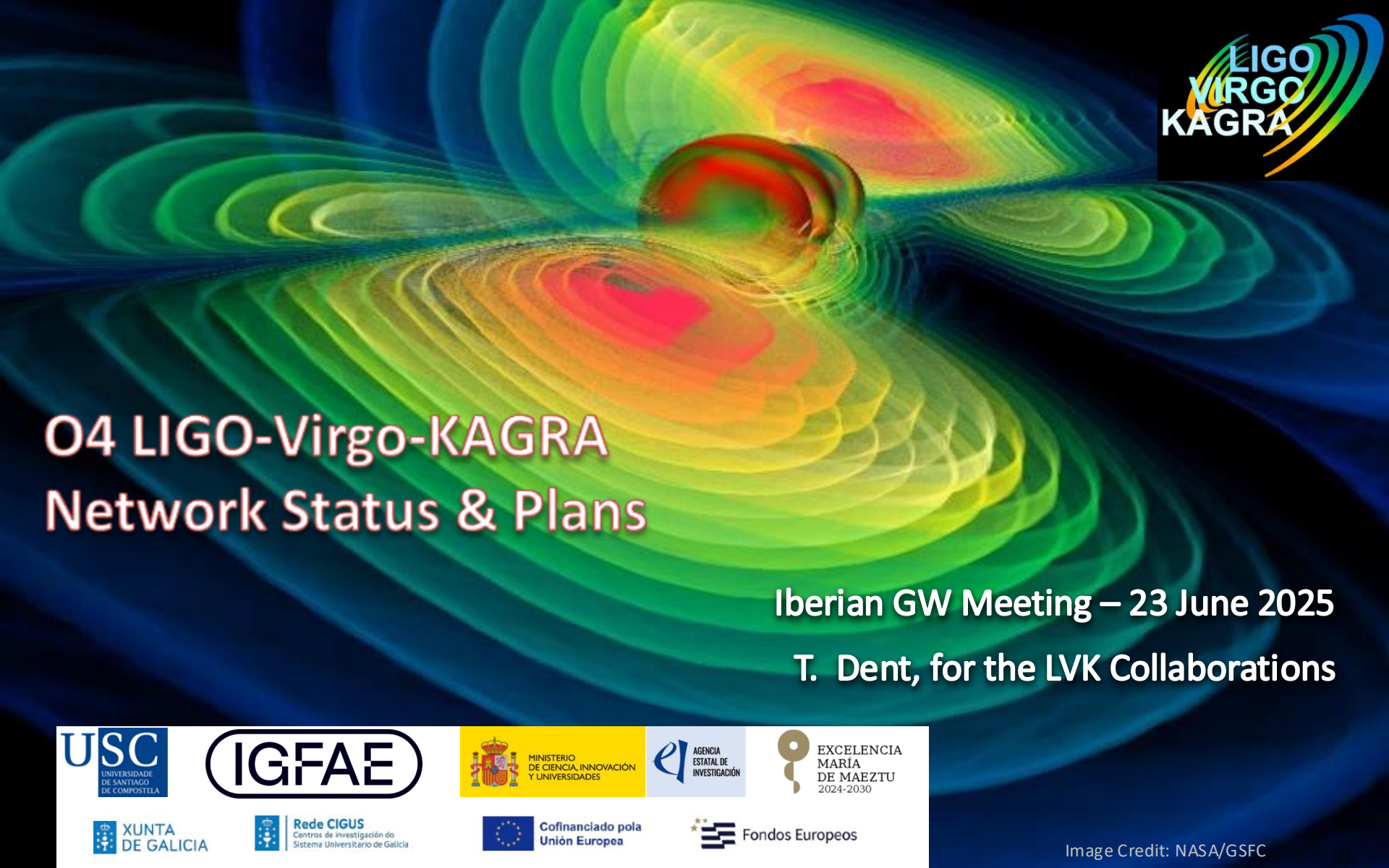


O4 LIGO-Virgo-KAGRA Network Status & Plans

Iberian GW Meeting – 23 June 2025

T. Dent, for the LVK Collaborations

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA
IGFAE
MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES
AGENCIA ESTATAL DE INVESTIGACIÓN
EXCELENCIA MARÍA DE MAEZTU 2024-2030
XUNTA DE GALICIA
Rede CIGUS Centros de investigación do Sistema Universitario de Galicia
Cofinanciado pola Unión Europea
Fondos Europeos

Image Credit: NASA/GSFC

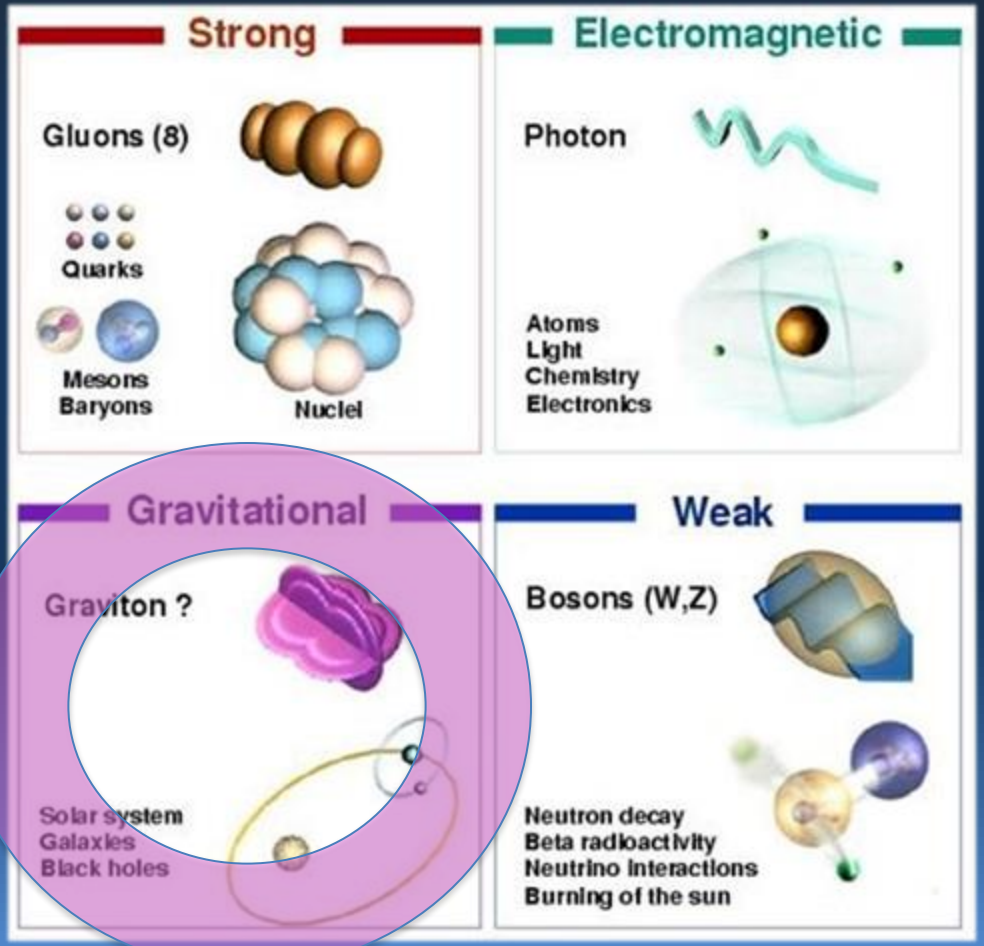
LIGO-Virgo-KAGRA collaborations

Plan of the talk

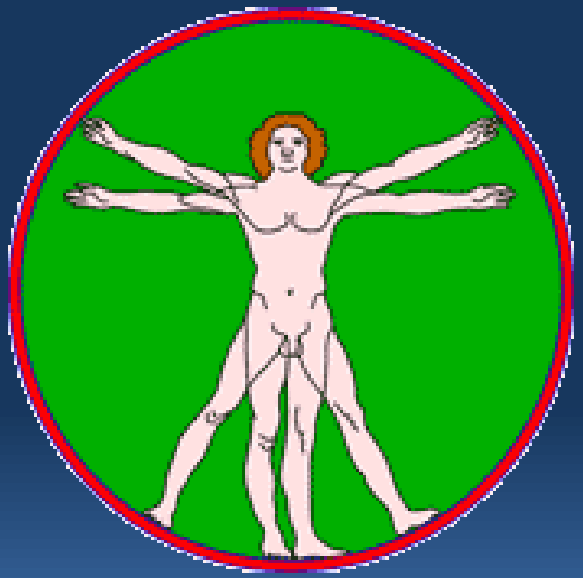
- The weakest force : gravity
- Ground-based GW detectors & sources
- CBC GW science : astrophysics, relativity, …
- LVK observations up to O3 (2015-2020)
- The O4 run (2023-2025)
- O5 and looking forward (A# et al.)

Image Credit: Aurore Simonnet/SSU

4 (known) fundamental forces



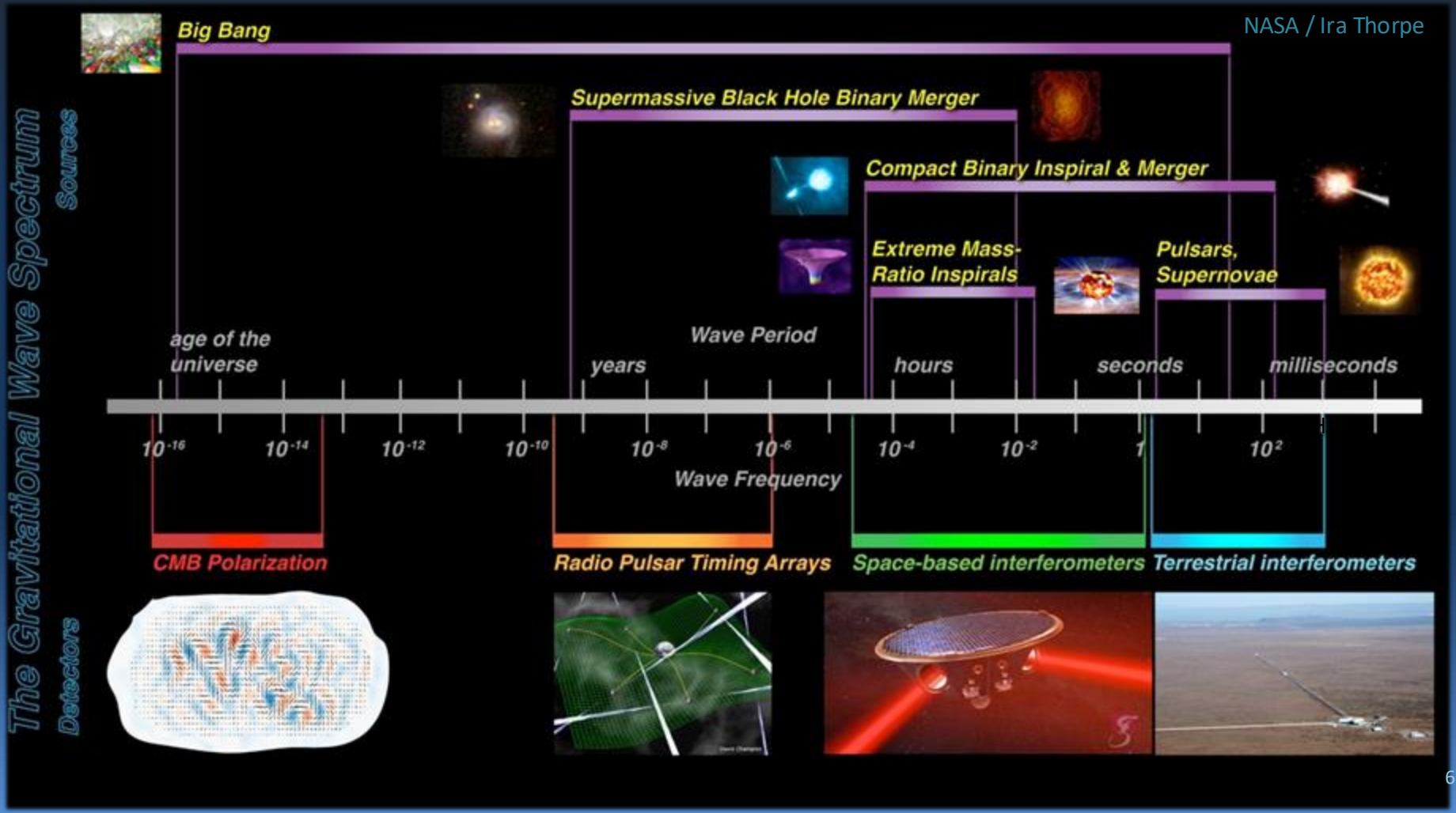
How to ‘see’ GW



- *Tidal* effect on spatially separated test particles
- Can extract energy – imagine a spring connecting particles
- Measure variations in *distance* or *travel time*

Strain $h(t) \sim \frac{\delta L(t)}{L}$

The broad spectrum of GW



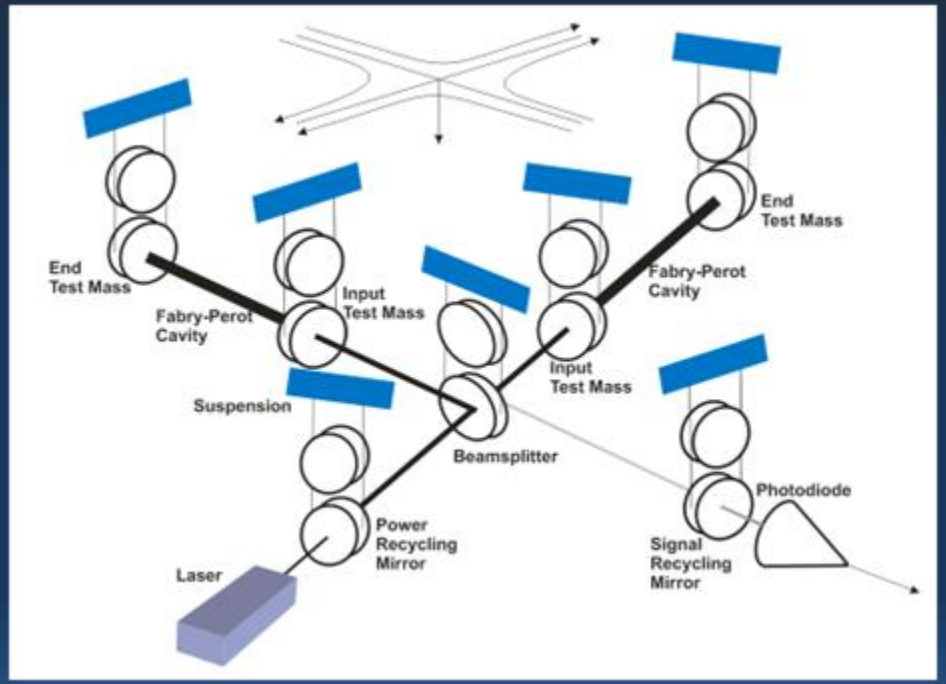
GROUND-BASED GW DETECTORS

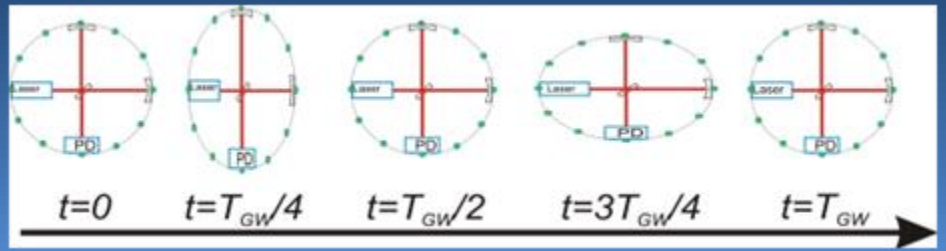
Laser interferometric detection

- 'Michelson interferometer' **end mirrors** free to move along arms

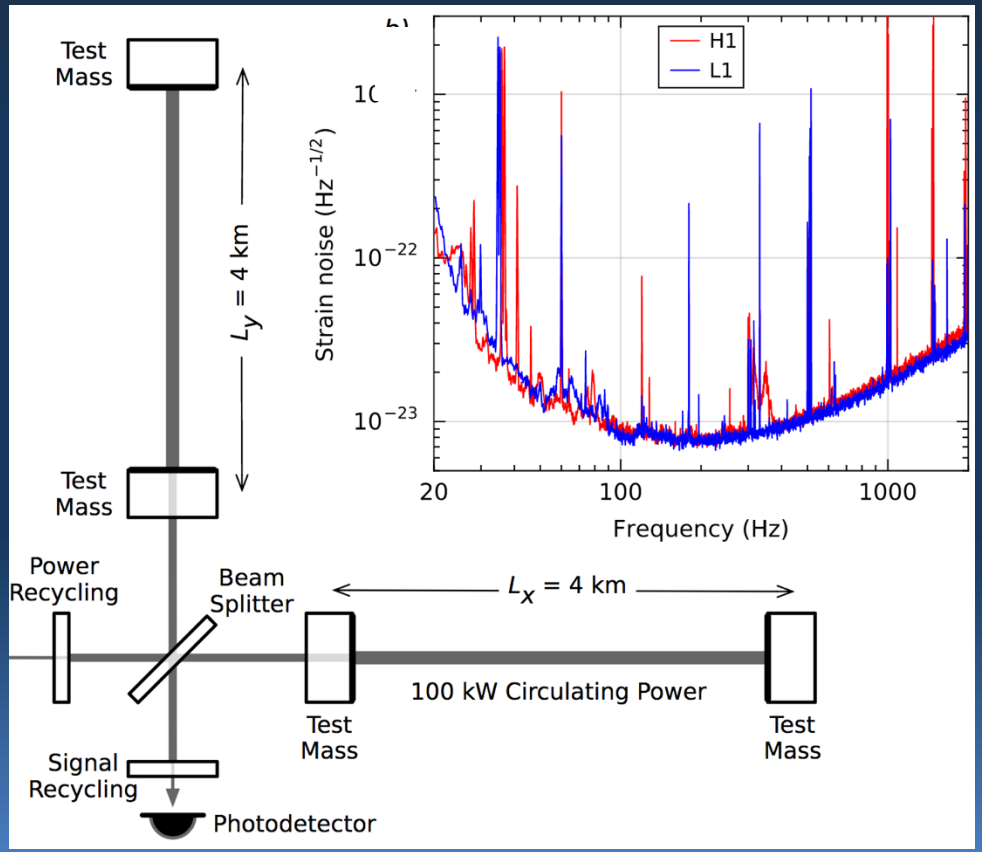
- Differential length change
  $\delta(L_x - L_y) = h(t) \cdot L$

  ⇒ time of flight difference
  ⇒ relative phase difference @ beam-splitter
  ⇒ transmitted intensity variation @ PD





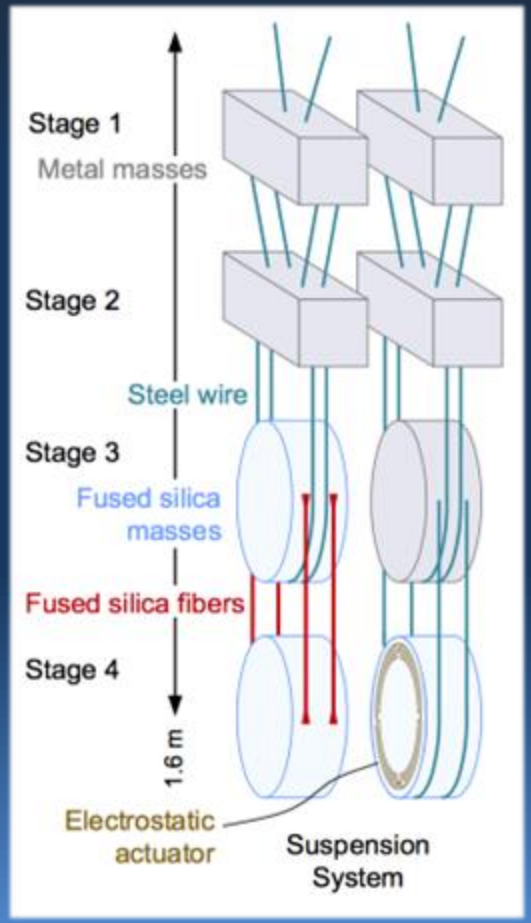
Down to <1e–23: Enhance the signal



- Long arms
- High power ultra-stable laser
- Power recycling (factor ~35)
- Resonant arm cavities (factor ~300)
- Signal recycling

LVC, PRL **116** 061102 (2016)

Down to <1e–23: Suppress noise



Seismic noise reduction

- Active seismic isolation
- Quadruple pendulum suspension
- ~10 orders of magnitude displacement noise suppression above 10Hz

Precision Interferometry : Understanding Measurement Noises

Fundamental Noises

I. Displacement Noises

→ **$\Delta L(f)$**

- Seismic noise
- Radiation Pressure
- Thermal noise
  - Suspensions
  - Optics

II. Sensing Noises

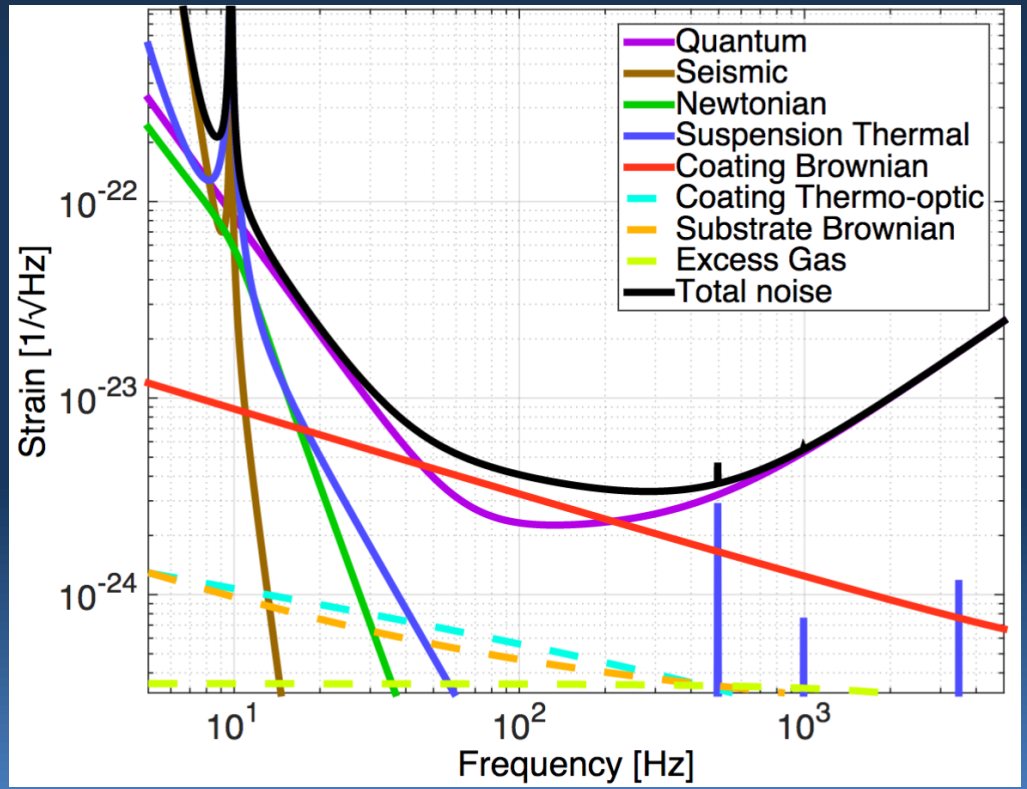
→ **$\Delta t_{photon}(f)$**

- Shot Noise
- Residual Gas

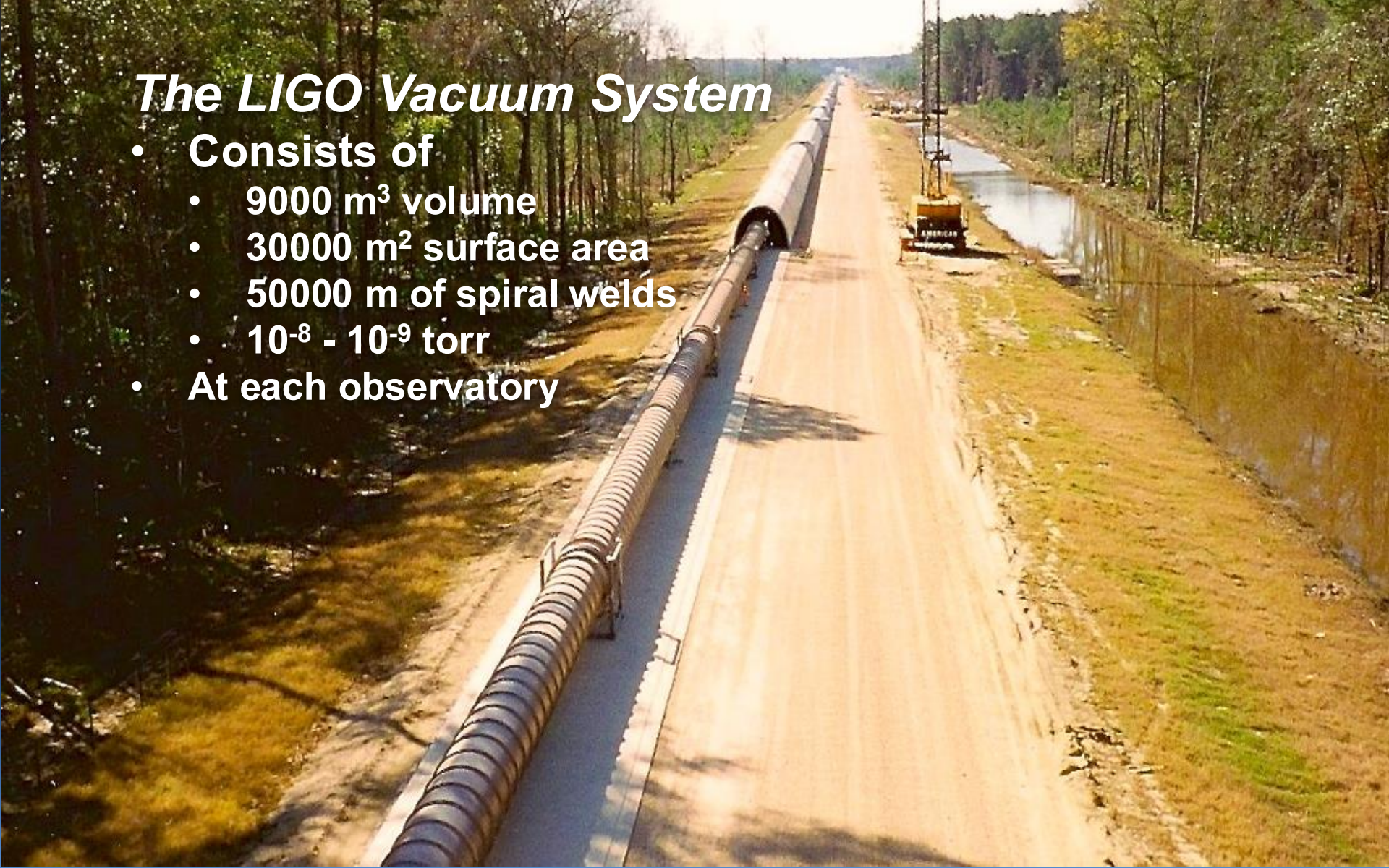
Technical Noises

→ *Hundreds of them …*

Advanced LIGO Design Noise Budget



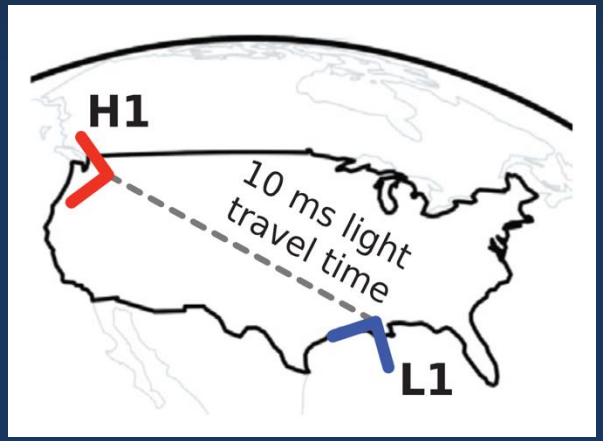
https://dcc.ligo.org/LIGO-T1800044/public



The LIGO Vacuum System

- Consists of
  - 9000 m^3 volume
  - 30000 m^2 surface area
  - 50000 m of spiral welds
  - 10^{-8} - 10^{-9} torr
- At each observatory

A global network



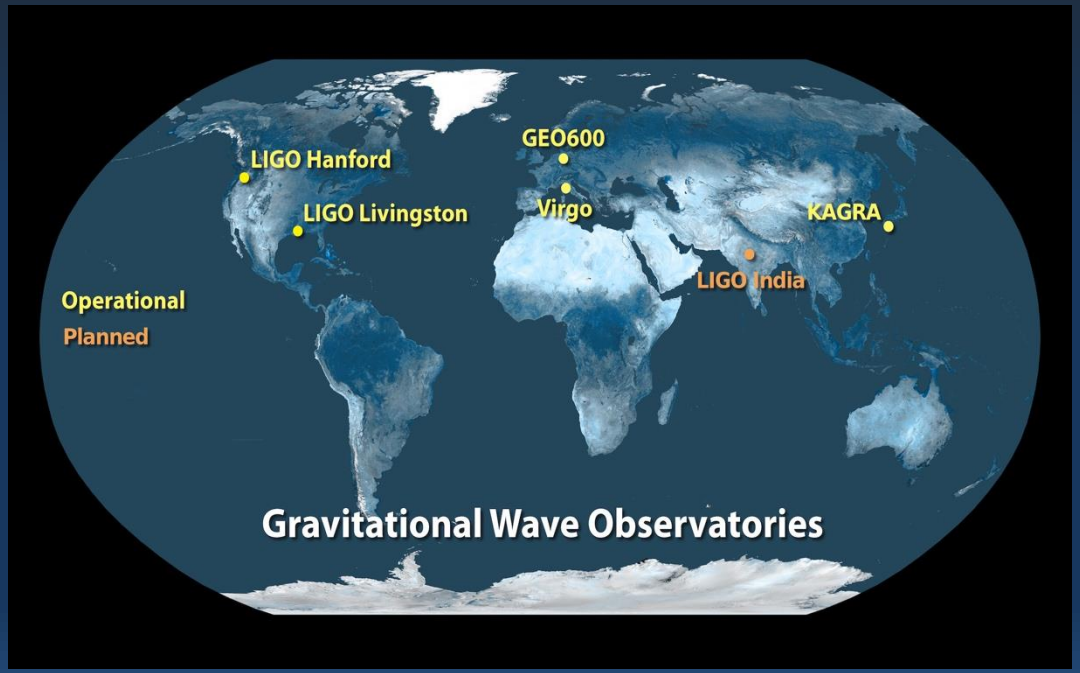


Image credit: LIGO Lab

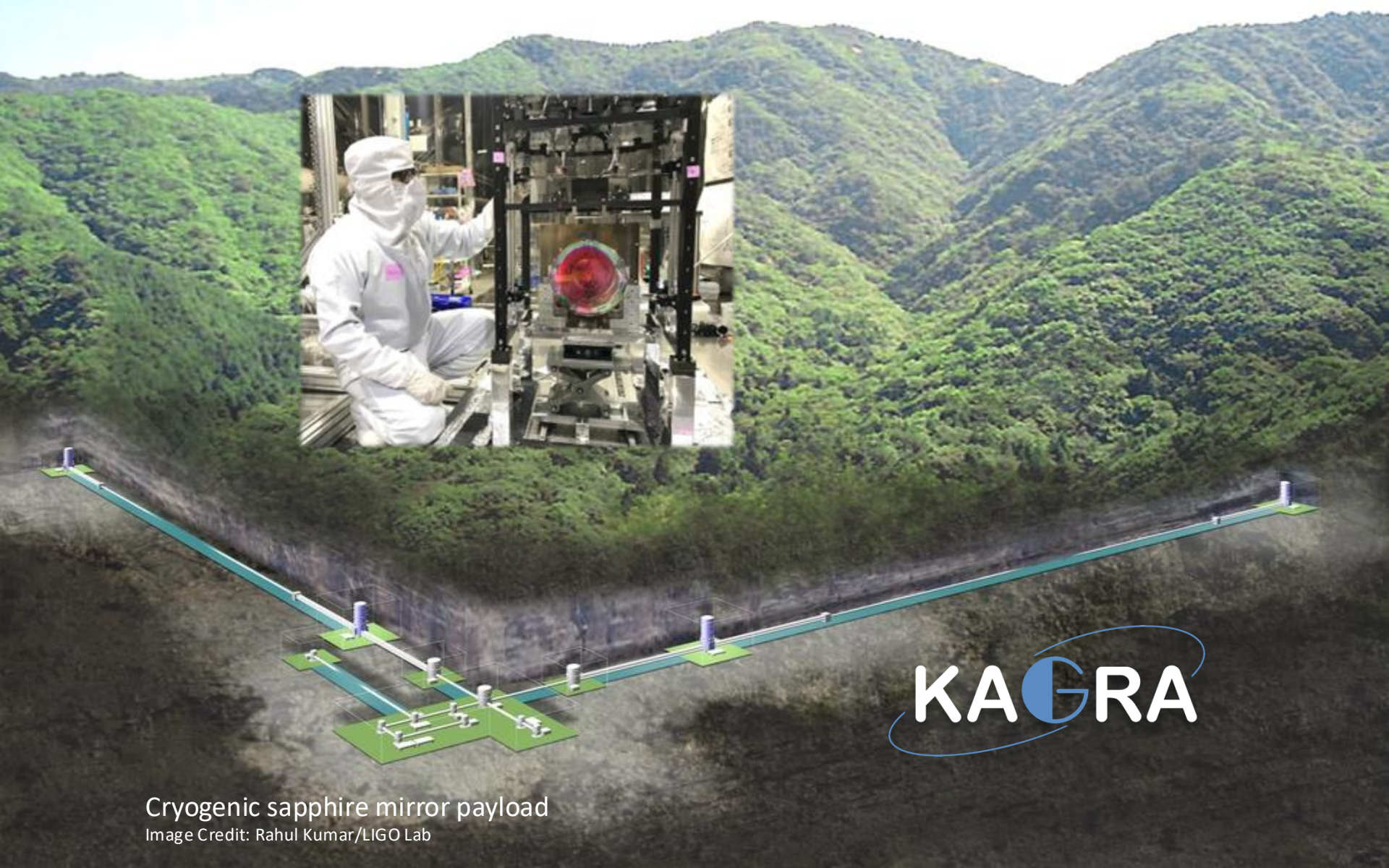
- Detection rate, sky coverage, network duty cycle
- Greater accuracy on source parameters
  - Distance, sky location, orientation of source ...

ADVANCED VIRGO

163 Institutions in 20 different countries

~915 collaboration members

Date



Cryogenic sapphire mirror payload
Image Credit: Rahul Kumar/LIGO Lab

Transient GW sources

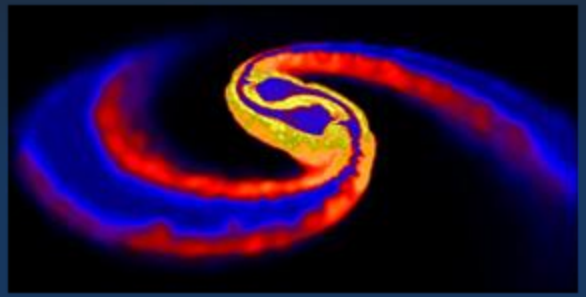
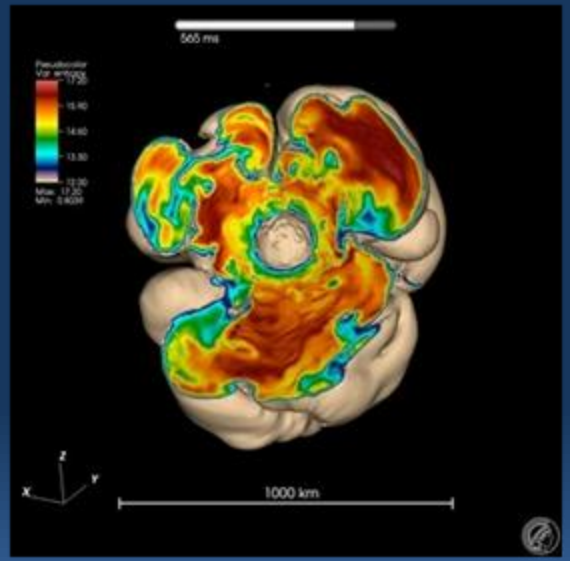


Image : D. Price (Exeter) & S. Rosswog (Bremen)

***Highly relativistic** systems*

CBC

Burst



Simulation: F. Hanke et al. (MPIA Garching)

Cataclysmic events of compact astrophysical objects

- **N**eutron**S**tar / **B**lack**H**ole binary mergers
- **C**ore**C**ollapse**S**uper**N**ovae
- Pulsar glitches / oscillation modes ?
- Exotics : cosmic string kinks ? ...

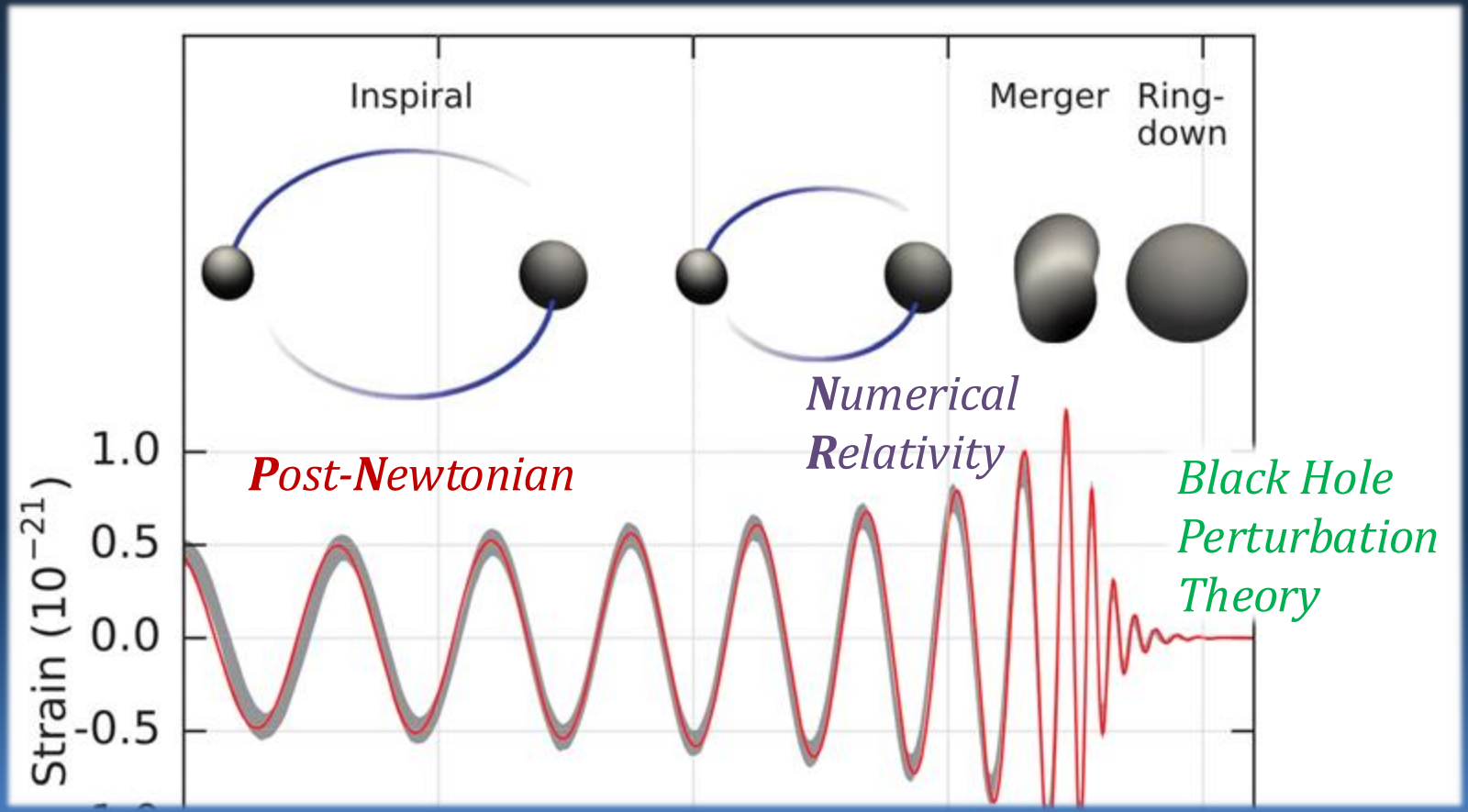
Persistent GW sources

- ***Continuous Wave*** : sinusoids from rotating NS
  - many potential sources in Galaxy

- ***Stochastic*** : random 'background' from superposition of unresolved sources
  - astrophysical
    transients at high redshift
  - primordial
    quantum fluctuations / critical phenomena in very early Universe

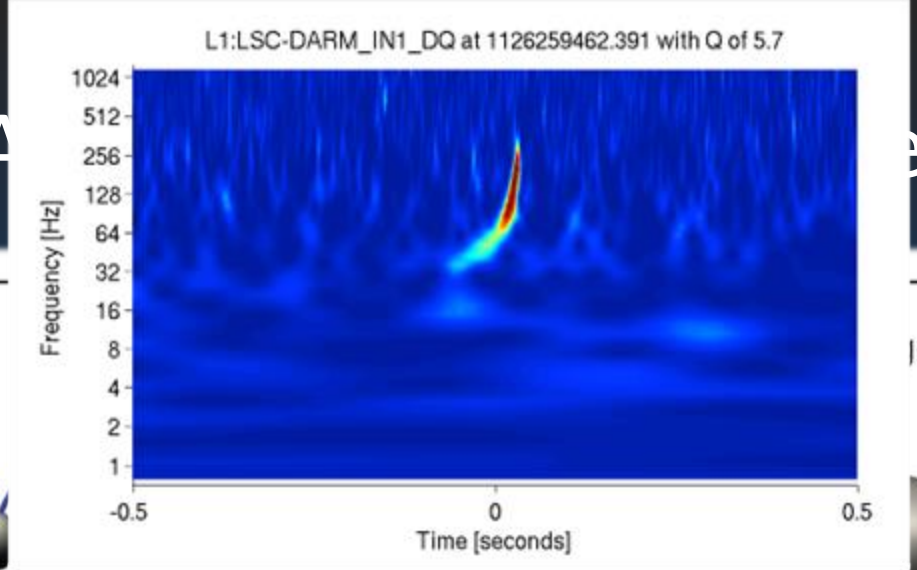
Chandra X-ray images of Crab pulsar

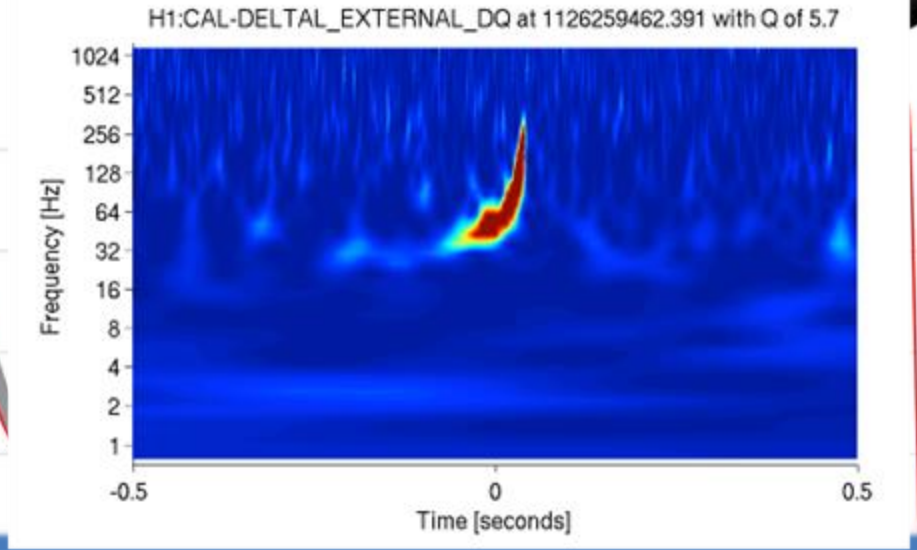
Anatomy of a binary merger



LVC PRL **116**, 061102 (2016)

A erger





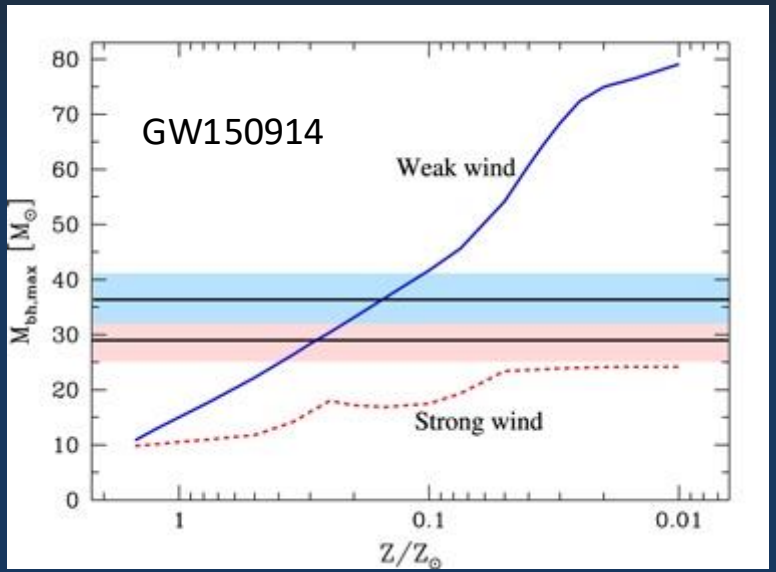
Black Hole Perturbation Theory

LVC PRL **116**, 061102 (2016)

14 September 2015, 09:50:45 UTC

Astrophysics from BBH mergers

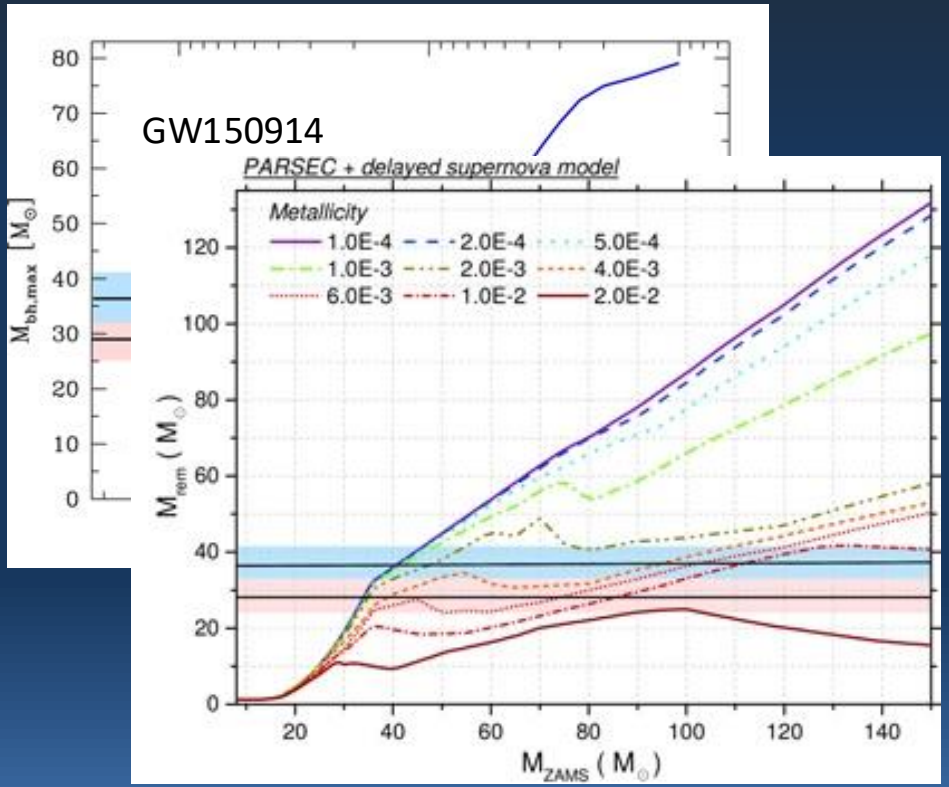
- **Stellar winds** 'weak' allowing ~30 $M_\odot$ BH to form



Astrophysics from BBH mergers

- **Stellar winds** 'weak' allowing ~30 $M_\odot$ BH to form

- Likely forming at **low metallicity**

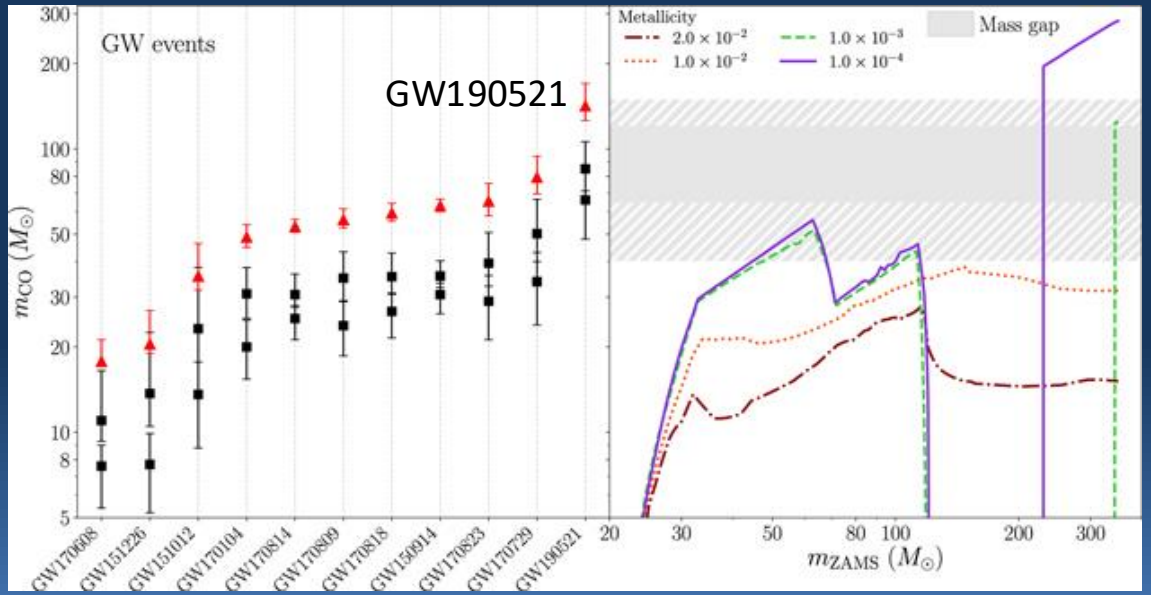


Astrophysics from BBH mergers

- **Stellar winds** 'weak'
  allowing ~30 $M_\odot$ BH to form

- Likely forming at
  low metallicity

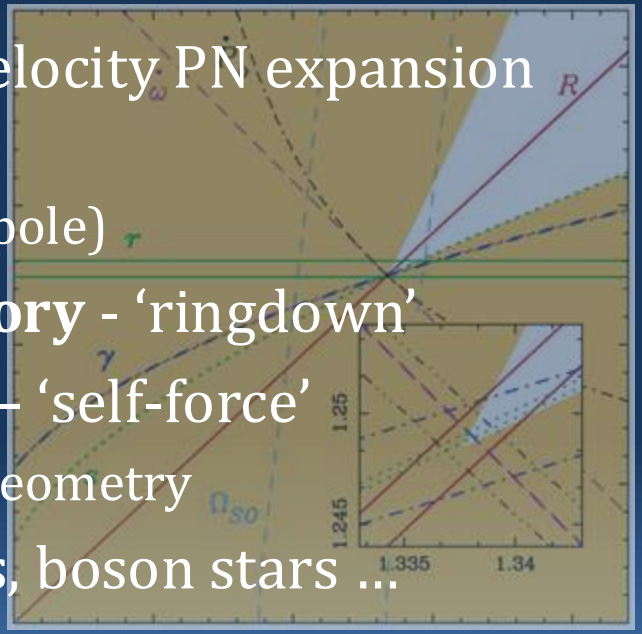
- ~85 $M_\odot$ BH above
  '**mass gap**' from
  SN pair instability



⇒ hierarchical formation?

Exploring GR with GW sources

- **Strong field :** compact objects (NS, BH) and behaviour 'close to' singularities via NR
- **Precise constraints** on low velocity PN expansion
  - v/c up to ~0.4
  - 'Higher modes' (beyond quadrupole)
- **Black hole perturbation theory** - 'ringdown'
- **Small mass ratio expansion –** 'self-force'
  - Probe of Schwarzschild / Kerr geometry
- **Exotics :** black hole mimickers, boson stars …
- **Early Universe** : quantum fluctuations … ??



Consistency of relativistic effects in double pulsar J0737–3039A, B (Image M. Kramer)

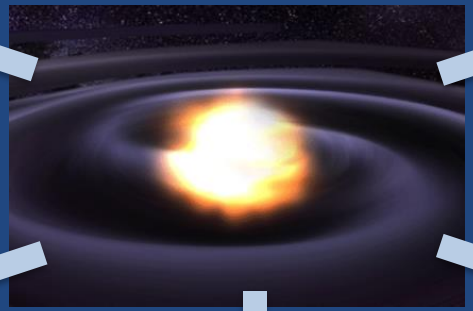
Exploring GR with GW propagation

- **Verify 2 transverse tensor polarizations**
- **Constrain non-GR dispersion** (eg graviton mass)
- Constrain Lorentz symmetry violation …
- ('Strong' or 'Weak') **Gravitational Lensing** of GW
  - Amplification of signal
  - Multiple transient "images", other possible effects
- **Verify speed of GW propagation**
  - Multi-messenger events with prompt emission

Multi-messenger Astronomy with GW

Gravitational Waves

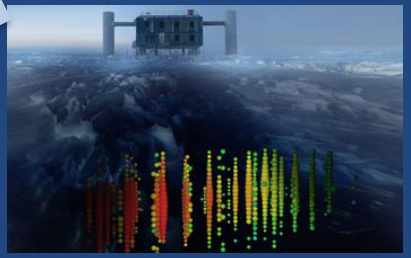
Binary Neutron Star / Neutron Star – Black Hole Merger



X-rays / Gamma-rays

UV / Visible / Infrared Light

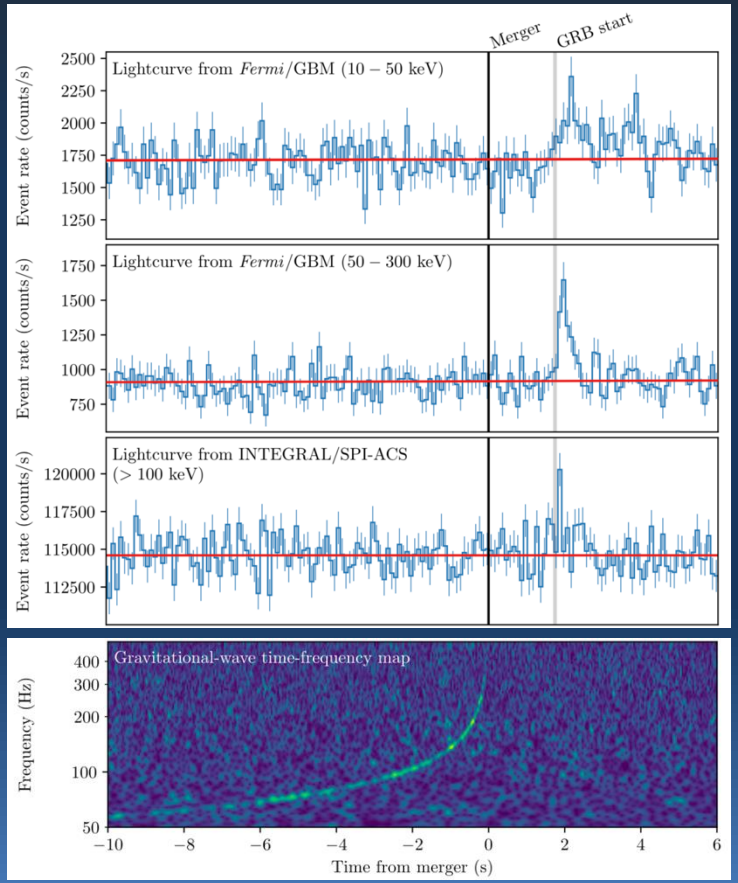
Radio



HE Neutrinos

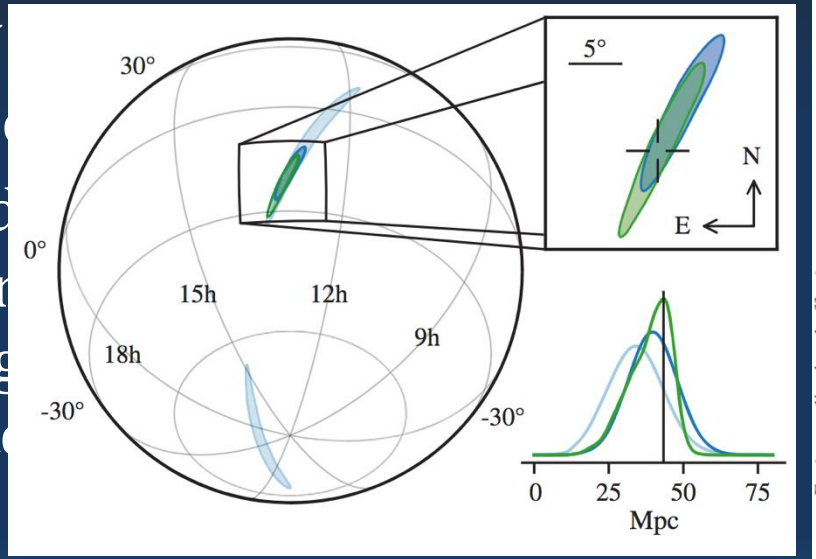
GW170817 / GRB 170817A

- First GW multi-messenger observation
- Time and sky position coincident between GW and gamma-ray observatories

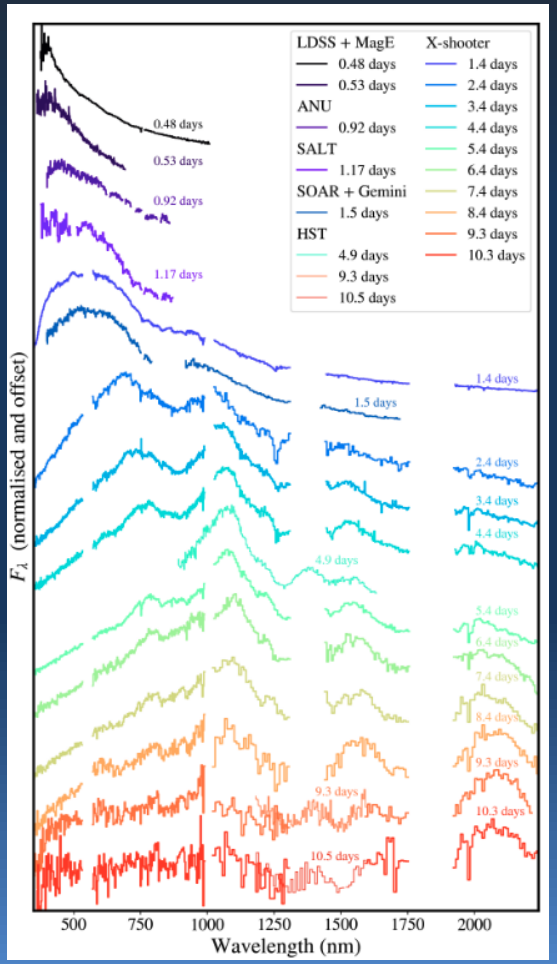


GW170817 / GRB 170817A

- First GW
  messeng
- Time and
  coincider
  GW and g
  observat

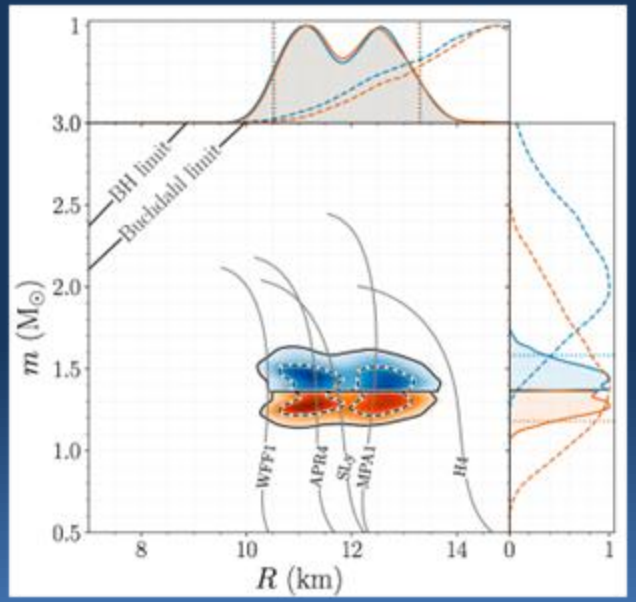


- **Optical, UV & IR counterpart ('kilonova')**



Sneppen et al. arXiv:2404.08730

Science from multi-messenger BNS detection



Speed of GW = speed of light

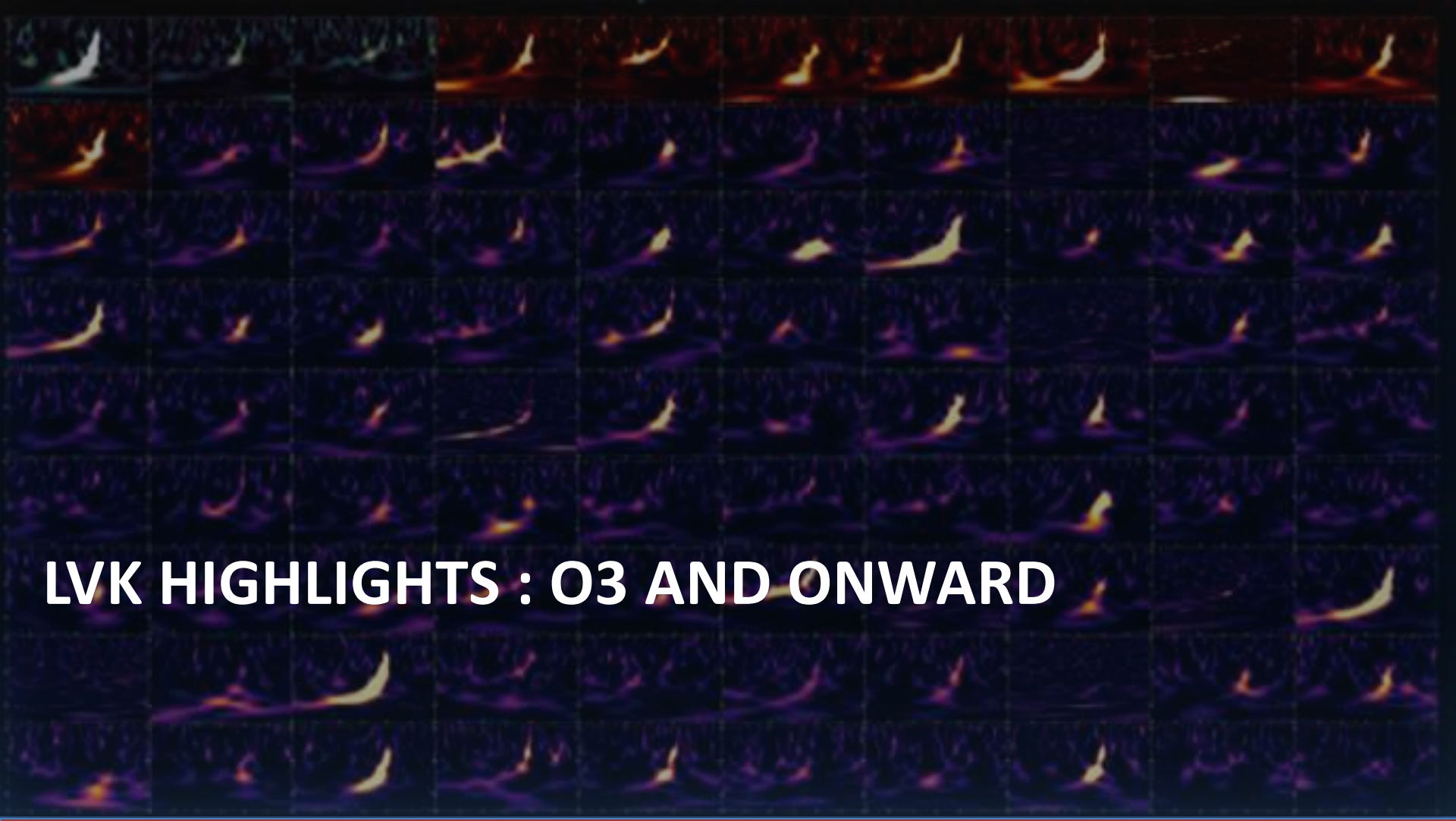
- Rules out many non-GR 'dark energy' theories

Heavy element nucleosynthesis in NS collisions

Independent estimate of Hubble constant

Bounds on NS tidal deformability & equation of state

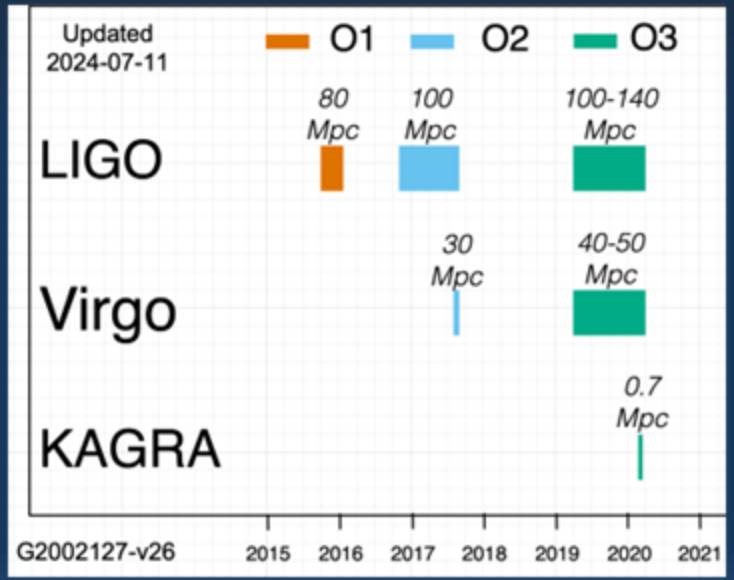
Bounds on high energy neutrino emission (IceCube, Pierre Auger)

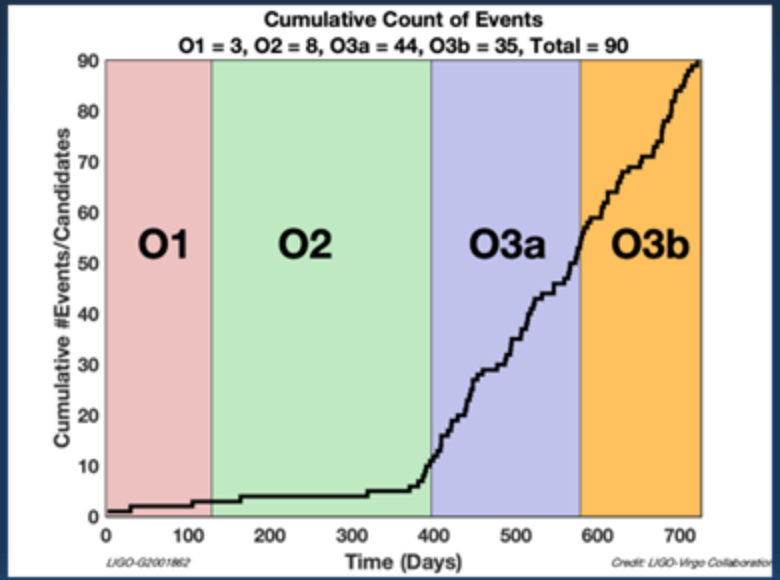


LVK HIGHLIGHTS : O3 AND ONWARD

Detections of compact binary mergers from 2015-2020
Image credit: LVK / S. Ghonge & K. Jani

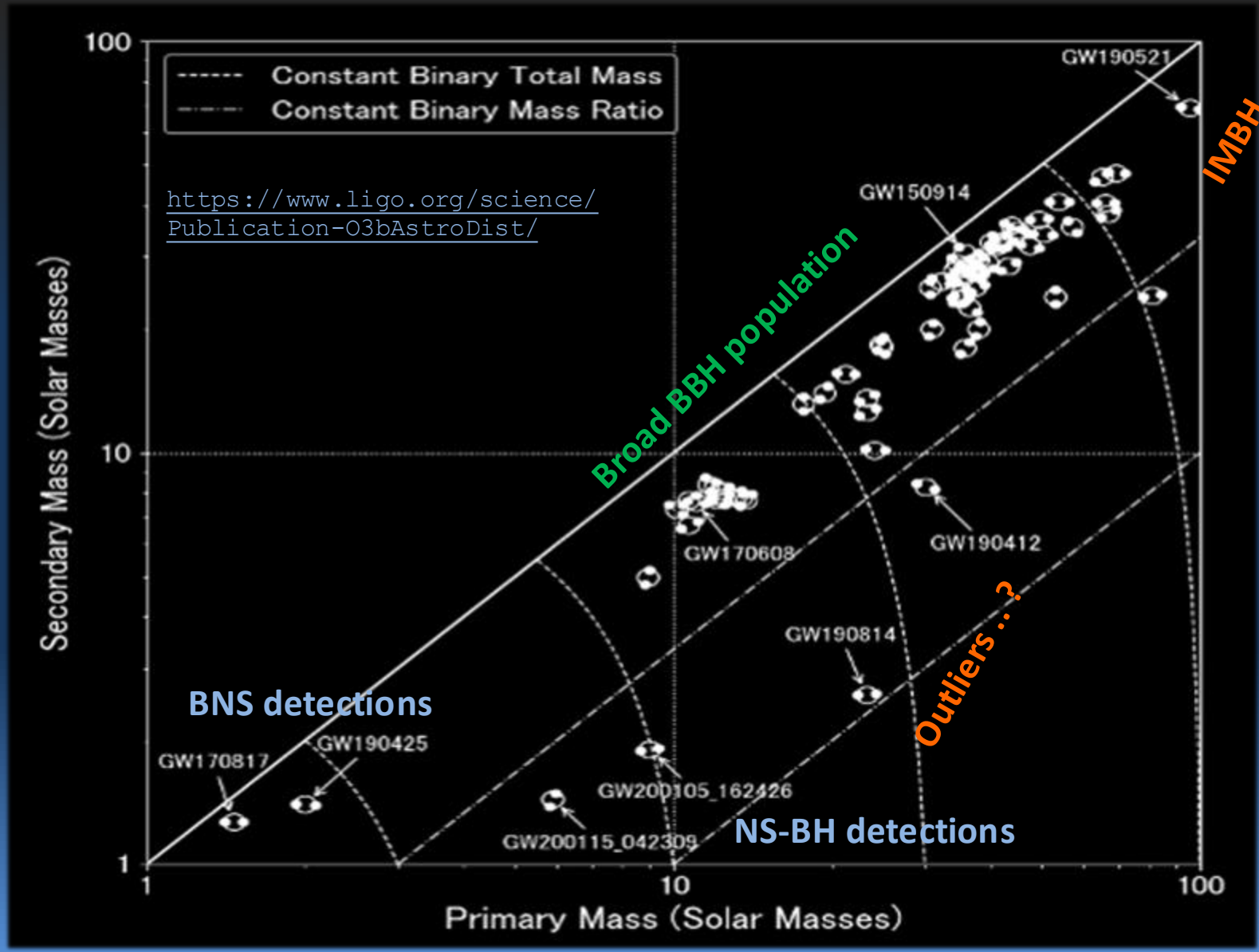
LIGO-Virgo observations up to 2020





O3 run : April 2019 through March 2020

- 90 ‘significant’ binary merger candidates (cumulative O1-O3)


Constant Binary Total Mass
Constant Binary Mass Ratio
https://www.ligo.org/science/Publication-O3bAstroDist/
Broad BBH population
IMBH …
Outliers …?
BNS detections
NS-BH detections
GW190521
GW150914
GW170608
GW190412
GW190814
GW190425
GW170817
GW200105_162426
GW200115_042309
Secondary Mass (Solar Masses)
Primary Mass (Solar Masses)
100
10
1
1
10
100

LVK public data products

- **GW Open Science Center** data on GWTC-3

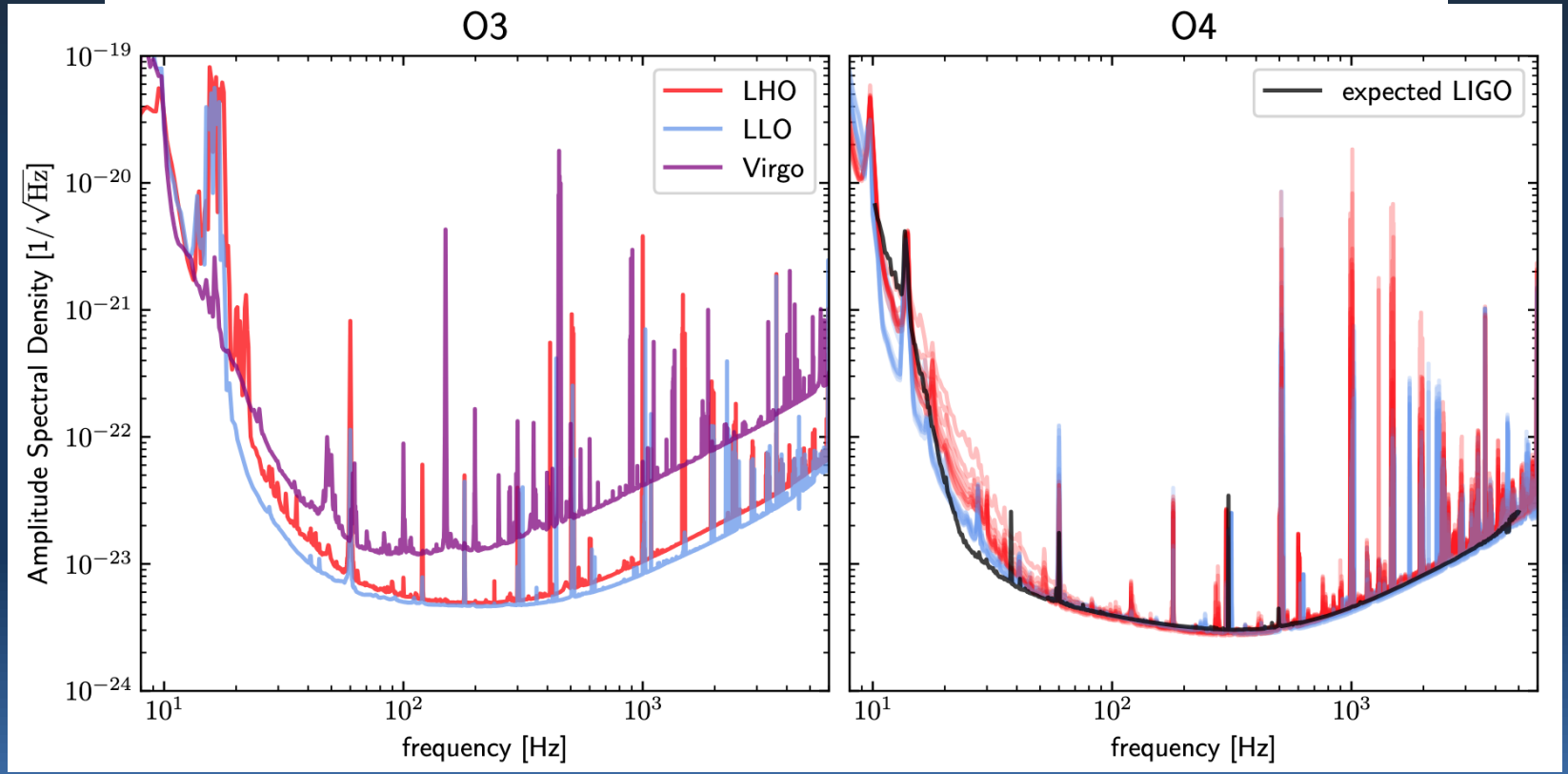
https://www.gw-openscience.org/eventapi/html/GWTC-3/

Name	Version	Release	GPS ↓	Mass 1 ($M_\odot$)	Mass 2 ($M_\odot$)	Network SNR	Distance (Mpc)	χ_{eff}	Total Mass ($M_\odot$)
GW190930_133541	v1	GWTC-2	1253885759.2	$12.3^{+12.4}_{-2.3}$	$7.8^{+1.7}_{-3.3}$	9.8	760^{+360}_{-320}	$0.14^{+0.31}_{-0.15}$	$20.3^{+8.9}_{-1.5}$

- Data release for papers : inference samples, table data, tutorial notebook …

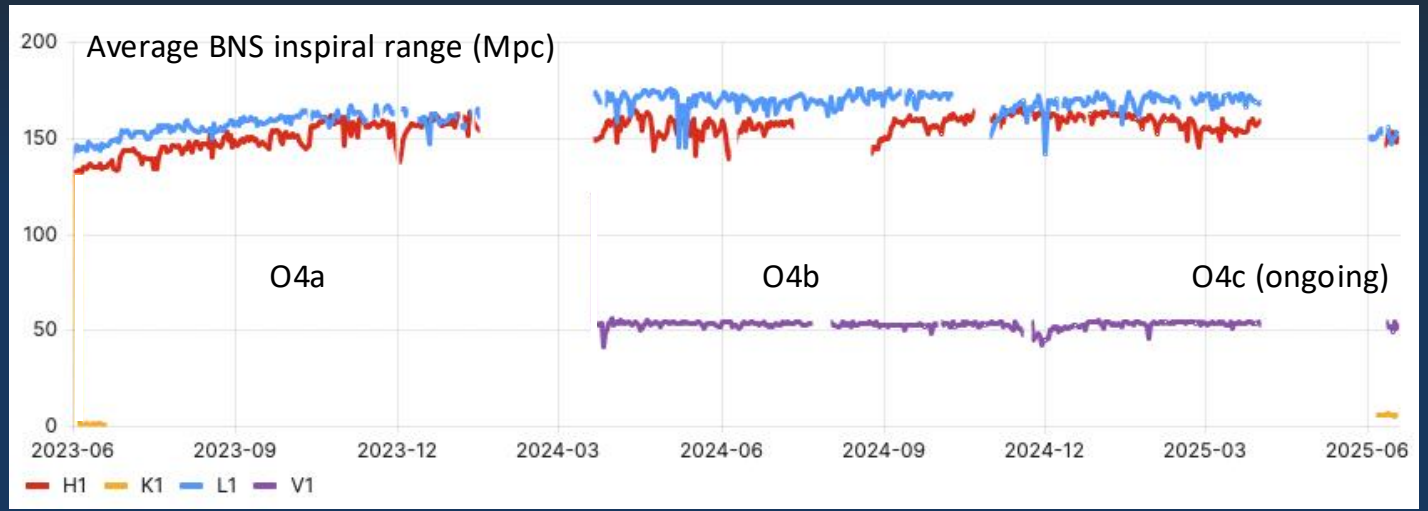
https://dcc.ligo.org/LIGO-P2100239/public
https://zenodo.org/record/5655785

O4 run : observing since May 2023



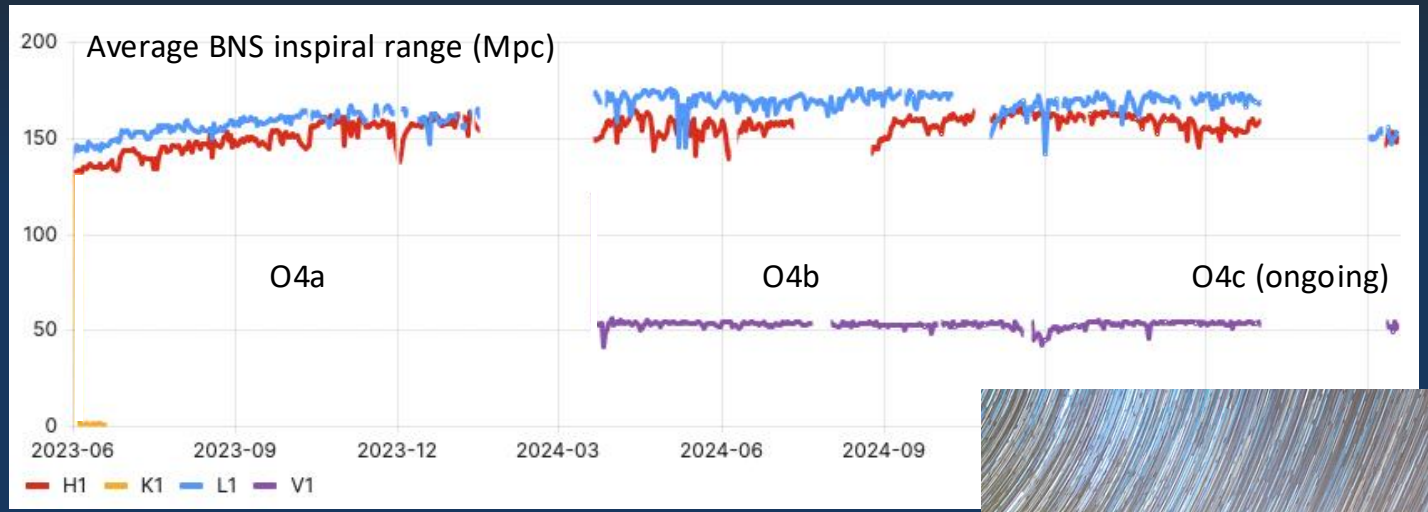
Essick+ (in prep.)

O4 run : observing since May 2023



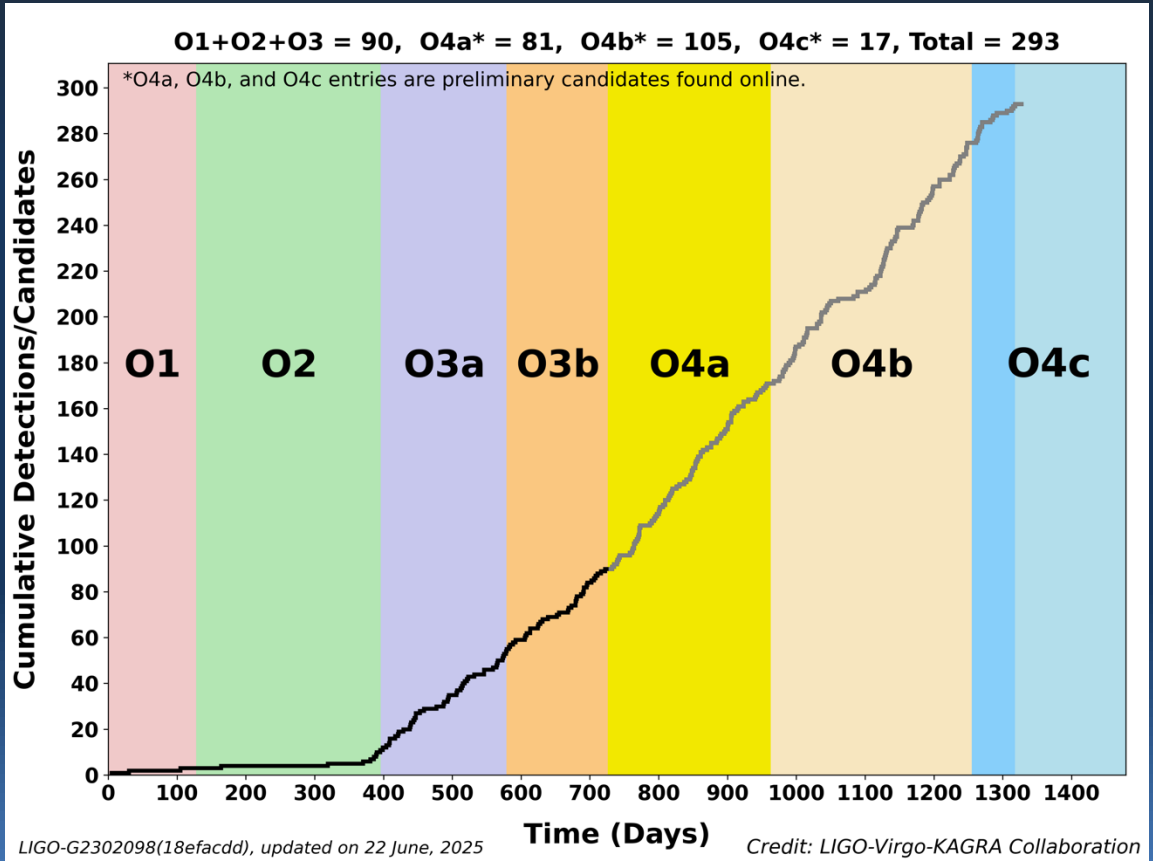
- LIGO using **frequency-dependent squeezing** of photon state
- **April 2024 : Virgo joined**

O4 run : observing since May 2023

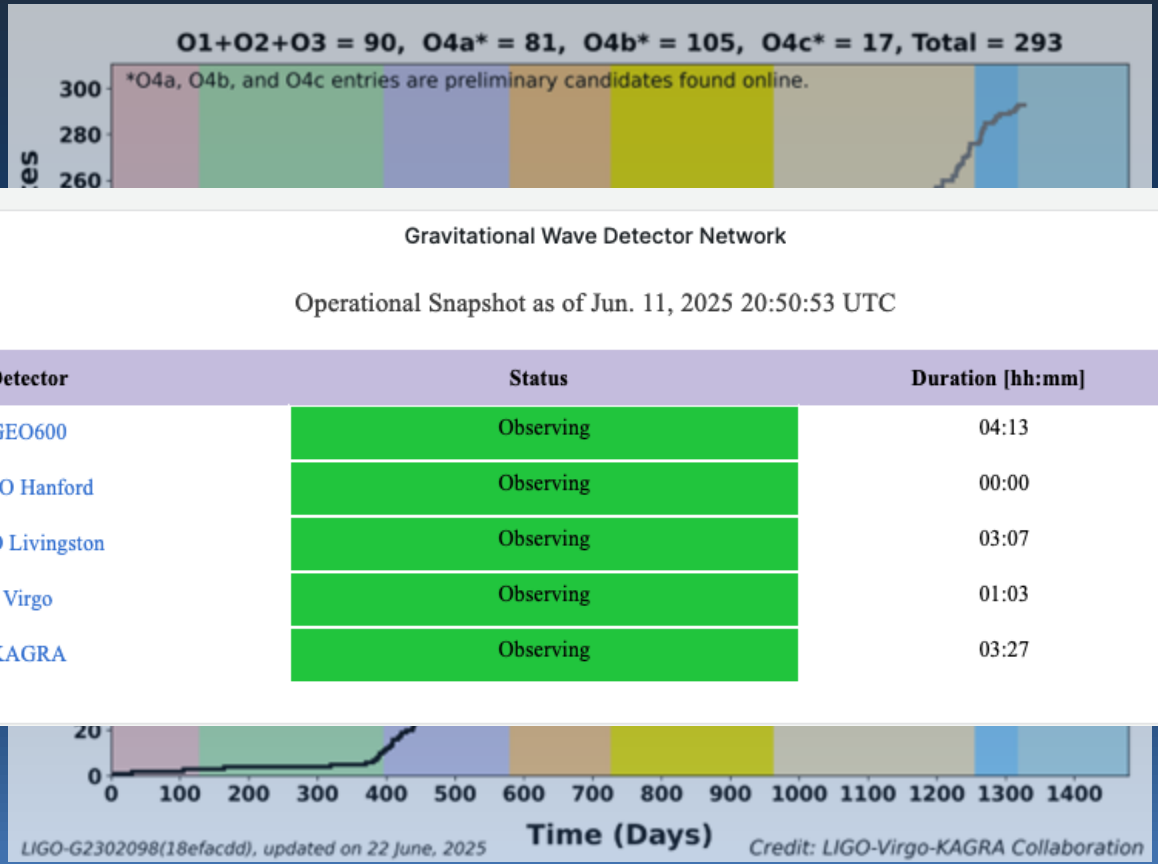


- LIGO using **frequency-dependent squeezing**
- **April 2024 : Virgo joined**
- **O4c extended through November 2025**
  - allow for preparation of O5 upgrade hardware & **joint followups with Rubin Observatory**
- KAGRA had significant setbacks from Noto Peninsula Earthquake (Jan 2024)
  - **Rejoined O4 with sensitivity ~10 Mpc**

O4 run : observing since May 2023



O4 run : observing since May 2023



Gravitational Wave Detector Network

Operational Snapshot as of Jun. 11, 2025 20:50:53 UTC

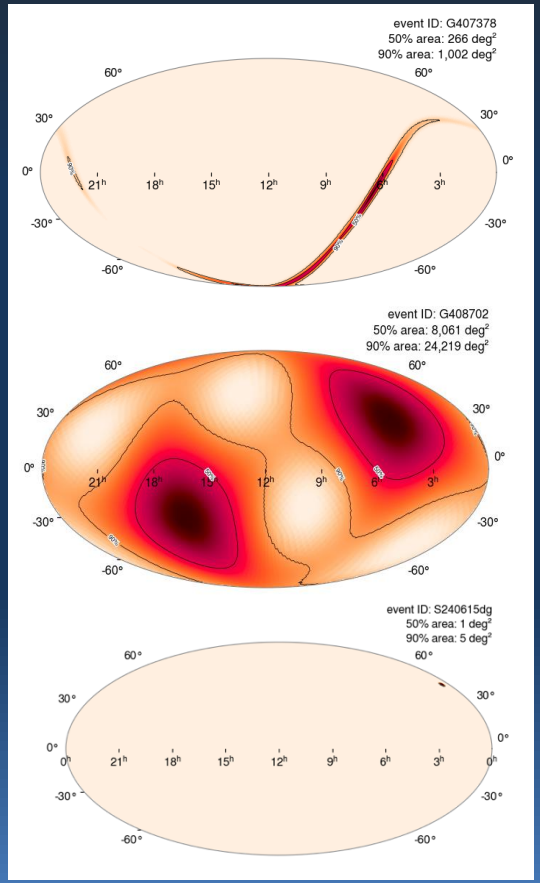
Detector	Status	Duration [hh:mm]	Latency [s]
GEO600	Observing	04:13	34
LIGO Hanford	Observing	00:00	59
LIGO Livingston	Observing	03:07	45
Virgo	Observing	01:03	52
KAGRA	Observing	03:27	21

O4 public event highlights

- *230518* : pre-run engineering data
  Probable NS-BH merger

- *230529* : single-detector event
  Another possible NS-BH merger
  (see next slide …)

- *240615* : smallest localization area
  5 deg^2 **due to 3 detectors**
  (first of 2 alerts on same day!)



https://gracedb.ligo.org/superevents/public/

GW230529 : the lightest NS-BH ?

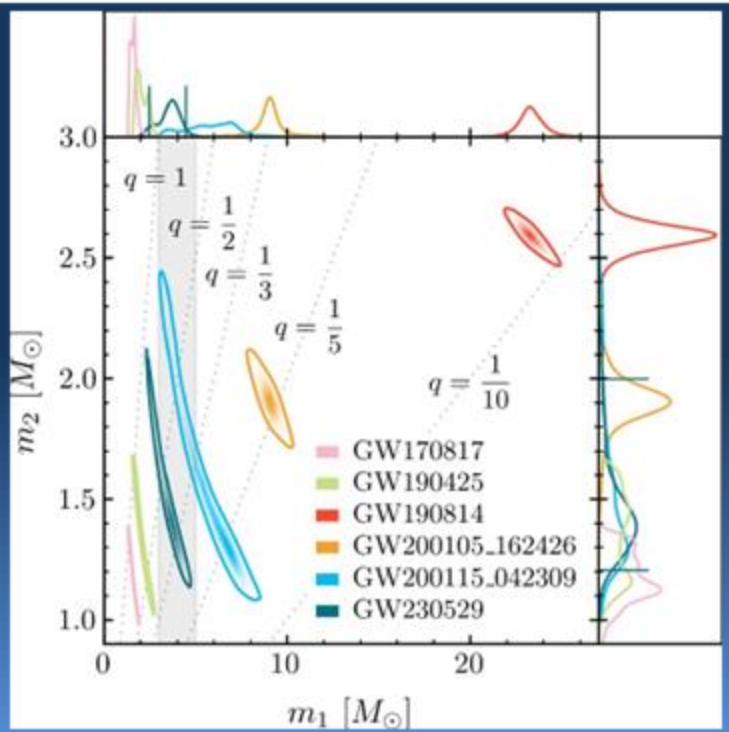
- **First publication of O4 run**

THE ASTROPHYSICAL JOURNAL LETTERS

OPEN ACCESS

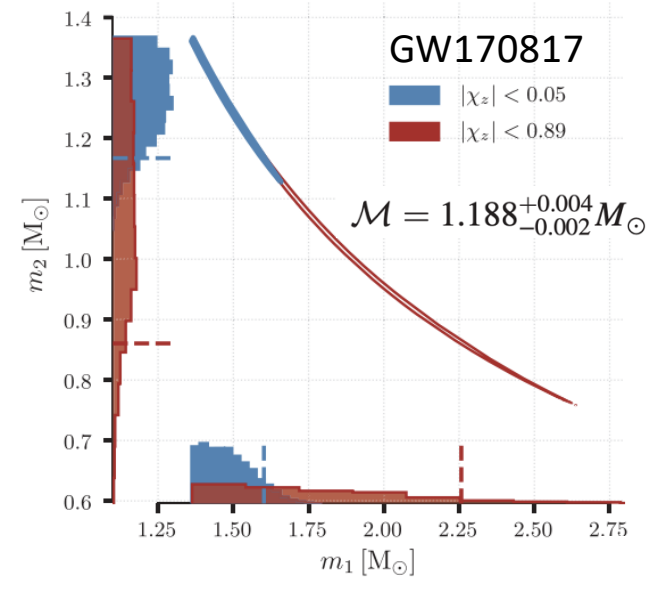
Observation of Gravitational Waves from the Coalescence of a 2.5–4.5 $M_\odot$ Compact Object and a Neutron Star

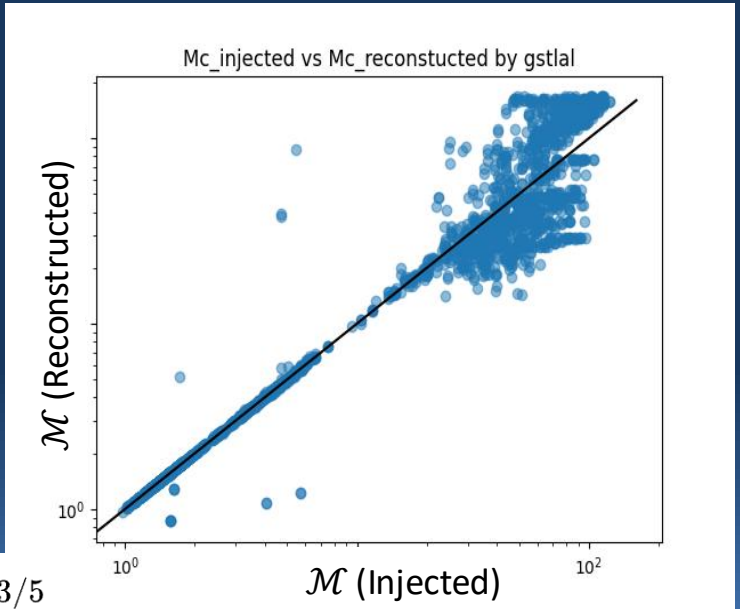
- Strengthens evidence against supposed 'mass gap' 3-5 $M_\odot$
- No direct measurement of tidal (NS matter) effects
- Increases estimated rate of future NS-BH mergers with EM emission



New for O4c : Public $\mathcal{M}$ estimates

- Precisely measured from inspiral signal in the low mass regime
- Accurately estimated by search pipelines in the low mass regime





$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$

Binned chirp mass information

New data product providing source chirp mass in the form of binned probabilities.

The predetermined bins are the following (in units of solar masses):
[0.1, 0.87, 1.0, 1.1, 1.2, 1.3, 1.4, 1.5, 1.7, 1.9, 2.1, 2.3, 3, 5.5, 11, 22, 44, 88, 1000]

Example: A chirp mass of 0.87 $M_\odot$ may correspond to a 1 $M_\odot$, 1 $M_\odot$ merger.

- Bins are 'fine' in the **HasSSM** and HasNS regime where chirp mass is recovered more accurately,
- Become coarse for higher masses in the BBH regime.

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Example: A chirp mass of 1.2 $M_\odot$ may correspond to a 1.4 $M_\odot$, 1.4 $M_\odot$ merger.
Example: A chirp mass of 3 $M_\odot$ may correspond to a 10 $M_\odot$, 1.4 $M_\odot$ merger.

- Bins are 'fine' in the HasSSM and **HasNS** regime where chirp mass is recovered more accurately
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New data product providing source chirp mass in the form of binned probabilities.

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Example: A chirp mass of 8.7 $M_\odot$ may correspond to a 10 $M_\odot$, 10 $M_\odot$ merger.
Example: A chirp mass of 44 $M_\odot$ may correspond to a 50 $M_\odot$, 50 $M_\odot$ merger.

- Bins are 'fine' in the HasSSM and HasNS regime where chirp mass is recovered more accurately
- Become coarse for higher masses in the **BBH** regime.

Integration into public alerts

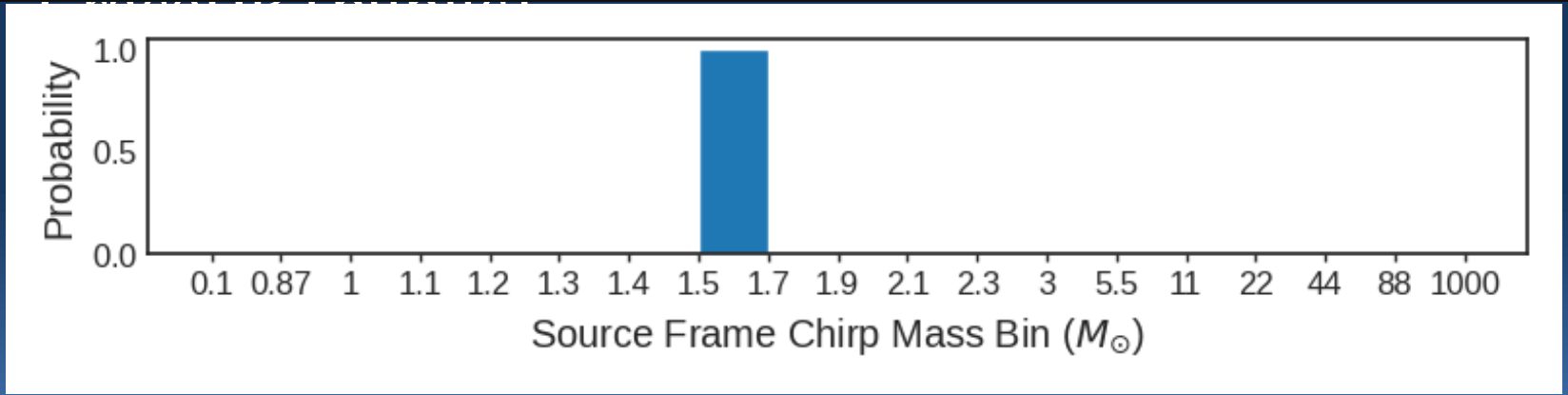
- The most probable bin is reported in the GCN circular

- .json of all bin probabilities and .png histogram on GraceDB (public)
  - Low-latency estimate available in ~seconds along with em-bright+p(astro) : `mchirp_source.json`
  - PE estimate available alongside update alert within ~hour(s) : `mchirp_source_PE.json`

Integration into public alerts

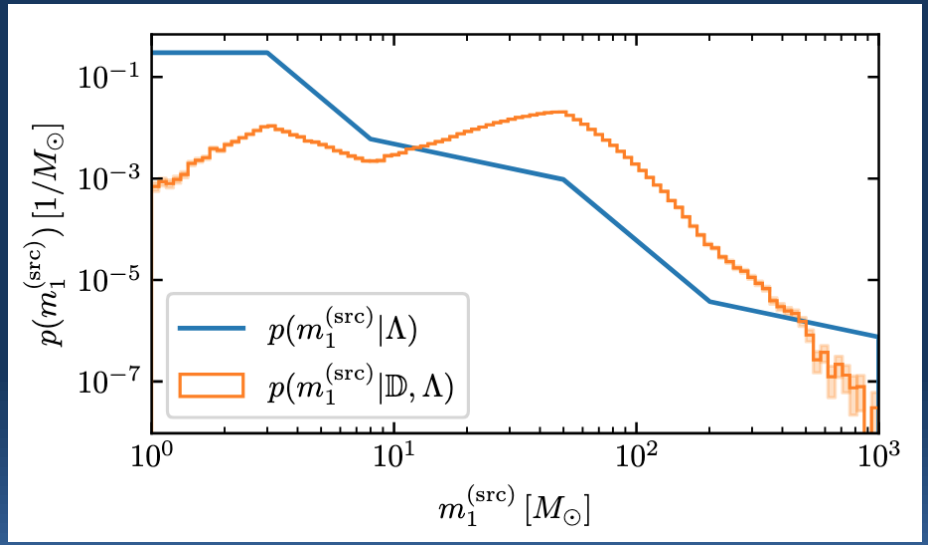
- The most probable bin is reported in the GCN circular


```
{
  "bin_edges": [0.1, 0.87, 1, 1.1, 1.2, 1.3, 1.4, 1.5, 1.7, 1.9, 2.1, 2.3, 3, 5.5, 11, 22, 44, 88, 1000],
  "probabilities": [0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1, 0, 0, 0, 0, 0]
}
```

CBC detection capabilities in O4a

- Extensive injection (simulated signal) campaign for CBC searches



Essick et al. in prep

CBC detection capabilities in O4a

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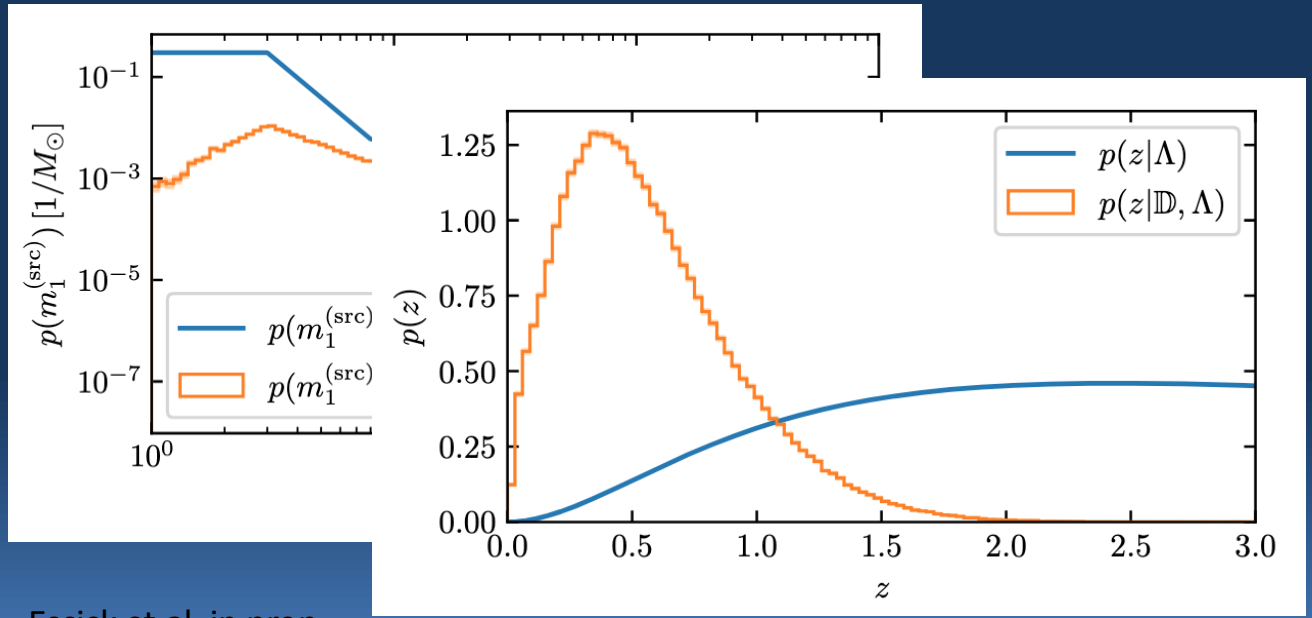

Essick et al. in prep

CBC detection capabilities in O4a

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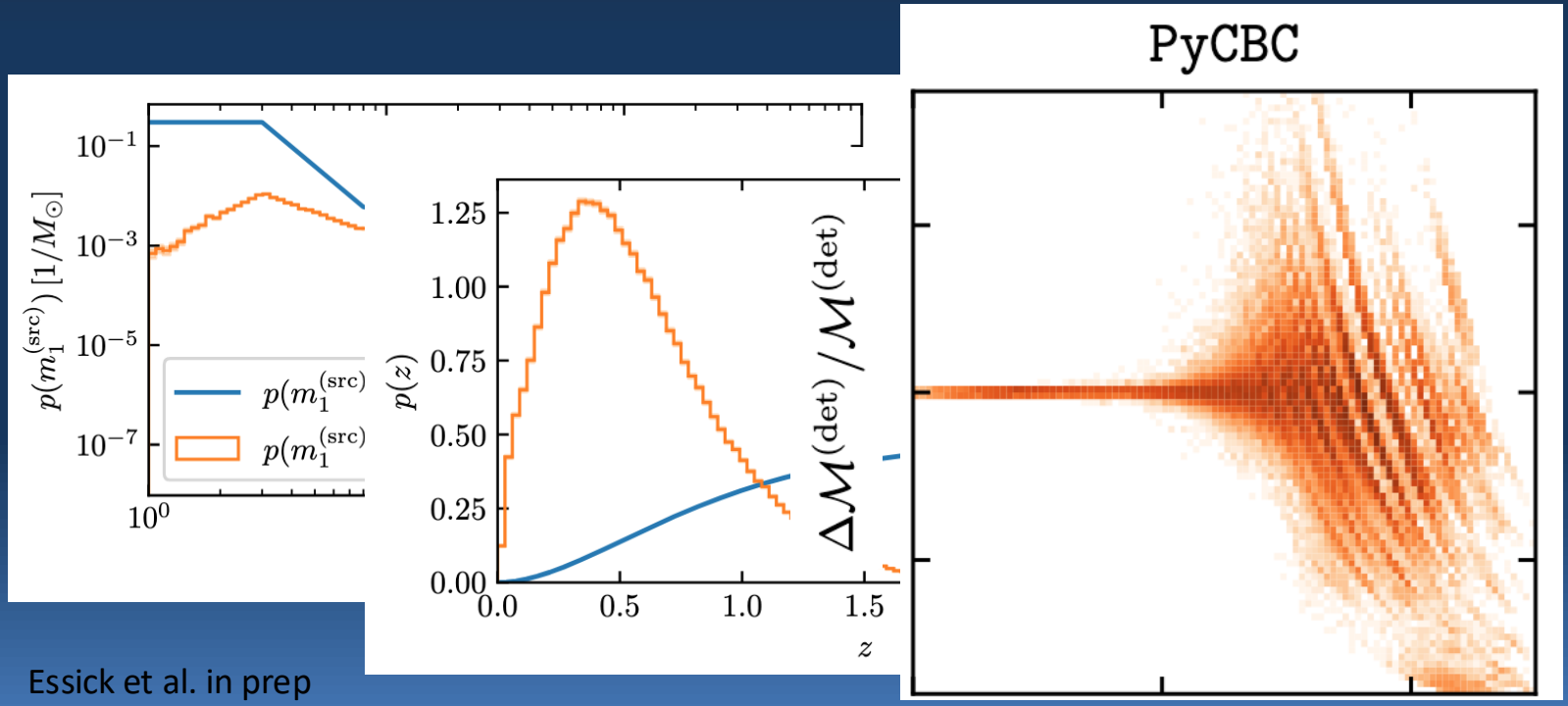


Essick et al. in prep

“What We Did Over The Summer Holidays”

Many upcoming O4a LVK papers (O4a data release late Aug.)
… watch this space !

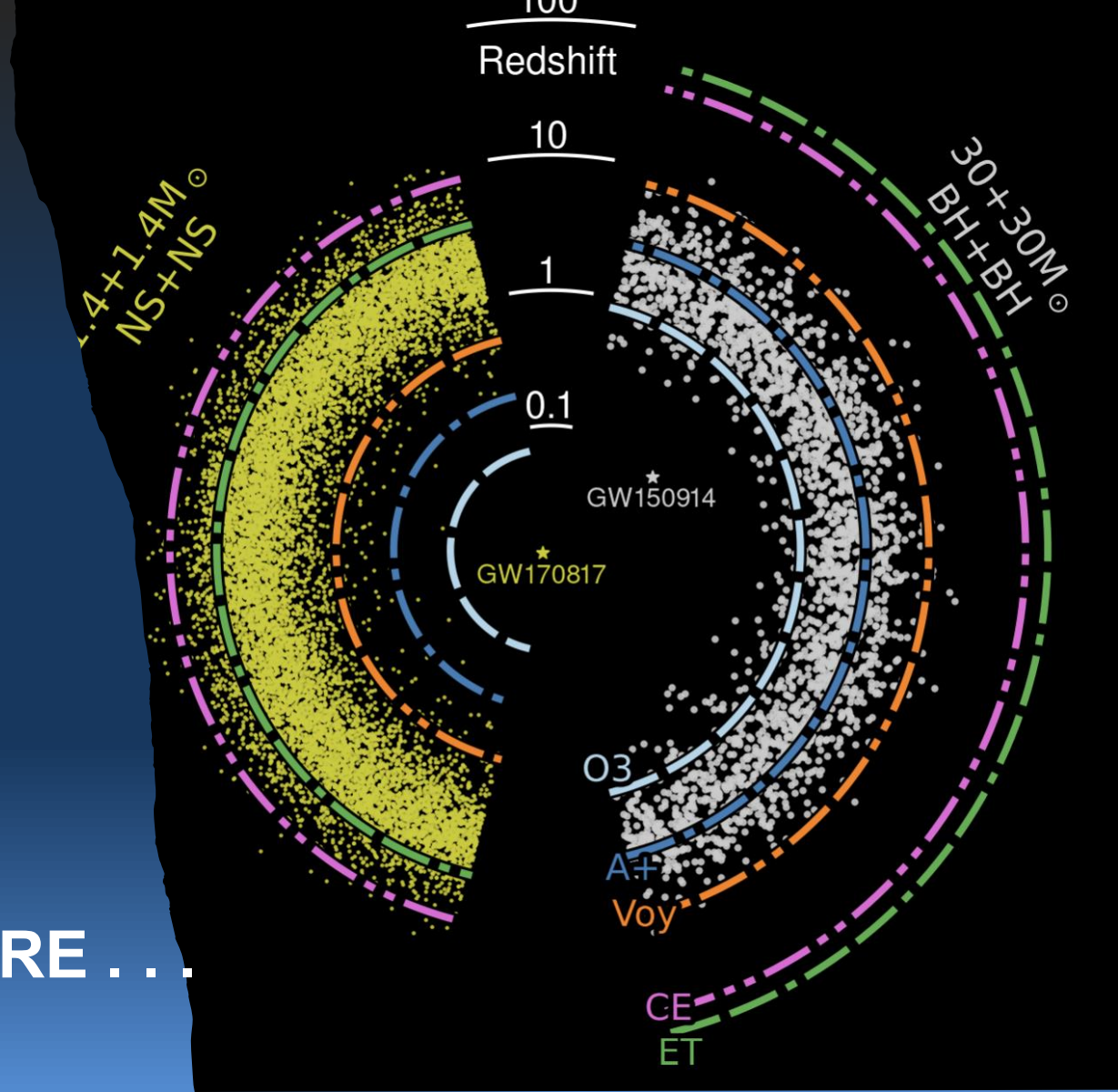
- Transient detection catalog : introduction, methods, results
- Burst, stochastic, continuous wave, sub-solar-mass CBC searches
- Population properties of CBC sources
- H0 measurement using CBC sources
- Tests of GR and search for GW lensing with CBC sources
- Exceptional event paper(s)

Some examples of exceptional events would be one that yields:

- a binary with a sub-solar-mass component;
- other astrophysically interesting component masses (large mass ratio, large black hole mass, large neutron star mass, etc.);
- clear statement on neutron star equation of state;
- measurement of a high-spin system;
- clear evidence of orbital eccentricity;
- a multi-messenger counterpart (externally-triggered or in electromagnetic/neutrino follow-up searches);
- substantial improvement in the measurement of the Hubble constant;
- clear evidence of deviation from general relativity;
- a gravitationally lensed gravitational wave detection;
- clear indication of a particular formation channel.
- first detection or finding signs of a signal with KAGRA.

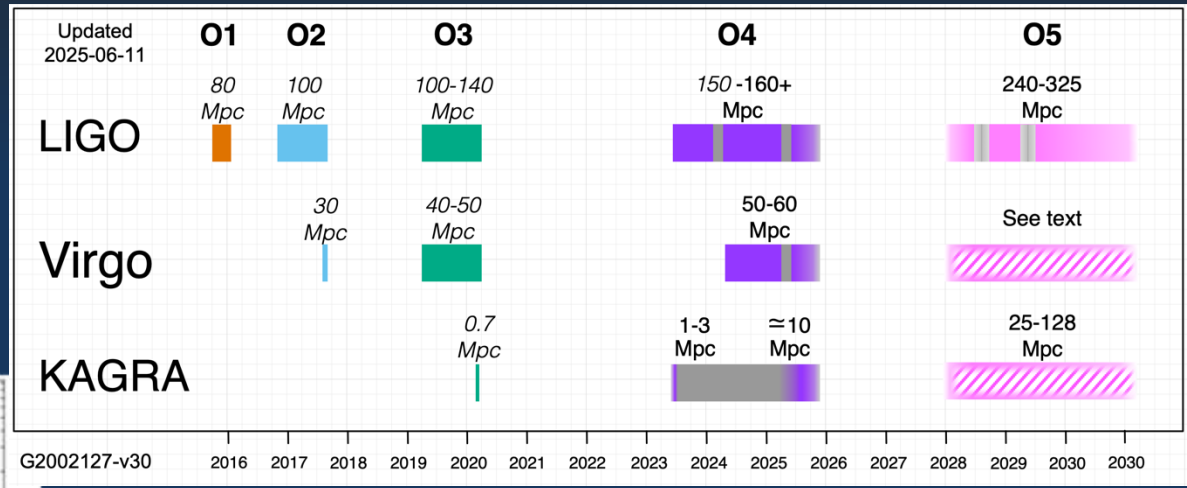
LVK Observational WP 2024-5 https://dcc.ligo.org/LIGO-T2400403/public

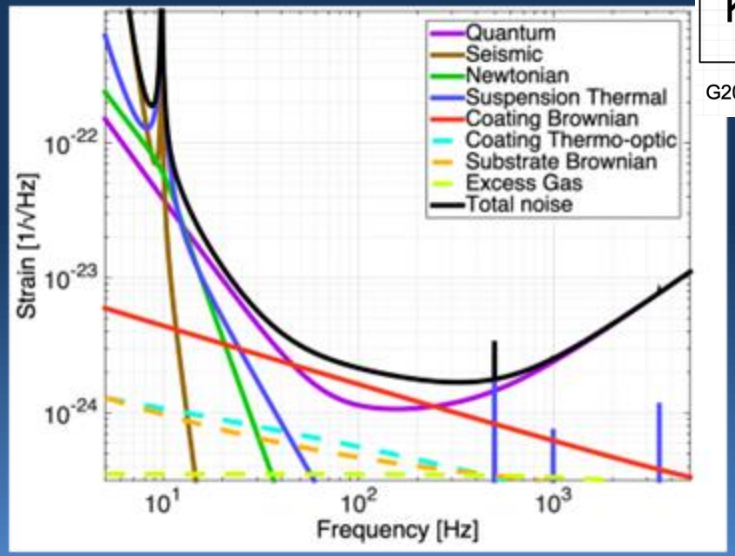
INTO THE FUTURE . . .



O5 : the 'A+' design

- Mid-scale upgrade of original 'Advanced LIGO'





LIGO-T1800042

- Most critical technology : **improved mirror coatings** to deal with higher arm power
- Virgo O5 plans currently under reassessment

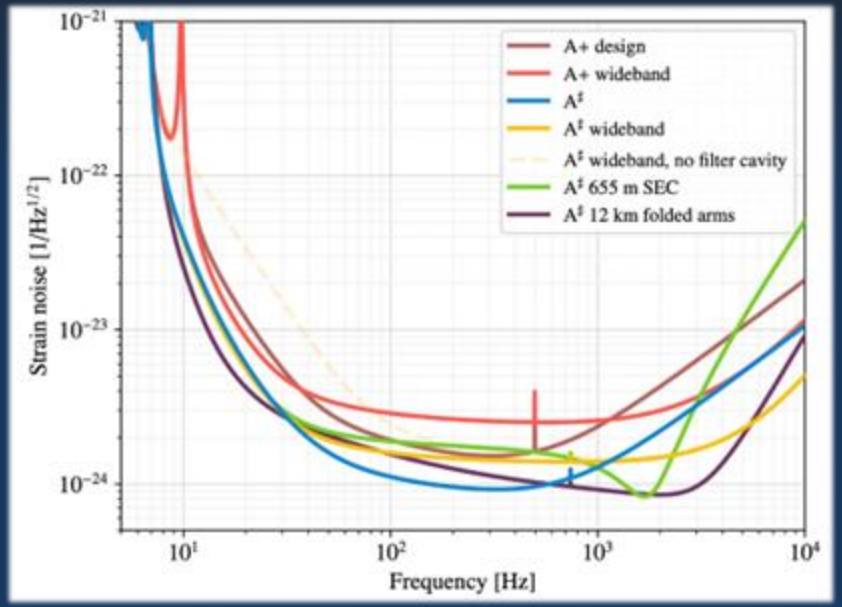
https://observing.docs.ligo.org/plan/

Post-O5 : A# / Virgo_nEXT /...

- Upgrades exploiting existing facilities to the limit
- Targets **factor ~2 increase in range** over O5
- Stepping stone to future detector technologies

Design parameter	A+	A♯	CE
Arm length	4 km	4 km	20 km, 40 km
Arm power	750 kW	1.5 MW	1.5 MW
Squeezing level	6 dB	10 dB	10 dB
Test mass mass	40 kg	100 kg	320 kg
Test mass coatings	A+	A+/2	A+
Suspension length	1.6 m	1.6 m	4 m
Newtonian suppression	0 db	6 db	20 db

D. Reitze, https://www.nsf.gov/mps/phy/nggw/present_ligo.pdf



- Fill gap in observational capability to 'next generation' of observatories
- **LIGO-India : LIO,** Aundha planned to operate early 2030s

Conclusions

- O4 run underway with Virgo & KAGRA ⇒ Nov 2025
- Lots of O4a results planned for release …
- O4b catalogue and results in the pipeline

- Many discoveries remain to be made !

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