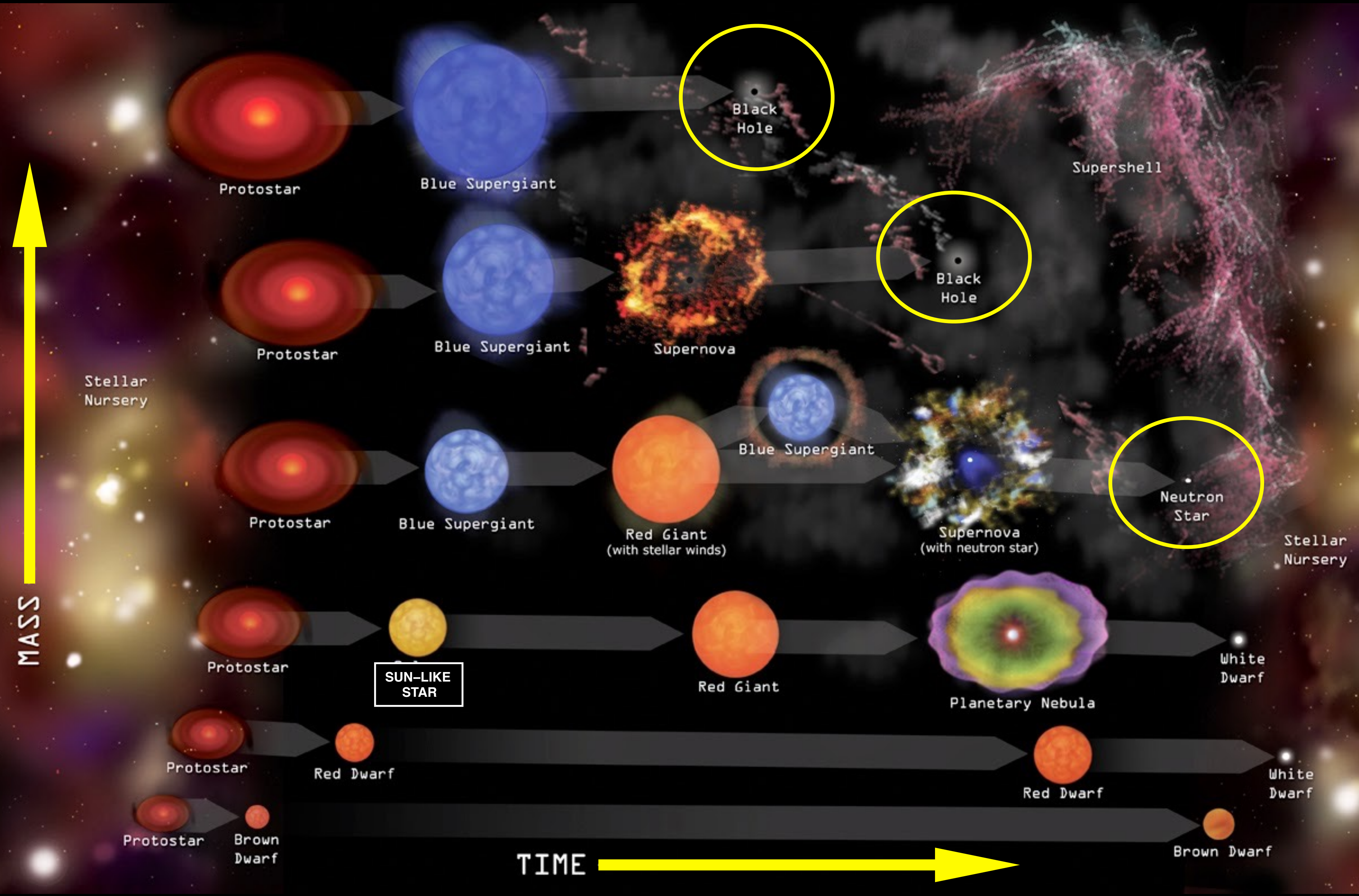
Black hole of stellar origin

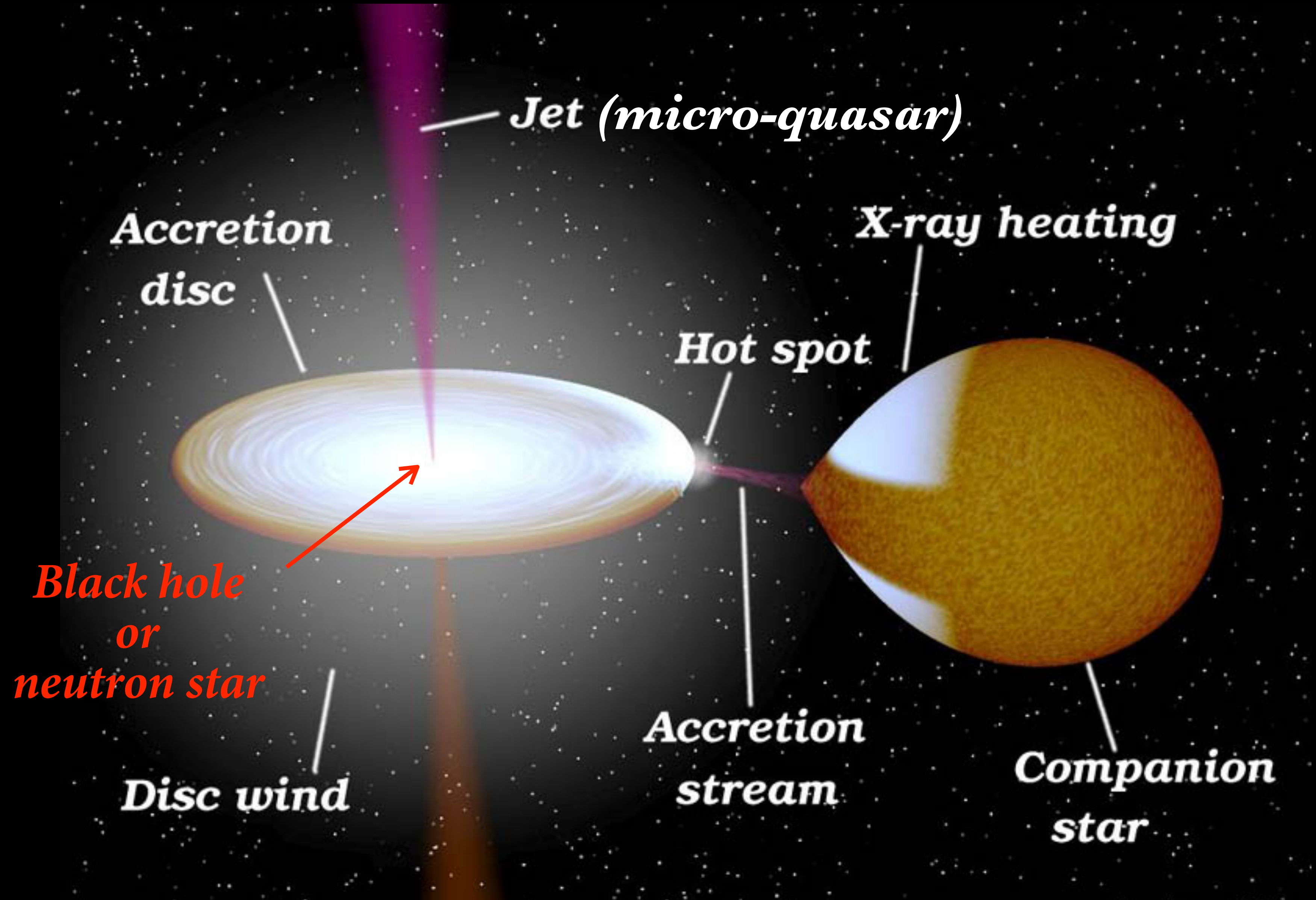
when the mass of the core is $M_{\mathrm{core}} > 3 - 5\ \mathrm{M}_{\odot}$

Black holes of stellar origin



Neutron stars or black holes in binary systems (*X-ray binary*)

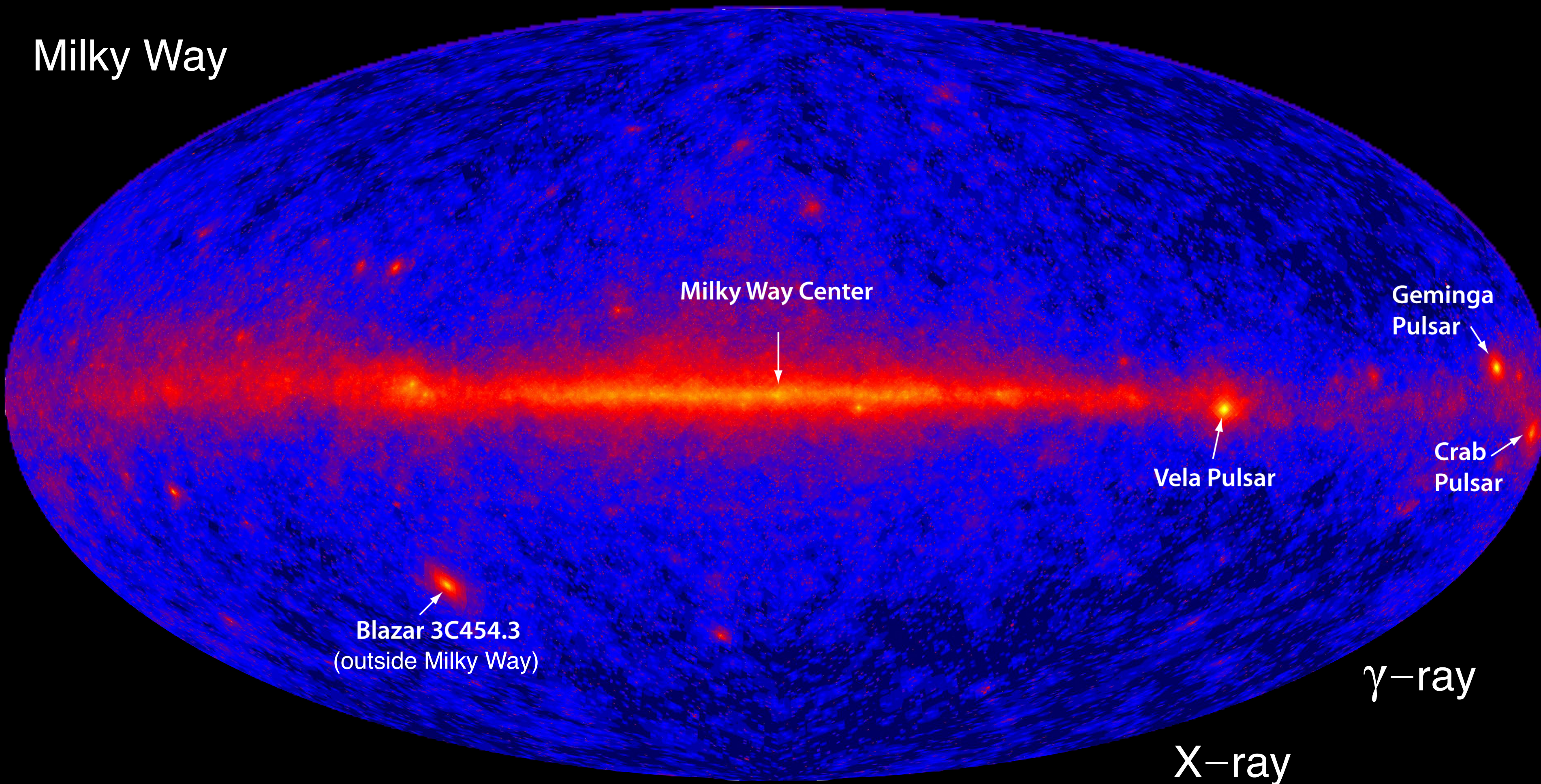
Surrounded by hot gas ($T = 10^6 - 10^8$ K) $\Longrightarrow$ strong X-ray emitters



Neutron stars or black holes in binary systems (*X-ray binary*)

Surrounded by hot gas ($T = 10^6 - 10^8$ K) $\Longrightarrow$ strong X-ray emitters

Milky Way

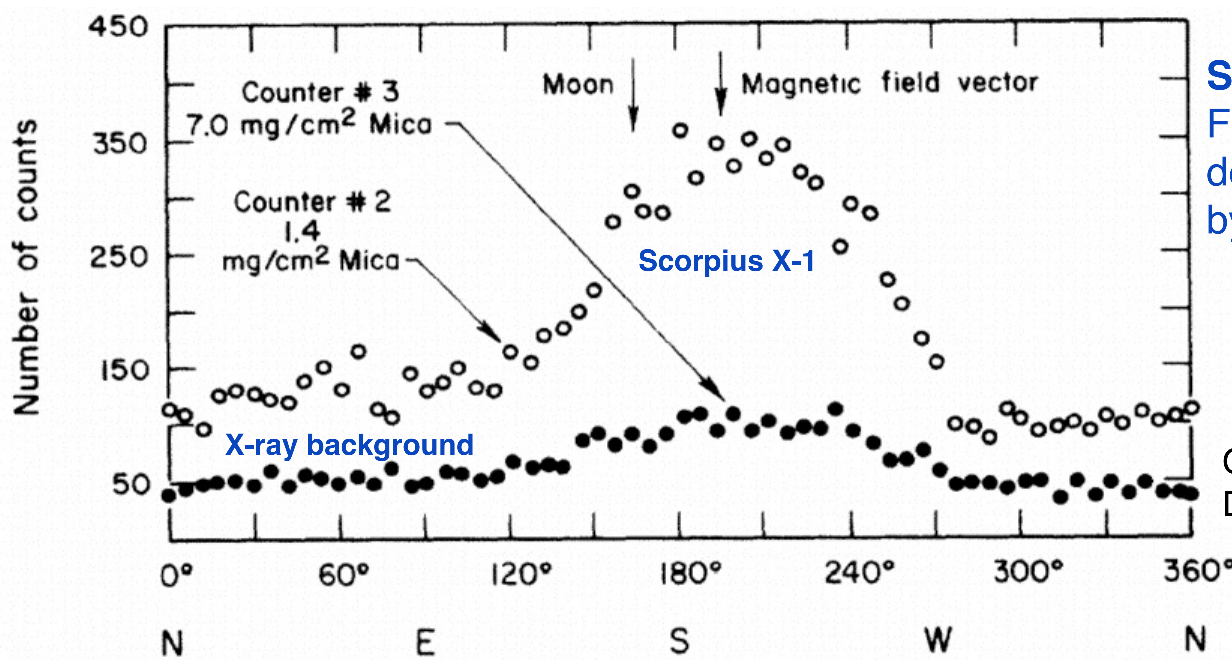


γ−ray

X−ray

X-ray binaries dominate X-ray sky

First X-ray source: *Scorpius X-1*

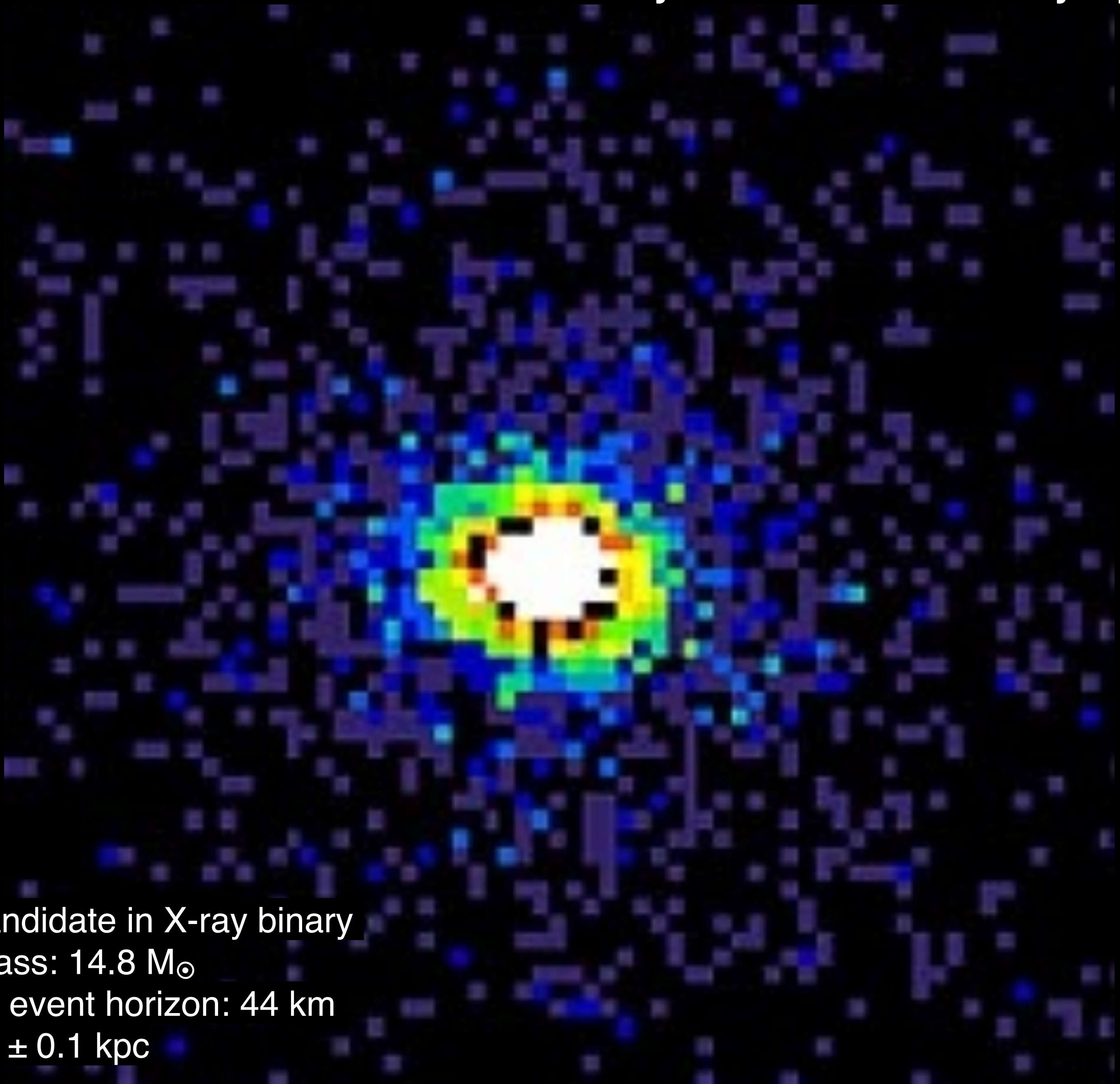


Scorpius X-1
First x-ray astronomical source ever detected, in 1962, using a rocket built by a team under Riccardo Giacconi

Optical apparent magnitude: $m_V = 12.2$
Distance: $d = 2800$ pc

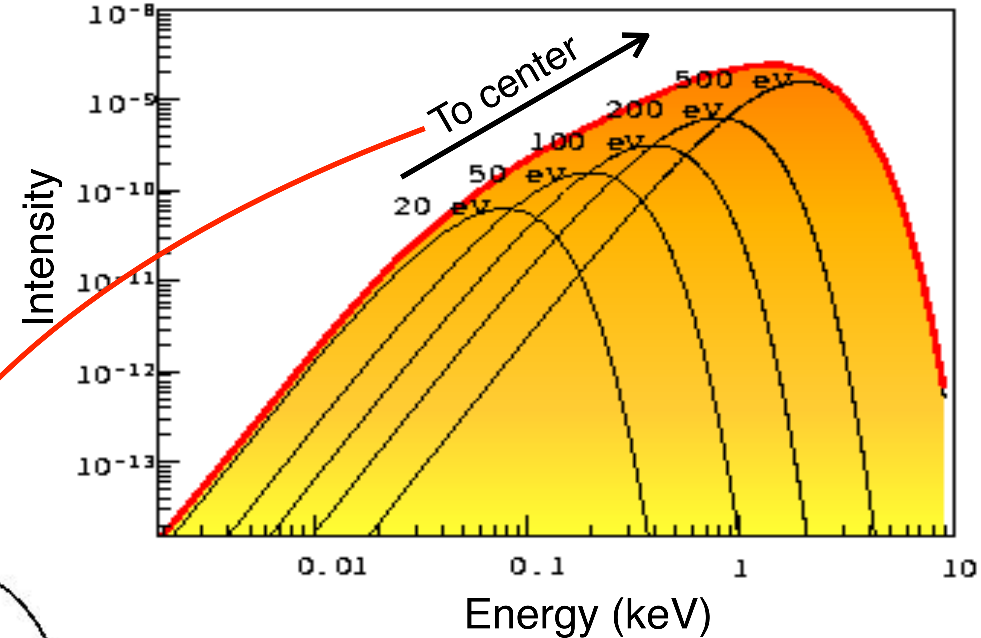
- Scorpius X-1 is the strongest X-ray source in the sky
- Detected up to 70 keV emission, corresponding to temperature $\boldsymbol{T = 8.1\times10^8}$ **K**
- X-ray emission is 10 000 times greater than its optical emission
- Gas is heated by the fall in the strong gravity field (energy source)
- It is a **neutron star** accreting matter from a companion star with $M = 0.42\ M_\odot$
- X-1 shows regular variations with a period of around 18.9 h

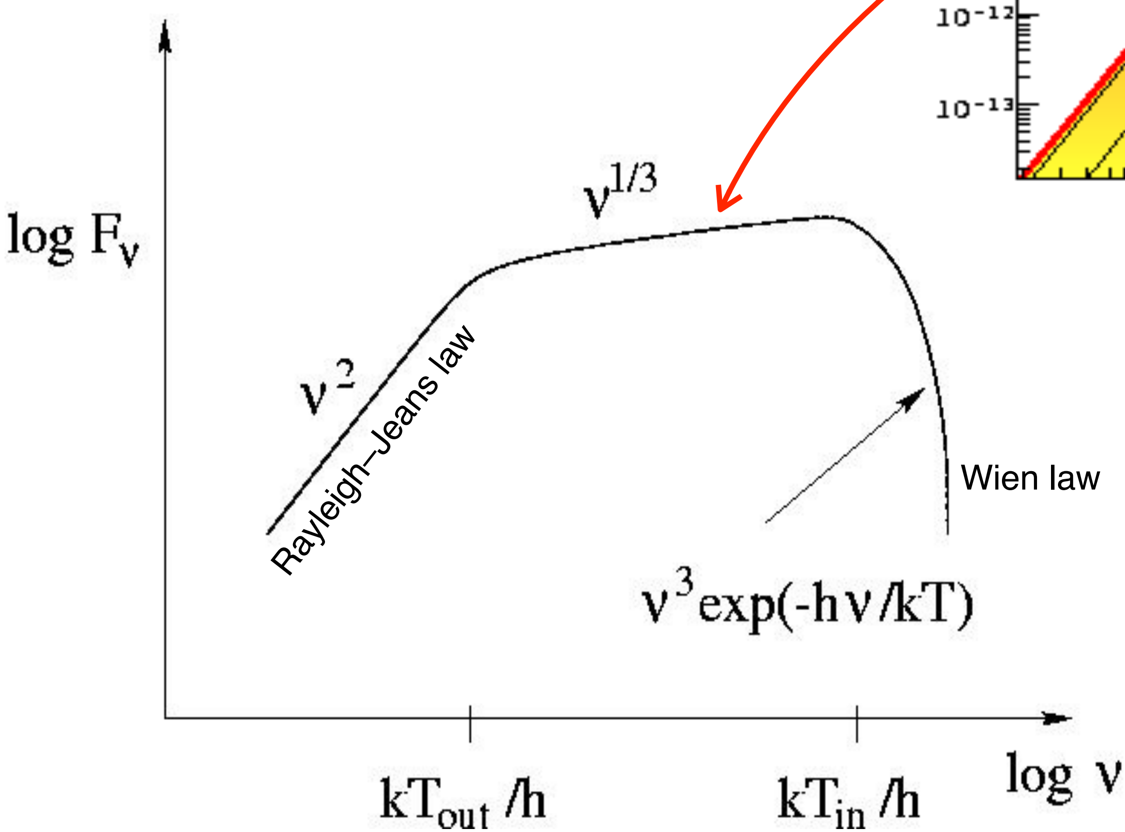
Stellar black holes detected from X-ray emission in binary systems



Cygnus X-1
X-ray image
Black hole candidate in X-ray binary
Black hole mass: 14.8 $M_{\odot}$
Radius of the event horizon: 44 km
Distance: 1.8 ± 0.1 kpc

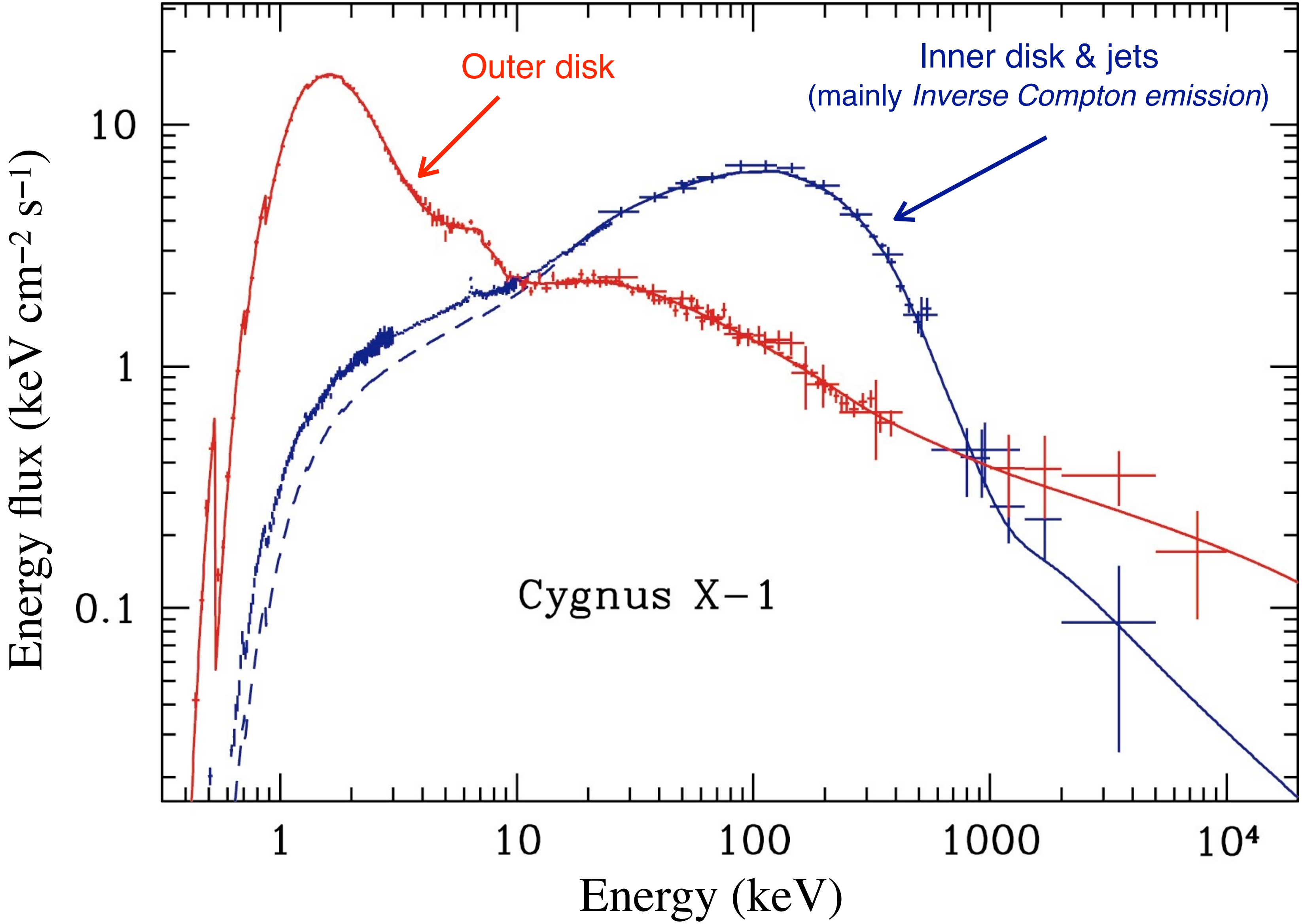
Several **black-body** spectra in accretion disk





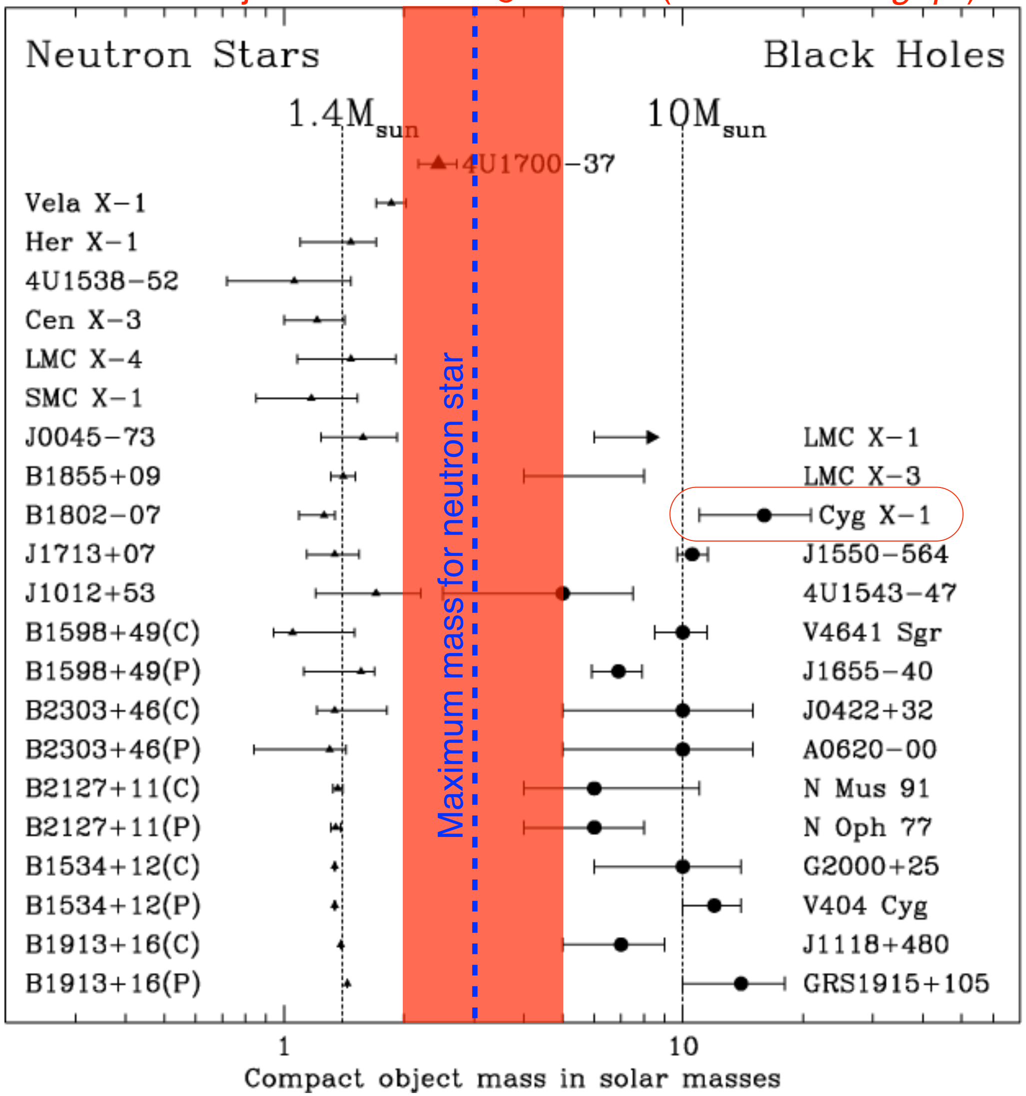
Accreting black hole

Cygnus X-1: first source widely accepted to be a black hole



Neutron stars and stellar black hole candidates

No objects in 2 – 5 M⊙ interval (called “*mass gap*”)

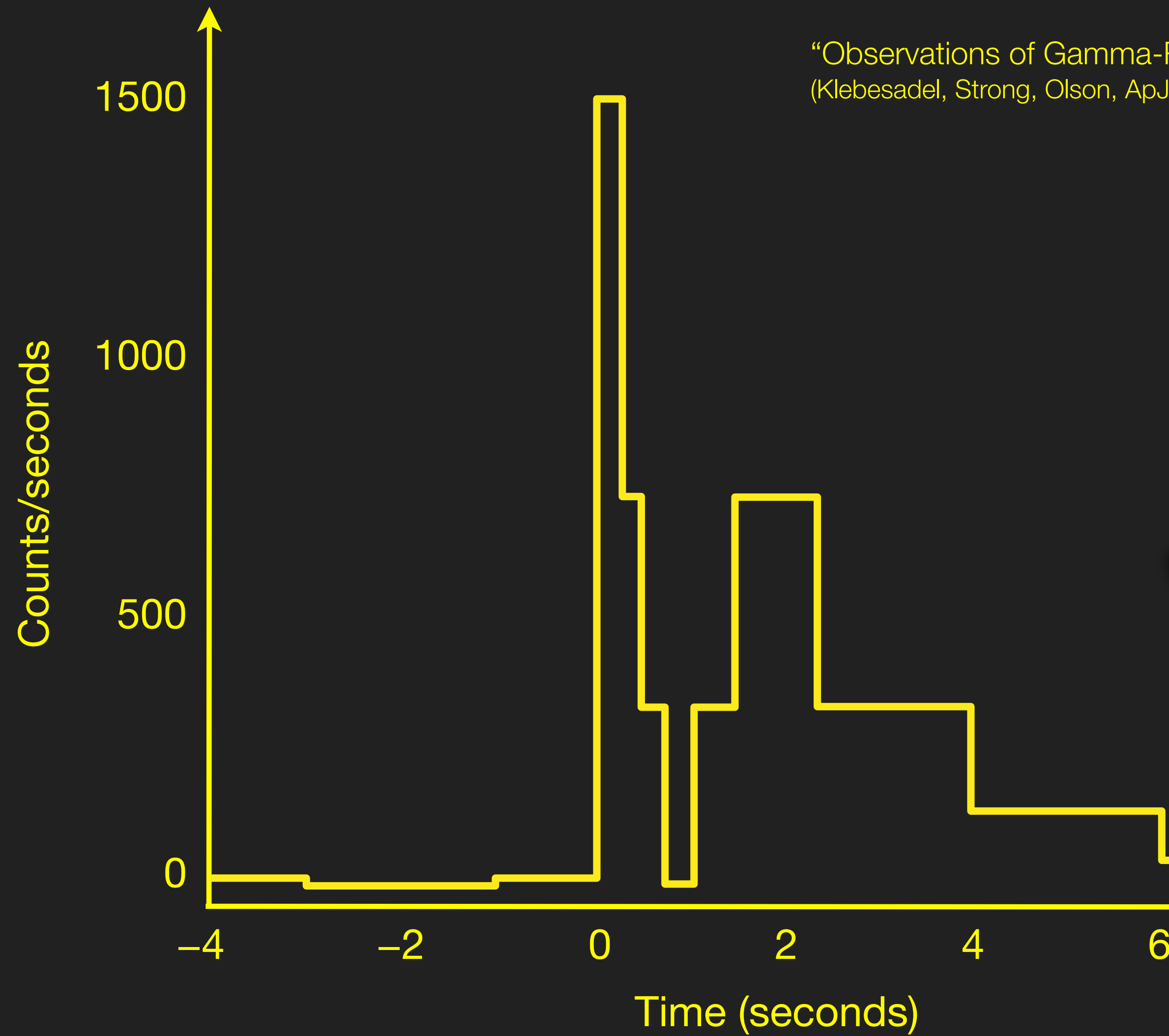


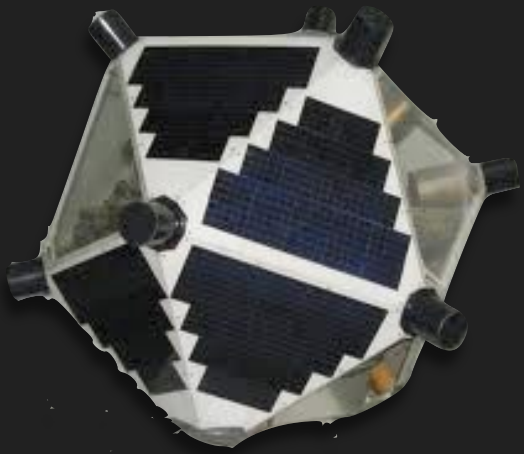
60 stellar black hole candidates in X-ray binaries in the Milky Way (as of October 2016)
(black-hole in X-ray binaries are vast majority of black-hole population)

The most energetic explosions in the universe after the Big Bang: ***gamma-ray bursts***

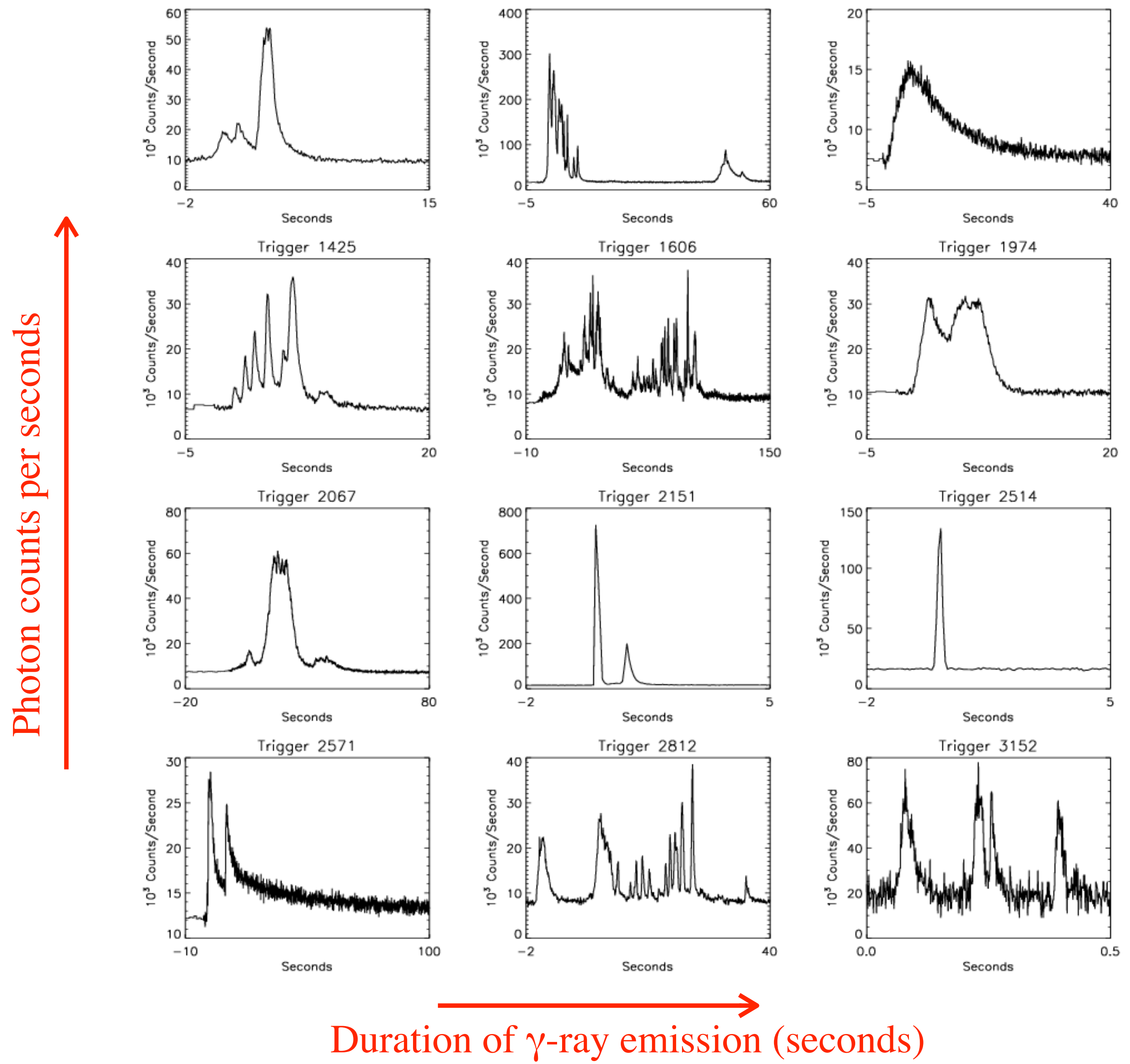
The **very first** gamma-ray burst

Detected on July 2 1967 (called: GRB 670702) by American satellite *Vela 4*





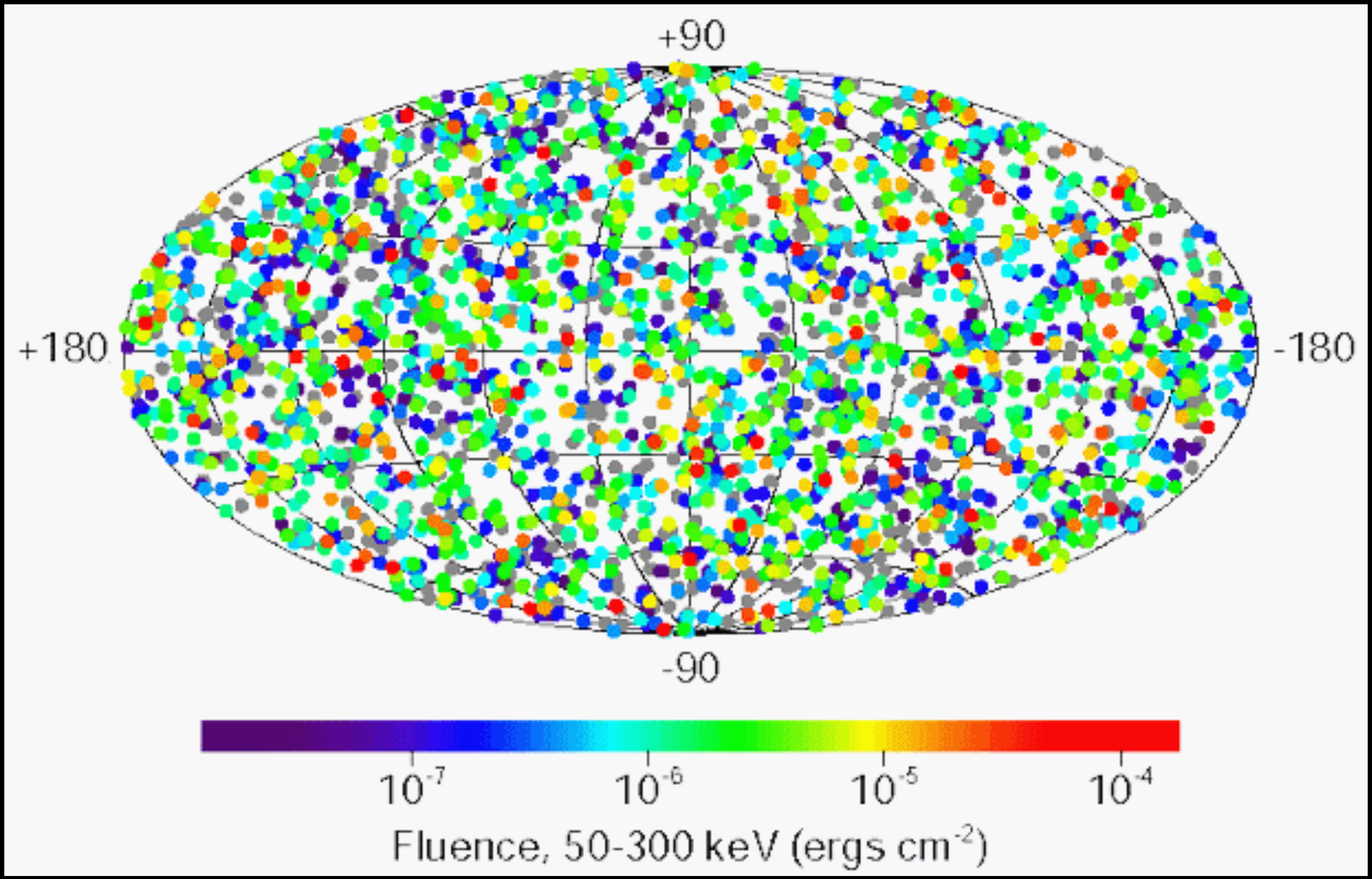
Duration of ***prompt emission*** of several gamma-ray bursts



Isotropically distributed in the sky

Thus GRBs can only be originating outside the Milky Way

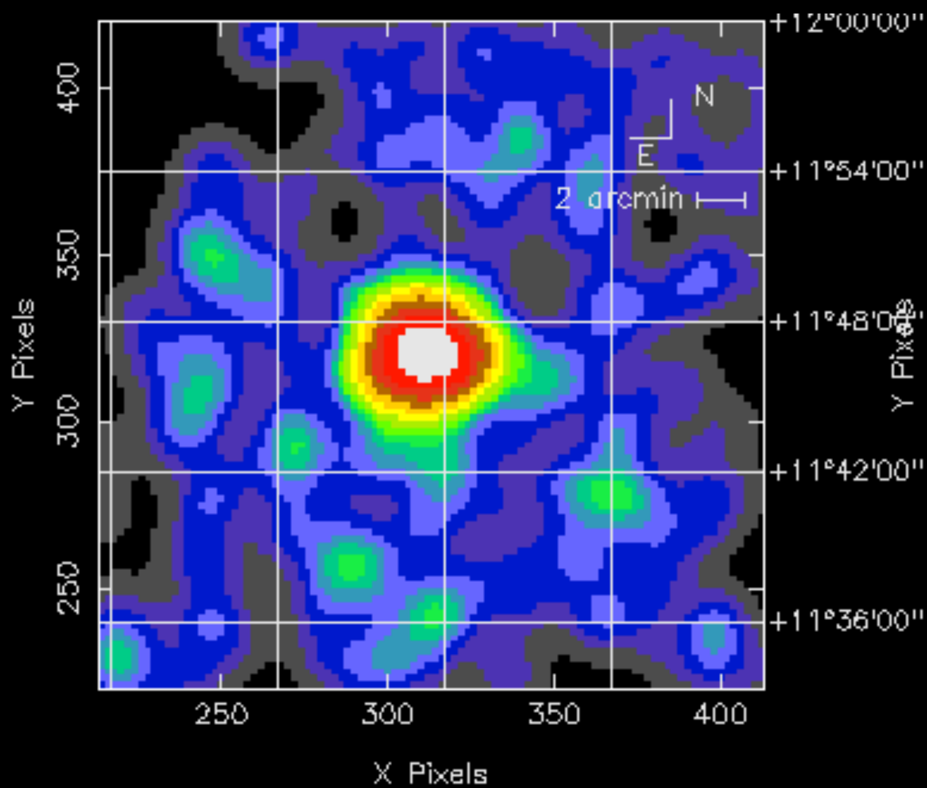
2704 gamma-ray bursts detected by space telescope *Compton Gamma Ray Observatory* (years 1991-2000)

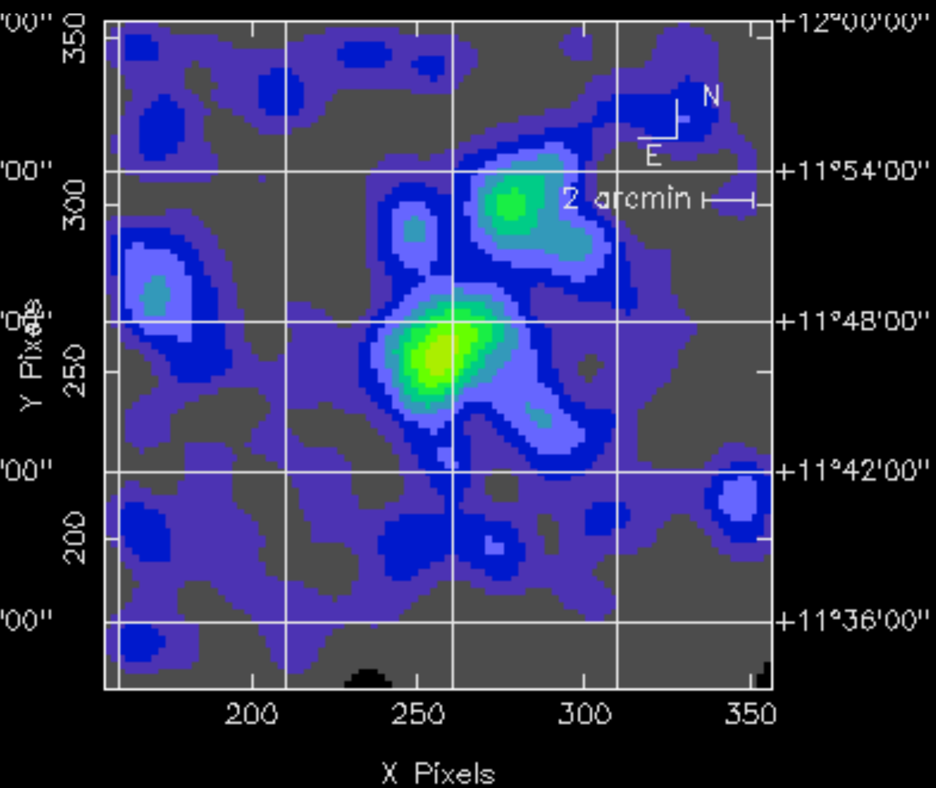


February 1997: the **first precise localisation**

(with arc-second precision)

X-ray emission of GRB 970228



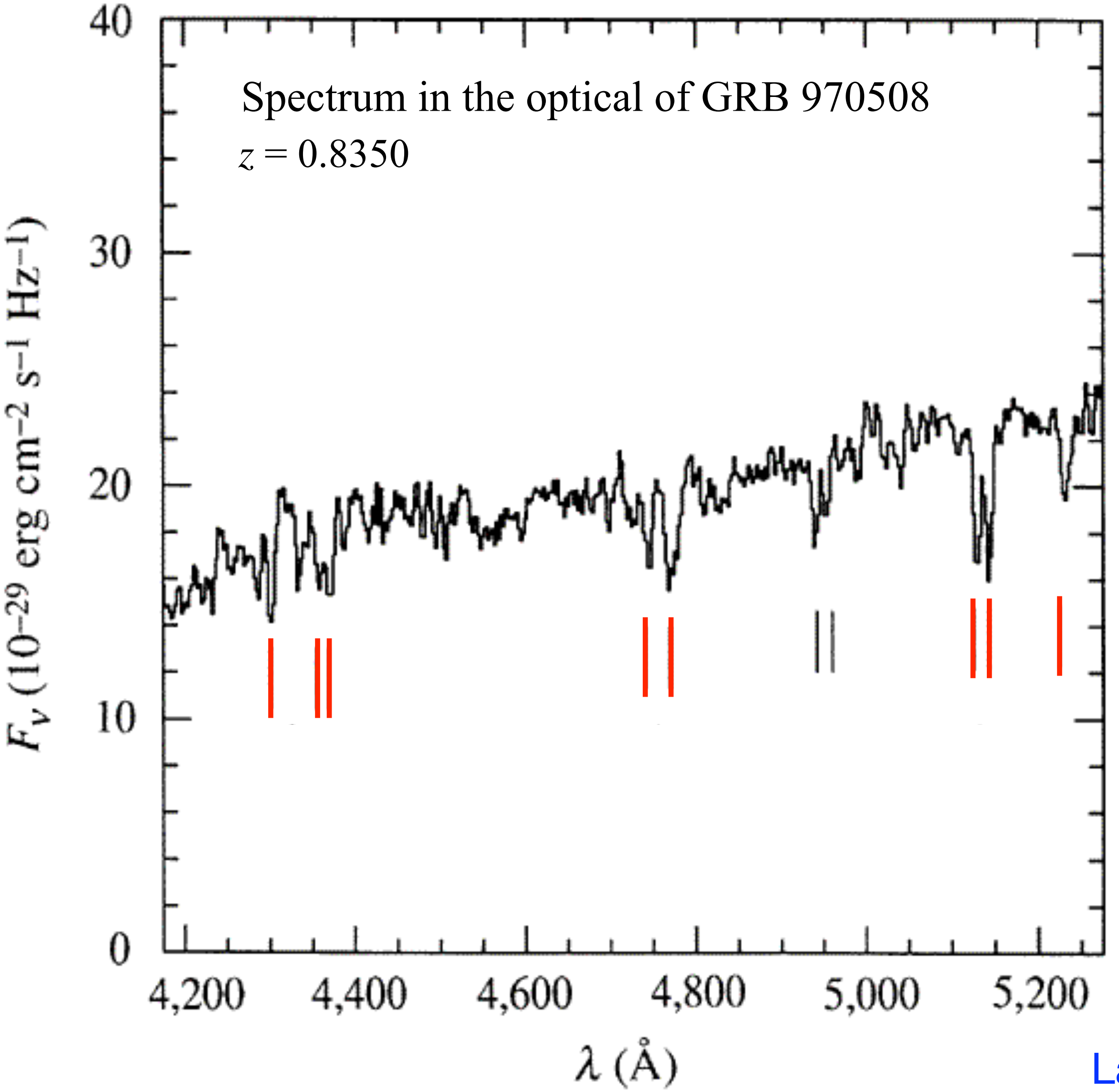


8 hours after γ-ray emission

3 days after γ-ray emission

May 1997: **first distance** determined for a gamma-ray burst

Measured from Doppler shift of wavelength (redshift: z)



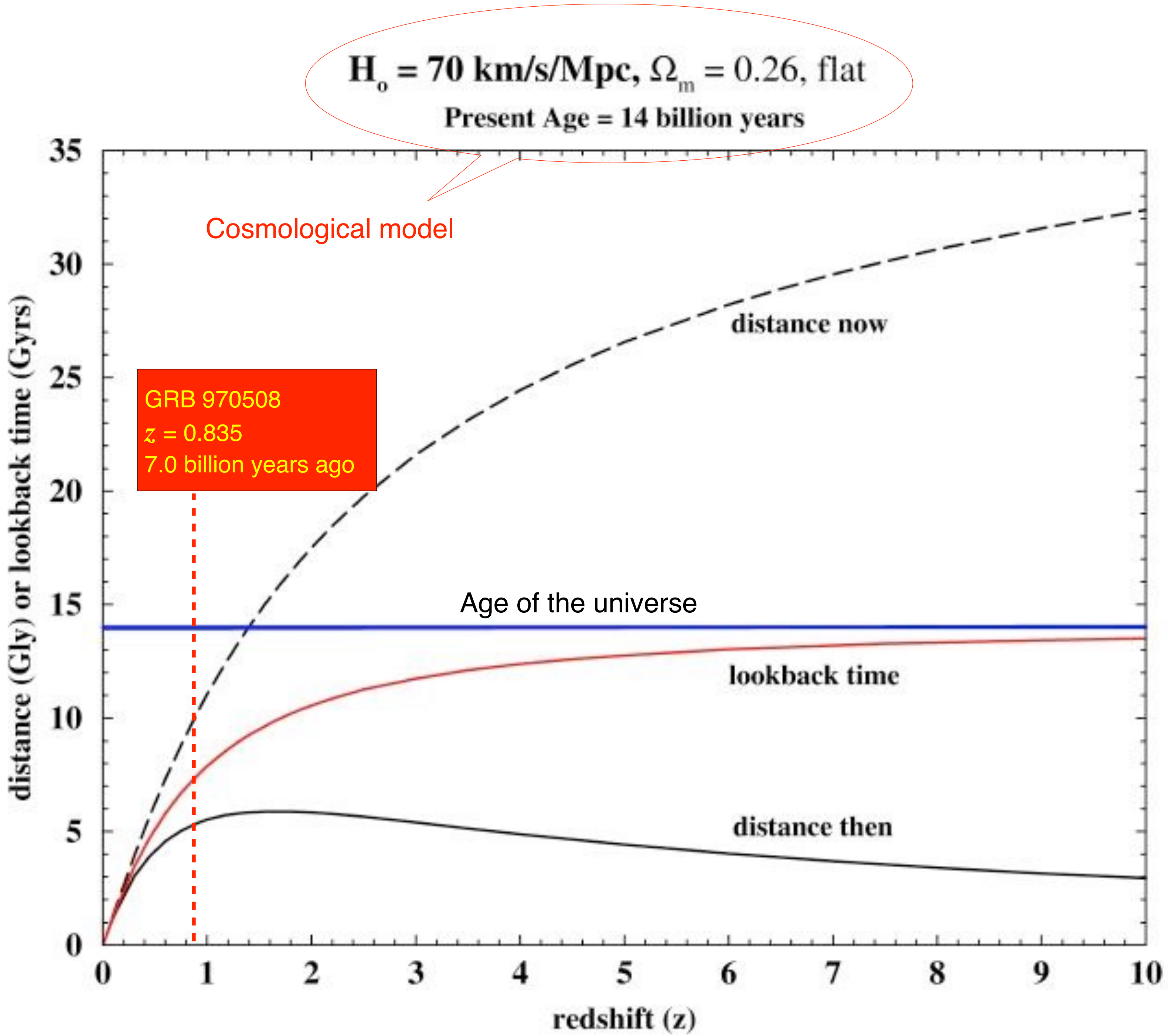
Ion	λ_r(Å)	λ_o(Å)
FeII-2344	2344.21	4301.63
FeII-2374	2374.46	4357.14
FeII-2382	2382.76	4372.37
MnII-2576	2576.88	4728.57
FeII-2586	2586.65	4746.50
MnII-2594	2594.50	4760.91
FeII-2600	2600.17	4771.32
MnII-2606	2606.46	4782.86
MgII-2796	2796.35	5131.31
MgII-2803	2803.53	5144.48
MgI-2852	2852.96	5235.19

λ_r: rest-frame wavelength

λ_o: observed wavelength

Redshift: $z = \dfrac{\lambda_o - \lambda_r}{\lambda_r}$

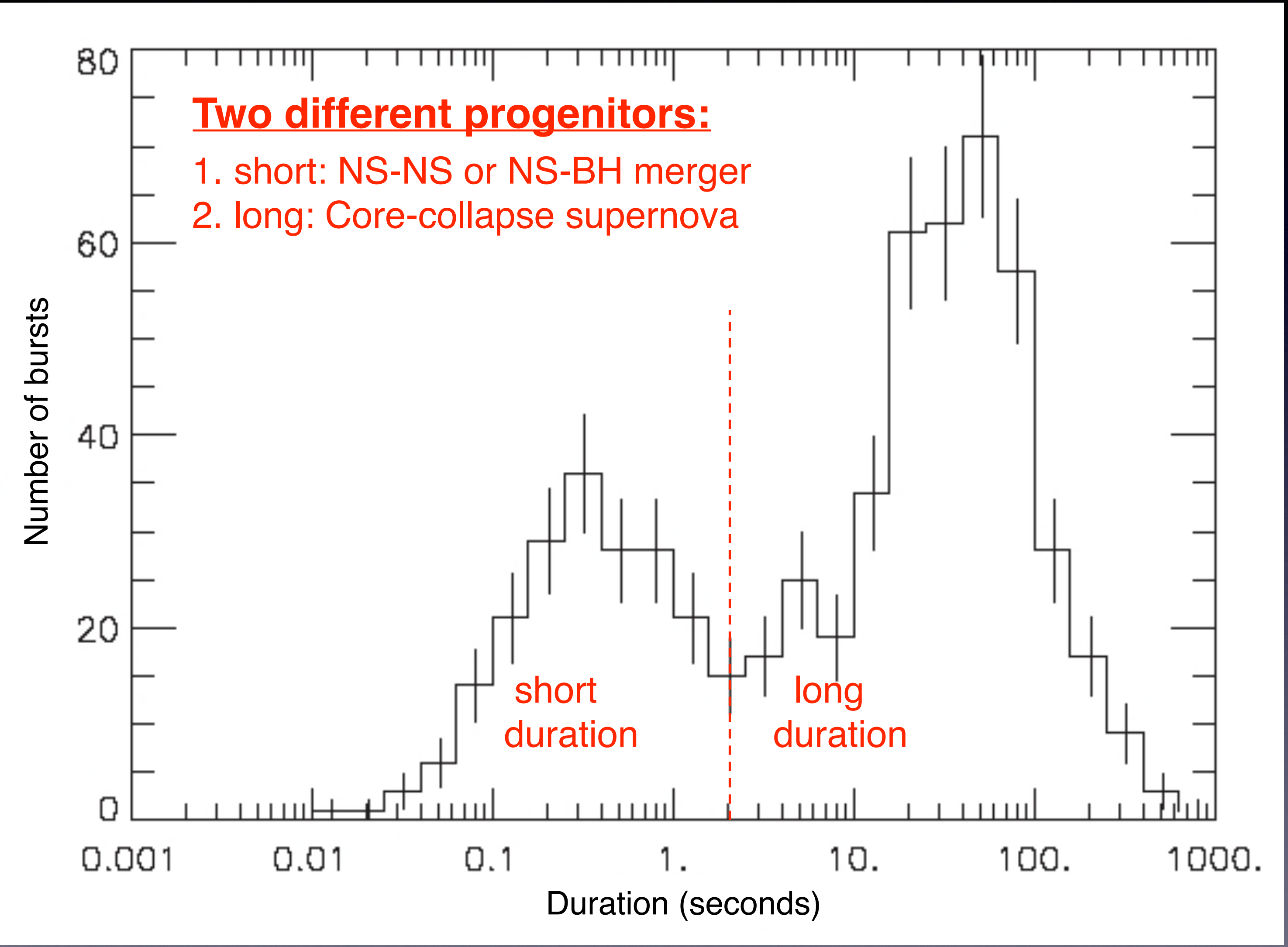
Larger $z \Longrightarrow$ more distant objects



H$_o$ = 70 km/s/Mpc, Ω_m = 0.26, flat
Present Age = 14 billion years
Cosmological model
distance now
GRB 970508
z = 0.835
7.0 billion years ago
Age of the universe
lookback time
distance then
distance (Gly) or lookback time (Gyrs)
redshift (z)
0
5
10
15
20
25
30
35
0
1
2
3
4
5
6
7
8
9
10


Gamma-ray burst *GRB 011121*
Detection on Earth on November 21 2001
Redshift: z = 0.362
Explosion occurred 3.98 billion years ago

Bi-modal distribution of duration of GRBs



shortest 6 ms
GRB 910711

longest > 7 hours
GRB 111209A

Gamma-ray Bursts (GRBs): the most energetic explosions in the universe after the Big Bang

Definition:

- Brief and intense flashes of γ-rays (photon energies $E = 0.01–1$ MeV)
- Associated with explosion of stars at large distances
- Total energy emitted equivalent to that emitted by the Sun over its entire life

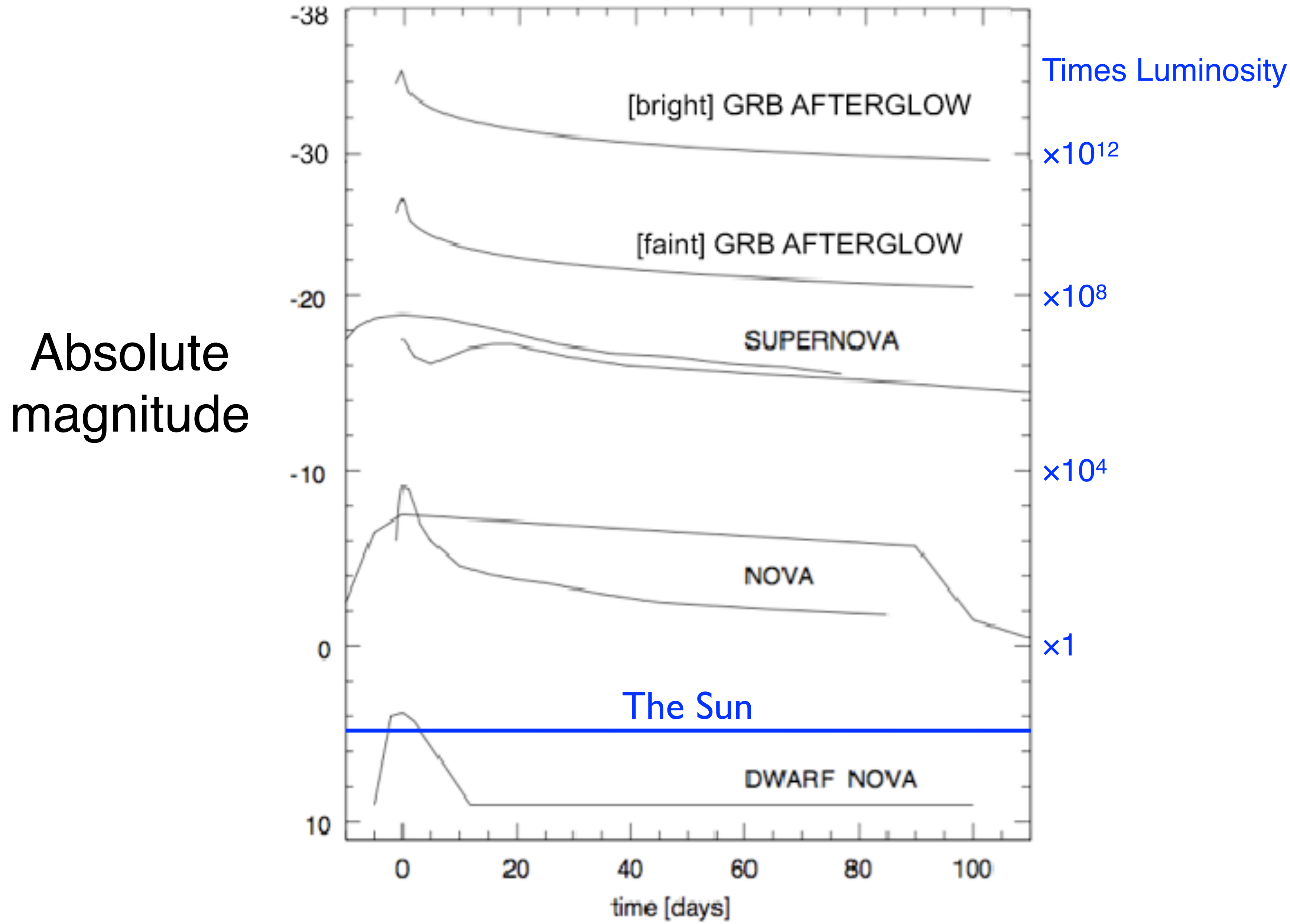
- Two types of GRBs: **short** ($t < 2$ sec) & **long** ($t > 2$ sec)
- For both, γ-ray photons originating in **collimated jets** emitted by compact and distant objects of stellar origin
- Final faith after explosion: **black hole**

Short-duration GRB ($t < 2$ s):

Long-duration GRB ($t > 2$ s):

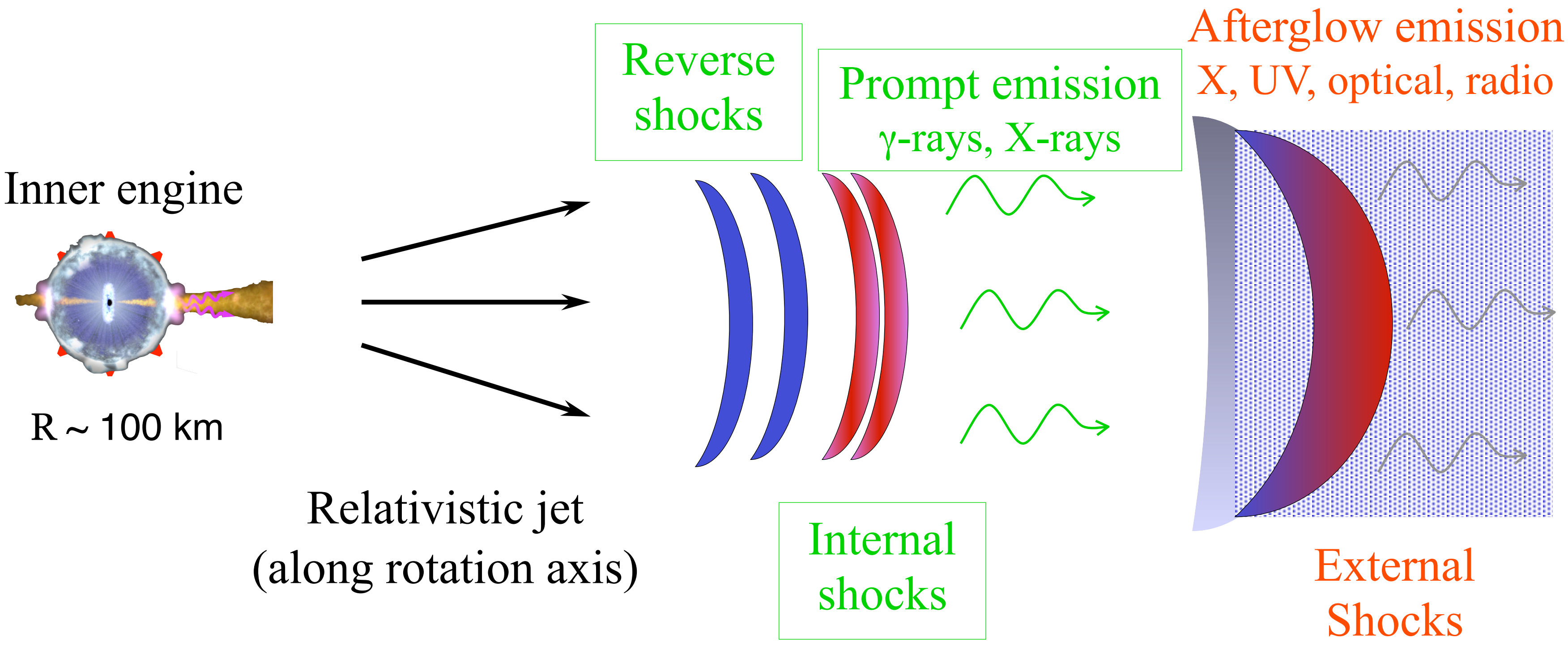
Very-massive ($M > 30\ M_{\odot}$) fast-rotating star $\longrightarrow$ gravitation collapse of core (core-collapse supernova) with energetic jet emission

Light curves in explosive events



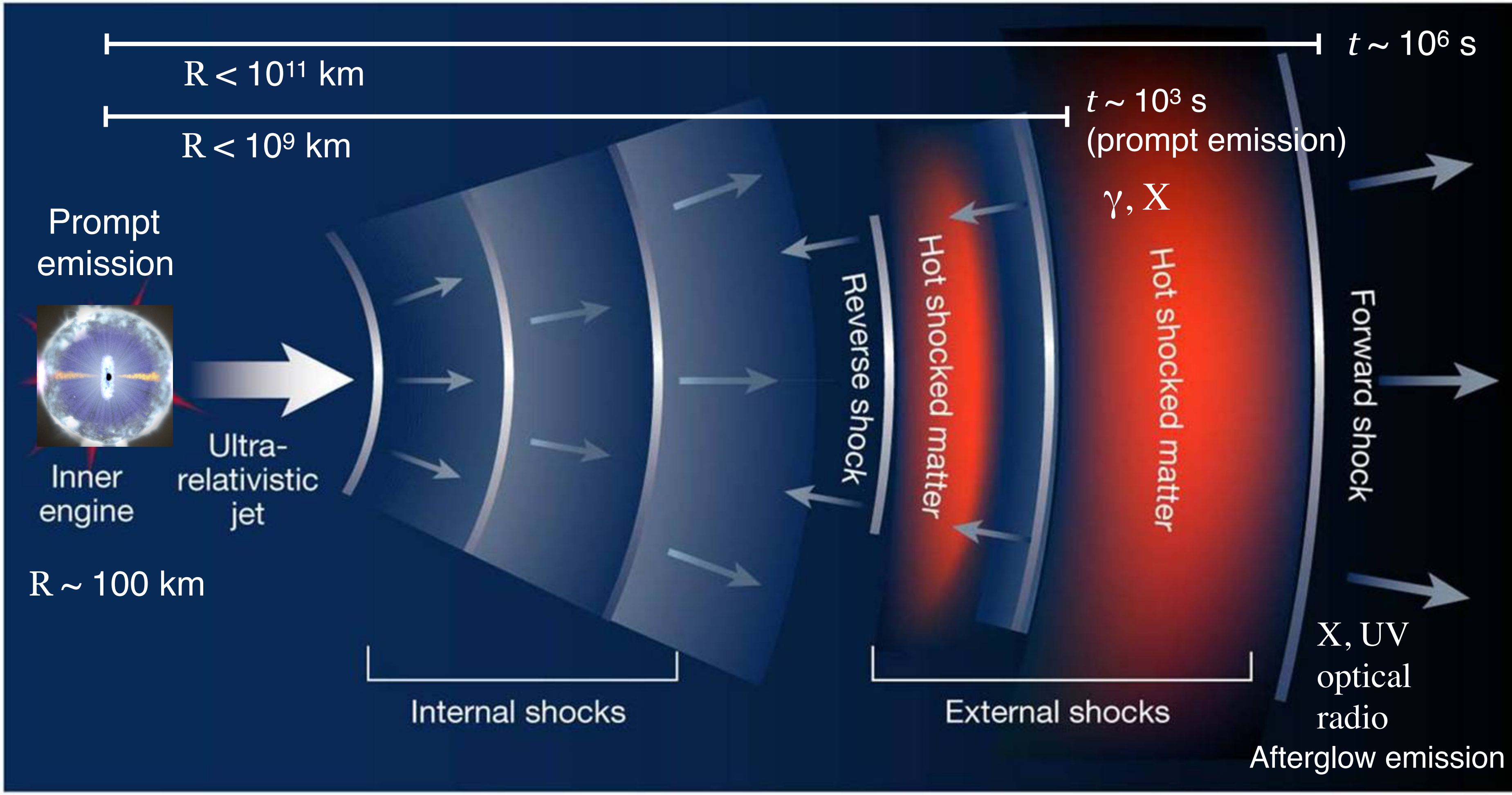
Internal-external *fireball* model for long GRB

Physical mechanism: core collapse of very massive rapidly rotating star into black hole in final stage of evolution



- No direct observations of inner engine
- γ-rays light curve: best evidence on inner engine
- Afterglow observations: surrounding of progenitor

Internal-external *fireball* model: physical scales

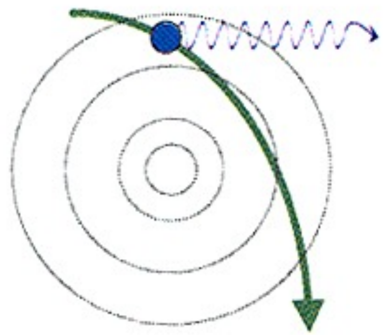


Lorentz factor:

$$\Gamma = \frac{1}{\sqrt{1 - v^2/c^2}} = \frac{1}{\sqrt{1-\beta^2}} = \frac{dt}{d\tau}$$

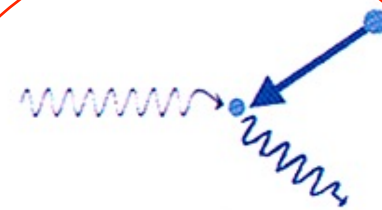
$$\Gamma \sim 10^3 \longrightarrow v/c \sim 0.999999$$

Basic radiation mechanisms for production of high-energy photons in the universe

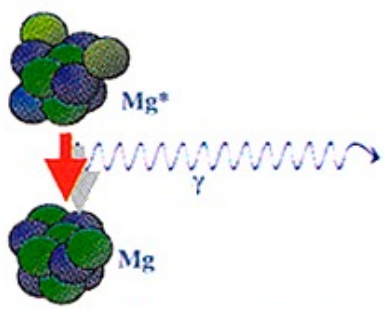


Accelerated Charged Particles

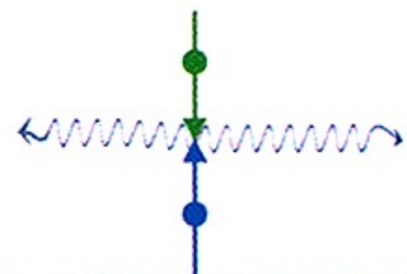
GRB
prompt emission



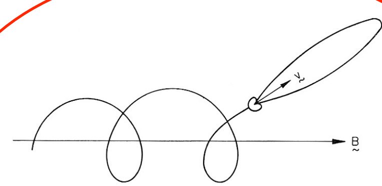
Inverse Compton Scattering



De-Excitation of Atomic Nuclei

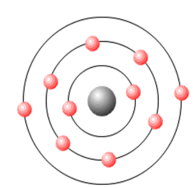


Annihilation of Particle-Antiparticle Pairs



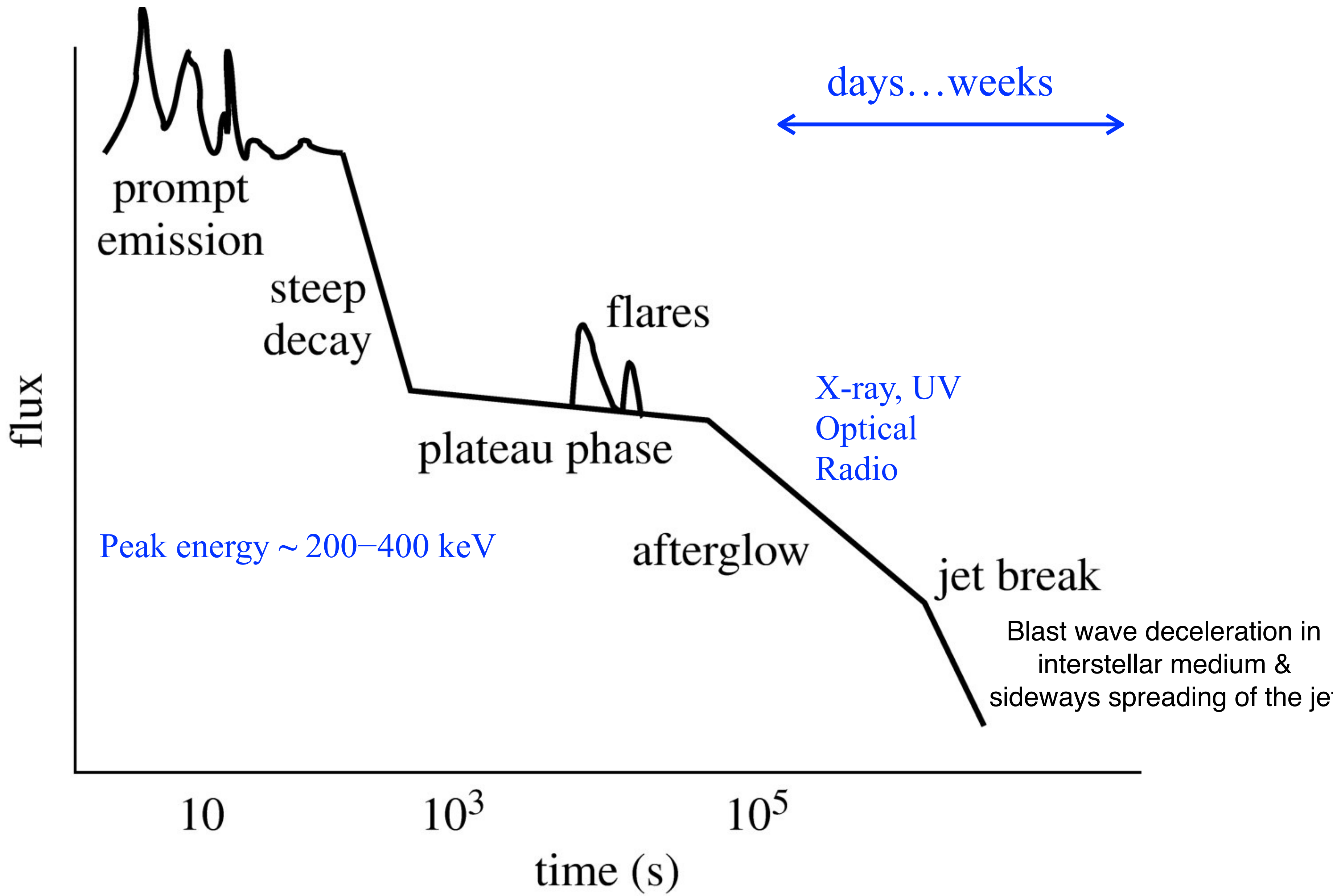
Synchrotron

GRB
prompt emission

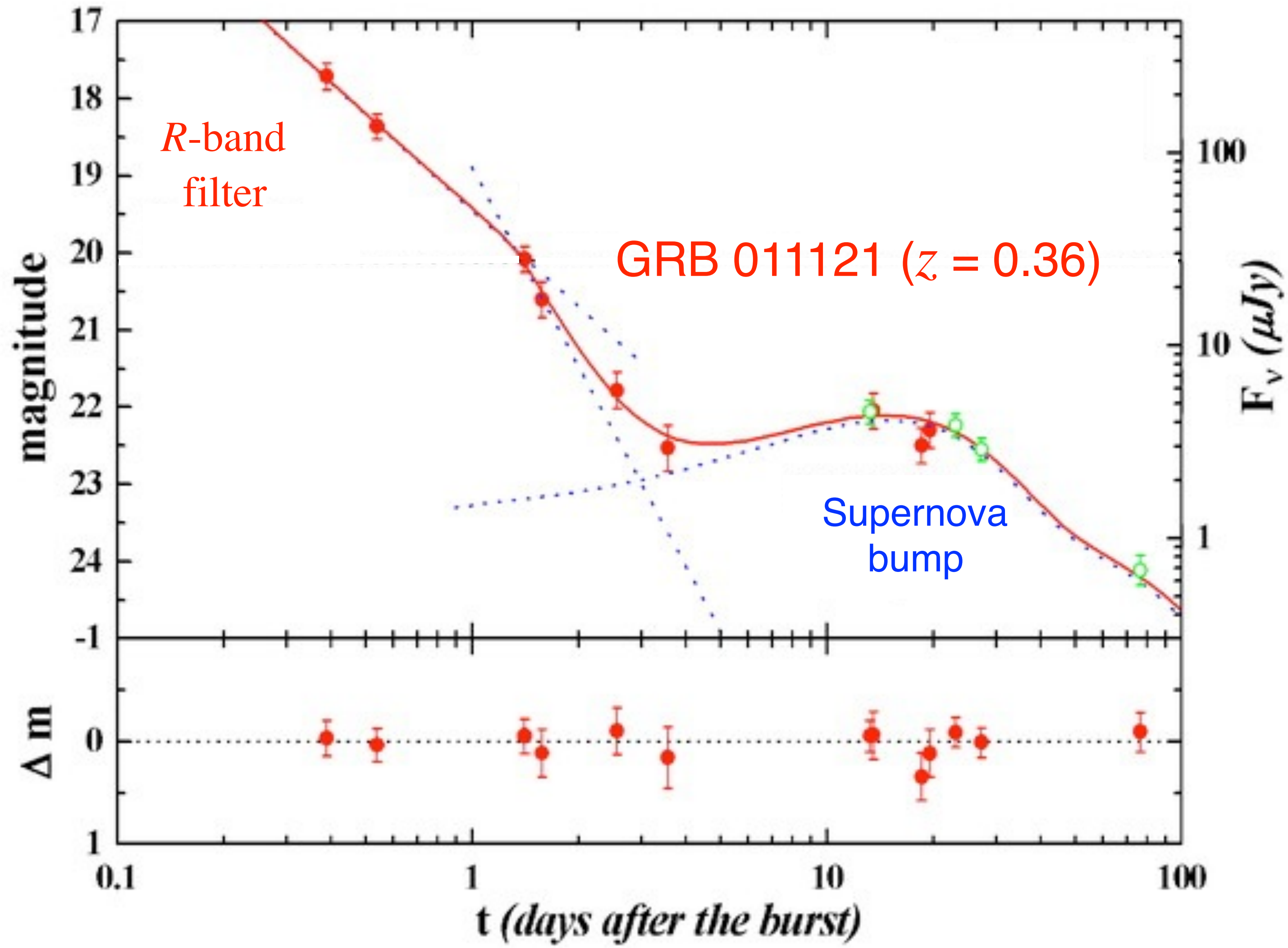


Characteristic X-rays

Light curve of a gamma-ray burst

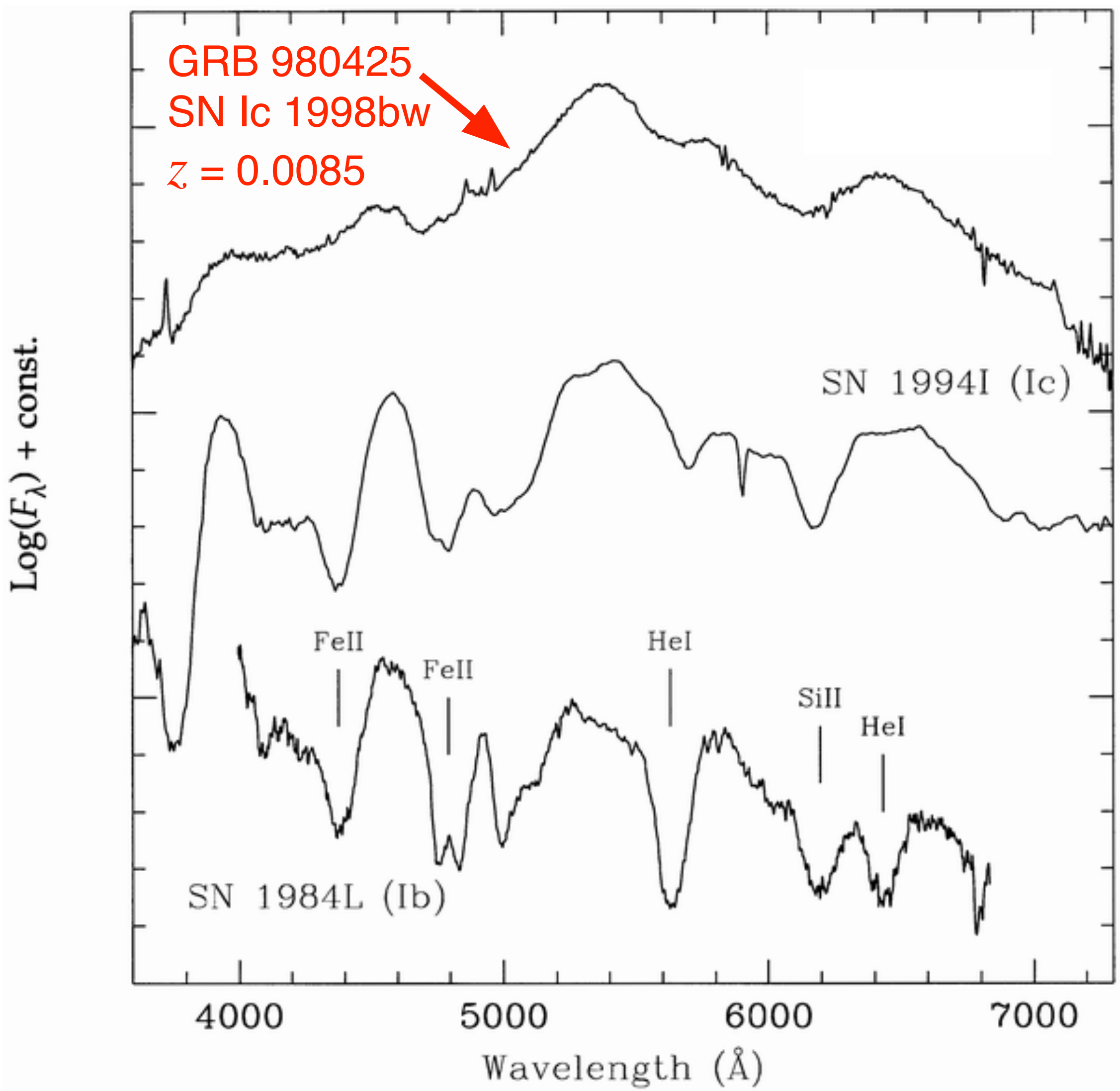


Long gamma-ray burst light curve with supernova bump



Long gamma-ray burst - supernova connection

Associated with SN Ic ($M > 30\ M_\odot$)



Gamma-ray burst statistics

Explosion of fast-rotating stellar system discovered in γ-ray

~ 1876 GRB detected since 1997

~ 1300 localized

447 with measured redshift (distance)

NS-NS or NS-BH merger
(short GRB t $\lesssim$ 2 sec)
~ 28 with redshift

Core-collapse supernova
(long GRB t $\gtrsim$ 2 sec)
~ 429 with redshift

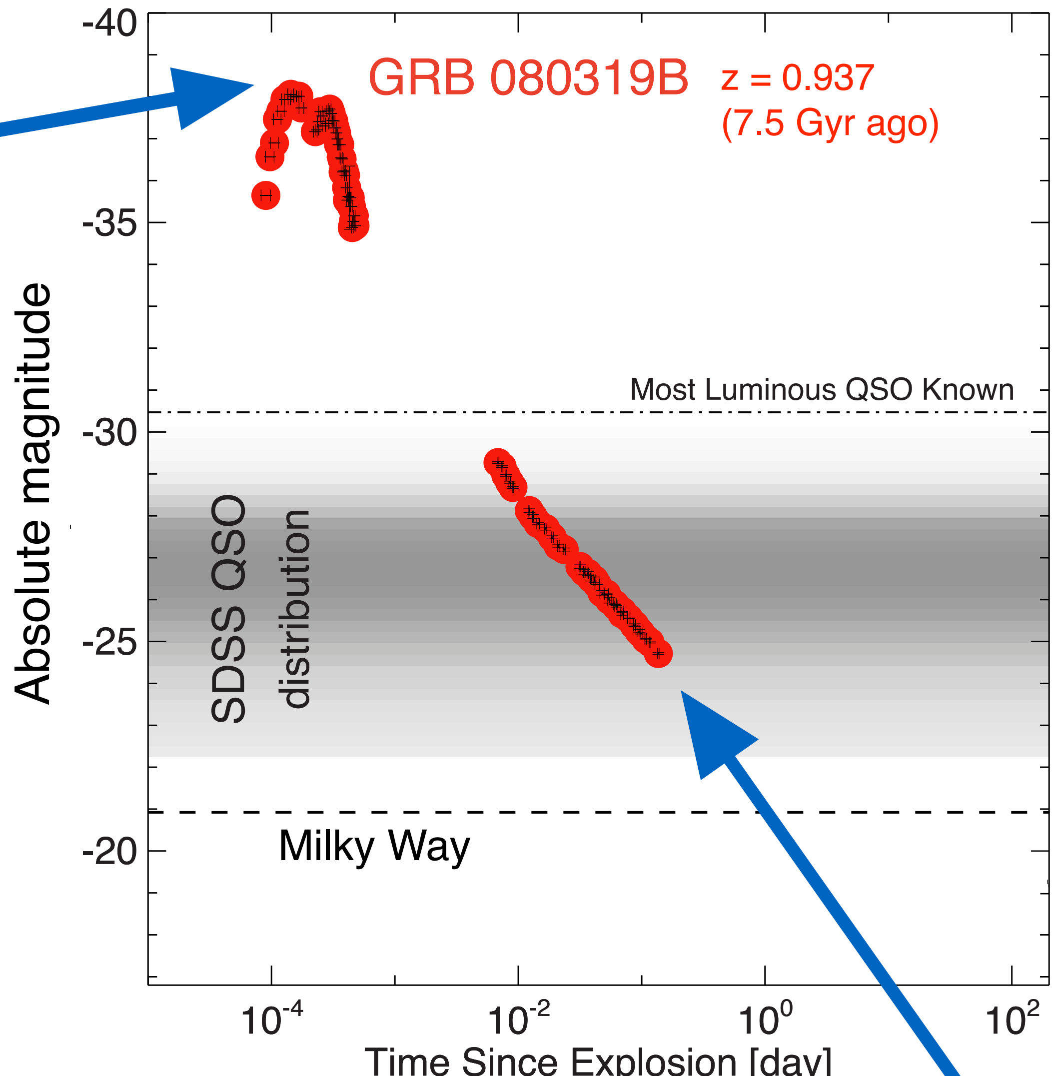
Rates for long GRBs (very uncertain):

GRB/CC–SN……………………………………….. $1/10^3 - 1/10^5$
Rate in a galaxy…………………………..……….. $1/10^5\ yr^{-1}$
Detectable in full sky from Earth…………….…. several a day

Intrinsically rare events, but universe full of stars!

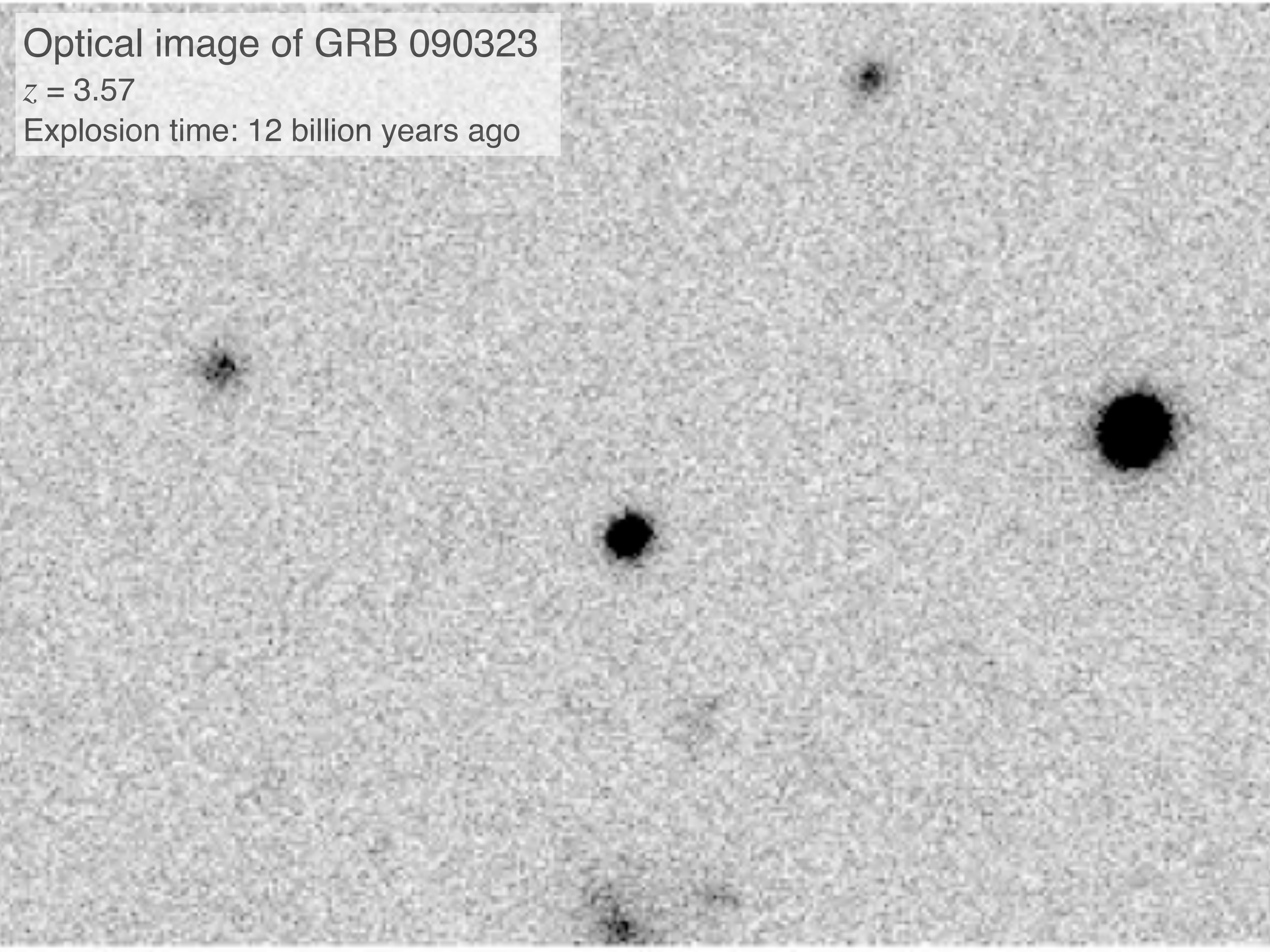
GRB 080319B: the brightest source recorded by humanity

Visual magnitude $m = 5.6$



Peak absolute magnitude: $M = -38$
(10^7 times brighter than the Milky Way)

6.9 hours after $m = 19$


Optical image of GRB 090323
z = 3.57
Explosion time: 12 billion years ago

GRB 090423 at redshift z = 8.3

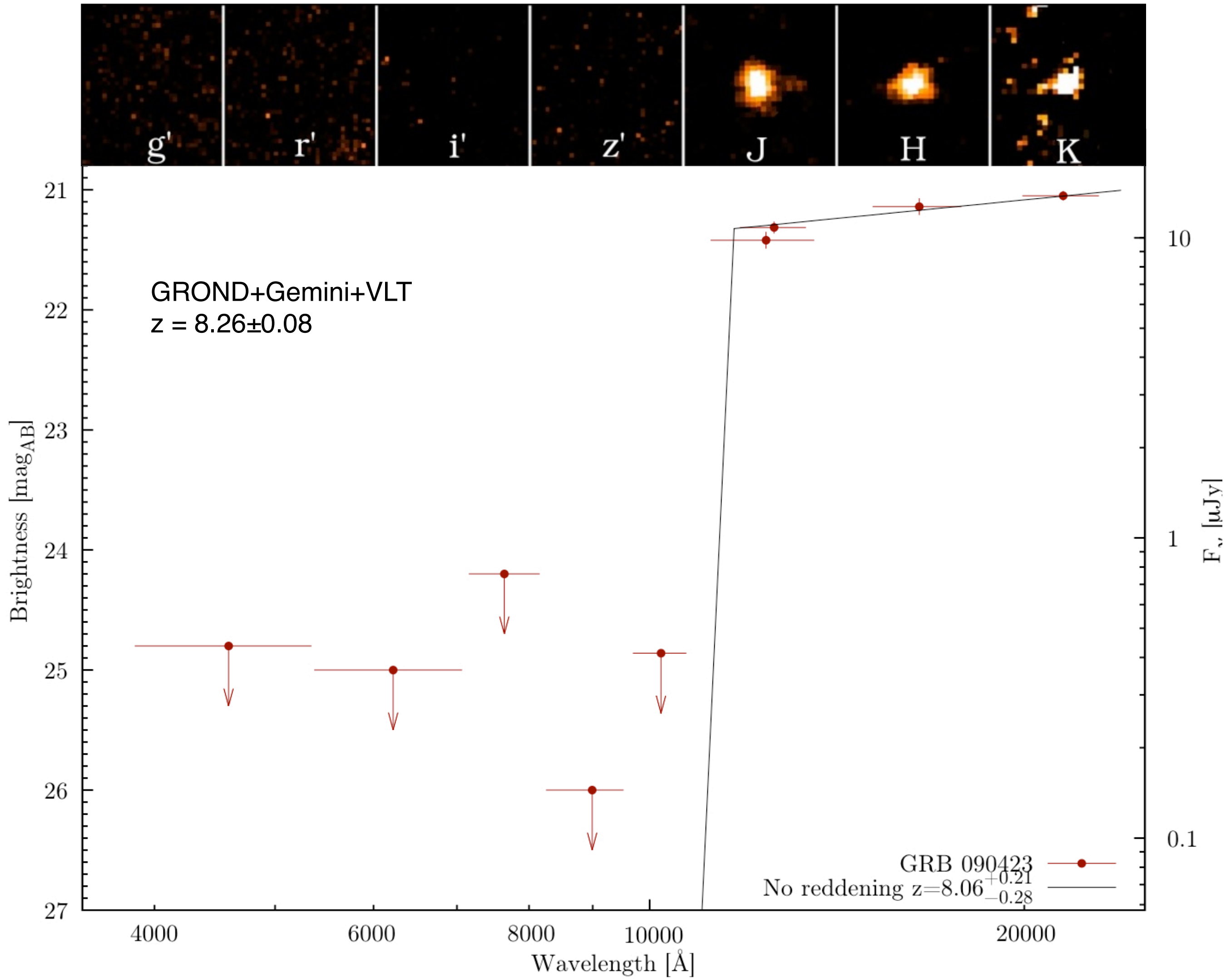
Among the most distant objects ever discovered by humanity

Detected on April 23 2009

Explosion time: 13.1 billion years ago

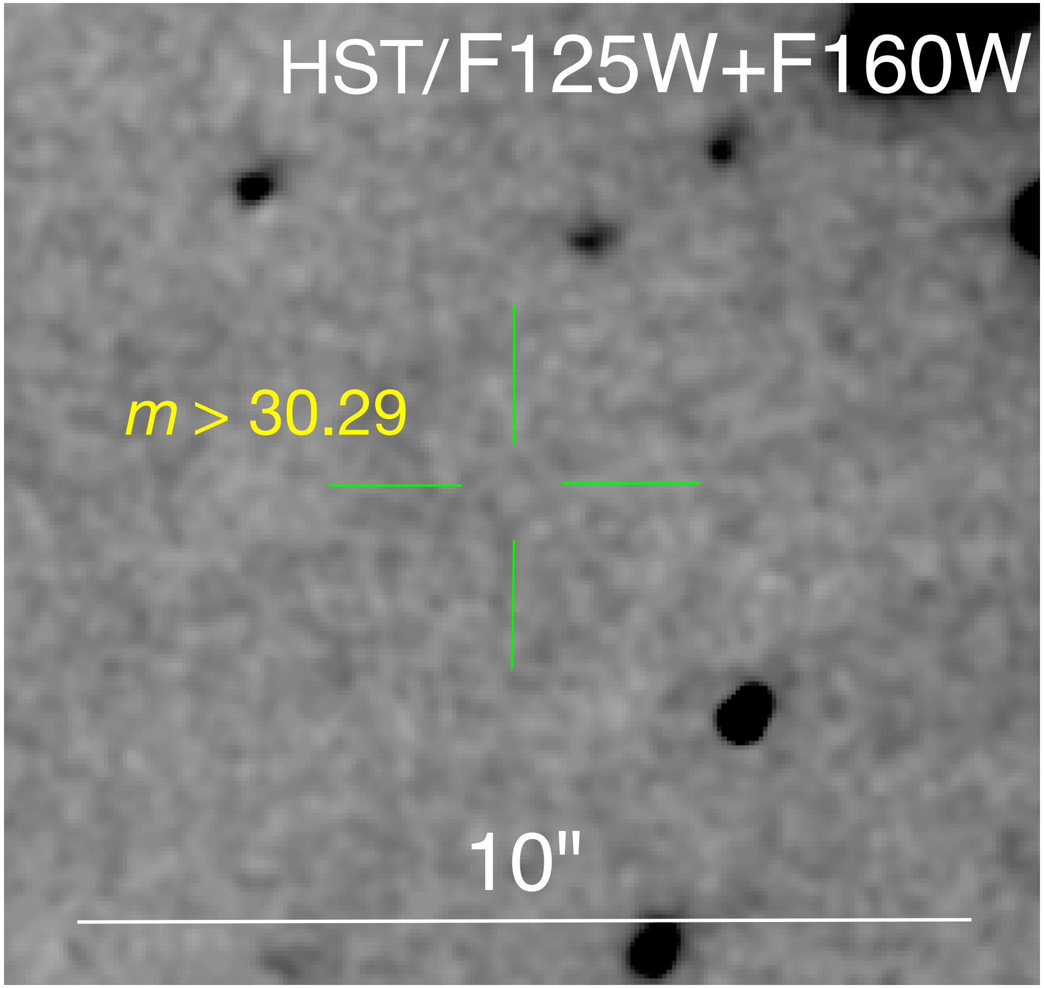
Age of the universe at time of explosion: 600 million years

GRB 090423 redshift z = 8.3

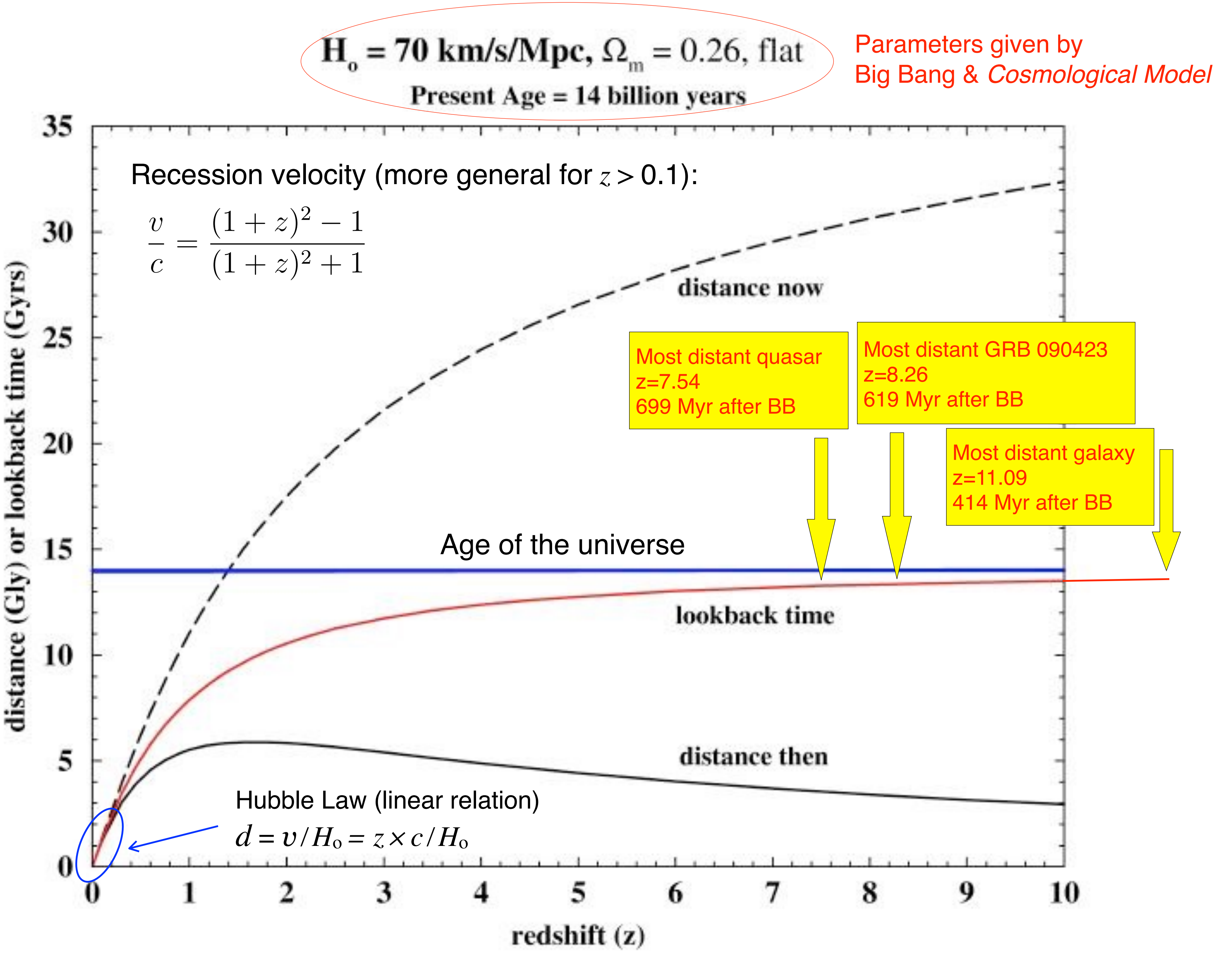


GRB 090423 redshift z = 8.23

The hosting galaxy is not detected to magnitude limit $m > 30.29$

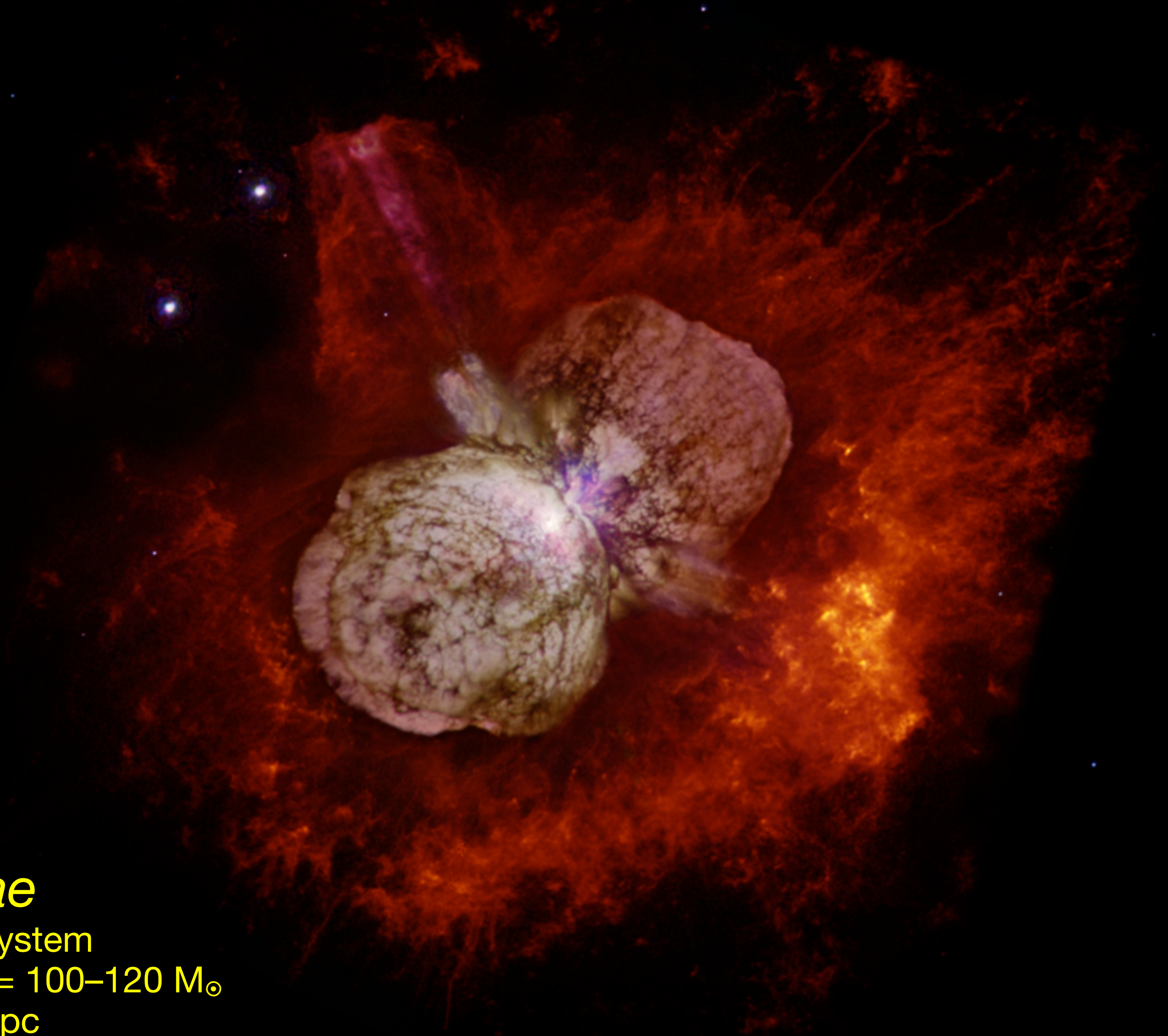


Stellar mass: $M_\star \lesssim 10^7\ M_\odot$



H_o = 70 km/s/Mpc, Ω_m = 0.26, flat
Present Age = 14 billion years
Parameters given by
Big Bang & *Cosmological Model*
Recession velocity (more general for $z > 0.1$):
$$\frac{v}{c} = \frac{(1+z)^2 - 1}{(1+z)^2 + 1}$$
distance now
Most distant quasar
z=7.54
699 Myr after BB
Most distant GRB 090423
z=8.26
619 Myr after BB
Most distant galaxy
z=11.09
414 Myr after BB
Age of the universe
lookback time
distance then
Hubble Law (linear relation)
$d = v/H_o = z \times c/H_o$
distance (Gly) or lookback time (Gyrs)
redshift (z)
0
5
10
15
20
25
30
35
0
1
2
3
4
5
6
7
8
9
10

Is there a possible future GRB in our Galaxy?



Eta Carinae

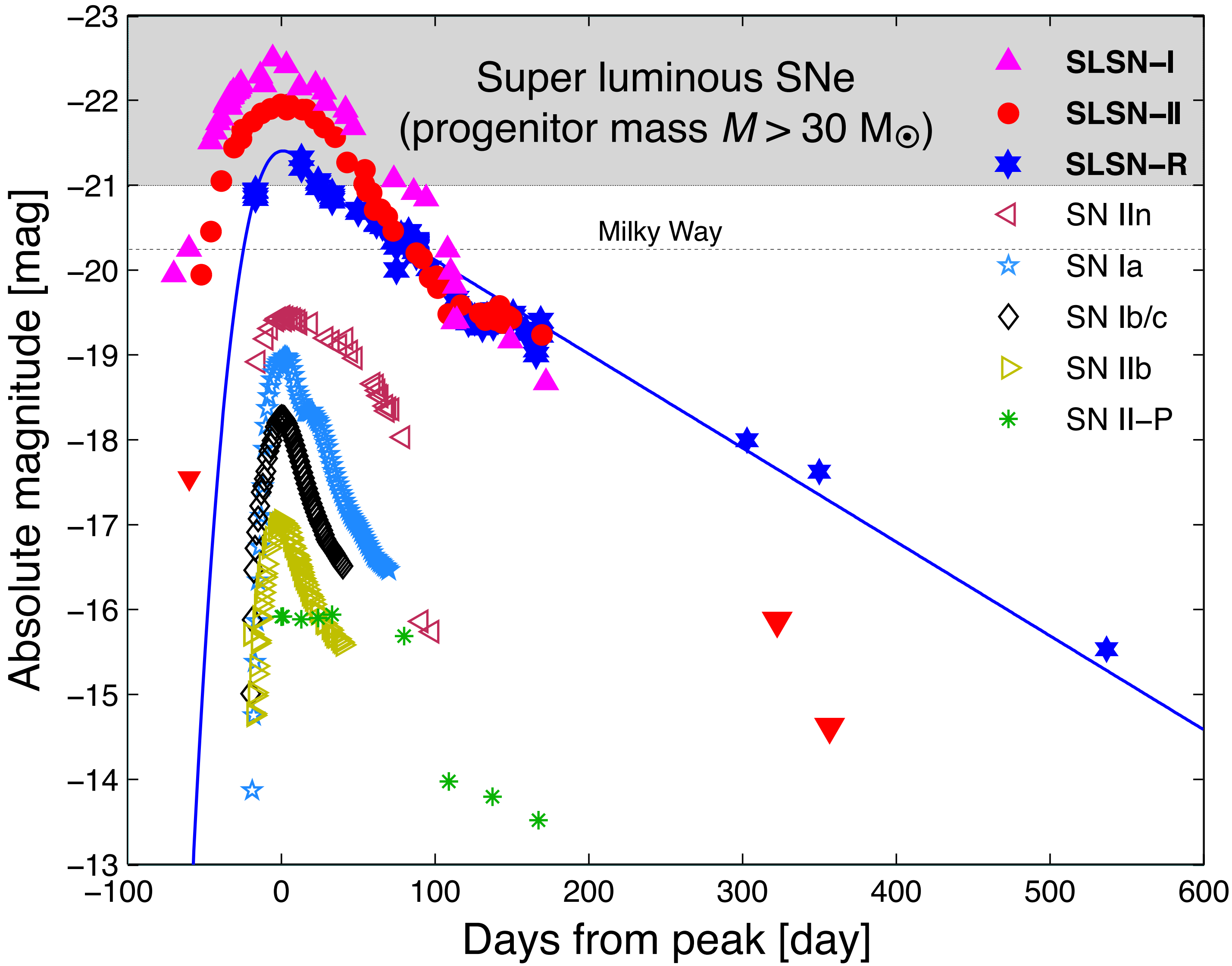
Binary stellar system

Total mass: M = 100–120 $M_\odot$

Distance: 2.3 kpc

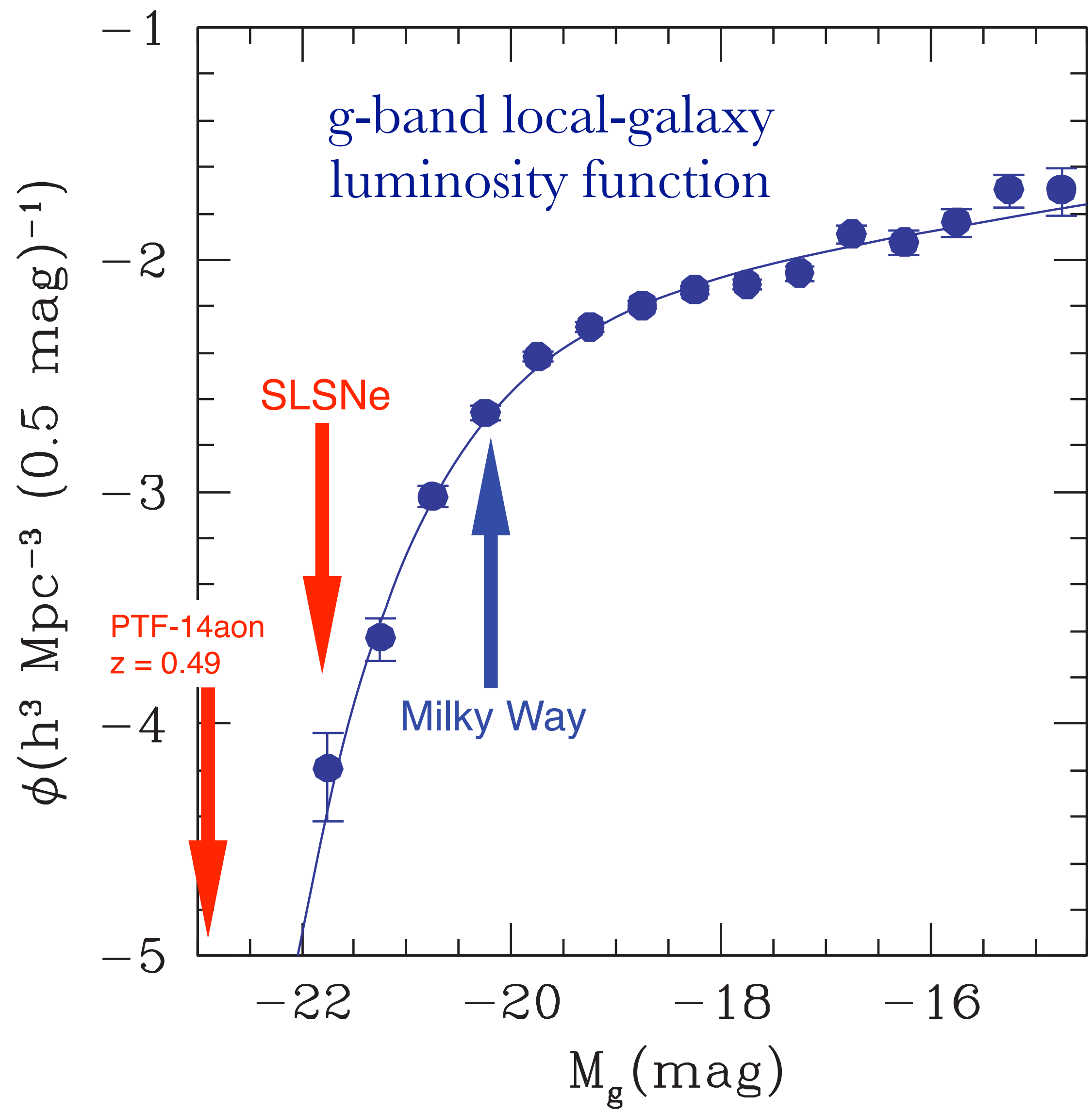
Super luminous supernova (SLSN)

Super luminous supernova (SLSN) light curve & peak luminosity



Gal-Yam (Science, 2012)

The most luminous SLSN



Hill et al. (2010)

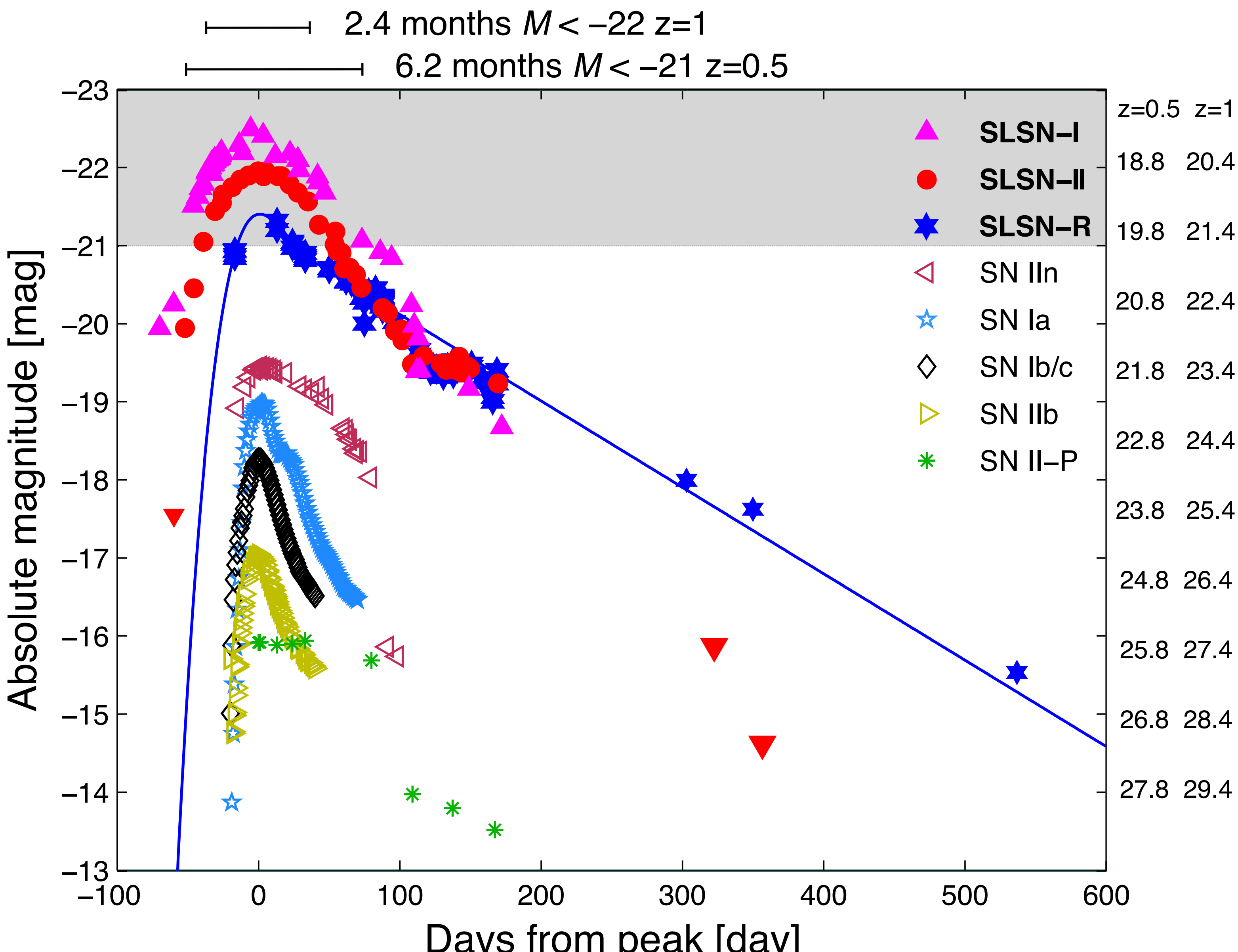
Super luminous supernova (SLSN)

Poorly understood, suggested mechanisms:

- Magnetar (neutron star with extreme magnetic field)
- Circumstellar interaction
- Pair instability supernova
- Gamma-ray burst
- ^{56}Ni decay not favoured

Slow evolution of light curve of super luminous supernovae

Effect amplified by time dilution: $t = t_0 \times (1+z)$ (up to years at high redshift)



Slow evolution of light curve of super luminous supernovae

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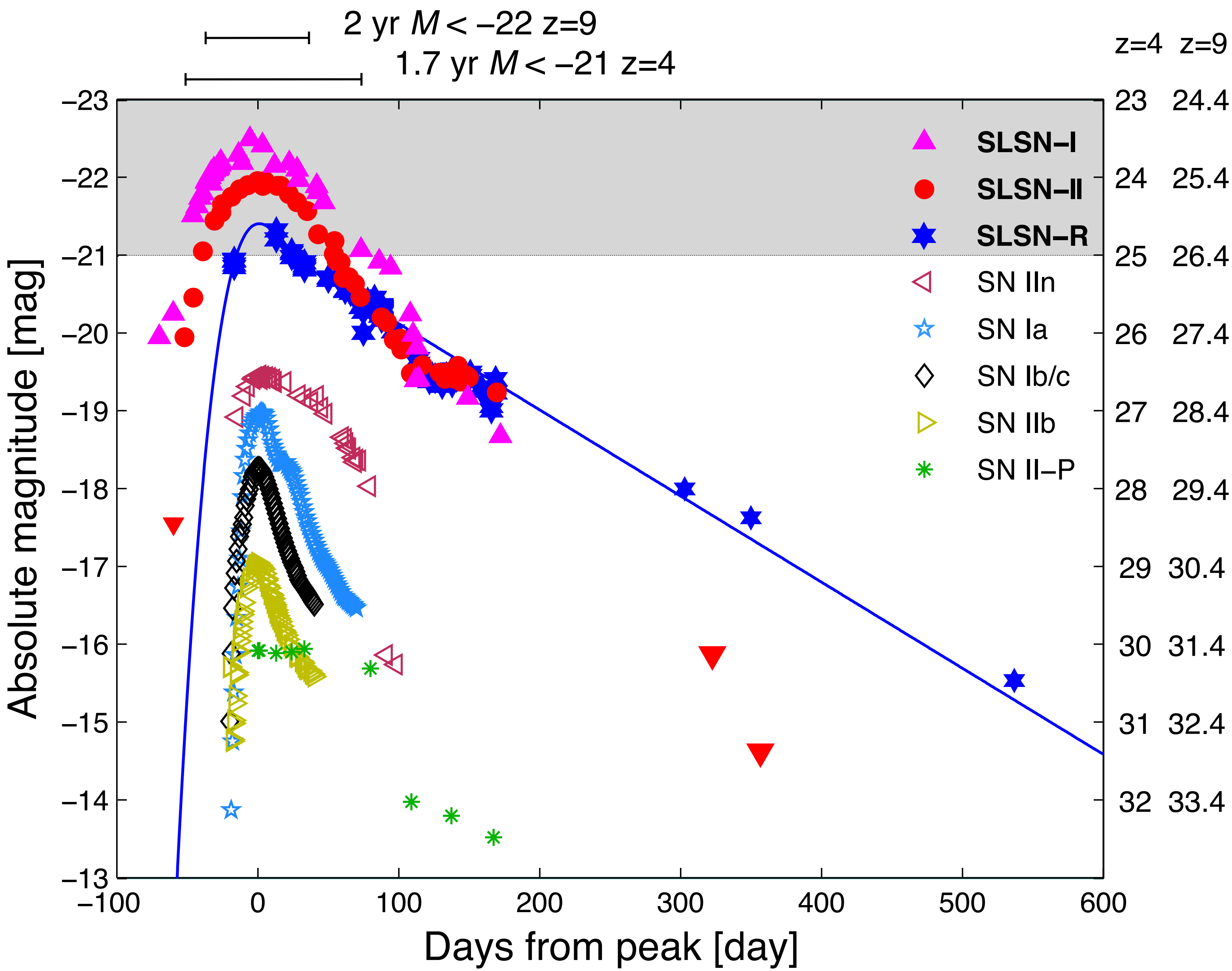
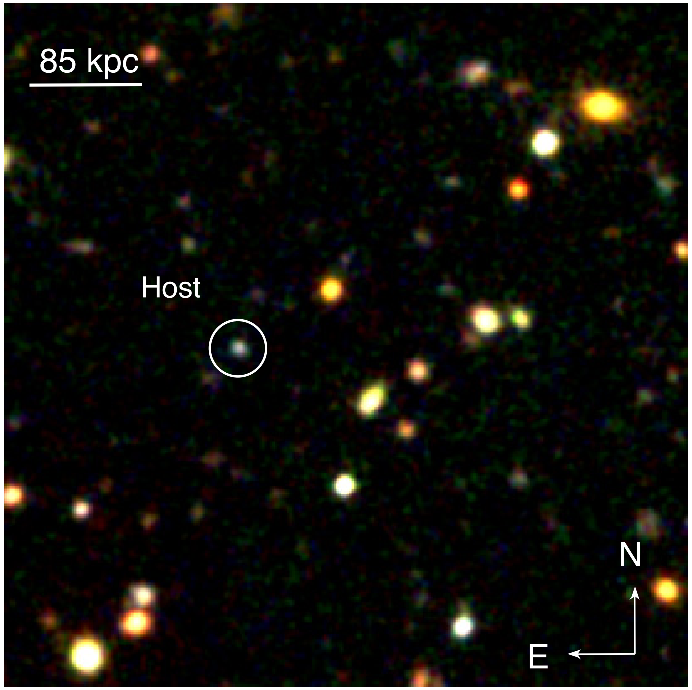
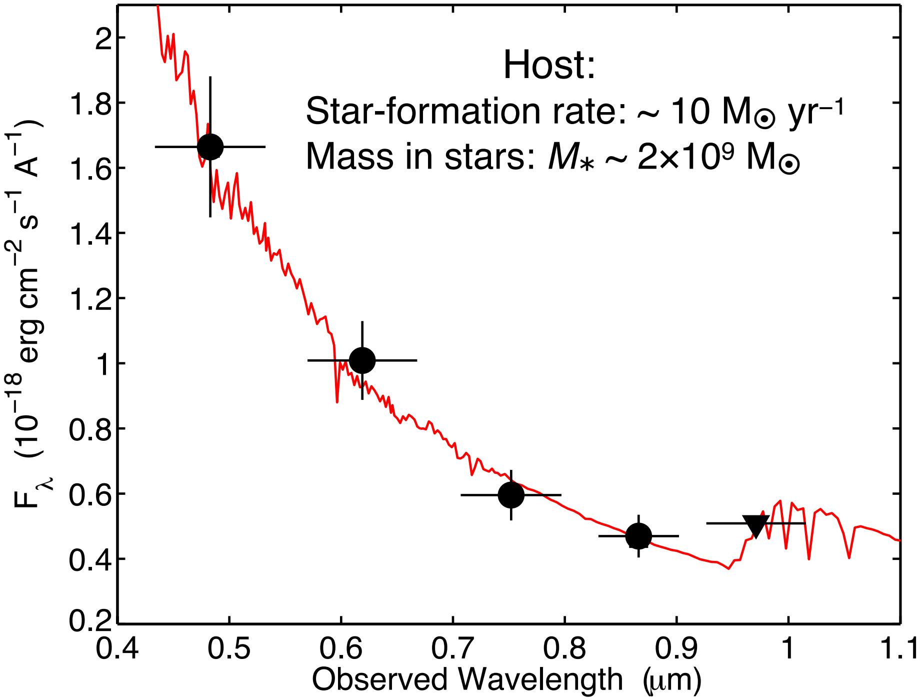


SLSN host galaxies

PS1-11bam z = 1.566

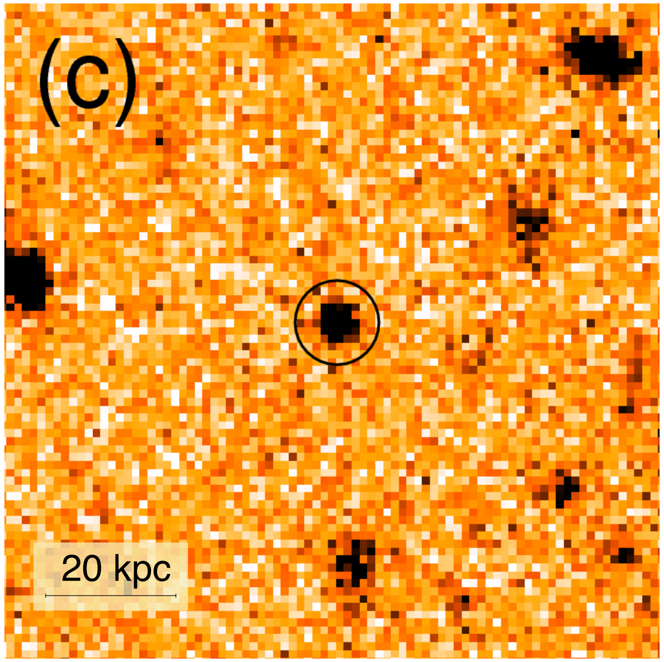




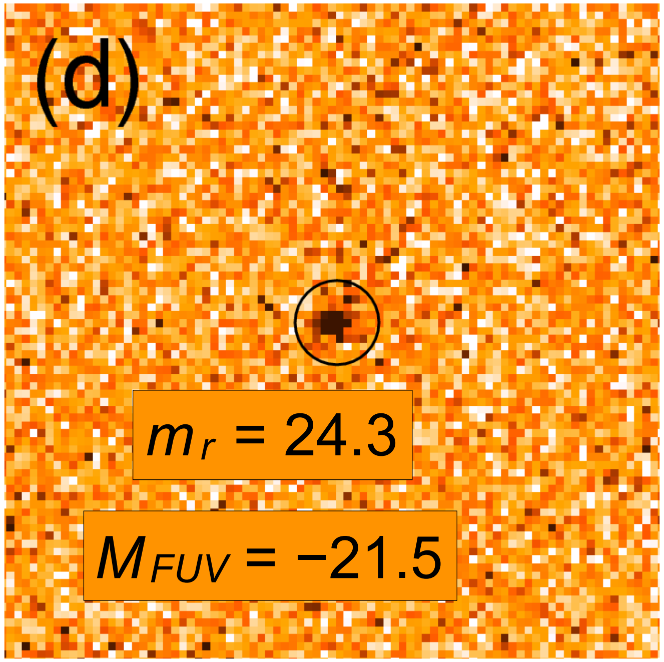
Berger et al. (2012)

Super luminous supernovae at high redshift

Galaxy z=3.899 (2005/2006)



SN 1000+0216 (2007/2008)



Cooke et al. (Nature, 2012)

Statistics of SLSNe today:

About 60 known at $z < 1.15$

About 20 between $1.15 < z < 3.9$

Rate of SLSNe at different redshifts

Type	redshift	Rate (Gpc^{-3} yr^{-1})
SLSN-I	~ 0.17	32^{+77}_{-26}
SLSN-II	~ 0.15	151^{+151}_{-82}
Total (I+II)	~ 0.16	199^{+137}_{-86}
SLSN-I	0.3 – 1.4	~ 36
SLSN	1.13	91
High-z SLSN	2 – 4	~ 400^{+76}_{-36}