Journée SFP 2024 – lumière sur la matière noire
Paris21 Mars 2024

Ondes gravitationnelles et Matière noire

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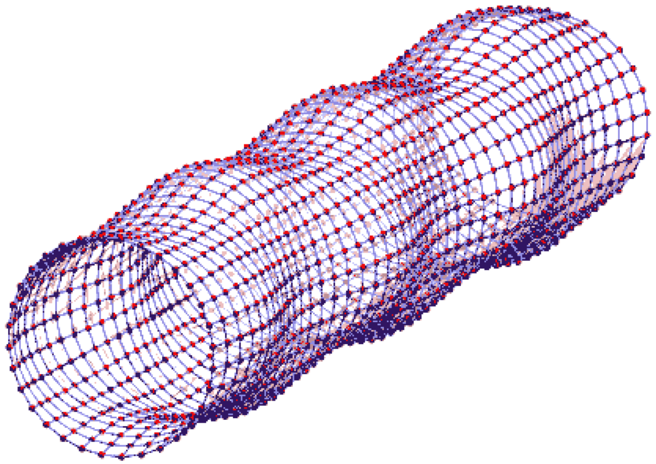
CNRS – IN2P3

Gravitational Waves

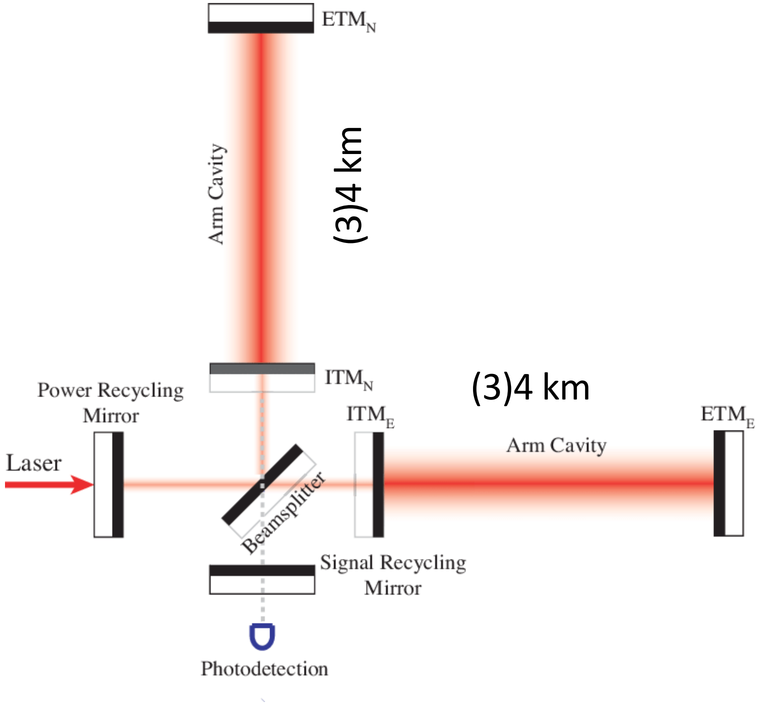


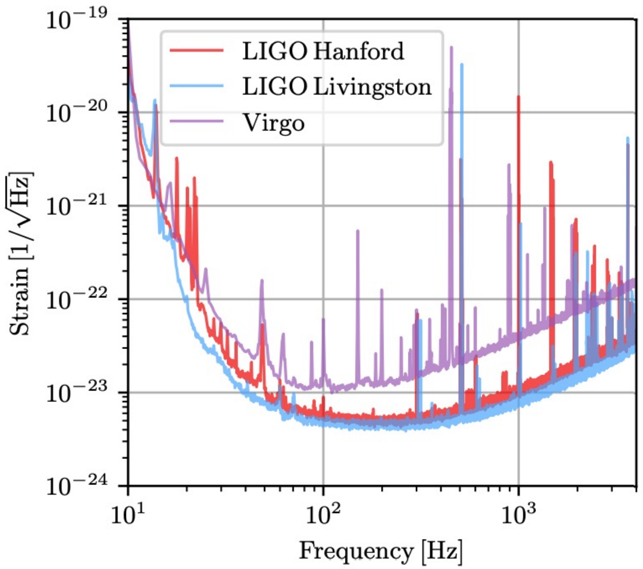
Ripples in the spacetime metric generated by the acceleration of masses, propagating at the speed of light

- GW cause the the space itself to stretch/compress
- Predicted by Einstein’s General Relativity (1916) - first direct observation 2015 (LIGO)
- Probe gravity in unprecedented conditions, new messenger from the Universe
- Possible sources of detectable GW are some of the most violent events in the Universe involving massive and compact objects in relativistic regime

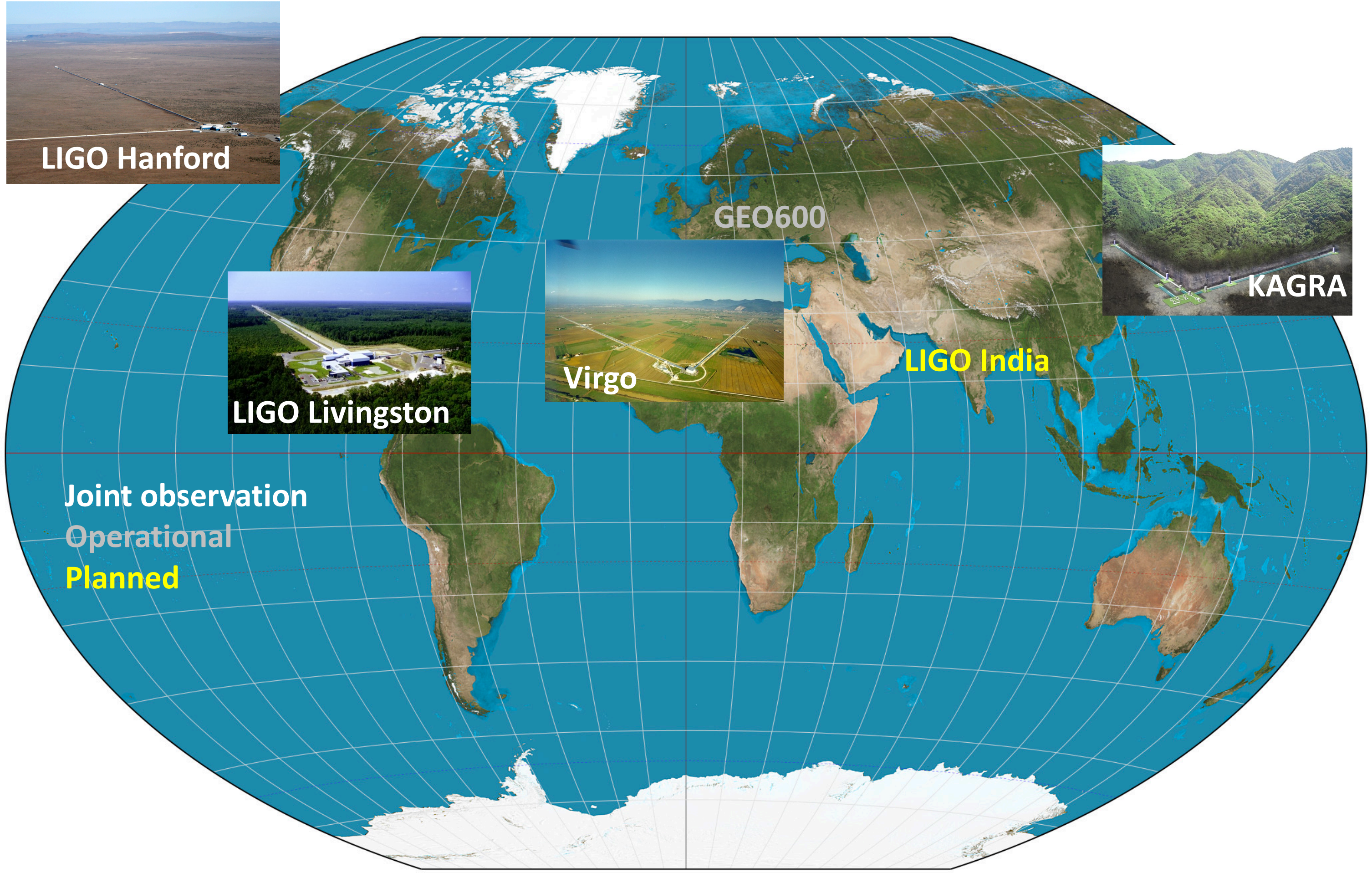
GW terrestrial detectors

- Michelson interferometers with Fabry-Pérot cavities in the arms, operating on dark fringe
- Observable: h(t) – "strain". $\delta L = hL$ → km-long arms ($h \sim 10^{-21}$)
- Sensitive in the ~10Hz – ~kHz frequency band



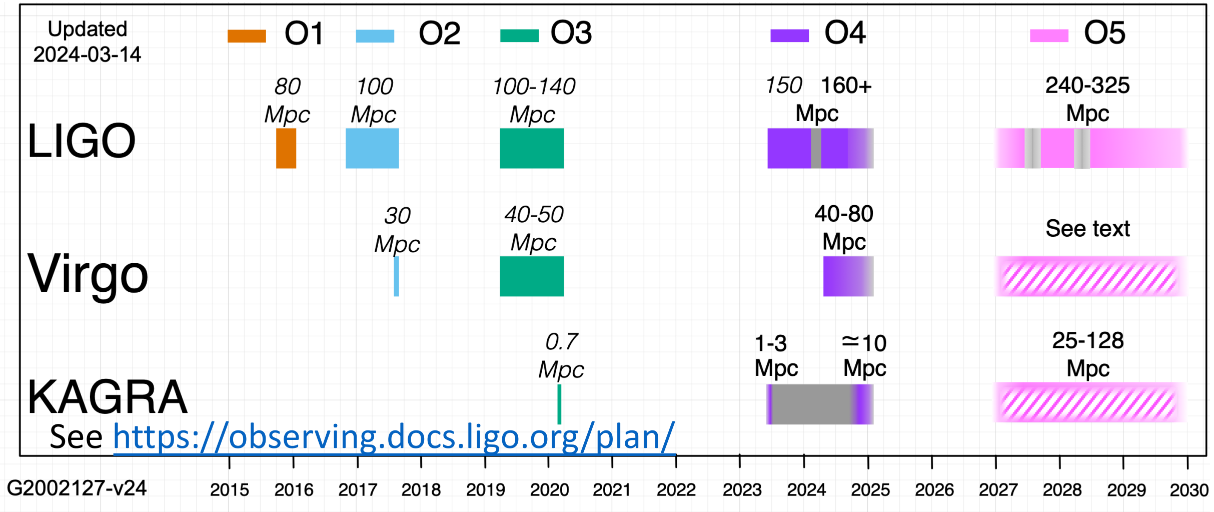


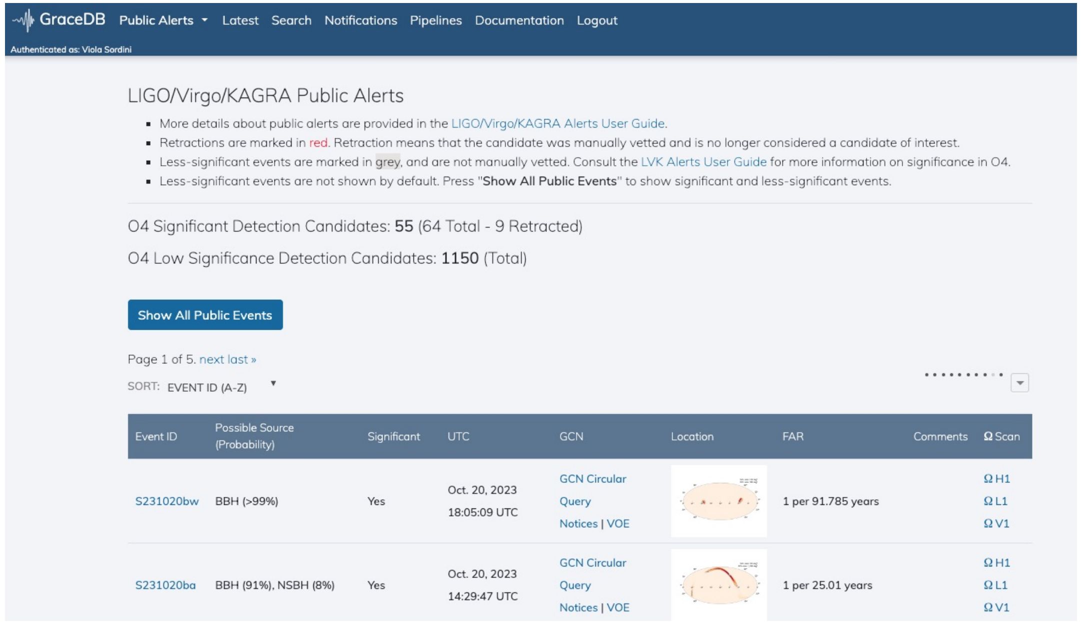
GW terrestrial detectors



LIGO-Virgo-KAGRA (LVK) network, evolving to IGWN

The LVK network

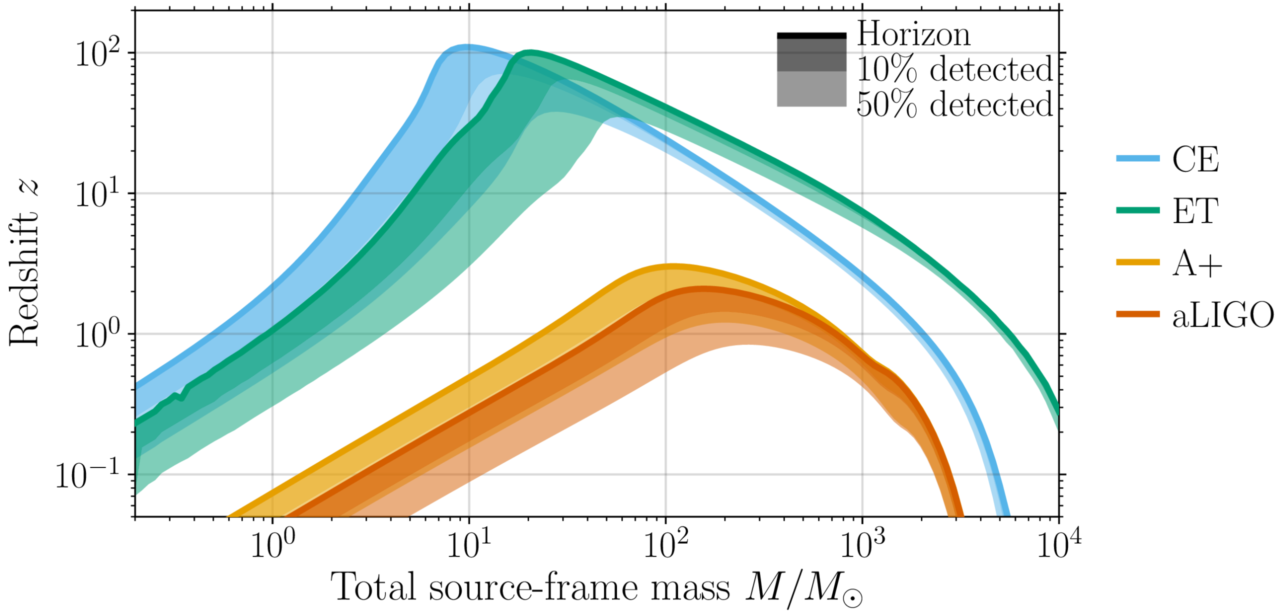


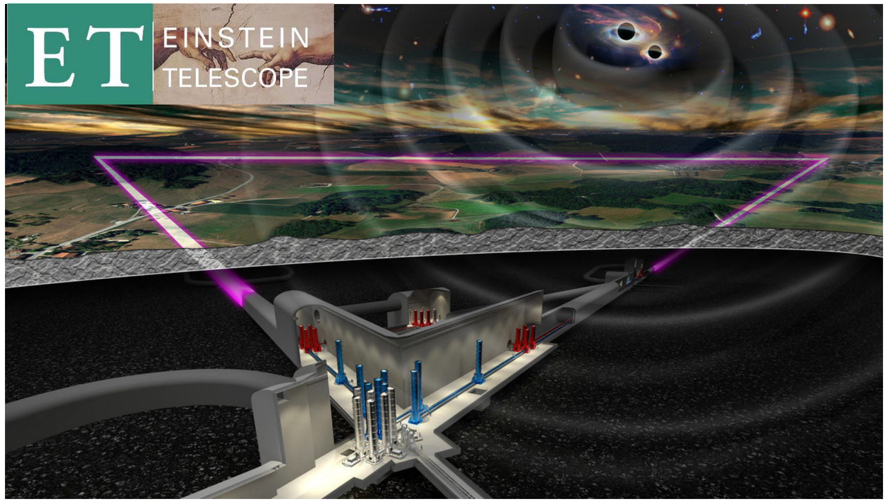


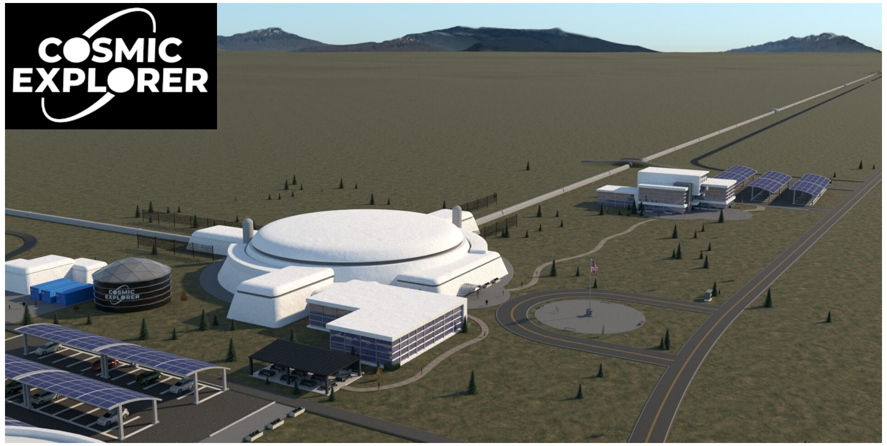
- All results and data available on GWOSC
- O4 ongoing since May 2023, until February 2025
- Alerts for CBC events include early warning searches on GraceDB and distributed through GCN and SCiMMA (all explanations here)

3G GW ground-based detectors

- Next generation ground-based detectors (data taking ~2040s?)
- Impressive event rate and reach
- Transition projects with LIGO and Virgo infrastructure are also under study

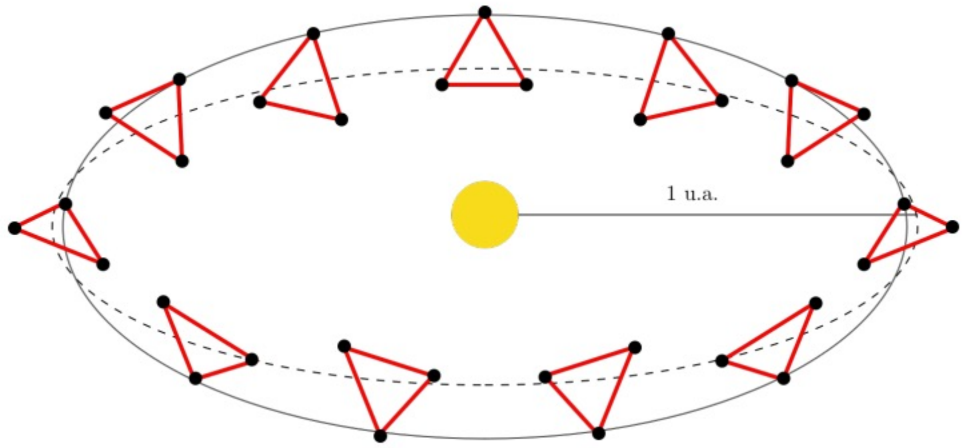


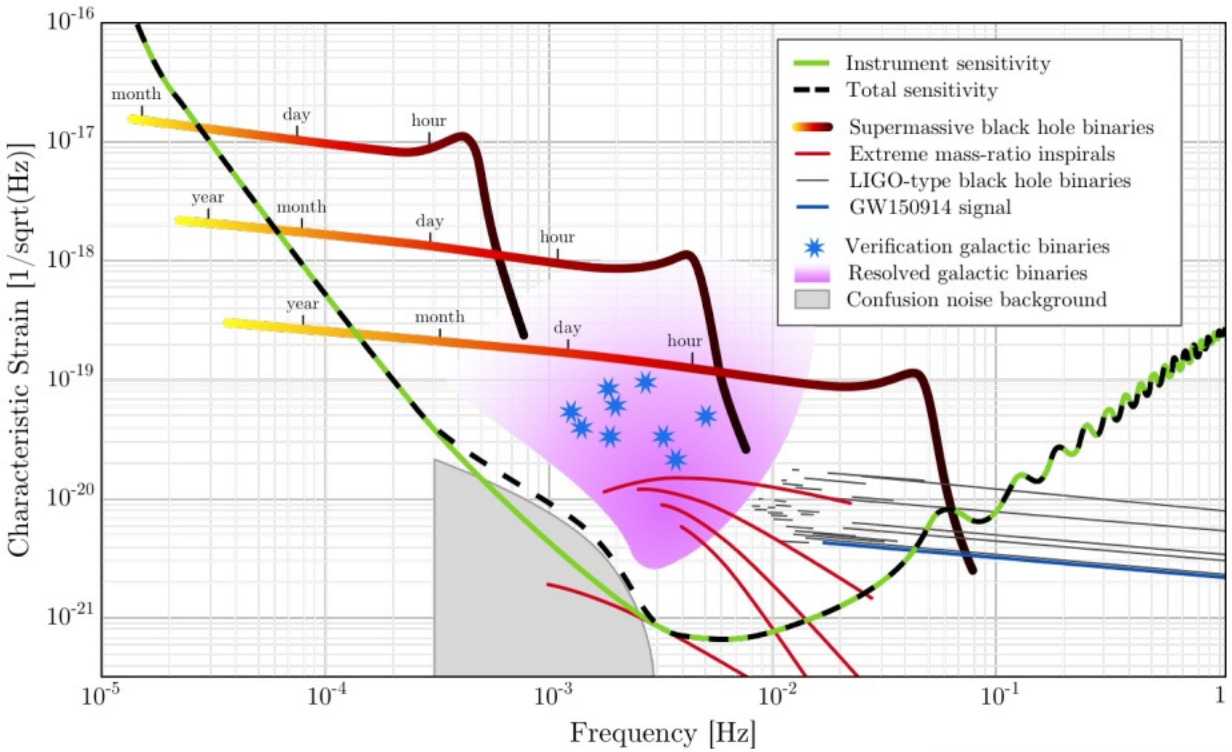




Laser Interferometer Space Antenna

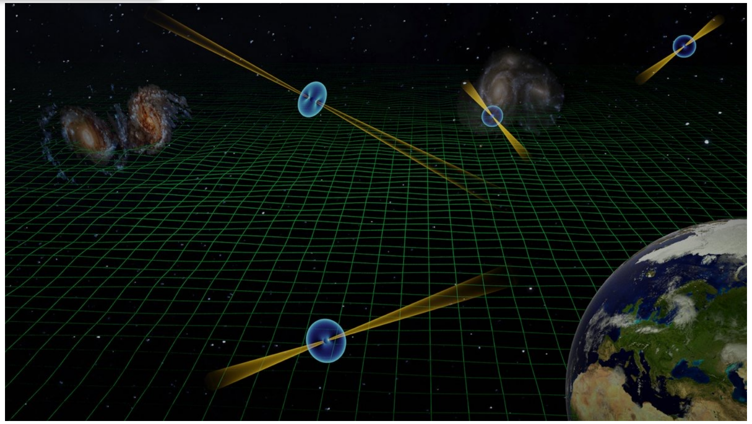
- Space-based GW observatory sensitive in mHz band (launch mid-2030s), arms 2.5M km
- Sensitive to merger of supermassive BH
- Dominated by signals (many long-lived), main background from unresolved GW
- Data analysis challenge!

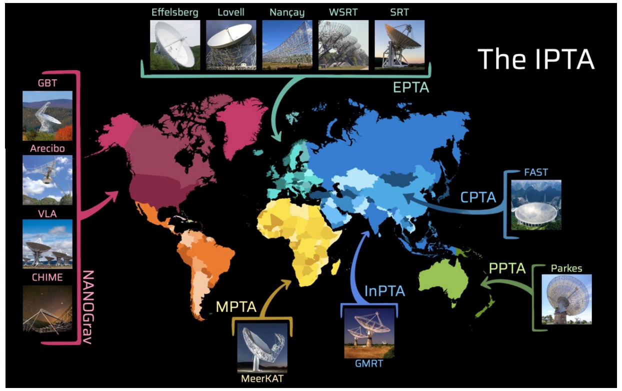




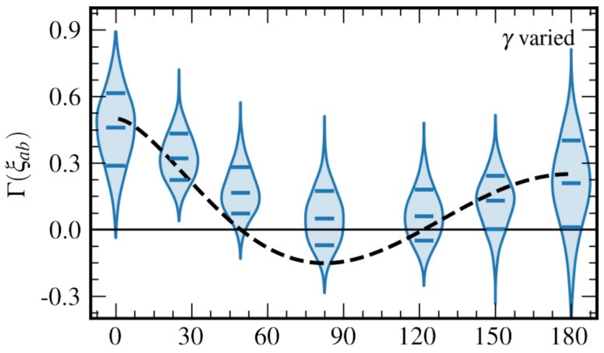
Pulsar Timing Arrays

- Network of telescopes observing pulsars signals in radio frequencies over time
- Sensitivity in the nHz band, SGWB from SMBHB
- Signal is correlated (can predict correlation pattern, depending on pulsars angular separation)

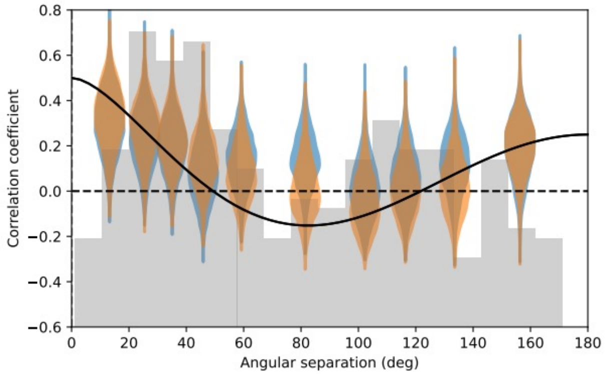




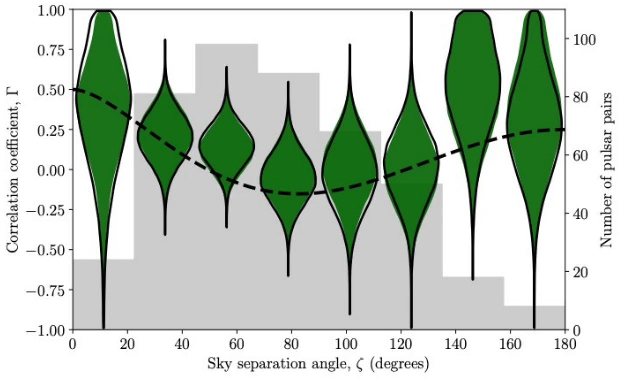
NANOGrav 2023
15yr, 70 PSRs, 4σ



EPTA + InPTA 2023
10.3yr, 25 PSRs, 3.5σ

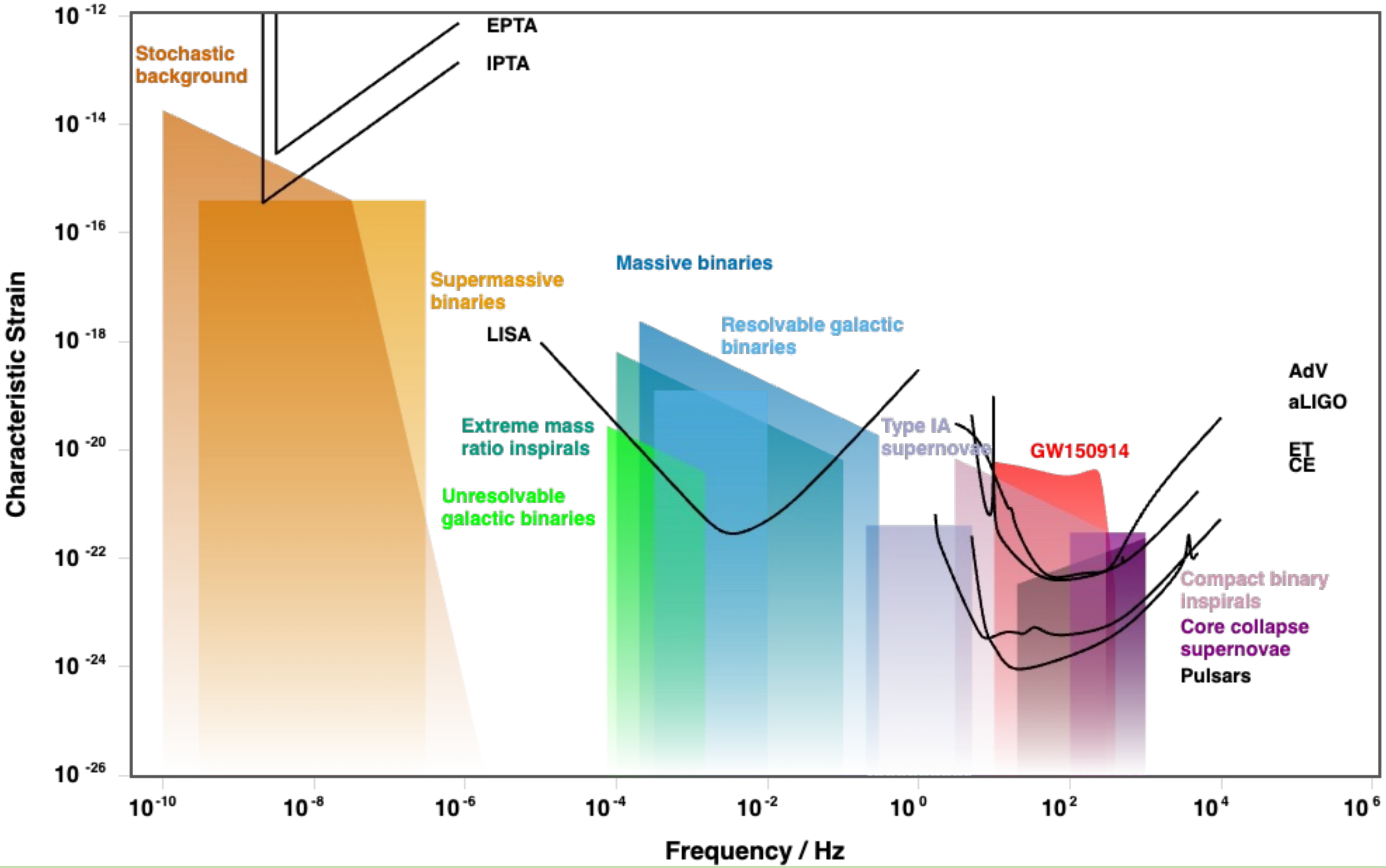


PPTA 2023
18yr, 32 PSRs, 2σ



GW spectrum

- Different facilities are complementary!

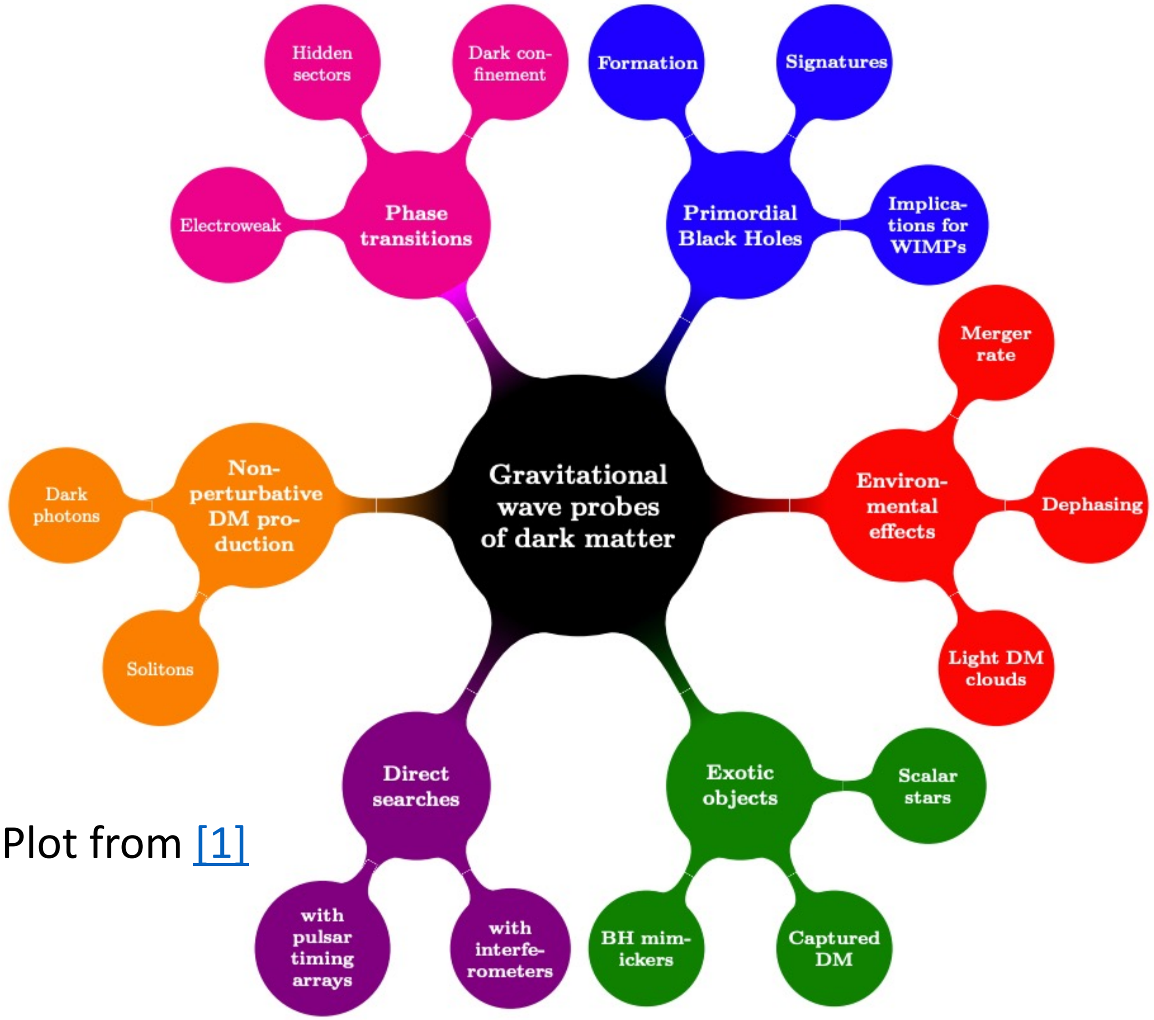


GW science

- Since the first detection in 2015, now ~hundreds of observations
- LVK – mostly BBH, but also NSBH, BNS (one multi-messenger), but keep looking for other signatures (continuous GW emission, non-modeled transients, GWB)
- PTA - Evidence of signal (SGWB from SMBHB most likely interpretation)
- These observations are interesting for
  - Understanding gravity (test beyond GR theories)
  - Astrophysics – understand the objects that generated the GW signal and the possible associated multi-messenger observations
  - Explore extremely dense nuclear matter
  - Cosmology – understand the history of the Universe
  - …how exciting if we could say something about Dark Matter ?

GW and DM

- GW can help probing Dark Matter in many ways
- From GW observations – often polluted by astrophysical unknowns
- Using GW detectors for direct searches
- In this talk – some results, ideas, links
- By no means a complete review! Apologies for the omissions



Plot from [1]

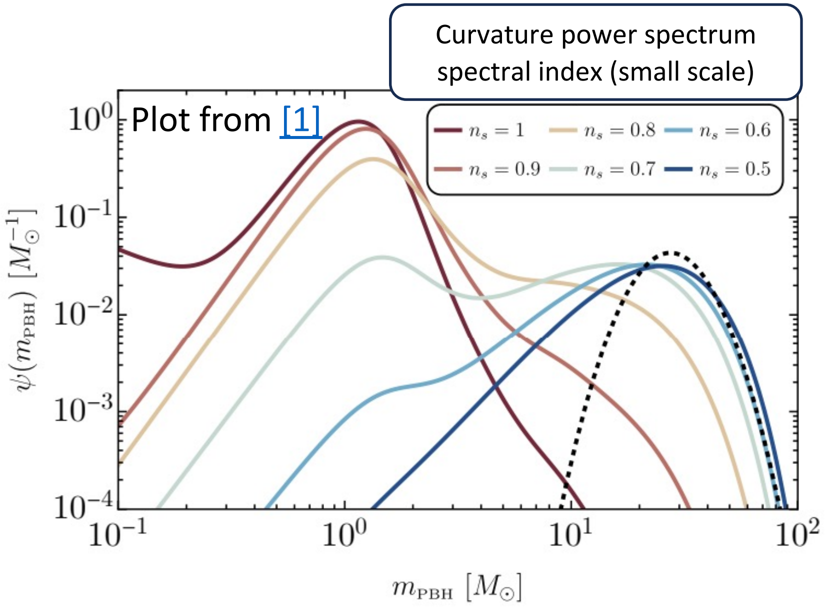
Primordial black holes

- PBH formed from the collapse of large overdensities in the primordial Universe, wide range of masses (10^{-16} to 10^{6} $M_{\odot}$) and different mass spectra.
- Candidates to form (a fraction) of DM
- Popular in late 90's after microlensing observation claims by MACHO survey, then more stringent limits from EROS/OGLE. Since GW detection, CMB limits less stringent, microlensing constraints are re-considered ([1], [2],[3],[4],[5]) → renewed attention in the region [1-100]$M_{\odot}$, relevant for LVK
- LISA would be sensitive to PBH coalescences if M 10^{3}-10^{4} $M_{\odot}$, PBH induced secondary SGWB, EMRI, down to asteroid-mass PBH
- PTA experiments sensitive to PBH SGWB, PBH galactic DM structures

Inspired from [6]

Primordial black holes

- Many models of PBH formation, with different phenomenology
- Mass spectrum influenced by QCD phase transition
- PBH can undergo accretion and can form DM halos
- **Early PBH binaries** (before matter-radiation equality), rate suppressed by binary disruption from multi-body PBH interaction, matter fluctuation or early clustering
- **Late PBH binaries** from dynamical capture in dense environments, with possible rate enhancement. Similar rate as early binaries for ~1$M_\odot$, with peak around 30-100 $M_\odot$
- If we observe something – how do we know it's primordial?
  - Focus on two regions: sub-solar mass and high redshift (z> ~40) 3G detectors
  - Solar mass region interpreted as NS, but needs tidal effects measurement ([1], [2]) or EM-counterpart.. (and we do observe sub-solar NS [3])
  - GW-LSS correlation can be different wrt stellar origin BH



Sub-solar mass search (LVK)

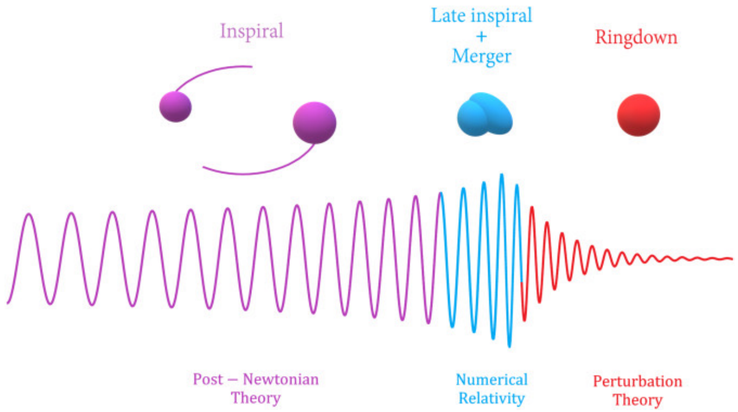
- Compact binary coalescences involving sub-solar mass objects (SSM-SSM, SSM-NS, SSM-BH)
- ISCO frequencies ~kHz, mostly sensitive to inspiral → Inspire-only waveforms, with phase terms up to 3.5PN and no amplitude corrections
- Effectively, as the CBC signals the LVK knows and loves, just longer time in band: duration up to ~450s (~100 in standard BNS search)
- Probed parameter-space in the O3 analysis [1]

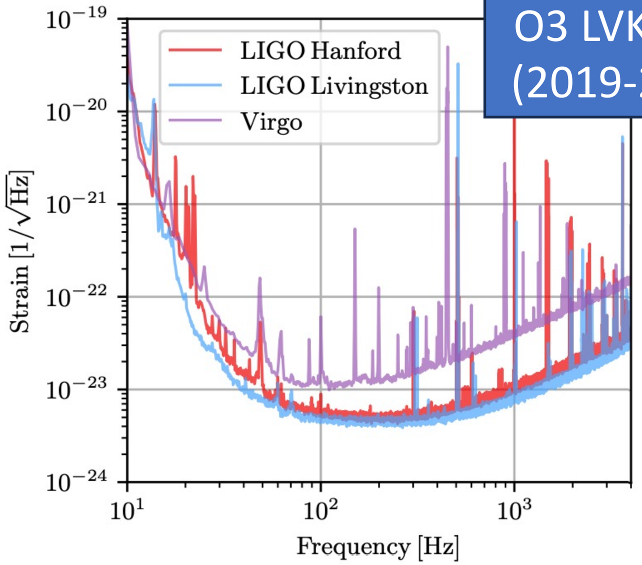
$$0.2 < m_1 < 10$$

$$0.2 < m_2 < 1$$

$$1 < \frac{m_1}{m_2} < 20$$

$$|\chi_i| < 0.1(0.9) \text{ if } m_i < 0.5 \text{ (otherwise)}$$



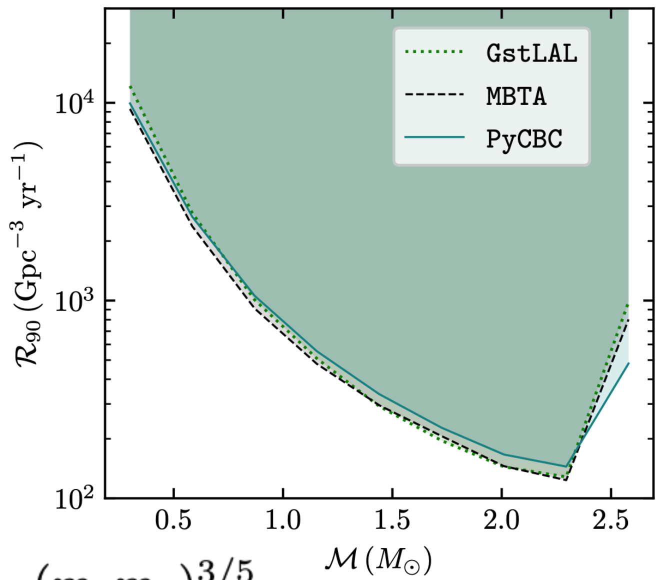


O3 LVK data (2019-2020)

Sub-solar mass search (LVK)

- Different searches have analysed the data collected during O3, finding **no significant detection** → we can set limits on the merger rate

1. Inject simulated signals in the data, covering the searched parameters space
2. Perform the search to determine the pipelines detection efficiencies
3. Sensitive volume associate limits on rate are evaluated differentially



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

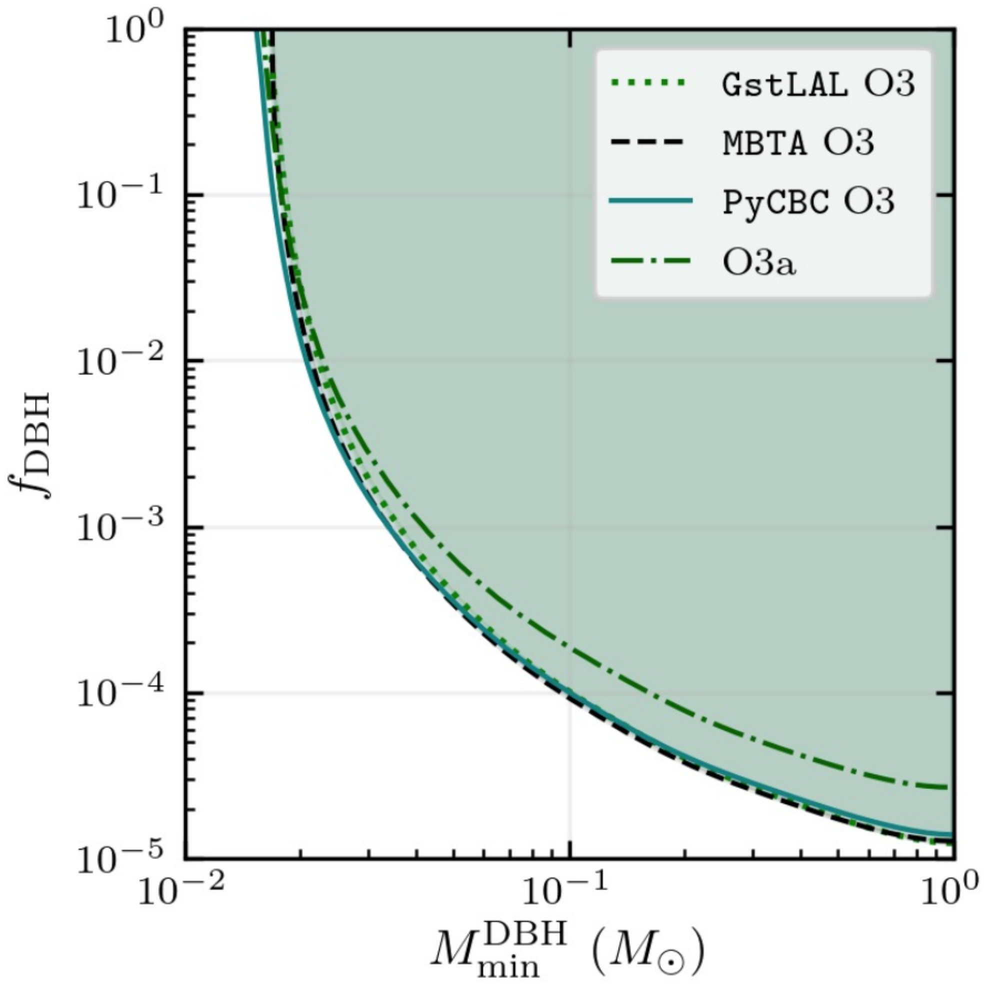
NB: Main results of the analysis

$\mathcal{R}_{90}(\mathrm{Gpc}^{-3}\mathrm{yr}^{-1})$

$m_2\ (M_\odot)$ \ $m_1\ (M_\odot)$	0.19 – 2.68	2.68 – 4.53	4.53 – 6.49	6.49 – 8.63	8.63 – 11.00
0.94 – 1.10	(5.33 ± 0.18)	(2.48 ± 0.08)	(1.64 ± 0.05)	(1.34 ± 0.04)	(2.89 ± 0.14)
0.78 – 0.94	(7.16 ± 0.23)	(3.04 ± 0.10)	(2.10 ± 0.07)	(1.63 ± 0.05)	(1.47 ± 0.05)
0.62 – 0.78	(9.91 ± 0.32)	(4.13 ± 0.14)	(2.78 ± 0.09)	(2.28 ± 0.08)	(1.85 ± 0.06)
0.43 – 0.62	(16.70 ± 0.50)	(6.32 ± 0.20)	(4.43 ± 0.14)	(3.43 ± 0.11)	(2.70 ± 0.10)
0.19 – 0.43	(45.77 ± 1.30)	(14.03 ± 0.46)	(8.14 ± 0.32)	(5.38 ± 0.35)	

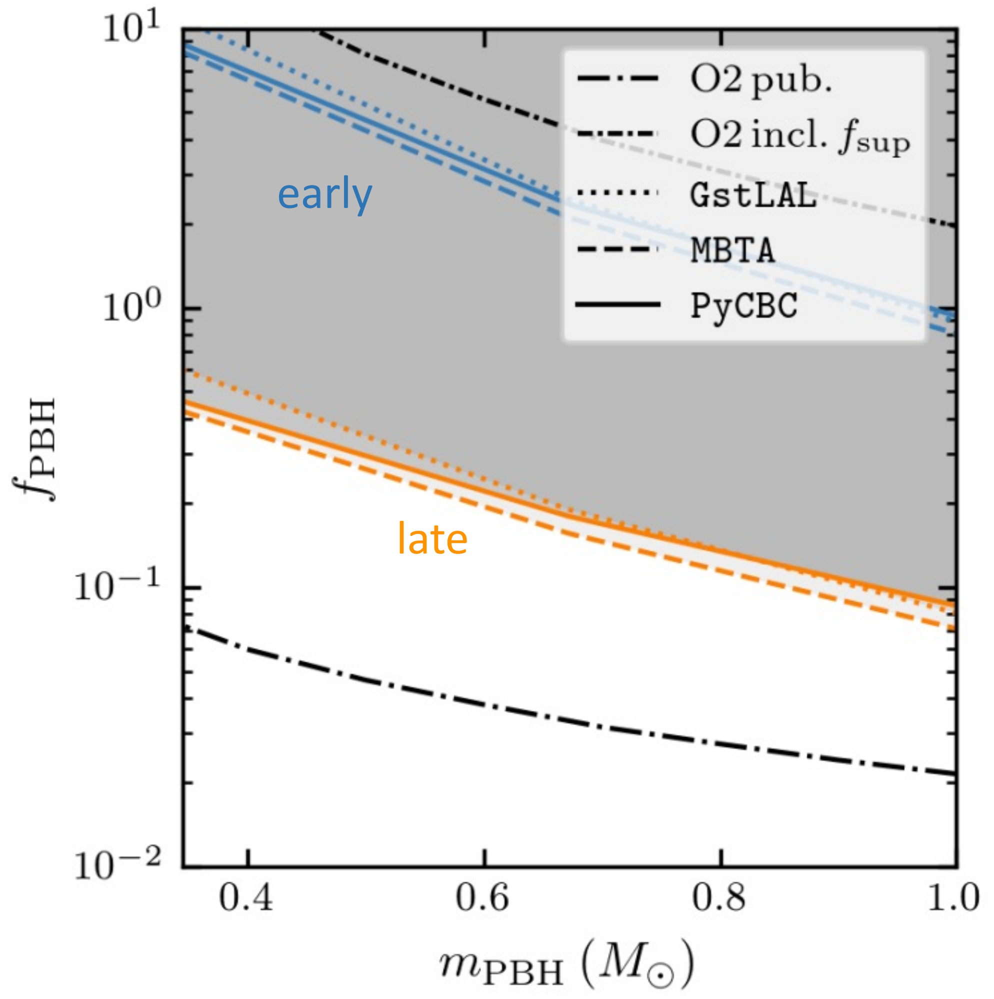
Sub-solar mass search intepretations (LVK)

- Dissipative DM model from [1]
- Two dark fermions + 1 massless dark photon, DM can form bound states and dissipate energy by radiation and collapse to form a BH
- Power-law distribution for BH masses (unknown cutoff M_{min})
- Upper limit (function of M_{min}) on the fraction of DM that ends up in BH



Sub-solar mass search intepretations (LVK)

- Phenomenological model where PBH produced at a single mass, and randomly distributed in space
- Update in merger rates for early [1] and late [2] binaries separately
- Importance of suppression factor, dependence of the results on the formations scenarios
- Merger rate depends on the abundance of PBH, parametrised as a fraction of the dark matter density



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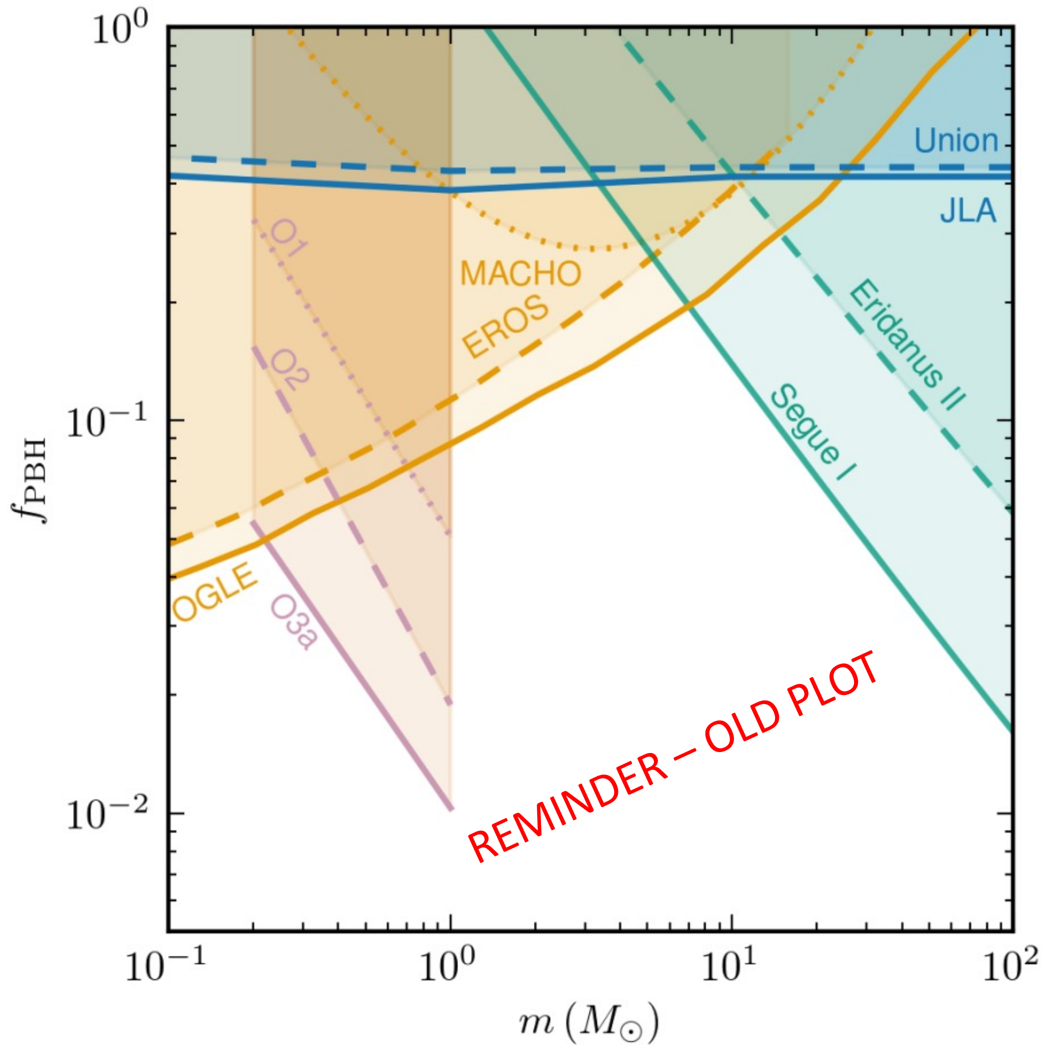

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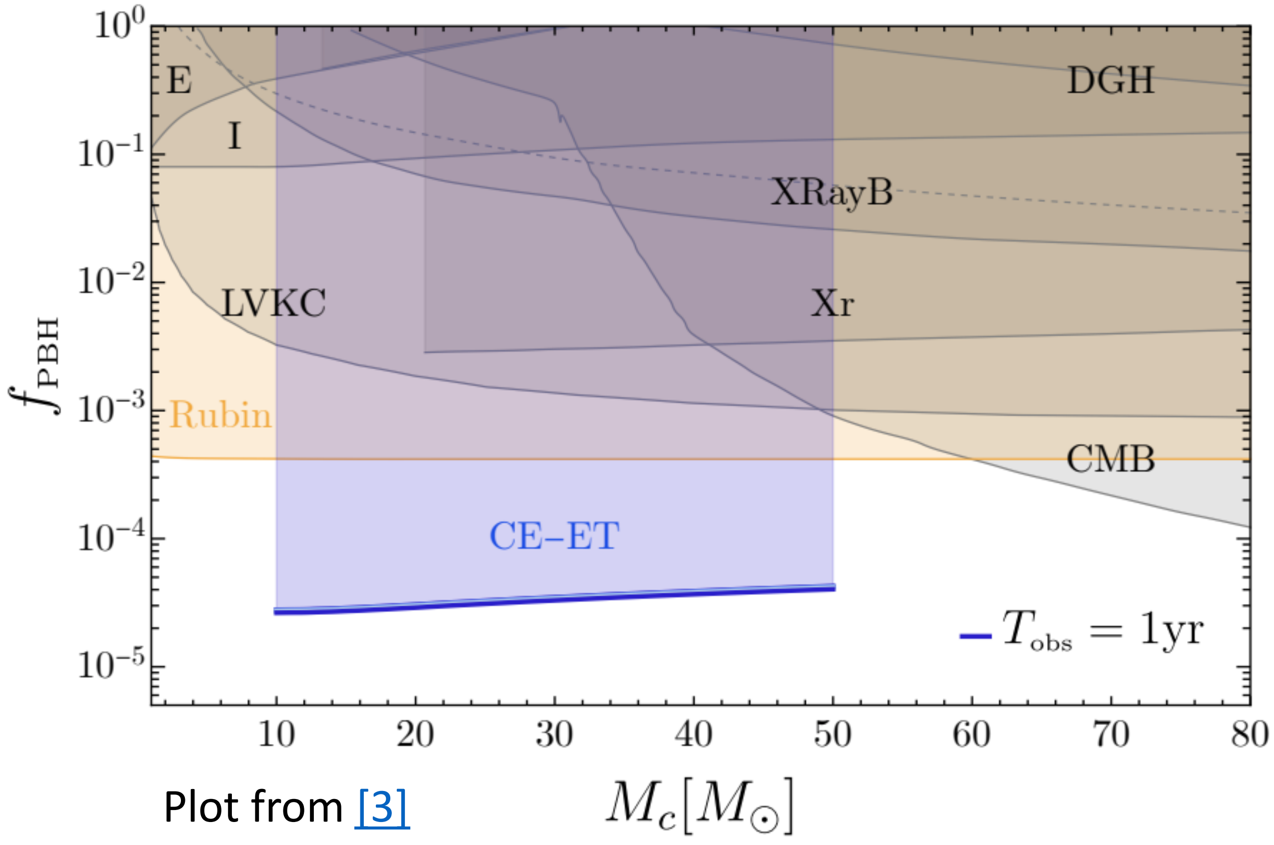
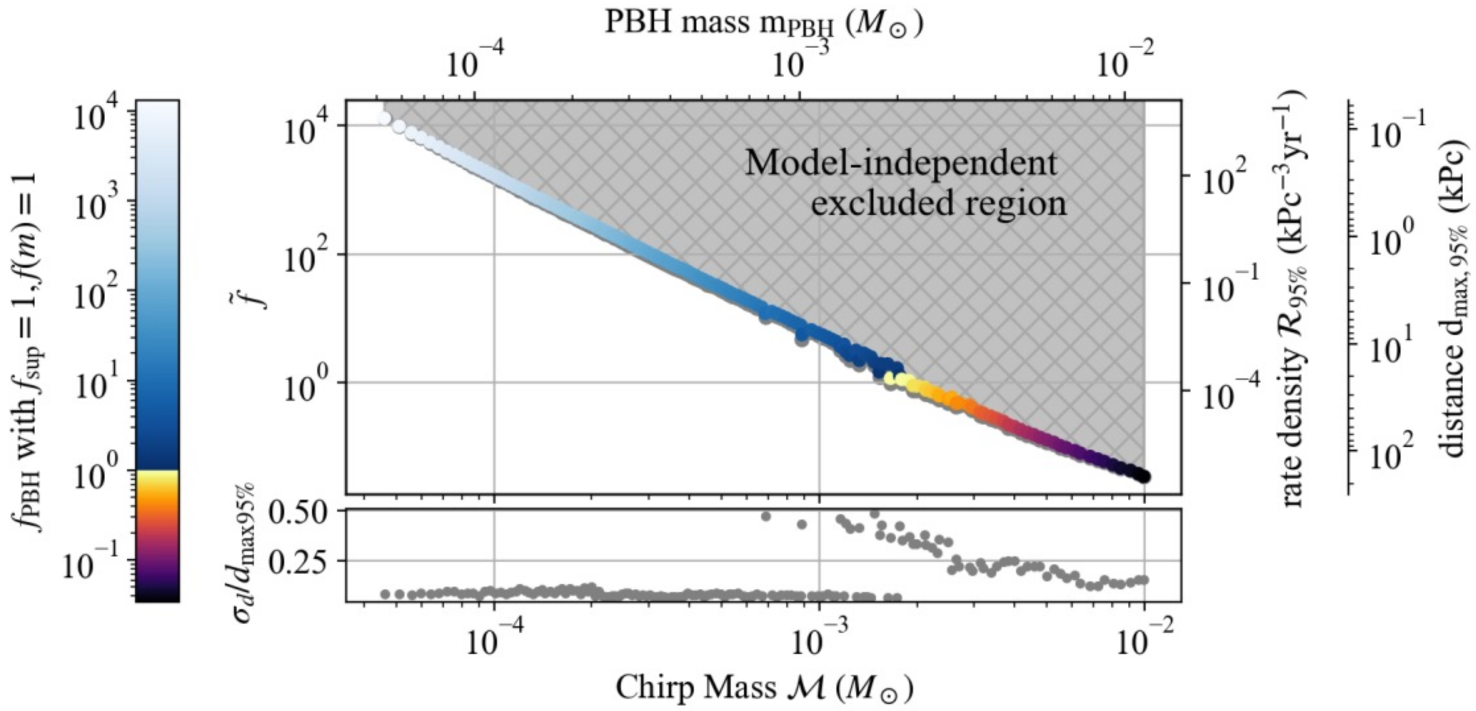


Plot from [3]

Planetary mass PBH - LVK

- Search for inspiraling planetary-mass PBH binaries in LVK O3 data ([1]).
- Generalized frequency-Hough maps points in the time/frequency plane of the detector to lines in the frequency/chirp mass plane of the source. No eccentricity.

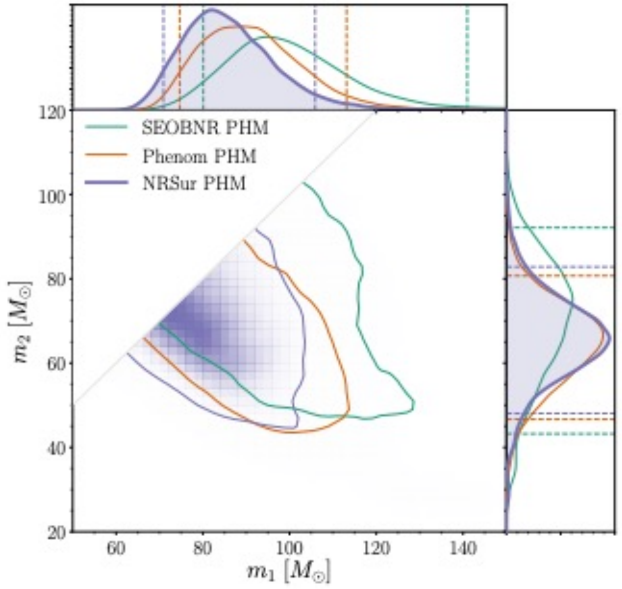


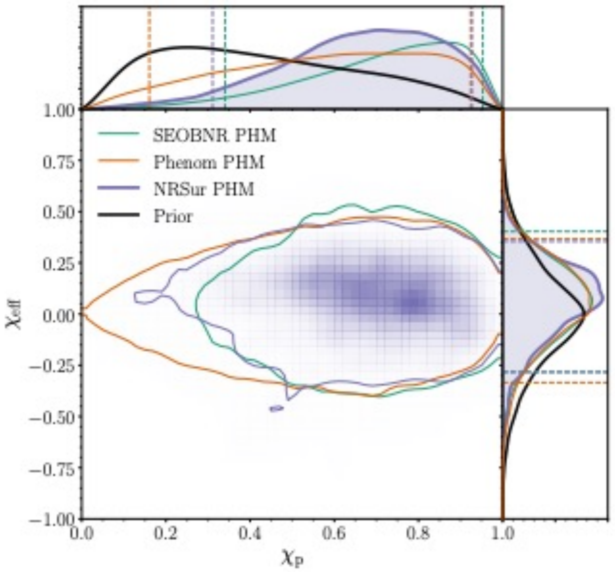
- Chirp mass in 10^{-4}-10^{-2} range, sensitive to binary PBHs within [0.1,100] kpc (depending on chirp mass), no significant candidate
- Equal-mass PBH binaries: f_{PBH} < [1, 0.04] for $m_{PBH} \in [2\ 10^{-3}, 10^{-2}]M_\odot$, respectively (if no rate suppression and monochromatic mass functions).
- Asymmetric systems, if m_1=2.5, f_{PBH}=0.1 and m_2>~1.5 10^{-5}, then $f(m_2)$<0.1

Exotic objects

- Exotic Compact Objects made of ultra-light bosonic particles
- Proca star – complex bosonic field oscillating at a typical frequency determining mass and compactness of the star
- GW190521 high-mass high-spin candidate from O3
- Interpretation of the GW190521 LVK observation as a head-on collision of Proca stars (BH head-on merger discarded) [1]

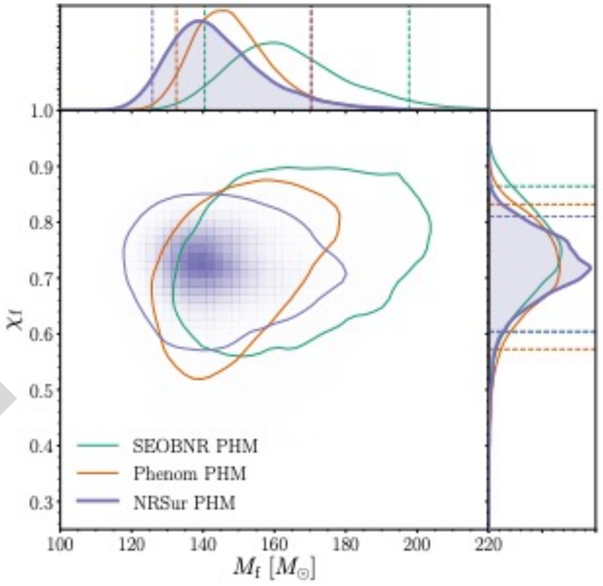
Waveform model	$\log \mathcal{B}$	$\log \mathcal{L}_{\max}$
Quasi-circular Binary Black Hole	80.1	105.2
Head-on Equal-mass Proca Stars	80.9	106.7
Head-on Unequal-mass Proca Stars	82.0	106.5
Head-on Binary Black Hole	75.9	103.2





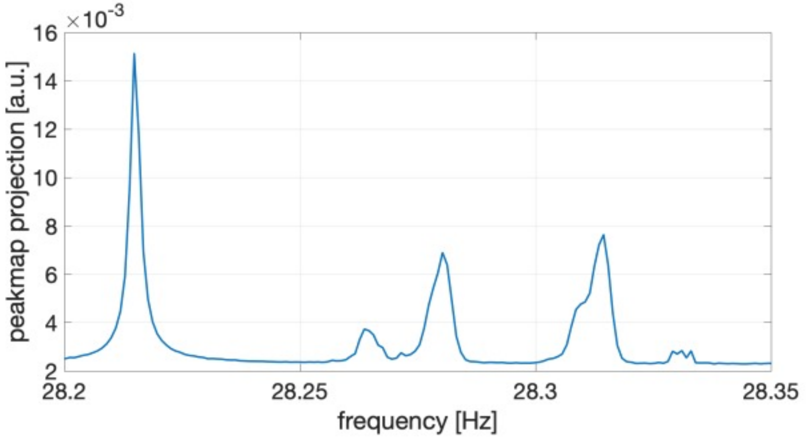
Binary system

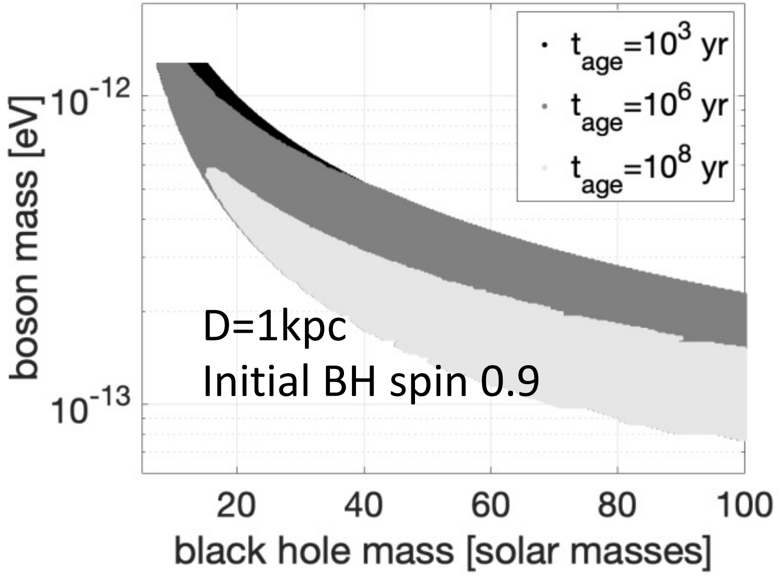
Final object



Environemental effects

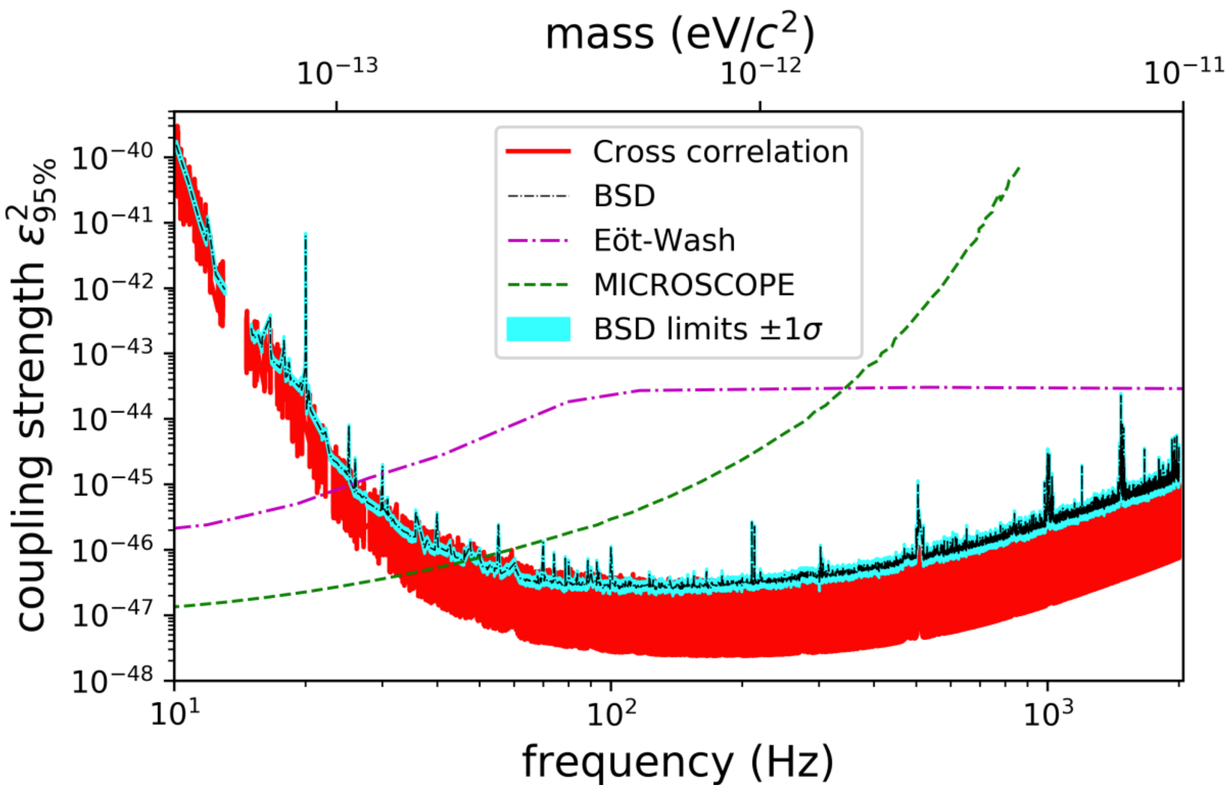
- Bosonic (non-axisymmetric) cloud around BH extracts energy and angular momentum (superradiance)→time-varying quadrupole moment
- Long-lasting, monochromatic GWs (frequency related to the boson mass)
- Semi-coherent all-sky search (Band Sampled Data) of O3 data from LVK [1]
- Outliers in peakmap followed up with more scrutiny → none significant
- Exclusion limits derived for different distances and spin hypotheses





Direct searches – LIGO-Virgo

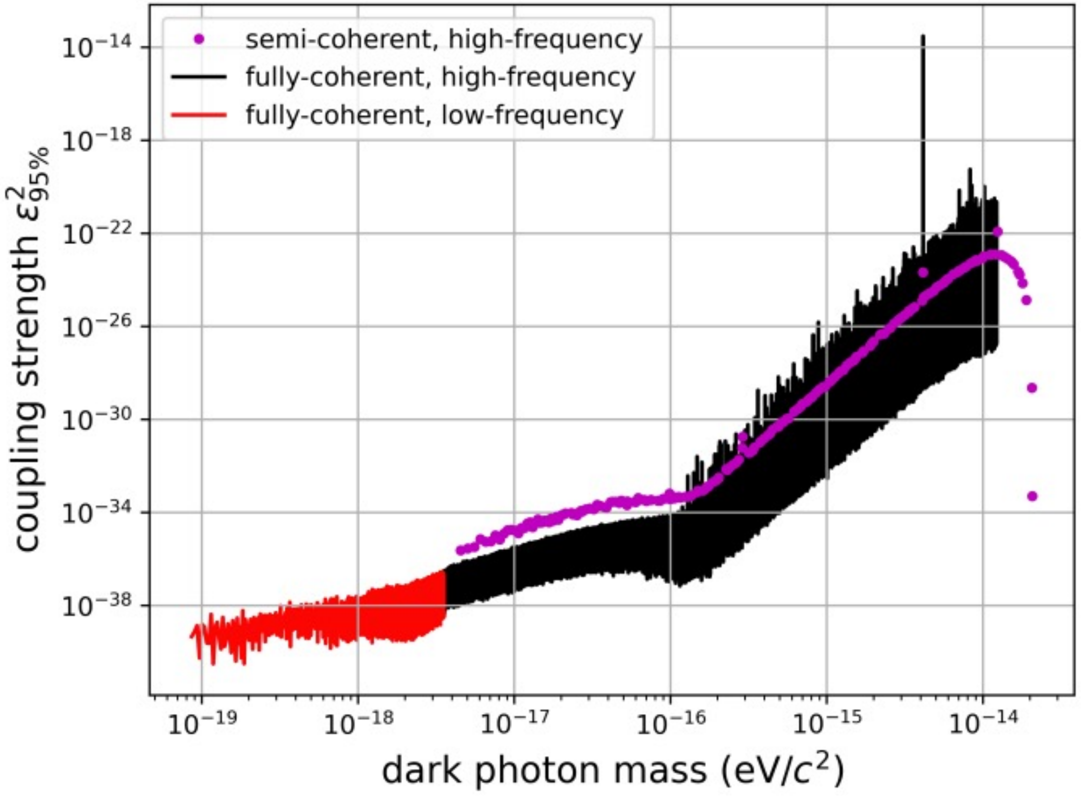
- Analysis of O3 LIGO-Virgo data [1]
- Ultralight dark photon dark matter is expected to cause time-dependent oscillations in the mirrors of the interferometers, which would lead to a differential strain in the detector
- Not a GW signature – a direct detection with GW interferometers!
- Cross-correlation between two detectors in stretches of 1800s, Band Samples Data with variable FFT lengths → look for outlier in frequency bins
- No significant candidates, set upper limits on dark-photon/baryon coupling



Similar DM candidates constrained by GR equivalence principle tests, axion-to-photon conversion in strong magnetic field in a resonant cavity

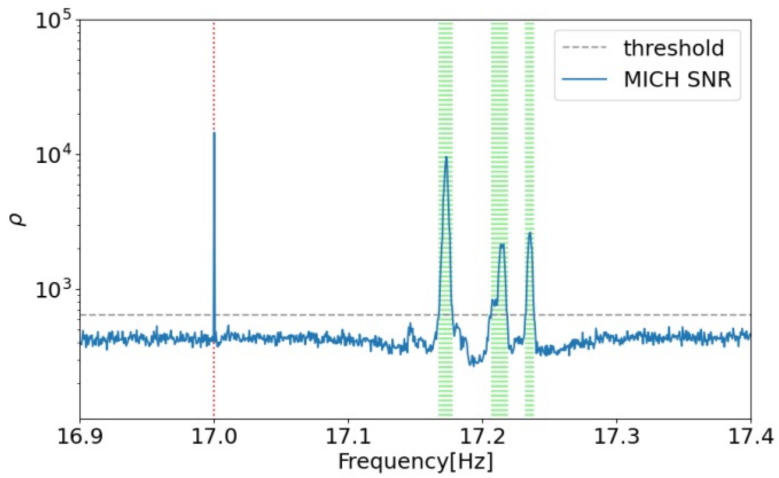
Direct searches LISA (pathfinder)

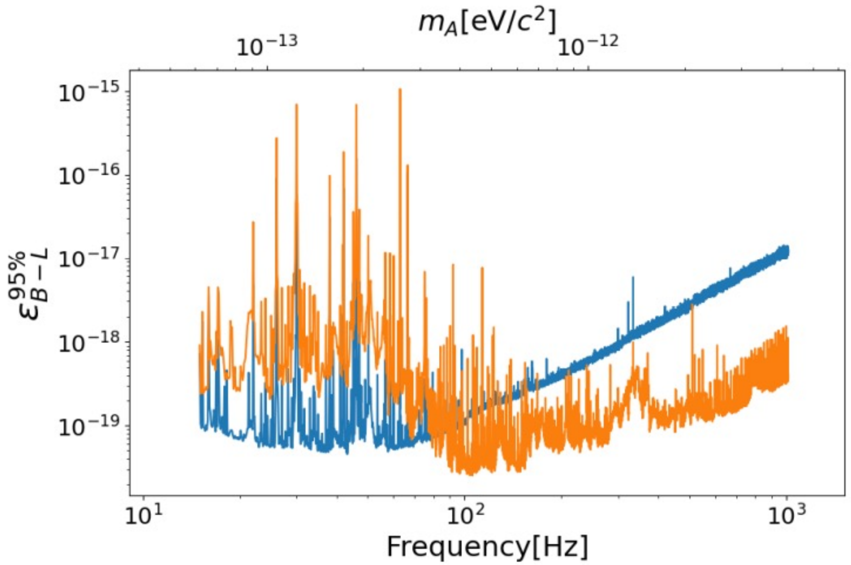
- Similar analysis on LISA pathfinder data in [1]
- Weaker constrains, but promising proof-of-concept for LISA!



Direct searches - KAGRA

- Dark photons interact via coupling to baryon or baryon-lepton number
- KAGRA employs sapphire for cryogenic test masses and fused silica for room temperature auxiliary mirrors. Difference in the materials charge-to-mass ratios → mirrors respond differently to the vector field
- ~2 weeks of 2020 KAGRA data analysed in [1] (recent result!)
- Search for periodic signal at specific frequencies in data chunks, vetoing experimental effects and non-persistent signals
- Derive upper limits on the coupling strength incorporating the stochastic nature of the DM
- More data are needed, but promising results

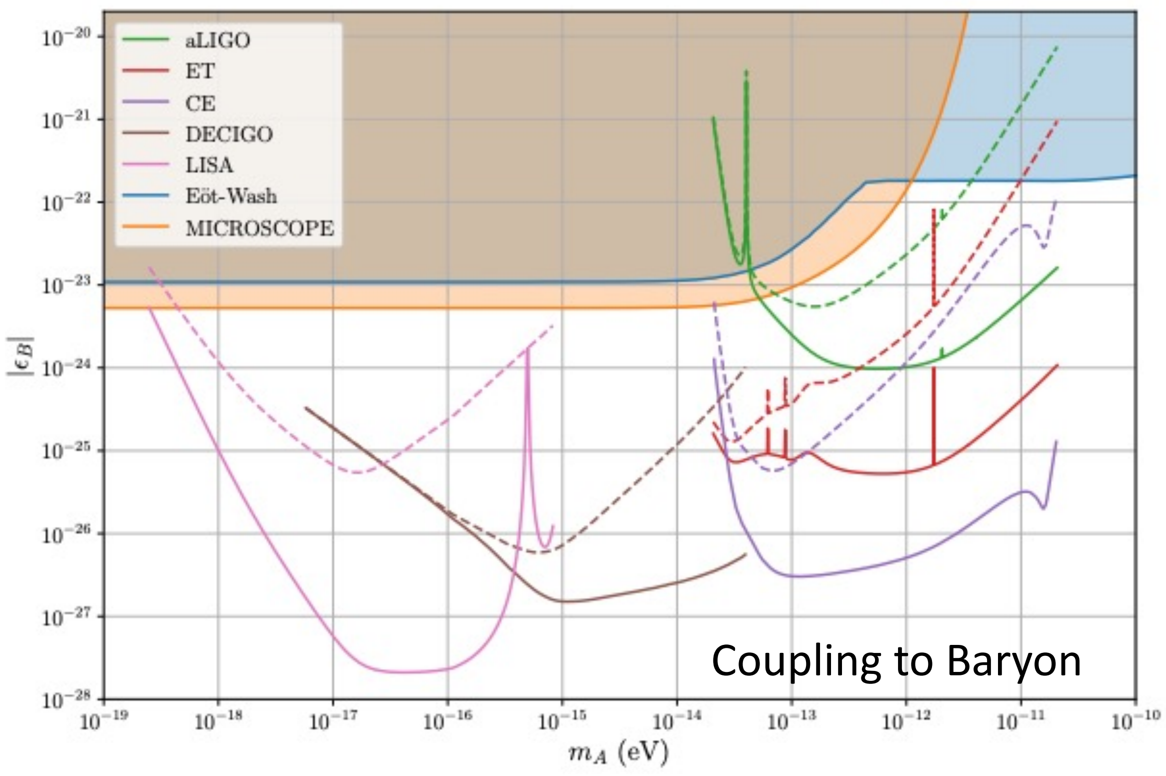


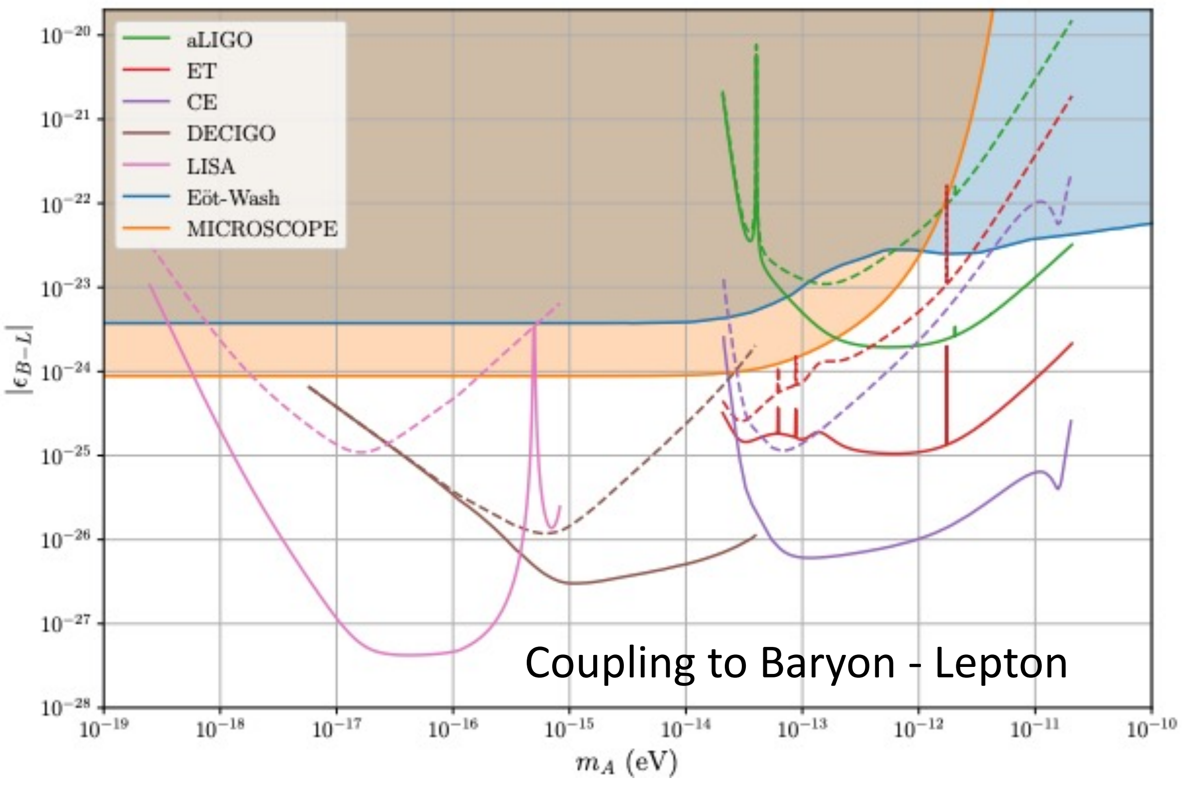


Dilatonic DM direct searches also performed with GEO600

Prospects for direct searches

- From the methods paper [1]





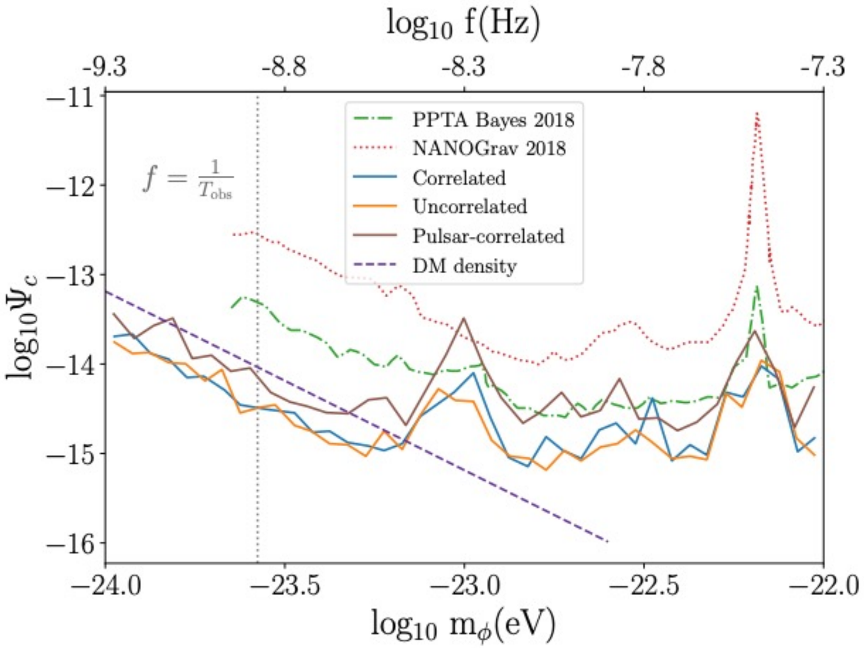
PTA and ULDM

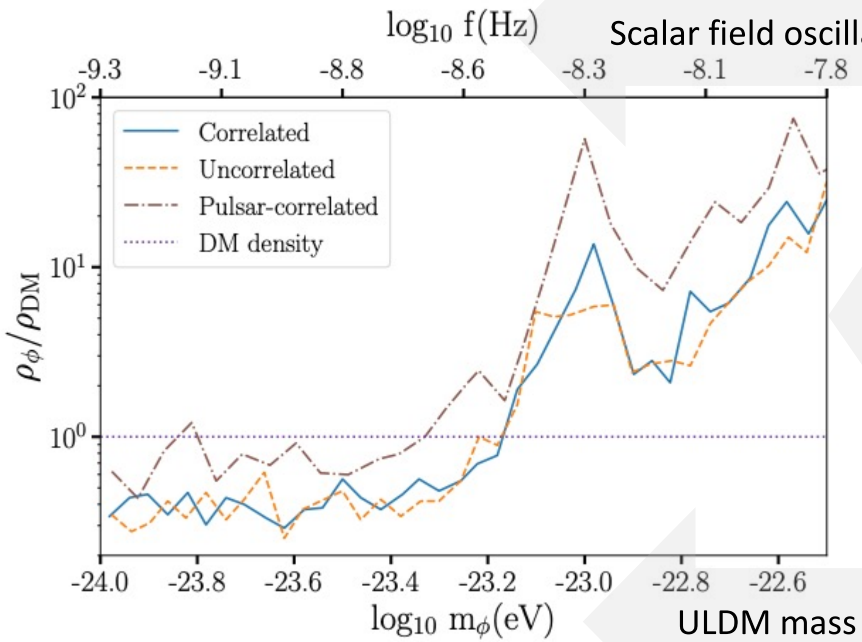
- ULDM as ultra-light scalar field would lead to periodic displacement in TOAs of pulsars signals
  - If ULDM coherence length >> distance Earth-pulsars → signals correlated.
  - PTA searches complementary to other constraints (CMB, measurements of the Lyman-α forest, galactic subhalo mass functions, stellar kinematics)
  - PTA searches for ULDM in the 10^{-23} eV mf 10^{-20} eV window
- PTA data can also be affected by DM substructures (galactic PBH population?)
  - Doppler signal (shift in the pulsar spin frequency, generated by the acceleration induced by the gravitational pull of a PBH).
  - Shapiro signal (shifts in the TOAs caused by metric perturbations along the photon geodesic from PBHs along the observer's line of sight).

EPTA constraints on ULDM

- UL scalar field with negligible self-interaction and no interaction with SM leads to periodic displacement in TOA of pulsars signals. EPTA results from [1] (superseding [2])

Dimensionless signal amplitude





Scalar field oscillation frequency

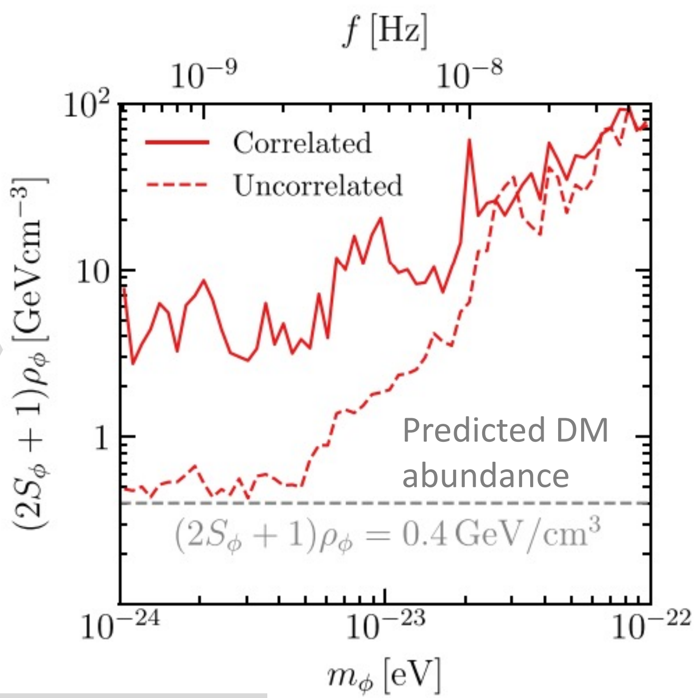
Fractional DM density

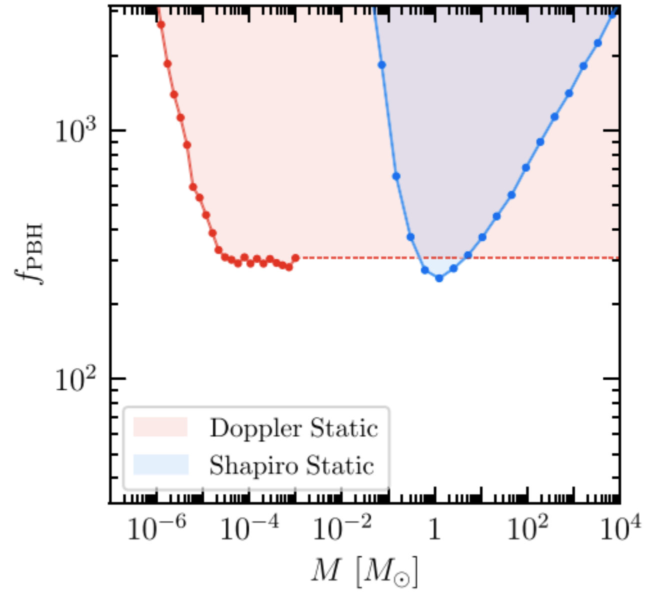
ULDM mass

- Ultralight particles with masses $10^{-24.0}$ eV $\lesssim$ m $\lesssim$ $10^{-23.3}$ eV cannot constitute 100% of DM, but can have at most local DM density $\rho \lesssim 0.3$ GeV/cm^3 .

NANOgrav constrains on ULDM

- NANOGrav analysis [1]
  - ULDM different searches (metric fluctuations, Doppler–U(1) forces, pulsars spin fluctuations, reference clock shifts)
  - Analysis of 15 yr dataset - only slight excess ULDM signal with frequency f ~4 nHz. Corresponding ULDM masses, mf ~ 2×10^{-23} eV in tension with other astrophysical bounds → derive constraints





Assume monochromatic PBH (on top of GWB fitted on data jointly), no significant signal → constrain f_{PBH}

Conclusion

- GW are a new messenger from the Universe and can constrain DM models
- GW detectors can also be used for direct DM searches
- For the moment no DM evidence, but constrains are complementary (and in some cases competitive) with other ‘classic’ observables
- More data is being collected and new, more sensitive, experiments are foreseen in the next ~decade
- Stay tuned for more exciting science!