Searching for Astrophysical Signatures of ultralight dark matter in pulsars and lensing

In collaboration with:
Elisa Ferreira, Qiuyue Liang at Kavli IPMU

Based on:
Eberhardt+, 2411.18051
Eberhardt+, 2502.20697

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Q-EYES 2025
Dec 2025

Ultra light dark matter

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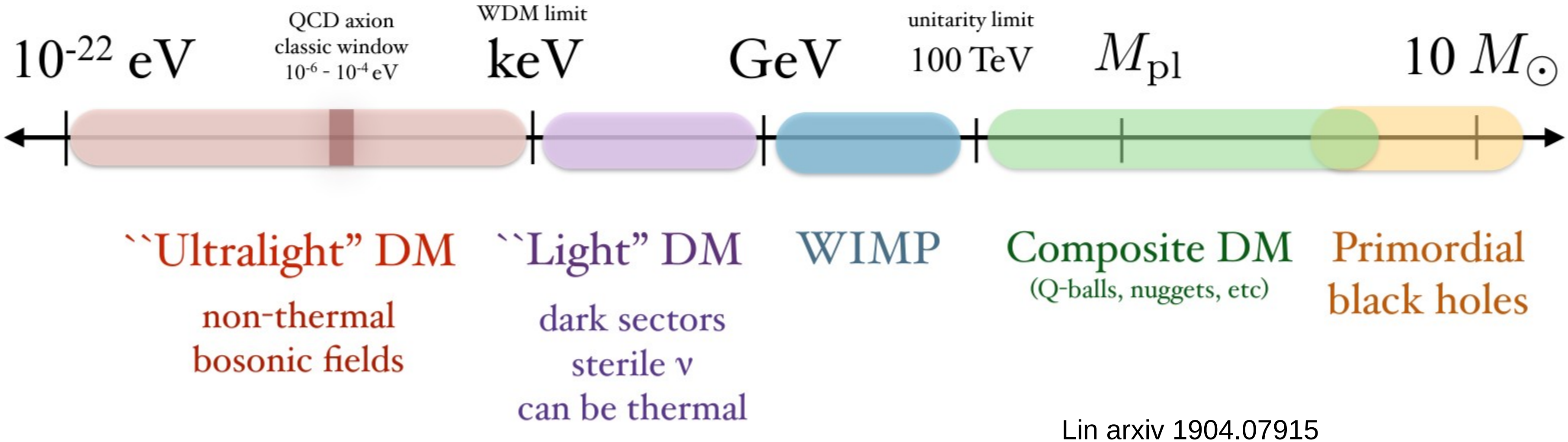
- Ultralight/Fuzzy/Scalar field/Wave/etc dark matter



Lin arxiv 1904.07915

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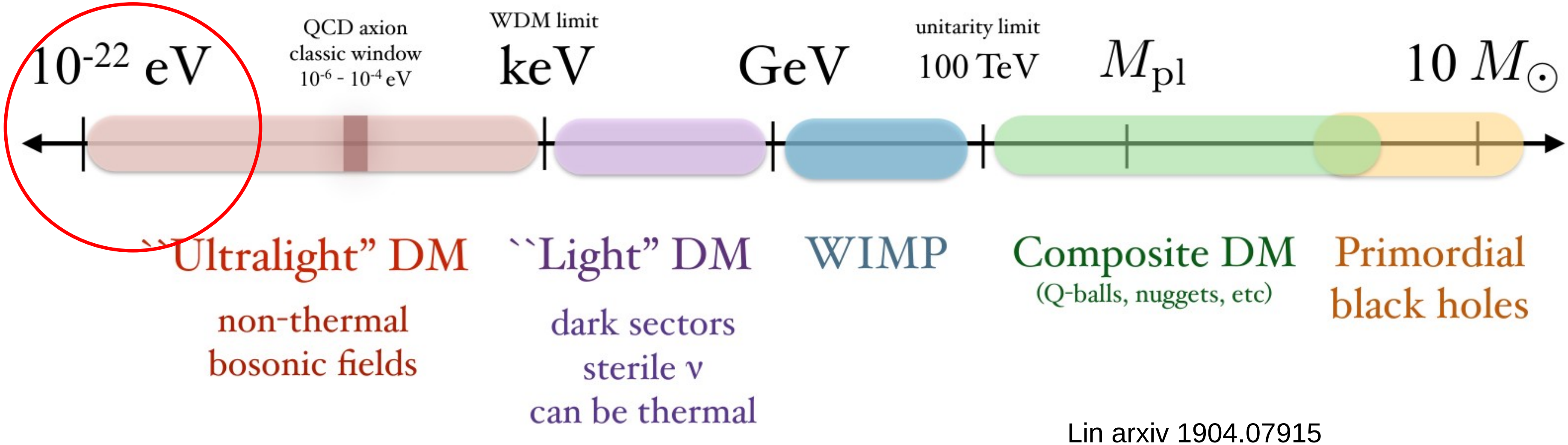

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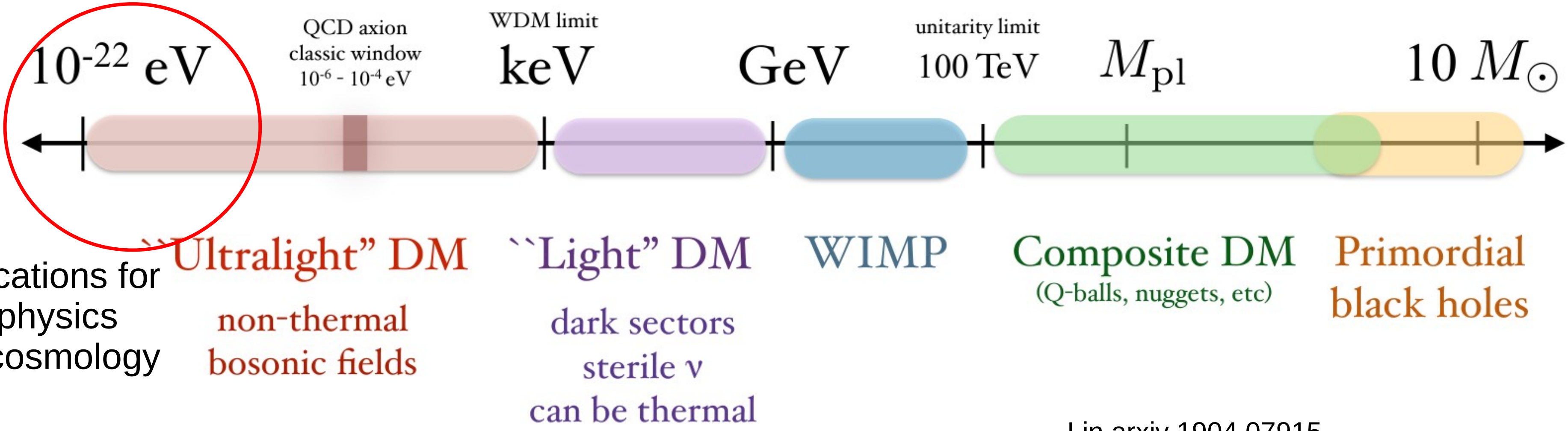

Implications for astrophysics and cosmology

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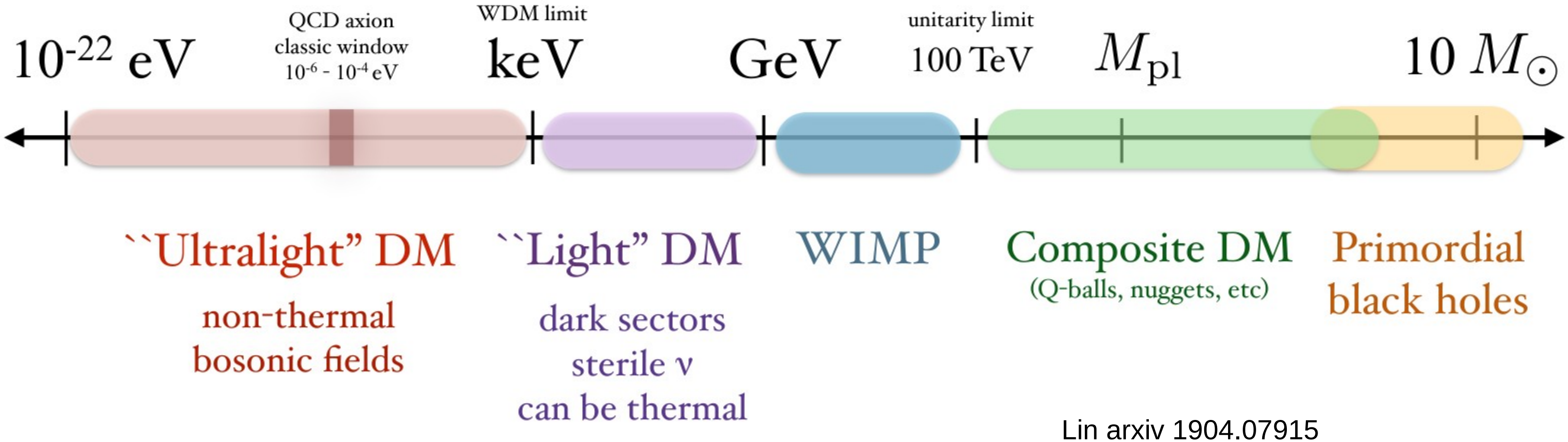
Ultra light dark matter

- Ultralight/Fuzzy/Scalar field/Wave/etc dark matter
- Ultralight fields are a generic prediction of string theory



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Ultra light dark matter

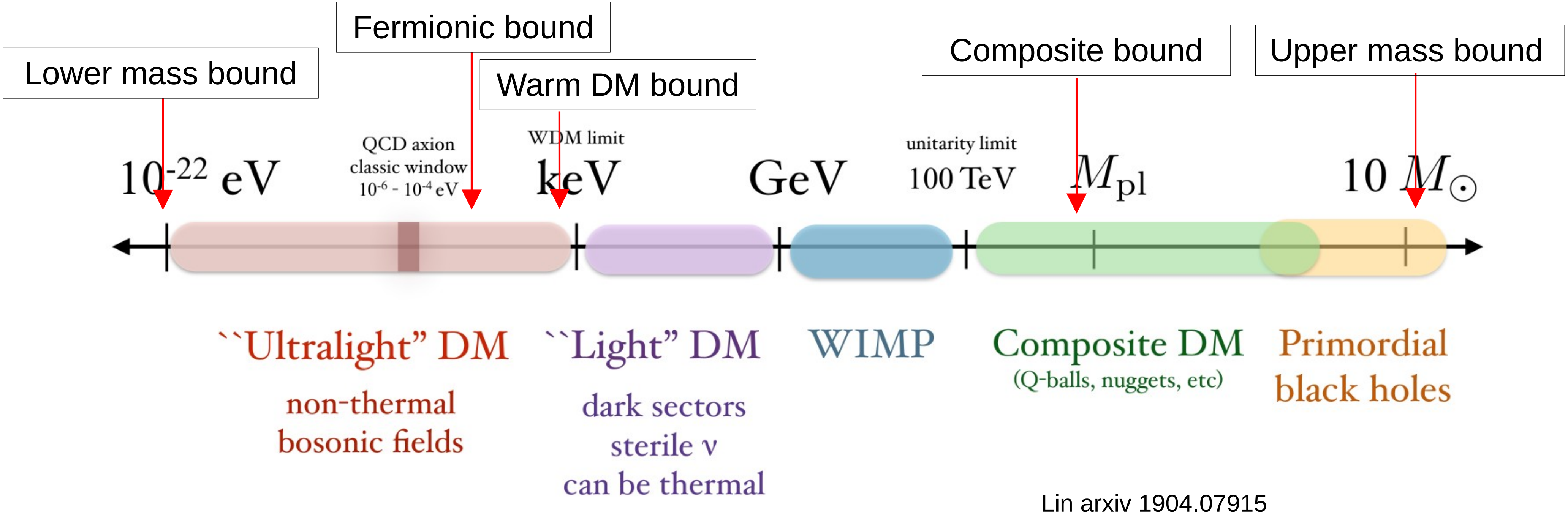
- Ultralight/Fuzzy/Scalar field/Wave/etc dark matter
- Ultralight fields are a generic prediction of string theory
- Much of the work on Ultralight dark matter is model agnostic (other than a single ultralight classical spin-0 field minimally coupled)

Ultra light dark matter

- Ultralight/Fuzzy/Scalar field/Wave/etc dark matter
- Ultralight fields are a generic prediction of string theory
- Much of the work on Ultralight dark matter is model agnostic
- Historically Ultralight dark matter is a postdiction meant to fix “small scale structure problems”

Ultra light dark matter

- Lower bound on minimally coupled dark matter



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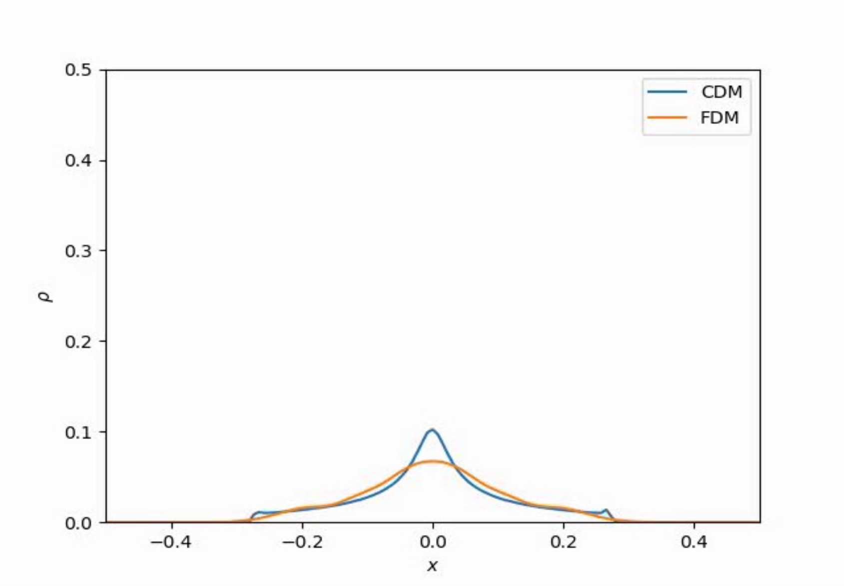
Pheno

Pheno

- “Quantum” pressure



Pheno

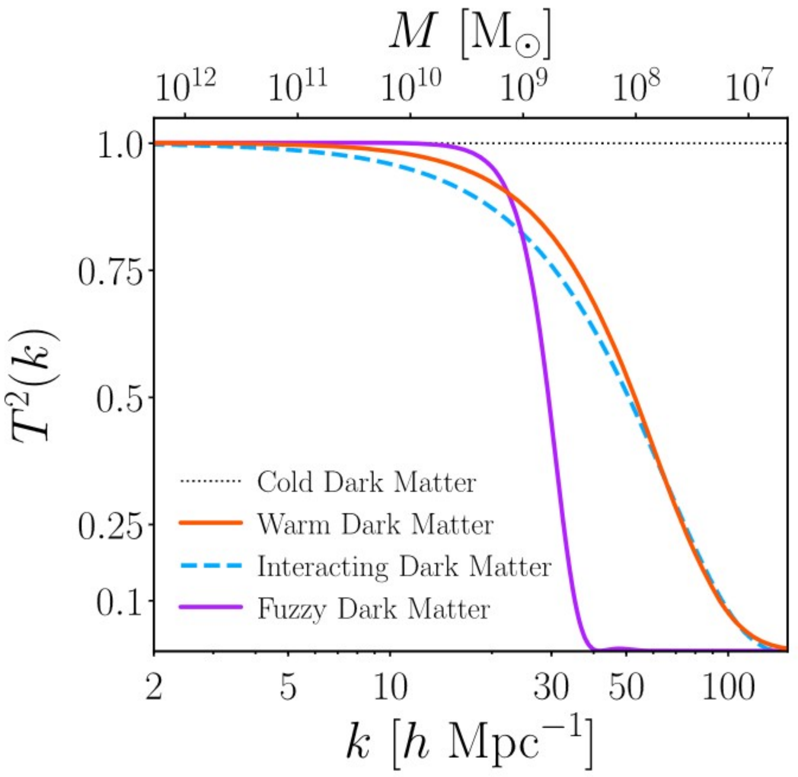
- “Quantum” pressure

$$x = 1.61\, m_{22}^{1/18} k/k_{J\mathrm{eq}}$$

$$k_{J\mathrm{eq}} = 9\, m_{22}^{1/2}\, \mathrm{Mpc}^{-1}$$

$$T_{\mathrm{F}}(k) \approx \frac{\cos x^3}{1+x^8}$$

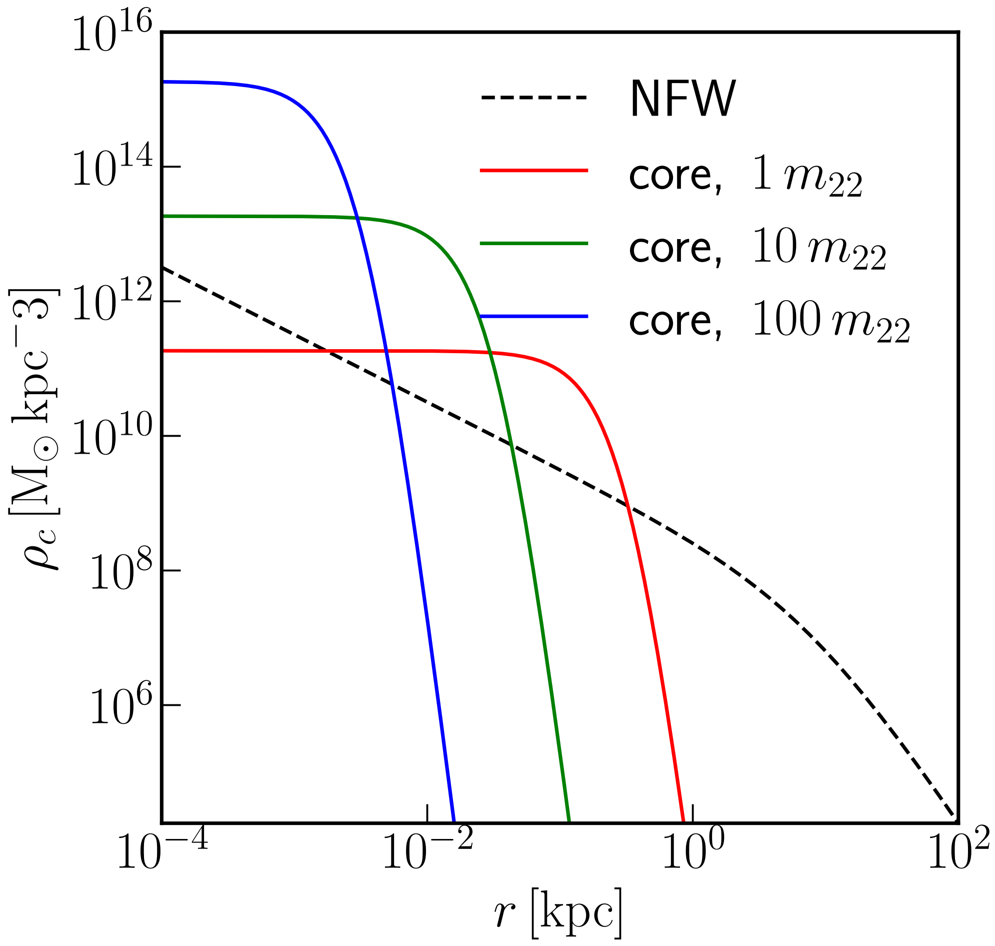
Hu et al., PRL (2000)



Nadler et al, PRL (2021)

Pheno

- “Quantum” pressure
- Solitons



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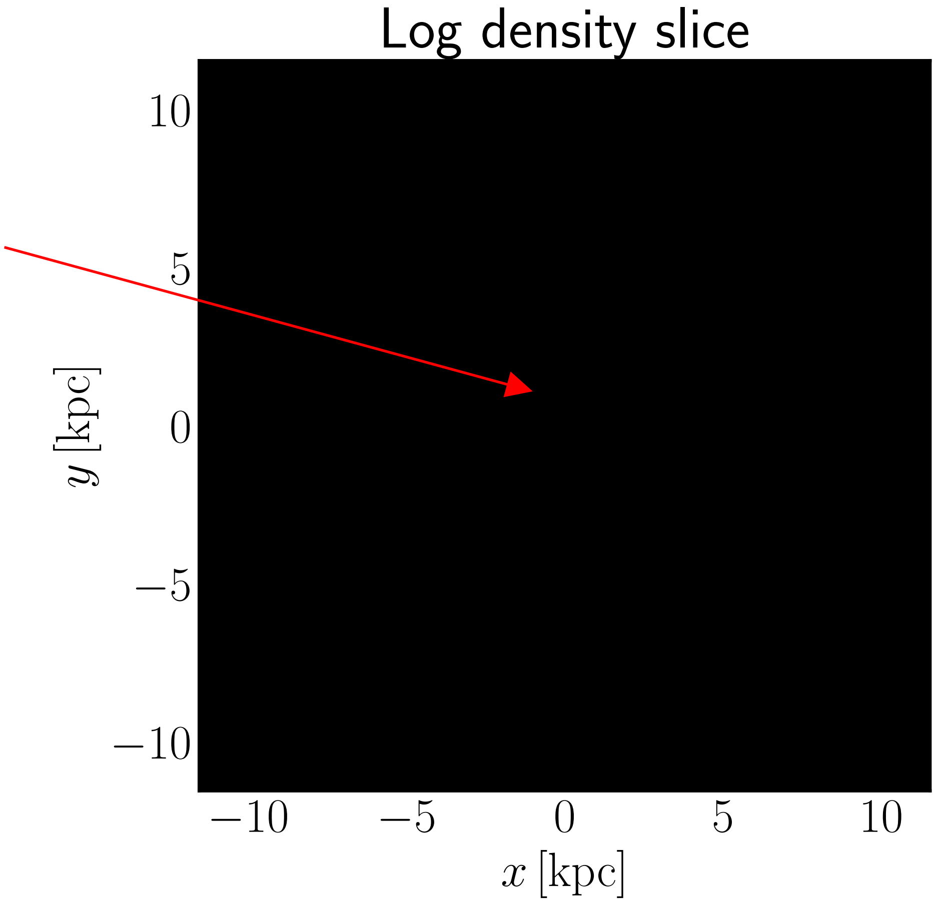
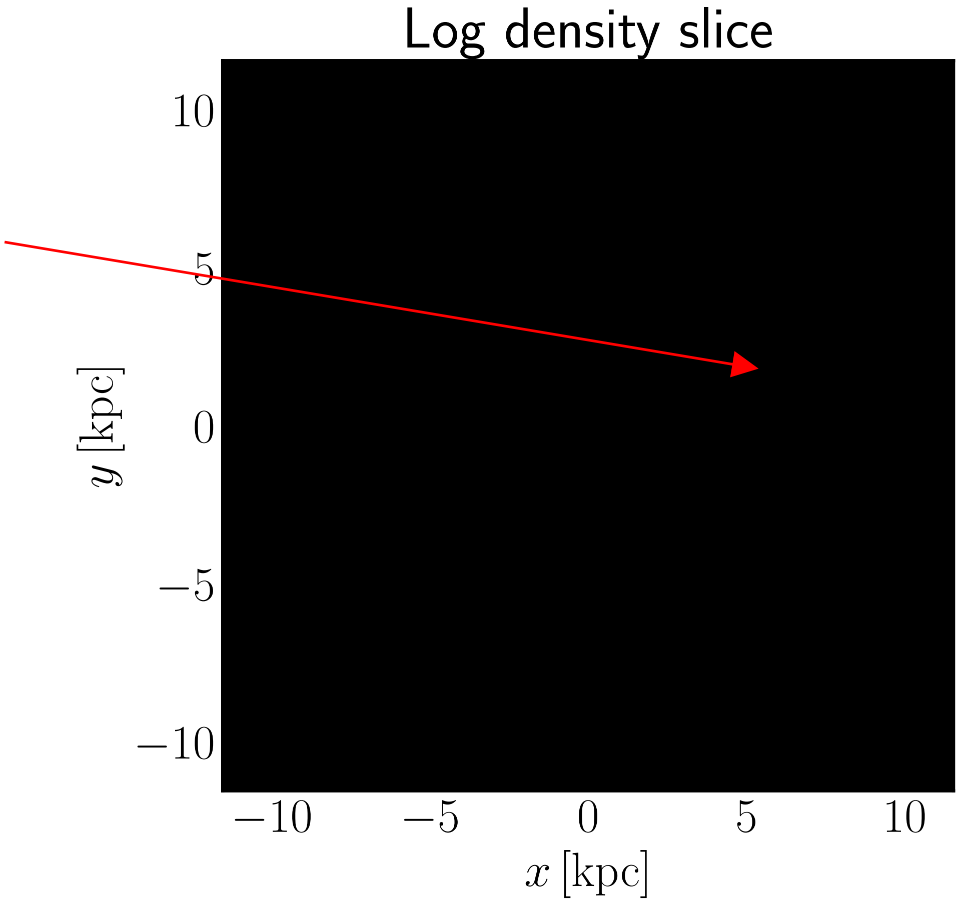


Pheno

- “Quantum” pressure
- Solitons
- Density granules
  - Halos exhibit ~O(1) fluctuations in the density



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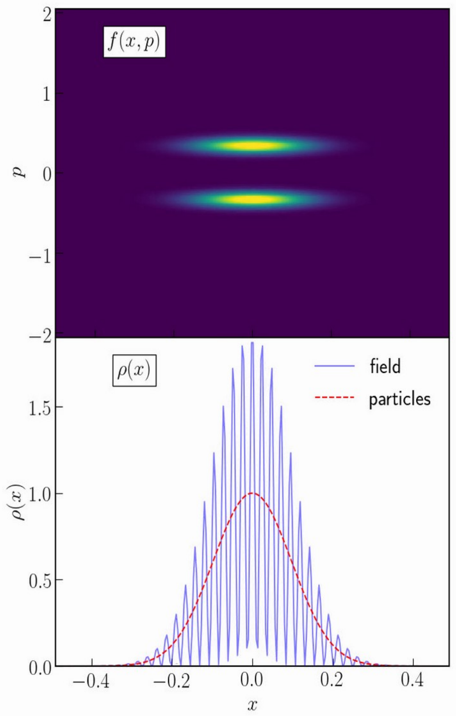
  - Interference between different momentum streams in phase space



Pheno

- "Quantum" pressure
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- Density granules
  - Halos exhibit ~O(1) fluctuations in the density
  - Interference between different momentum streams in phase space
  - Fluctuate on de Broglie time and length scales

$$\tau_{\rm db} = 2\pi\hbar/m\sigma^2 \sim 3\left(\frac{10^{-22}\,{\rm eV}}{m}\right)\left(\frac{200\,{\rm km/s}}{\sigma}\right)^2\,{\rm Myr}\,,$$
$$\lambda_{\rm db} = 2\pi\hbar/m\sigma \sim 0.6\left(\frac{10^{-22}\,{\rm eV}}{m}\right)\left(\frac{200\,{\rm km/s}}{\sigma}\right)\,{\rm kpc}\,.$$

Quantumness

Quantumness

- Often describe ultralight dark matter pheno as “quantum” behavior on astrophysical scales

$$\partial_t \psi(x,t) = \frac{-i}{\hbar}\left(\frac{-\hbar^2\nabla^2}{2m} + mV\right)\psi(x,t)$$

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Quantumness

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- Most of the pheno is classical field “wave” effects
- Classical field is assumed for most studies (including the ones I will discuss today)

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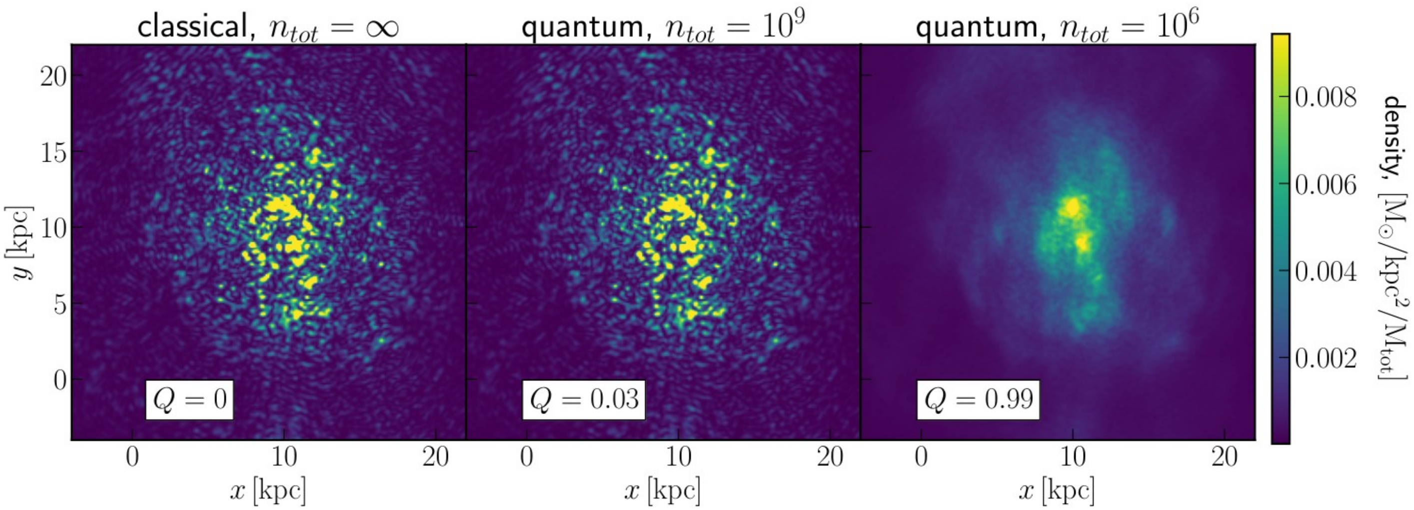

Eberhardt+ PRD 2023

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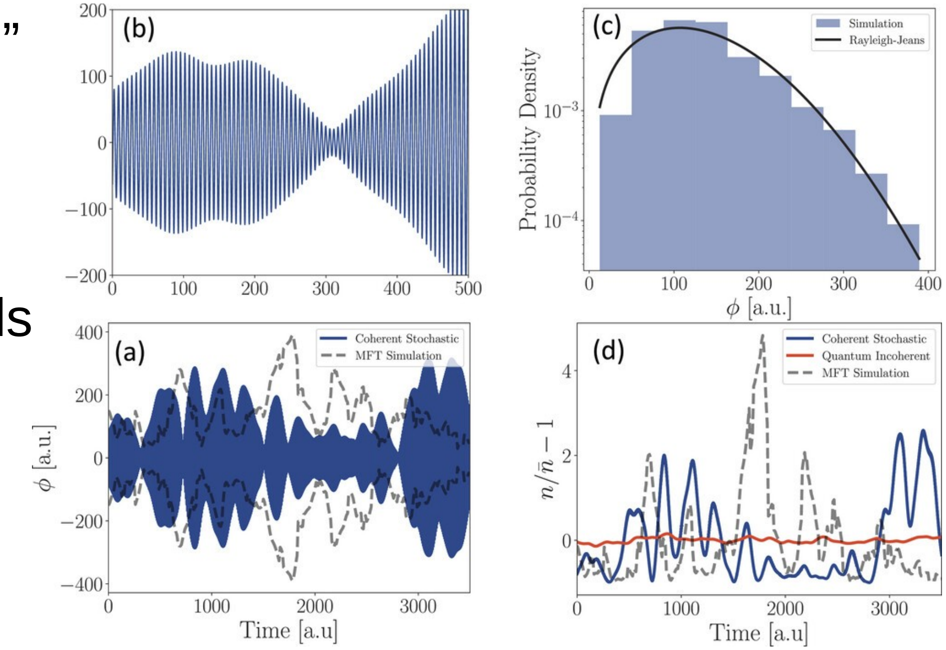
Allali and Hertzberg PRD 2021
Lentz+ MNRAS 2020

Quantumness

- There is a lot of literature looking at “real” (ie second quantized) effects
- This has been studied in terms of large scale structure
- And studied in terms of haloscope signals

Marsh Annalen Phys. 2024
Lentz arxiv 2509.03877
Bao+ arxiv 2510.05198



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Quantumness

- There is a lot of literature looking at “real” (ie second quantized) effects
- This has been studied in terms of large scale structure
- And studied in terms of haloscope signals
- In this work I will assume that the field is classical

Probes and constraints

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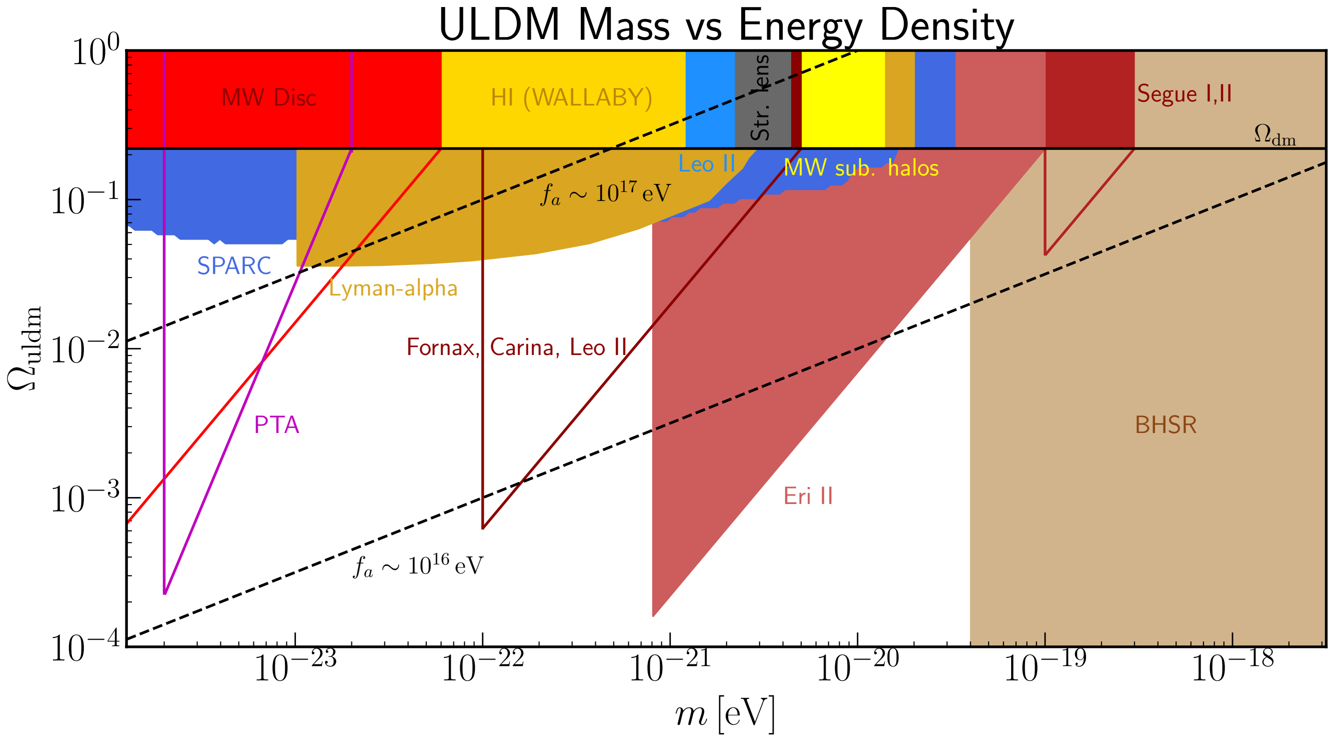
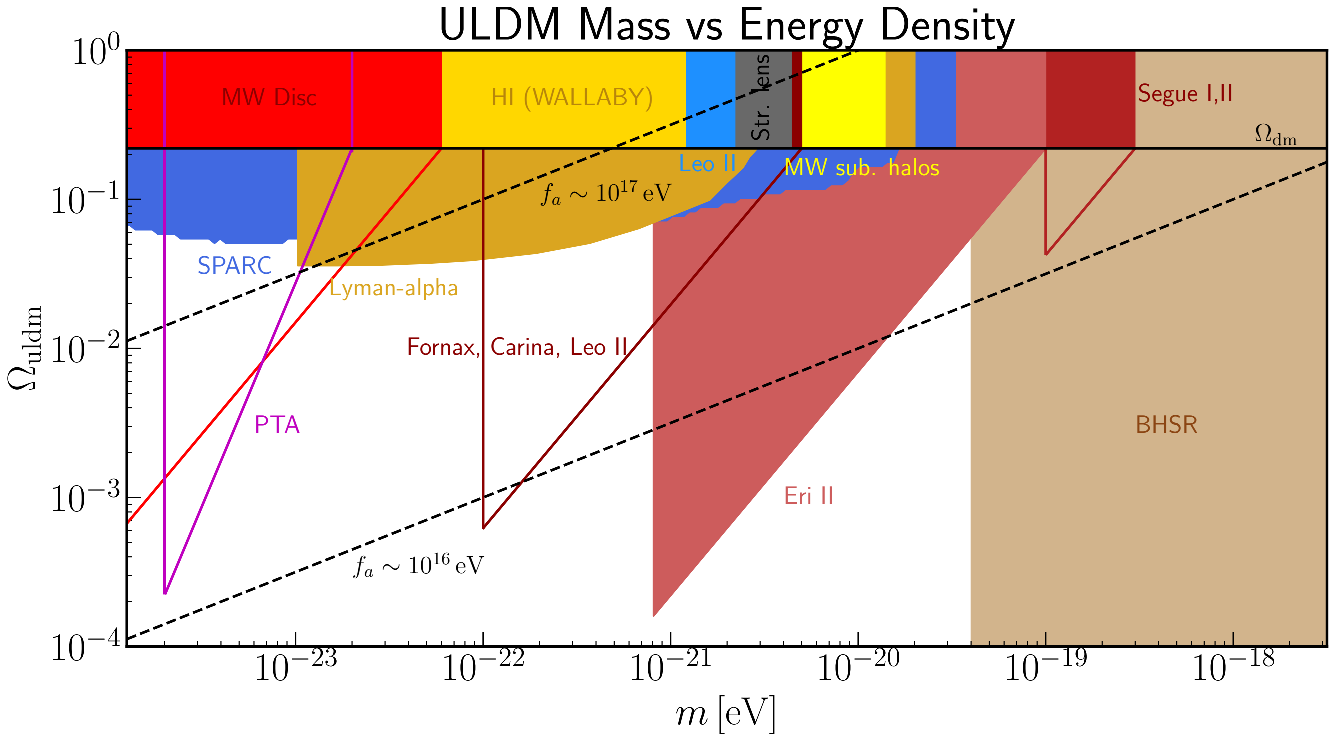


Eberhardt and Ferreira arxiv 2507.00705

Probes and constraints

- General effort is to push to higher masses and produce complementary constraints



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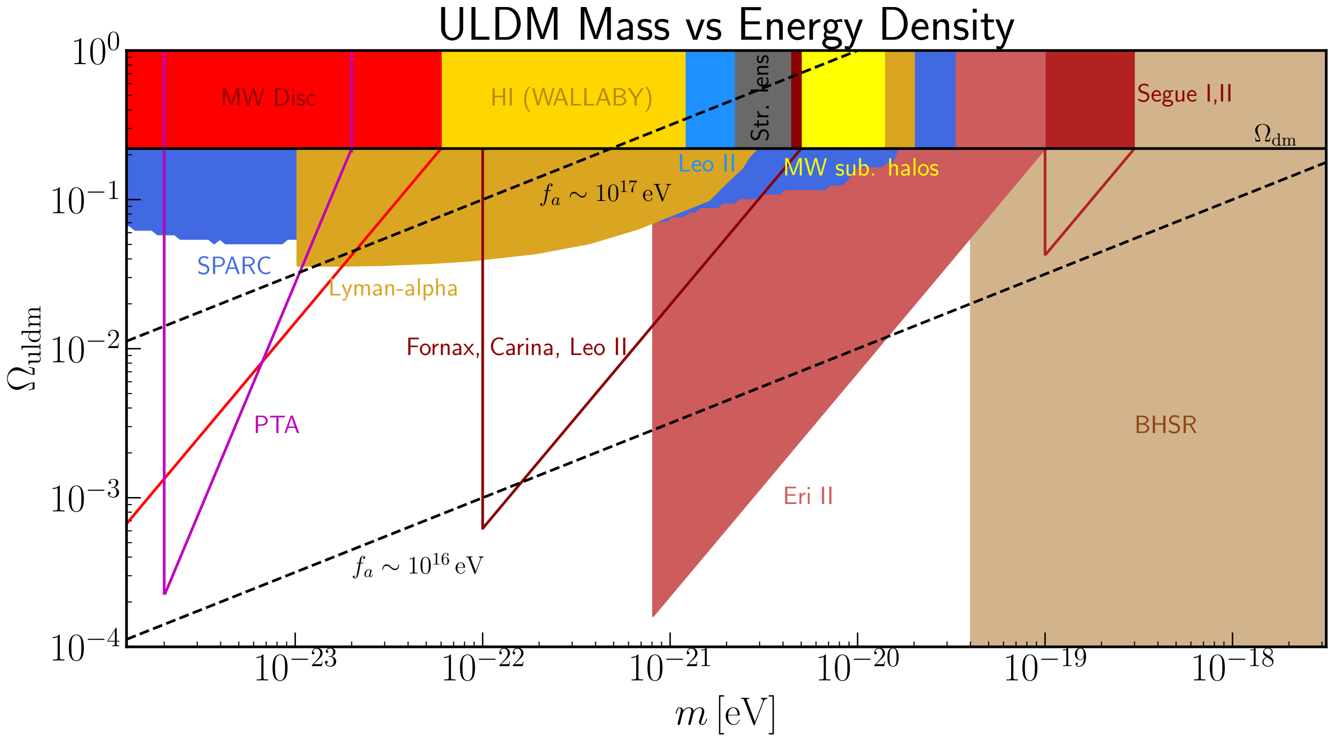
Probes and constraints

- General effort is to push to higher masses and produce complementary constraints
- Astrophysical/cosmological probes are increasingly interesting as other dark matter experiments find no signals and astro data improves



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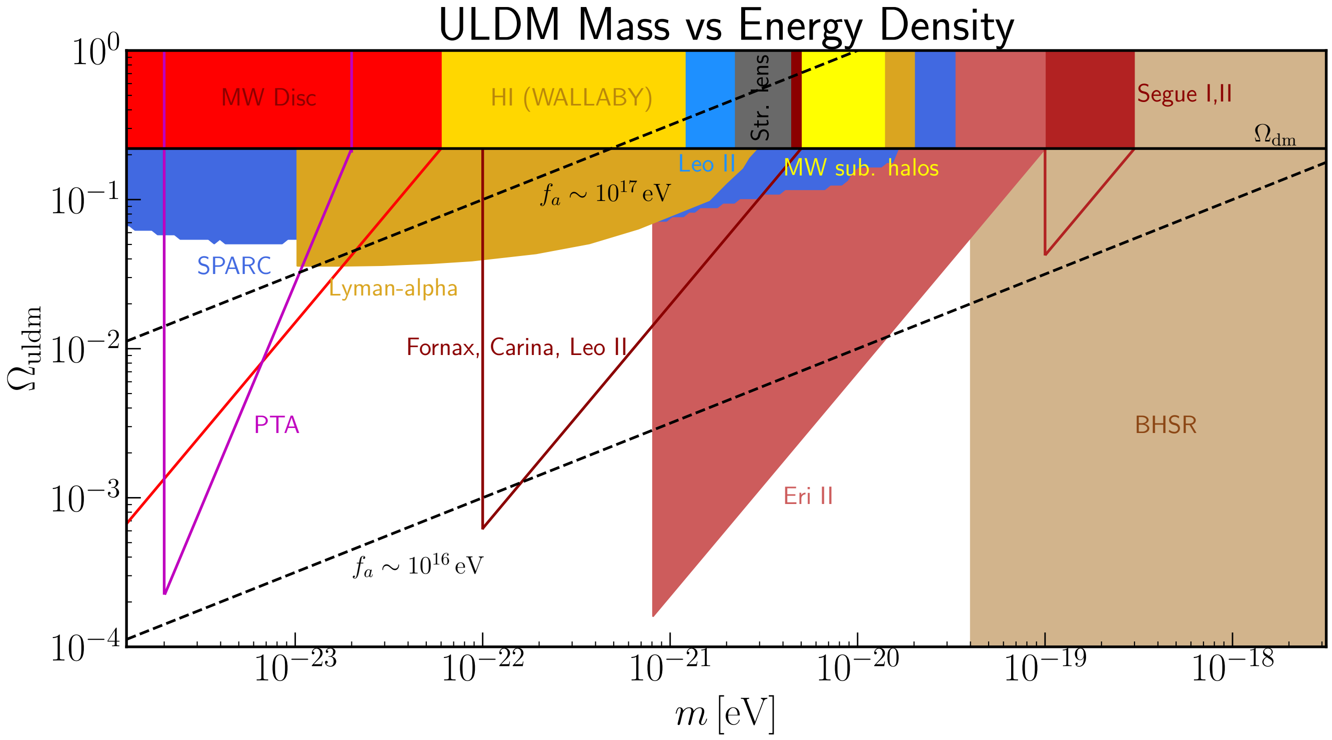
Probes and constraints

- Some of the strongest constraints here involve dark matter granules



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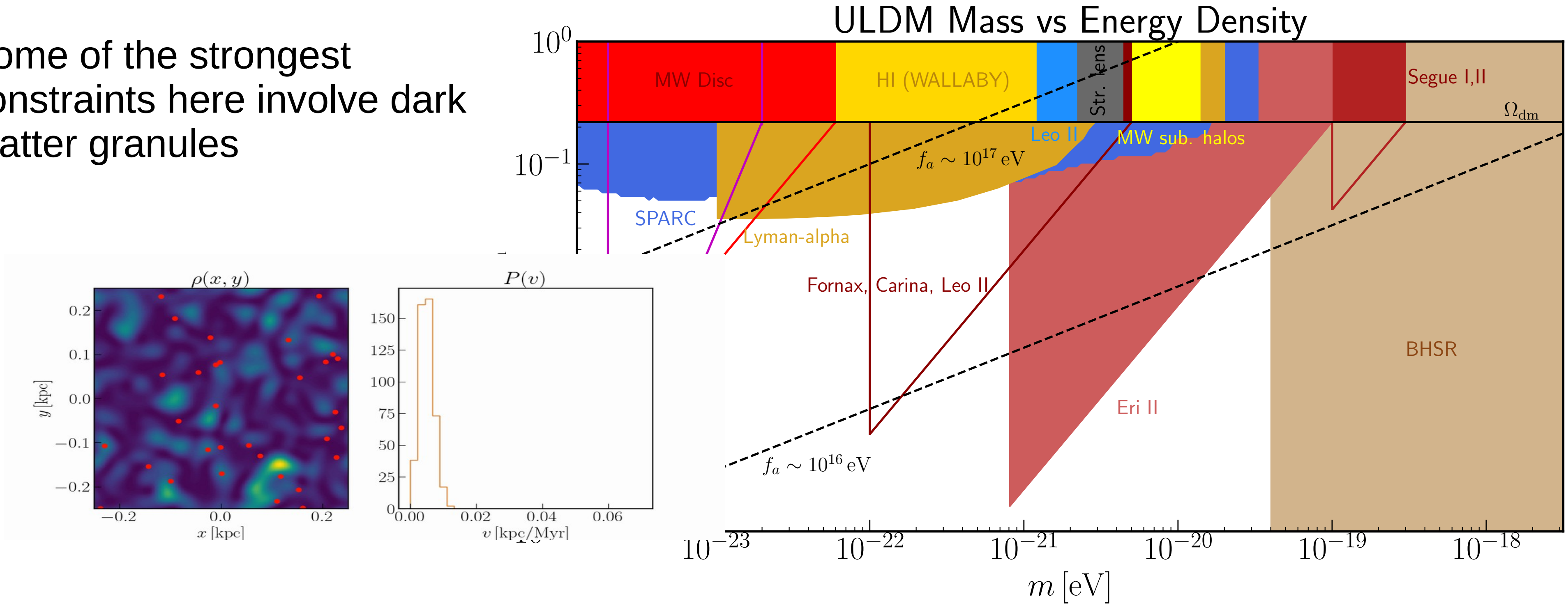

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Probes and constraints

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- Studying these granules is promising to push to higher masses

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- Studying these granules is promising to push to higher masses
- At higher masses the dynamical times of the granules becomes observable
- Hope is that sensitive observations of the gravitational potential can probe this region
- Density perturbations from the granules changes by O(1) on the timescale of my experiment

Astrophysical observations

- Astrometry [Kim 2406.03539, Dror and Verner 2406.03526]
- Stochastic lensing [Eberhardt+ 2502.20697]
- Pulsar timing Doppler shifts [Kim and Mitridate 2312.12225, Eberhardt+ 2411.18051]
- Pulsar timing Shapiro delay [Eberhardt+ 2411.18051]
- Pulsar timing gravitational redshift [Eberhardt+ 2411.18051]
- Pulsar timing Compton scale redshifts [Khmelnitsky and Rubakov 1309.5888]

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We simulated and analytically modeled some of these effects

Simulations

Simulations

- Simulated stars in a “plane-wave” box whose density fluctuations mimic those of the local halo

$$\psi(\vec{r}) = \sqrt{\rho_0} \sum_{i}^{n_s} e^{-im\vec{v}_i \cdot \vec{r}/\hbar}$$

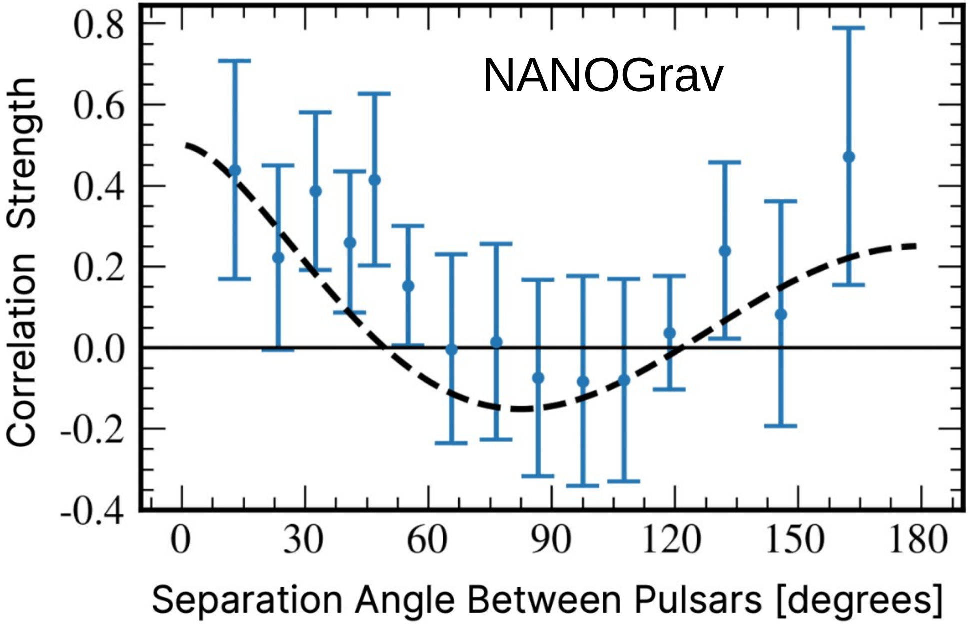
$$f(v) = \sqrt{\frac{2}{\pi}} \frac{v^2}{\sigma^2} e^{-v^2/2\sigma^2}$$

Simulations

- Simulated stars in a “plane-wave” box whose density fluctuations mimic those of the local halo
- Simulate the Doppler shift, gravitational redshift, and Shapiro delay of the pulsars

Pulsar Timing Array

- Pulsars are very precise clocks, which are sensitive to metric perturbations



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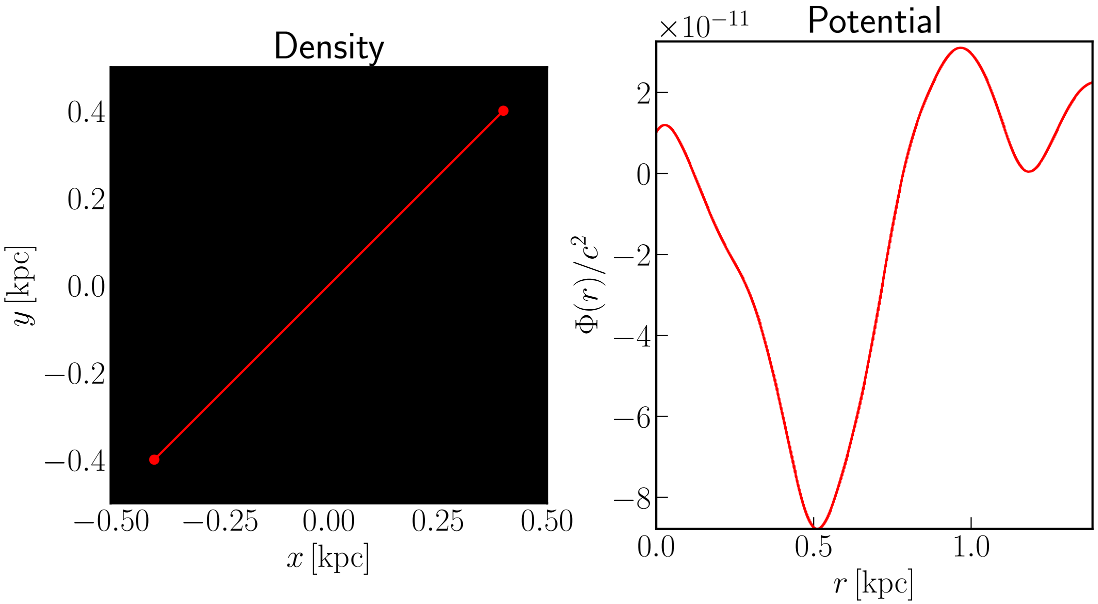
- Ultralight dark matter granules also perturb the metric



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Shapiro delay

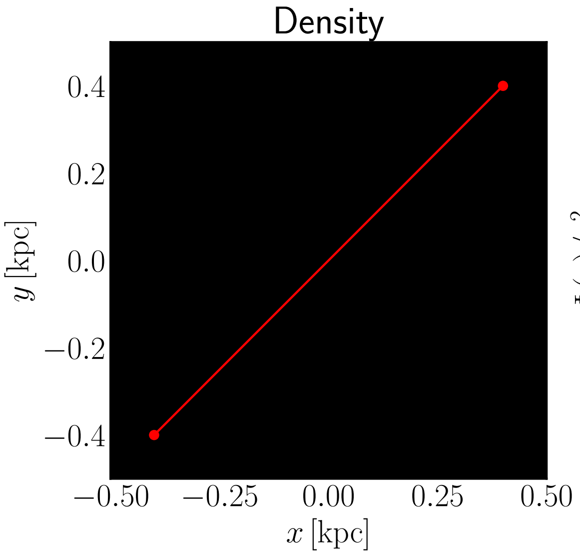
$$\delta t_j^{sh}(t_i) = \int_{r_p^j}^{r_e} \frac{dl}{c} \frac{\Phi(l, t_i)}{c^2} \,,$$

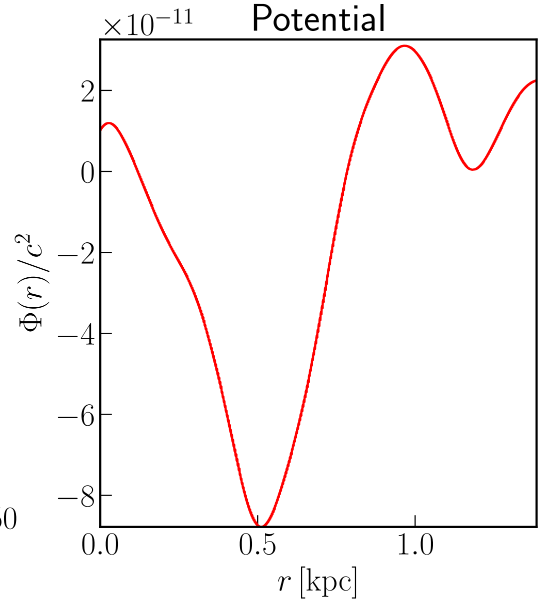
Gravitational redshift

$$z_j(t_i) = \frac{\Phi(\vec{r}_e) - \Phi(\vec{r}_p^{\,j})}{c^2} \,,$$

Doppler shift

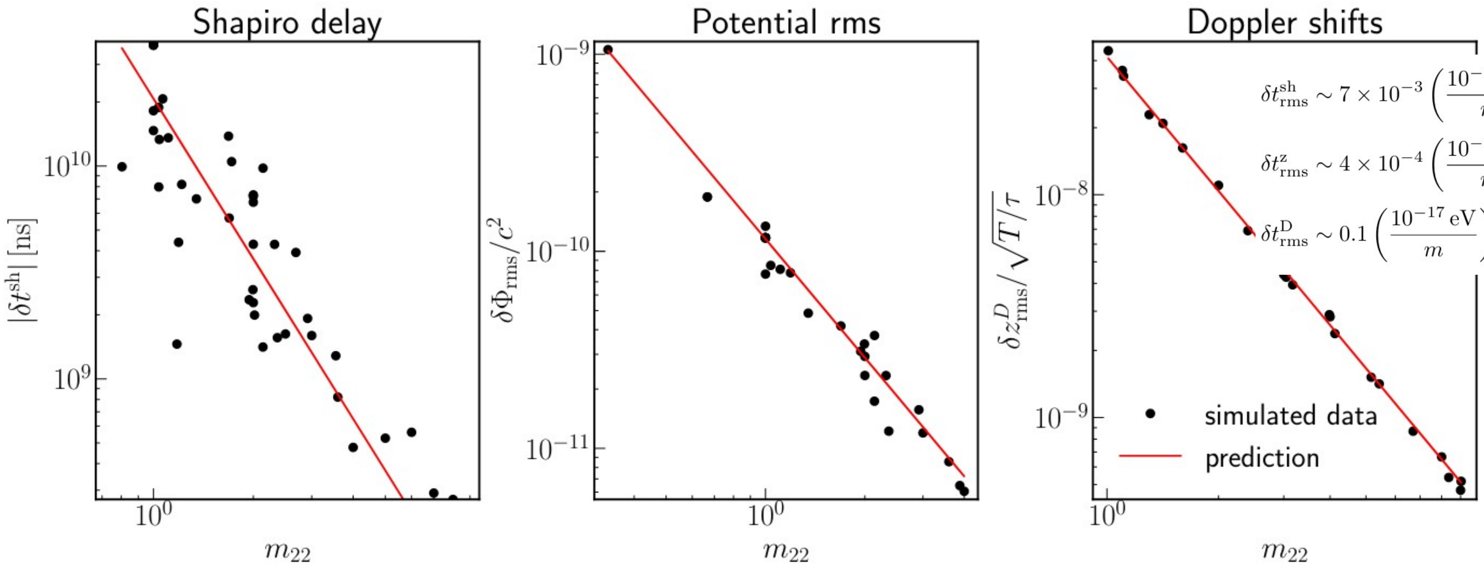
$$z_D^i(t) = \frac{\hat{n}_i \cdot \vec{v}_i}{c}$$





Pulsar Timing Array

- Simulated a fake pulsars in an oscillating ultralight dark matter box
- Worked out
  - rms oscillation



$$\delta t^{\rm sh}_{\rm rms} \sim 7\times10^{-3}\left(\frac{10^{-17}\,{\rm eV}}{m}\right)^{1/2}\left(\frac{200\,{\rm km/s}}{\sigma}\right)^{5/2}\left(\frac{\rho}{10^7\,{\rm M_\odot/kpc^3}}\right)\left(\frac{D}{\rm kpc}\right)^{1/2}\,{\rm ns}\,,$$

$$\delta t^{\rm z}_{\rm rms} \sim 4\times10^{-4}\left(\frac{10^{-17}\,{\rm eV}}{m}\right)^{3/2}\left(\frac{200\,{\rm km/s}}{\sigma}\right)^{4}\left(\frac{\rho}{10^7\,{\rm M_\odot/kpc^3}}\right)\left(\frac{T}{30\,{\rm yrs}}\right)^{3/2}\,{\rm ns}\,,$$

$$\delta t^{\rm D}_{\rm rms} \sim 0.1\left(\frac{10^{-17}\,{\rm eV}}{m}\right)^{3/2}\left(\frac{200\,{\rm km/s}}{\sigma}\right)^{2}\left(\frac{\rho}{10^7\,{\rm M_\odot/kpc^3}}\right)\left(\frac{T}{30\,{\rm yrs}}\right)^{3/2}\,{\rm ns}\,,$$

Pulsar Timing Array

- Simulated a fake pulsars in an oscillating ultralight dark matter box
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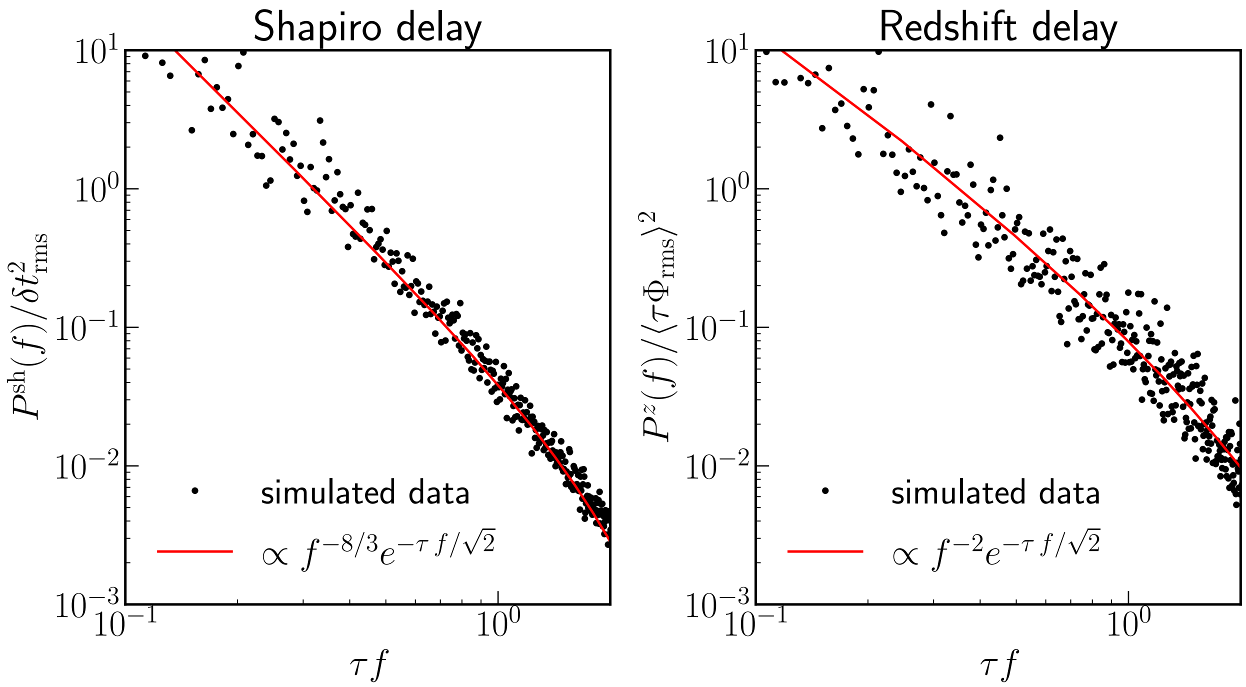
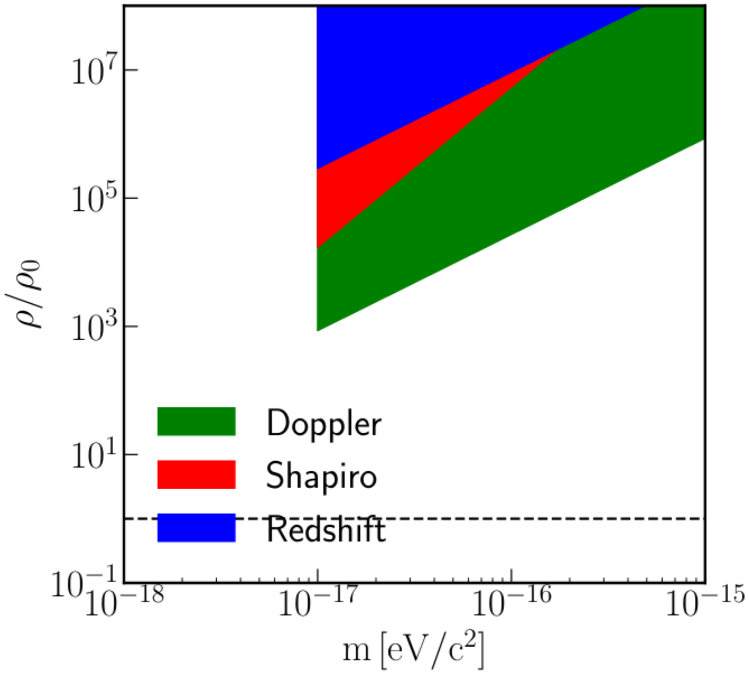
  - rms oscillation
  - Temporal spectrum



Pulsar Timing Array

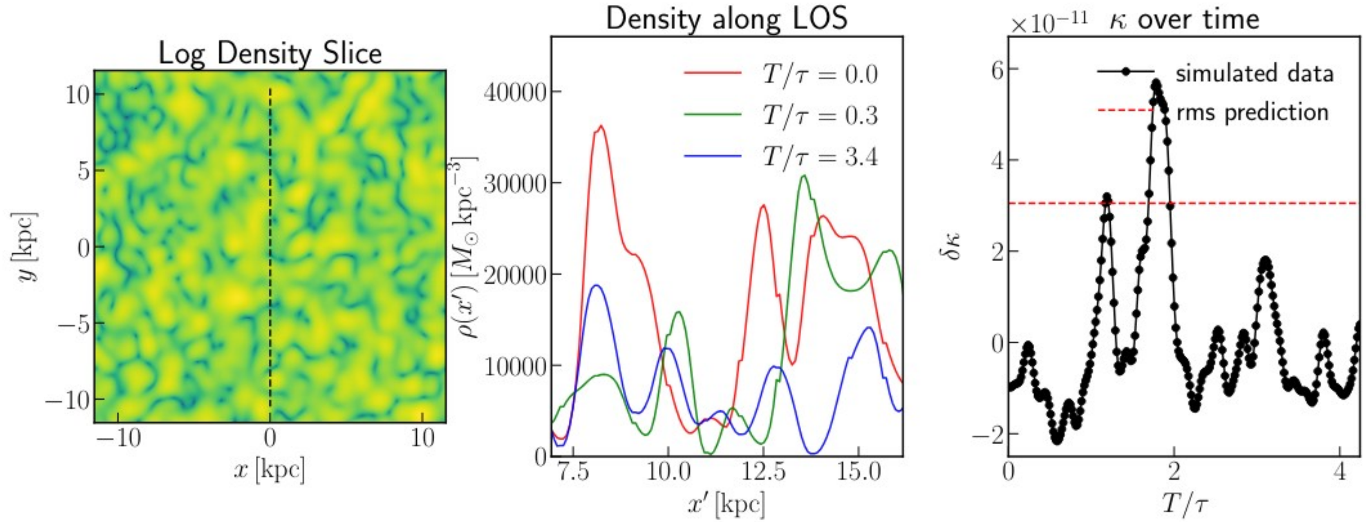
- Simulated a fake pulsars in an oscillating ultralight dark matter box
- Worked out
  - rms oscillation
  - Temporal spectrum
- Current sensitivity insufficient for detection



Stochastic lensing

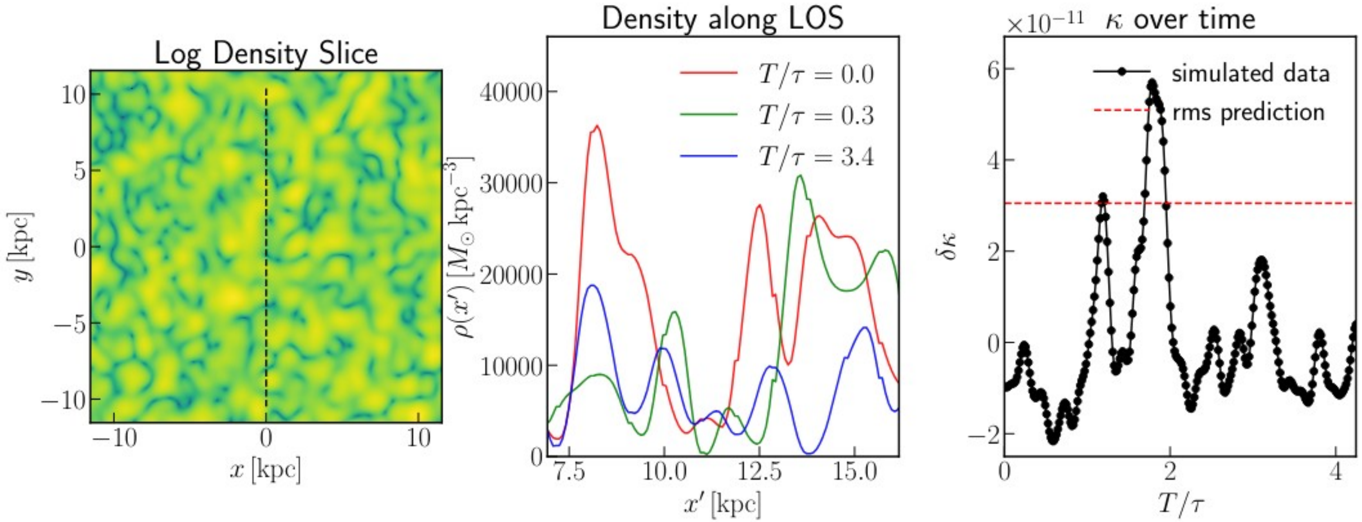
Stochastic lensing

- An oscillating density along the line of sight should also make a lensing signal



Stochastic lensing

- An oscillating density along the line of sight should also make a lensing signal
- Interesting because we are always viewing an bright object through the dm halo
- Unlike PBH/MACHO microlensing the granules are tightly packed always present



Stochastic lensing

- An oscillating density along the line of sight should also make a lensing signal
- Interesting because we are always viewing an bright object through the dm halo
- Unlike PBH/MACHO microlensing the granules are tightly packed always present
- Every (group of) bright object(s) potentially places a constraint

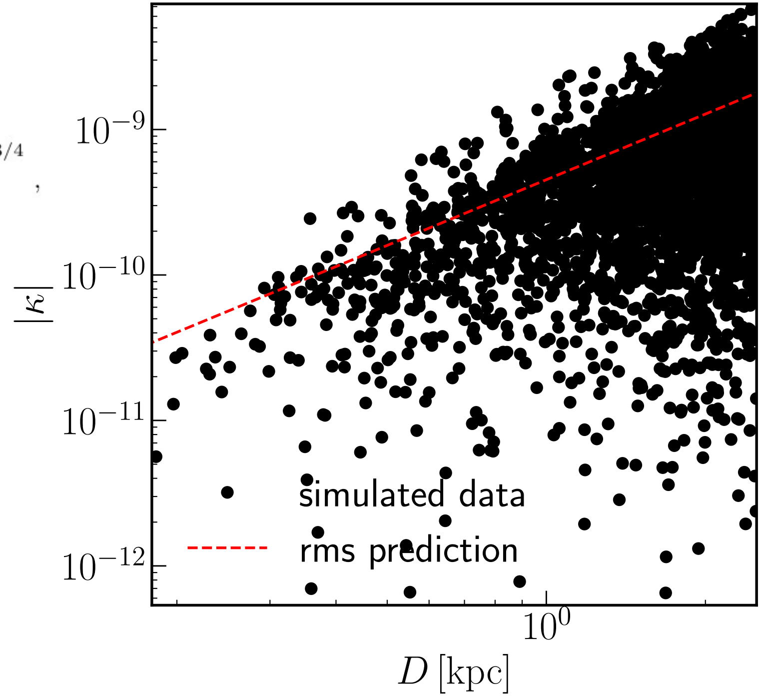
Stochastic lensing

- Ran simulations of ultralight dark matter densities over a range of masses

Stochastic lensing

- Ran simulations of ultralight dark matter densities over a range of masses
- Worked out
  - rms lensing

$$\delta\kappa^{\rm gr}_{\rm rms} \sim 3\times10^{-12}\left(\frac{m}{10^{-17}\,{\rm eV}}\right)^{-1/2}\left(\frac{\sigma}{200\,{\rm km/s}}\right)^{-1/2}\left(\frac{\rho}{10^7\,{\rm M_\odot/kpc^3}}\right)\left(\frac{D}{\rm kpc}\right)^{3/4},$$



Stochastic lensing

- Ran simulations of ultralight dark matter densities over a range of masses
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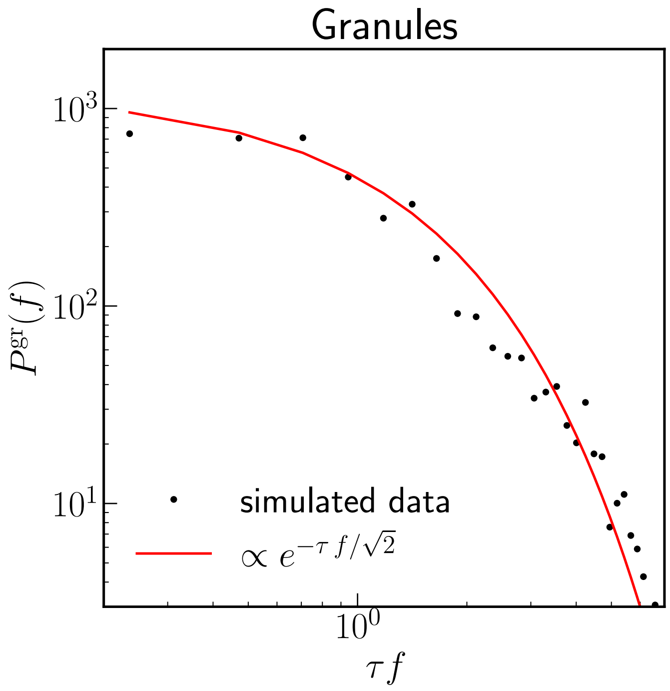
  - Temporal spectrum



Stochastic lensing

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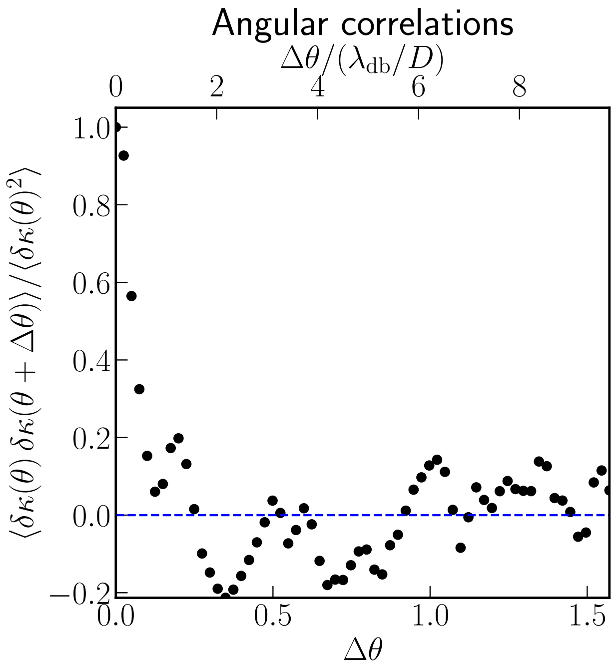
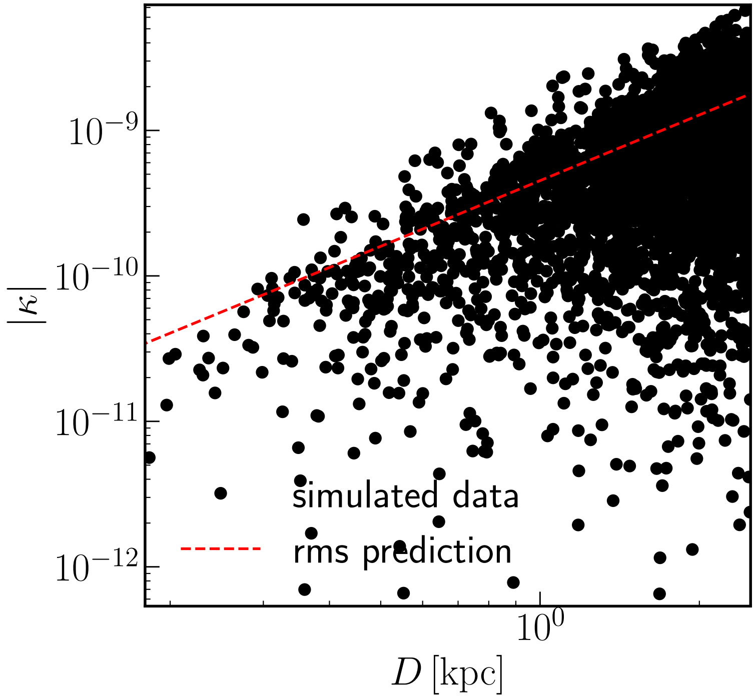
  - Temporal spectrum
  - Angular correlations



Stochastic lensing

- Ran simulations of ultralight dark matter densities over a range of masses
- Worked out
  - rms lensing
  - Temporal spectrum
  - Angular correlations
- Too small to detect currently but upcoming exoplanet surveys may be a good place to start



$$\delta\kappa_{\rm rms}^{\rm gr} \sim 3 \times 10^{-12} \left(\frac{m}{10^{-17}\,{\rm eV}}\right)^{-1/2} \left(\frac{\sigma}{200\,{\rm km/s}}\right)^{-1/2} \left(\frac{\rho}{10^{7}\,{\rm M}_{\odot}/{\rm kpc}^3}\right) \left(\frac{D}{\rm kpc}\right)^{3/4},$$

Conclusion

- Ultralight dark matter granules can create Shapiro delays, gravitational redshifts, and stochastic lensing
- Signals are too small to detect with current data
- Future work will look into using correlations between objects
- But if we can detect these signals we may be able to probe higher mass ultralight dark matter

Eberhardt et al, arxiv 2502.20697
Eberhardt et al, arxiv 2411.18051