Fuzzy Dark (matter) Imprints in Galaxies

Quantum effects on galactic scales…

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Subject matter:

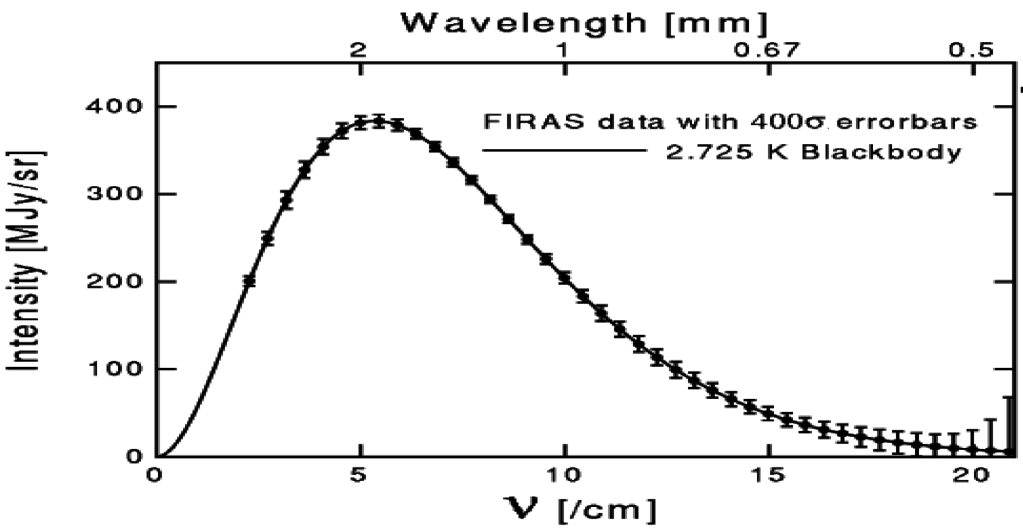
For typical galactic speeds FDM has

De Broglie wavelength $\frac{h}{m\,v}$ $\sim$ 100 pc or more at galactic speeds → $m \sim 10^{-22}$ eV

Outline:

- Why ultra light axions? (from a galactic perspective)
- Characterization of Fuzzy Dark Matter fluctuations
- Effect on stellar dynamics, central supermassive BH and associated constraints

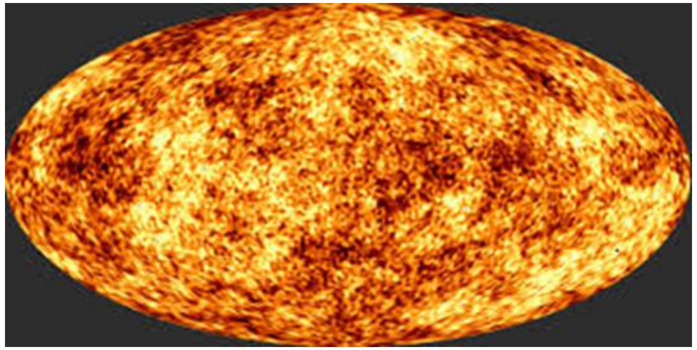
Hot Big Bang and Cold Dark Matter Driven Structure Formation



→ Early thermal equilibrium

Baryons coupled to photon bath
→ cannot collapse early enough

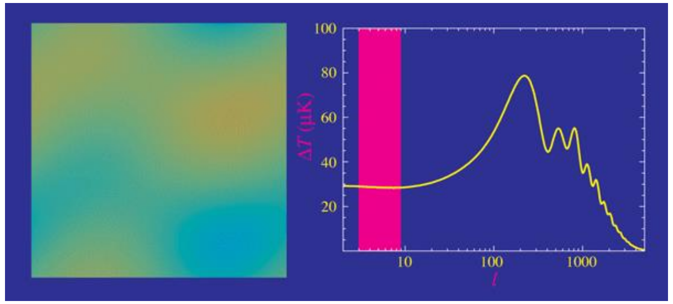
But weakly interacting, massive particles (WIMPs)



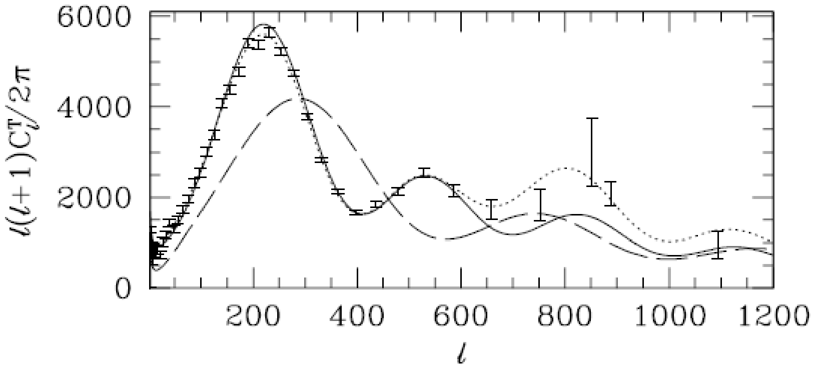
$$mv^2 \sim k_B T \quad \rightarrow \quad m\uparrow -> v\downarrow$$

Decouple early with small speed → → Drives galaxy formation

The Case for CDM

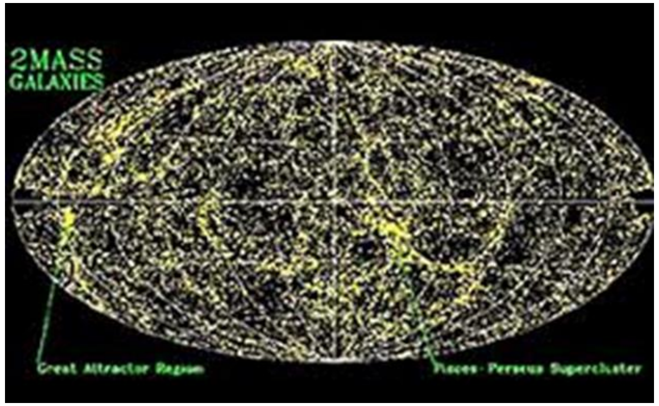


- DM needed for structure formation and CMB



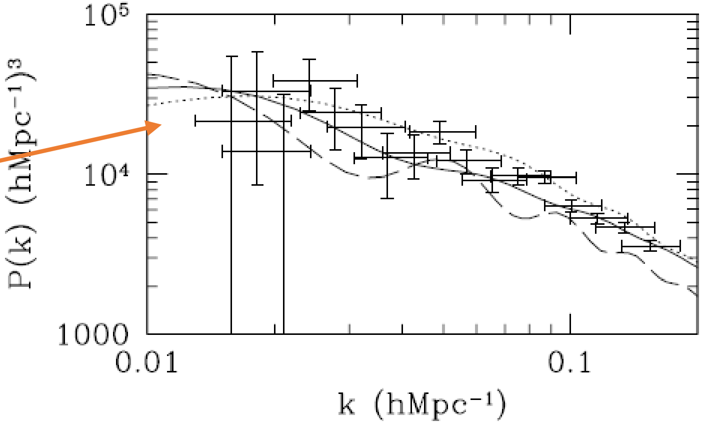
- Not easily explainable by modified gravity

- Cold dark matter → Fits cosmological data



Power spectrum of

cosmic structure



CMB. LSS in MOND
(Skordis et. al. 2006)

→ Predicted by natural Susy theories (until recently a big plus!)

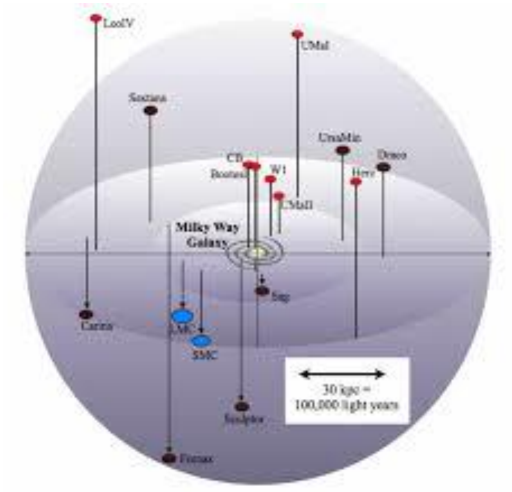
→ Right abundance from weak interaction freeze out from thermal equilibrium

Galactic Scale Problems with CDM

DM compensates for mass deficit in outer parts

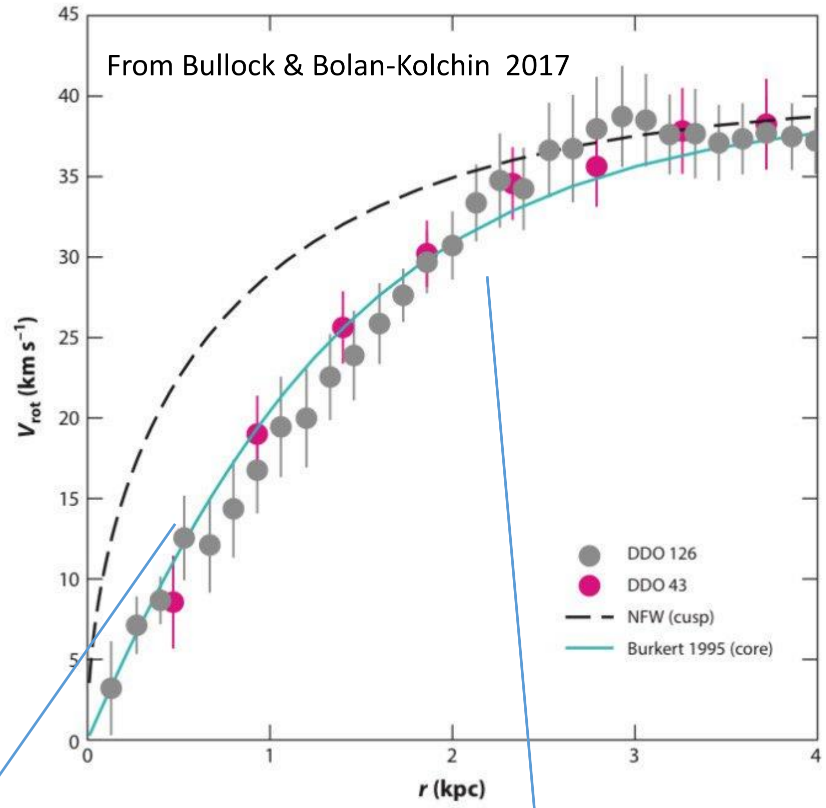
BUT contributes too much mass to central parts

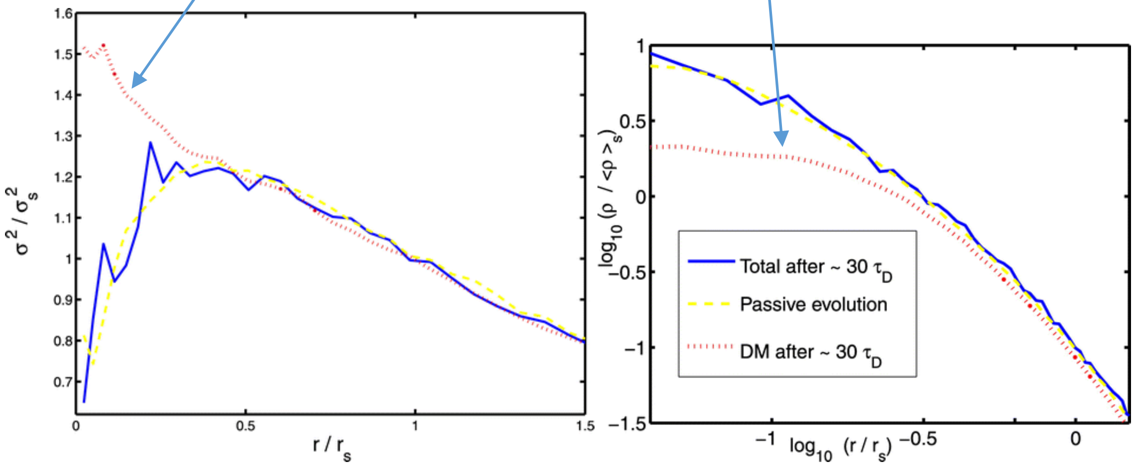
****Probably related problems: Excess of small haloes and wrong dynamics**



Simulation M.Y. size halo .vs. Dwarf galx. pop.

→ constraints





- **Need smaller density**

  + more random motion in centre of halo: Heating of central cusp by dynamical friction; El-Zant (2008)

Some Proposed Solutions

'Heat' DM → decrease DM density:

** **Baryonic solutions:** baryons pump energy into DM

(e.g., El-Zant et. al 2001, 2004; Pontzen & Governato 2014; El-Zant et. al. 2016, Hashim et. al. 2022)

** **Self interacting DM** → Conduction

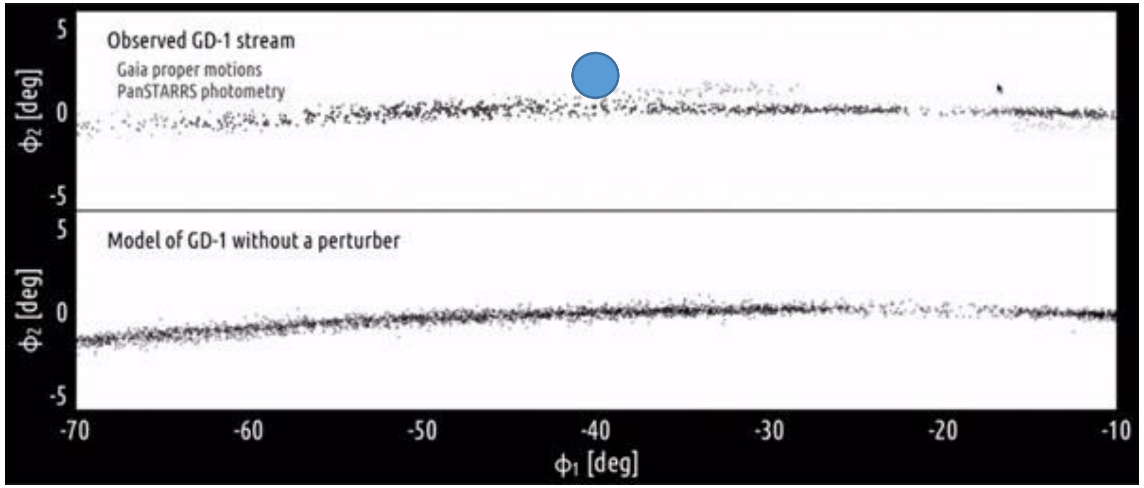
** **Warm DM** → preheat!

** **Quantum fluctuations** **('Fuzzy Dark Matter' of ultra light bosons)**

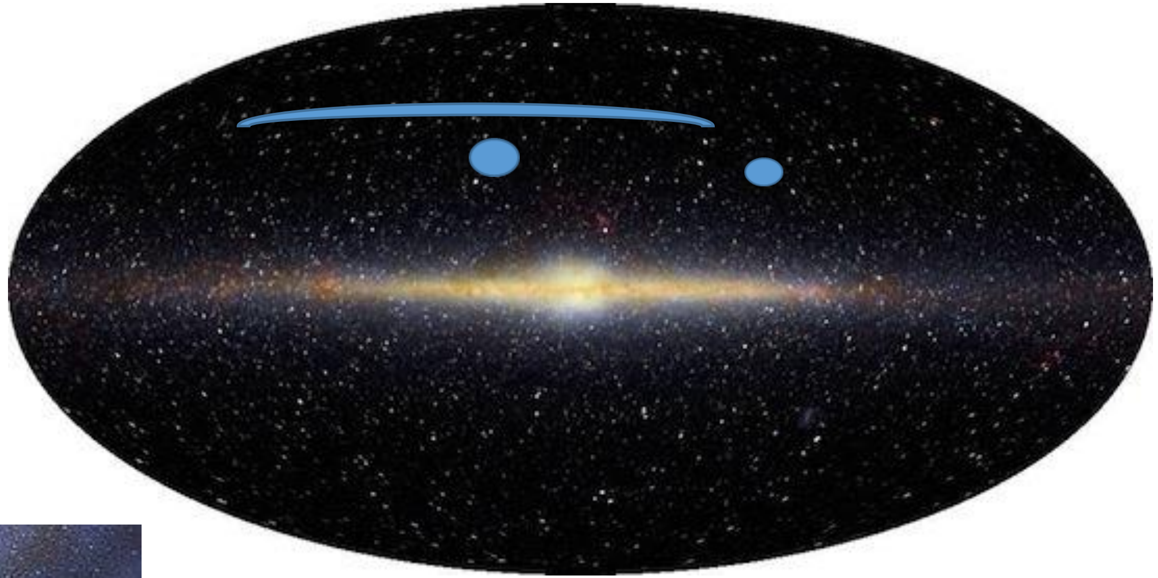
e.g., Hu et al. (2000), Peebles (2000), Hui et. al. (2017), El-Zant et. al. (2019, 2020)

Couple of **effects** of DM **fluctuations**

Tidal streams: thickness and gaps (Bonaca et. al. 2019)



Thickness and Dyn. of Galactic Disk



GAIA

Worked Example: Ultra-light Axion → "Fuzzy DM"

Tiny Mass ~ →Astrophysical de Broglie wavelength

$$\frac{\lambda}{2\pi} = \frac{\hbar}{mv} = 1.92\,\mathrm{kpc}\left(\frac{10^{-22}\,\mathrm{eV}}{m}\right)\left(\frac{10\,\mathrm{km\ s}^{-1}}{v}\right)$$

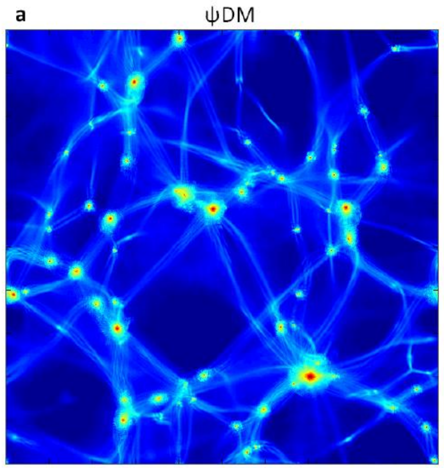
- Large number of particles in same state and non-relativistic **on galactic scales**

→ Schrodinger-Poisson system

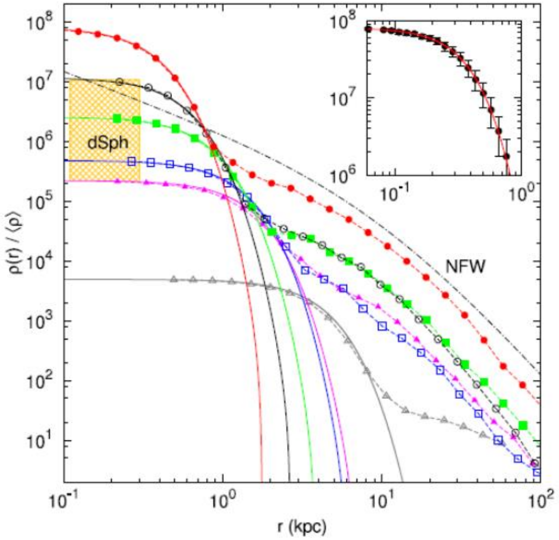
$$i\hbar\frac{d\Psi}{dt} = -\frac{\hbar^2}{2m_\chi}\boldsymbol{\nabla}^2\Psi + m_\chi V\Psi,$$

$$\boldsymbol{\nabla}^2 V = 4\pi G m_\chi |\Psi|^2.$$

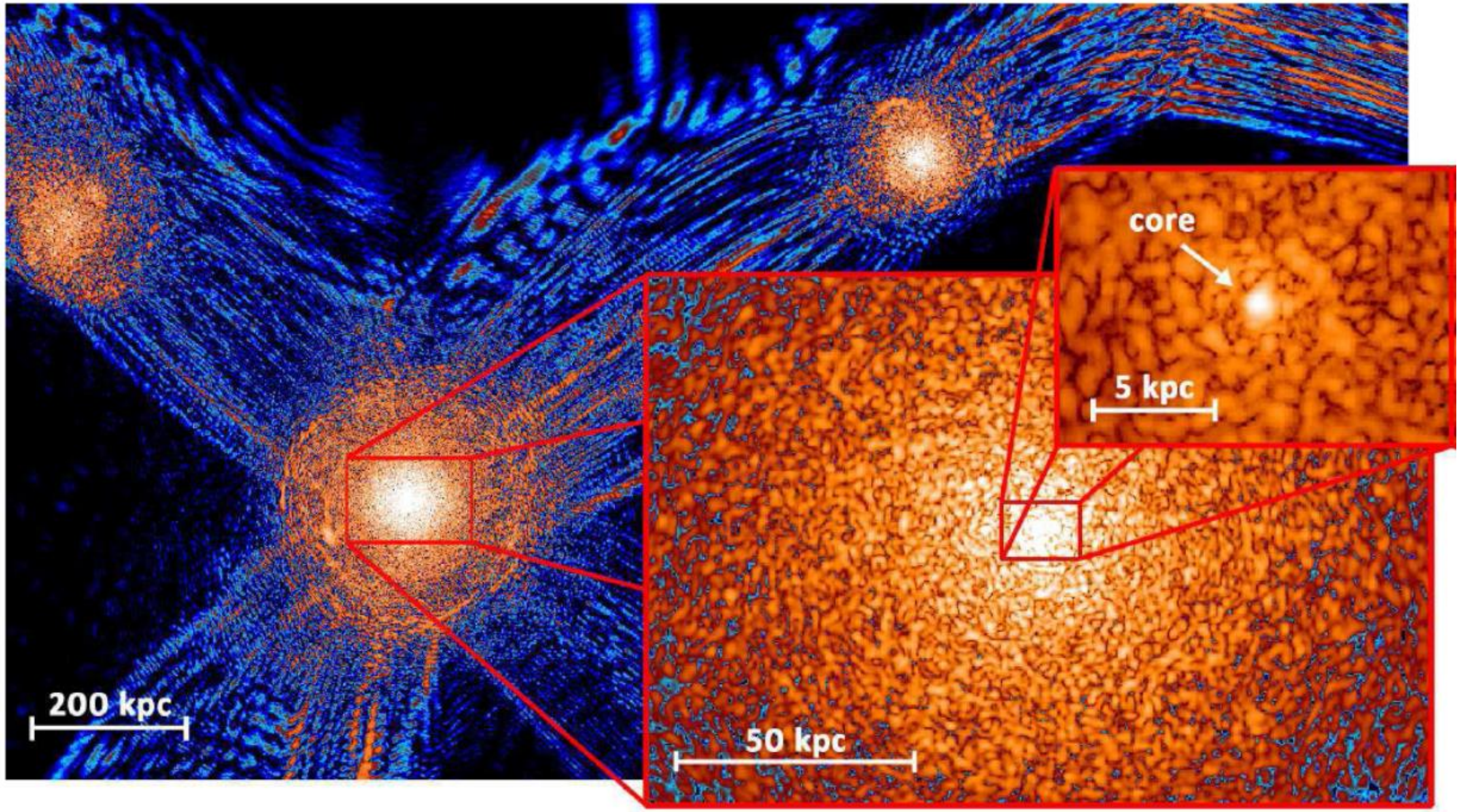
Structure Formation and fluctuations with fuzzy DM (Schive et. al. 2014)



~as CDM on large scales



~Constant density cores



Few smaller halos (note however interference pattern and flcutuations!)

Axion Fluctuations as Random Gaussian Field

Expand *fluctuations* in modes ρ_k moving at phase velocity v such that $\mathbf{k}.\mathbf{v} = \omega$

This is the case if

$$\phi_{\mathbf{k}}(t) = \phi_{\mathbf{k}}(0)e^{-i\mathbf{k}.\mathbf{v}t} \quad \text{and} \quad \psi(\mathbf{r},t) = \int \phi_{\mathbf{k}}(t)e^{i\mathbf{k}.\mathbf{r}}\, d\mathbf{k}$$

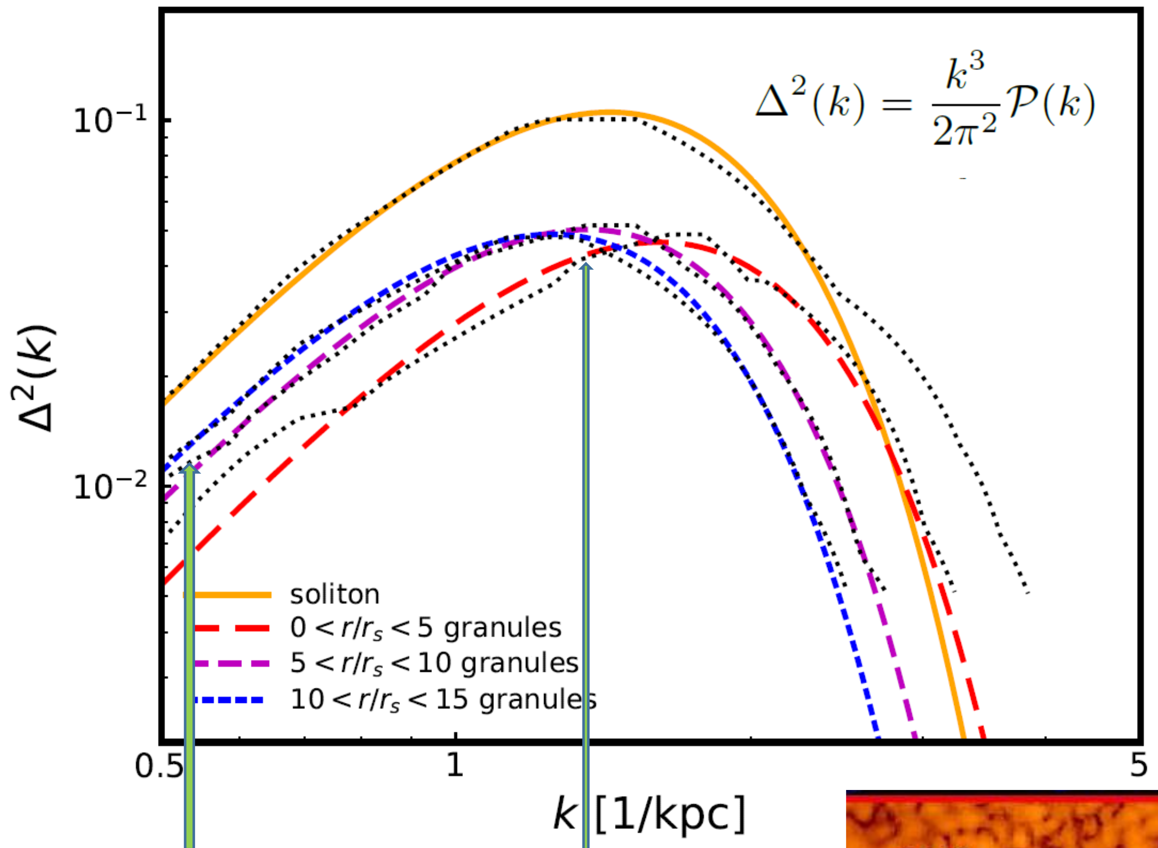
Wave function power spectrum → k-space density → $\langle \phi_{\mathbf{k}} \phi^{\star}_{\mathbf{k}'} \rangle = f_{\mathbf{k}}(\mathbf{k})\delta_{\mathrm{D}}(\mathbf{k}-\mathbf{k}')$

Power spectrum of density fluctuations interference pattern →

$$\mathcal{P}(\mathbf{k},t) = \frac{(2\pi)^3}{\rho_0^2} \times \iint f_{\mathbf{k}}(\mathbf{k}_1) f_{\mathbf{k}}(\mathbf{k}_2) e^{-i[\omega(\mathbf{k}_1)-\omega(\mathbf{k}_2)]t} \delta_{\mathrm{D}}(\mathbf{k}-\mathbf{k}_1+\mathbf{k}_2) d\mathbf{k}_1 d\mathbf{k}_2$$

Power Spectrum of Density Fluctuations

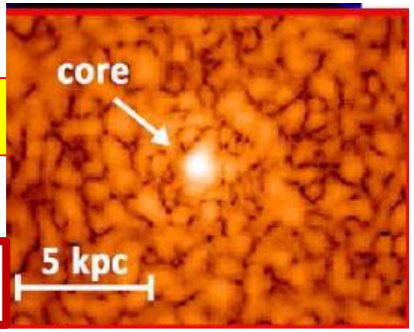
Interpretation and Comparison with simulations (of Chan et. al. 2018)



White noise

Effective fluctuation scale

~ Randomly scattered masses ~ m_{eff}



→ Conservation of probability (number density)

→ Correspondence of wavenumber and FDM vely distn function

$$f_{\mathbf{k}}(\mathbf{k})d\mathbf{k} = f(\mathbf{v})d\mathbf{v}$$

Maxwellian velys

$$f(v) = \frac{\rho_0}{(2\pi\sigma^2)^{3/2}} e^{-\frac{v^2}{2\sigma^2}}$$

→ Power spectrum

$$\mathcal{P}(\mathbf{k}, 0) = \left(\frac{2\sqrt{\pi}}{m_\hbar \sigma}\right)^3 e^{-\frac{k^2}{\sigma^2 m_\hbar^2}}$$

$m_\hbar = 2m/\hbar.$

From Density to Force fluctuations

- Use Poisson equation

$$\nabla^2\Phi = 4\pi G\rho_0\delta$$

- Homogeneous process →

$$\phi_{\mathbf{k}} = -4\pi G\rho_0\delta_{\mathbf{k}}k^{-2}$$

- Force fluctuation power →

$$\mathcal{P}_F(k) = Vk^2\langle|\phi_k|^2\rangle$$

Fourier Transform → Force Correlation Function

$$\langle \mathbf{F}(0,0).\mathbf{F}(r,t)\rangle = \frac{1}{(2\pi)^3}\int \mathcal{P}_F(k,t)e^{i\mathbf{k}.\mathbf{r}}d\mathbf{k}$$

Stochastic equation → Random velocity from fluctuations

$$d\mathbf{v}/dt = \mathbf{F} \longrightarrow \langle(\Delta v_p)^2\rangle = 2\int_0^T (T-t)\langle \mathbf{F}(0).\mathbf{F}(t)\rangle dt$$

Maxwellian →

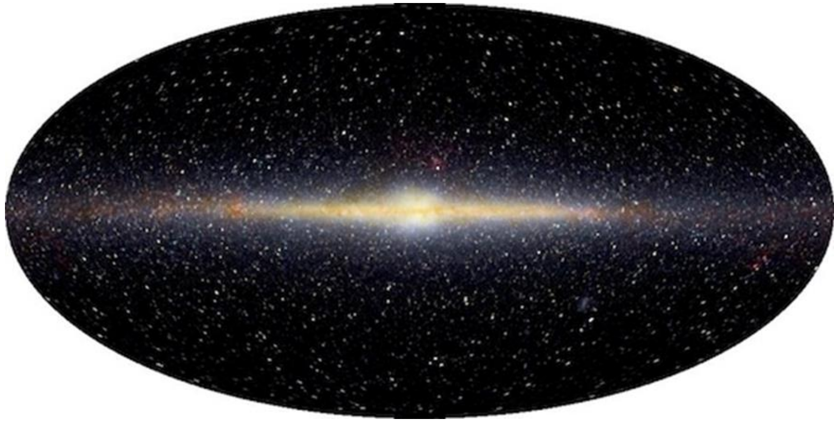
$$\langle(\Delta v_p)^2\rangle = T\frac{8\pi G^2\rho_0 m_{\rm eff}\ln\Lambda}{v_p}\mathrm{erf}(X_{\rm eff}) \quad m_{\rm eff} = \frac{8\pi^{3/2}\rho_0}{m_\hbar^3\sigma^3}$$

Observable Effect: Galactic Disk Velocity Dispersion

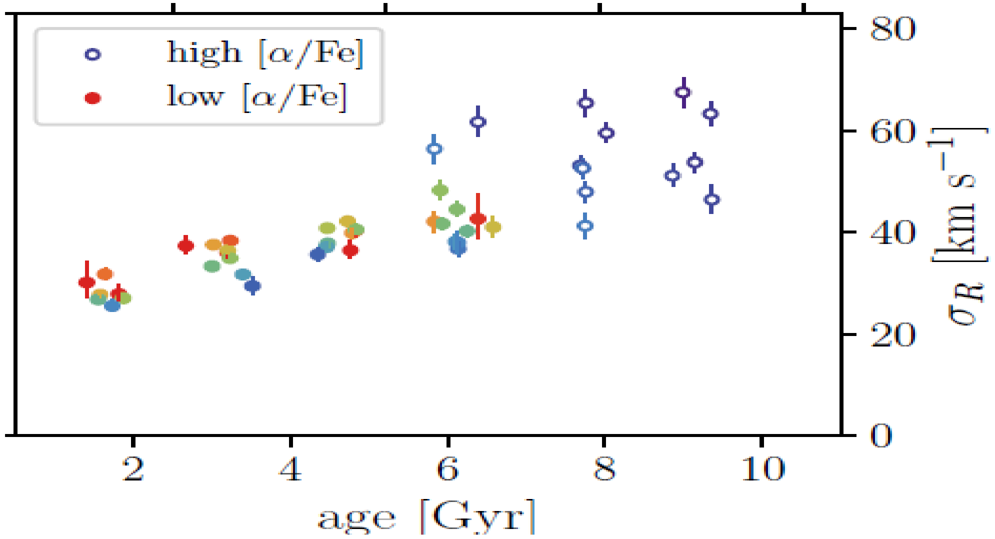
-- Decompose energy input to disk via fluctuations into vertical and radial components

→ Prediction: radial velocity dispersion of disk stars increases a

$$\sigma_R = 4.5\ \mathrm{km/s} \left(\frac{10^{-22}\mathrm{eV}}{m}\right)^{3/2} \left(\frac{8\mathrm{kpc}}{r}\right)^2 \left(\frac{T}{10\mathrm{Gyr}}\right)^{1/2} \ln \Lambda^{1/2}$$



Observed dispersion does increase BUT as $\sigma_R \sim t^{1/3}$ **→ Axion fluctuation contribution**



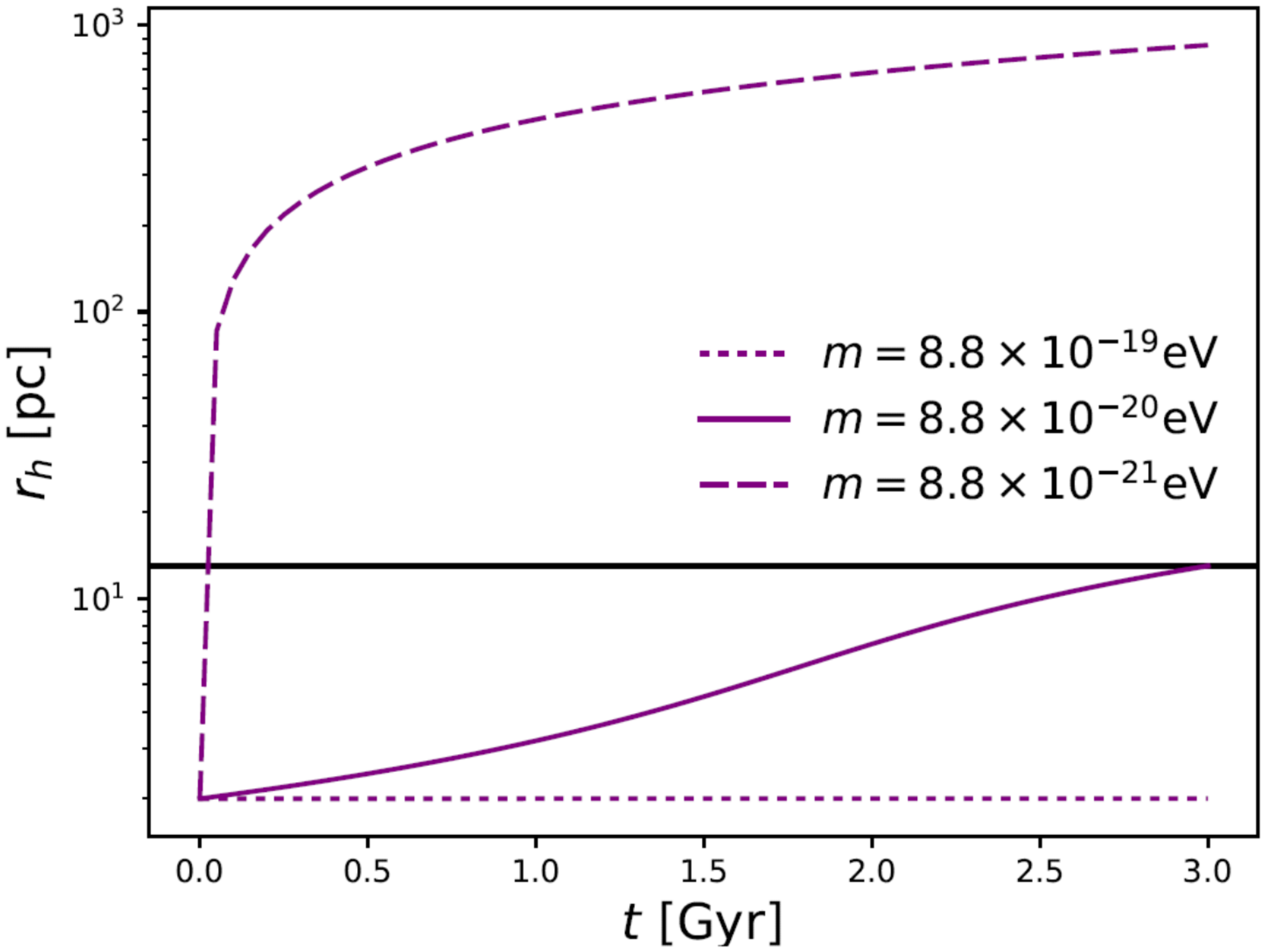
$$\sigma_R \sim 3\mathrm{km/s}$$

→ Limit on axion mass

$$m \gtrsim 2 \times 10^{-22}\mathrm{eV}$$

Observed radial dispersion increase and power law exponent. From Mackareth et. al. (2019)

Expansion of the Central Cluster of Dwarf Eridanus II



Cluster expansion in context of El-Zant et. al. (2019) model

Basic idea (Marsh & Niemeyer 2019):

-- Fluctuations cause central cluster to expand

-- If axion mass too small → cluster too large

→ quite severe constraints on axion mass

BUT does cluster expand or gets displaced?

$$\frac{dr_h}{dt} = \frac{D}{G}\left(\frac{\alpha M_\star}{r_h^2} + 2\beta\rho_0 r_h\right)^{-1}$$

$$D\left[(\Delta v)^2\right] = \frac{4\sqrt{2}\pi G^2 \rho_0 m_{\rm eff}}{\sigma_{\rm eff}} \ln\Lambda \left[\frac{\mathrm{erf}(X_{\rm eff})}{X_{\rm eff}}\right]$$

Observable Effect: Central Black Hole Displacement

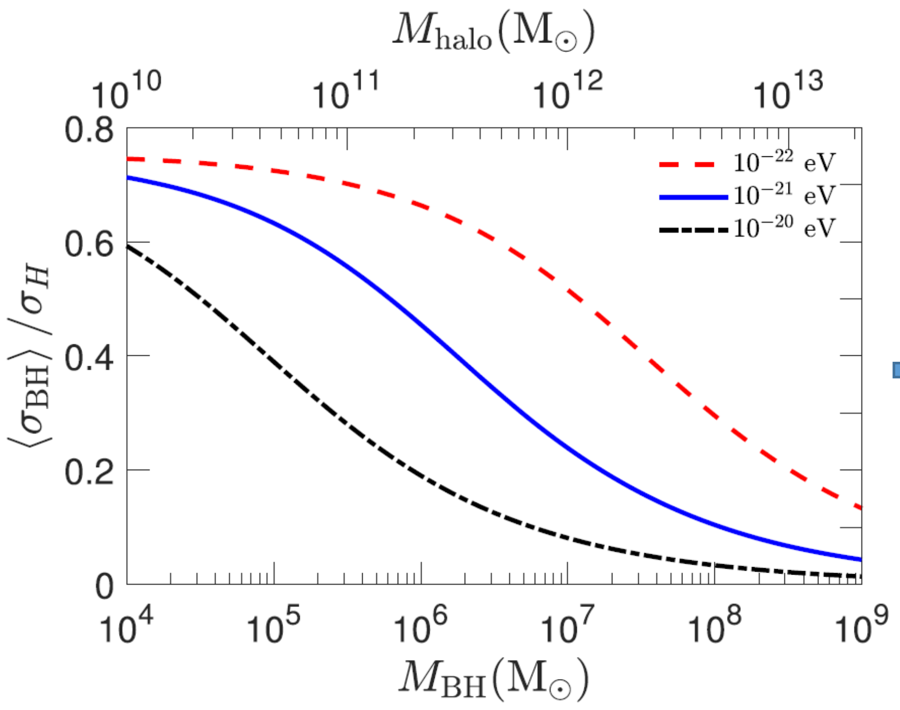
Equipartition of SMBH KE with FDM heat bath →

$$M_B \sigma_B^2 = m_{\text{eff}} \sigma_{\text{eff}}^2$$

→ **Virial theorem** at low masses →

$$\sqrt{\langle r^2 \rangle} \approx 2.6\ \text{kpc} \left(\frac{m_{\text{ax}}}{10^{-22}\ \text{eV}}\right)^{-\frac{3}{2}} \left(\frac{M_B}{10^7 M_\odot}\right)^{-\frac{11}{18}}$$

Averaging over thermal distribution



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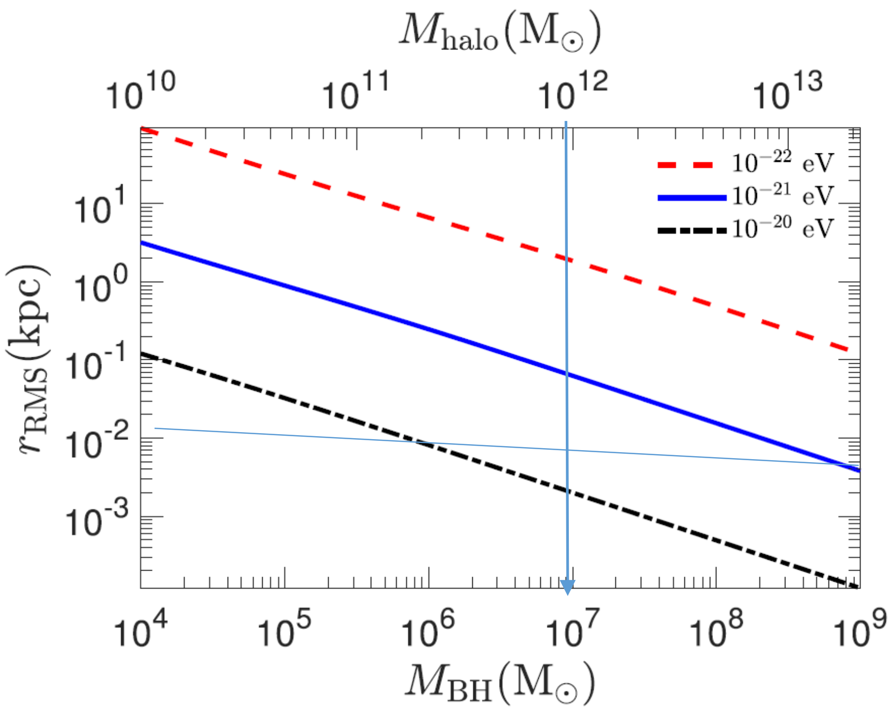
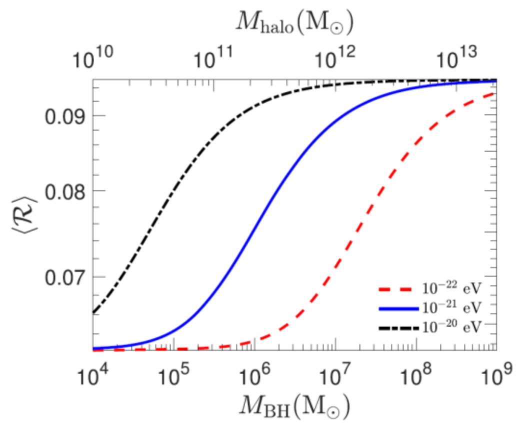


Reduction in merger rate



Conclusions and Prospects:

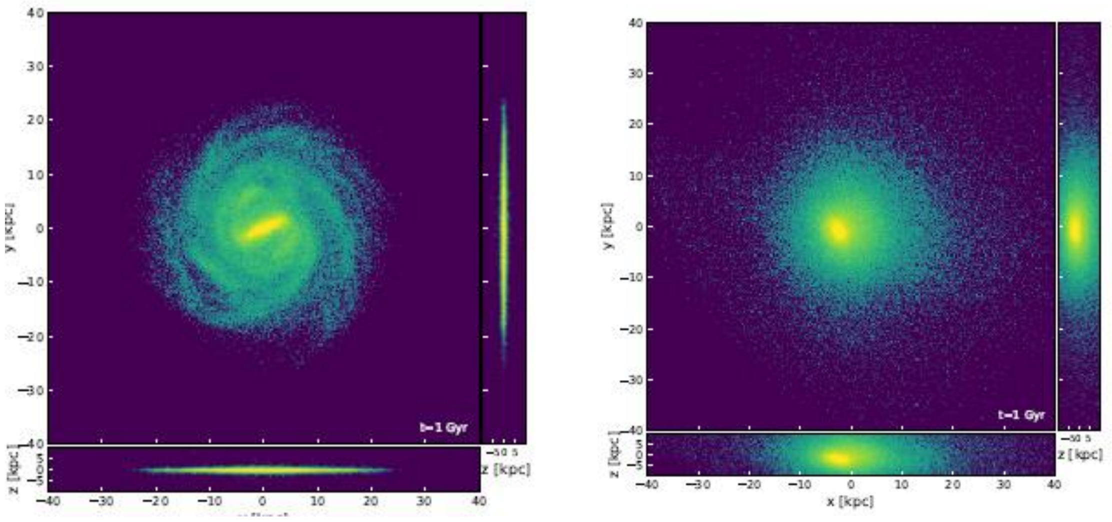
- **CDM Threatened: small scale problems part of a parcel of problems**
- **Alternatives can have observable consequences on galaxies**
- **FDM Alternative: Fluctuations from uncertainty principle →'hotter' DM**
- **But are fluctuations needed to solve core-cusp problem etc., too large?**

Ongoing and prospective work:

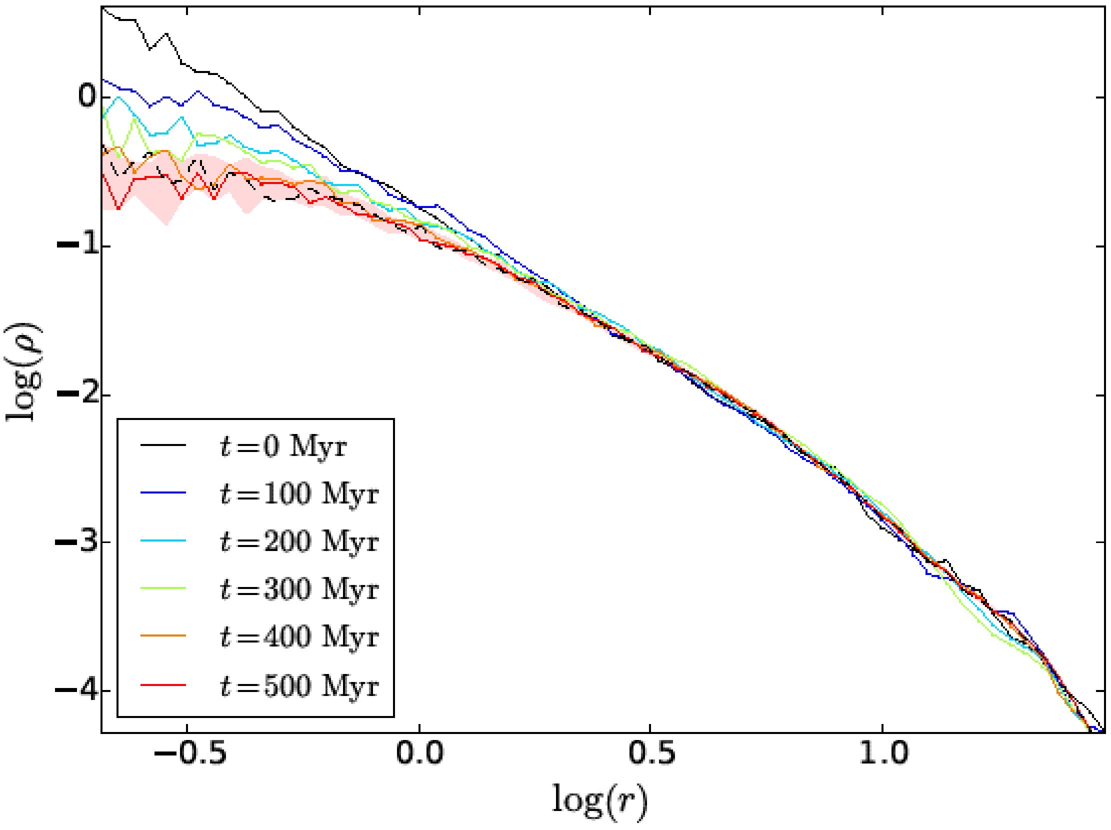
** **FDM** **Simulations of disks with FDM noise**

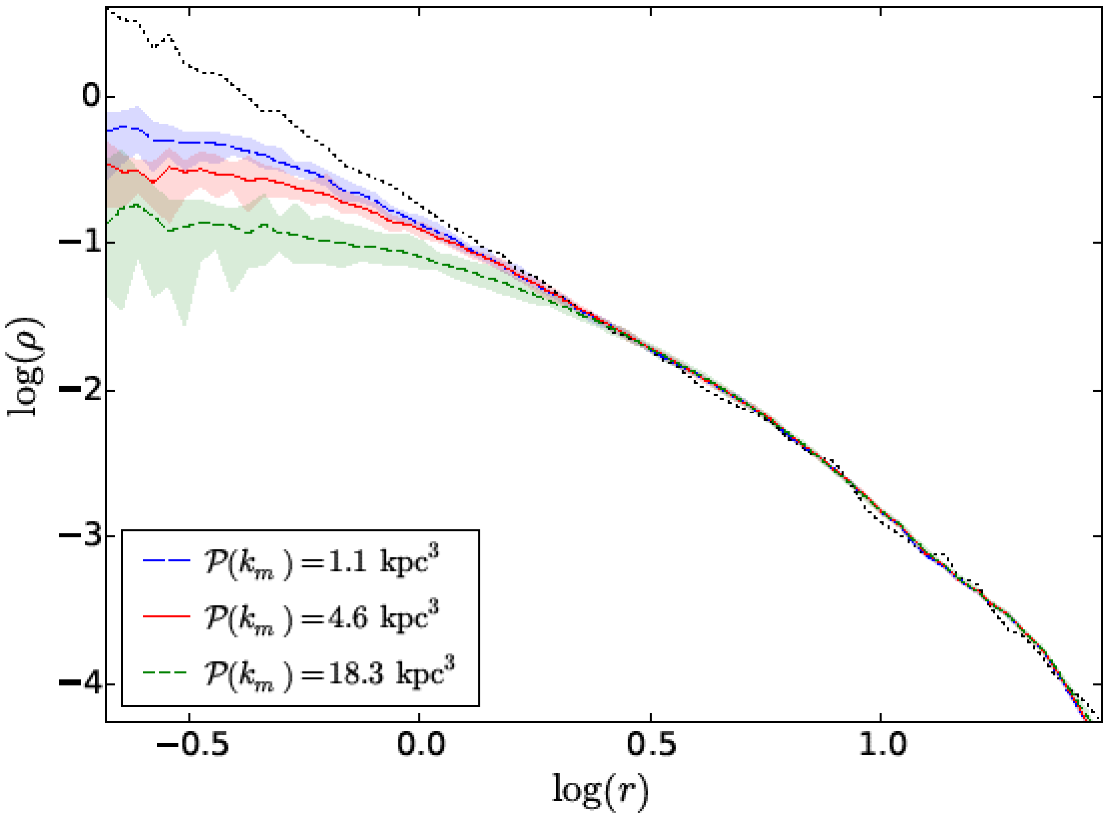
++ Full S-P simulations

- **Effect on tidal stream (already much work)**
- **FDM self interaction… baryons etc…**



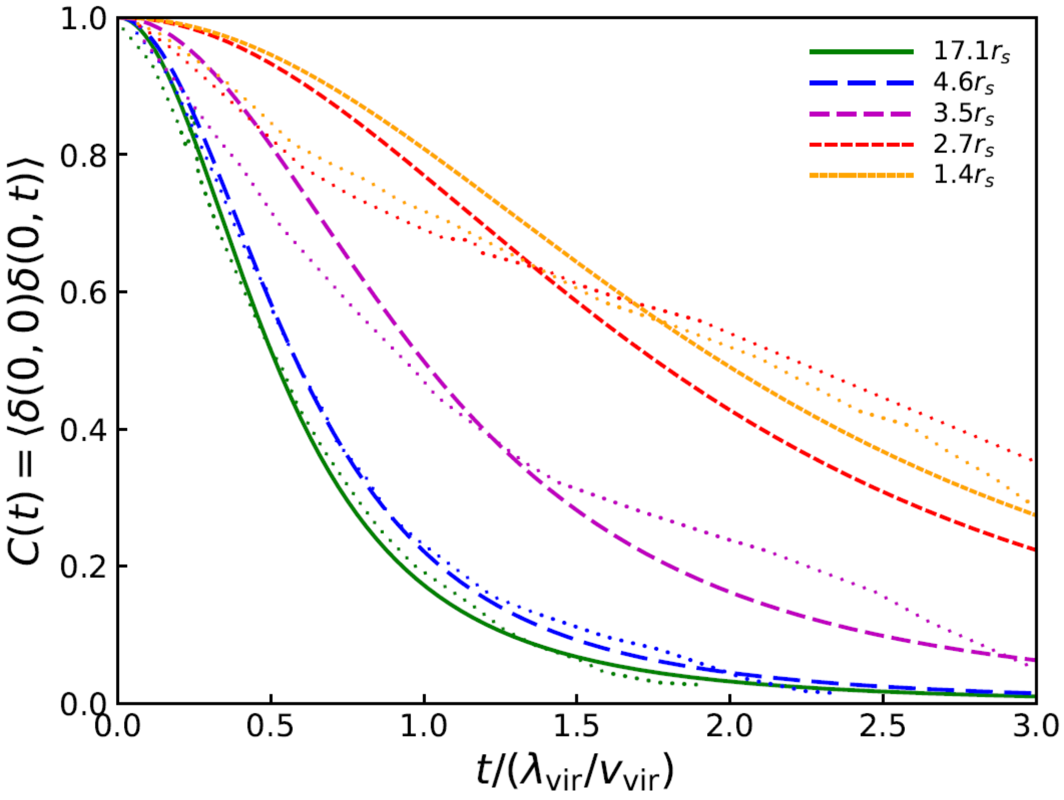
Effect of Non-radial Modes and Power Input

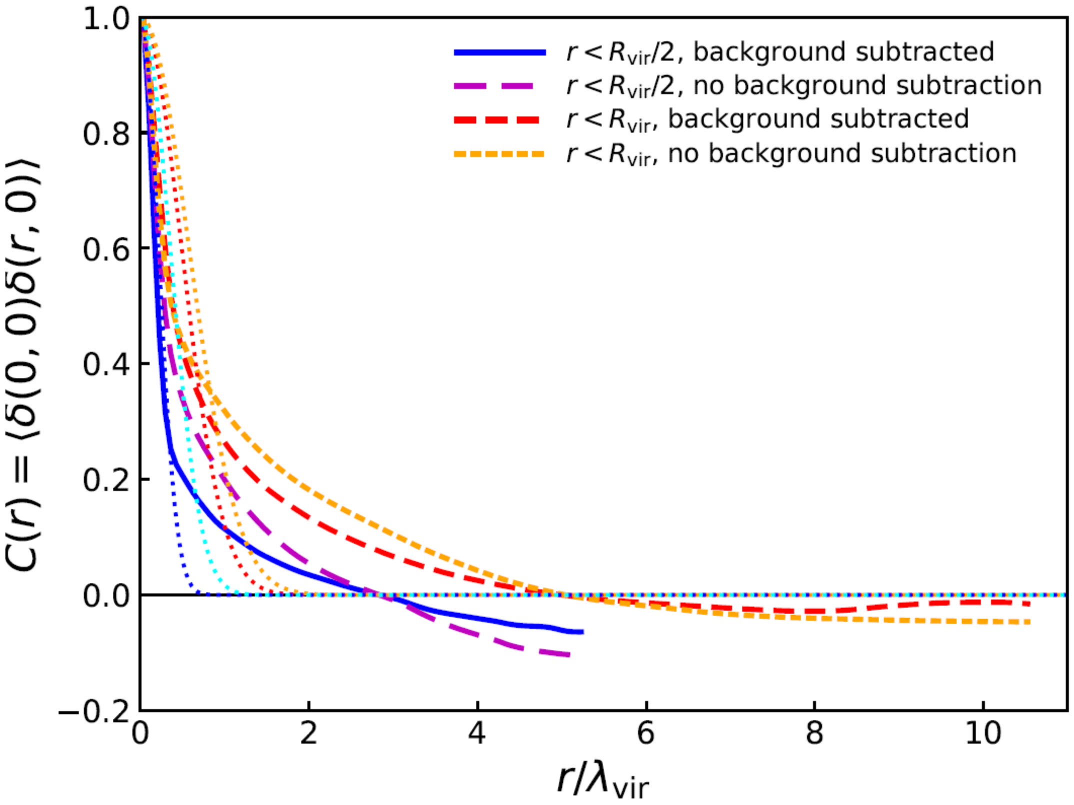




Same power input as previous case but evolution on a tenth of the timescale

Space and Time Correlations





$$\langle\delta(0,0)\delta(r,t)\rangle = \frac{1}{(1+\sigma^2 t^2/\lambda_\sigma^2)^{3/2}} e^{-\frac{r^2/\lambda_\sigma^2}{1+\sigma^2 t^2/\lambda_\sigma^2}}$$