Gravitational Wave Astronomy after the first discoveries

John Veitch

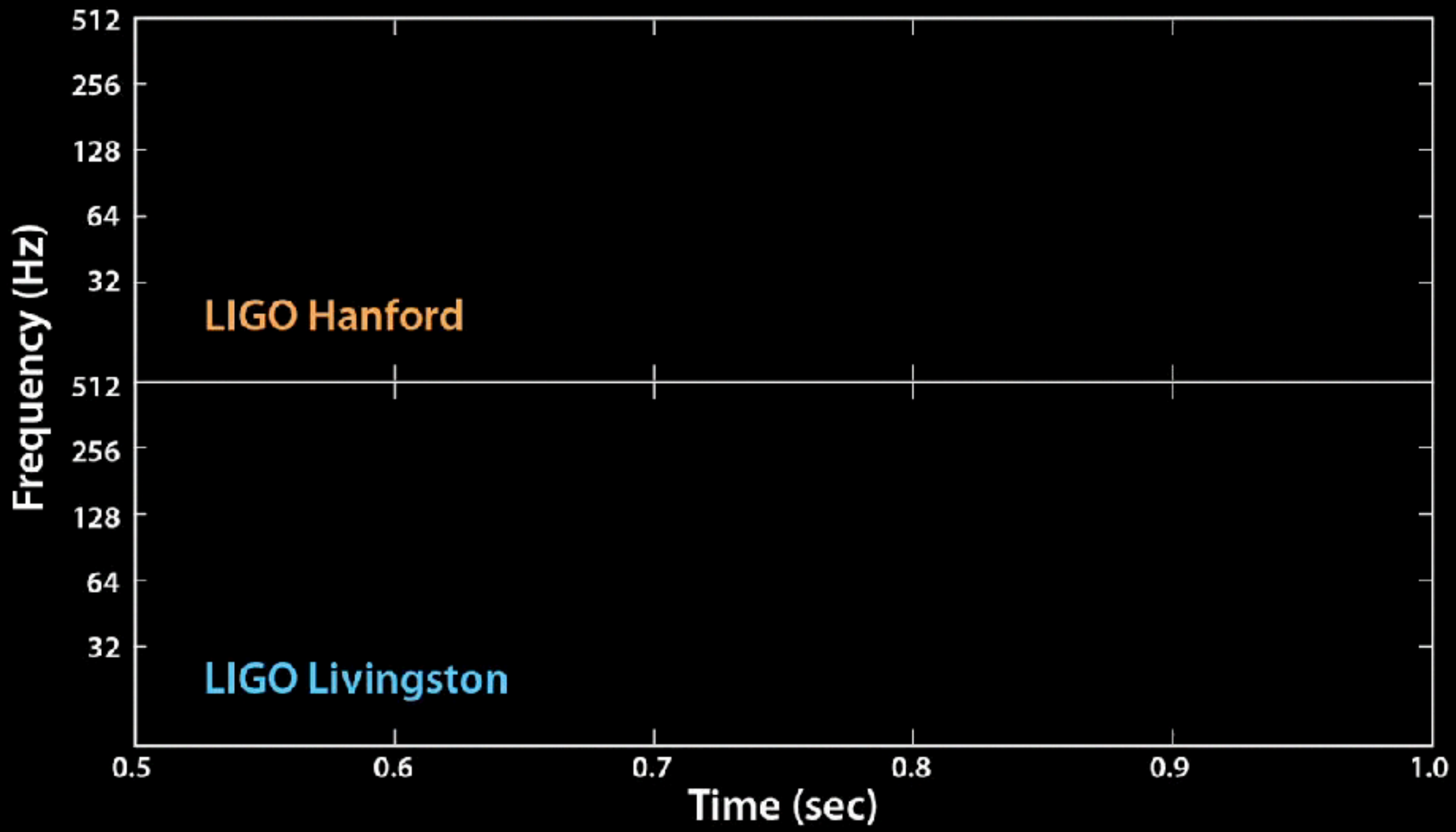
Belgian-Dutch GW Meeting

2018-05-29

LSC VIRGO

University of Glasgow

14 Sept 2015


512
256
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64
32
LIGO Hanford
512
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LIGO Livingston
Frequency (Hz)
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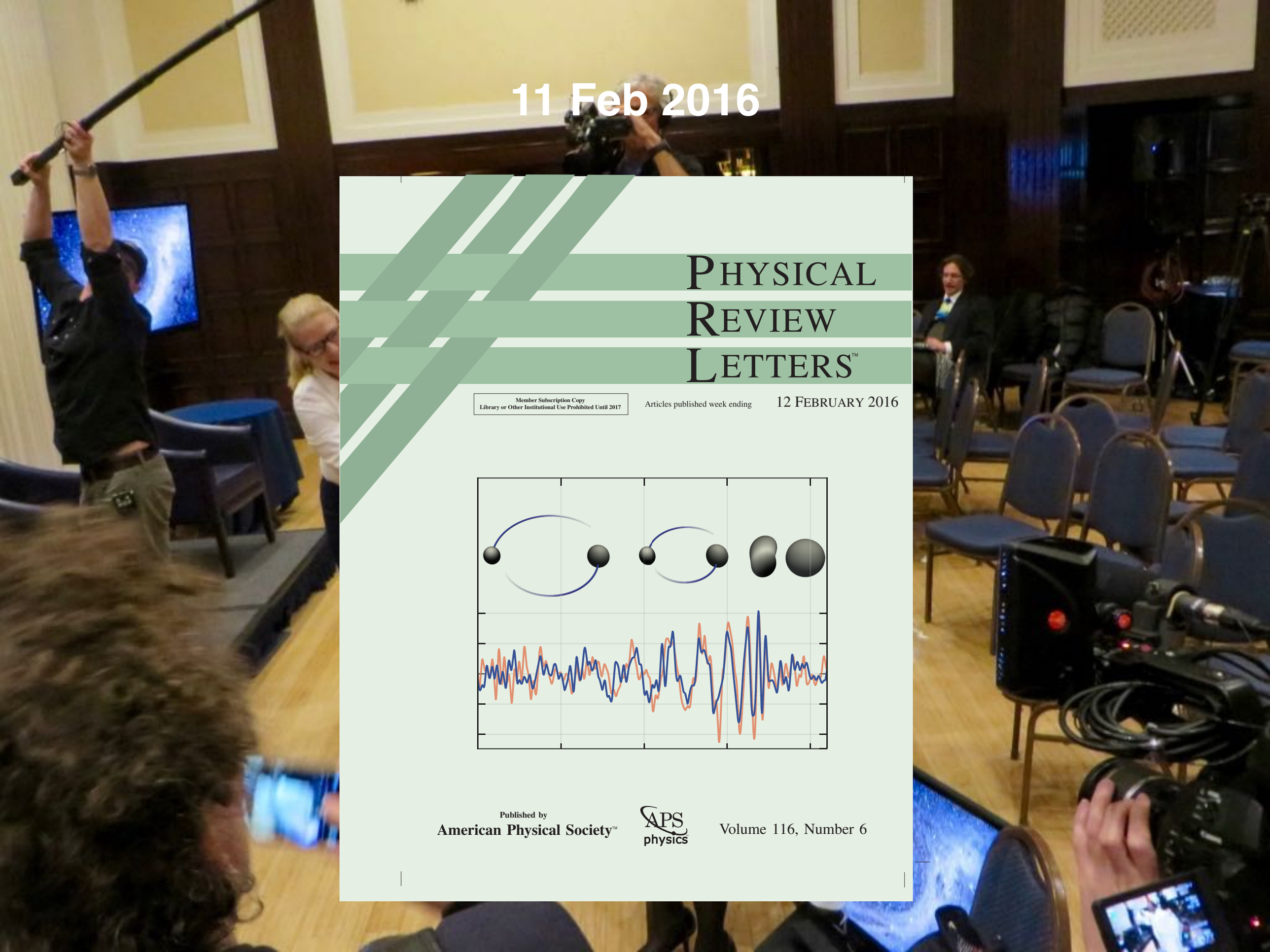
0.6
0.7
0.8
0.9
1.0
Time (sec)

11 Feb 2016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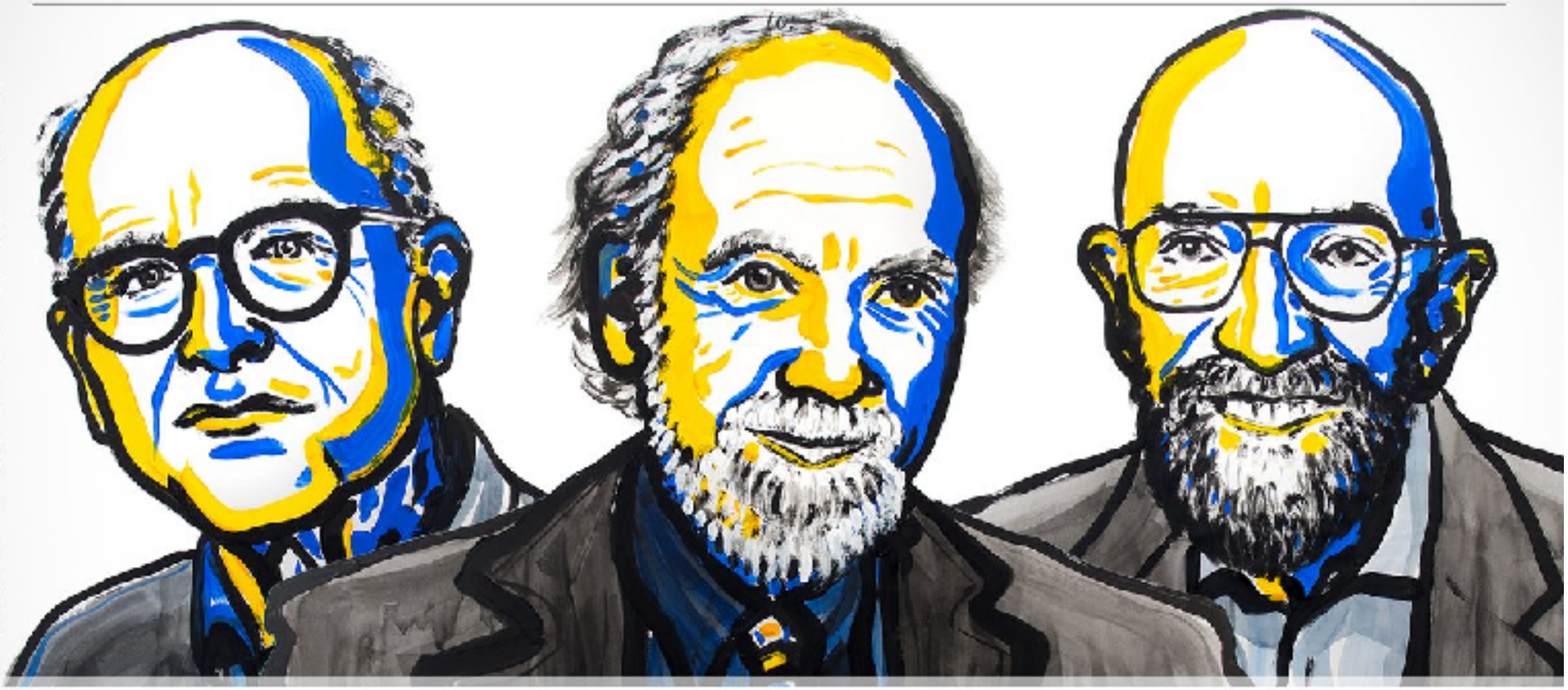
APS physics
Volume 116, Number 6

"For the greatest benefit to mankind"

Alfred Nobel

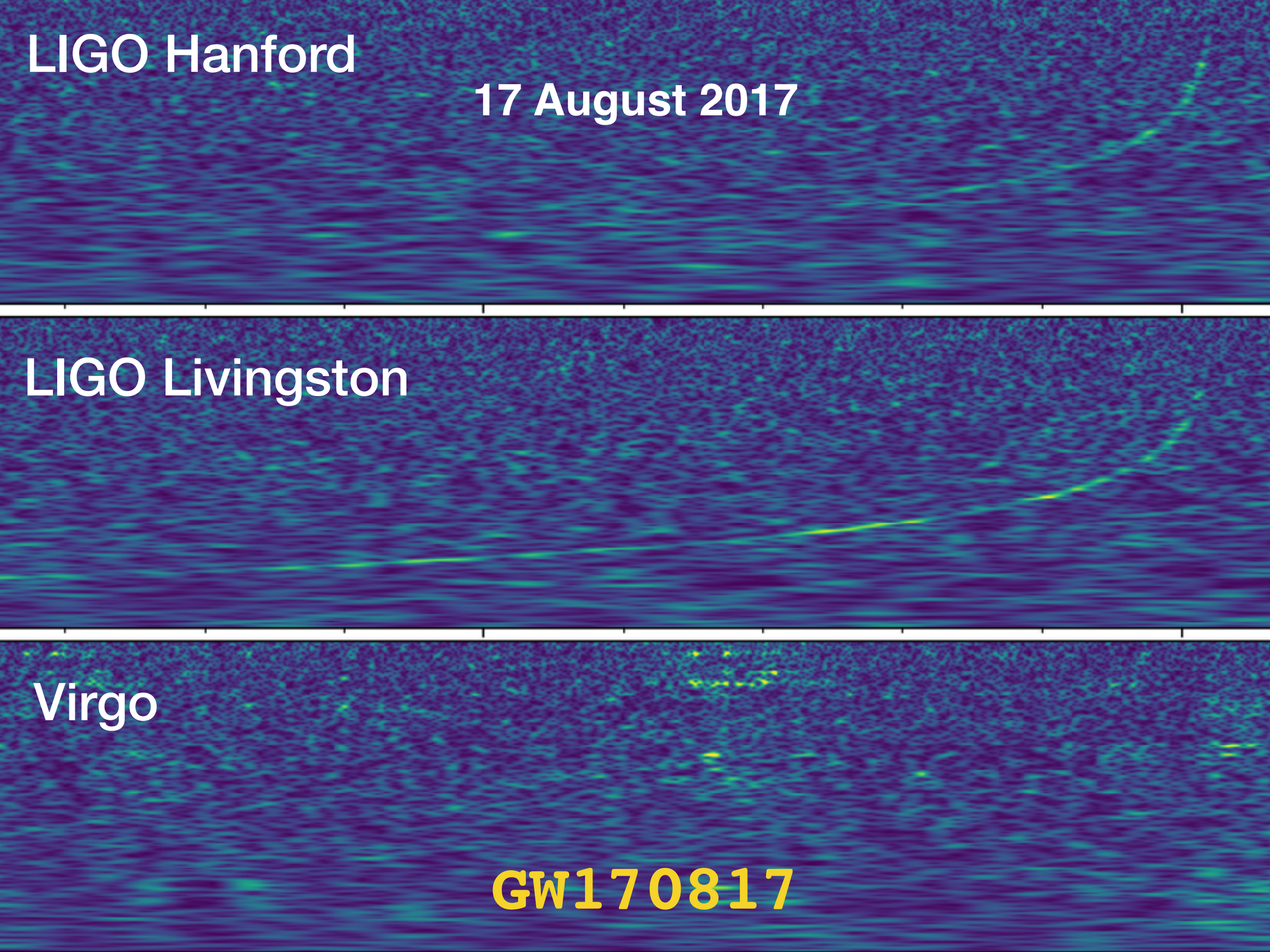
The Royal Swedish Academy of Sciences has decided to award the

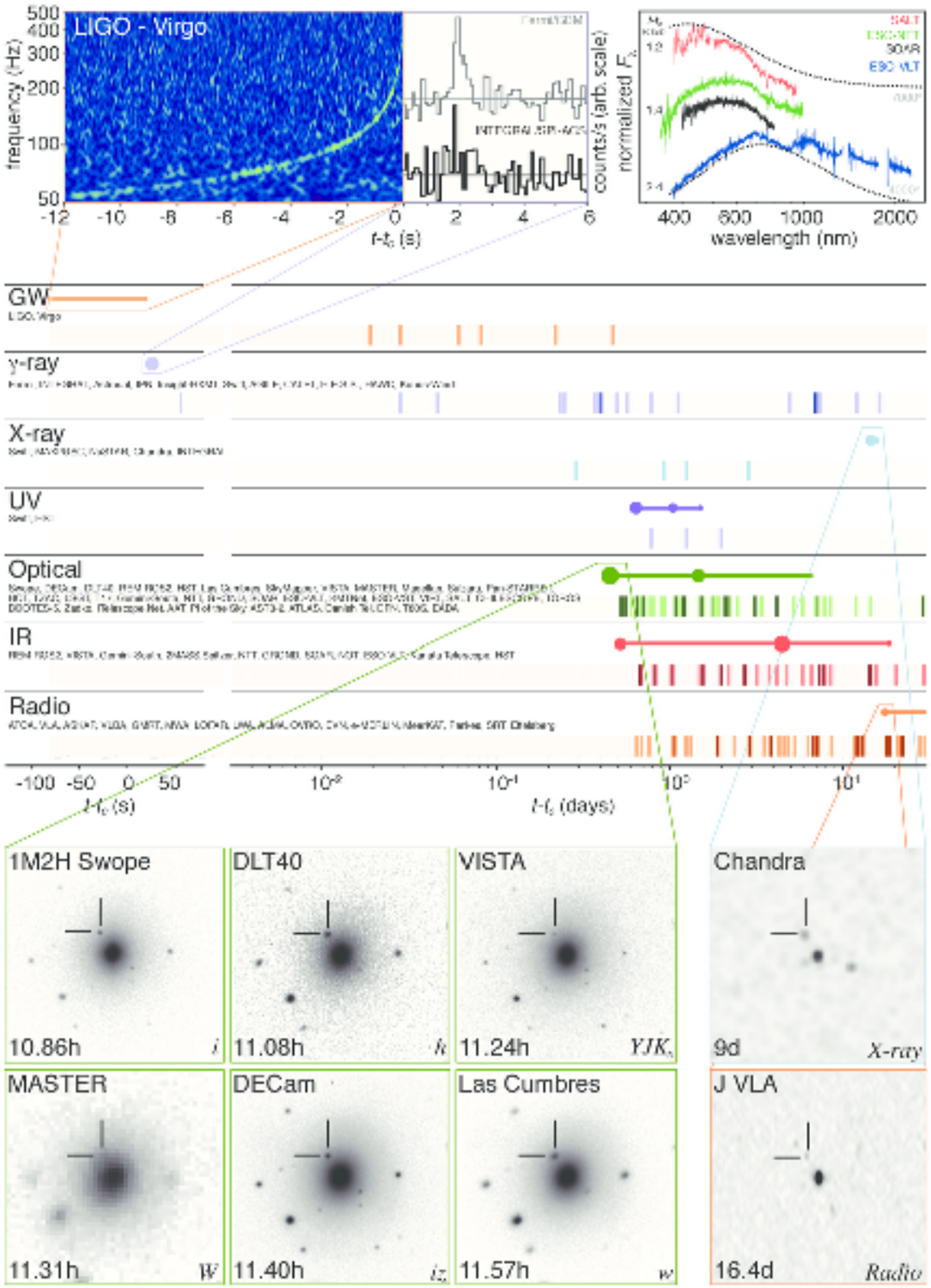
2017 NOBEL PRIZE IN PHYSICS



Rainer Weiss
Barry C. Barish
Kip S. Thorne

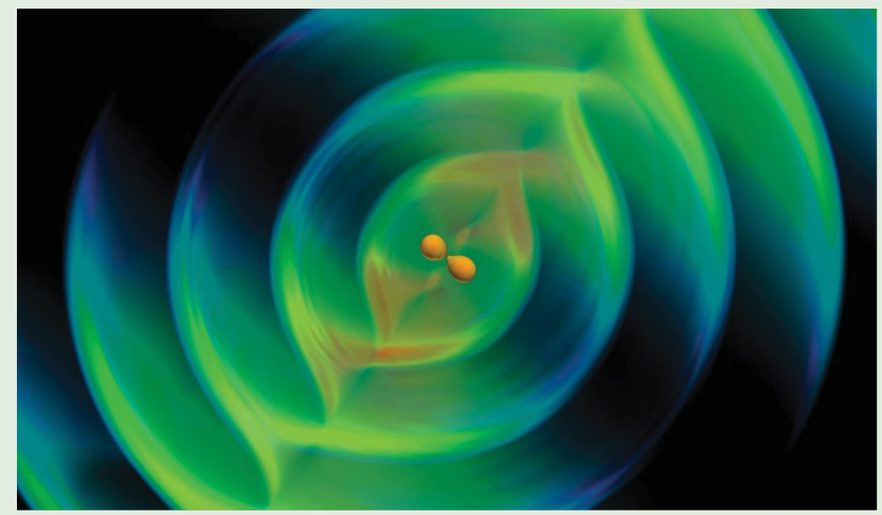
"for decisive contributions to the LIGO detector and the observation of gravitational waves"


LIGO Hanford
17 August 2017
LIGO Livingston
Virgo
GW170817



Physical Review Letters

Articles published week ending 20 October 2017



Published by
American Physical Society

Volume 119, Number 16

29 May 2018

Where do we stand?

Where do we stand?

- 2nd Observing Run Completed Dec 16 - Aug 17
  - Several more BBH detections
    - After slow start, GW170104, GW170608, GW170814
  - Binary neutron star! Birth of multi-messenger GW astronomy
- Preparations for O3
- Looking further ahead

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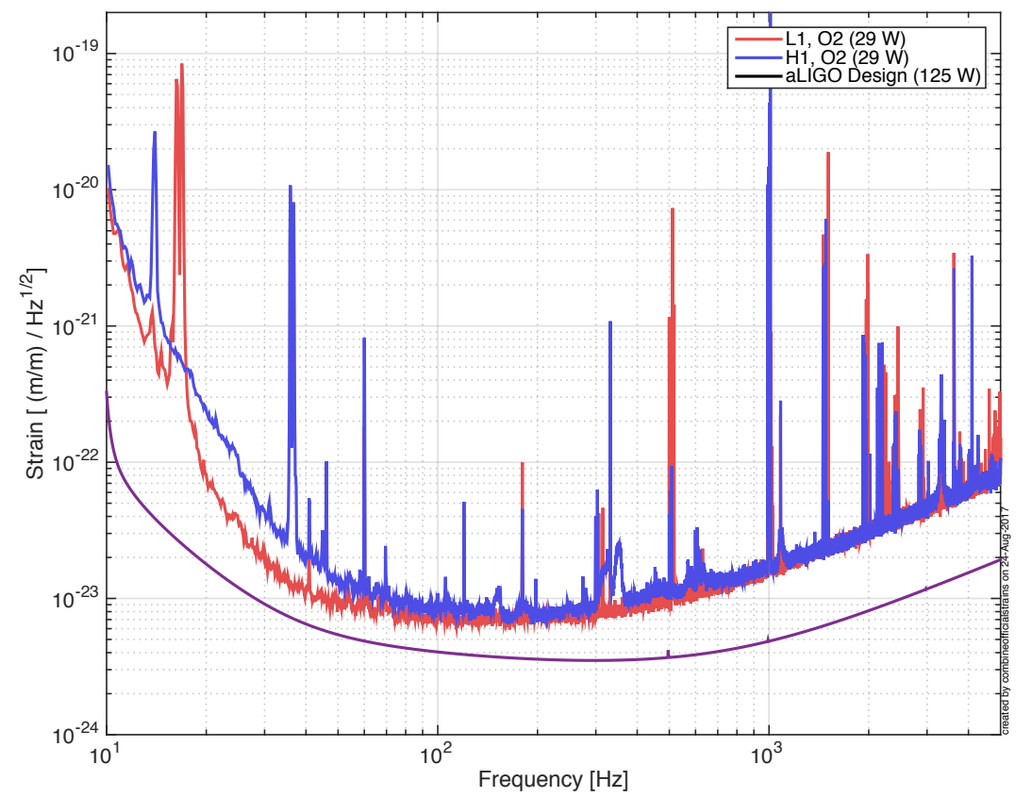
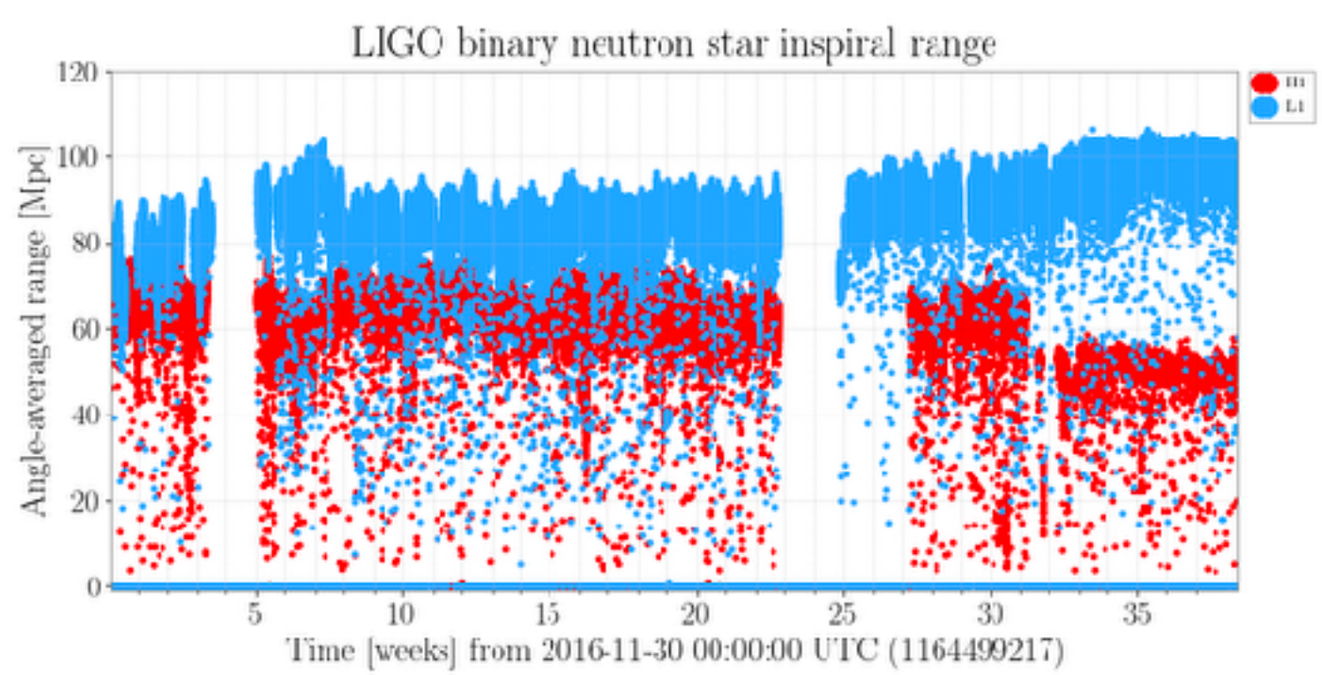
Advanced LIGO in O2

- Dec 16 - Aug 17
- L1 ~90-100 Mpc BNS range
- H1 ~70 / 50 after break
  - Offline noise subtraction to improve range
- Analysis ongoing…





Advanced Virgo joins!

- aVirgo joined O2 with competitive BNS range
- Hierarchical analysis with HL providing significance and V1 improving SkyLoc & PE
- 8 Mpc (ER12) to 27 Mpc (O2) in a very short period of time
- Included in analysis from June 17 onwards
- 1st clear detection (GW170814)
- Has had a significant impact in source resolution and parameter estimation
- Possible first constraints on non-GR polarisations due to GW detector network

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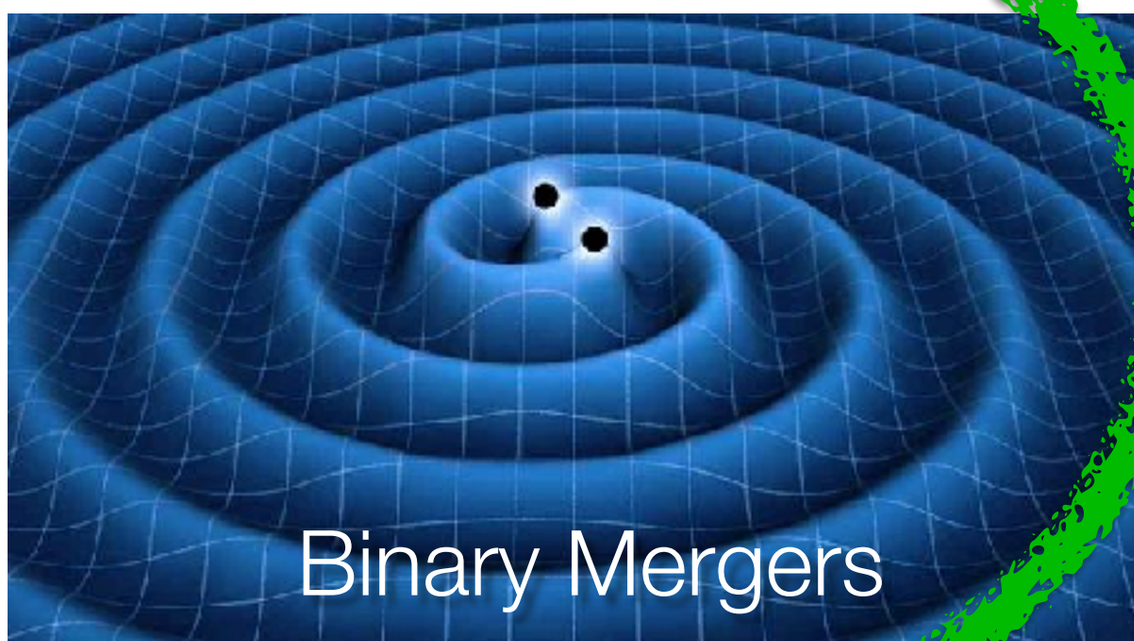
Ground-based GW Sources

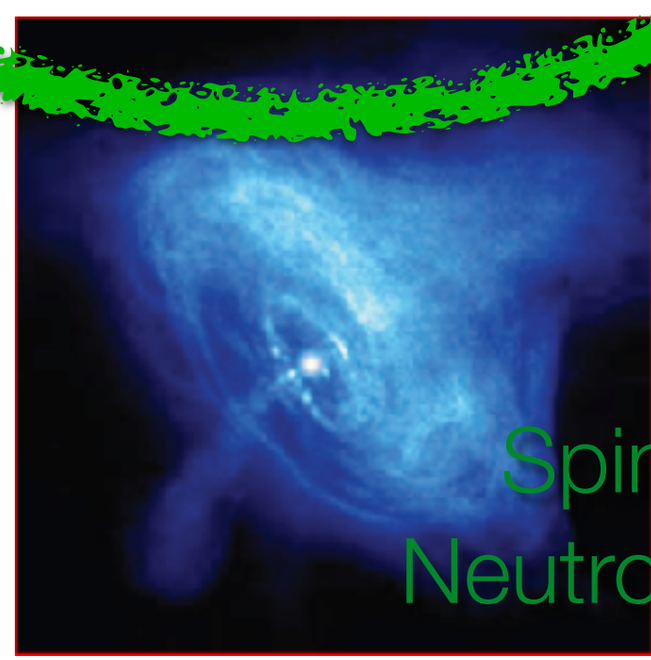
Modelled

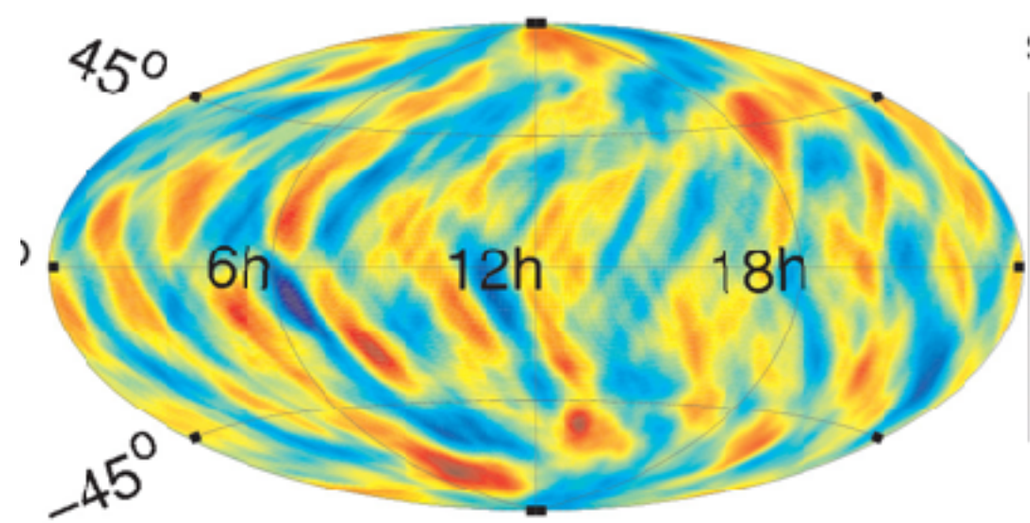
Unmodelled

Transient



Continuous





Stochastic Background

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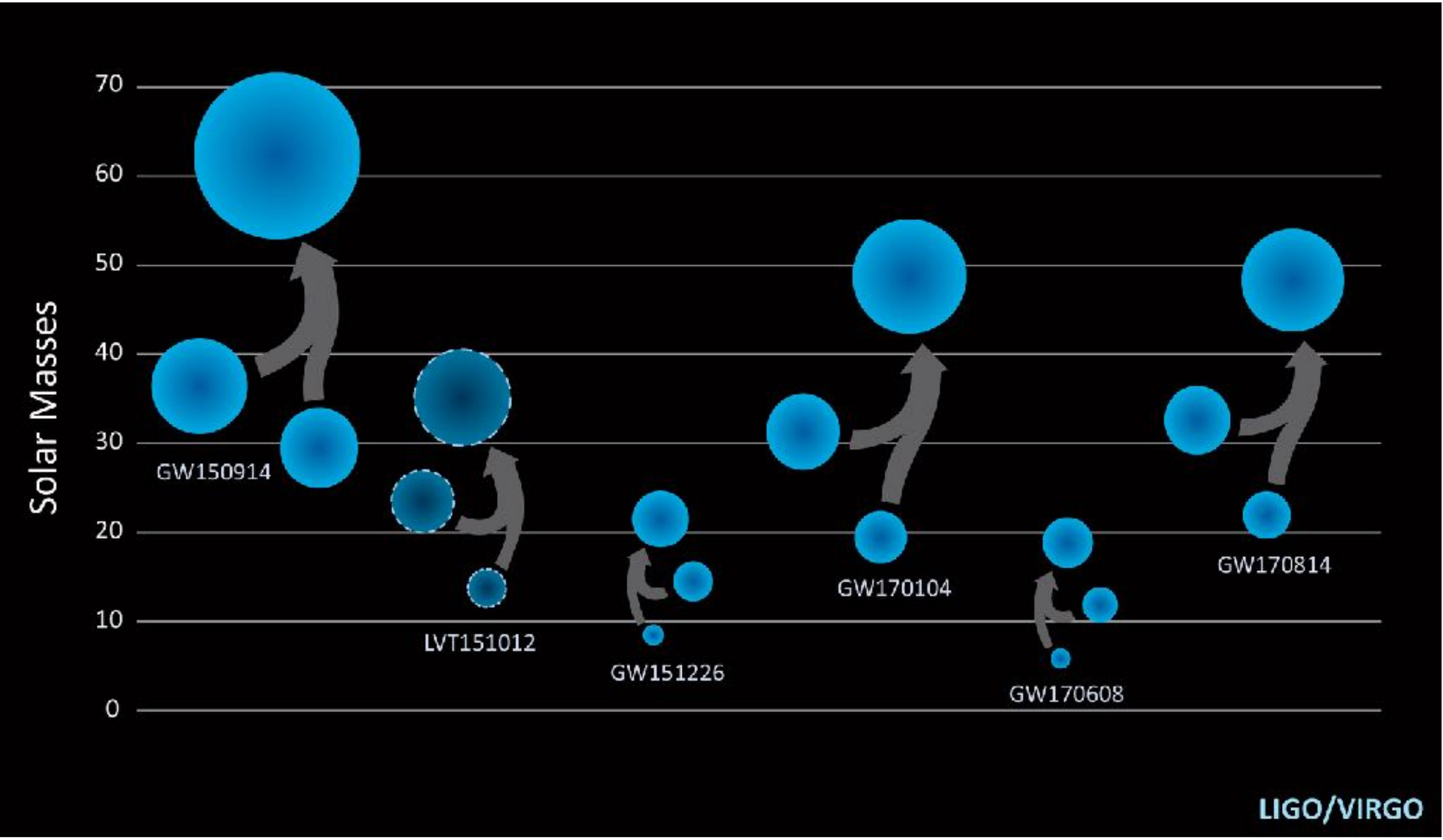
Binary Black Holes



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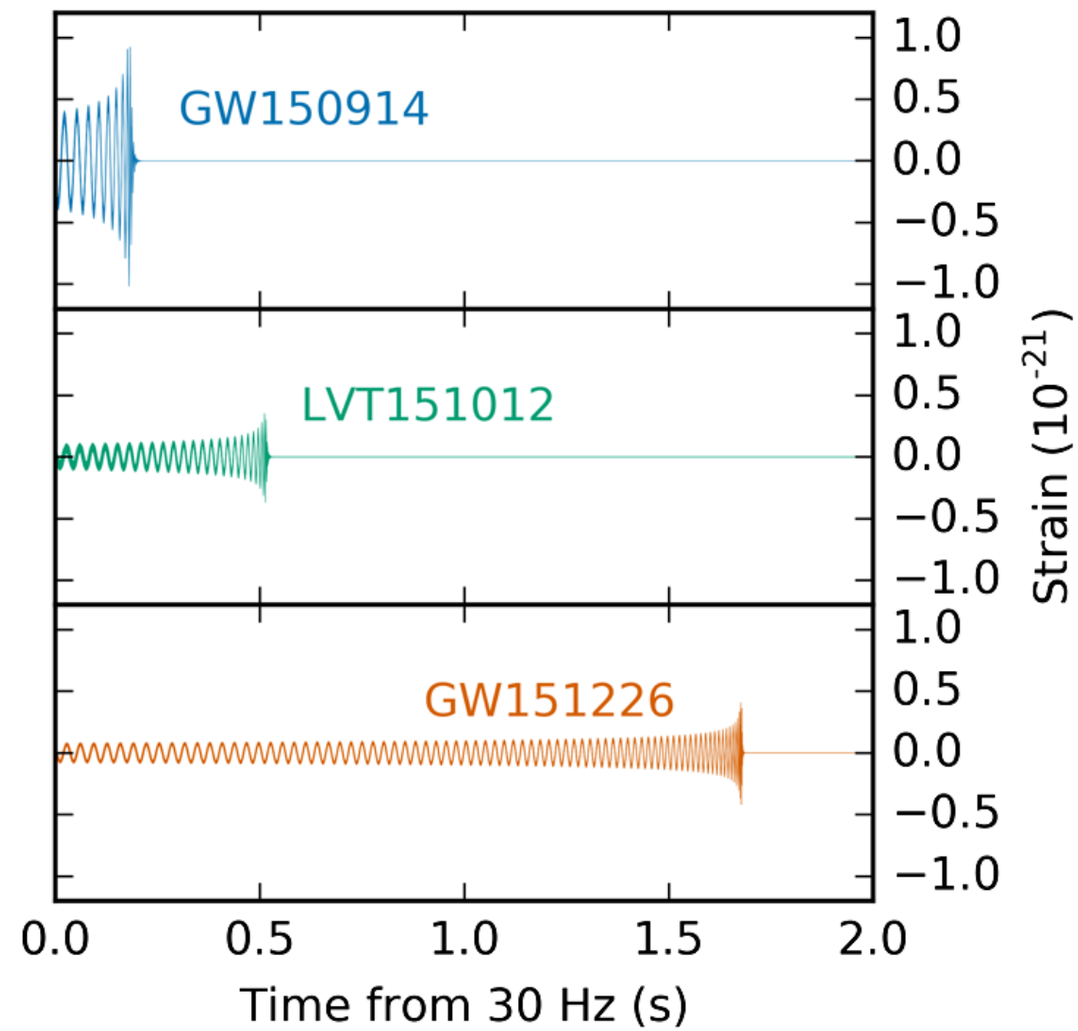
BBHs in O1

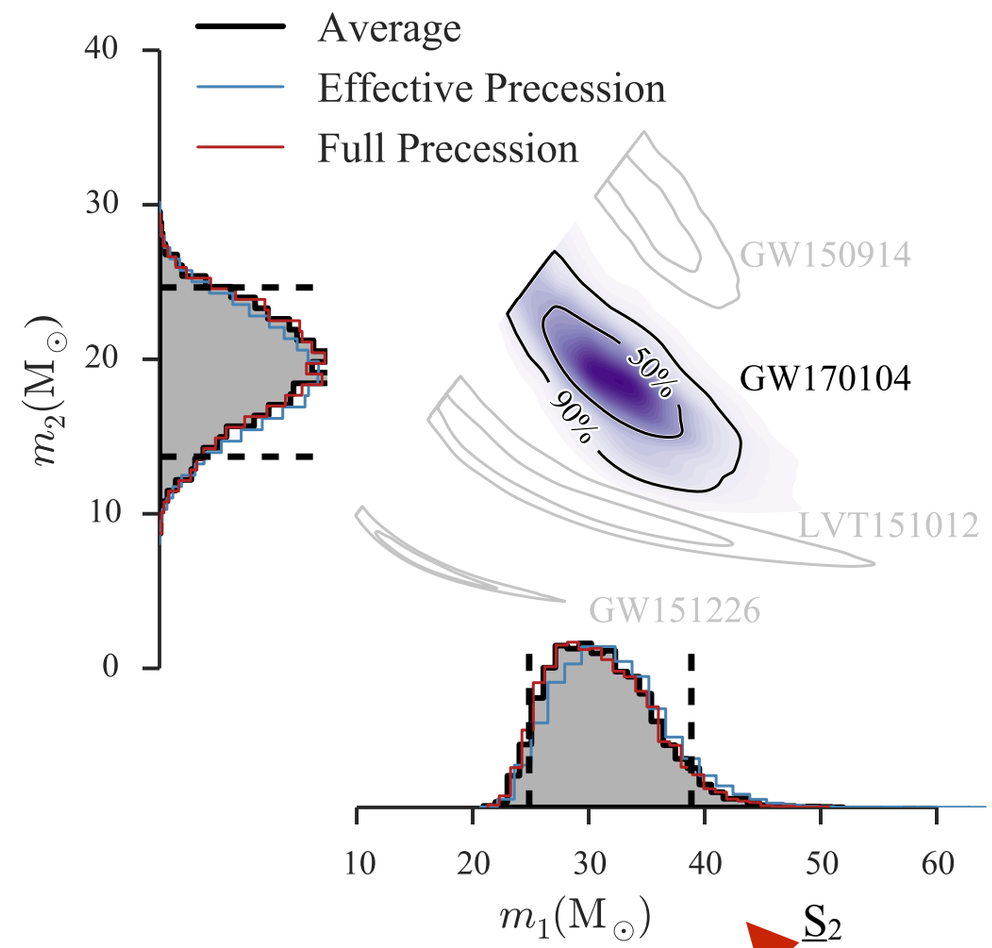
- 2 clear detections and a likely third (LVT)
- Established population of coalescing BBH with component masses up to ~36 $M_\odot$
  - Clear these would form a large fraction of GW detections
- Enabled novel EM followups, population studies, tests of GR, …
- Prompted development of waveforms, NR, …
- But I will focus on what's new since O2!

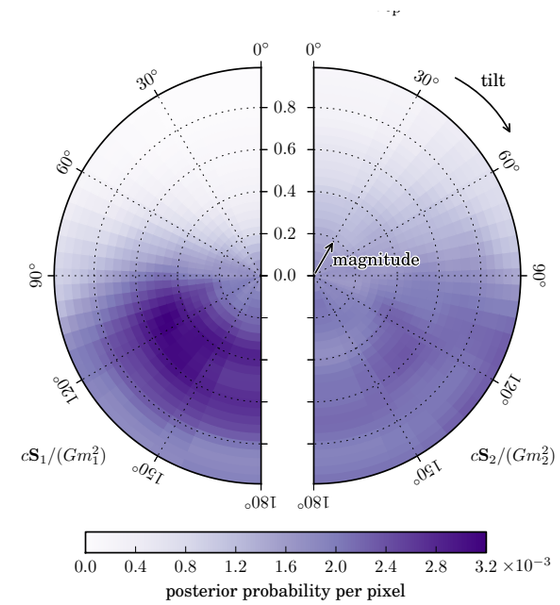


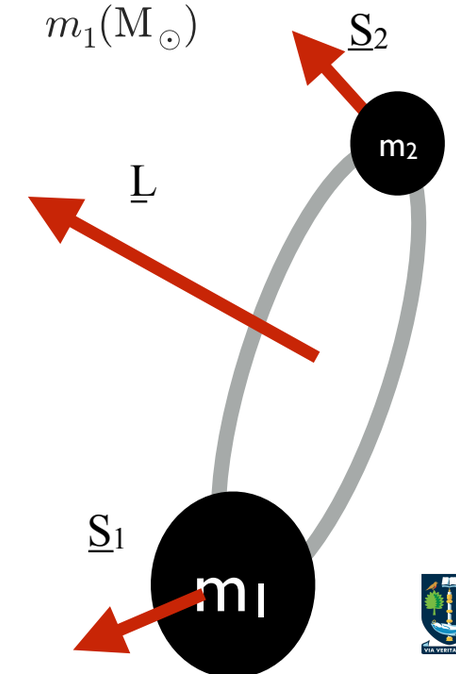
Abbott+ Phys. Rev. X 6, 041015

GW170104

- 50 $M_\odot$ total mass
  - sits between masses of O1 events
- 880Mpc (z~0.2)
  - most distant BBH
  - stringent tests of $m_{graviton}$ through dispersion
- Spins likely not positively aligned (although could be non-spinning)
- `LVC 2017 1706.01812`

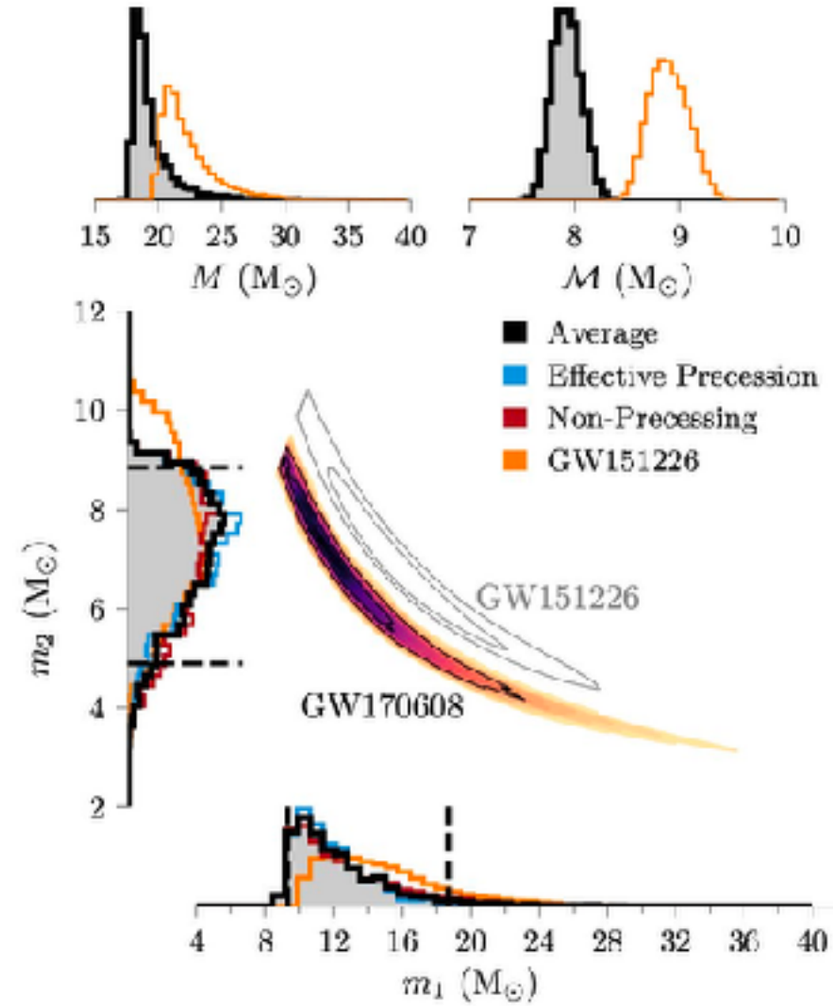


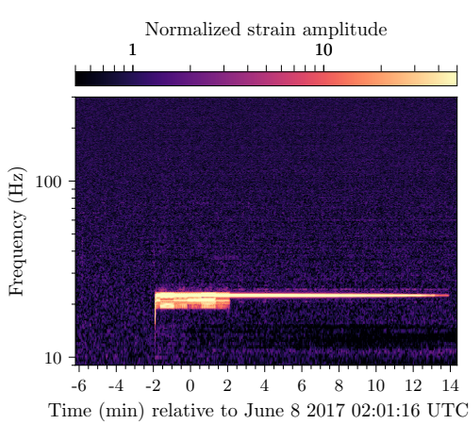


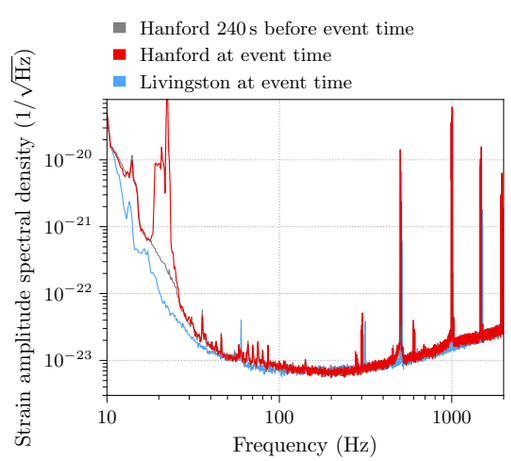


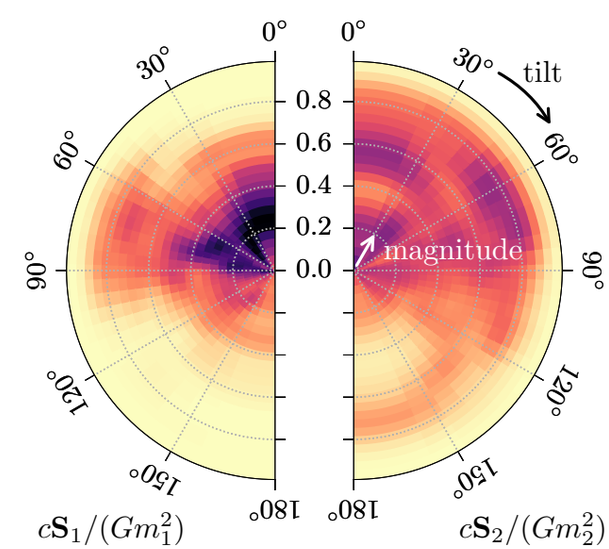
GW170608

- Lightest binary BH yet discovered
  - ~12 + 7 $M_\odot$
  - *Comparable with galactic BH systems known from X-ray observations*
- ~1 M_{sun} radiated as GW energy
- Distance: 340 Mpc (z~0.07)
- Detected during time when Hanford being commissioned
- See arXiv:1711.05578 for details

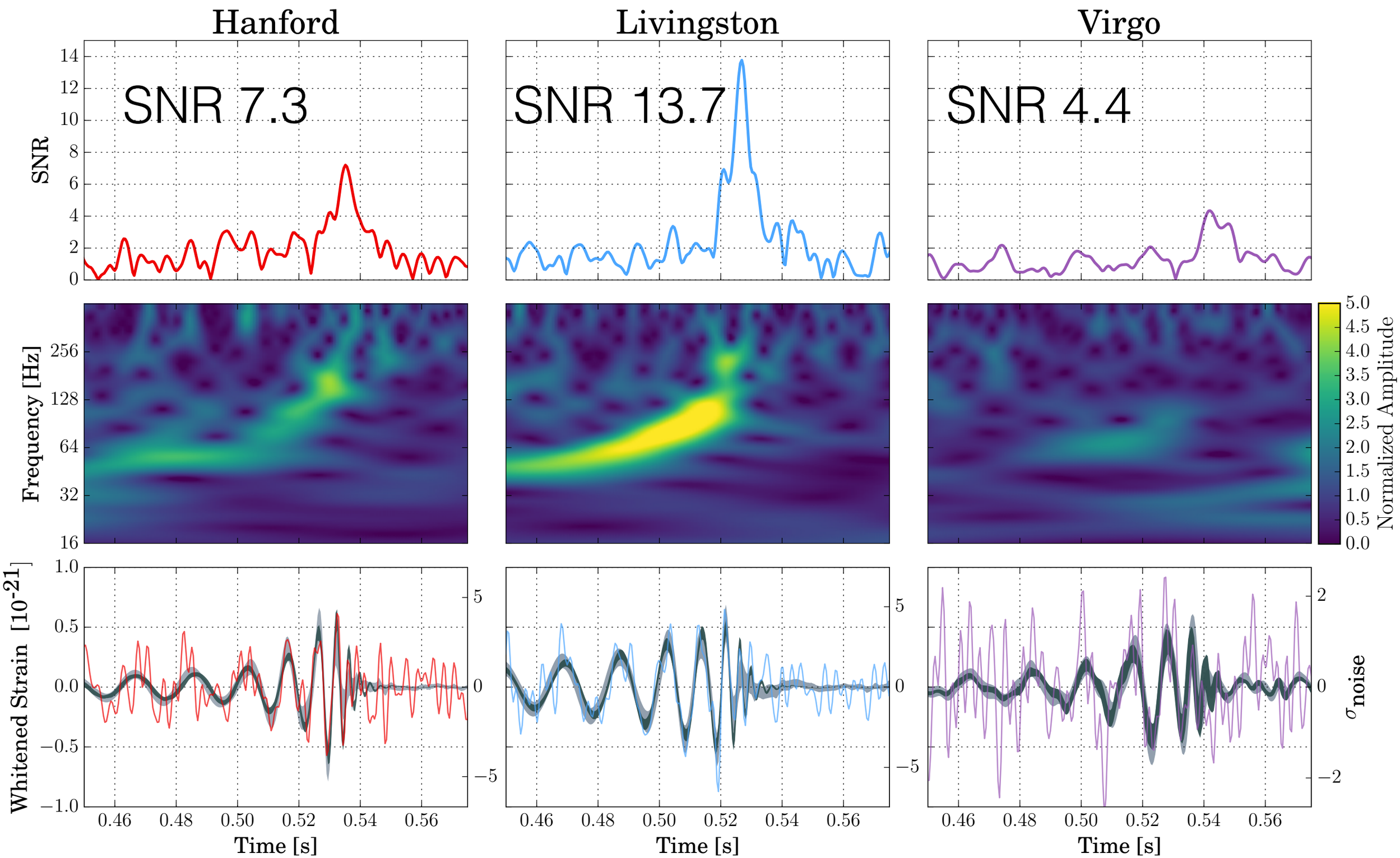








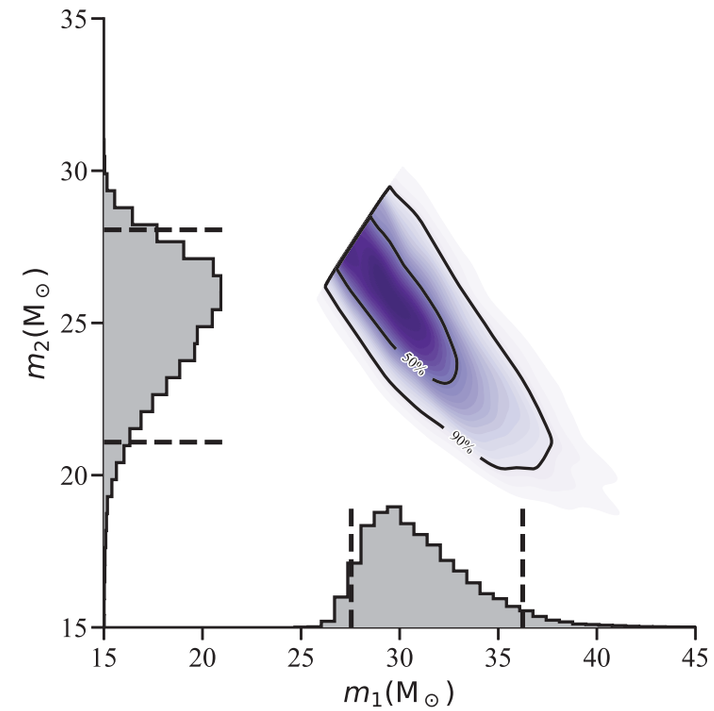
GW170814

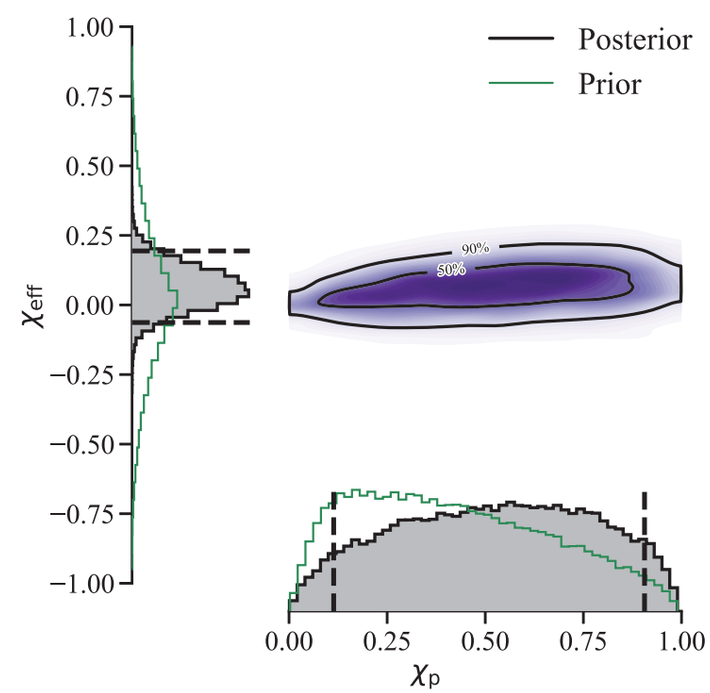


LVC PRL **119** (2017)

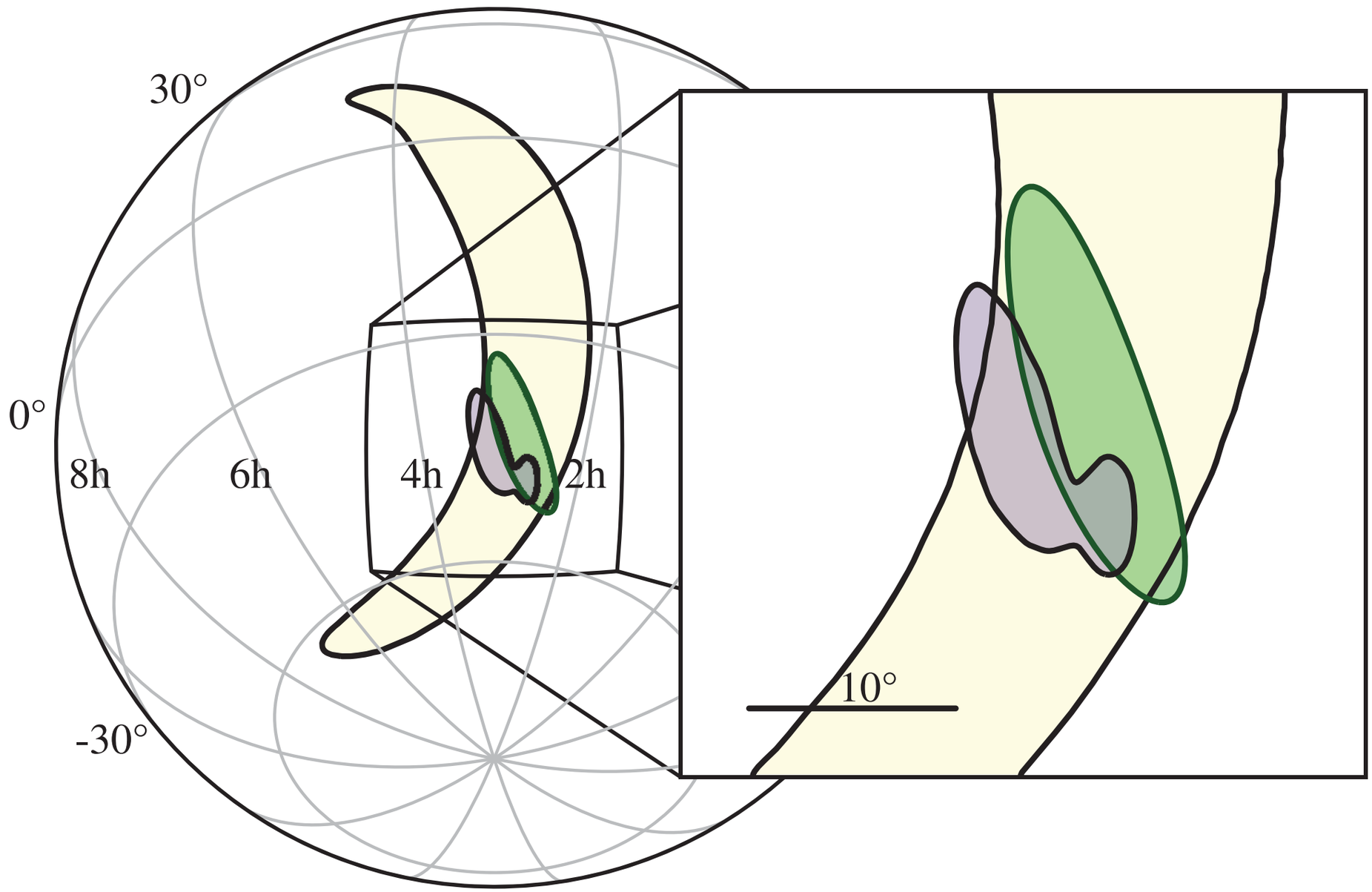
GW170814

- $M_{tot} \sim 56\ M_\odot$
- $d_L \sim 540$Mpc ($z \sim 0.11$)
- Poor constraint on spin tilts
- But novel checks of GW polarisation states
- `LVC PRL 119 (2017)`





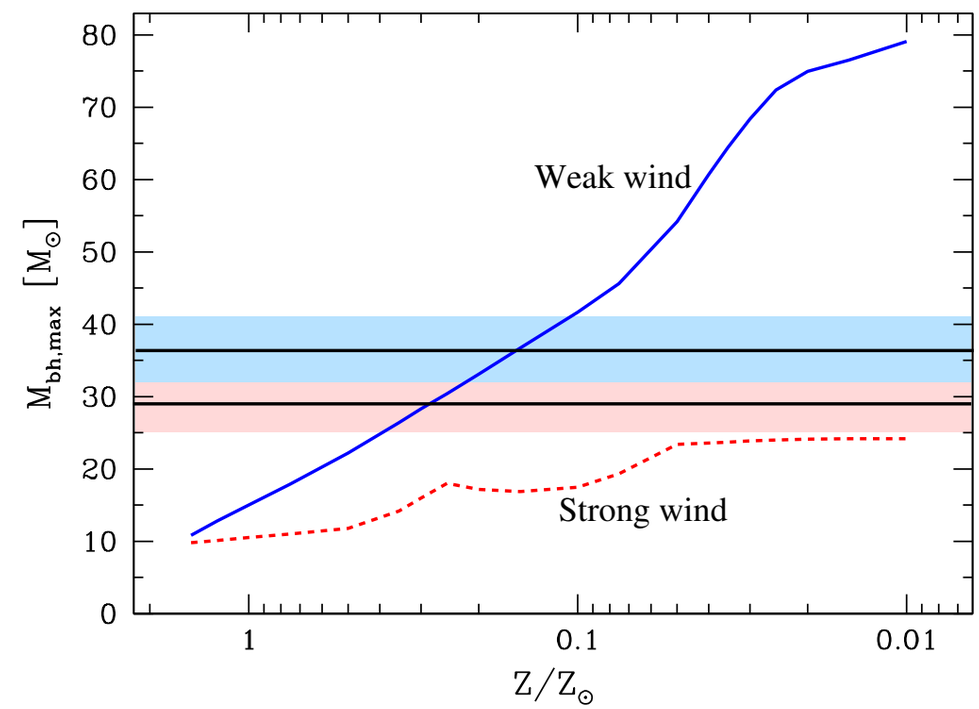
GW170814



LVC PRL **119** (2017)

Black Hole Astrophysics

- Know now that “heavy” Binary Black Holes exist in nature
- LIGO BBHs tend to be heavier than BH in X-ray Binaries
  - Down to selection effects?
  - Why are spins so different?
- How are massive BHs formed?
- What is are the limits of stellar BH masses?

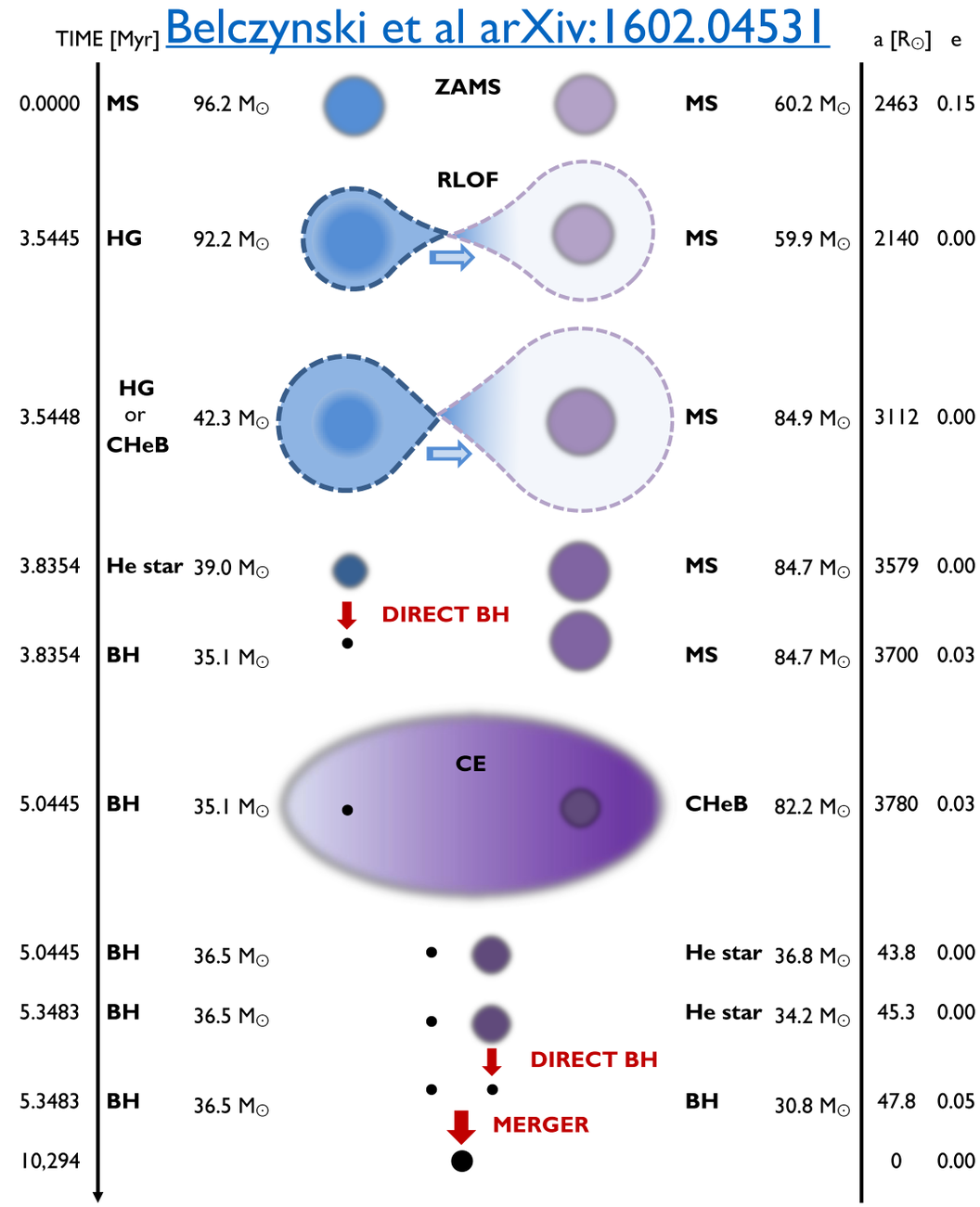


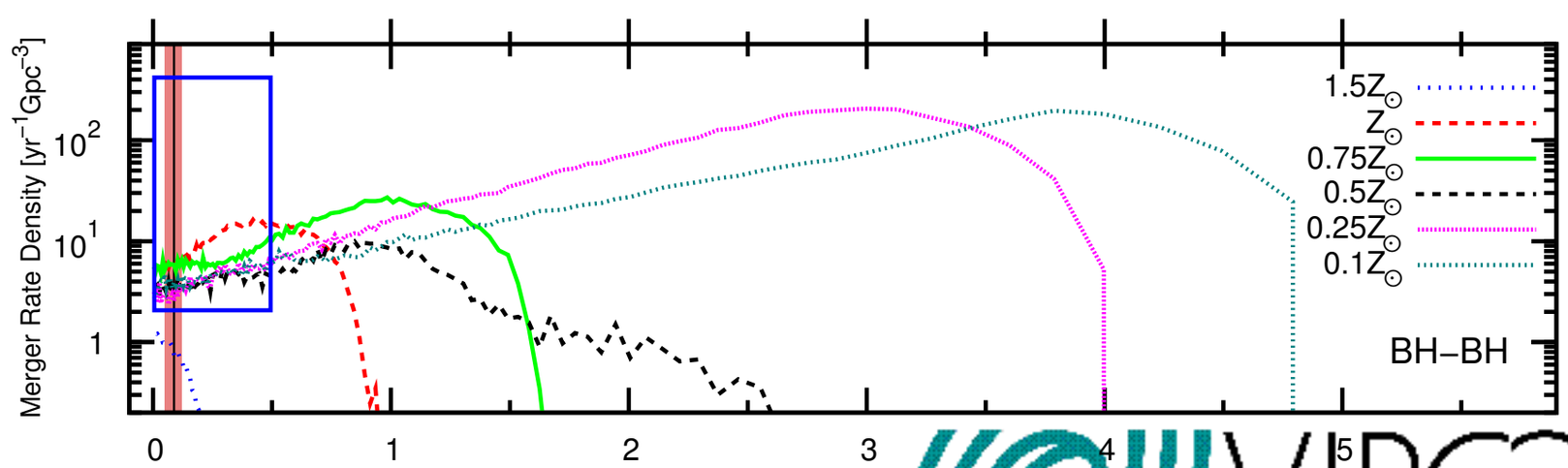
LVC, Astrophysical Implications of binary BH merger GW150914, Ap.J.Lett. 818 2 (2016)

LSC VIRGO University of Glasgow

Field Binaries

- Typical life-cycle (>90% BBH progenitors)
  - Mass transfer 1
  - Core collapse 1
  - Mass transfer 2 (Common envelope)
  - Core collapse 2
  - GW-driven inspiral
- Affected by: IMF, mass-loss, mass transfer, tides, common envelope, SN kicks
- Age?
  - Pop III binary / long merger time





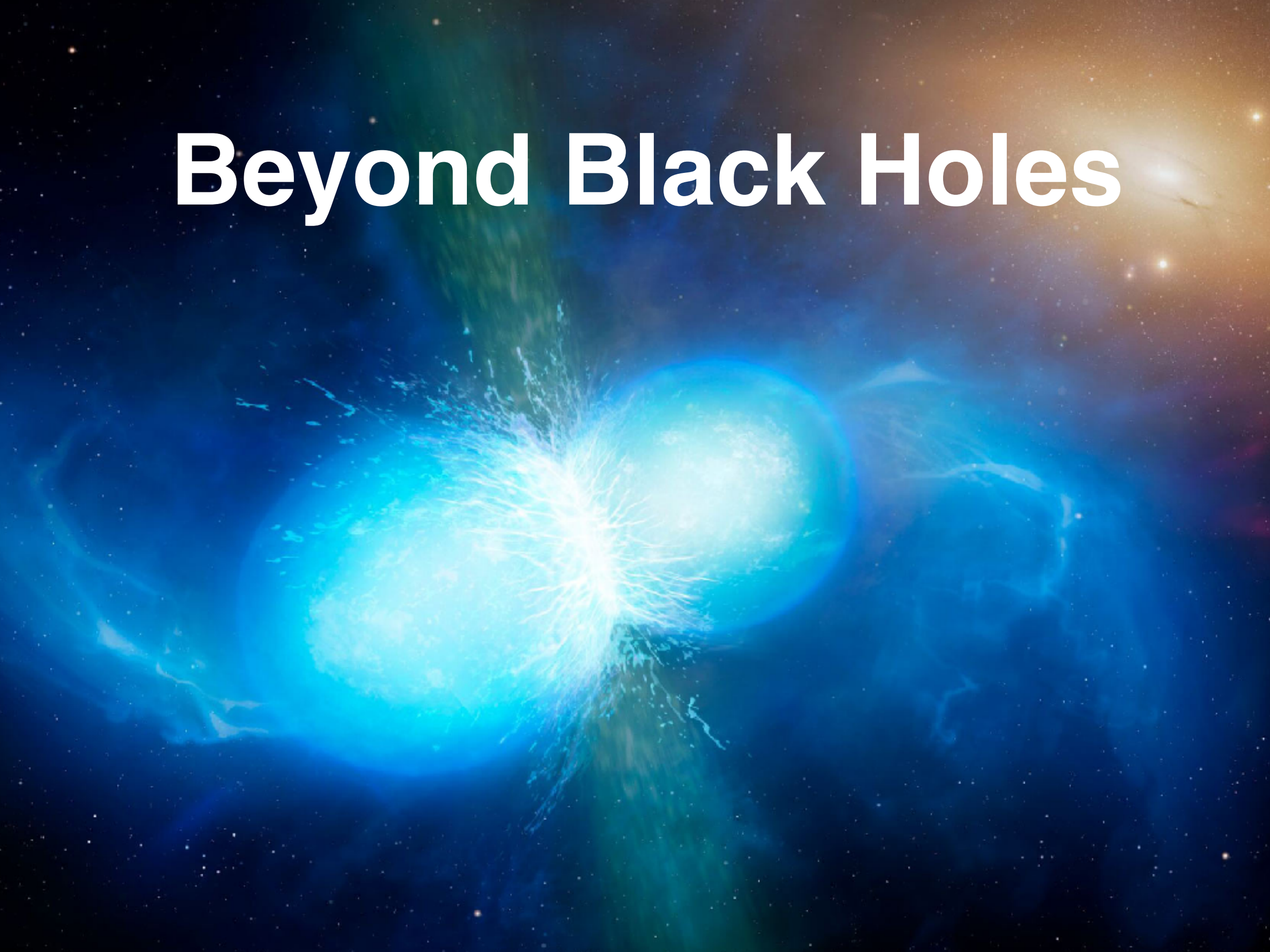
Ap.J.Lett. 818 2 (2016)

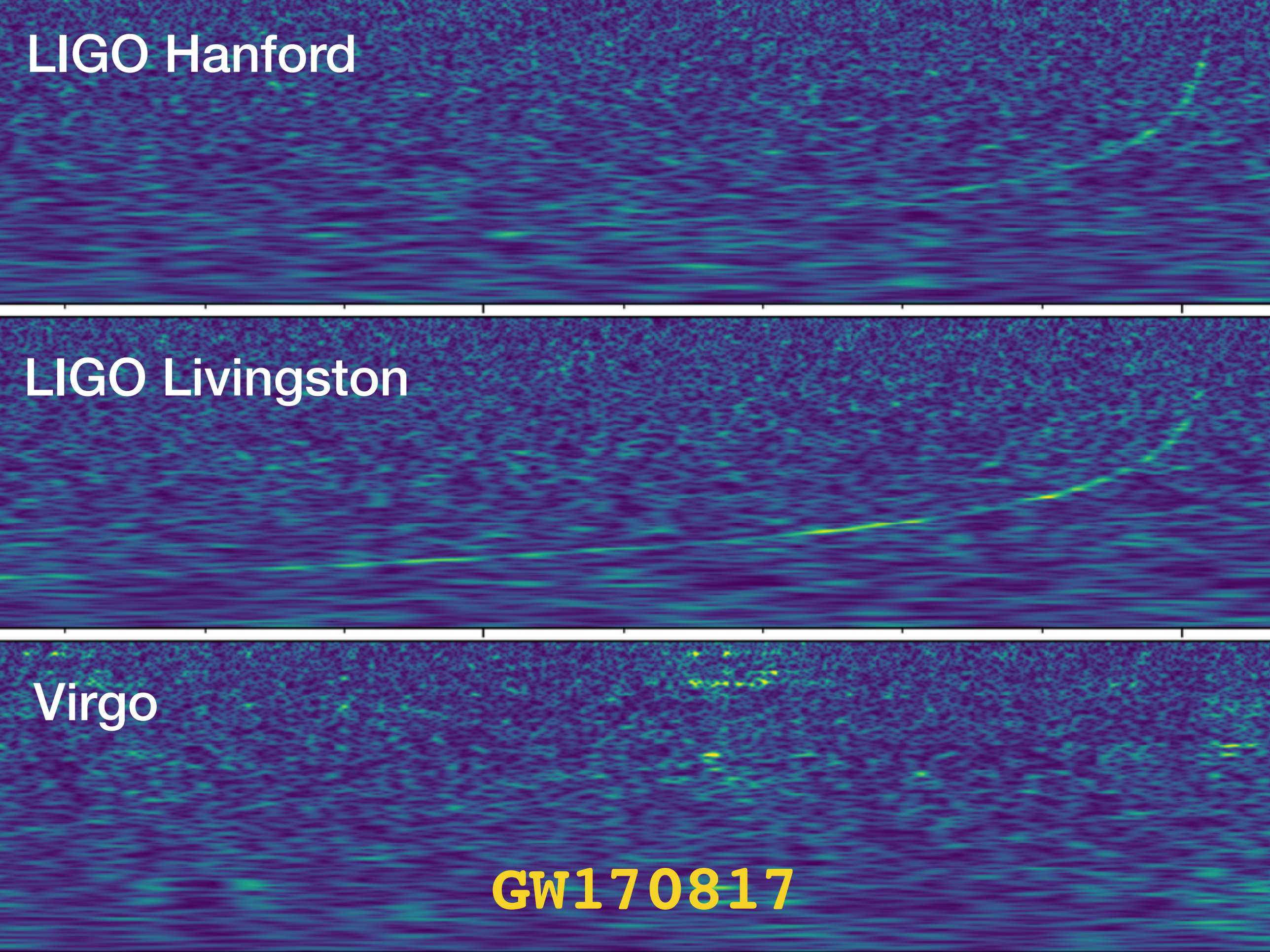
Dynamical Capture

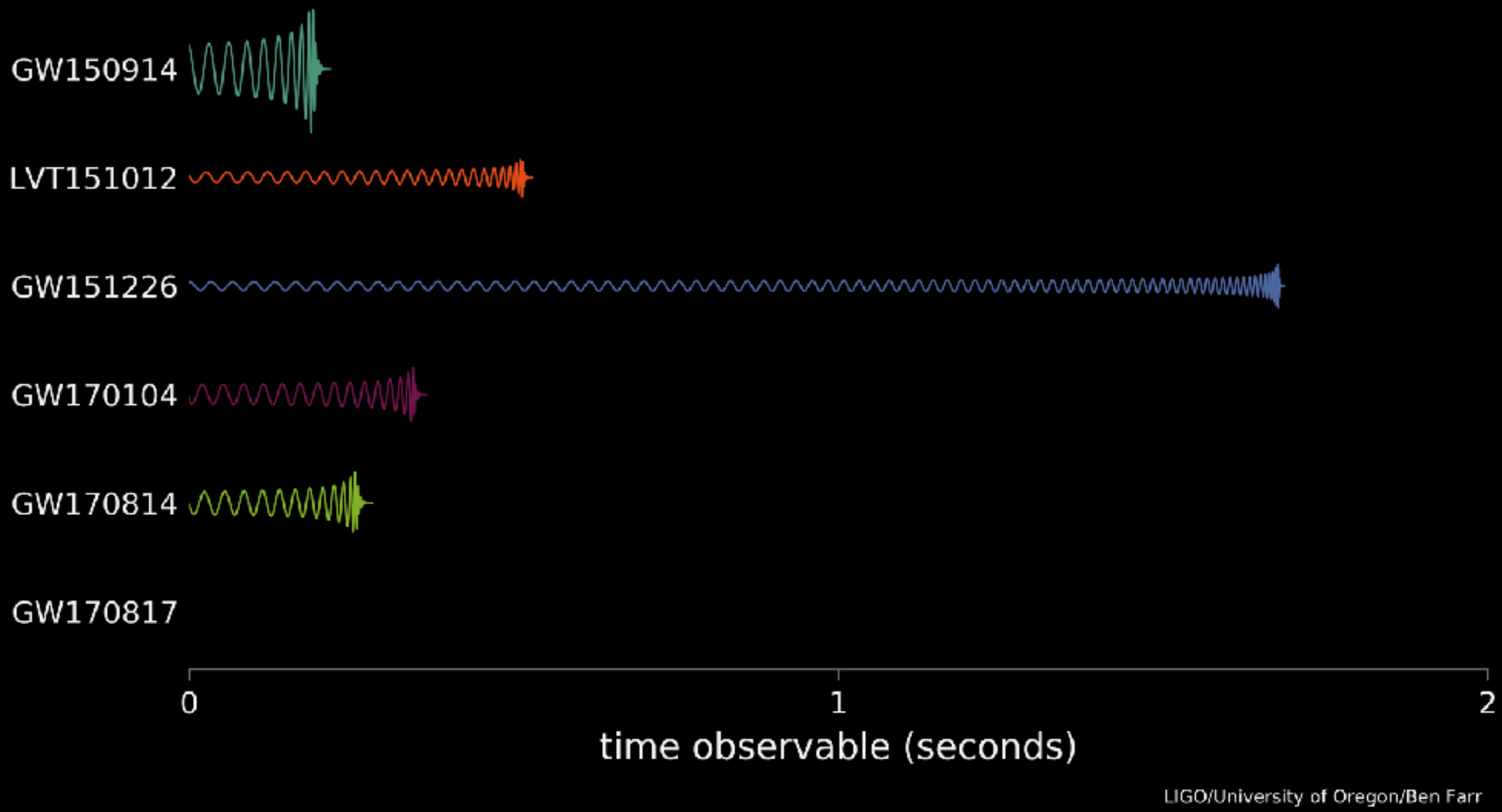
- Globular cluster or galactic centre
- Dense stellar environments → 3 body interactions
  - More massive pair end up in binary
  - BBH usually ejected from cluster
- Binary often produced with high eccentricity, misaligned spins

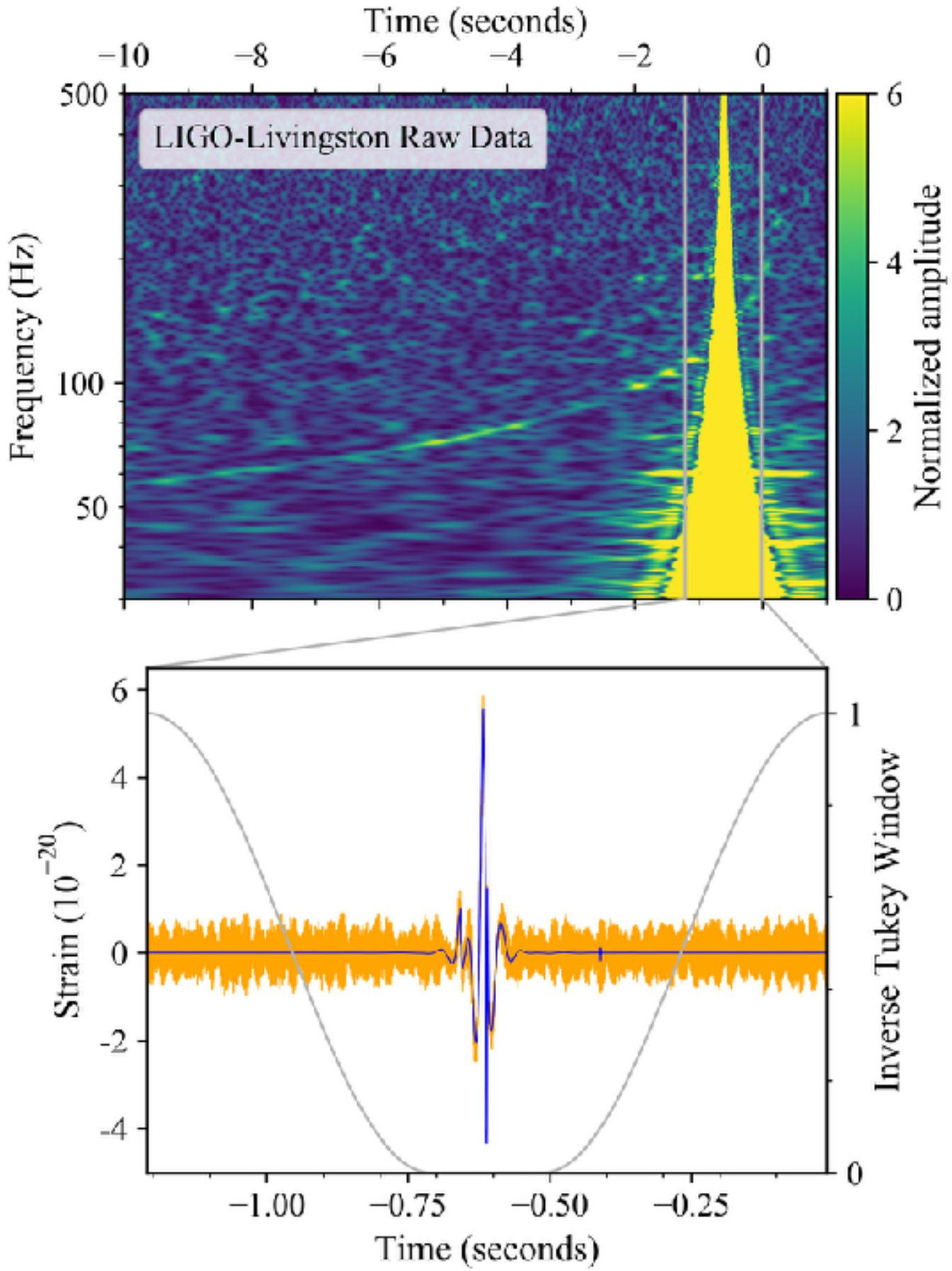
Ap.J.Lett. 818 2 (2016)

Beyond Black Holes



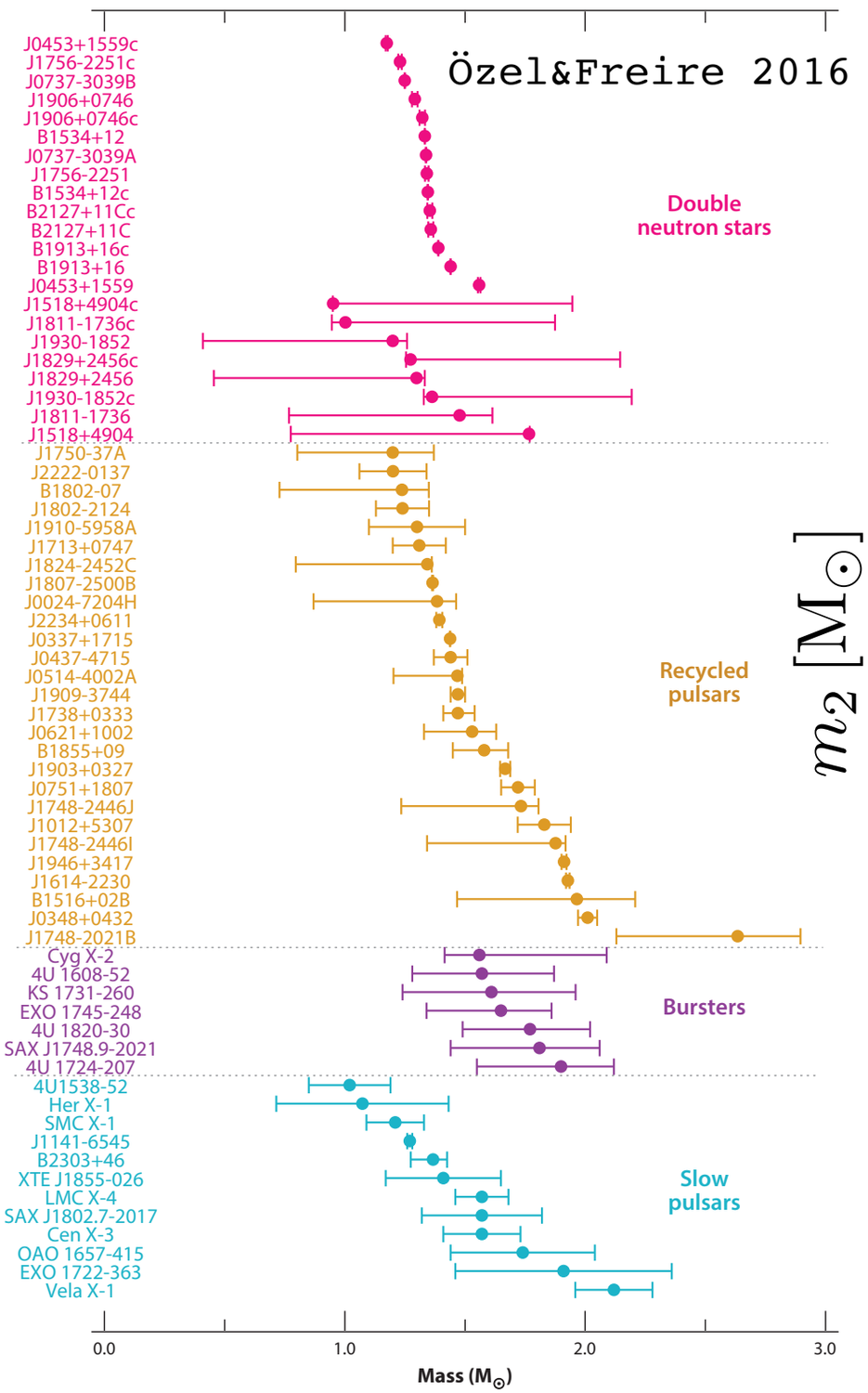

LIGO Hanford
LIGO Livingston
Virgo
GW170817

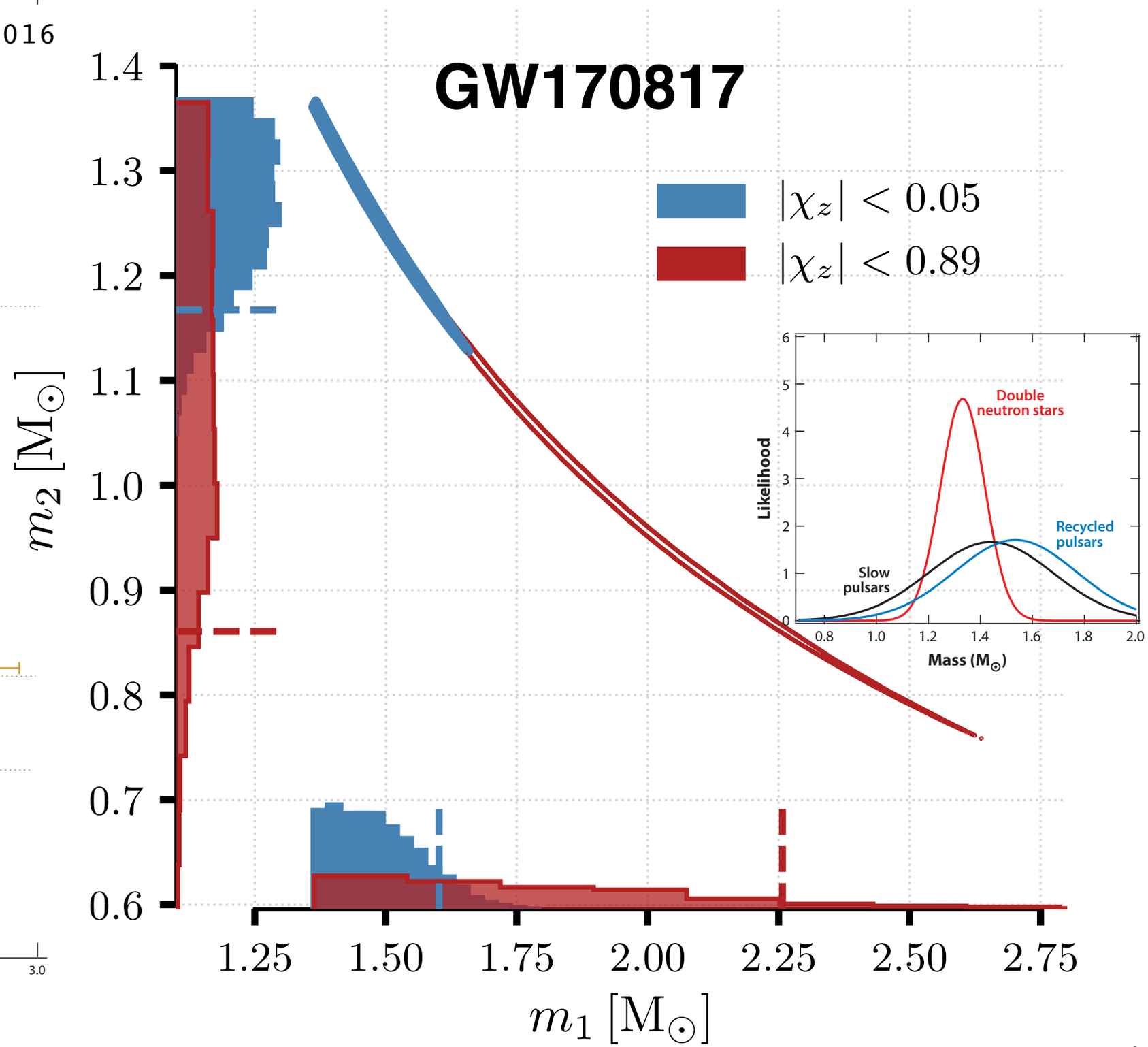

GW150914
LVT151012
GW151226
GW170104
GW170814
GW170817
0
1
2
time observable (seconds)
LIGO/University of Oregon/Ben Farr



Abbott+ PRL 119, 161101 (2017)

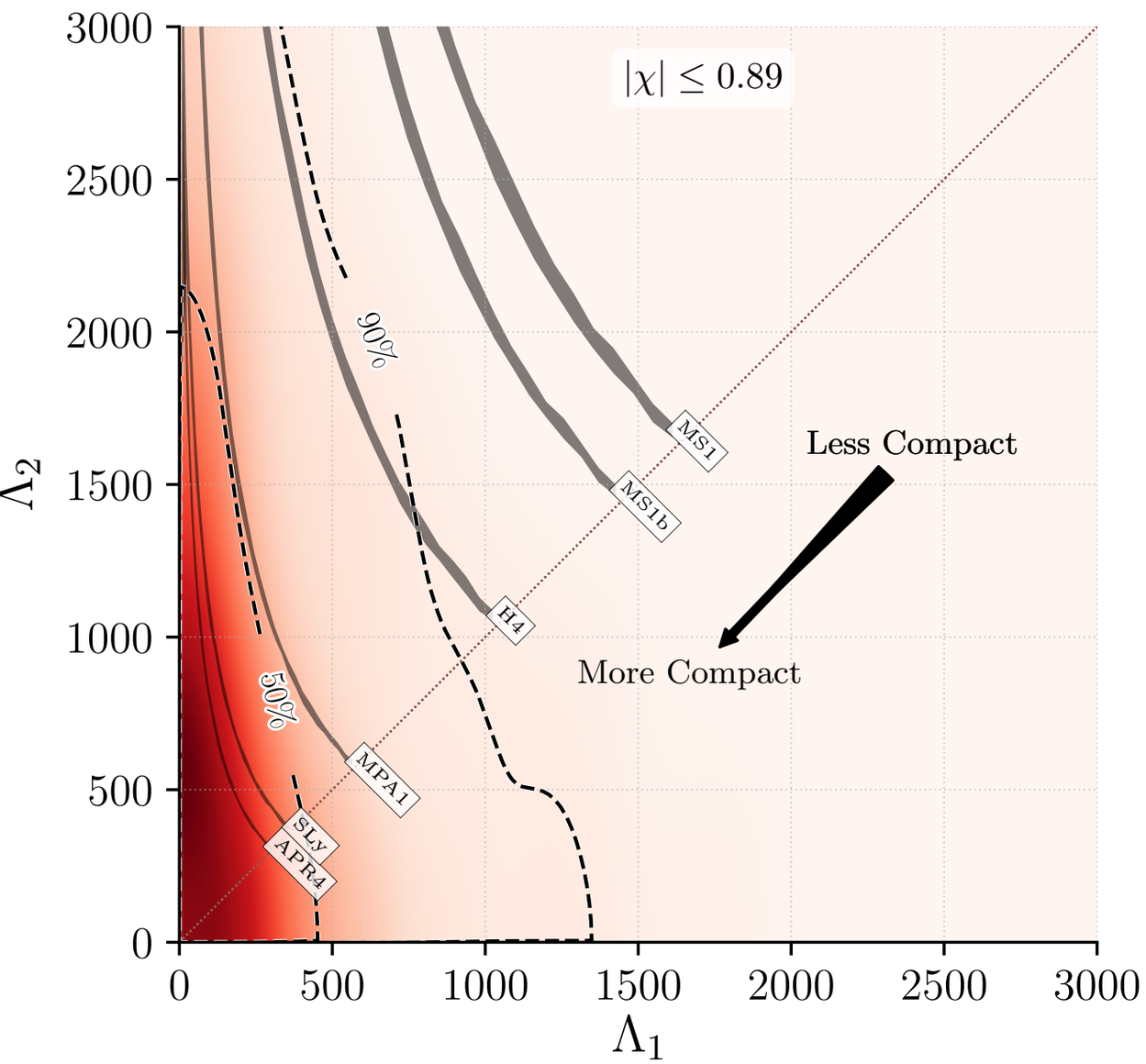
Neutron star masses

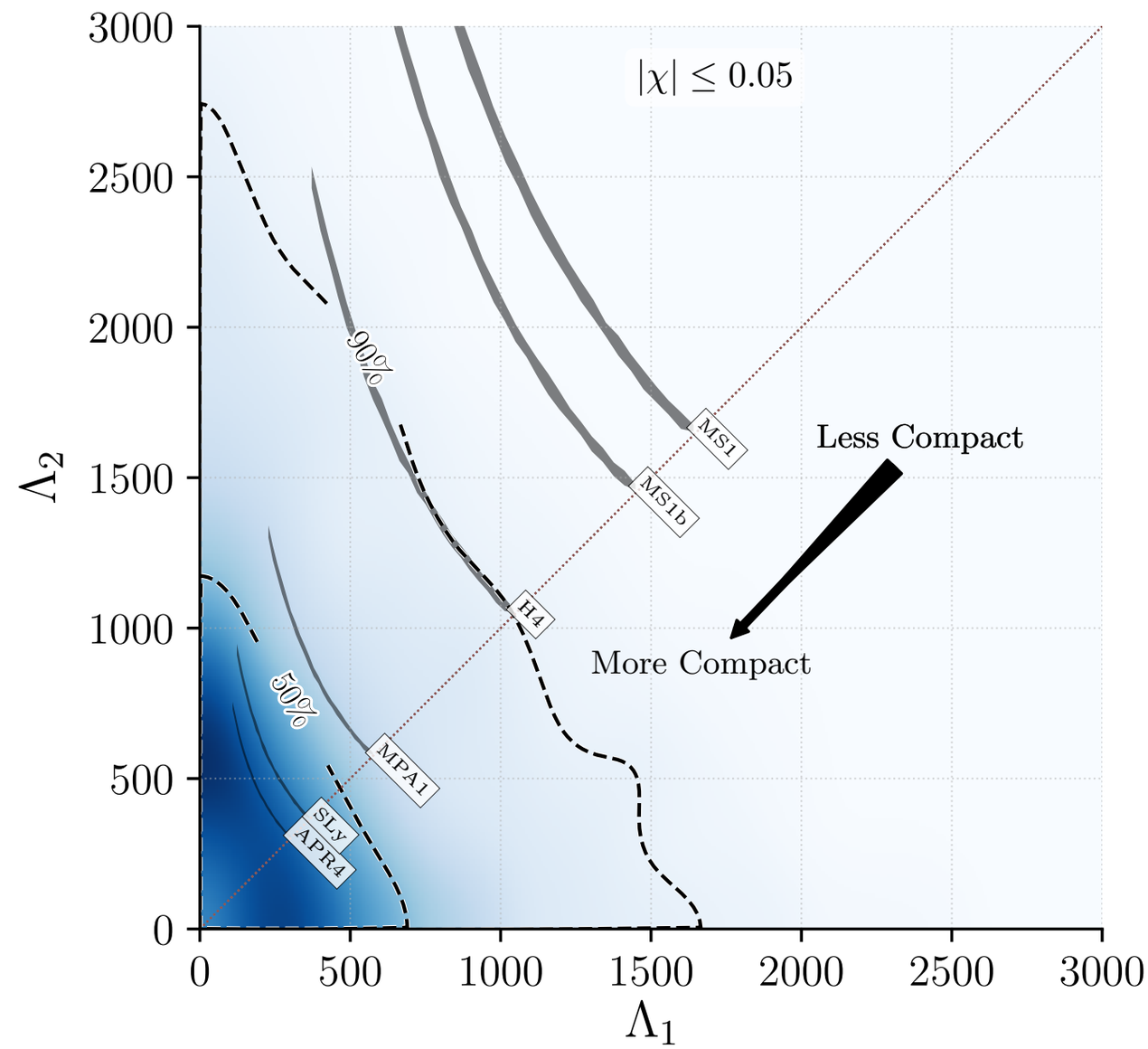




Abbott+ PRL 119, 161101 (2017)

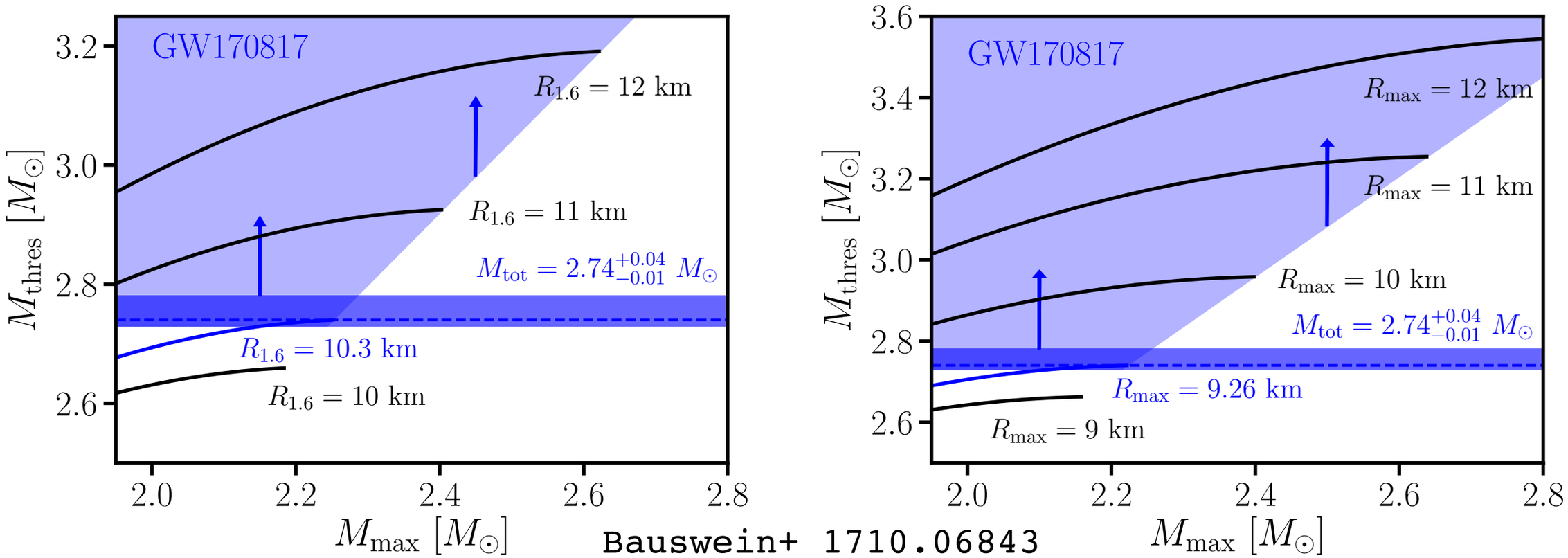
Neutron Star Equation of State





Abbott+ PRL 119, 161101 (2017)

Remnant

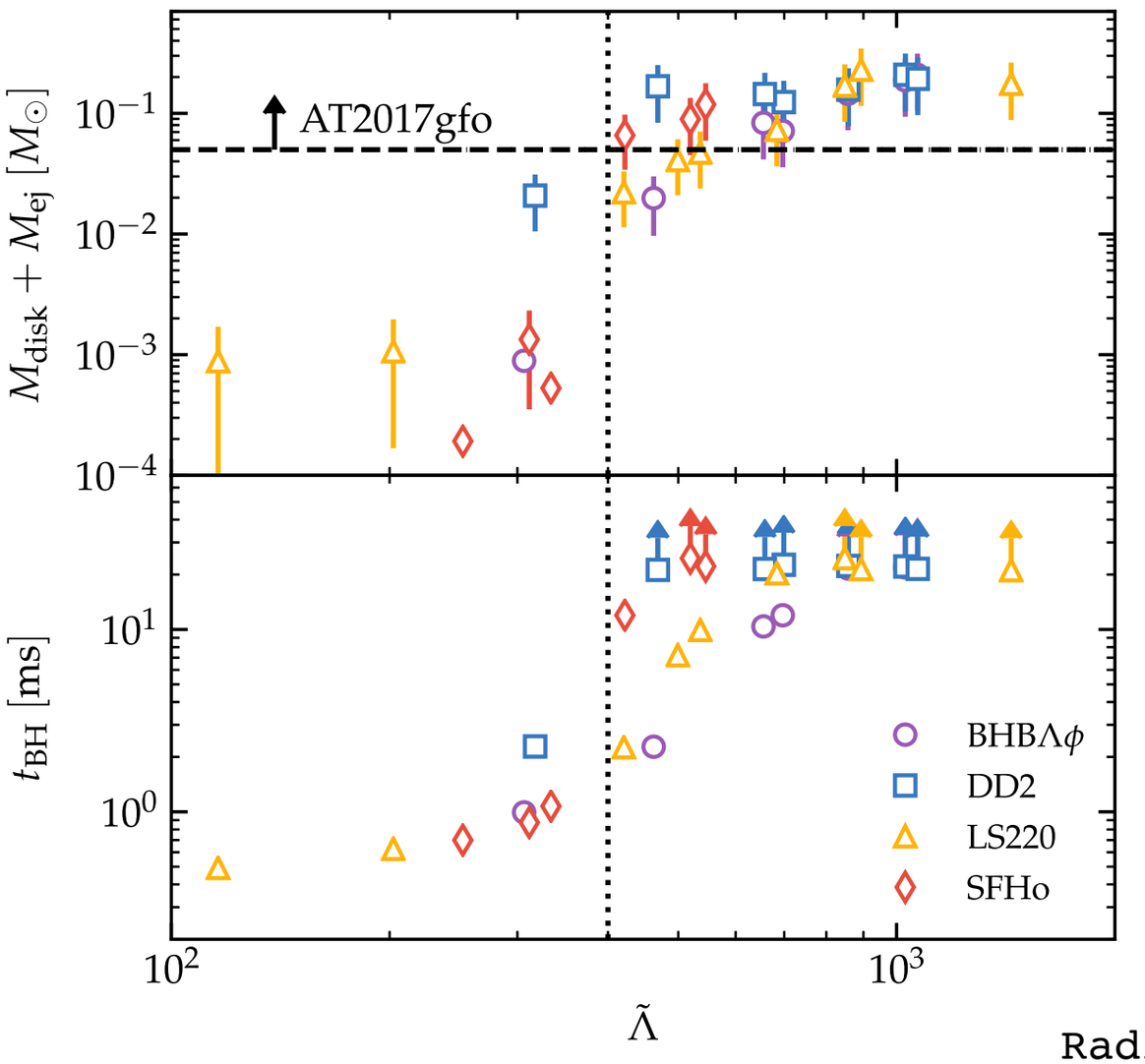


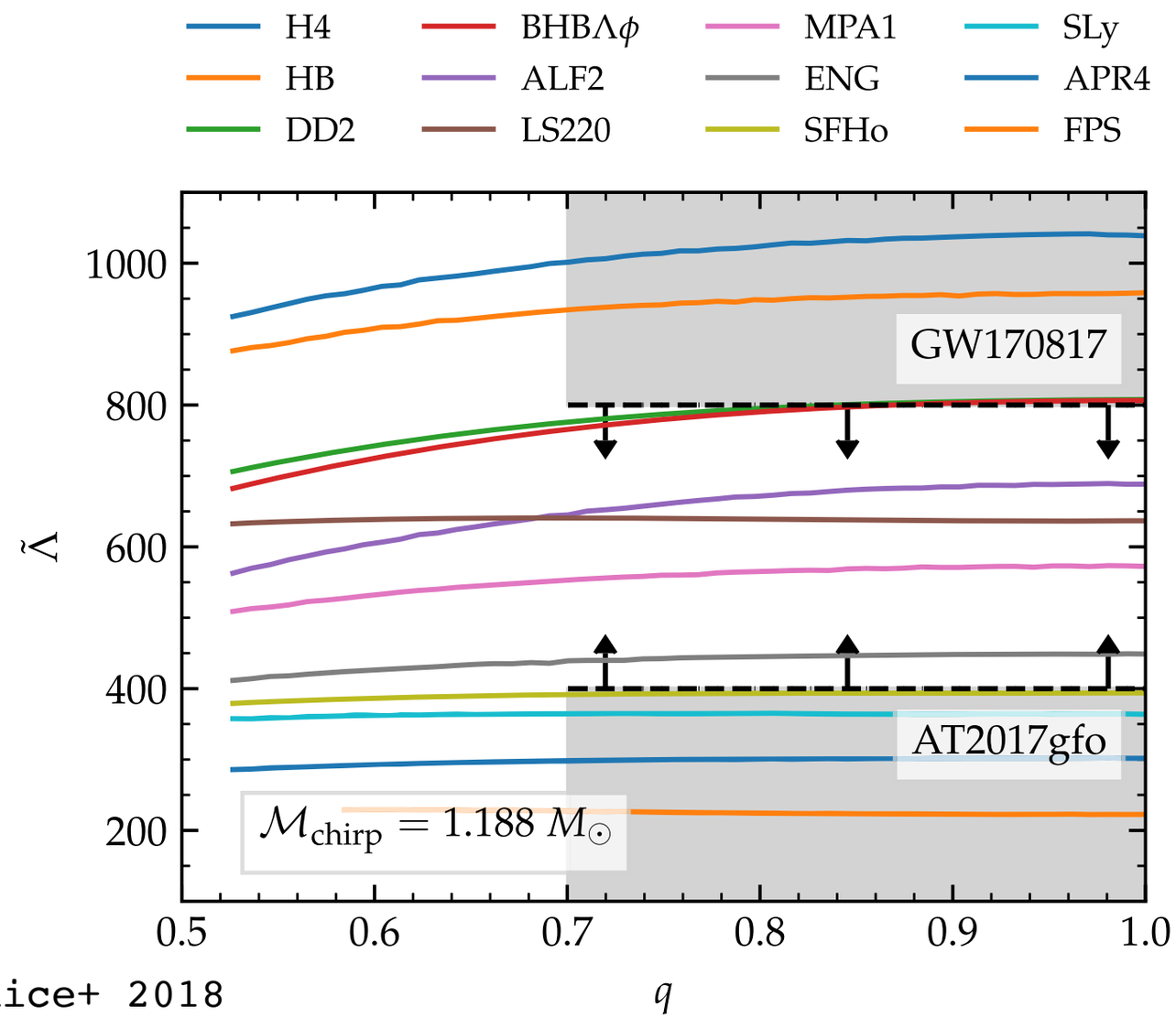
Bauswein+ 1710.06843

After collision, what happens to remnant?

- Low stiffness: prompt collapse to BH - less disk wind
- Higher stiffness: Hypermassive Neutron star exists for unknown time period (probably ~milliseconds)

Joint constraints



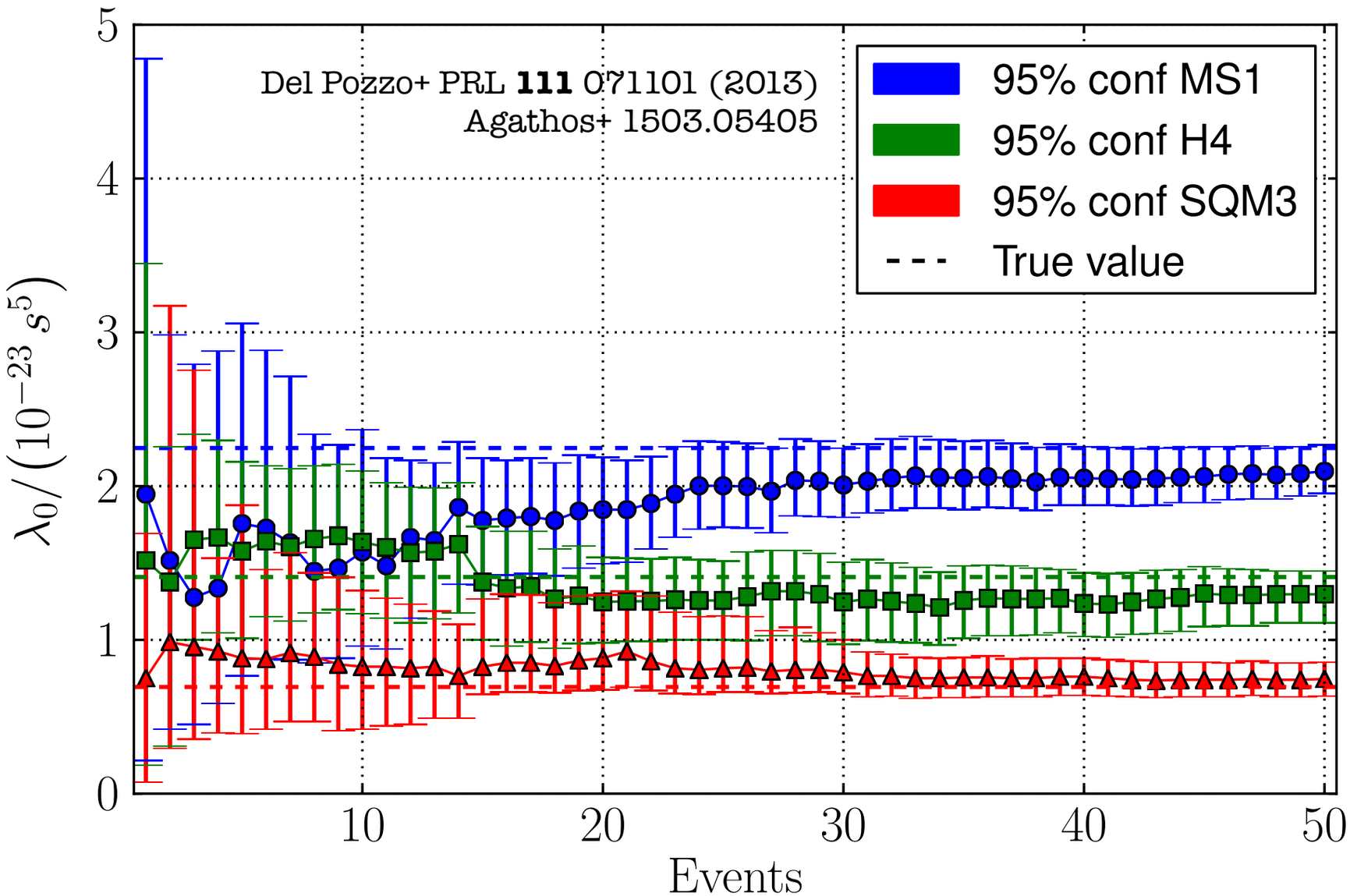


Radice+ 2018

Combine inspiral-driven upper limits with EM-driven lower limits

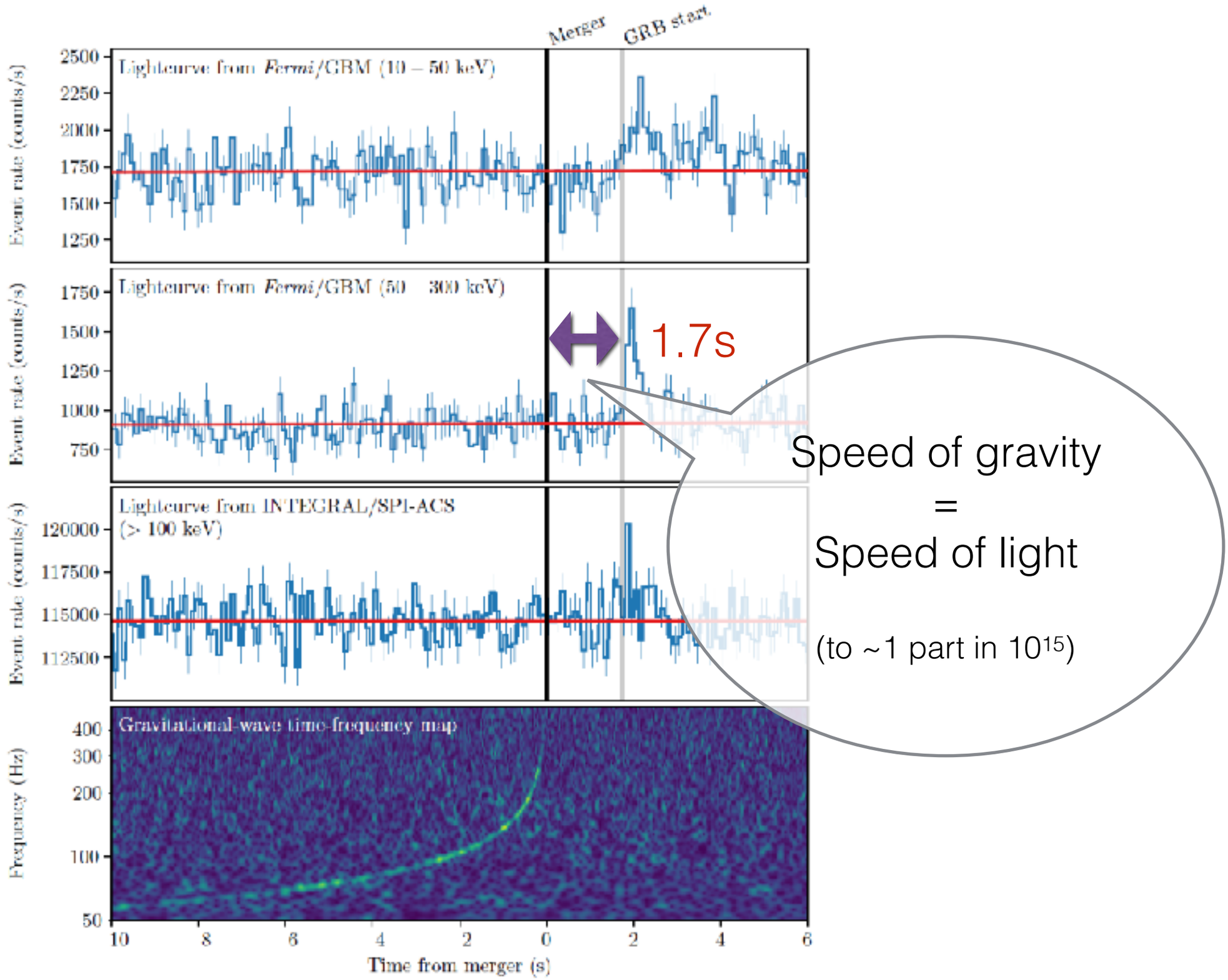
- Require ejecta+disk to form GRB
- Implies lower limit on NS radius -> stiffness

Tides - Future prospects

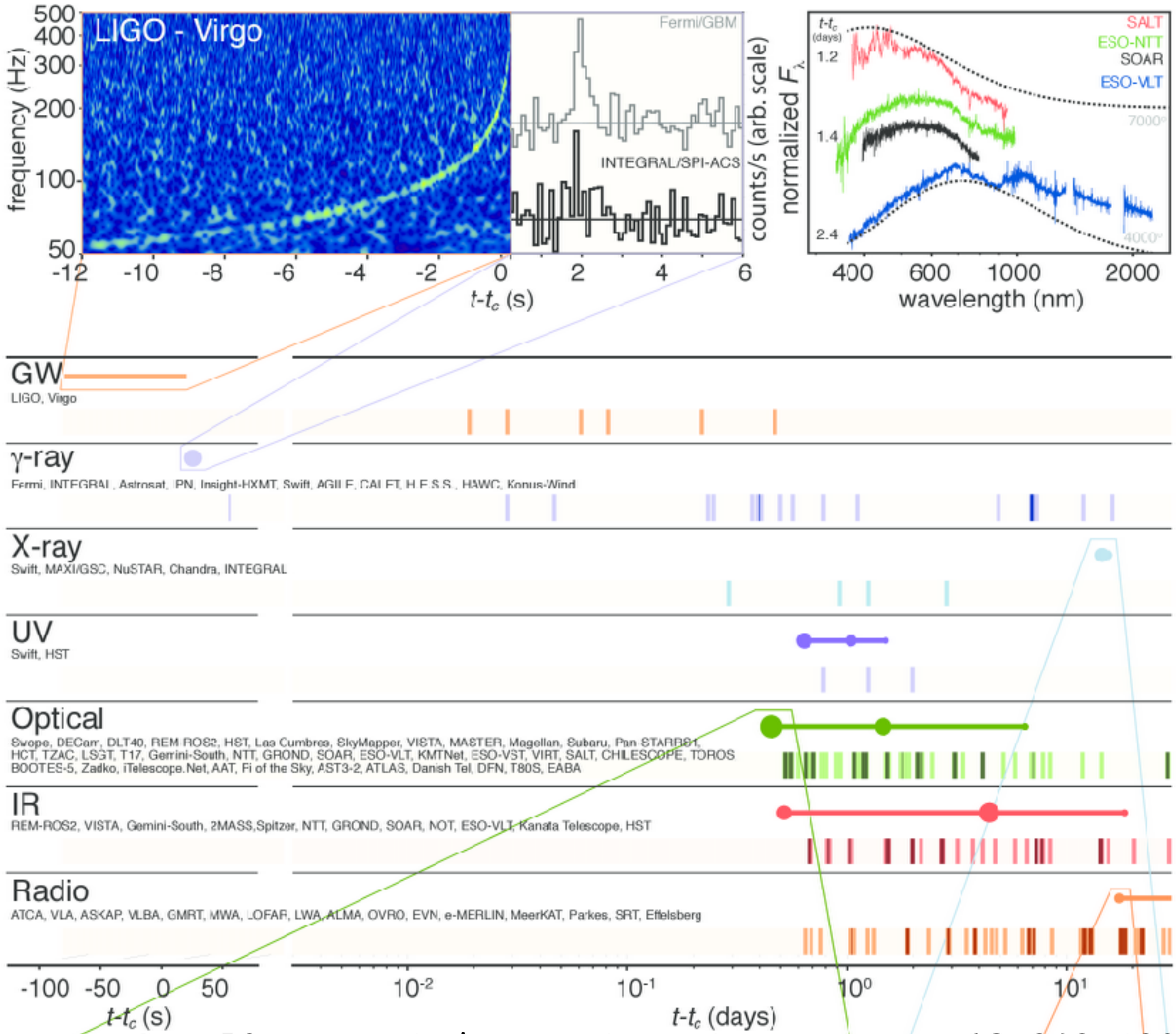


- Combine multiple events to improve precision

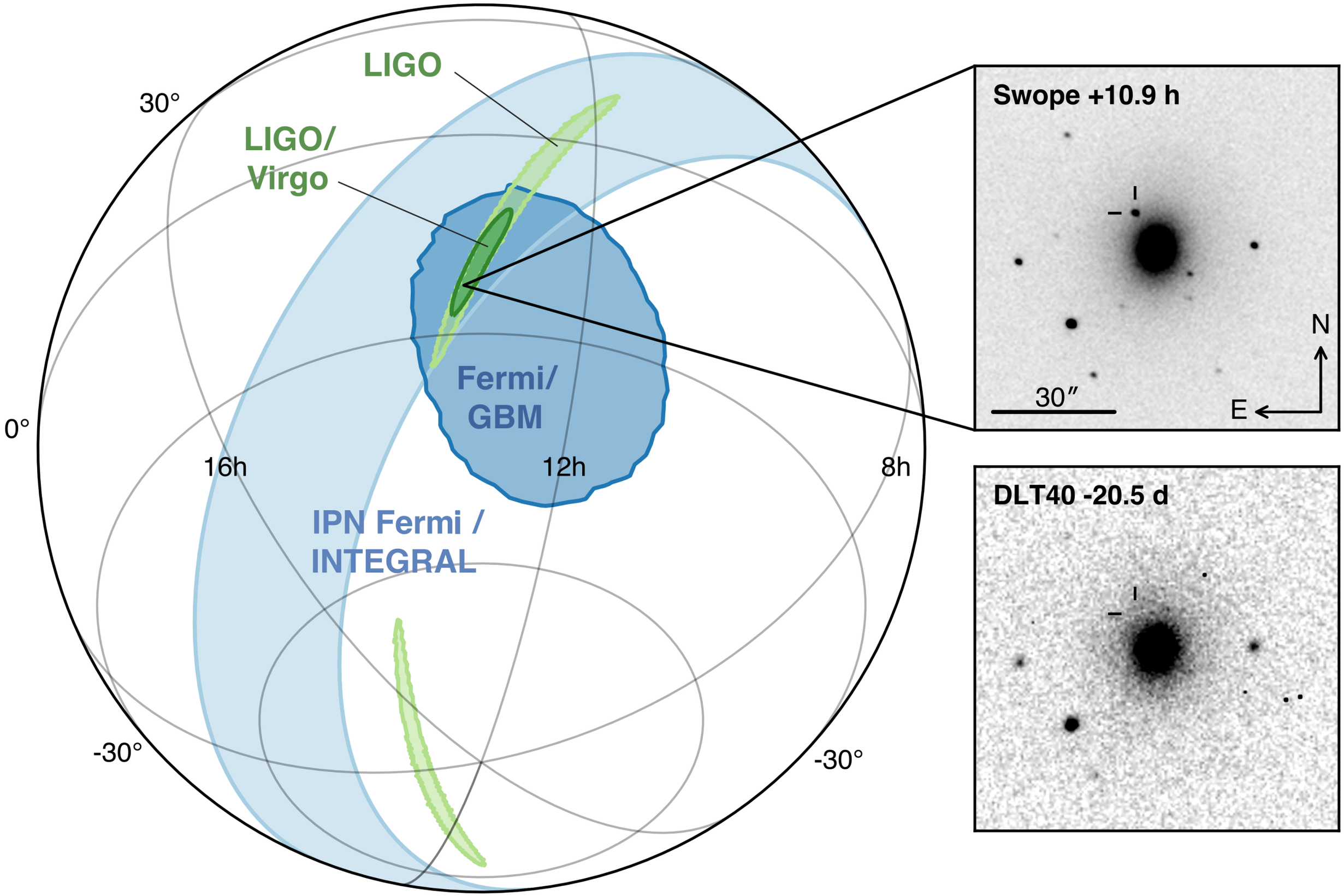
GW170817 + GRB170817A



LVC+FermiGBM+INTEGRAL, ApJ L848, 2 (2017)

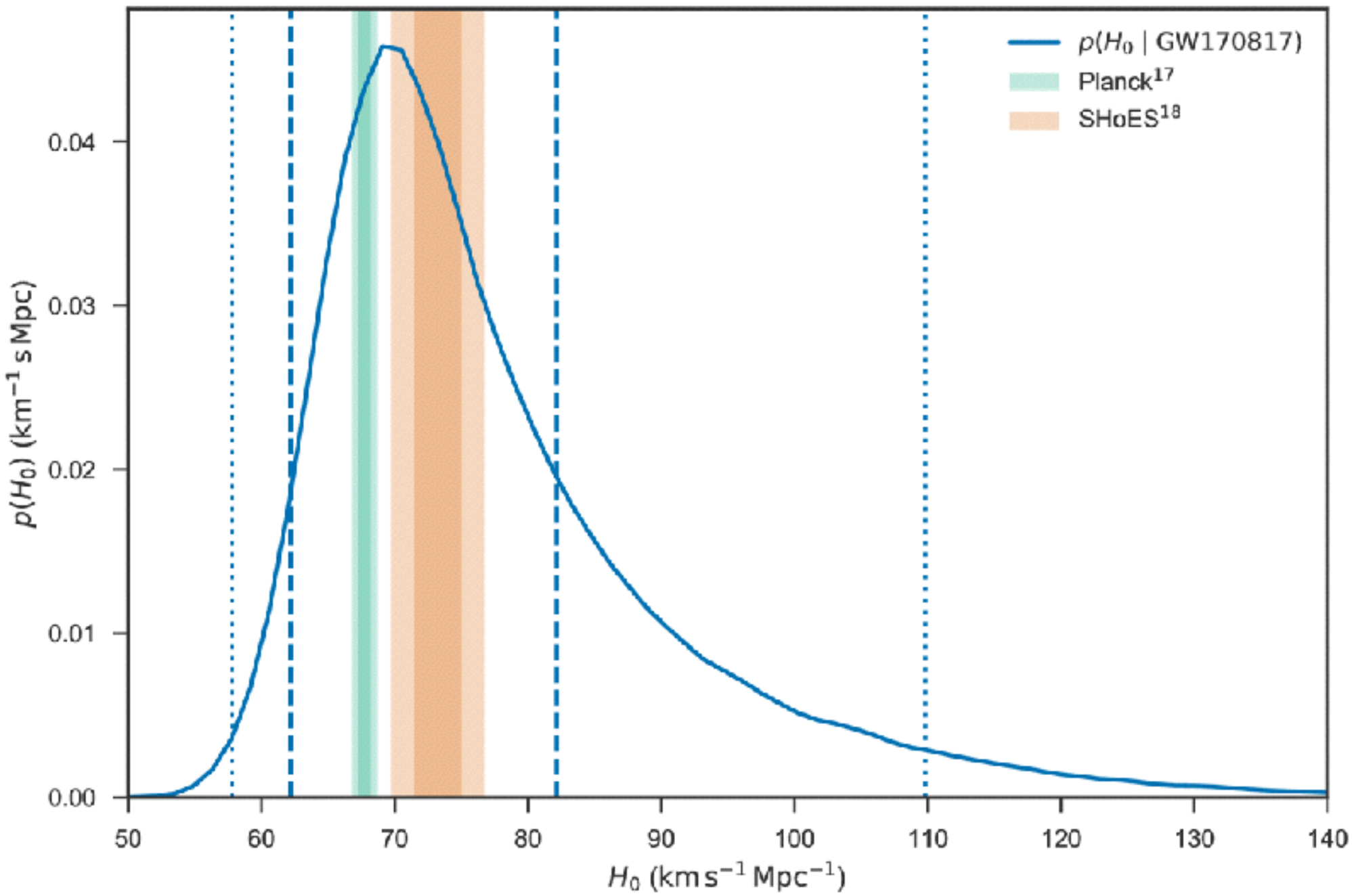


LVC + 50 EM+neutrino partner teams, ApJL **12** 848 (2017)



LVC + 50 EM+neutrino partner teams, ApJL **12** 848 (2017)

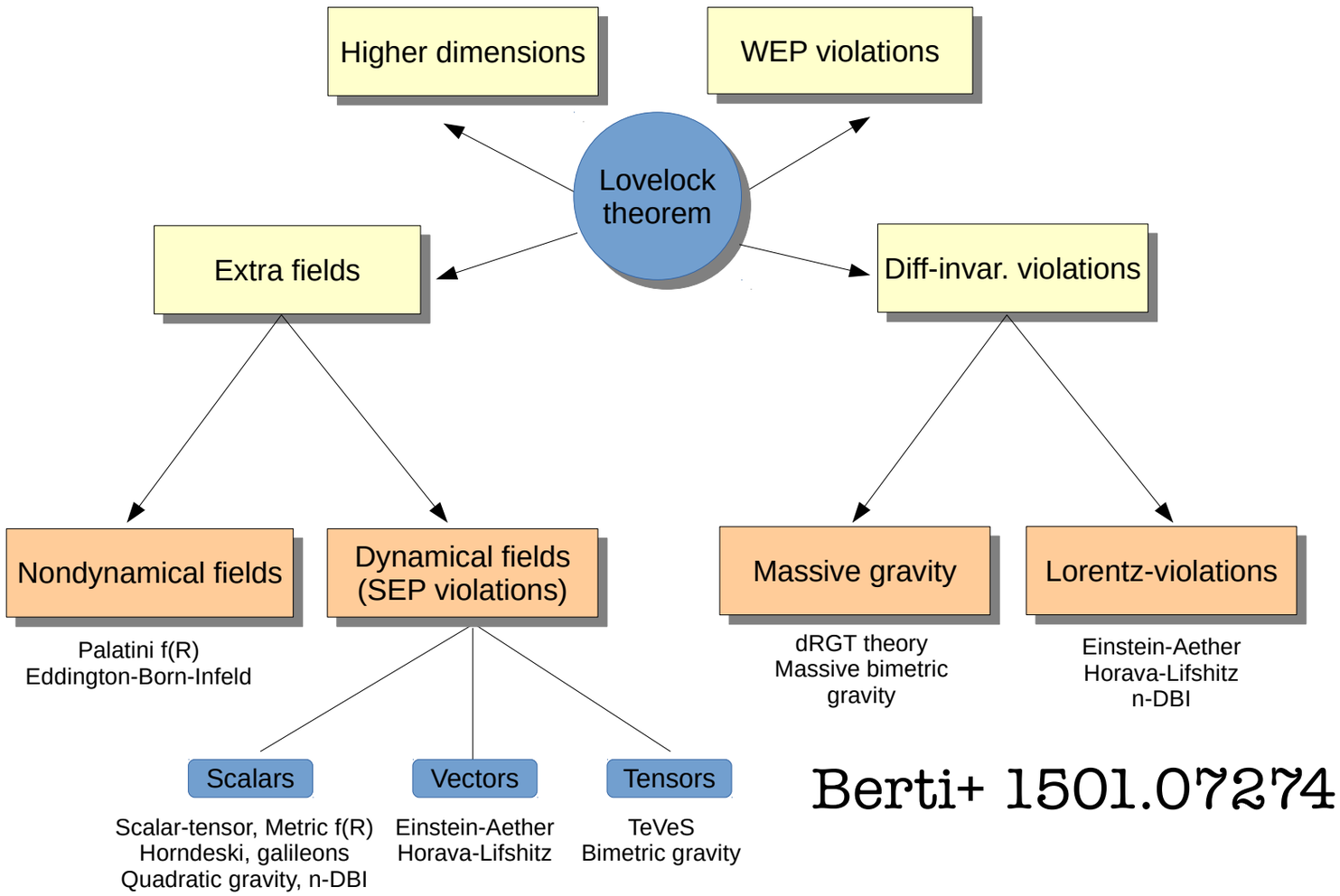
Cosmology without the distance ladder



LIGO, Virgo, 1M2H, DECam GW-EM / DES, DLT40, LCO, VINROUGE, and MASTER Collaborations, Nature 551 85 (2017)

Alternative Theories

- From Baker+, PRL **119** 251301 (2017)
- Scalar-Tensor
  - ~~Quartic, quintic galileons~~, f(R), quintessence
- Vector-tensor
  - require fine-tuning or minimal couplings to be compatible
  - ~~Generalised TeVeS~~ [Gong+ 1801.03382]
- Bimetric / massive graviton
  - $m_g < 10^{-22}$ eV
- Large Extra dimensions? e.g. Visinelli+ 1711.06628



Berti+ 1501.07274

BNS Questions

- How Lucky? Will the next one look anything like this?
  - masses, angles, distance, etc all factors
- Is there a population of previously undetected sub-luminous sGRBs?
- Optical followup search for kilonova emission. Blue component visiblility
  - BlackGEM, ZTF: ~100-200 Mpc
  - LSST: 1Gpc!
- How does ejecta, core behaviour change with chirp mass, mass ratio? Threshold for prompt collapse?
  - NR simulations, GW and EM observations
- Constraints on EOS from GWs
- Behaviour of Hypermassive Neutron Star?
- Implications for cosmology, gravitation, etc

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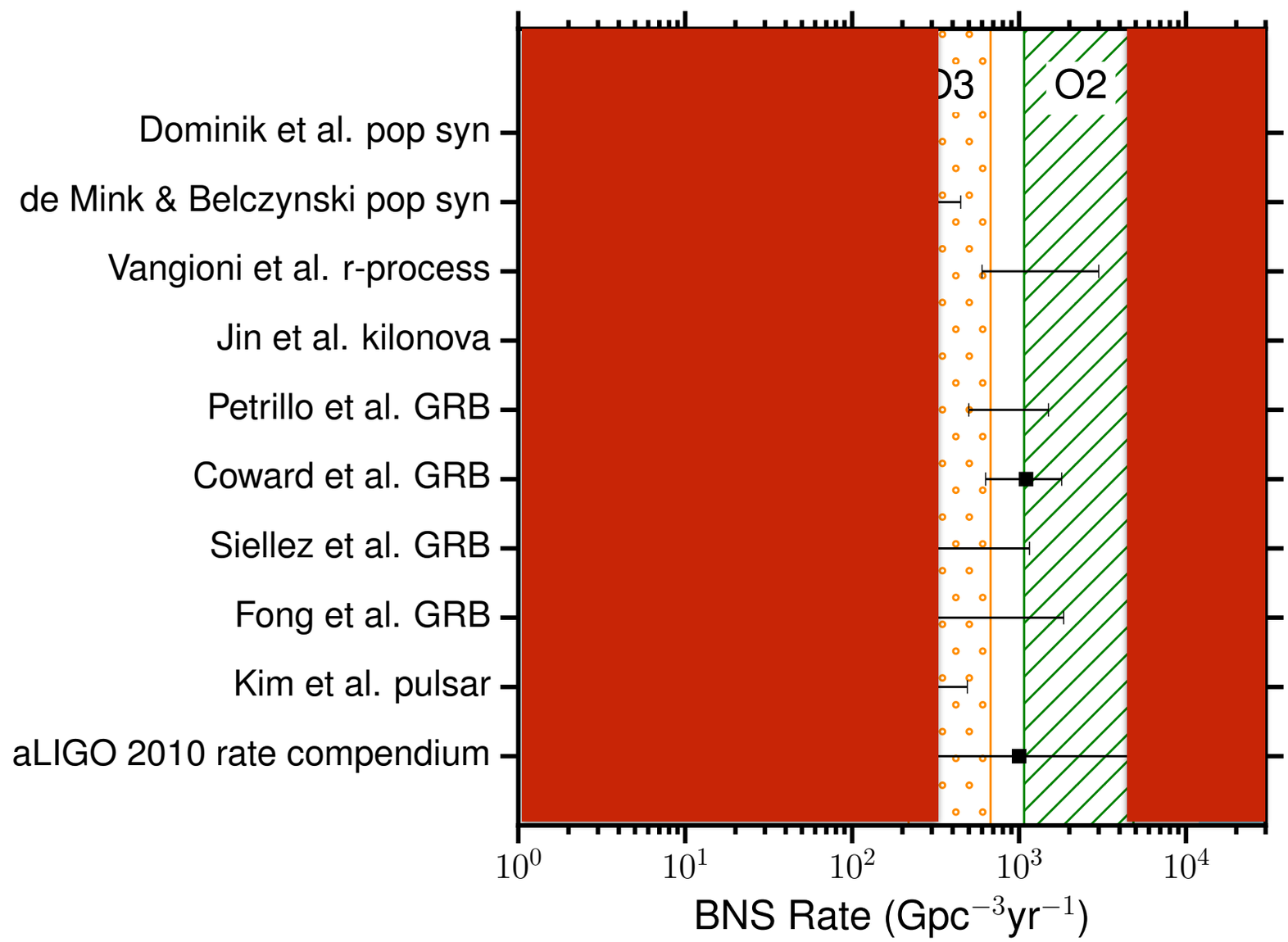
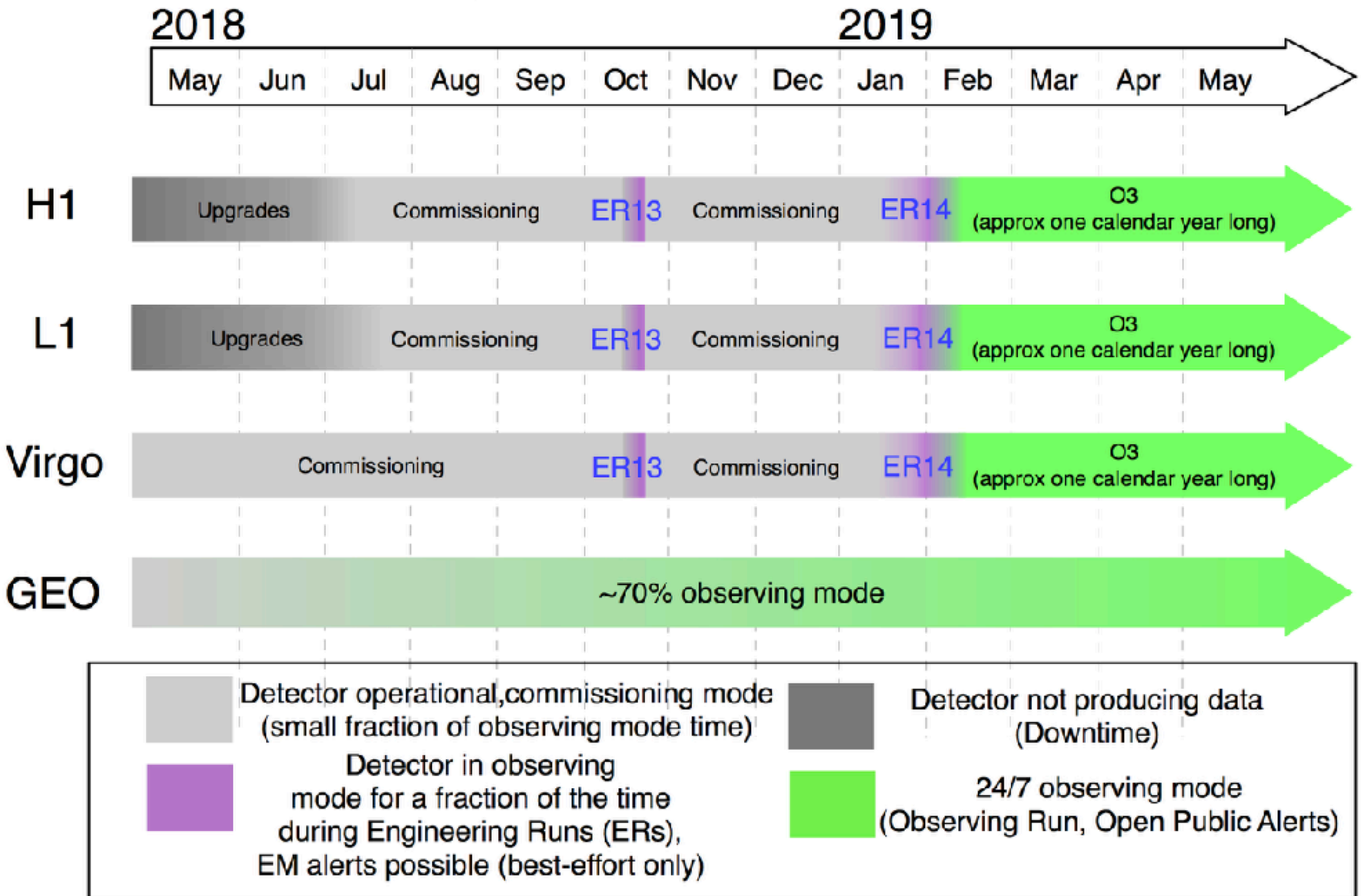
BNS Rates

- O1 BNS rate
  - R< 12600 $Gpc^{-3}yr^{-1}$
- O2 BNS rate
  - 320 < R< 4740 $Gpc^{-3}yr^{-1}$
- “realistic” rate holds
- Look for pop synth updates soon



LIGO-VIRGO Joint Run Planning Committee

Working schedule for O3 (LIGO-G1800889-v4)



O3 Expectations

- 3-detector network with improved sensitivity
  - LIGO targets 120Mpc BNS range, Virgo 60 Mpc
    - high power, squeezing, scattered light, …
  - expected start ~Feb 2019
- Should detect several BBHs per month
- Open public alerts!
  - See https://dcc.ligo.org/LIGO-M1000066-v25/public for details

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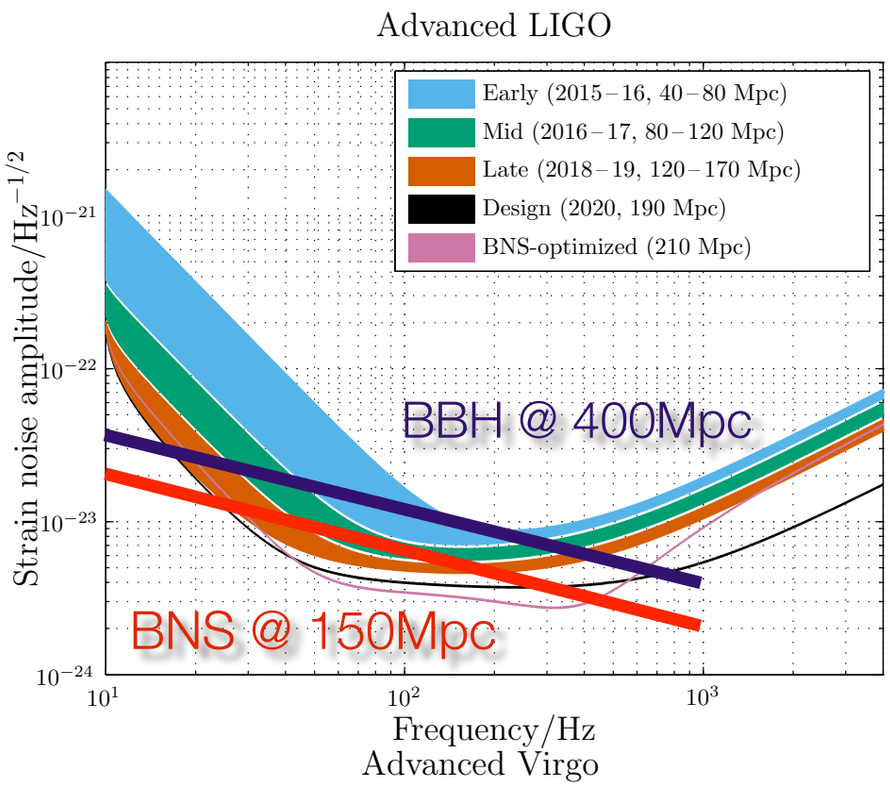
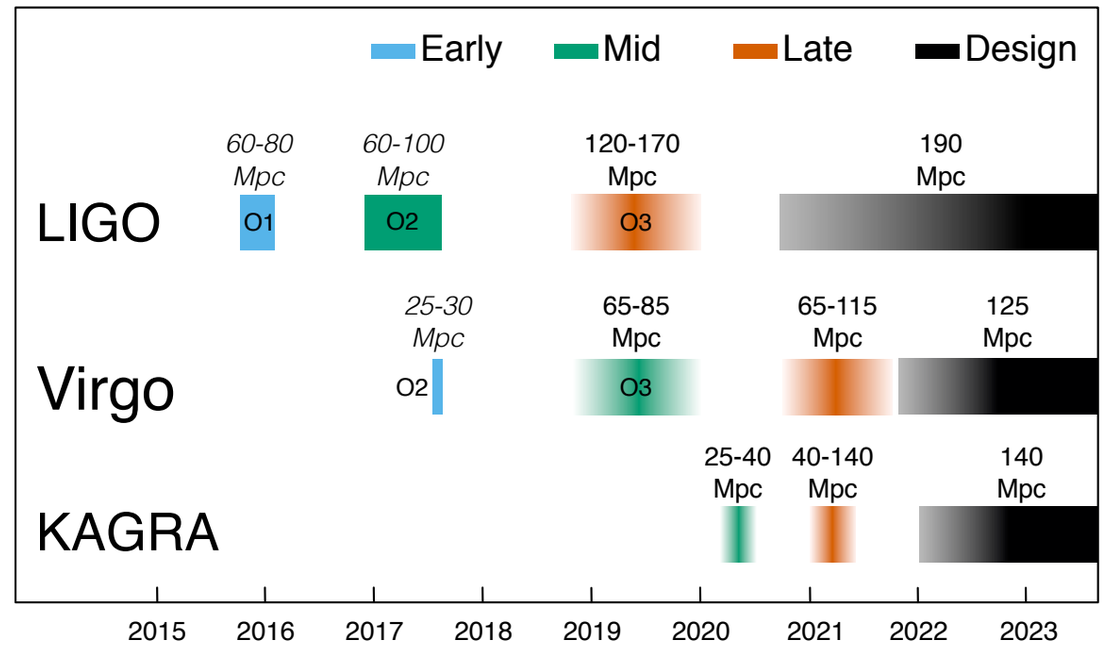
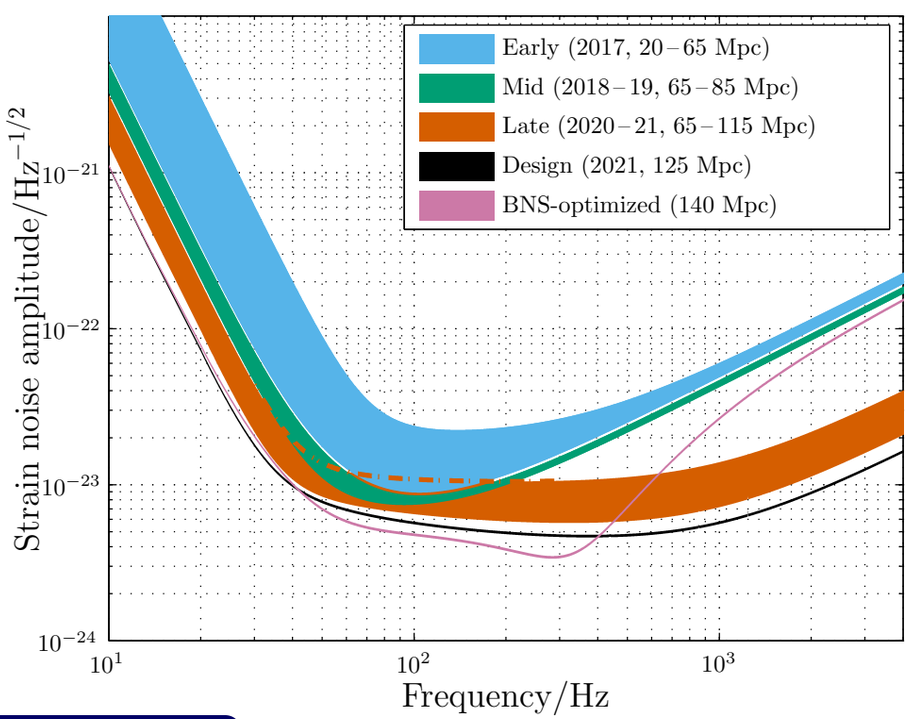
Beyond O3







- Commissioning continuing at current facilities.
- Design sensitivity goal 2020/21
- KAGRA plans to join O3 with 3-8Mpc range.
    - Aims for 40-140 Mpc by 2022
- LIGO-India c.2024
- Full network should make 11-180 BNS detections / year
- Hundreds of BBH!
- Beyond 2020 facility upgrades? aLIGO+, AdVirgo+, KAGRA+?

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Abbott+, Liv. Rev. Relativity **21** (2018)

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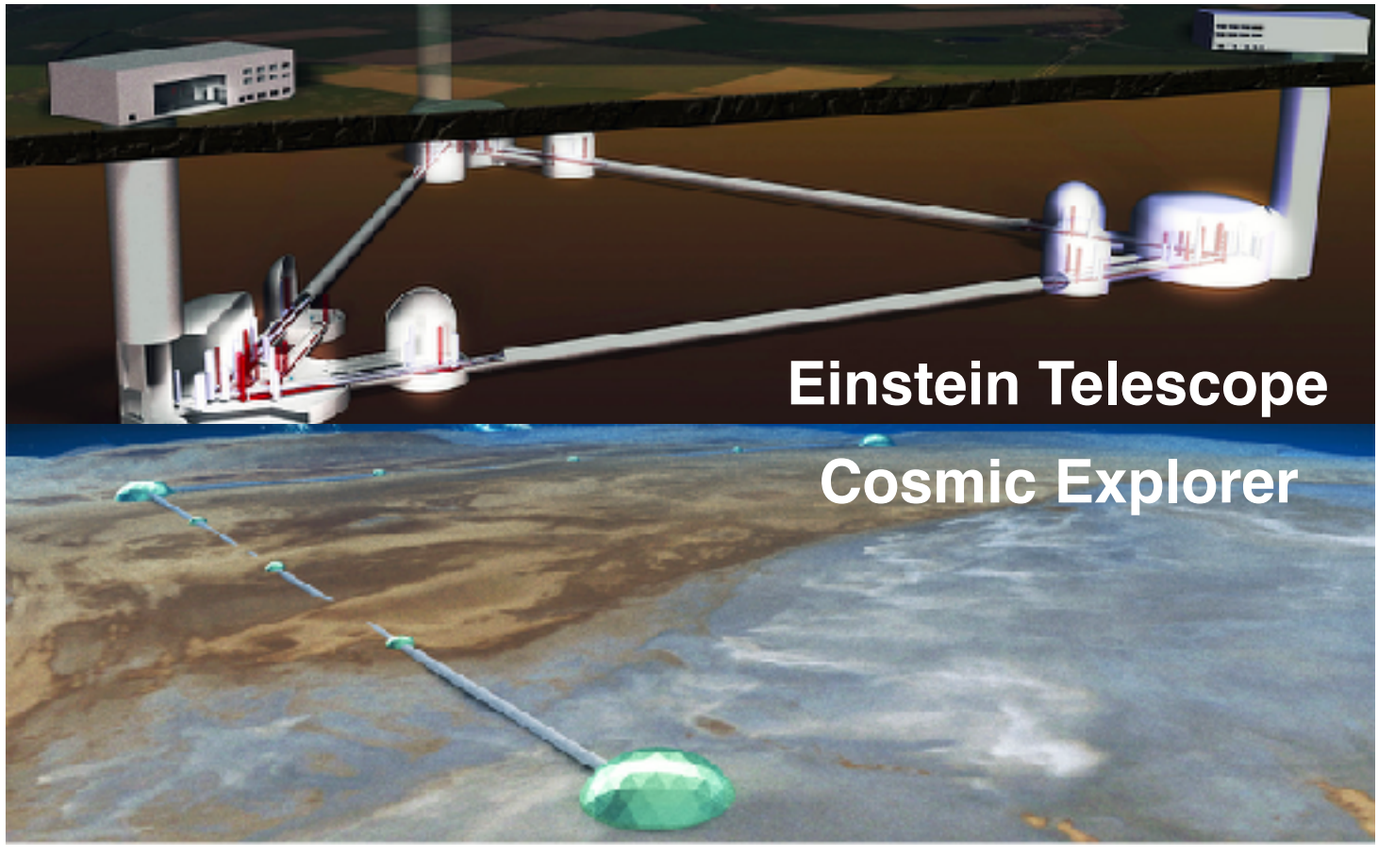
3rd Generation

- Increased activity on 3G, coordinated by GWIC
  - Science case being refreshed for observational era.
- Cosmic Explorer and Einstein Telescope new facilities under study
  - International R&D coordination committee



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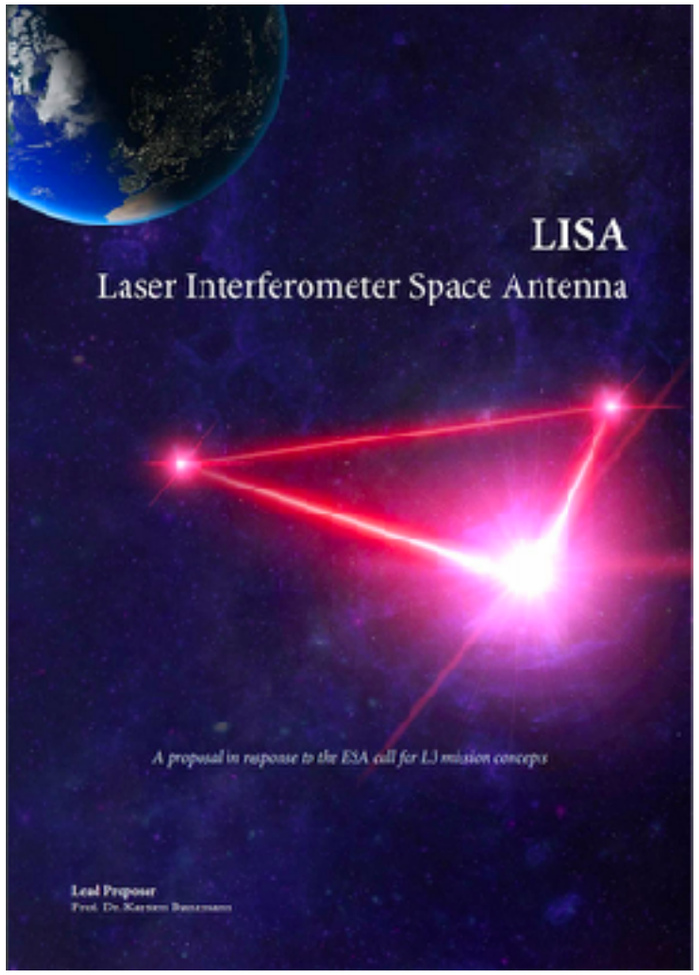
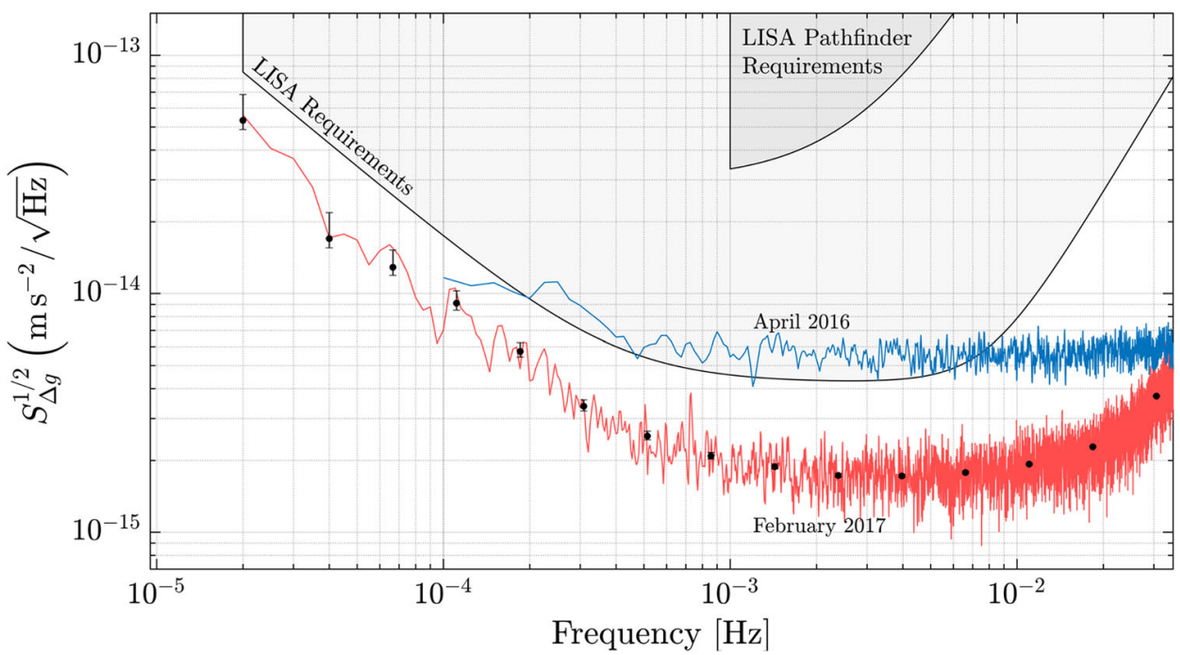
LISA

- LISA selected by ESA as L3 mission in June 2017
  - 2.5M km triangular configuration
  - 2034 launch date
- LISA Pathfinder exceeded LISA requirements!
  - Final results `Armano+ PRL 120 061101 (2017)`
- ESA-led collaboration working on technologies and infrastructure
- LISA consortium reformed www.lisamission.org





`Armano+ PRL 120 061101 (2017)`

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Summary

- O1 brought first detection, O2 regular BBH and multi-messenger astronomy!
  - Perhaps the “end of the beginning” of GW astronomy
- Renewed excitement across field: multi-messenger, 3G and LISA all accelerating.
- Appetite from astro community for more detections, more information. Open Public Alerts will change way we engage.
- As always… hope for surprises in O3!

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