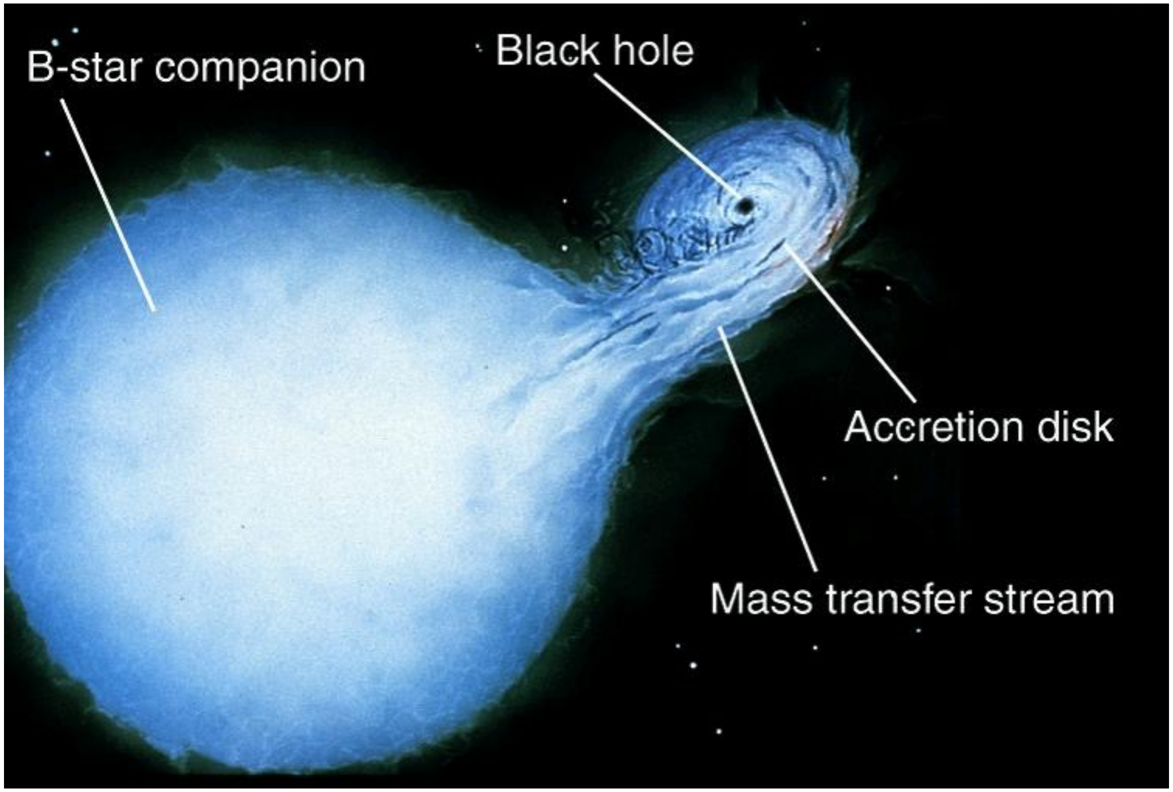
Do Black Holes Really Exist? Good Candidate: Cygnus X-1

- Binary system: 30 M_{Sun} star with unseen companion.

- Binary orbit => companion > 7 M_{Sun}.

- X-rays => million degree gas falling into black hole.

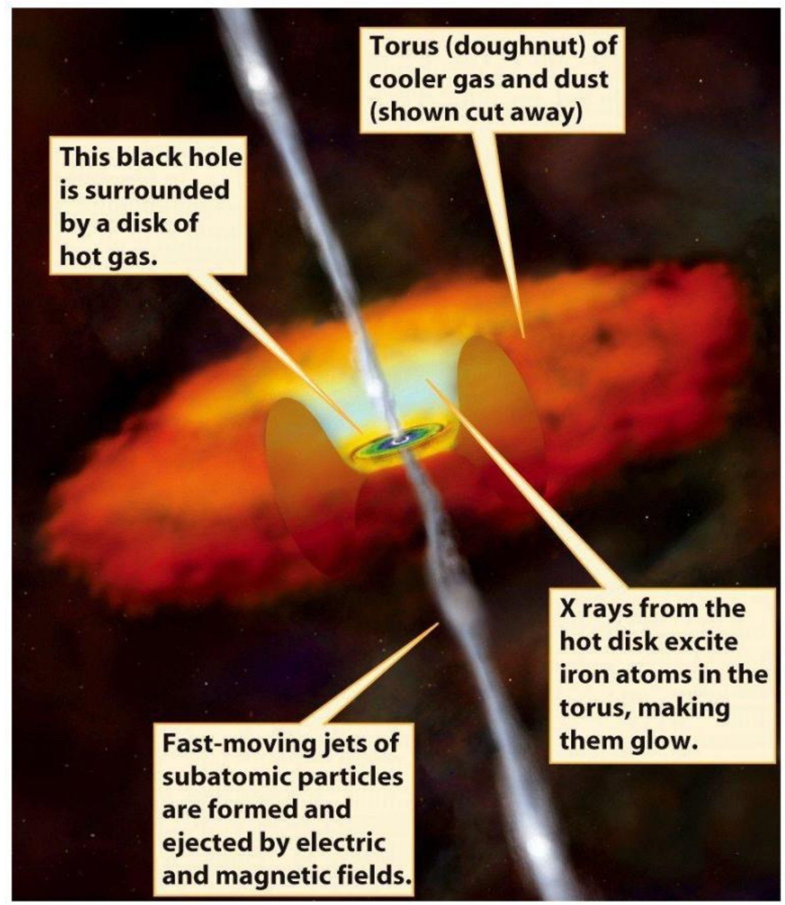


Supermassive black holes

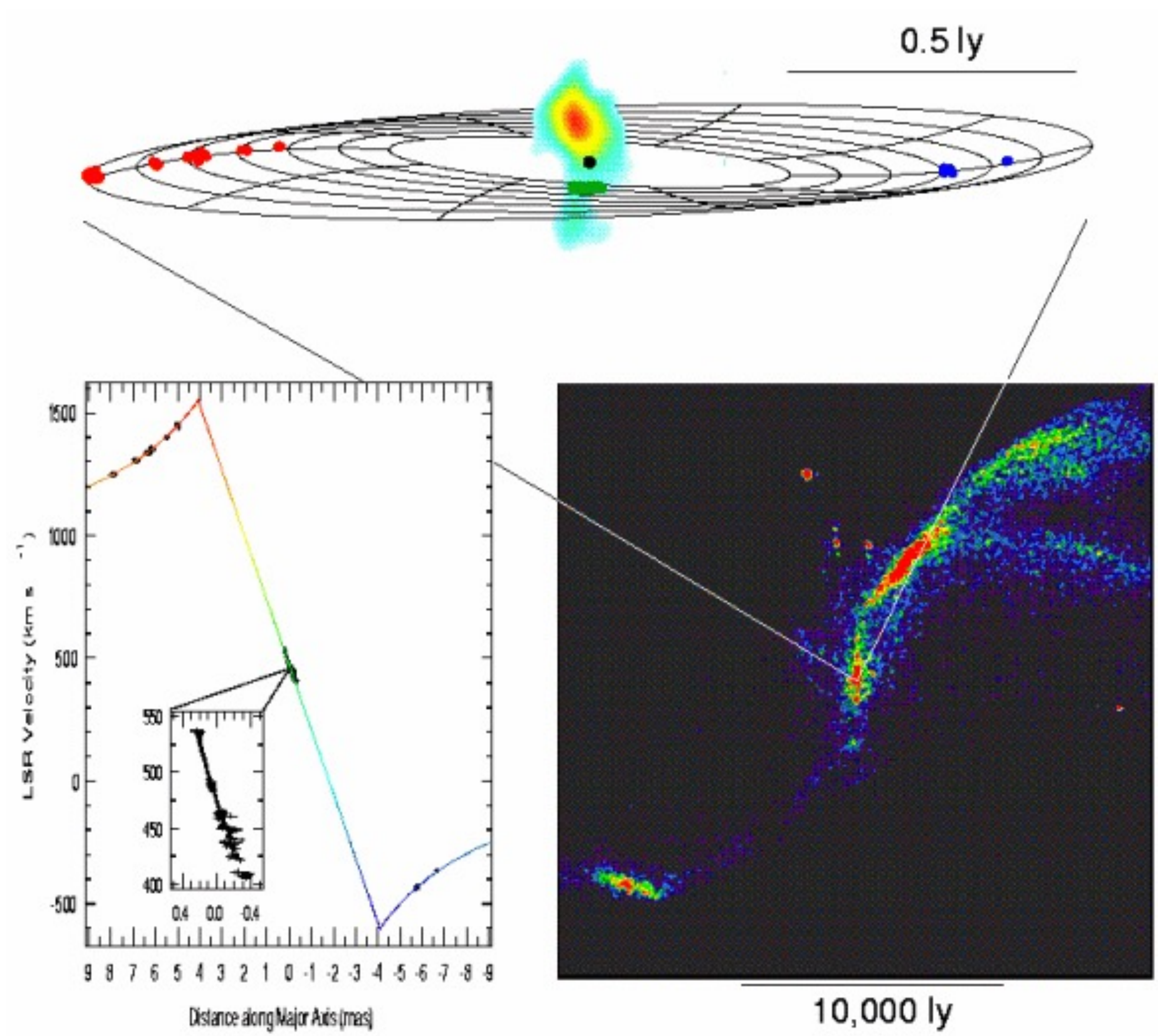
We find supermassive black holes at the centers of essentially all large galaxies.

Evidence comes from high orbital speeds of nearby gas or stars. Masses range from 10^6 $M_\odot$ to 10^9 $M_\odot$.

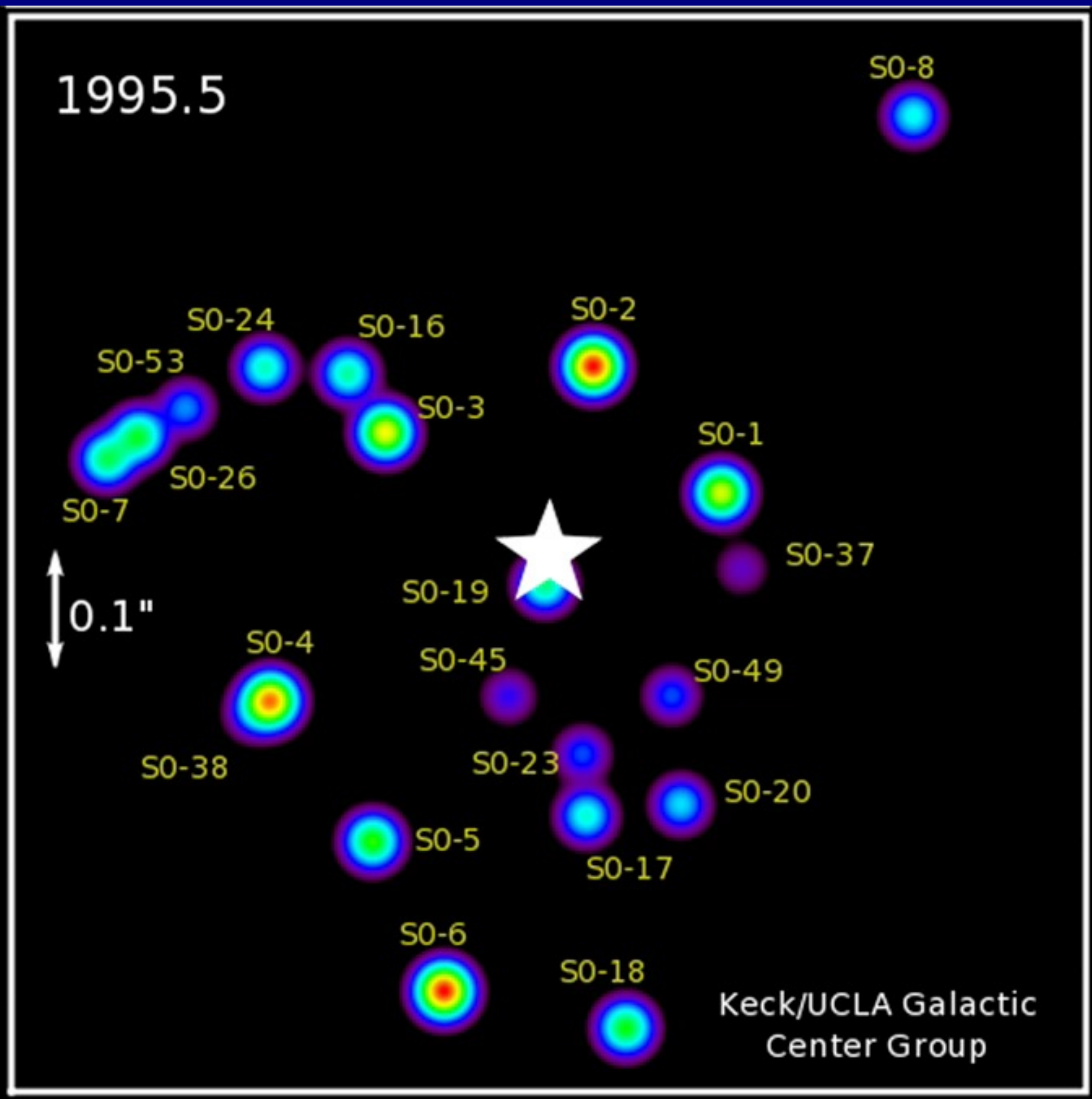
These objects show themselves by their accretion disks or jets.



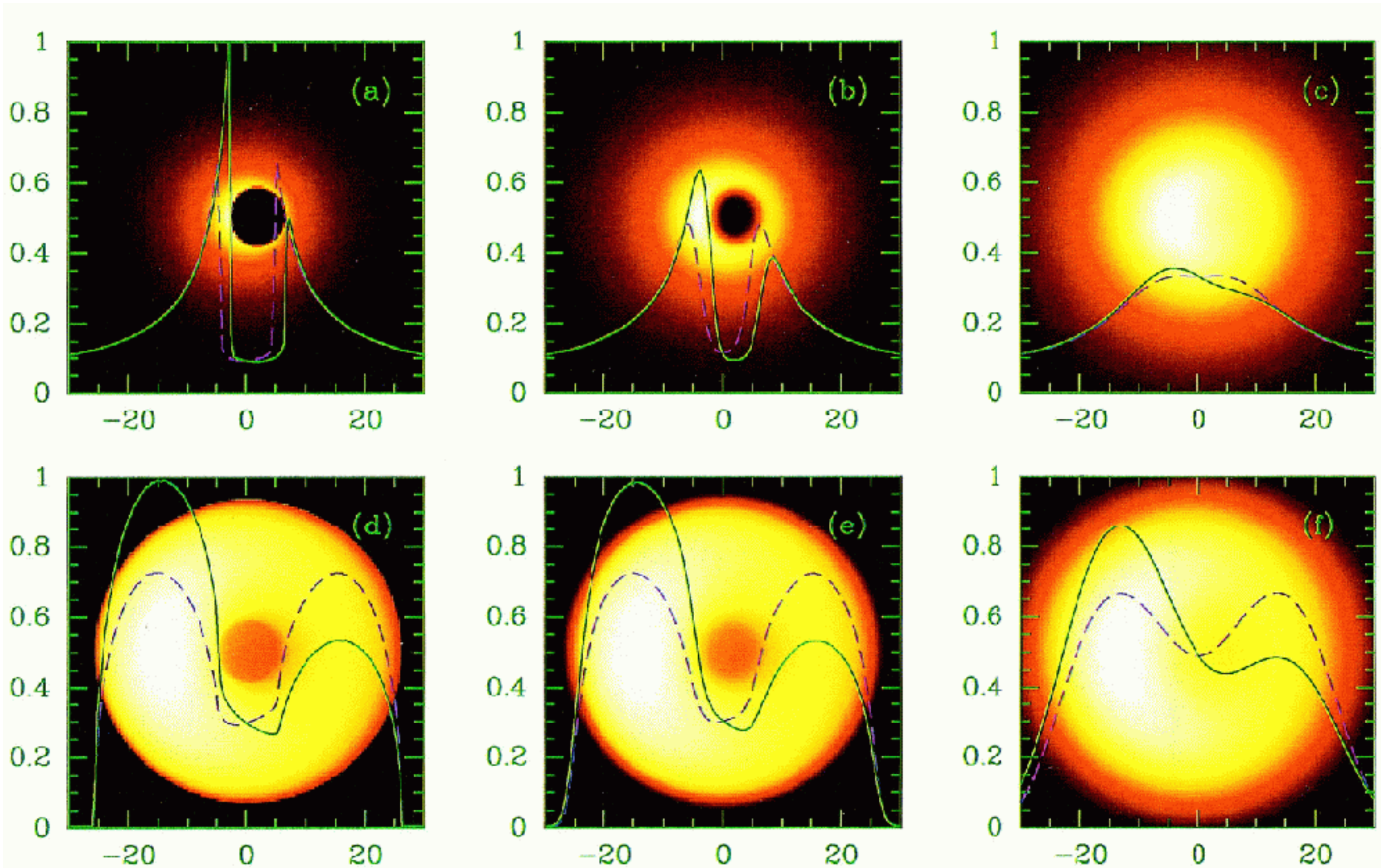
First evidence: NGC4258

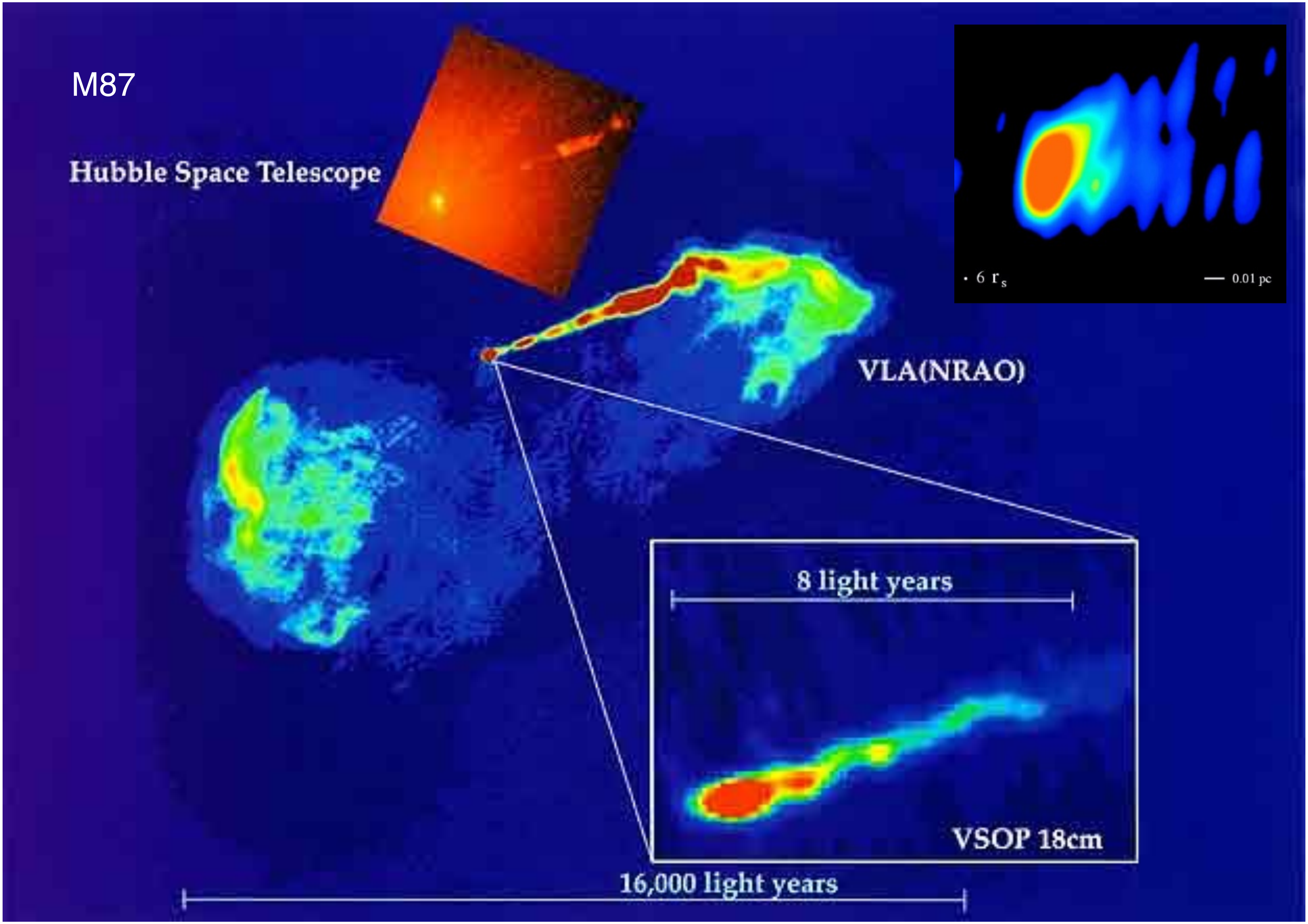


Supermassive (3 million solar mass) Black Hole at the Galactic Center

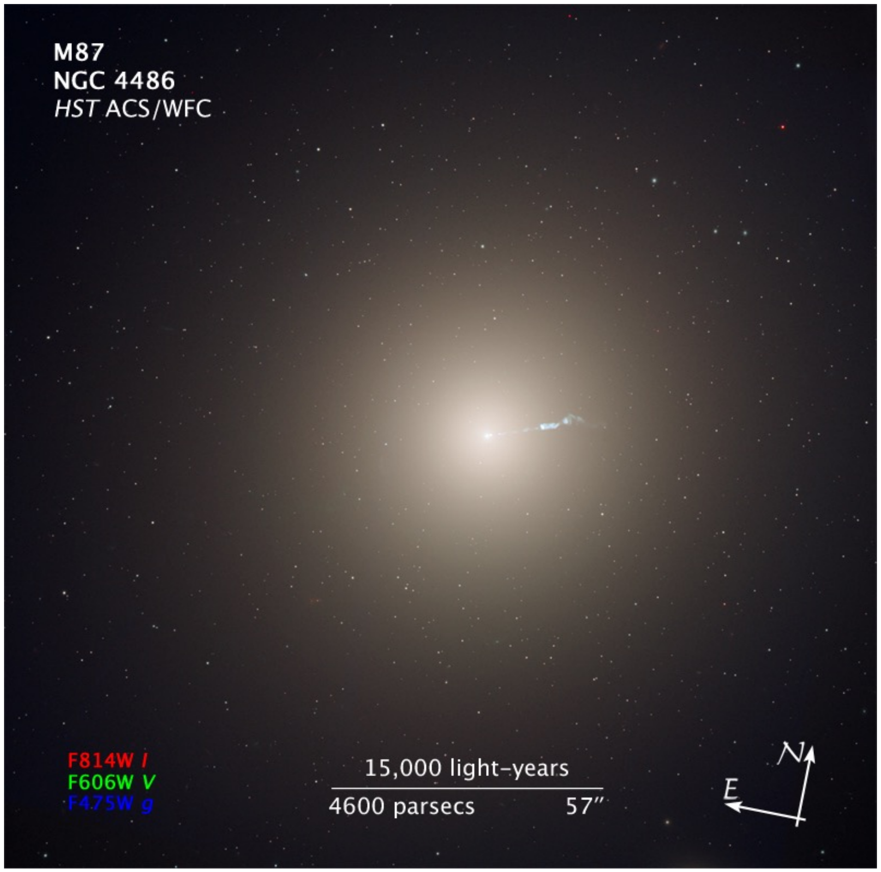


Shadow of a Black Hole

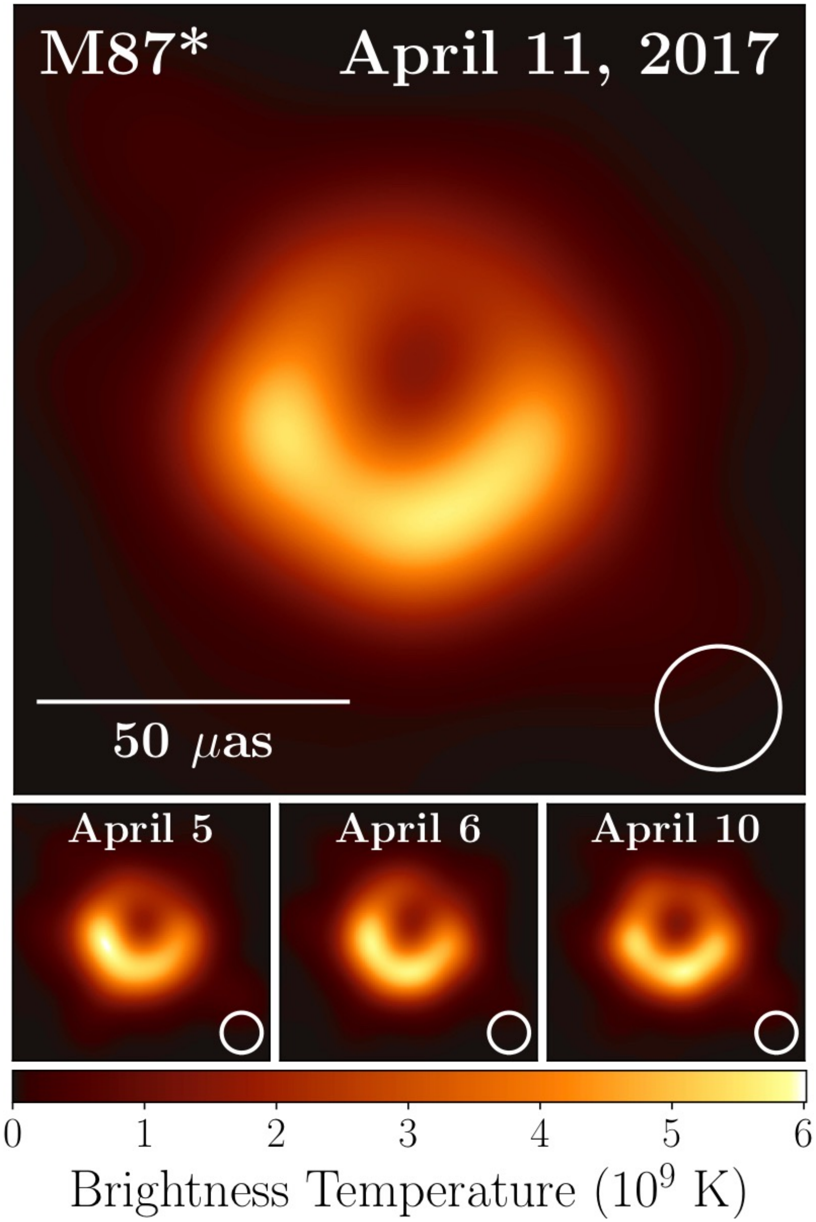



M87
Hubble Space Telescope
VLA(NRAO)
6 r s
0.01 pc
8 light years
VSOP 18cm
16,000 light years

Shadow of a Black Hole



Optical image of the host galaxy

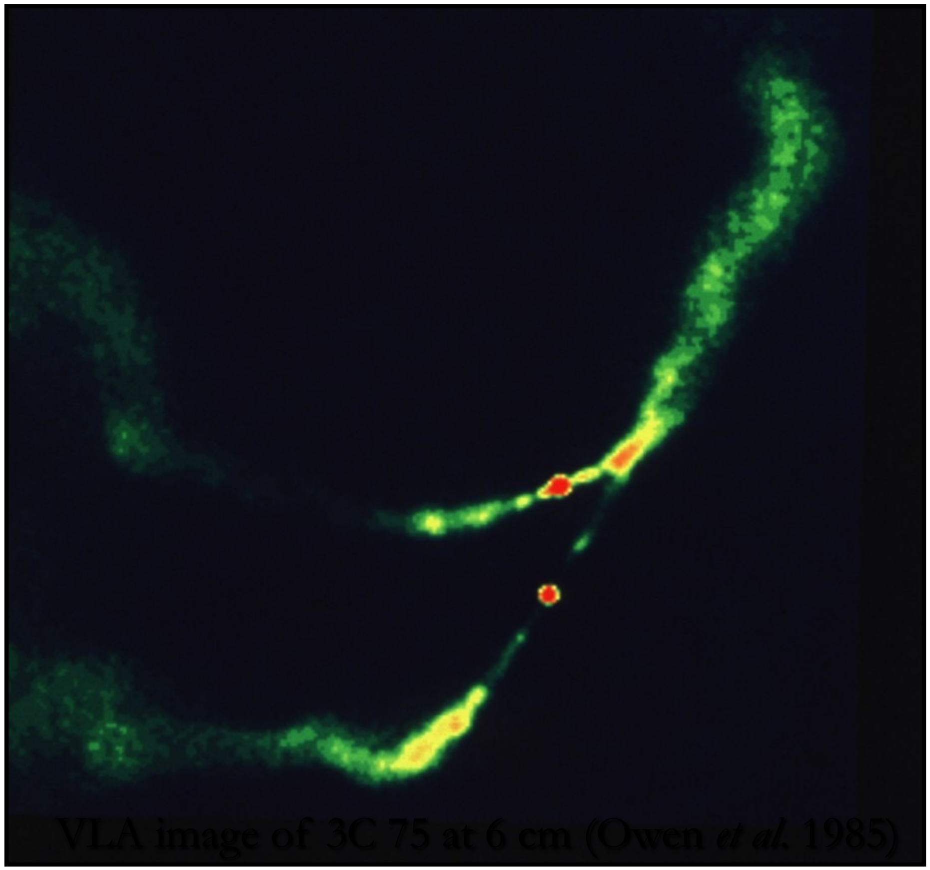


Radio image from Event Horizon Telescope

Supermassive Binary Black Holes

3C 75

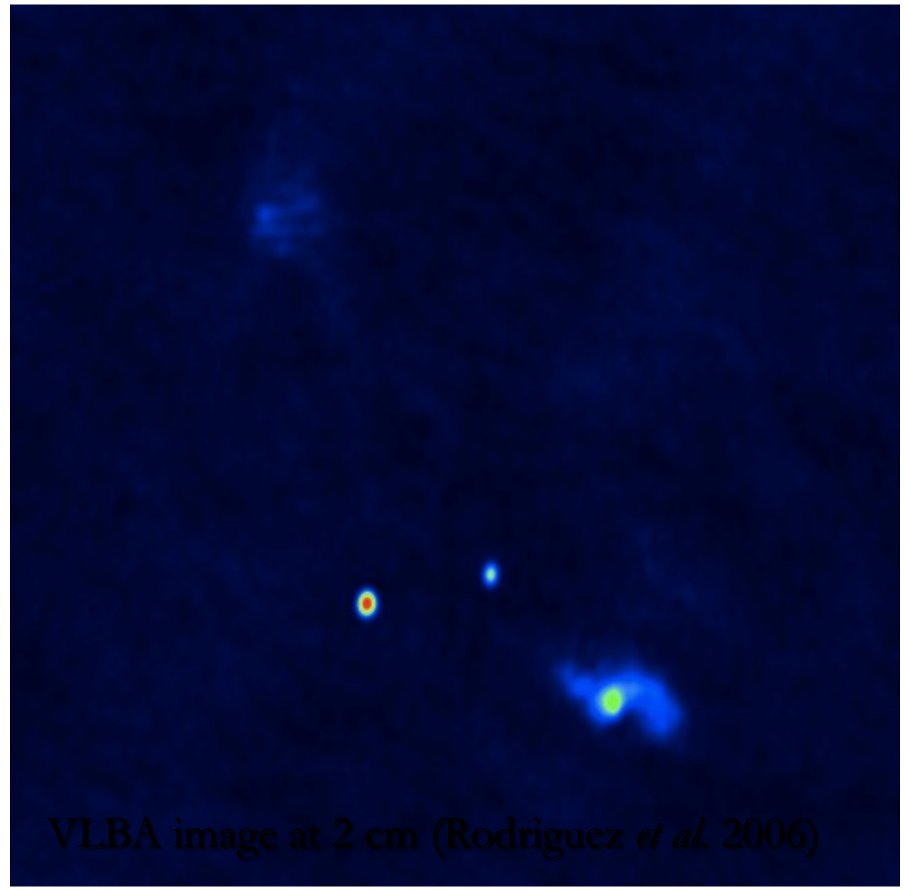
⇨ 7 kpc separation



VLA image of 3C 75 at 6 cm (Owen *et al.* 1985)

0402+379

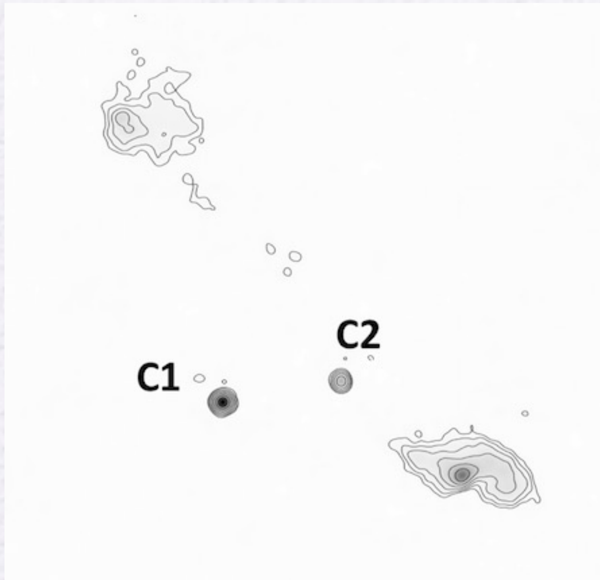
7 pc separation



VLBA image at 2 cm (Rodriguez *et al.* 2006)

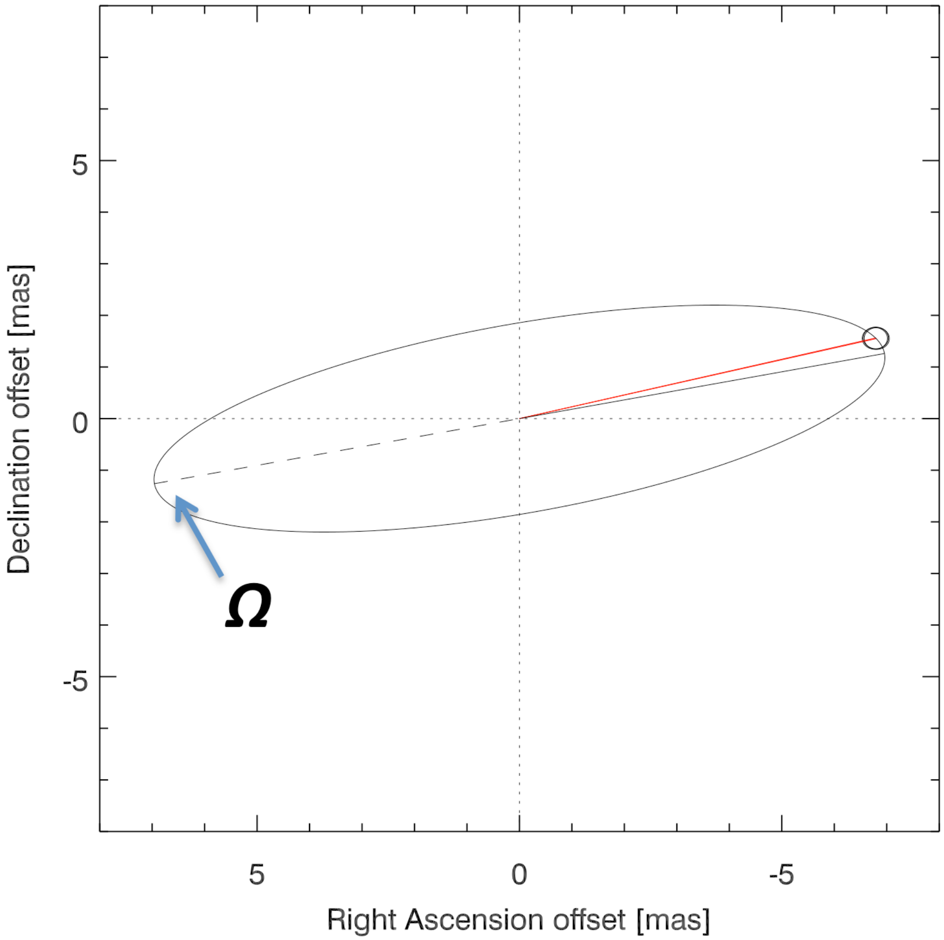
Constraining the Orbit in 0402+379

Supermassive binary black hole system 0402+379

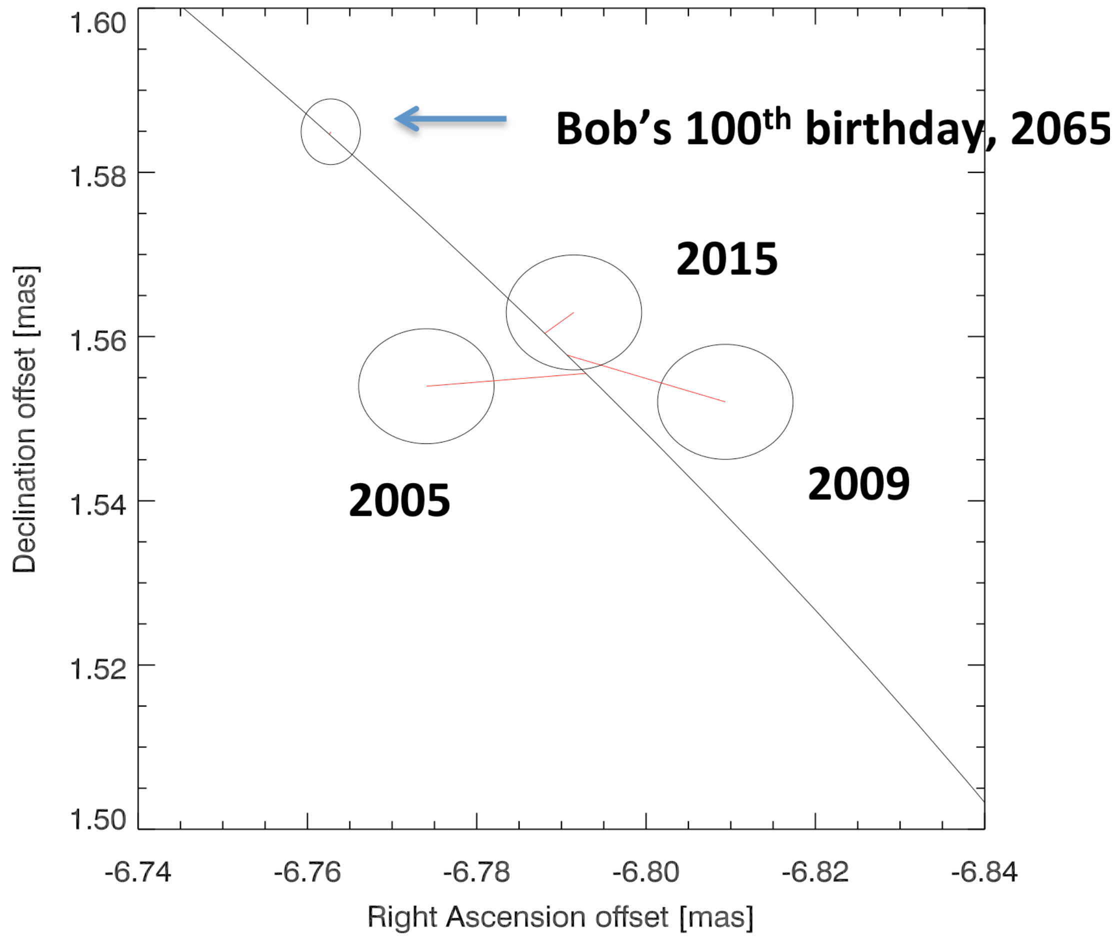


Bansal et al. 2017

Orbital Fitting



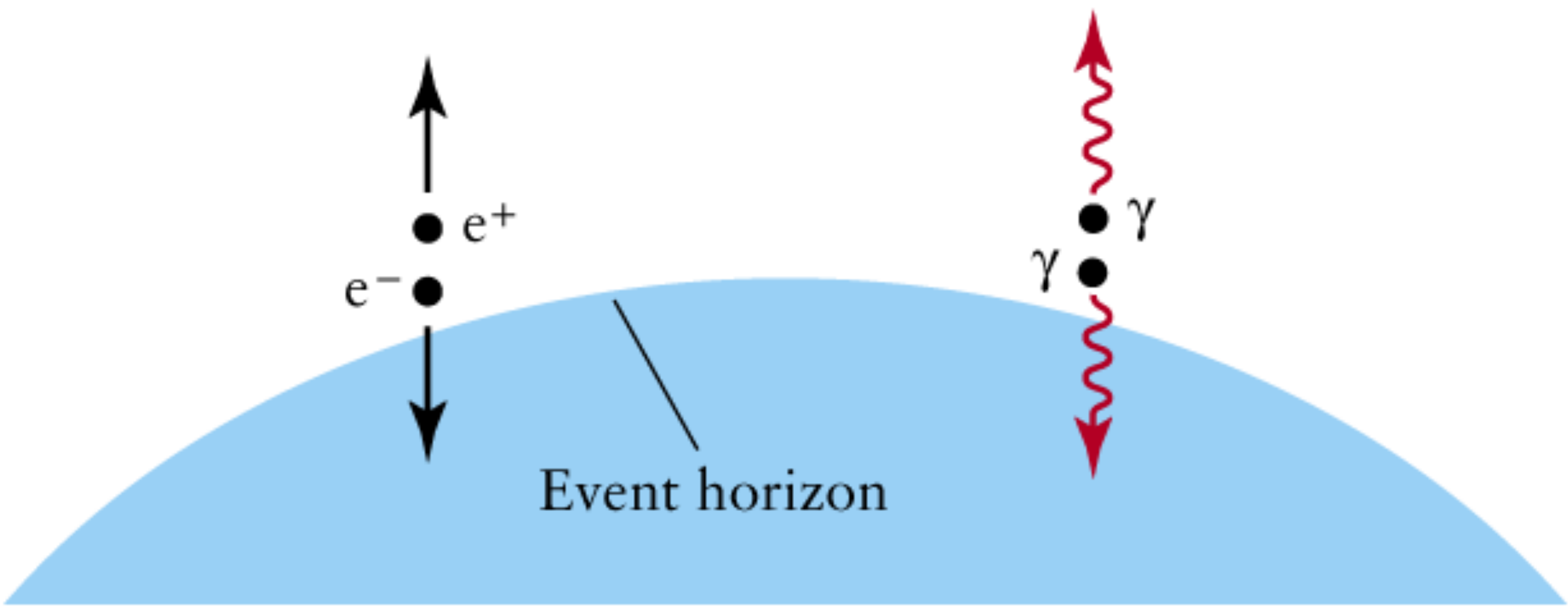
Circular orbit at an inclination



Close-up view

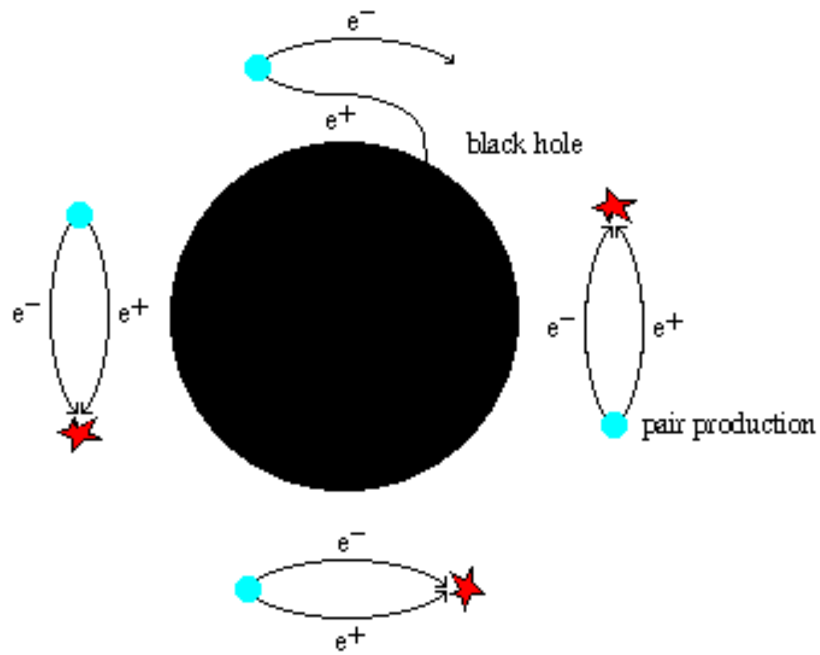
Do black holes exist forever?

- Maybe not: there may be something called *Hawking radiation.*
- Virtual pairs of particles pop in and out of existence. If they are near the event horizon, one might get caught, the other escape, cause the black hole to evaporate. Relevant only for mini-black holes.



Hawking Radiation

the strong gravitational field around a black hole causes pair production



$$T = \frac{\hbar c^3}{8\pi G M k_B}$$

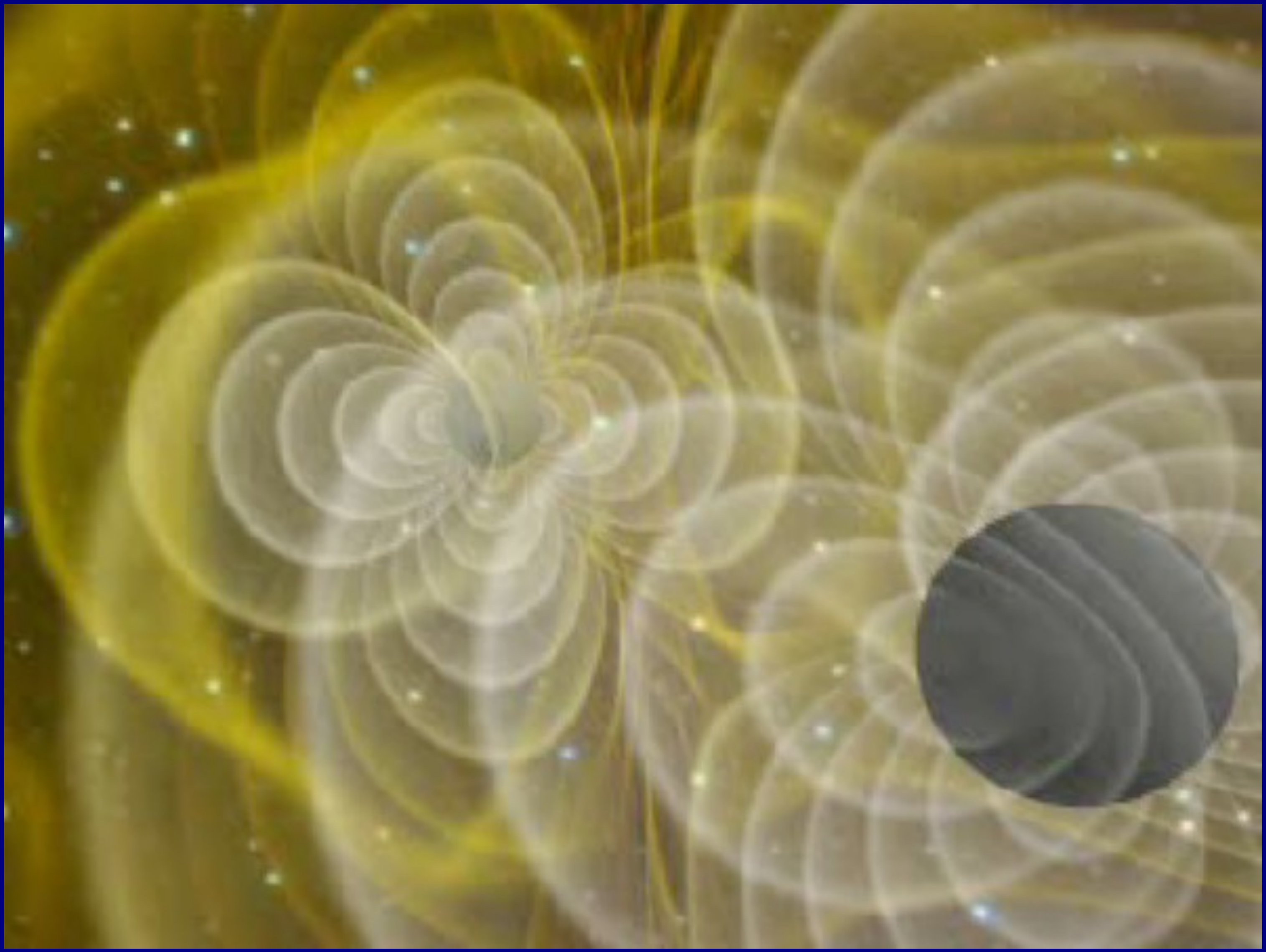
$T \sim 10^{-7}\, M_{Sun}/M$ K

if a pair is produced outside the event horizon, then one member will fall back into the black hole, but the other member will escape and the black hole loses mass

- BHs slowly lose mass and energy by Hawking Radiation

$$t_{evap} \approx \left(\frac{M}{M_\odot}\right)^3 x\ 2x10^{67} yrs$$

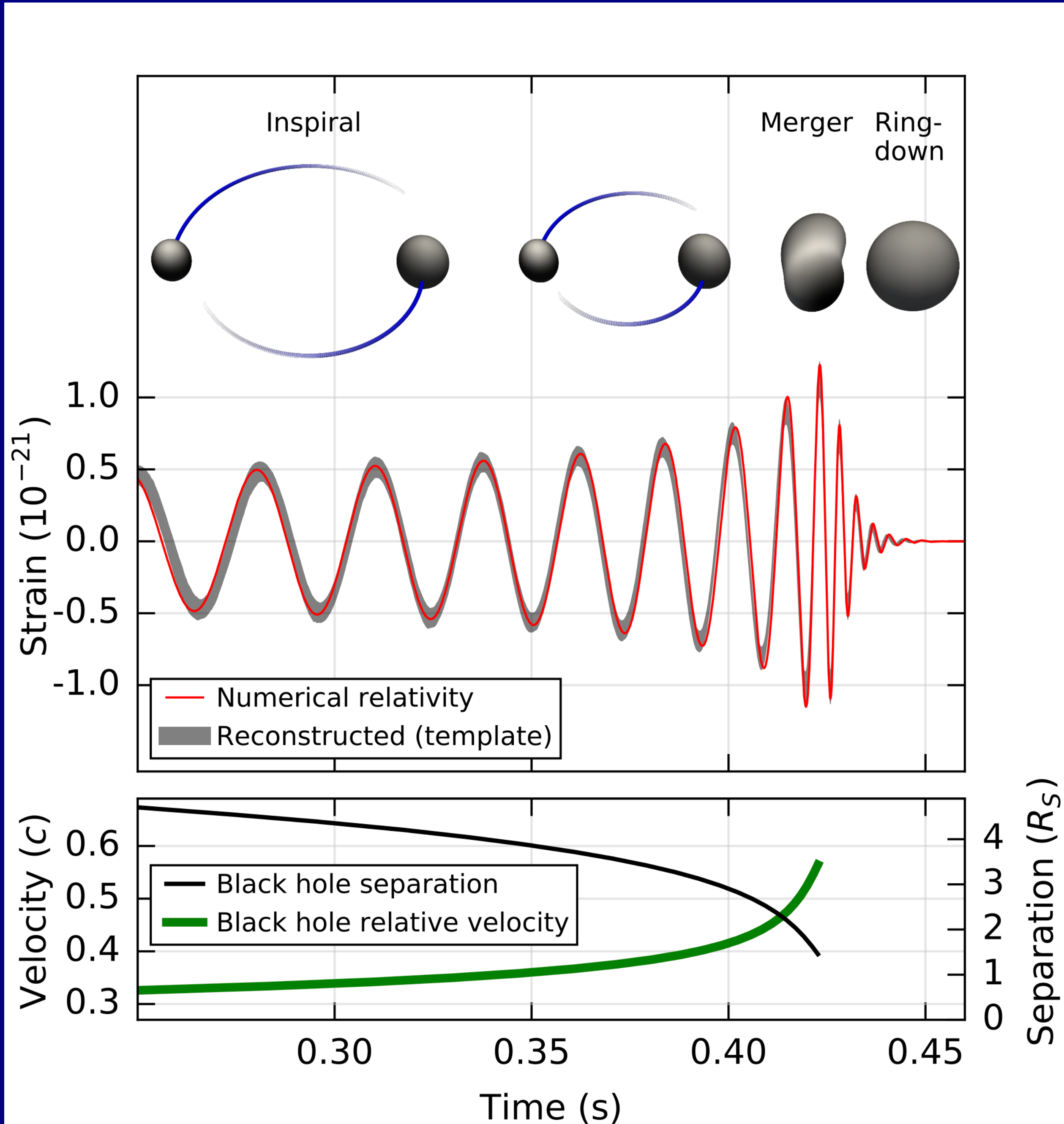
BHs of mass < 10^{11} kg would have evaporated by now.



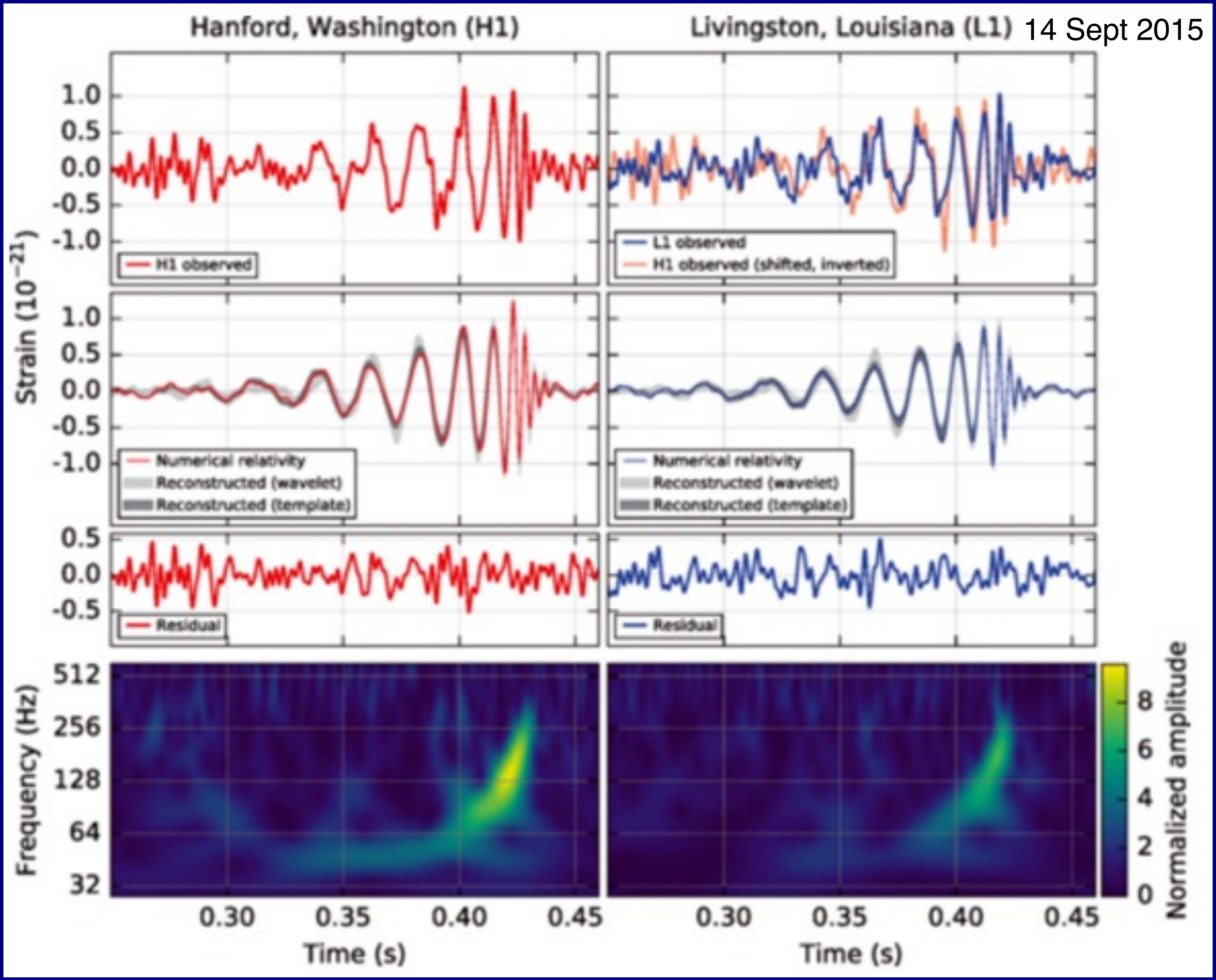
Gravitational Waves

LIGO (Laser Interferometric Gravity-Wave Observatory)

Gravitational Waves



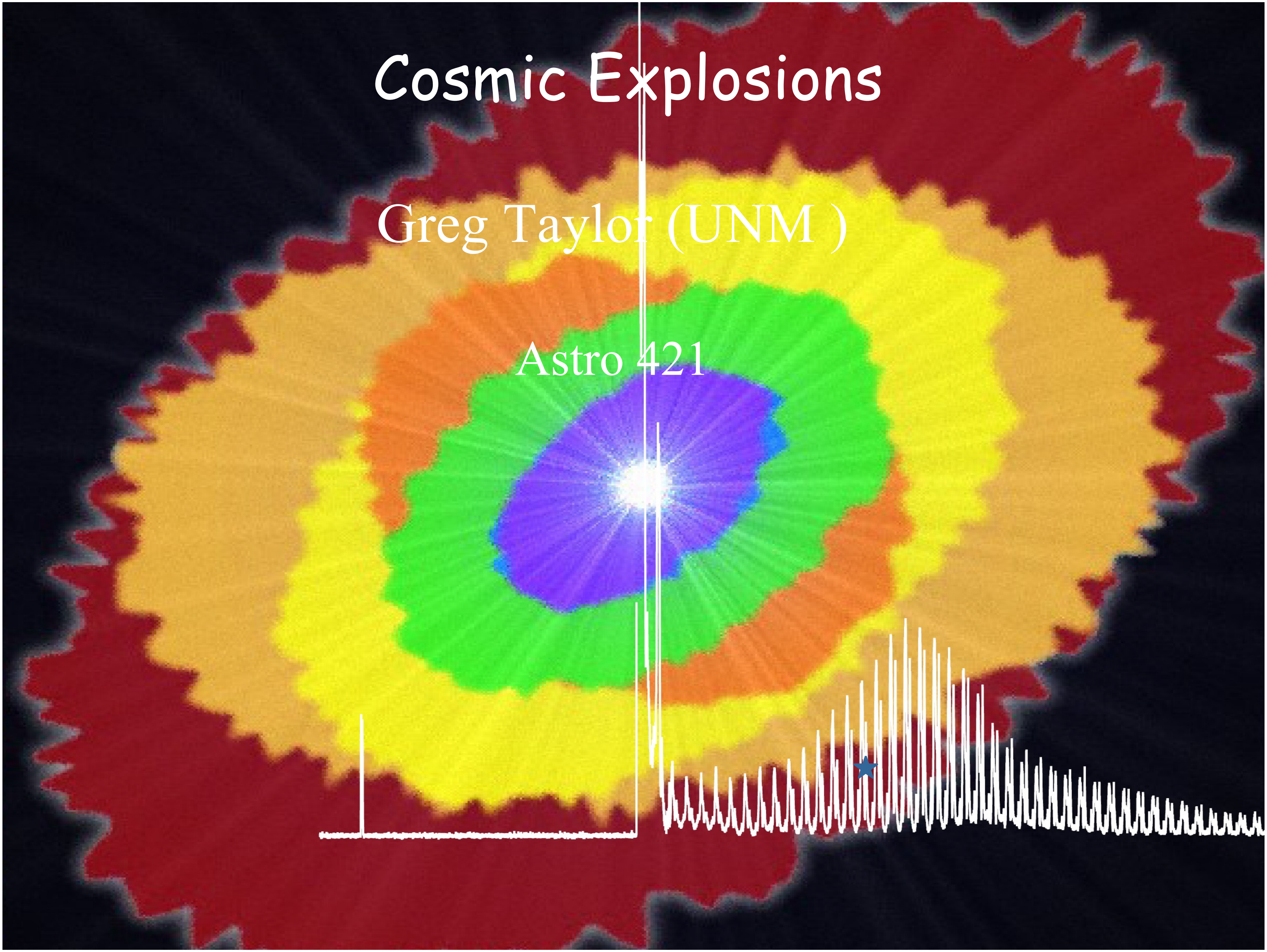
Gravitational Waves



Cosmic Explosions

Greg Taylor (UNM)

Astro 421



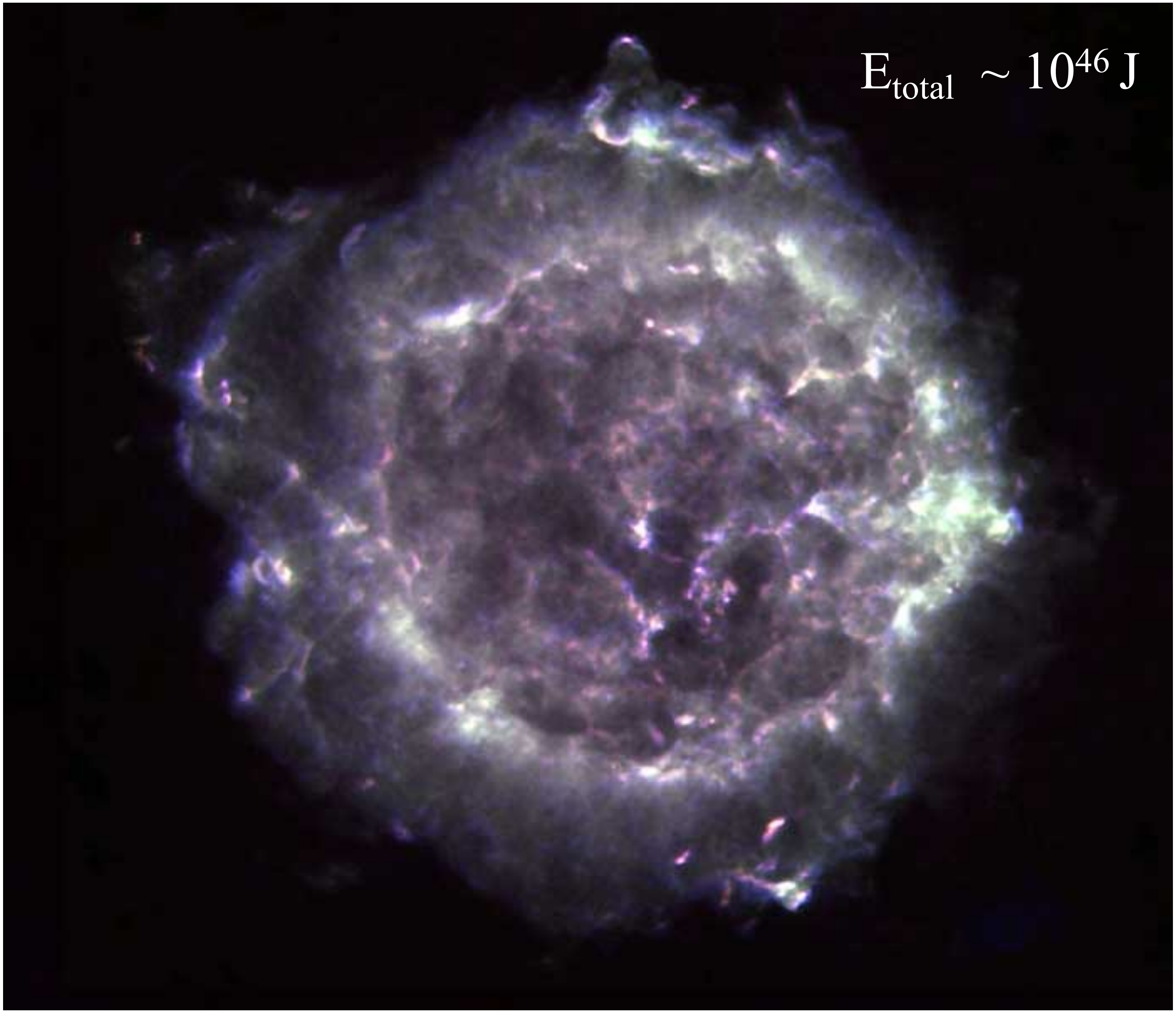
Announcements

- Review on Th. Nov 17
- Exam 3 on Tu. Nov 22
- Peer review reports due Mo. Nov 28
- Panel review in class on Tu. Nov 29
- Term Paper presentations Dec 6: (10 min each)
  Jesus, Christine, Talia, Sharleen, Joaquin, Jake, Soumyodipta
- Term Paper presentations Dec 8: (10 min each)
  Will, Simon, Damen, Tousif, Matthew, Skylar, Prat
- Written paper deadline Dec 12

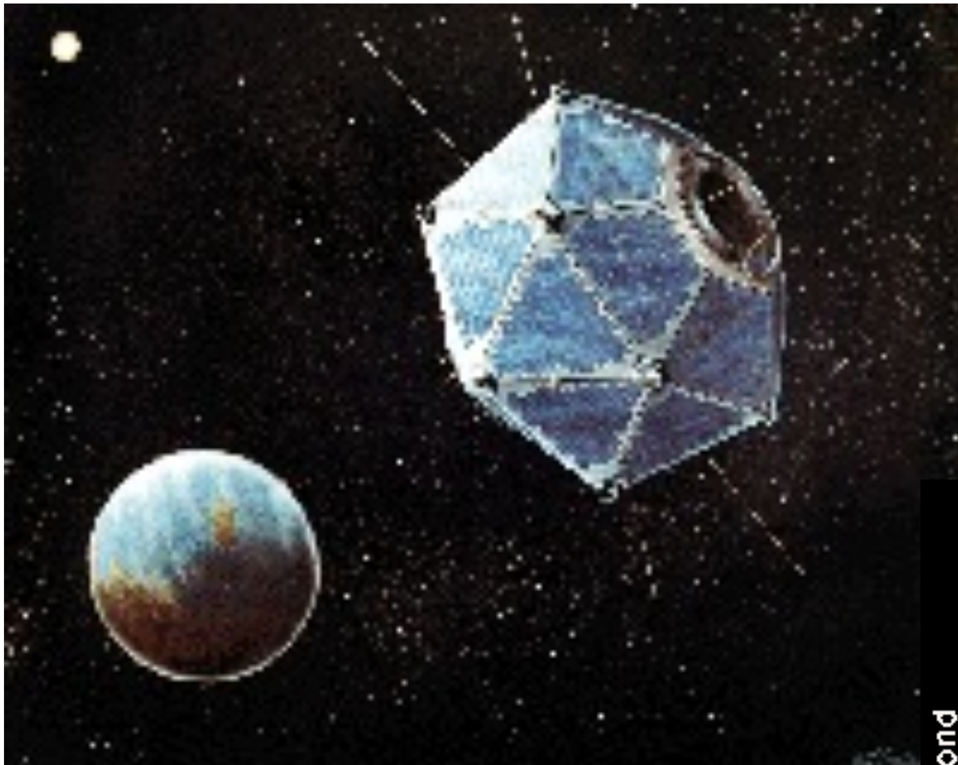
HW8/Panel Review

- How to review a scientific proposal
- Read 4 proposals each ~3 pages
- Rank the 4 proposals from best to worst & score 0-5
- Write a brief evaluation consisting of:
  - Two sentences explain the nature of the proposal
  - Paragraph on the strengths
  - Paragraph on the weaknesses
  - Two sentence summary and recommendation
- Peer review reports due noon Mo. Nov 28
- Panel review in class on Tu. Nov 29

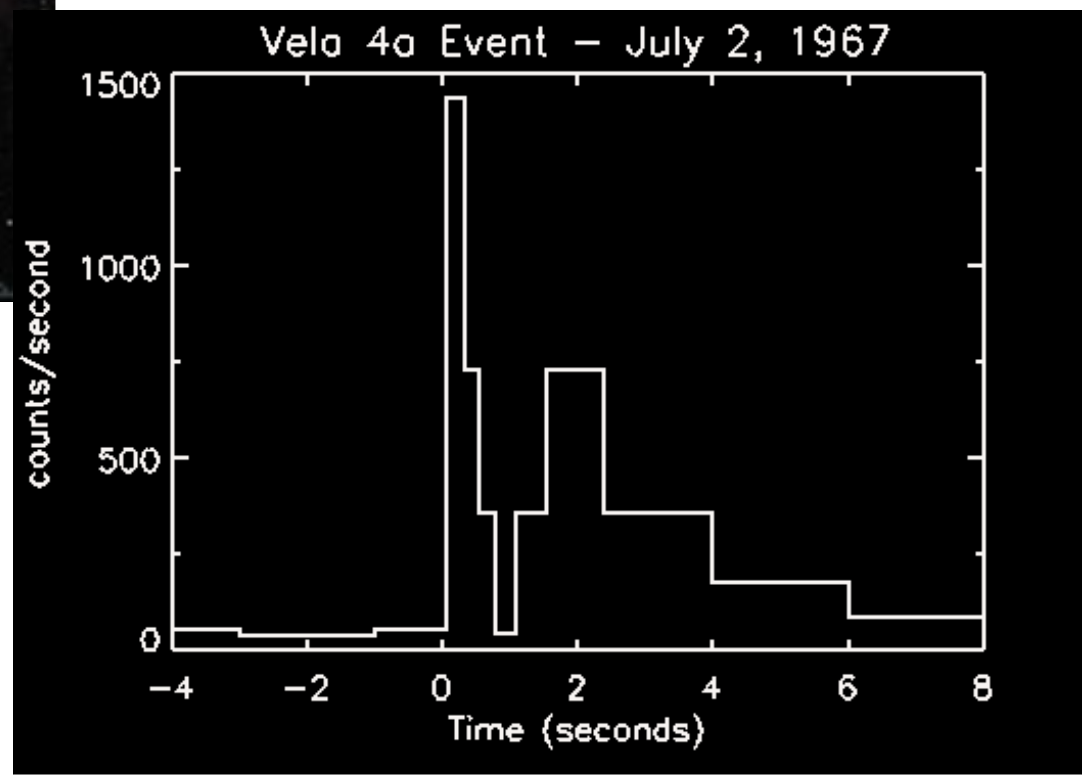
Cassiopeia A: Supernova Remnant



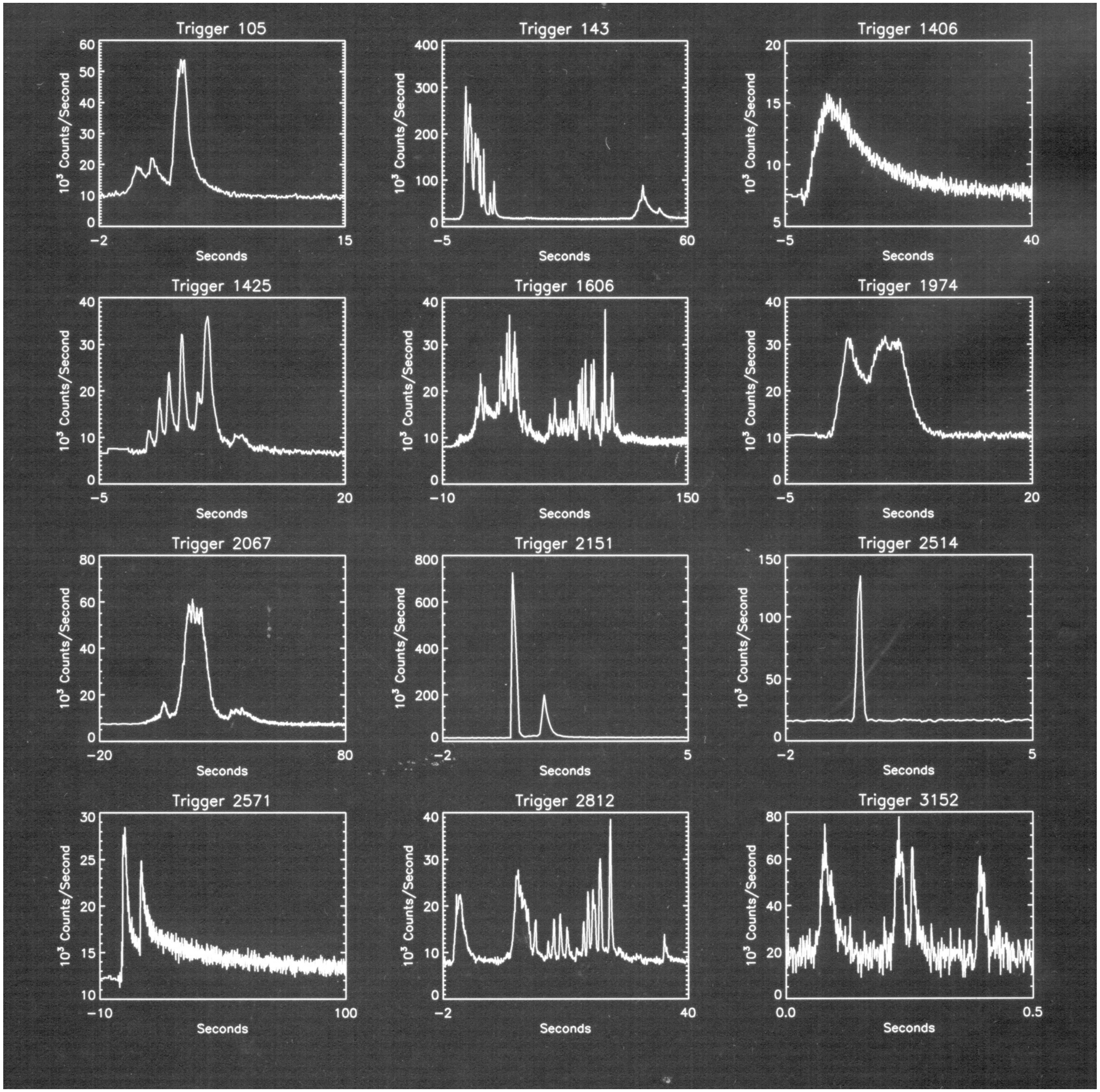
An early gamma ray-burst

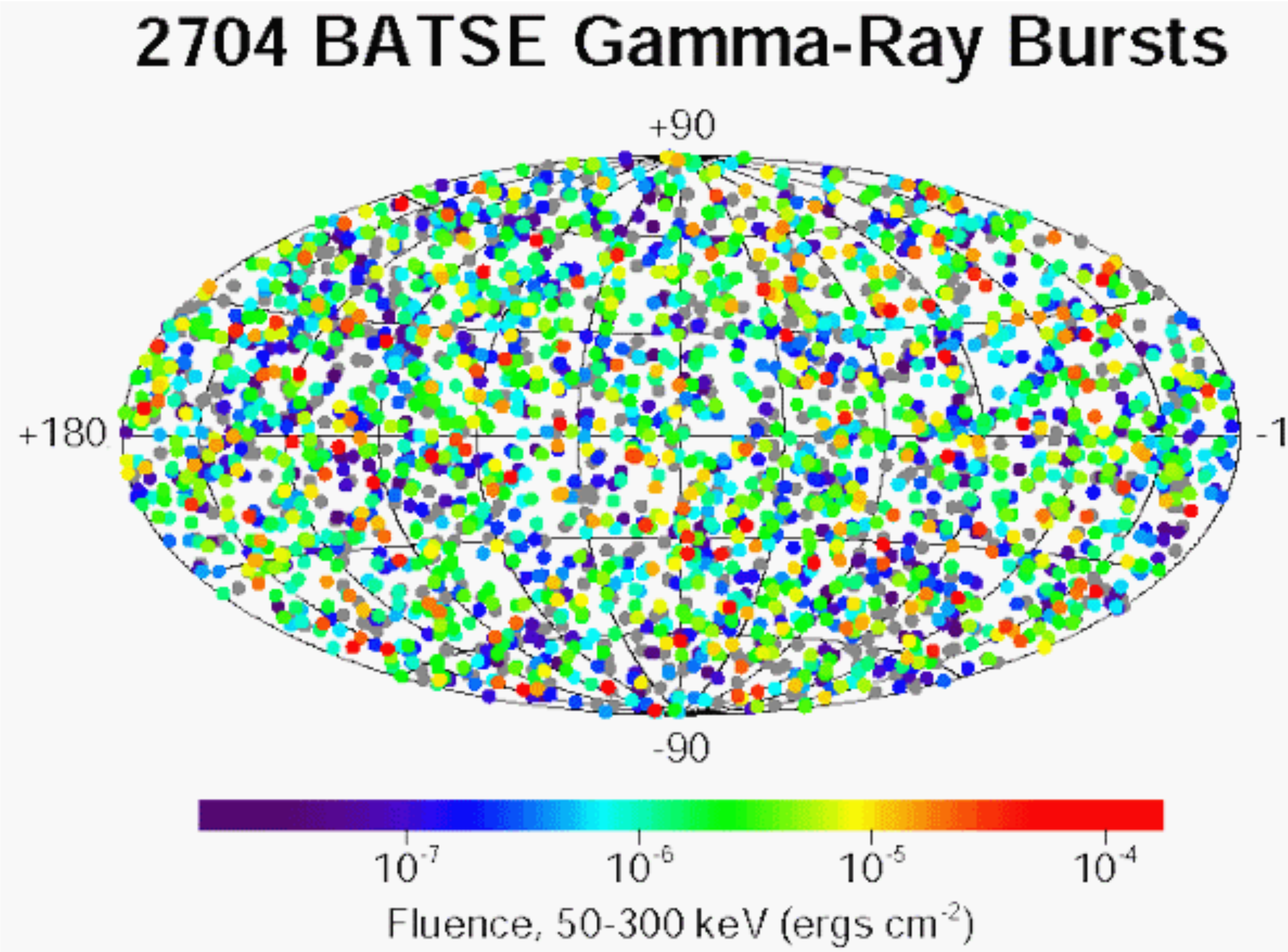


Vela satellite



A Gamma Ray Burst Sampler

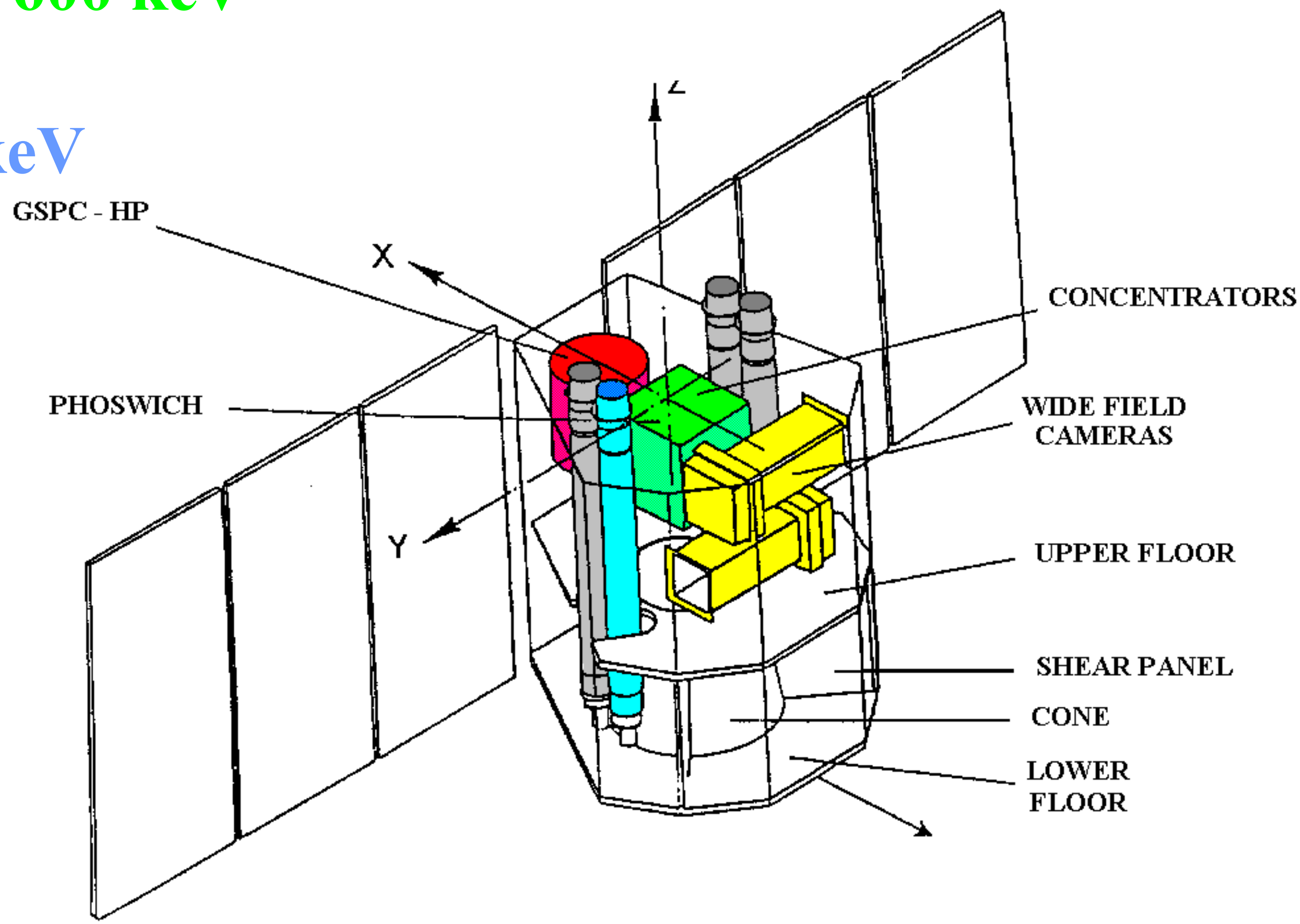



2704 BATSE Gamma-Ray Bursts
+90
+180
-18
-90
10-7
10-6
10-5
10-4
Fluence, 50-300 keV (ergs cm-2)

The BeppoSAX Satellite

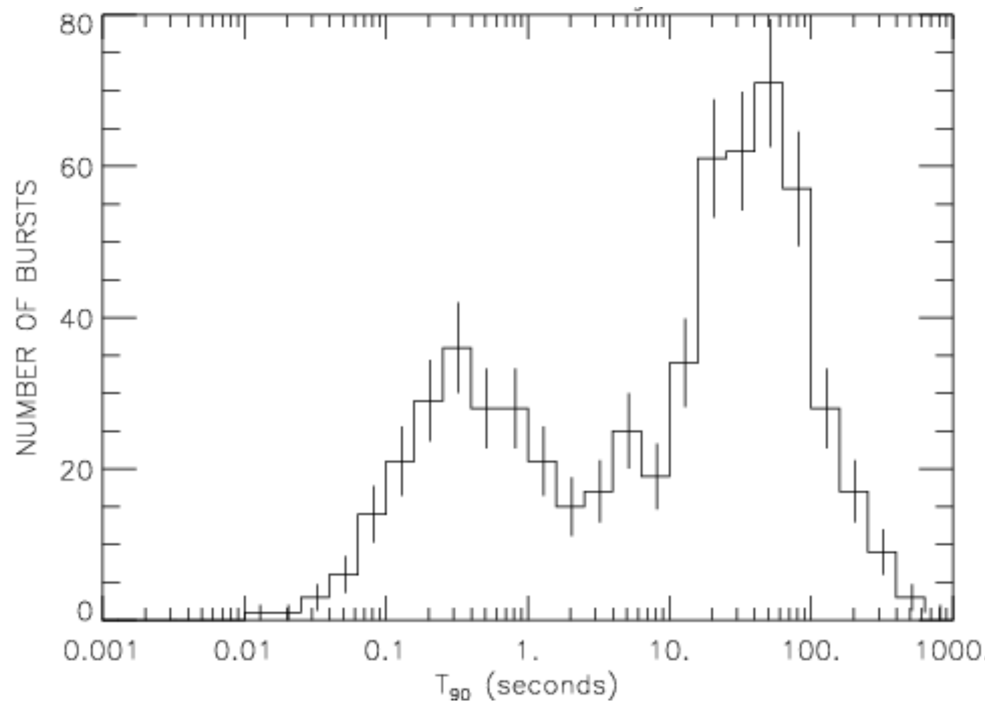
GRBM: 40-600 keV

NFI: 2-10 keV



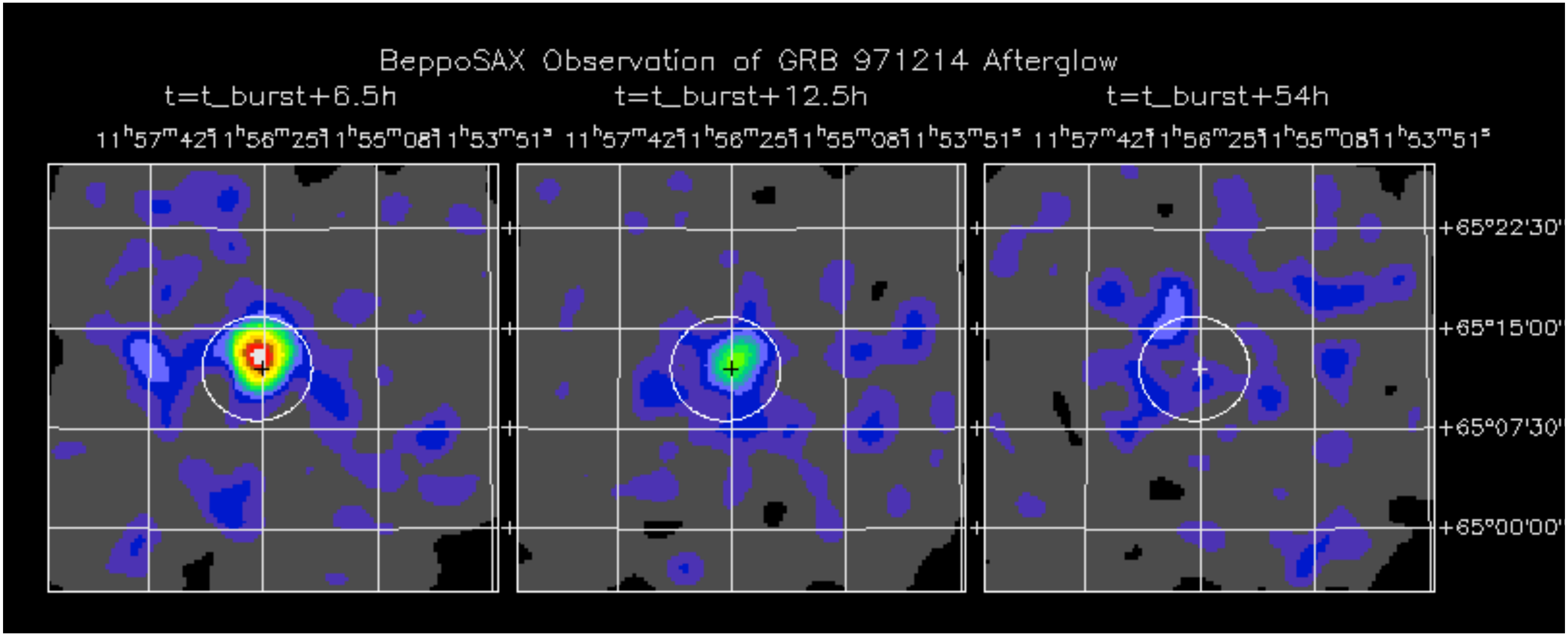
GRB classification

- Long bursts
  - > 2 sec, mean 30 sec
  - Afterglows commonly observed
- Short bursts
  - < 2 sec, mean 0.3 sec
  - Fewer afterglows observed



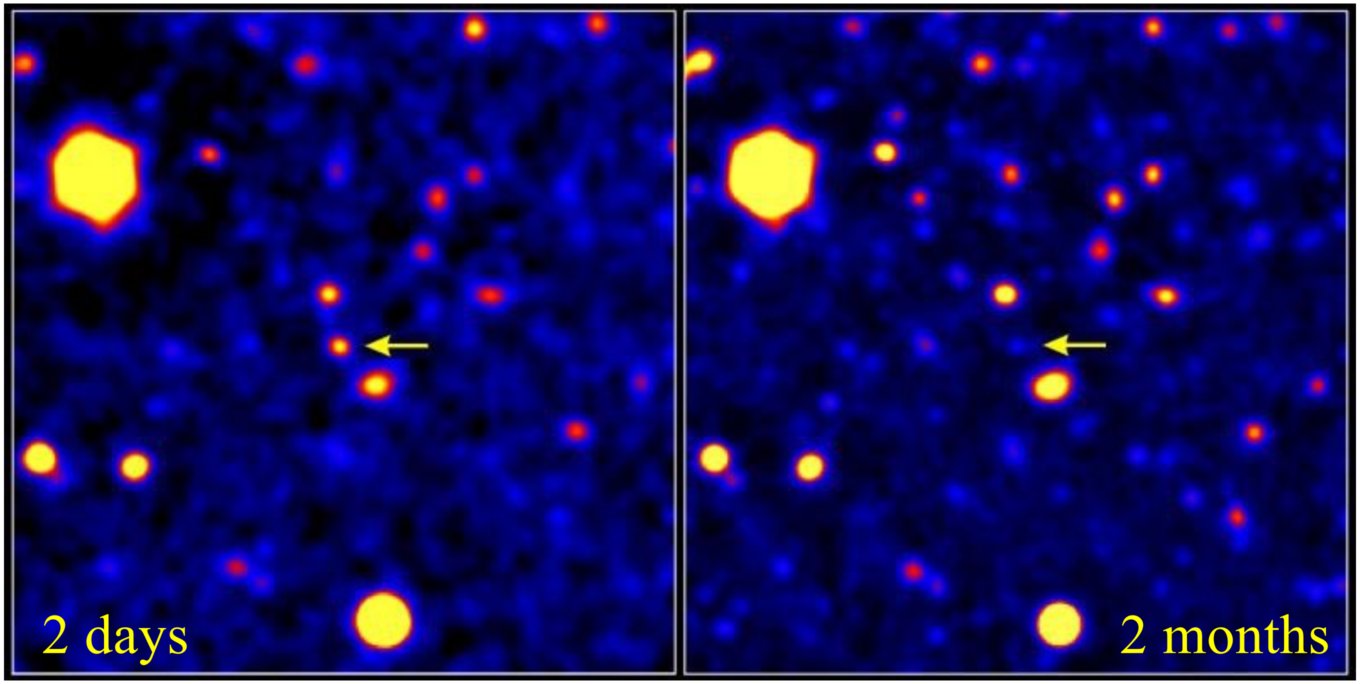
BATSE burst duration

X-Ray Afterglow from GRB 971214

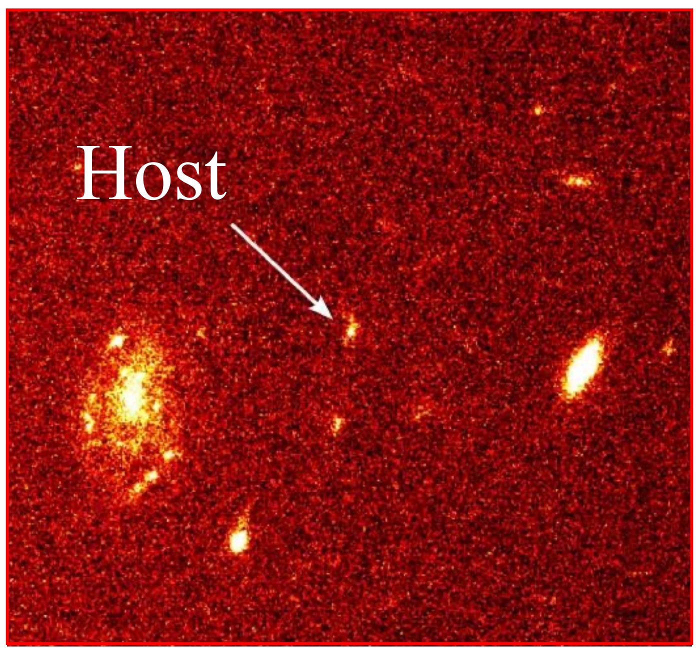


t=6.5 hrs t=12.5 hrs t=54 hrs

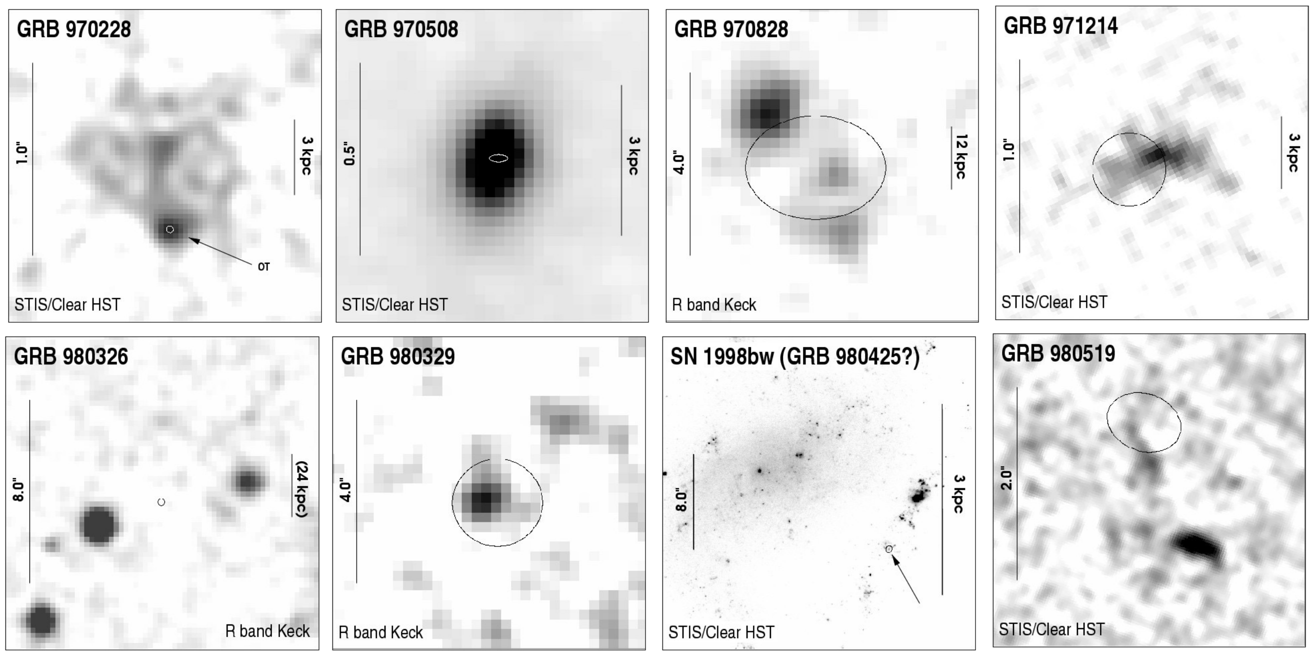
Optical Afterglow from GRB 971214



Keck Images

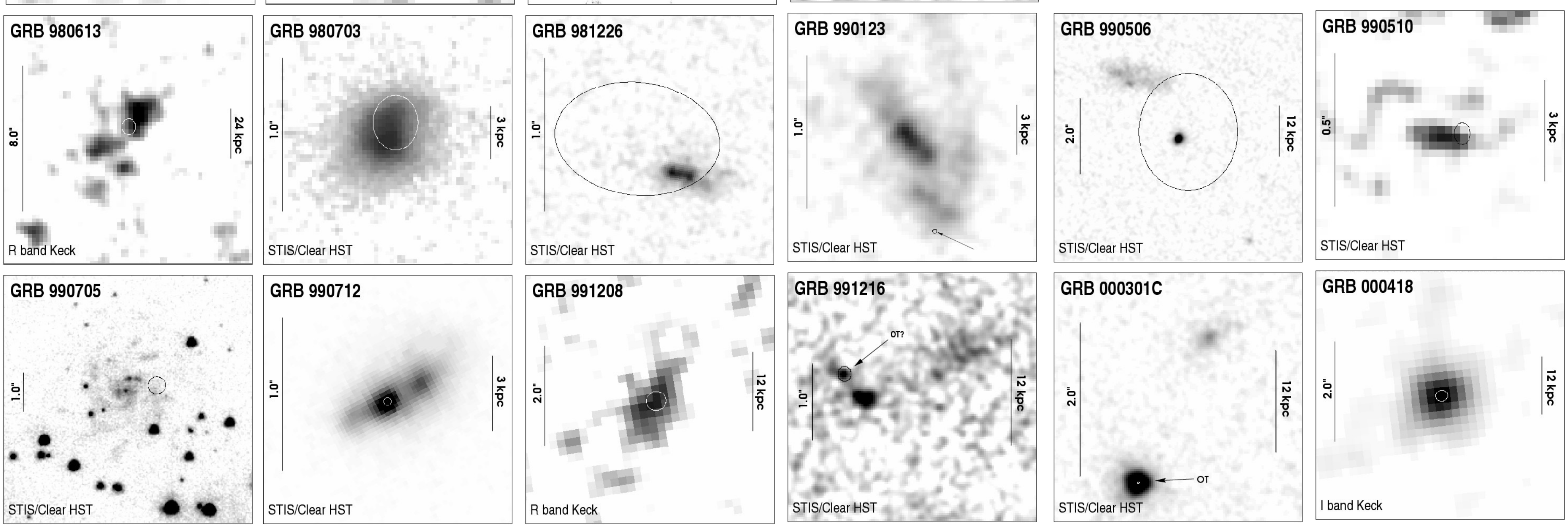


HST Image



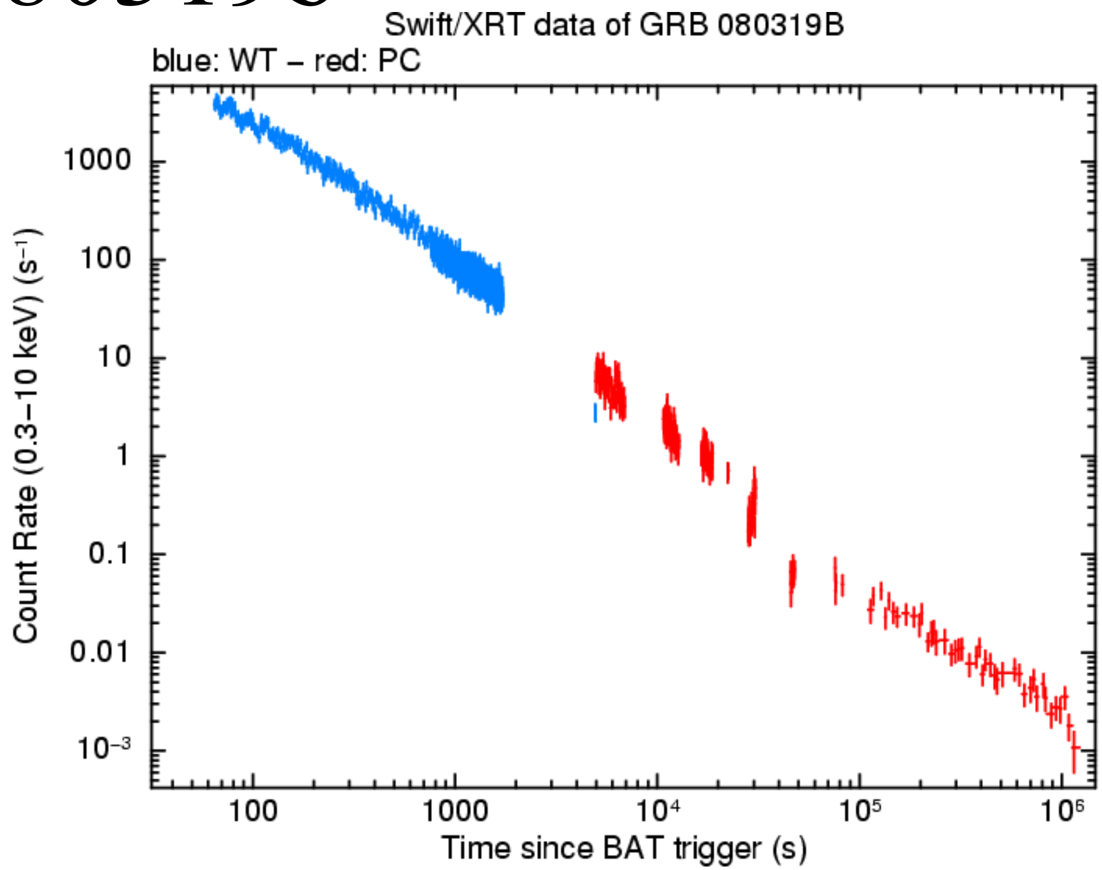
Implications of GRB host galaxies:

Location matching with SF regions would be consistent with collapsar model etc.



Optical Afterglow from GRB 080319b

Swift Image



Light Curve

Naked-eye visible for ~30 sec. Distance = 7.5 billion ly

E_{total} ~ 10^{47} J and highly beamed

Impact of discovery of afterglows:

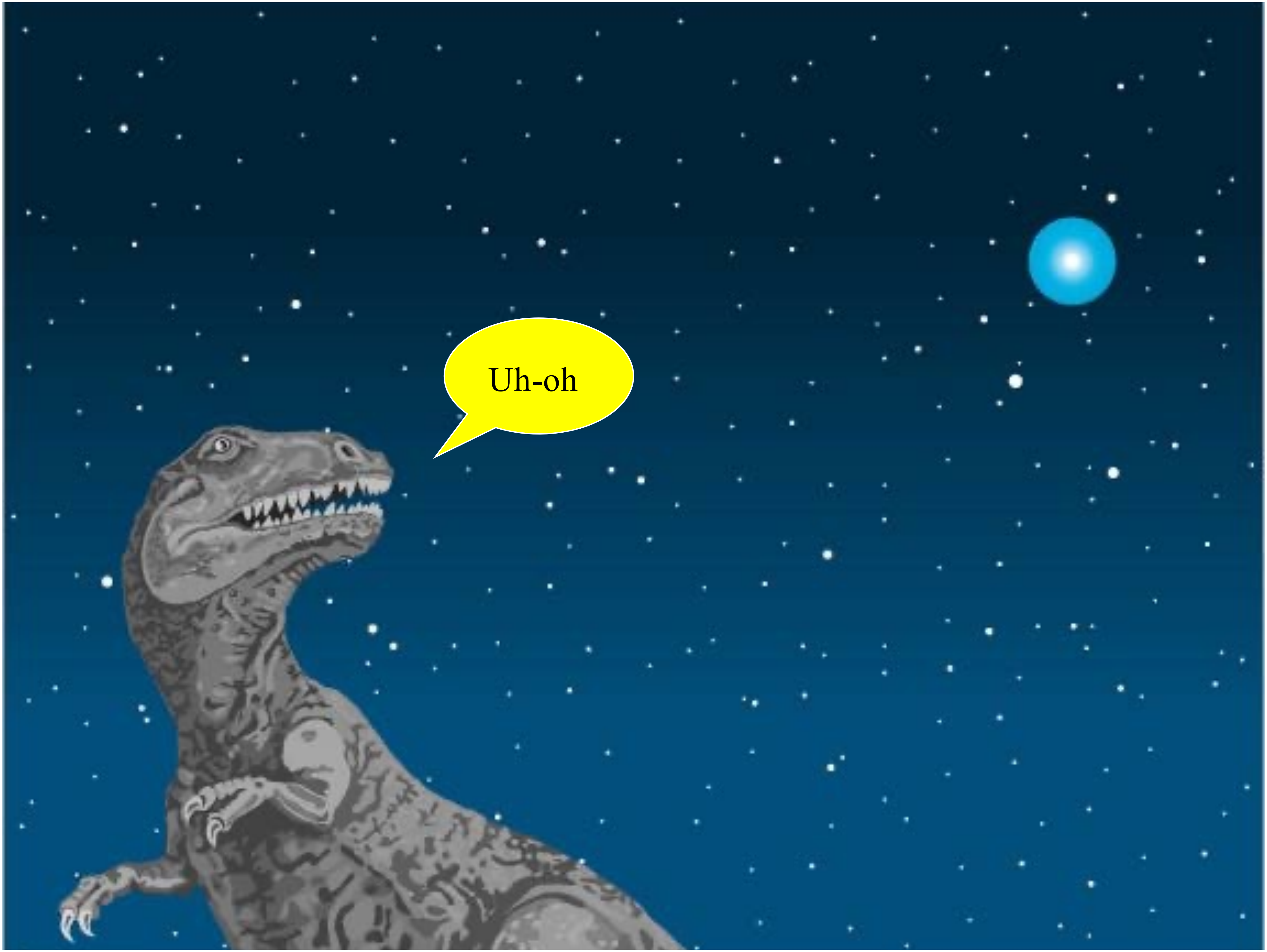
Afterglows have provided crucial info to test GRB models, especially since they have enabled measurement of redshifts

– Confirmation of cosmological distances

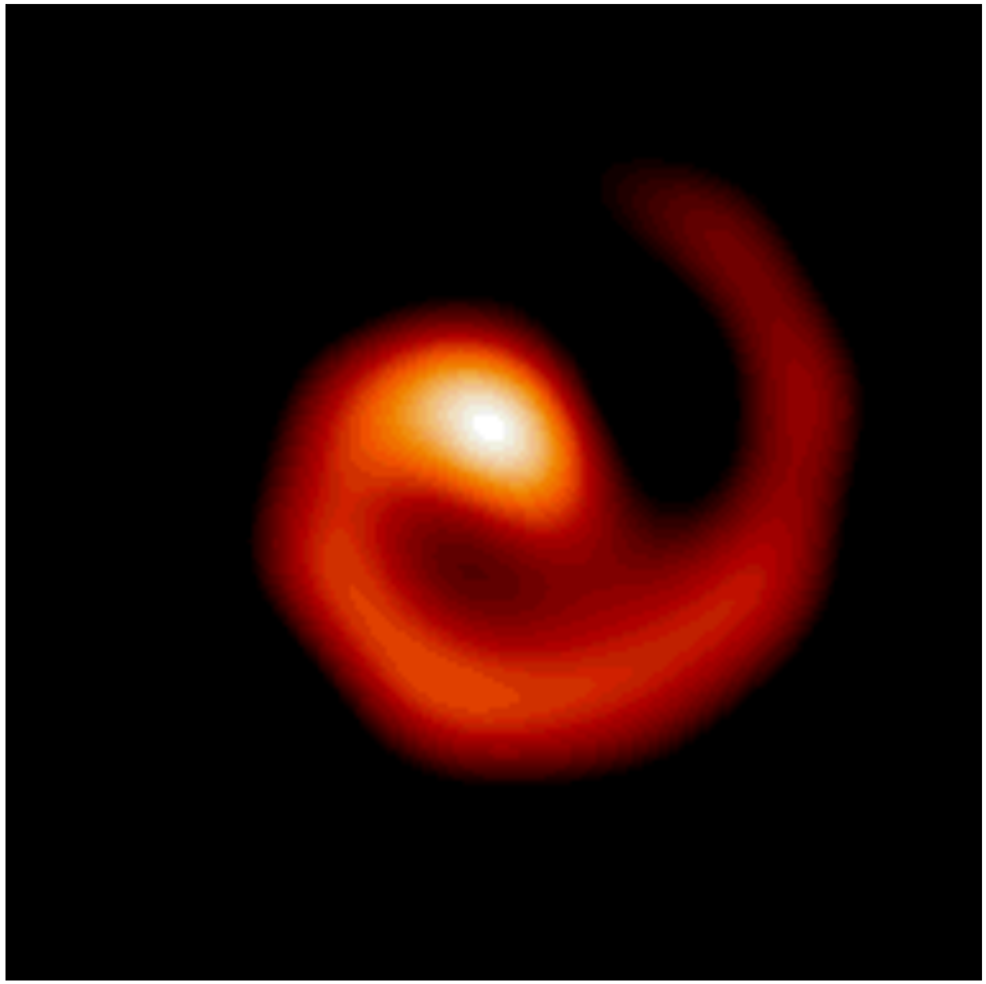
– Distance allowed accurate calculations of energy (causality arguments indicate sizes <100 km, time scales ~ seconds)

– Fireball shock model suggested (relativistic expanding debris shells)

Collimation is needed to explain the energy output: the largest ones exceed that available from stellar collapse if the radiation is isotropic.

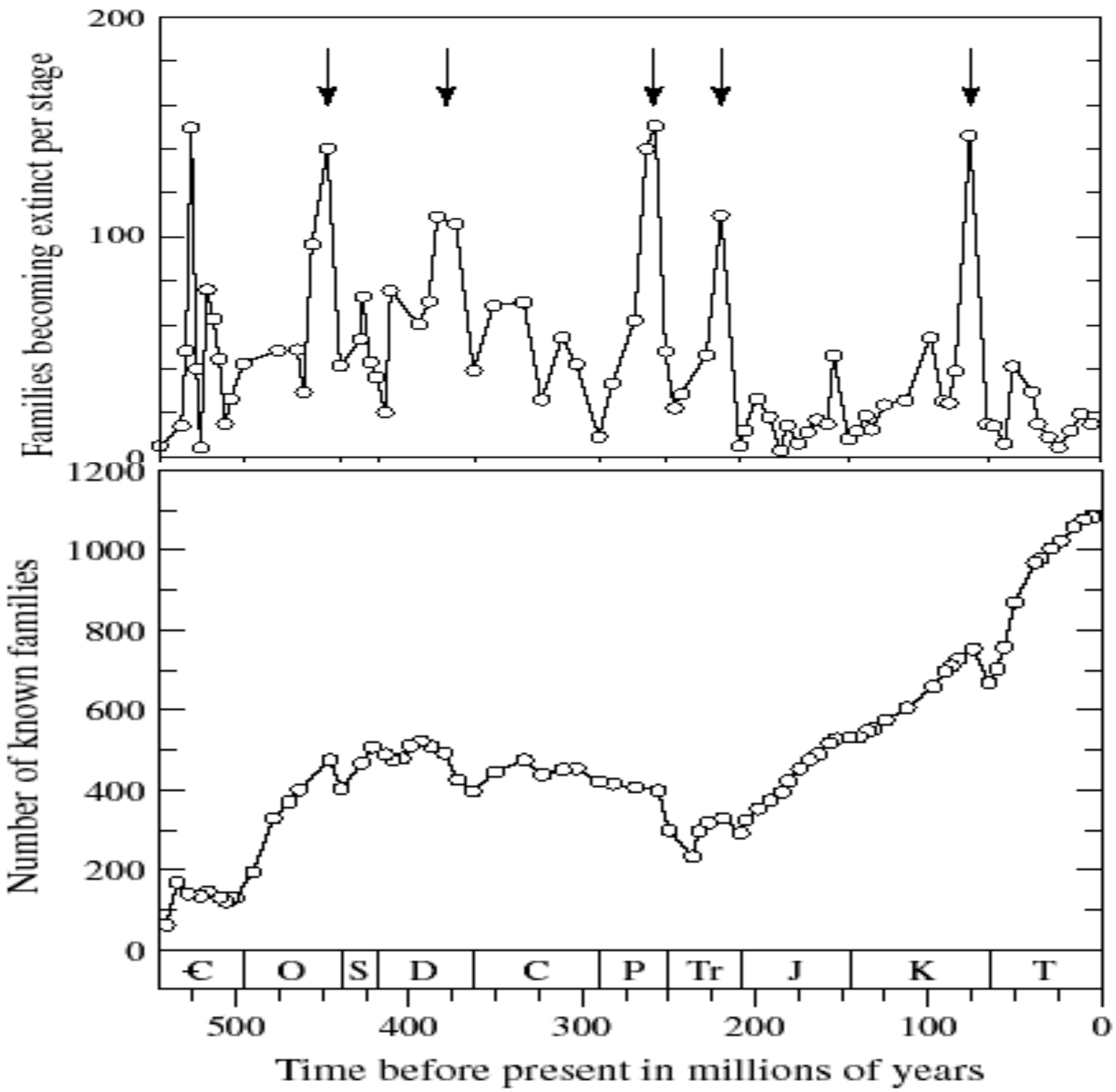

Uh-oh

WR104 - Looking Down the Barrel of a GRB system 8000 lt-years from us



Tuthill et al.

The Fossil Record is Marked by Mass Extinction Events

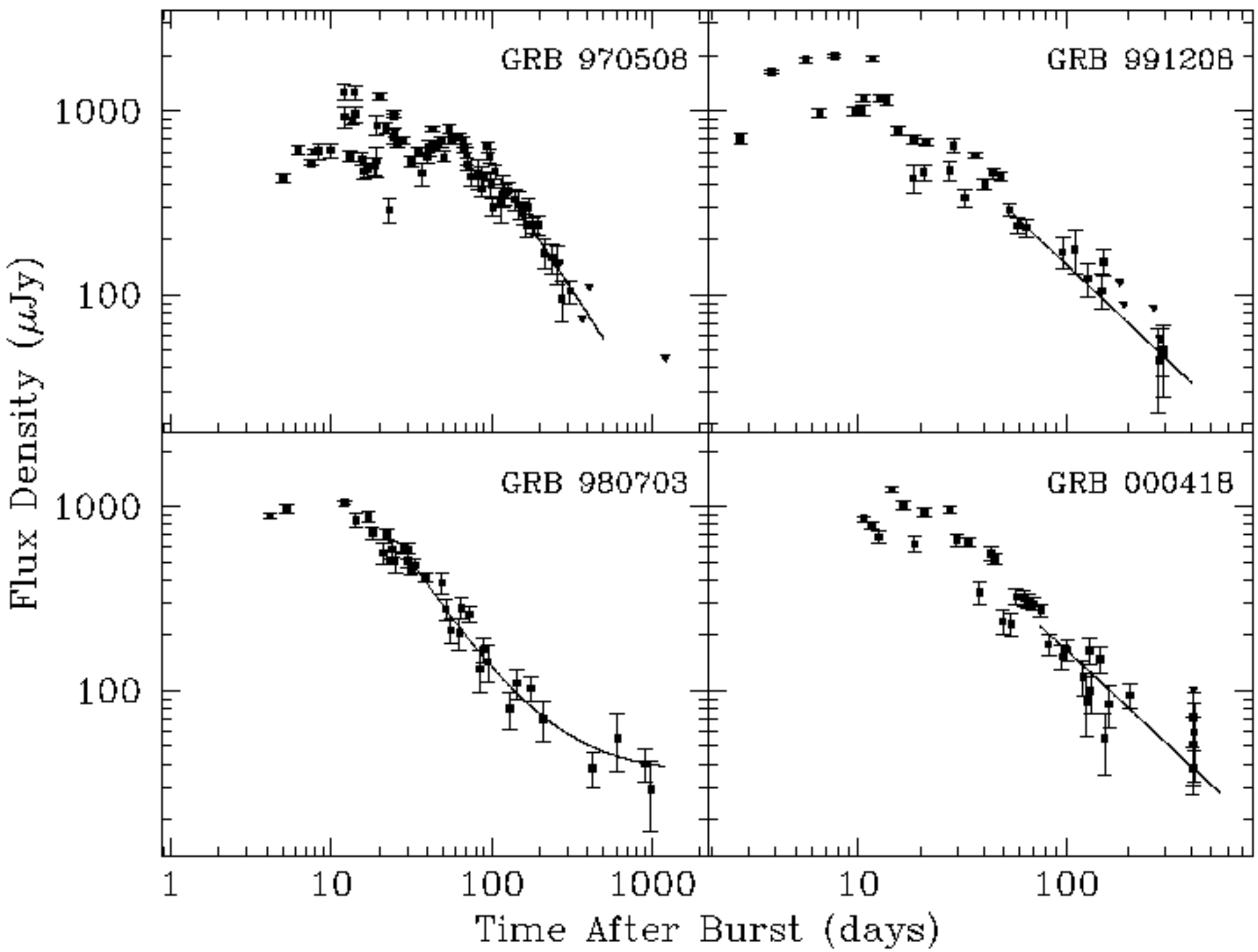


Extinction	Genus loss
End Ordovician	60%
End Devonian	57%
End Permian	82%
End Triassic	53%
End Cretaceous	47%

From Solé & Newman 2002

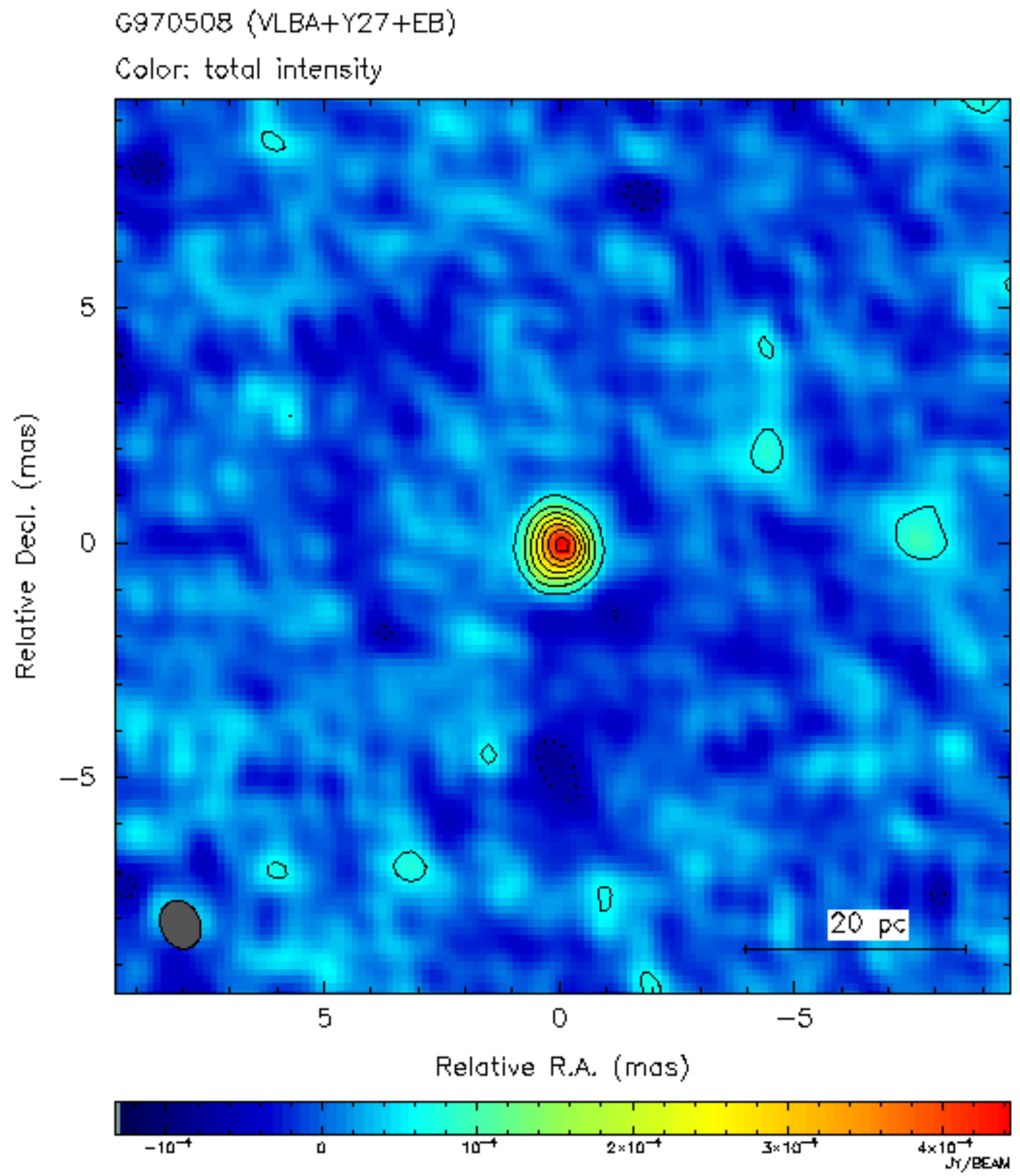
Radio Light Curves

Frail et al.



GRB 970508

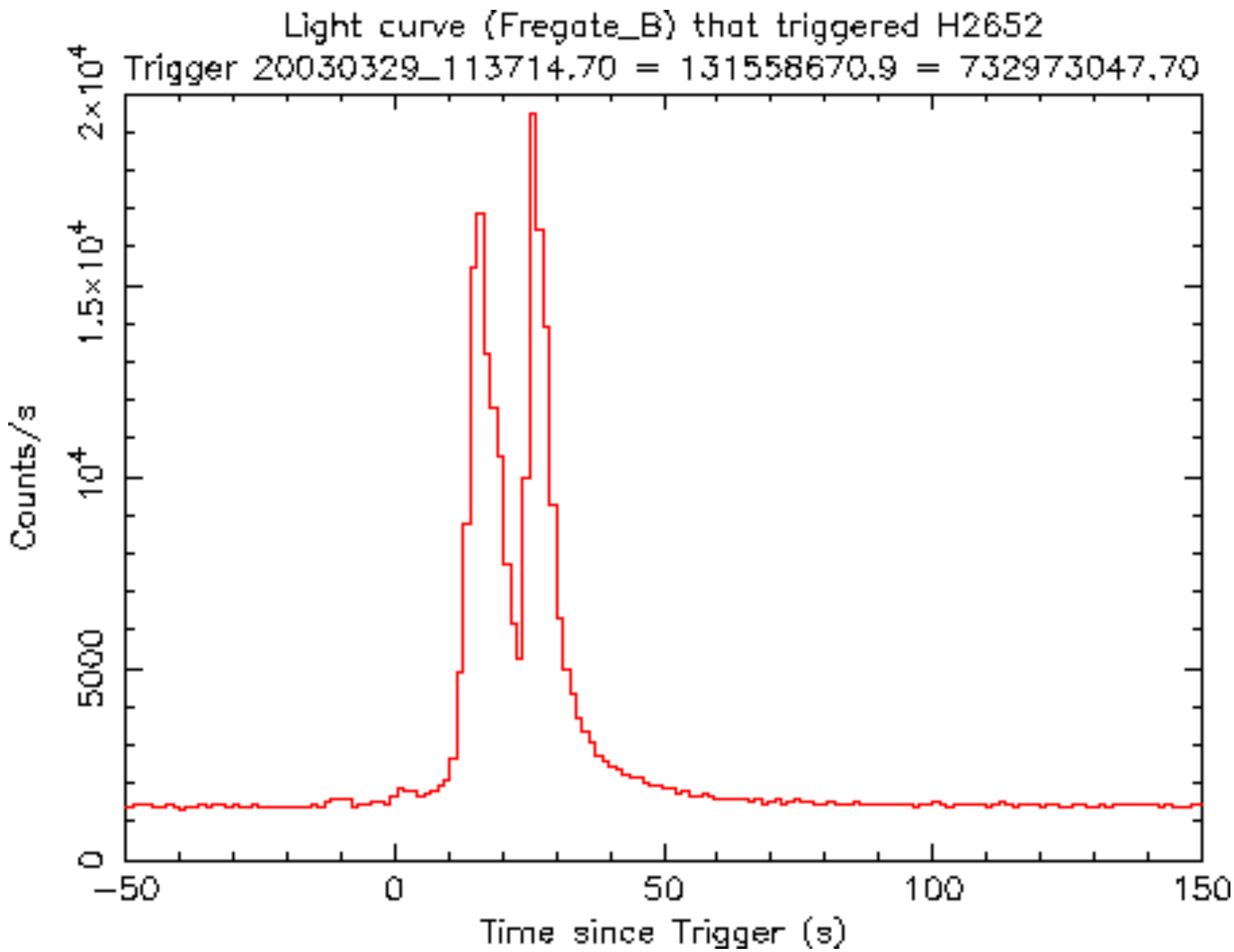
- First VLBI detection of a GRB Afterglow
- absolute position to < 1 mas
- Size < 10^19 cm (3 lt years)
- Distance > 10000 lt years (Redshift z = 0.835)



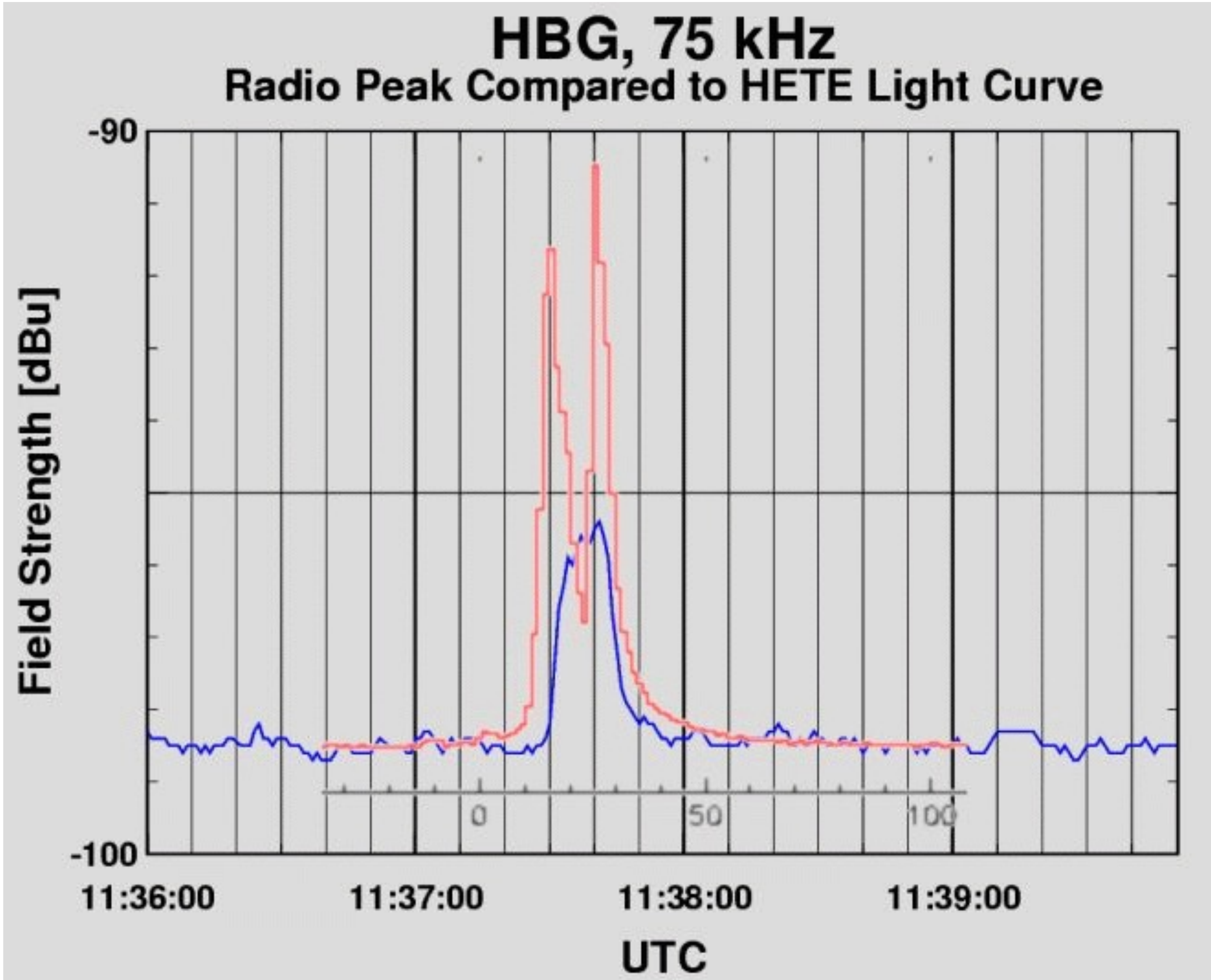
Taylor et al 1997

GRB 030329: The Burst of the Decade

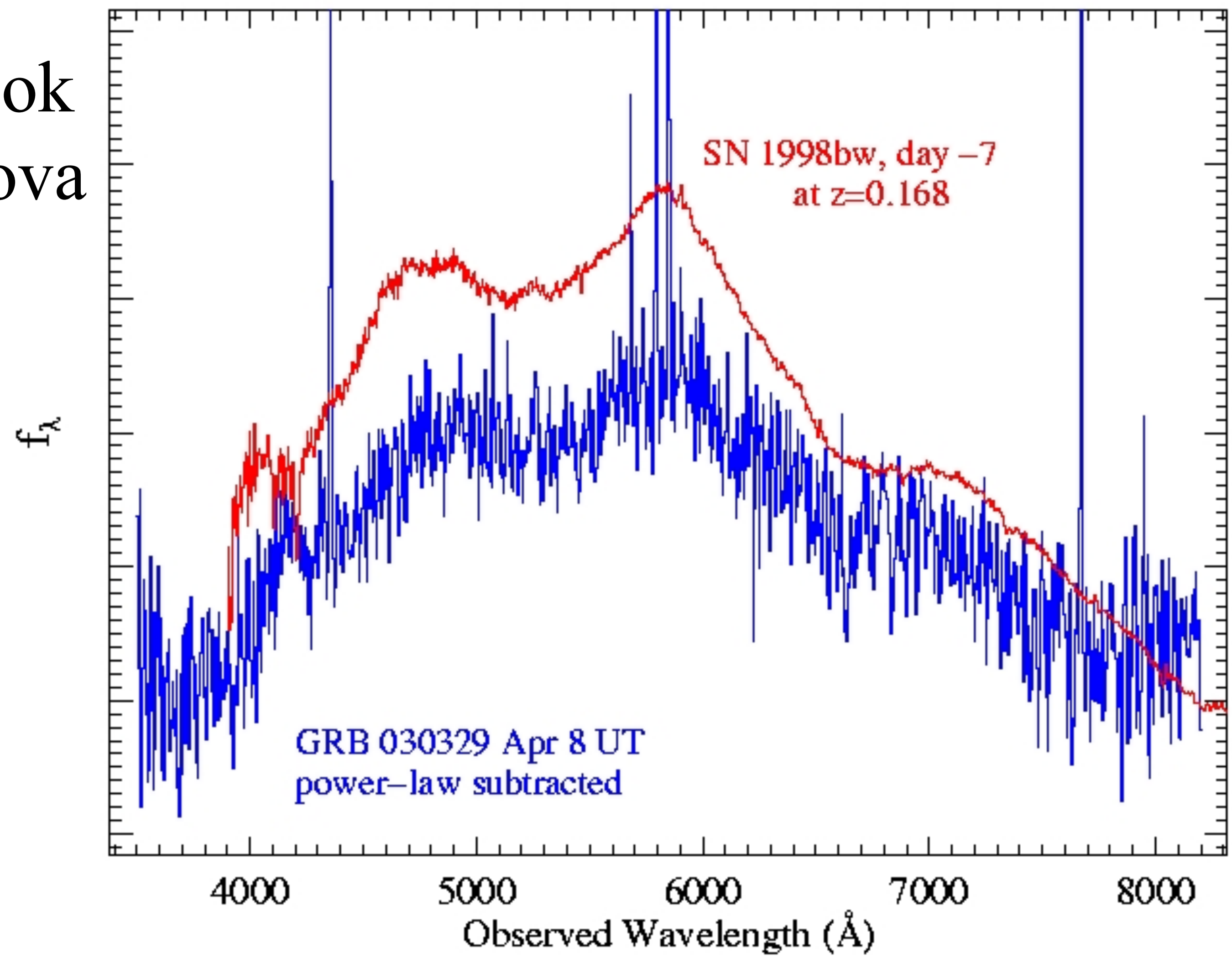
- World-wide armada of optical telescopes (~60) observed this burst 24/7
- A very bright burst (m_V=12.5). In radio it is 50 times brighter than any previous GRB!
- Better yet at z=0.168 it is <u>only</u> 740 Mpc away.
- Still visible in the radio 10 years later



Light curve (Fregate_B) that triggered H2652
Trigger 20030329_113714.70 = 131558670.9 = 732973047.70
Counts/s
0
5000
10⁴
1.5×10⁴
2×10⁴
−50
0
50
100
150
Time since Trigger (s)

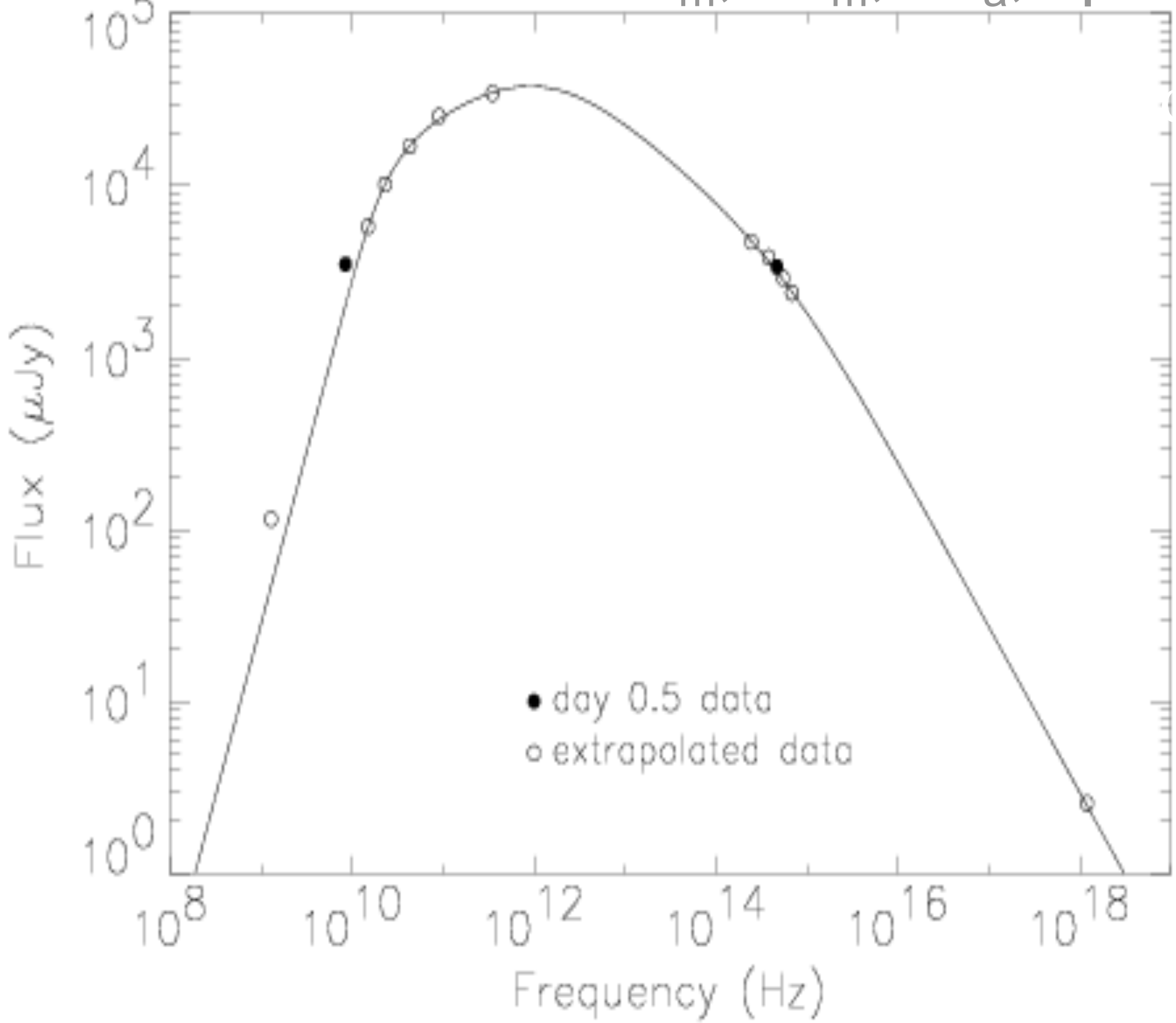

HBG, 75 kHz
Radio Peak Compared to HETE Light Curve
-90
-100
Field Strength [dBu]
0
50
100
11:36:00
11:37:00
11:38:00
11:39:00
UTC

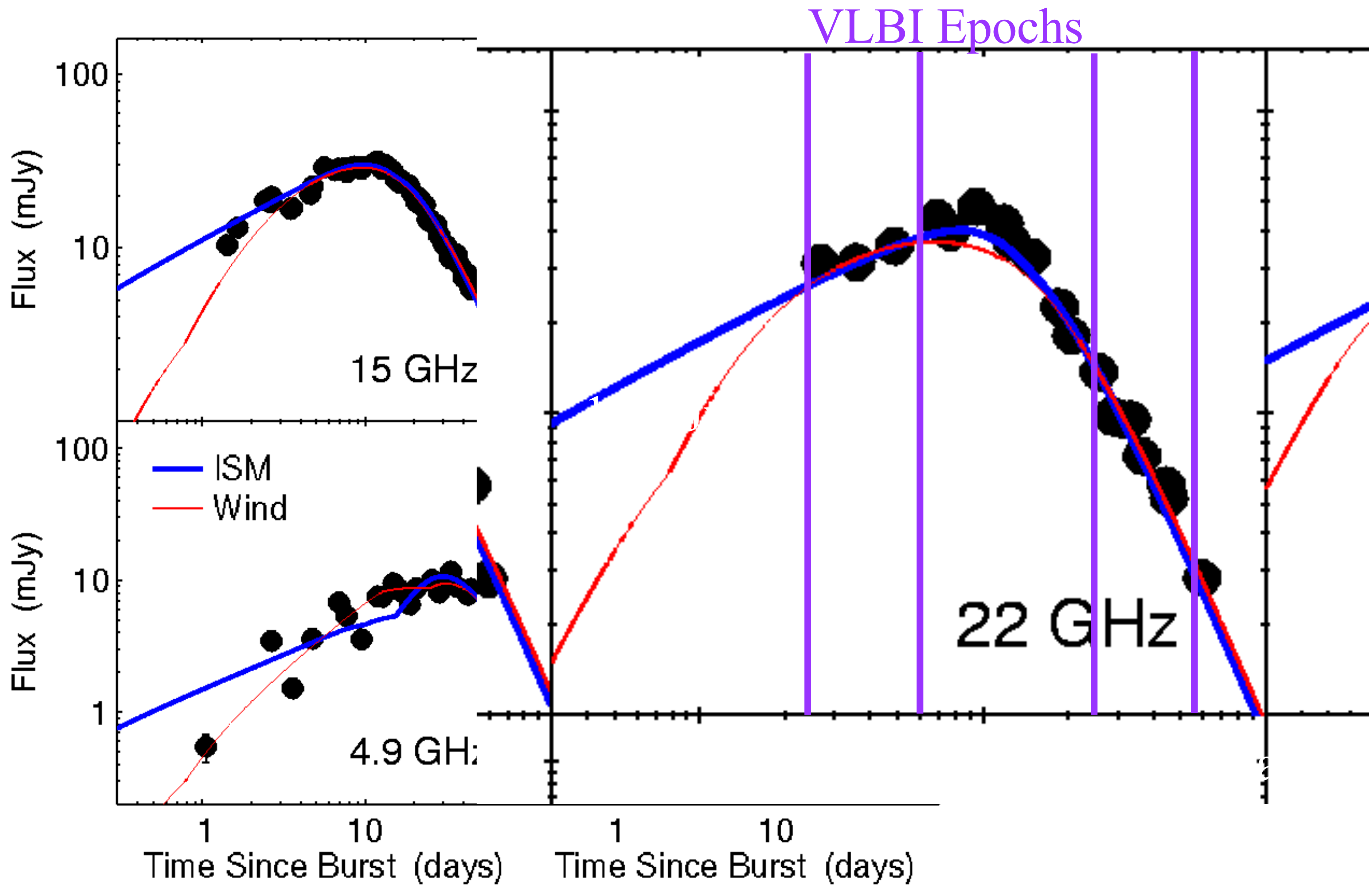
Starting to Look like a Supernova



GRB 030329 Synchrotron Spectrum

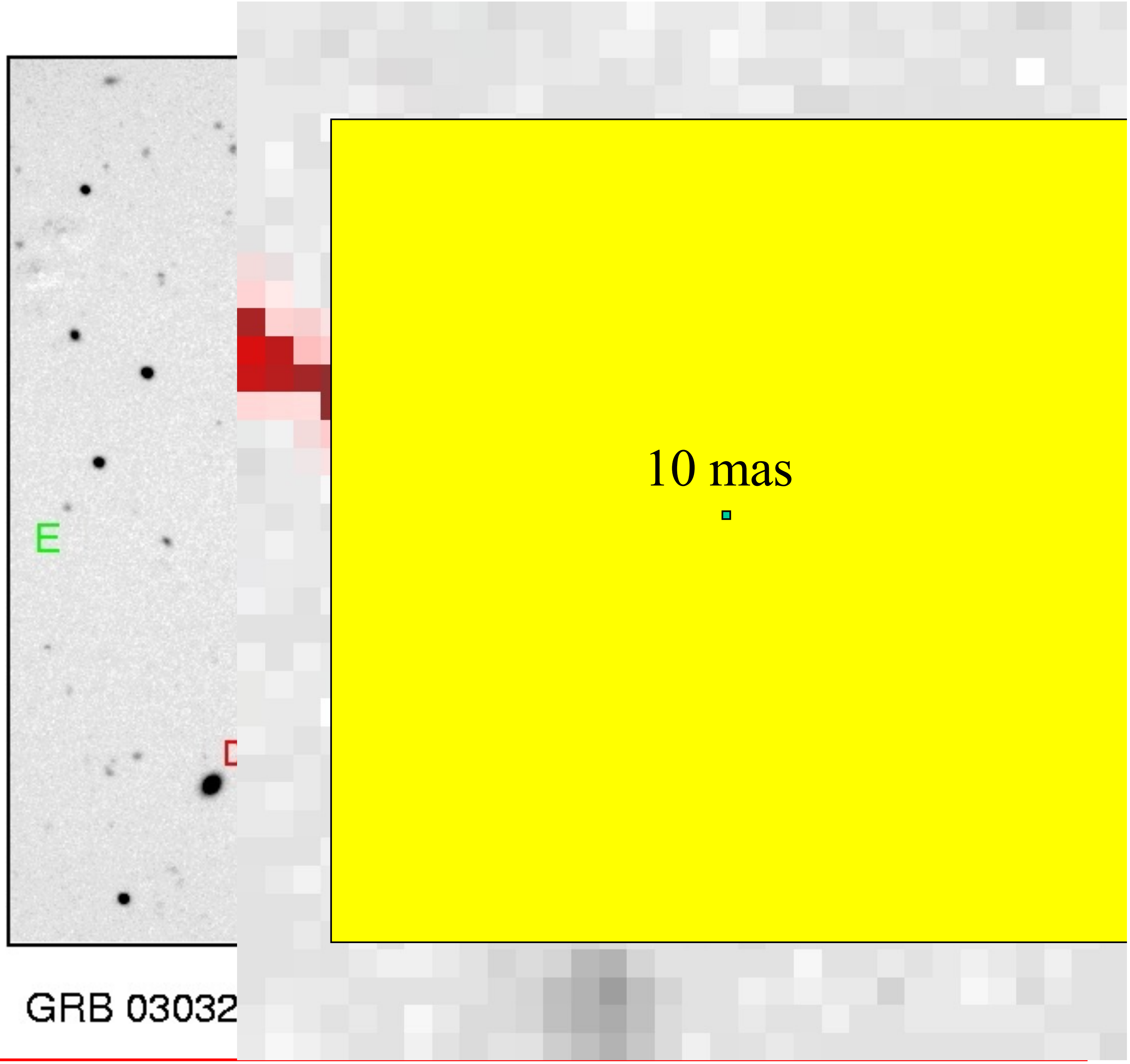
Basic Parameters: f_m, nu_m, nu_a, spectral index (p)



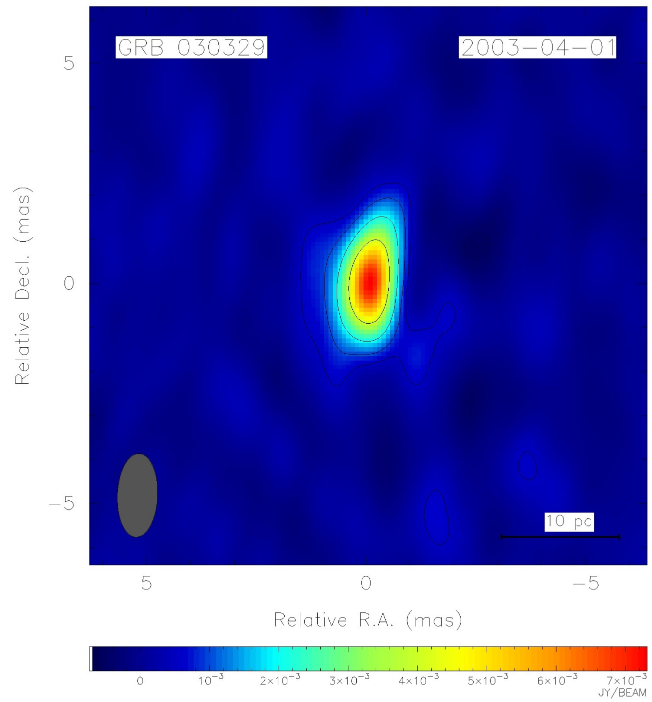


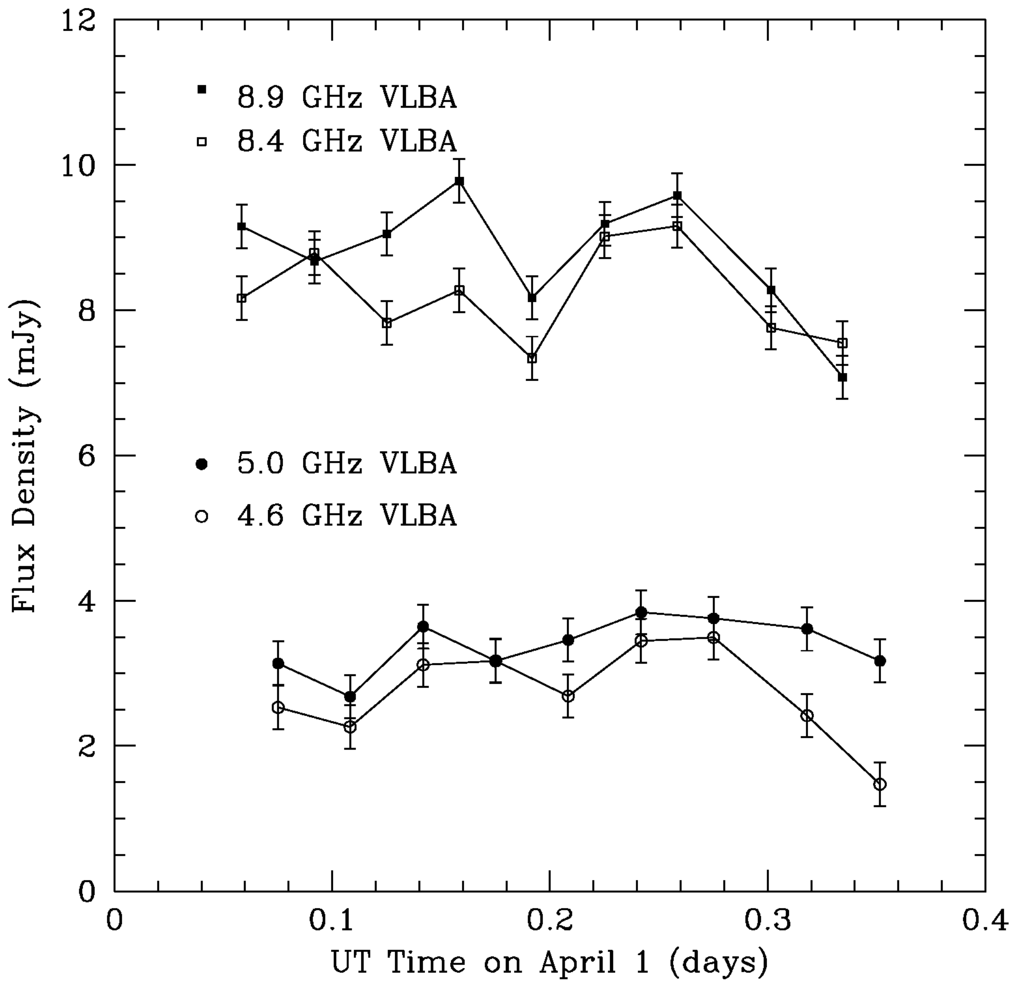
VLBI Epochs
Flux (mJy)
100
10
15 GHz
ISM
Wind
1
4.9 GHz
22 GHz
Time Since Burst (days)
Time Since Burst (days)

The Optical Transient (OT)



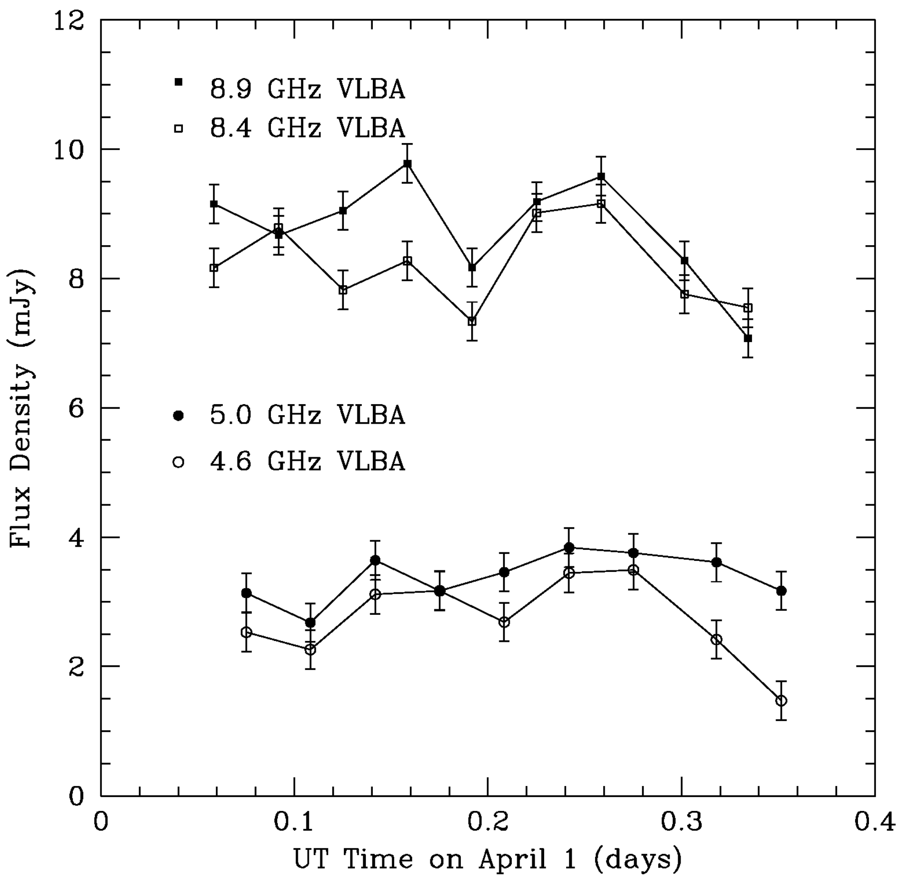
VLBA on April 1 (t+2.7 days)





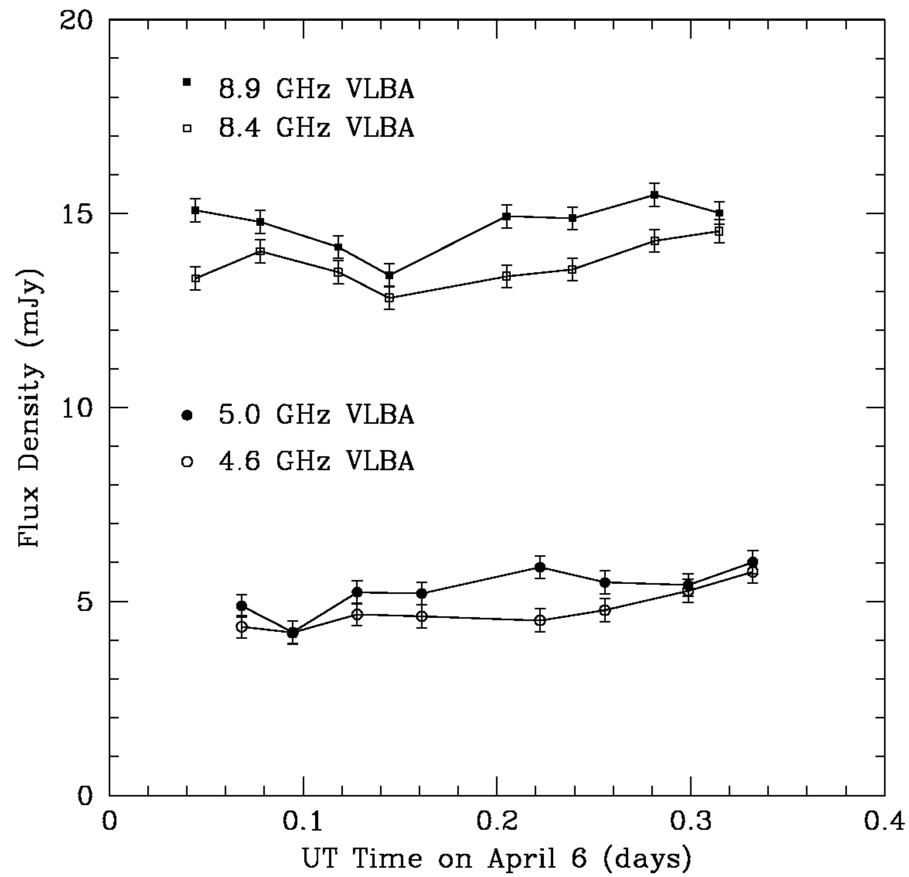
A Scintillating Result

April 1



Modest Scintillation

April 6



Scintillation quenching
size ~ 20 microarcsec

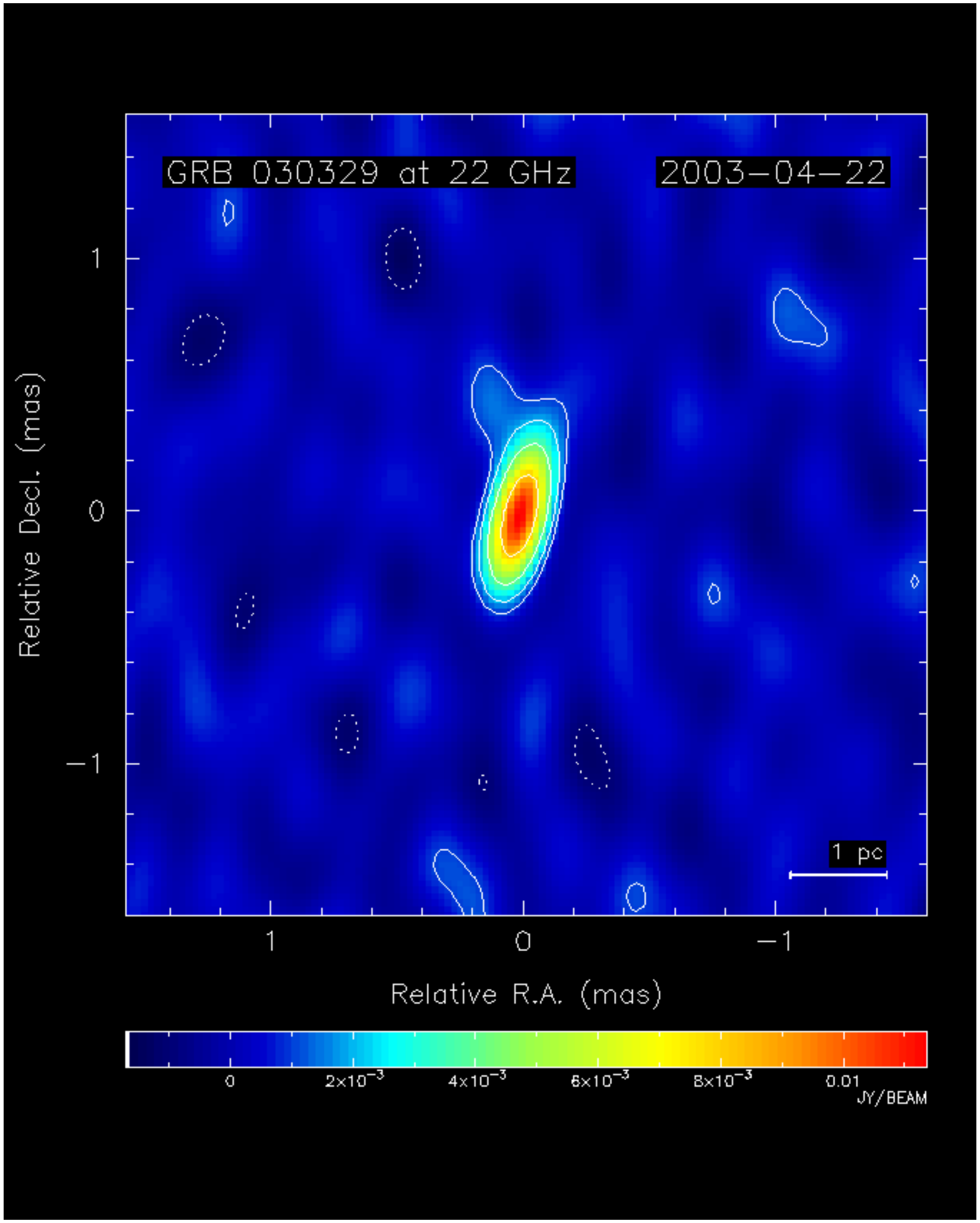
Resolving the Afterglow

3rd Epoch – April 22
VLBA + EB

Beam is 0.45 x 0.15 mas (22 GHz)

Estimated size is
22 GHz : 0.077 +/- 0.036 mas
15 GHz : 0.065 +/- 0.022 mas
(10**18 cm)
(0.2 pc)

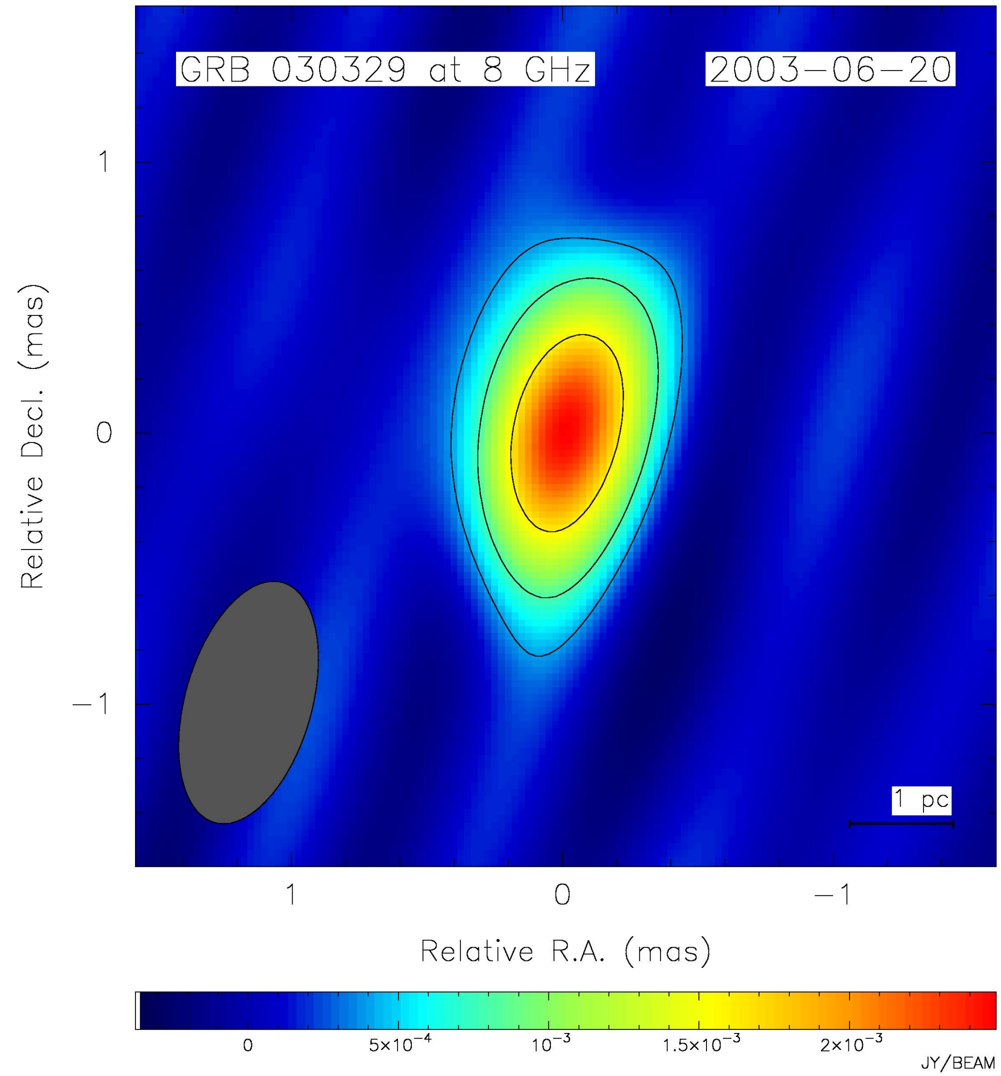
average expansion velocity of 5c



June 20, 2003

+83 days

Peak ~ 3 mJy
Size 0.172 +/- 0.043 mas
0.5 +/- 0.1 pc
average velocity = 3c

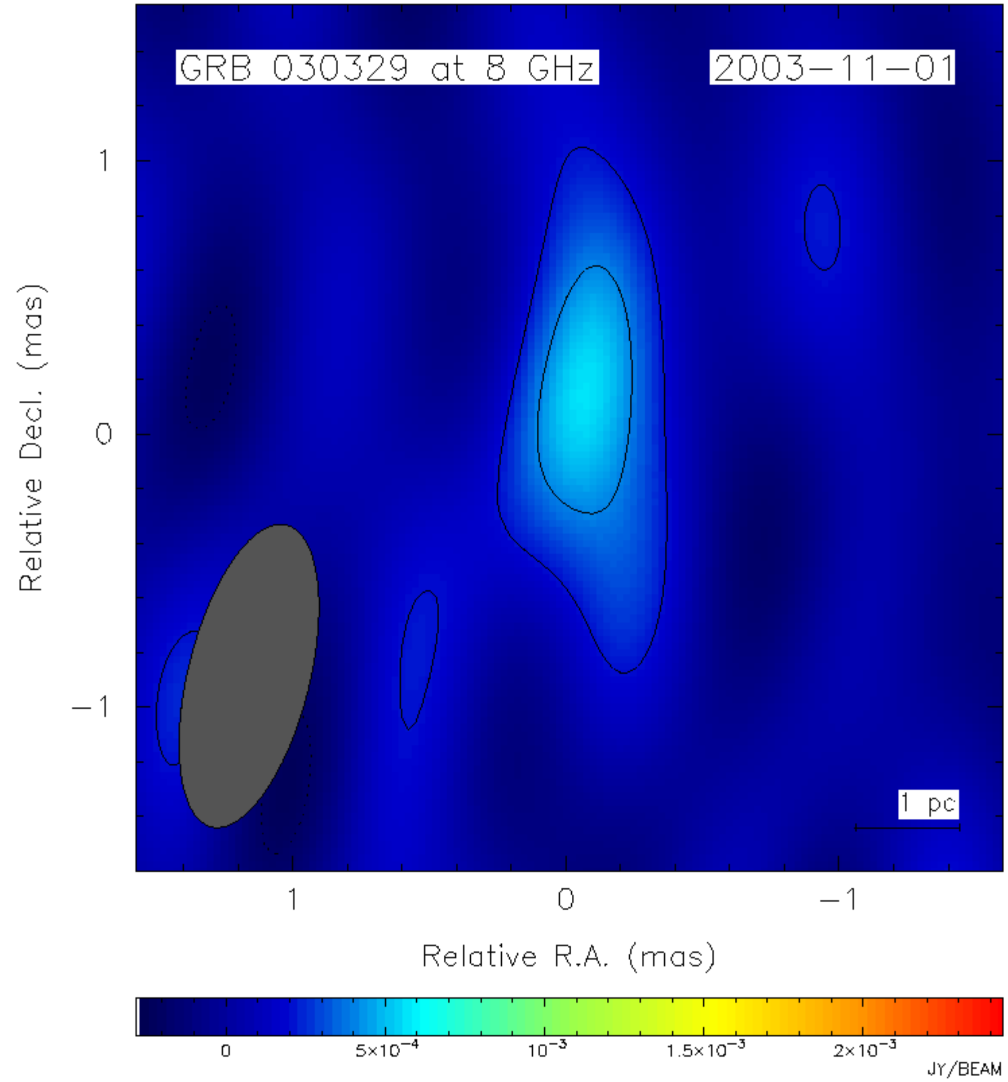


VLBA+Y27+GBT+EB+AR+WB = 0.11 km^2

Nov 1, 2003

+217 days

Peak ~ 0.5 mJy
Size 0.176 +/- 0.08 mas
0.5 +/- 0.2 pc
average velocity = 1.6c



VLBA+Y27+GBT+EB+AR+WB+NT+MC = 0.12 km^2

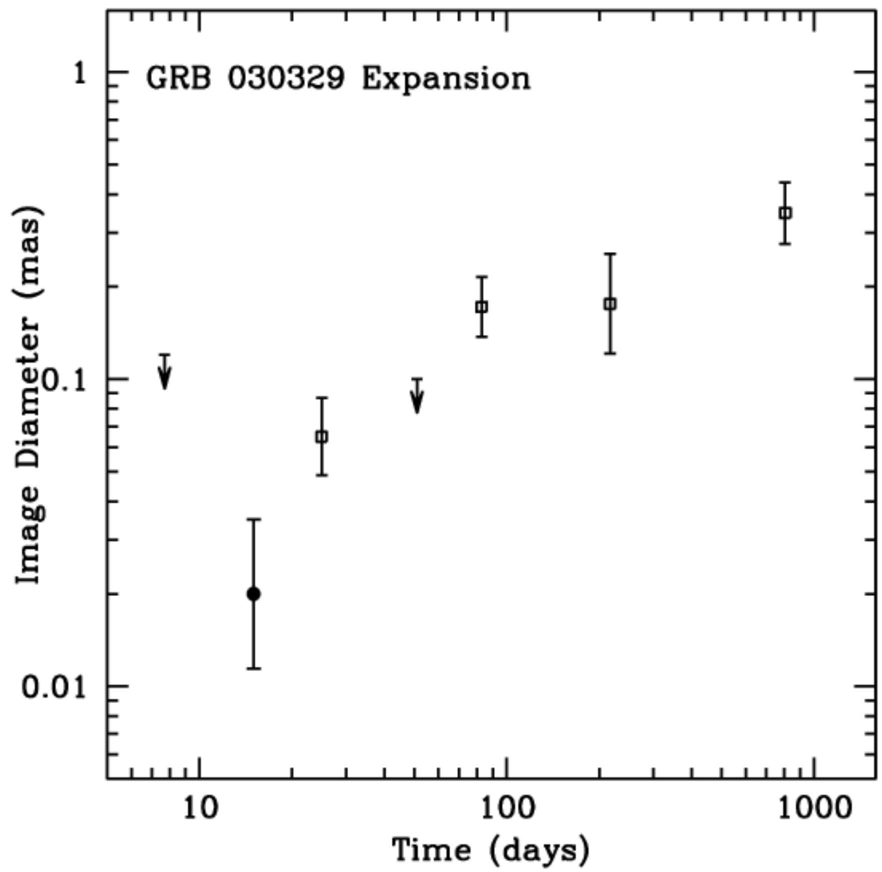
Expansion of GRB030329

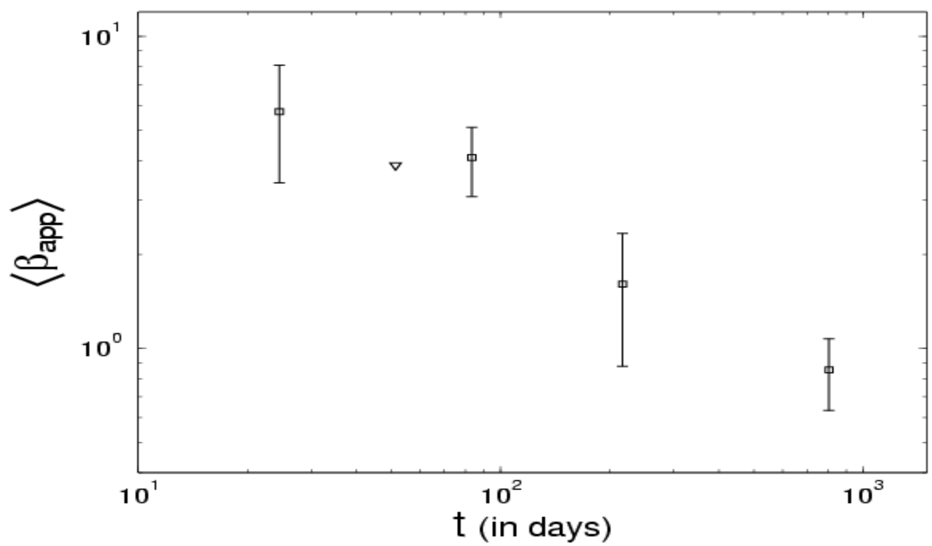
Relativistic
Expansion v ~ 0.96c

E ~ 10^53 ergs
(isotropic equivalent)

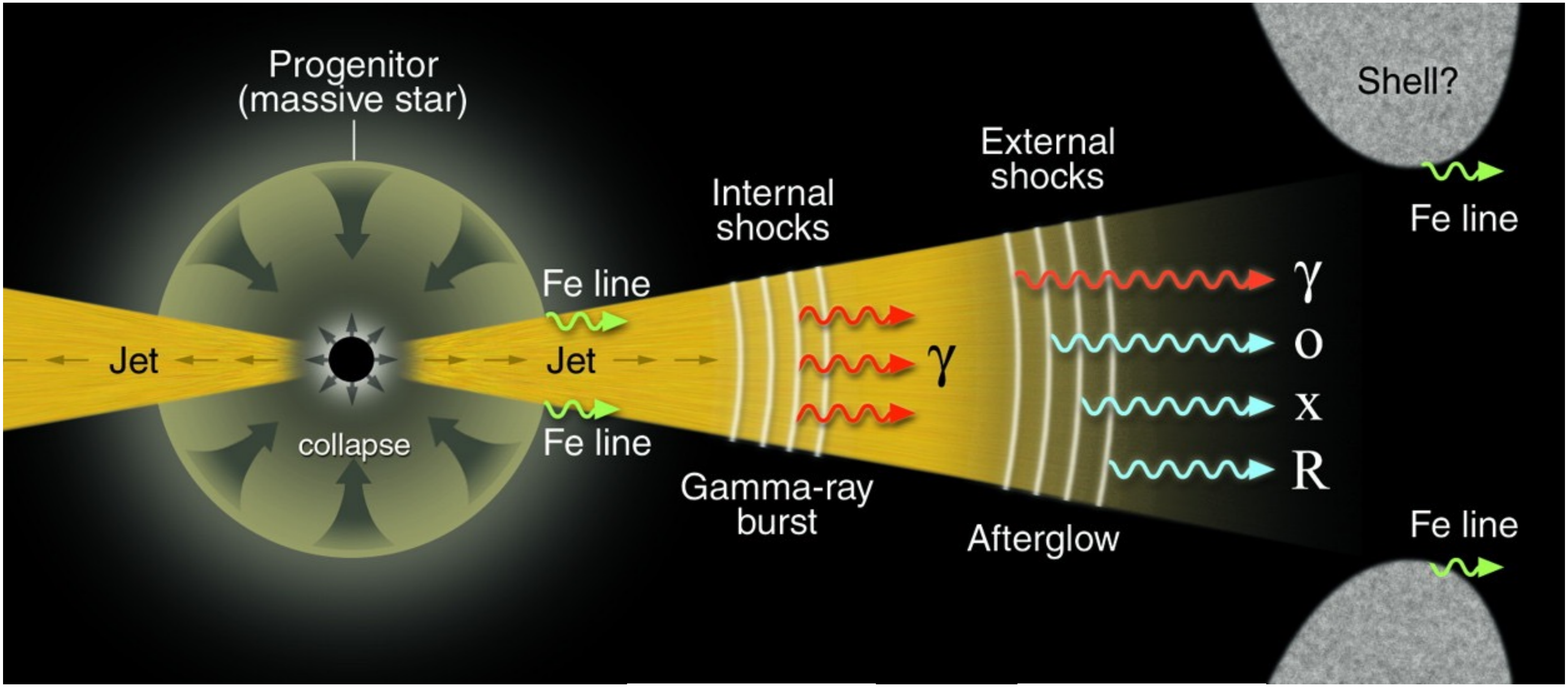
R ~ (E/n)^1/8

Taylor et al 2004
Pihlstrom et al 2007
Mesler et al 2013





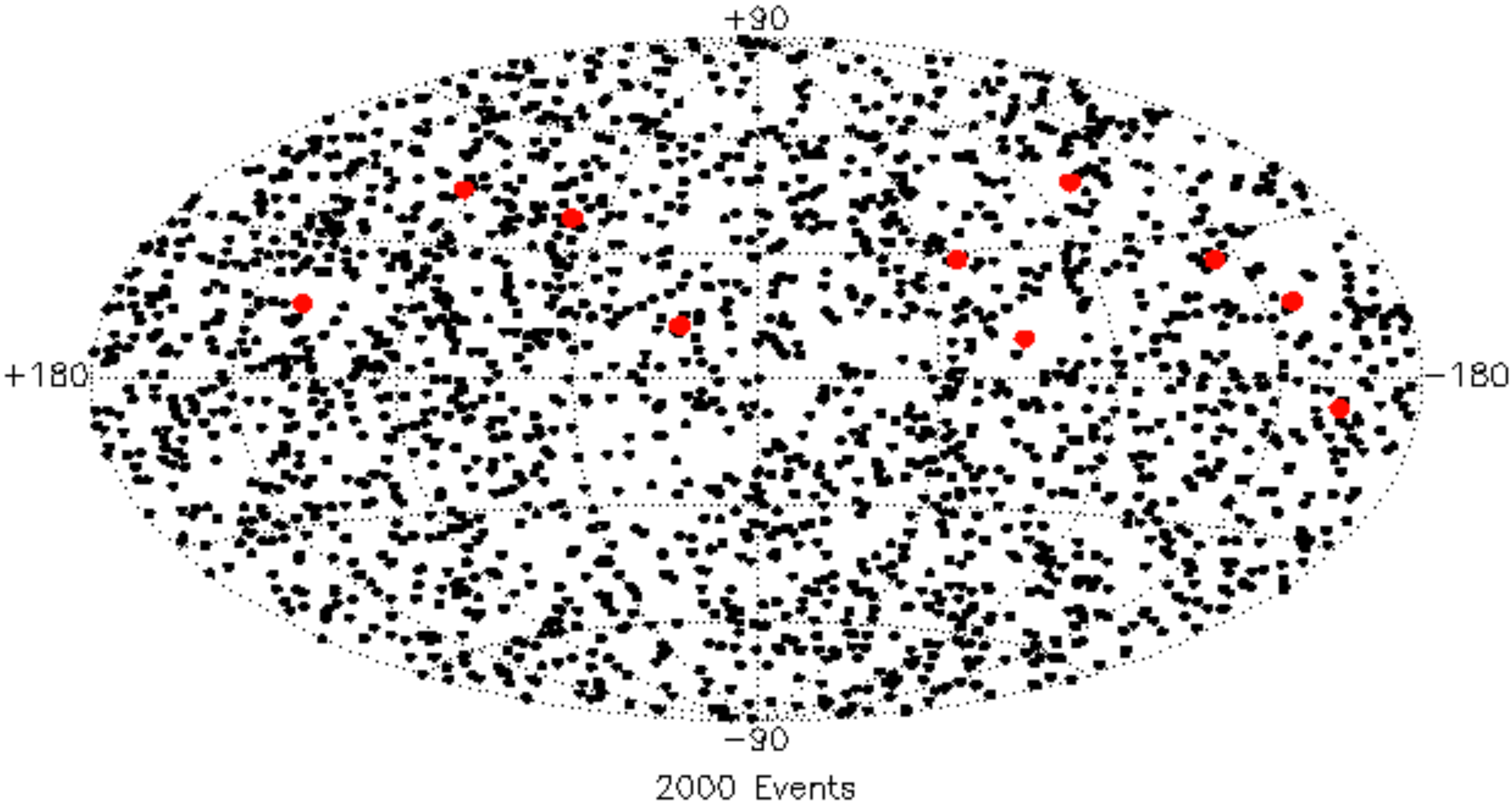
Death of a very high mass star ($M > 25\ M_{sun}$)



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

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

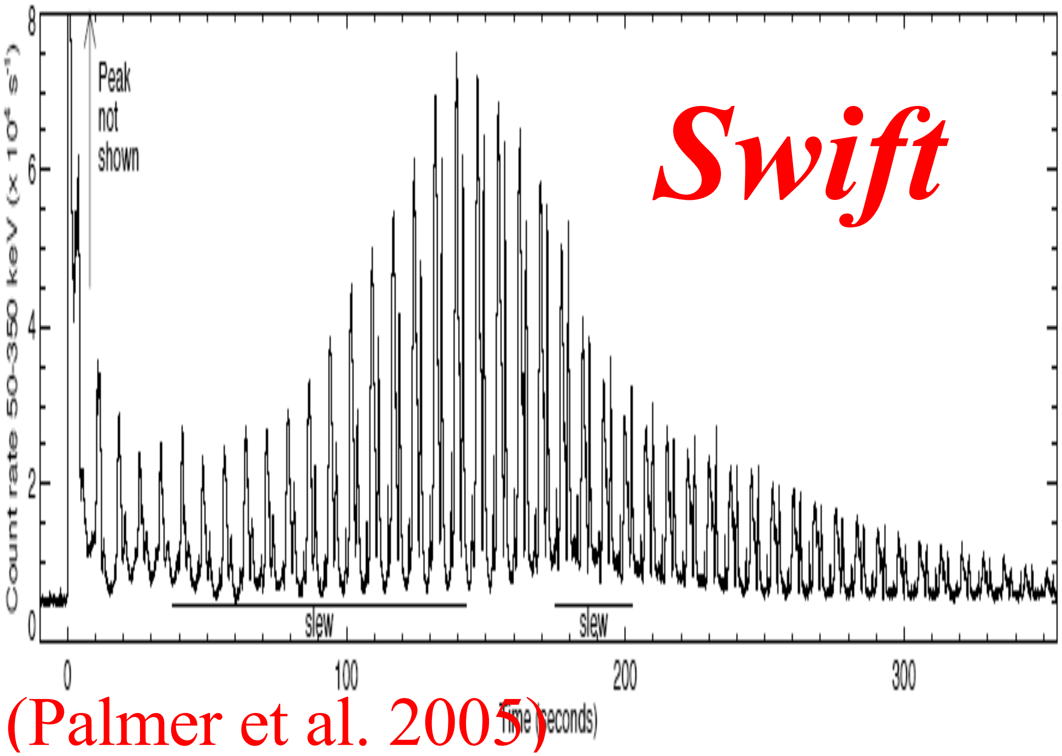
Soft Gamma ray Repeaters (SGRs)



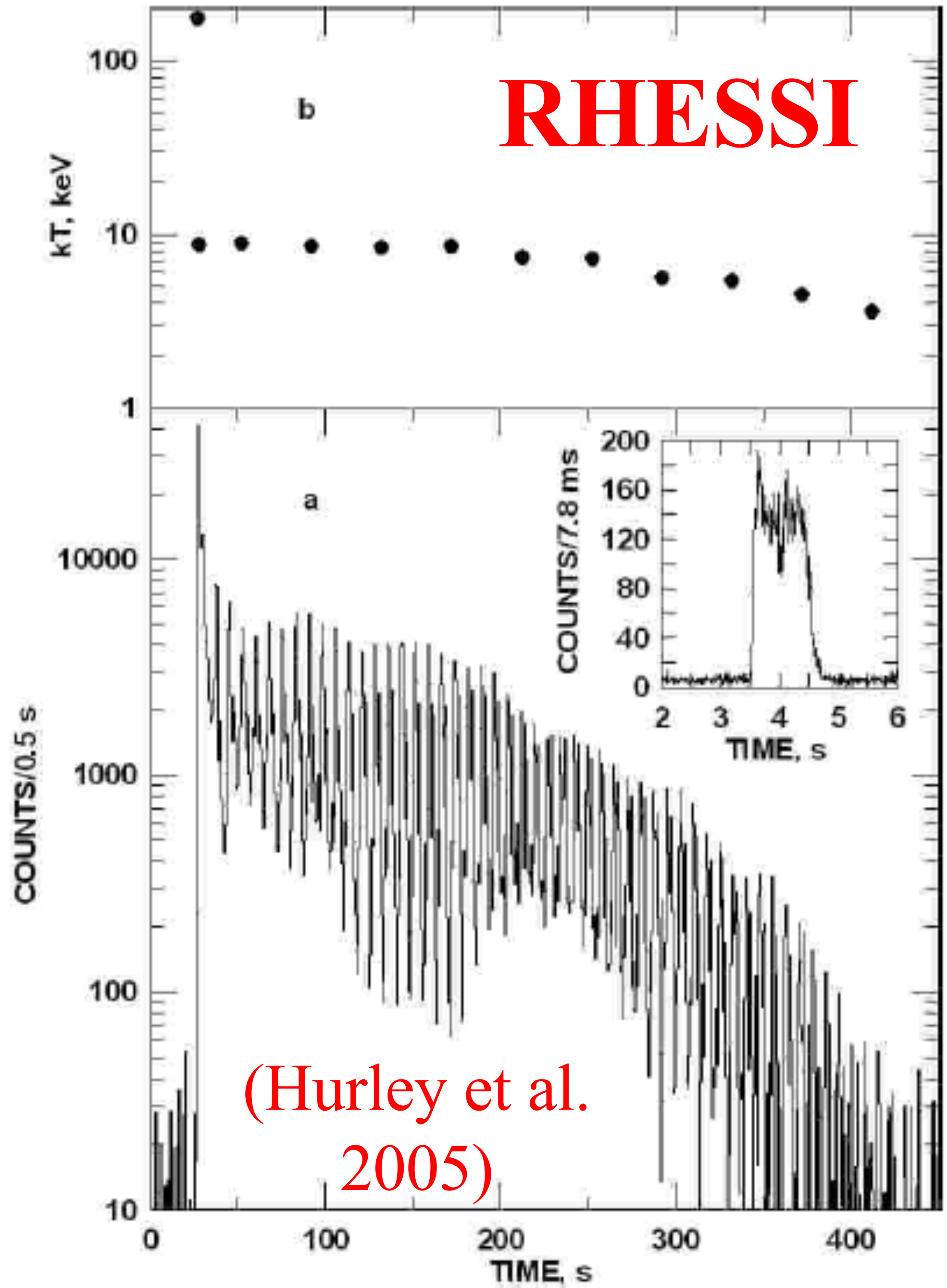
BATSE

The 2004 Dec. 27 Giant Flare

- SGR1806-20
- was ~5^{o} from the sun
- Its distance ≈ 15 kpc
- $E_{iso} \sim 10^{46}$ erg

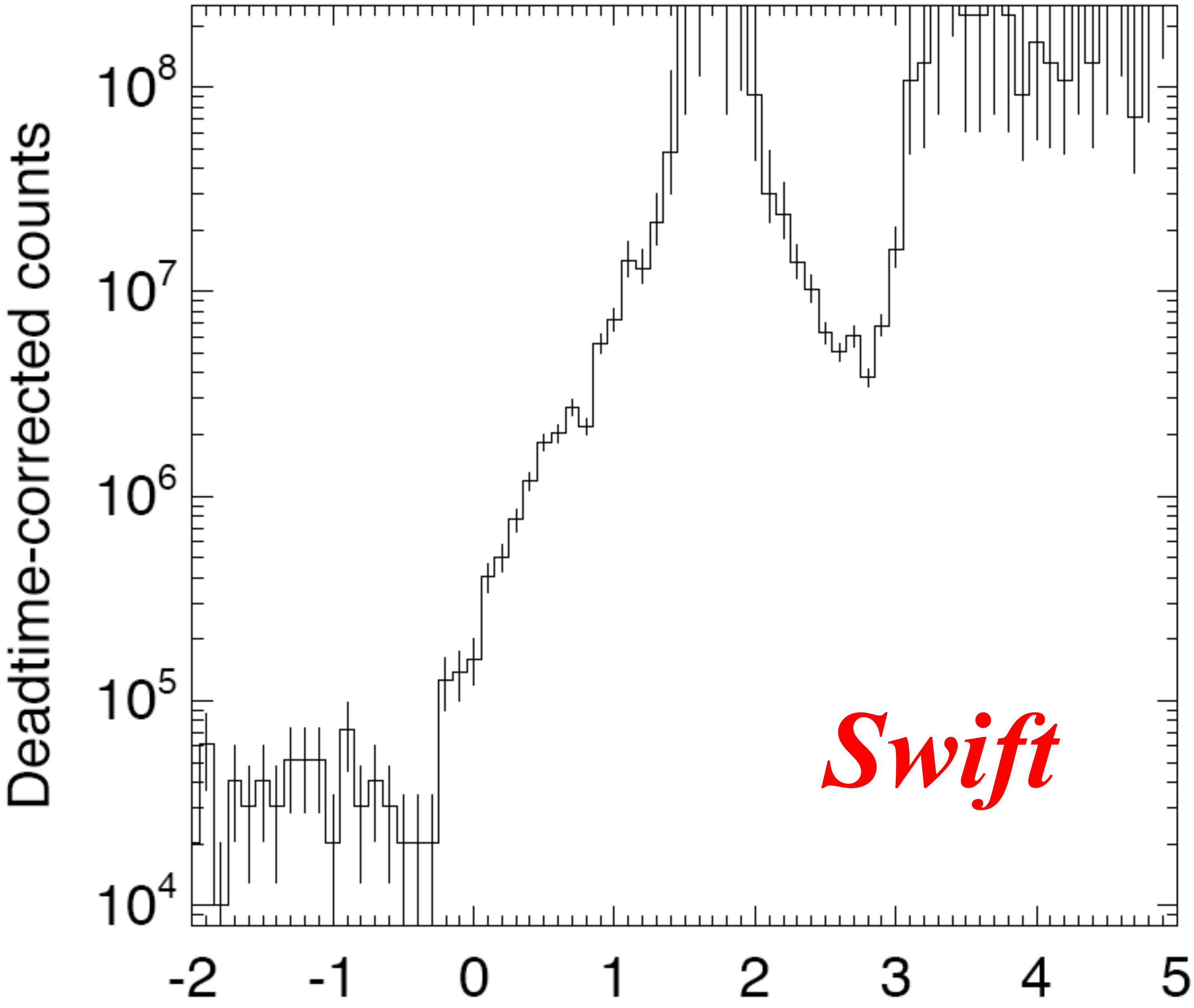


(Palmer et al. 2005)



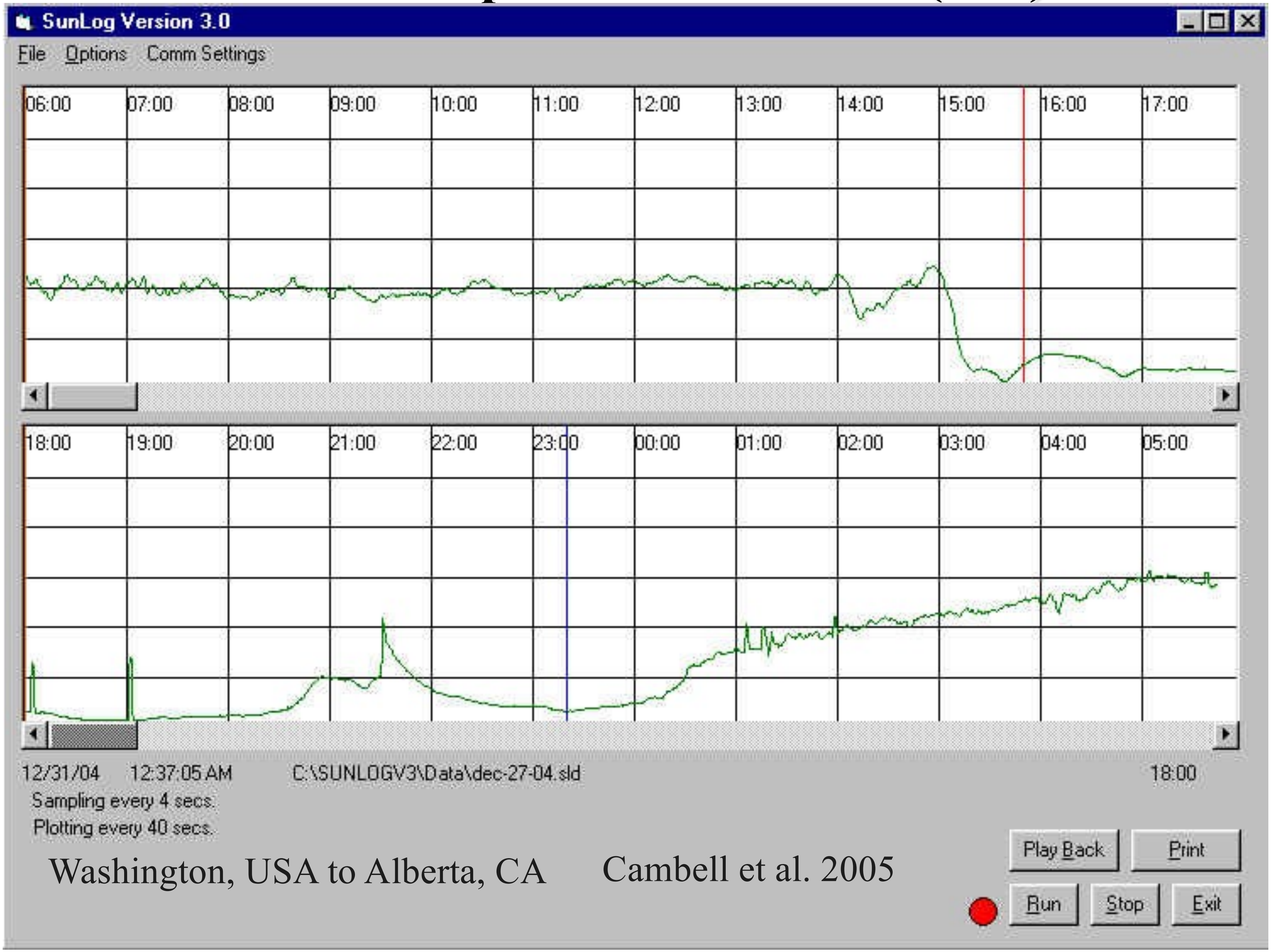
(Hurley et al. 2005)

Rise time: < 1 ms



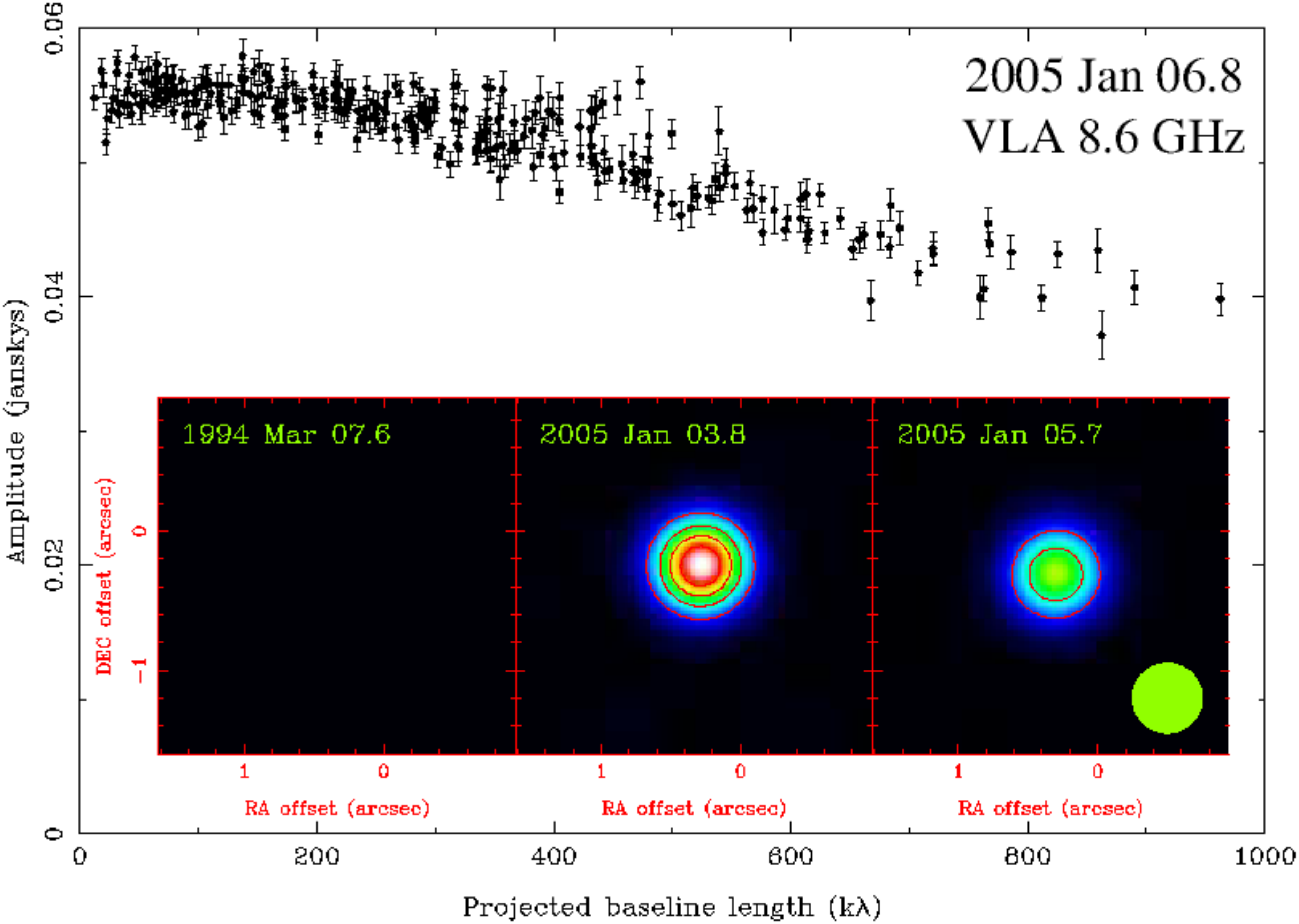
(Palmer et al. 2005)

Sudden Ionospheric Disturbance (SID)



Washington, USA to Alberta, CA

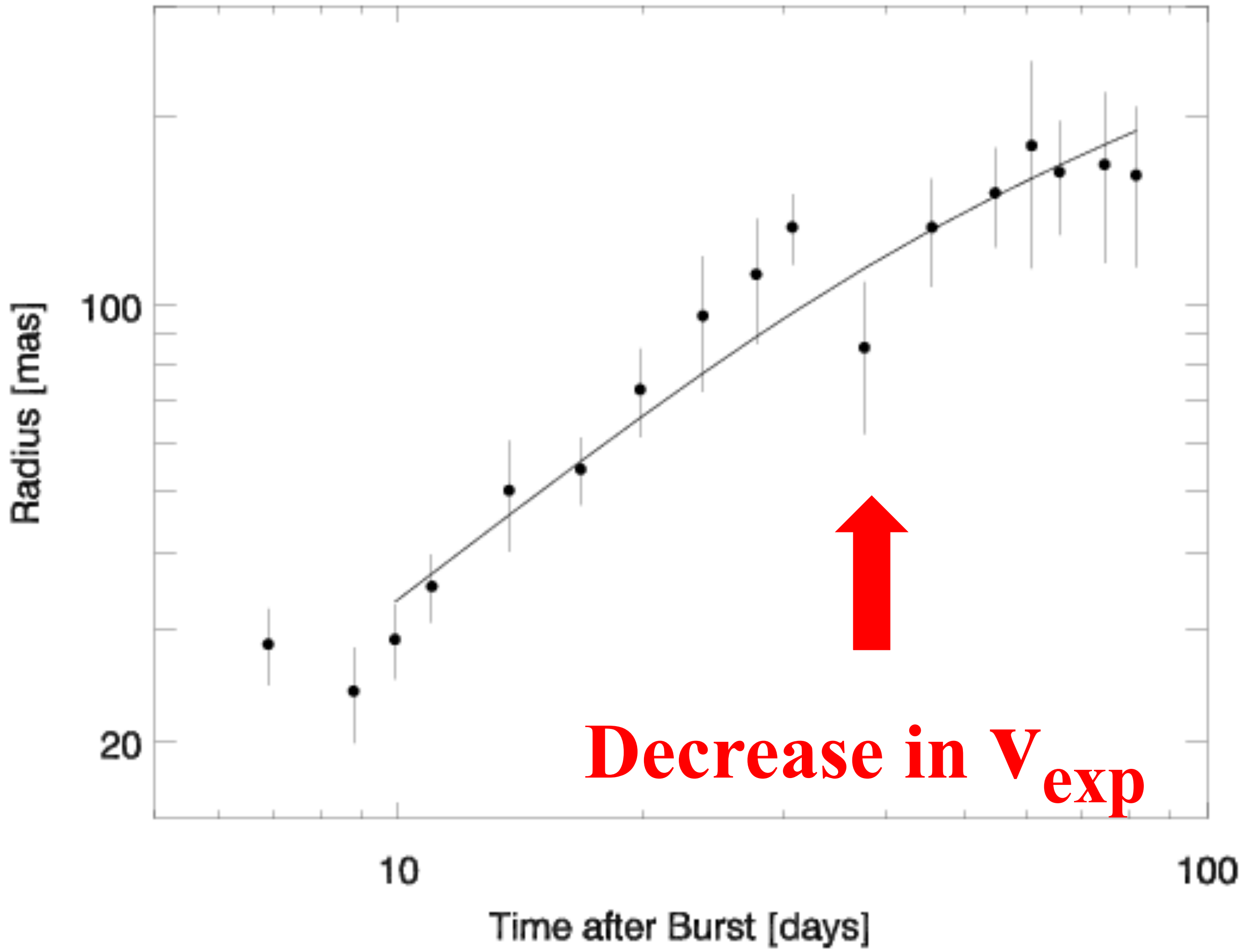
Cambell et al. 2005



2005 Jan 06.8
VLA 8.6 GHz
Amplitude (janskys)
0.06
0.04
0.02
0
1994 Mar 07.6
2005 Jan 03.8
2005 Jan 05.7
DEC offset (arcsec)
RA offset (arcsec)
Projected baseline length (kλ)
0
200
400
600
800
1000

Growth of the Radio Afterglow

Size at
t+7 days
10^{16} cm
(1000 AU)



VLA
8.5 GHz

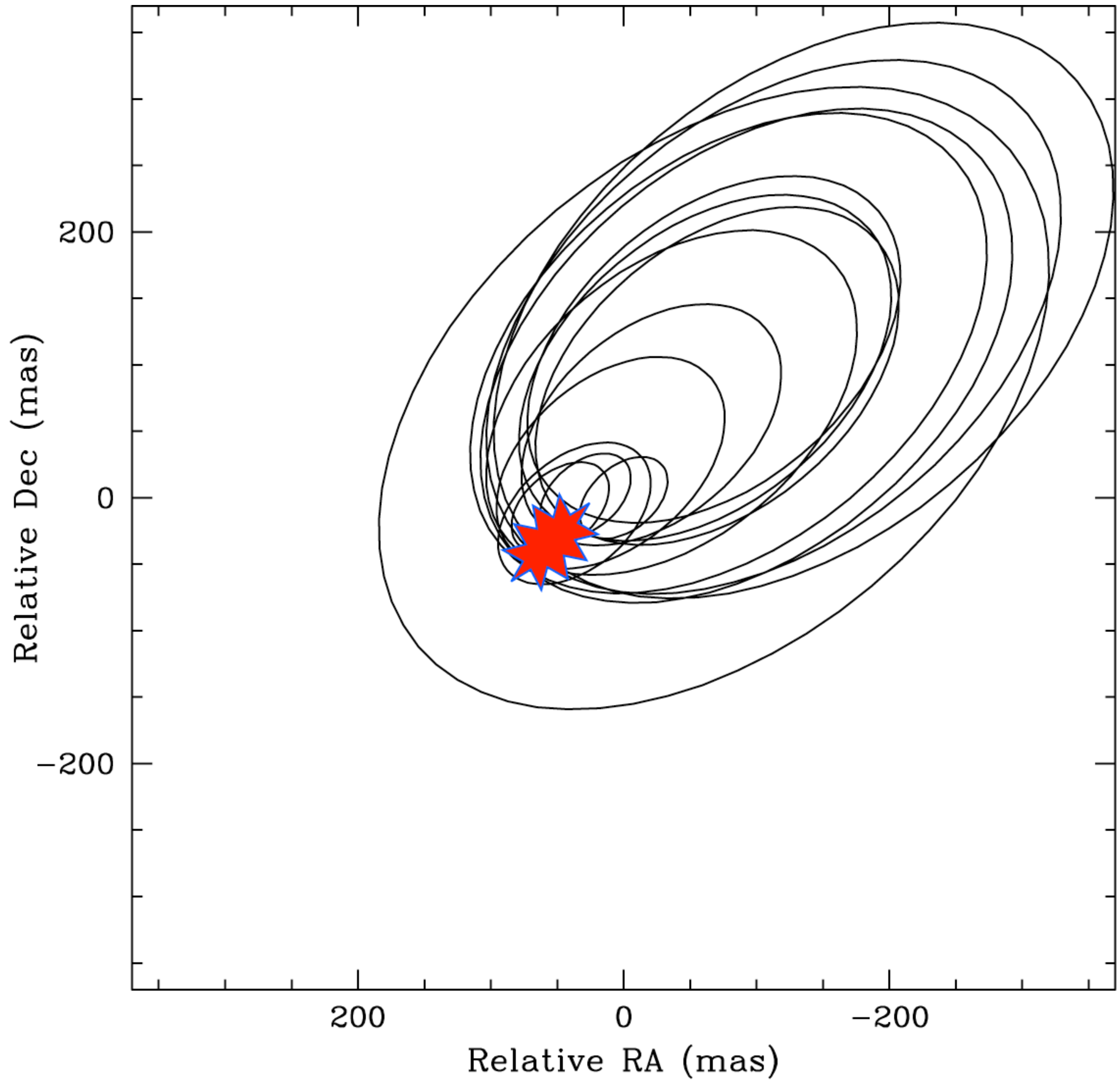
Velocity to
t + 30 days
~ 0.8 c

Image Evolution

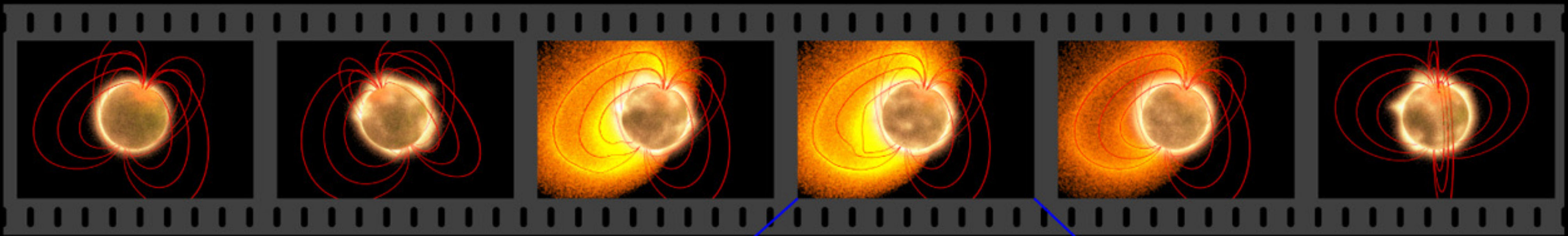
VLA 8.5 GHz

E ~ 10^45 ergs

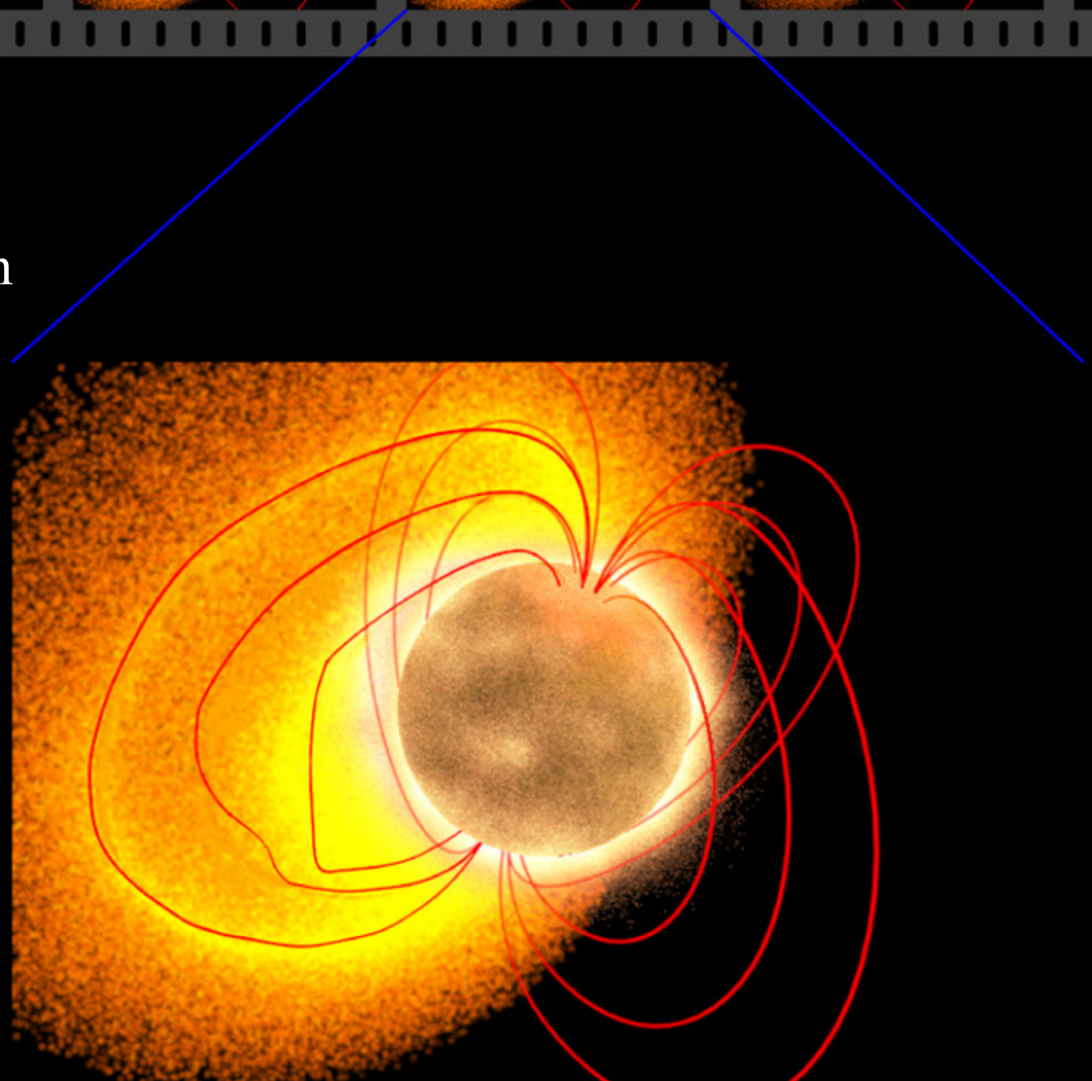
One-sided (anisotropic) outflow

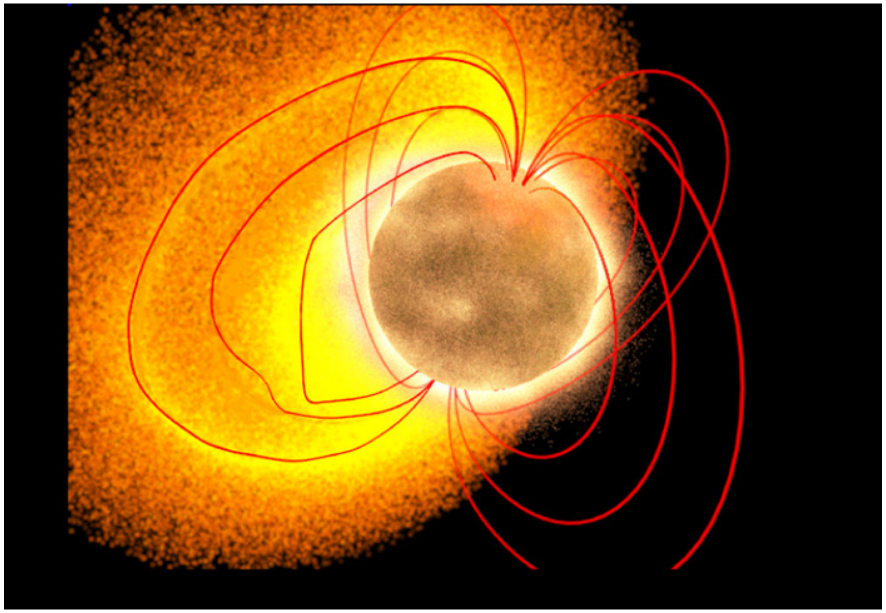


Magnetar burst sequence



Adapted from
Duncan and Thompson
1992

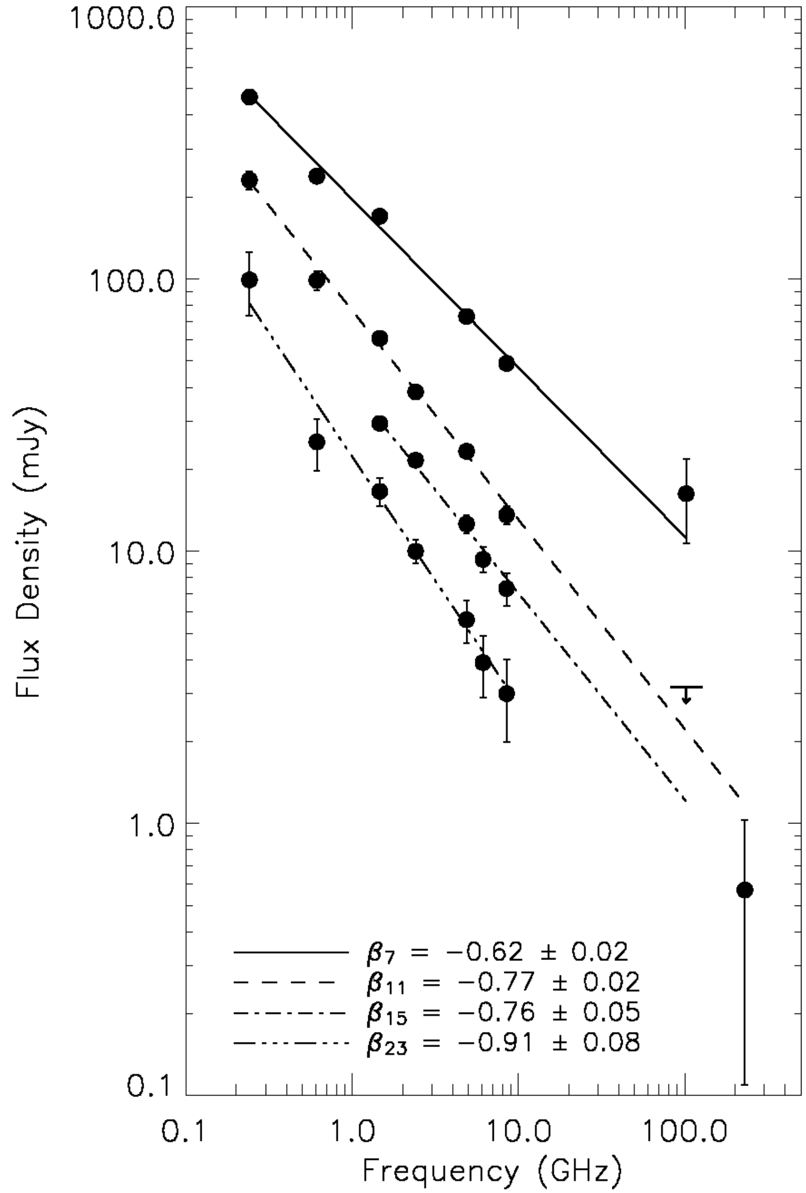




SGR1806-20 : Radio Afterglow has a Steep Spectrum ~ $\nu^{-0.6}$ at t+7 days down to at least 220 MHz

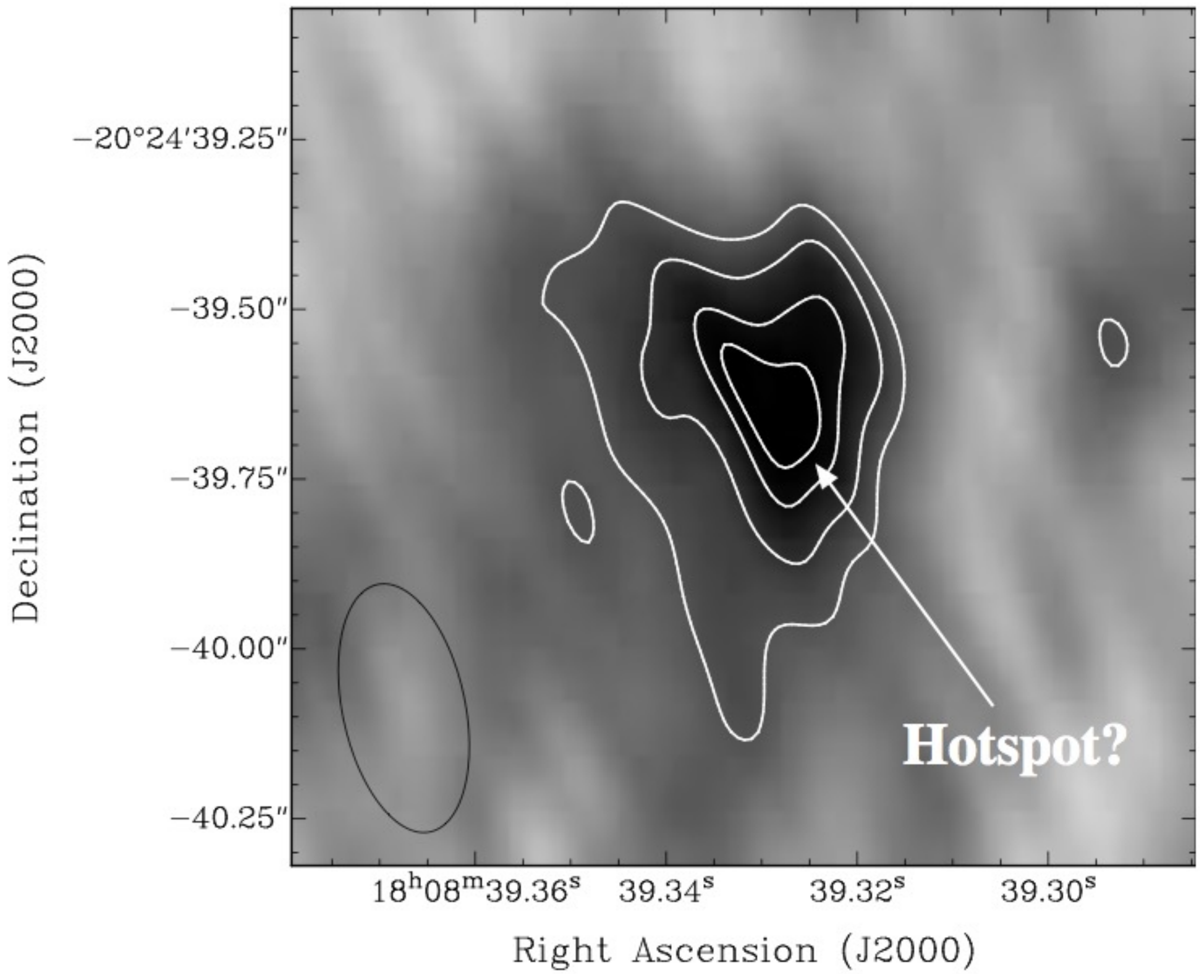
Flux > 1 Jy at early times and low frequencies.

Visible out to ~ 1 Mpc

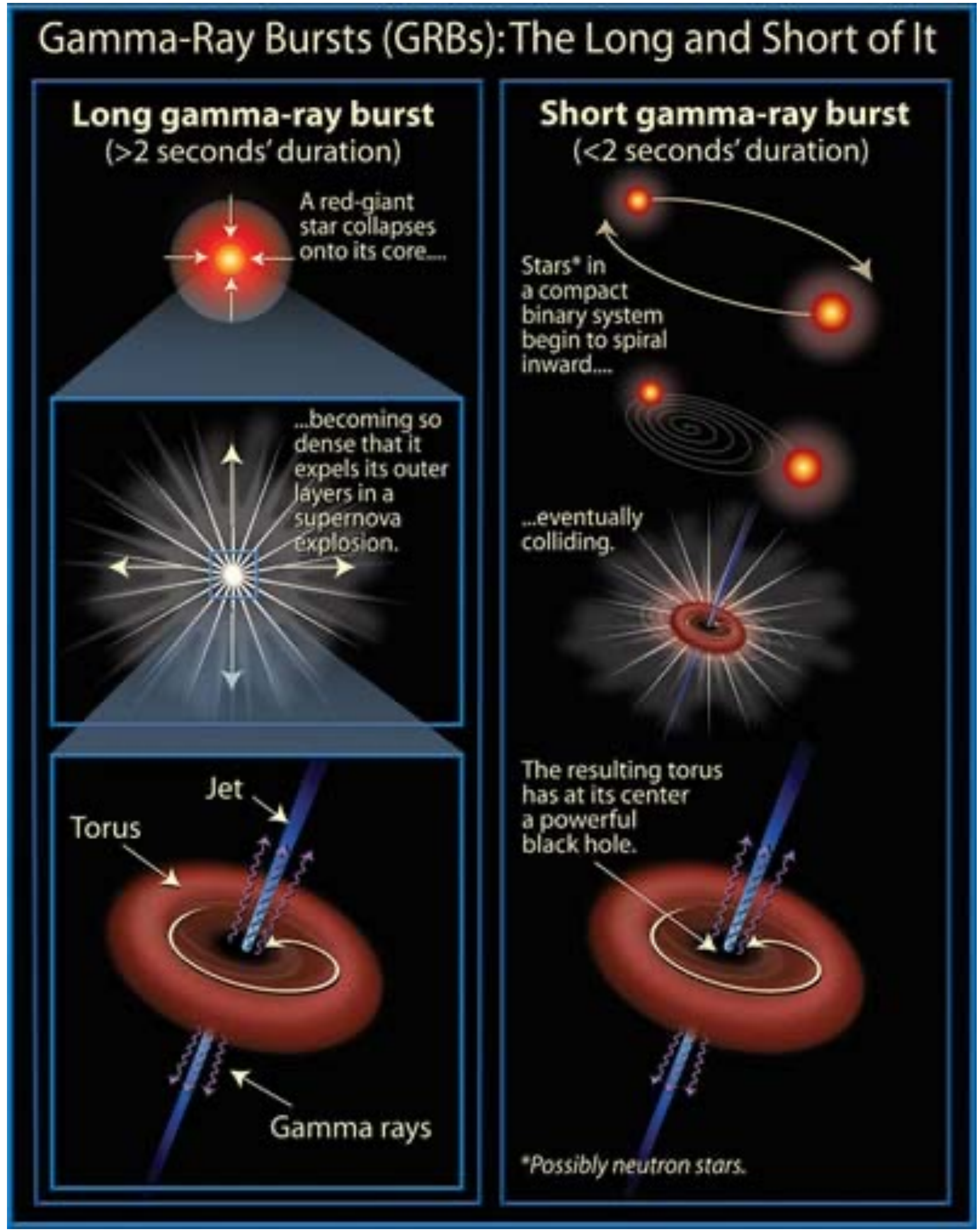


8.4 GHz Image of SGR1806

VLA + PT
t+430 days



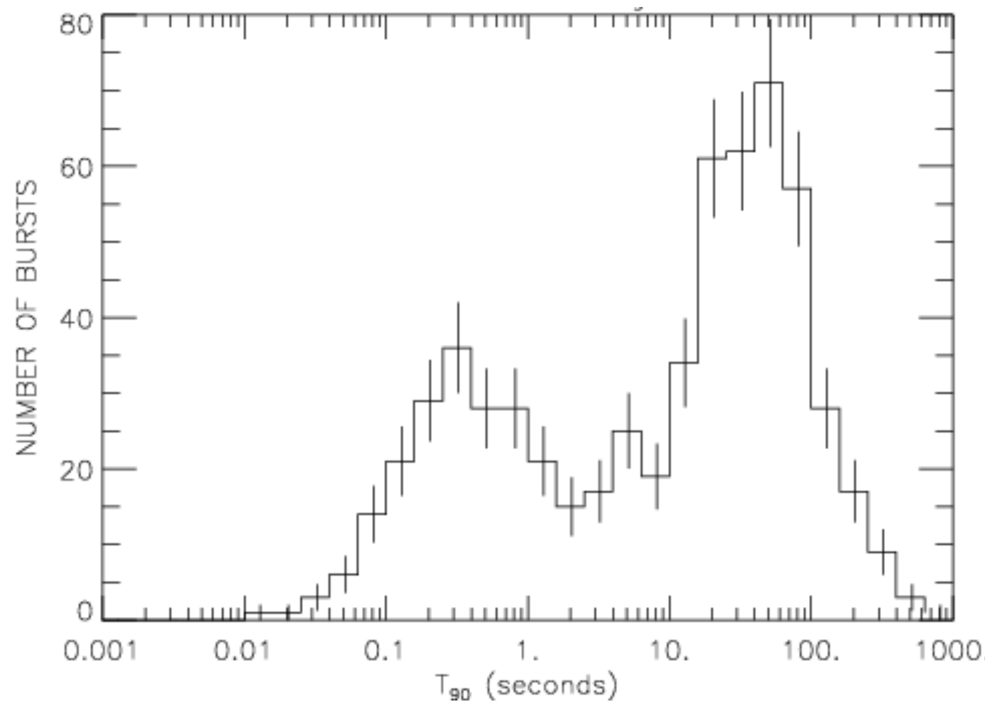
- Long GRBs associated with supernovae
- Short GRBs associated with star-forming and elliptical galaxies (old stellar population, broadly consistent with NS and/or BH coalescence. Compact merger or giant flare from magnetar



GRB classification

- Long bursts
  - > 2 sec, mean 30 sec
  - Afterglows commonly observed
  - From massive stars

- Short bursts
  - < 2 sec, mean 0.3 sec
  - Fewer afterglows observed
  - From compact binaries and/or neutron stars



BATSE burst duration