Probing Dark Matter Substructure with Pulsar Timing Arrays

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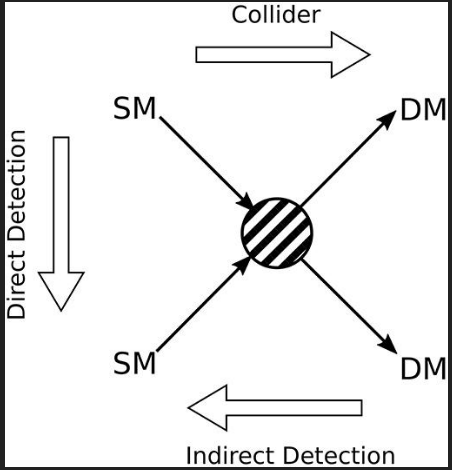
Introduction

- Nightmare scenario: DM does not interact with SM via anything but gravity
- Direct detection of DM would be extremely difficult… (not impossible)
- Do we have a way to distinguish between DM models using only gravity?

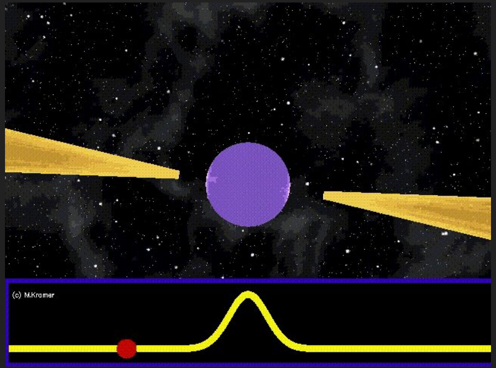
⇒ Pulsar timing arrays (PTAs)



Giagu (2019)

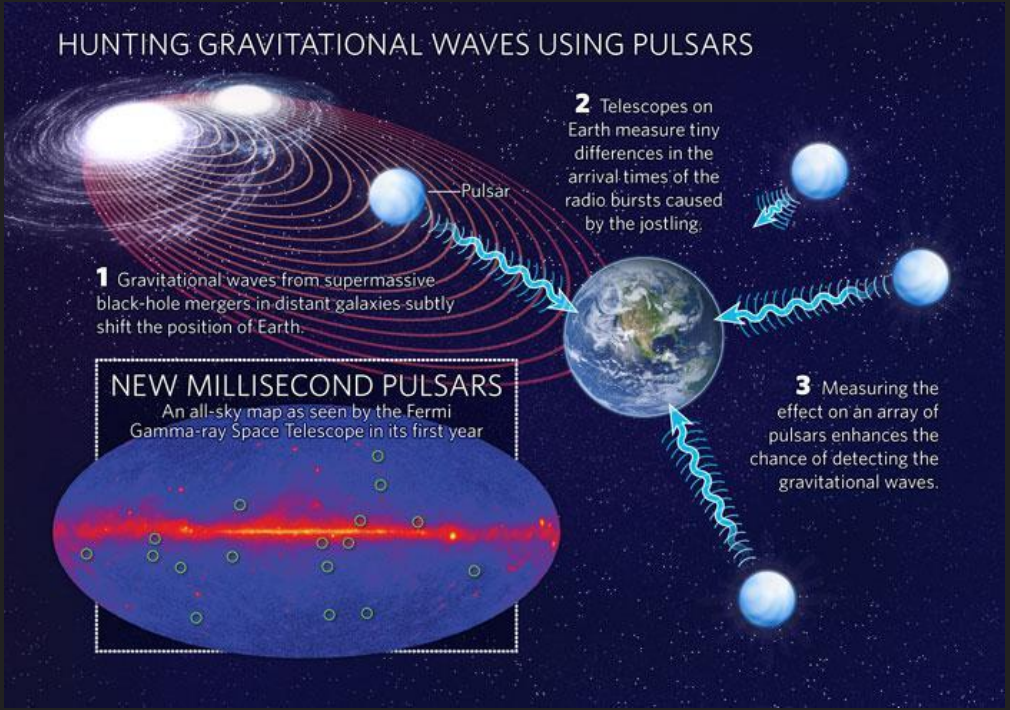
What are pulsars?

- Rapidly rotating neutron stars that emit electromagnetic radiation
- Very accurate clocks with well-understood timing models, stable rotational frequency across long periods of time (>20 years)
- Can be used to detect astrophysical phenomenon by studying time-of-arrivals (TOAs)
- We are mostly interested in millisecond pulsars



[Image: Michael Kramer]

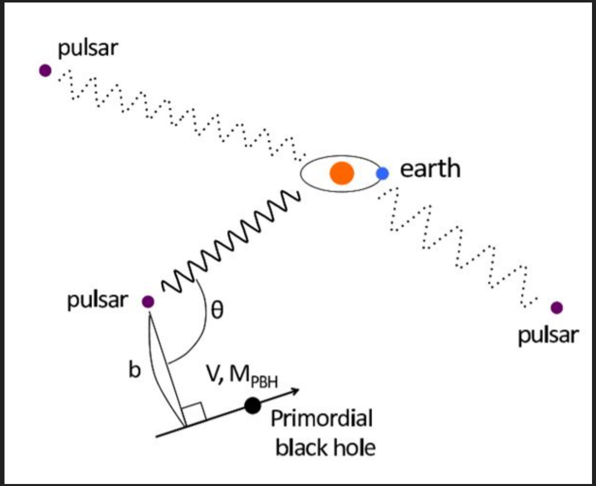
Pulsar Timing Array



[Image: NASA/DOE/FERMI/ LAT Collaboration]

Dark Matter Signals

- Dark matter (DM) subhalos induce a gravitational acceleration to the pulsar
- The pulsar frequency is shifted due to Doppler effect



[Kashiyama and Seto (2012) 1208.4101]

Comparison of different models

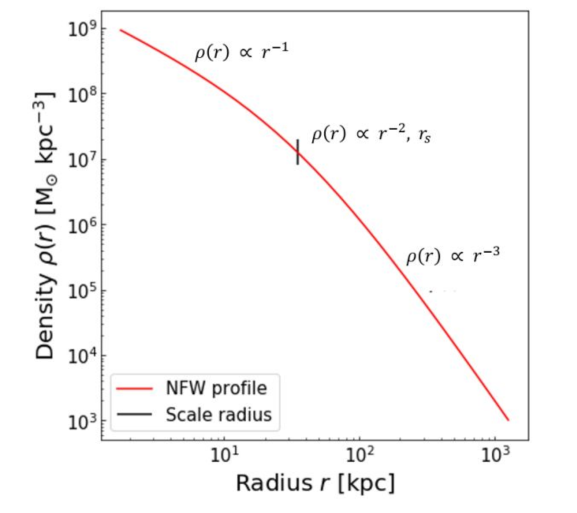
Dark matter subhalo signals for specific dark matter models have two distinctive characters

- (sub)-halo mass function: statistical distribution of halo as a function its mass (e.g. for ΛCDM, the mass function is dn/dlogM~M^{-2})

  - can be estimated using the Press-Schechter formalism [Press and Schechter (1974) ApJ 1874, 425]

- density profile: Navarro-Frenk-White (NFW) profile [Navarro, Frenk and White (1996) astro-ph/9508025]

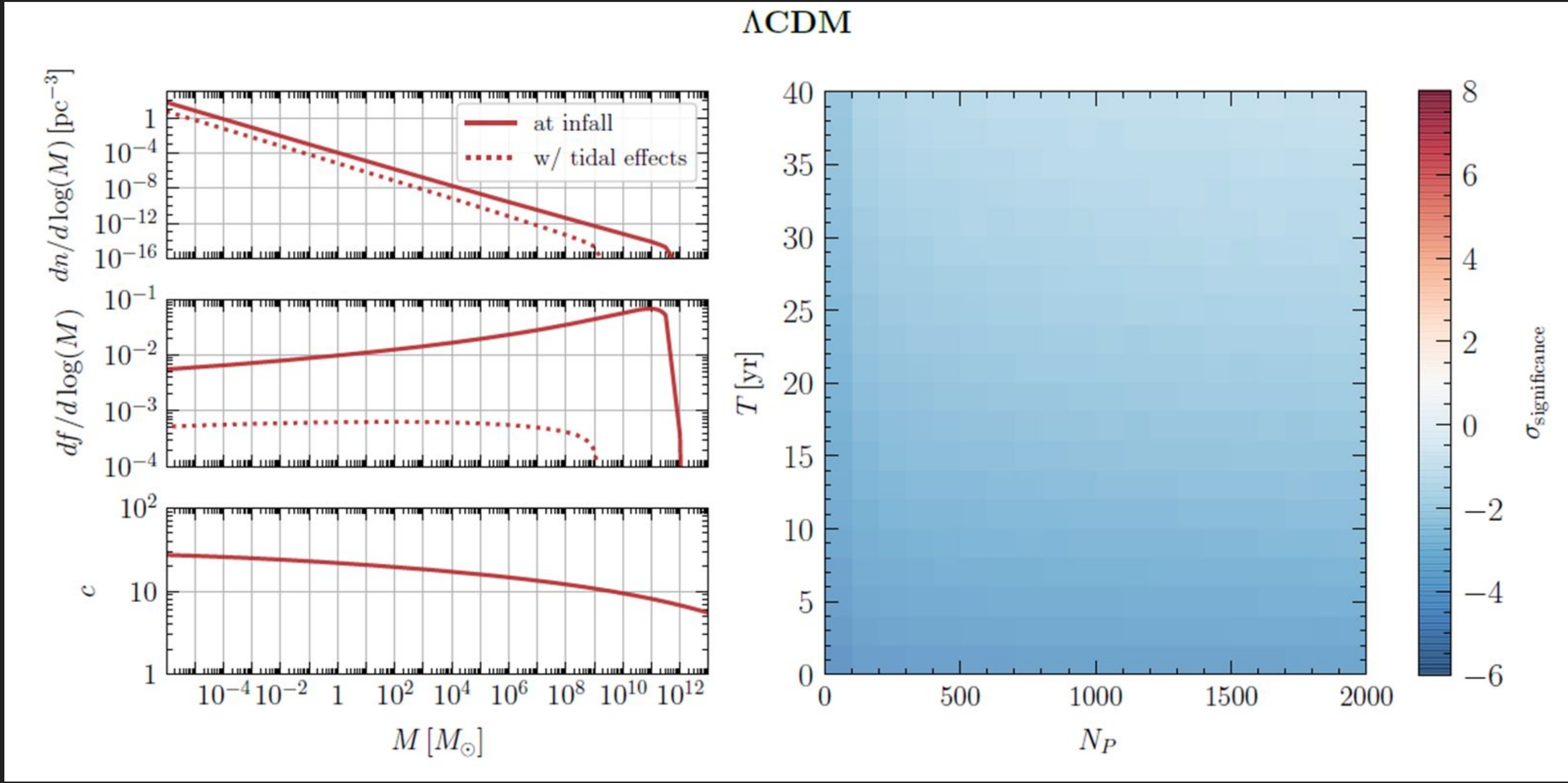
NFW profile



[Lund (2020)]

ΛCDM subhalos are too weak to be detected by PTAs

ΛCDM projection from Monte Carlo Simulations



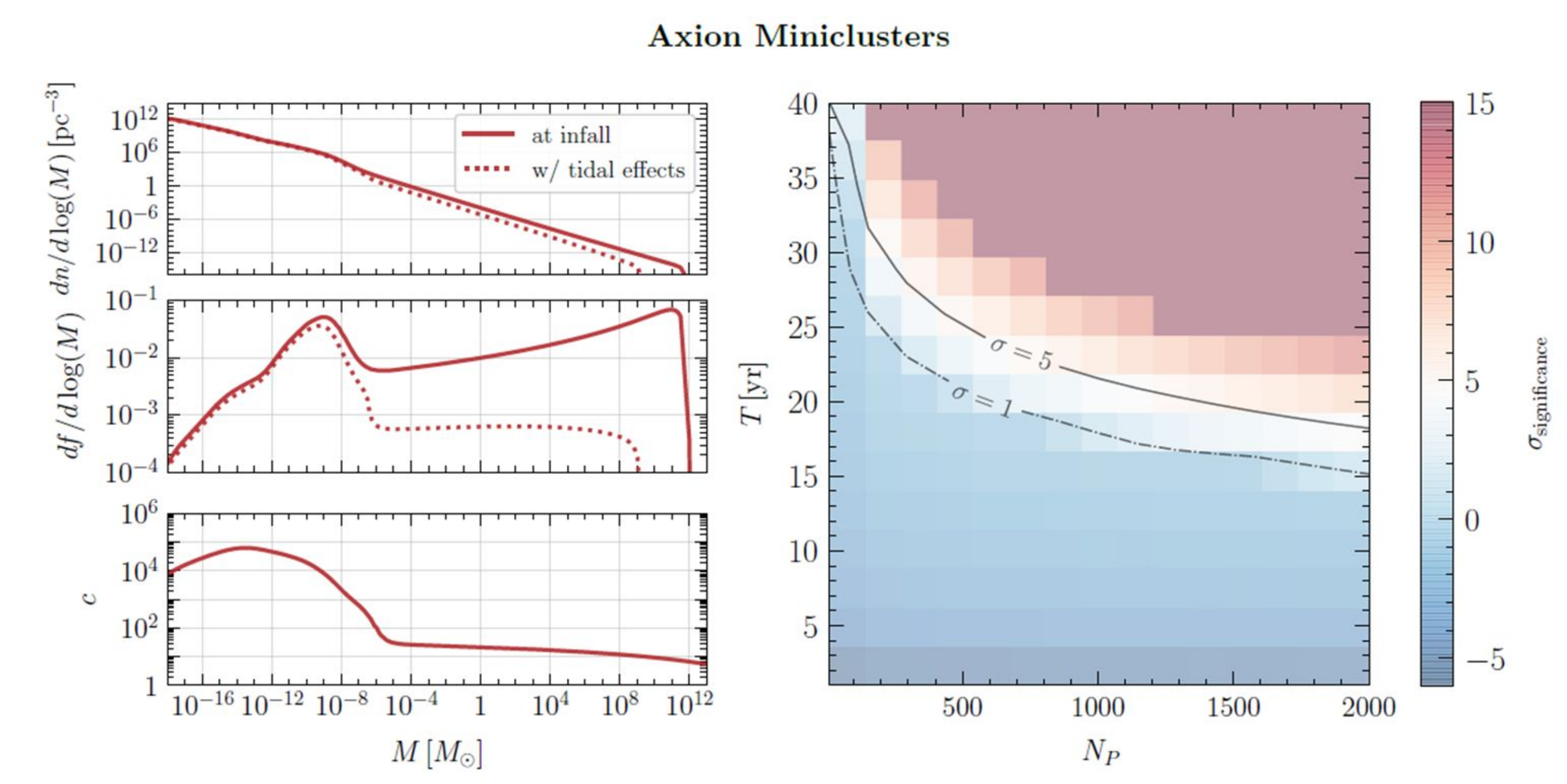
[VL, Mitridate, Trickle and Zurek (2020) 2012.09857]

Enhanced Power Spectrum

- Some DM models exhibit enhanced power spectrum at small scale (<pc)
- e.g. post-inflationary QCD Axion [Hogan and Ress (1988), Phys. Lett. B 205, 228]
- Other models: early matter domination (EMD) [Erickcek and Sigurdson (2011), 1106.0536], vector dark matter [Graham,Mardon and Rajendran (2015), 1504.02102]
- Disruption of DM subhalos due to tidal disruption and stellar disruption
- Survival rate of subhalos for first two models: ~80% in number in the solar neighborhood [Shen, Xiao, Hopkins and Zurek (2023), 2207.11276] by N-body simulation + analytic methods

Power spectrum from
[Vaquero, Redondo and Stadler (2019), 189.09241]

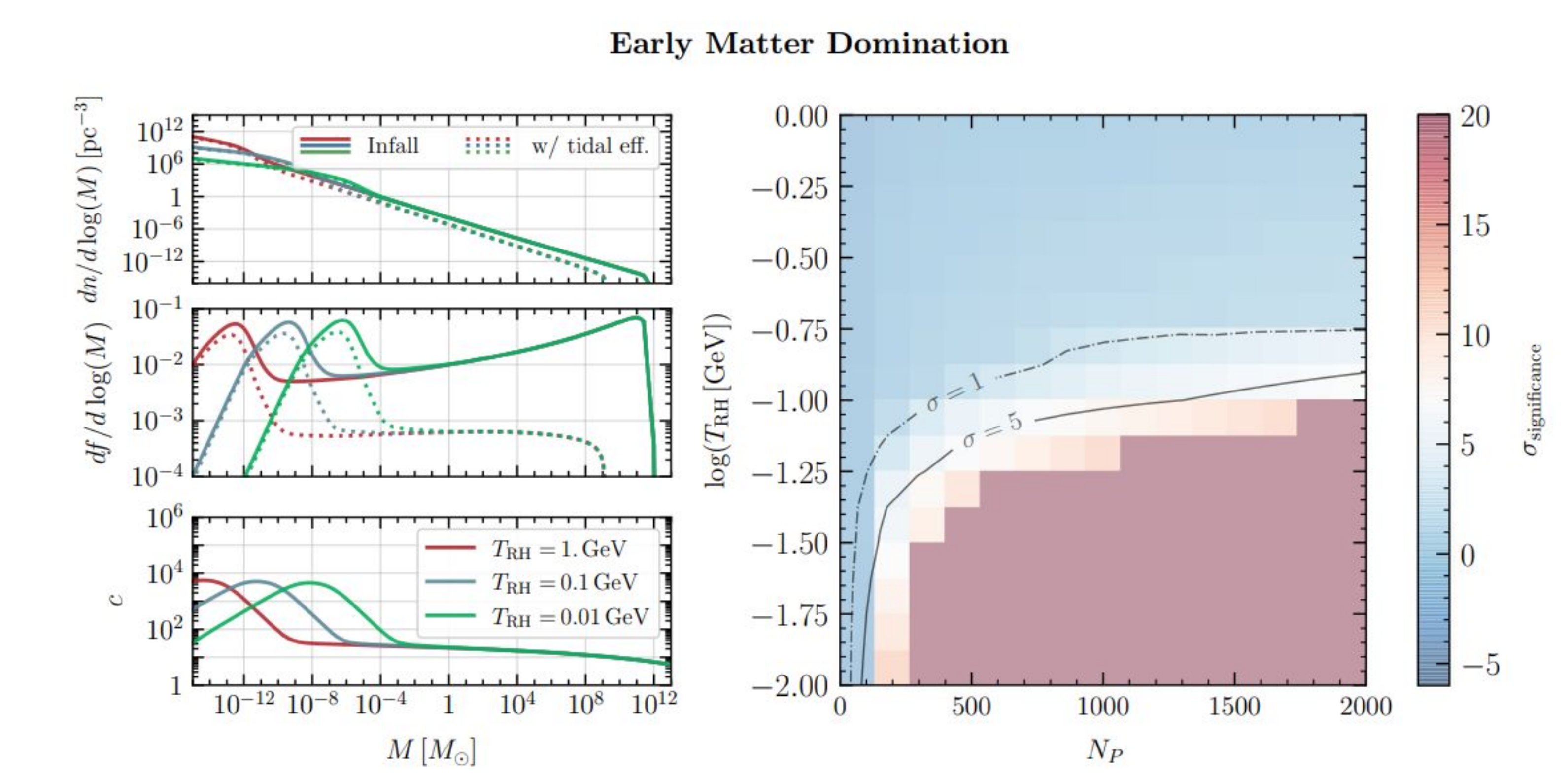
Axion Minicluster



[VL, Mitridate, Trickle and Zurek (2020) 2012.09857]

Early Matter Domination

Power spectrum from
[Erickcek and Sigurdson (2011), 1106.0536]



[VL, Mitridate, Trickle and Zurek (2020) 2012.09857]

Monte Carlo (MC) Simulation Code

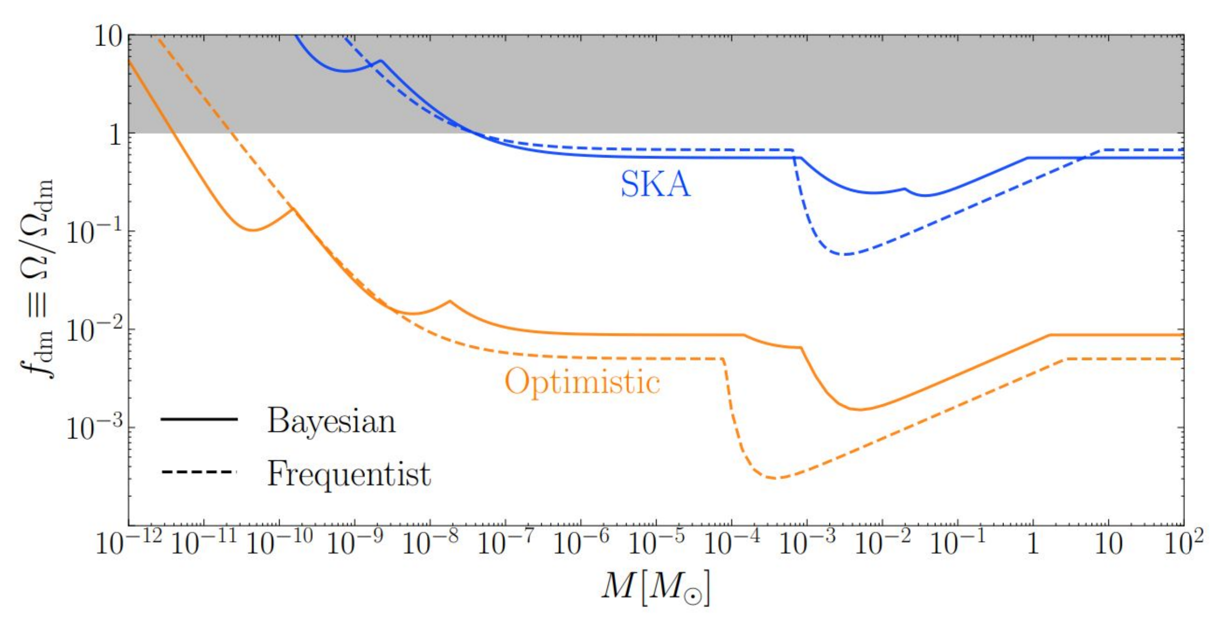
- Randomly distribute DM halos and compute the total time shifts from all halos
- Publicly available at: https://github.com/szehiml/dm-pta-mc

(more) Realistic PTA data

- Previous plots are projected SNR computed using our MC code
- The PTA community has their pipeline in searching for gravitational-wave signal with real PTA data

- We developed a Bayesian framework [VL, Taylor, Trickle and Zurek (2021) 2104.0577] to combine our MC code with NANOGrav's analysis pipeline, and computed SNR projections on point-mass DM subhalos using mock data (current data is not yet sensitive enough to subhalos)

Projected Constraints with mock data injected with white noise



[VL, Taylor, Trickle and Zurek (2021) 2104.0577]

Injection of red noise leads to a deterioration of constraints by ~1 order of magnitude with the current method. Smarter analysis method in mitigating the red noise is needed (work in progress).

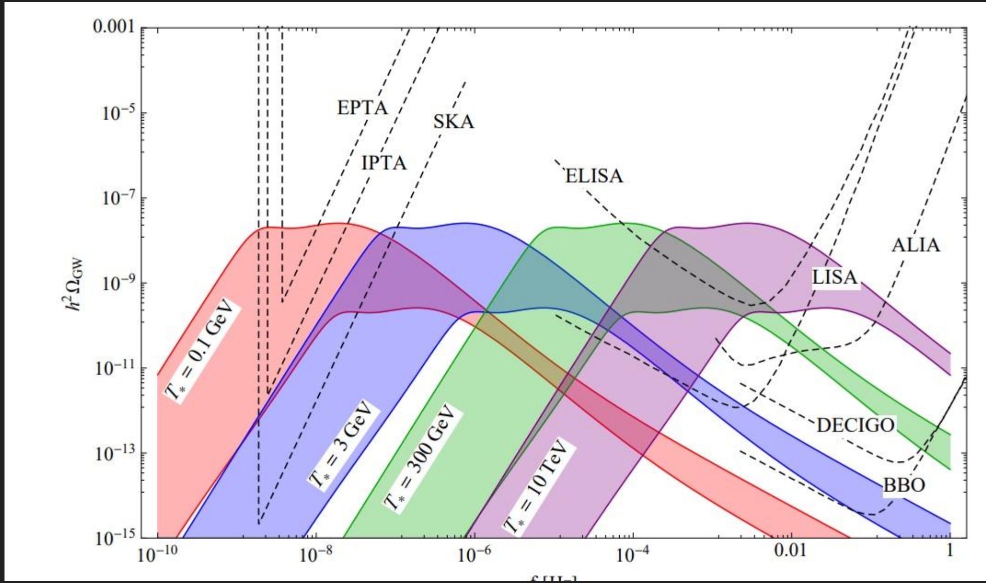
What can we learn about dark matter using existing PTA data?

1. Cosmological Phase Transition

2. Long-range DM-baryon interaction (fifth force)

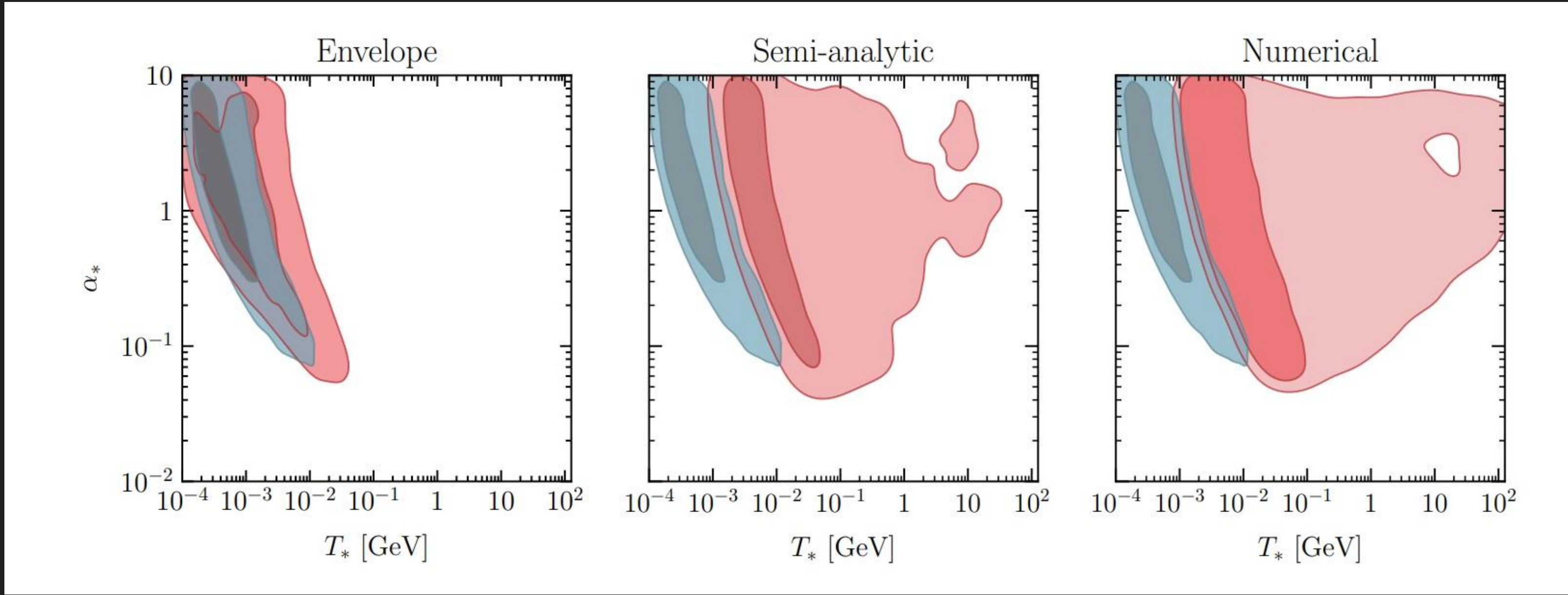
1. Cosmological Phase Transition

- A first-order phase transition in the early universe will produce a stochastic gravitational wave background
- NANOGrav's sensitivity corresponds to a phase transition temperature just below the electroweak scale (~100 GeV)
- However, a large class of dark sector models feature first-order phase transitions (e.g. SIMP [Hochberg et al. (2014) 1402.5143, Schwaller (2015) 1504.07263], SU(5) asymmetric dark matter [Murgui and Zurek (2021) 2112.08374])



[Schwaller (2015) 1504.07263]

Current Constraint



[NANOGrav (2022) 2104.13930]

- Constraints derived using the NANOGrav's 12.5-yr dataset [NANOGrav (2020) 2005.06490, 2009.04496], which found strong evidence (Bayes factor > 10000) for common red-noise process across pulsars, but no evidence for Hellings-Downs correlation
- Instead of specific models, we parameterize the gravitational wave spectrum with a few phase transition parameters [Jinno and Takimoto (2016) 1605.01403; Lewicki and Vaskonen (2021) 2012.07826; Cutting et al. (2021) 2005.13537]

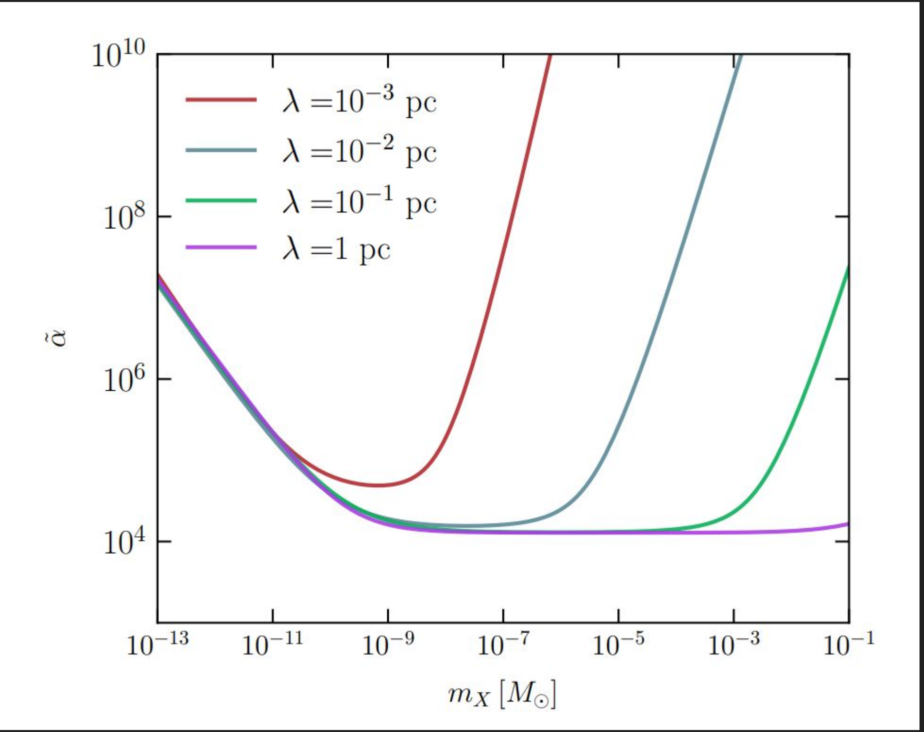
2. Long-range DM-Baryon Interaction

- Attractive fifth-force between DM subhalos and baryons can be much stronger than gravity
- e.g. asymmetric dark matter (ADM) nuggets [Gresham, Lou and Zurek (2018) 1805.04512]
-
- Yukawa force $$V_{\rm Yuk}(r) = -\tilde{\alpha}\frac{GMm_X}{r}e^{-r/\lambda}$$

- Can arise from a very general effective Lagrangian: $\mathcal{L} \supset g_X\phi\bar{X}X + g_n\phi\bar{n}n$
- PTAs are sensitive to λ>~ 10^{-3} pc (mediator mass m_ϕ<~10^{-21} eV)

Current Constraints

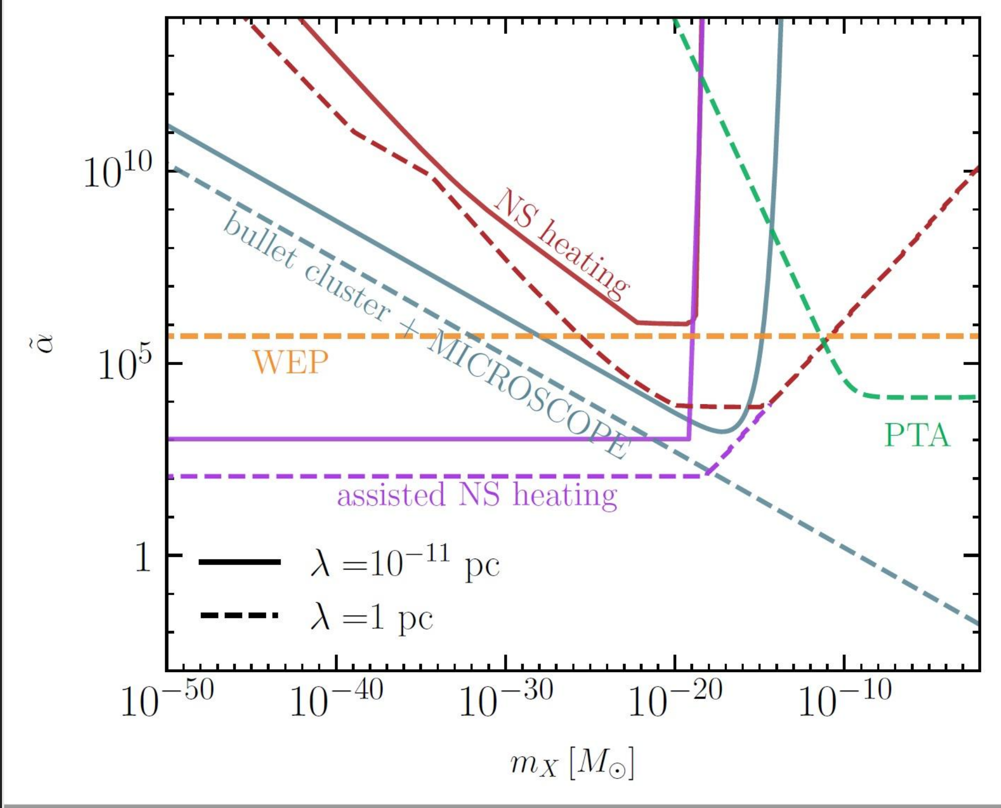
- 90-th percentile constraints derived using the NANOGrav's 11-yr dataset [NANOGrav (2018), 1801.01837, 1801.02617]
- Expect the constraint to further improve with new data



[Gresham, VL, and Zurek (2023) 2209.03963]

Other Existing Constraints

- Bullet cluster [Spergel and Steinhardt (2000) astro-ph/9909386] + MICROSCOPE [Bergé et al (2018) 1712.00483] is a combined constraints based on DM-DM and baryon-baryon constraints
- If only a sub-component (e.g. ~O(1%)) of DM is charged under fifth force, then the bullet cluster constraint does not apply, but the other constraints only deteriorate linearly with the subcomponent fraction



[Gresham, VL, and Zurek (2023) 2209.03963]

Conclusions

- Pulsar Timing Arrays are powerful tools in studying DM, both in the present and in the future

Future directions:

- Mitigate the effects of red noise
- Search for stochastic DM signals [Ramani, Trickle and Zurek (2020) 2005.03030] with real PTA data

Thank You!

Backup Slides

Pulsar Timing Arrays (PTAs)

- Accurate timing measurements on multiple pulsars
- Current experiments

Square Kilometer Array (SKA)

- Radio telescope based in Africa and Australia
- Projected to be able to observe ~200 pulsars
- Benchmark for experimental parameters

[Image: SKA Observatory]

Result: SKA Reach

- Assumes monochromatic mass
- SKA parameters (with white noise):

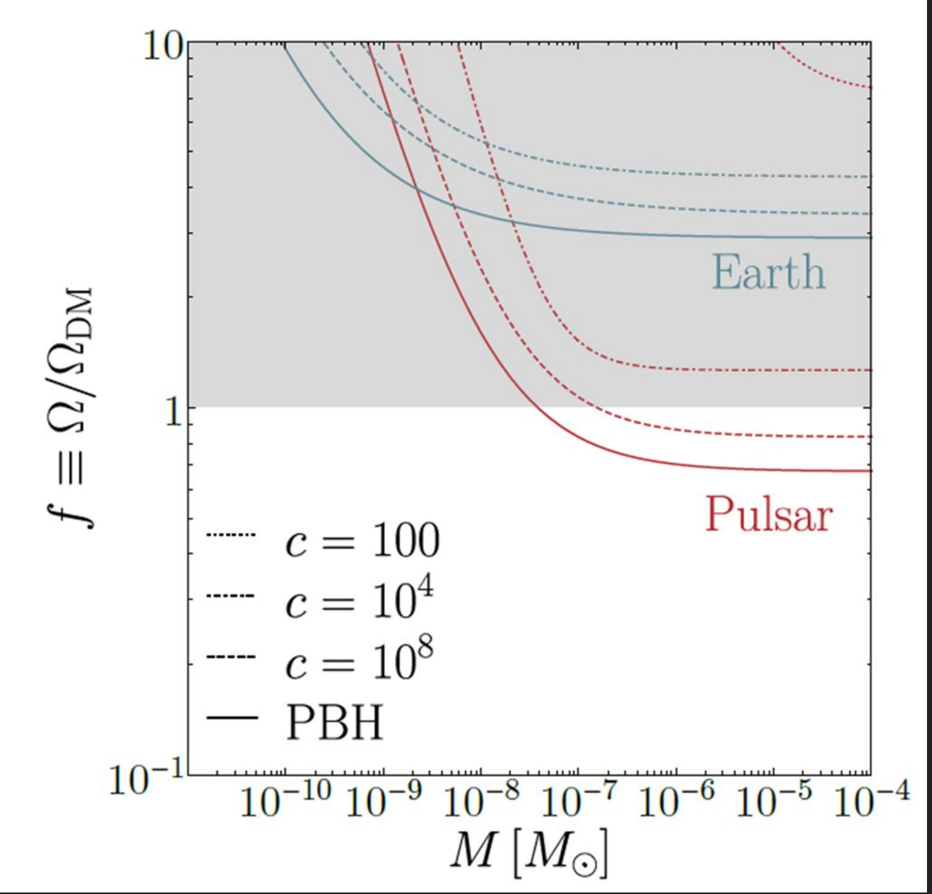
200 pulsars

20 years of observation

5 kpc of pulsar distance

2 weeks of cadence

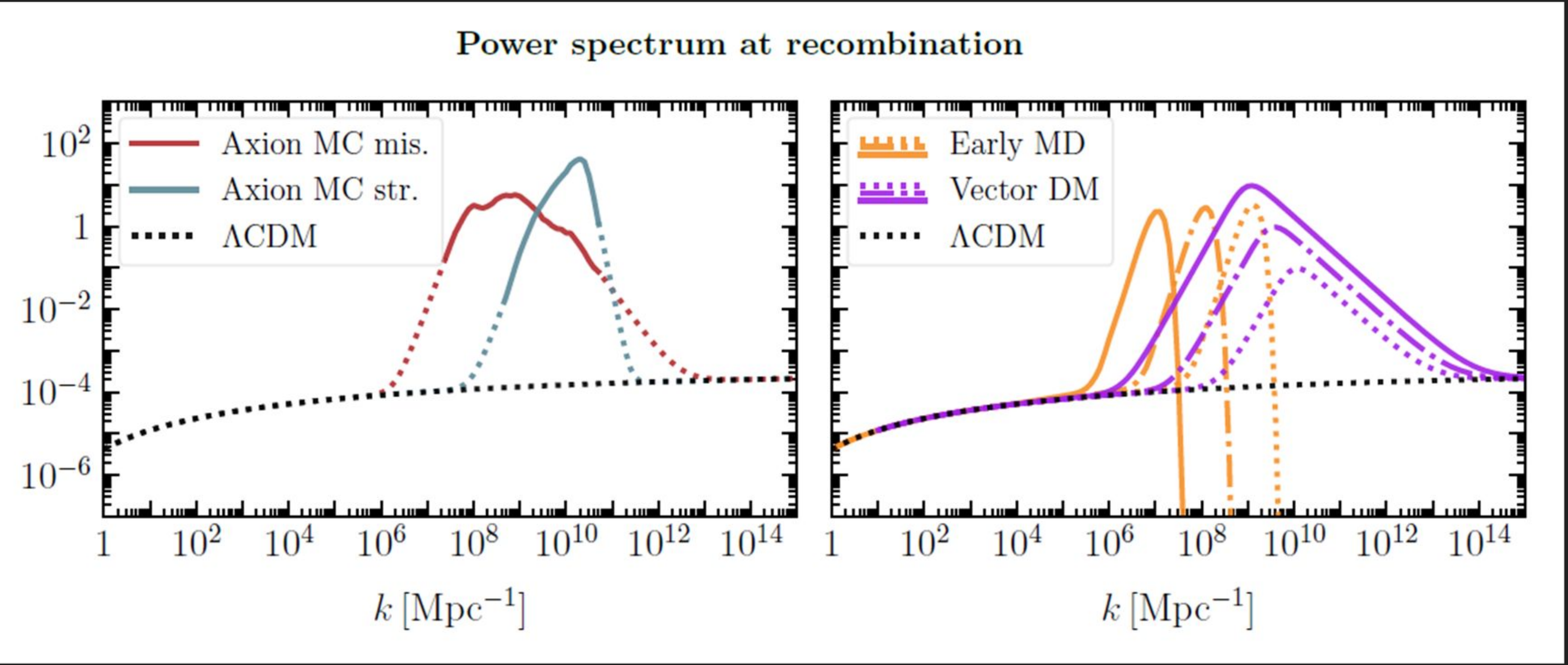
50 ns of rms time measurements



[VL, Mitridate, Trickle and Zurek (2020) 2012.09857]

Enhanced Power

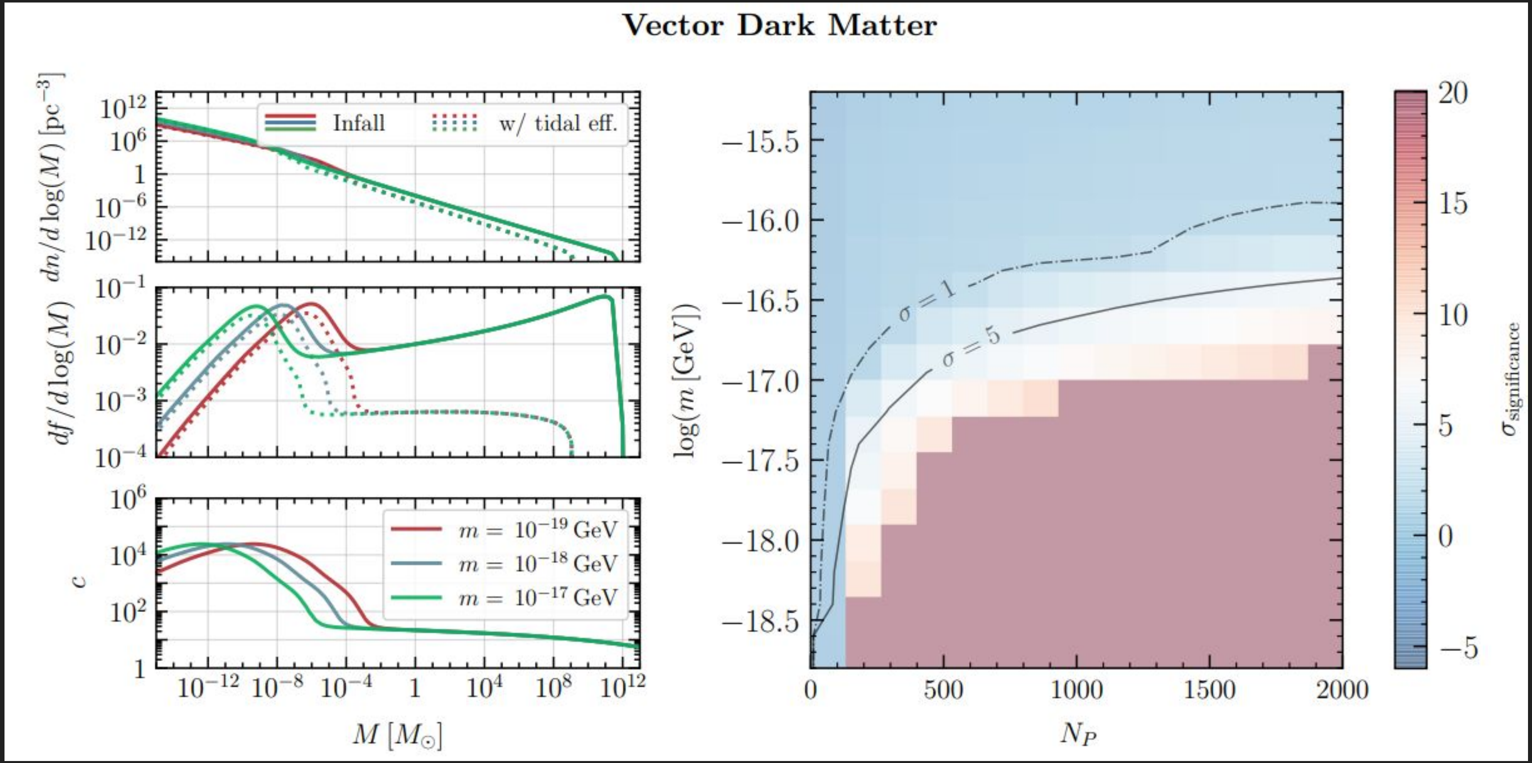
same power for large scale, but enhanced at small scale (k >= 1/pc)



[VL, Mitridate, Trickle and Zurek (2020) 2012.09857]

Vector Dark Matter

Power spectrum from
[Graham,Mardon and Rajendran (2015), 1504.02102]



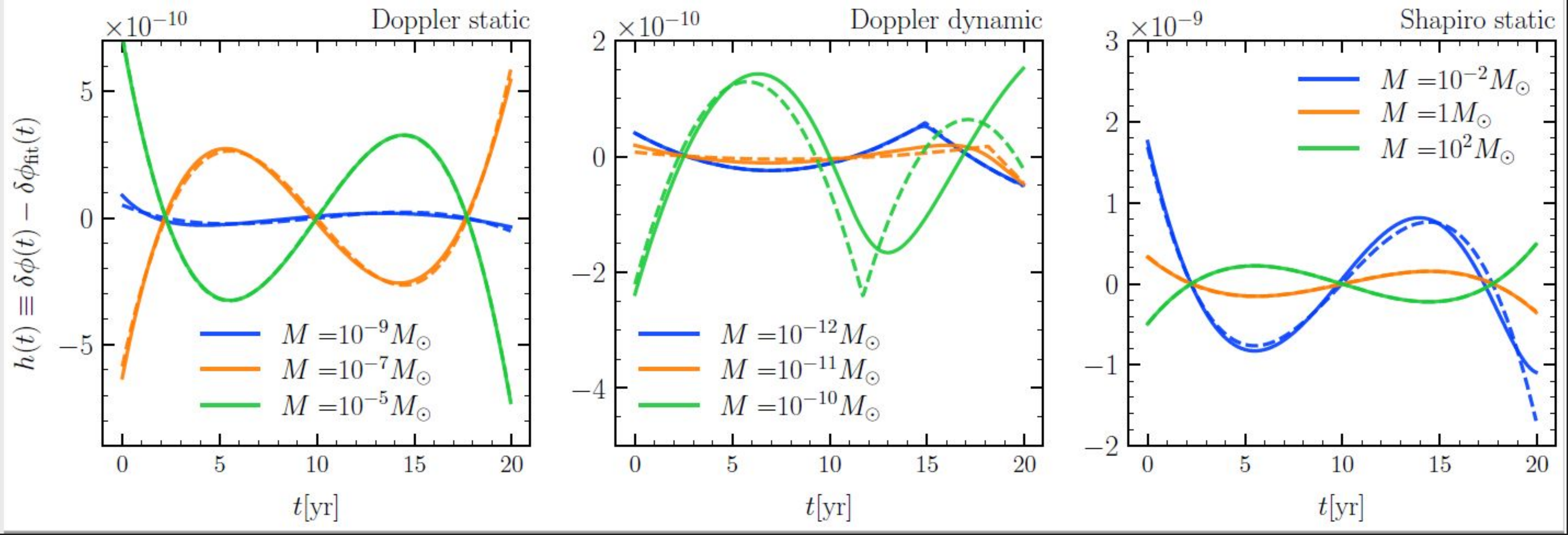
[VL, Mitridate, Trickle and Zurek (2020) 2012.09857]

Parameterization of DM Signals

solid: numerical signal shape from MC
dashed: analytic approximation

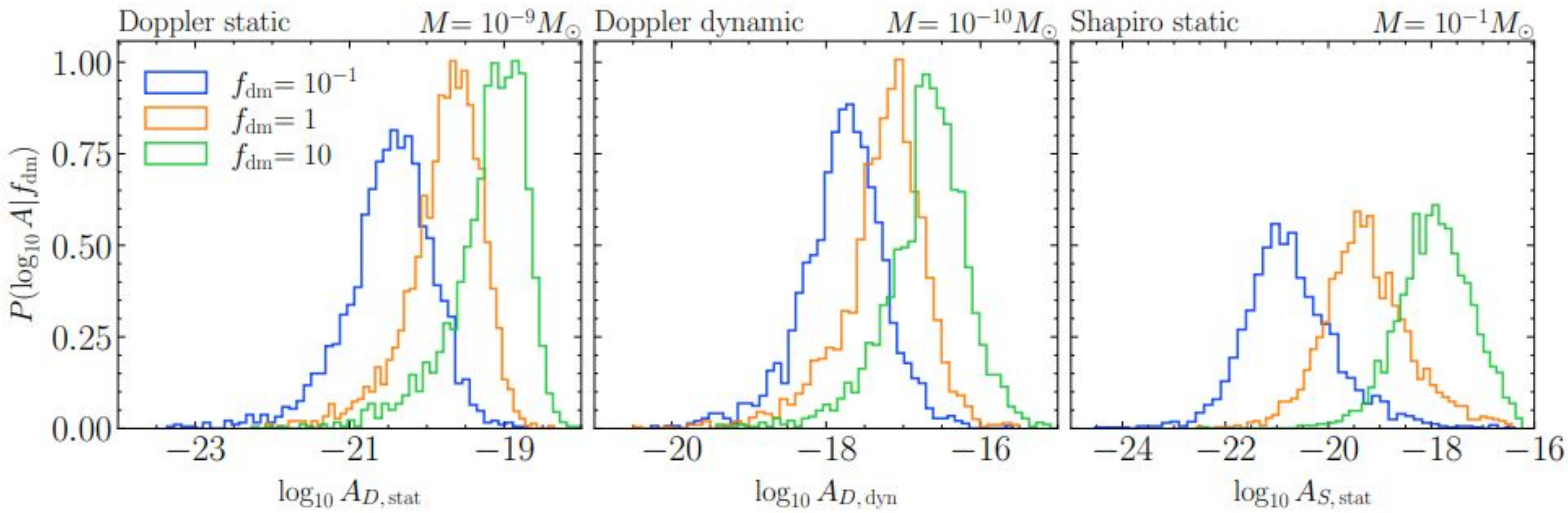
DM amplitudes should be treated as random variables

$$\frac{\delta\phi_{D,\,\mathrm{stat}}(t)}{\nu} = \frac{A_{D,\,\mathrm{stat}}}{\mathrm{yr}^2}t^3 \qquad \frac{\delta\phi_{D,\,\mathrm{dyn}}(t)}{\nu} = A_{D,\,\mathrm{dyn}}(t-t_{D,0})\Theta(t-t_{D,0}) \qquad \frac{\delta\phi_{S,\,\mathrm{stat}}(t)}{\nu} = \frac{A_{S,\,\mathrm{stat}}}{\mathrm{yr}^2}t^3$$



[VL, Taylor, Trickle and Zurek (2021) 2104.0577]

Probability Distribution function of DM amplitude

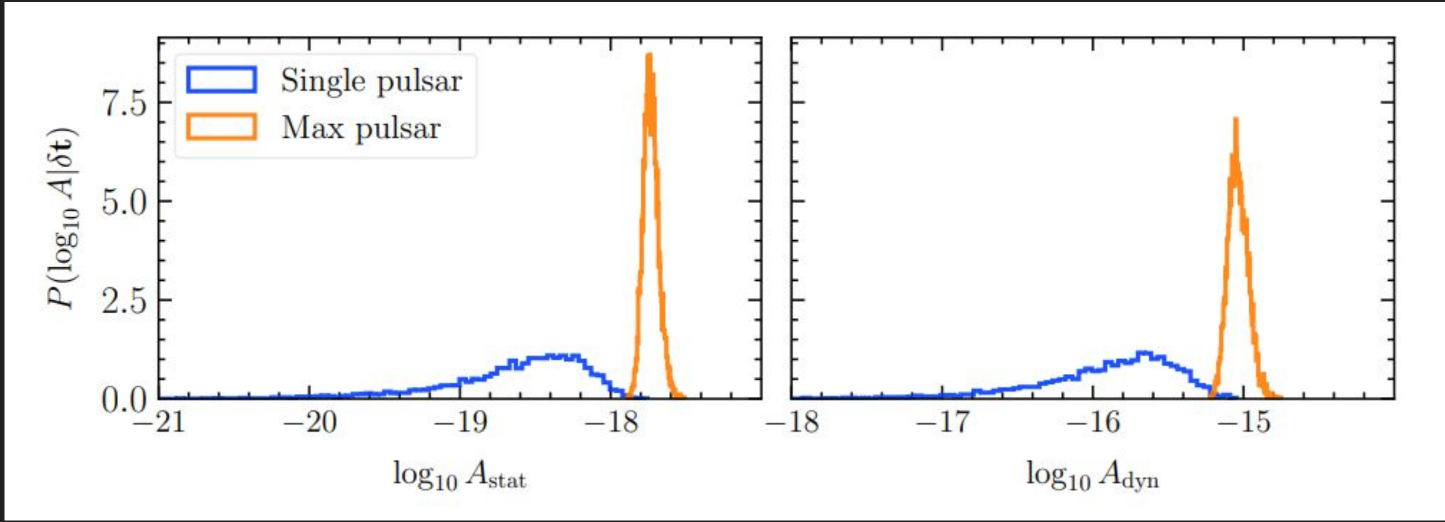


[VL, Taylor, Trickle and Zurek (2021) 2104.0577]

Data Analysis with realistic PTA data

We use NANOGrav's flagship Bayesian data analysis code "enterprise"

- Given a timing signal with some parameter and some priors, the code returns its posterior distribution while marginalizing other nuisance parameters



White noise only, SKA parameters, 200 pulsars

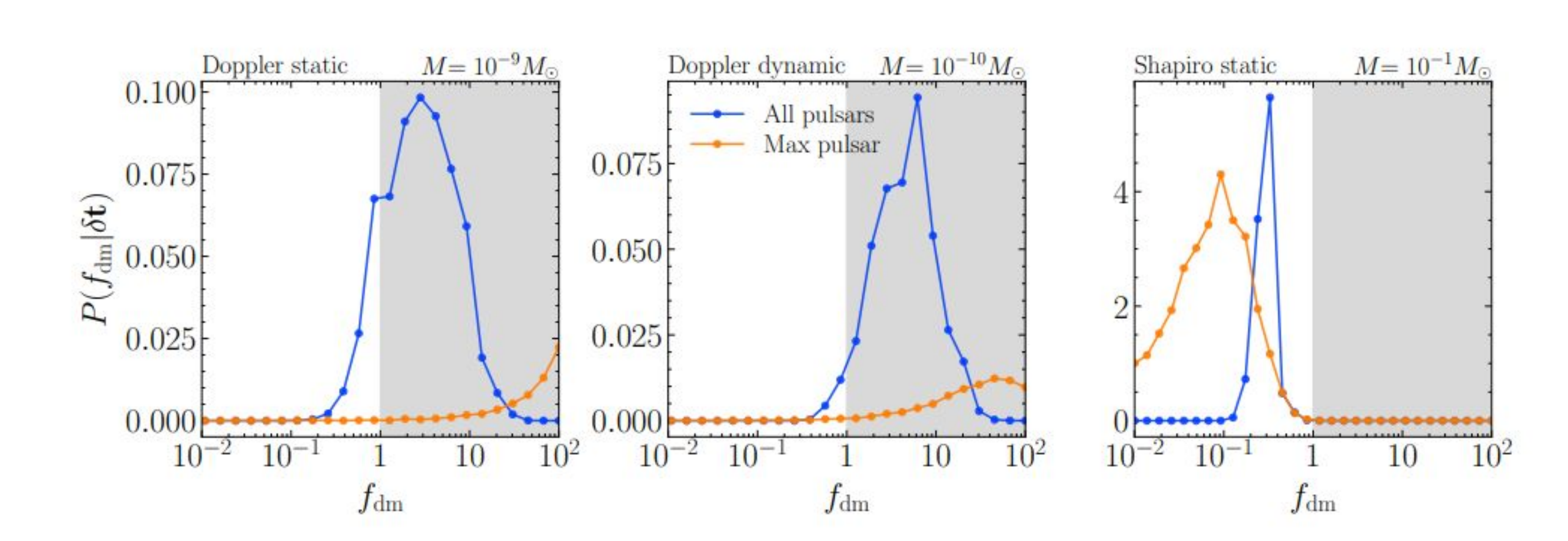
[VL, Taylor, Trickle and Zurek (2021) 2104.0577]

Upper limits on f

$$P_{\rm all}(f_{\rm dm}|\delta\mathbf{t}) \propto \prod_{i=1}^{N_P} \int_{-\infty}^{\infty} P(A_i|f_{\rm dm}) P(A_i|\delta\mathbf{t}) dA_i$$

$$P_{\rm max}(f_{\rm dm}|\delta\mathbf{t}) \propto \int_{-\infty}^{\infty} P(A_{\rm max}|f_{\rm dm}) P(A_{\rm max}|\delta\mathbf{t}) dA_{\rm max}$$

Upper limit on dark matter fraction *f* can be computed by combining the MC result and the enterprise result



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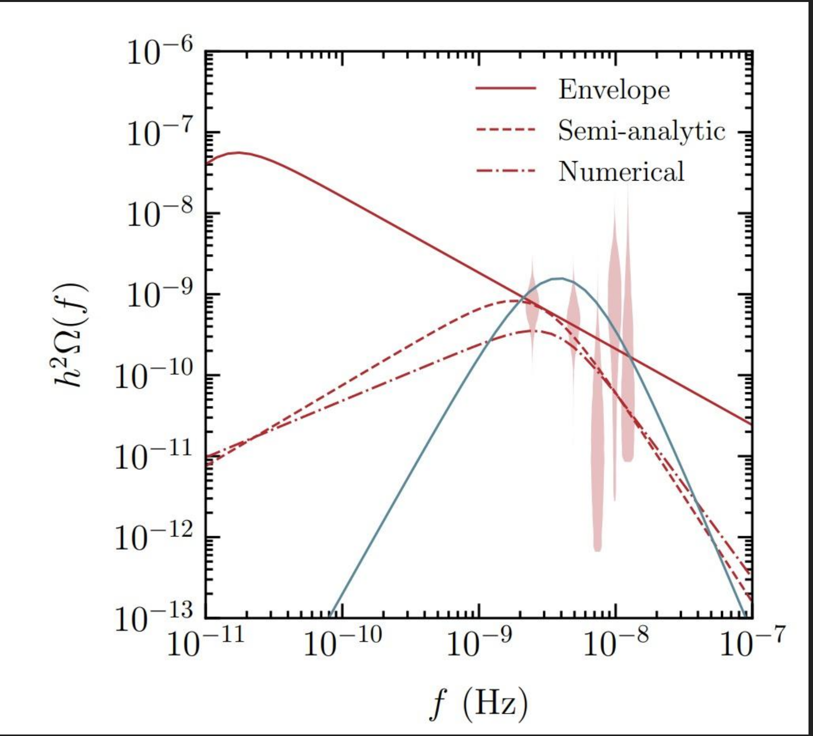
Phase transition spectrum



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