Snowmass 2021 CF7

Cosmology 2 -- Beyond the Standard Model & Dark Matter

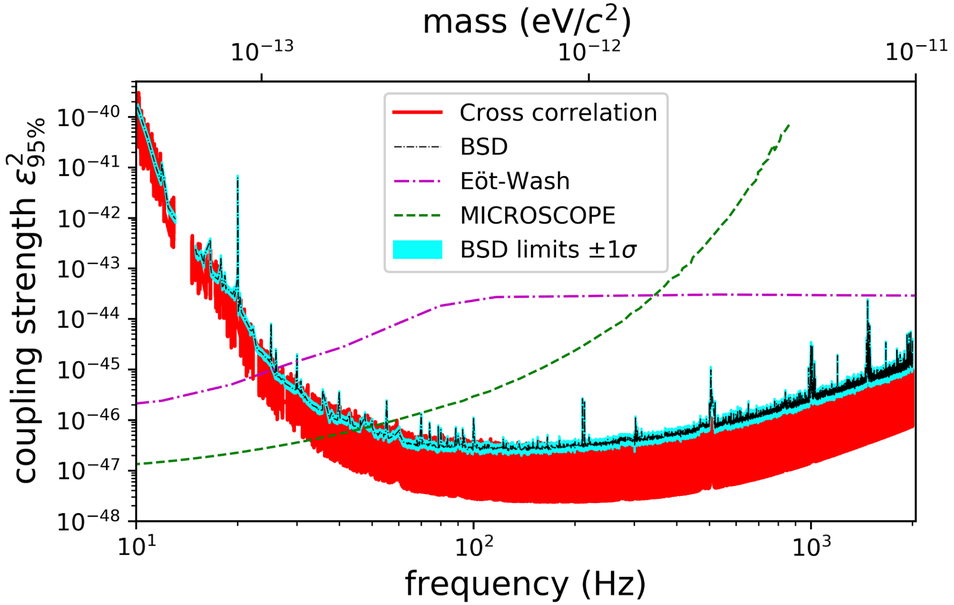
Ling Sun on behalf of CF7 WP5 authors
Leading authors: S. Chakrabarti, S. Clesse, C. Dvorkin, J. Meyers, A. Miller, S. Shandera, L. Sun
November 18, 2021

Overview

Cosmology 2 -- Beyond the Standard Model & Dark Matter

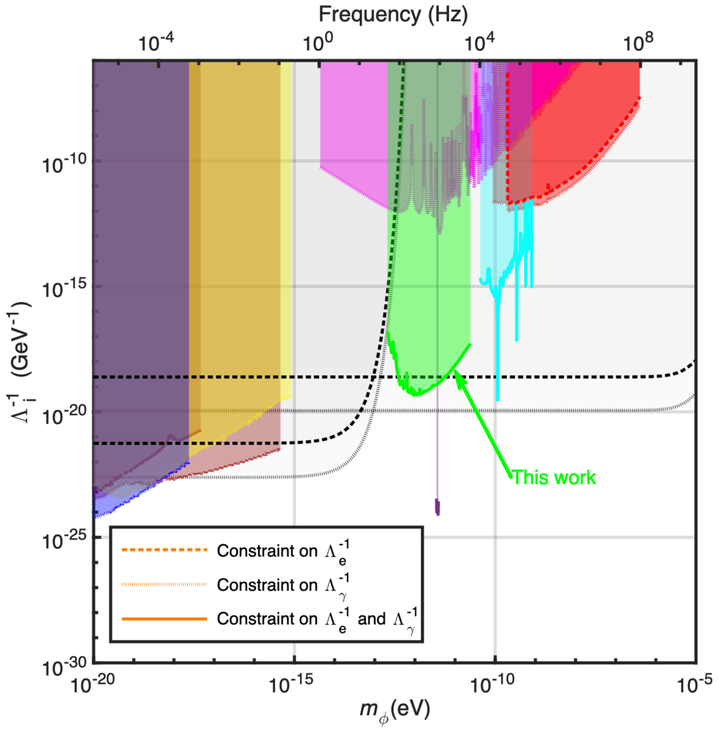
- Using gravitational wave interferometers as particle detectors to directly probe dark matter (CF#072)
  - Andrew Miller andrew.miller@uclouvain.be
- Search for gravitational waves from ultralight boson clouds around black holes (CF#136)
  - Ling Sun ling.sun@anu.edu.au
- Gravitational waves from primordial black holes (CF#091)
  - Sebastien Clesse sebastien.clesse@ulb.be
- Gravitational wave observations as a probe of dissipative dark matter (CF#228)
  - Sarah Shandera ses47@psu.edu
- Novel dynamical probes of dark matter on small scales (CF#014)
  - Sukanya Chakrabarti chakrabarti@astro.rit.edu
- Insights for fundamental physics and cosmology with light relics (CF#147)
  - Joel Meyers jrmeyers@smu.edu, Cora Dvorkin cdvorkin@g.harvard.edu

Search for ultralight dark matter directly interacting with gravitational-wave detectors



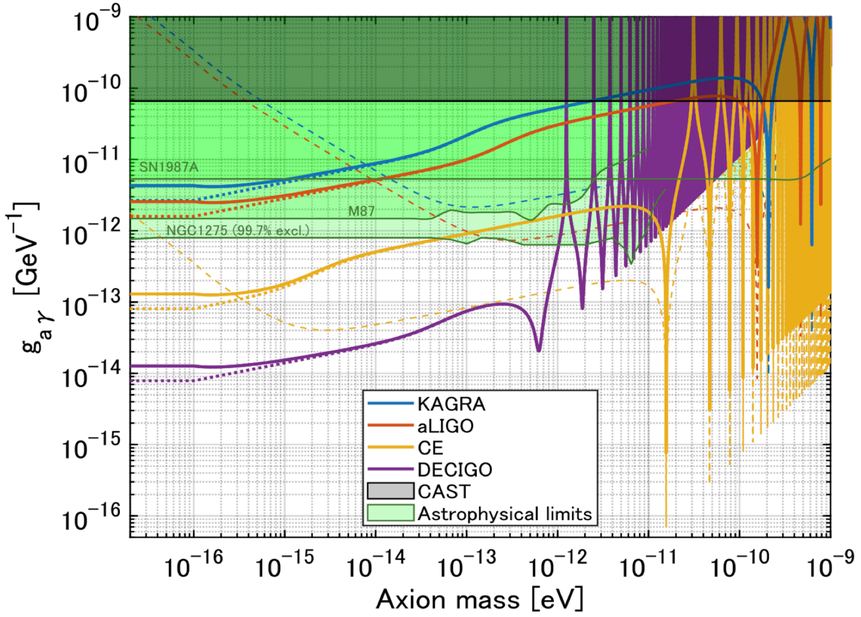
Abbott+ (LVK), arXiv:2105.13085 (2021)

Constraints on the coupling strength of dark photons to baryons in the mirrors using two methods (LIGO/ Virgo O3): cross-correlation and excess power (BSD)



Vermeulen+, arXiv:2103.03783 (2021)

Constraints on scalar field dark matter coupling to GEO600. The scalar field dark matter would alter fine structure constant and electron mass, and change the size and index of refraction of the beamsplitter.

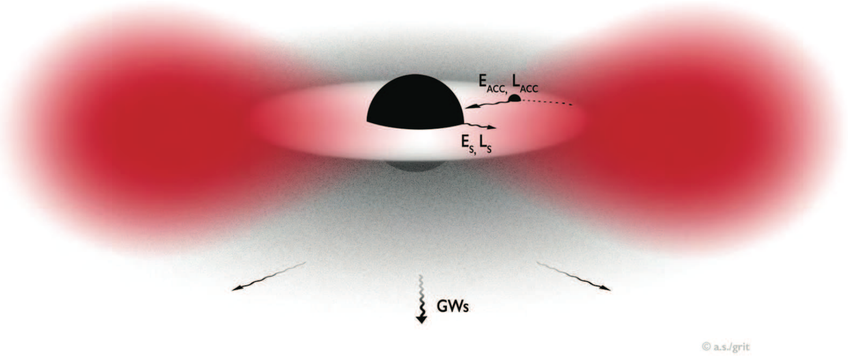


Nagano+, PRD 104, 062008 (2021)

Projected constraints on axion-photon coupling constant. The background axion field modifies the photon dispersion relation between the left- and right-handed circularly polarized photons.

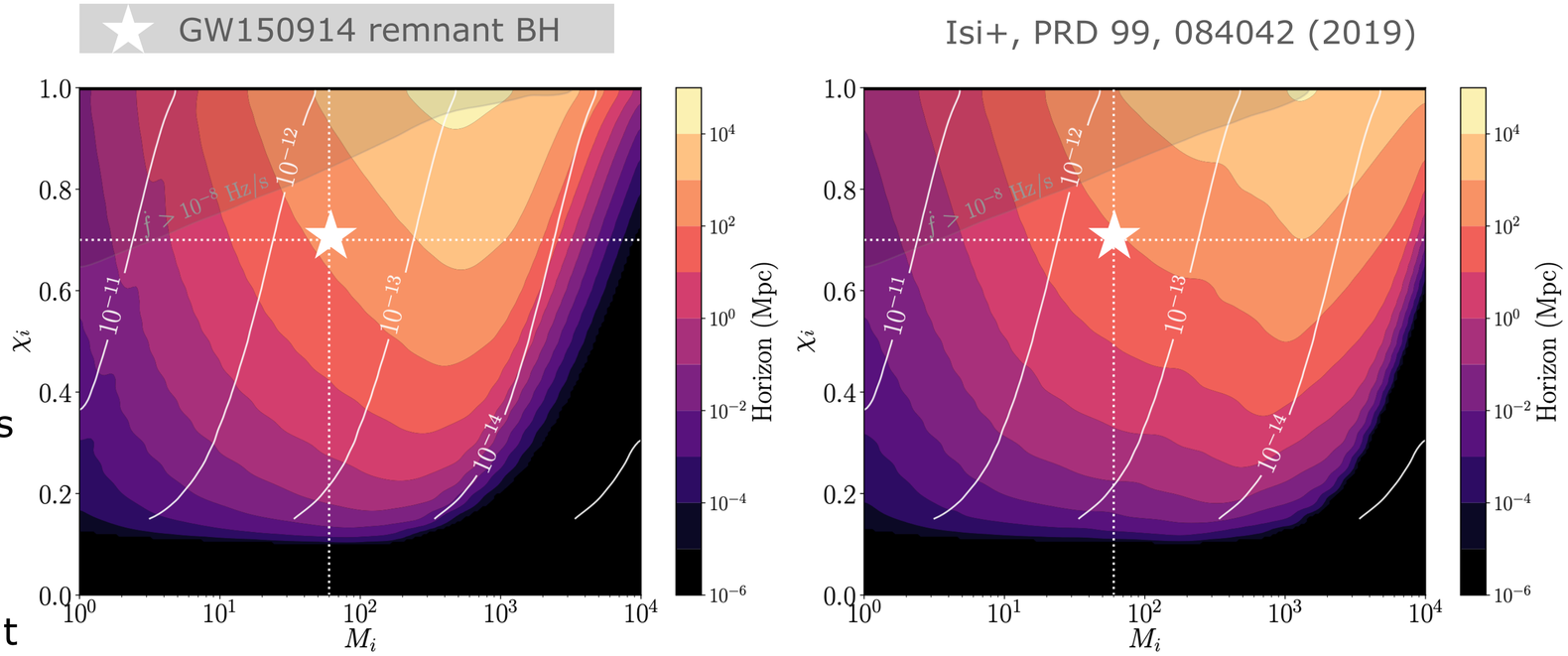
- Dark matter could couple to interferometers in different ways and produce quasi-monochromatic, quasi-infinite duration signals.
- Current and future interferometers could either detect or place extremely stringent constraints on these couplings.

Search for gravitational waves from ultralight boson clouds around black holes



Brito, Cardoso, Pani (2015)

- Ultralight boson fields around Kerr black holes can extract the black hole's rotational energy through superradiance.
- Such clouds are expected to emit continuous quasi-monochromatic gravitational waves that could be detected by gravitational-wave detectors.
- With this astrophysical approach, we can probe a parameter space that is largely inaccessible by conventional particle physics experiments, and may detect new particles in an optimal scenario.



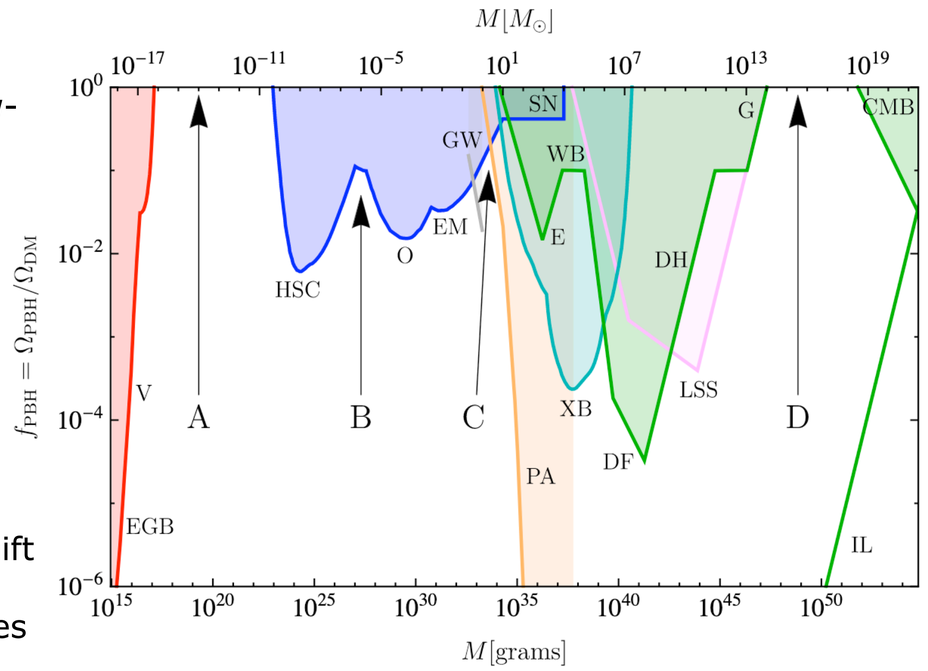
(a) Cosmic Explorer (b) Einstein Telescope

Maximum detectable luminosity distances (color) for optimal scalar clouds around BHs with initial mass and spin for (a) Cosmic Explorer and (b) Einstein Telescope (one year of observation by a single detector). White contour lines indicate the values of the corresponding boson rest-energy (eV).

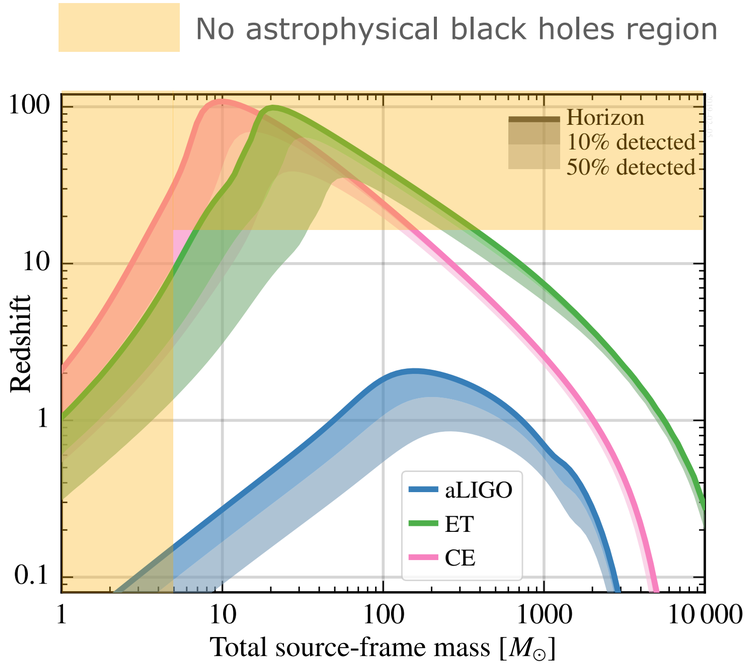
Gravitational waves from primordial black holes (PBHs)

PBHs may have formed in the early Universe, and the ground-based GW detectors can probe the origin of BHs (stellar or primordial) through different methods and observations.

- Sub-solar-mass black holes (almost certainly primordial)
- Black holes in the neutron star range and low-mass gap (probe the origin via multi-messenger)
- Intermediate-mass black holes, in the pair-instability mass gap and beyond (distinguish PBHs from secondary mergers with spin measurements)
- Black hole mergers at high redshifts before star formation (z: ~20–100)
- Distinguishing the mass, rate, spin and redshift distributions of astrophysical vs primordial black holes with Bayesian inference techniques
- GW backgrounds from PBHs: from early/late binaries, hyperbolic encounters, second order perturbations, Poisson fluctuations
- Continuous GWs and high-frequency GWs from planetary-mass PBHs
- GW bursts from PBH hyperbolic encounters



Astrophysical limits on the PBH density with respect to Dark Matter (DM), for a monochromatic PBH mass function. The arrows point to the mass windows where PBHs can constitute a substantial part of DM. [Carr+,2020]



Astrophysical range in redshift as a function of the total binary mass for Advanced LIGO (aLIGO), Einstein Telescope (ET) and Cosmic Explorer (CE). [Maggiore+,2020]

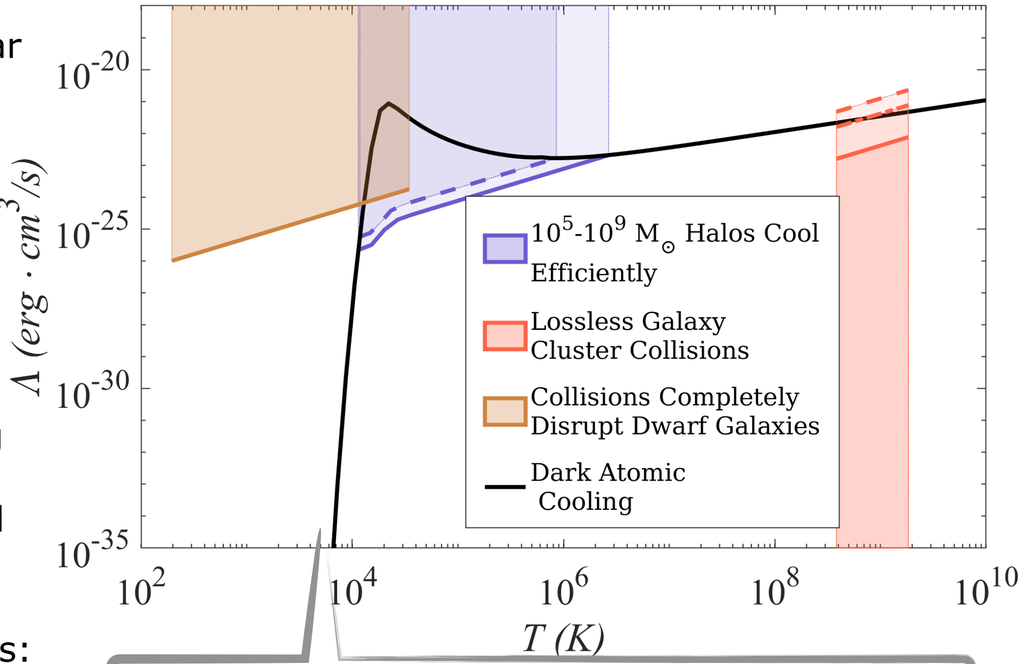
Gravitational wave observations as a probe of dissipative dark matter

Compact objects can form with an astrophysical or dark matter origin
Dissipative dark matter can allow new formation channels for compact objects

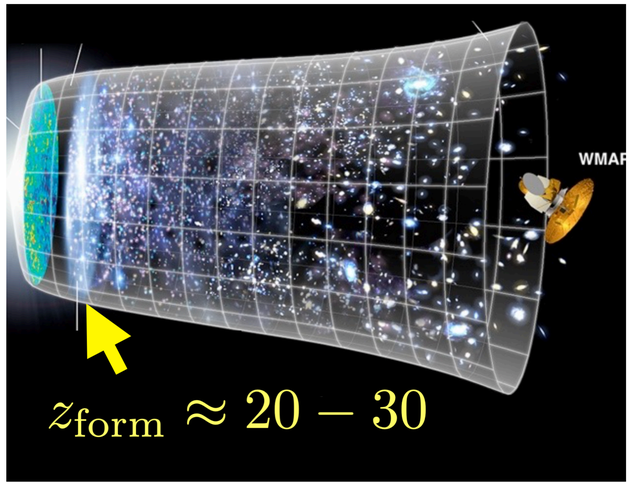
- Dark black holes (DBHs) may be sub-solar if the heavy dark fermion is heavier than the proton — search for sub-solar-mass compact objects (also related to PBHs)

$$M_{\rm Chand.}^{\rm Dark} \approx 1.4 M_\odot \left(\frac{m_p}{m_H}\right)^2$$

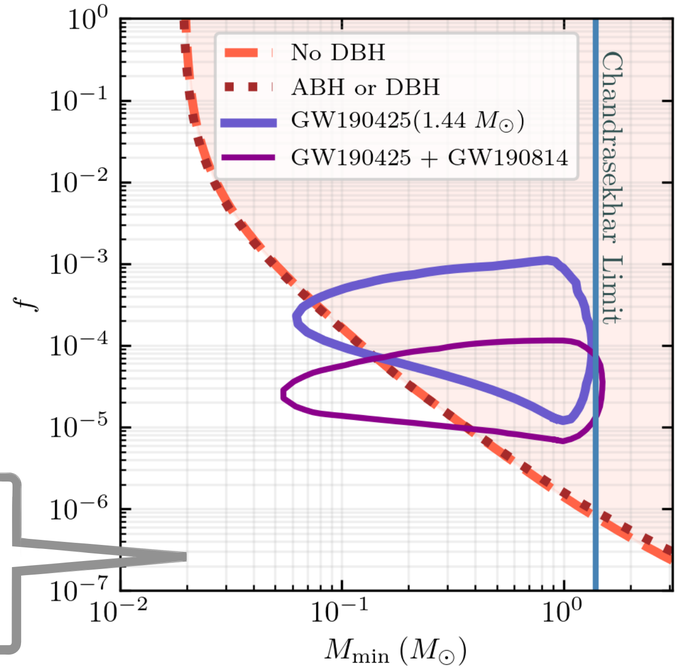
- DBHs form from direct collapse of cooling in dense dark matter regions — constraining the cooling function & bound state energy levels that enable cooling.
- Model two different black hole populations: stellar origin vs dark matter origin
- Use data to constrain theories about compact object formation in dissipative dark matter models
- Develop a framework to treat large-scale structure constraints on dissipation together with GW constraints.



Cooling rate constraints from dark black hole detections combined with large-scale structure collisions. Solid curve: cooling function for an example atomic dark matter model consistent with the interpretation that GW190425 is a binary DBH.



Singh+, arXiv:2009.05209 (2021)

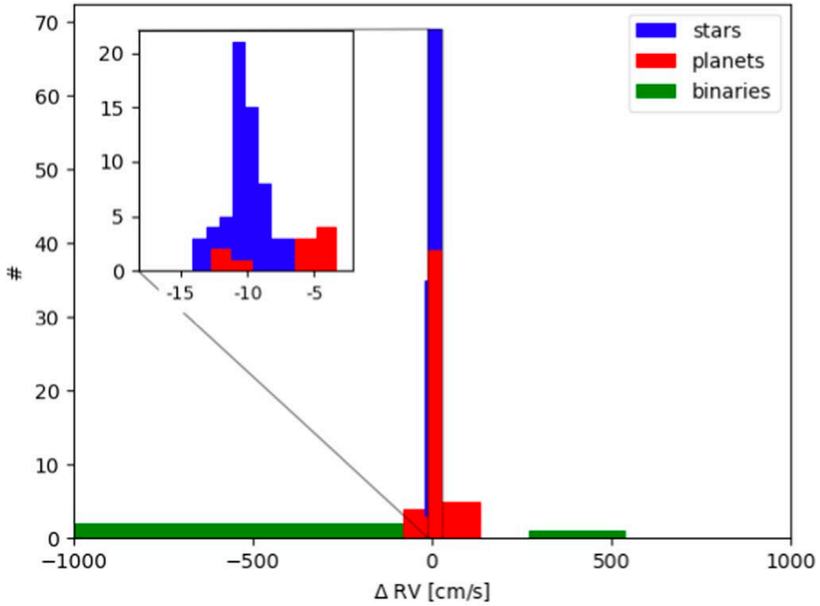


Constraint on the fraction of dark matter in DBHs against the minimum allowed mass of DBH, for the dissipative dark matter model of [Shandera+,2018].

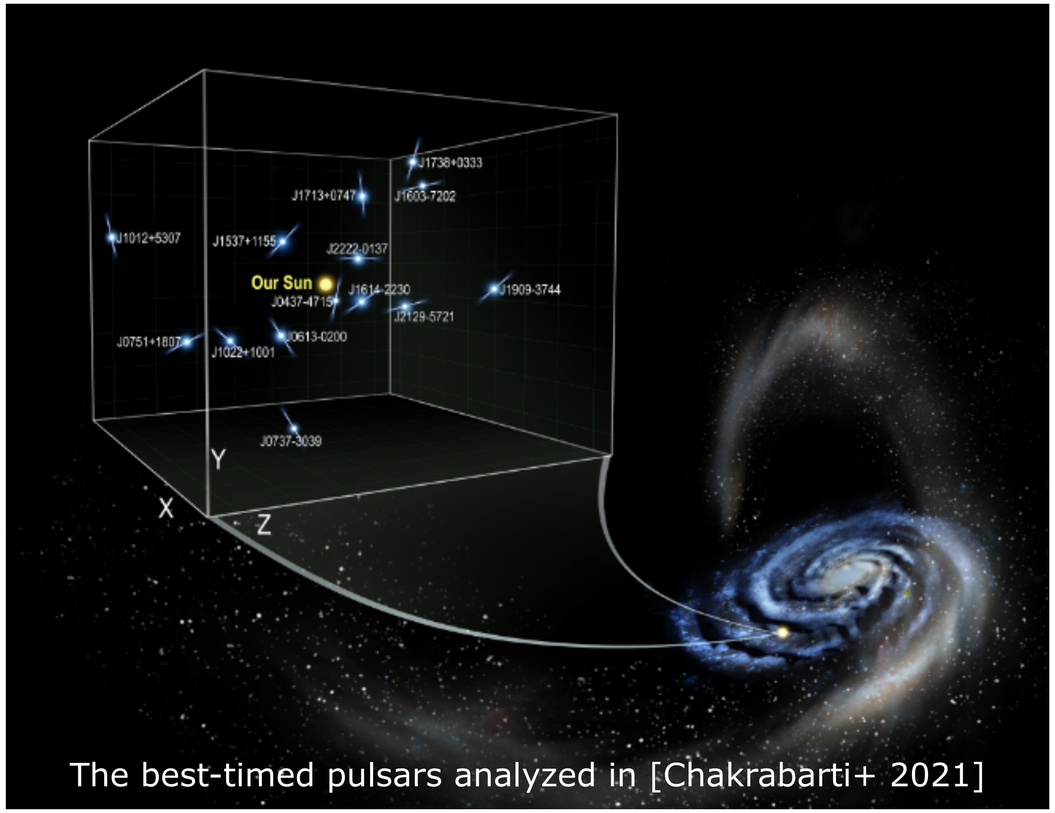
Novel dynamical probes of dark matter on small scales (nearby ~10 kpc from the Sun)

Extreme-precision radial velocity (RV) observations

- Current generation of spectrographs (ESPRESSO, NEID, and others that are typically used to hunt for planets) with ~30 cm/s RV precision can also directly measure the small accelerations of stars in the Galaxy, and therefore the mass distribution [Chakrabarti+ 2020], without assumptions of equilibrium as in kinematic analysis, but are limited to a few kpc from the Sun.



Histogram of ΔRV over a 10 year baseline in a population of single stars, stars with planets on circular Keplerian orbits, and stellar binaries. Low-mass, long-period planets are a contaminant to the Galactic acceleration signal, but their contribution is very small. Can reject null hypothesis that signal is due to stars with planets at high confidence. [Chakrabarti+ 2020]

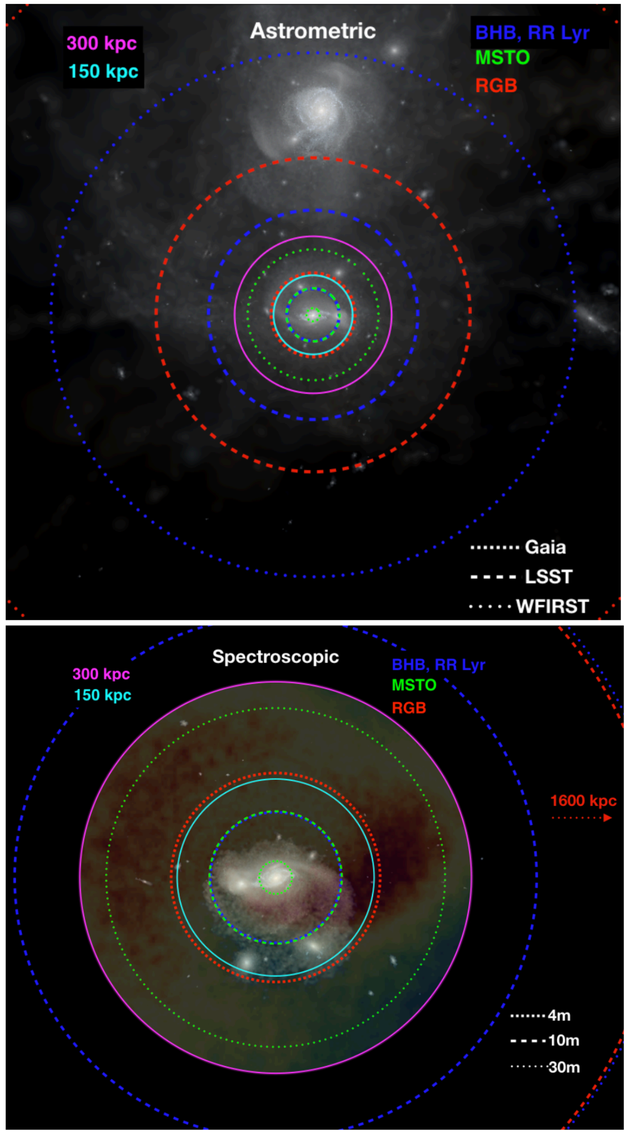


The best-timed pulsars analyzed in [Chakrabarti+ 2021]

Pulsar timing

- Compiled pulsar timing observations have been used to measure the Galactic acceleration and determine fundamental parameters (mid-plane density, local dark matter density, oblateness) that describe the Galaxy [Chakrabarti+ 2021].
- Local dark matter density and Oort limit (volume mass density at the Galactic mid-plane) are close to but lower than kinematic estimates. Pulsars trace a disk-like structure. There are differences at a factor of ~2 level between acceleration measurements and kinematic estimates [Chakrabarti+ 2021].
- Future pulsar timing observations provide a complementary approach to constrain slope of rotation curve and dark matter sub-structure. With Square Kilometer Array, the measurement may extend to nearby galaxies.

Novel dynamical probes of dark matter on small scales (distant stellar halo)



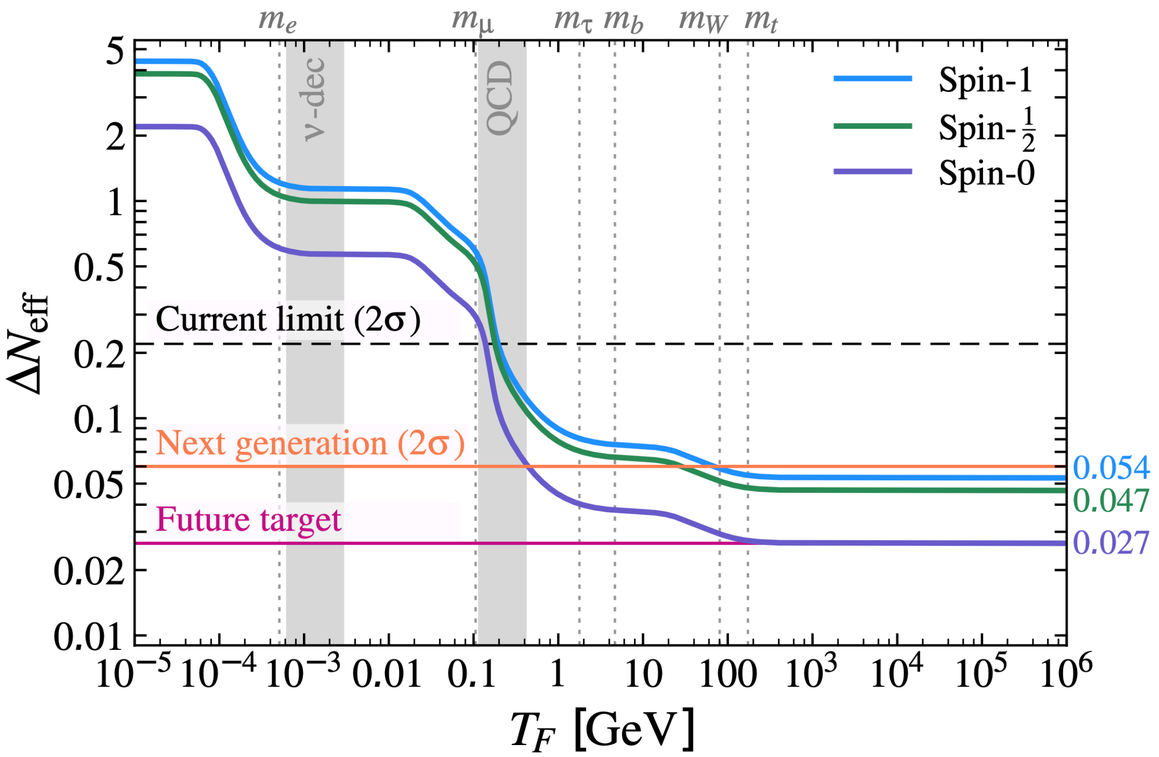
- Extremely large telescopes (ELTs) will be able to directly measure accelerations across the Galaxy (and beyond).
- The planned and proposed astrometric, spectroscopic and photometric surveys, building on recent advances by the Gaia astrometric survey will lead to a complete multidimensional view of our Galaxy, going beyond the Gaia frontier — from the edge of the Galactic disk to the edge of our Galaxy's dark matter halo.

Distances to which individual stellar tracers will be detected by astrometric (top), and spectroscopic (bottom) instruments proposed for the next decade, superimposed on a simulated pair of galaxies resembling the MW and M31 [Sanderson+ 2019].

Insights for fundamental physics and cosmology with light relics

- Long-lived species produced during the expansion of the early Universe leave imprints in cosmological observables.
- Future cosmological observations can be orders of magnitude more sensitive than current experiments. A detection of an excess light relic abundance would provide direct information about the hot Universe prior to neutrino decoupling. The absence of a signal would place powerful constraints on dark sectors.
- Cosmic neutrino background provides an example of the physics of cosmological light relics.
- New light particles: The contribution to effective number of neutrino species (N_{eff}) can be predicted from the final temperature at which the energy density is in equilibrium and the number of internal states (e.g. spin configurations).
- Violent phase transitions and other nonlinear dynamics in the primordial universe could produce a GW background peaked at high frequencies; the GW energy density could be large enough to make a measurable contribution to N_{eff}.

Presence of any additional species is characterised by $\Delta N_{\rm eff} \equiv N_{\rm eff} - N_{\rm eff}^{\rm SM}$



Contributions of a single massless particle to the effective number of relativistic species (decoupled from the Standard Model at temperature T_F).

Questions & Discussion