ICHEP 2022 BOLOGNA

ICHEP 2022 XLI International Conference on High Energy Physics Bologna (Italy)

6 13 07 2022

# Gravitational Wave detection: status and outlook


*Giovanni A. Prodi, Università di Trento and INFN-TIFPA, Trento*

*Virgo Collaboration*


LIGO VIRGO KAGRA

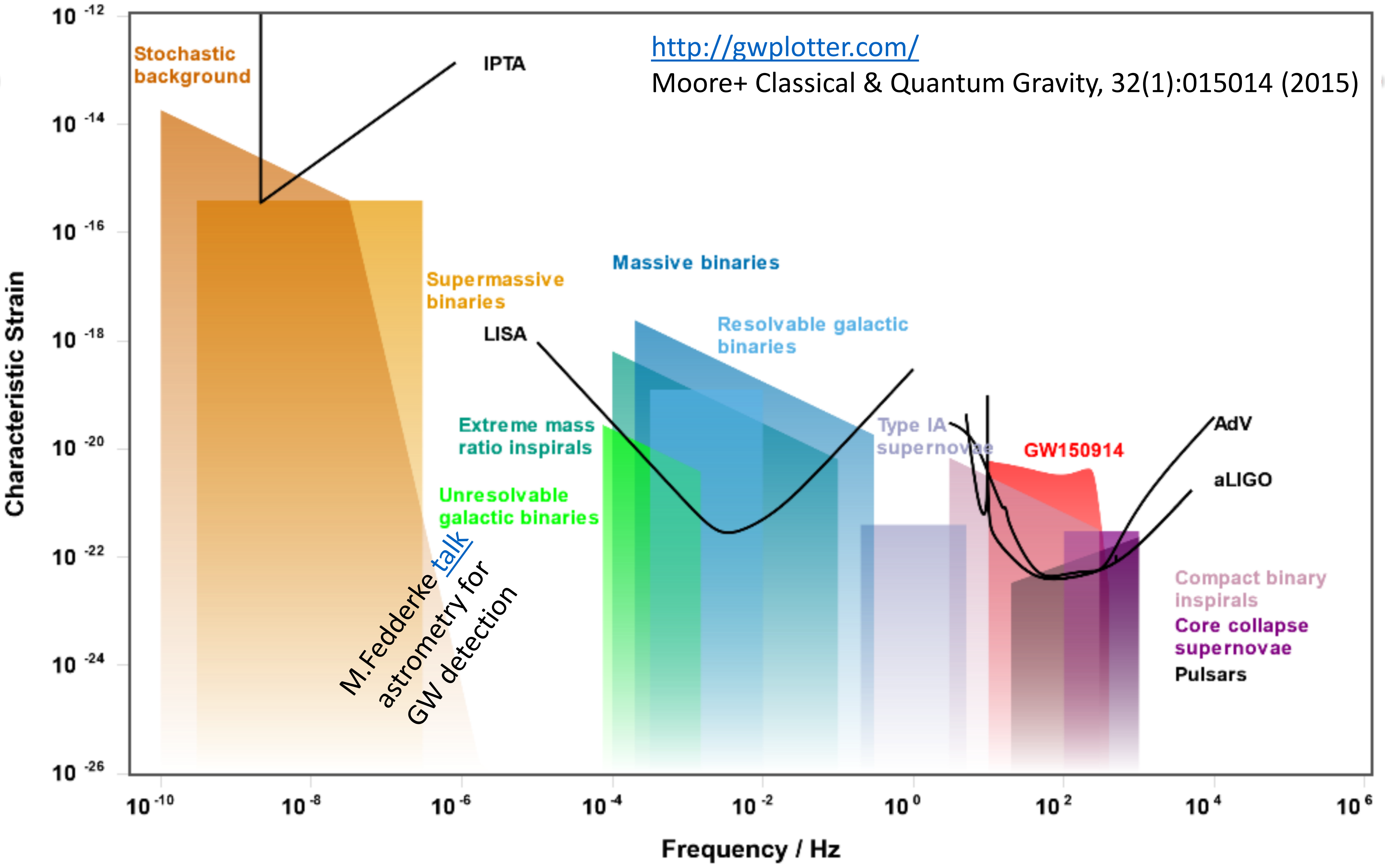
UNIVERSITÀ DI TRENTO

INFN Istituto Nazionale di Fisica Nucleare

TIFPA Trento Institute for Fundamental Physics and Applications

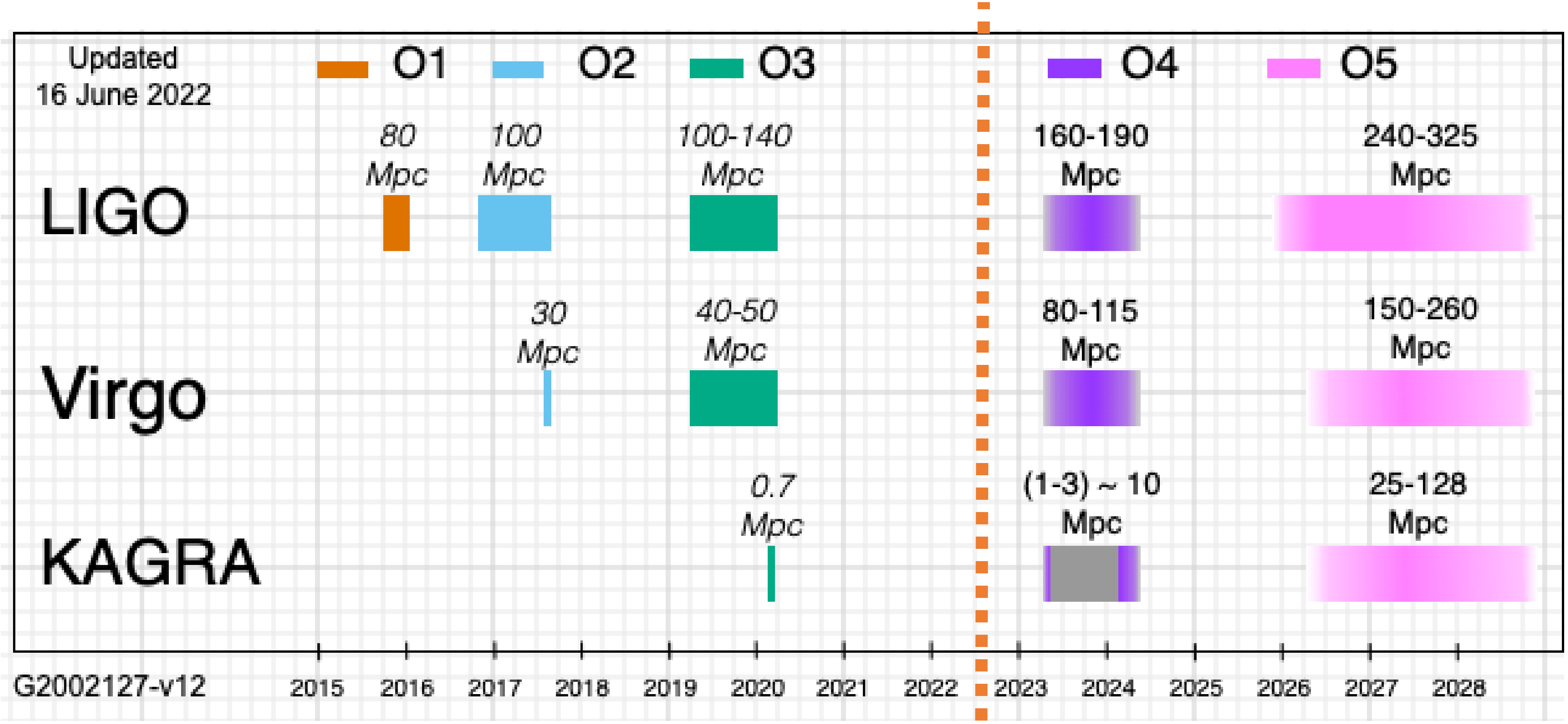
# Plan of the talk

- **a look to gravitational wave detections and selected science questions**
- **short term plans by LIGO-Virgo-KAGRA**
- **a glimpse into the 2030s and multiband GW astronomy**



http://gwplotter.com/
Moore+ Classical & Quantum Gravity, 32(1):015014 (2015)
Characteristic Strain
Frequency / Hz
$10^{-12}$
$10^{-14}$
$10^{-16}$
$10^{-18}$
$10^{-20}$
$10^{-22}$
$10^{-24}$
$10^{-26}$
$10^{-10}$
$10^{-8}$
$10^{-6}$
$10^{-4}$
$10^{-2}$
$10^{0}$
$10^{2}$
$10^{4}$
$10^{6}$
Stochastic background
IPTA
Supermassive binaries
LISA
Massive binaries
Resolvable galactic binaries
Extreme mass ratio inspirals
Unresolvable galactic binaries
Type IA supernovae
GW150914
AdV
aLIGO
Compact binary inspirals
Core collapse supernovae
Pulsars
M.Fedderke talk astrometry for GW detection

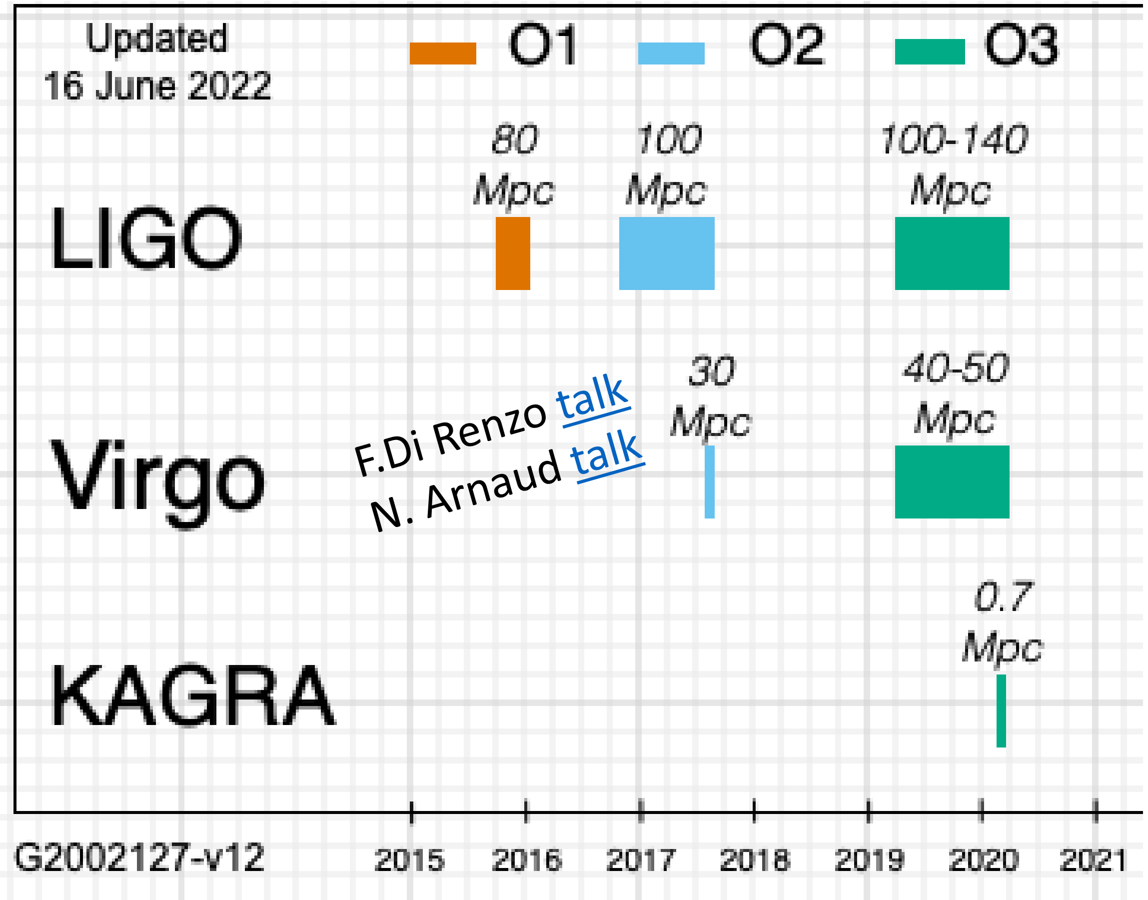
# advanced interferometric detectors in operation

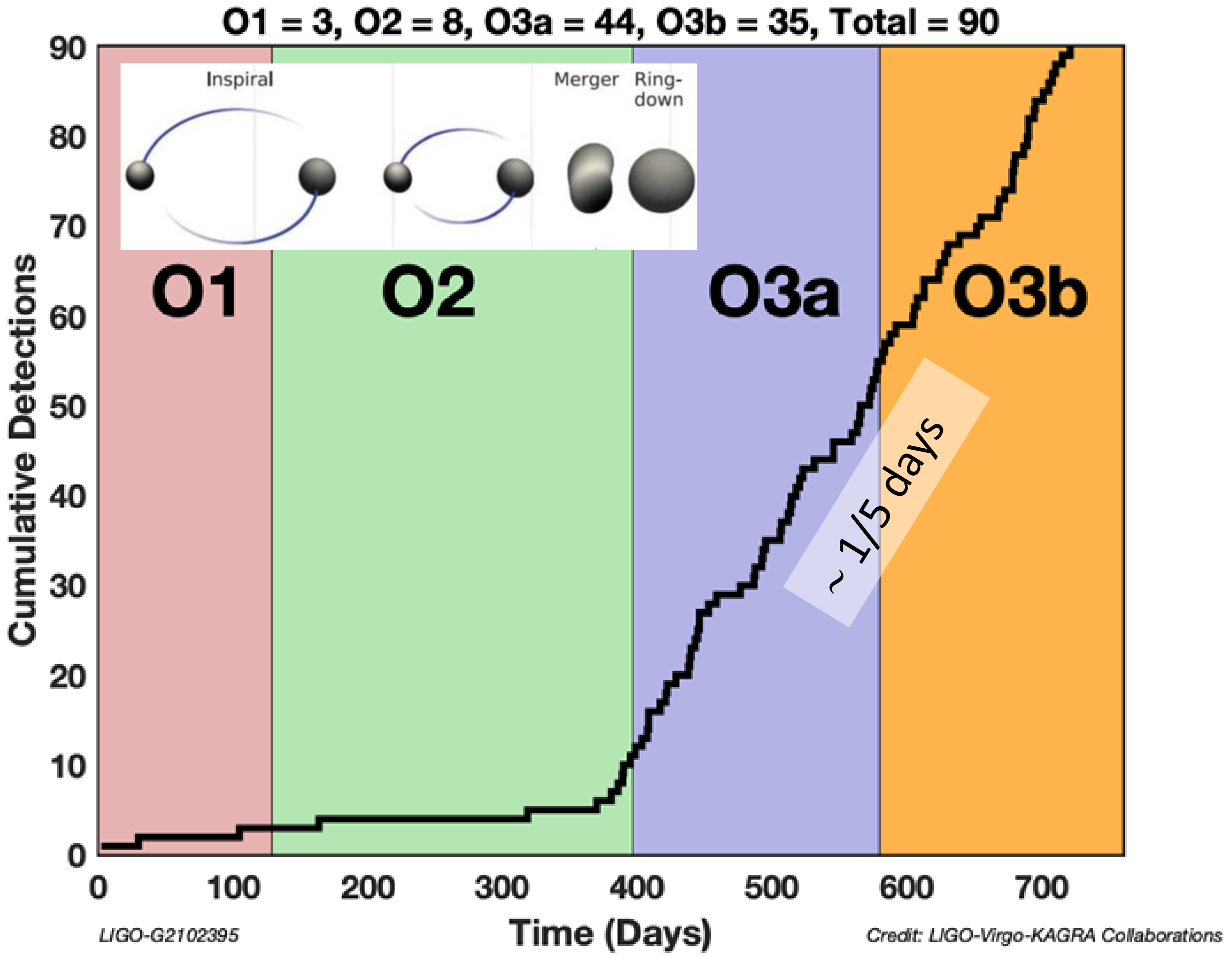



**All data is public:**
[Gravitational Wave Open Science Center]

coordinated plans at:
https://observing.docs.ligo.org/plan/

# first 5 years: from GW discovery to GW astronomy



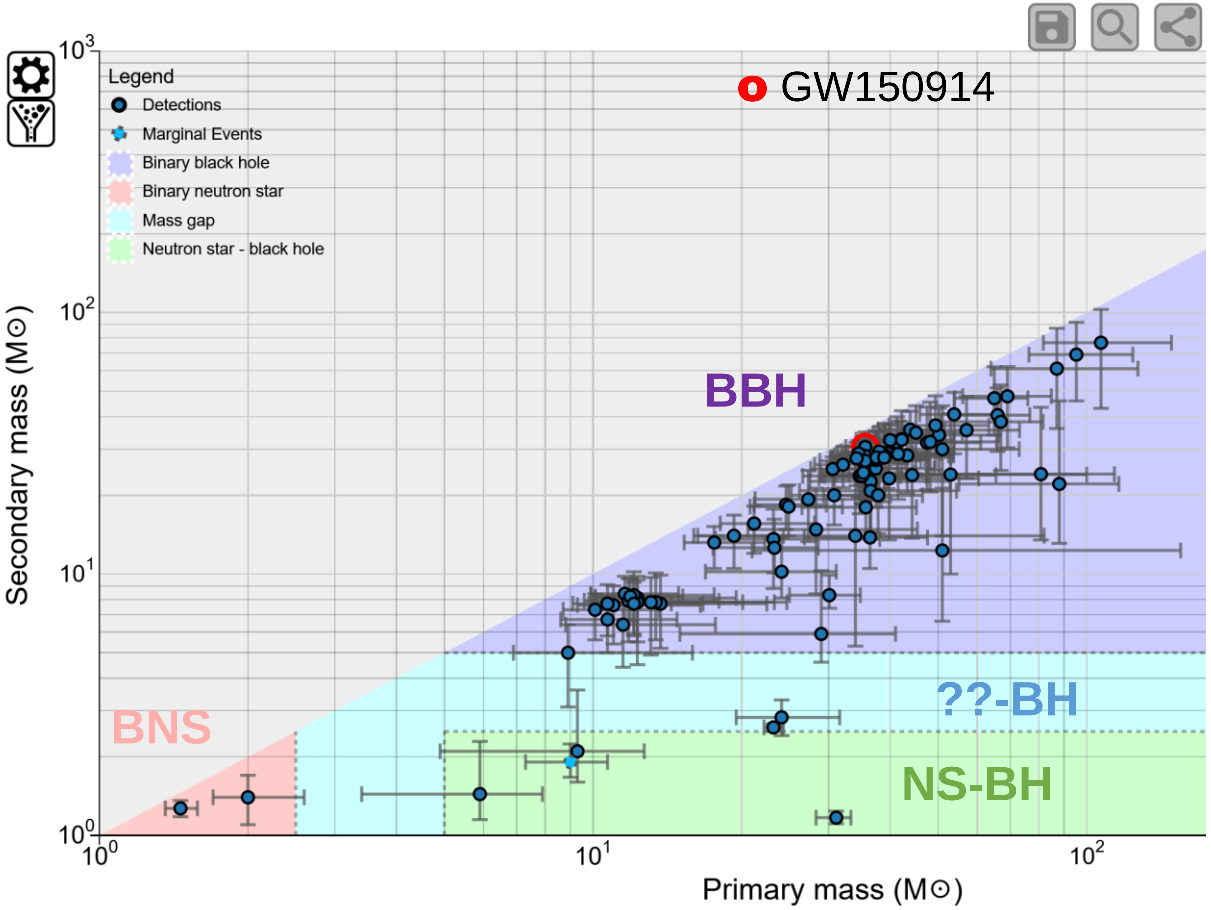

**All data is public:**
Gravitational Wave Open Science Center

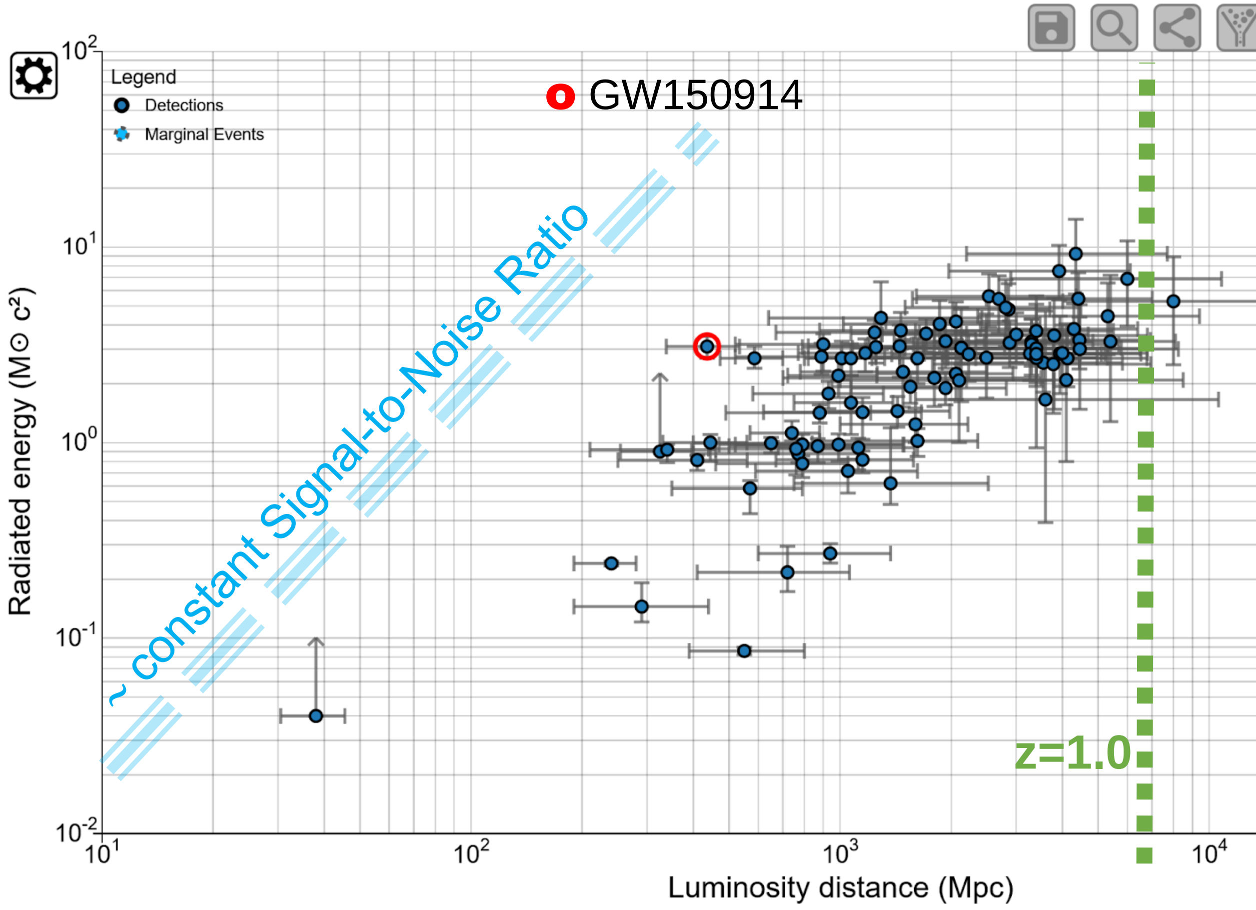
**all detections consistent with compact binary mergers**
LIGO-Virgo-KAGRA Publications

# first 5 years: from GW discovery to GW astronomy

Gravitational Wave Transient Catalogs:
GWTC-3 [arxiv:2111.03606](arxiv:2111.03606) GWTC-2.1 [arxiv:2108.01045](arxiv:2108.01045)

plots from catalog.cardiffgravity.org :




**All data is public:**
Gravitational Wave Open Science Center

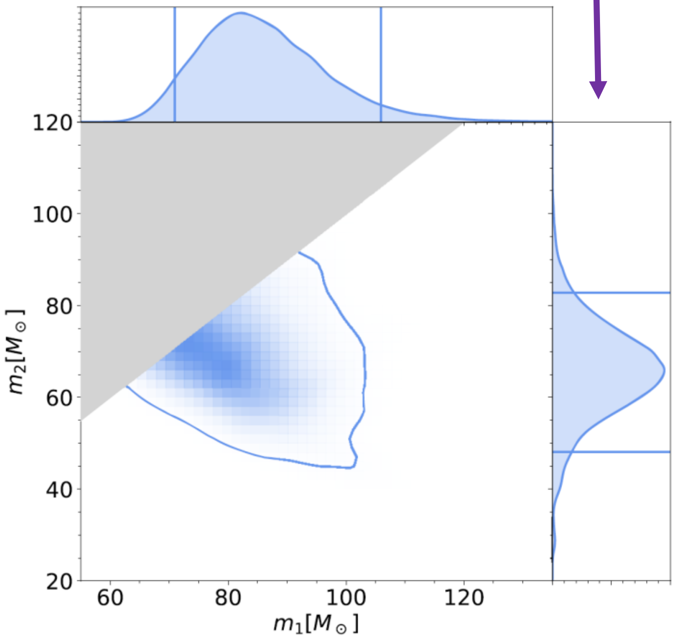
**Peak luminosity of BBH mergers ~ 1-5 e56 erg/s**
~ 1e-3 of the upper limit set by GR (~ Planck Luminosity)

# first 5 years: from discovery to GW astronomy

90 confirmed detections of compact binary mergers.

source classification based on mass estimates:

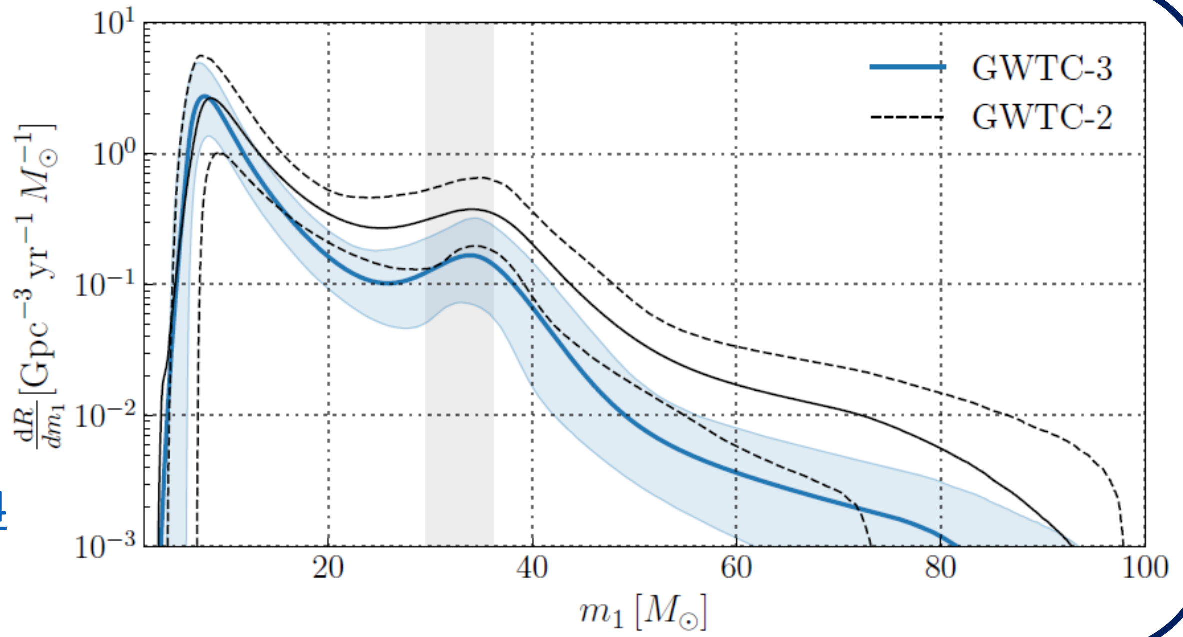
- ❑ mostly **BBHs**
- ❑ 3 **Intermediate Mass BH**: remnant masses > 100 $M_\odot$




unveiling the distribution of BH masses

power law + peak

[LVK arxiv:2111.03634]




**GW190521**

- **remnant**: first direct observation of a ~ 150 $M_\odot$ BH
- **higher mass progenitor**: first direct observation of a BH in the pulsational instability mass gap, [65,120] $M_\odot$

[LV Phys. Rev. Lett. **125**, 101102 (2020)]

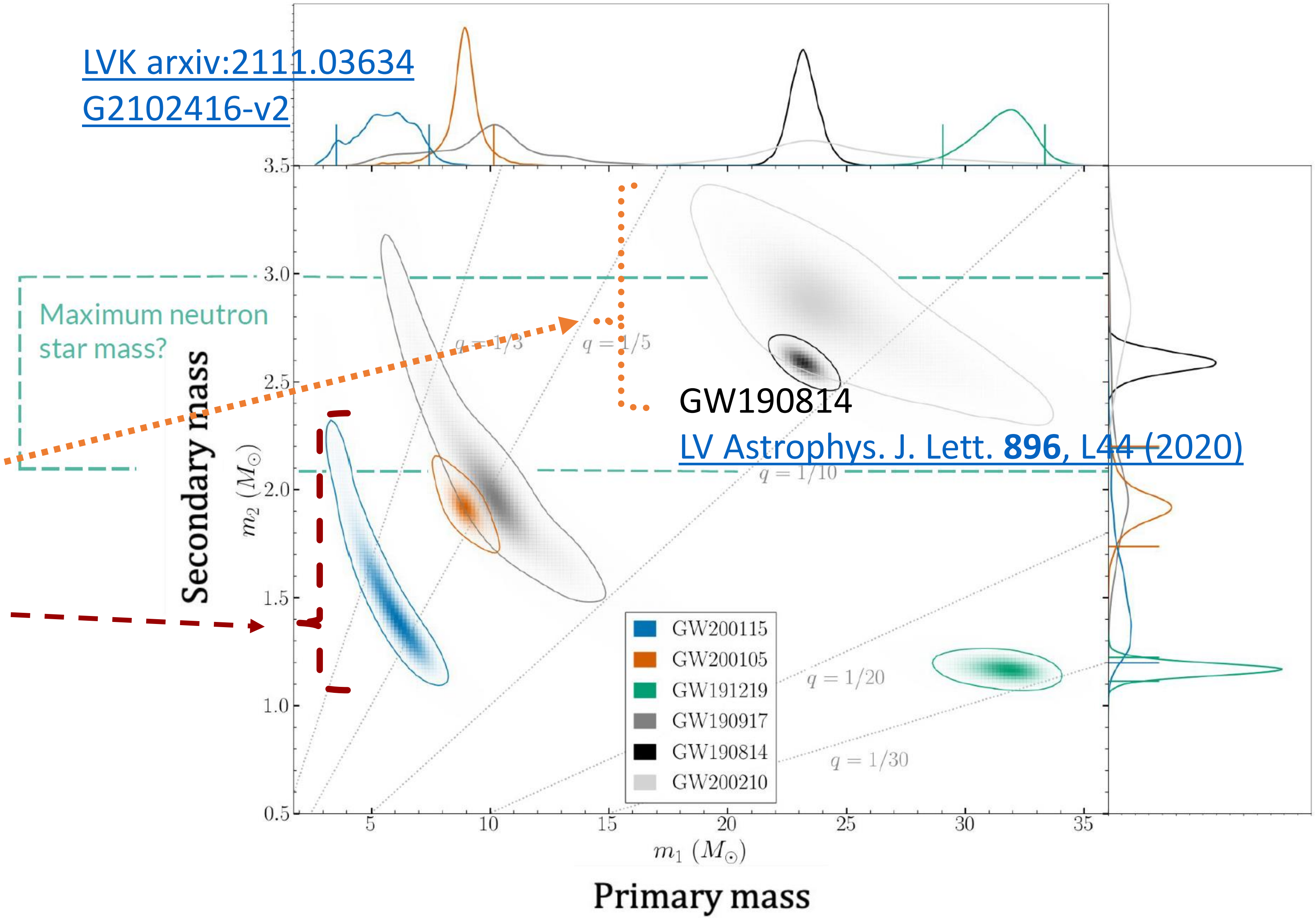
# first 5 years: from discovery to GW astronomy

90 confirmed detections of compact binary mergers.

Source classification based on mass estimates:

- ❑ mostly **BBHs**
- ❑ 3 **Intermediate Mass BH**
- ❑ 2 **??-BH:** lower mass component **in between NS and BH mass ranges**
- ❑ 3 **NS-BH**
  LVK Astrophys. J. Lett. **915**, L5 (2021)
  +1 marginal trigger (single detector)

LVK arxiv:2111.03634
G2102416-v2



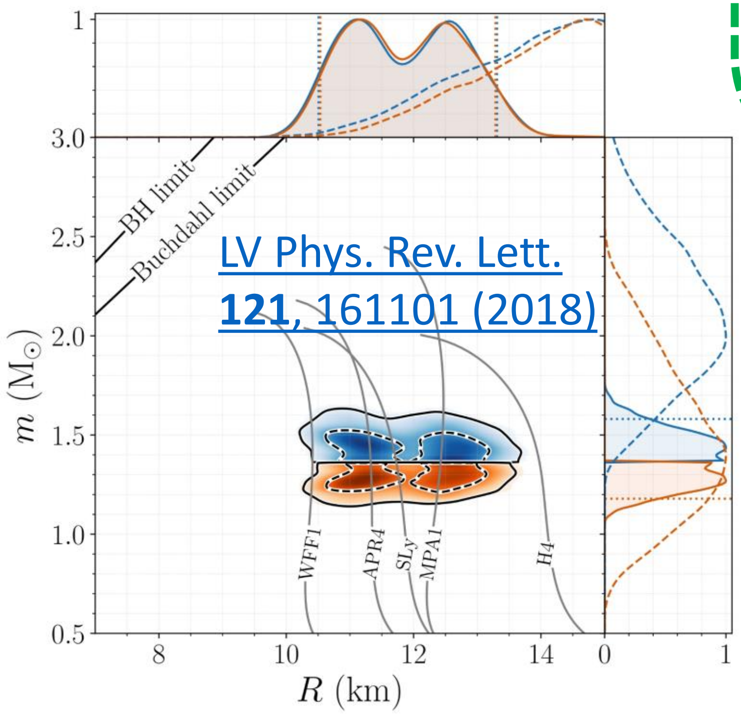
# first 5 years: from discovery to GW astronomy

90 confirmed detections of compact binary mergers.

Source classification based on mass estimates:

- ❑ mostly **BBHs**
- ❑ 3 **Intermediate Mass BH**
- ❑ 2 **??-BH**
- ❑ 3 **NS-BH**

- ❑ 2 **BNS**

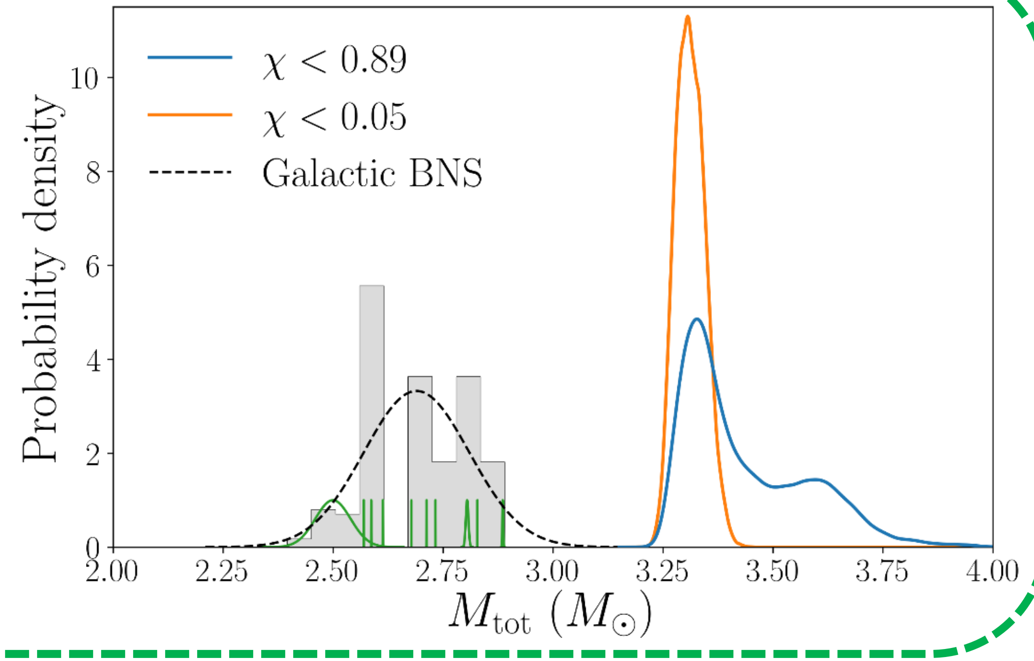



LV Phys. Rev. Lett. **121**, 161101 (2018)

**GW190425**

total mass much higher than that of known galactic BNS

LV Astrophys. J. Lett. **892**, L3 (2020)




**GW170817**

**& GRB170817A & AT2017gfo**

still the only multimessenger one in the GW Transient catalog

Phys. Rev. Lett. **119**, 161101 (2017)

Astrophys. J. Lett. **848**, L12 (2017) .........

$$-3 \times 10^{-15} \leqslant \frac{\Delta v}{v_{\rm EM}} \leqslant +7 \times 10^{-16}.$$

$$\Delta v = v_{\rm GW} - v_{\rm EM}$$

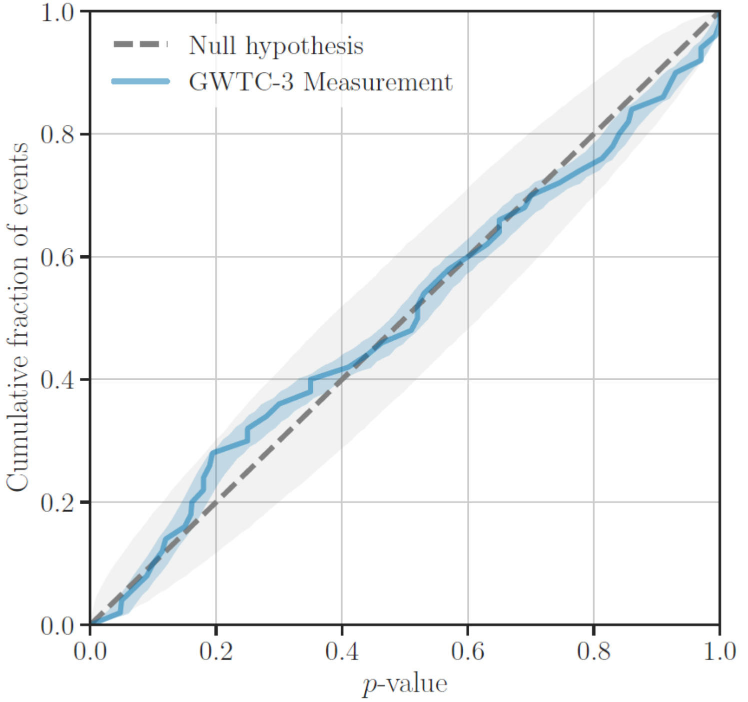
Astrophys. J. Lett. **848**, L13 (2017)

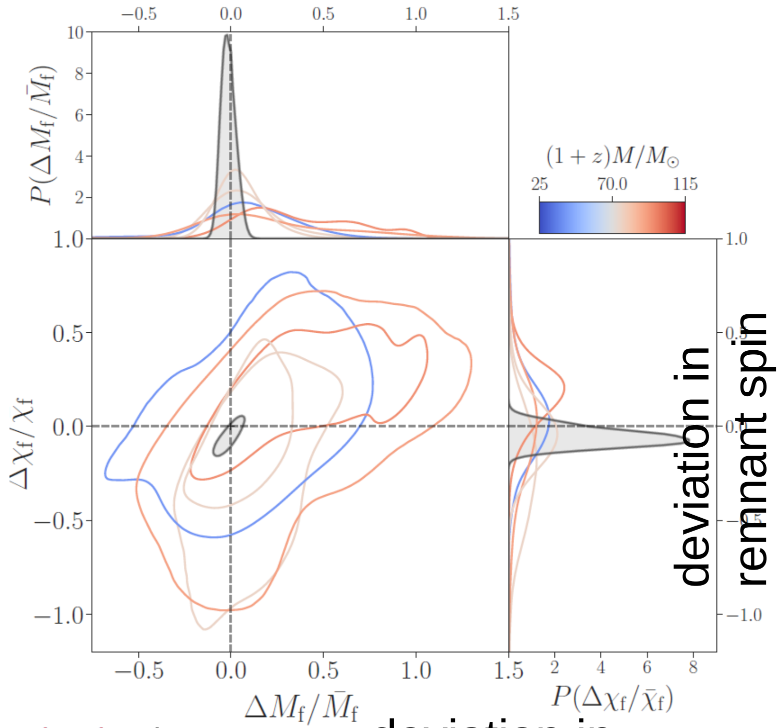
# first 5 years: investigating gravity

Testing General Relativity
LVK arxiv:2112.06861

- ❑ consistency tests of predictions vs data
- ❑ consistency checks of GW emission model using different data portions (inspiral-merger-ringdown)
- ❑ tests of GW generation
- ❑ check of BH properties
- ❑ tests of GW propagation

see more in L.Haegel talk



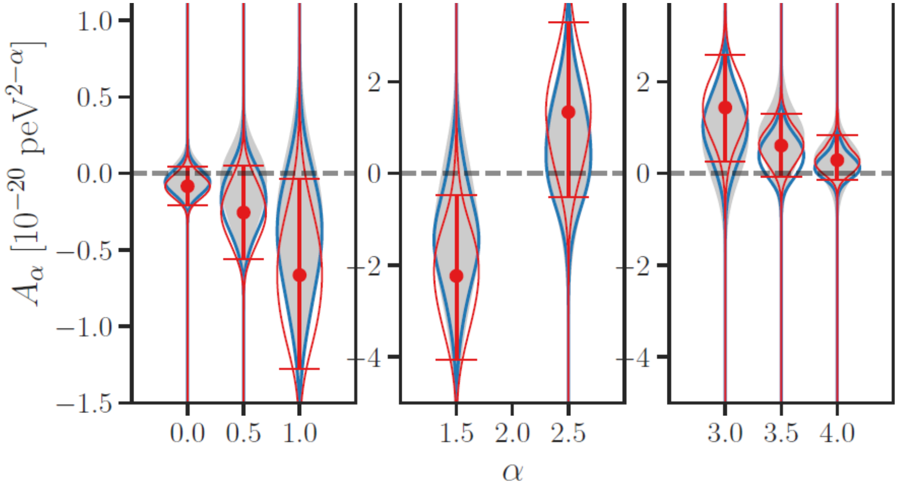




deviation in remnant spin

deviation in remnant mass

e.g. modified dispersion relation:

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




massive graviton:

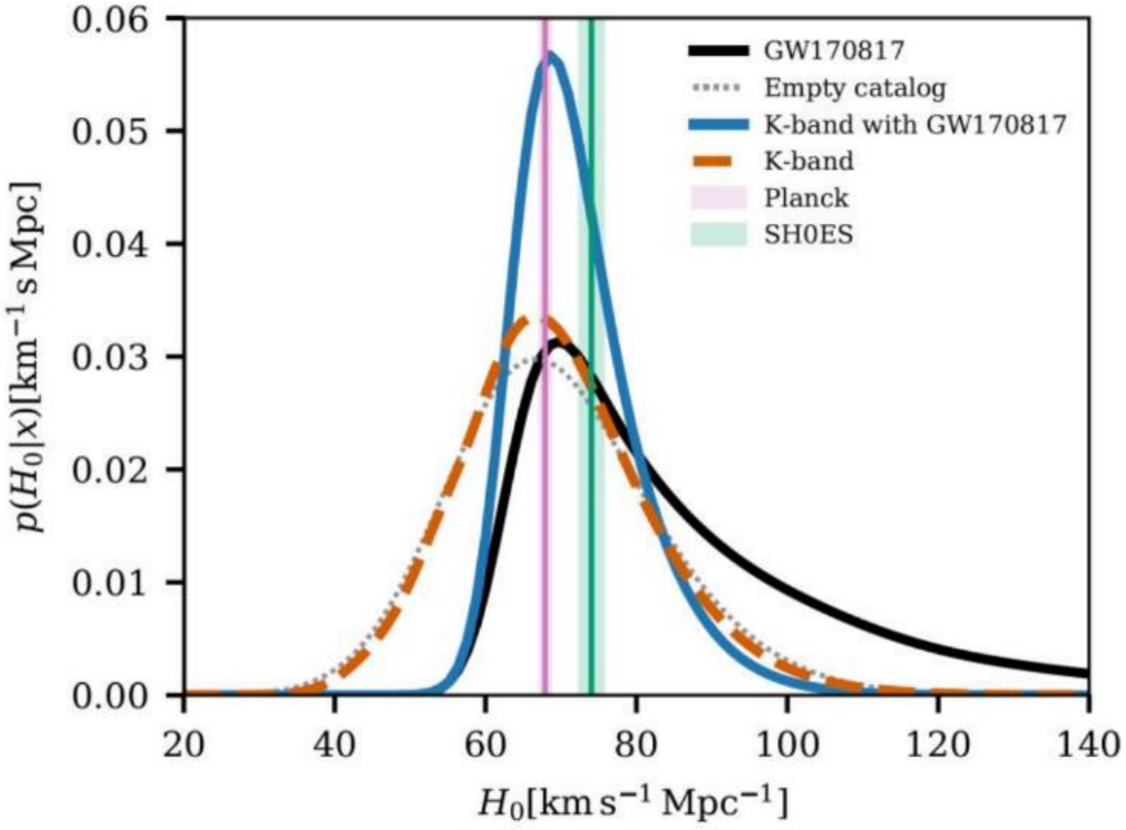
$$m_g \leq 1.27 \times 10^{-23}\,\mathrm{eV/c^2}$$

LIGO VIRGO KAGRA

# first 5 years: cosmology and dark matter searches

**Hubble constant**

- **GW170817 + AT2017gfo**
- **dark sirens (BBHs + galaxy catalog)**
- **combined**

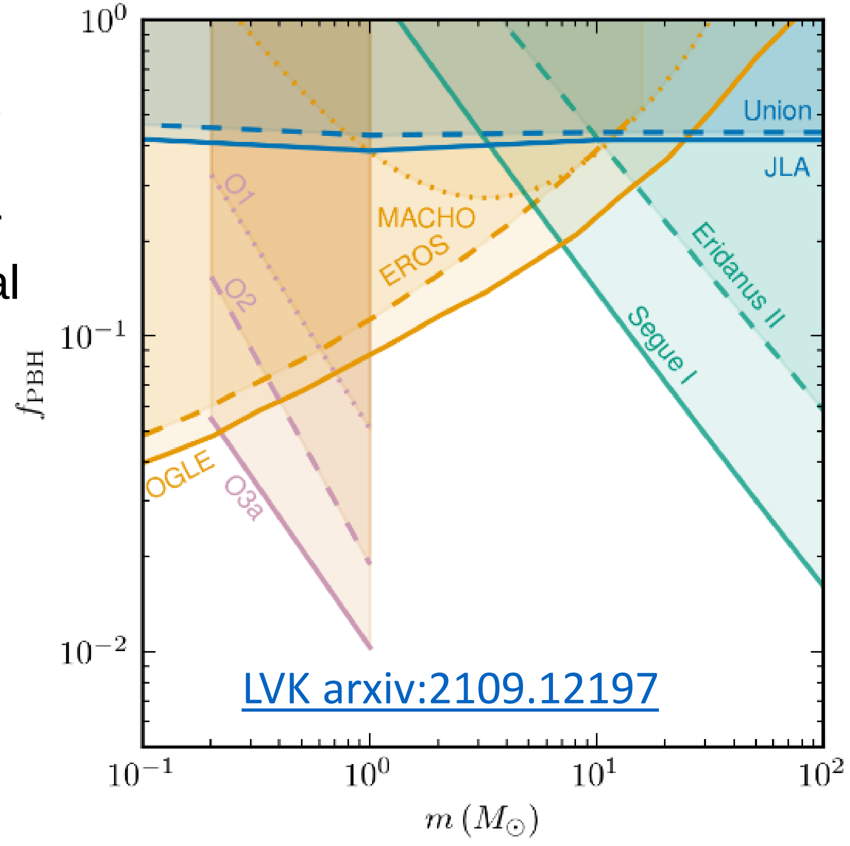



LVK arxiv:2111.03604

**Dark matter searches**

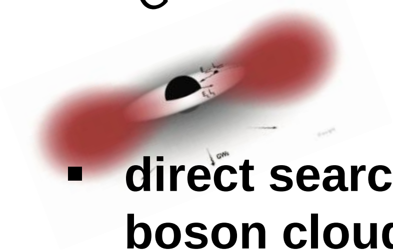
- **direct search for sub-solar-mass BHs**

limits to the fraction of dark matter in primordial BHs




LVK arxiv:2109.12197

G.Bertone talk

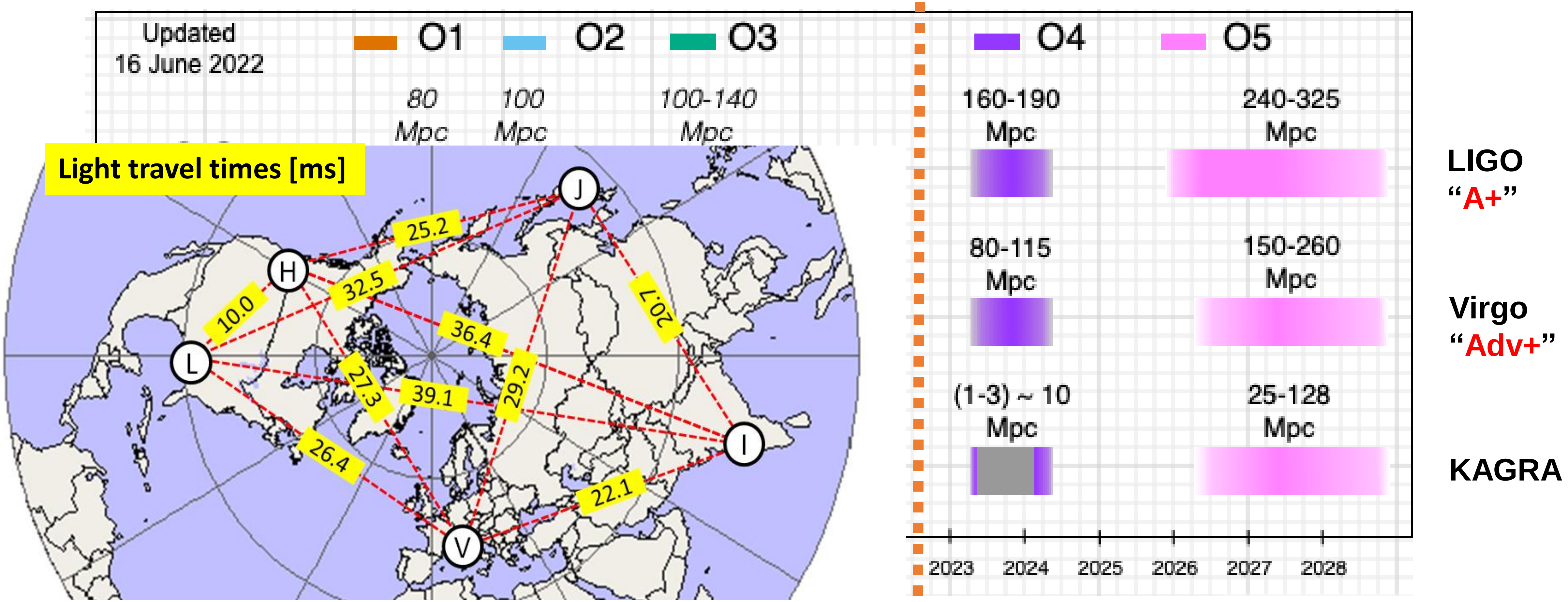


- **direct search for ultralight scalar boson clouds around Kerr BHs**

LVK Phys. Rev. D **105**, 102001 (2022)

# upcoming observations

**LIGO INDIA** is expected to join in this decade




~ almost 1 merger / day

~ a few mergers / day

coordinated plans at:
https://observing.docs.ligo.org/plan/

**detection rate ∝ (range)$^3$** i.e. surveyed volume

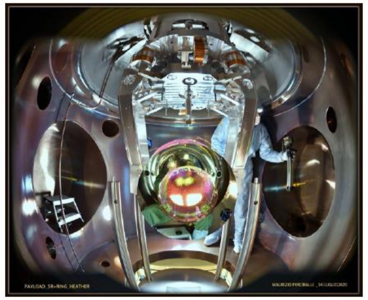
# 2G detectors upgrades: Advanced Virgo +

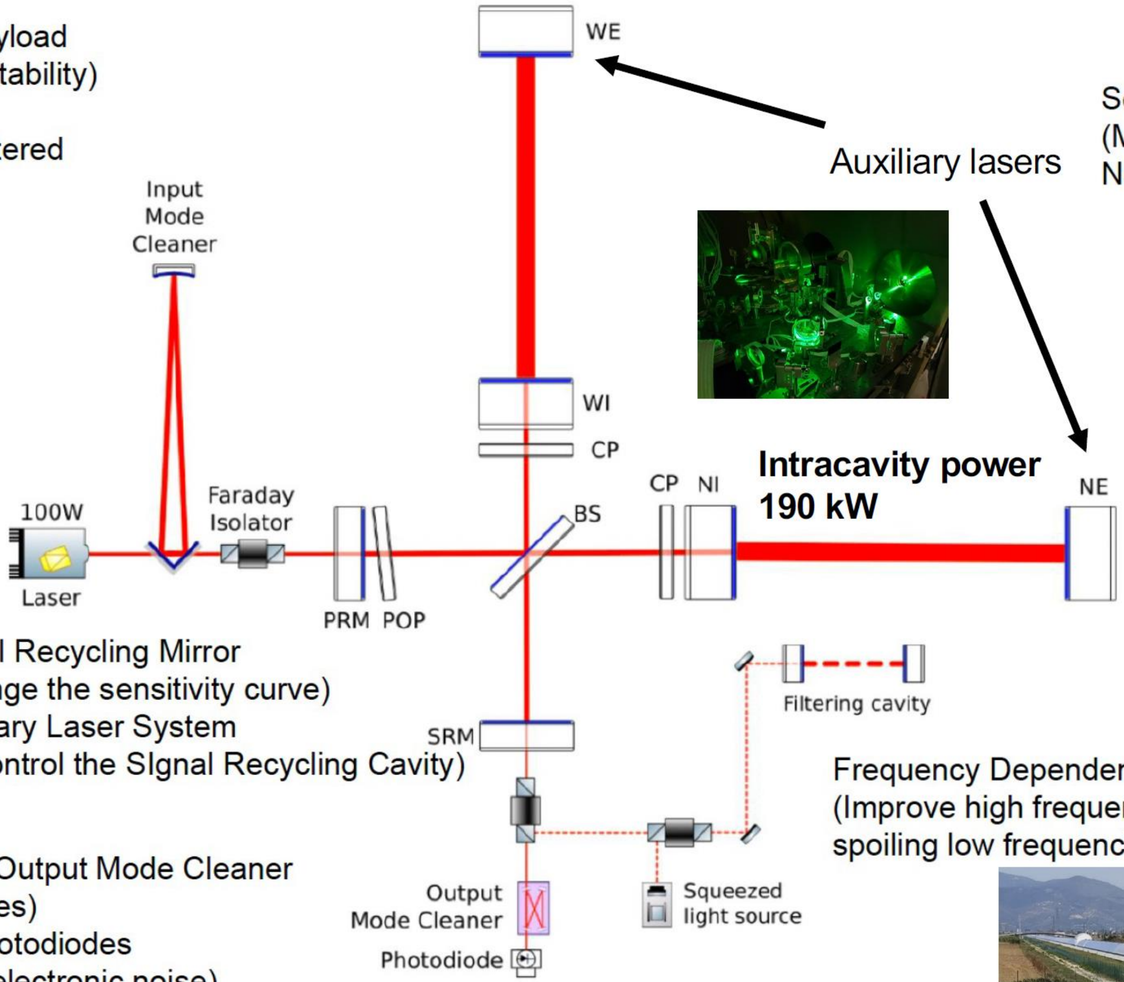
Path towards O4: reduce quantum noise, hit against thermal noise.

*credits: V. Fafone, EAS 2022*

New Input Mode Cleaner Payload
(Improve controllability and stability)
Instrumented Baffle
(Direct measurement of scattered light)

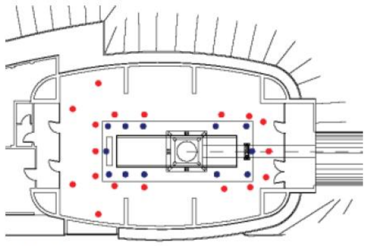
High-power Laser
(Increase the circulating power)

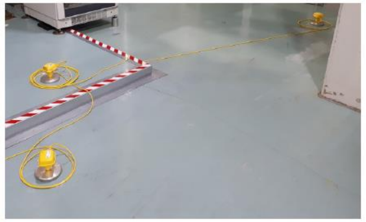





Auxiliary lasers

Seismometer Array
(Measurement and cancellation of Newtonian Noise)



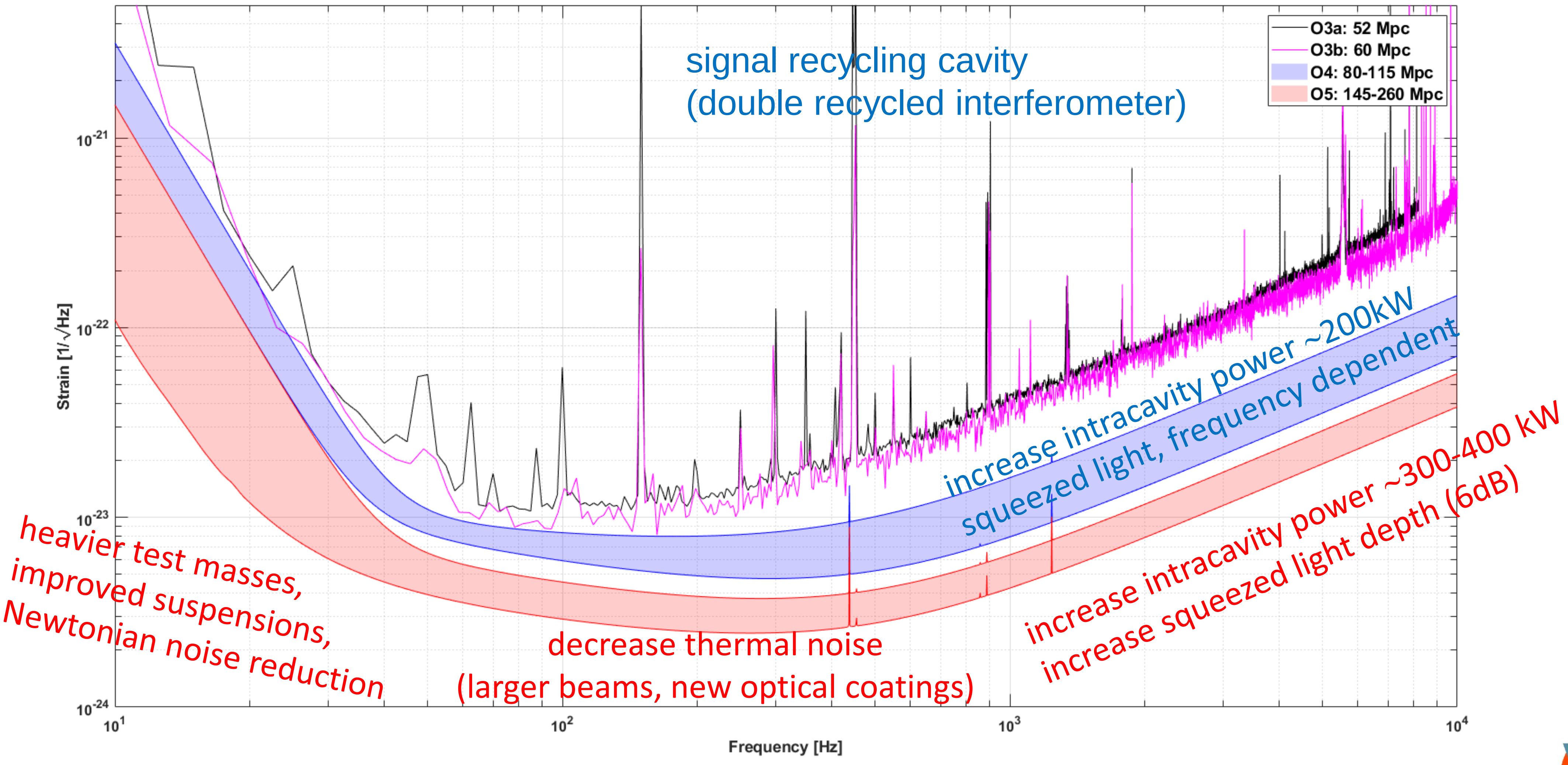
Signal Recycling Mirror
(Change the sensitivity curve)
Auxiliary Laser System
(To control the SIgnal Recycling Cavity)

High-finesse Output Mode Cleaner
(Reduce losses)
Low-noise photodiodes
(Reduce the electronic noise)

Frequency Dependent Squeezing
(Improve high frequencies without spoiling low frequencies)

**Goal: 4.5 dB**

# 2G detectors upgrades: Advanced Virgo +



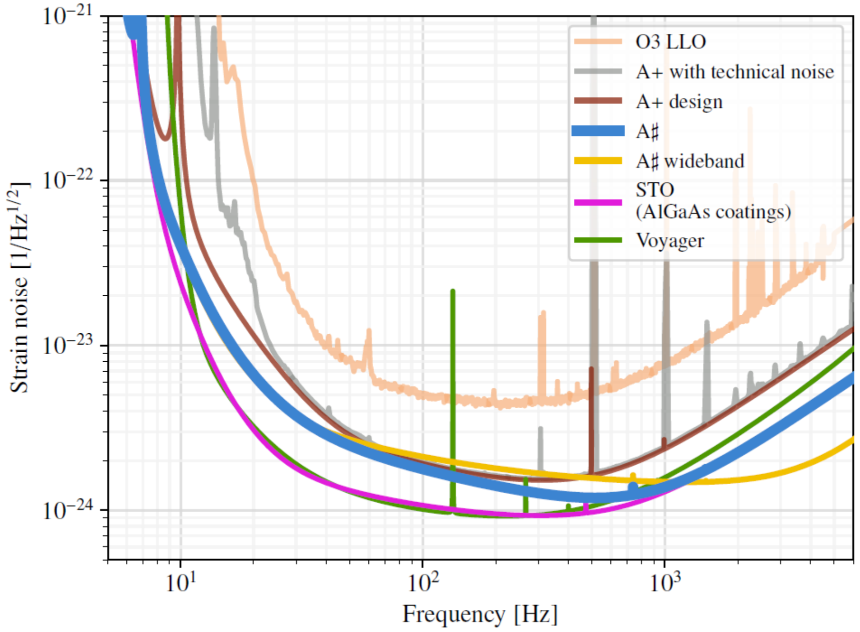
# post-O5 concept study

LIGO and Virgo are evaluating how to exploit current infrastructures for observations in the early 2030s

- readiness/cost/impact of more detector upgrades

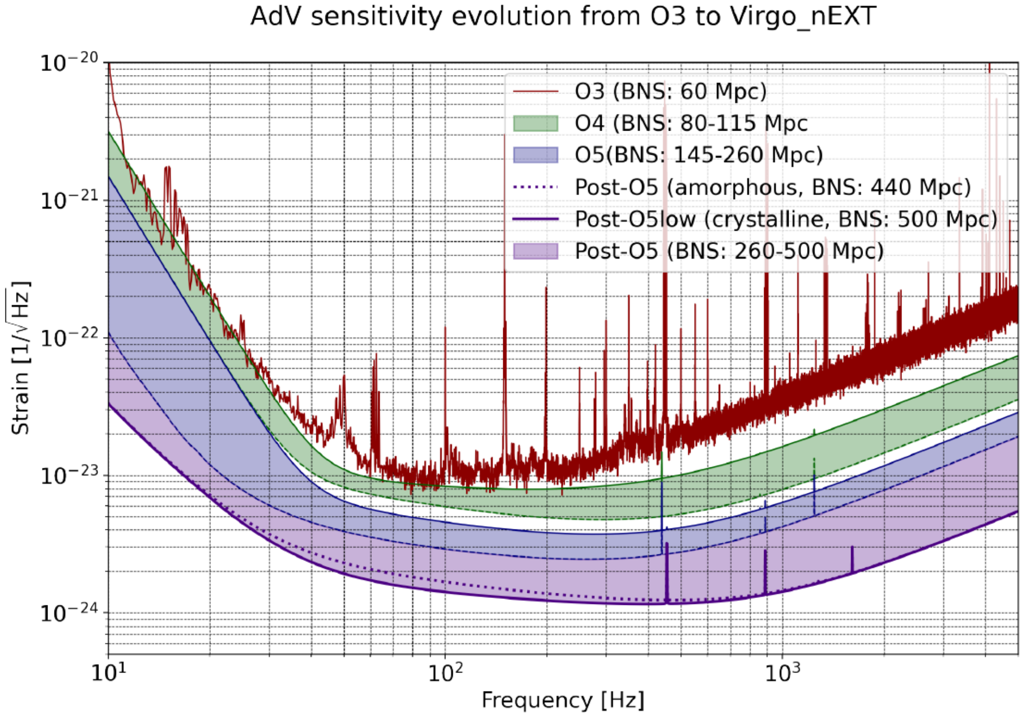
  **LIGO A#** **Voyager (cryogenic)** **Virgo_nEXT**

- R&D synergies and risk mitigation with future generation detectors 3G



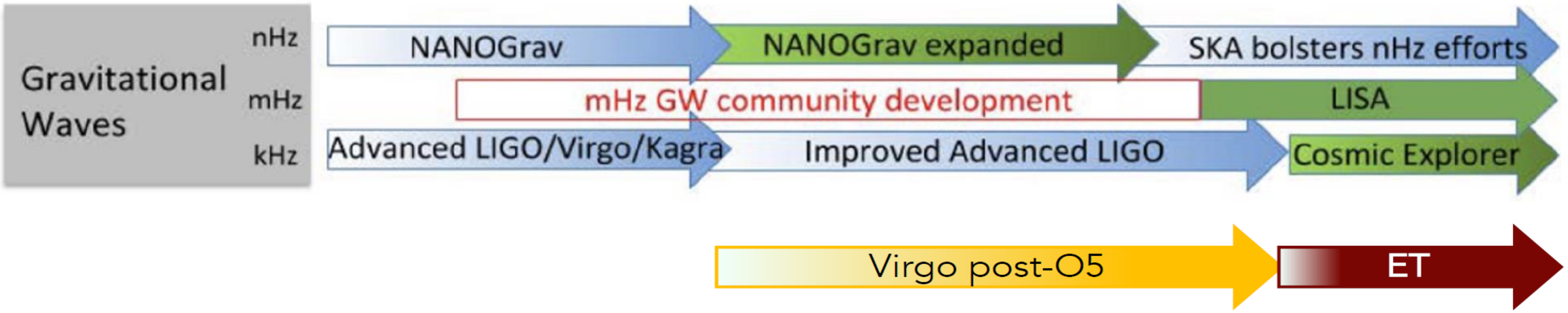

A# versus A+:

- *Low frequencies*: close to a factor of 2 reduction
- *High frequencies*: factor of 2 reduction
- *Mid frequencies*: minimal reduction, limited by coating thermal noise

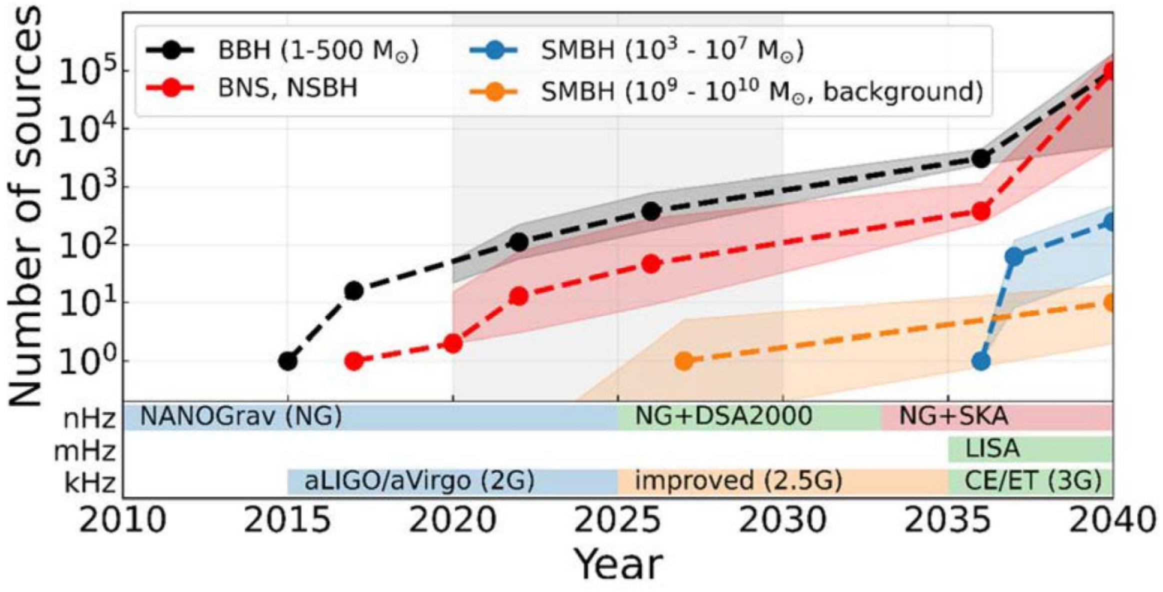


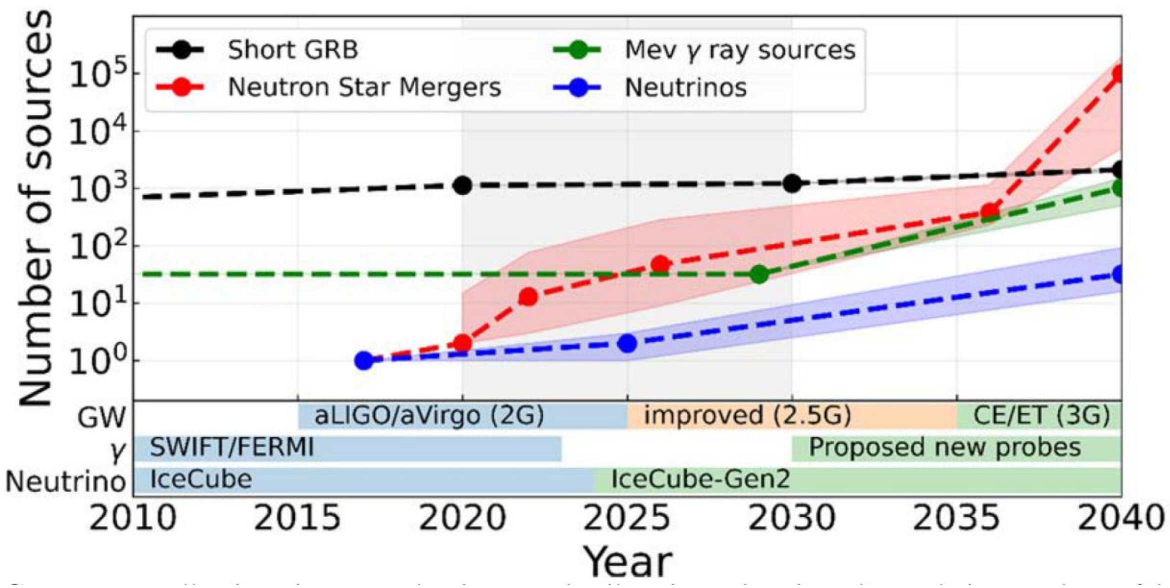

more in P.Puppo's talk at the XII ET Symposium, June 2022
https://indico.ego-gw.it/event/411/

# a glimpse into the 2030s



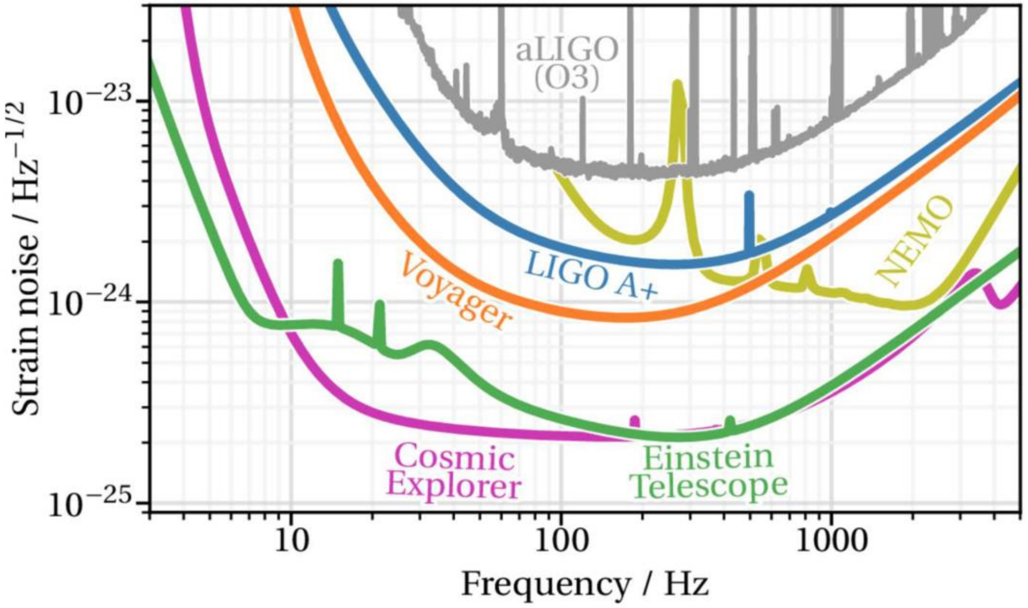

adapted from "**Astro2020**"
*Pathways to Discovery in Astronomy and Astrophysics in the 2020s*
Committee for a Decadal Survey on Astronomy and Astrophysics



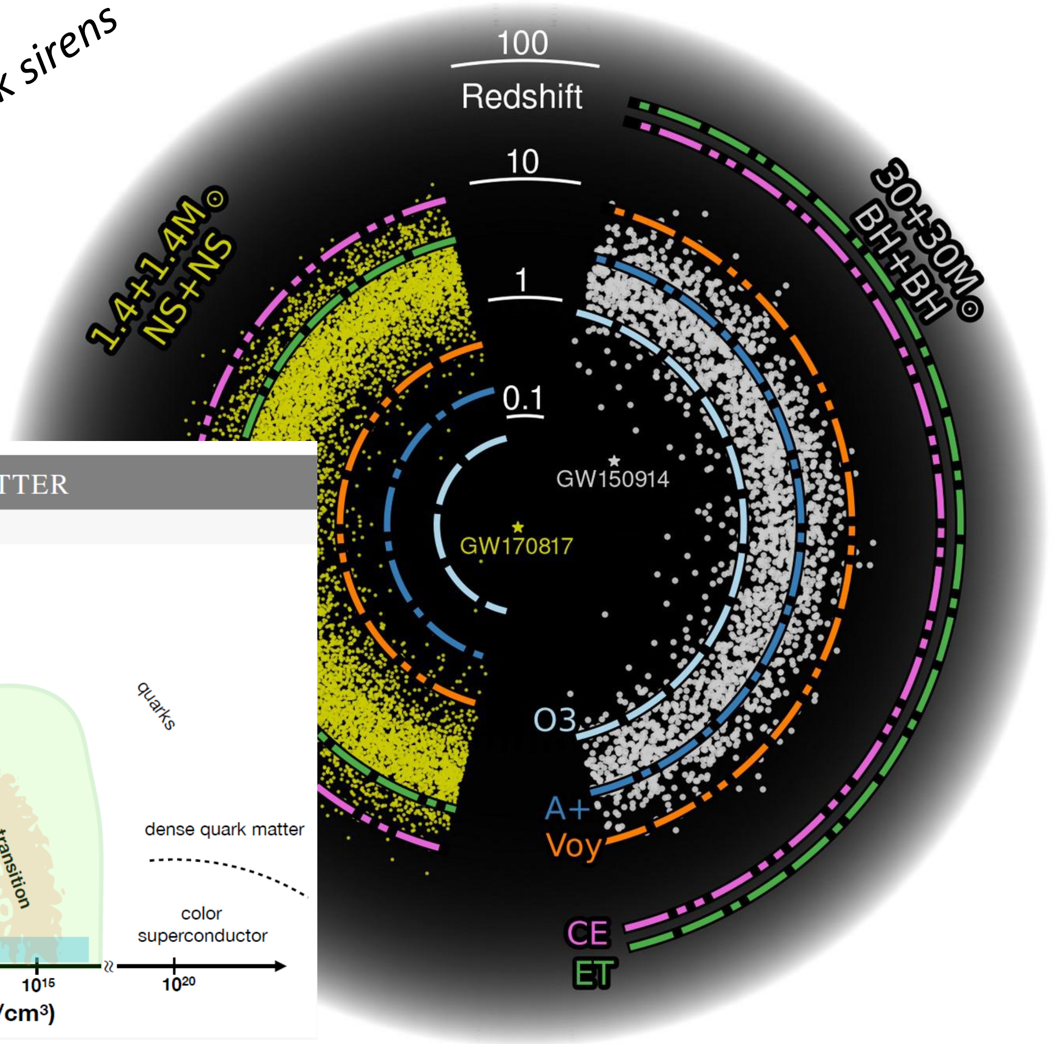




- these are future expectations for known populations of sources,
- there are high expectations for new source classes and phenomena yet to be discovered and measured

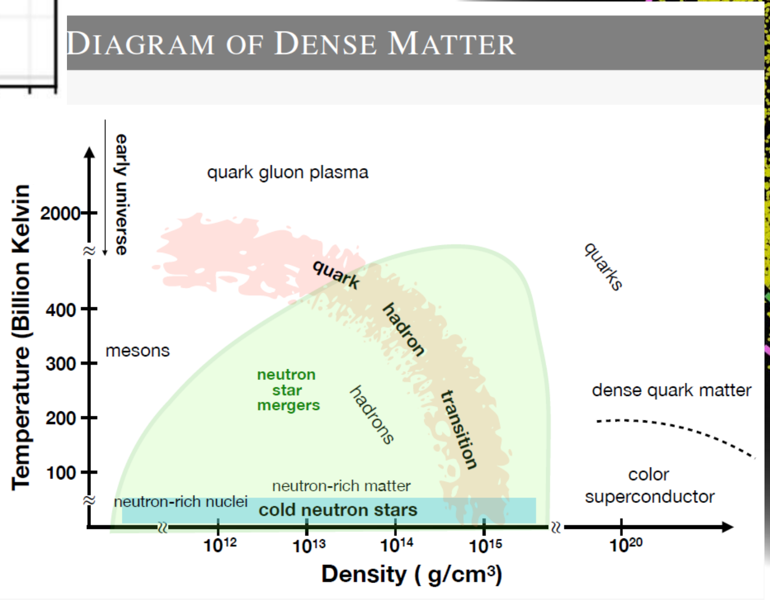
# a glimpse into the 2030s: Earth based detectors




M.Mancarella talk
cosmology with dark sirens





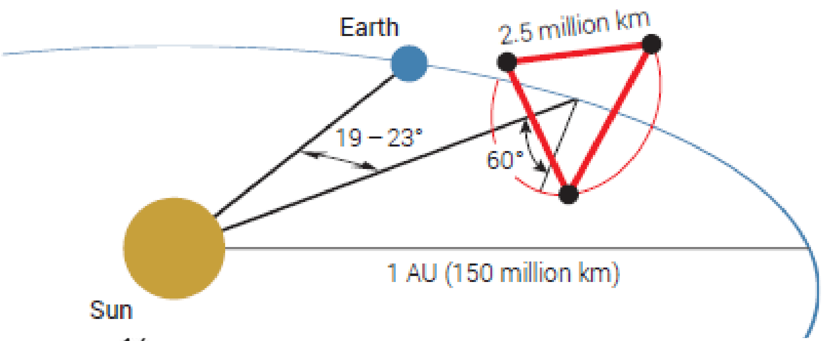




Cosmic Explorer: https://dcc.cosmicexplorer.org/P2100003/public
Einstein Telescope: http://www.et-gw.eu

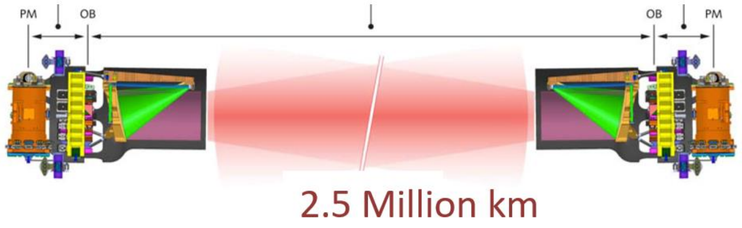
GWIC 3G reports
https://gwic.ligo.org/3Gsubcomm/

# a glimpse into the 2030s: LISA

C.Tamarit [talk](#)
cosmic history

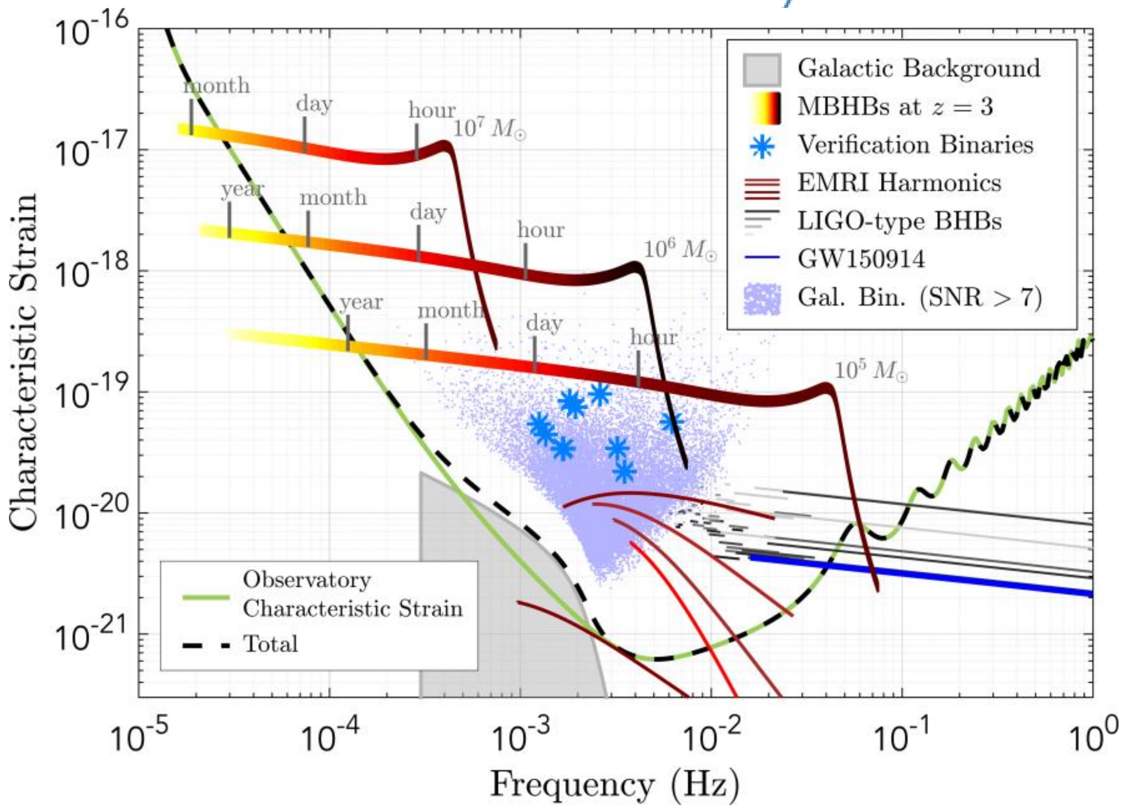



target mission adoption: end of 2023

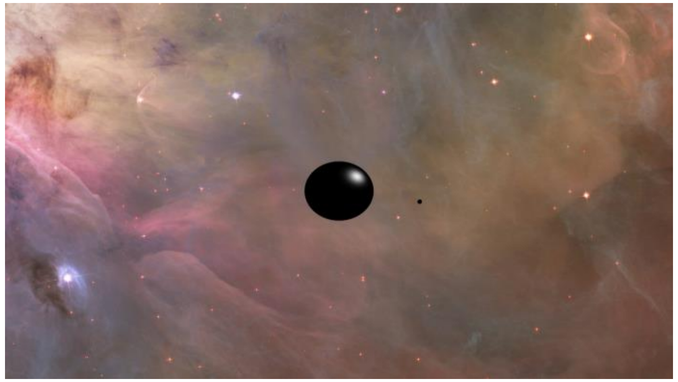



Measure acceleration between free-falling test masses 2.5 million km apart

- 3 parts: TM-SC, SC-SC, SC-TM
- Time delay interferometry
- Drag-free SC

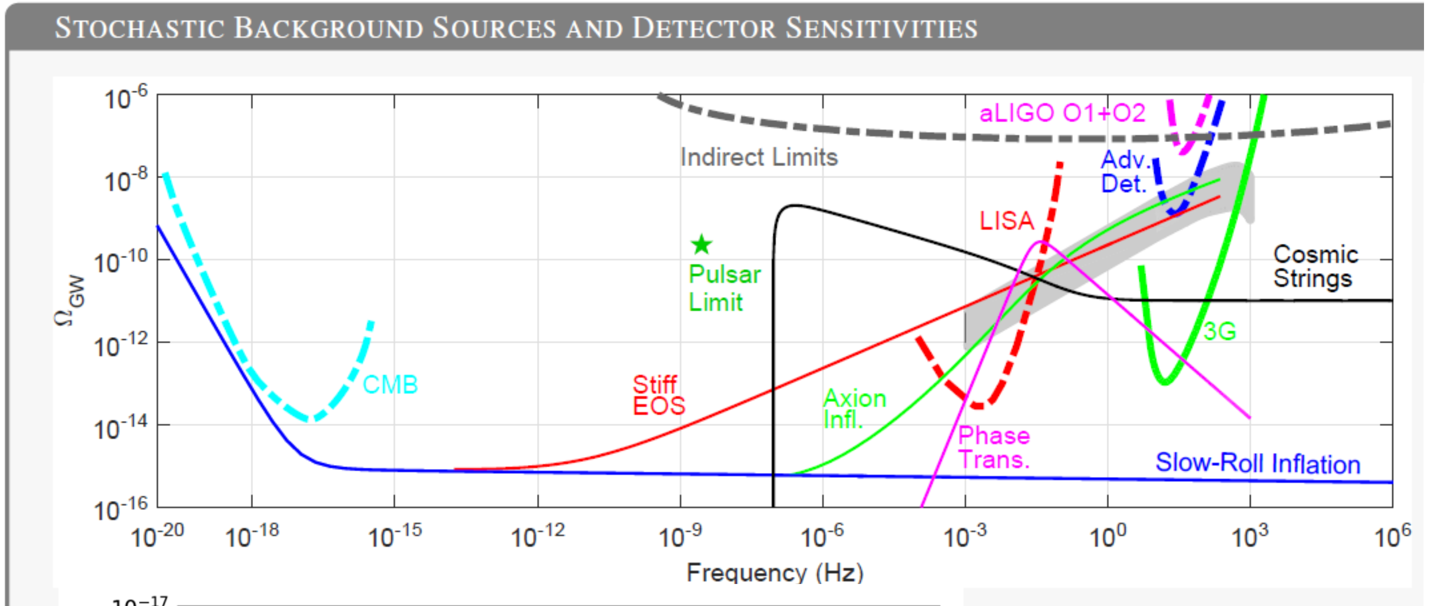


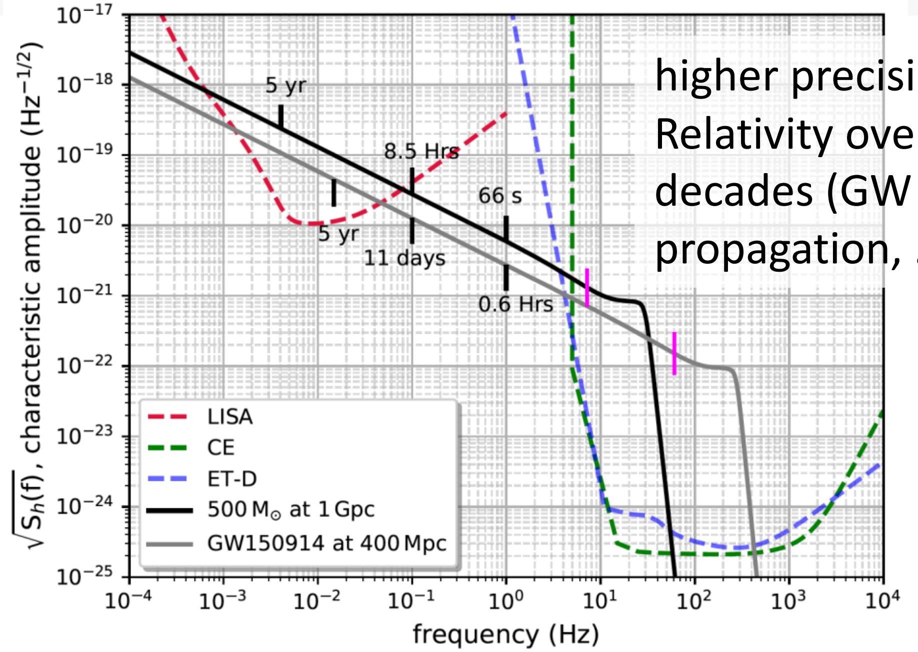

- (Super) Massive BH mergers detectable in all the accessible Universe [103, 107] $M_\odot$
- Milky Way: some 104 discernable binaries + foreground
- Extreme Mass Ratio Inspirals: compact object inspiralling and plunging into a (Super) Massive BH. Enable a precise mapping of Gravity and precise tests of MBH characteristics



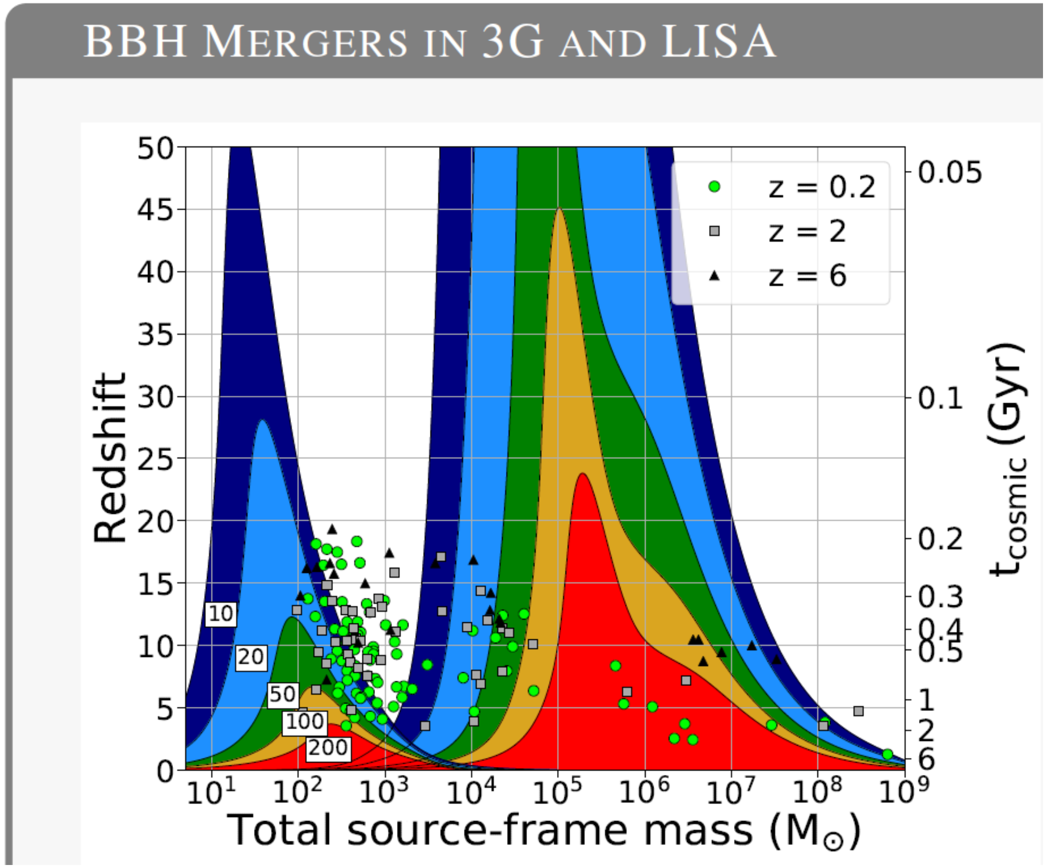
[Astrophysics with LISA arXiv:2203.06016](#)

# a glimpse into the 2030s: multiband GW astronomy




higher precision tests of General Relativity over ~5 frequency decades (GW generation, propagation, …)




**ET** **LISA**

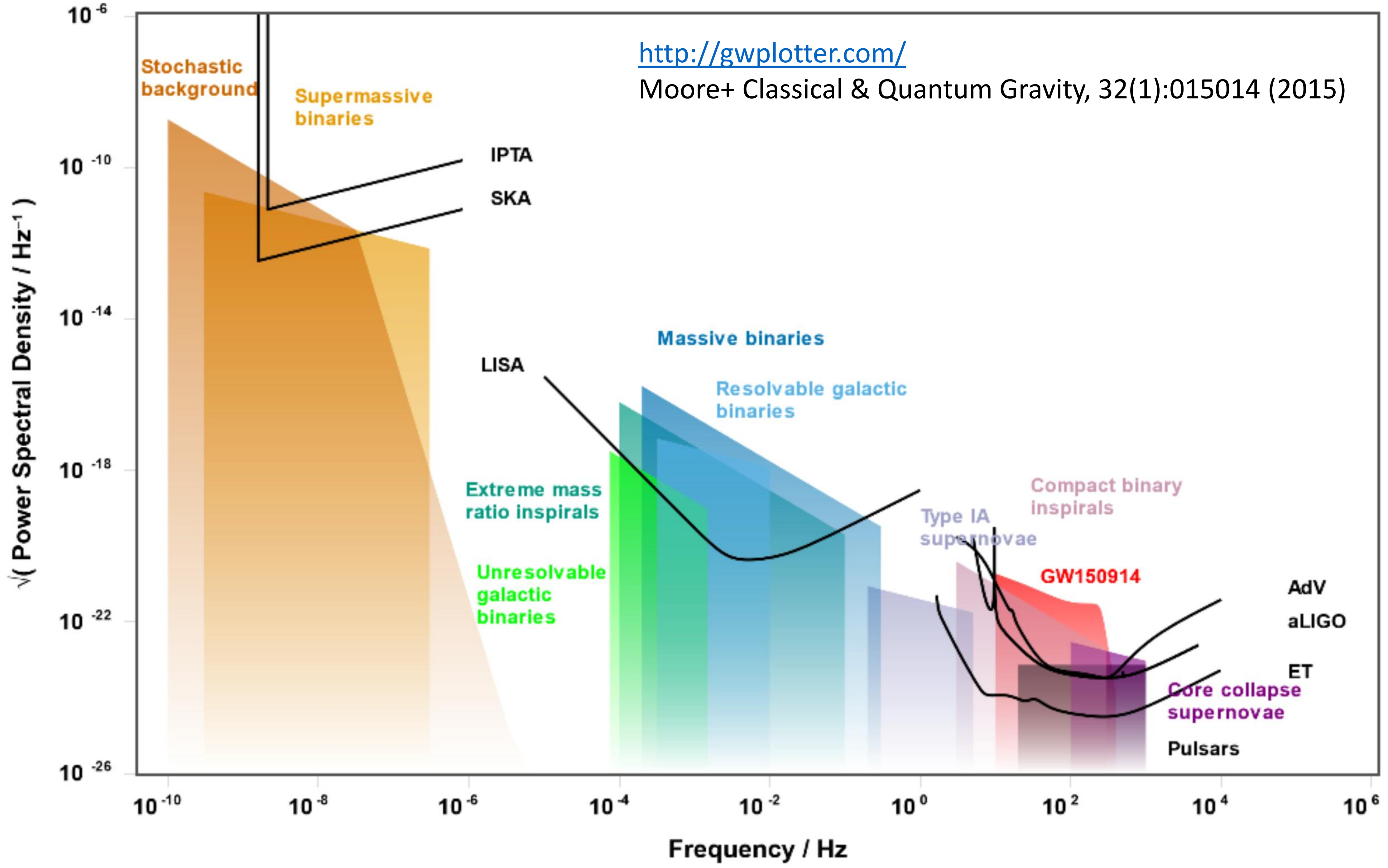
Tracking the entire mass spectrum of seeds of SMBH

# *remarks*

- LIGO-Virgo-KAGRA observations are unveiling populations of **compact object binaries**, enabling investigations in **astrophysics**, **gravity**, **cosmology** and **dark matter**
- the GW **detection rates** of known sources **will increase steeply** as the surveyed volume of Universe. This will boost also **multimessenger observations** as well as investigations of **equation-of-state of NS matter**.
- future **higher precision observations** and **yet-to-be-observed phenomena** will enable new science.
- **multiband GW astronomy** across 12+ orders of magnitude in frequency will bloom in the next decade

ACKNOWLEDGEMENTS: this material is based upon work supported by NSF's LIGO Laboratory which is a major facility fully funded by the National Science Foundation. The authors gratefully acknowledge the Italian Istituto Nazionale di Fisica Nucleare (INFN), the French Centre National de la Recherche Scientifique (CNRS) and the Netherlands Organization for Scientific Research (NWO), for the construction and operation of the Virgo detector and the creation and support of the EGO consortium. …

# SPARES

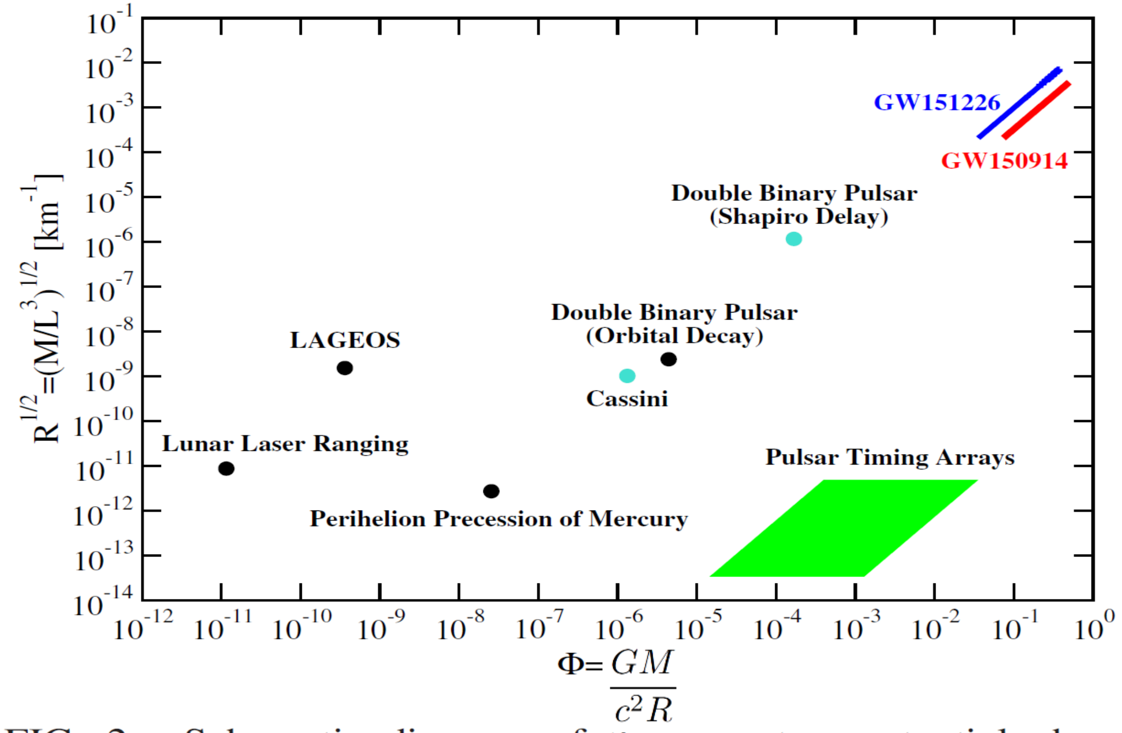


http://gwplotter.com/
Moore+ Classical & Quantum Gravity, 32(1):015014 (2015)
Stochastic background
Supermassive binaries
IPTA
SKA
LISA
Massive binaries
Resolvable galactic binaries
Extreme mass ratio inspirals
Unresolvable galactic binaries
Type IA supernovae
Compact binary inspirals
GW150914
AdV
aLIGO
ET
Core collapse supernovae
Pulsars
√( Power Spectral Density / Hz⁻¹ )
Frequency / Hz

# investigating gravity

PHYSICAL REVIEW D **94,** 084002 (2016)
YUNES, YAGI, and PRETORIUS

curvature



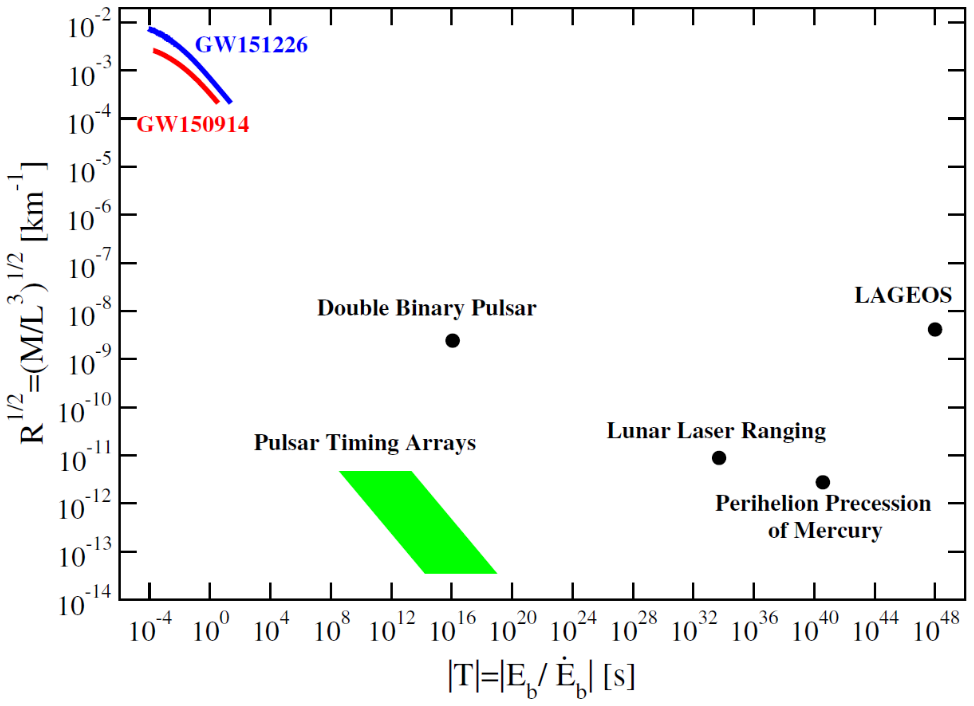




FIG. 2. Schematic diagram of the curvature-potential phase space sampled by various experiments that test GR. The vertical axis shows the inverse of the characteristic curvature length scale, while the horizontal axis shows the characteristic gravitational potential, based on Table II. GW150914 and GW151226 sample

except that the abscissa is now the radiation-reaction time scale sampled by each observation. We model this via $|T| = |E_b/\dot{E}_b|$, where $E_b$ is the characteristic gravitational binding energy and $\dot{E}_b$ is the rate of change of this energy,

# investigating gravity 2

The Astrophysical Journal, 802:63 (19pp), 2015 March 20 Baker, Psaltis, & Skordis

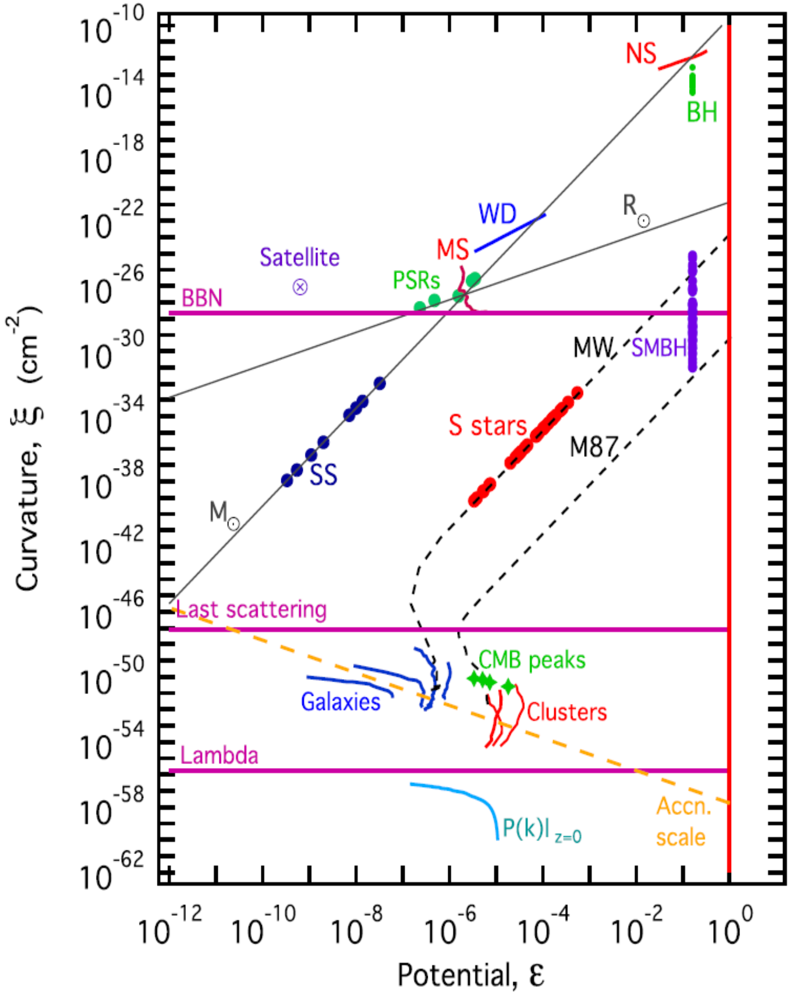



**Figure 1.** A parameter space for gravitational fields, showing the regimes probed by a wide range of astrophysical and cosmological systems. The axes variables are explained in Section 2 and individual curves are detailed in Section 3. Some of the label abbreviations are: SS—planets of the Solar System, MS—Main Sequence stars, WD—white dwarfs, PSRs—binary pulsars, NS—individual neutron stars, BH—stellar mass black holes, MW—the Milky Way, SMBH—supermassive black holes, BBN—Big Bang Nucleosynthesis.

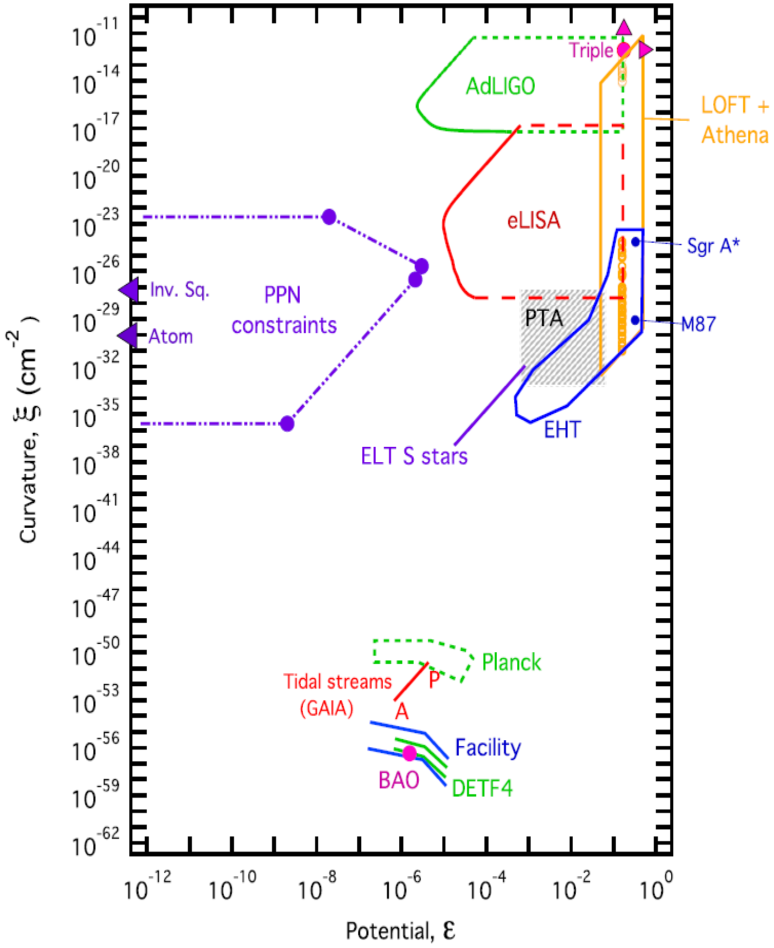
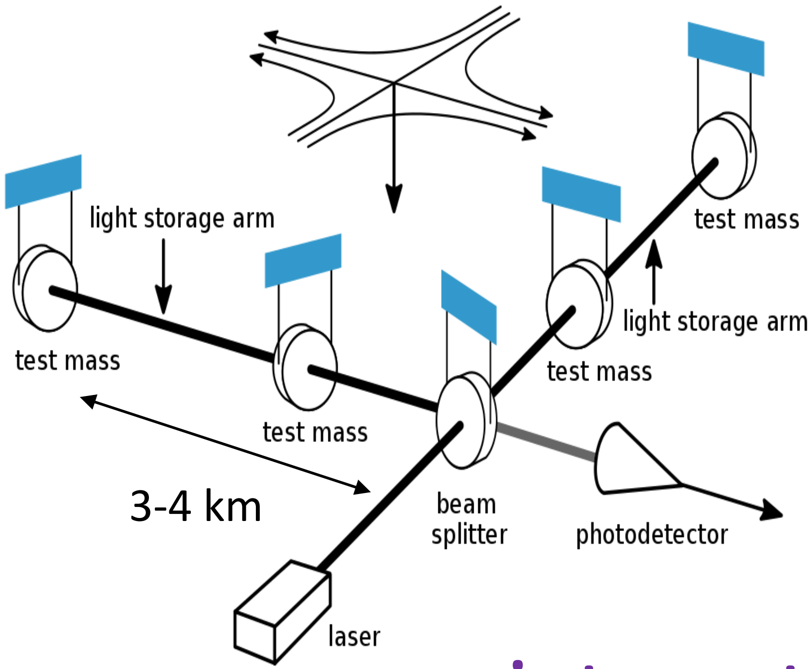
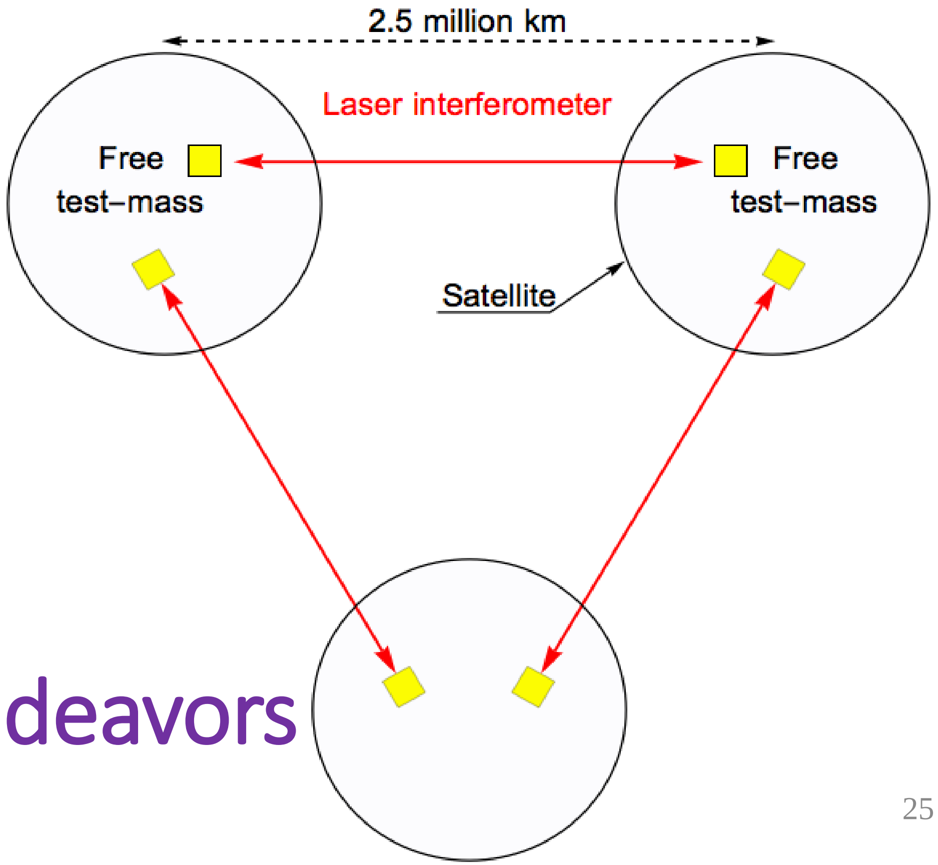



**Figure 2.** The experimental version of the gravitational parameter space (axes the same as in Figure 1). Curves are described in detail in the text (Section 4). Some of the abbreviations in the figure are: PPN—Parameterized Post-Newtonian region, Inv. Sq.—laboratory tests of the $1/r^2$ behavior of the gravitational force law, Atom—atom interferometry experiments to probe screening mechanisms, EHT—the Event Horizon Telescope, ELT—the Extremely Large Telescope, DETF4—a hypothetical "stage 4" experiment according to the classification scheme of the Dark Energy Task Force (Albrecht et al. 2006), Facility—a futuristic large radio telescope such as the Square Kilometre Array.

# Gravitational Wave Detectors

| | LIGO/Virgo/KAGRA: in operation | LISA: preparing the mission |
|---|---|---|
| Size | 3-4 km | $2.5 \times 10^6$ km |
| Frequency | 10 Hz ÷ few kHz | 20 μHz ÷ 1 Hz |




international endeavors

# post-O5 concept study

LIGO and Virgo are evaluating how to exploit current infrastructures for observations in the early 2030s

- readiness/cost/impact of more detector upgrades

**Virgo_nEXT** **LIGO A#** **Voyager (cryogenic)**

| Parameter | O5 high | O5 low | VnEXT_low |
|---|---|---|---|
| Power injected | 60 W | 80 W | 277 W |
| Arm power | 290 kW | 390 kW | 1.5 MW |
| PR gain | 35 | 35 | 39 |
| Finesse | 446 | 446 | 446 |
| Signal recycling | Yes | Yes | Yes |
| Squeezing type | FDS | FDS | FDS |
| Squeezing detected level | 4.5 dB | 6 dB | 10.5 |
| Payload type | AdV | AdV | Triple pendulum |
| ITM mass | 42 kg | 42 kg | 105 kg |
| ETM mass | 105 kg | 105 kg | 105 kg |
| ITM beam radius | 49 mm | 49 mm | 49 mm |
| ETM beam radius | 91 mm | 91 mm | 91 mm |
| Coating losses ETM | 2.37e-4 | 0.79e-4 | 6.2e-6 |
| Coating losses ITM | 1.63e-4 | 0.54e-4 | 6.2e-6 |
| Newtonian noise reduction | 1/3 | 1/5 | 1/5 |
| Technical noise | "Late low" | None | None |
| BNS range | 145 Mpc | 260 Mpc | 500 Mpc |

VIRGO

Paola Puppo, ET Symposium, June 2022

P.Puppo's talk at the XII ET Symposium, June 2022
https://indico.ego-gw.it/event/411/

## Comparison of Parameters

LIGO

| Parameter | Units | A+ | A$^\sharp$ | STO | Voyager |
|---|---|---|---|---|---|
| Arm power | kW | 750 | 1500 | 1500 | 3000 |
| Laser wavelength | μm | 1 | 1 | 1 | 2 |
| Test mass material | | Silica | Silica | Silica | Silicon |
| Temperature | K | 295 | 295 | 295 | 123 |
| Mass | kg | 40 | 100 | 200 | 200 |
| Observed squeezing | dB | 7 | 10 | 10 | 7 |
| Rayleigh wave suppression | dB | 0 | 6 | 20 | 20 |
| Horiz. susp. pt. at 1 Hz | $\mathrm{pm}/\sqrt{\mathrm{Hz}}$ | 10 | 10 | 0.1 | 0.1 |
| Final susp. stage blade | | No | No | Yes | Yes |
| Filter cavity length | m | 300 | 300 | 4000 | 300 |

LIGO VIRGO KAGRA

# Gravitational plane Waves far away from sources

❑ weak-field linear approximation of General Relativity: $g_{\alpha\beta} = \eta_{\alpha\beta} + h_{\alpha\beta}$ $|h_{\alpha\beta}| << 1$

oversimplified separation between GWs and static space-time in the background

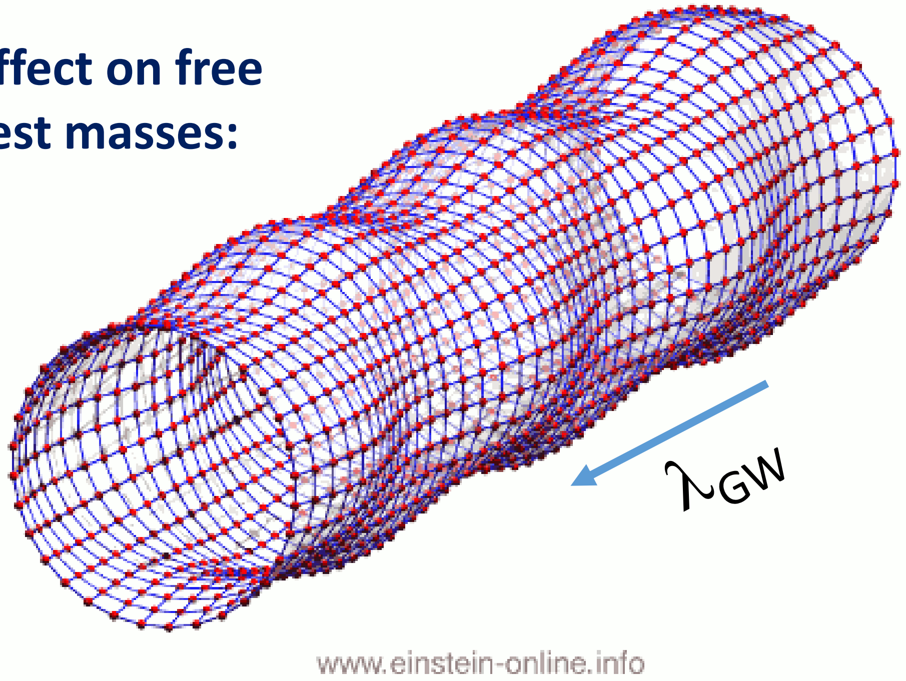
- analogies with electromagnetic waves:

  *light speed, transverse, 2 polarization components*

- peculiarities of GWs:

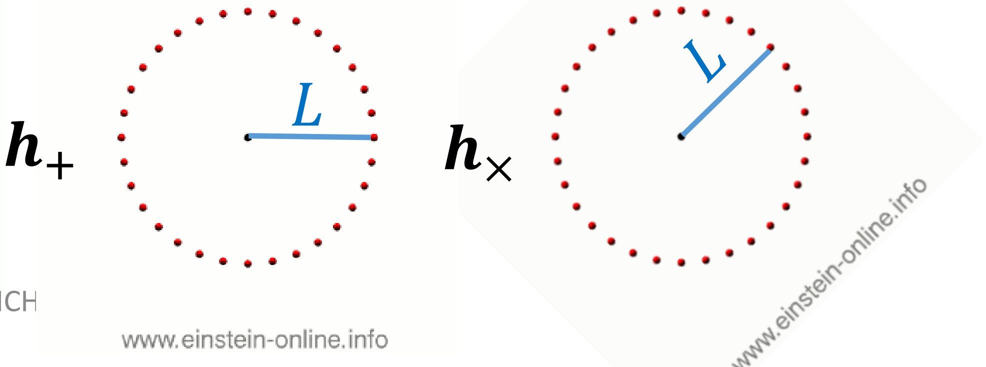
  *tidal deformations of extended bodies, no measurable local effect*

**Effect on free test masses:**




**GW amplitude is strain:** $\frac{\Delta L}{L} = \frac{1}{2}\boldsymbol{h}$

*tensor polarizations* $\boldsymbol{h}_+$ $\boldsymbol{h}_\times$ *rotated by* $\frac{\pi}{4}$ ***in the wavefront plane:***



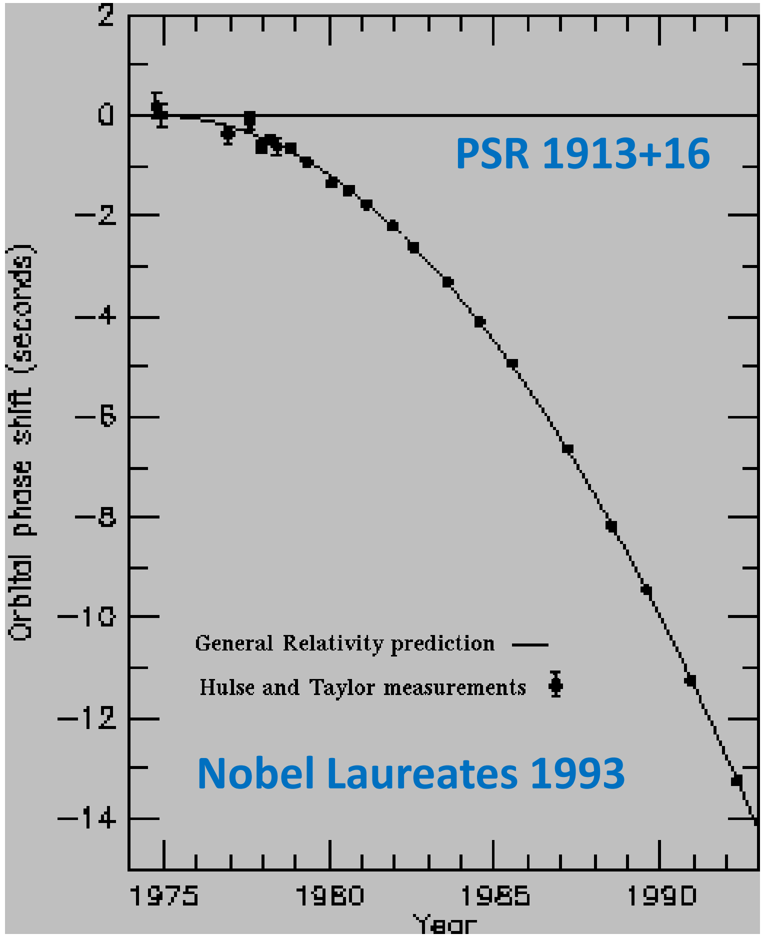
# Sources of Gravitational Waves

- **mass-Dipole Moment**, [M R], position of the Center of Mass of the system:
  "almost forbidden" dipolar emission of GWs from isolated systems

- leading order emission is **mass-Quadrupole Moment $Q_{\mu\nu}$** , [M R$^2$] :
  GW Luminosity is driven by $\dddot{Q}_{\mu\nu} \neq 0$

$$P \approx \frac{G}{5c^5}\dddot{Q}_{\mu\nu}\dddot{Q}^{\mu\nu} \sim 10^{39} W \left(\frac{f}{Hz}\right)^2 \left(\frac{M}{M_\odot}\right)^2 \left(\frac{v}{c}\right)^4$$

dimensional argument




- generating detectable GWs as in Hertz-like experiment is NOT feasible

- astrophysical sources (e.g. **Hulse & Taylor binary pulsar**) are emitting in agreement with General Relativity

# GW150914: the first direct observation

PRL 116, 061102 (2016)

**unexpected signal: detected first by wide-scope transient search not assuming waveform model**