# First Structures in Fuzzy Dark Matter

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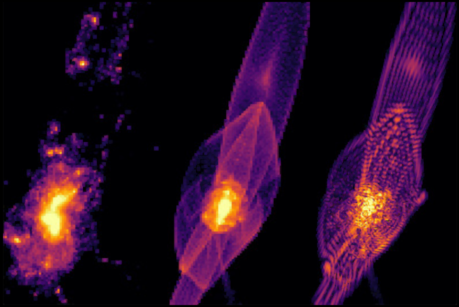
Einstein Fellow

Jul 9, 2020



Göttingen
FDM-workshop

# Outline

- Fuzzy Dark Matter (FDM) motivations and tensions
- New probes for FDM:
- Full-physics cosmological simulations (**Mocz** et al., 2019; Mocz et al., 2020)
  - First galaxies uniquely probe physical nature of dark matter
  - Test with James Webb Space Telescope (JWST)
- Large axion mass limit (**Mocz** et al., 2018)
  - connection between FDM & CDM
- Adding in the strong-CP scale to FDM
- Further probes: small-scale astrophysical features of FDM [student works]
  - dynamical friction (Lancaster, Giovanetti, **Mocz**,..., 2020)
  - dynamical heating (Church, **Mocz** & Ostriker, 2019)
  - soliton + SMBH (Davies & **Mocz**, 2019)

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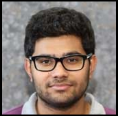
# People

highlight student


Mustafa Amin
Rice


Fernando Becerra
Harvard


Mike Boylan-Kolchin
UT Austin


Sownak Bose
Harvard


Pierre-Henri Chavanis
Toulouse

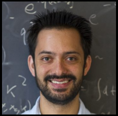

Ben Church
Columbia


Elliot Davies
Princeton


Anastasia Fialkov
Cambridge


Cara Giovanetti
Princeton


Lars Hernquist
Harvard


Yoni Kahn
Illinois


Lachlan Lancaster
Princeton


Mariangela Lisanti
Princeton


Federico Marinacci
Bologna


Jerry Ostriker
Columbia


Victor Robles
Yale


David Spergel
Flatiron


Sauro Succi
CNR Rome


Mark Vogerlsberger
MIT


Jesús Zavala
Iceland

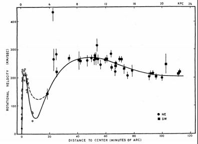
# What is dark matter?

The nearly century-old dark matter problem is one of the most intriguing mysteries in modern physics. (Zwicky, 1933)

We do not know the nature of 84% of matter in the Universe, yet it is thought to govern cosmic structure and hold galaxies and clusters together.

# What is dark matter?

rotation curve



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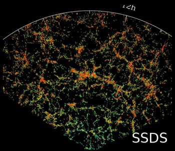


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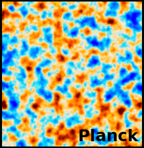


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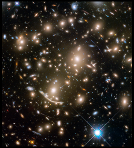
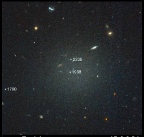
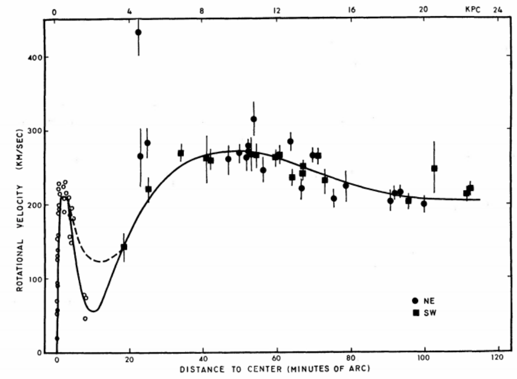


no-DM




van Dokkum, ... (2019)



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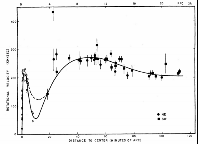

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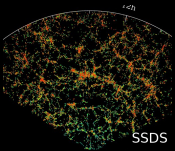


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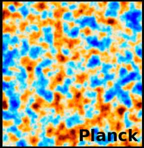


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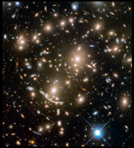

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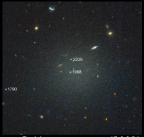

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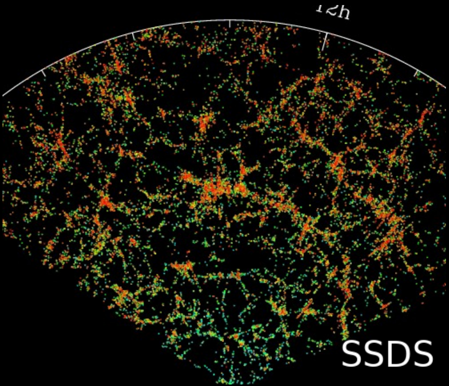

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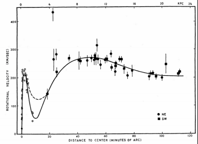


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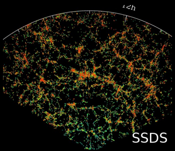


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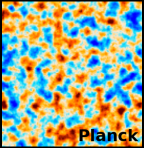


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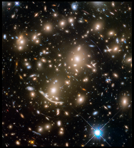

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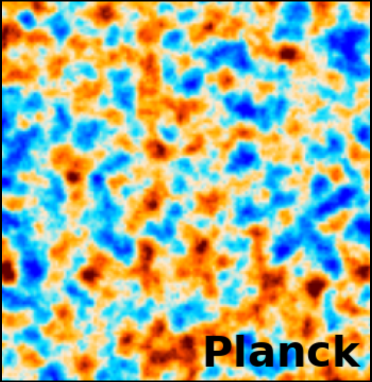

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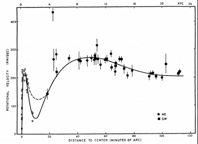

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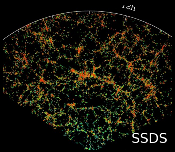


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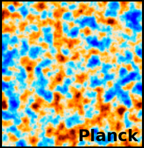


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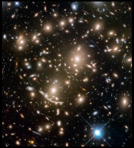

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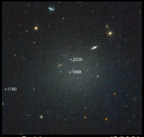

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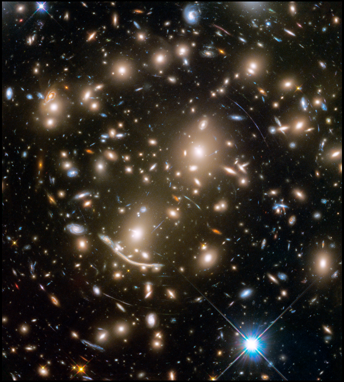

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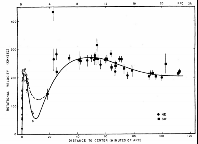


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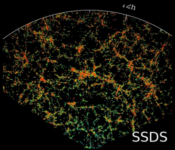


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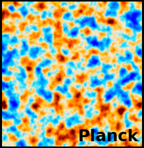


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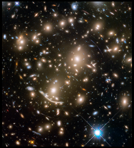

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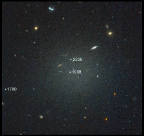


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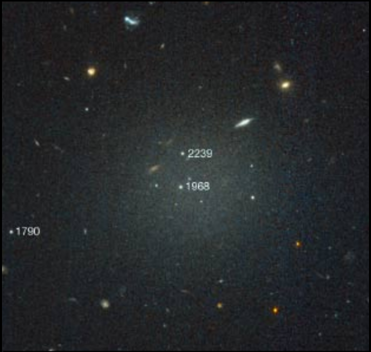


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- Assume DM is a cold, ultralight scalar field (Peebles, 2000; Hu, Barkana & Gruzinov, 2000; Hui et al., 2017)
- $T = 0$ in early universe, forms a BEC $\Rightarrow$ macroscopic quantum properties
- 'Quantum Pressure' suppresses gravitational collapse below de Broglie wavelength
  - Require $m \sim 10^{-22}$ eV to have $\lambda_{\mathrm{dB}} \sim 1$ kpc for $v \sim 100$ km s$^{-1}$
- Governed by Schrödinger–Poisson

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

- Two Key features: suppressed small-scale power + large soliton cores (there are also other features!)

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# Motivation for FDM

- Astrophysics
  - CDM small scale challenges (Primack, 2009)
    - 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
  - 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; Bachlechner et al., 2019)

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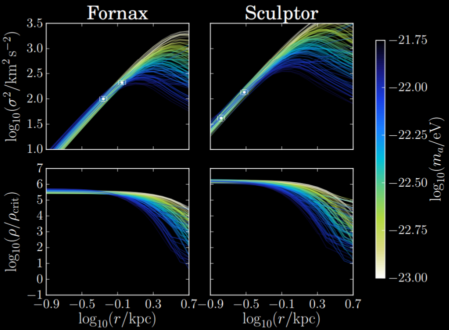
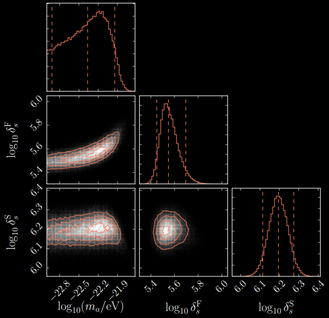
# FDM particle mass constraints from dwarf spheroidals

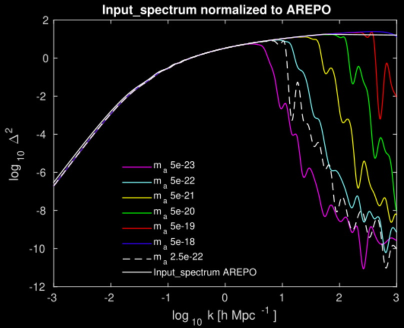


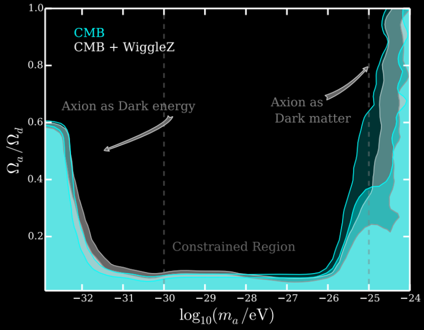

- Particle needs to be light ($m \sim 10^{-22}$ eV) to explain DM-dominated dwarf spheroidals (Fornax, Sculptor) as a pure fuzzy dark matter soliton core (Marsh & Pop, 2015)

# FDM particle mass constraints from CMB

initial power spectrum



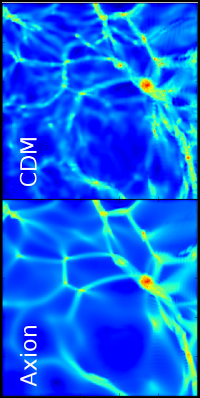

excluded mass range

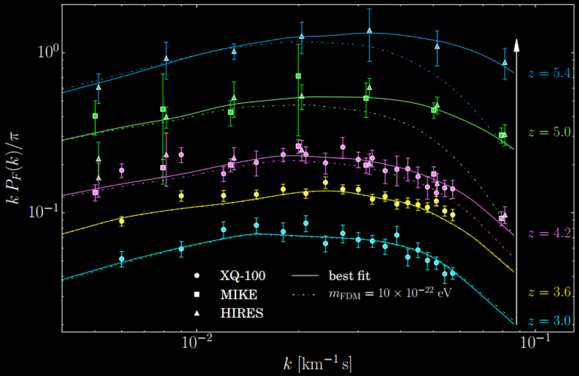



- A small boson mass suppresses large $k$ initial DM power spectrum
- need $m \geq 10^{-24}$ eV, otherwise inconsistent with CMB fluctuations

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

# FDM particle mass constraints from Ly-$\alpha$ forest

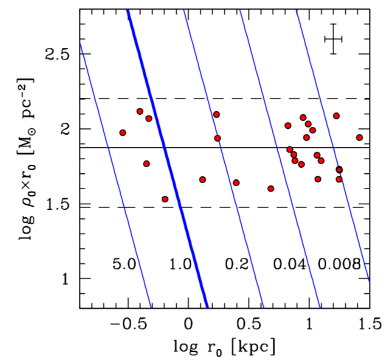



- $m \gtrsim 10^{-21}$ eV, otherwise not enough Mpc-scale power in the Ly-$\alpha$ forest (Armengaud et al., 2017; Iršič et al., 2017)

# Catch-22

- Catch-22 Problem: moderate tension in setting the particle mass to simultaneously capture large cores and right amount of substructure
- Also, simple soliton core model cannot simultaneously explain constant DM surface density ($\sim 75\ M_\odot/\mathrm{pc}^2$) inferred from observations of satellite galaxies (Burkert, 2020) (see also Safarzadeh & Spergel (2020)):



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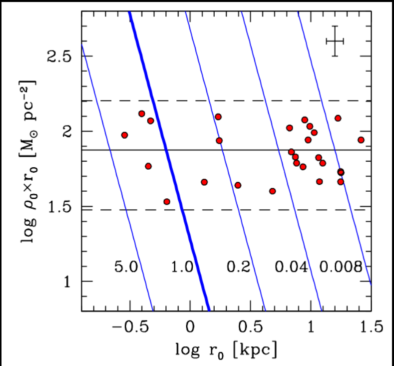
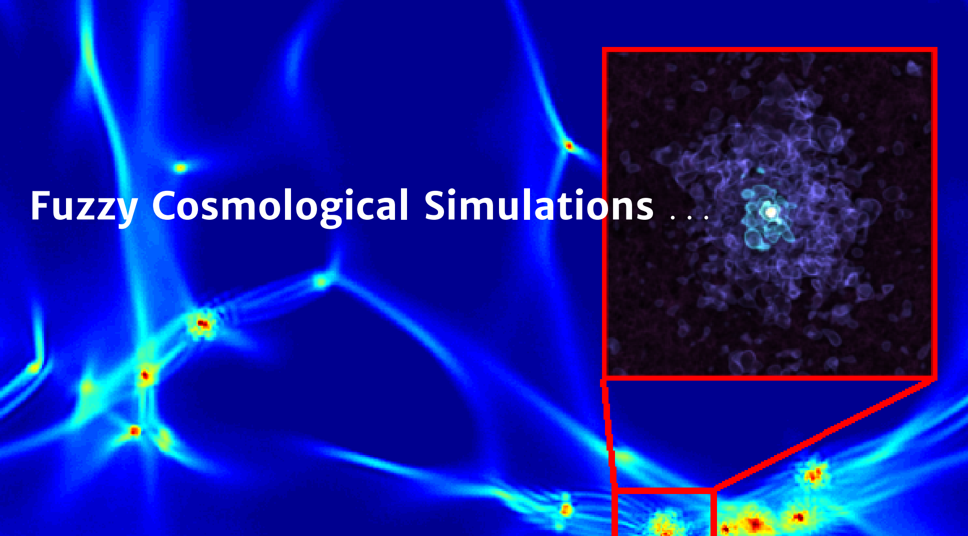


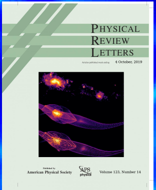
# Catch-22

We need simulations to investigate:

- possibility additional nonlinear structure formation?
- modifications to soliton profile in context of cosmology, baryons

# Fuzzy Cosmological Simulations . . .

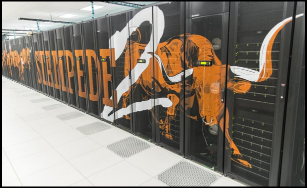





* (Mocz & Succi, 2015), (Mocz et al., 2017), (Mocz et al., 2020), Mocz+ (2019) Phys. Rev. Lett.

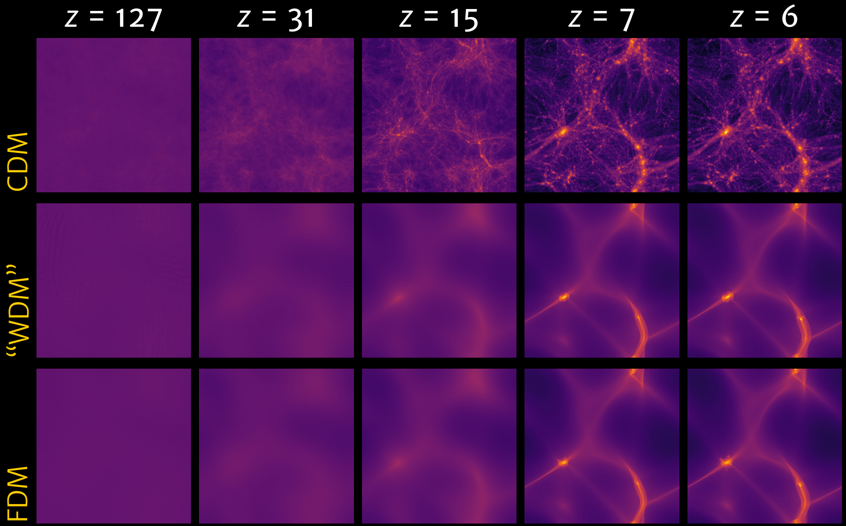
# Cosmological simulations

- Full-physics (baryons, star formation, feedback) quantum mechanical simulations with quantum wave effects
- Proper initial conditions at $z = 127$ from AxionCAMB
- 5 million core hours on *Stampede2* and *Odyssey*

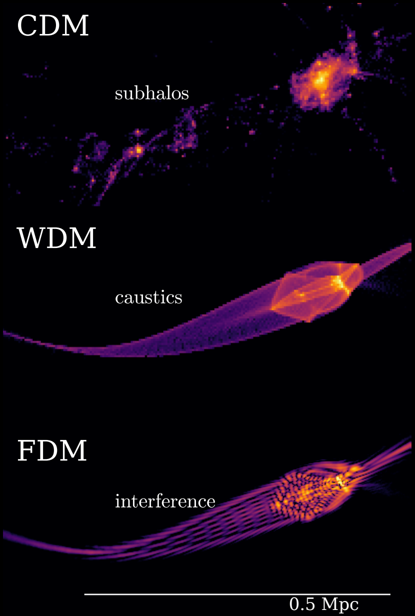



- Limitation: method is memory-expensive (need to resolve kpc interference)
- Restricted to study of first galaxies/structures at $z \sim 6$, small box size ($\sim 2$ Mpc)

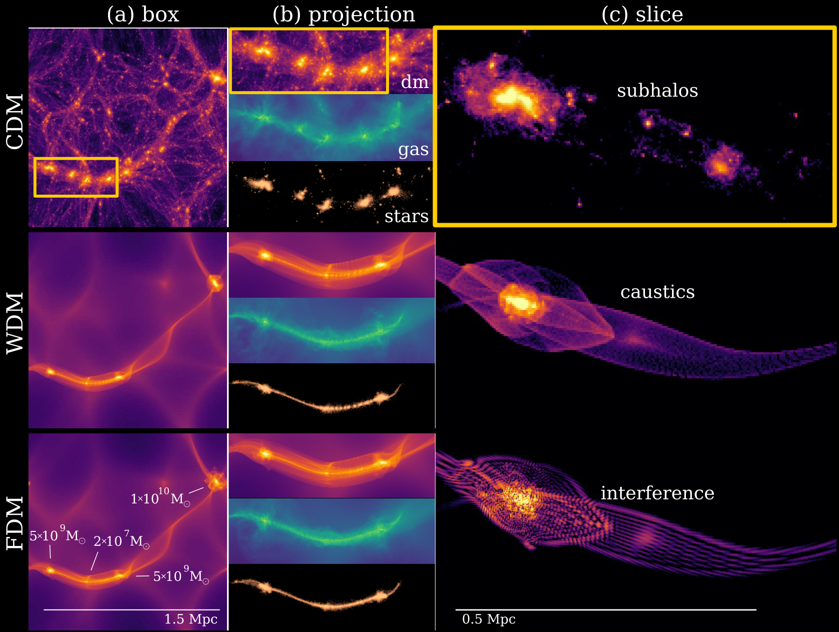
# Cosmological simulations – dark matter



# Small scales: anatomy of a filament



# Summary

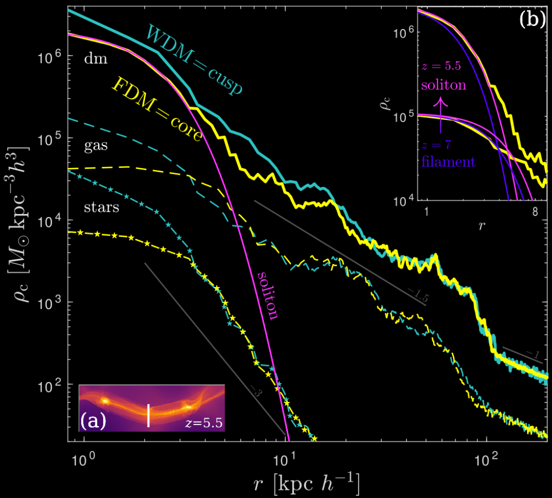


(a) box
(b) projection
(c) slice
CDM
WDM
FDM
dm
gas
stars
subhalos
caustics
interference
1×10^10 M⊙
5×10^9 M⊙
2×10^7 M⊙
5×10^9 M⊙
1.5 Mpc
0.5 Mpc

# JWST Mock Images

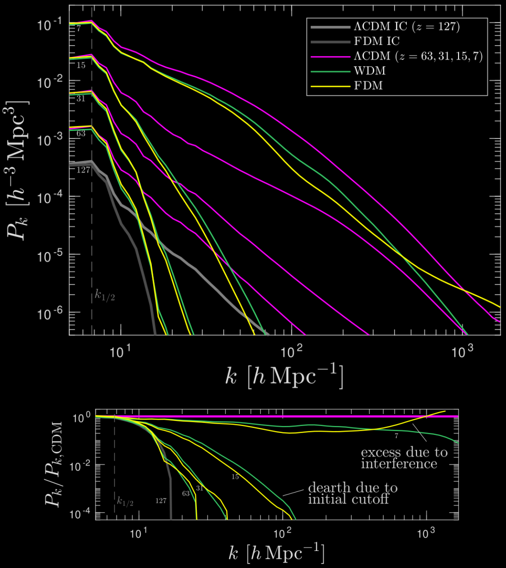
FDM CDM

# Collapse of cylindrical filament




- we identified a nonlinear structure formation channel:
- in cosmological context, filaments form first
- cylindrical ‘soliton’ core unstable to spherical collapse

# DM power spectrum




- quantum pressure tensor adds extra suppression of small-scale power
- but we found extra power from interference at 10s kpc by $z = 7$
- agreement with CDM above 1 Mpc

# Conclusions

## cosmological first objects summary

- First galaxies uniquely probe the physical nature of dark matter
- Future missions (e.g. JWST) will open an observational window into this emergent world
- Nonlinear structure formation eases *Catch-22* problem
- In FDM:
  - Primordial stars form along dense dark matter filaments
  - Dark matter filaments show coherent interference patterns
  - Dark matter filaments develop cylindrical soliton-like cores which are unstable under gravity and collapse into spherical solitons
  - Gas & stars trace cored dark matter profile

# Numerical Method: (**Mocz** et al., 2017)

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

- Calculate potential:

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

- 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:

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

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

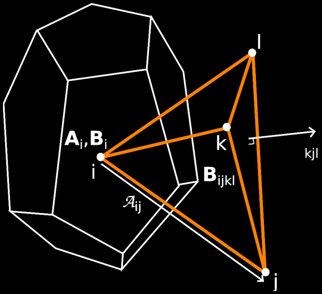
$$\psi \leftarrow \textbf{ifft}\left[\hat{\psi}\right] \tag{6}$$

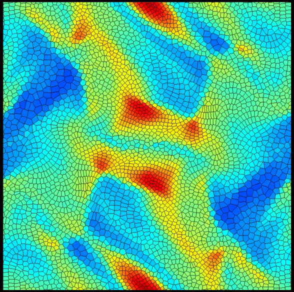
- Another 'kick'

(*unitary algorithm adaptable to quantum computers)

# Numerical Method: Gas (**Mocz** et al., 2014; **Mocz**, Vogelsberger & Hernquist, 2014; **Mocz** et al., 2015, 2016; **Mocz**, 2017)

## Moving Mesh Magnetohydrodynamics



# Schrödinger/Vlasov–Poisson correspondence

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

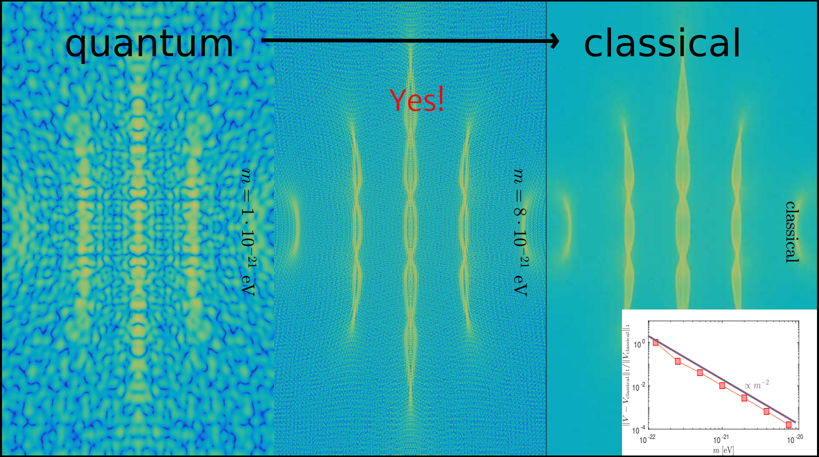
$$i\hbar\frac{\partial\psi}{\partial t} = -\frac{\hbar^2}{2m}\nabla^2\psi + mV\psi \quad (7)$$

$$\iff (?)$$

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

In **Mocz** et al. (2018) we explore the limiting behavior of large boson mass (e.g., QCD axion)

# Schrödinger/Vlasov–Poisson correspondence

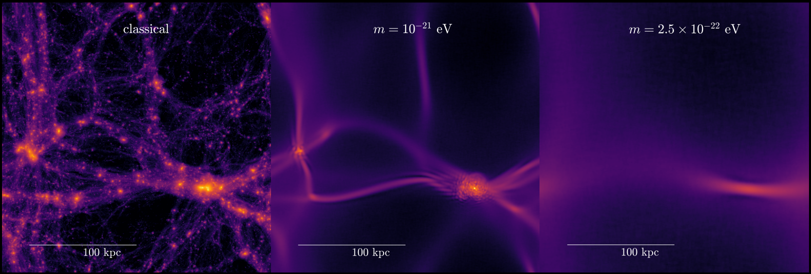


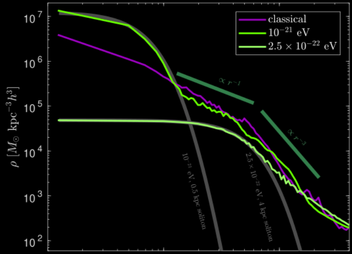

3D wave function can encode 6D distribution function:

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

# Schrödinger/Vlasov–Poisson correspondence

CDM | $m = 10^{-21}$ eV | $2.5 \cdot 10^{-22}$ eV



# Conclusions

## SP–VP correspondence summary

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

# Future Work

- Larger statistical simulations samples
  - need approximate particle-based simulation methods

Fuzzy Dark Matter

- Simultaneously constrain particle mass & strong-CP symmetry-breaking scale using a variety of techniques
  - Lyman-$\alpha$
  - nonlinear halo mass function
  - dynamics in a soliton core
  - soliton - black hole interaction
  - stellar streams
  - dynamical heating/timing problems
  - gravitational lensing
  - ...

# Return to Catch-22

- Catch-22 Problem: moderate tension in setting the particle mass to simultaneously capture large cores and right amount of substructure
- Resolutions:
  - Dark matter is not fuzzy
  - FDM wave interference
  - Substructure forms below exponential cutoff (nonlinear effects)
  - Baryonic physics/feedback (connection between galaxies and their dark matter halos (Wechsler & Tinker, 2018))
  - Attractive self-interaction that arises from strong-CP symmetry-breaking scale (Desjacques, Kehagias & Riotto, 2018)

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# Strong-CP symmetry-breaking scale

Starting point

$$S[\phi] = \int d^4x\sqrt{-g}\left[\frac{1}{2}(\partial\phi)^2 - \left(m^2 f^2\right)\left(1 - \cos\frac{\phi}{f}\right)\right] \qquad (9)$$

$f \simeq 10^{17}$ GeV is the decay constant, $m^2/f^2 = 10^{-96}$ $\leftarrow$ *tiny!*

$\Rightarrow$ Gross–Pitaevskii–Poisson equations in expanding universe

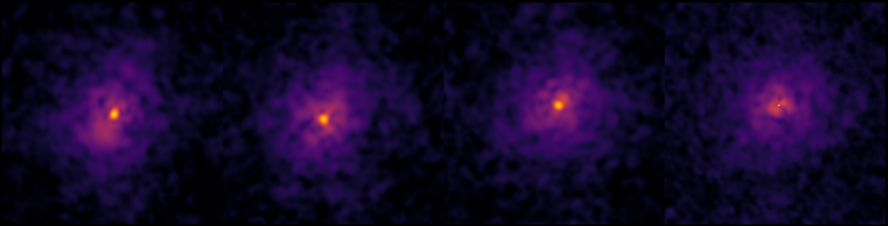
$$i\hbar\left(\frac{\partial}{\partial t} + \frac{3}{2}H\right)\psi = -\frac{\hbar^2}{2m}\nabla^2\psi + mV\psi - \frac{4\pi\hbar^2 a_s}{m^2}|\psi|^2\psi \qquad (10)$$

$$\nabla^2 V = 4\pi G(\rho - \bar{\rho}) \qquad (11)$$

$a_s$ is effective $s$–scattering cross section

# Strong-CP symmetry-breaking scale

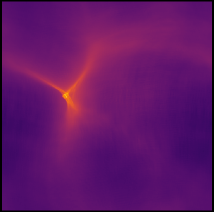
- Phase-transition: dilute to dense solitons above a critical mass



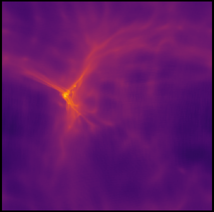
increasing self-interaction →

- Work in progress with undergrad Noah Notis

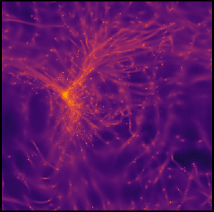
# Strong-CP symmetry-breaking scale



FDM: $a_s = 0$

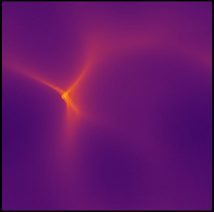


$a_s = 1 \cdot 10^{-75}$ cm

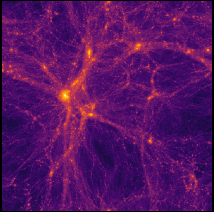


$a_s = 2 \cdot 10^{-75}$ cm

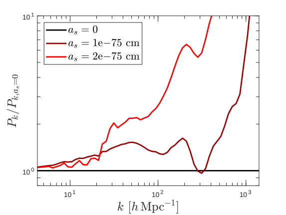
(not fully-converged @prelim res.)



WDM



CDM




relative power-spectrum

# Small-scale features of FDM

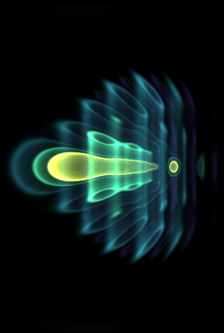
## Student work highlights

FDM dynamical friction

Lachlan Lancaster,

Cara Giovanetti,

Mocz+ 2019



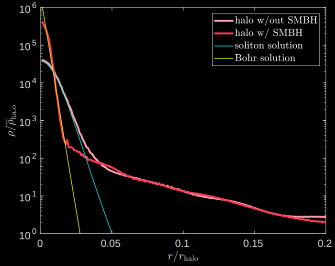
- Applications:
  - satellite infall / timing problem
  - final parsec problem

- Different regimes:
  - gravity vs quantum pressure
  - gravity vs velocity dispersion
    - random walk
  - gravity vs mixed

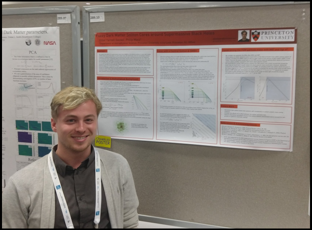
# Small-scale features of FDM

## Student work highlights

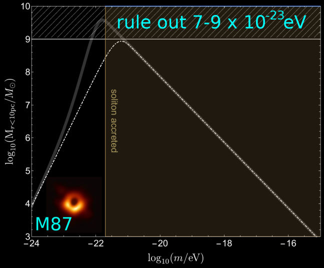
Soliton + SMBH




Elliot Davies & Mocz (2020)



- BH makes soliton more compact, $\Rightarrow$ hydrogen Bohr solution



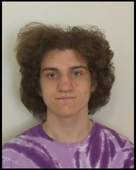

#AAS235
Honolulu, HI

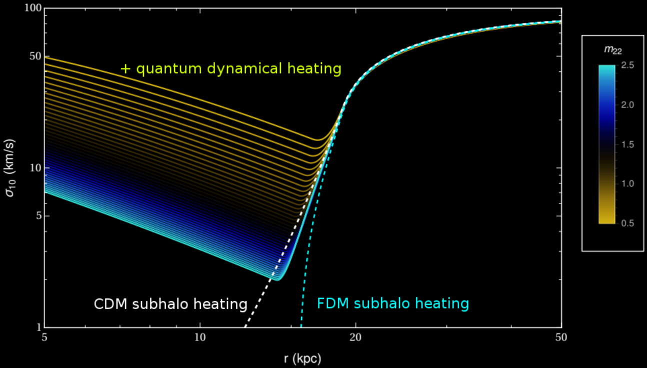
# Small-scale features of FDM

## Student work highlights

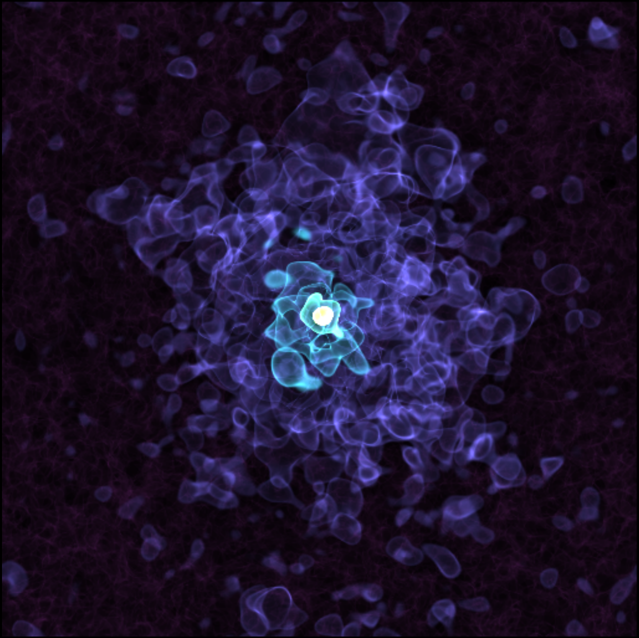
### FDM dynamical heating

Ben Church,
Mocz+ 2019






- FDM interference fluctuations heat Milky Way old stellar disk



(**Mocz** et al., 2017)

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