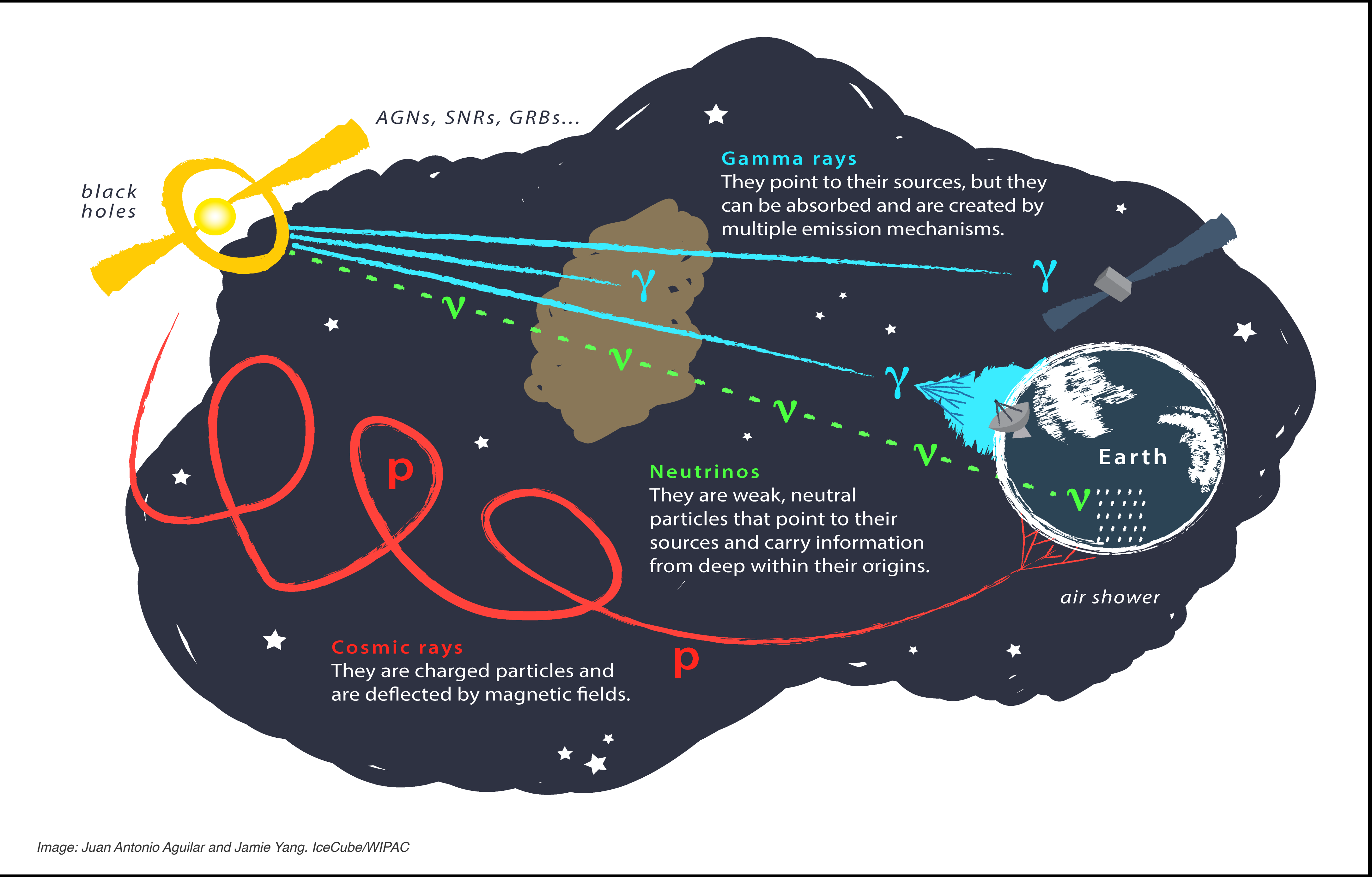
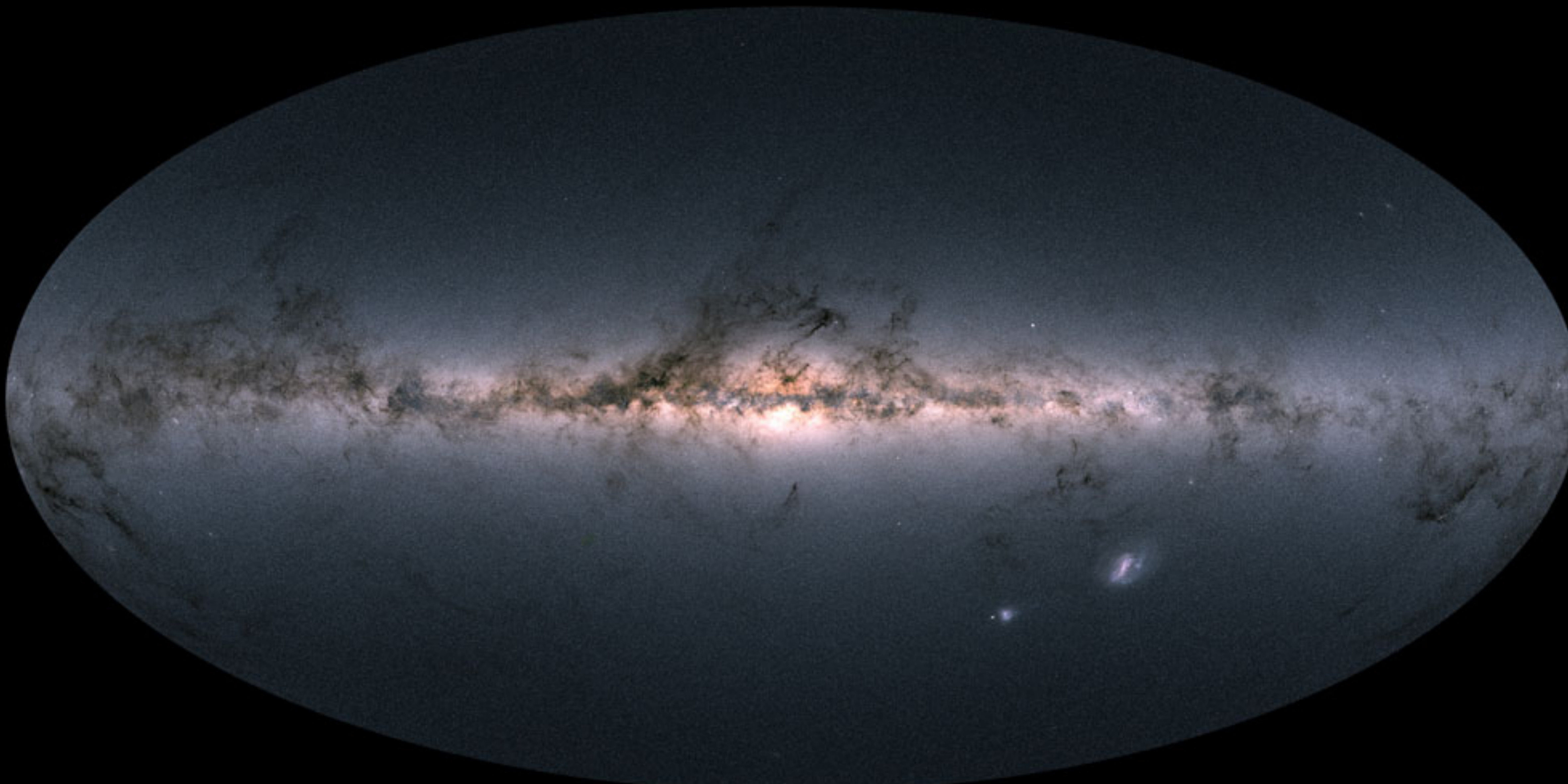
Meet the messengers!

Astrophysical messengers, pre-2015:

photons,
neutrinos,
cosmic rays
(and rocks)

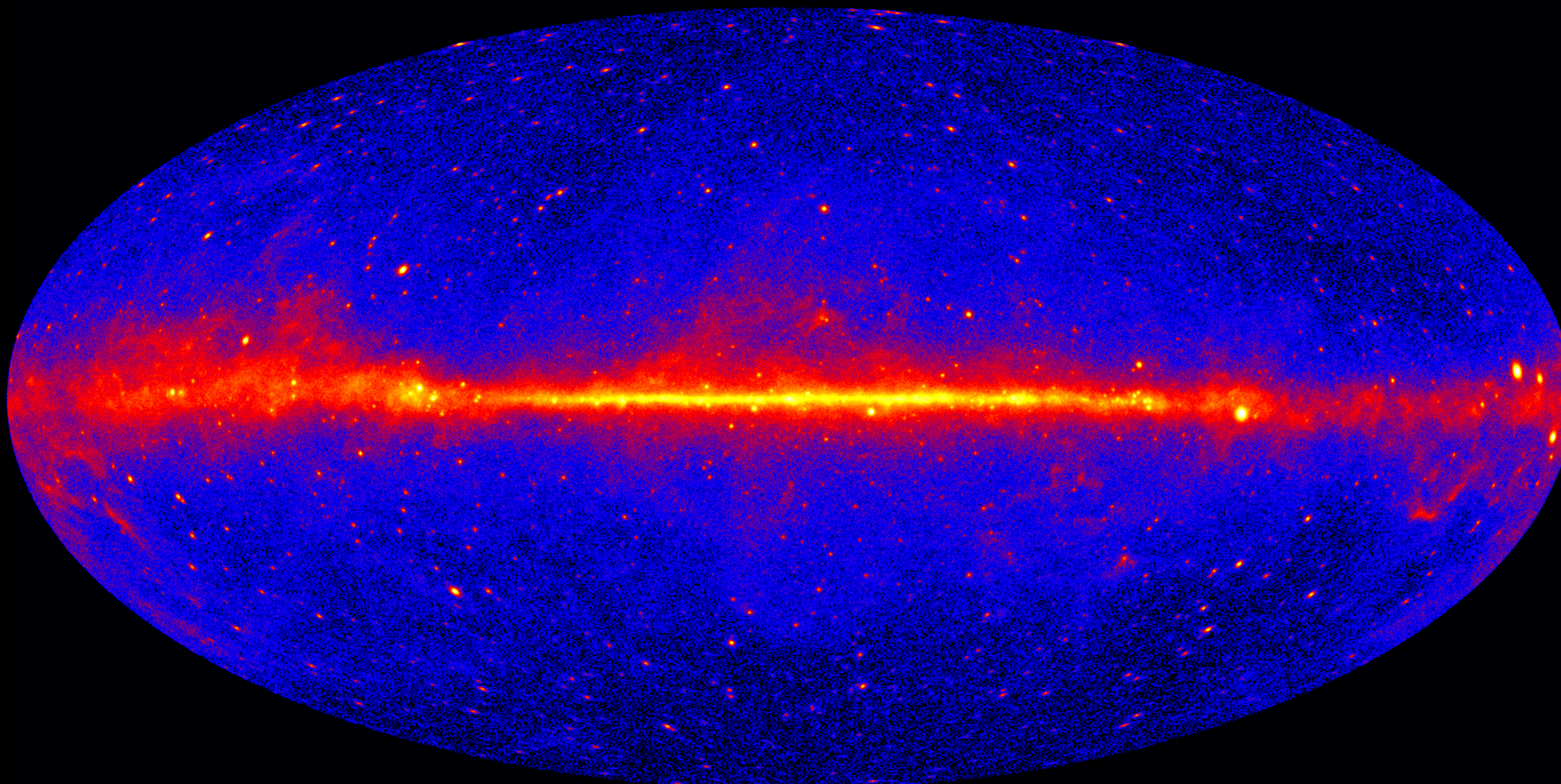


Photons encode temperature, density, kinematics, composition of matter

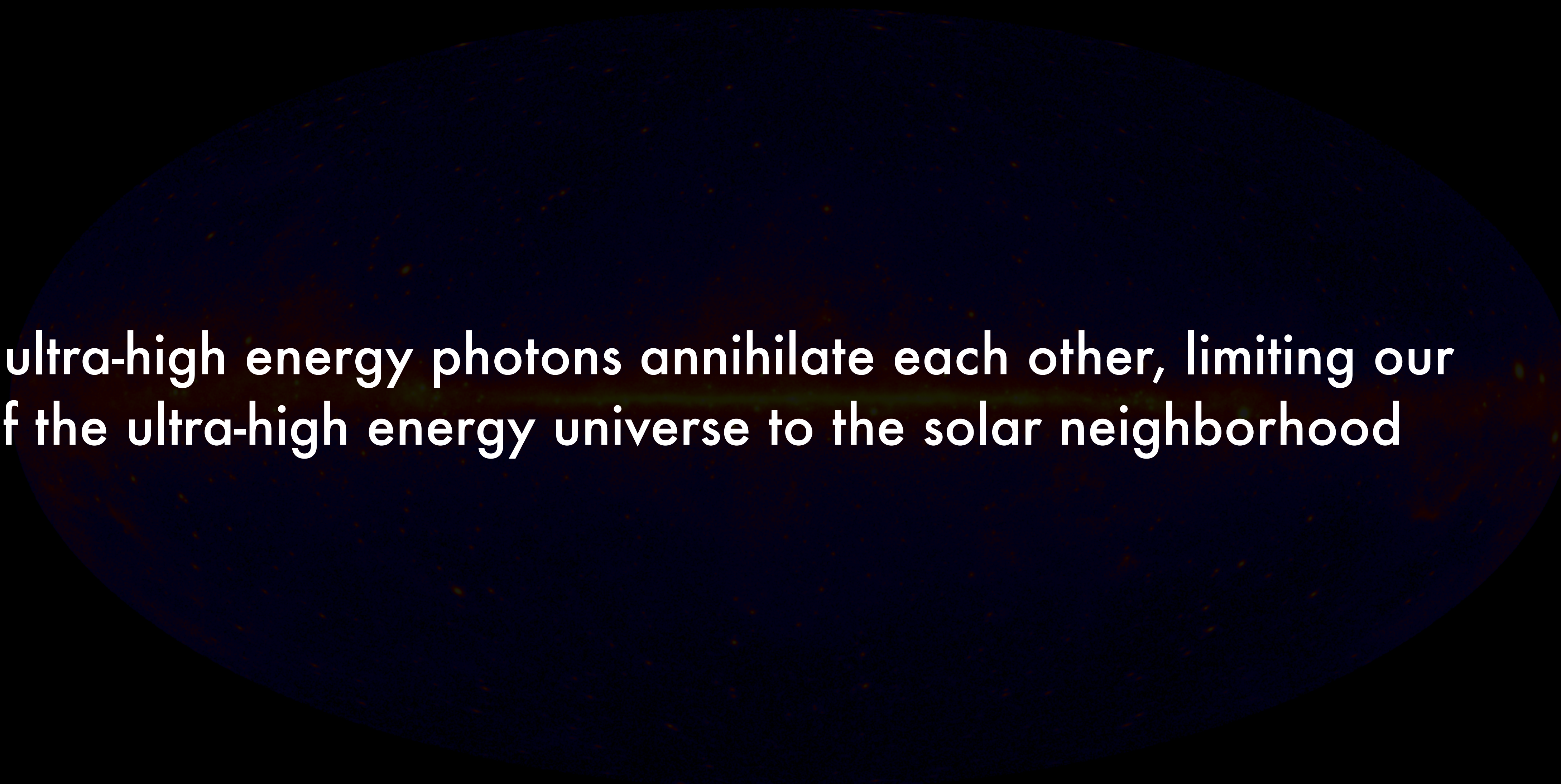


...but are easily distracted by other matter, magnetic fields, other photons

Photons encode temperature, density, kinematics, composition of matter



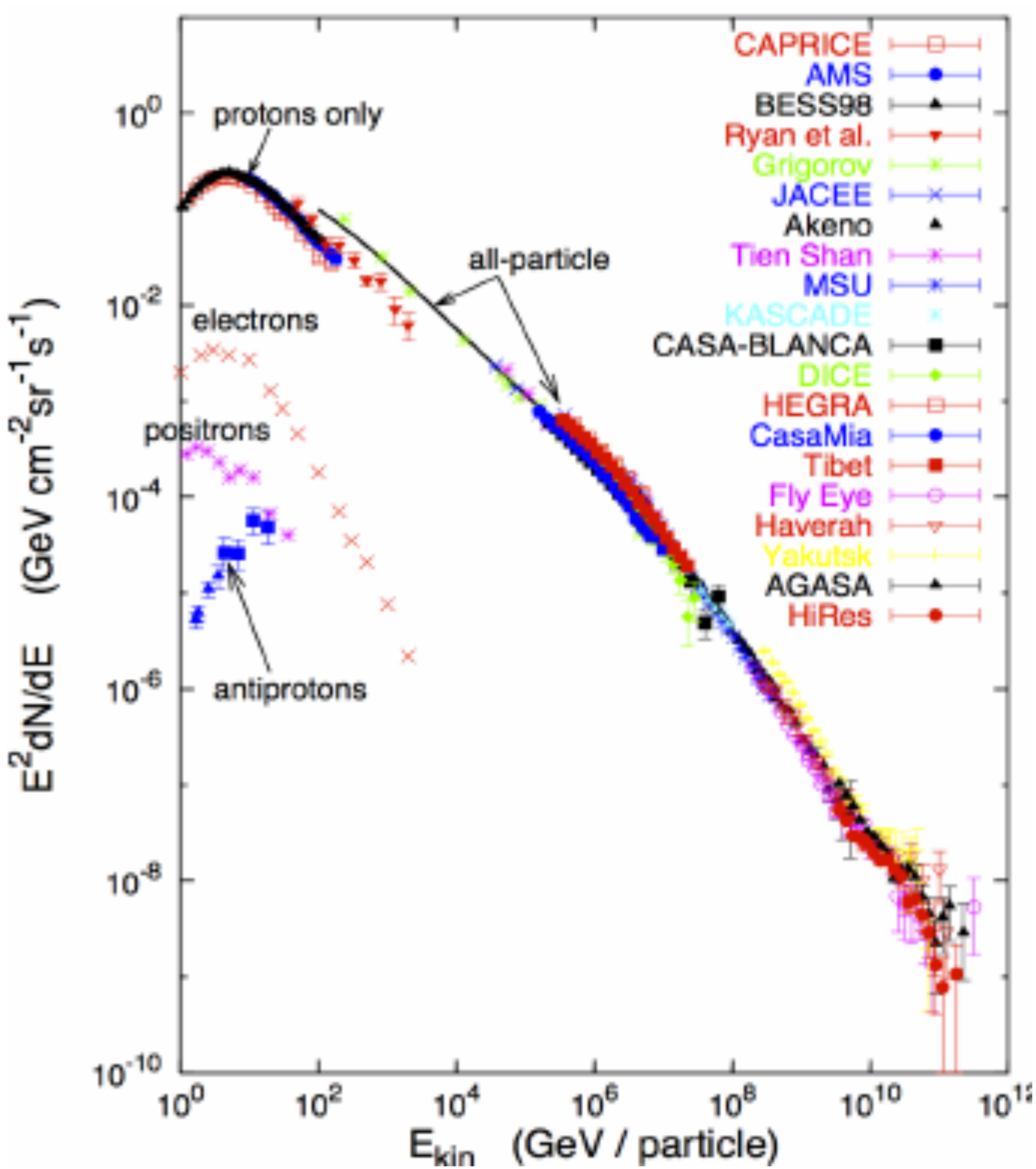
...but are easily distracted by other matter, magnetic fields, other photons

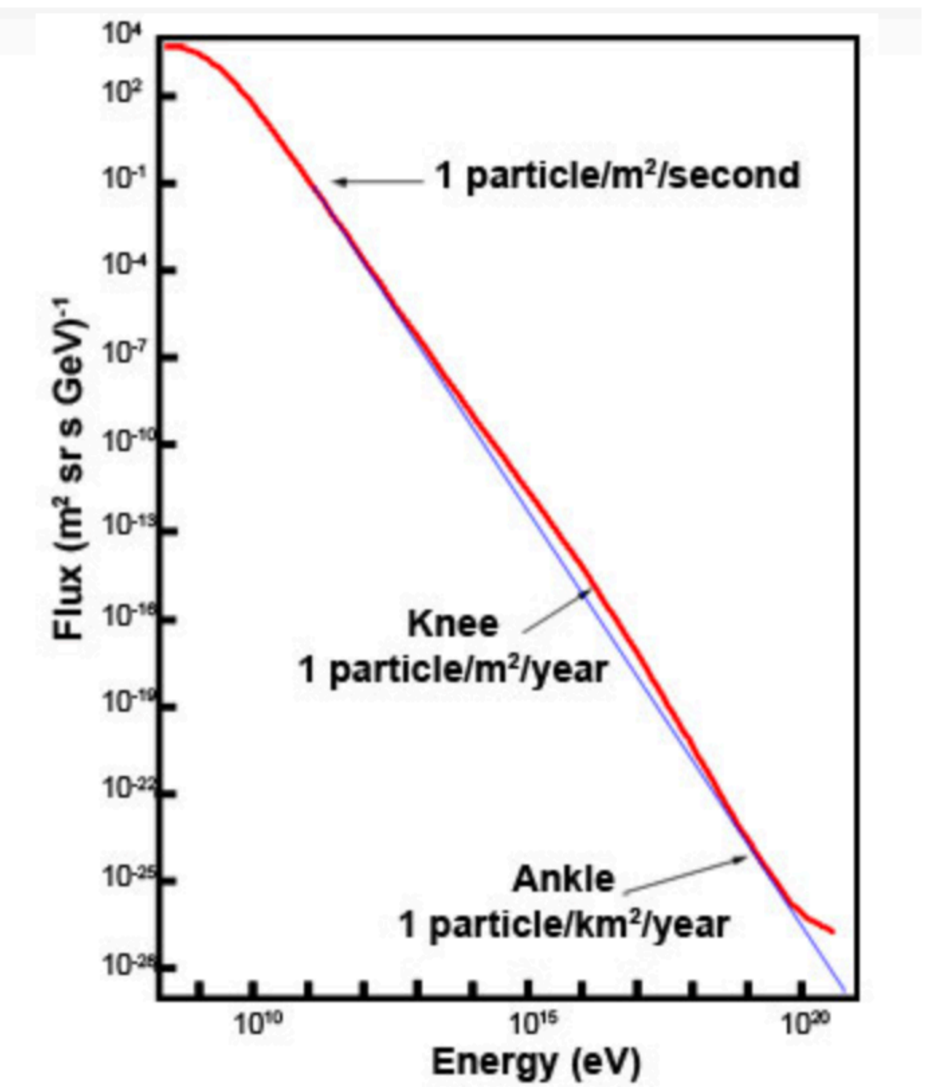


…and ultra-high energy photons annihilate each other, limiting our view of the ultra-high energy universe to the solar neighborhood

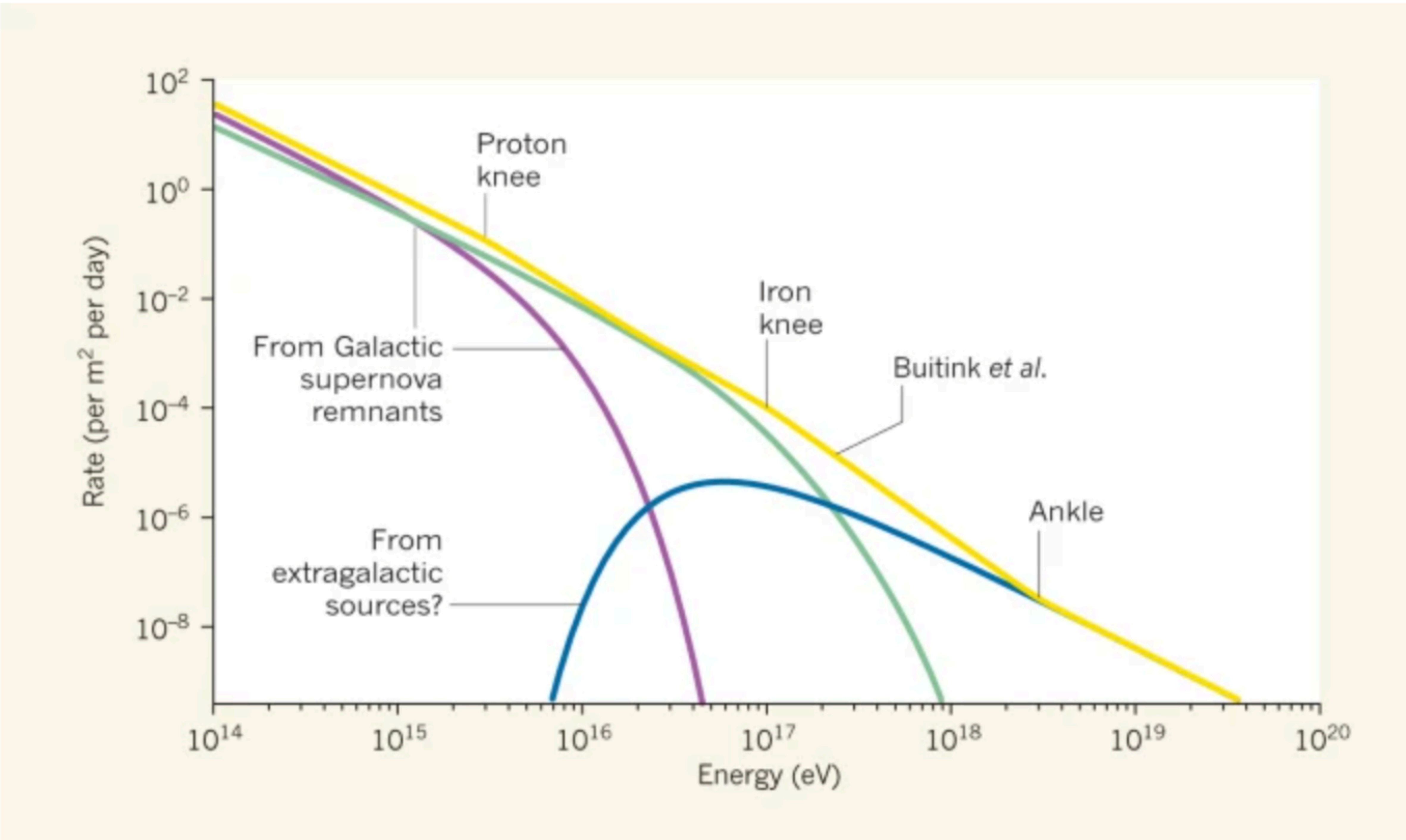
100 TeV photons travel ~ few kpc

Cosmic Rays are charged particles



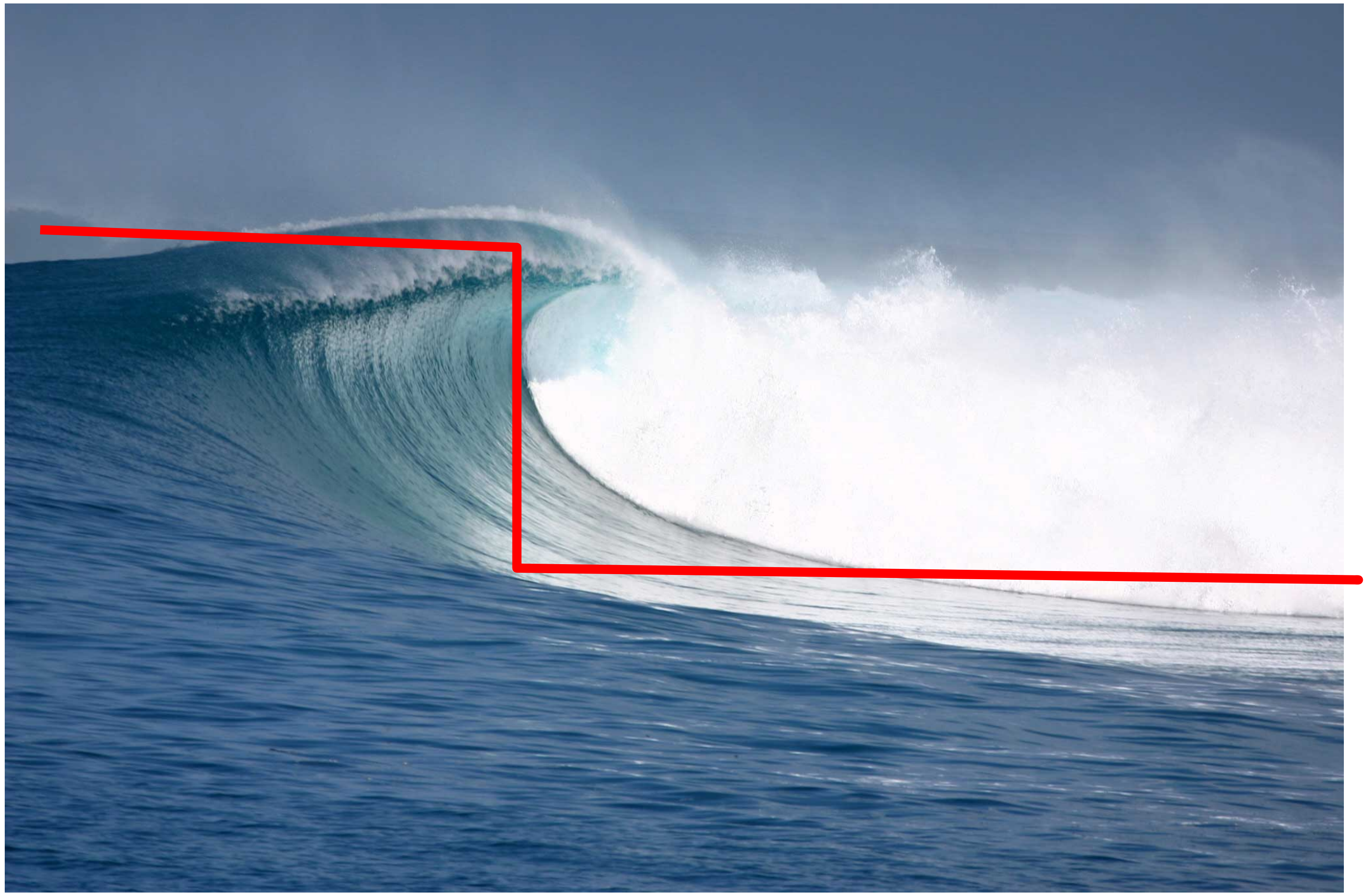


Astrophysical cosmic rays built from a variety of sources



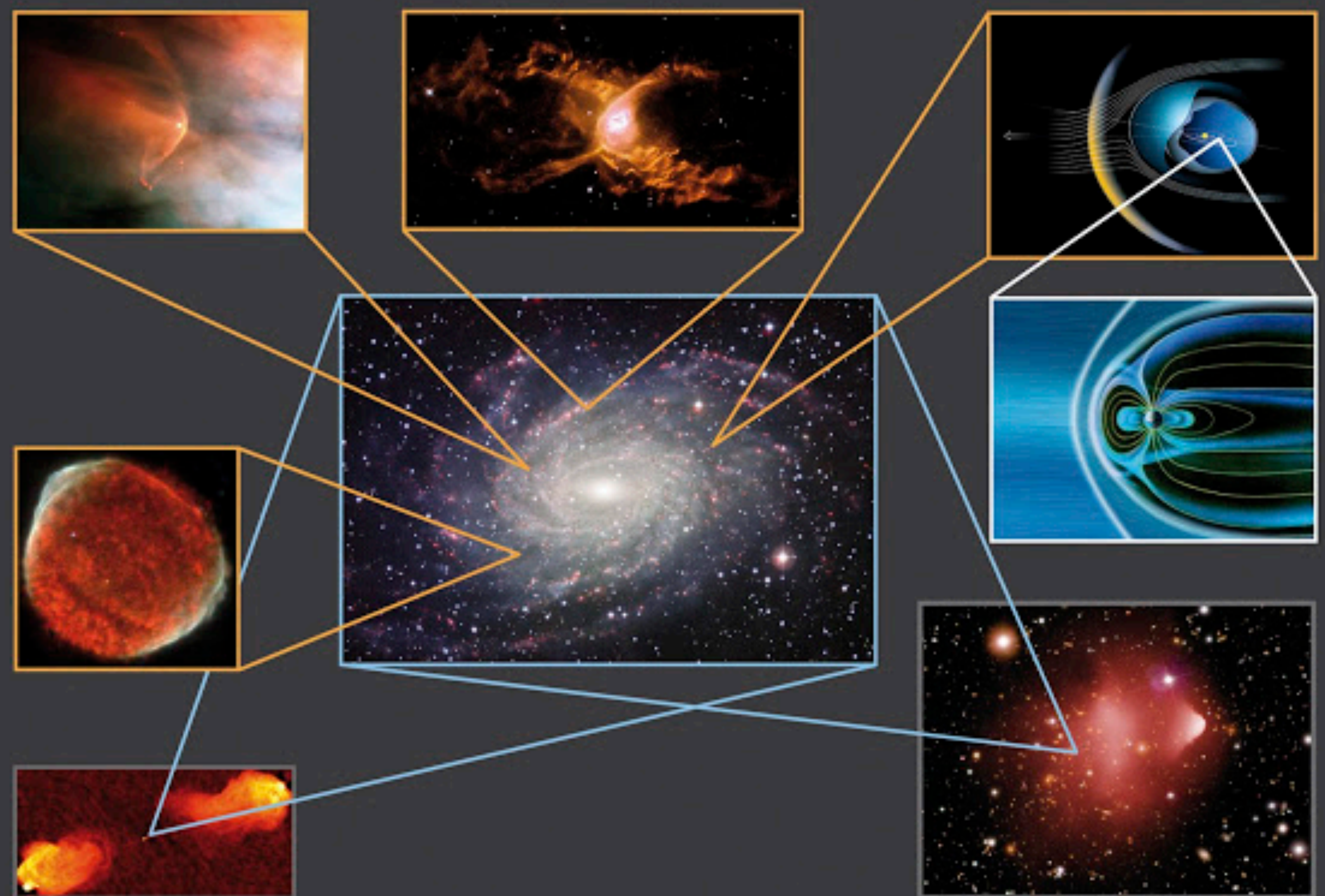
Cosmic Rays are made by shocks

- Shocks occur when a supersonic flow encounters an obstacle or decelerates to subsonic speed
  - In a situation where a transverse wave would “break”, a longitudinal wave forms a shock front
    - velocity, density and pressure change discontinuously across the shock



- Astrophysical shocks are usually ***collisionless shocks***
  - shock front is much thinner than particle mean free path

Astrophysical shocks happen at all scales

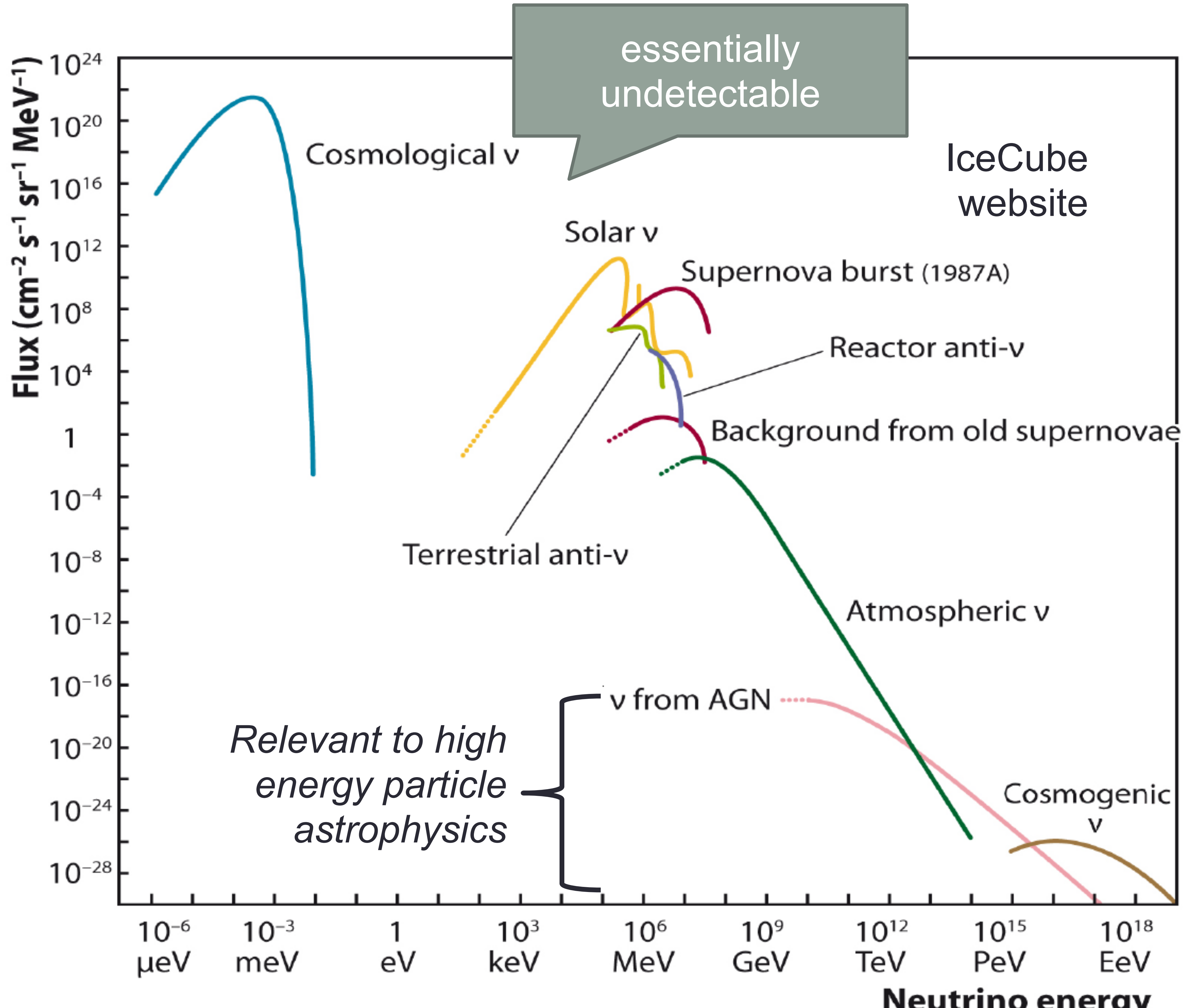


http://minsex.blogspot.co.uk/2011/11/astrophysical-shock-waves.html

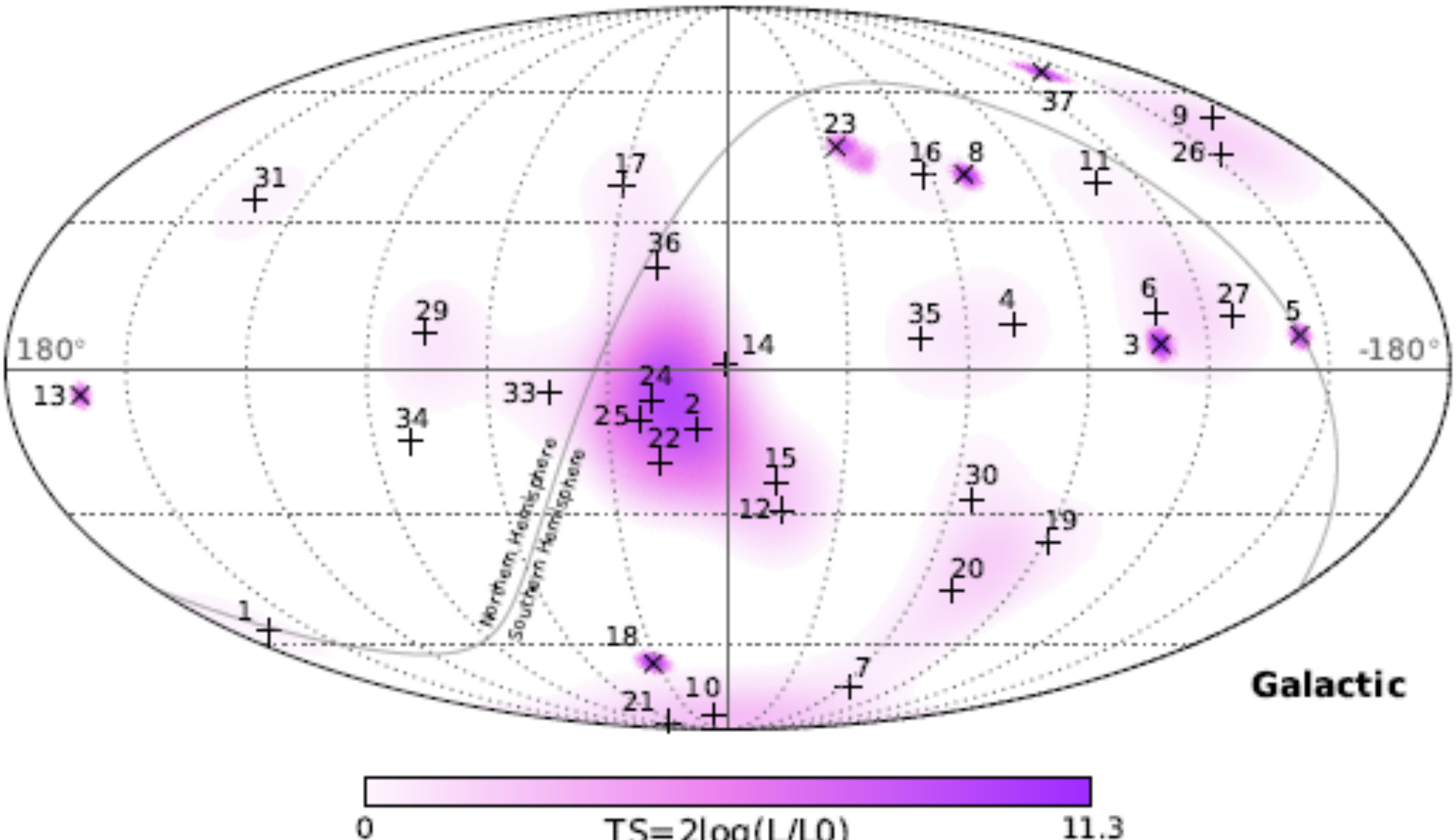
Outside the solar system, shocks are observed as sharp edges in emission, with characteristic shape

Many are clearly associated with acceleration, e.g. seen in synchrotron radiation

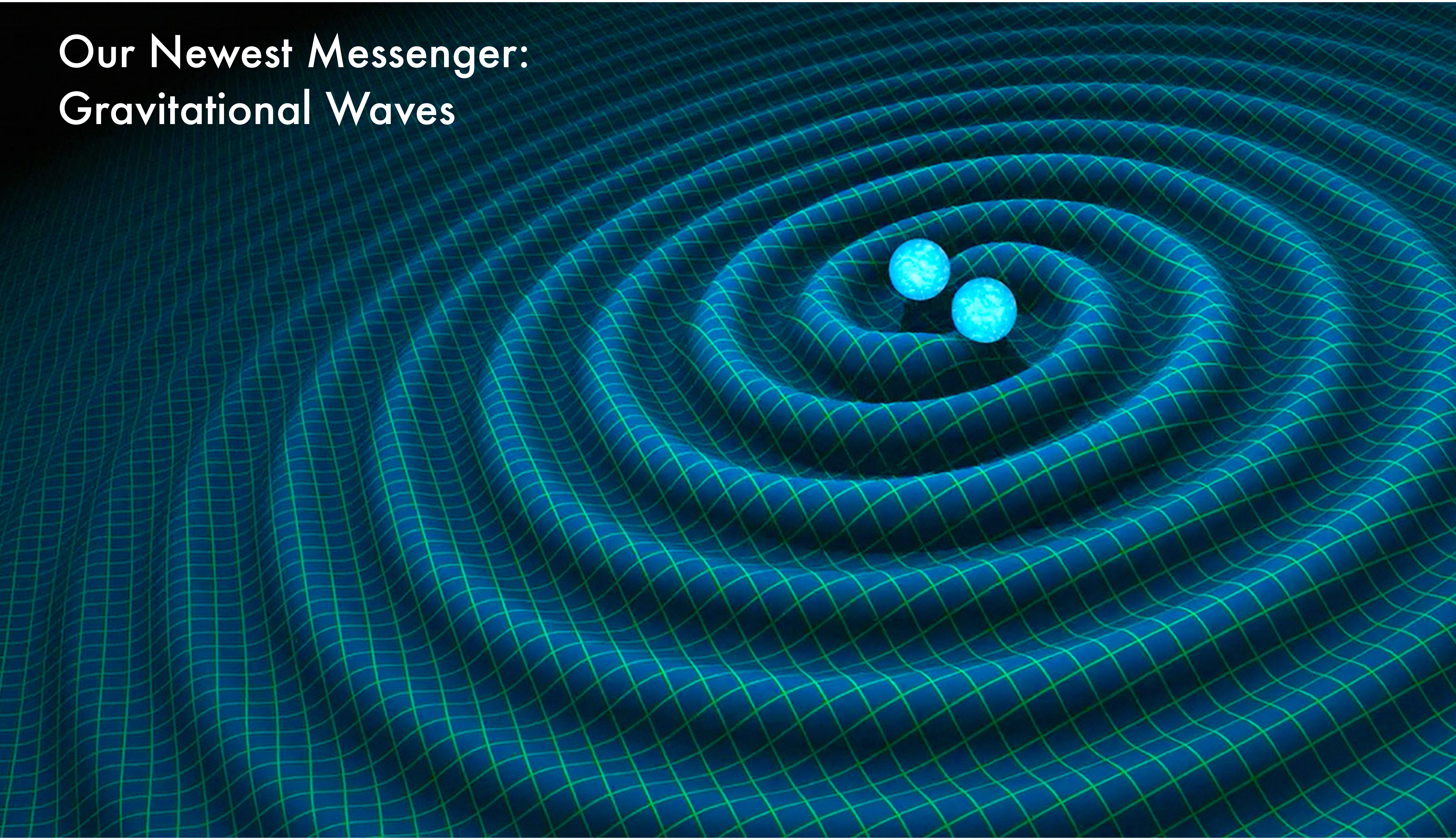
Neutrinos encode nuclear reactions



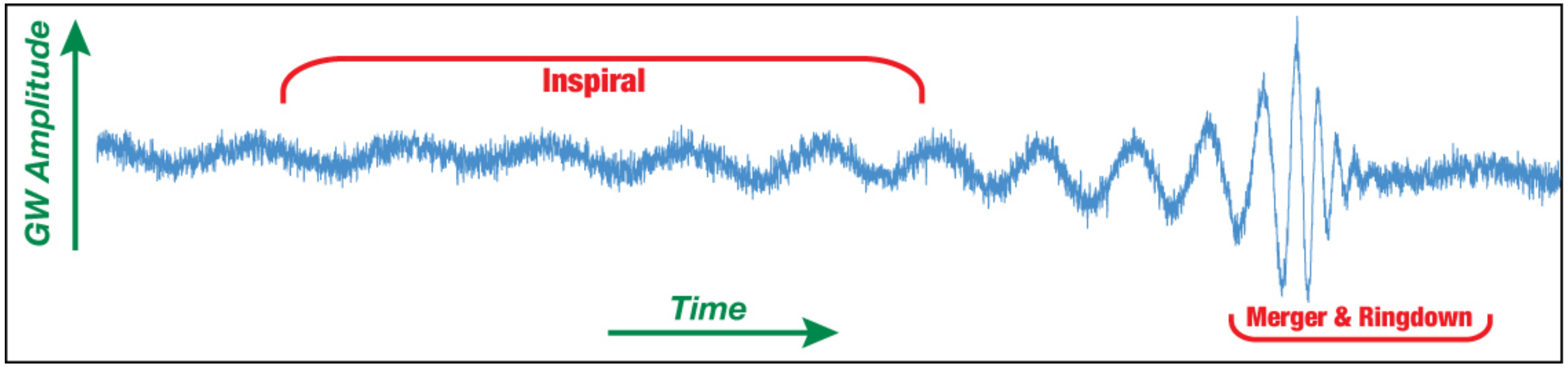
…but the mean-free-path is larger than a Hubble radius

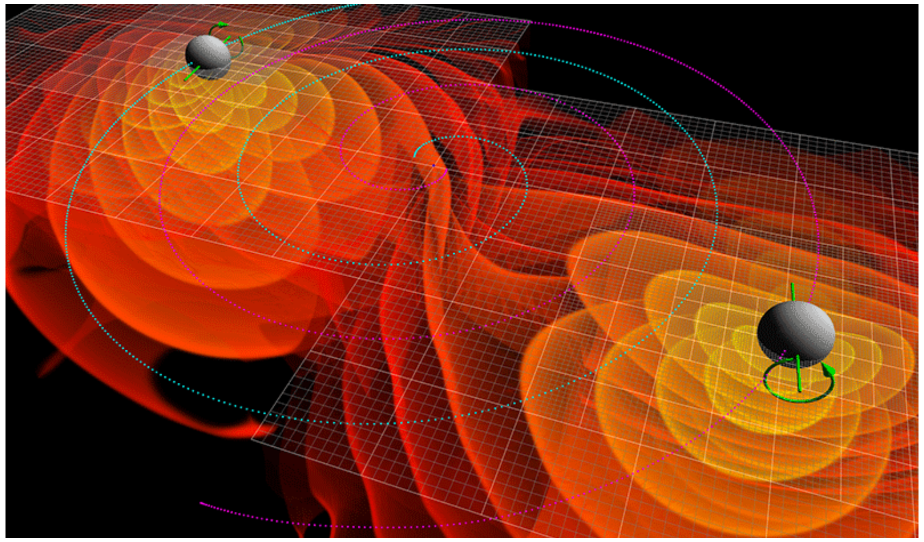


3-year IceCube observation of astrophysical neutrinos

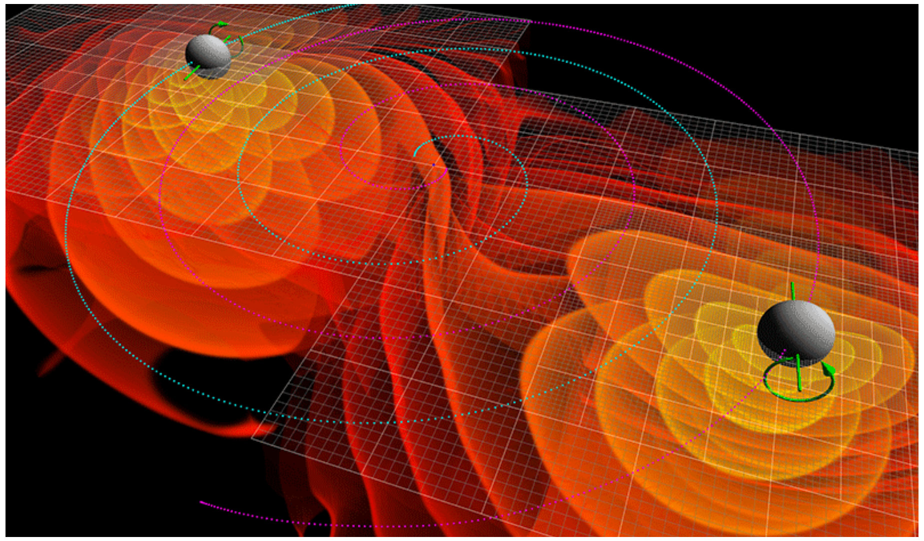

Our Newest Messenger:
Gravitational Waves

Gravitational waves encode mass, spin (and spin direction), orbit and distance





BBH no spin



BBH with spin

Multimessenger Case Studies

Event type	EM	GW	Particle	Example
The Sun	Yes		Yes	SOL 1942-02-28
Supernova	Yes	Predicted	Yes	SN 1987A
Neutron star mergers	Yes	Yes	Predicted	GW 170817
Blazar	Yes		Yes	TXS 0506+056
Active galactic nucleus	Yes		Yes	Messier 77 (squid galaxy)
Tidal disruption event	Yes		Yes	AT2019dsg, AT2019fdr

MMA Events, an incomplete history

1940s – some cosmic rays identified as forming in solar flares.

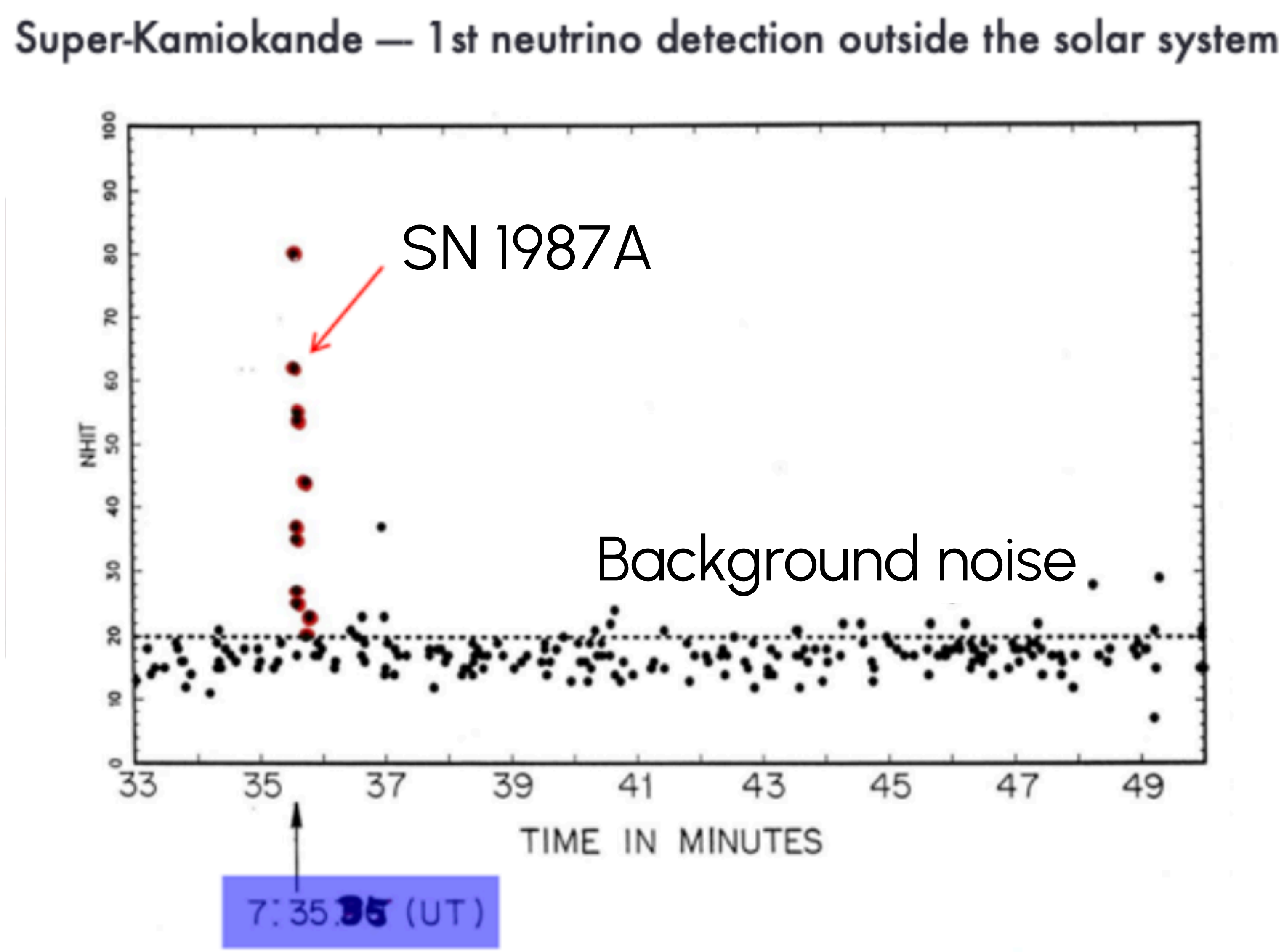
1987 – SN 1987A neutrinos detected by Kamiokande-II, IMB, and Baksan. Optical telescopes detect it hours later.

17 August, 2017 – Collision of two neutron stars in NGC 4993 detected in GWs by LIGO and Virgo. EM counterparts start being detected 1.7 seconds later...

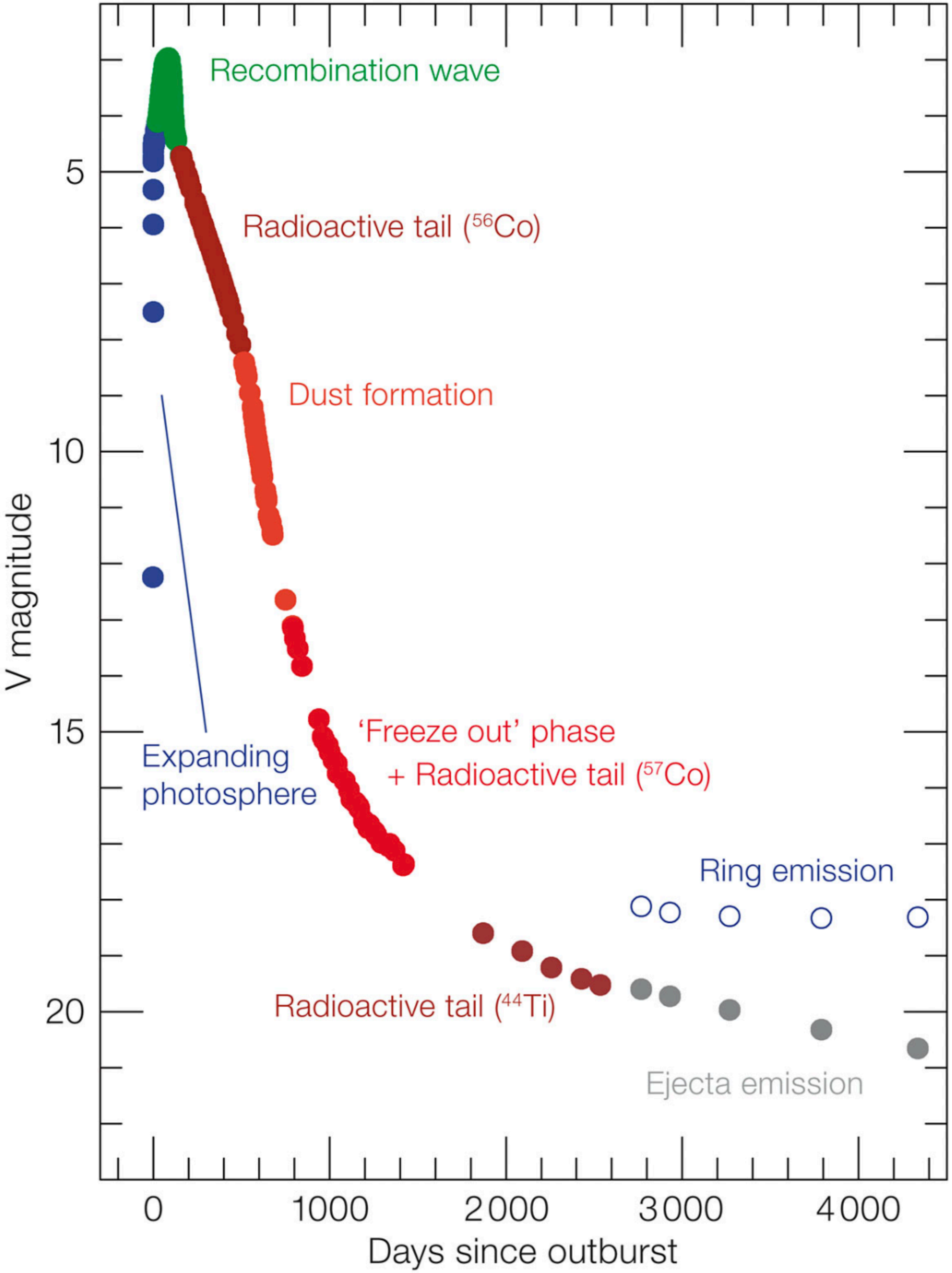
22 September 2017 – ~300 TeV neutrino produced in a blazar, with high-energy gamma rays subsequently detected. Neutrinos used to localize event in space.

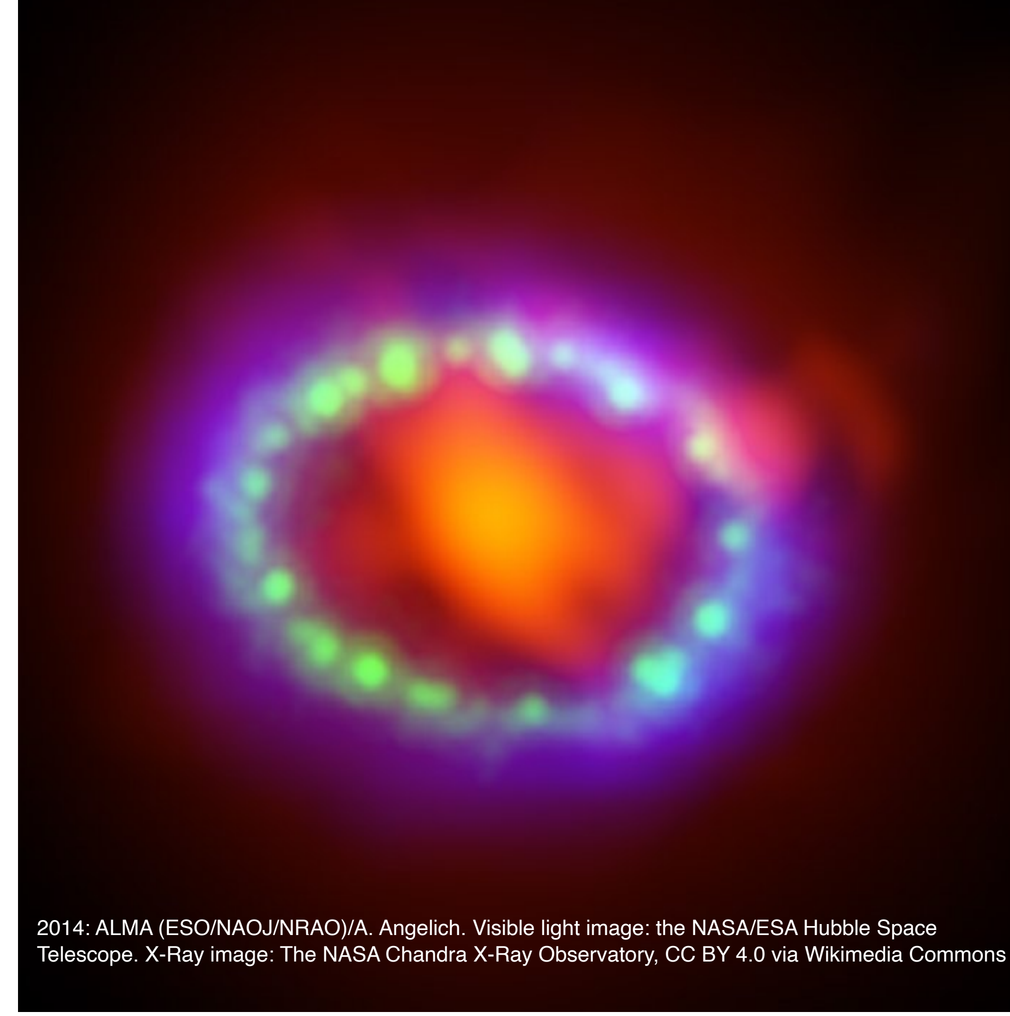
1 October 2019 – High-energy neutrino detected by IceCube, with follow-up EM counterparts identifying a tidal disruption event.

SN 1987A — Type II supernova



Neutrinos respond to the weak force and gravity...
100 trillion are passing through you every second!





2014: ALMA (ESO/NAOJ/NRAO)/A. Angelich. Visible light image: the NASA/ESA Hubble Space Telescope. X-Ray image: The NASA Chandra X-Ray Observatory, CC BY 4.0 via Wikimedia Commons

NASA, ESA, CSA, M. Matsuura (Cardiff University), R. Arendt (NASA's Goddard Spaceflight Center & University of Maryland, Baltimore County), C. Fransson (Stockholm University), J. Larsson (KTH Royal Institute of Technology), A. Pagan (STScI), CC BY 4.0 via Wikimedia Commons

Supernova neutrinos

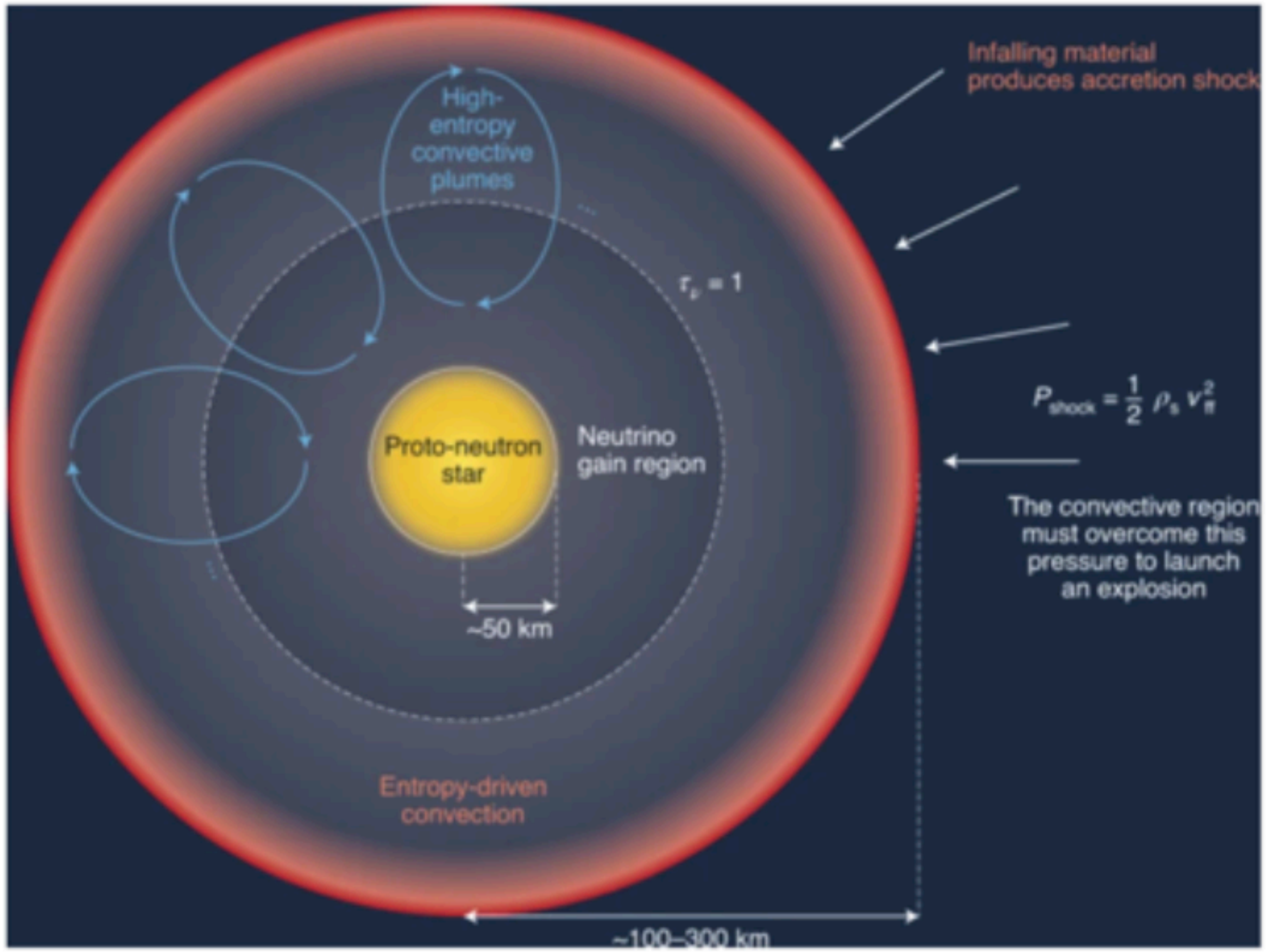
Early stage of supernova involves electron capture by protons bound inside iron nuclei.

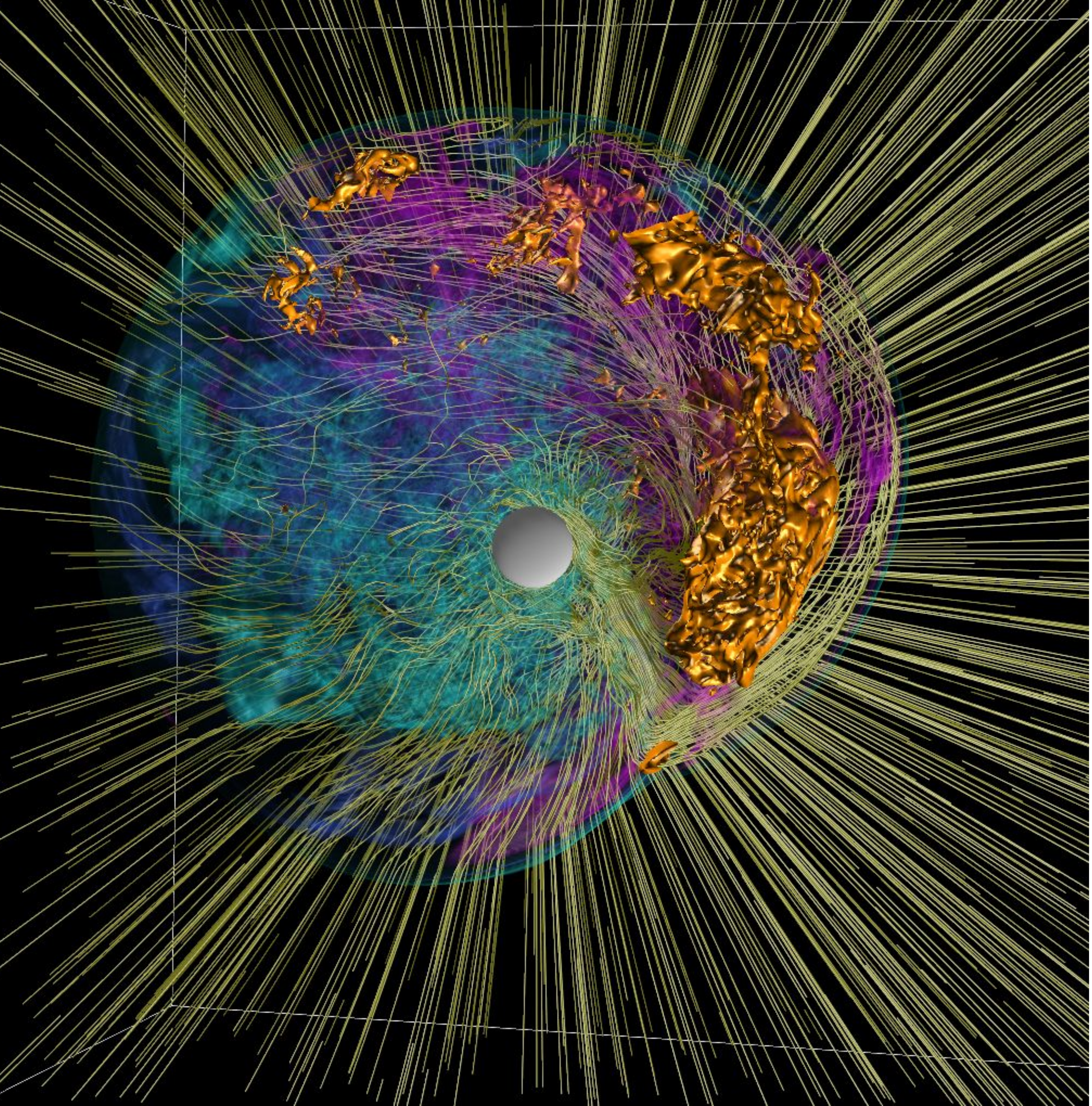
$$\mathrm{e}^- + \mathrm{p} \rightarrow \nu_e + \mathrm{n}$$

This leads to neutronization of the core.

Some of these neutrons undergo beta decay, producing anti-neutrinos.

$$\mathrm{n} \rightarrow \mathrm{p} + \mathrm{e}^- + \bar{\nu}_e$$



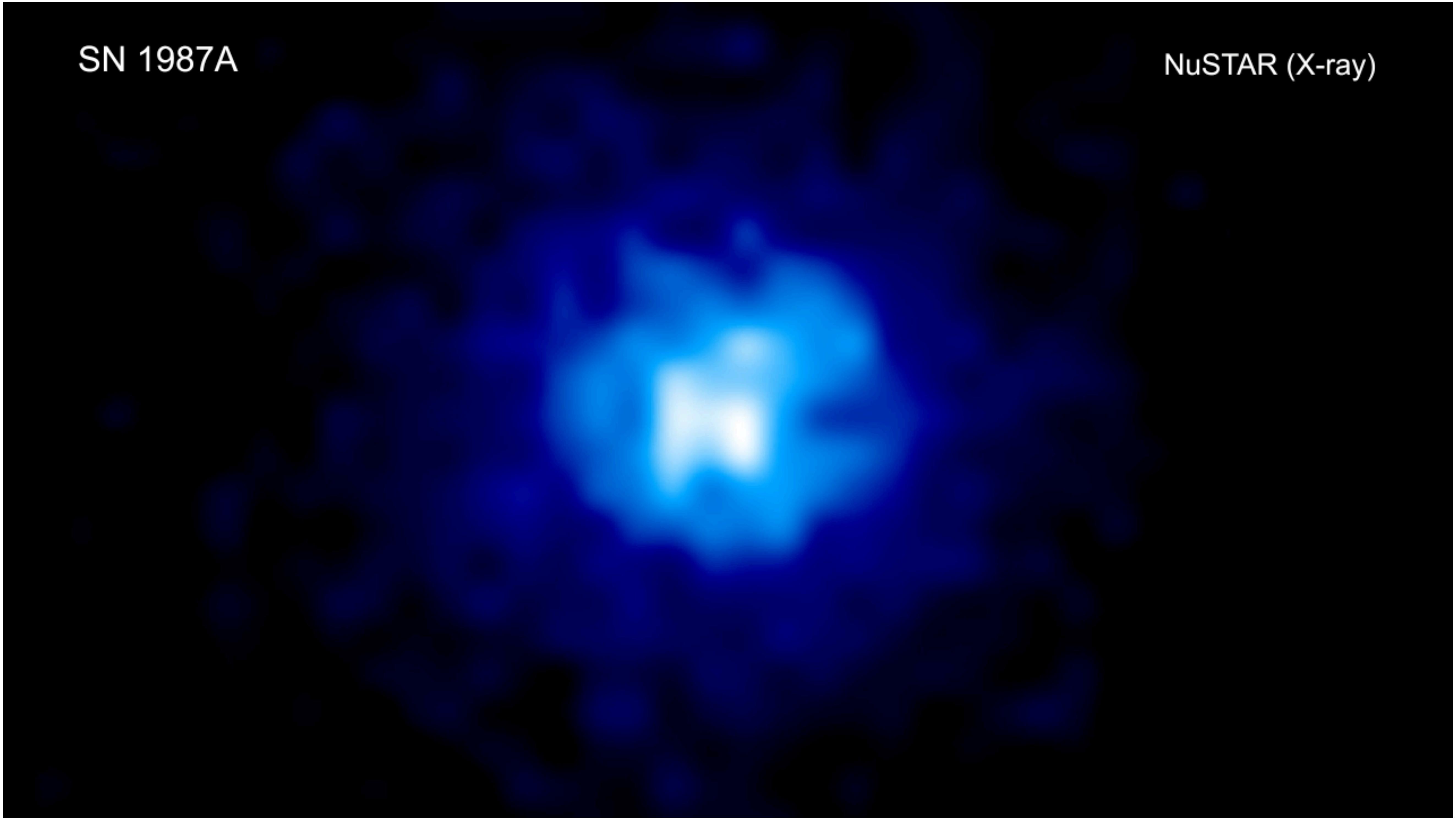


Neutrinos (lines) get entrained in matter, heat it, drive instabilities, and (we think) cause SNe to explode

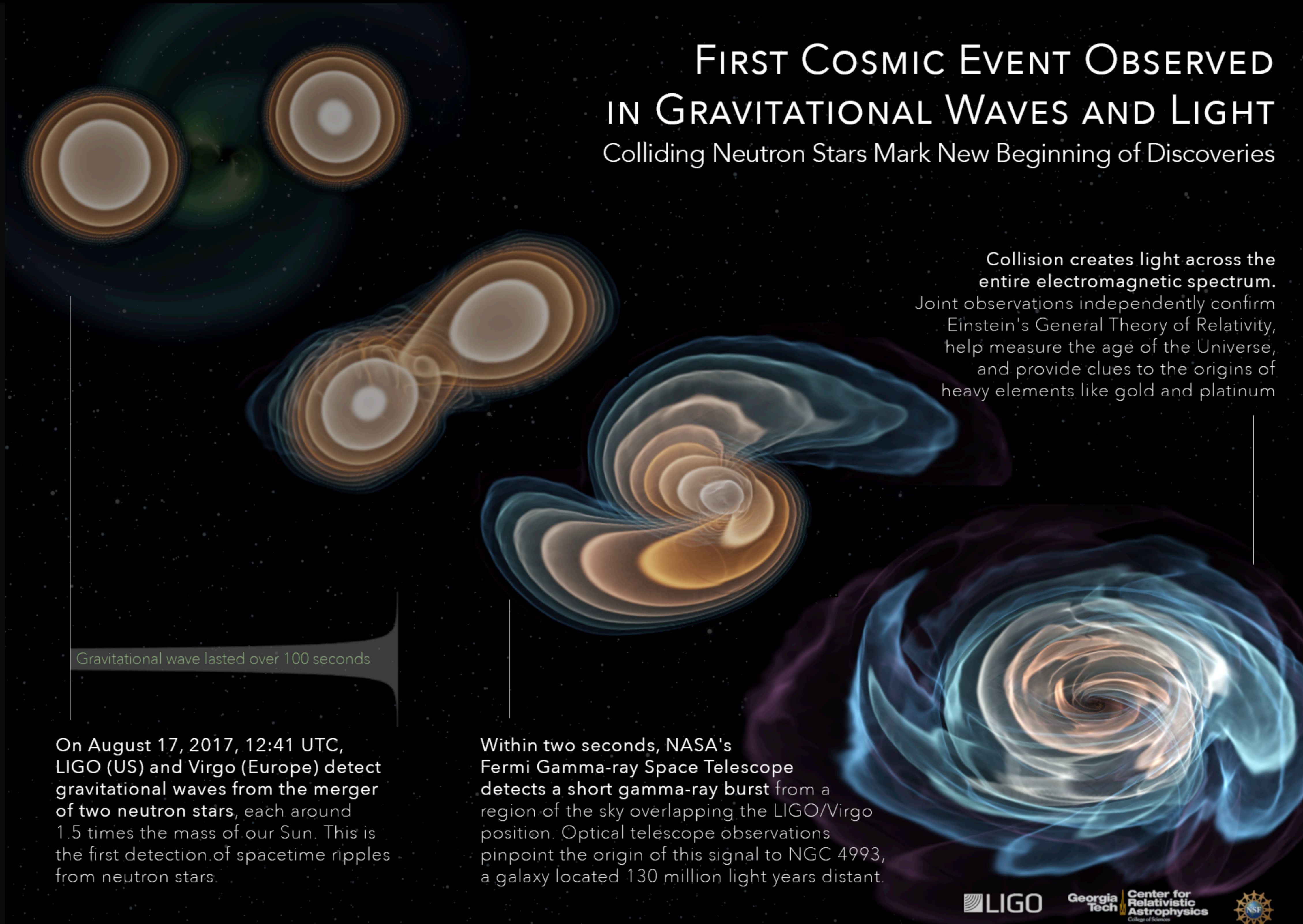
90% of the luminosity is in neutrinos!

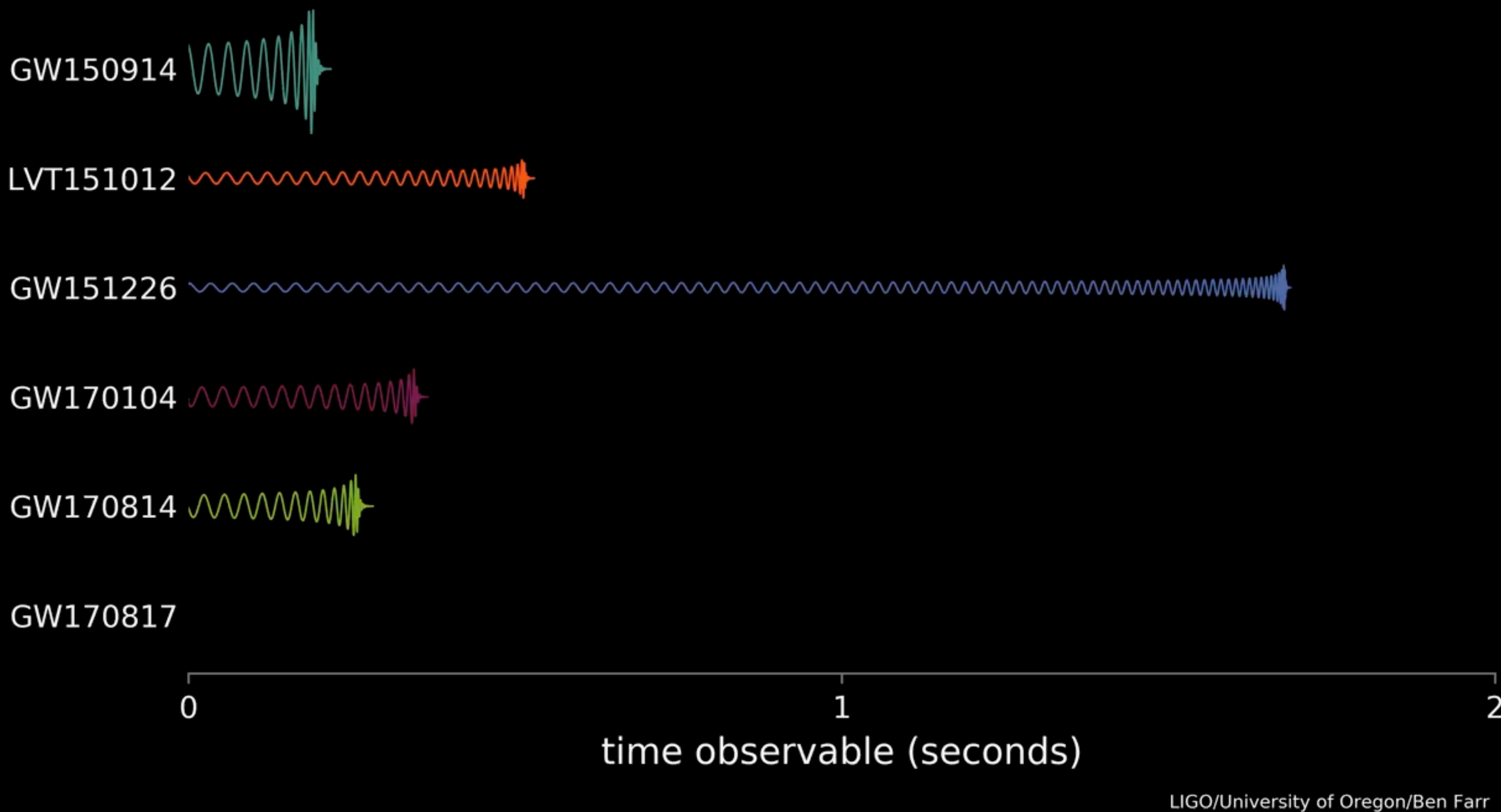
Blondin and Mezzacappa

Neutrinos indicated that a neutron star was created, and we may have indirectly found the pulsar!



Greco et al. 2021


First Cosmic Event Observed
in Gravitational Waves and Light
Colliding Neutron Stars Mark New Beginning of Discoveries
Collision creates light across the entire electromagnetic spectrum.
Joint observations independently confirm Einstein's General Theory of Relativity, help measure the age of the Universe, and provide clues to the origins of heavy elements like gold and platinum
Gravitational wave lasted over 100 seconds
On August 17, 2017, 12:41 UTC, LIGO (US) and Virgo (Europe) detect gravitational waves from the merger of two neutron stars, each around 1.5 times the mass of our Sun. This is the first detection of spacetime ripples from neutron stars.
Within two seconds, NASA's Fermi Gamma-ray Space Telescope detects a short gamma-ray burst from a region of the sky overlapping the LIGO/Virgo position. Optical telescope observations pinpoint the origin of this signal to NGC 4993, a galaxy located 130 million light years distant.
LIGO
Georgia Tech
Center for Relativistic Astrophysics
NSF

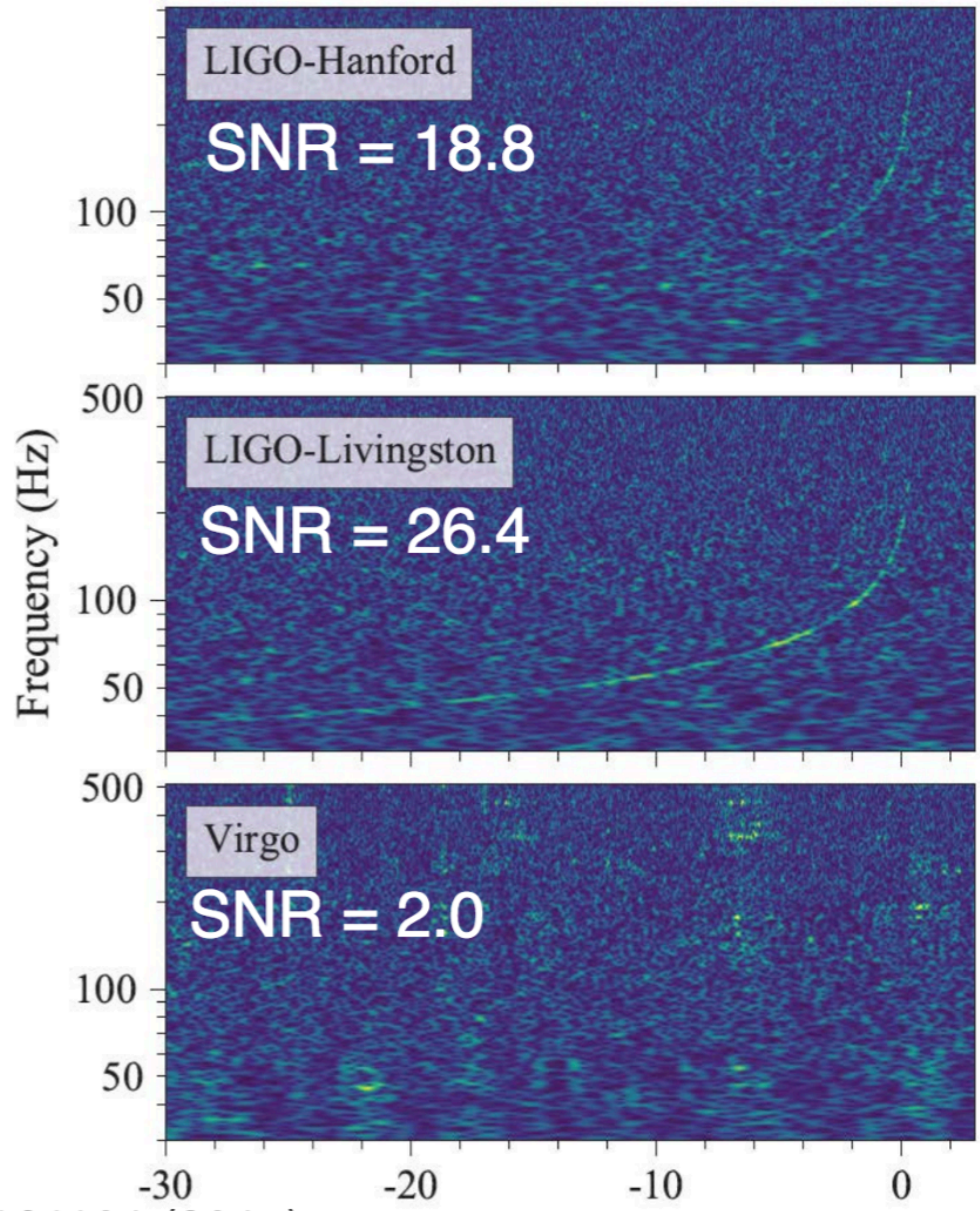

GW150914
LVT151012
GW151226
GW170104
GW170814
GW170817
0
1
2
time observable (seconds)
LIGO/University of Oregon/Ben Farr

Slowest signal implies low mass

$0.86 - 2.25\ M_{\odot}$

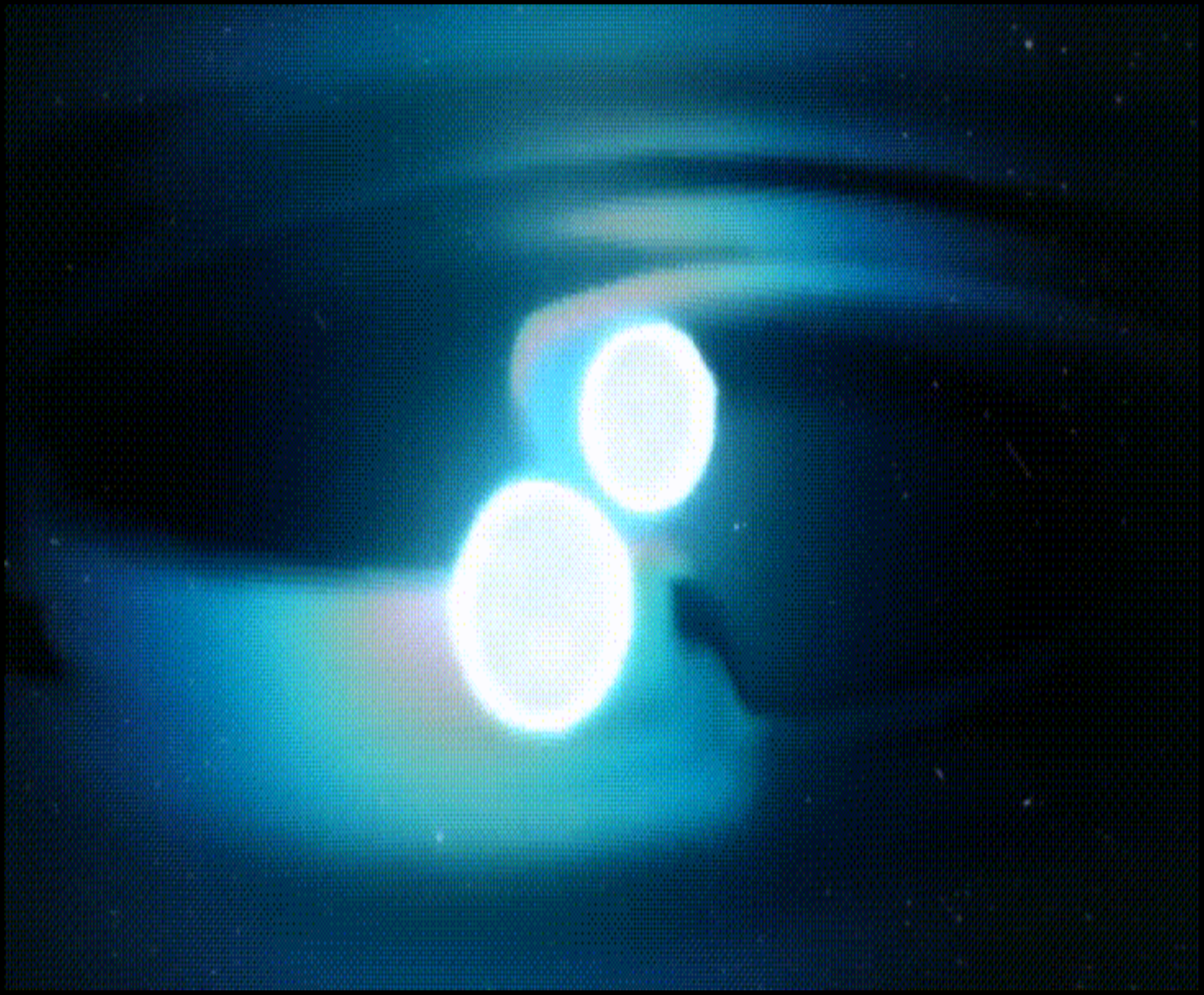
Total SNR: 32.4 loudest GW detected

In Virgo's blind spot



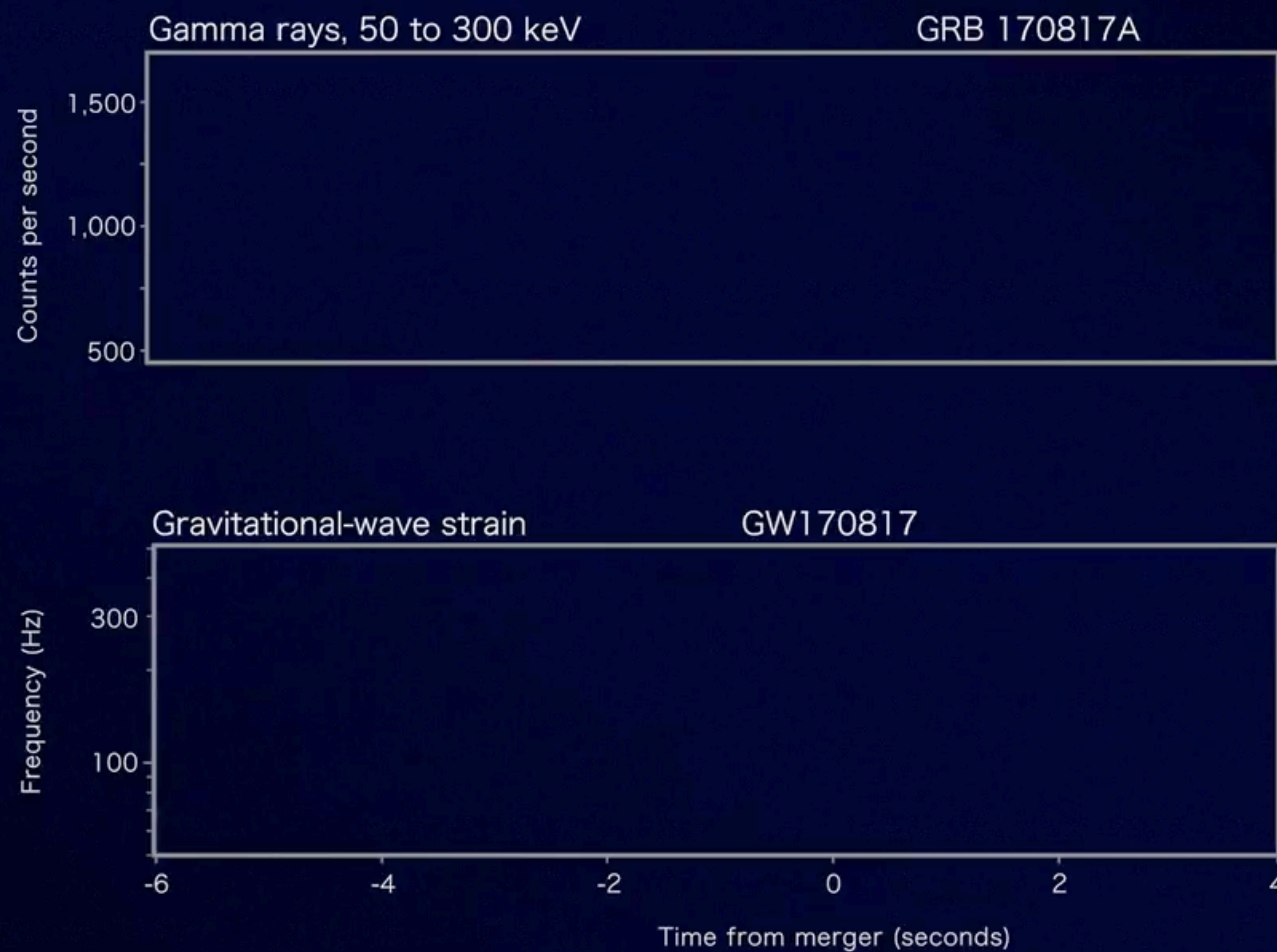
PRL, 119, 161101 (2017)

GW 170817 — binary neutron star merger

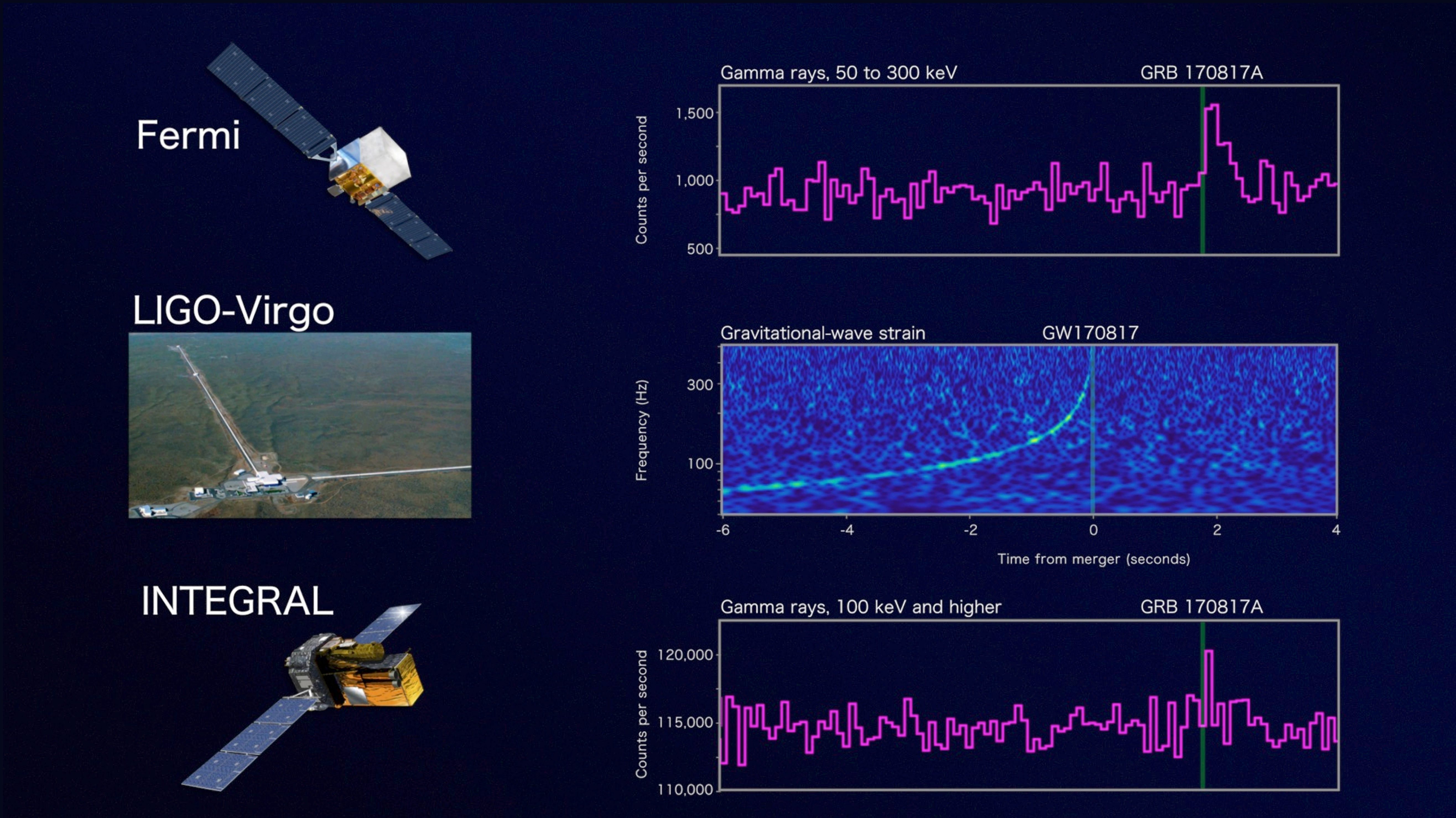


Fermi

LIGO

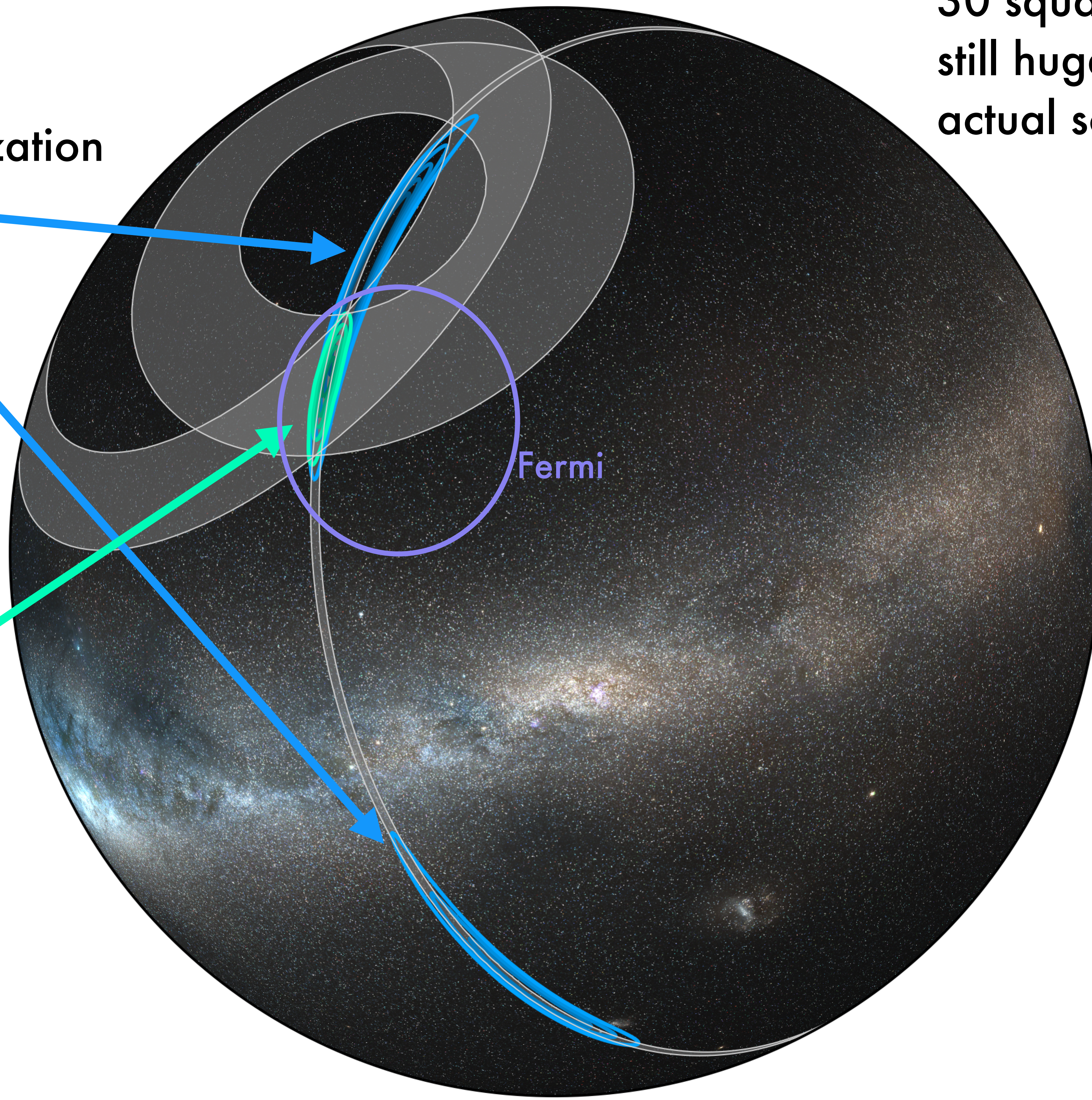

Gamma rays, 50 to 300 keV
GRB 170817A
Counts per second
1,500
1,000
500
Gravitational-wave strain
GW170817
Frequency (Hz)
300
100
-6
-4
-2
0
2
4
Time from merger (seconds)

A gamma-ray burst coincidence in time and overlap in sky position – an EM counterpart!!



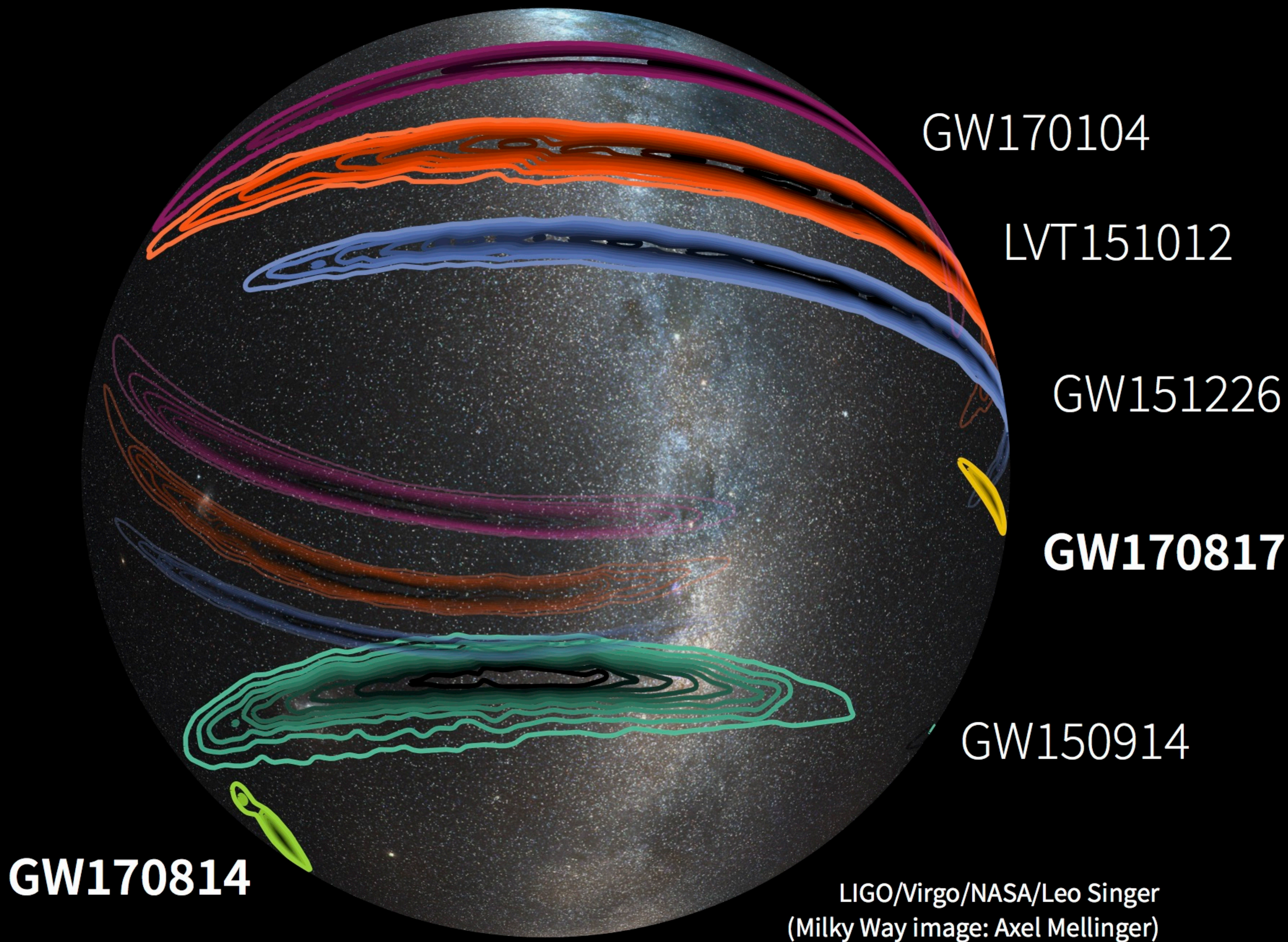
30 square degrees is still huge to find the actual source

Quick localization



Final GW localization

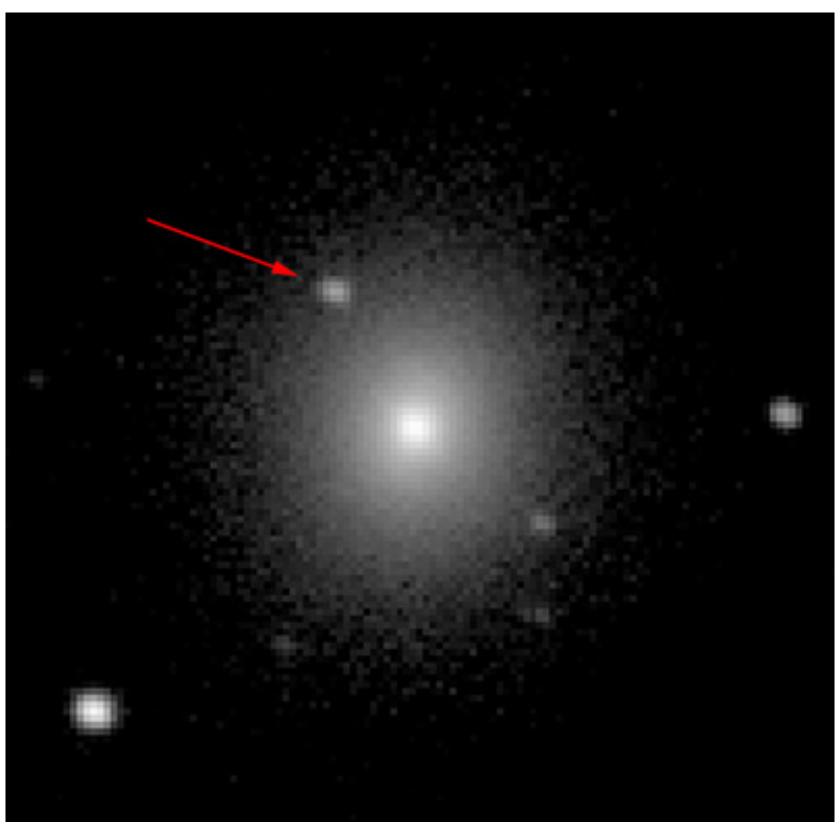
Credit: LIGO/Virgo/NASA/Leo Singer (Milky Way image: Axel Mellinger)

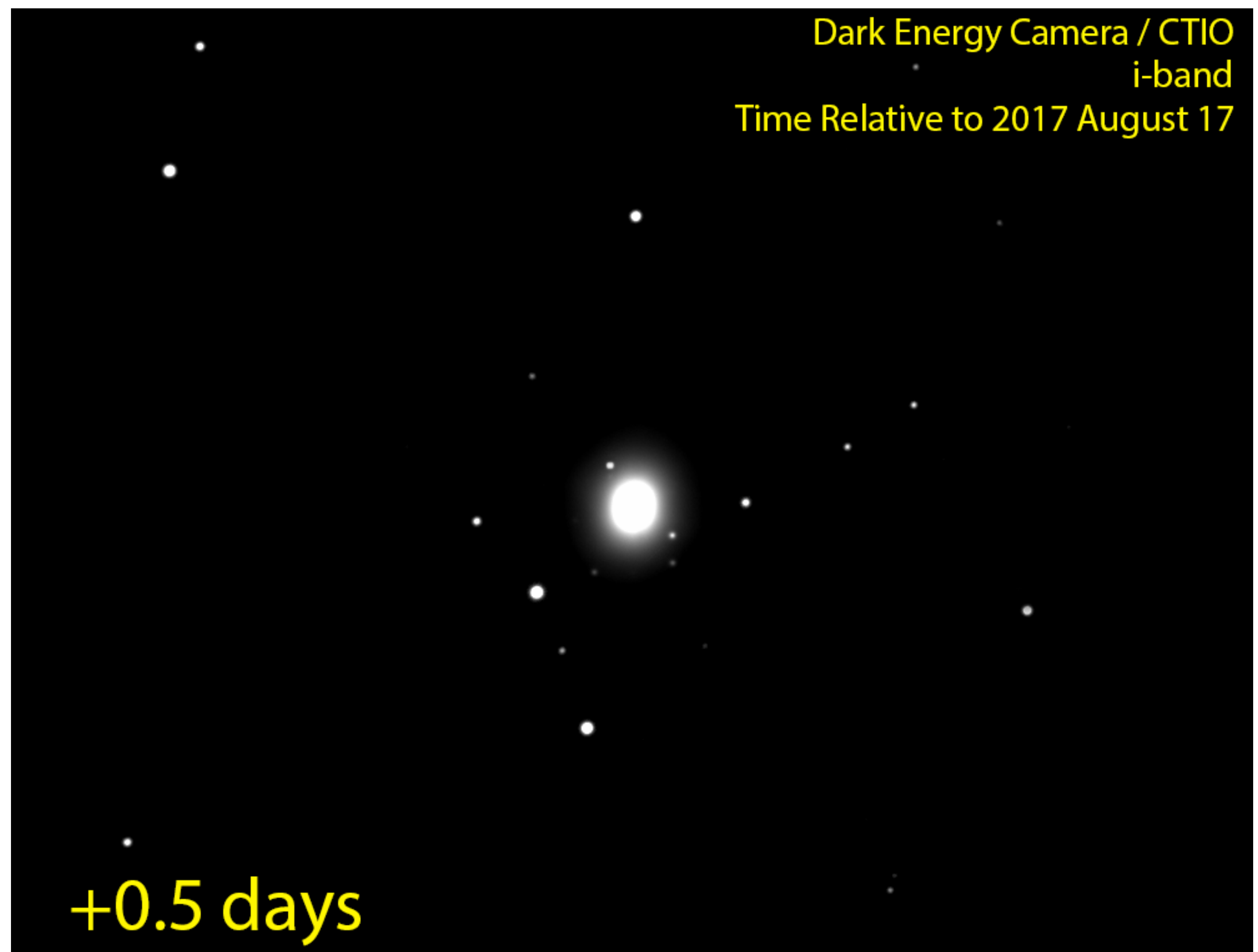

GW170104
LVT151012
GW151226
GW170817
GW150914
GW170814
LIGO/Virgo/NASA/Leo Singer
(Milky Way image: Axel Mellinger)

Over 1/3 of astronomy community joined in to follow the event!

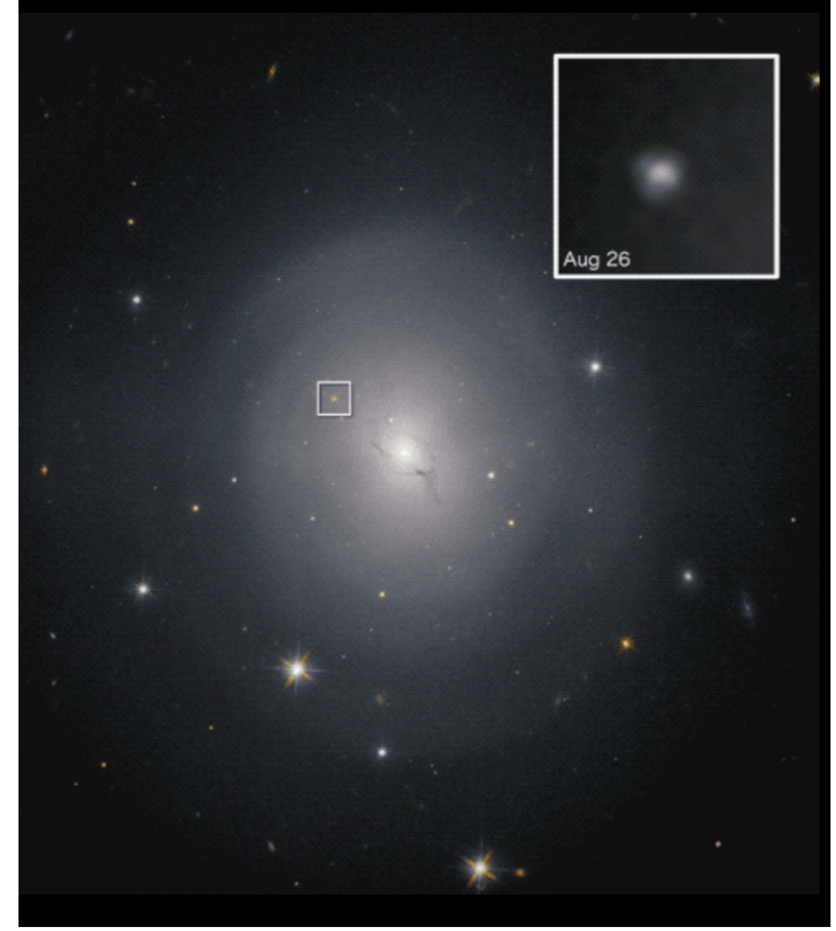
Swopes 1m

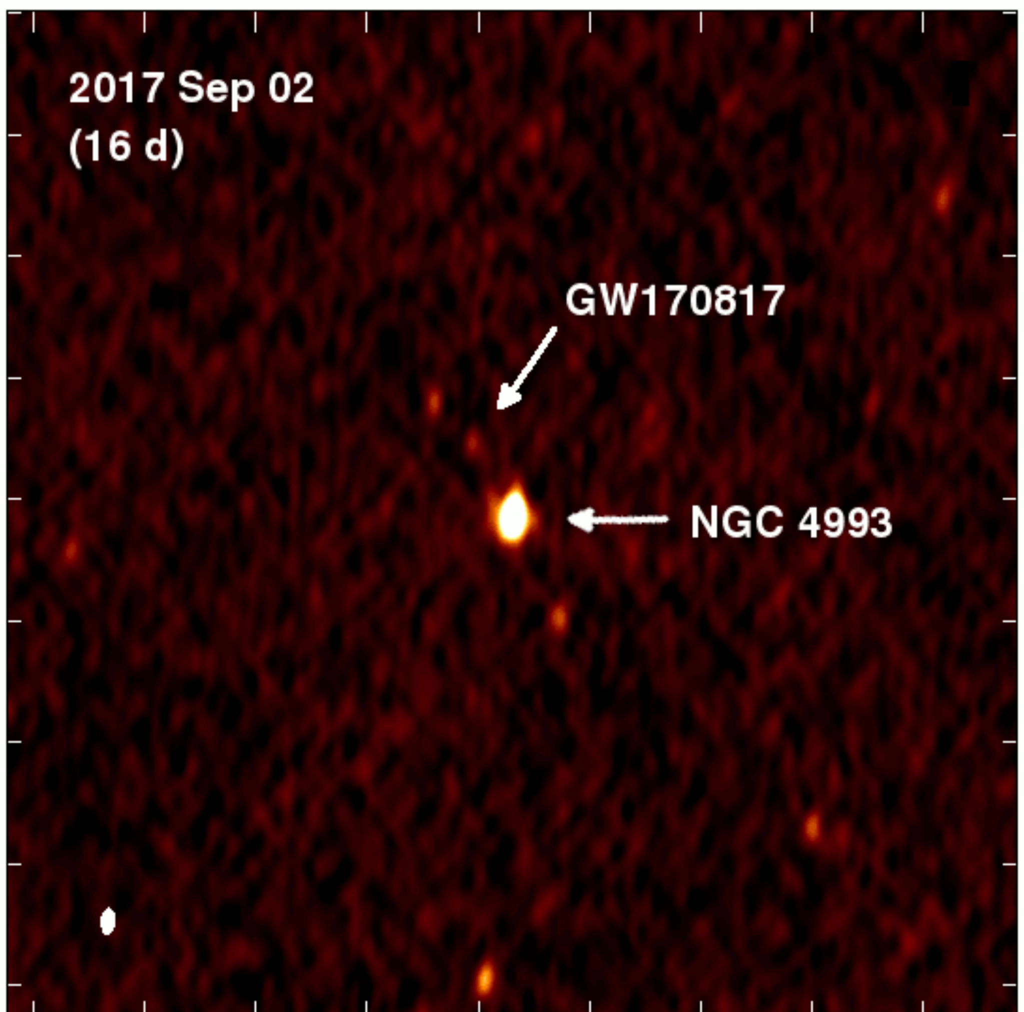
Blanco 4m



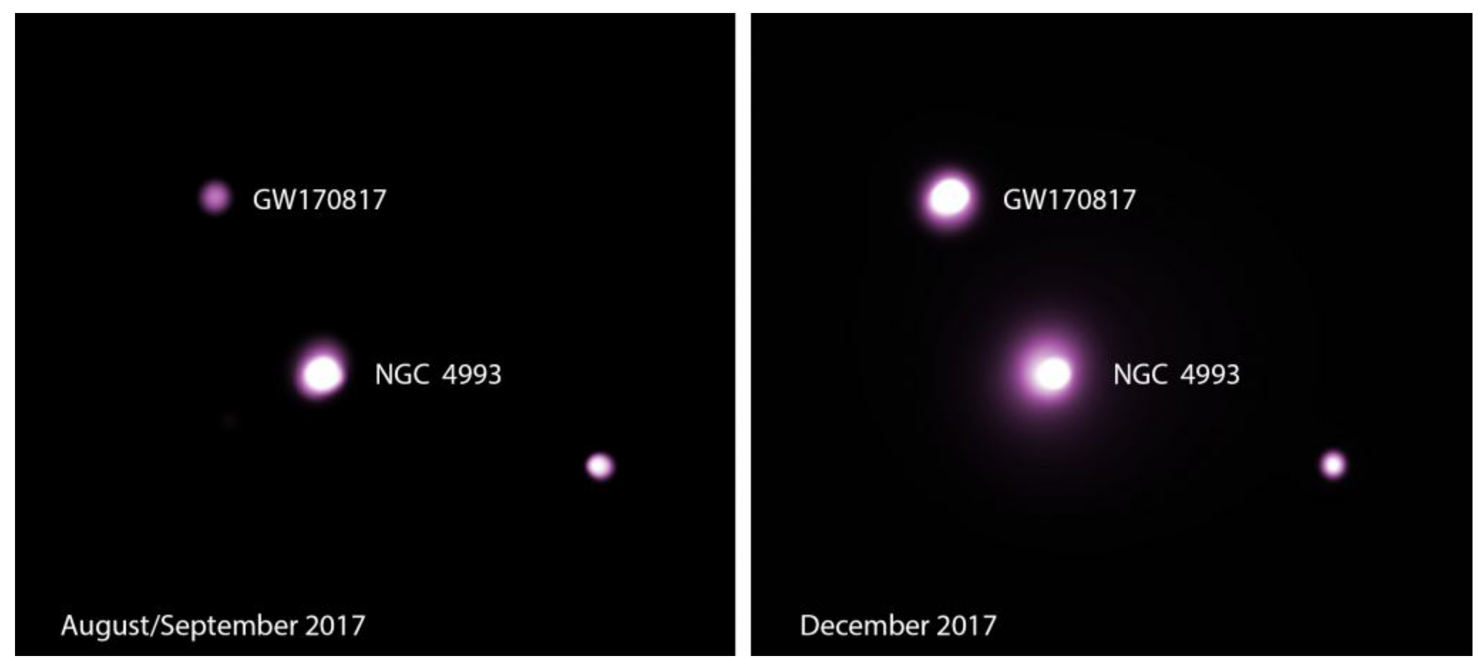


IGW170817 is in the outskirts of NGC 4993 – distance is ~40Mpc





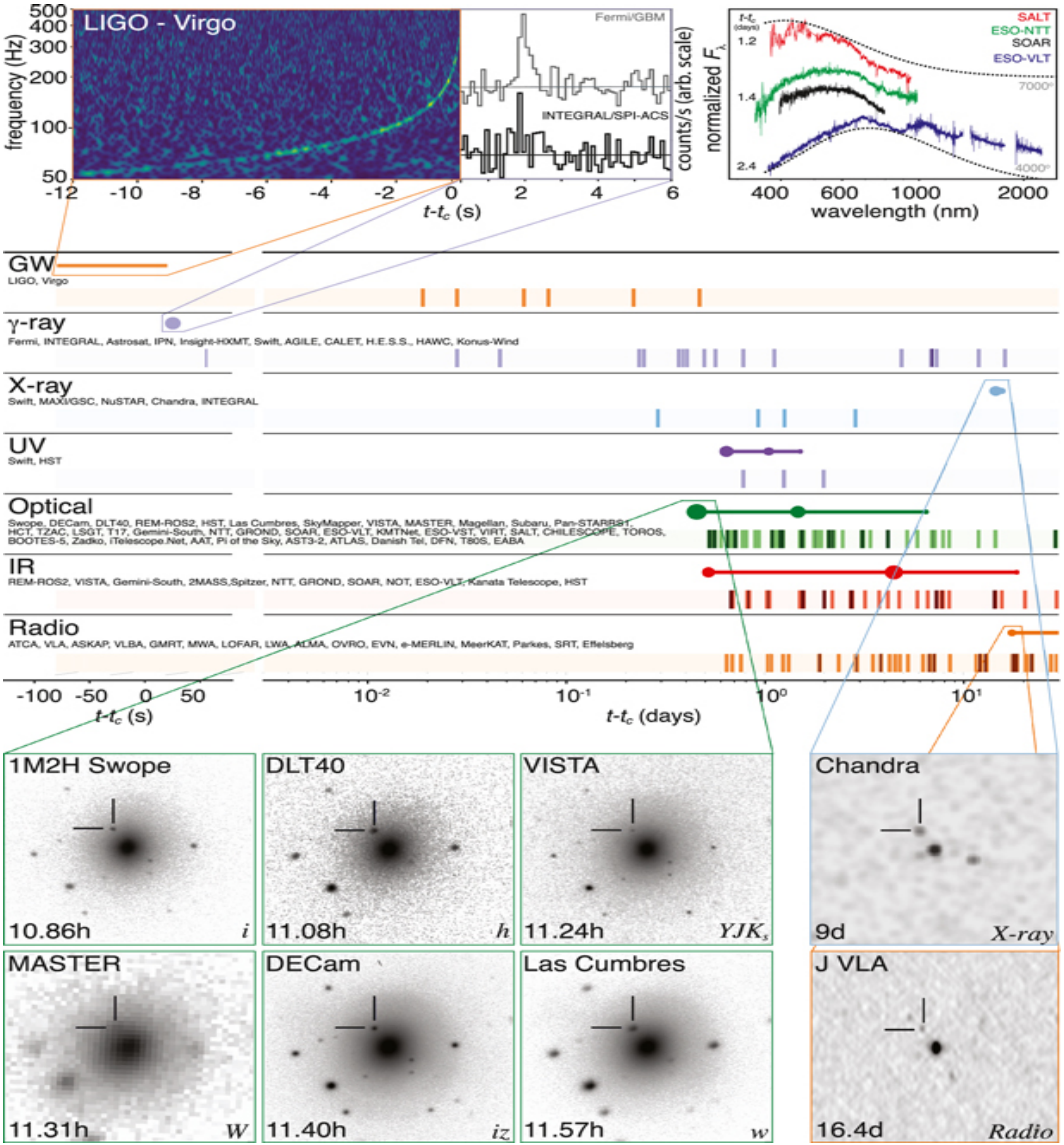
Radio – VLA



Credit: NASA/CXC/McGill University/J. Ruan et al.

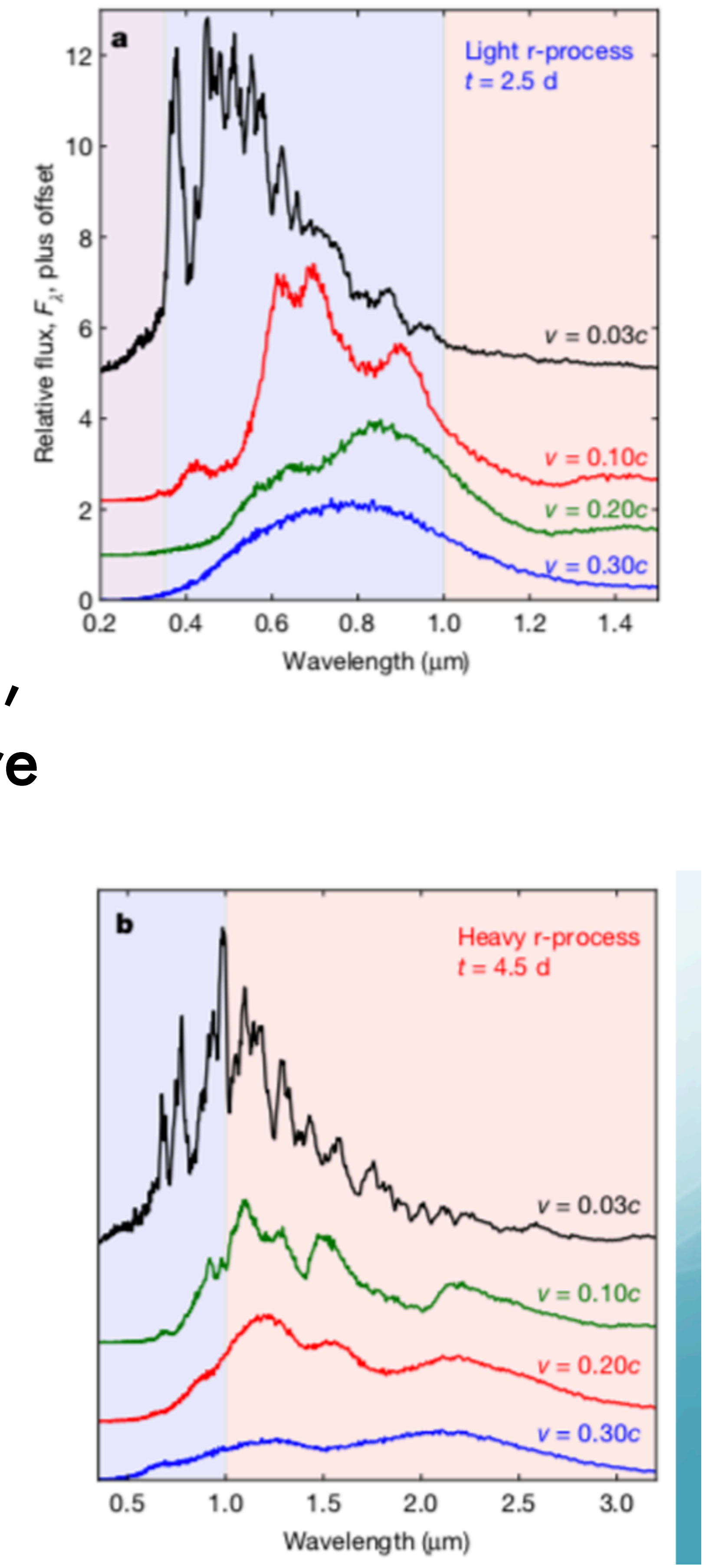
Xray – Chandra

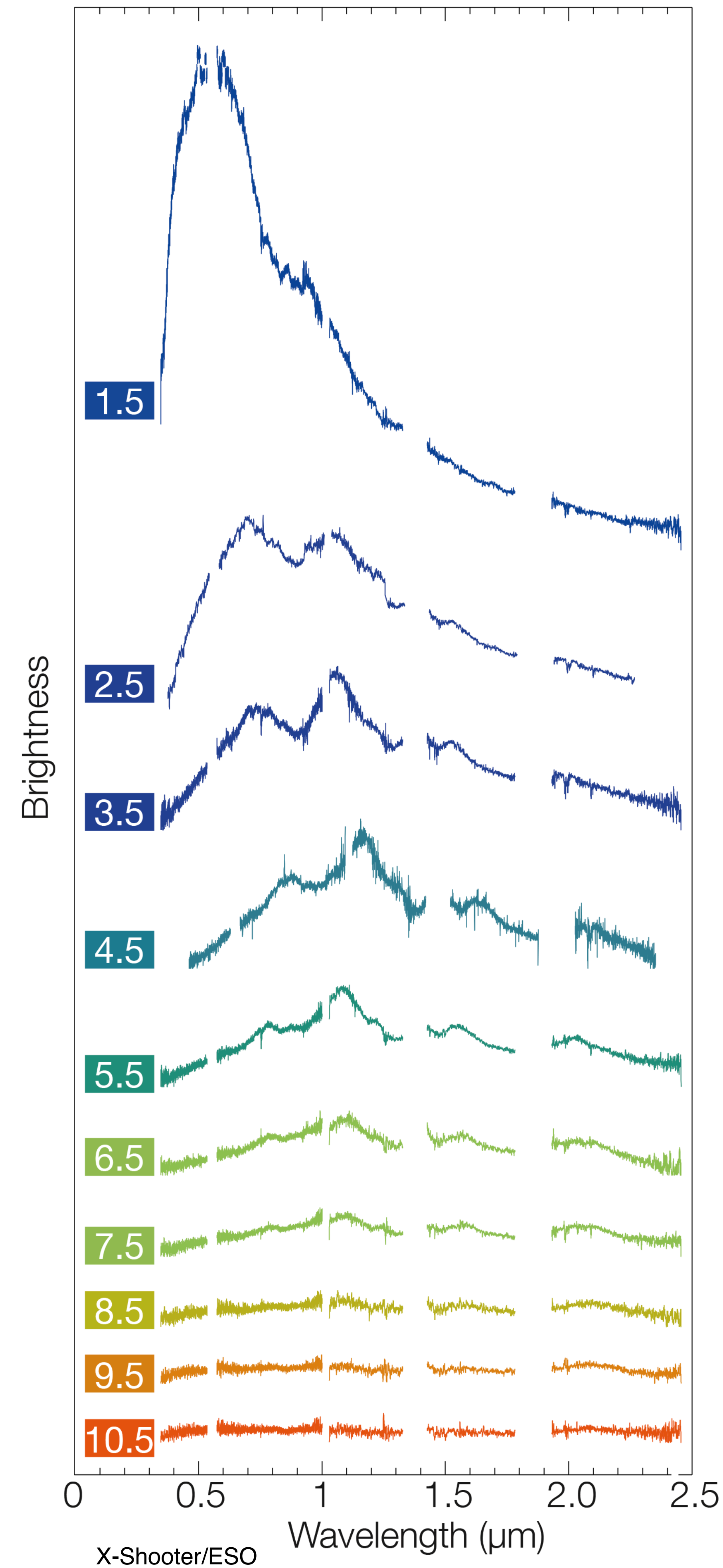
Observed at all wavelengths…and still observe it today.



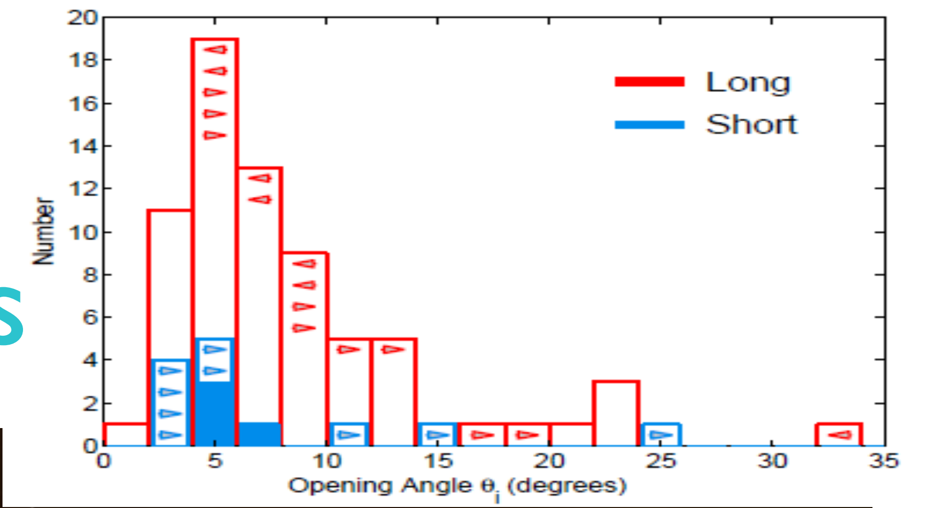
LIGO - Virgo
frequency (Hz)
Fermi/GBM
INTEGRAL/SPI-ACS
counts/s (arb. scale)
t-tc (s)
SALT
ESO-NTT
SOAR
ESO-VLT
normalized Fλ
7000°
4000°
wavelength (nm)
GW
LIGO, Virgo
γ-ray
Fermi, INTEGRAL, Astrosat, IPN, Insight-HXMT, Swift, AGILE, CALET, H.E.S.S., HAWC, Konus-Wind
X-ray
Swift, MAXI/GSC, NuSTAR, Chandra, 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
t-tc (s)
t-tc (days)
1M2H Swope
10.86h
i
DLT40
11.08h
h
VISTA
11.24h
YJKs
Chandra
9d
X-ray
MASTER
11.31h
W
DECam
11.40h
iz
Las Cumbres
11.57h
w
J VLA
16.4d
Radio

GW 170817 started blue, quickly turned red, as r-process elements are generated

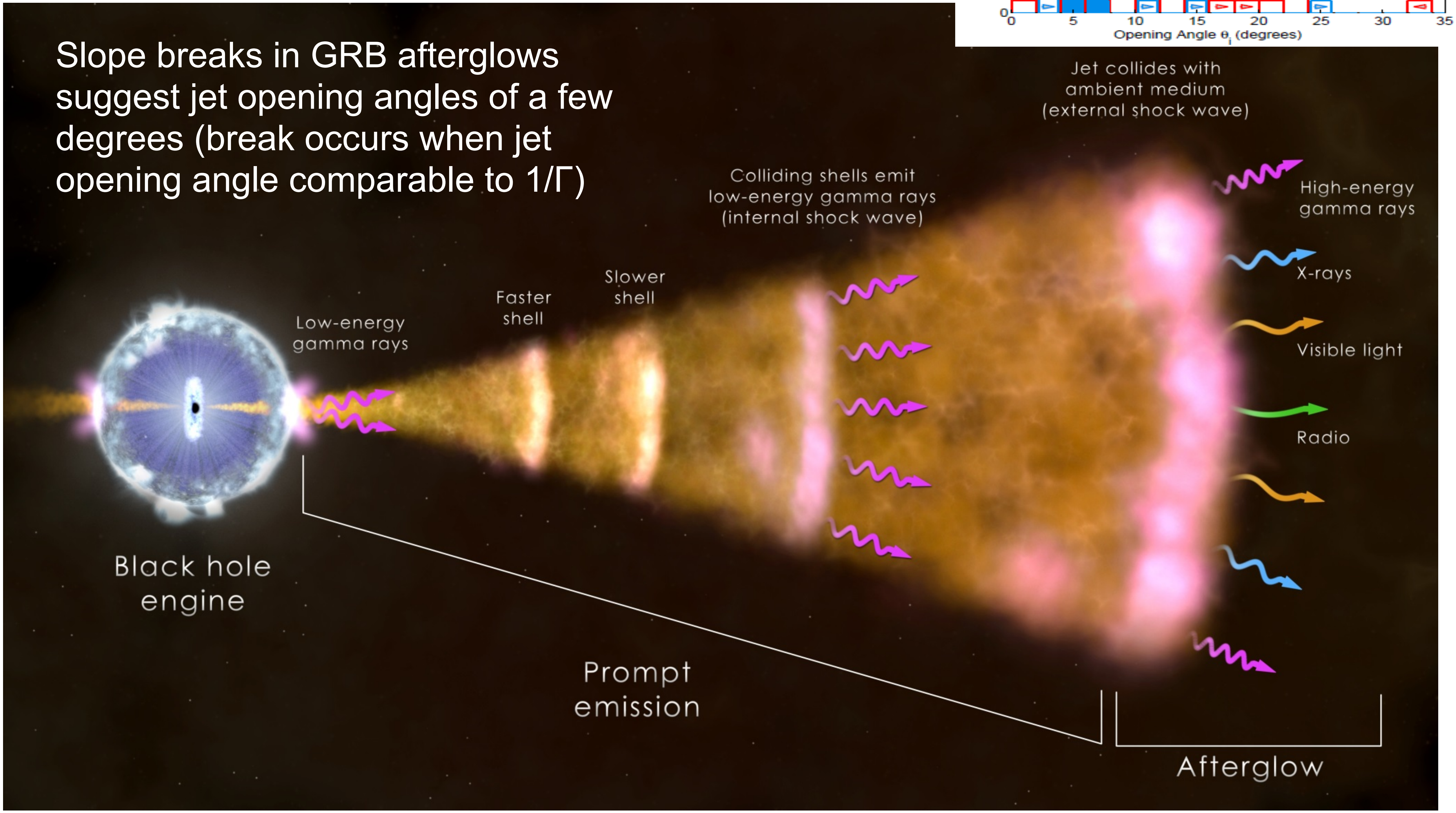




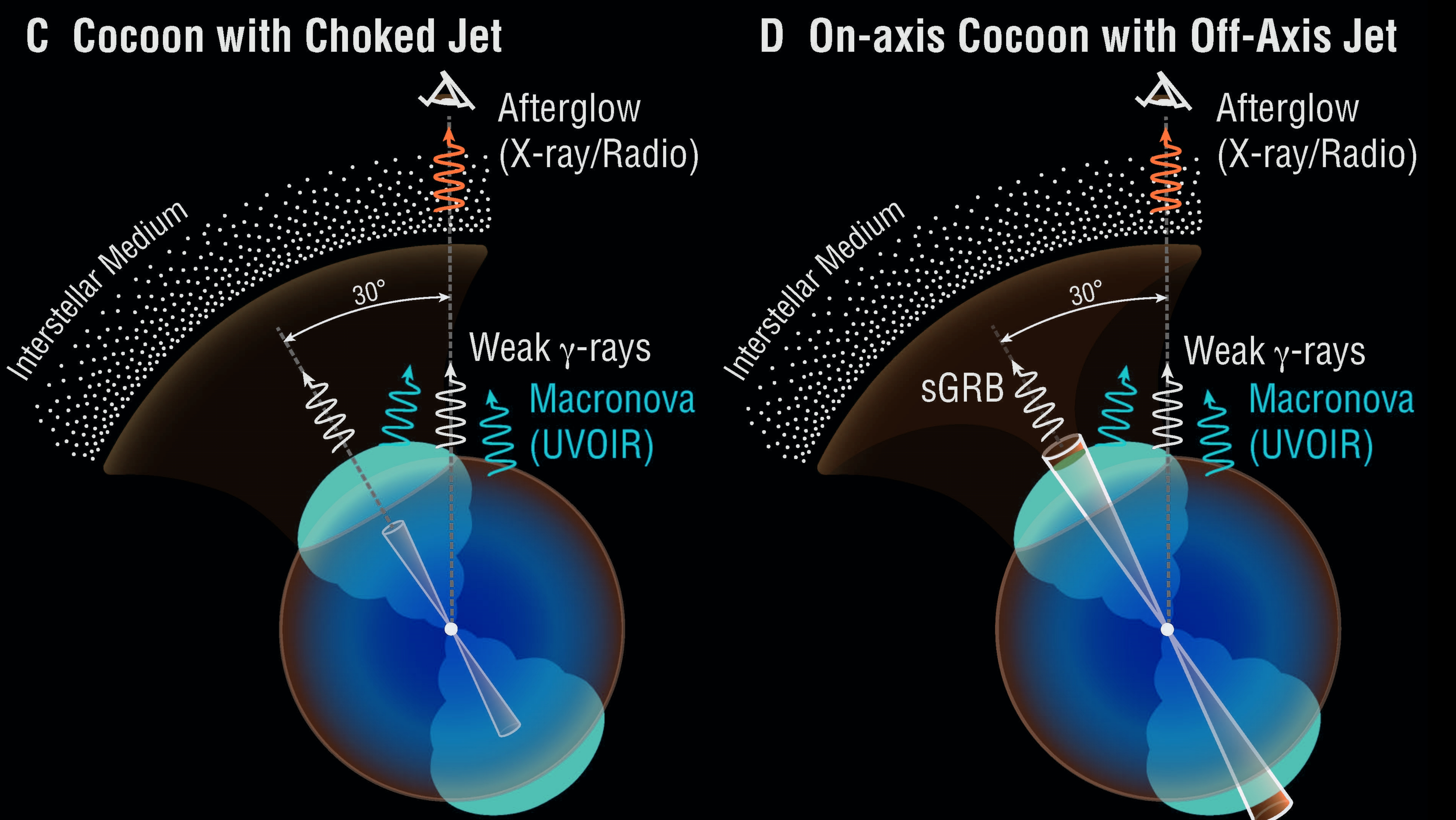
We used to think gamma ray bursts featured clean jet signatures



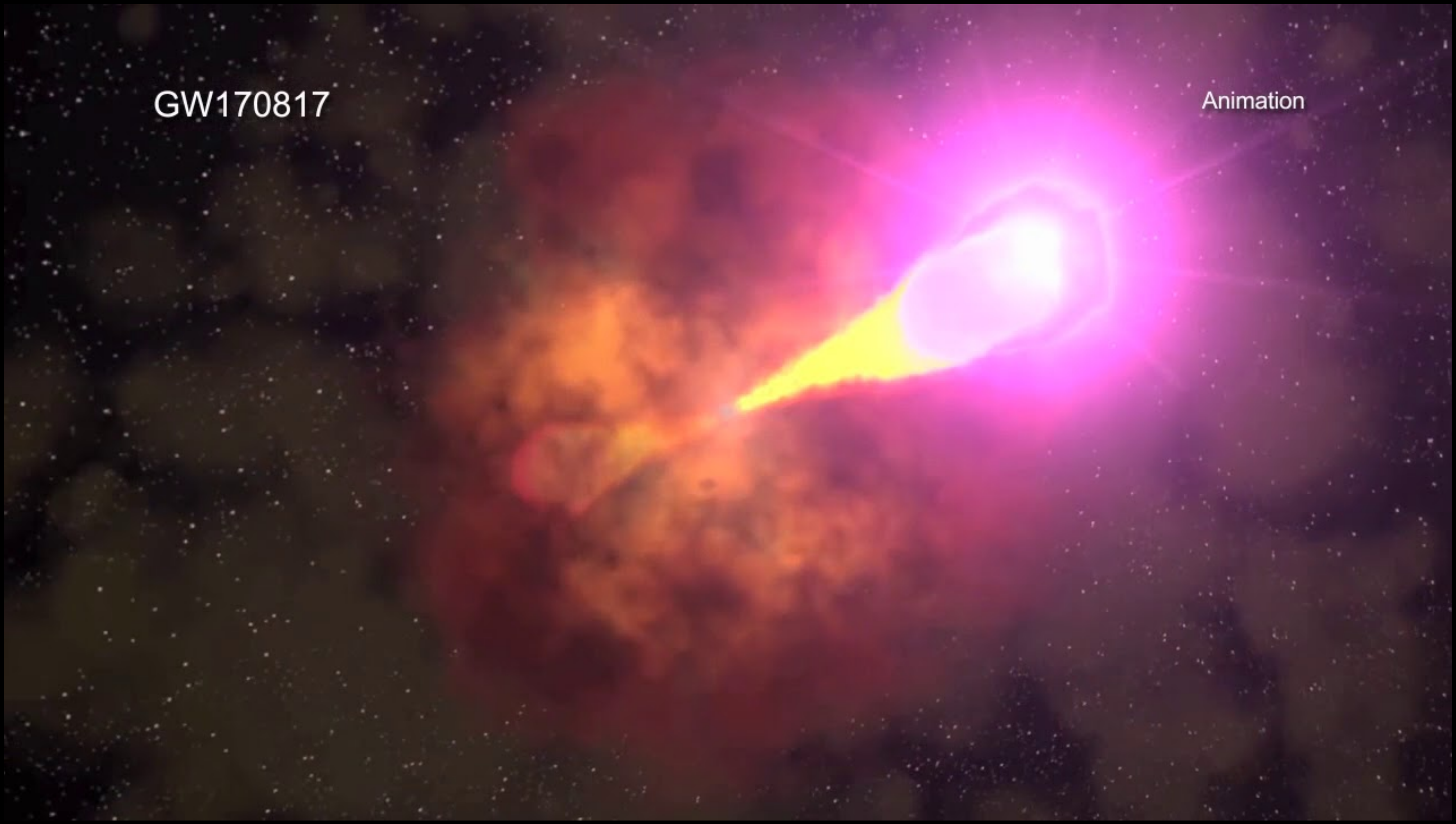
Slope breaks in GRB afterglows suggest jet opening angles of a few degrees (break occurs when jet opening angle comparable to 1/Γ)



Now, we think jets are enveloped in material



So this happened:



‘r’ stands for ‘rapid – quick pile-on of lots of neutrons that make unstable elements

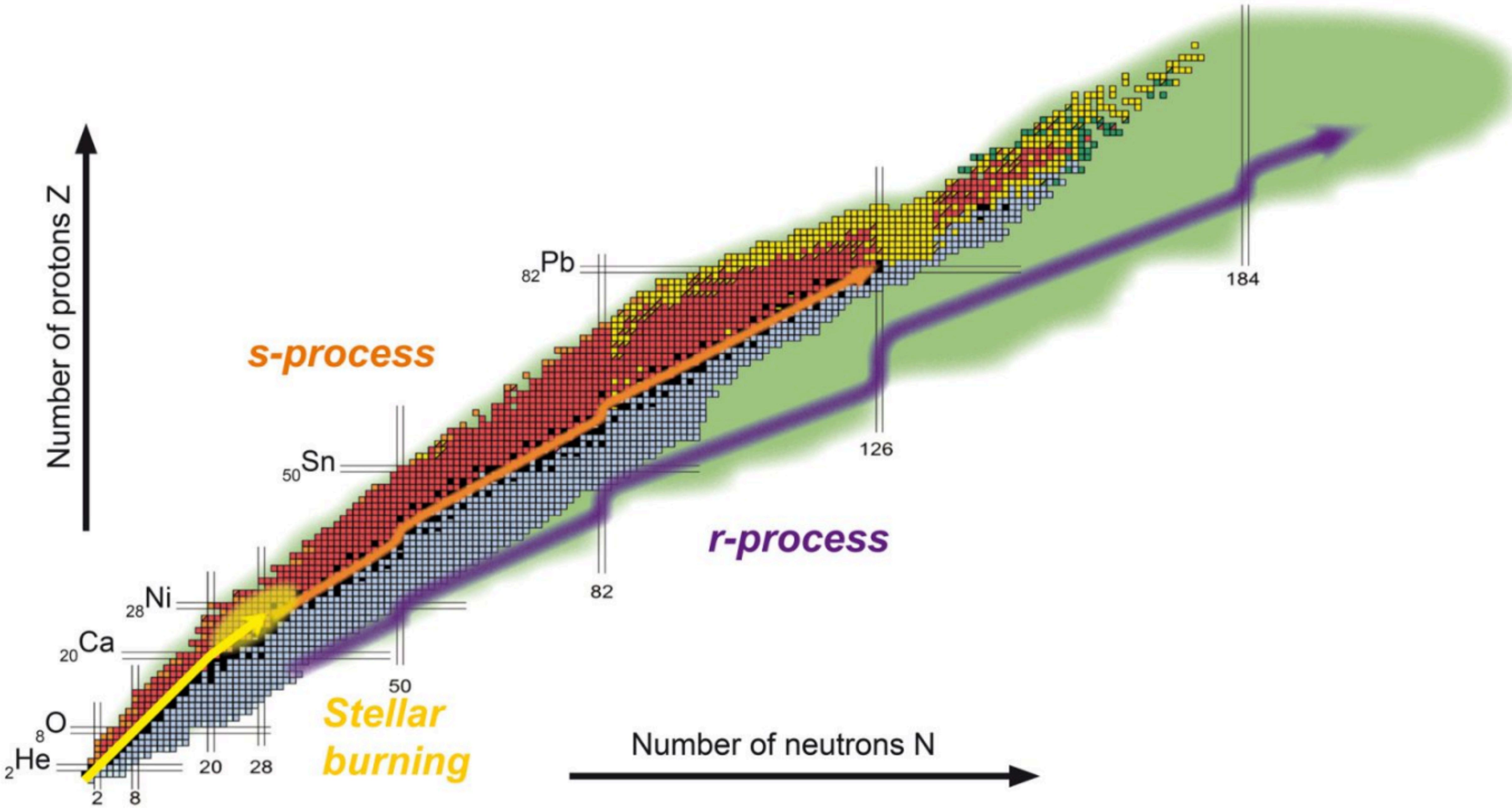
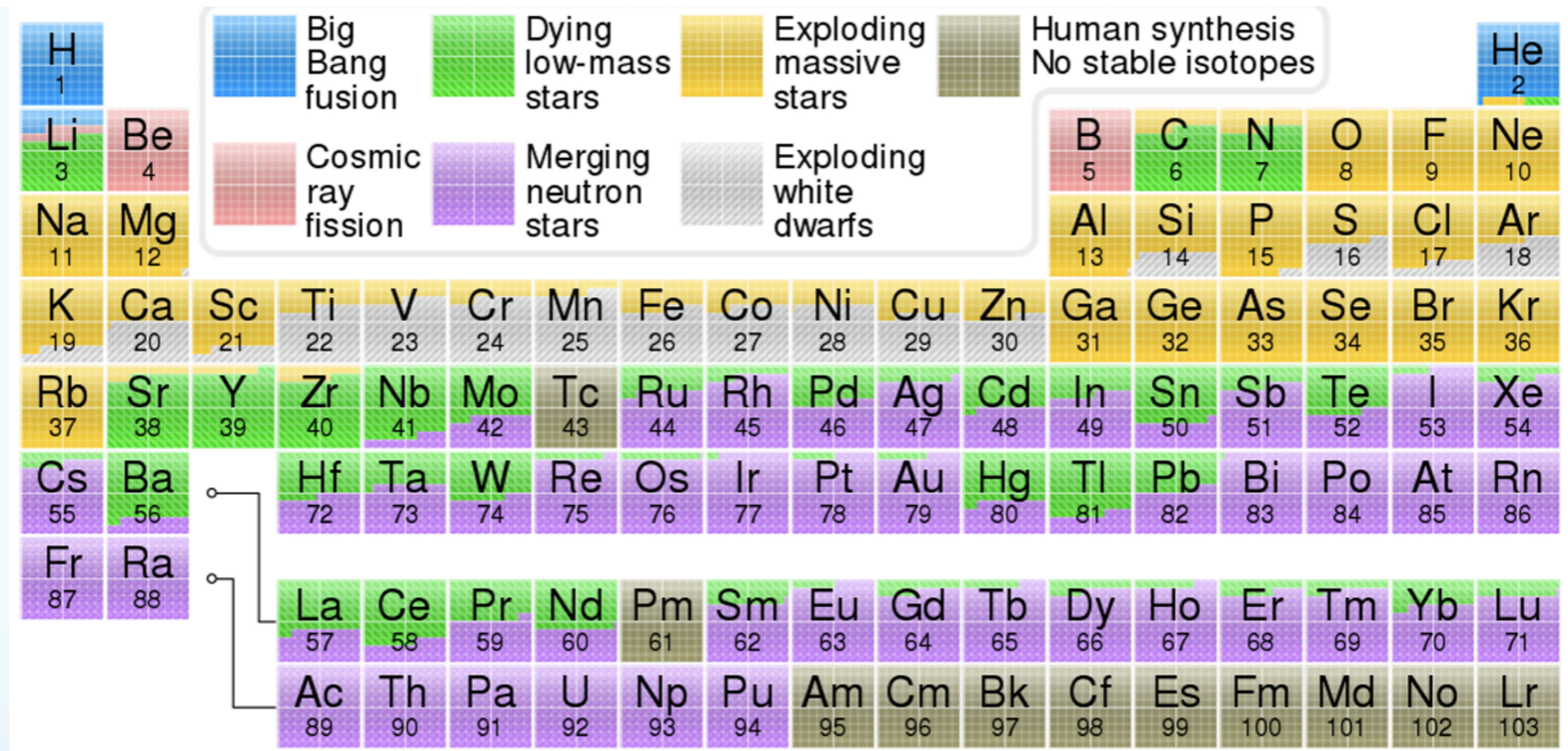


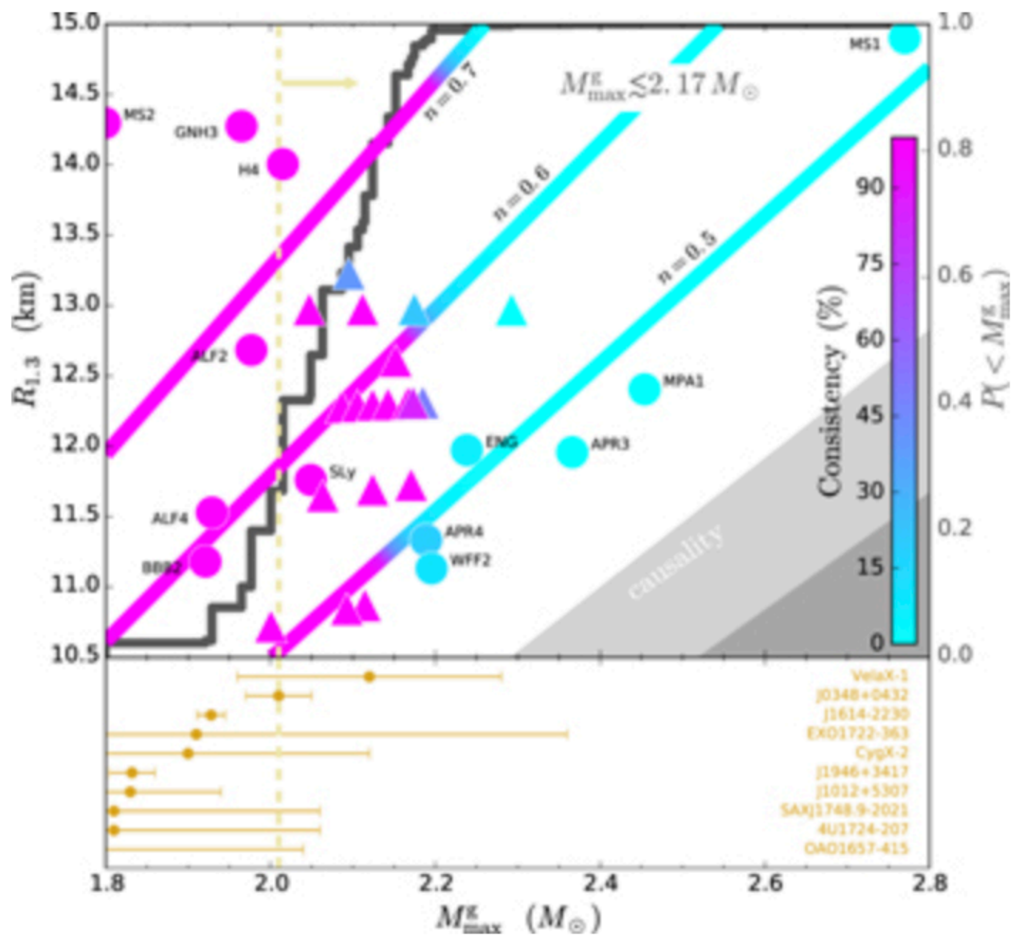
Fig. 1: Nuclear chart showing the nucleosynthesis processes occurring during stellar burning (yellow), the s-process (orange) and the r-process (violet) (credit: EMMI, GSI/Different Arts)

"All" the (really) heavy elements in the universe are made in merging neutron stars!



The nature of the remnant is still uncertain

Probably not a direct collapse to a black hole



Margalit + Metzger 2017

Figure 4. Constraints on properties of the NS EOS—radius of a $1.3\, M_{\odot}$ NS, $R_{1.3}$, and maximal non-rotating gravitational mass, M^{g}_{max}—based on joint GW-EM observations of GW170817. Different EOSs are represented as points, the color of which corresponds to the consistency of the given EOS with observational constraints. The similarly colored diagonal curves represent polytropic EOSs of index *n*, while the gray shaded regions to the bottom right are ruled out by the requirement of causality (see the text). Clearly, a low NS maximal mass is preferred due to constraints ruling out SMNS formation. The background gray curve shows the cumulative probability distribution function that the maximum mass M^{g}_{max} is less than a given value (see the text), from which we find $M^{g}_{max} \lesssim 2.17\, M_{\odot}$ at 90% confidence. The bottom panel shows masses of observed Galactic NSs, from which a lower limit on M^{g}_{max} can be placed (vertical dashed line).

We might have seen the spin-down of a magnetar!

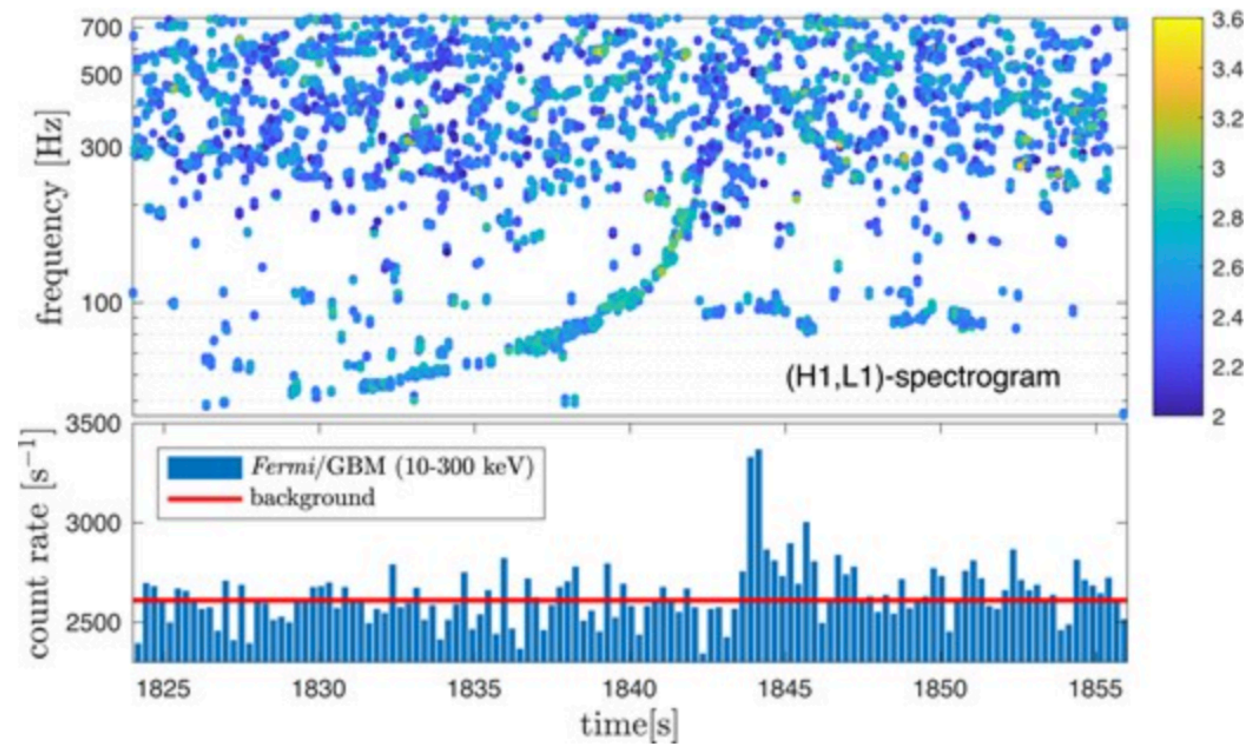


Figure 2. Ascending–descending chirp in the (H1,L1)-spectrogram produced by the double neutron star merger GW170817 concurrent with GRB170817A (Goldstein et al. 2017) past coalescence (t_c = 1842.43 s). Minor accompanying features around 100 Hz (1840-1852 s) are conceivably due to dynamical mass ejecta. Colour coding (blue-to-yellow) is proportional to amplitude defined by butterfly output ρ of time-symmetric chirp-like template correlations to data.

Van Putten + Della Valle 2019

Hubble constant measurement

$$v_H = H_0 d$$

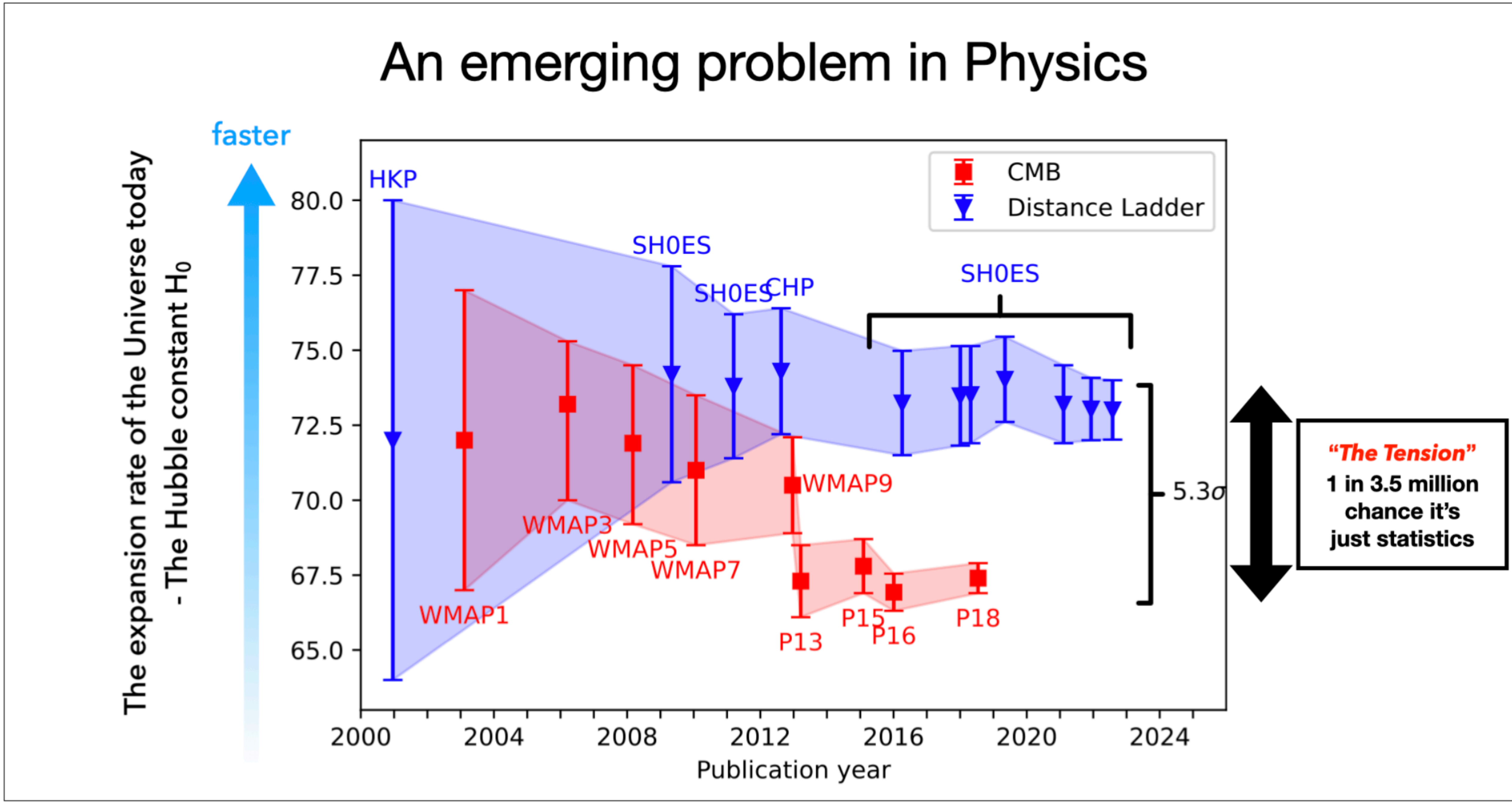
- Luminosity distance determined from GW amplitude
  - "standard siren"

$$d = 43.8^{+2.9}_{-6.9}\,\mathbf{Mpc}$$

- v_H 'Hubble flow velocity' : *average* recession velocity of galaxies at given distance

$$v_H = 3017 \pm 166\,\mathrm{km\,s^{-1}}$$

  - estimated via redshifts of surrounding group & bulk flow peculiar velocity

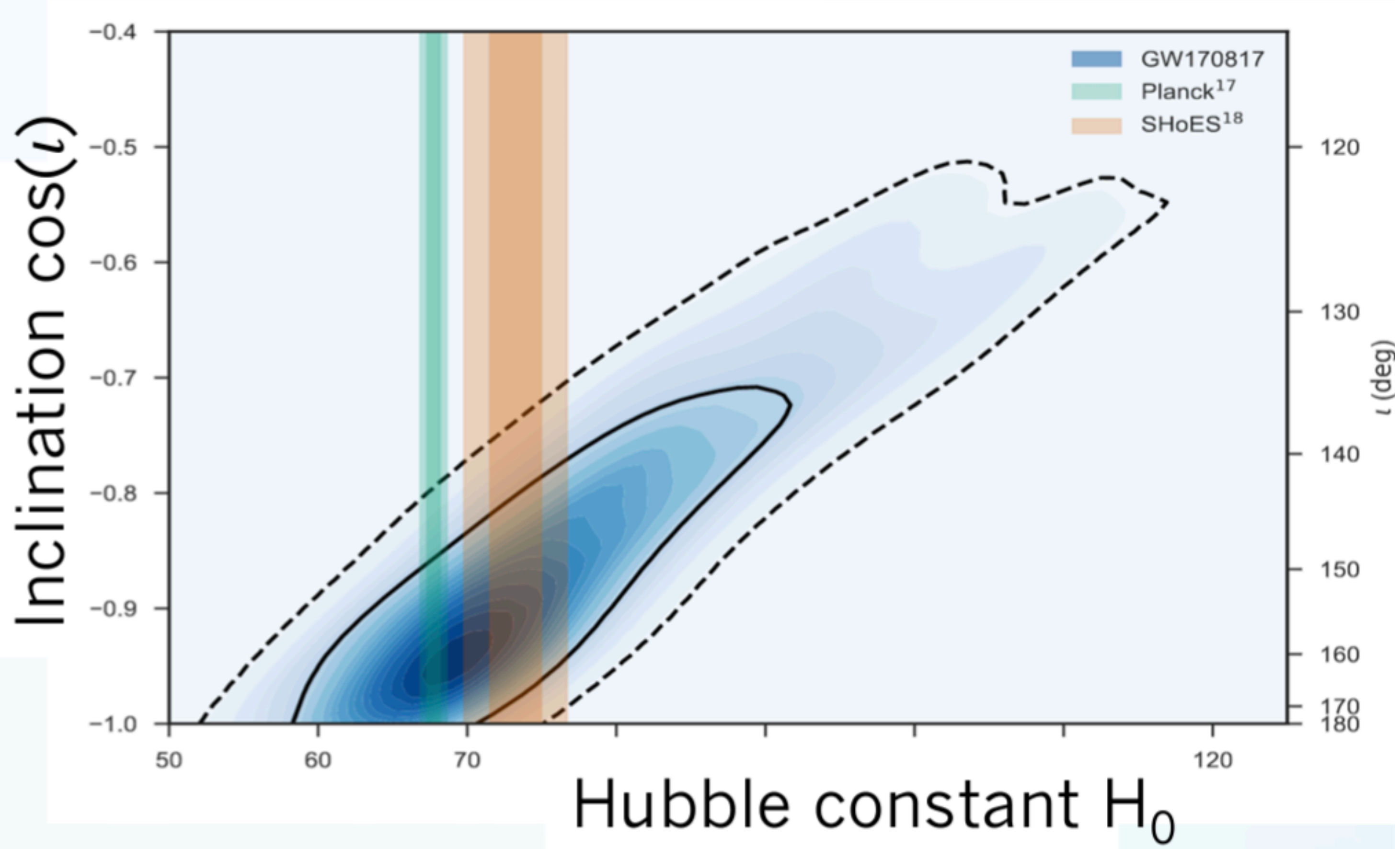


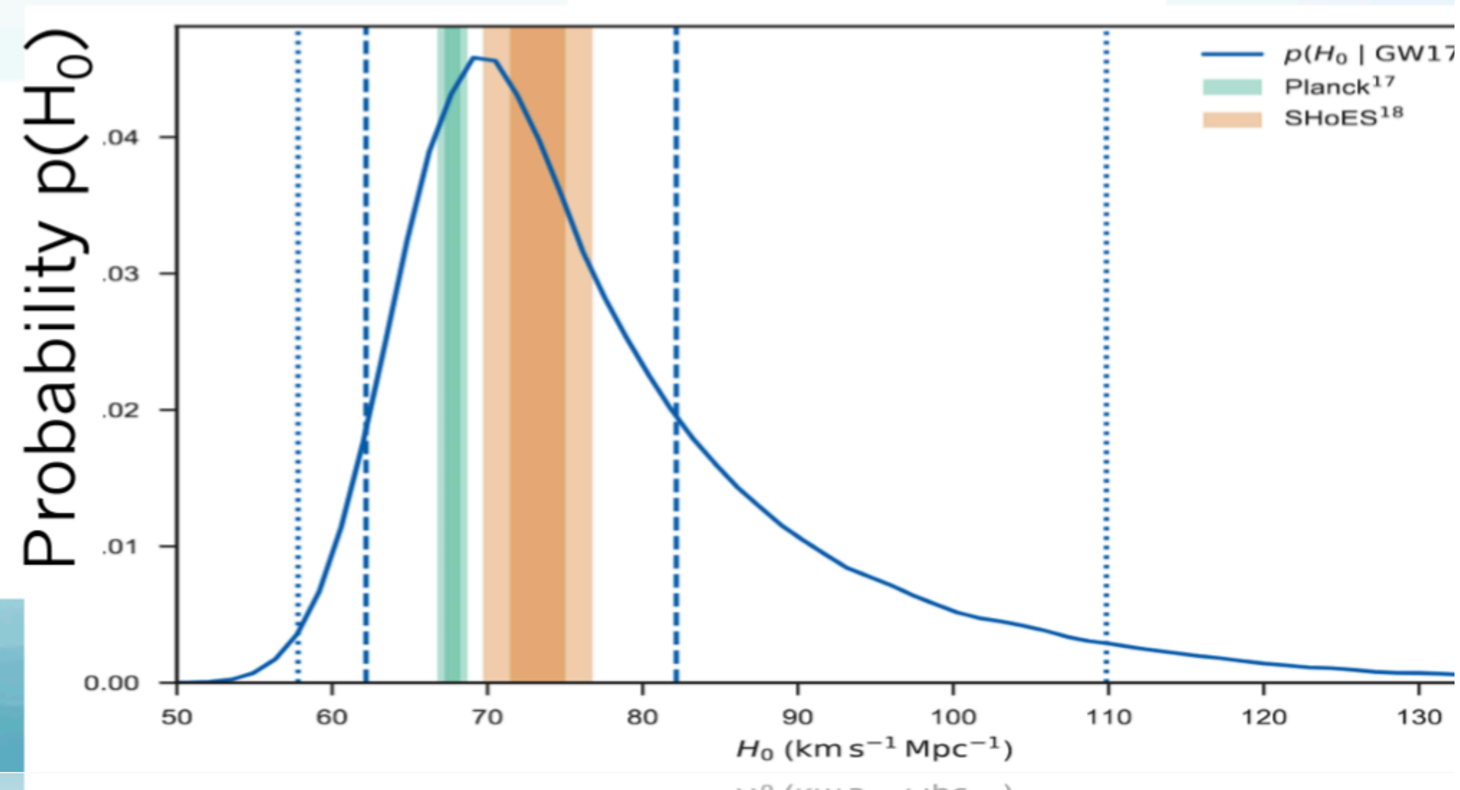
Evolution of the Hubble tension (determinations of the Hubble constant) in the last 23 years using direct measurements from the distance ladder in the local universe (in blue) and models based on the early universe cosmic microwave background (CMB) (in red). The tension is the gap between the two measurements which is growing and is now statistically significant. Image Credit: D'arcy Kenworthy

GW as tie-breaker on H_0 ?

- Inclination is largest uncertainty on H_0 measurement

- Consistent with both **CMB-based** and **distance ladder** determinations

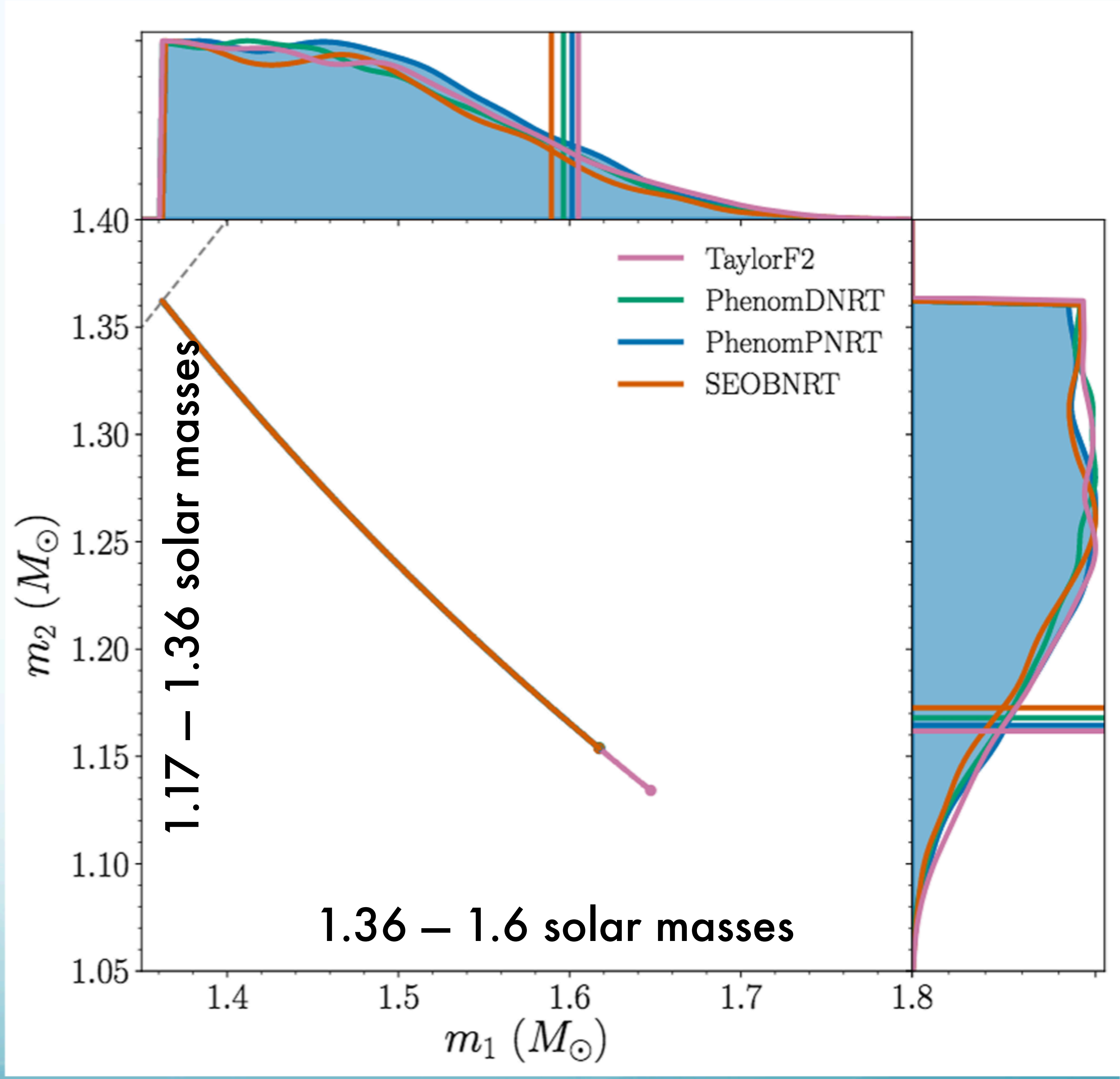




NS masses from the GW signal

- Assume NS spins are $\chi < 0.05$

(weaker bounds if high spin allowed)



Bounds on non-GR theories

- GRB recorded ~2s after BNS merger time
- GW and light travel at the same average speed !

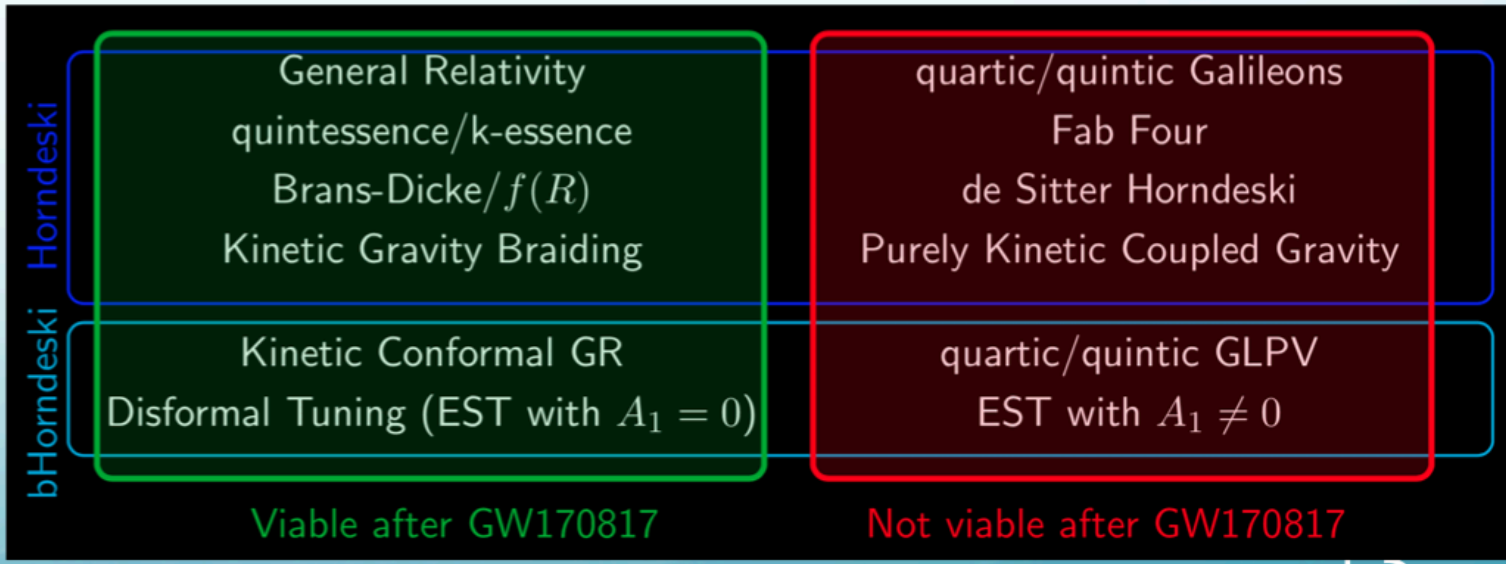
$$-3 \times 10^{-15} \leq \frac{\Delta v}{v_{\rm EM}} \leq +7 \times 10^{-16}$$

- GW and light experience same delay travelling through gravitational potential !

$$-2.6 \times 10^{-7} \leqslant \gamma_{\rm GW} - \gamma_{\rm EM} \leqslant 1.2 \times 10^{-6}$$

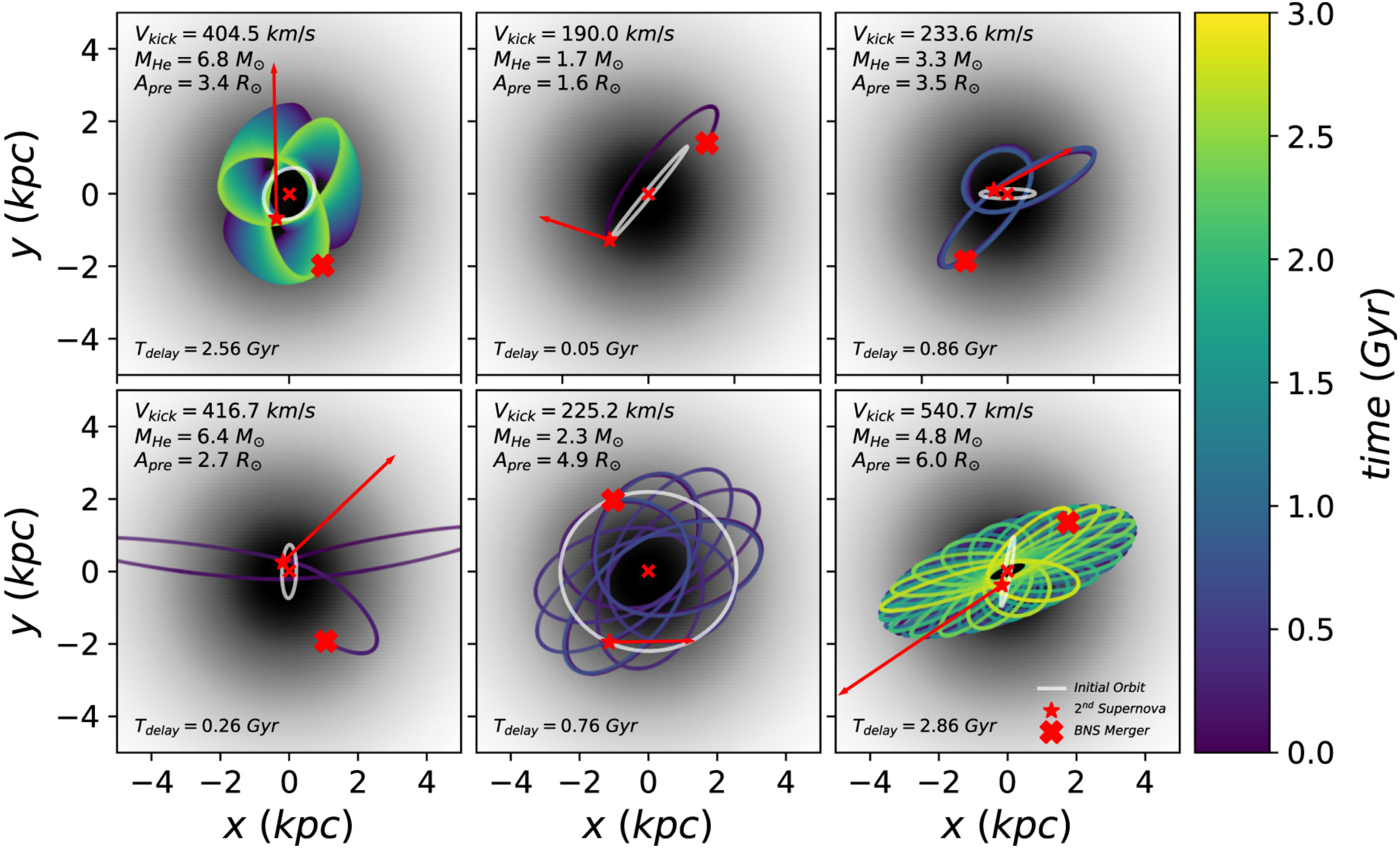
LVC+Fermi-GBM+INTEGRAL ApJL (2017)

Rules out many non-GR theories proposed to avoid dark matter/dark energy



Ezquiaga & Zumalacárregui PRL (2017)

Constraining SNe kicks in the host galaxy...



ApJ, 2017, 850,L40

GW170817

Binary neutron star merger

A LIGO / Virgo gravitational wave detection with associated electromagnetic events observed by over 70 observatories.

H L V

Distance
130 million light years

Discovered
17 August 2017

Type
Neutron star merger

12:41:04 UTC
A gravitational wave from a binary neutron star merger is detected.

gravitational wave signal
Two neutron stars, each the size of a city but with at least the mass of the sun, collided with each other.

gamma ray burst
A short gamma ray burst is an intense beam of gamma ray radiation which is produced just after the merger.

+ 2 seconds
A gamma ray burst is detected.

GW170817 allows us to measure the expansion rate of the universe directly using gravitational waves for the first time, and gives us a new way to infer its age.

+10 hours 52 minutes
A new bright source of optical light is detected in a galaxy called NGC 4993, in the constellation of Hydra.

Detecting gravitational waves from a neutron star merger allows us to find out more about the structure of these unusual objects.

kilonova
Decaying neutron-rich material creates a glowing kilonova, producing heavy metals like gold and platinum.

+11 hours 36 minutes
Infrared emission observed.

GW170817 allows us to measure the expansion rate of the universe directly using gravitational waves for the first time, and gives us a new way to infer its age.

Detecting gravitational waves from a neutron star merger allows us to find out more about the structure of these unusual objects.

This multimessenger event provides confirmation that neutron star mergers can produce short gamma ray bursts.

The observation of a kilonova allowed us to show that neutron star mergers could be responsible for the production most of the heavy elements, like gold, in the universe.

Observing both electromagnetic and gravitational waves from the event provides compelling evidence that gravitational waves travel at the same speed as light.

+10 hours 52 minutes

A new bright source of optical light is detected in a galaxy called NGC 4993, in the constellation of Hydra.

kilonova

Decaying neutron-rich material creates a glowing kilonova, producing heavy metals like gold and platinum.

+11 hours 36 minutes

Infrared emission observed.

+15 hours

Bright ultraviolet emission detected.

radio remnant

As material moves away from the merger it produces a shockwave in the interstellar medium - the tenuous material between stars. This produces emission which can last for years.

+9 days

X-ray emission detected.

+16 days

Radio emission detected.

Stay Tuned! TXS 0506+056