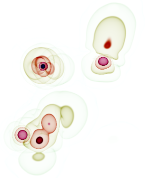
Small-scale features in fuzzy dark matter cosmology



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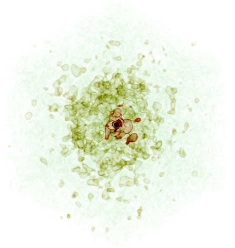
Oct 2, 2018



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Outline

- Intro to Fuzzy Dark Matter (FDM)
  - motivation
  - observational constraints
- Simulations of virialized halos (Mocz et al., 2017)
  - halo properties
  - quantum turbulence in halos
- Numerical methods
  - spectral (Mocz et al., 2017)
  - SPH (Mocz & Succi, 2015)
- Schrödinger/Vlasov–Poisson correspondence (Mocz et al., 2018)
  - Does a 3D wave function encode 6D collisionless dynamics for large m?
- Full–physics cosmological simulations (PM+ in prep)
- Dynamical Heating / Friction (Church, PM, Ostriker 2018; PM+ in prep)
- Direct radial collapse and soliton cores (PM+ in prep)

What is fuzzy dark matter?

What if dark matter is … *very light*?

- Assume DM is a cold, ultralight scalar field (Peebles, 2000; Hu, Barkana & Gruzinov, 2000; Schive et al., 2014; Schwabe, Niemeyer & Engels, 2016)
- $T = 0$ in early universe, forms a BEC $\Rightarrow$ macroscopic quantum properties
- Uncertainty principal suppresses gravitational collapse below de Broglie wavelength
- Require $m \sim 10^{-22}$ eV to get $\lambda_{\mathrm{DB}} \sim 1\mathrm{kpc}$ for $10^8\ M_\odot$, $z = 5$ halo virial velocity (Chavanis, 2011)
- Schrödinger–Pitaevski–Poisson equation evolution

$$i\hbar\frac{\partial\psi}{\partial t} = -\frac{\hbar^2}{2m}\nabla^2\psi + mV\psi, \quad \nabla^2 V = 4\pi G(\rho - \overline{\rho}), \quad \rho = |\psi|^2 \tag{1}$$

Properties: Soliton core solitions

Stable soliton core solutions (Schive et al., 2014)

$$\rho_{\text{soliton}}(r) \simeq \rho_0 \left[1 + 0.091 \times \left(\frac{r}{r_c}\right)^2\right]^{-8} \tag{2}$$

where

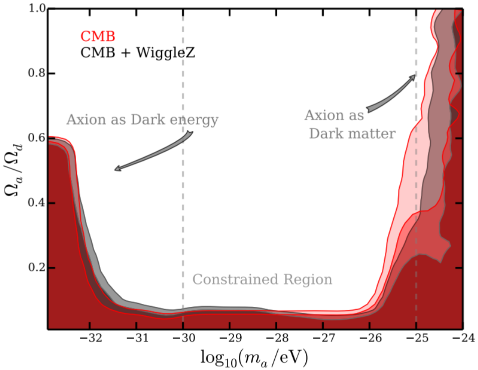
$$\rho_0 \simeq 3.1 \times 10^{15} \left(\frac{2.5 \times 10^{-22}\ \text{eV}}{m}\right)^2 \left(\frac{\text{kpc}}{r_c}\right)^4 \frac{M_\odot}{\text{Mpc}^3} \tag{3}$$

- core + r^{-16} outer profile
- more massive = more compact

Motivation for FDM

- Astrophysics
  - ΛCDM small scale shortcomings
    - deficit of dwarf galaxies (missing satellites problem Klypin et al. 1999; Moore et al. 1999)
    - problem with the abundance of isolated dwarfs (Zavala et al., 2009; Papastergis et al., 2011; Klypin et al., 2015)
    - too-big-to-fail problem (Boylan-Kolchin, Bullock & Kaplinghat, 2011, 2012)
    - cusp-core problem (Moore, 1994; Flores & Primack, 1994; Gentile et al., 2004; Donato et al., 2009; de Blok, 2010)
- Theoretical Physics
  - Ultralight axions solve the strong CP problem in QCD (Peccei-Quinn theory; $m \sim 10^{-5}$–10^{-3} eV)
  - String-theory compactifications provide class of ultralight axions ($m \sim 10^{-22}$ eV) (Arvanitaki et al., 2010)

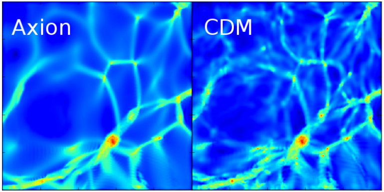
Axion mass constraints from CMB

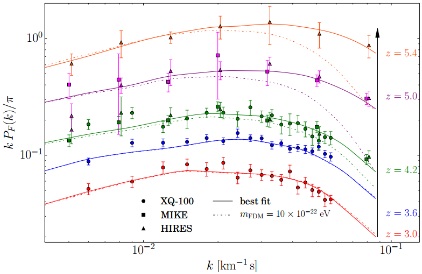


- Axion can't be too light, else λ_{dB} is inconsistent with CMB fluctuations: $m \geq 10^{-24}$ eV

Hlozek et al. (2015); Hlozek, Marsh & Grin (2017)

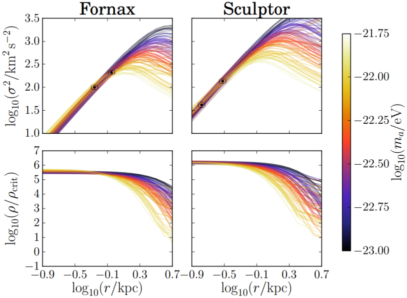
Axion mass constraints from Ly-α forest

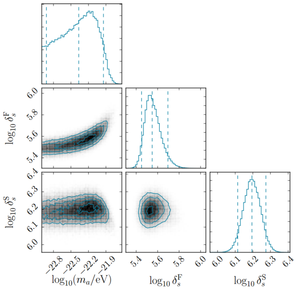




- Current studies consider the cut-off in the linear matter power spectrum and make analogies to WDM, using collisionless N-body hydro simulations. Quantum/wave effects are ignored. Armengaud et al. (2017); Iršič et al. (2017)
- suggest $m \gtrsim 10^{-21}$ eV, but remains to be verified by fully self-consistent simulations

Axion mass constraints from Dwarf Spheroidals



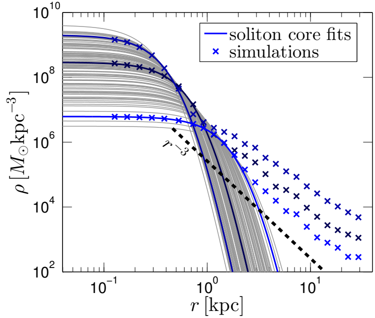


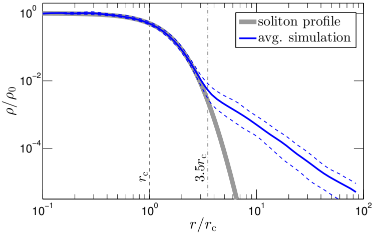
- Model DM-dominated dwarf eroidals (Fornax, Sculptor) with pure soliton core potential e.g., Marsh & Pop (2015); Gonzalez-Morales et al. (2016)
- suggest $m \lesssim 10^{-22}$ eV

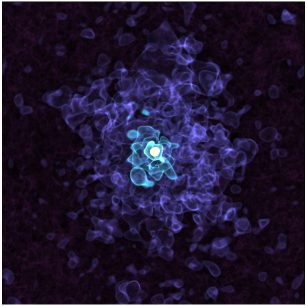
Simulations

- Galaxy formation with BECDM – I. Turbulence and relaxation of idealized haloes (Mocz et al., 2017)
  - simulate virialized DM halos
  - virialized profiles
  - self-similarity? soliton core-halo mass relation
  - quantum turbulence

FDM profiles

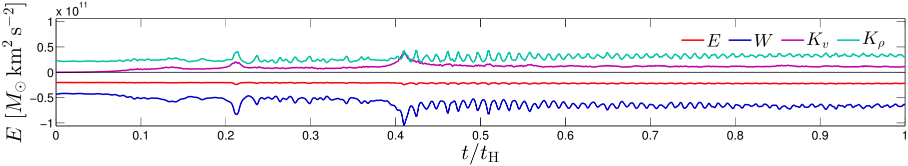


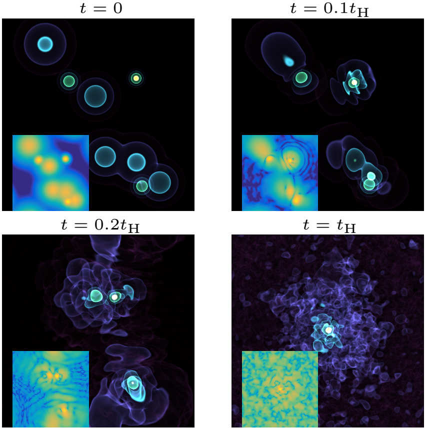




- Soliton core ($r^0 \to r^{-16}$)
- NFW–like outer profile (r^{-3}) or flatter (r^{-2} isothermal)
- c.f. NFW ($r^{-1} \to r^{-3}$)

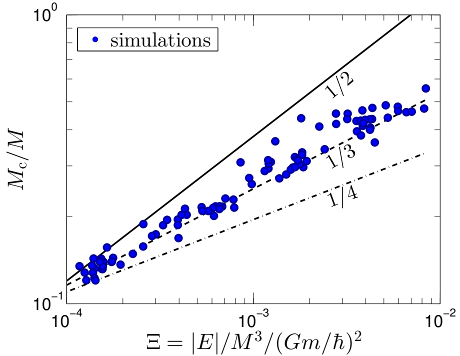
FDM energies





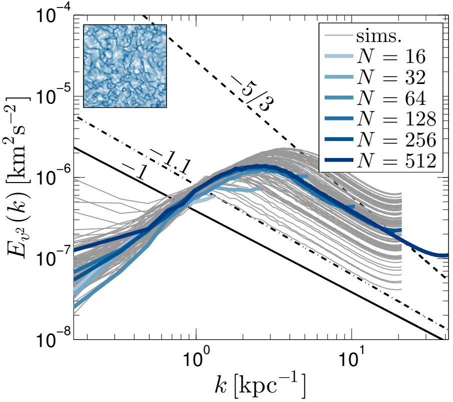
- Energies:
  - $W = \int \frac{1}{2}\rho V\ d^3x$
  - $K_v = \int \frac{1}{2}\rho v^2\ d^3x$
  - $K_\rho = \int \frac{\hbar}{2m^2}\left(\nabla\sqrt{\rho}\right)^2\ d^3x$
- Approx. virial equilibrium: $|W| = 2(K_v + K_\rho)$

FDM soliton cores

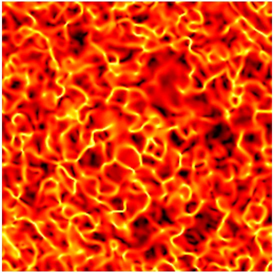


- scaling symmetry:
  - $t \to \lambda^2 \hat{t}$
  - $x \to \lambda^{-1} \hat{x}$
  - $\psi \to \lambda^2 \hat{\psi}$
  - $M \to \lambda M$
  - $E \to \lambda^3 E$
- find:
  $M_c/M \propto (|E|/M^3)^{1/3}$
  fundamental relation
- means core & halo binding energy in equipartition
- previously reported relation $M_c \propto (|E|/M)^{1/2}$ (Schive et al., 2014) actually is just scaling symmetry

FDM quantum turbulence



- similar to ‘thermal’ turbulence seen in condensed matter BEC systems: thermal bump, k^{-1}
- Kolmogorov $k^{-5/3}$ may be possible if system driven at largest scales



Numerical methods

- spectral (Mocz et al., 2017)
- SPH (Mocz & Succi, 2015)

Spectral (Mocz et al., 2017)

2nd-order in time leap-frog scheme. 'Kick-drift-kick'

- Calculate potential:

$$V = \text{ifft}\left[-\text{fft}\left[4\pi G(\rho - \overline{\rho})\right]/k^2\right] \tag{4}$$

- Potential half-step 'kick':

$$\psi \leftarrow \exp\left[-i(\Delta t/2)(m/\hbar)V\right]\psi \tag{5}$$

- Full 'drift' (kinetic) step in Fourier-space:

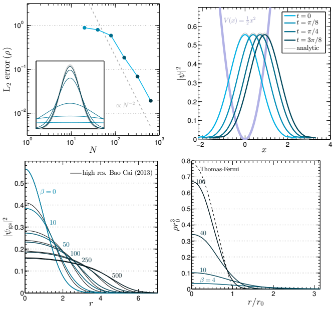
$$\hat{\psi} = \text{fft}\left[\psi\right] \tag{6}$$

$$\hat{\psi} \leftarrow \exp\left[-i\Delta t(\hbar/m)k^2/2\right]\hat{\psi} \tag{7}$$

$$\psi \leftarrow \text{ifft}\left[\hat{\psi}\right] \tag{8}$$

- Another 'kick'

SPH (Mocz & Succi, 2015)



- Madelung fluid form, use SPH estimate of quantum pressure tensor

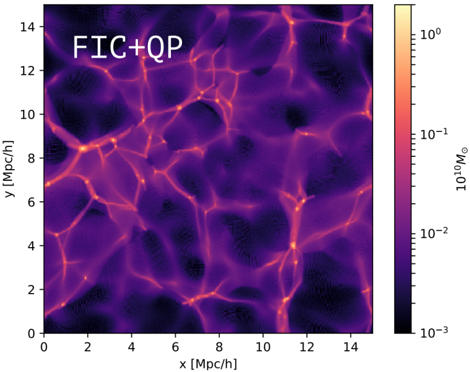
$$\partial_x \rho_i = \sum_j m_j \partial_x W_{ij}.$$

$$\partial_{xy} \rho_i = \sum_j \frac{m_j}{\rho_j} \left(\rho_j - \rho_i\right) \partial_{xy} W_{ij},$$

$$\mathsf{P}_{i,xy} = \sum_j \frac{m_j}{\rho_j} \frac{1}{4} \left[\frac{(\partial_x \rho_j)(\partial_y \rho_j)}{\rho_j} - \partial_{xy} \rho_j \right] W_{ij}$$

- Lagrangian, adaptive
- can add viscosity $\Rightarrow$ find ground states!

SPH: AX-Gadget (Nori & Baldi 2018)

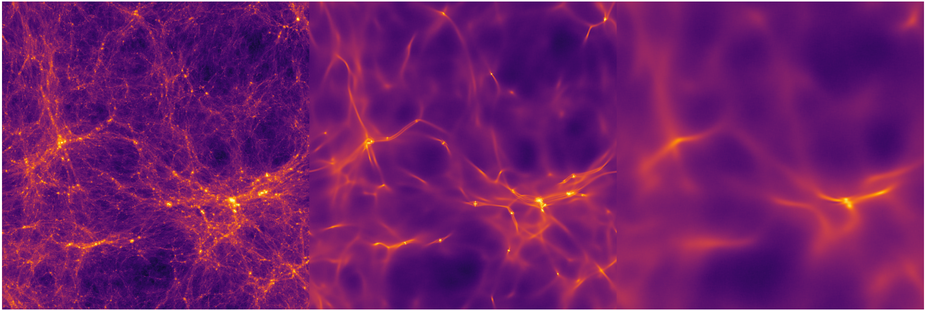


- captures large-scale quantum pressure
- based on SPH idea (Mocz & Succi, 2015)

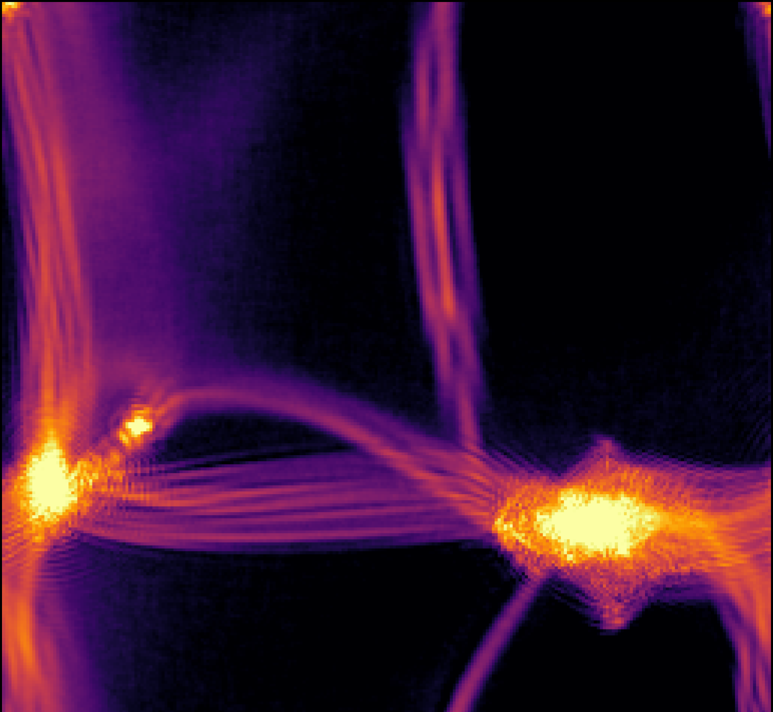
Cosmological simulations

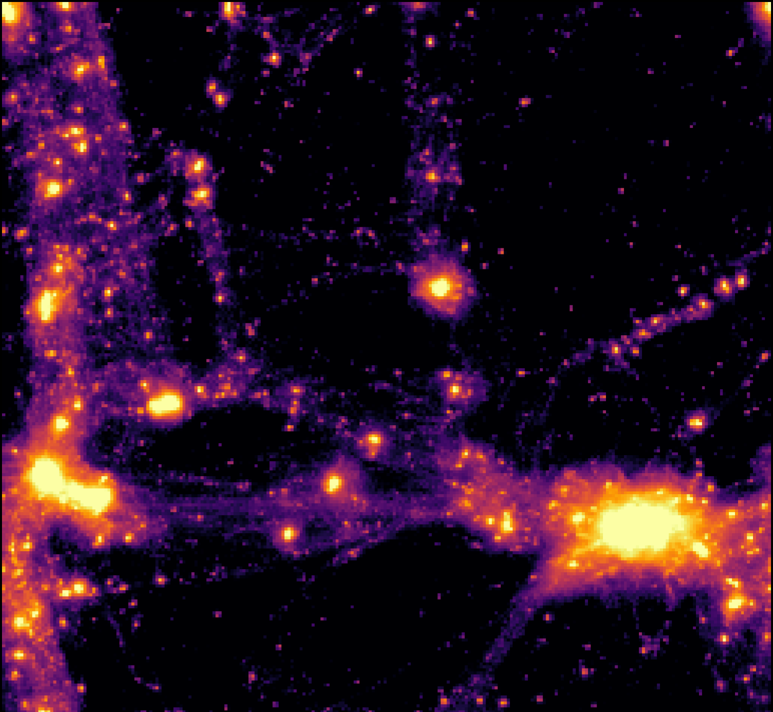
Cosmological simulations

- Added to AREPO, coupled with baryon model with feedback
- self-consistent quantum wave effects, baryon coupling

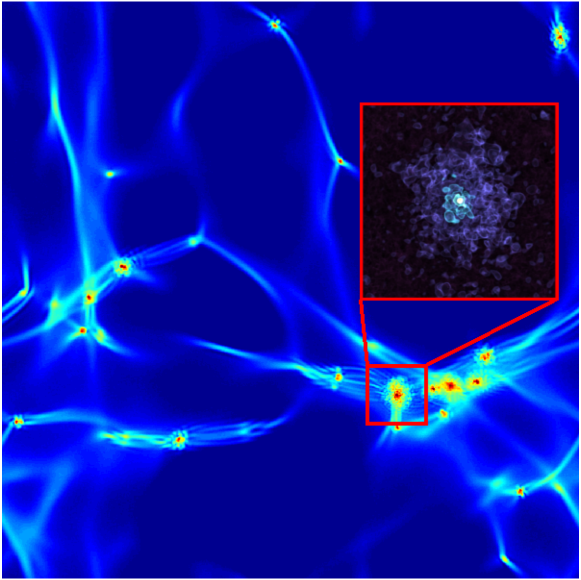


ΛCDM 2.5e−21 eV 2.5e−22 eV





Cosmological sims: idealized sims in context



- Turbulent relaxed cores found in cosmological simulations

Schrödinger/Vlasov–Poisson correspondence

Limiting behaviour for large boson mass (e.g., QCD axion) (Mocz et al., 2018)

- do the 3D Schrödinger equations encode collisionless dynamics (6D)?

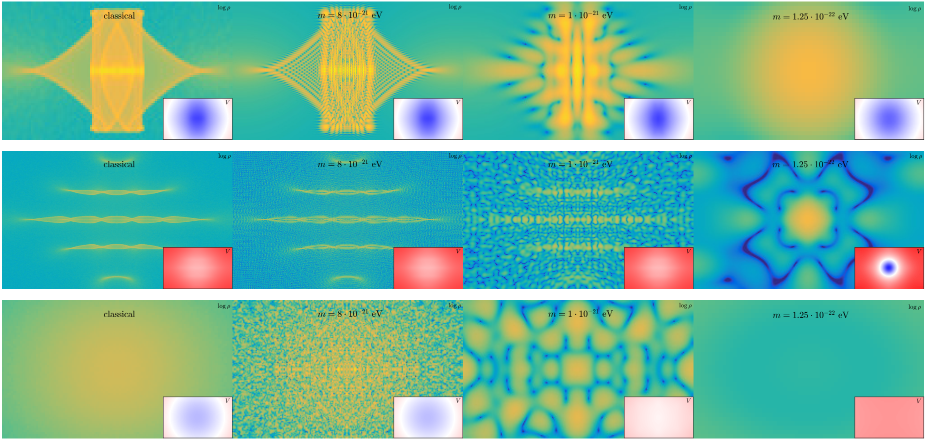
$$i\hbar\frac{\partial\psi}{\partial t} = -\frac{\hbar^2}{2m}\nabla^2\psi + mV\psi \tag{9}$$

$$\iff \quad (?)$$

$$\frac{\partial f}{\partial t} + \mathbf{v}\cdot\frac{\partial f}{\partial \mathbf{x}} - \nabla V\cdot\frac{\partial f}{\partial \mathbf{v}} = 0 \tag{10}$$

Schrödinger/Vlasov–Poisson correspondence

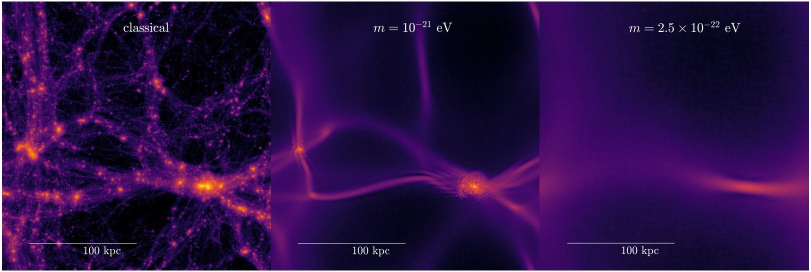
(Mocz et al., 2018)

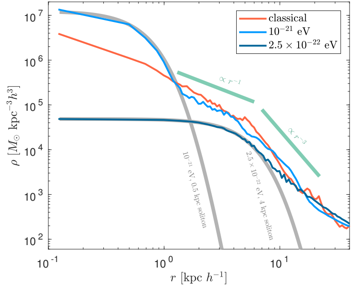


$$\psi(\mathbf{x}) \propto \sum_{\mathbf{v}} \sqrt{f(\mathbf{x},\mathbf{v})}\mathrm{e}^{im\mathbf{x}\cdot\mathbf{v}/\hbar + 2\pi i \phi_{\mathrm{rand},\mathbf{v}}}\, d^3v$$

$V \to V_{\mathrm{classical}}$ as m^{-2}

Schrödinger/Vlasov–Poisson correspondence

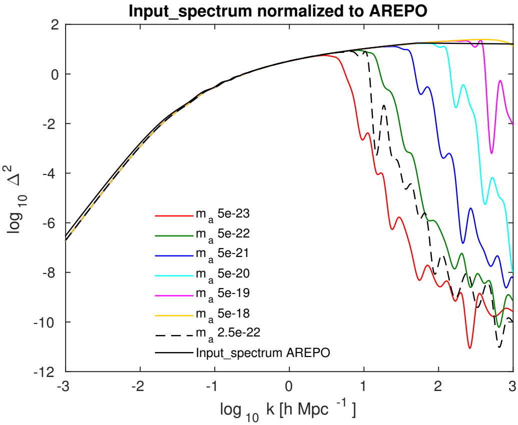


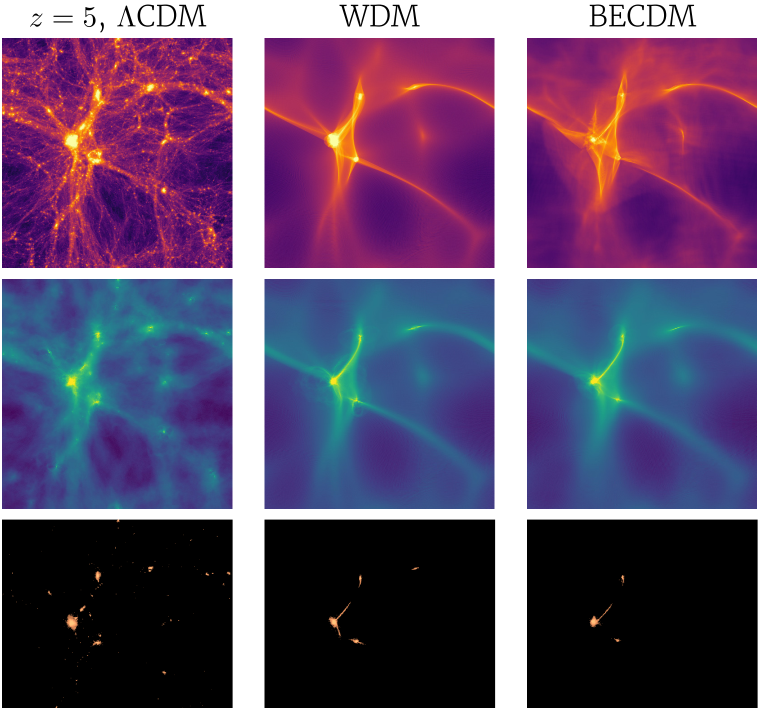


Full–physics cosmological simulations

BECDM + hydrodynamical simulations with galaxy formation physics
(PM+in prep.)

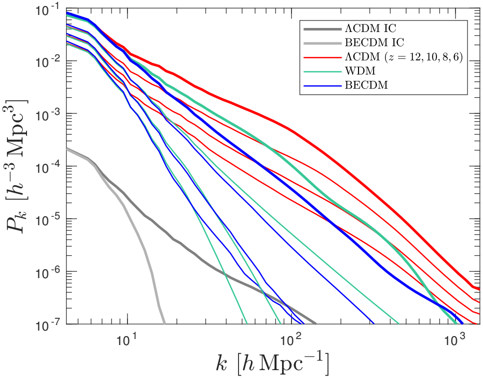
- $m = 2.5 \cdot 10^{-22}$ eV axion
- axionCAMB initial conditions





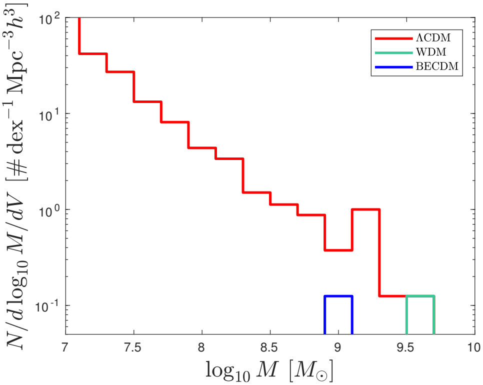
$z = 5$, ΛCDM
WDM
BECDM

DM power spectrum



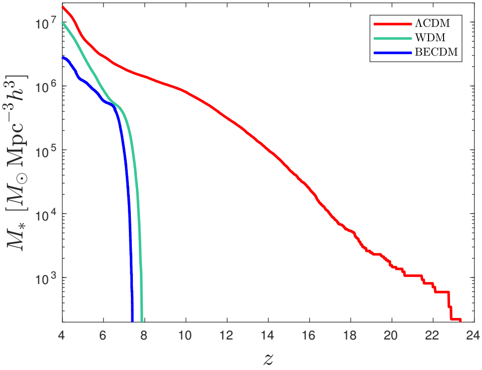
- quantum pressure tensor adds extra suppression of small-scale power
- agreement with CDM above 1 Mpc

“Halo mass function” ($z = 6$)



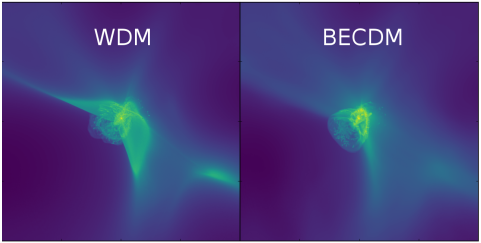
- $m = 2.5 \cdot 10^{-22}$ eV axion erased all structure below $10^9 M_\odot$

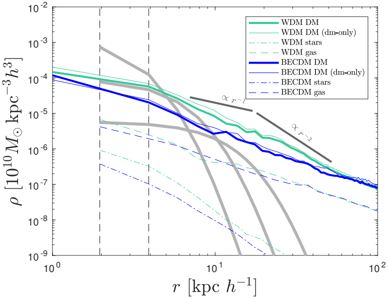
Cosmic Star formation history



- star formation hugely delayed

Radial profiles





- quantum pressure tensor smooths out caustic–tracing baryon structure
- soliton cores form late ($z < 6$)
- can see r^{-2} isothermal profiles for such low axion mass

Work in prep.: Astrophysical effects of BECDM

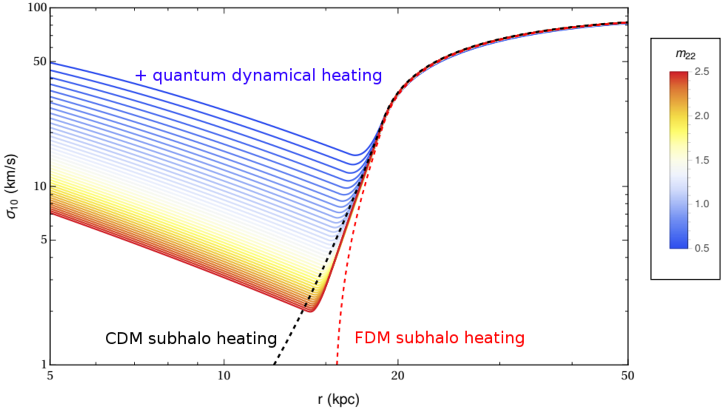
Qualitative effects to be quantified ...

- formation of first stars & galaxies delayed
- filaments are formation sites for stars
- interference granules heat baryons
- suppression in power spectrum at small scales
- soliton cores (halo relationship, baryonic modifications)
- stellar populations, galaxy sizes, JWST image predictions

Dynamical Heating (Church, PM, Ostriker subm)

- quantum interference patterns heat / thicken discs
- $\Rightarrow$ stochastic solenoidal force–field, random–walk

$$\frac{d\sigma_D^2}{dt} = \int_{b_{\min}}^{b_{\min}} (2\pi b)\ db\, n v_p \left(\frac{M_l G}{b v_p}\right)^2$$

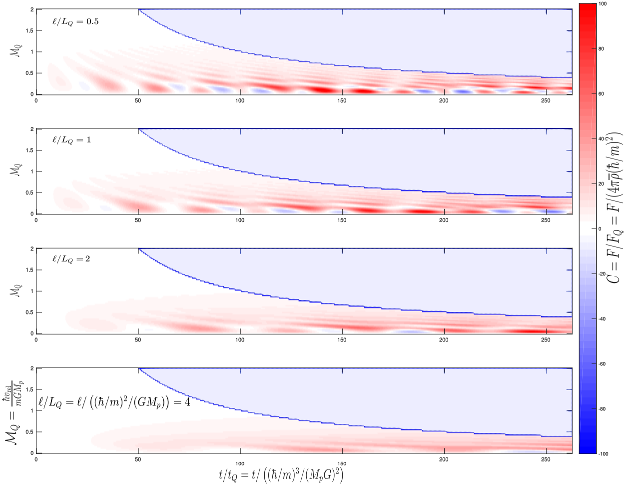


- constraint: $m_{\text{axion}} > 0.6 \times 10^{-22}$ eV

Dynamical Friction (PM, Lancaster in prep)

- Perturber of mass M_p, size ℓ. System is characterized by the quantum length scale $L_Q = (\hbar/m)^2/(GM_p)$

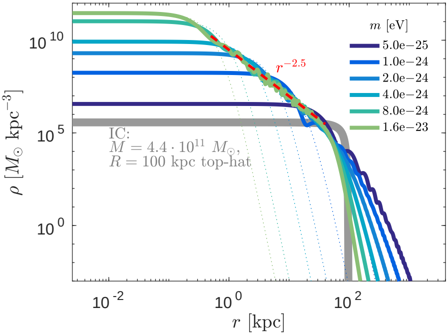
Dynamical Friction Coefficient

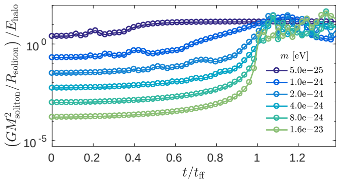


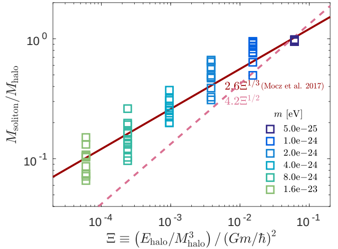
- **Dynamical friction coefficient C** encodes object size. Drag effective at low relative velocities, small perturber sizes

1D direct radial collapse (PM+ in prep)

- What is the resulting soliton core mass after a free–fall time as a function of m_{boson}?



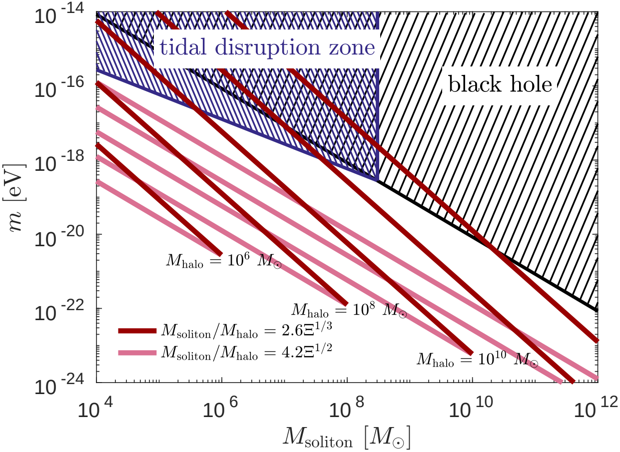




- Soliton core energy is independent of m_{boson}, traces halo total energy

1D direct radial collapse (PM+ in prep)

- What is the fate of the soliton core?



Conclusions

- FDM is a physically-motivated alternative to CDM that modifies small-scale structure
- rich mathematical structure (SP–VP correspondence; Mocz et al. 2018)
- Small-scale features $\Rightarrow$ astrophysical consequences
  - soliton cores (tidal disruptions? seed BHs?)
  - dynamical heating (random walk forcing field, disk thickening)
  - dynamical friction (from quantum pressure, effective at low relative velocities, small perturber sizes)

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