The LIGO-Virgo-KAGRA network and observations in the O4 run

POTOR 10th conference

Kazimierz Dolny, 16-20 September 2024

Thomas Dent

(IGFAE, University of Santiago de Compostela)

For the LIGO-Virgo-KAGRA collaborations

LIGO-G2401768

Image Credit: NASA/GSFC

LIGO-Virgo-KAGRA collaborations

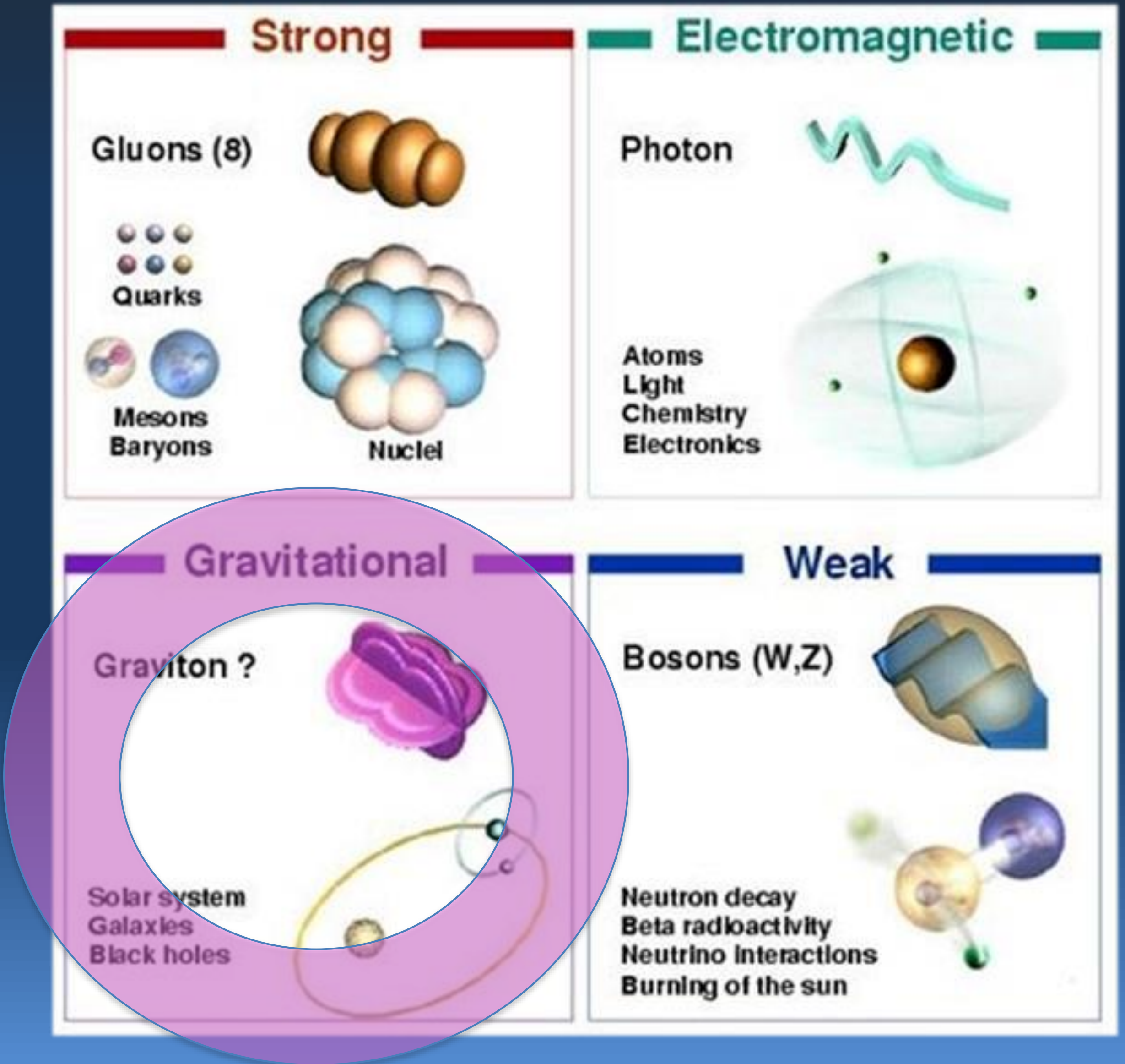
& others outside Europe !

Plan of the talk

- The weakest force : gravity
- Ground-based GW detectors & sources
- GW as a natural relativity laboratory
- LVK observations up to O3 (2015-2020)
- The O4 run (2023-2025)
- O5, XG and looking forward

Image Credit: Aurore Simonnet/SSU

4 (known) fundamental forces



Exploring the cosmos via fundamental forces

Electromagnetism : light ! ([pre-]C17 -)

- optical, UV, IR, radio, X-ray, gamma-ray

Strong force : Cosmic ray astronomy (1912 -)

Weak force : Neutrino astronomy

- solar neutrinos (1968 -)
- supernova neutrinos (1987 -)
- UHE neutrinos (2013 -)

Gravitation : **G**ravitational **W**aves (Einstein 1916)

- indirect via effects on binary pulsars (1981 -)
- **direct GW detection (2015 -)**

Einstein 1916 : Gravitational waves

Näherungsweise Integration der Feldgleichungen der Gravitation.

Von A. Einstein.

Bei der Behandlung der meisten speziellen (nicht prinzipiellen) Probleme auf dem Gebiete der Gravitationstheorie kann man sich damit begnügen, die $g_{\mu\nu}$ in erster Näherung zu berechnen. Dabei bedient man sich mit Vorteil der imaginären Zeitvariable $x_4 = it$ aus denselben Gründen wie in der speziellen Relativitätstheorie. Unter »erster Näherung« ist dabei verstanden, daß die durch die Gleichung

$$g_{\mu\nu} = -\delta_{\mu\nu} + \gamma_{\mu\nu} \qquad (1)$$

definierten Größen $\gamma_{\mu\nu}$, welche linearen orthogonalen Transformationen gegenüber Tensorcharakter besitzen, gegen 1 als kleine Größen behandelt werden können, deren Quadrate und Produkte gegen die ersten Potenzen vernachlässigt werden dürfen. Dabei ist $\delta_{\mu\nu} = 1$ bzw. $\delta_{\mu\nu} = 0$, je nachdem $\mu = \nu$ oder $\mu \neq \nu$.

Wir werden zeigen, daß diese $\gamma_{\mu\nu}$ in analoger Weise berechnet werden können wie die retardierten Potentiale der Elektrodynamik. Daraus folgt dann zunächst, daß sich die Gravitationsfelder mit Lichtgeschwindigkeit ausbreiten. Wir werden im Anschluß an diese allgemeine Lösung die Gravitationswellen und deren Entstehungsweise untersuchen. Es hat sich gezeigt, daß die von mir vorgeschlagene

radialer Symmetrie ($J_{11} = J_{22} = J_{33}$; $J_{23} = J_{31} = J_{12} = 0$) mit (20) überein. Man erhält aus ihm also die Ausstrahlung A des Systems pro Zeiteinheit durch Multiplikation mit $4\pi R^2$:

$$A = \frac{\varkappa}{24\pi} \sum_{\alpha\beta} \left(\frac{\partial^3 J_{\alpha\beta}}{\partial t^3} \right)^2. \qquad (21)$$

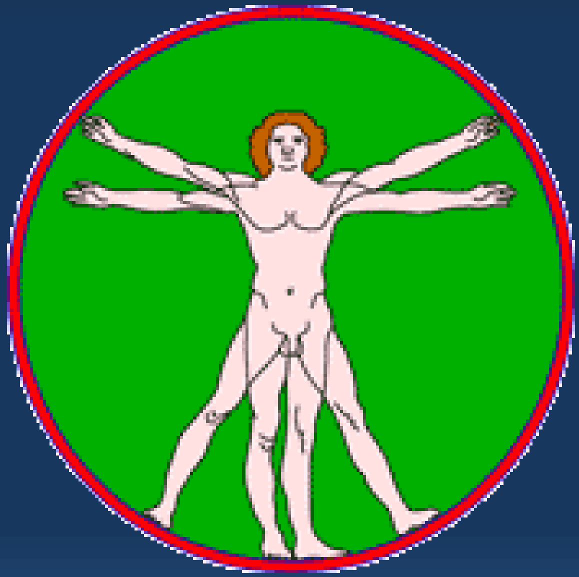
Würde man die Zeit in Sekunden, die Energie in Erg messen, so würde zu diesem Ausdruck der Zahlenfaktor $\frac{1}{c^4}$ hinzutreten. Berücksichtigt man außerdem, daß $\varkappa = 1.87 \cdot 10^{-27}$, so sieht man, daß A in allen nur denkbaren Fällen einen praktisch verschwindenden Wert haben muß.

$$G_{m} = \frac{8pG}{c^4} T_{m}$$

$\sim 10^{-43}$

- Linearized approximation
- GW propagate with light speed
- GW emission "**vanishingly small in all conceivable cases**"

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*

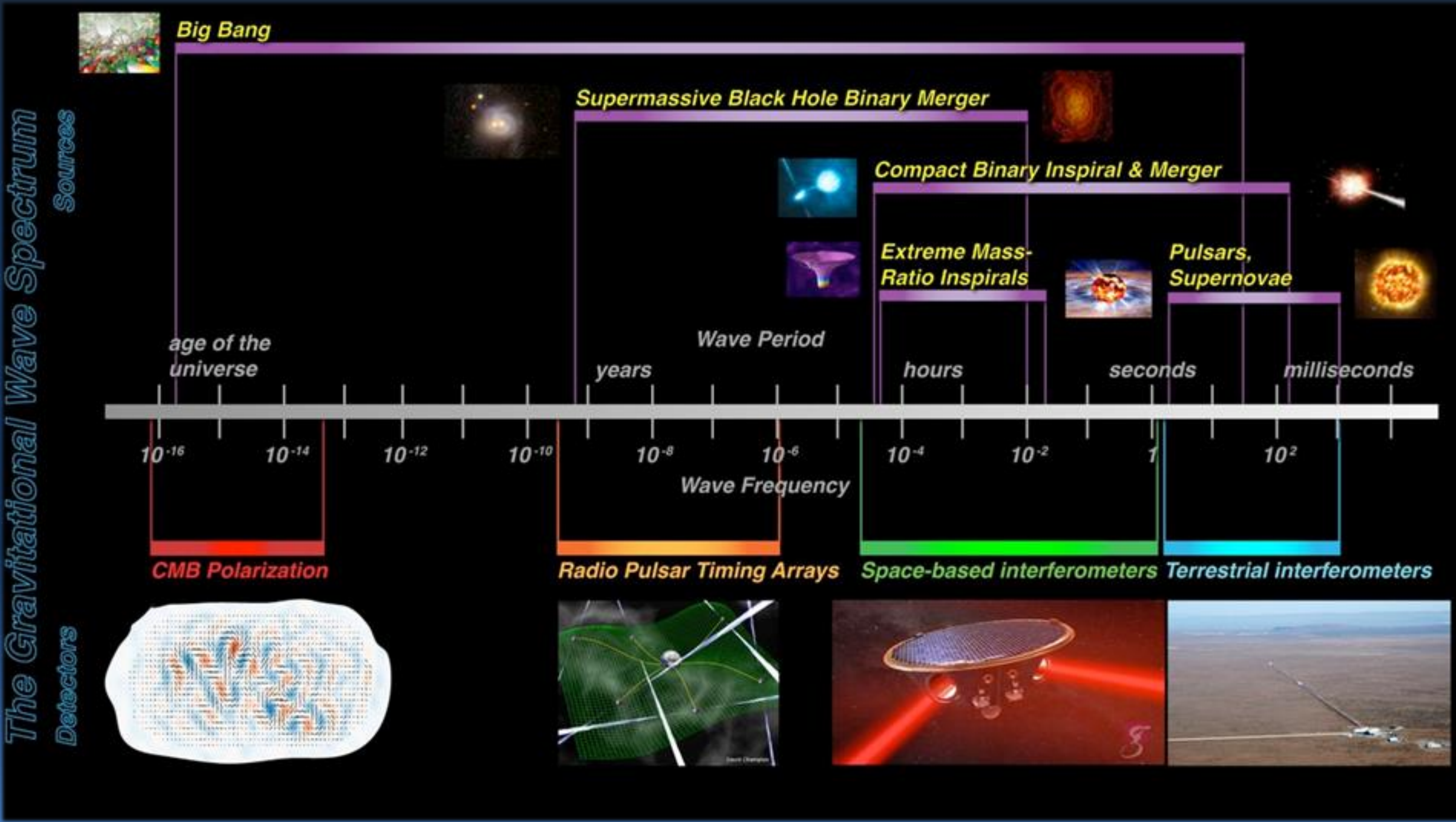
Strain $h(t) \sim \dfrac{\delta L(t)}{L}$

GW are really small !

- Closest known **n**eutron **s**tars 10^2 – 10^3 pc away (scale of Galaxy $\sim 10^4$ kpc)
- Most efficient GW emitters are *compact binaries* e.g. binary NS

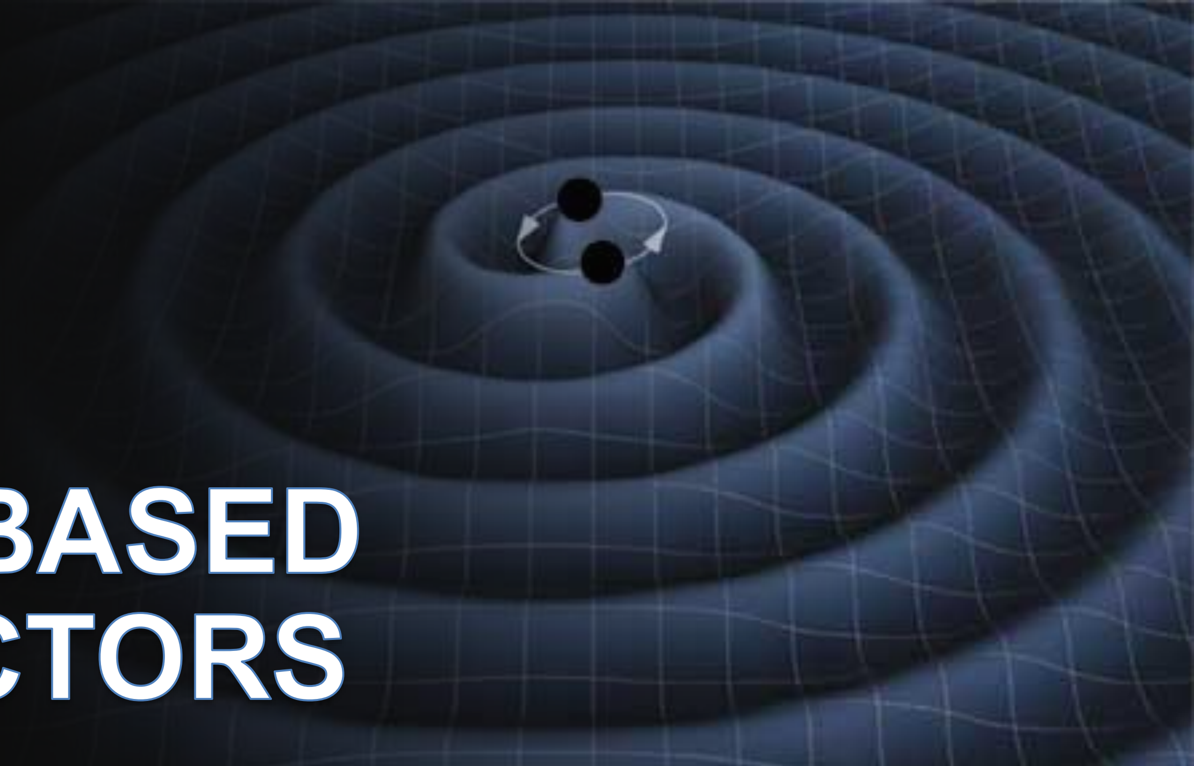
$$h(r) \approx 10^{-22} \left(\frac{M}{2.8\, M_\odot} \right)^{5/3} \left(\frac{0.01\ \mathrm{s}}{P} \right)^{2/3} \left(\frac{100\ \mathrm{Mpc}}{r} \right)$$

The broad spectrum of GW



NASA / Ira Thorpe

GROUND-BASED GW DETECTORS

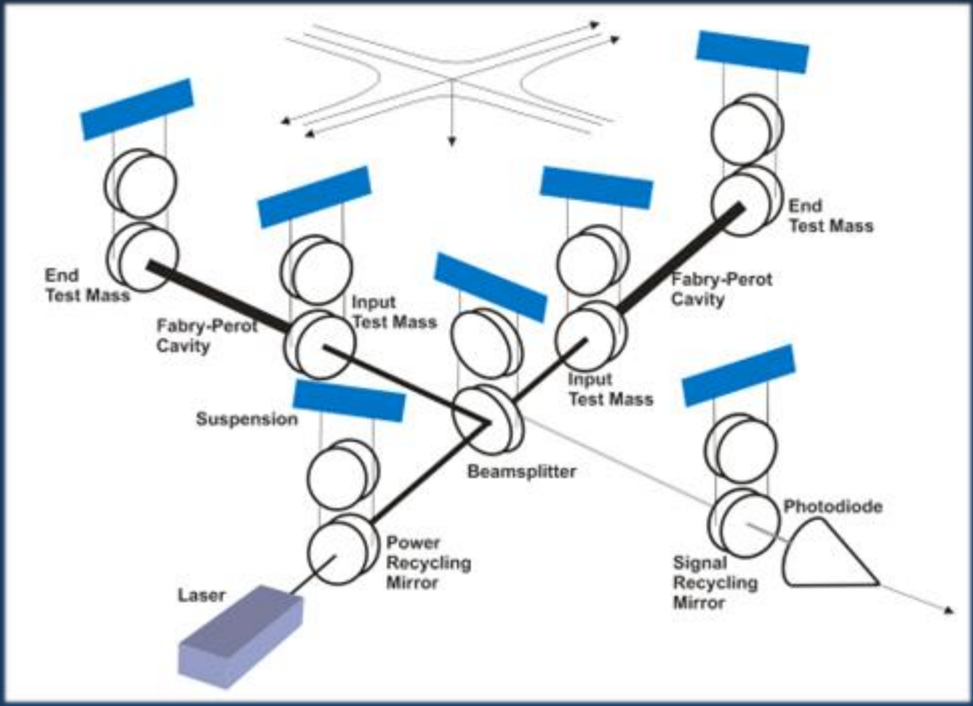


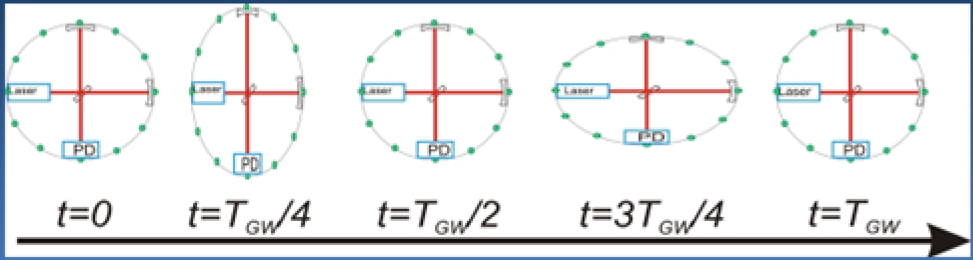
Laser interferometric detection

- ‘Michelson interferometer’ **end mirrors** free to move along arms

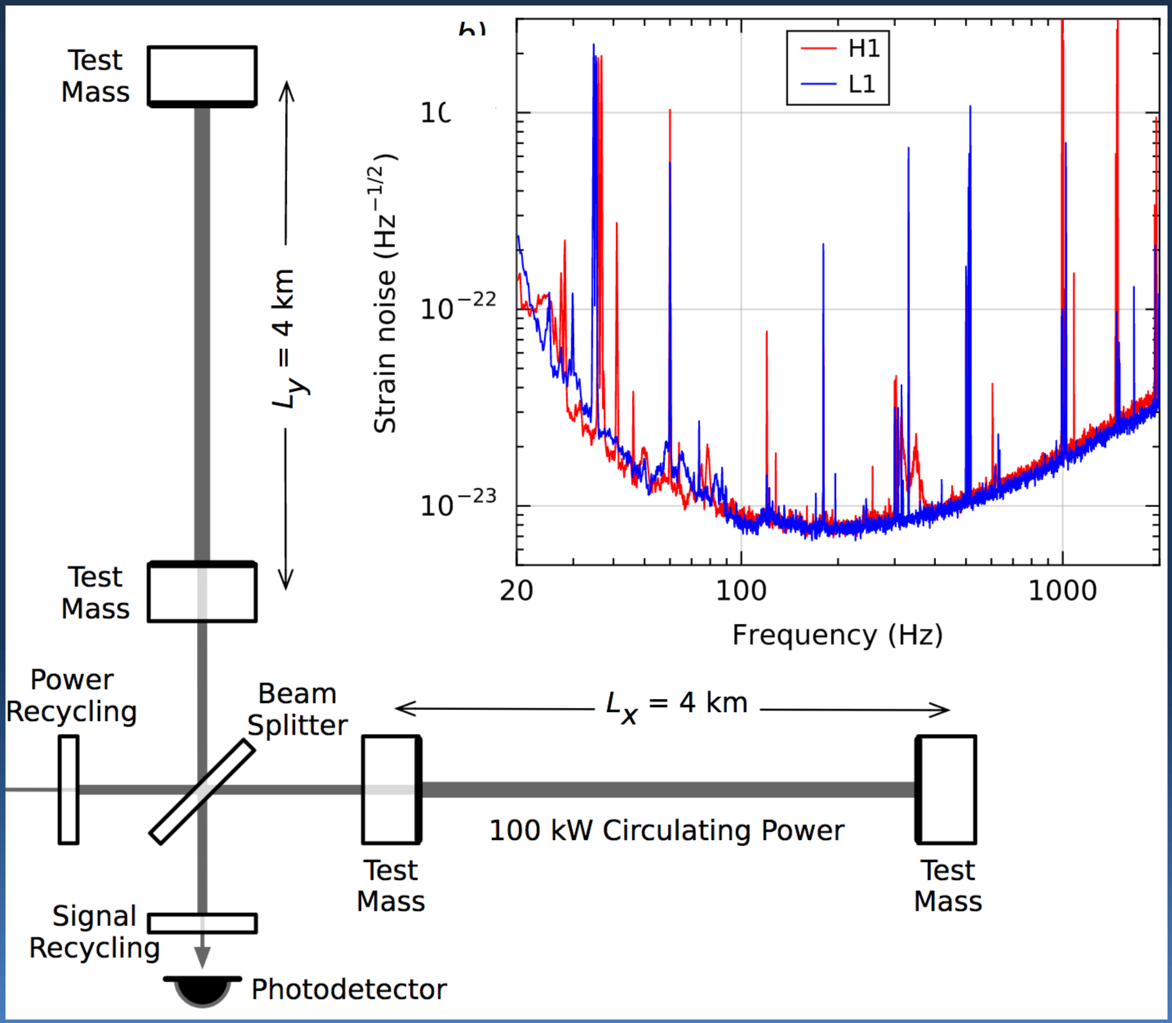
- Differential length change
  $\delta(L_x - L_y) = h(t) \cdot L$

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





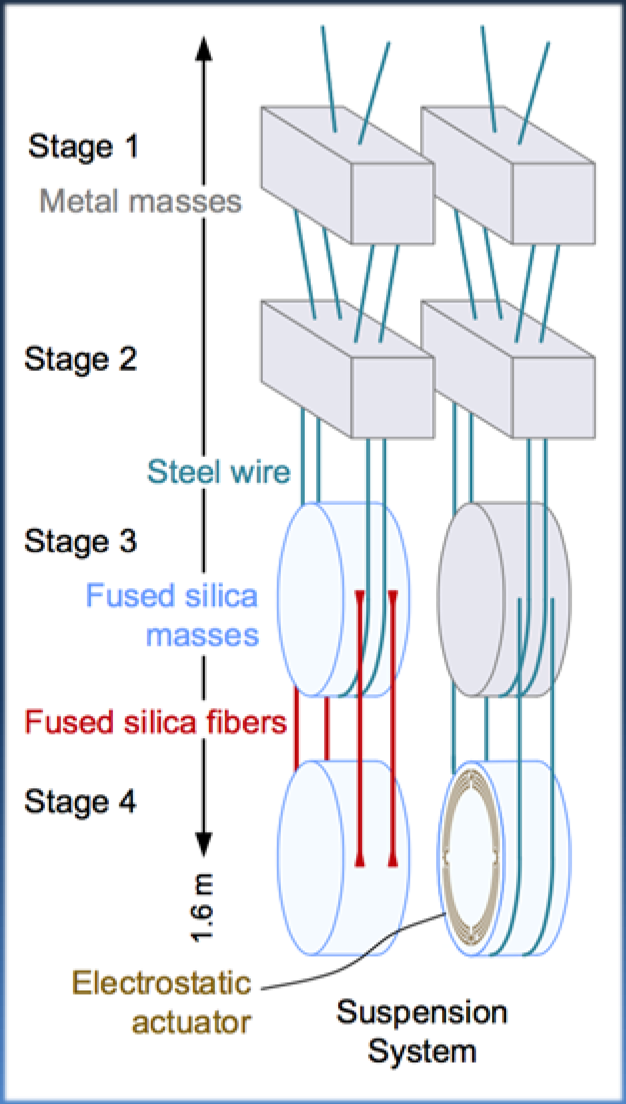
Down to <1e–23: Enhance the signal



- 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

→ ΔL(f)

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

II. Sensing Noises

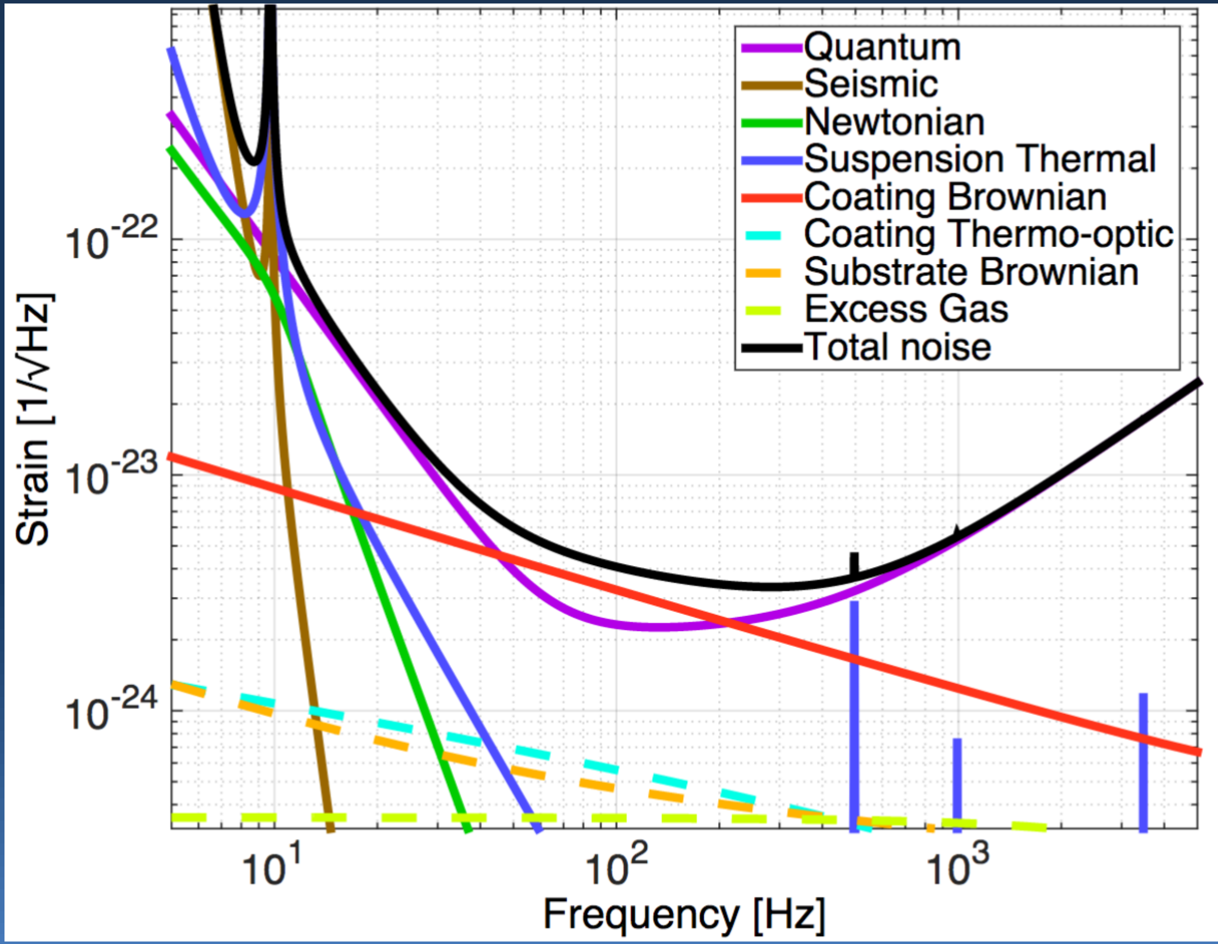
→ $\Delta t_{photon}(f)$

- Shot Noise
- Residual Gas

Technical Noises

→ *Hundreds of them …*

Advanced LIGO Design Noise Budget

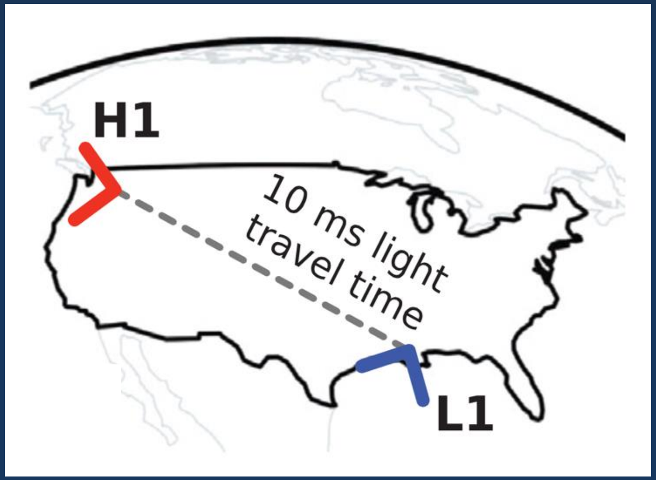


https://dcc.ligo.org/LIGO-T1800044/public

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



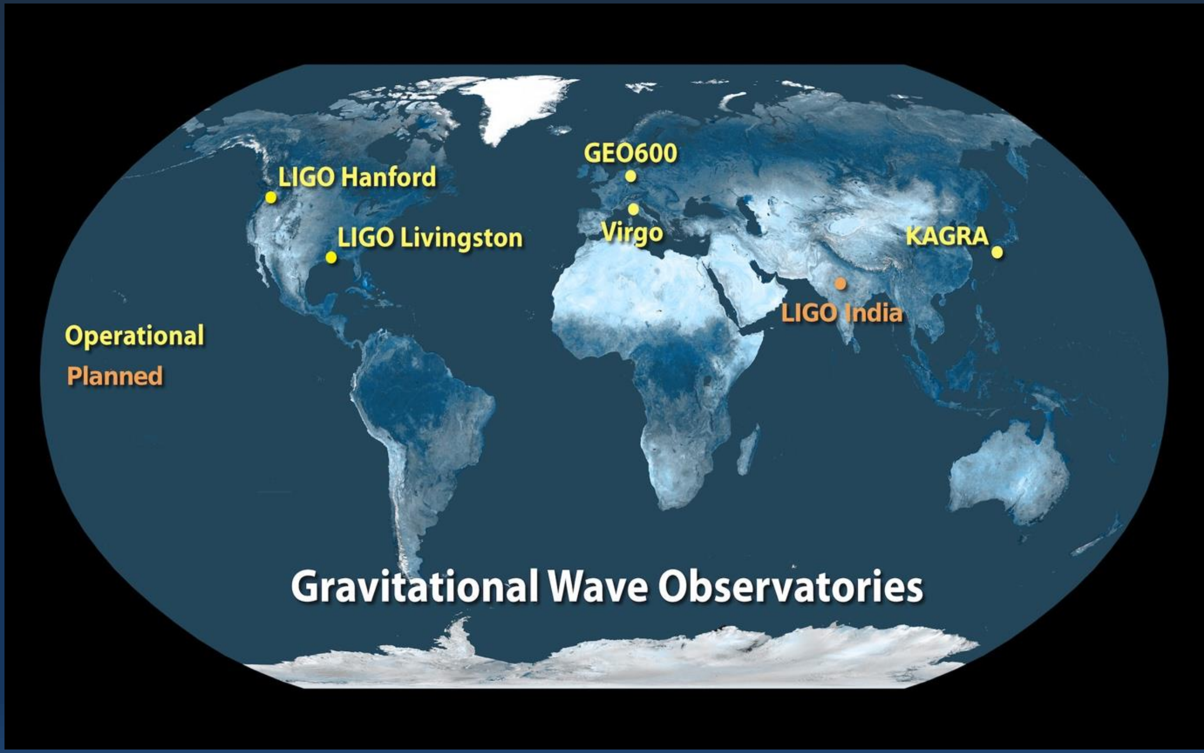


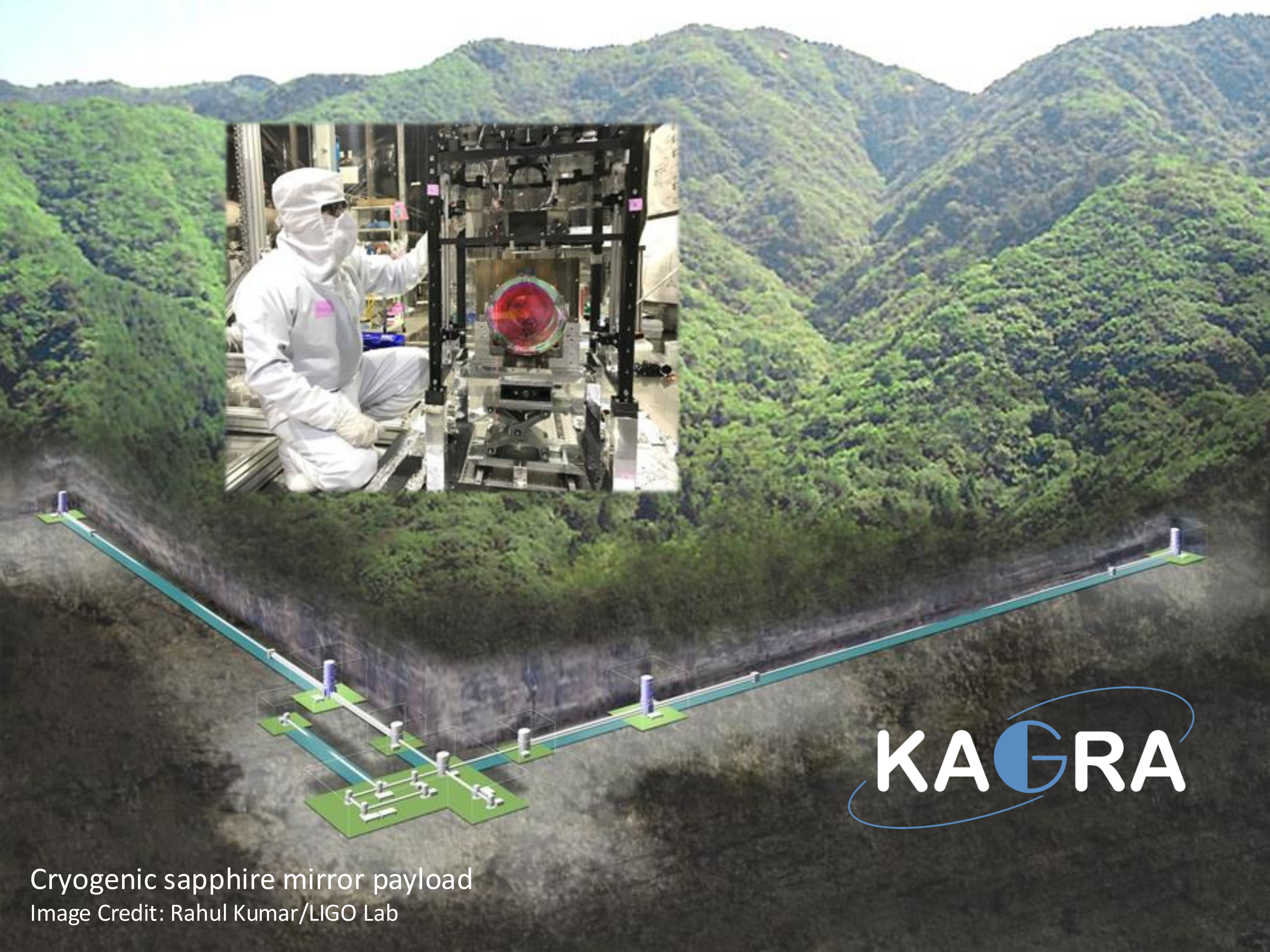
Image credit: LIGO Lab

- 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

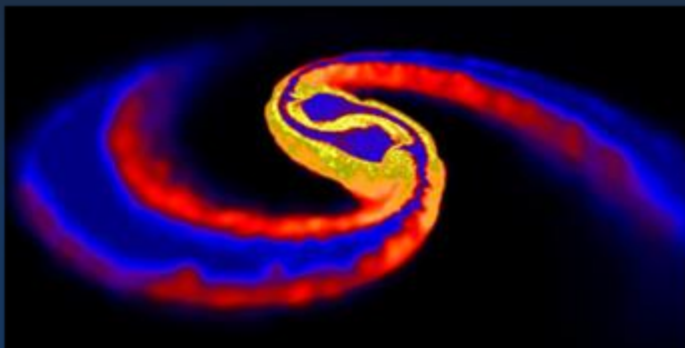
~915 collaboration members



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

Transient GW sources

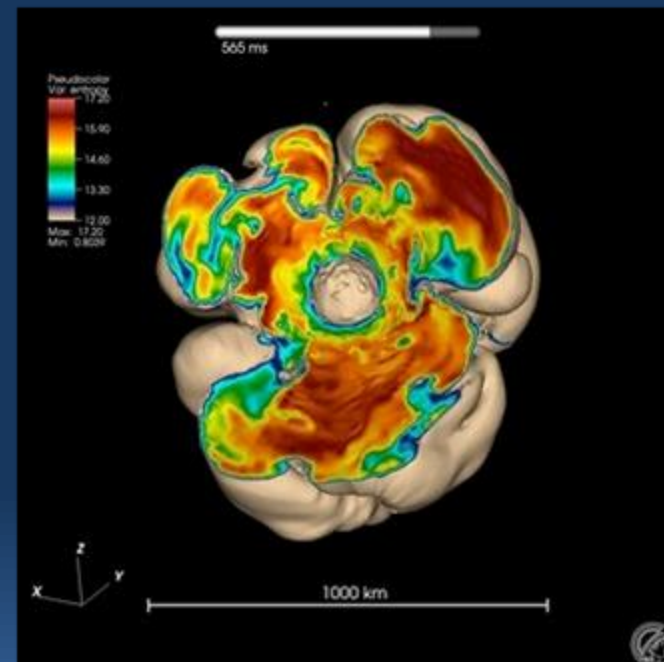
***Highly relativistic** systems ...*



CBC

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

Burst



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

Cataclysmic events of compact astrophysical objects

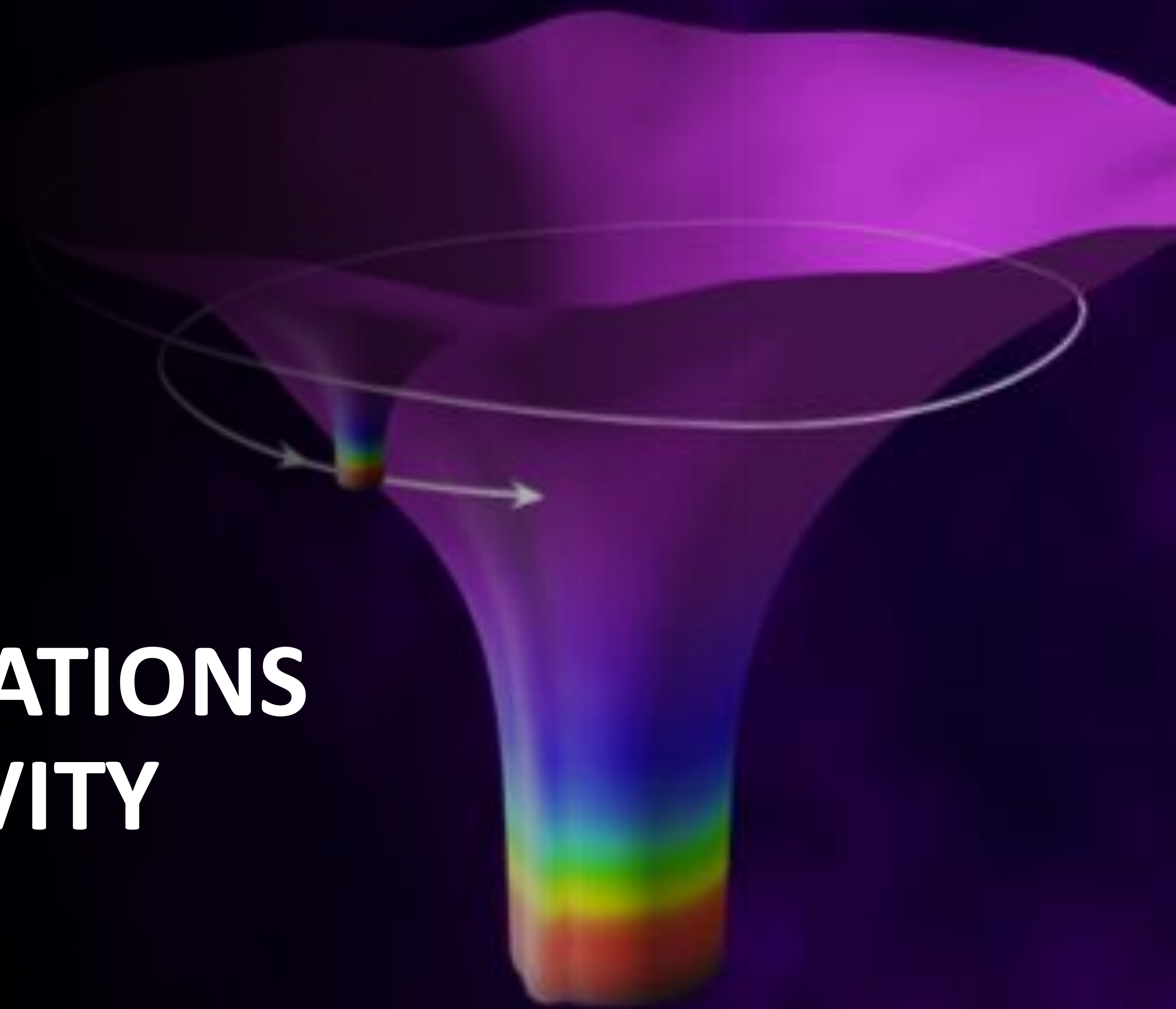
- **N**eutron**S**tar / **B**lack**H**ole binary mergers
- **C**ore**C**ollapse**S**uper**N**ovae
- Pulsar glitches / oscillation modes ?
- Exotics : cosmic string kinks ? ...

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



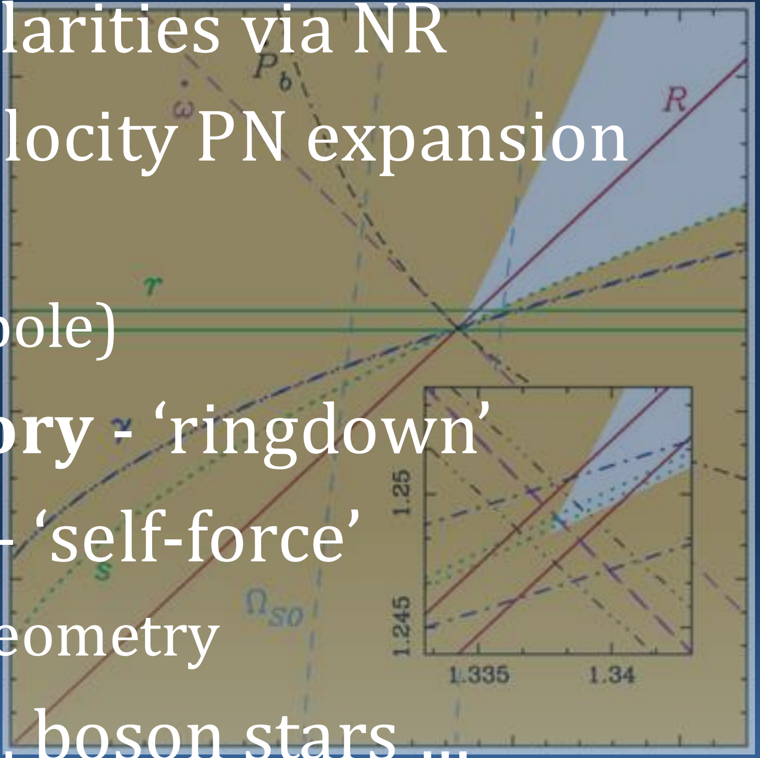
GW OBSERVATIONS AND RELATIVITY

‘Non-GW’ probes of GR

- GR light deflection
- Perihelion shift of Mercury
- Solar System tests (Lunar Laser Ranging …)
- (Strong) Equivalence Principle tests
- Precision clock measurements, GPS, …
- Dynamics of galaxies & galaxy clusters, cosmological tests

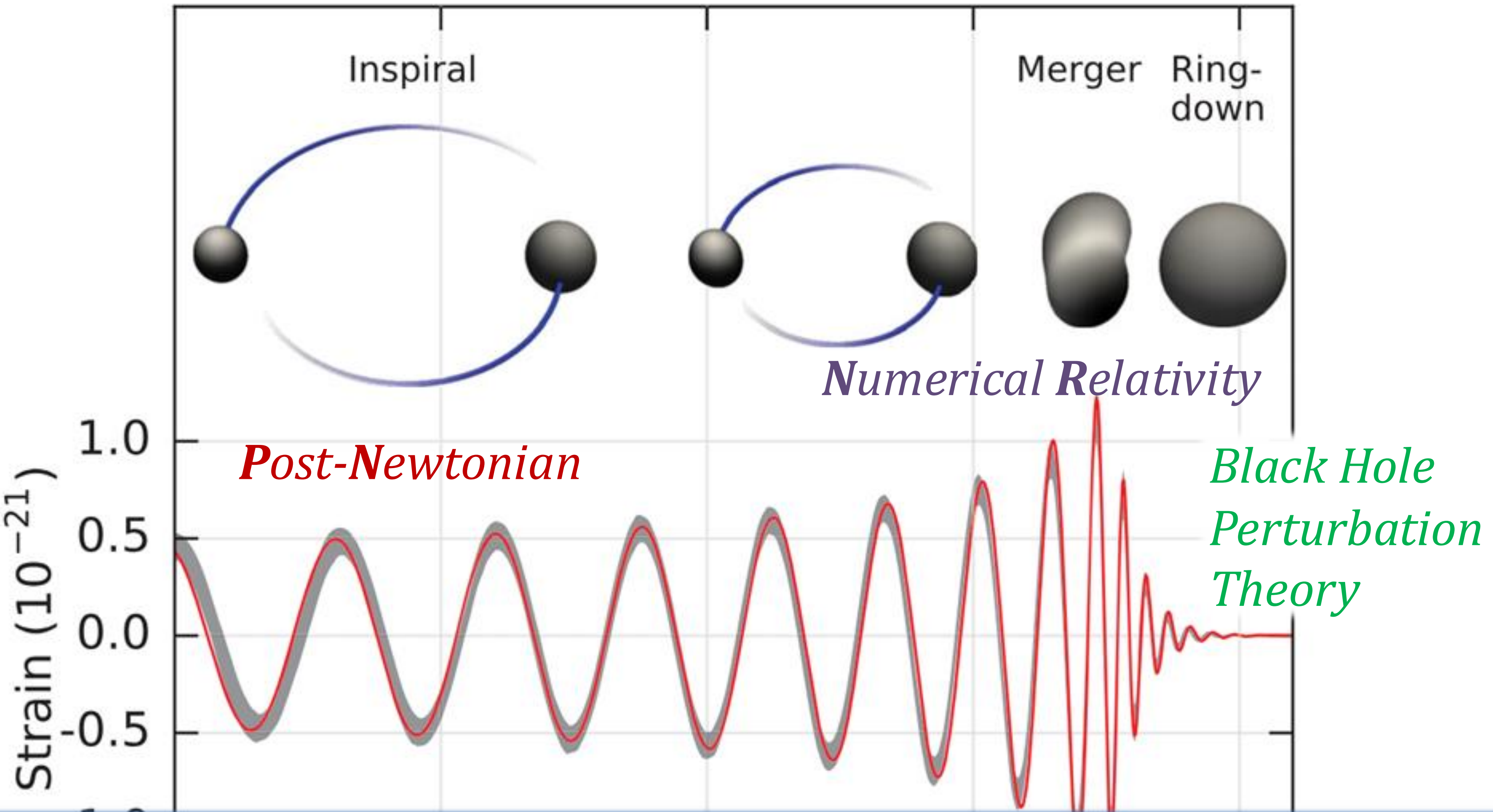
Exploring general relativity with GW sources

- **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)

Anatomy of a binary merger



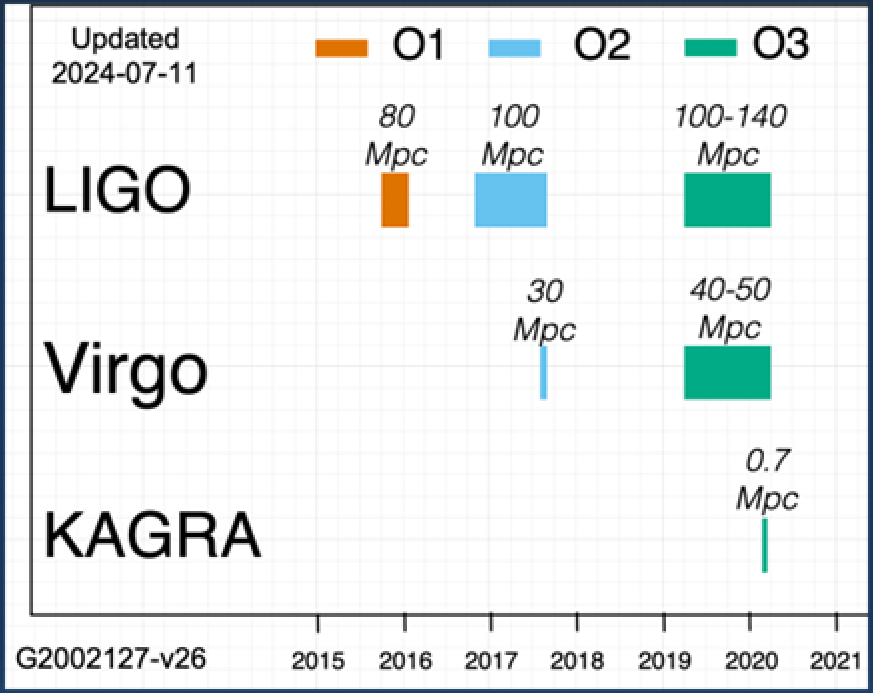
Exploring general relativity with GW propagation

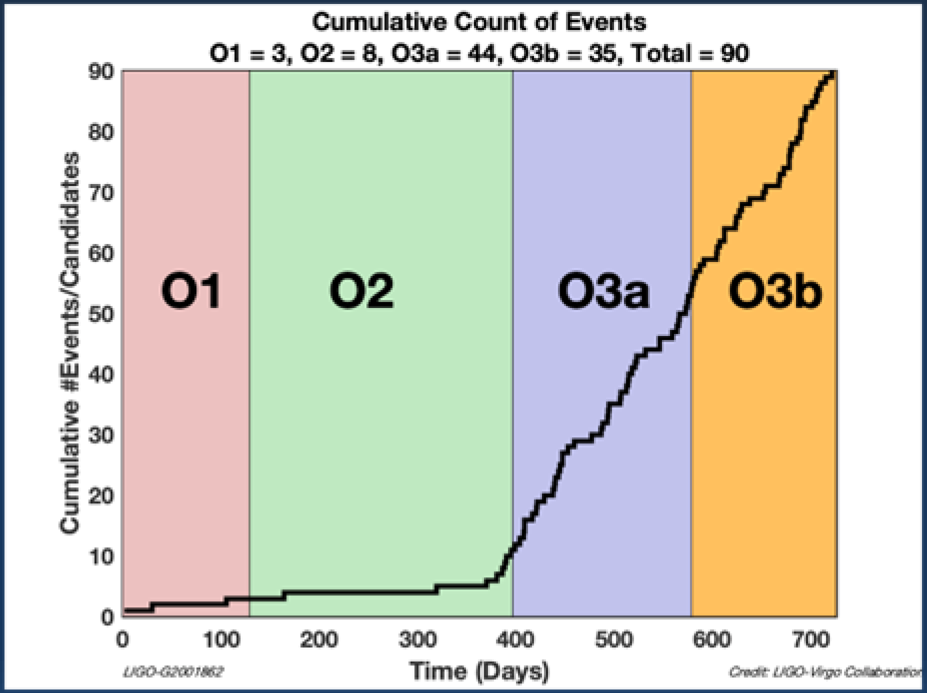
- **Verify 2 transverse tensor polarizations**
- **Verify speed of GW propagation**
  - Multi-messenger events with prompt emission [GW170817 !]
- **Constrain non-GR dispersion** (eg graviton mass)
- (‘Strong’ or ‘Weak’) **Gravitational Lensing** of GW
  - Amplification of signal
  - Multiple transient “images”, other possible effects

LVK : HIGHLIGHTS UP TO O3

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

LIGO-Virgo observations up to 2020



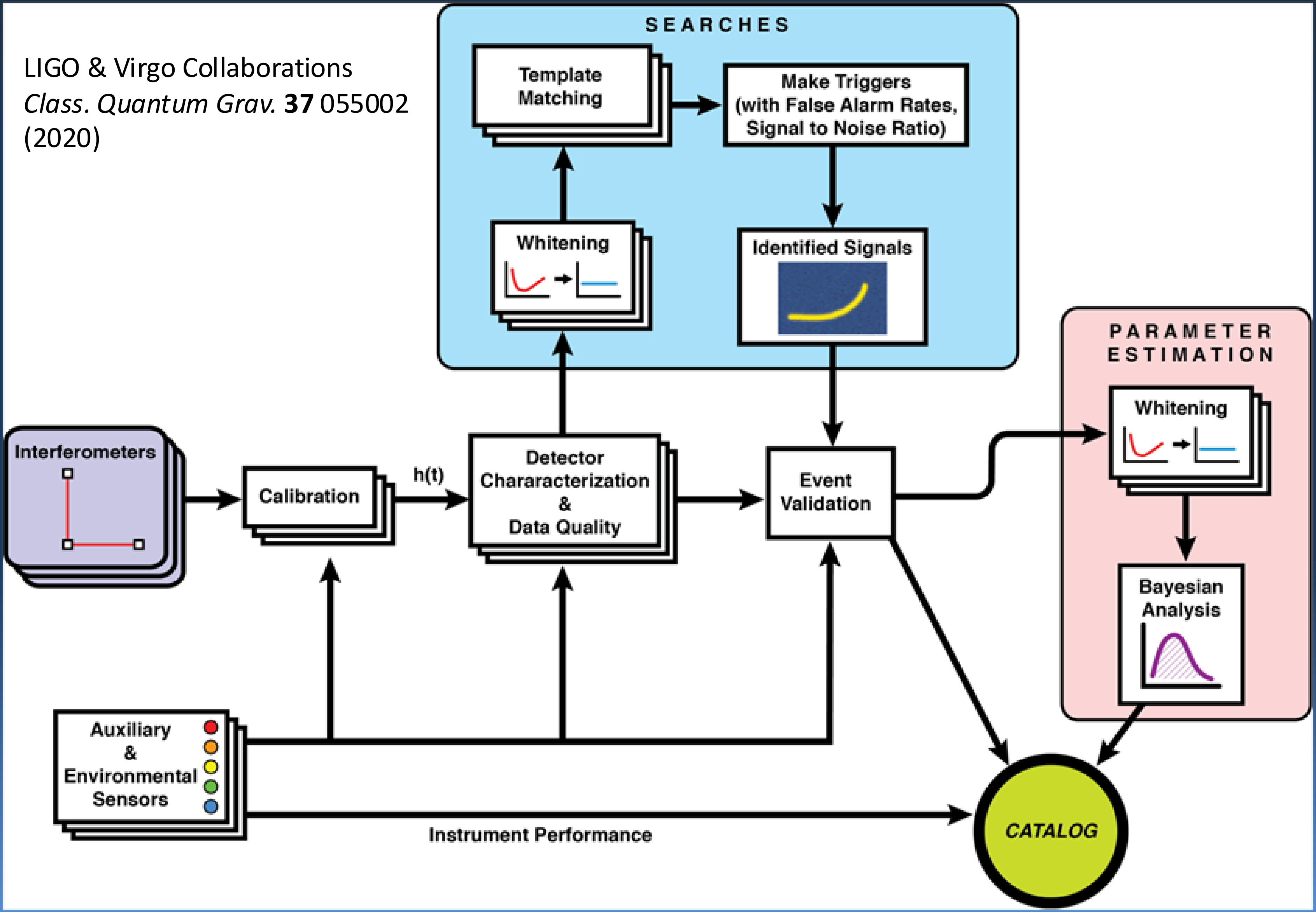


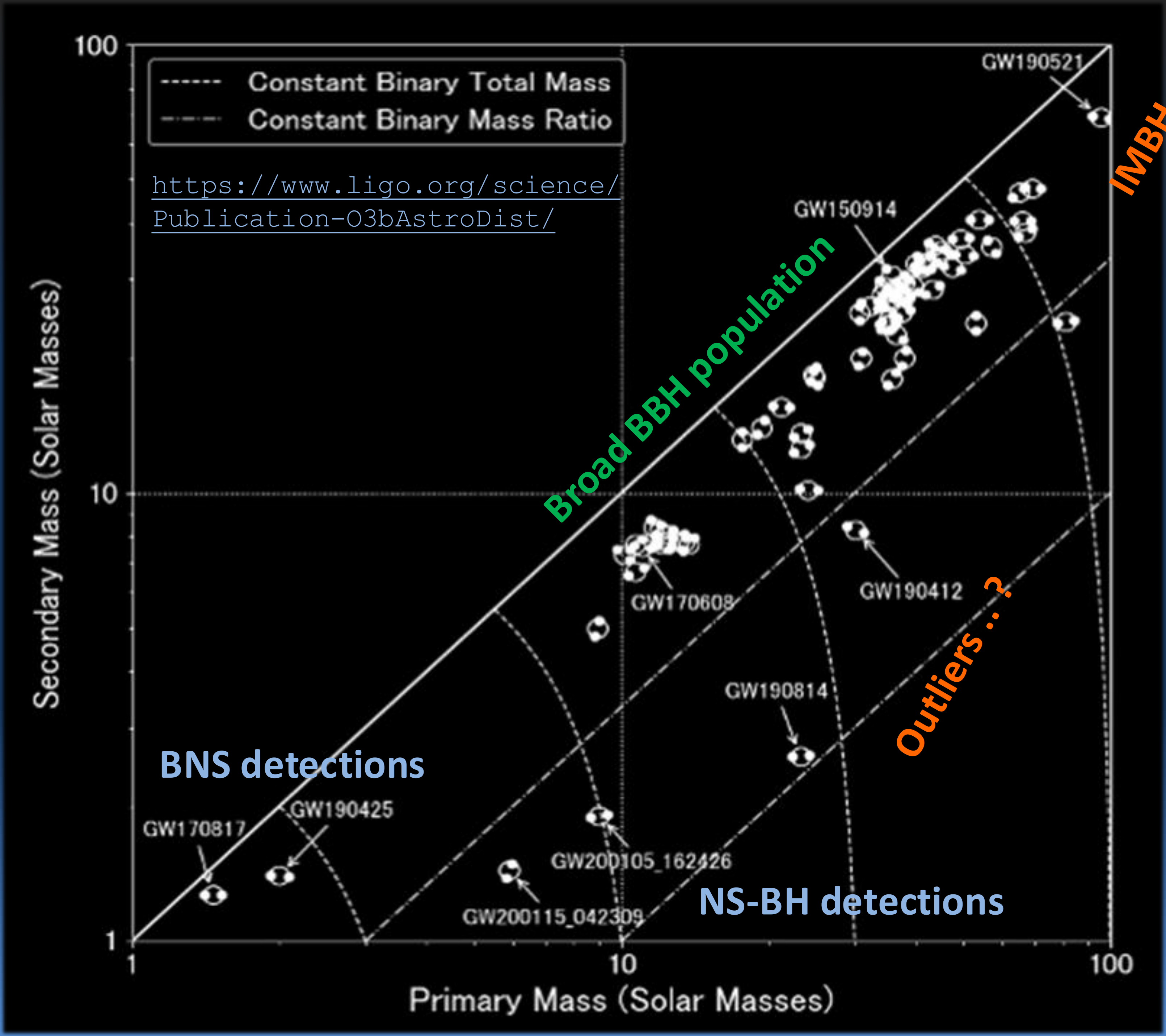
O3 run : April 2019 through March 2020

- 90 'significant' binary merger candidates (cumulative O1-O3)

From the detectors to the events

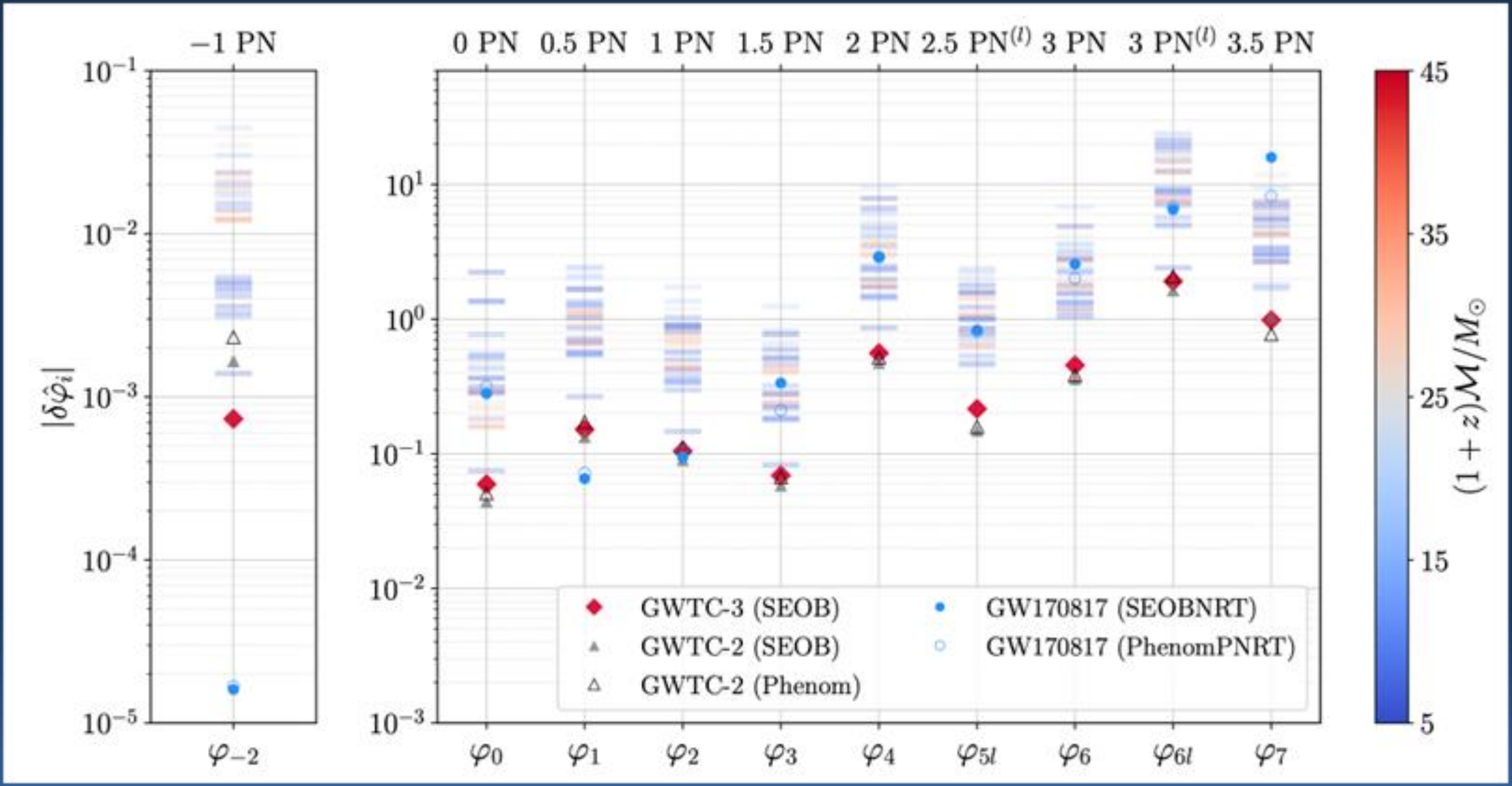
LIGO & Virgo Collaborations
Class. Quantum Grav. **37** 055002 (2020)





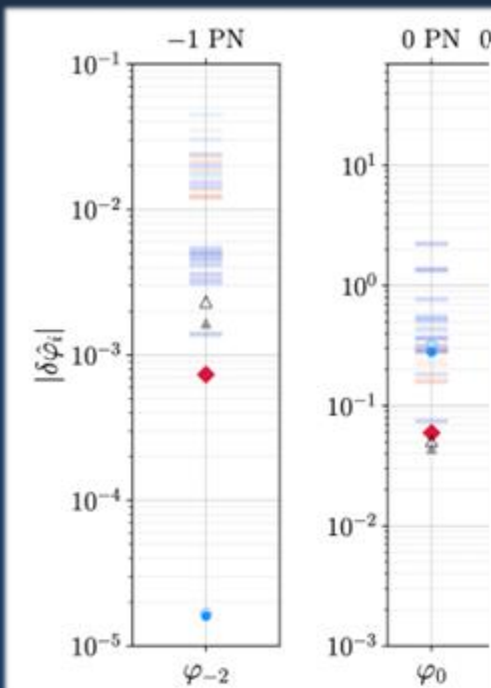
Constant Binary Total Mass
Constant Binary Mass Ratio
https://www.ligo.org/science/Publication-O3bAstroDist/
GW190521
IMBH ...
GW150914
Broad BBH population
GW170608
GW190412
Outliers .. ?
GW190814
BNS detections
GW190425
GW170817
GW200105_162426
GW200115_042309
NS-BH detections
Secondary Mass (Solar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

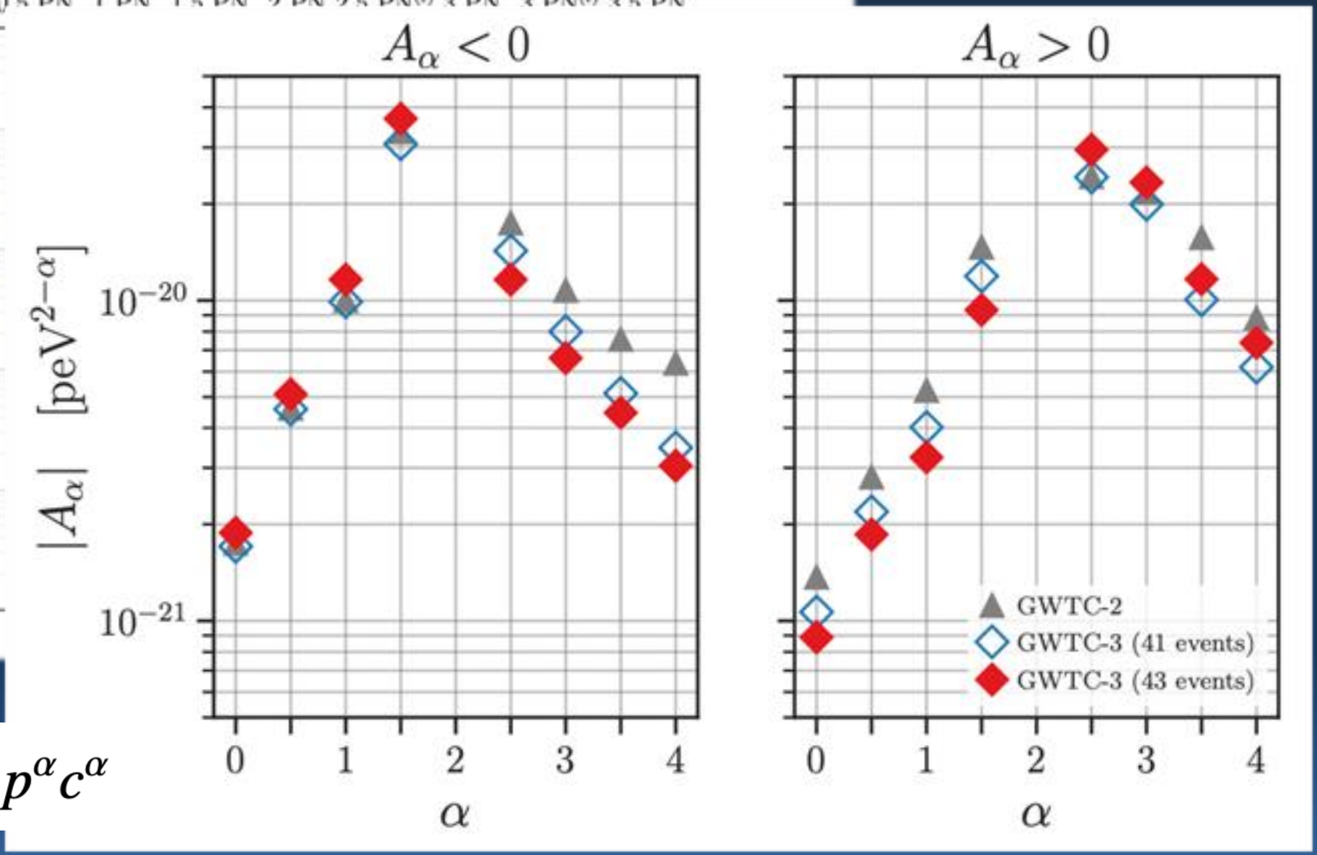
How is relativity doing ?



LVK, arXiv:2112.06861 (accepted, PRD)

How is relativity doing ?





$$E^2 = p^2c^2 + A_\alpha p^\alpha c^\alpha$$

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 …

zenodo Search Upload Communities

November 5, 2021 Dataset Open Access

The population of merging compact binaries inferred using gravitational waves through GWTC-3 - Data release

LIGO Scientific Collaboration and Virgo CollaborationLIGO Scientific Collaboration and Virgo Collaboration and KAGRA Collaboration

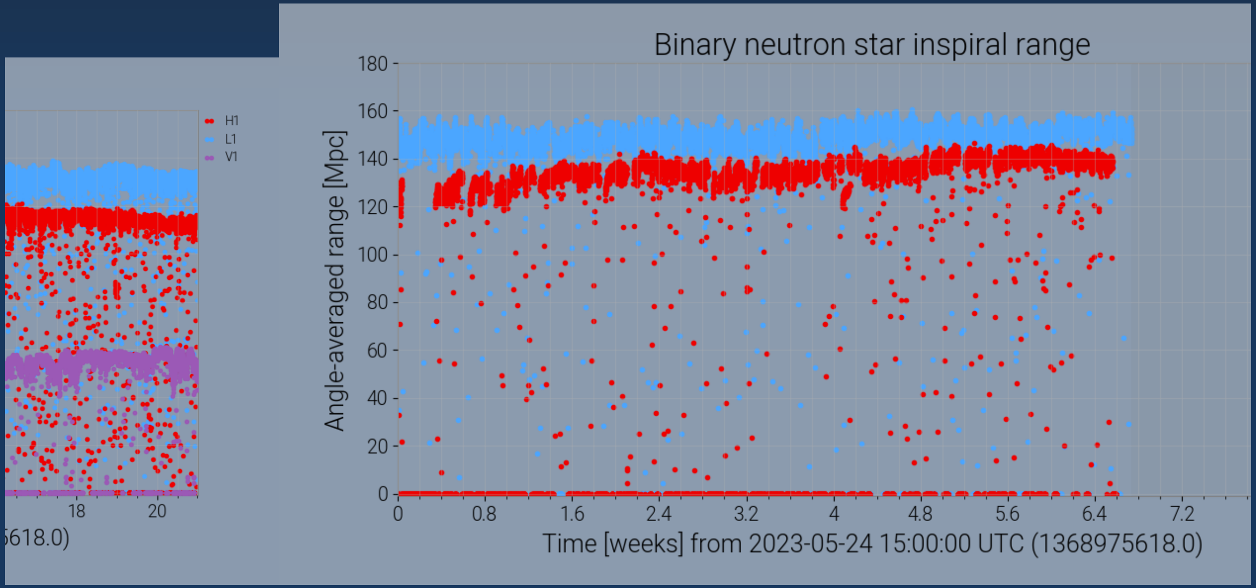
Data associated with Figures, Tables, and population parameter samples associated with **The population of merging compact binaries inferred using gravitational waves through GWTC-3** , LIGO DCC, arXiv.

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

From O3 to O4a …

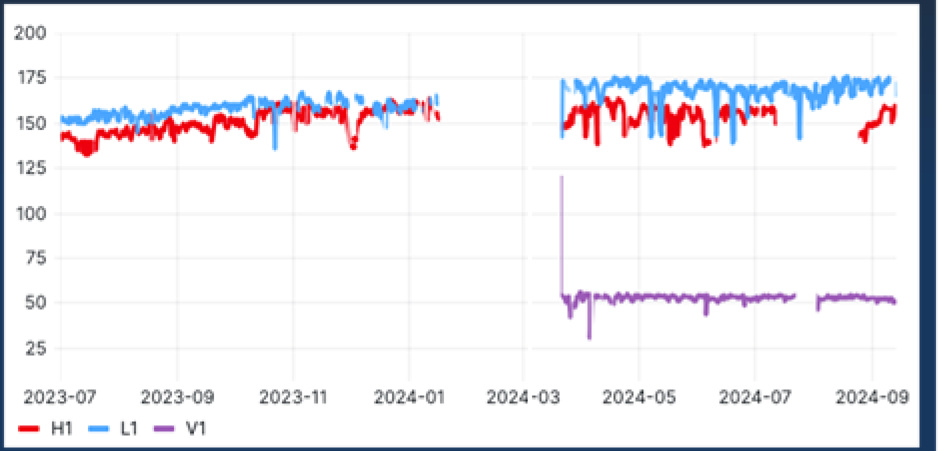
- O4 started May 2023

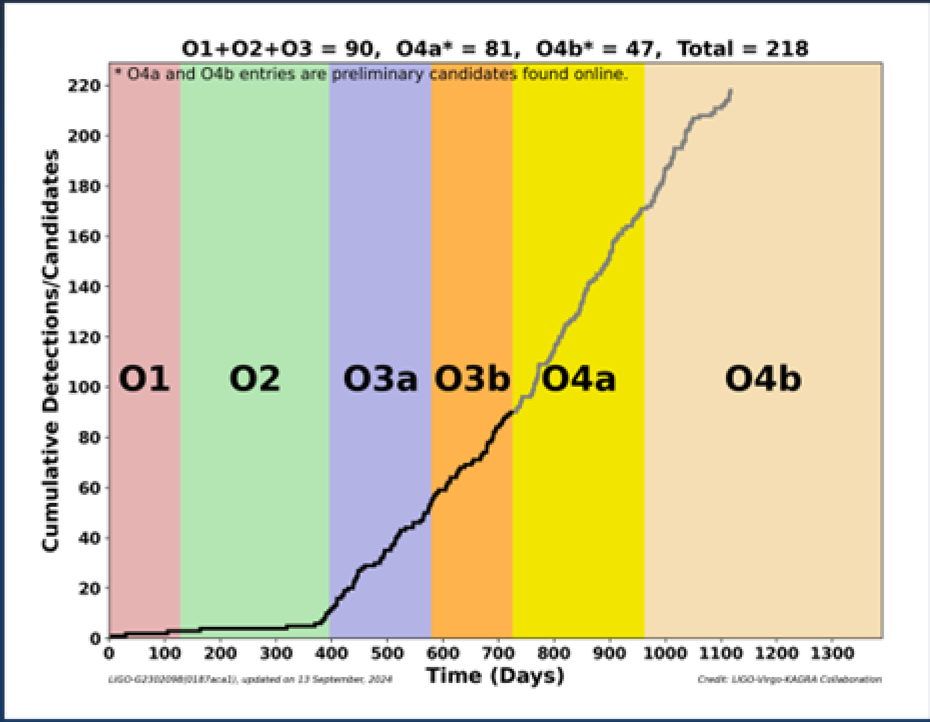
Last part of O3 (same scale)



  - **Frequency-dependent vacuum squeezing** in LIGO
    New 300m filter cavities, increased arm power …
  - KAGRA joined for 1mo, working to improve sensitivity
  - Virgo ~~commissioning problems~~ *joined in O4b (see next slides!)*

The news from O4b …





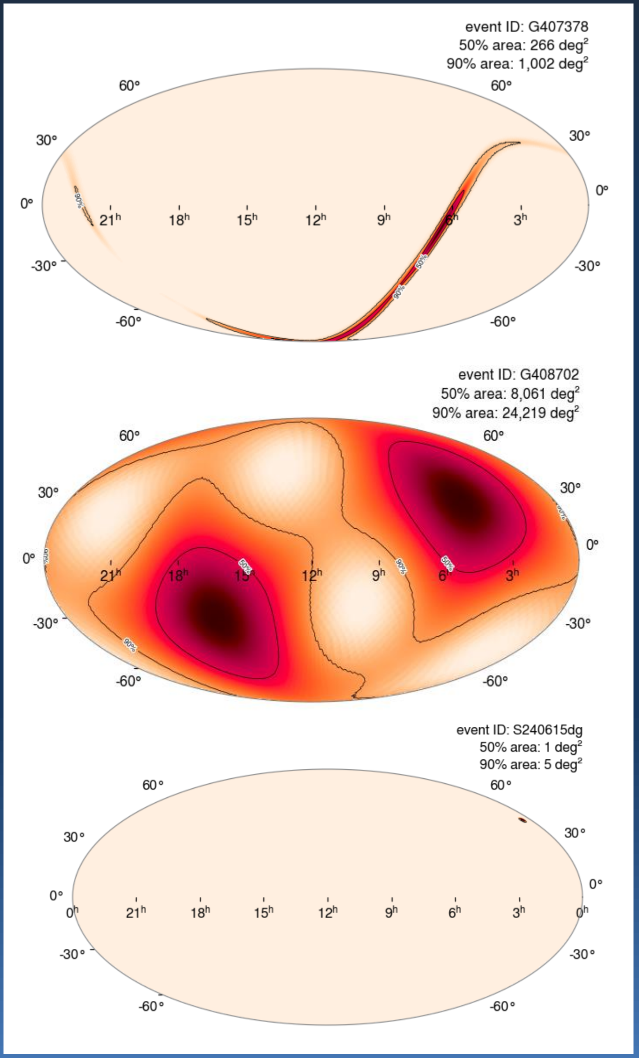
- **April 2024 : Virgo joined**
  - Sensitivity similar to O3 atm
  - ongoing 'noise hunting'
- LIGO continues to improve …
- **O4 extended to June 2025**
  - allow for preparation of O5 upgrade hardware
- KAGRA had significant setbacks from Noto Peninsula Earthquake (Jan 2024)
  - All repairs now complete, commissioning work ongoing
  - Goal to **rejoin O4 with sensitivity ~10 Mpc or higher**

A few 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 ?

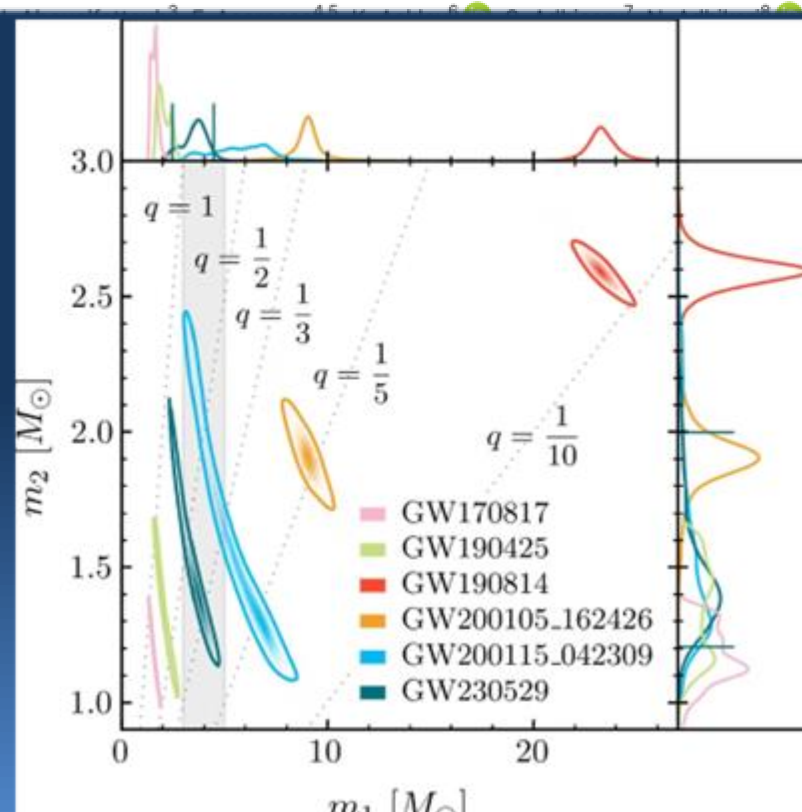
THE ASTROPHYSICAL JOURNAL LETTERS

- **First publication of O4 run**

OPEN ACCESS

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

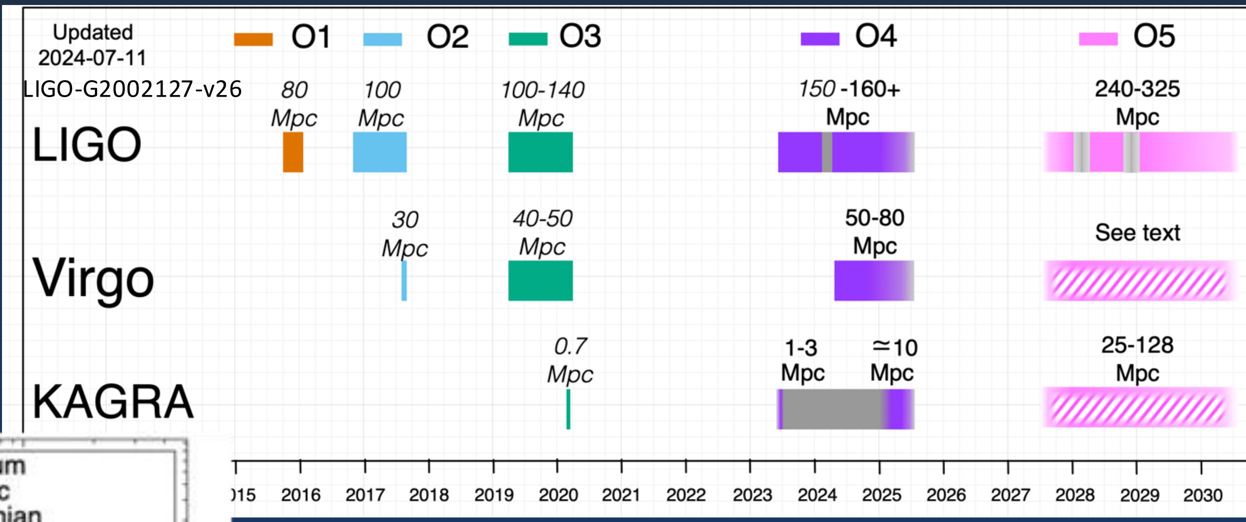
- Strengthens evidence against supposed ‘mass gap’ 3-5 $M_{\odot}$
- No direct measurement of tidal (NS matter) effects
- Increases our estimates for future NS-BH mergers with EM emission

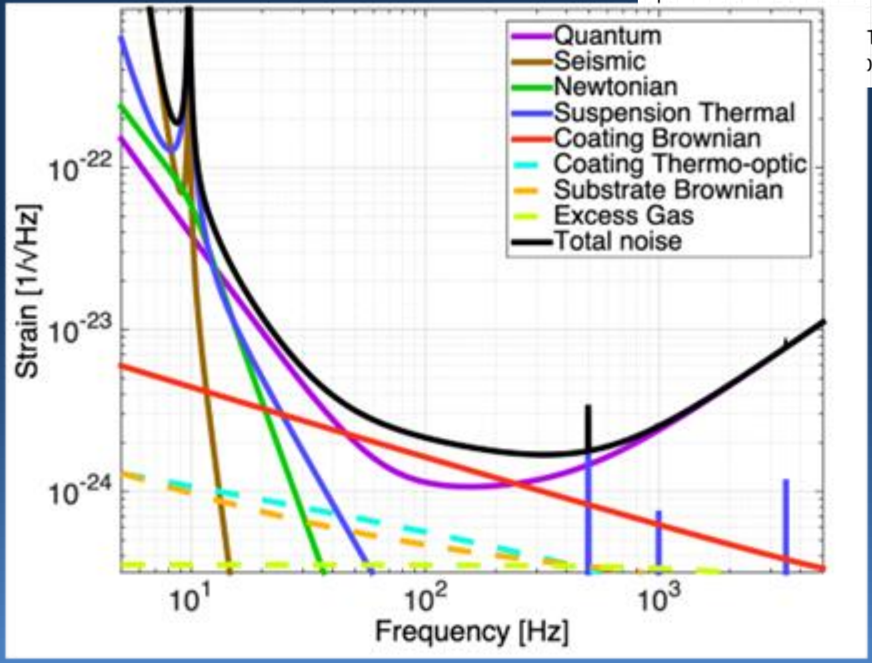


INTO THE FUTURE . . .

O5 : the ‘A+’ design

- Mid-scale upgrade of original ‘Advanced LIGO’
- Frequency-dependent squeezing already in O4 (LIGO) !





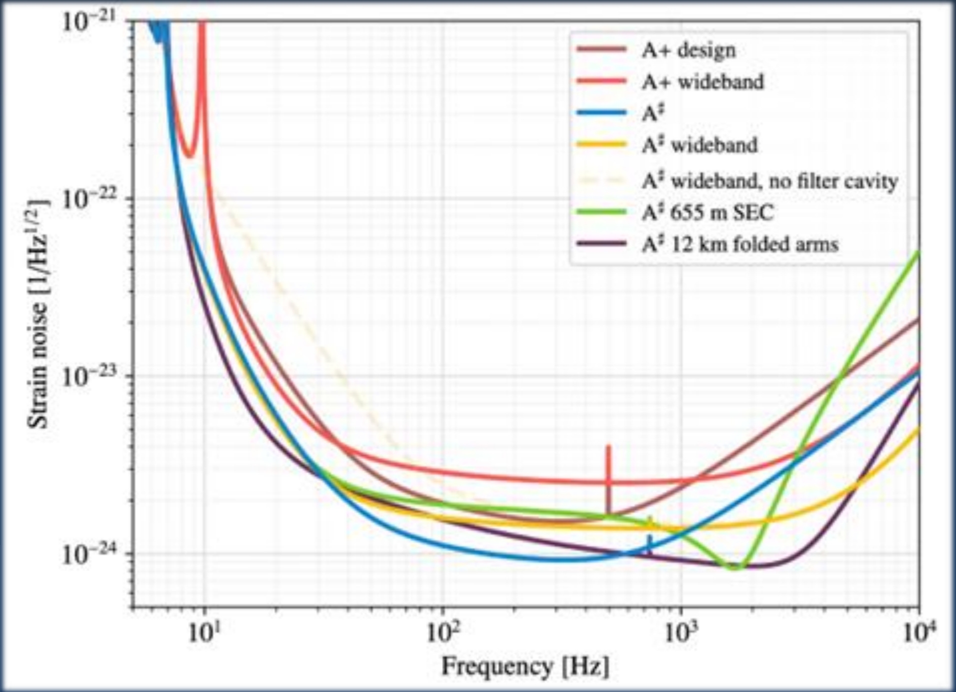
LIGO-T1800042

- Most critical technology : **improved mirror coatings** to deal with higher arm power
- Virgo O5 plans & sensitivity 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

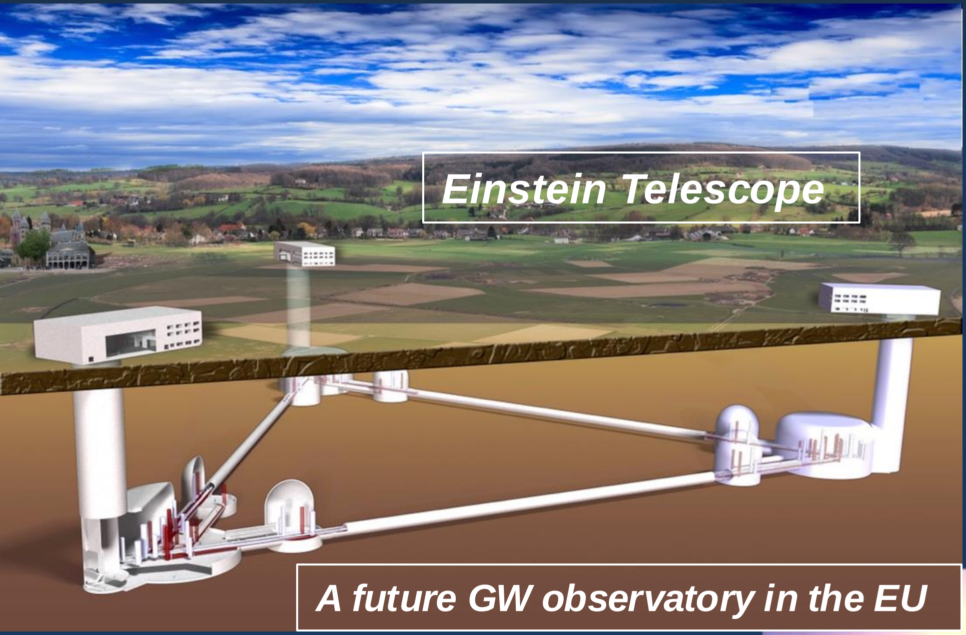


Design parameter	A+	A♯	CE
Arm length	4 km	4 km	20 km, 40 km
Arm power	750 kW	1.5 MW	1.5 MW
Squeezing level	6 dB	10 dB	10 dB
Test mass mass	40 kg	100 kg	320 kg
Test mass coatings	A+	A+/2	A+
Suspension length	1.6 m	1.6 m	4 m
Newtonian suppression	0 db	6 db	20 db

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

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

Further on :
Einstein Telescope, Cosmic Explorer

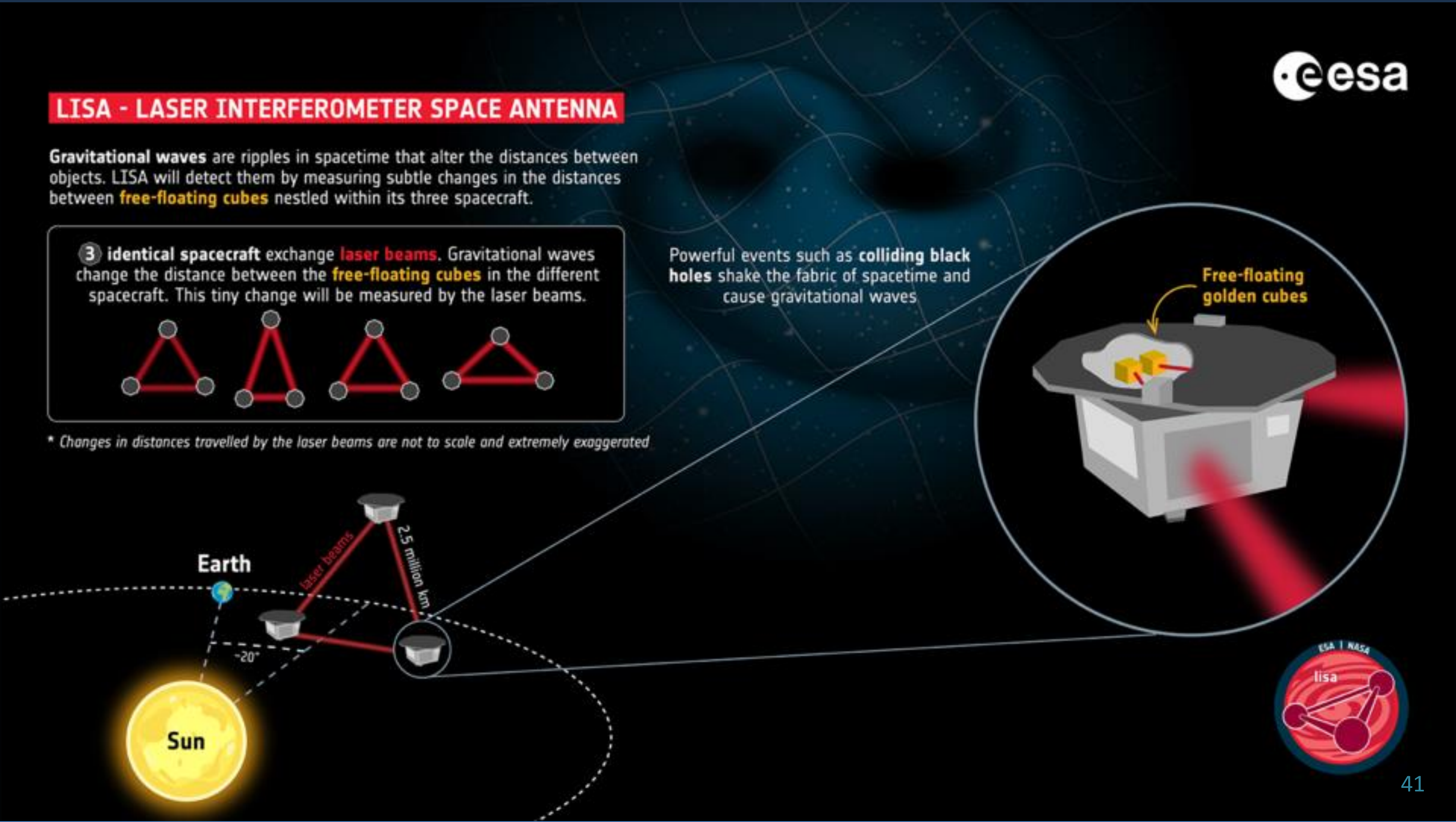


- New facilities to continue reducing noise floor
- 10km arms, underground + cryogenic : ET
- 40km arms : Cosmic Explorer

- Observe BBH mergers over our entire past light-cone !

News from space

Jan 2024 : **ESA adopted the LISA mission !** Launch planned 2035 …



Summary

- ✓ Gravitational waves are an (observationally) new arena for relativists
- ✓ Many surprises for astrophysicists in the first 9 years of GW detection ...
- ✓ None (yet) for GR !
- ✓ LIGO-Virgo-KAGRA continue steady improvement ⇒ new astro source types ?
- ✓ The opening of new frequency windows is in sight (... PTA ?)

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