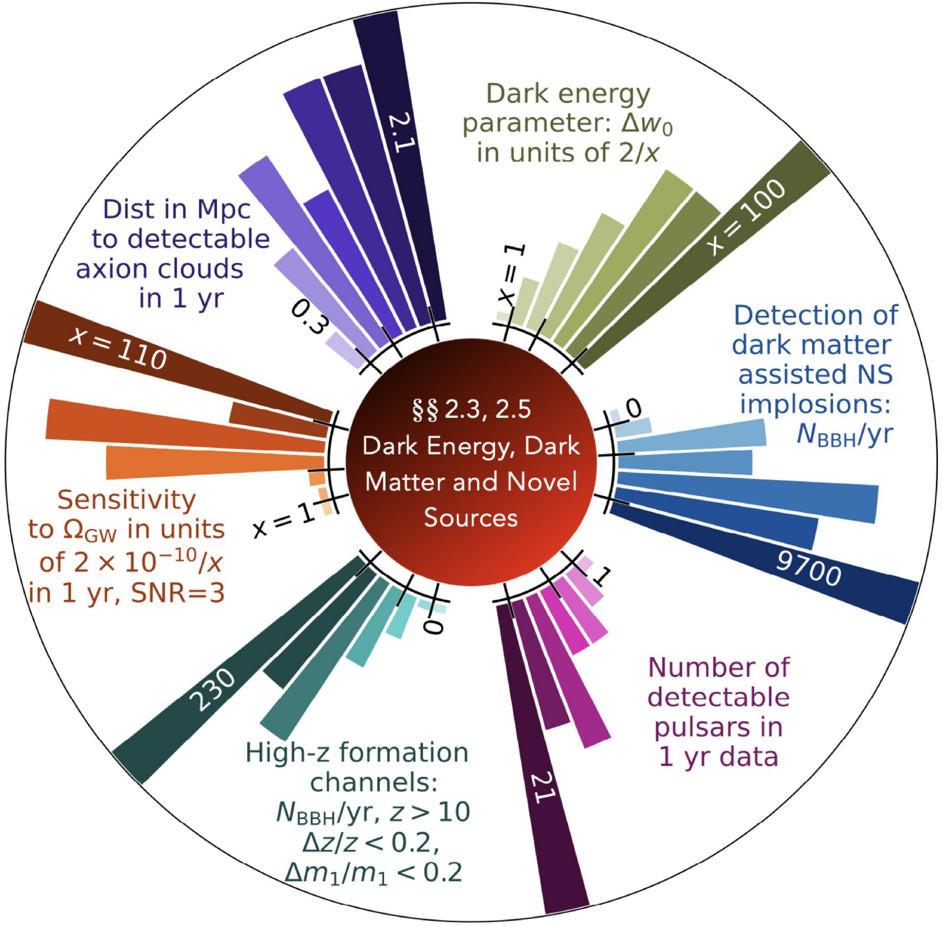
Dark Matter

PAX-X and CE Symposium

Panelists: David A. Nichols, Divya Singh, Ling Sun (chair), Tanner Trickle



Evans et al., arXiv:2306.13745 (2023)

Direct Interactions	Astrophysical Probes	Cosmological Probes
Lab experiments for particle interactions, searches for oscillating wave-like fields, etc.	Dissipative dark matter, compact objects, primordial BHs, BH superradiance, environmental effects, etc.	Lensing, CMB, large-scale structure, etc.

Questions

- ❏ What are the recent exciting developments?
- ❏ What can be achieved in the upcoming decade(s) with new advanced facilities? Challenges and opportunities?
- ❏ Are there synergies between these topics?
- ❏ What are the pressing issues to be addressed in theory and practice?

We need your input!

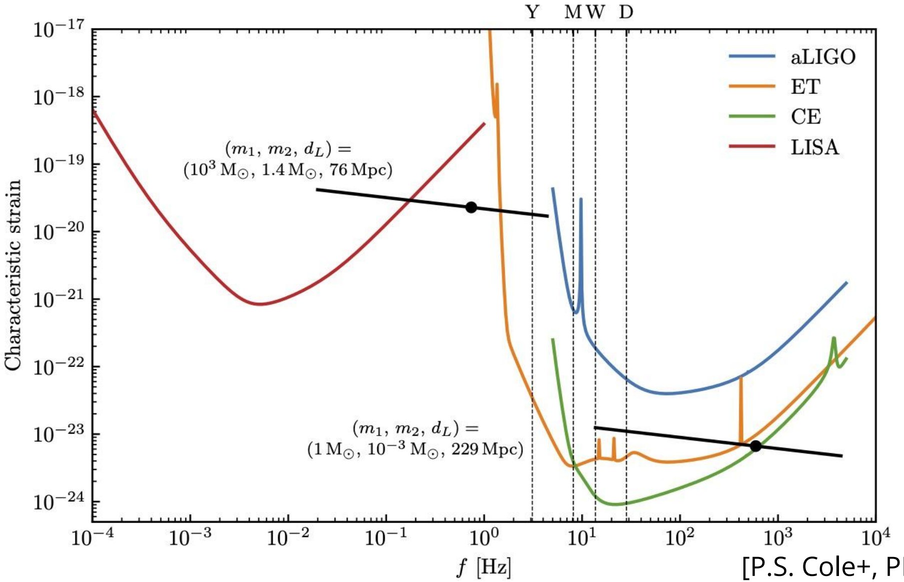
Ground-based detectors	Space-based detectors	PTAs	High-frequency detectors
Exotic compact objects Dissipative DM Primordial BHs BH superradiance Direct interactions	DM environmental effects BH superradiance	Compact objects Ultralight DM	DM detectors for GWs

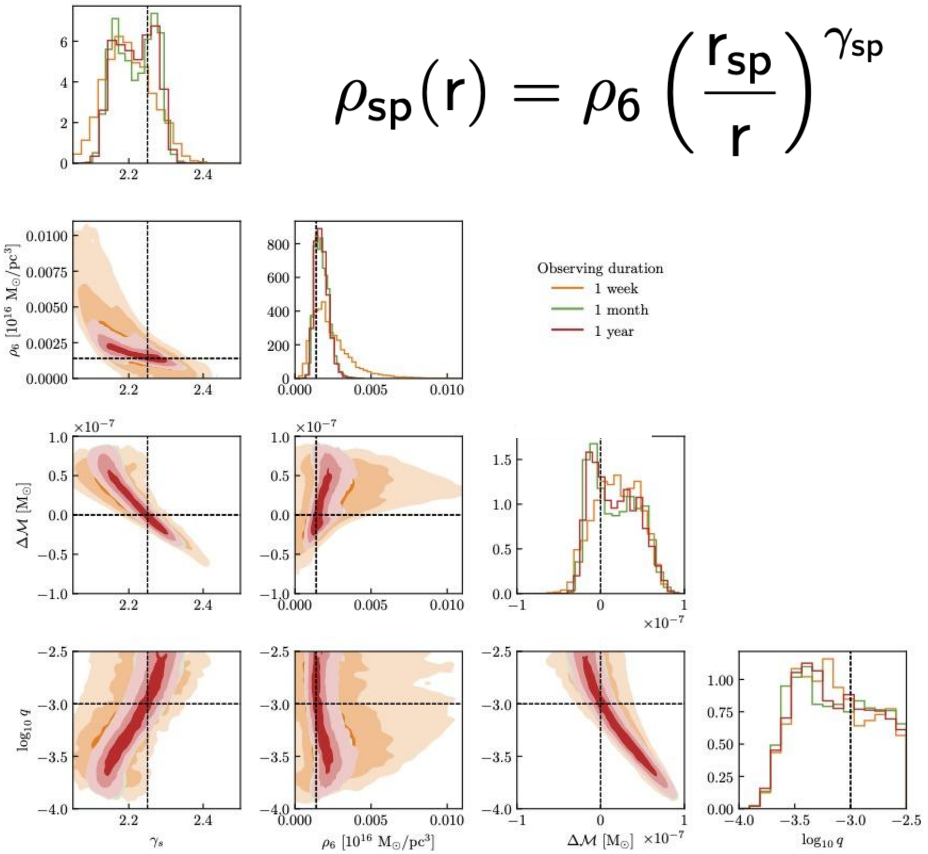
Topic 1: DM Environmental Effects in IMRIs

Context

- Need enhanced DM densities—DM spike
- Dynamical friction leads to faster dephasing
- Must jointly evolve DM and binary
- Can measure "standard" IMBH IMRI w/ LISA
- Can measure primordial BH IMRI w/ CE if PBHs are a fraction of the total DM

$$\rho_{sp}(r) = \rho_6 \left(\frac{r_{sp}}{r} \right)^{\gamma_{sp}}$$





[P.S. Cole+, PRD (2023)]

Topic 1: DM Environmental Effects in IMRIs—Discussion

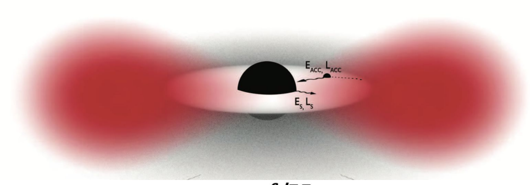
Opportunities

- A small scale DM measurement, $O(1\text{-}10^3)$ of km not pc (for CE/LISA, resp.), and can infer dynamics of DM on day-year timescales
- For CE, can show existence of primordial BHs, and that they are a fraction of the DM, not all
- Purely a gravitational measurement; valid for particle DM of most masses

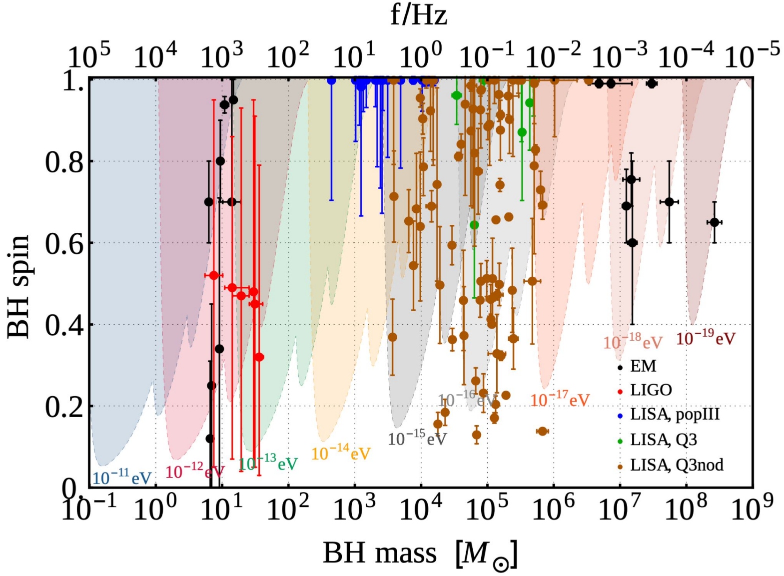
Challenges/Questions

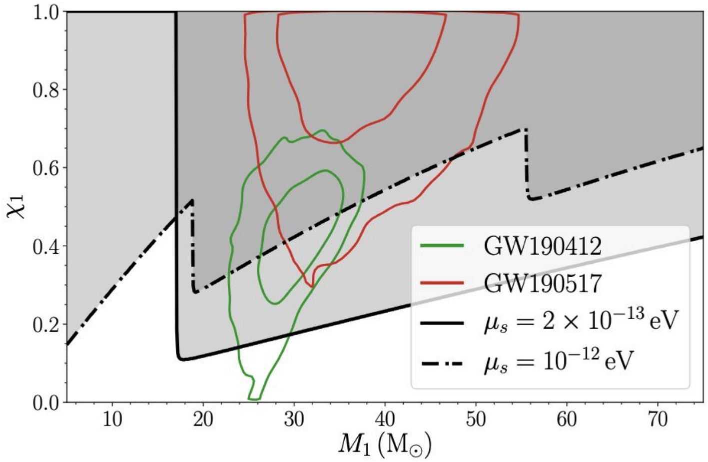
- [Waveform Modeling]: Almost all calculations are Newtonian, can we get relativistic waveforms that cover the relevant binary + DM parameter space?
- [Searches]: Dynamical friction effects are most important at low frequency, can they be found and disentangled from other signals?
- [PE]: How challenging are the extra parameters + long signals as a PE problem?
- [Fundamental Physics]: Can fundamental cross sections or couplings be learned from environment?

Topic 2 Superradiance (spin constraints/population studies)



- Spin measurements from EM observations
- Spin measurements from GW events
- Better constrained spin measurements and larger number of events in the future
- Superradiance can rapidly spin down BHs and may form more hierarchical mergers and hence massive BHs in dense stellar environment





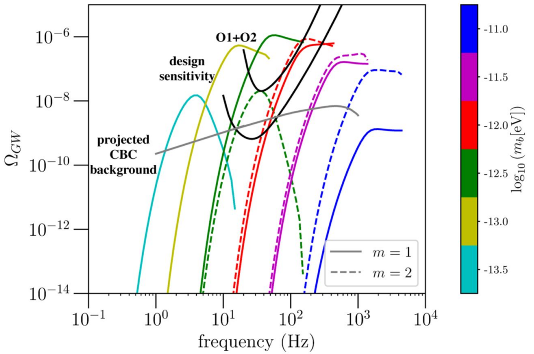
Arvanitaki+ (2010), Arvanitaki & Dubovsky (2011), Yoshino & Kodama (2014), Arvanitaki+ (2015), Arvanitaki+ (2017), (2015), Brito+ (2017), Baryakhtar+ (2017), Cardoso+ (2018), East (2018), Ng+ (2021), Payne+ (2022), etc.

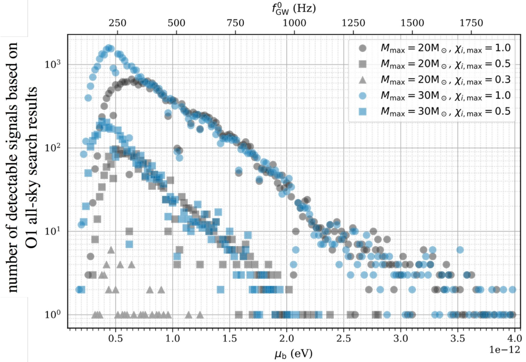
Ground-based detector
$10^{-14} \lesssim \mu/\text{eV} \lesssim 10^{-11}$

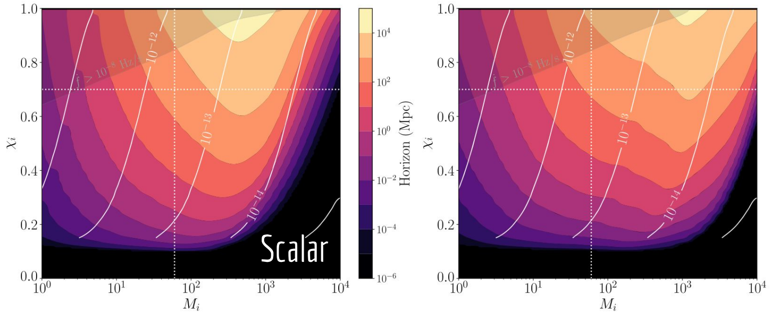
Space-based detector
$10^{-19} \lesssim \mu/\text{eV} \lesssim 10^{-15}$

Topic 2 Superradiance (searches)

- ❑ Stochastic GW background
- ❑ Blind all-sky search for galactic sources
- ❑ Directed search targeting CBC remnants
- ❑ Directed search targeting galactic BHs
- ❑ Probes for interactions with SM and self-interactions

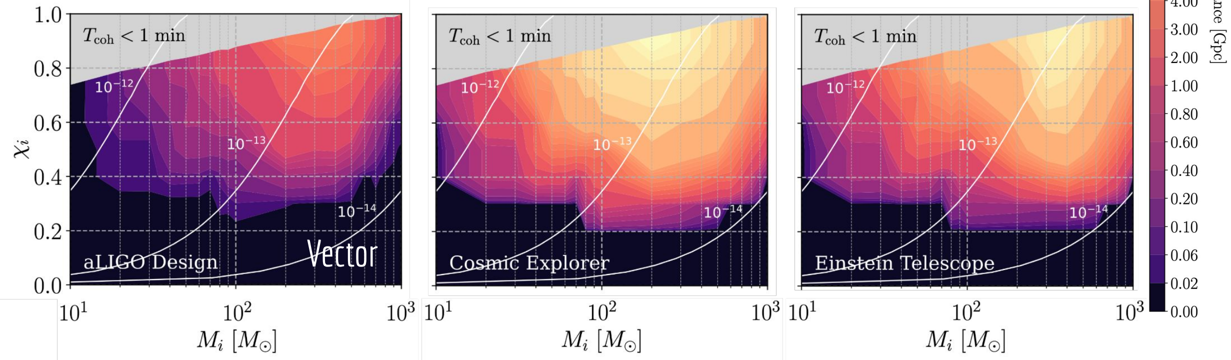






(c) Cosmic Explorer

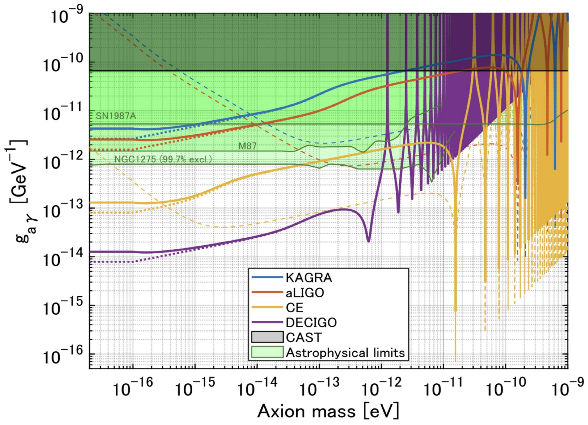
(d) Einstein Telescope

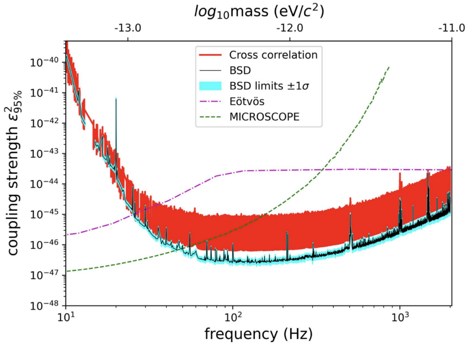


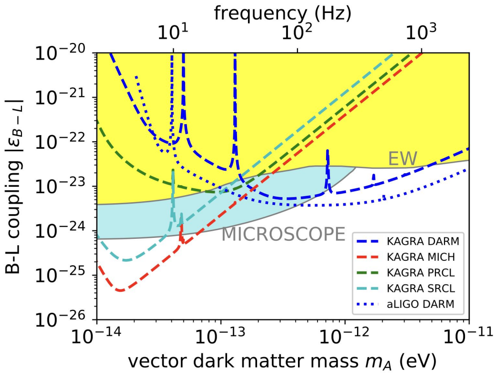
Arvanitaki+ (2017), Tsukada+ (2019), Tsukada+ (2021), Yuan+ (2022) Dergachev+ (2019), Palomba+ (2019), Abbott+ (2022), Zhu+ (2020), Sun+ (2020), Baryakhtar+ (2021), Collaviti+ (2024), Isi+ (2019), Jones+ (2023), Jones+ (2024), etc.

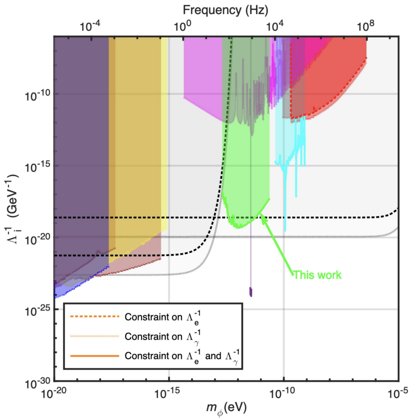
Topic 3 - Direct Interactions

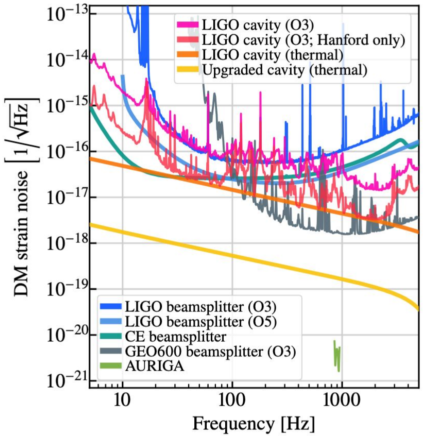
- Interaction with optics (test masses, beamsplitter, auxiliary mirrors, etc.), photon polarization, etc.
- GW detectors are extremely sensitive to displacements – can be directly used as dark matter detectors
- GW instrumental technologies lead to new DM detection ideas
- Future detectors have the capability to probe some interesting parameter space









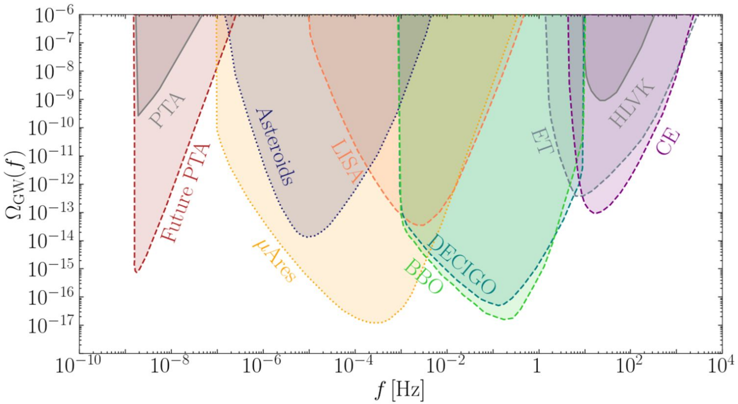


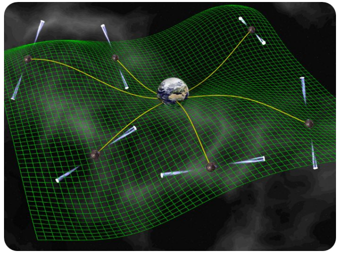
Abbott+ (LVK), PRD 105, 063030 (2022), PRD 109, 089902 (2024),
Michimura+ PRD 102, 102001 (2020), Abac+ (LVK), PRD 110, 042001 (2024),
Obata+ PRL 121, 161301 (2018), Nagano+, PRL 123, 111301 (2019), PRD 104, 062008 (2021),
Vermeulen+, Nature 600, 424 (2021), Hall, Aggarwal, arXiv:2210.17487 (2022), etc...

Topic 2-3: Ultralight particles

- These two types of studies probe complementary parameter regimes of particle’s interaction
- Theoretically, what are the most preferred candidates? How to search more effectively? Need closer collaboration with theorists
- How does the constraints contribute to the large-scale observations?

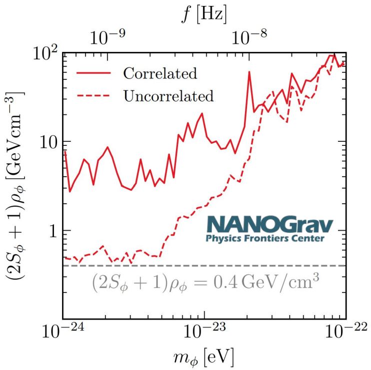
Topic 4 - Searches For Ultralight DM with PTAs

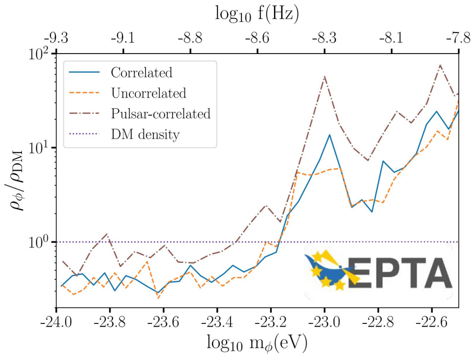




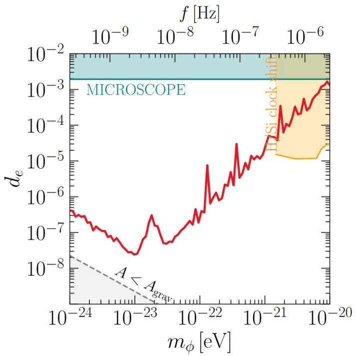
$$m_{\rm DM} \sim 10^{-23}\,{\rm eV}\left(\frac{f}{\rm nHz}\right)$$

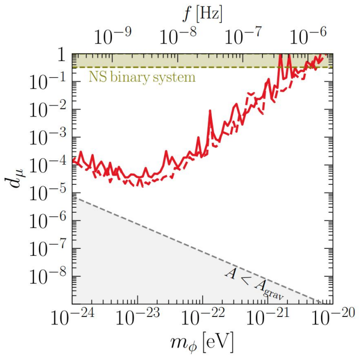
Gravitational Interactions





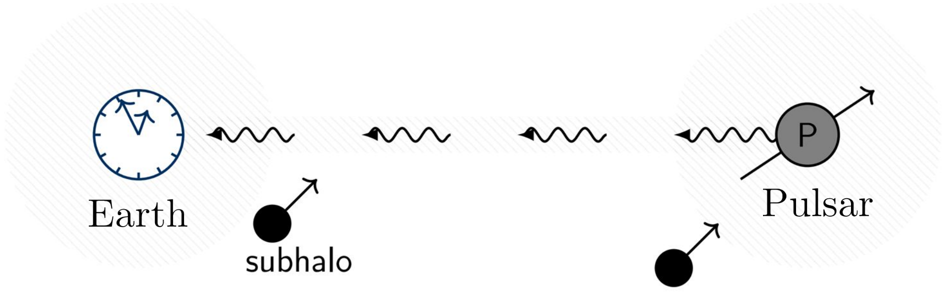
Direct Couplings $\mathcal{L} \supset \frac{d_i \phi}{\Lambda} m_i \bar{\psi}_i \psi_i$

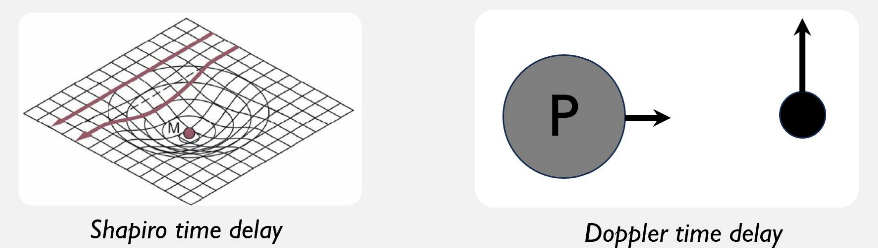


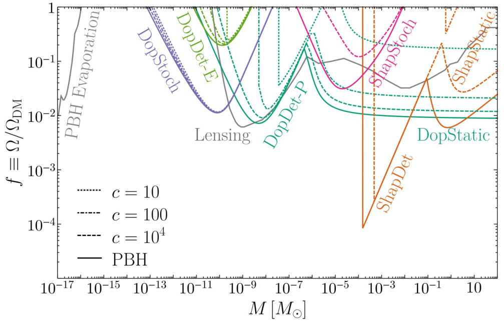


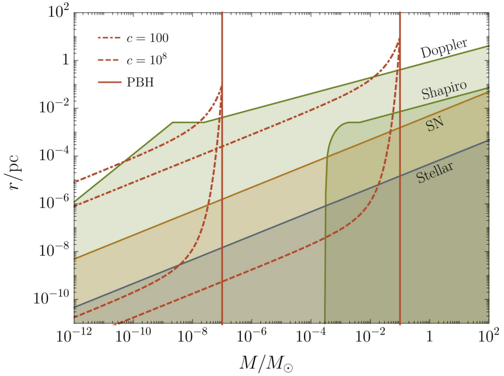
- [1309.5888] Pulsar timing signal from ultralight scalar dark matter
- [1512.06165] Dark Matter Direct Detection with Accelerometers
- [2205.06817] Constraining Fundamental Constant Variations from Ultralight Dark Matter with Pulsar Timing Arrays
- [2306.16219] The NANOGrav 15-year Data Set: Search for Signals from New Physics
- [2306.16228] The second data release from the European Pulsar Timing Array: VI. Challenging the ultralight dark matter paradigm

Topic 5 - Searches For Compact Objects with PTAs

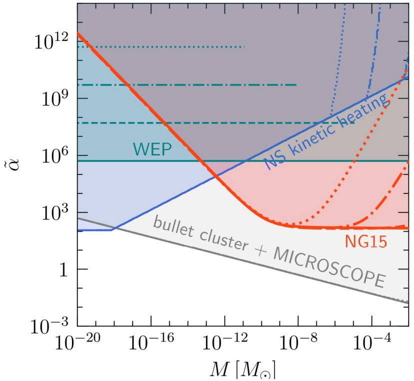








Direct Couplings



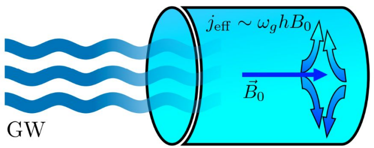
- [1901.04490] Pulsar Timing Probes of Primordial Black Holes and Subhalos
- [2005.03030] Observability of Dark Matter Substructure with Pulsar Timing Correlations
- [2012.09857] Probing Small-Scale Power Spectra with Pulsar Timing Arrays
- [2104.05717] Bayesian Forecasts for Dark Matter Substructure Searches with Mock Pulsar Timing Data
- [2306.16219] The NANOGrav 15-year Data Set: Search for Signals from New Physics

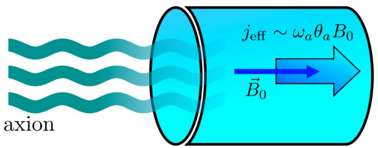
- PTAs are sensitive to less compact substructures relative to lensing.

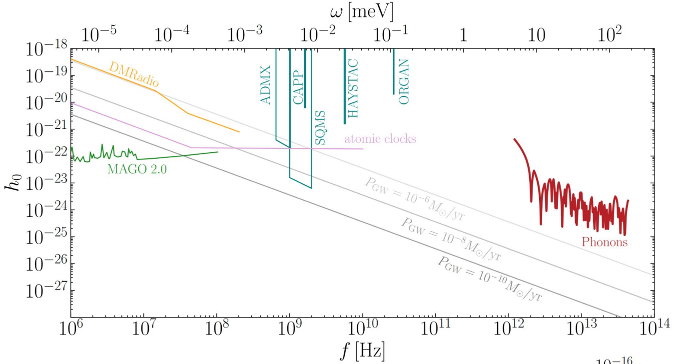
Topic 6 - High-Frequency GW Searches with DM Detectors

DM Searches → High Frequency GW Searches

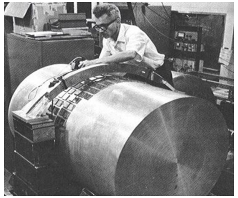
Cavity Haloscopes

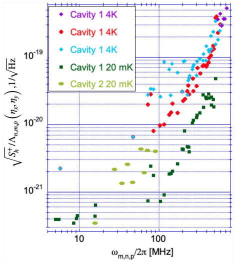




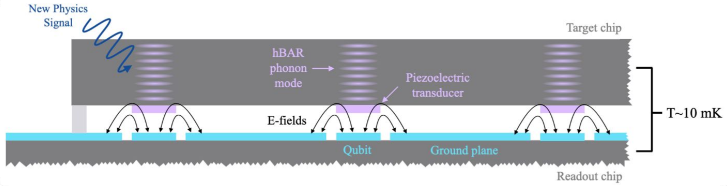


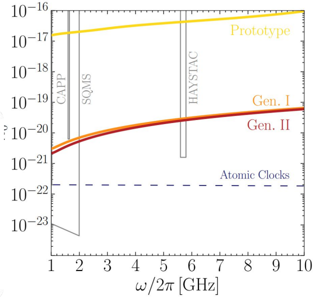
Bulk Acoustic Resonators





Quantum Acoustics





- [1410.2334] Gravitational Wave Detection with High Frequency Phonon Trapping Acoustic Cavities
- [2112.11465] Detecting High-Frequency Gravitational Waves with Microwave Cavities
- [2011.12414] Challenges and Opportunities of Gravitational Wave Searches at MHz to GHz Frequencies
- [2311.17147] Searching for High Frequency Gravitational Waves with Phonons
- [2410.17308] Listening For New Physics With Quantum Acoustics

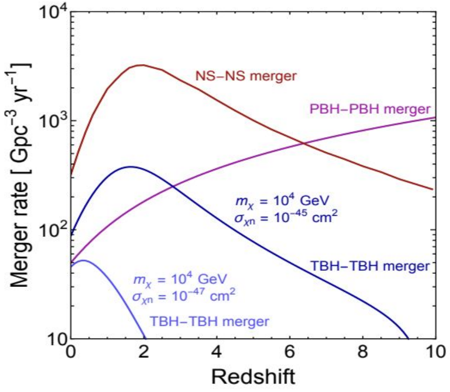
- [ ] Major Challenge: theoretically motivated sources?

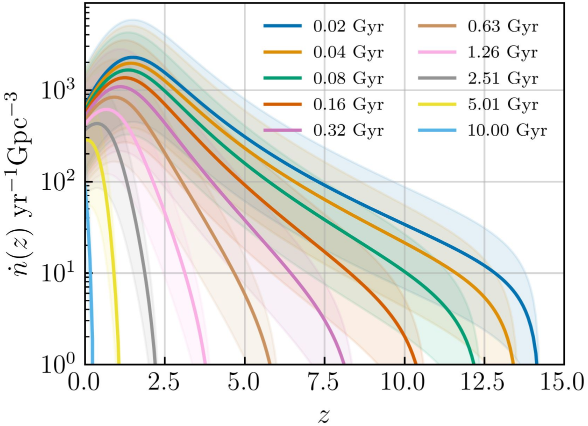
Recap of plenary talk

BH from DM accumulation in NS cores: 1-3 solar masses

Challenges:

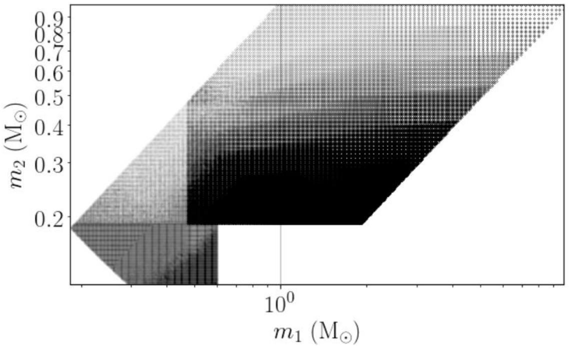
- ❏ Delay time distributions
- ❏ Local BNS merger rate

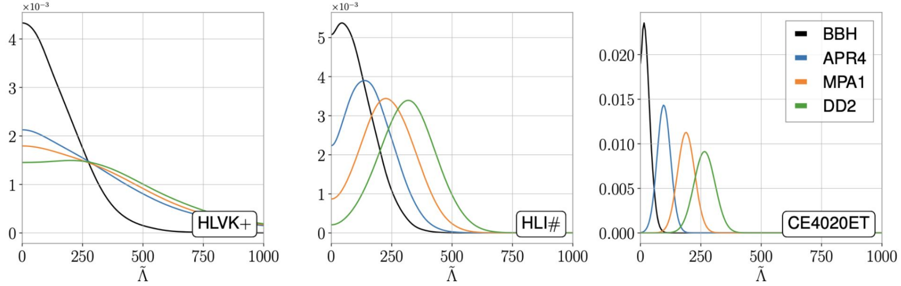




Sub-solar mass searches:

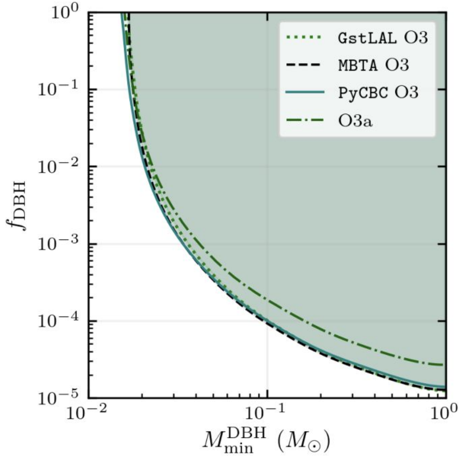
- ❏ Continue to build bigger and denser template banks?
- ❏ If matched filtering, what about effects of DM environment on waveform?





BHs from collapse of DM halos:

- ❏ merger rate density - where does it peak?



Effects of DM on NS-EOS?

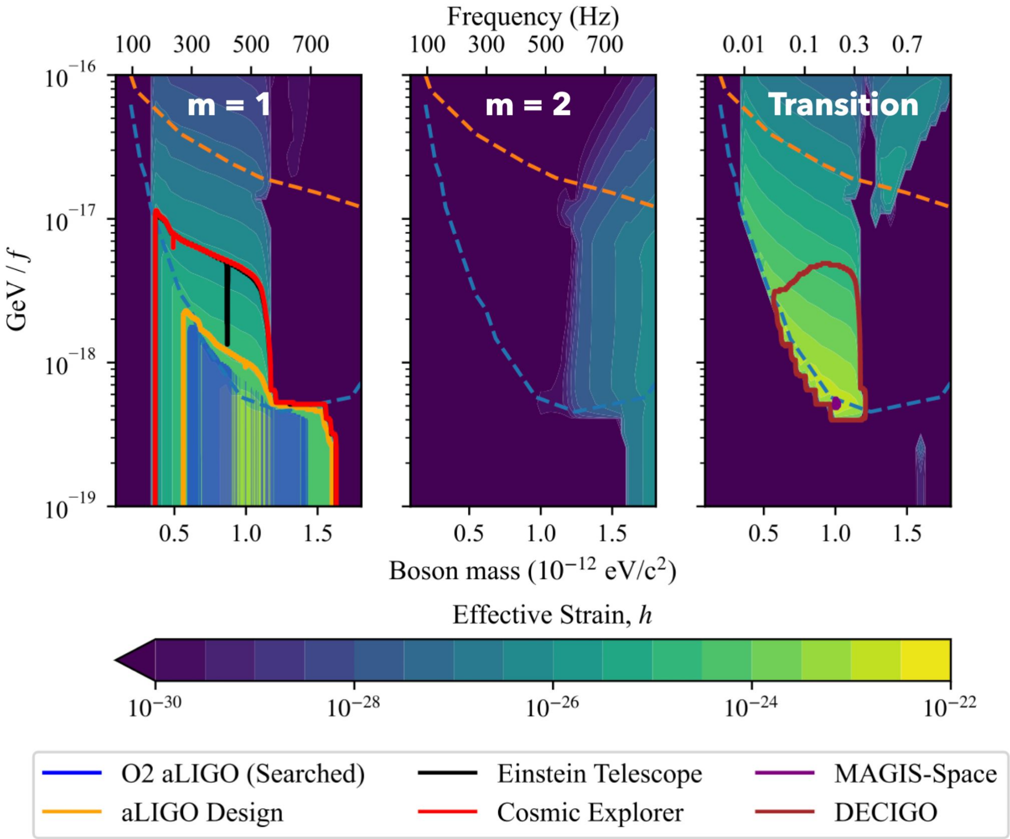
CE: STM Dark Matter (from Alex Nitz)

https://app.sli.do/event/8AFpvSPmSqwv8gatH4En5M/live/polls

Backup Slides

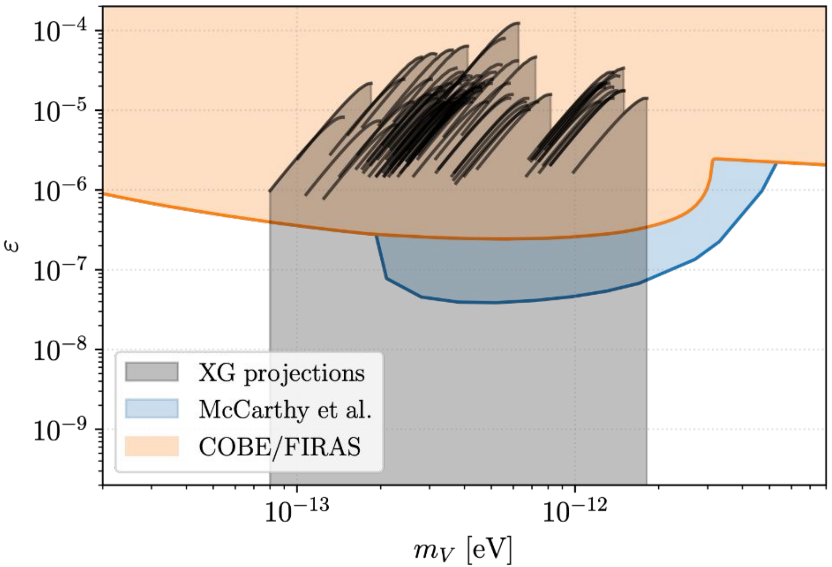
Self-interacting scalar bosons

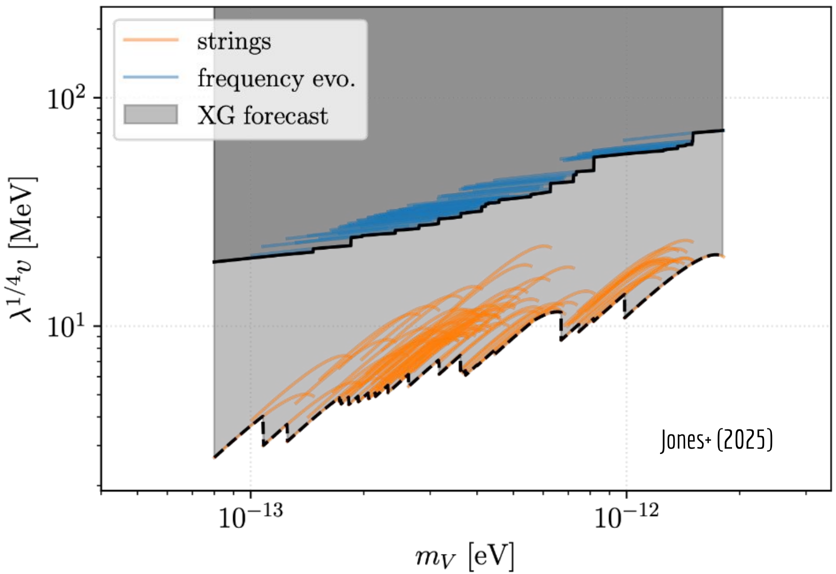
- Self-interaction leads to smaller clouds and faster growth of the next level
- There are potential observational prospects of level transition signals
- Further numerical studies in high boson mass regime that capture full dynamics of the cloud will facilitate future searches



Collaviti+ (2024), Baryakhtar+ (2021)

Consider vector weak couplings

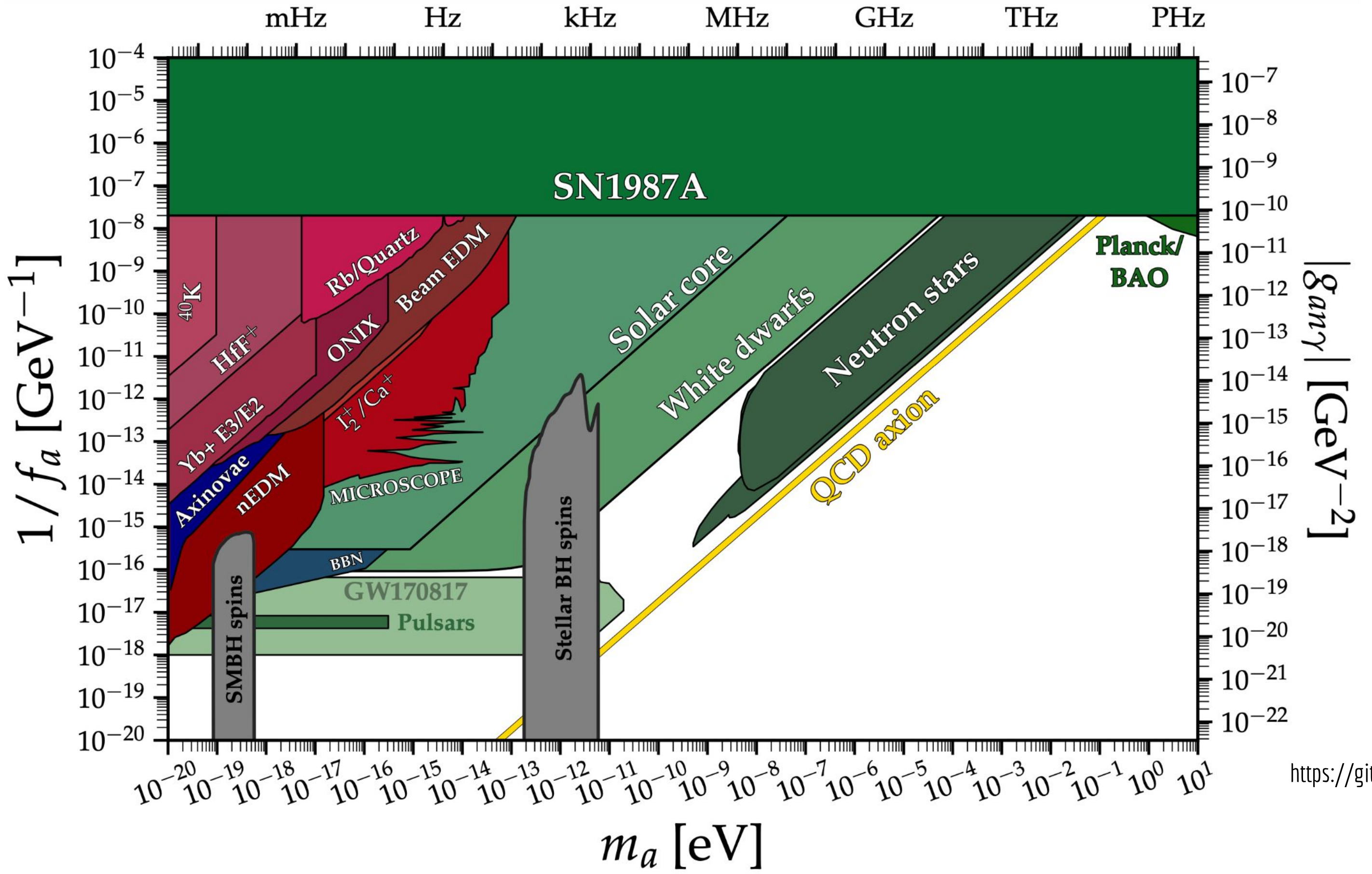




- Test weak coupling of kinetically mixed dark photon –– With a non-vanishing kinetic mixing, the superradiant cloud also dissipates energy through electromagnetic radiation.

- Test the dark Higgs-Abelian sector –– Depending on the relevant coupling strengths, the presence of the Higgs boson may lead to additional frequency evolution/dark radiation or an explosive bosenova forming strings

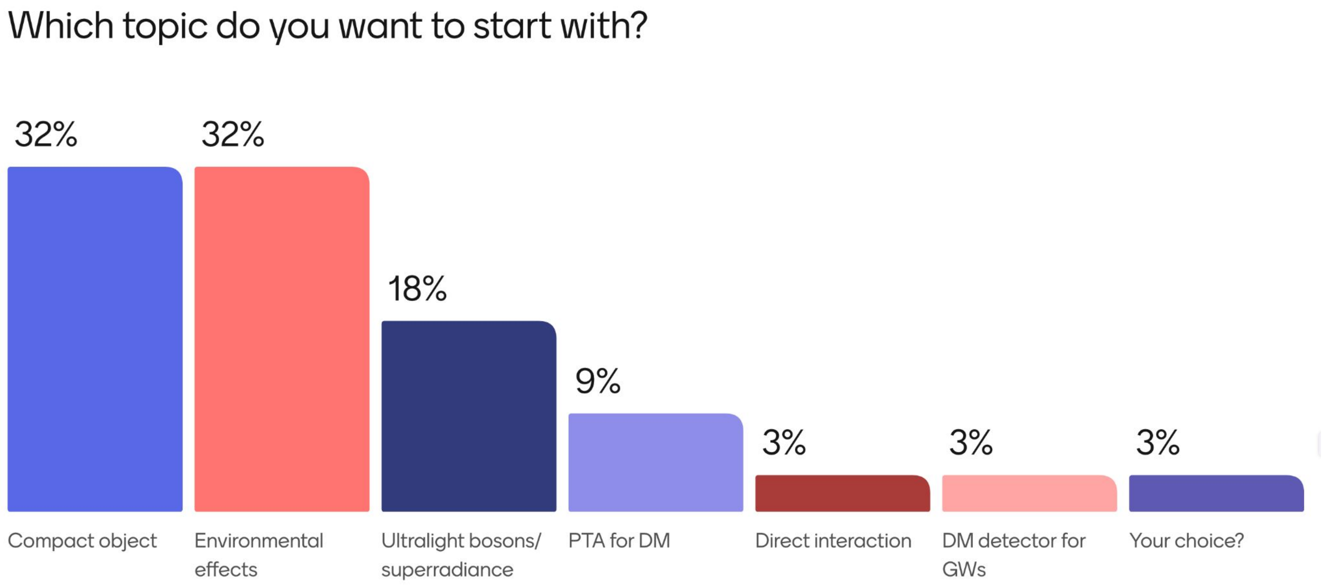
Axion constraints from different studies



https://github.com/cajohare

Summary - Dark Matter Panel

Thank you all for the great discussion!!



Panelists: David A. Nichols, Divya Singh, Ling Sun (chair), Tanner Trickle

Main outcome

- **DM environment around I/EMRIs:** Can measure high particle DM densities and determine the DM distribution with LISA and CE. With CE, requires primordial BHs.
- **Compact objects:** Interesting studies are carried out in various aspects, including sub-solar mass BHs, primordial BHs, BH from DM accumulation in NS cores, BHs from collapse of DM halo, DM's effect on NS observables like size and tides, etc.
- **BH Superradiance** studies (both spin constraints and searches) for ultralight bosons start to become relevant with current detectors and promising with CE/ET
- **Pulsar Timing Arrays** offer a complementary probe of the gravitational interactions of both ultralight, and ultra-heavy, DM candidates.

Challenges/Lessons learnt

- **DM environment around I/EMRIs:** There are challenges in search/PE/waveform, e.g., these are long, low-SNR signals (need long integration), with DM effects dominant at low frequencies, and need waveforms similar to vacuum I/EMRIs + evolution of the DM distribution.
- **Compact objects of DM origin:** waveform challenges; modelling assumptions and their motivations, scaling up searches for low mass compact objects
- **Ultralight bosons** do not necessarily contribute to dark matter. Theoretically, what are the most preferred candidates for DM? How to search more effectively? Need closer collaboration with theorists
- **Pulsar Timing Arrays:** How do we disentangle astrophysical backgrounds from cosmological sources? Are there other ways we can use the data that is collected to search for DM? What are the most relevant sources for high-frequency gravitational waves?

The DM topic is as broad as the mass range of DM candidates; We need to understand the assumptions associated with various studies and the most promising science cases.