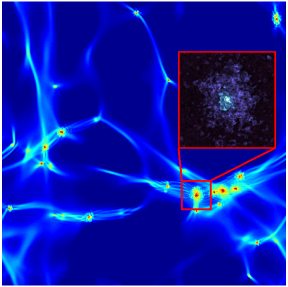
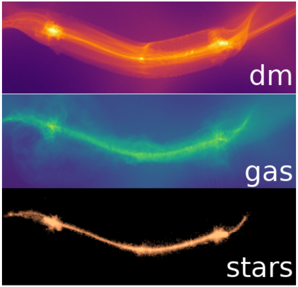
Fuzzy dark matter: overview



Philip Mocz

Princeton University,
Einstein Fellow

Sep 30, 2019



w/ Anastasia Fialkov (Cambridge), Mark Vogelsberger (MIT), Jesús Zavala (Iceland)

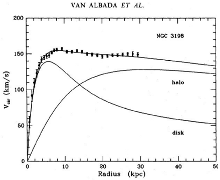
"Competing Structure
Formation Models" – Iceland

Outline

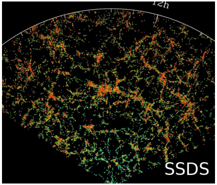
- Introduction to fuzzy dark matter (FDM)
- Full-physics cosmological simulations (PM+2019 PRL)
- Numerical Method (Mocz et al., 2017)
- Idealized virialized halo simulations (Mocz et al., 2017)
  - halo properties
- Schrödinger/Vlasov–Poisson correspondence (Mocz et al., 2018)
  - connection between FDM (3D wavefunction) and CDM (6D collisionless)

What is dark matter?

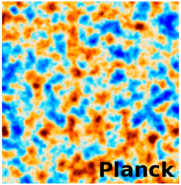
rotation curve



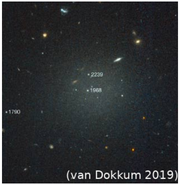
LSS



CMB



no-DM galaxy



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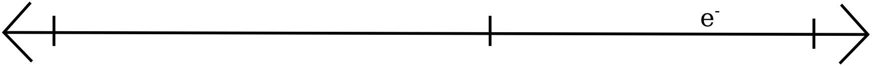


Fuzzy DM
$\sim 10^{-22}$eV

Warm DM
~ keV

Cold DM
~GeV

What is fuzzy dark matter (FDM)?

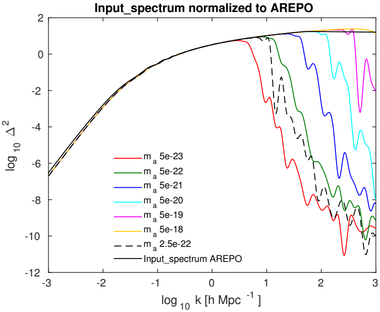
- Assume DM is a cold, ultralight scalar field (Peebles, 2000; Hu, Barkana & Gruzinov, 2000; Schive et al., 2014; Schwabe, Niemeyer & Engels, 2016)
- $T = 0$ in early universe, forms a BEC $\Rightarrow$ macroscopic quantum properties
- Uncertainty principal suppresses gravitational collapse below de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

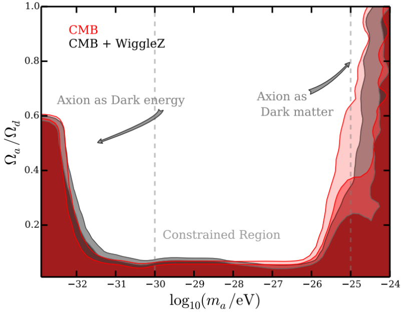
$$i\hbar\frac{\partial\psi}{\partial t} = -\frac{\hbar^2}{2m}\nabla^2\psi + mV\psi, \quad \nabla^2 V = 4\pi G(\rho - \overline{\rho}), \quad \rho = |\psi|^2 \tag{1}$$

Motivation for FDM

- Astrophysics
  - ΛCDM small scale challenges
    - 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

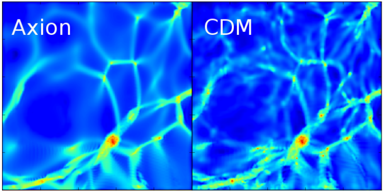


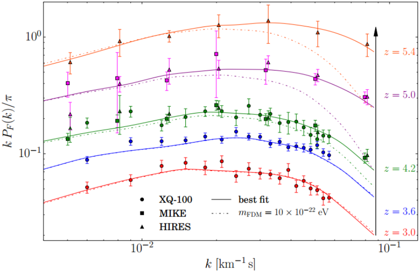


- A small axion mass suppresses large k initial DM power spectrum
- $m \geq 10^{-24}$ eV, otherwise inconsistent with CMB fluctuations

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

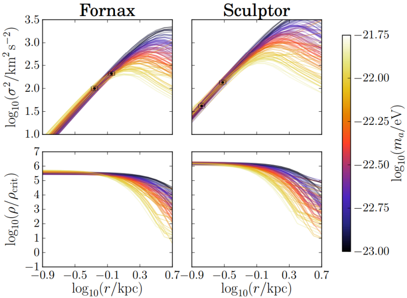
Axion mass constraints from Ly–α forest

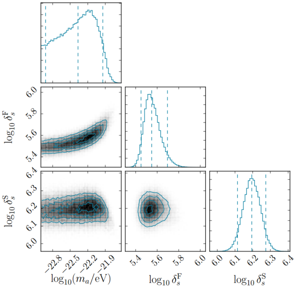




- $m \gtrsim 10^{-21}$ eV, otherwise not enough Mpc–scale power in the Ly–α forest Armengaud et al. (2017); Iršič et al. (2017)

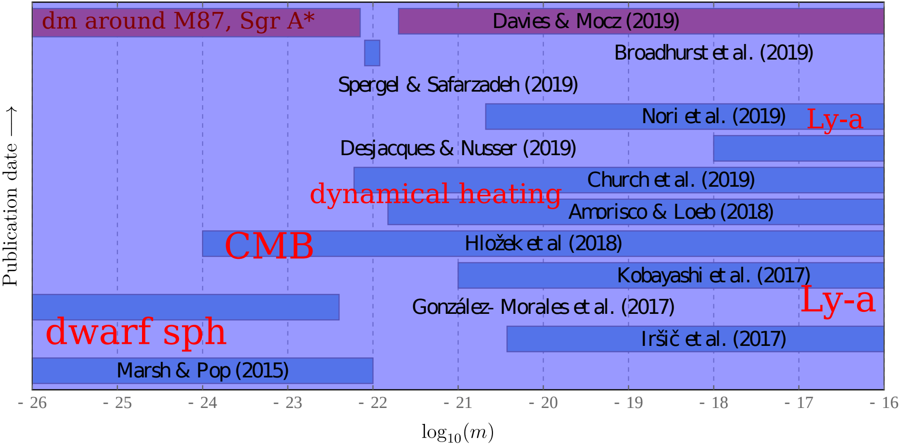
Axion mass constraints from dwarf spheroidals



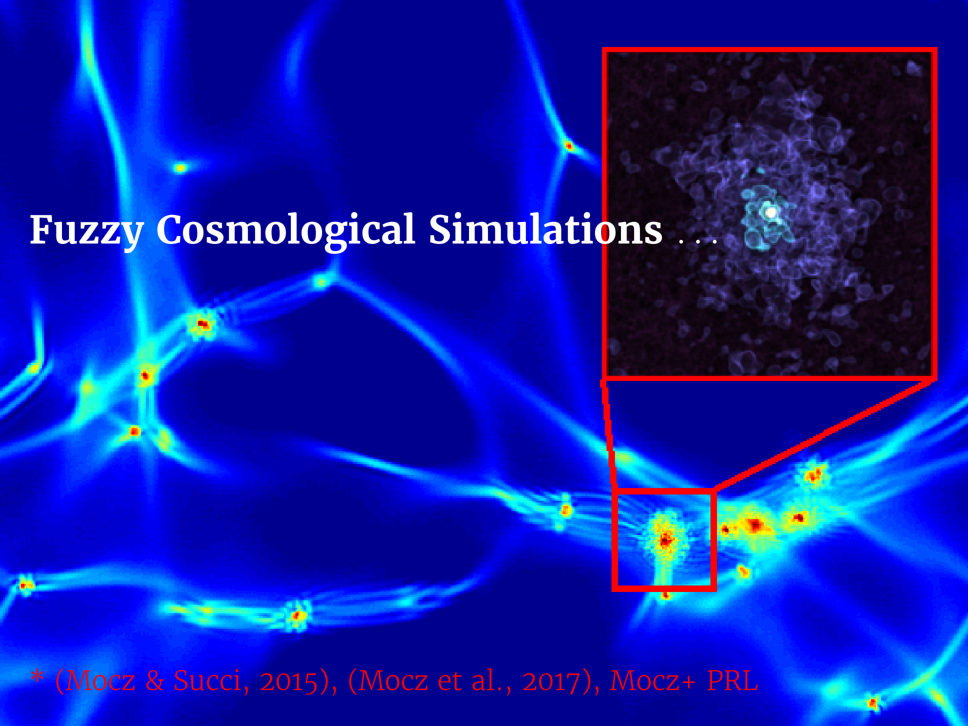


- Particle needs to be pretty light ($m \sim 10^{-22}$ eV) to explain DM-dominated dwarf spheroidals (Fornax, Sculptor) with pure fuzzy dark matter soliton core potential

Summary of particle mass constraints



Fuzzy Cosmological Simulations . . .

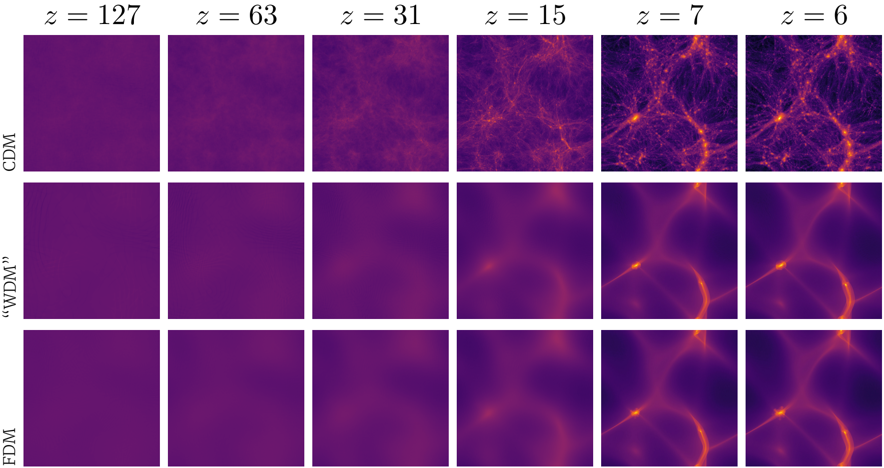


* (Mocz & Succi, 2015), (Mocz et al., 2017), Mocz+ PRL

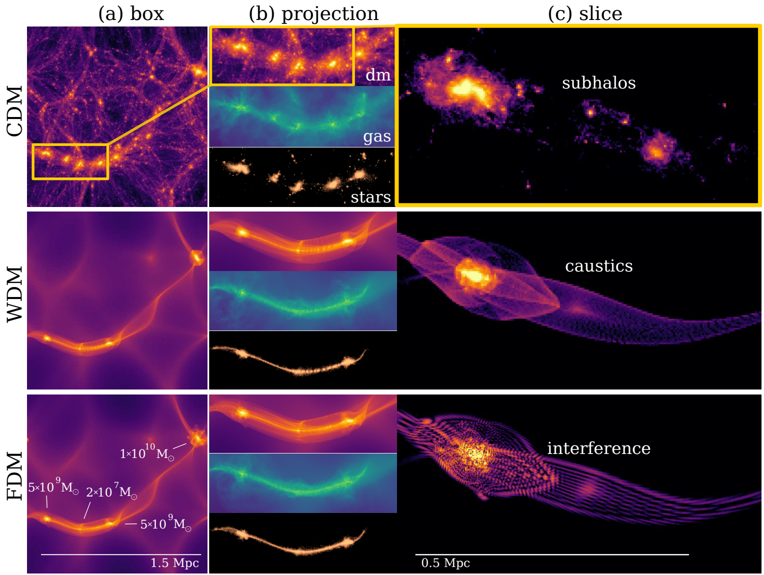
Cosmological simulations

- Full-physics (baryons, feedback) quantum mechanical simulations with quantum wave effects
- Initial conditions at $z = 127$ from AxionCAMB
- 3 million core hours on TACC *Stampede2*
- limitation: method is memory-expensive (need to resolve kpc interference)
- restricted to study of first galaxies/structures at $z \sim 6$, small box size (~ 2 *Mpc*)

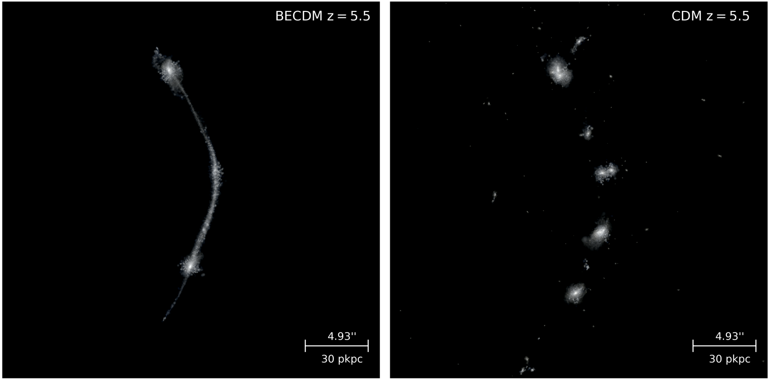
Cosmological simulations – dark matter



Summary

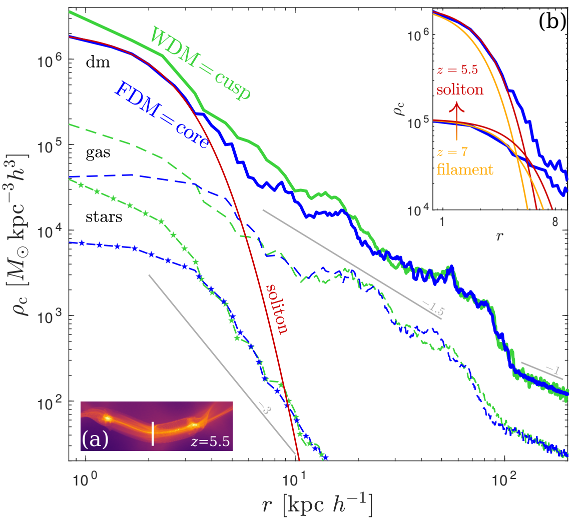

(a) box
(b) projection
(c) slice
CDM
WDM
FDM
dm
gas
stars
subhalos
caustics
interference
$1\times10^{10}M_\odot$
$5\times10^{9}M_\odot$
$2\times10^{7}M_\odot$
$5\times10^{9}M_\odot$
1.5 Mpc
0.5 Mpc

JWST Mock Images



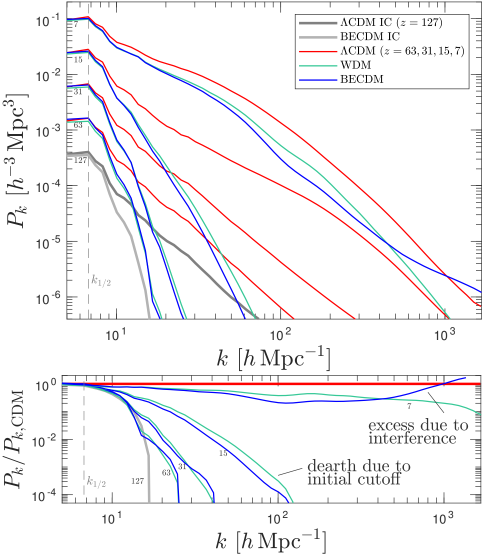
w/ Xuejian Shen (MIT)

Collapse of cylindrical filament



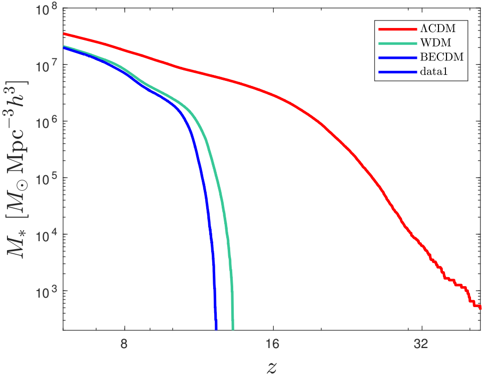
- cylindrical ‘soliton’ core unstable to spherical collapse

DM power spectrum



- quantum pressure tensor adds extra suppression of small-scale power
- but extra power from interference at kpc scale
- agreement with CDM above 1 Mpc

Cosmic star formation history



- first star formation hugely delayed
- reionization sets limit on axion mass

Conclusions

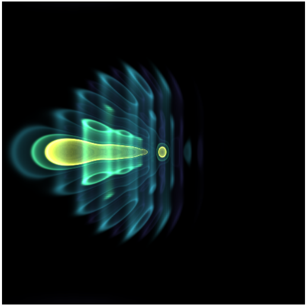
cosmological first objects summary

- First galaxies probe the physical nature of dark matter
- Future missions (e.g. JWST) will open an observational window into this emergent world
- In FDM:
  - Primordial stars form along dense dark matter filaments
  - Dark matter filaments show coherent interference patterns on the boson de Broglie scale
  - Dark matter filaments develop cylindrical soliton-like cores which are unstable under gravity and collapse into kpc-scale spherical solitons
  - Gas and stars trace cored dark matter profile

Student work highlights

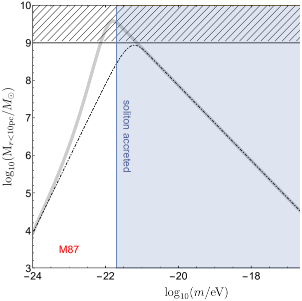
FDM dynamical friction

Lachlan Lancaster+ 2019



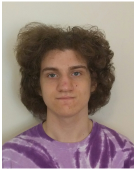
FDM solitons around SMBHs

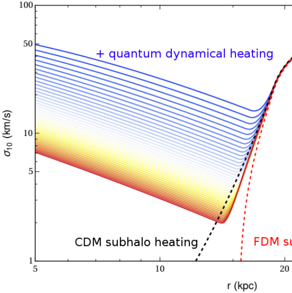
Elliot Davis+ 2019



FDM dynamical heating

Ben Church+ 2018





Numerical Method: (Mocz et al., 2017)

2nd-order unitary spectral leap-frog scheme.
'Kick-drift-kick'

- Calculate potential:

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

- Potential half-step 'kick':

$$\psi \leftarrow \exp\left[-i(\Delta t/2)(m/\hbar)V\right]\psi \tag{3}$$

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

$$\hat{\psi} = \mathrm{fft}\left[\psi\right] \tag{4}$$

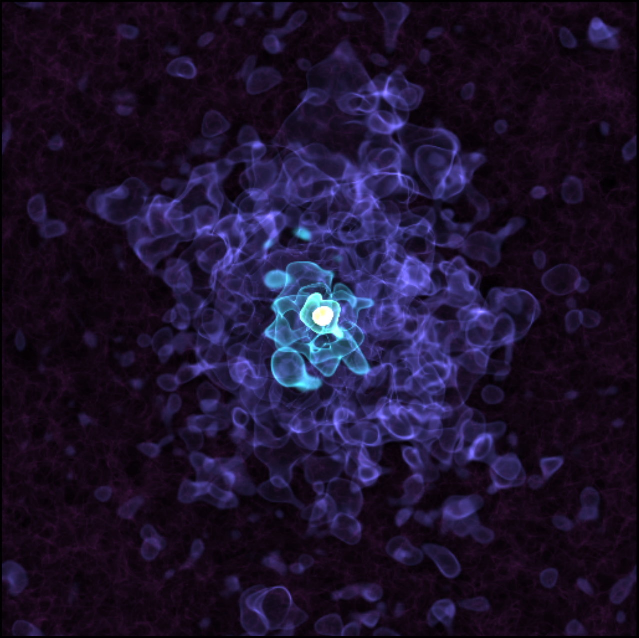
$$\hat{\psi} \leftarrow \exp\left[-i\Delta t(\hbar/m)k^2/2\right]\hat{\psi} \tag{5}$$

$$\psi \leftarrow \mathrm{ifft}\left[\hat{\psi}\right] \tag{6}$$

- Another 'kick'

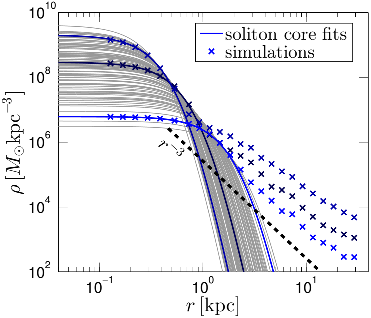
Idealized simulations

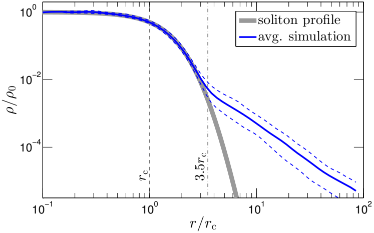
- Galaxy formation with BECDM– I. Turbulence and relaxation of idealized haloes (*Mocz et al.*, 2017)
  - simulate virialized DM halos
  - virialized profiles
  - self-similarity? soliton core–halo mass relation



(Mocz et al., 2017)

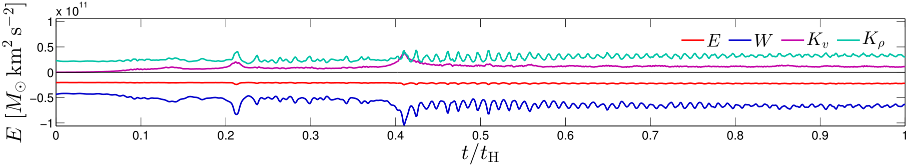
FDM profiles

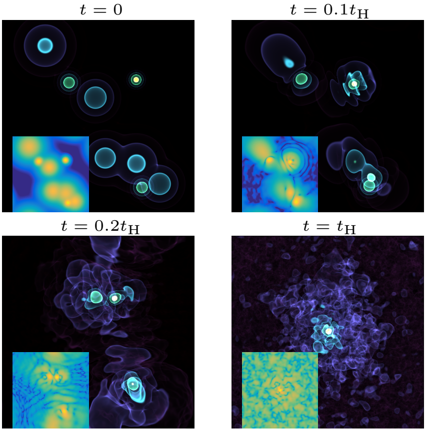




- Soliton core ($r^0 \to r^{-16}$)
- NFW-like outer profile (r^{-3}) or flatter (r^{-2} isothermal)
- c.f. NFW ($r^{-1} \to r^{-3}$)

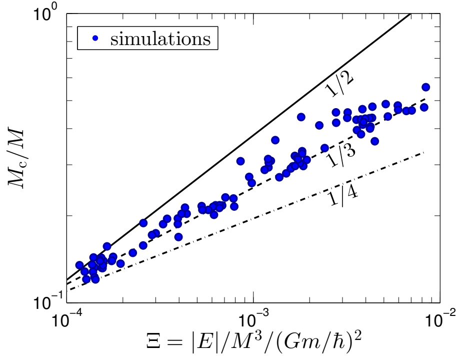
Axion DM energies





- 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: $|W| = 2(K_v + K_\rho)$

Axion DM 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:
  $\boxed{M_c/M \propto (|E|/M^3)^{1/3}}$
  fundamental relation
- means core & halo binding energy in equipartition
- c.f. $M_c \propto (|E|/M)^{1/2}$ (Schive et al., 2014) in cosmological simulations

Conclusions

FDM virialized halo summary

- soliton core, r^{-3} outer profile
- virial equilibrium
- fundamental relation says $E_{\text{core}} \propto E_{\text{halo}}$
  - cosmological simulations instead see $R_{\text{core}} \sim \frac{\hbar}{m\sigma_{\text{disp}}}$

Schrödinger/Vlasov–Poisson correspondence

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

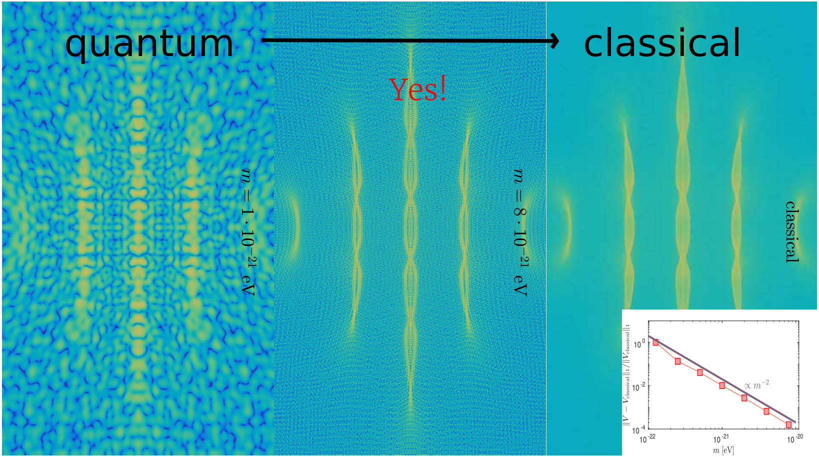
$$i\hbar\frac{\partial\psi}{\partial t} = -\frac{\hbar^2}{2m}\nabla^2\psi + mV\psi \tag{7}$$

$$\iff \; (?)$$

$$\frac{\partial f}{\partial t} + \mathbf{v}\cdot\frac{\partial f}{\partial \mathbf{x}} - \nabla V \cdot \frac{\partial f}{\partial \mathbf{v}} = 0 \tag{8}$$

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

Schrödinger/Vlasov–Poisson correspondence



3D wave function can encode 6D distribution function:

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

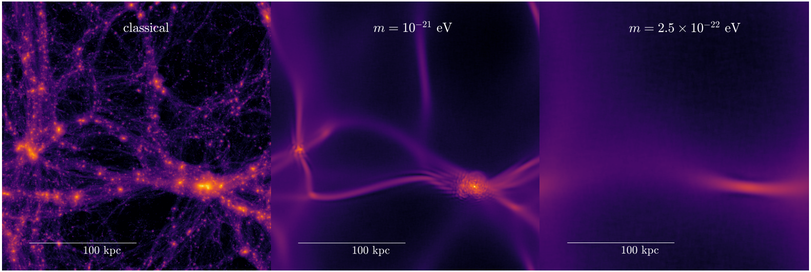
Gravitational potential converges as: $V \to V_{\rm classical}$ as m^{-2}

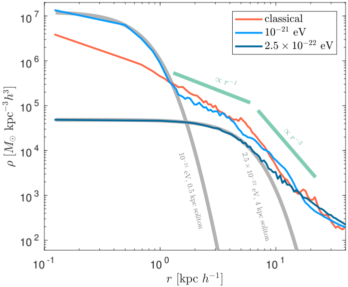
Schrödinger/Vlasov–Poisson correspondence

CDM

$m = 10^{-21}$ eV

$2.5 \cdot 10^{-22}$ eV





Conclusions

SP–VP correspondence summary

- classical limit for V recovered as $\mathcal{O}(m^{-2})$ ($\Rightarrow$ forces as $\mathcal{O}(m^{-1})$), while density has $\mathcal{O}(1)$ interference patterns on scale of λ_{dB}
- soliton cores regularize caustic singularities
- fuzzy halos are NFW–like with a soliton core

Final Conclusions

- FDM is a physically-motivated alternative to CDM that modifies small-scale structure
- First 'galaxies' are expected to be are filamentary
  - quantum pressure sets the cored filamentary structure
  - to be revealed by next-gen space telescopes (JWST)
- Rich mathematical structure (SP-VP correspondence)
- Small-scale features $\Rightarrow$ astrophysical consequences
  - cosmic interference patterns, dynamical heating
  - dynamical friction (from quantum pressure, effective at low relative velocities, small perturber sizes)

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