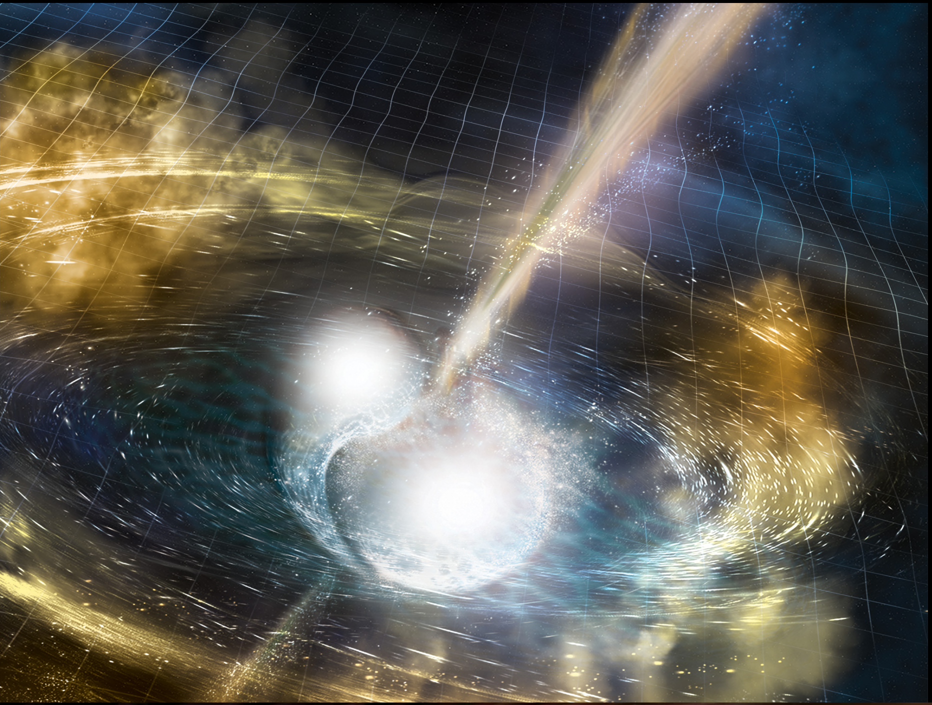
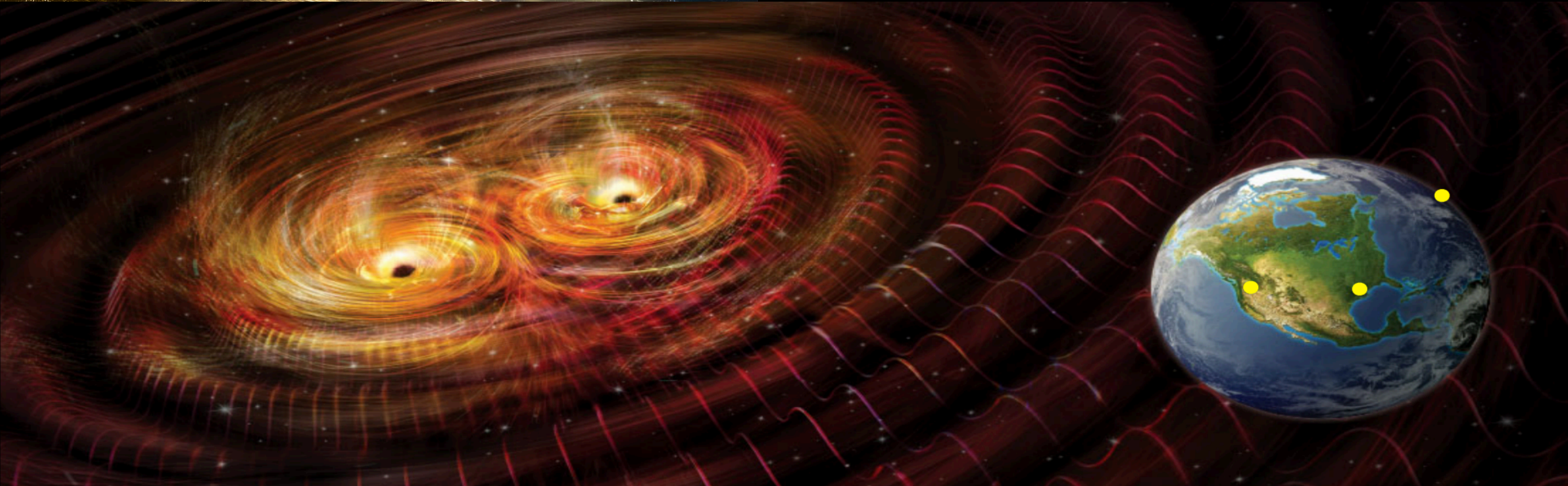
Why do we need larger network of observatories?



M. Branchesi
Gran Sasso Science Institute
INFN/LNGS and INAF



A new window into the Universe

Earth

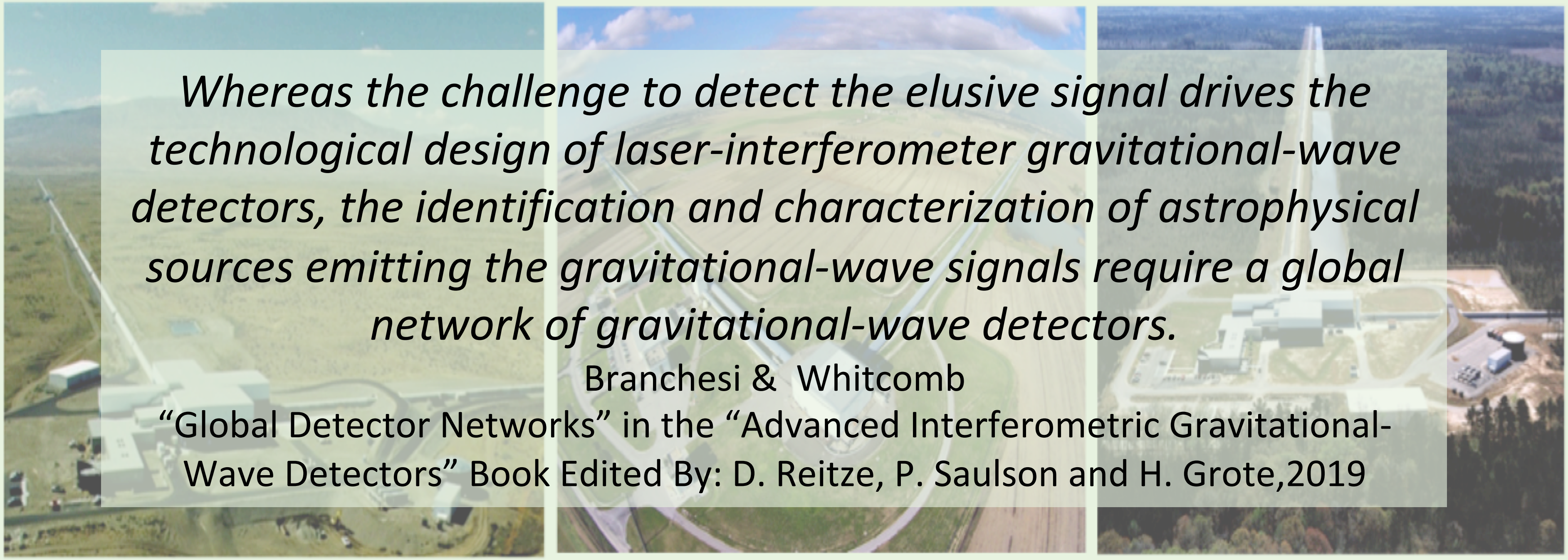
Credit: LIGO–Virgo

KAGRA, Japan

LIGO, Livingston, LA

LIGO, Hanford, WA

Virgo, Cascina, Italy



Whereas the challenge to detect the elusive signal drives the technological design of laser-interferometer gravitational-wave detectors, the identification and characterization of astrophysical sources emitting the gravitational-wave signals require a global network of gravitational-wave detectors.

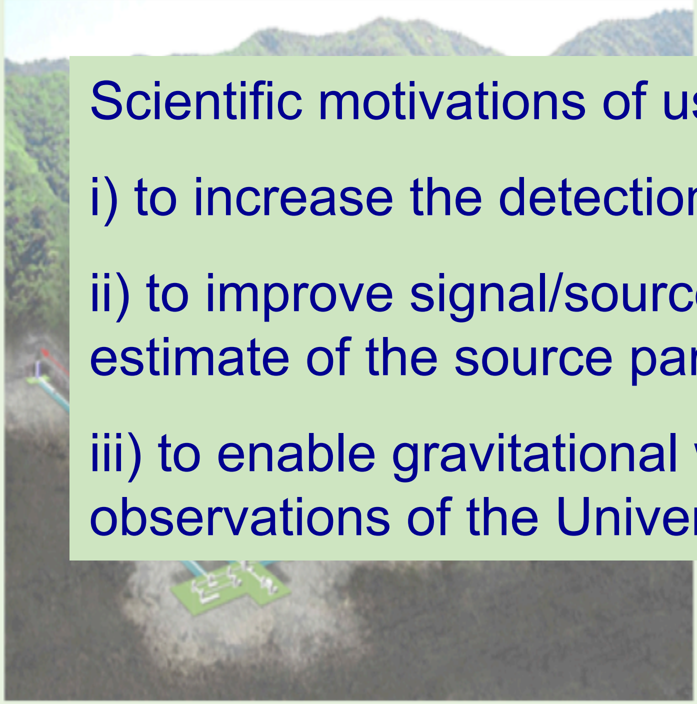
Branchesi & Whitcomb
“Global Detector Networks” in the “Advanced Interferometric Gravitational-Wave Detectors” Book Edited By: D. Reitze, P. Saulson and H. Grote,2019

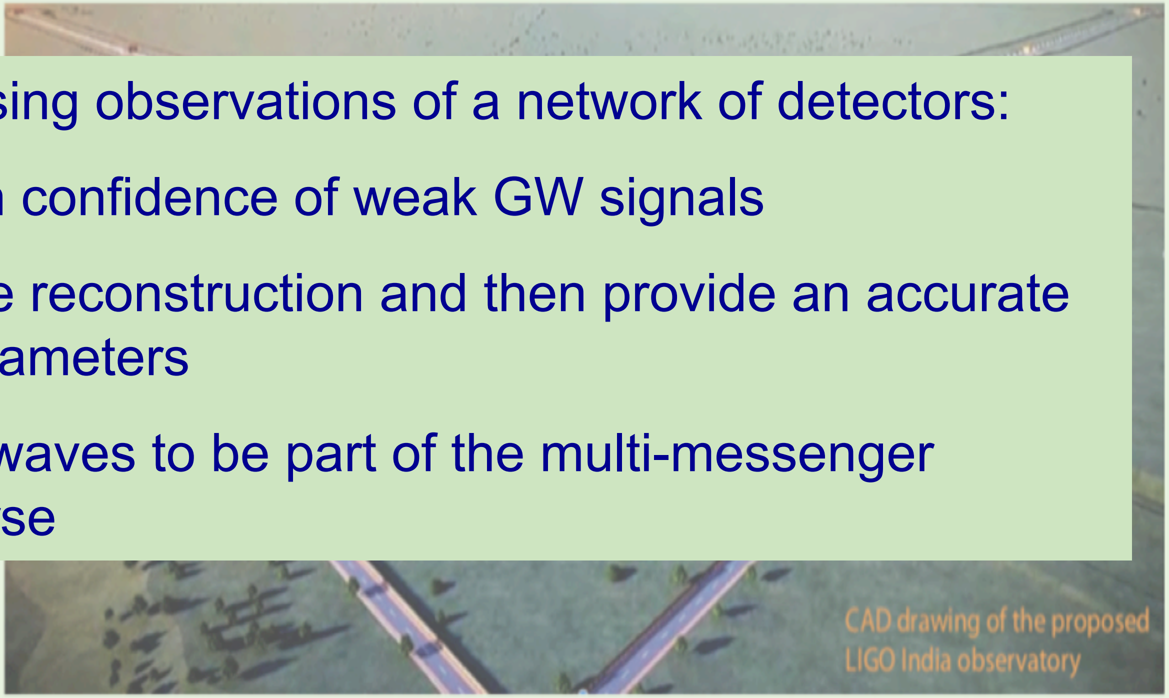
Scientific motivations of using observations of a network of detectors:

i) to increase the detection confidence of weak GW signals

ii) to improve signal/source reconstruction and then provide an accurate estimate of the source parameters

iii) to enable gravitational waves to be part of the multi-messenger observations of the Universe

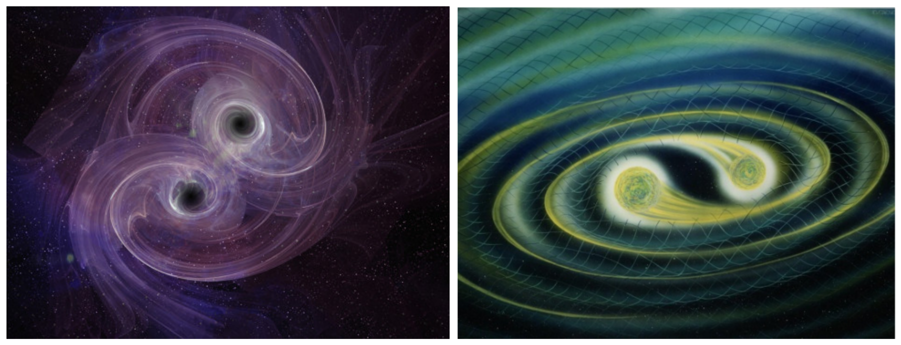




CAD drawing of the proposed LIGO India observatory

ASTROPHYSICAL SOURCES emitting transient GW signals detectable by LIGO and Virgo (10-1000 Hz)

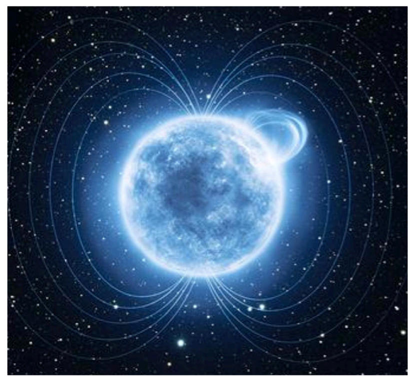
Coalescence of binary system of neutron stars and/or stellar-mass black-hole



- Orbital evolution and GW signals accurately modeled by post-Newtonian approximation and numerical simulations
  → precise waveforms
- **Energy emitted in GWs (BNS): ~$10^{-2} M_o c^2$**

Isolated neutron-star instabilities

Core-collapse of massive stars

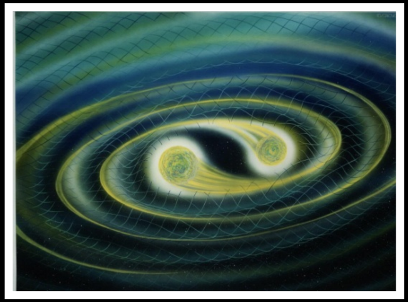


- Modeling of the GW shape and strength is complicated → **uncertain waveforms**
- **Energy emitted in GWs:**

~ $10^{-9}\ M_o c^2$ for the core-collapse

~$10^{-16} - 10^{-6}\ M_o c^2$ for isolated NSs

RARE EVENTS



Milky-way equivalent galaxy:

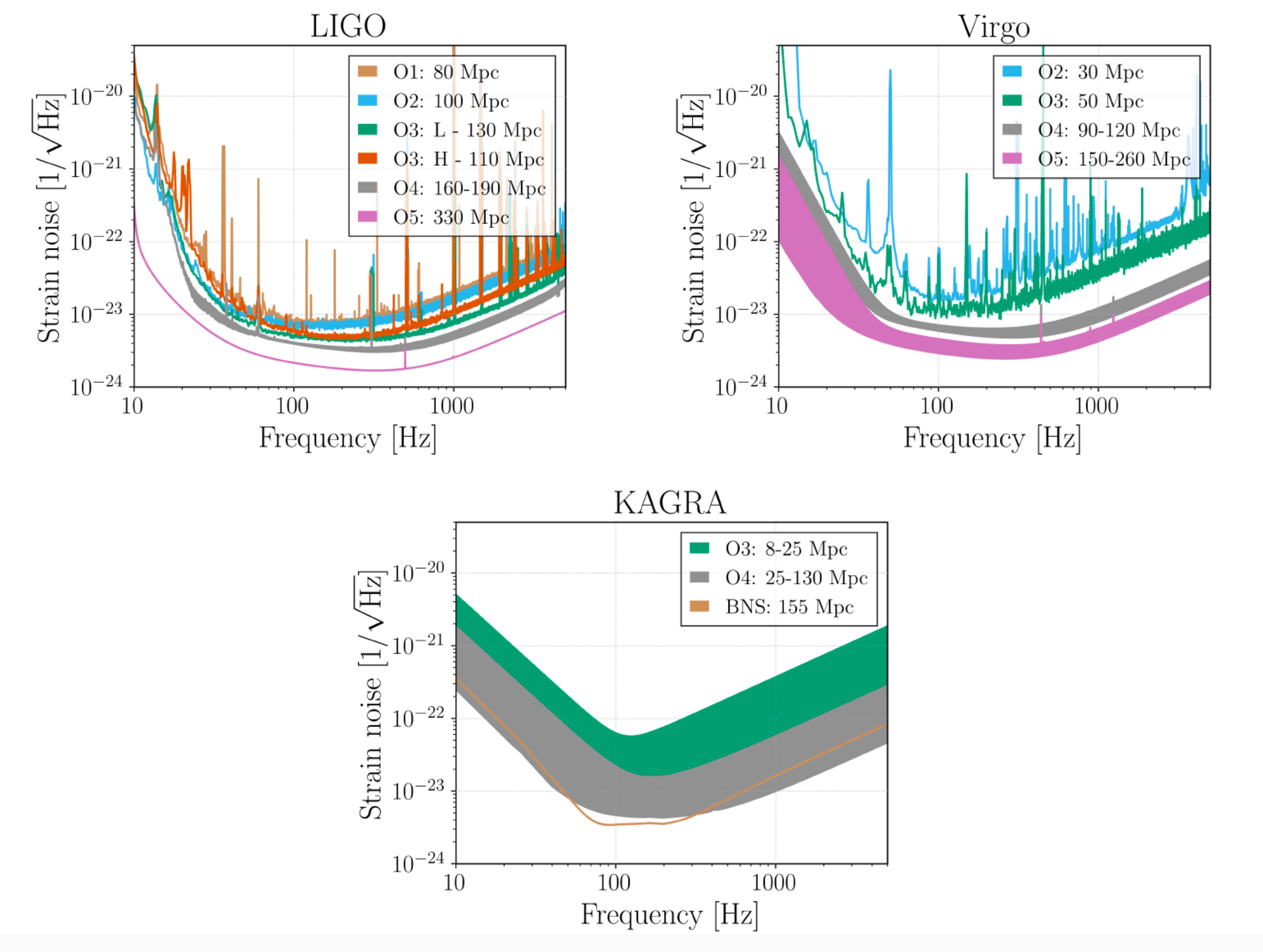
- BNS a few tens per milion years
- BBH a few per milion years

Milky-way equivalent galaxy:

- core-collpse SN one per 100 year

IMPERATIVE TO ENLARGE THE OBSERVABLE UNIVERSE

Strain sensitivities as a function of frequency



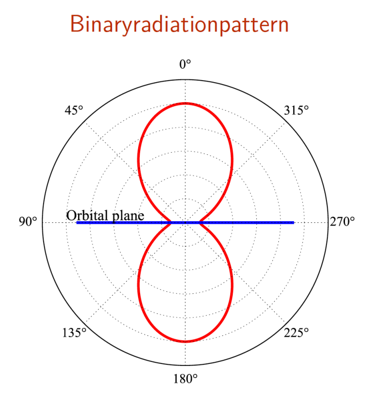
Abbott et al. 2020, LRR

SENSITIVITY IN TERMS OF RANGE/HORIZON DISTANCE

- Range: the volume- and orientation-averaged distance at which a compact binary coalescence gives a matched filter SNR of 8 in a single detector

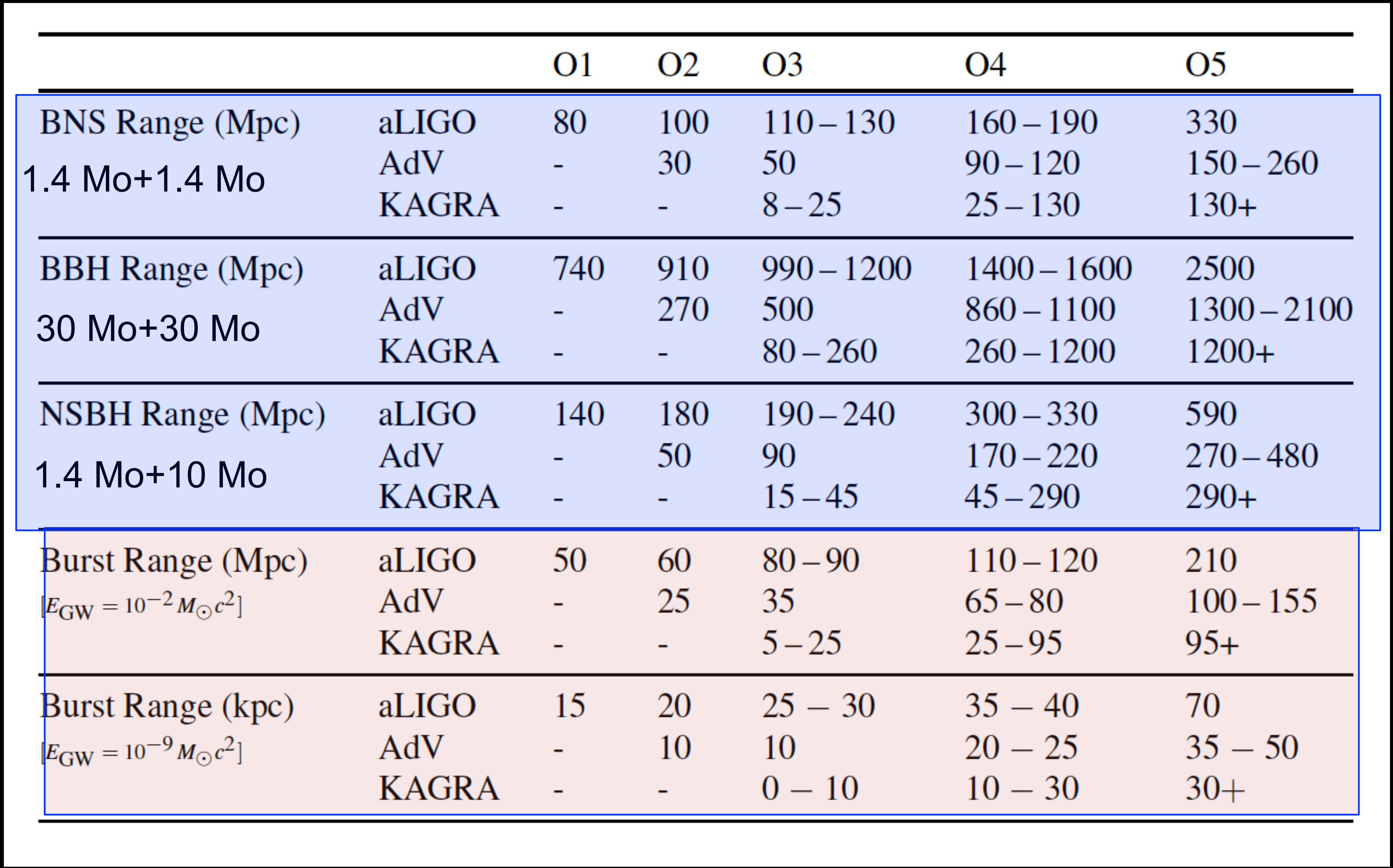
- Distance for face-on system: distance at which an optimally oriented system (orbital plane perpendicular to the line of sight) would be observed with an SNR of 8: range x 1.5

- Horizon: distance at which an optimally oriented and located binary system would be observed with an SNR of 8: range x 2.26



RANGES corresponding to the orientation-averaged spacetime volumes surveyed per unit detector time

SNR = 8 in each detector



		O1	O2	O3	O4	O5
BNS Range (Mpc) 1.4 Mo+1.4 Mo	aLIGO	80	100	110 – 130	160 – 190	330
	AdV	-	30	50	90 – 120	150 – 260
	KAGRA	-	-	8 – 25	25 – 130	130+
BBH Range (Mpc) 30 Mo+30 Mo	aLIGO	740	910	990 – 1200	1400 – 1600	2500
	AdV	-	270	500	860 – 1100	1300 – 2100
	KAGRA	-	-	80 – 260	260 – 1200	1200+
NSBH Range (Mpc) 1.4 Mo+10 Mo	aLIGO	140	180	190 – 240	300 – 330	590
	AdV	-	50	90	170 – 220	270 – 480
	KAGRA	-	-	15 – 45	45 – 290	290+
Burst Range (Mpc) $[E_{GW} = 10^{-2} M_{\odot} c^2]$	aLIGO	50	60	80 – 90	110 – 120	210
	AdV	-	25	35	65 – 80	100 – 155
	KAGRA	-	-	5 – 25	25 – 95	95+
Burst Range (kpc) $[E_{GW} = 10^{-9} M_{\odot} c^2]$	aLIGO	15	20	25 – 30	35 – 40	70
	AdV	-	10	10	20 – 25	35 – 50
	KAGRA	-	-	0 – 10	10 – 30	30+

LVK arXiv:1304.0670

SENSITIVITY and TEMPORAL COVERAGE of the different detectors
→ determines the **effective sensitivity of the network**

- *network sensitivity improves with the square root of the number of detectors (assuming equivalent detector sensitivities and under the assumption of Gaussian noise)*
- *increasing the number of detectors also improves the network duty cycle*
- *weak signals rely strongly on coincident/coherent detection among the detectors in the network.*

ORIENTATIONS OF THE DETECTORS in the network
→ determine the ability to reconstruct the full waveforms (two polarizations) and more accurately evaluate the parameters of the gravitational-wave sources.

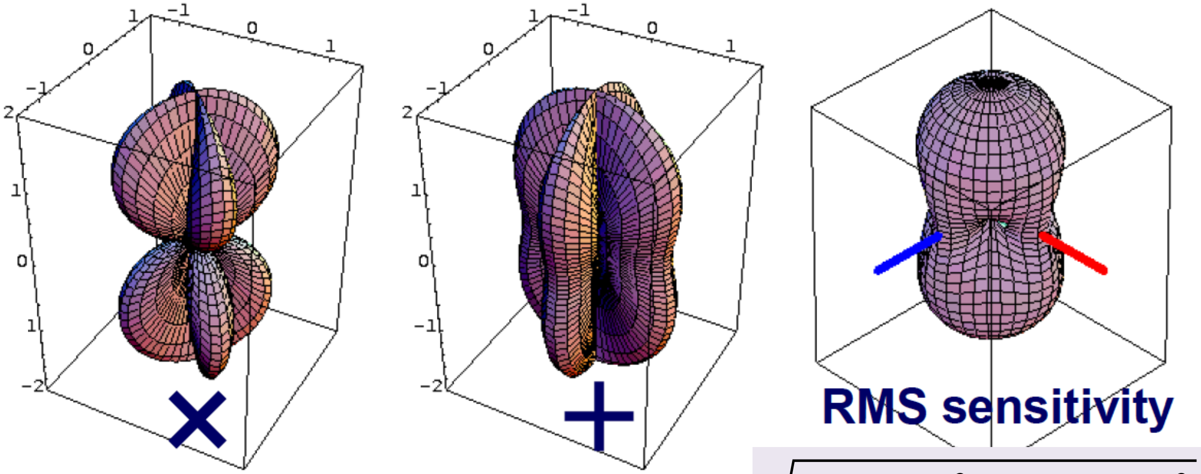
SPATIAL DISTRIBUTION of the detectors
→ determines their ability to locate source positions

LOCALIZATION CAPABILITY

Sky location - single GW detector directional sensitivity

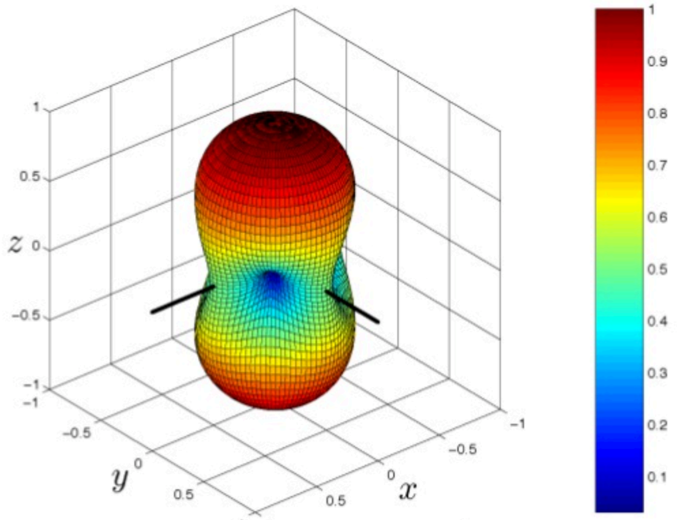
$$\frac{\Delta L}{L} = h_{\text{det}}(t) = F_+ h_+(t) + F_x h_x(t)$$

The **antenna pattern** depends on the polarization in a certain (x,+) basis



RMS sensitivity

$$\sqrt{F_+(\theta,\phi)^2 + F_x(\theta,\phi)^2}$$

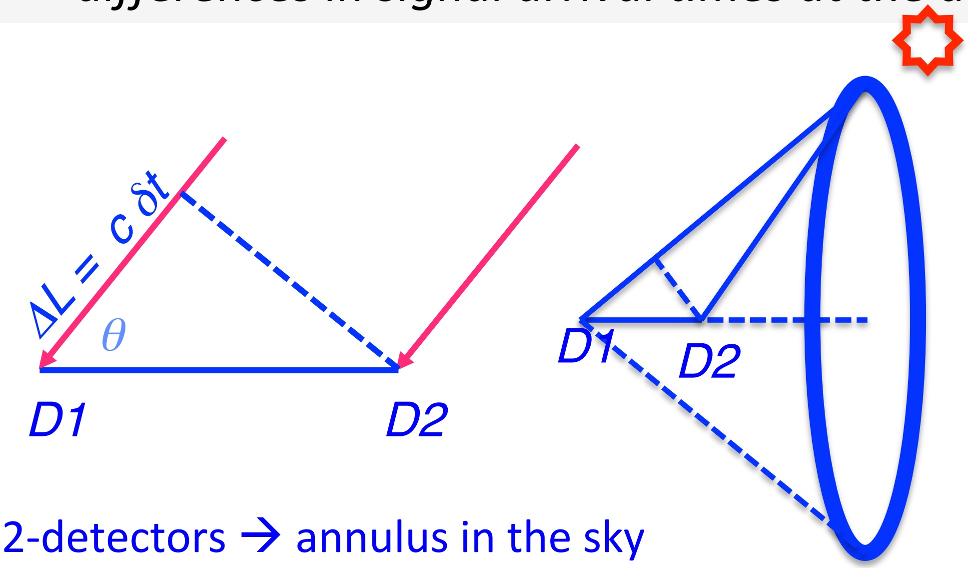


$$\sqrt{F_+^2(\theta,\phi,\psi=0) + F_\times^2(\theta,\phi,\psi=0)}$$

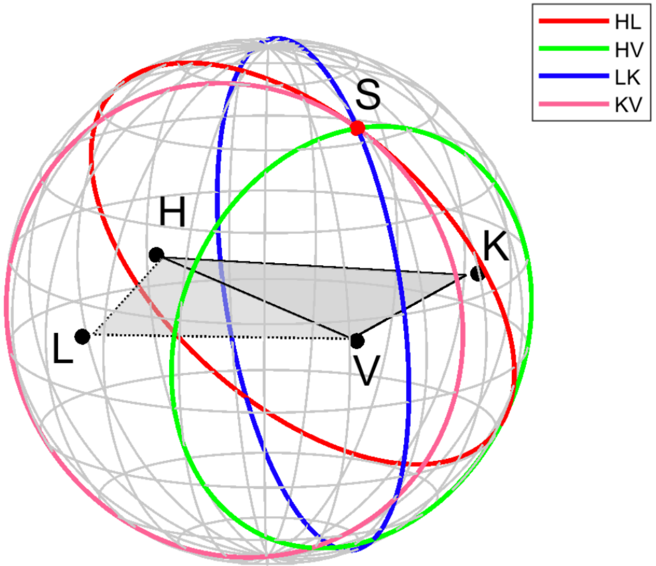
- ➢ Single GW detector is a **good all-sky monitor**, nearly omni-directional (the transparency of Earth to GWs)
- ➢ But does not have good directional sensitivity, **not a pointing instrument!** It has a very poor angular resolution (about 100 deg)

The source localization requires a network of GW detectors

*The **sky position** of a GW source is mainly **evaluated by triangulation**, measuring the differences in signal arrival times at the different network detector sites*



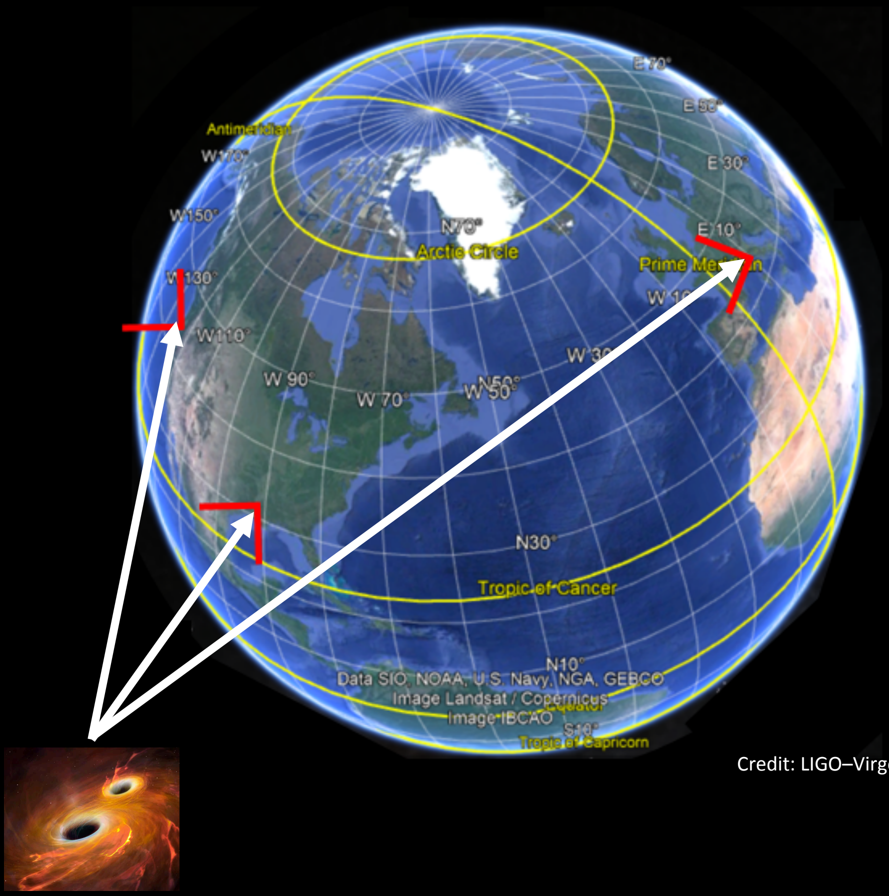
2-detectors → annulus in the sky



4-detectors → localize

The localization capabilty improves with signal SNR → the sky localization area scales inversely with the square of the SNR

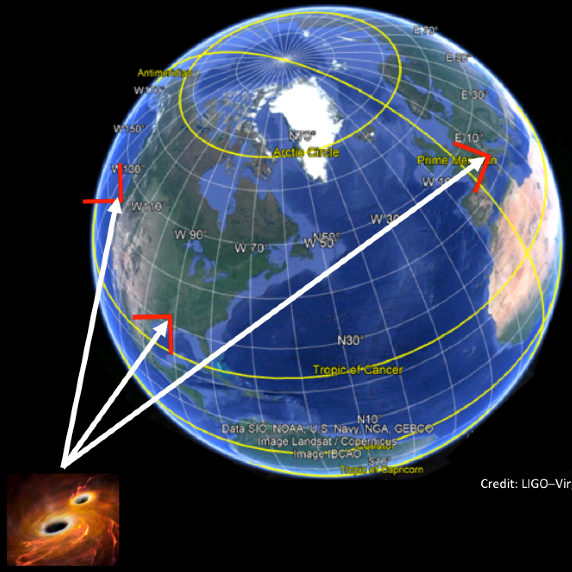
2017 August 14, 10:30:43 UT



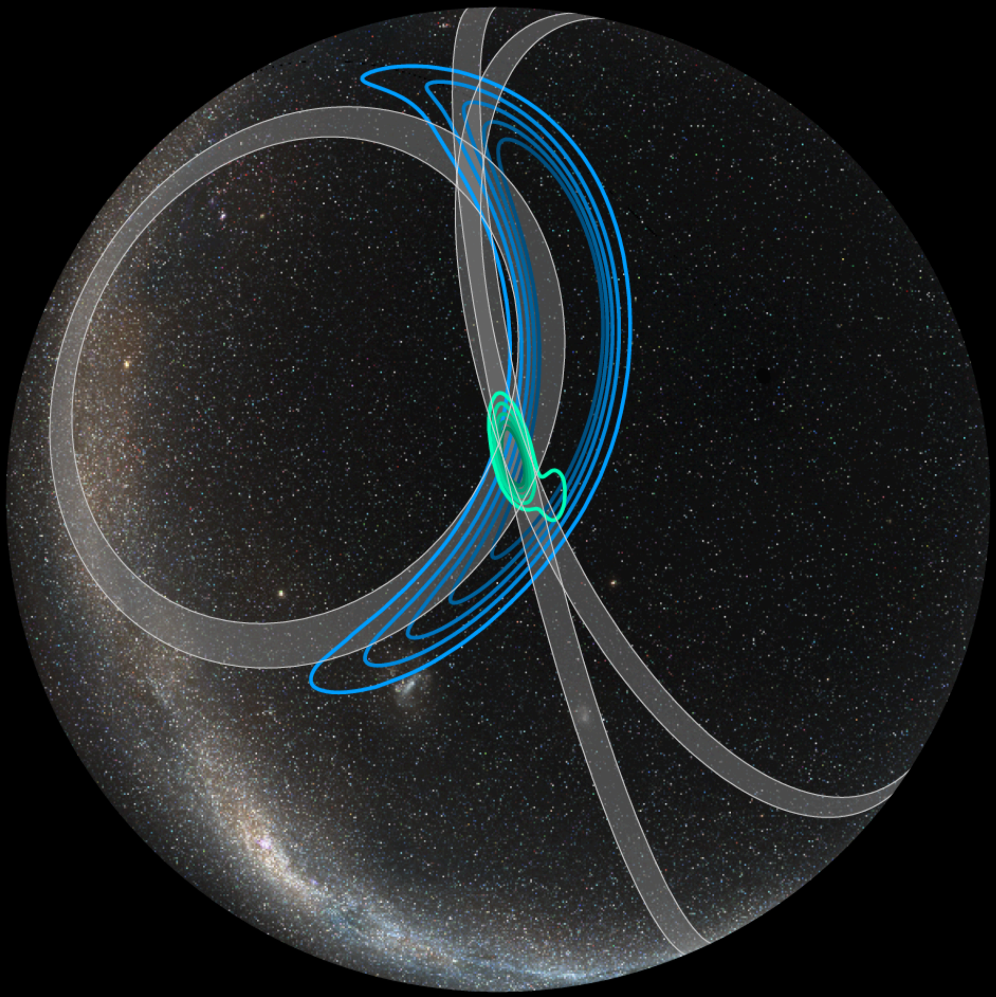
Credit: LIGO–Virgo

Virgo observed its first BBH coalescence, GW170814

2017 August 14

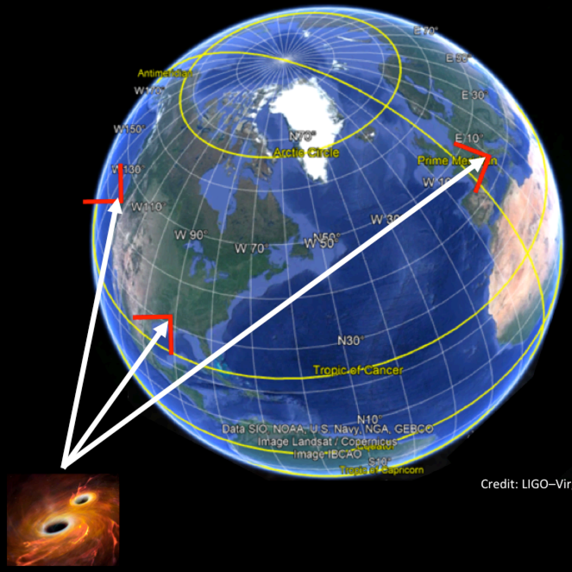


Credit: LIGO–Virgo

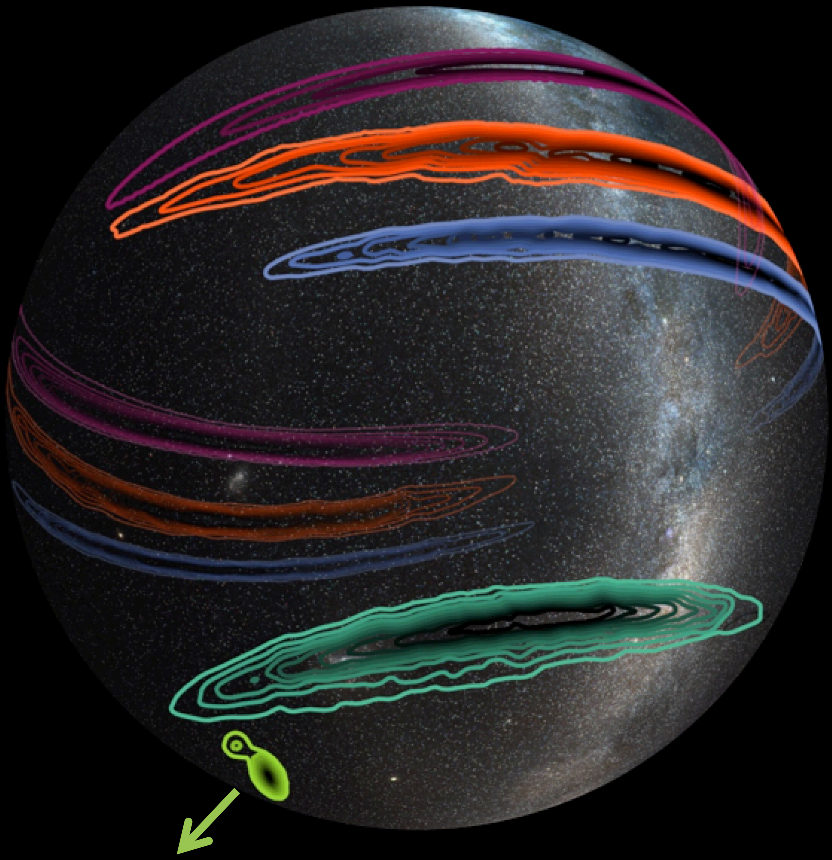


Credit: Leo Singer

2017 August 14



Credit: LIGO–Virgo



GW170814

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

LH 1160 square degrees

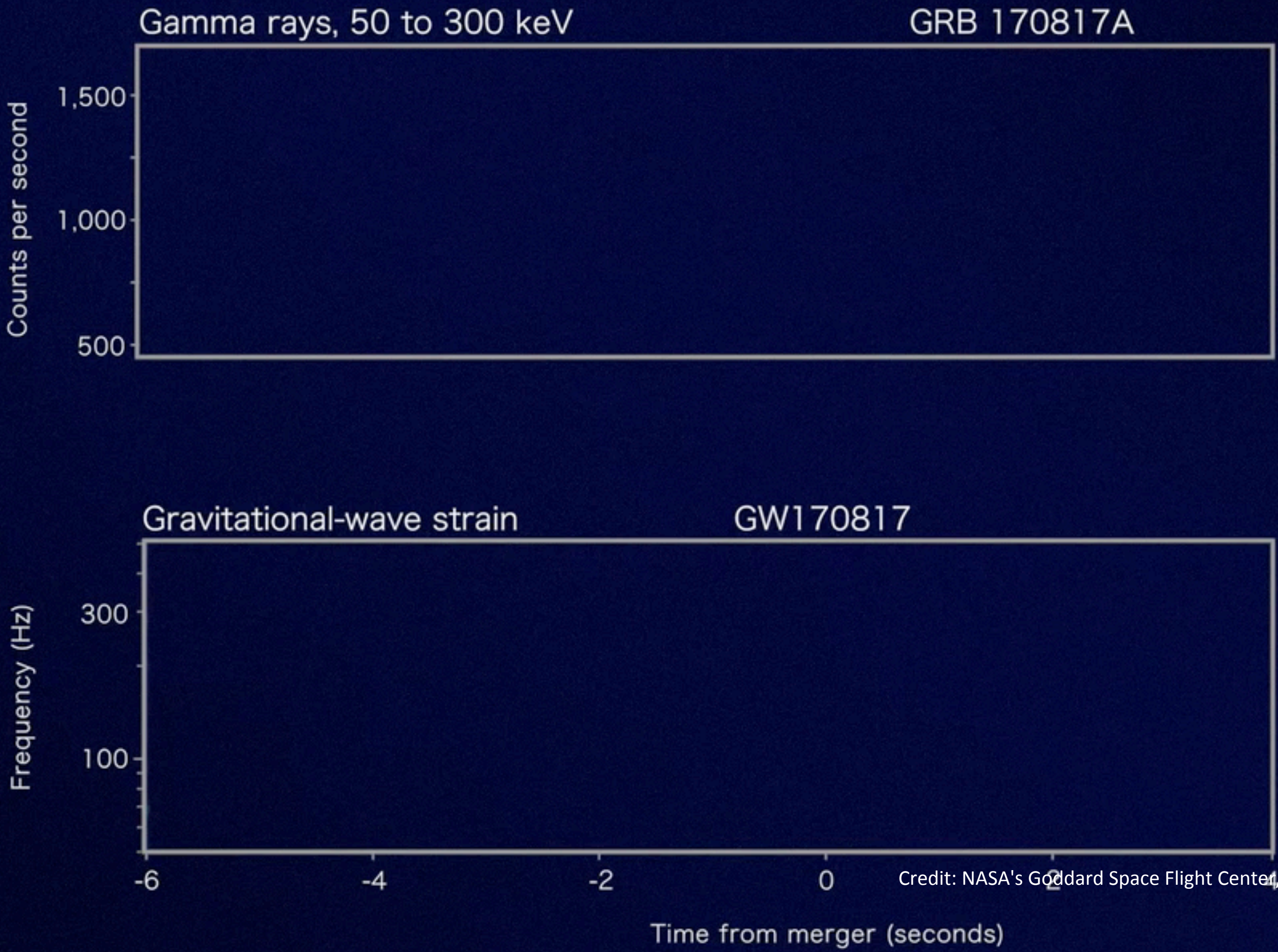
LHV 60 square degrees

…searching for electromagnetic signals…

- Detecting the EM counterpart
- Identifying the host galaxy
- Measure the redshift

17 August 2017, 12:41:04 UT

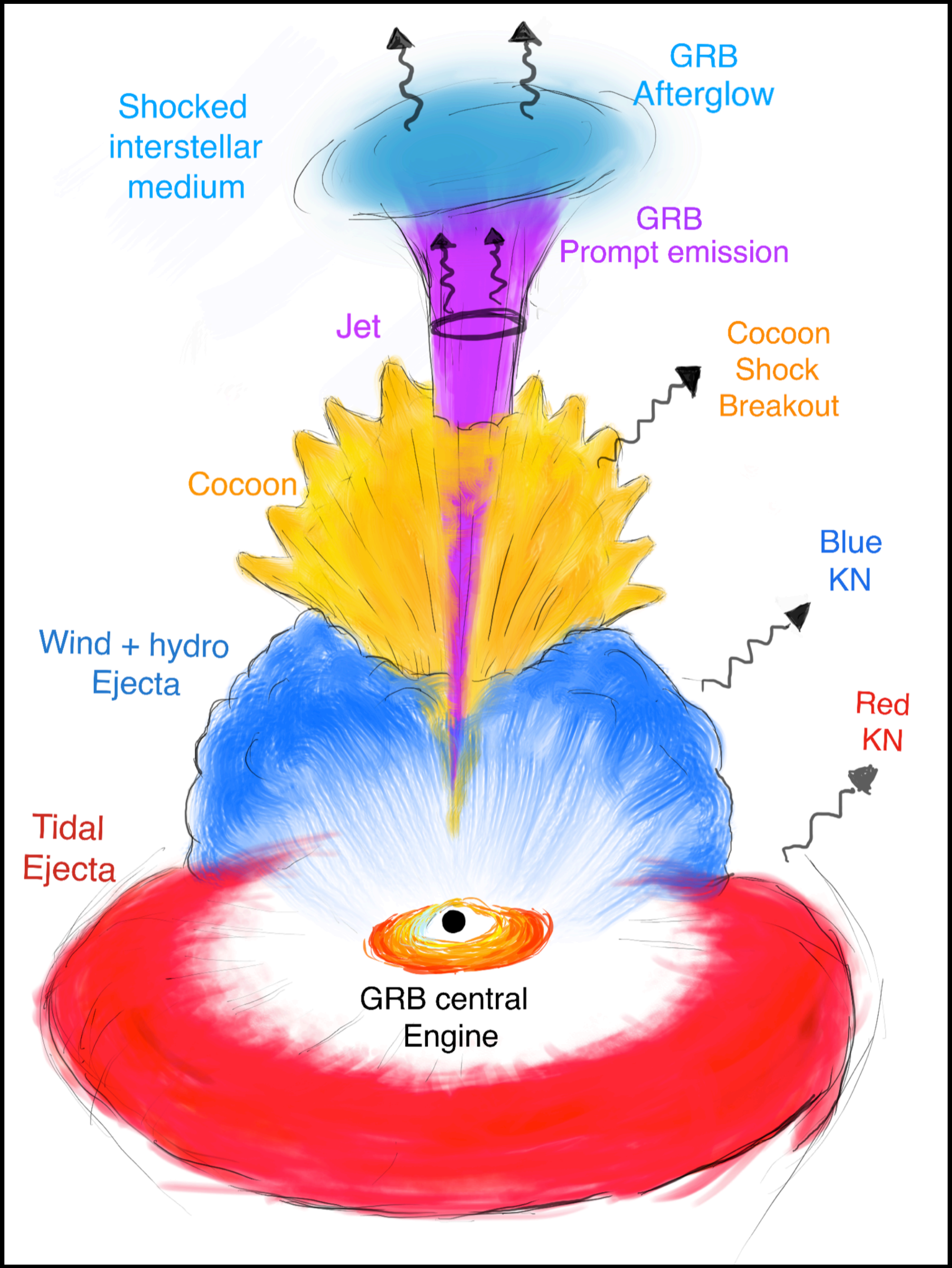
Credit: University of Warwick/Mark Garlick



Credit: NASA's Goddard Space Flight Center/CI Lab

Coalescence of neutron star binary

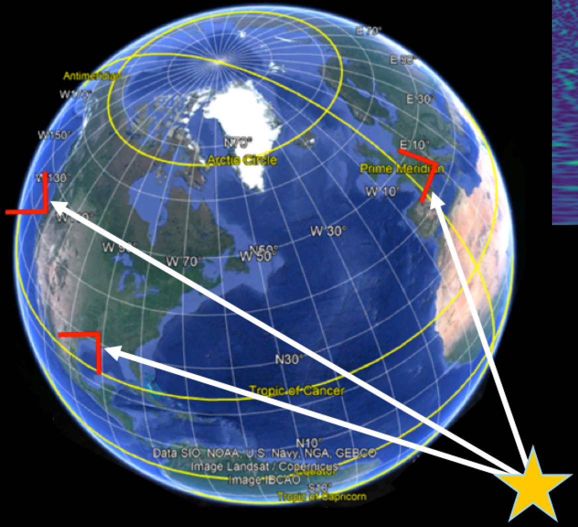
Credit: NASA's Goddard Space Flight Center/CI Lab

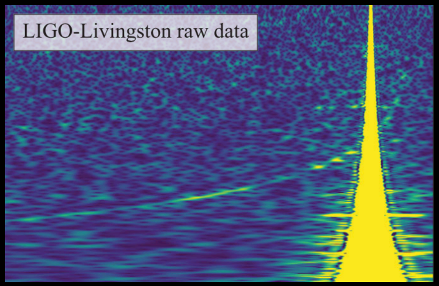


Thermal and non thermal emission components associated with BNS and NSBH merger

Ascenzi et al. 2021

17 August 2017, 12:41:04 UT



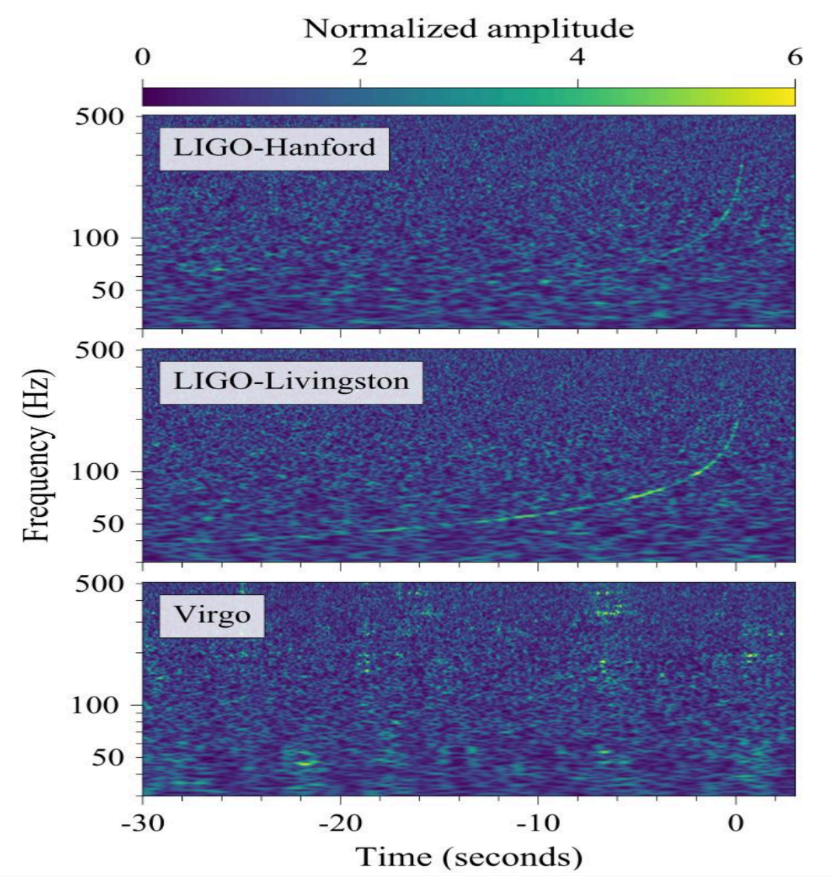


→ 17:54:51

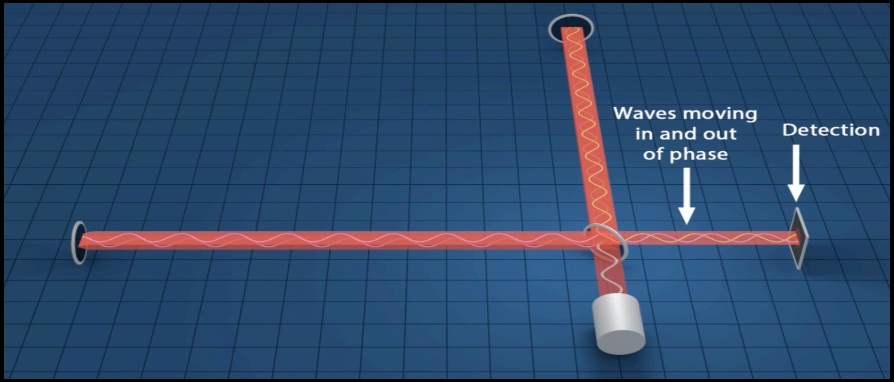
Credit: LIGO/Virgo/NASA/Leo Singer

Credit:N. Risinger (skysurvey.org), LIGO-Virgo, Digitized Sky Survey 2, ESO.

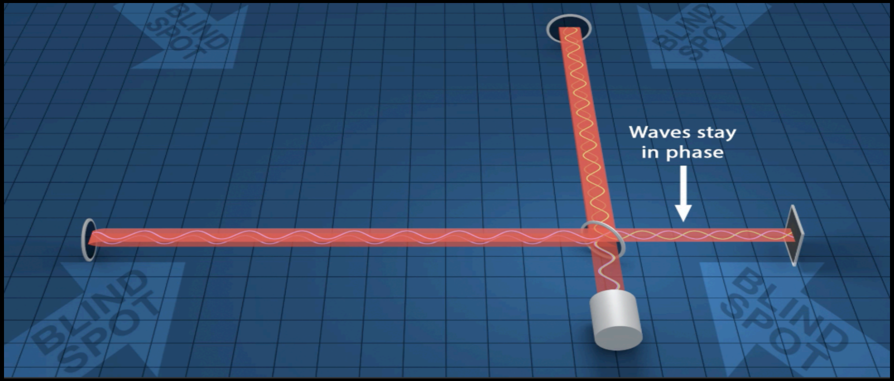
GW170817



Combined signal-to-noise ratio of 32.4

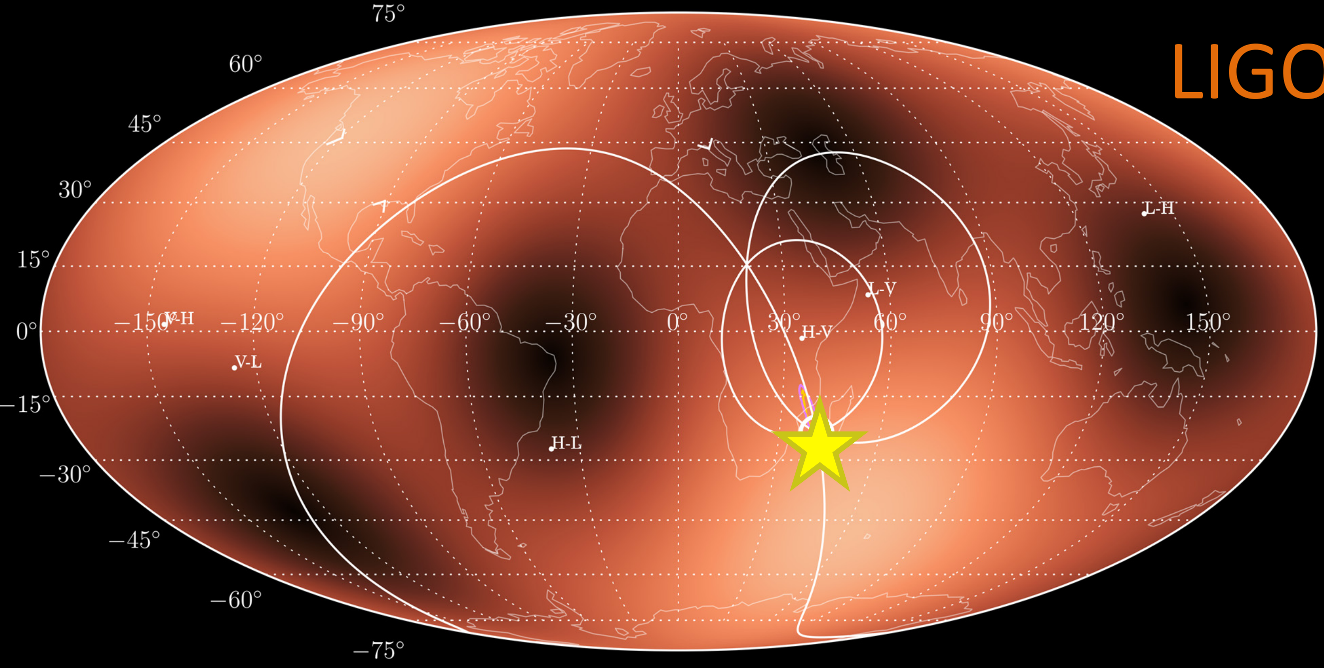


The signal comes from "blind spot"

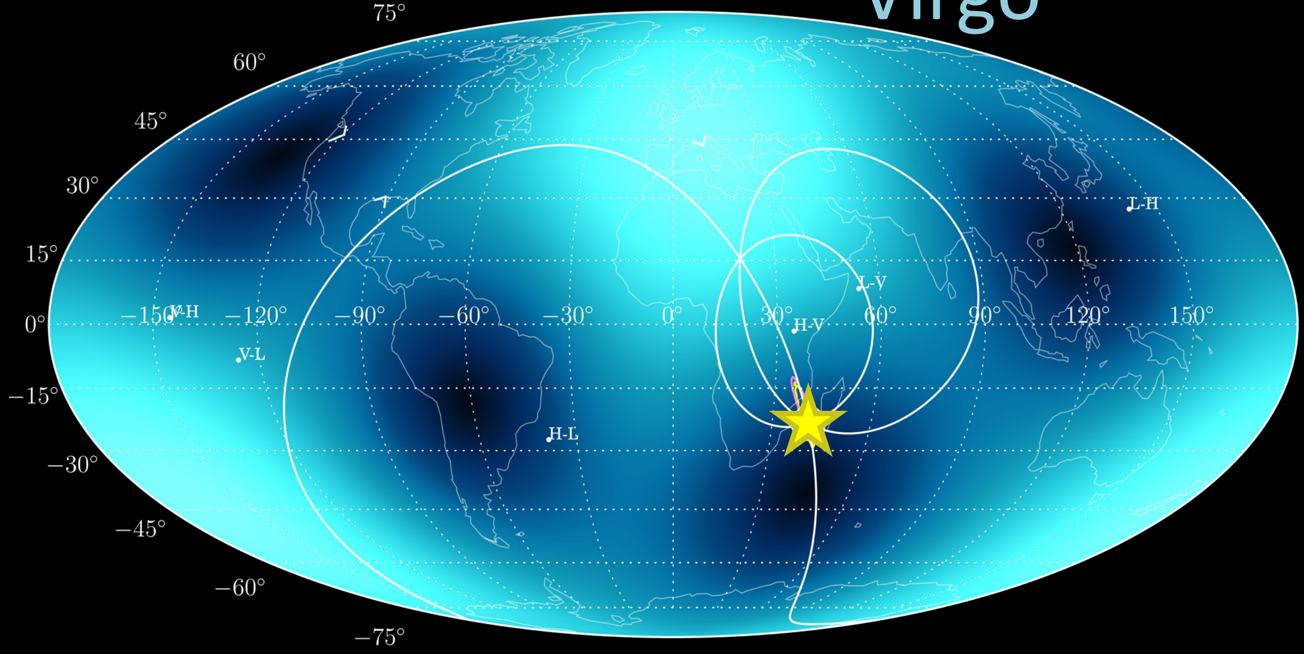


The low signal amplitude observed in Virgo significantly constrained the sky position

LIGO


75°
60°
45°
30°
15°
0°
−15°
−30°
−45°
−60°
−75°
−150°
−120°
−90°
−60°
−30°
0°
30°
60°
90°
120°
150°
L-H
L-V
H-V
V-H
V-L
H-L

Virgo


75°
60°
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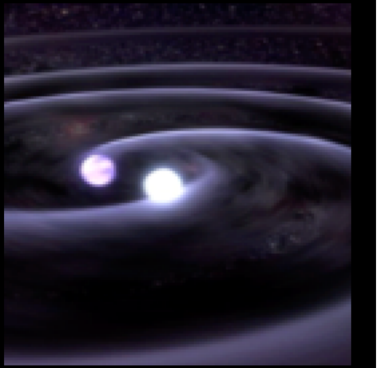
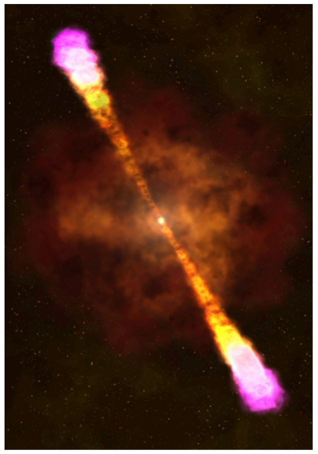
15°
0°
−15°
−30°
−45°
−60°
−75°
−150°
−120°
−90°
−60°
−30°
0°
30°
60°
90°
120°
150°
L-H
L-V
H-V
V-H
V-L
H-L

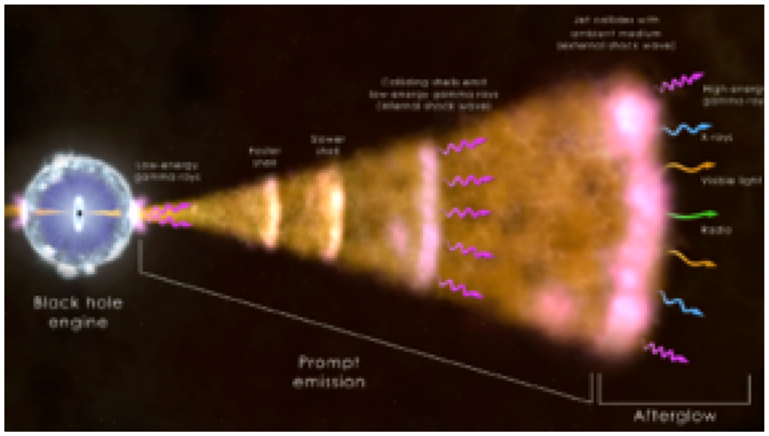
A global space and ground multi-messenger network….



NS merger



Short GRB



X-ray

Radio afterglow

t0

1.7s

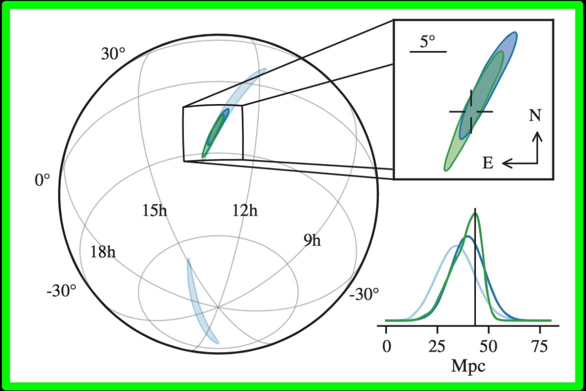
+5.23hrs

+10.87 hrs

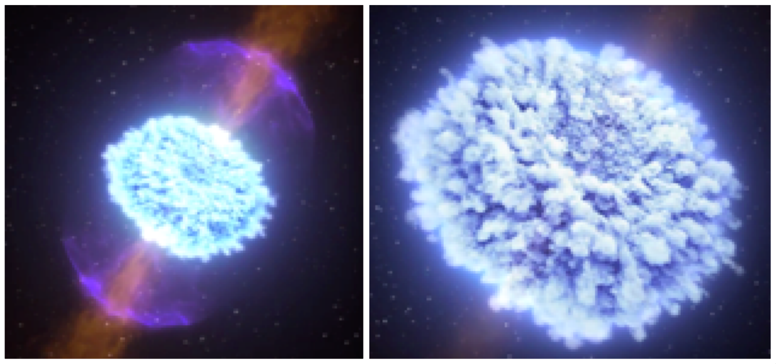
+9 days

+16 days

LHV sky localization



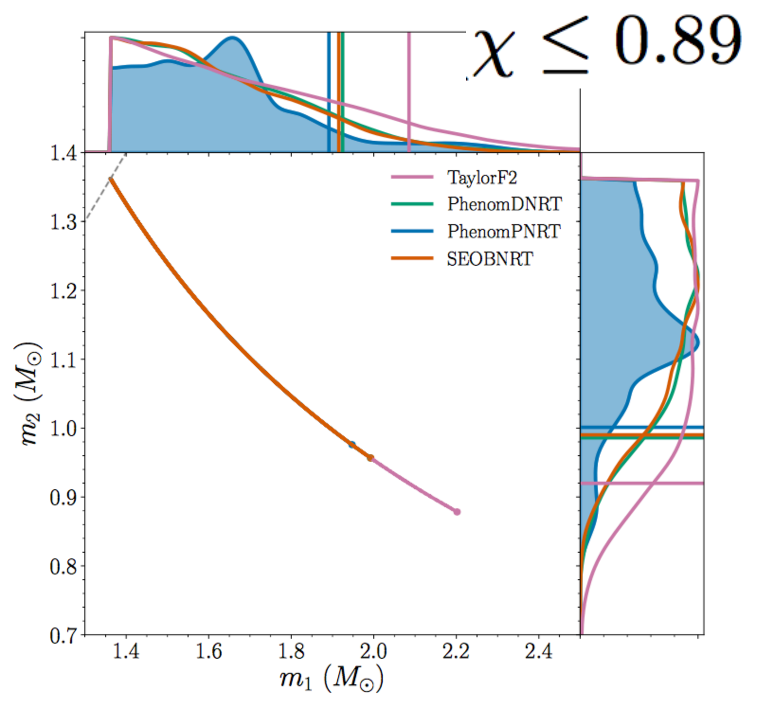
UV/Optical/NIR Kilonova

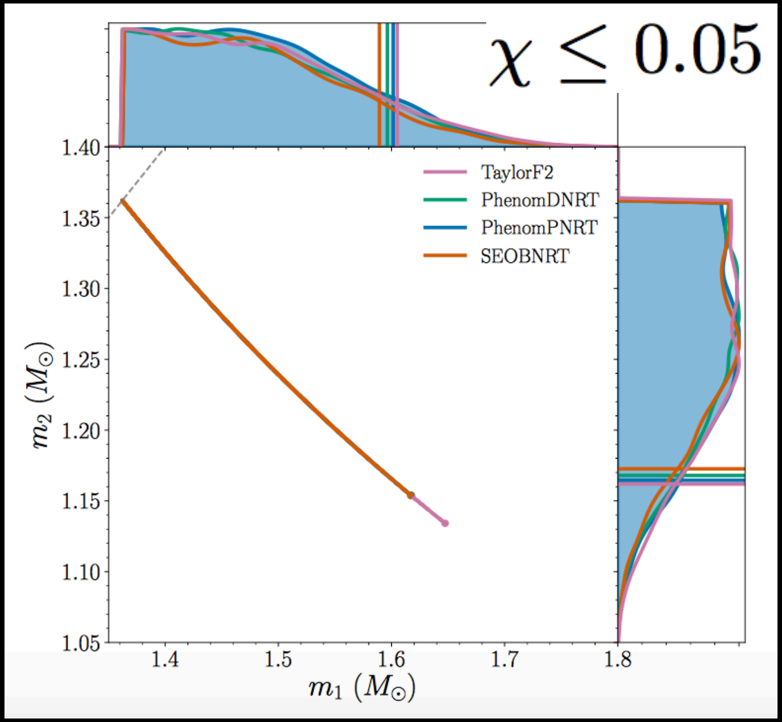


LVC + astronomers, ApJL, 848, L12

GW observables

GW170817: PARAMETERS OF THE SOURCE





$23 < f\,/Hz < 2048$

Analysis uses source location from EM

- **Mass range 1.0 – 1.89 Mo**

  1.16 – 1.60 Mo low spin

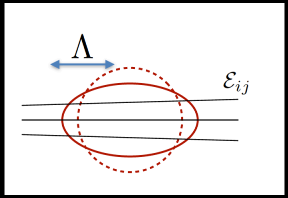
Masses are consistent with the masses of all known neutron stars!

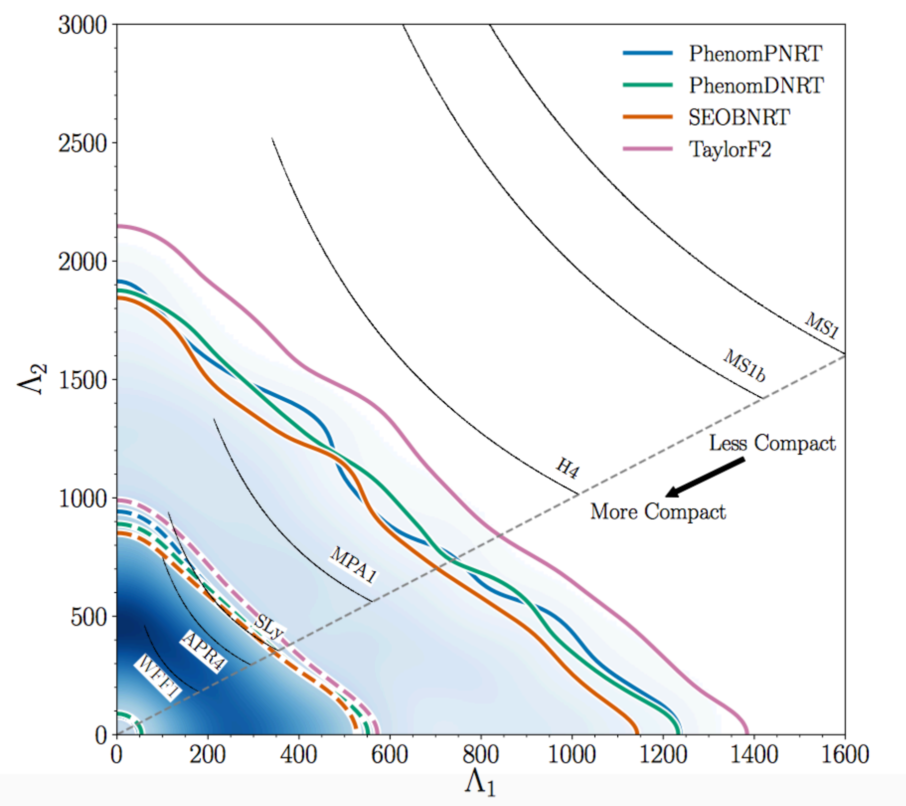
LSC VIRGO

Abbott et al. 2019, Phys Rev X

TIDAL DEFORMABILITY

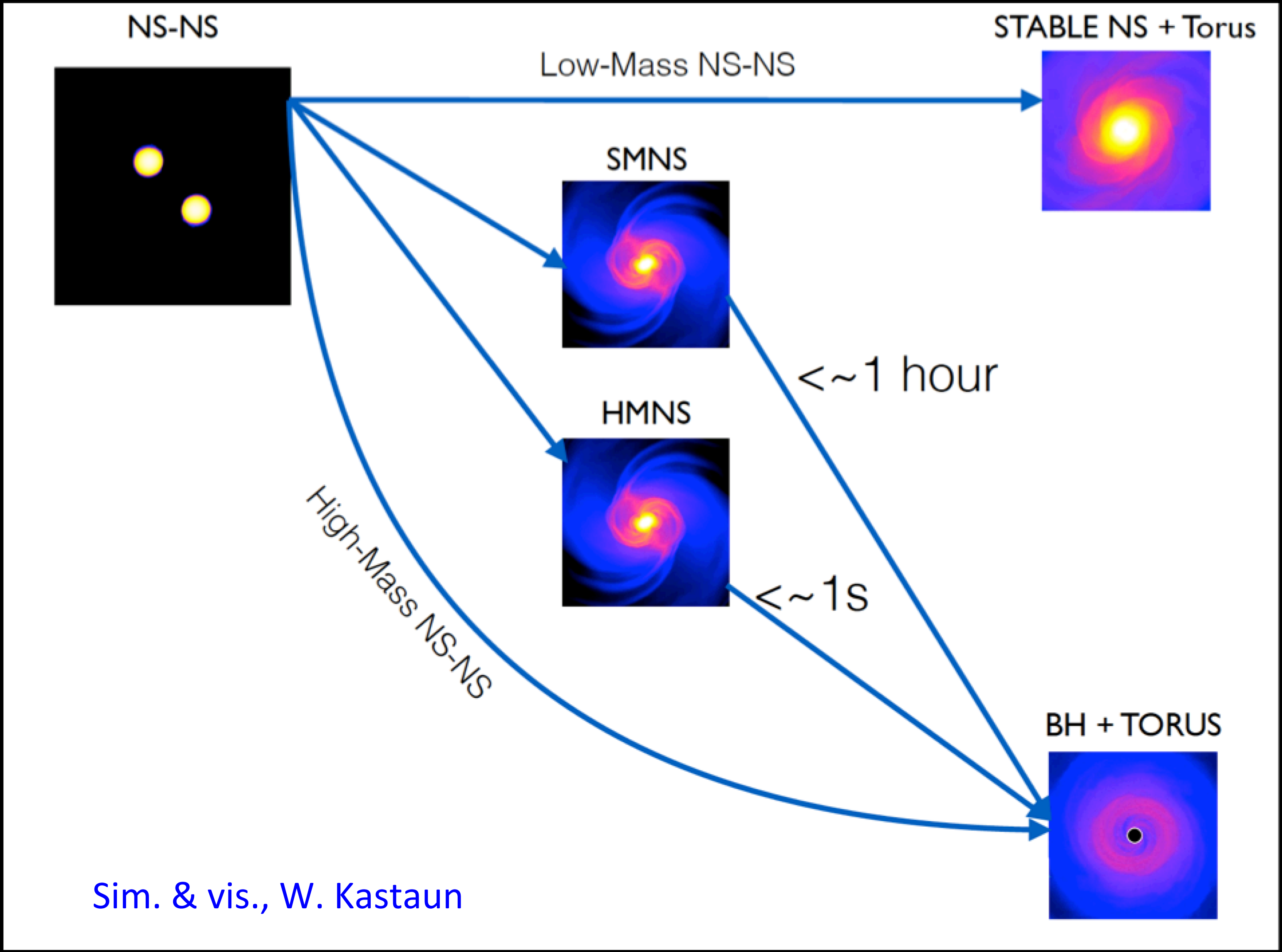
$$\Lambda = (2/3)k_2[(c^2/G)(R/m)]^5$$





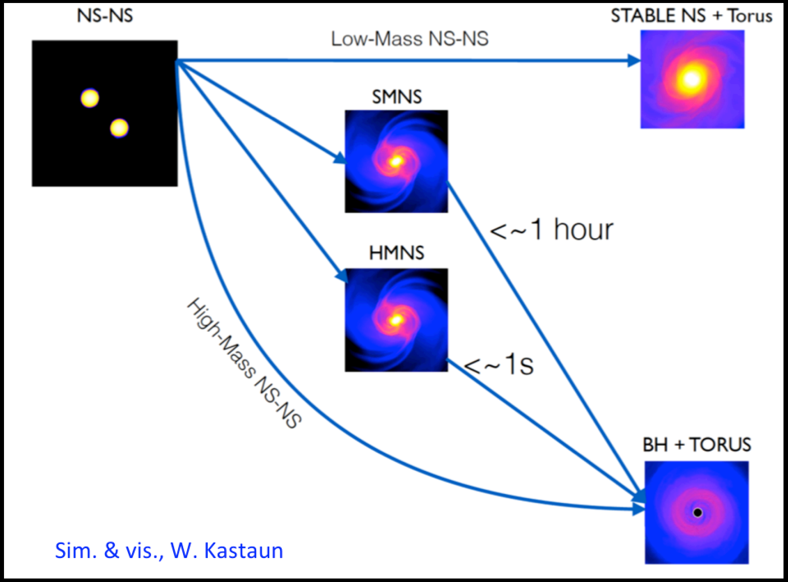
From only GWs we cannot say both components of the binary were NS

Post merger remnant?



Sim. & vis., W. Kastaun

Post merger remnant?



Sim. & vis., W. Kastaun

Abbott et al. 2017, ApJL,851

GW search:

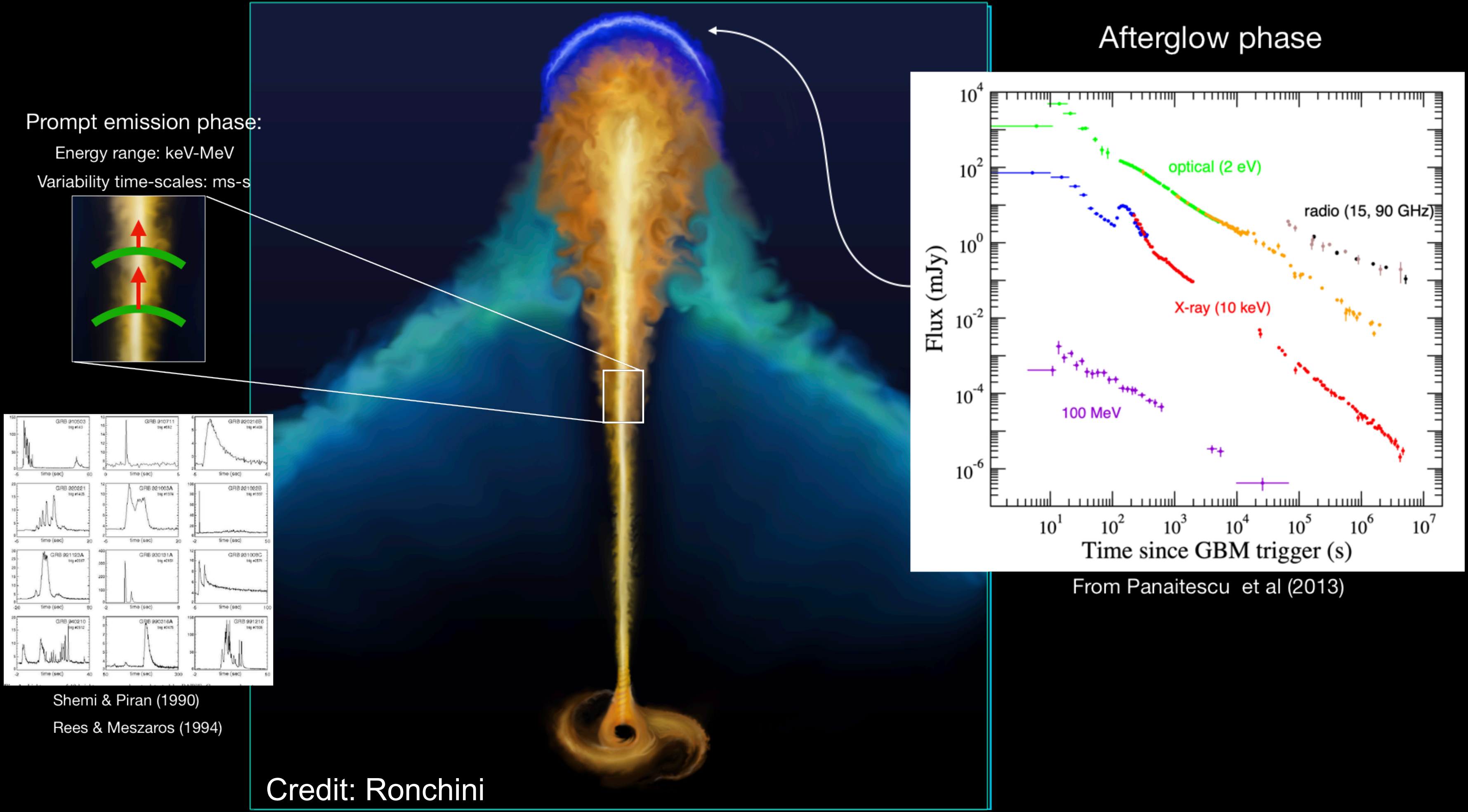
- **ringdown of BH** around 6 kHz

→ LIGO/Virgo response strongly reduced

- **short (tens of ms) and intermediate duration (≤ 500 s) GW signals** up to 4 kHz

→ no evidence of postmerger signals, but it cannot rule out short- or long-lived NS

EM non-thermal emission



Prompt emission phase:

Energy range: keV-MeV

Variability time-scales: ms-s

Shemi & Piran (1990)

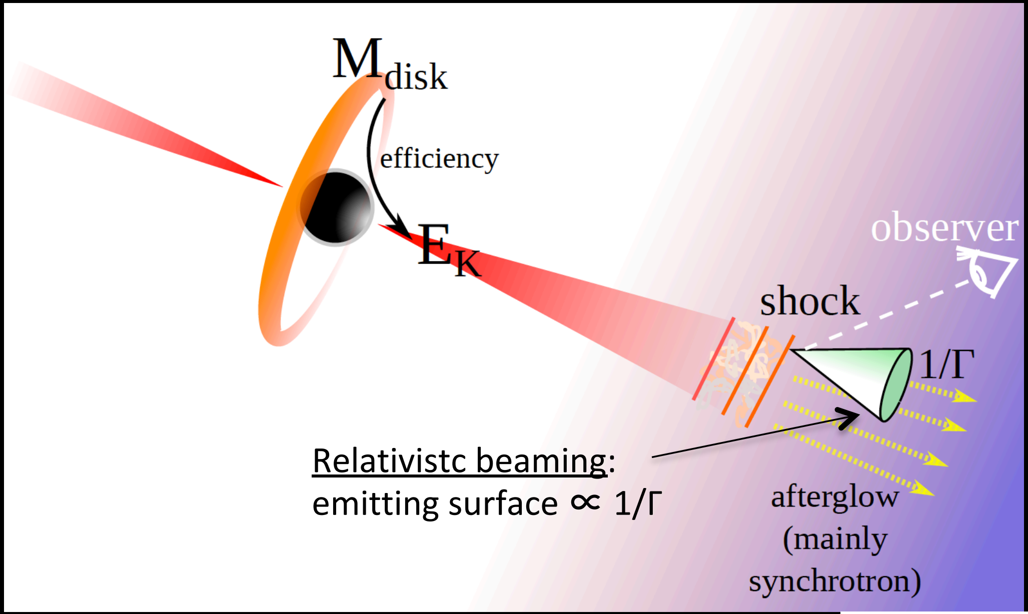
Rees & Meszaros (1994)

Credit: Ronchini

Afterglow phase

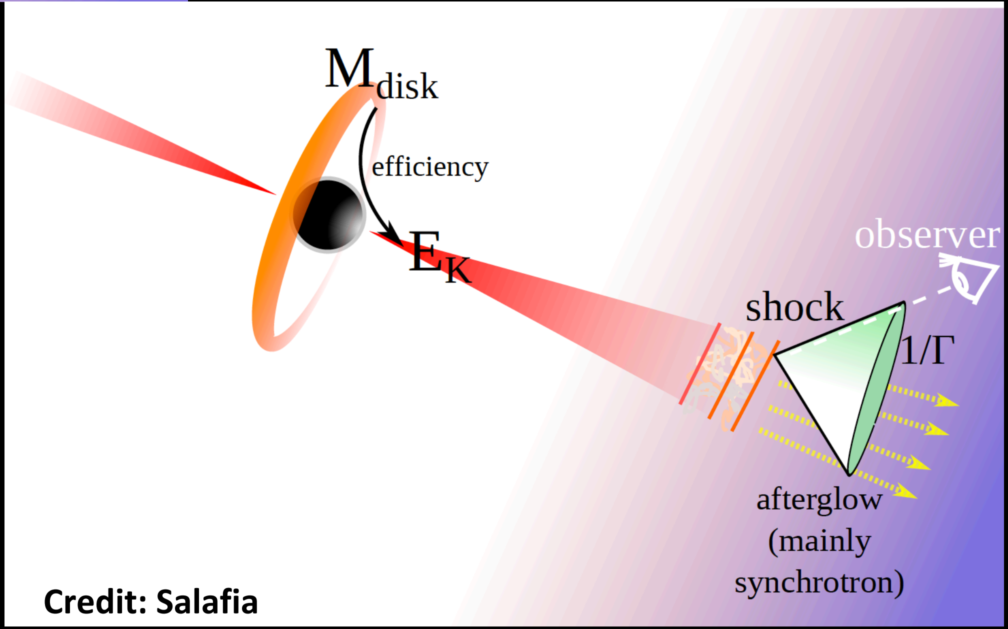
From Panaitescu et al (2013)

Short Gamma Ray Burst



Early EM emission detectable only by on-axis observers

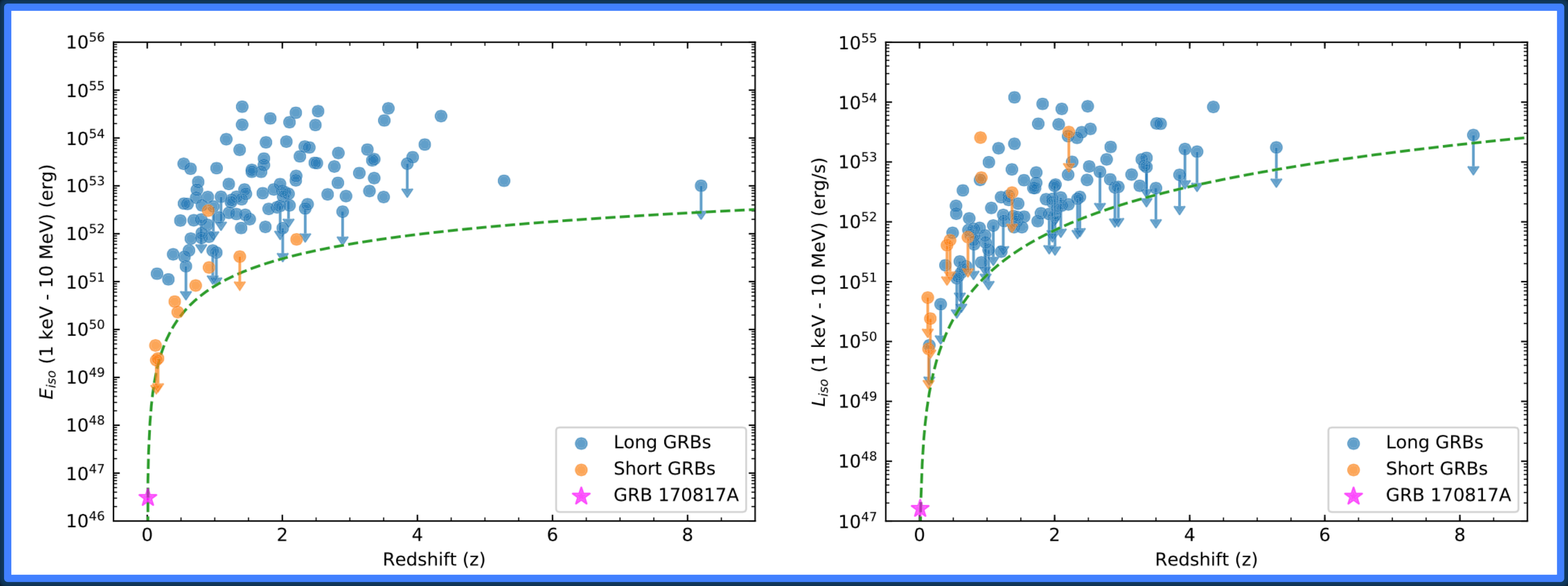
EM emission detectable also by off-axis observers



Credit: Salafia

GRB 170817A

- 100 times closer than typical GRBs observed by Fermi-GBM
- it is also "subluminous" compared to the population of long/short GRBs
- $10^2 – 10^6$ less energetic than other short GRBs



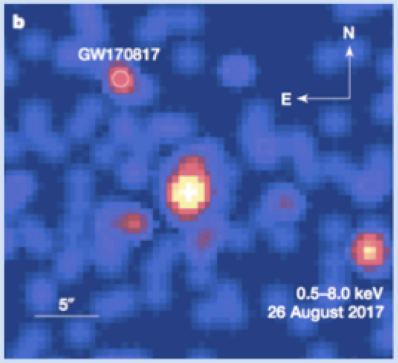
Abbott et al. 2017, APJL, 848, L13

Intrinsically sub-luminous event

or a classical short GRB viewed off-axis?

X-ray and radio emissions 9 and 16 days after the merger

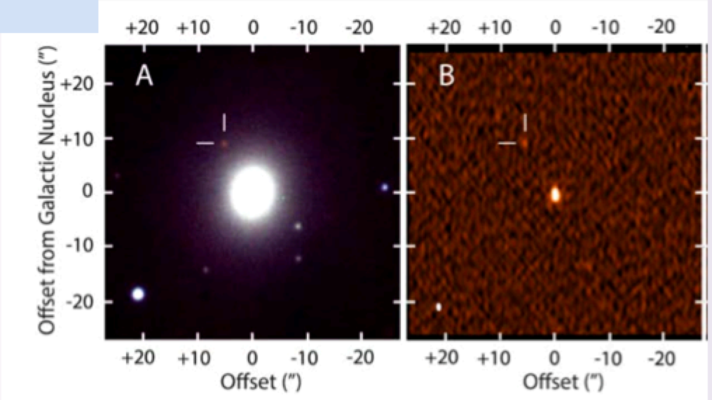
Chandra observation



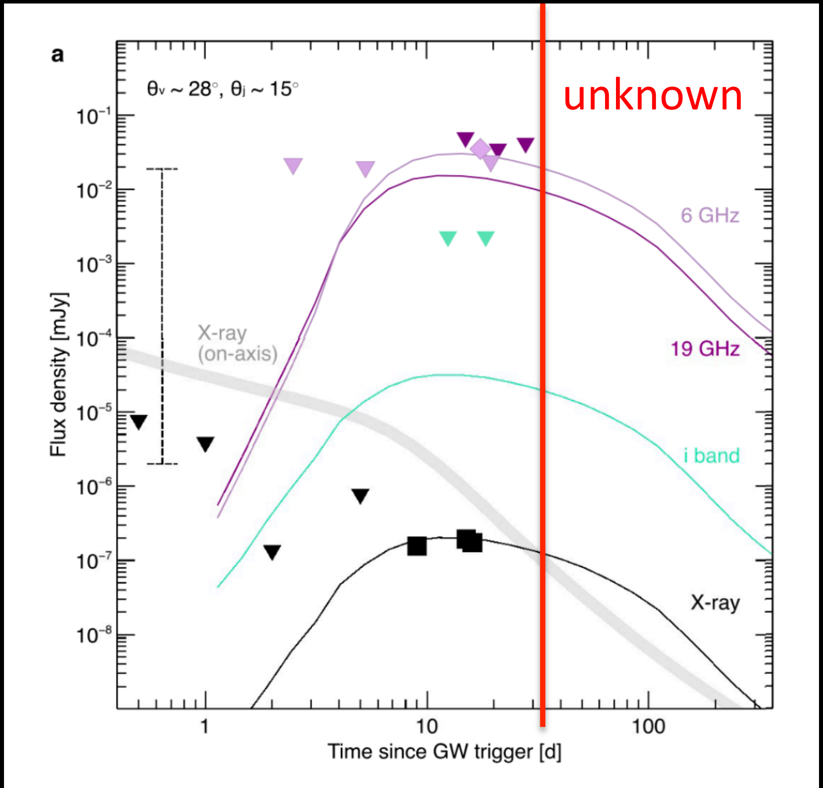
> “..Our observations are instead consistent with the onset of an off axis afterglow from the GRB jet. This would explain the low luminosity of the observed gamma-ray emission, and the lack of early afterglow detections.”

Troja, et al. Nature 2017

VLA observation

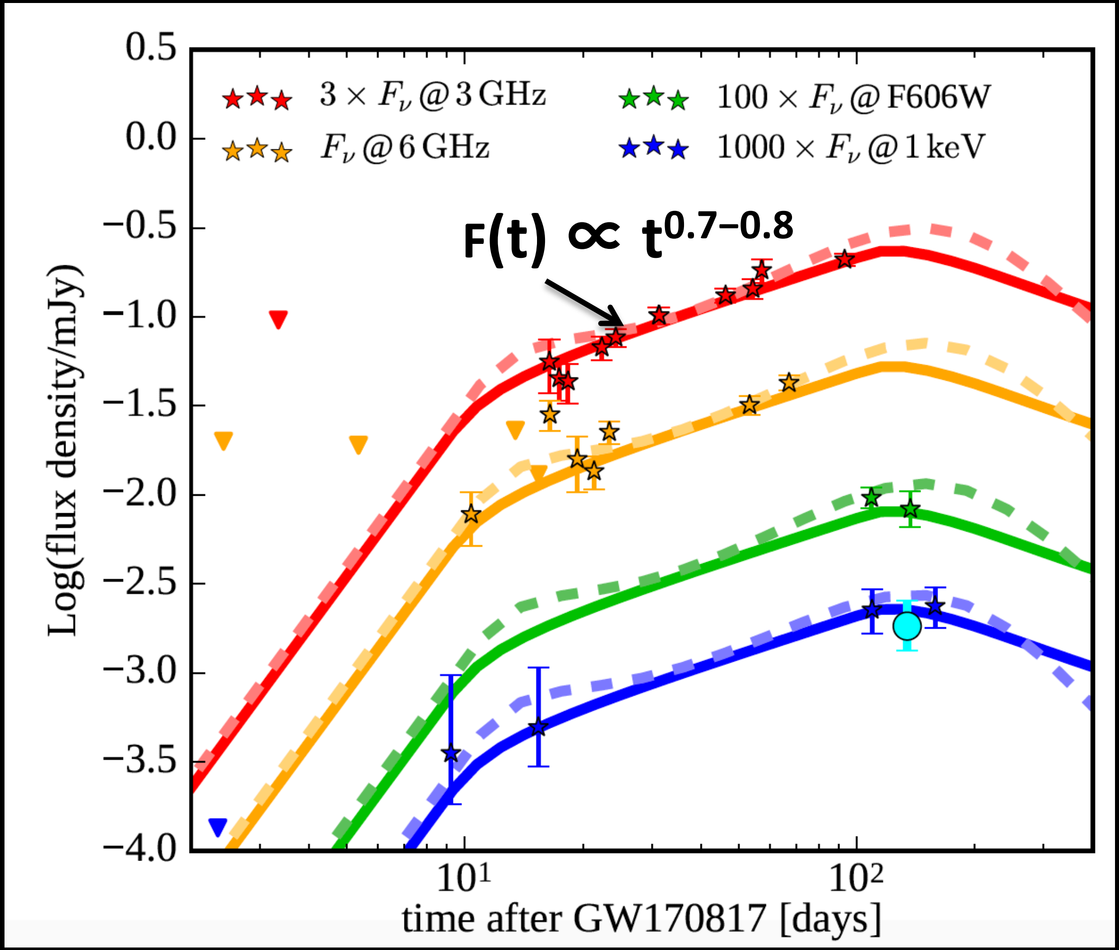


Hallinan et al. Science, 2017



First GRB observed off-axis?

After 150 days from the BNS merger…

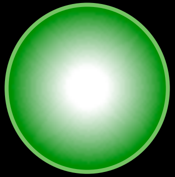


$F(t) \propto t^{0.7-0.8}$

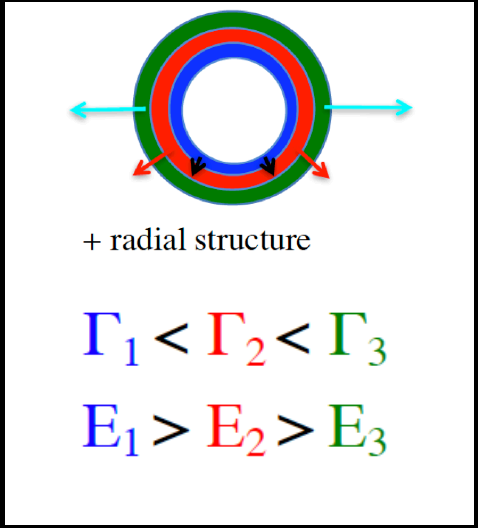
D'Avanzo et al. 2017, A&A

..unexpected slow achromatic flux–rise until ~ 150 days!

RADIAL or ANGULAR STRUCTURE?



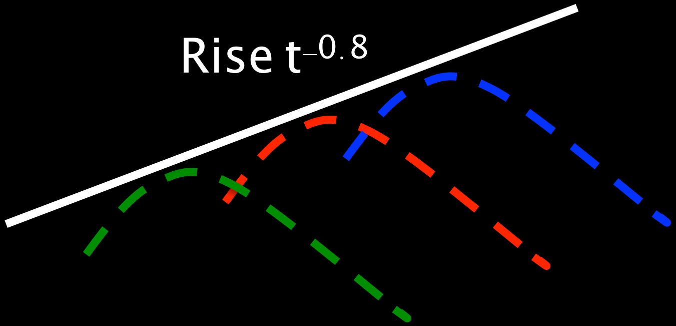
Mildly relativistic isotropic outflow (choked jet)



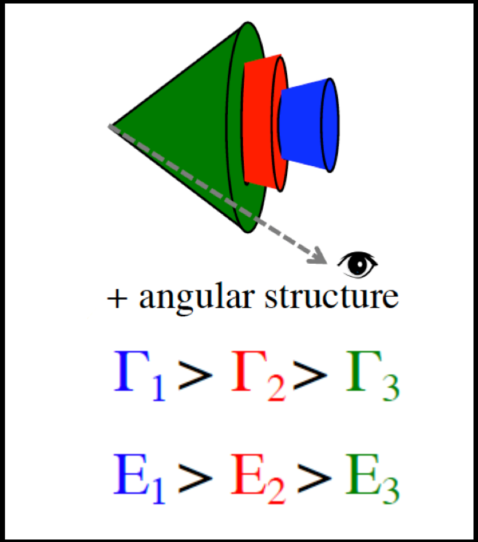
+ radial structure

$\Gamma_1 < \Gamma_2 < \Gamma_3$

$E_1 > E_2 > E_3$



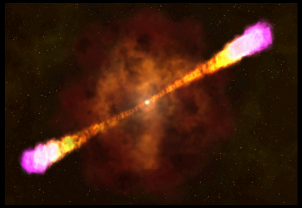
Structured Jet (successful) off-axis jet



+ angular structure

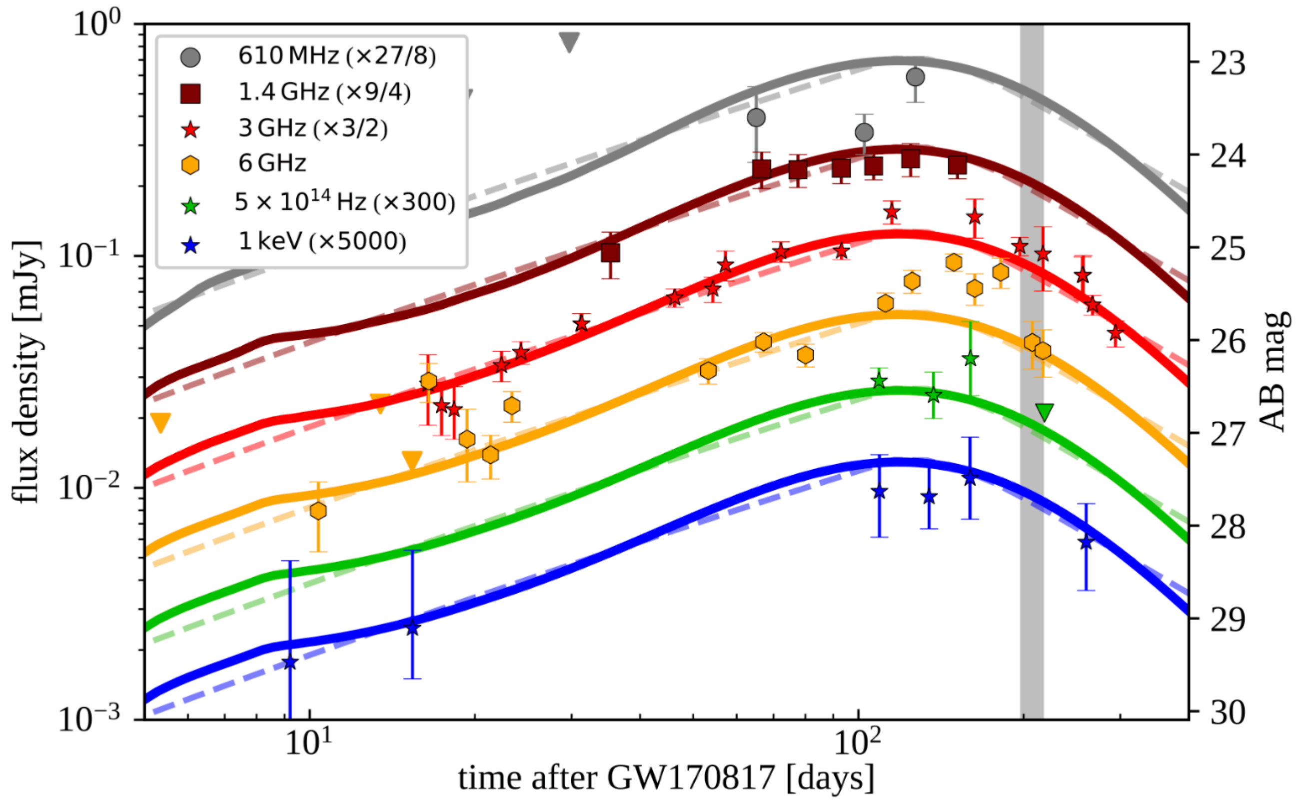
$\Gamma_1 > \Gamma_2 > \Gamma_3$

$E_1 > E_2 > E_3$

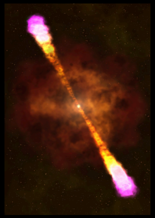


[see e.g. Rossi et al. 2002, Zhang et al. 2002, Ramirez-Ruiz et al. 2002, Nakar & Piran 2018, Lazzati et al. 2018, Gottlieb et al. 2018, Kasliwal 2017, Mooley et al. 2017, Salafia et al. 2017, Ghirlanda et al. 2019]

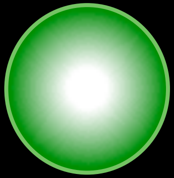
After 150 days from the BNS merger…decaying phase!



Ghirlanda et al. 2019



Solid lines



Dashed lines

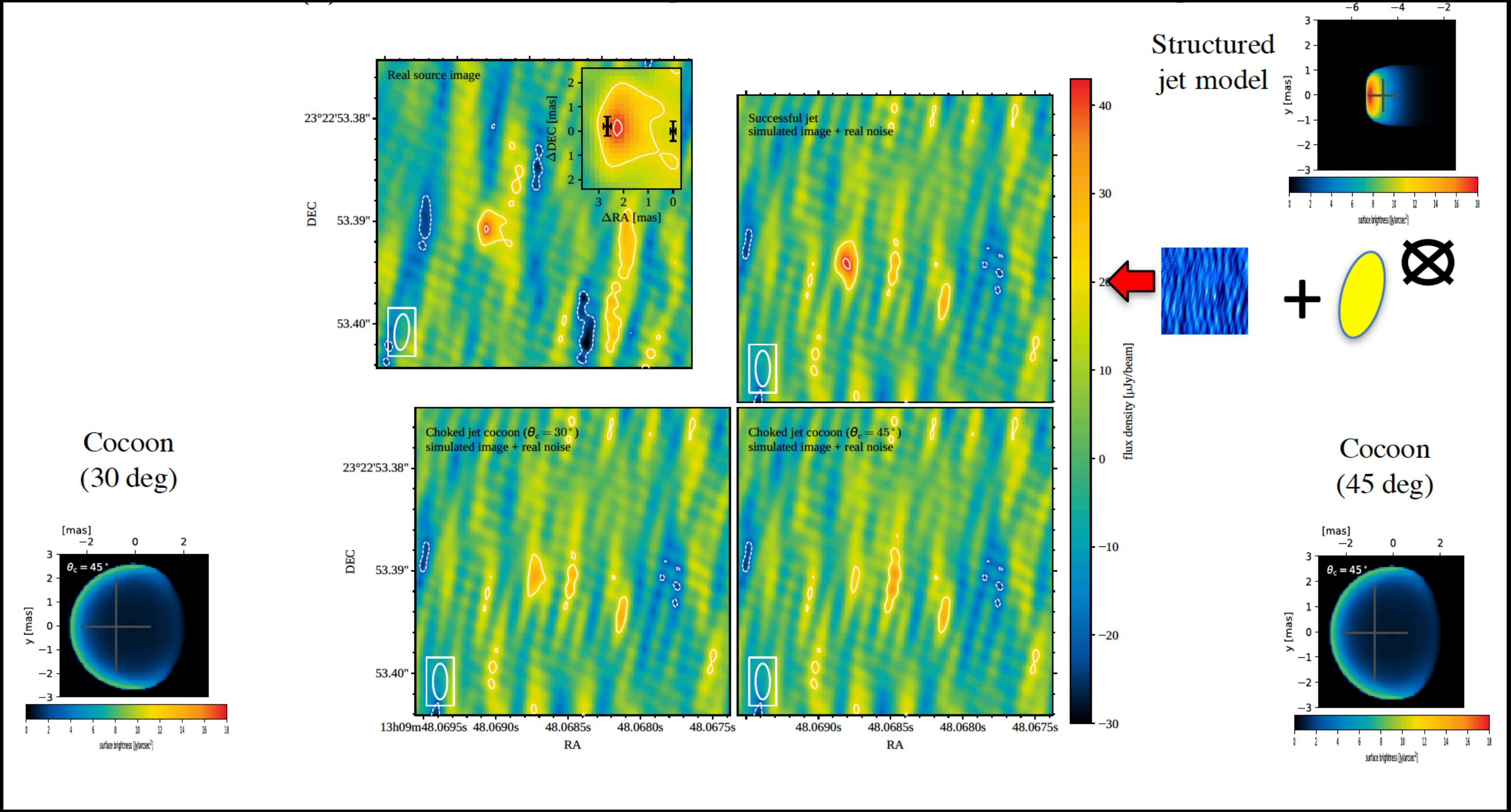
MULTI-WAVELENGTH LIGHT CURVES CANNOT DISENTANGLE THE TWO SCENARIOS!

[Margutti, et al. 2018, Troja, et al. 2018, D’Avanzo et al. 2018, Dobie et al. 2018, Alexander et al. 2018, Mooley et al. 2018, Ghirlanda et al. 2018]

SIZE CONSTRAINTS

Observations 207.4 days after BNS merger by global VLBI network of 33 radio telescopes over five continents constrain SOURCE SIZE < 2 mas

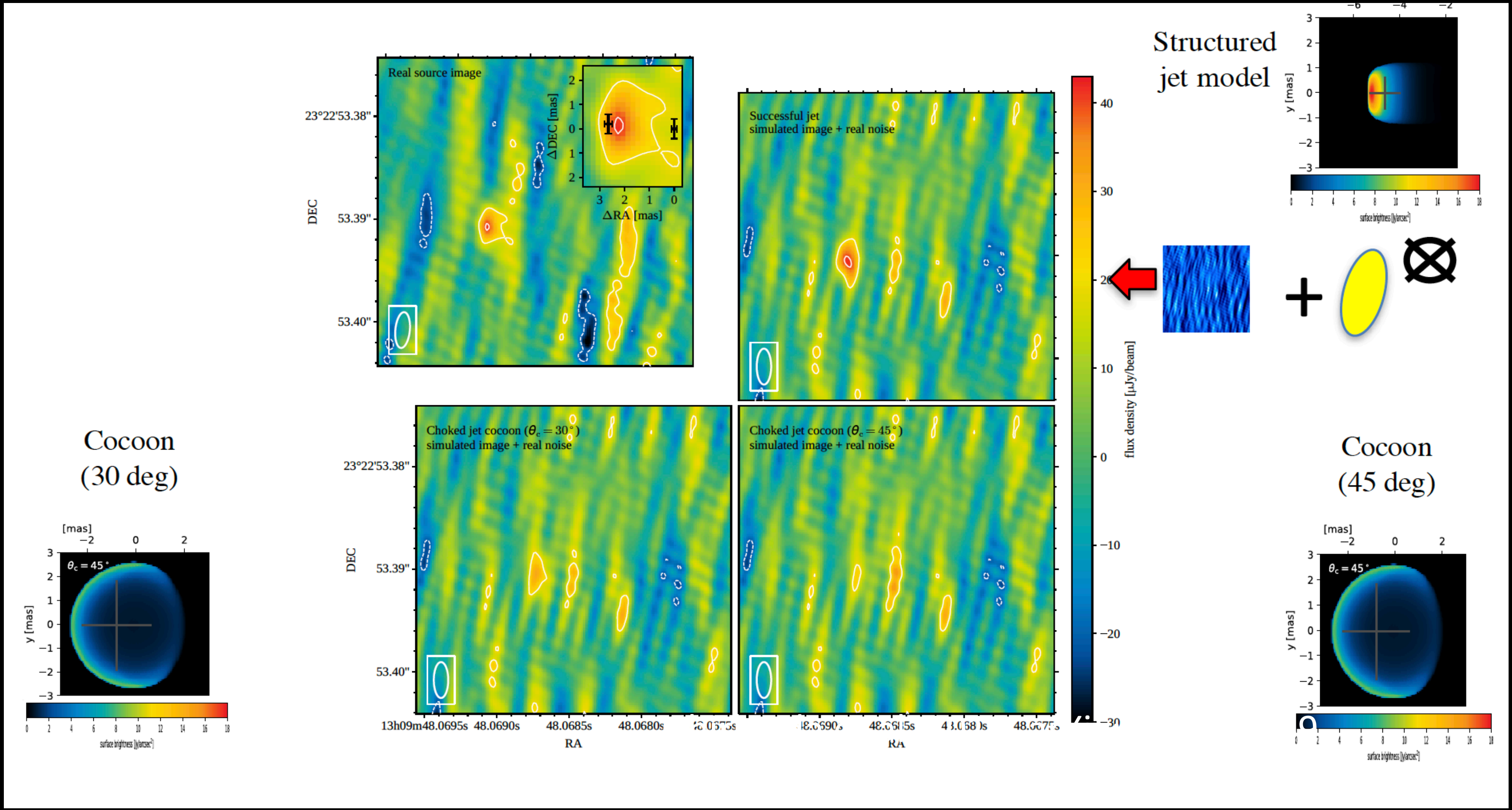
Ghirlanda et al. 2019, Science

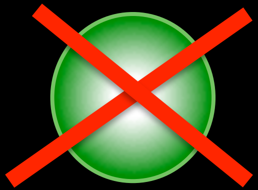


See also Mooley, Deller, Gottlieb et al. 2018

SIZE CONSTRAINTS

Ghirlanda et al. 2019, Science





Ruled out nearly isotropic, mildly relativistic outflow , which predicts proper motion close to zero and size > 3 mas after 6 months of expansion

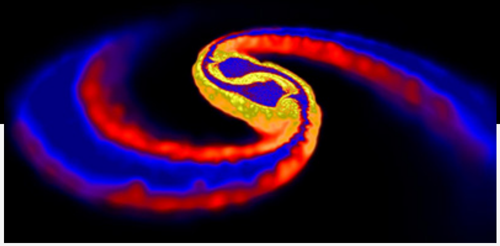
Ghirlanda et al. 2019, Science

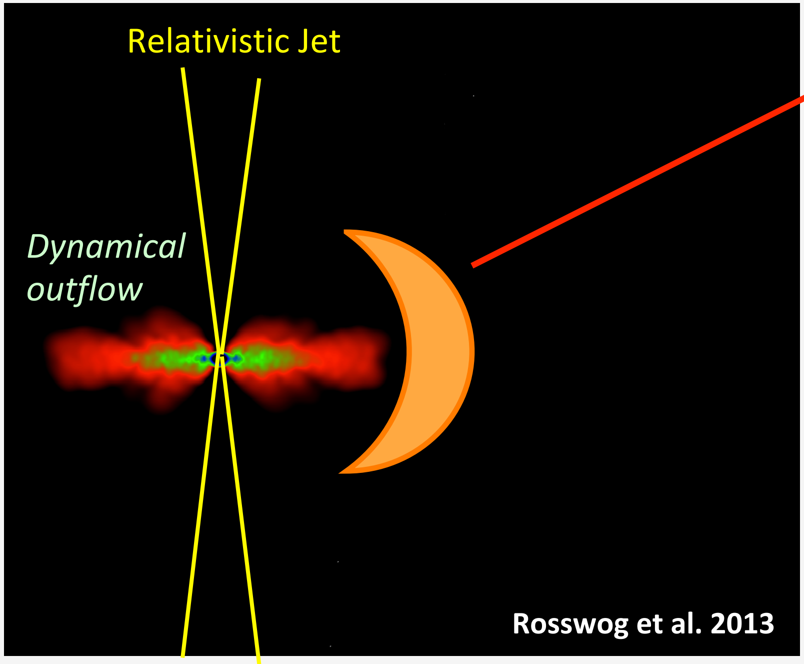
A relativistic energetic and narrowly-collimated jet successfully emerged from neutron star merger GW170817!

Thermal-emission

Credit: NASA's Goddard Space Flight Center/CI Lab

Kilonova





Rosswog et al. 2013

Tidal-tail ejecta → r-process

Neutron capture rate much faster than decay, special conditions: T > 10^9 K, high neutron density 10^{22} cm^{-3}

↓

nucleosynthesis of heavy nuclei

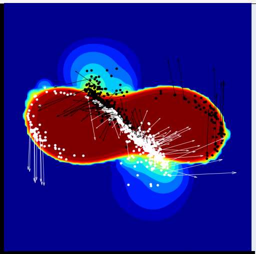
↓

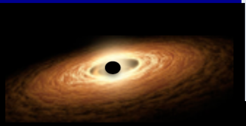
radioactive decay of heavy elements

↓

Power short lived RED-IR signal (days)

Li & Paczynski 1998; Kulkarni 2005 Metzger et al. 2010; Tanaka et al. 2014; Barnes & Kasen 2013





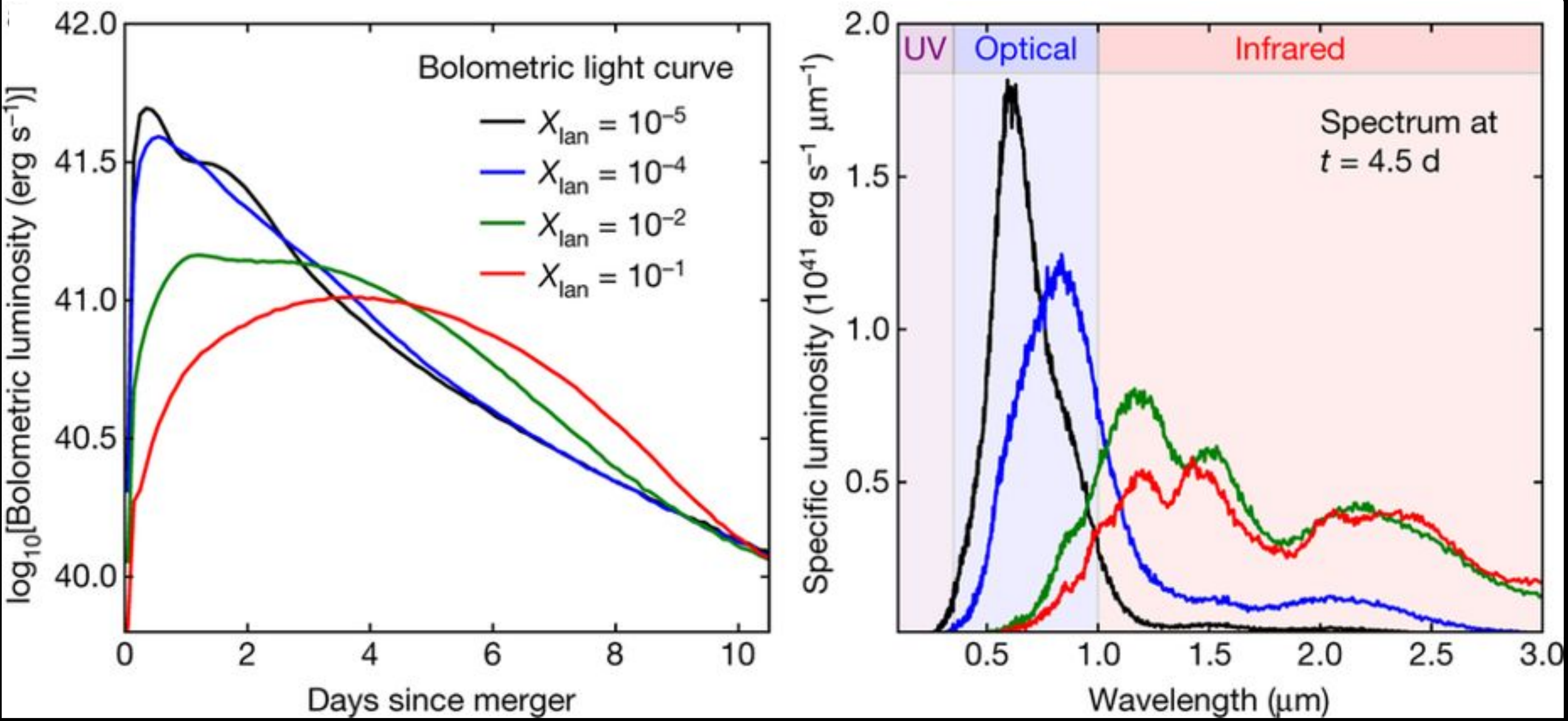
Shock-heated ejecta, accretion disc wind outflow, secular ejecta

- → Weak interactions: neutrino absorption, electron/positron capture
- → Higher electron fraction, no nucleosynthesis of heavier element
- → Lower opacity
- → brief (~ 2 day) **blue optical transient**

Kasen et al. 2015, Perego et al. 2014, Wanajo et al. 2010

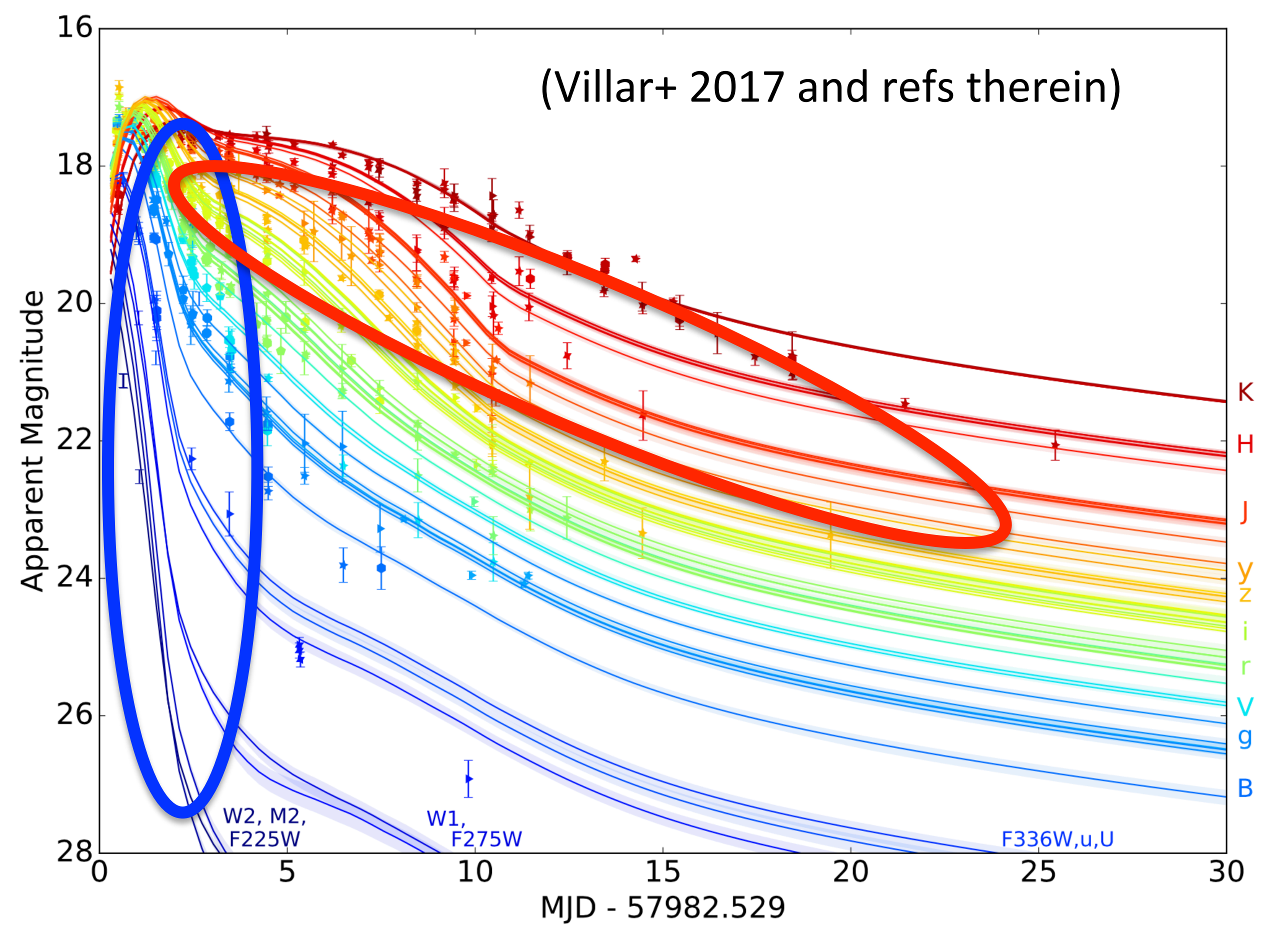
Observables: expectations

Kasen et al. 2017



Light curve shape (duration and peak luminosity) and spectarl shape are dramatically affected by lanthanides

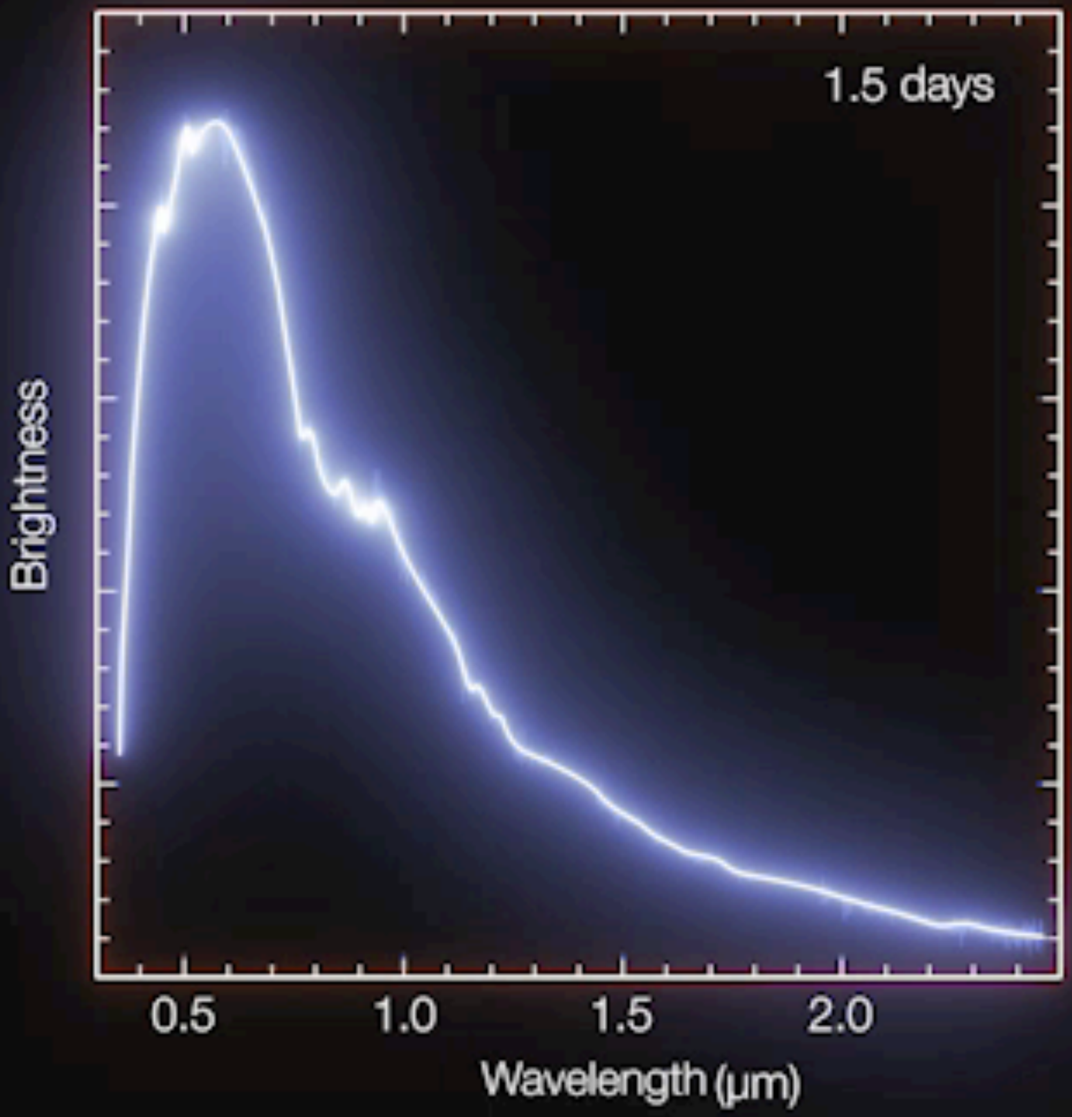
UV/Optical/NIR Light Curves



Extremely well characterized photometry of a Kilonova:

thermal emission by radiocative decay of heavy elements synthesized in multicomponent (2-3) ejecta!

ESO-VLT/X-Shooter



Credit: ESO/E. Pian et al./S. Smartt & ePESSTO/L. Calçada

EJECTED MASS ~ 0.03 – 0.05 $M_\odot$

EXPANSION VELOCITY ~ 0.1 – 0.3 c

First spectral identification of the kilonova emission

- the data revealed signatures of the radioactive decay of **r-process nucleosynthesis**

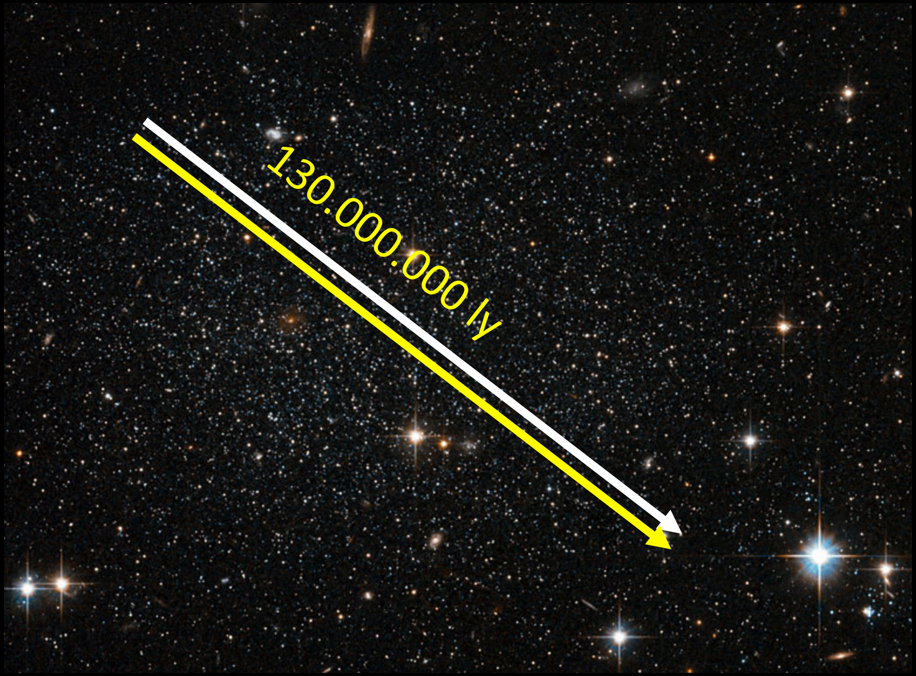
(Pian et al. 2017, Smartt et al. 2017)

- BNS merger **site for heavy element production in the Universe!**

(Cote et al. 2018, Rosswog et al. 2017)

Multi-messenger studies

GRB/GW FUNDAMENTAL PHYSICS/COSMOLOGY



GRB/GW delay

$$\Delta t = (1.74 \pm 0.05)\ s$$

and 40 Mpc distance
→ difference speed of gravity
and speed of light between

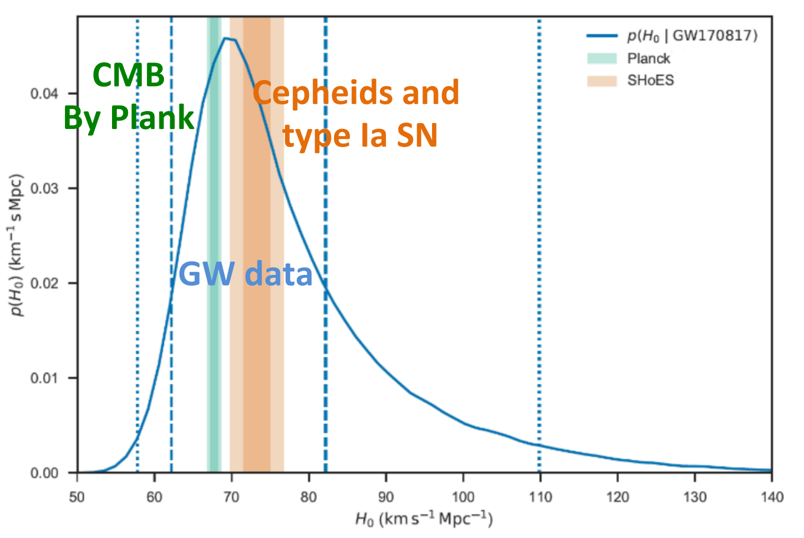
$$-3 \times 10^{-15} \leqslant \frac{\Delta v}{v_{\mathrm{EM}}} \leqslant +7 \times 10^{-16}$$

GWs propagate at the speed of light to within 1:10^{15}!

LVC 2017, APJL, 848, L13

Consequences of multi-messenger detection of GW170817 for cosmology →
Constraint on the speed of GWs ruled out many classes of modified gravity models
(quartic/quintic Galileons, TeVeS, MOND-like theories, see, e.g., Baker et al. ’17, Creminelli & Vernizzi ’17)

GRAVITATIONAL-WAVE COSMOLOGY



Recession velocity /redshift

GW distance

$$v_H = H_0 d$$

Combining the distance measured from GWs

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

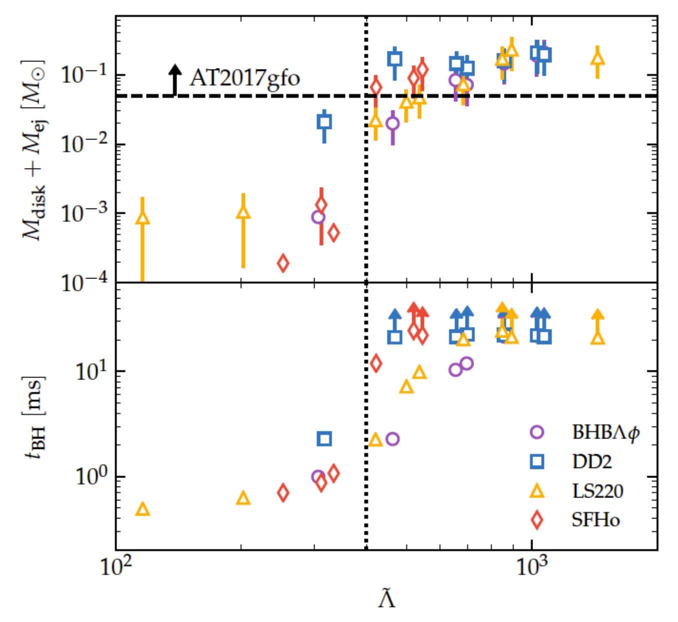
and NGC4993 recession velocity

$$\rightarrow H_0 = 70.0^{+12.0}_{-8.0}\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$$

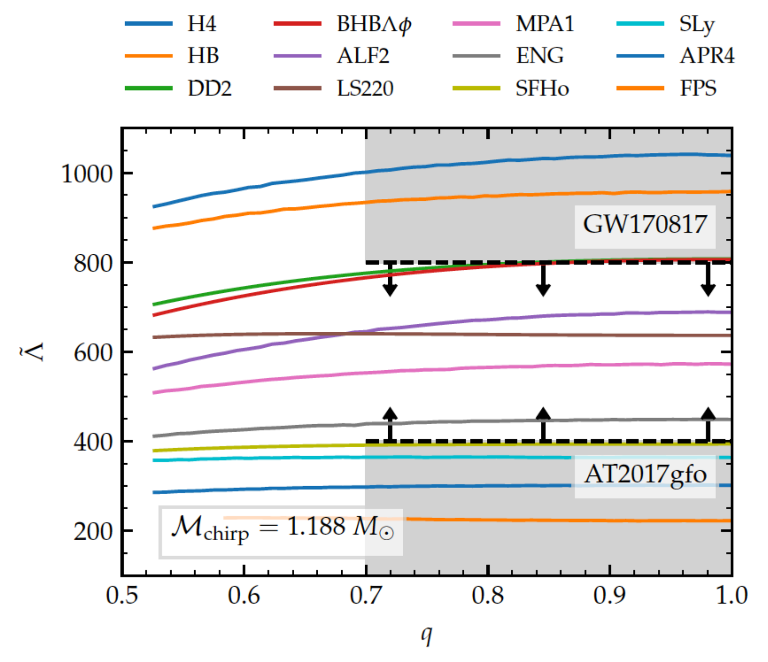
Abbott et al. 2017, Nature, 551, 85A

MULTIMESSENGER CONSTRAINTS ON NUCLEAR EOS

Simulations in NR



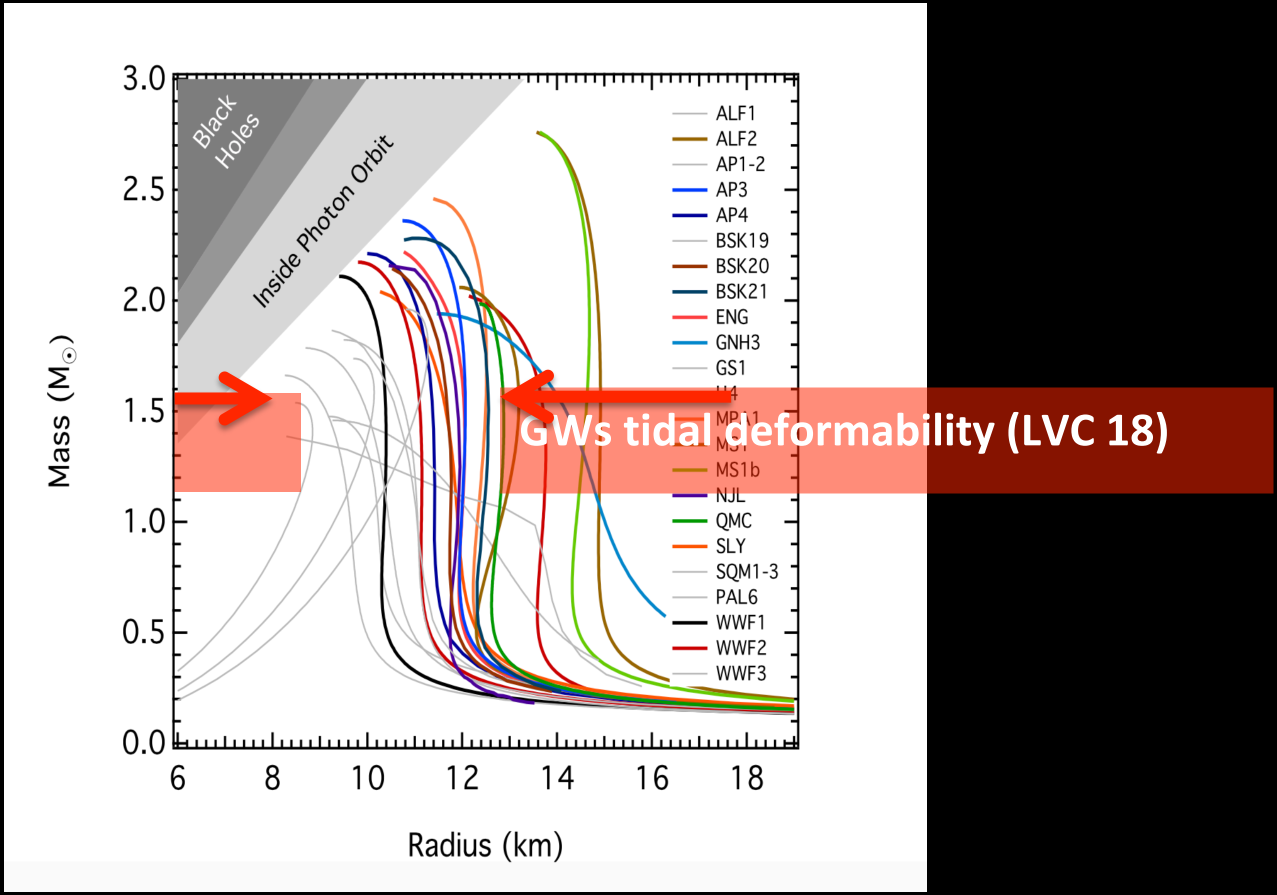
EM observations → Mej,tot > 0.05Mo suggests a lower limit Λ > 400



EM observations exclude very soft EOS!

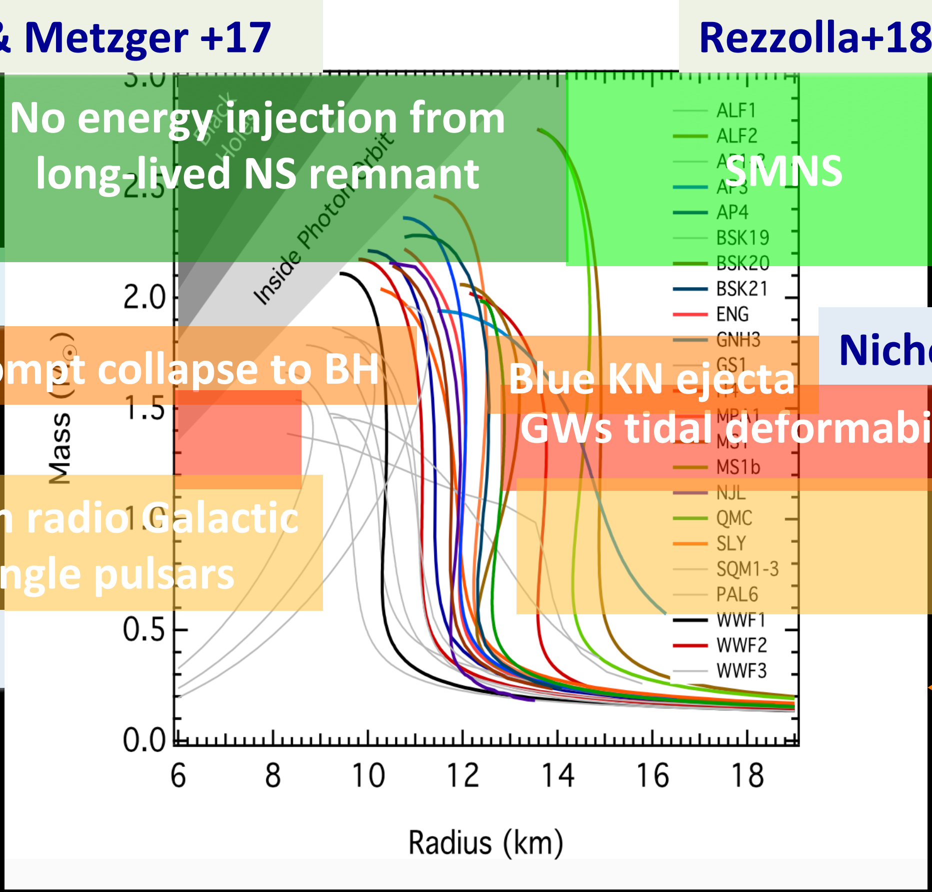
Radice, Perego, Zappa, Bernuzzi 2017

EM constraints on the TYPE OF REMNANT and multi-messenger constraints on RADII and maximum MASS of (TOV) NSs



GWs tidal deformability (LVC 18)

EM constraints on the TYPE OF REMNANT and multi-messenger constraints on RADII and maximum MASS of (TOV) NSs



Margalit & Metzger +17

Rezzolla+18

No energy injection from long-lived NS remnant

SMNS

Bauswein+17

No prompt collapse to BH

Nicholl+ 17

Blue KN ejecta

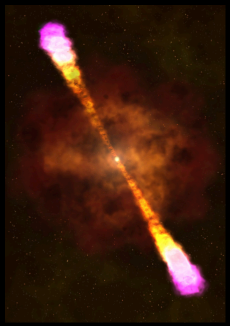
GWs tidal deformability (LVC 18)

Mass priors from radio Galactic double NS, single pulsars

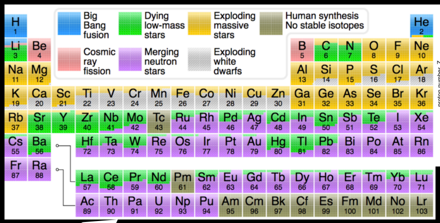
Soumi+ 18

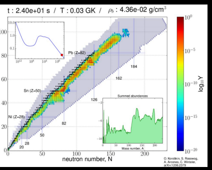
Radioactively powered transients

Relativistic astrophysics



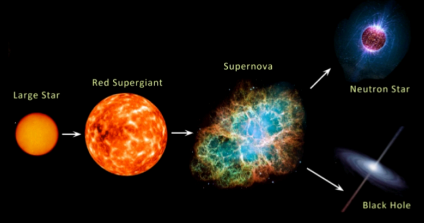
Nucleosynthesis and enrichment of the Universe



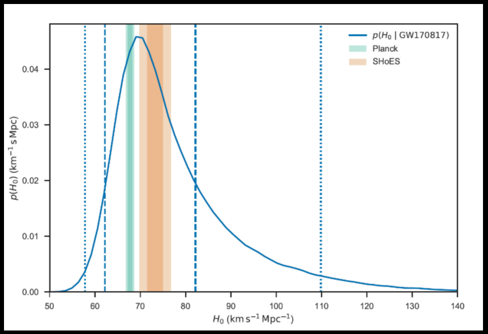


GW170817

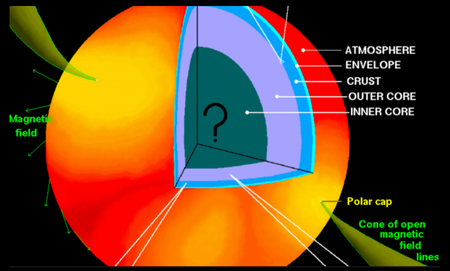
Compact object formation and evolution



Cosmology

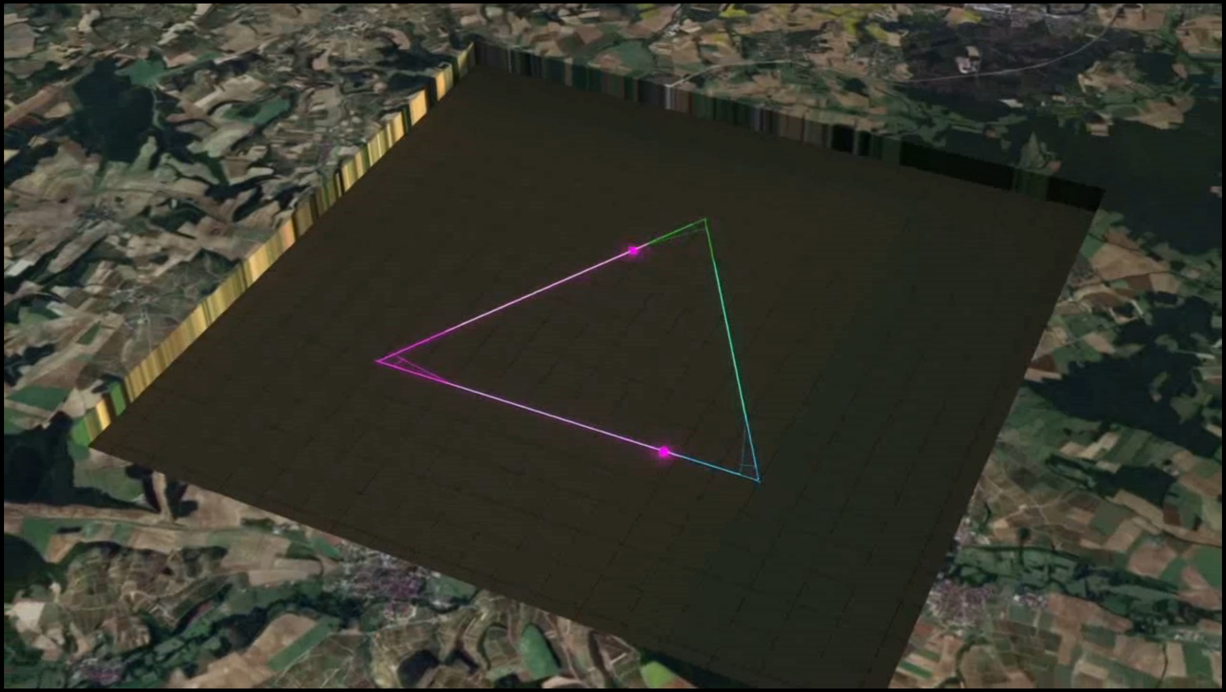


Nuclear matter physics

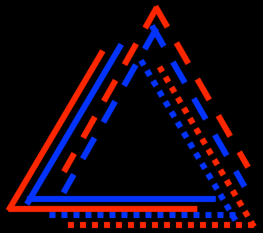


The future of GW and Multimessenger astronomy

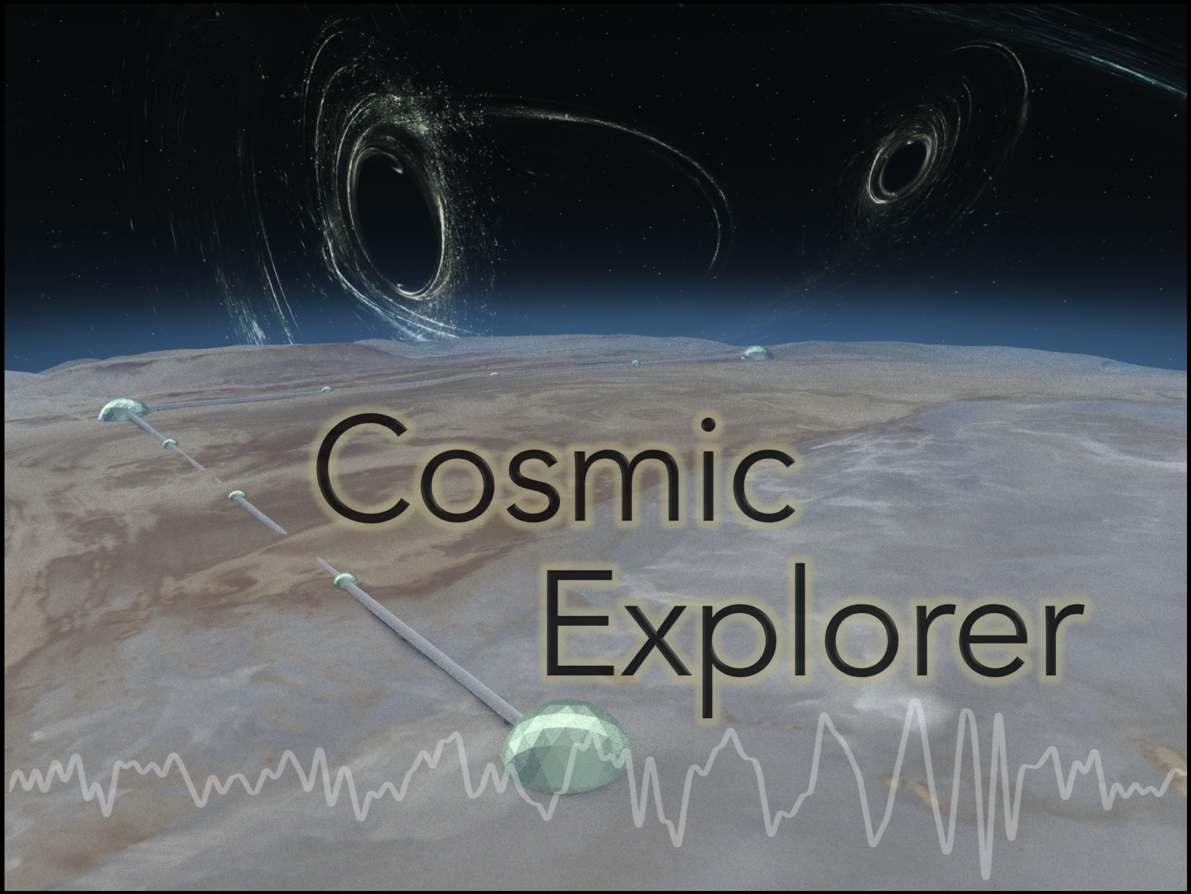
ET: the European 3G GW observatory concept



Triangular shape
Arms: 10 km
Underground
Cryogenic
Increase laser power
Xylophone
...

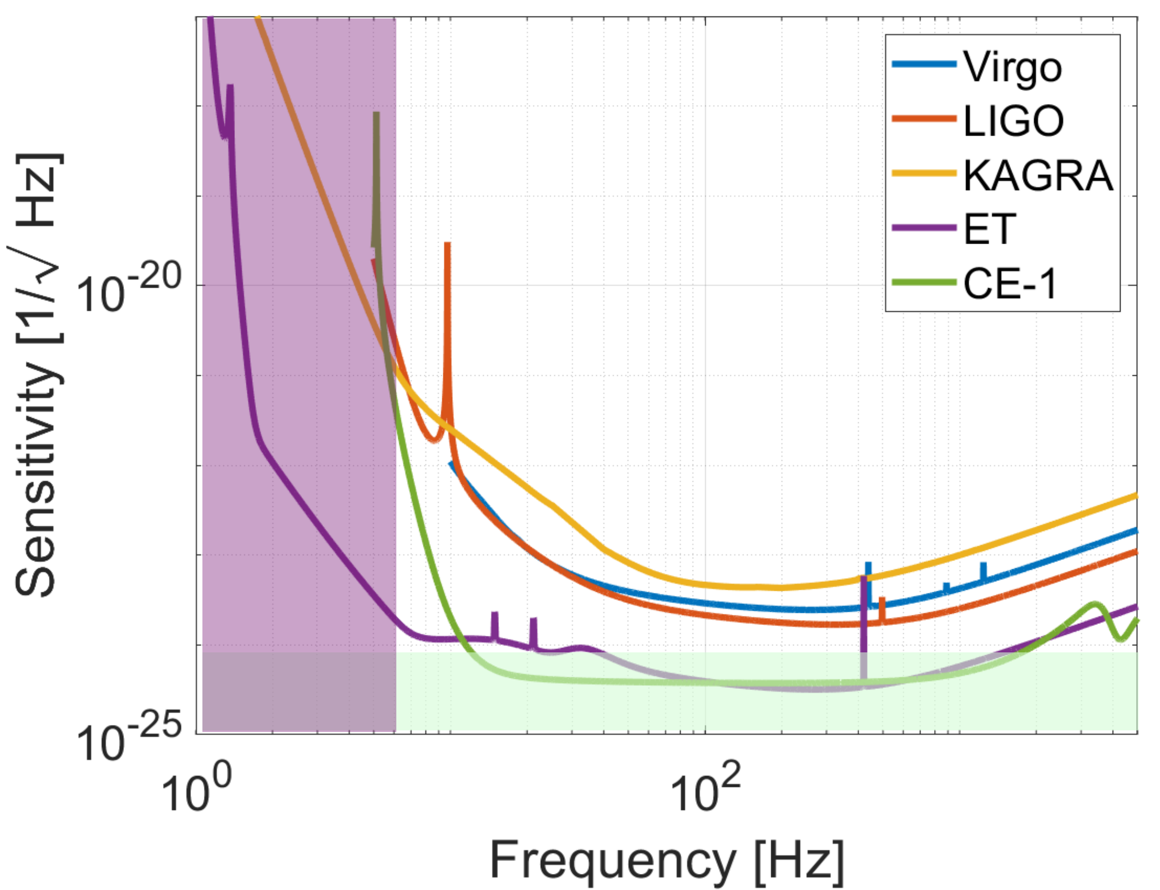


3G effort worldwide



NSF funded in 2018 the Conceptual Design Study of a 3G facility: Cosmic Explorer: 40km – L shaped detector

EXPECTED SENSITIVITY

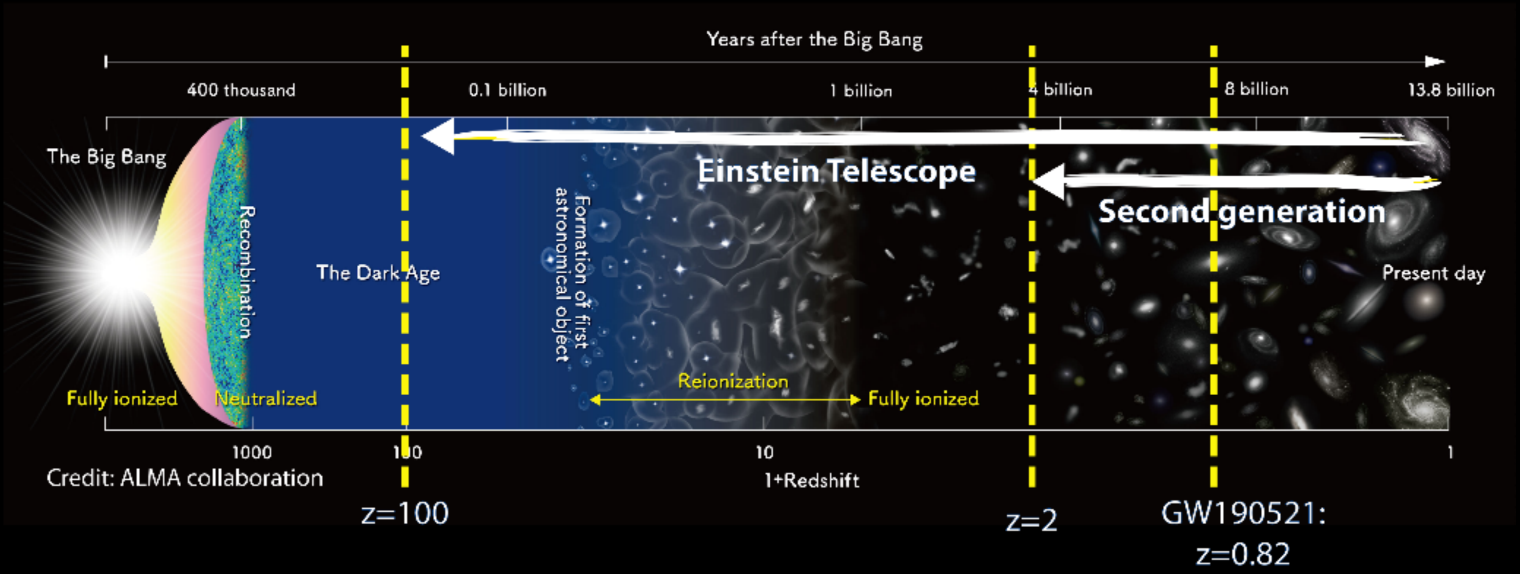


- Factor 10 better (x1000 Volume) than 2G detectors
- Wide frequency, with special attention to low frequency (few Hz)

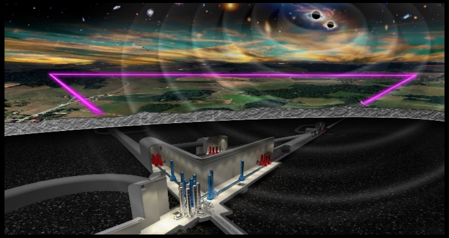
The ET sensitivity will make it possible:

- Large distances back to the EARLY UNIVERSE

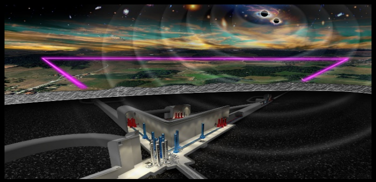
Detection horizon for black-hole binaries



Credit: ALMA collaboration

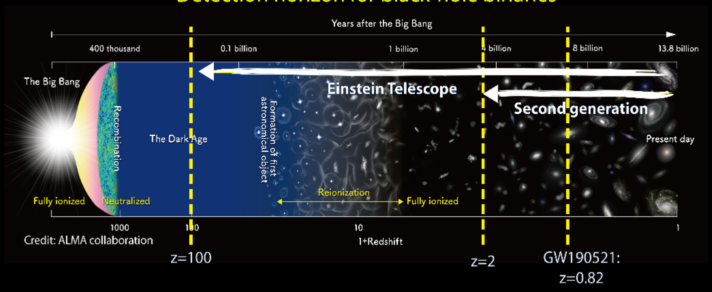


The ET sensitivity will make it possible:



- Large distances back to the EARLY UNIVERSE

Detection horizon for black-hole binaries

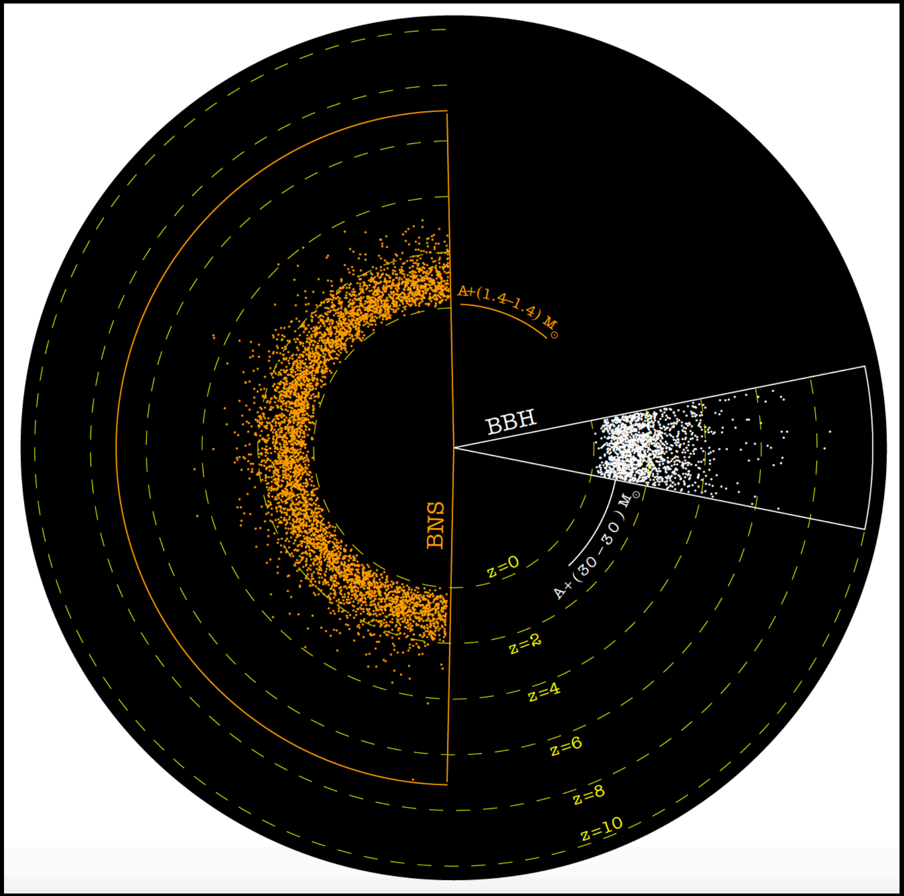


Credit: ALMA collaboration

- POPULATION:
  increase number of detections

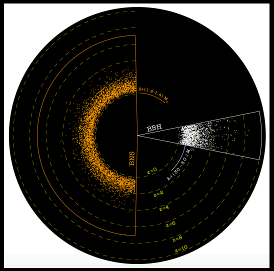
10^5 BNS detections per year

10^5 BBH detections per year

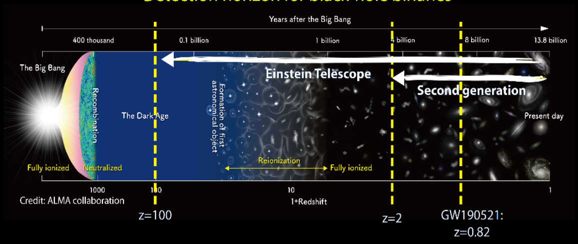


The ET sensitivity will make it possible:

- EARLY UNIVERSE
- POPULATION

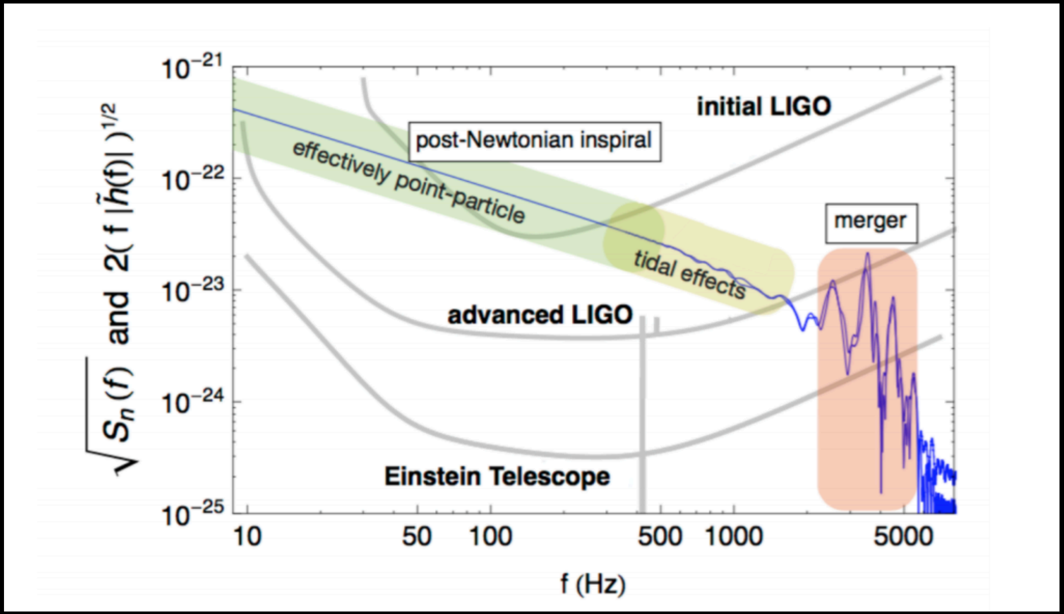


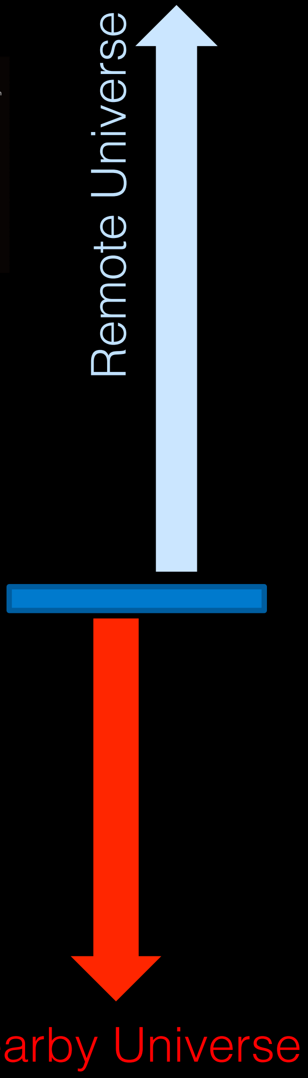
Detection horizon for black-hole binaries



Credit: ALMA collaboration

- PRECISE GW ASTRONOMY: exceptional parameter estimation accuracy for very high SNR events



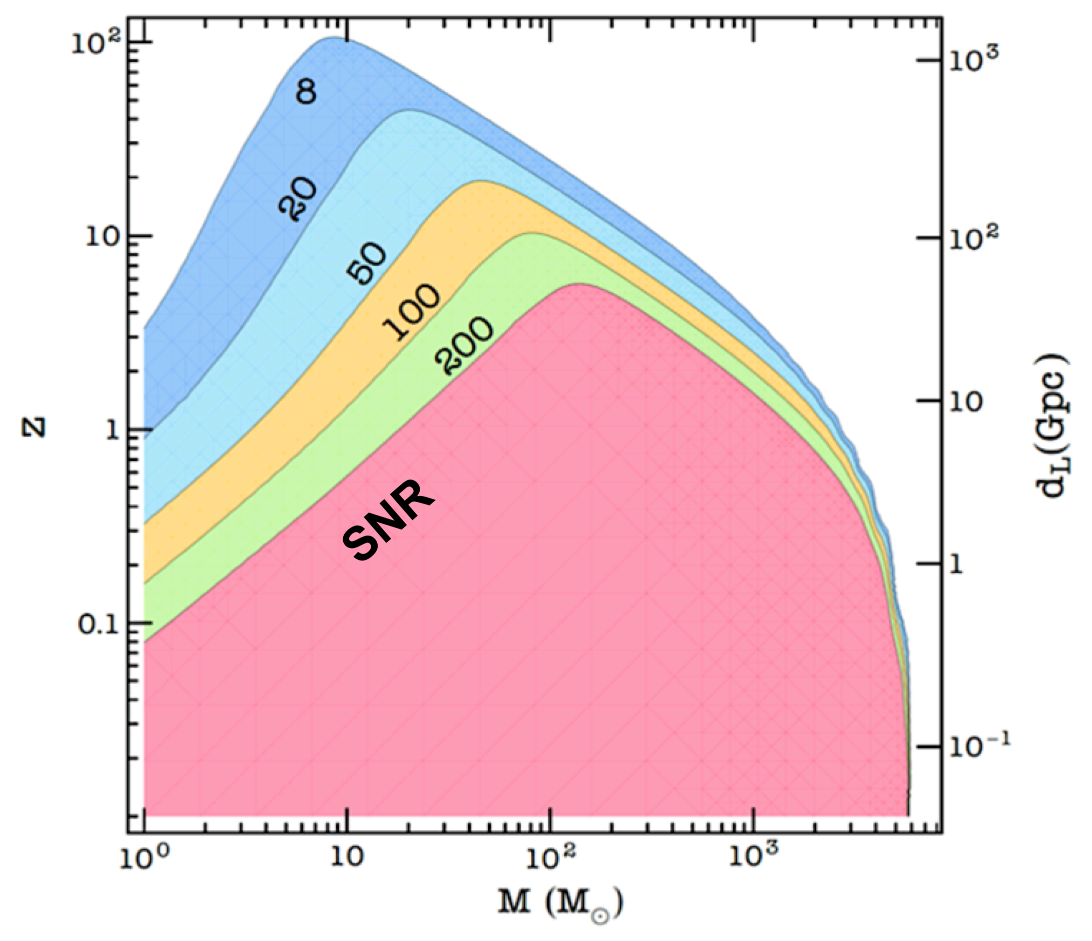


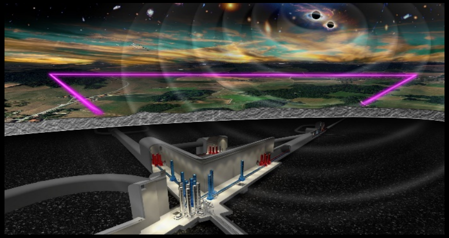
Remote Universe

Nearby Universe

The ET wide frequency band will make it possible:

- Access UNEXPLORED MASS up to 10^3 Mo





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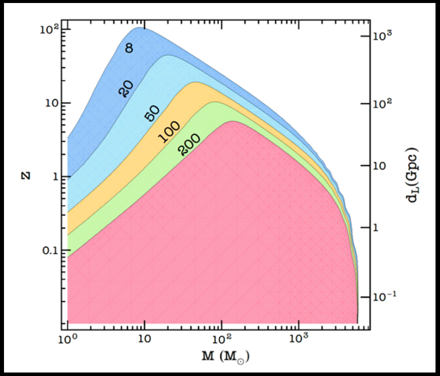
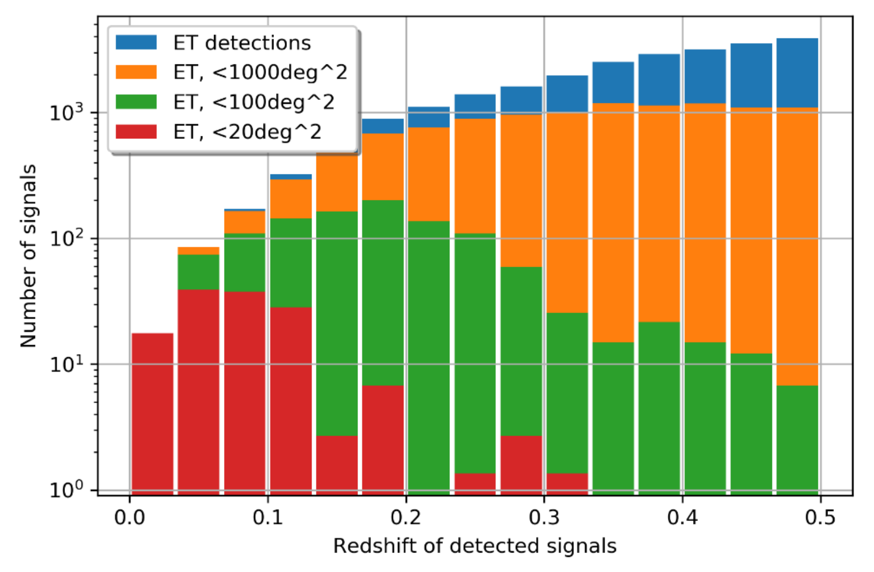
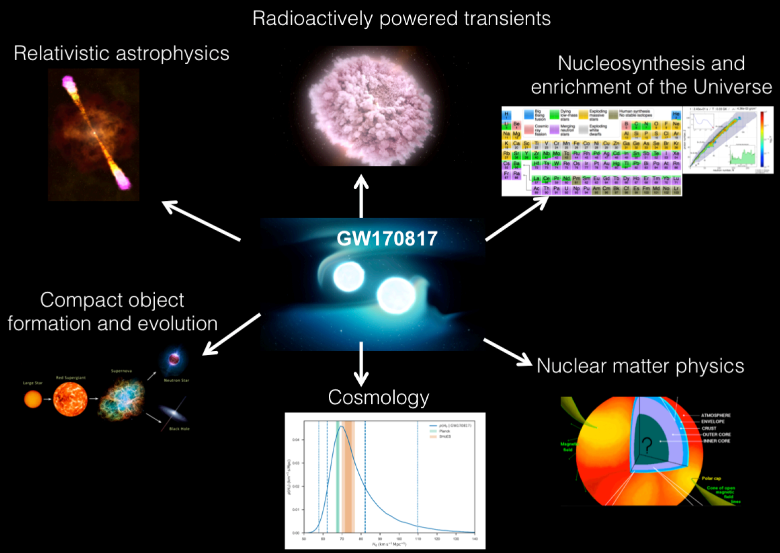
- Access UNEXPLORED MASS up to 10^3 Mo



- ET sky-localization capabilities



BNS simulation



Radioactively powered transients

Relativistic astrophysics

Nucleosynthesis and enrichment of the Universe

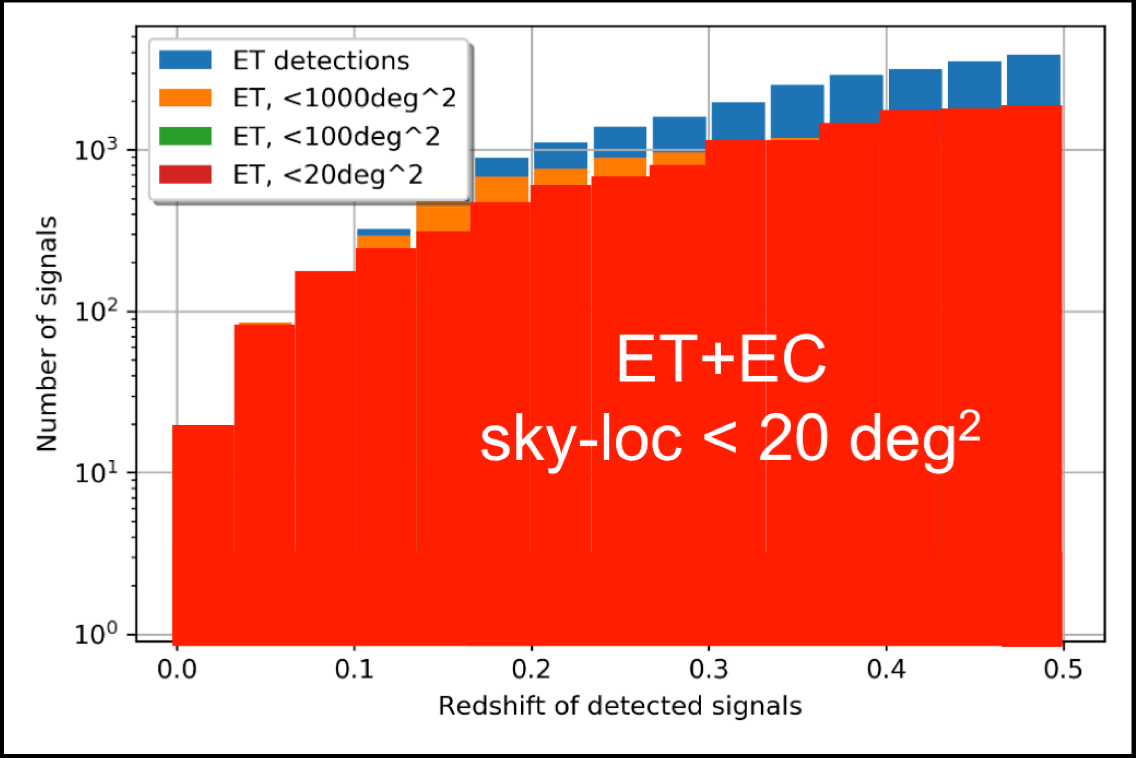
Compact object formation and evolution

Cosmology

Nuclear matter physics

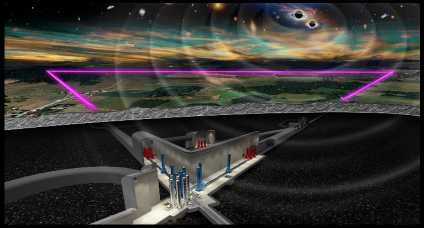
Network sky-localization capabilities

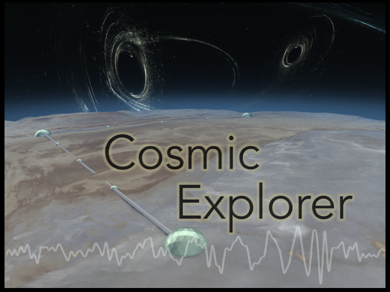
ET sky-localization capabilities

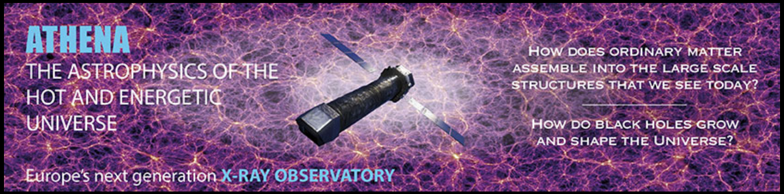


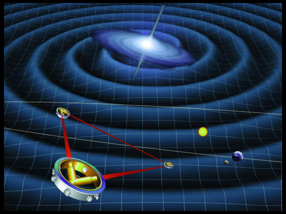
ET+EC

sky-loc < 20 deg^2









AMEGO

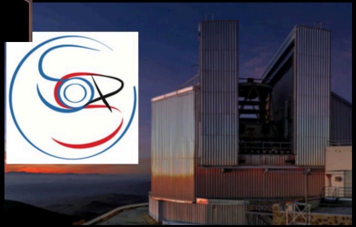
ALL-SKY MEDIUM ENERGY GAMMA-RAY OBSERVATORY

HERMES SP

theseus

TRANSIENT HIGH ENERGY SKY AND EARLY UNIVERSE SURVEYOR

SVOM



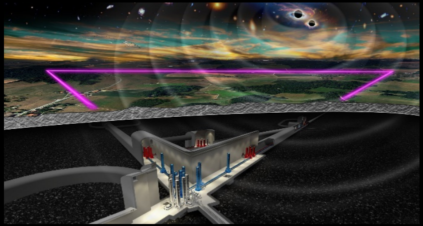
SKA

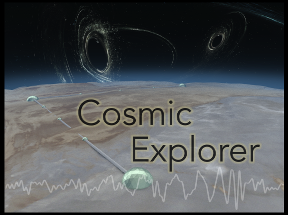
SQUARE KILOMETRE ARRAY

LIGO

INDIA

Rubin Observatory





ICECUBE GEN2

KM3NeT

Hyper-Kamiokande