# EC(H)Os in the dark

## Hunting for ECOs with Gravitational Waves at Atom Interferometers

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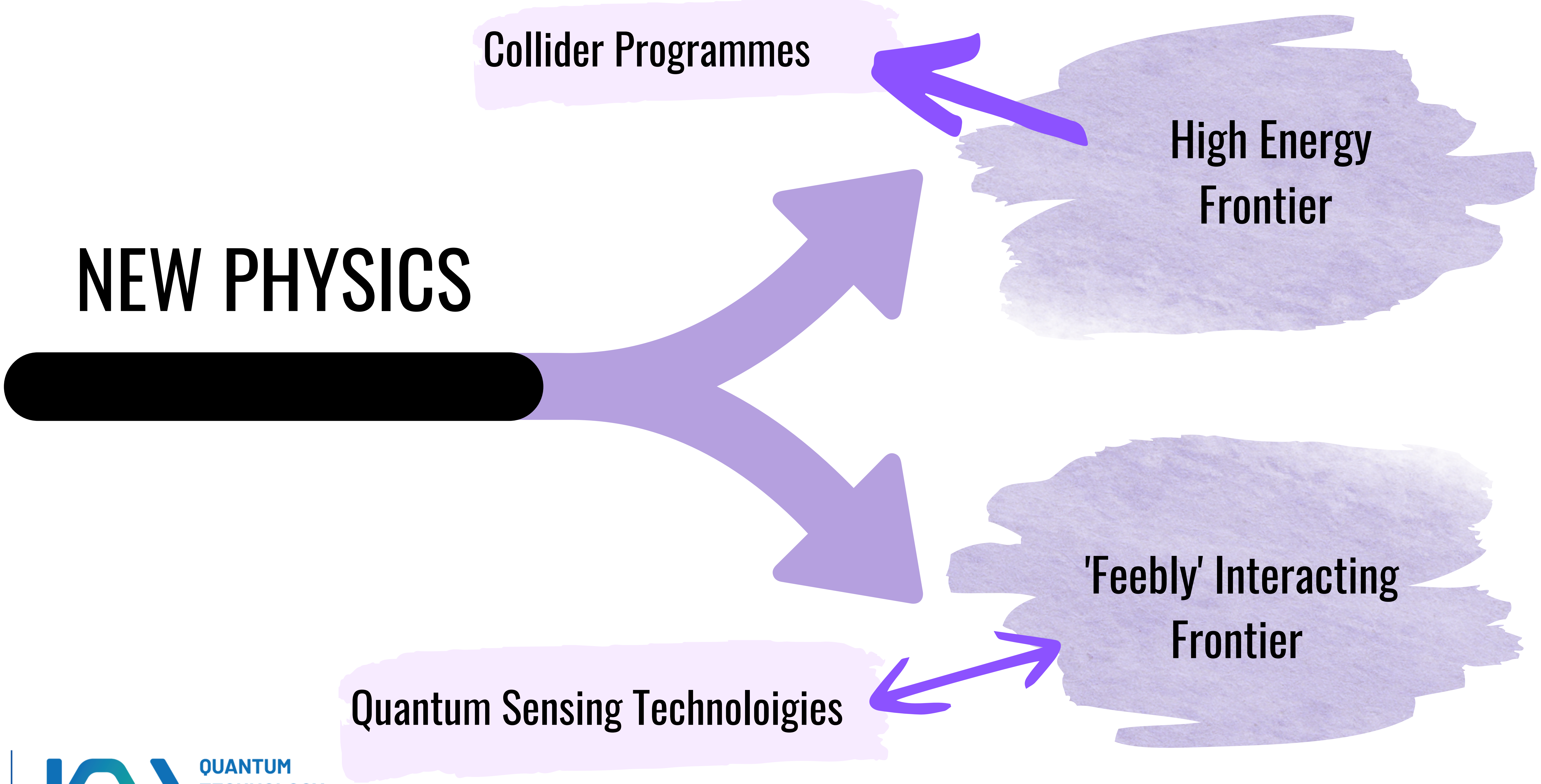
Based on work with Matthew McCullough & Dorota Grabowska

# Motivation: A Quantum Revolution

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# Quantum Sensing for Fundamental Physics

Advances in Quantum Sensing Technologies

Manipulate quantum states of light and matter

Precision  measurements of fundamental forces & fields

New ways to probe fudamental physics at the feebly interacting frontier

e.g exotic foces, new sources gravitational waves, hidden sectors of particles ....

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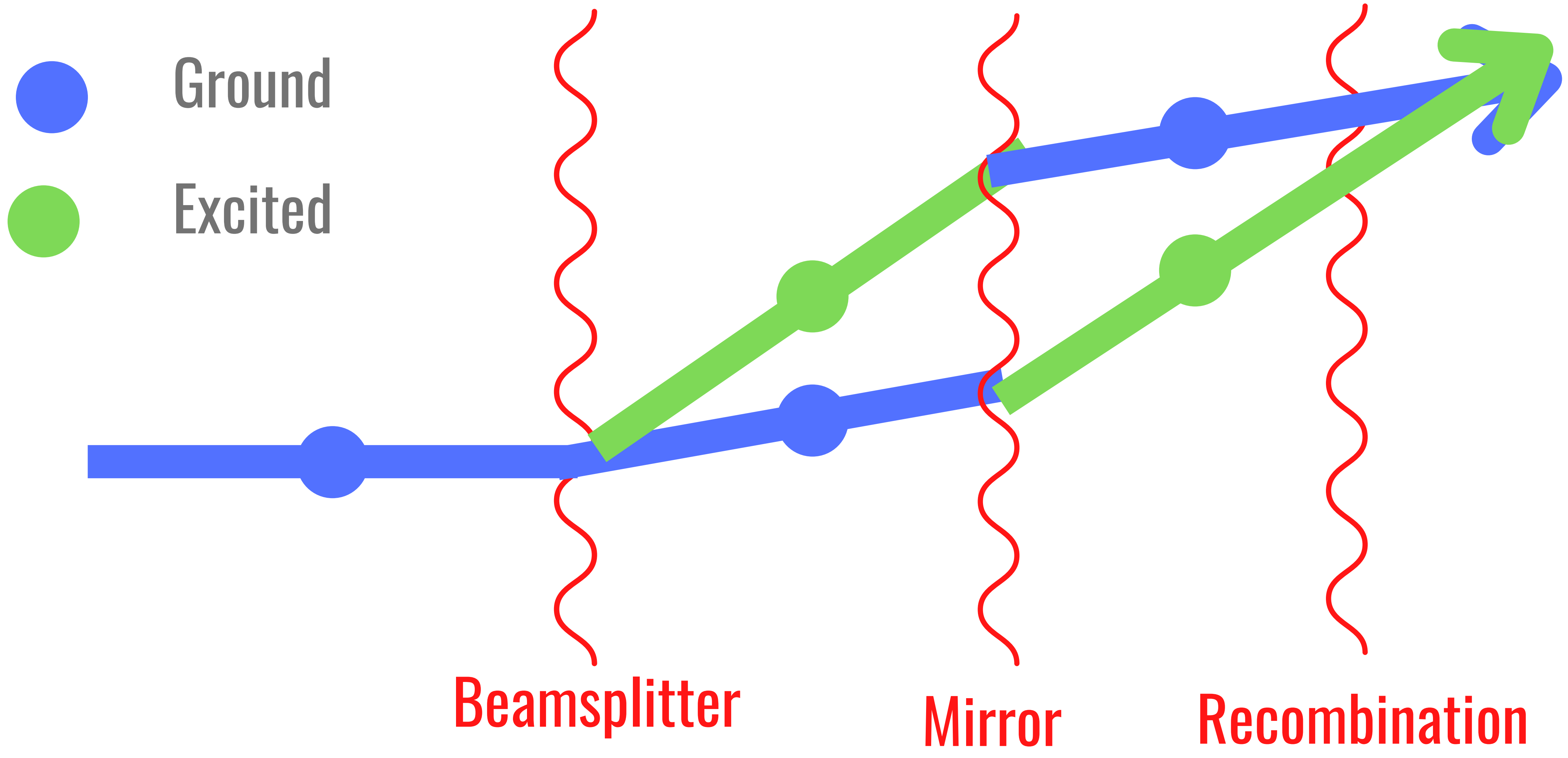
# Atom Interferometry




**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 between the two systems

# Long Baseline Atom Interferometers

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

Prototypes

AION-10
MAGIS-100
MIGA
VLBAI
ZAIGA

In development...

km -scale

AION-km
MAGIA-advanced
ELGAR
MAGIS-km
advanced ZAIGA

mid 2030's..

space based

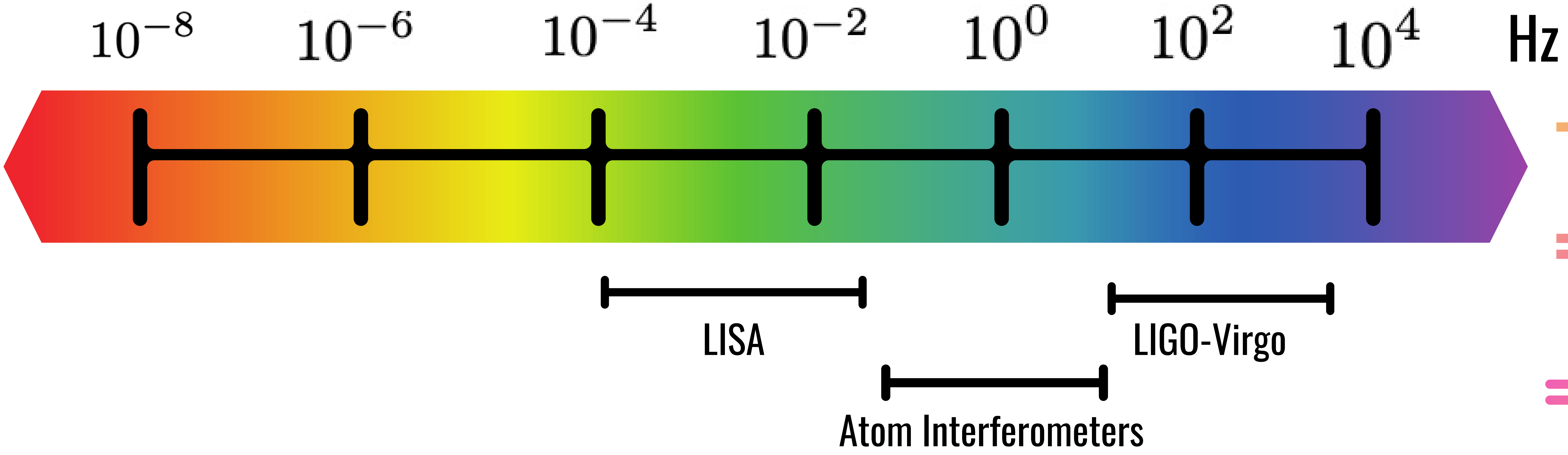
AEDGE

2040's

Searches for Ultra-light DM

Mid-band Gravitational Waves

# Long Baseline Atom Interferometers




- Complimentary to other GW observatories
- Sensitivity to mid-band frequencies
- Access new regions in parameter space/ new sources of GW

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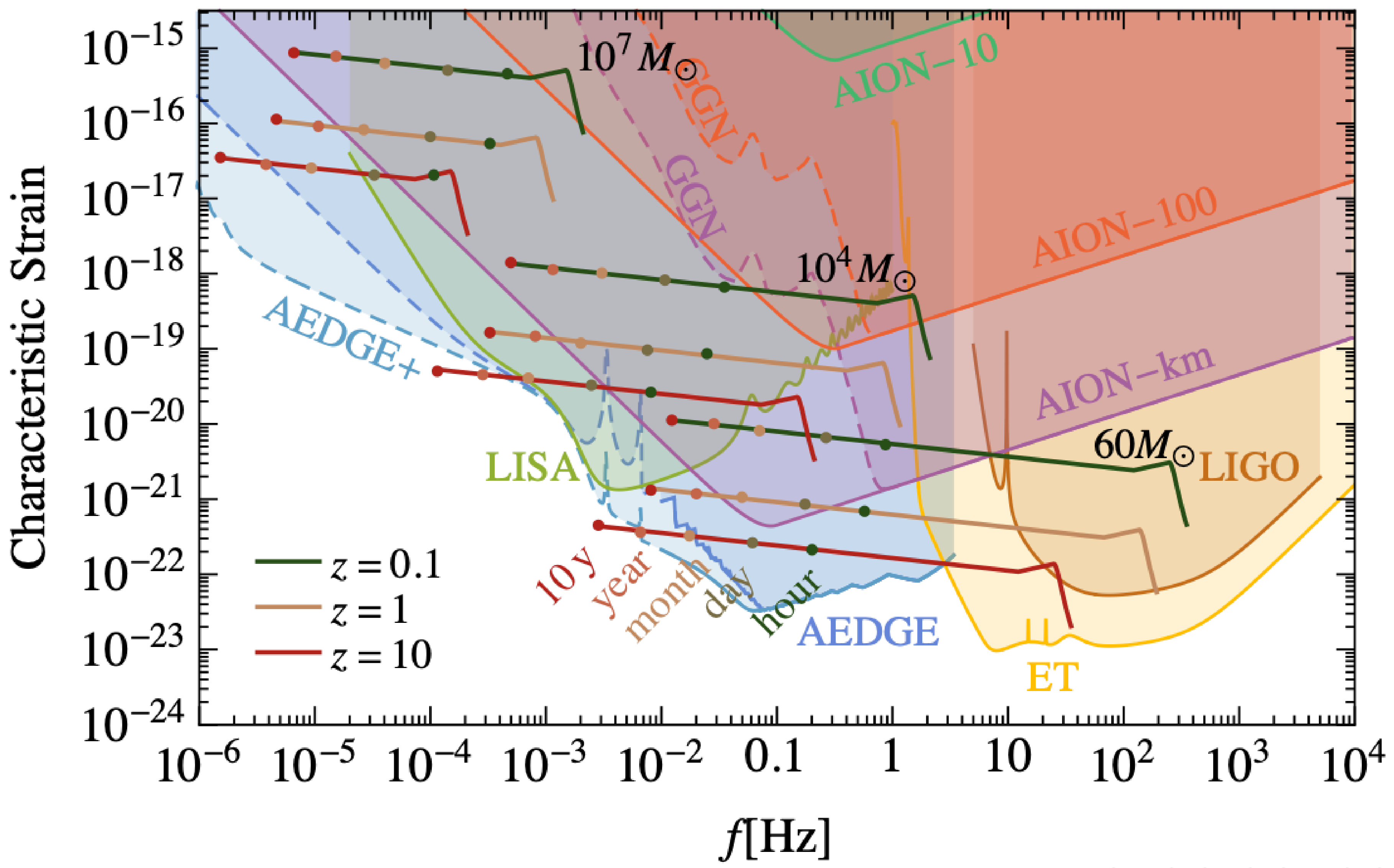
# The Science Case

- Largely focused on observing resolved signals from individual mergers e.g. of Intermediate Mass Black Holes




arXiv:2108.02468

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# An Alternative Lens: Gravitational Wave Backgrounds

- Instead, look at the cumulative Gravitational Wave energy density emitted by a population of objects, including BOTH resolved and unresolved signals = Gravitational Wave Background

Characterise by:

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

We will find::

- An important astrophysical signal well with reach of Atom interferometers
  - Needs accounting for in other searches
  - Has a lot of information to reveal
- A possible 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

# LIGO Stellar Mass Compact Binaries

- Numerous observations of mergers of stellar mass Binary Black Holes (BBH) by LIGO-Virgo
- 2 `Confirmed Neutron Star (NS) Mergers
- 1 possible BH-NS merger

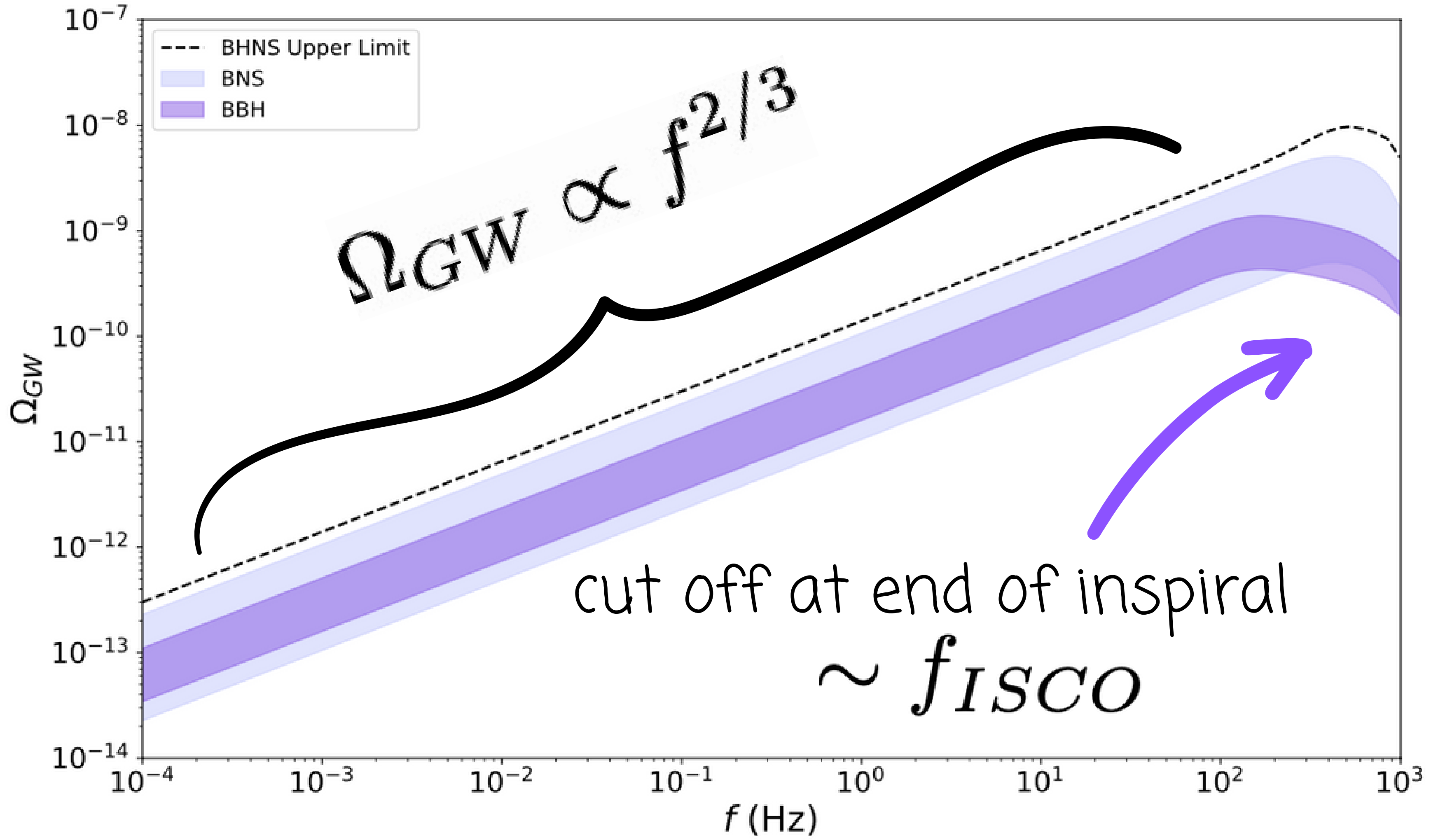
Observations of resolved mergers @ $\sim 10^2 - 10^4\mathrm{Hz}$

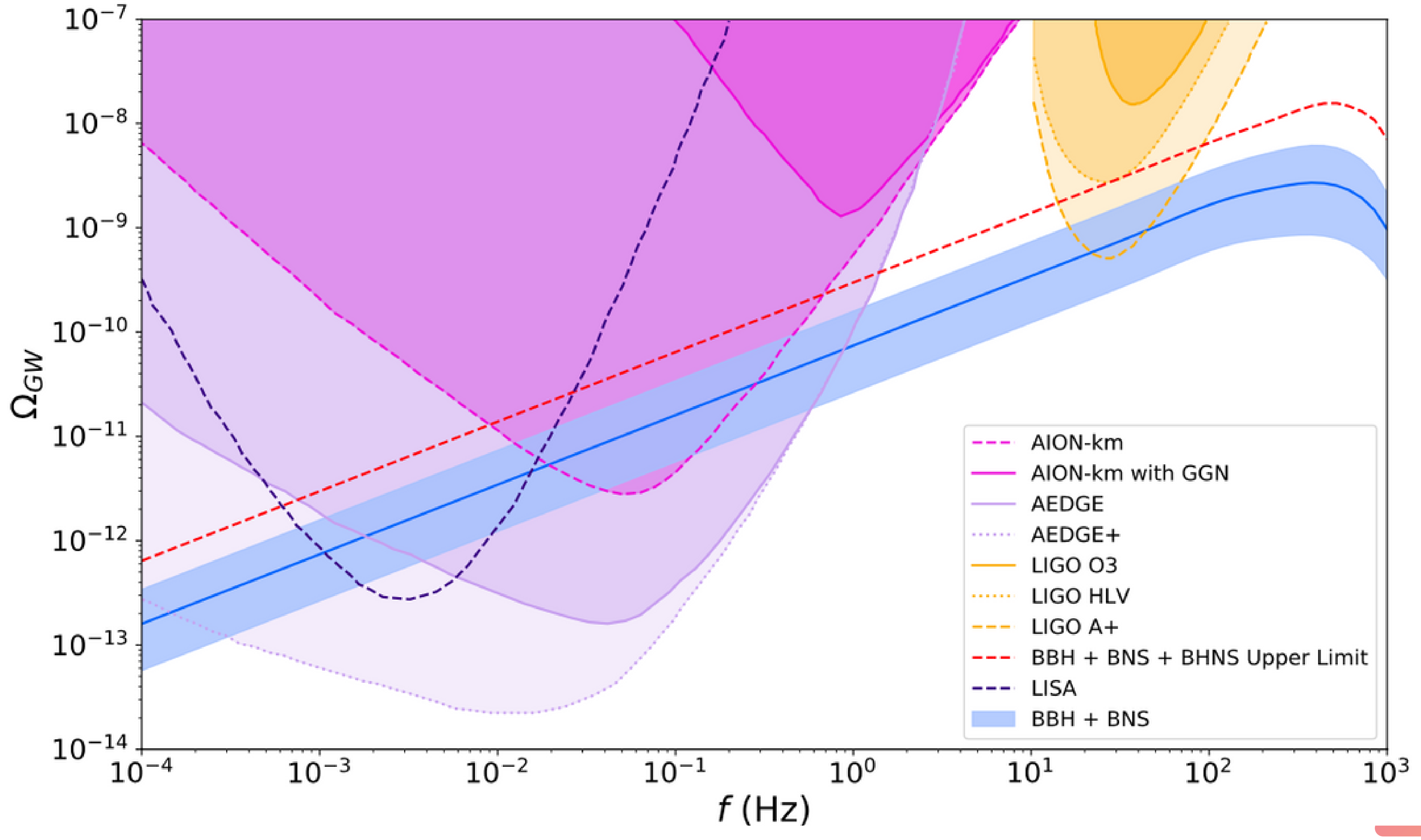
For BH:

- Redshift distribution known (convolution of stellar formation rate with distribution of of delay times between formation and merger
- Merger/Ringdown Waveforms known

- Extract Mass distribution
- Extract present event rate

# LIGO Stellar Mass Compact Binaries




Predicted Astrophysical Background from known populations of compact binaries well within reach !

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# Implications & Opportunities

Relevant background to searches for both resolved signals (need to incl. in noise) & searches for cosmological (primordial) backgrounds

**But, measurements of this background could give:**

- Complimentary information to individual mergers - probes higher z
- Determine the characteristics of the population as a whole and how they evolve with redshift e.g. masses, binary occurrence rate, BH angular momentum, NS ellipticity, NS magnetic fields
- Extract information on stellar formation rates, evolution of metallicity with redshift
- Investigate possibility of multichannel primordial and astrophysical mergers

# 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
Possibility of coalescing under gravity to form extended macroscopic objects

ECOs could include…

- Fermion Stars
- Boson Stars
- Dark Matter Stars

If these objects form binaries, mergers could produce GW in direct analogy to SM counterparts !

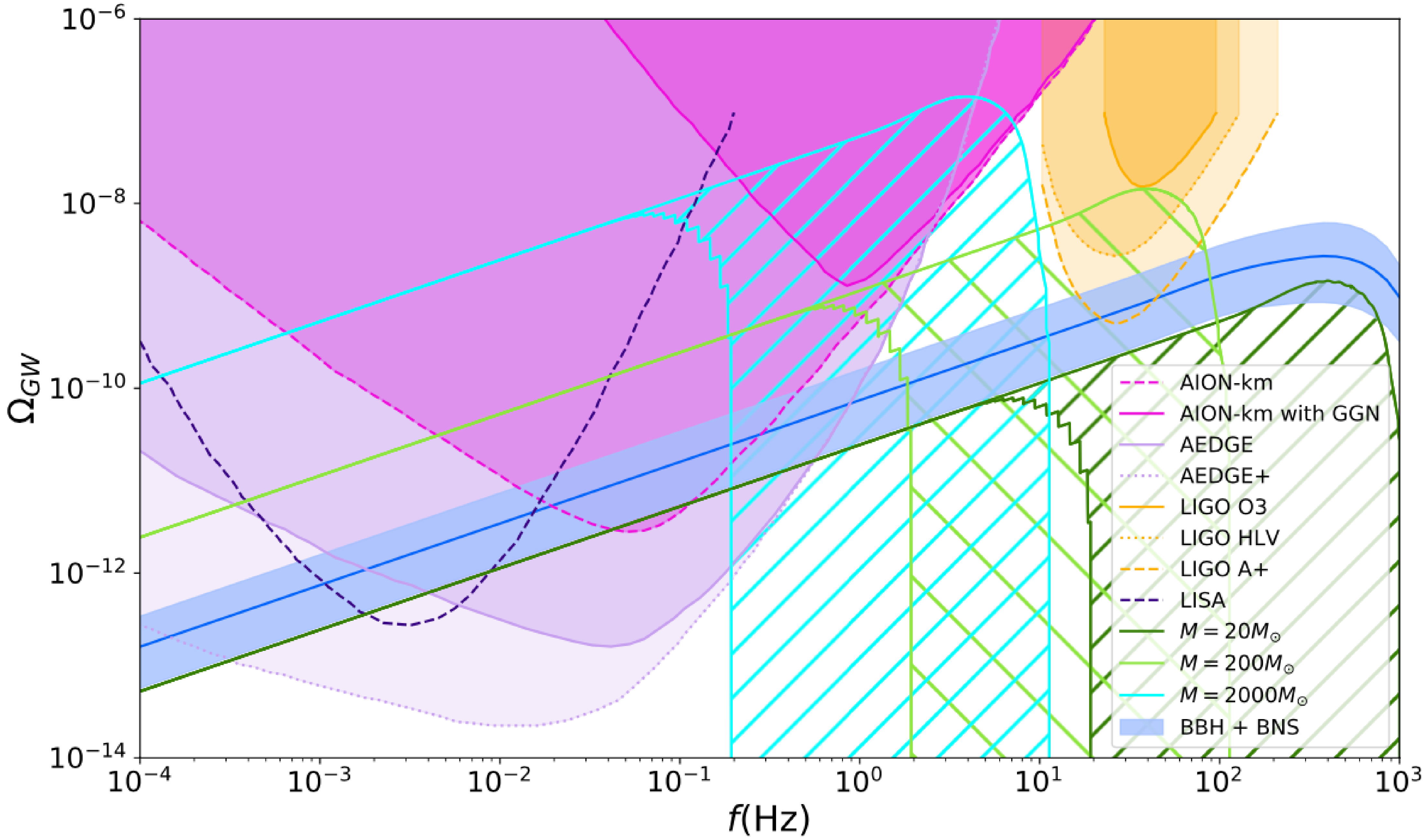
# A population of ECOs...

Assume:

- Population of equal mass objects in binaries
- Same redshift distr. & present 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 Wavefunctions for ringdown/merger




Higher masses = lower cut off

Mismatch between detectors -> probe DS structures

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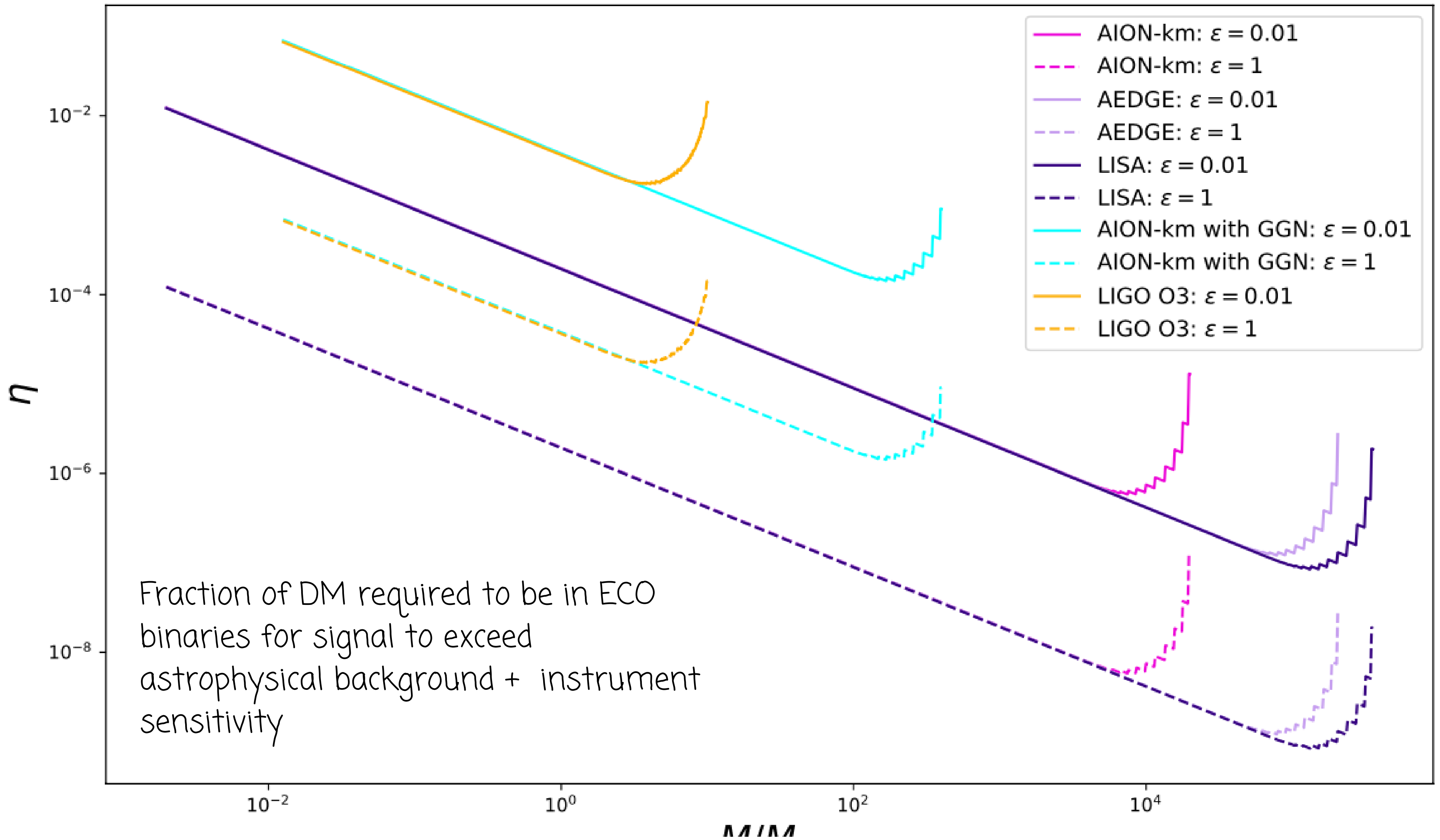
# Are these signals reasonable?

Let $\eta$ be fraction of Dark Matter in ECO binaries

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

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



# Conclusions

- LIGO Stellar Mass Compact Binaries will produce a measurable signal at long baseline atom interferometers - relevant to searches for both resolved individual mergers & stochastic cosmological backgrounds
- The background spectral shape contains a lot of astrophysical information (e.g. population parameters, stellar formation rates) & offers ways to probe new scenarios e.g. multichannel primordial-astrophysical BH mergers

Background Measurements could provide a unique way to probe complexity in the Dark Sector:

- Mismatch between extrapolated & measured signals at different observatories could indicate the existence of the presence of a population of ECOs of a different mass scale
- Cut off frequency could be used to gain an idea of object mass -> probe structure & complexity in the Dark Sector
- Tiny fractions of Dark Sector could produce significant signals!

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