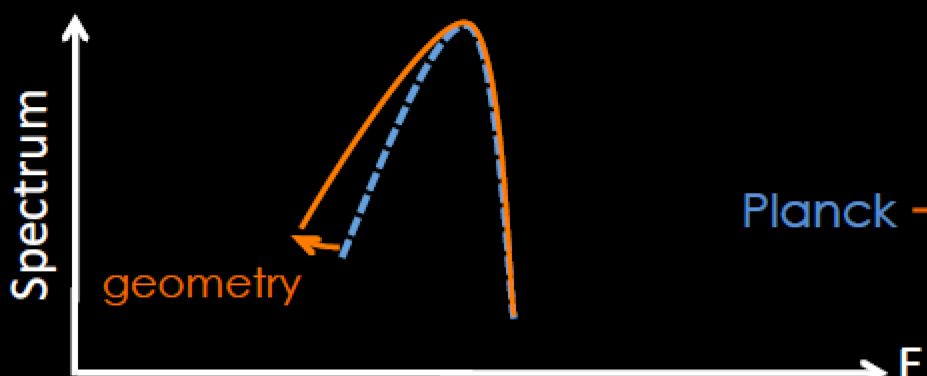
-The relativistic outflow becomes transparent

-Internal energy can be released as radiation

-Almost no theoretical uncertainties
(still: lateral geometry of the jet; initial magnetizatio

-Spectrum is quasi-thermal: exp. cutoff at high-er
PL at low-energy with

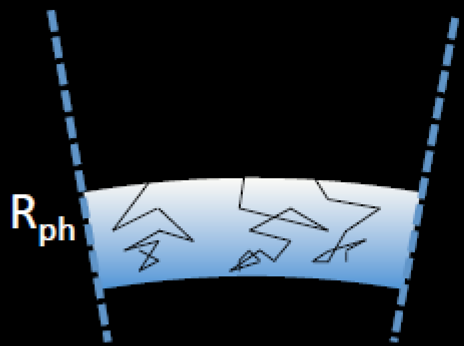



Planck → Photosphere

# Internal dissipation (1) photosphere

- PHOTOSPHERE:




-The relativistic outflow becomes transparent

-Internal energy can be released as radiation

-Almost no theoretical uncertainties

-Spectrum is quasi-thermal


- DISSIPATIVE PHOTOSPHERE:

-Sub-photospheric dissipation: non-thermal electro

-Large uncertainties: details of the dissipation proc
neutron heating ? internal shocks ? reconnect

-Non thermal spectrum: Comptonization & Synchro

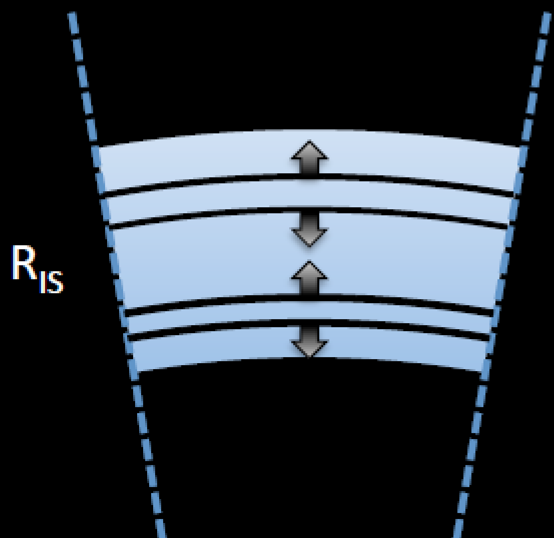
# Internal dissipation (2) optically thin

Non-thermal emission can be produced above the photosphere if ther
dissipation processes producing non-thermal electrons.

SSC is ruled out by *Fermi* observations – Synchrotron ?

Bosnjak & Daigne 20
Piran et al. 2009

- INTERNAL SHOCKS:




-Assumes: Variability of the central engine
+ low magnetization at large dista

-Large uncertainties:
microphysics (B amplification, e acceleration)

-Non-thermal spectrum, several components (

Rees & Meszaros 1994 ;
Kobayashi et al. 1997 ; Daigne & Mochkovitch 1998

- RECONNECTION:

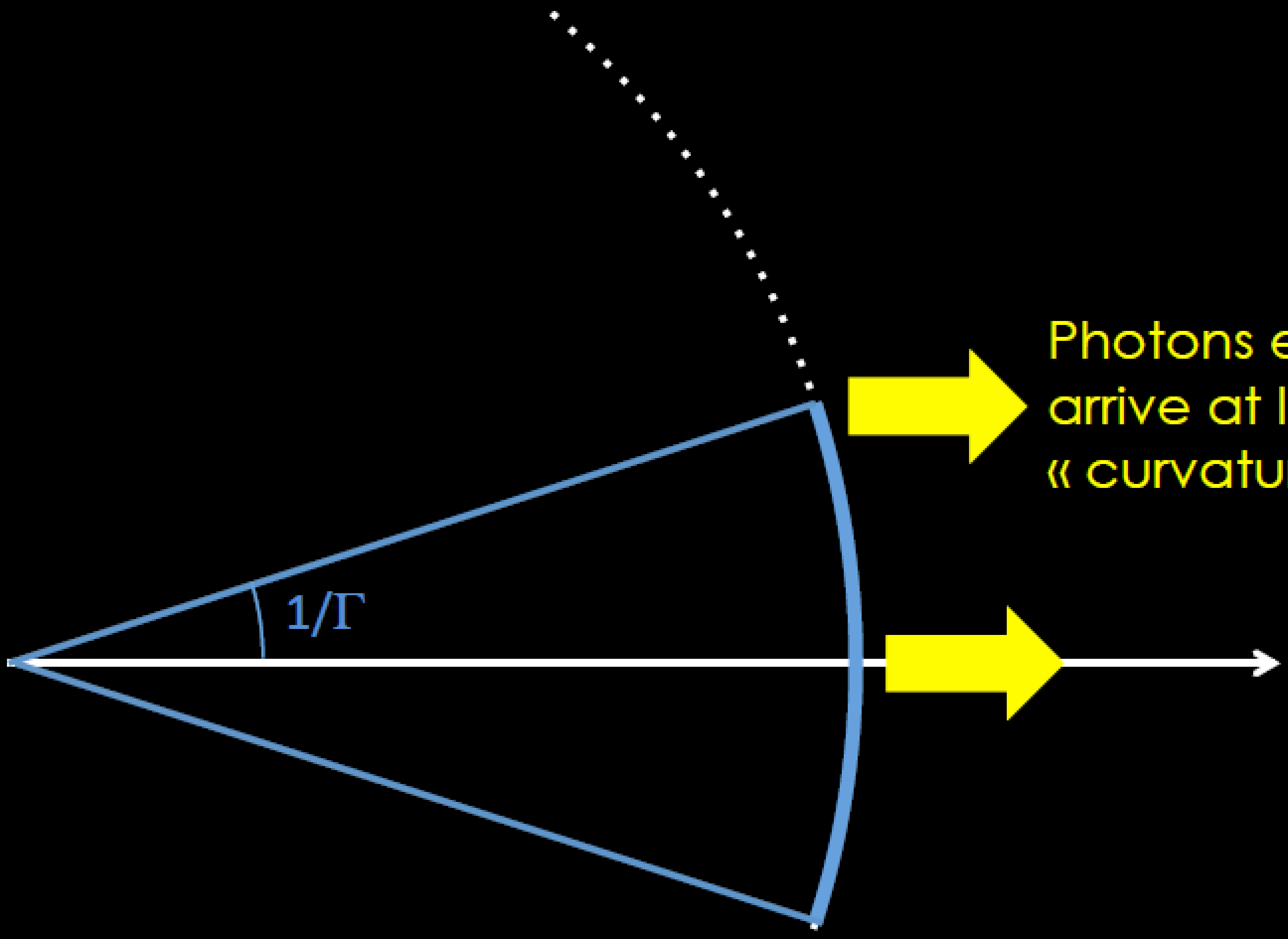
-Assumes: Variability + large mag. at large d

-Large uncertainties:
radius ? microphysics ?

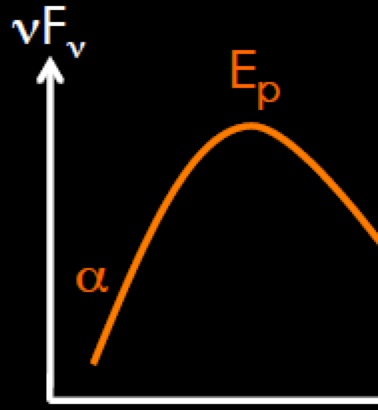
-Non-thermal spectrum

# Light curves

All possible sites for the prompt emission can reproduce the observed v
light curves, but with important differences due to very different radii.



# Spectrum (1) models




General shape ("Band") / Low-energy photon index $\alpha$ (obs: $\alpha \approx -1$)

- PHOTOSPHERE: ? — $\alpha$ too large except for peculiar lateral

Time-integ.

- DISSIPATIVE PHOTOSPH.: ✔? — -$\alpha$ correct (depends on magnetizatior

- INTERNAL SHOCKS: ? — -Synchrotron only: $\alpha$ = -3/2 (fast coolin

(a) Daigne et al. 11 ; Beniamini & Piran 13
(b) Derishev et al. 01 ; Bosnjak et al. 09 ; Wang et al. 09 ; Daigne et al. 11
(c) Derishev 07 ; Lemoine 13 ; Uhm & Zhang 14 ; Zhao et al. 14

-Possible mechanisms to increase $\alpha$
(a) Marginally fast cooling ;
(b) IC in KN regime ; (c) B decay

- RECONNECTION: ? — -$\alpha$ correct ? (slow heating in turbulent

Uhm & Zhang 2014

# The end of the prompt emission: X-ray early steep decay

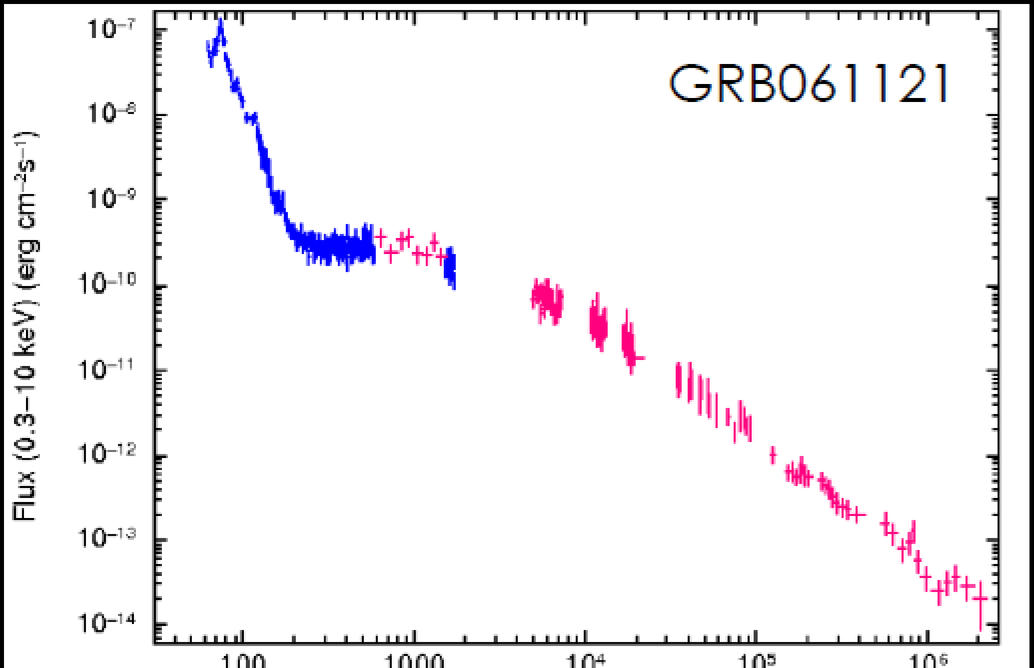
- A natural explanation: high-latitude emission from the prompt (fits well

See Willingale's talk

-(Dissipative) photosphere: ✗ (radius is too small)

-Internal shocks: ✔ (final radius of the order of $\Gamma^2$ c $t_{burst}$)

-Reconnection: ✔? (final radius ?)

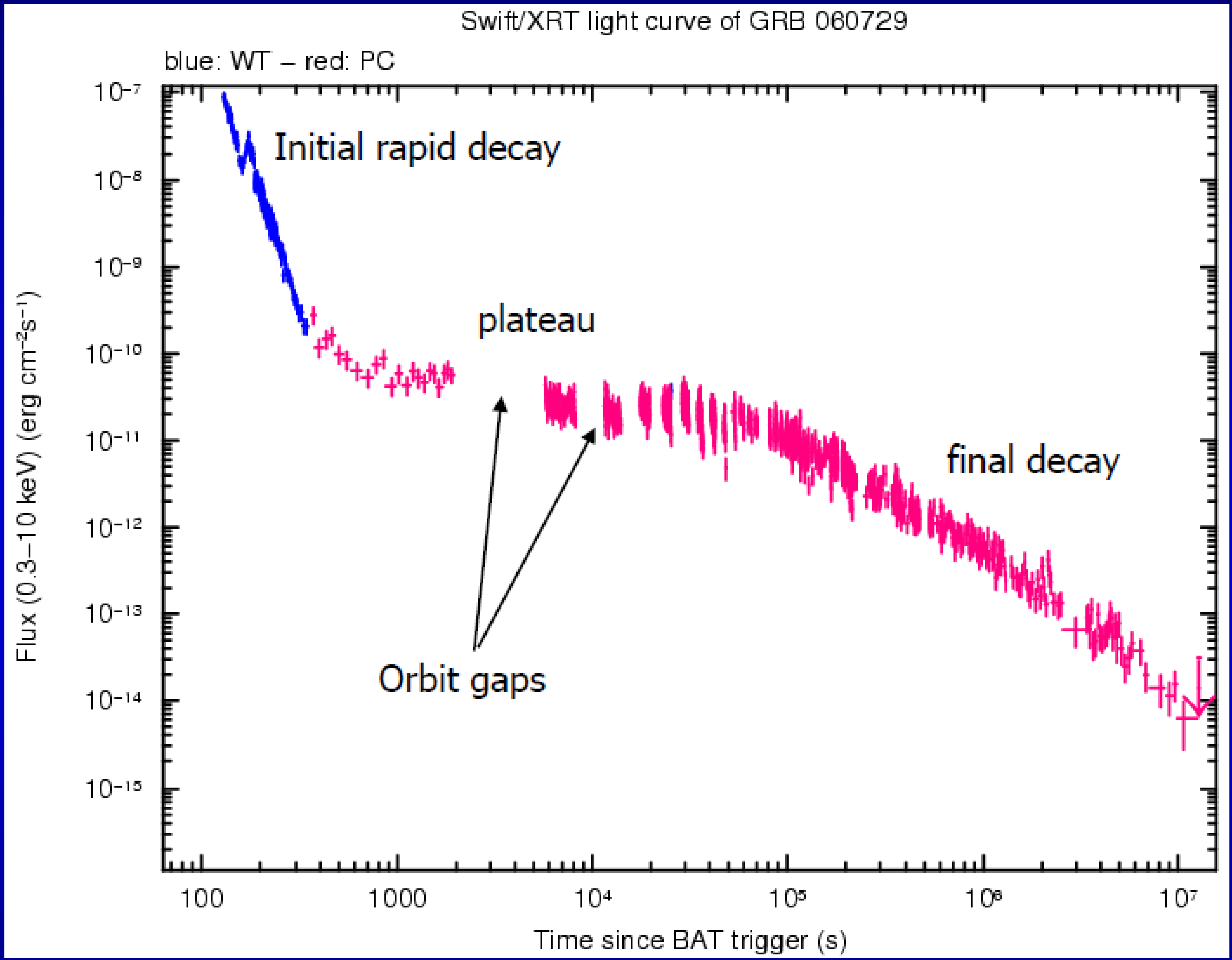


# Summary

Understanding the physical origin of the GRB emission is difficult, especial
the prompt emission.

- Dissipative photospheres are promising, however:
  - strong constraints on the unknown dissipation process
  - "complicated" model: different mechanisms for different compone in the prompt (soft $\gamma$-rays, optical, GeV)
- Reconnection above the photosphere looks promising, however:
  - uncertainties both on the dynamics and the microphysics
  - difficult to conclude without any predictions for the spectrum
  - potential problem with the spectral shape (broadening by multi-em
- Internal shocks can produce emission from optical to GeV. The model explored in details (spectral evolution, etc.). Results are promising, howev
  - large uncertainties on the microphysics
  - is there a problem with $\alpha$ ? With the efficiency ?
  - is there a problem with the general shape of the spectrum ? (too br

# Canonical X-ray Afterglow

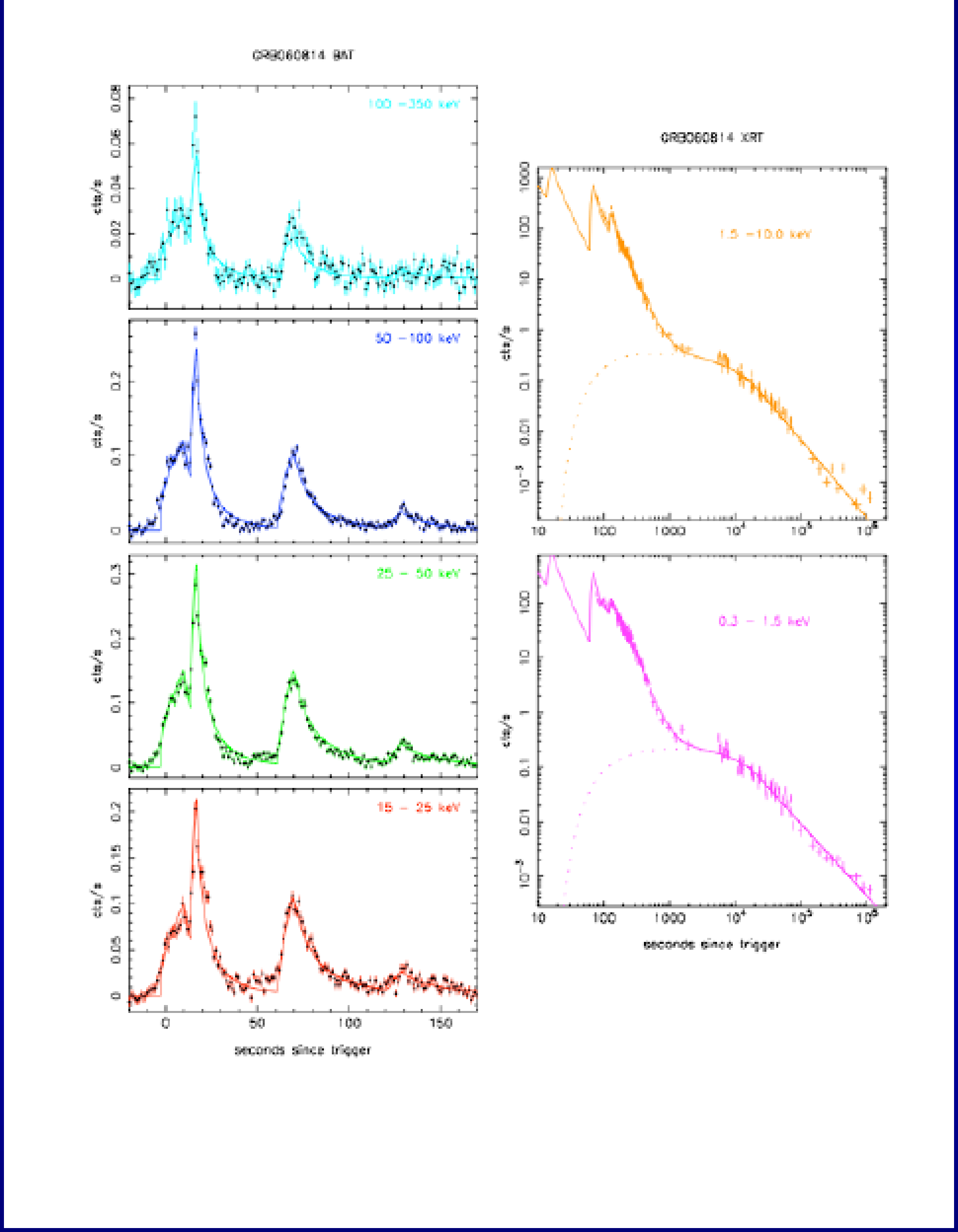



not expect
to have th
form
pre-Swift

We can track the
afterglow to very
flux levels

(Nousek et al. 2006, Evans et al. 2007)

# Prompt through afterglow

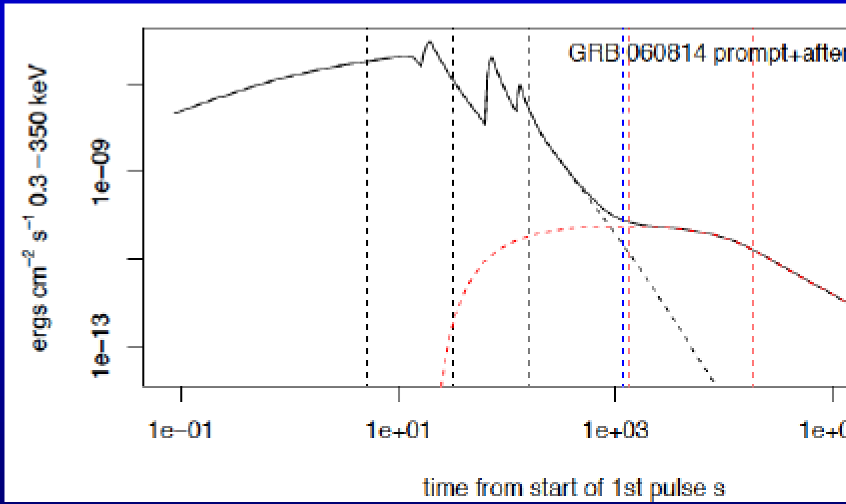



To date fitted 128 GRBs with prompt + afterglow model

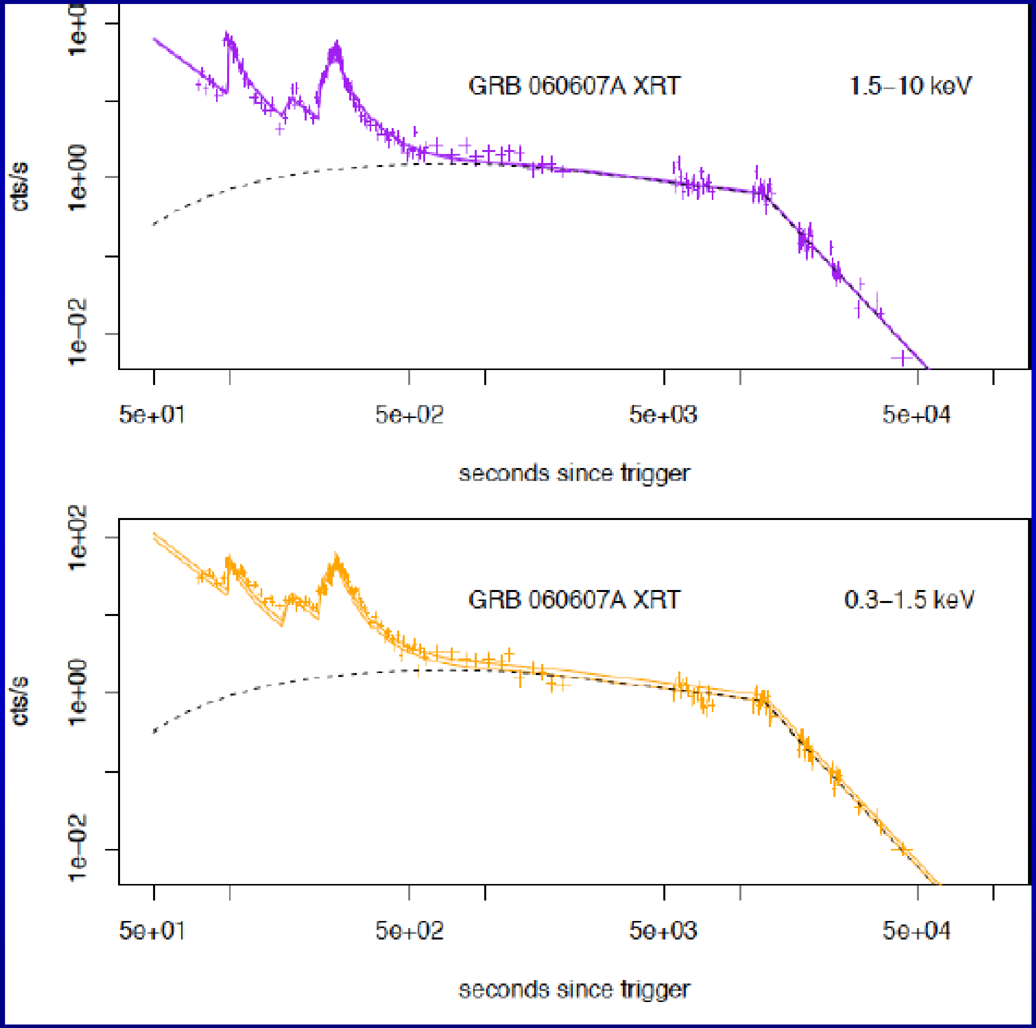
Initial afterglow decay always fit by latitude emission from pulses

Plateau and final decay a separate component – external shock

Energy injection continues until end plateau



# X-ray flares

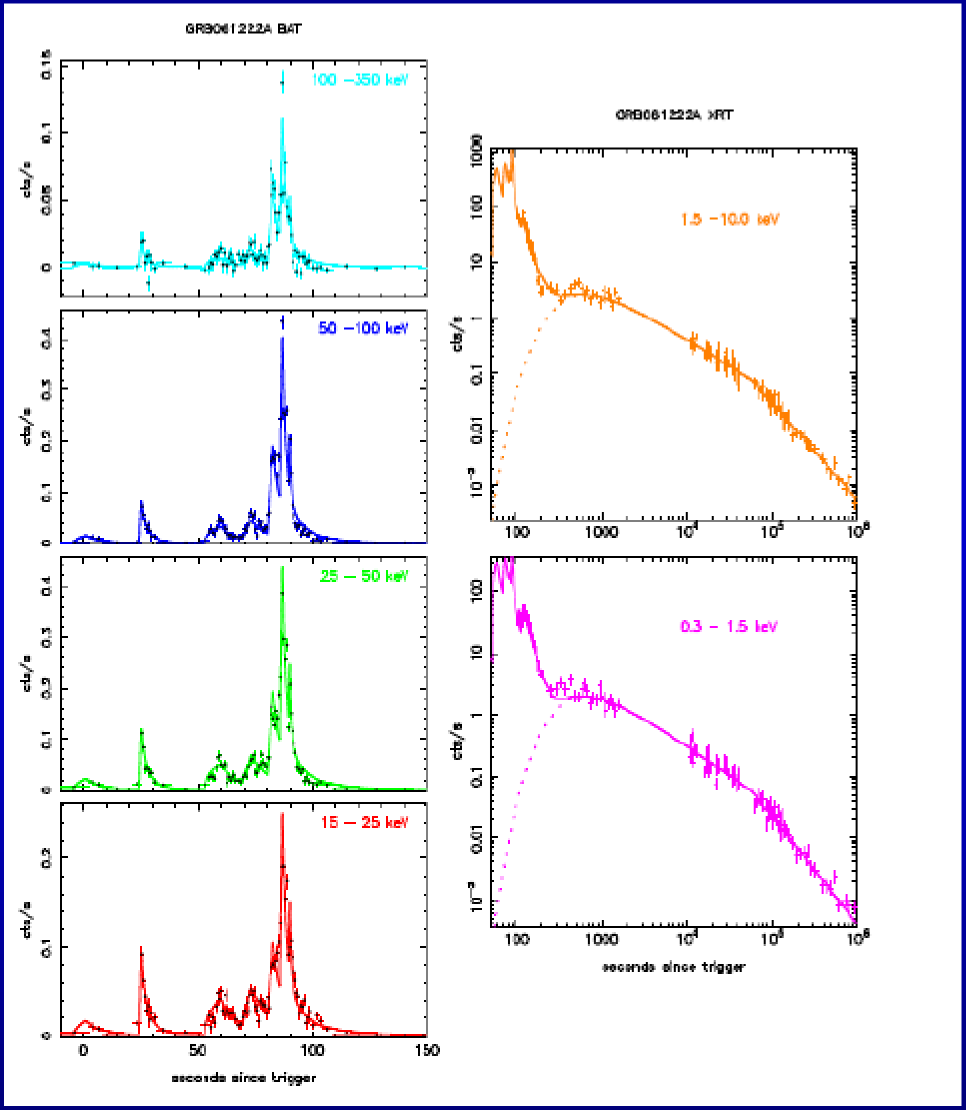



Continued prompt activity not seen by BAT

Chincarini et al. (2007)

Empirical afterglow model
Willingale et al. (2007)

# Late breaks



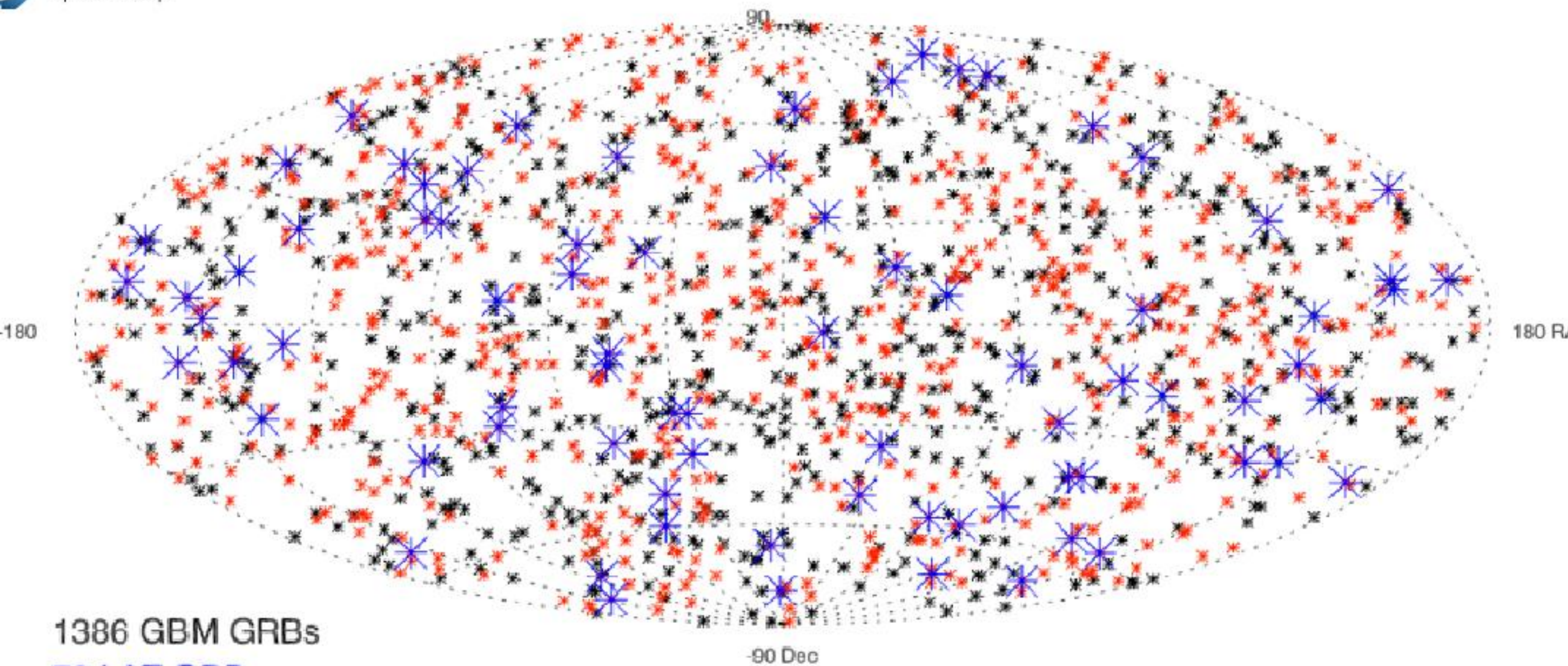

Sometimes a late break is seen

achromatic

Jet breaks?

# Fermi observations of GRBs

## *Fermi* GRBs as of 140620




1386 GBM GRBs

79 LAT GRBs

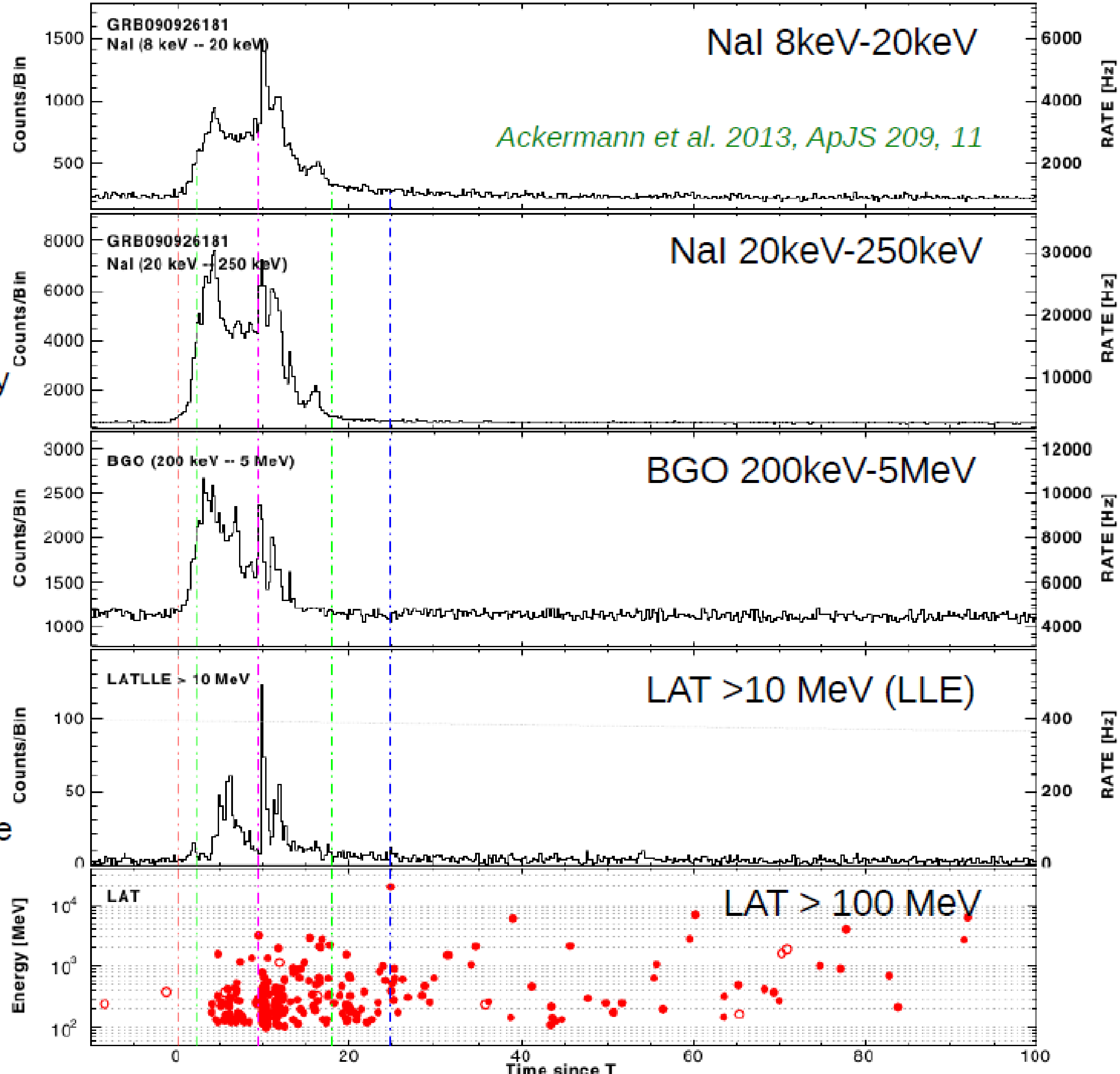
In Field-of-view of LAT (716)

Out of Field-of-view of LAT (670)

- **The GBM detects ~240 GRBs / year, ~45 of them are short GRBs**
- **The LAT sees ~10% of GBM GRBs in its field-of-view above 100 MeV**

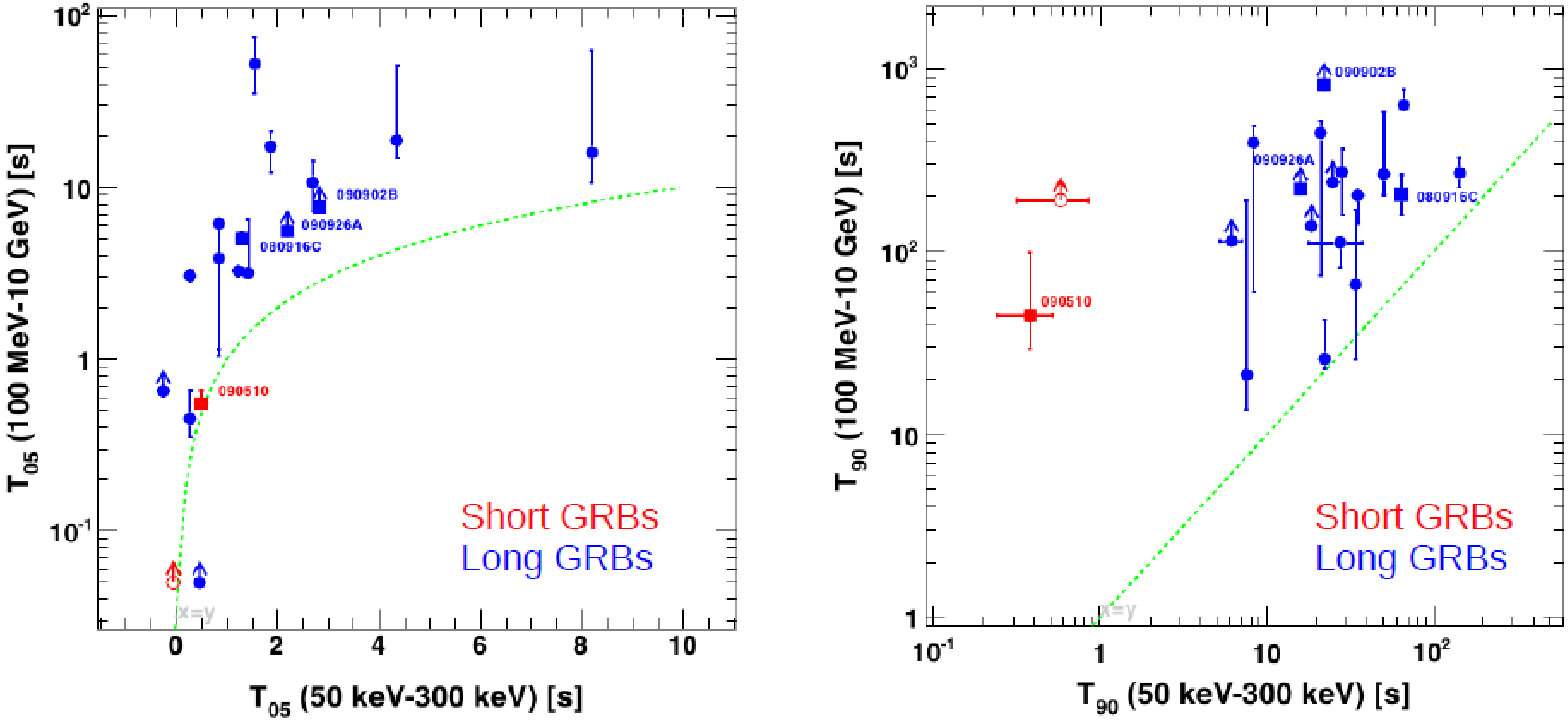
# GRB 090926A multi-detector light curve

- **Correlated variability in various bands with a sharp spike at $T_0$+10 s**
  - All energy ranges synchronized (<50 ms)
  - Low and high energies are co-located or even causally correlated
- **LAT >100 MeV emission is delayed (~4 s)**
  - Delay > spike widths
- **LAT >100 MeV emission is temporally extended**
  - Well after the prompt phase
  - 19.6 GeV photon detected at $T_0$+24.8 s



# Broad-band temporal properties

*Ackermann et al. 2013, ApJS 209, 11*

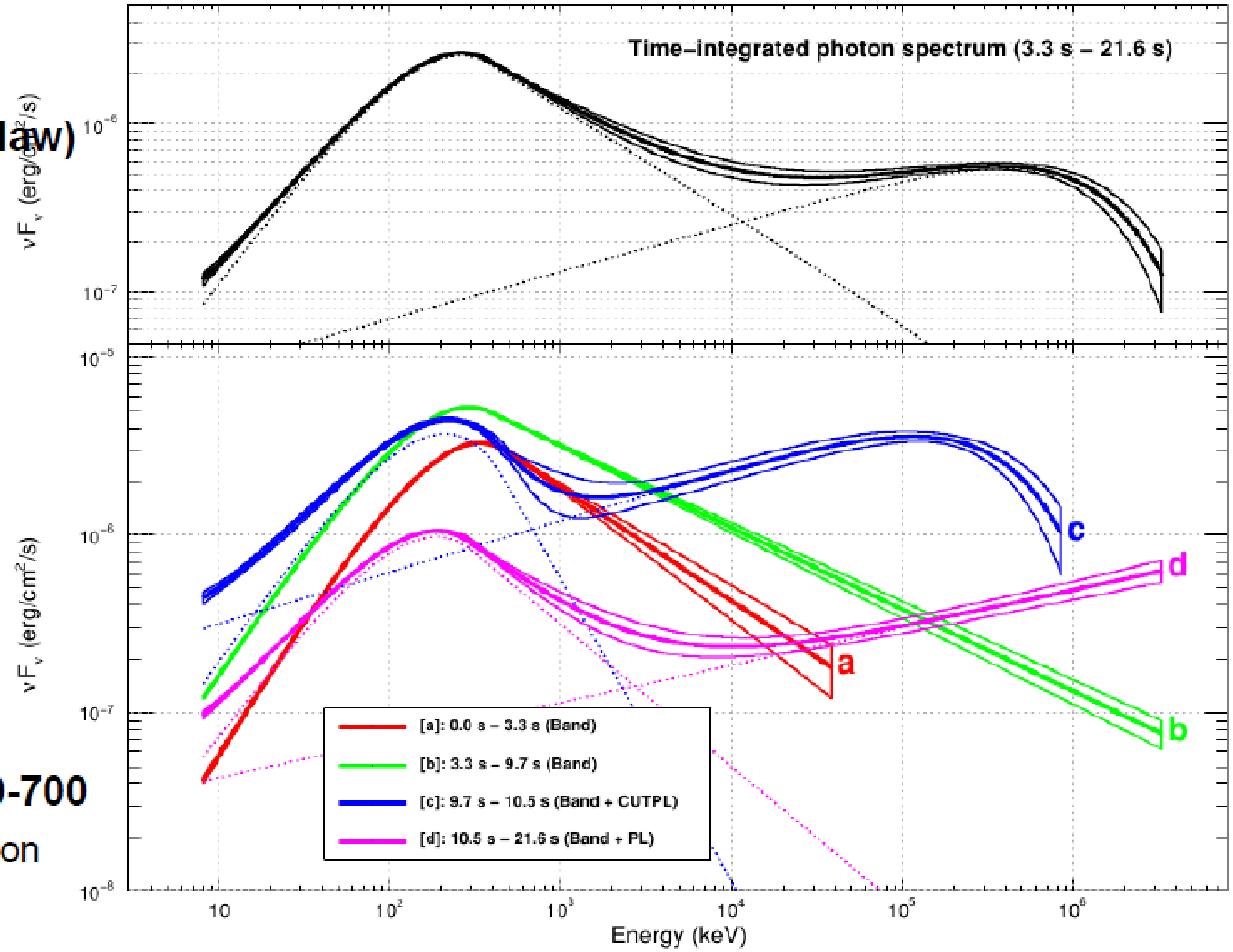



- **GeV emission onset is delayed and temporally extended**
  - Most (but not all) of this emission likely comes from early afterglow: external shock → synchrotron emission from accelerated electrons
  - Confirmed by individual broad-band (visible to GeV domains) analyses (GRBs 090510, 110731A)
  - Late internal shocks (inverse Compton scattering) or hadronic emission (proton synchrotron and/or photopion-induced cascades) still possible

# GRB 090926A broad-band spectrum

*Ackermann et al. 2011, ApJ 729, 114*

- **$E_{iso}$ = 2.2 x $10^{54}$ erg**
- **Extra component (power law)**
  - Starts delayed (~9 s)
  - Persists at longer times
  - Dominates > 10 MeV
- **Spectral cutoff**
  - Significant in bin c, marginally in bin d
  - Shape not constrained
- **First measurement of the jet Lorentz factor: Γ ~ 200-700**
  - If cutoff due to γγ absorption
  - Model dependent

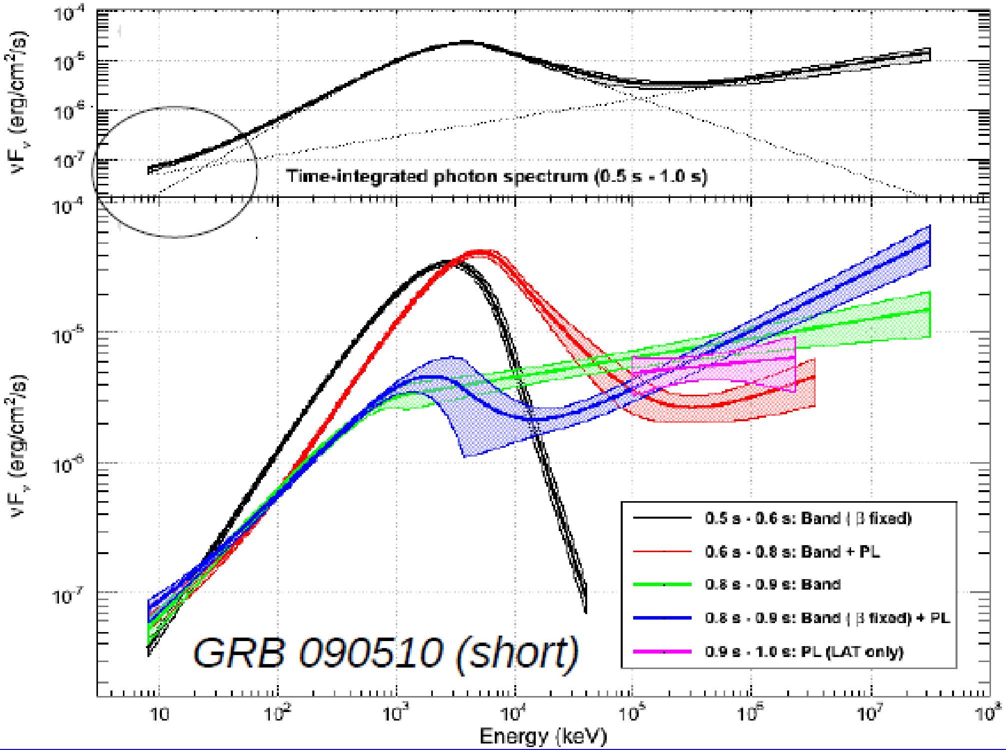


# Broad-band spectral properties

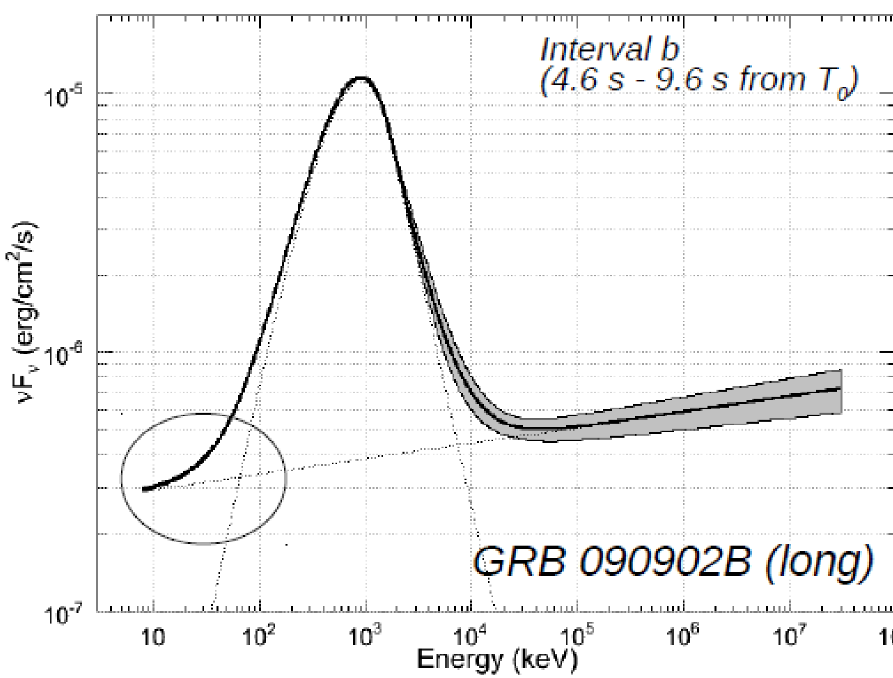
- **The Band function is no longer the best phenomenological model**
  - Deviation from the Band function at low energy
  - Additional power law component at high energy
  - High-energy cutoff measured in the spectrum

→ **Broad-band physical models are needed** (Cf talks on emission mechanisms later this week)

*Ackermann et al. 2010, ApJ 716, 1178*

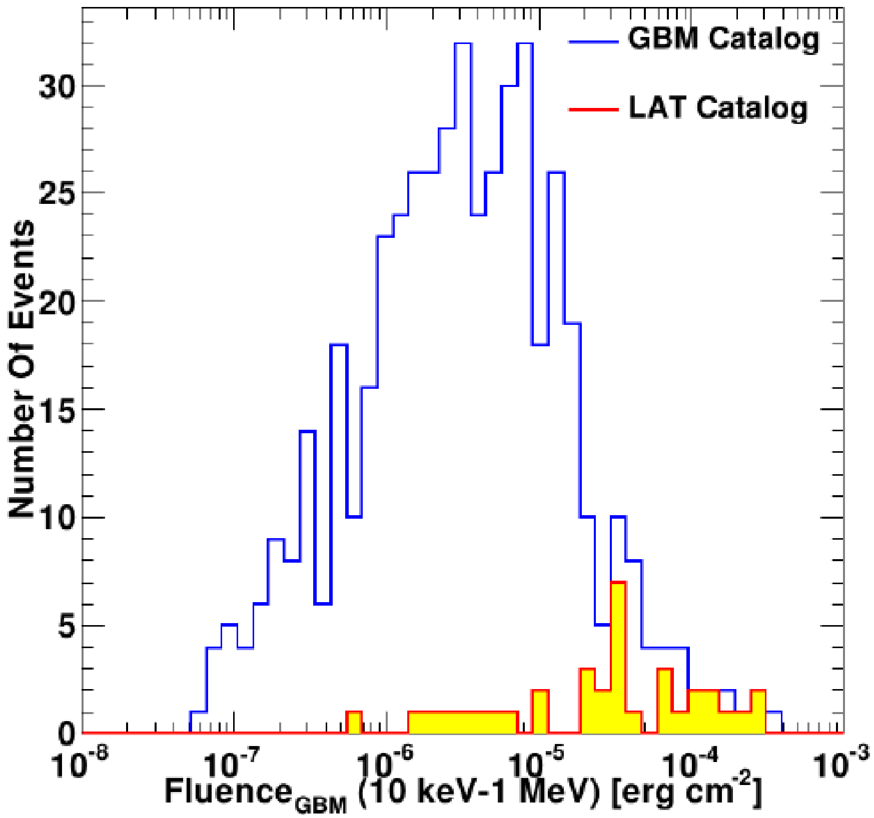


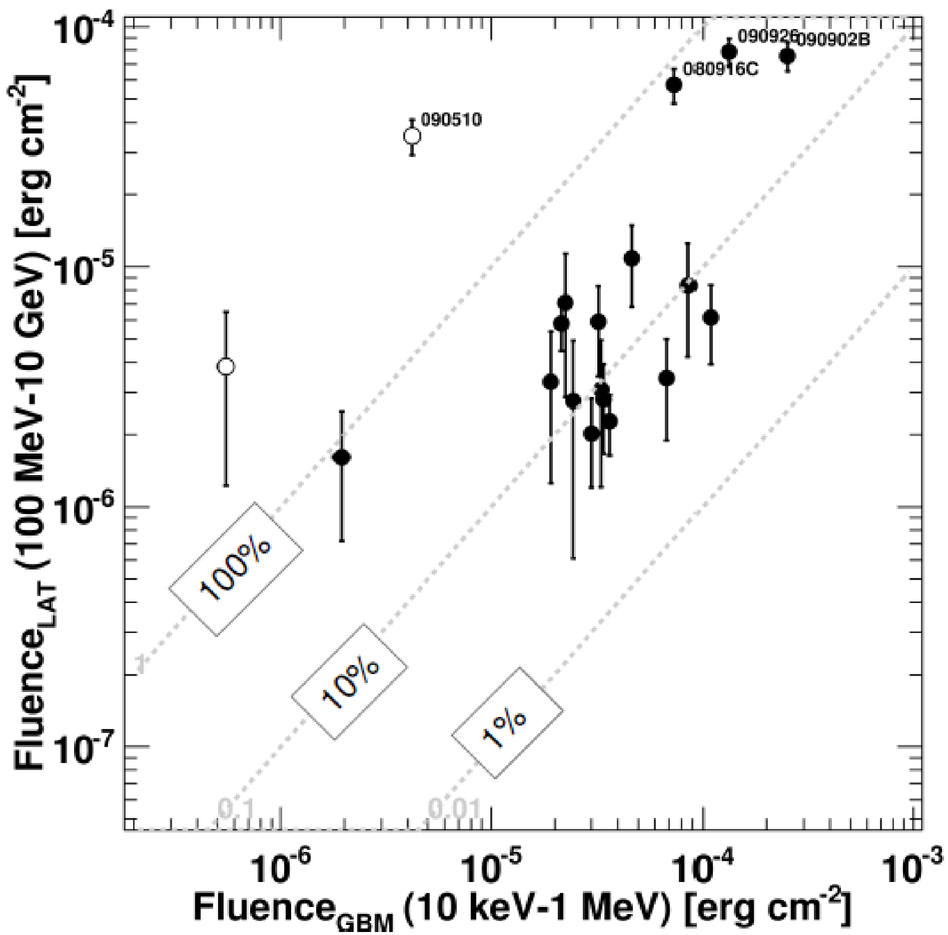

*Abdo et al. 2009, ApJL 706, 138*
*(See also Ryde et al. 2010, ApJ 709, L172)*



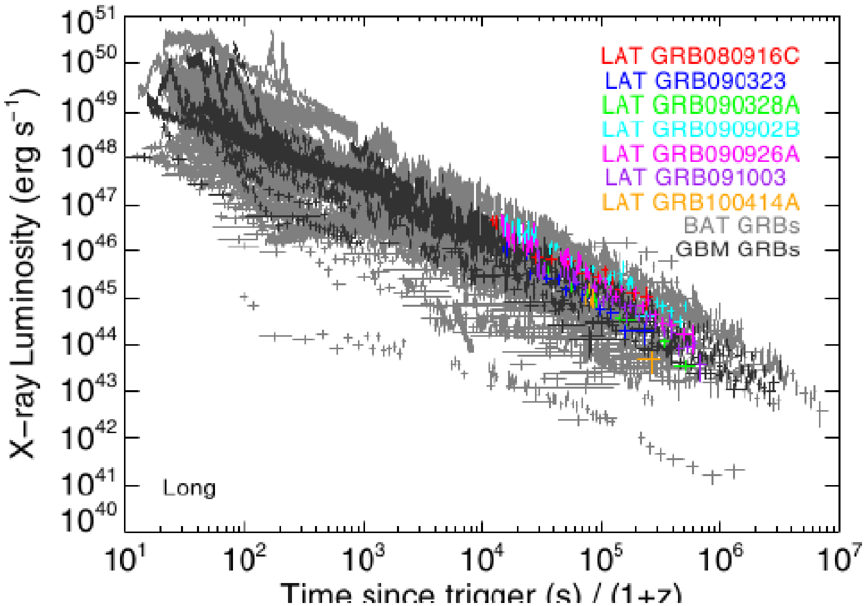
# GBM & LAT fluences

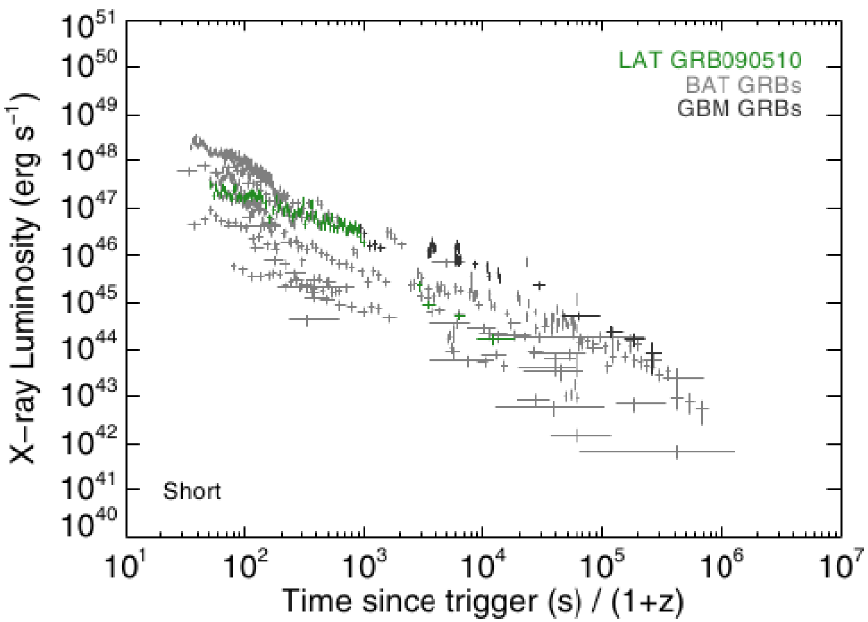
- **Not surprisingly, LAT GRBs are among the most fluent GBM GRBs**
- **Short GRBs (LAT fluence > GBM fluence) are harder than long GRBs (LAT/GBM fluence ~10%)**



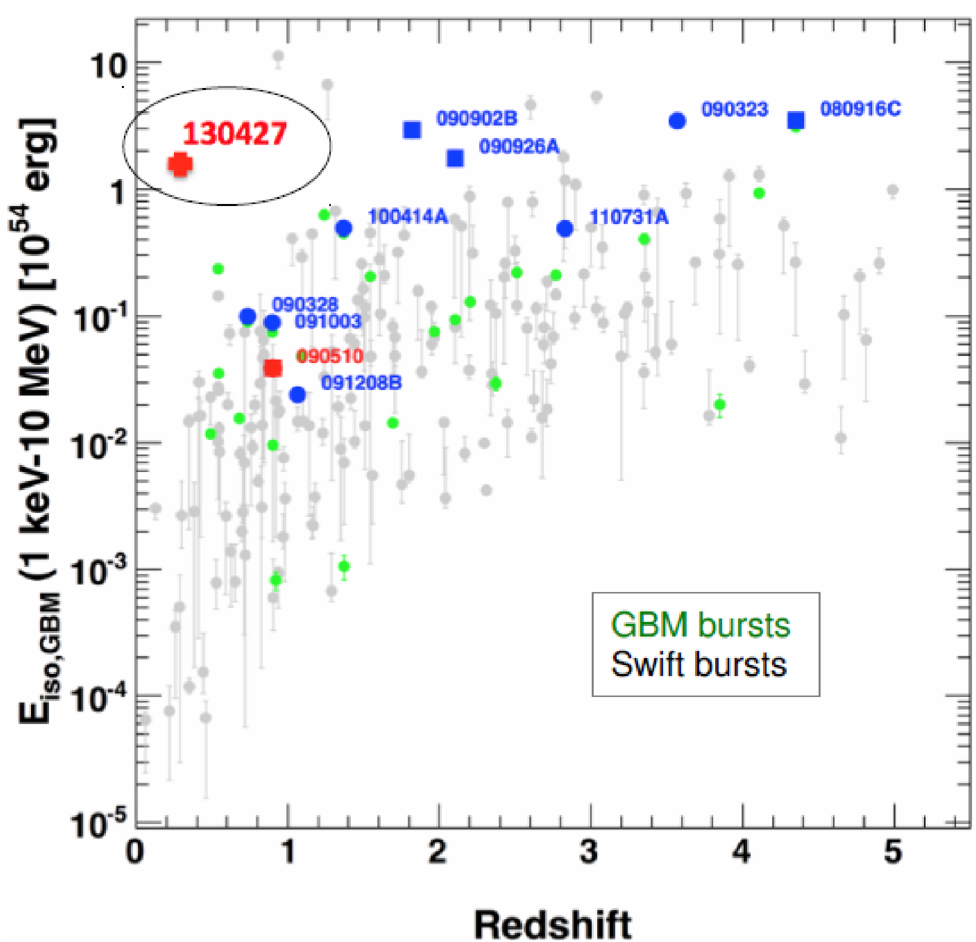



# LAT bursts: bright, fluent and energetic




- **Comparing *Swift* and *Fermi* GRB samples:**
  - *Butler et al. 2007, ApJ 671, 656 (see also Sakamoto et al. 2011, ApJS 195, 2)*
  - *Racusin et al. 2011, ApJ 738, 138*
  - *Goldstein et al. 2012, ApJS 199, 19*
  - *Ackermann et al. 2013, ApJS 209, 11*



# Constraining LIV with LAT GRB photons

Fermi Gamma-ray Space Telescope

- Quantum Gravity (QG) effects at Planck scale ($E_{Planck}$=1.2 x $10^{19}$ GeV) may induce an energy-dependent speed of light (Lorentz Invariance Violation):

$$v_{\rm ph}(E) \simeq c \times \left[1 \mp \frac{n+1}{2}\left(\frac{E}{E_{\rm QG}}\right)^{n}\right]$$

  with $n$=1 or 2

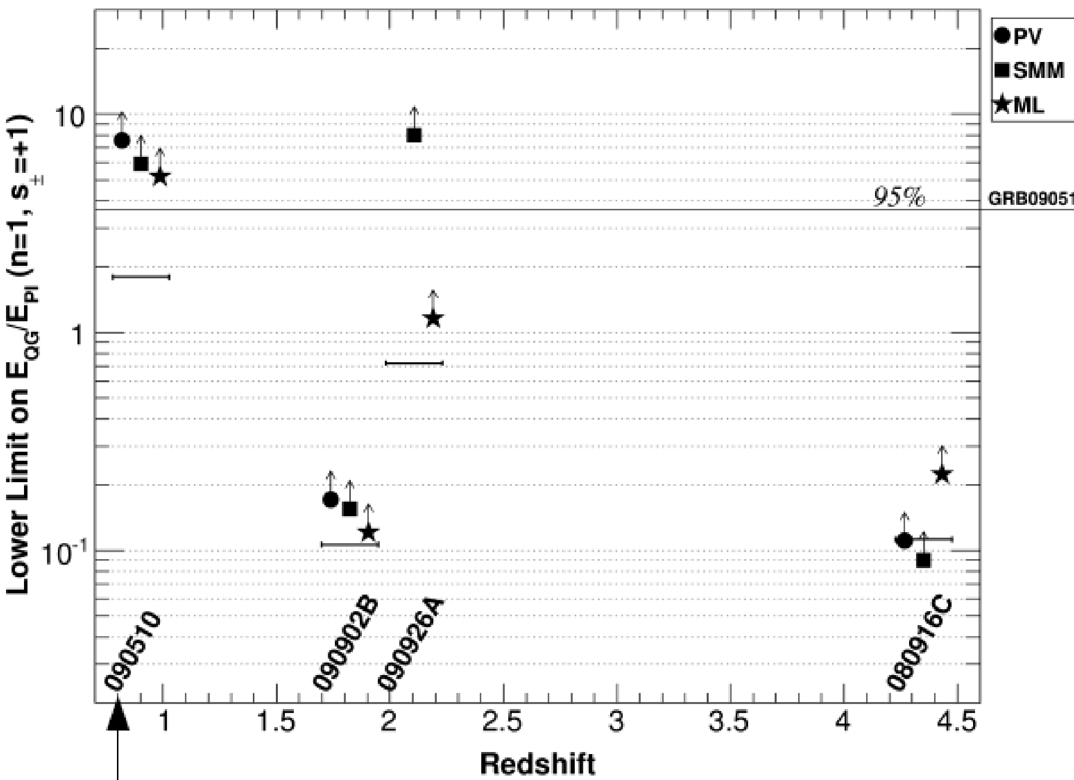
- Time-of-flight technique: 3 methods applied on *Fermi*-LAT bright GRBs

$$\frac{\Delta t}{10\ \rm ms} \approx \left(\frac{\Delta E}{1\ \rm GeV}\right)\left(\frac{E_{\rm Planck}}{E_{\rm QG}}\right)\left(\frac{L}{1\ \rm Gpc}\right)$$

- Robust and well tested analysis, including GRB-intrinsic effects
  → the most stringent limits ever

- Results in the linear case *(n=1)*:
  - $E_{QG}$ > 7.6 x $E_{Planck}$ (95%)
  - Theoretical models predicting $E_{QG} \lesssim E_{Planck}$ are excluded

*Abdo et al. 2009, Nature 462, 331*
*Vasileiou et al. 2013, PRD 87, 122001*




- Our best constraints from GRB 090510 (z=0.93)
  - 31 GeV photon coincident with a narrow (~0.4 s) pulse
  - Dispersion ≲ ms/GeV

# Summary and conclusions

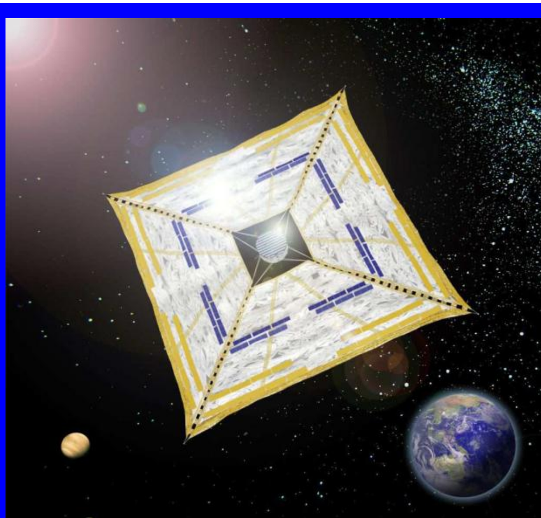
- **GRB population studies at high energy are now possible with *Fermi***
  - LAT bursts are bright, fluent & energetic
  - GRB >100 MeV emission is delayed & temporally extended w.r.t. the emission in the MeV range
  - Short and long GRBs seem to have similar high-energy properties
  - The distribution of GRB jet Lorentz factors might be broad

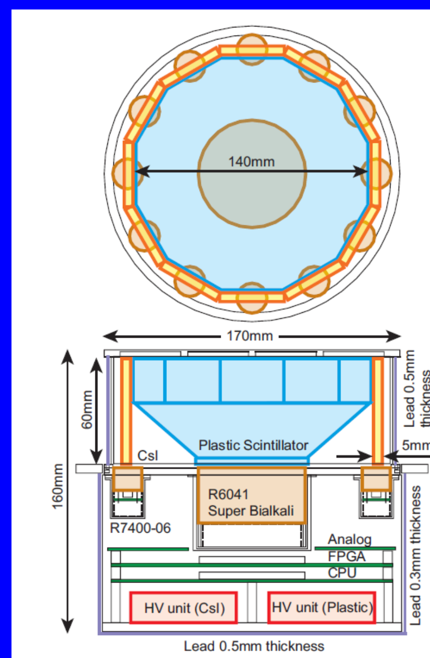
- **Prompt emission phase observed over a wide energy range**
  - Complex spectral shapes are needed to reproduce the spectrum
  - Origin of the delayed onset of the LAT >100 MeV emission?
  - Transition from prompt emission phase to early afterglow phase?
- **Long-lived GeV emission is consistent with the canonical afterglow model**

# Polarization of prompt gamma-ray emission

- Gamma-ray burst polarimeter (GAP) aboard IKAROS solar sail mission measured linear polarization for 3 bright GRBs: GRB 100826A, $\Pi=27\pm11\%$ ($2.9\sigma$), GRB 110721A, $\Pi=70\pm22\%$ ($3.7\sigma$), GRB 110301A $\Pi=84(-28,+16)\%$ ($3.3\sigma$)
- Synchrotron emission in globally ordered field(?) (may be advected from the central engine through the jet)

$$\frac{d\sigma}{d\Omega} = \frac{r_0^2}{2}\frac{E^2}{E_0^2}\left(\frac{E_0}{E} + \frac{E}{E_0} - 2\sin^2\theta\cos^2\phi\right)$$





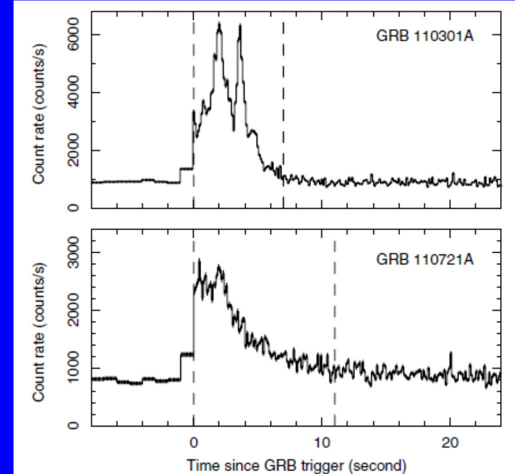




**Figure 1.** Light curves of the prompt gamma-ray emission of GRB 110301A (top) and GRB 110721A (bottom) detected by GAP. The vertical dashed lines indicate the time interval of polarization analyses for each burst.

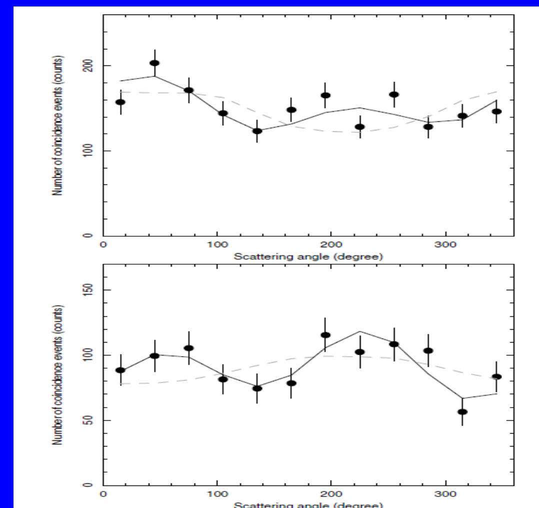



**Figure 2.** Number of coincidence gamma-ray photons (polarization signals) against the scattering angle of GRB 110301A (top) and GRB 110721A (bottom) measured by the GAP in the 70–300 keV band. Black filled circles are the angular distributions of Compton scattered gamma rays after the background subtraction. The solid lines are the best-fit models of each event calculated with the Geant4 Monte Carlo simulations. The model functions of the non-polarized cases are superposed on each panel for easy comparison.

IKAROS = Interplanetary Kite-craft Accelerated by the Radiation Of the Sun

# Short-hard GRBs~ another population

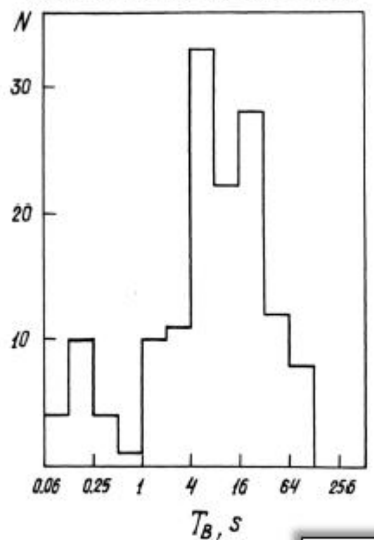


Fig. 164

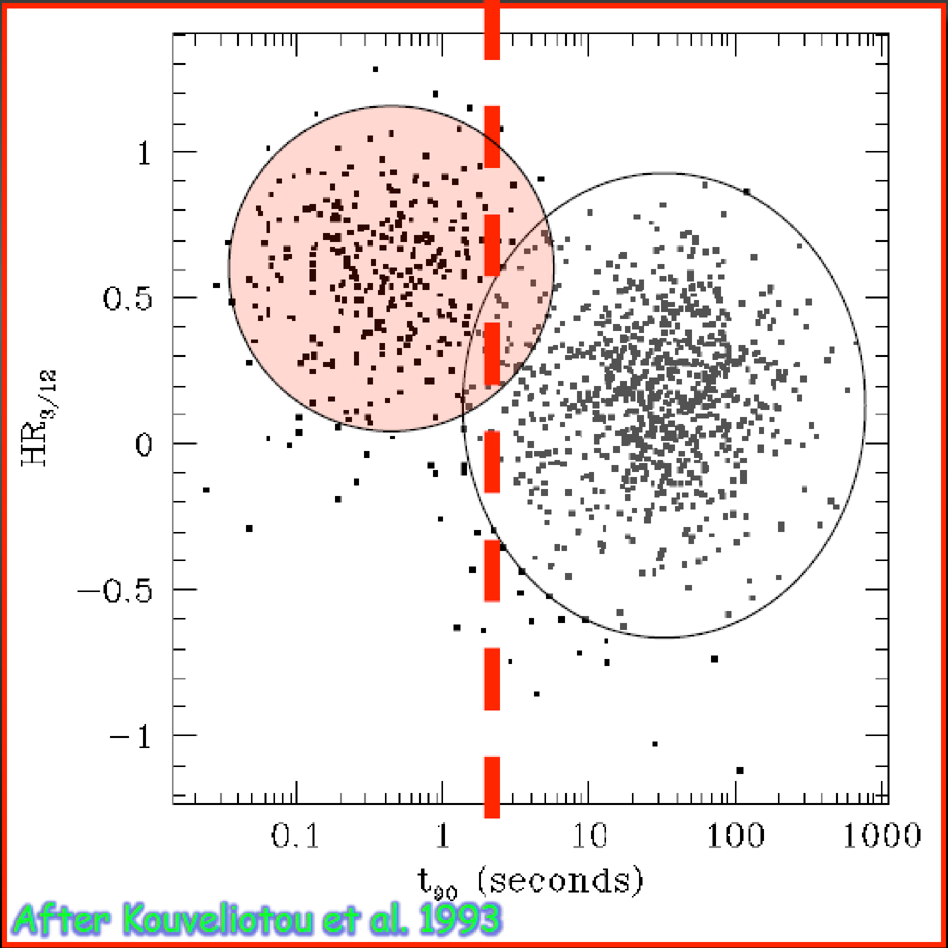
Identified as a distinct population in 1981 by Mazets et al. in a series of papers on the KONUS experiment on Venera 11 & 12.


A. The distribution of bursts in duration

The essential differences in the gamma-burst time structure are reflected in the distribution of the observed events in duration $T_b$. Figure 164 shows an experimental distribution drawn for 143 events. It displays the number of bursts per equal logarithmic interval of $T_b$. Since some of the bursts may have long tails, the duration of the event in this case is taken to be the interval of time within which fall 80–90% of the measured burst intensity $S$. The distribution differs substantially from the uniform one. The main peak in the distribution is connected primarily with single and multipulse bursts. The right-hand wing is composed of double and long structureless bursts. Narrow peak in the beginning of the graph indicates the existence of a separate class of short bursts.

# Short-hard GRBs~ another population

$T_{90}=2$ s

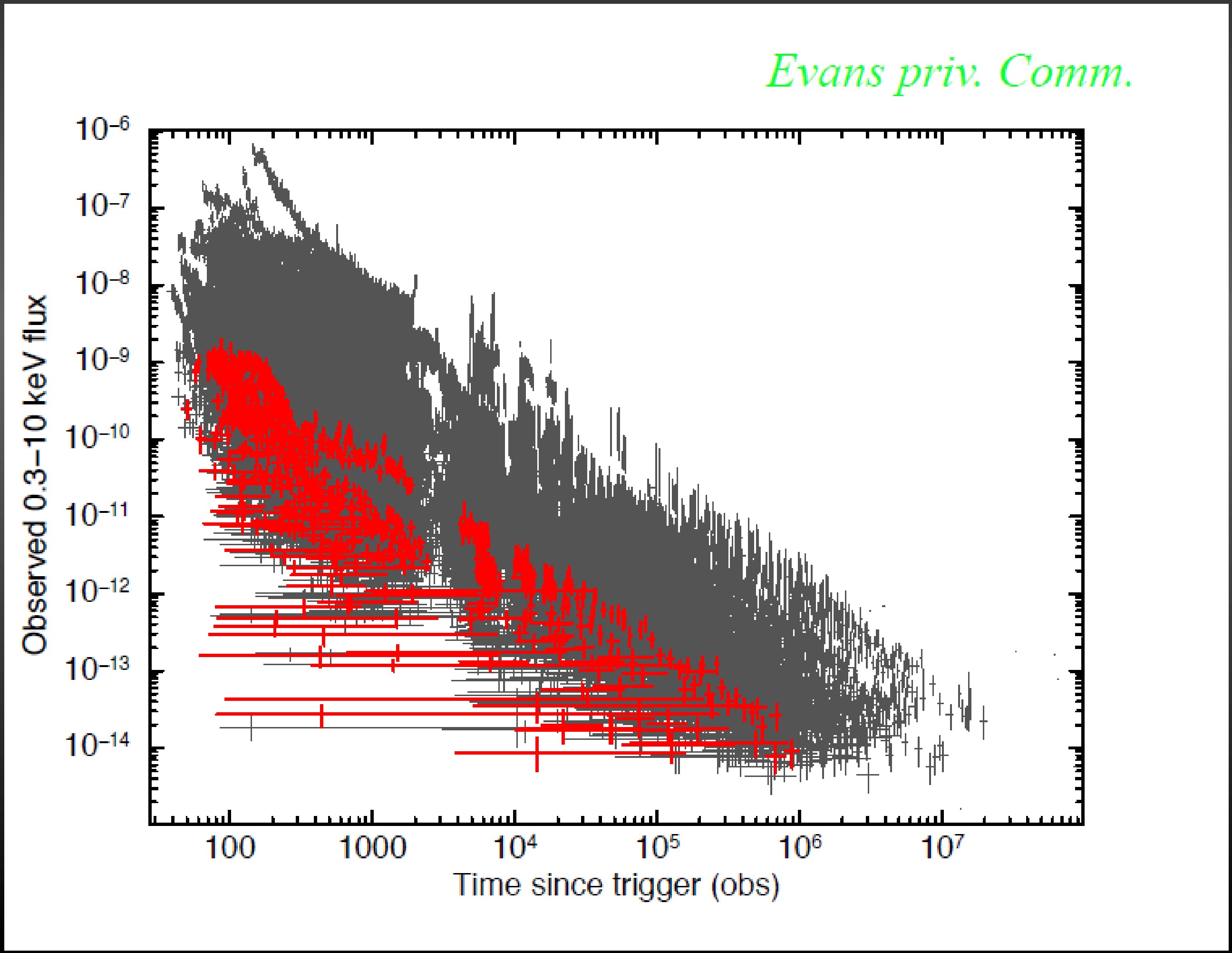



Around 25% of BATSE GRBs were "short", but:

- Populations obviously overlap
- Detector dependent (e.g. *Swift* sees fewer sGRBs, with "borderline" probably rather shorter).
- Both axes redshift dependent (in complicated ways)

# Short-duration bursts

X-ray afterglows fainter than for LGRBs (several cases have no detection despite prompt slew).



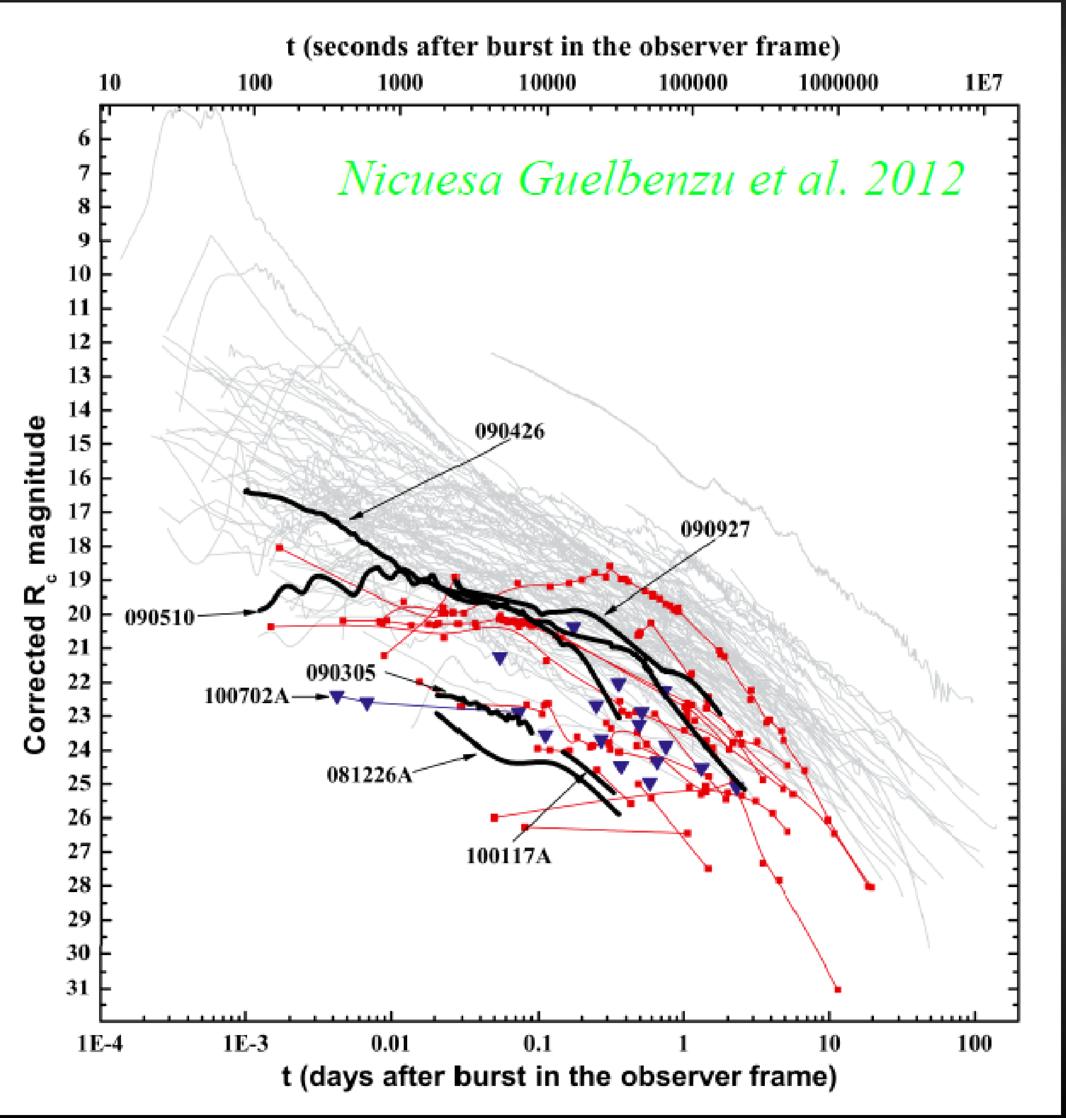
# Short-duration bursts

Generally lower luminosity (hence lower <z>~0.5)

*Never associated with supernovae.*

*May break into sub-classes e.g. a proportion have "extended soft emission".*

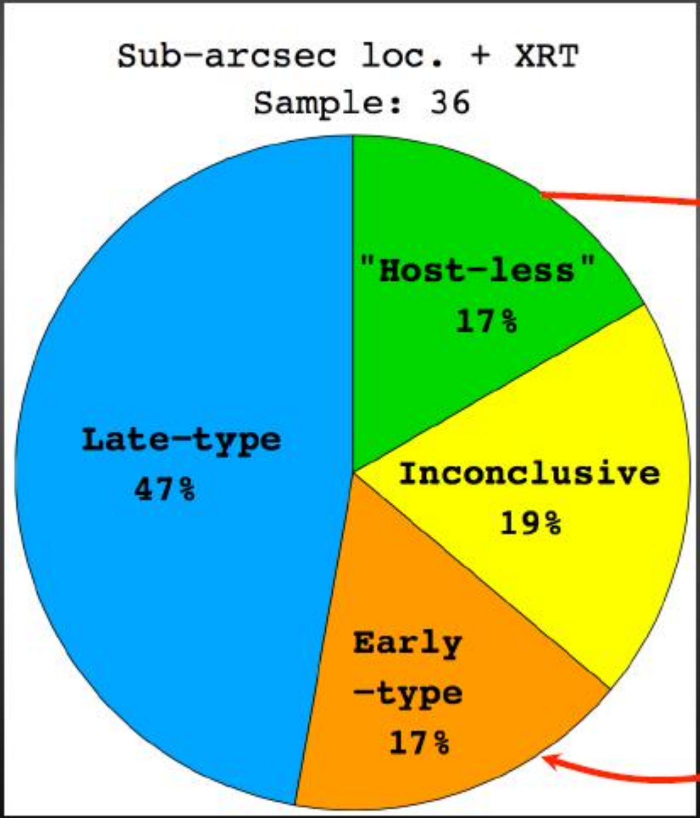
*Optical afterglows usually also very faint with weak spectral features – hard to find and hard to obtain redshifts (in practice, nearly always rely on host redshift).*



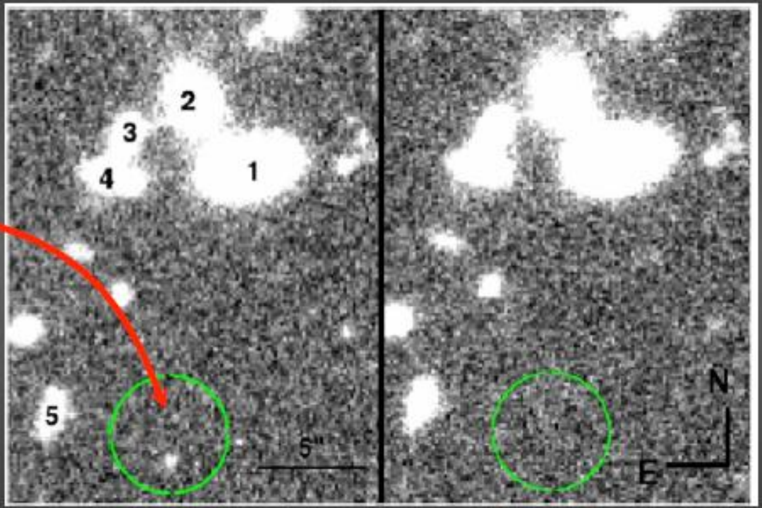
# Short-hard GRBs - compact binary mergers?

- Associated with a range of host stellar populations.
- Sometimes apparently far from their host.

e.g. GRB090515 afterglow R~26.5 at 2 hours post burst. No obvious host.



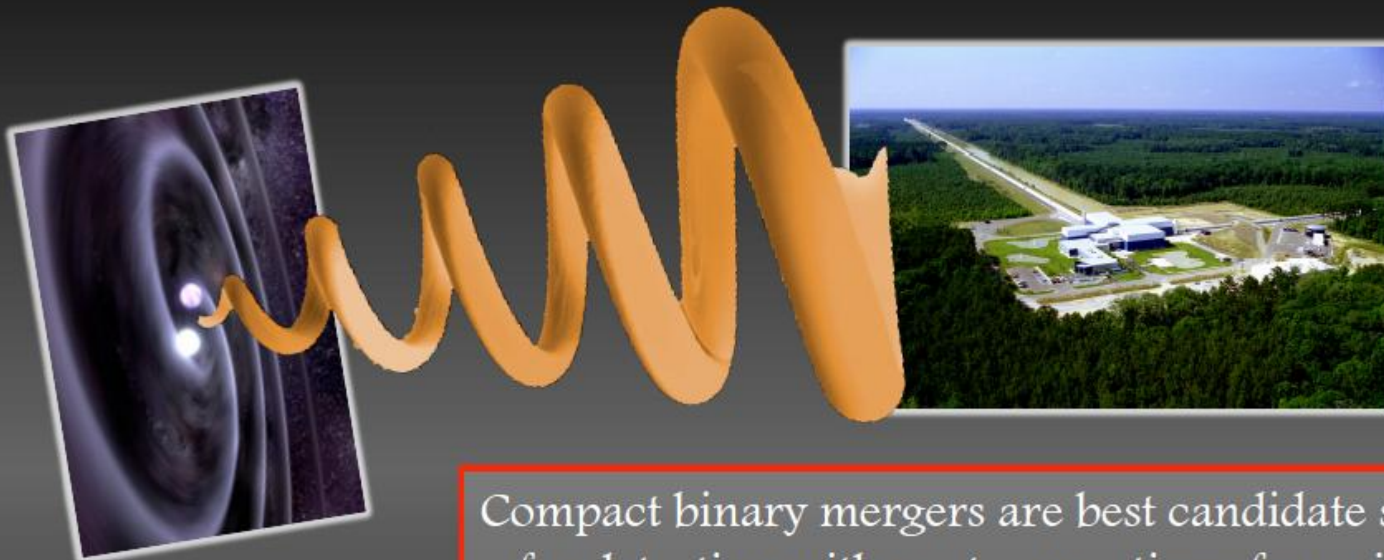

Fong et al. 2013



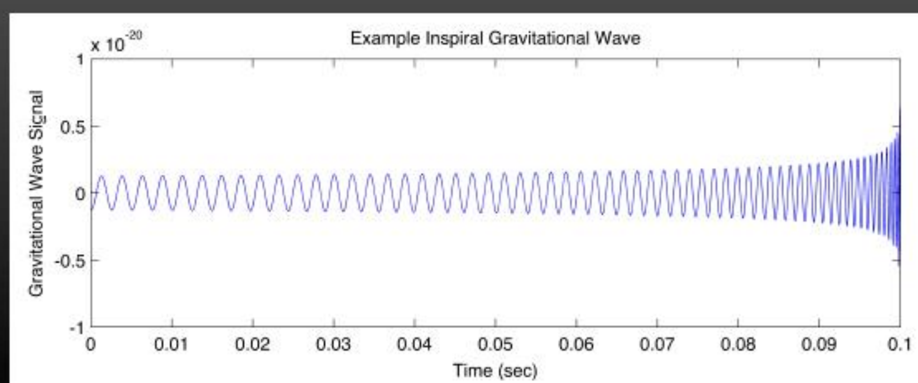

Rowlinson et al. 2010

Note, the number associated with ancient stellar populations is not high, suggesting inspiral times ~100s Myr are most common.

# Short-hard GRBs~ prospects for GW



Compact binary mergers are best candidate systems for detection with next generation of gravitational wave detectors e.g. A-LIGO, from ~2015.



# Детектирование гравитационных волн от GRBs

- ground-based interferometric GW detectors: LIGO (Laser Interferometer Gravitational-Wave Observatory), Virgo, GEO600 (Initial sensitivity NS-NS for D <~15 Mpc)
- Second generation detectors: Advanced LIGO and Advanced Virgo (2015), Large Scale Cryogenic Gravitational Wave Telescope (LCGT) (2018). The detectors are designed to observe:
  - NS-NS mergers to an average distance of 200 Mpc (z ~0.05), and
  - NS-BH mergers to 400 Mpc (z ~0.1).
  - Predicted rates: NS-NS 40 yr$^{-1}$ (0.4-400), N

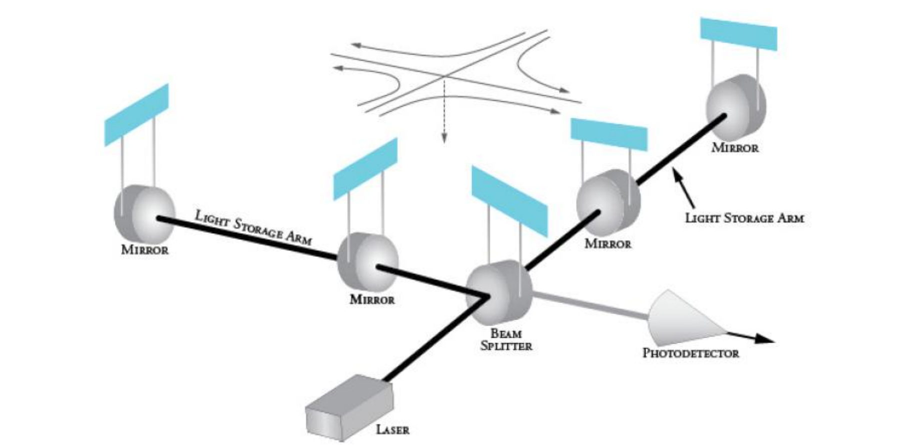



FIGURE 4. Schematic drawing of a ground-based laser interferometer for GW detection. The beam splitter sends light down the two arms; the beams are then interfered at the photodetector. A passing GW changes the arm lengths, causing phase changes in the laser beams. These phase changes appear in the interference patterns at the photo detector, giving the GW signal. Figure courtesy of the LIGO Laboratory, used with permission.

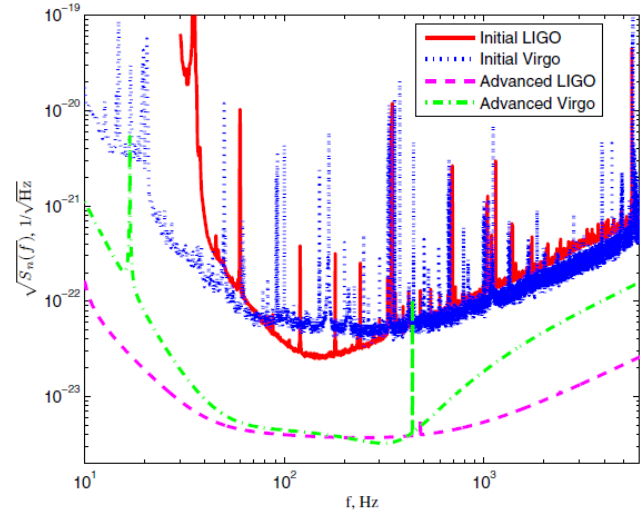
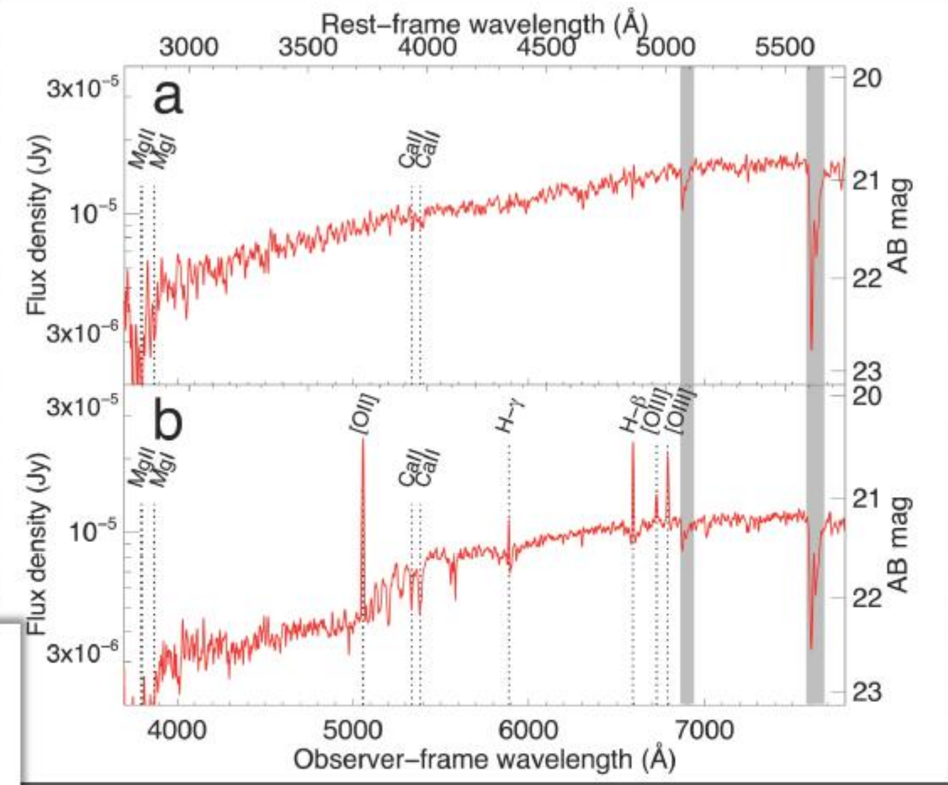
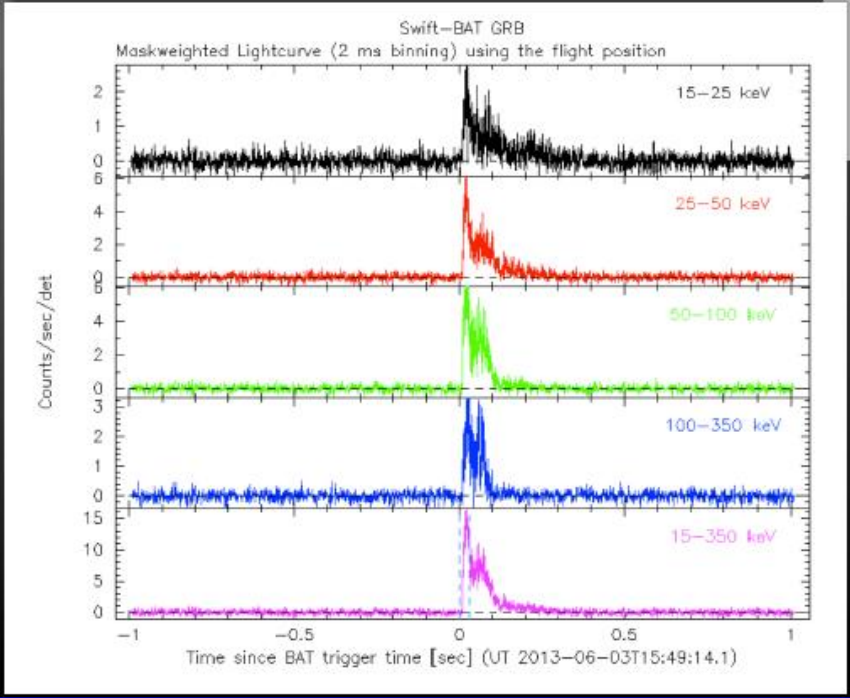



Figure 2. Noise amplitude spectral densities (ASDs) as a function of frequency. The Initial LIGO noise ASD (solid red curve) corresponds to the typical detector sensitivity as measured from data taken during the S5 run [28]. The Advanced LIGO noise ASD (dashed magenta) represents a possible Advanced LIGO configuration with high laser power and zero detuning [29]. The Initial Virgo noise ASD (dotted blue) was measured during Virgo's VSR2 run [30]. The Advanced Virgo noise ASD (dash-dotted green) is based on the Advanced Virgo Baseline Design [31].

# GRB 130603B

Bright burst and unambiguously short duration.




de Ugarte Postigo et al. 2013

Afterglow provided afterglow redshift with GTC, $z \sim 0.36$

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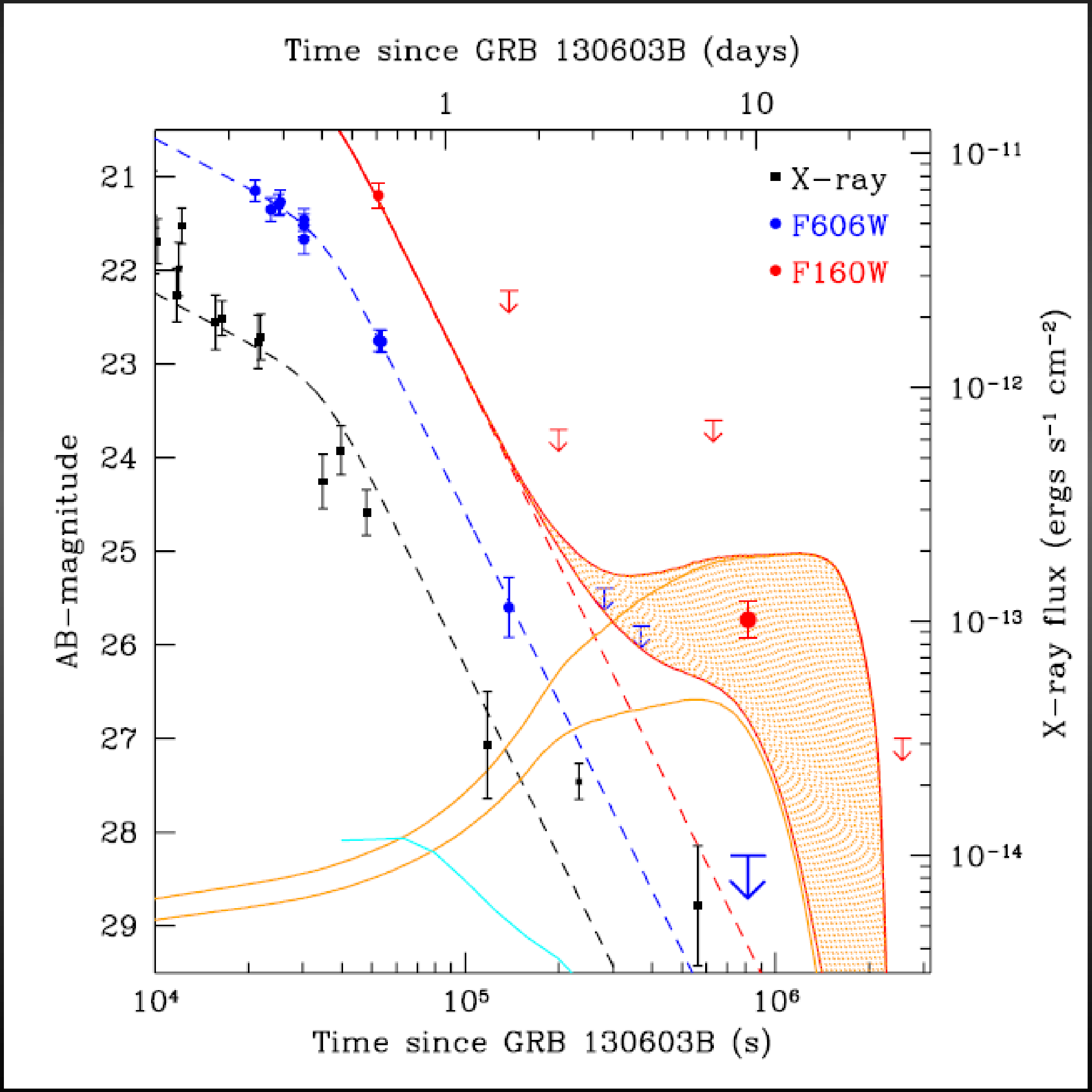



Comparison to Barnes & Kasen (2013) models suggests ejected mass ~0.05 $M_\odot$

Compact binary mergers ~ likely site of significant (possibly dominant) production of r~process elements in universe.

KN emission likely to be roughly isotropic and environment independent.

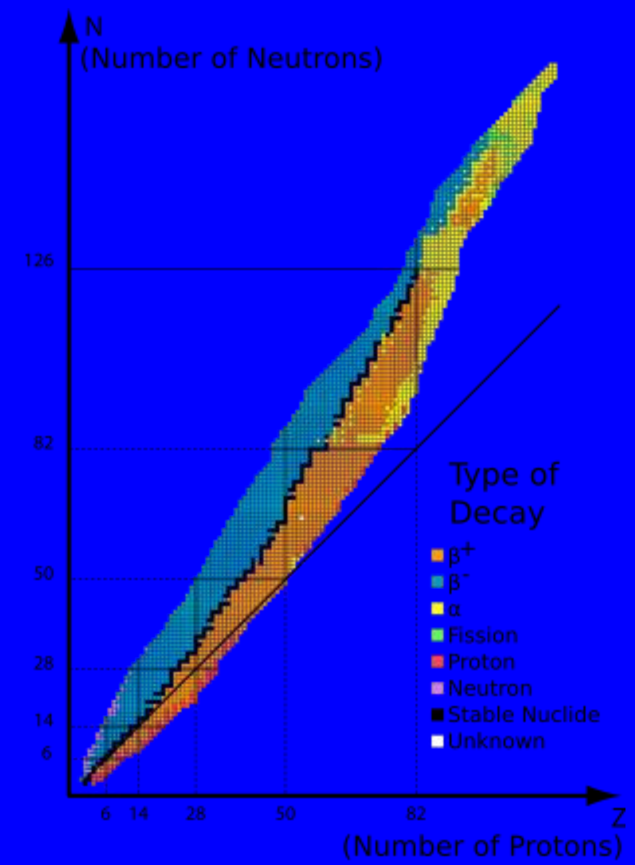

Tanvir, Levan et al. 2013

Berger et al. 2013

Fong et al. 2014

# r-process

- Ядра за группой железа (A>90-100) должны формироваться за счет захвата нейтронов
- Два процесса захвата – медленный (s) и быстрый (r): $\tau_\beta << \tau_n$ или $\tau_\beta >> \tau_n$
- Слияние нейтронных звезд может полностью объяснить распространенность элементов с
- A >~ 130



# Conclusions and prospects

- Compelling evidence that compact object mergers produce both sGRBs and r-process kilonovae.
- Electromagnetic signatures therefore include prompt emission, afterglow emission and radioactive emission (also probably late-time radio emission as slow outflows produce shocks; Nakar & Piran 2011).
- Best prospects for electromagnetic detection may be near-IR searches for accompanying kilonovae, and optical searches for faint off-axis afterglow emission.
- Further KN studies required to understand range of behaviour.
- Outflows (both relativistic and not) should also produce longer-lived, late-time radio emission, which may also be detectable (e.g. Nakar and Piran 2011).
- All such searches will require significant dedicated follow-up and effort in chasing down false positive detections.

# Нейтрино высоких энергий от GRBs

GRBs – кандидаты в источники КЛ сверхвысоких энергий ($E>10^{18}$ eV)
Взаимодействие протонов высоких энергий с гамма-излучением должно при водить к генерации нейтрино высоких энергий

$$p+\gamma \rightarrow \Delta^{+} \rightarrow n+\pi^{+}$$

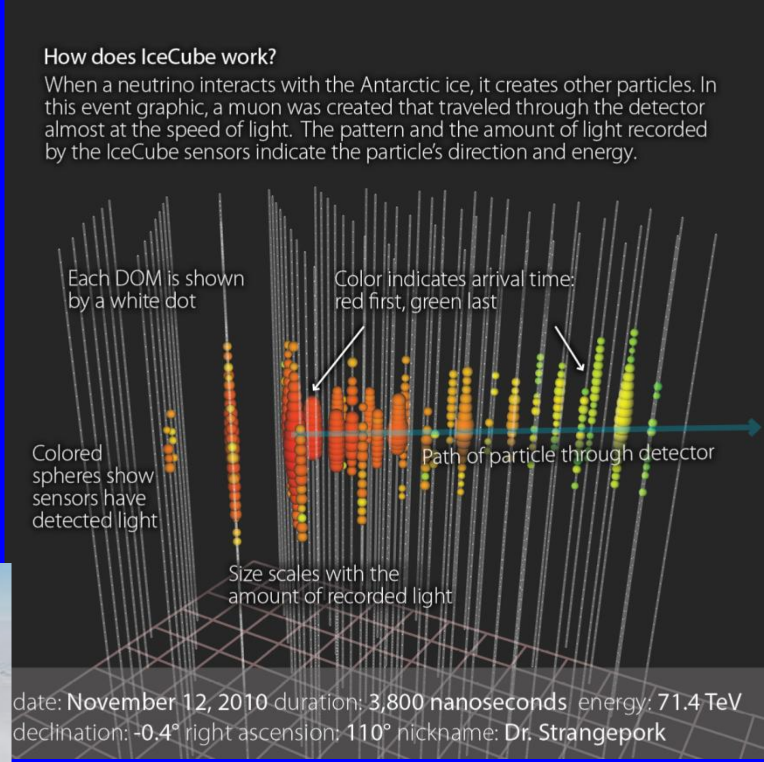
$$\pi^{+} \rightarrow \mu^{+}+\nu_{\mu}$$
$$\mu^{+} \rightarrow e^{+}+\overline{\nu_{\mu}}+\nu_{e}$$

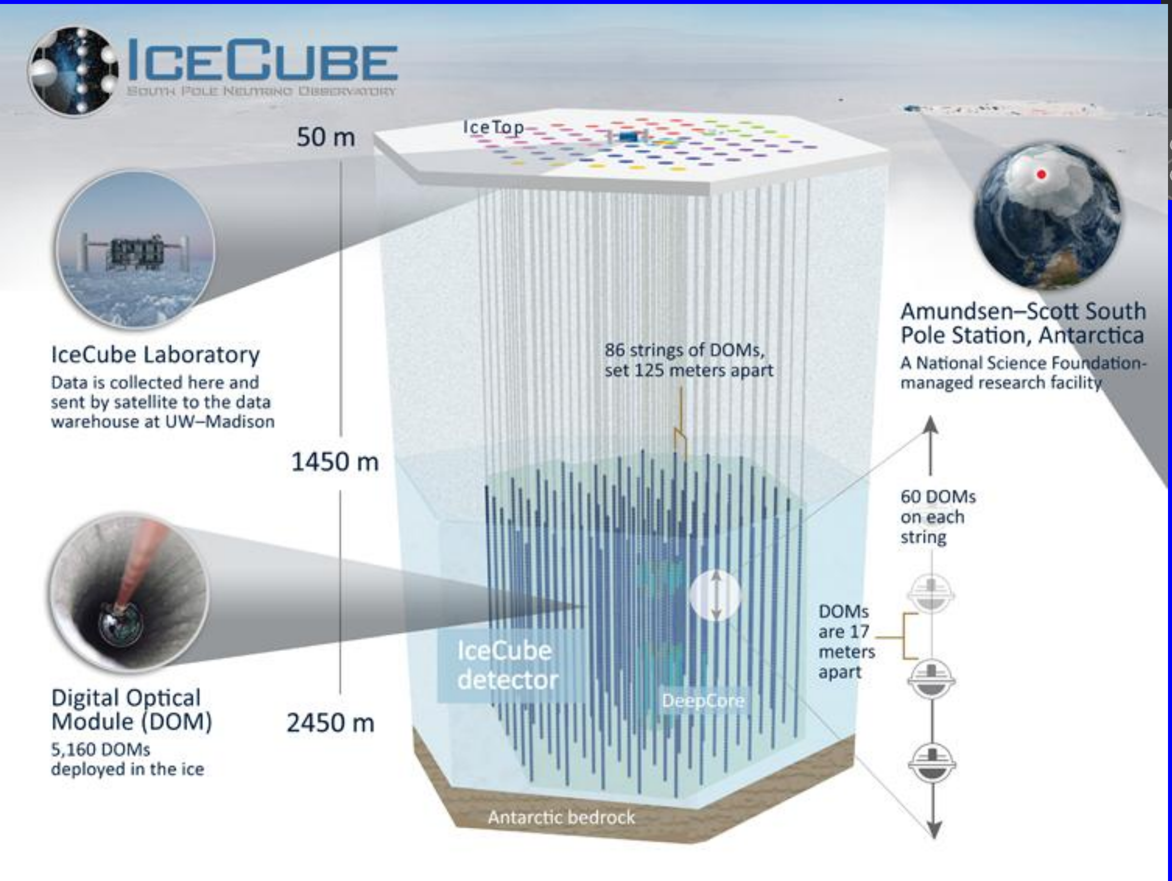
(порог $E_{\gamma}E_{p}=0.2\Gamma^{2}\text{GeV}^{2}$ т.е. для $\Gamma\cong300$ и $E_{\gamma}\cong1\text{MeV}$, $E_{p}\sim10^{16}$ eV)
~5% энергии протона переходит в нейтрино, т.е. $E_{\nu}$ >~ $10^{14}$ eV
: $E_{\nu}$ ~100 TeV -10 PeV ($10^{14}$-$10^{17}$ eV)
Ожидаемый поток нейтрино:

$$\begin{aligned} E_{\nu}^{2}\Phi_{\nu} &\approx 0.2\frac{f_{\pi}}{0.2}E_{\nu}^{2}\Phi_{\nu}^{\mathrm{WB}} \\ &\approx 0.9\times10^{-8}\frac{f_{\pi}}{0.2}\mathrm{GeV\,cm^{-2}s^{-1}sr^{-1}} \end{aligned}$$

Для детектора ~1 $km^{3}$ такой поток дает ~20 событий в год
Наблюдения нейтрино высоких энергий дало бы бесспорное доказательство того, что в GRBs происходит ускорение адронов до сверхвысоких энергий

# IceCube


How does IceCube work?
When a neutrino interacts with the Antarctic ice, it creates other particles. In this event graphic, a muon was created that traveled through the detector almost at the speed of light. The pattern and the amount of light recorded by the IceCube sensors indicate the particle's direction and energy.
Each DOM is shown by a white dot
Color indicates arrival time: red first, green last
Colored spheres show sensors have detected light
Path of particle through detector
Size scales with the amount of recorded light
date: November 12, 2010 duration: 3,800 nanoseconds energy: 71.4 TeV
declination: -0.4° right ascension: 110° nickname: Dr. Strangepork


ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY
50 m
IceTop
IceCube Laboratory
Data is collected here and sent by satellite to the data warehouse at UW–Madison
86 strings of DOMs, set 125 meters apart
Amundsen–Scott South Pole Station, Antarctica
A National Science Foundation-managed research facility
1450 m
60 DOMs on each string
DOMs are 17 meters apart
IceCube detector
DeepCore
Digital Optical Module (DOM)
5,160 DOMs deployed in the ice
2450 m
Antarctic bedrock

# Результаты IceCube по измерению нейтрино от GRBs

- Найден верхний предел на поток высокоэнергетичных нейтрино, который по крайней мере в 3.7 раза ниже предсказанного
- Это означает, что или GRBs не единственные источники UHECR или эффективность генерации таких нейтрино в GRBs намного меньше предсказанной

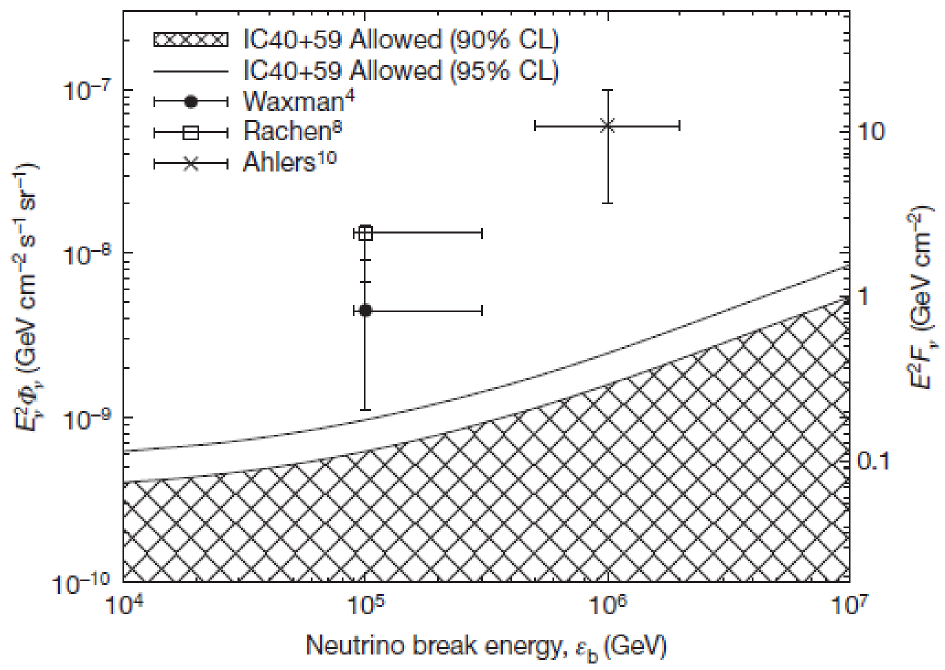



**Figure 3 | Compatibility of some neutrino flux predictions based on cosmic ray production in GRBs with observations.** The cross-hatched area ('IC40+59 Allowed 90% CL') shows the 90% confidence allowed values of the neutrino flux (vertical axes, as in Fig. 1) versus the neutrino break energy ($\varepsilon_b$) in comparison to model predictions with estimated uncertainties (points); the solid line labelled 'IC50+59 Allowed 95% CL' shows the upper bound of the 95% confidence allowed region. Data were taken from the model-independent analysis from the time window corresponding to the median duration of the GRBs in our catalogue ($|\Delta t| = 28$ s). Spectra are represented here as broken power laws ($\Phi_\nu \cdot \{E^{-1}/\varepsilon_b, E < \varepsilon_b; E^{-2}, E > \varepsilon_b\}$) with a break energy $\varepsilon_b$ corresponding to the $\Delta$ resonance for $p$–$\gamma$ interactions in the frame of the shock.