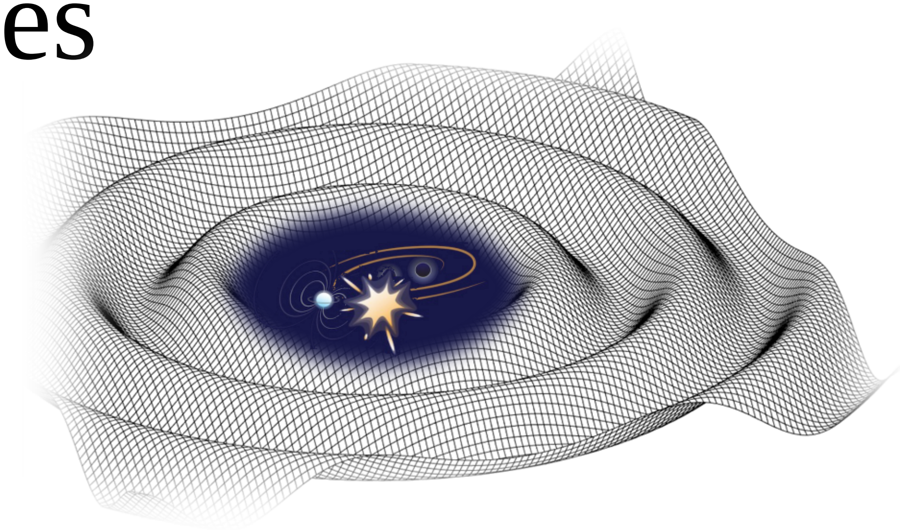
COSMIC WISPers
1st General Meeting

Search for WISPs with gravitational-wave detectors

Lorenzo Pierini (INFN Roma)
lorenzo.pierini@roma1.infn.it
on behalf of the LIGO-Virgo-KAGRA collaborations

Gravitational Waves



- Gravitational Waves (GWs) are solutions of the linearized Einstein field equations in vacuum:

Space-time metric perturbation

$$\Box h_{ij} = -\frac{16\pi G}{c^4} T_{ij}$$

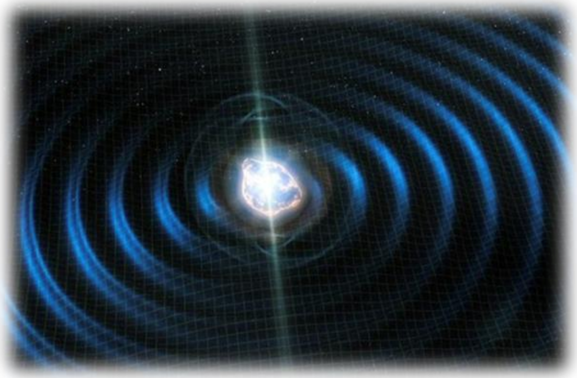
Matter

- Produced by the bulk motion of matter. Some sources we search for:

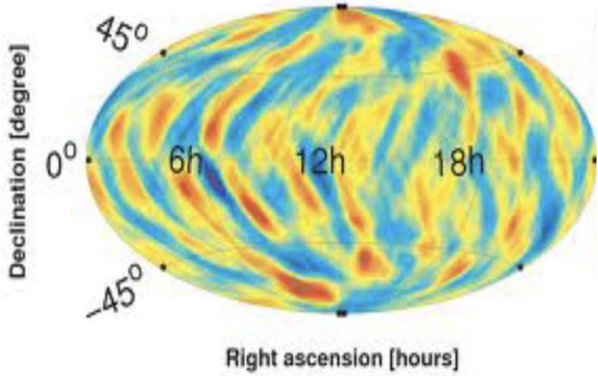
Coalescing compact binaries (black holes, neutron stars)

Supernova explosions

Continuous Waves (e.g., spinning neutron stars)



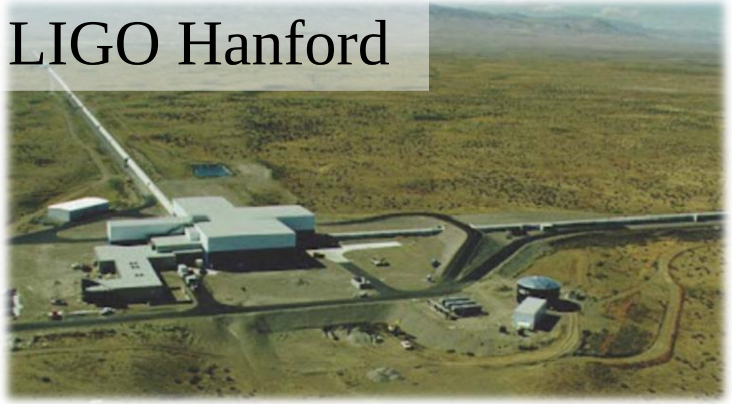
Stochastic background (Astrophysical, Cosmological)



Transient signals (duration ~0.001— 100 s)

Persistent (duration > observing time)

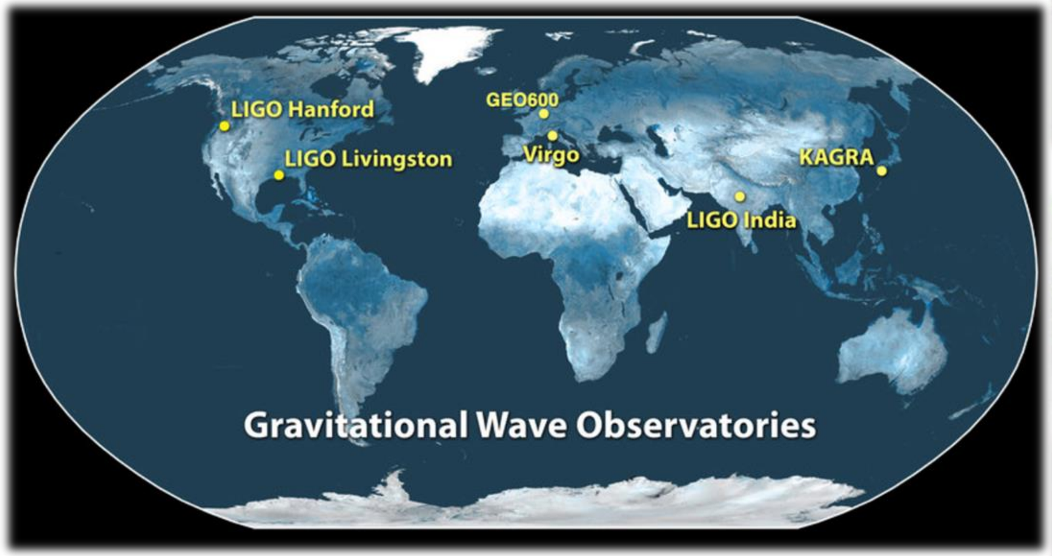
Gravitational-wave detectors network


LIGO Hanford


GEO600


Virgo

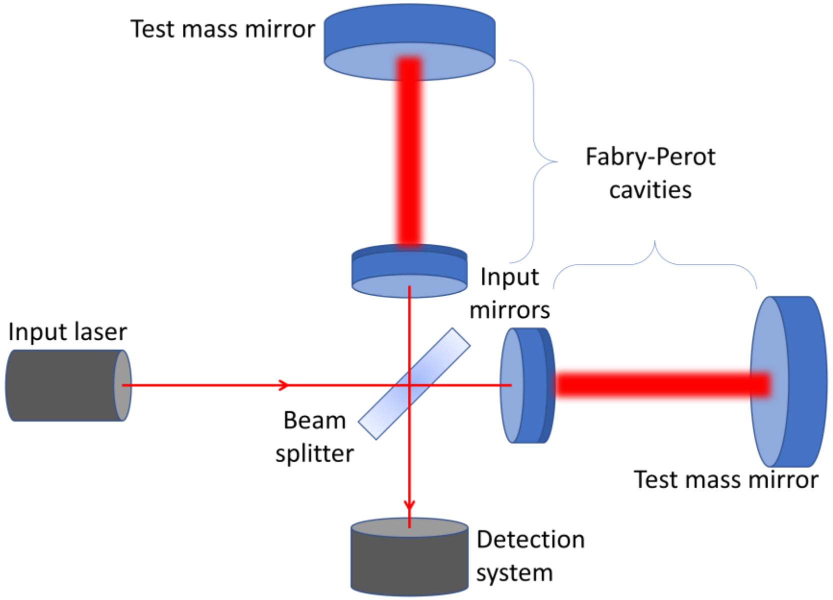

LIGO Livingston

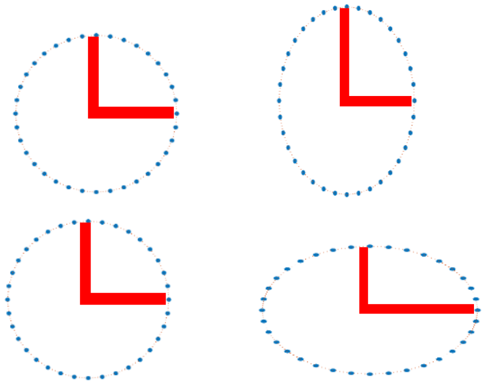



KAGRA

- Three observing runs completed in the Advanced configuration from 2015 to 2020 (O1-O3).
- Run O4 started on 24th May 2023, expected duration 1.5 years.
  LIGO has started O4 and is already observing. Virgo has postponed to face extra noises.
  KAGRA has joined the run and then stopped to continue commissioning and join again later.

Gravitational-wave detectors basics





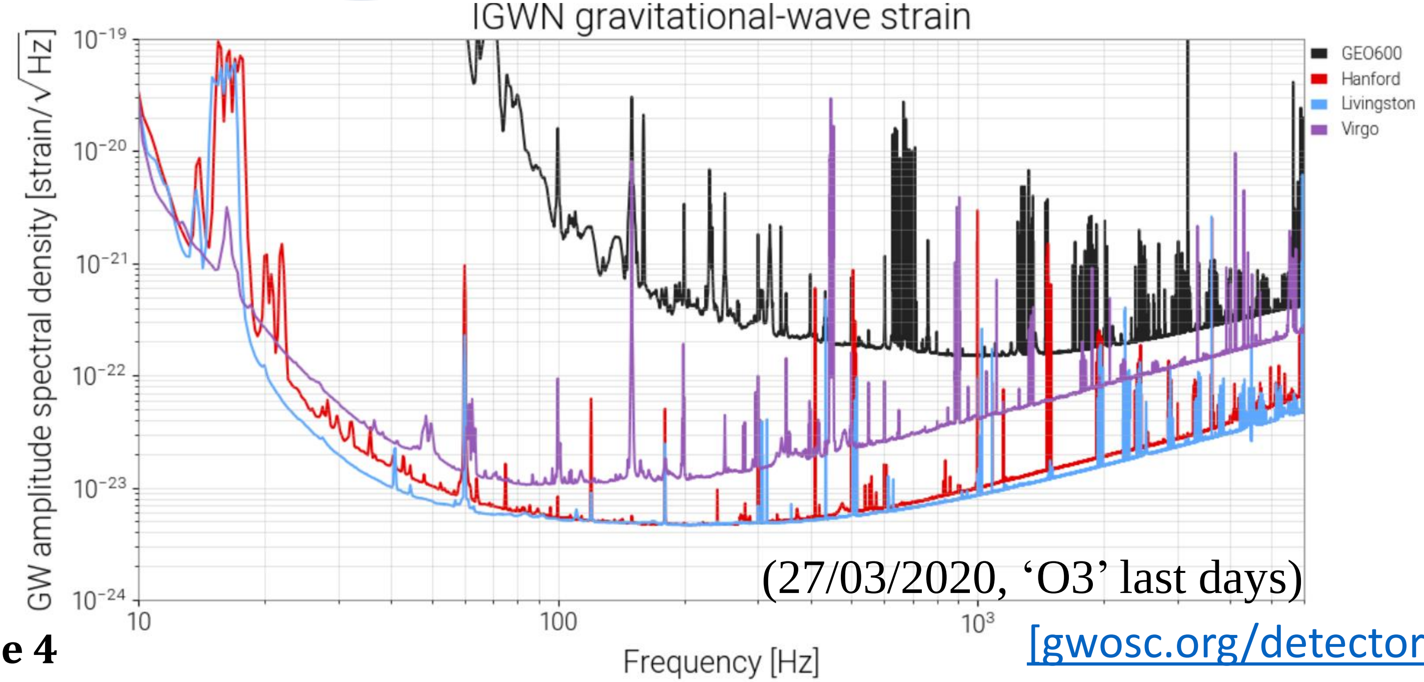
- Michelson interferometers with Fabry-Perot cavities.
- GW effect: perturbation of the laser optical path in the arms.
- Output → phase shift between two recombined laser beams.
- → $h(t)$ time series.

Limiting noises:

(< 80 Hz) Newtonian, seismic, thermal, quantum radiation pressure, technical noises.

(80 – 300 Hz) Thermal noise.

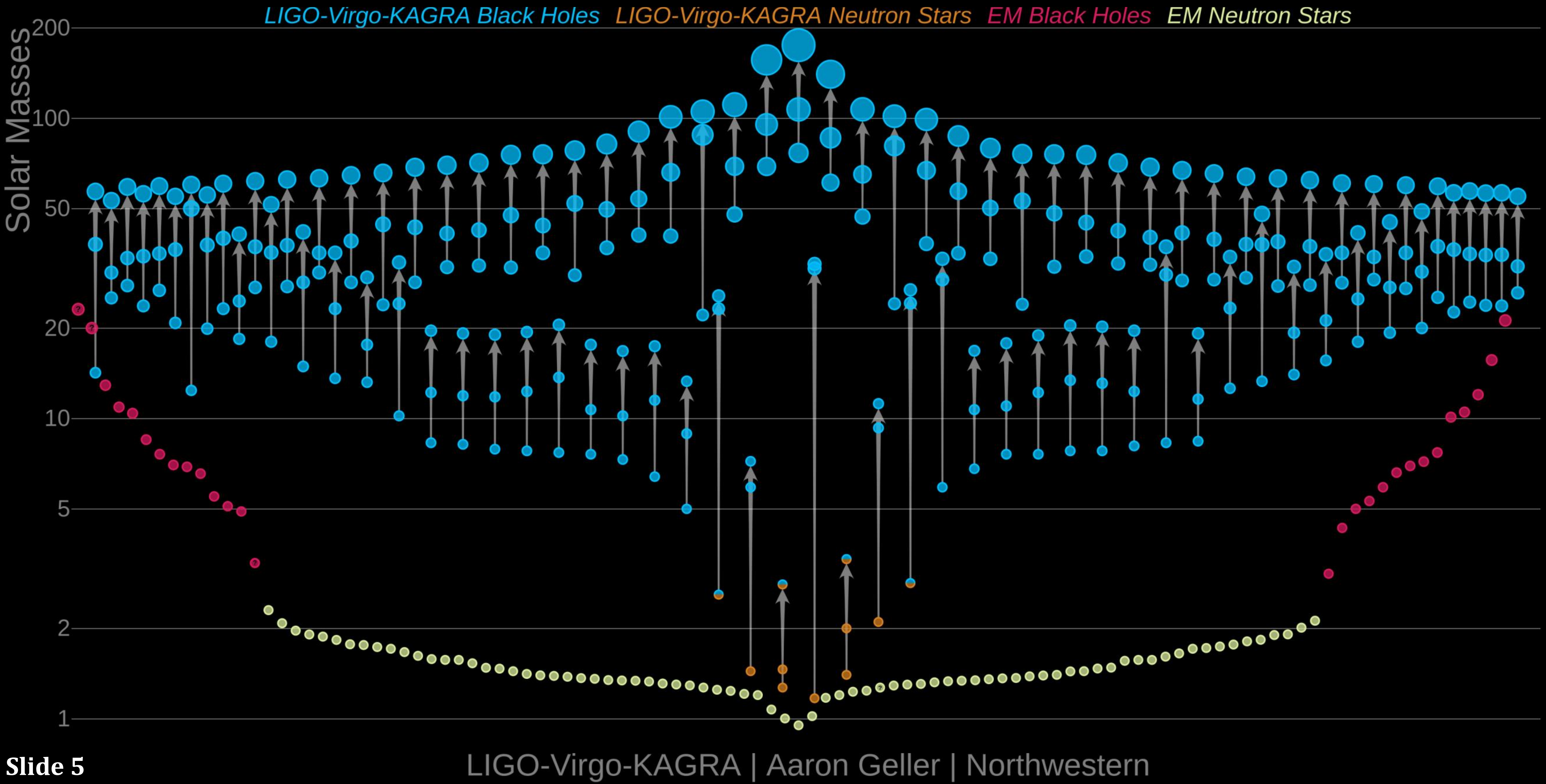
(> 300 Hz) Quantum shot noise.



(27/03/2020, ‘O3’ last days)

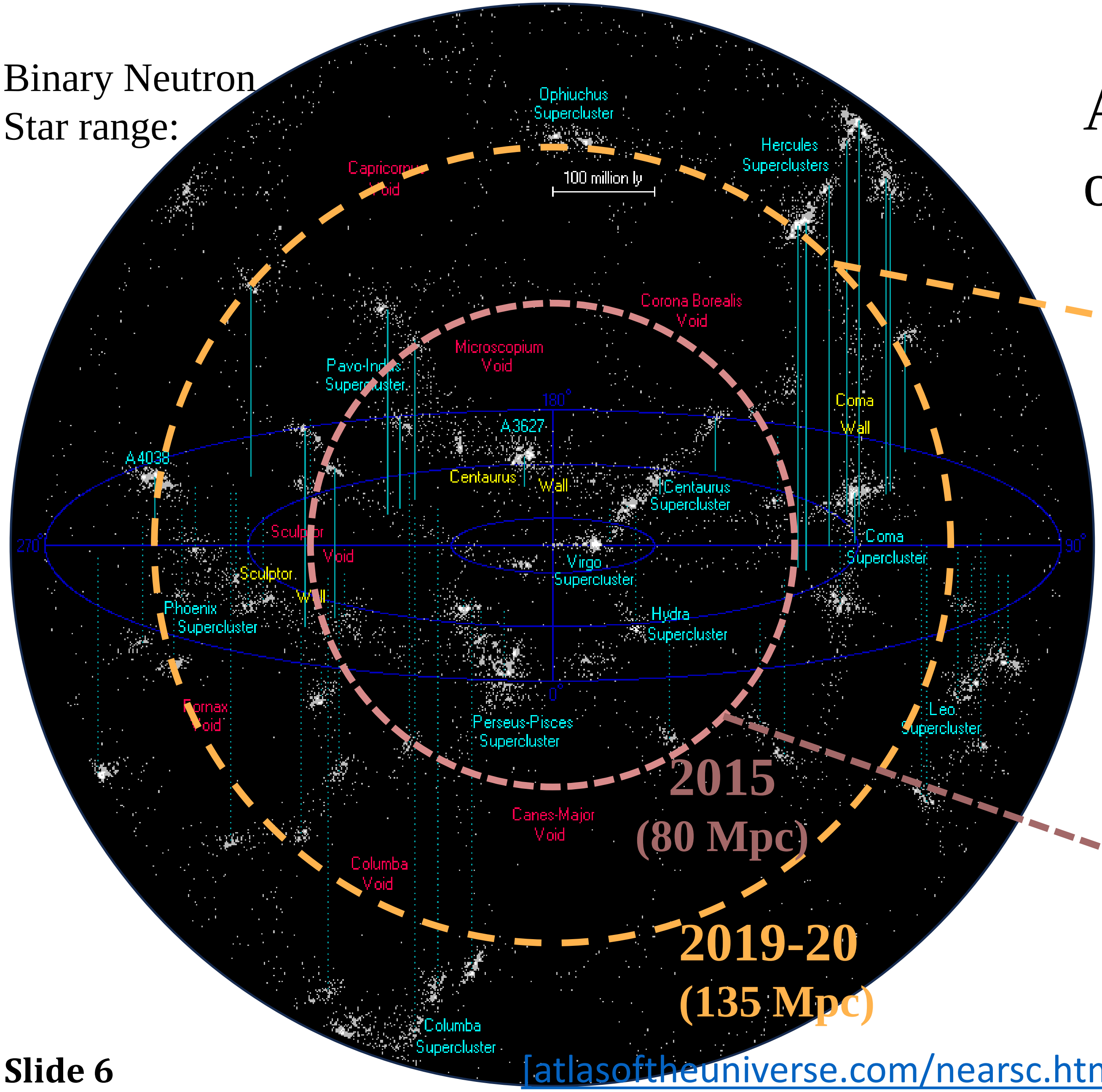
[gwosc.org/detector_status]

90 coalescing binaries detected in the first 3 runs

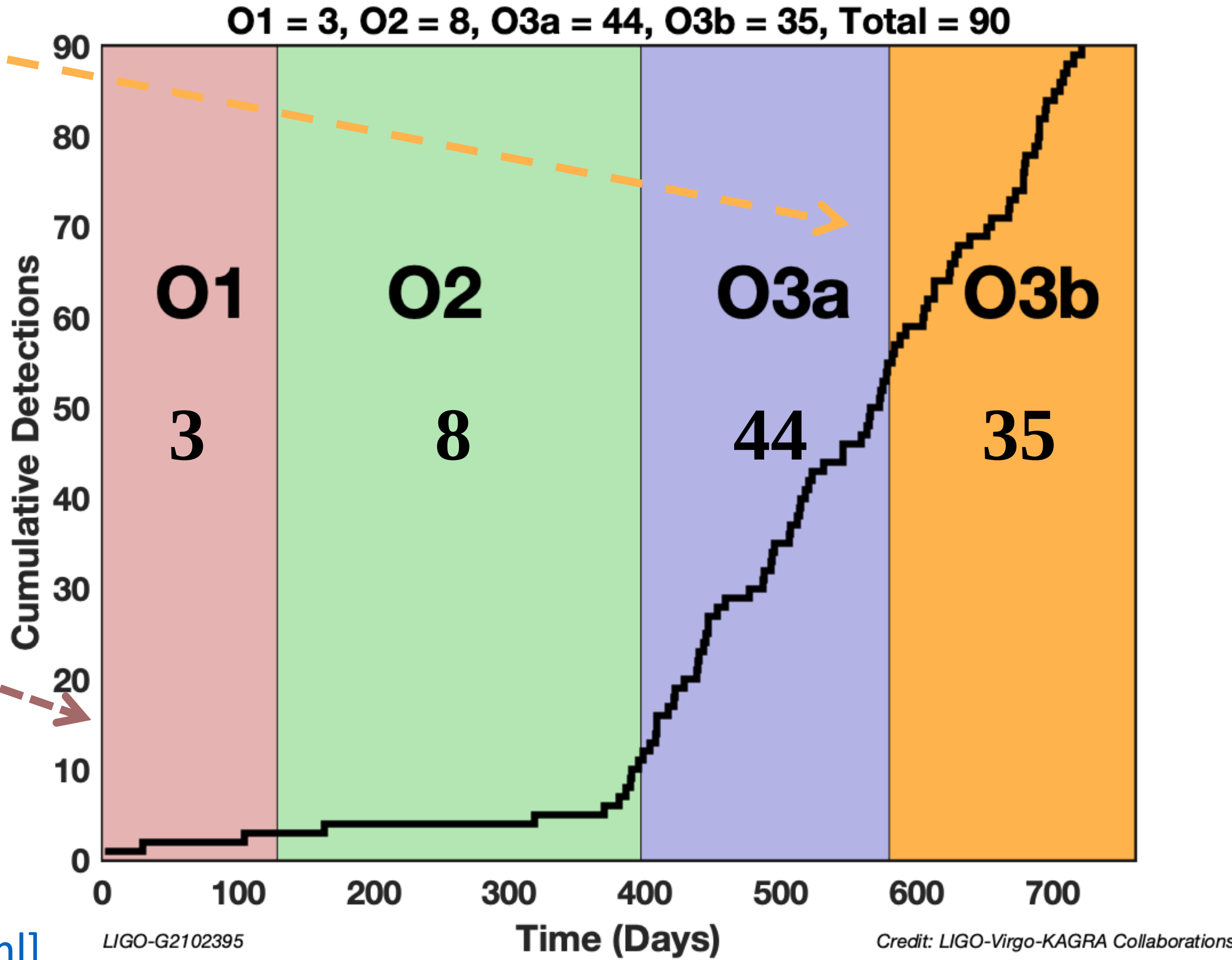


The rate of detections is continuously growing

Binary Neutron
Star range:



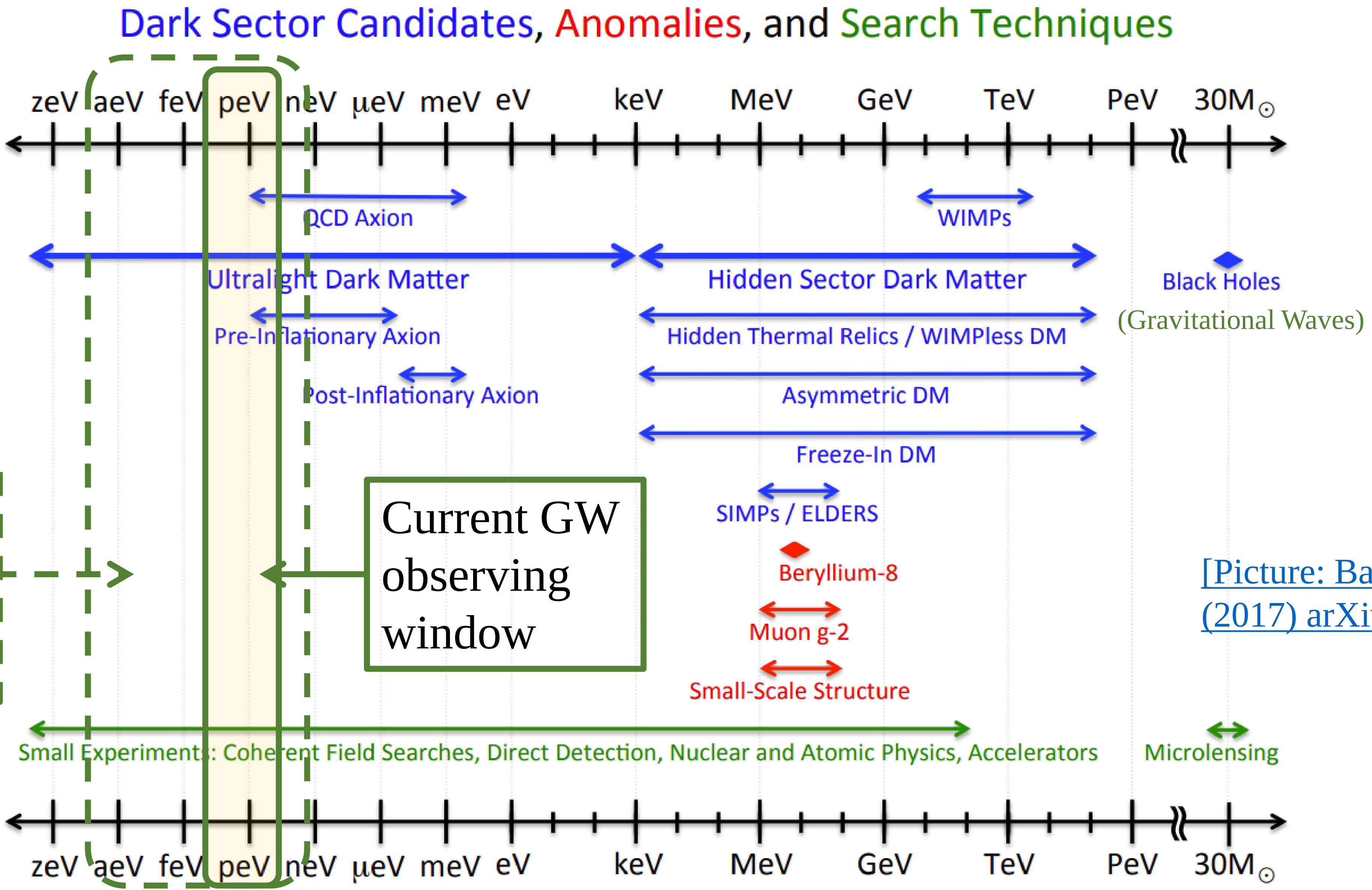
As the sensitivity increases, the volume of inspected universe scales as r^3



[atlasoftheuniverse.com/nearsc.html]

The Dark Matter energy scale we can probe

Dark Matter (DM) candidates cover ~90 orders of magnitude in mass



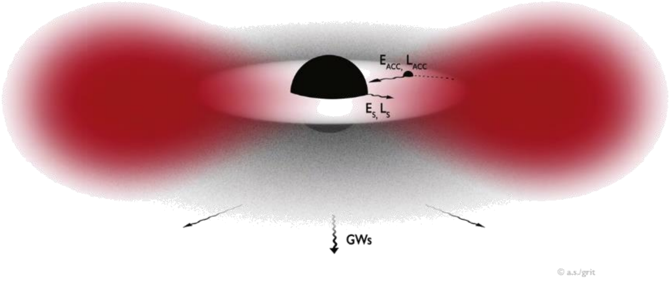
Future GW detectors observing window

Current GW observing window

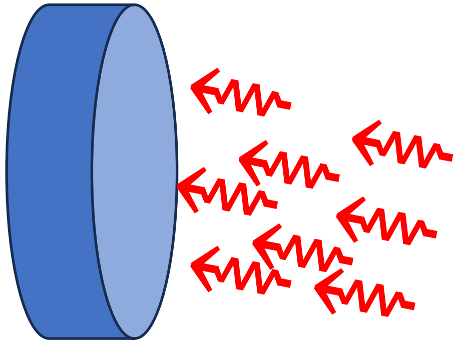
[Picture: Battaglieri et al. (2017) arXiv:1707.04591]

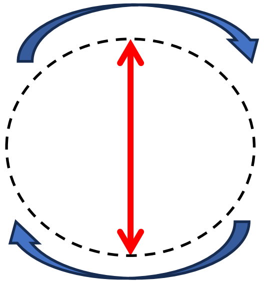
WISPs searches with Earth-based GW detectors

- Ultra-light boson condensates around compact objects.
  These condensates could directly emit GW,
  but can also interact with the object's dynamics.



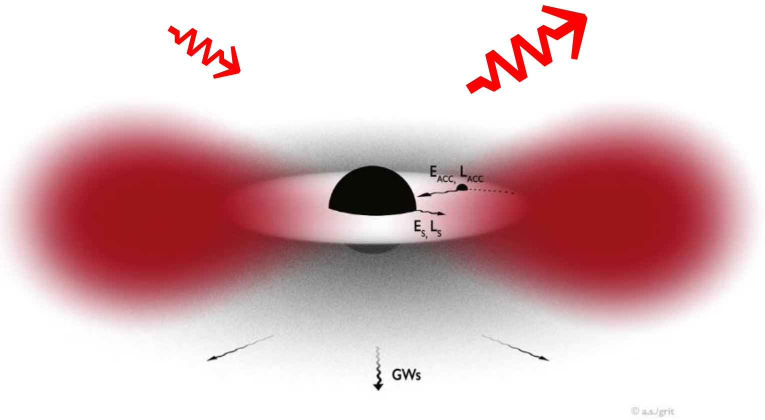
- Direct interaction of DM fields with detectors.
  They can produce a differential strain on the
  detectors data without being GWs.
  - Interaction with optics
  - Rotation of laser polarization





Ultra-light *boson clouds*

- Typical subjects: dark photon, QCD axion, axion-like particles from string theory.
  Considered masses in the range $[10^{-20}, 10^{-11}]\mathrm{eV}$
- If they exist in that mass range, they can trigger superradiant instability around spinning black holes.
- Condition: Compton wavelength (λ) comparable with the black hole size (r_s).
- The bosonic field can bind to the BH, forming a "gravitational atom".
  Gravitational fine-structure constant: $\alpha = \dfrac{r_s}{\lambda} = \dfrac{G\mathrm{M_{bh}}}{c^3}\dfrac{m_\mathrm{b}}{\hbar}$



[Picture credit: *Ana Sousa Carvalho*]

➢ Impact on BH spins and dynamics. → Searches affordable with future detectors

[Ng *et al.* (2021) **PRD 103**, 063010.] [De Luca, Pani (2021) **JCAP**, **032**(08)] [Qing Yang *et al.* (2018) **RAA 18** 065]

➢ Emission of GW from the depletion of the boson cloud. → Searches already started!

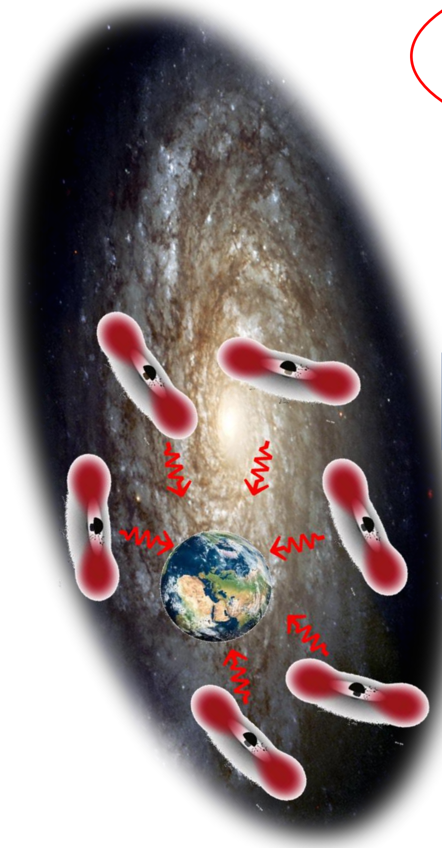
[Arvanitaki *et al.* (2010) **PRD 81**, 123530] [Brito *et al.* (2017) **PRD 96**, 064050]

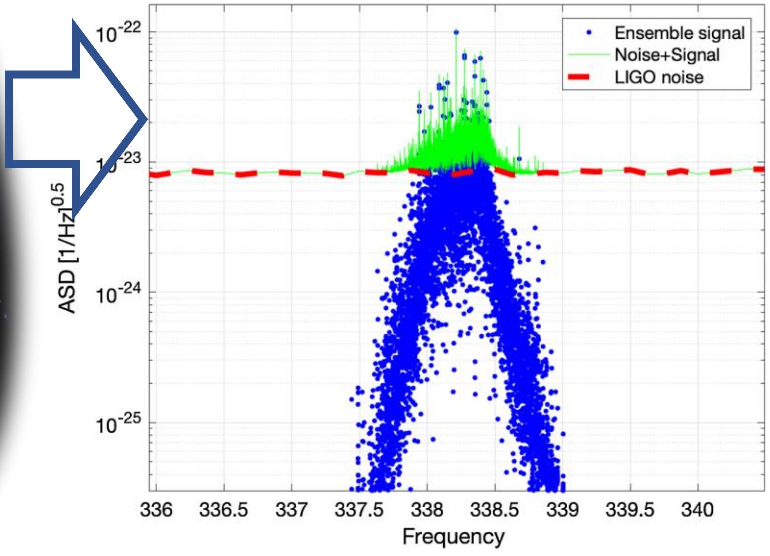
GWs from ultra-light scalar boson clouds

In the case of scalar bosons:

- Cloud forms in ~ day timescale
- Annihilation of bosons into gravitons (GWs).
- ➢ Quasi-monochromatic GWs with $\sim 10^4$ years timescale.

$$f_{\mathrm{gw}} \simeq 483\ \mathrm{Hz}\ \frac{m_b}{10^{-12}\mathrm{eV}}\left[1-\underbrace{7\cdot 10^{-4}\left(\frac{\mathrm{M_{BH}}}{10M_{\odot}}\cdot\frac{m_b}{10^{-12}\mathrm{eV}}\right)^2}_{\text{2nd order correction}}\right]$$

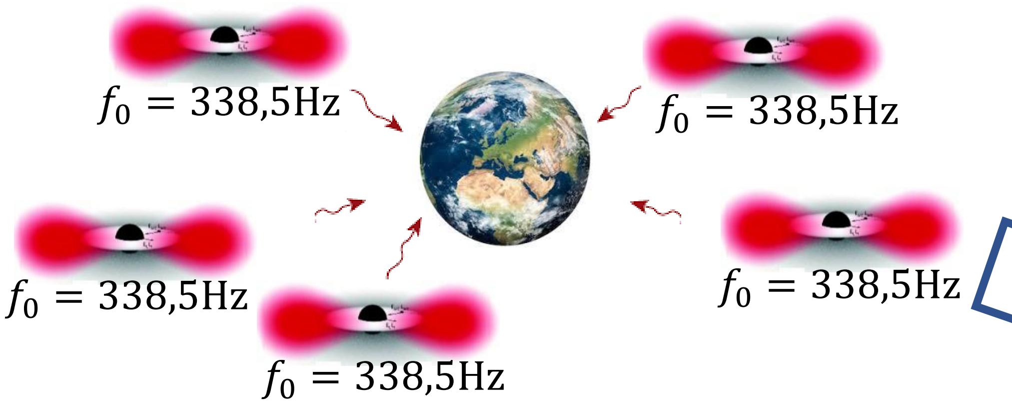




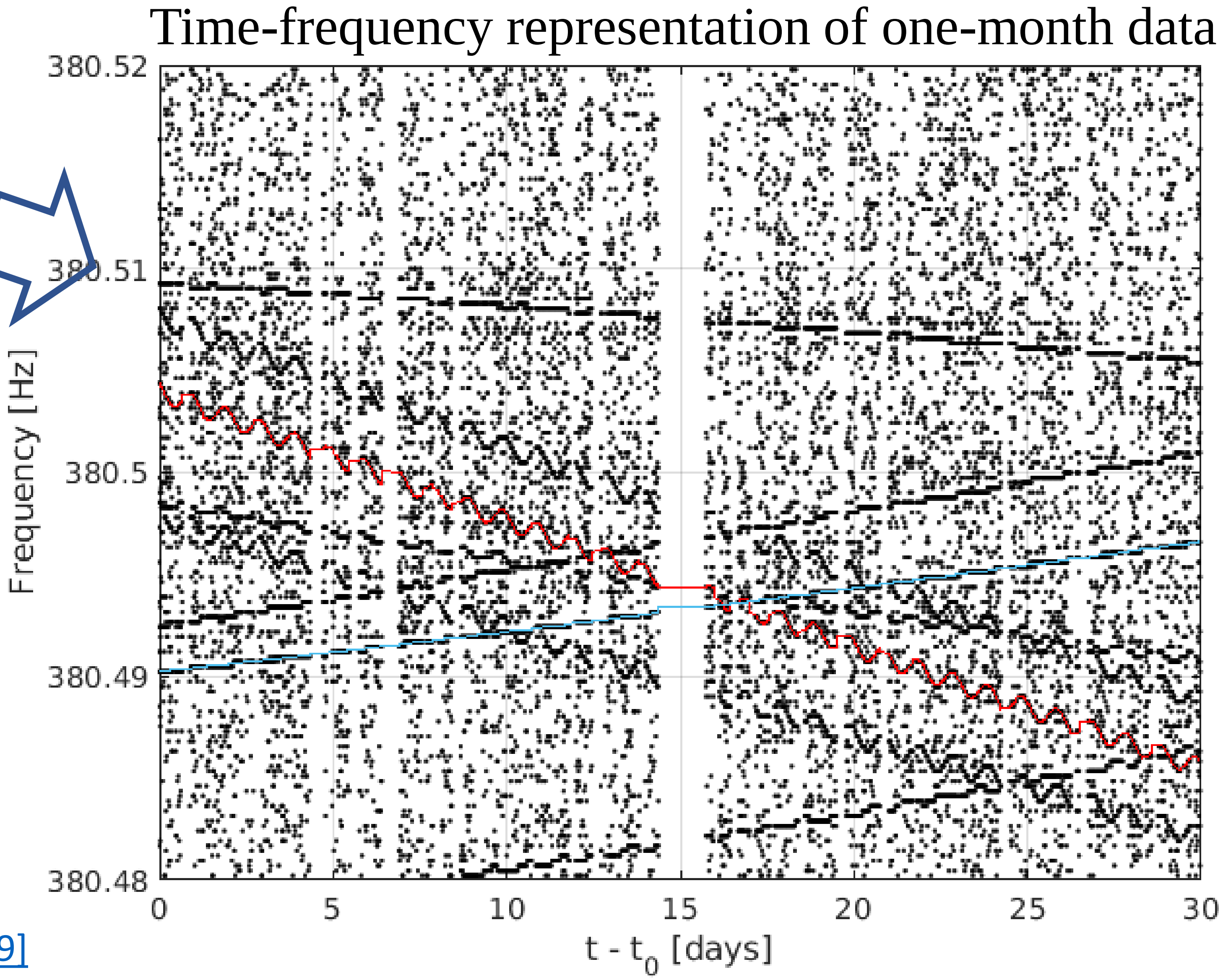
If the superradiance affects a significant fraction of galactic black holes, we would expect to have several GWs all around a same frequency!

- ➢ Search them as an ensemble of signals.
  [Zhu *et al*. (2020) **PRD 102**, 063020]
- ➢ Search them as multiple individual signals.
  [D'Antonio *et al*. (2018) **PRD 98(10)**, 103017]

Multiple signals can be resolved!



Time-frequency representation of one-month data



- The daily and annual Doppler effect due to the Earth motion modulates the observed signal.
- Exploiting the Doppler, we can resolve individual signals up to the sky resolution.

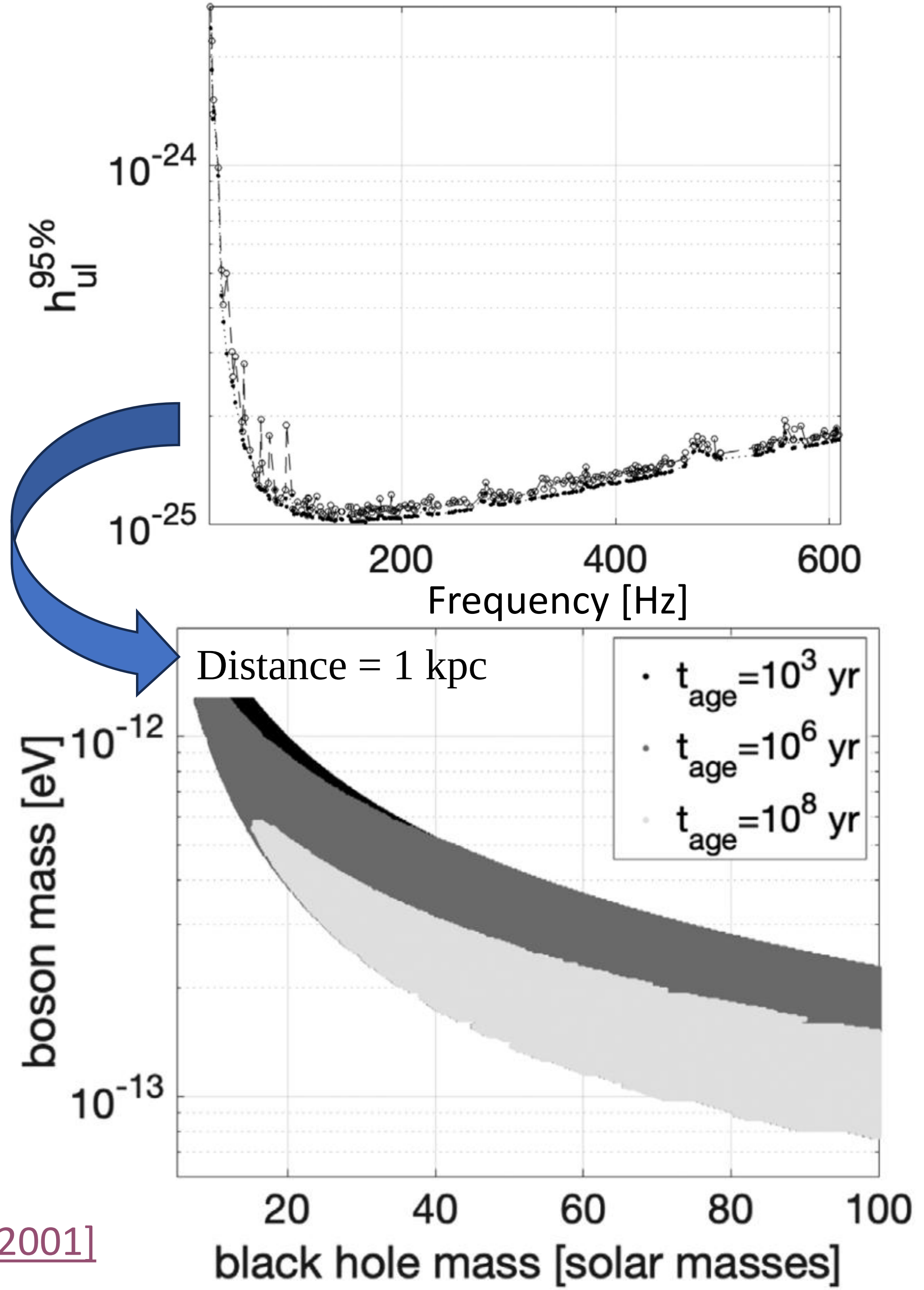
[Pierini et al. (2022) PRD 106(4), 042009]

Exclusion regions from the last observing run O3

- The LVK collaboration makes all-sky searches for boson clouds around spinning BHs in the Galaxy.
- No significant candidates have been found
  → upper limits in the GW amplitude
  → exclusion regions for the boson mass.

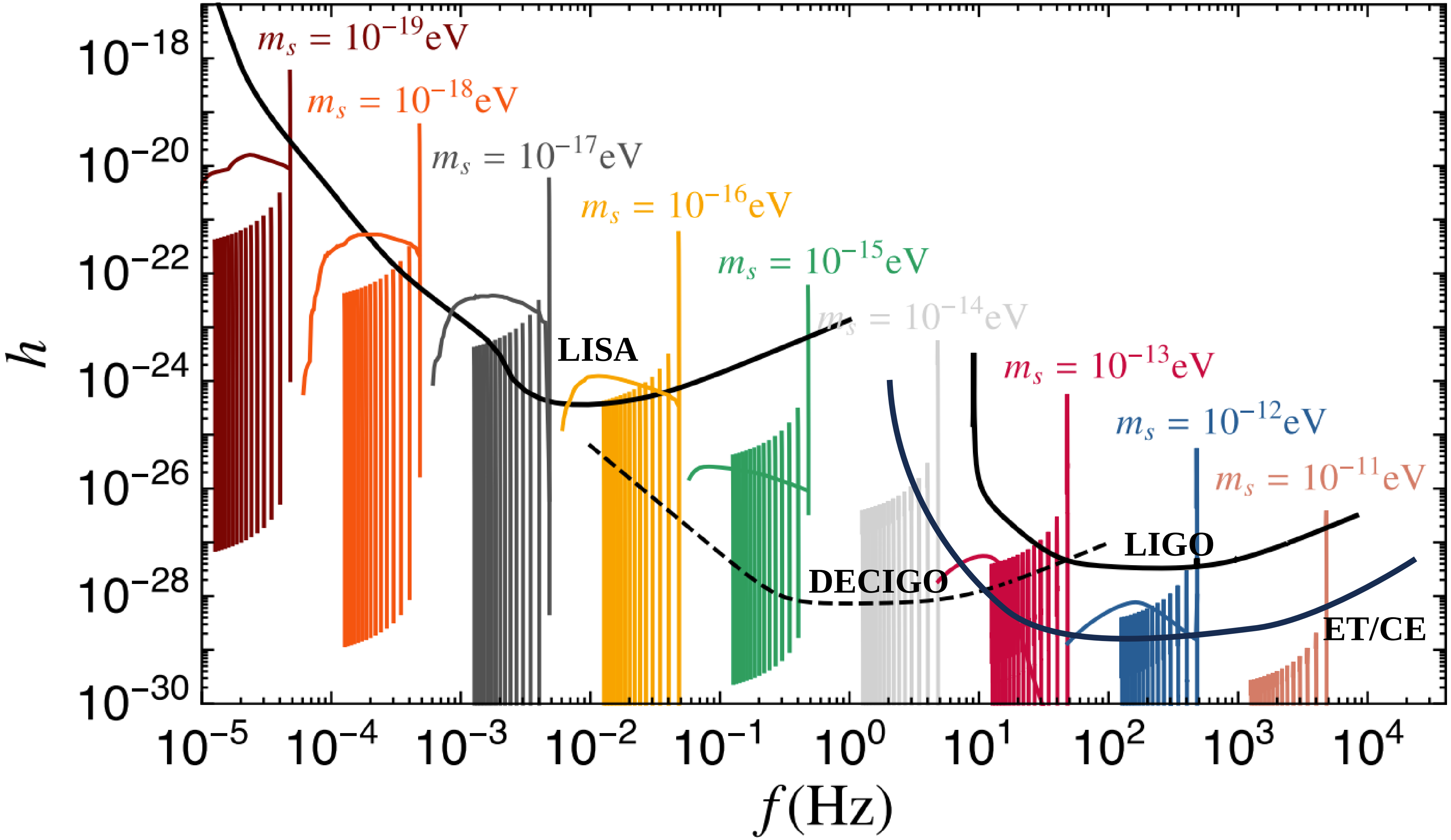
$$h_0 \sim 6 \cdot 10^{-24} \left(\frac{\mathrm{M_{bh}}}{10\mathrm{M}_\odot}\right)\left(\frac{\alpha}{0.1}\right)^7 \left(\frac{1\,kpc}{r}\right)(\chi_i - \chi_c)\left(1 + \frac{t}{\tau_{\mathrm{age}}}\right)^{-1}$$

- At fixed distance, spin and age of black hole, we can exclude there are black holes with boson clouds with masses such to produce a detectable GW.
- At growing distance or age, the exclusion region becomes smaller.



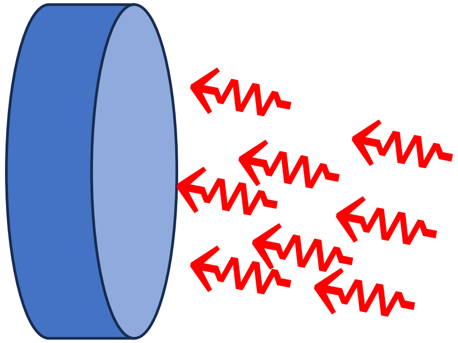
[Abbott *et al.* (2022) **PRD 105**, 102001]

Future observations



[Brito *et al*. (2017) **PRL 119**, 131101]

Direct detection of dark matter



- Ultra-light DM can directly interact with interferometer optical components producing a potentially detectable signal

  ➞ It is not a GW signal, but nevertheless the interaction can cause a differential strain.

- The mass scale to which detectors are sensitive is set by the particle field frequency $f_0 = m_A c^2/h$

  Earth-based detectors sensitivity window: 10 – 1000 Hz.

  ➢ Probed particle masses: $10^{-14} - 10^{-11}$eV

[Pierce *et al*. (2018) **PRL 121**, 061102] [Nagano *et al*. (2019) **PRL 123**, 111301]

Dark photon

- Dark Photon (DP) couples to baryon ($U(1)_B$) or neutron number ($U(1)_{B-L}$)

[Nelson & Scholz (2011) **PRD 84**, 103501]

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}m_{\mathrm{A}}^2 A^\mu A_\mu - \epsilon_D e J_D^\mu A_\mu$$

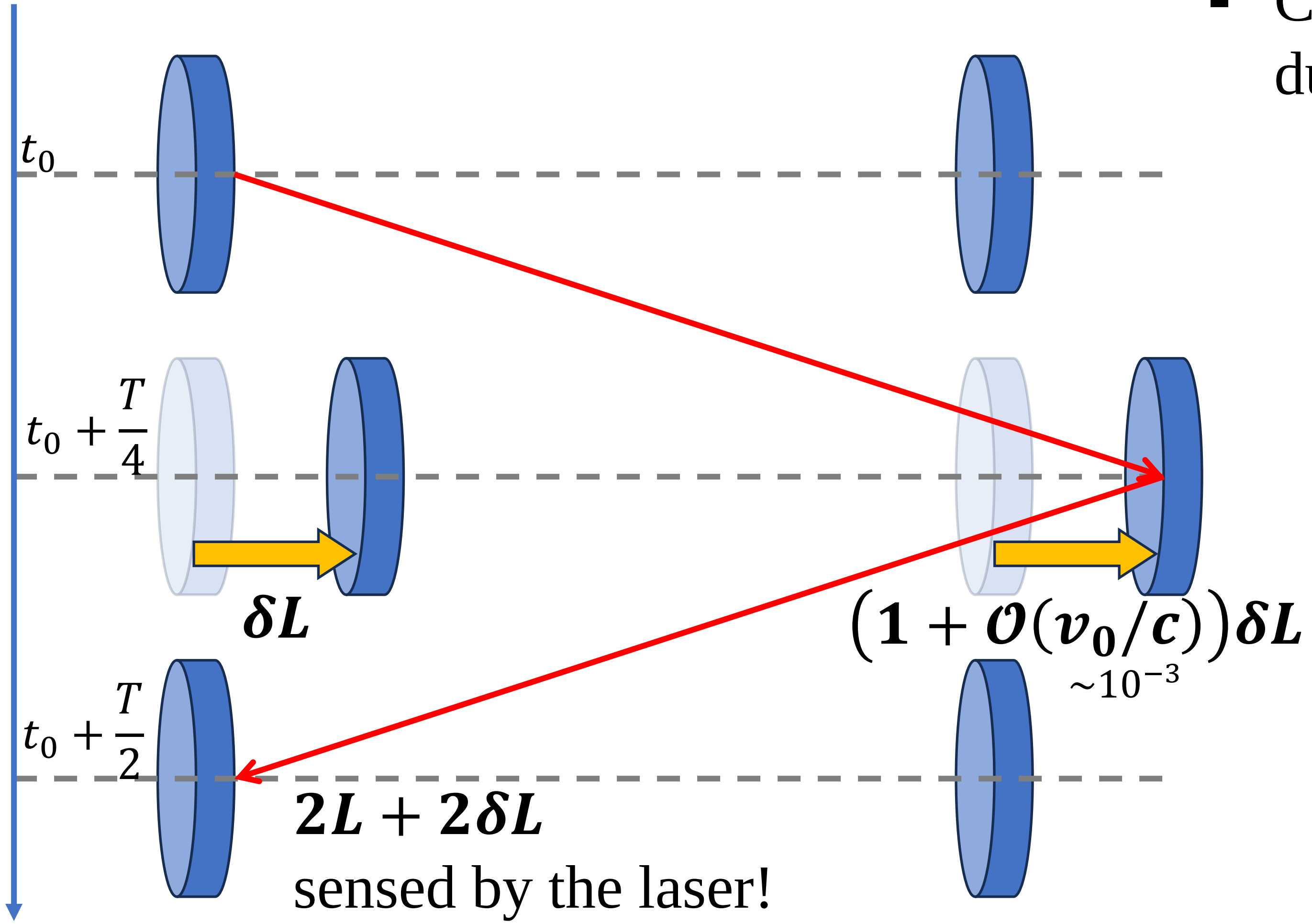
$F_{\mu\nu}$: DP field strength tensor
A_μ : DP potential
m_A: DP mass
ϵ_D : DP normalized coupling strength

- For DP masses $10^{-14} - 10^{-11}$eV and a local DM density $\rho_{DM} \approx 0.4\ \mathrm{Gev/cm^3}$ the resulting occupation number is $O(10^{54})$
  - The DP field can be described as a superposition of plane waves

$$\vec{A}(\vec{x}) = \sum_i \vec{A}_i \cos(2\pi f_i t - \vec{k}_i \cdot \vec{x} + \phi_i)$$

  - Frequency spread due to the Maxwell-Boltzman velocity distribution of DPs around the virial velocity $v_0 \sim 220\mathrm{km/s} \rightarrow \ \Delta f/f \sim 10^{-6}$

Dark photon interaction with detectors



sensed by the laser!

(in the example $\frac{T}{4} = \frac{L}{c}$)

T: oscillation period

- Coupling with mirrors → differential strain due to the spatial gradient of the DP field:

$$\sqrt{\langle h_D^2 \rangle} \sim 6.56 \cdot 10^{-27} \left(\frac{\epsilon_D}{10^{-23}}\right)\left(\frac{100\text{Hz}}{f_0}\right)$$

[Pierce *et al*. (2018) **PRL 121**, 061102]

- Equivalent differential strain due to finite light-traveling time in the arms:

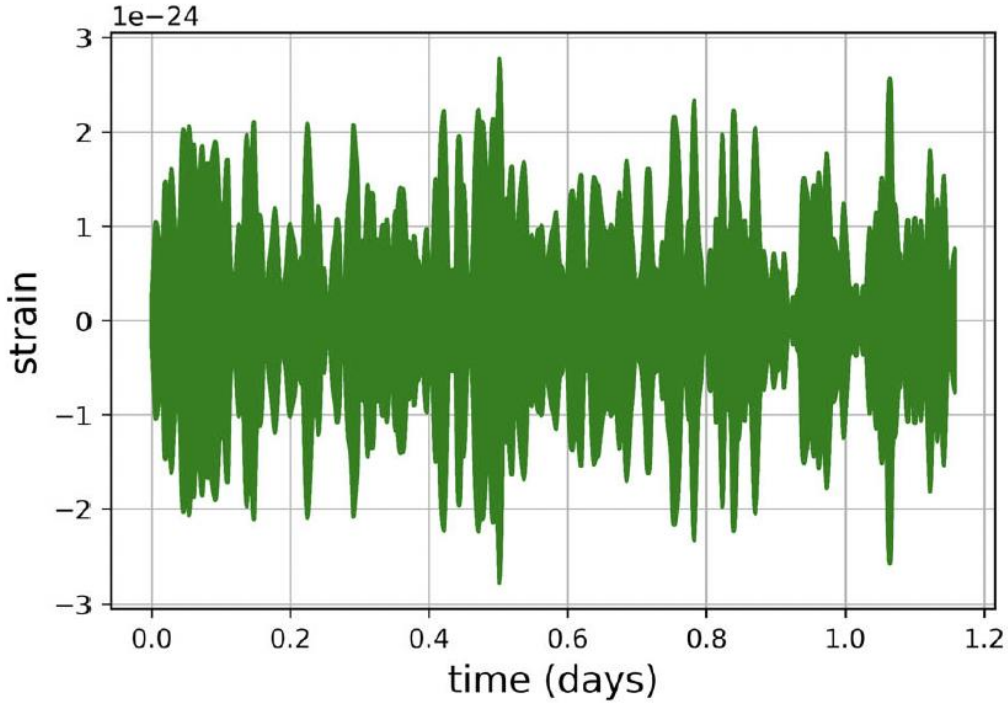
$$\sqrt{\langle h_C^2 \rangle} = \frac{\sqrt{3}}{2} \boxed{\frac{2\pi f_0 L}{v_0}} \sqrt{\langle h_D^2 \rangle}$$

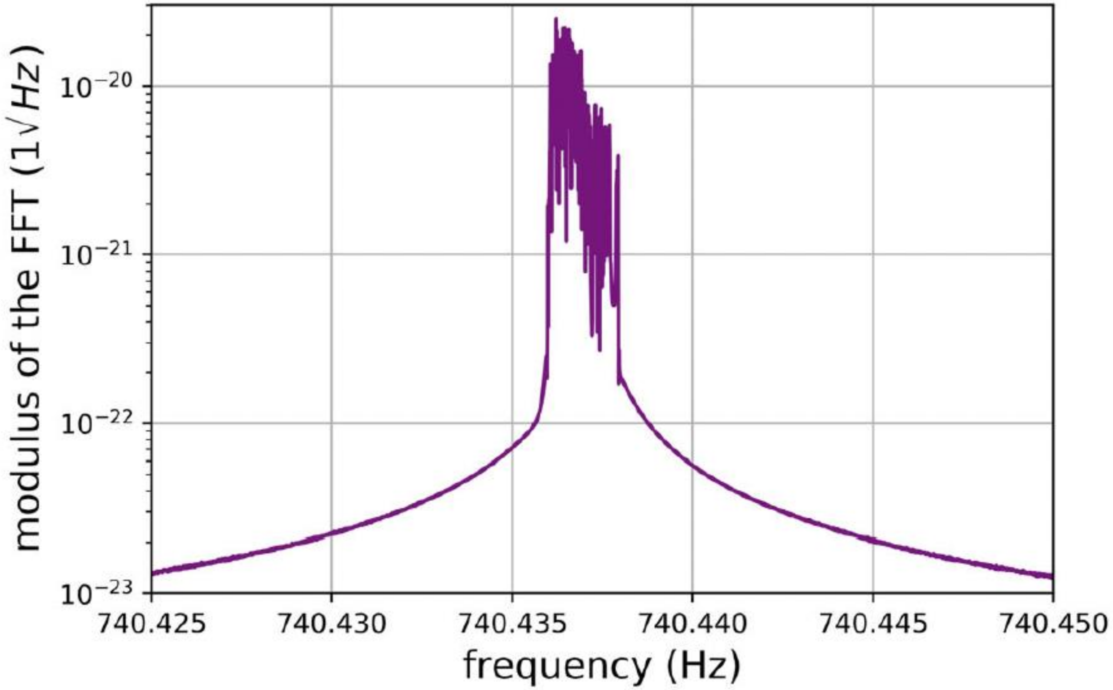
$$\sim 6.58 \cdot 10^{-26} \left(\frac{\epsilon_D}{10^{-23}}\right)$$

[Morisaki *et al*. (2021) **PRD 103**, L051702]

The expected signal from dark photon

Stochastic, narrow-band signal



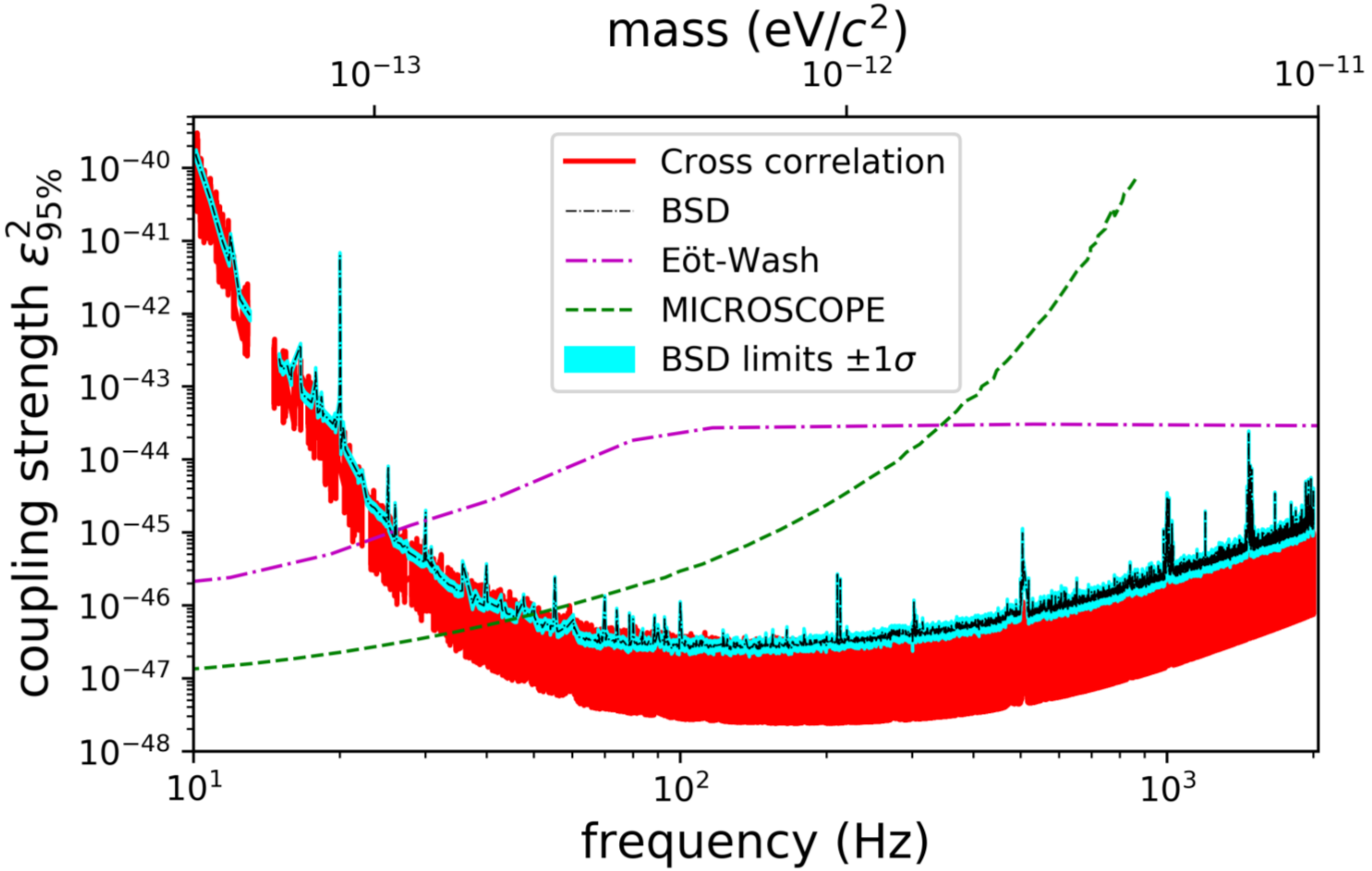


Most recent analysis carried on LIGO-Virgo O3 data, using two different analysis methods:

- Cross-correlation between different detectors. [Pierce *et al.* (2018) **PRL 121**, 061102]
- Excess-of-power statistics. [Miller *et al.* (2021) **PRD 103**, 103002]

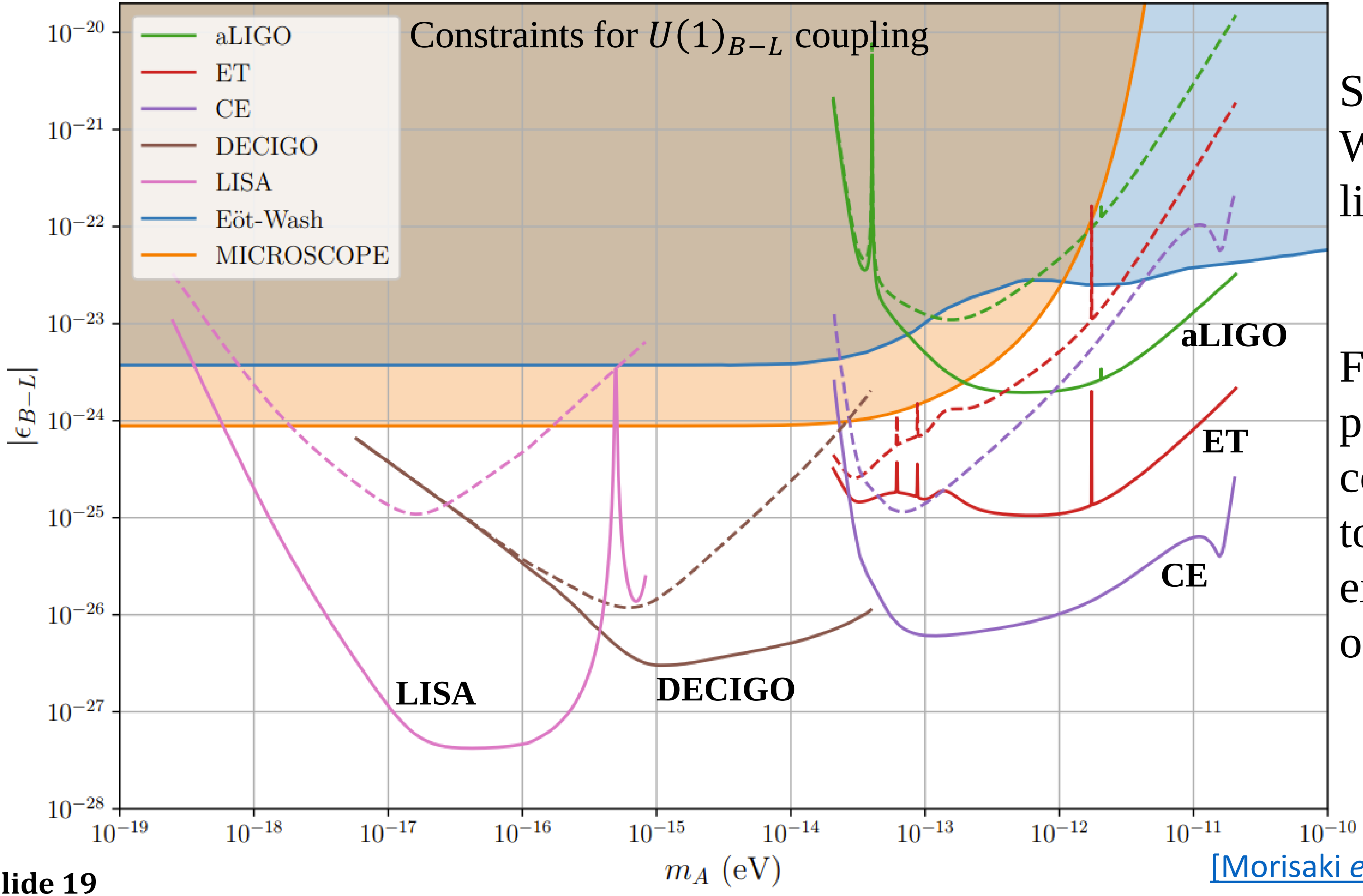
Upper limits on the coupling strength

- No detection, but competitive upper limits are computed.
- Compared to limits from existing torsion balance experiments (Eöt-Wash) and MICROSCOPE satellite.
- Improvement of two order of magnitude w.r.t. direct search experiments, assuming $U(1)_B$.
- For $U(1)_{B-L}$ upper limits are comparable to direct search experiments.



[Abbott *et al.* (2022) **PRD 105**, 063030]

Future observations

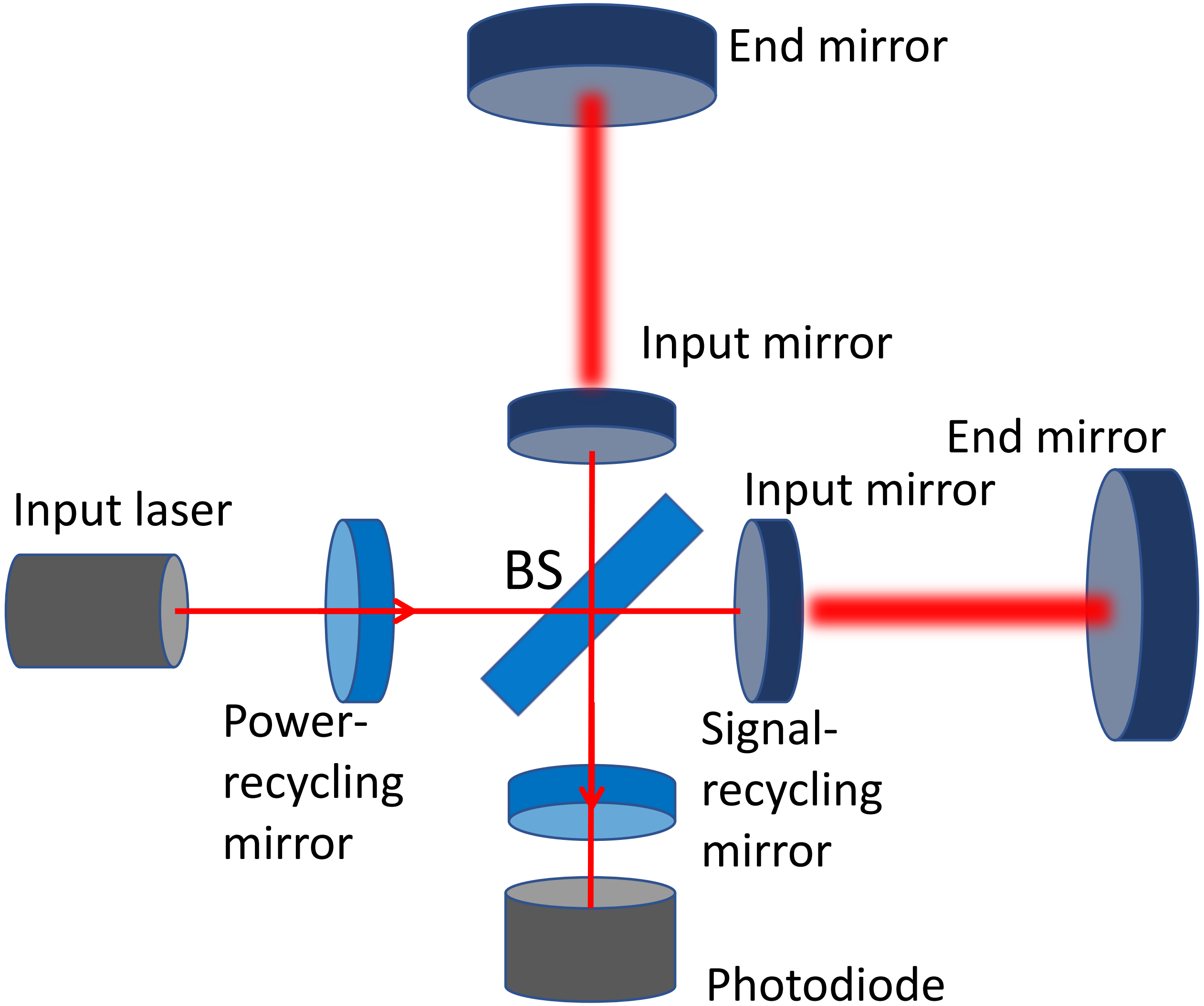


Solid/Dashed: Without/With finite light-traveling time.

Future detectors will provide better constraints with respect to Equivalence Principle experiments by orders of magnitude!

[Morisaki *et al.* (2021) **PRD 103**, L051702]

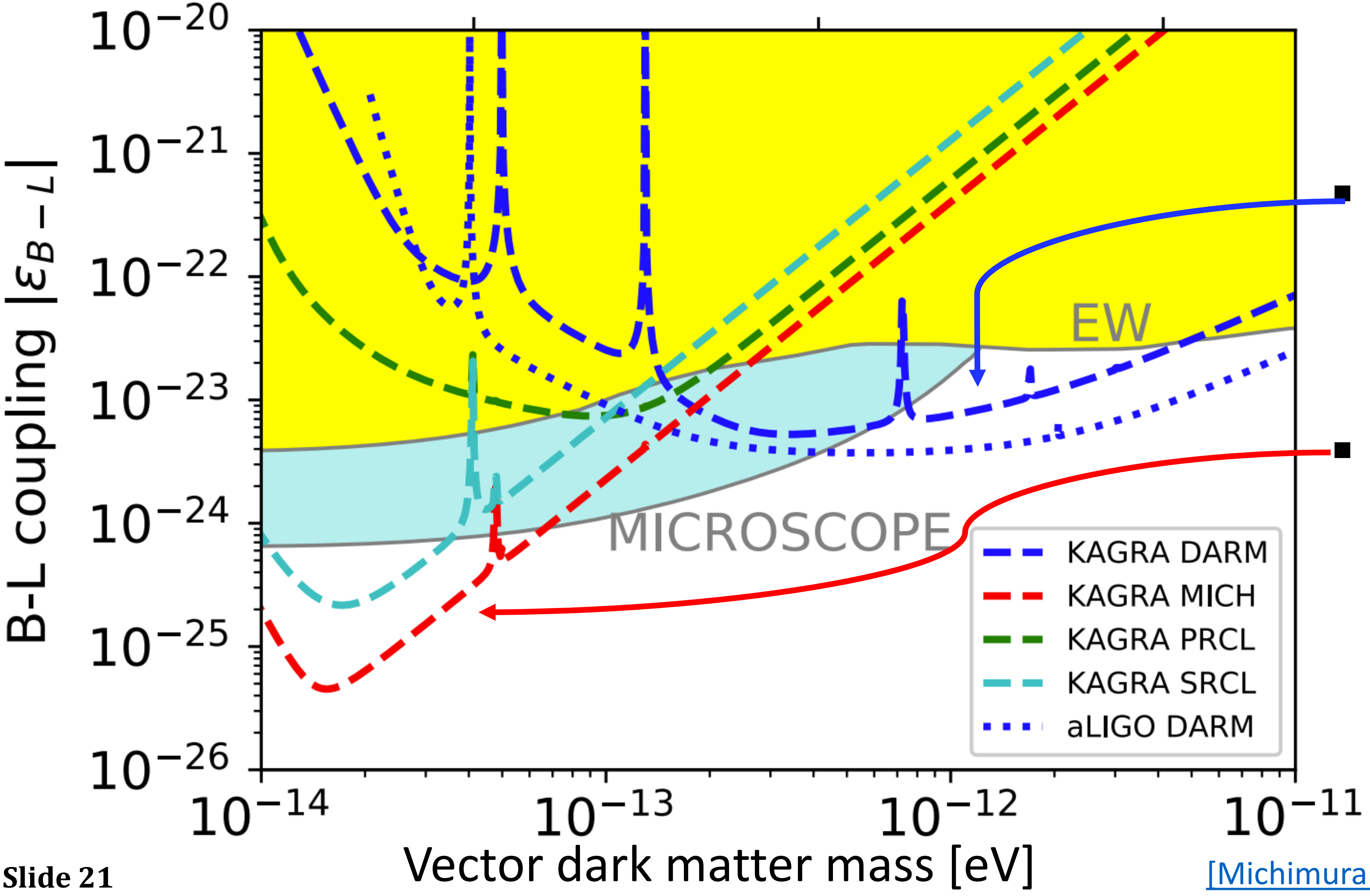
The peculiarity of KAGRA: hardware



- End and Input mirrors are made by **sapphire** (and are cryogenic).
- Beam-splitter and recycling mirrors are made by **fused-silica**.
- The force on the optics is composition-dependent!
- The effect can be observed by the auxiliary channels, which monitor the intra-optics distances.
- Will provide meaningful results in the next observing runs.

[Michimura *et al*. (2020) **PRD 102**, 102001]

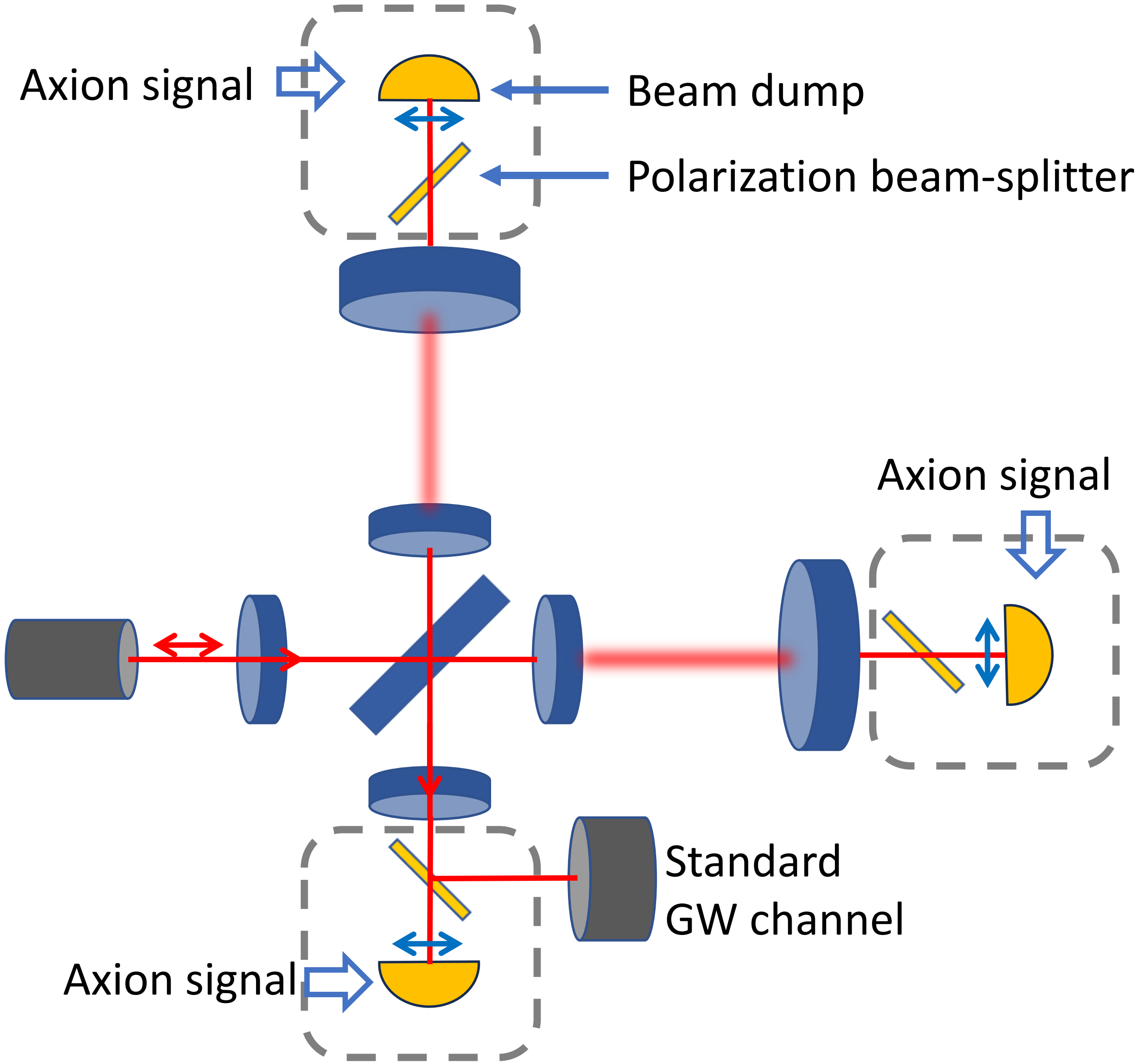
The peculiarity of KAGRA: future observations



- Standard output from KAGRA not so different from aLIGO…
- Auxiliary channels from KAGRA useful to probe the low-mass region!

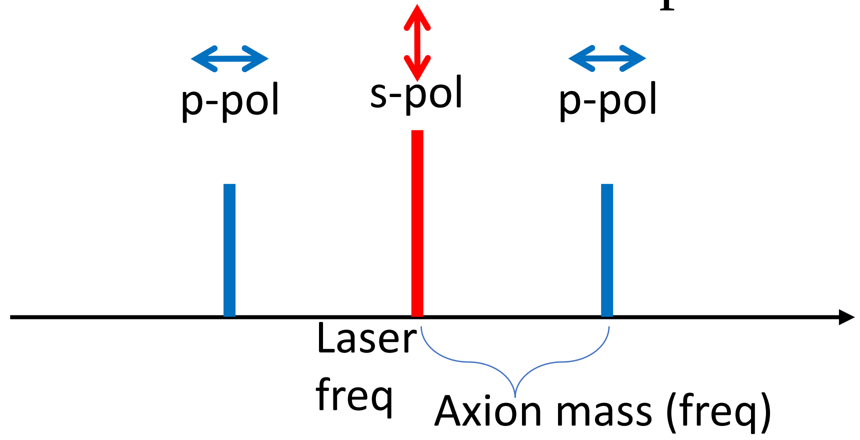
[Michimura *et al.* (2020) **PRD 102**, 102001]

Direct interaction of axions in the detector



ADAM-GD scheme:

- Effect of axions coupling to photons in a cavity: induce modulated linear polarization from s-like to p-like.



- The signal accumulates over multiple, <u>odd</u> round trips.
- The detection would require additional optics at end masses and detection system.

[Nagano *et al.* (2019) **PRL 123**, 111301] [Nagano *et al.* (2021) **PRD 104**, 062008]

Conclusions

- Interferometric, Earth-based gravitational-wave detectors have just opened a new window to observe the universe.

- LIGO, Virgo, KAGRA (and future detectors) have proven to be valid probes for ultra-light dark matter.

- A new observing run (O4) has just started on 24th May 2023
  - Improved sensitivity.
  - Longer observing time (1.5 years)

- Stay tuned!

THANK YOU!

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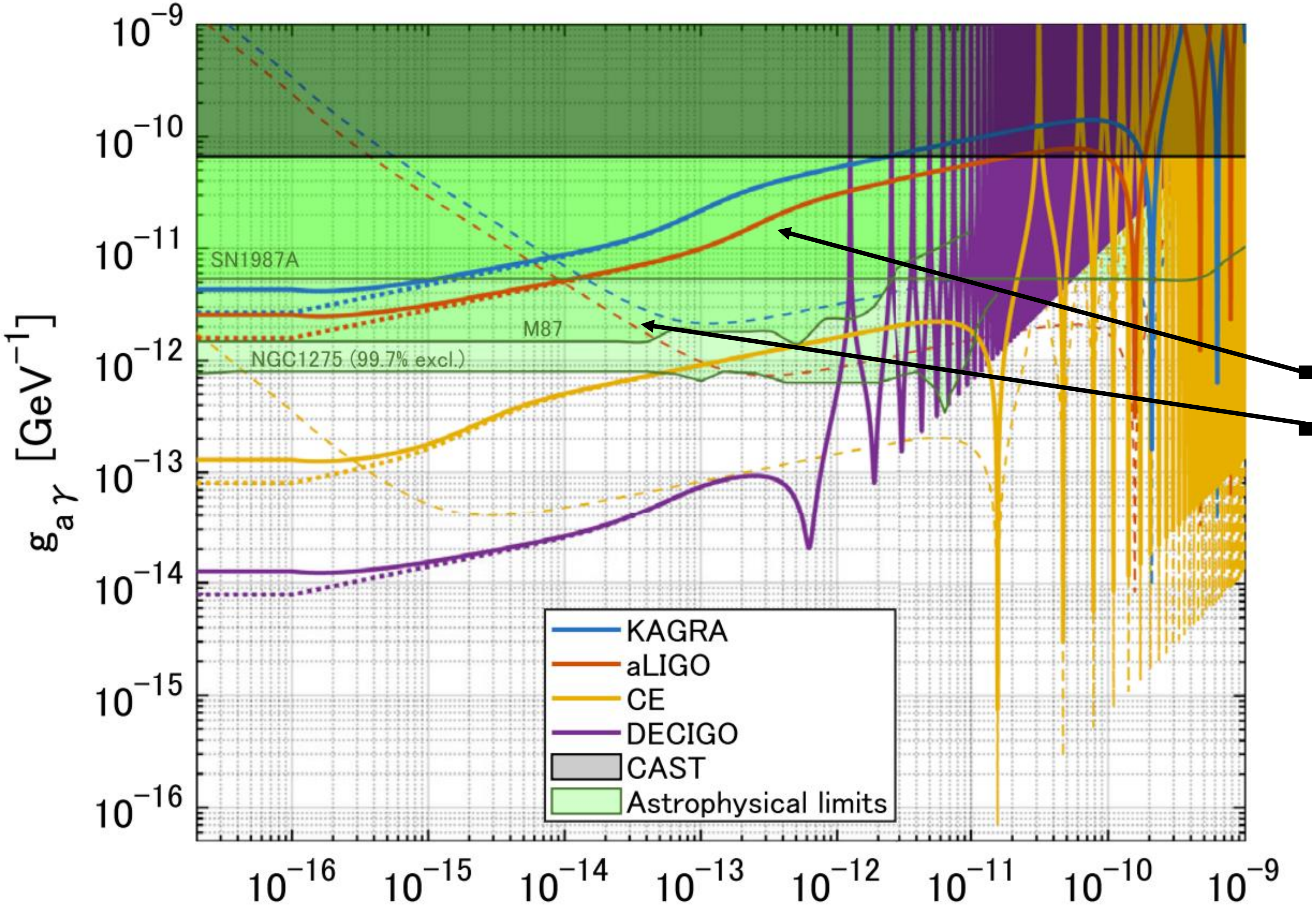
Direct interaction of axions in the detector



- Axion transmission port.
- Axion detection port.