Gamma Ray Bursts

Probes of Star Formation in the Early Universe

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Age of the Universe: 13.7 billion years

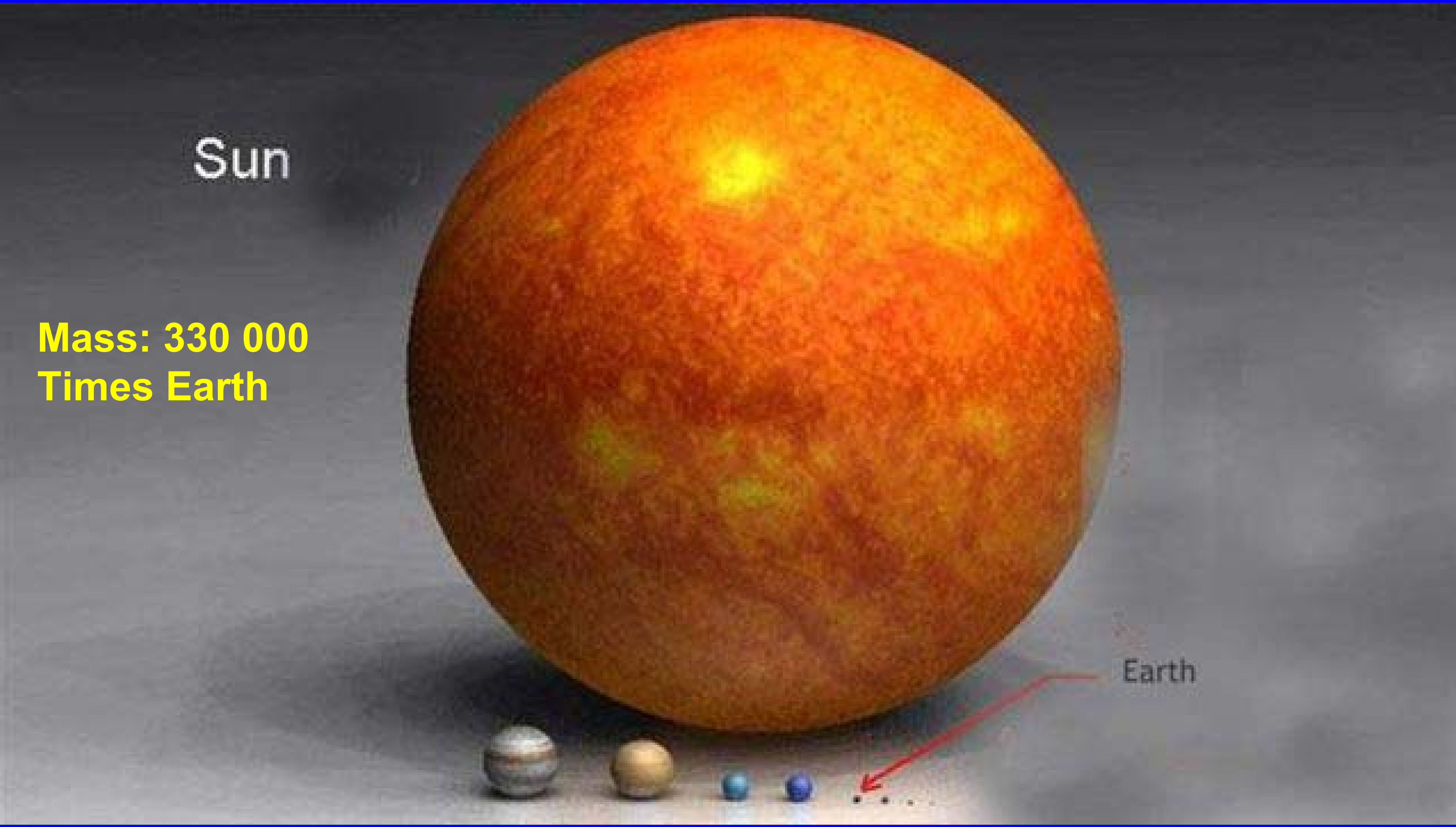
Age of our Milky Way Galaxy: at least 13 billion years

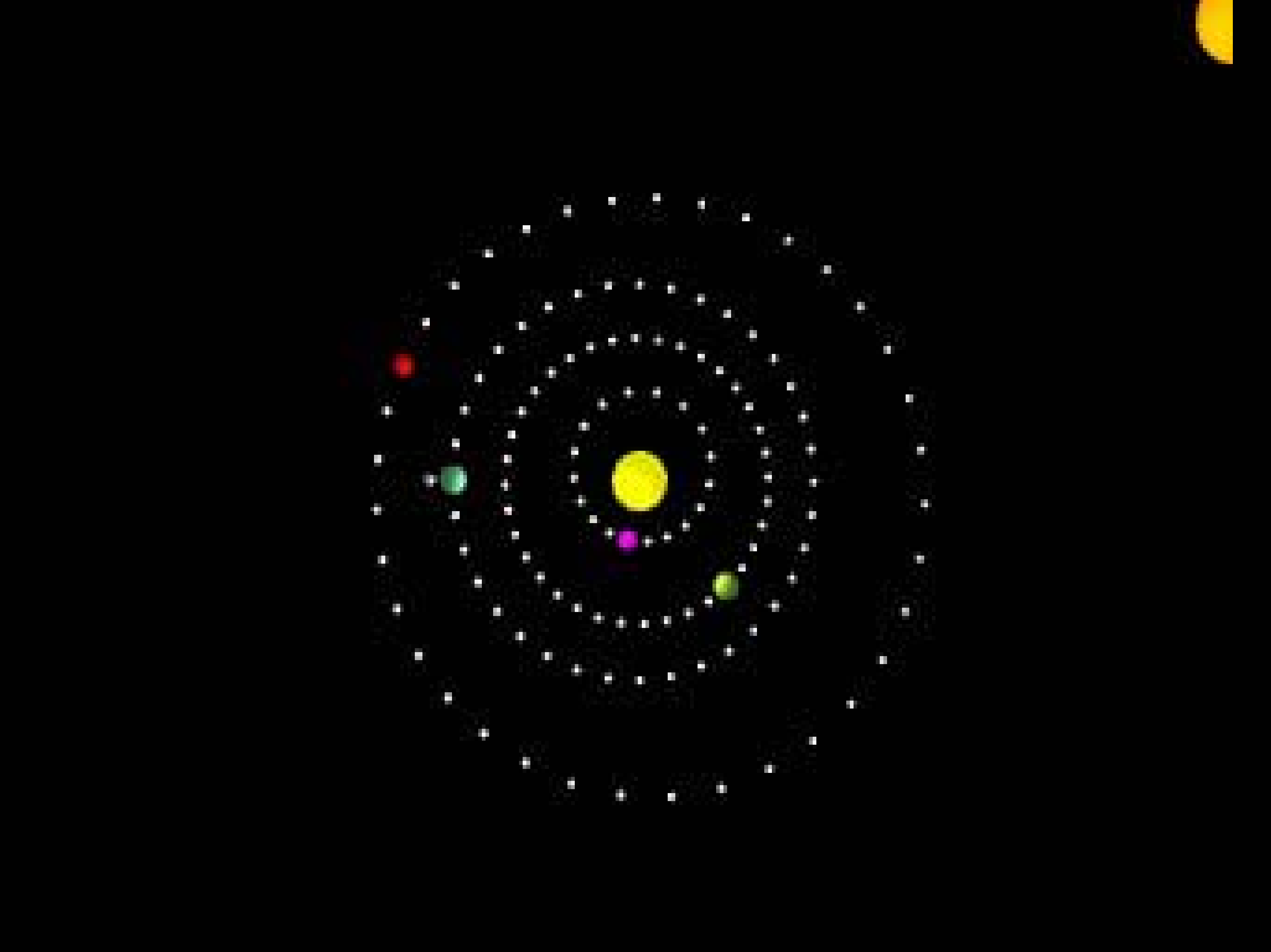
Age of our Solar System and Earth: 4.6 billion years

Hydrogen (H) and helium (He) were made in the Big Bang, all other elements were made in earlier generations of (massive) stars

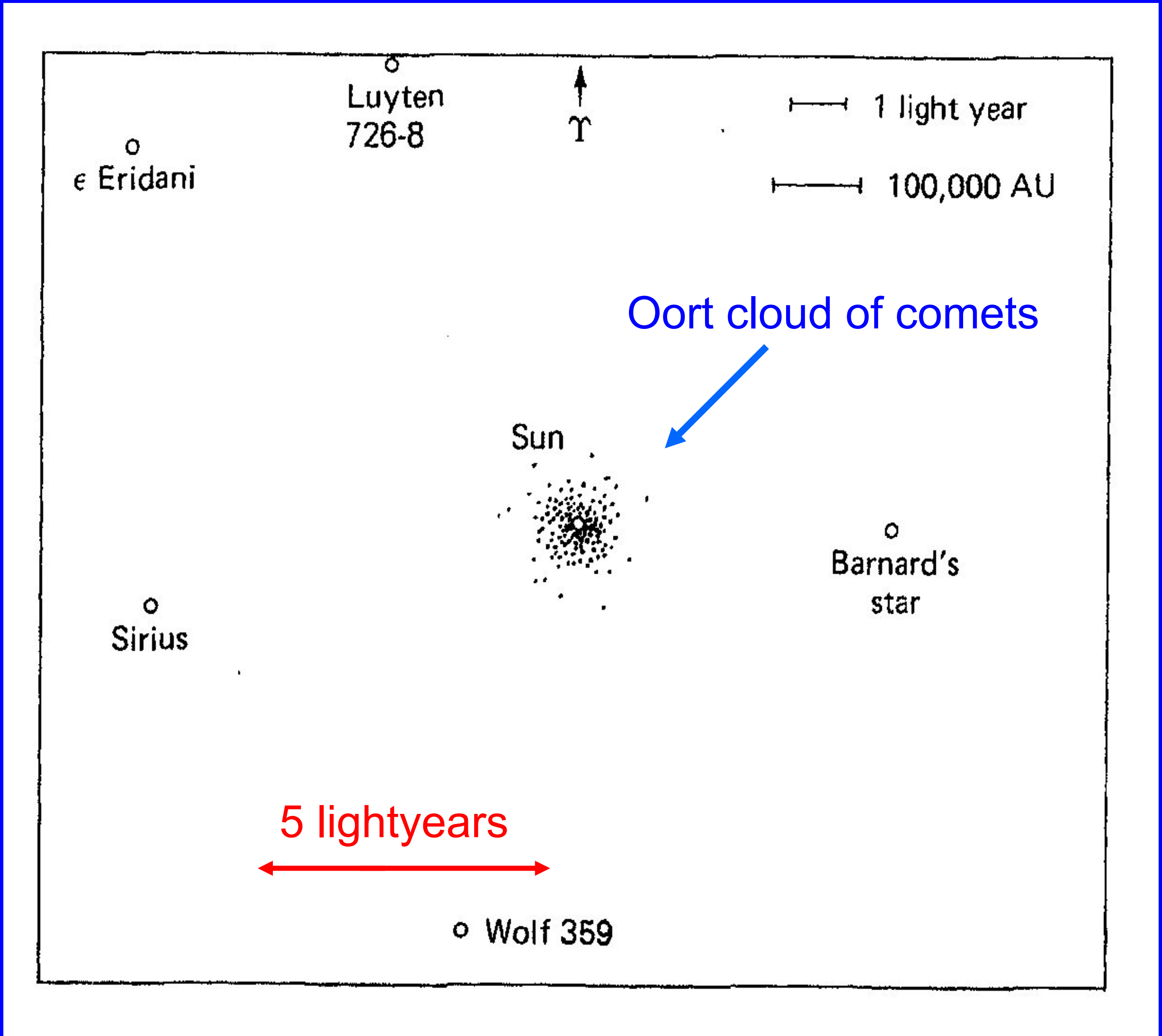
We are made of Stardust

Sun and Planets to the same scale

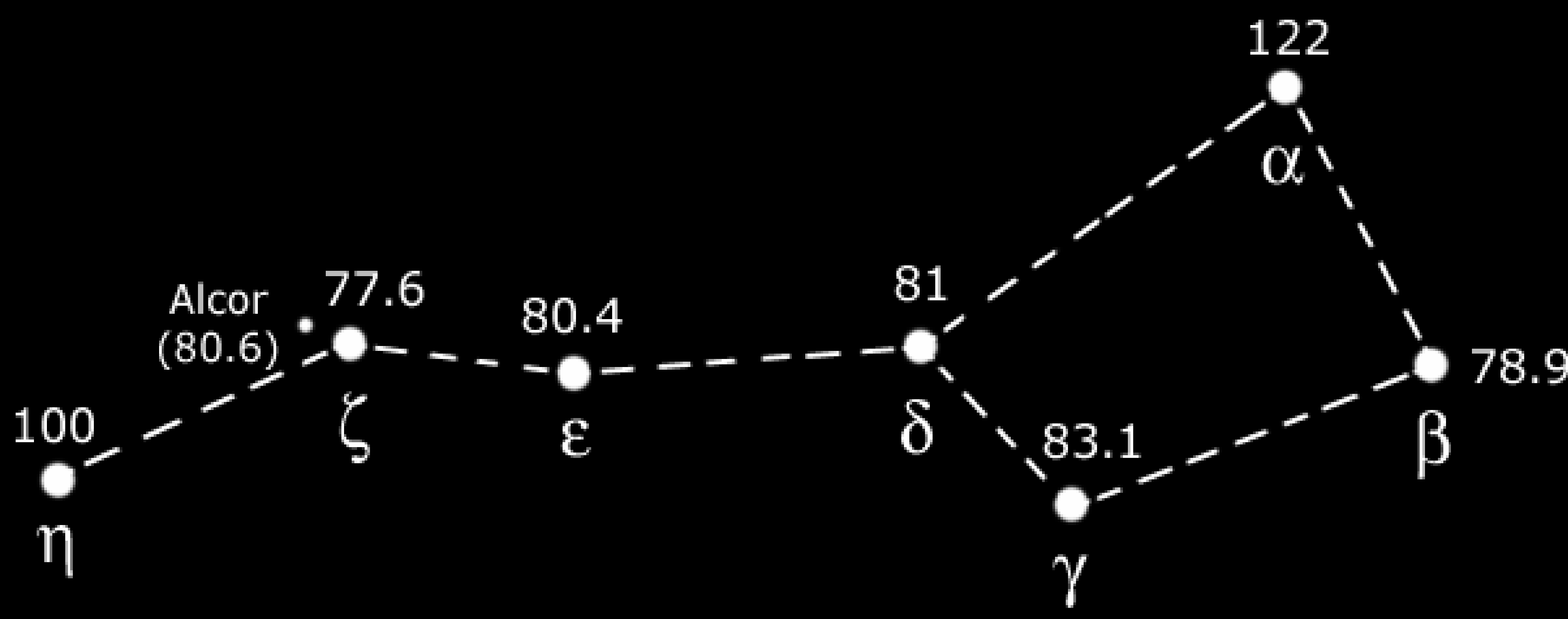




Solar Neighbourhood



Big Dipper with distances in Lightyears



Velocity of light is finite: 300 000 Km/second

$$\Downarrow$$

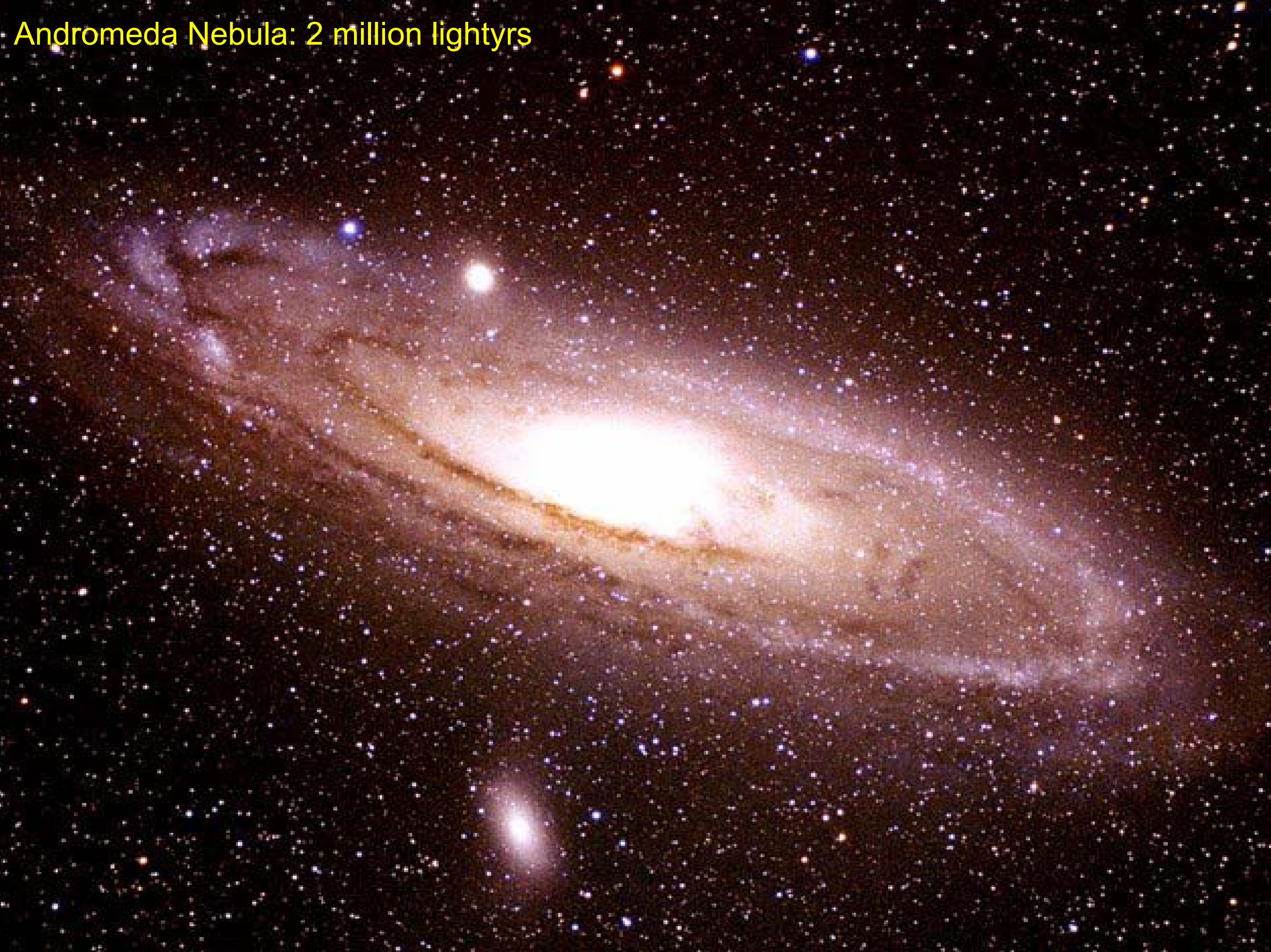
FAR AWAY = LONG AGO

European Southern Observatory’s Very Large Telescope, Chile

100 billion stars like our sun

Sun is 30000 lightyrs from Galactic center

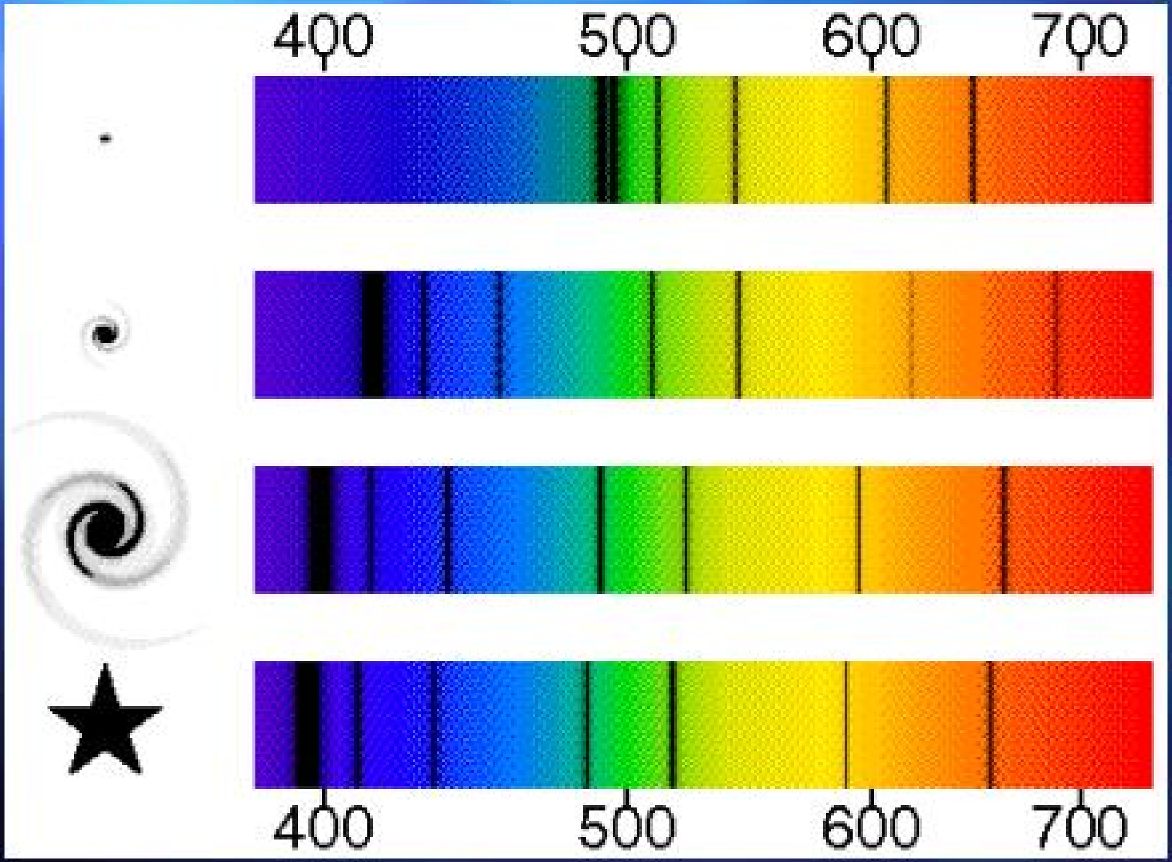
Andromeda Nebula: 2 million lightyrs




HUDF-2005,Adv.Cam

Hubble's "Law"

The more distant a galaxy, the more its spectrum shifted towards the Red

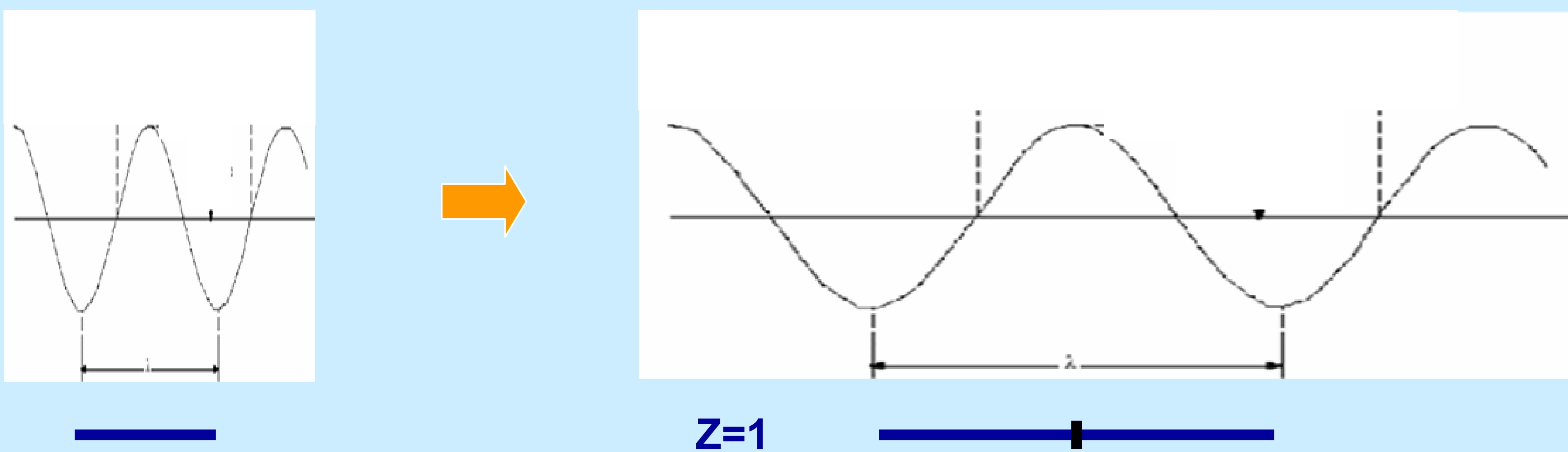


Distant galaxy: large redshift

Nearby star: no redshift

Space expands: lightwave is stretched out: gets redder

Redshift z: measured wavelength is (z+1) times larger than wavelength at the time of emission



Original wavelength

Measured wavelength

At z=1 : We observe universe as it was 9 billion yrs ago (universe 4.7 billion yrs old, in linear dimension 2 times smaller than now; in volume 8 times)

At z= 6, most distant Quasars, 12.6 billion yrs ago! Volume 350x smaller!

LIFETIME OF A STAR: TIME REQUIRED TO BURN ALL ITS NUCLEAR FUEL (HYDROGEN= 70% OF ITS MASS)

SUN: 10 BILLION YRS

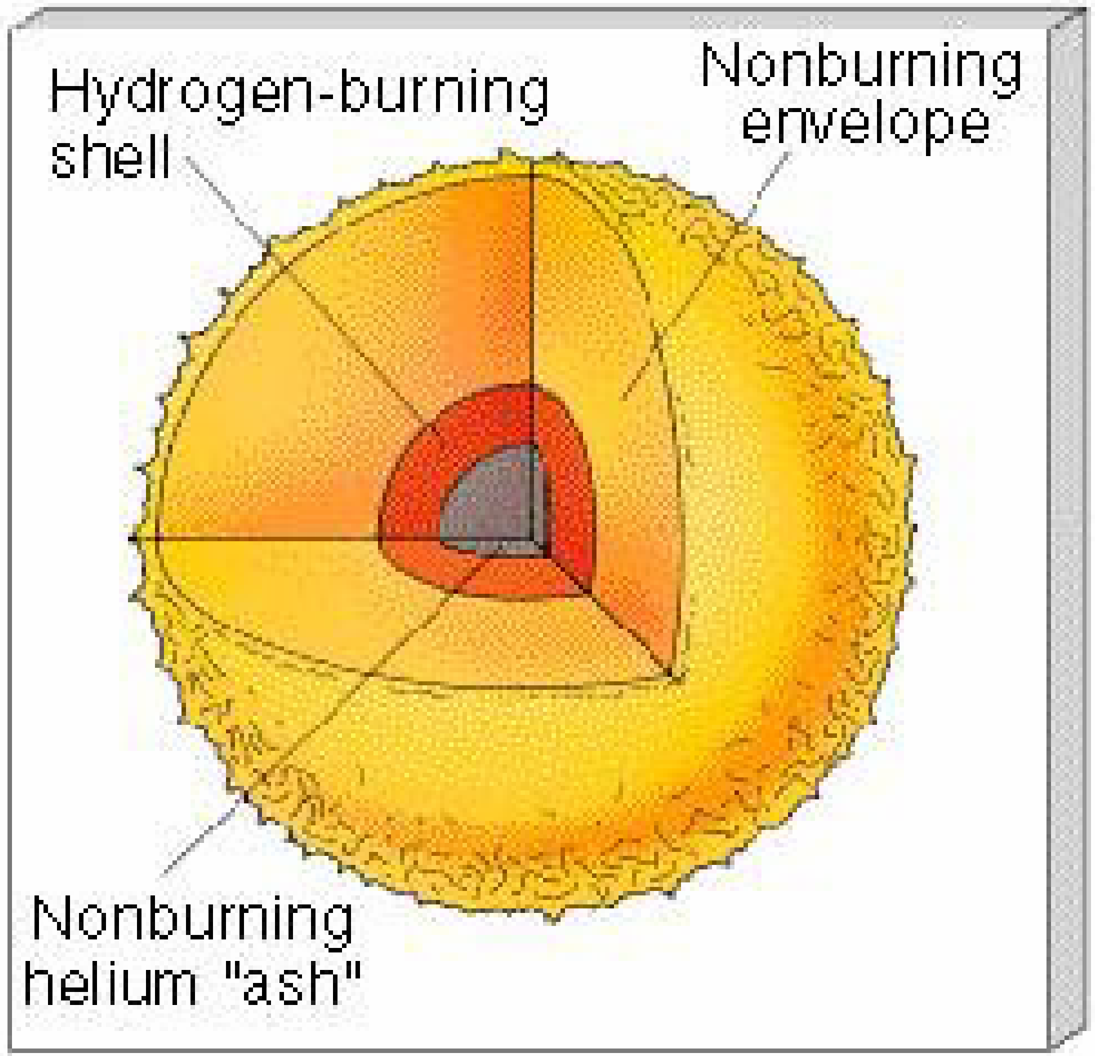
PRESENT AGE:

4.6 BILLION YEARS

STAR OF 25 SOLAR MASSES:

BURNS ITS FUEL 50 000 TIMES FASTER: LIVES 2000 TIMES SHORTER:

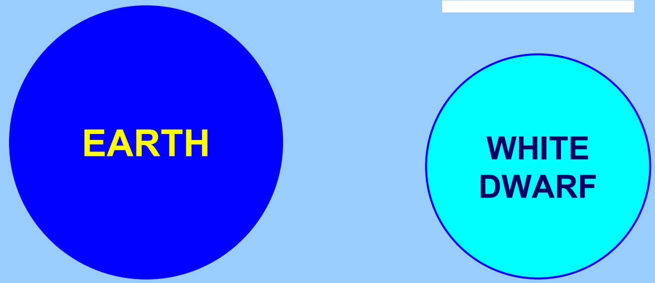
5 MILLION YEARS



FINAL STAGES OF STARS

10000 KM

BELOW 8 SOLAR MASSES



300 000 EARTH MASSES

BETWEEN 8 AND ~ 20 SOLAR MASSES

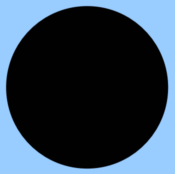
LIVE SHORTER THAN 20 MILLION YEARS

450 000 EARTH MASSES

20 km

MORE MASSIVE THAN ~ 20 SOLAR MASSES

LIVE SHORTER THAN 6 MILLION YEARS

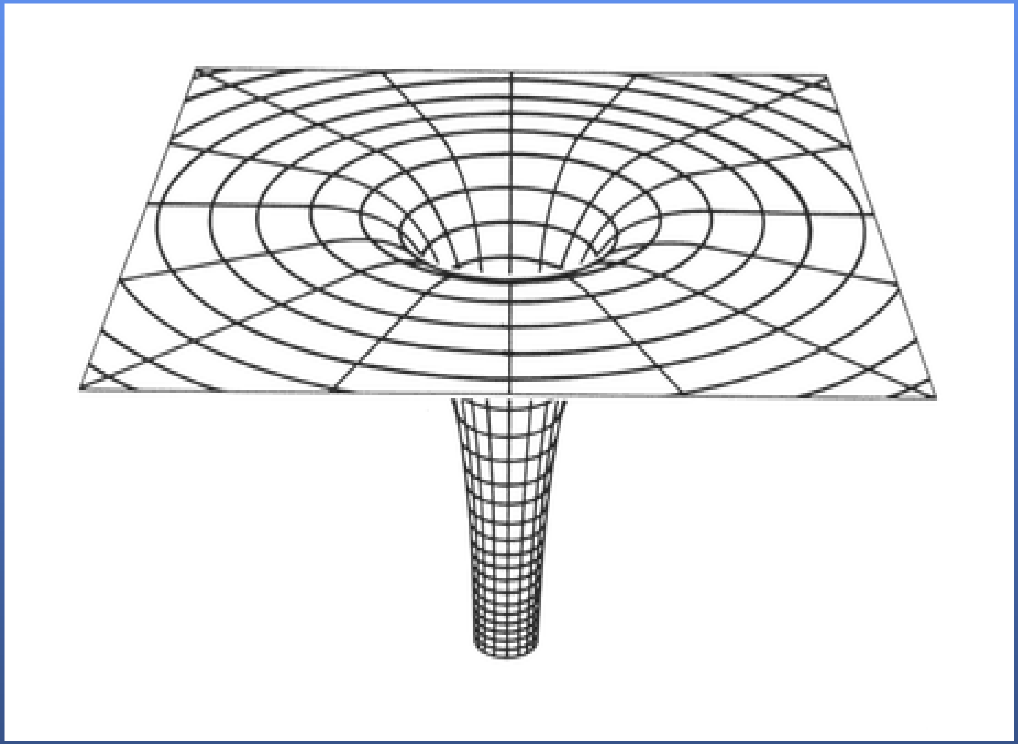


1 MILLION EARTH MASSES

BLACK HOLE

Black Hole: hole *without a bottom,* in Spacetime

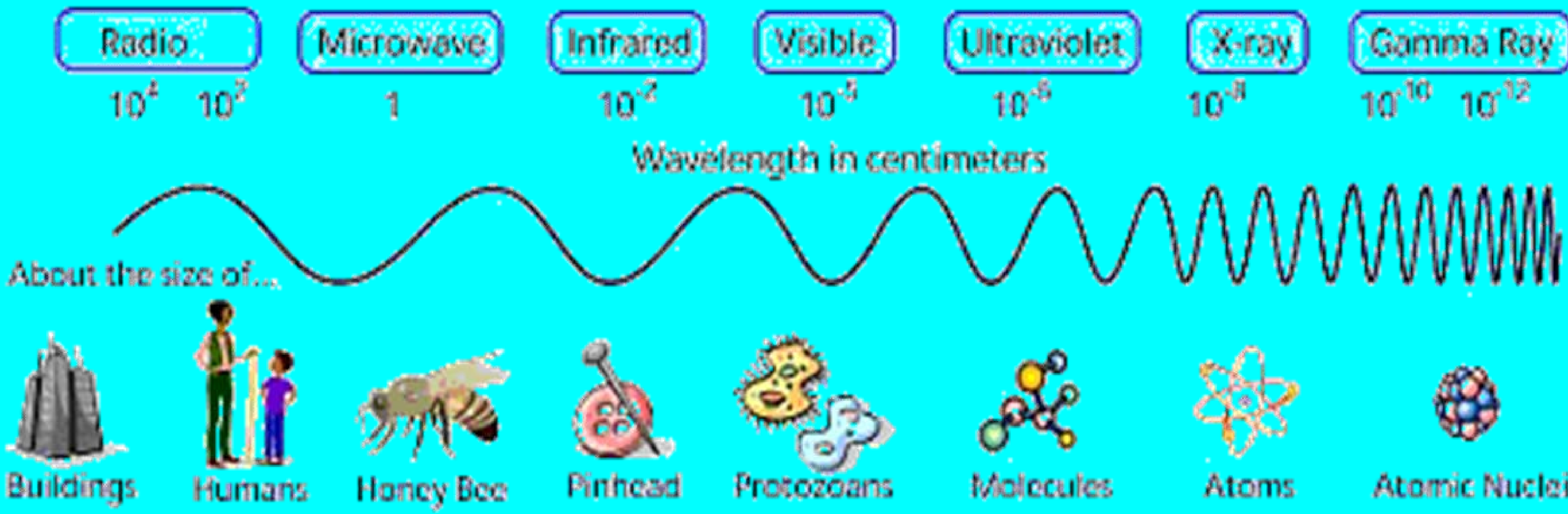
Completely collapsed star



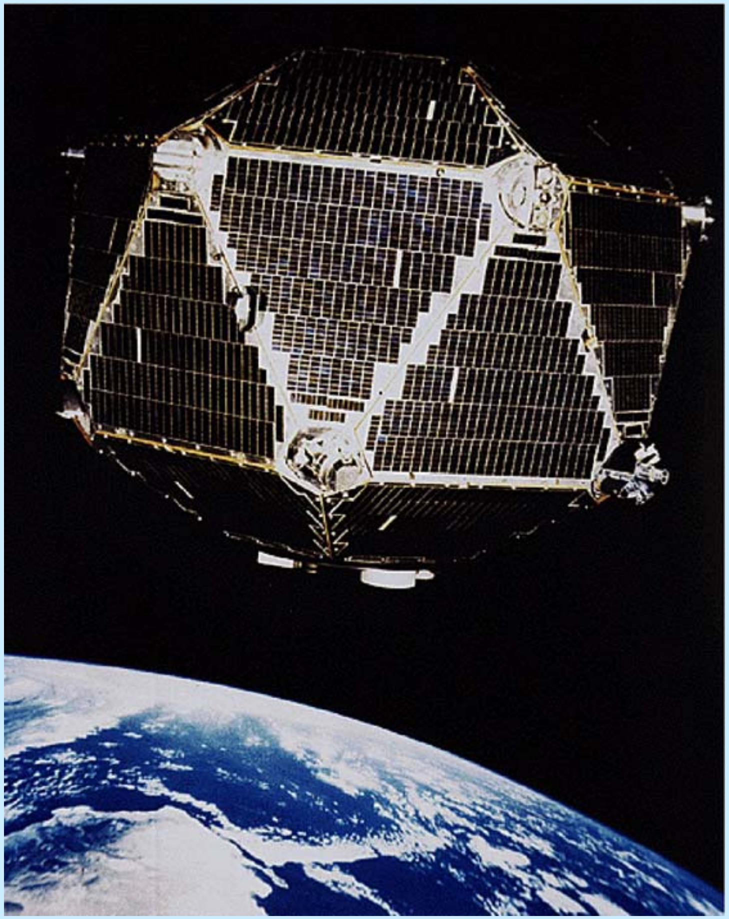
Gamma-Ray Bursts

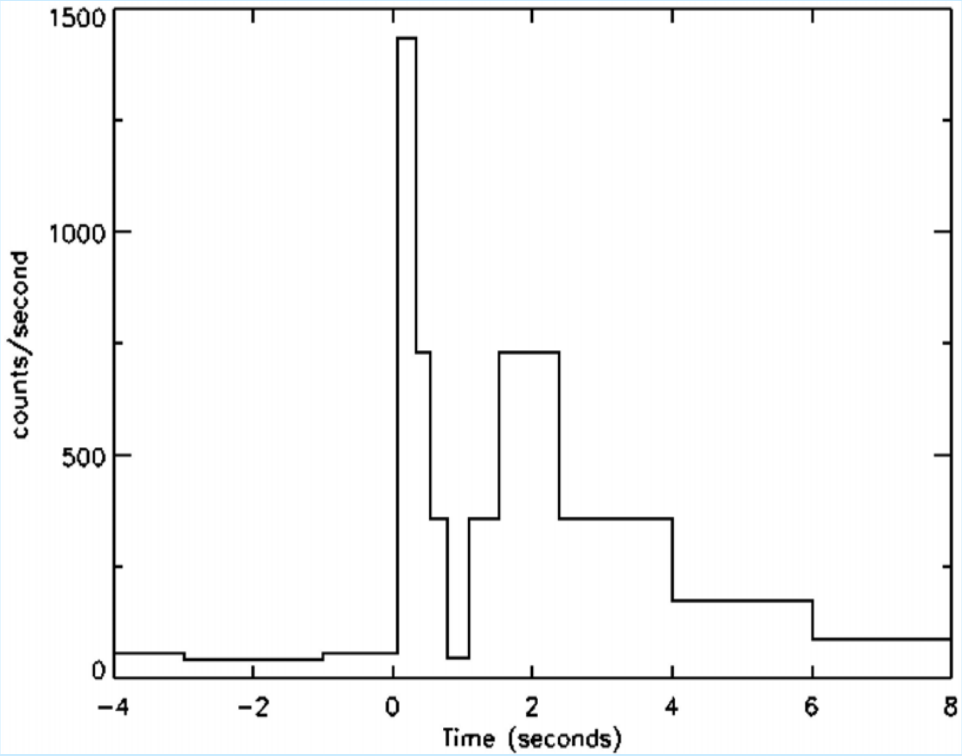
DIFFERENT TYPES OF ELECTROMAGNETIC WAVES

PROPAGATE WITH THE VELOCITY OF LIGHT: 300 000 Km/s



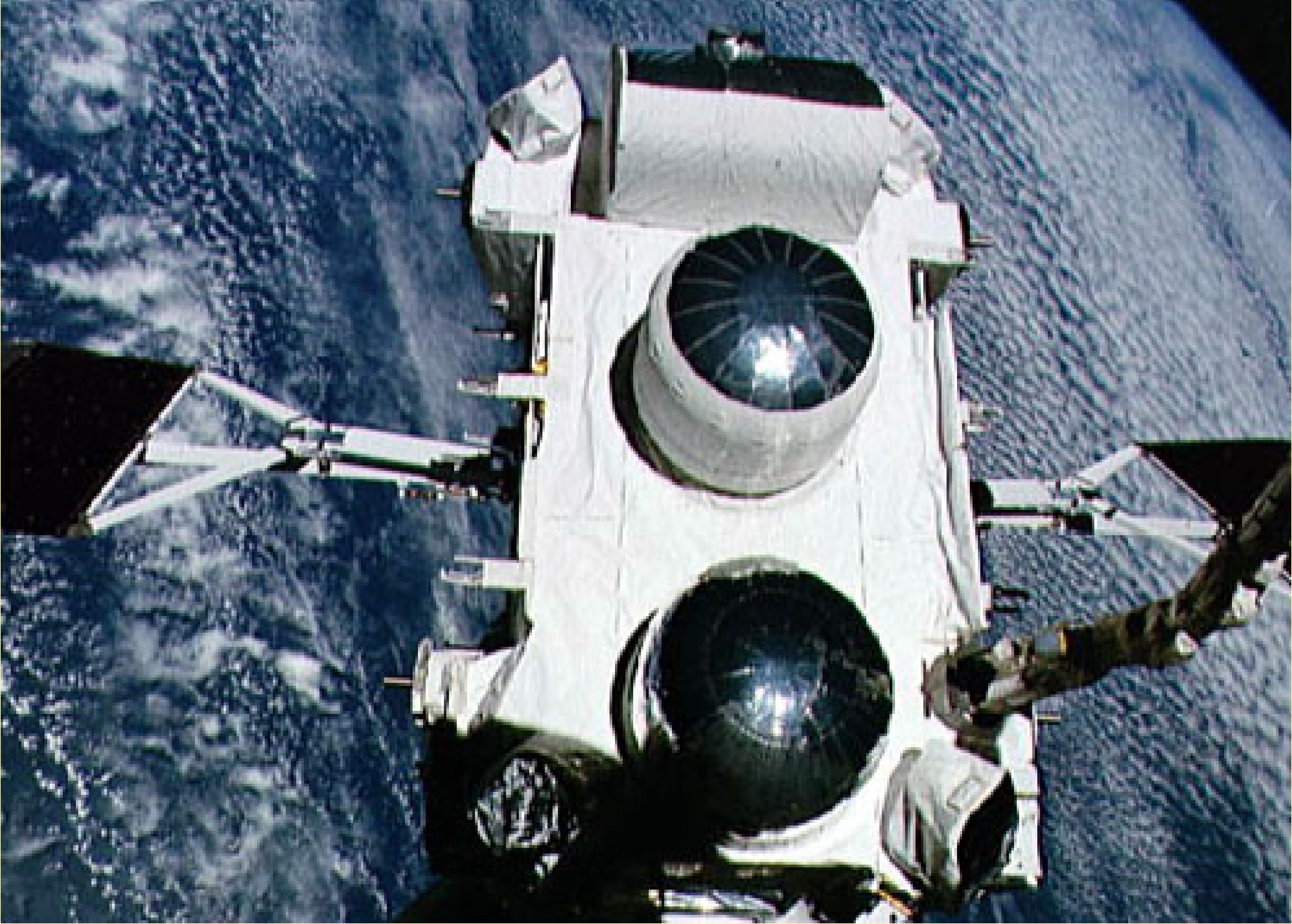
A Cold War riddle

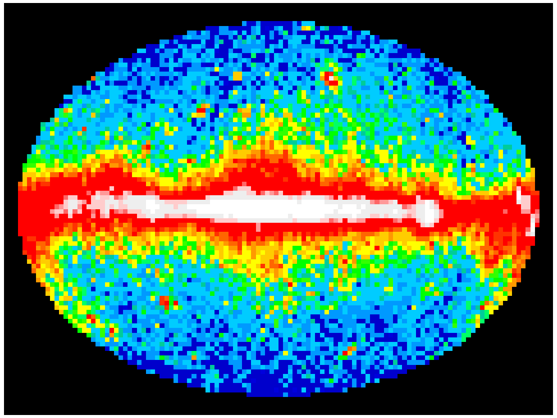




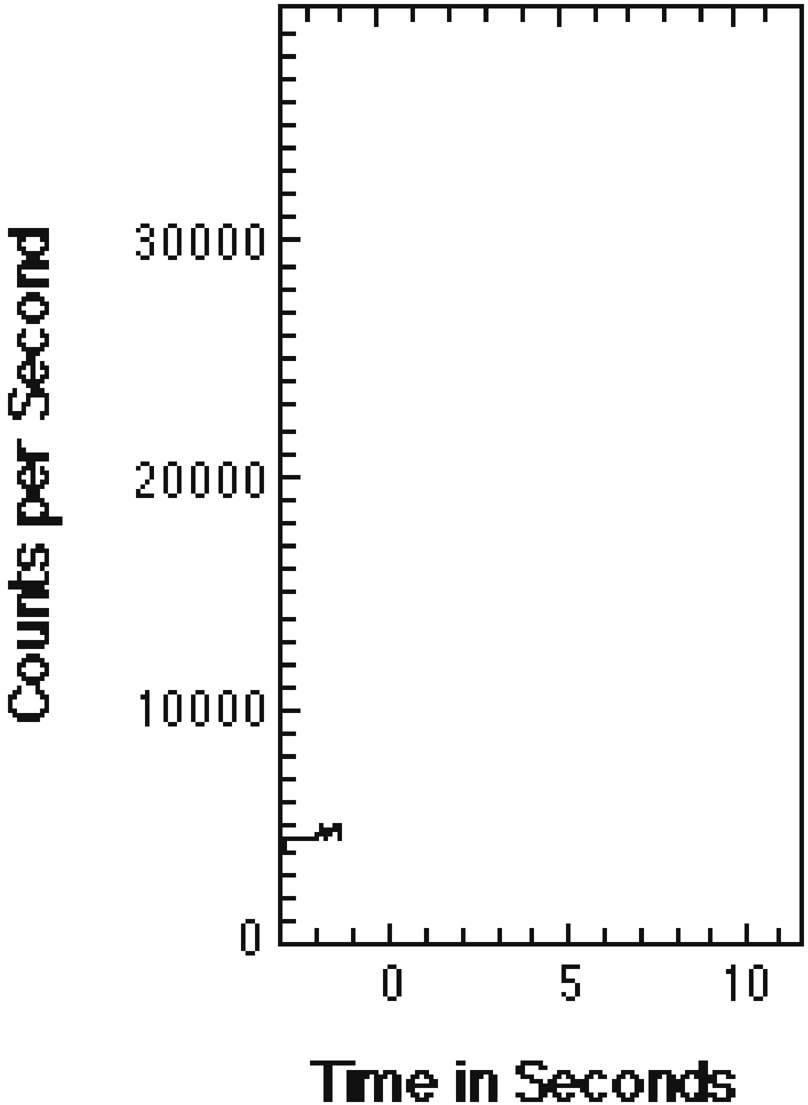
2 July 1967 : Not the Soviets

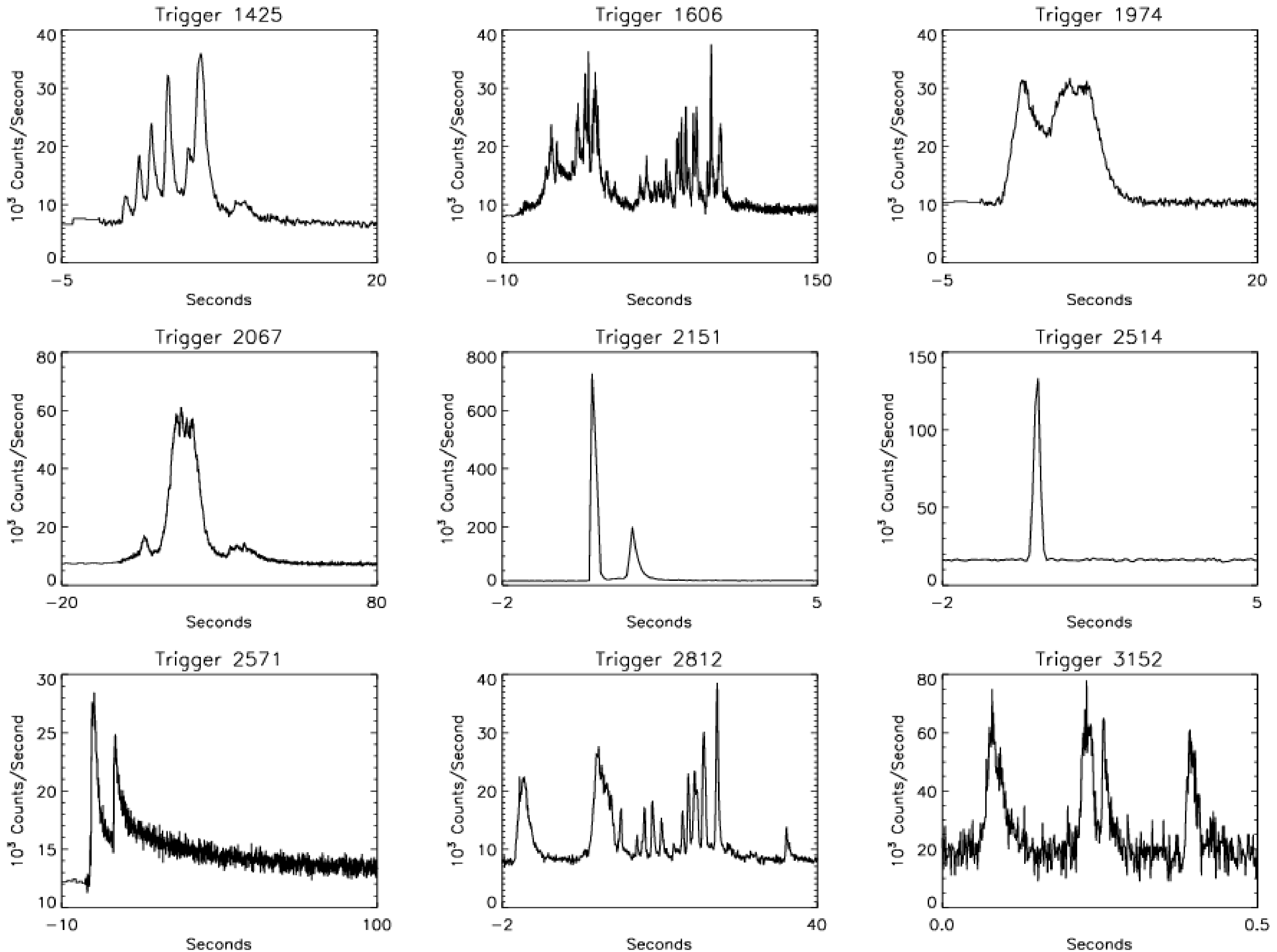
NASA’s Gamma-Ray Observatory 1991-1999





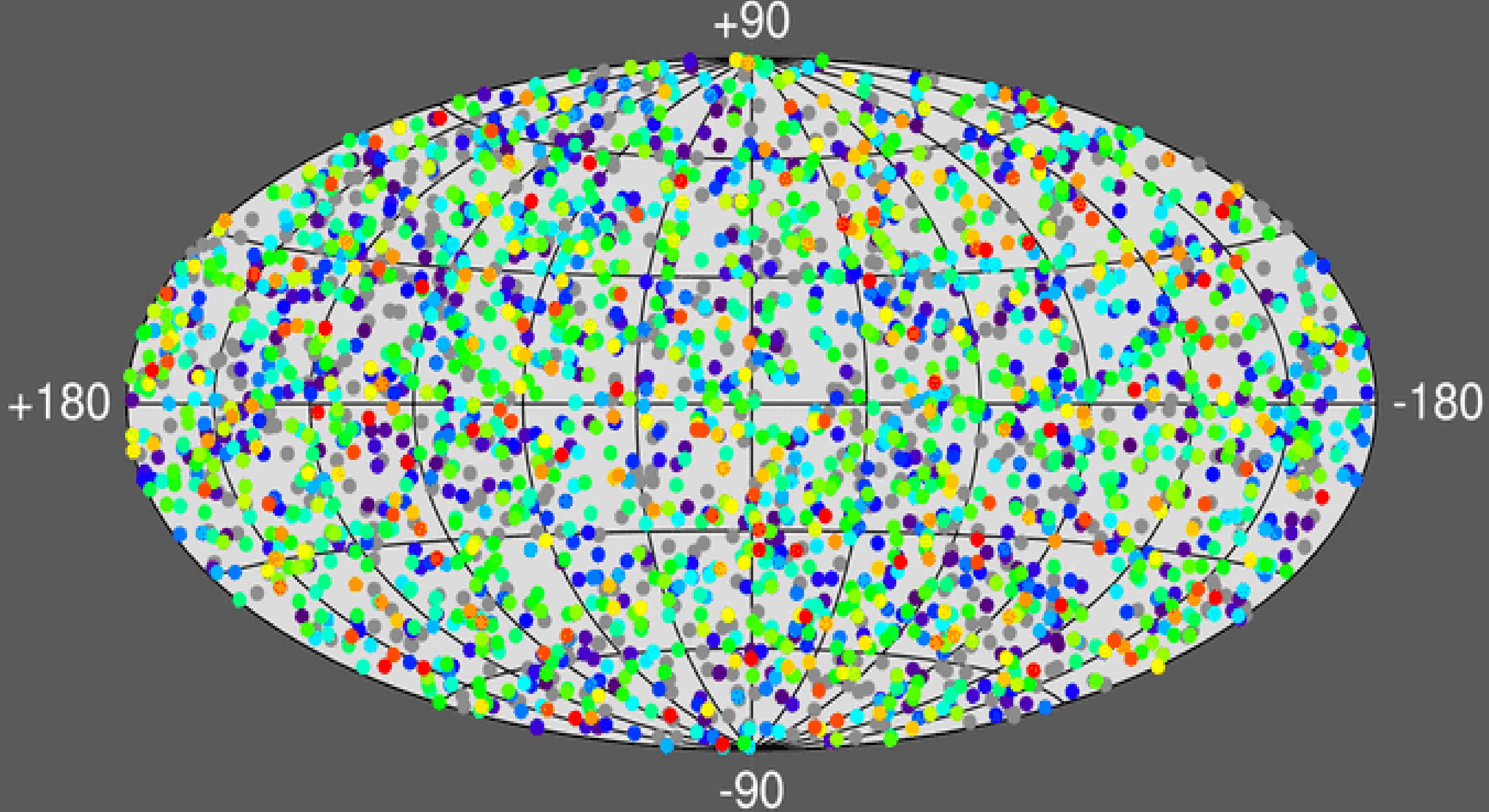
GRB 910421





Trigger 1425
Trigger 1606
Trigger 1974
Trigger 2067
Trigger 2151
Trigger 2514
Trigger 2571
Trigger 2812
Trigger 3152
10^3 Counts/Second
Seconds

2704 BATSE Gamma-Ray Bursts



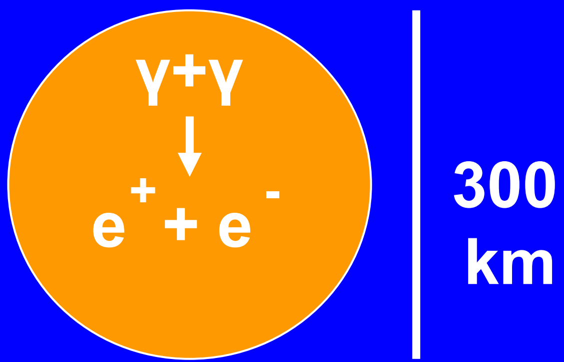
Compactness problem

Burst Energy:

At d= 10^5 lyrs (galactic): E = 10^{44} ergs(= 10^{37} J)

At d= 10^{10} lyrs (cosmolog.): E = 10^{54} ergs

1 ms spikes: Source size < 300 km

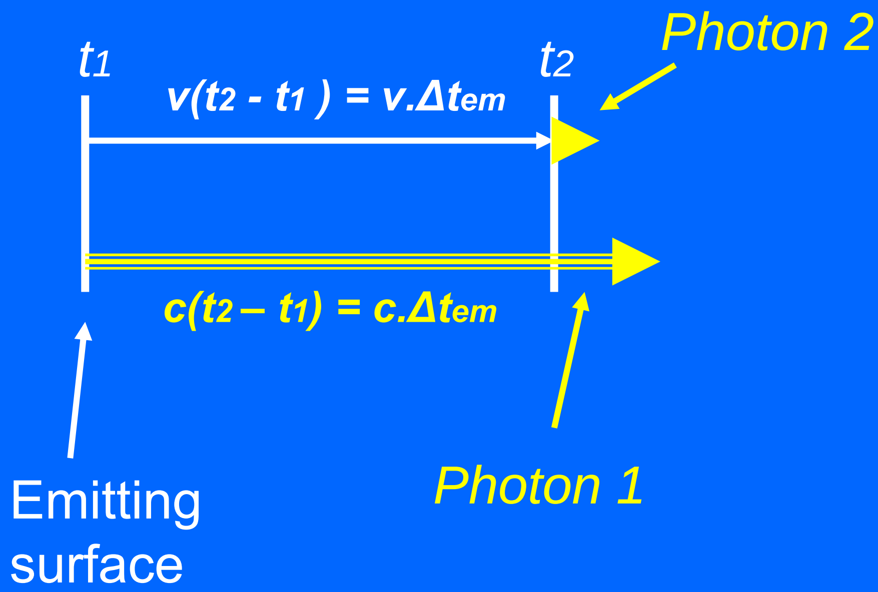


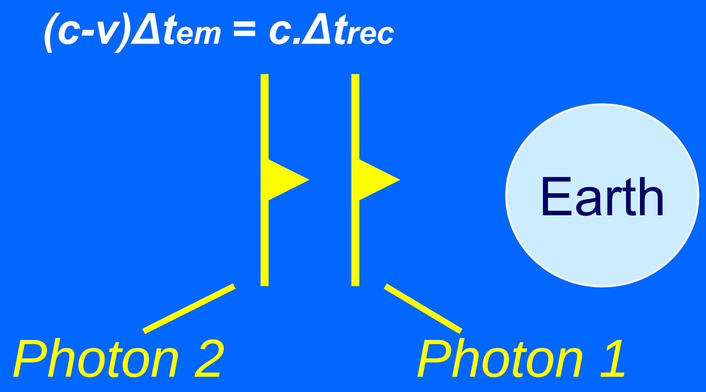
Enormous γ-photon energy density in this small volume leads to pair creation → completely opaque to γ-rays → no gamma rays can escape!!!

Solution *(Carvalho and Rees 1980):* **"Relativistic Fireball":**

Solution of "Compactness Problem" *(Carvalho and Rees, 1980)* **:**

Surface that is emitting the γ-rays is moving relativistically towards us with a high Lorentz-factor $\Gamma \sim 100$ to 1000



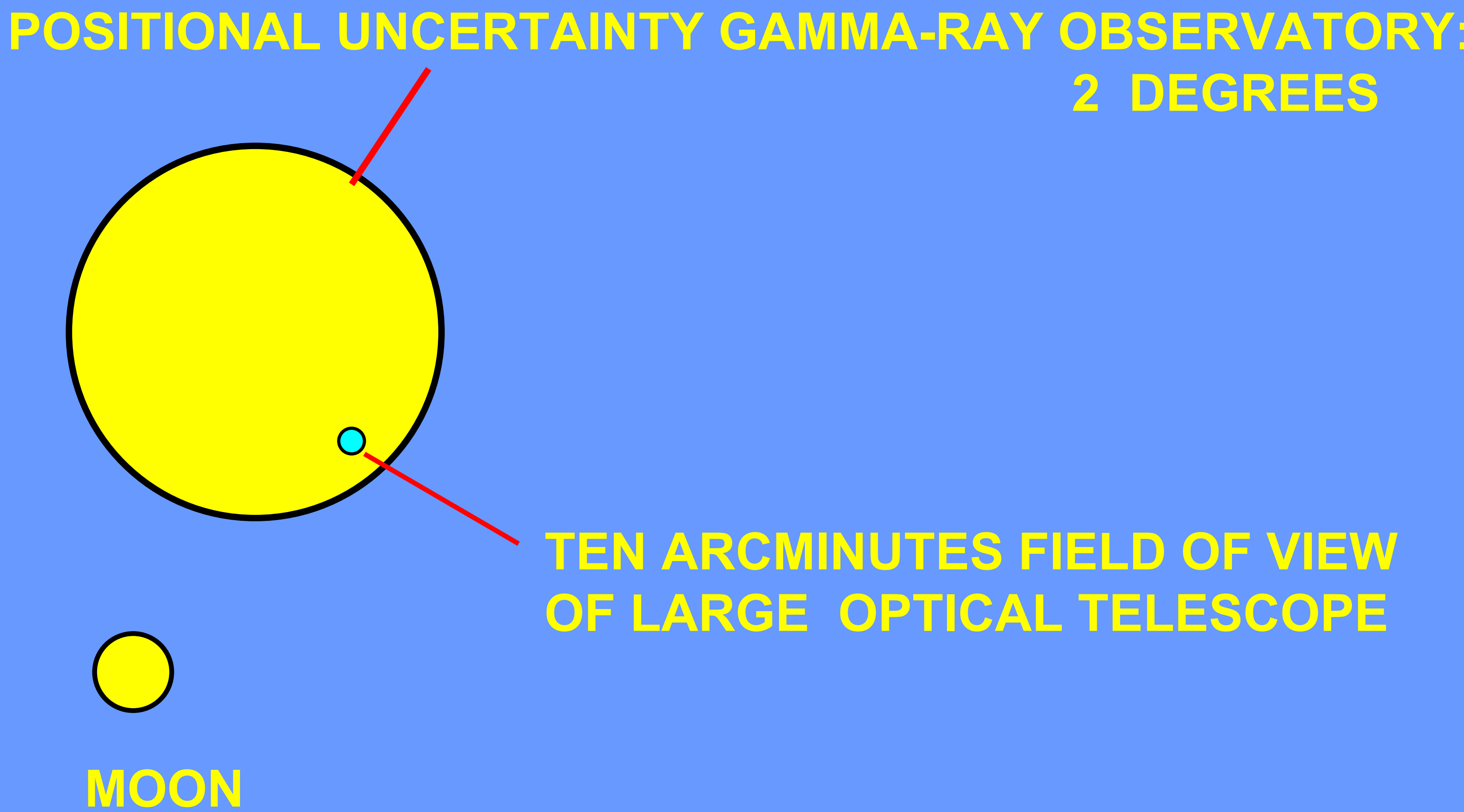


At arrival on Earth

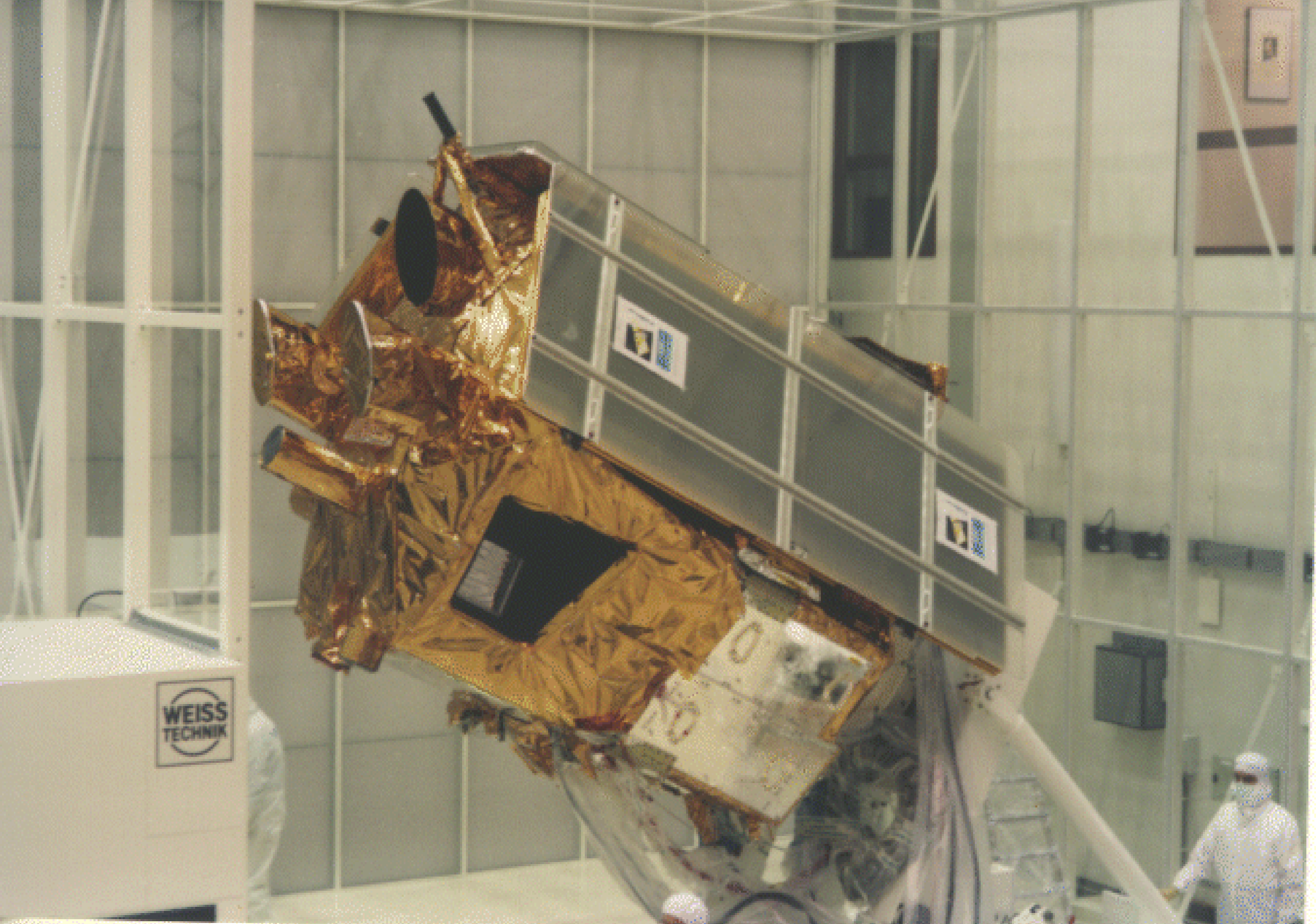
Arrival time difference $\Delta t_{rec} = (1 - v/c)\Delta t_{em} = \{(1-(v/c)^2)/(1+v/c)\}\Delta t_{em} = \Delta t_{em}/2\Gamma^2$

Where Γ = Lorentz factor. So, for $\Gamma = 1000$, $\Delta t_{em} = 2.10^6.\Delta t_{rec} = 2000$ **sec**

Source size 2000 lightsec = 4AU (HUGE): very diluted!!
This solves "compactness problem"


POSITIONAL UNCERTAINTY GAMMA-RAY OBSERVATORY:
2 DEGREES
TEN ARCMINUTES FIELD OF VIEW
OF LARGE OPTICAL TELESCOPE
MOON

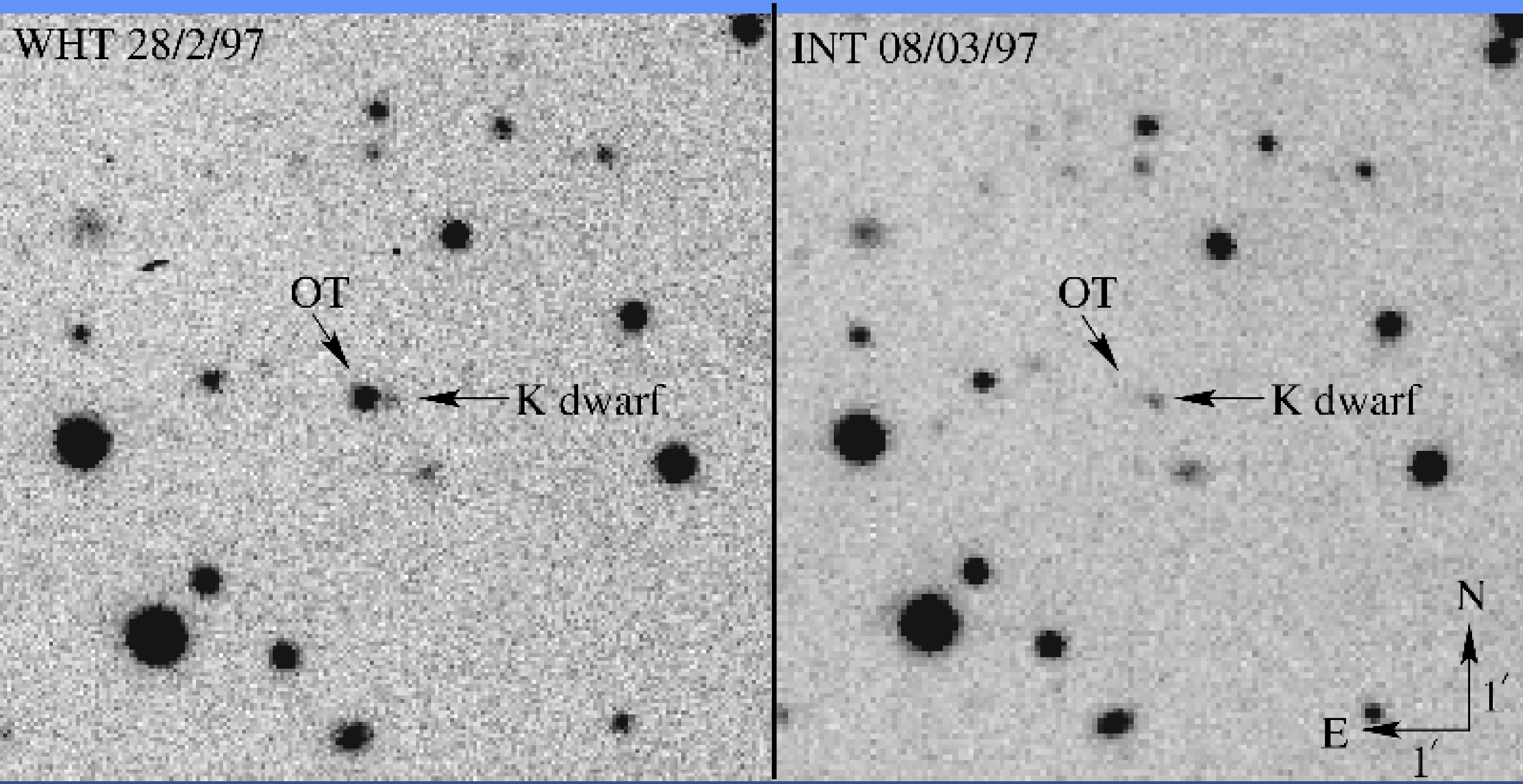
Italian-Dutch BeppoSAX satellite, 1996 - 2003



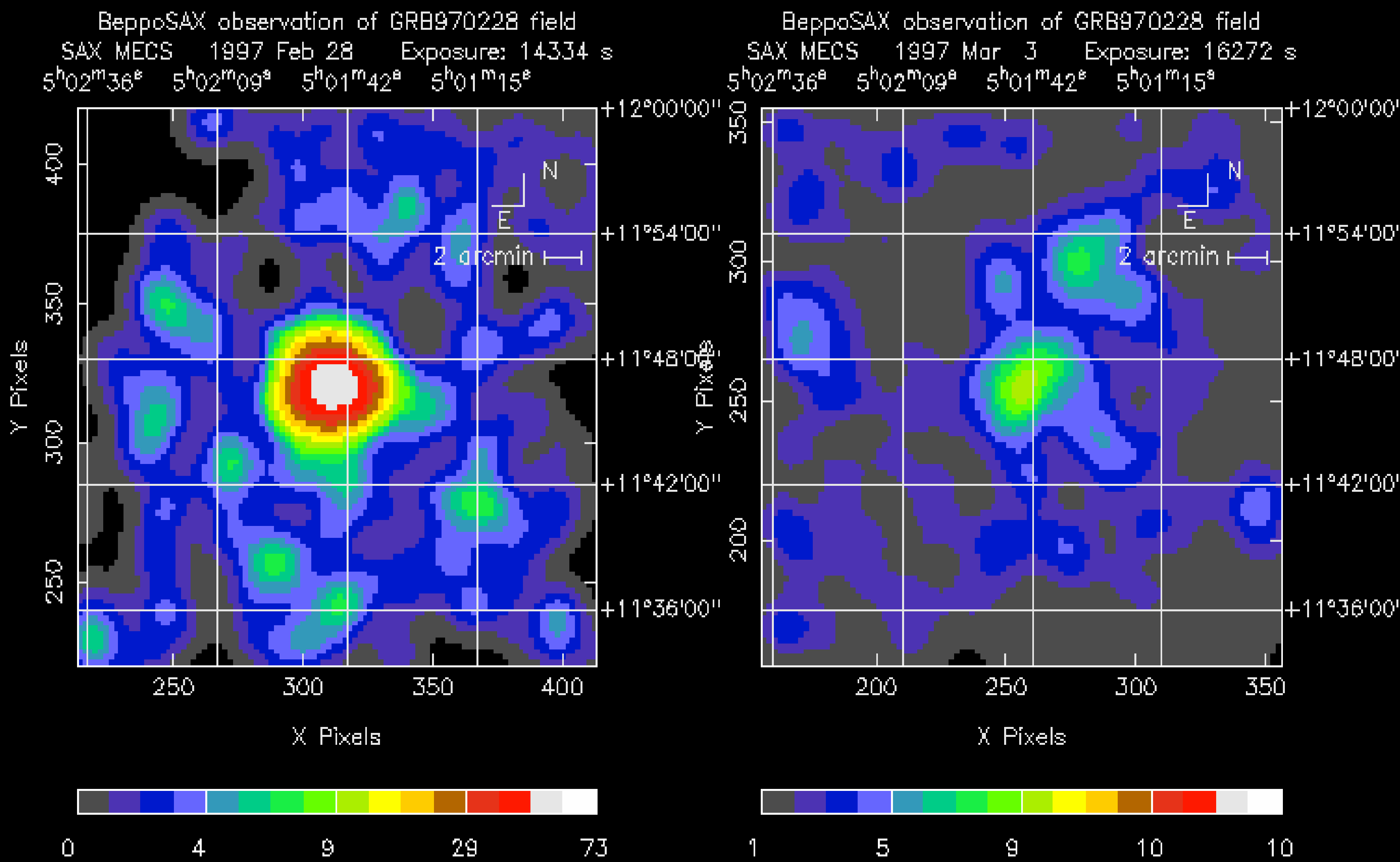
4.2 meter William Herschel Telescope on La Palma

First ever optical identification of a Gamma-ray Burst : 28 February 1997

20 hours after the burst **8 days after the burst**



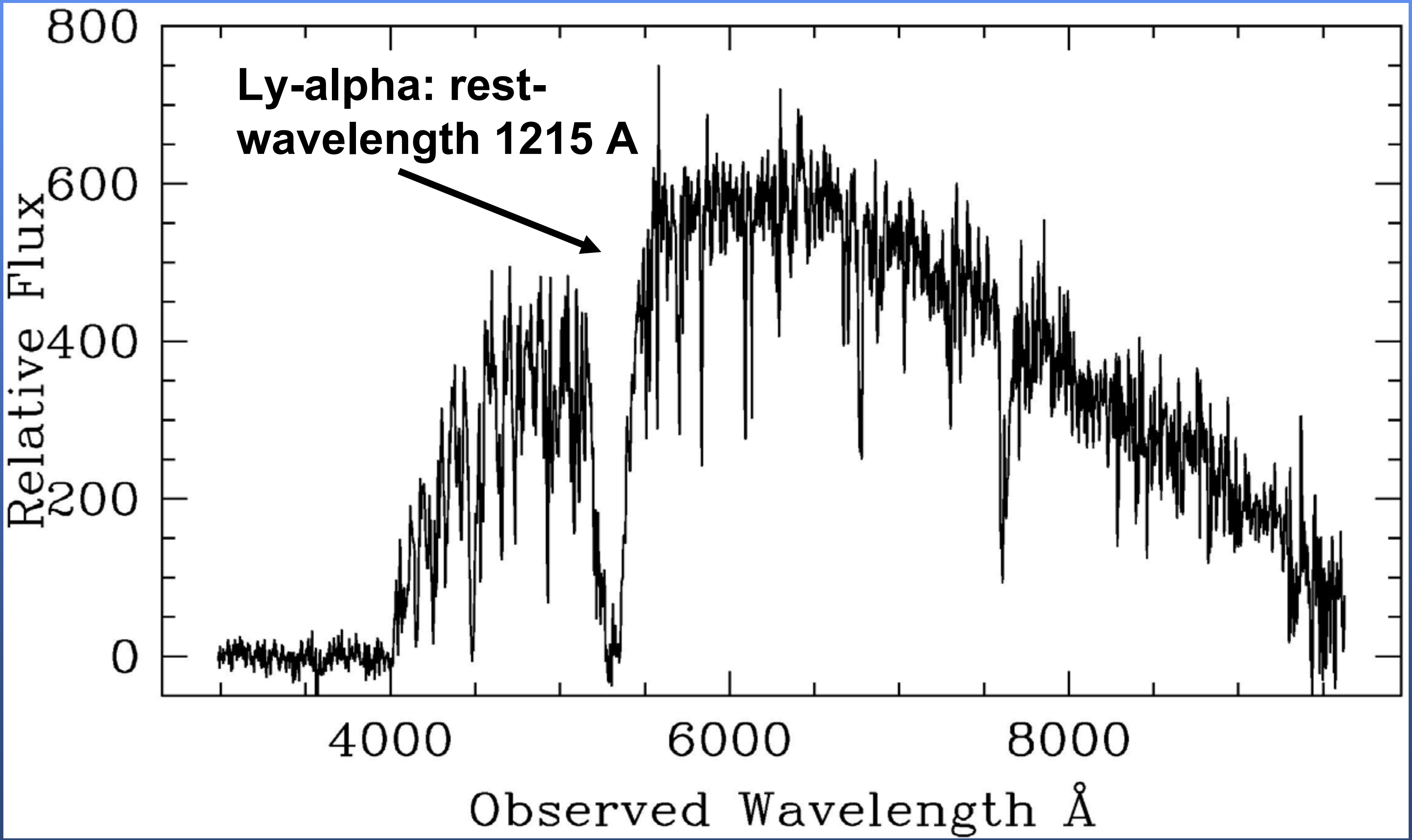
Van Paradijs, Groot, Galama et al., Nature, April 1997



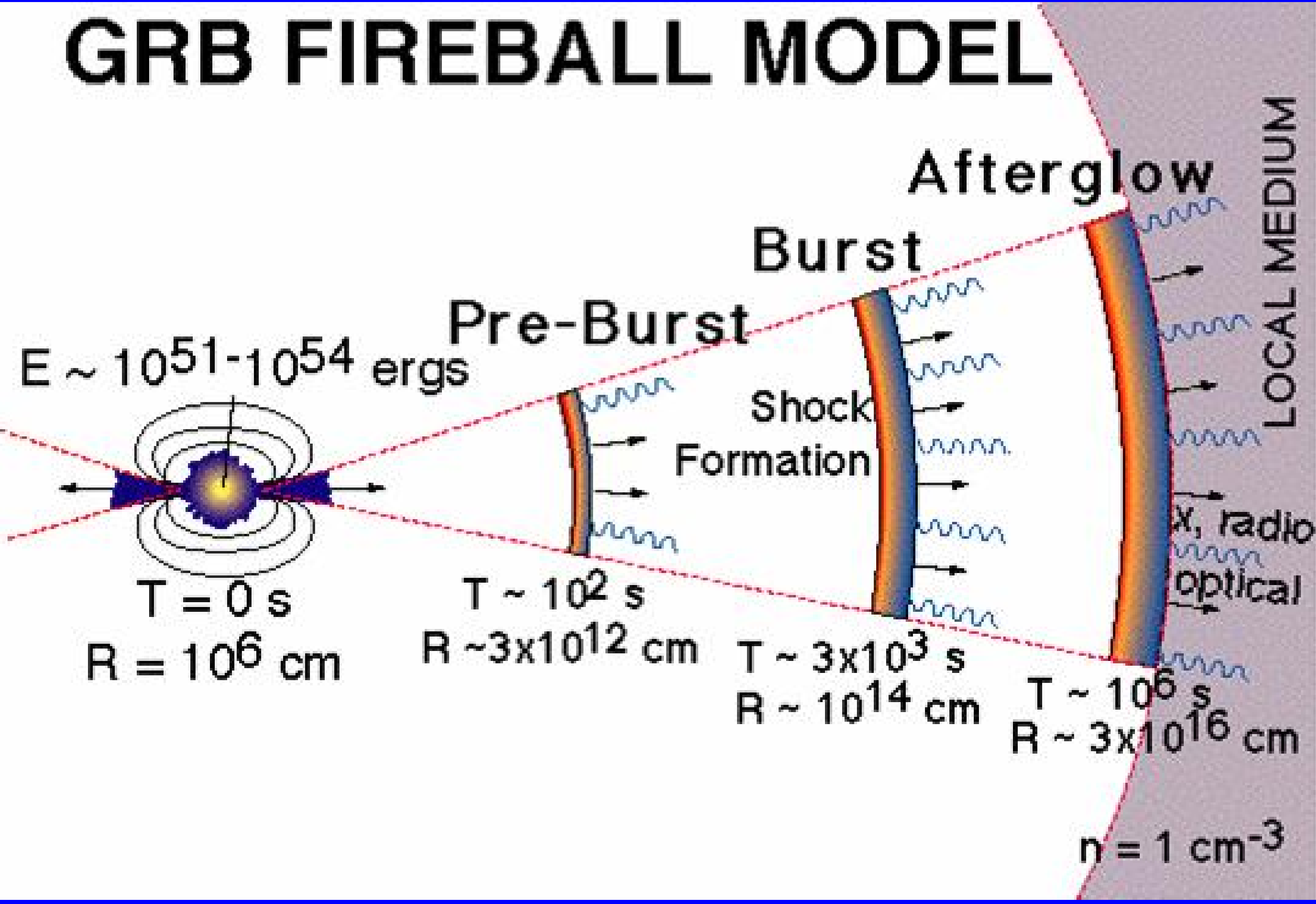
BeppoSAX observation of GRB970228 field
SAX MECS 1997 Feb 28 Exposure: 14334 s
5h02m36s 5h02m09s 5h01m42s 5h01m15s
+12°00'00"
+11°54'00"
+11°48'00"
+11°42'00"
+11°36'00"
N
E
2 arcmin
Y Pixels
X Pixels
0 4 9 29 73
BeppoSAX observation of GRB970228 field
SAX MECS 1997 Mar 3 Exposure: 16272 s
5h02m36s 5h02m09s 5h01m42s 5h01m15s
+12°00'00"
+11°54'00"
+11°48'00"
+11°42'00"
+11°36'00"
N
E
2 arcmin
Y Pixels
X Pixels
1 5 9 10 10

Gamma-ray Burst of 23 March 2003: Redshift z= 3.28 , 11.7 billion years ago (Universe was 4.28 times smaller than now; in volume: ~ 100 times smaller)

GRACE-collaboration with the ESO VLT



GRB FIREBALL MODEL

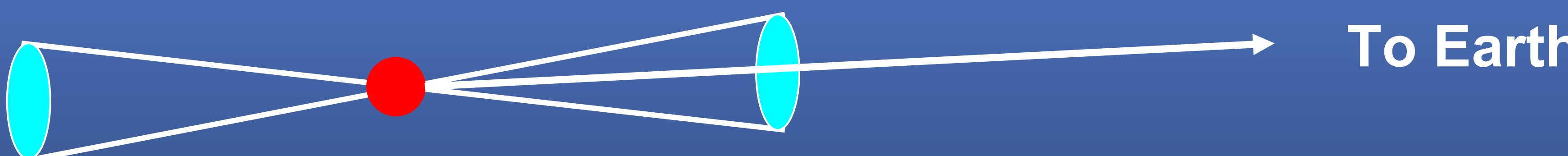


ENERGY OF THE GAMMA-RAY BURST

* IF EMITTED WITH SAME STRENGTH IN ALL DIRECTIONS:

AS MUCH AS THE SUN PRODUCES IN 10 000 BILLION YEARS (1000 TIMES THE LIFETIME OF THE SUN): COMPLETE CONVERSION INTO ENERGY OF 1 SOLAR MASS = 330 000 x EARTH (~10^{54} ergs)

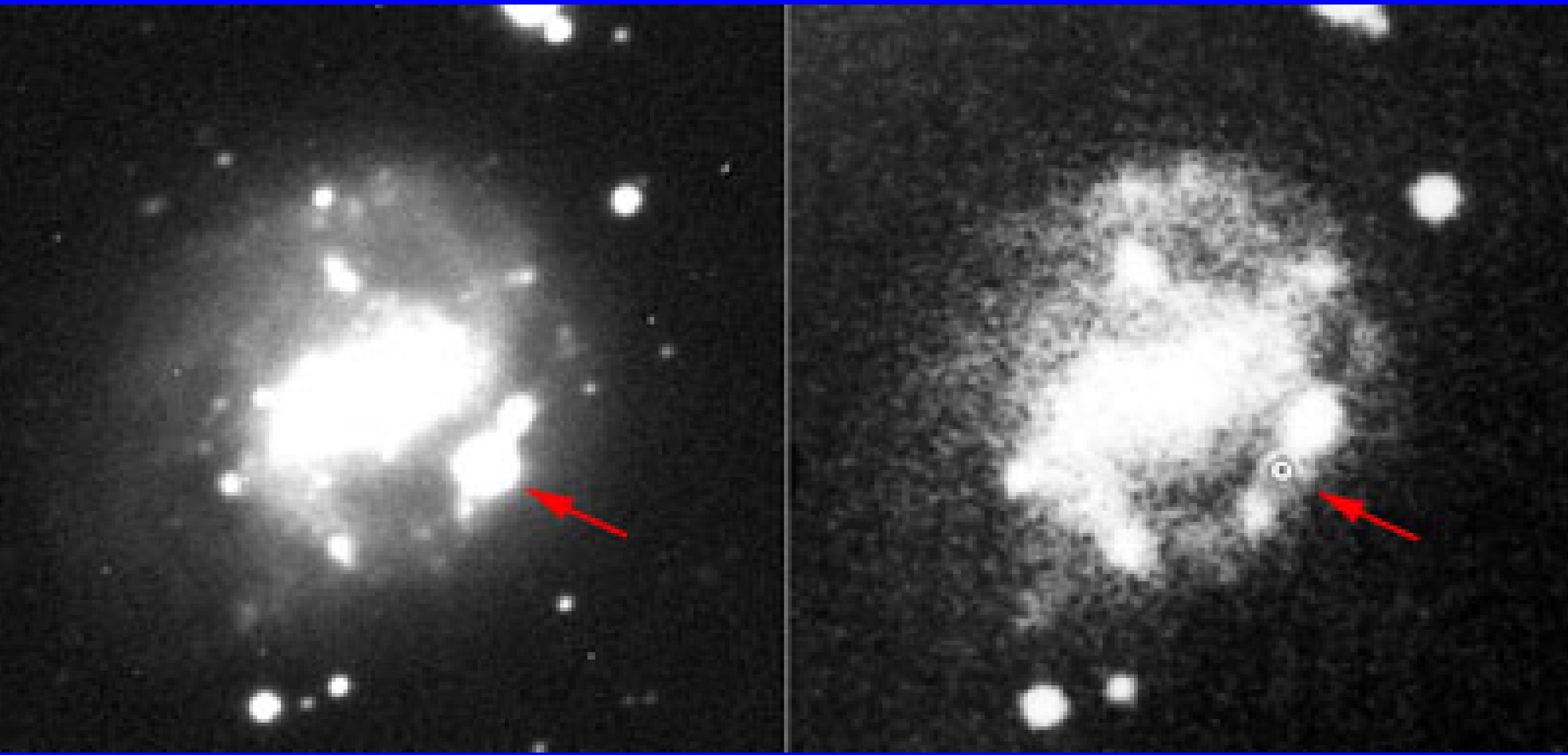
*IF RADIATED IN NARROW BEAMS (CONES OF 10 DEGREES):



1000 TIMES LESS ENERGY: AS MUCH AS SUN EMITS IN ENTIRE LIFE = ENERGY OF SUPERNOVA EXPLOSION (~10^{51} ergs)

Supernova 1998bw / Gamma-Ray Burst of 25 April 1998

Picture of 1 May 1998 | Picture from 1985

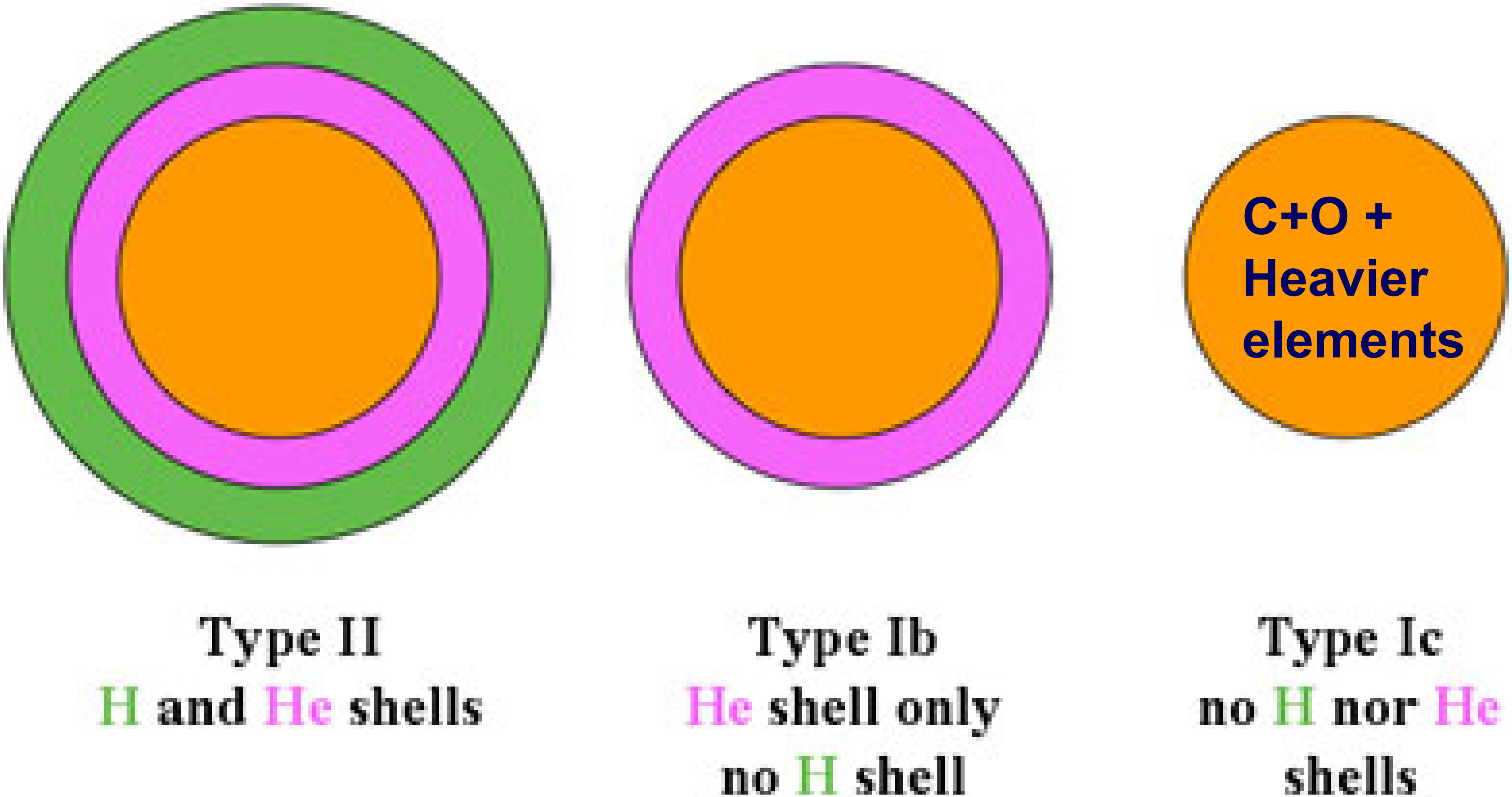


Galaxy ESO 0184-G82 at 140 million lightyears distance

Supernova had no H or He in spectrum: Type Ic (peculiar)

Outflow velocities 40 000 km/s (4x larger than “normal” Ic)

Types of Core-collapse supernovae

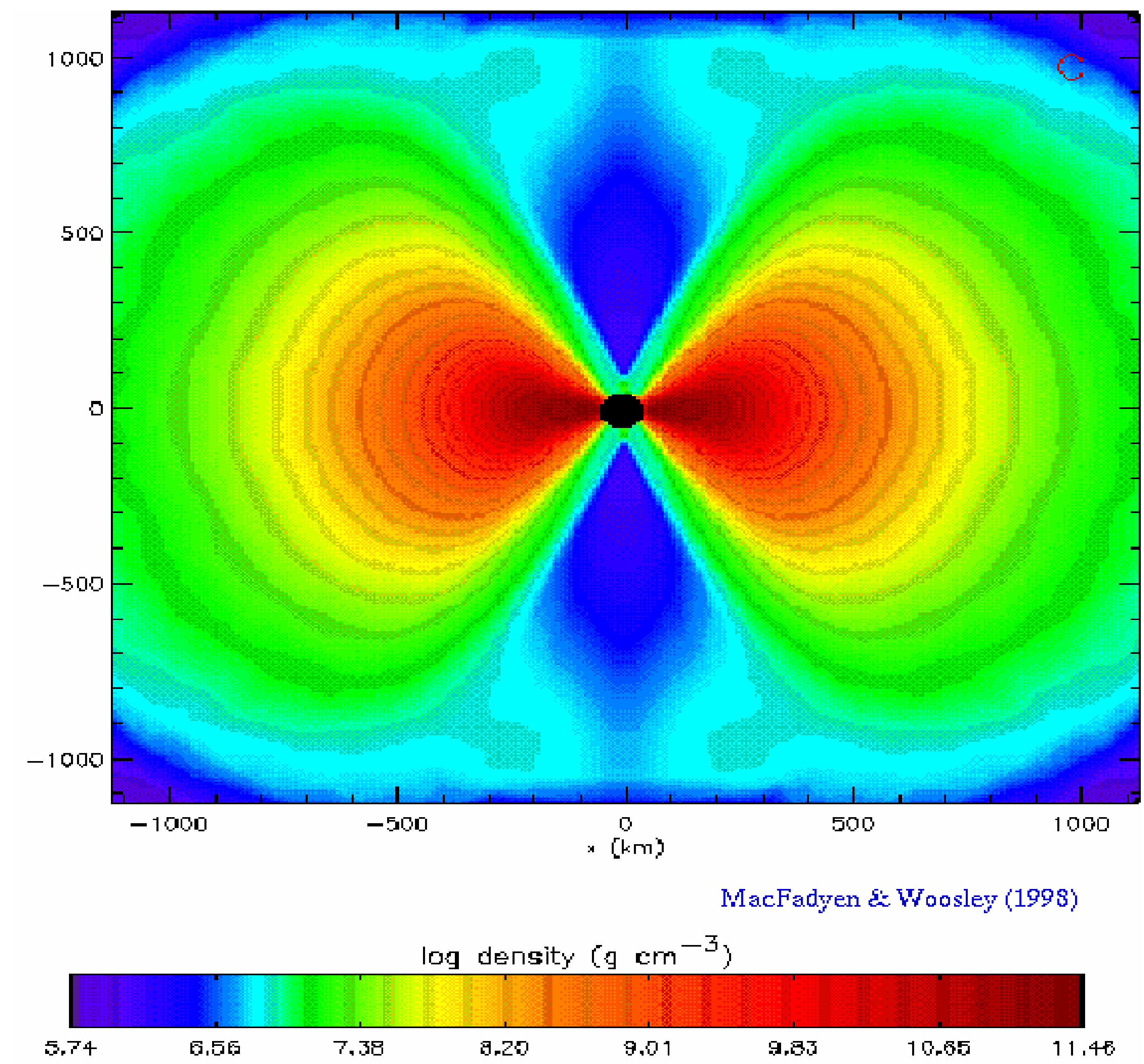


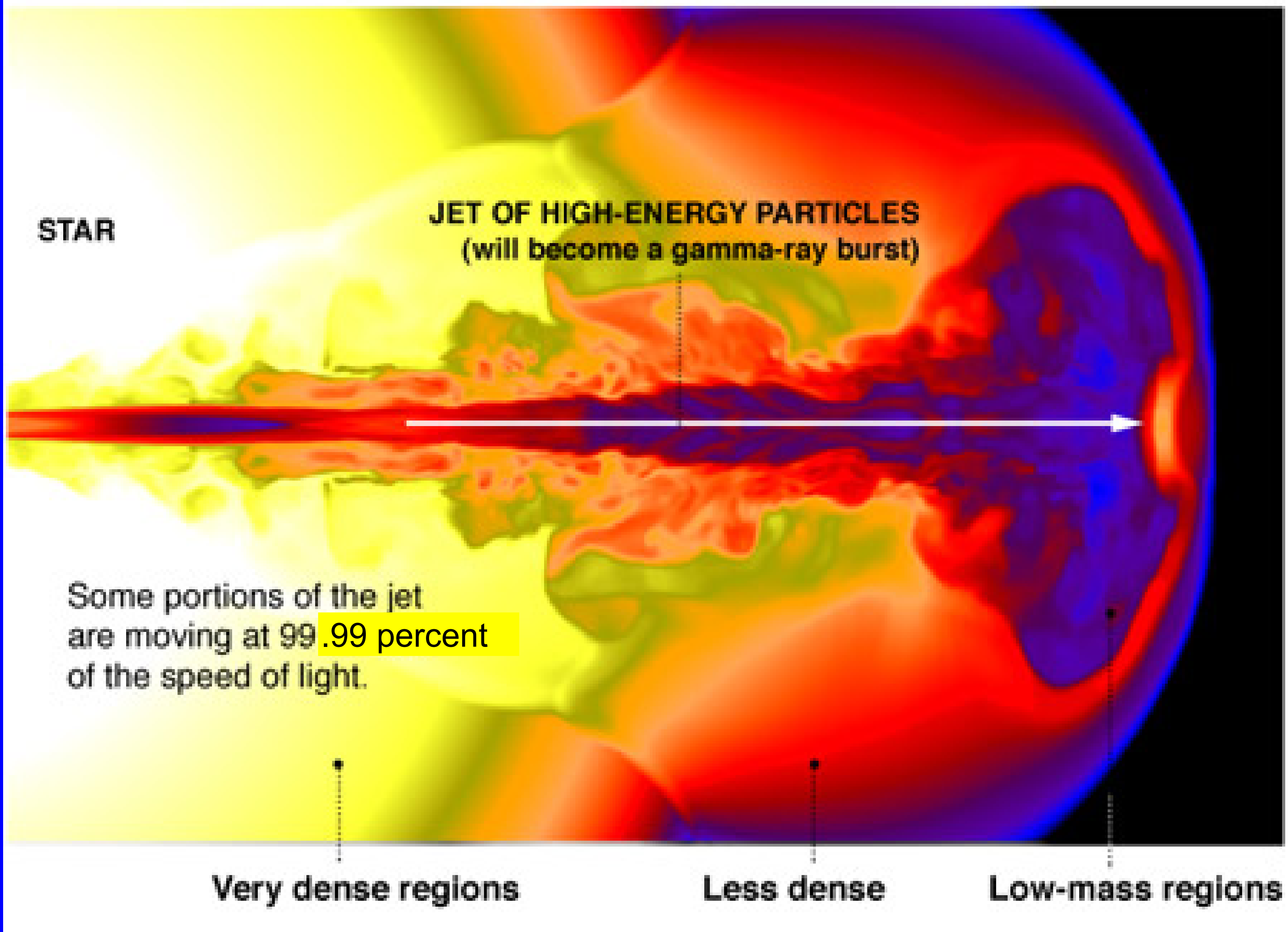
Energy of SN 1998bw requires a > 6 solar mass C-O core with a collapsing Fe-core > 3 solar masses ⟶ Black Hole

Rapidly Rotating Disk of NUCLEAR matter around a recently-formed BLACK HOLE produces neutrino-driven JETS perpendicular to the disk.

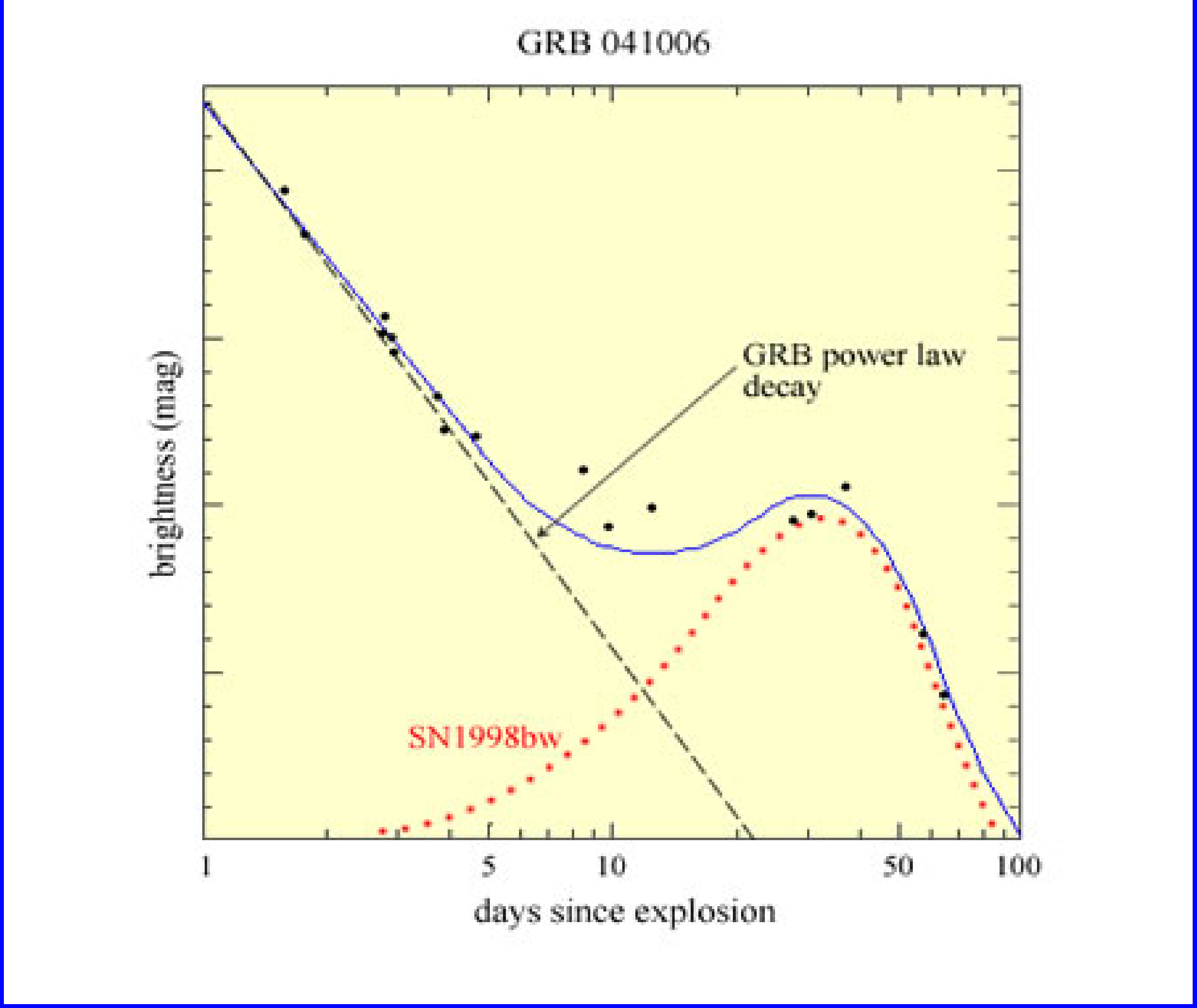
(Woosley, 1993, and MacFadyan & Woosley 1998)

“Hypernova” or “Collapsar”

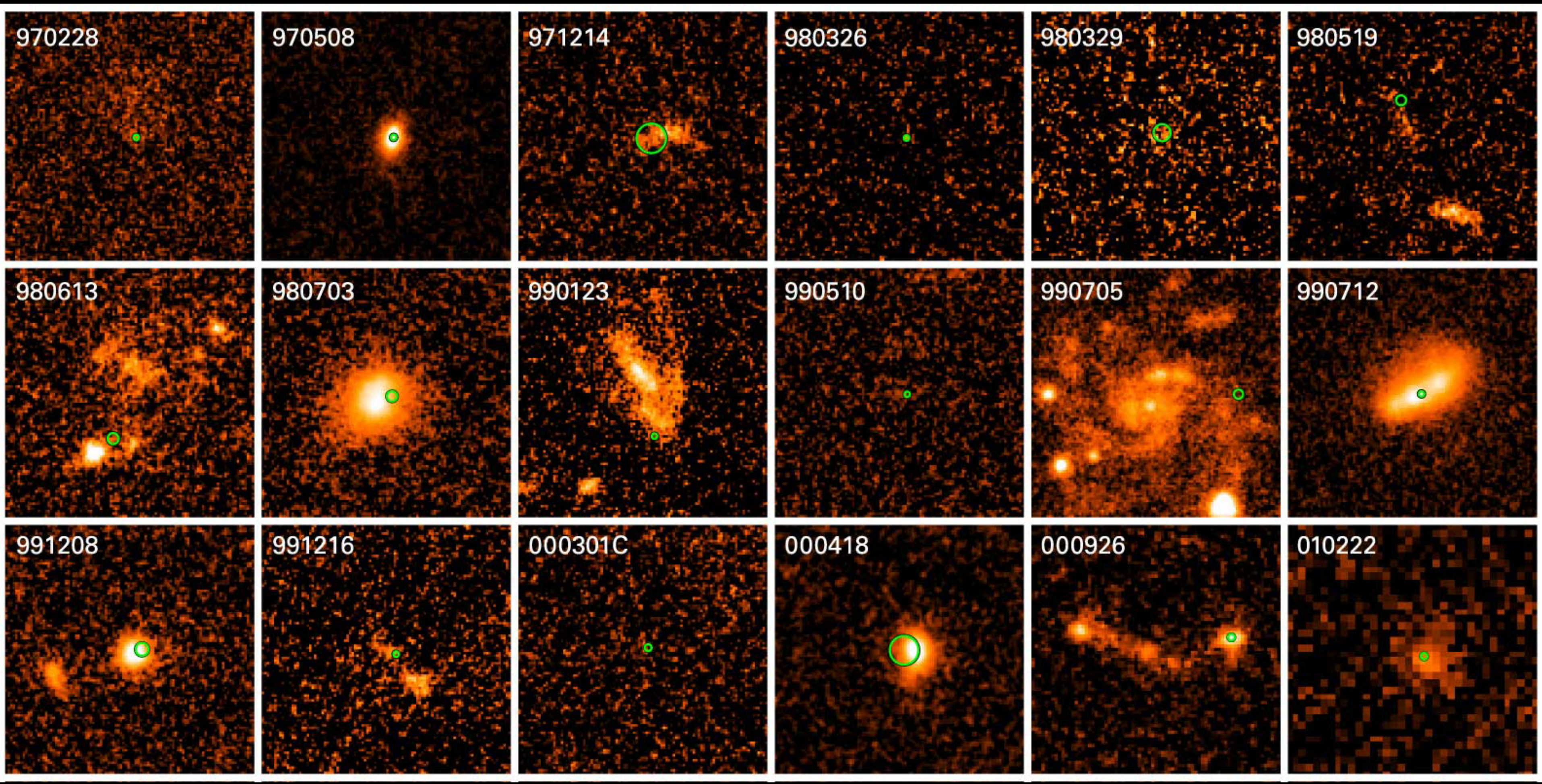




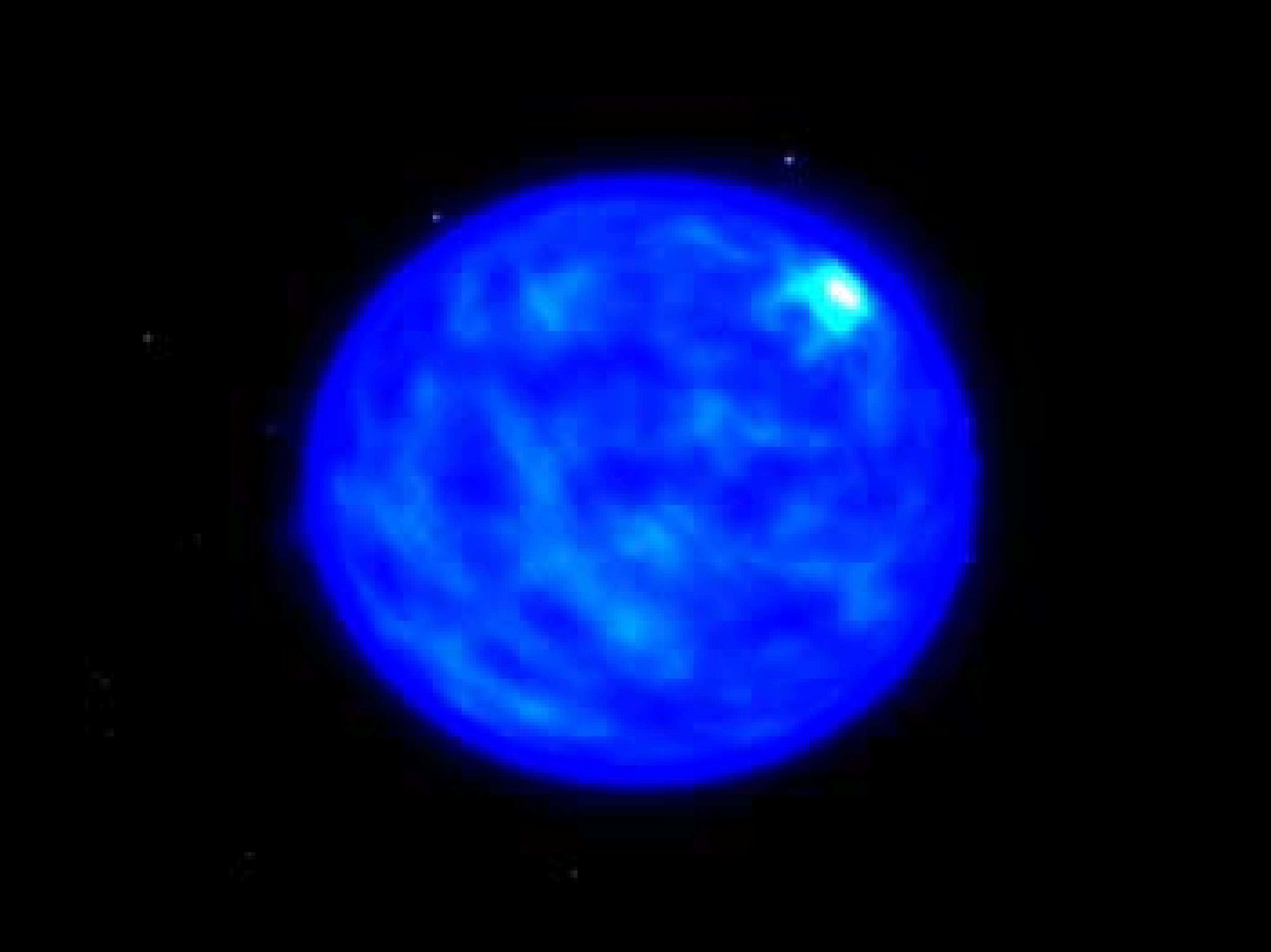
Sources: Weiqun Zhang and Stan E. Woosley, University of California at Santa Cruz

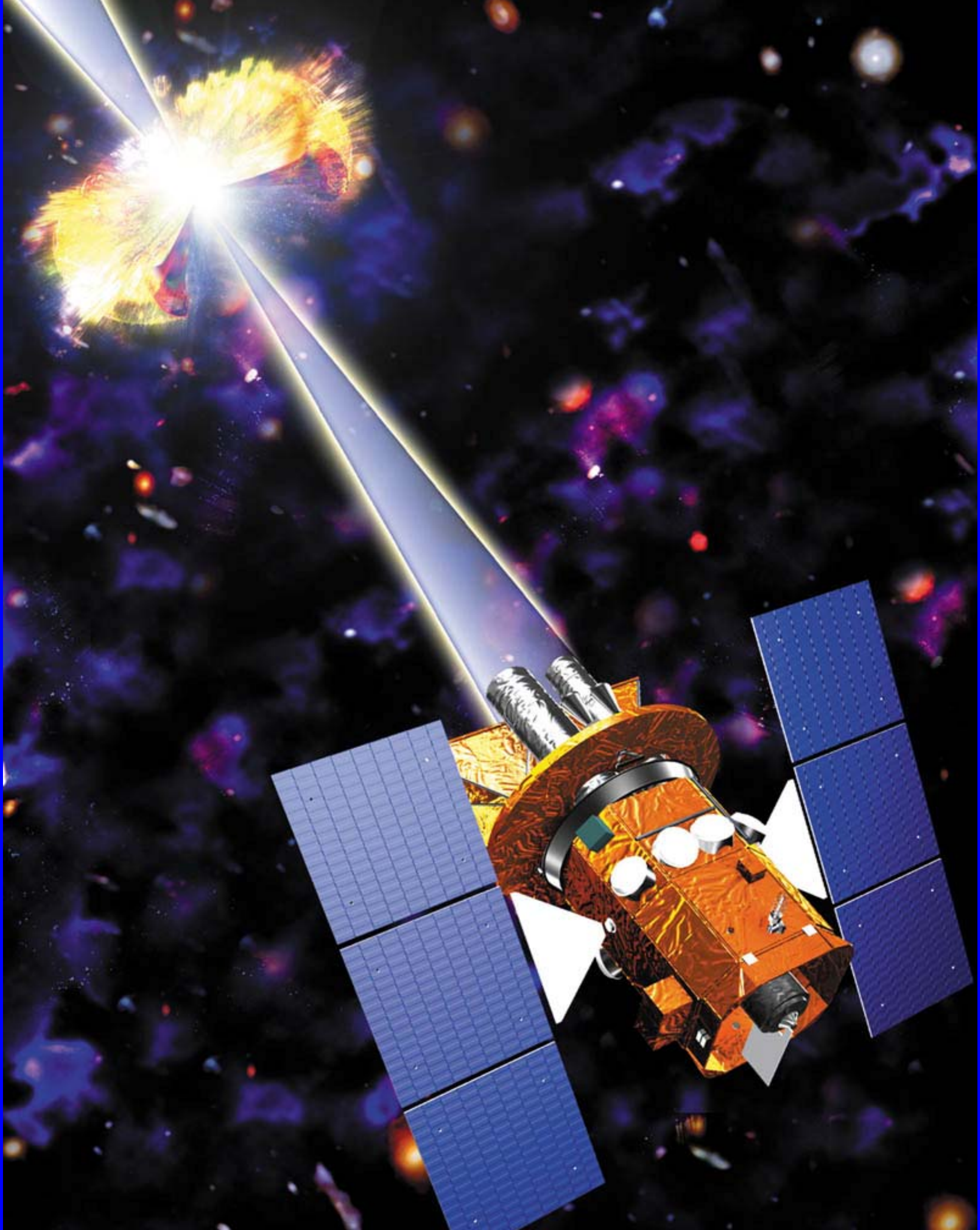


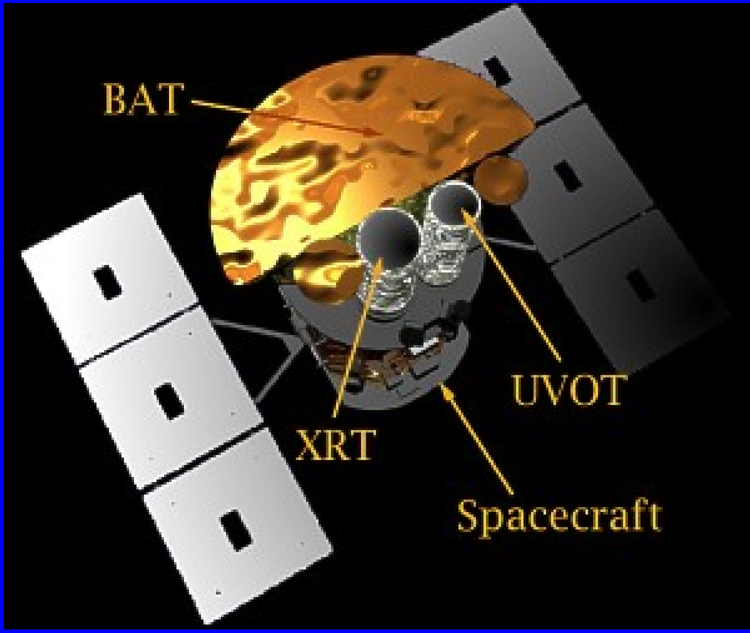
Many long bursts at high z have shown a late-time Supernova “bump” in lightcurve, further confirming the “Collapsar” model for long-duration GRBs



HST Host galaxies of 18 long-duration GRBs



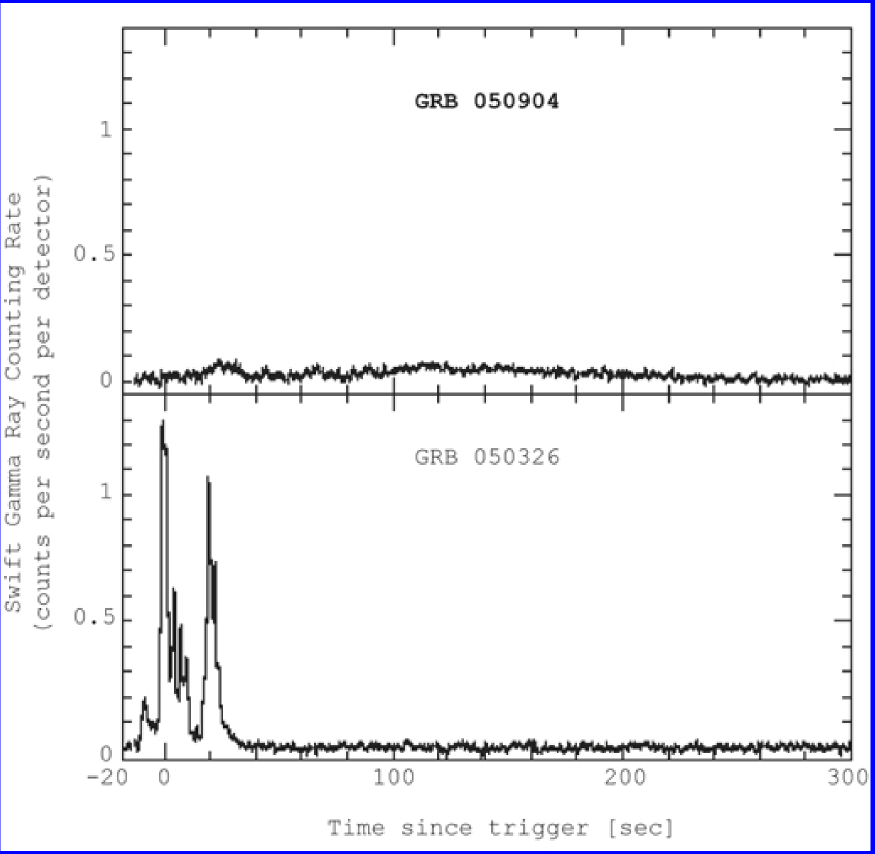


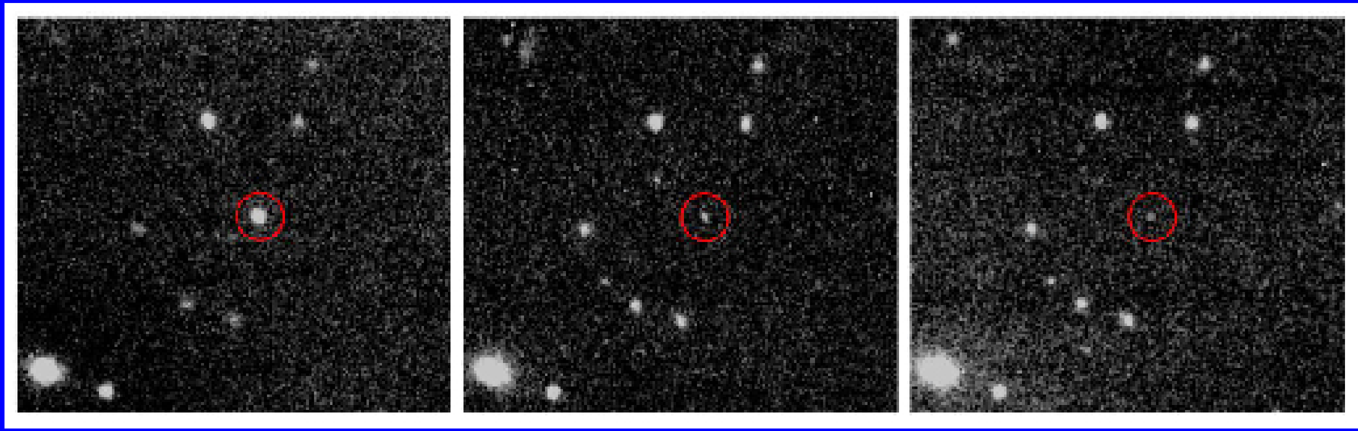


Swift Satellite
Launched
20 Nov 2004

GRB 050904 (4 sept. 2005)
Most distant GRB ever recorded: z= 6.29

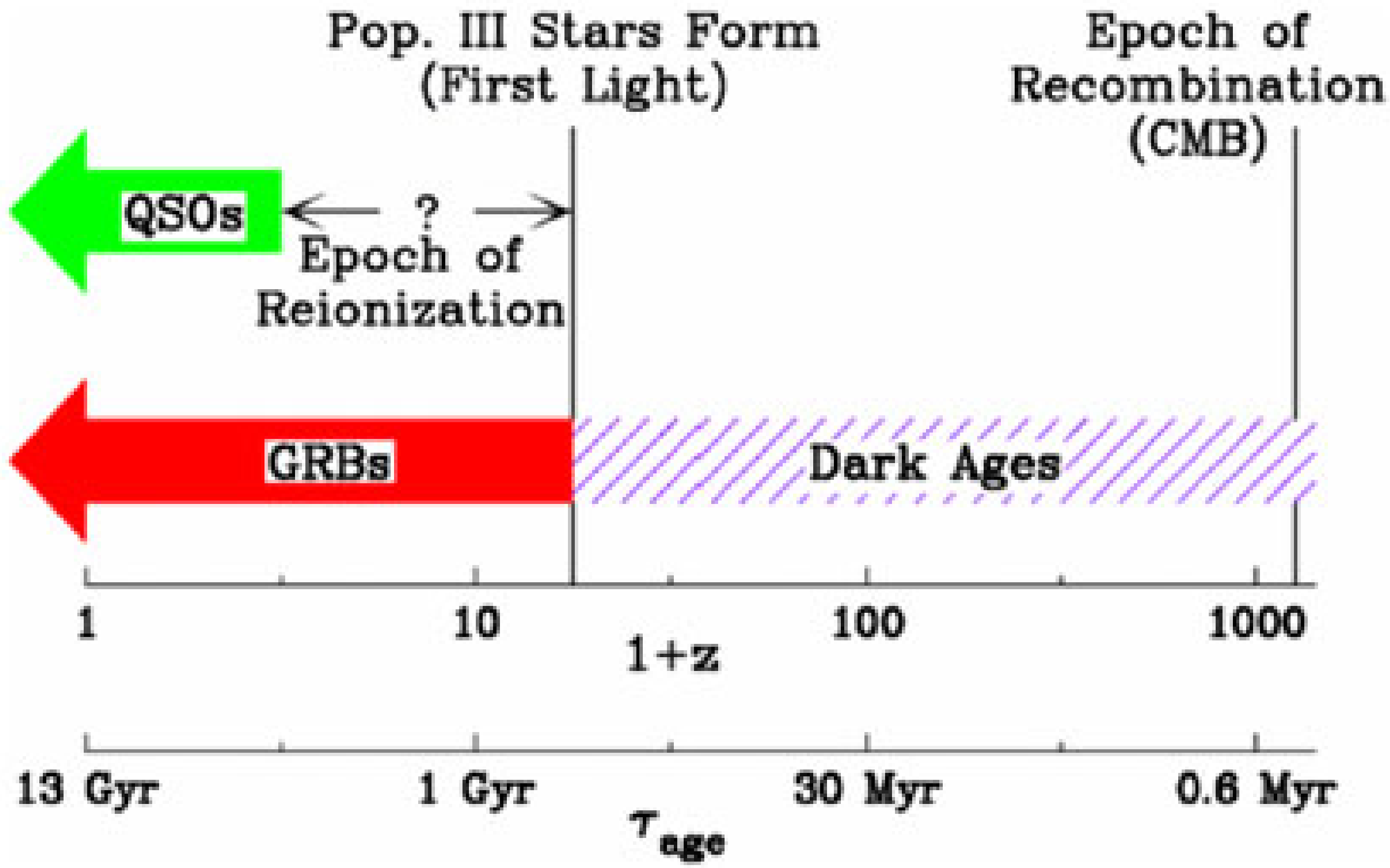
[12.6 Billion years ago]



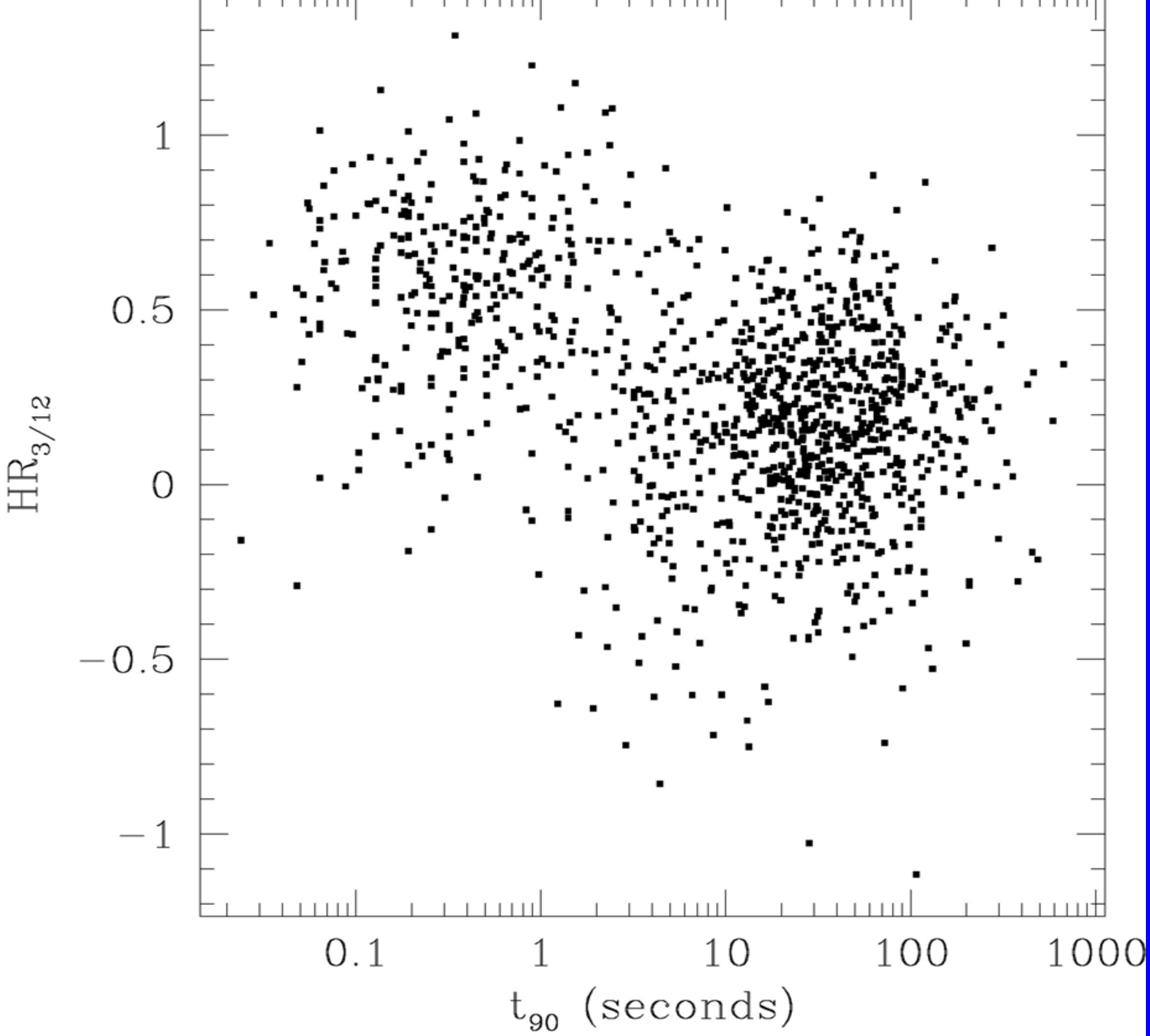


Infrared afterglow: discovery picture (left), and subseq. Nights (4.1 meter SOAR telescope Chile)

GRBs in Cosmological Context

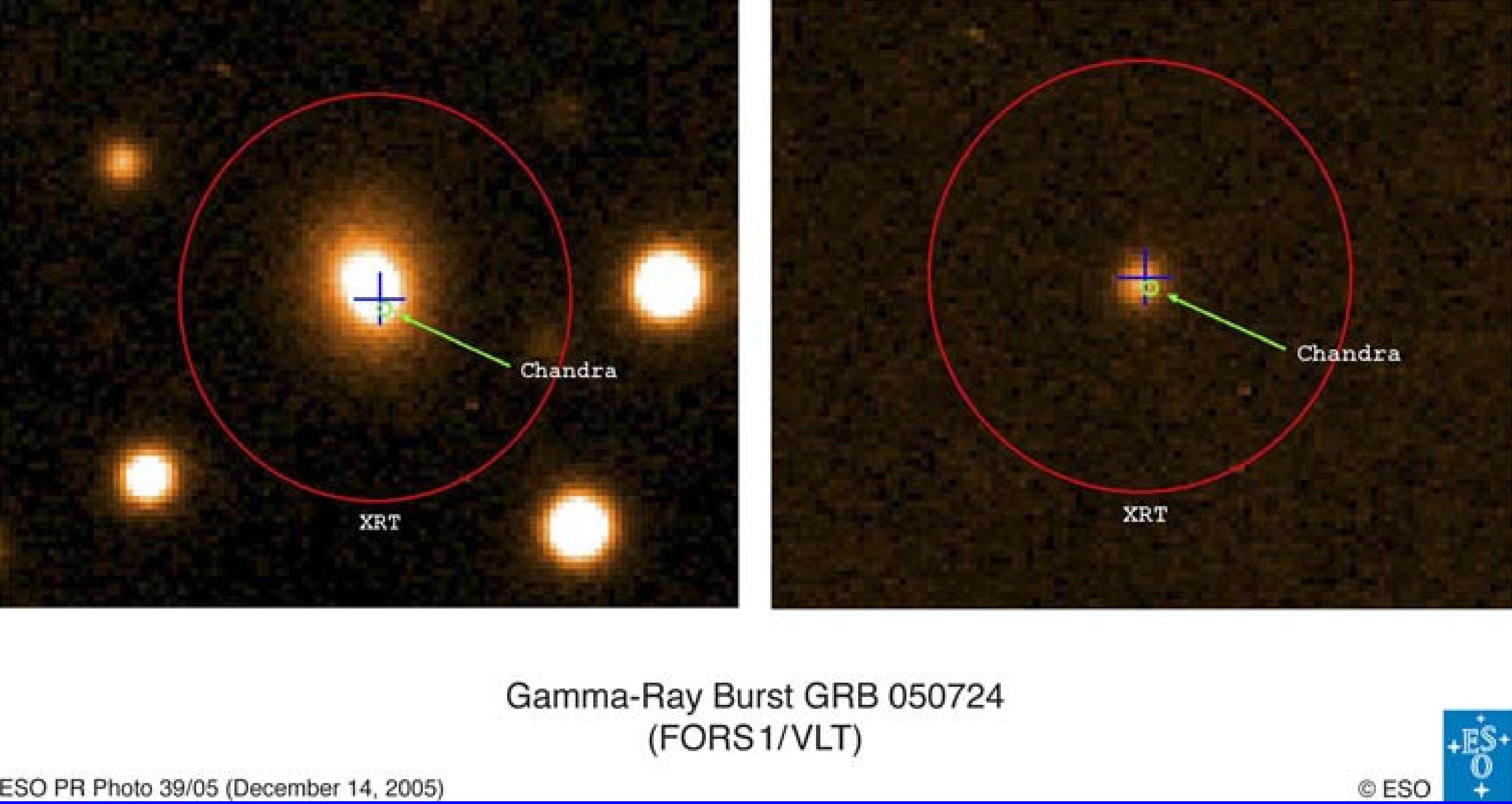


Lamb and Reichart (2000)



Long versus Short Gamma-ray Bursts

Very probably different origin



Left: VLT exposure 24 July 2005, 12 hours after the burst:
Cross: SWIFT XRT position; circle: CHANDRA position X-afterglow

Right: difference beween the VLT- pictures of 29 and 24 July 2005 shows visible afterglow of the burst on 24 July. Redshift z = 0.258

Conclusions

- GRBs are beamed phenomena (opening angle < 10º): ejection of a few Earth masses of baryons at Γ = 100 - 1000

- **Long-duration GRBs (> 2s) are related to black-hole formation at the death of short-lived stars > 20 solar masses: "Collapsars"/"Hypernovae" (pec. energetic SNe)**
  * Requirement of Collapsar: rapid rotation and no H or He
  * Occur preferentially in small disturbed "starburst" galaxies in early Universe : redshift typically between 1 and 6 (low "metallicity" may be a requirement).

- **Short-duration GRBs (< 2s) consistent with black-hole formation by Double Neutron Star mergers**
  Occur in elliptical (old-population) galaxies AND in star-forming galaxies, at redshifts typically 0.2 to 0.8.

Literature:

G.Schilling: ”Flash”, Cambridge University Press, 2002

J.I.Katz: “The Biggest Bangs”, Oxford University Press, 2002.

Some Websites:

Heasarc.gsfc.nasa.gov/docs/swift/swiftsc.html

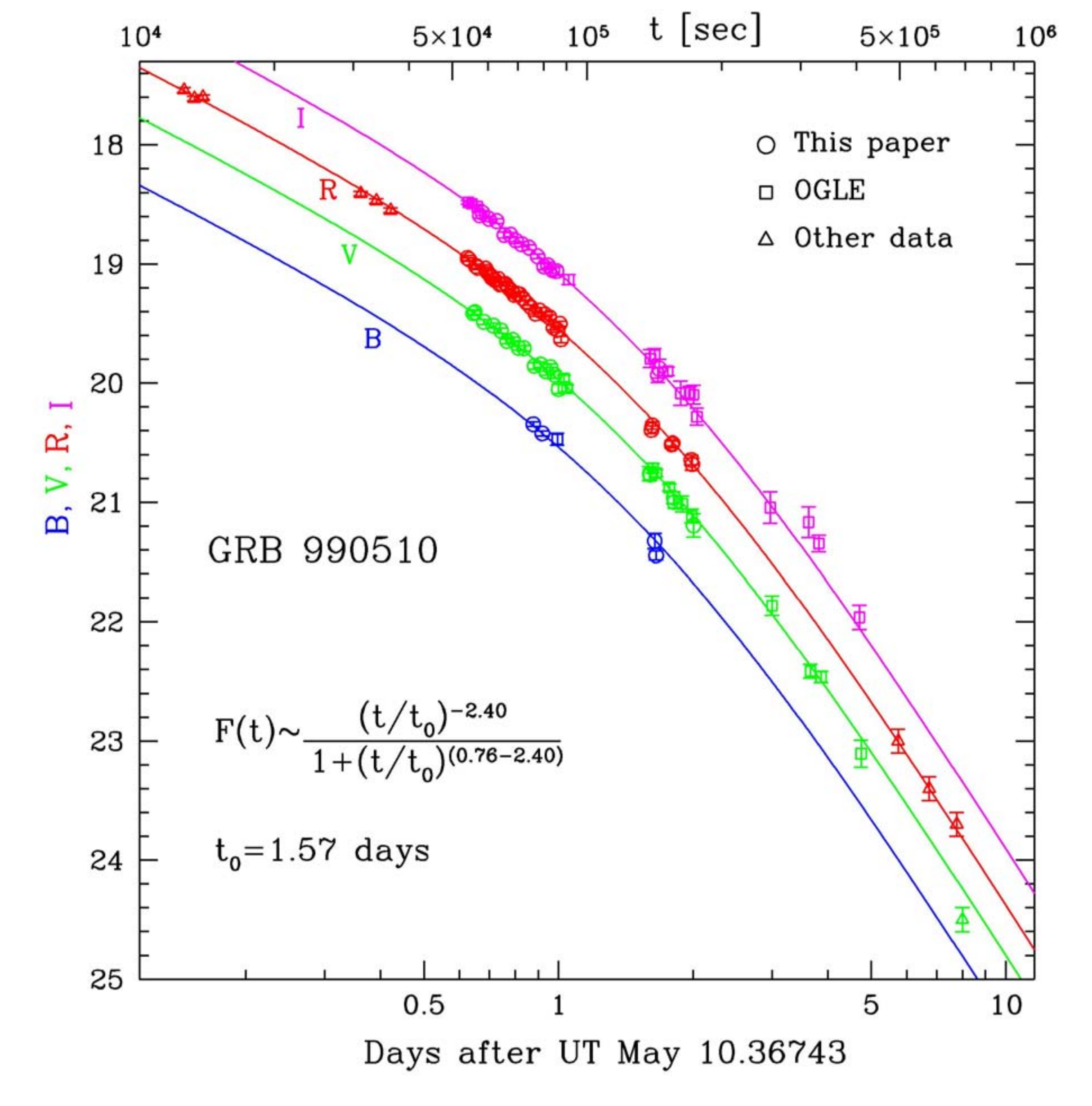
www.nasa.gov/swift

www.swift.psu.edu

www.swift.ac.uk

Swift.sonoma.edu/education

Beaming and true energy



- Energy in Jets: opening angle <10deg
- Reduces required Gamma Energy from E 53.5 to E 50.5 ergs (=Supernova-like)

(Galama et al.1999; Frail et al. 2001)