100 years of photon

38 years of Gamma Ray Bursts and perspectives for future

GRB's are the most powerfull sources of photons in the Universe from radio waves to TeV

Grzegorz Wrochna
Soltan Institute for Nuclear Studies, Warsaw / Świerk

1963 – Treaty banning nuclear weapon tests in space

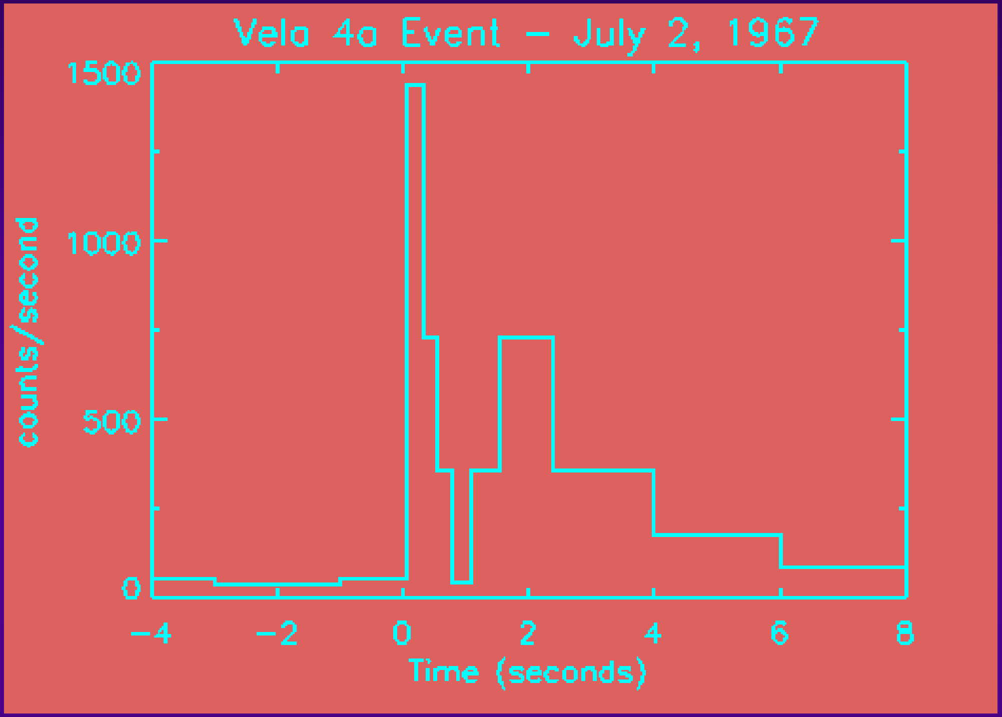
Military satellites VELA launched

- equipped with γ-ray detectors
- orbit R=100 000 km, period=4.5 days
- could detect nuclear explosion at the other side of the Moon

1958 – USA plan nuclear tests at the other side of the Moon

(uncovered in 2000)

2.6.1967 – VELA register γ burst

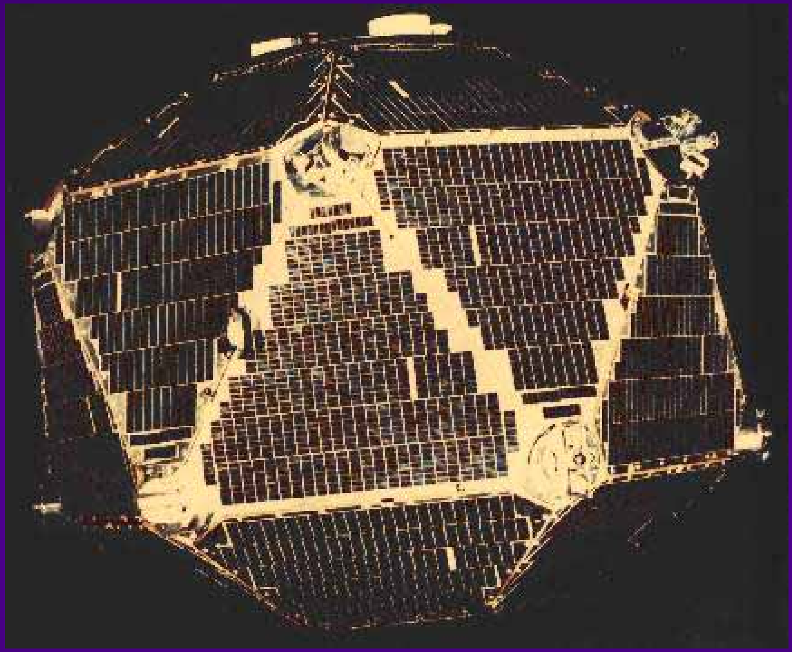


- Ray Klebesadel & Roy Olson from Los Alamos National Laboratory
  compare printouts from VELA 4A i 4B
- They find a burst seen by both satellites
  USSR broken the treaty?
- Pulse shape different from nuclear one
  no information about direction and distance

1969 – Launch of VELA 5 i 6

- time resolution 1/64 s
- direction (~5°) & distance estimate

1969-73 – 16 γ bursts detected



1973 – publication

- distance > 1 mln km
- directions exclude Sun and planets
- distribution ~isotropic
- journalists suspect nuclear war between E.T.'s
- astronomers got excited

The first hypothesis

1974 – Ruderman's review quotes dozens of theories

Where?

Solar System, Galaxy, Universe?

What?

main sequence stars, white drawfs, black holes, neutron stars, planets, comets, dust grains, white holes, cosmic strings, wormholes, etc.

How?

energy: grawitational, thermonuclear, magnetic, kinetic (rotational)

Comet falling on neutron stars

Diversity of pulse shapes well explained by
diversity of shapes and sizes of comets.
Neutron stars are inside galactic disk.
How to get isotropic distribution?
Possible, if we see only nearby neutron stars.
Having the number of neutron stars
(from pulsar observations and supernovae)
and the numer of comets (from the Solar System)
one can calculate frequency of GRB.

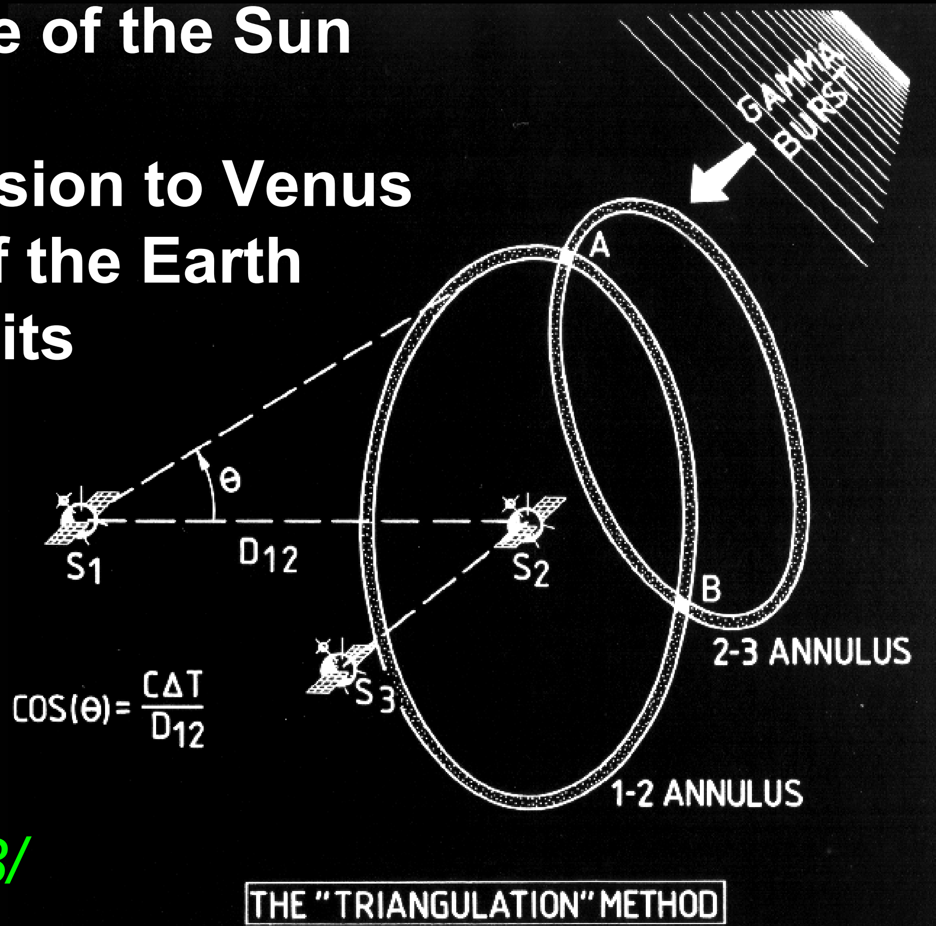
Assuming typical comet and netron star sizes one
can calculate released energy.
Comparing to the observed energy one can
estimate the distance: 10-1000 l.y.

10 l.y. ~ distance to closest neutron stars
1000 l.y. ~ thickness of the galactic disk

Inter-Planetary Network (IPN)

1978 – several spacecrafts far from the Earth equipped with gamma detectors

- **Prognoz 7 (USSR) – satellite of the Earth**
- **Helios 2 (Germany) – satellite of the Sun**
- **Pioneer Venus Orbiter (USA)**
- **Wenera 11 i 12 (USSR) – mission to Venus**
- **Kosmos (USSR) – satellite of the Earth**
- **Vela 5 i 6 (USA) – distant orbits around the Earth**



K.Hurley – Berkeley

http://www.ssl.berkeley.edu/ipn3/

Burst in the Large Magellanic Cloud

5.3.1979 – exceptionaly strong burst detected by IPN
followed by damped oscillations with 8 s period

Direction from Large Magellanic Cloud
(nearby galaxy, 160 000 l.y. from Earth)

Position coincides with supernowa remnant

Gigantic energy exludes hypothesis of comet

Position at SN remnant and 8 s oscillations
suggests a neutron star (pulsar)

Hypothesis of gigantic magnetic storm at neutron star
with huge magnetic field explains well the observed burst

Spectral lines

Spectrum of GRB 79 03 05 has peaks ~800 i 400 keV
in agreement with anihilation $e^+e^- \rightarrow$ 1 or 2 γ
(1022 or 511 keV minus energy to escape neutron star)

1979-81 – dozens of γ burst spectra registered by
Japan. sat. Ginga and Russion group of Evgeni Mazets
exhibit „hollows" (absorbsion lines) ~30-60 keV

Interpreted as cyclotron frequencies of electrons
in magnetic fields of neutron stars.
Obtained values ~$3 \cdot 10^{12}$ gauss, typical for neutron stars

Argument for galactic origin of GRB, because larger
distances wold imply much higher fields.

Archive optical observations

1981 – Bradley Schaefer (MIT) egzamined old sky images

- **he found an optical flash on 1928.11.17 in the place of GRB 1978.11.19**

1984 – another search

- **GRB 1979.11.05 = optical flash in 1901**
- **GRB 1979.01.13 = optical flash in 1944**

$\Rightarrow$ **average frequency of flashes of an object = 1.1/year**
$\Rightarrow$ **it must live >50 years $\Rightarrow$ >50 explosions**
$\Rightarrow$ **explosions not fatal $\Rightarrow$ energies not too high**
$\Rightarrow$ **yet another confirmation of short distances**

Compactness problem

Short burst duration (0.01-100s) suggests compact source (~1000 km) – light must go through the source

High luminosity and large distance imply high energy released.

Compact source implies high energy density

$\Rightarrow$ photons interact and produce e^+e^- pairs

$\Rightarrow$ spectrum should not contain γ with E>511keV

Such photons are observed $\Rightarrow$ sources are close to us

False trail – two loopholes in the arguments:

- if the object expands, only part of it could be seen
- photons able to produce e+e- must have higher energy (Lorentz boost)

Conclusion: bursts might be distant, if γ's are created at the wave front of fast moving wave

Distance and intensity distributions

Assuming izotropic distribution of sources,
the number of sources N inside a sphere with radius R:

$$N \sim R^3$$

Observed intensity $L \sim 1/R^2$
Hence, the number of observed sources
($L>L_0$, where L_0 – apparatus sensitivity)

$$N \sim L_0^{-3/2}$$

1982 – data shows deviation from $L_0^{-3/2}$ formula:
deficit of weak bursts

- **contradiction with galactic origin**
- **argument for cosmological distances**
  ⇒ perhaps less bursts in early Universe

Status in 1990

>95% astronomers: galactic origin

Ed Fenimore, Martin Rees, Donald Lamb, ...

- **GRB in Magellanic Cloud in place of old SN**
- **spectral lines**
- **small energy enough to explain**
- **optical flashes found at old photo-plates**
- **compactness problem** (γ >1MeV $\Rightarrow$ e^+e^-)

<5% astronomers: extragalactic origin

Bohdan Paczyński, ...

- **deficit of weak bursts**
- **izotropic distribtion**

Today we know that all the arguments were irrelevant or false ...

False trails

- **Isotropic distribution**

  possible if GRB's are in the galactic halo

- **Spectral lines**

  probably deconvolution effect (inversion of matrix with elements having large errors)

  measured puls = γ energy $\times$ detector response

- **Repeatable optical flashes**

  1989 – reanalysis of the images by Anna Żytkow:
  „we should treat with great causion the suggestion, that the GRB are necessarily accompanied by optical flashes"

- **Deficit of weak bursts**

  detectors sensitive to maximum, not to total energy
  $\Rightarrow$ missing detection of long but low pulses

- **Burts in Magellanic Cloud 1979.03.05 at SN remnant**

  turned out to belong to a different class of γ bursts called Soft Gamma Repeaters (SGR)
  (Attention! SN's strike back 1998.04.25
  SGR's strike back 2004.12.27)

Soft Gamma Repeaters (SGR)

1986 – γ burst observed in place of the GRB 1979.01.07
- >100 bursts of this object found in old data in 1979-84
- most of them in 1983.11, some in groups, some single

Soon, more SGR discovered
- all in our Galaxy
- all at SN remnants ~10 000 years old
- X-ray oscillations found with ~8s period

Puzzle solved in 1998
- in 3 years, the period of SGR 1806-20 decreases by 0.008s
- reason – magnetic field calculated to be 10^{11} T !
- magnetar – neutron star withmagnetic field of ~10^{11} T
- fast rotation cause flattening and strong radiation
- energy loss slows down rotation
  and the star becomes more spherical
- shell breaking – „star quakes” cause gigantic magnetic
  storms observed as gamma burts

The Great Debate bis

1920.04.26 – The Great Debate
about distances in the Universe

What are nebulas?
Galaxies or objects in our Galaxy?
Harlow Shapley – Heber Curtis

1995.04.22 – The Great Debate 2
GRB are in our Galaxy
or in distant Universe?
Don Lamb – Bohdan Paczyński
Lead by: **Martin Rees**

Burst And Transient Source Experiment

1973 – Gerald Fishman heard the talk on VELA results and started to work on new γ detectors

1975 – 2 baloon flights of 12h: only solar γ

1980, 82 – flights 19+48h: 1 GRB / 40 expected

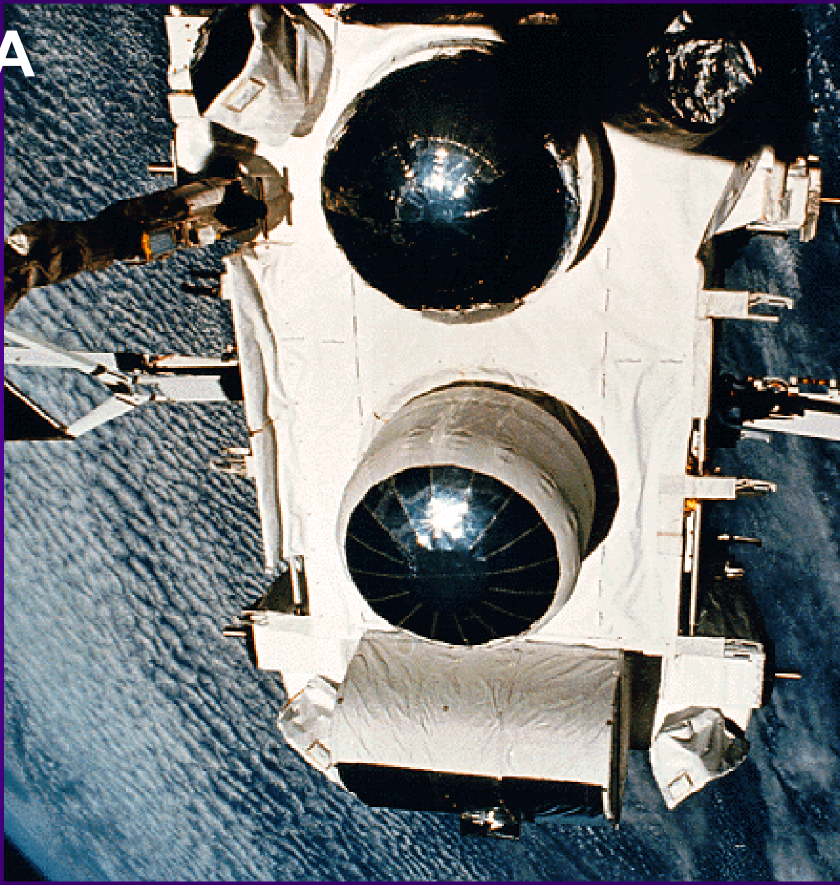
1978 – BATSE planned for GRO satellite in 1985

1991 – in orbit!

- **cost 12M$**
- **+ 400 manyear**
- **18 years preparation**
- **6 years delay**

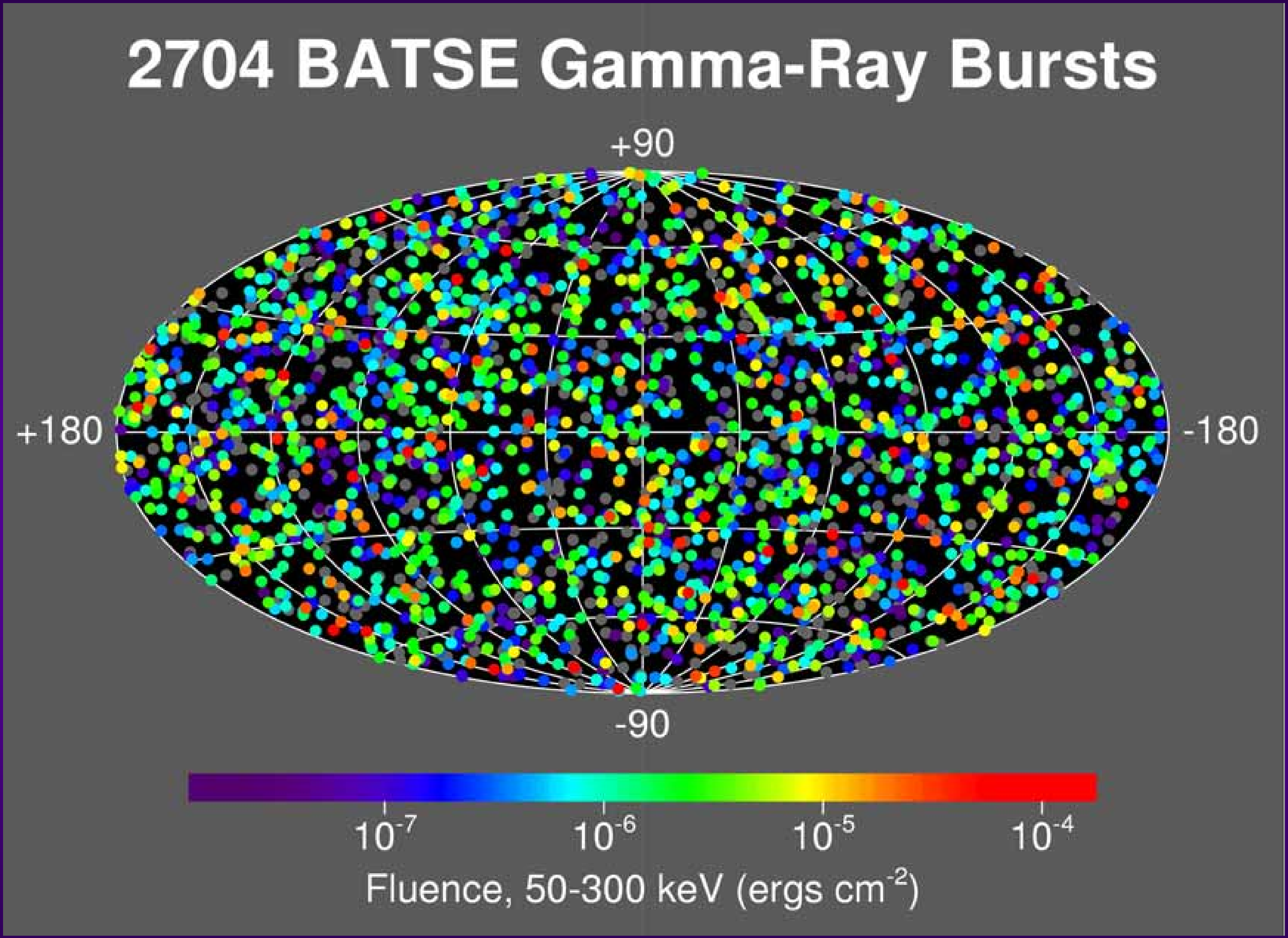
BATSE / GRO

Designed to record data on tape
and transmit while flying over USA
In 1992, tape recorders broken
NASA built telemetric stations
in Africa and Australia
Thanks to direct transmision
ground based telescopes could
immediately follow the bursts

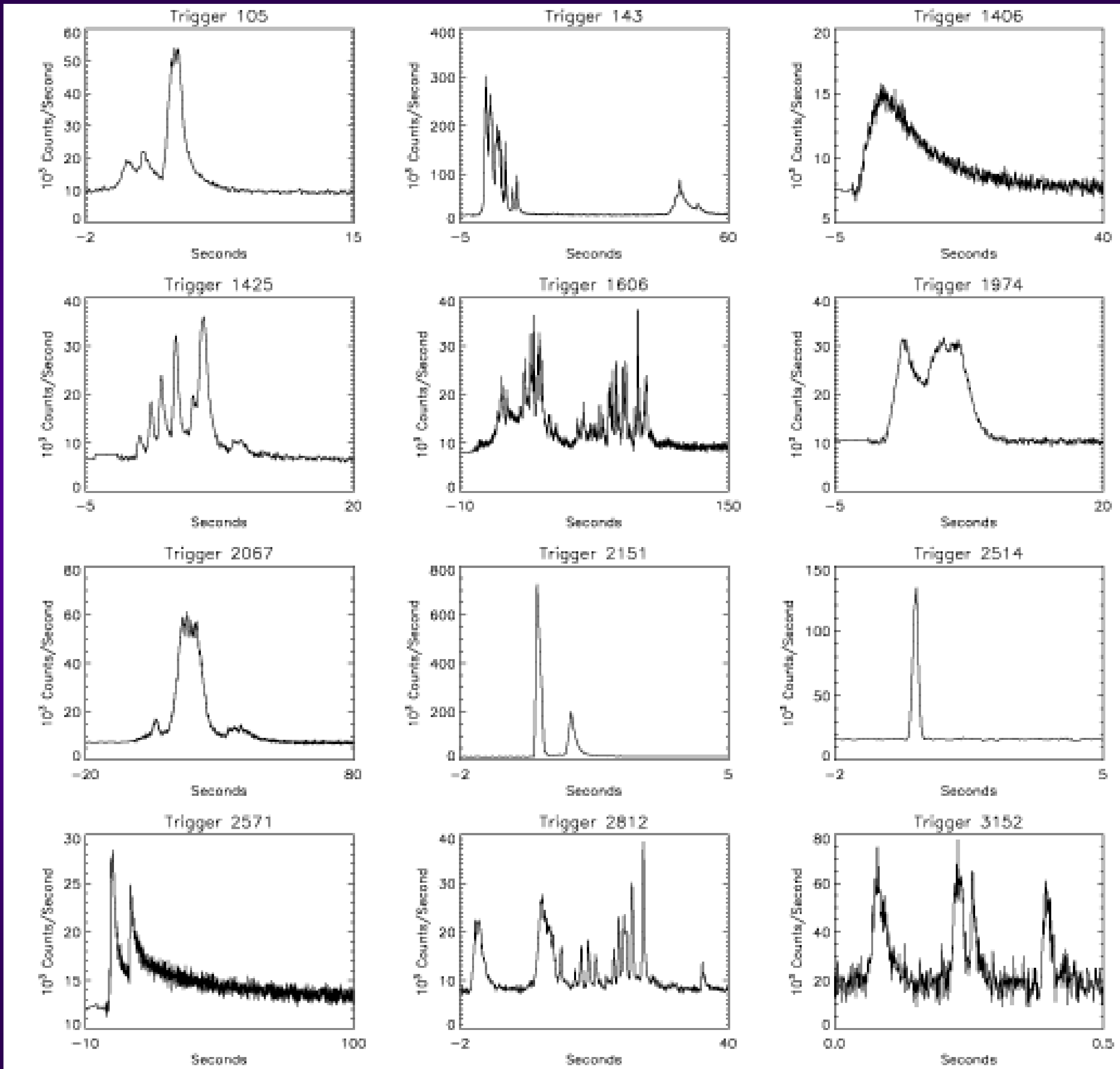


- discovered ~1 GRB daily
- GRB position: 4-10°
- ~3000 GRB observed

2000 – GRO was burned (for political reasons?) in spite of
perfect state of the apparatus and against scientists ☹



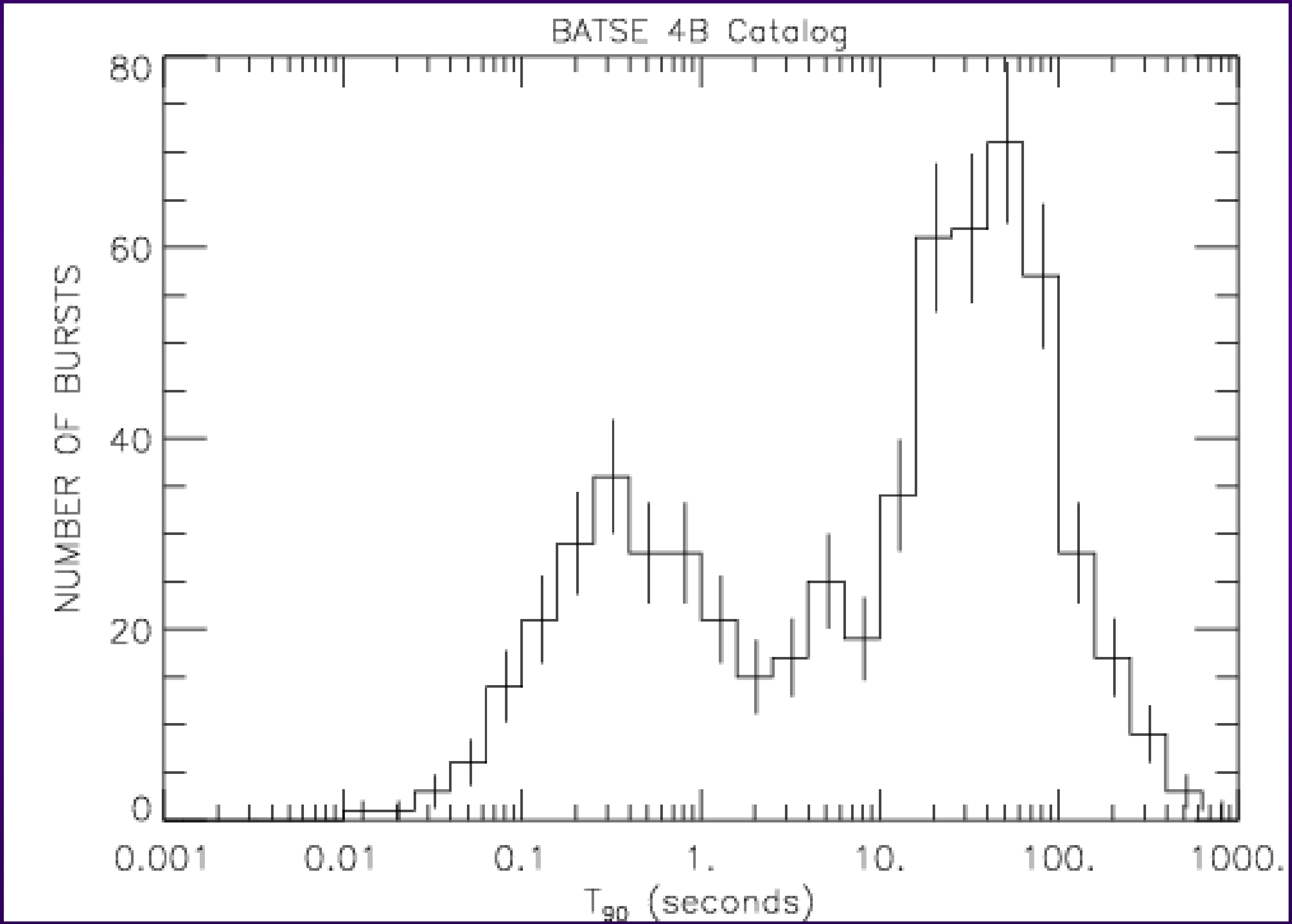
Izotropic distribution in galactic coordinates



Different shapes

Time: 0.01-100s

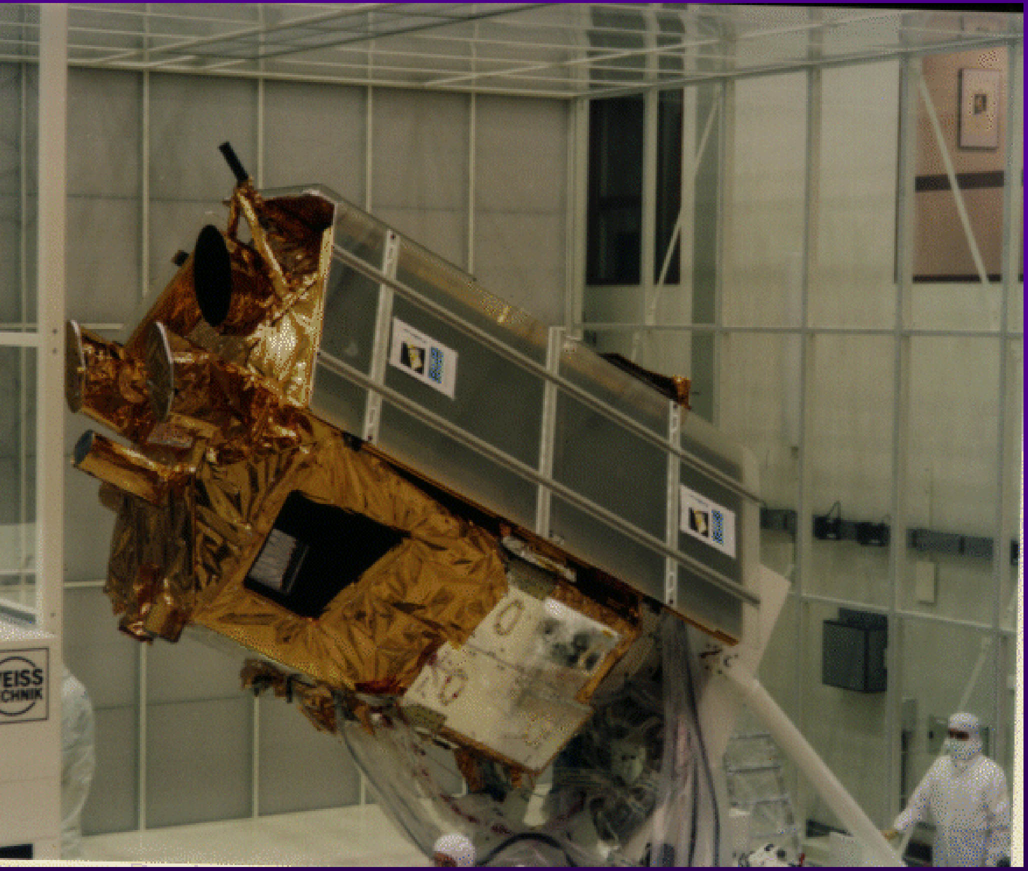
„Short” and „long” bursts



BeppoSAX

Italian-Dutch satellite launched in 1996

- **wide field (40°) X-ray camera**
- **precise (resolution 3’) X-ray camera**
- **γ-ray monitor**



- **1980 – project begins**
- **1986 – planned launch**
- **1996 – in orbit!**

- **10 years delay**
- **planned cost 28 M$**
- **actual cost:**
  - **200 M$ satellite**
  - **150 M$ launch**

  + telemetric stations

Run for the flash

1996.04.30 – BeppoSax in orbit

1996.07.20 – the first GRB seen in X-rays

1996 ... – many GRB, nothing in X (camera = 2% sky)

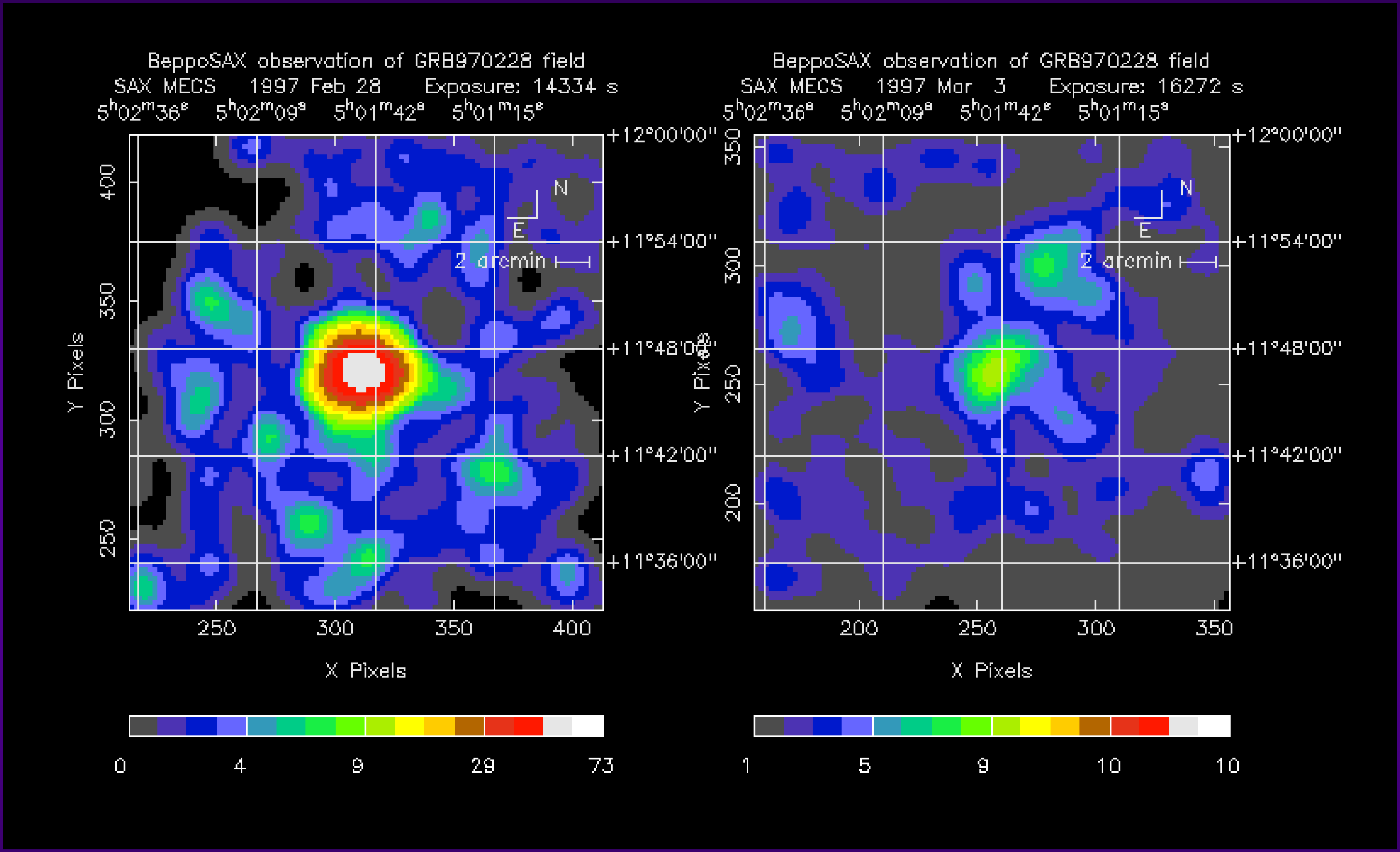
1997.01.11 – GRB + X-ray source

- **VLA radiotelescope: fading radio souce**
- **KECK telescope (10 m): galaxy**
- **articles submitted to Nature**
- **just before printing, the results turned out to be false**

1997.02.28 – strong GRB + X

- **Dutch team discovers optical afterglow**
  7 weeks later the paper published in Nature
- **Italian paper on GRB+X published 2 months later,**
  because the English required a lot of corrections

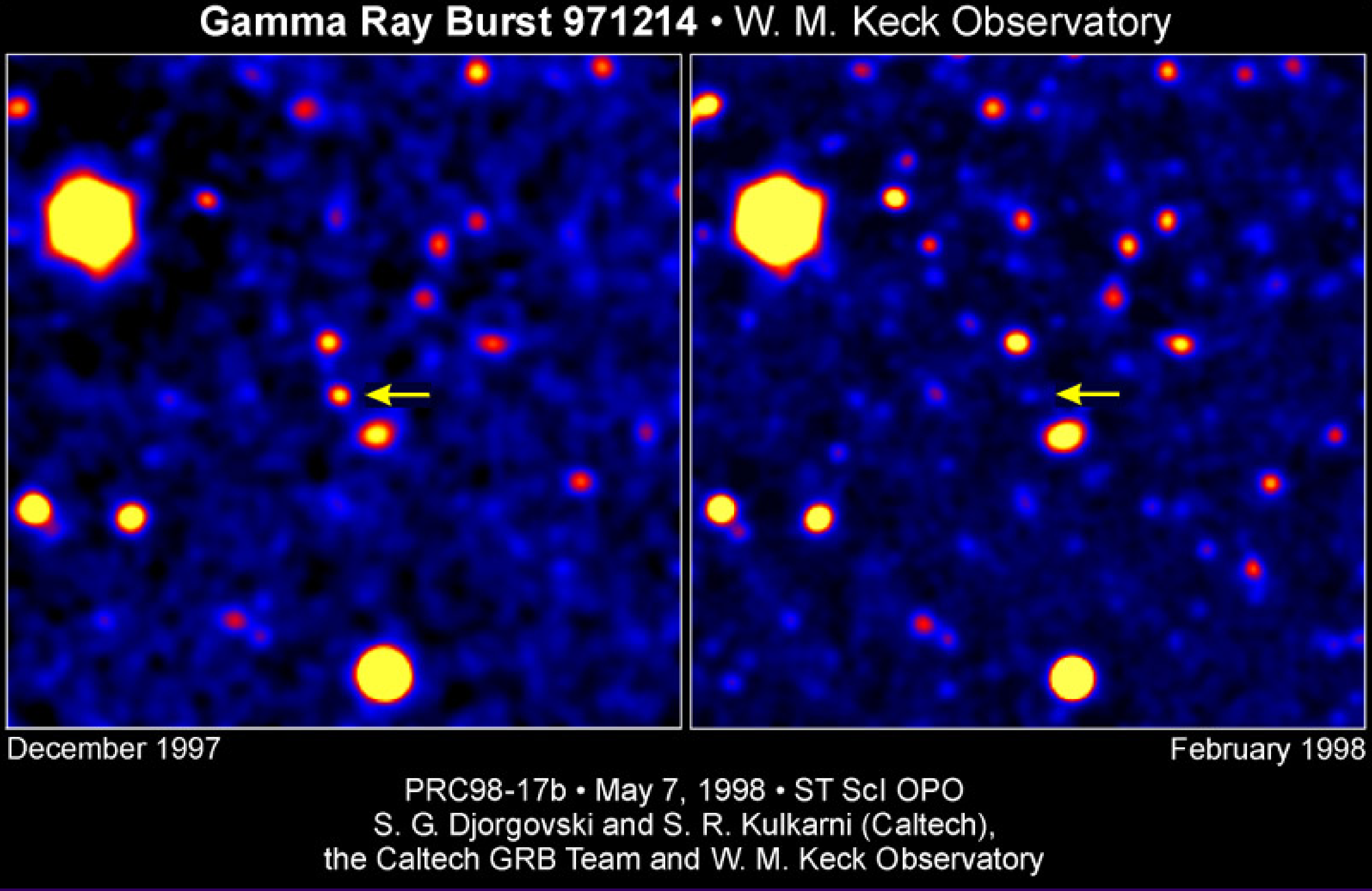
First afterglows

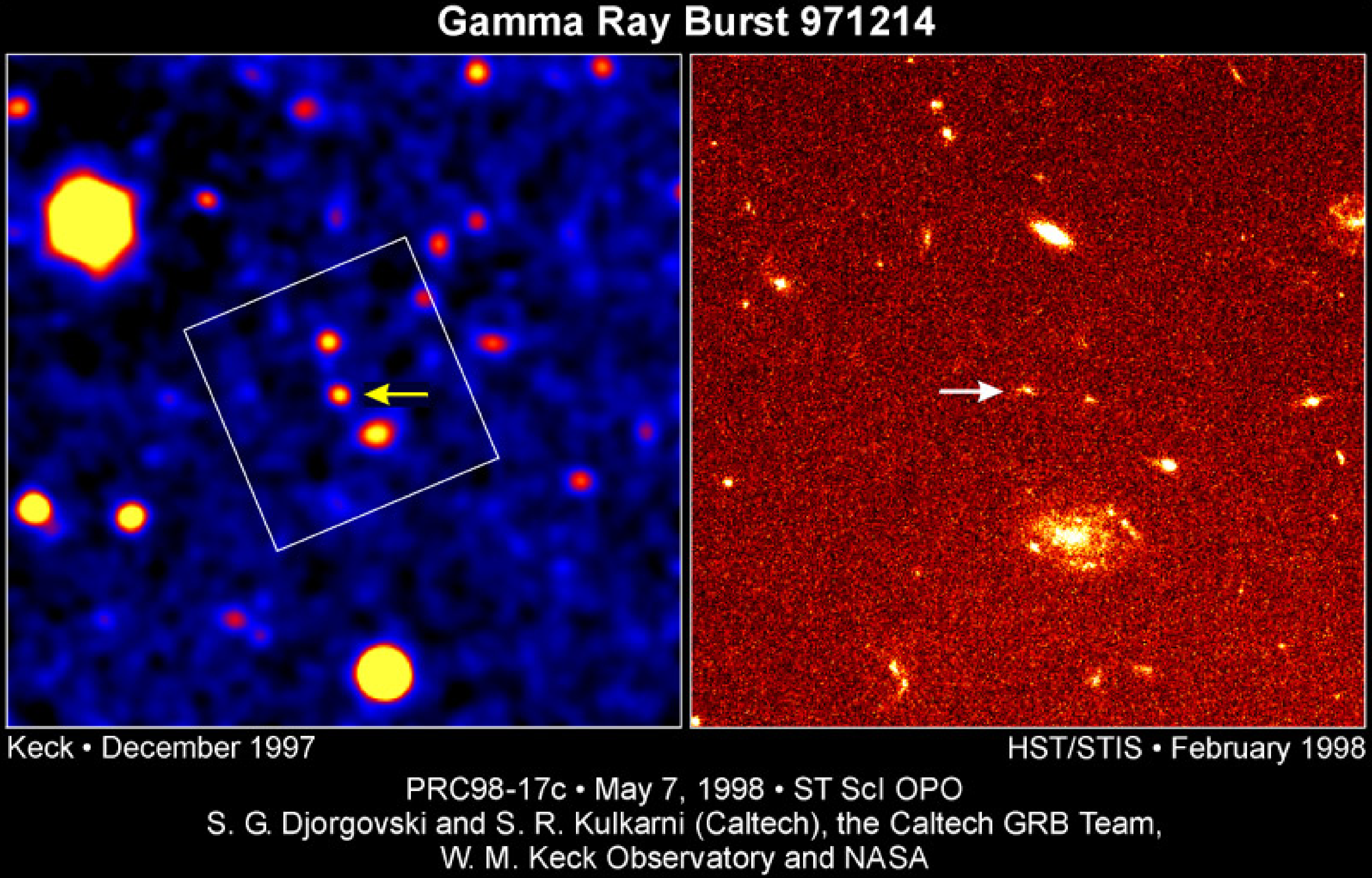


1997.02.28 – GRB observed in X-rays

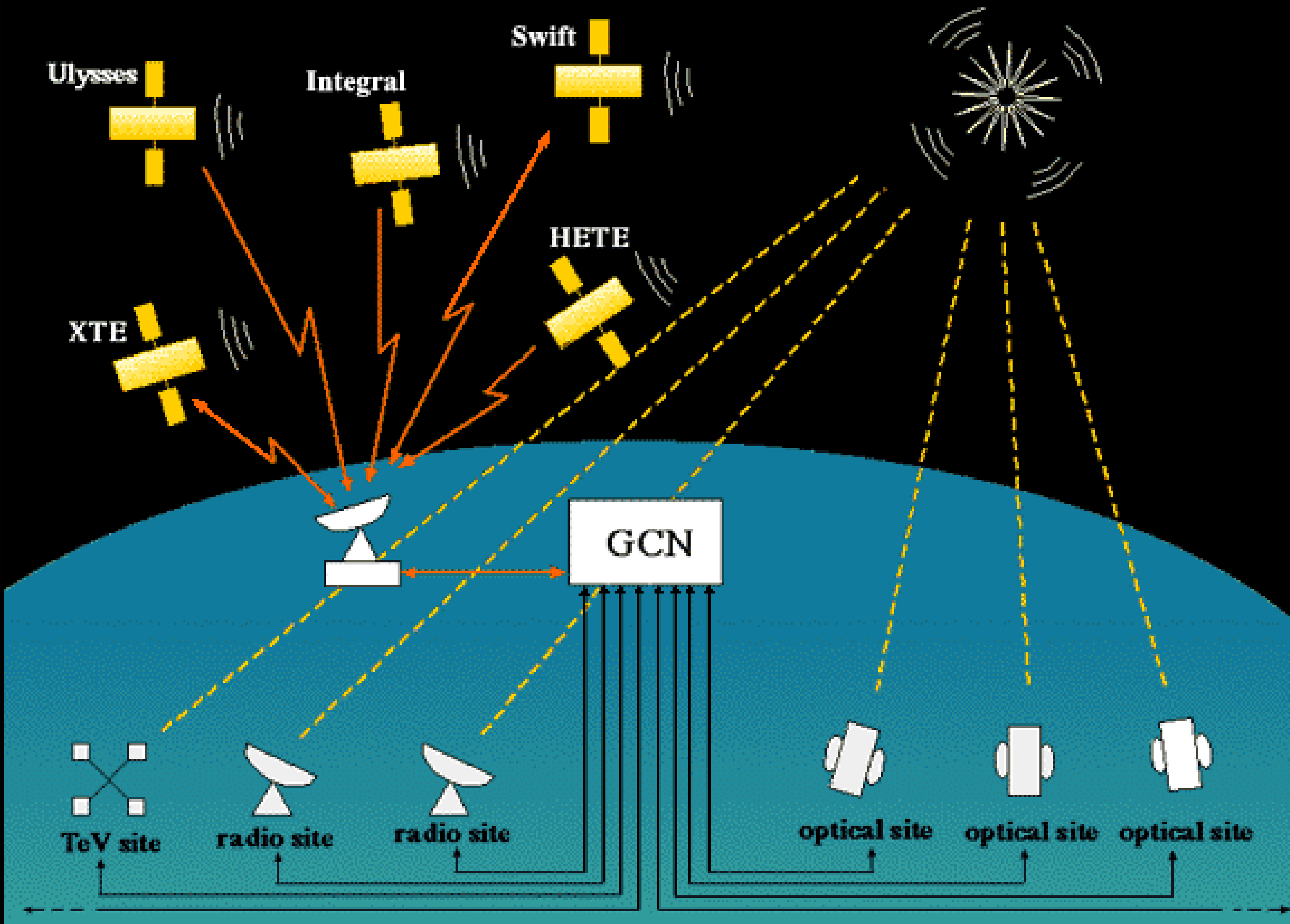
21 h later – optical observation

William Herschel Telescope, 4.2m, La Palma


Gamma Ray Burst 971214 • W. M. Keck Observatory
December 1997
February 1998
PRC98-17b • May 7, 1998 • ST ScI OPO
S. G. Djorgovski and S. R. Kulkarni (Caltech),
the Caltech GRB Team and W. M. Keck Observatory


Gamma Ray Burst 971214
Keck • December 1997
HST/STIS • February 1998
PRC98-17c • May 7, 1998 • ST ScI OPO
S. G. Djorgovski and S. R. Kulkarni (Caltech), the Caltech GRB Team,
W. M. Keck Observatory and NASA

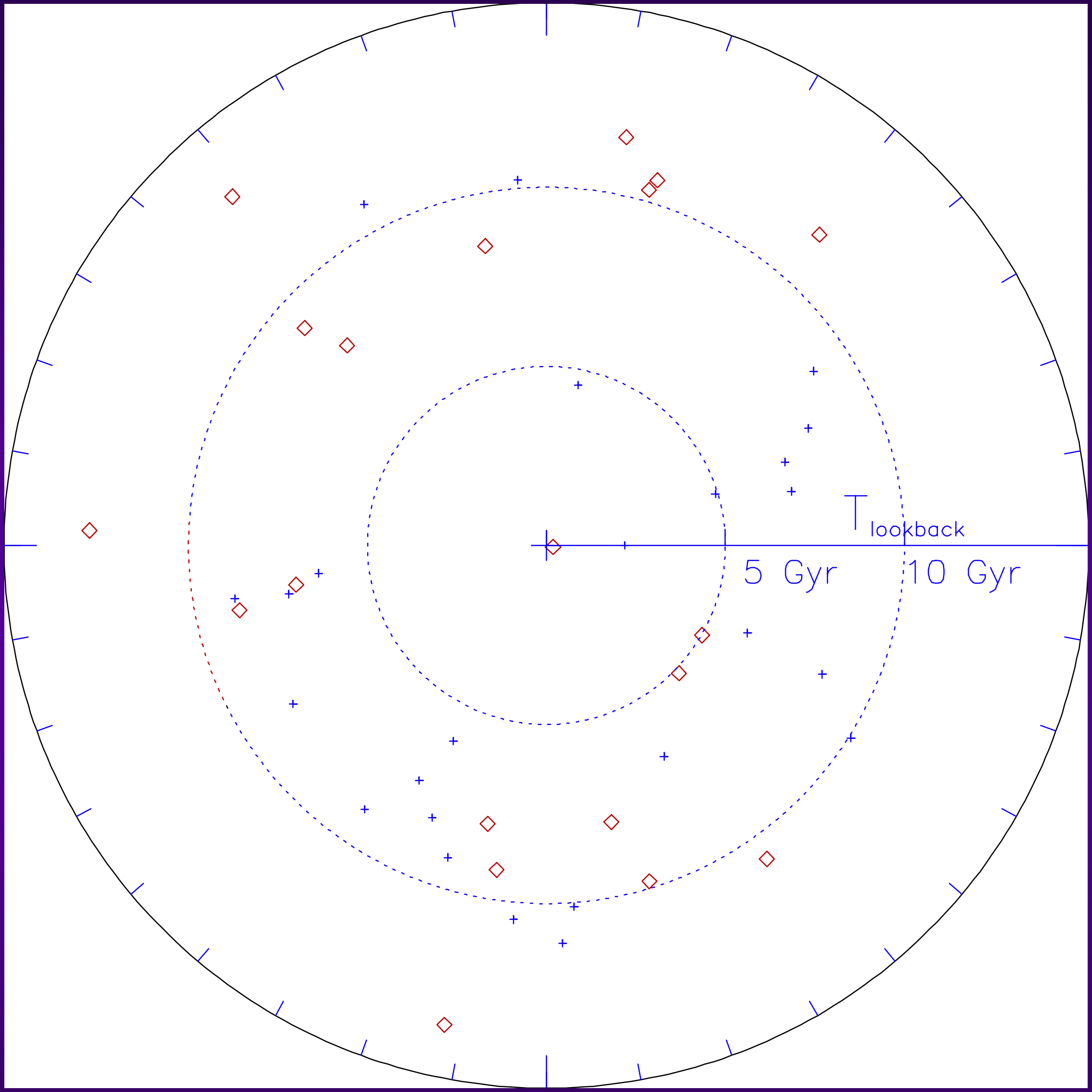
GRB Coordinate Network (GCN)



Distances

up to z=4.5
⇒ $13 \cdot 10^9$ light years

could be used
to probe Universe
farther than SN



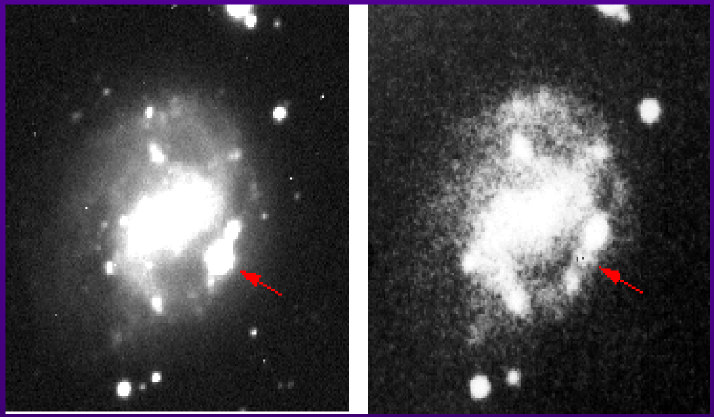
GRB's projected on galactic plane

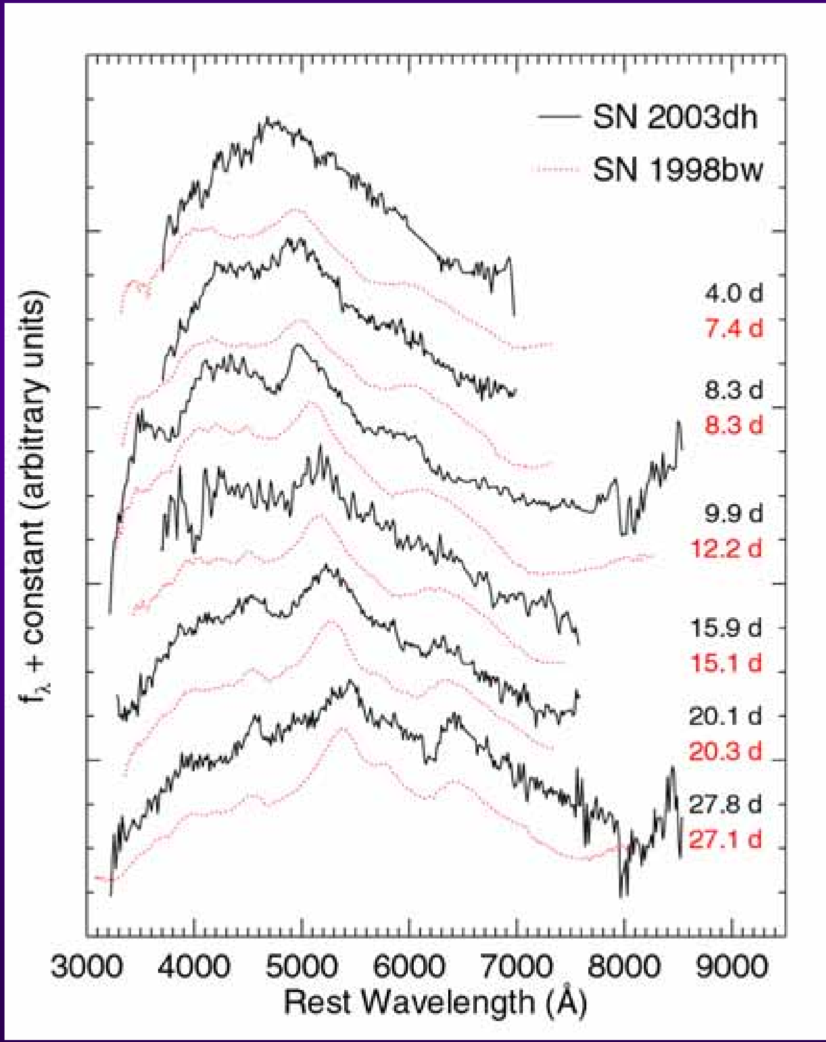
visible Universe radius ≈14G light years

Supernowa SN1998bw

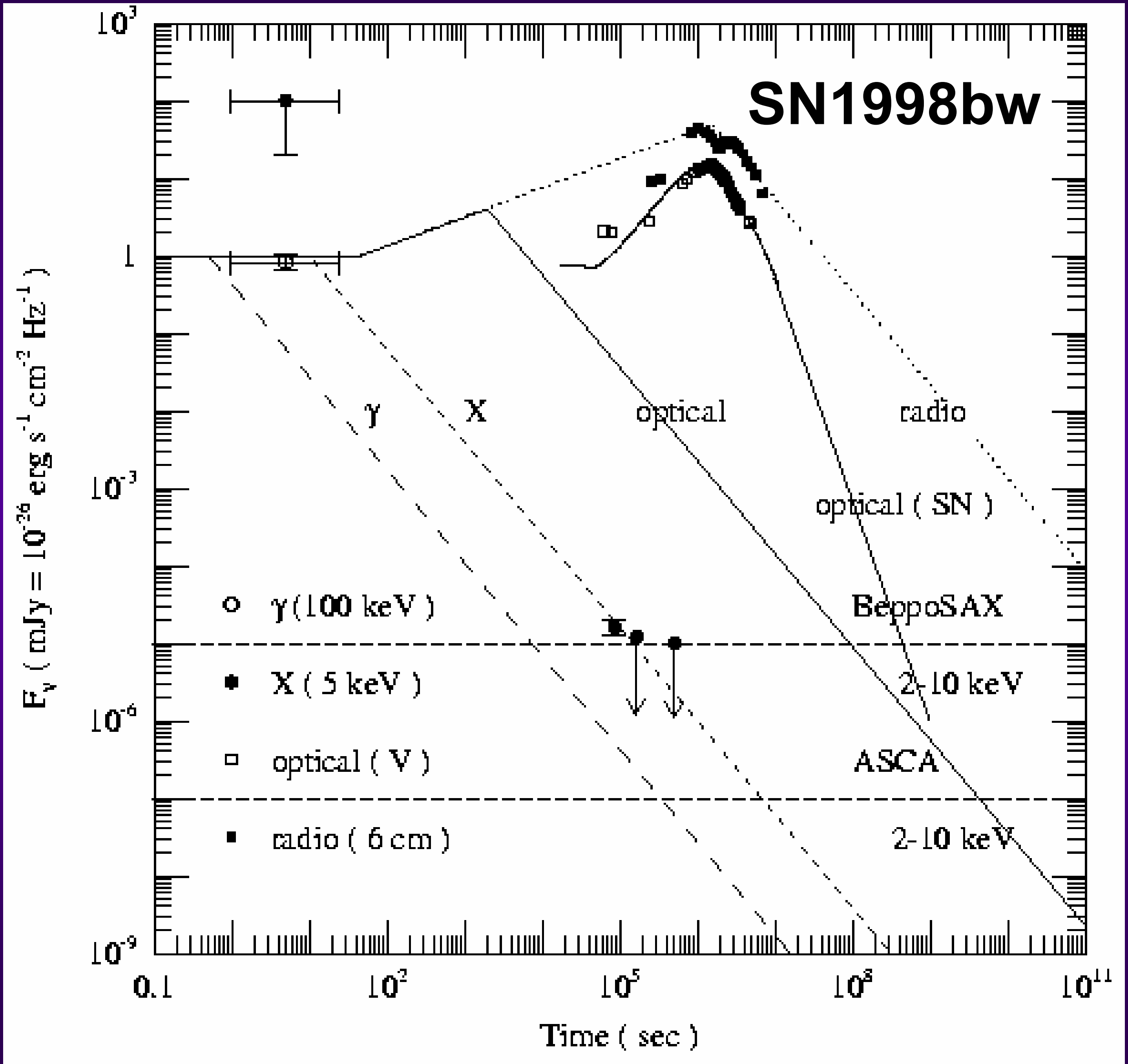
1998.04.25 – GRB discovered by BeppoSAX

- very bright afterglow – 14^m
  (all so far $>20^m$)
- SN-like spectrum
- max. after 2 weeks

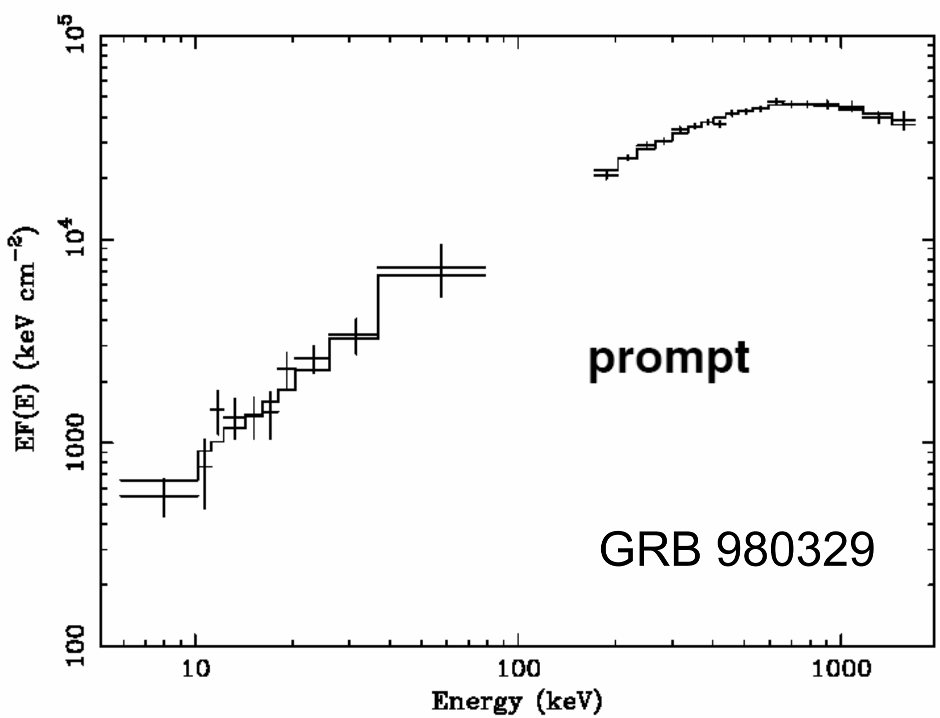


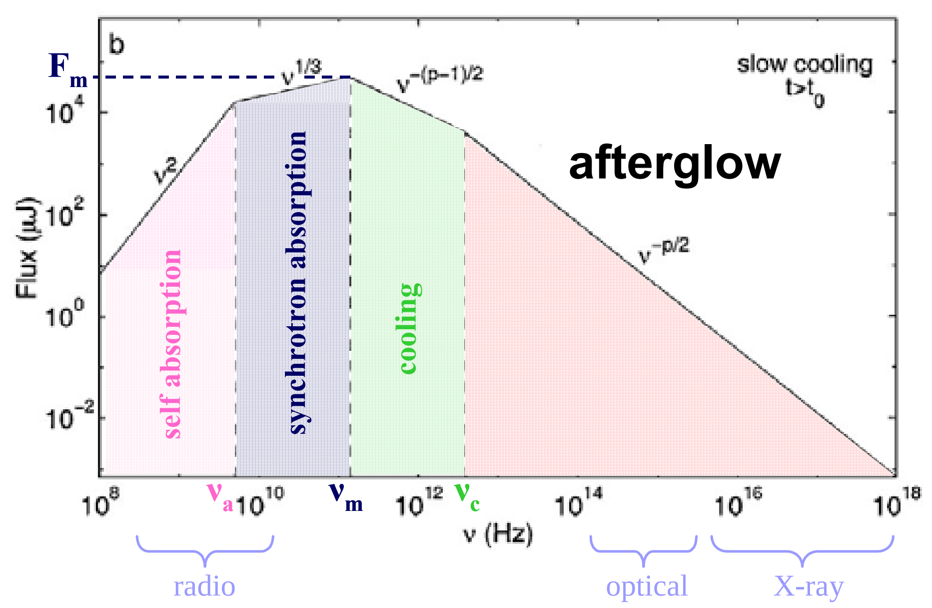


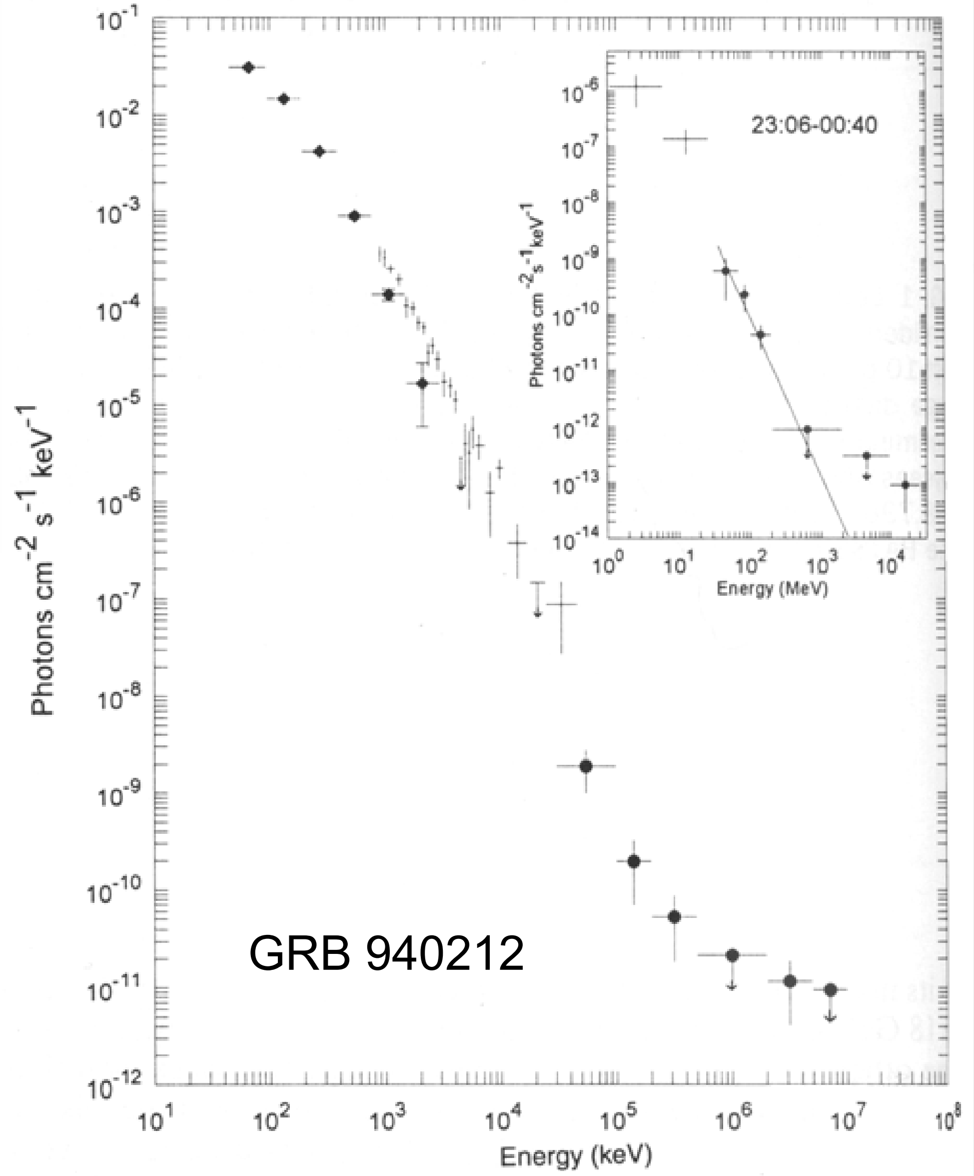
Several GRB-SN pairs found so far


SN1998bw
γ
X
optical
radio
optical (SN)
γ (100 keV)
X (5 keV)
optical (V)
radio (6 cm)
BeppoSAX
2-10 keV
ASCA
2-10 keV
Time (sec)
0.1
10^2
10^5
10^8
10^{11}
10^3
1
10^{-3}
10^{-6}
10^{-9}
F_ν (mJy = 10^{-26} erg s^{-1} cm^{-2} Hz^{-1})

GRB spectrum



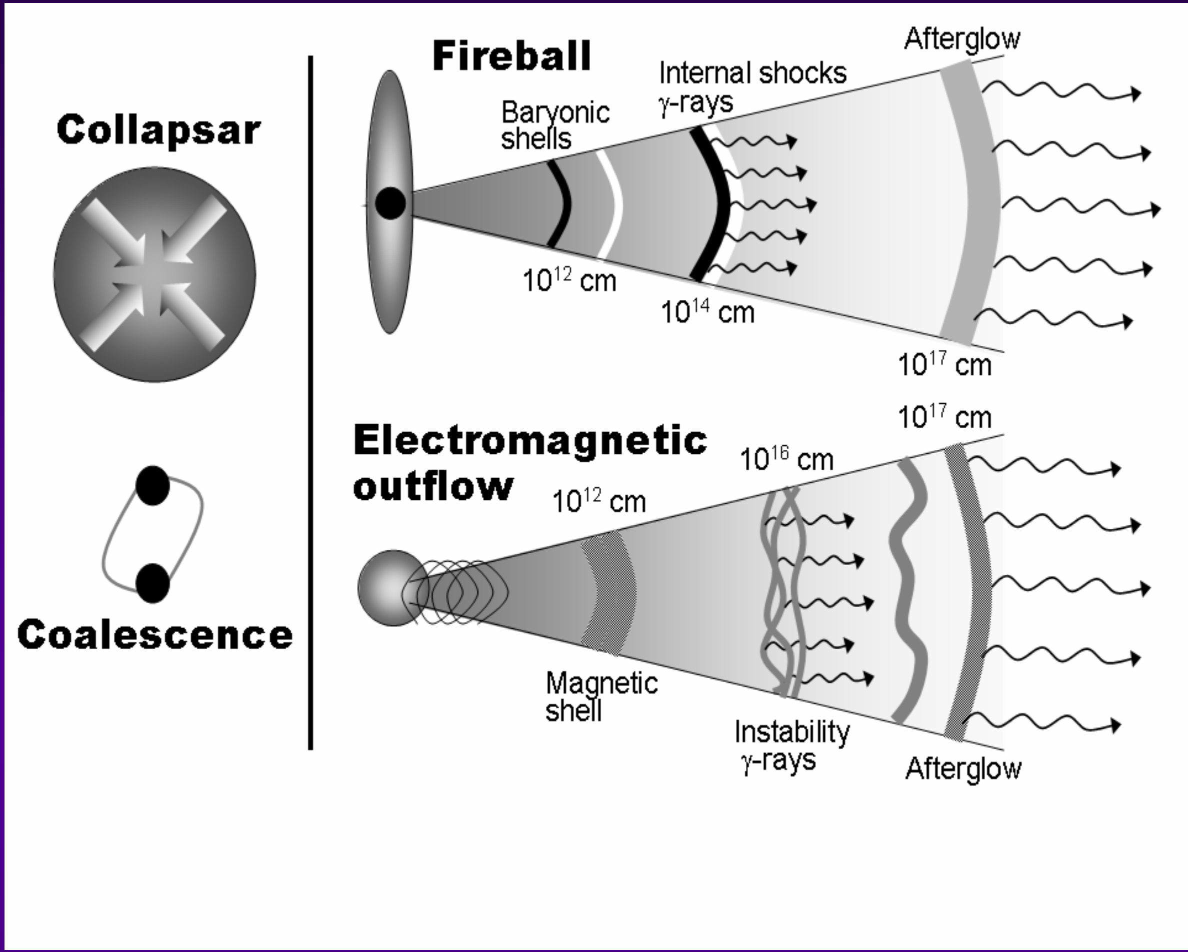




Central engines

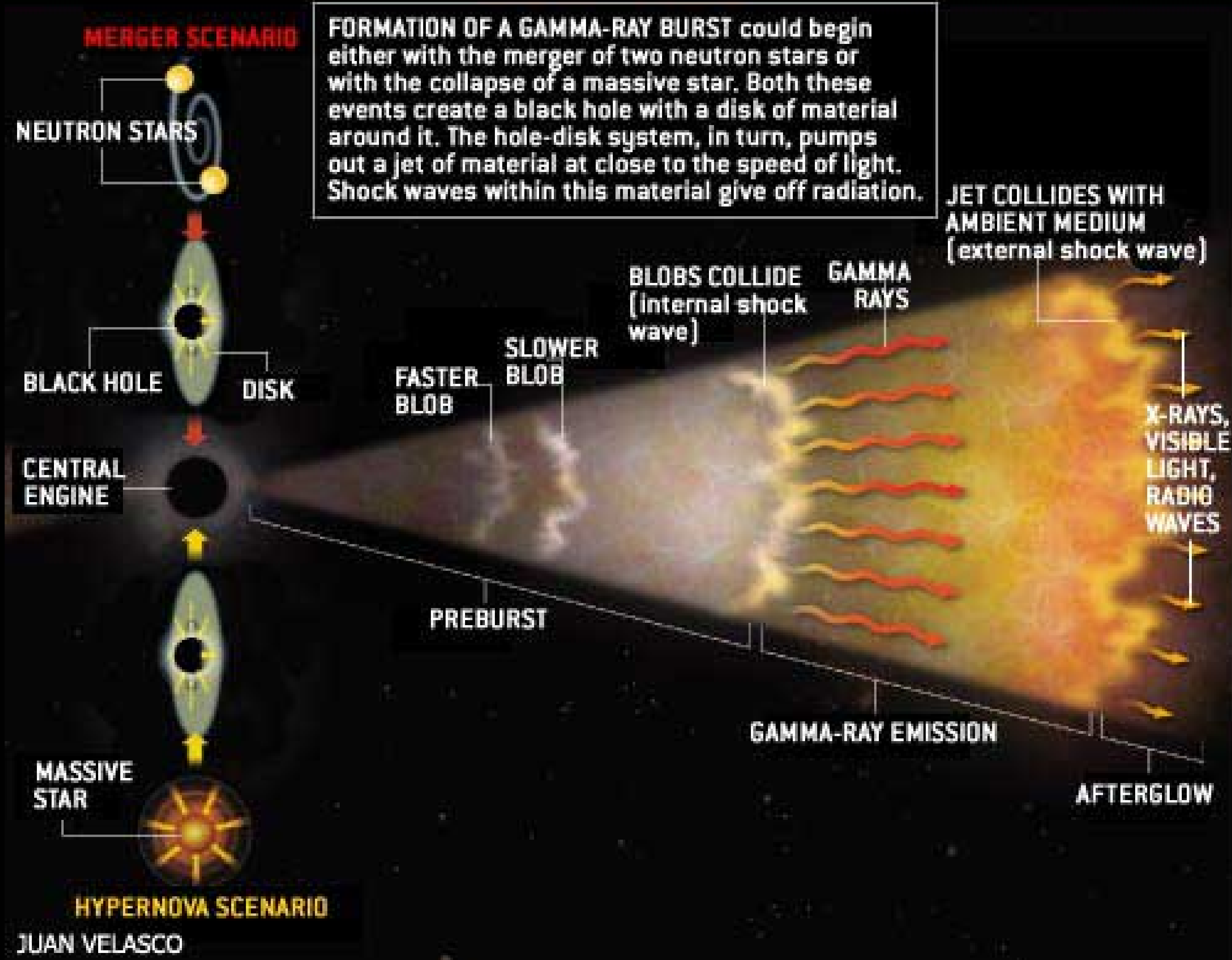
Collapsar (hypernova)
big, rotating star collapsing to neutron star and/or black hole
(long bursts?)

Coalescence (merger)
of two neutron stars or NS and BH
(short burts?)

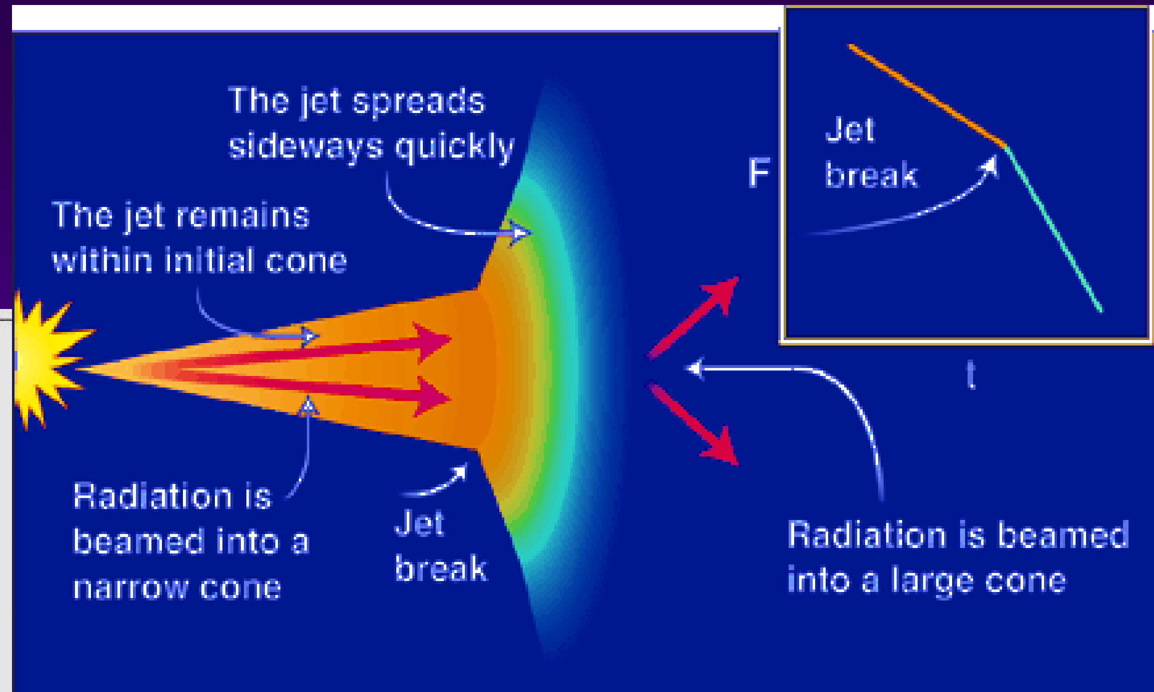


Engine → energy transport → conversion to γ–rays → afterglow

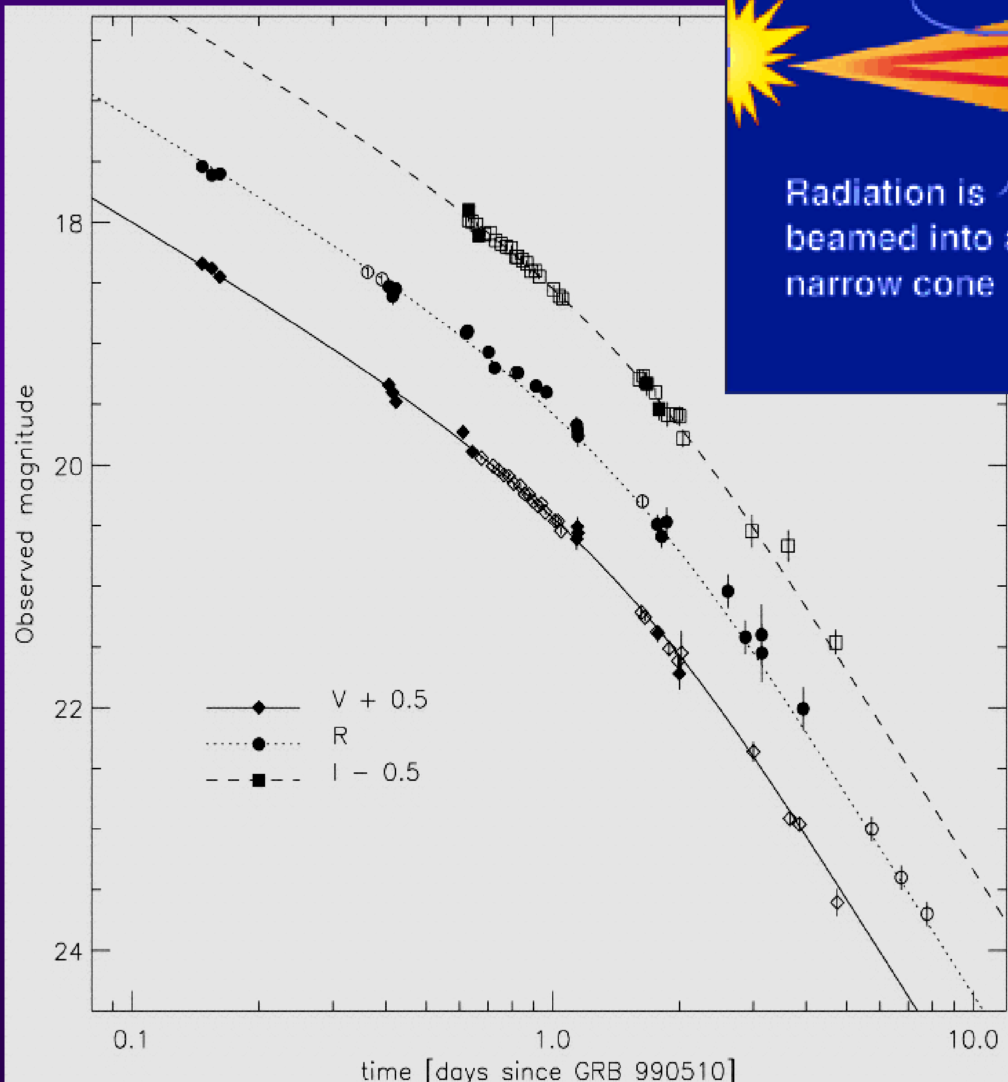
Engine	Energy transport	Conversion to γ–rays	Afterglow
Collapsar Coalescence	Baryonic Magnetic	Internal Shocks Magnetic instability	External Shock


MERGER SCENARIO
FORMATION OF A GAMMA-RAY BURST could begin either with the merger of two neutron stars or with the collapse of a massive star. Both these events create a black hole with a disk of material around it. The hole-disk system, in turn, pumps out a jet of material at close to the speed of light. Shock waves within this material give off radiation.
NEUTRON STARS
JET COLLIDES WITH AMBIENT MEDIUM (external shock wave)
BLOBS COLLIDE (internal shock wave)
GAMMA RAYS
SLOWER BLOB
FASTER BLOB
BLACK HOLE
DISK
X-RAYS, VISIBLE LIGHT, RADIO WAVES
CENTRAL ENGINE
PREBURST
GAMMA-RAY EMISSION
MASSIVE STAR
AFTERGLOW
HYPERNOVA SCENARIO
JUAN VELASCO

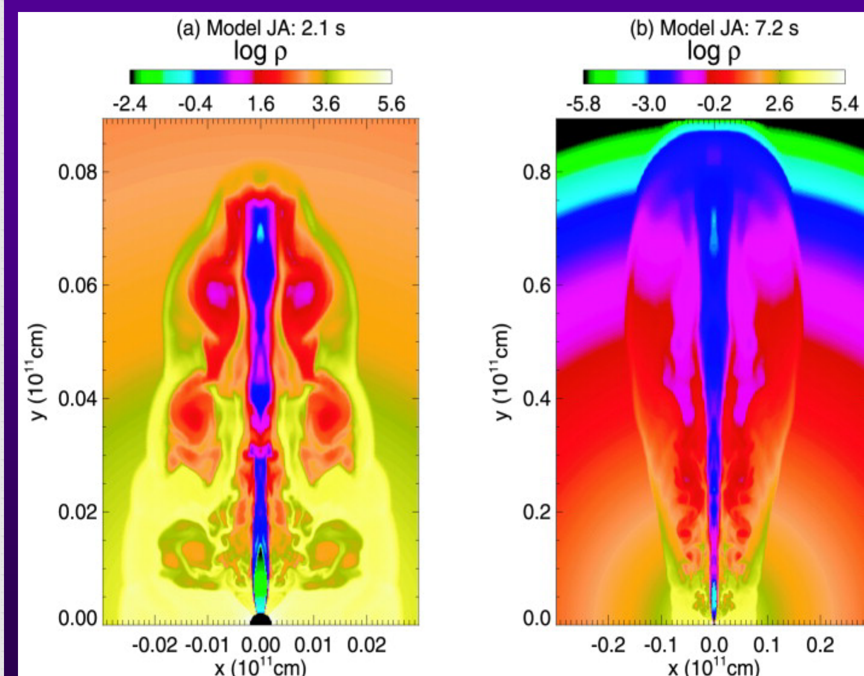
Jets



The jet spreads sideways quickly
The jet remains within initial cone
Radiation is beamed into a narrow cone
Jet break
Radiation is beamed into a large cone
F
Jet break
t



Observed magnitude
18
20
22
24
0.1
1.0
10.0
time [days since GRB 990510]
V + 0.5
R
I − 0.5



(a) Model JA: 2.1 s
log ρ
-2.4 -0.4 1.6 3.6 5.6
y (10^11 cm)
0.00 0.02 0.04 0.06 0.08
-0.02 -0.01 0.00 0.01 0.02
x (10^11 cm)
(b) Model JA: 7.2 s
log ρ
-5.8 -3.0 -0.2 2.6 5.4
y (10^11 cm)
0.0 0.2 0.4 0.6 0.8
-0.2 -0.1 0.0 0.1 0.2
x (10^11 cm)

Rejected proposals

1974 – Paul Boynton proposed to search for GRB optical couterparts with vidicon
NSF: „failed to show that they would, in fact, observe anything”

1983 – MIT: Explosive Transient Camera
(16 cameras = 43% sky, d=25mm)
Raipdly Moving Telescope, d=180mm
rejected by NFS, descoped version in 1991
software not able to deal with huge background

1993 – Scott Barthelmy (NASA) creates
BAtse COorDInate NEtwork
and proposes project GTOTE – rejected by NASA

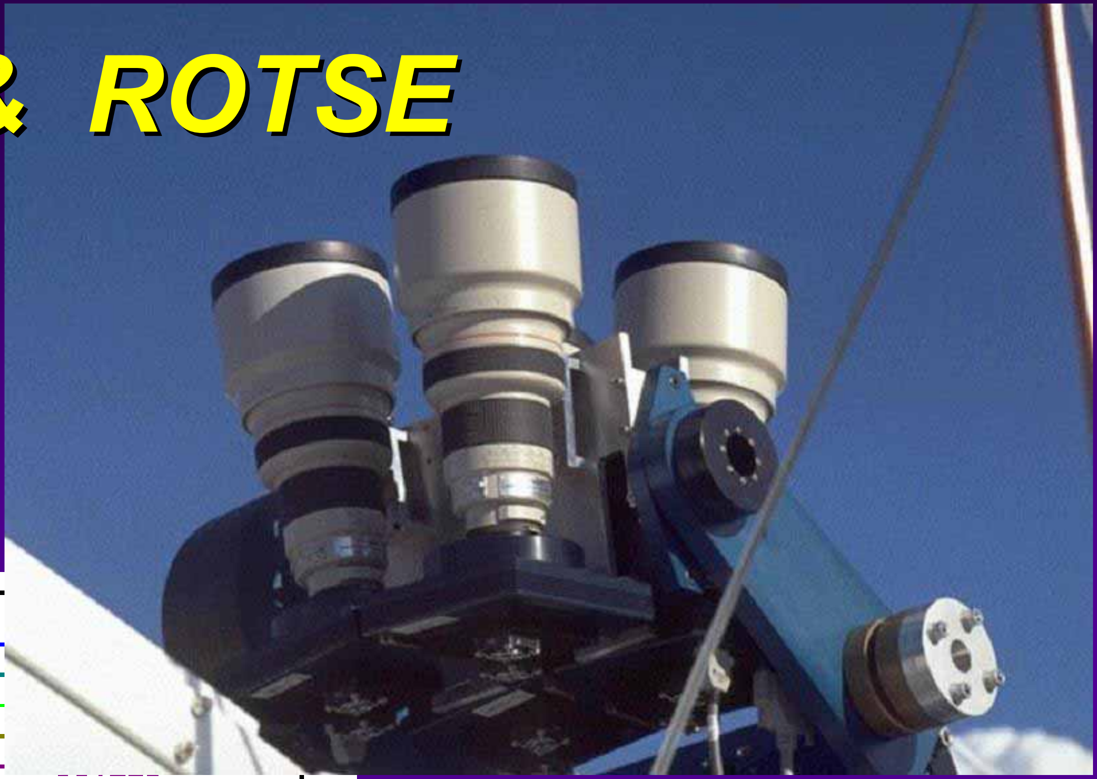
~1989 – Lawrence Livermore NL works on camera for „Star Wars” defence system. Project terminated.

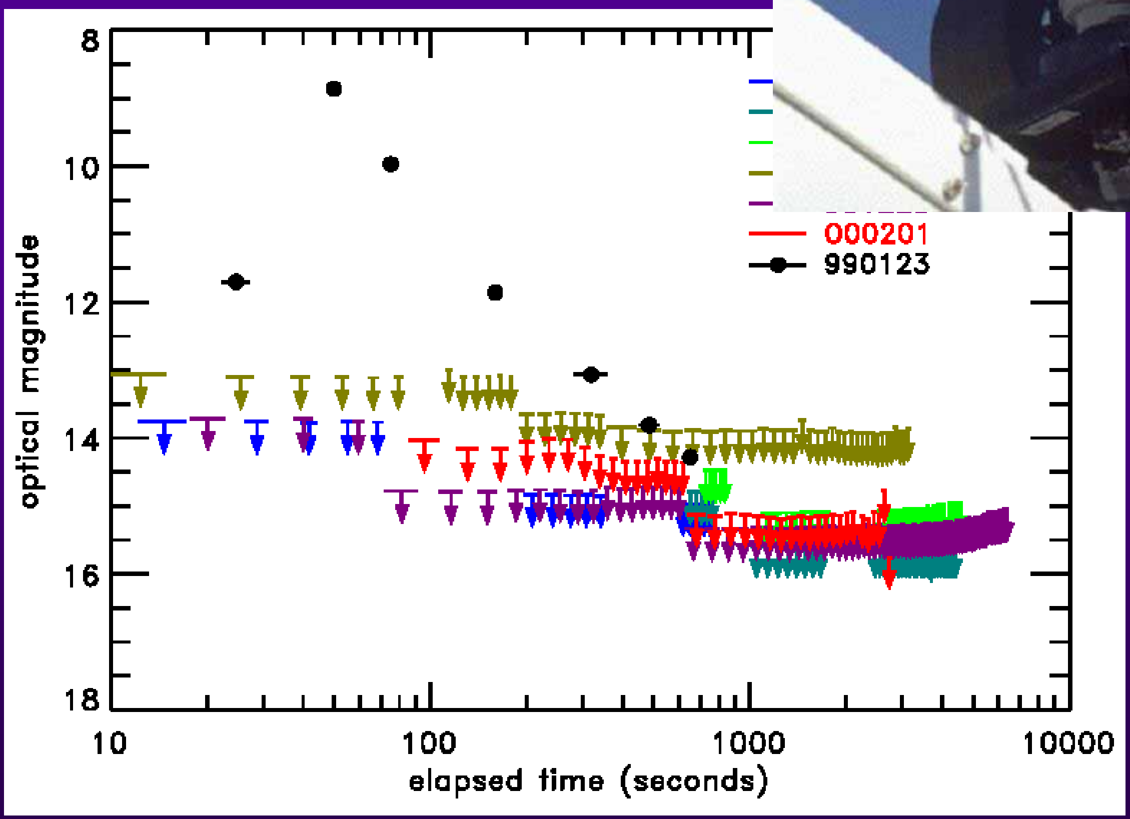
Salomon judgement ?

- 1992 – Carl Akerlof, particle physicist (e.g. MACHO) goes to LLNL
- Someone told him about „Star Wars" camera
- The camera became the GROCSE detector nothing interesting has been observed
- 1994-95 – propozal GROCSE-II rejected by NFS 4x
- 1996 – conflict in the team camera divided between two groups
  - Livermore group builds LOTIS
  - Los Alamos group builds ROTSE
- 1999.01.23 – BATSE sends GRB alert
  - clouds over Livermore
  - clear skies over Los Alamos ...

BATSE & ROTSE

4 telephoto lenses
CANON d=10 cm
robotic mount
follows GCN alerts





Images 1999.01.23
20 s after BATSE alert

Optical flash 9^m !
could be seen by binocular!

The brightest so far

HETE satellites

1983 – project begins
1994 – planned launch

Pegasus XL rocket has 2 crushes out of 5 launches

cost 14.5M$, 17 years work
6 years delay

1996.11.04
HETE launched, but trapped inside the rocket & destroyed ☹

2000.10.09
Launch of HETE-2
field of view 50°×50°

Sweat, blood and tears ...

VELA satellites observed nothing over 4 years
New satellites & 6 year work resulted in 16 GRB

Pre-BATSE after 7 years: 1 GRB instead of 40
BATSE: 18 years preparation, 6 years delay

BeppoSAX: 16 years preparation, 10 years delay
The first optical afterglow: 1 year after launch

Optical observations: 15 years of rejecting grants
ETC+RMT: nothing, GROCSE: nothing, ...
ROTSE: 10 years work, 1 flash 20s after GRB990123

HETE: 17 years preparation, 6 years delay
rocket crushes, first satellite destroyed

GRB 030329 = SN 2003 dh

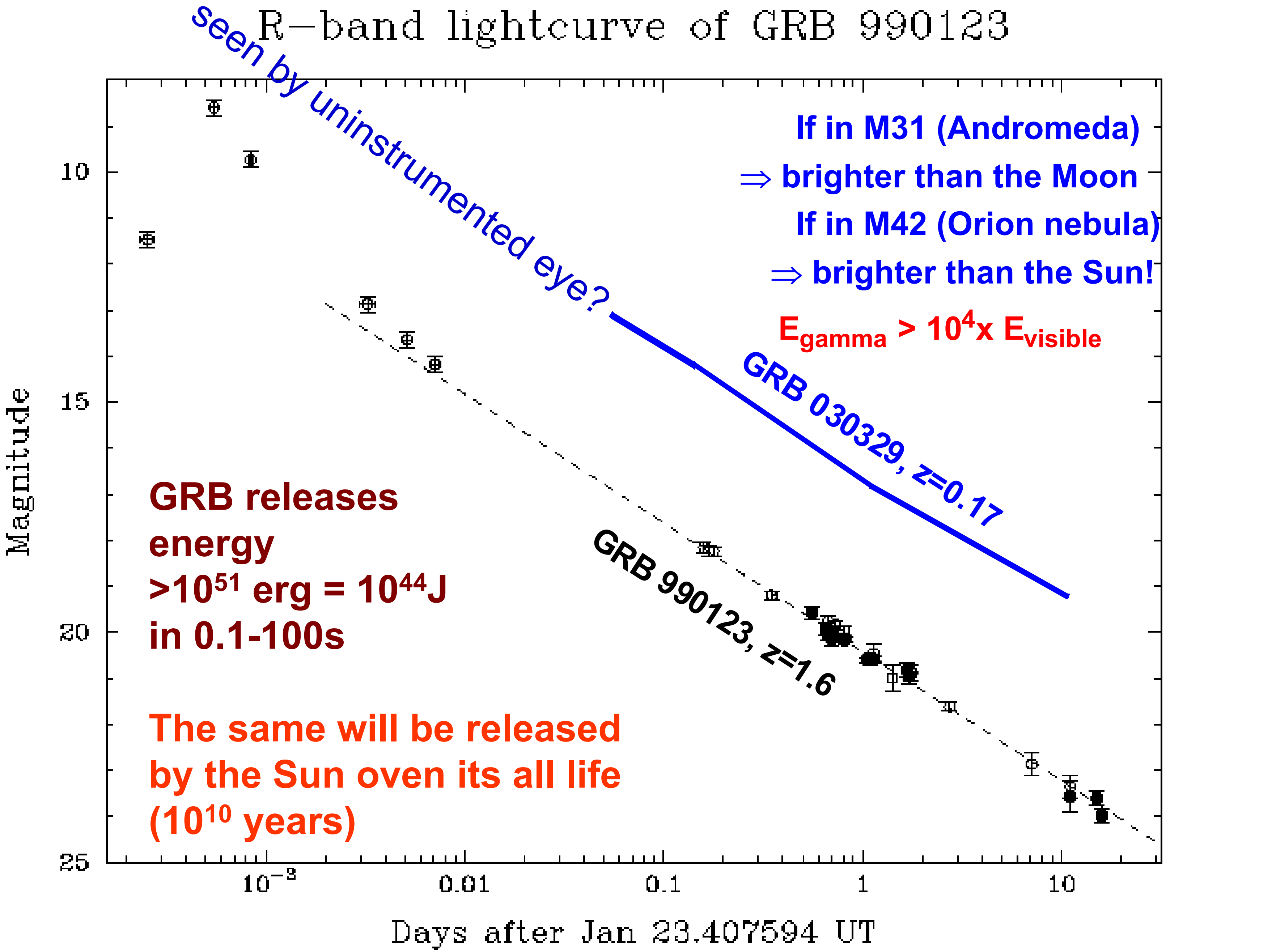
Triggered by HETE

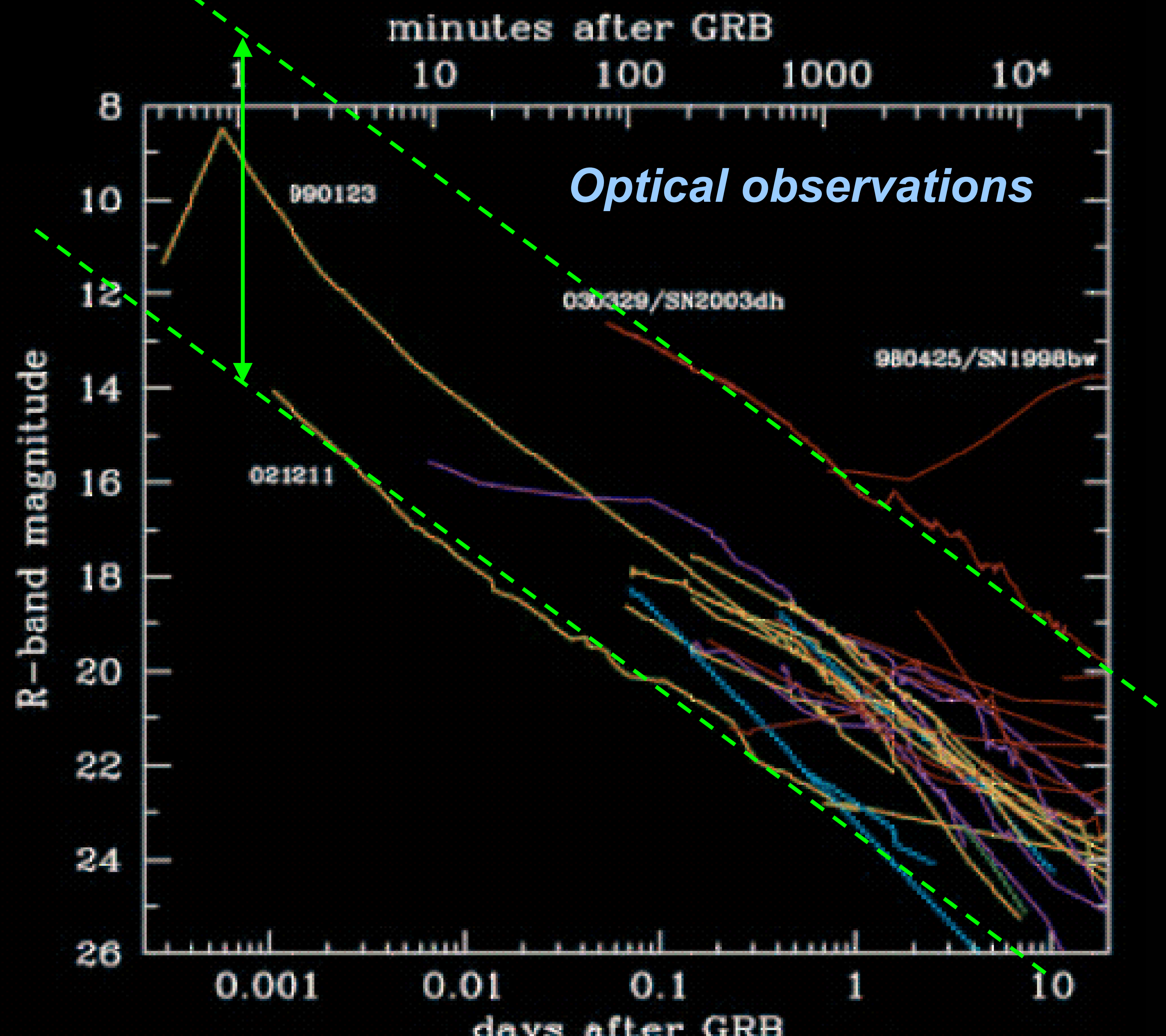
1 h 16 min after GRB: 13^m

1 h 15 min after GRB: 13^m

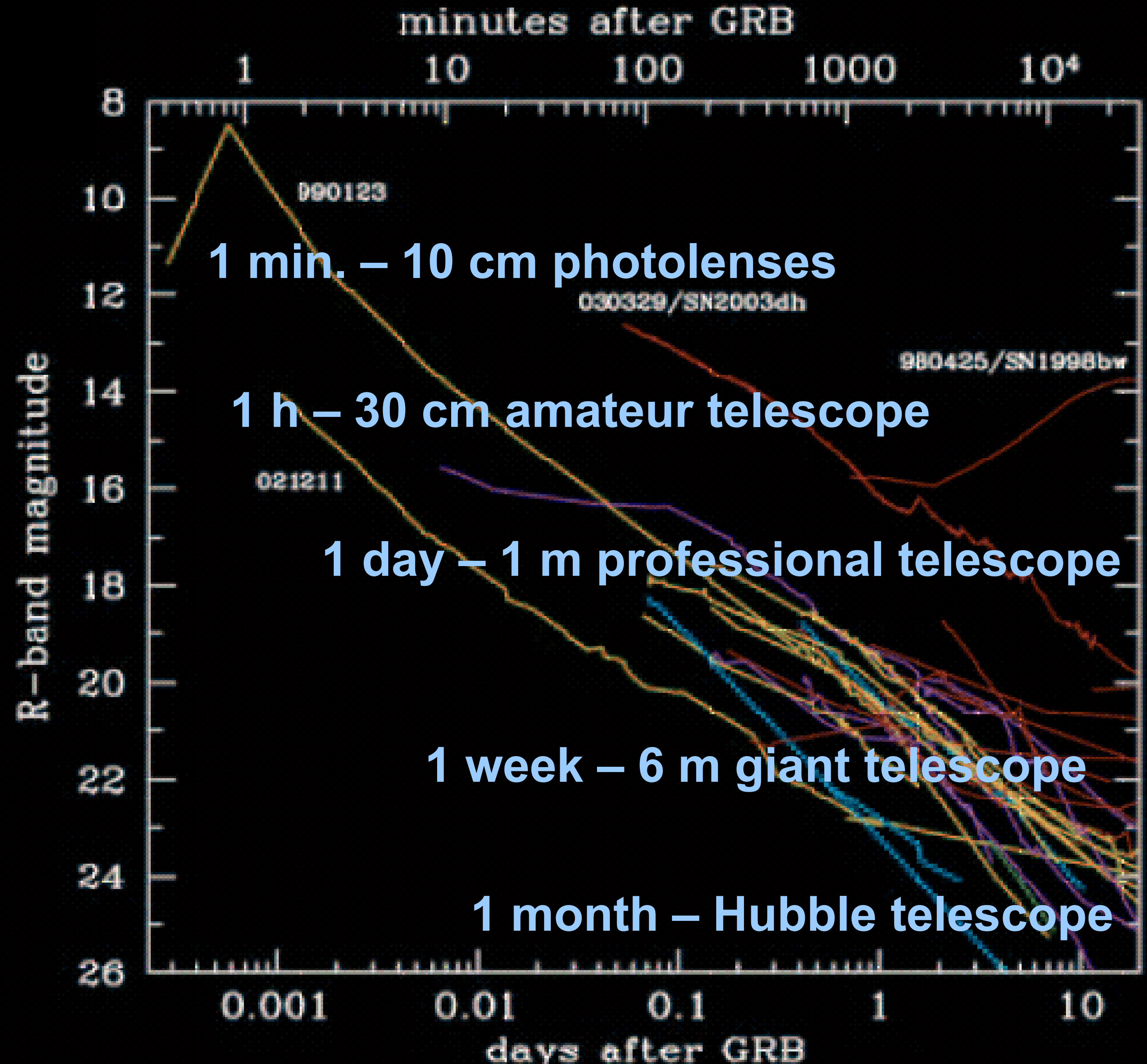
Riken, d = 25 cm

Kyoto, d = 30 cm


R-band lightcurve of GRB 990123
seen by uninstrumented eye?
If in M31 (Andromeda)
⇒ brighter than the Moon
If in M42 (Orion nebula)
⇒ brighter than the Sun!
$E_{gamma} > 10^4 x E_{visible}$
GRB 030329, z=0.17
GRB 990123, z=1.6
GRB releases energy
$>10^{51}$ erg = 10^{44}J
in 0.1-100s
The same will be released
by the Sun oven its all life
(10^{10} years)
Magnitude
10
15
20
25
10^{-3}
0.01
0.1
1
10
Days after Jan 23.407594 UT



minutes after GRB
1
10
100
1000
10⁴
Optical observations
990123
030329/SN2003dh
980425/SN1998bw
021211
R-band magnitude
8
10
12
14
16
18
20
22
24
26
0.001
0.01
0.1
1
10
days after GRB


minutes after GRB
1
10
100
1000
10⁴
8
10
12
14
16
18
20
22
24
26
R−band magnitude
090123
030329/SN2003dh
980425/SN1998bw
021211
0.001
0.01
0.1
1
10
days after GRB
1 min. – 10 cm photolenses
1 h – 30 cm amateur telescope
1 day – 1 m professional telescope
1 week – 6 m giant telescope
1 month – Hubble telescope

Gamma Ray Bursts - GRB

- **Short (0.01-100s) γ–ray pulses**
- **From pointlike sources in the sky**
- **Brighter than the rest of the sky** (in γ-rays)
- **Energy 10^{51} erg** (=10^{10} years of Sun emission)
- **Distance up to z=4.5** ($13 \cdot 10^{9}$ light years)
- **Frequency 2-3 per day**
- **So far >3000 observed**
  including ~100 in visible light
  distance measured for ~70
- **Observed in radio waves, X-rays, γ ~GeV,TeV**

GRB's today and tomorrow

Today:

- **gamma emission well understood**
- **central engine(s) still uncertain**

Tomorrow:

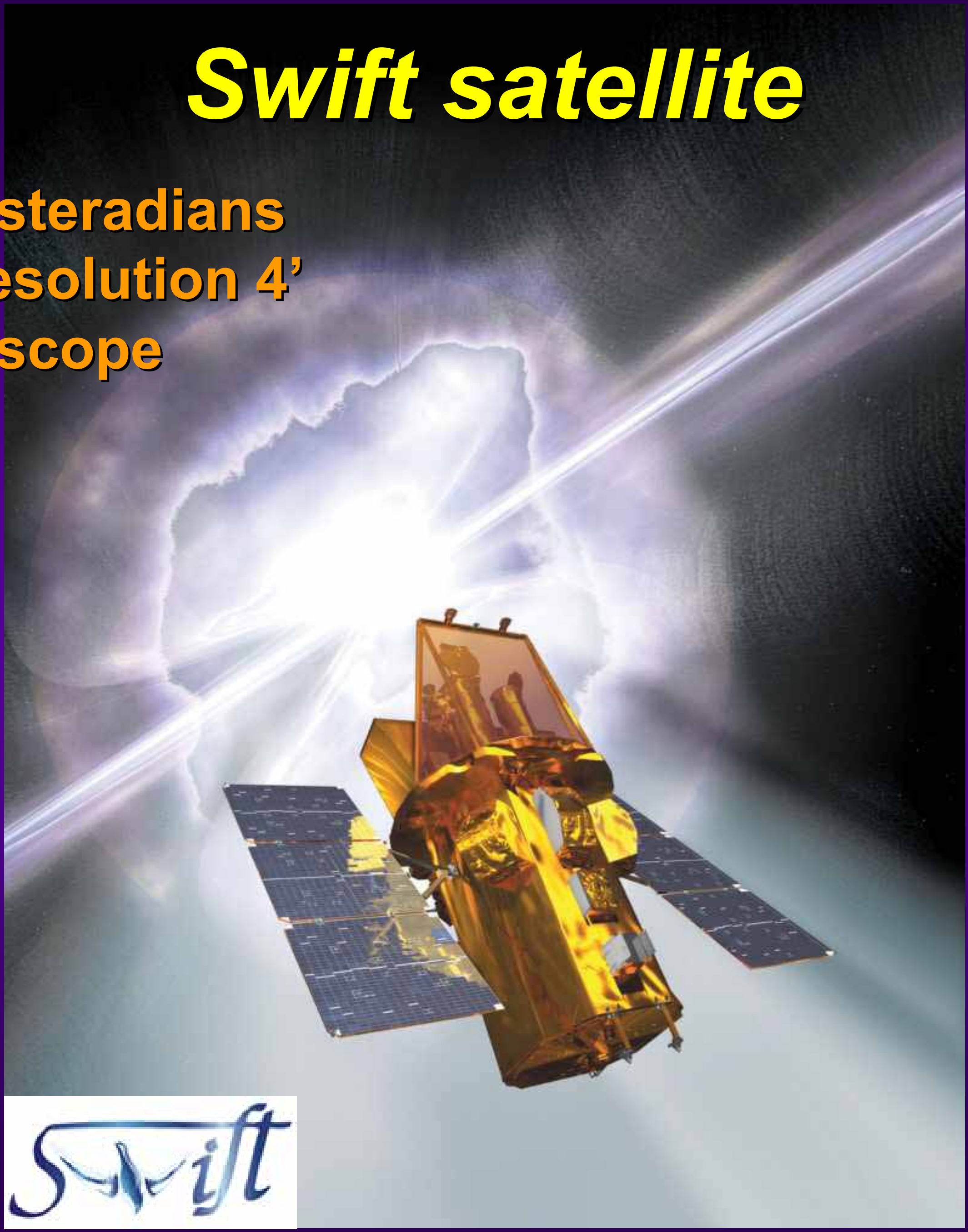
- **coincidence with TeV photons, neutrinos, etc**
- **optical observations before and during GRB**

Swift satellite

Launched Nov. 2004

3 instruments:

- **BAT – γ-ray detector: 2 steradians**
- **XRT – X-ray detector: resolution 4’**
- **UVOT – optical+UV telescope**



Short GRB puzzle

So far, no optical counterpart of short (<1s) GRB has been found

2005.05.09 – GRB 050909B lasting 30ms

X-ray afterglow found

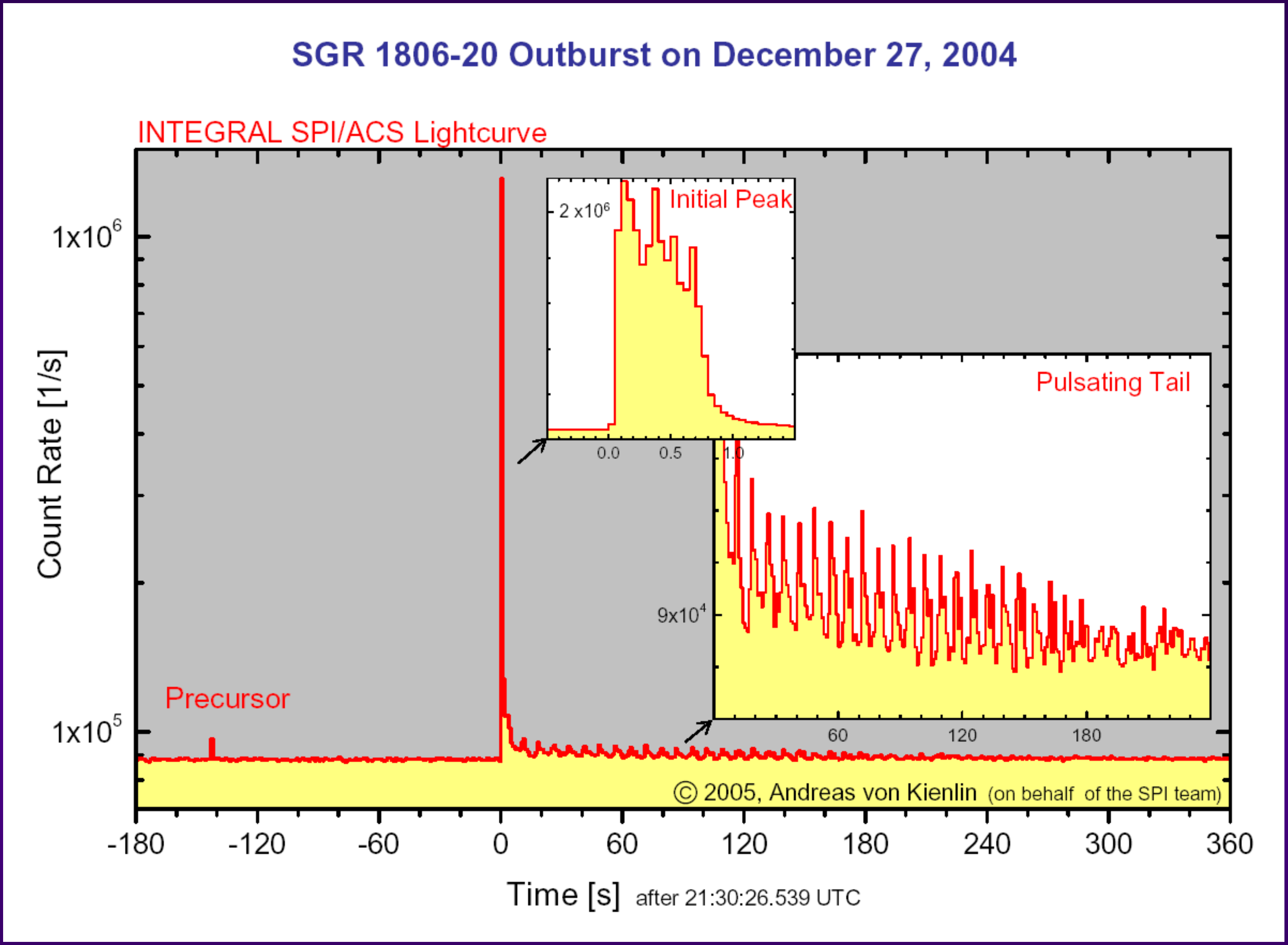
Possible host galaxy identified

- Roumors in newspapers

The afterglow itself – not seen

Short GRB's remain unvisible

Soft Gamma Repeater 1806-20



Gigantic outburst of SGR 1806

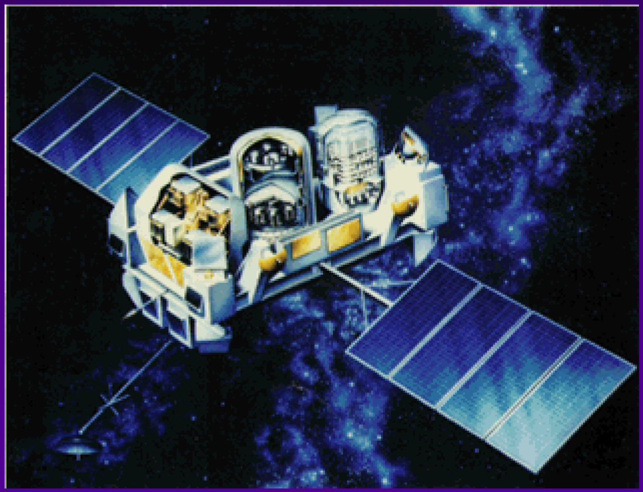
New hypothesis: short GRB are superbursts of distant SGR?

(weaker bursts are to faint to be observed)

GeV photons from GRB's

Cosmic spark chamber EGRET

GRB	Max γ energy	Emission time
910503	10 GeV	84 s
910601	0.3 GeV	200 s
930131	1.2 GeV	100 s
940217	18 GeV	1.5 h
940301	0.2 GeV	30 s



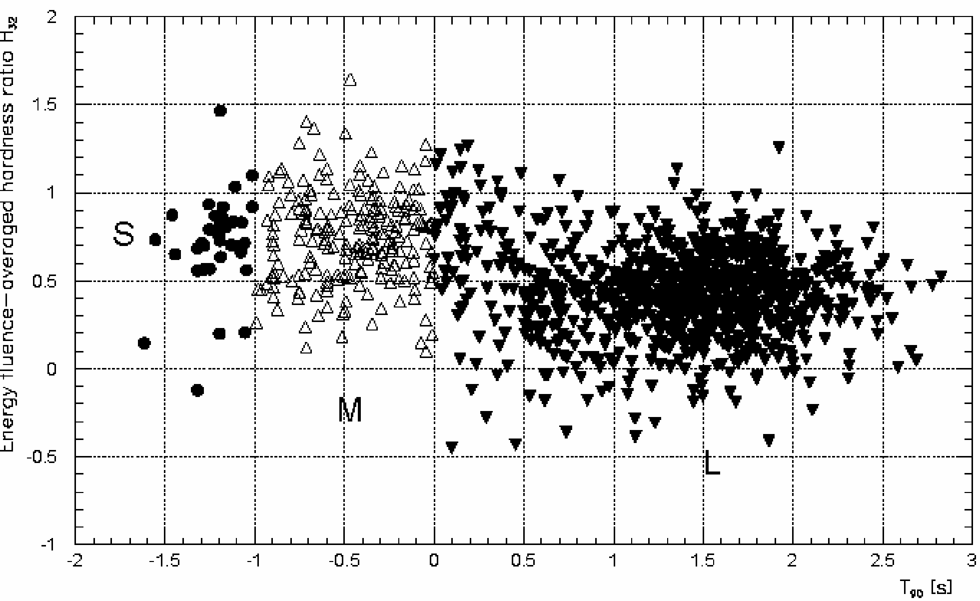
GRB 940217

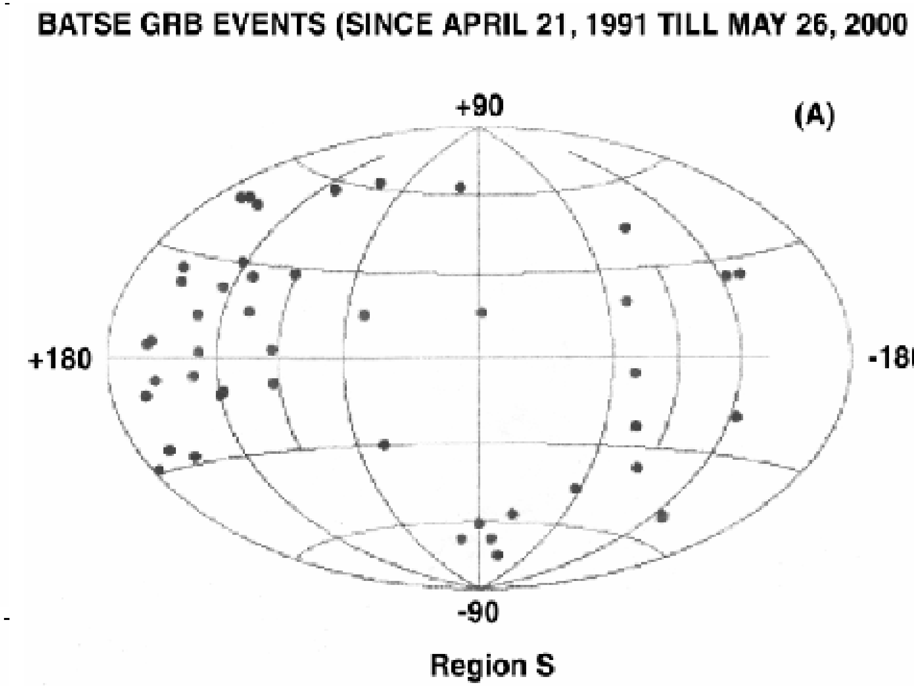
Ulysses/BATSE observed GRB (25-150 keV) 180 s long
EGRET observed 18 photons (>40 MeV) over 1.5 h !
3 of them had energy > 2 GeV

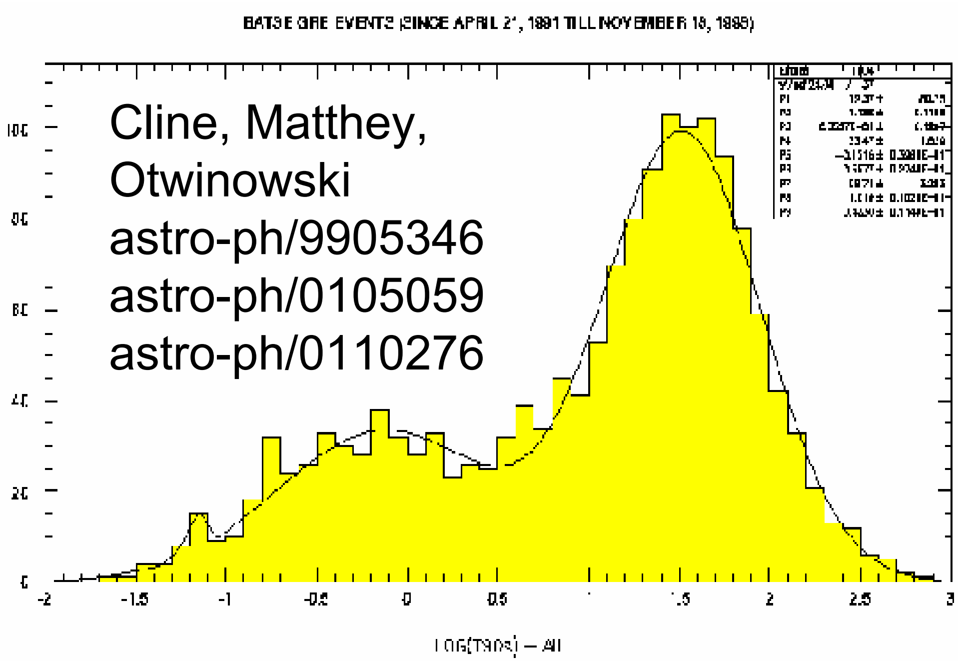
Why hard photons are late?
Different production mechanism?
Different speed?!

- quantum gravity effects (J.Ellis et al., Nature 393, p.763)
- extra spacial dimensions (K.S.Cheng, T.Harko, astro-ph/0407416)

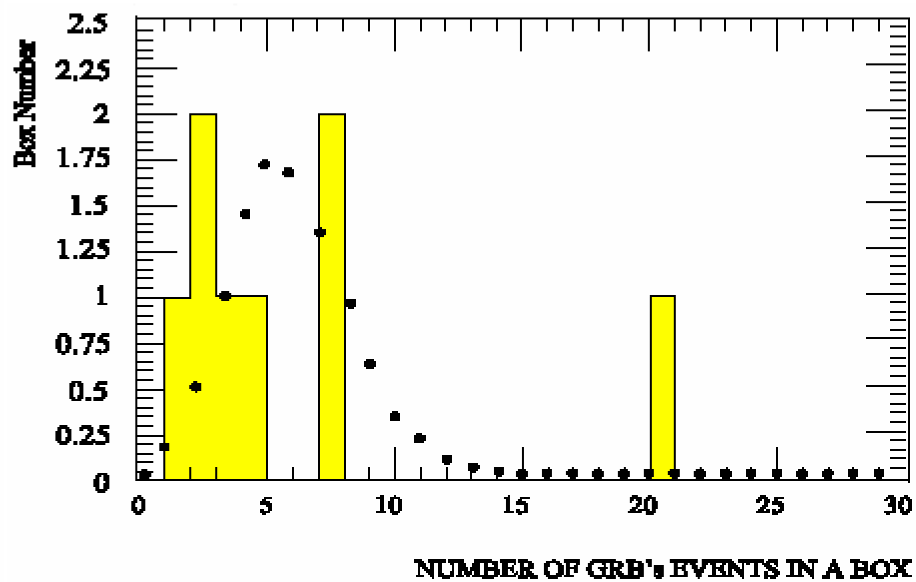
Anisotrophy of very short (<0.1s) GRB?



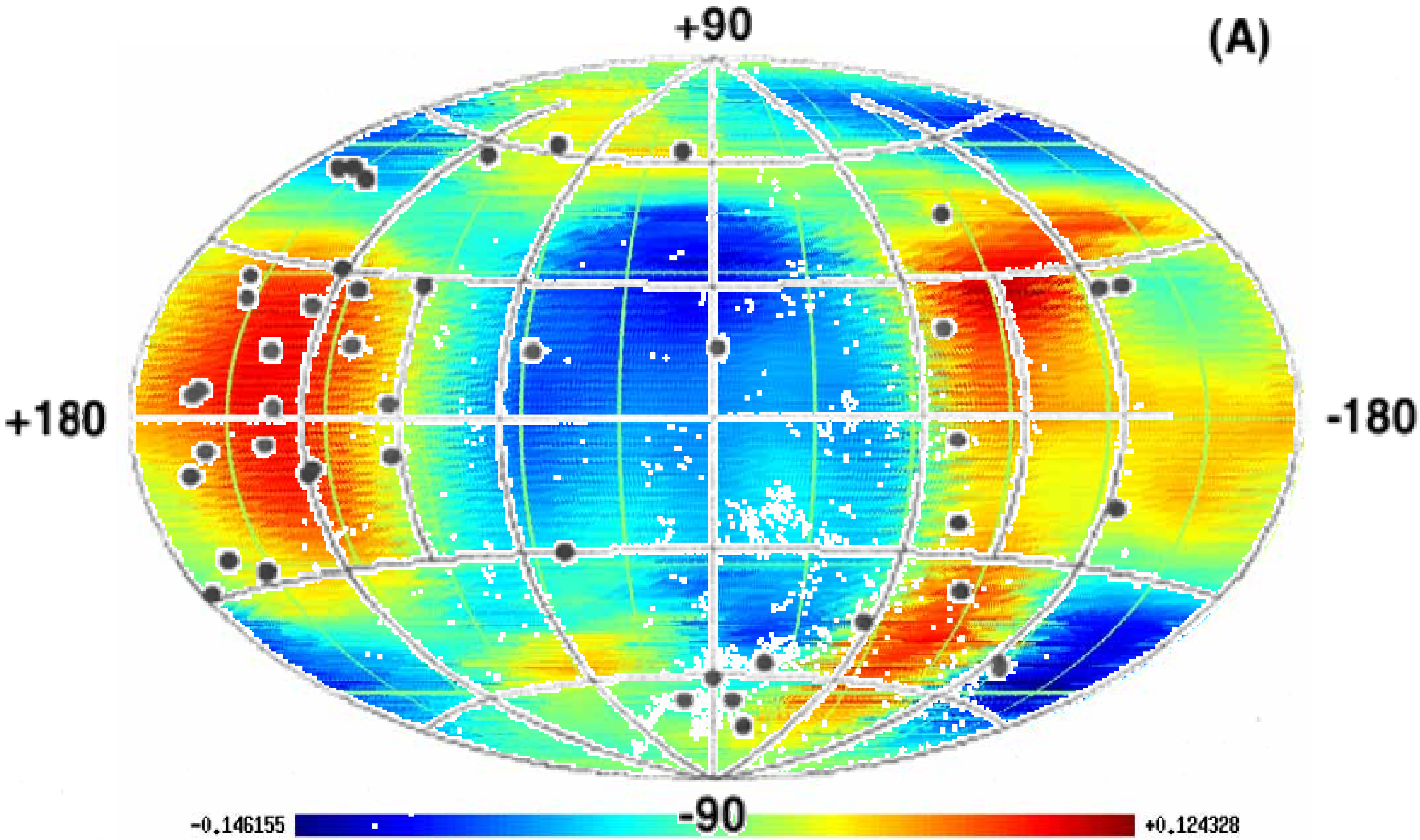




Cline, Matthey, Otwinowski
astro-ph/9905346
astro-ph/0105059
astro-ph/0110276



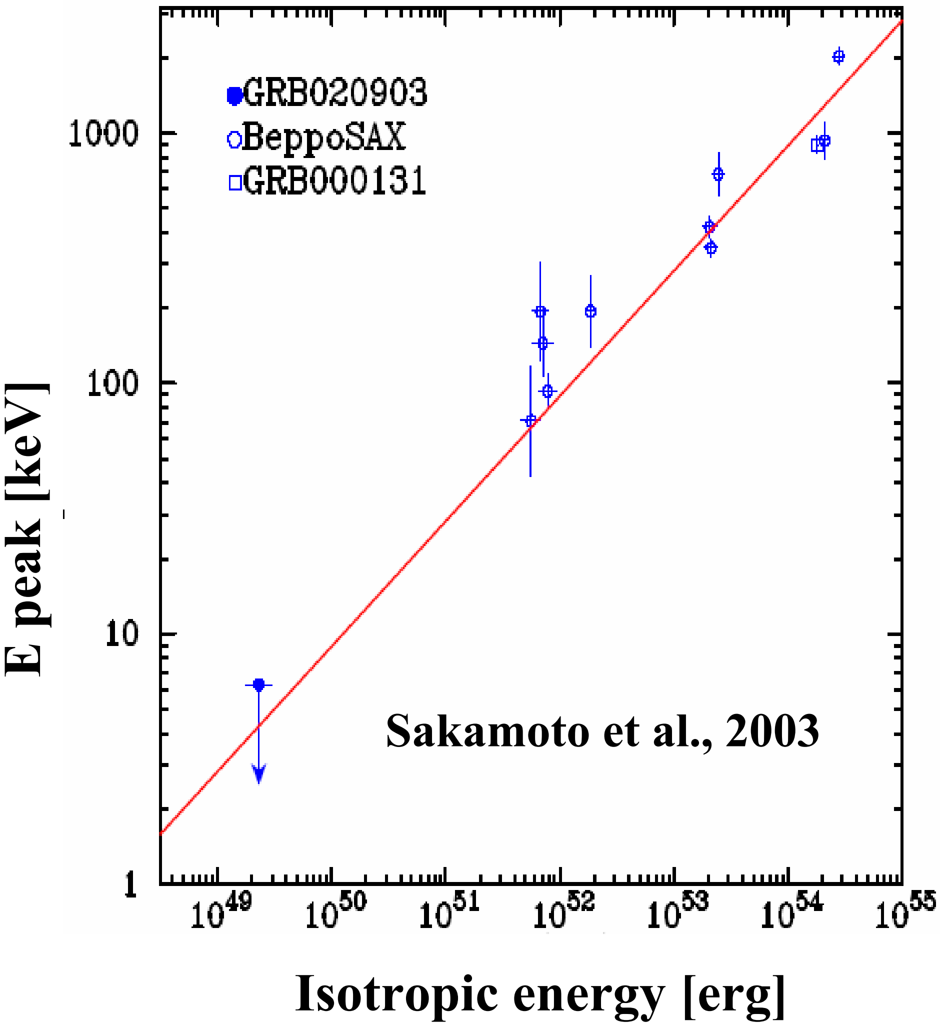
V. short GRB / CMB correlation?!

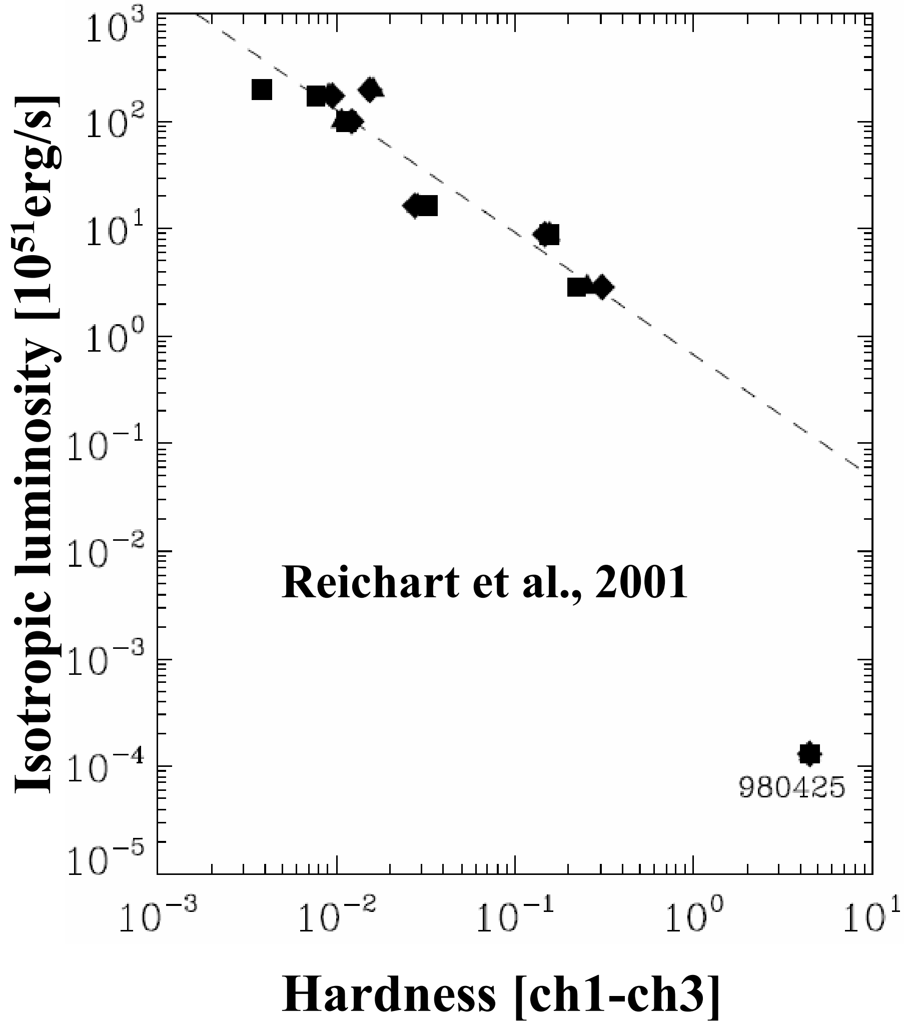


Colour map – CMB (WMAP) **/ GeV γ** (EGRET) **correlations**

Wibig, Wolfendale, 2005

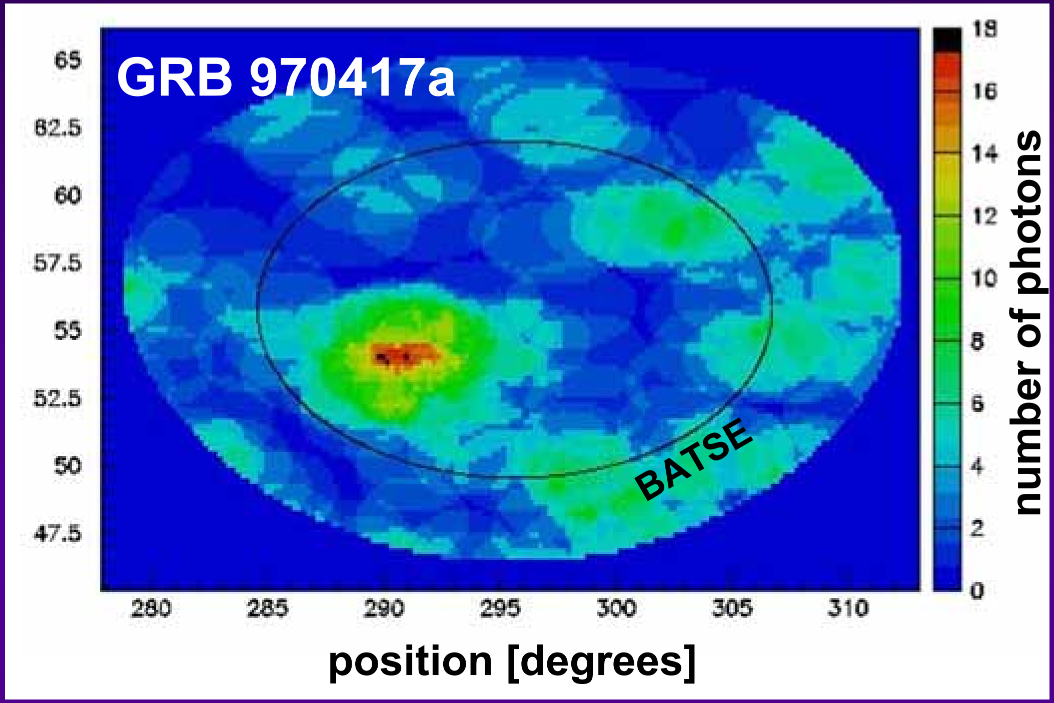
GRB as standard candels

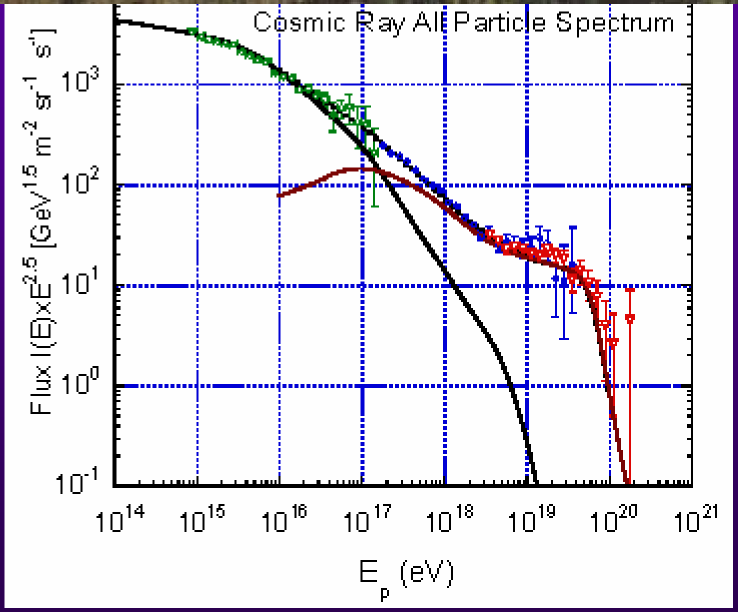




Cepheides-like correlations might allow us to study the Universe much farther than Supernovae

TeV photons from GRB





18 photons > 650 GeV during 8 s

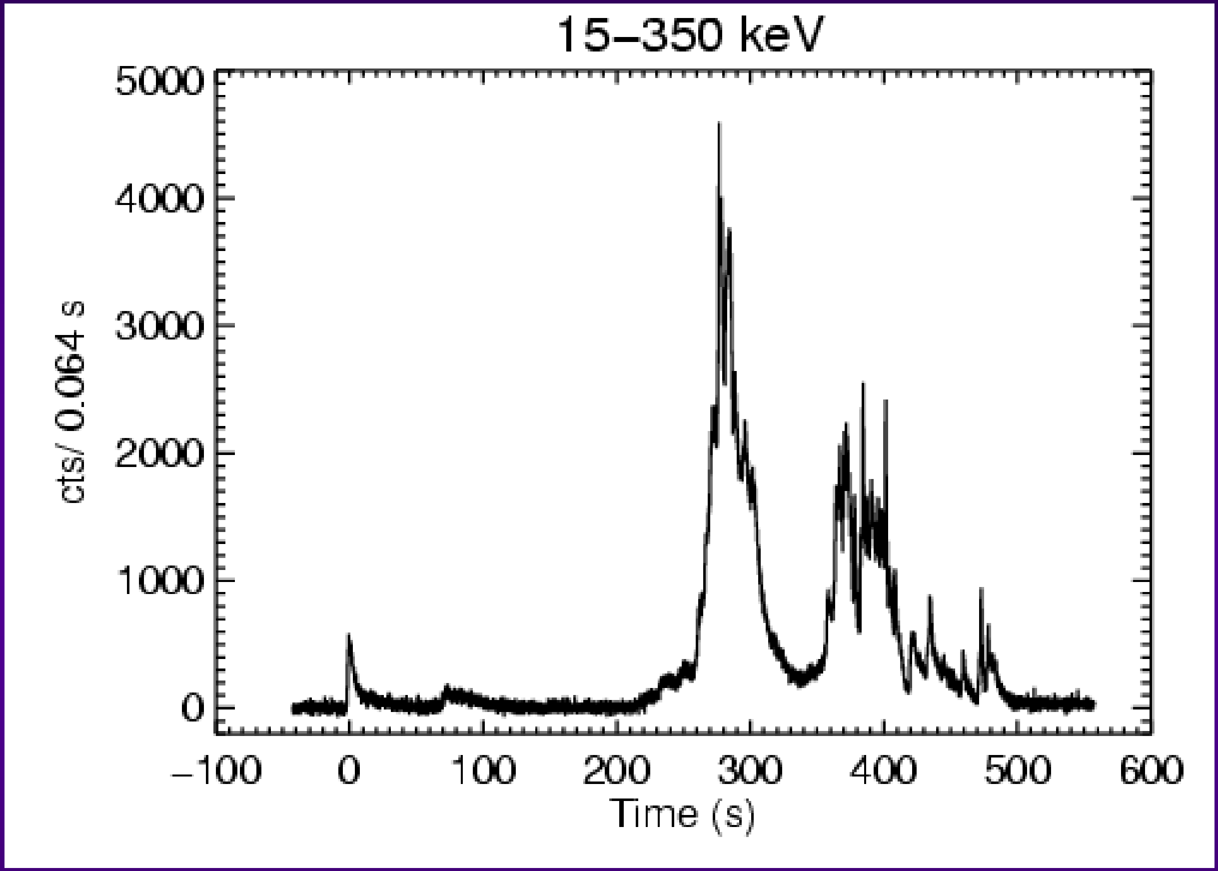
Models proposed with GRB as cosmic ray sources.

E.g. astro-ph/0310667

points: KASKADE + HIRES I + HIRES II

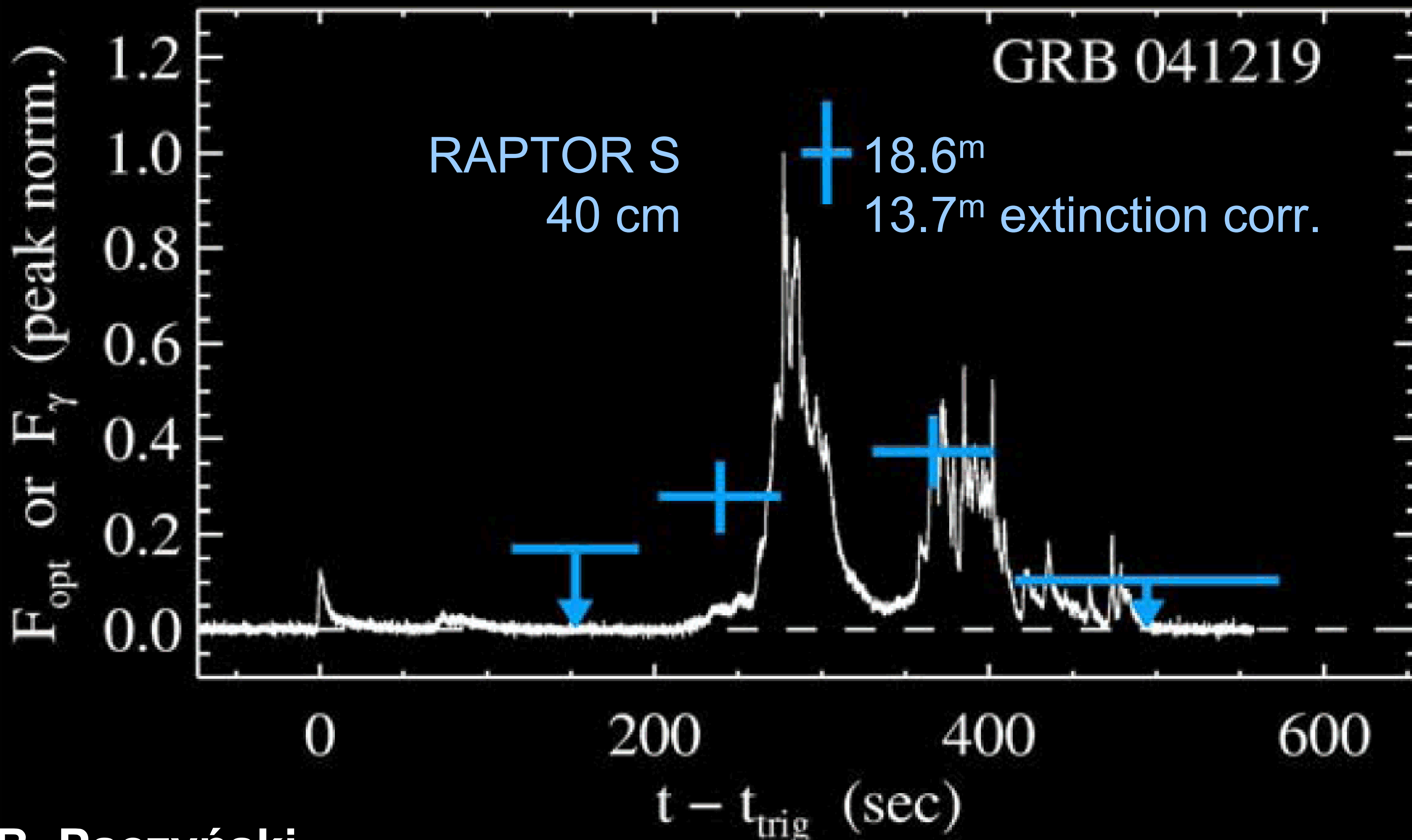
curves: 1. galactic, 2. extragalactic

Swift GRB 2004.12.19



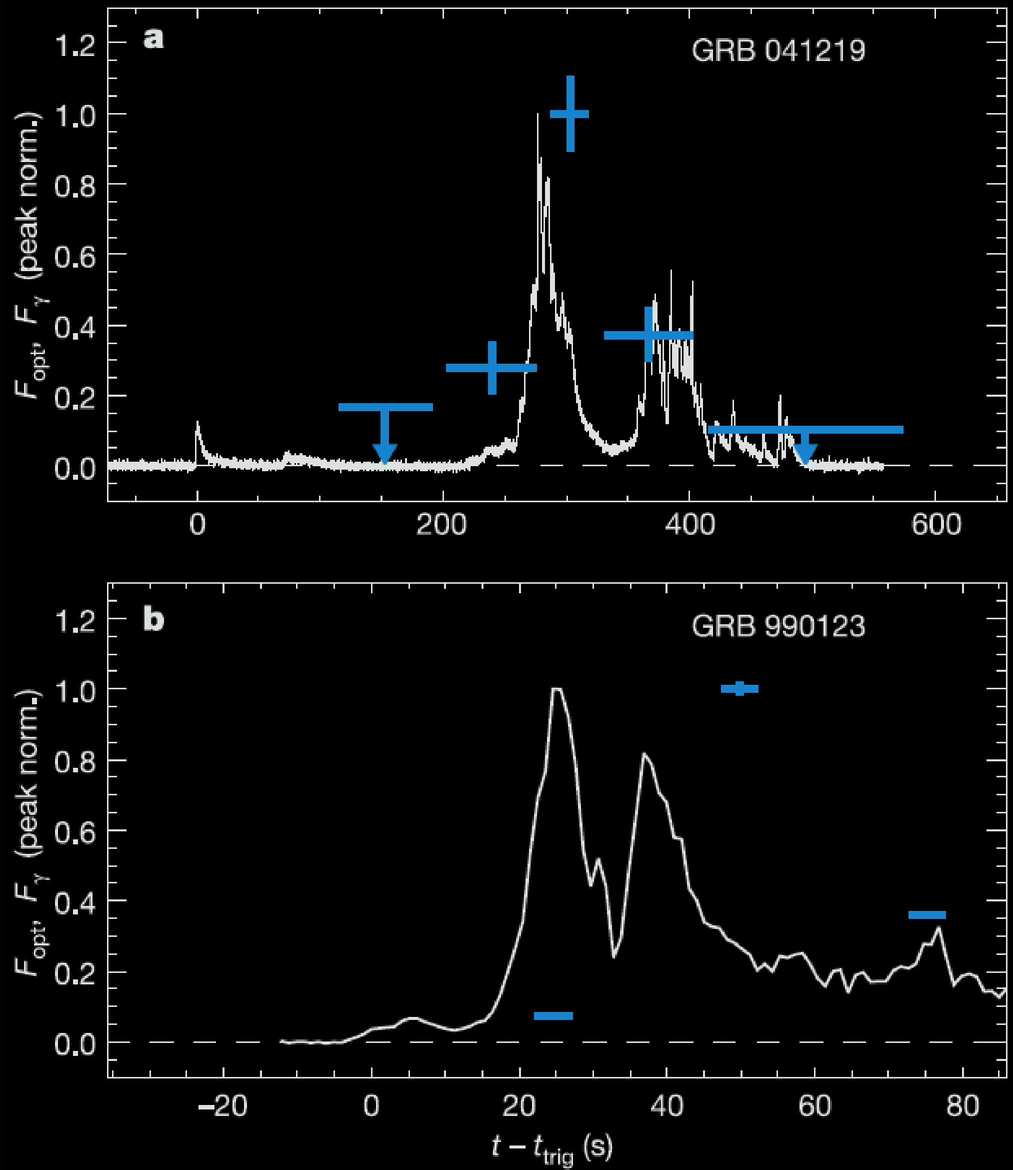
Precursor seen also in GRB 2005.01.24 and some others
B.Paczyński and P.Haensel (astro-ph/0502297)
interpret prekursor as a collaps to a neutron star
and the main burst as creation of a quark star

Optical observation before GRB!



B. Paczyński

„*Optical Flashes Preceding GRBs*", astro-ph/0108522



GRB 050820
optical peak 7 min. after GRB

Prompt optical emission

Crucial to understand GRB central engine

Begins before, during or after GRB?

- **3 observed cases**
- **3 different answers**

More observations very much needed!

General Rule for Bursts

H – arbitrary hypothesis about GRB

G_1, G_2 – gamma ray burts

$$\forall_{H} \; \exists_{G_1, G_2} \; G_1 \Rightarrow H, \; G_2 \Rightarrow \sim H$$

Examples:

- **optical emission begins before / after GRB**
- **GRB out of / in the Galaxy** (SGR / „normal” GRB)
- **GRB with / without Supernova**
- **GRB = single, double, multi-pulses**
- **GRB with / without precursor**

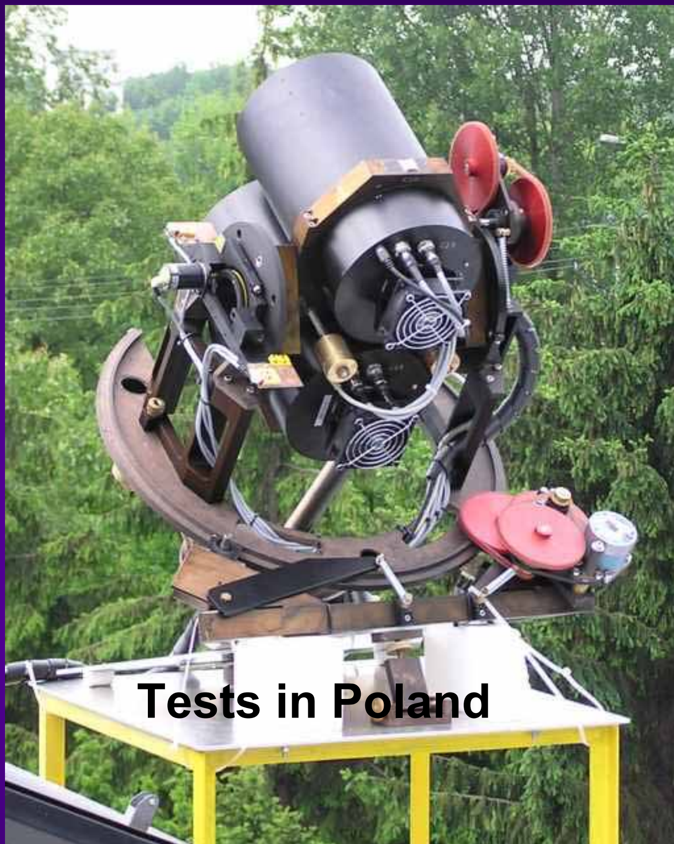
Catching prompt optical emission

No one knows were the next GRB will happen

Two approaches:

- wait for GRB alert and move there quickly
  - robotic telescopes listening to GCN:
  - BOOTES, (SUPER)LOTIS, MASTER, RAPTOR, REM, ROTSE, TAROT, ...
- look everywhere
  - robotic telescopes with self-triggering watching ~all sky continuously:
  - „π of the Sky" – π steradians field of view, 2×16 cameras, 32×3000 images/night, 1 TB/night

„π of the Sky” prototype



- 2 CCD cameras 2000×2000 pixels
- common field of view 33°×33°
- 32 cameras under construction

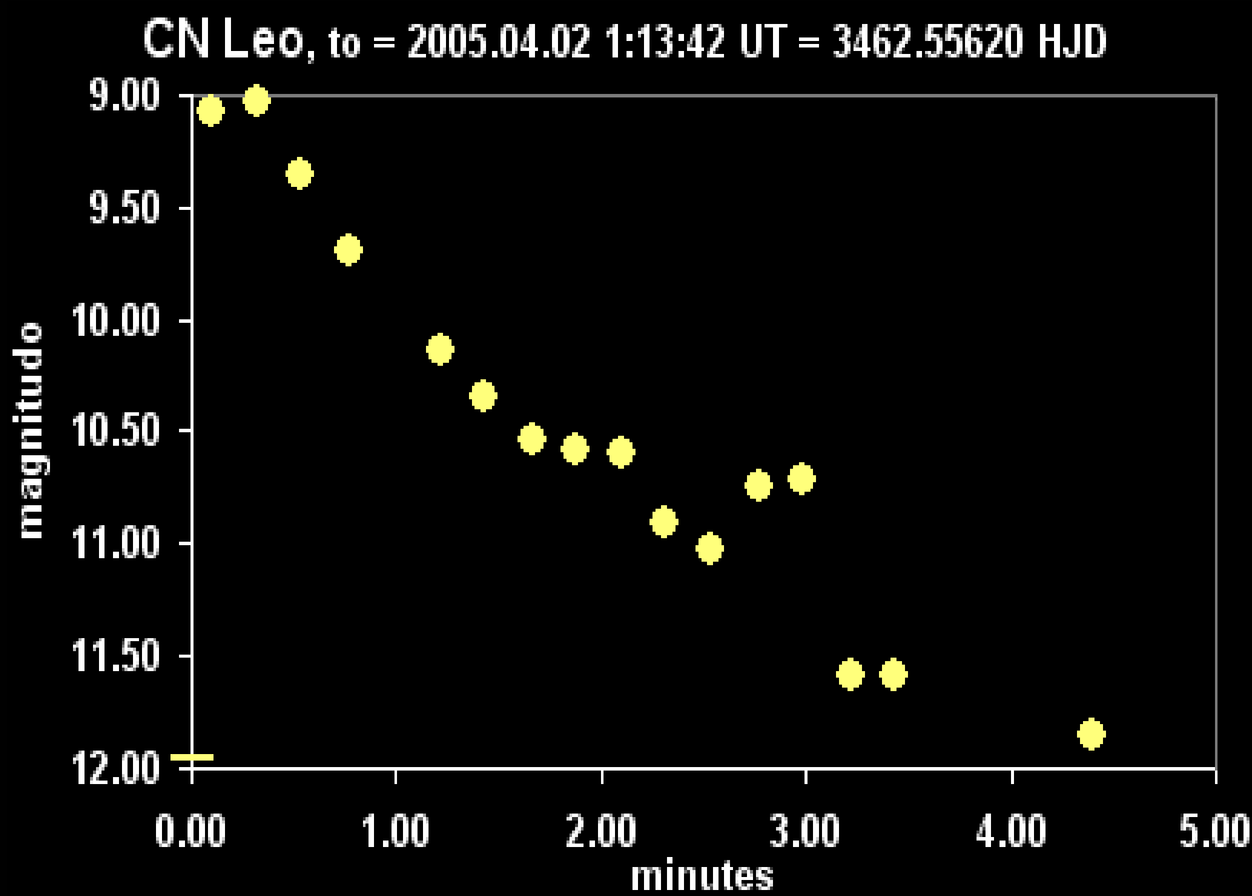
- robotic mount
- < 1 min. to any point in the sky

http://grb.fuw.edu.pl

Search for cosmic flashes

„π of the Sky” prototype at LCO, July 2004 – July 2005

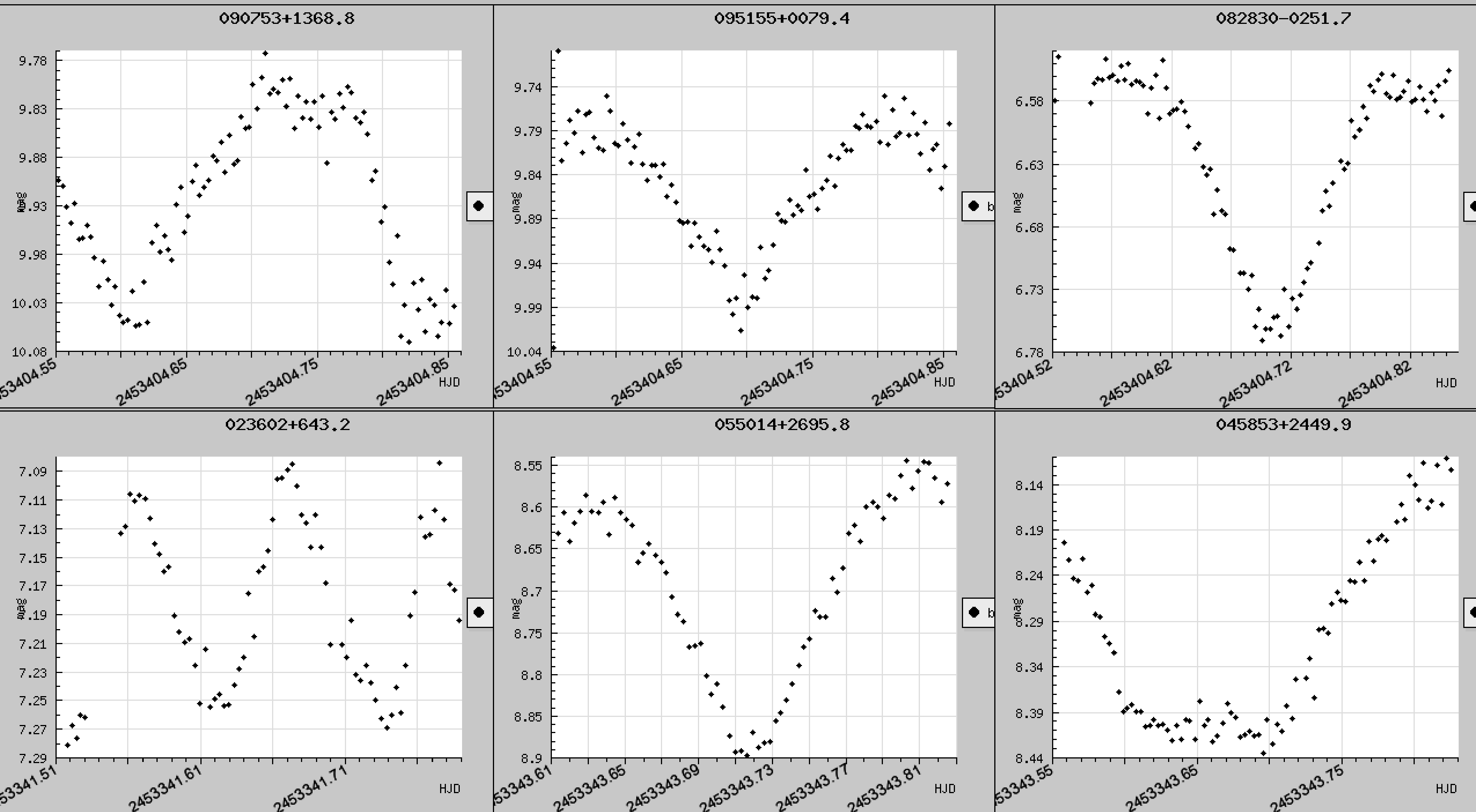
- no GRB optical counterpart observed so far
  - limits 11-12^m for 2 GRB before and during γ burst
  - several limits ~minutes after GRB
- several flashes observed
  - neither confirmed nor excluded by others
- 1 flash identified as CN Leo flare star outburst
  - 100× brighter in <1s, faded in 5 min



„π of the Sky” general goal:

study objects varying on scales from seconds to months

Examples of night-life of stars - brightness vs time (one night)



„π *of the Sky*” and education

The team:

- 0.5+0.5+0.2 senior physicists
- 0.7 postdoc
- many students

The project made by students & for students:

- they design hardware, write software, take shifts and analyse the data
- they are responsible for achievements & failures
- they write papers and go to conferences

How to get good students?

- see **grb.fuw.edu.pl → *education***

Bringing science to schools

Less and less students choose to study physics

It is difficult to present modern science in school

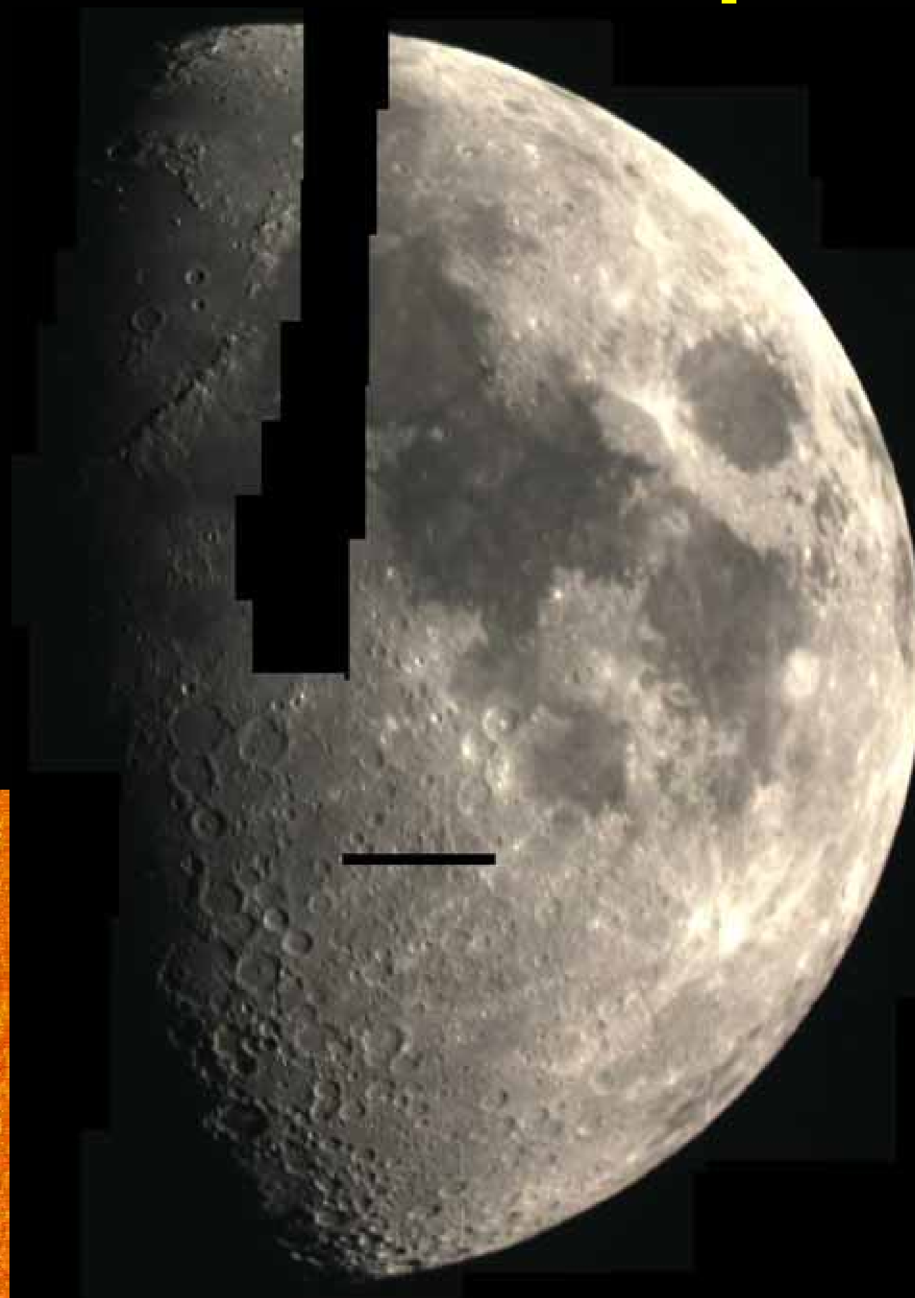
Rapid technological developement increases the gap between front-line science and school education

Let us use modern technology to our advantage!

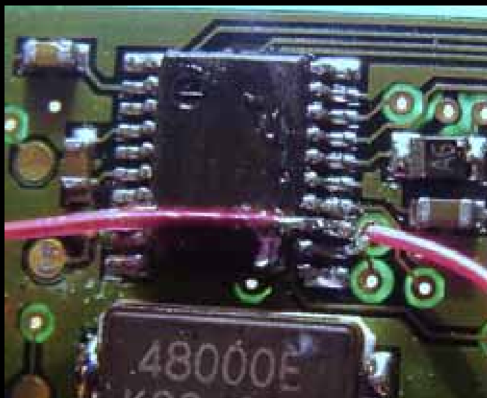
e.g. CCD sensors which made revolution in astronomy are now available in daily use devices

We propose to build digital school observatory for 120 €

Webcam + telescope



Webcam long exposures (~20s)



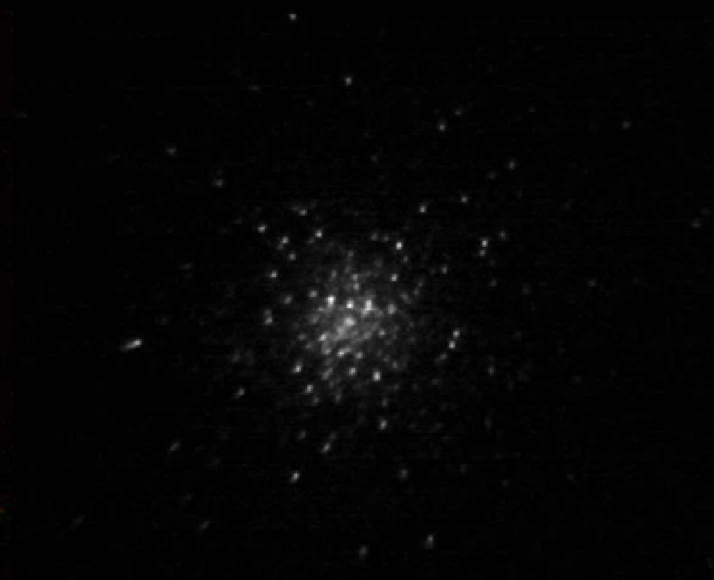
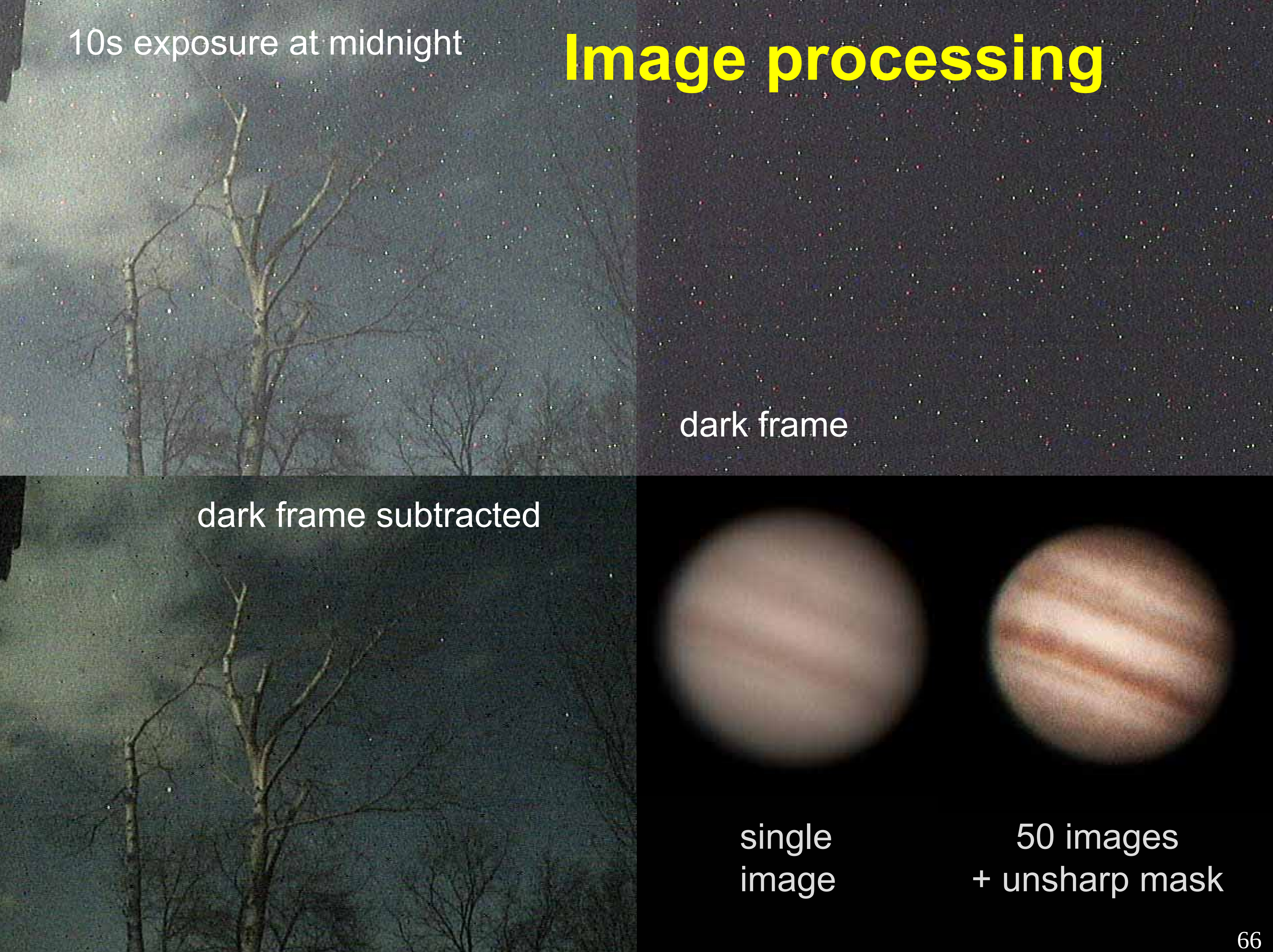
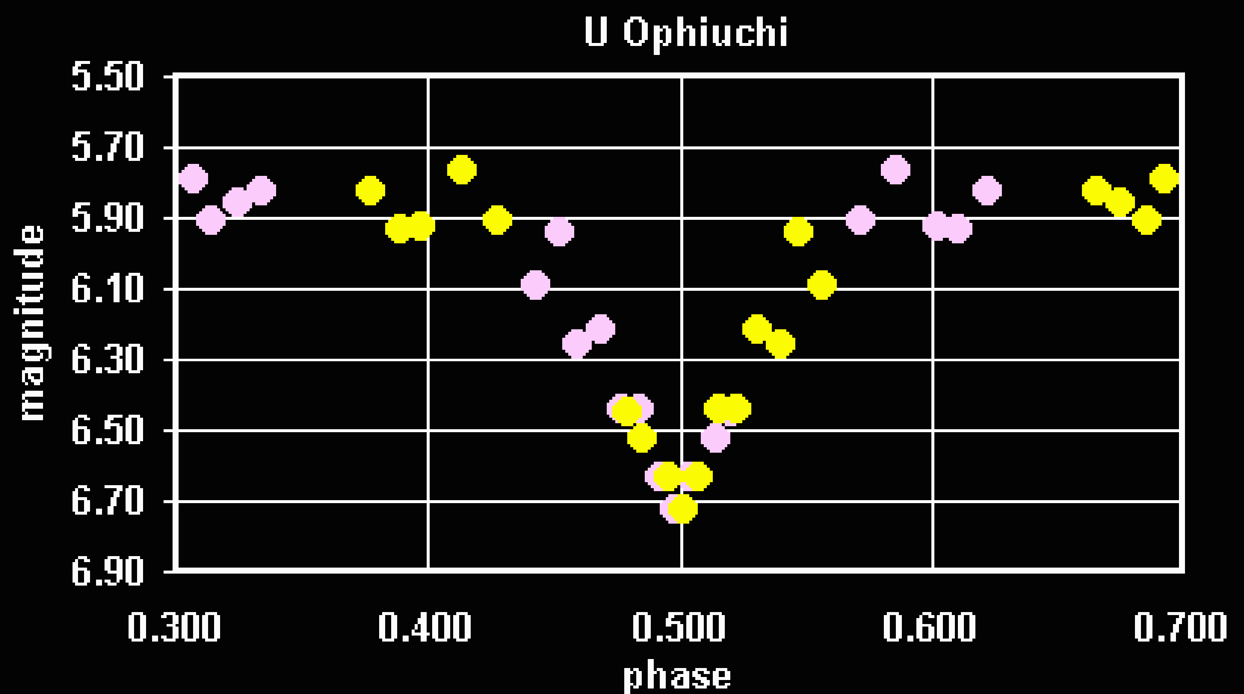


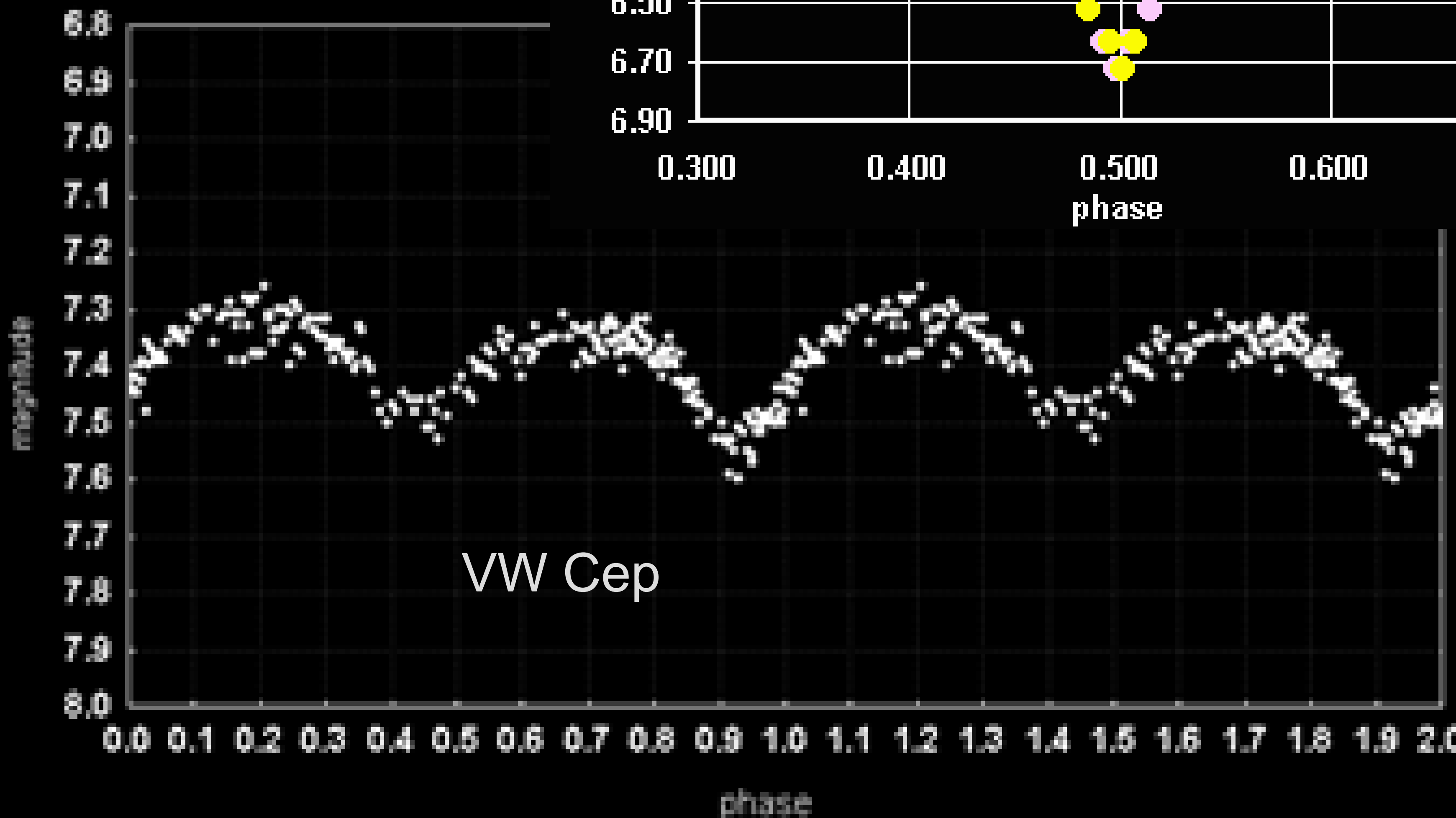
Image processing



Webcam + photo lenses f=50mm

Variable stars





Hands on Universe - Europe

EU grant ~800 k€

Polish section ~30 k€

- **lead by Lech Mankiewicz** (Center for Theoretical Physics, Warsaw)

160 digital school observatories

- **Philips ToU Cam PCVC 840K webcam (~80 €)**
- **Long exposures modification (~25 €)**
- **Zenith lenses f=50mm (~10 €)**
- **Mechanical adapter (~10 €)**
- **Software (custom written) + courses for teachers**

You are welcome to join:

grb.fuw.edu.pl → education