Gamma-ray Bursts

Homework Assignment #5 due by:
TUESDAY 12/15 before 9AM.

Observational evidence for black holes

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NOBELPRISET I FYSIK 2020
THE NOBEL PRIZE IN PHYSICS 2020
KUNGL. VETENSKAPS AKADEMIEN
THE ROYAL SWEDISH ACADEMY OF SCIENCES
Photo: Penrose Institute
Photo: Max Planck Institute for Extraterrestrial Physics
Photo: Christopher Dibble, UCLA
Roger Penrose
Reinhard Genzel
Andrea Ghez
"för upptäckten att bildandet av svarta hål är en robust förutsägelse av den allmänna relativitetsteorin"
"for the discovery that black hole formation is a robust prediction of
ral theory of relativity"
"för upptäckten av ett supermassivt kompakt objekt i Vintergatans centrum"
"for the discovery of a supermassive compact object at the centre of our galaxy"
#nobelprize
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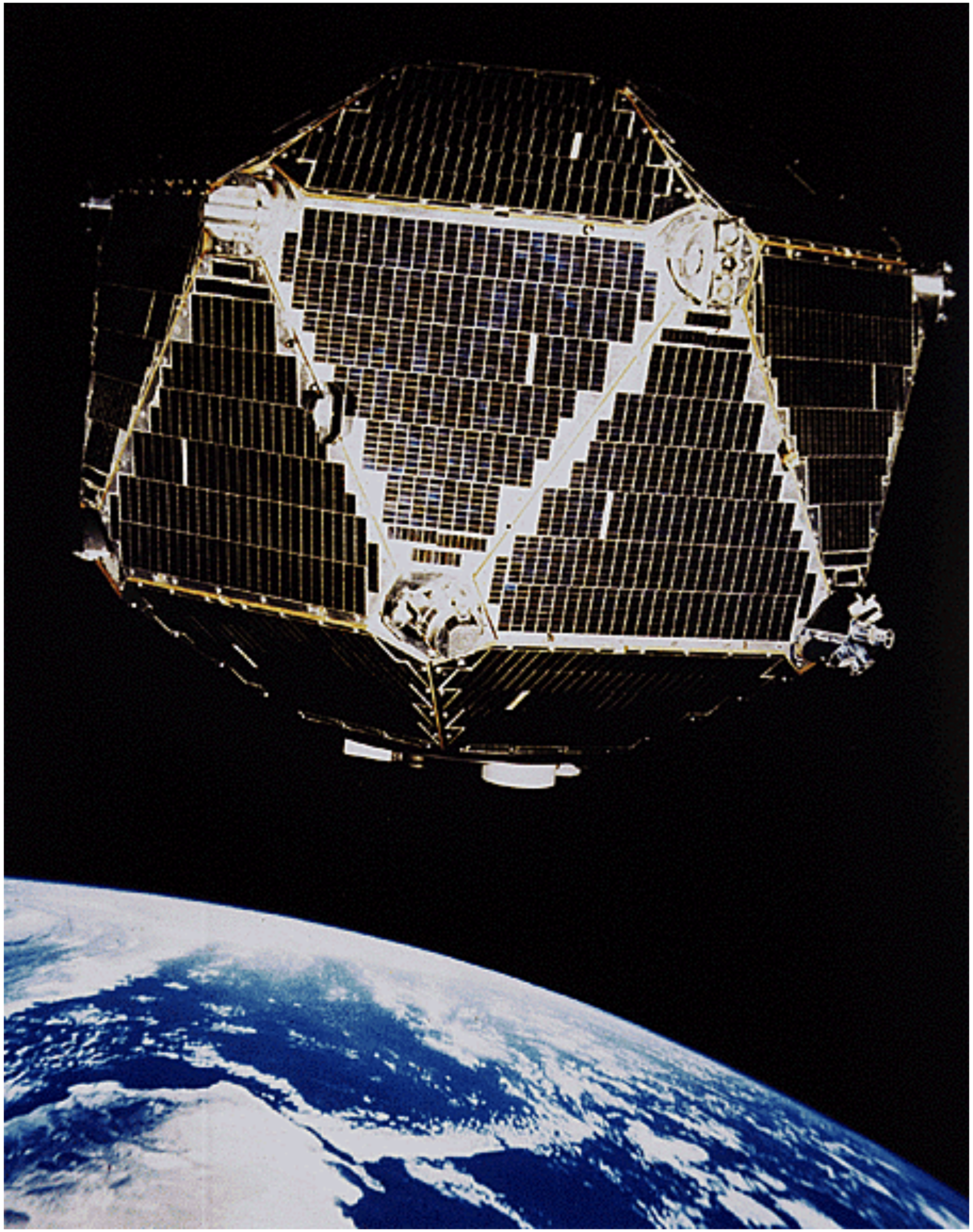
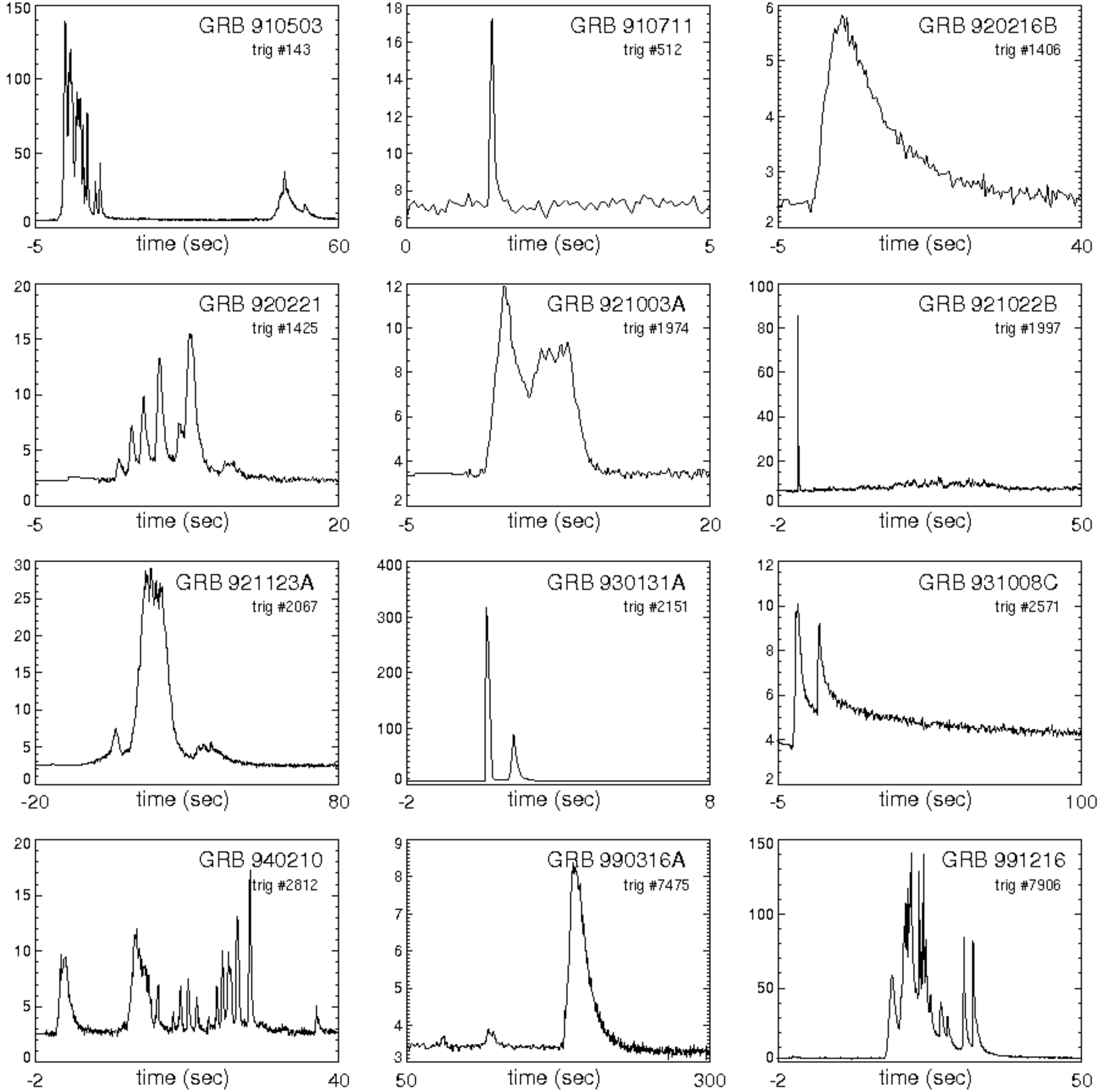


Gamma-ray Bursts (GRBs)

The Vela satellite (designed to monitor Soviet nuclear test ban compliance) first detected **gamma-ray bursts**.

These happen ~1 a day and last from 10^{-2} to 10^{3} s, with rise times as short as 10^{-4} s, followed by exponential decay.

Gamma-rays are the most energetic photons. The gamma-ray regime extends from ~1 KeV to GeVs (or really as high as detectable).



GRB light curve: wide range of potential shapes here!

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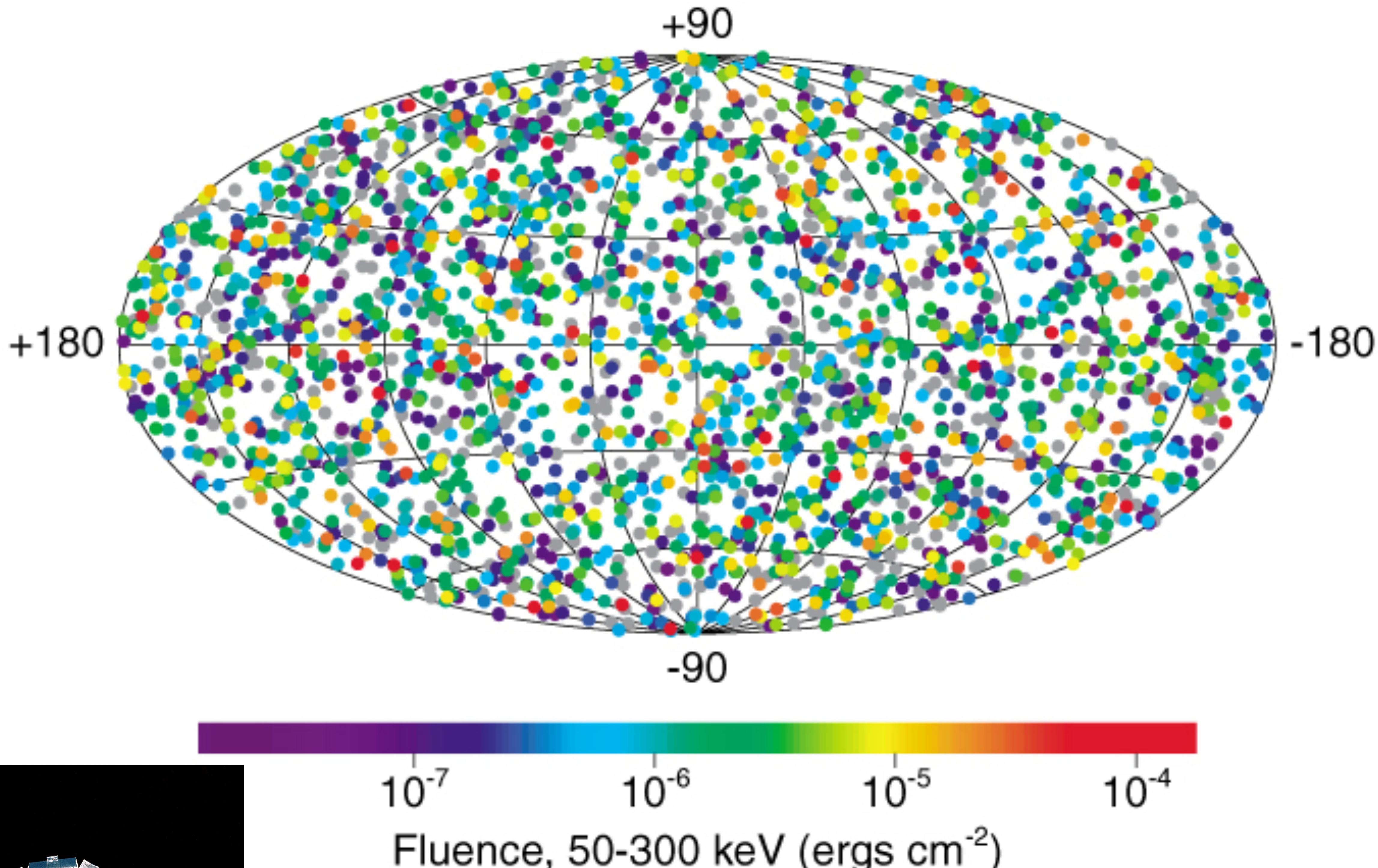
2704 BATSE Gamma-Ray Bursts



fluence = total energy received over the course of a burst

Compton Gamma Ray Observatory satellite

Although the sources are spread evenly across the sky, they do not appear to be distributed homogeneously throughout space, i.e., not the same number of sources independently of distant or direction. The argument in support of this is the logN-logS distribution.

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Assuming all burst with same intrinsic E, then for a specific value of S (i.e., S_0), all the sources within a sphere of radius $d(S_0)$ will be observed to have a fluence $S>S_0$.

If there are n burst sources per unit of volume, then the number of sources with a fluence equal to or greater than S_0 is:

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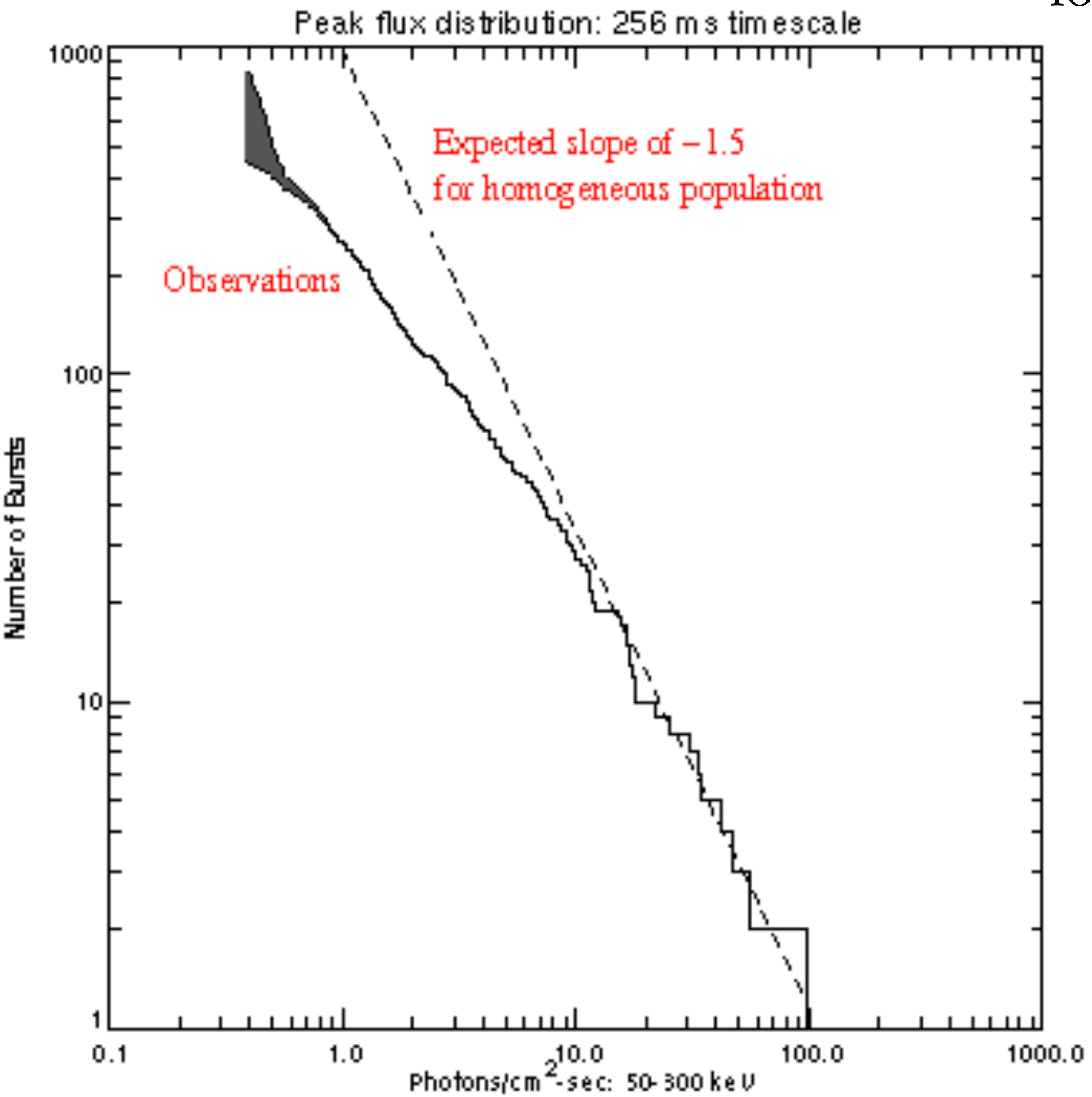

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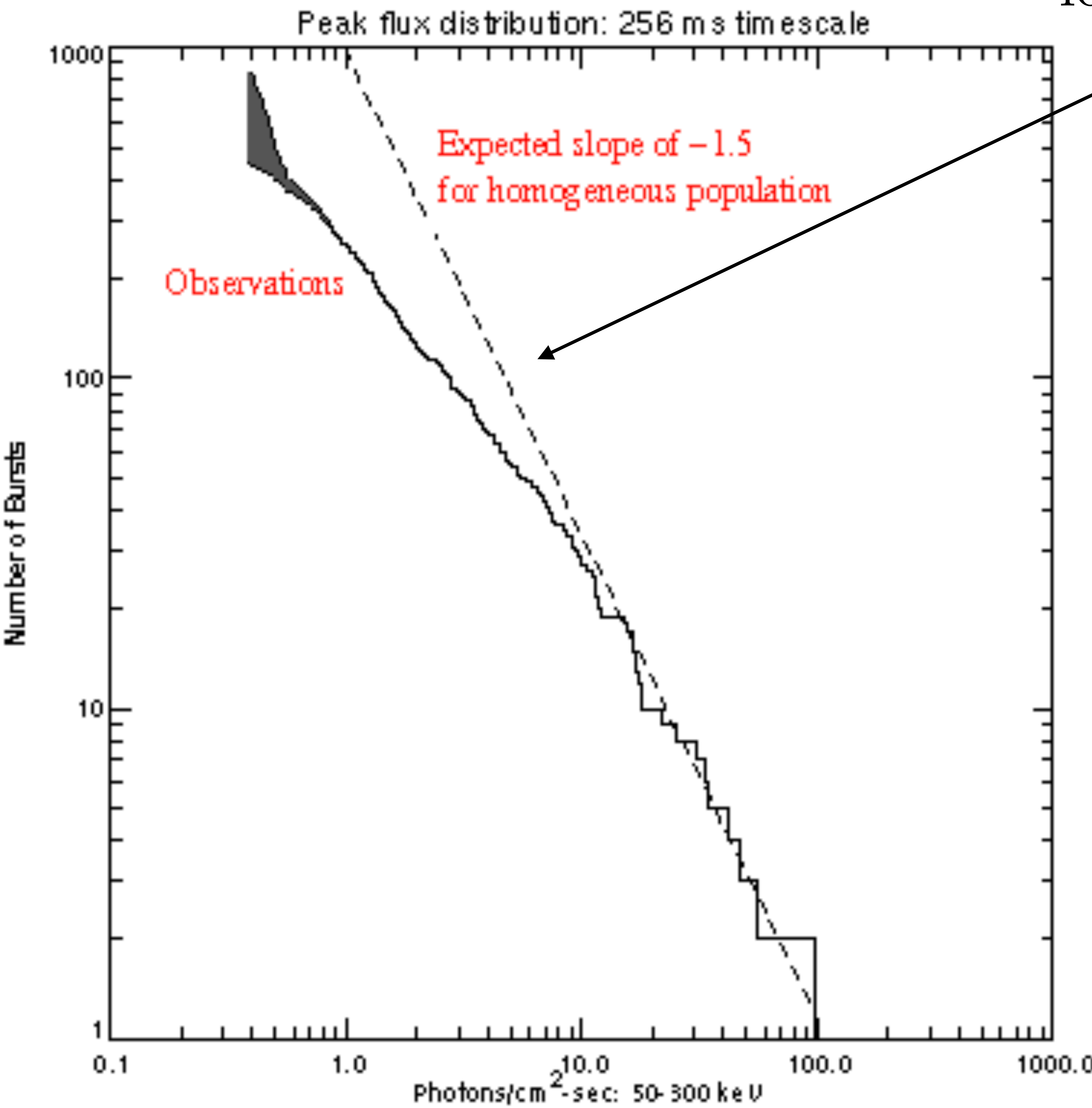

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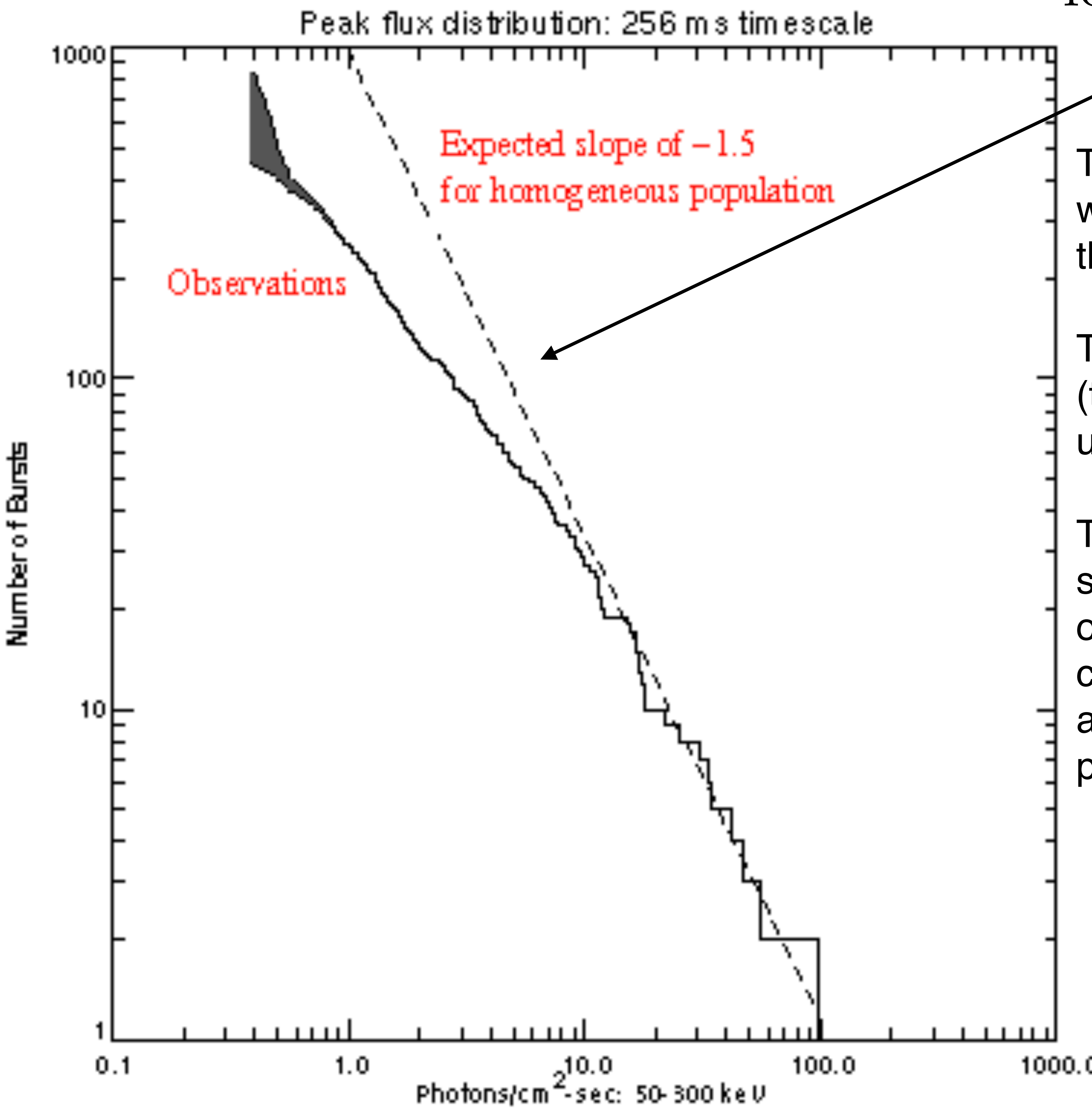

This proportionality is violated when S is small enough to include the more distant, fainter sources.

There is an edge to the distribution (the limit could be the observable universe).

The Earth is near the center of a spherically symmetric distribution of GRBs, hence GRBs are of cosmological origin, and the GRBs are among the most energetic phenomena in the universe.

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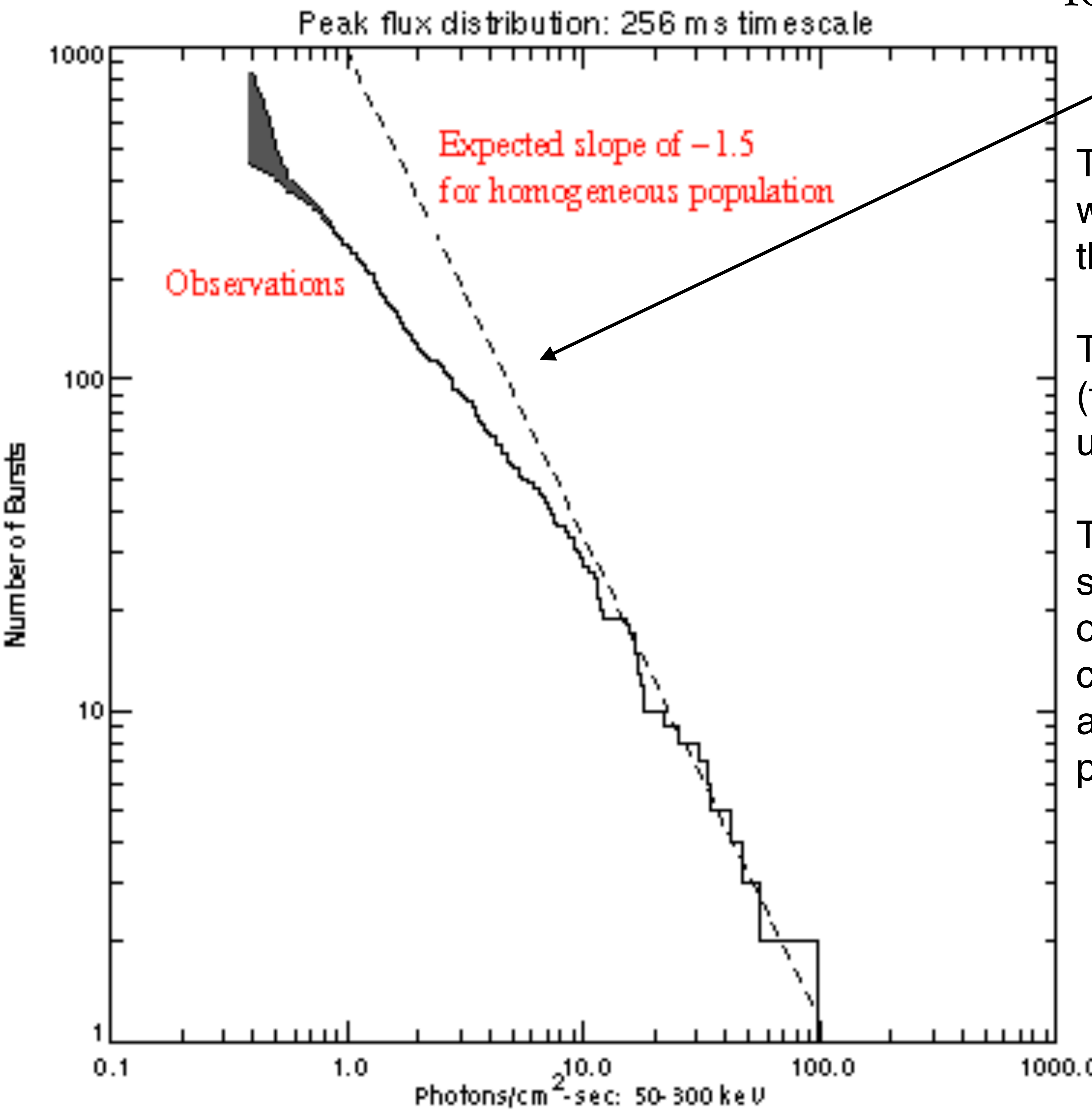

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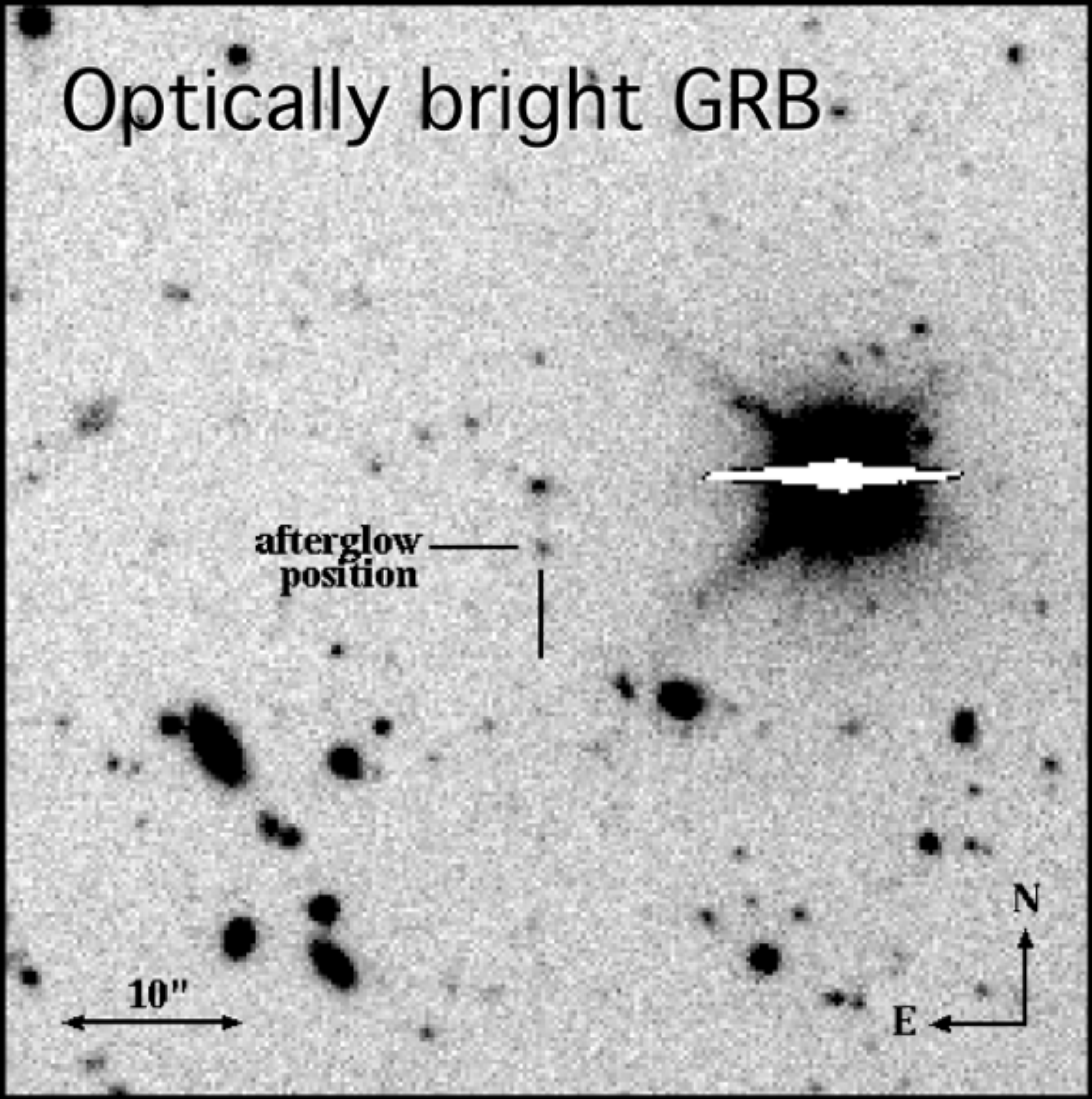
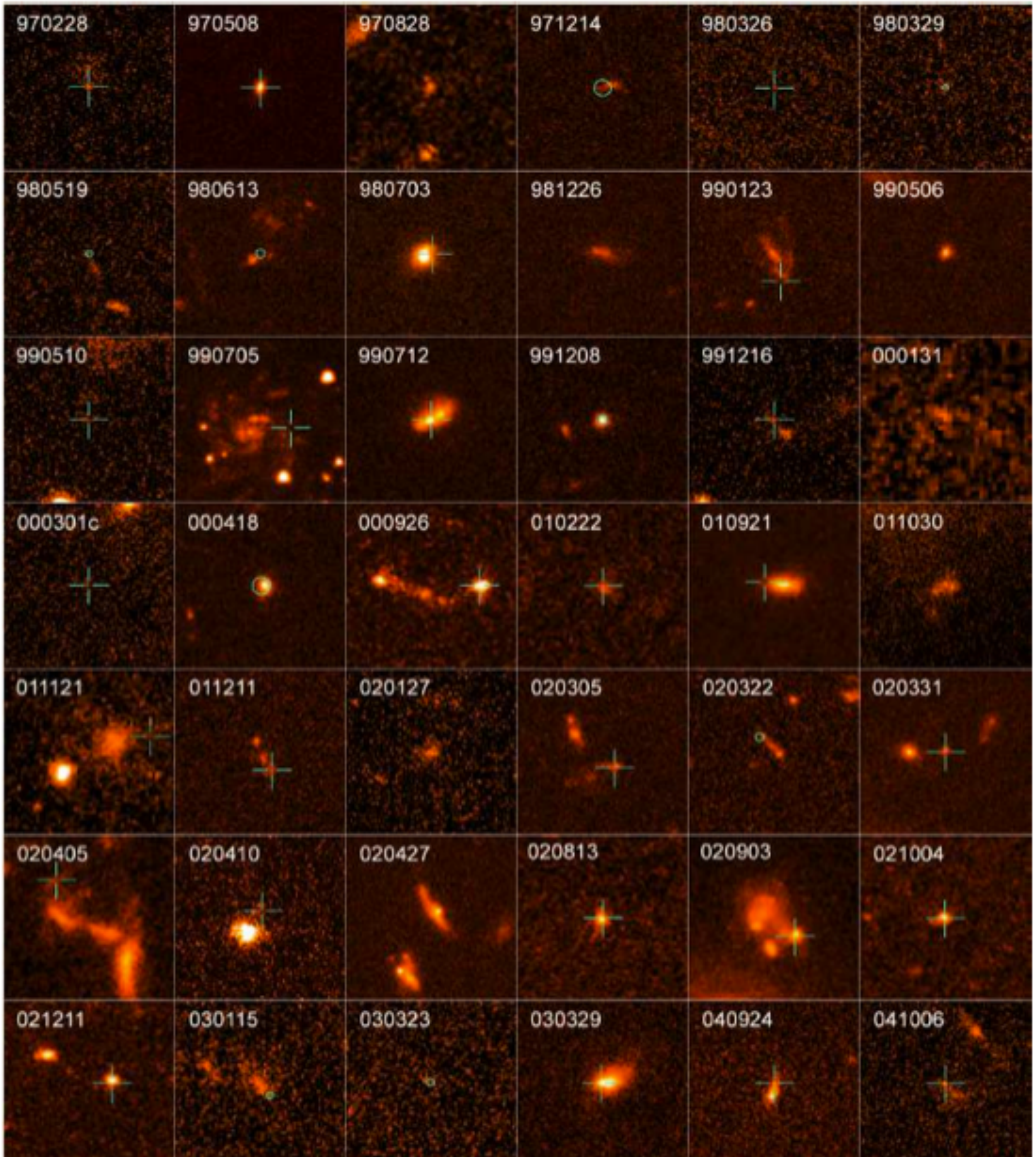
If extragalactic, the fluence implies energy release (in gamma rays alone) comparable to the *total* energy release of Type II supernovae (~10^{45} J).

The GRB host galaxies (hence distances) were finally identified thanks to detections of optical afterglows.



The simplest but crucial task in host search is to find them

Accurate astrometry from afterglow images


970228
970508
970828
971214
980326
980329
980519
980613
980703
981226
990123
990506
990510
990705
990712
991208
991216
000131
000301c
000418
000926
010222
010921
011030
011121
011211
020127
020305
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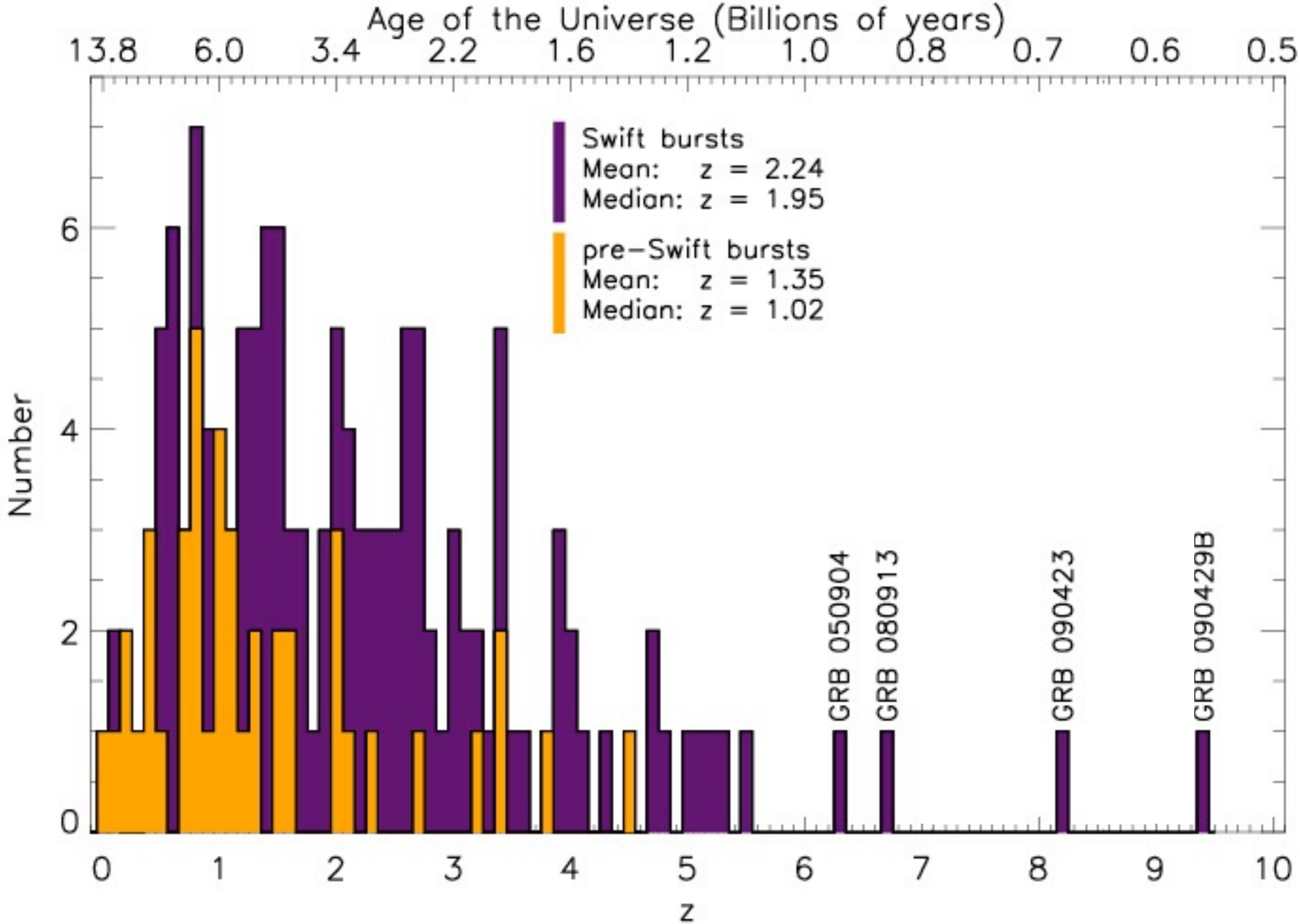
030329
040924
041006

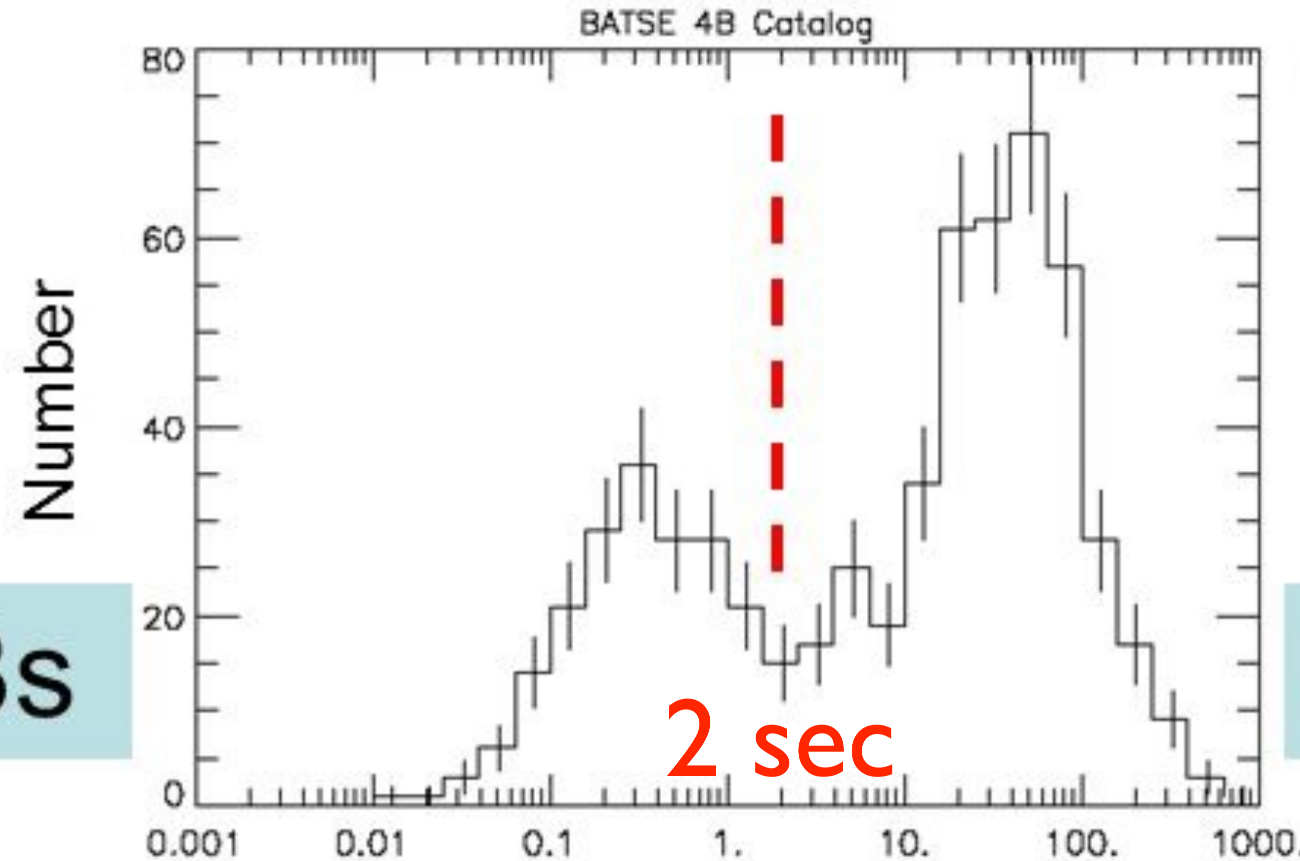


Age of the Universe (Billions of years)
13.8
6.0
3.4
2.2
1.6
1.2
1.0
0.8
0.7
0.6
0.5
Swift bursts
Mean: z = 2.24
Median: z = 1.95
pre-Swift bursts
Mean: z = 1.35
Median: z = 1.02
Number
0
2
4
6
GRB 050904
GRB 080913
GRB 090423
GRB 090429B
0
1
2
3
4
5
6
7
8
9
10
z

Short & Long Gamma-Ray Bursts (GRBs)

Distribution of T90 durations of GRBs is bimodal.

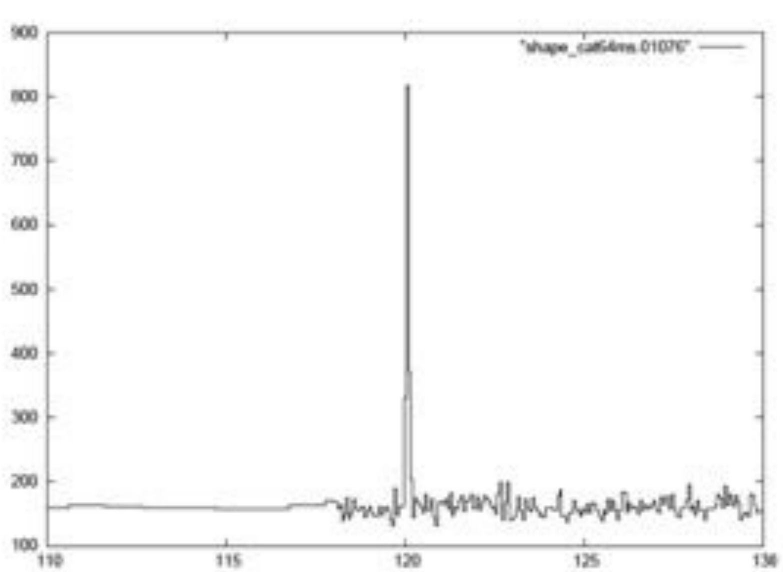
(BATSE Web page)



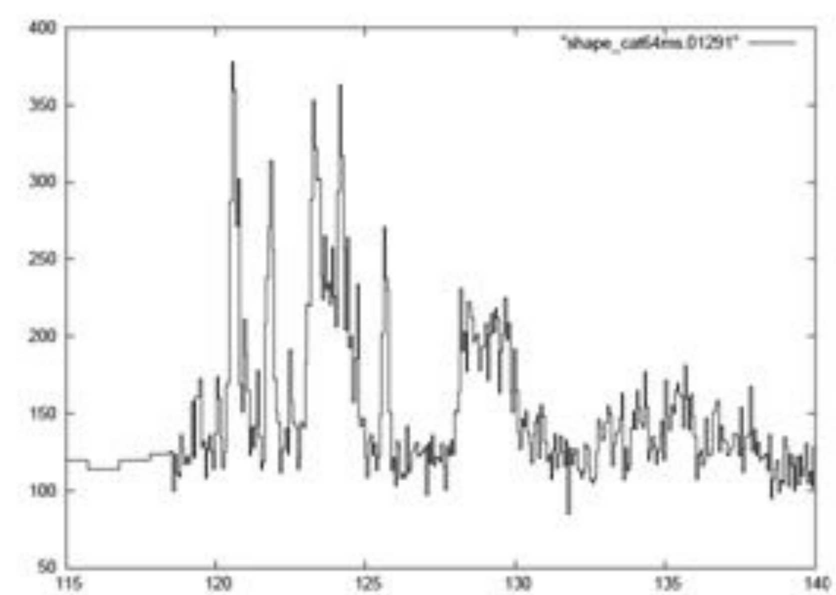
$T_{90}[s]$

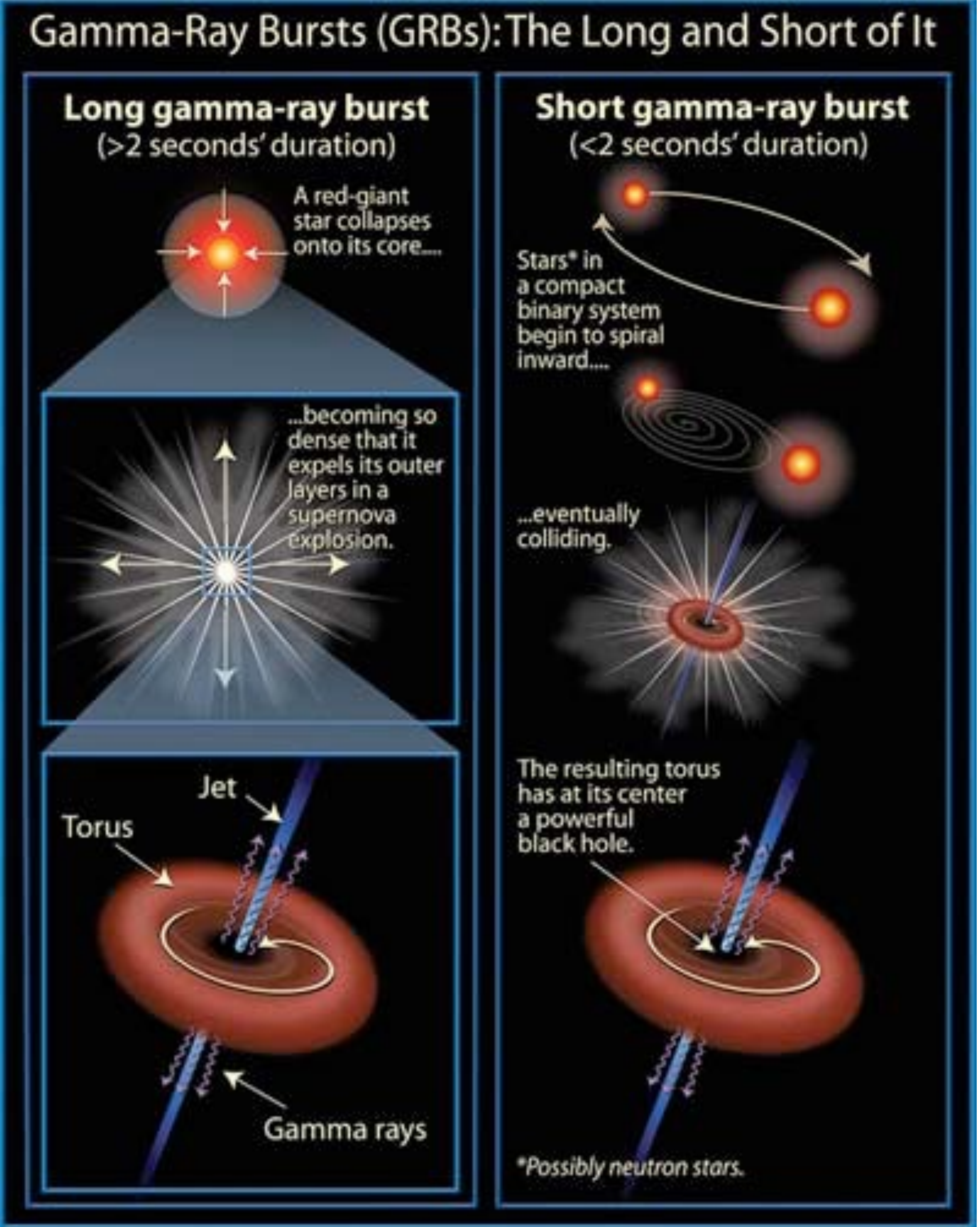
(time for 90% of released emission energy)

Short GRBs



Long GRBs

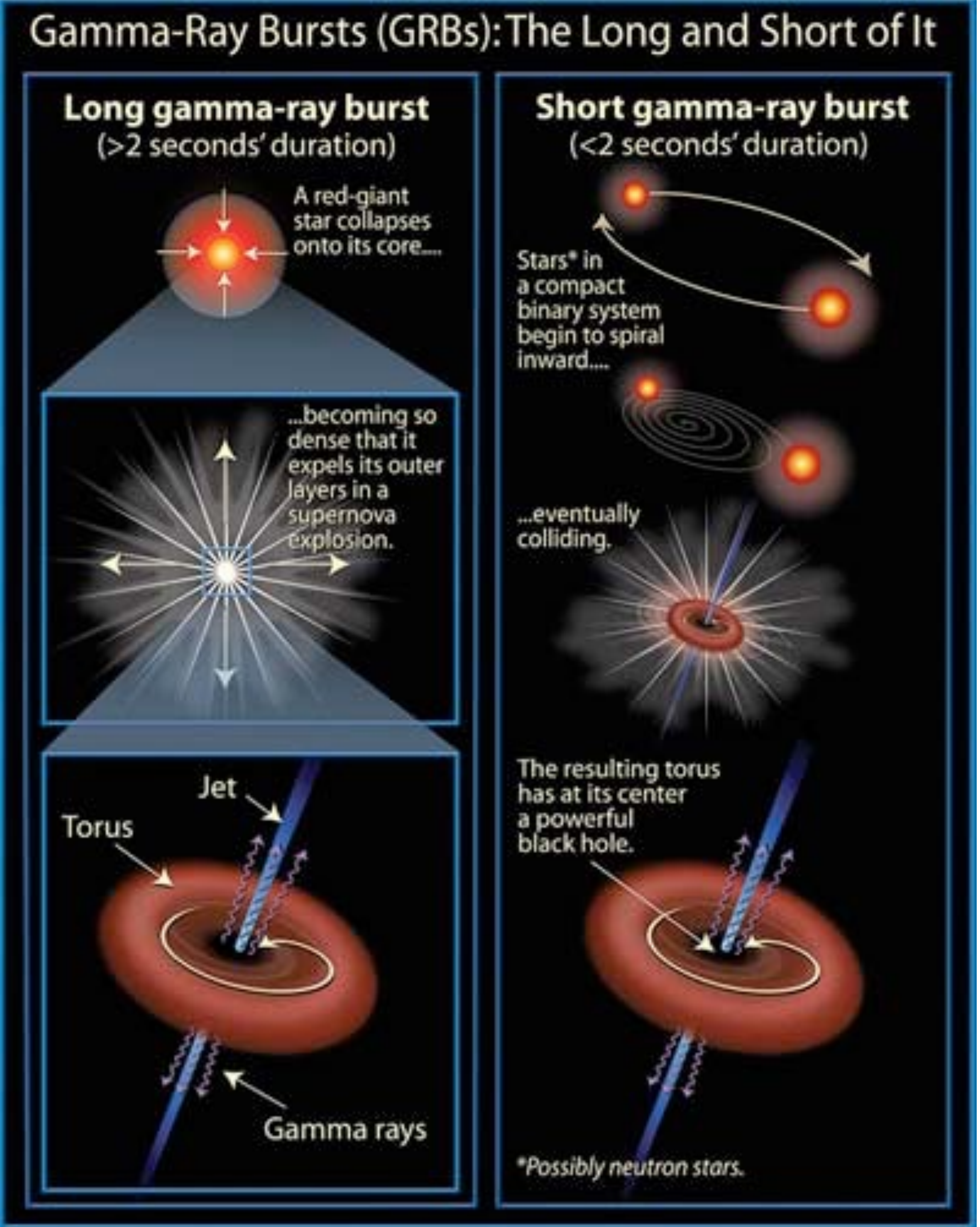




Main theory:

Long-duration GRB: collapsar (basically burst associated with a particularly massive core collapse supernova), likely producing a black hole.

Short-duration GRB: merging neutron stars (or neutron star and a black hole)



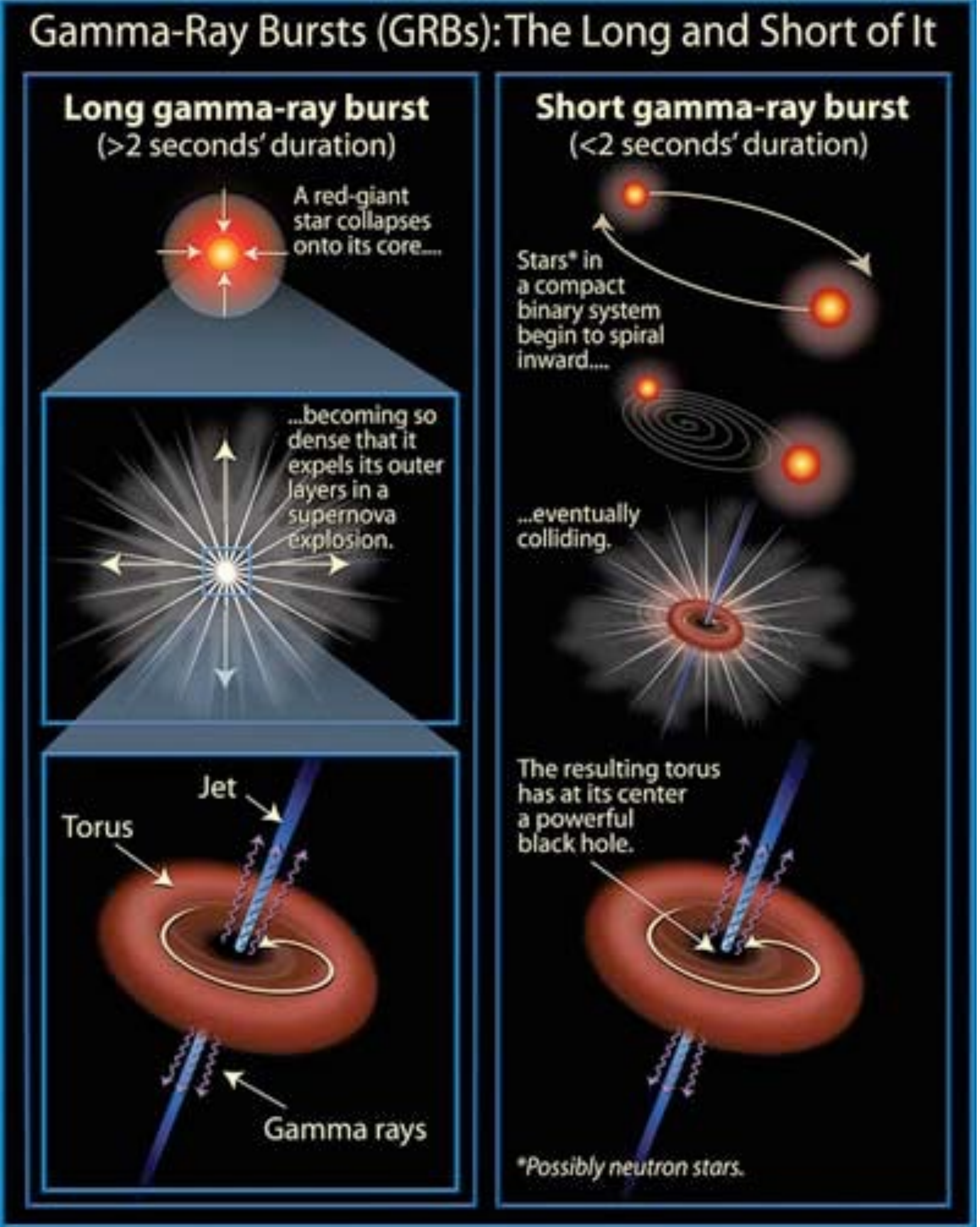
Common ingredient is the beaming of highly relativistic matter. The emission is not isotropic, but there is a relativistic jet. Radiation is emitted in a cone having an opening angle of half width:

$$\theta \sim \frac{1}{\gamma} \qquad \gamma \gg 1$$

Lorentz factor:

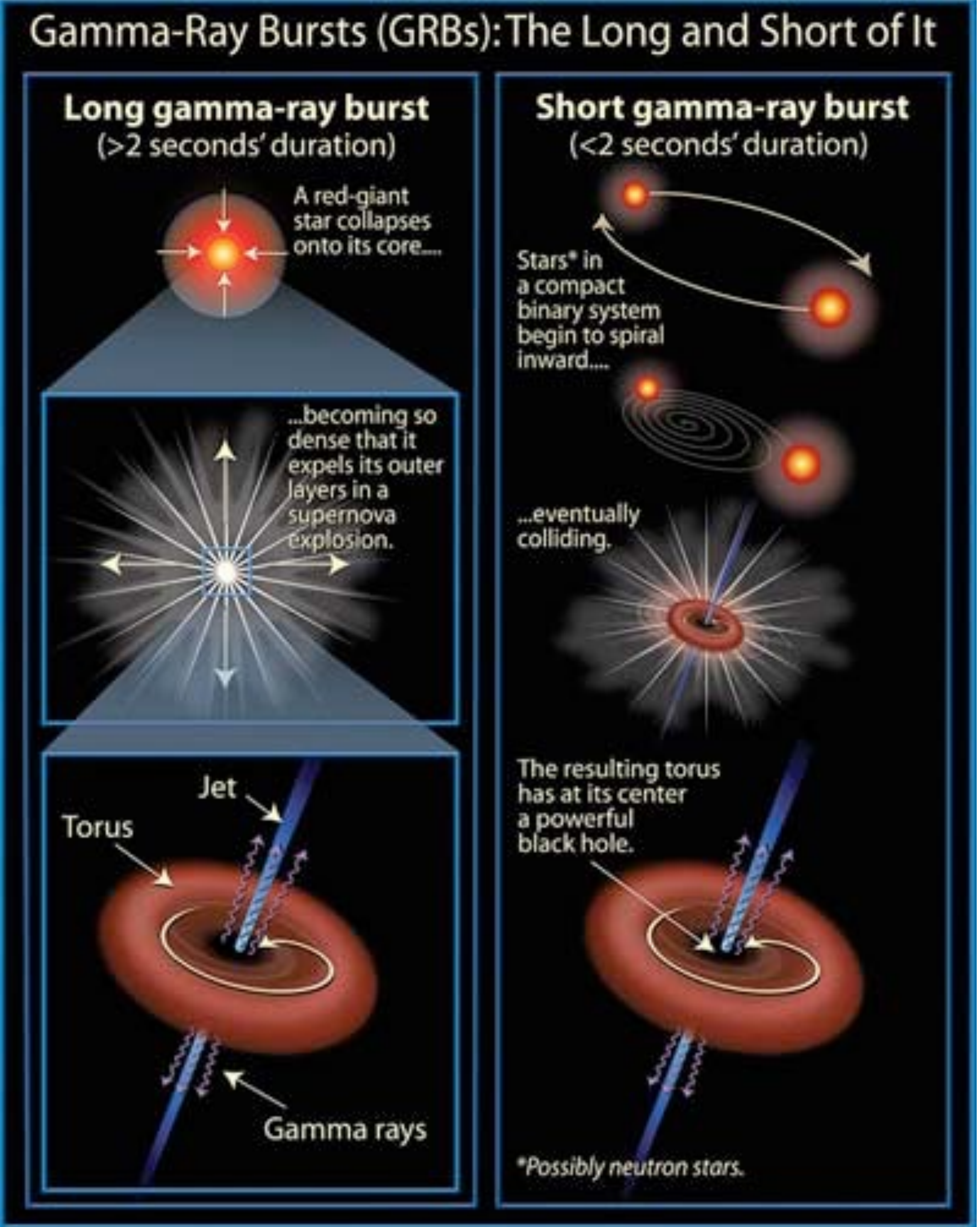
$$\gamma = \frac{1}{\sqrt{1 - \frac{u^2}{c^2}}}$$

v^2



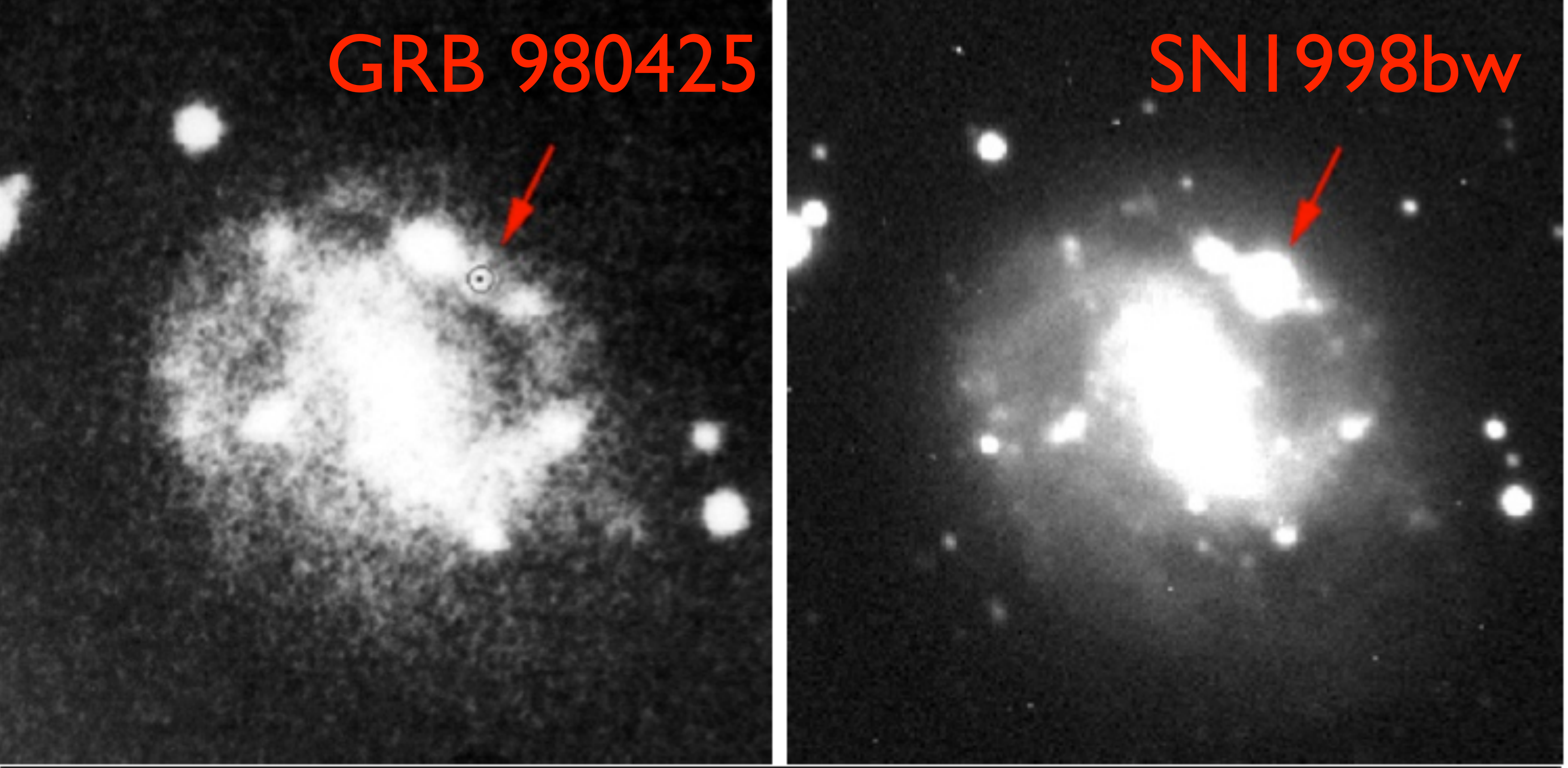
Collapsar model or hypernova (long GRBs):

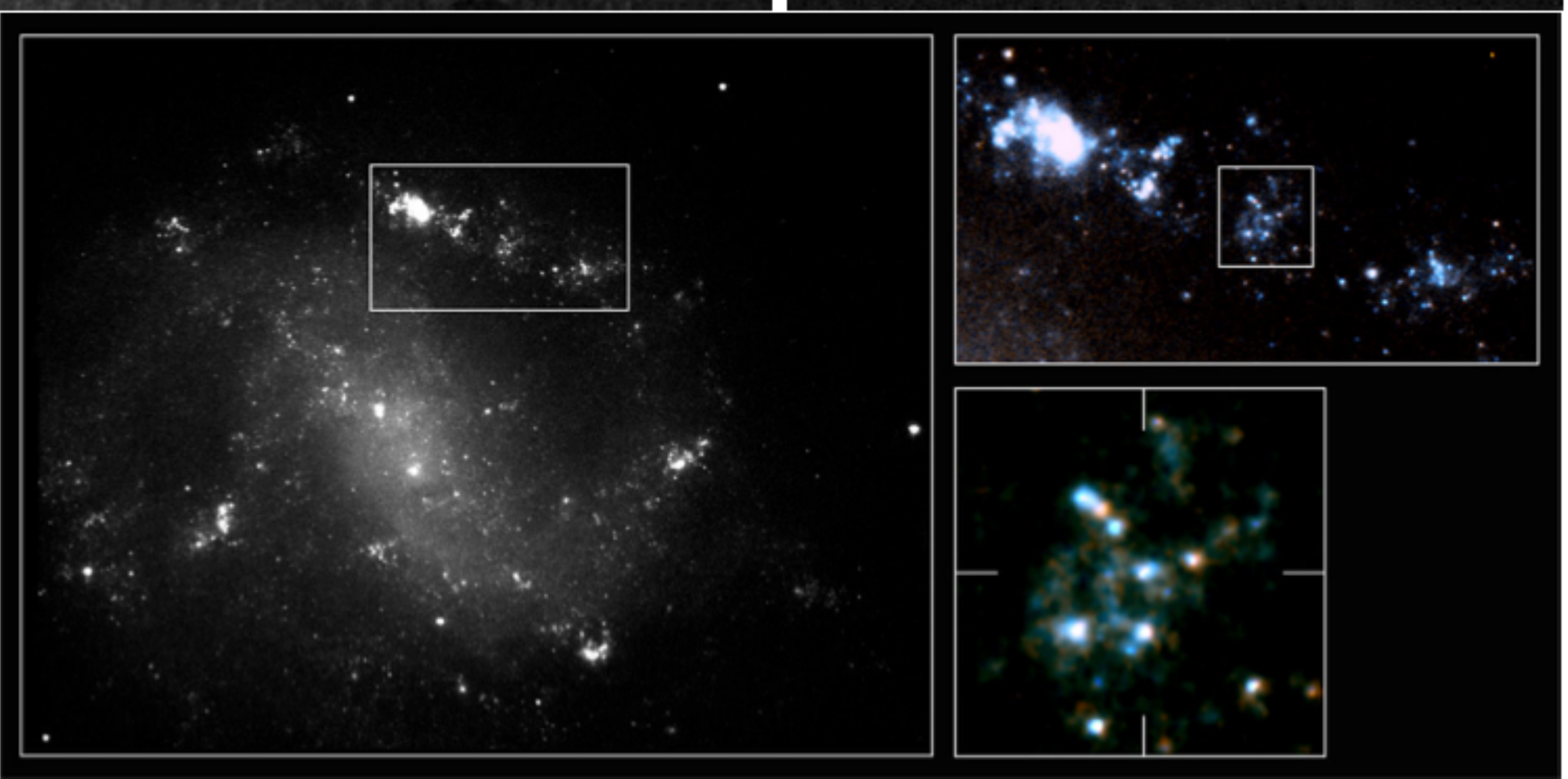
When a core-collapse SN occurs, either a NS or a BH will form depending on mass, metallicity, and rotation of progenitor. For a progenitor with a large enough mass, the central object will be a BH with a debris disk surrounding it. The collimating effect of the debris disk and associated magnetic fields would lead to a jet emanating from the center of the SN. The jet will plow its way through the overlaying material of the infalling stellar envelope, producing the bursts of gamma ray.



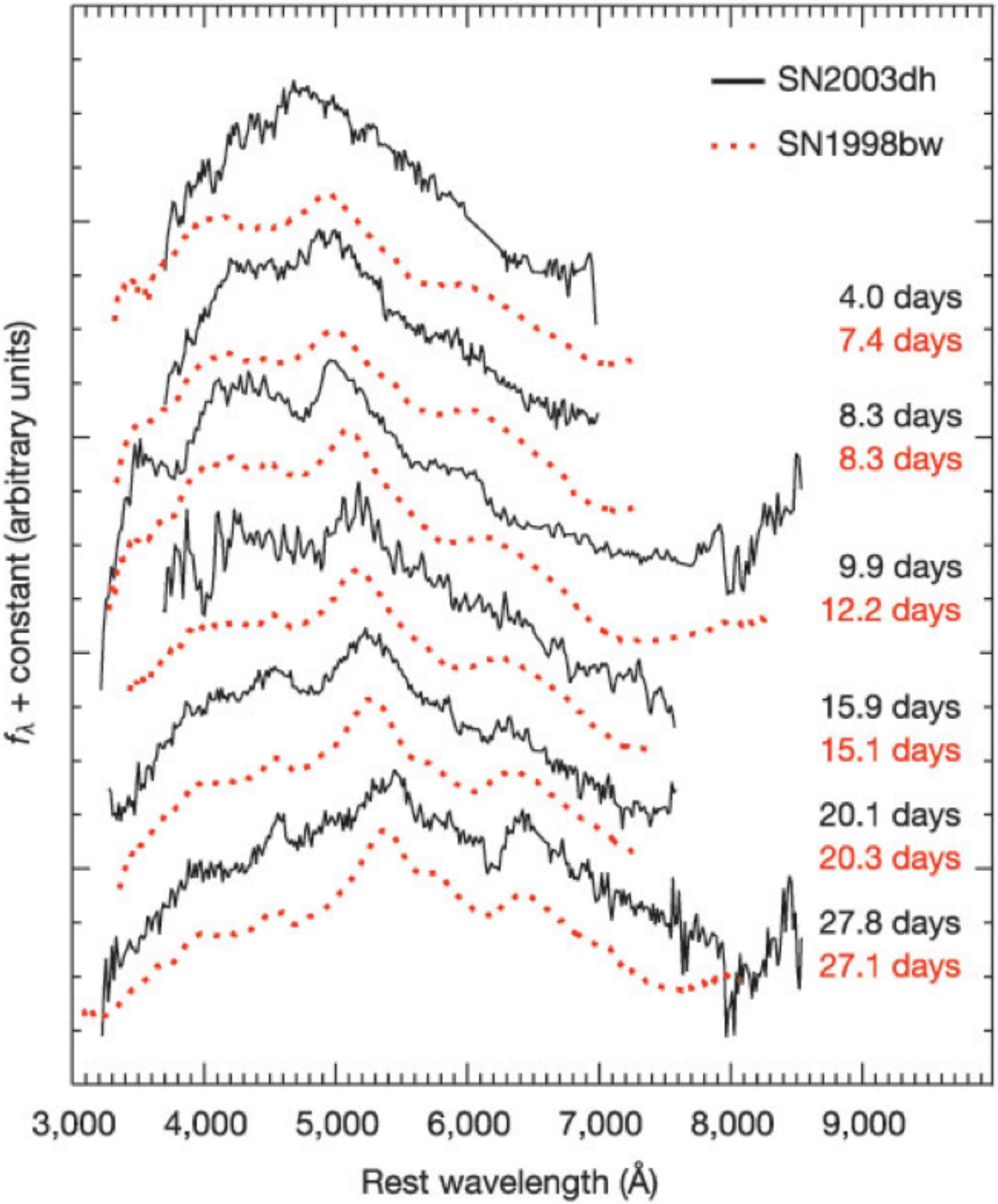
Evidence for collapsar model: long GRBs found exclusively in galaxies with active star formation (i.e., lots of short lived massive stars). Several known cases where a supernova is observed directly following a long duration GRB.

Short GRBs tend to be found in all types of galaxies including those with no active star formation. Merging neutron stars are strong sources of gravitational waves - this detection would be the definitive proof of this theory.





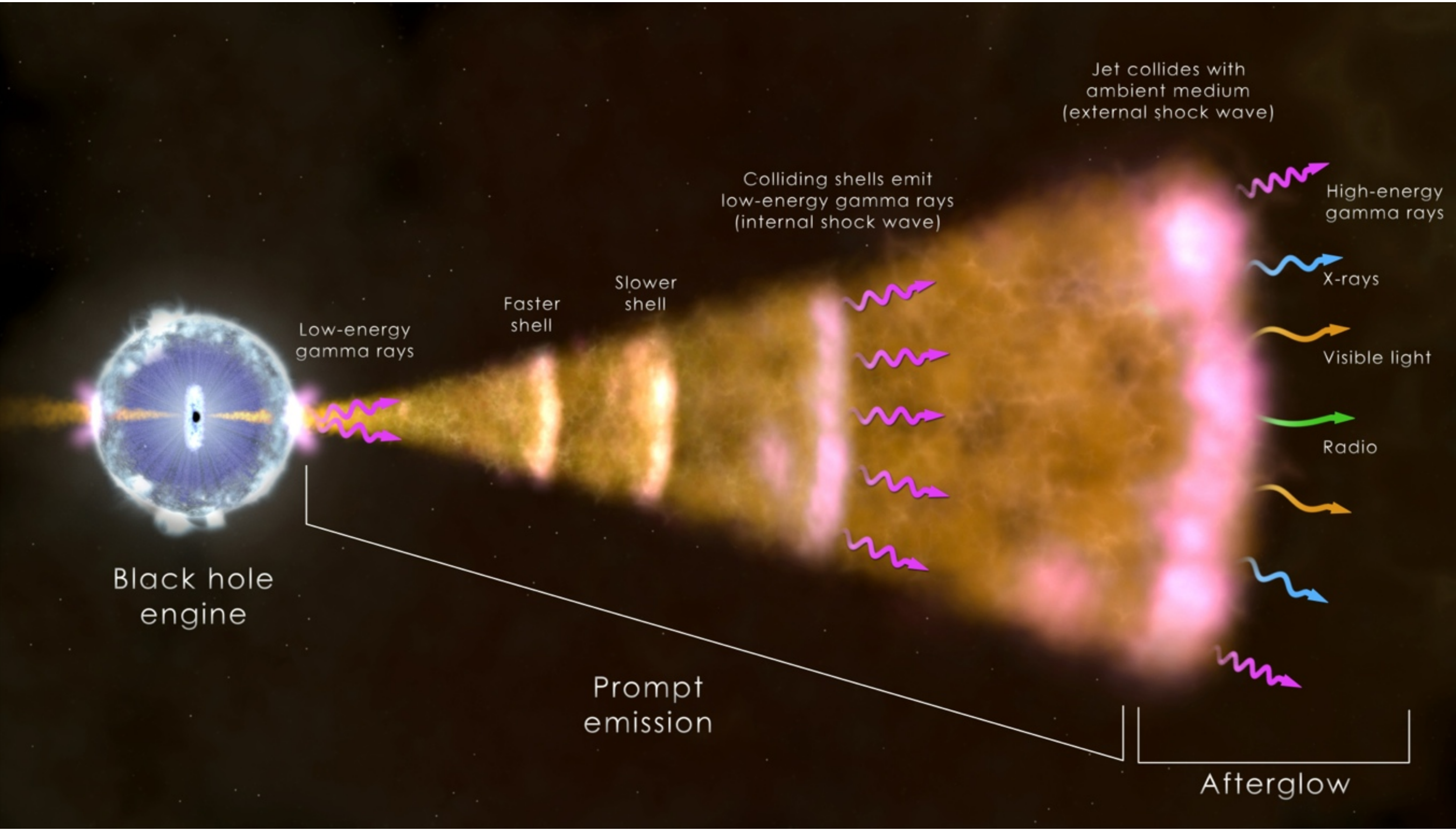
HST image of host galaxy 778 days after SN explosion, showing a large star-forming region of a spiral arm (Fynbo+2000)



Connection between long GRBs and core-collapse SN explosions

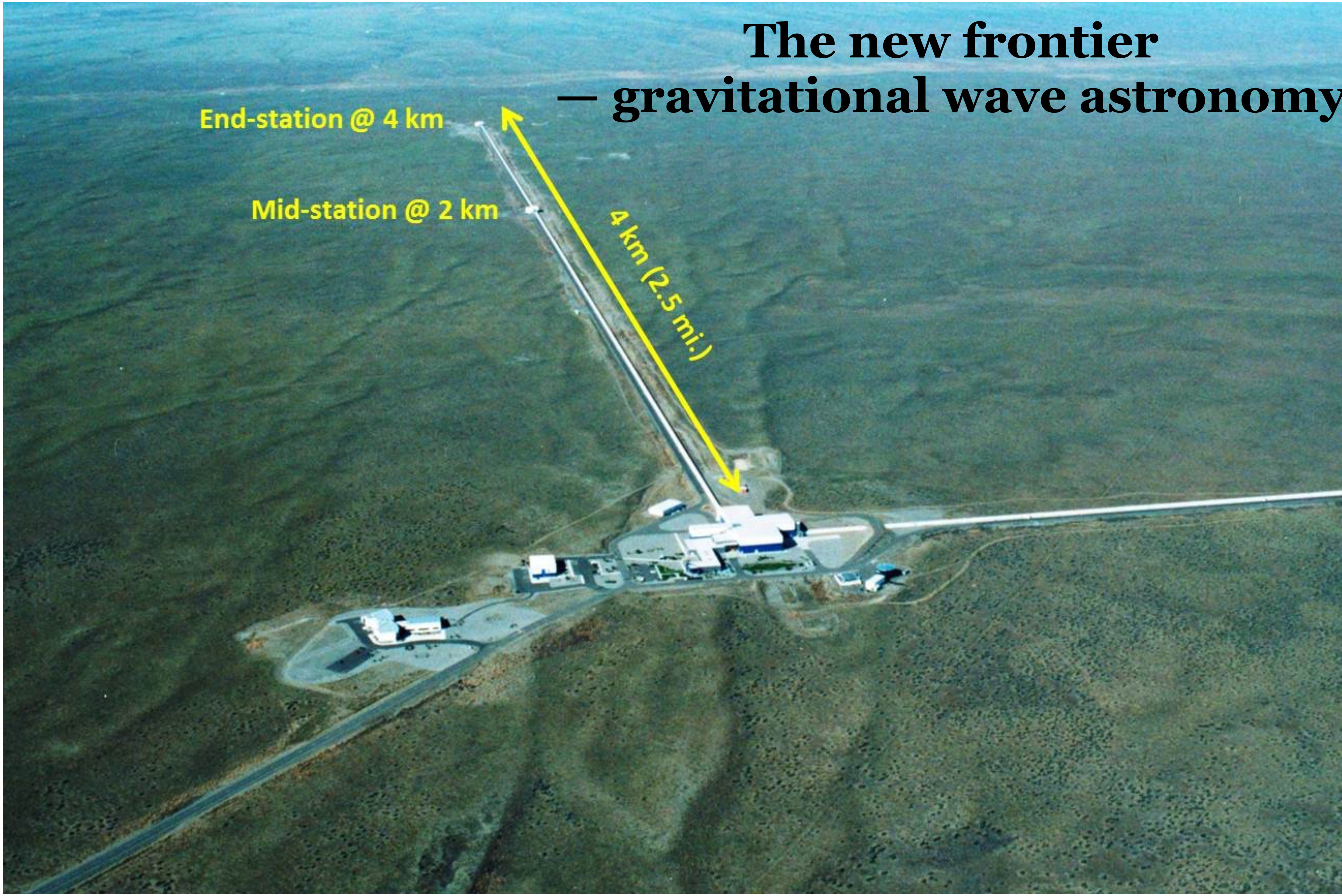
Spectral evolution of GRB-SNe 1998bw (Patat+2001) and 2003dh (Hjorth+2003).

Solid lines indicate spectra of SN 2003dh obtained by subtracting a model for the afterglow and host galaxy contributions from the spectra. Dotted red lines indicate spectra of SN 1998bw taken at similar epochs. Times after the GRB are indicated in the rest frame.

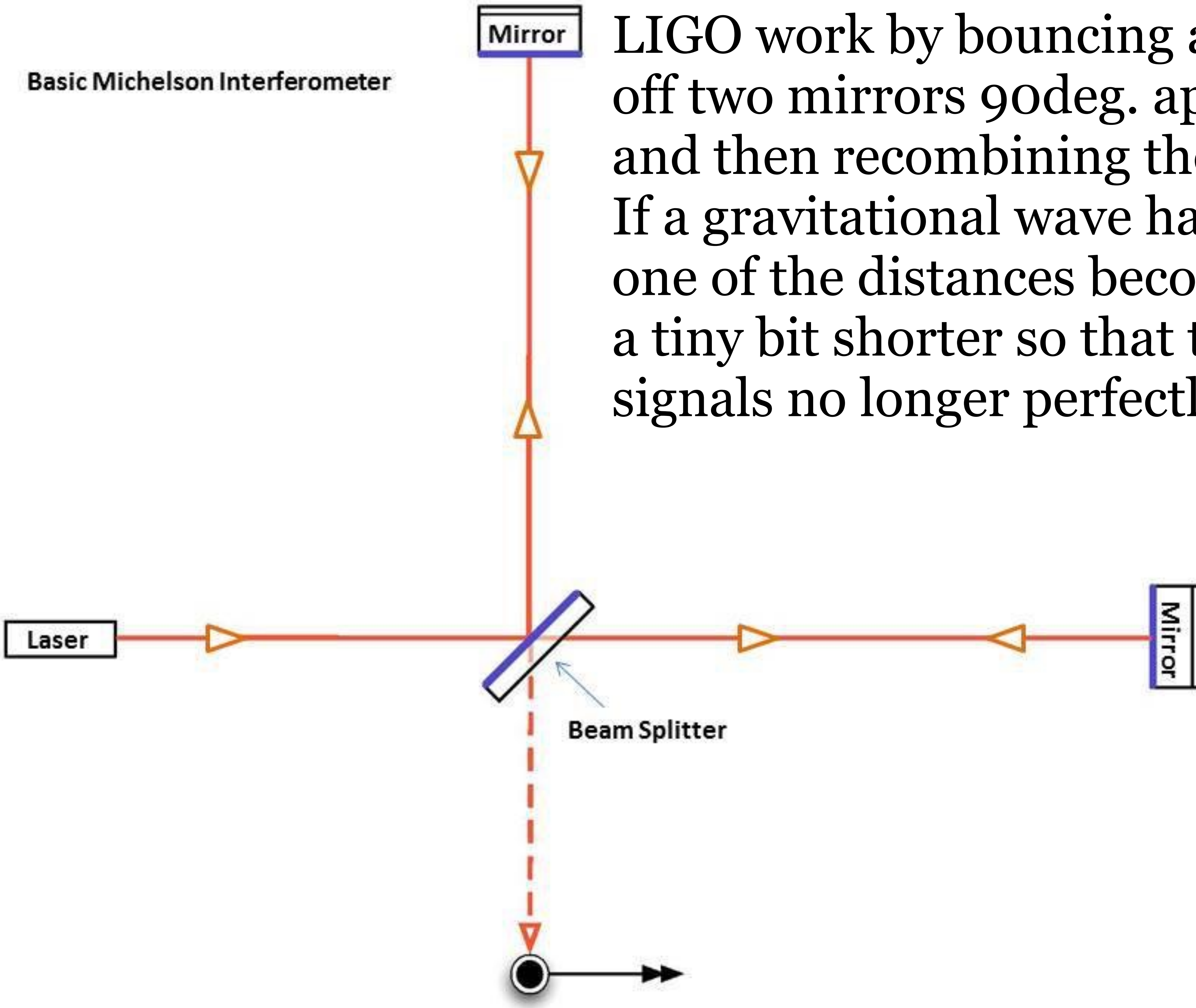


Jet collides with
ambient medium
(external shock wave)
Colliding shells emit
low-energy gamma rays
(internal shock wave)
High-energy
gamma rays
X-rays
Visible light
Radio
Slower
shell
Faster
shell
Low-energy
gamma rays
Black hole
engine
Prompt
emission
Afterglow

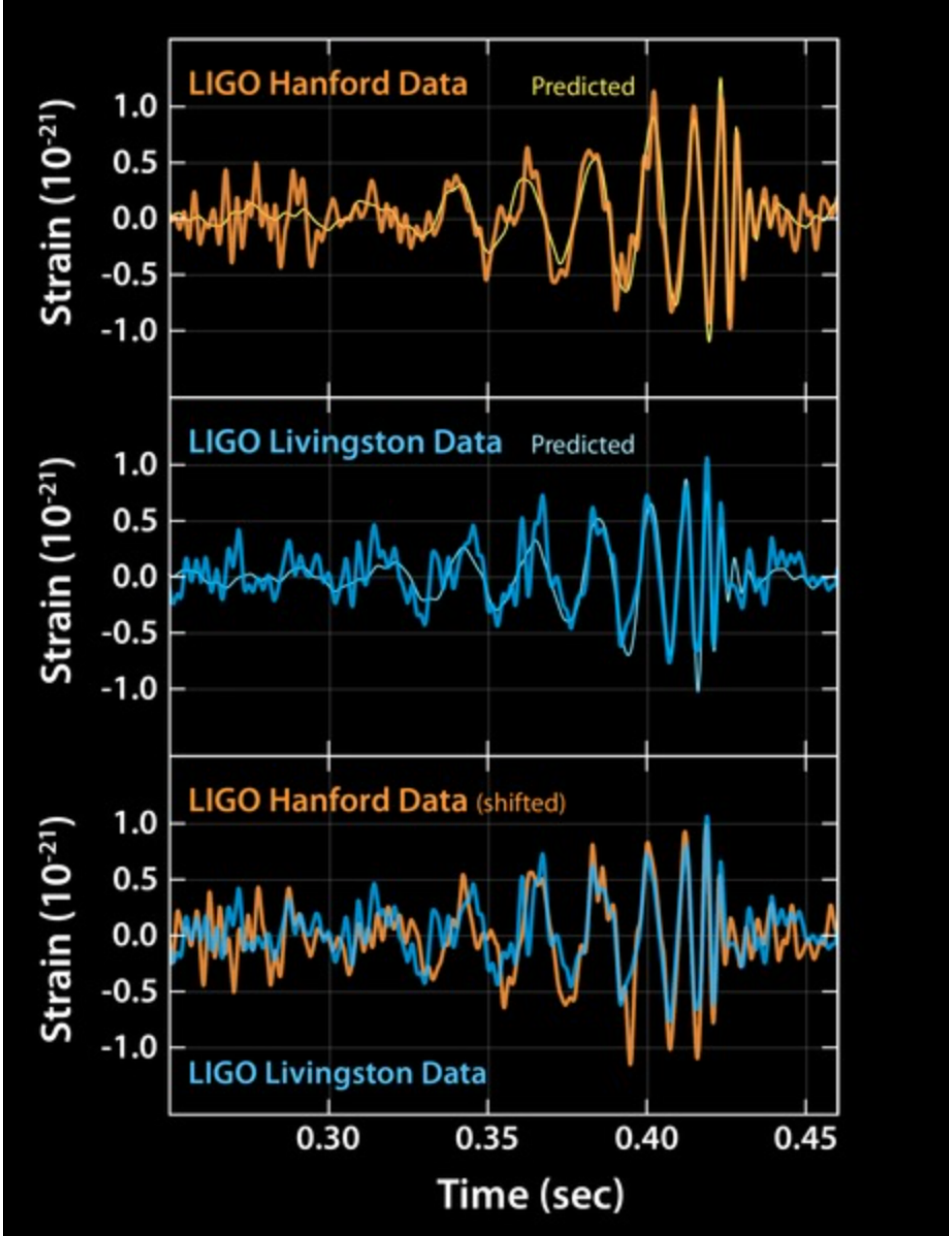
The new frontier — gravitational wave astronomy



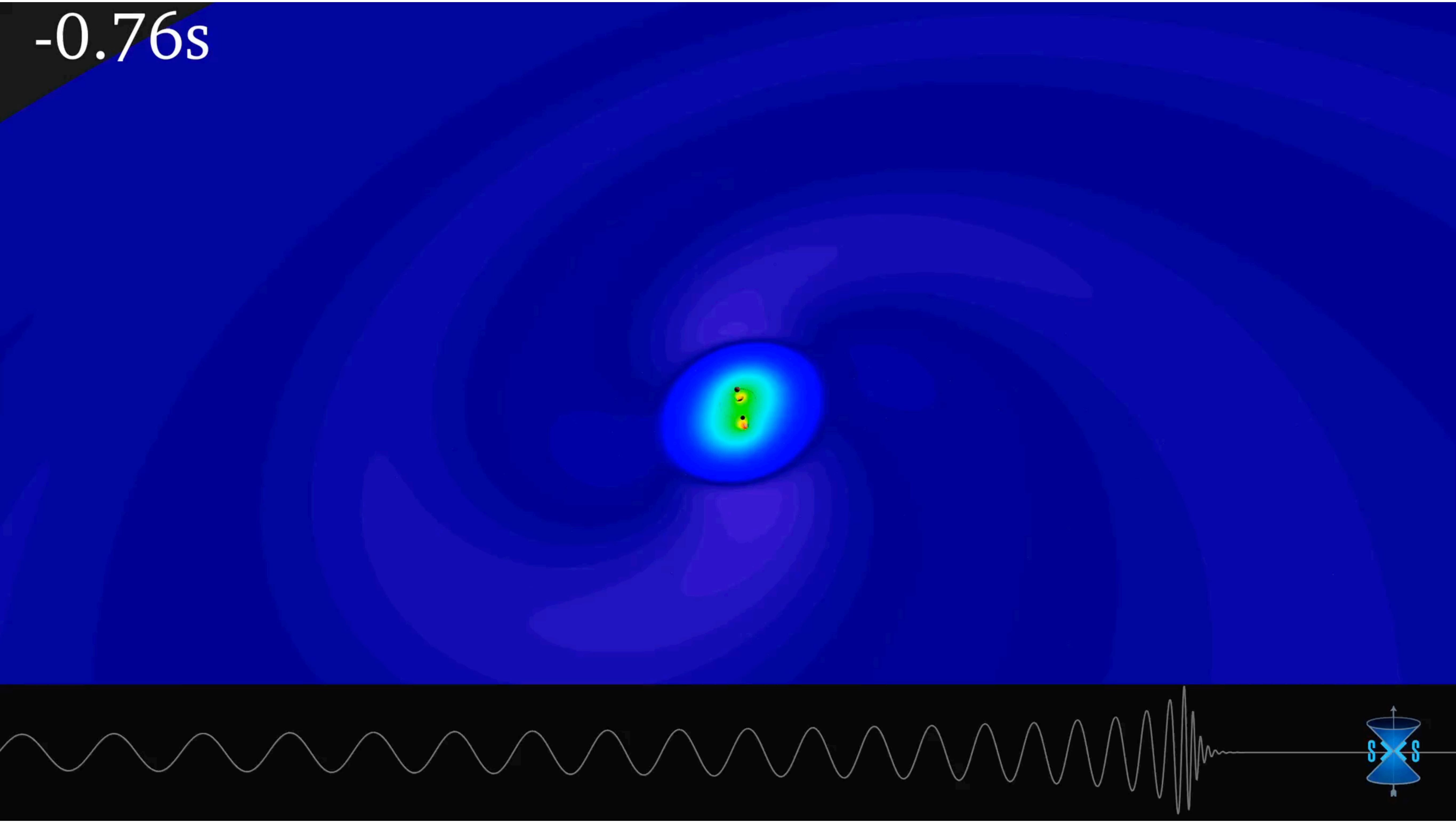
(image: ligo.caltech.edu)



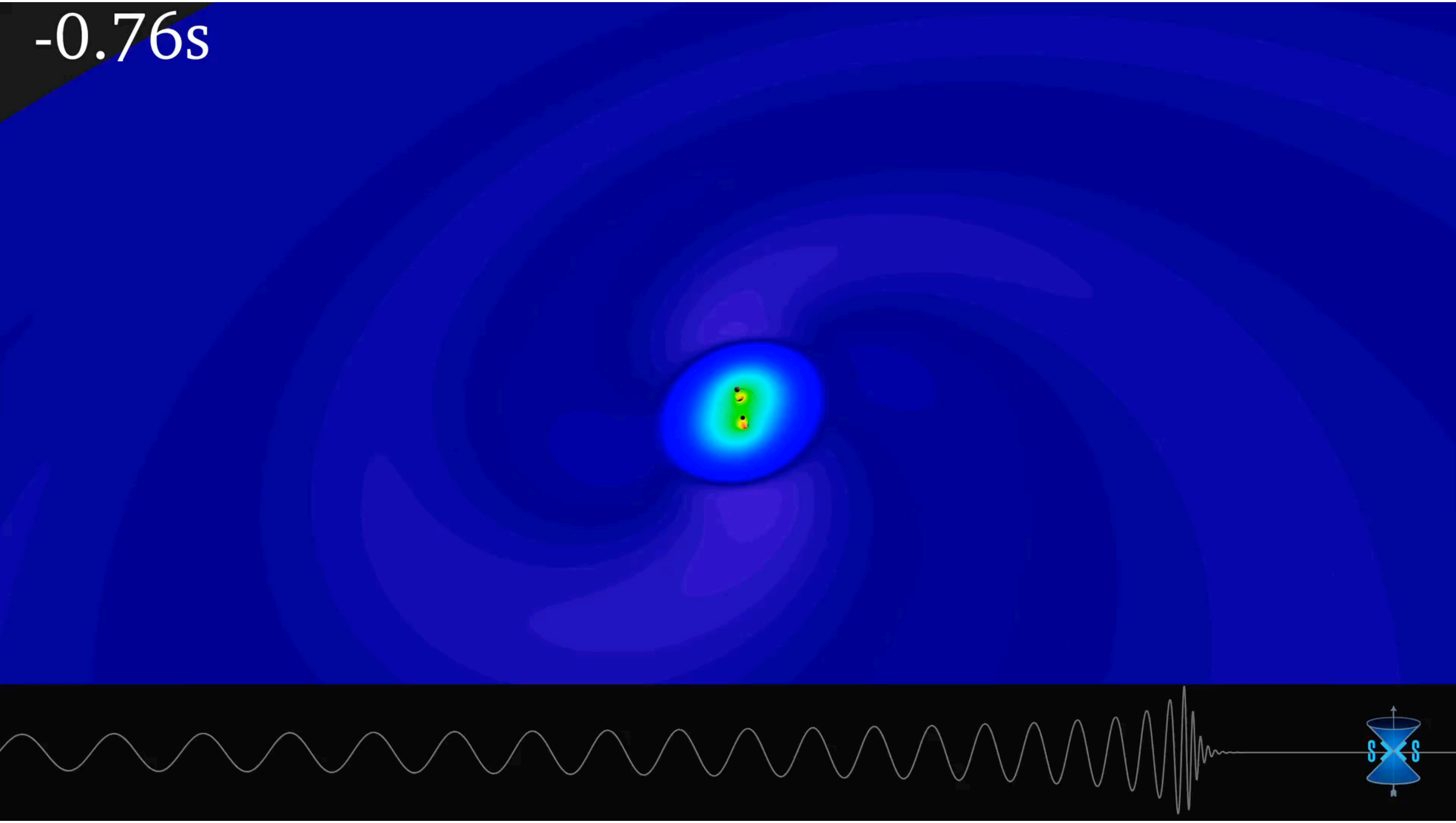
LIGO work by bouncing a laser
off two mirrors 90deg. apart
and then recombining the signal.
If a gravitational wave has passed by,
one of the distances becomes
a tiny bit shorter so that the two
signals no longer perfectly line up.



The first ever gravitational wave signal was detected — data completely matched from the two LIGO facilities and predictions from theory of two 30 M_{Sun} black holes merging.



Simulation of merging black holes and expected grav. wave signal (ligo.caltech.edu).



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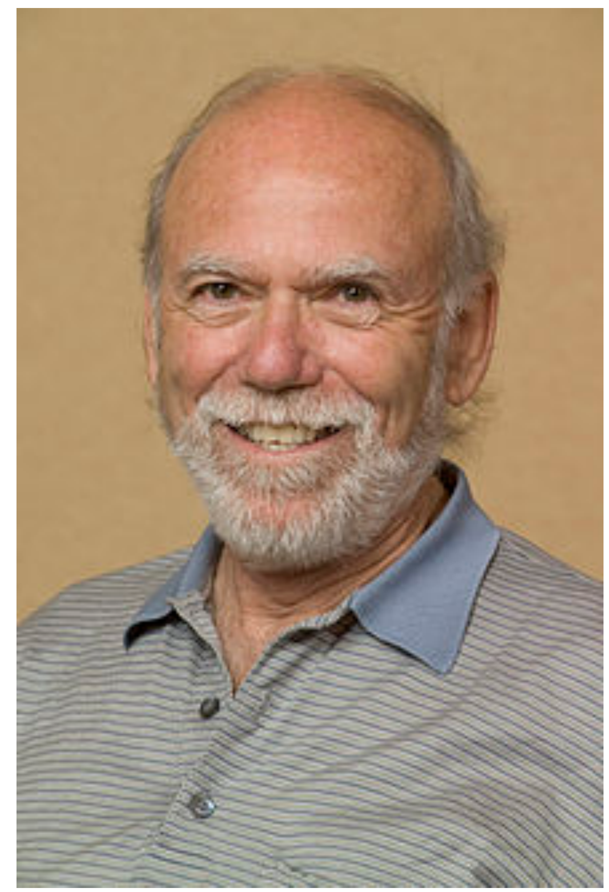
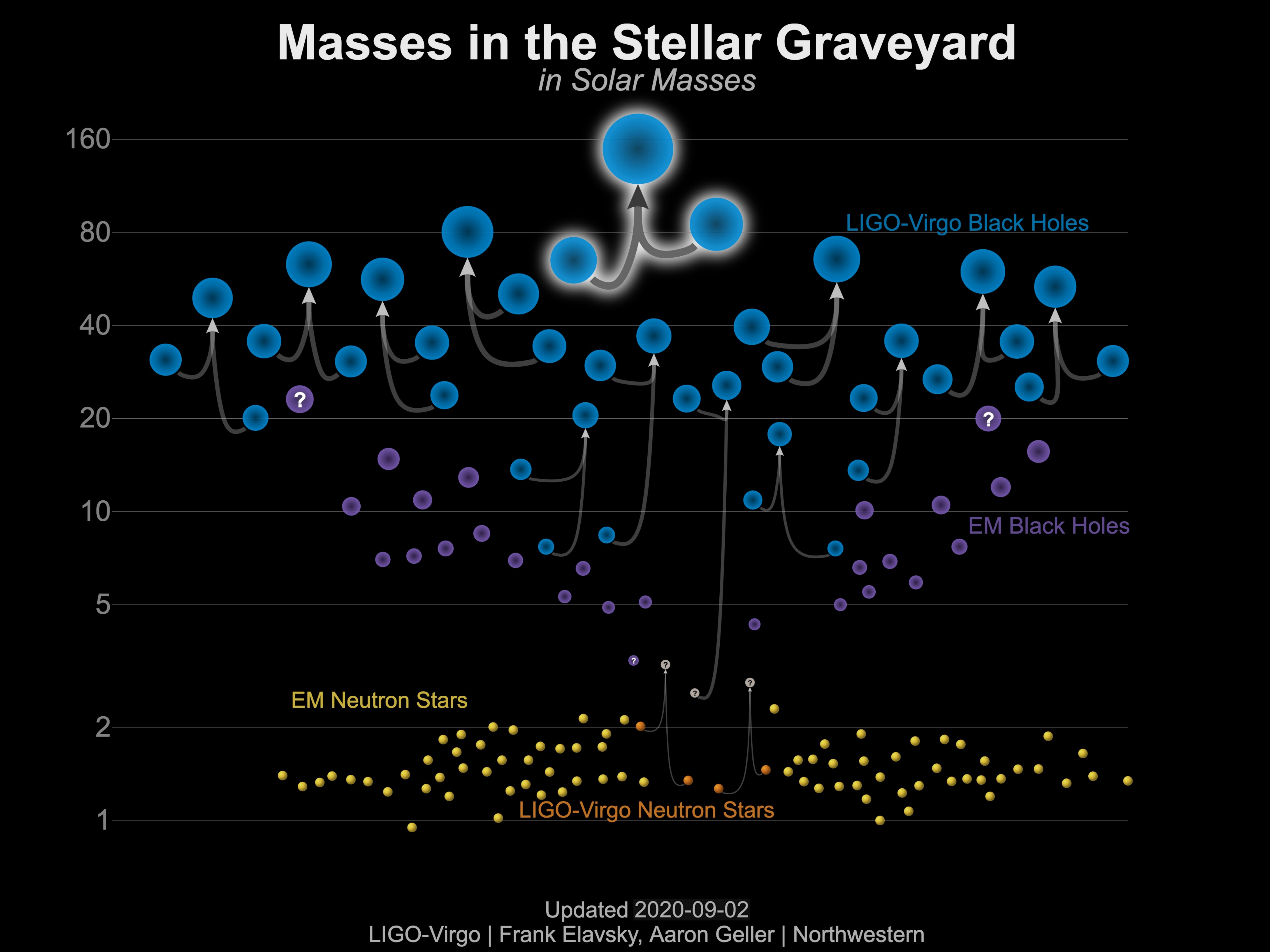
Nobel prize in physics in 2017 went to
the LIGO team for this discovering confirming Einstein's GR,
below are its leaders.

Ray Weiss (MIT)

Kip Thorne
(Caltech)

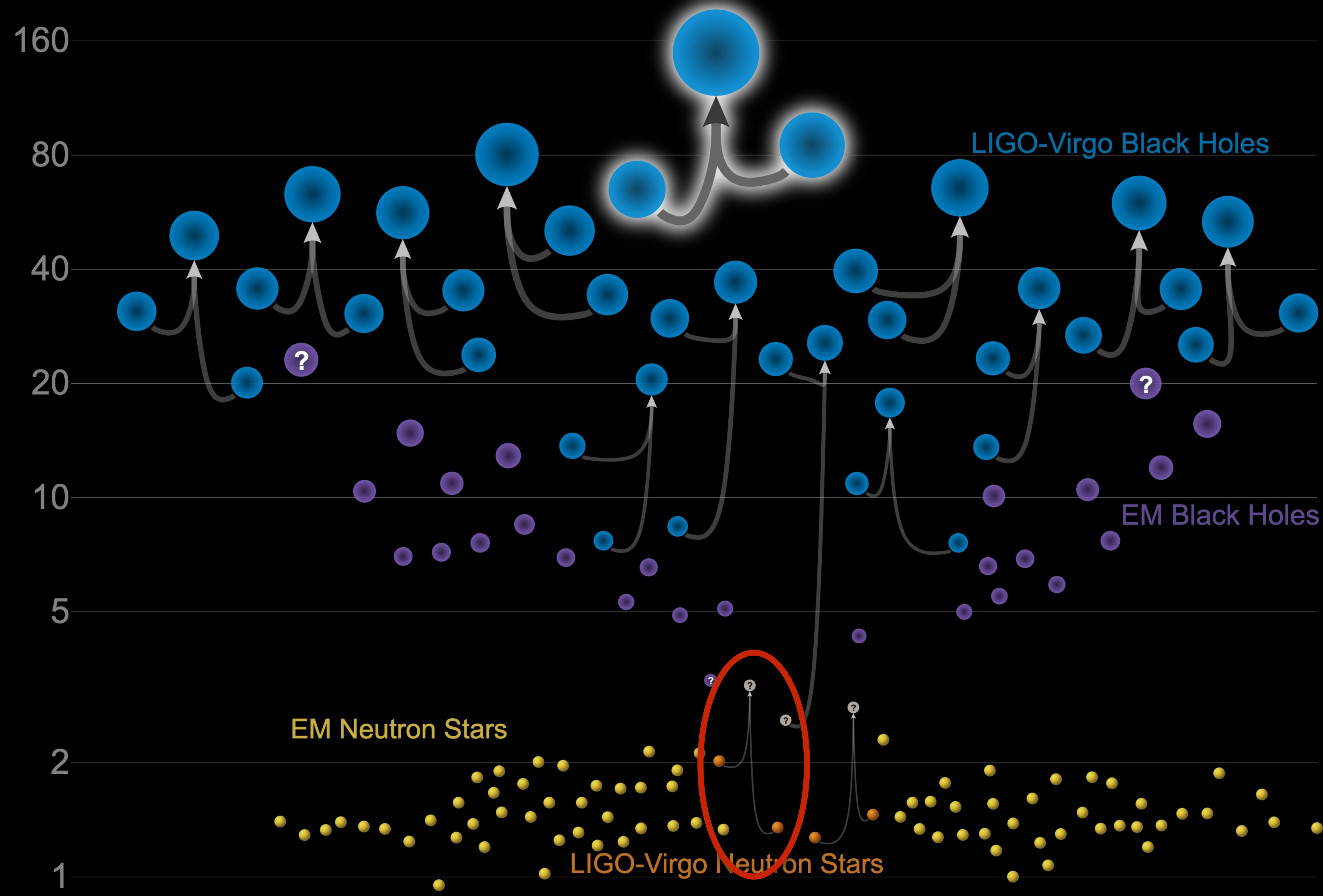


Barry Barrish
(Caltech)


Masses in the Stellar Graveyard
in Solar Masses
160
80
40
20
10
5
2
1
LIGO-Virgo Black Holes
EM Black Holes
EM Neutron Stars
LIGO-Virgo Neutron Stars
Updated 2020-09-02
LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern

Masses in the Stellar Graveyard

in Solar Masses



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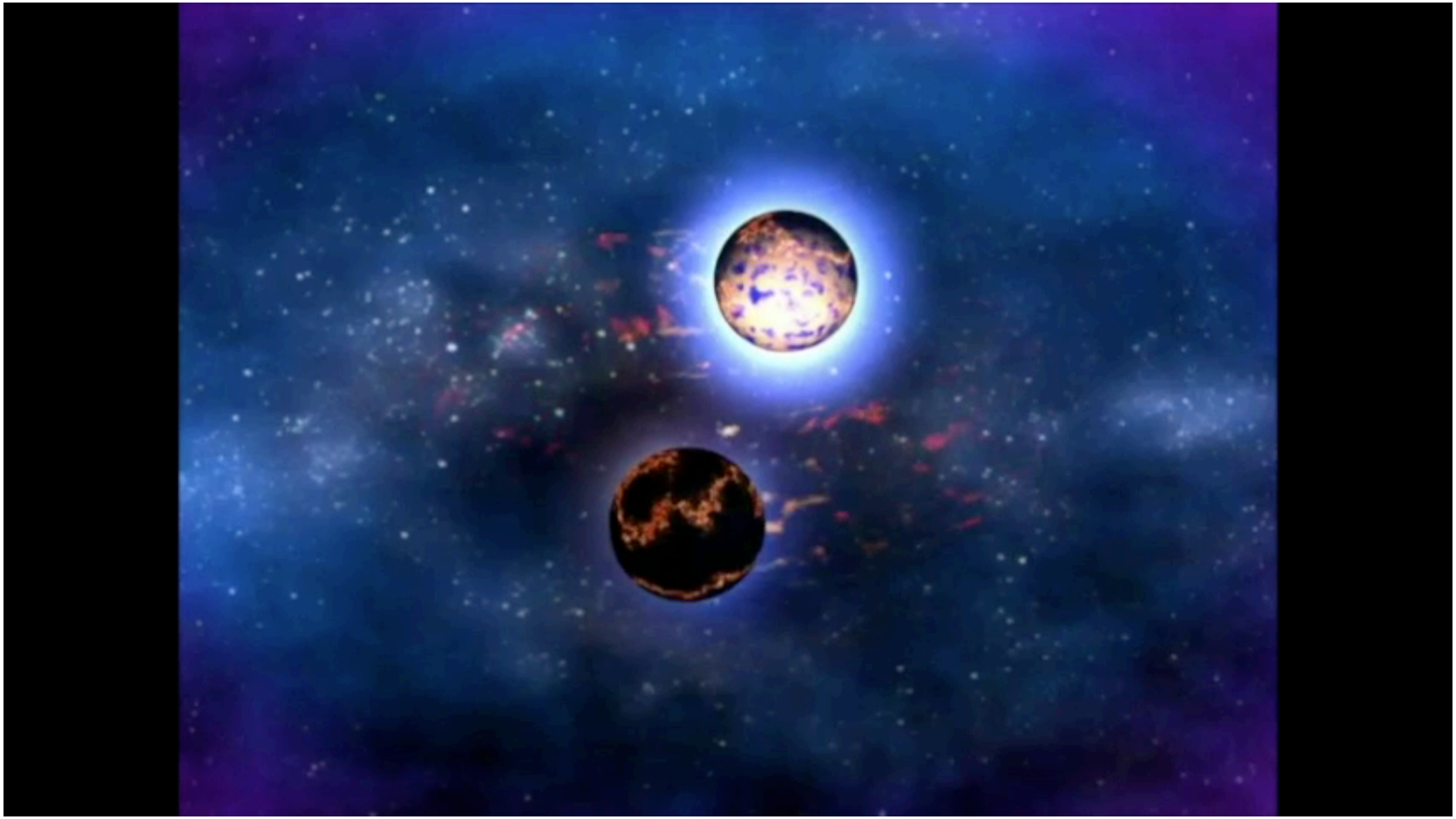
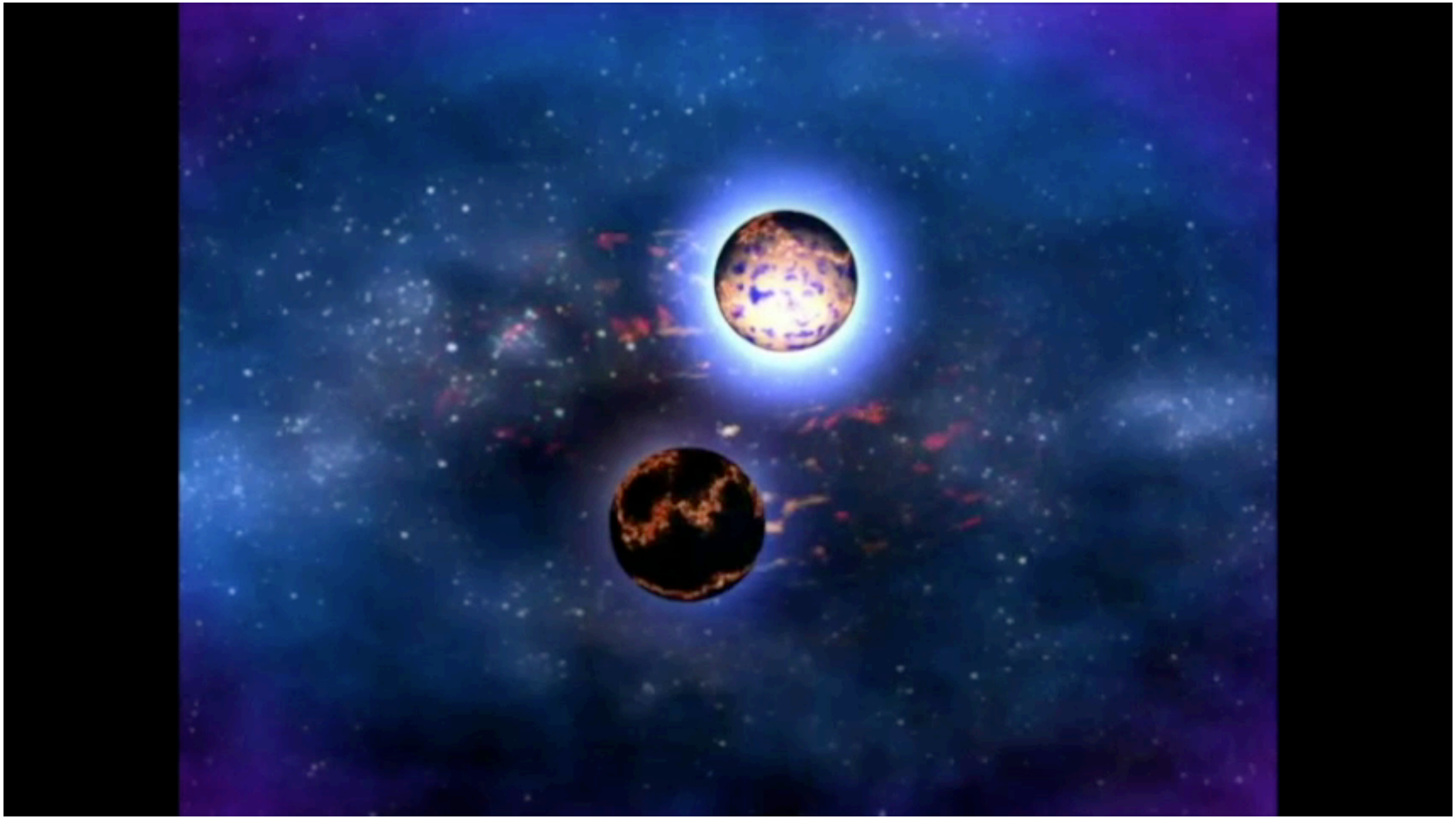
LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern

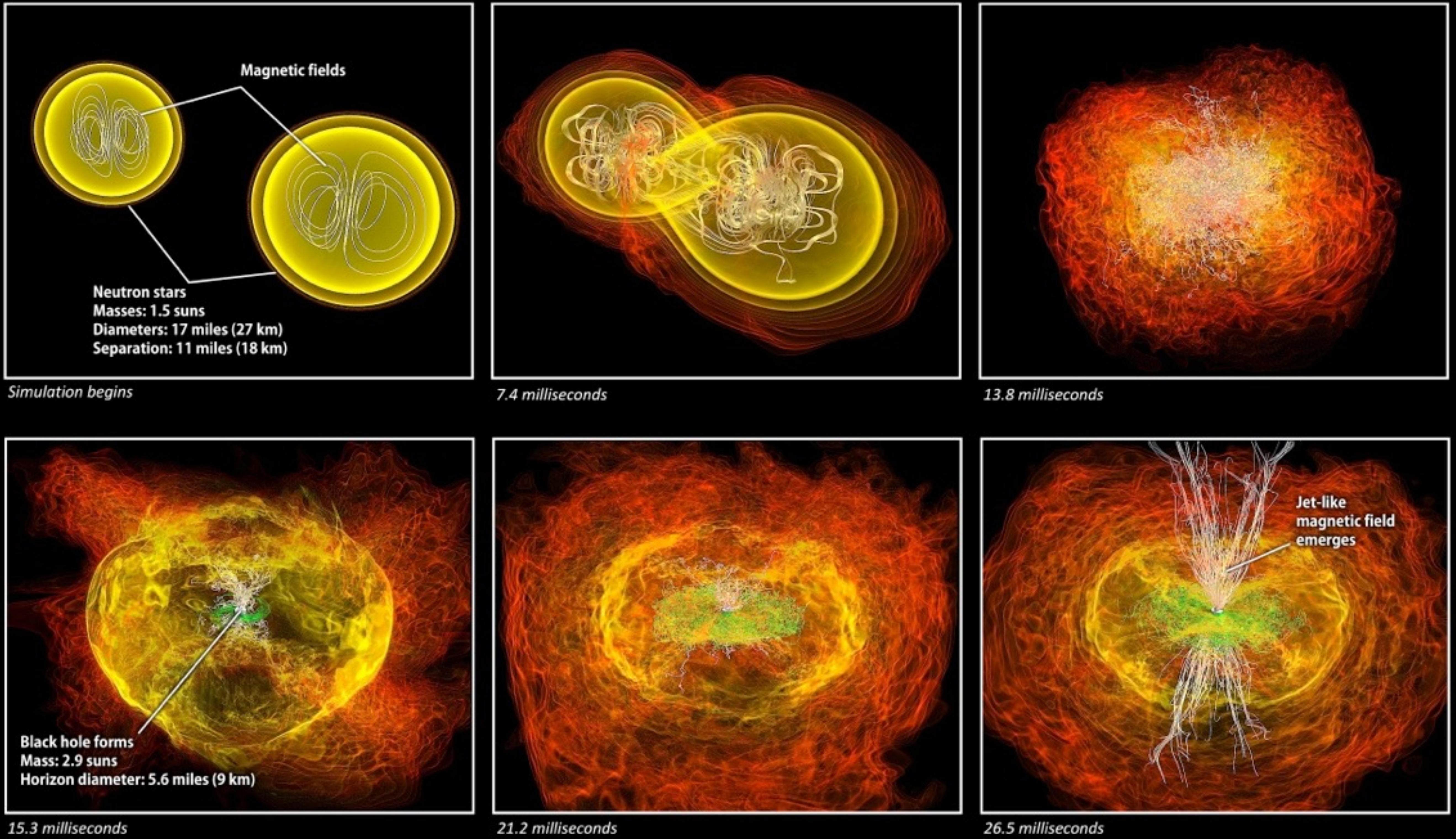


animation NASA/Goddard Space Flight Center

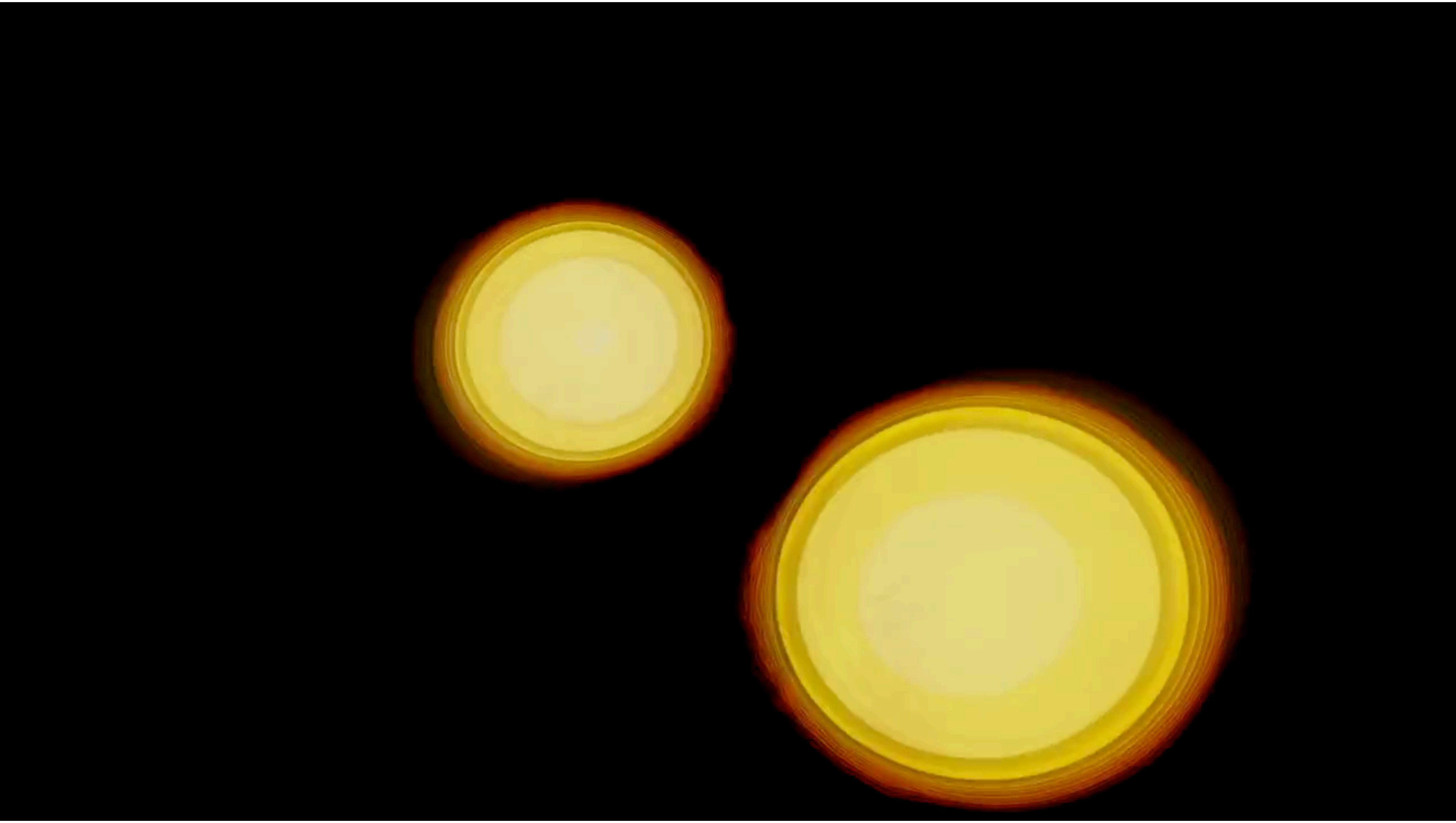


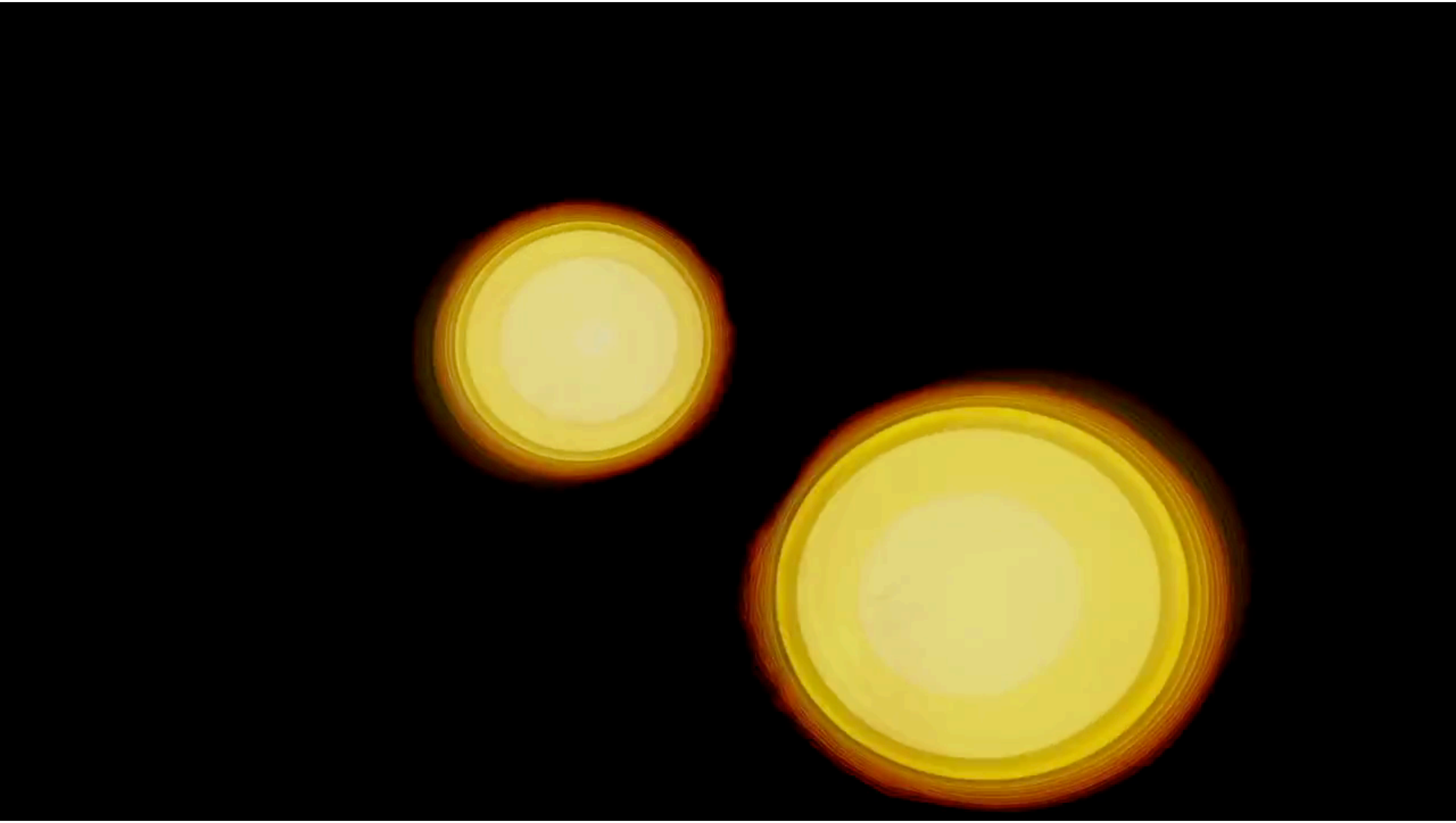
animation NASA/Goddard Space Flight Center

Crashing neutron stars can make gamma-ray burst jets

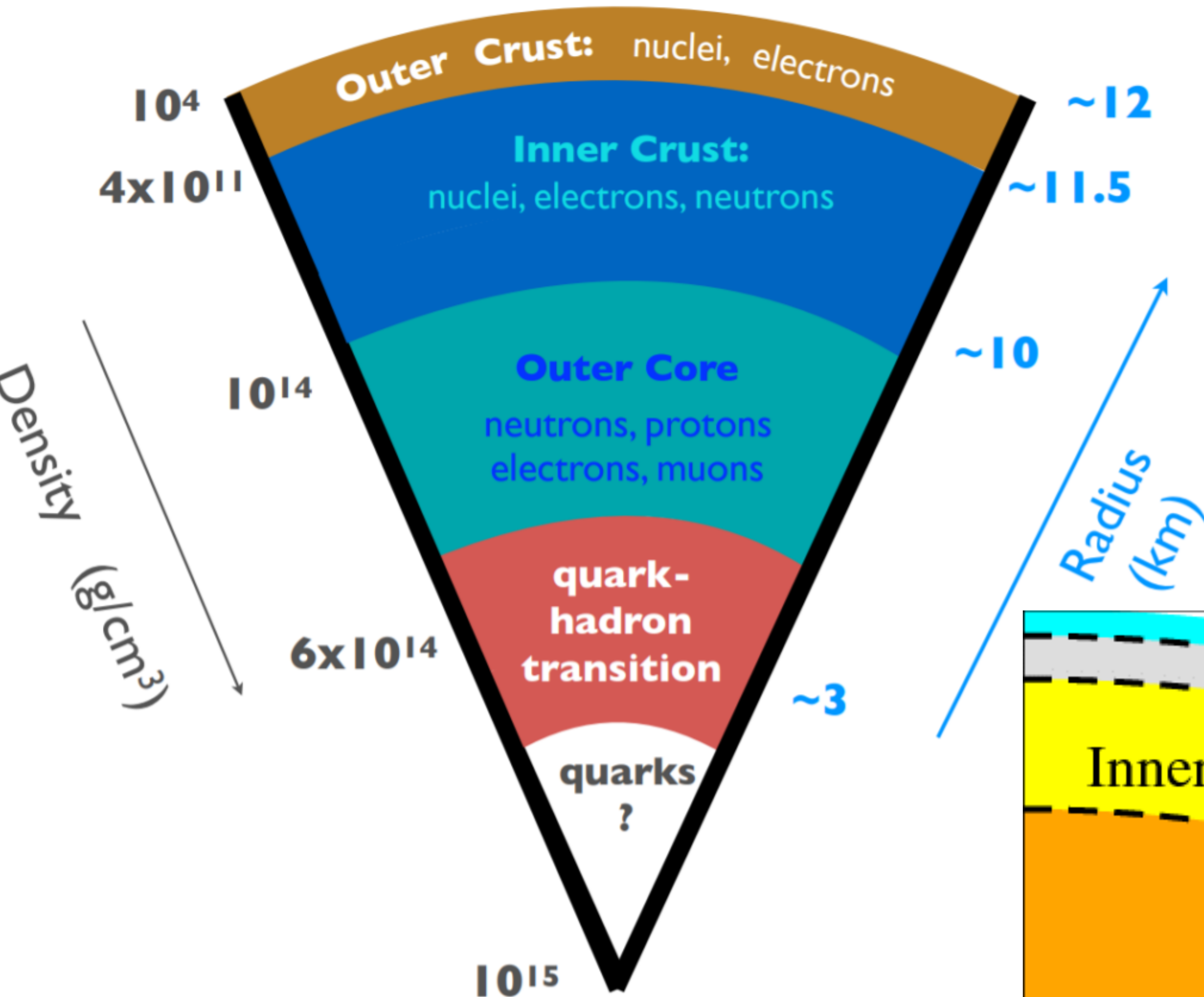


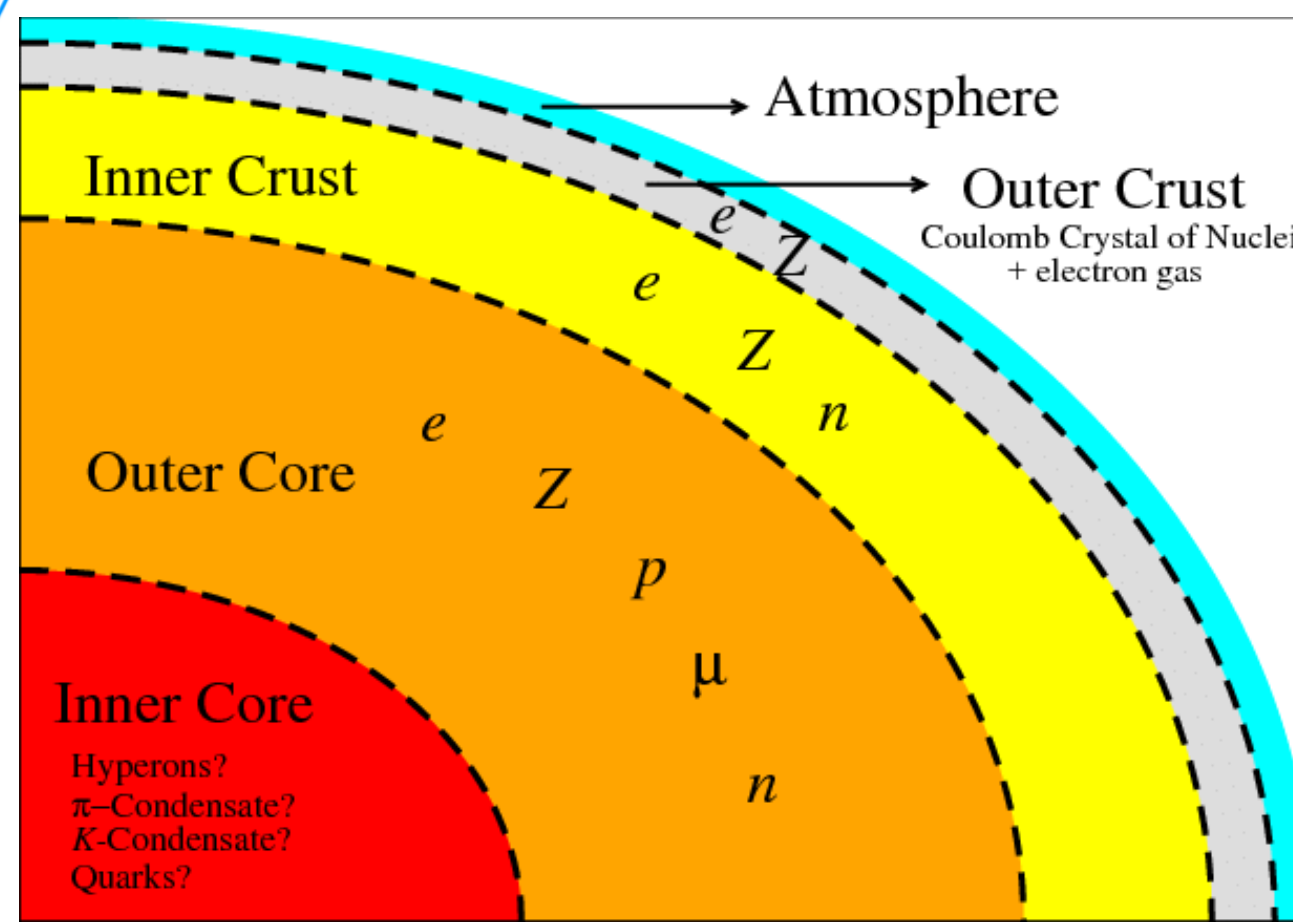
Credit: NASA/AEI/ZIB/M. Koppitz and L. Rezzolla





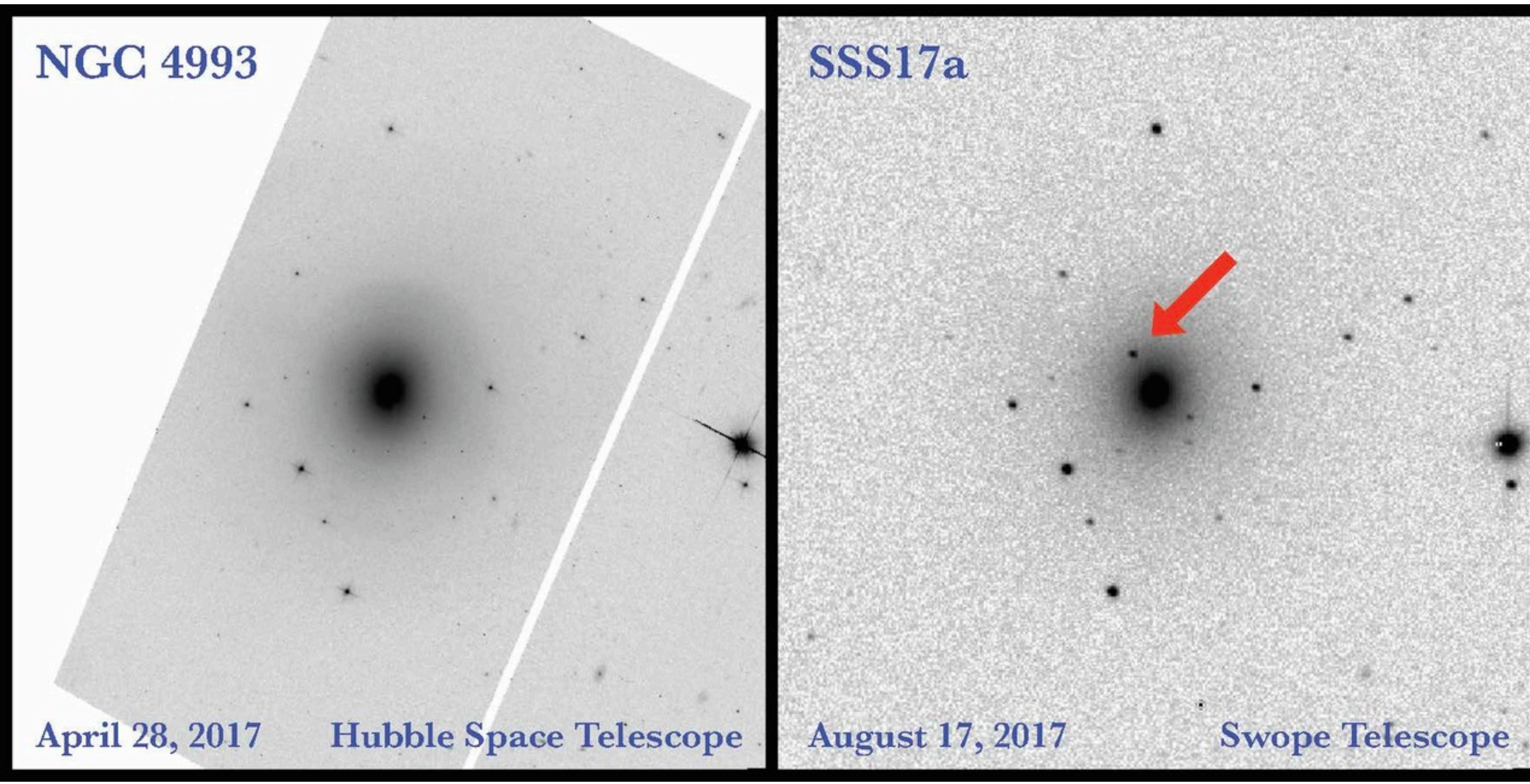
The LIGO signal now can place constraints on how distant this merger was (roughly where on the sky it was), the masses of the progenitors and even constraints on their initial radii — which **helps constrain the very uncertain equation of state**!





This was **the first object ever, to be studied in gravitational waves as well as then found in gamma-rays, X-rays, optical, IR, radio** — just about everybody on a telescope at the time looked at the part of the sky that LIGO saw this event. Astronomers are still processing all the information, but it is clear that the added constraints from the gravitational-wave signal coupled with the EM signal mean that **we are at the beginnings of a real revolution in our ability to study these exotic objects**.

GW170817 optical counterpart



Gamma-ray Bursts

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