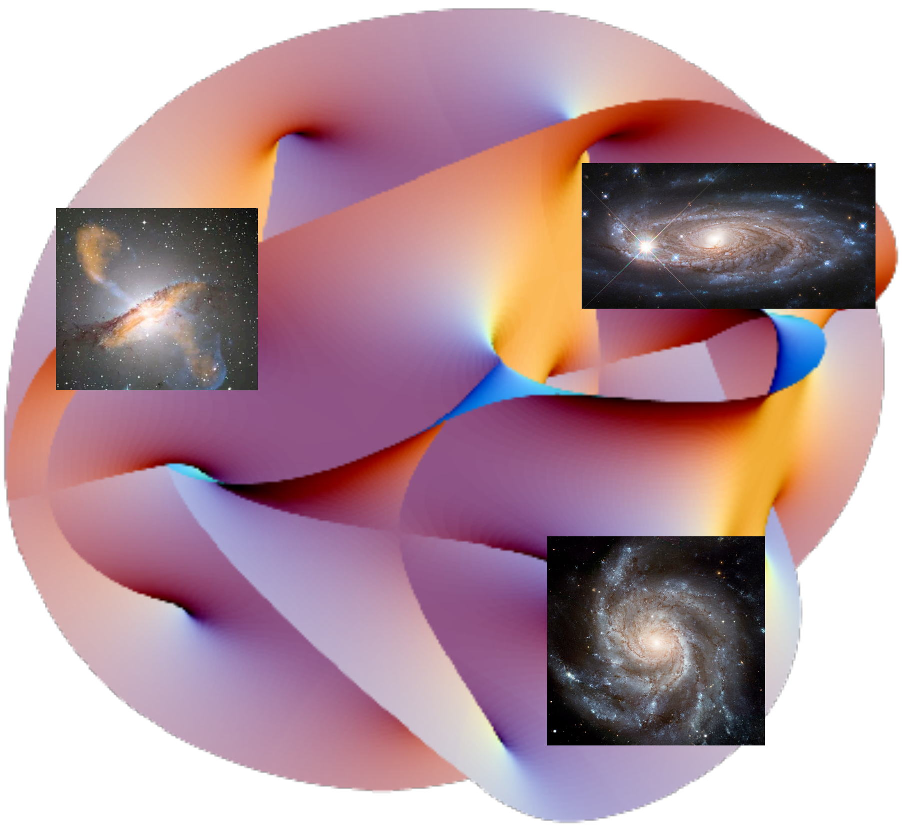
Galaxies in the Axiverse

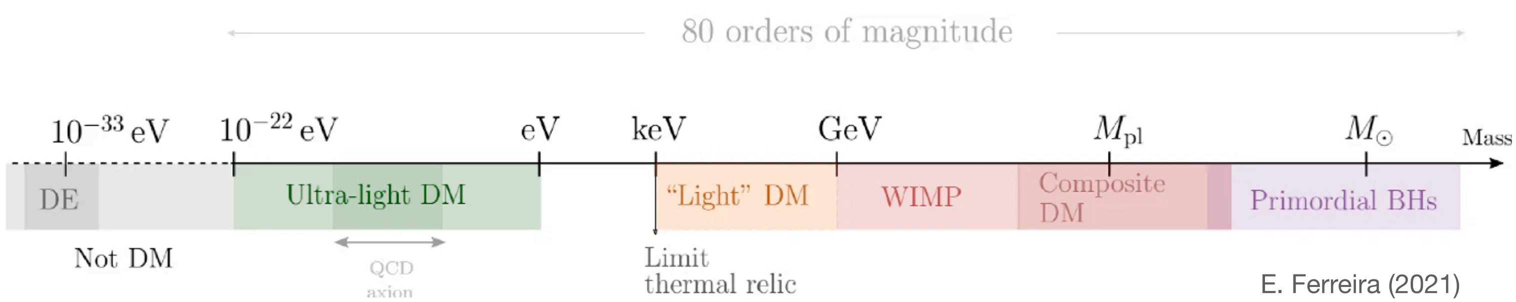


Neal Dalal
Perimeter Institute

With Andrey Kravtsov
(U. Chicago)

Dark Matter

- Most of the mass that clusters is DM. Properties remain poorly known!
- For example, mass of DM particle is unknown to many orders of magnitude

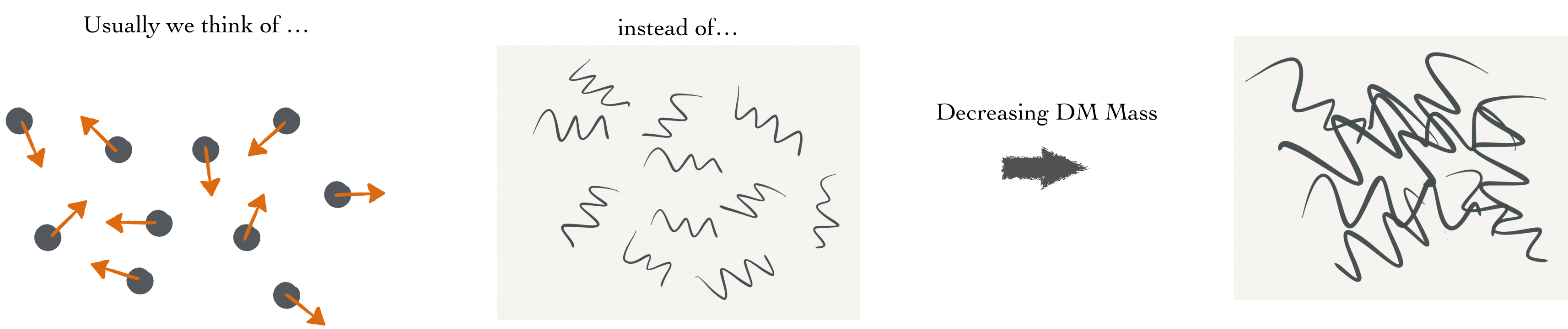


E. Ferreira (2021)

- String "axiverse" allows possible masses spanning many orders of magnitude, including **ultra-light** (m < eV/c^2).

Ultra-light Dark Matter

- In ultra-light regime, particles overlap significantly

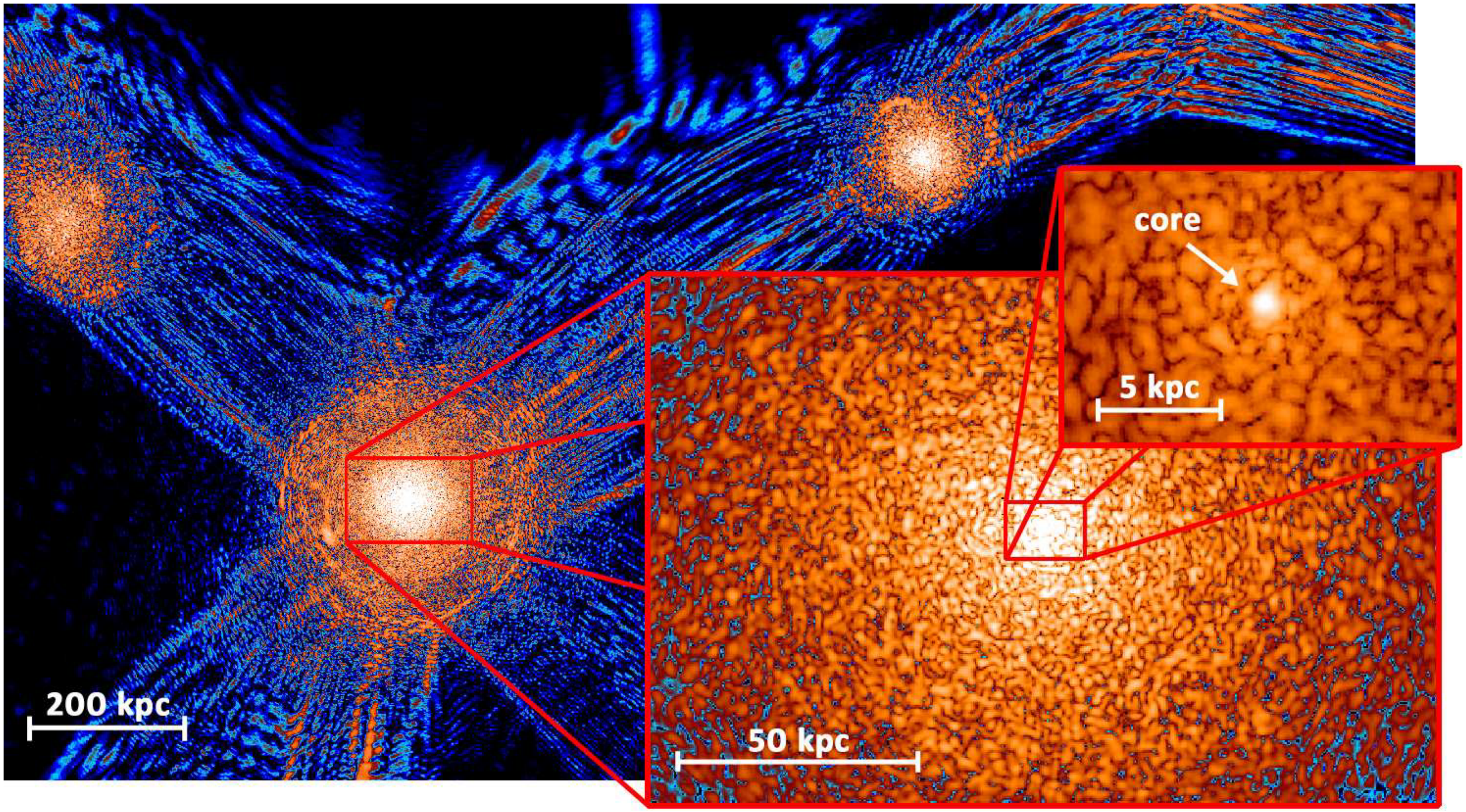


- Number density $n = \rho/m$, and de Broglie wavelength $\lambda = h/mv$
- In our Galaxy, $n(\lambda/2\pi)^3 > 1$ for $m < 1\,\mathrm{eV}/c^2$. In this regime, can think of overlapping particles as a coherent field, oscillating at frequency $\omega = mc^2/\hbar$, with coherence length $r = \lambda/2\pi$, and coherence time $\delta t \sim r/\sigma_v = \hbar/m\sigma_v^2$.

Ultra-light Dark Matter in galaxies

- In this regime, DM exhibits wave-like behaviour.
- For most of ultra-light mass range, wave-like DM is indistinguishable from regular CDM.
- But for $m \in 10^{-22} - 10^{-20}\,\mathrm{eV}$, the de Broglie wavelength is relevant for galaxy astrophysics. This regime is called "fuzzy" dark matter (FDM).
  - e.g., in Milky Way with v=200 km/s, m=10^{-22} eV gives $\lambda = \dfrac{h}{mv} \approx 0.6\,\mathrm{kpc}$.
- This can do interesting things for galaxies, like removing central DM cusps, or suppressing low-mass DM substructure. But one particular effect captured the interest of many DM researchers…

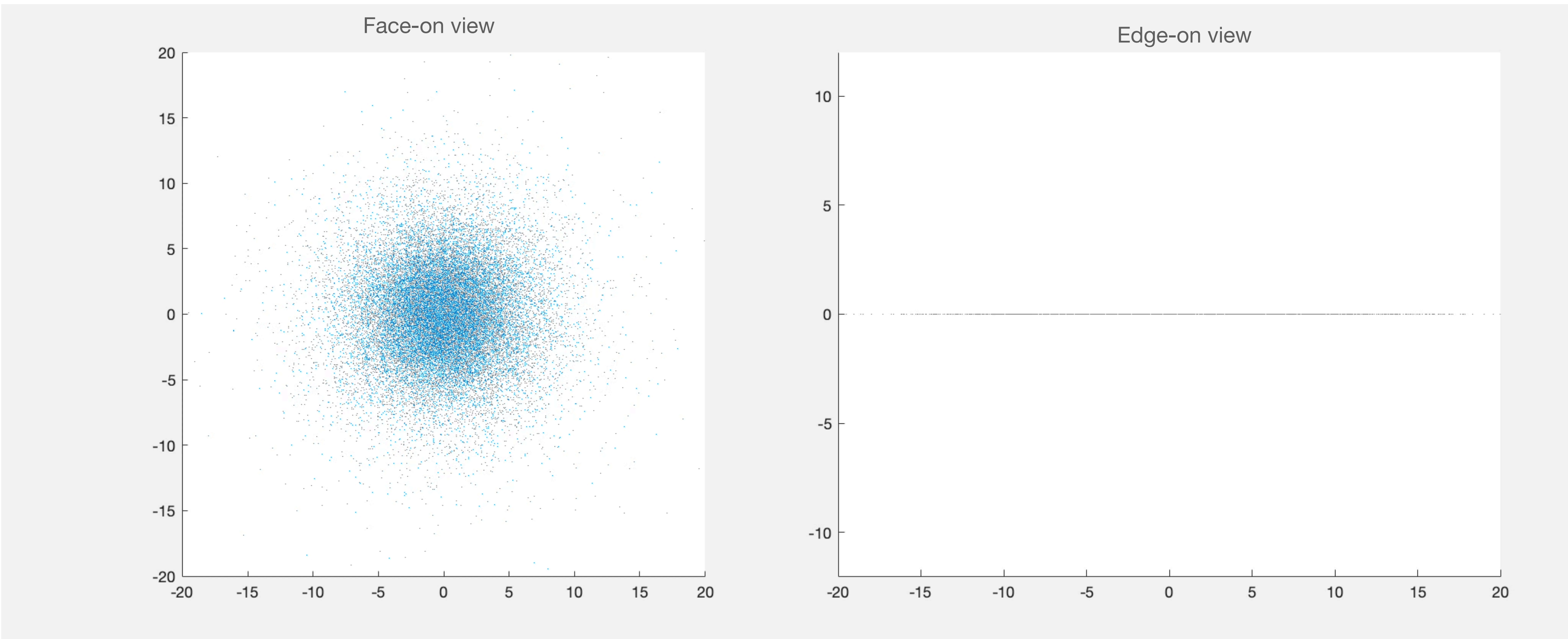
FDM wave interference



Schive et al., Nature Physics, 10, 496 (2014)

Gravitational heating from FDM

- Interference fringes have density contrast $\delta\rho \sim \rho$ everywhere all of the time
- These lead to fluctuating gravitational forces that can perturb stars
- Where to look for this signature of FDM? Crude estimate:
  - $\delta M \sim \delta\rho\,\lambda^3 \propto \rho/\sigma_v^3$ ⇒ acceleration perturbation $\delta a \sim G\,\delta M/\lambda^2 \propto G\rho/\sigma_v$
  - At that location, enclosed mass $M \sim \rho\,R^3$, so $a \sim GM/R^2 \propto G\rho\,R$
  - So fractional effect $\delta a/a \propto (R\,\sigma_v)^{-1}$
- Biggest effect where R is small and σ_v is small, i.e. **centres of smallest halos**.



Face-on view
Edge-on view

Ultra-faint dwarf galaxies

- Best place to look for FDM effects is the centre of smallest, DM-dominated galaxies.
- Local group has lots of tiny galaxies, e.g. Boötes I, Grus II, Leo IV, etc…
- Completely DM dominated (e.g., M/L ~ 300 inside $r_{1/2}$)
- Stellar ages $\gtrsim$10 Gyr, so plenty of time to experience FDM effects.
- Unlike soliton, heating effect is understood! Allows us to use even just 1-2 galaxies to constrain FDM.

Segue 1 and Segue 2

- Smallest & darkest known UFDs (but not huge outliers).
- Have half-light radii of 26 pc and 37 pc
- Velocity dispersions $\lesssim 2 - 3$ km/s
- Extensive spectroscopic observations of member stars

THE ASTROPHYSICAL JOURNAL, 733:46 (20pp), 2011 May 20 doi:10.1088/0004-637X/733/1/46

A COMPLETE SPECTROSCOPIC SURVEY OF THE MILKY WAY SATELLITE SEGUE 1: THE DARKEST GALAXY*

JOSHUA D. SIMON[1], MARLA GEHA[2], QUINN E. MINOR[3], GREGORY D. MARTINEZ[3], EVAN N. KIRBY[4,8], JAMES S. BULLOCK[3],
MANOJ KAPLINGHAT[3], LOUIS E. STRIGARI[5,8], BETH WILLMAN[6], PHILIP I. CHOI[7], ERIK J. TOLLERUD[3], AND JOE WOLFE[3]

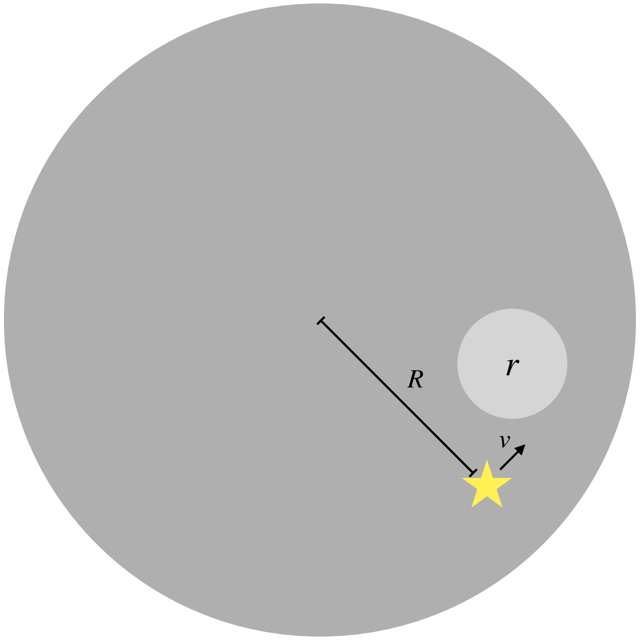
THE ASTROPHYSICAL JOURNAL, 770:16 (16pp), 2013 June 10 doi:10.1088/0004-637X/770/1/16

SEGUE 2: THE LEAST MASSIVE GALAXY*

EVAN N. KIRBY[1,4], MICHAEL BOYLAN-KOLCHIN[1,4], JUDITH G. COHEN[2], MARLA GEHA[3],
JAMES S. BULLOCK[1], AND MANOJ KAPLINGHAT[1]

Ballpark estimate

- Consider typical star in galaxy of size R, moving at velocity $v \sim \sigma_v$.
- Enclosed mass is $M \sim 3\,\sigma_v^2\,R/G$
- FDM fluctuation of size r, with $\delta\rho \sim \rho$.
  - $\delta M \sim (r/R)^3\,M,\;\; \delta\Phi \sim G\,\delta M/r \approx 3\,\sigma_v^2\,(r/R)^2$
  - $\delta v \sim \delta\Phi/v \approx 3\,\sigma_v\,(r/R)^2$
- In time t, star encounters $N \sim vt/r$ blobs, so variance increases by $\Delta\sigma_v^2 \approx N\,\delta v^2 \approx 9\,\sigma_v^3\,t\,r^3/R^4 \approx 9\,(\hbar/m)^3\,t\,R^{-4}$.
- So we can solve for mass m that makes $\Delta\sigma_v^2 \approx \sigma_v^2$ in time t. Plugging in t =10 Gyr, R=50 pc, σ_v = 3 km/s gives $m \sim 10^{-19}$ eV.



FDM constraints from UFDGs

- We use simulation-based inference to constrain FDM using UFDs, i.e. we compute how often simulations reproduce observed data.
  - Data are velocities of individual member stars.
  - We could also use positions of individual stars, but spectroscopic selection function is unknown to us, so we instead fit half-light radius of population.
- Simulations evolve stars in FDM potentials for 10 Gyr.
- Marginalize over unknown halo parameters ($M_{\rm vir}$, $c_{\rm vir}$), and initial stellar distribution, by running lots of different sims.
- Problem: Schrödinger-Poisson sims cannot be done yet for masses of interest, since computational expense scales like $m_{\rm FDM}{}^5$! Need different approach…

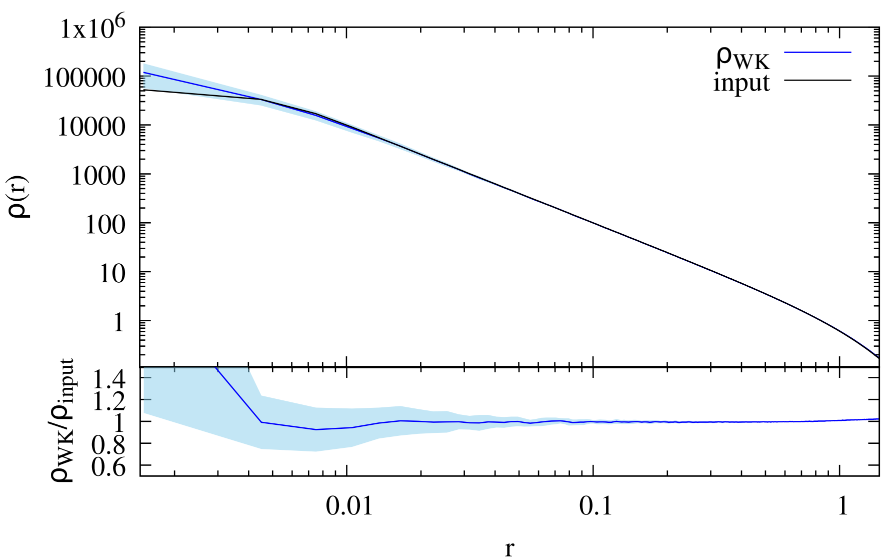
Alternative method

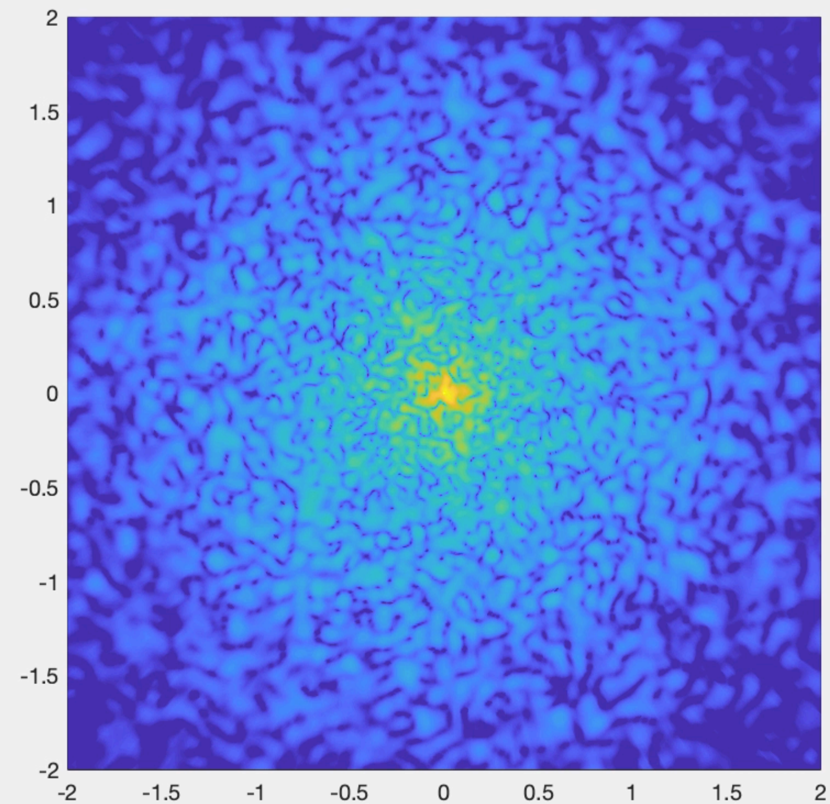
- If we have a known (time-averaged) potential for the halo, we can determine the eigenfunctions of the (average) Hamiltonian. Each eigenfunction evolves trivially in time $\propto e^{-iEt/\hbar}$.
- So let's find the combination of eigenfunctions that adds up on average to the desired density profile $\langle \rho \rangle = m\langle |\psi|^2 \rangle$, with $\psi(\mathbf{x}, t) = \sum_i a_i e^{-i\omega_i t} F_i(\mathbf{x})$
- Widrow & Kaiser (1993): use $\langle |a_i|^2 \rangle \sim f(E_i)$, for distribution function $f(E)$.
- In simple cases (e.g. spherical potential), we can solve for $f(E)$ analytically.
- This gives a simple way to evolve realistic wavefunctions, and is faster by *orders of magnitude*! Instead of giant supercomputers, our simulations run on 1 node. **Caveat: only accurate to 1st order.**

$$\rho = m|\psi|^2,$$

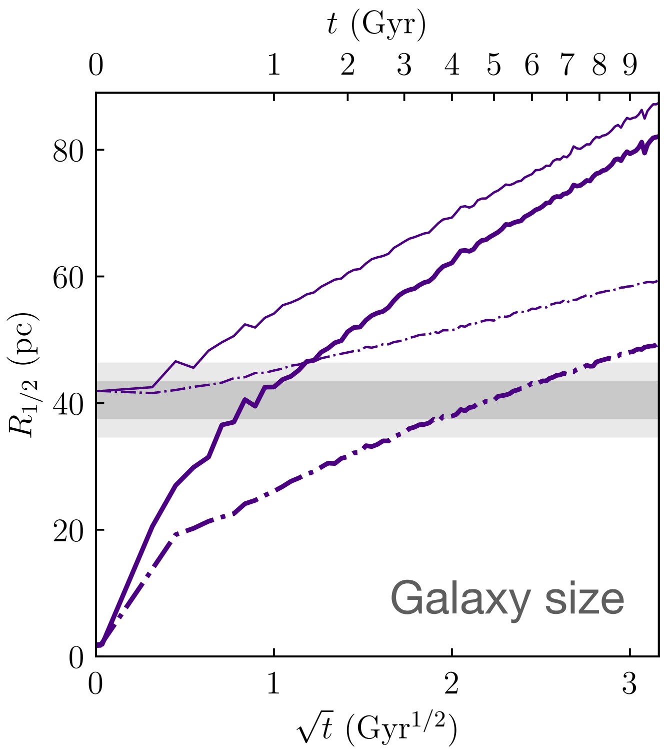
$$\psi(\mathbf{x}, t) = \sum_i a_i e^{-i\omega_i t} F_i(\mathbf{x})$$

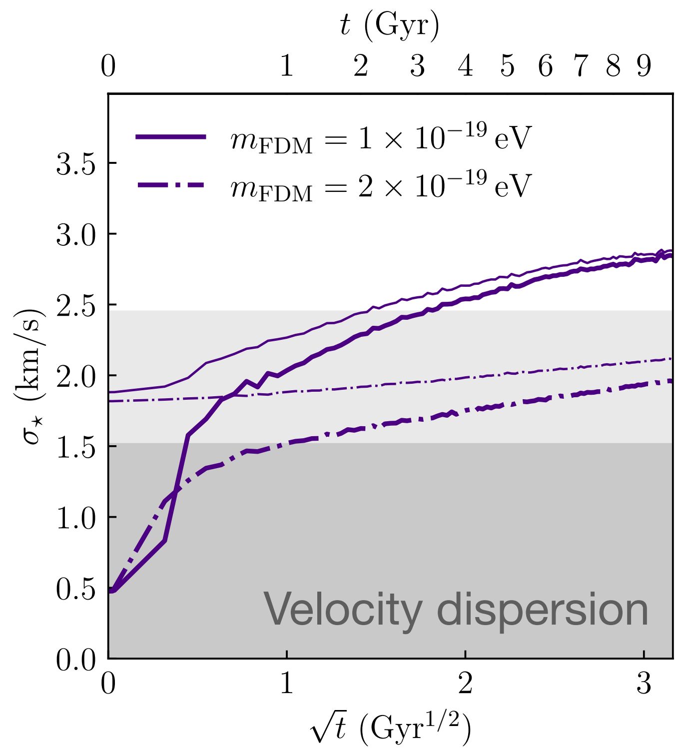
(Widrow-Kaiser wavefunction)





Heating in sims



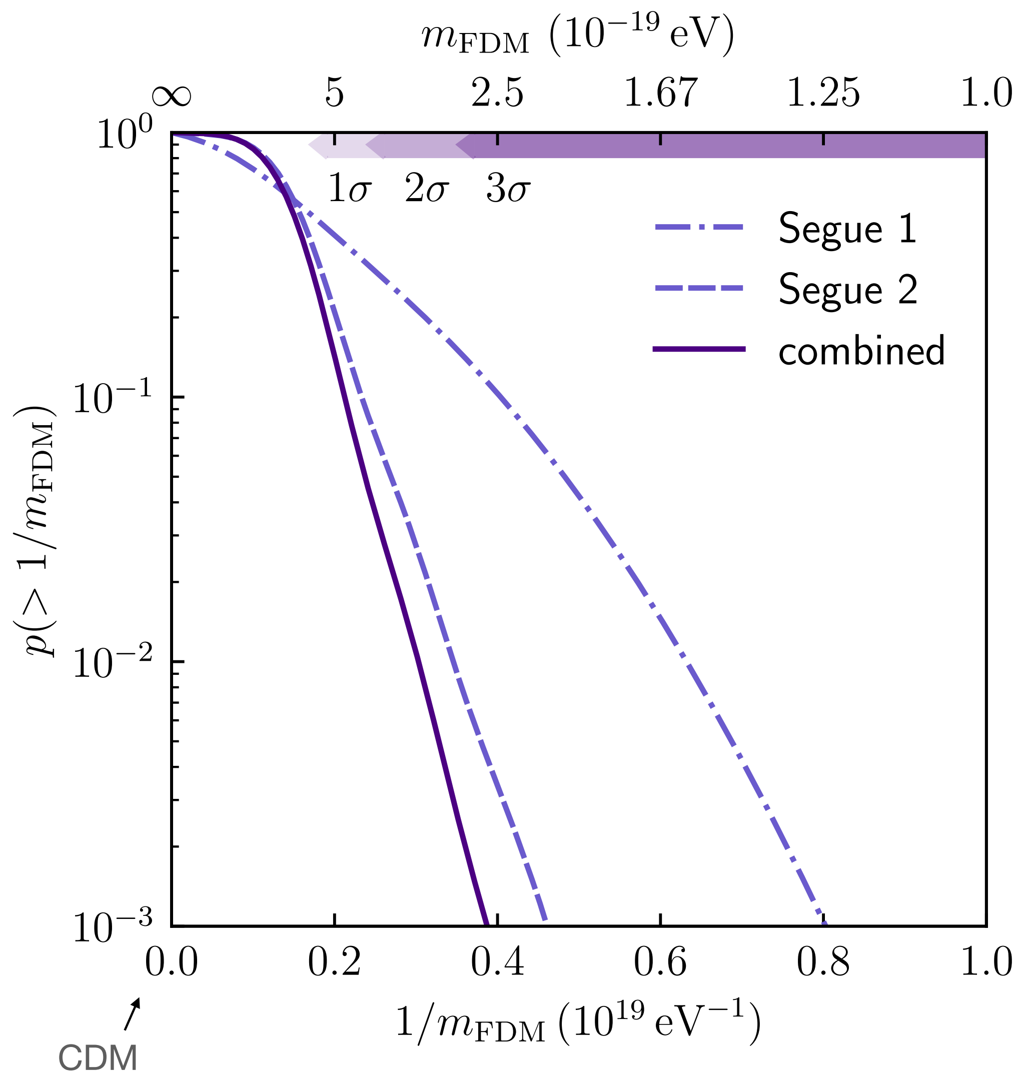


$$p_{\rm size} = \frac{1}{\sqrt{2\pi}\sigma_{1/2}} \exp\left[-\frac{(R_{1/2,\rm sim} - R_{1/2,\rm obs})^2}{2\sigma_{1/2}^2}\right]$$

$$p_{\rm vel} = \prod_i \int dv_i \, p_{\rm sim}(v_i \,|\, r_i) \, p_{{\rm obs},i}(v_i)$$

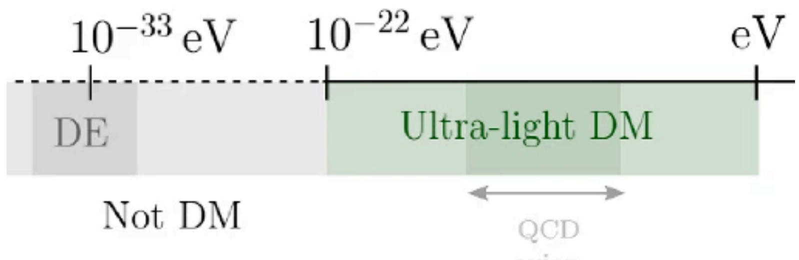
Results

- Find $m_{\mathrm{FDM}} > 3 \cdot 10^{-19}\,\mathrm{eV}$ at >99% confidence, using Segue 1 & Segue 2. Previous bounds from LyαF are $m \gtrsim 10^{-21}\,\mathrm{eV}$
- Our constraints are highly conservative due to neglect of soliton, and assumed prior $P \sim m_{\mathrm{FDM}}^{-2}$.
- Essentially, rules out "fuzzy" regime:
  - linear power spectrum identical to ΛCDM out to $k \sim 200\ \mathrm{Mpc}^{-1}$.
  - halo mass function identical to ΛCDM down to $M \sim 2 \cdot 10^5 M_\odot$



Upshot

- Using galaxies — either individually, or in large-scale structure — we can probe ultra-light particles over a huge range of masses!



- Galaxies probably can't probe even higher masses (e.g., $m > 10^{-18}\,\mathrm{eV}$). But we can extend the constraints using another probe: black hole super-radiance! Has the potential to go another ~8 orders of magnitude in m!