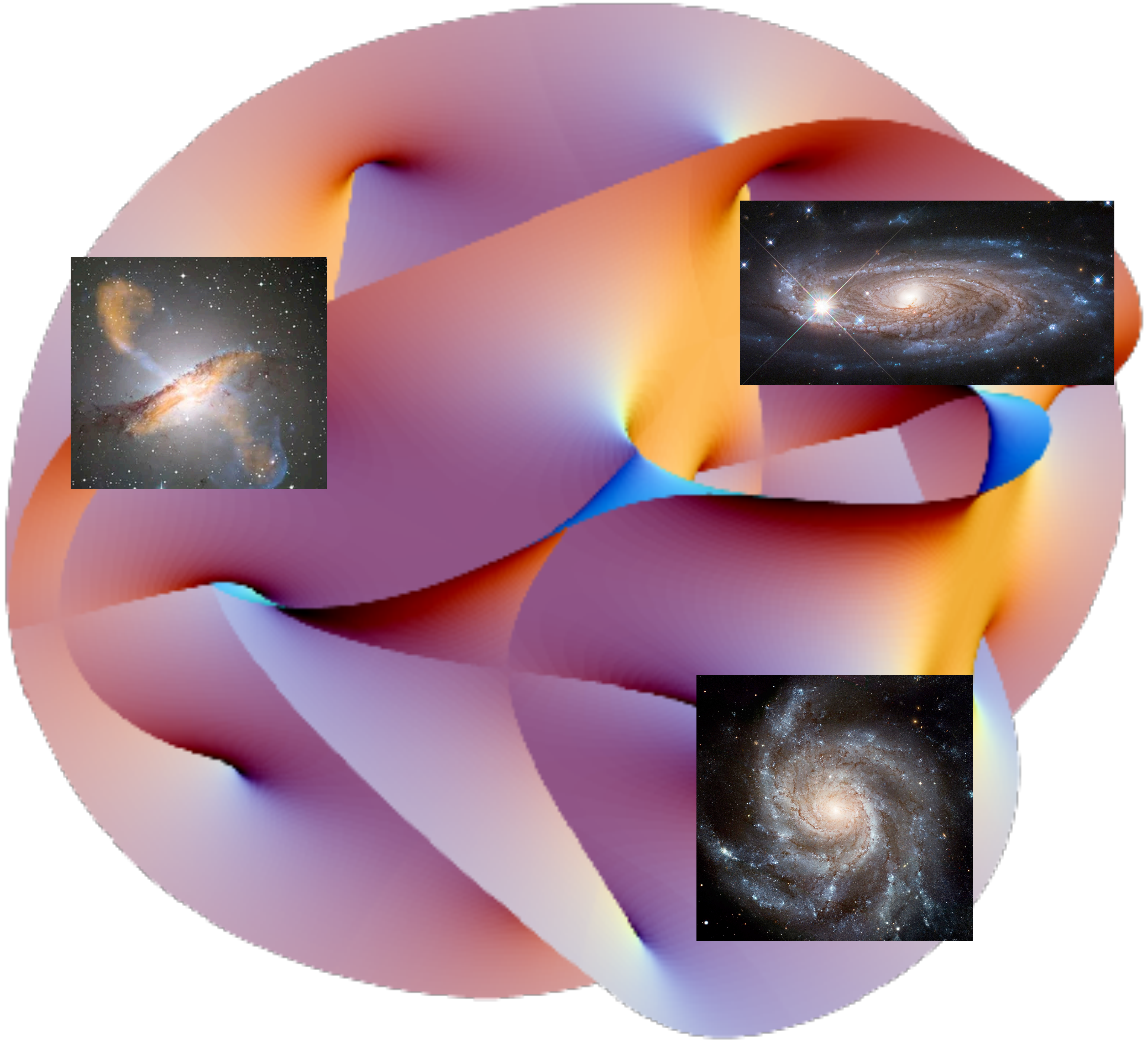
# Galaxies in the Axiverse

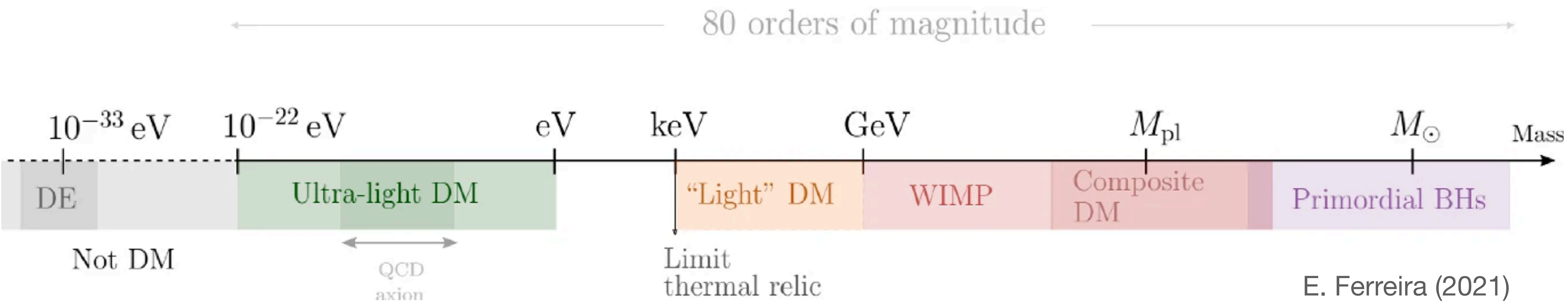


Neal Dalal
Perimeter Institute

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

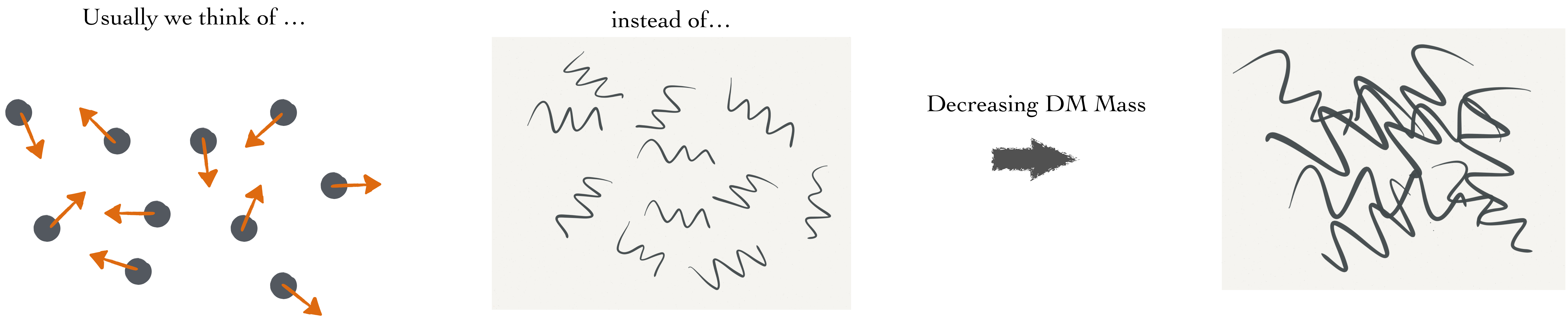



E. Ferreira (2021)

- 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

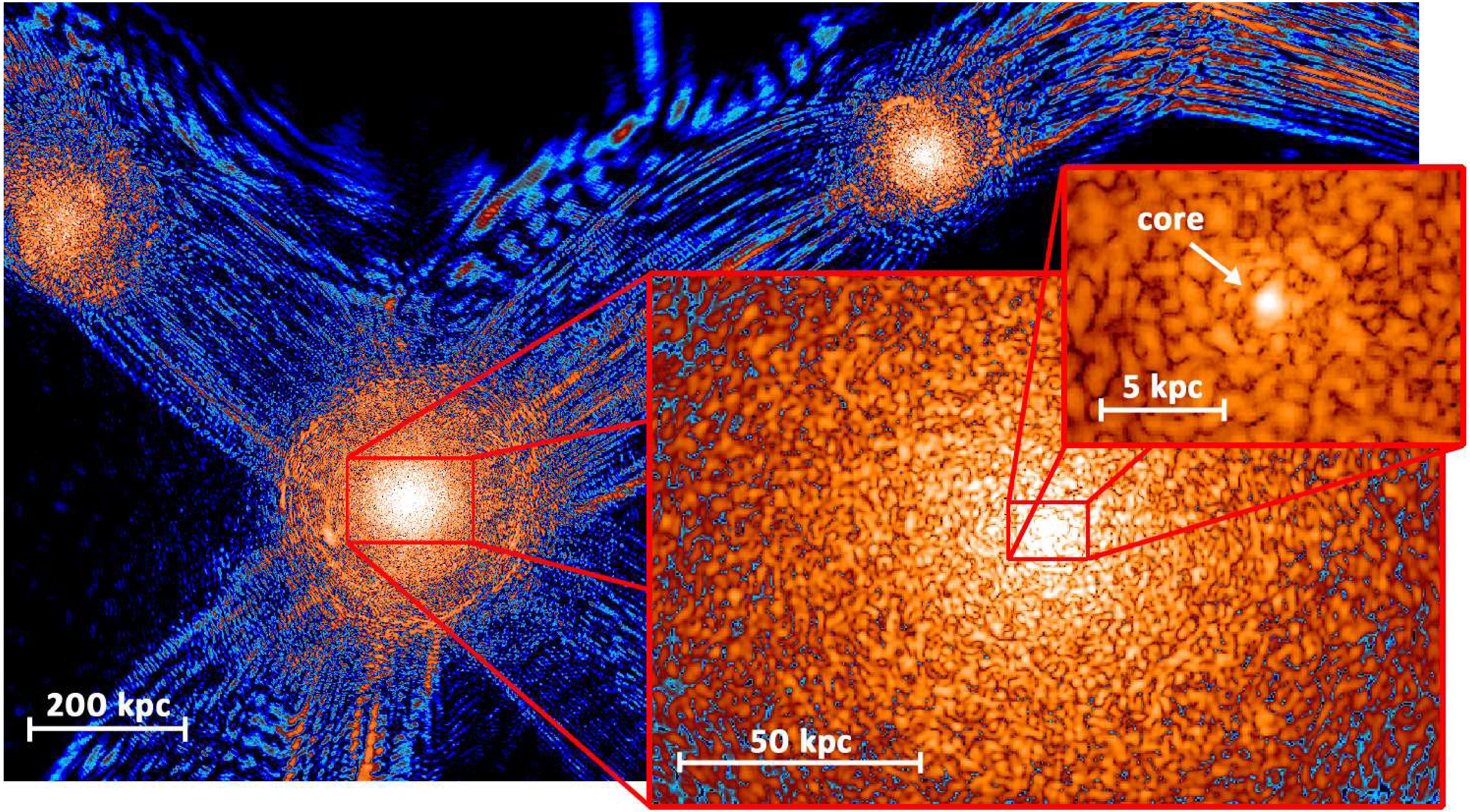



- Number density $n = \rho/m$, and de Broglie wavelength $\lambda = h/mv$
- In our Galaxy, $n(\lambda/2\pi)^3 > 1$ for $m < 1\,\mathrm{eV}/c^2$. In this regime, can think of overlapping particles as a coherent field, oscillating at frequency $\omega = mc^2/\hbar$, with coherence length $r = \lambda/2\pi$,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

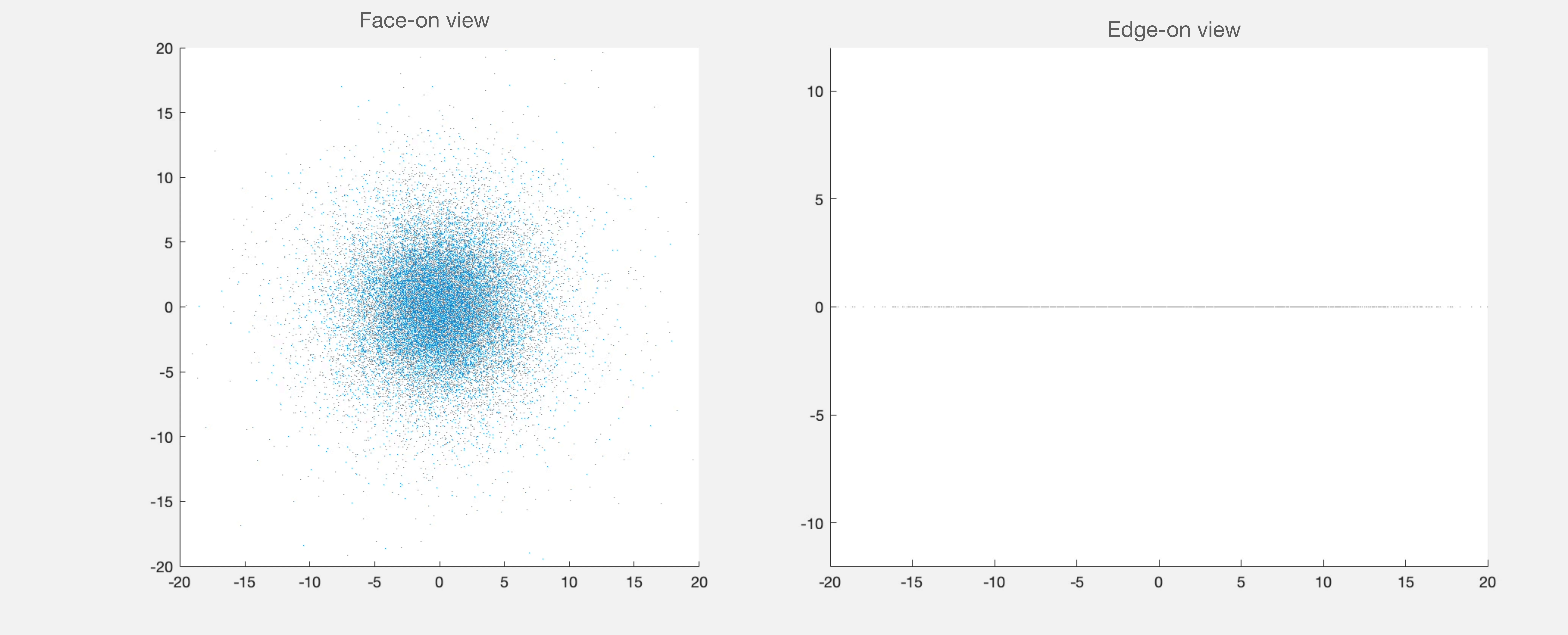
# FDM wave interference




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:
  - $\delta M \sim \delta\rho\, \lambda^3 \propto \rho/\sigma_v^3 \Rightarrow$ 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 $\sigma_v$ is small, i.e. **centres of smallest halos**.



Face-on view
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# 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]

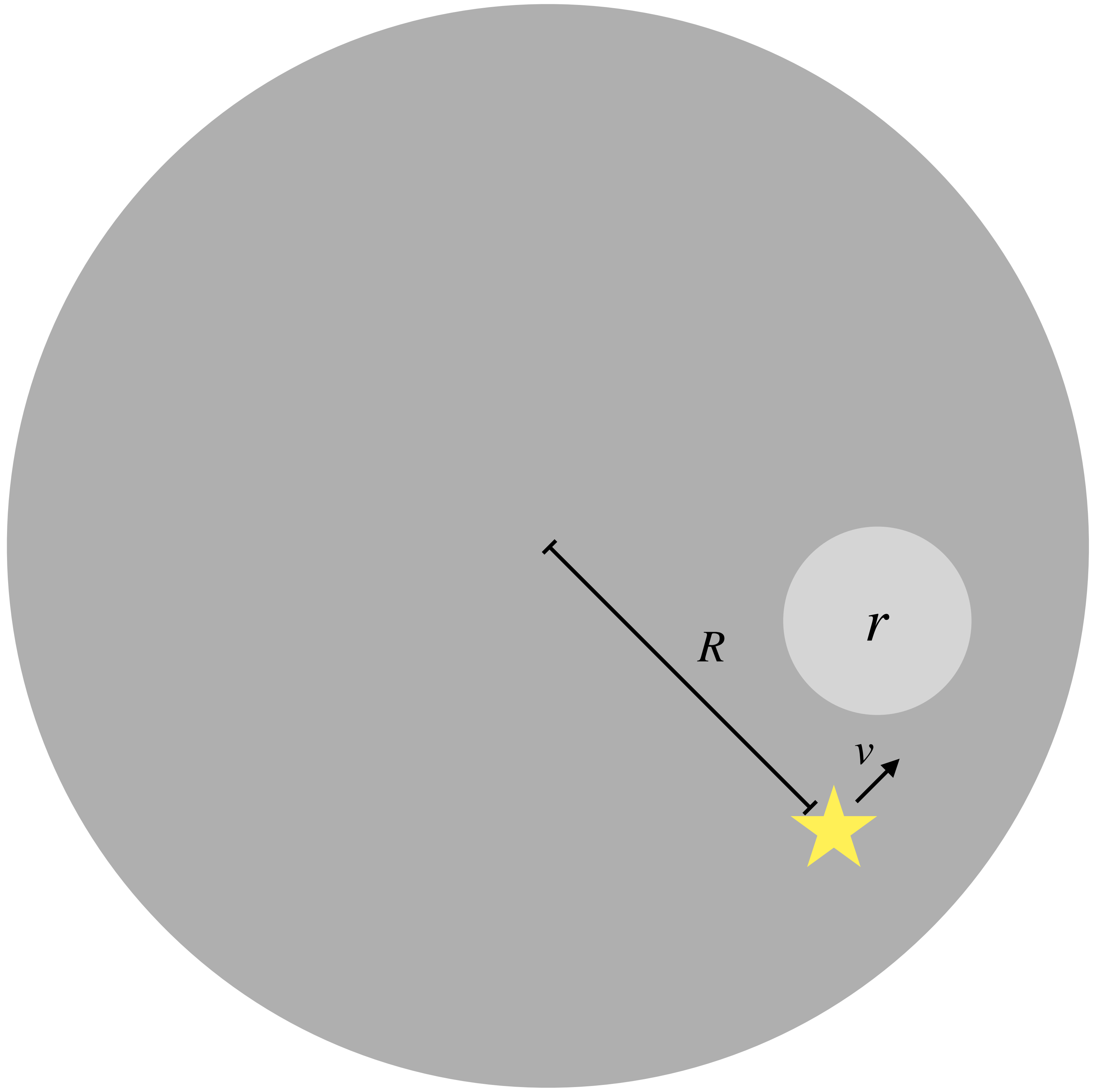
The Astrophysical Journal, 770:16 (16pp), 2013 June 10 doi:10.1088/0004-637X/770/1/16


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, $\sigma_v$ = 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…

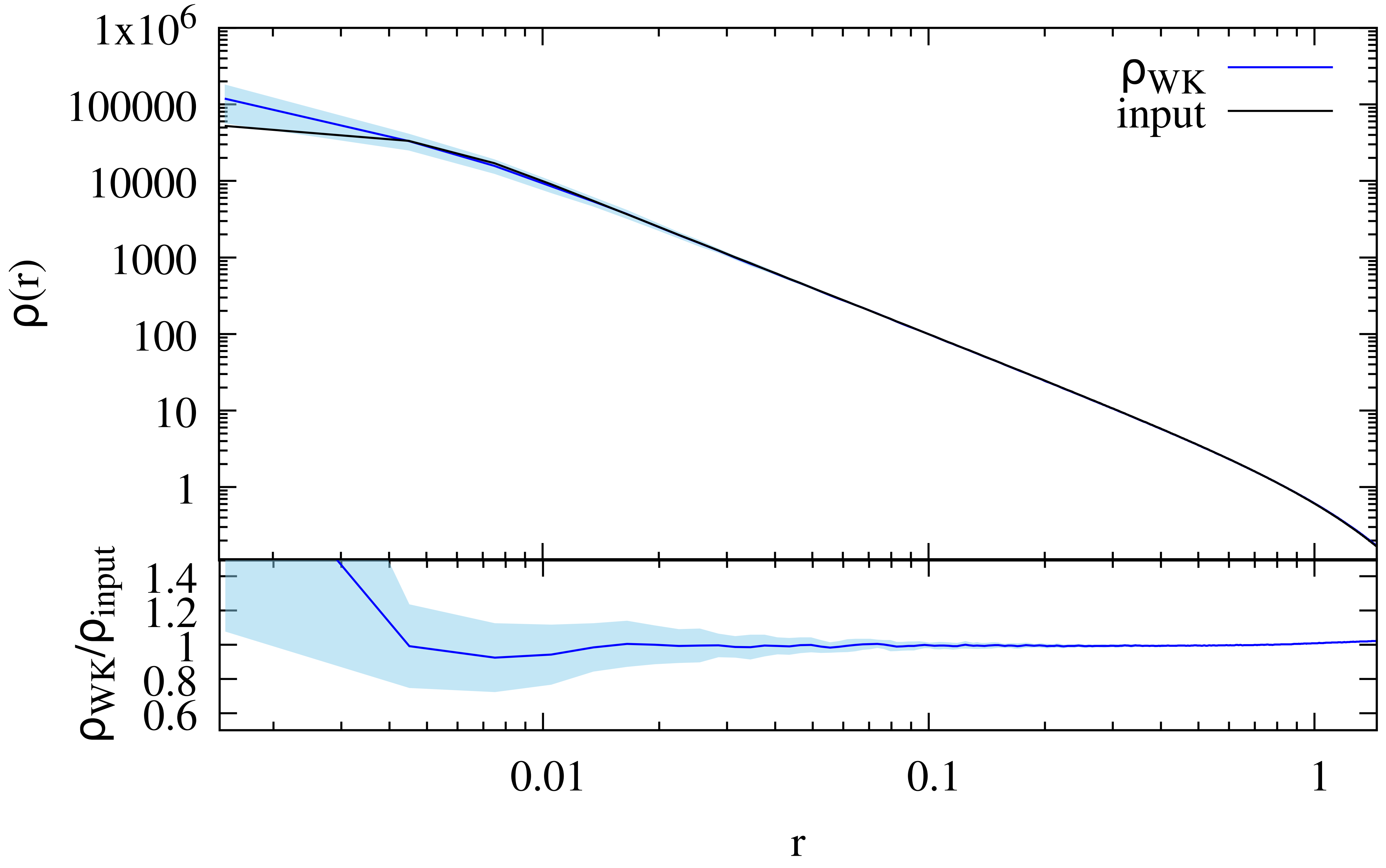
# Alternative method

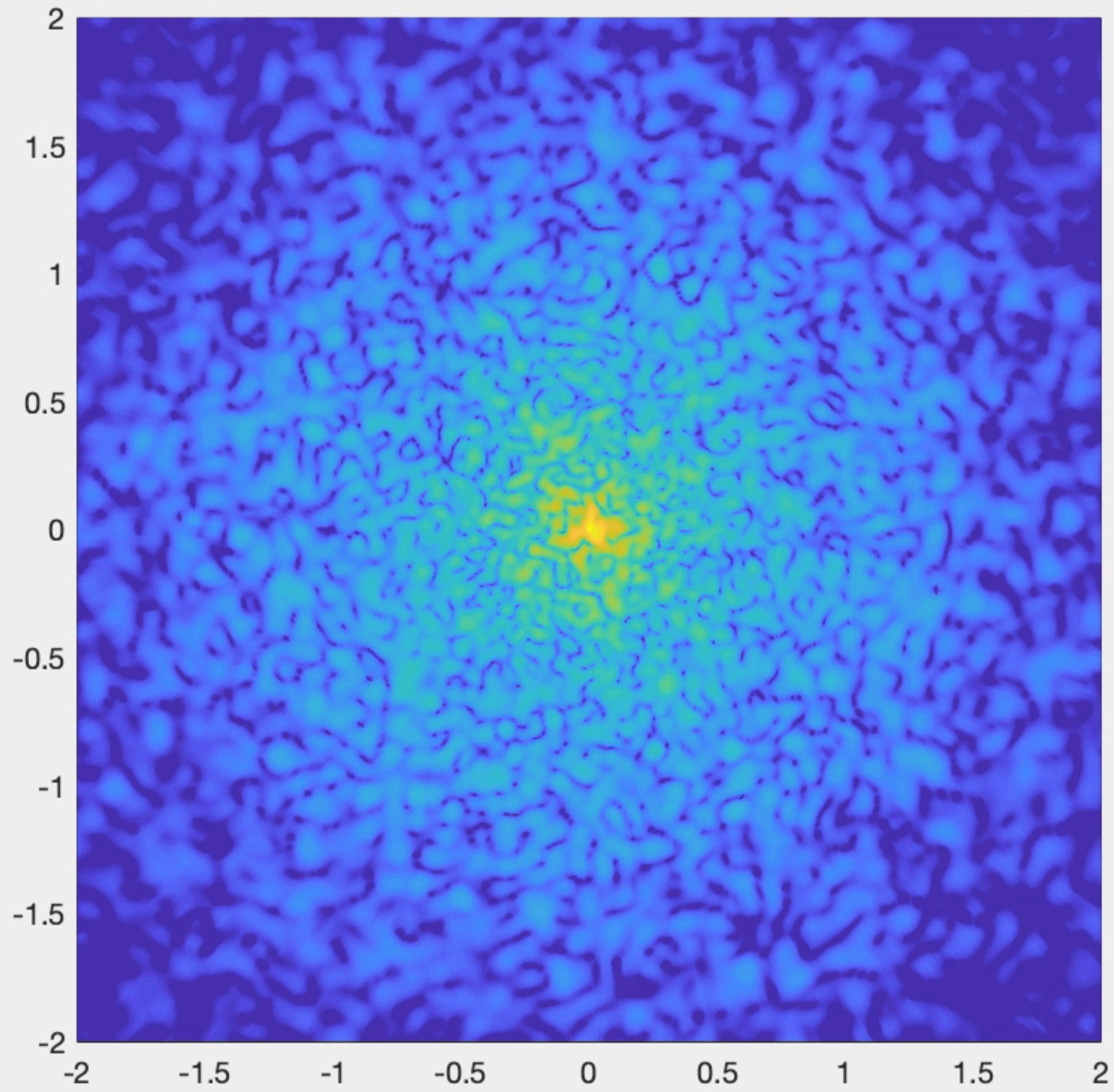
- If we have a known (smooth) potential for the halo, we can determine the eigenfunctions of the Hamiltonian. Each eigenfunction evolves trivially in time $\propto e^{-iEt/\hbar}$.
- So let's find the combination of eigenfunctions that adds up on average to the desired density profile $\langle \rho \rangle = m \langle |\psi|^2 \rangle$, 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.**

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

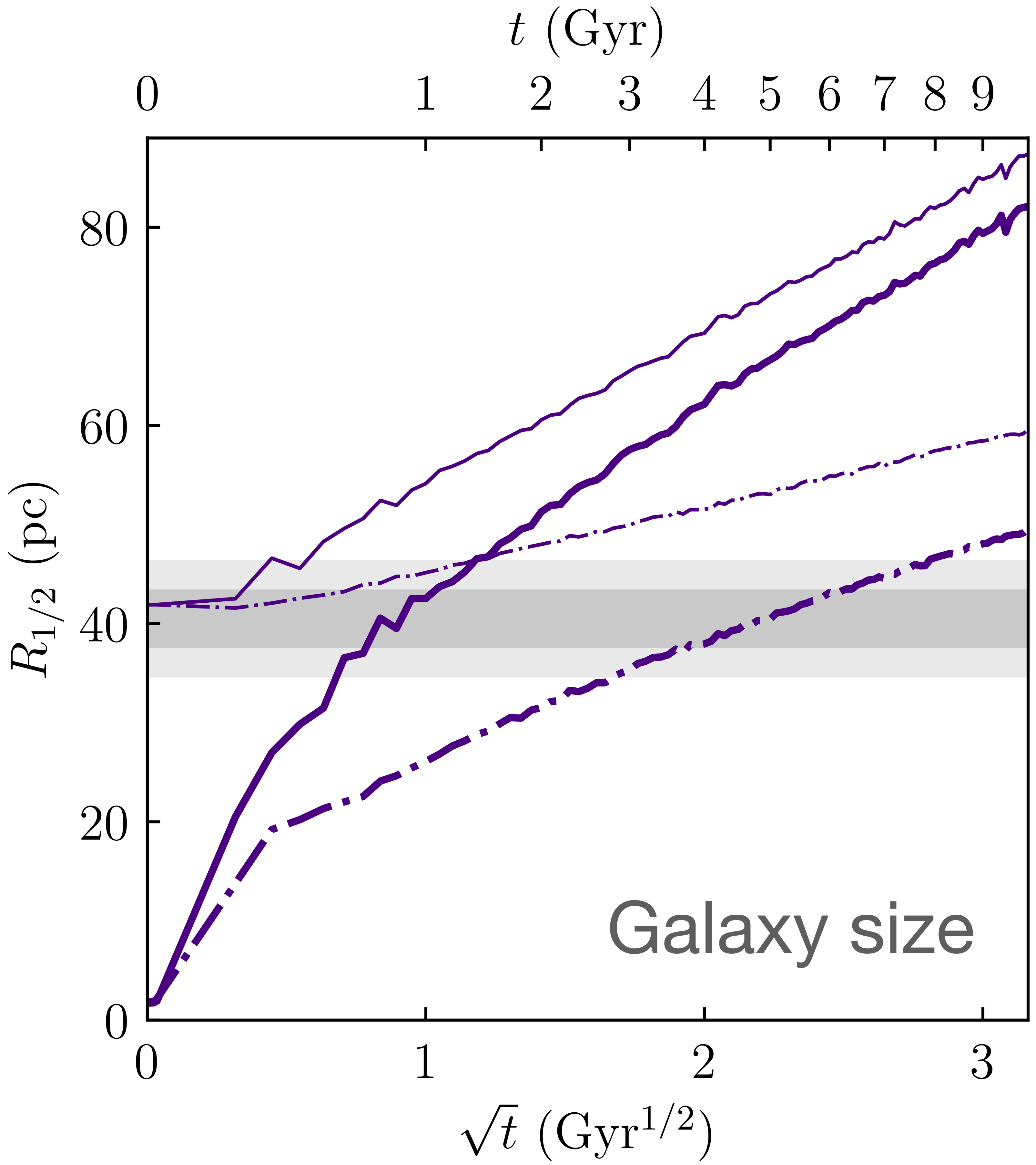
$$\psi(\mathbf{x}, t) = \sum_i a_i\, e^{-i\omega_i t} F_i(\mathbf{x})$$

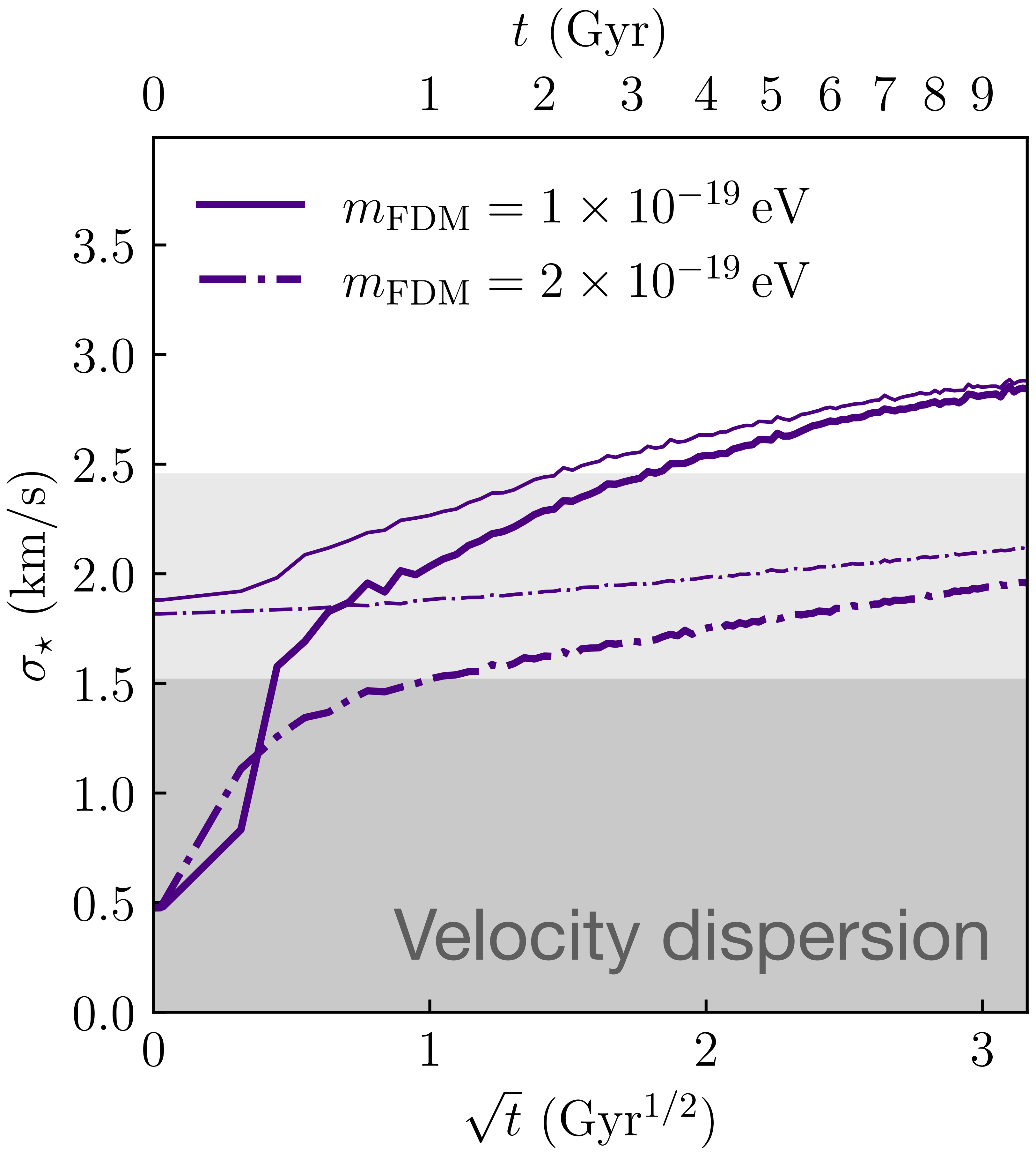
(Widrow-Kaiser wavefunction)



# Heating in sims



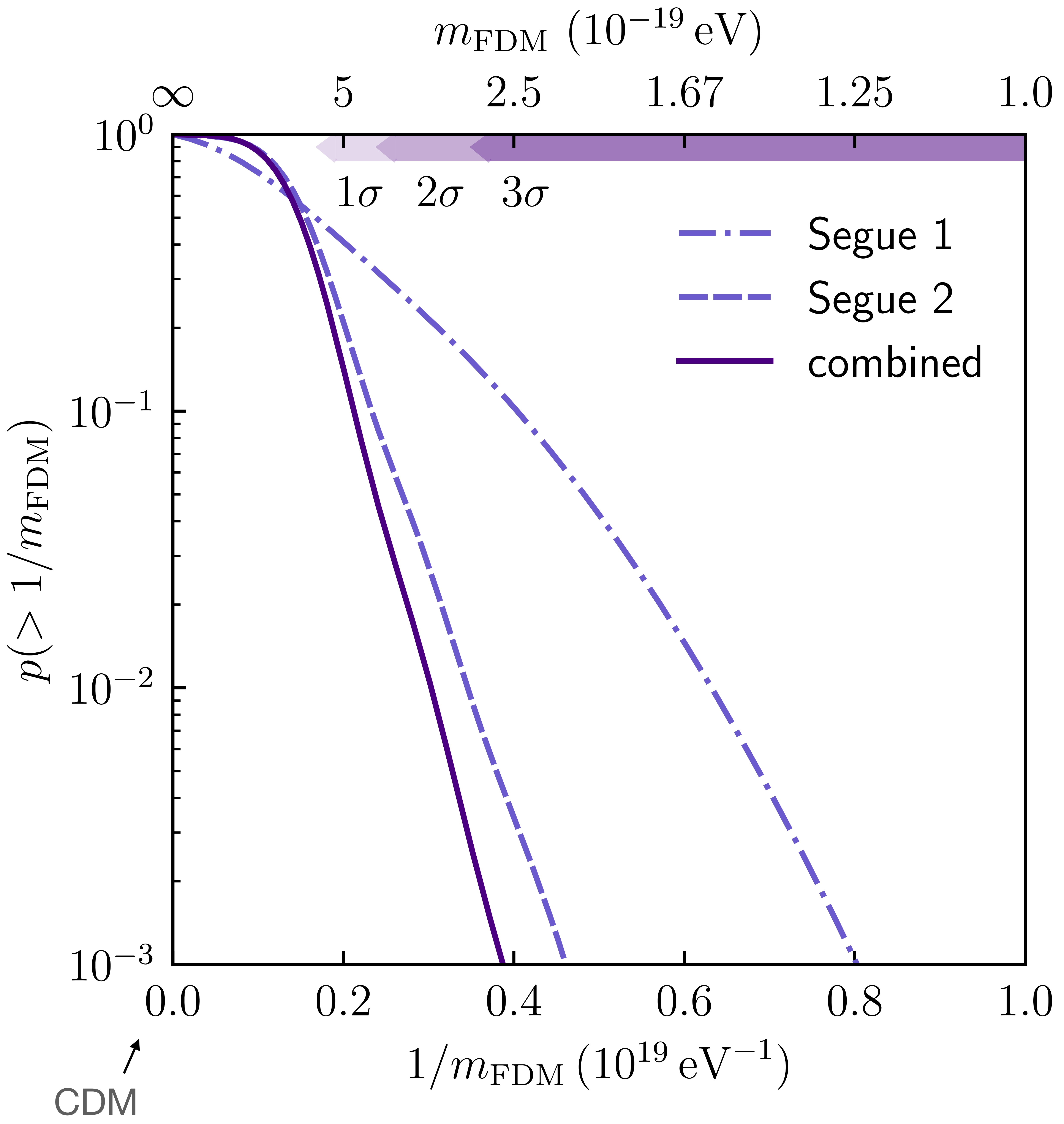




$$p_{\rm size} = \frac{1}{\sqrt{2\pi}\sigma_{1/2}} \exp\left[-\frac{(R_{1/2,\rm sim} - R_{1/2,\rm obs})^2}{2\sigma_{1/2}^2}\right]$$

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

# 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 $M \sim 2 \cdot 10^5 M_\odot$



# FAQ

- Wait, so FDM is ruled out?
  - Yes. DM can be ultra-light, but not in the range $(m < 10^{-20}\,\mathrm{eV})$ that helps for CDM problems.

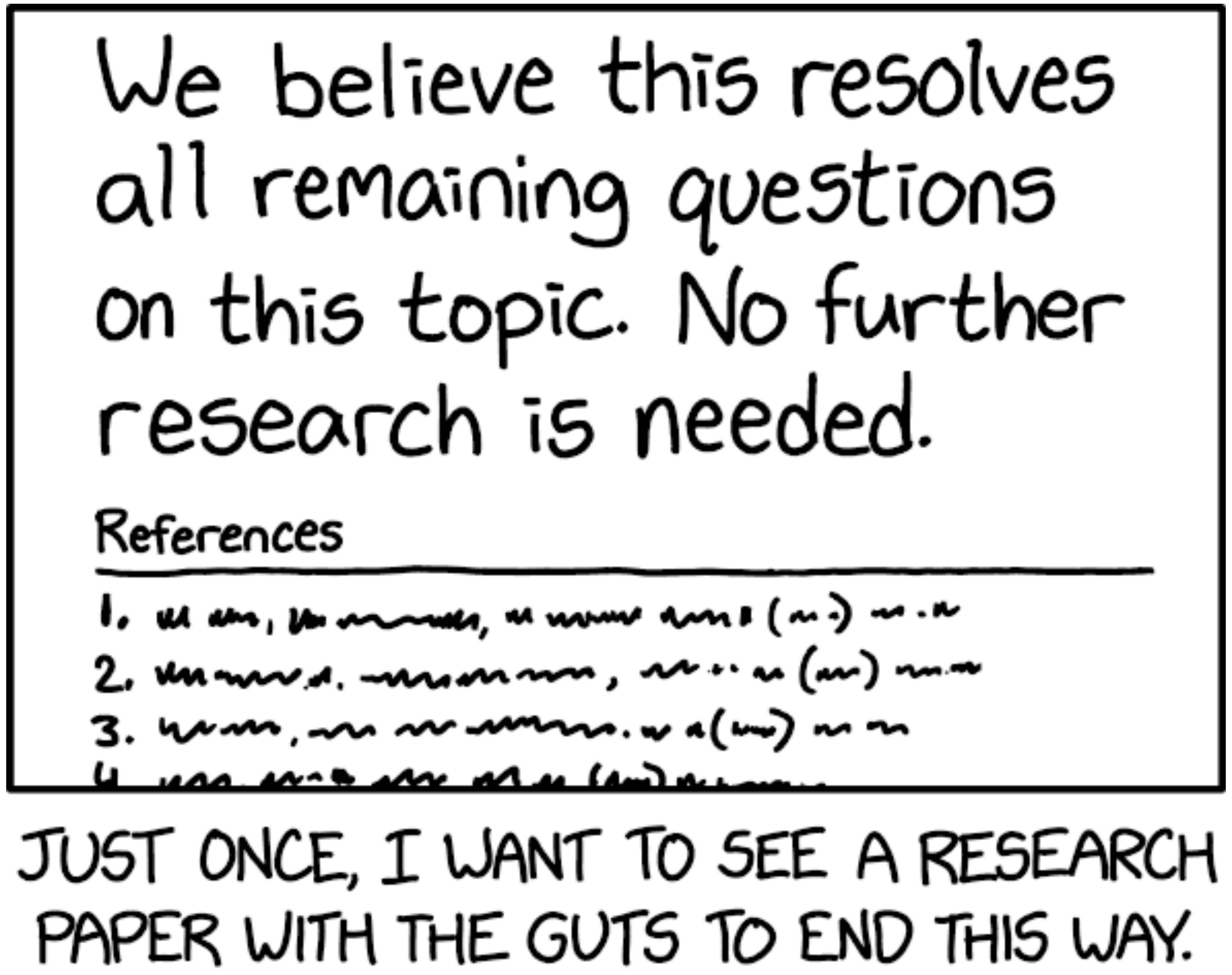
# FAQ

- Can we really do cosmology with 1 object? What about sample variance?
  - The constraint is based on $\lambda = h/mv$, and velocity $v$ is directly measured. There is no sample variance in $\hbar$. So yes, we can do cosmology with just 1 (or 2) object(s).

# FAQ

- Can we trust this perturbative eigenfunction expansion?
  - Many independent authors have shown that properties of FDM fluctuations in full Schrodinger-Poisson simulations are described accurately by interference of eigenfunctions (Li et al. 2021, Yavetz et al. 2021, Zagorac et al. 2021, … ). Specifically, the **amplitude**, coherence **length**, coherence **time** of fluctuations.
  - That is all we need to compute the heating effect, i.e. why the ballpark estimate agrees with our simulations.
  - Since heating rate scales like $m^{-3}$, then to change our lower limit by a factor of 30, our calculation must be wrong by factor of 30,000!

# What next?



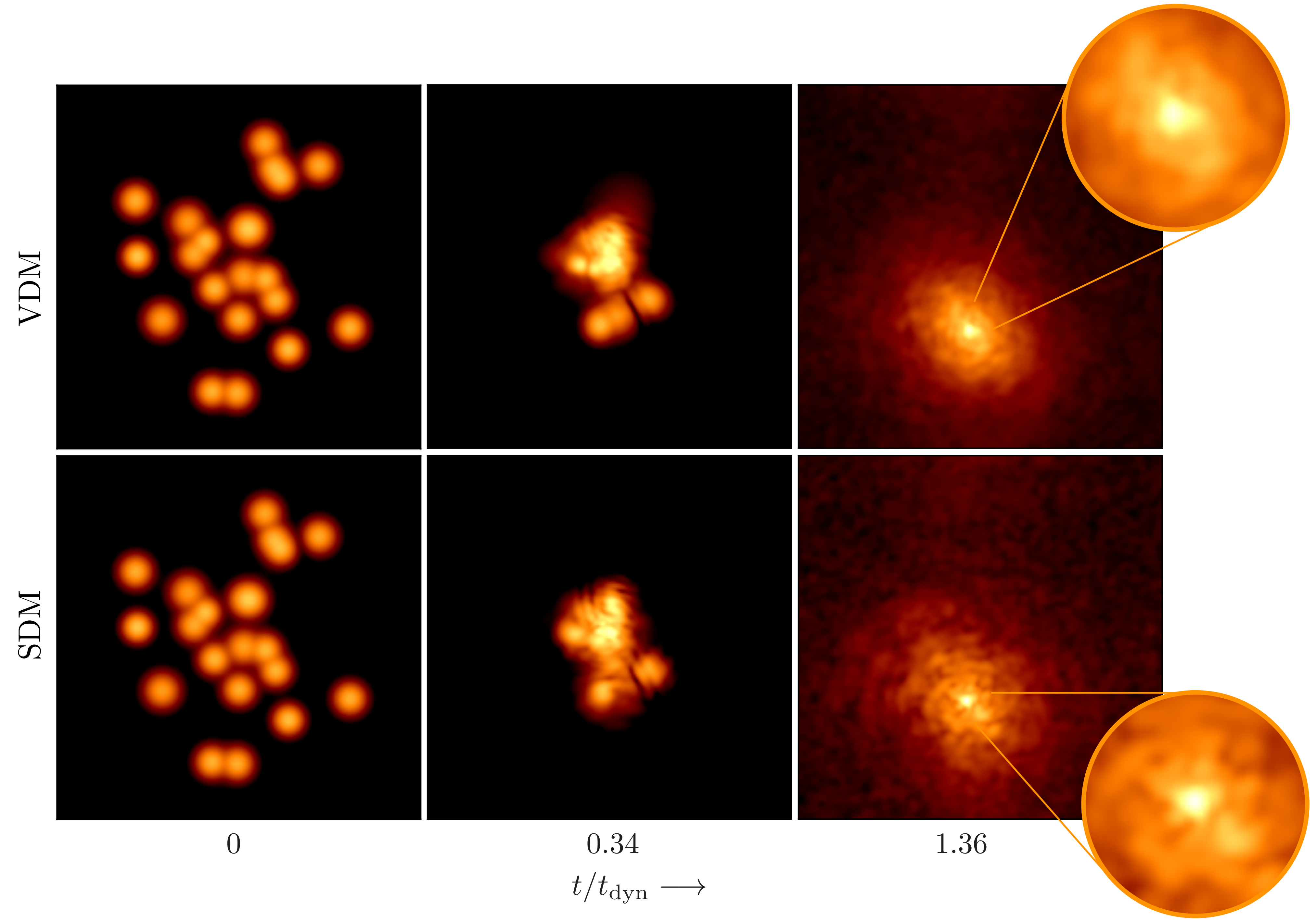

https://xkcd.com/2268

**TBD**:

- Higher spin (e.g., dark photons)
- Fractional component of DM
- Add solitons (strengthens bounds)…

# Higher spin

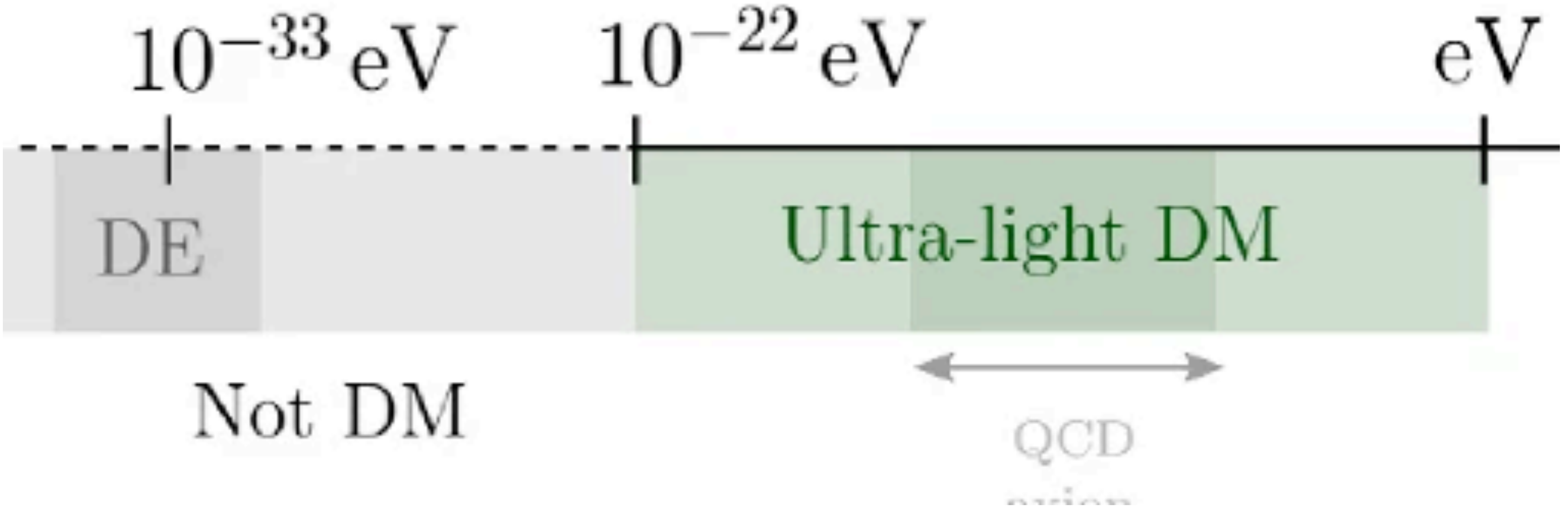
- Besides ultra-light scalars, ultra-light bosons can also have higher spin
- Simulations by Amin et al. (2022) indicate that spin $s$ ULDM behaves like $(2s + 1)$ incoherent FDM fields, except in central soliton.




- So at fixed mass, the heating rate for spin $s$ is reduced by factor $(2s + 1)^{-1}$
- Since heating rate scales with FDM mass like $m^{-3}$, then lower limit on mass is weakened by factor $(2s + 1)^{-1/3}$, e.g. $m > 3 \times 10^{-19}$ eV for $s = 0$ becomes $m > 2 \times 10^{-19}$ eV for $s = 1$ (dark photon).

# Upshot

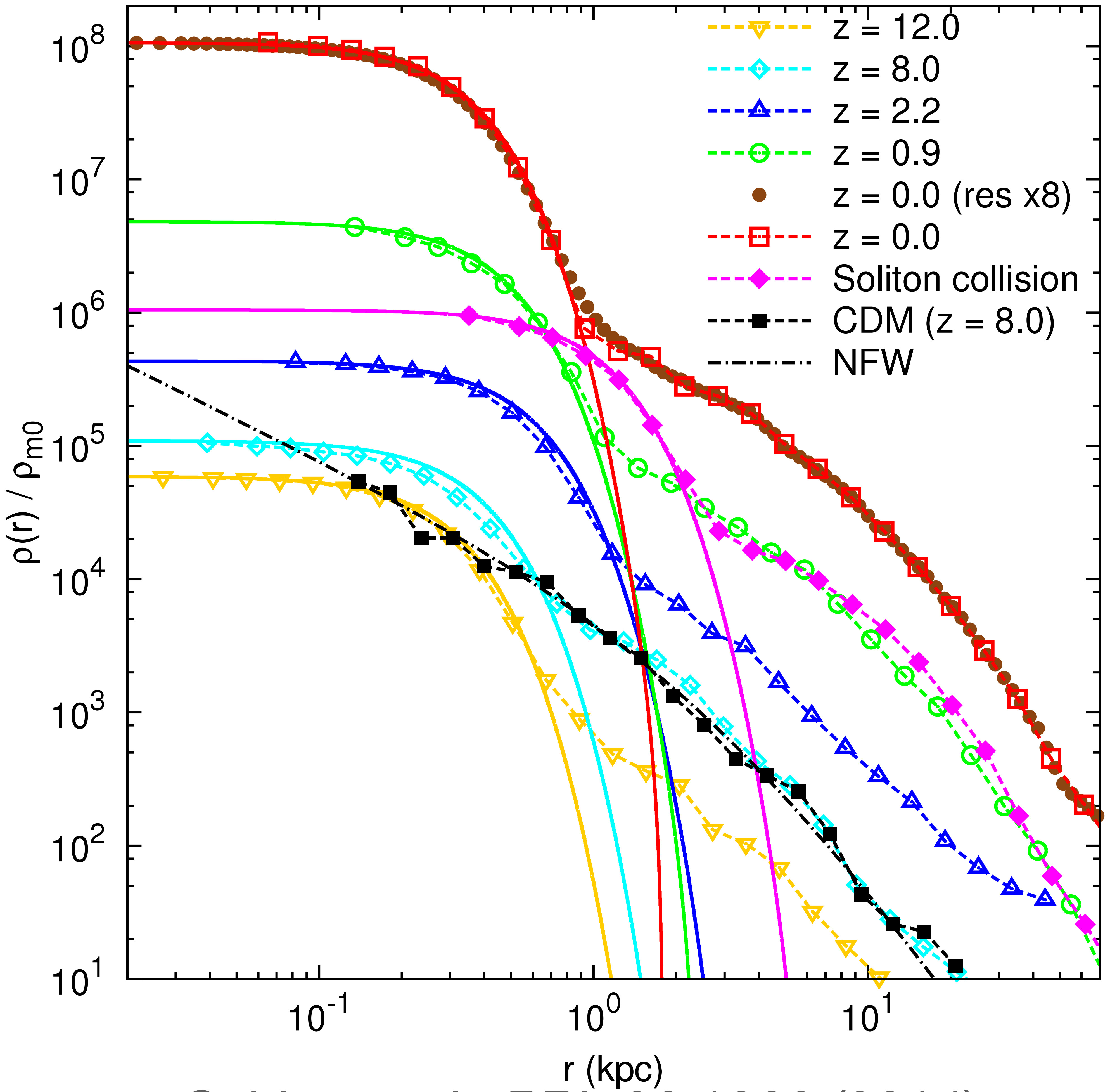
- Using galaxies — either individually, or in large-scale structure — we can probe ultra-light particles over a huge range of masses!




- 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 $m$!

# Soliton

- FDM halos appear to form dense concentration at their centres, called a **soliton**.
- Early work found a tight scaling relation between soliton mass & halo mass, $M_{\rm sol} \propto M_{\rm vir}^{1/3}/m_{\rm FDM}$
- Led to flurry of papers trying to constrain FDM mass by either detecting or excluding soliton in nearby galaxies, e.g. Safarzadeh & Spergel (2020), Hayashi et al. (2021), Pozo et al. (2022)…




Schive et al., PRL 26 1302 (2014)

# Soliton

- Recent sims find large scatter between soliton mass & halo mass (May et al. 2021)

- Sims of individual halos find that solitons far off the initial scaling relation (either direction!) can stably persist for Hubble time (Chan et al. 2021, Yavetz et al. 2021).

- This large scatter means we can't predict soliton behaviour in specific galaxies.  So we neglect soliton heating in our sims, to be conservative.

Chan et al., arXiv:2110.11882