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EC(H)Os in the dark

Hunting for **Exotic Compact Objects** (ECOs) with Gravitational Waves at **Atom Interferometers**

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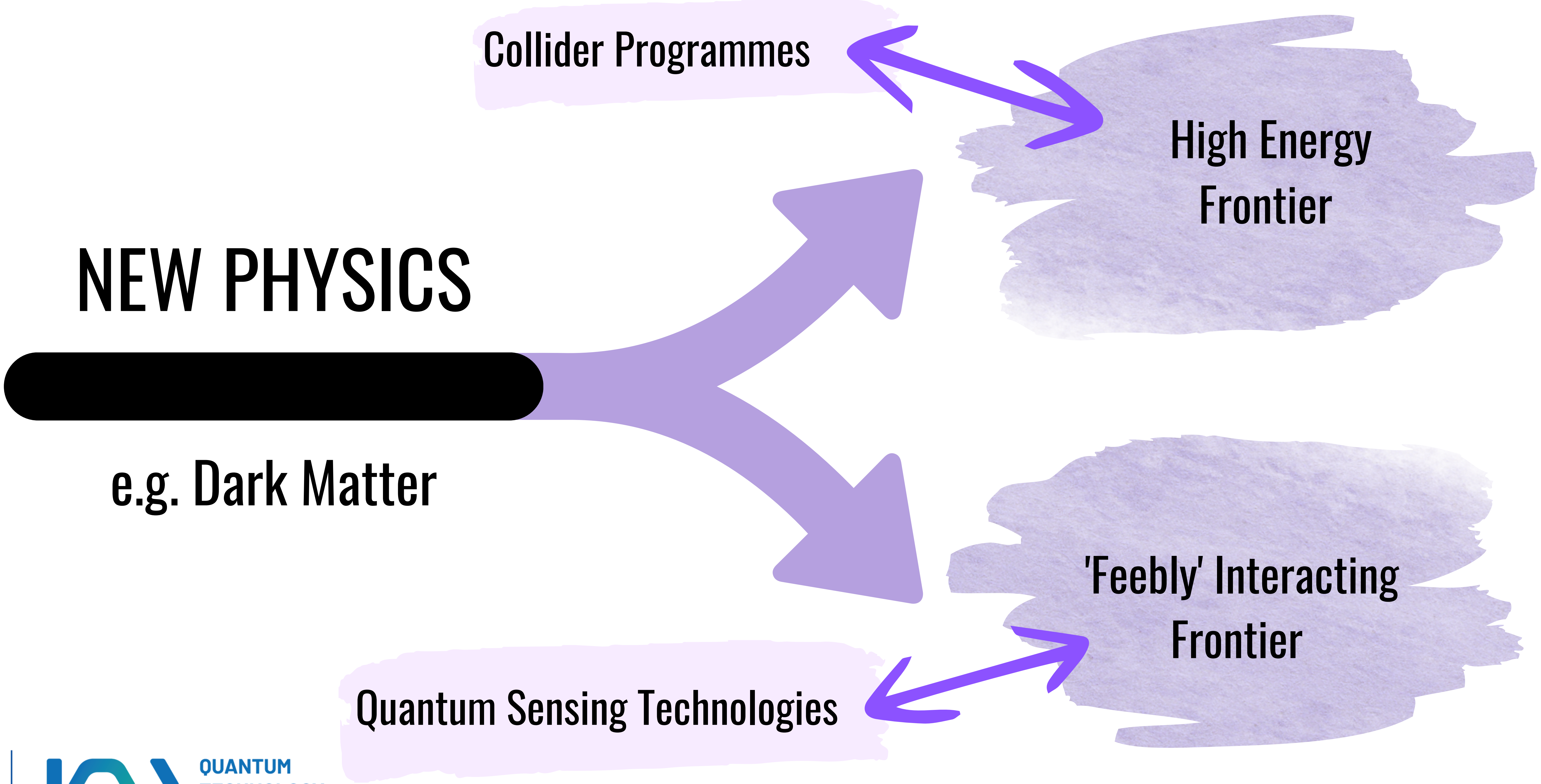
Based on **arXiv:2302.07887** with Matthew McCullough & Dorota Grabowska

Motivation: A Quantum Revolution



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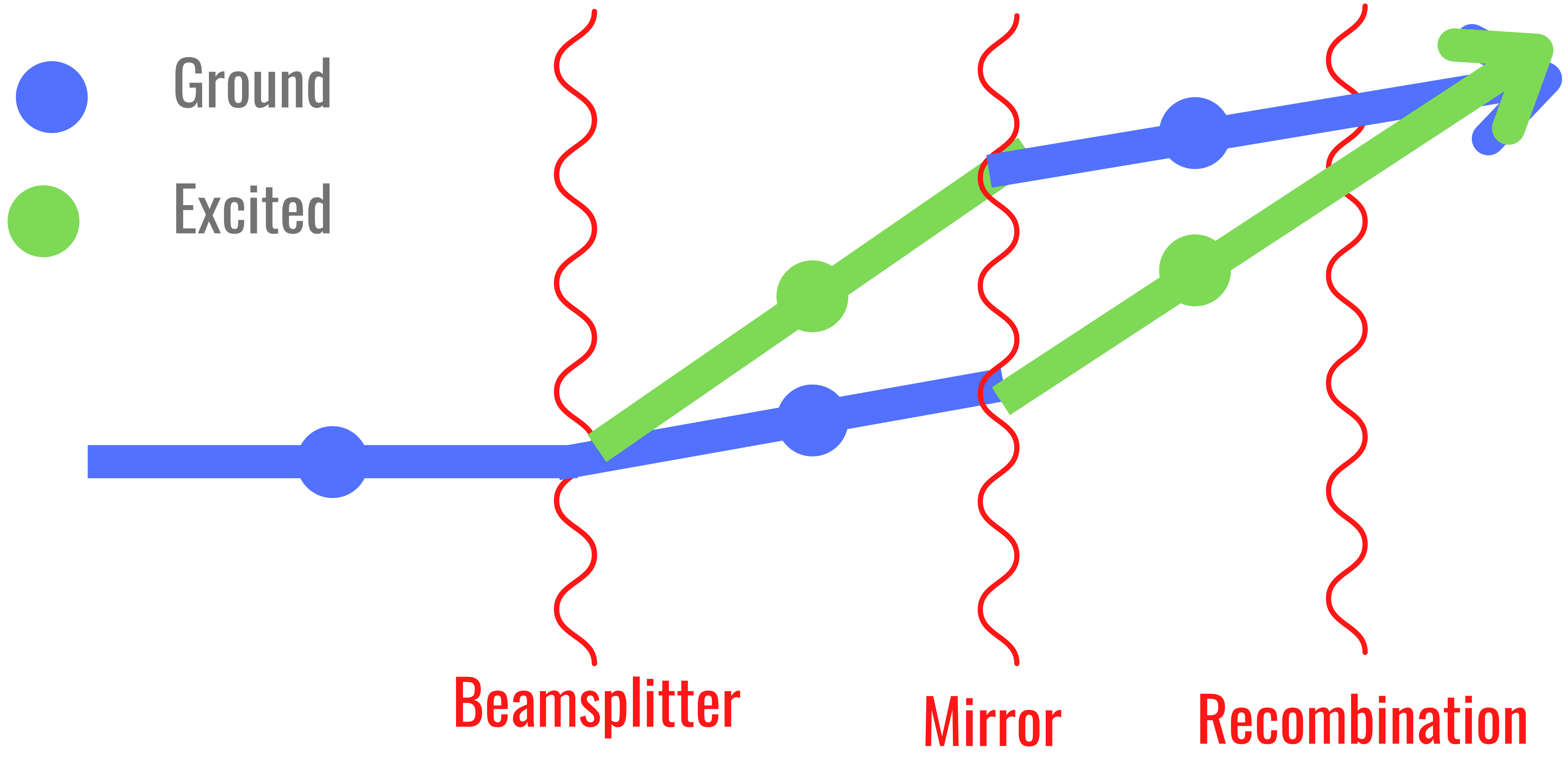
Atom Interferometers



Single Atom Inteferometer:

Measures the **phase difference** between **matter waves** travelling along **two different paths**

As a GW Detector:

- Operate **two single atom interferometers** with the same laser source, **separated by a distance L**
- **GW modifies L**, changing the phase difference recorded by the two systems

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Long Baseline Atom Interferometers

Several proposals to upsize Atom Interferometers to km scales to gain sensitivity to lower frequencies

Prototypes	km -scale	space based
AION-10 MAGIS-100 MIGA VLBAI ZAIGA	AION-km MAGIA-advanced ELGAR MAGIS-km advanced ZAIGA	AEDGE
In development...	mid 2030's..	2040's

Searches for Ultra-light DM

Mid-band Gravitational Waves

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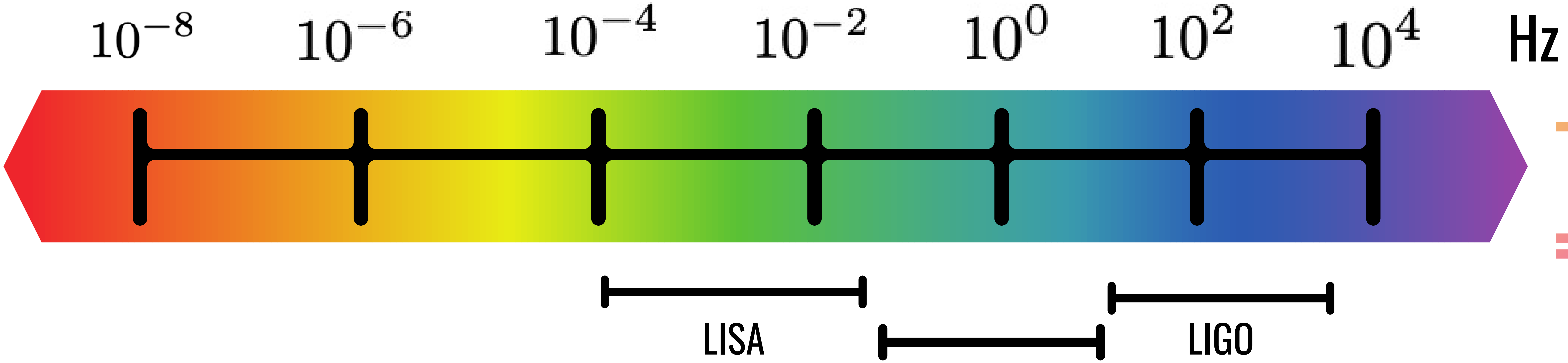
The GW Detector Landscape



Atom Interferometers e.g. AION-km

- Complimentary to other GW observatories
- Unique access to mid-band frequencies
- New sources of GW?

Resolved mergers of solar mass compact binaries

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Gravitational Waves @ Atom Interferometers ...

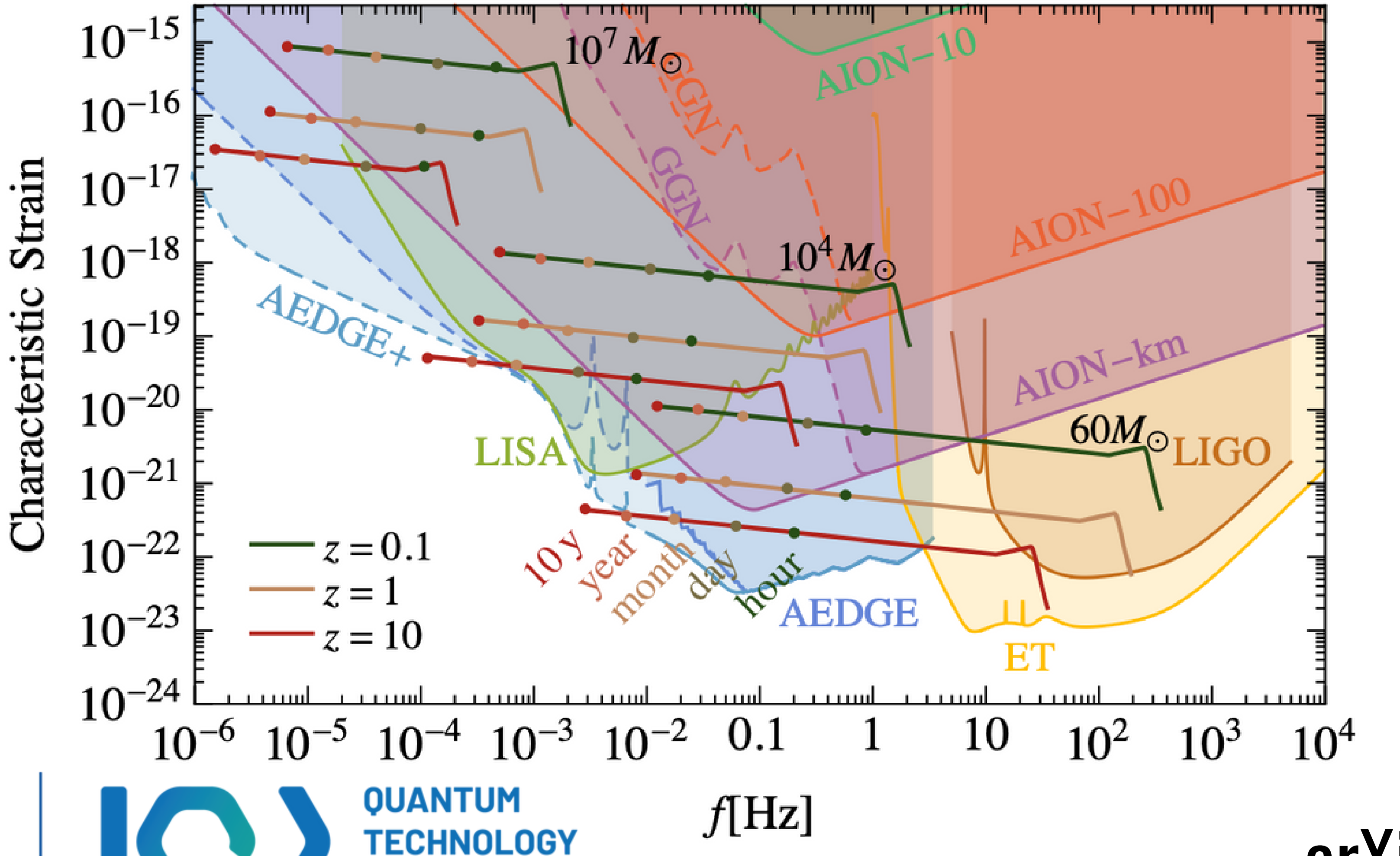
So far:

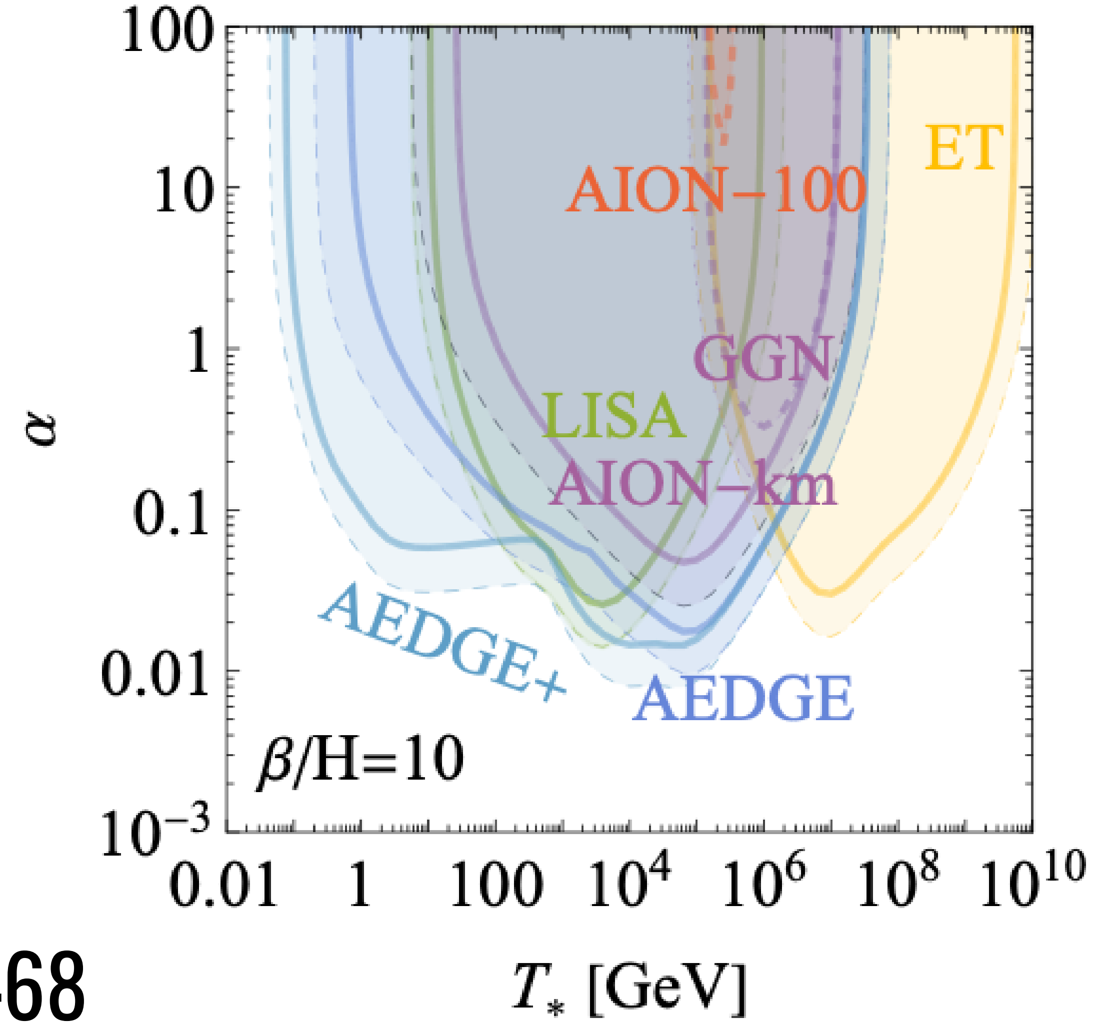
1

Resolved mergers of intermediate mass black hole binaries

2

Stochastic Backgrounds from first order phase transitions, cosmic strings...





arXiv:2108.02468

A New Lens

Gravitational Wave Background (GWB) = Total GW energy density emitted by a population of binaries, including **resolved & unresolved signals**

Characterise by:

$$\Omega_{GW}(f) = \frac{f}{\rho_c}\frac{\mathrm{d}\rho_{GW}(f)}{\mathrm{d}f}$$

This lens:

- Reveals an **important astrophysical signal** well with reach of Atom interferometers
  - Needs accounting for in other searches
  - Has a lot of information to reveal
- Offers a **unique** new **way to probe the Dark Sector**

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Gravitational Wave Backgrounds

For a population of binary compact objects:

Cosmology

Differential Merger Rate

Energy Density spectrum for a single binary

$$\Omega_{\mathrm{GW}} = \int \mathrm{d}m_1 \mathrm{d}m_2 \int \frac{1}{\rho_c} \frac{\mathrm{d}V_c}{1+z} \frac{\mathrm{d}\mathcal{R}(z)}{\mathrm{d}m_1 \mathrm{d}m_2} \frac{\mathrm{d}\tilde{\rho}_{\mathrm{GW}}(m_1, m_2)}{df}$$

- Present merger rate
- Mass Distribution
- Redshift Distribution

Waveforms of Inspiral, Merger and Ringdown Phases

During inspiral: $\Omega_{GW} \propto f^{2/3}$ independent of system

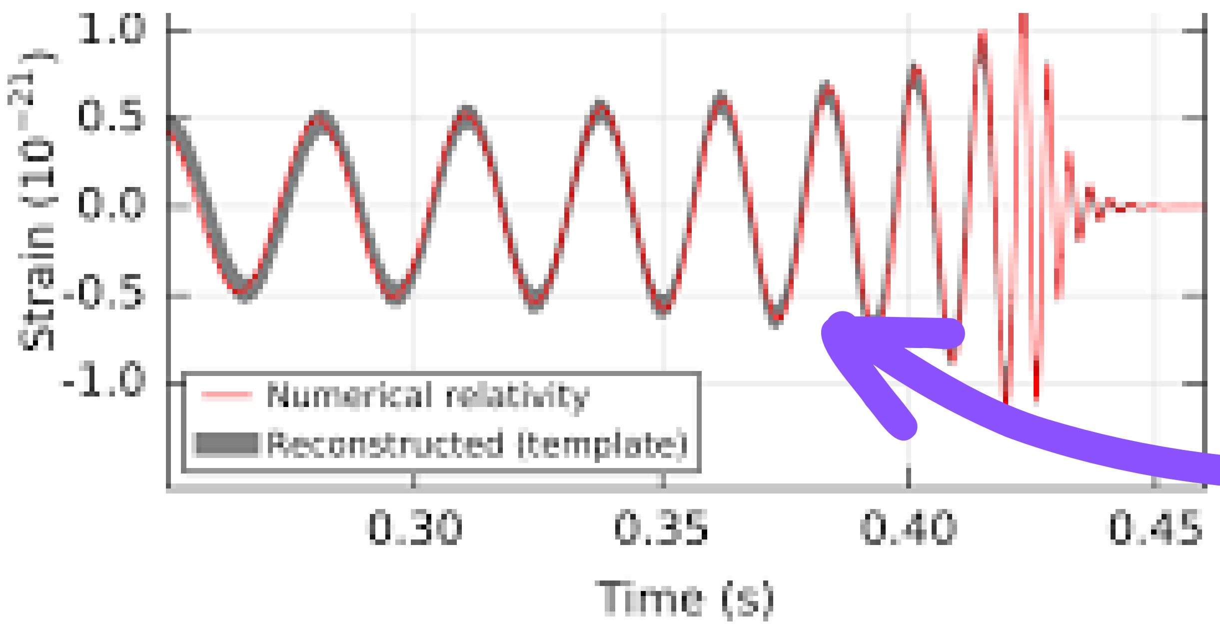
Source: LIGO Stellar Mass Compact Binaries

LIGO has observed many **stellar-mass binaries** merging @ $10^2 - 10^4 \mathrm{Hz}$

- Hundreds of **stellar mass Binary Black Holes (BBH)**
- 2 confirmed **Binary Neutron Star (BNS)**
- 4 **black hole-neutron star (BHNS)**

- Extract **Mass distribution**
- Extract **present event rate**

Stellar-mass populations are **well characterised!**



Emit **lower frequency** radiation during **inspiral** phase

Observable at Atom Interferometers?

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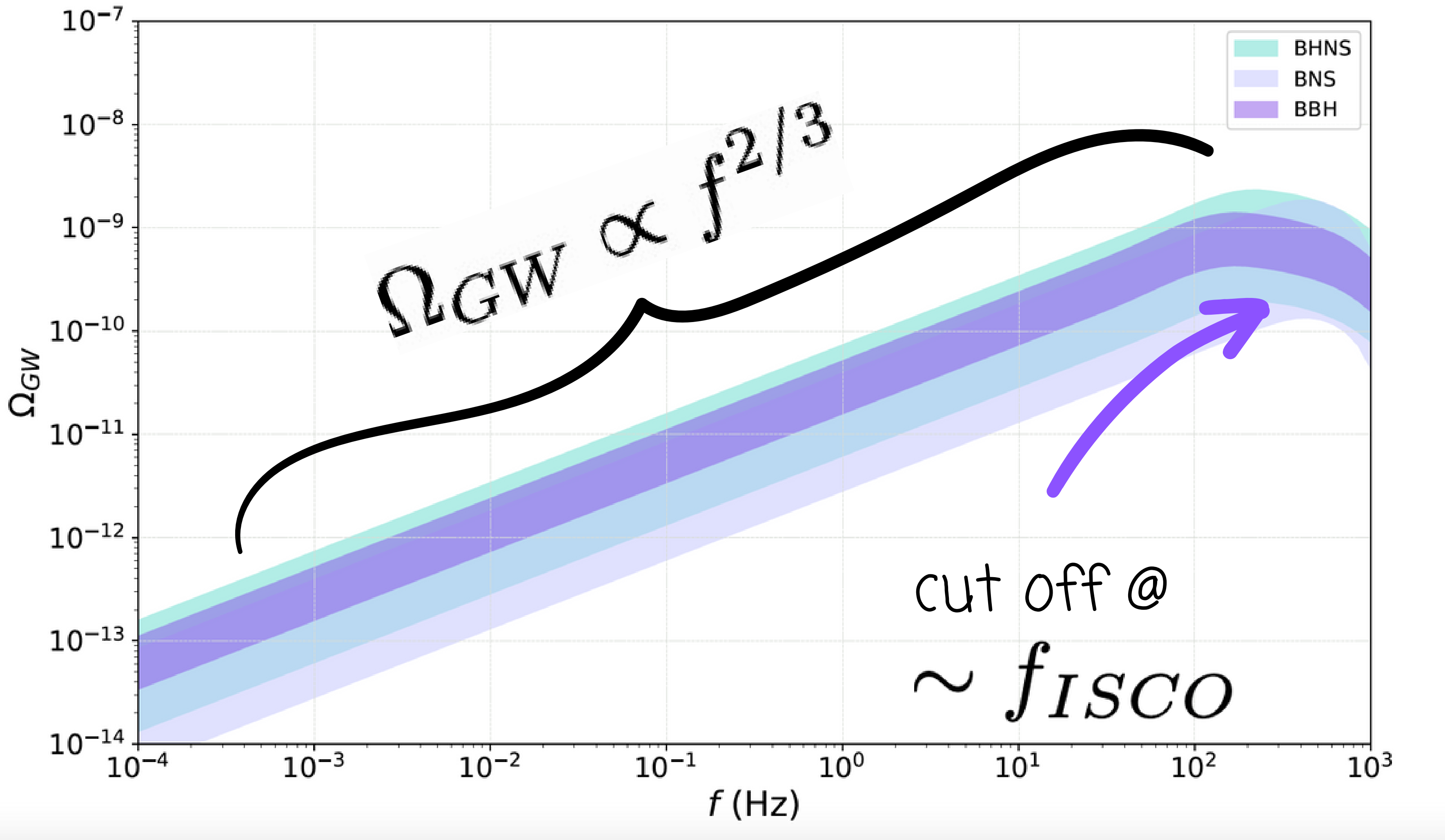
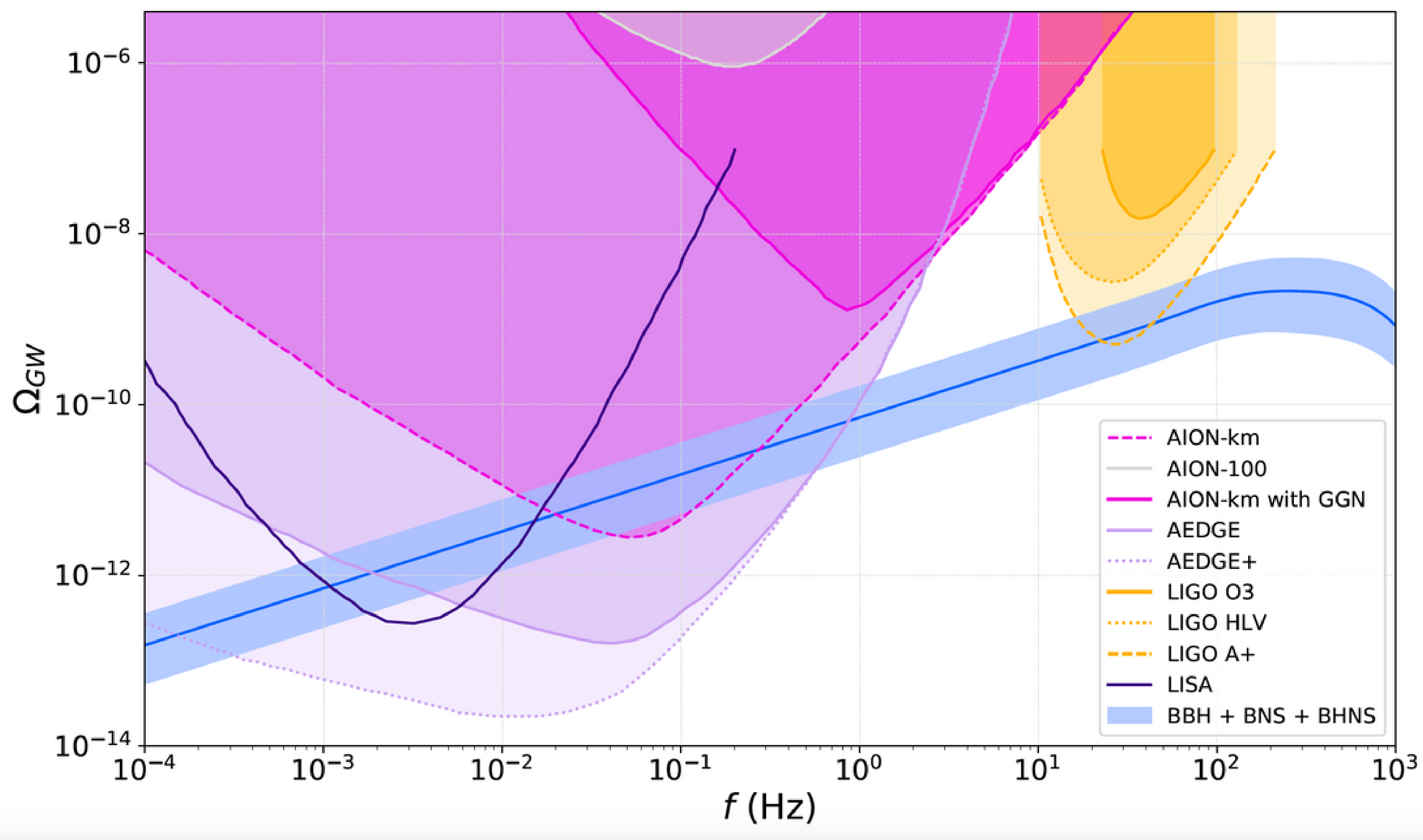
LIGO Stellar Mass Compact Binaries





Predicted **astrophysical background** from **known populations** of compact binaries **well within reach** !

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Implications & Opportunities

1

Relevant **background** to searches for other sources (both resolved & stochastic) that **needs to be taken into account**.

2

Interesting Signal:

- **Complimentary** to individual mergers - **probes higher z**
- Determine **population characteristics** and their **redshift dependence** e.g. masses, binary occurrence rate, BH angular momentum, NS ellipticity, NS magnetic fields
- **Test astrophysics** e.g. stellar formation rates, evolution of metallicity with redshift
- **Probe** possibility of **Primordial Black Holes**

Exotic Compact Objects (ECOs) ?

- SM is **extraordinarily rich and diverse** - same true of Dark Sector?
- Possibility of **new states over a great range of scales** which could **coalesce** under gravity to form **extended macroscopic objects**

ECOs may include:

Fermion Stars

Boson Stars

Dark Matter Stars

If form **binaries**, would produce **GWs**!

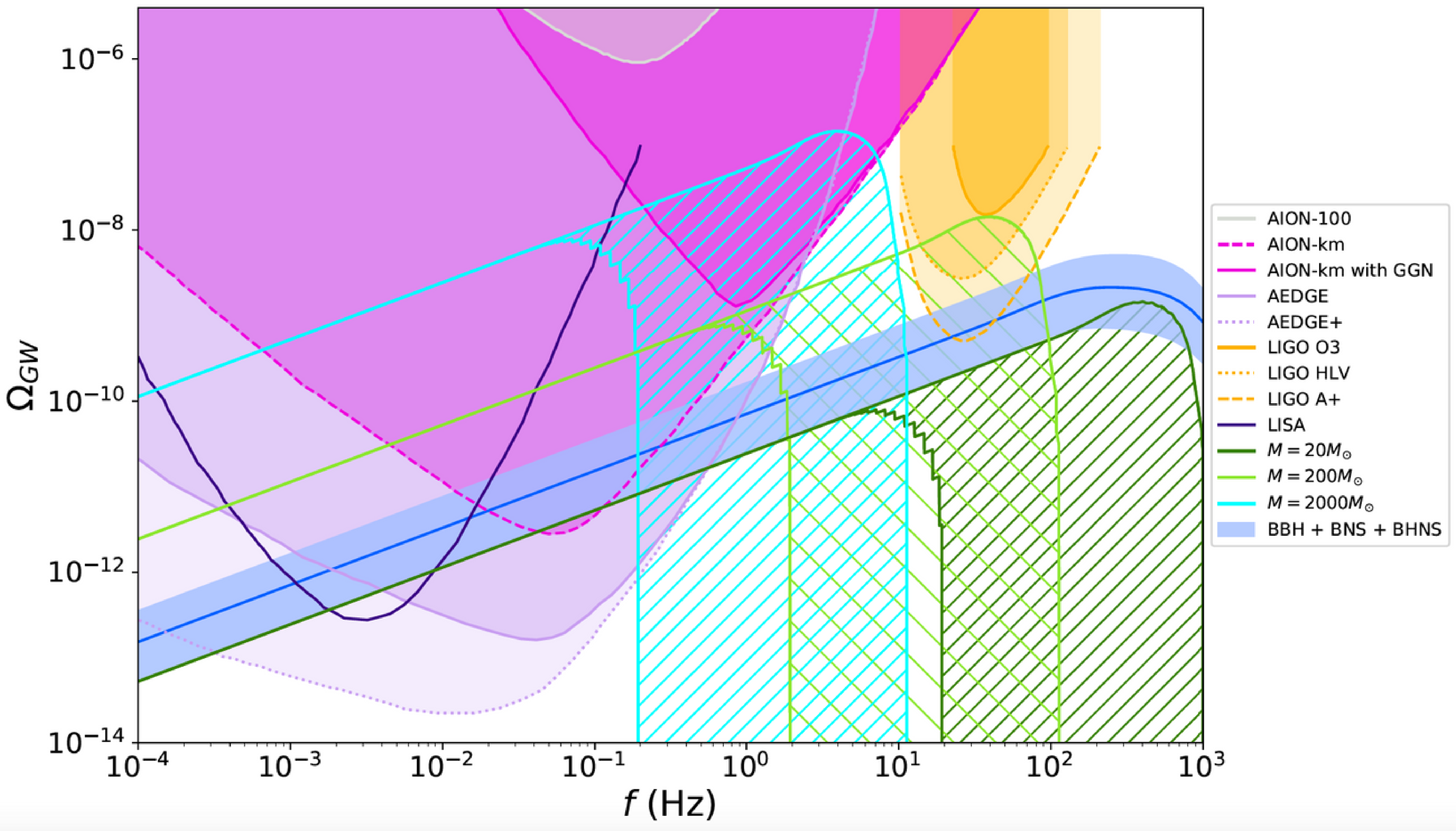
GWs from ECOs...

Assume:

- Population of equal mass objects in binaries
- Same redshift distr. & merger rate as LIGO BH
- Either:
  - Inspiral only up to

$$f_{ISCO}^{ECO} = \frac{C^{3/2}}{3^{3/2}\pi G M} \quad C = \frac{M}{R}$$

  - BH waveforms for ringdown/merger



Higher masses = lower cut-off

Mismatch between detectors = **probe** of **dark sector complexity**

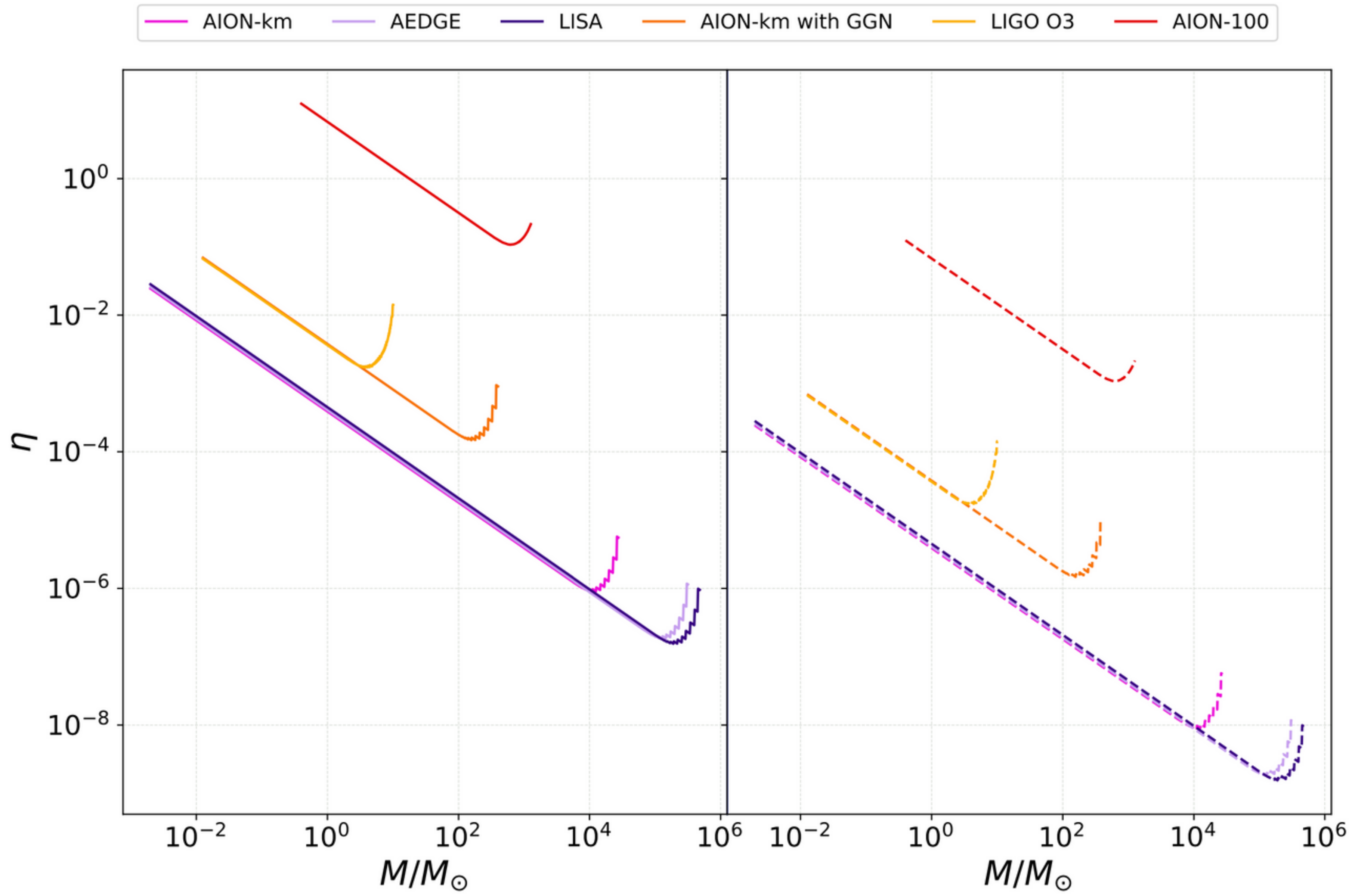
Is this reasonable?

Let η be **fraction of Dark Matter** in **ECO binaries**

$$\eta = \frac{\rho_{\mathrm{ECO}}}{\rho_{\mathrm{DM}}} \approx 6.4 \times 10^{-7} \times \left(\frac{R}{10}\right) \times \left(\frac{M}{2M_\odot}\right) \times \left(\frac{0.01}{\epsilon}\right)$$

What fraction is required to **exceed astrophysical background + instrument sensitivity**?

Sizeable signals even if ECOs harbour just a **tiny fraction** of **Dark Sector energy**



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Summary

- **Background** from LIGO stellar mass binaries **will be observable** at atom interferometers - **needs to be accounted for!**
- Opportunity to **extract** lots of **interesting astrophysical information**

- **ECOs** harbouring just **tiny fractions of DM** abundance could produce **significant signals**
- **Mismatch** between extrapolated and observed signals at different detectors could be a **smoking gun** for a **new binary population**
- Spectrum **cut-off sensitive to ECO mass** - probe of **dark sector complexity**

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