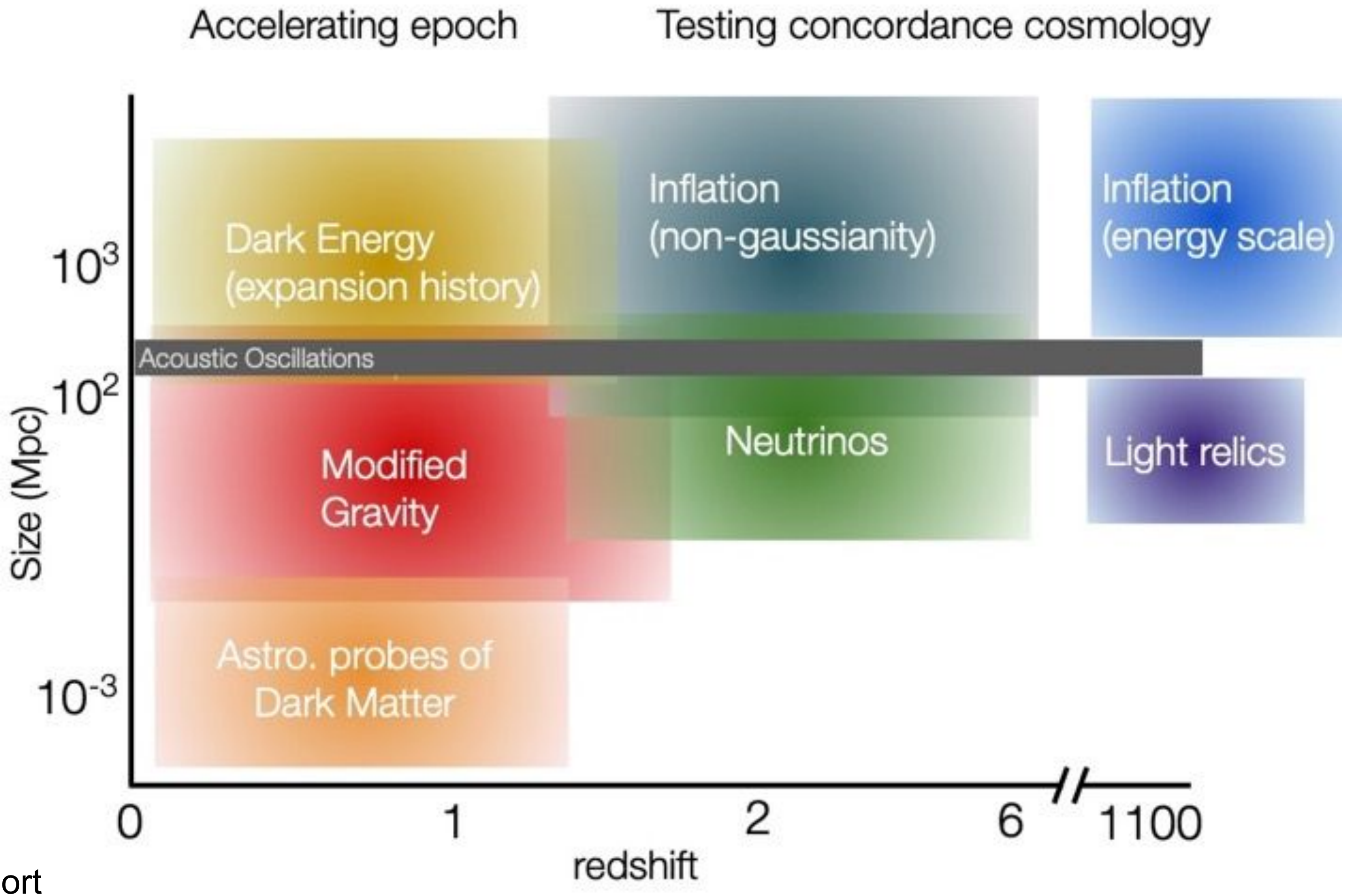
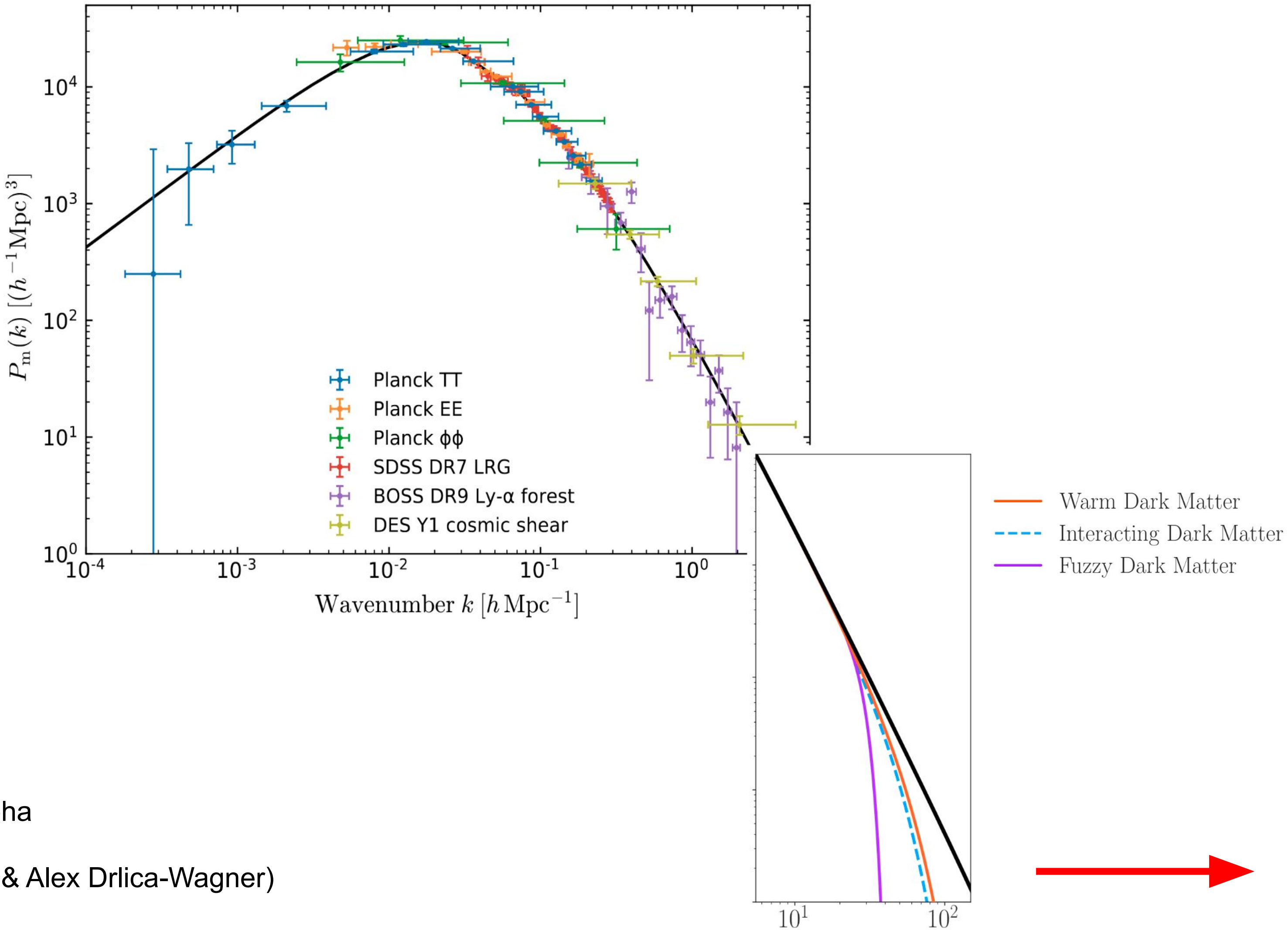
Snowmass 2021:
Very Small Scale Structure

Telecon 13 July 2020
Slack: #cosmic-high-k
Scratch space: google doc


Accelerating epoch
Testing concordance cosmology
Dark Energy (expansion history)
Inflation (non-gaussianity)
Inflation (energy scale)
Acoustic Oscillations
Modified Gravity
Neutrinos
Light relics
Astro. probes of Dark Matter
Size (Mpc)
10^3
10^2
10^{-3}
0
1
2
6
1100
redshift

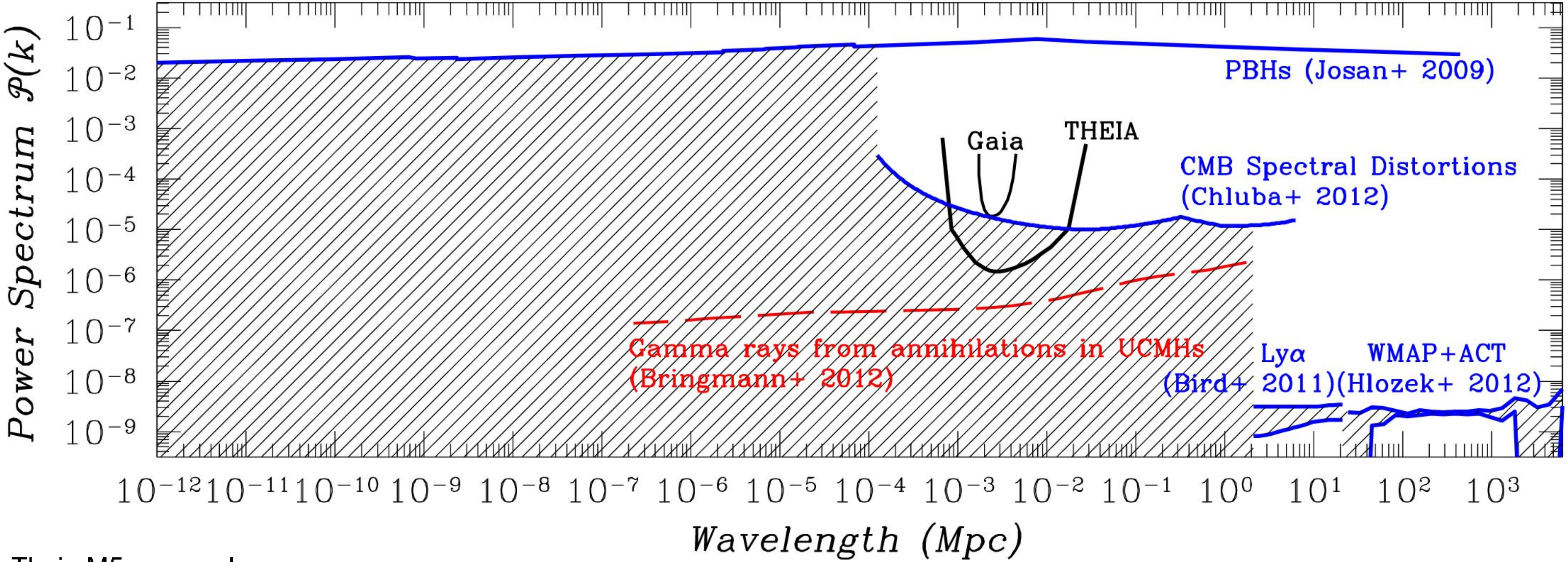
BRN Report

Premise



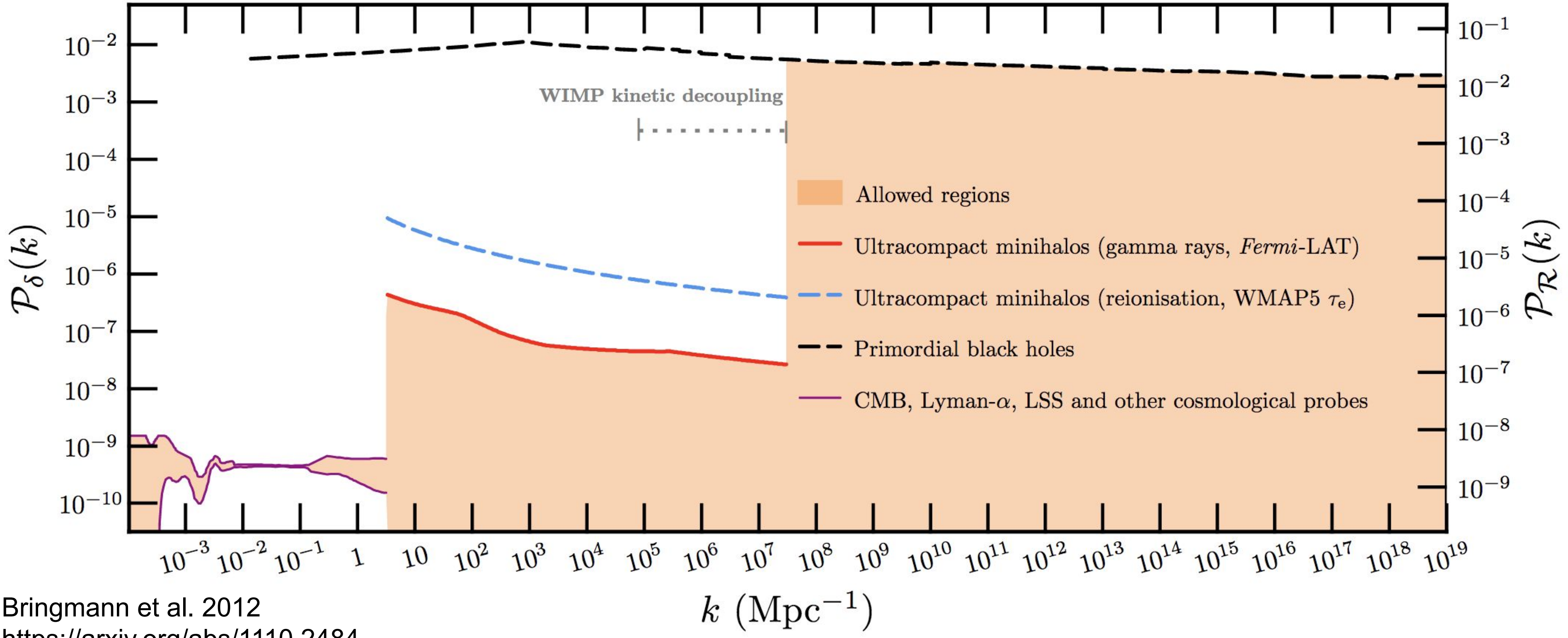
Planck + LSS + WL + Ly-alpha
[+ MW satellite galaxies]
(image credit: Ethan Nadler & Alex Drlica-Wagner)

Premise



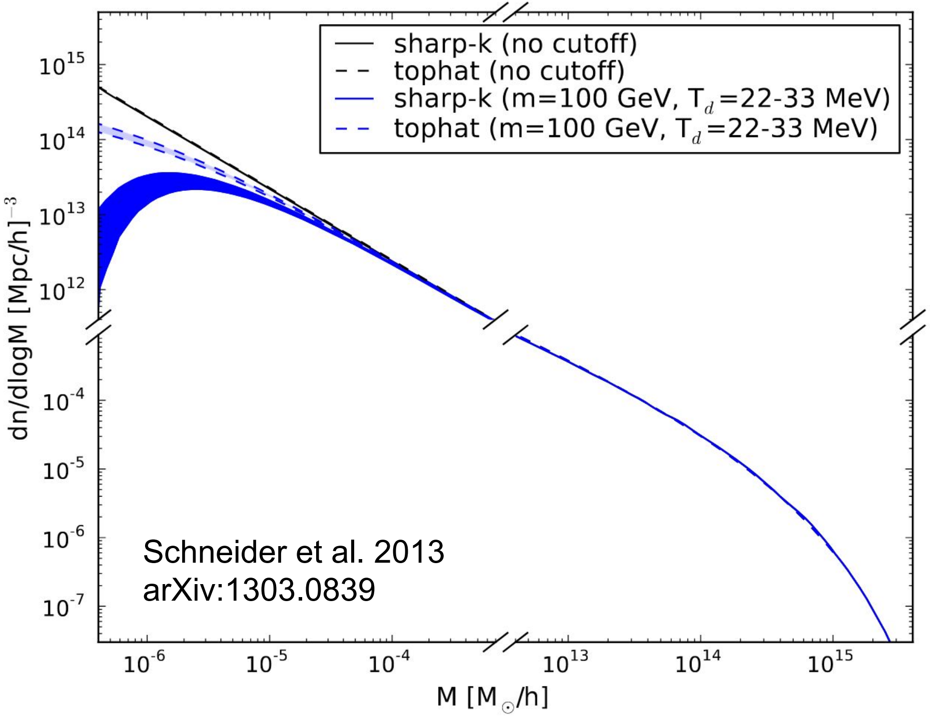
Theia M5 proposal
arXiv:1707.01348

Premise



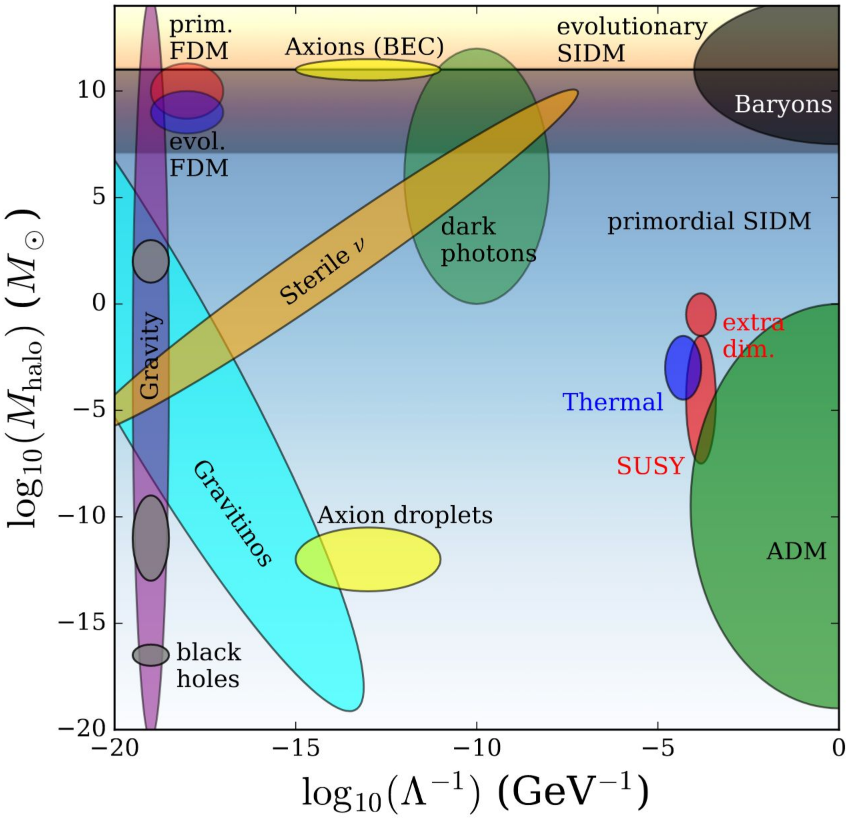
Bringmann et al. 2012
https://arxiv.org/abs/1110.2484

Premise



Schneider et al. 2013
arXiv:1303.0839

Premise



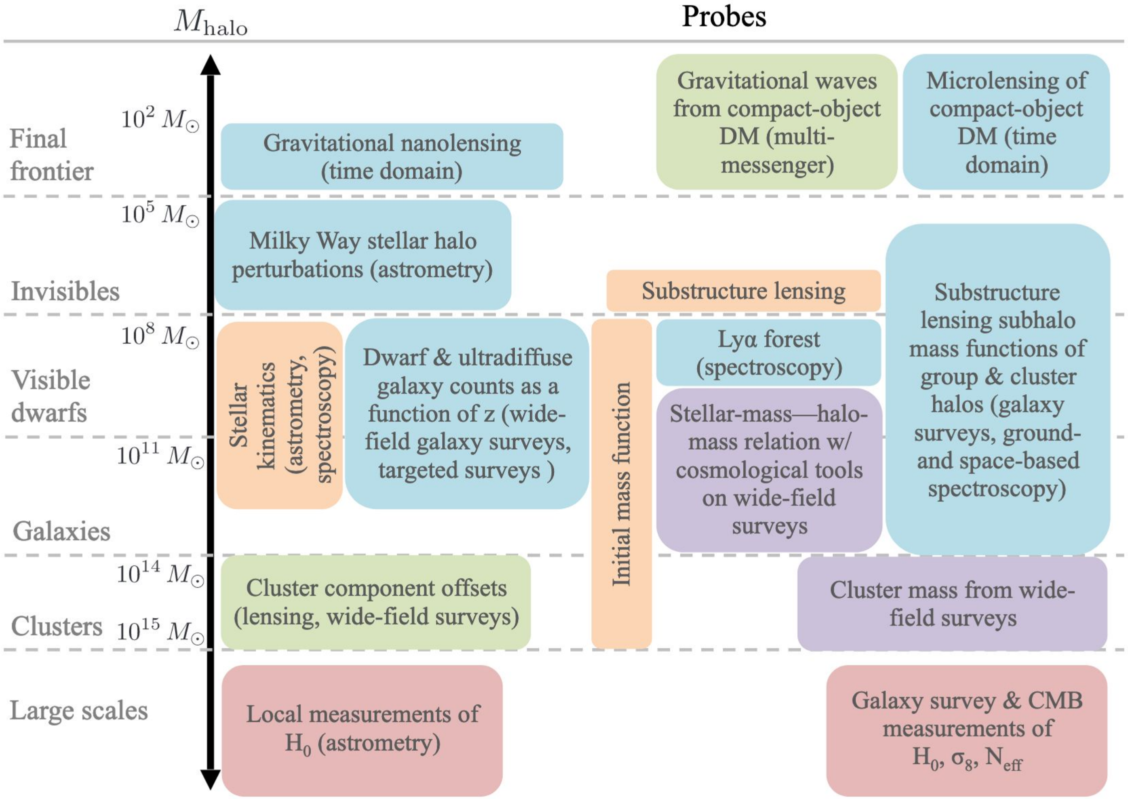
Buckley & Peter
arXiv:1712.06615

Premise

Let's focus our attention here for this LOI specifically

Next 5-10 years (?)

We are ~here



Buckley & Peter
arXiv:1712.06615

Premise

- Many orders of magnitude of discovery space for cosmic structure at small scales
- dark matter microphysics × initial conditions (inflation) → observable results of structure formation at small scales
    - Generically sensitive to both dark matter microphysics AND inflation physics
    - “Problem” to disentangle the underlying physics
    - Thought experiment: how would measurement of small-scale structure cut-off scale (or other feature) compare to a detection of new dark matter candidate particle at a direct detection or collider experiment?

How small is small?

- Seems possible that multiple “established” methods will attain sensitivity to halo mass scales $M_{halo} \sim 10^7 M_{Solar}$, wavenumbers $k \sim 100\ h\ Mpc^{-1}$ within the next 5-10 years
    - ~1 order of magnitude improvement in halo mass
    - We should absolutely write Snowmass LOIs on this important work
- At scales smaller than this, halos likely contain too few stars to be recognized as “galaxies” in traditional sense
    - Qualitative jump in sense that these halos would be nearly baryon free

How small is small?

- Suggest we consider ambitious goal to reach scales *several orders of magnitude smaller* than current reach
  - Likely requires new methods that push precision, statistics, sensitivity, and theory frontiers
  - Suggest that we target sensitivity to halos in vanilla CDM scenario; ultra-compact minihalos and primordial black holes will be easier to detect
- Let’s not miss this opportunity to consider bold ideas
  - Consider a possible future in which dark energy looks like a cosmological constant, and collider and direct dark matter experiments have not found any new particles…
  - What could be done at the billion dollar / decade scale in terms of dedicated experiment?

What is our ask for the Snowmass process?

A few possibilities:

- Support for theory work?
- Support for simulation work?
- Support for dedicated analysis efforts for one or more current and/or planned experiments?
  - Also modified observing strategy or operations for current and/or planned experiment
- Support for R&D efforts in one or more novel experimental directions?

Possible Outline of Snowmass LOI (due 31 August)

- Science case for very small scales ($M_{halo} << 10^7 M_{Solar}$, $k >> 100$ h Mpc^{-1})
  - Dark matter microphysics
  - Inflation
- Briefly describe up to three (?) techniques that might achieve orders of magnitude gains in sensitivity
- Briefly describe theoretical efforts needed to interpret those experiments

One Possible Path Forward

- Document for us to use as scratch space
    - Inventory of probes, with associated references and commentary
- Review methods that seem most promising to achieve transformational sensitivity to small-scale structure
    - Perhaps we split into small working groups for this task?
    - Perhaps we reach out to authors of relevant papers?
- Identify a few methods that seem particularly compelling for further investigation
    - One or two well understood approaches seem higher value than several less understood techniques (??)

Theory + Numerical Aspects

- Mapping dark matter microphysics and inflation physics to cosmic structure
- Evolution of cosmic structure on very small scales
  - Sub-galactic scales (subhalos)
  - Extragalactic scales
- Phenomenology of various methods
  - Signal
  - Background

Details on specific approaches in the following slides...

Van Tilburg et al. 2018
https://arxiv.org/abs/1804.01991

Premise

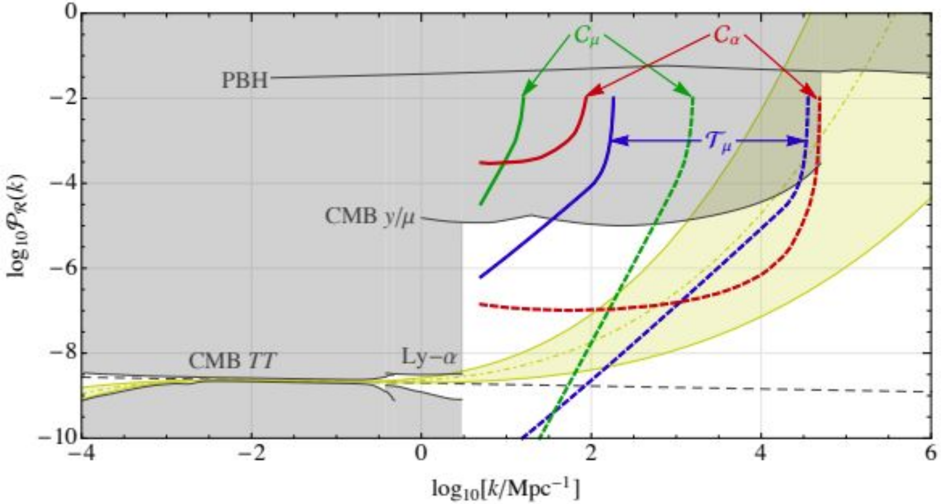


Figure 3. Sensitivity projections and constraints on the primordial curvature power spectrum $\mathcal{P}_\mathcal{R}$ as a function of comoving wavenumber k (in units of Mpc^{-1}). Forecasts for where on-going and future astrometric surveys can reach unit signal to noise ratio are shown by solid and dashed lines respectively, using velocity templates $\mathcal{T}_\mu$ (blue), velocity correlations $\mathcal{C}_\mu$ (green), and acceleration correlations $\mathcal{C}_\alpha$ (red), for the same parameters as in figure 7. Gray regions are excluded at 95% CL by temperature anisotropies in the cosmic microwave background (CMB *TT*), Lyman-α observations, nondetection of spectral distortions of $y-$ and μ-type in the CMB, and limits on primordial black holes (PBH). The black dashed line is the best fit to the *Planck* CMB data assuming a constant spectral tilt n_s, while the yellow band indicates the parameter space where $\mathrm{d}n_s/\mathrm{d}\ln k$ and $\mathrm{d}^2 n_s/(\mathrm{d}\ln k)^2$ were allowed to float by 1σ from their best fit values (dot-dashed yellow). We refer to sections 3.2 and 6.1 for more details.

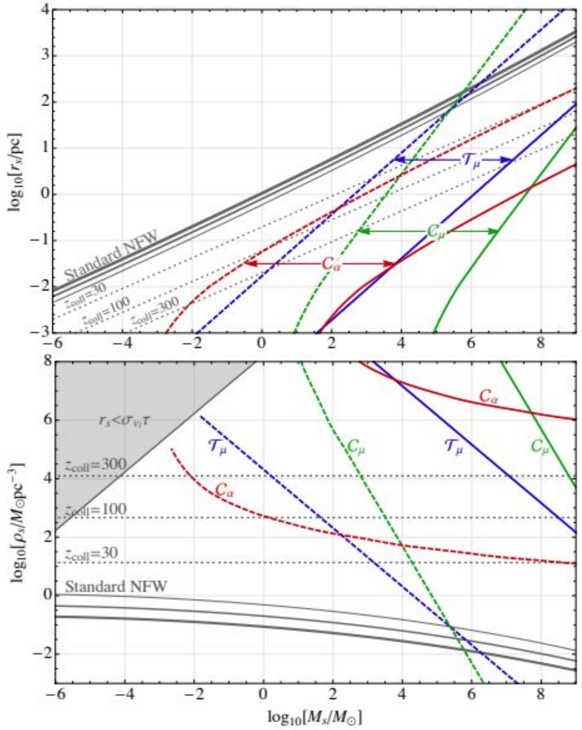


Figure 7. Sensitivity projections for NFW subhalos as a function of core mass M_s. Vertical axes are the scale radius r_s (**Top**) and density $\rho_s = M_s/[r_s^3 16\pi(\ln 2 - 1/2)]$ (**Bottom**). At fixed mass, more compact objects (smaller r_s, larger ρ_s) are easier to see. The blue solid (dashed) curves show the local SNR $= 1$ curve for the template velocity test statistic $\mathcal{T}_\mu$, assuming $\sigma_{\mu,\mathrm{eff}} = 200(1)$ μas y^{-1}, $N_0 = 10^7(10^8)$, and $\Delta\Omega = 0.01(4\pi)$, representative of *Gaia* observations toward the Magellanic Clouds (SKA radioastrometry of quasars). The green solid (dashed) curves show the global $\mathcal{C}_\mu$ velocity correlation test statistic sensitivity for $\sigma_{\mu,\mathrm{eff}} = 10(1)$ μas y^{-1}, $N_0 = 10^6(10^8)$, and $\Delta\Omega = 4\pi$, representative of near-future (far-future) astrometric observations of quasars in the radio and visible bands. The red solid (dashed) curve depicts the global SNR $= 1$ sensitivity for acceleration correlations $\mathcal{C}_\alpha$, assuming $\sigma_{\alpha,\mathrm{eff}} = 10(0.1)$ μas y^{-2}, $N_0 = 10^9(10^{10})$, and $\Delta\Omega = 0.2$ for *Gaia* (*Theia*) observations of Galactic disk stars. Also shown in solid gray is the "standard" NFW subhalo median relation between M_s and r_s from ref. [45] for three subhalo distances $R_\mathrm{sub} = \{240, 10, 5\}$ kpc away from the Galactic Center (closer ones are denser), as well as a rough estimates (in dotted gray) for the scale radius and density for nonstandard collapse redshifts z_coll.

https://arxiv.org/abs/1908.01773

https://arxiv.org/abs/1804.03149

https://arxiv.org/abs/1502.03362

https://arxiv.org/abs/2005.03030

https://arxiv.org/abs/1911.11144

Substructure with lensing

https://iopscience.iop.org/article/10.1086/340303/pdf

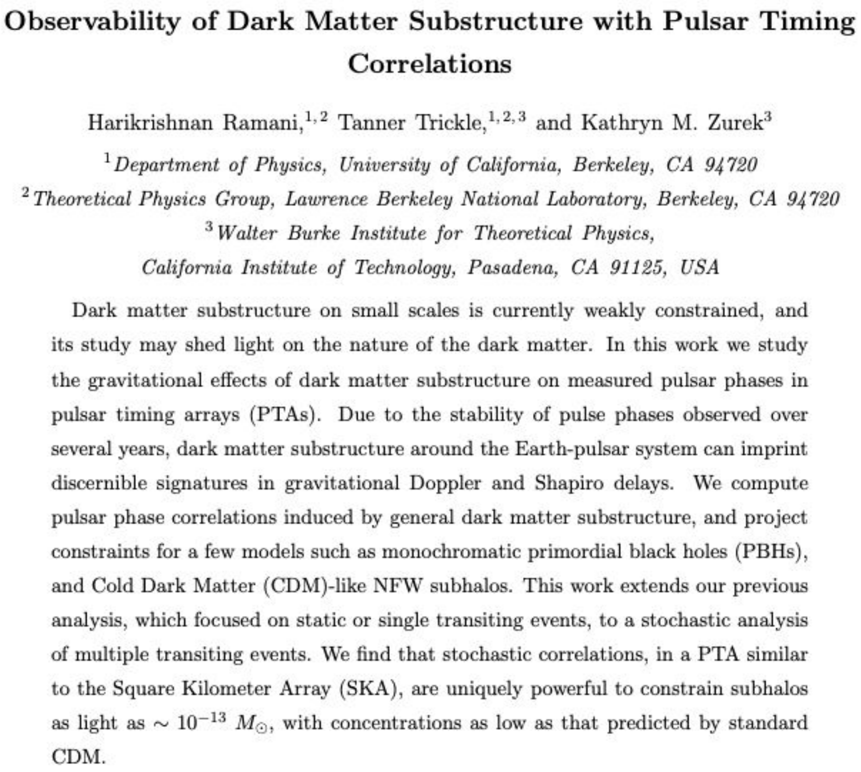
https://iopscience.iop.org/article/10.1086/323695/pdf

https://iopscience.iop.org/article/10.1088/0004-637X/767/1/9/pdf

https://academic.oup.com/mnras/article/339/3/607/970924

https://iopscience.iop.org/article/10.1086/421436/pdf

Pulsar Timing Correlations



Observability of Dark Matter Substructure with Pulsar Timing Correlations

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Dark matter substructure on small scales is currently weakly constrained, and its study may shed light on the nature of the dark matter. In this work we study the gravitational effects of dark matter substructure on measured pulsar phases in pulsar timing arrays (PTAs). Due to the stability of pulse phases observed over several years, dark matter substructure around the Earth-pulsar system can imprint discernible signatures in gravitational Doppler and Shapiro delays. We compute pulsar phase correlations induced by general dark matter substructure, and project constraints for a few models such as monochromatic primordial black holes (PBHs), and Cold Dark Matter (CDM)-like NFW subhalos. This work extends our previous analysis, which focused on static or single transiting events, to a stochastic analysis of multiple transiting events. We find that stochastic correlations, in a PTA similar to the Square Kilometer Array (SKA), are uniquely powerful to constrain subhalos as light as $\sim 10^{-13}\ M_\odot$, with concentrations as low as that predicted by standard CDM.

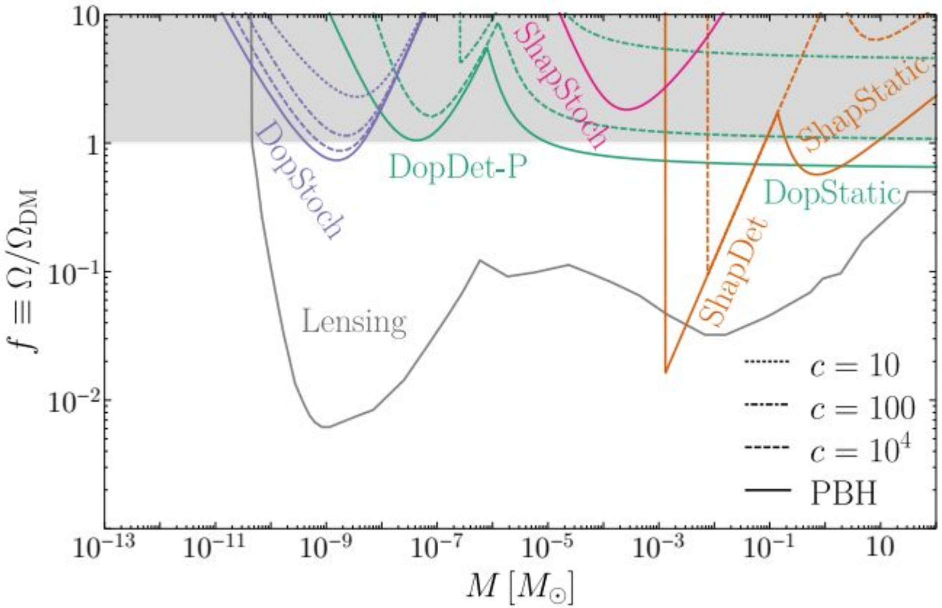

FIG. 2: Limits from PTAs on the dark matter mass fraction $f = \Omega/\Omega_{\rm DM}$ in subhalos of mass M for different subhalo concentration parameters, $c = 10, 100, 10^4$, and the PBH limit, $c \to \infty$. Results derived in Ref. [30] from deterministic single transiting objects and static signals are labeled 'DopDet-P', 'DopStatic', 'ShapDet', and 'ShapStatic' and shown in green and orange. The 'DopDet-P' and 'ShapDet' constraints have been weakened relative to Ref. [30] due to the subtraction procedure discussed in Appendix B. New results of this paper utilizing a stochastic signal induced by multiple transiting subhalos are labeled 'DopStoch' and 'ShapStoch', and shown in blue and pink, respectively. An SKA-like PTA, described in Sec. II C, with identical pulsars was assumed. Lensing constraints in gray are from Refs. [22–26, 53], and disappear for $c < 10^7$.

Probing the Small-Scale Matter Power Spectrum with Large-Scale 21-cm Data

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(Dated: March 18, 2020)

The distribution of matter fluctuations in our universe is key for understanding the nature of dark matter and the physics of the early cosmos. Different observables have been able to map this distribution at large scales, corresponding to wavenumbers $k \lesssim 10$ Mpc^{-1}, but smaller scales remain much less constrained. In this work we study the sensitivity of upcoming measurements of the 21-cm line of neutral hydrogen to the small-scale matter power spectrum. The 21-cm line is a promising tracer of early stellar formation, which took place in small haloes (with masses $M \sim 10^6 - 10^8 M_\odot$), formed out of matter overdensities with wavenumbers as large as $k \approx 100$ Mpc^{-1}. Here we forecast how well both the 21-cm global signal, and its fluctuations, could probe the matter power spectrum during cosmic dawn ($z = 12-25$). In both cases we find that the long-wavelength modes (with $k \lesssim 40$ Mpc^{-1}) are highly degenerate with astrophysical parameters, whereas the modes with $k = (40-80)$ Mpc^{-1} are more readily observable. This is further illustrated in terms of the principal components of the matter power spectrum, which peak at $k \sim 50$ Mpc^{-1} both for a typical experiment measuring the 21-cm global signal and its fluctuations. We find that, imposing broad priors on astrophysical parameters, a global-signal experiment can measure the amplitude of the matter power spectrum integrated over $k = (40-80)$ Mpc^{-1} with a precision of tens of percent. A fluctuation experiment, on the other hand, can constrain the power spectrum to a similar accuracy over both the $k = (40-60)$ Mpc^{-1} and $(60-80)$ Mpc^{-1} ranges even without astrophysical priors. The constraints outlined in this work would be able to test the behavior of dark matter at the smallest scales yet measured, for instance probing warm-dark matter masses up to $m_{\rm WDM} = 8$ keV for the global signal and 14 keV for the 21-cm fluctuations. This could shed light on the nature of dark matter beyond the reach of other cosmic probes.