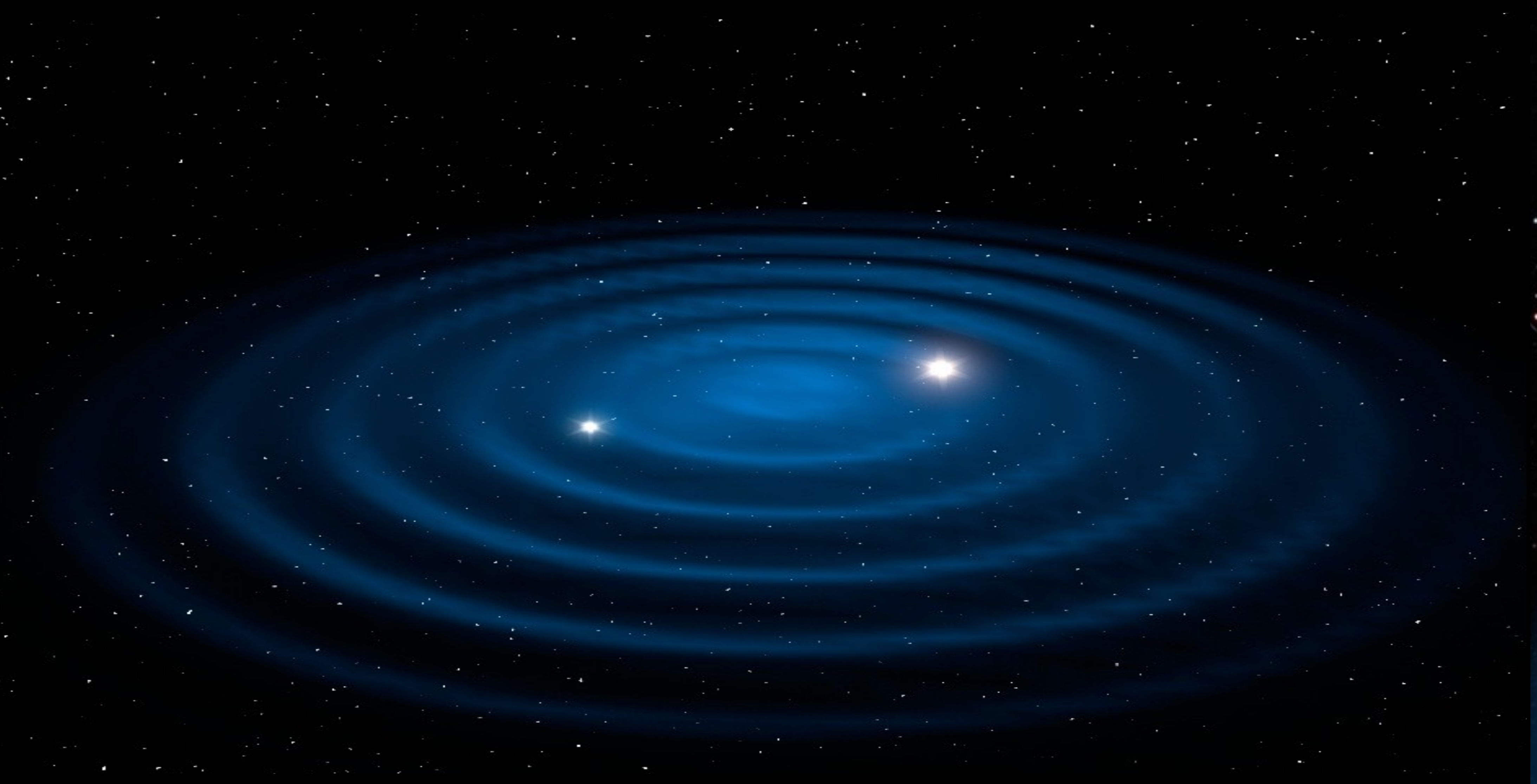
Gravitational Waves & high-energy Astrophysics: a Multi-Messenger approach

Raffaella Margutti (UC Berkeley)



"We always find something, eh Didi, to give us the impression we exist?"

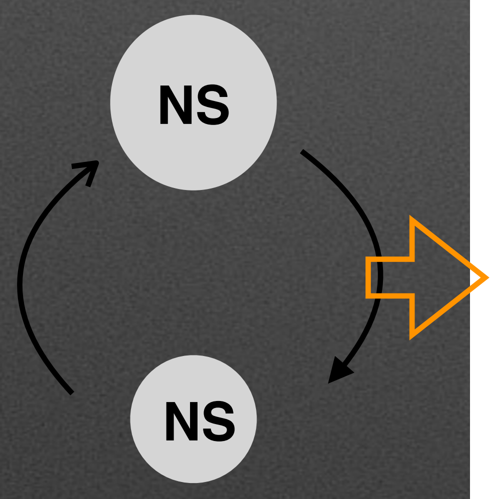

STELLAR Disruptions, Mergers and Explosions
Star tidally disrupted by Super Massive Black Hole
Neutron Stars Merger
Stellar Explosions
Gravitational Waves
Neutrinos
RADIO
MICROWAVE
INFRARED
VISIBLE
UV
X-RAYS
γ-RAYS

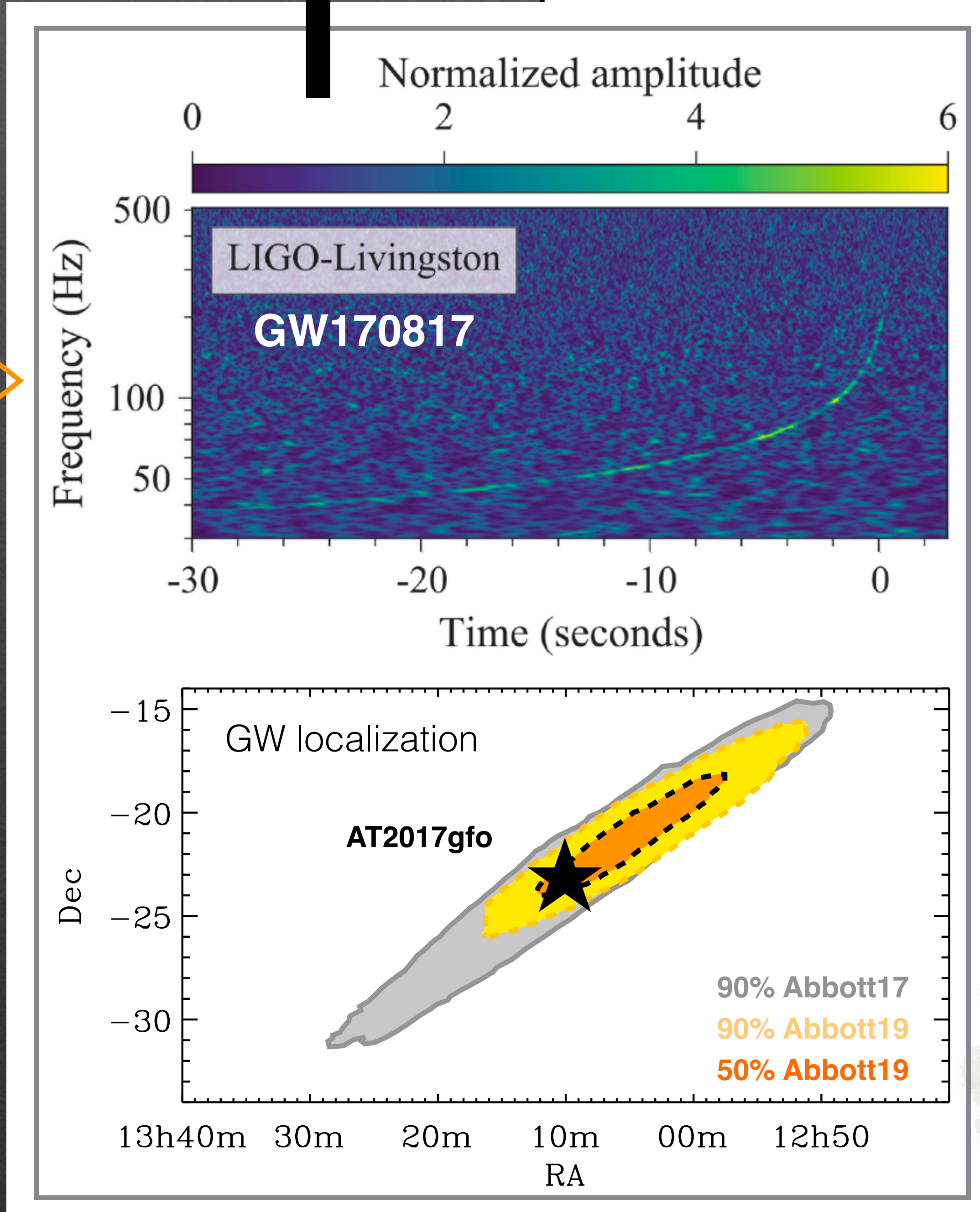
A new era of investigation of our Universe

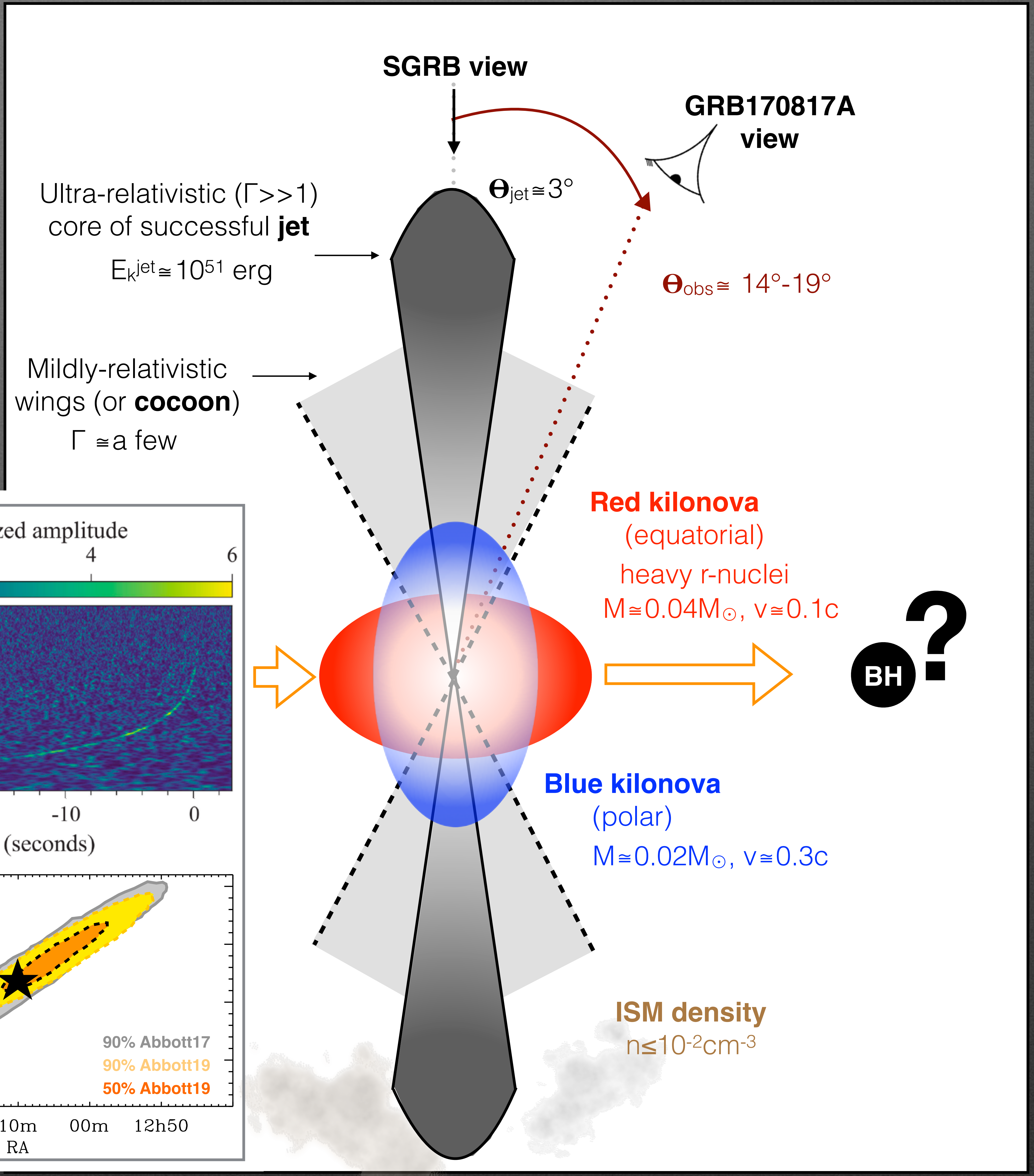
	Low-spin prior ($\chi \leq 0.05$)
Binary inclination θ_{JN}	146^{+25}_{-27} deg
Binary inclination θ_{JN} using EM distance constraint [108]	151^{+15}_{-11} deg
Detector-frame chirp mass $\mathcal{M}^{det}$	$1.1975^{+0.0001}_{-0.0001}$ $M_\odot$
Chirp mass $\mathcal{M}$	$1.186^{+0.001}_{-0.001}$ $M_\odot$
Primary mass m_1	(1.36, 1.60) $M_\odot$
Secondary mass m_2	(1.16, 1.36) $M_\odot$
Total mass m	$2.73^{+0.04}_{-0.01}$ $M_\odot$
Mass ratio q	(0.73, 1.00)
Effective spin $\chi_{\rm eff}$	$0.00^{+0.02}_{-0.01}$
Primary dimensionless spin χ_1	(0.00, 0.04)
Secondary dimensionless spin χ_2	(0.00, 0.04)
Tidal deformability $\tilde{\Lambda}$ with flat prior	300^{+500}_{-190}(symmetric)/300^{+420}_{-230}(HPD)

Abbott+2019

GW170817







Margutti & Chornock ARA&A, 2021

The first and only GW+EM celestial object

GW170817 "firsts":

- ✓ Some SGRBs originate from NS mergers

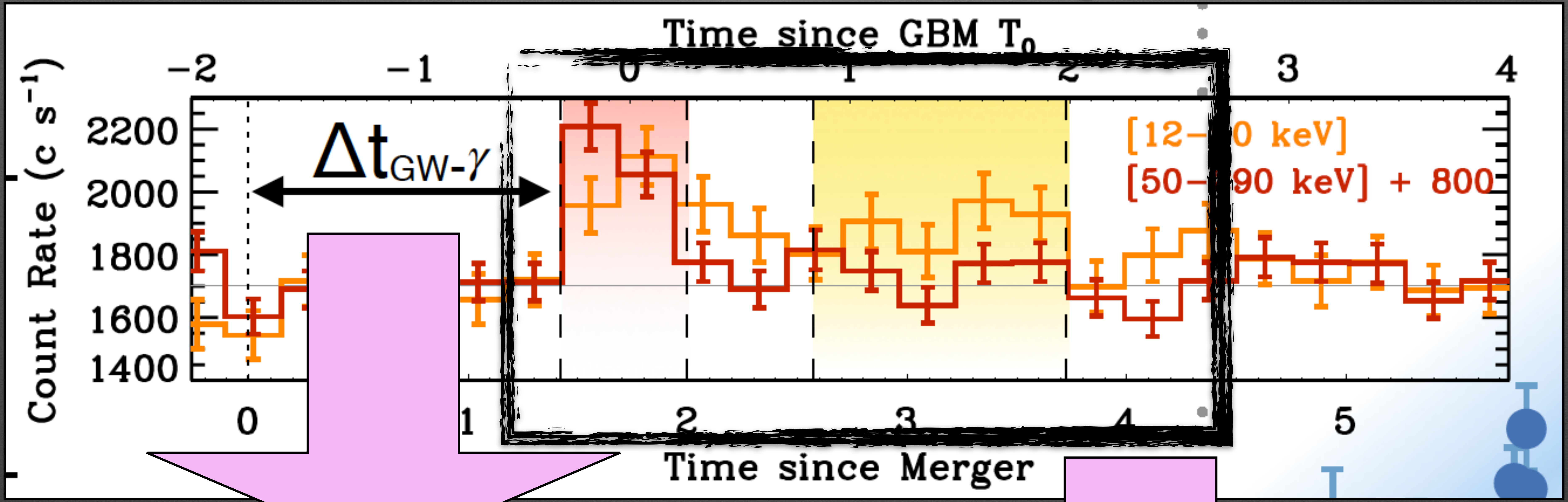
SATELLITE "VELA"
1960's: discovers
Gamma Ray Bursts

Are these colliding
Neutron Stars?

YES
(some are)

The Gamma-Ray counterpart of GW170817: GRB170817A

Margutti & Chornock, ARA&A 2022



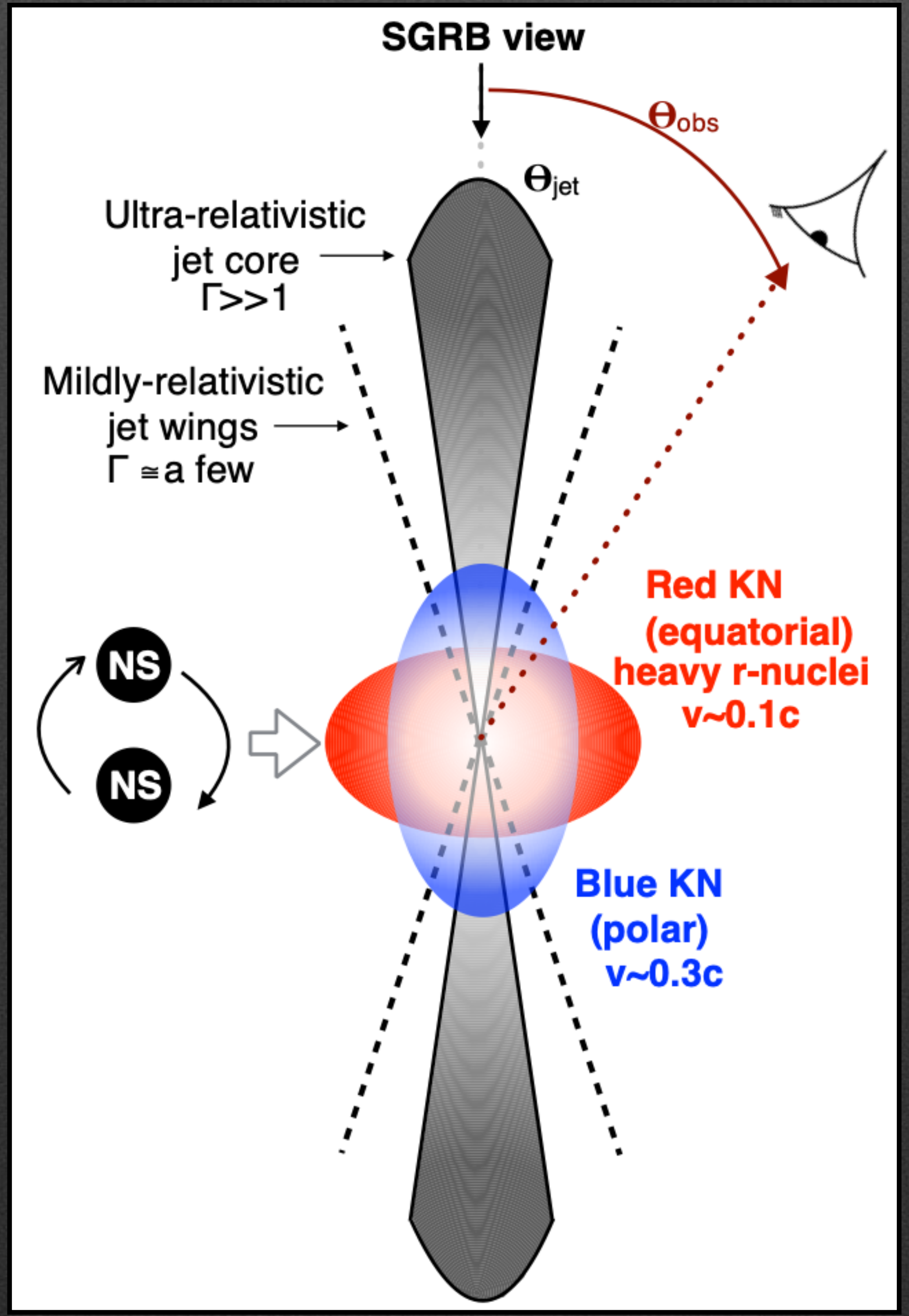
MULTI-MESSENGER parameter =

- Jet launching time (BH formation?) +
- Jet/cocoon breakout time +
- Travel time to transparency radius

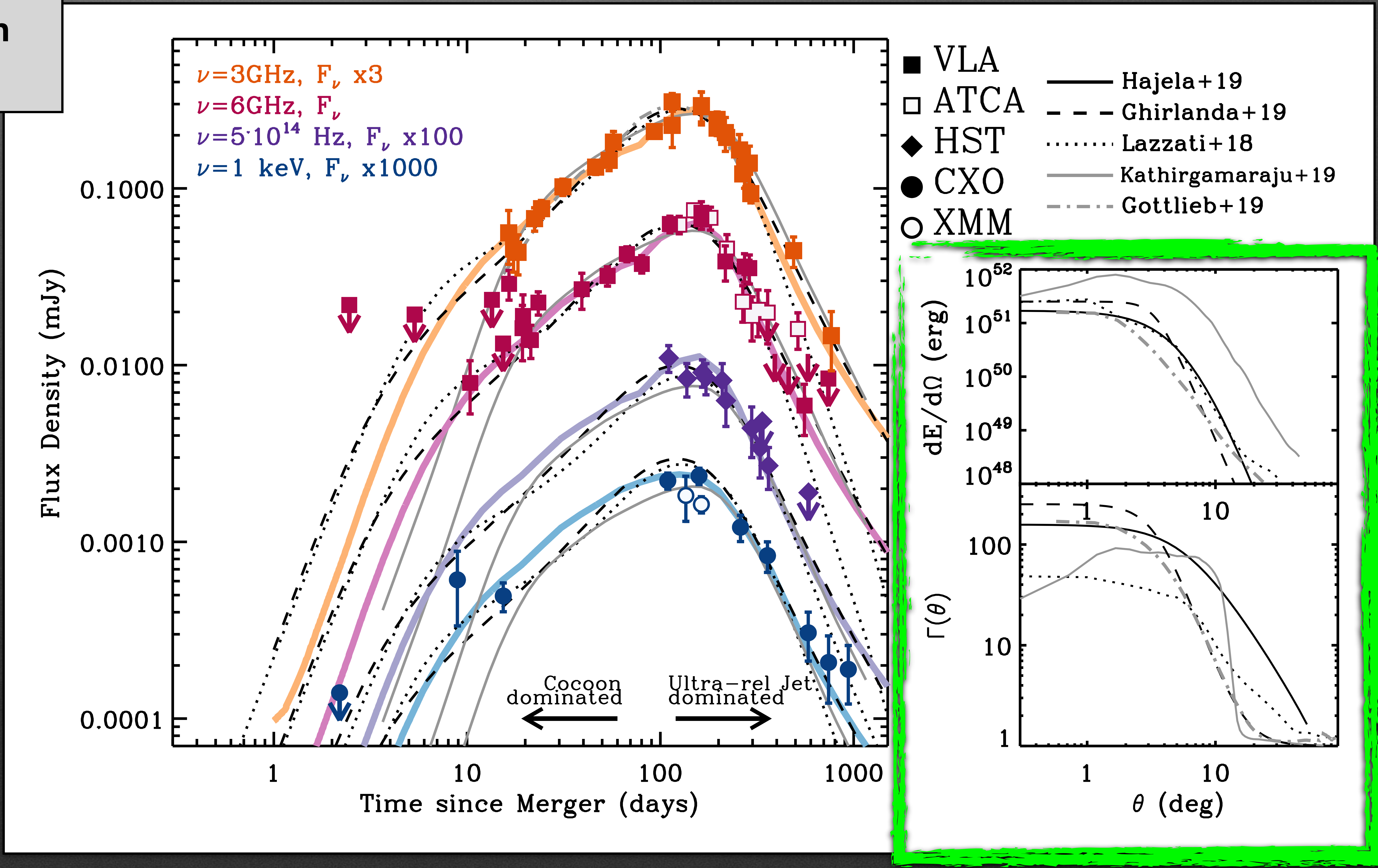
STRUCTURE of jets launched by NS-NS mergers

GW170817 launched a relativistic jet + cocoon

Synchrotron emission from the jet + cocoon



Jet structure E(θ) and Γ(θ)



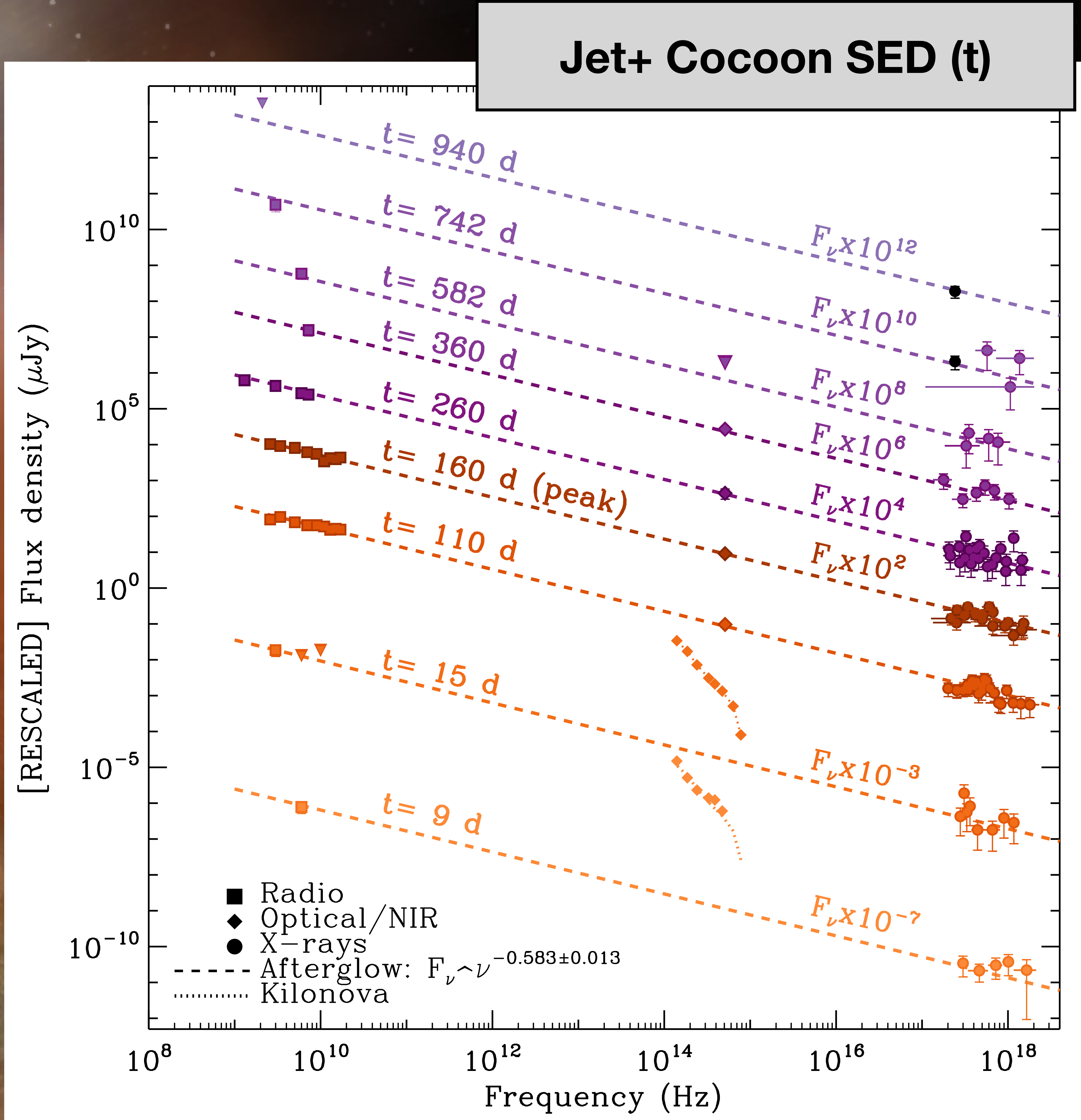
Margutti & Chornock, ARA&A 2022 and references therein

GW170817 “firsts”:

Some SGRBs originate from NS mergers,
i.e. NS mergers can launch UR collimated outflows

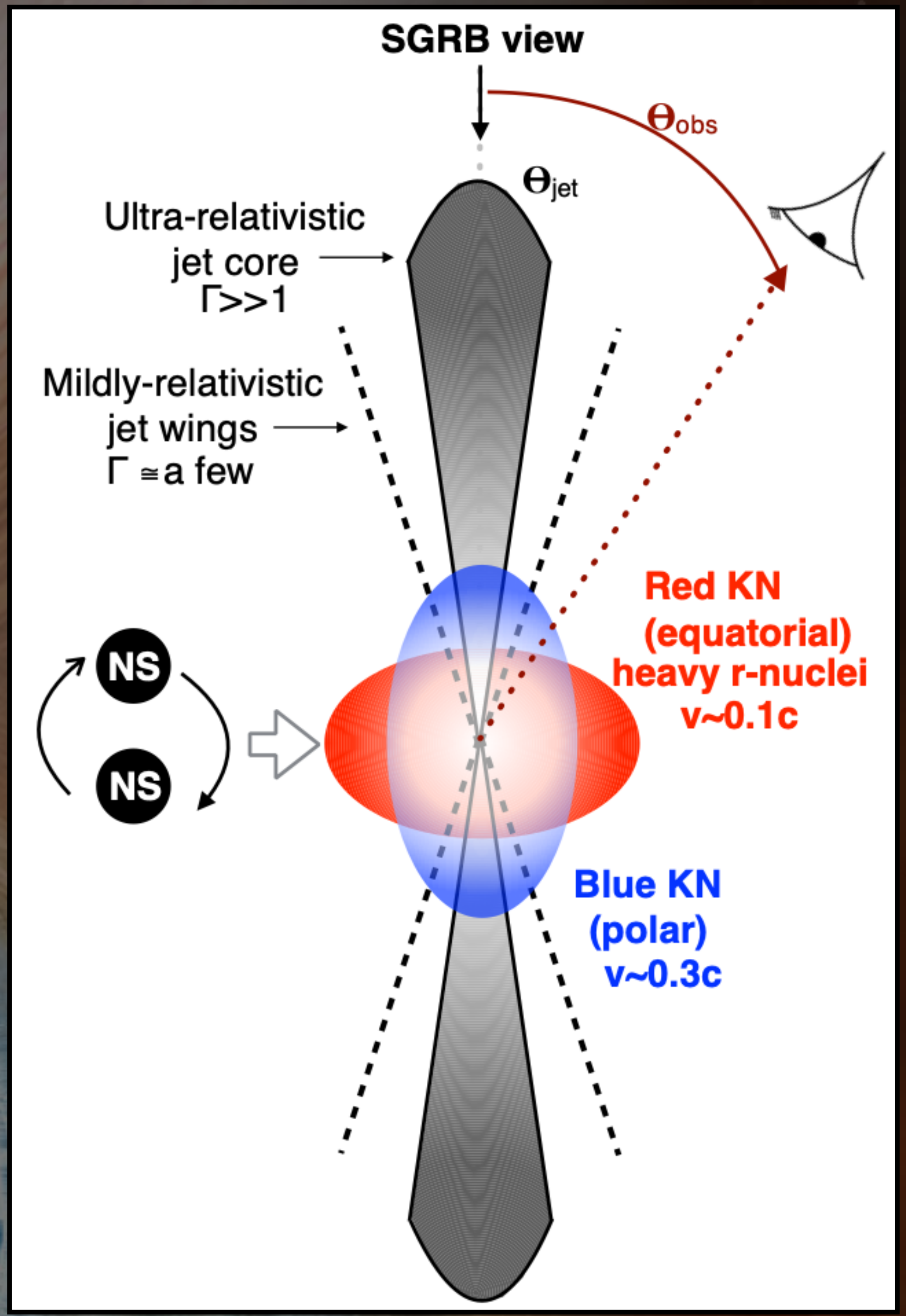
Extremely **well-behaved** SPL spectrum over 8 orders of magnitude in frequency

Particle acceleration by trans-relativistic shock in action!
Emitting material has
Γ~3-10



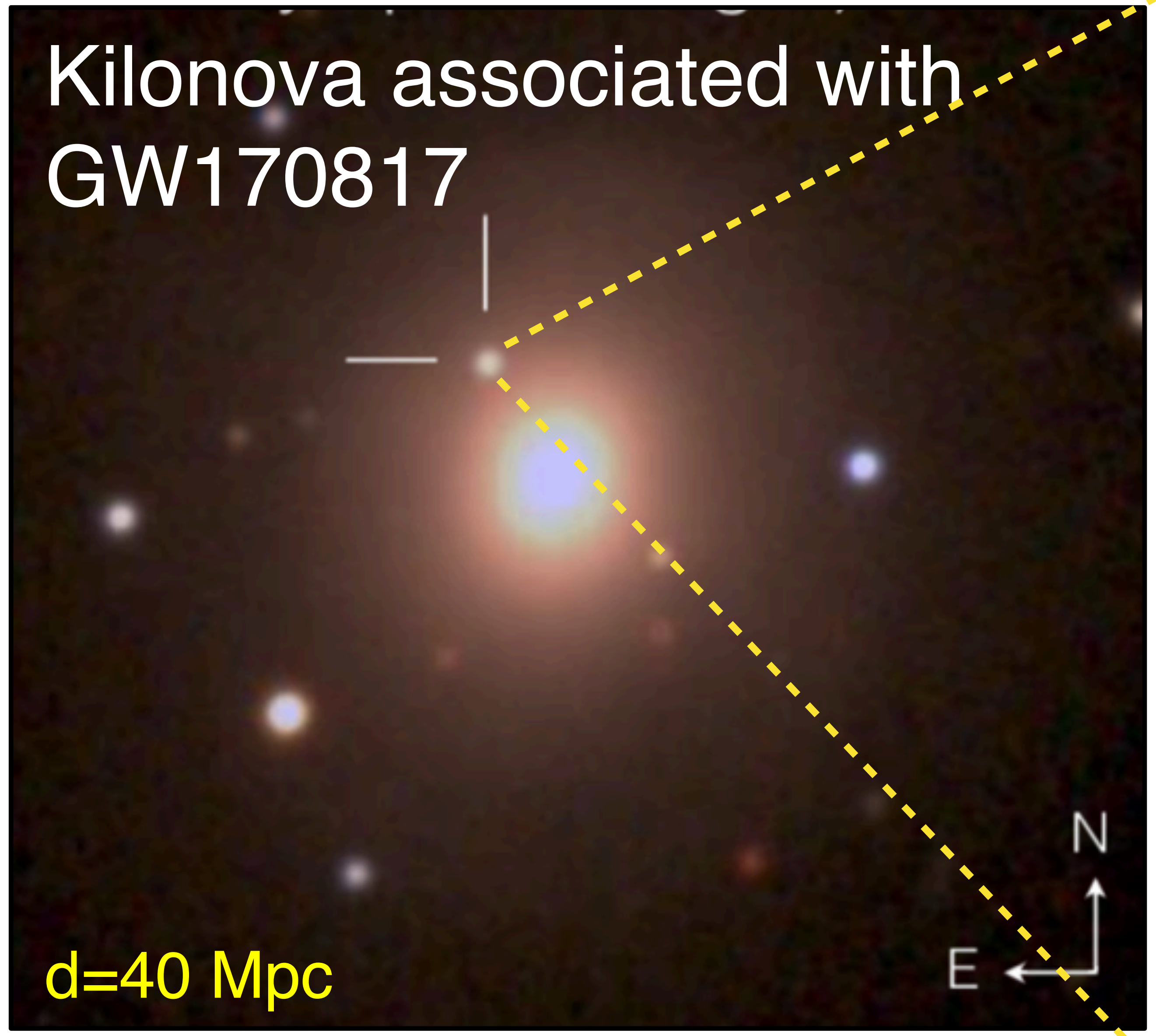
GW170817 "firsts":

- Some SGRBs originate from NS mergers, i.e. NS mergers can launch UR collimated outflows
- Discovery of a kilonova



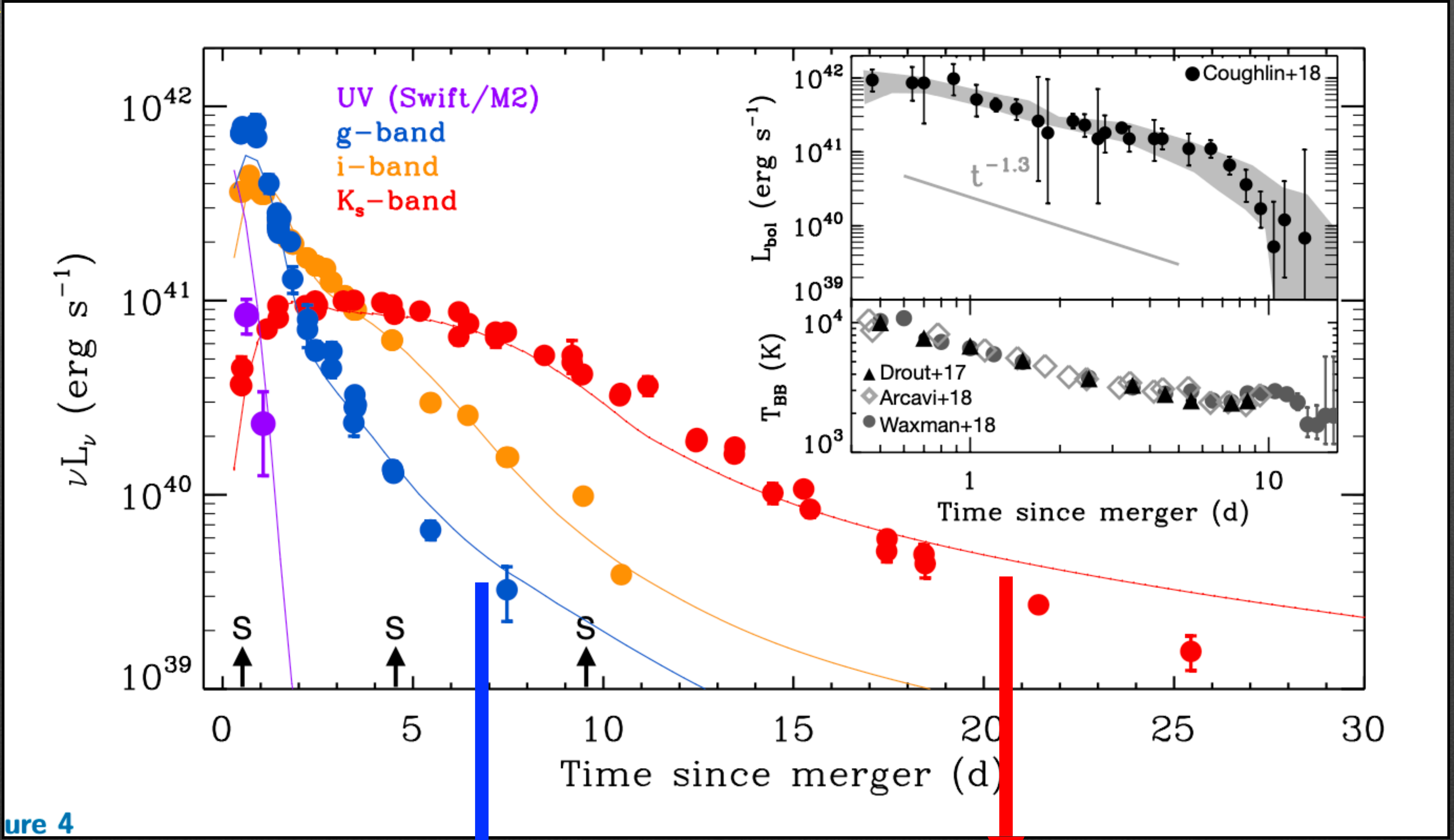
Kilonova emission in GW170817 (UV-optical phot)

RED + **BLUE** components



DECam image from Soares-Santos+17; Cowperthwaite+17

Photometry from ~70 telescopes worldwide



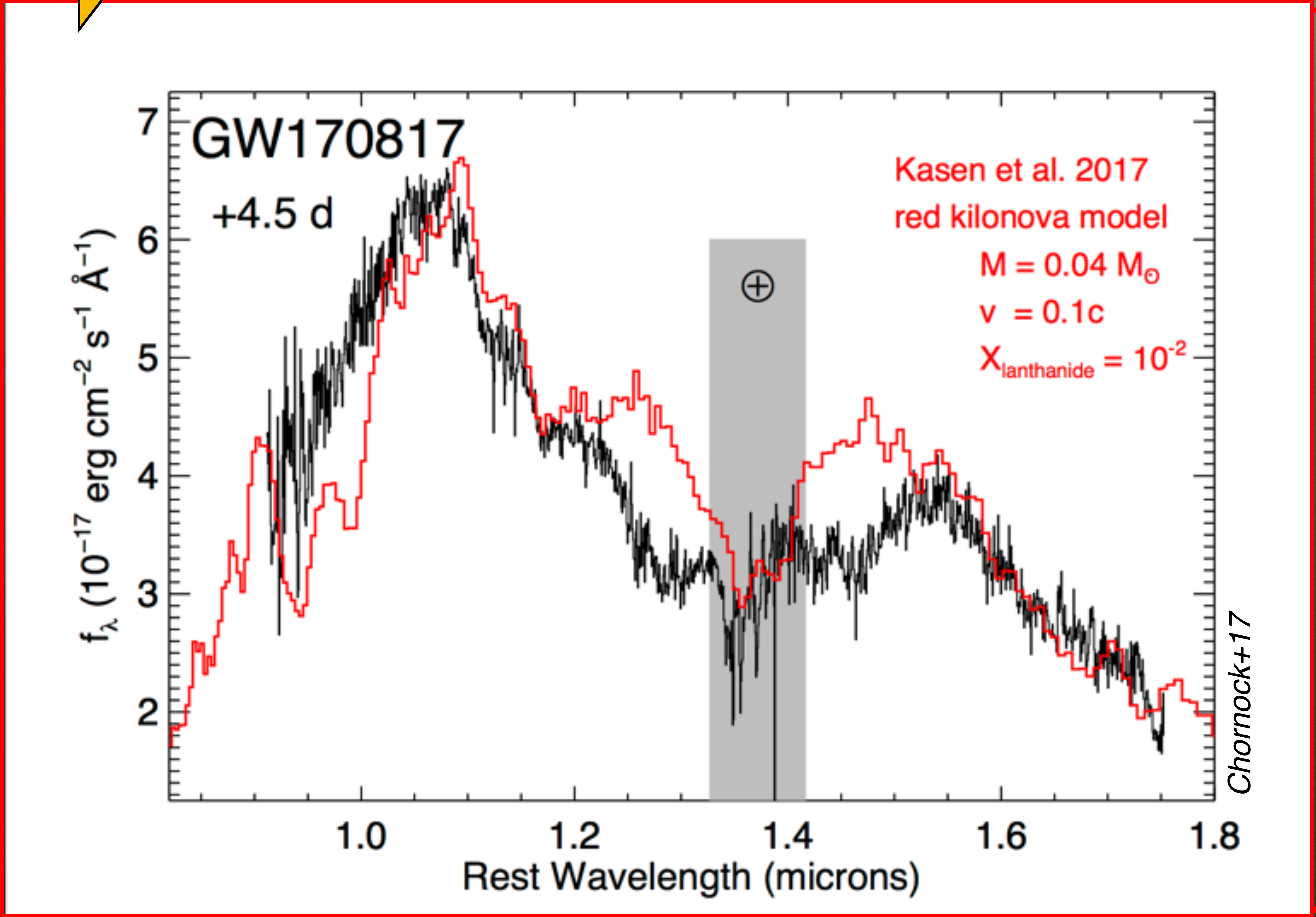
Mej~0.01 Msun
Velocity~0.3c

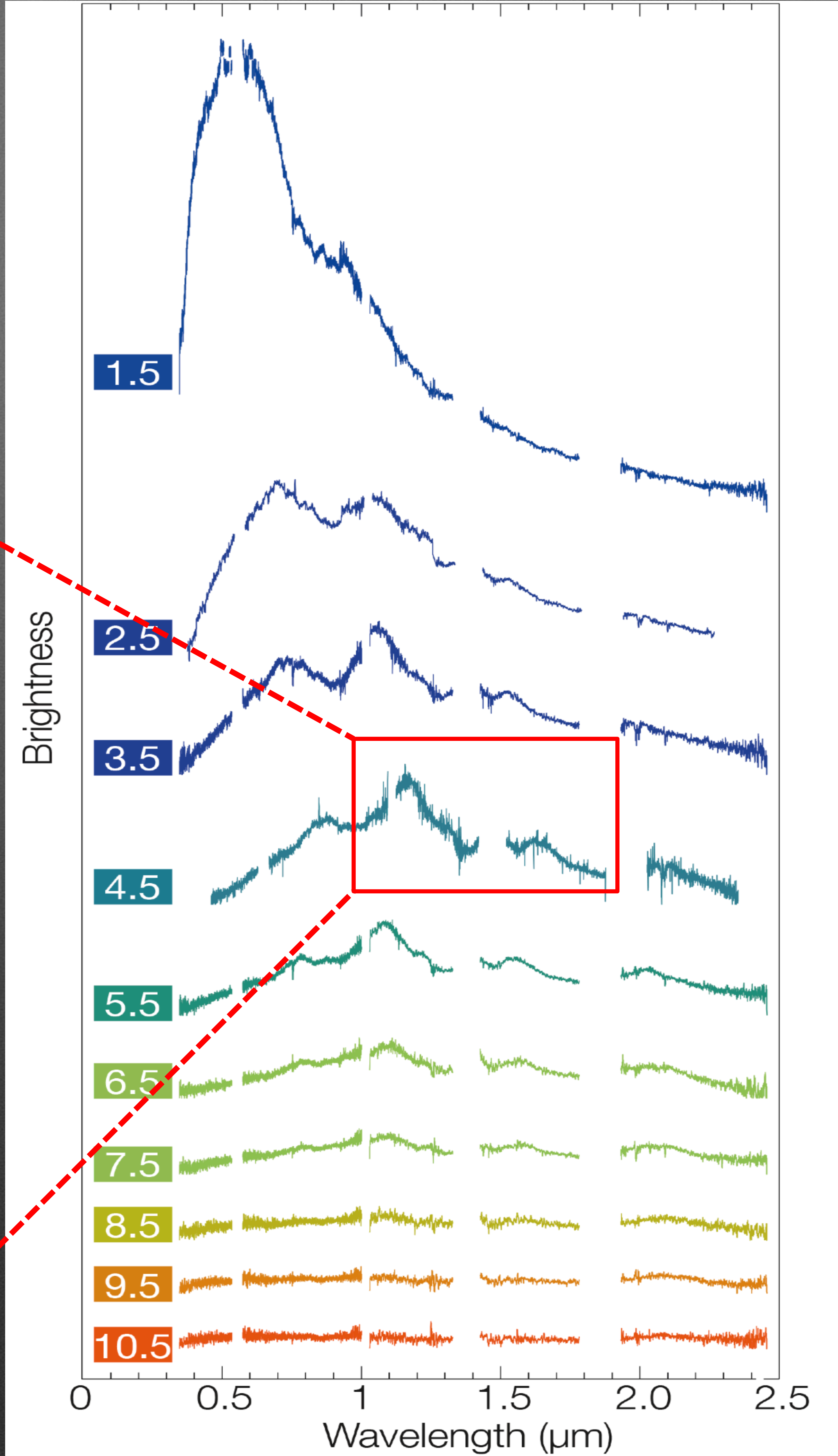
Mej~0.04 Msun
Velocity~0.1c

Models by Metzger+17
Data from 1000+ scientists!!!

Evidence for r-process nucleosynthesis from NIR spectroscopy of the kilonova

Chemical enrichment of the Universe

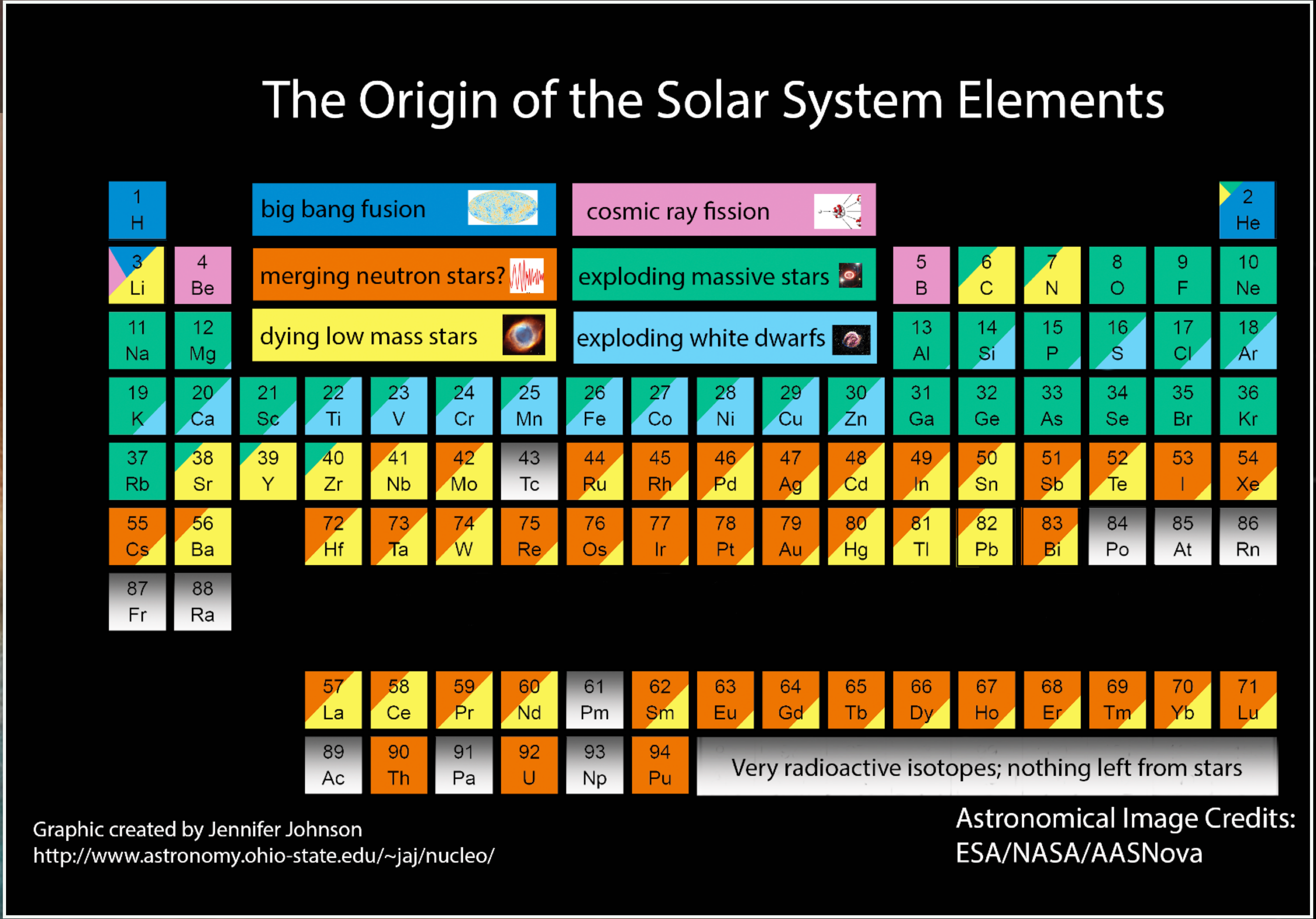




GW170817 "firsts":

- Some SGRBs originate from NS mergers, i.e. NS mergers can launch UR collimated outflows

- NS mergers are one of the r-process sites in the Universe

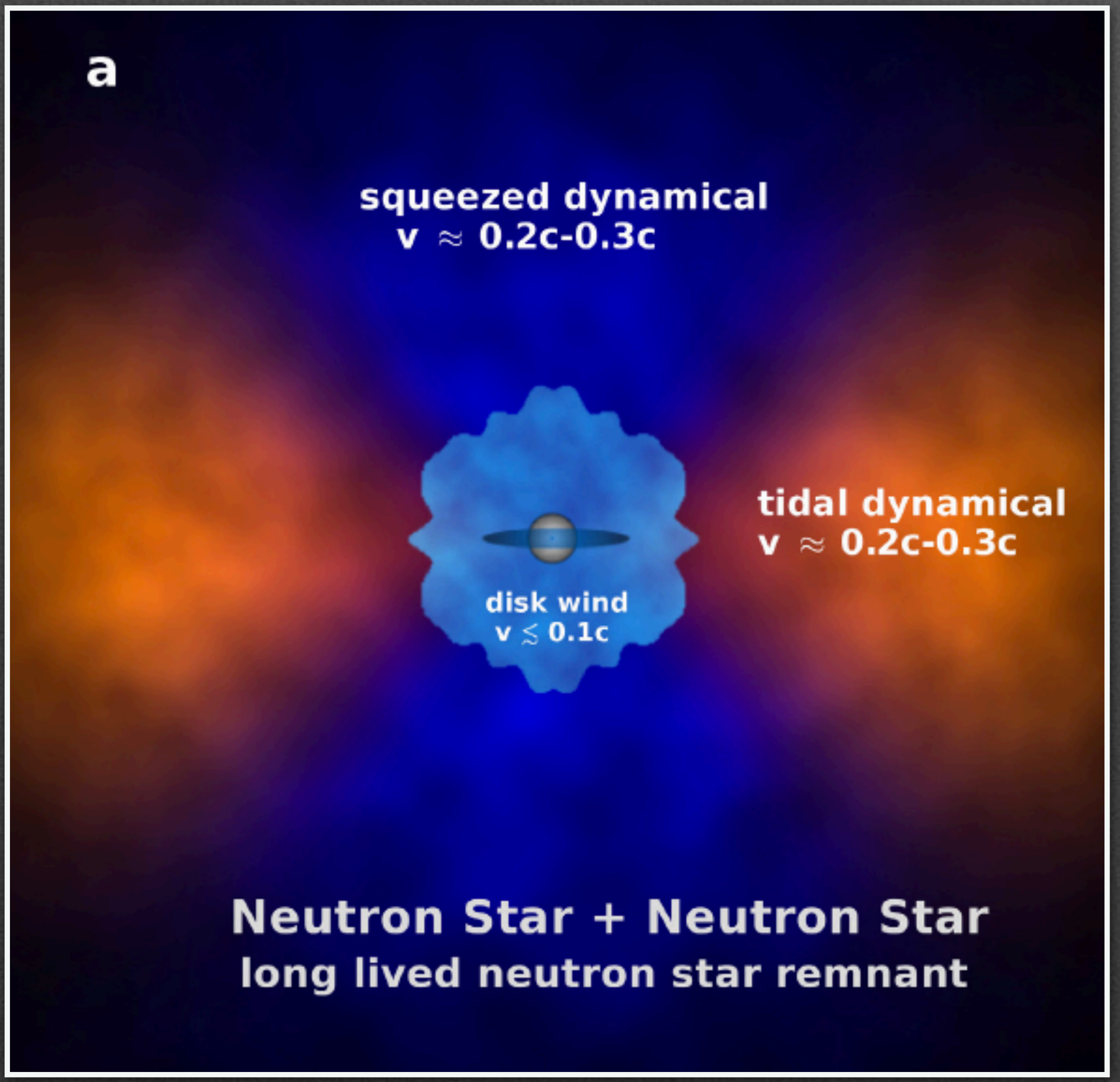


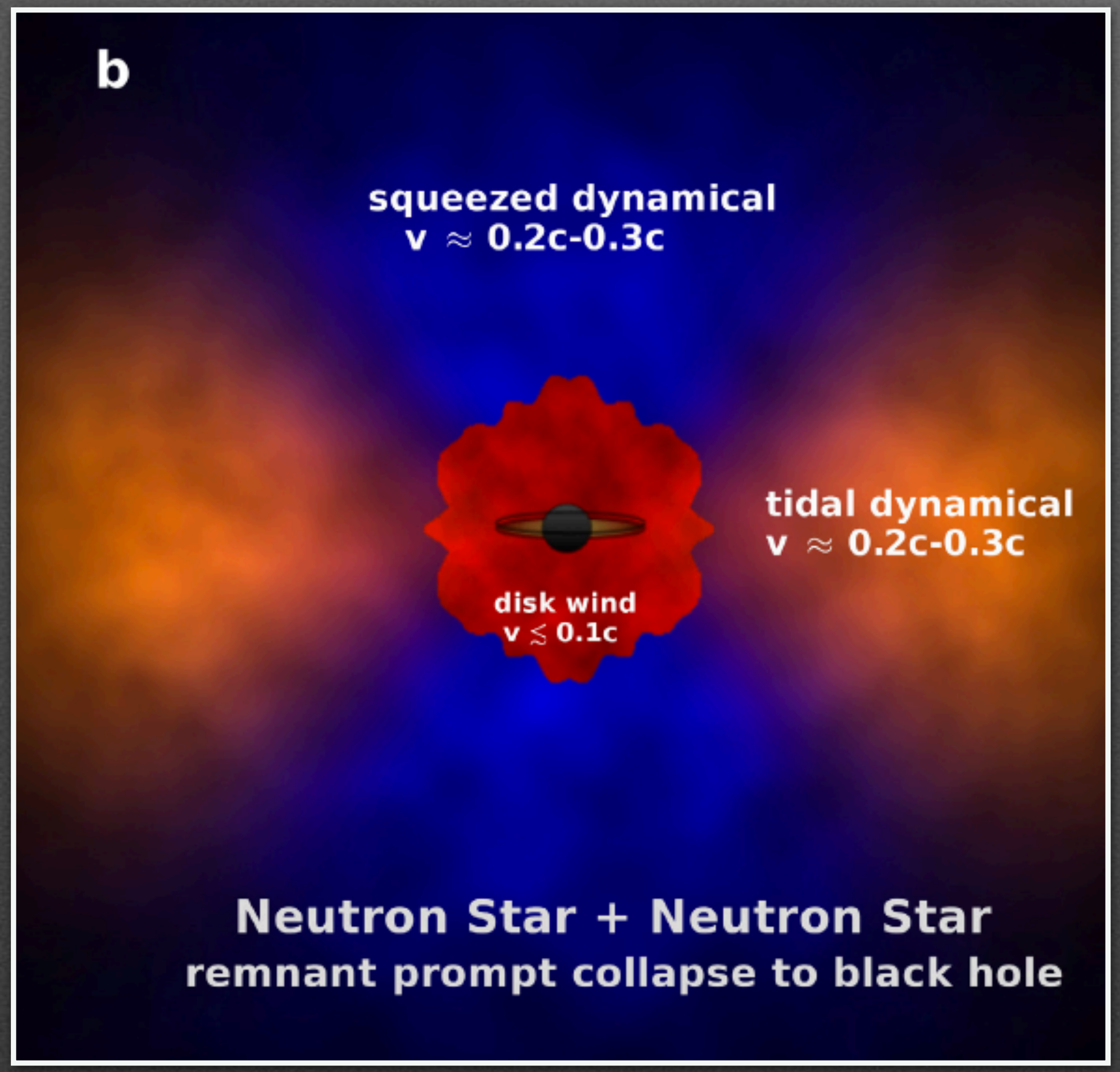
GW170817 “firsts”:

- Some SGRBs originate from NS mergers, i.e. NS mergers can launch UR collimated outflows
- NS mergers are one of the r-process sites in the Universe
- Fundamental Physics (NS EoS)

Fundamental Physics: EoS

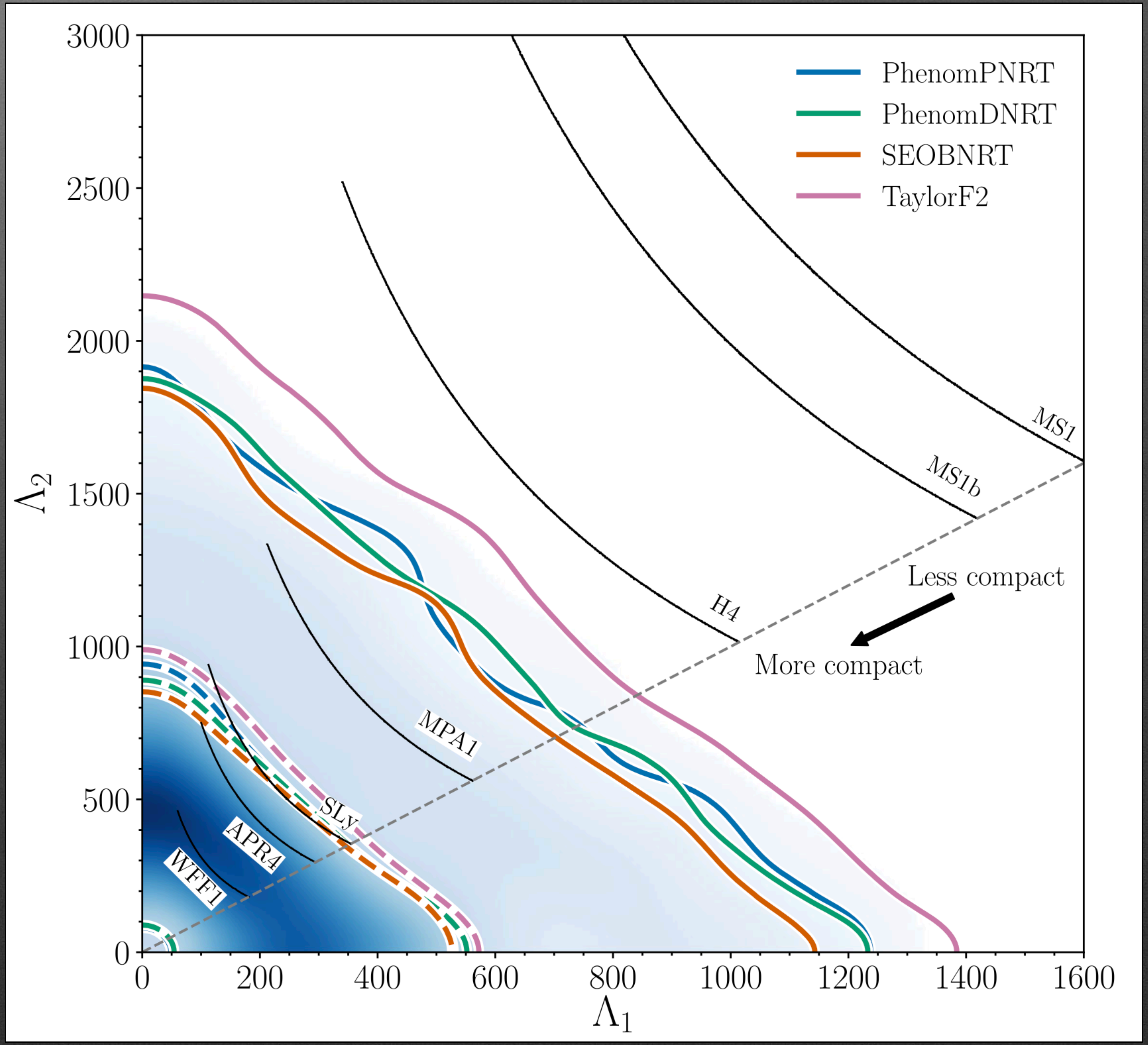
Inferences from the electromagnetic emission
(nature of the merger remnant)





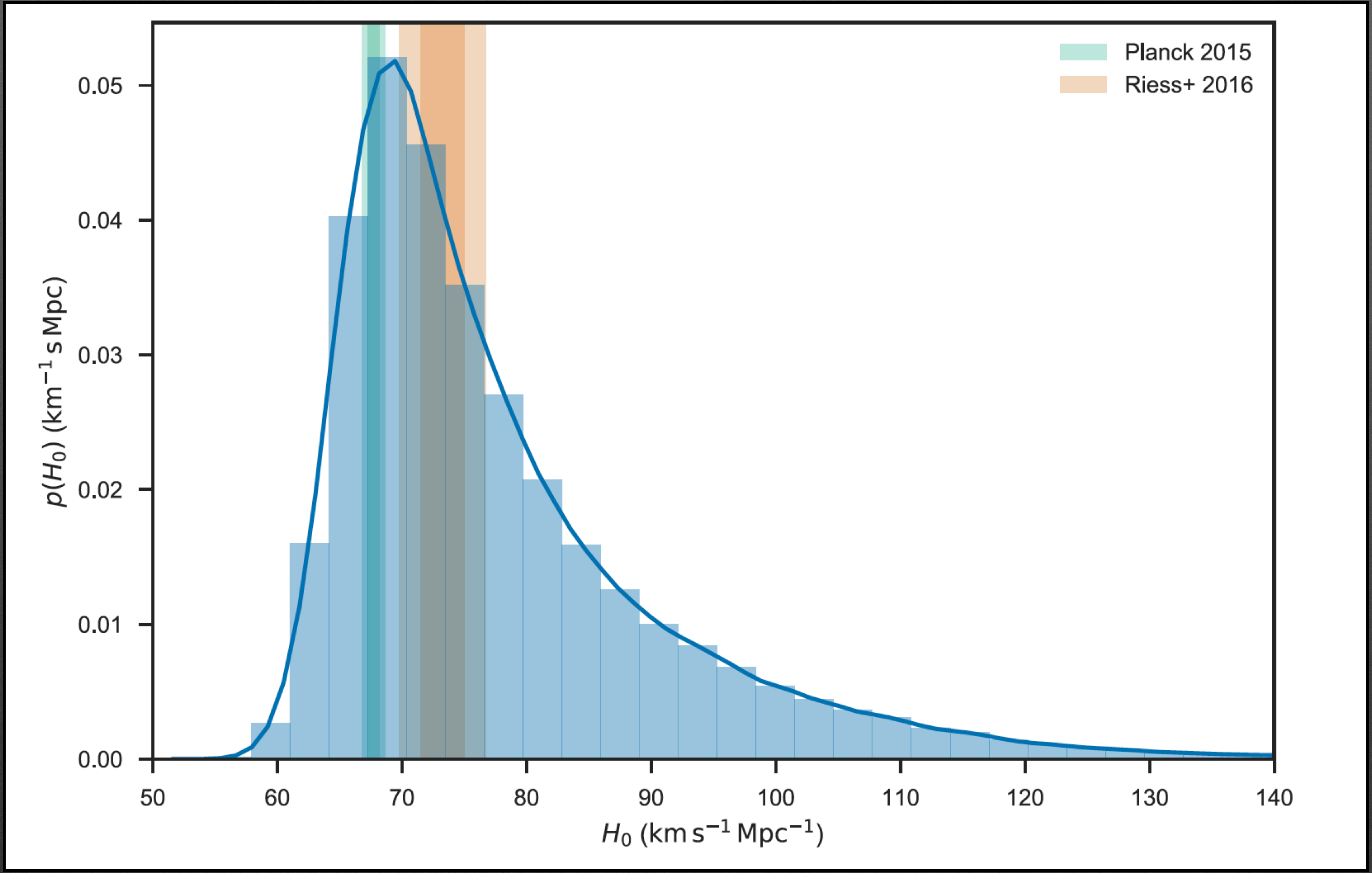
Kasen+17, Metzger+17, Margalit+19

Inferences from the tail deformability parameter (GWs)



Abbott+2019

Fundamental Physics: Cosmology



Abbott+17,
Guidorzi+17,
Hotokezaka+18

GW170817 “firsts”:

- ✓ Some SGRBs originate from NS mergers, i.e. NS mergers can launch UR collimated outflows
- ✓ NS mergers are one of the r-process sites in the Universe
- ✓ Fundamental Physics (NS EoS)
- ✓ Fundamental Physics (Cosmology)

…We have roughly 9 months left of LVK O4…

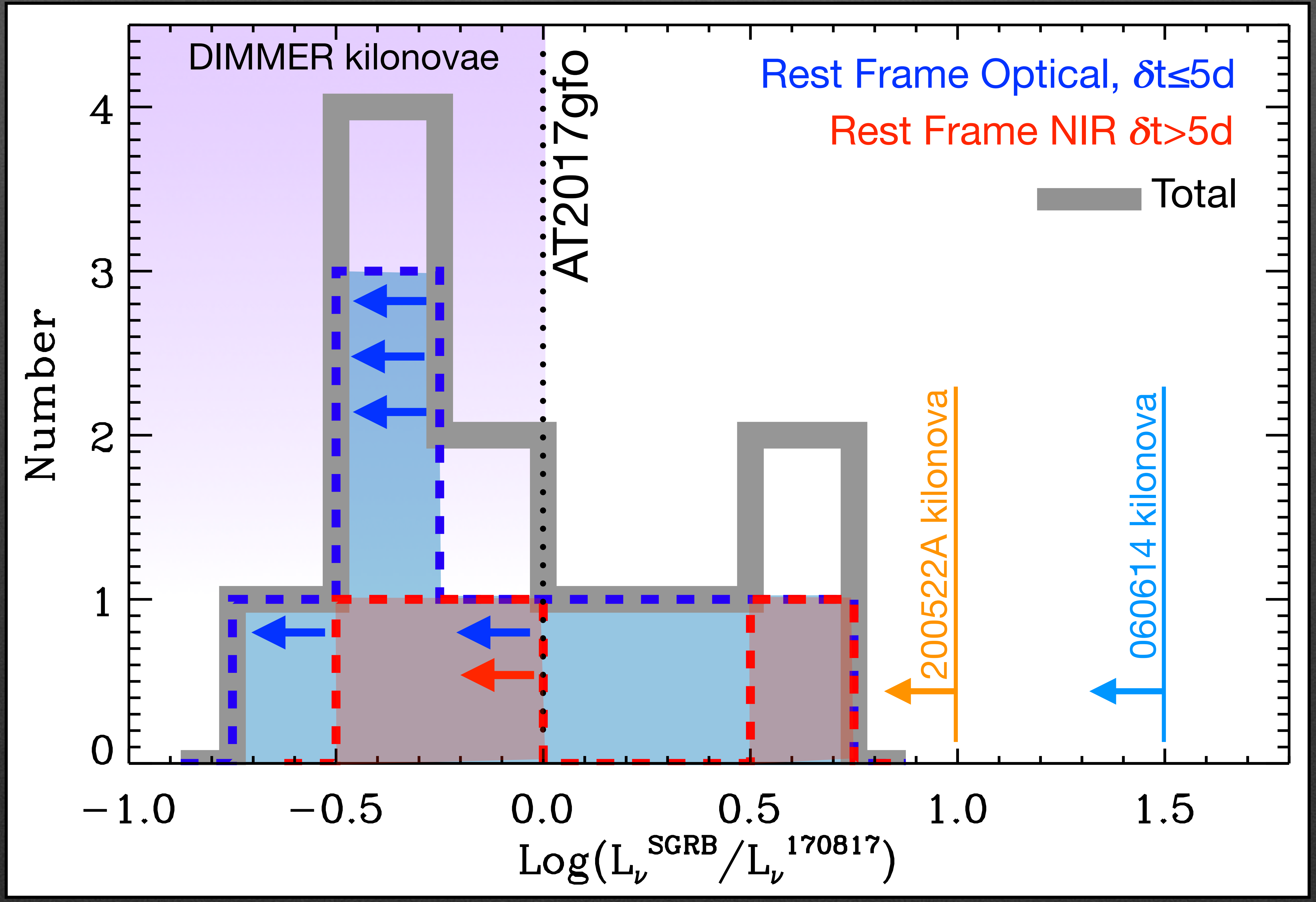
So, where do we go from here?

(As far as we know, photo is public domain)

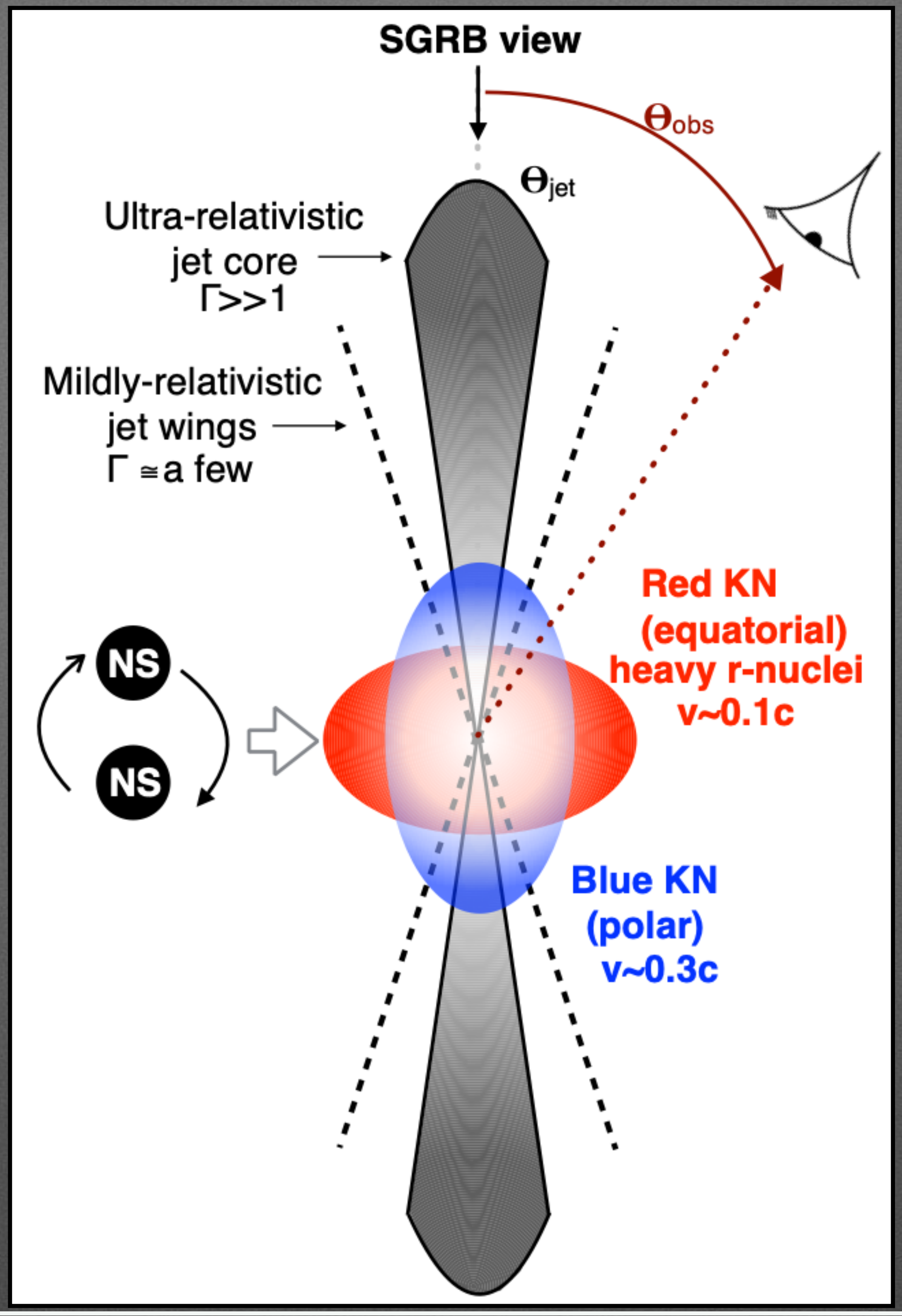
Where is the frontier after GW170817?

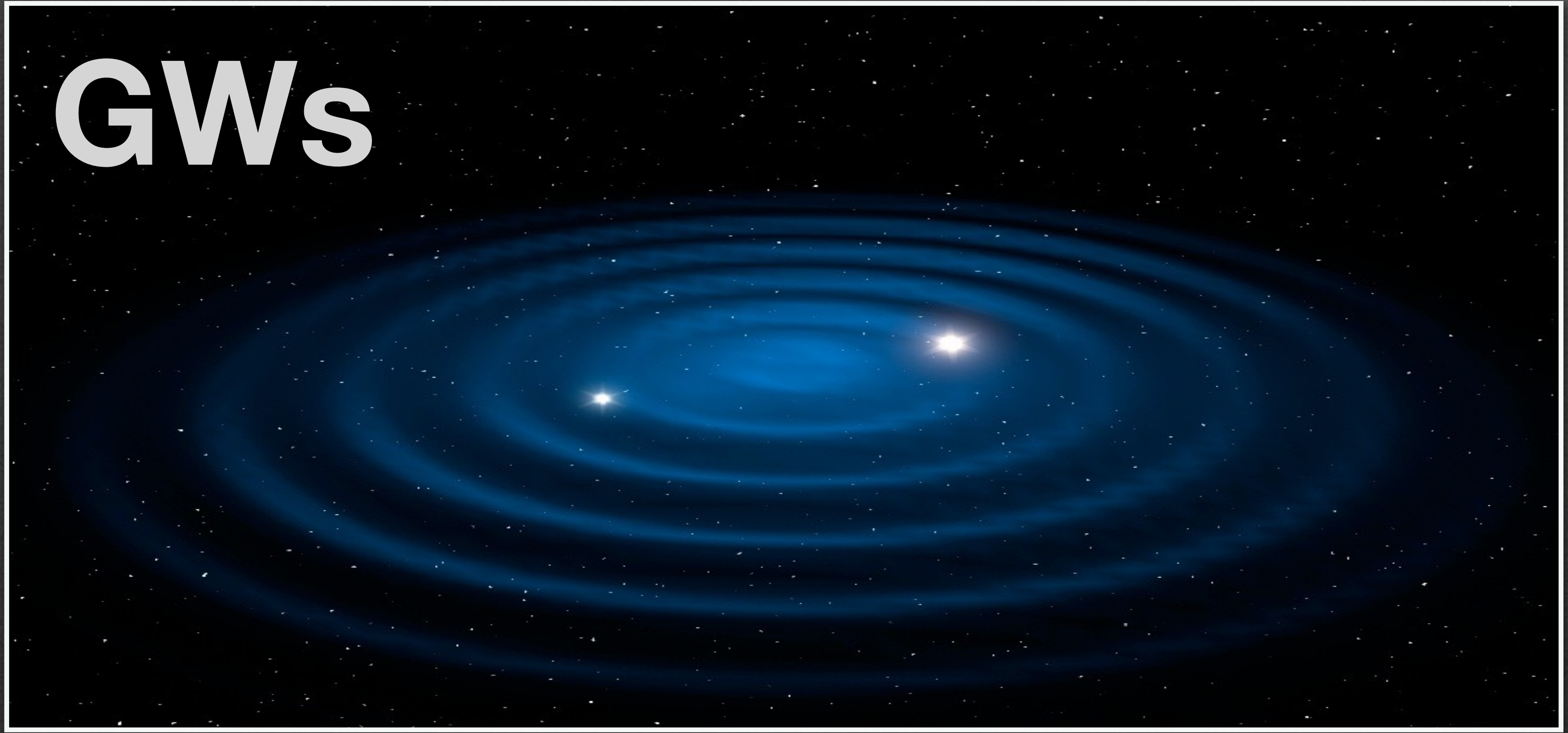
1. Population studies, i.e. mapping the diversity of BNS mergers outcomes and initial conditions

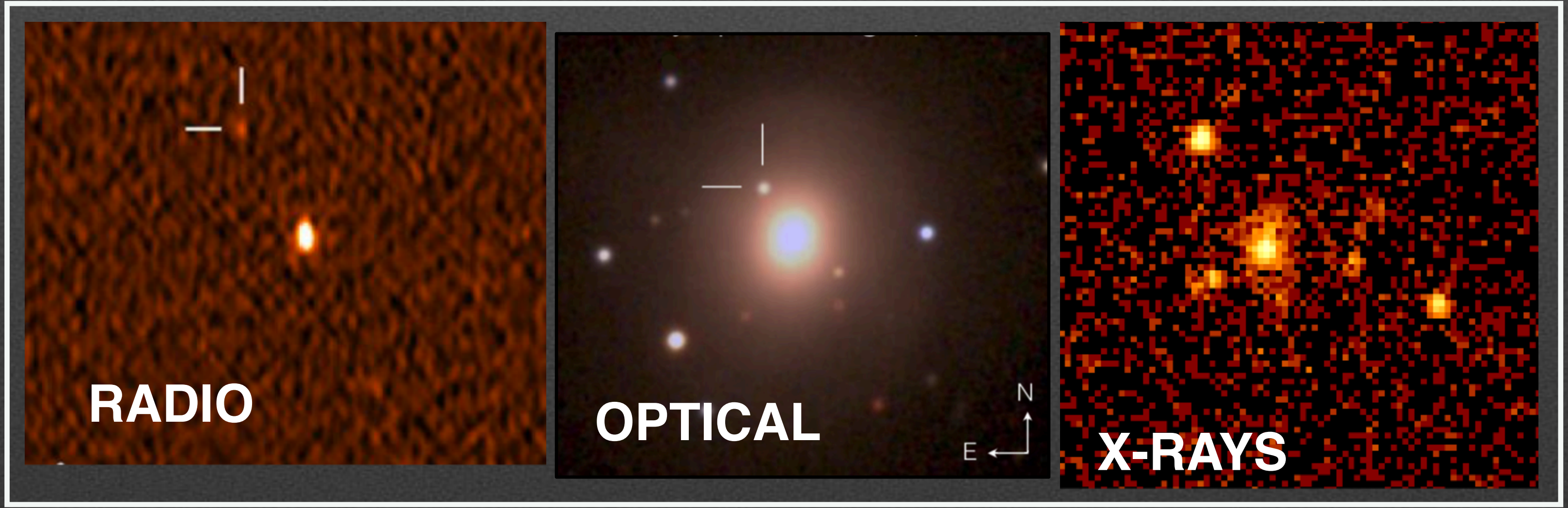
Known diversity of kilonovae

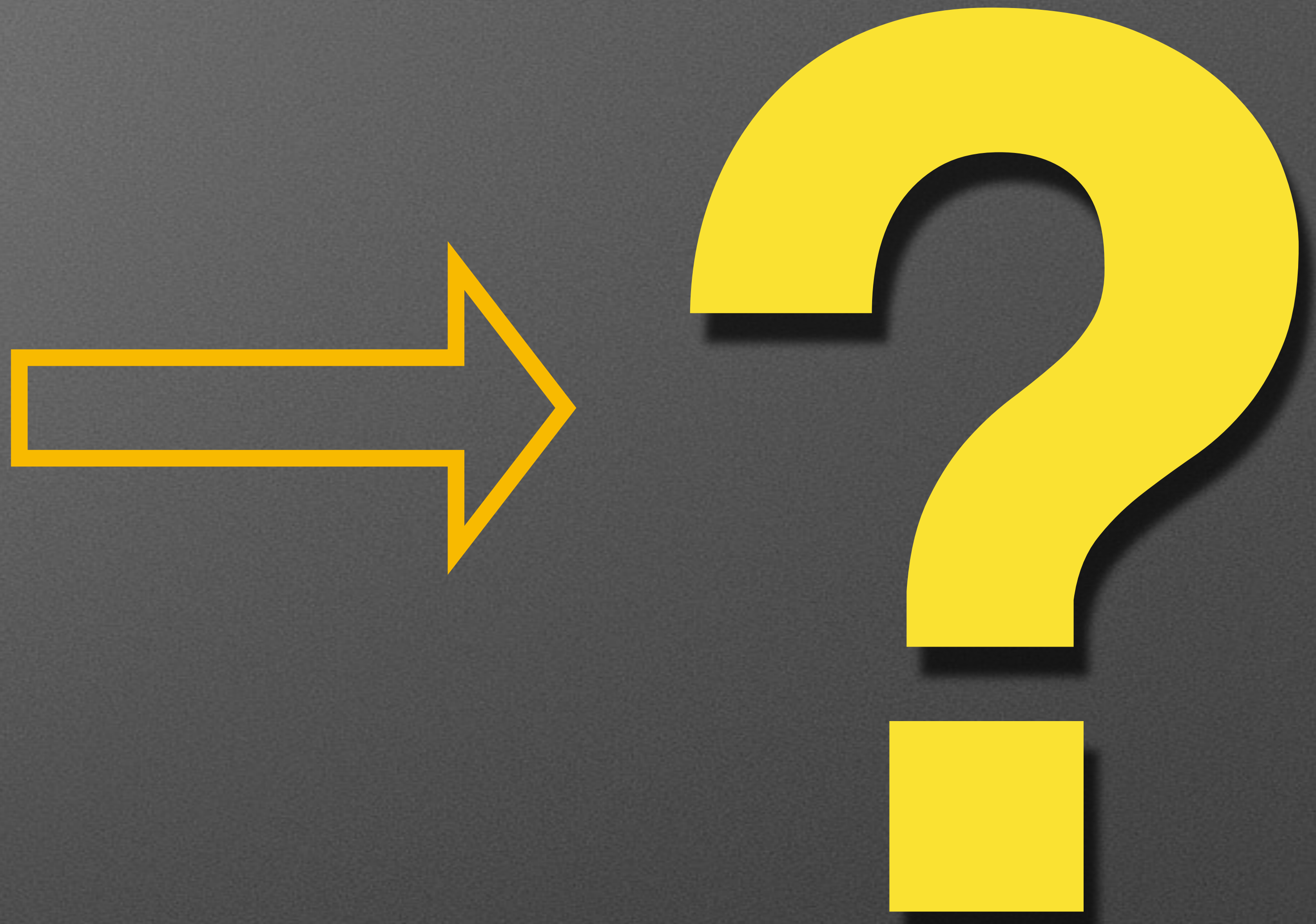


Margutti & Chornock ARA&A, 2021









Pre-merger properties and physical conditions

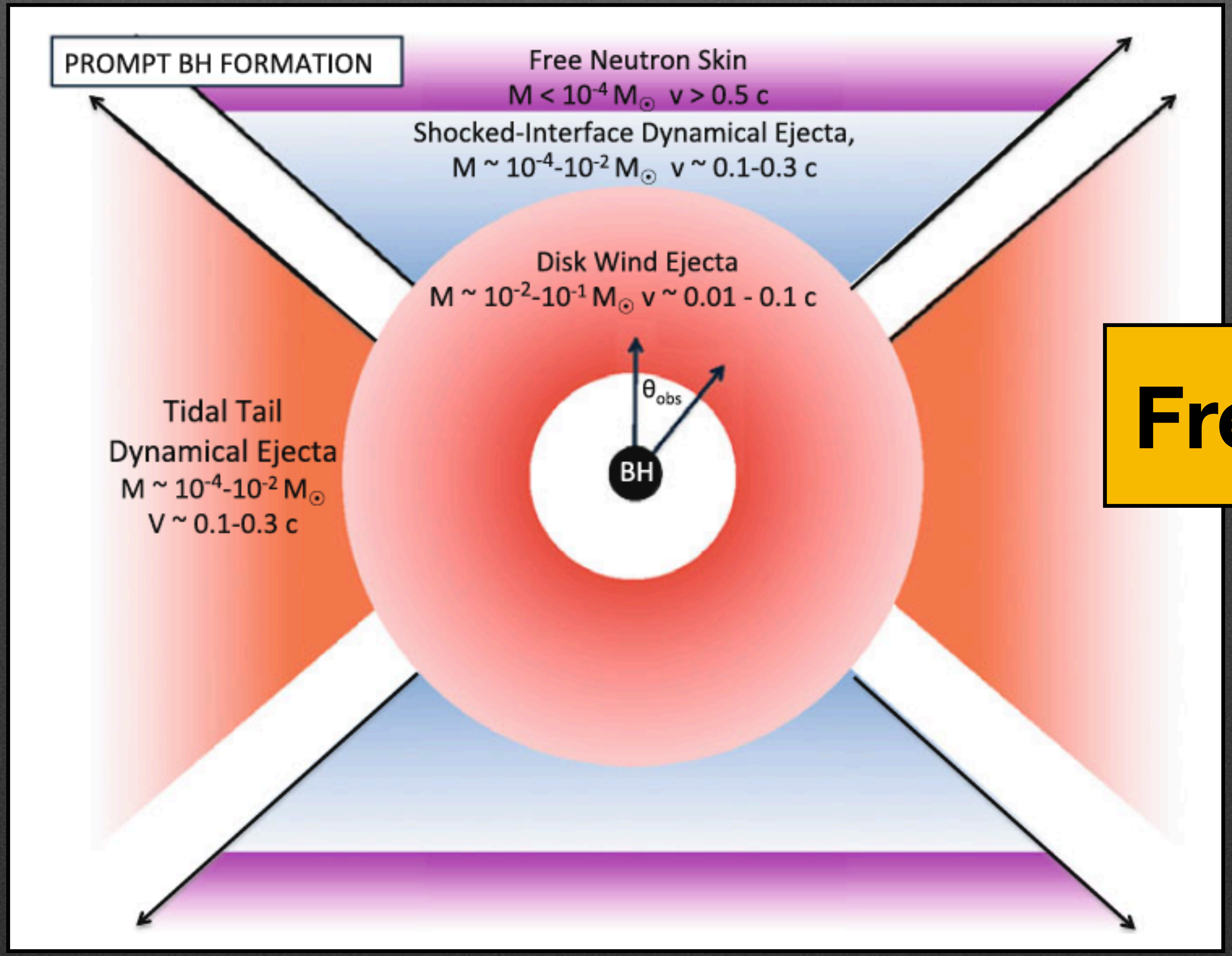
Properties of merger outflows

Nature/properties of the Remnant Compact object

Where is the frontier after GW170817?

1. Population studies, i.e. mapping the diversity of BNS mergers outcomes and initial conditions

2. New EM components in BNS mergers



Metzger+17

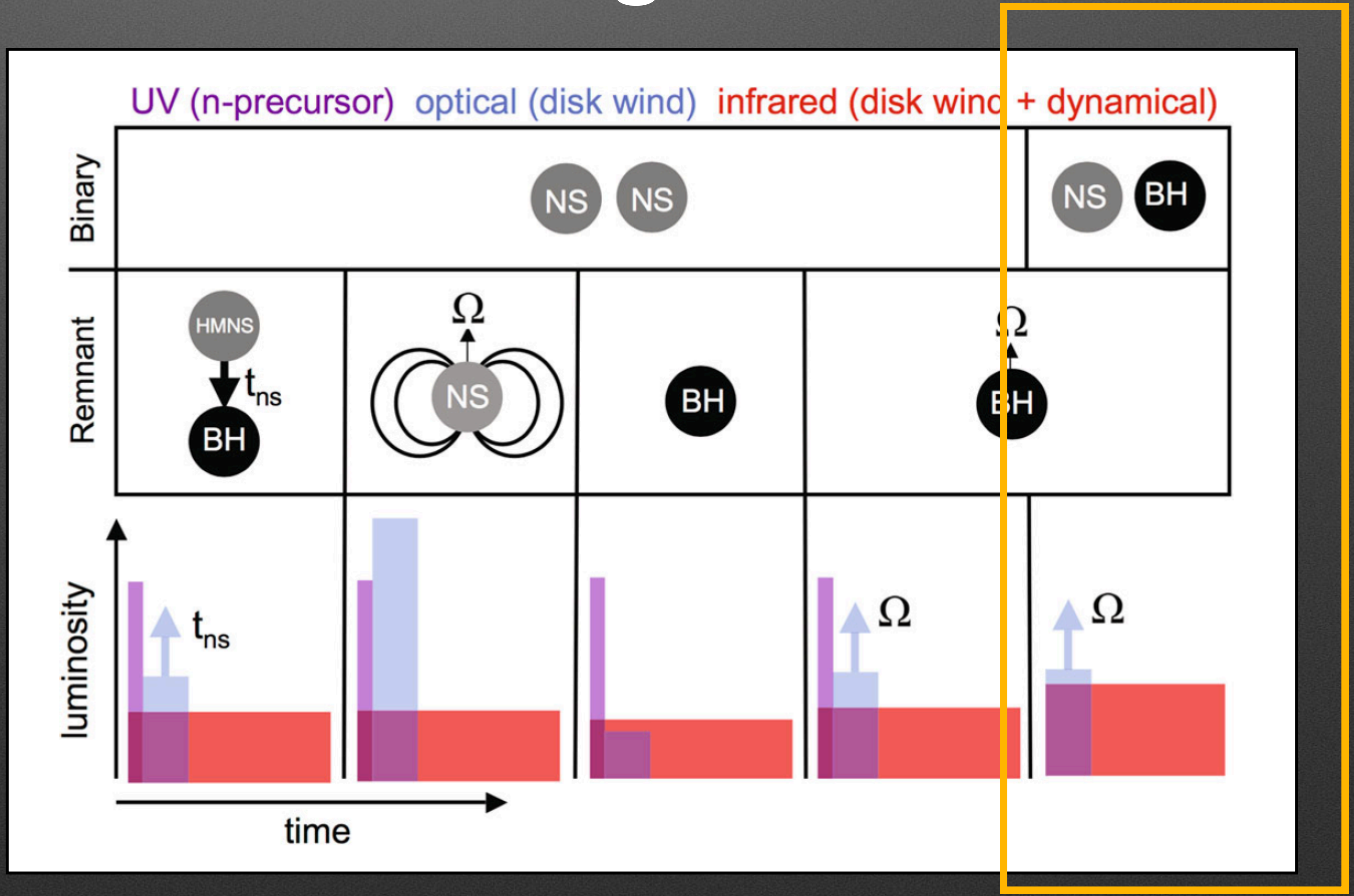
Free-neutron component

Where is the frontier after GW170817?

1. Population studies, i.e. mapping the diversity of BNS mergers outcomes and initial conditions

2. New EM components in BNS mergers

3. EM counterparts to BH-NS mergers



Metzger+17

All or NOTHING

Where is the frontier after GW170817?

1. Population studies, i.e. mapping the diversity of BNS mergers outcomes and initial conditions
2. New EM components in BNS mergers
3. EM counterparts of BH-NS mergers
4. EM counterparts of BH-BH mergers
5. EM counterparts of GW unidentified sources

Do all NS mergers produce SGRBs?

Do all NS mergers launch relativistic jets? If not, what are the special conditions that lead to the most relativistic outflows in nature?

What are the counterpart of NS-BH mergers? Do they produce SGRBs?

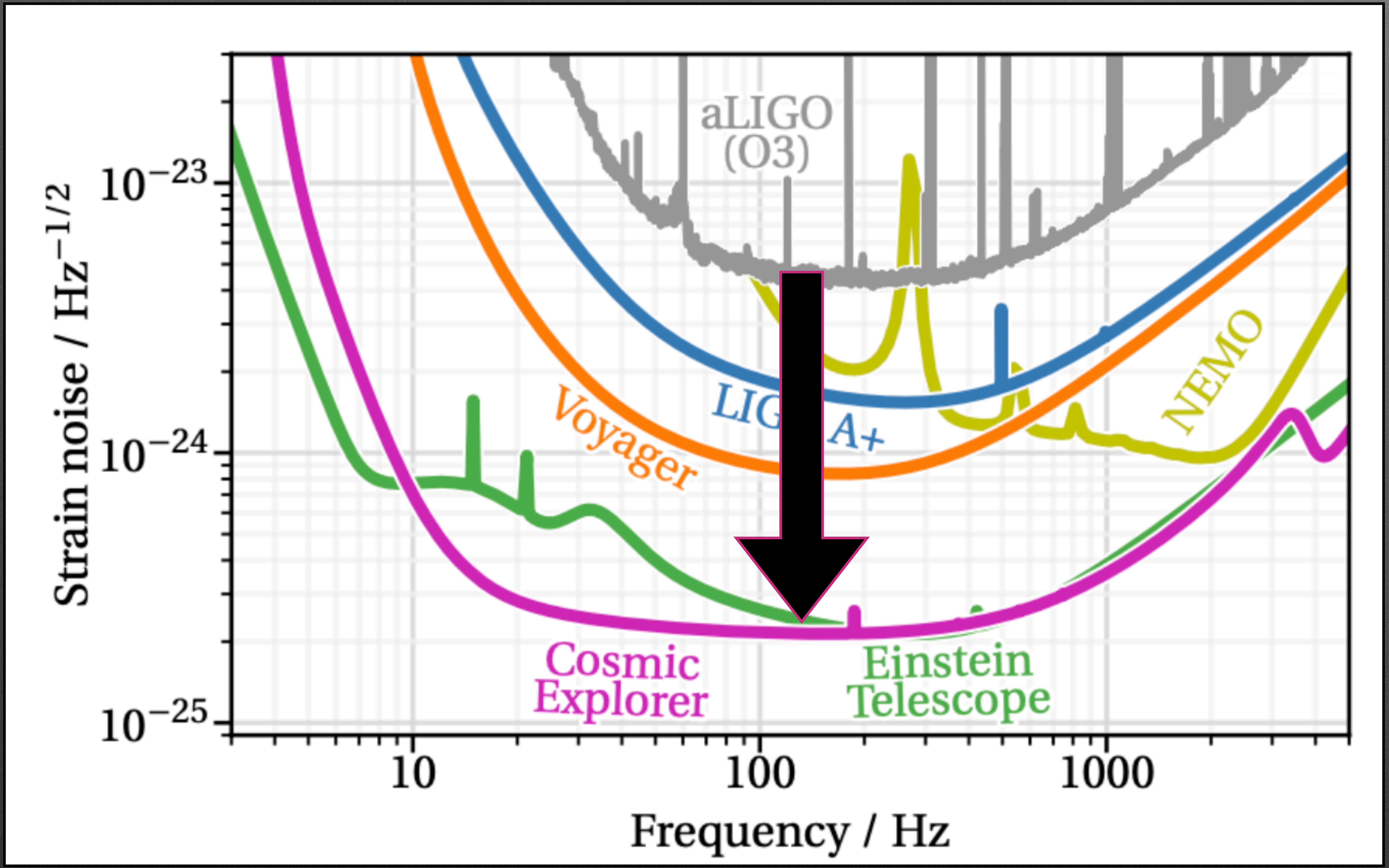
Are NS mergers the major r-process site?

Stringent Cosmology constraints + EoS constraints

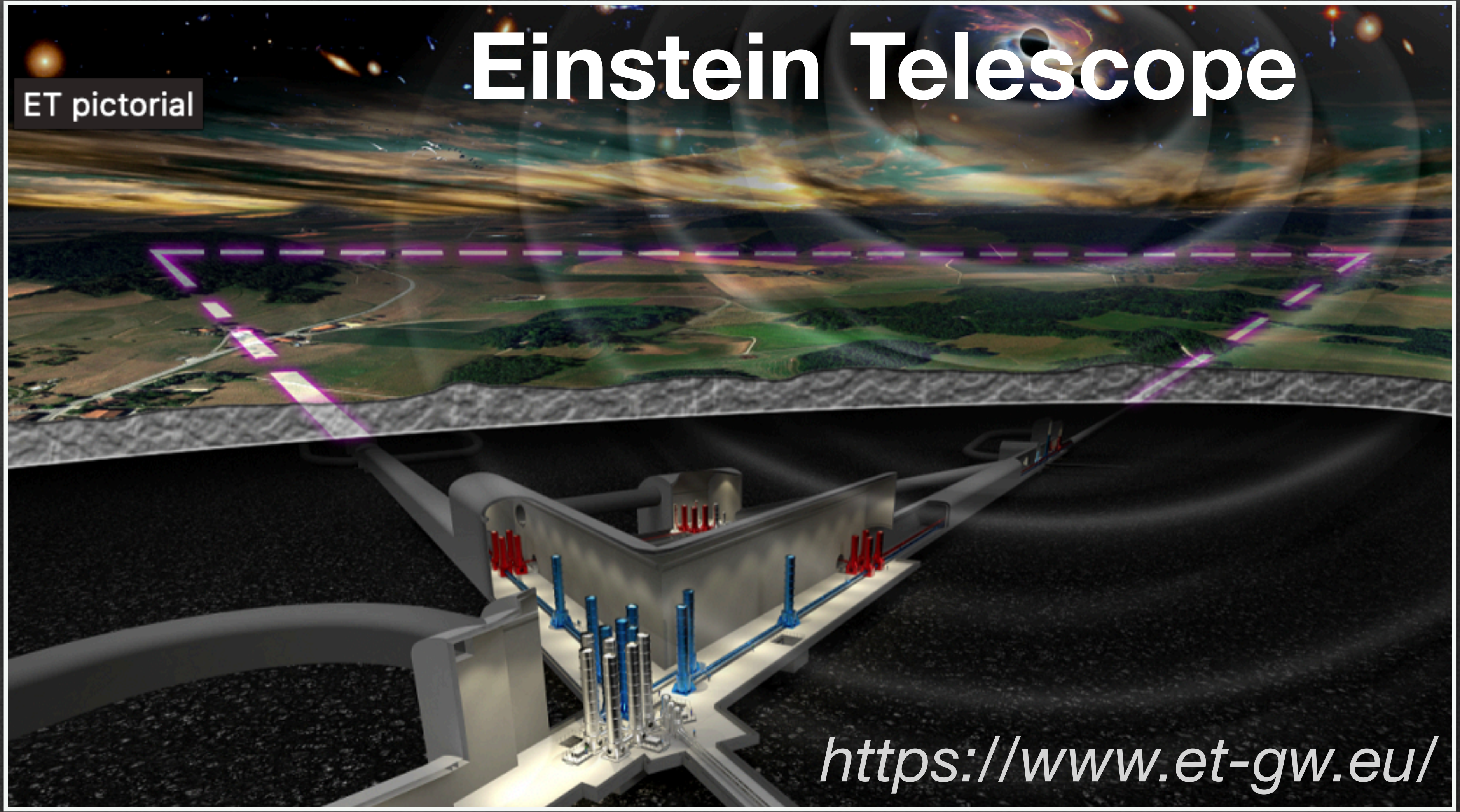
Large sample of EM+GW detections

Direct knowledge of the remnant property and nature

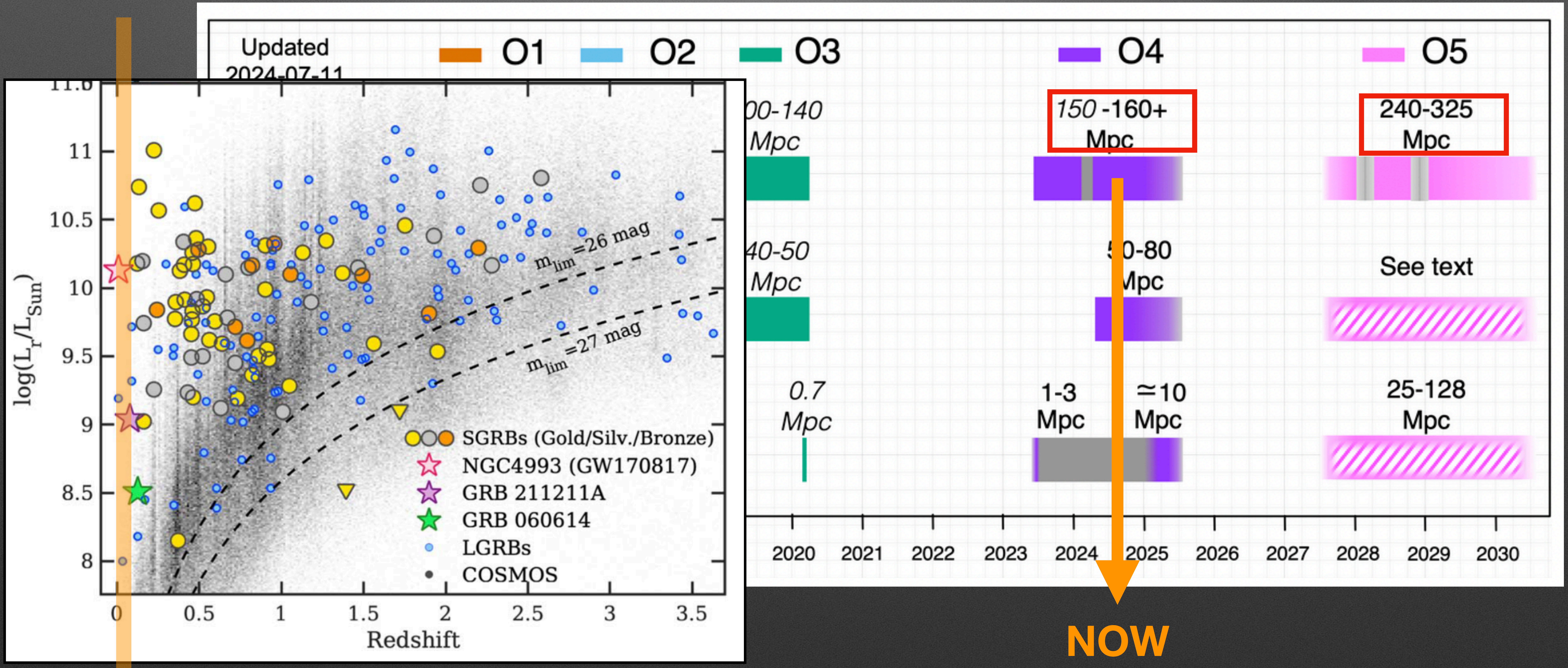
Next-Gen GW Observatories



Evans+2021, “A horizon study for CE”



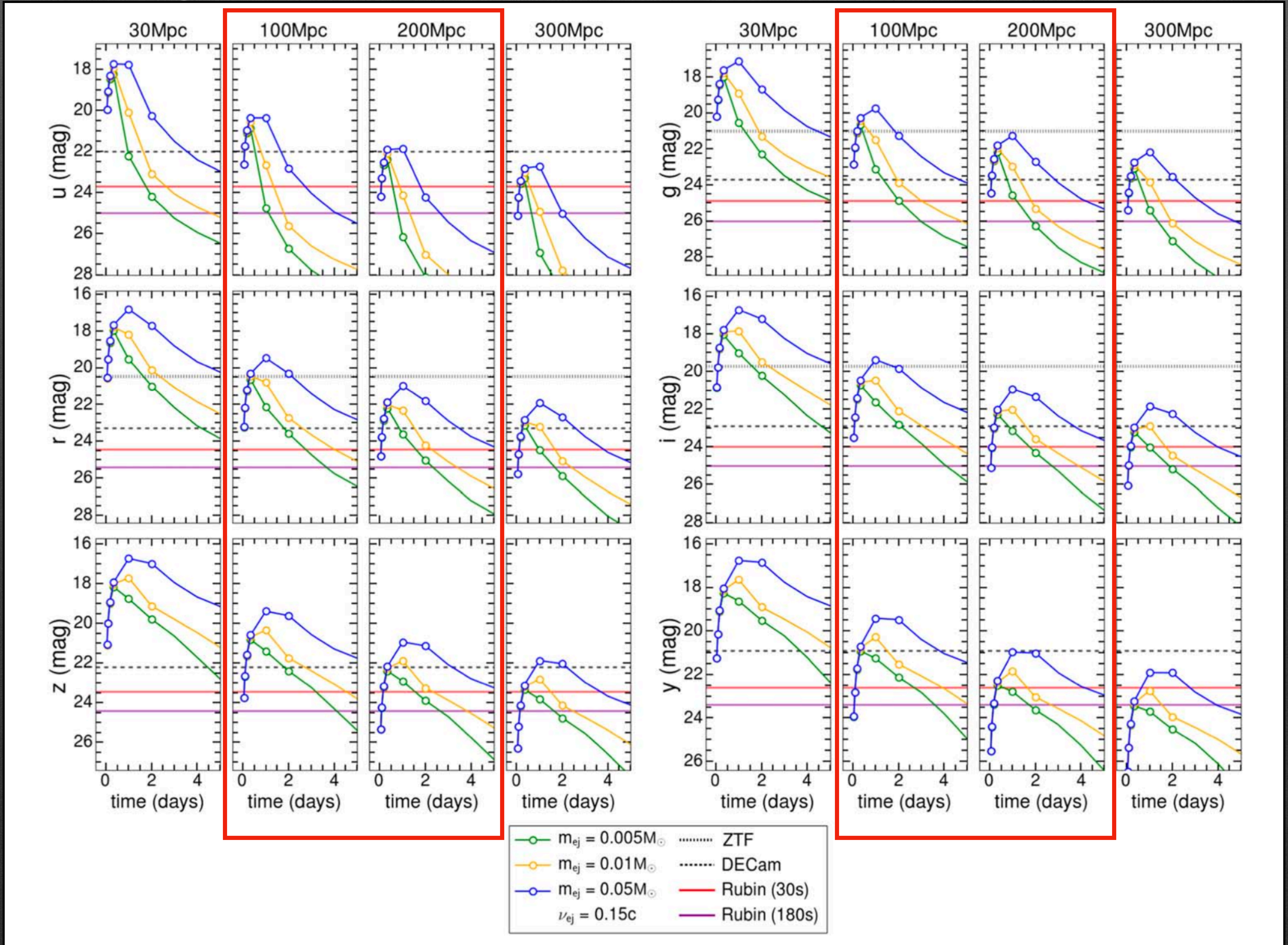
Where do we stand…



Fong+22

Where do we stand...

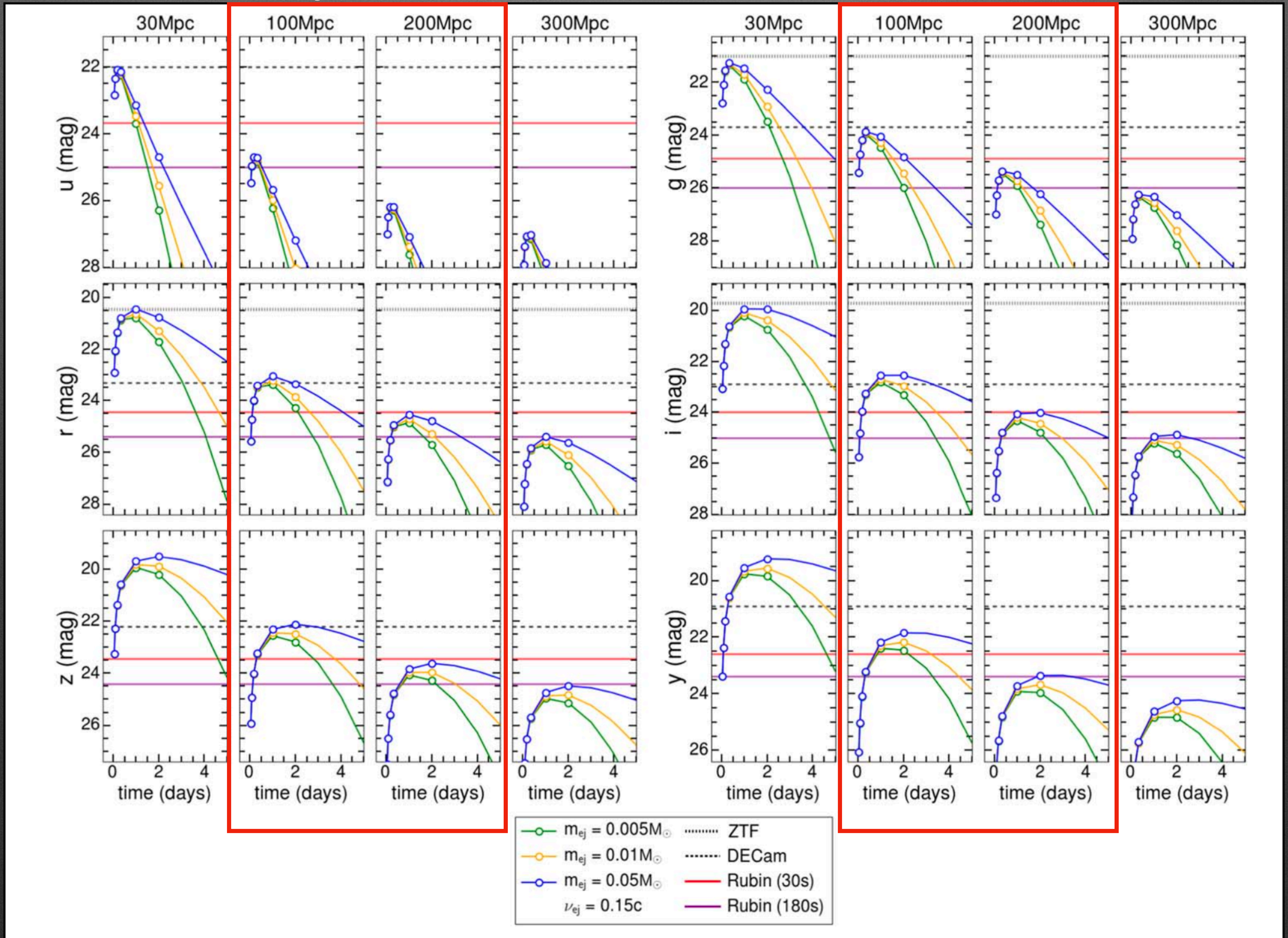
Kilonova light-curves in different optical bands: blue + red component



Andreoni, RM+2022

Where do we stand...

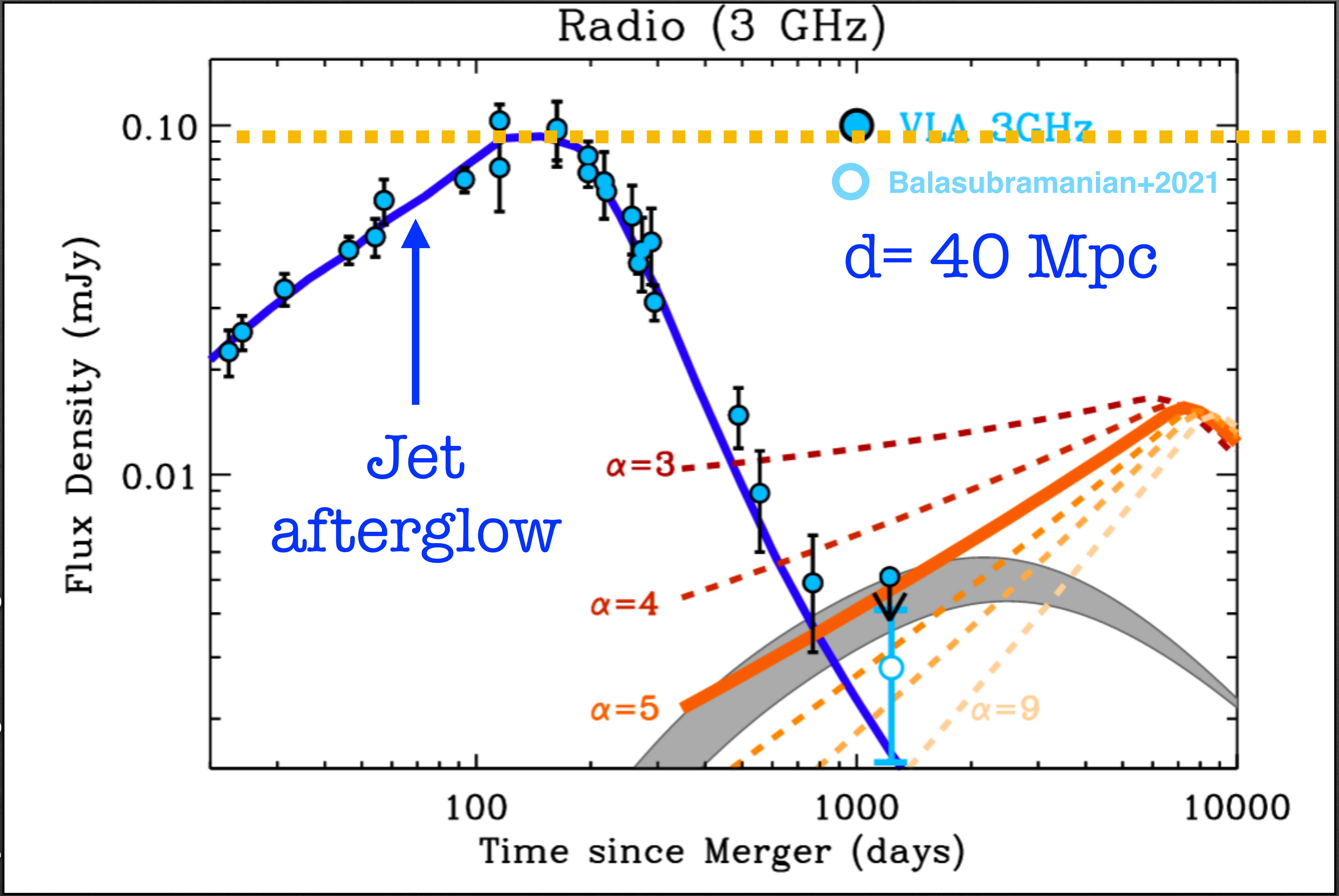
Red kilonova only —> FAINTER!!!



Andreoni, RM+2022

Where do we stand…

The RADIO afterglow of the off-axis jet of GW170817



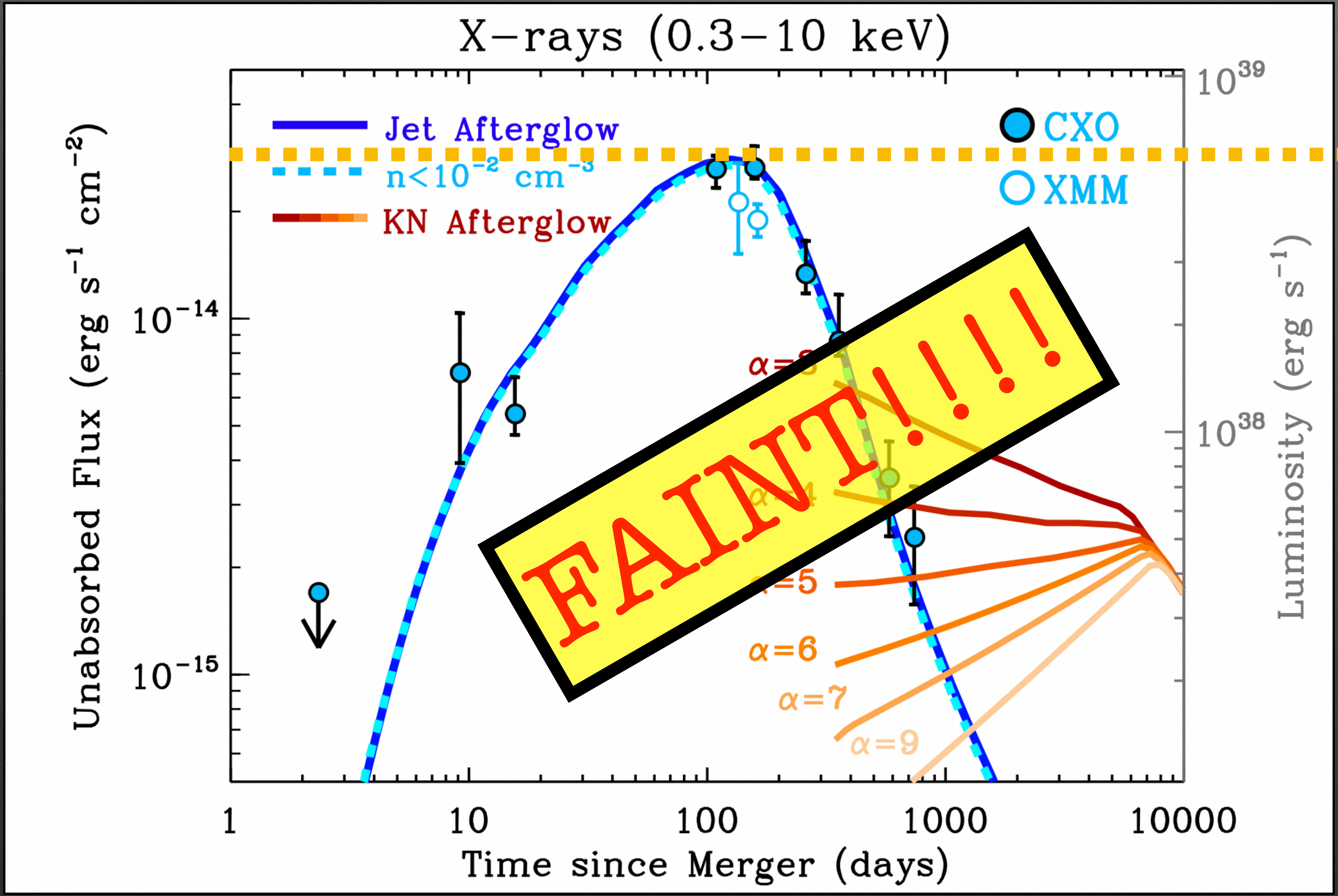
Factor ~3ish in max distance (i.e. d~150 Mpc) to detect this source with VLA
(1) at peak
(2) IF we know where to point

Hajela, Margutti, Bright et al., 2021

Models by: Kathirgamaraju+2019; Nedora+2021

Where do we stand…

The X-RAY afterglow of the off-axis jet of GW170817



Factor ~3ish in max distance (i.e. d~150 Mpc) to detect this source with Chandra
(1) at peak
(2) IF we know where to point

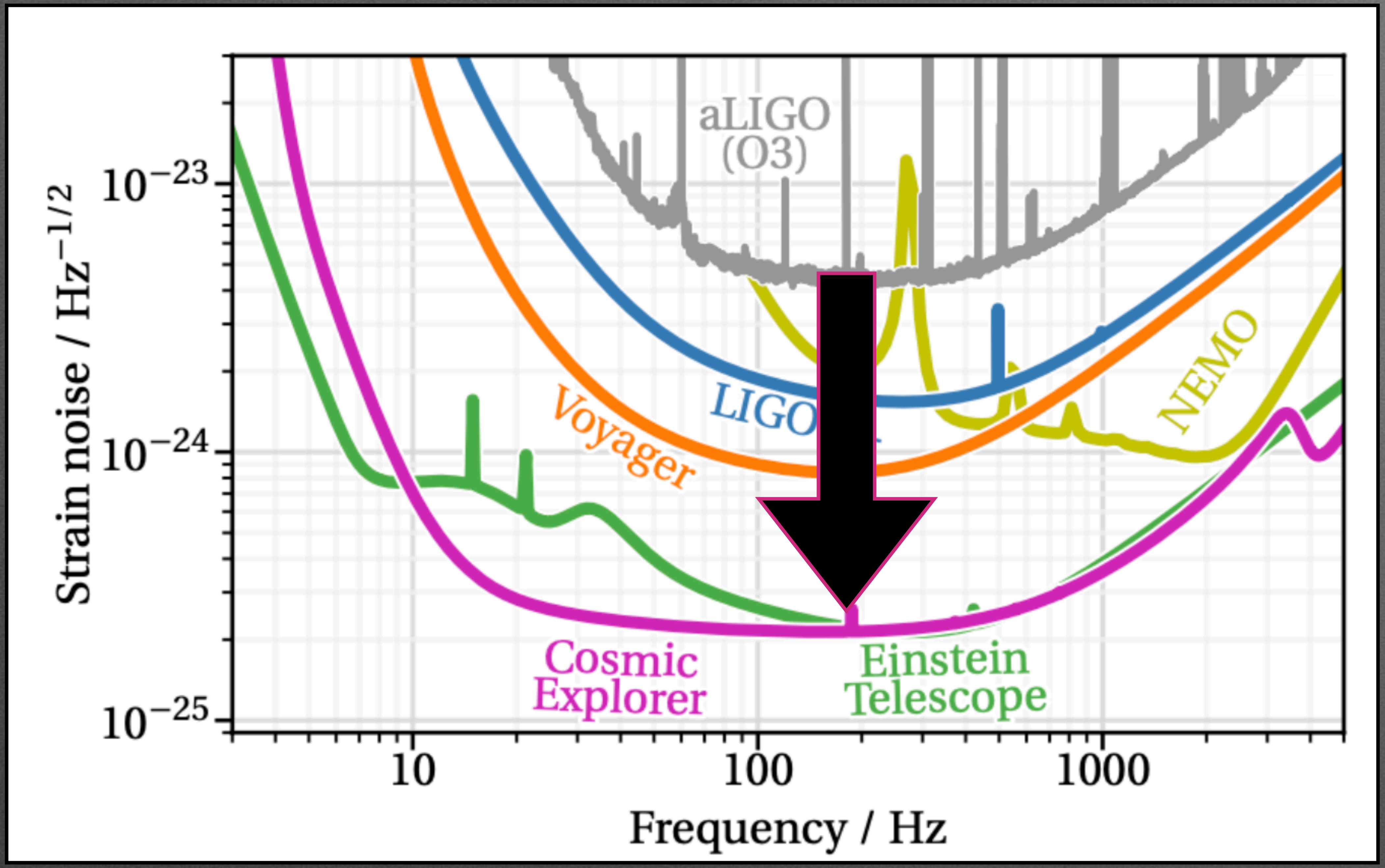
KN Models by: Kathirgamaraju+2019

Hajela, Margutti, et al., 2019

Current mismatch between GW and EM sensitivities + intrinsically different scaling of of the signal with distance

The Way Forward...

Next-Gen GW observatories



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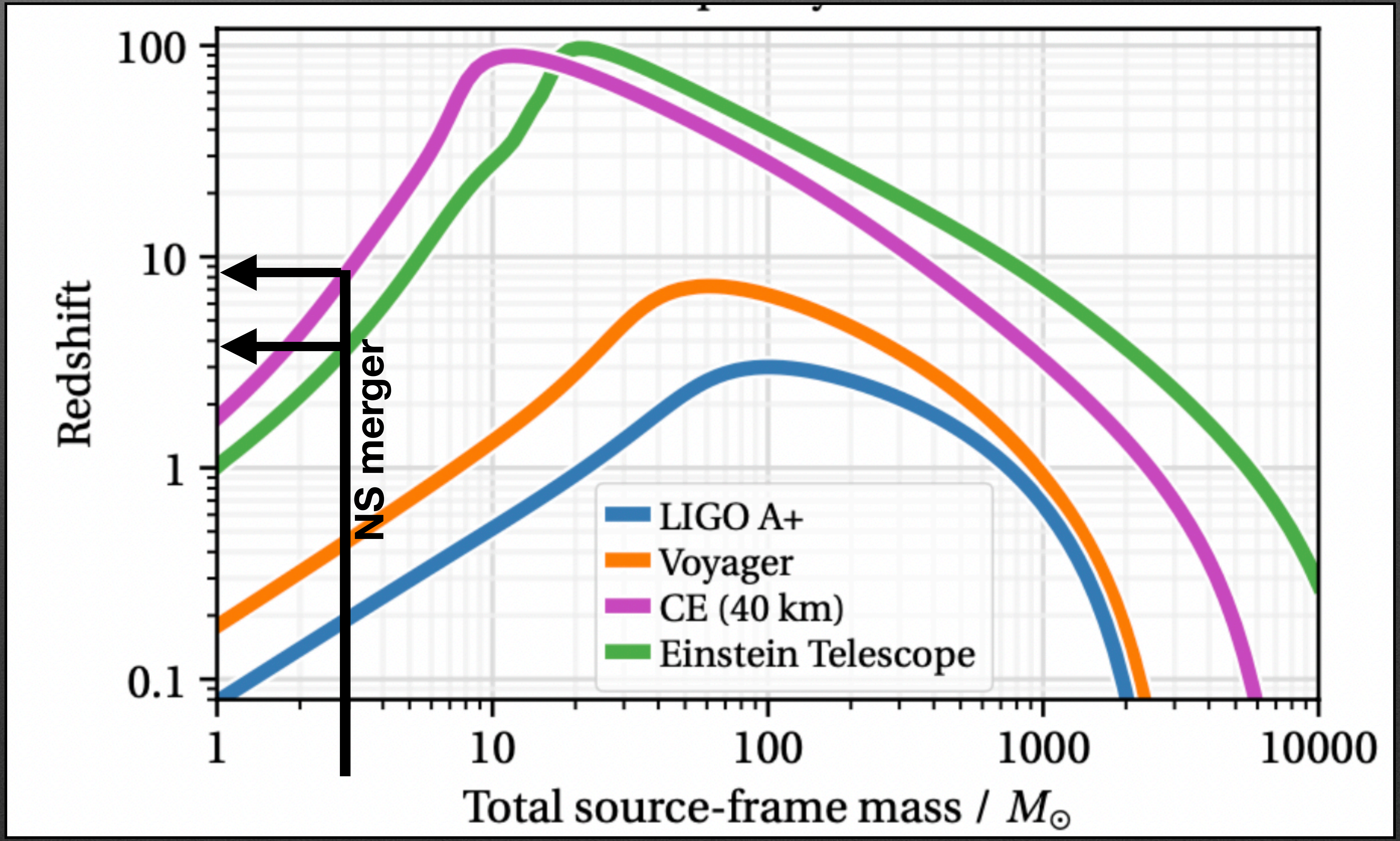


The Way Forward...

Next-Gen GW observatories

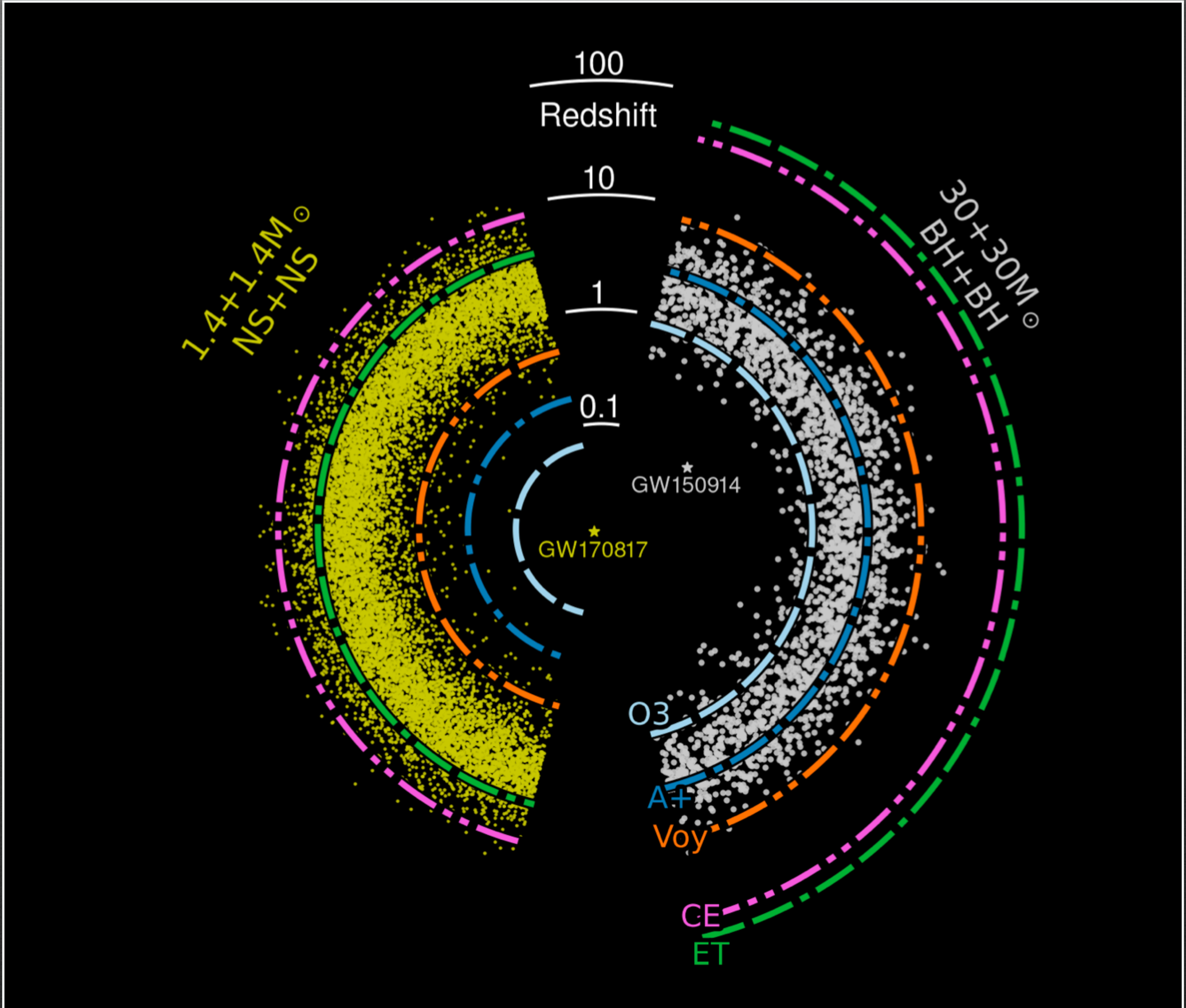
Sensitive to BNS mergers at z>>1 (potentially up to z of 10)

—> We will have a GW counterpart to SGRBs detected with gamma-rays (that we can already localize with EM)

—> We will be able to associate jet properties to pre-merger binary properties

Significantly improved localizations of louder events
(CE: 20/yr localized to within 0.1 deg2)

—> Significantly improvement on chances of identifying the EM counterpart
(which is key to any MMA endeavor)



Evans+2021, “A horizon study for CE”

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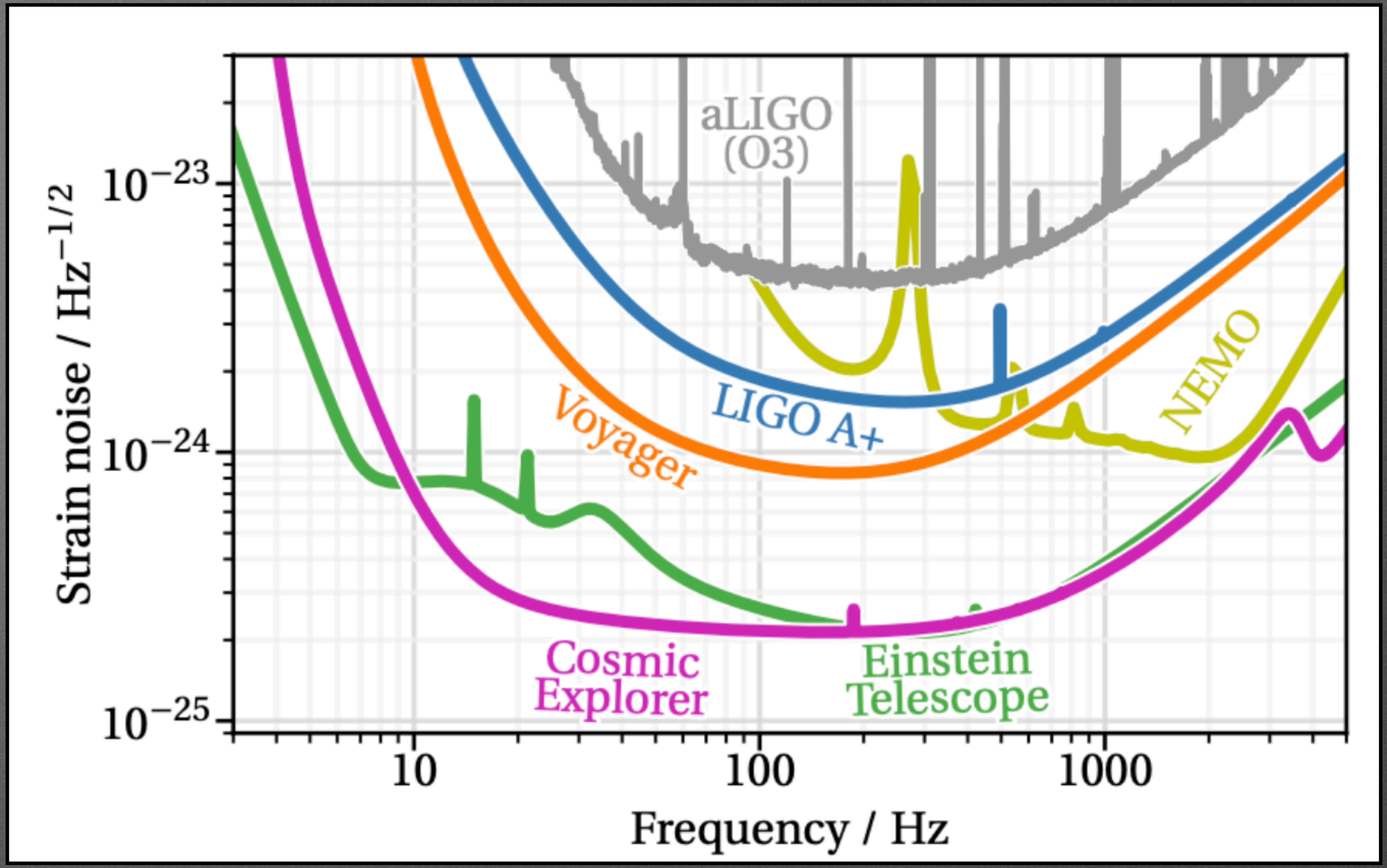


Evans+2021, "A horizon study for CE"

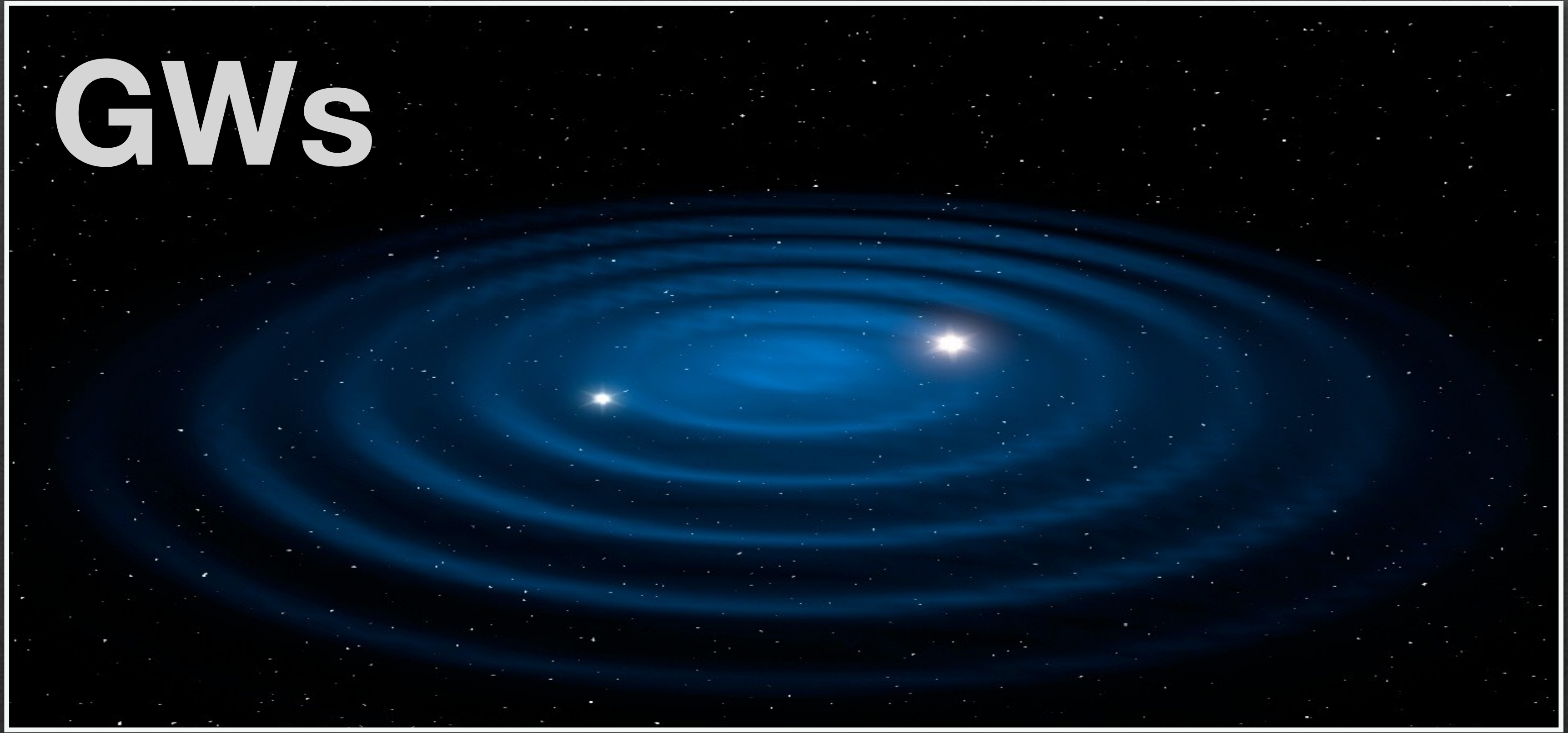
Sensitive to the post-merger GW emission

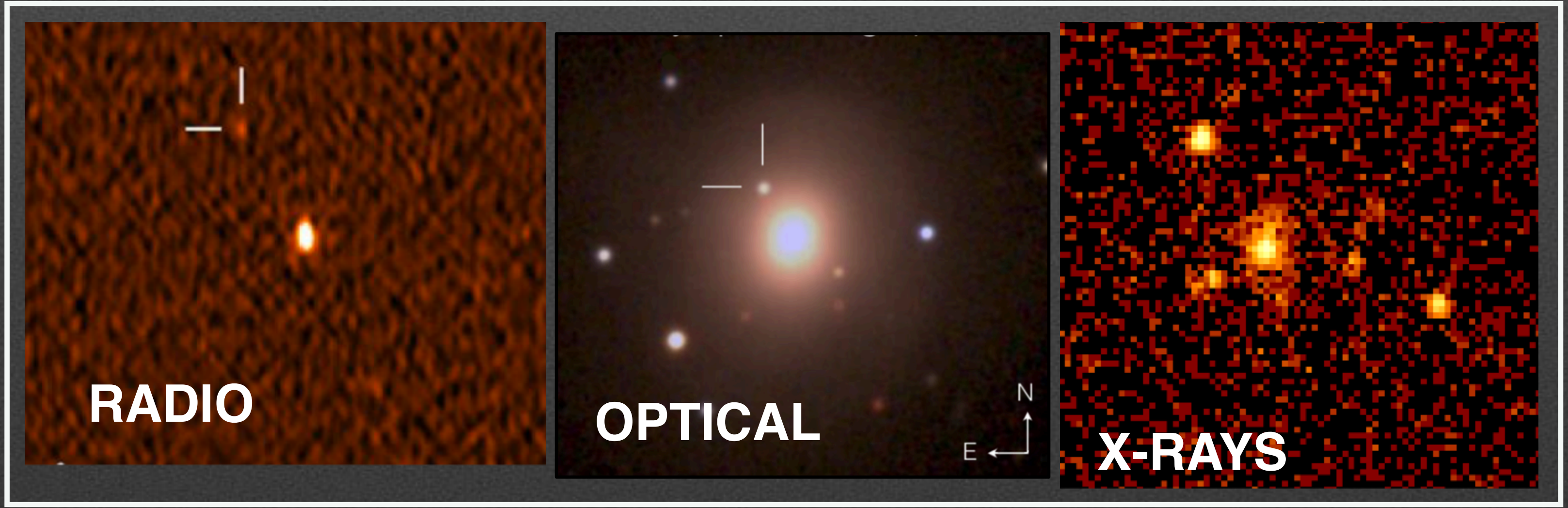
—> Direct constraints on the post-merger remnant

Next-Gen GW Observatories

An End-to-End experiment

(Full realization of the promises of MMA w. GW)





Pre-merger properties and physical conditions ⟷ Properties of merger outflows ⟷ Nature/properties of the Remnant Compact object

Need for rapid scheduling and re-pointing capabilities on ALL electromagnetic facilities

i.e. ToOs and DDTs

Note: Adoption of ToOs by Rubin became official in Feb 2023, see here: PSTN-055 https://pstn-055.lsst.io/

Rubin SCOC endorsed the strategy (07/2024):
https://lssttooworkshop.github.io/images/Rubin_2024_ToO_workshop_final_report.pdf

(This is not)

....The End...

"What we call the beginning is often the end. And to make an end is to make a beginning. The end is where we start from."

T. S. Eliot

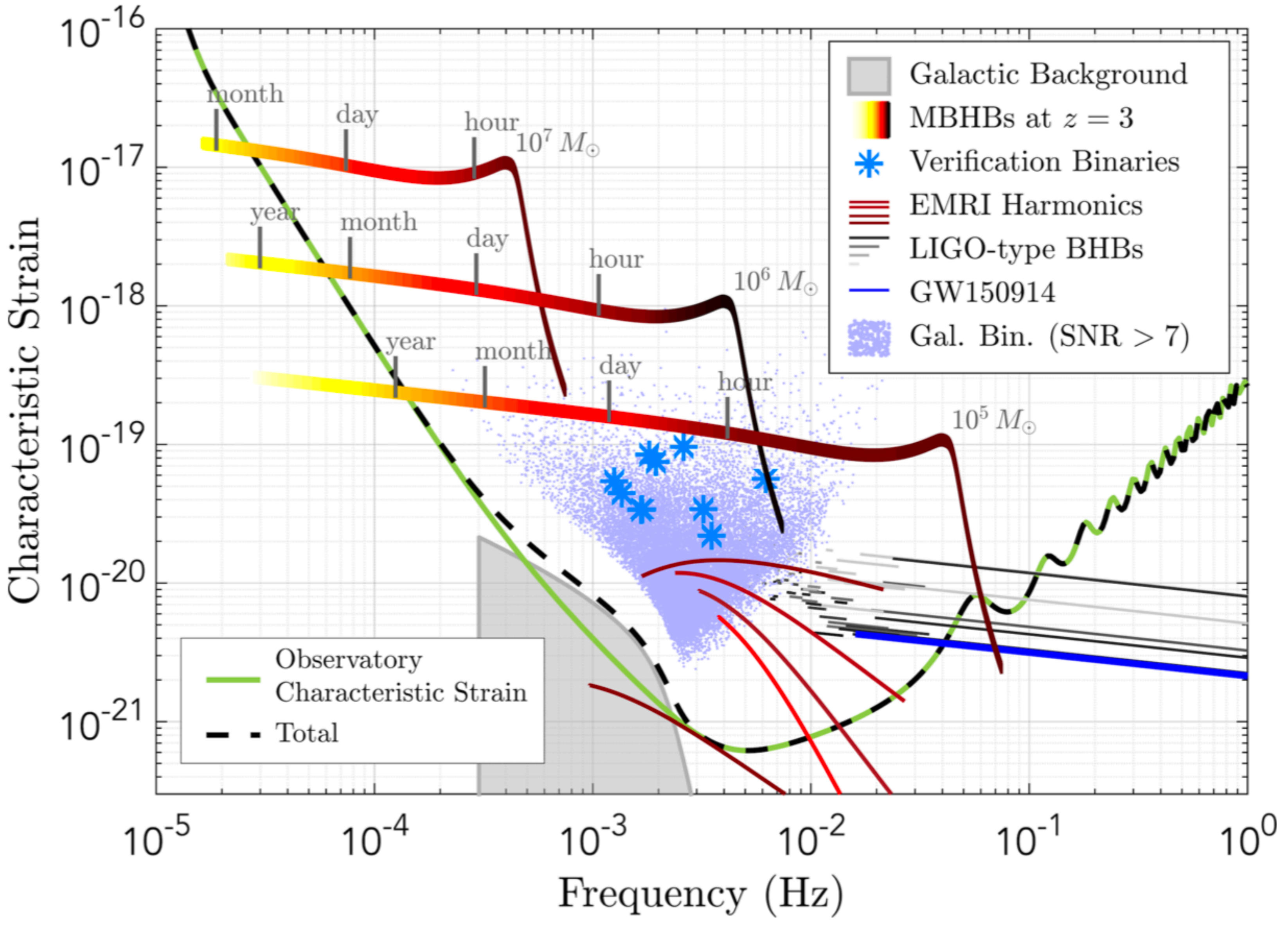
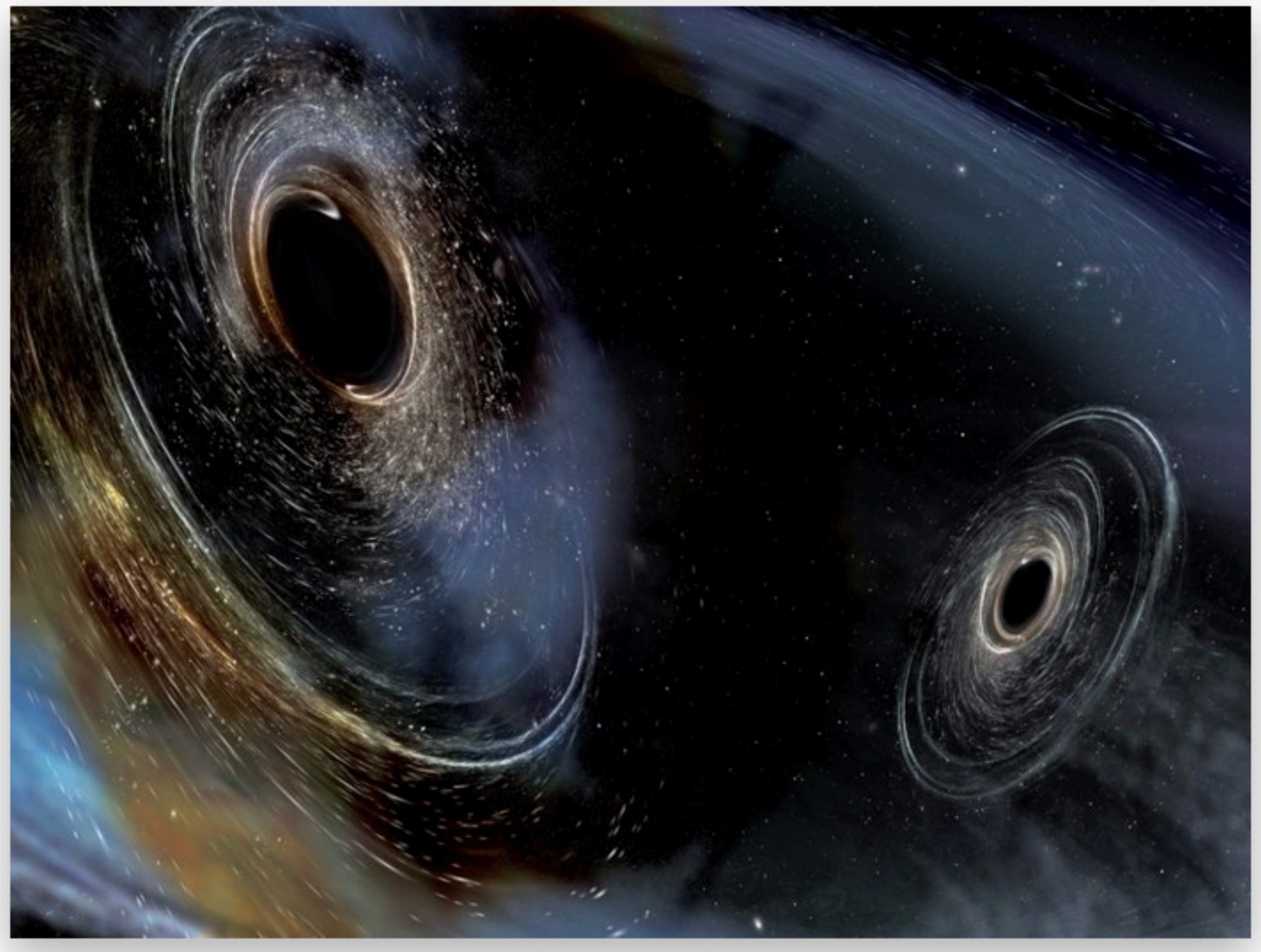


Figure 1: Representative examples of LISA sources compared with the instrument sensitivity. Sources and instrument sensitivity are plotted as frequency spectra of characteristic GW strain. All sources are observed simultaneously and individually extracted through a global fit of the LISA time-series data. *Figure 1 from [13]*.

Cosmic Explorer

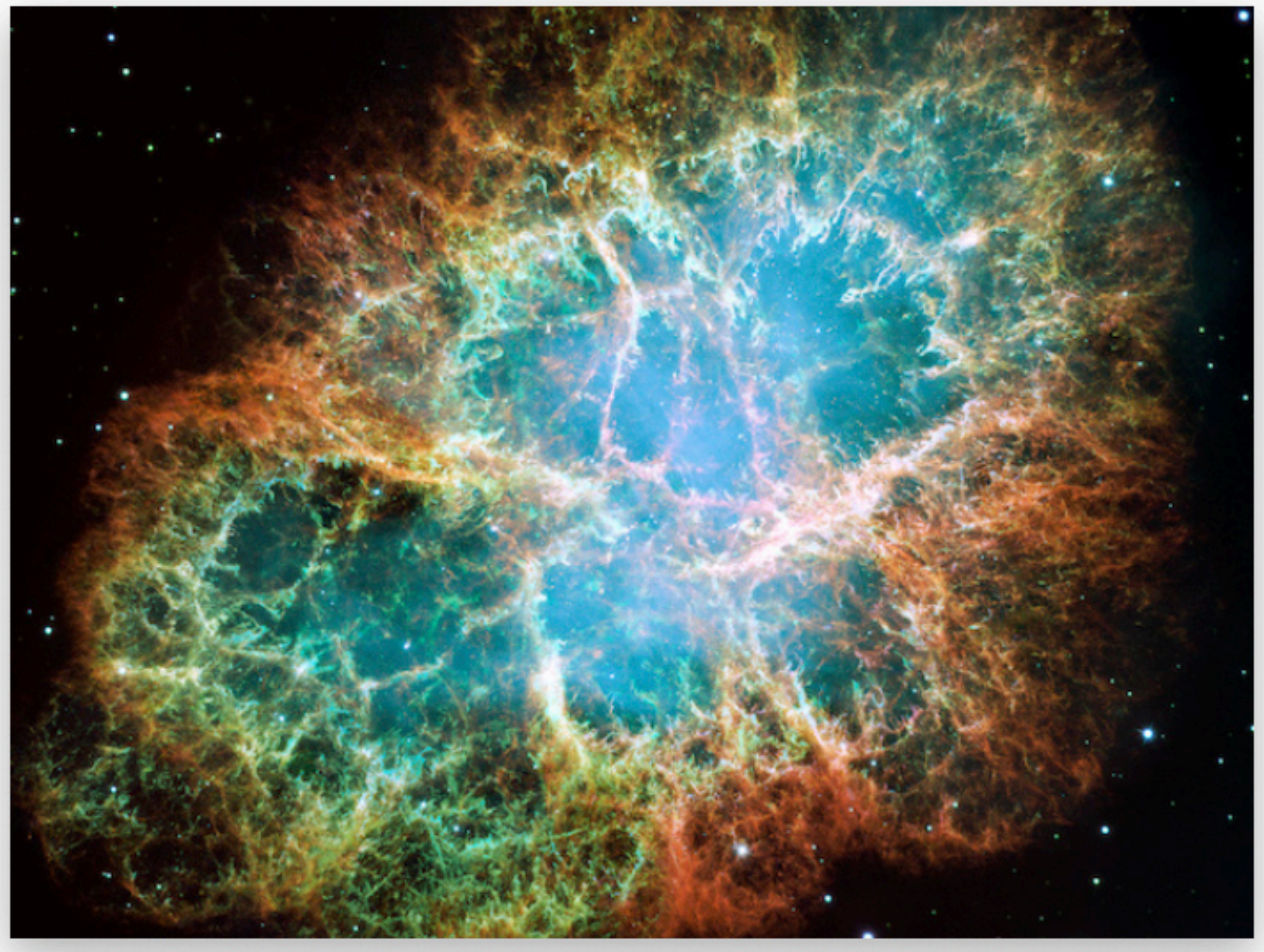
Cosmic Explorer's 40 km arms (20 km for the second site), 10 (5) times longer than Advanced LIGO's, will increase the amplitude of the observed signals with effectively no increase in the noise. Although there are areas of detector technology where improvements will lead to increases in the sensitivity and bandwidth of the instruments, the dominant improvement will come from significantly increasing the arm lengthCosmic Explorer's 40 km arms (20 km for the second site), 10 (5) times longer than Advanced LIGO's, will increase the amplitude of the observed signals with effectively no increase in the noise. Although there are areas of detector technology where improvements will lead to increases in the sensitivity and bandwidth of the instruments, the dominant improvement will come from significantly increasing the arm length. Planned one order of mag improvement vs. aLIGO. Cosmic Explorer might see other spectacular sources, the detection of any one of which would be revolutionary. Examples include the core collapse of a massive star in the Milky Way or Magellanic Clouds, emissions from mountains or quakes in pulsars, and glitches in magnetars in our galaxy. Cosmic Explorer might also see gravitational waves from forms of dark and exotic matter around black holes or in the cores of neutron stars, the mergers of primordial black holes formed in the early universe, or gravitational-wave emission from cosmic (super)strings. ~10x sensitivity of aLIGO, will push to z=100 the search for compact binary mergers. Larger sensitivity is mostly a consequence of the increased arm length (which is also what drives the cost of the facility!)

From CE website



Seeing Black Holes Merge throughout Cosmic Time

Investigating the Densest Matter in the Universe



Exploring the Gravitational Wave Frontier

LISA **Eistein Telescope**

EM facilities are already outpaced (usual thing about the horizon: use GW170817 as an example) for off-axis events.
The opposite is true for on-axis events

Broader impact: **does it imply a new way to do science?** i.e. gigantic collaborations
Astro2020 white paper: https://arxiv.org/abs/1907.06970 : A major goal for the astronomy and astrophysics communities is the pursuit of diversity, equity, and inclusion (DEI) in all ranks, from students through professional scientific researchers. Large scientific collaborations - increasingly a primary place for both professional interactions and research opportunities - can play an important role in the DEI effort. Multimessenger astronomy, a new and growing field, is based on the principle that working collaboratively produces synergies, enabling advances that would not be possible without cooperation. The nascent Multimessenger Diversity Network (MDN) is extending this collaborative approach to include DEI initiatives. After we review of the current state of DEI in astronomy and astrophysics, we describe the strategies the MDN is developing and disseminating to support and increase DEI in the fields over the coming decade: provide opportunities (real and virtual) to share DEI knowledge and resources, include DEI in collaboration-level activities, including external reviews, and develop and implement ways to recognize the DEI work of collaboration members.

Discovery in Astro results from
Exploration of new parts of the parameter space
NEW PARTS = sensitivity that enables depth never reached before (seeing far away, or the weakest signals), or enable better precision measurements, OR new parts as a whole [like GWs in addition to EM]

Promise==> see GWs across the history of the Universe

Black Holes and Neutron Stars Throughout Cosmic Time. Understanding how the universe made the first black holes, and how these first black holes grew, is one of the most important unsolved problems in astrophysics. Cosmic Explorer will detect gravitational waves from binary black holes and neutron stars out to the edge of the visible universe, providing a view of Cosmic Dawn complementary to that of the James Webb Space Telescope. Cosmic Explorer will see evidence for the first stars by detecting the mergers of the black holes they leave behind. The millions of mergers detected by Cosmic Explorer will map the population of compact objects across time, detect mergers of the first black holes that contributed to seeding the universe's structure, explore the physics of massive stars, and reveal the processes that create black holes and neutron stars

Dynamics of Dense Matter. While a quantitative theory of nuclei, neutron-rich matter and deconfined quark matter has begun to emerge, understanding the nature of strongly interacting matter is an unsolved problem in physics. By observing many hundreds of loud neutron star mergers and measuring the stars' radii to 100 m or better, Cosmic Explorer will probe the phase structure of quantum chromodynamics, revealing the nuclear equation of state and its phase transitions. Cosmic Explorer's ability to detect and study the hot, dense remnants of neutron star mergers will provide an entirely new way of mapping out the dense, finite-temperature region of the quantum chromodynamics phase space, a region that is currently unexplored. A plethora of multimessenger observations will map heavy-element nucleosynthesis, explain the build-up of the chemical elements that are the building blocks of our world, and explore the physics of the binary-merger engine powering short gamma-ray bursts.

This Horizon Study includes a preliminary study (summarized in Table 1.1) that shows that although the reference concept can achieve Cosmic Explorer's science goals without other next- generation gravitational-wave detectors, its scientific output is enhanced when operating as part of an **international network.**

Post-merger signatures of BNS is another beautiful venue

Formation and evolution of the first compact objects

BHs from the first stars

Chemical evolution of the Universe

GRB jet engine: we can associate jets to GW signals in the distant Universe (right now we can't): we can either detect many jets at large distances from which we do not see GWs, or we can see GWs out to large distances where we cannot see sources unless they are pointing at us!!!

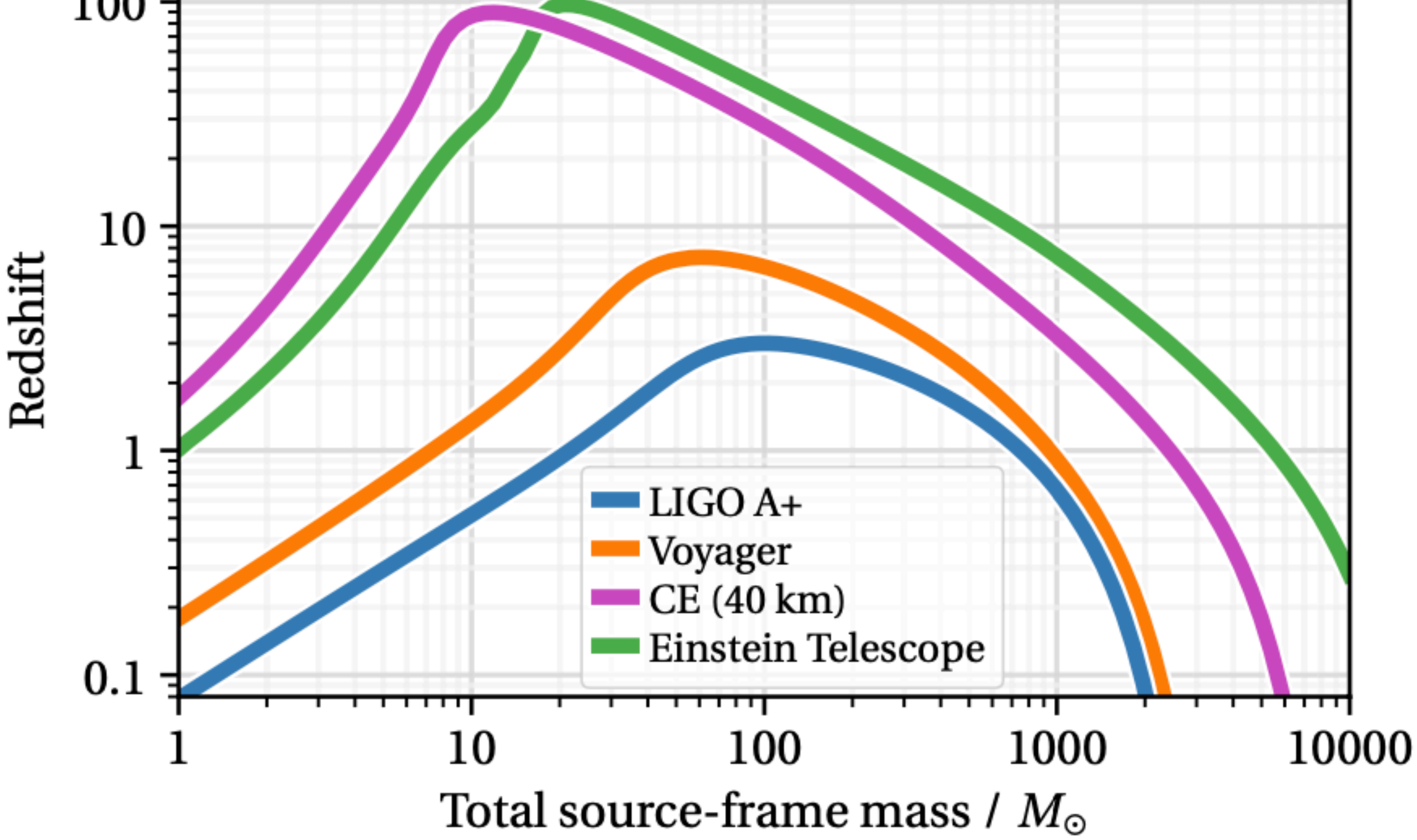


Figure 3.3: *Top:* Amplitude spectral densities of detector noise for Cosmic Explorer (CE), the current (O3) and upgraded (A+) sensitivities of Advanced LIGO, LIGO Voyager, NEMO, and the three paired detectors of the triangular Einstein Telescope (see §4 for observatory descriptions). At each frequency the noise is referred to the strain produced by a source with optimal orientation and polarization. *Bottom:* Maximum redshift (vertical axis) at which an equal-mass binary of given source-frame total mass (horizontal axis) can be observed with a signal-to-noise ratio of 8.[11] Different curves represent different detectors. For binary neutron stars (total mass $\sim 3M_\odot$), CE will give access to redshifts larger than 1, where most of the mergers are expected to happen. For binary black holes, it will enable the exploration of redshifts of 10 and above, where mergers of black holes formed by either the first stellar population in the universe (Pop III stars) or by quantum fluctuations shortly after the Big Bang (primordial black holes) might be found.

Focus on NS bearing binaries:
(1) detecting many more (2) detecting the post-merger GW

But of course nature can surprise us and we might be seeing BH-BH mergers with light

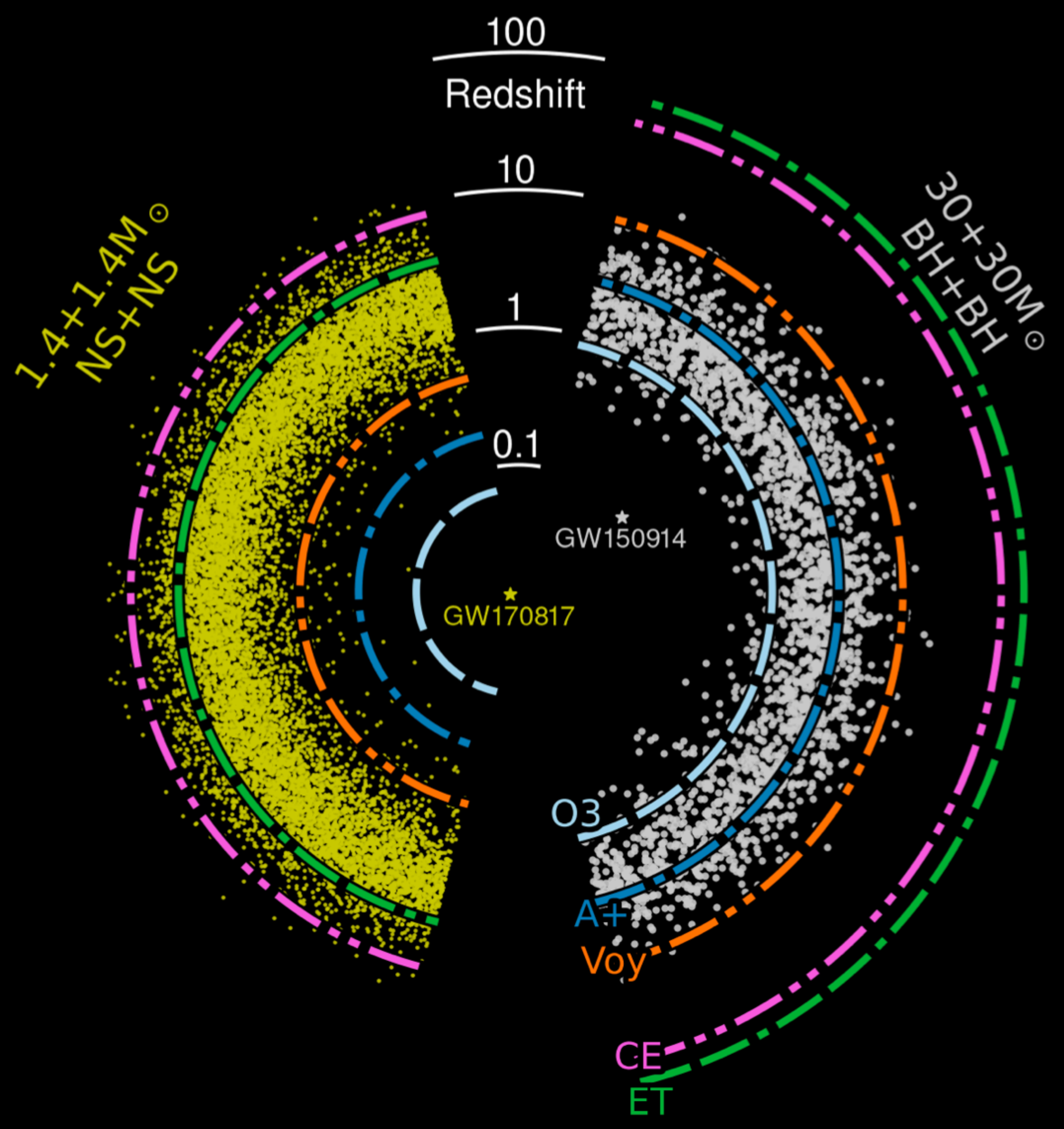


Figure 3.4: Astrophysical horizon of current and proposed future detectors for compact binary systems. As in the bottom of Fig. 3.3, the lines indicate the maximum redshift at which a detection with signal-to-noise ratio 8 could be made. The detectors shown here are Advanced LIGO during its third observing run ("O3"), Advanced LIGO at its anticipated sensitivity for the fifth observing run ("A+"), a possible cryogenic upgrade of LIGO called Voyager ("Voy"), the Einstein Telescope ("ET"), and Cosmic Explorer ("CE", see §4 for observatory descriptions). The yellow and white dots are for a simulated population of binary neutron star mergers and binary black hole mergers, respectively, following Madau and Dickinson [12]

The discovery of GW190425,[96] a binary neutron star system much heavier than known systems in our galaxy suggests that the astro- physical properties of neutron stars might be more diverse than what has been observed in the Milky Way. Next-generation observatories will provide access to neutron star binaries all the way to redshift ~10, and give us a clear picture of how their parameters vary across cosmic history and galactic environments.

Cosmic Explorer will detect ~10^5 binary neutron star mergers per year out to a redshift of 4, of which ~10 are expected to have signal-to-noise ratios above 300. Cosmic Explorer could also detect signals from the 3000 known neutron stars in our Galaxy. The dense-matter science these

After a binary neutron star merges, oscillations of the hot, extremely dense remnant produce postmerger gravitational radiation. This heretofore undetected signal probes the unexplored high-density, finite-temperature region of the quantum chromodynamic phase diagram. As indicated in Fig. 5.1, this region is inaccessible to collider experiments and difficult to observe directly with electromagnetic astronomy. This is where novel forms of matter are most likely to appear.[129–132] Cosmic Explorer is well-suited to observing postmerger gravitational waves:[133–135] it is expected to detect ~100 postmerger signals every year in a 3G network.

Measurements of the dominant postmerger gravitational-wave frequency[136–144] will reveal dense-matter dynamics with finite temperature,[145] rapid rotation[146] and strong magnetic fields.[147] These observations will shape theoretical models describing fundamental many-body nuclear interactions and answer questions about the composition of matter at its most extreme, such as whether quark matter is realized at high densities.[132,148,149] Direct gravitational-wave observations of postmerger remnants will also help determine the threshold mass for collapse of a rotationally supported neutron star,[140,150–153] which has implications for the neutron-star mass distribution,[154] compact binary formation scenarios[155] and predictions for electromagnetic emission from neutron star mergers.[156]

What we learned from GW170817 (heavy element production, BNS mergers produce SGRBs+ all the firsts)

Where is the discovery frontier now
Population studies
Mapping the pre-merger to post-merger
Are BNS the sole site of heavy element production
Do all NS merger launch a jet?
Pre-merger properties to jet properties
Do NS-BH produce SGRBs?
What are the current limitations (1/d business + we do not know what we produce + localizations are big issues)

How CE will solve the issues

End with note on exotic binaries

Cosmic Explorer will localize ~20 binary neutron star mergers in the nearby universe to within ~0.1 deg.^{2} every year.

This will enable localization, then HG identification, study of the environmental properties

Synergy with ELTs, Roman, JWST. Cosmic Explorer will also record essentially all neutron star mergers out to redshift 1.

A third-generation gravitational-wave detector network will measure the inclination angle of each jet, providing a comprehensive view of jet structures,[190–193] the time delay between merger and prompt emission,[194,195] and the nature of afterglow emission.[191] Gravitational-wave information will also distinguish binary neutron star from neutron-star black-hole coalescences, revealing possible phenomenological differences in their gamma-ray emission

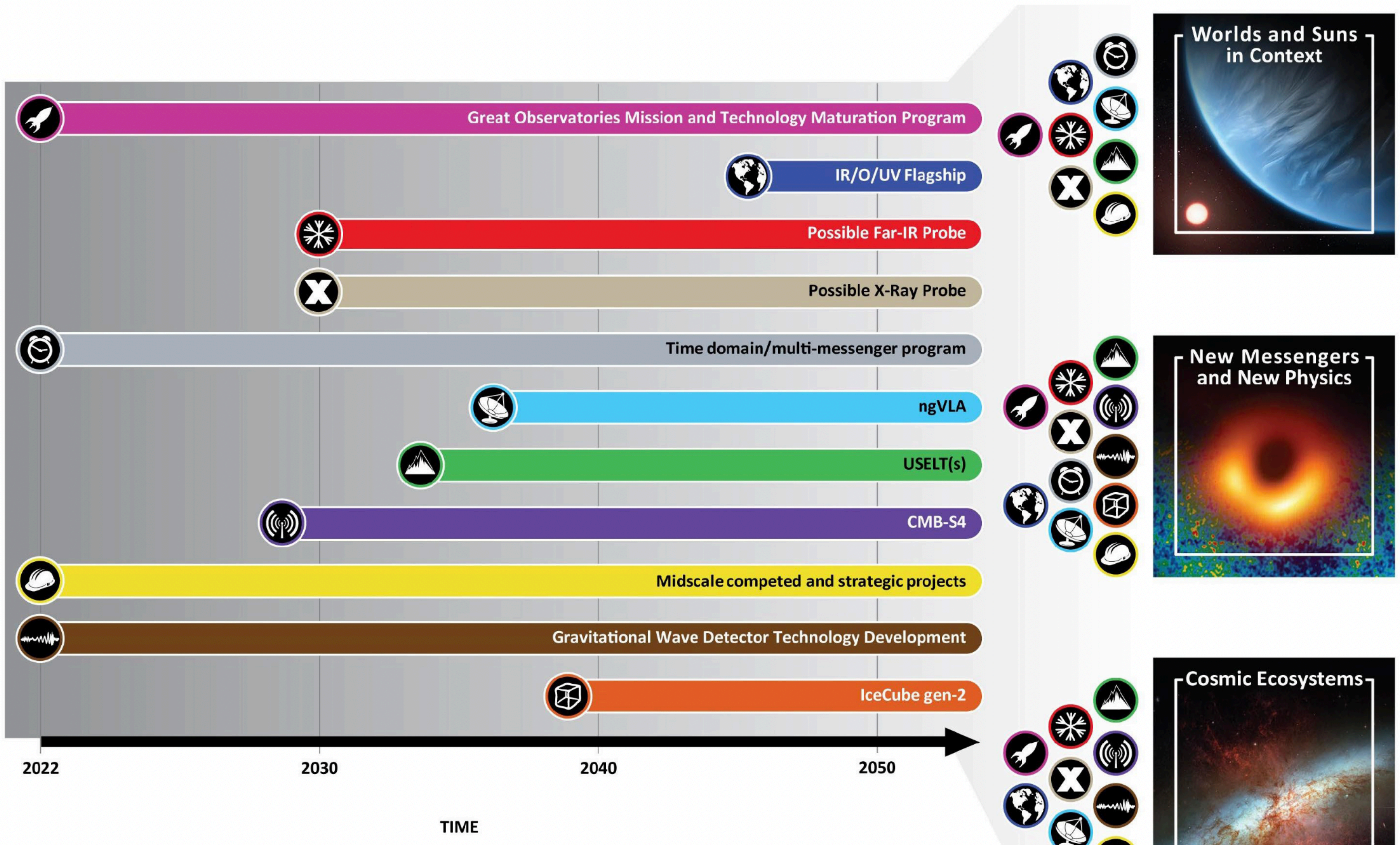
Exotic stuff

Cosmic Explorer's high-fidelity observations of stellar-mass coalescing objects, together with its cosmological reach, will present an excellent opportunity for exploring the nature of merg- ing compact objects. The large number of detected stellar-mass black-hole and neutron-star mergers will likely include uncommon mergers too rare for even upgraded detectors in the current observatories, such as black holes with extremal spin, the inspiral of a neutron star into an intermediate-mass black hole,[229,230] a binary black hole with enough surrounding matter to produce an electromagnetic counterpart,[87,231,232] or binaries with a supernova precursor.[233] Measuring the properties of these rare mergers could revolutionize our understanding of the nature of compact objects.

Historically, major discoveries in astronomy have been facilitated by three related improvements in detector technology: deeper sensitivity, new bands of observation and higher precision. Improved sensitivity helps sample larger volumes and provide more complete surveys, enabling the discovery of rare events that otherwise do not make the cut, e.g., Type Ia supernovae that eventually led to the discovery of the recent accelerated expansion of the universe. Opening

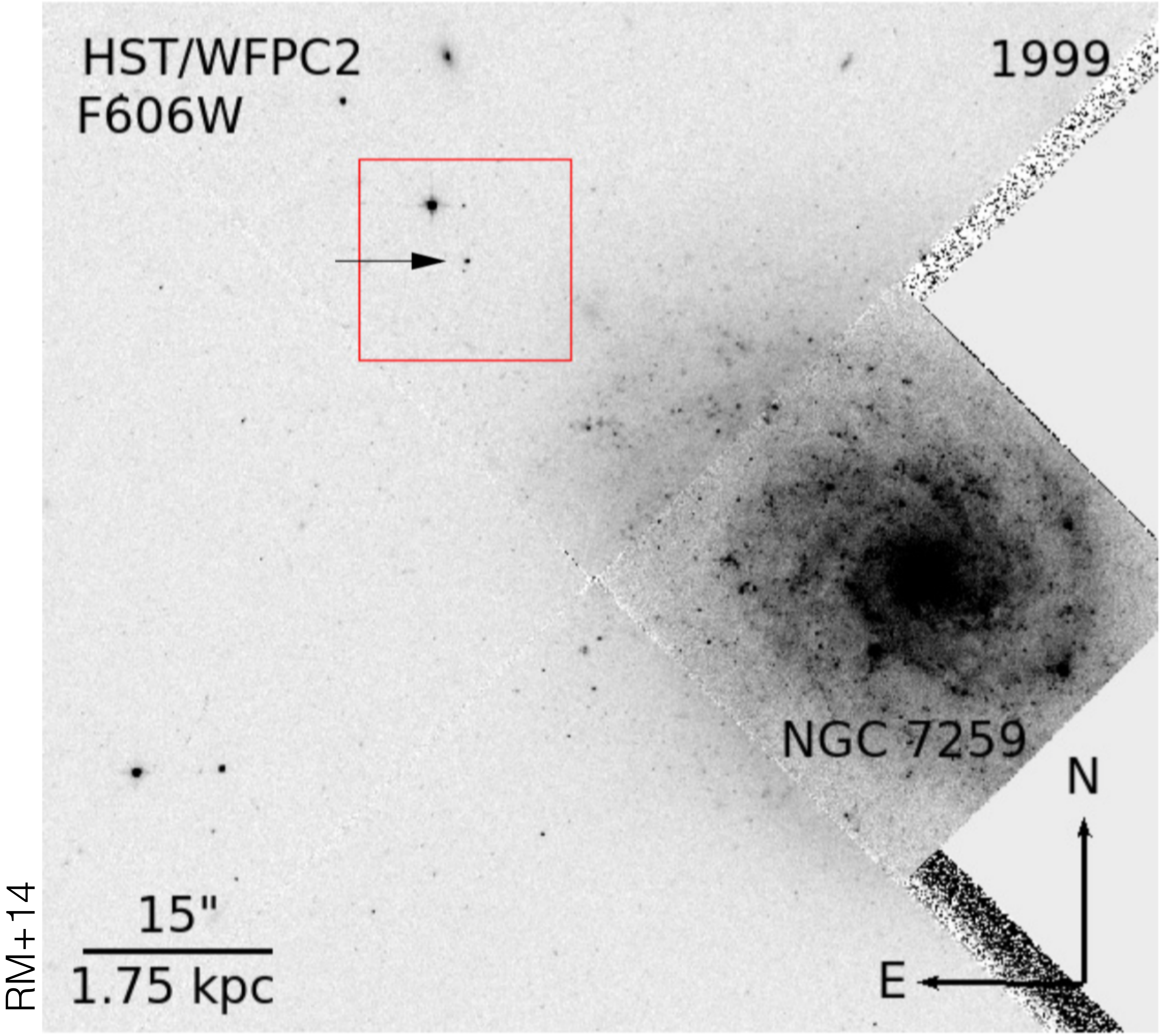
a new frequency window has been critical to identifying entirely new classes of sources — the cosmic microwave background, quasars and gamma-ray bursts are just the tip of the iceberg examples. Increased precision has often helped discover subtle physical effects or phenomena, e.g., the discrepancy in the Hubble constant inferred from Type Ia supernovae and the Planck mission.

From the decadal summary slides



nap.edu/astro2020

www.nap.edu/26141



Hubble pre-explosion image of SN2009ip

From our Fermi+VLA proposal submitted a few hrs ago:

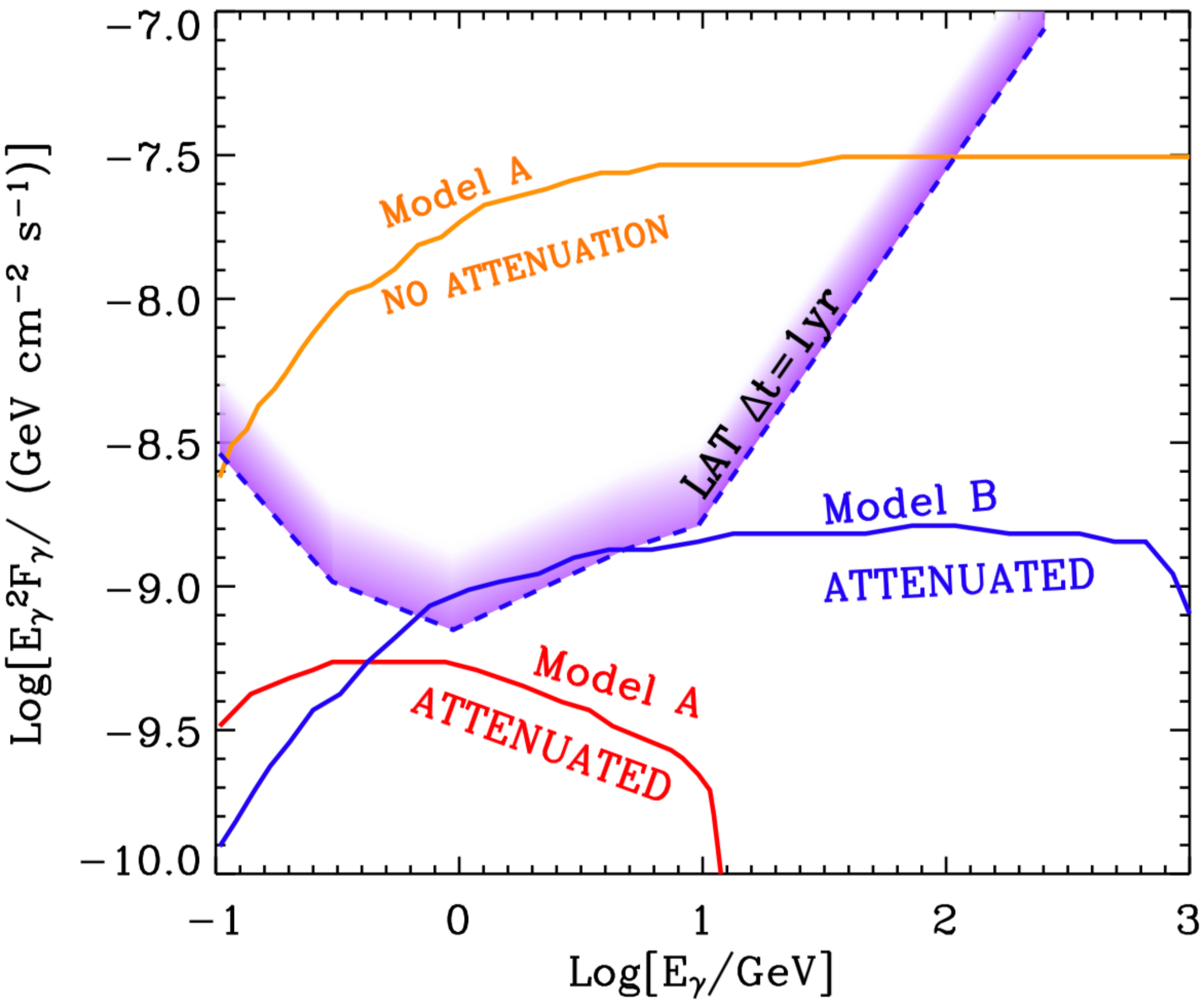


Figure 2: Predicted γ-ray flux from SN shocks running into a CSM shell with density n_{sh}=10^{11} cm^{-3} and radius R_{sh}=$10^{15.5}$ cm (model A) or n_{sh}=$10^{7.5}$ cm^{-3} and R_{sh}=$10^{16.5}$ cm (model B). In both cases $E_k = 10^{51}$ erg, d =10 Mpc and $\epsilon_{CR} = 10\%$. Model A is close to SLSNe like 2006gy [22], while model B is for normal SNe. For

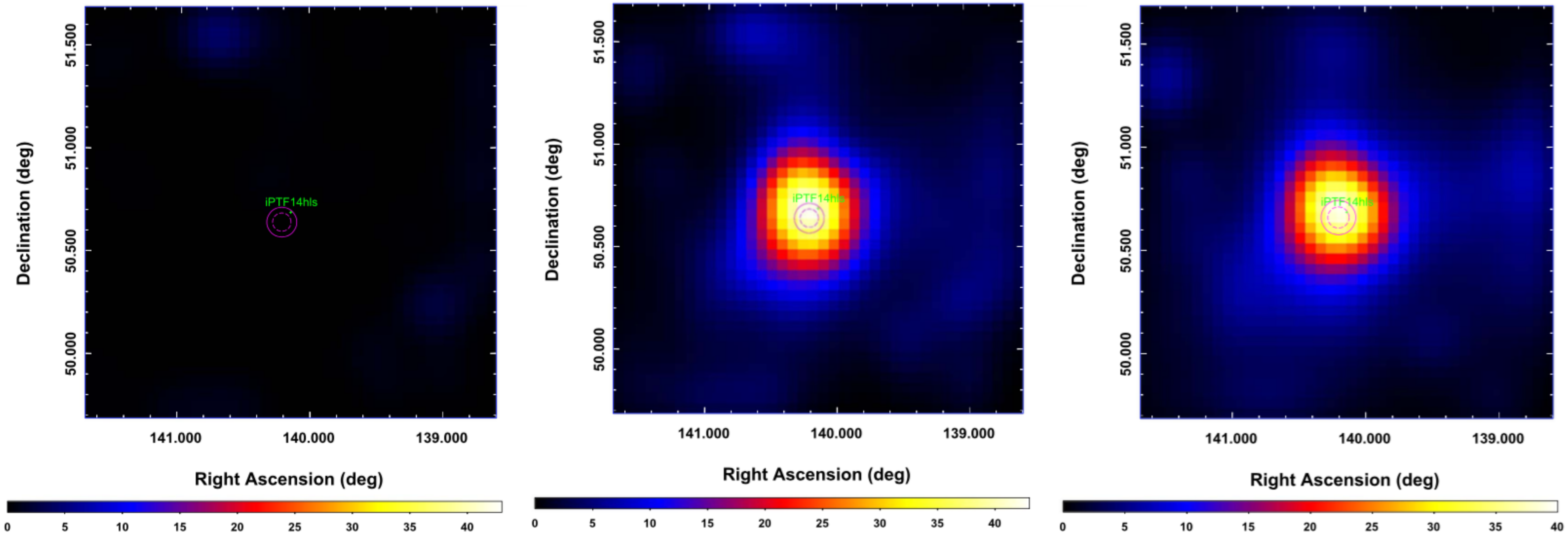
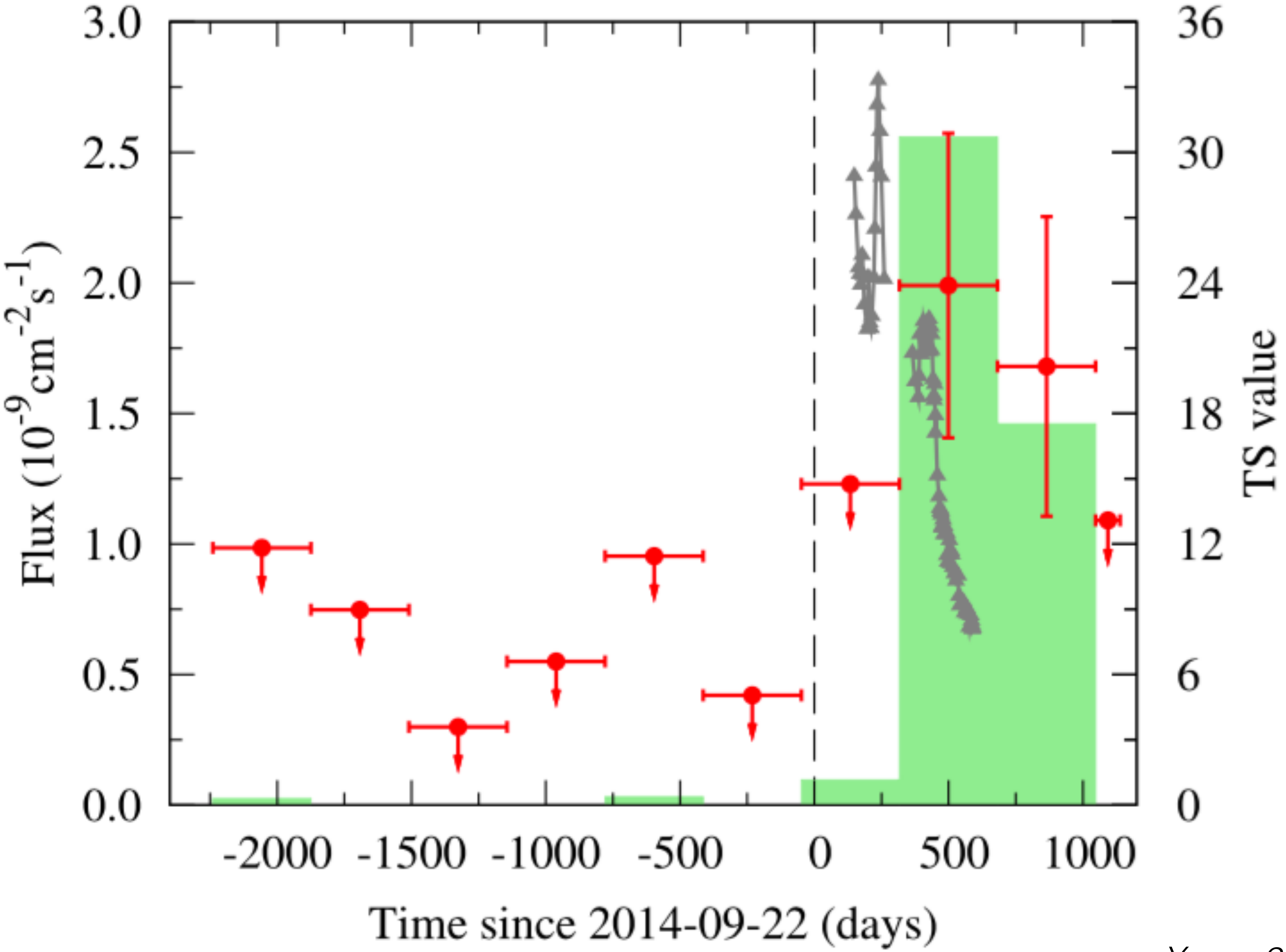


Figure 1. TS maps for a 2° × 2° region centered at iPTF14hls, for the *Fermi*-LAT data before (left) and after (middle) 2014 September 22. The right panel shows the TS map for the past two years of data. All the maps are smoothed with a Gaussian kernel with a width of 0°.2. Magenta circles in these plots show the 68% (inner) and 95% (outer) error regions of the γ-ray localization.

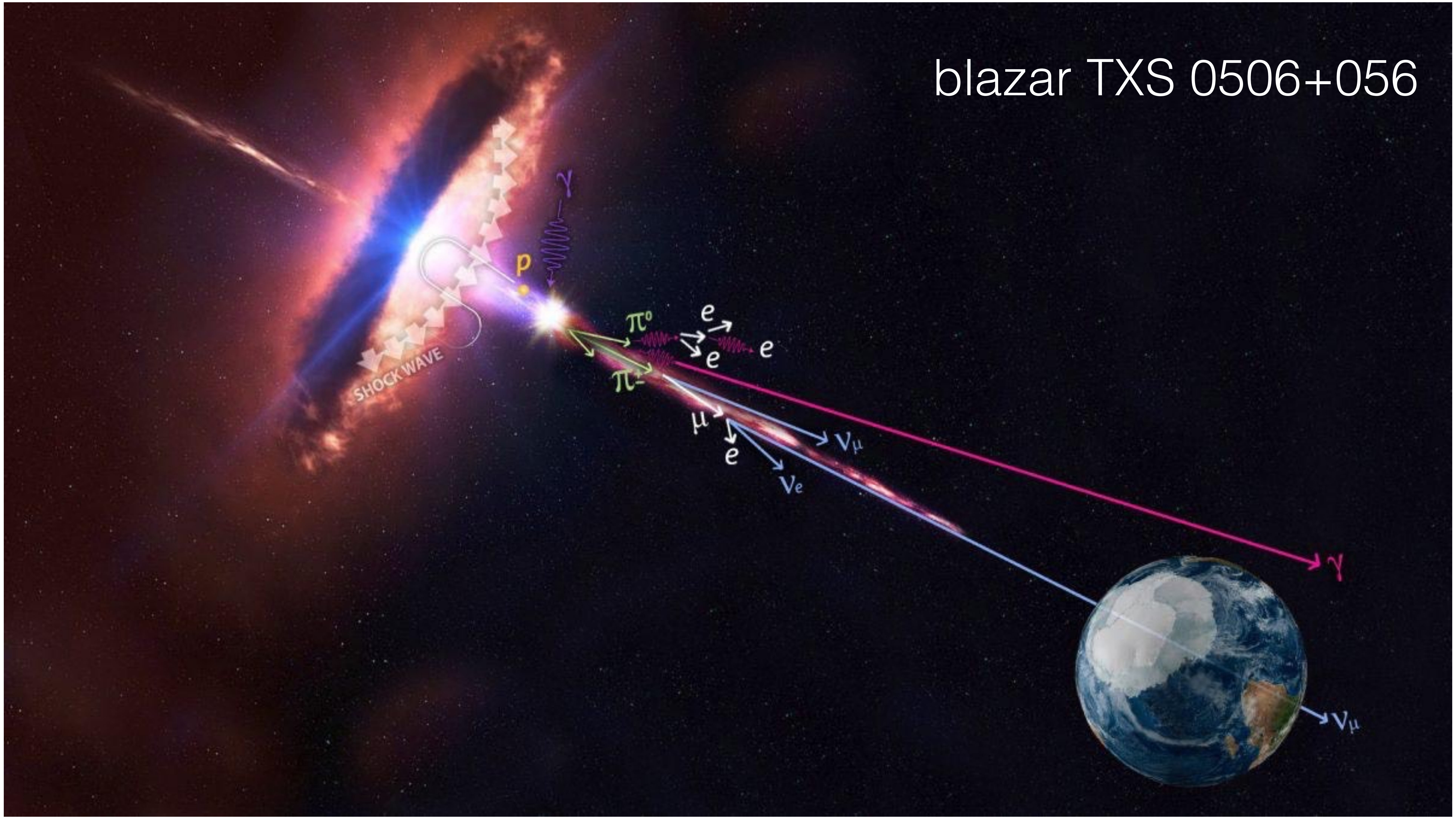
Yuan+2018



3.0
2.5
2.0
1.5
1.0
0.5
0.0
36
30
24
18
12
6
0
Flux (10^{-9}cm^{-2}s^{-1})
TS value
-2000
-1500
-1000
-500
0
500
1000
Time since 2014-09-22 (days)

Yuan+2018

Blazars as sources of high-energy neutrinos

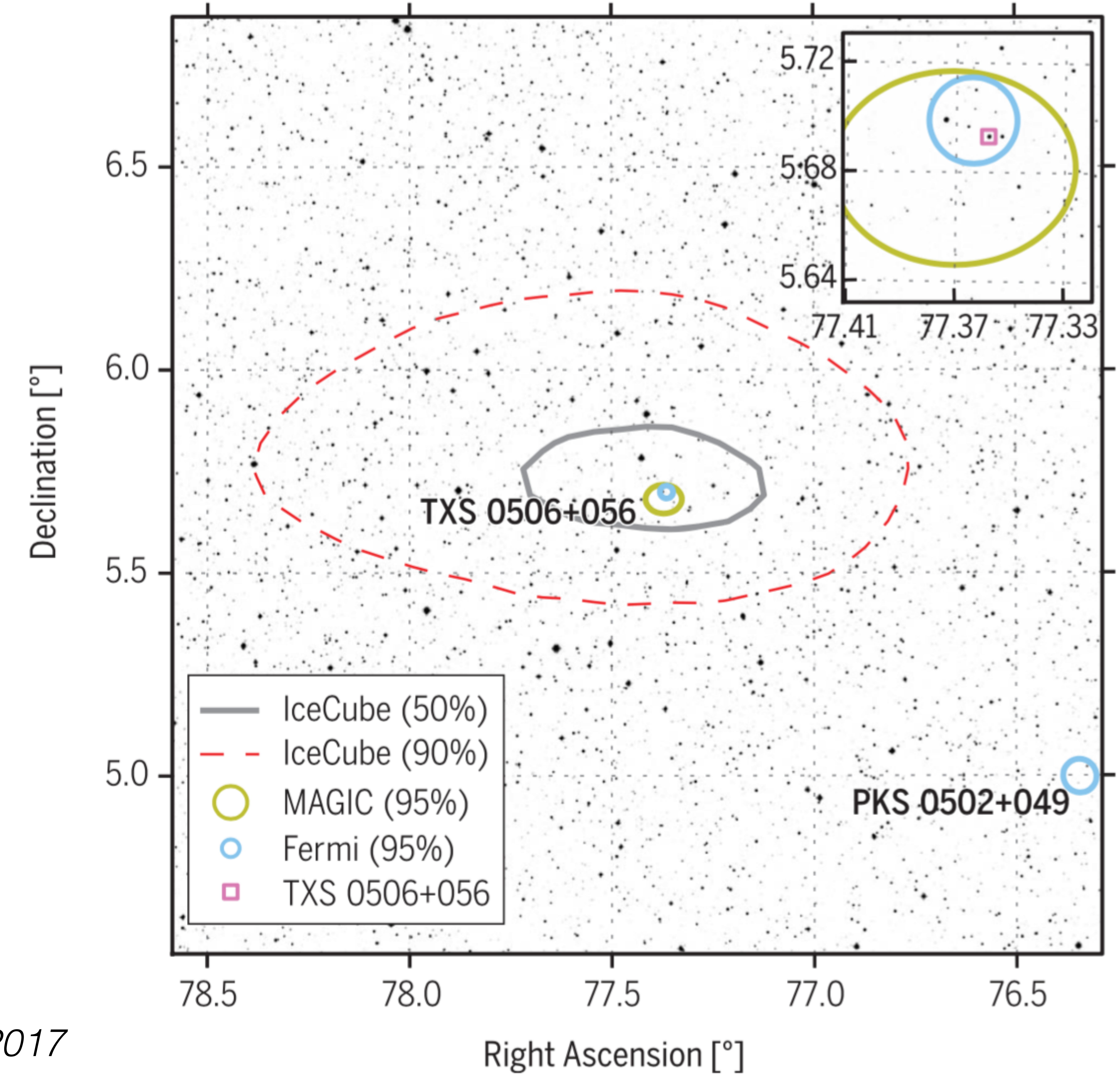


IceCube collaboration, 2017

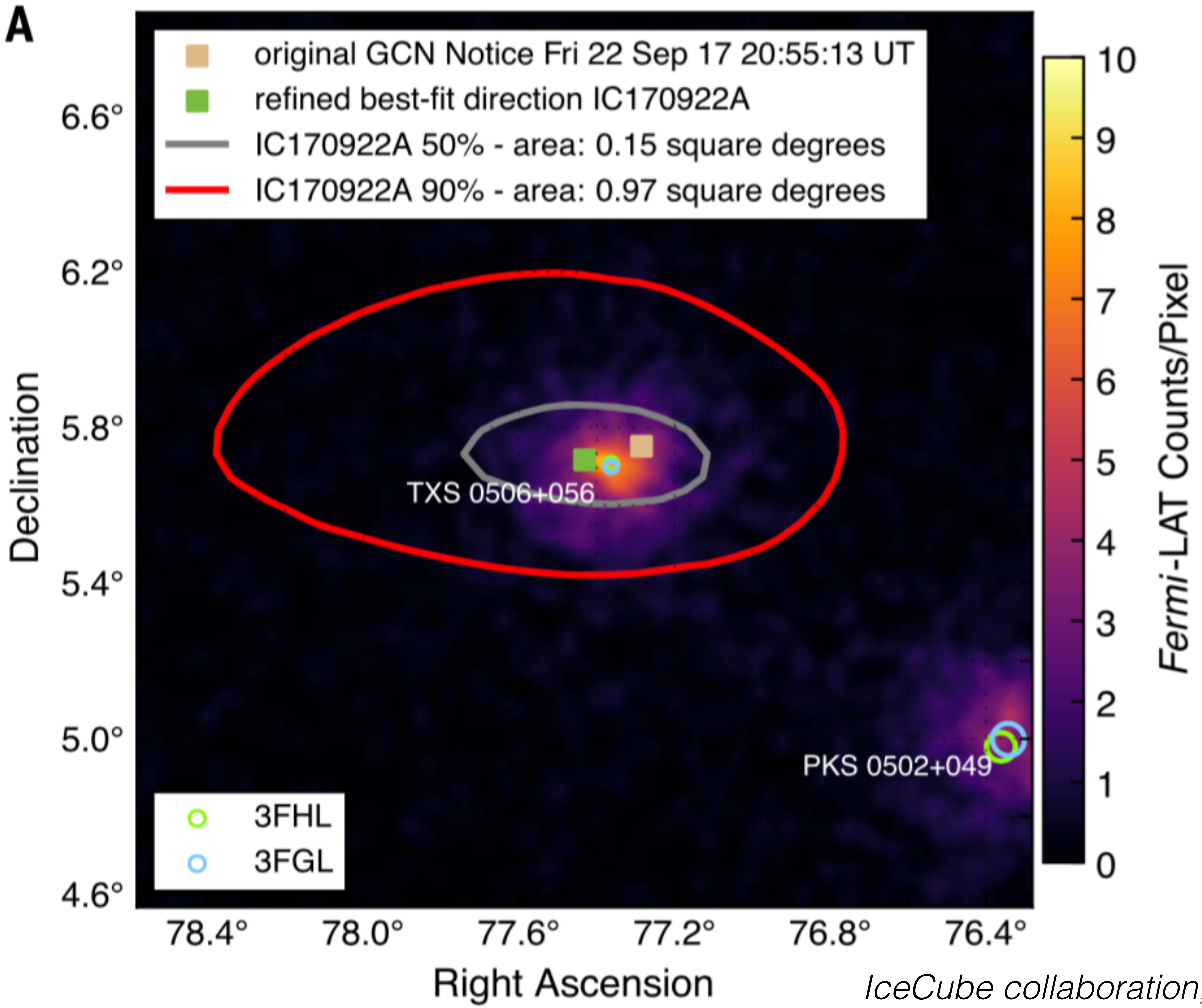
Link to press:
https://icecube.wisc.edu/news/press-releases/2018/07/icecube-neutrinos-point-to-long-sought-cosmic-ray-accelerator/

One ≈290-TeV neutrino by IceCube

Detected on Sep 22, 2017



IceCube collaboration, 2017



IceCube collaboration, 2017

ARTICLES
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nature astronomy

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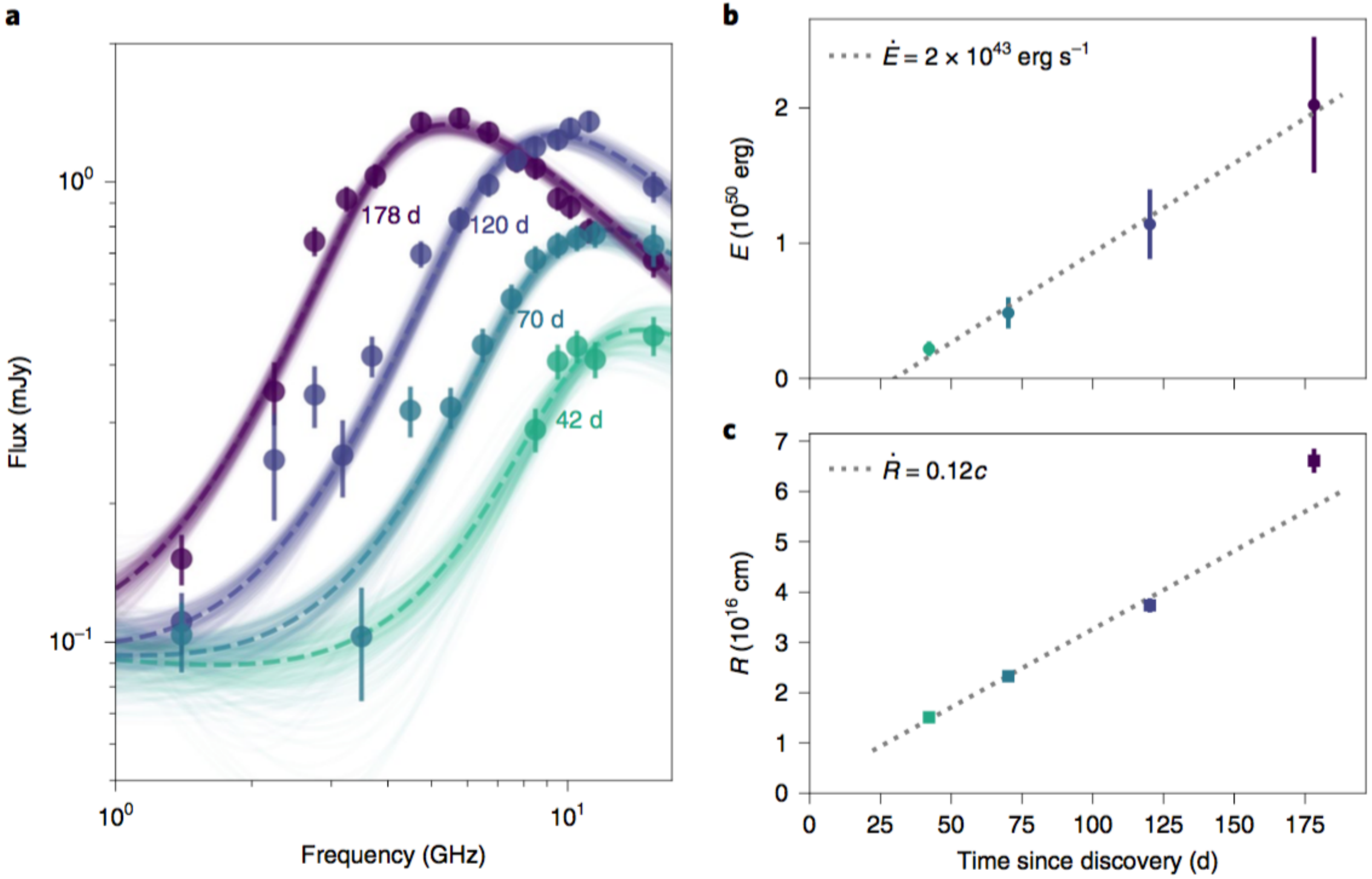
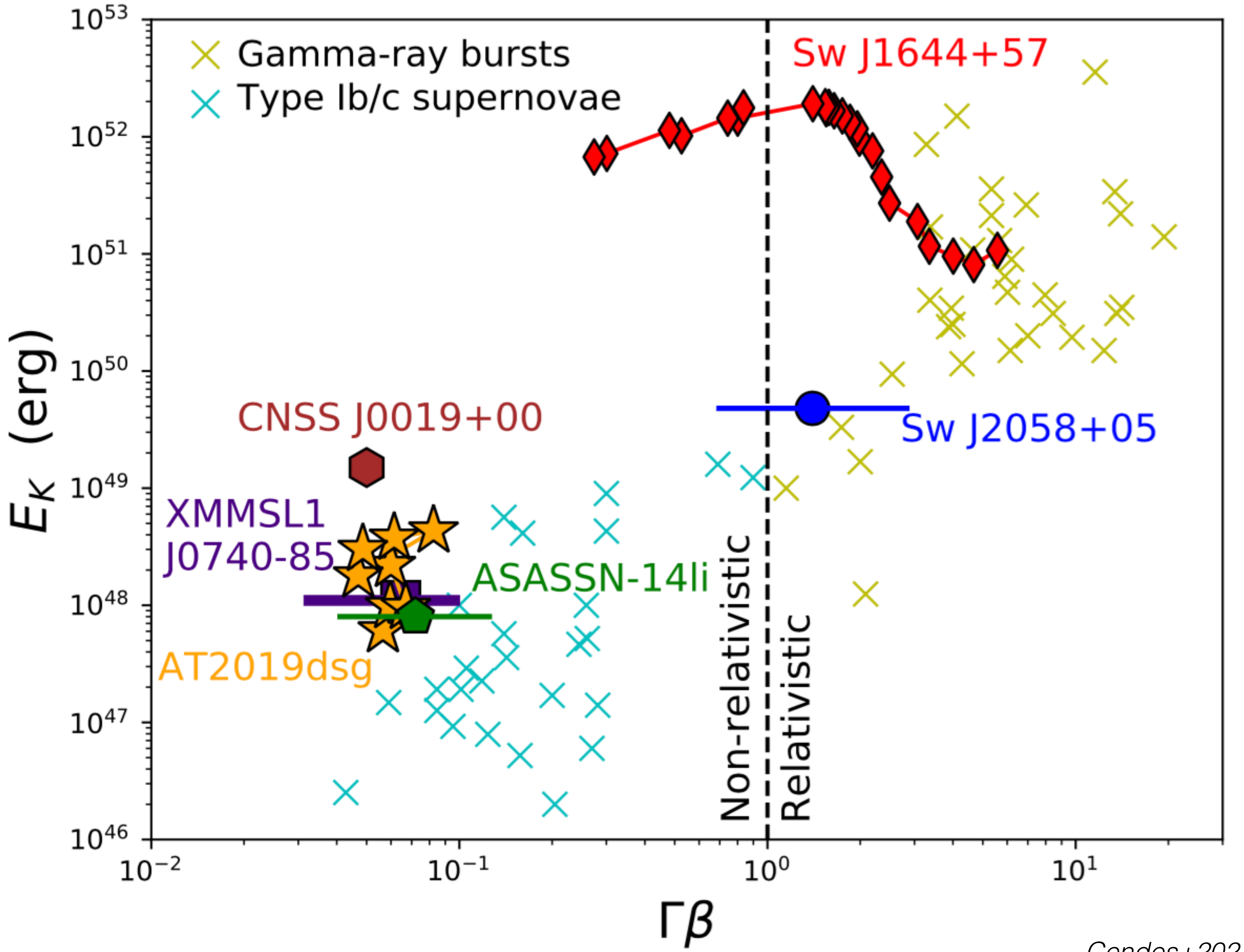
A tidal disruption event coincident with a high-energy neutrino

Robert Stein[1,2]✉, Sjoert van Velzen[3,4,5]✉, Marek Kowalski[1,2,6]✉, Anna Franckowiak[1,2], Suvi Gezari[4,7], James C. A. Miller-Jones[8], Sara Frederick[4], Itai Sfaradi[9], Michael F. Bietenholz[10,11], Assaf Horesh[9], Rob Fender[12,13], Simone Garrappa[1,2], Tomás Ahumada[4], Igor Andreoni[14], Justin Belicki[15], Eric C. Bellm[16], Markus Böttcher[17], Valery Brinnel[2], Rick Burruss[15], S. Bradley Cenko[7,18], Michael W. Coughlin[19], Virginia Cunningham[4], Andrew Drake[14], Glennys R. Farrar[3], Michael Feeney[15], Ryan J. Foley[20], Avishay Gal-Yam[21], V. Zach Golkhou[16,22], Ariel Goobar[23], Matthew J. Graham[14], Erica Hammerstein[4], George Helou[24], Tiara Hung[20], Mansi M. Kasliwal[14], Charles D. Kilpatrick[20], Albert K. H. Kong[25], Thomas Kupfer[26], Russ R. Laher[24], Ashish A. Mahabal[14,27], Frank J. Masci[24], Jannis Necker[1,2], Jakob Nordin[2], Daniel A. Perley[28], Mickael Rigault[29], Simeon Reusch[1,2], Hector Rodriguez[15], César Rojas-Bravo[20], Ben Rusholme[24], David L. Shupe[24], Leo P. Singer[18], Jesper Sollerman[30], Maayane T. Soumagnac[21,31], Daniel Stern[32], Kirsty Taggart[28], Jakob van Santen[1], Charlotte Ward[4], Patrick Woudt[13] and Yuhan Yao[14]

TDE radio SED





Gamma-ray bursts
Type Ib/c supernovae
Sw J1644+57
Sw J2058+05
CNSS J0019+00
XMMSL1 J0740-85
ASASSN-14li
AT2019dsg
Non-relativistic
Relativistic
E_K (erg)
$\Gamma\beta$
10^{53}
10^{52}
10^{51}
10^{50}
10^{49}
10^{48}
10^{47}
10^{46}
10^{-2}
10^{-1}
10^{0}
10^{1}

Cendes+2021