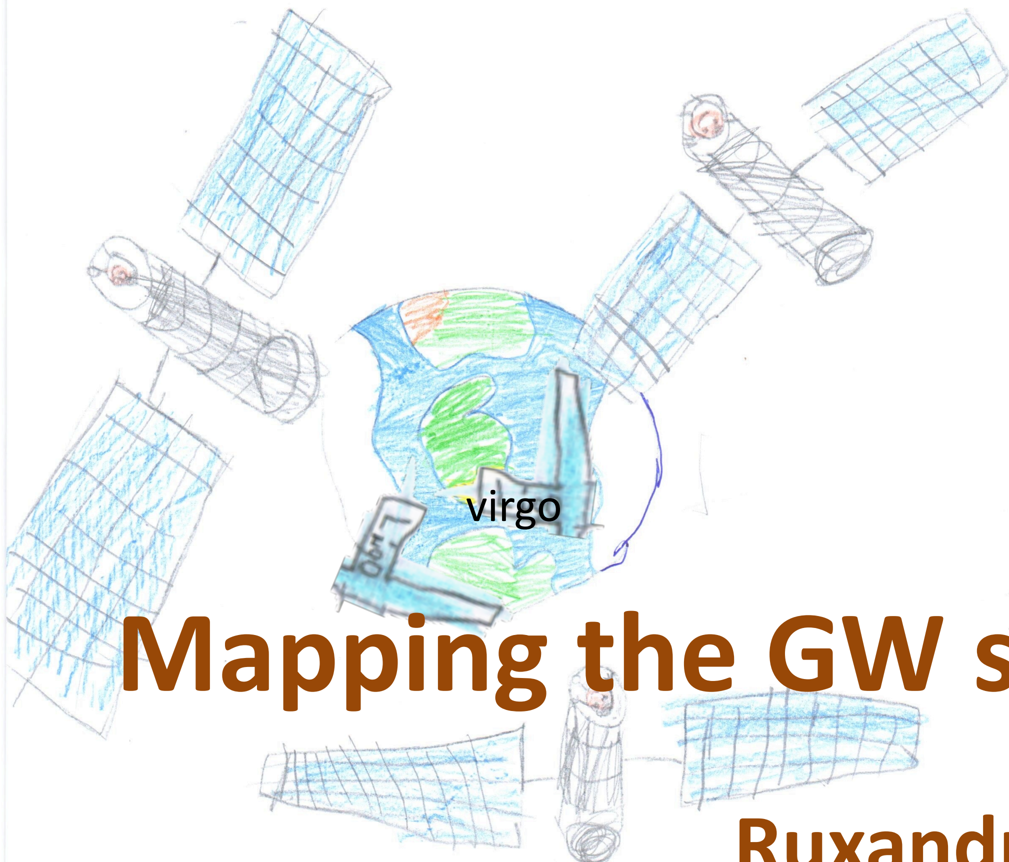
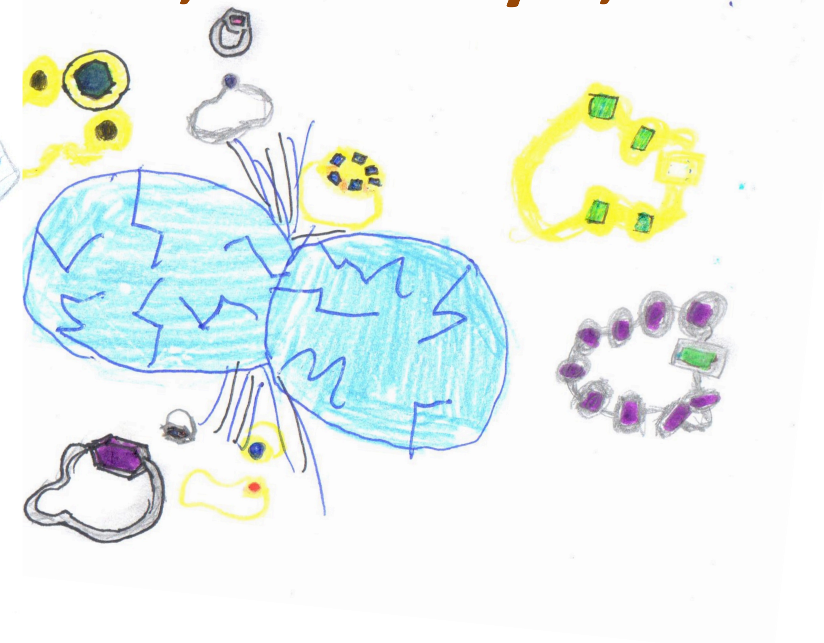
ICCUB, February 7, 2022



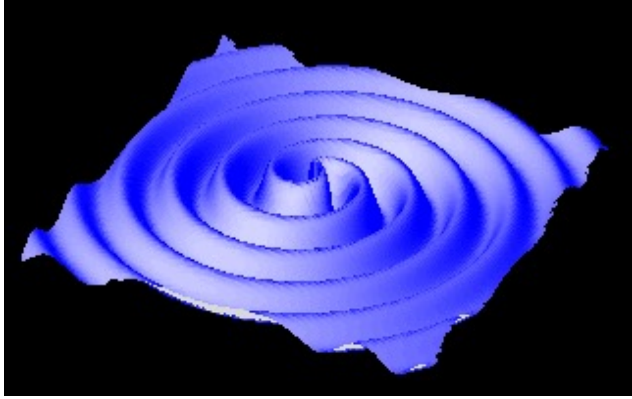


Mapping the GW sky with the LVK

Ruxandra Bondarescu

University of Barcelona

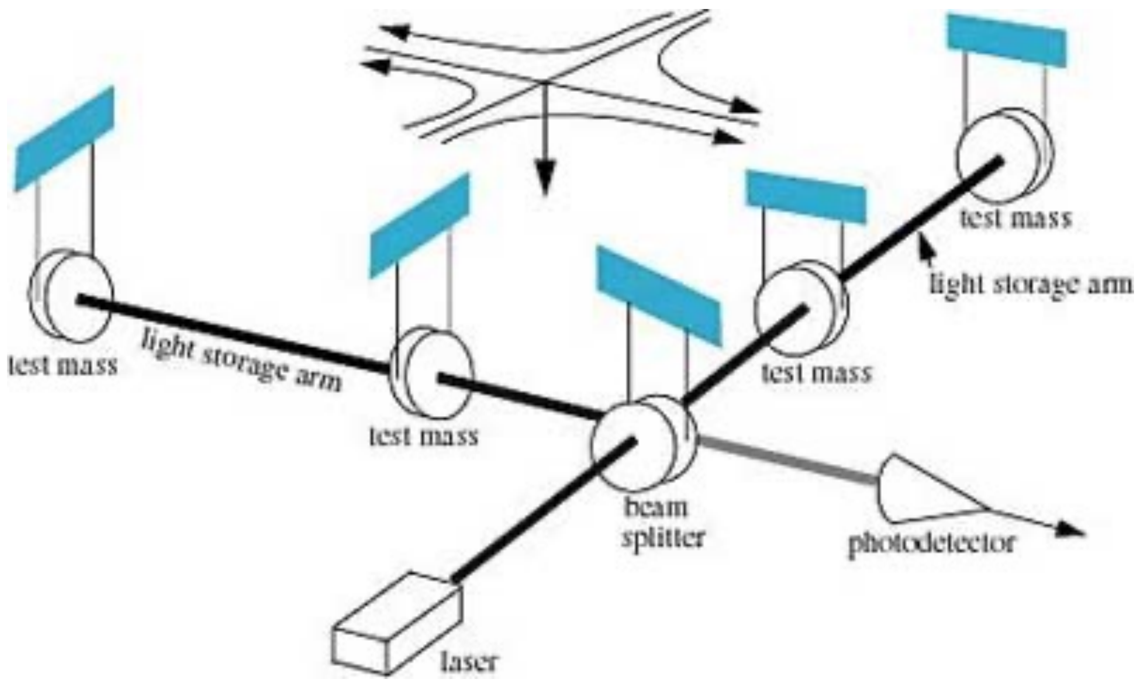
EM waves versus GWs



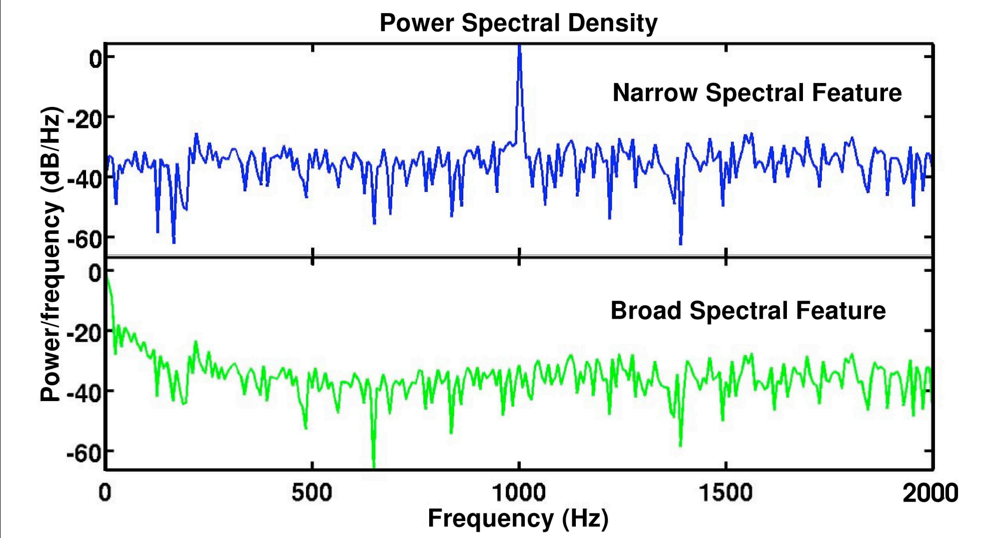
- EM waves are produced by accelerated charges, whereas GWs are produced by accelerated "masses".
- EM waves propagate through space-time, GWs are oscillations of space-time itself.
  - Gravitational-waves are not absorbed by intervening matter & propagate at the speed of light
- Typical frequencies of EM waves range from (10^7 Hz – 10^{20} Hz) whereas GW frequencies range from ~ (10^{-9} Hz – 10^4 Hz). They are more like sound waves.

***L**aser **I**nterferometer **G**ravitaional wave **O**bservatory*

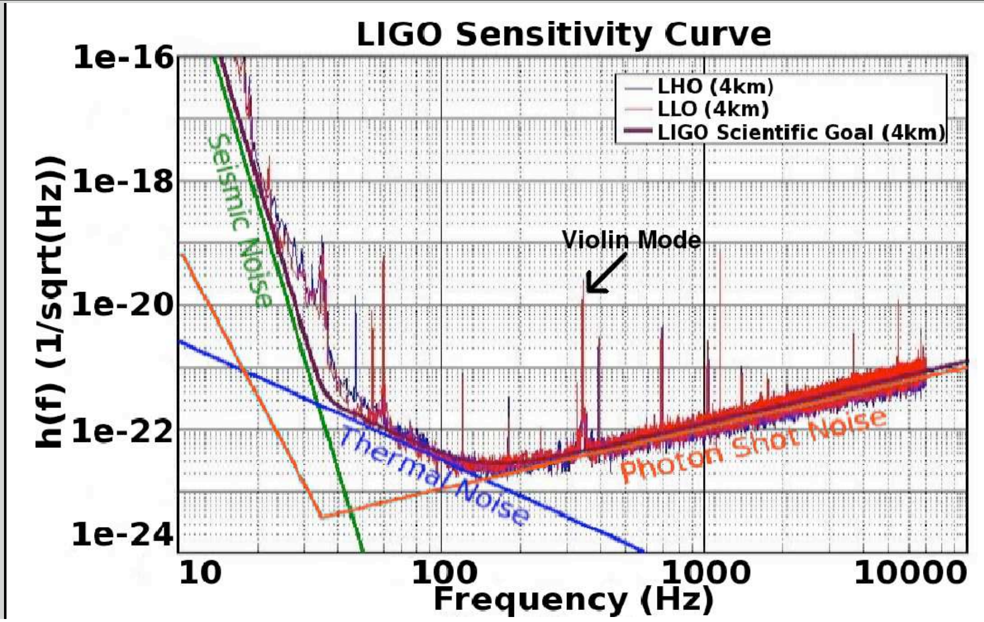
- LIGO



- Length of each arm, L = 4 km,
- frequency range , f = 10 Hz – 10^4 Hz
- ΔL ~ 10^{-18} meters, size of proton ~ 10^{-15} meters



Example of Broad and Narrow Spectral Features

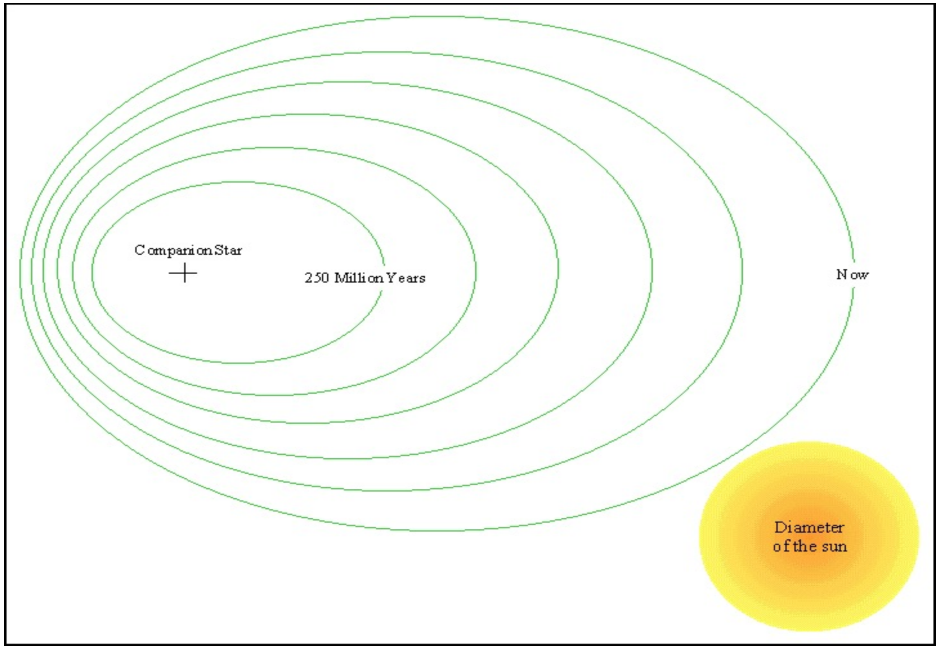


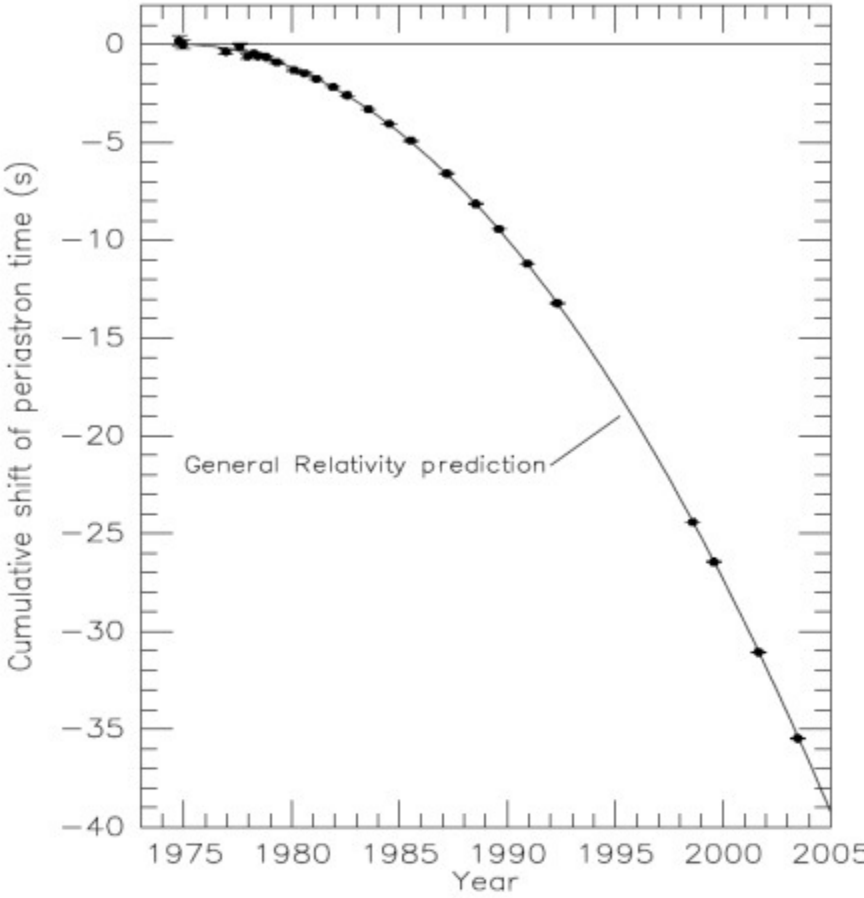
LIGO Noise

- **Complex mixture of broad and narrow features**
- **Narrow Spectral features: noise at isolated frequencies**
  - **narrow resonances excited by internal or external noise sources**
- **Broad spectral features: noise that varies with frequency**
  - **Systematic background noise**
    - **seismic (< 40 Hz; rapidly decreases with f)**
    - **thermal (40 – 200 Hz; slowly decreases with f, (Lundgren Bondarescu *et al.* PRD 2008)**
    - **shot noise (> 200 Hz; slowly increases with f)**

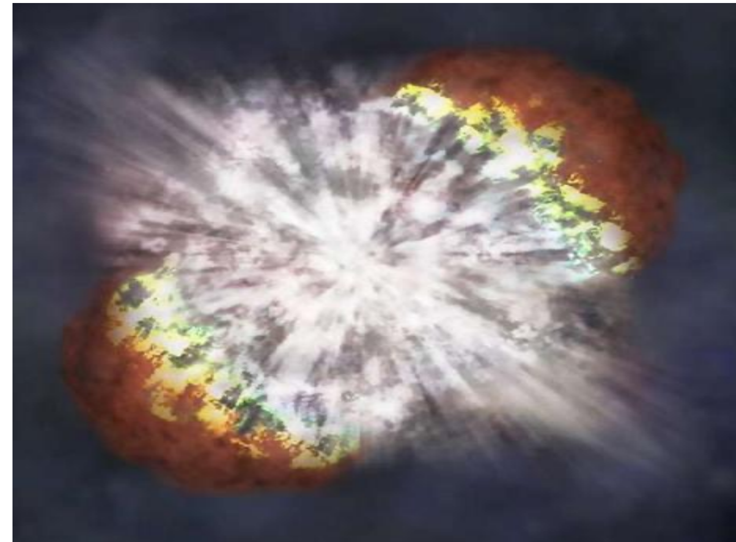
How did we know GWs exist ? Indirect proof.

- Hulse-Taylor binary pulsar (Nobel prize 1993)
- Steady decrease in orbital separation due to loss of energy through GWs.





Sources of GWs



- **Binary Neutron stars (pulsars)**,
- **Binary black holes**
- or **a combination of these**

"known unkowns" (i.e., not seen yet)

- **Exploding stars: Core collapse Supernovae**

- **Pulsars (rotating Neutron stars)**
  - Mountains
  - Unstable modes (e.g., r-modes)
- **Stochastic sources**: Jumble of weak signals from lot of sources that cannot be resolved or gravitational waves from inflation

"….***there are known knowns, there, are known unknowns But there are also unknown unknowns***…."

---- Don Rumsfeld

What did we expect to see?

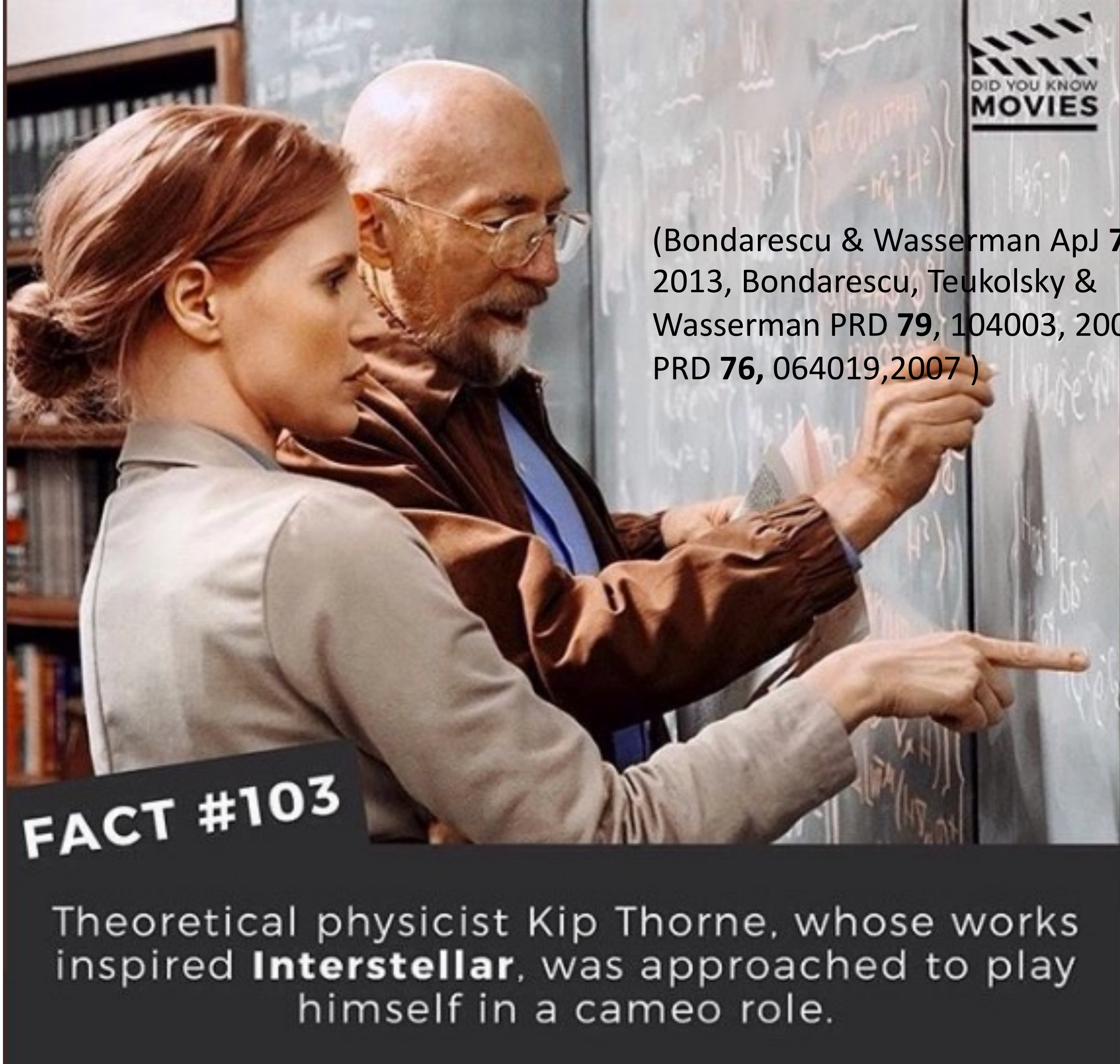
- **NS binaries**
  - Hulse-Taylor & a few other pulsars
  - **EM Observations:** 17 galactic neutron star pairs, total mass ranges 2.5 to 2.9 M_{sun}
- Xray observations: BHs could be 10 M_{Sun}

2003: first GW course at LSU

https://cosmolearning.org/courses/overview-of-gravitational-wave-science-400/

Students at Xmas and New Years Eve
Course based on Kip Thorne's lectures,
Thorne, Bondarescu, Chen

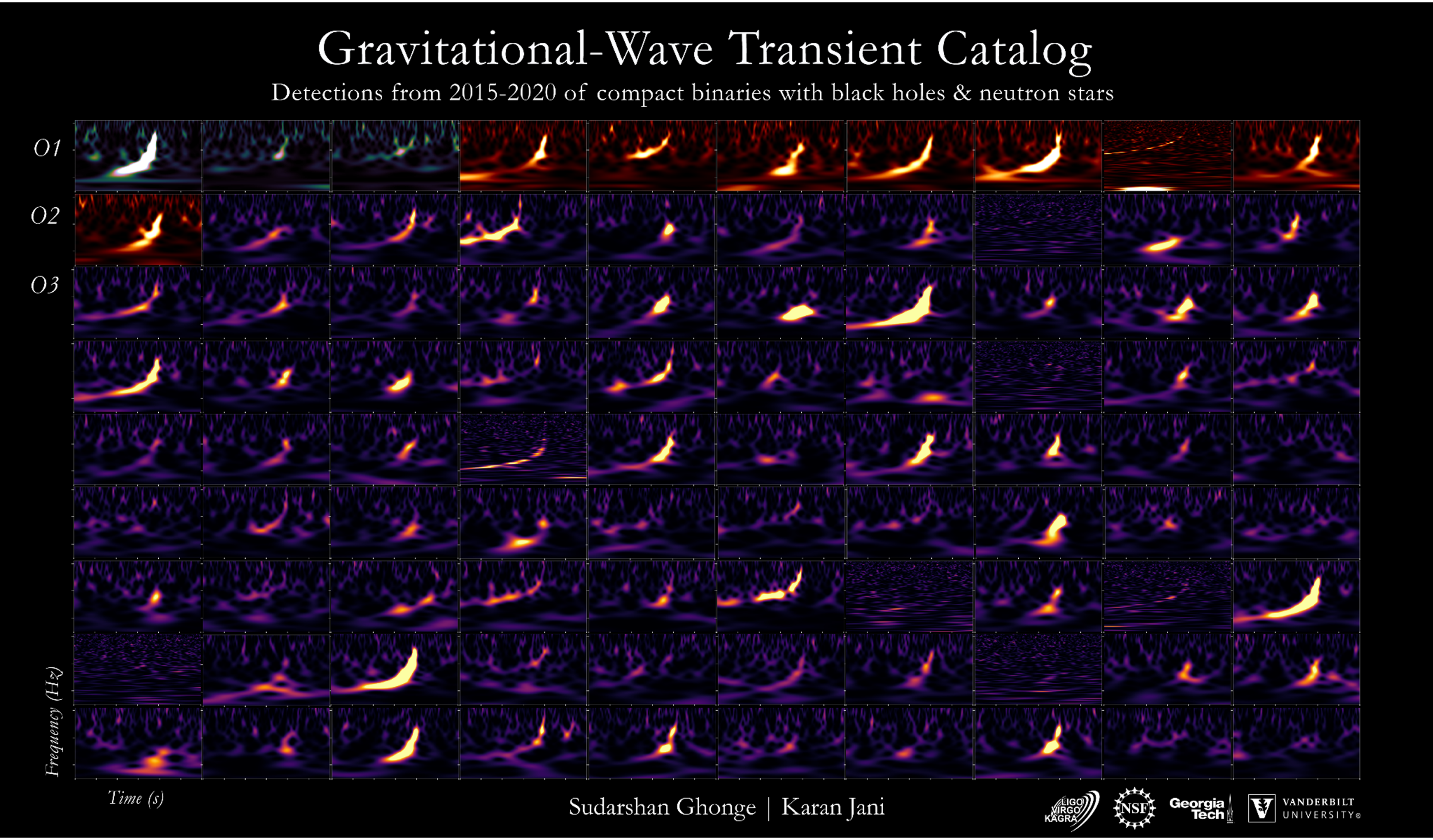
(Bondarescu & Wasserman ApJ **778**, 9, 2013, Bondarescu, Teukolsky & Wasserman PRD **79**, 104003, 2009, PRD **76,** 064019,2007)



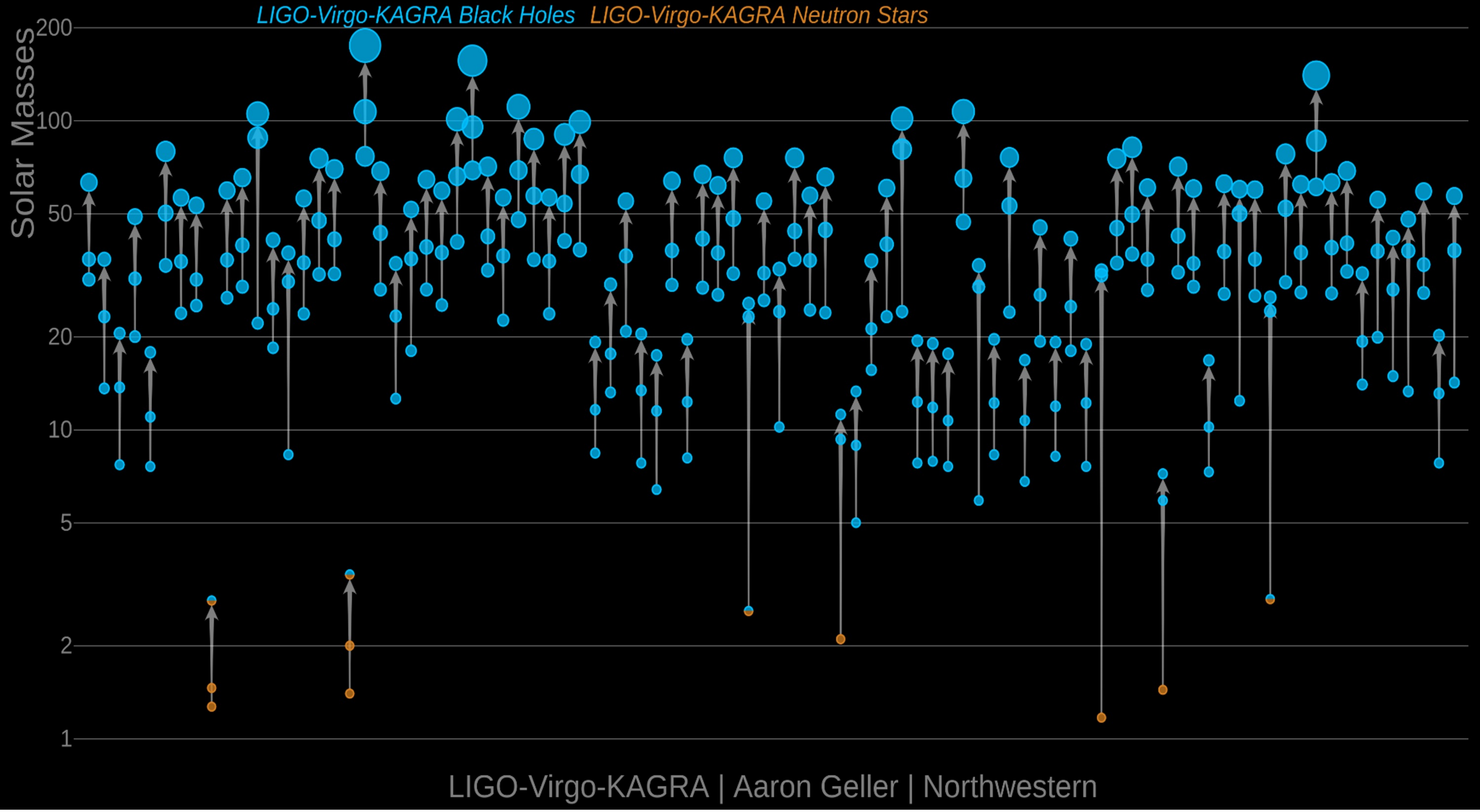
ICCUB Gravitational Waves Group

- Jordi Portell (Data Analysis, Team Leader)
  - Pablo Barneo (data analysing, denoising pipeline)
- Mark Gieles (BH formation, stellar dynamics and evolution)
  - Daniel Marin Pina (Ph Student, earlier talk)
  - Stefano Torniamenti (collaborator, U. Padova)
- Tomas Andrade (numerical relativity, earlier talk)
  - Juan Trenado (PhD student, numerical relativity)
- Oleg Bulashenko (GW lensing)
  - Helena Ubach (PhD student, GW lensing)
- Ruxandra Bondarescu (GW wave astronomy)
- David Gascon Fora (Technical Unit)

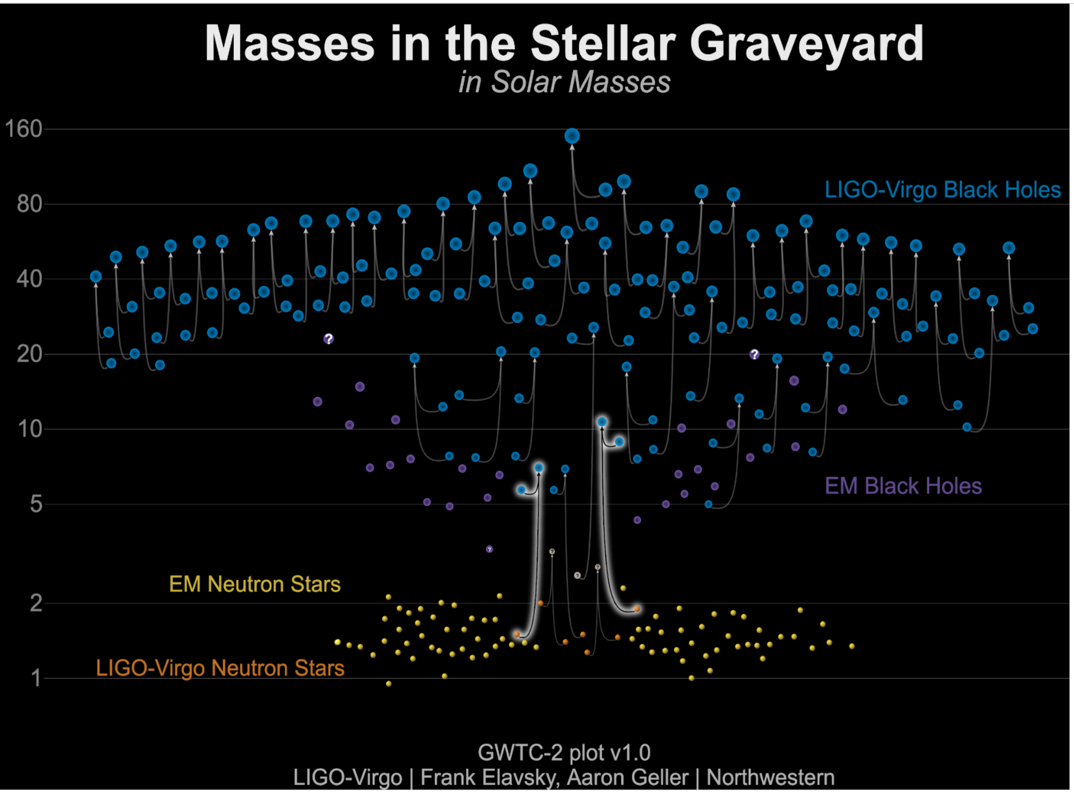
2022: a glimpse of the GW sky

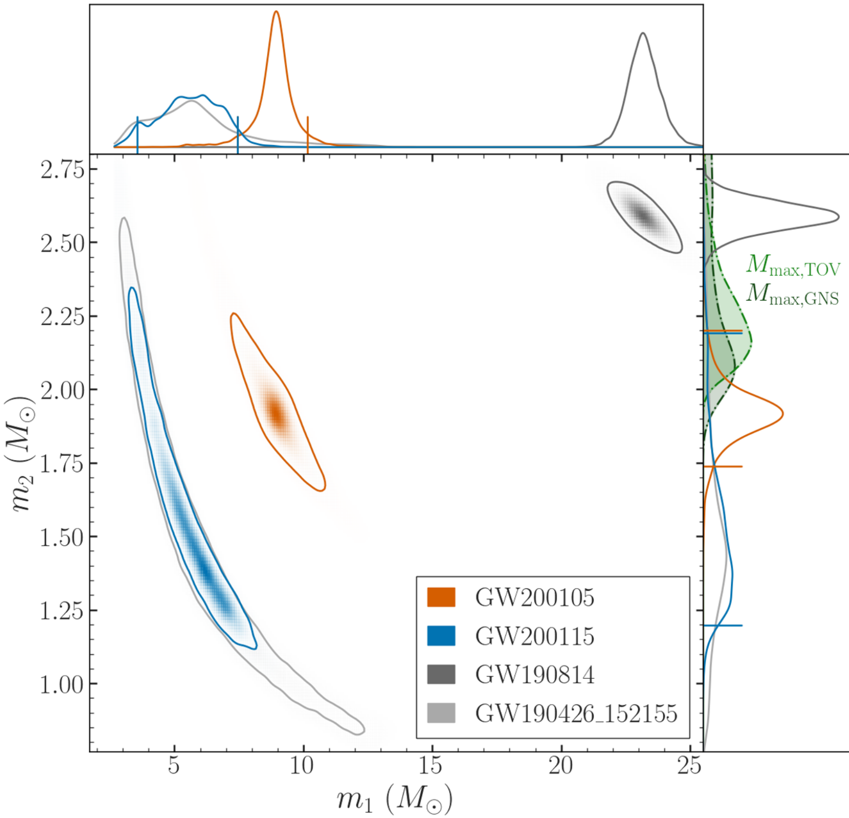


Masses in the Stellar Graveyard



NS – BH binaries: first time detection!

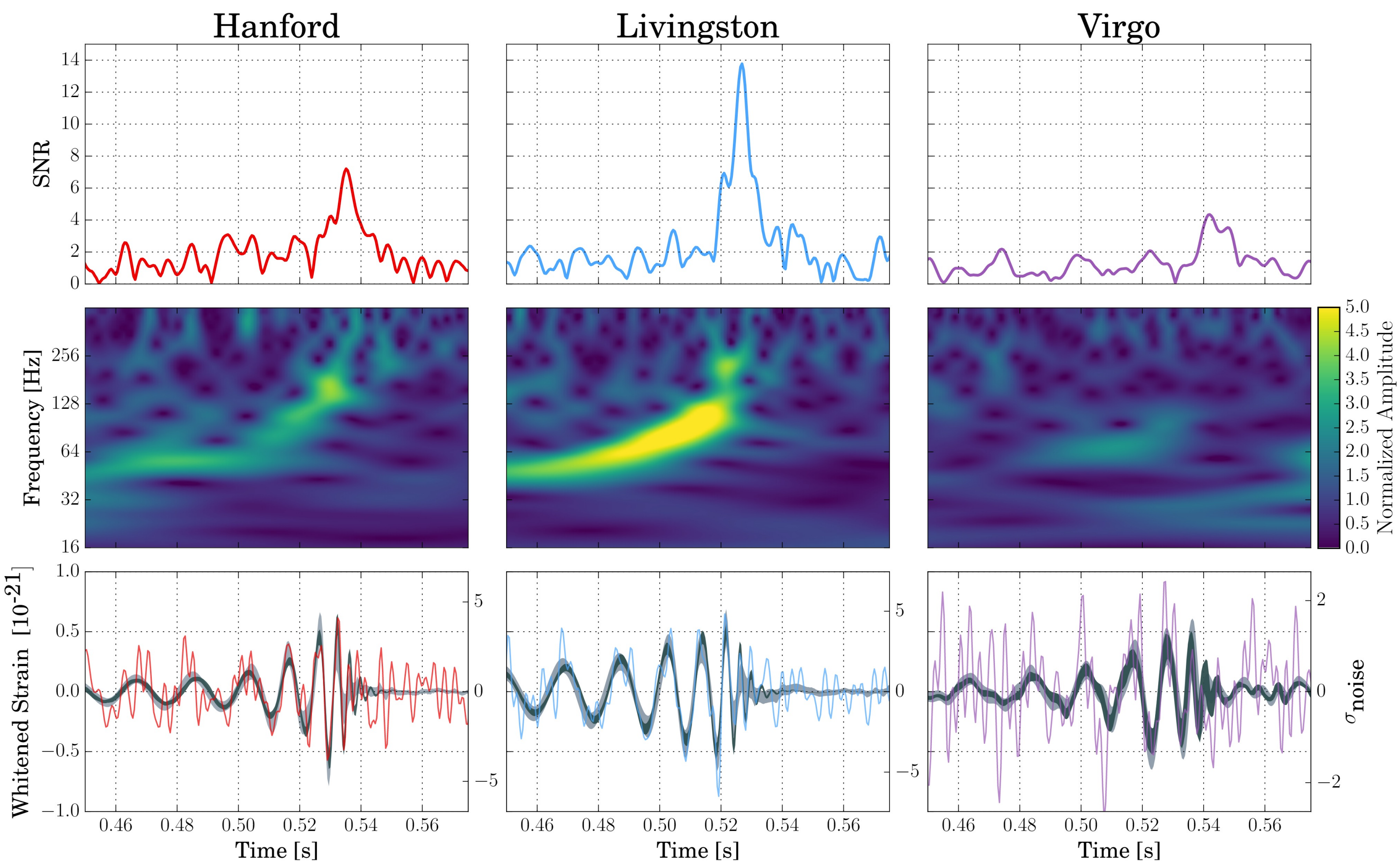




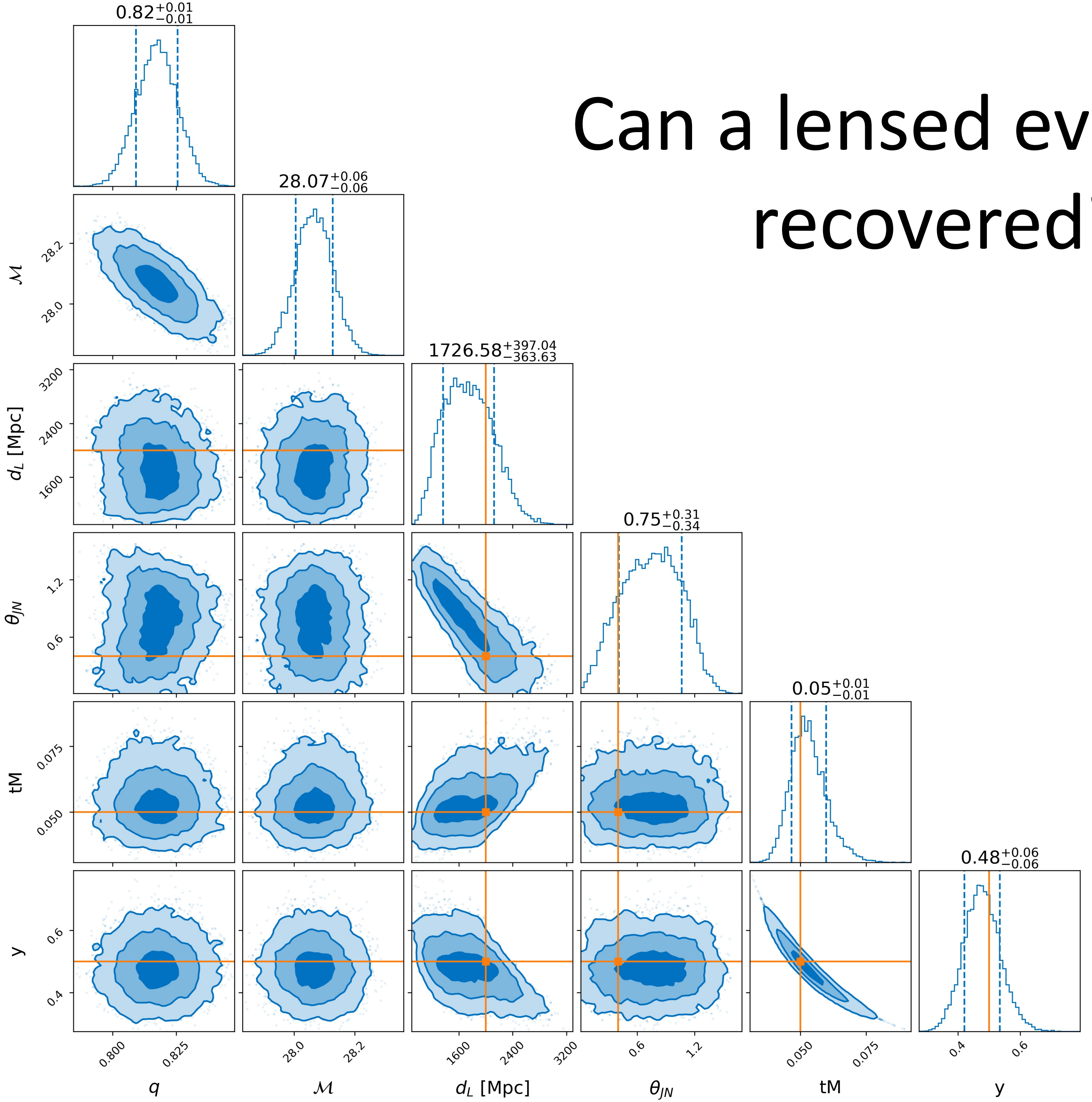
Topics of Interest

- GW lensing
- GW polarization
- GW in eccentric or hyperbolic binaries
- Detecting single, perturbed neutron stars (are continous waves really continous?)
- Data analysis (burst searches)

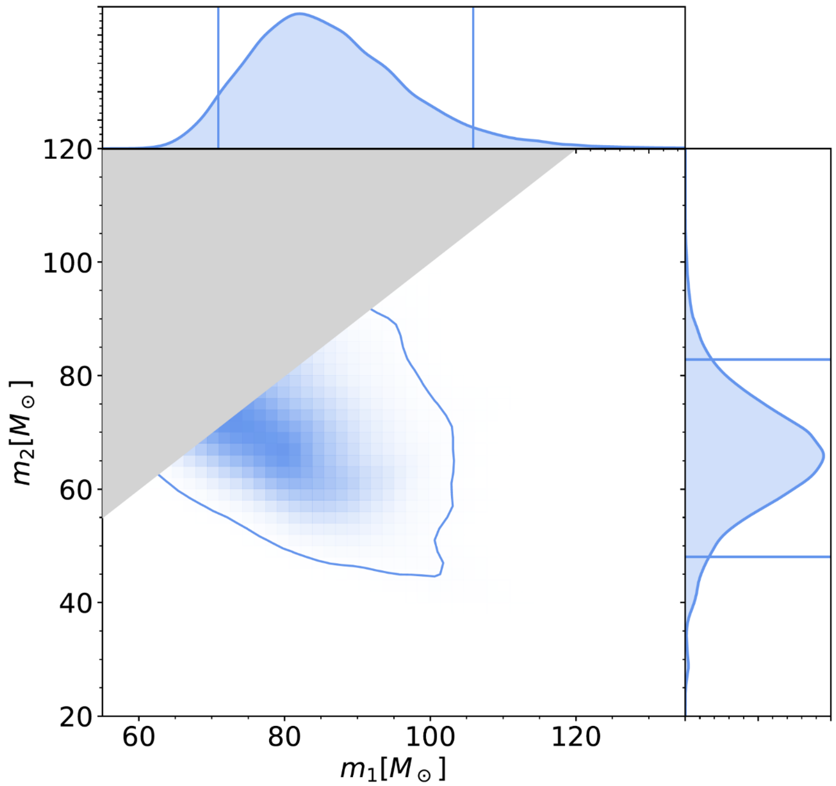
Lensed events? (e.g., GW170814)

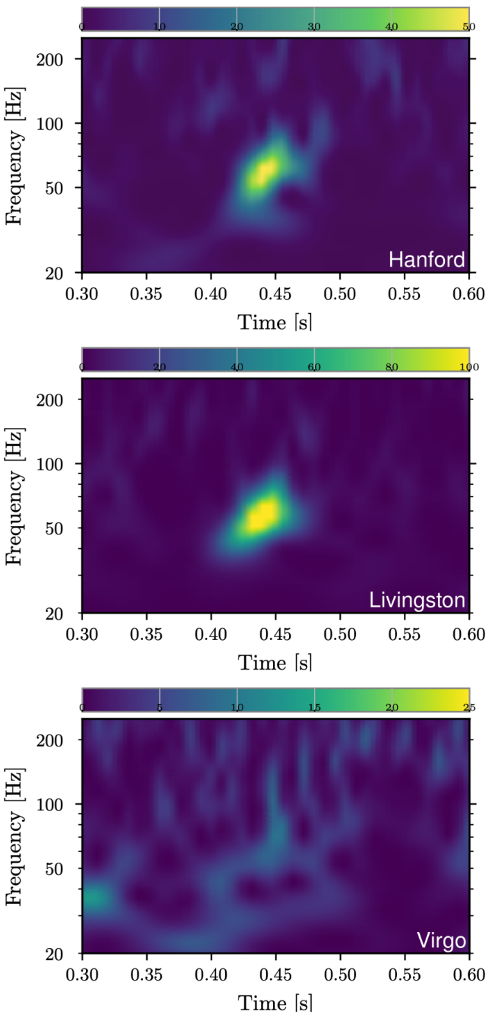


Can a lensed event be recovered?



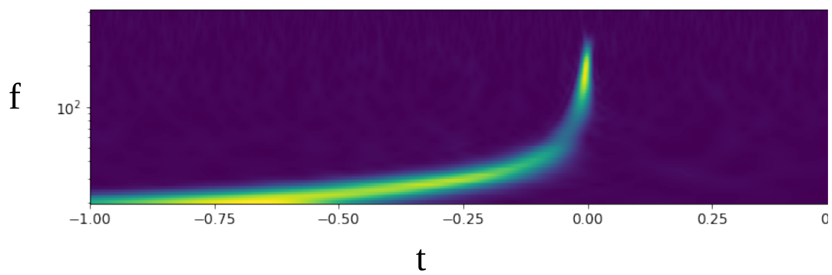
Most massive merger

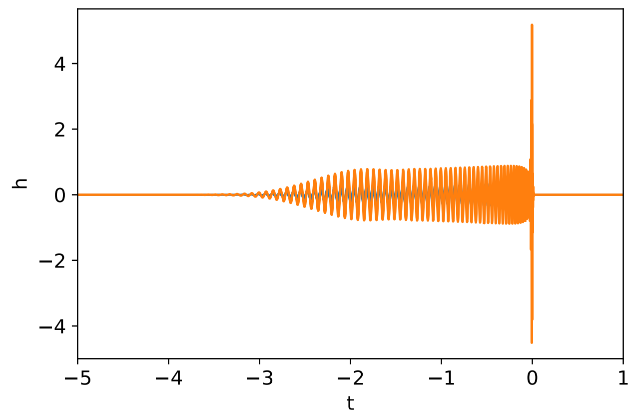




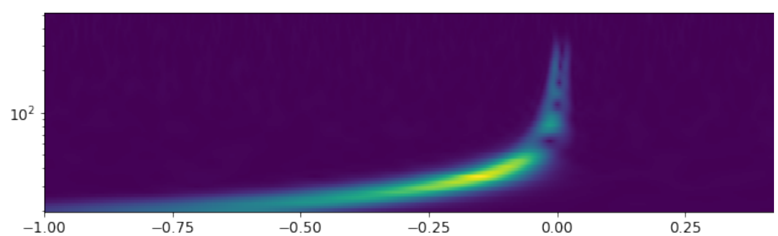
GW lensing (Helena U., RB, Oleg)

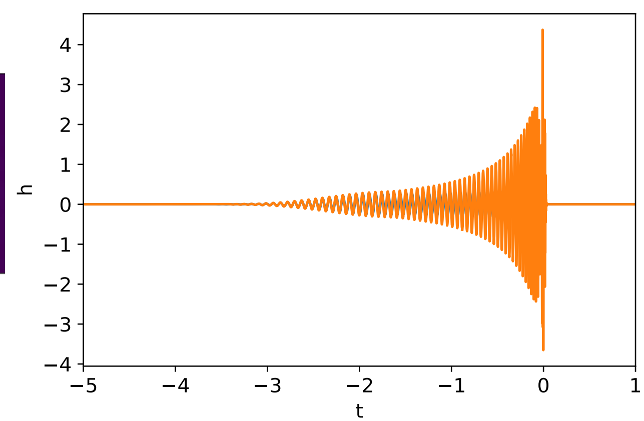
$y = 0.2 \Rightarrow \tau_{21} \approx 0.4$





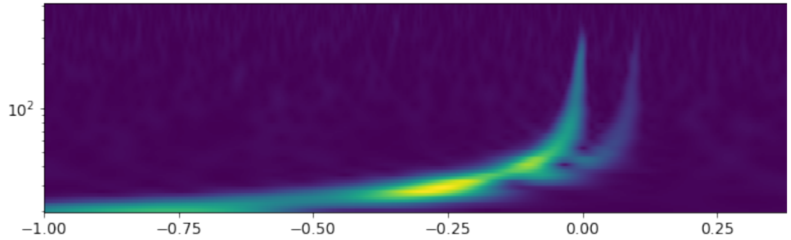
$t_M = 0.01\,\mathrm{s}\,,\, M_L = 500 M_\odot$



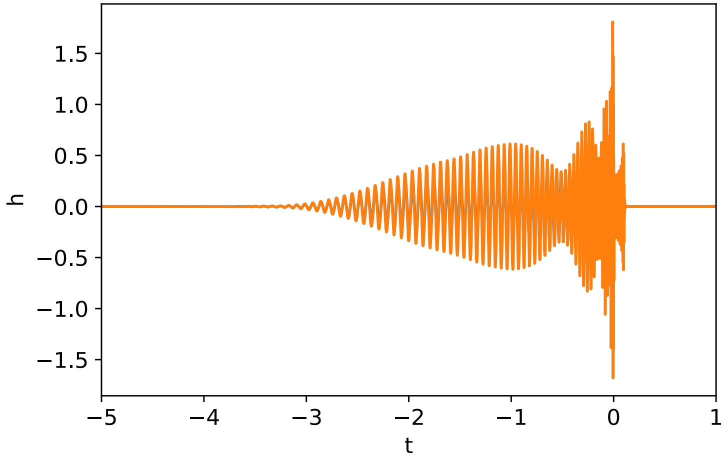


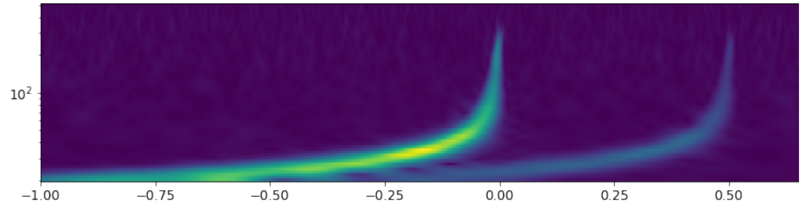
$t_M = 0.05\,\mathrm{s}\,,\, M_L = 2500 M_\odot$

GW lensing (Helena U., RB, Oleg)

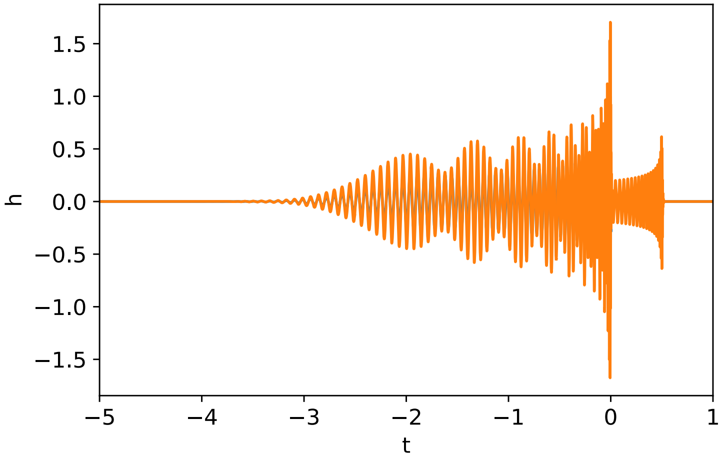


$t_M = 0.1\,\mathrm{s}\,,\, M_L = 5000 M_\odot$





$t_M = 0.5\,\mathrm{s}\,,\, M_L = 25000 M_\odot$



Detecting GW polarization?

$$\begin{aligned} I &= \tilde{h}_+\tilde{h}_+^* + \tilde{h}_\times\tilde{h}_\times^* \quad \text{(total intensity in the wave)} \\ Q &= \tilde{h}_+\tilde{h}_+^* - \tilde{h}_\times\tilde{h}_\times^* \quad \text{(linear polarization)} \\ U &= \tilde{h}_+\tilde{h}_\times^* + \tilde{h}_\times\tilde{h}_+^* \quad \text{(linear polarization)} \\ V &= \tilde{h}_\times\tilde{h}_+^* - \tilde{h}_+\tilde{h}_\times^* \quad \text{(circular polarization)}, \end{aligned} \tag{1}$$

where $\tilde{h}_+$ and $\tilde{h}_\times$ denote Fourier transforms applied to the gravitational wave amplitudes.

The degree of linear polarization can be calculated by

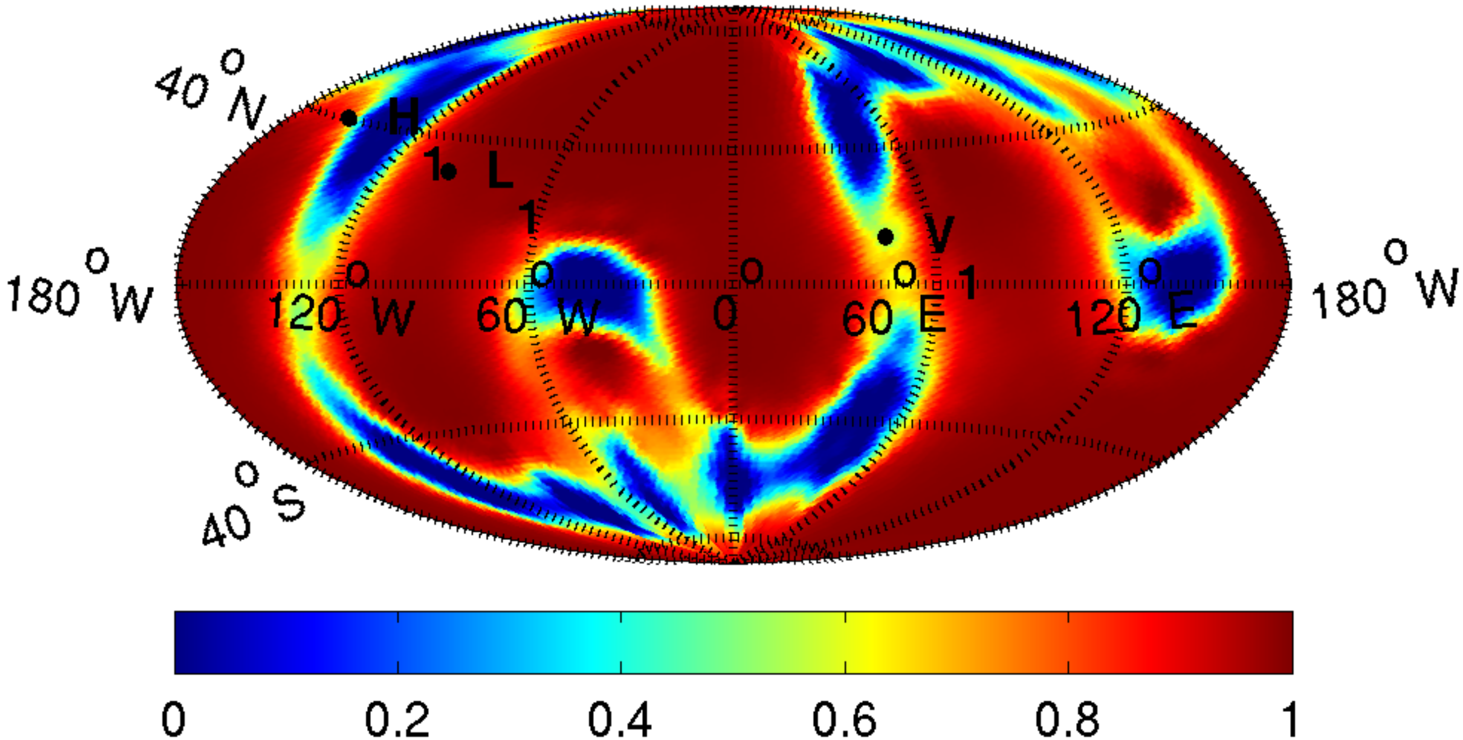
$$\mathbf{d_l} = \frac{\sqrt{\mathbf{Q^2 + U^2}}}{\mathbf{I}} \tag{2}$$

and **the degree of circular polarization** is found from

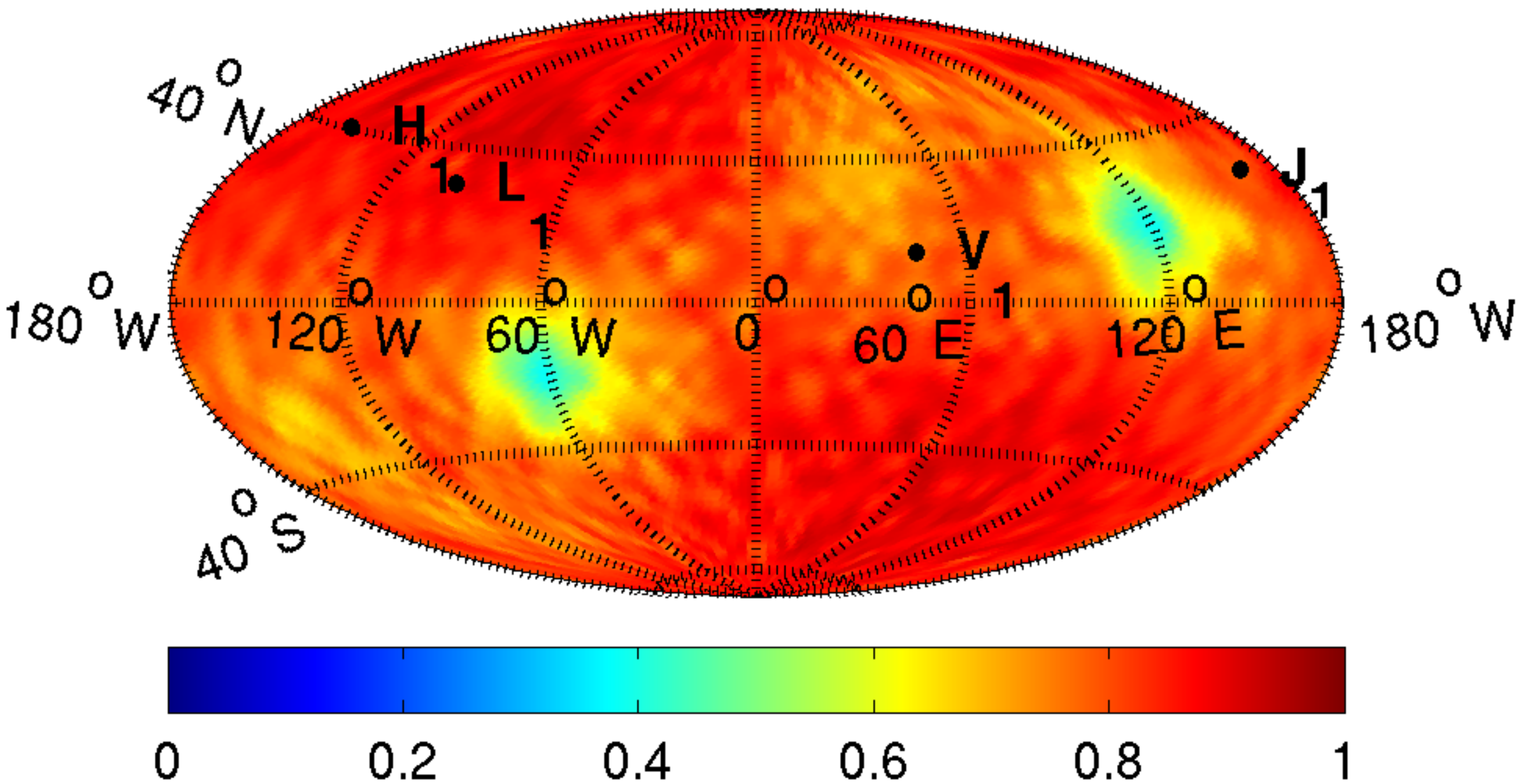
$$\mathbf{d_c} = \frac{|\mathbf{V}|}{\mathbf{I}}. \tag{3}$$

A linearly polarized wave would have $d_c = 0,\ d_l = 1$, whereas a circularly polarized wave has $d_c = 1,\ d_l = 0$.

L-H-V network: no noise limit



LVK network



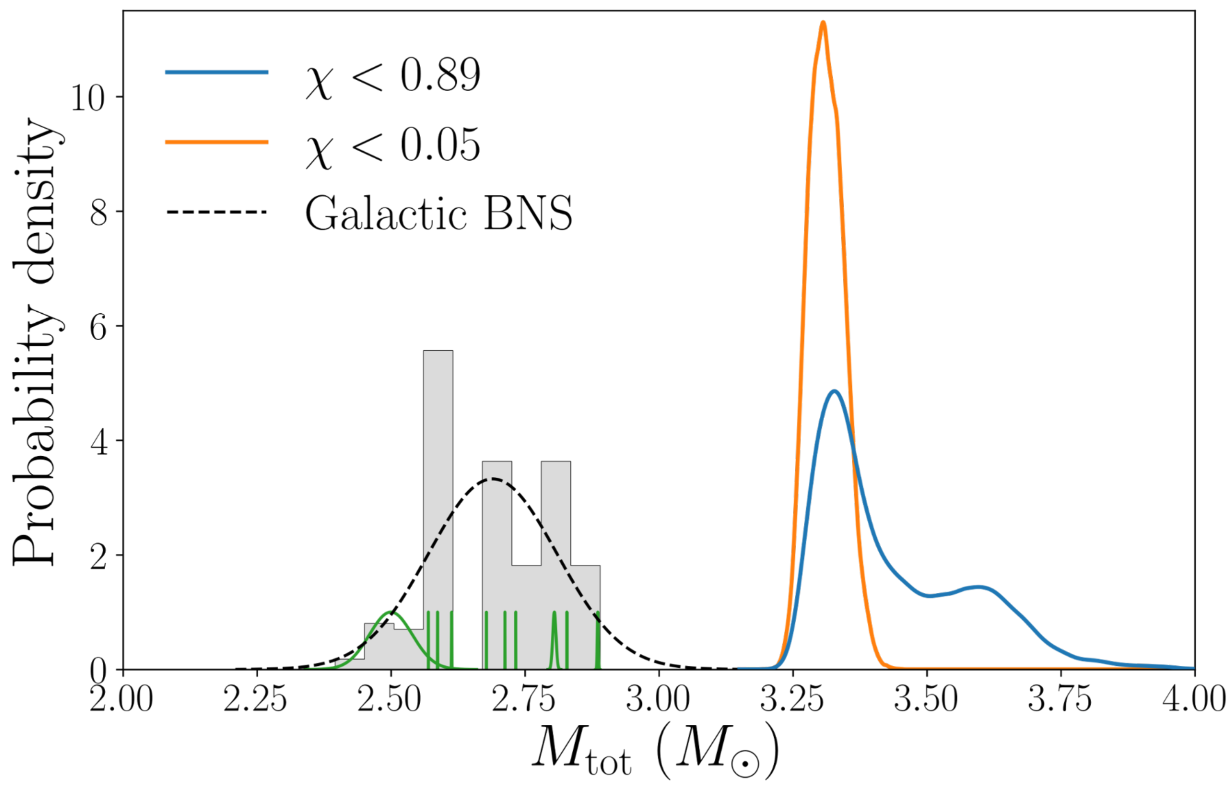
Detecting eccentricity?

- Multiple harmonics?
- Eccentric obits add other harmonics

$$\bar{h}_{ij} = \frac{2G}{c^4 D}\ddot{\mathcal{I}}_{ij}(t - D/c)\ .$$

$$\begin{aligned} h_+ &= -\frac{4}{1+e}\frac{G^2 M\mu}{c^4 D\, r_{min}}\left(\cos 2\theta + \frac{e}{4}\cos 3\theta\right) \\ h_\times &= -\frac{4}{1+e}\frac{G^2 M\mu}{c^4 D\, r_{min}}\left(\sin 2\theta + \frac{e}{4}\sin 3\theta\right) \end{aligned}$$

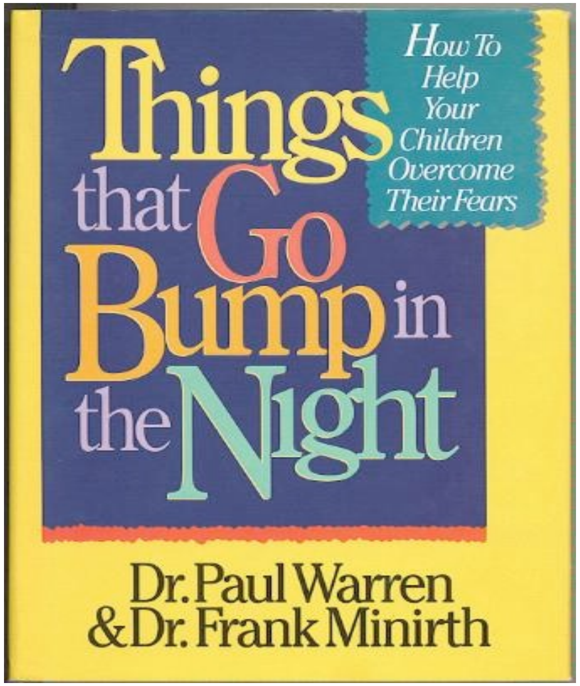
Binary neutron star - well above Chandrasekhar mass



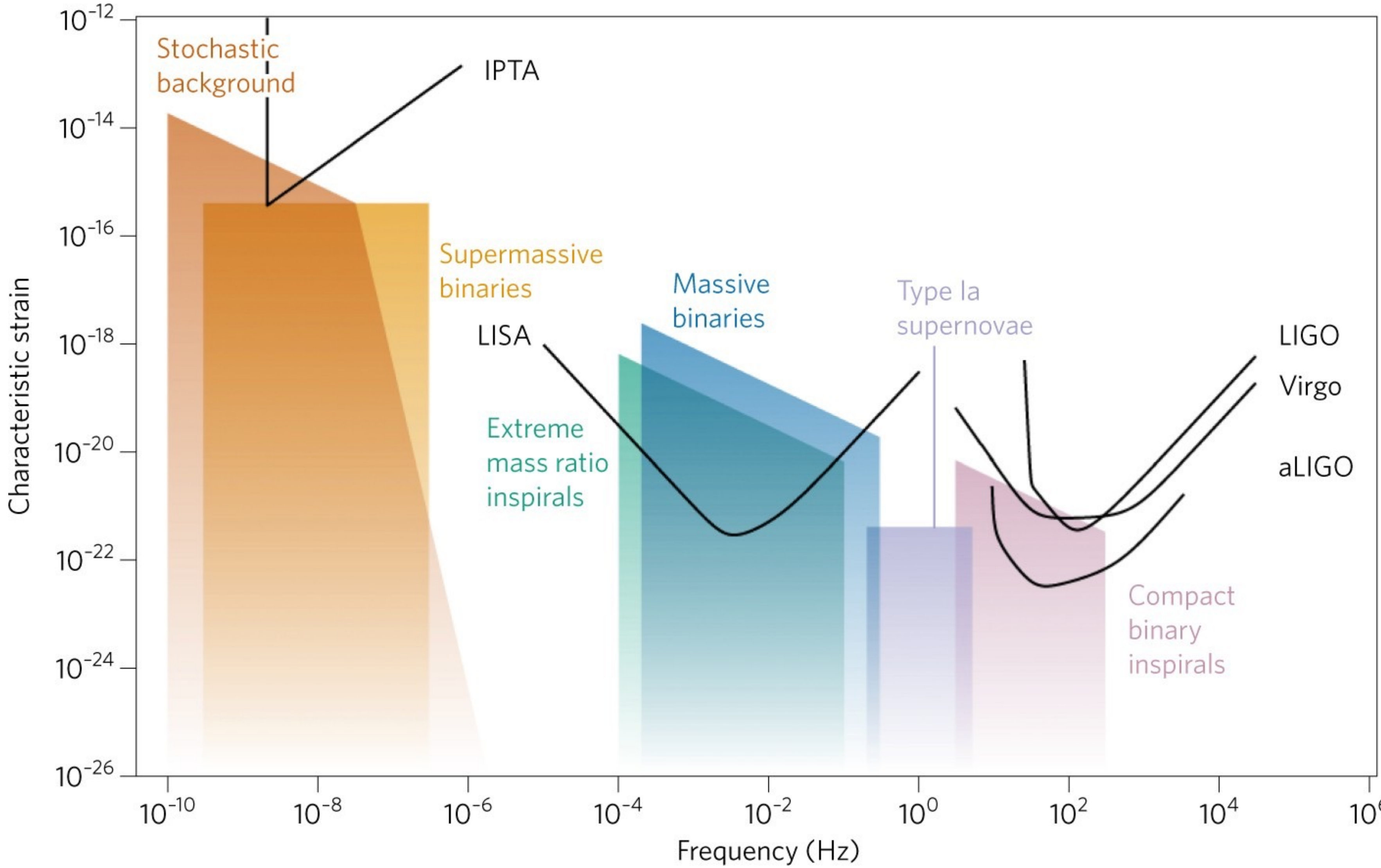
LIGO-Virgo+GR

a tool to learn about the universe

- O1: 3 detections, 2015
- O2: 7 BBH+BNS, 2017
- O3: Apri 1st, 2019 to March 27, 2020 (stopped by COVID-19)
- 56 candidates
  - One a week
- Flood of signals, **one every day**? Daily new info about the universe?



The End

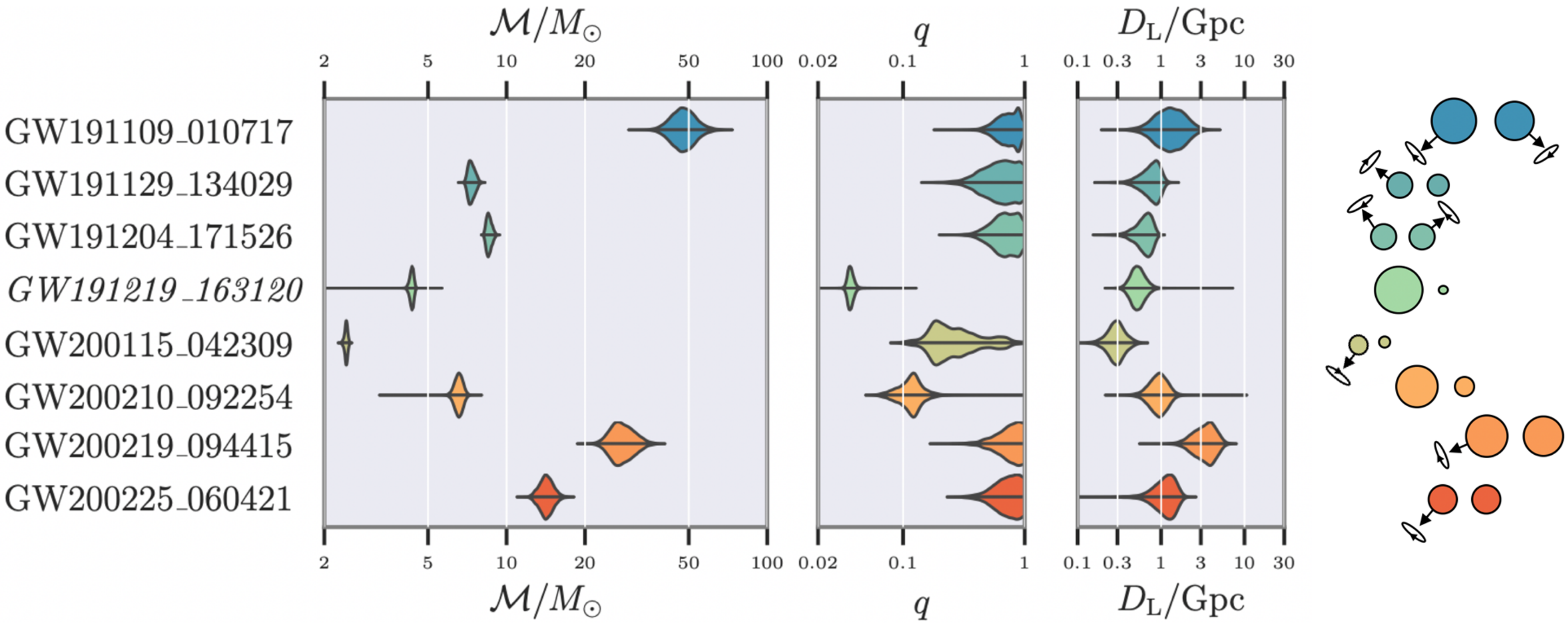

Stochastic background
IPTA
Supermassive binaries
Massive binaries
Type Ia supernovae
LISA
LIGO
Virgo
aLIGO
Extreme mass ratio inspirals
Compact binary inspirals
Characteristic strain
Frequency (Hz)
10^{-12}
10^{-14}
10^{-16}
10^{-18}
10^{-20}
10^{-22}
10^{-24}
10^{-26}
10^{-10}
10^{-8}
10^{-6}
10^{-4}
10^{-2}
10^{0}
10^{2}
10^{4}
10^{6}

- Livingston, Louisiana

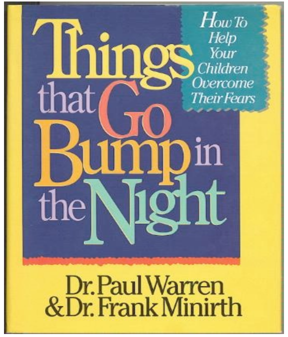
•

Virgo in Cascina. near Pisa

Parameters of some interesting events



What’s the big deal ?

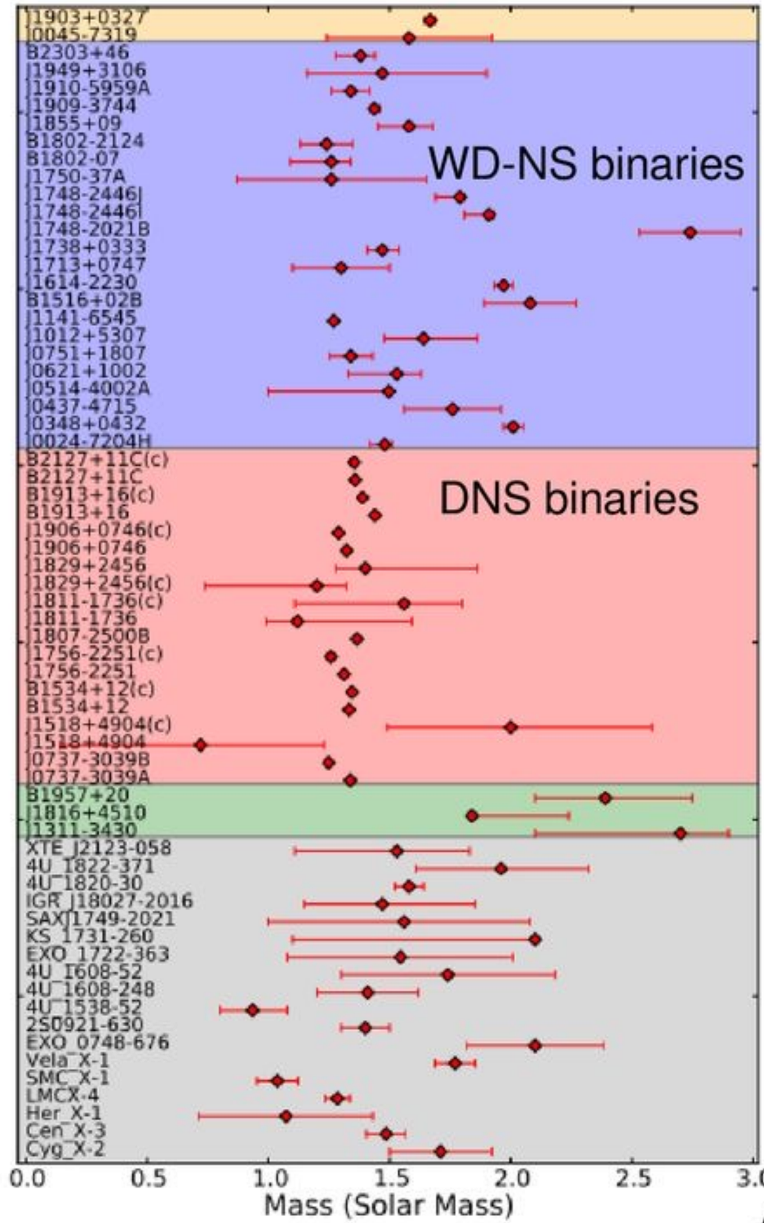


- Continuous measurements of lengths 1000 times smaller than proton size!! Science, not science fiction.
- GWs bring info about objects that can not be seen with EM observations and vice-versa.
- This is a radically different field than EM observations.
- We talked about signals and sources that we ****know**** about. Any new field has it’s own surprises (radio, gamma-ray).

“….***there are known knowns, there, are known unknowns But there are also unknown unknowns***….”

---- Don Rumsfeld

Mass

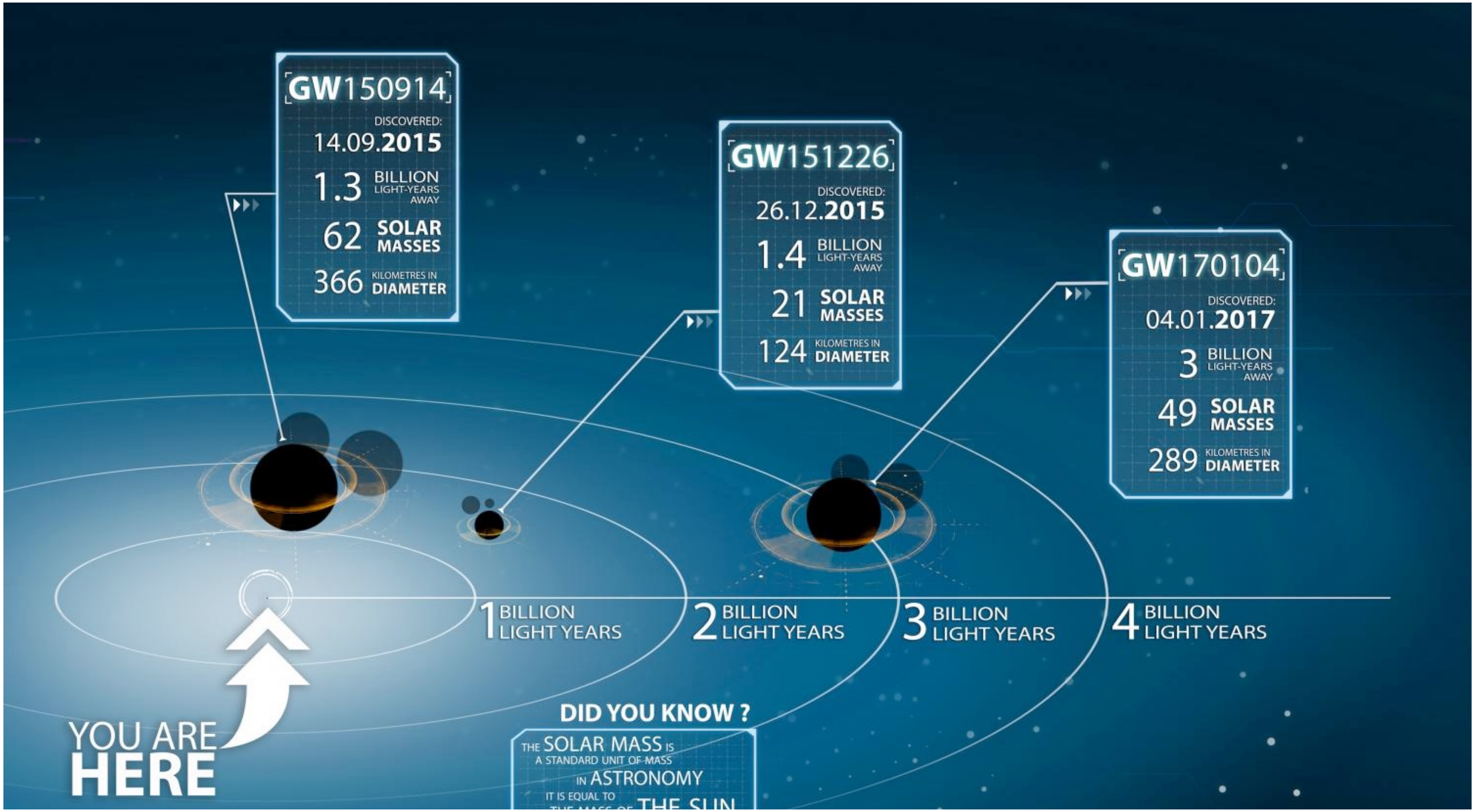


Main sequence NS binaries

Black widow pulsar

X-ray/Optical binaries

Anna Watts et al.2014


GW150914
DISCOVERED:
14.09.2015
1.3 BILLION LIGHT-YEARS AWAY
62 SOLAR MASSES
366 KILOMETRES IN DIAMETER
GW151226
DISCOVERED:
26.12.2015
1.4 BILLION LIGHT-YEARS AWAY
21 SOLAR MASSES
124 KILOMETRES IN DIAMETER
GW170104
DISCOVERED:
04.01.2017
3 BILLION LIGHT-YEARS AWAY
49 SOLAR MASSES
289 KILOMETRES IN DIAMETER
1 BILLION LIGHT YEARS
2 BILLION LIGHT YEARS
3 BILLION LIGHT YEARS
4 BILLION LIGHT YEARS
YOU ARE HERE
DID YOU KNOW ?
THE SOLAR MASS IS A STANDARD UNIT OF MASS IN ASTRONOMY
IT IS EQUAL TO

BH mergers from O1&O2

- **10 BH mergers** in O1 & O2: all equal mass, no spin
  - No spin retained from birth or accretion
  - Born this way! Not from prior mergers!
  - Unequal mass events: more rare
  - Most likely field binaries – form in the galaxy, stars that form are binaries because of the way the disk fragments => born with equal masses
  - Dense environments equalize binaries, lighter one will be kicked out

Unequal masses: GW190412

- 2.4 billion light years away
- SNR = 19
- 30 M_{Sun} + 8 M_{Sun}
- Spin of larger BH about 0.4, marginal precession
- For the first time: more than one GW frequency, higher order multipoles
- How did it form?
  - Big BH from the merger of two smaller ones?
  - Dense environment? Isolation?

Mystery Object in “Mass Gap” GW190814

- 2.6 M_{Sun} + 23 M_{sun}
  - Most unequal mass measured in GWs
  - No measurable tidal deformation
- SNR = 25 in the LVC network, SNR = 21.4 Livingston and 4.3 in Virgo
- 241 Mpc , z= 0.05, localized to 18.5 deg^2
- What is 2.6 M_{sun}object?
  - Merger of 2 neutron stars?
  - Heavy NS (generally unstable above 2.2-2.3 M_{Sun})
  - Very light BH

Candidate GW190521g: light & BHs?

- Flare by a distant active supermassive BH J1249+3449 from the region of the GW emission (Graham *et al.* Phys. Rev. Lett. **124,** 251102, 2020**)**
- Flare due to the BH merger around the quasar?
  - Final black hole (100 M_{Sun}) kicked through the gas in the accretion disk of the quasar
  - Creates a bright flare visible with telescopes
  - Flare reappear in 1.6 years? When BH re-encounters accretion disk.

First neutron star merger **GW170817**

- Signal of about 100 seconds, started at 24 Hz, first at Virgo, total mass 2.82 M_{Sun}
- Fermi & Integral: GW170817A – short GRB of about 2 sec, about 1.7 sec after the merger
- Optical transient AT 2017gfo (SSS 17a) – 11 hours after the merger in **NGC 4993**, also seen in X-ray and radio – a rapidly cooling cloud of neutron rich material
  - 140 million light years away
  - Old stellar population
- A new class of objects, kilonova, on-off in Xrays
  - GRB 150101B, GRB 130603B ?
  - Produced heavy elements: strontium, gold, platinum

Second NS merger: GW190425

- Total mass: 3.4-3.7 M_{sun}
- **EM observations:** 17 galactic neutron star pairs, total mass ranges 2.5 to 2.9 M_{sun}
- LIGO Livingston – SNR = 12.5
- 520 million light years away, 160 Mpc
- Will see such sources up to $z < 0.1$, 400 Mpc

Why is GW190425 so heavy?

- Formation scenarios
  - Low metallicity environment
    - Energetic kicks caused by supernova suppressed
    - Close binary system after their evolution into neutron stars
    - Tight orbits could evade EM detection
    - A population that has not been observed before
  - One is a BH?
    - Lighter than any black holes observed
  - Dense environment
    - Three body process: companion swapped for a heavy NS
  - Younger stellar population: supernova different?

Summary

LIGO-Virgo+GR: a tool to learn about the universe

- What can LIGO-Virgo see?
- BH binaries
  - Most 20-40 M_{Sun}
  - Up to when do we have waveforms?
  - When to the waveforms start to disagree
  - Tidal deformations and ringdown are not yet measured well. Will change.
- NS-binaries
  - Borderline events in terms of EM that could be seen by LVC
  - Deviations in the waveform caused by tidal perturbations. Modeled via adiabatic approx. (Hinderer *et al*. 2017)
    - Matter out of equilibrium? Not polytrope?
    - Final object: NS or BH – waveforms differ
    - Equation of state? Unclear how much it matters.
    - Resonances that kick in with i-modes or f-modes e.g., resulting in the shattering of the crust (Tsang, Bondarescu et al., 2012, Andersson et al. in progress)