PHZ 7097 | Modern Astrophysics

Lecture XXVII.

Gamma-ray bursts

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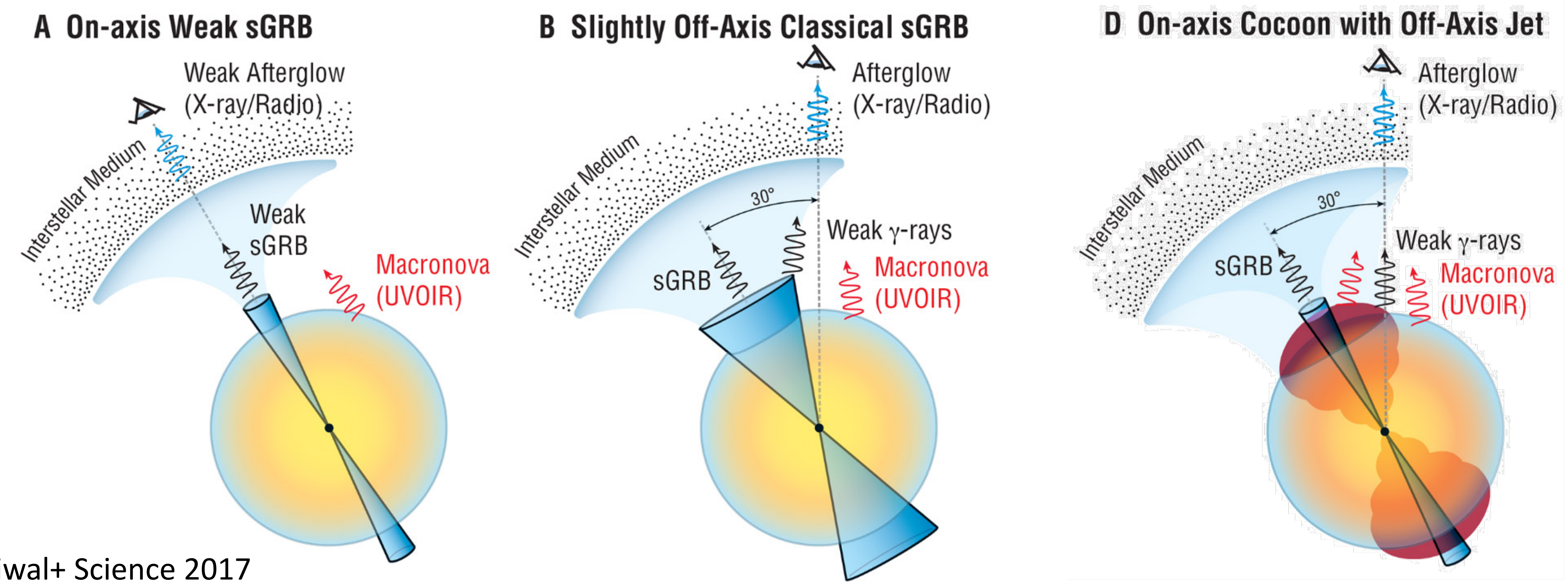
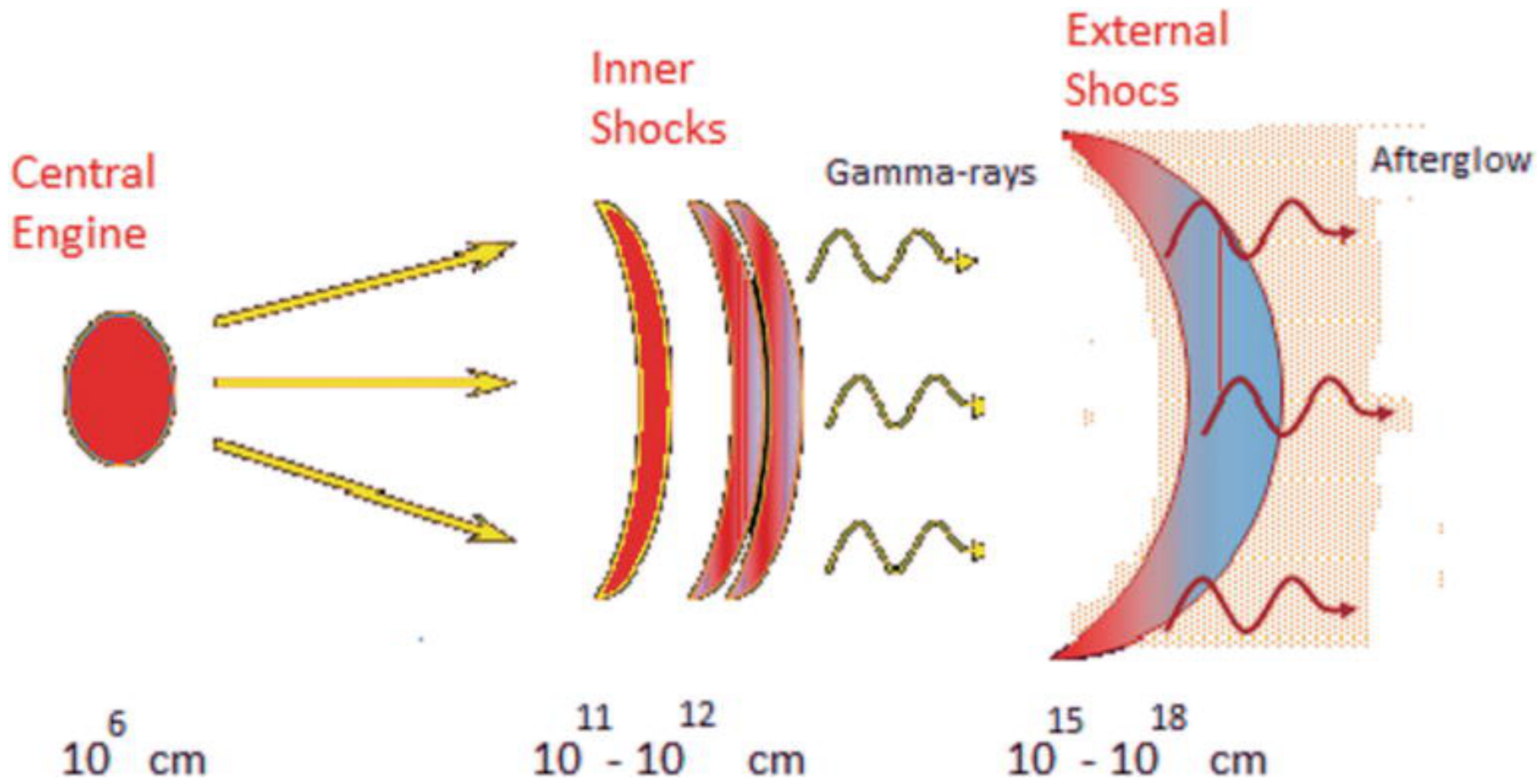
Gamma-ray burst

- Very weak --- energy orders of magnitude below weakest GRB detected
- Short-hard --- consistent with binary neutron star picture
- Host galaxy --- low star formation, probably very old NSs (Blanchard+ 2017)
- X-ray/Radio delay (9 and 15 days) --- unusual, consistent with off-axis scenario
- There was a GRB → merger remnant collapsed to a black hole
- 1.7 s delay --- e.g. jet propagation before shock
- Fundamental limits: Constraint on speed of gravity: ~10^{-15}c | rules out DM emulators | etc.

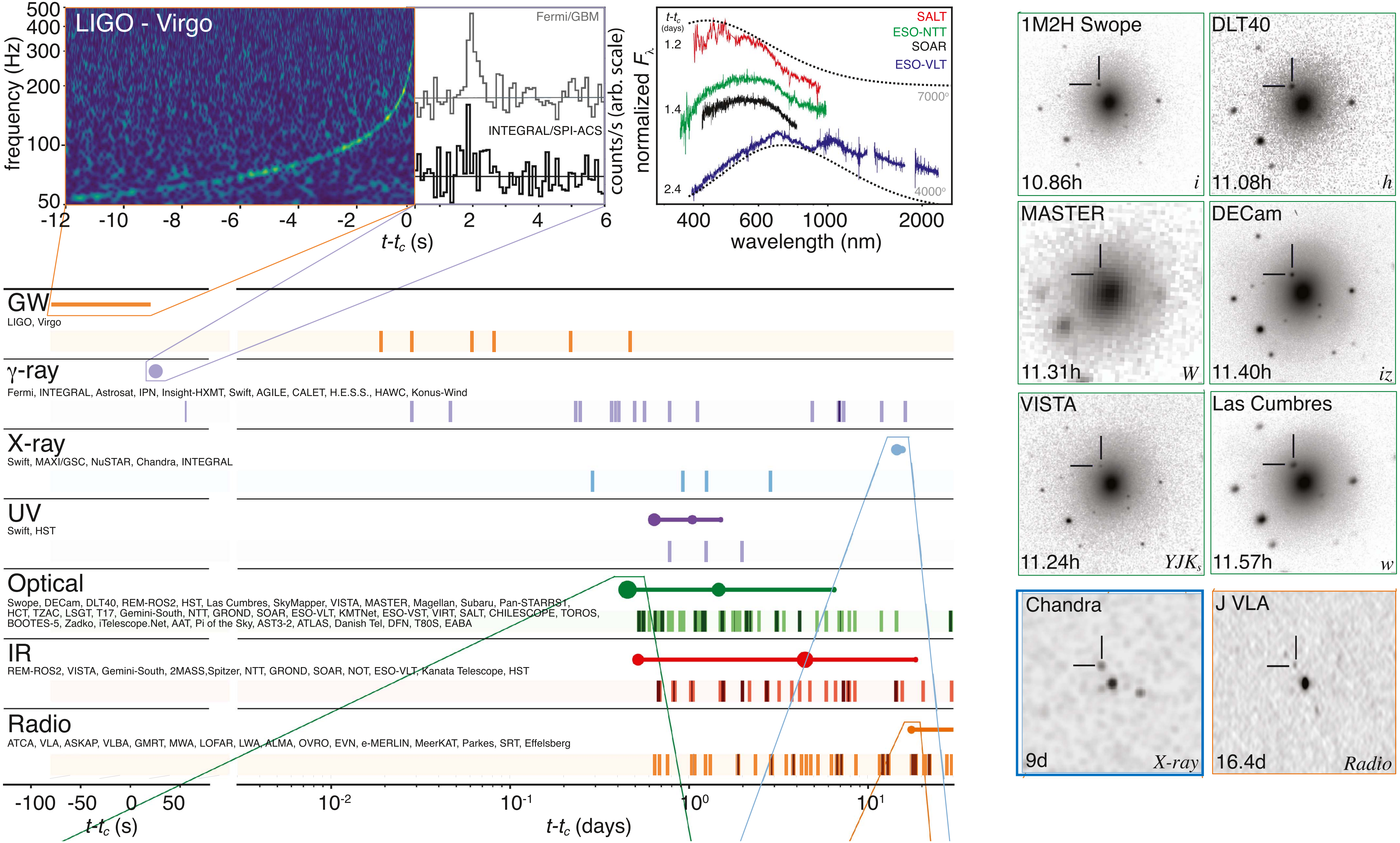


Kasliwal+ Science 2017

Afterglow

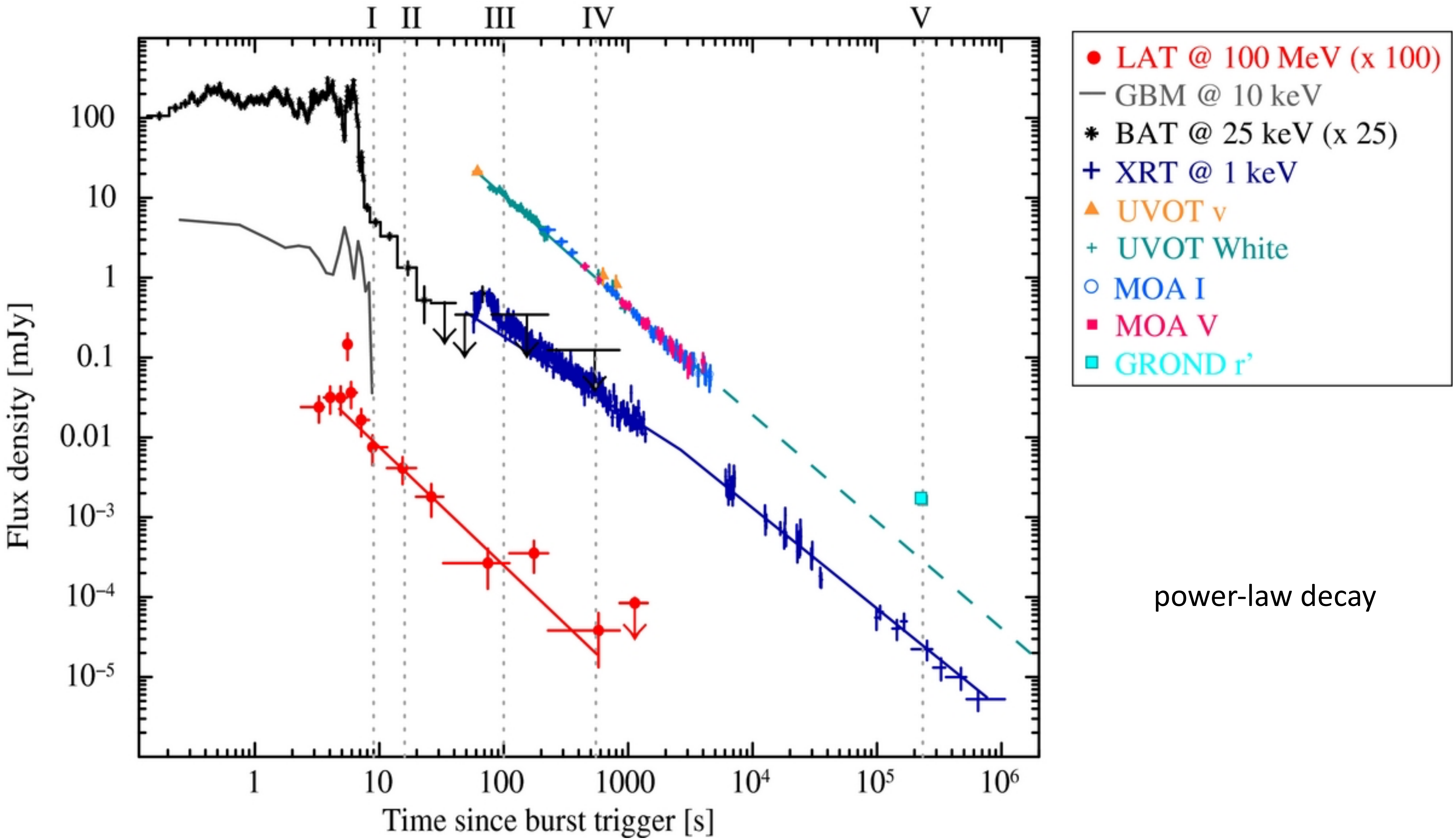


Central
Engine
Inner
Shocks
Gamma-rays
External
Shocs
Afterglow
10^6 cm
10^{11} - 10^{12} cm
10^{15} - 10^{18} cm



LIGO - Virgo
frequency (Hz)
500
400
300
200
100
50
-12
-10
-8
-6
-4
-2
0
2
4
6
t-t_c (s)
Fermi/GBM
INTEGRAL/SPI-ACS
counts/s (arb. scale)
t-t_c (days)
1.2
1.4
2.4
normalized F_λ
SALT
ESO-NTT
SOAR
ESO-VLT
7000°
4000°
400
600
1000
2000
wavelength (nm)
GW
LIGO, Virgo
γ-ray
Fermi, INTEGRAL, Astrosat, IPN, Insight-HXMT, Swift, AGILE, CALET, H.E.S.S., HAWC, Konus-Wind
X-ray
Swift, MAXI/GSC, NuSTAR, Chandra, INTEGRAL
UV
Swift, HST
Optical
Swope, DECam, DLT40, REM-ROS2, HST, Las Cumbres, SkyMapper, VISTA, MASTER, Magellan, Subaru, Pan-STARRS1, HCT, TZAC, LSGT, T17, Gemini-South, NTT, GROND, SOAR, ESO-VLT, KMTNet, ESO-VST, VIRT, SALT, CHILESCOPE, TOROS, BOOTES-5, Zadko, iTelescope.Net, AAT, Pi of the Sky, AST3-2, ATLAS, Danish Tel, DFN, T80S, EABA
IR
REM-ROS2, VISTA, Gemini-South, 2MASS,Spitzer, NTT, GROND, SOAR, NOT, ESO-VLT, Kanata Telescope, HST
Radio
ATCA, VLA, ASKAP, VLBA, GMRT, MWA, LOFAR, LWA, ALMA, OVRO, EVN, e-MERLIN, MeerKAT, Parkes, SRT, Effelsberg
-100
-50
0
50
t-t_c (s)
10^-2
10^-1
10^0
10^1
t-t_c (days)
1M2H Swope
10.86h
i
DLT40
11.08h
h
MASTER
11.31h
W
DECam
11.40h
iz
VISTA
11.24h
YJK_s
Las Cumbres
11.57h
w
Chandra
9d
X-ray
J VLA
16.4d
Radio

Tipical multi-wavelength lightcurve



power-law decay

Time and viewing angle dependence

Peak flux:

- Higher for lower angles
- Delayed for greater angles

➢ After peak there is ~power law decay

➢ Spectrum is also ~power law above some peak frequency

➢ Spectrum softens with time

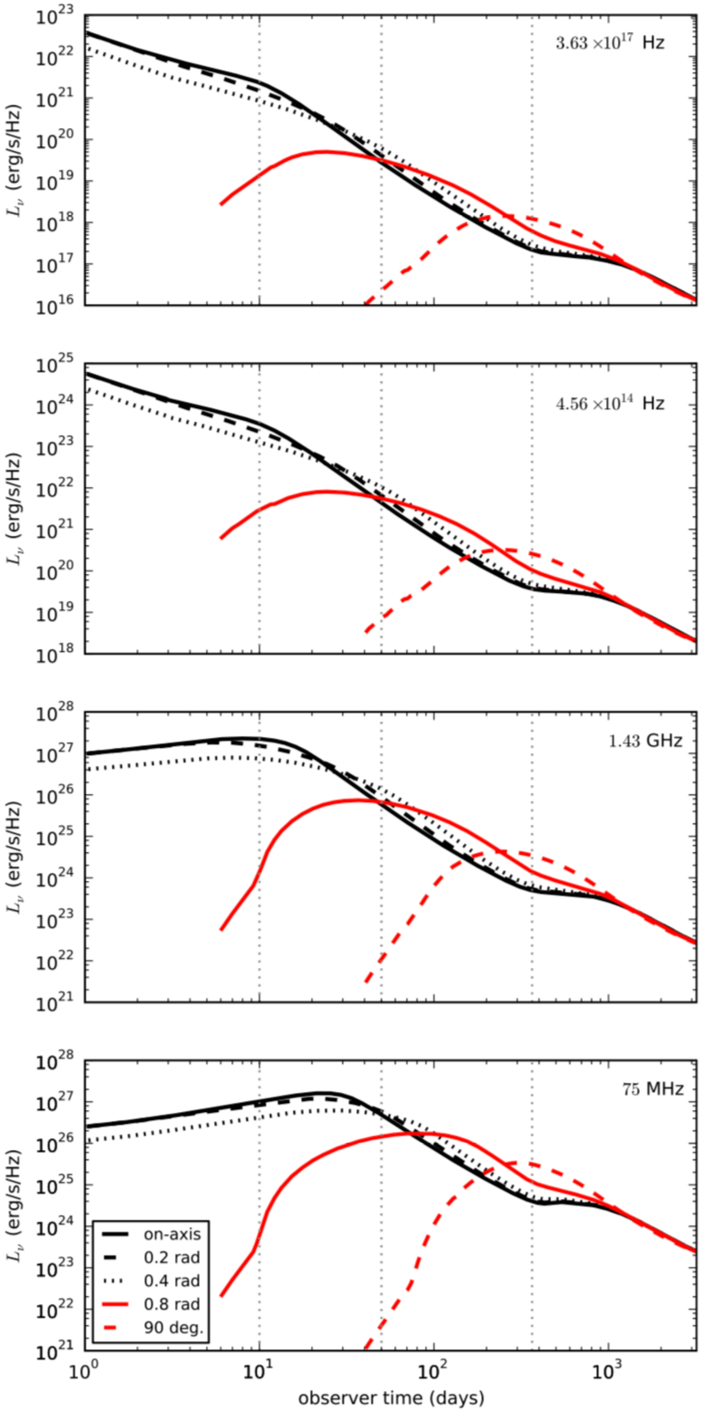


Figure 1. Observed luminosity light curves for $E_j = 10^{48}$ erg, $\theta_j = 0.4$ rad, and $n = 10^{-3}$ cm^{-3} (case B). Observer frequencies from top to bottom: 3.63×10^{17} Hz, 4.56×10^{14} Hz, 1.43 GHz, and 75 MHz. The legend applies to all plots. 10 days, 50 days, and 1 yr have been marked with vertical dotted gray lines. Spectra for these times are provided in Figure 2.

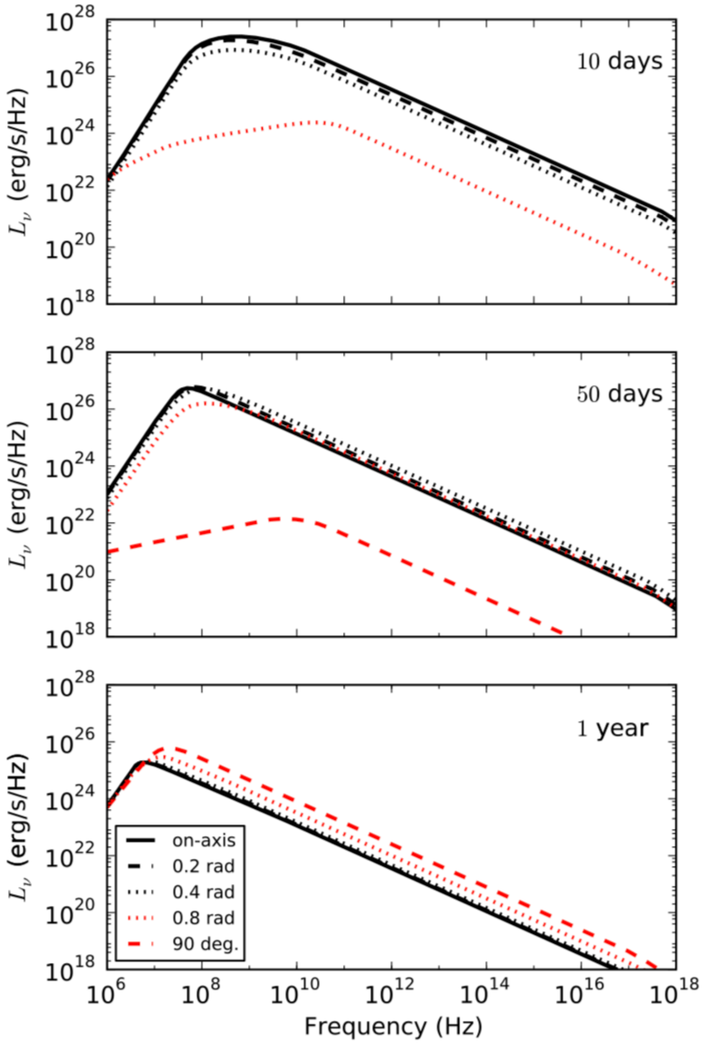
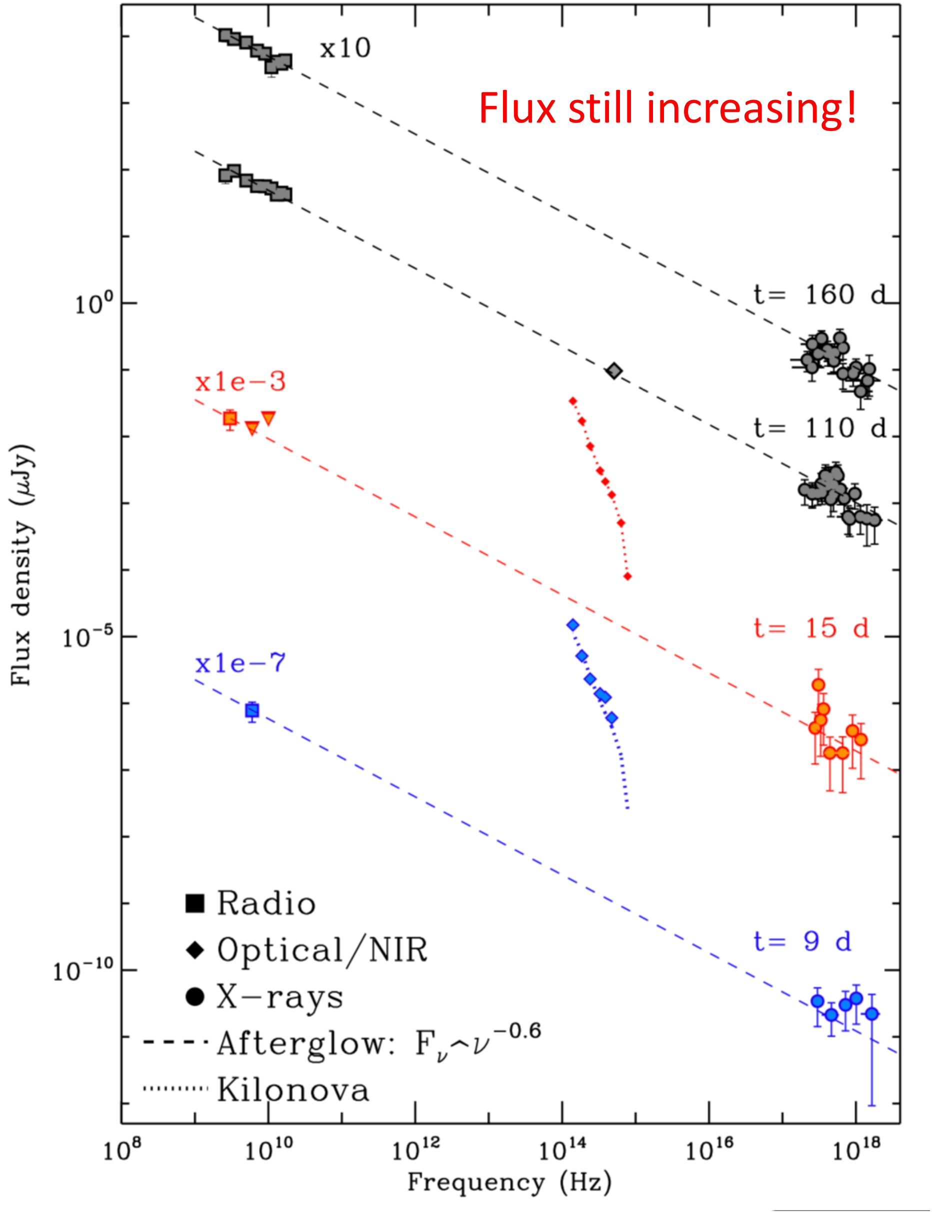
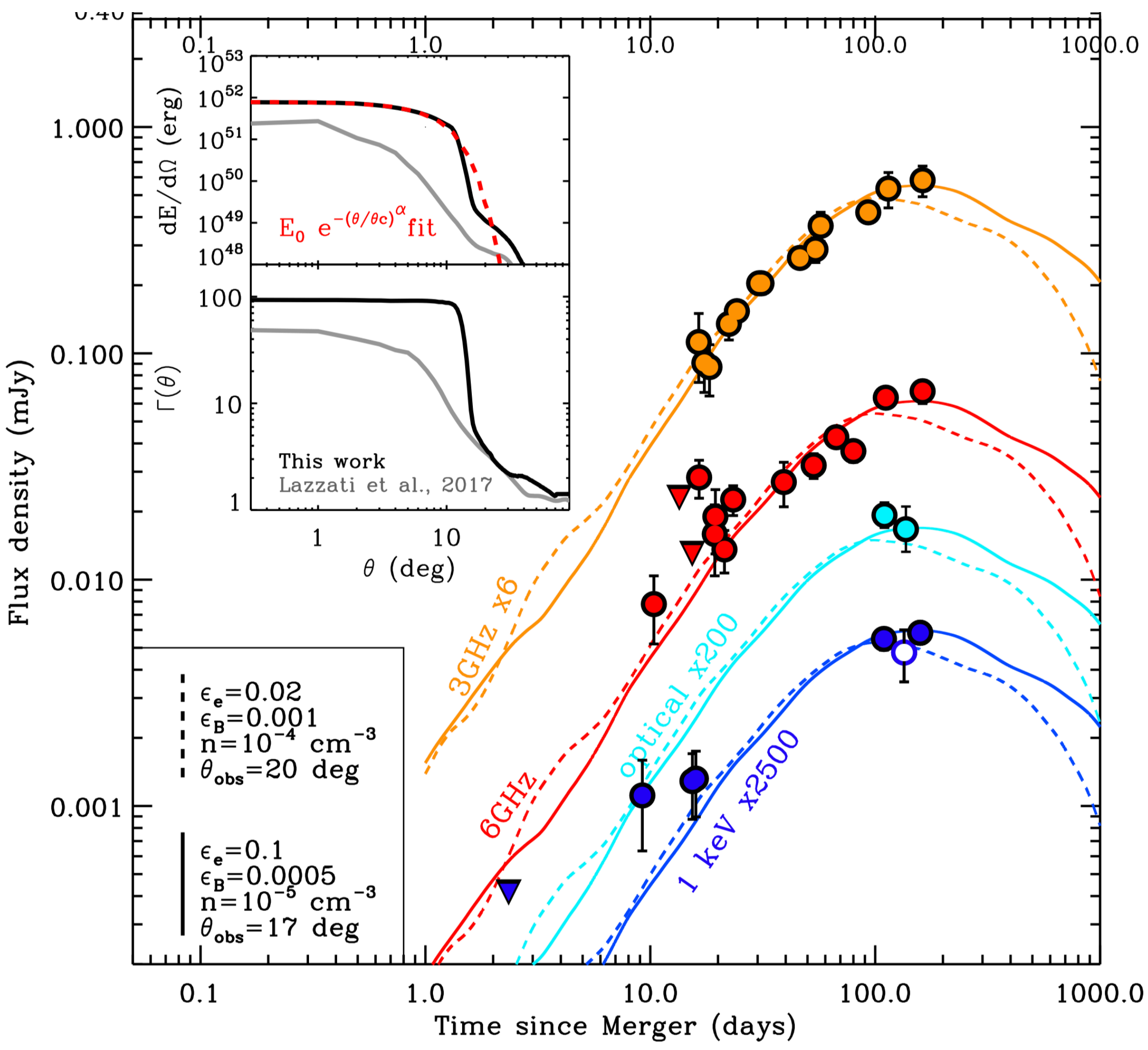


Figure 2. Spectra for $E_j = 10^{48}$ erg, $\theta_j = 0.2$ rad, and $n = 10^{-3}$ cm^{-3} at $t_{\rm obs} = 10$ days, 50 days, and 1 yr (top to bottom plot), for various observer angles. The legend applies to all plots.

Van Eerten+ ApJL 2011

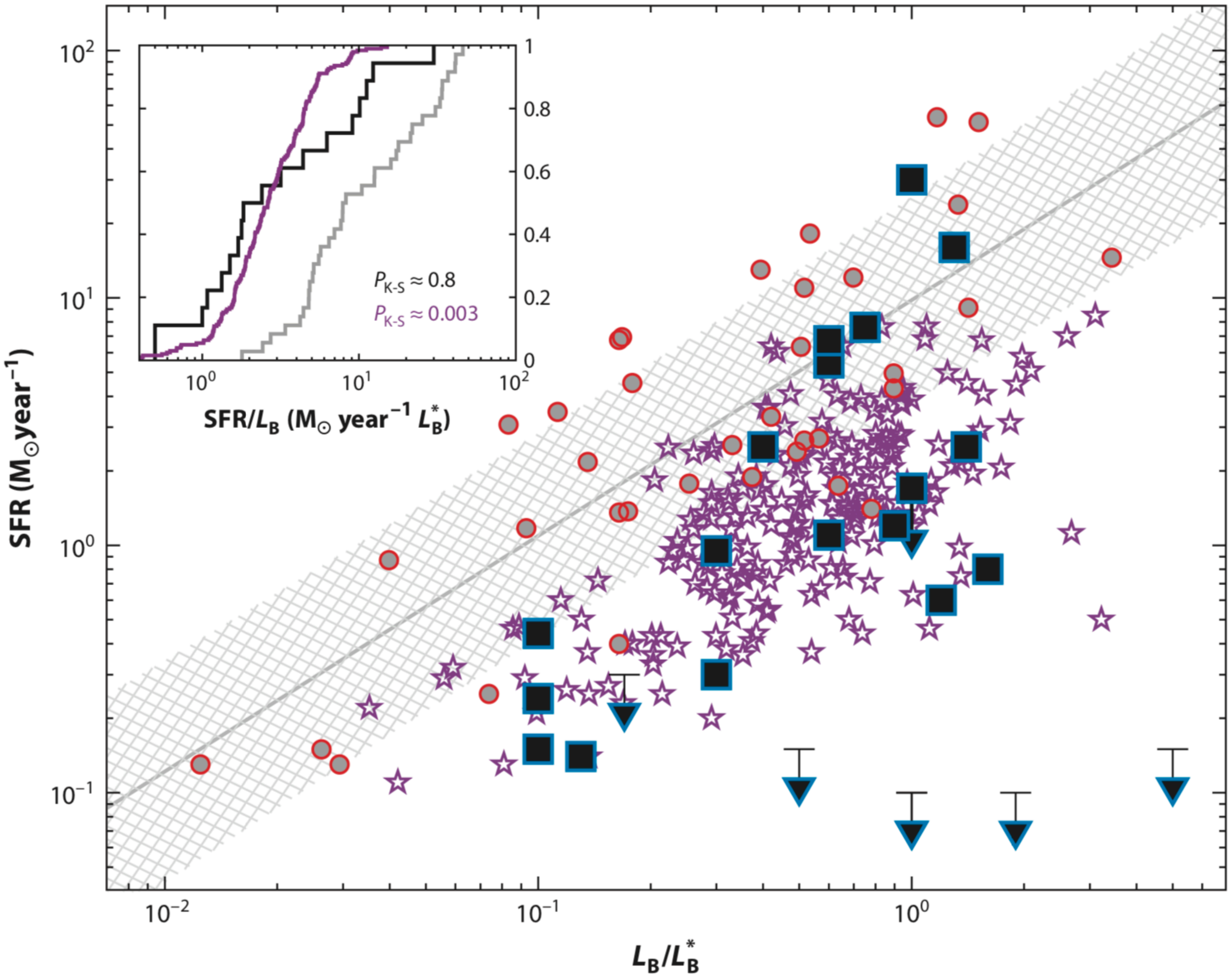
GW170817





Margutti+ 2018

Star formation in host galaxies

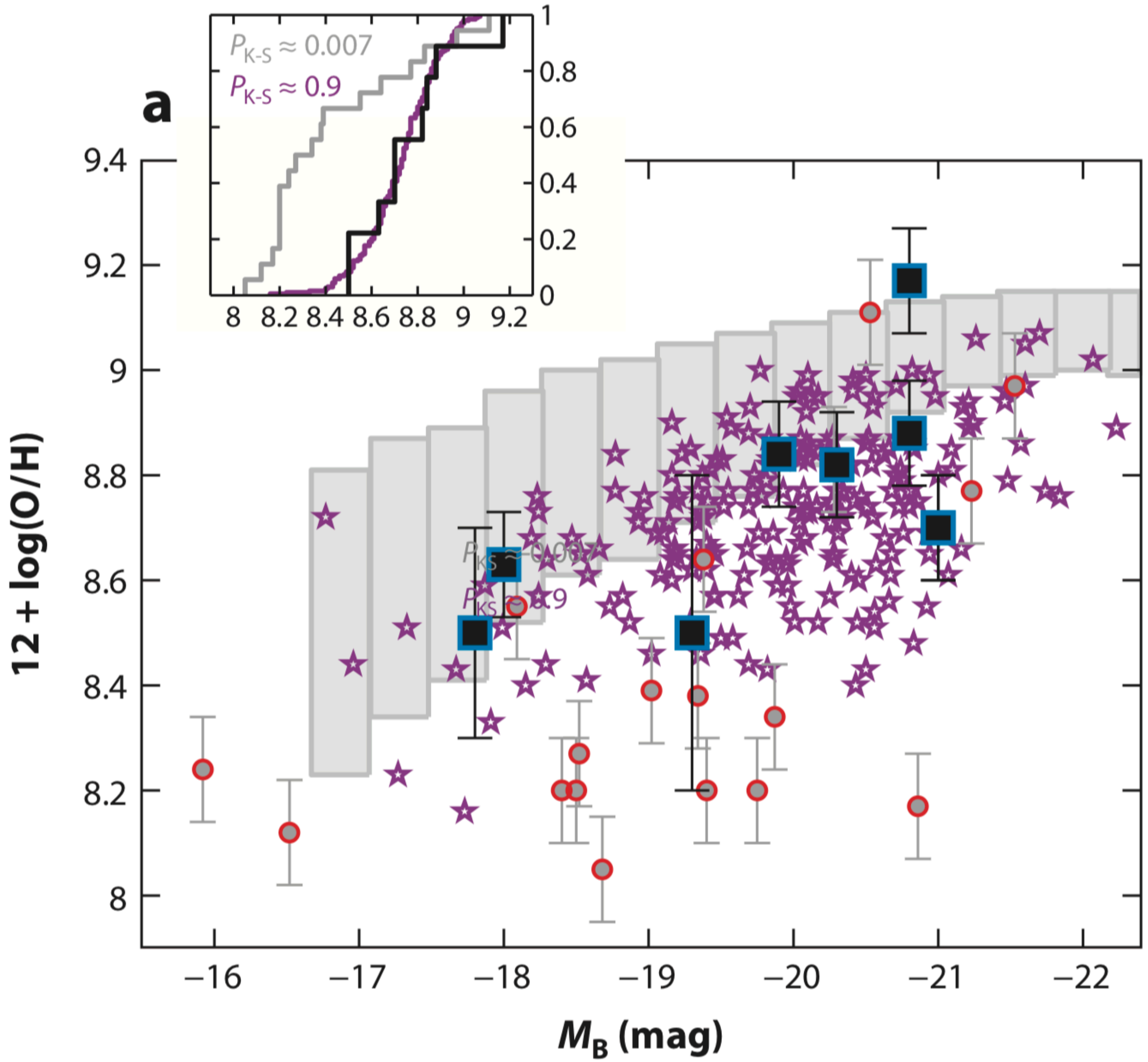


Star-formation rate (SFR) as a function of rest-frame B-band luminosity for the host galaxies of short GRBs (*squares*), long GRBs (*circles*), and field star-forming galaxies at similar redshifts to short GRB hosts (*stars*; Kobulnicky & Kewley 2004).

Low star formation indicates that the binary formed a long time ago.

Berger 2014

Metallicity of host galaxy

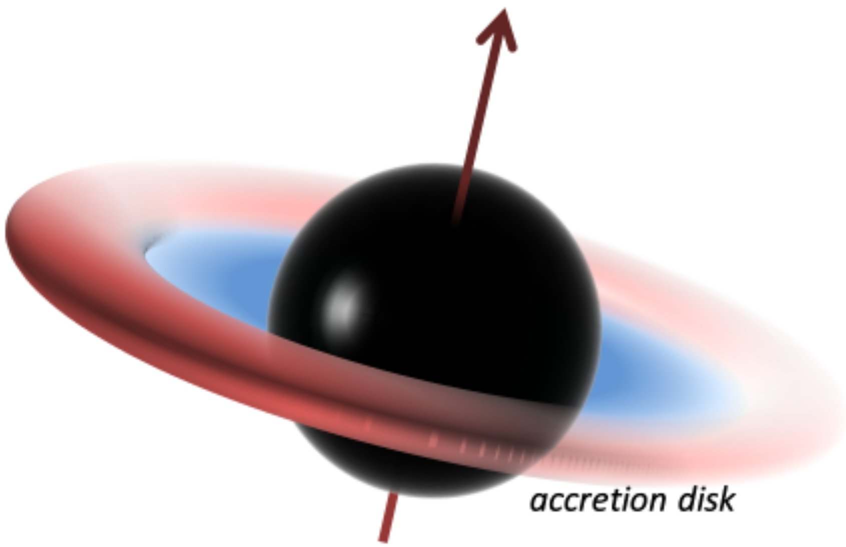


Metallicity as a function of host-galaxy rest-frame B-band luminosity for short GRBs (*squares*), long GRBs (*circles*), field galaxies at similar redshifts to short GRB hosts (*stars*; Kobulnicky & Kewley 2004), and the Sloan Digital Sky Survey luminosity-metallicity relation (Tremonti et al. 2004). Short GRB host galaxies have higher metallicities than long GRB hosts, but they closely track the luminosity-metallicity relation for the field galaxy population (*inset*).

Long GRBs prefer low-metallicity environments --- favorable for massive stellar explosions

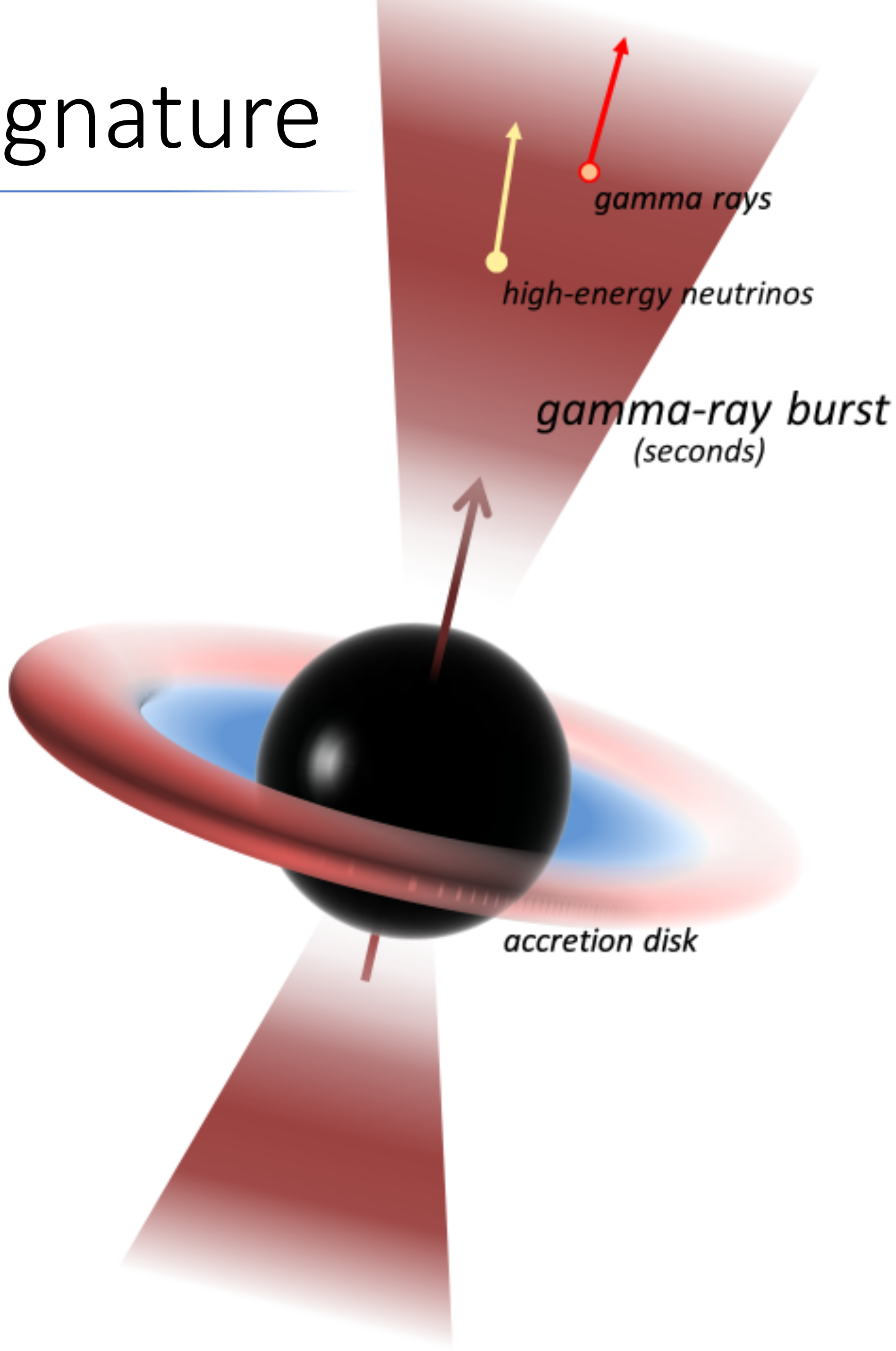
Berger 2014

Electromagnetic signature

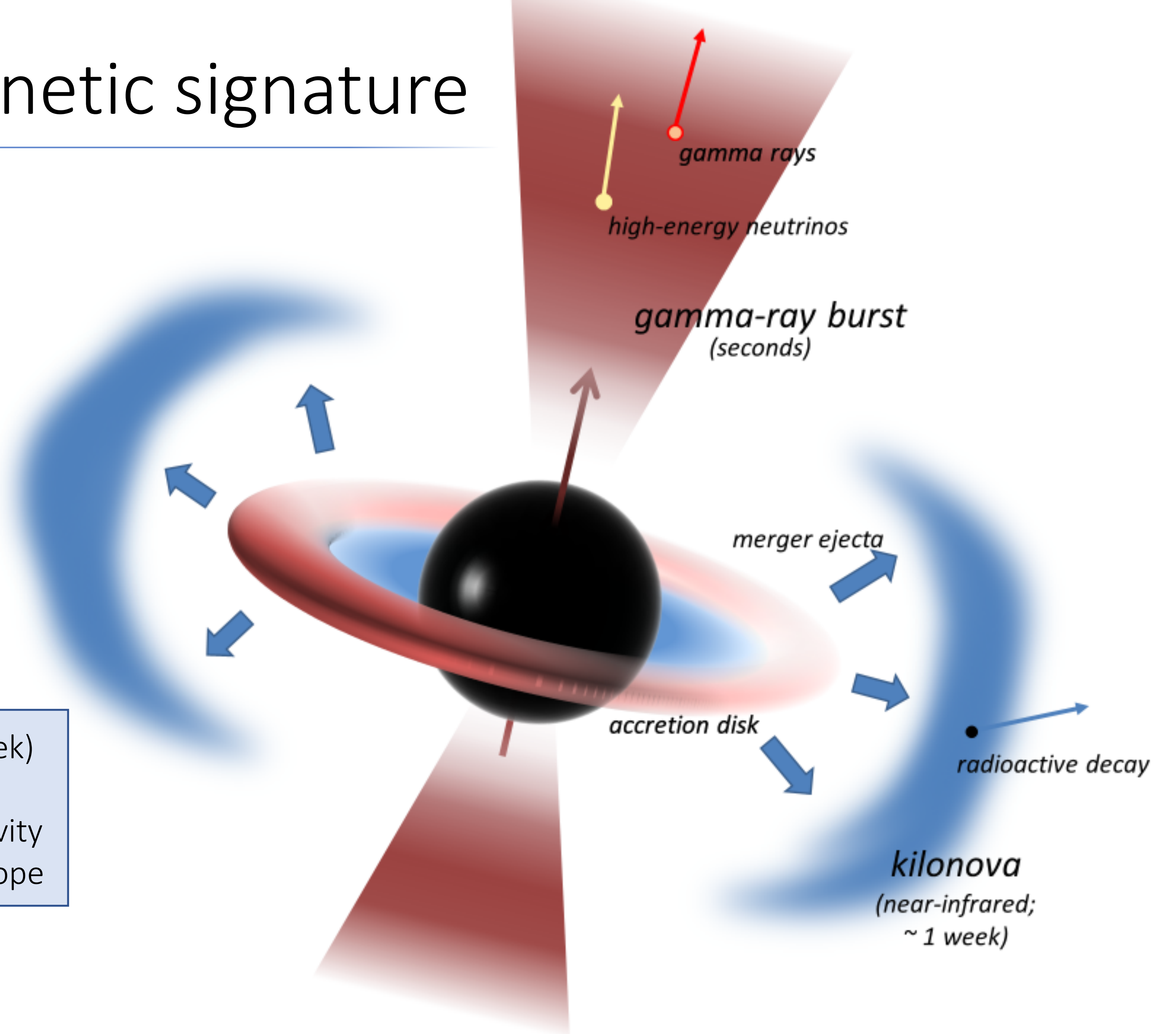


Electromagnetic signature

- Beamed
- Good gamma-ray FoV
- Limited localization (difficult to follow-up)



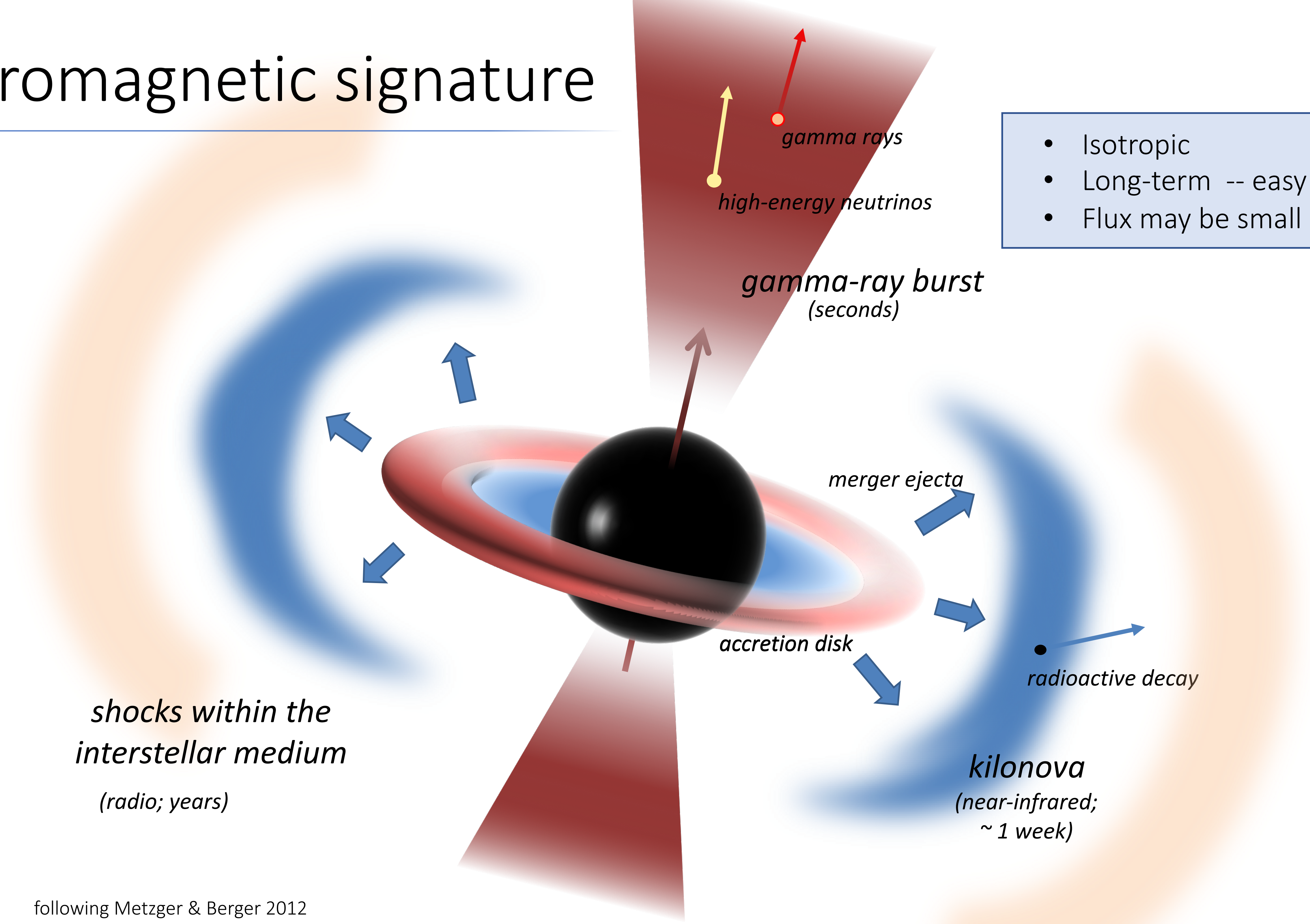
Electromagnetic signature



- Good time frame (~week)
- ~Isotropic
- Limited IR FoV / sensitivity
  → not for every telescope

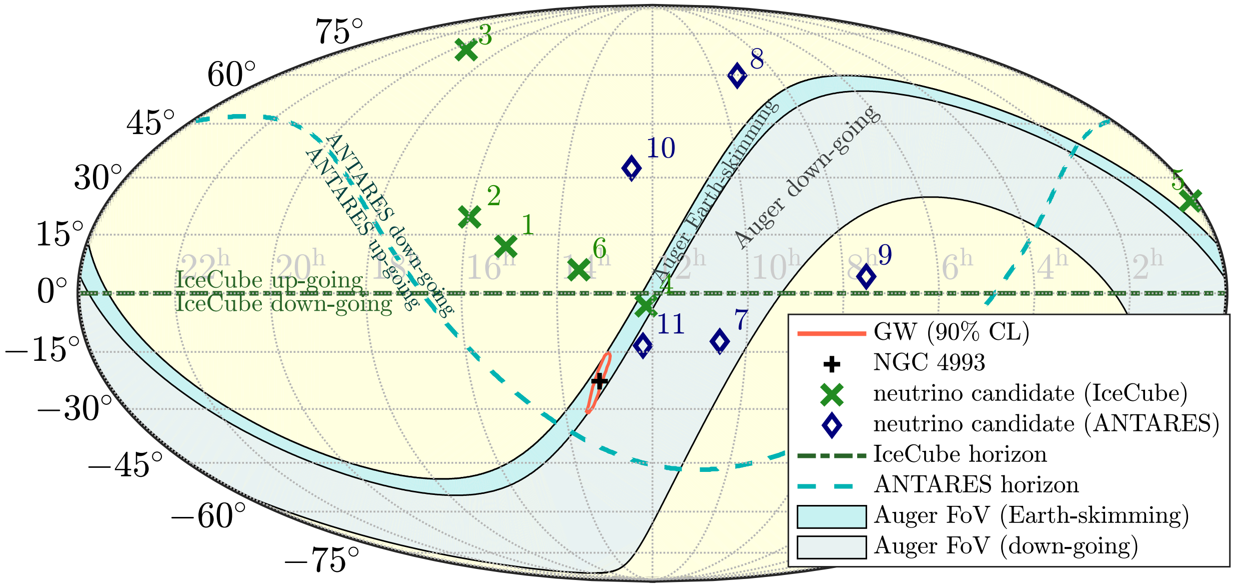
Electromagnetic signature

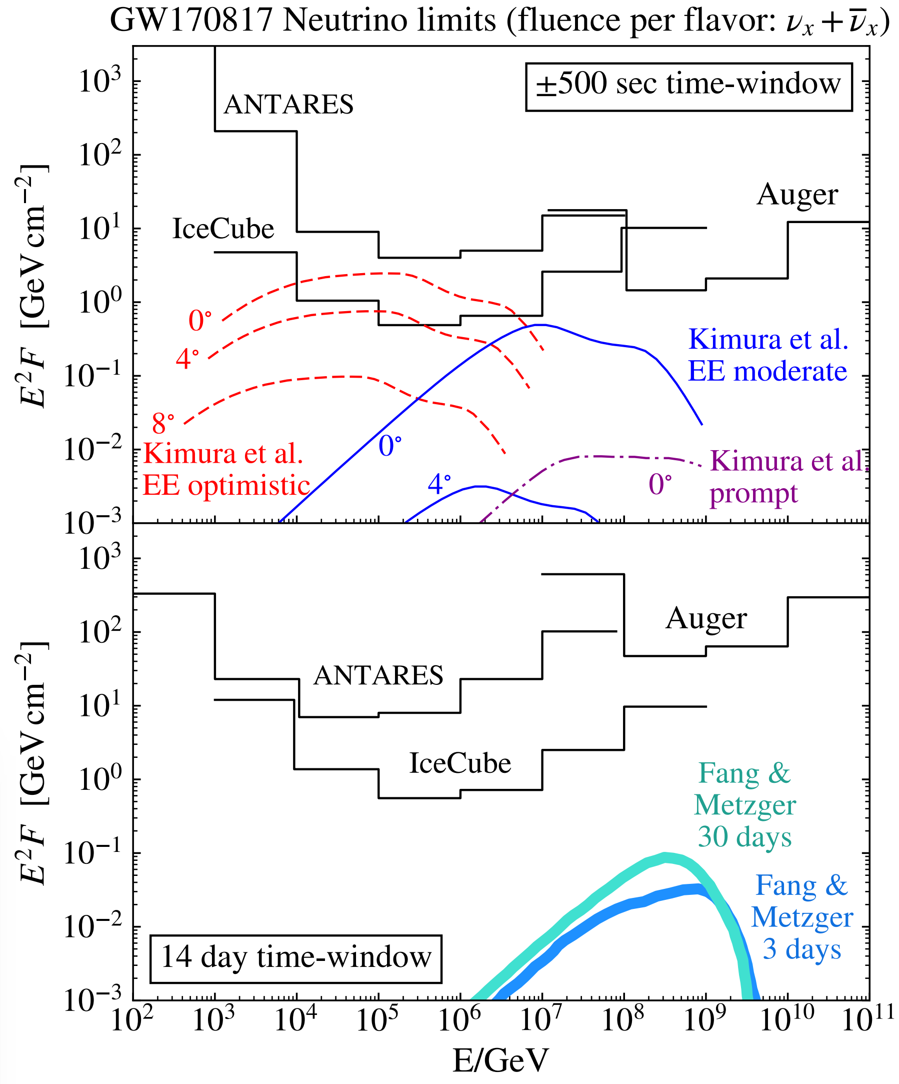
- Isotropic
- Long-term -- easy follow-up
- Flux may be small

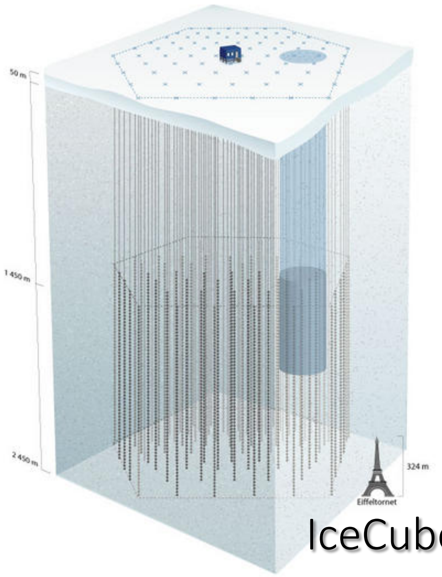


following Metzger & Berger 2012

Search for ultrahigh-energy emission (neutrinos)

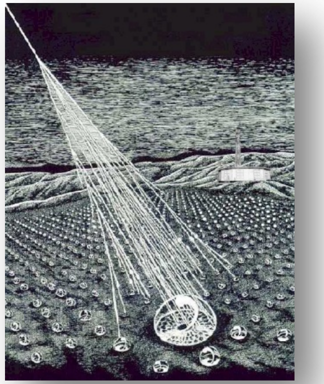




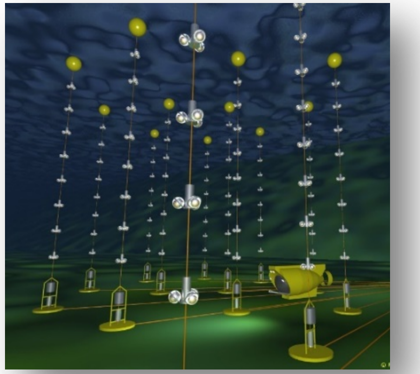


IceCube

Pierre Auger

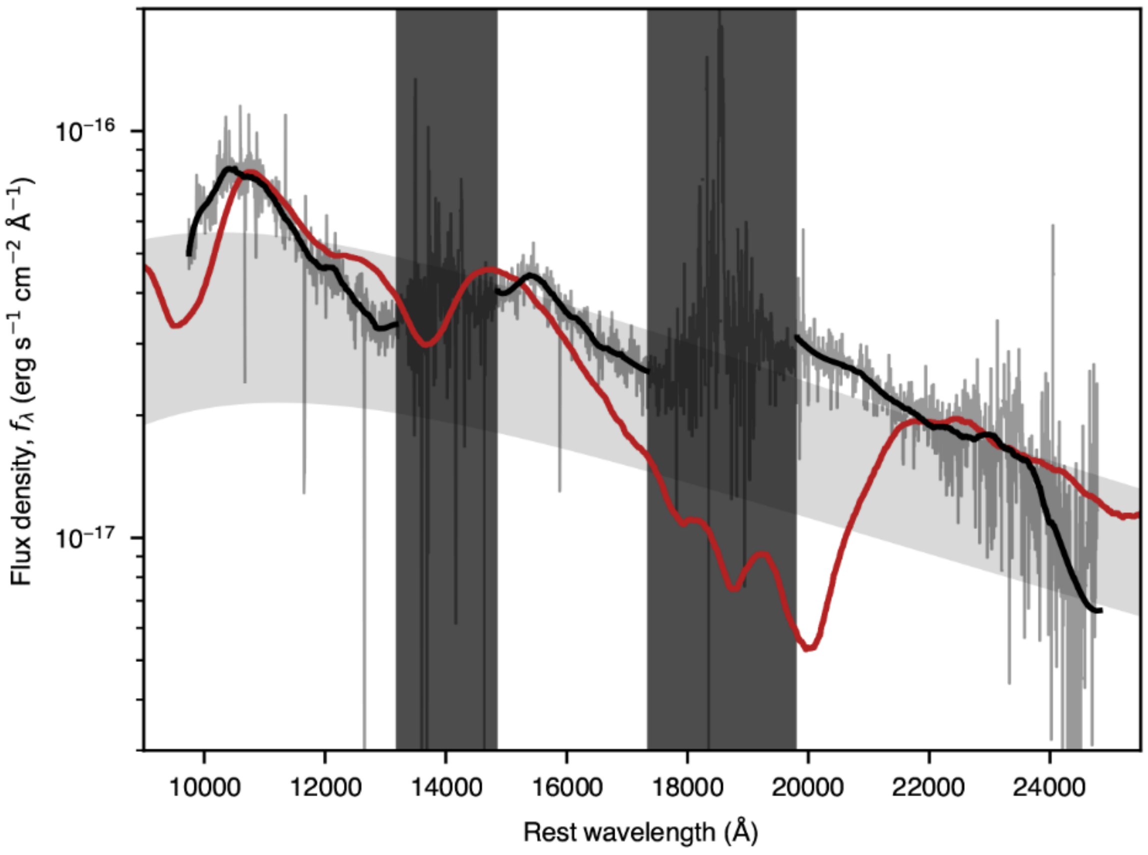


ANTARES



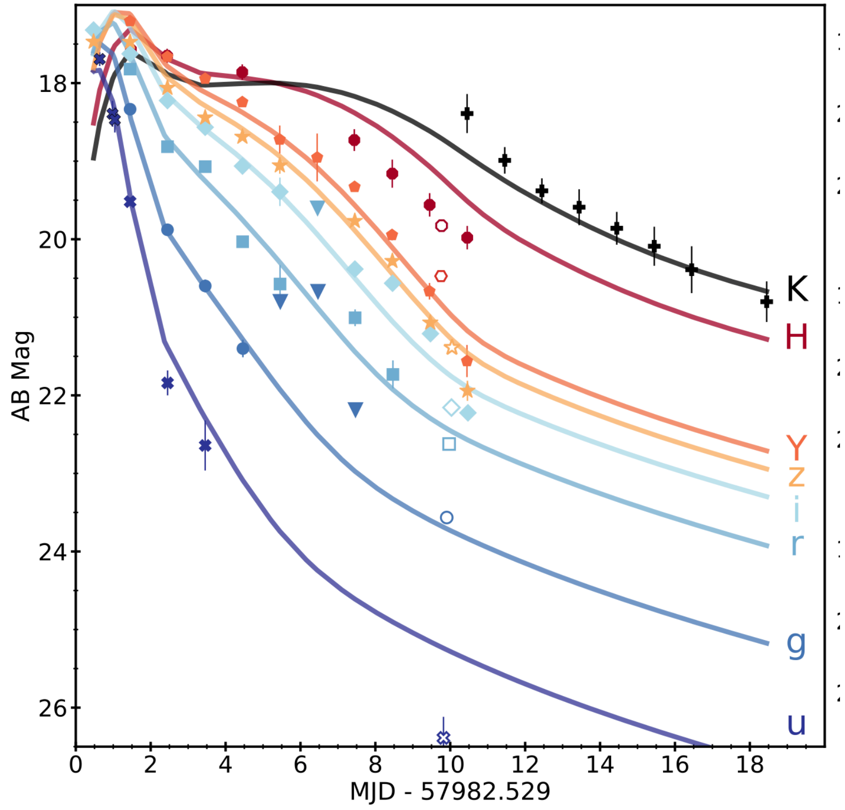
Auger, IceCube, ANTARES, LIGO, Virgo 2017

Optical counterpart: kilonova



Red: kilonova at 4.5 days, M=0.05Msun, v=0.1c
Black: observation

- Evolution inconsistent with GRB afterglow
- Roughly consistent with kilonova emission



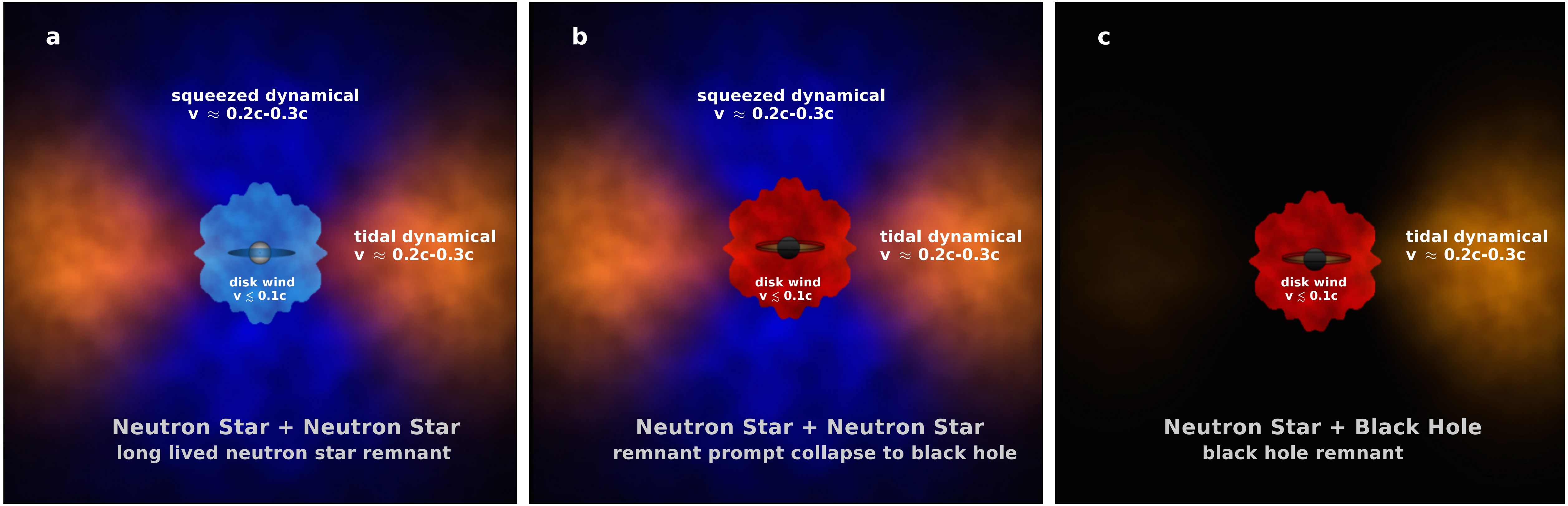
- We need a combination of two outflows to explain observations

Dark Energy Camera (DECam), Gemini-South/FLAMINGOS-2 (GS/F2), and the *Hubble Space Telescope* (*HST*)

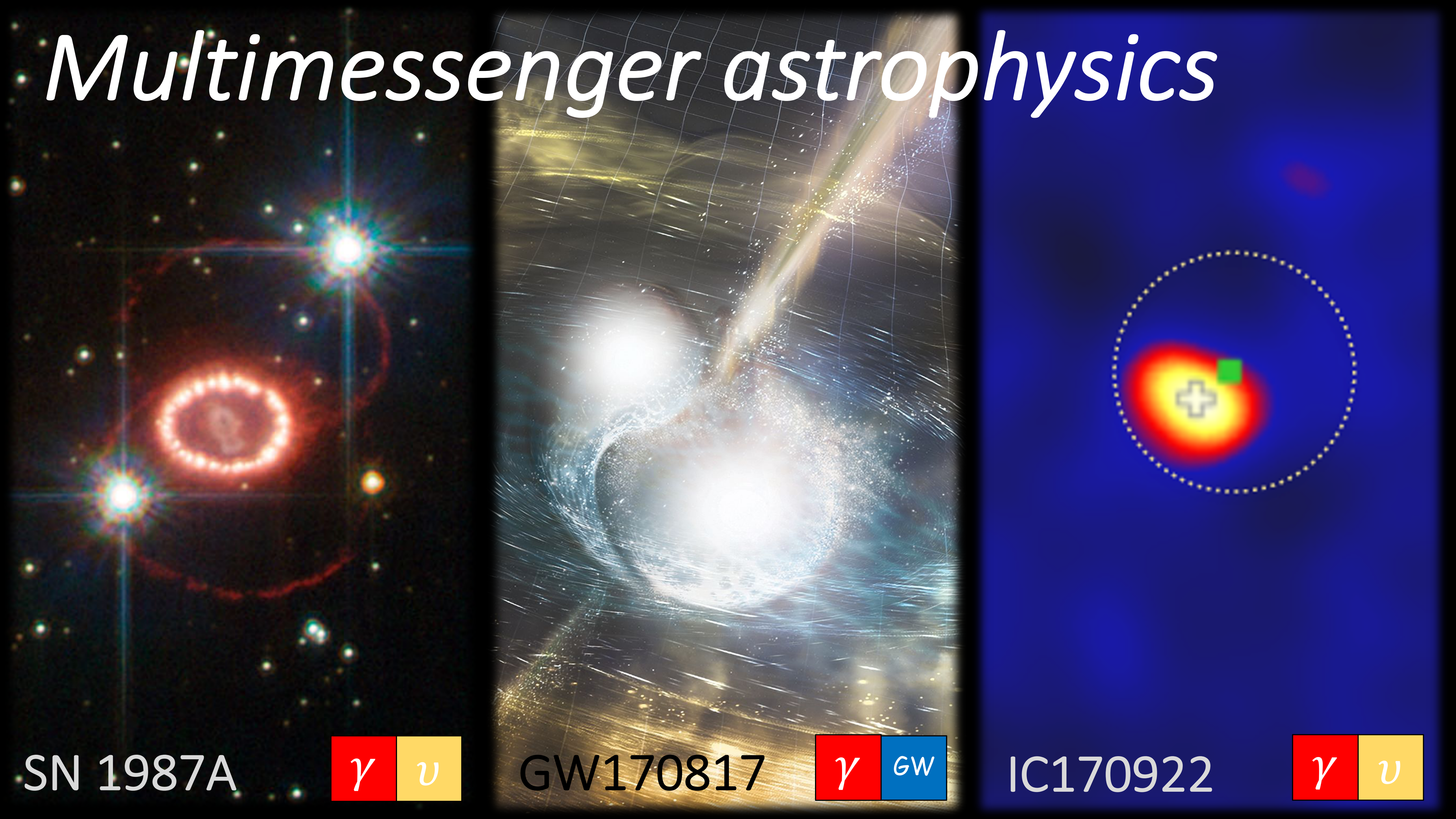
Cowperthwaite+ ApJL 2017

Possible explanations

- Dynamical ejecta: $v = 0.2 - 0.3\ c$, $M = 10^{-3} - 10^{-2}\ M_\odot$, neutron rich → absorption → red, slower
- Winds: $v = 0.05 - 0.1\ c$, $M = 10^{-2} - 10^{-1}\ M_\odot$, less neutron rich → blue, faster
- Winds can come from a NS that doesn't collapse immediately, or the accretion disk.

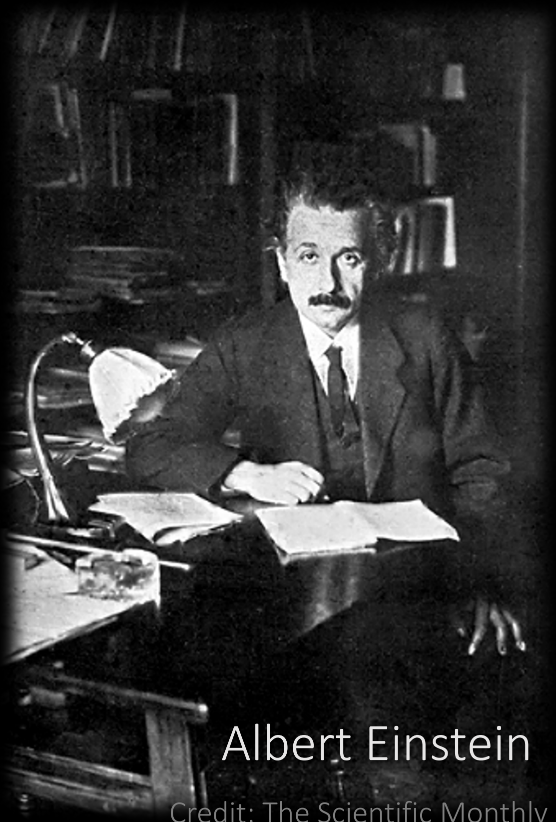


Kasen+ Nature 2017


Multimessenger astrophysics
SN 1987A
γ υ
GW170817
γ GW
IC170922
γ υ

1916

Einstein just published his General Theory of Relativity, and is looking for ways to observationally test it.

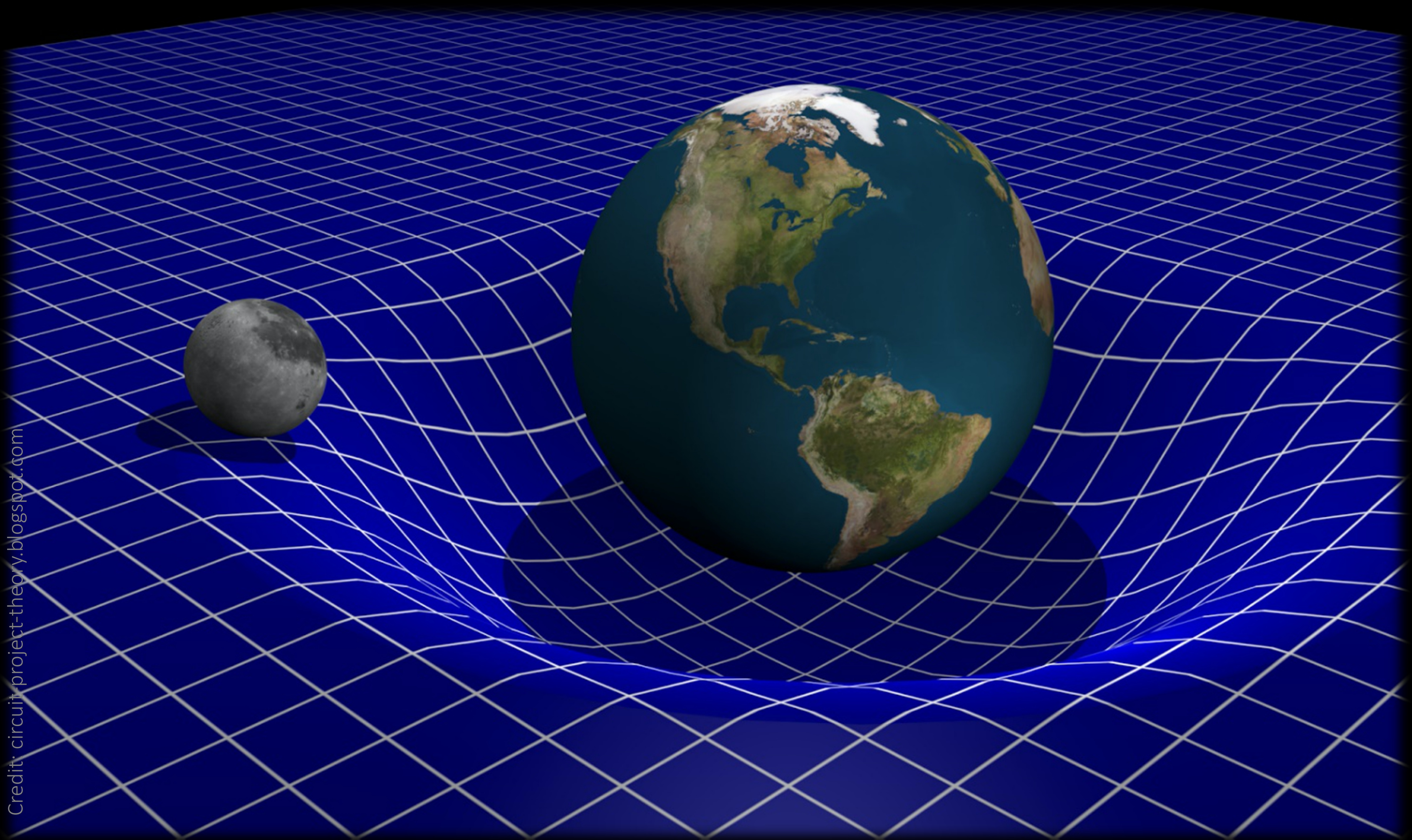


Albert Einstein

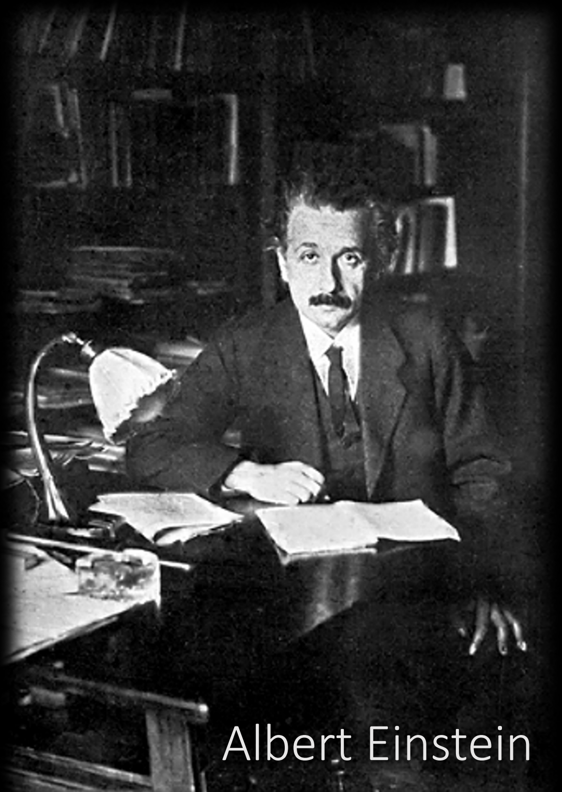
Credit: The Scientific Monthly

1916

gravity = curved spacetime



Credit: circuit-project-theory.blogspot.com



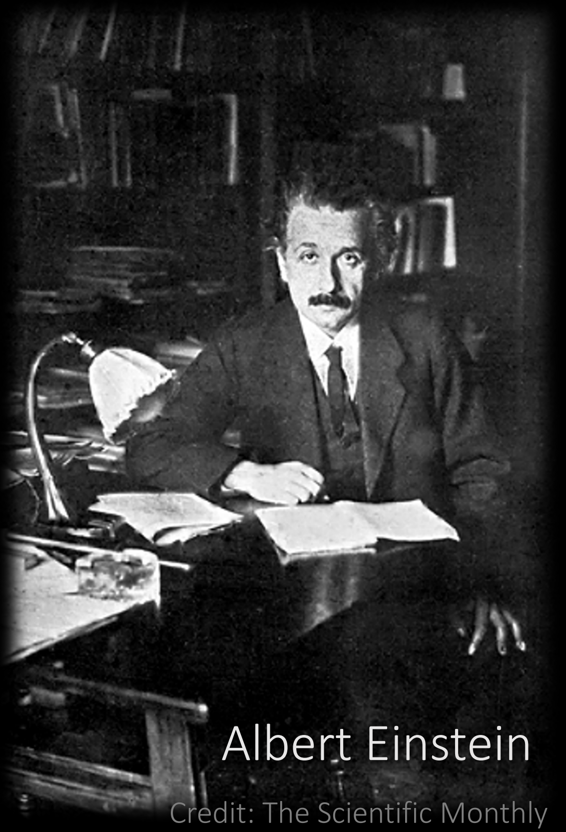
Albert Einstein

Credit: The Scientific Monthly

1916

<u>gravitational waves</u>: disturbances in the curvature of spacetime, generated by accelerated masses, that propagate as waves.

Credit:Shutterstock.com

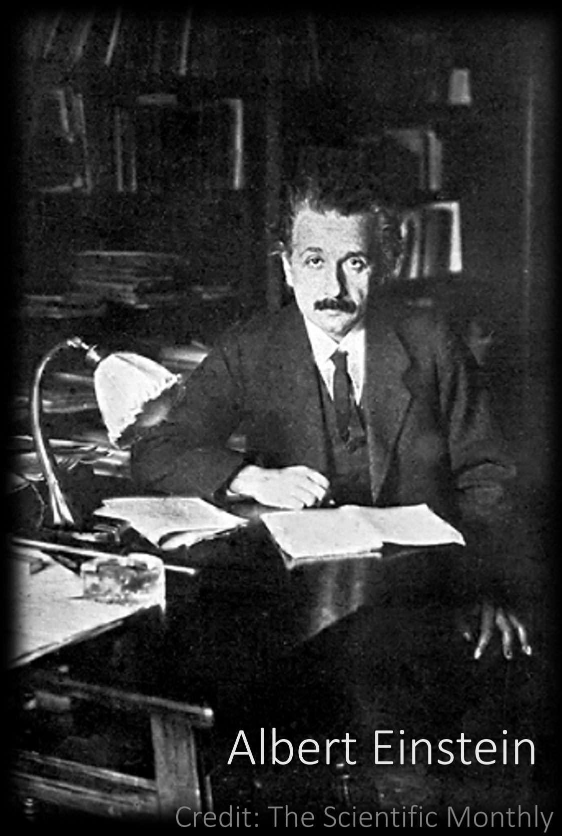


Albert Einstein

Credit: The Scientific Monthly

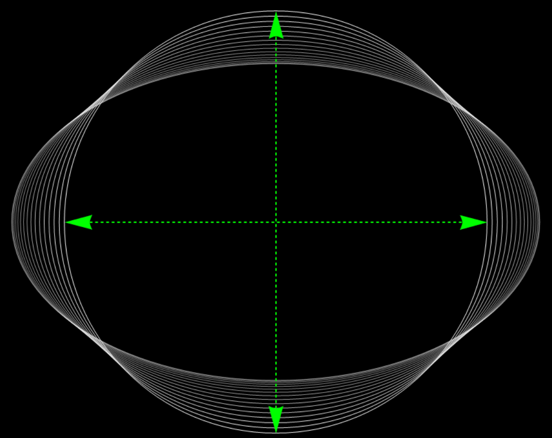
1916

To a large extent, gravitational waves are produced like electromagnetic waves.



- ✓ *An accelerated charged particle will emit waves.*
- ✓ *Acceleration cannot be spherically symmetric.*
- ✓ *Propagates with the speed of light.*

- ❖ *Gravitational wave emission requires a changing quadrupole moment.*
- ❖ *It is effectively changing distances perpendicular to the propagation (transverse wave).*
- ❖ *Polarizations: + and X (plus and cross).*
- ❖ *Amplitude decreases as 1/r.*



1916

gravity is weak ➔ *impossible to detect (?)*

Albert Einstein

Credit: The Scientific Monthly

1960’s

Richard Feynman convinced the community at the 1957 Chapel Hill conference (under pseudonym Mr. Smith) that gravitational waves are real using the “sticky bead” argument.

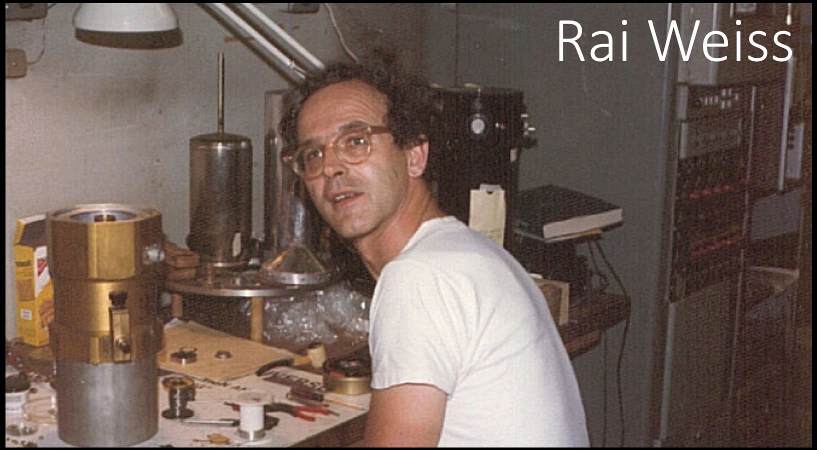
Resonance bar detectors (Joseph Weber)

<u>Concept:</u> tidal forces due to gravitational waves distort the bar. It resonates if the distortion changes at the resonance frequency.

<u>1969:</u> Weber claims discovery of gravitational waves. He starts claiming regular detections. Others try but can’t reproduce his results.

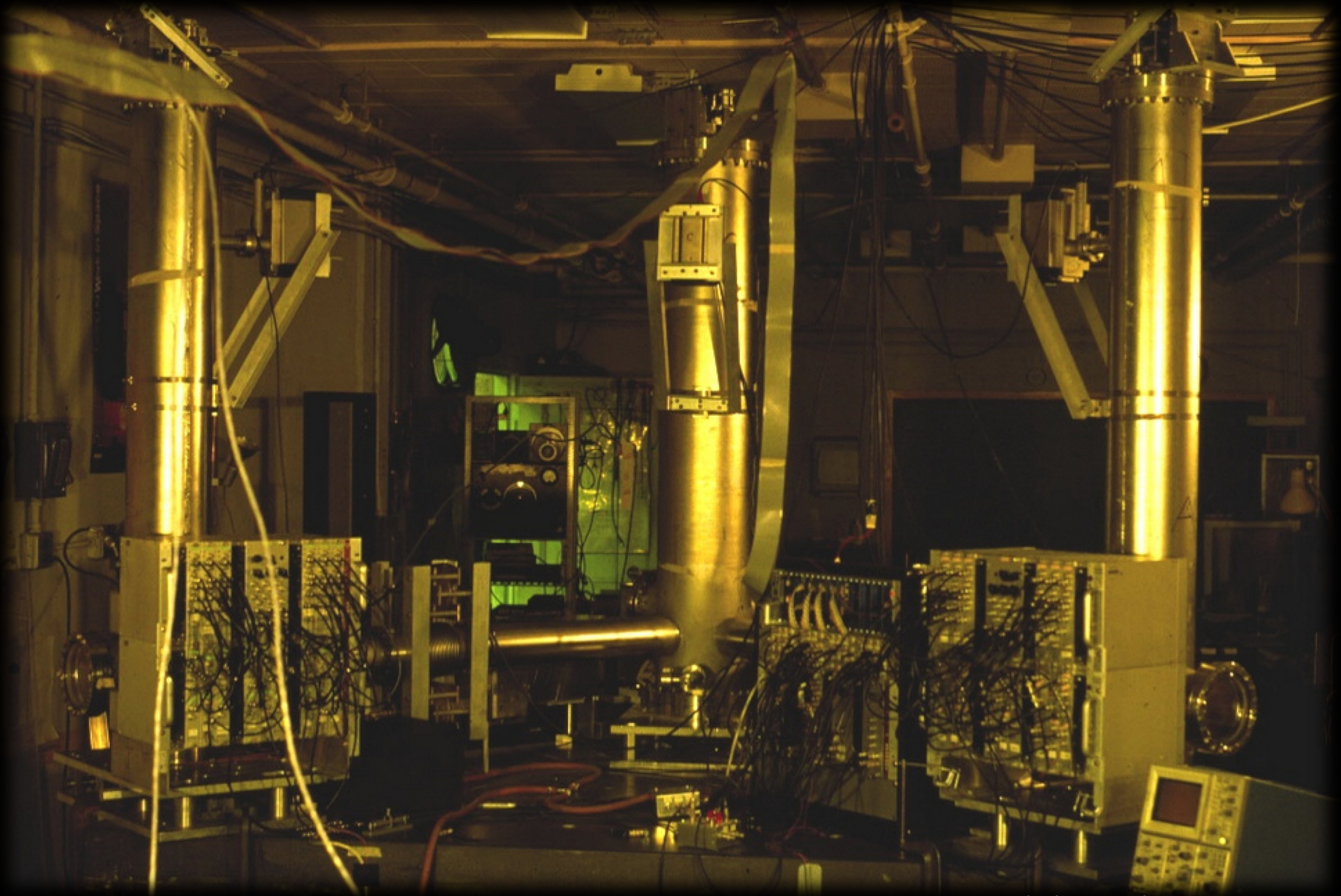
1968

Laser Interferometer Gravitational-wave Observatory (LIGO)

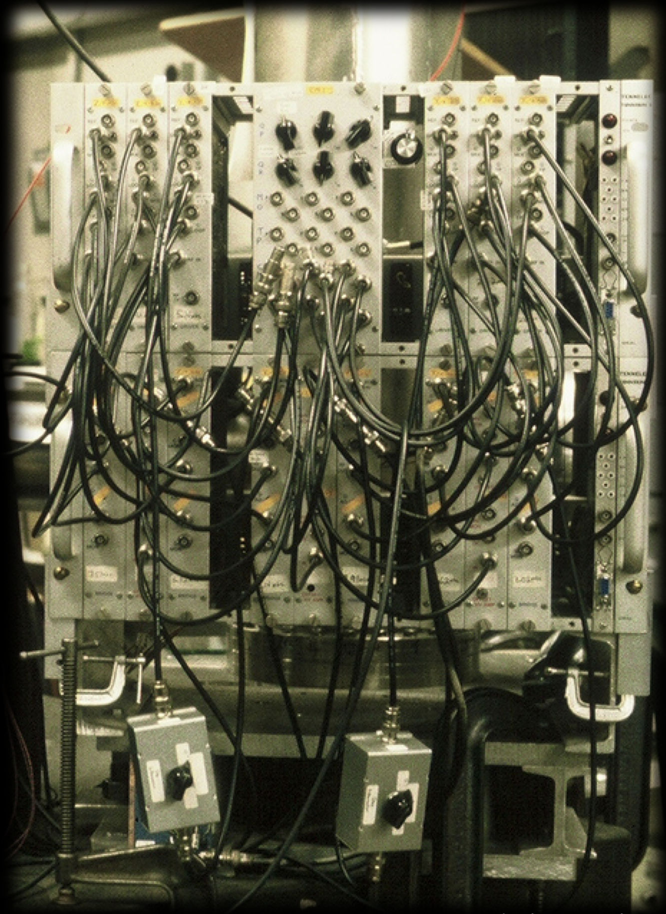


Courtesy: David Shoemaker

First experiment: laser interferometer with ~1m armlength.

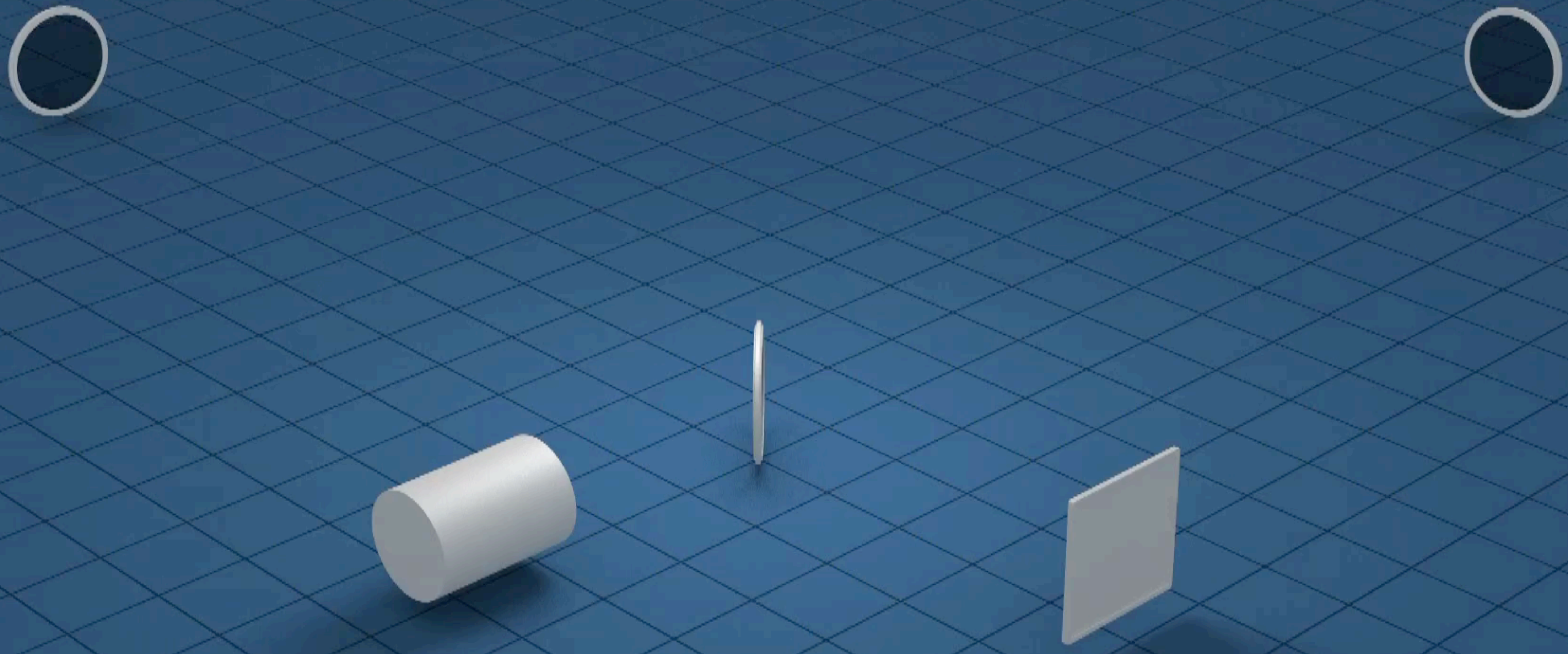


Courtesy: David Shoemaker



Courtesy: David Shoemaker

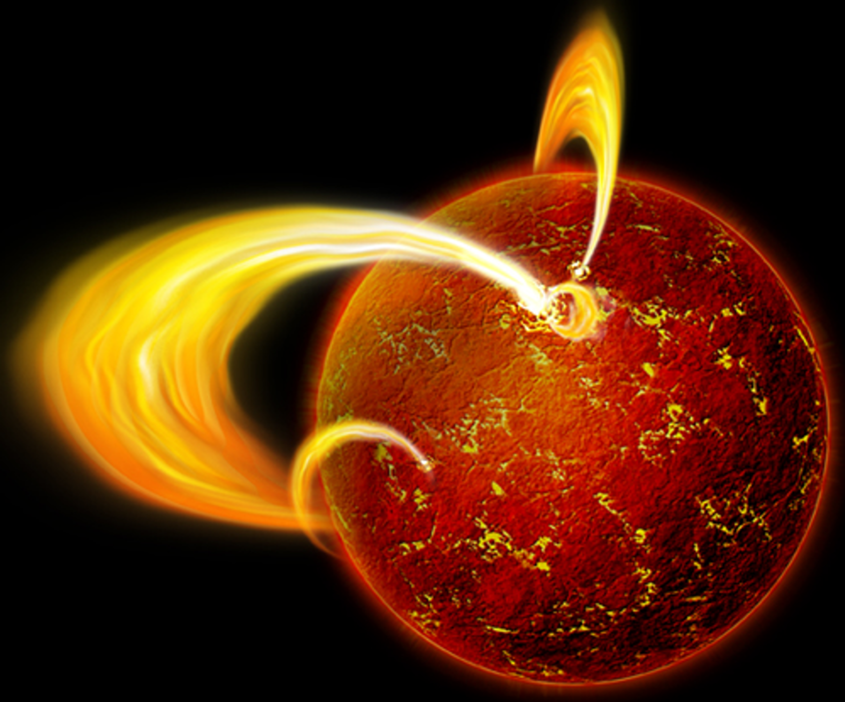
Laser interferometer

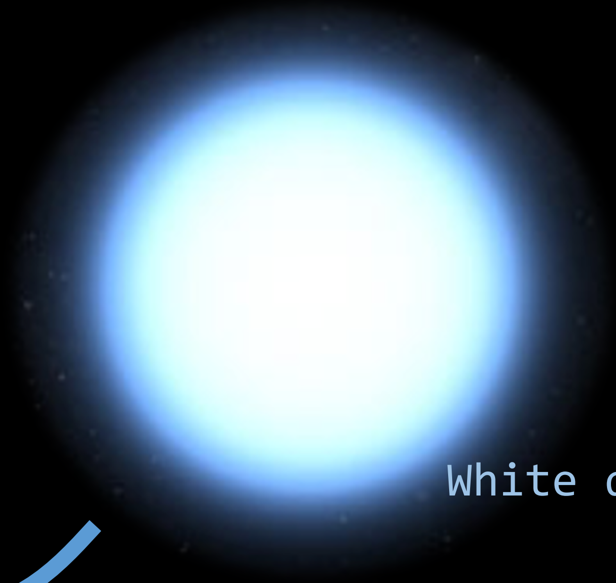


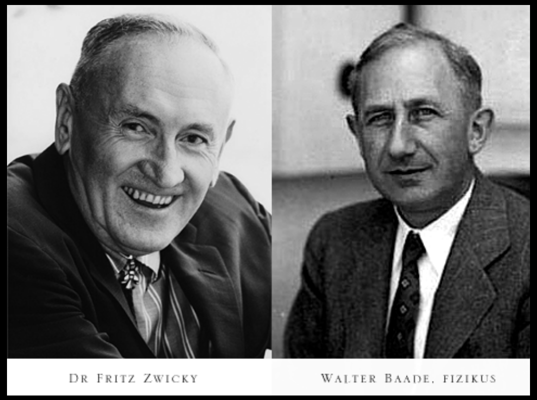
Kipp Thorne started thinking about what could actually produce detectable gravitational waves.

Image credit: Paramount pictures/Warner bros.

neutron stars





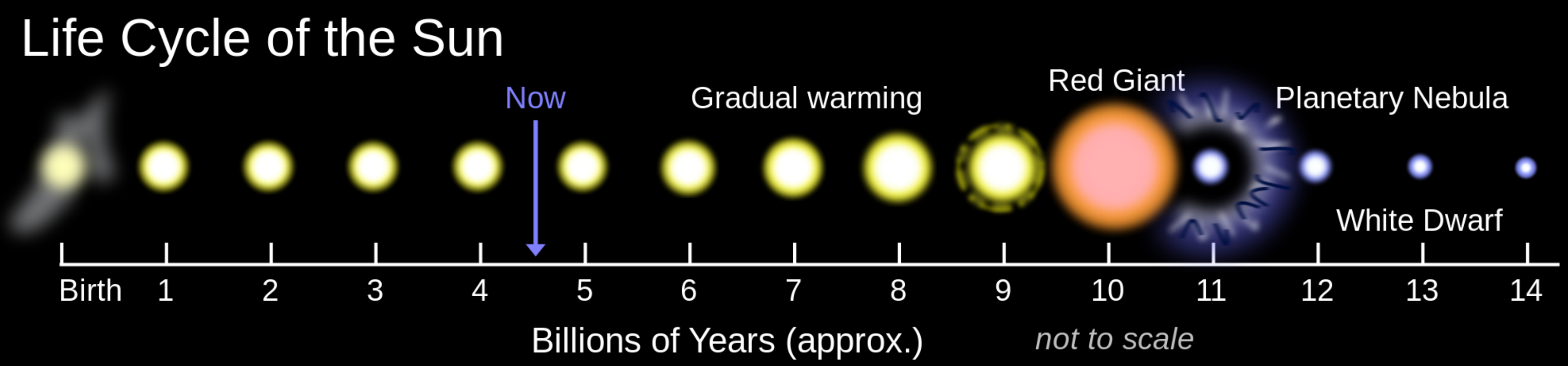


White dwarf

Neutron stars are born when the electric force is not strong enough to compensate the gravitational pull. Happens at a critical $1.4 M_{\odot}$ mass (Charandrasekhar mass). Can be reached gradually in accreting white dwarfs or in stellar core collapse.

Proposed in 1934, ~1 year after the discovery of the neutron by James Chadwick!

Not taken seriously until the 60’s when pulsars were detected (Scorpius X-1, 1967).



neutron

Letters to the Editor

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Possible Existence of a Neutron

IT has been shown by Bothe and others that beryllium when bombarded by α-particles of polonium emits a radiation of great penetrating power, which has an absorption coefficient in lead of about 0·3 (cm.)$^{-1}$. Recently Mme. Curie-Joliot and M. Joliot found, when measuring the ionisation produced by this beryllium radiation in a vessel with a thin window, that the ionisation increased when matter containing hydrogen was placed in front of the window. The effect appeared to be due to the ejection of protons with velocities up to a maximum of nearly 3×10^9 cm. per sec. They suggested that the transference of energy to the proton was by a process similar to the Compton effect, and estimated that the beryllium radiation had a quantum energy of 50×10^6 electron volts.

I have made some experiments using the valve counter to examine the properties of this radiation excited in beryllium. The valve counter consists of a small ionisation chamber connected to an amplifier, and the sudden production of ions by the entry of a particle, such as a proton or α-particle, is recorded by the deflexion of an oscillograph. These experiments have shown that the radiation ejects particles from hydrogen, helium, lithium, beryllium, carbon, air, and argon. The particles ejected from hydrogen behave, as regards range and ionising power, like protons with speeds up to about $3{\cdot}2 \times 10^9$ cm. per sec. The particles from the other elements have a large ionising power, and appear to be in each case recoil atoms of the elements.

If we ascribe the ejection of the proton to a Compton recoil from a quantum of 52×10^6 electron volts, then the nitrogen recoil atom arising by a similar process should have an energy not greater than about 400,000 volts, should produce not more than about 10,000 ions, and have a range in air at N.T.P. of about 1·3 mm. Actually, some of the recoil atoms in nitrogen produce at least 30,000 ions. In collaboration with Dr. Feather, I have observed the recoil atoms in an expansion chamber, and their range, estimated visually, was sometimes as much as 3 mm. at N.T.P.

These results, and others I have obtained in the course of the work, are very difficult to explain on the assumption that the radiation from beryllium is a quantum radiation, if energy and momentum are to be conserved in the collisions. The difficulties disappear, however, if it be assumed that the radiation consists of particles of mass 1 and charge 0, or neutrons. The capture of the α-particle by the Be^9 nucleus may be supposed to result in the formation of a C^{12} nucleus and the emission of the neutron. From the energy relations of this process the velocity of the neutron emitted in the forward direction may well be about 3×10^9 cm. per sec. The collisions of this neutron with the atoms through which it passes give rise to the recoil atoms, and the observed energies of the recoil atoms are in fair agreement with this view. Moreover, I have observed that the protons ejected from hydrogen by the radiation emitted in the opposite direction to that of the exciting α-particle appear to have a much smaller range than those ejected by the forward radiation. This again receives a simple explanation on the neutron hypothesis.

If it be supposed that the radiation consists of quanta, then the capture of the α-particle by the Be^9 nucleus will form a C^{13} nucleus. The mass defect of C^{13} is known with sufficient accuracy to show that the energy of the quantum emitted in this process cannot be greater than about 14×10^6 volts. It is difficult to make such a quantum responsible for the effects observed.

It is to be expected that many of the effects of a neutron in passing through matter should resemble those of a quantum of high energy, and it is not easy to reach the final decision between the two hypotheses. Up to the present, all the evidence is in favour of the neutron, while the quantum hypothesis can only be upheld if the conservation of energy and momentum be relinquished at some point.

J. CHADWICK.

Cavendish Laboratory,
Cambridge, Feb. 17.

The Oldoway Human Skeleton

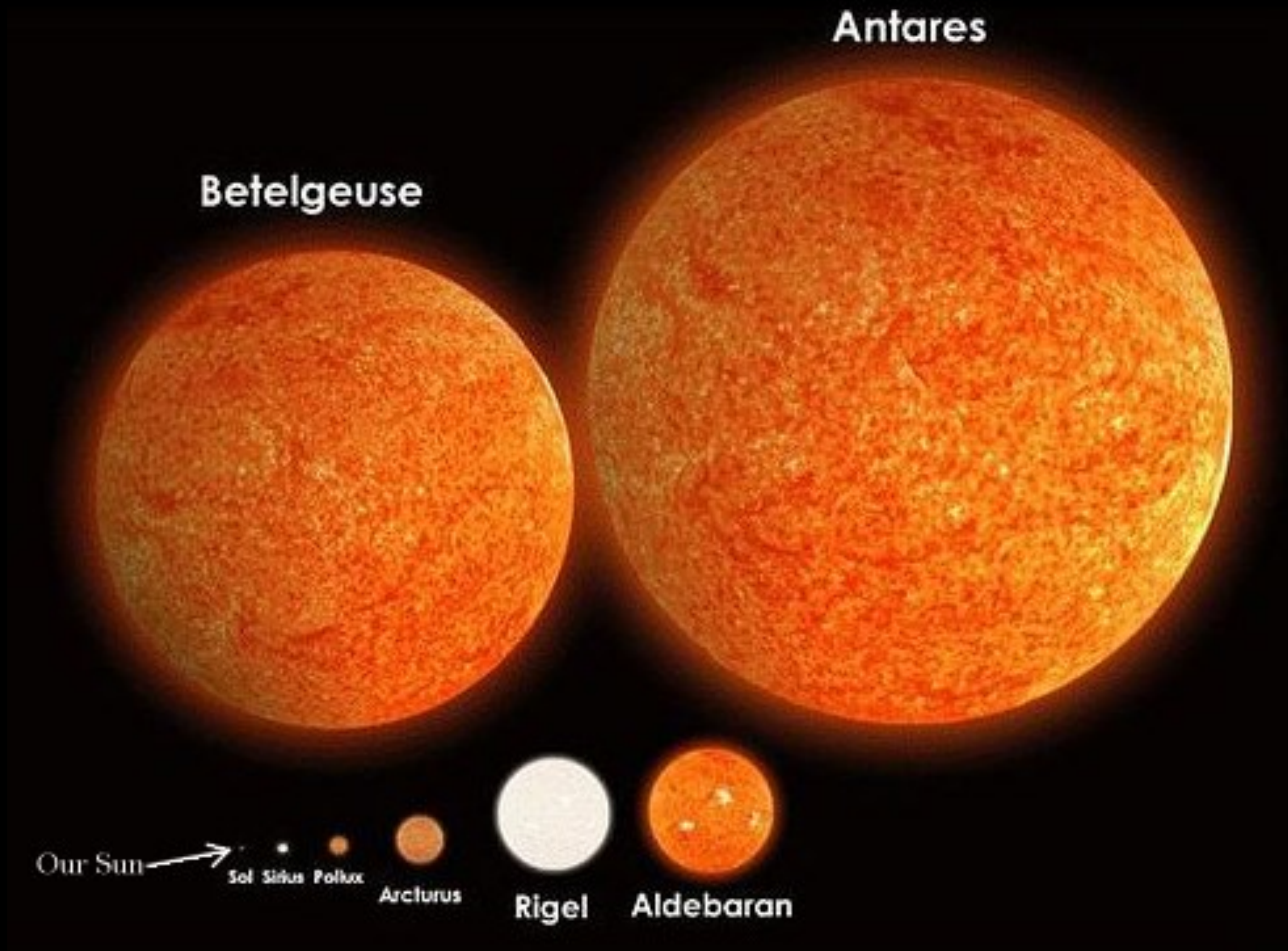
A LETTER appeared in NATURE of Oct. 24, 1931, signed by Messrs. Leakey, Hopwood, and Reck, in which, among other conclusions, it is stated that "there is no possible doubt that the human skeleton came from Bed No. 2 and not from Bed No. 4". This must be taken to mean that the skeleton is to be considered as a natural deposit in Bed No. 2, which is overlaid by the later beds Nos. 3 and 4, and that all consideration of human interment is ruled out.

If this be true, it is a most unusual occurrence. The skeleton, which is of modern type, with filed teeth, was found completely articulated down even to the phalanges, and in a position of extraordinary contraction. Complete mammalian skeletons of any age are, as field palæontologists know, of great rarity. When they occur, their perfection can usually be explained as the result of sudden death and immediate covering by volcanic dust. Many of the more or less perfect skeletons which may be seen in museums have been rearticulated from bones found somewhat scattered as the result of death from floods, or in the neighbourhood of drying water-holes. We know of no case of a perfect articulated skeleton being found in company with such broken and scattered remains as appear to be abundant at Oldoway. Either the skeletons are all complete, as in the *Stenomylus* quarry at Sioux City, Nebraska, or are all scattered and broken in various degrees, as in ordinary bone beds. The probability, therefore, that the Oldoway skeleton represents an artificial burial is thus one that will occur to palæontologists.

The skeleton was exhumed in 1913, and published photographs show that the excavation made for its disinterment was extensive. It is, therefore, very difficult to believe that in 1931 there can be reliable evidence left at the site as to the conditions under which it was deposited. If naturally deposited in Bed No. 2, the skeleton is of the highest possible importance, because it would be of pre-Mousterian age, and would be in the company of *Pithecanthropus* and the Piltdown, Heidelberg, and Peking men, all of whose remains are fragmentary to the last degree. Of the few other human remains for which such antiquity is claimed, the Galley Hill skeleton and the Ipswich skeleton are, or apparently were, complete. The first of these was never seen *in situ* by any trained observer, and the latter has, we believe, been withdrawn by its discoverer. The other fragments, found long ago, are entirely without satisfactory evidence as to their mode of occurrence.

½ page
1 Nobel prize

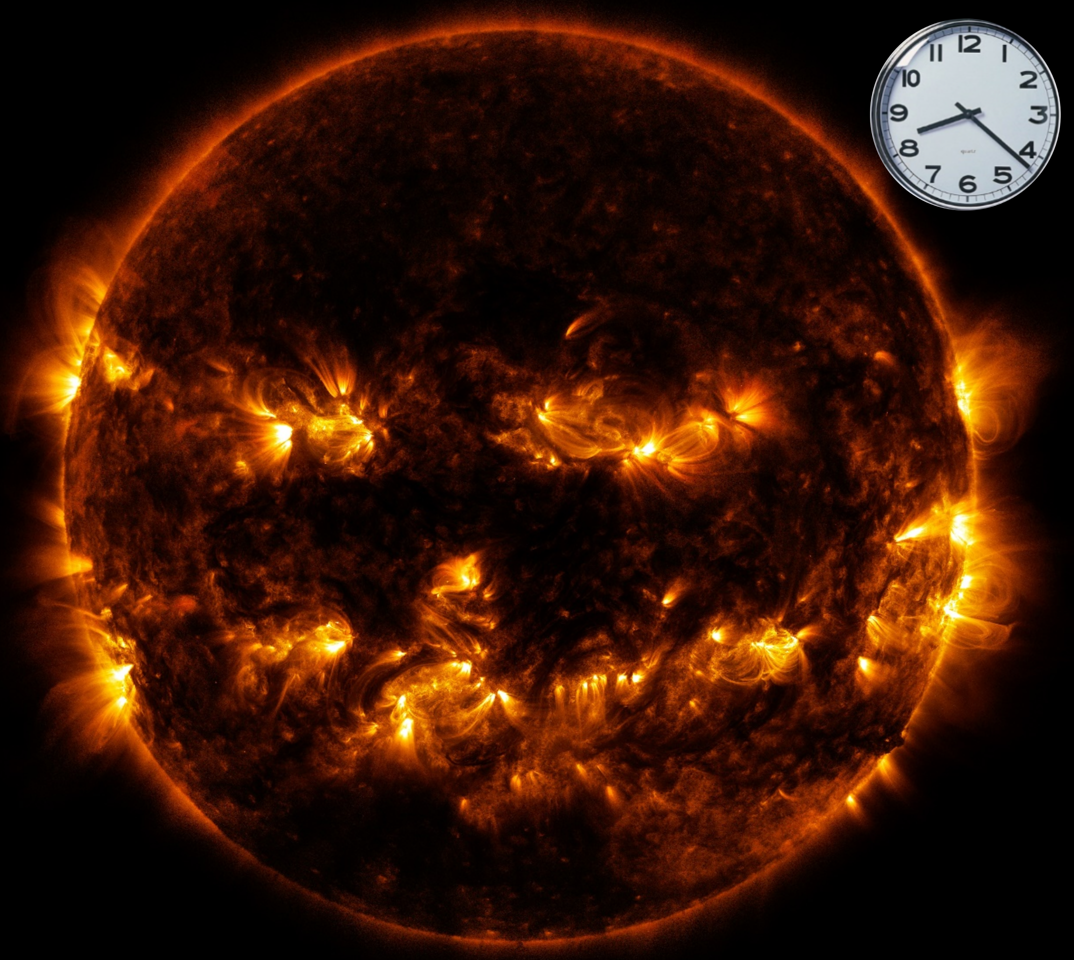
dark stars



John Michell (1783)

- Matter could be even denser – if nuclear forces are also not sufficient keep matter from collapsing under gravity.
- “Dark stars”: hypothesized in the 1700’s that in stars that are sufficiently massive gravity can pull photons back, making the star dark.

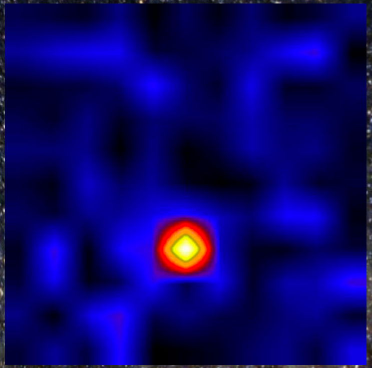
“frozen stars”

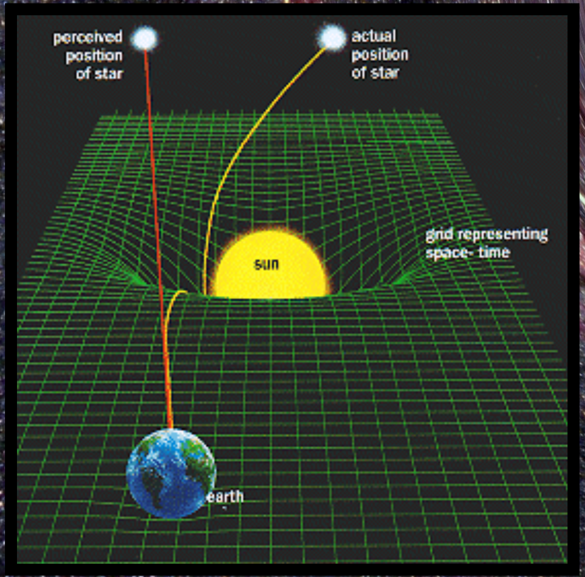


above some mass limit ($3M_\odot$), neutron stars collapse too
(Tollman, Oppenheimer, Volkoff, 1939)
for an outside observer, time on the collapsing star stops

black holes

First observational clue in 1972 in an X-ray binary (Cygnus X-1)





Massive “spheres” defined by their surface of no return (event horizon).