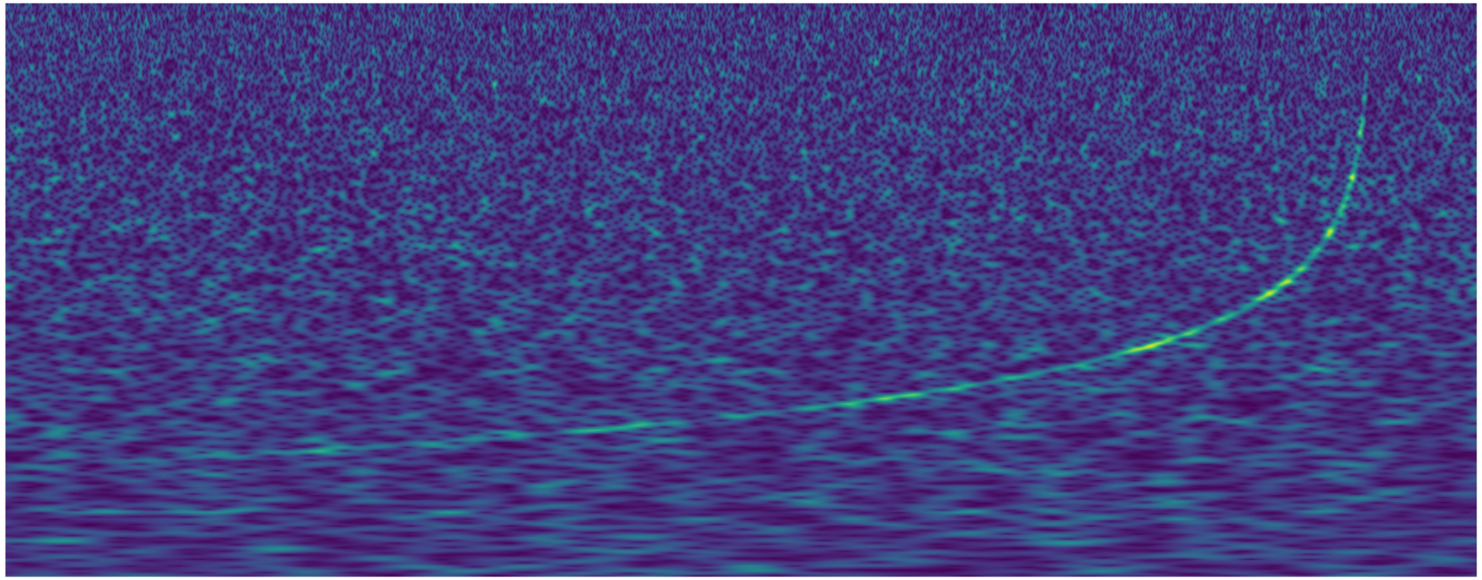
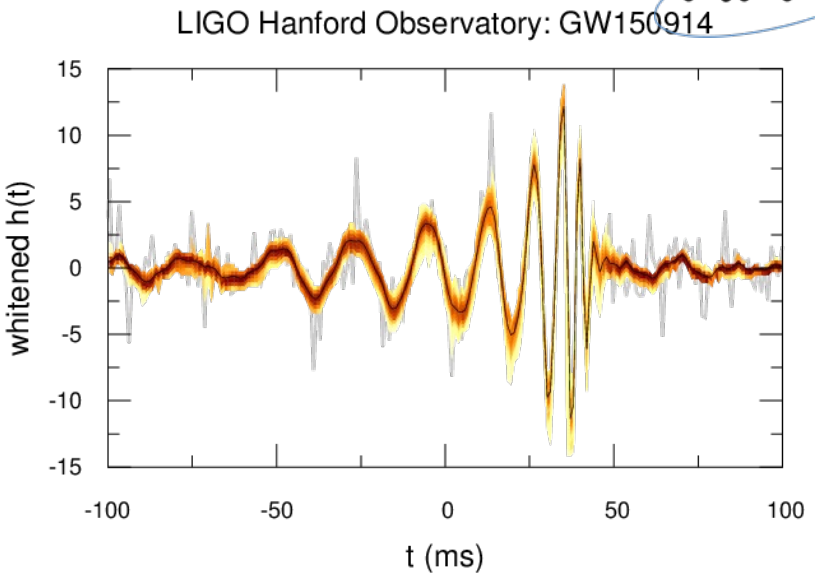
Gravitational Wave Astronomy -- Avant le De´luge



GW170817



Keith Riles – University of Michigan

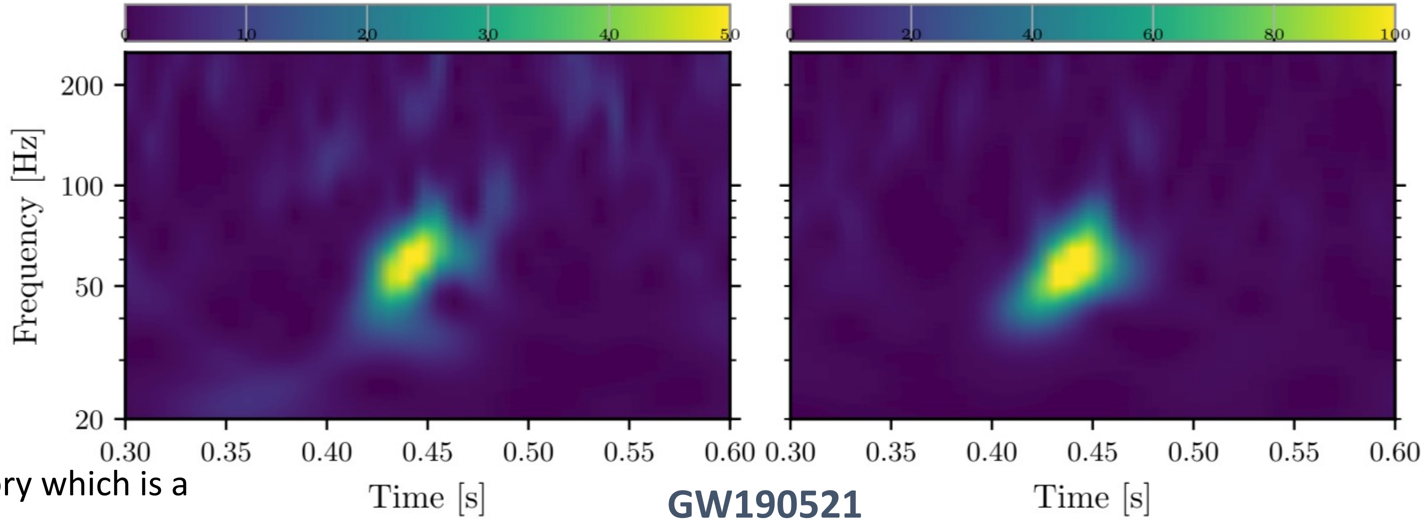
for the LIGO Scientific Collaboration,
Virgo Collaboration and KAGRA Collaboration

LIGO G2201057-v2

POTOR 8

September 19, 2022

This material is based upon work supported by NSF's LIGO Laboratory which is a major facility fully funded by the National Science Foundation.



GW190521

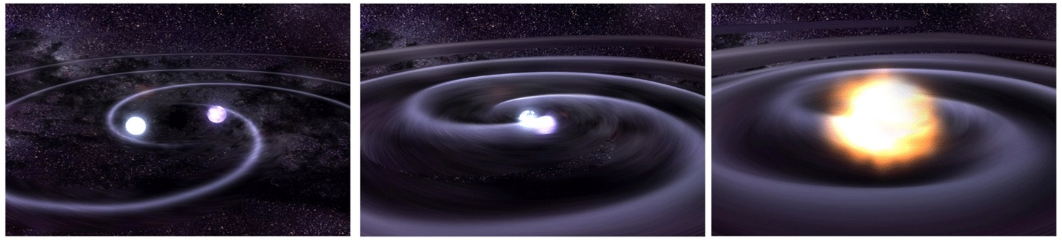
Gravitational Wave Signal Types

Short-Lived ⟷ **Long-Lived**

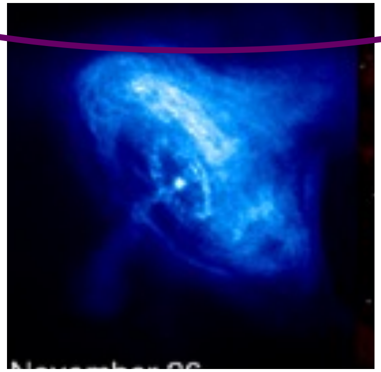
Detections (so far)

Known waveform ↕ **Unknown waveform**

Compact Binary Coalescences (NS-NS, NS-BH, BH-BH)

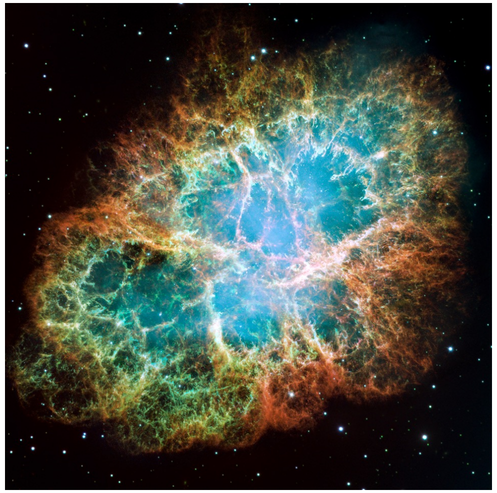


Continuous waves (pulsars)

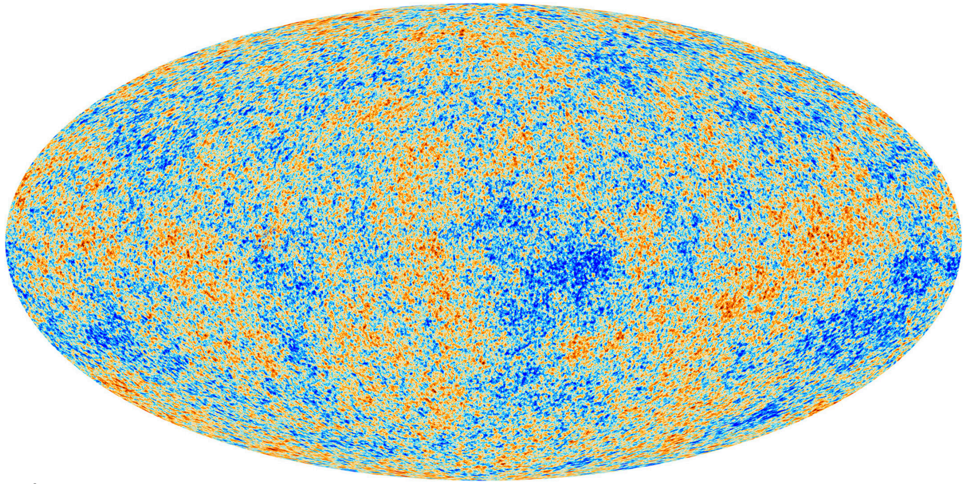


Next?

Bursts (Supernovae)



Stochastic background (Cosmological)



The Global Interferometer Network

The LIGO, Virgo, KAGRA and GEO interferometers are part of a Global Network.

Multiple signal detections will increase detection confidence and provide better precision on source locations and wave polarizations

V1

L1

G1

LIGO

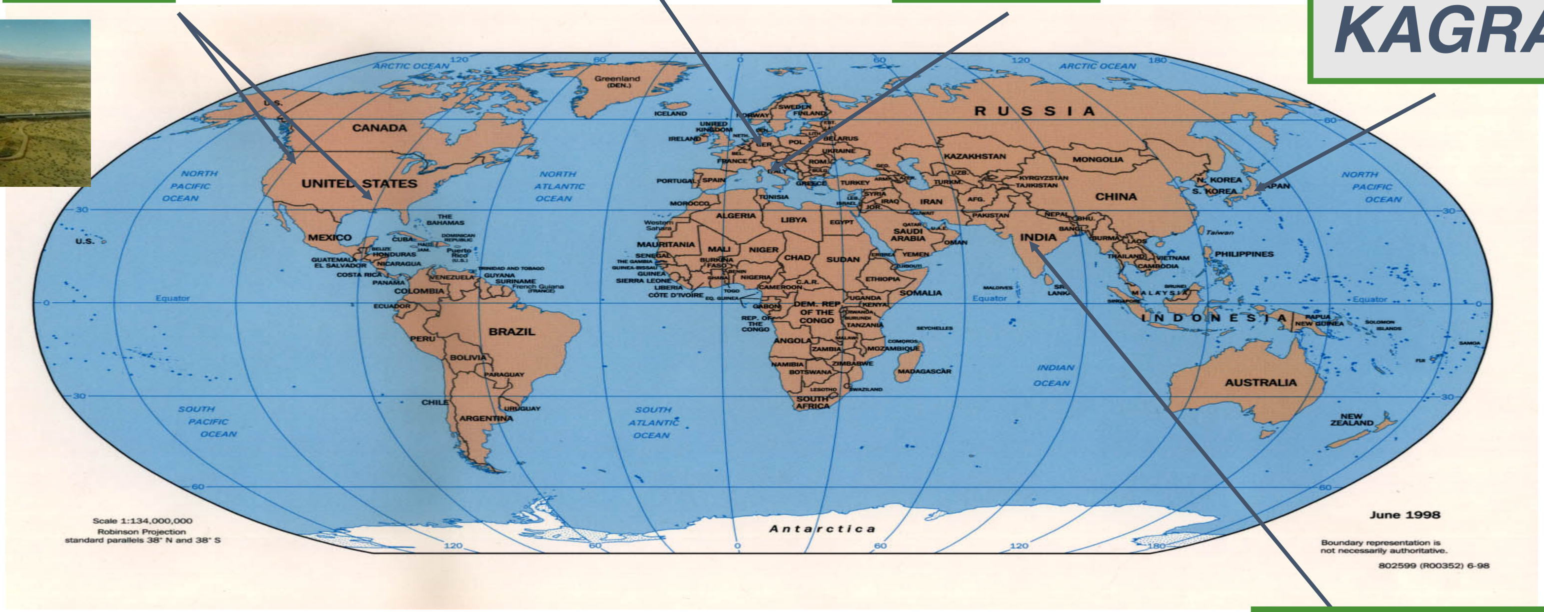
GEO

Virgo

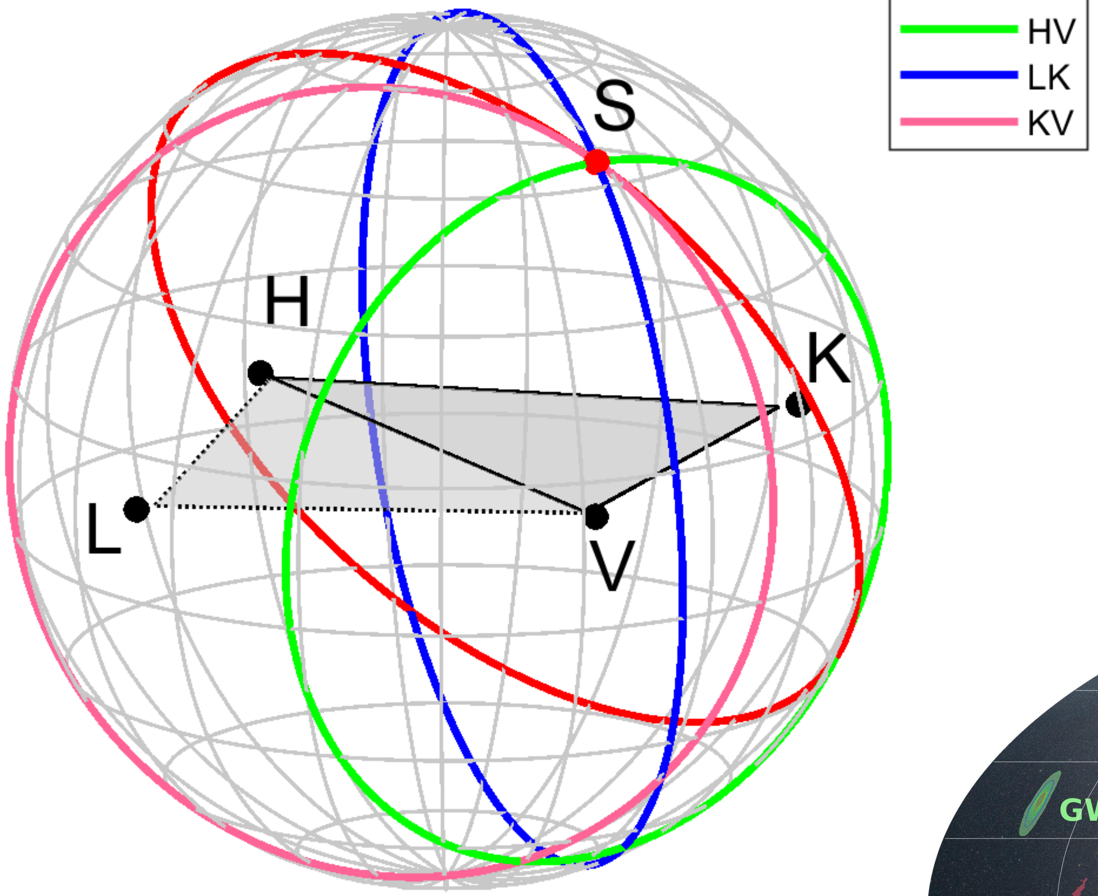
K1

H1

KAGRA



LIGO – India



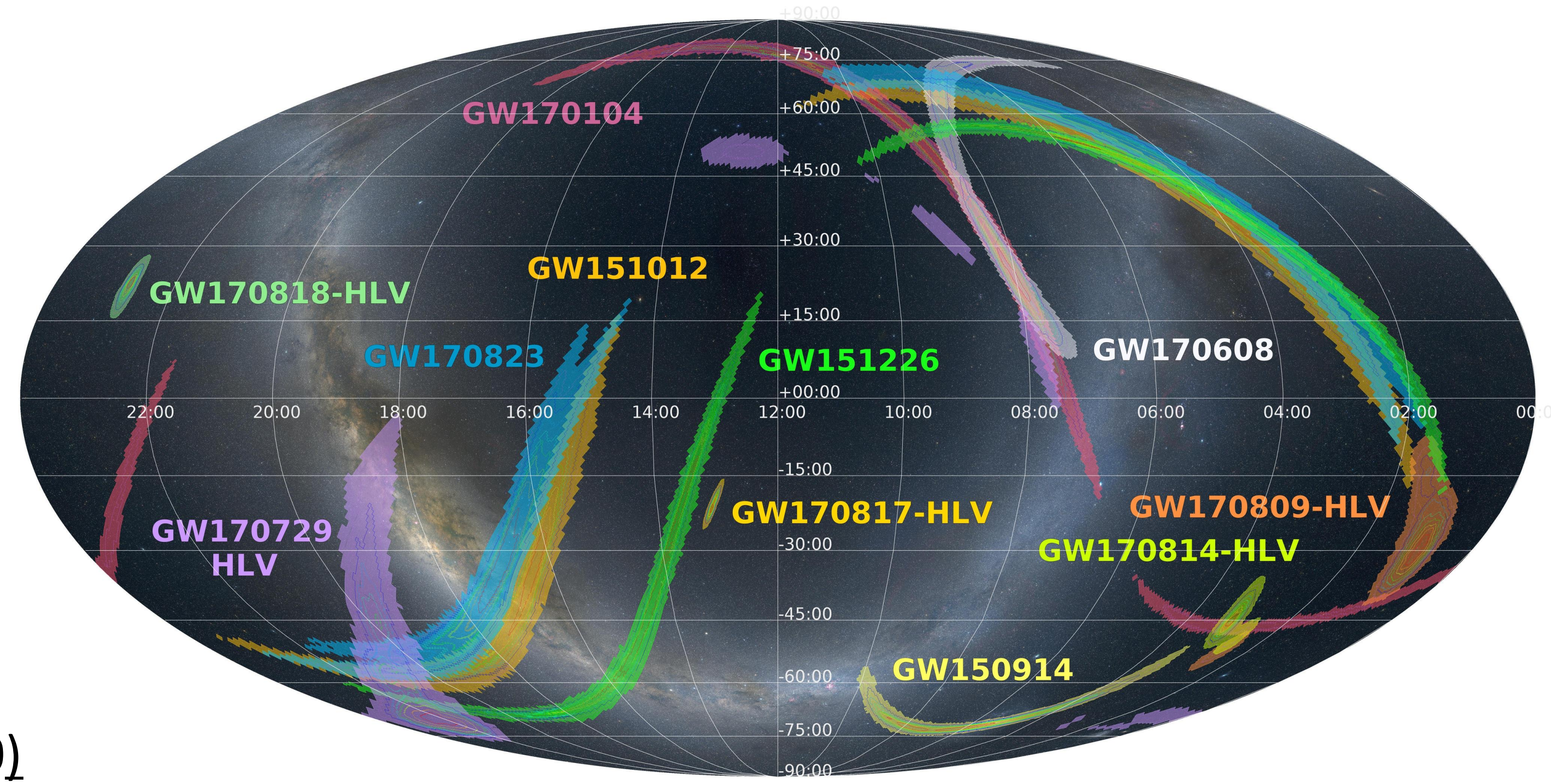
Nearly simultaneous signals (within 10-20 ms) across the globe rule out terrestrial artifacts

Each time difference (with error) between two detectors defines a sky ring

½N(N-1) rings for N detectors → Intersections

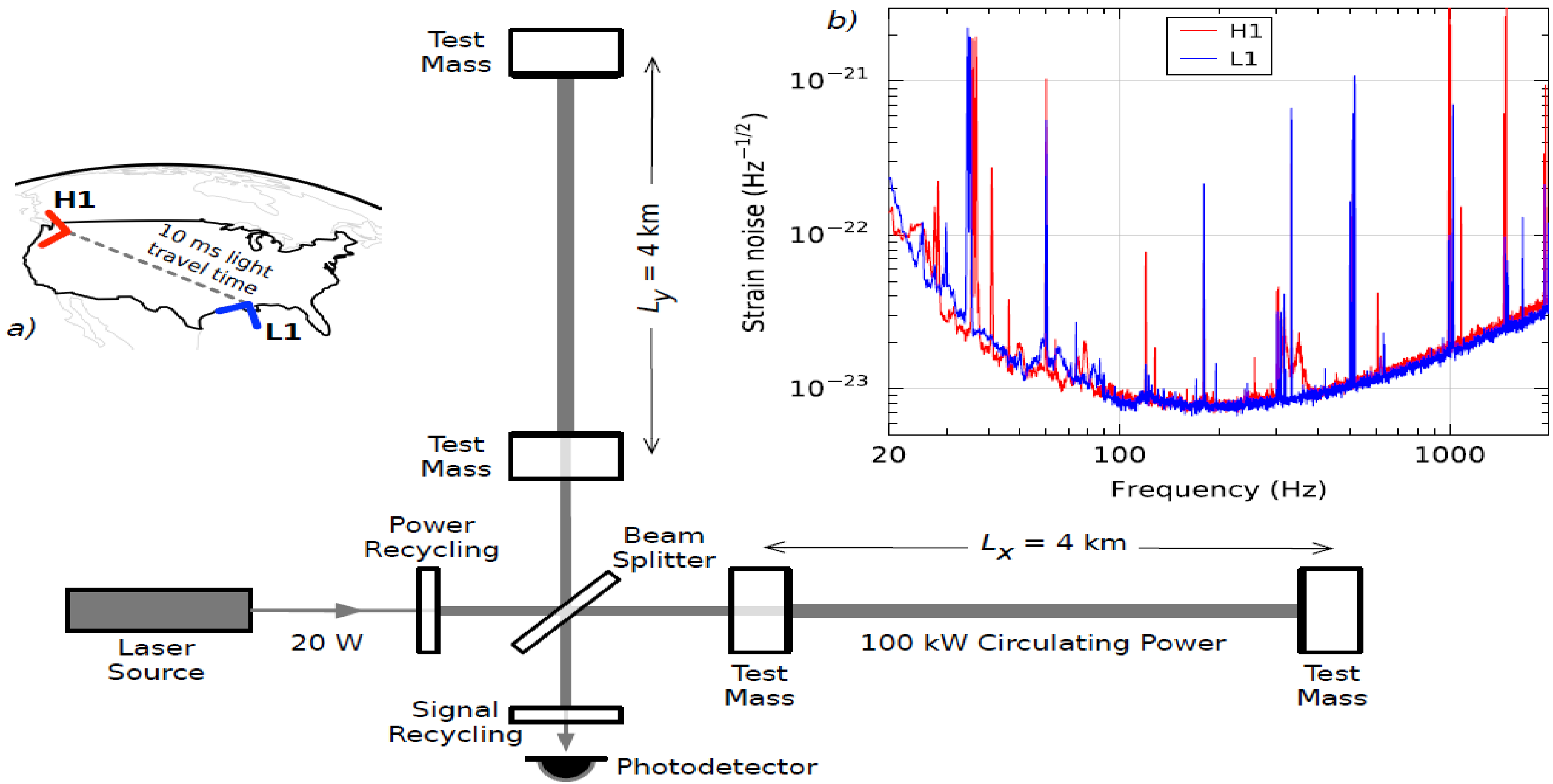
Antenna pattern sensitivity favors arcs of rings

Localization from 2-3 detectors in first two LIGO-Virgo observing runs (O1–O2)



B.P. Abbott *et al*, Liv. Rev. Rel **23**, 3 (2020)

O1 Data Run



B.P. Abbott *et al*, PRL **116**, 061102 (2016)

Gravitational Wave GW150914

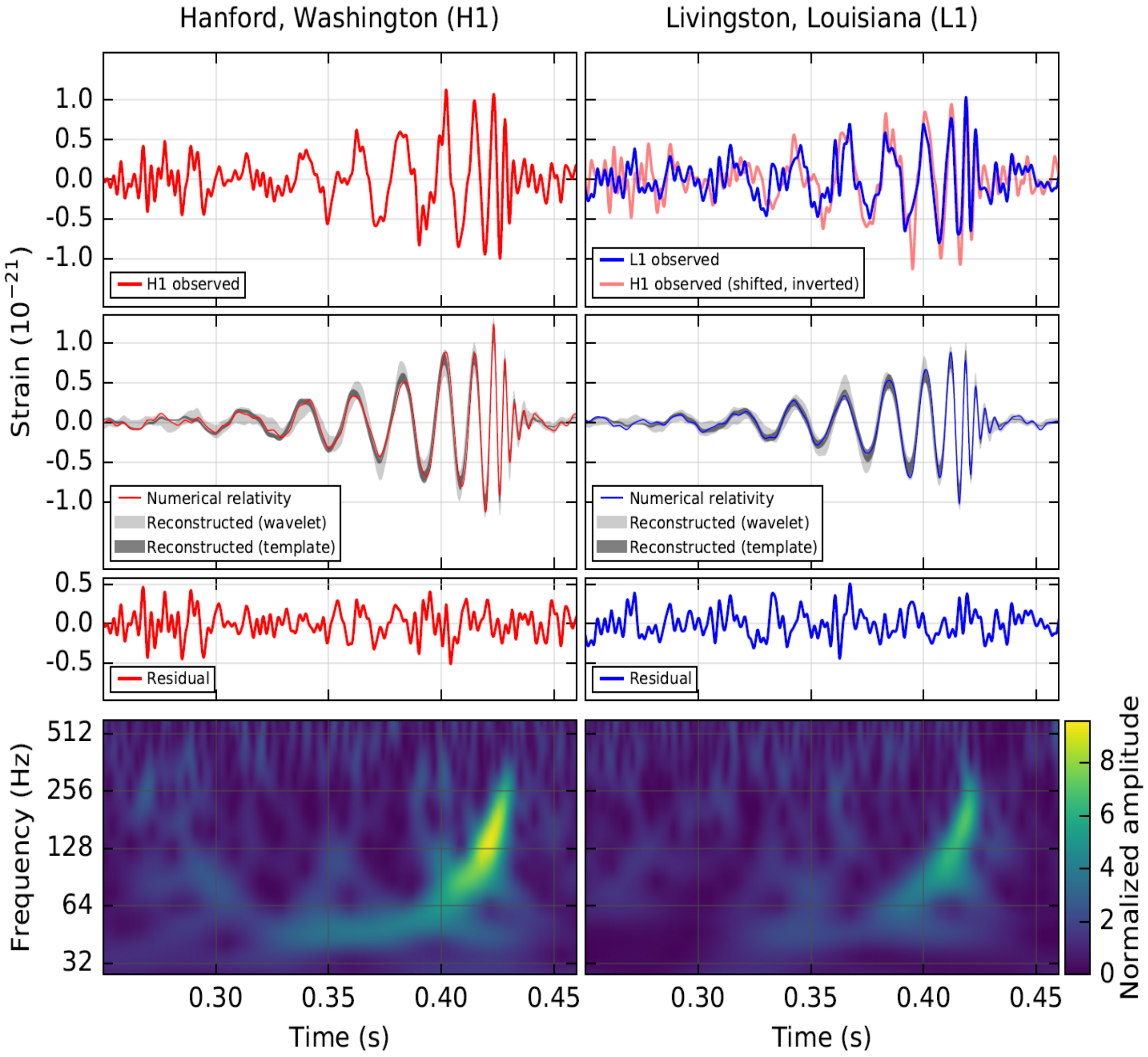
Data bandpass filtered between 35 Hz and 350 Hz

Time difference 6.9 ms with Livingston first

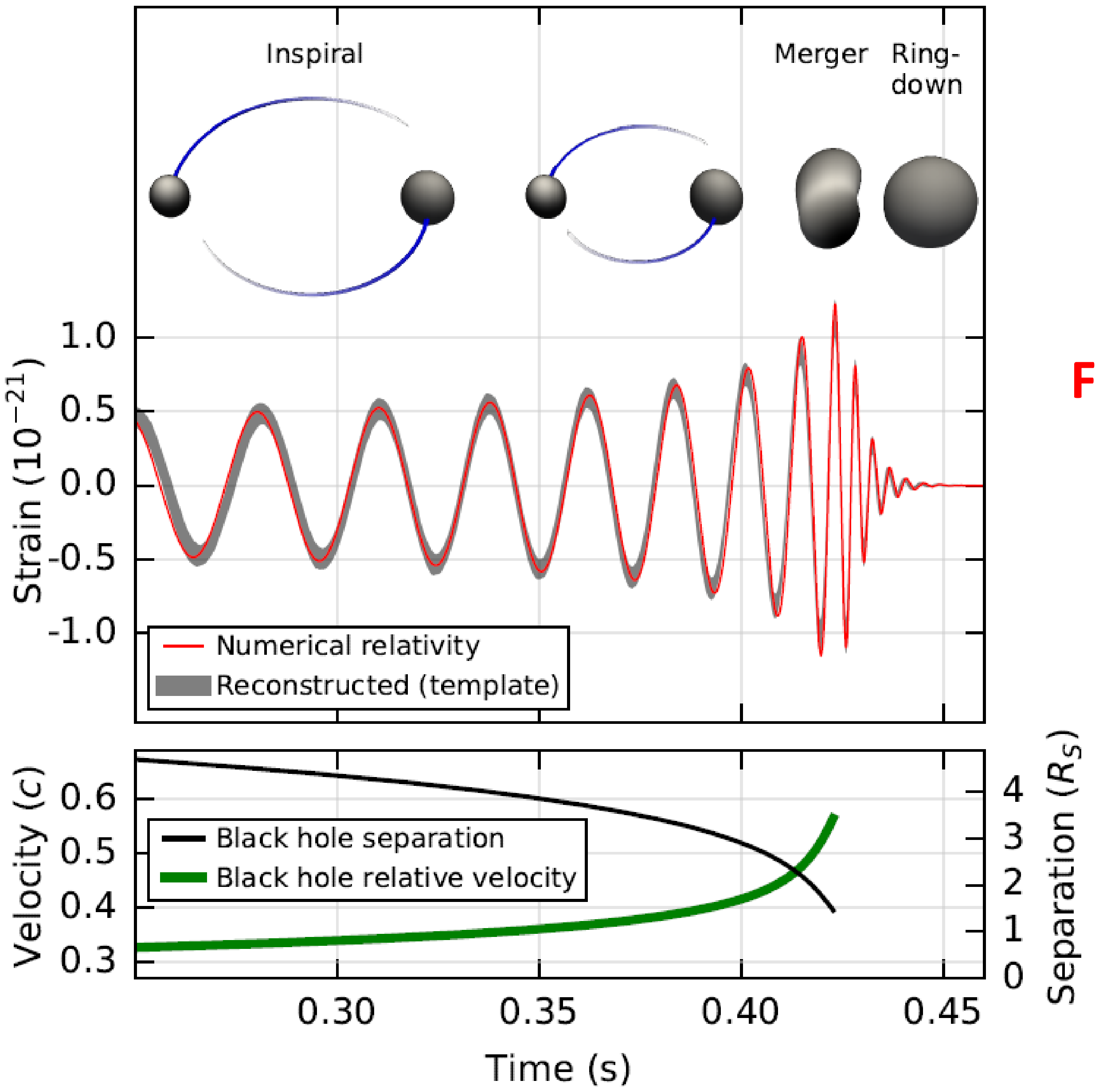
Second row – calculated GW strain using Numerical Relativity Waveforms for quoted parameters compared to reconstructed waveforms (Shaded)

Third Row –residuals

Bottom row – time frequency plot showing frequency increases with time (chirp)



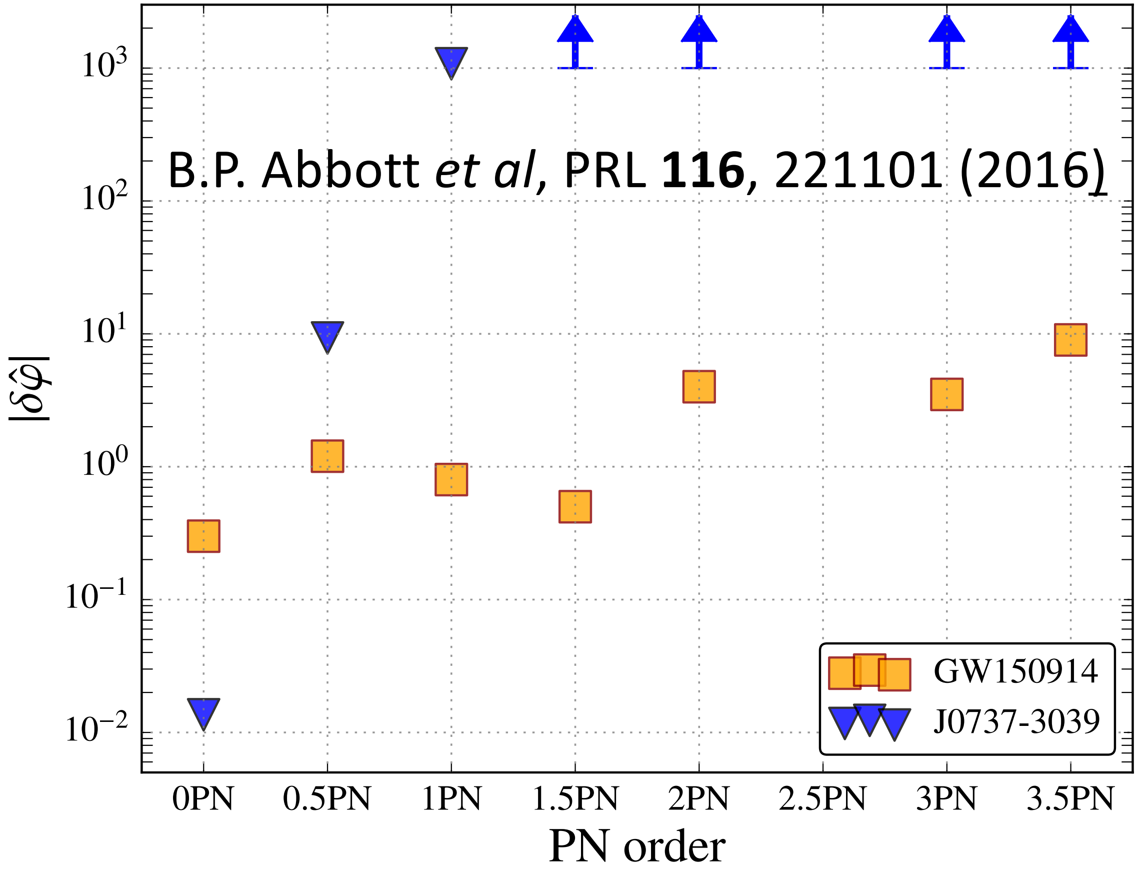
 B.P. Abbott *et al*, PRL **116**, 061102 (2016)



B.P. Abbott *et al*, PRL **116**, 061102 (2016)

Broad interpretation:

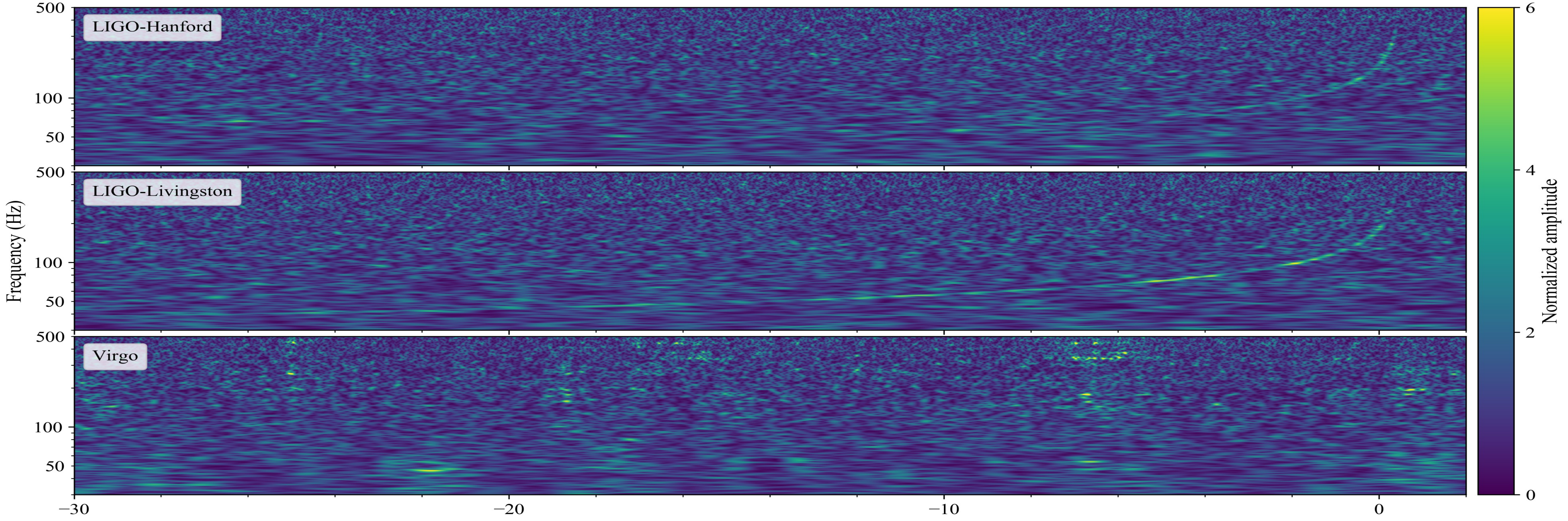
Finer interpretation:



B.P. Abbott *et al*, PRL **116**, 221101 (2016)

Gravitational Wave Event GW170817

a.k.a. GRB 170817A   a.k.a. SSS17a (AT 2017gfo)

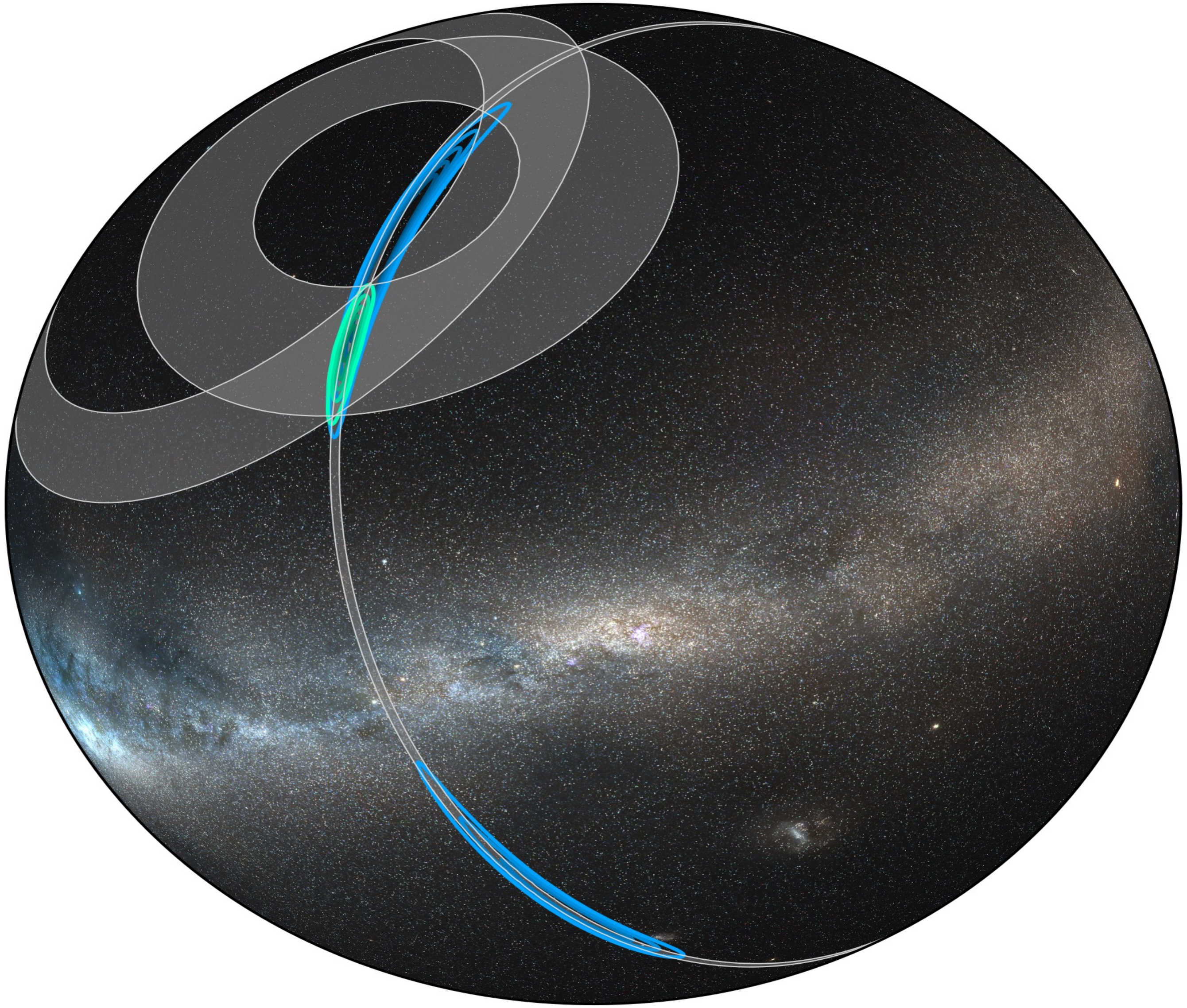


30 seconds

Binary Neutron Star Merger!

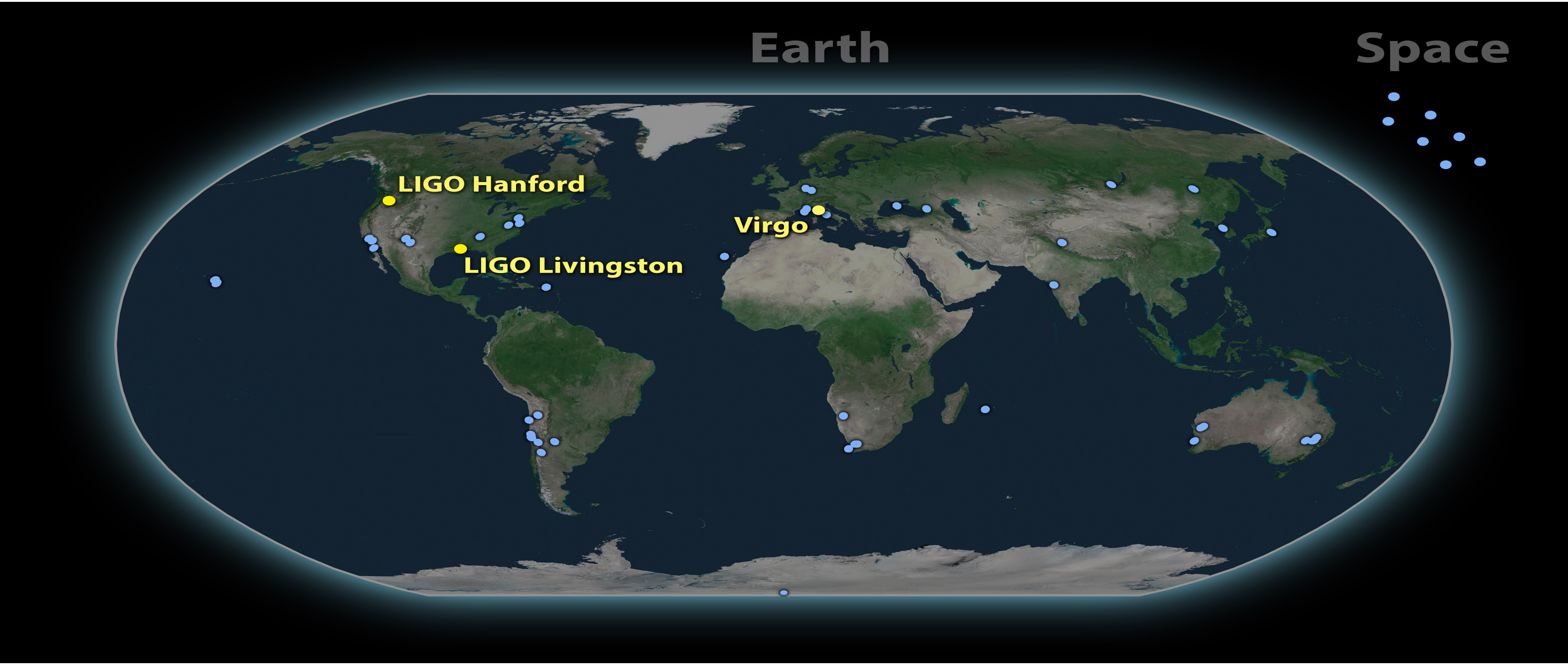
B.P. Abbott *et al*, PRL **119**, 161101 (2017)

Sky localization



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

Observatories (~70) on the Earth and in orbit



→ **Ready to point upon receiving LIGO/Virgo alert – Earth/Sun permitting**

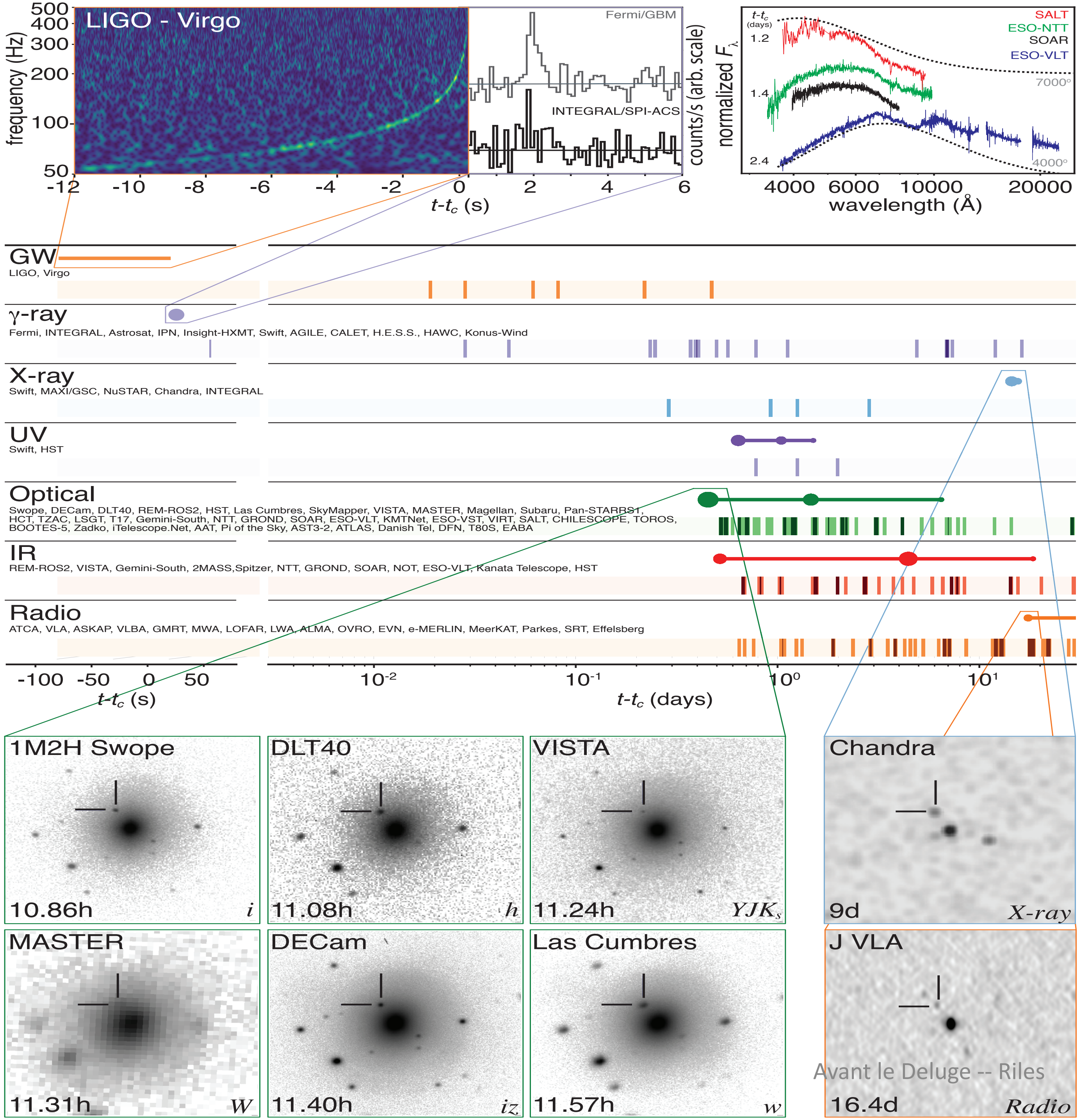


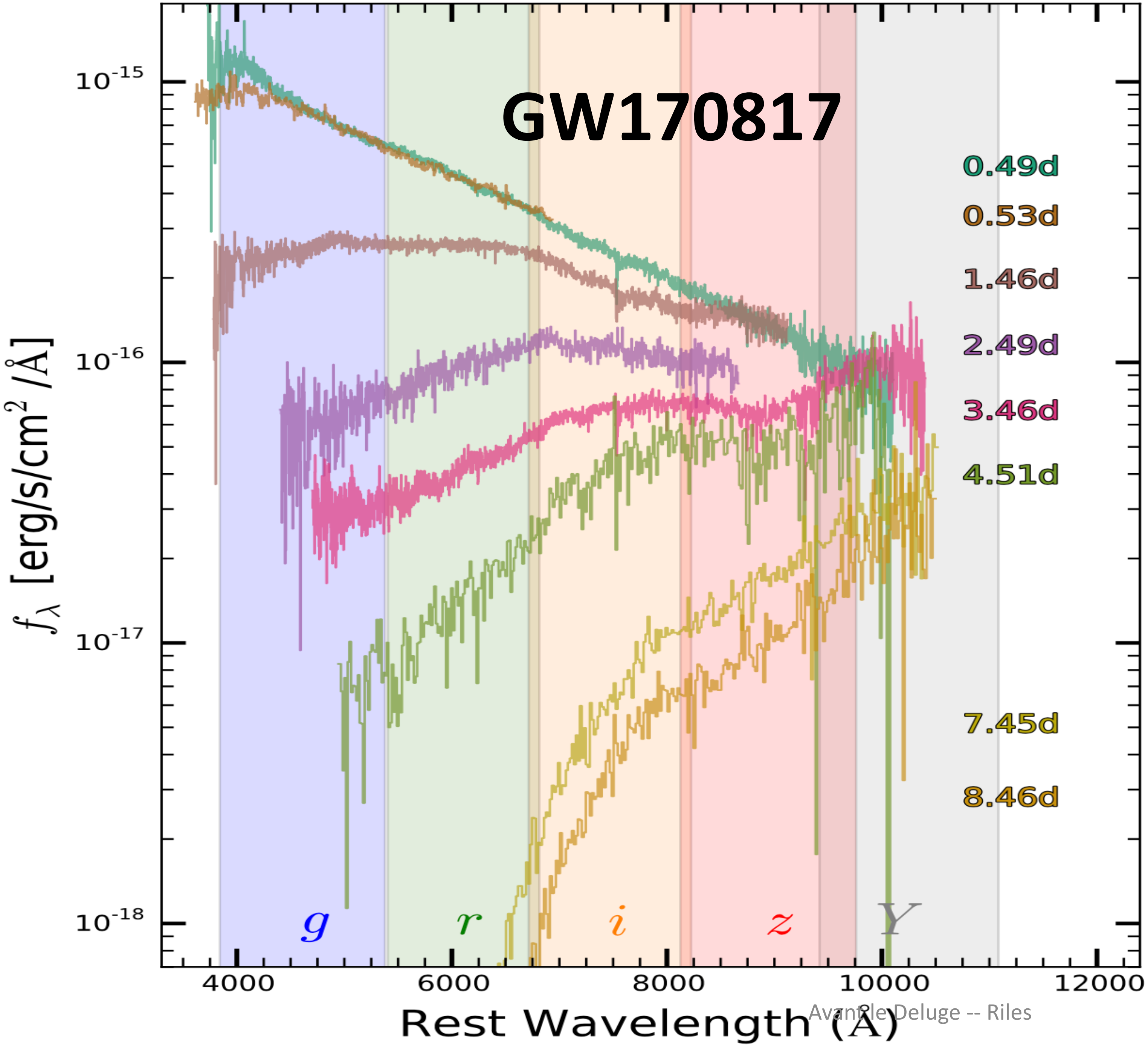
Figure from

“Multi-Messenger Observations of a Binary Neutron Star Merger”

Ap. J. Lett. **848** L12 (2017)

59-page “letter” (!)
More than 3000 authors,
~70 collaborations

Related talk at POTOR 8:
S. Nissanke (Tuesday)



Spectral evolution of optical counterpart over first week

Blue → Infrared

B. J. Shappee et al., *Science*, **358** 1574 (2017)

→ **"Kilonova"**

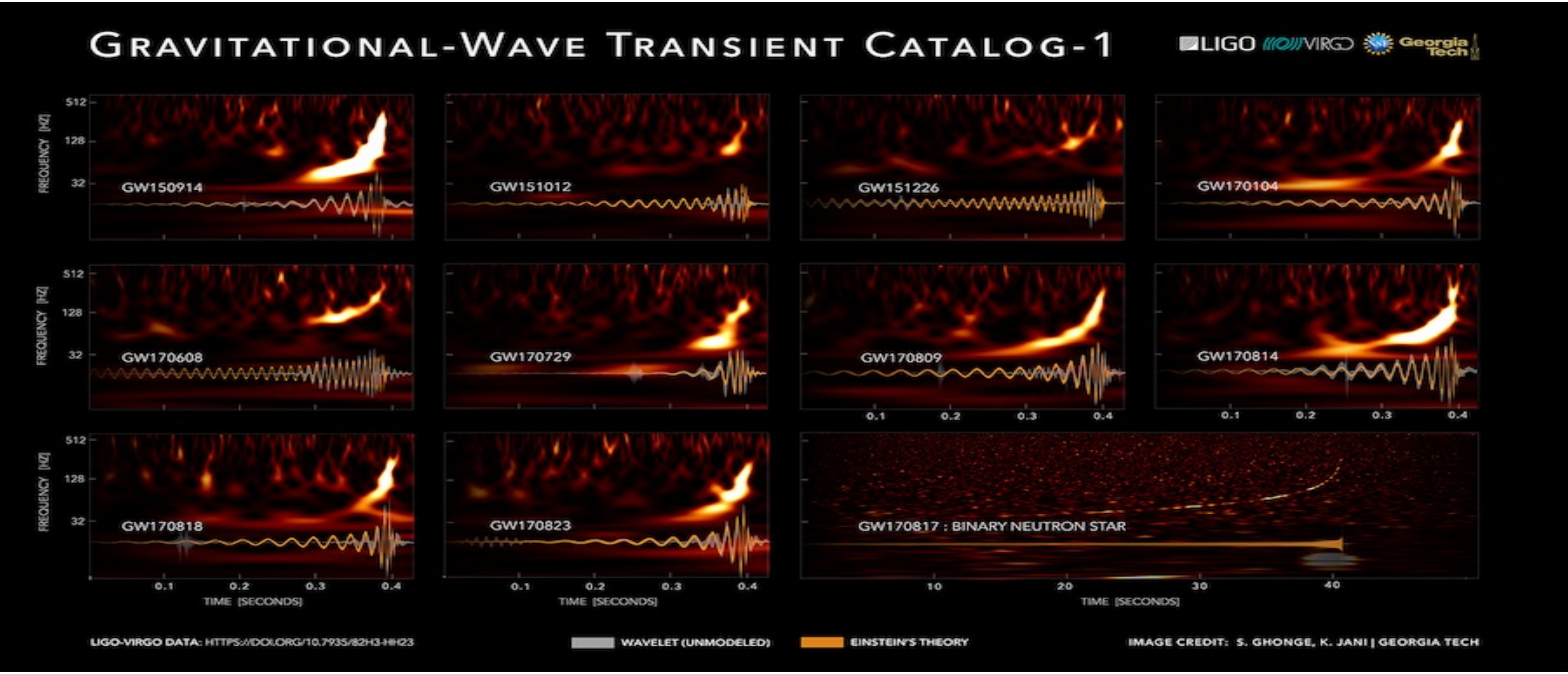
(production of neutron-rich heavy elements via r-process)

The Future: (2023?)

Some loud BNS events will be detected before merger

→ Early warning alert!

10 binary black hole mergers & 1 binary neutron star merger from O1 and O2 runs

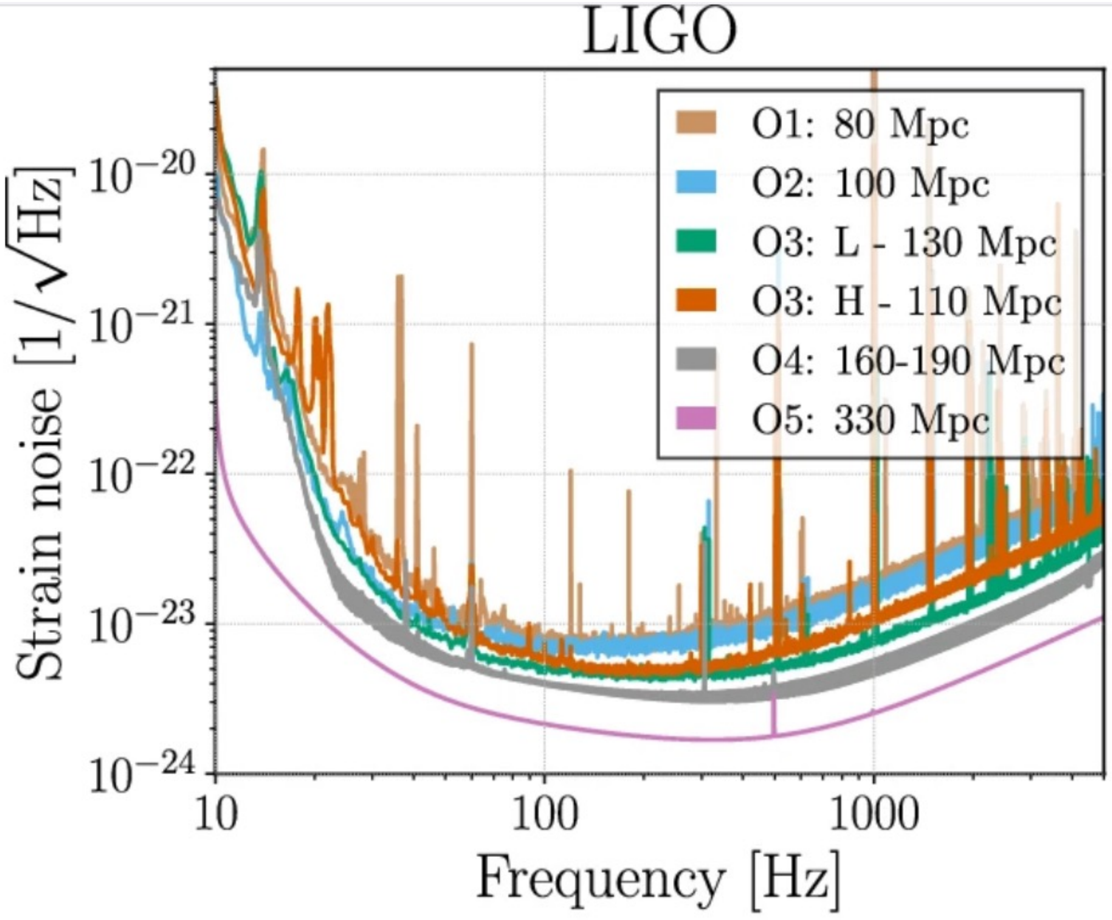


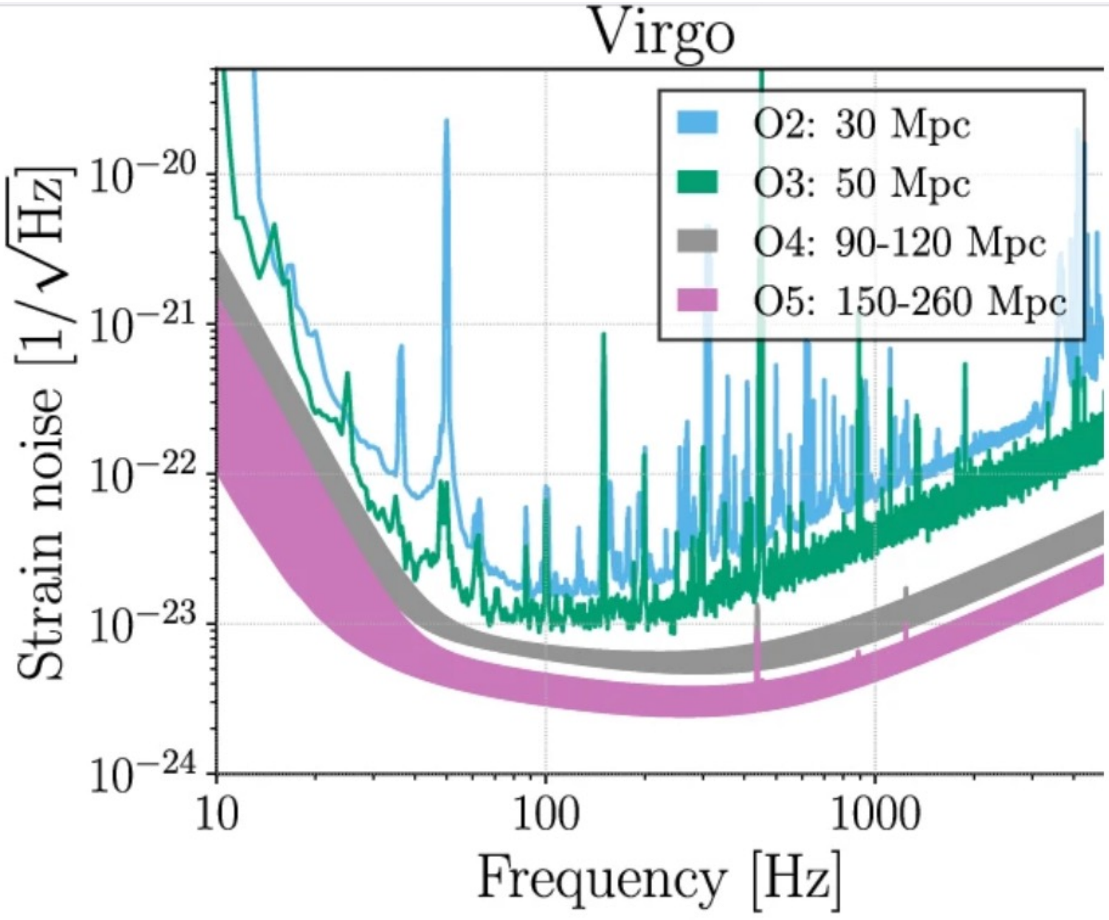
Observing runs to date:

O1: September 2015 – January 2016 (LIGO)

O2: November 2016 – August 2017 (LIGO, Virgo)

O3: April 2019 – March 2020 (LIGO, Virgo) & 2-week pilot run of KAGRA with GEO

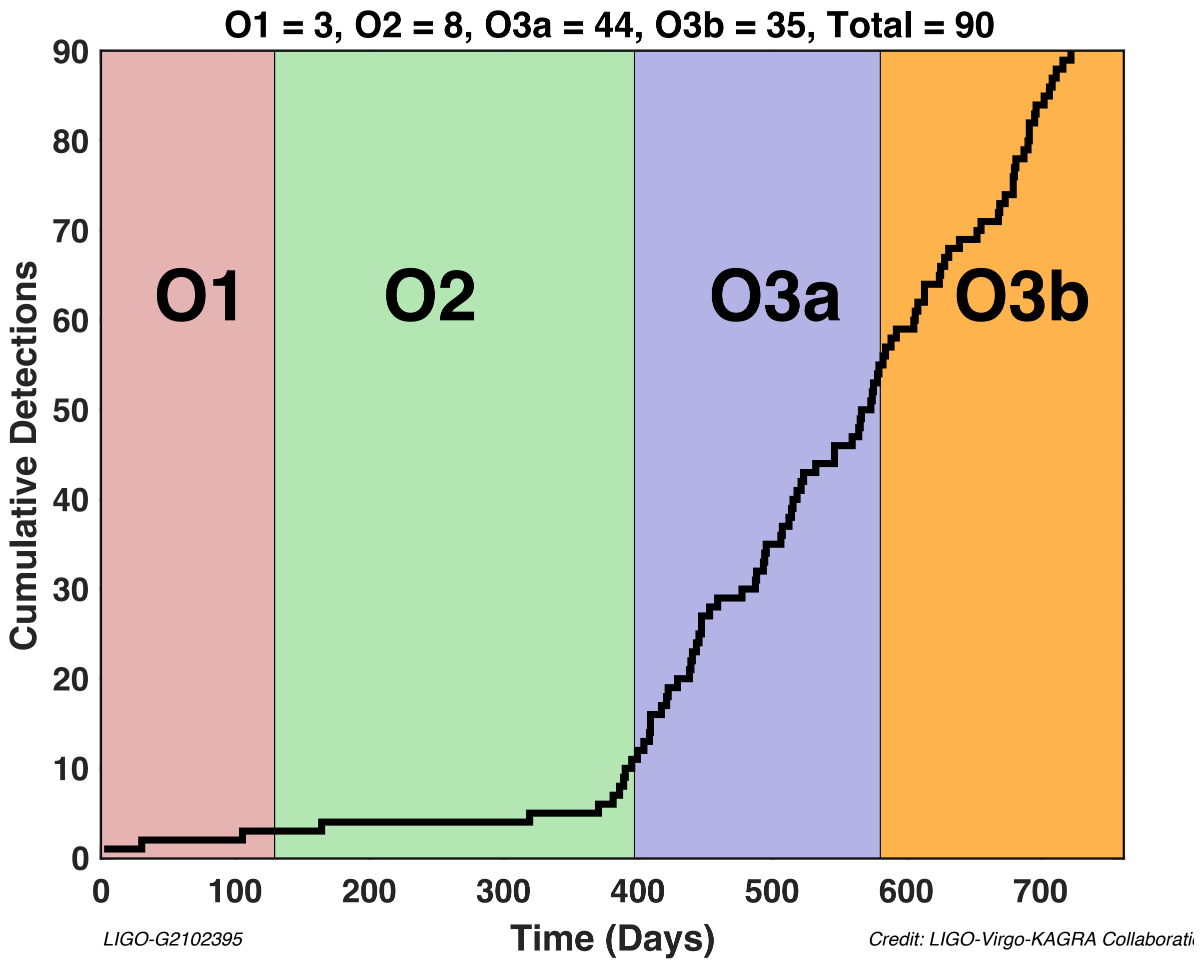




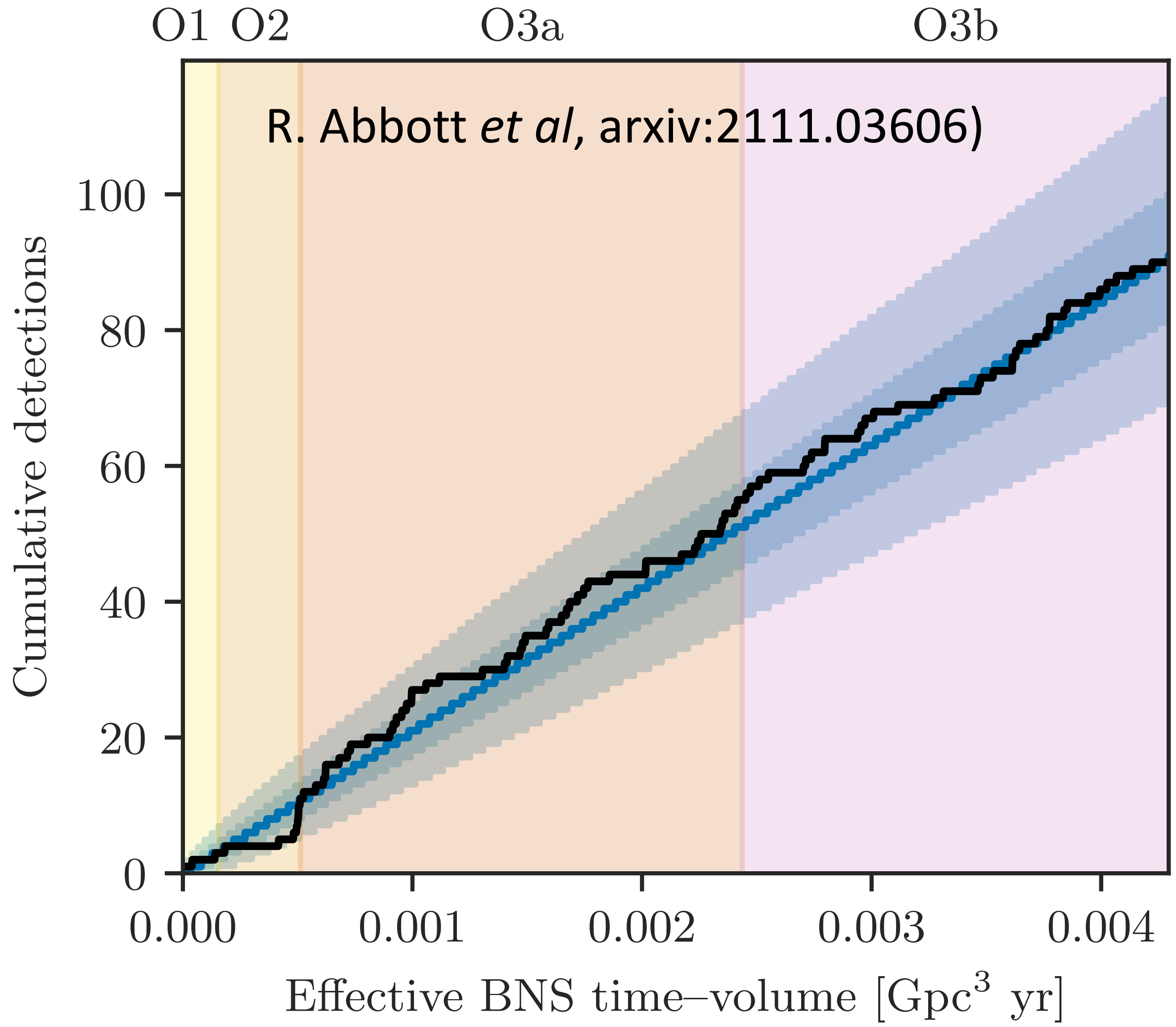
B.P. Abbott et al, Liv. Rev. Rel. **23**, 3 (2020)

Detection rate α Search volume α (Range)^3

O1—O3 detections vs time:



Detections vs (volume)x(time):



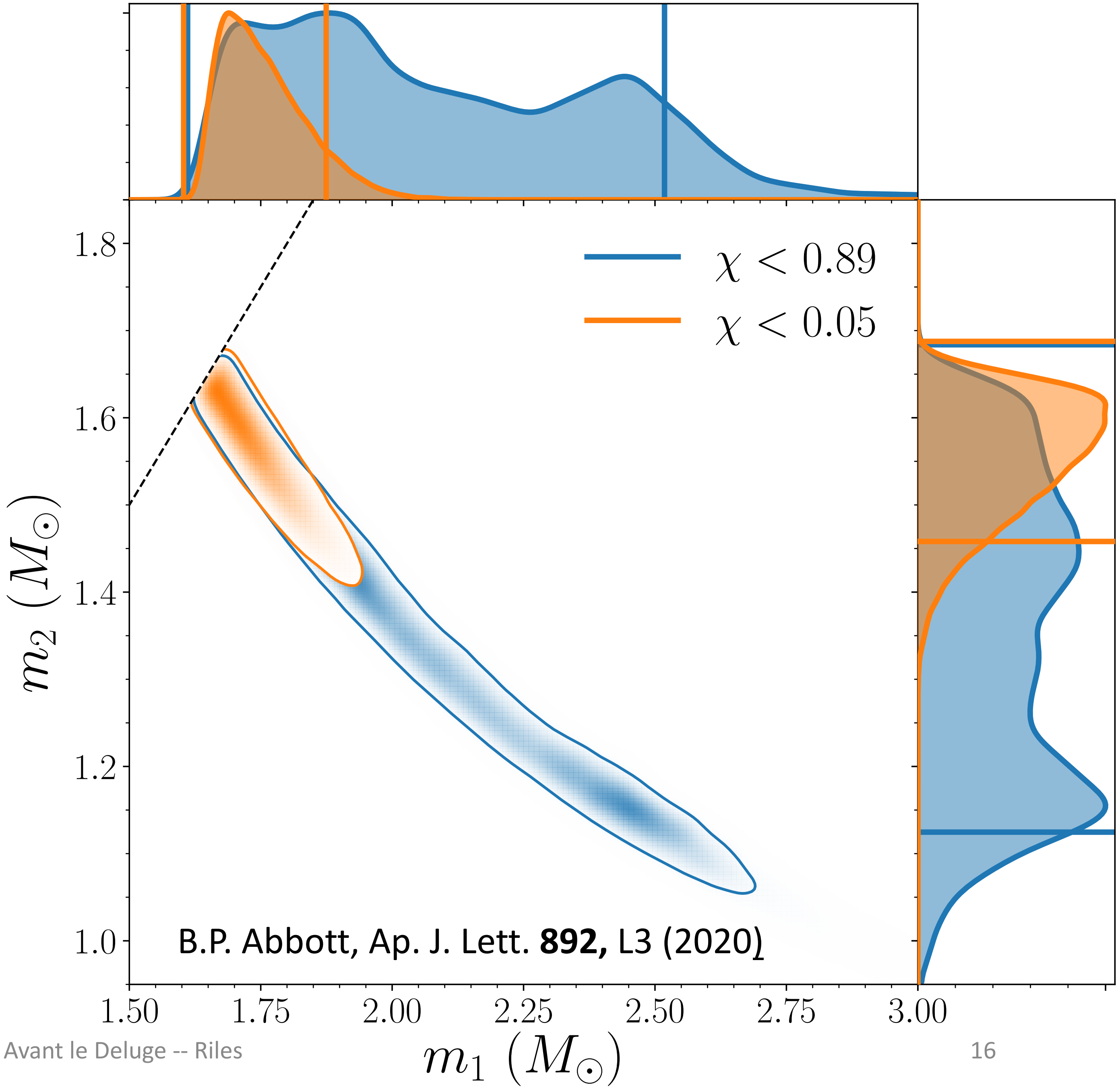
Avant le D

Binary neutron star merger GW190425

Not as dramatic as GW170817:

- **Lower SNR: 13 vs 32**
- **Seen clearly by only one detector (Hanford not on at time)**
- **Sky localization very poor**
- **No electromagnetic counterpart observed**

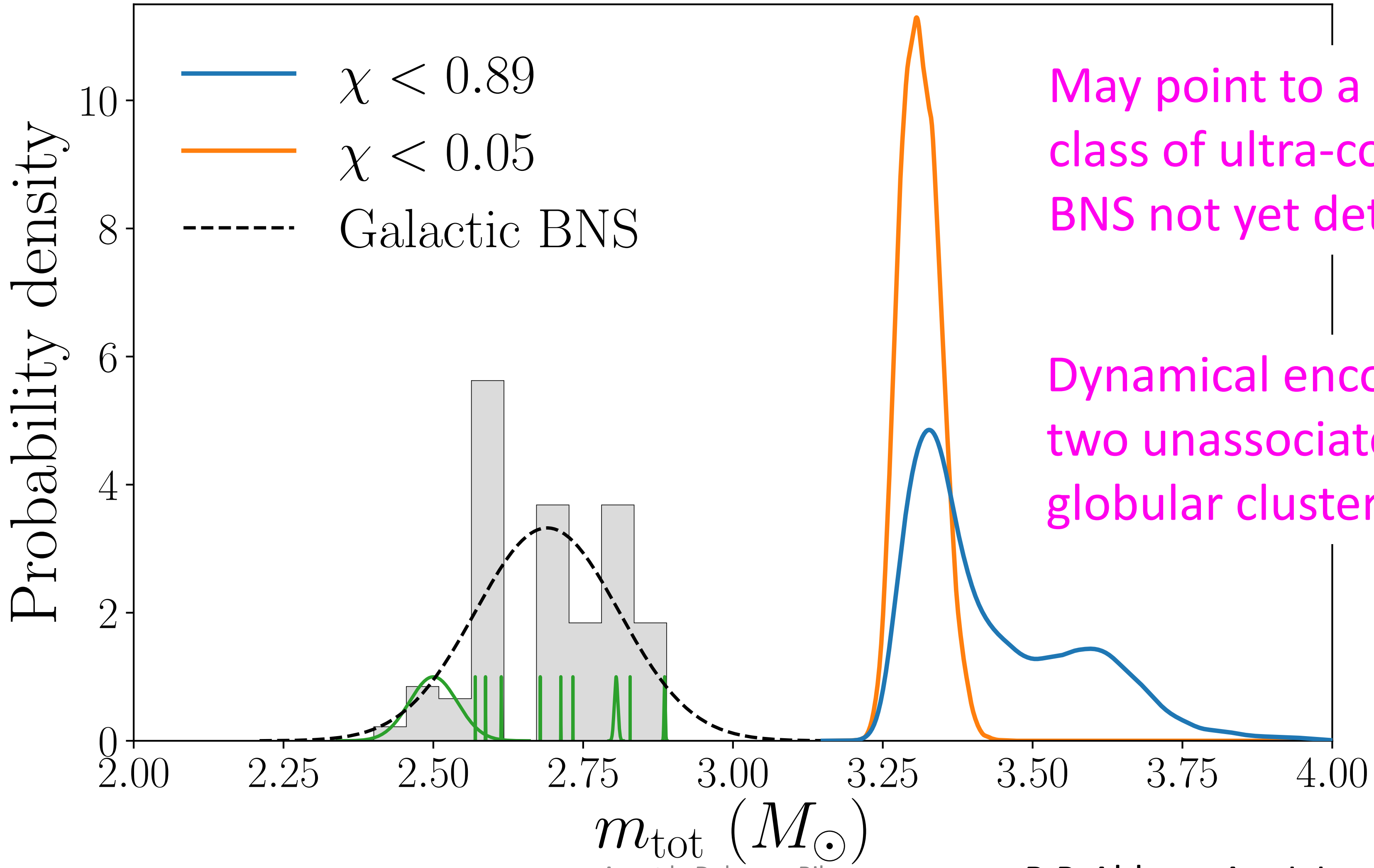
But not entirely uninteresting…



B.P. Abbott, Ap. J. Lett. **892,** L3 (2020)

Sum of masses much larger than seen in any known Milky Way binary neutron star systems

GW190425

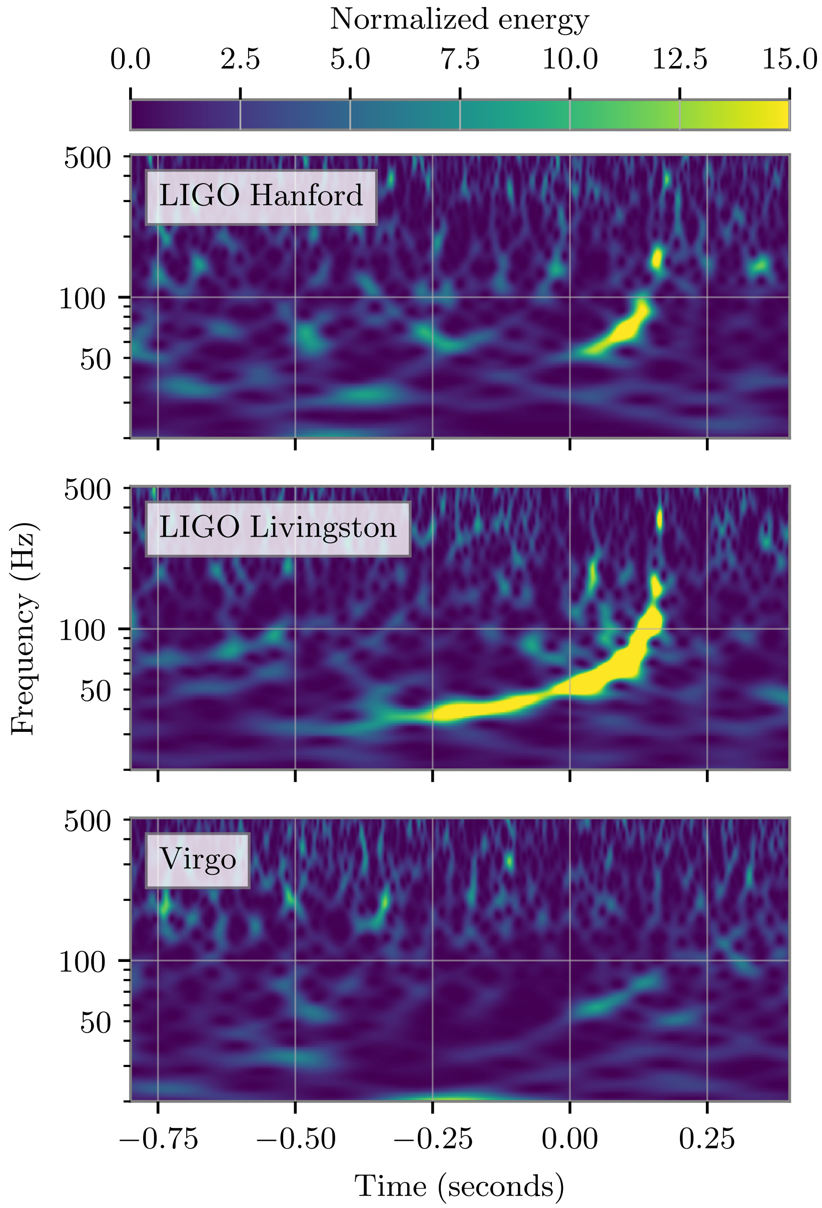


May point to a new sub-class of ultra-compact BNS not yet detected

Dynamical encounter of two unassociated NSs in globular cluster?

B.P. Abbott, Ap. J. Lett. **892,** L3 (2020)

Black hole merger GW190412



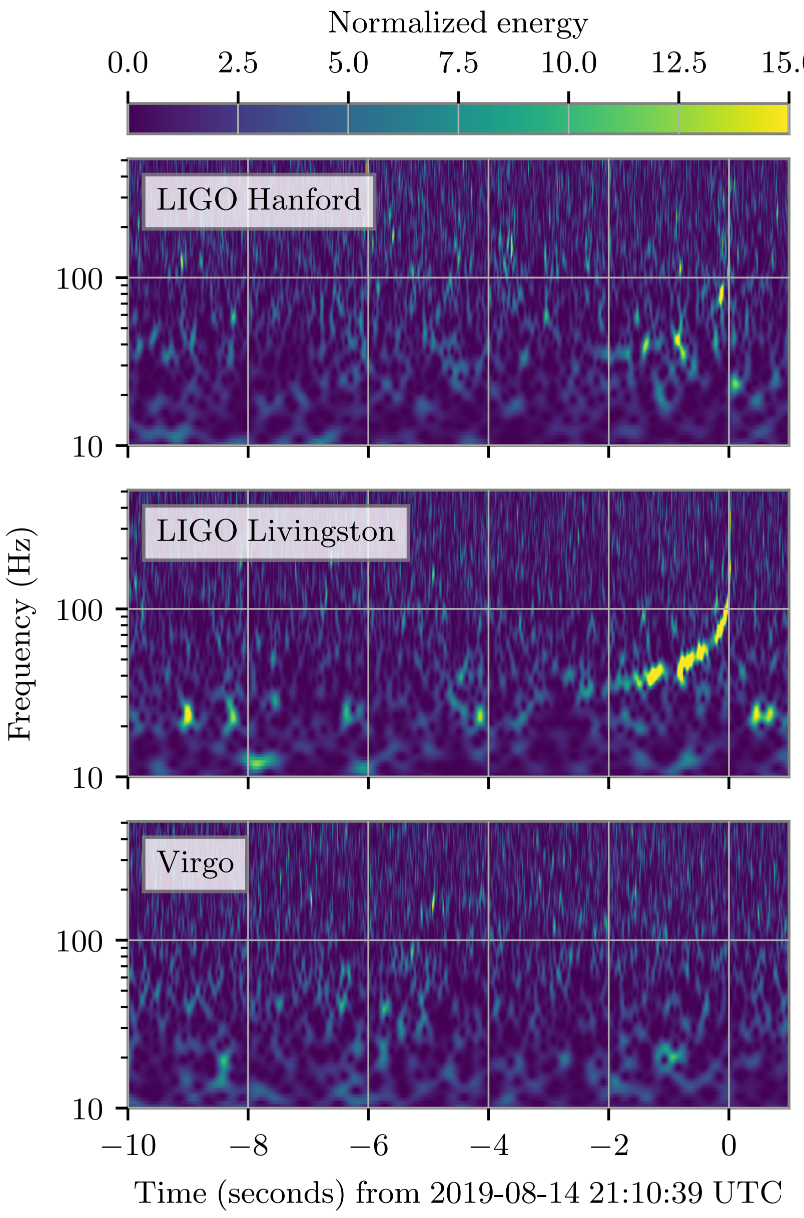
Notable property:

- $M_1 \sim 30\ M_\odot$
- $M_2 \sim 8\ M_\odot$

→ Distinctly unequal masses

R. Abbott et al., Phys. Rev. D **102**, 043015 (2020)

Black hole merger GW190814



Notable properties:

- $M_1 \sim 23\ M_\odot$
- $M_2 \sim 2.6\ M_\odot$
  → Even more unequal masses

- Well localized (~18 deg^2)
  – But no EM counterpart

- What is the secondary? (!)

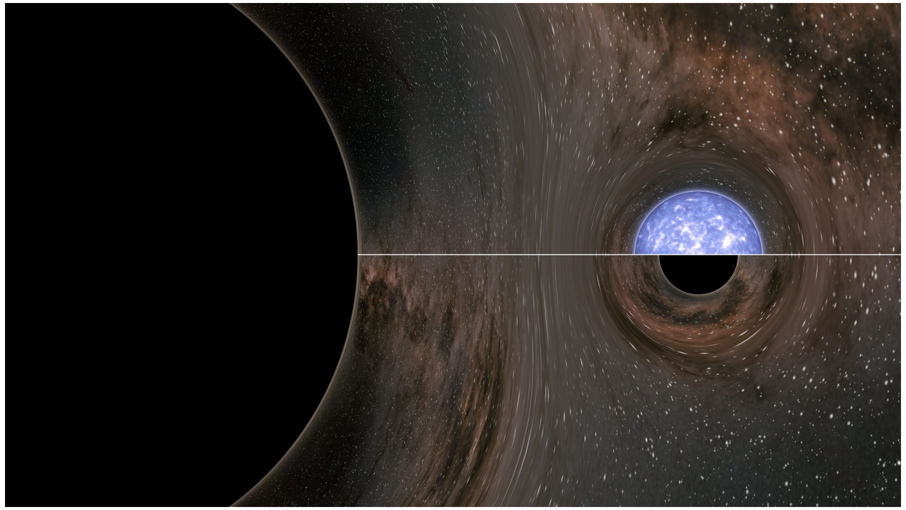
R. Abbott *et al*, Ap. J. Lett. **896**, L44 (2020)

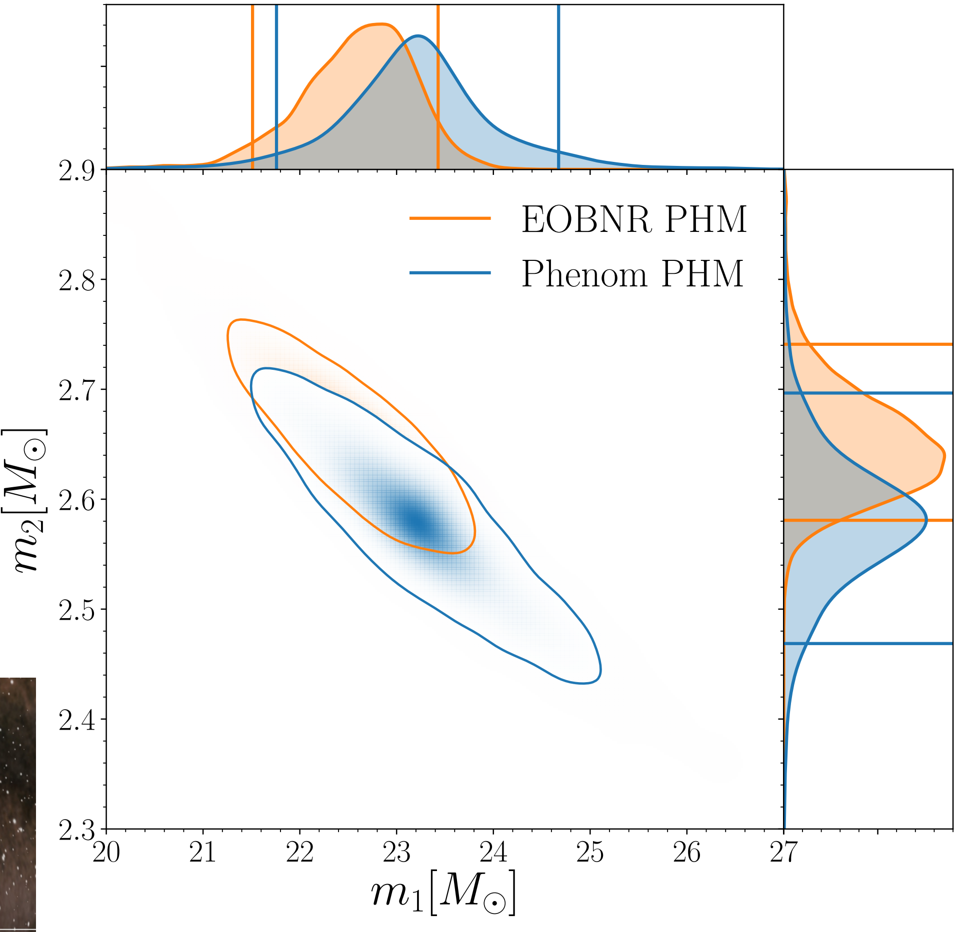
Black hole merger GW190814

Extreme asymmetry in mass

Secondary mass is strange:

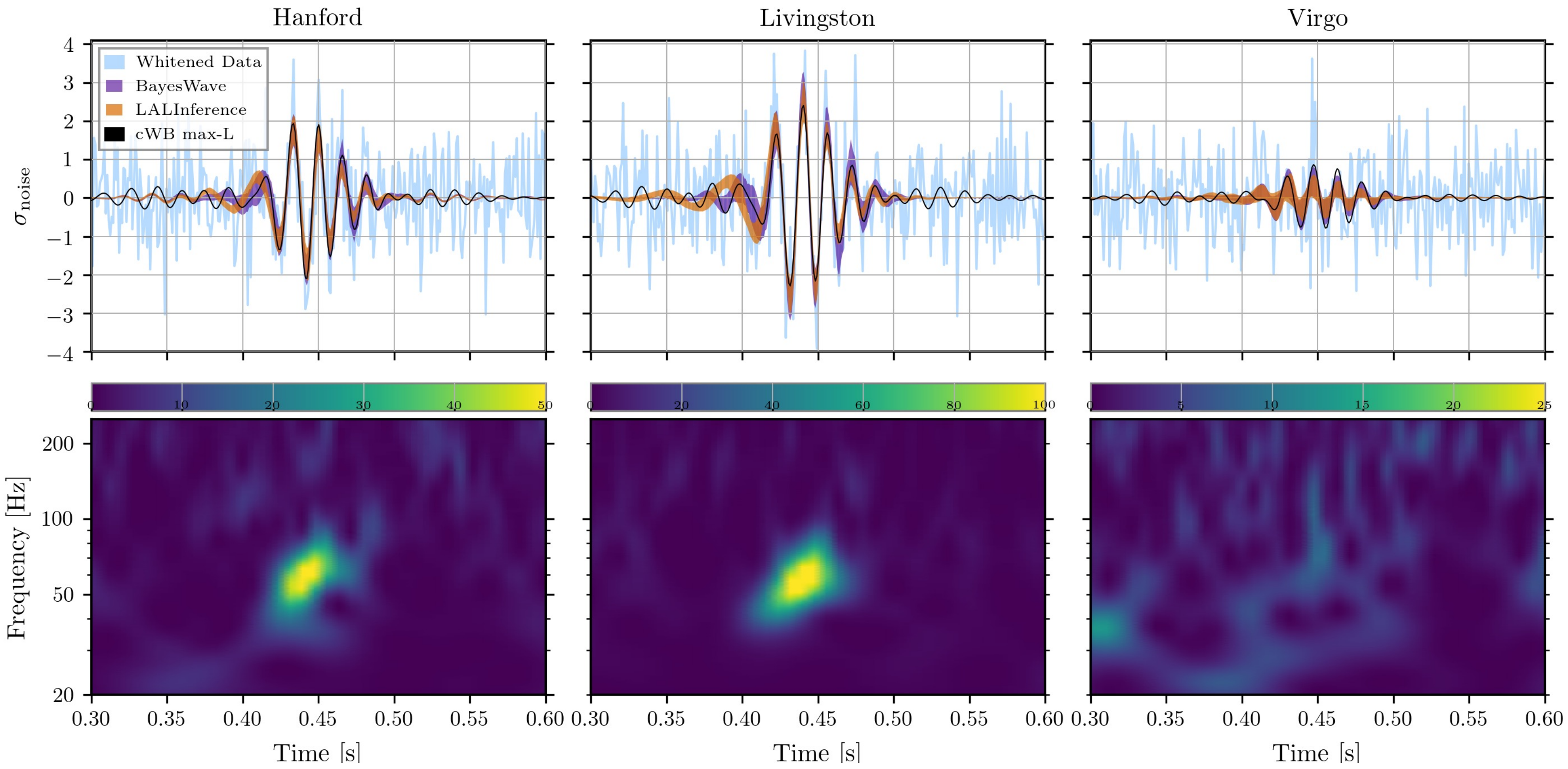
- Too heavy for conventional NS
- Very light for a BH
- Falls into ”lower mass gap”
- System challenges ordinary stellar formation models





R. Abbott *et al*, Ap. J. Lett. **896,** L44 (2020)

Black hole merger GW190521



- Short but strong signal
- Peaks at low frequency

→ Massive system

R. Abbott *et al*, Phys. Rev. Lett. **125**, 101102 (2020)
R. Abbott *et al*, Ap. J. Lett. **900**, L13 (2020)

Black hole merger GW190521

How massive?

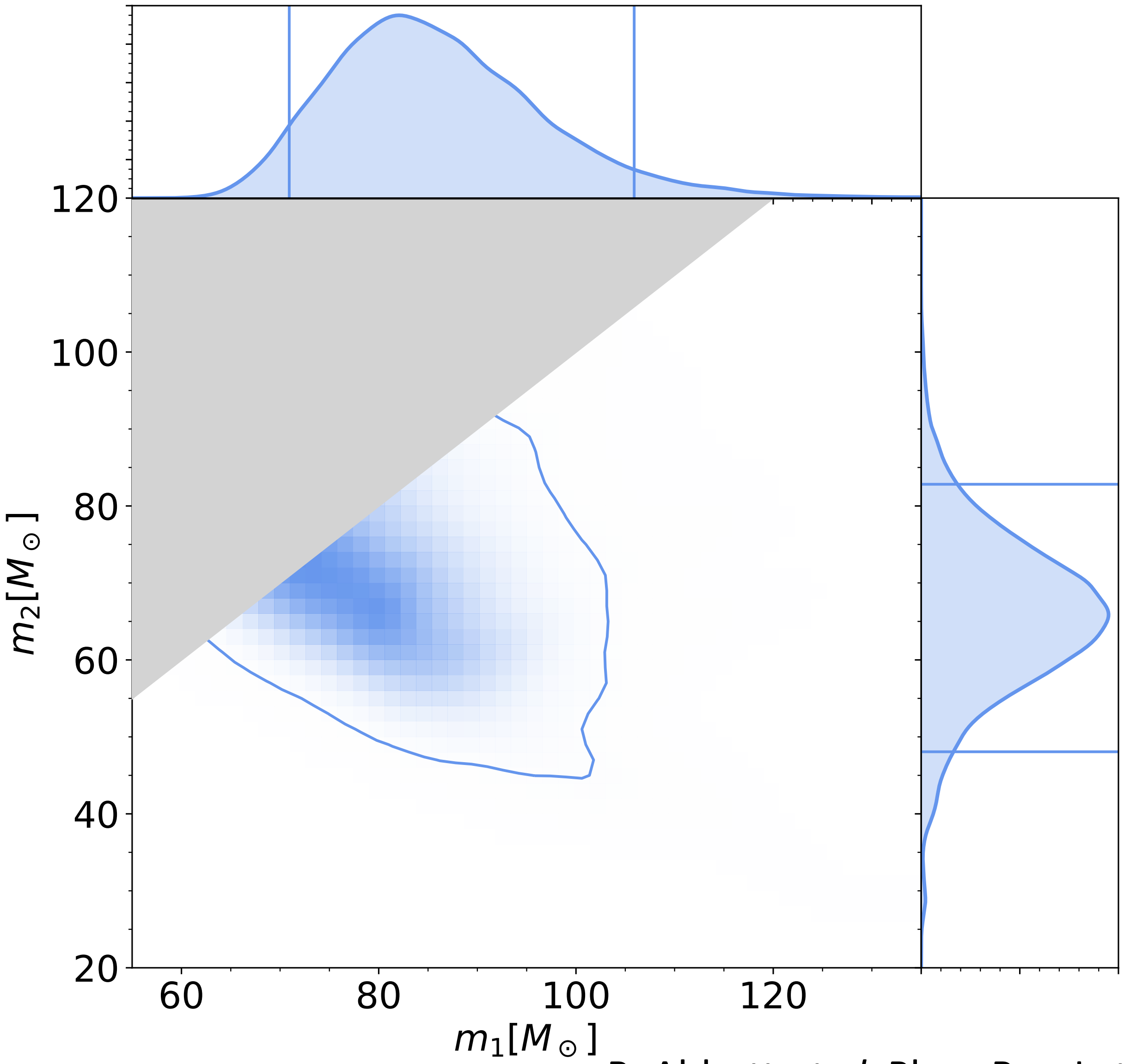
M_1 = 71–106 $M_\odot$
M_2 = 49–84 $M_\odot$

Surprising values because of the "high mass gap" ~(65-135 $M_\odot$) expected from pulsational pair instability

Hierarchical merger?

Total mass makes remnant first known intermediate mass black hole (>100 $M_\odot$):

M_f ~ 150 $M_\odot$



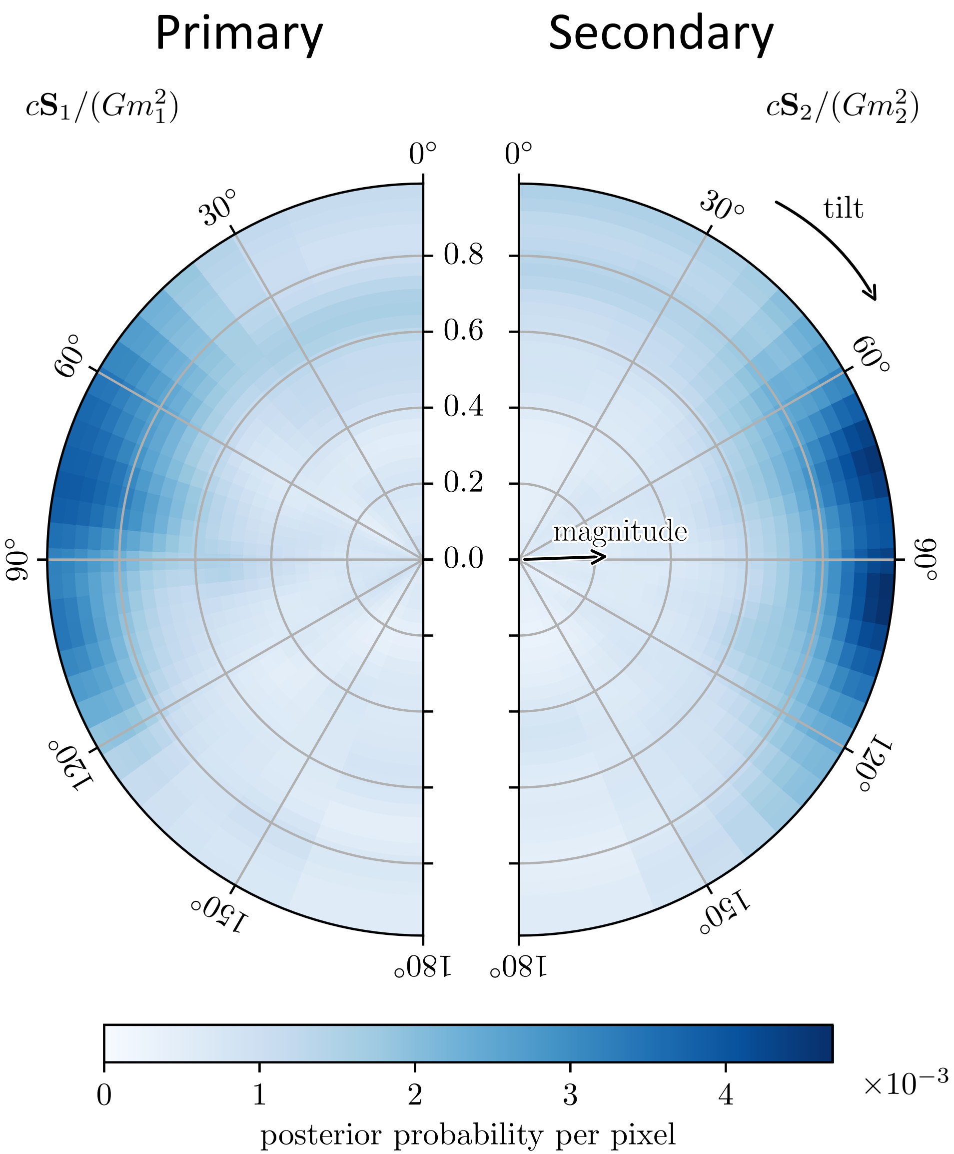
R. Abbott *et al*, Phys. Rev. Lett. **125**, 101102 (2020)
R. Abbott *et al*, Ap. J. Lett. **900,** L13, (2020)

Black hole merger GW190521

Evidence for spin dynamics, perhaps significant precession

Consistent with hierarchical merger with both initial BHs due to previous mergers

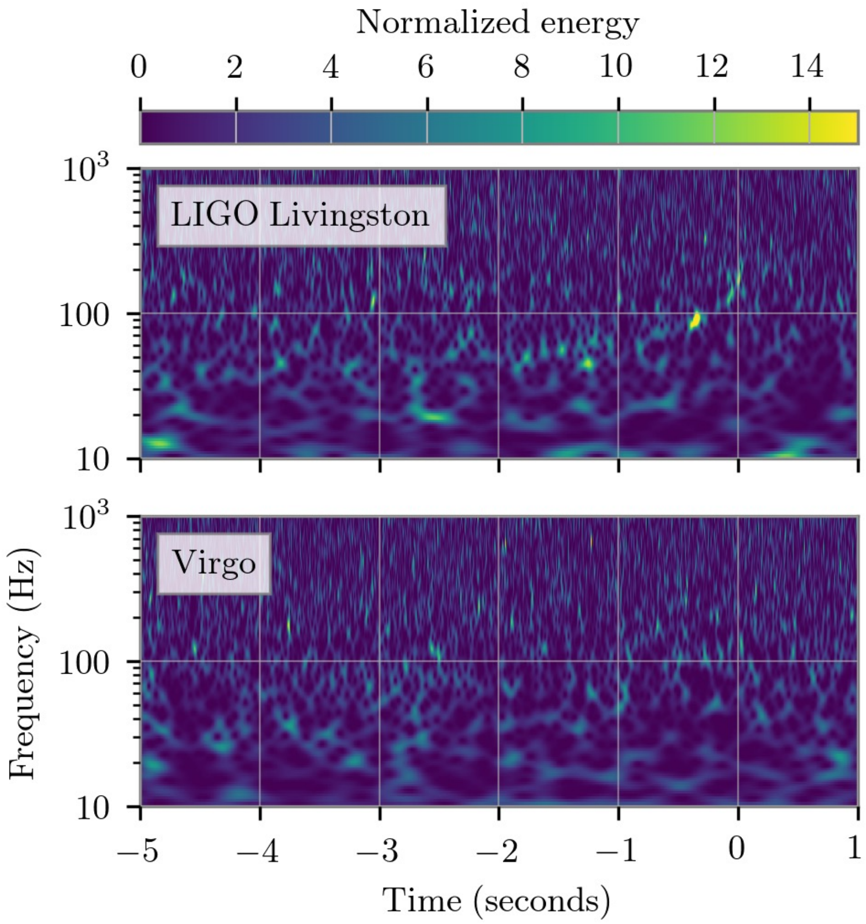
Related talk at POTOR 8:
D. Rosinksa (Monday)



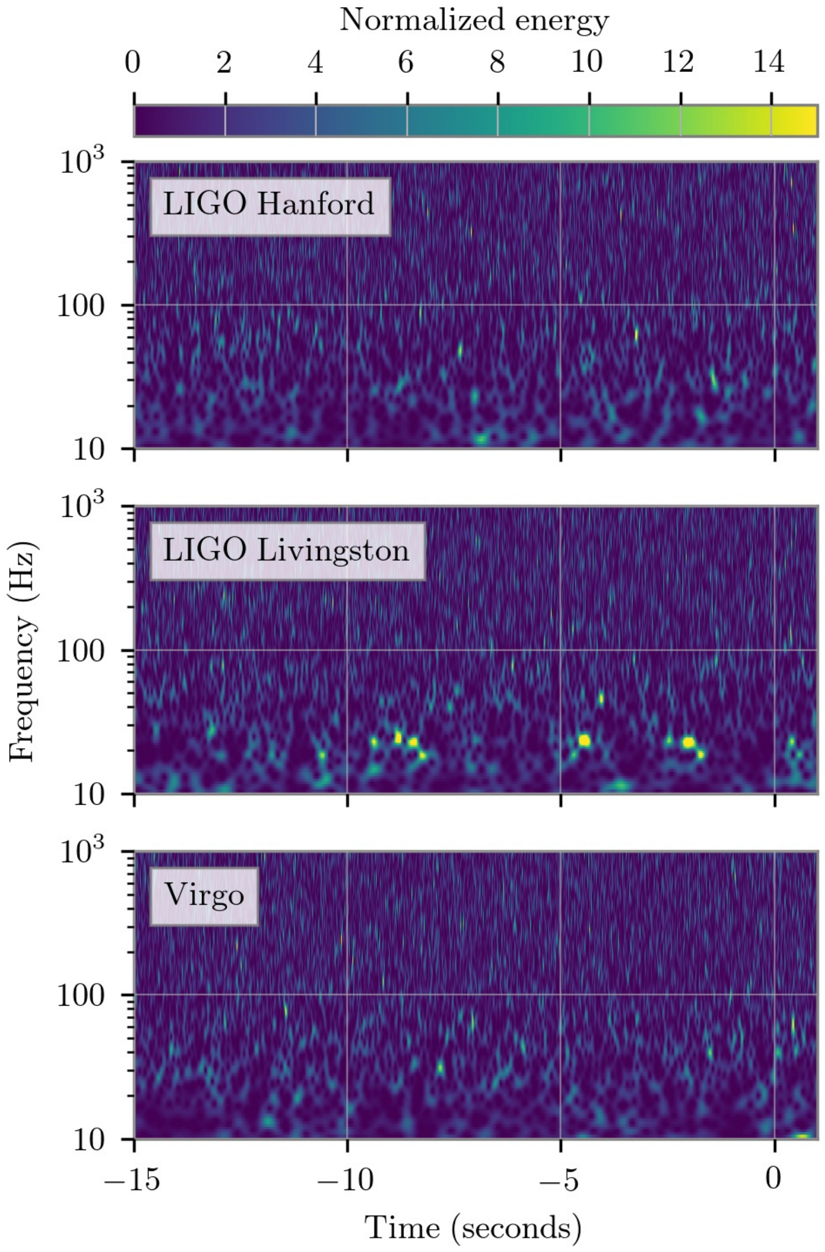
R. Abbott *et al*, Phys. Rev. Lett. **125**, 101102 (2020)
R. Abbott *et al*, Ap. J. Lett. **900**, L13, (2020)

Neutron star – Black hole mergers

GW200105

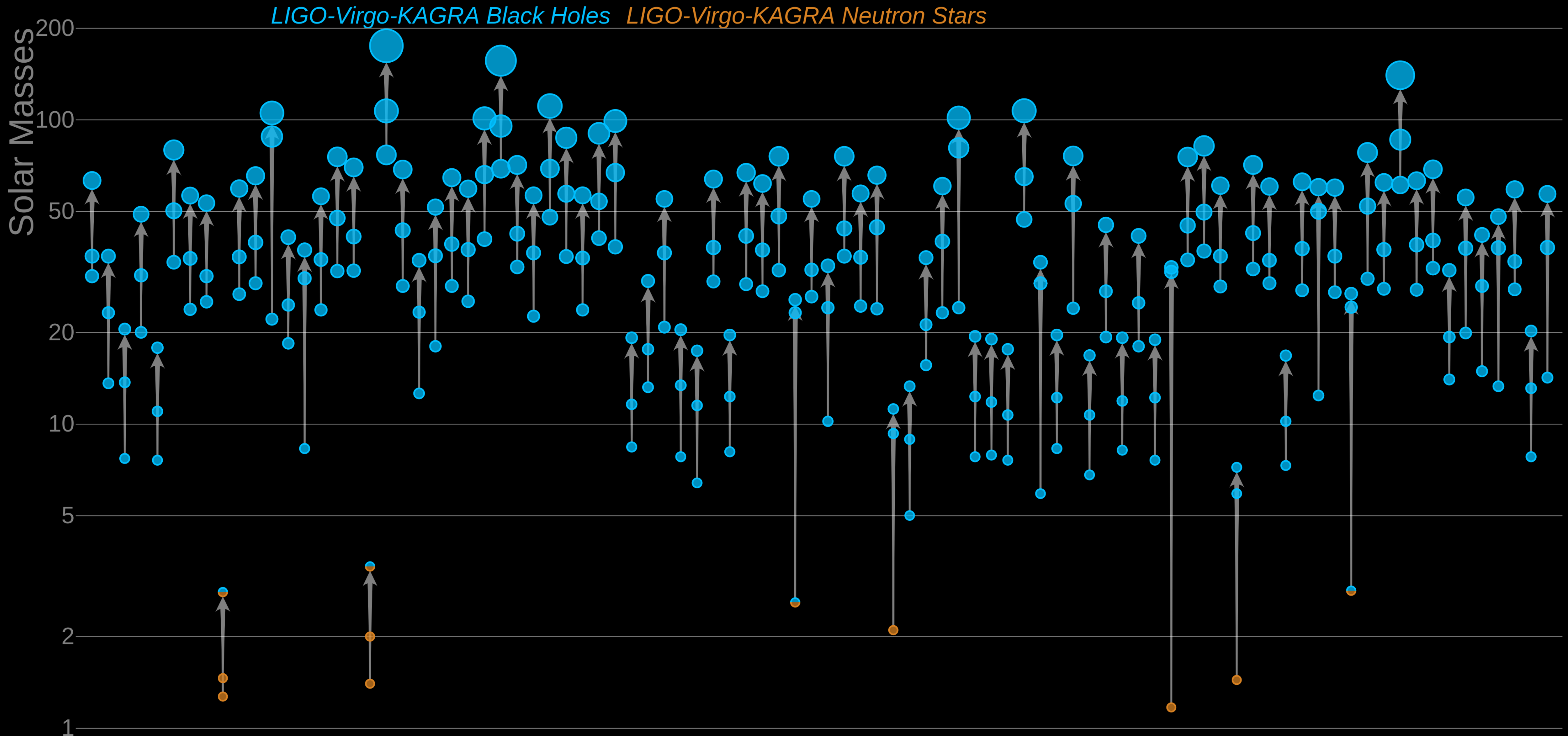


GW200115

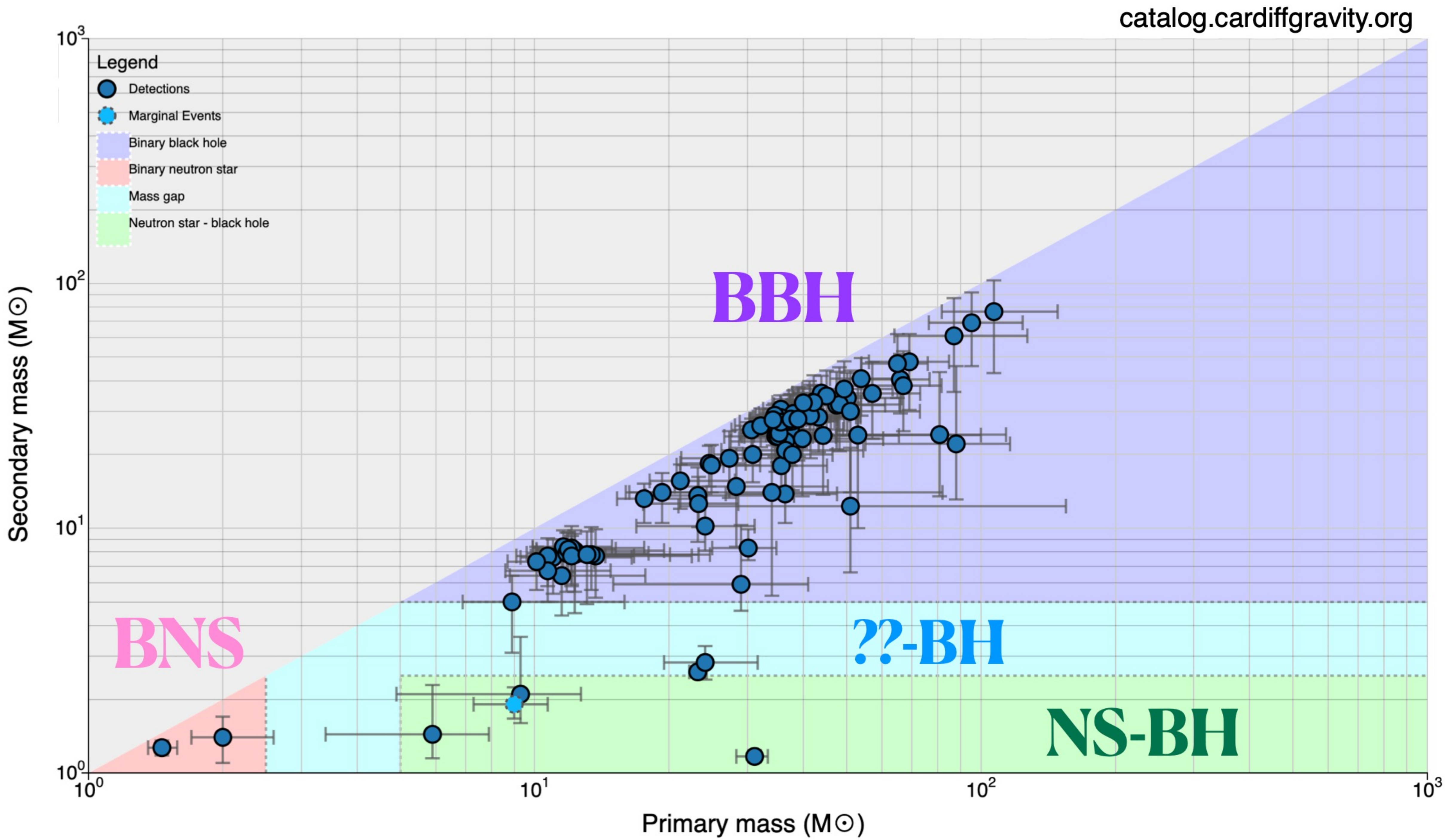


R. Abbott *et al*, ApJ. Lett. **915**, L5 (2021)

Masses in the Stellar Graveyard



LIGO-Virgo-KAGRA | Aaron Geller | Northwestern



catalog.cardiffgravity.org
Legend
Detections
Marginal Events
Binary black hole
Binary neutron star
Mass gap
Neutron star - black hole
BBH
BNS
??-BH
NS-BH
Secondary mass (M⊙)
Primary mass (M⊙)
10^0
10^1
10^2
10^3

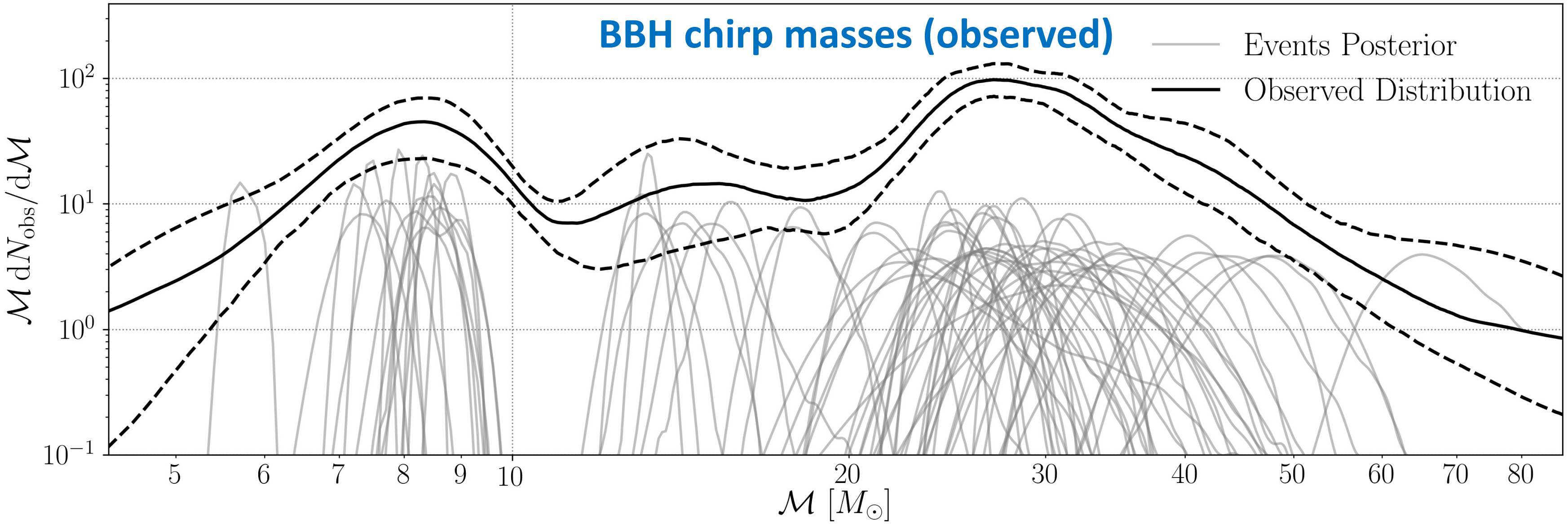
Cumulative BBH properties (sampling)

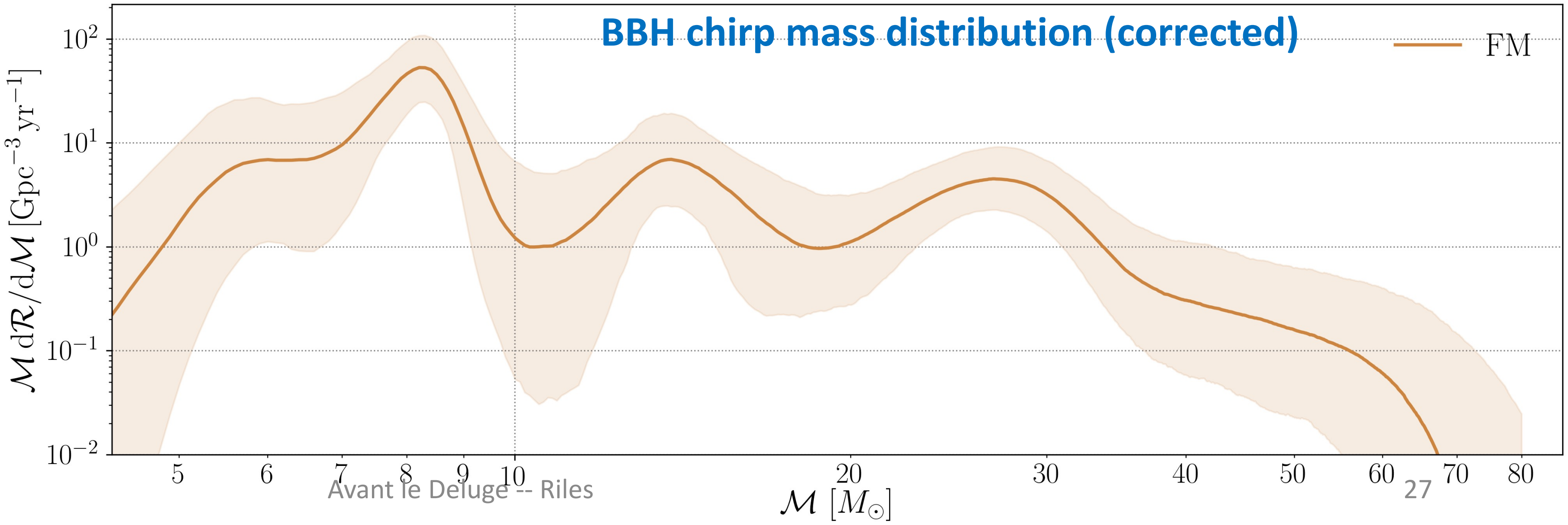
R. Abbott *et al*, arXiv:2111.03634

Evidence of structure in mass distributions

BBH merger rate (z = 0.2):
17—45 $Gpc^{-3}\,yr^{-1}$

Merger rate increases with redshift

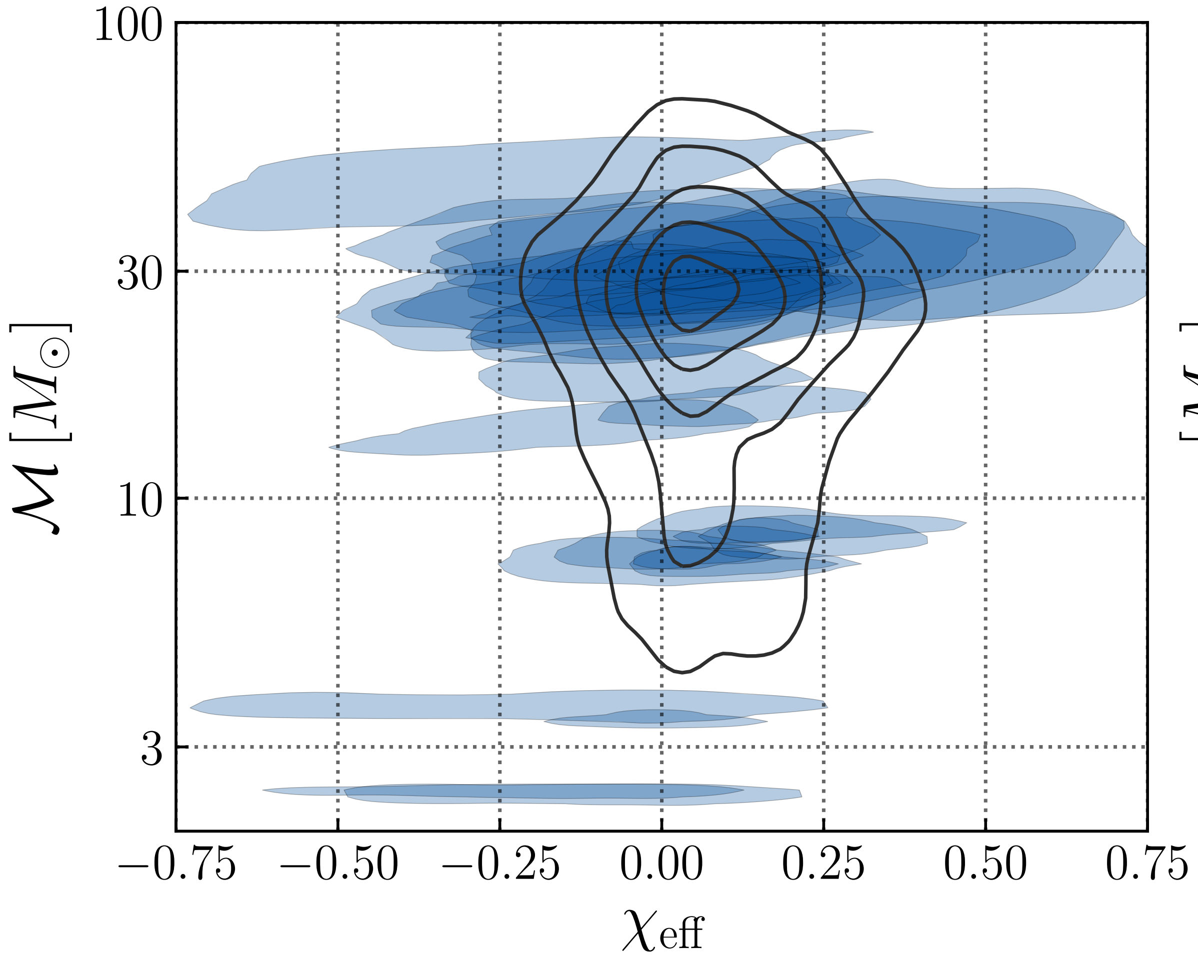


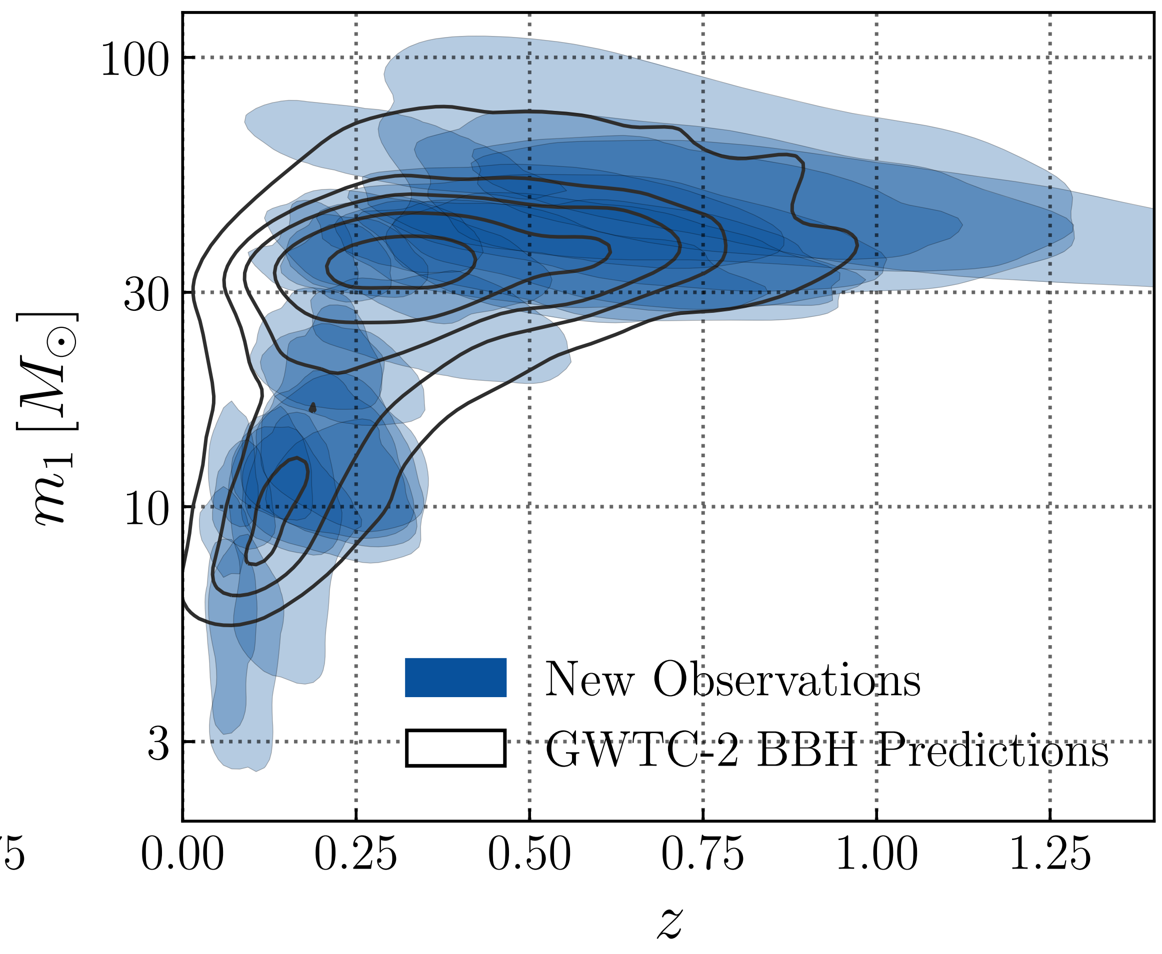


BH spin distributions:
-- Low magnitudes
-- Some misalignment with orbital angular momentum

Primary mass vs redshift

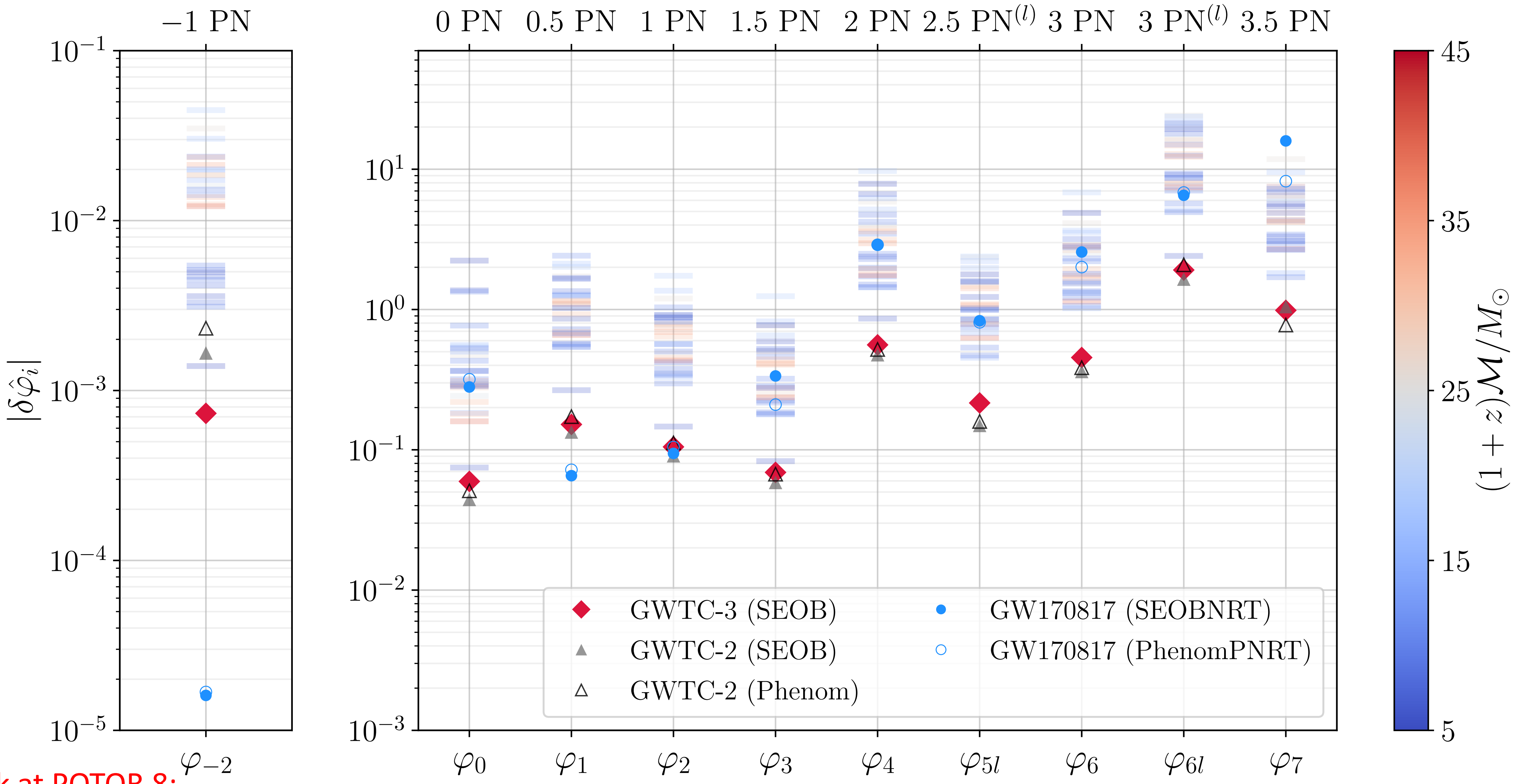
R. Abbott *et al*, arXiv:2111.03634





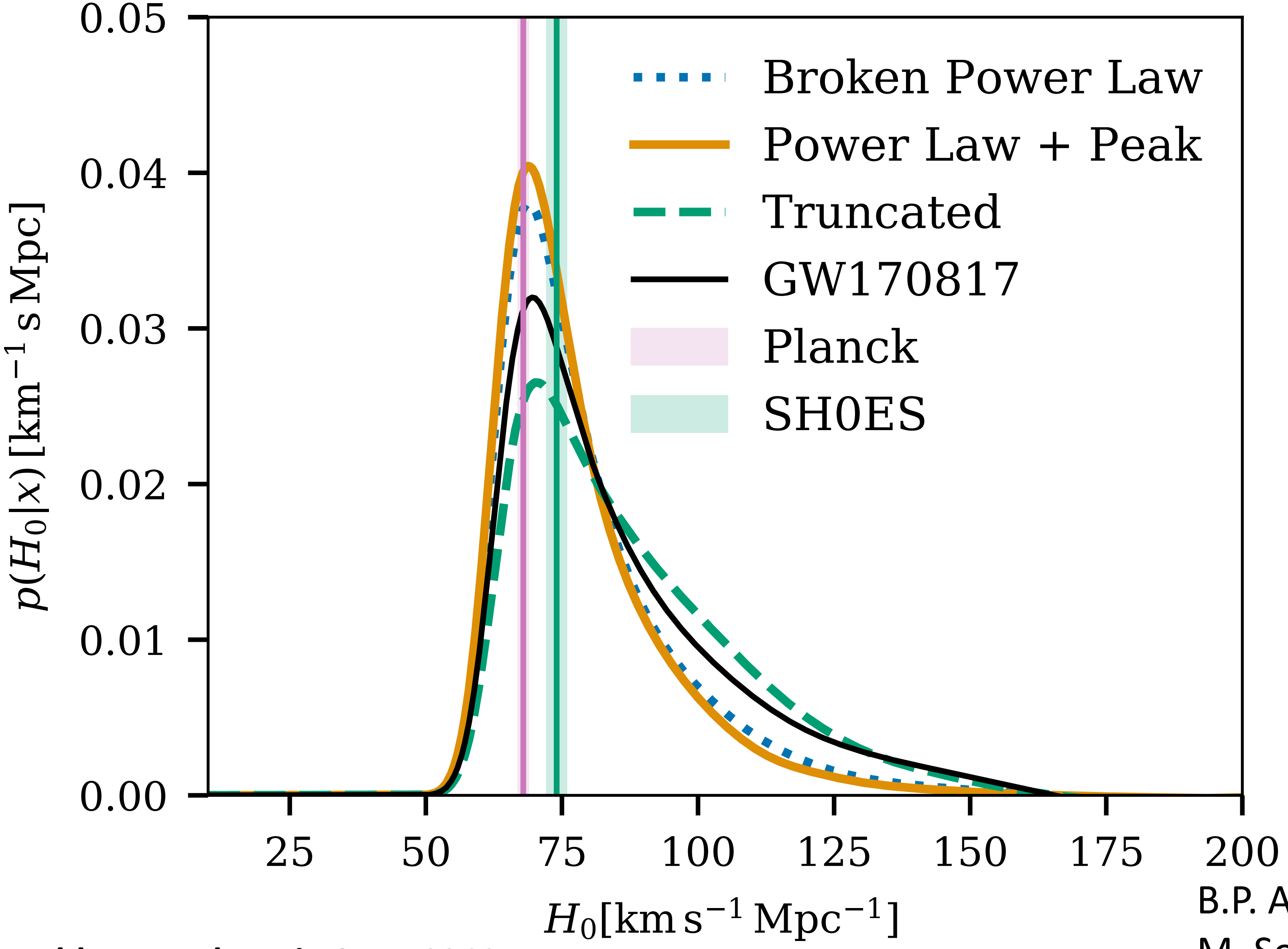
Revisiting tests of GR after analysis of O1—O3 data

R. Abbott *et al*, to appear in PRD (arXiv:2112.06861)



Related talk at POTOR 8: G. Schaefer (Tuesday)

First steps in GW Cosmology



R. Abbott et al, arXiv:2111.03604

Principle:

- GW waveform → BH/NS masses
- Masses & amplitude → Distance
- Separate measurement of redshift z

→ **Hubble constant**

First measurement from GW170817 galactic redshift (BNS "siren")

Reinforced by BBH "dark sirens" using galaxy catalogs

Currently limited by statistics and uncertainty on inclination angle of orbital plane

Future: Lensed GW signals (limits for now)

Related talk at POTOR 8:
M. Biesiada (Monday)

B.P. Abbott et al, Nature **551**, 85 (2017)

M. Soares-Santos et al, ApJL **876**, L7 (2019)

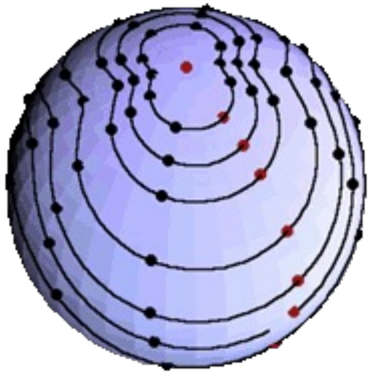
Possible sources of continuous waves (CW)

NASA

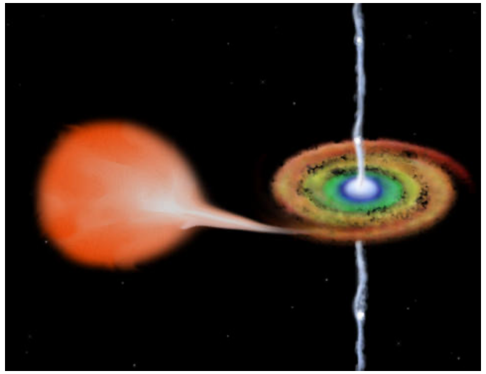
Conventional:

Galactic neutron stars with residual non-axisymmetry

- Crustal deformation from cooling
- Buried magnetic field energy
- r-modes (quadrupolar mass currents)
- Driven by accretion from a companion



B. Owen



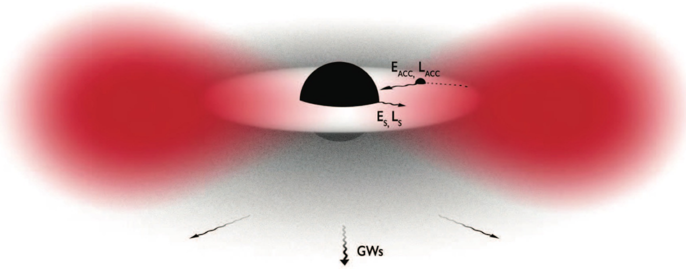
McGill U.

Strange quark stars

Exotic sources:

Black hole superradiance from condensed of ultralight bosons (“cloud”)

- Scalars (*e.g.*, QCD axions)
- Vectors (*e.g.*, dark photons)



Brito
Cardoso
Pani

Related talk at POTOR 8:
R. Sharma (Tuesday)

Search limits often interpreted via equatorial ellipticity ε_{equat}

Radiation generated by quadrupolar mass movements: ($I_{\mu\nu}$ = quadrupole tensor, r = source distance)

$$h_{\mu\nu} = \frac{2G}{rc^4}\frac{d^2}{dt^2}\left[I_{\mu\nu}\right] \qquad \varepsilon_{\text{equat}} = \frac{|I_{xx} - I_{yy}|}{I_{zz}}$$

No GW from axisymmetric object rotating about symmetry axis (ε = 0)

Expected strain amplitude h ($f_{GW} = 2 \bullet f_{Rot}$):

$$h = 1.1\times10^{-24}\left[\frac{kpc}{r}\right]\left[\frac{f_{GW}}{kHz}\right]^2\left[\frac{\varepsilon}{10^{-6}}\right]\left[\frac{I_{zz}}{10^{38}\ \text{kg}\cdot\text{m}^2}\right]$$

Maximum ε value: ~10^{-5}

N.K. Johnson-McDaniel & B.J. Owen, PRD 88 (2013) 044004

Equating "measured" rotational energy loss (from measured period increase and reasonable moment of inertia) to GW emission gives:

$$h_{SD} = 2.5\times10^{-25}\left[\frac{kpc}{d}\right]\sqrt{\left[\frac{1kHz}{f_{\text{GW}}}\right]\left[\frac{-df_{\text{GW}}/dt}{10^{-10}\,Hz/s}\right]\left[\frac{I}{10^{45}\,g\cdot cm^2}\right]}$$

Example:

Crab → **h_{SD} = 1.4 × 10^{-24}**

(d=2 kpc, f_{GW} = 59.5 Hz, $df_{GW}/dt = -7.4\times10^{-10}$ Hz/s)

Three broad categories of CW searches have dominated analyses to date*:

Targeted searches for known pulsars using radio / X-ray / γ-ray ephemerides
→ Exact phase tracking over O(years) – low trials factor (3 methods)
→ Variation ("narrowband") allows for EM/GW $\Delta f \sim O(10^{-3})\, f_{EM}$

Computationally cheap

Directed searches for known sources / locations
(unknown / poorly known frequencies)
- Isolated and binary sources treated separately
- Fully coherent searches over days/weeks
- Semi-coherent searches over full data runs

Computationally demanding

All-sky searches for unknown sources
- Isolated and binary sources treated separately (binary esp. challenging)
- Semi-coherent searches over full data runs

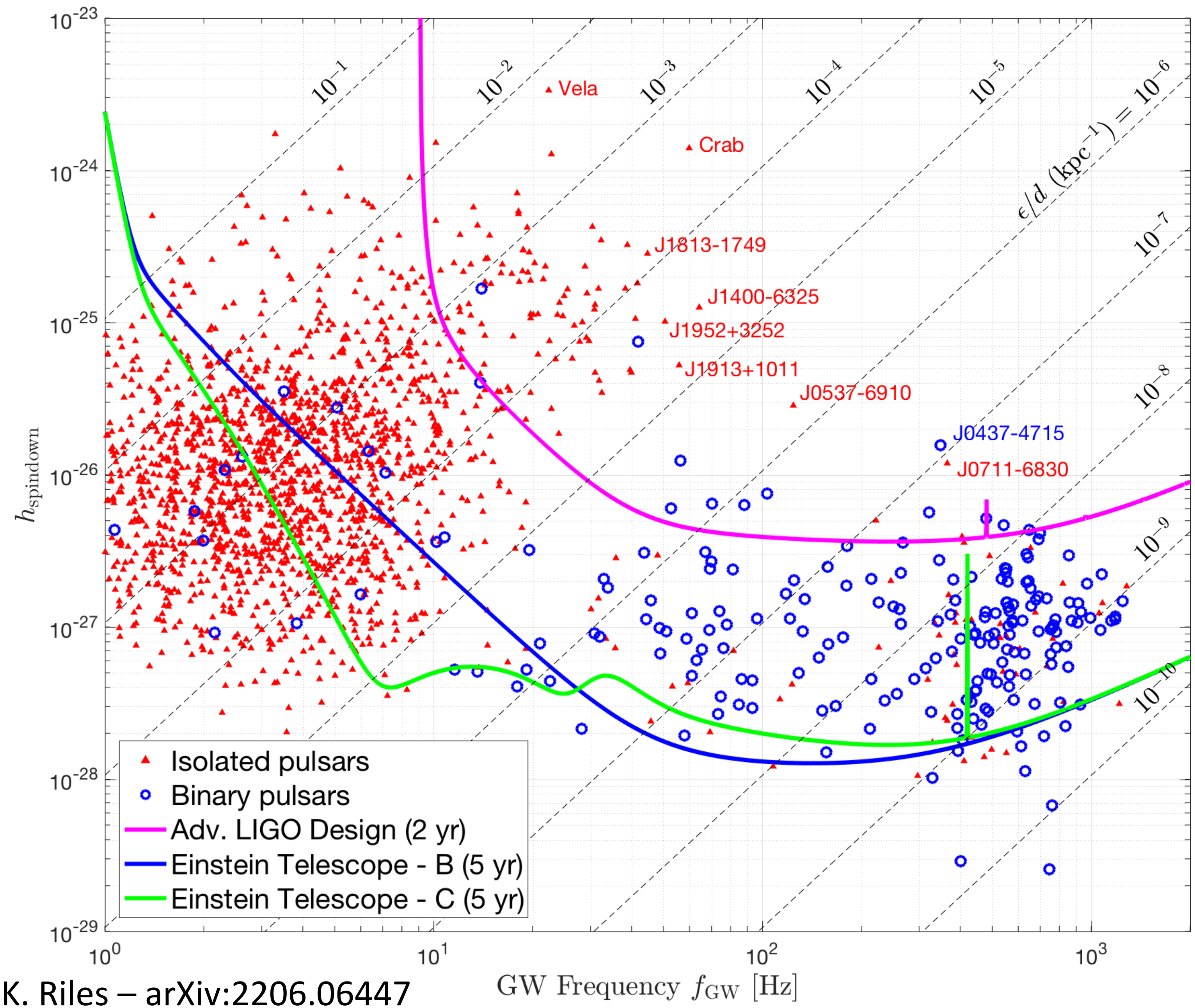
Computationally formidable!!!

Will present only a sampling of recent O3 results

CW analysis "JKS Bible":
P. Jaranowski, A. Krolak & B. Schutz, Phys. Rev. D 58, 063001 (1998)

***Recent review of CW searches: K. Riles – arXiv:2206.06447**

Population of known pulsars with GW frequencies > 10 Hz



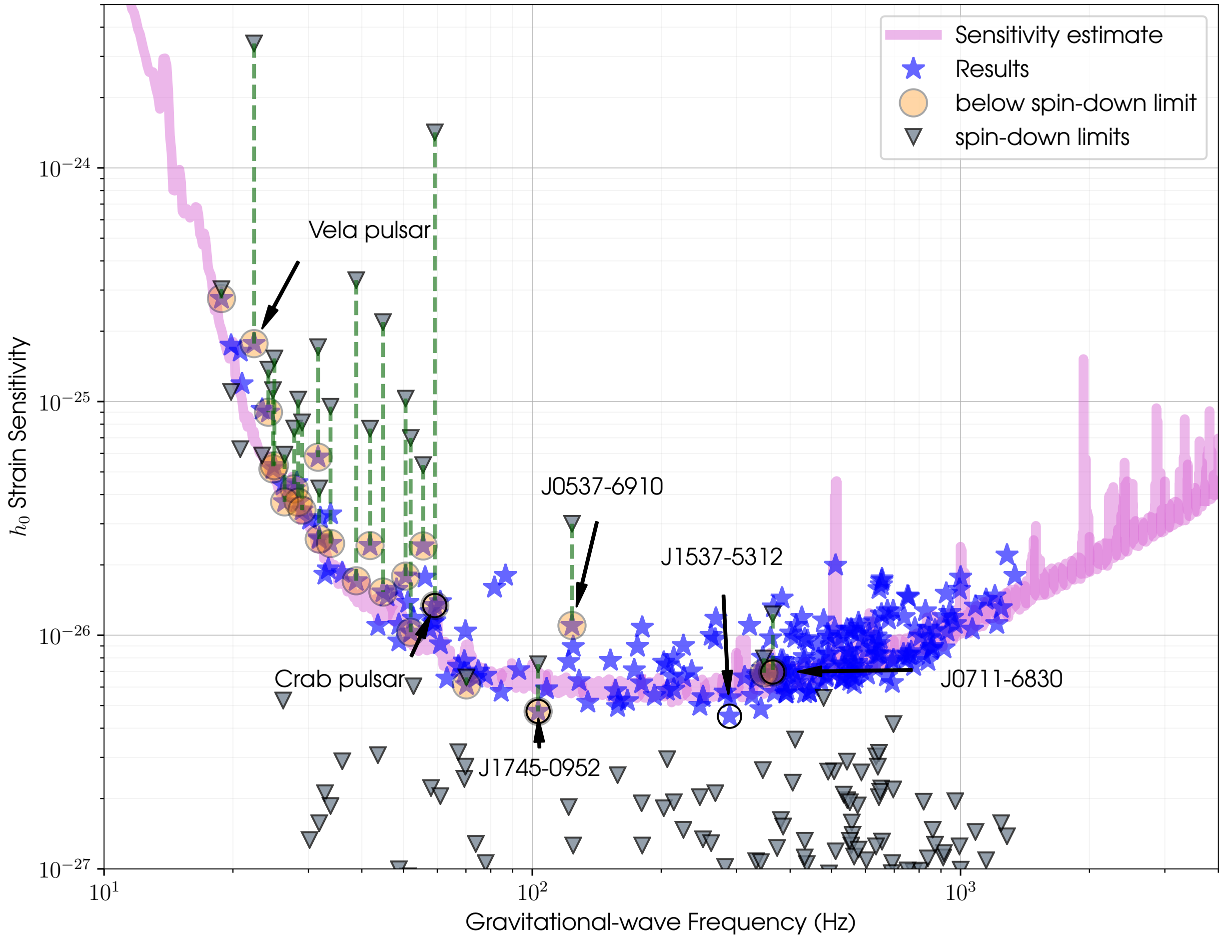
K. Riles – arXiv:2206.06447

Graph shows spin-down strain limits (energy conservation) and nominal targeted-search sensitivities in next few years and in the 2030's

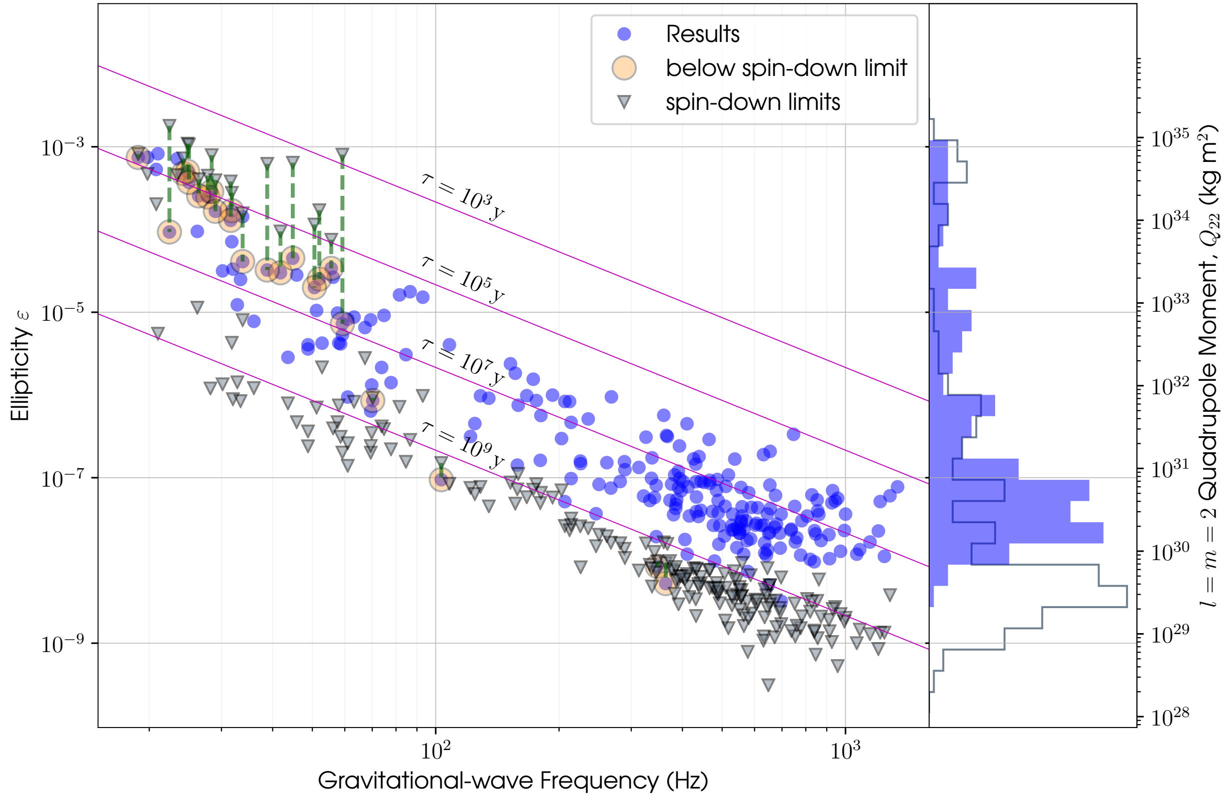
Binary systems dominate at high frequencies ("recycled" millisecond pulsars)

Dashed lines mark fixed ratios of ellipticity / distance

Targeted searches for 236 known pulsars (O1-O2-O3 runs)



- 23 spin-down limits beaten (incl. 2 millisecond pulsars)
- Crab: fractional energy ratio $\dot{E}_{GW}/\ \dot{E}_{rot} < 9 \times 10^{-5}$
- Lowest h_0 upper limit: 4.7×10^{-27} (J1745−0952, 103 Hz)
- Lowest ε upper limit: 5.3×10^{-9} (J0711−6830, 364 Hz)

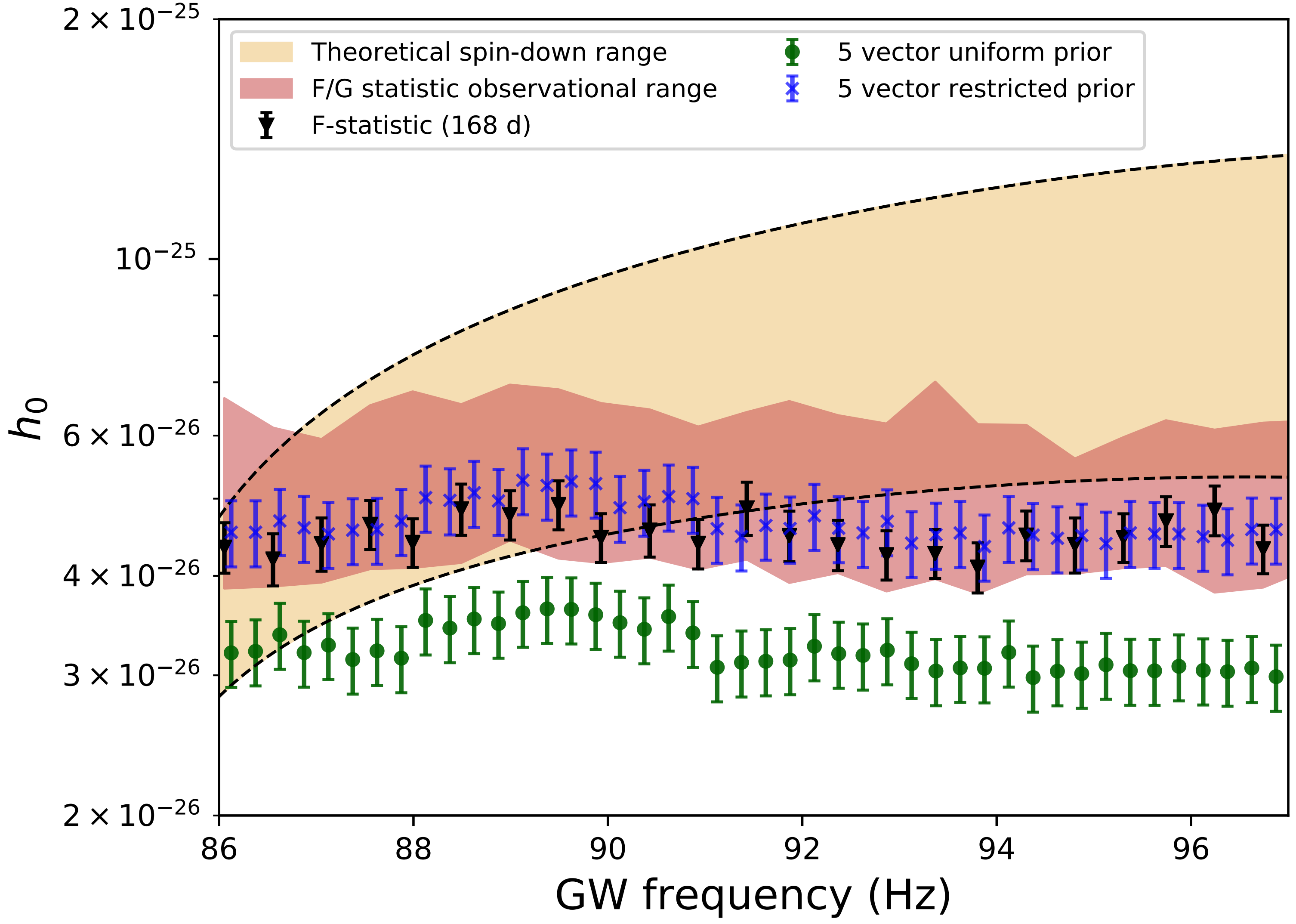


R. Abbott *et al.*, Ap. J. **935**, 1 (2022)

Related talk at POTOR 8:
P. Verma (Monday)

Avant le Del

Narrowband search for r-modes in J0537-6910

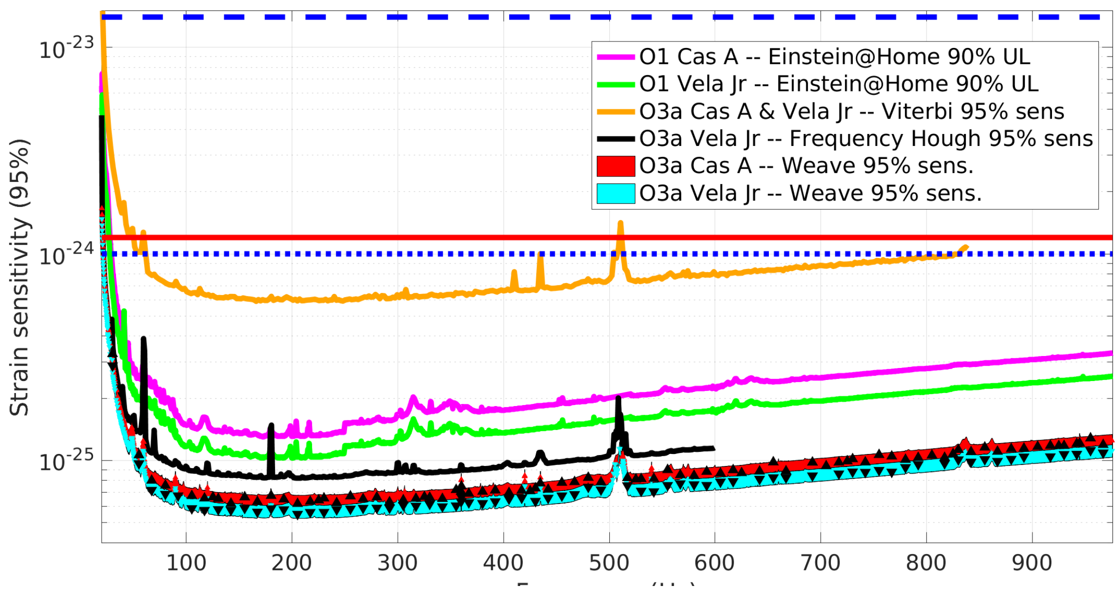


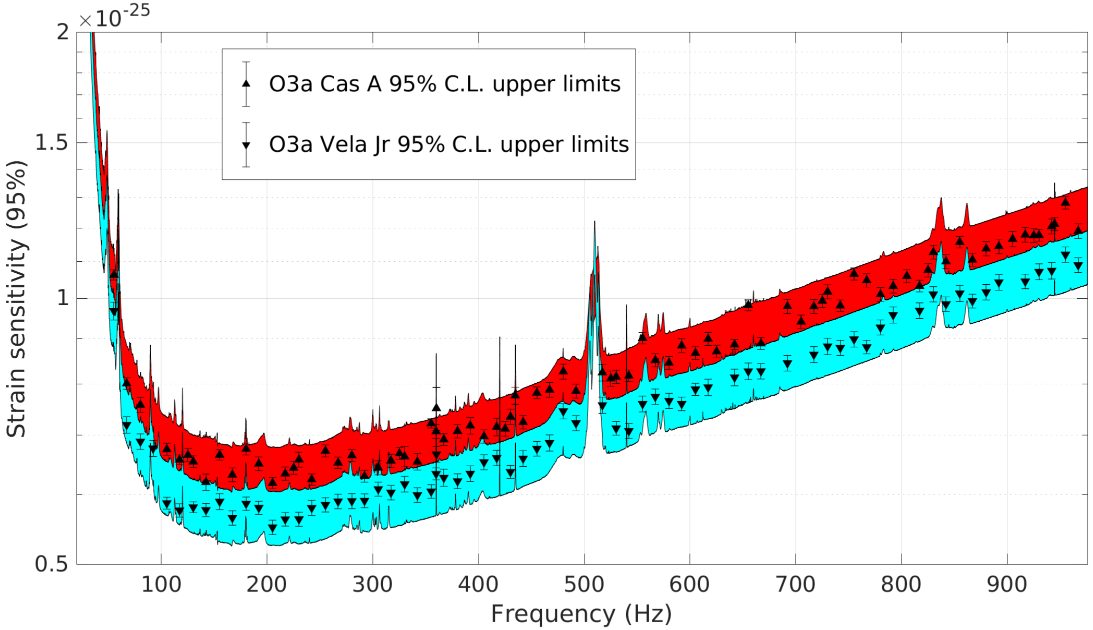
R. Abbott *et al.*, Ap. J. **922**, 71 (2021)

J0537-6910 is intriguing:

- Fastest young pulsar, with high rotational energy loss rate
- Glitches frequently
- Second frequency derivative between glitches asymptotically approaches value expected for GW r-mode emission (N. Andersson *et al.*, Ap. J, 864, 137 (2018)

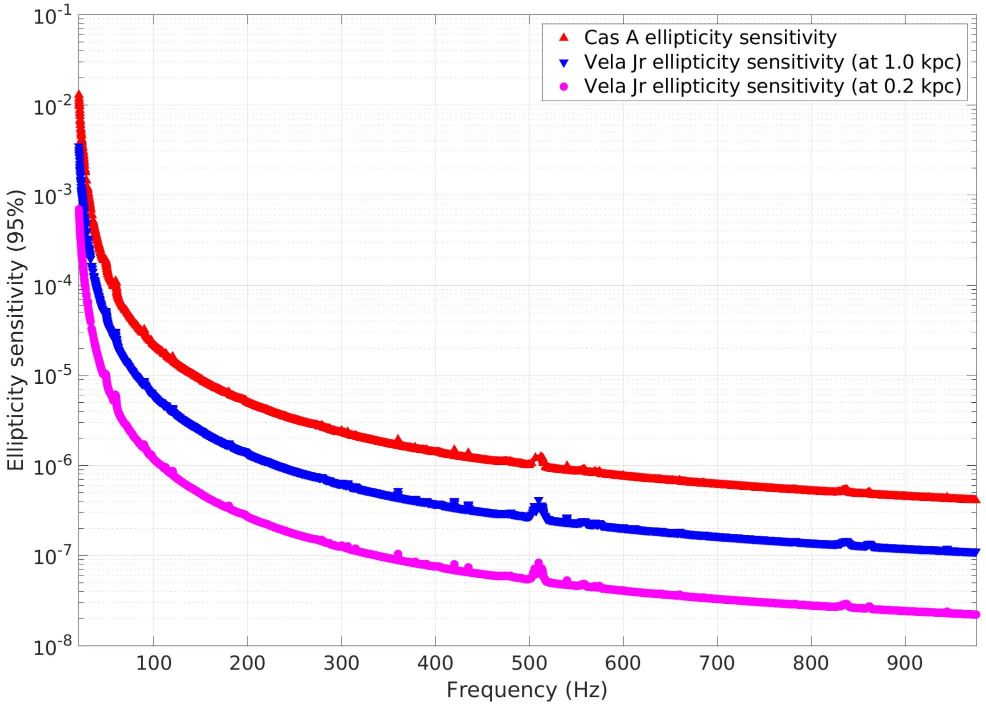
Directed searches for Cassiopeia A and Vela Jr



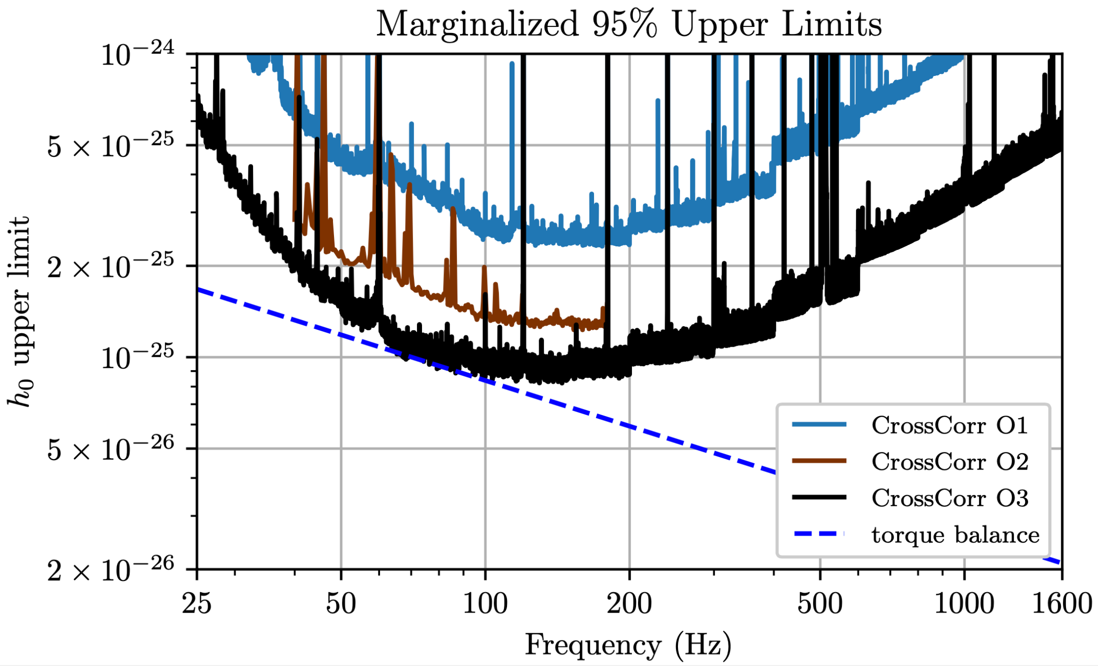


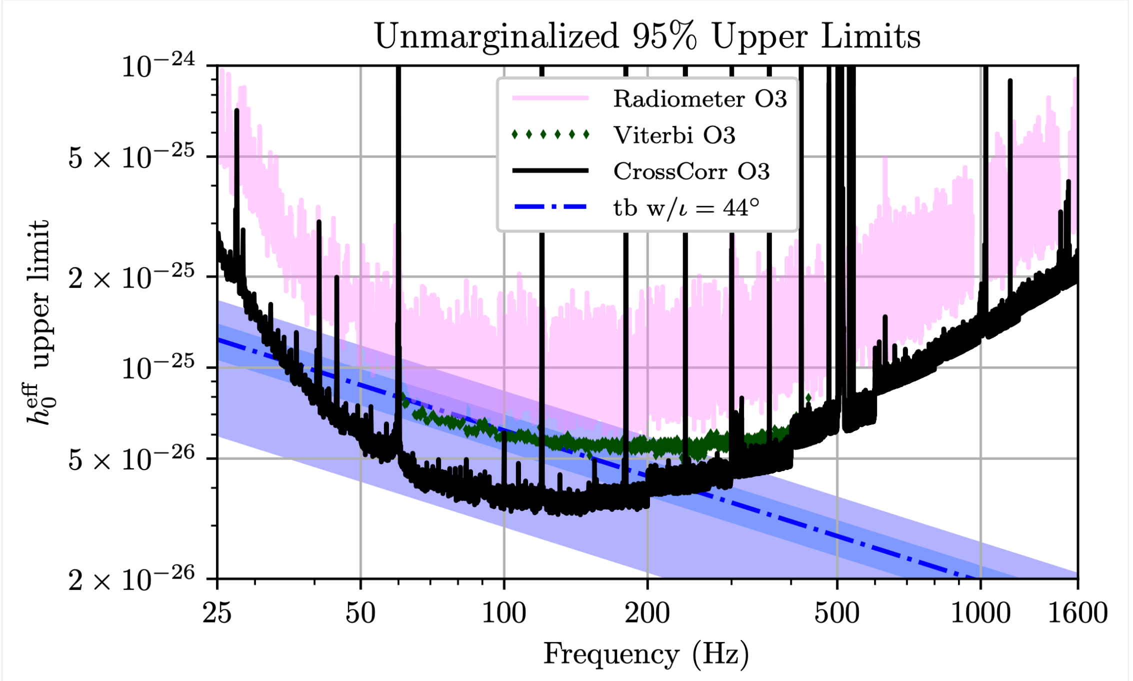
Interesting nearby supernova remnants (central compact objects seen in X-rays):

- Cas A: ~300 years old, 3.3 kpc away
- Vela Jr: ~700 years old(?), 0.2 kpc(?)



R. Abbott *et al.*, Phys. Rev. D **105**, 082005 (2022)





R. Abbott *et al.*, arXiv:2209.02863

Directed searches for Scorpius X-1

- Sco X-1 is brightest (non-solar) X-ray source
- GW intensity scales with X-ray intensity from accretion disk

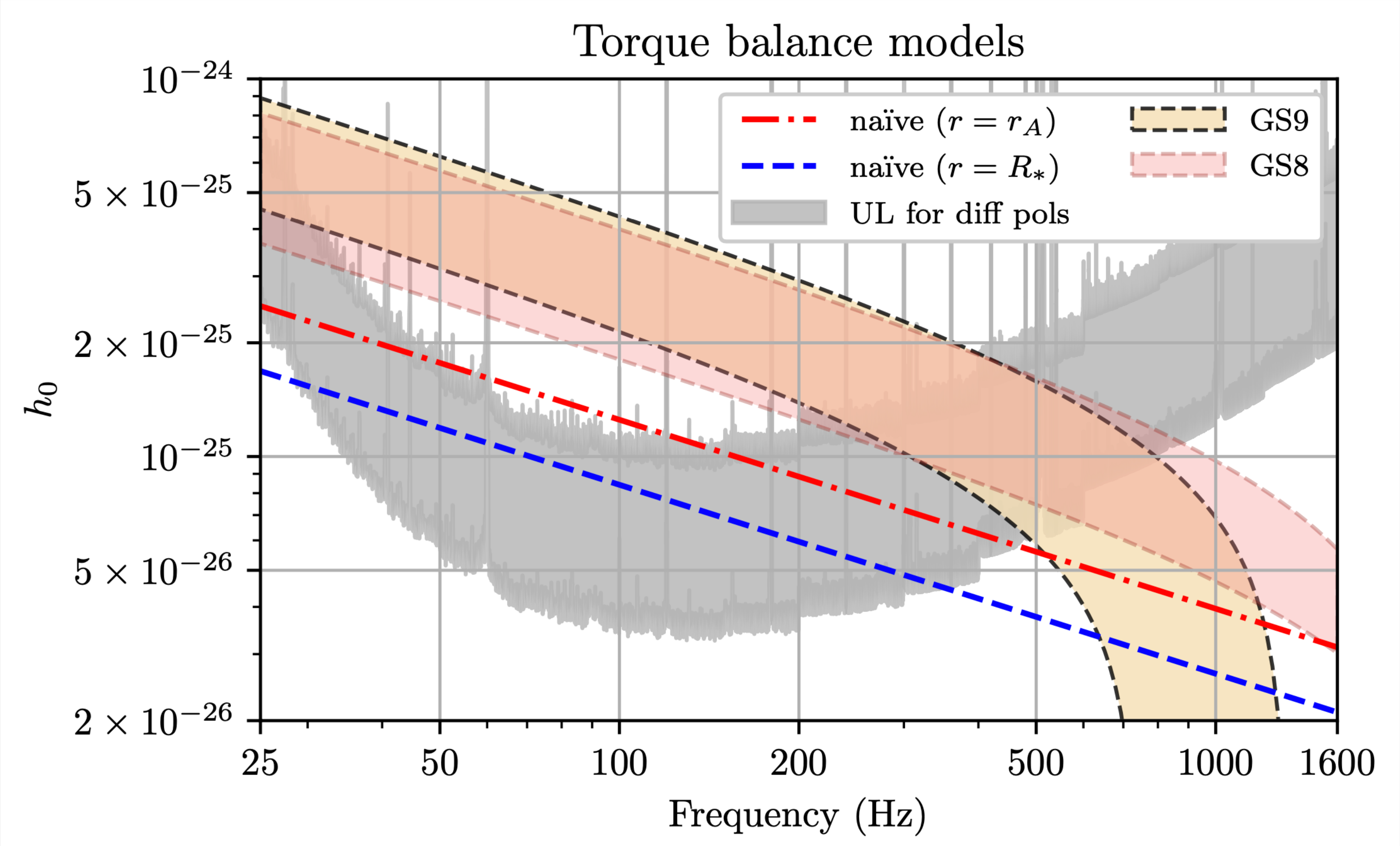
  J. Papaloizou & J.E. Pringle, MNRAS, **184**, 501 (1978)
  R.V. Wagoner, Ap. J. **278**, 345 (1984)

- Torque-balance argument: angular momentum gained from accretion balanced by GW radiation

  L. Bildsten, Ap. J. Lett. **501**, L89 (1998)

- Most promising low-mass X-ray binary

Directed searches for Scorpius X-1

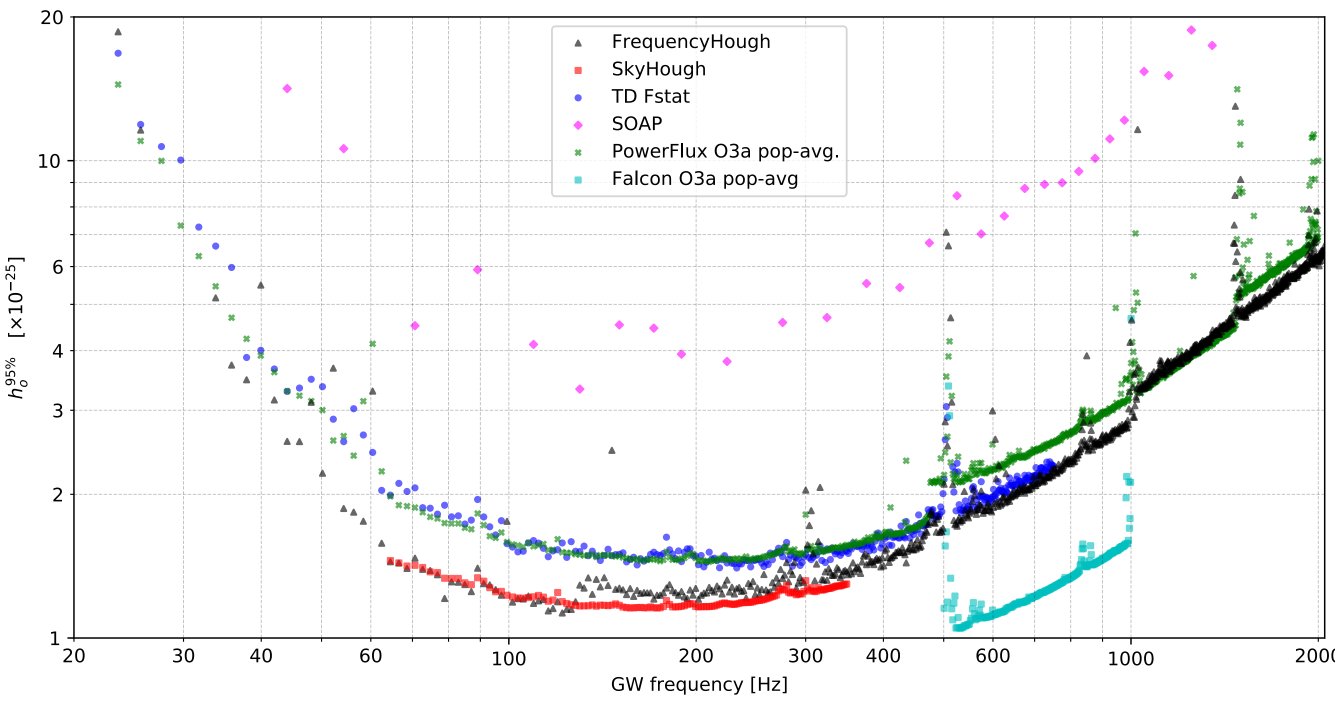


R. Abbott *et al.*, arXiv:2209.02863

Observations now allow confronting / excluding specific models of accretion-powered GW emission at lower frequencies

[K. Glampedakis & A.G. Suvorov, MNRAS, **508**, 2399 (2021)]

All-sky search for CW sources in isolated systems



K. Riles, arXiv:2206.06447

R. Abbott *et al.*, Phys. Rev. D **104**, 082004 (2021)

R. Abbott *et al.*, arXiv:2201.00697

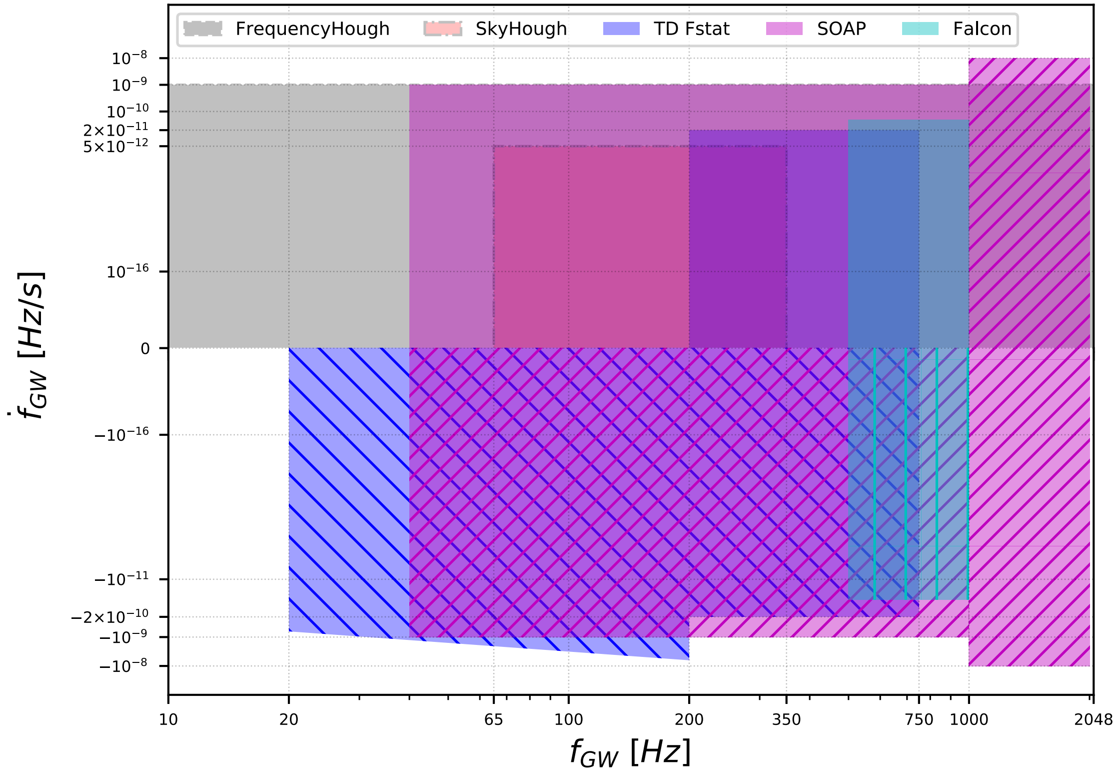
V. Dergachev & M.A. Papa, arXiv:2202.10598

Related talk at POTOR 8:
A. Pisarski (Monday)

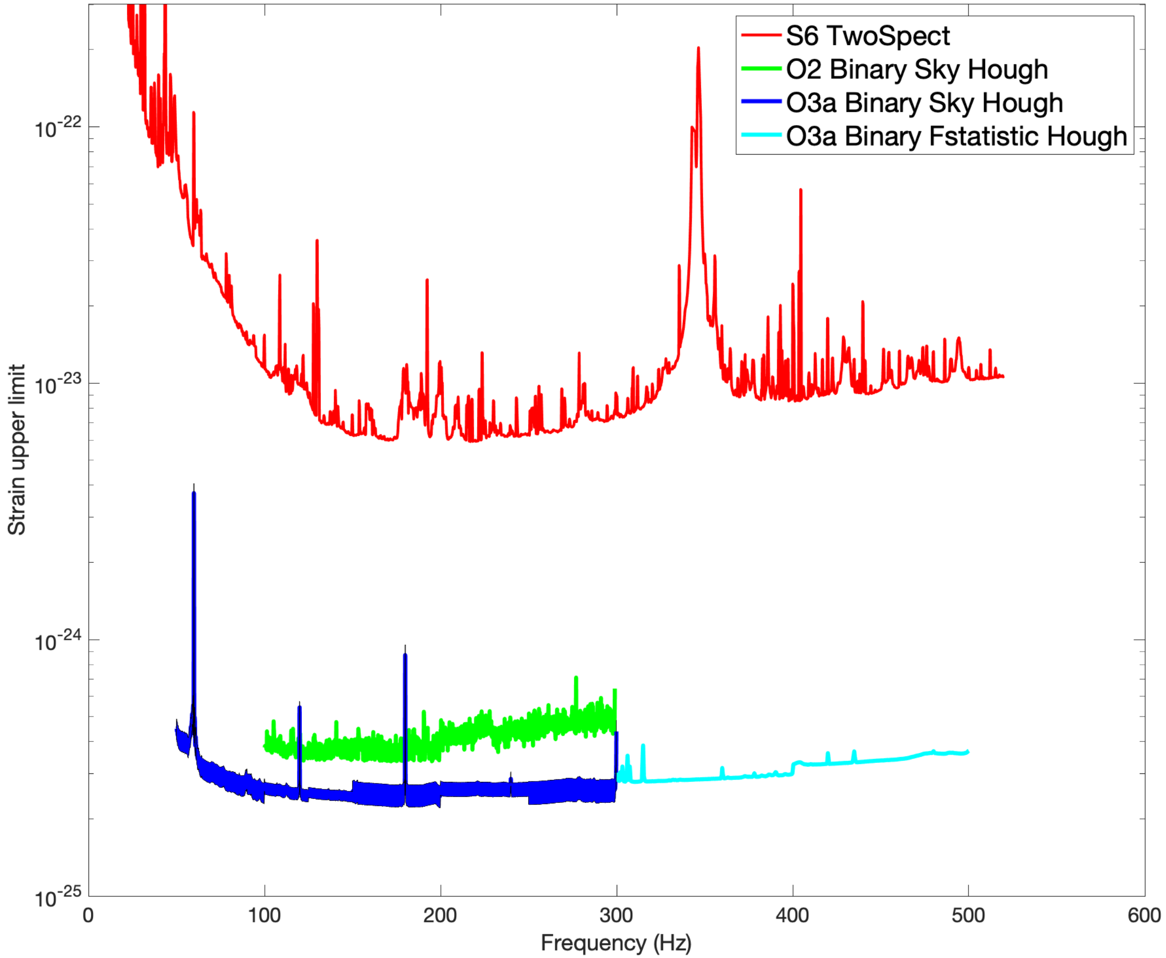
Comparison of all-sky approaches:

- Traditional broadband, high-spin-down (deep in space, "eyes wide open")
- Alternative focus on low-spin-down, necessarily nearby sources (deep in strain)

→ Complementary



All-sky search for CW sources in binary systems



The most demanding GW search:

- Parameter space is formidable, even with usual assumptions of circular orbits and negligible intrinsic spin-down
- GPUs and recent algorithmic improvements have boosted sensitivity since first attempt in Initial LIGO
- Will be especially interesting to extend to higher frequencies where binary systems dominate millisecond pulsars

K. Riles – arXiv:2206.06447

P.B. Covas & A.M. Sintes., Phys. Rev. Lett. **124**, 191102 (2020)

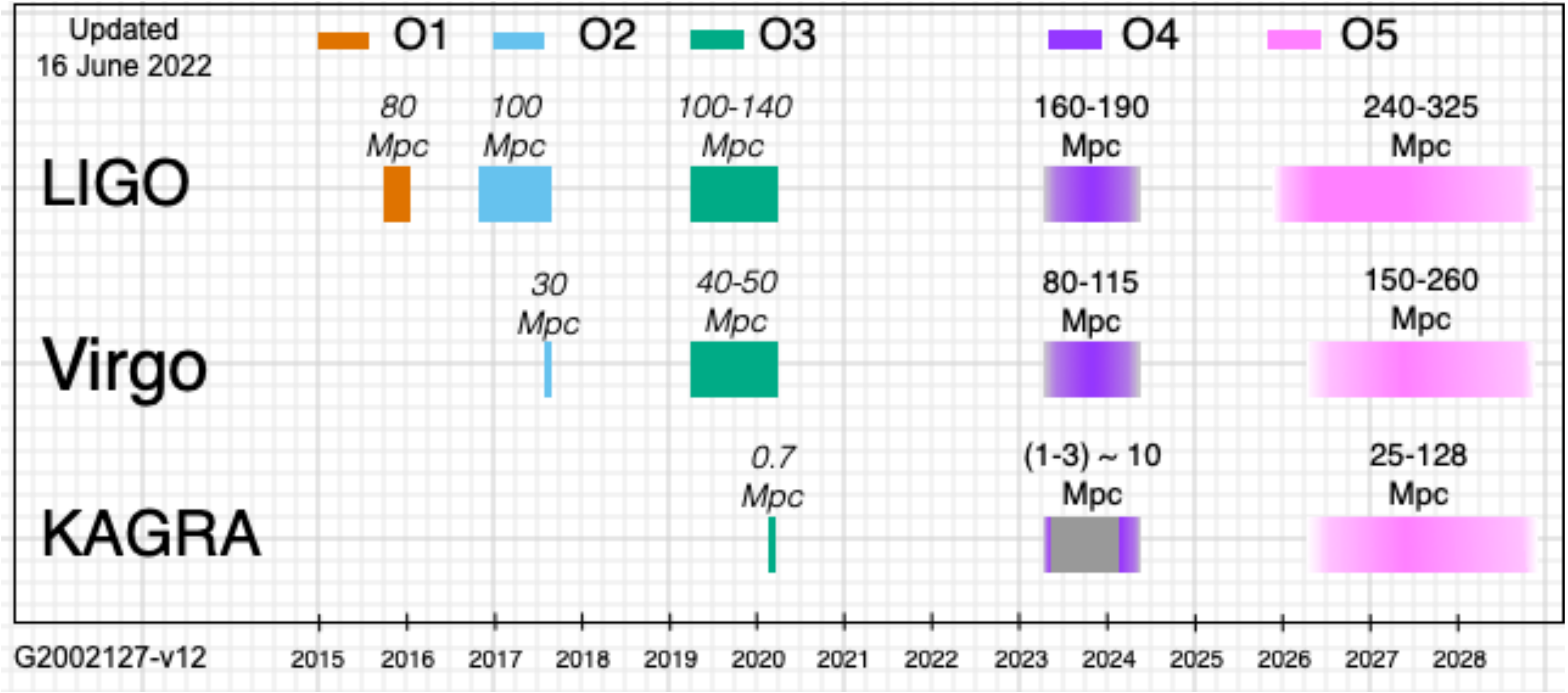
R. Abbott *et al.,* Phys. Rev. D **103**, 064017 (2021)

P.B. Covas, M. A. Papa, R. Prix, B. J. Owen., arXiv:2203.01773, to appear in Ap. J. Lett.

Stay tuned...

- **Analysis of O3 run winding down**
  - Recently released “catalog” of CBC mergers
  - Limits on stochastic radiation (cosmological, distant mergers)
  - Residual searches wrapping up (CBC, bursts)
- **Culminating Advanced LIGO / Virgo O4 run starting ~March 2023**
  - Aiming at Advanced LIGO design sensitivity
  - Hundreds of mergers
  - Interesting Hubble Constant measurement
  - Surprises are likely...
- **Upgrade to current detectors for O5 run (Advanced LIGO → A+)**
  - Improve LIGO sensitivity by another ~1.7 (improved optics / “squeezing”)
    → 5 times more events / week
  - Approved / funded by NSF/UK/Australia → work well under way

Current (tentative) timeline through the O5 run:

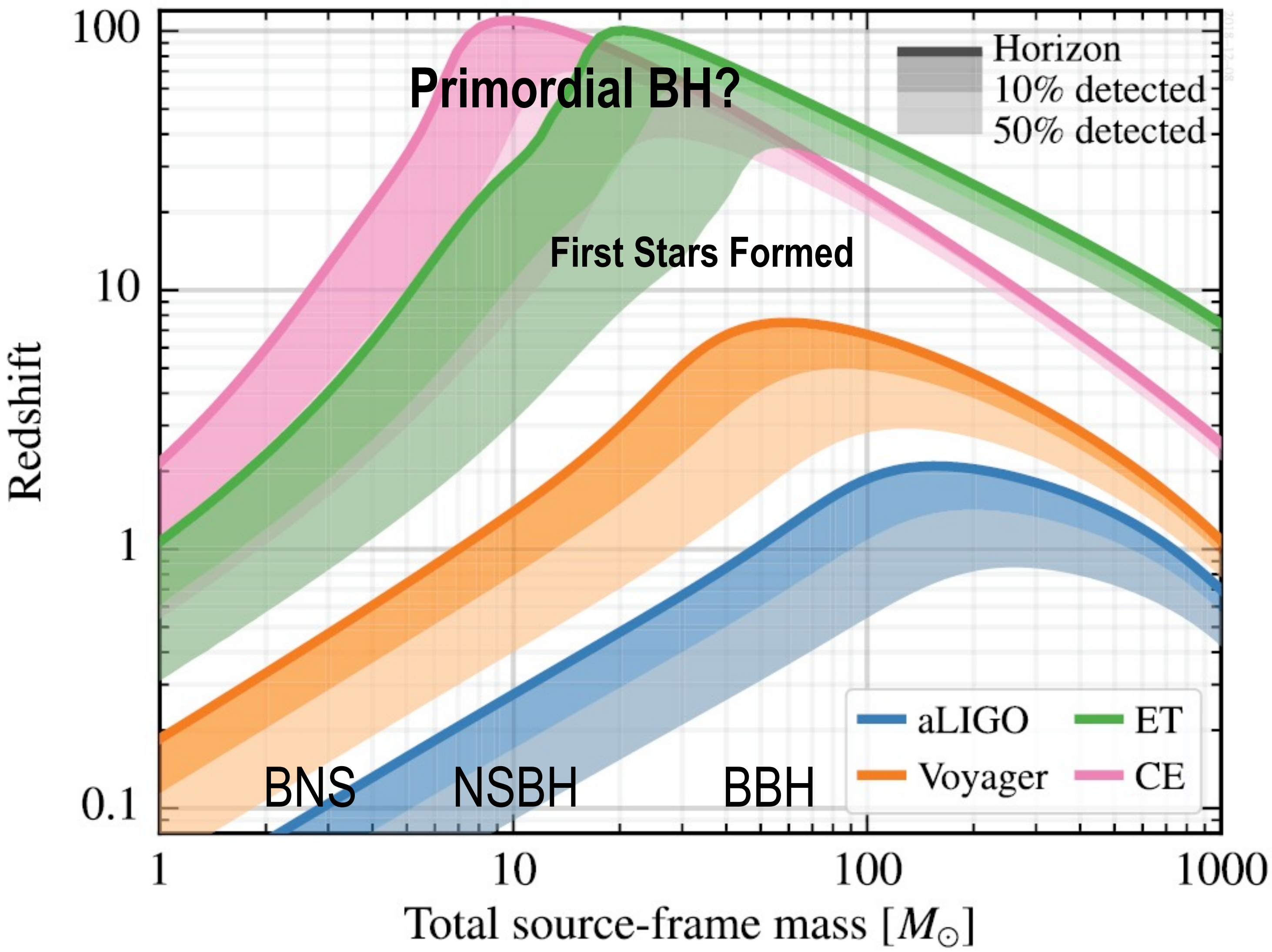


https://observing.docs.ligo.org/plan/

Stay tuned...

- Further (post-O5) upgrades to current facilities are under study
  - Conventional:
    - Higher laser power
    - Stronger quantum squeezing
    - Heavier mirrors
    - Improved ground isolation
  - More ambitious (Voyager option):
    - Use silicon mirrors to allow modest cryogenics (~120K) – needs longer laser wavelength (2 μm)
- Longer term (2030s) – Planning for new facilities
  - U.S. – **Cosmic Explorer** – **40-km** LIGO (*e.g.*, in Utah desert)
  - Europe: **Einstein Telescope** (10-km underground triangle)
  - Running in parallel with older facilities

Possible progression of cosmological reach



E. Hall & M. Evans,
Class. & Quant. Grav. **36** 225002 (2019)

Summary

LIGO / Virgo have observed gravitational waves from the mergers of stellar mass black holes (~90 definitive discoveries published)

- **Several discoveries of binary neutron star mergers and NS-BH mergers**
  → EM follow-up campaign stunningly successful on GW170817
  → Gamma rays, X-rays, UV, optical, IR, radio observed
  → Strongly supports kilonova explanation of heavy element production in the Universe

- **Now seeing unusual BBH systems that challenge conventional models:**
  → Asymmetric masses (GW190412, GW190814)
  → Object in lower mass gap (GW190814)
  → Perhaps two objects in higher mass gap (GW190521 et al)
  → Formation of intermediate mass black holes

Much more to come…

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