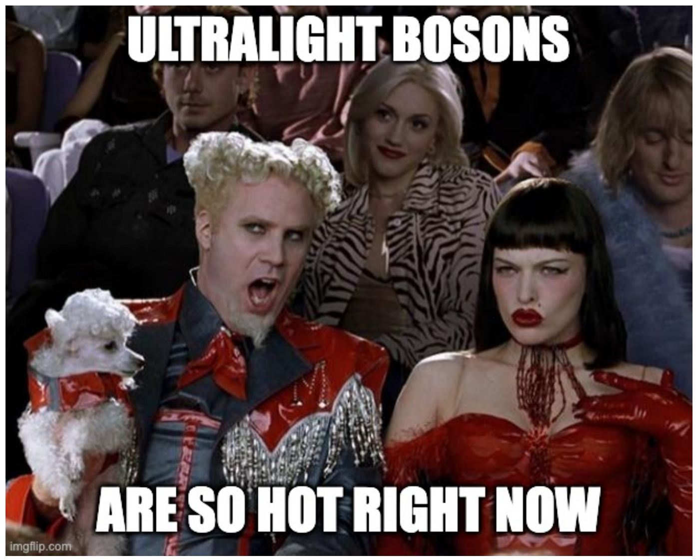
# DM and Astroparticle Physics

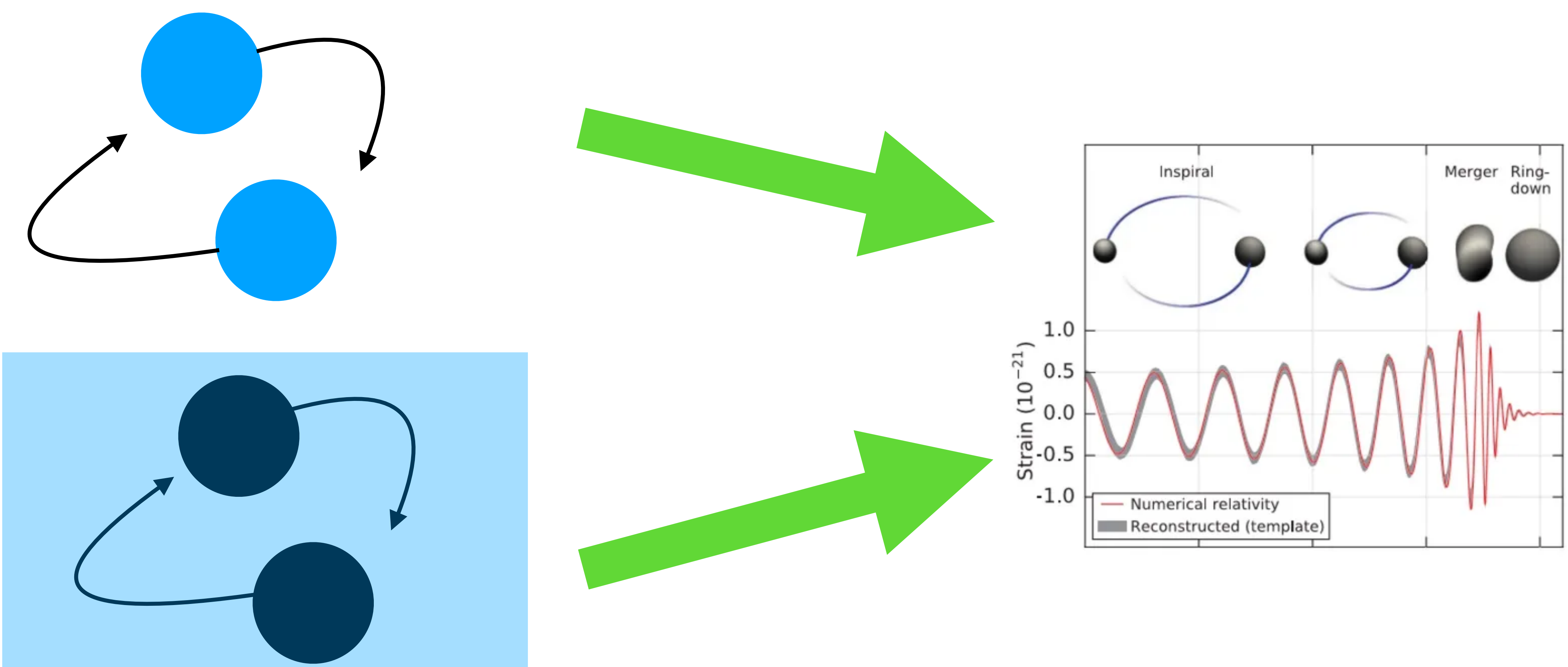
Panel members :
**Pippa Cole (Milano-Bicocca) : Overview**
**Djuna Croon (Durham) : Astroparticle DM and GW**
**Ed Daw (Sheffield) : Axions**
**Ema Dimastrogiovanni (Groningen) : Stochastic GW from DM**
**Eugene Lim (KCL) : Coherent GW from DM**

# Coherent GW from ECO/DM




$$V(\phi) = \frac{1}{2}m^2\phi^2 \ , \ m = 10^{-21} \sim 10^{-3}\mathrm{eV}$$

$$M_{\mathrm{ECO}} \sim M_p/m^2 \ , \ m \sim 10^{-11}\mathrm{eV} \rightarrow M_{\mathrm{ECO}} \sim M_\odot$$



# Coherent GW from ECO/DM

| **Black hole** | ***vs*** | **ECO/Boson stars** |
| --- | --- | --- |
| Single dynamic scale $M_{BH}$ | | Multiple scales $M, m, \ldots$ |
| No hair! | | Lots of hair (equilibrium vs excited states) |
| BH horizon "protection" from poor high curvature dynamics | | No horizon : need to resolve physics at large curvature ranges |
| Initial conditions easy (Vacuum solutions!) | | Initial conditions hard/unsolved (matter fields!) |

# Coherent GW from ECO/DM

**What do we need?**

**Initial Conditions for Binaries**

Equilibrium? Excited? GIGO!

**Stable and precise evolution**

Multiple dynamic scales, no horizon (expensive!)

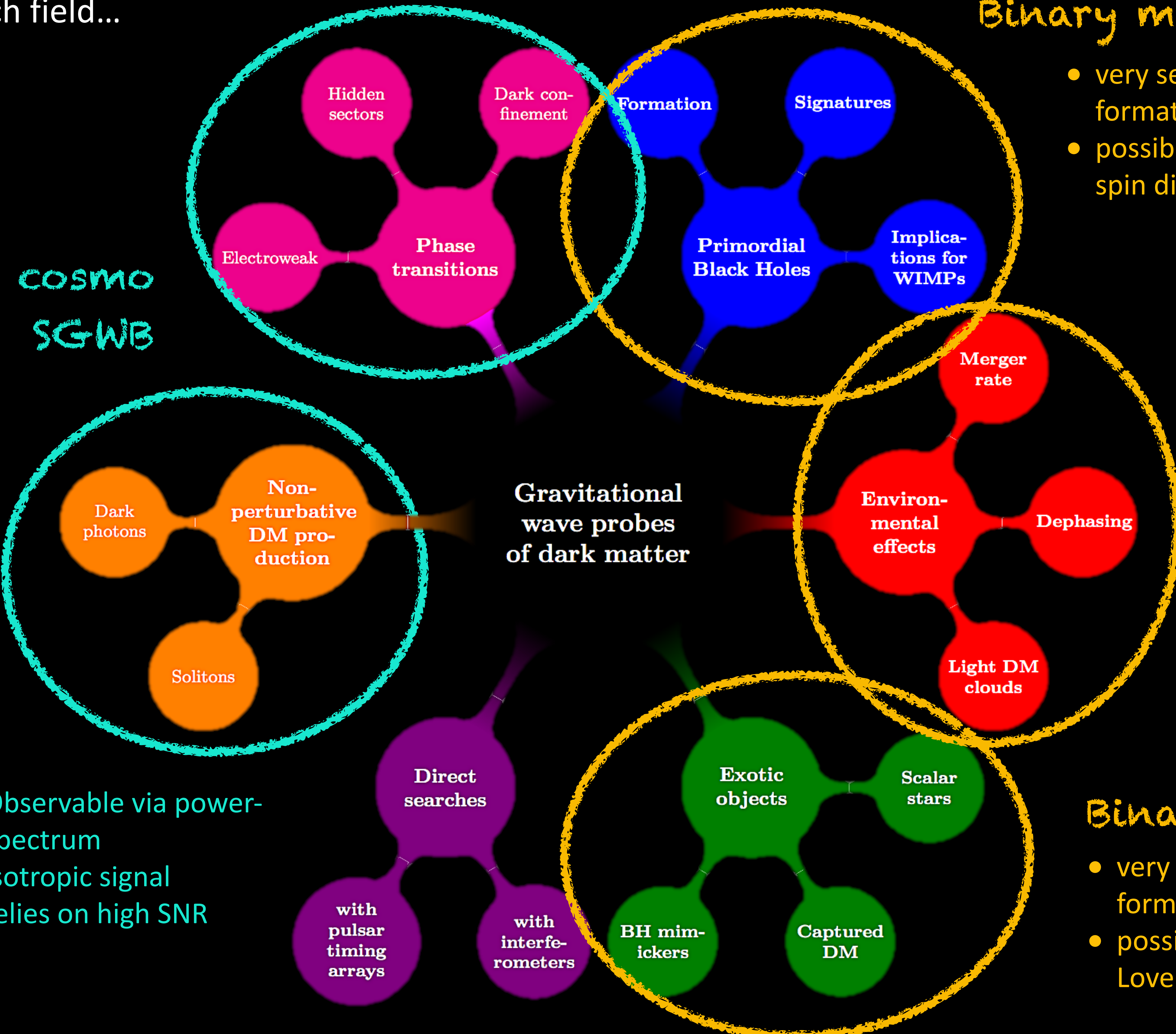
**Waveform signal modeling**

None so far. “IMRPhenom for ECO/DM”

# DM + GW

*Background image from G. Bertone, DC, et al. Scipost, arXiv:1907.10610*

A rich field…




cosmo SGWB

- Observable via power-spectrum
- Isotropic signal
- relies on high SNR

Binary mergers

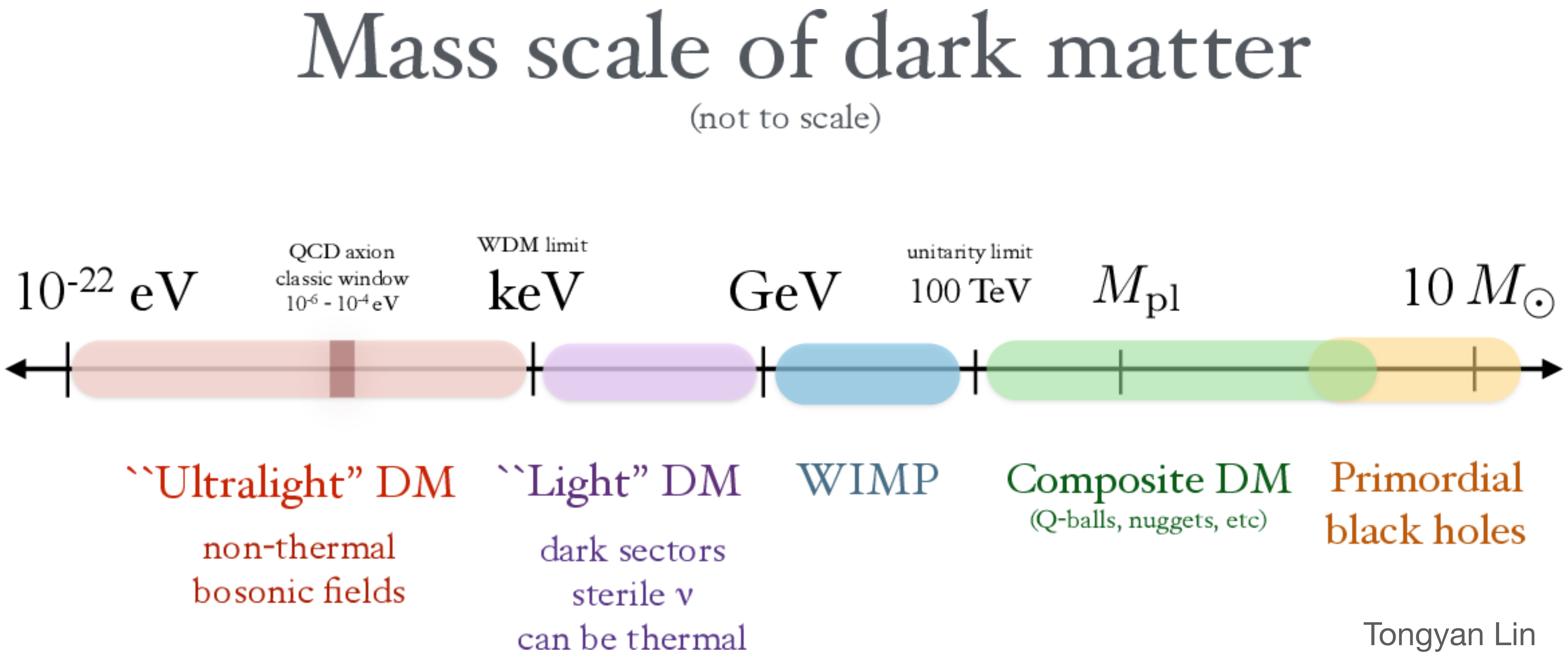
- very sensitive to assumed formation mechanism
- possible identification: mass, spin distribution

EMRI Binaries

- relies on our understanding of EMRI waveforms
- relies on DM *spikes*

Binary mergers

- very sensitive to assumed formation mechanism
- possible identification: tidal Love number, mass, spin




# 1. Dark matter that produces GWs

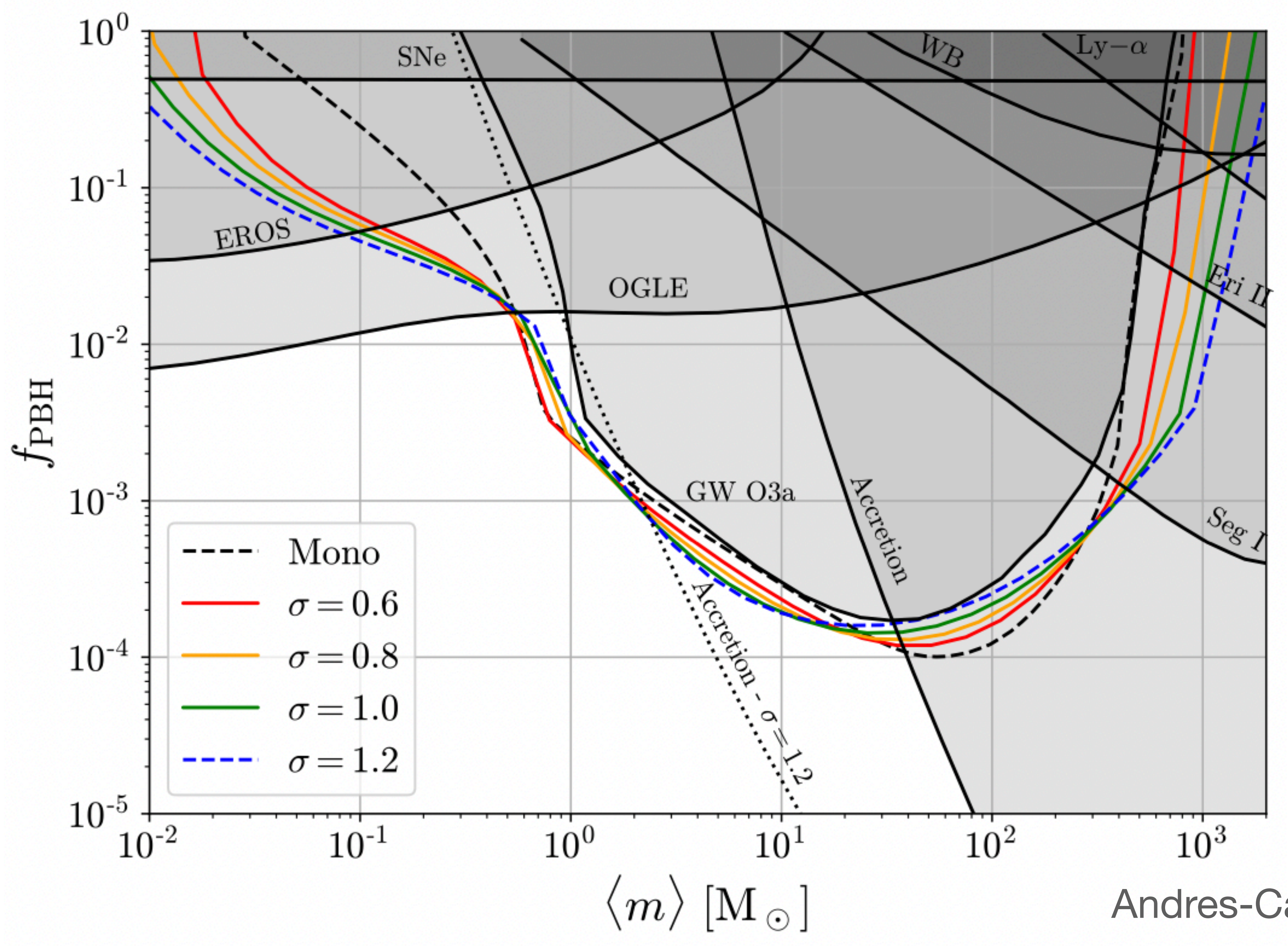
# 2. GWs from black hole mergers affected by the presence of dark matter

# 1. Dark matter that produces GWs

## Primordial black holes

- If primordial black holes explain some of the dark matter, mergers could be detected with current and future detectors

- Sub-solar or very high redshift most convincing, otherwise very difficult to distinguish




Andres-Carcasona et al. 2024

$$\sim 10^{-3} - 10^{4}\, M_\odot$$

Primordial black hole mergers

# 1. Dark matter that produces GWs

## Axion-like particles

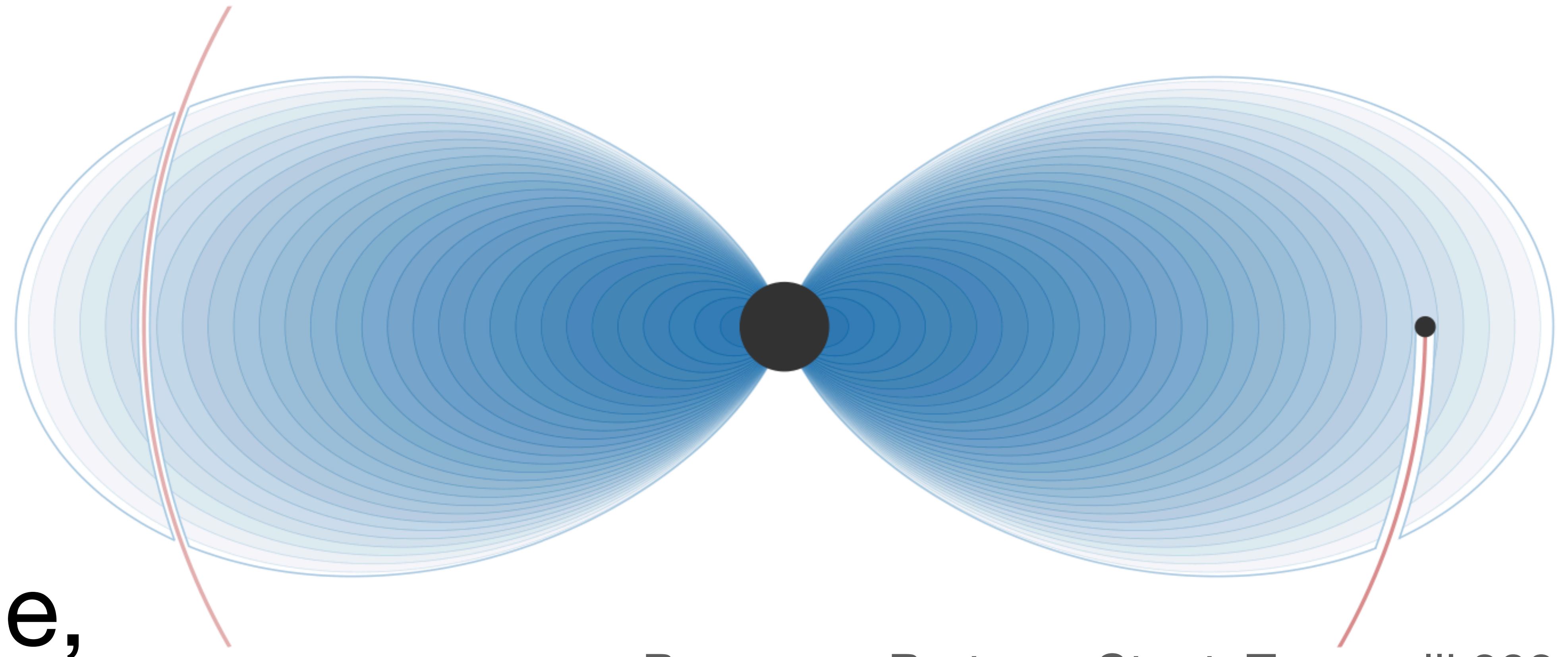
- Axions could decay or annihilate and produce gravitational waves
- Frequency of GWs for annihilation vs decay channel
- $f = \frac{1}{2}(2)\left(\frac{m_a}{10^{-9}\, eV}\right) 10^6\, Hz$
- For annihilations to be efficient, need super radiant cloud

$m_a \sim 10^{-20} - 10^{-7}\, eV$

$M_{\rm BH} \sim 10^{10} - 10^{-3}\, M_\odot$

Monochromatic signals
= continuous wave searches
(also BH spin limits)

# Superradiance



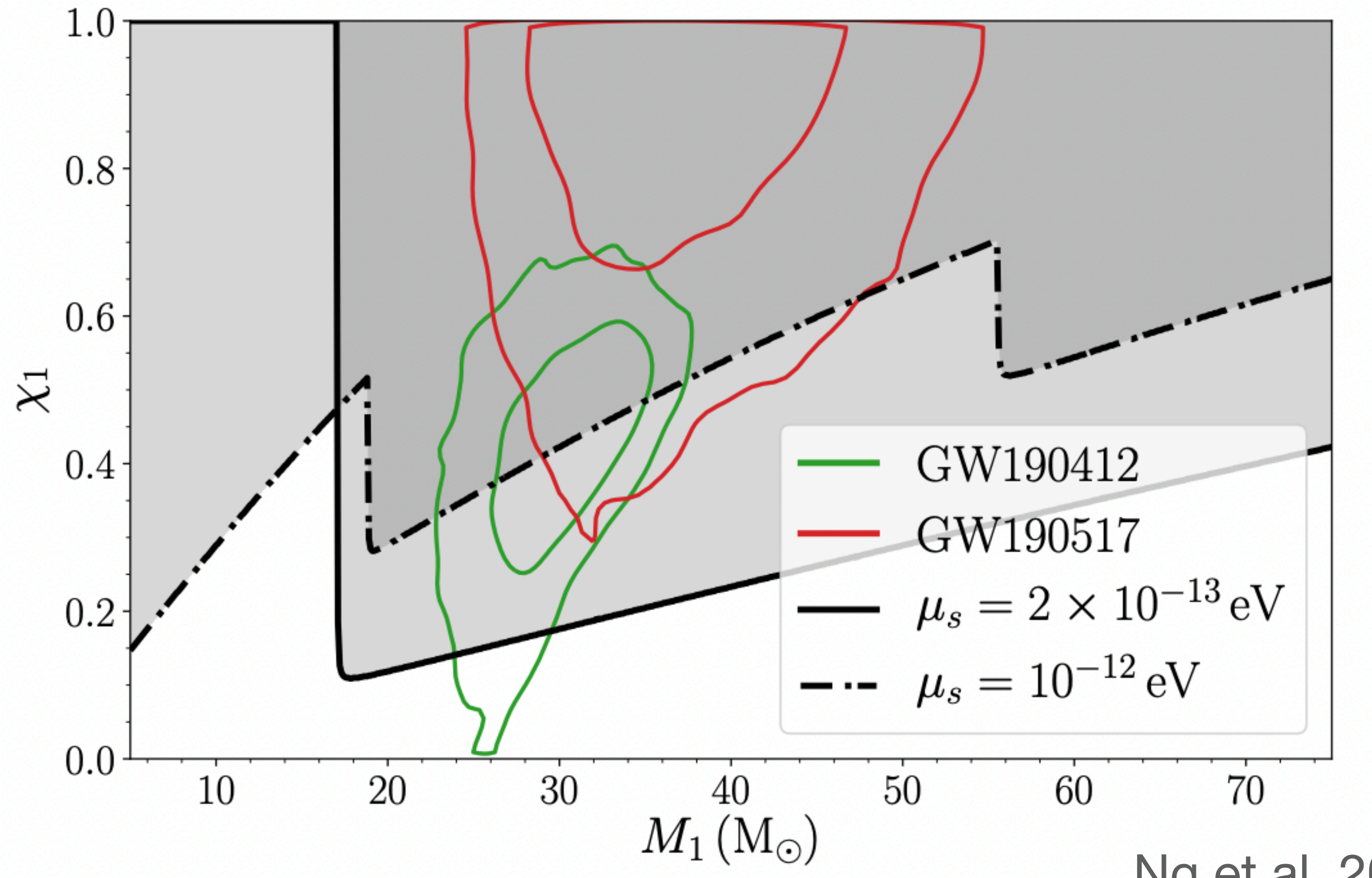
Baumann, Bertone, Stout, Tomaselli 2021

- If Compton wavelength of axion-like particle is comparable to Schwarzschild radius of black hole, a superradiant cloud forms as angular momentum is extracted from the spinning black hole.
- $m_a = \left(\frac{M_\odot}{M}\right) 10^{-10}\, eV$

$$m_a \sim 10^{-20} - 10^{-7}\, eV$$

$$M_{\rm BH} \sim 10^{10} - 10^{-3}\, M_\odot$$

- Measurements of high black hole spins can therefore place constraints on axion masses.




Ng et al. 2021

Axions

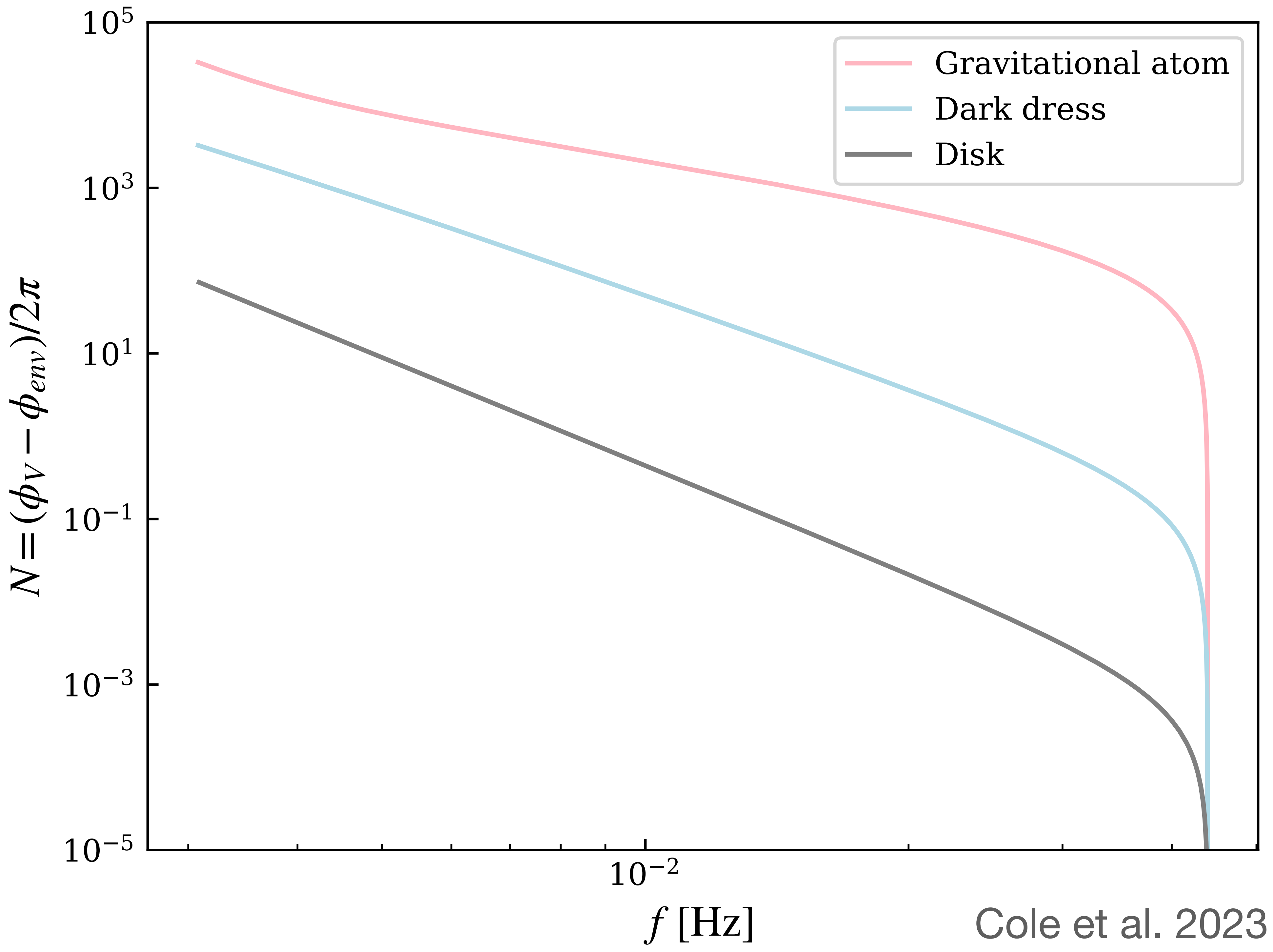
# 2. GWs from black hole mergers affected by the presence of dark matter

## Environmental effects

- Cold dark matter - dynamical friction and accretion

- Superradiance - ionisation and accretion

- Need long duration inspirals and extreme mass ratio systems - LISA (maybe PTA?), but scenarios possible with ET/CE (PBHs)



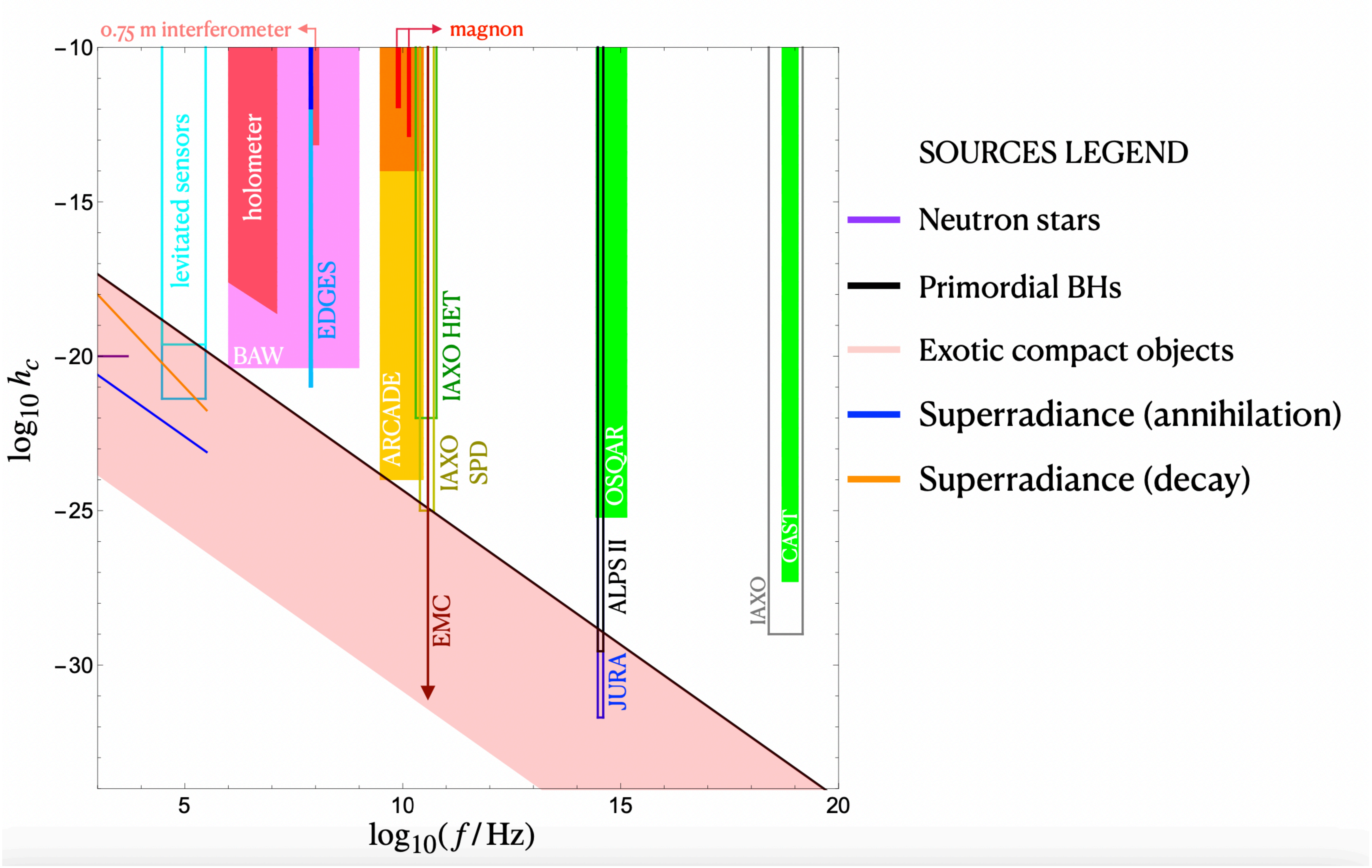

Cole et al. 2023

Environmental effects

Environmental effects? 3G

# High frequency searches

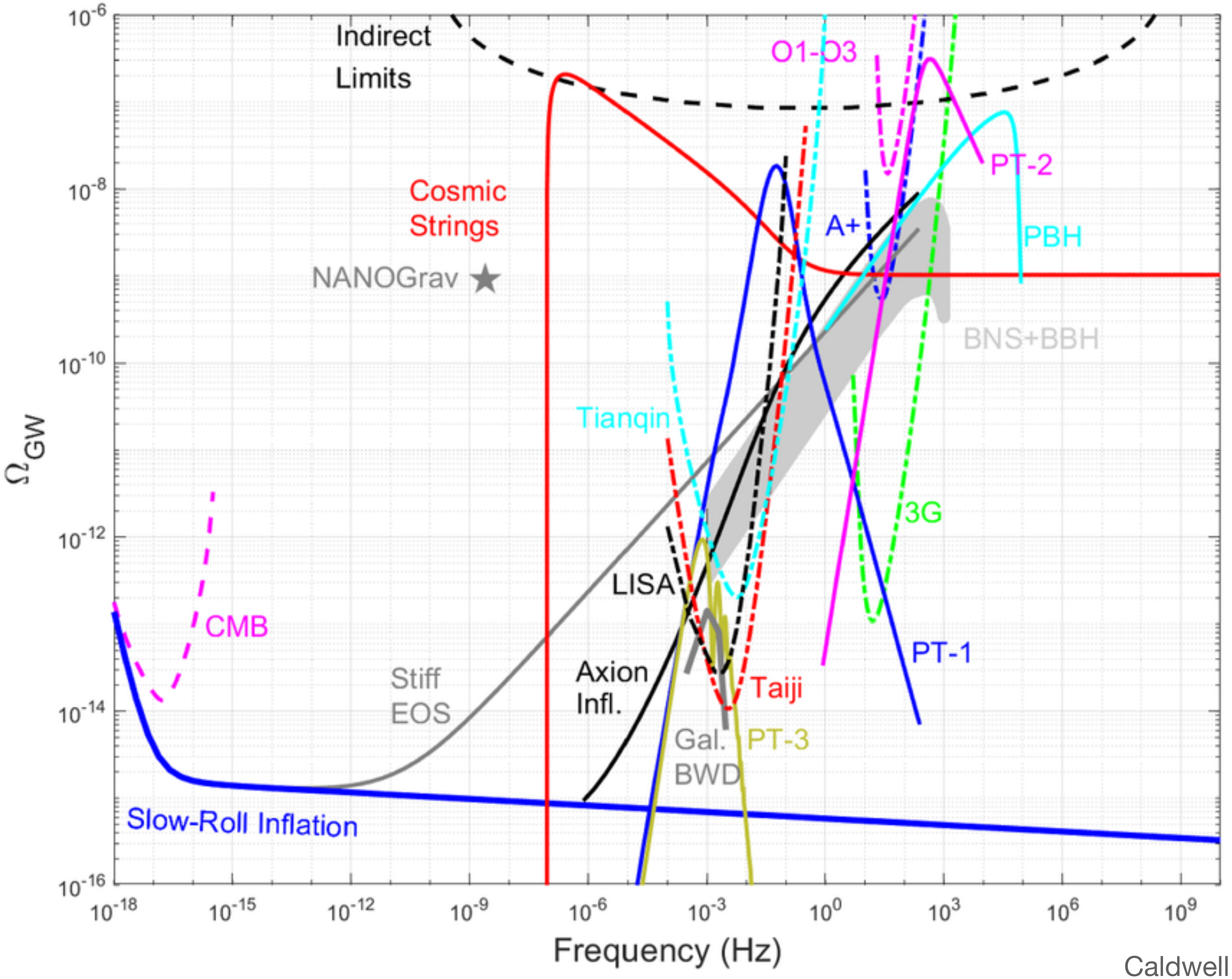
- "Clean" signals of new physics
- But narrow band, and sensitivities at the moment a long way off




Aggarwal et al. 2020

# Stochastic sources

- Indirect probes of dark matter from early universe signatures
- A population of PBHs would produce a SGWB
- NanoGRAV? Did it detect BSM physics?




Caldwell et al 2022

# Questions…

- Can we model the effects of dark matter well enough to extract them from the data?
- Will they be degenerate with other effects?
- Should we put energy into this when there's lots of 'simpler' questions yet to be answered?
- Should we think about composite dark matter models?
- How can we be sure we've found 'it'?

# Axions during inflation: Gravitational waves and more signatures

**Ema Dimastrogiovanni**
*The University of Groningen*

**PAX IX - Physics and Astrophysics at the eXtreme - July 25th 2024**

# Inflation with axions and gauge fields: Chern-Simons coupling

axion-like field

$$\phi F_{\mu\nu} \tilde{F}^{\mu\nu}$$

gauge-field strength and its dual

## Theoretical motivations:

- naturally light inflaton (solution to eta problem)
- axions generic prediction of string theory / UV completion
- axions and gauge fields ubiquitous in particle physics

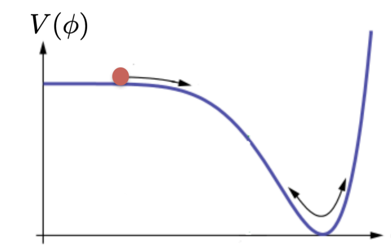
## Added bonus: rich phenomenology and signatures

- CS friction to reconcile natural inflation with observations
- Rich set of signatures (from CMB to interferometers):
  — sourced (chiral) GW
  — non-Gaussianity
  — PBH formation
  — supports reheating
  — mechanism for baryogengesis…

**[Freese - Frieman - Olinto 1990, Anber - Sorbo 2009, Cook - Sorbo 2011, Barnaby - Peloso 2011, Adshead - Wyman 2011, Maleknejad - Sheikh-Jabbari, 2011, ED - Fasiello - Tolley 2012, ED - Peloso 2012, Namba - ED - Peloso 2013, Adshead - Martinec -Wyman 2013, ED - Fasiello - Fujita 2016, Garcia-Bellido - Peloso - Unal 2016, Agrawal - Fujita - Komatsu 2017, Fujita - Namba - Obata 2018, Domcke - Mukaida 2018, Kaloper-Westphal 2021, Iarygina - Sfakianakis 2021, ED - Fasiello - Papageorgiou 2024, …]**

# Inflation with axions and gauge fields: Chern-Simons coupling

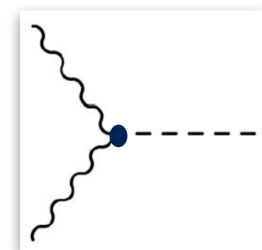
the ALP rolls down its potential during inflation



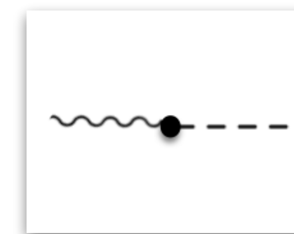

the C-S coupling allows for gauge field production
(kinetic energy of the ALP “absorbed” by gauge field)

$$\phi F_{\mu\nu}\tilde{F}^{\mu\nu}$$

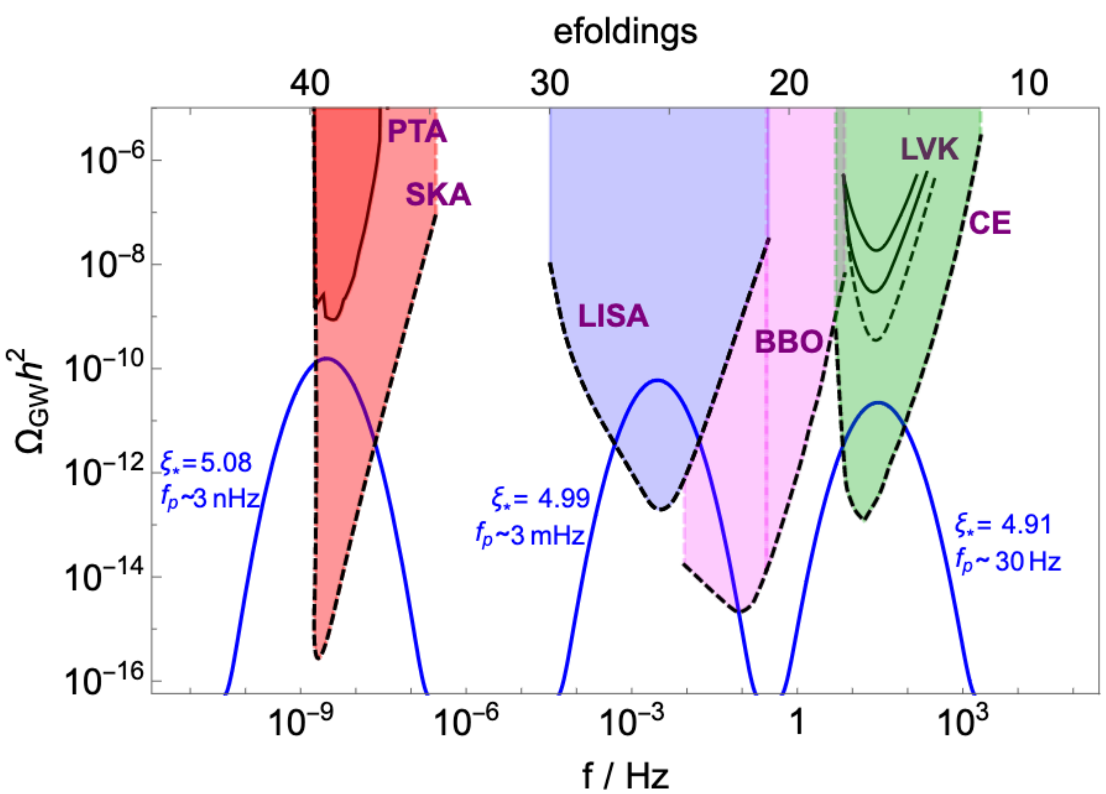
the gauge field fluctuations in turn source scalar perturbations and GW



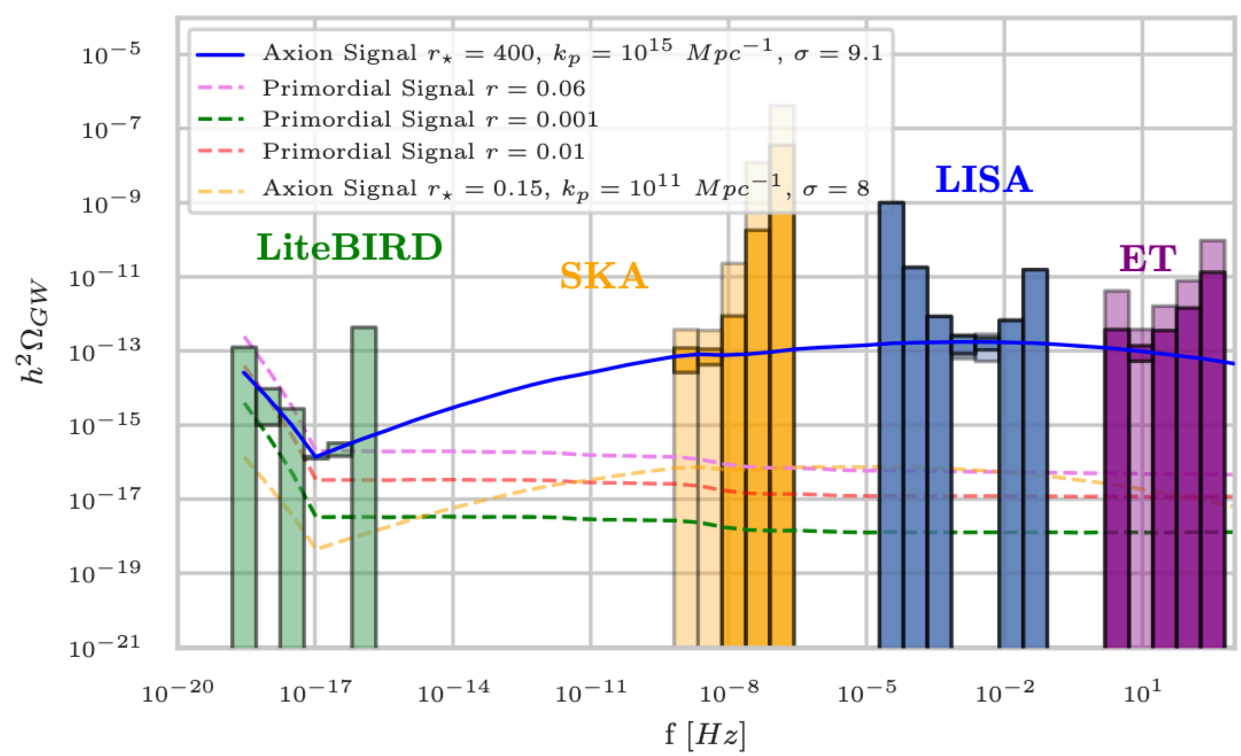
U(1) gauge field



SU(2) gauge field

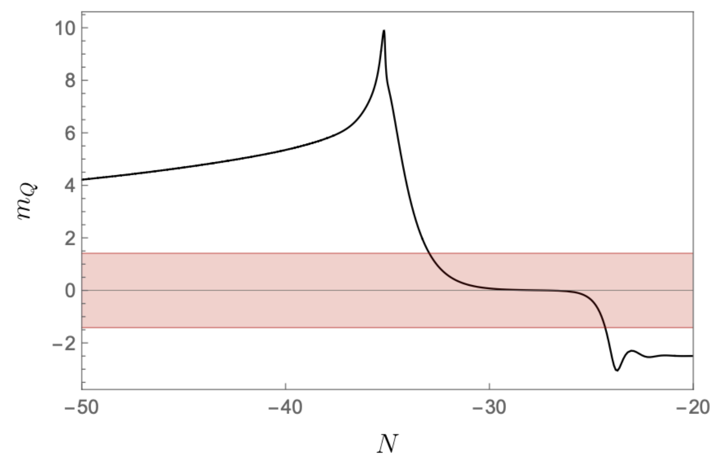



Garcia-Bellido, Peloso, Unal - 2017

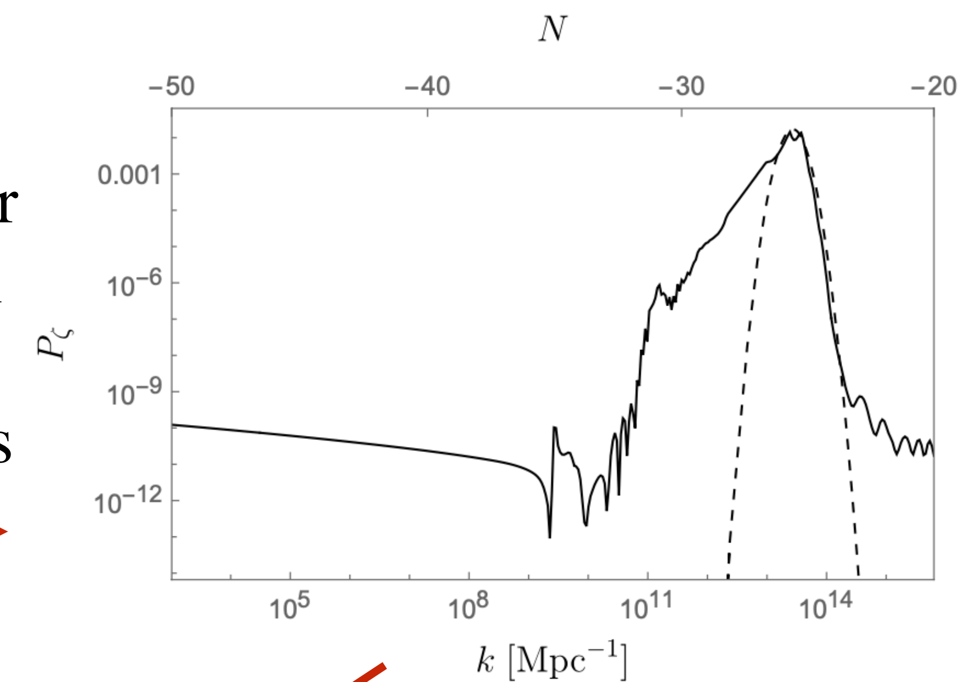


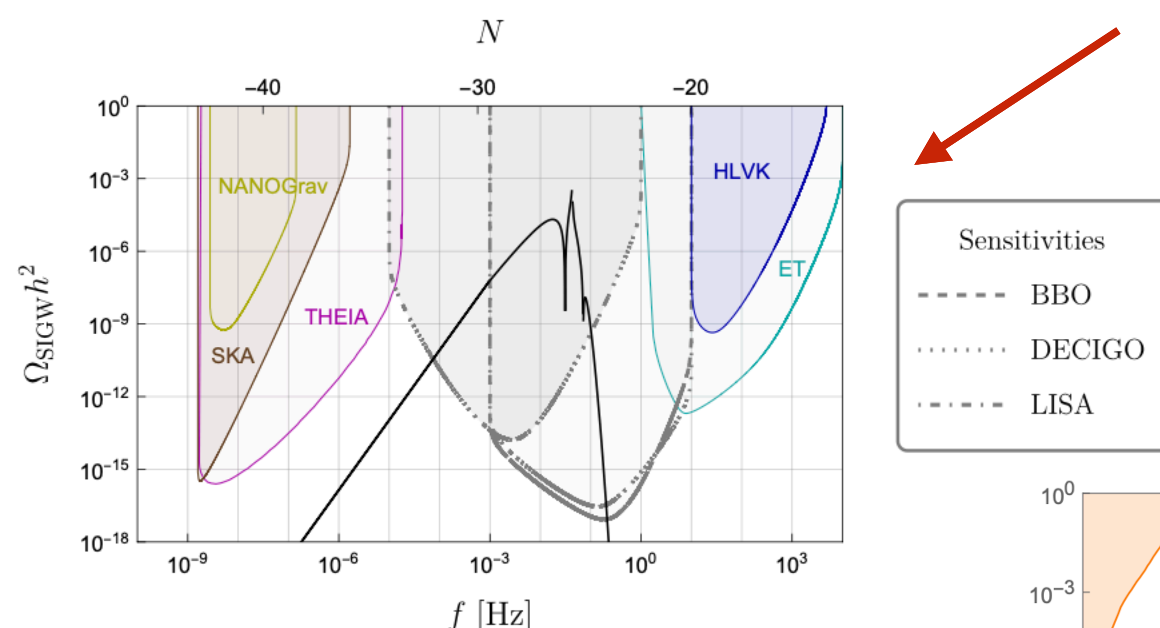

Campeti et al - 2021

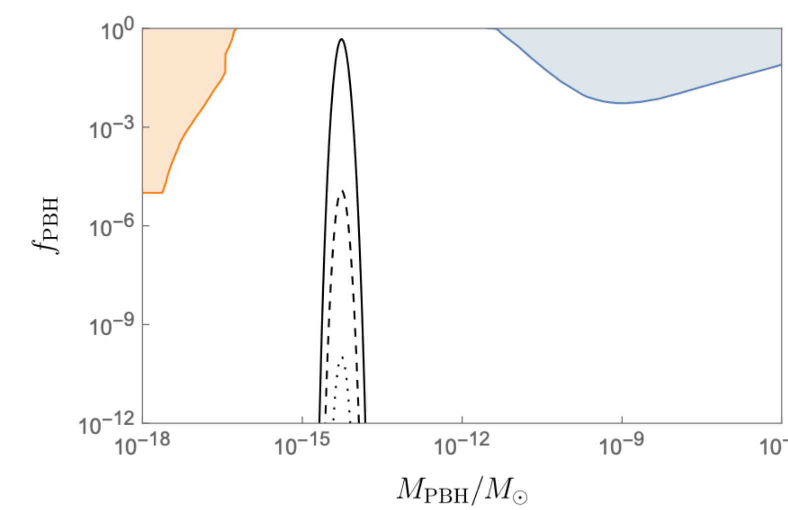
# Recent development (1):
# a new PBH formation mechanism from axion+SU(2) gauge fields




Particle production parameter <u>inevitably</u> driven into region of transient exponential growth for scalar fluctuations



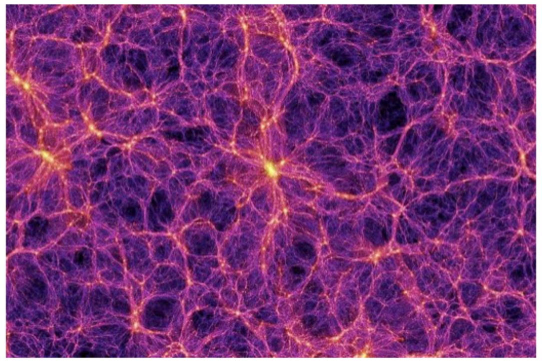
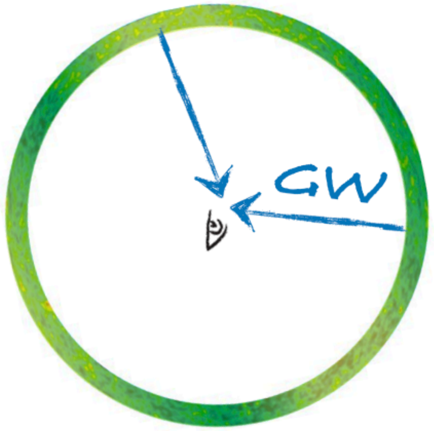

<u>Enhancement of scalar fluctuations relies solely on</u>:

* the inflation being an ALP
* existence of a CS coupling
* existence of an SU(2) gauge field with non-zero vev

**[ED - Fasiello - Papageorgiou 2024]**

# Recent development (2): gravitational wave background anisotropies to probe peaked spectra

looking for spatial variations in the contributions to the GW energy density spectrum

| From propagation through the perturbed universe | Initial/intrinsic to the production mechanism |
| --- | --- |
|  |  |

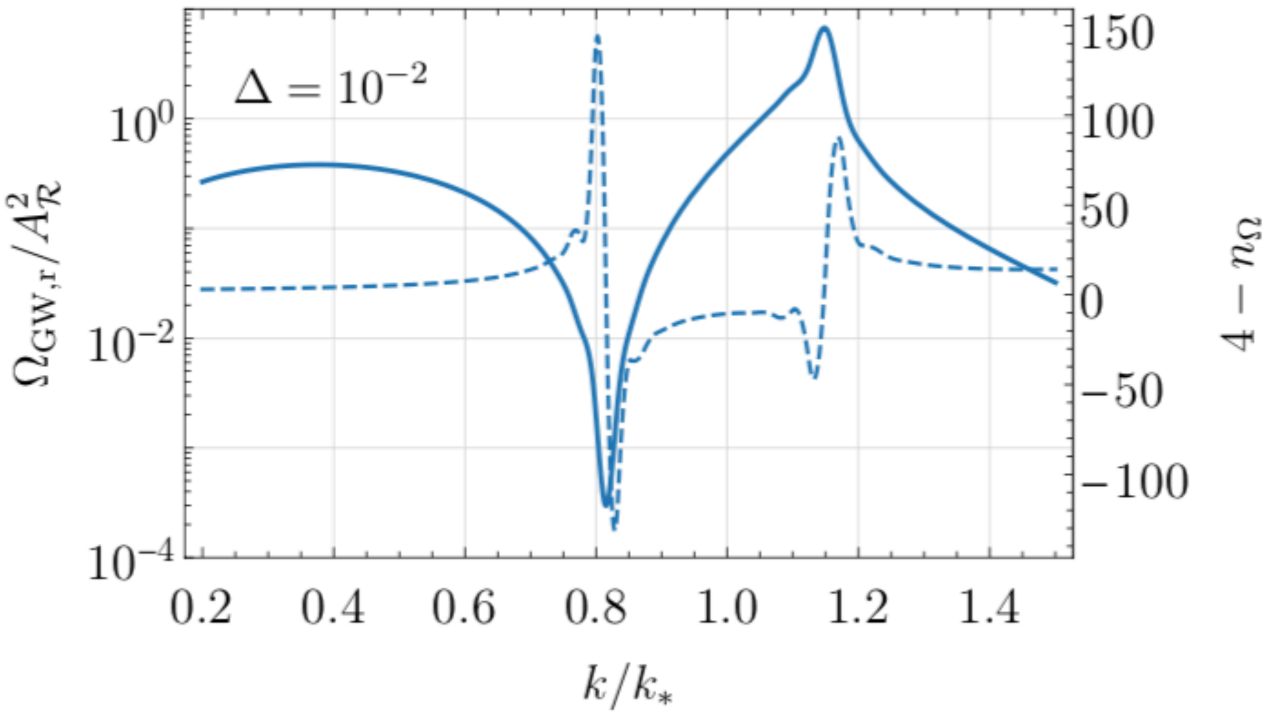
Anisotropies from propagation:

amplitude proportional to the slope of the spectrum

$$\delta_{\rm GW} \sim \left( \frac{\partial \ln \Omega_{\rm GW}}{\partial \ln k} \right) \zeta_{\rm L}$$

pronounced slope → larger anisotropies

# Recent development (2): gravitational wave background anisotropies to probe peaked spectra




$$\Omega_{\rm GW,r}(k) = 3\int_0^\infty dv \int_{|1-v|}^{1+v} du \frac{\mathcal{T}(u,v)}{u^2 v^2}\mathcal{P}_{\mathcal{R}}(vk)\mathcal{P}_{\mathcal{R}}(uk)\,,$$

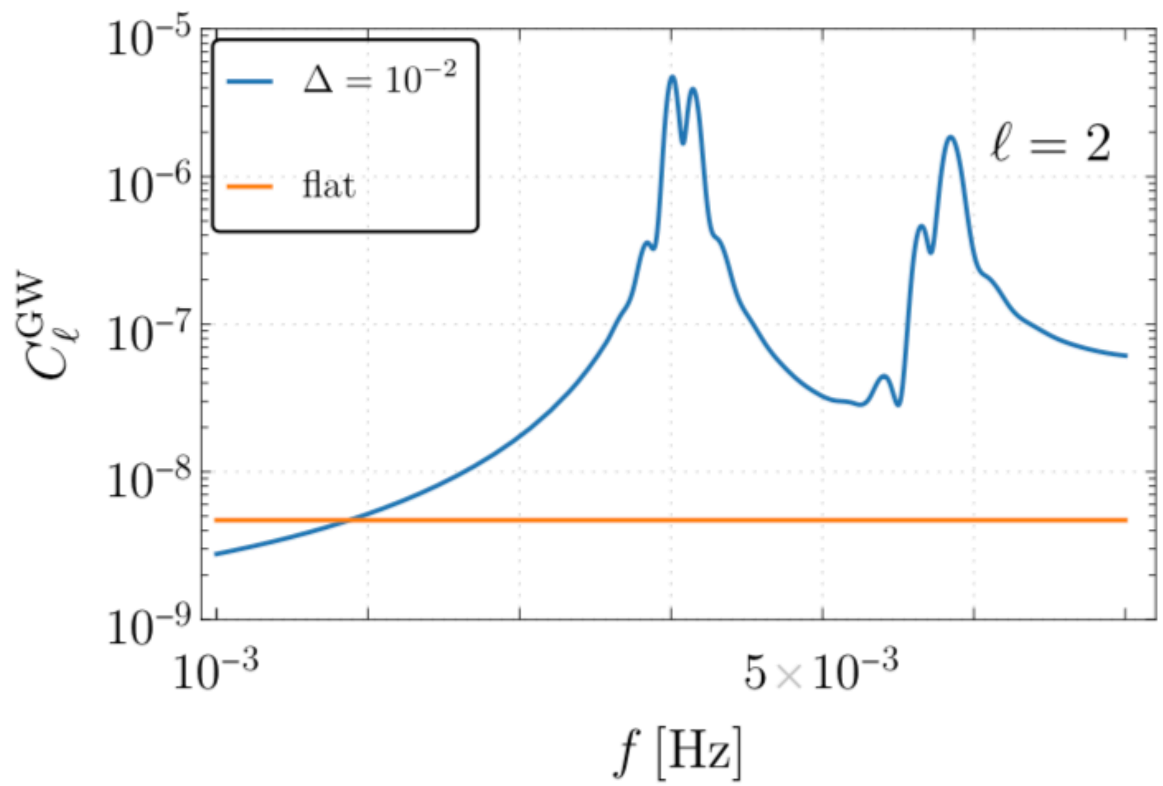
$$\mathcal{P}_{\mathcal{R}}(k)|_{k\gg k_{\rm CMB}} = \frac{A_{\mathcal{R}}}{\sqrt{2\pi}\Delta}\exp\left[-\frac{\ln^2(k/k_*)}{2\Delta^2}\right]$$

| | |
|---|---|
| $\Delta$ | $10^{-2}$ |
| $f_*$ | $5\times 10^{-3}$ Hz |
| $k_*$ | $3\times 10^{12}$ Mpc$^{-1}$ |
| $A_{\mathcal{R}}$ | $7.5\times 10^{-3}$ |

- the anisotropies can be typically enhanced by O(10-100)

$$\delta_{\rm GW} \sim \left(\frac{\partial \ln \Omega_{\rm GW}}{\partial \ln k}\right)\zeta_{\rm L}$$

- the angular power spectrum of the GW anisotropies inherits the frequency dependence




[ED, Fasiello, Malhotra, Tasinato 2022]

# Prospects and challenges (model-building perspective)

- Reconciling naturalness with CMB predictions (possibly also with interesting small-scale signatures)

- Incorporating effects of strong back reaction regime (can lead to unexpected new results, such as the new PBH formation mechanism we uncovered)

- Compute perturbativity constraints (CS-born interactions feeding loop-diagrams)

- Figuring out UV embedding (e.g. UV theories may dictate magnitude of couplings)

- What happens to the spectator fields after inflation? Reheating, isocurvature modes…

- Coming up with observables useful to characterise the primordial signal

# Searches for Axions and Gravitational Waves

Ed Daw - The University of Sheffield

**My career: Summer 1992, Tevatron, CDF experiment [didn't like it much, but got some good career advice]**
**1993-1997, ADMX dark matter axion search [first student to graduate on this experiment]**
**1997-2003, Postdocs on LIGO, first at MIT, then at Louisiana State University (and LIGO Livingston)**
**2003-2008, Lecturer at Sheffield, working on early liquid xenon WIMP detectors (Zeplin 2).**
**2009-2017, Reader at Sheffield, working on gravitational wave data instrumentation, data analysis.**
**2017-2024, Professor at Sheffield, working on Quantum Sectors for the Hidden Sector, an axion search.**

## 1. Gravitational Wave Experiments - my perspective.

*** Absolutely fascinating experiment technology! I have learned how to stabilise an unstable machine with feedback, a technique that I now try to apply to axion searches ( NIM A, and https://arxiv.org/abs/1805.11523 )**

*** The field is now mature. Binary inspirals were the predicted first signal, and they showed up. Rainer, Kipp and Barry deserve their Nobel prize. It was a fantastic example of scientific teamwork. LSC/LIGO members should be proud of this.**

*** We will certainly detect many more binaries, and studying them may alone justify new ground-based instrument. We hope also to see stochastic/cw/bursts, but there are no guarantees. It is reasonably likely that ET/cosmic explorer will happen. More robust estimates of signal strengths would be a very useful tool, but it's very hard.**

*** All next generation instruments are more than a decade away.**

# Axion searches

- There were VERY FEW axion enthusiasts in 1993, even in the USA. Direct dark matter was dominated by WIMP searches (in the UK this is still the case) and MACHOS. Dark energy wasn't even discovered.

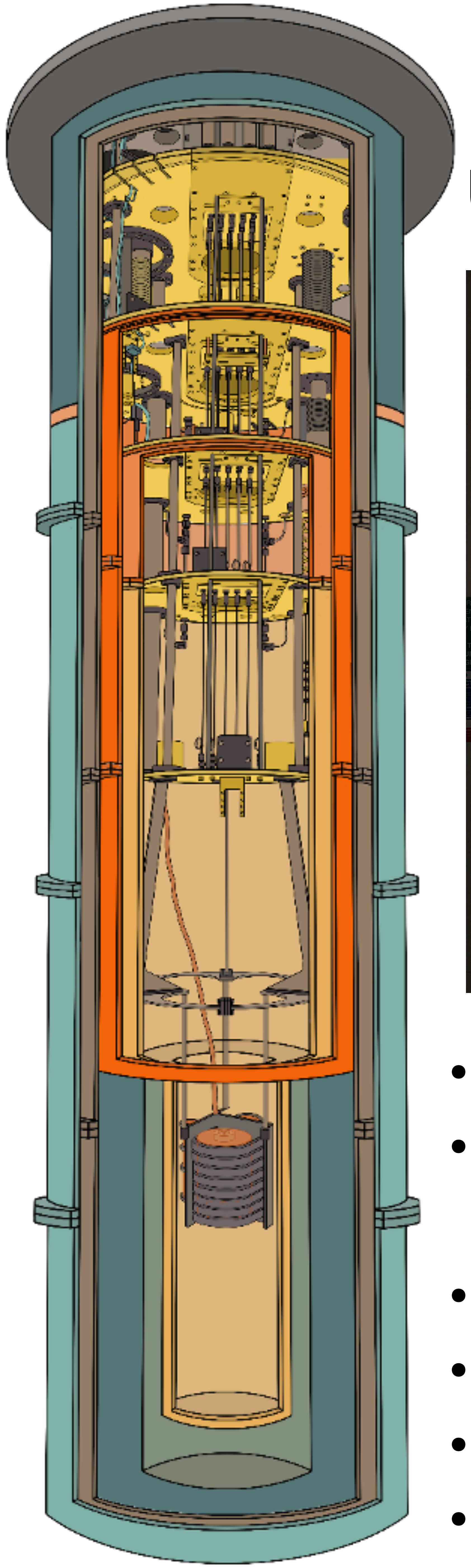
- In the UK, there were two experimentalists who had conducted axion searches (me, Ian Bailey) up until 2017. Then, all of a sudden, I started getting invited to give lots of talks on axions!

- What had happened was, the failure of the LHC to detect any 'new physics' apart from the Higgs (which isn't new) completely changed the landscape. First the phenomenology community, then the experimentalists, slowly started to move away from high energy phenomena and drift back to the focus before the electroweak revolution - strong interaction physics, and with it, AXIONS!

- The Quantum Technology for Fundamental Physics (QTFP) programme in the UK funded 7 large and 17 smaller new experimental efforts to do low(ish) energy non-accelerator experiments.

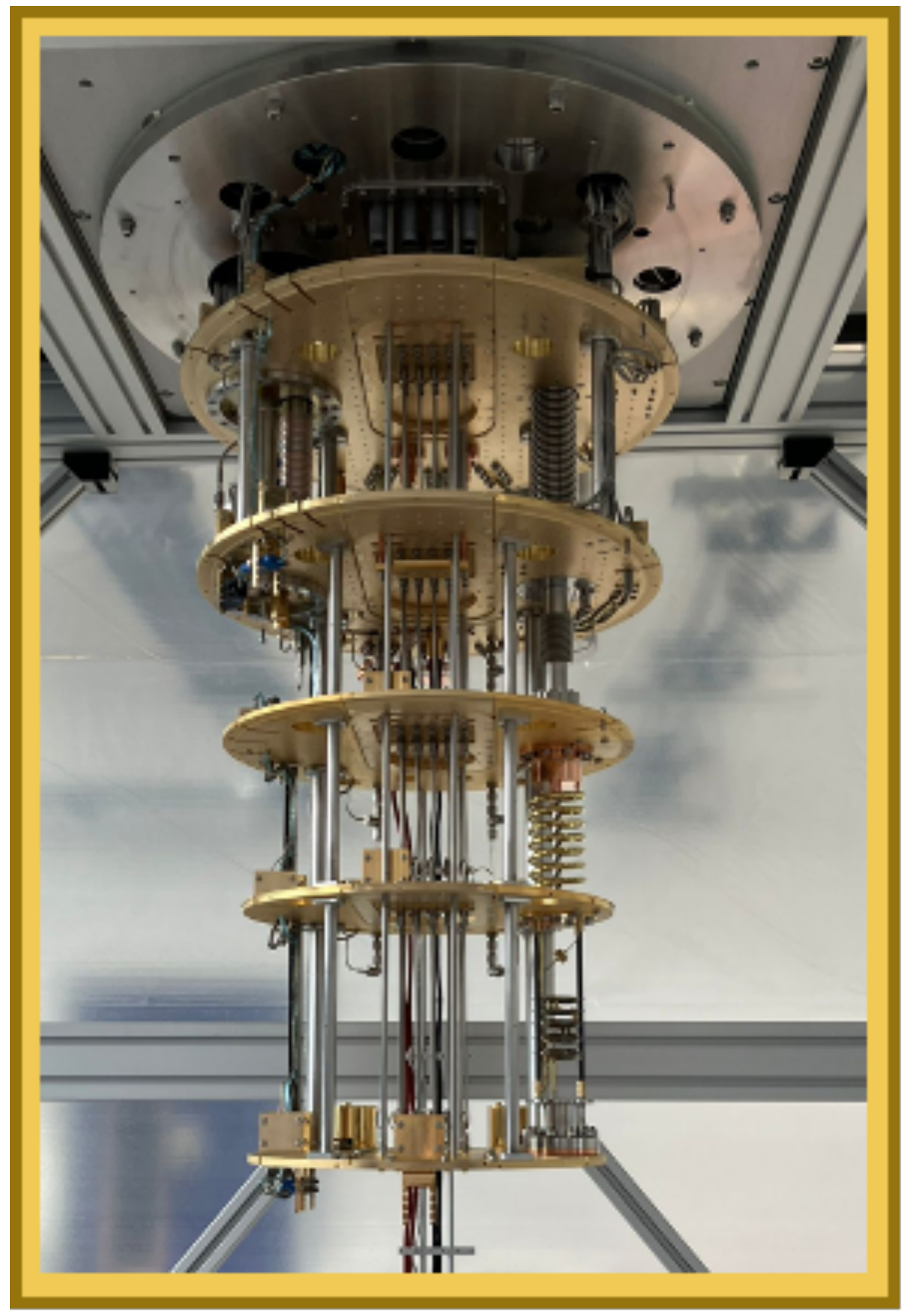
- **Quantum Sensing for the Hidden Sector** is one such collaboration - we aim initially to explore very low temperature (sub 10mK) axion searches, to develop new quantum electronics for readout, and to search for axions at hopefully ever-increasing sensitivity.

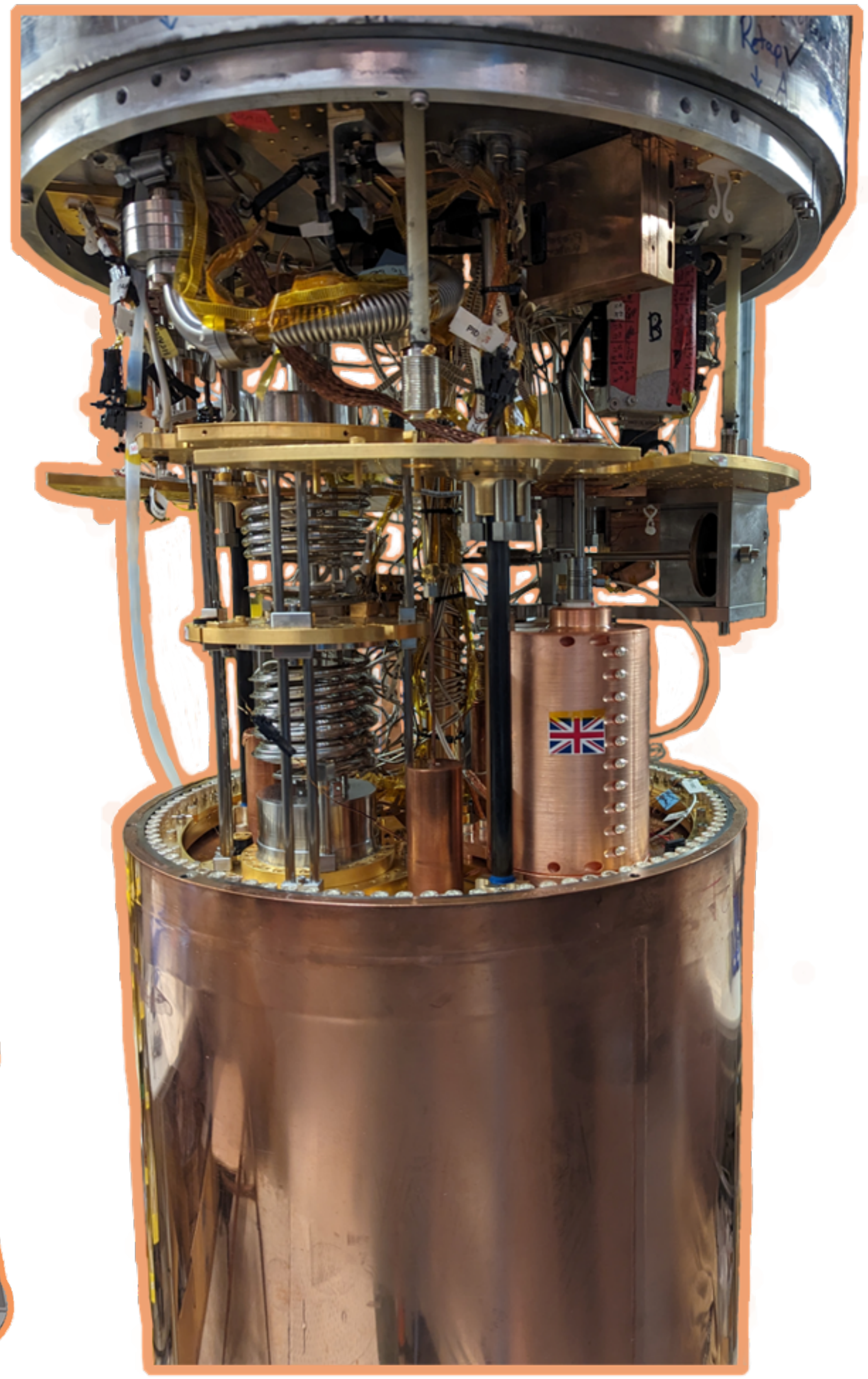
- It's not a bonanza! £40M for the whole QTFP programme, and no guarantee yet of continued support.



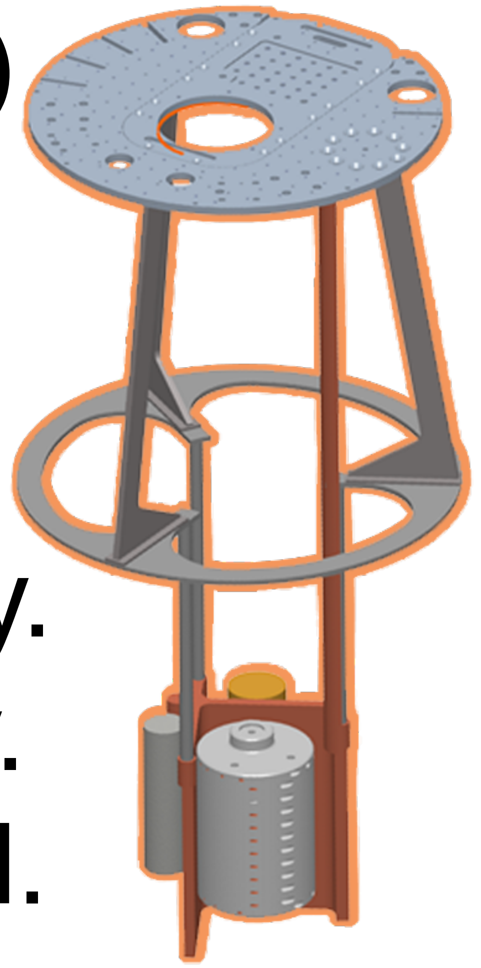
# QSHS

Ultra low physical temperature (8.5mK) resonant axion search at 25 to 40 micro-eV.





- Dilution fridge installed, cooled to 8.5mK (already)
- Cavities and tuning rods manufactured and installed in ADMX.
- Currently preparing to cool cavity in QSHS.
- Magnetic field shield almost finished, ready in July.
- Magnet already reached 6T, 8T version underway.
- Cryogenic amplifier design R&D rather like QTNM.



# The larger landscape

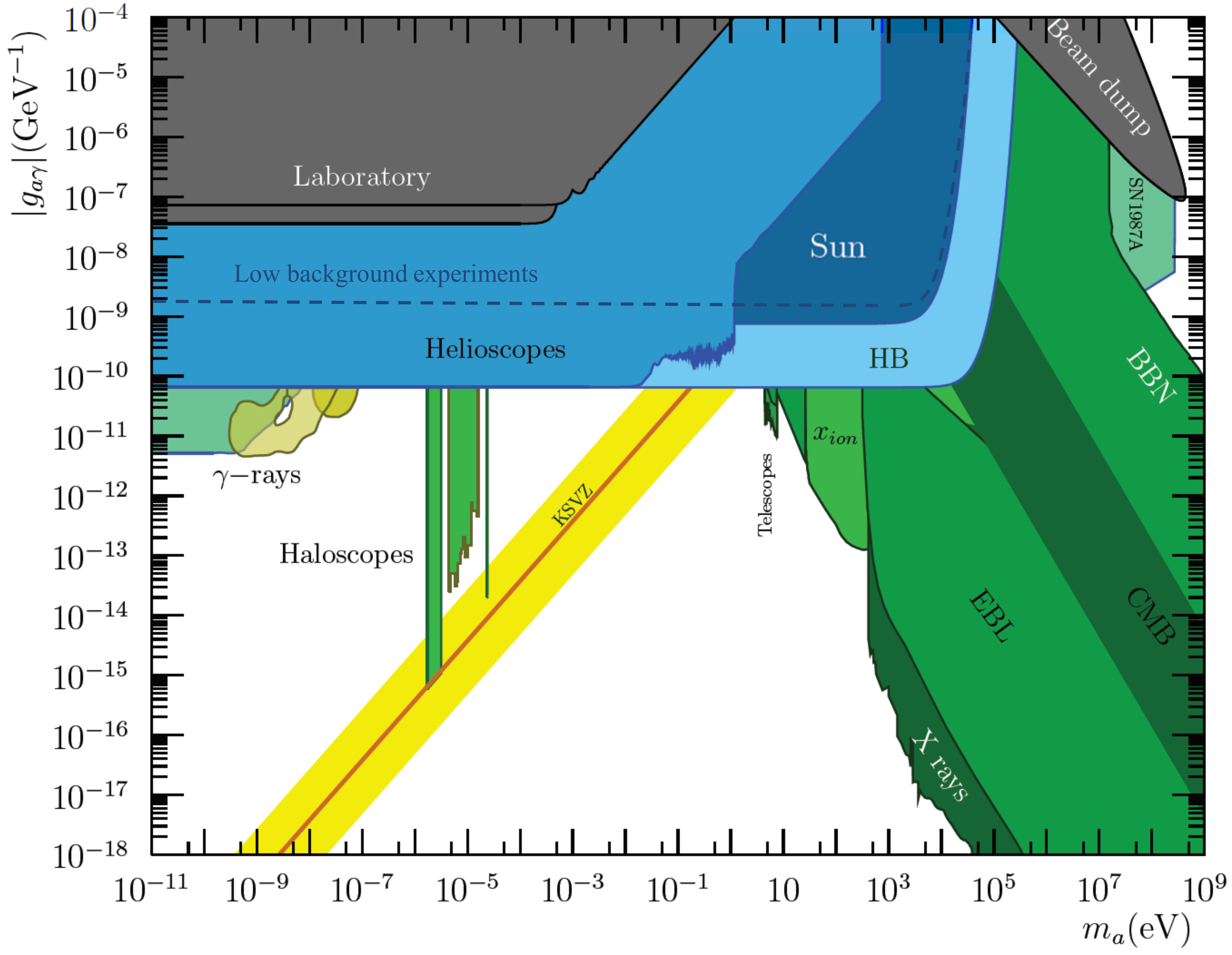
**Direct Detection of Dark Matter – APPEC Committee Report** *

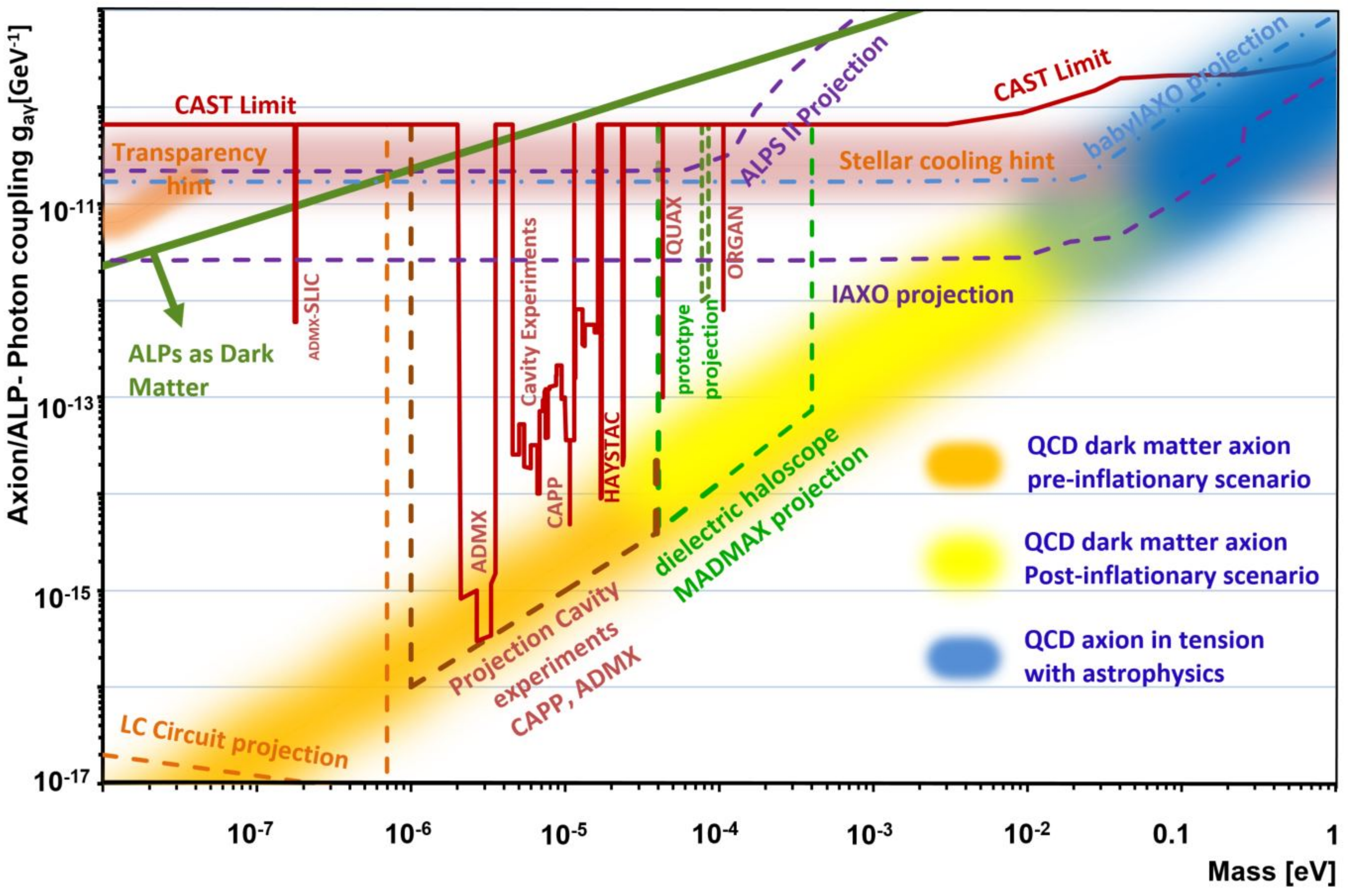

**Committee Members:**

Julien Billard,[1] Mark Boulay,[2] Susana Cebrián,[3] Laura Covi,[4]
Giuliana Fiorillo,[5] Anne Green,[6] Joachim Kopp,[7] Béla Majorovits,[8]
Kimberly Palladino,[9,12] Federica Petricca,[8] Leszek Roszkowski (chair),[10] Marc Schumann[11]



arXiv:2104.07634v1 [hep-ex] 15 Apr 2021

# Searching for Axions with Gravitational Wave Detectors

**AXION SUPERRADIANCE**

**Idea: sufficiently low mass axions have very long de-Broglie wavelengths and are massive. Such axions could be bound in the 1/r gravitational potential of a compact object just as electrons are bound in the 1/r coulomb potential of a nucleus. GMm/r^2 = mv^2/r, quantise with mvr=n*hbar.**

**By requiring that the orbit radius is of order of the Schwarzschild radius, assuming a solar mass source of the gravitaitonal field, we can work out that axions of masses around 1peV could form such bound states.**

**The important difference compared to atoms is that axions are scalars, so Bose-Einstein condensation is possible.**

**Coherent de-excitation of populated states could lead to a gravitational wave signal.**

**In large experiments, the more popular channels are dominated by large working groups, and it can be difficult for junior scientists to make an impact of the type necessary for making their reputation.**

**Axion superradiance searches (and other non-standard exploitation of gravitational wave instruments) is one way for newcomers to overcome these problems. People already work on this, some of them may even be at this conference!**

# Summary

- LIGO and experimental gravitational waves is still an area where careers can (and are) being made. The collaborations can be tough to work in, but you will learn a lot of science and the new discoveries are strong motivators.
- Axions are now also a growth area. I try always to make a strong distinction between searches for axions of the QCD variety and ALPs. I treat any group that states vaguely that they are looking for axions without being specific about which they mean with some suspicion.
- The only axion search technology with sensitivity to QCD axions remains sikivie-type axion haloscopes that assume dark matter halos are axion dominated. Their resonant character means that they cover small portions of the range of plausible axion masses.
- What is a 'plausible' axion mass depends on who you ask.
- New and vigorous theoretical activitiy in the area is leading to a flood of papers proposing an enormous variety of axion models. This is quite treacherous for the budding experimentalist - whose models do you take seriously?