Probing Dark Matter 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)
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
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 of its mass (e.g. for ΛCDM, the mass function is \(dn/d\log M \sim M^{-2}\))

- density profile: Navarro-Frenk-White (NFW) profile

[NFW profile] [Lund (2020)]
$\Lambda$CDM projection from Monte Carlo Simulations

$\Lambda$CDM subhalos are too weak to be detected by PTAs

[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]
Axion Minicluster

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

[VL, Mitridate, Trickle and Zurek (2020) 2012.09857]
Real 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
NANOGrav recently found positive evidence (3.5-4 sigma) for the presence of a low-frequency GW background using the 15-yr dataset (67 pulsars) [NANOGrav (2023) 2306.16213 “GWB”]

- No evidence for deterministic signals -> upper limits are reported [NANOGrav (2023) 2306.16219 “New Physics”]
NANOGrav 15-yr Data

[Image]

[NANOGrav (2023) 2306.16219 “New Physics”]
What other things can we learn about dark matter using existing PTA data?

1. Cosmological Phase Transition
2. Long-range DM-baryon interaction (fifth force)
3. Ultralight Dark Matter (ULDM)
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]).
If the observed GWB originates from phase transition...

Bayes factor against SMBHB interpretation ~20

[NANOGrav (2023) 2306.16219 “New Physics”]
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 \[\text{[Gresham, Lou and Zurek (2018) 1805.04512]}\]
- Yukawa force

\[
V_{\text{Yuk}}(r) = -\alpha \frac{GMm_X}{r} e^{-r/\lambda}
\]

- 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 $\lambda > 10^{-3}$ pc (mediator mass $m_\phi < 10^{-21}$ eV) \[\text{[Gresham, VL, and Zurek (2023) 2209.03963]}\]
Current Constraints

- $\lambda = 10^{-3} \sim 1\,\text{pc}$
- If only a sub-component (e.g. $\sim O(1\%)$) 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

[NANOGrav (2023) 2306.16219 “New Physics”]
Ultralight Dark Matter (ULDM)

ULDM can give rise to signals in PTA via a few different mechanisms

- Metric fluctuation [Khmelnitsky and Rubakov (2013), 1309.5888]
- Pulsar spin fluctuation [Kaplan, Mitridate and Trickle (2022), 2205.06817]
Current Constraints

\[ (2S_\phi + 1) \rho_\phi = 0.4 \text{ GeV/cm}^3 \]

[NANOGrav (2023) 2306.16219 “New Physics”]
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 ($k \geq 1/pc$)

[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

DM amplitudes should be treated as random variables

\[
\begin{align*}
\frac{\delta \phi_D, \text{stat}(t)}{\nu} &= A_{D, \text{stat}} \frac{t^3}{\nu} \\
\frac{\delta \phi_D, \text{dyn}(t)}{\nu} &= A_{D, \text{dyn}} (t - t_{D,0}) \Theta(t - t_{D,0}) \\
\frac{\delta \phi_S, \text{stat}(t)}{\nu} &= A_{S, \text{stat}} \frac{t^3}{\nu}
\end{align*}
\]

[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.
Upper limits on $f$

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

$$P_{m}(f_{dm} | \delta t) \propto \prod_{i=1}^{N_{P}} \int_{-\infty}^{\infty} P(A_{i} | f_{dm}) P(A_{i} | \delta t) dA_{i}$$

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

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

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

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

[Phase transition spectrum image]

[NANOGrav (2022) 2104.13930]