Title: Dark Matter Substructure as a Window to Fundamental Physics (Virtual)

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Abstract:

The matter power spectrum on subgalactic scales is very weakly constrained so far. While inflation predicts a nearly scale-invariant primordial power spectrum down to very small scales, many new physics scenarios can lead to significantly different predictions, such as axion dark matter in the post-inflationary scenario, vector dark matter produced during inflation, early matter domination, kinetic misalignment axions, self-interacting dark matter, atomic dark matter, etc. Therefore, any successful measurement on the matter power spectrum tests inflation extensively and probes early universe dynamics and the nature of dark matter, making it a new frontier in cosmology and dark matter physics. We proposed observing fast radio bursts (FRB) with solar-system scale interferometry by sending radio telescopes to space, which allows us to greatly expand the sensitivity on the matter power spectrum from Mpc to AU scales. Two sightlines looking at the same FRB source can sample different regions of the Universe in the transverse direction and thus obtain an arrival time difference that depends on the matter power spectrum. Our calculations show that this setup will be sensitive to the scale-invariant power spectrum predicted by inflation on small scales and can also probe QCD axion miniclusters predicted in the post-inflationary scenario.

Dark Matter Substructure as a Window to Fundamental Physics

Huangyu Xiao, Fermilab and U Chicago

Perimeter Institute Particle Theory Seminar

Outline

1. Overview of dark matter substructures
2. Dark matter substructures from axions (axion miniclusters and axion stars)
3. New detection ideas: Fast Radio Burst Timing
4. Conclusion

Dark Matter substructures

- The large scale structure agrees well with primordial power spectrum from inflation.
- Substructures, refer to dark matter halos or structures on much smaller scales.
- **Very little** observational constraints so far on dark matter substructures.

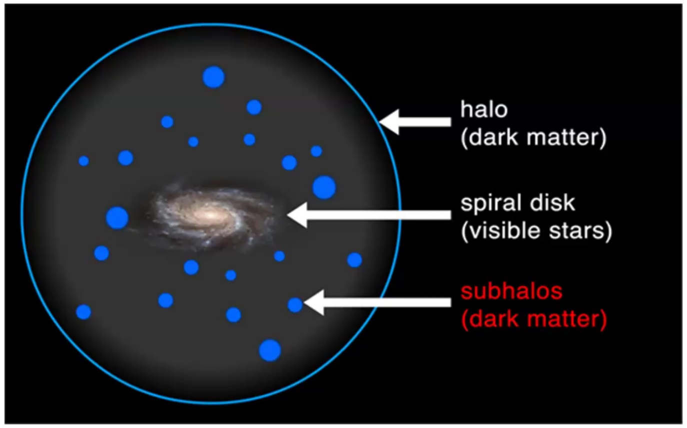
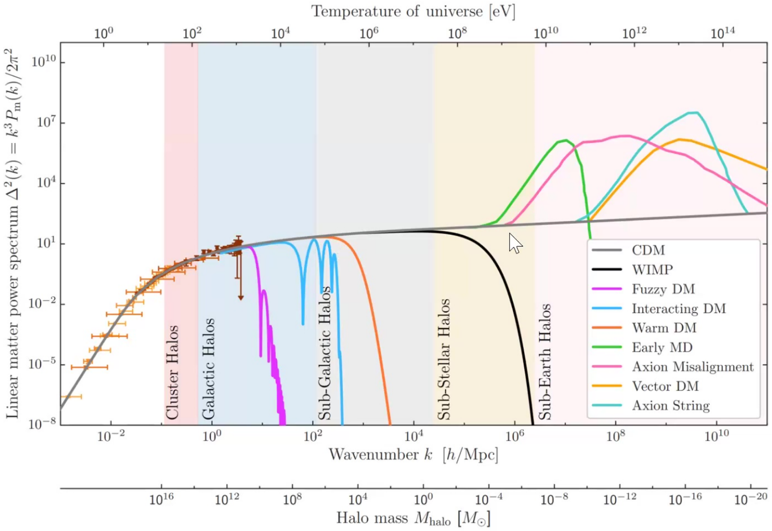


Image source: https://kids.frontiersin.org/.

Dark matter substructures are very weakly constrained

- The current matter power spectrum at $k > 10\ \mathrm{Mpc}^{-1}$ is weakly constrained.
- Contains information about early Universe or dark matter physics.
- Not yet tested the prediction of inflation on small scales.



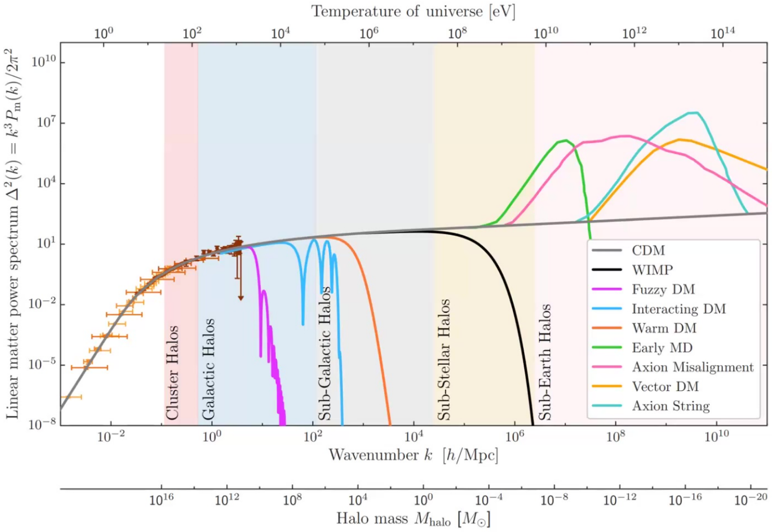
Snowmass2021 Cosmic Frontier White Paper: Dark Matter Physics from Halo Measurements, arXiv: 2203.07354

DM substructure as a probe of dark matter physics

1. Axions
- Vacuum misalignment mechanism if the symmetry breaking is after inflation
- Large misalignment mechanism and kinetic misalignment mechanism;

2. Vector DM produced during inflation;

3. Warm dark matter; Fuzzy dark matter; Self-interacting dark matter



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Current Ideas of Detecting DM Substructures

Subgalactic scales

- Weak lensing of the apparent motions of stars (K. Van Tilburg, A. Taki, N. Weiner, 2018)
- Dynamical heating of stars in ultra-faint dwarfs (P. Graham, H. Ramani, 2024)
- Stellar streams
- Lyman-alpha forest
- …

Subplanetary scales

- Pulsar timing arrays (J. A. Dror, H. Ramani, T. Trickle, and K. M. Zurek, 2019)
- Lensing in Highly Magnified Stars (L. Dai and J. Miralda-Escudé, 2019)
- **Fast Radio Bursts Timing** (H. Xiao, L. Dai, and M. McQuinn, 2024)

DM substructure as a probe of early Universe dynamics

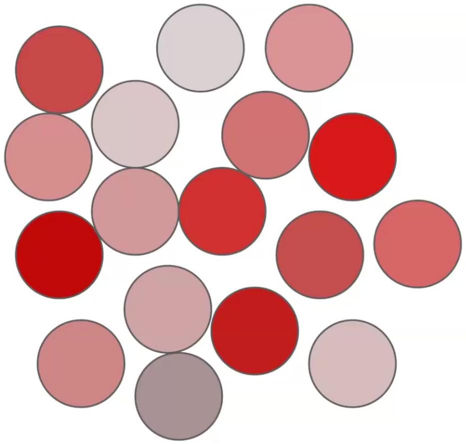
1. Inflation models with enhanced curvature perturbations on small scales.

2. Nonstandard thermal history before BBN.

- Early matter domination needed in scenarios like B meson baryogenesis (A. Nelson, and H. Xiao, 2019).
- Baryogenesis needs a reheating temperature of ~20MeV, resulting in dark matter substructures with masses $\sim 10^{-5} M_{\odot}$.
- Can also alter axion cosmology (A. Nelson, and H. Xiao, 2018).

Substructure formation from axion perturbations

Symmetry breaking happens **after inflation**.



Uncorrelated field values $\theta \in (-\pi, \pi)$ at different horizon patches.

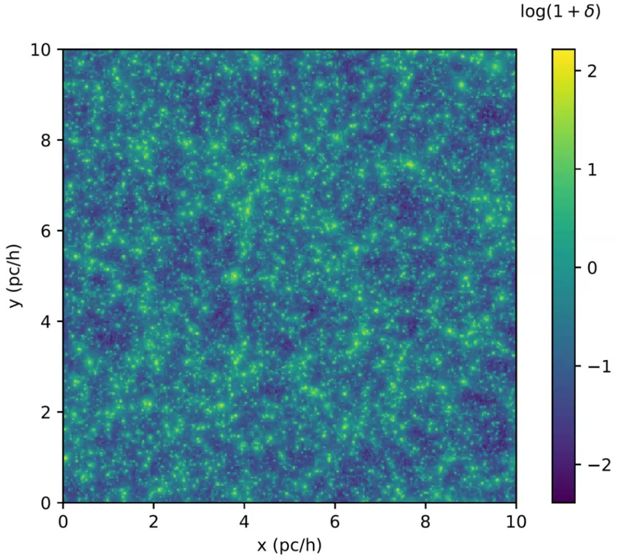
Leads to the formation of axion miniclusters around matter radiation equality, with masses $M \sim 10^{-12} M_{\odot}$.

Extremely difficult to detect!

Axion miniclusters

- For QCD axion miniclusters, currently there is no observational constraints.

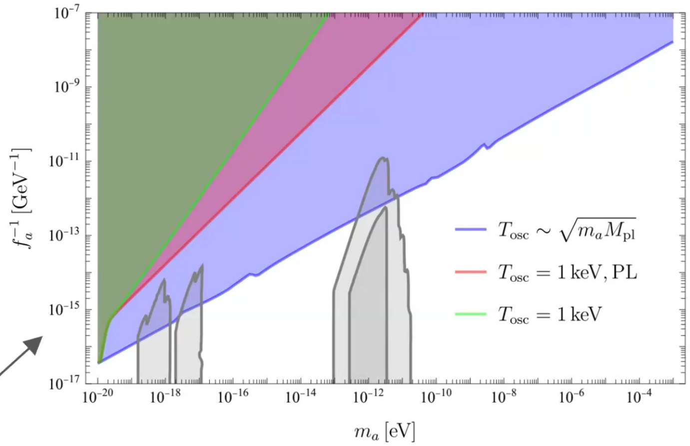
- For axion-like particles, observational constraints from Lyman-alpha excludes masses $m_a < 10^{-18}$ eV. (V. Irsic, H. Xiao, M. McQuinn, 2020)

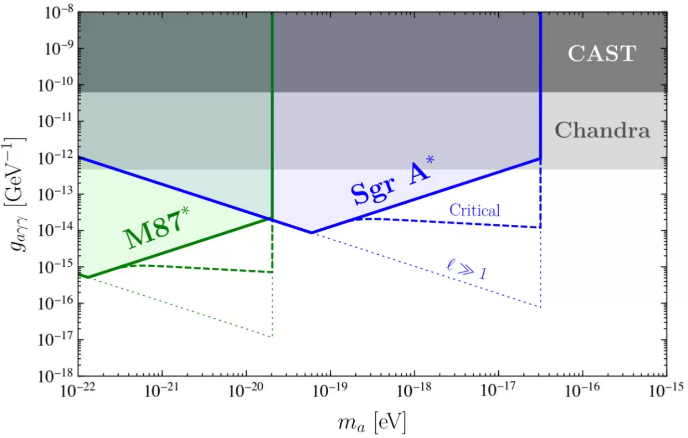


H. Xiao, I. Williams, M. McQuinn, 2021

Axion stars

- For axion-like particles, massive axion stars can be constrained by ultra-faint dwarfs, giving the best constraints on mass $m_a > 3 \times 10^{-17}$ eV. (J.H. Chang, P. Fox, and H. Xiao, 2024).
- The collapse of axion stars can change cosmology, imposing new axion limits (P. Fox, N. Weiner, H. Xiao, 2023)
- Axion stars can form near supermassive black holes, providing signals in polarization angle measurements. (X. Gan, L-T. Wang, H. Xiao, 2023)

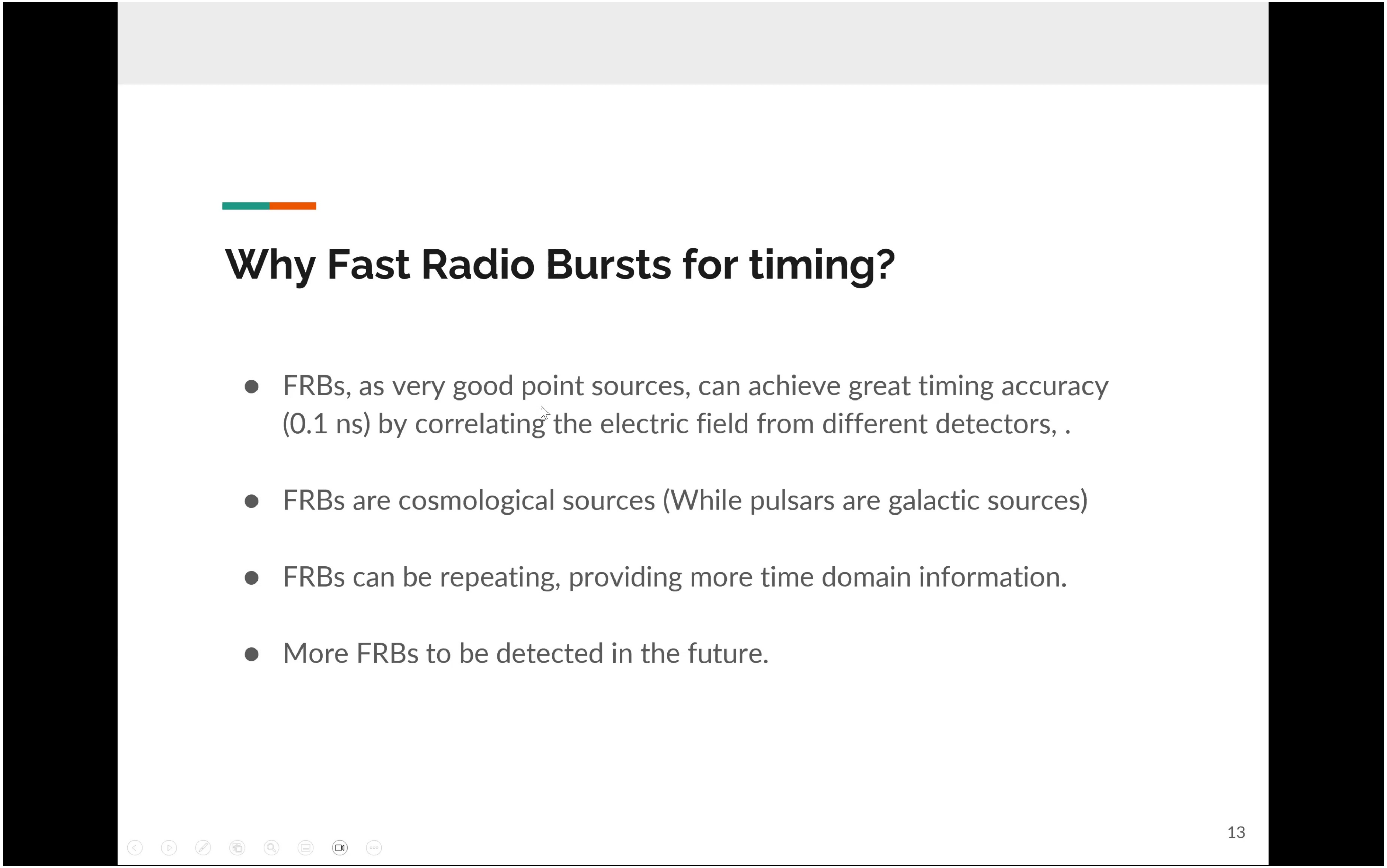




Fast Radio Bursts

- Transient radio pulses with lengths of ~1ms (very brief);
- Each FRB has unique fingerprint (and you can correlate them).
- Very bright
- Strongly lensed FRBs are good probes of compact objects such as cosmic strings (H. Xiao, L. Dai, M. McQuinn, 2022)

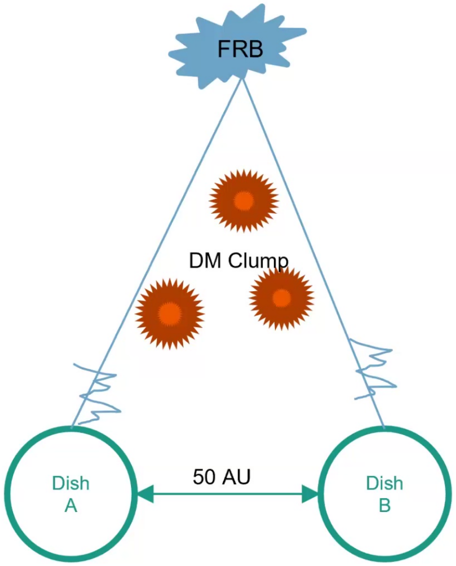
Image credit: Danielle Futselaar/artsource.nl



Why Fast Radio Bursts for timing?

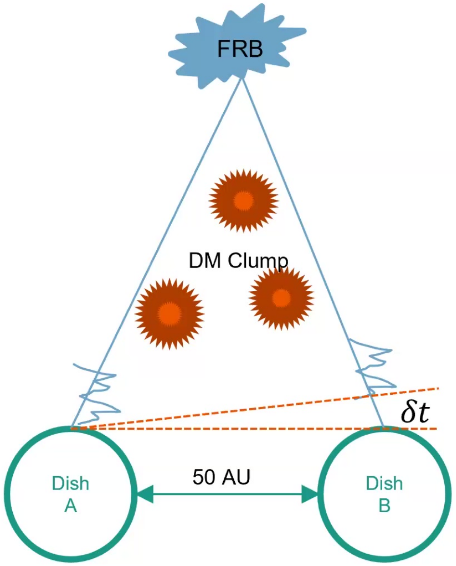
- FRBs, as very good point sources, can achieve great timing accuracy (0.1 ns) by correlating the electric field from different detectors, .
- FRBs are cosmological sources (While pulsars are galactic sources)
- FRBs can be repeating, providing more time domain information.
- More FRBs to be detected in the future.

FRB timing with two dishes



- Send two dishes to space, separated by 50 AU
- Looking at the same FRB source.
- Sampling different slices of the Universe.
- FRB signal from 2 dishes can be coherently correlated, providing **arrival time difference.**
- Could also measure cosmological distances. (K. Boone, M. McQuinn, 2022)

FRB timing vs Pulsar timing



Pulsars themselves act as the reference clock. We create our own.

Time varying electron density in the solar wind will affect the quality of pulsar timing, but not FRB timing.

Credit: Tonia Klein / NANOGrav

Time variance on the Shapiro time delay

The Shapiro time delay difference along two sightlines are

$$\langle \delta t^2 \rangle = 4\,\mathrm{Var}\left[\int_0^D dx\;\Phi(x, x_\perp) - \int_0^D dx\;\Phi(x, 0\,)\right]$$

$$= 8\int_0^D dx_1 \int_0^D dx_2\,\left(\langle \Phi(x_1, 0)\Phi(\mathrm{x}_2, 0)\rangle - \langle \Phi(x_1, 0)\Phi(\mathrm{x}_2, x_\perp)\rangle\right)$$

Therefore the matter power spectrum on small scales will give the variance of the arrival time difference.

The signal is proportional to power of $x_\perp$ (dish separation).

Correlation function on small scales

$$\langle \delta t^2 \rangle = 8 \int_0^D dx_1 \int_0^D dx_2 \left(\langle \Phi(x_1, 0) \Phi(\mathrm{x}_2, 0) \rangle - \langle \Phi(x_1, 0) \Phi(\mathrm{x}_2, x_\perp) \rangle \right)$$

Decompose the momentum mode at different directions

$$\langle \Phi(x_1, 0) \Phi(\mathrm{x}_2, x_\perp) \rangle = \int \frac{dk^3}{(2\pi)^3} P_\Phi(k) \exp\left(-i\, k_\parallel (x_1 - x_2) - i\, k_\perp \cdot x_\perp\right)$$

Large $k_\parallel$ will not contribute much due to the oscillatory feature along the line of sight and thus we can ignore the $k_\parallel$ dependence on P_Φ (Limber's approximation),

$$\langle \Phi(x_1, 0) \Phi(\mathrm{x}_2, x_\perp) \rangle = \int \frac{dk_\perp^2}{(2\pi)^2} P_\Phi(k_\perp) \delta_D(x_1 - x_2) \exp(-i\, k_\perp \cdot x_\perp)$$

Correlation function on small scales

The matter power spectrum gives the arrival time difference:

$$\langle \delta t^2 \rangle = 8(4\pi G \bar{\rho}_m)^2 \int \frac{dz}{H} \int \frac{dk}{2\pi} \frac{1}{k^3} P_\delta(k,z)(1 - J_0(k\, x_\perp))$$

In the limit of $k x_\perp \ll 1$, we can expand the Bessel function. The first relevant term is the quadrupole term

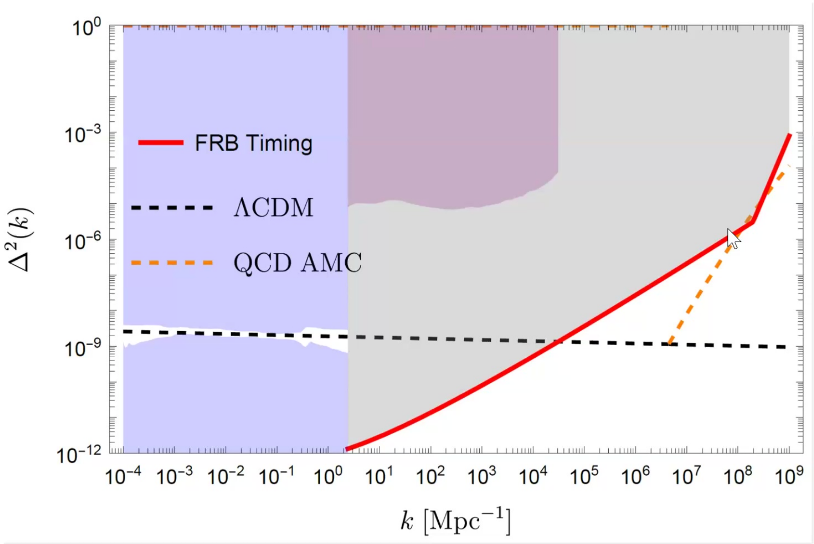
$$\langle \delta t^2 \rangle = \frac{1}{8}(4\pi G \bar{\rho}_m)^2 \int \frac{dz}{H} \int \frac{dk}{2\pi}\, k\, P_\delta(k,z) x_\perp^4$$

The longer the baseline, the larger the signal.

Sensitivity to Matter Power Spectrum

FRB timing with dish separation of 20 AU can even probe QCD axion miniclusters

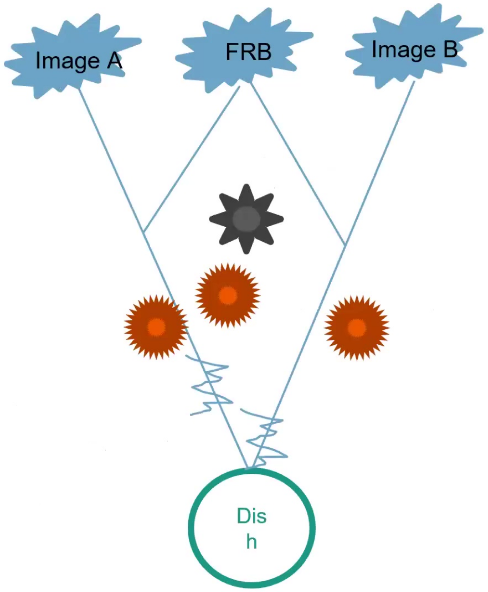
Here, some forward model is used to evolve the primordial axion perturbation to the current Universe.

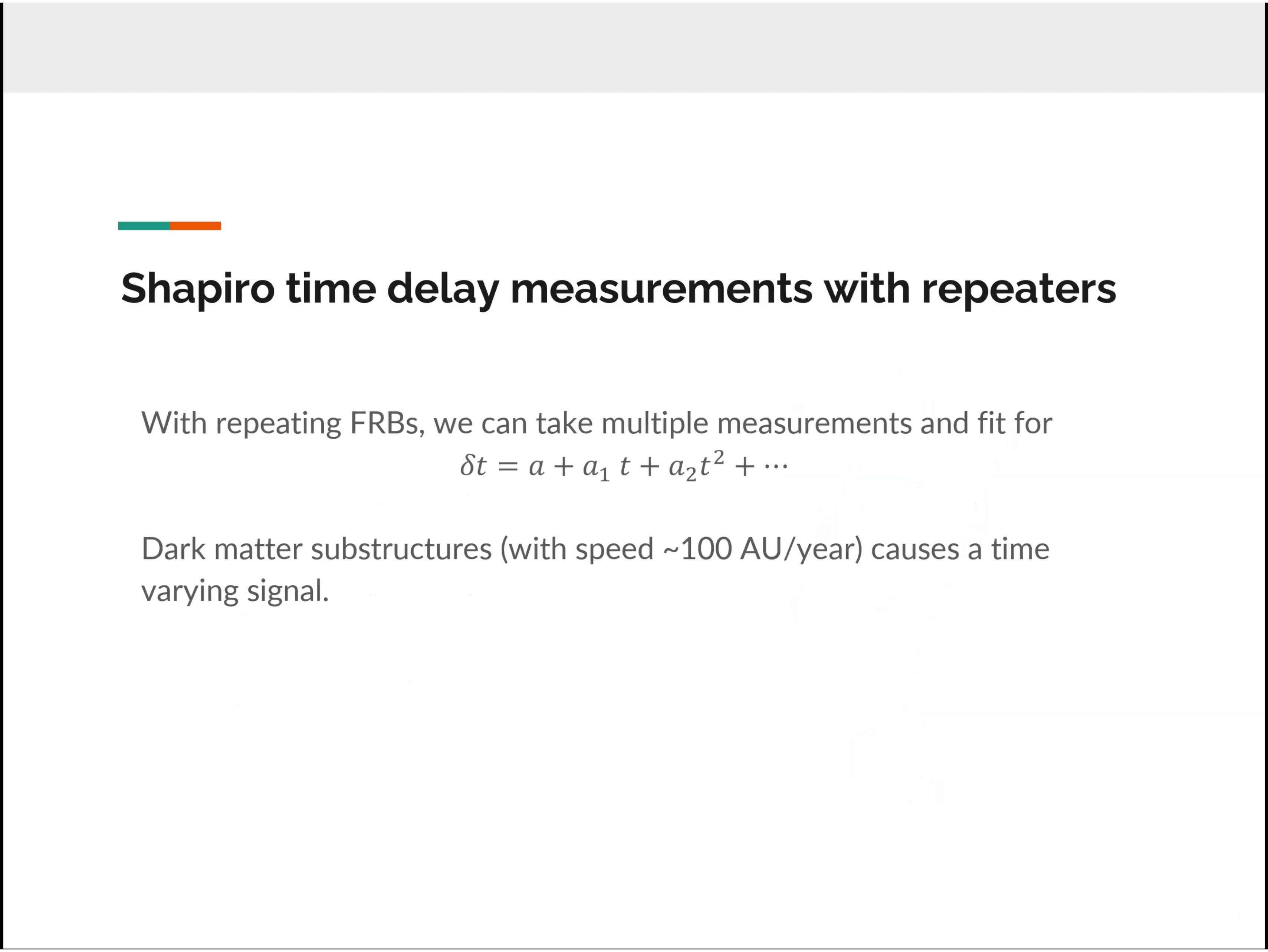


Strongly lensed FRBs that are repeating

- Now if you tell me you cannot fund my proposal…
- I will need more FRBs to do the same thing.
- Suppose we have some FRBs that are strongly lensed by galaxies or other objects, we have two sightlines as well!

Such event is expected to happen when we observe $\sim 10^5$ FRBs.





Shapiro time delay measurements with repeaters

With repeating FRBs, we can take multiple measurements and fit for

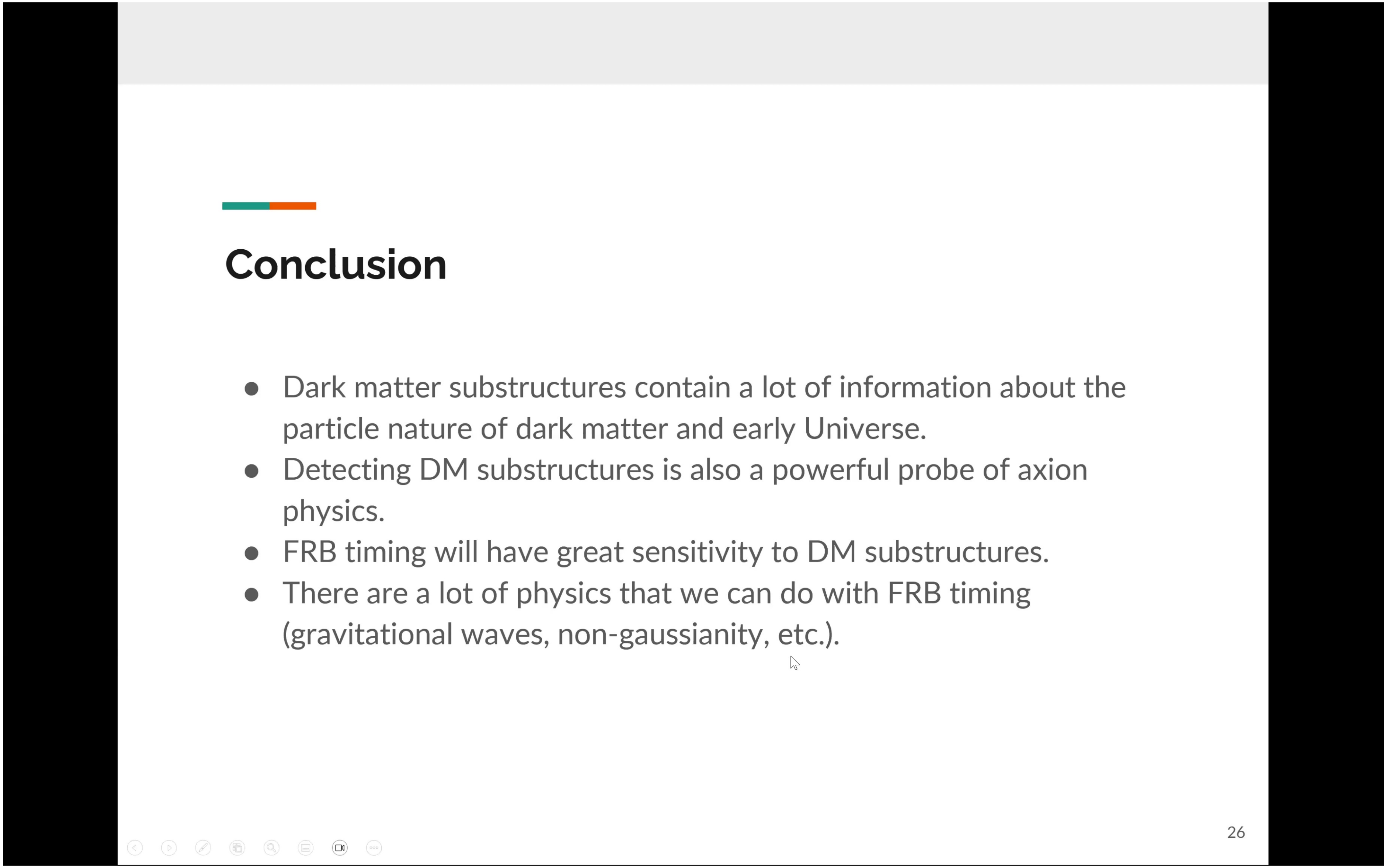
$$\delta t = a + a_1\, t + a_2 t^2 + \cdots$$

Dark matter substructures (with speed ~100 AU/year) causes a time varying signal.

Possible Systemastics

Scattering effect from the Milky Way’s interstellar medium. (Can be suppressed at higher frequencies)

Scattering effect in the FRB host galaxy to make it not point-like. (Not relevant for the 2-Dish set-up)



Conclusion

- Dark matter substructures contain a lot of information about the particle nature of dark matter and early Universe.
- Detecting DM substructures is also a powerful probe of axion physics.
- FRB timing will have great sensitivity to DM substructures.
- There are a lot of physics that we can do with FRB timing (gravitational waves, non-gaussianity, etc.).