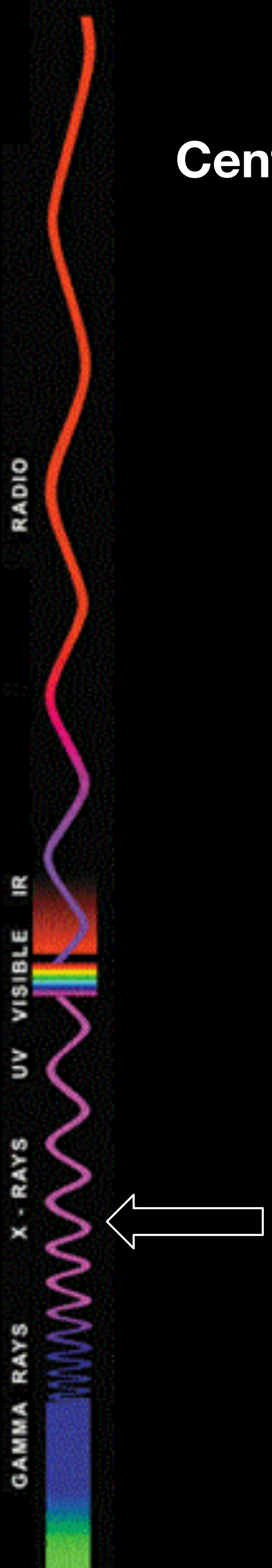
The complementarity of EM and GW observations

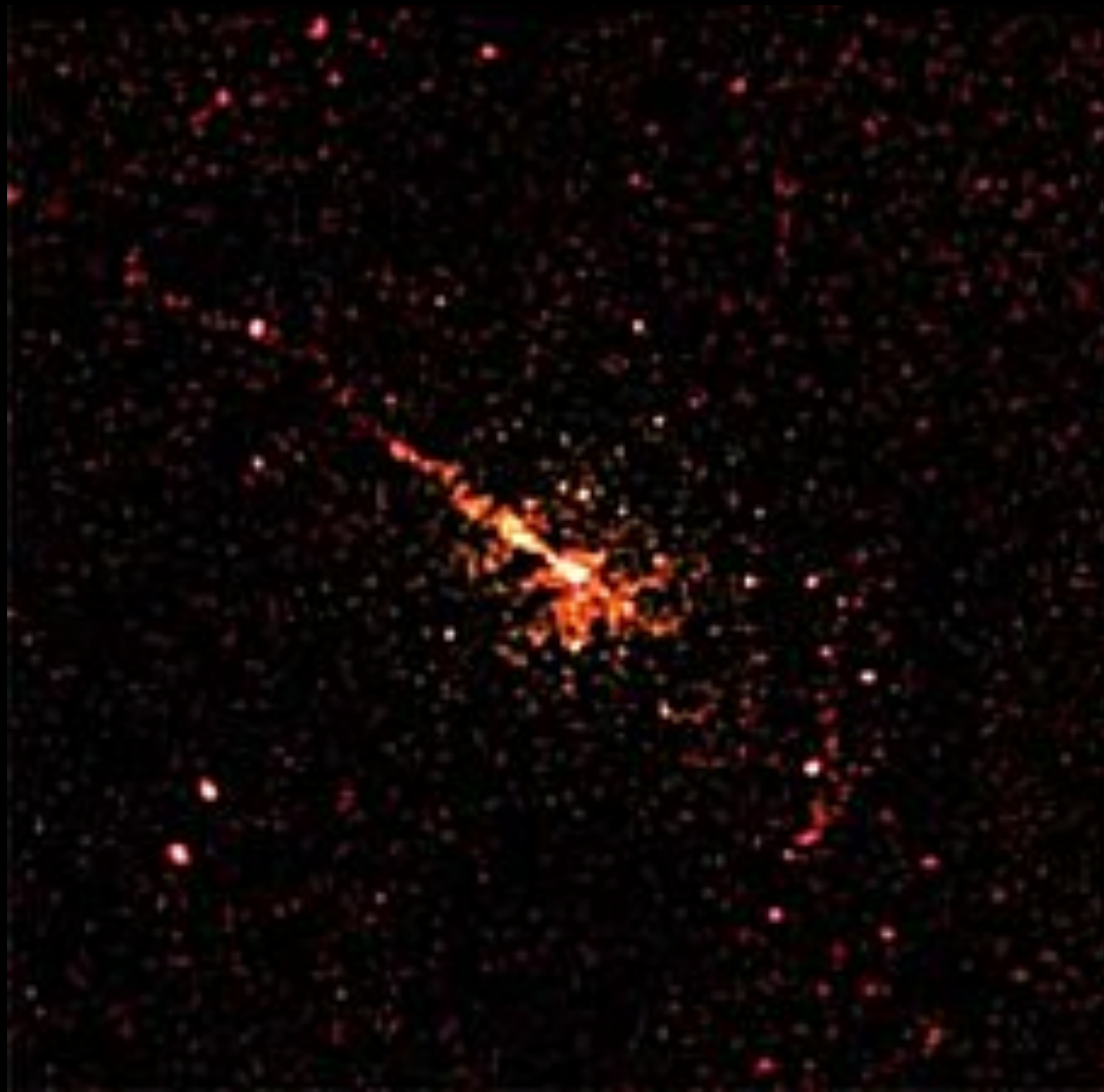
J.D. Romano
Texas Tech University
AAPT Winter Meeting 2019

How we can use EM and GW observations from GW170817 to estimate the Hubble constant

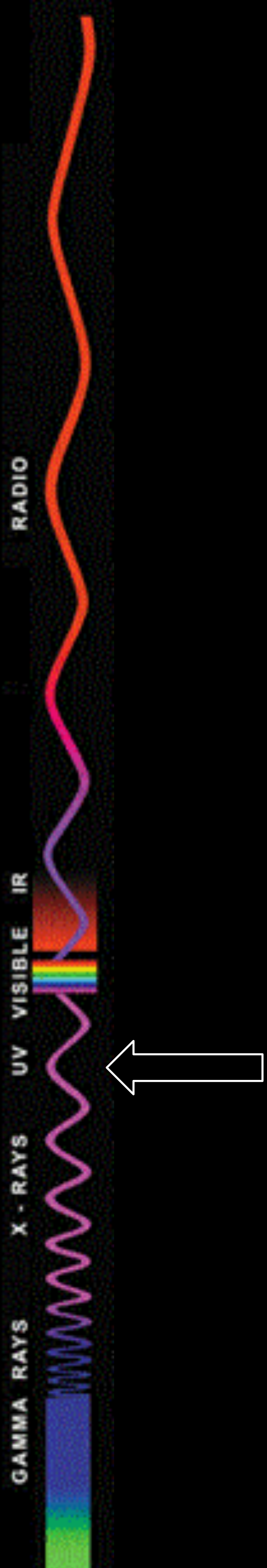
Centaurus A

X-ray

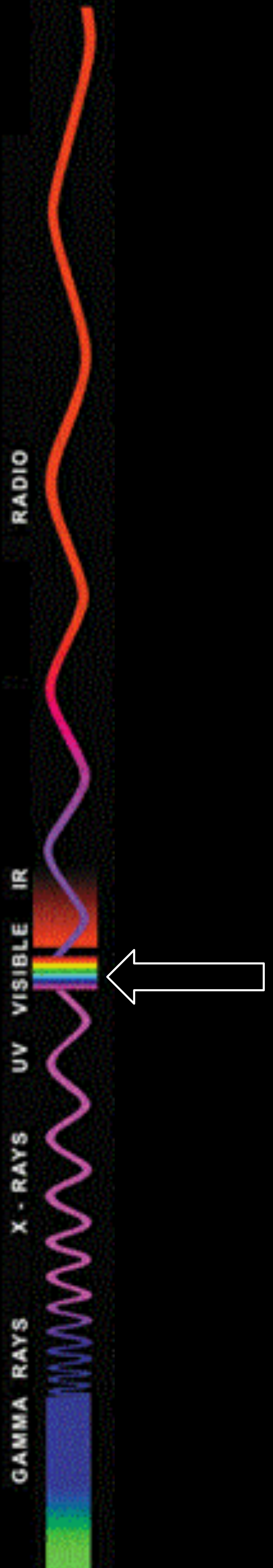




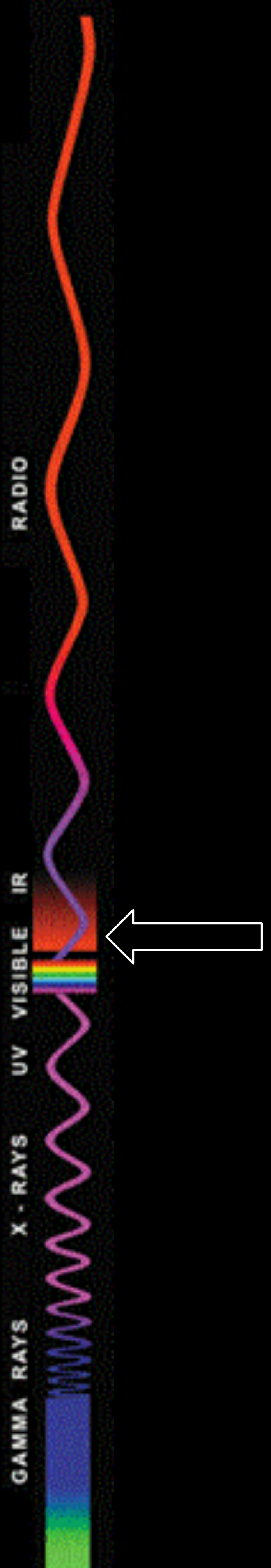
Ultraviolet



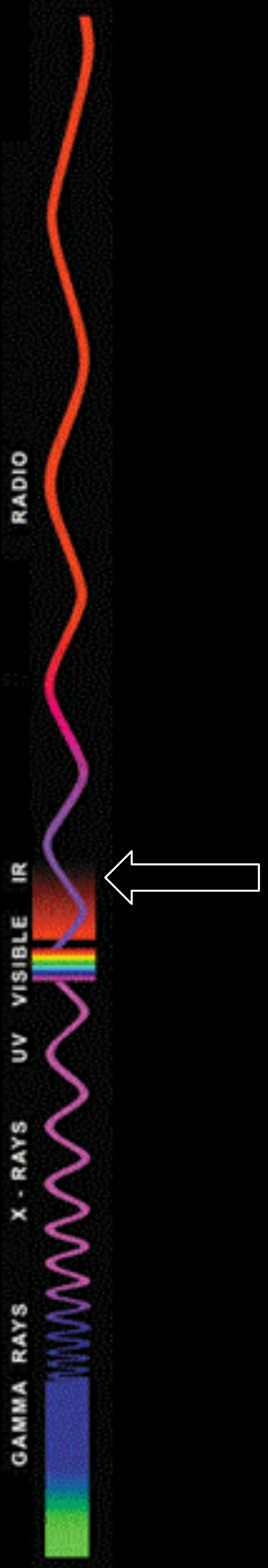
Visible Light



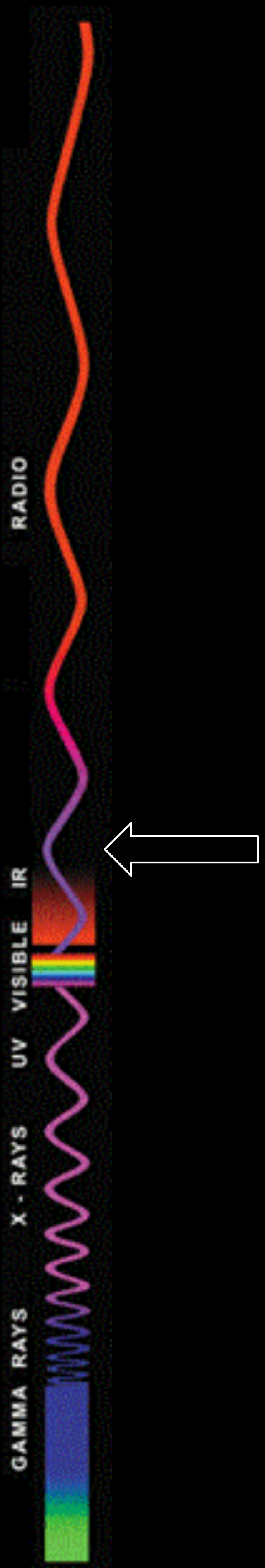
Near-Infrared

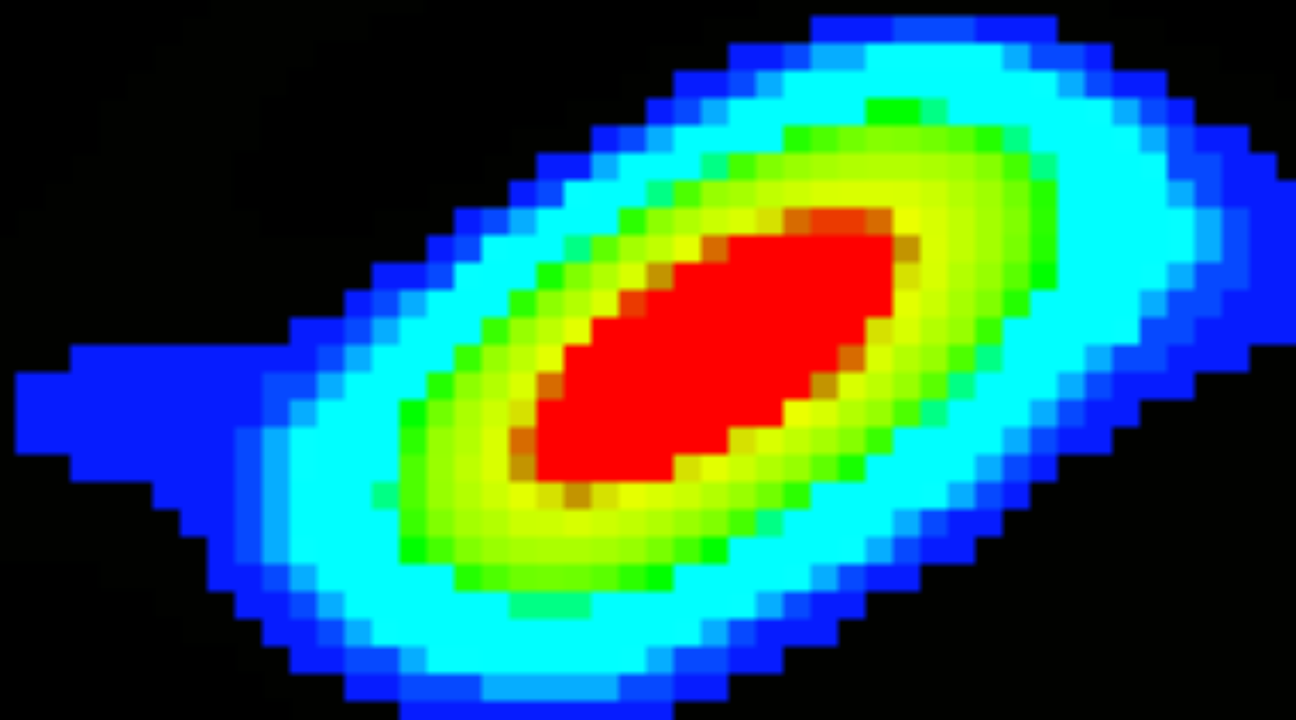


Mid-Infrared

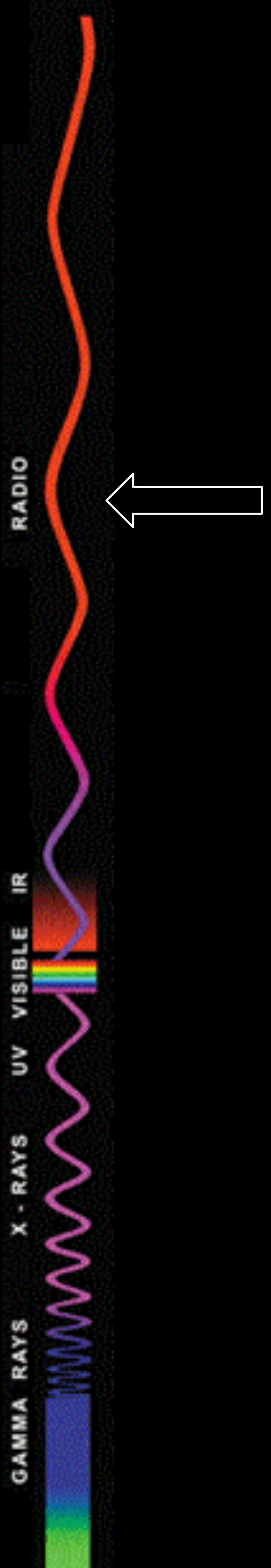


Far-Infrared

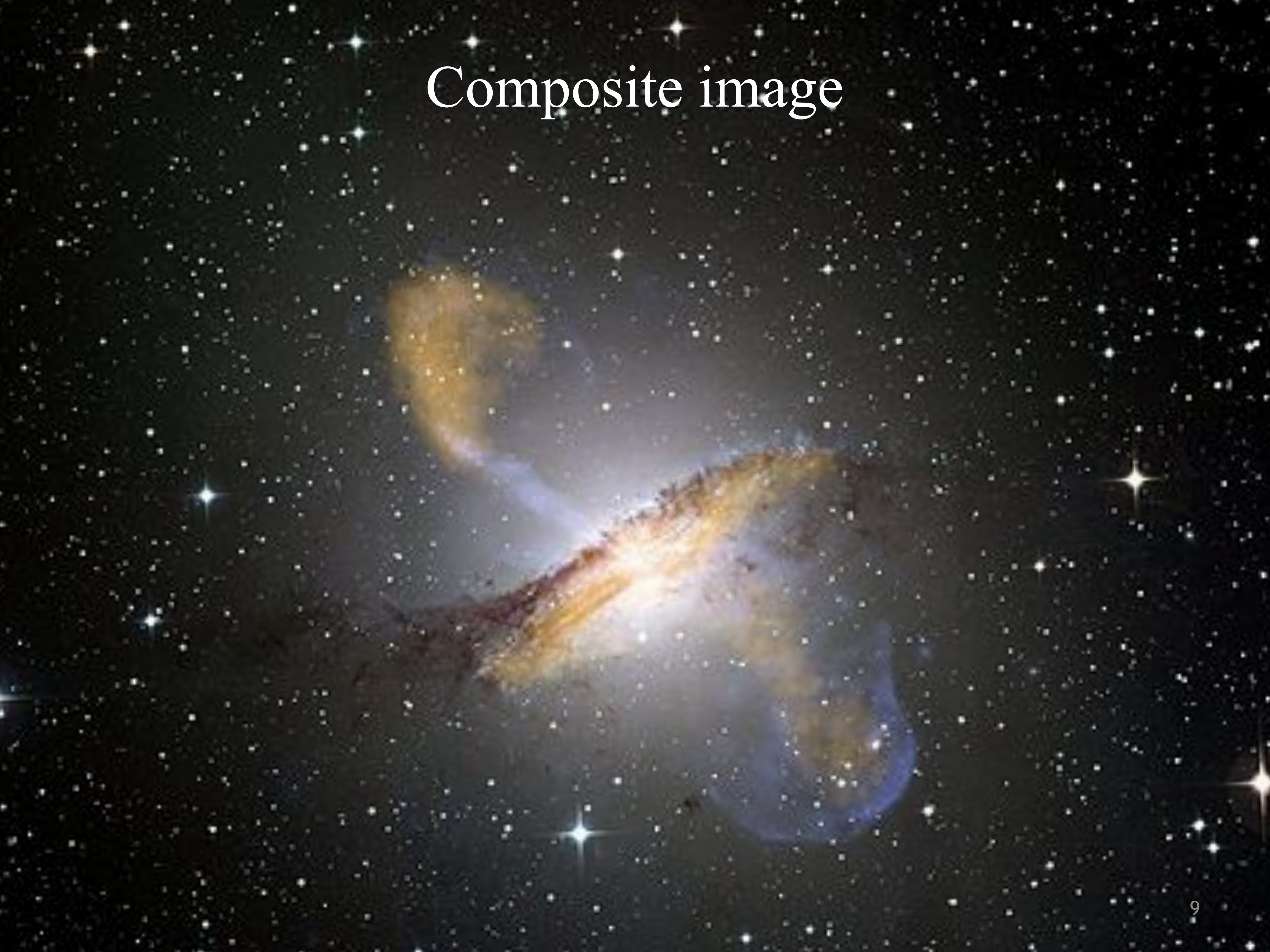




Radio



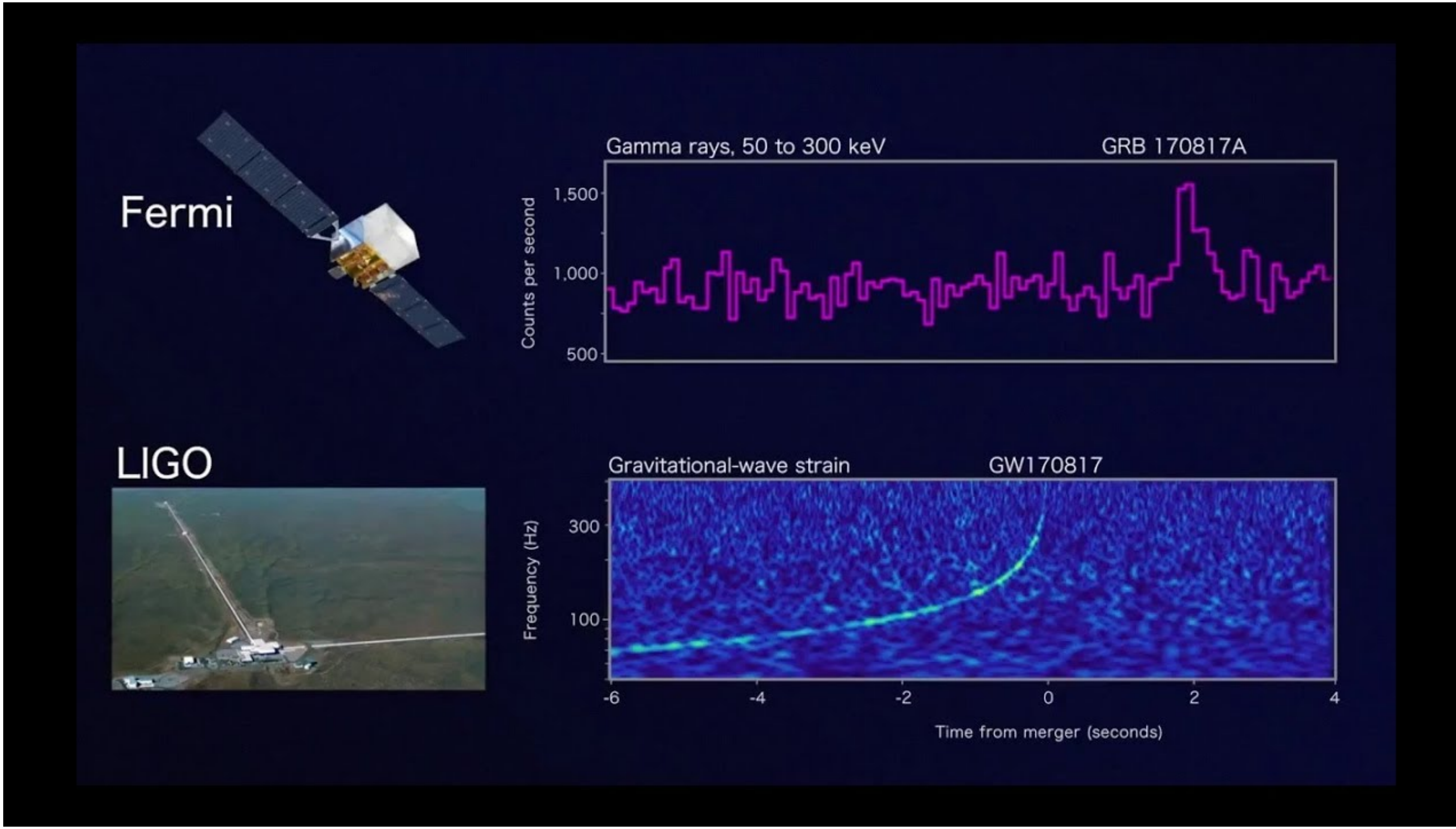
Composite image



But now we can do even better… (multi-messenger astronomy)

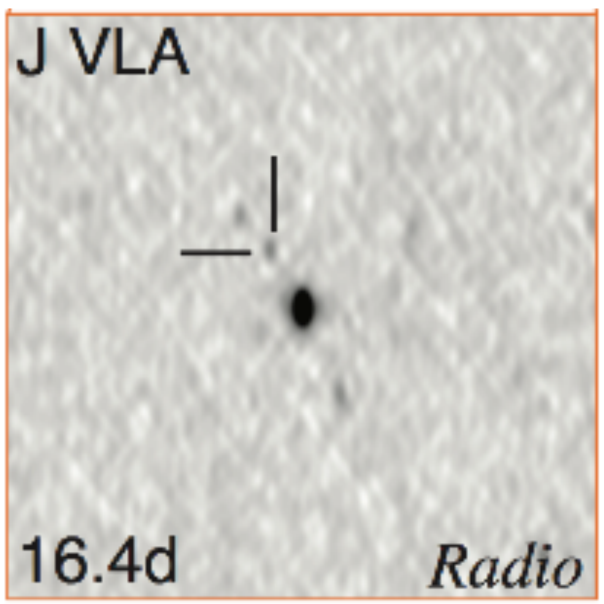
- Since Sep 14th 2015 we have the capability of observing the universe in gravitational waves (GWs)
- Totally different medium, analogous to adding hearing to our sense of sight
- This multi-messenger approach should provide insights about the cosmos that we couldn’t get from just EM or GW observations alone

GW170817 - A multi-messenger observation

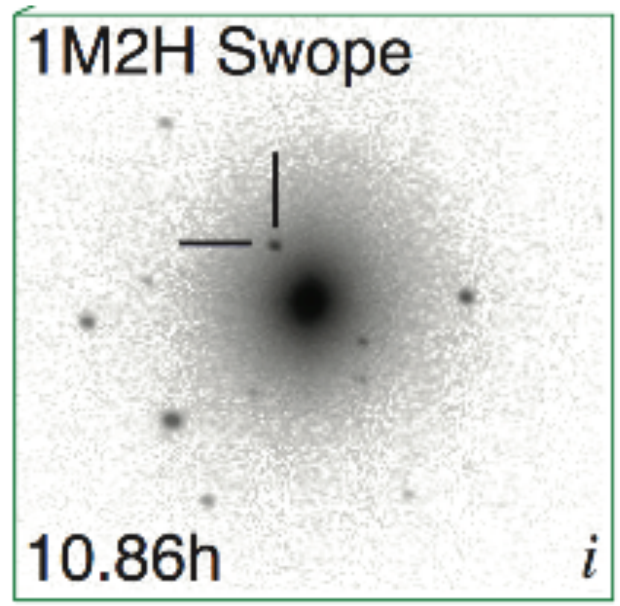


Binary neutron star merger observed in both GWs & across the EM spectrum

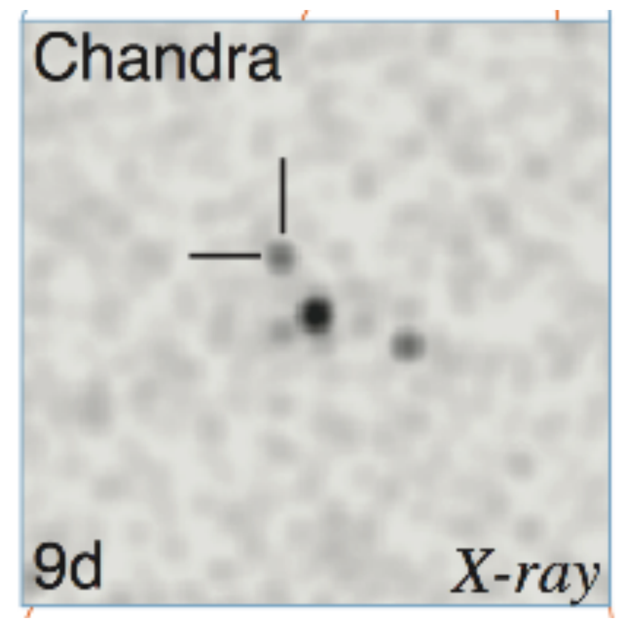
Also seen in other EM wave bands



Radio waves

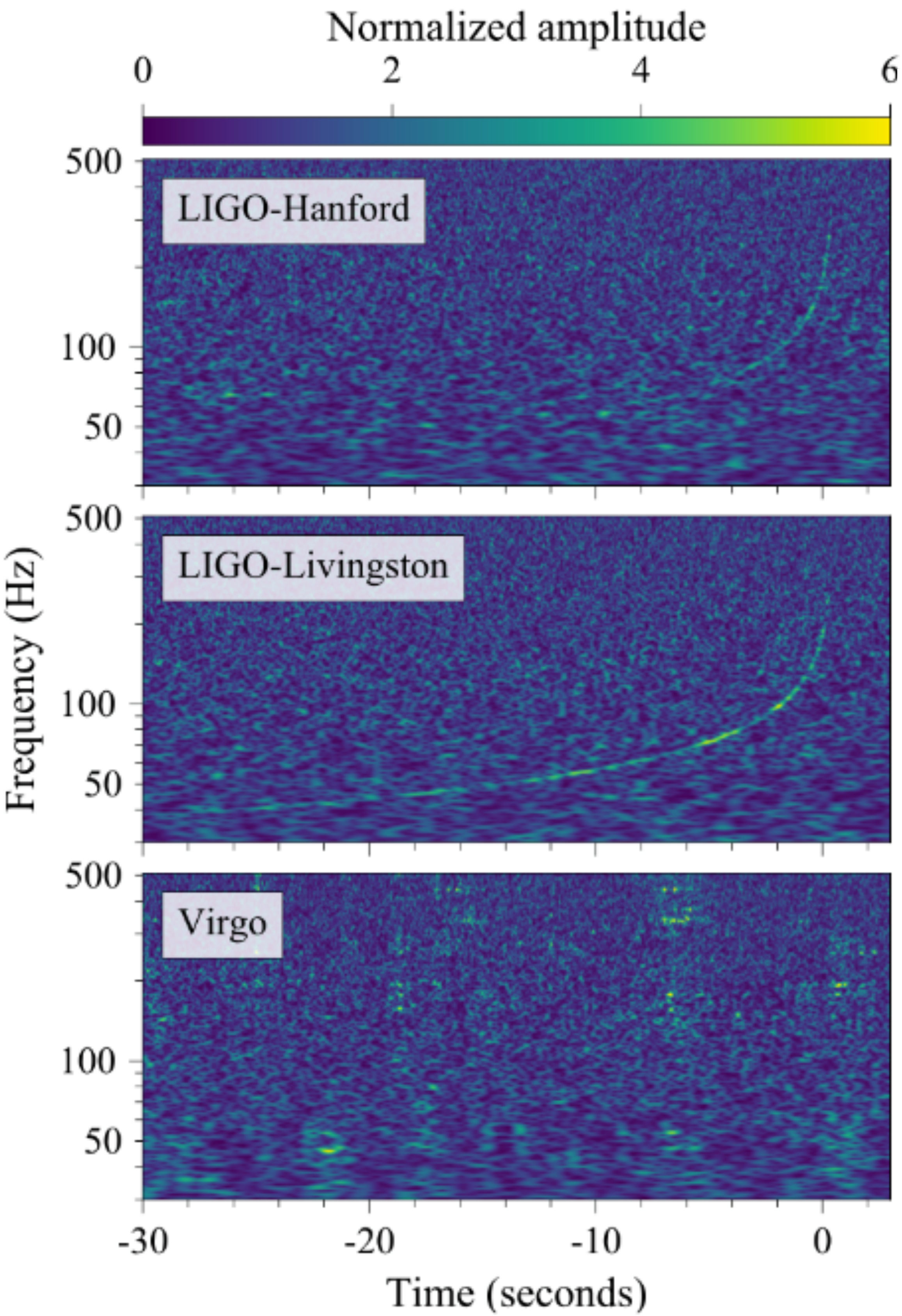


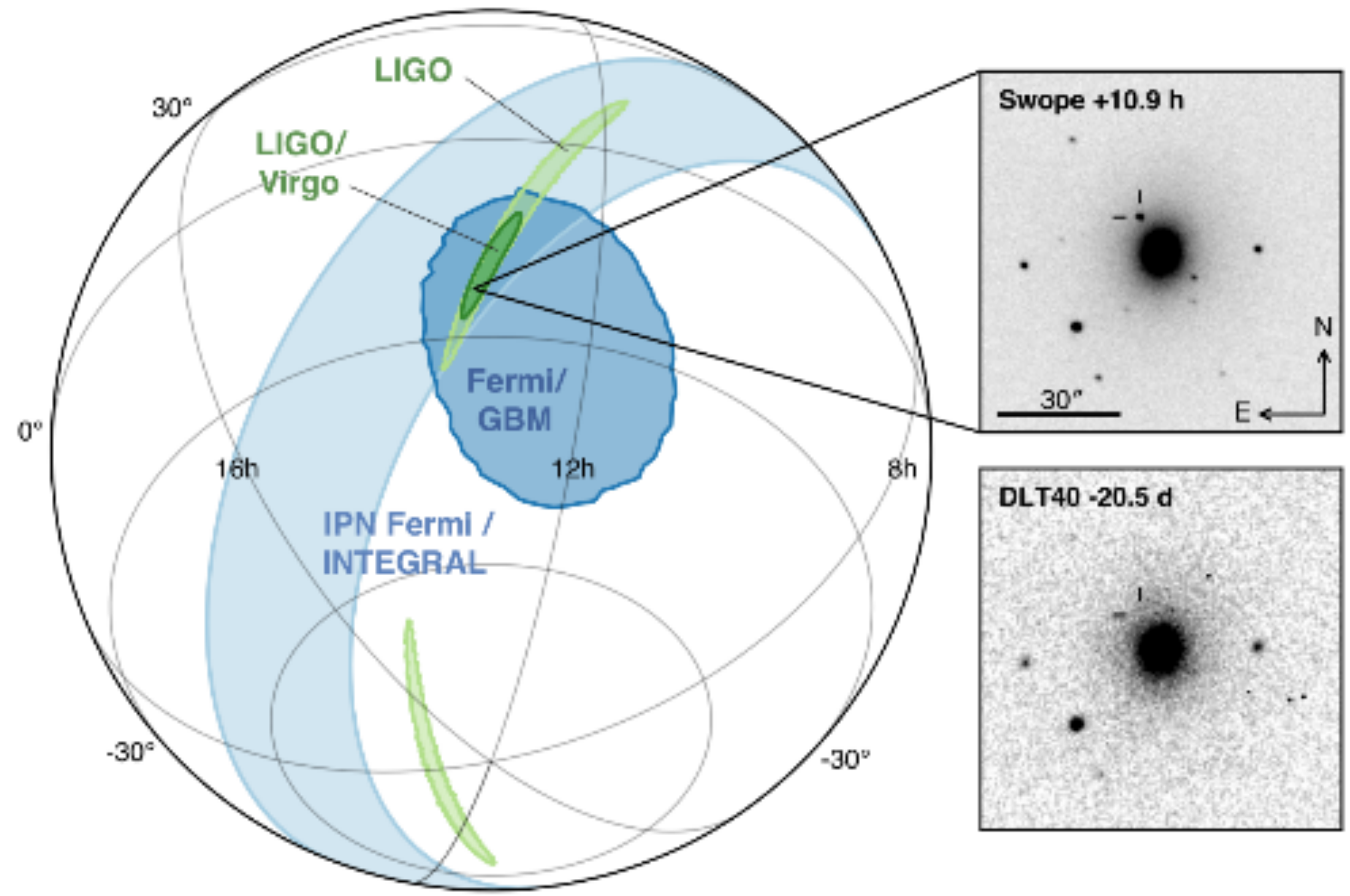
Visible



X-rays

“Detected” by three GW interferometers





- non-detection by Virgo allowed for precise sky localization (~30 deg^2)
- identification of NGC 4993 as the host galaxy allows us to do cosmology with the GW & EM obs

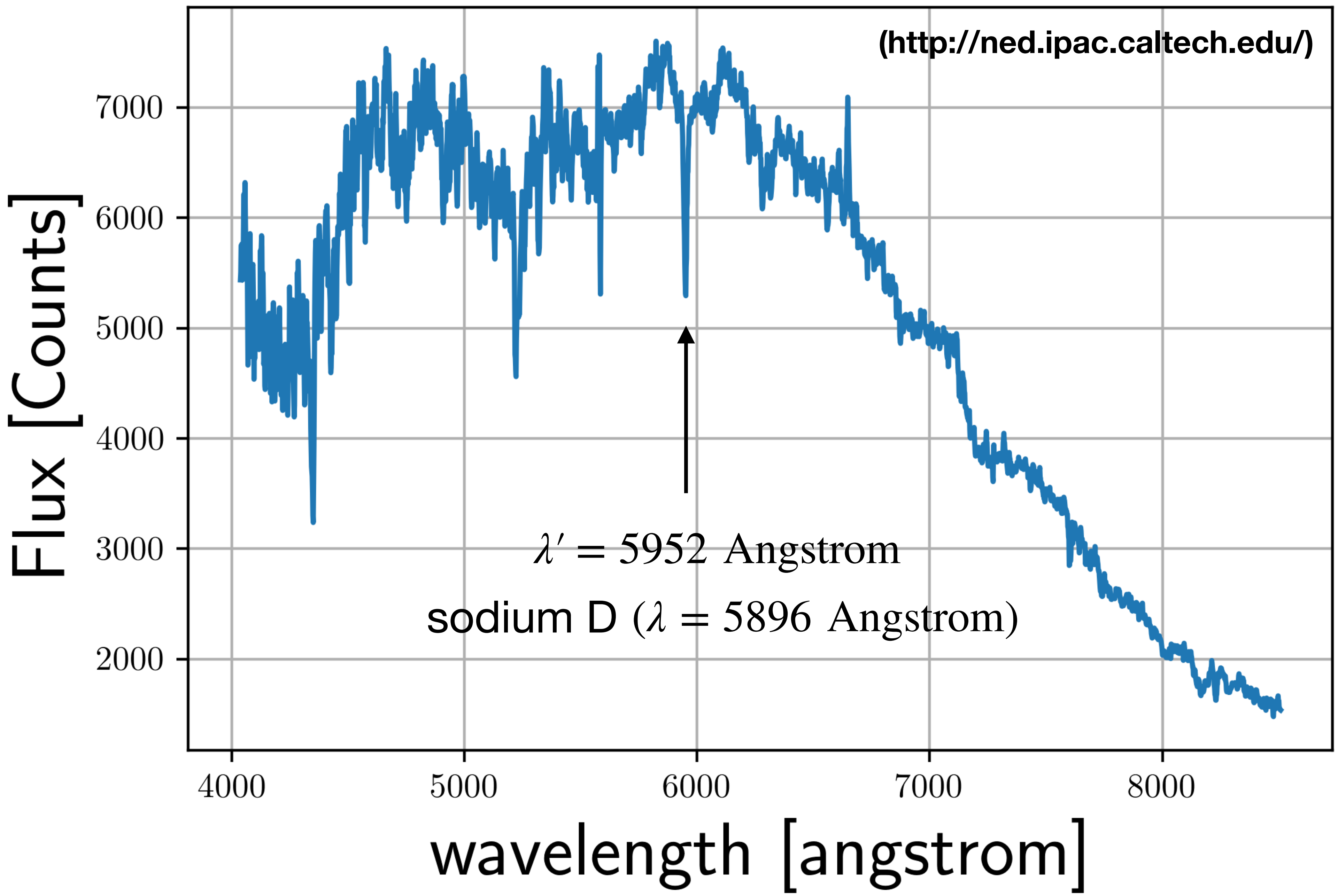
Determining the Hubble constant

- The universe is uniformly expanding with distant objects receding from us with $v = H_0 D$
- (i) EM observations are good at giving us recession velocities via redshift measurements
- (ii) GW observations are good at giving us distances for so-called "standard sirens"
- So given v and D:

$$H_0 = v/D$$

(i) velocity (redshift) measurement

$$z \equiv \frac{\Delta\lambda}{\lambda} \equiv \frac{\lambda' - \lambda}{\lambda} \approx \frac{v}{c}$$



$$z = 0.0094 \approx 0.01$$
$$v = 2831 \text{ km/s}$$

compare to

$z = 0.0098$

$v = 2924$ km/s

(Hjorth et al, 2017)

(ii) distance measurement

- Distances in astronomy are only calculable for objects that have known absolute luminosities, so called "standard candles":

$$F = \frac{L}{4\pi D^2} \quad \Leftrightarrow \quad D = \sqrt{\frac{L}{4\pi F}}$$

apparent brightness

known or measurable

measure

- A "standard siren" is the GW analogue of a standard candle—binary inspiral being an example:

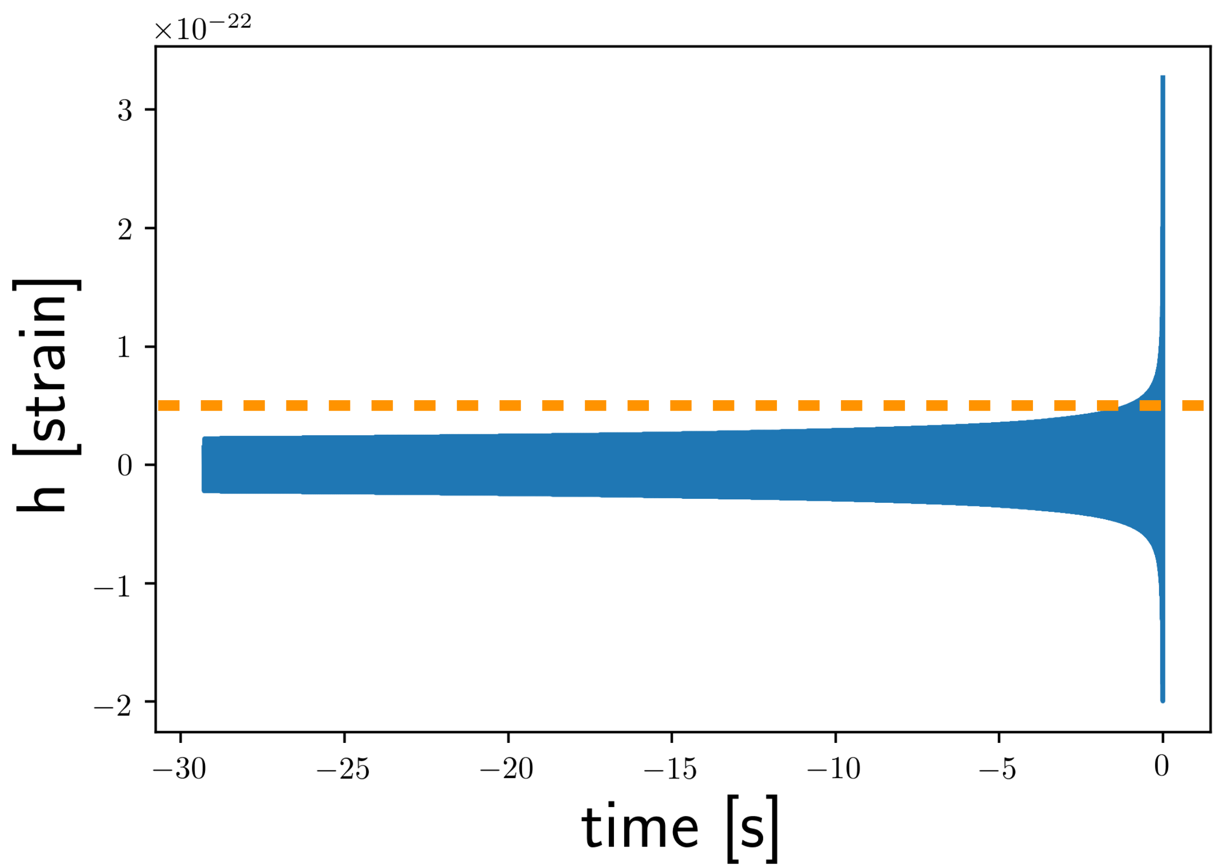
Quadrupole formula: $h_{jk} = \frac{2G}{c^4}\frac{1}{D}\ddot{Q}_{jk}$

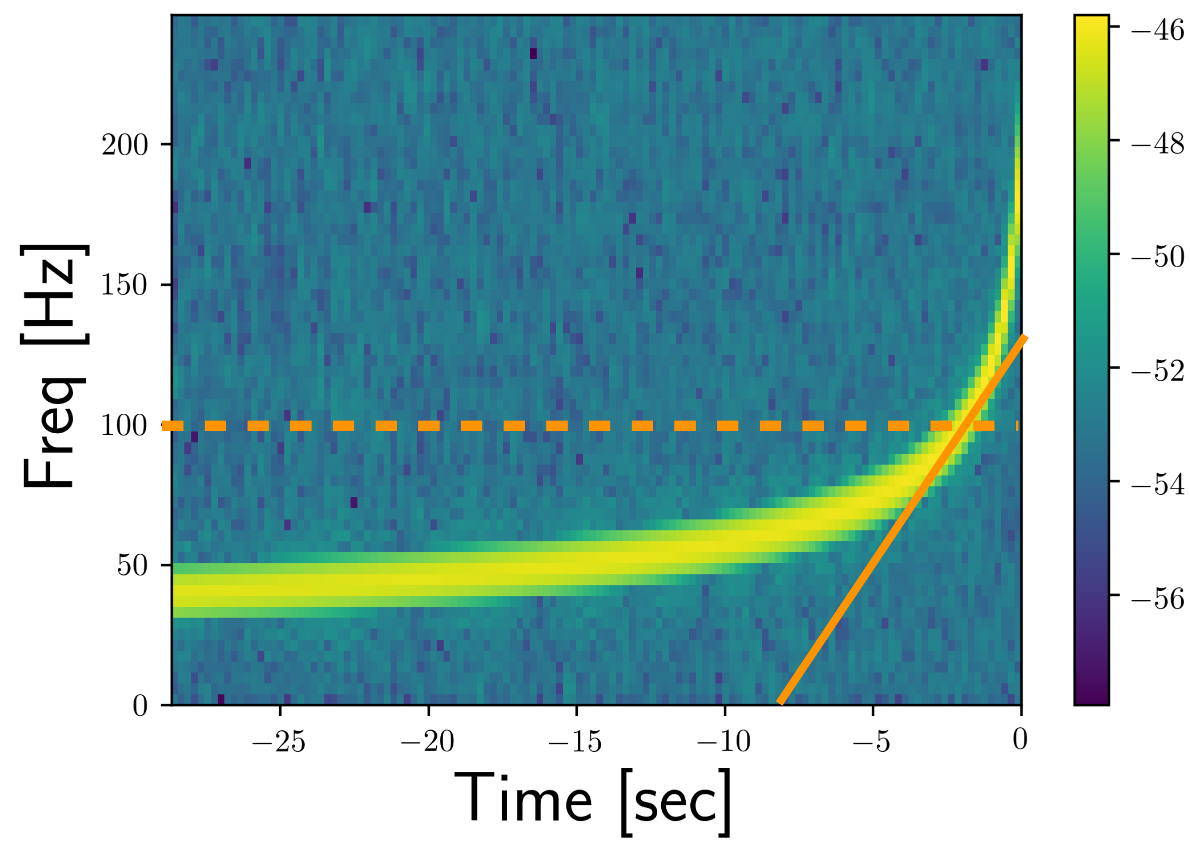
Binary inspiral: $h = \frac{4c}{D}\pi^{2/3} f_{\mathrm{gw}}^{2/3}\left(\frac{GM_c}{c^3}\right)^{5/3} \quad \Leftrightarrow \quad D = \frac{4c}{h}\pi^{2/3} f_{\mathrm{gw}}^{2/3}\left(\frac{GM_c}{c^3}\right)^{5/3}$

$$D = \frac{4c}{\pi^2}\frac{5}{96}\frac{\dot{f}_{\mathrm{gw}}}{f_{\mathrm{gw}}^3 h}$$

measurable from detected waveform

Using GW170817 data





$$f_{\rm gw} = 100 \text{ Hz}\,, \qquad \dot{f}_{\rm gw}\Big|_{100 \text{ Hz}} = \frac{125 \text{ Hz}}{8 \text{ s}}\,, \qquad h\Big|_{100 \text{ Hz}} = 5 \times 10^{-23}$$

$$\Rightarrow \boxed{D = 64 \text{ Mpc} \quad \text{and} \quad H_0 = v/D = 44 \text{ km s}^{-1}\,\text{Mpc}^{-1}}$$

compare to $\quad D_L = 40^{+8}_{-14} \text{ Mpc}\,, \quad H_0 = 70^{+12}_{-8} \text{ km s}^{-1}\,\text{Mpc}^{-1}$

Q: WHY SUCH A LARGE DISCREPANCY?

We ignored some relevant details…

- Actual waveform measured by a detector is a linear combination of the + and x polarizations of the GW:

$$h = h_+ F_+ + h_\times F_\times$$

polarization amplitudes depend on inclination of source relative to line of sight

interferometer responds differently to + and x polarizations

- So we were estimating a different "effective" distance:

$$D_{\text{eff}} = \frac{D_L}{\sqrt{F_+^2(\theta,\phi,\psi)\left(\frac{1+\cos^2\iota}{2}\right)^2 + F_\times^2(\theta,\phi,\psi)\,\cos^2\iota}} \geq D_L$$

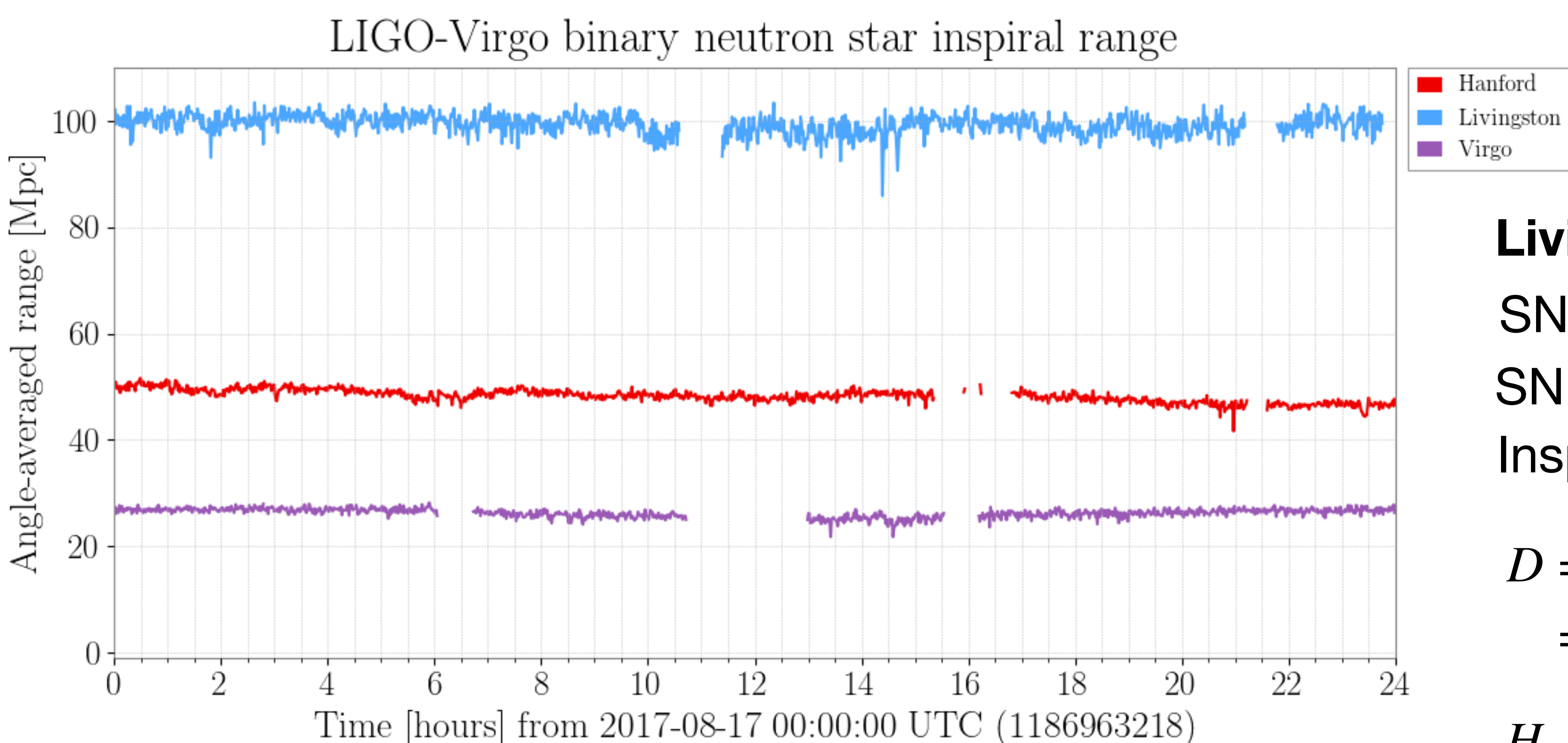
Calculating the denominator is somewhat involved, but doable; requires polarization measurement for inclination

An alternative way of estimating the distance…

- Use the BNS inspiral range (which is a measure of the volume of space surveyed by a detector for sources with SNR > $\text{SNR}_{\text{threshold}}$) and the actual measured SNR to estimate D:

$$\text{SNR} \propto 1/\text{distance} \quad \Leftrightarrow \quad \text{SNR} \cdot \text{distance} = \text{const}$$

$$D = (\text{Inspiral range}) \cdot \text{SNR}_{\text{threshold}}/\text{SNR}_{\text{measured}}$$



Livingston

$\text{SNR}_{\text{threshold}} = 8$

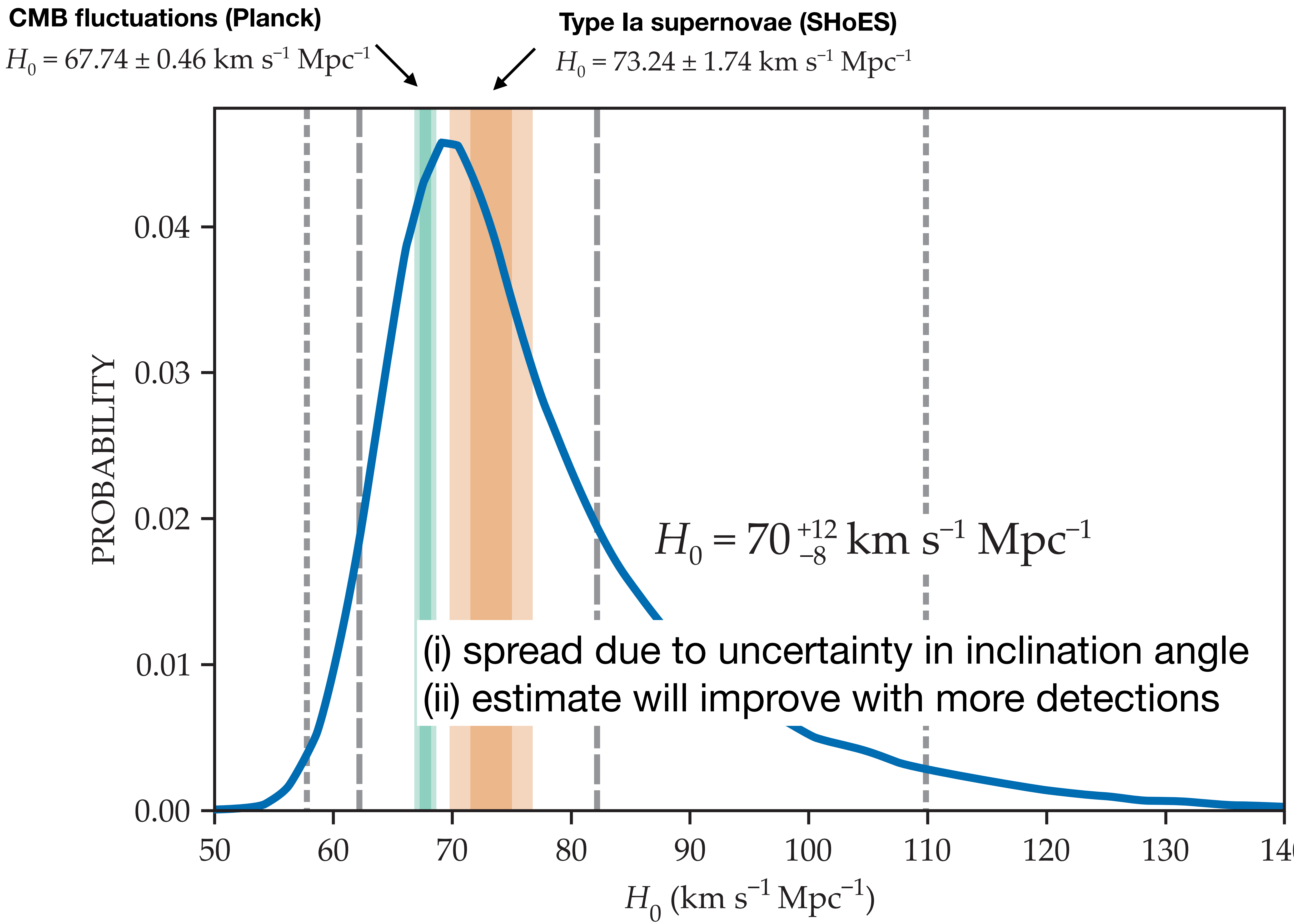
$\text{SNR}_{\text{measured}} = 26.4$

Inspiral range = 100

$$D = 100\ \text{Mpc} \cdot 8/26.4$$
$$= 30\ \text{Mpc}$$

$$H_0 = 93\ \text{km}\,\text{s}^{-1}\,\text{Mpc}^{-1}$$

https://www.gw-openscience.org**/detector_status/day/20170817/**



(i) spread due to uncertainty in inclination angle

(ii) estimate will improve with more detections

Nature 551, 85-88 (2 Nov 2017)

References

- “Measuring cosmic distances with standard sirens,” D.E. Holz, S.A. Hughes, B.F. Schutz, Physics Today 71,12, 34 (2018).

- “A gravitational-wave standard siren measurement of the Hubble constant,” Nature 551, 85-88, (2 Nov 2017).

- “GW170817: Observation of gravitational waves from a binary neutron star inspired,” PRL 119, 161101 (2017)

- “Determining the Hubble constant from gravitational wave observations,” B.F. Schutz, Nature 323, (25 Sep 1986).