Ultralight dark matter, review and future extensions

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Copernicus Webinar
July, 2024

Ultra light dark matter

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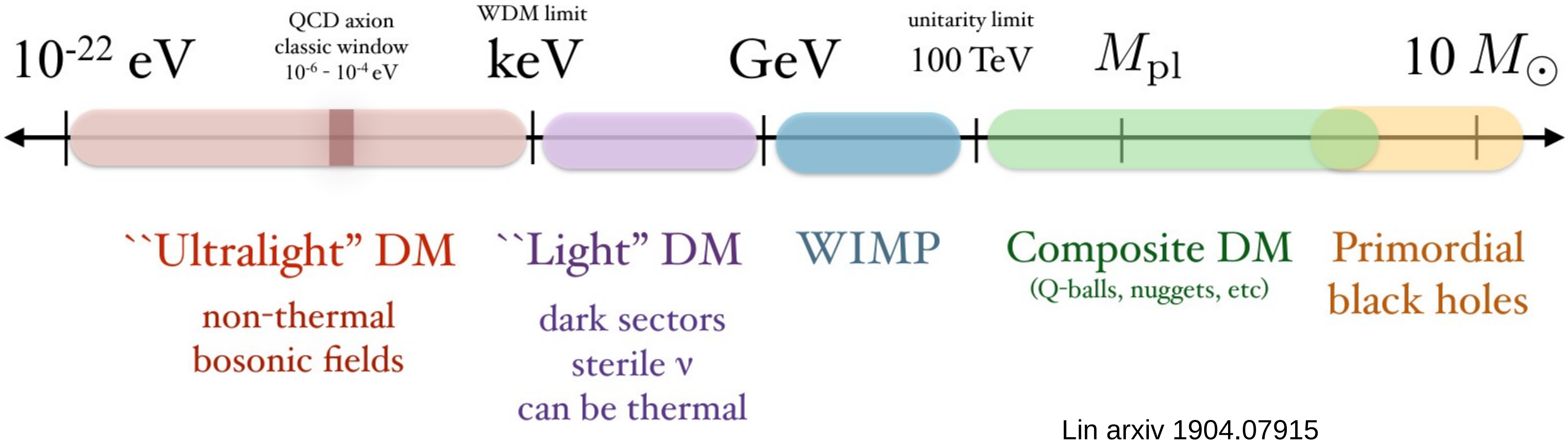
- Ultralight/Fuzzy/Scalar field/Wave/etc dark matter



Lin arxiv 1904.07915

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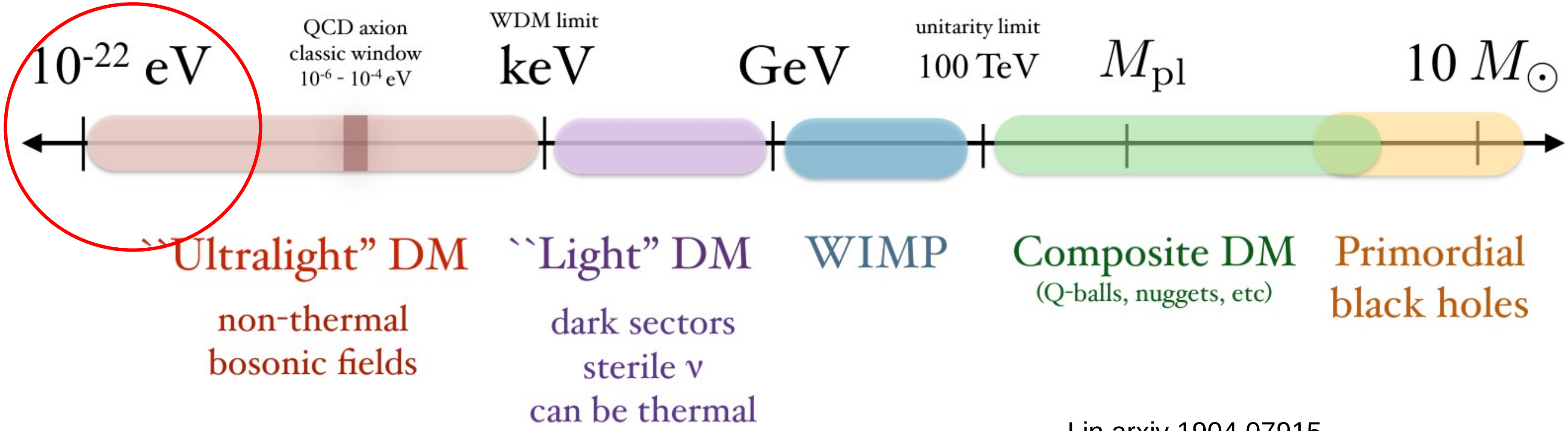

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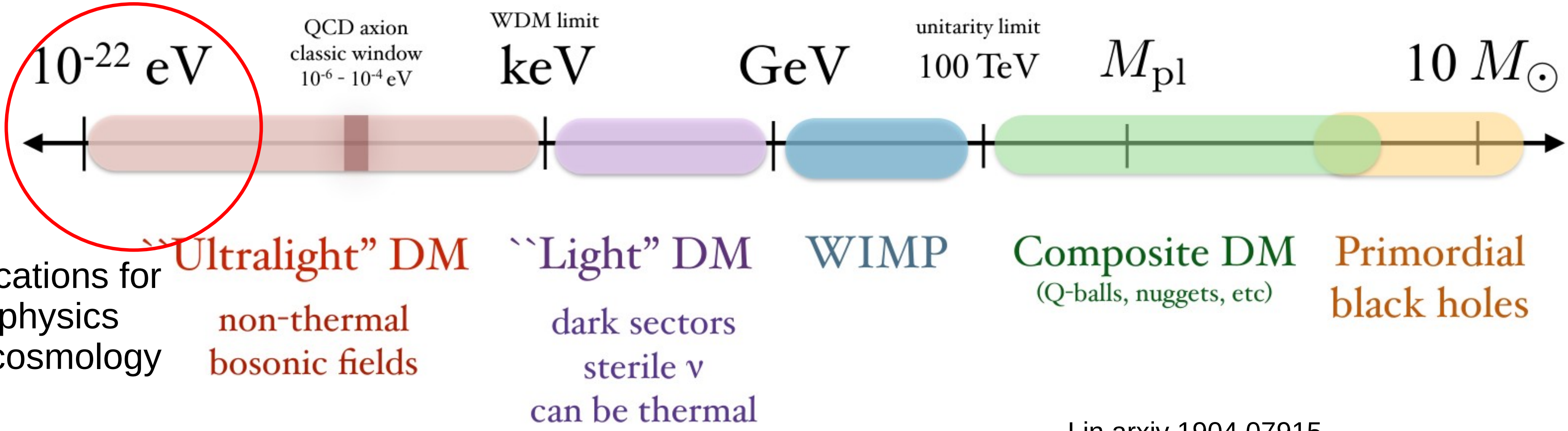

Implications for astrophysics and cosmology

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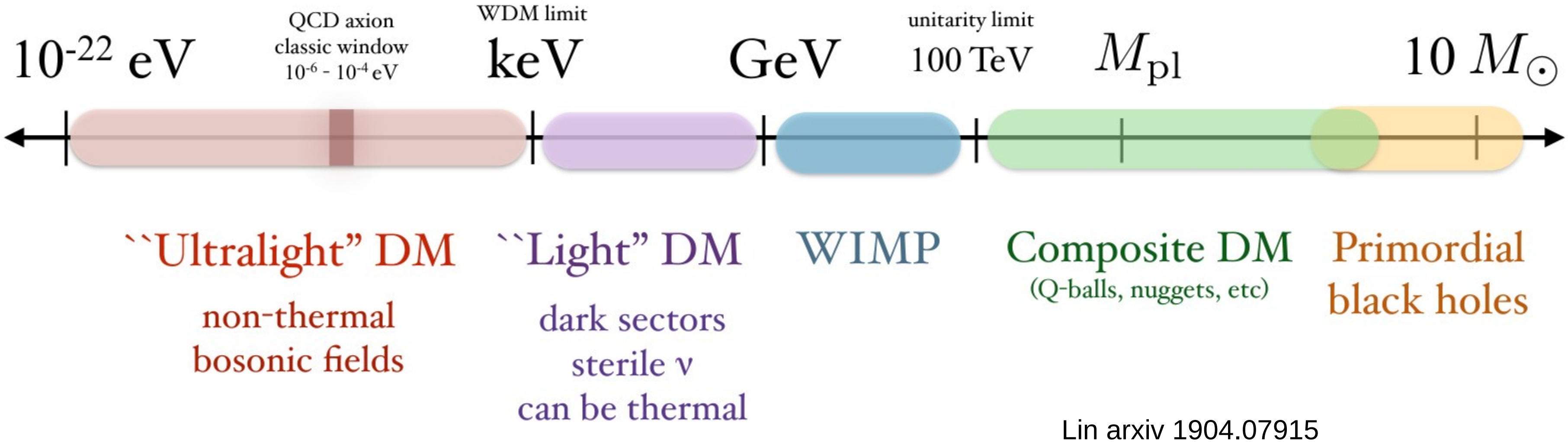
Ultra light dark matter

- Ultralight/Fuzzy/Scalar field/Wave/etc dark matter
- Ultralight fields are a generic prediction of string theory



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Ultra light dark matter

- Ultralight/Fuzzy/Scalar field/Wave/etc dark matter
- Ultralight fields are a generic prediction of string theory
- Model in which we describe the dark matter a single, spin-zero, non-relativistic, classical field

$$\partial_t \psi(x) = \frac{-i}{\hbar}\left(-\frac{\hbar^2 \nabla^2}{2m} + mV(x)\right)\psi(x)$$

$$\nabla^2 V(x) = 4\pi G\, m\, |\psi(x)|^2$$

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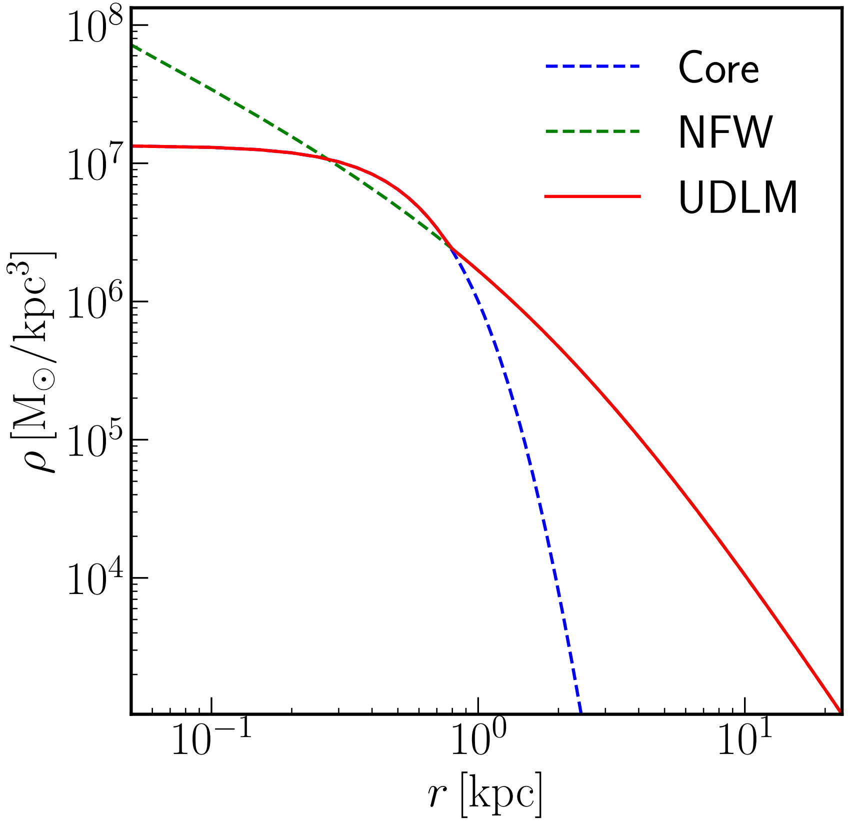
Ultra light dark matter

- Originally motivated by the core-cusp problem and other small scale structure problems
  - core/cusp



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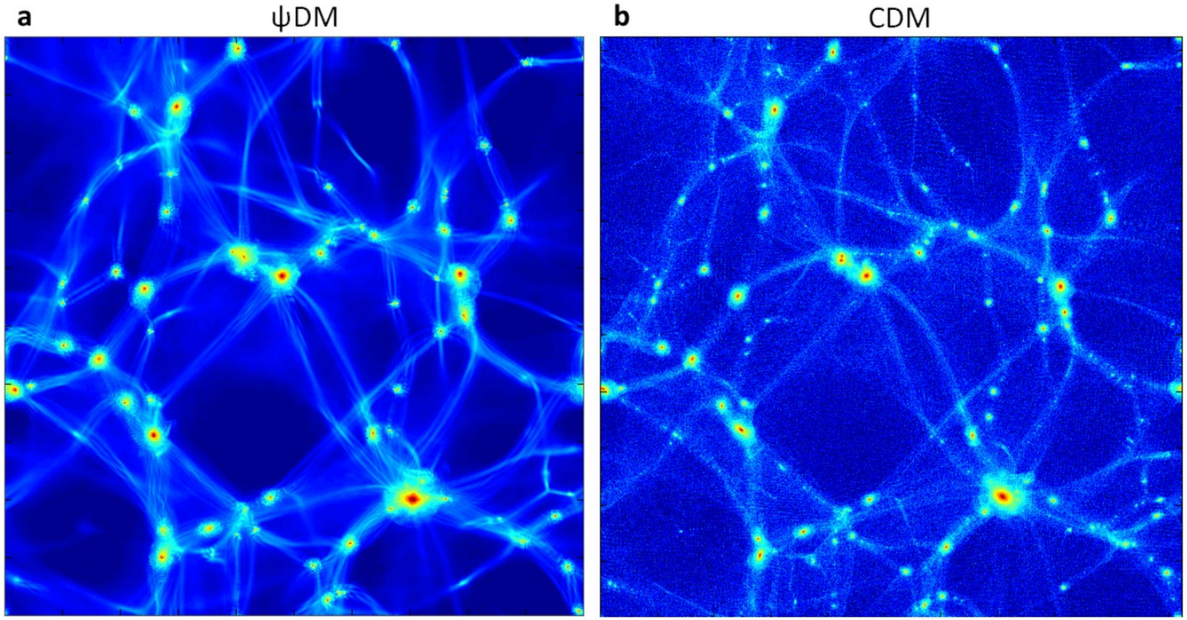
  - missing satellites

Schive et al (Nature 2014)



Ultra light dark matter

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  - core/cusp
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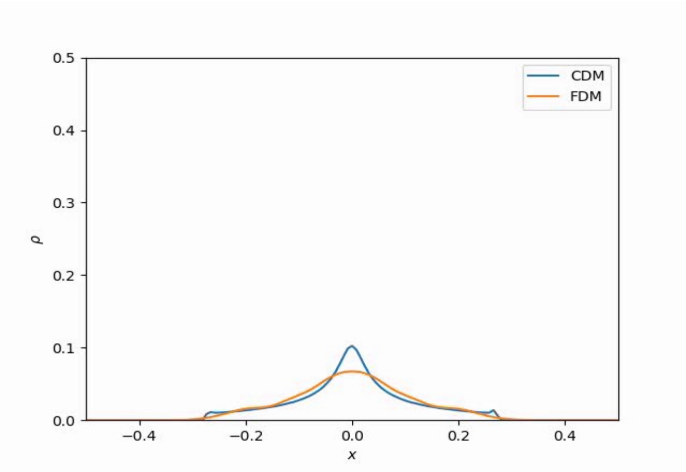
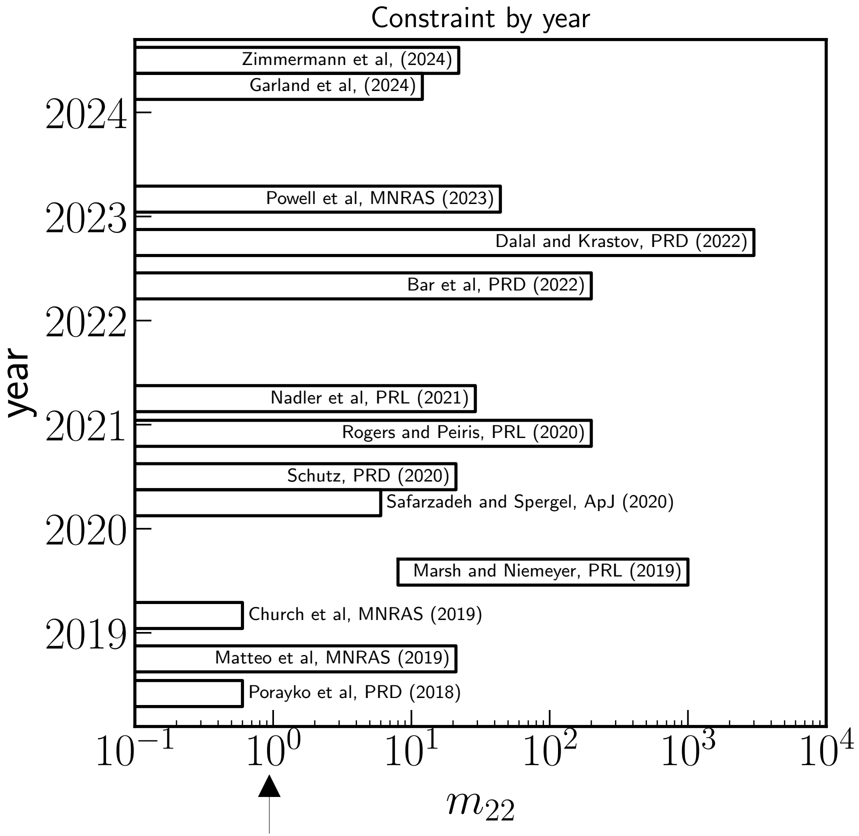
$$m \sim 10^{-22}\,\mathrm{eV}$$



Gravitational collapse in 1D

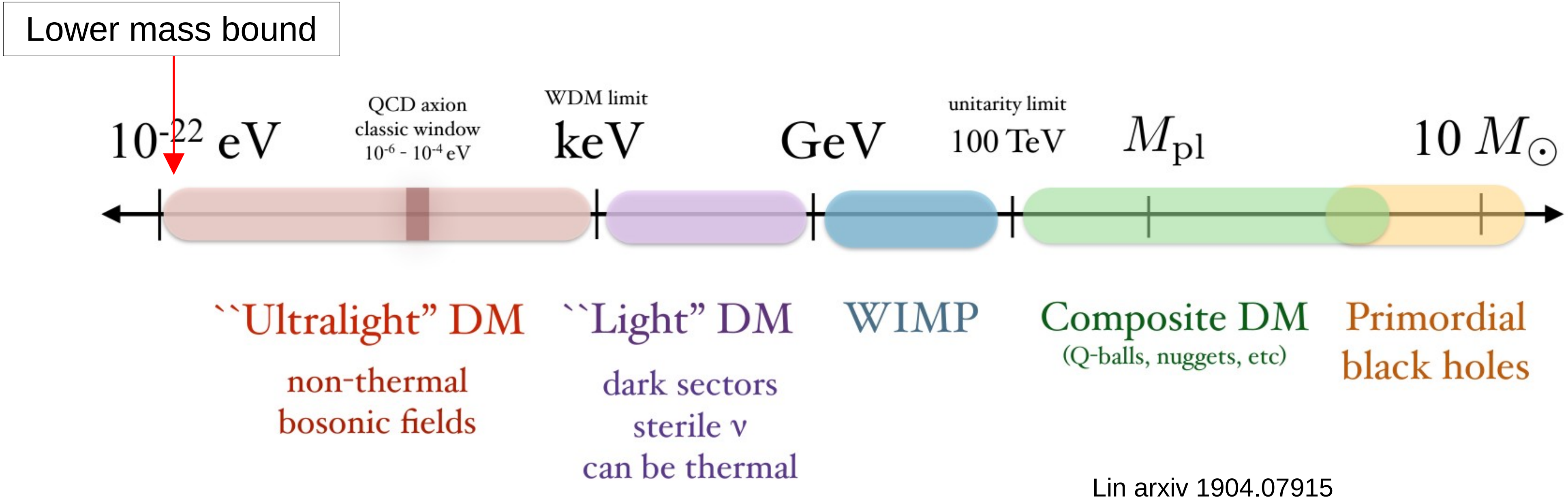
Ultra light dark matter

- Historically this mass range has received a lot of attention



Ultra light dark matter

- Recent work focuses more on putting a lower bound on the dark matter mass



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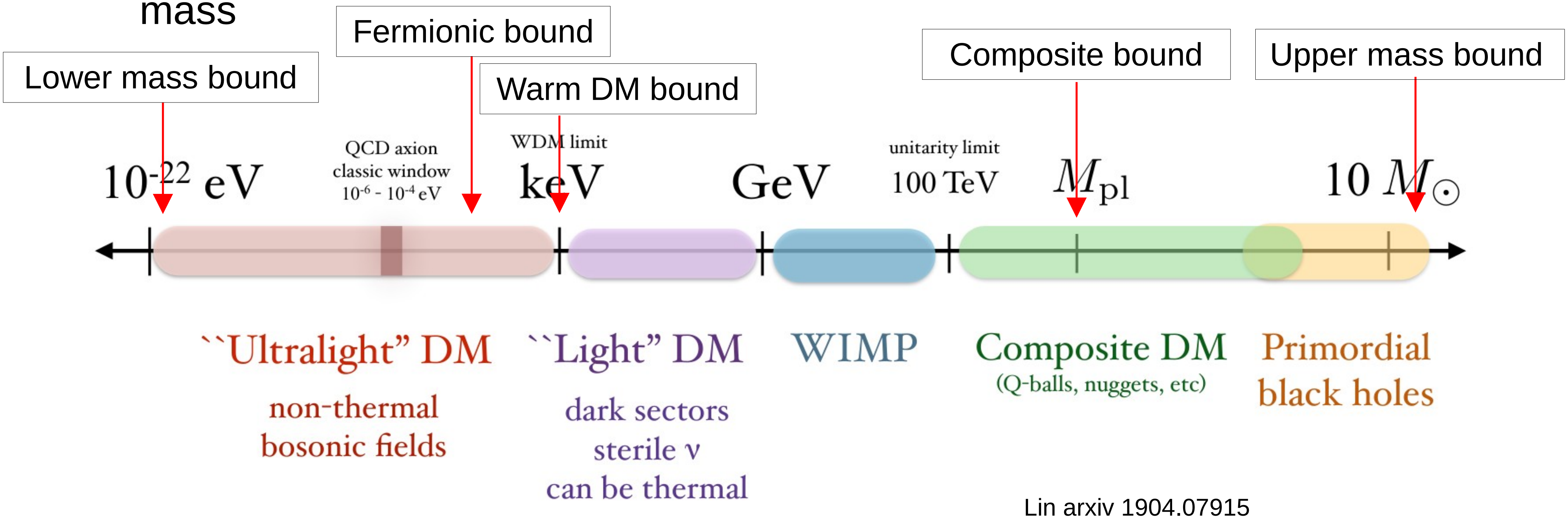

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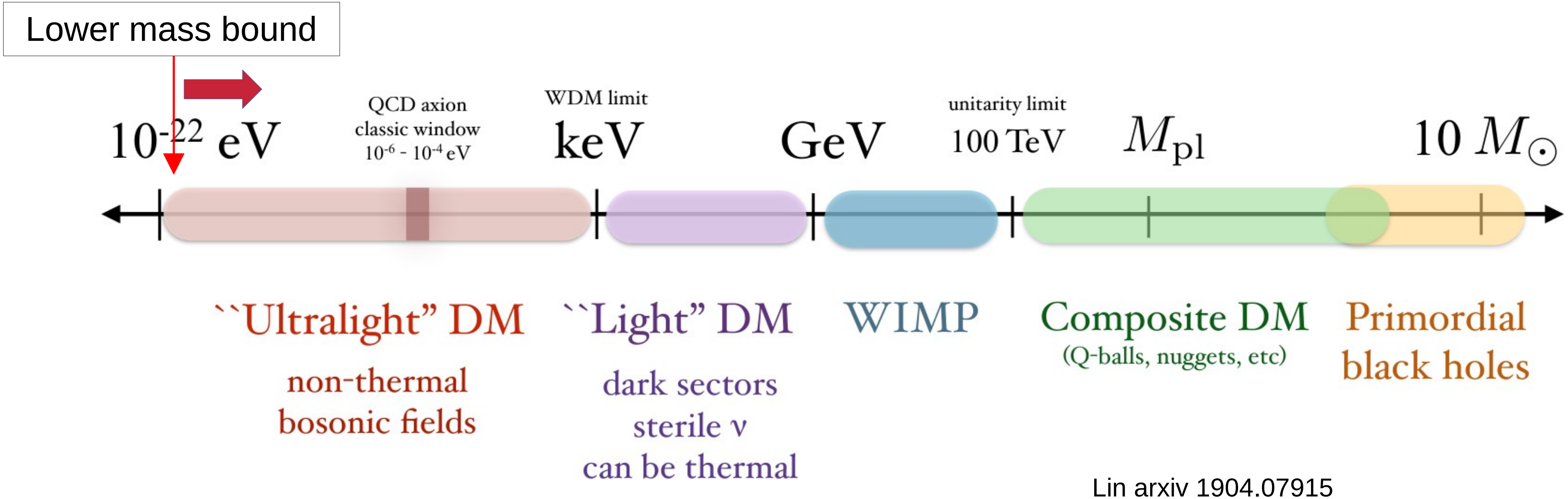

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Ultra light dark matter

- Recent work focuses more on putting a lower bound on the dark matter mass
- Limit the scope of this review to work on ultralight (fuzzy) dark matter with implications for structure   Hui, Annu. Rev. Astron. Astrophys (2021)

Ultra light dark matter

- Recent work focuses more on putting a lower bound on the dark matter mass
- Limit the scope of this review to work on ultralight (fuzzy) dark matter with implications for structure Hui, Annu. Rev. Astron. Astrophys (2021)
- Not include but still very interesting and important:
  - Ultraultra light dark matter (below 1e-22 eV) Ferreira, Astro and Astroph Review (2021)
  - Black hole SR (above 1e-19 eV) Arvanitaki and Dubovsky, PRD 2011 Stott and Marsh, PRD (2018)
  - Ultralight dark matter with non gravitational interactions with the standard model

Pheno

Pheno

- “Quantum” pressure

$$e^{\gamma t}$$

$$\gamma^2 = 4\pi G\rho - (k^2/2m)^2$$

$$r_J = \pi^{3/4}(G\rho)^{-1/4}m^{-1/2}$$

Hu et al., PRL (2000)

Pheno

- "Quantum" pressure

Gravitational timescale — Field oscillation timescale

$$e^{\gamma t}$$

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Pheno

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$$e^{\gamma t}$$

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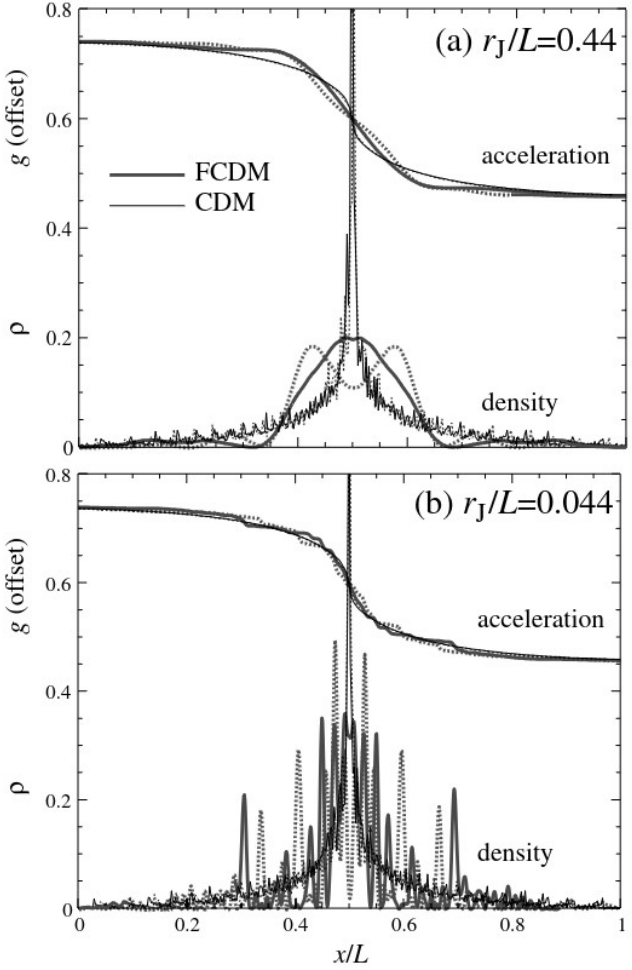
Scale dependent growth →

$$r_J = \pi^{3/4}(G\rho)^{-1/4}m^{-1/2}$$

Hu et al., PRL (2000)

Pheno

- “Quantum” pressure



Hu et al., PRL (2000)

Pheno

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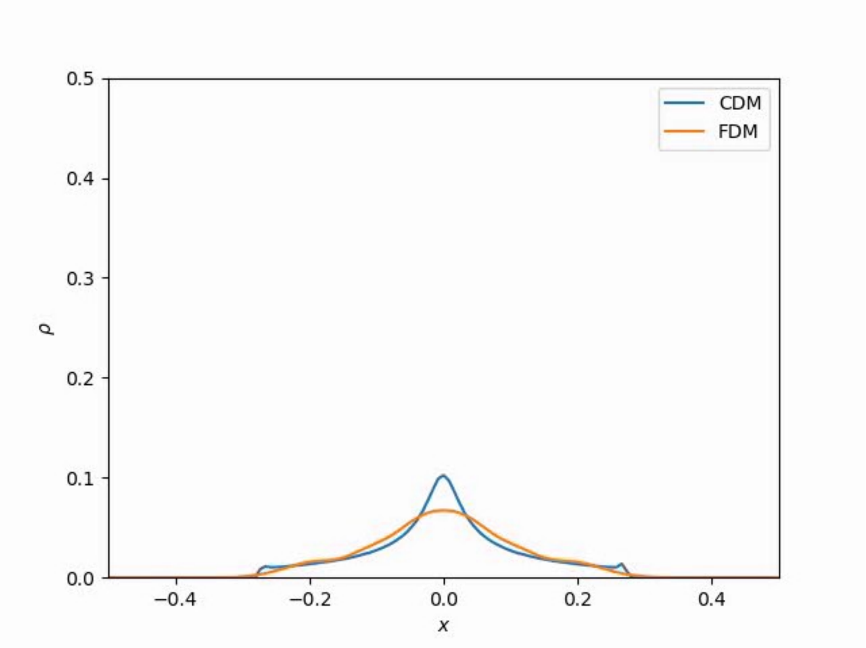

Pheno

- “Quantum” pressure

$$x = 1.61\, m_{22}^{1/18} k/k_{J\mathrm{eq}}$$

$$k_{J\mathrm{eq}} = 9\, m_{22}^{1/2}\,\mathrm{Mpc}^{-1}$$

$$T_{\mathrm{F}}(k) \approx \frac{\cos x^3}{1+x^8}$$

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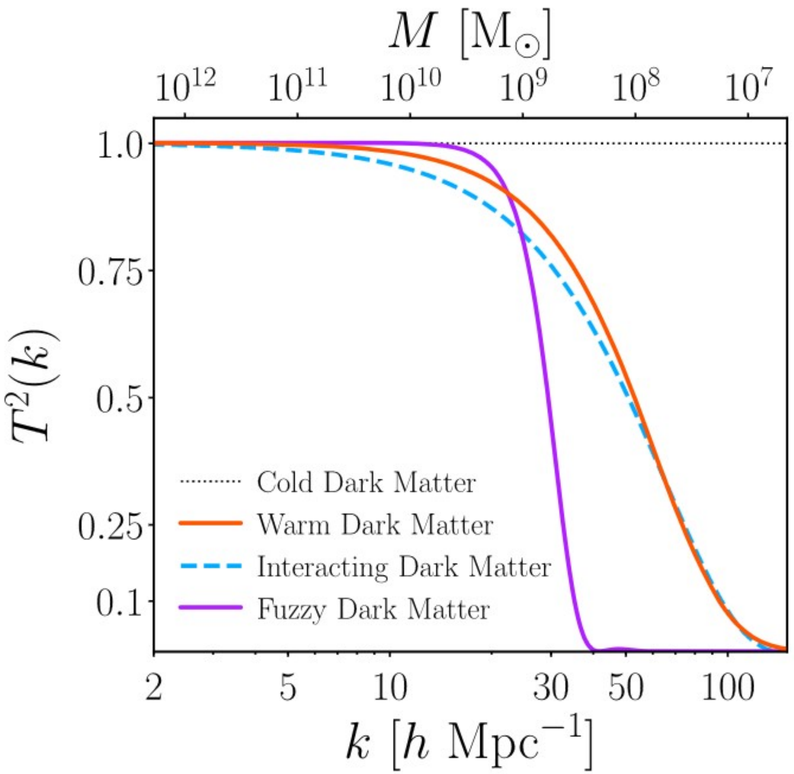
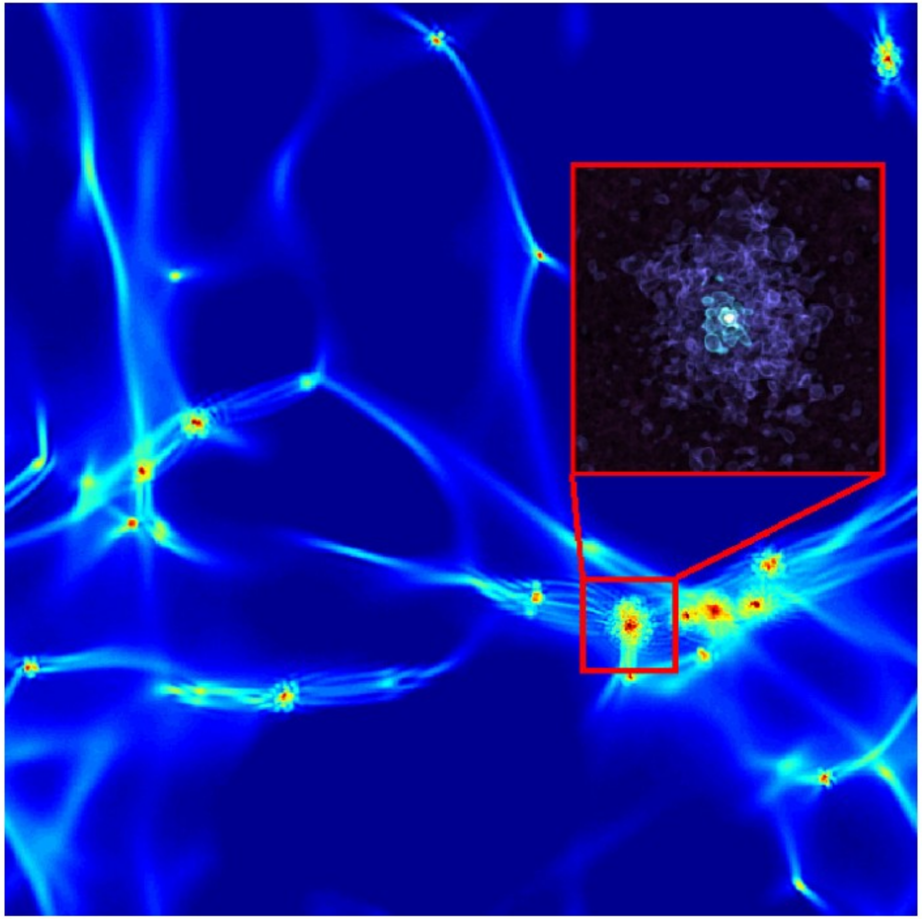


Nadler et al, PRL (2021)

Pheno

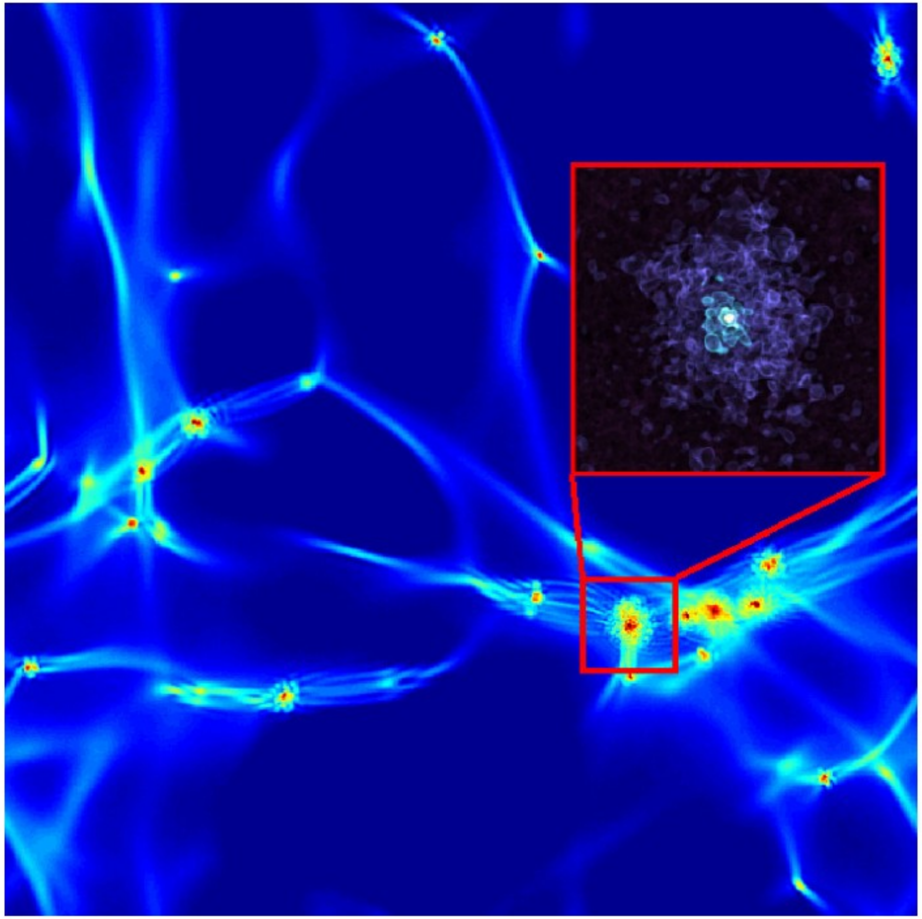
- “Quantum” pressure
- Solitons



Mocz et al., MNRAS (2017)

Pheno

- “Quantum” pressure
- Solitons
  - At the center of fdm halos



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- "Quantum" pressure
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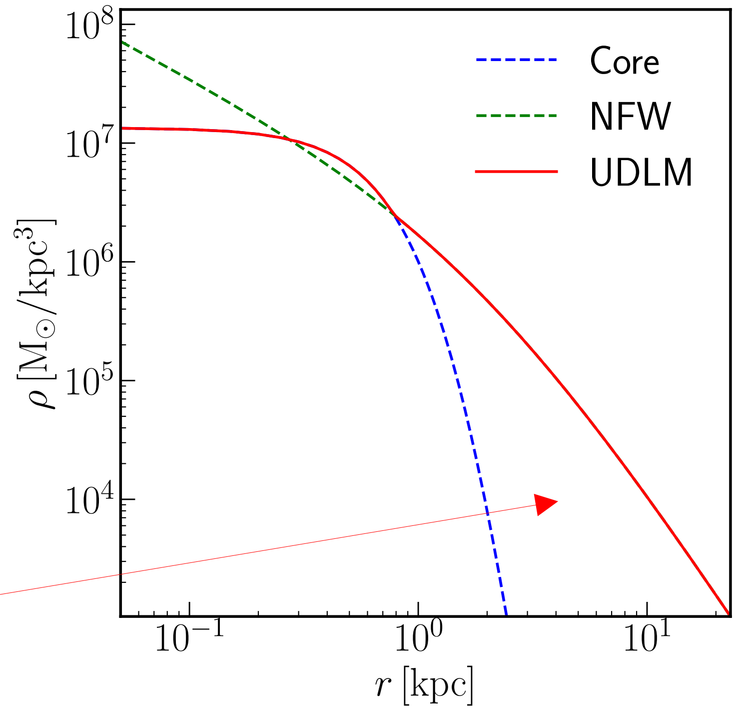
  - Ground state of the halo potential



$$\left(-\frac{\hbar^2}{2m_i}\nabla_r^2 + m_i V(r) + \frac{\hbar^2}{2m}\frac{(l+l)l}{r^2}\right)\phi_n(r) = E_n\phi_n(r)$$

$$\nabla_r^2 V(r) = 4\pi G\,\rho(r)$$

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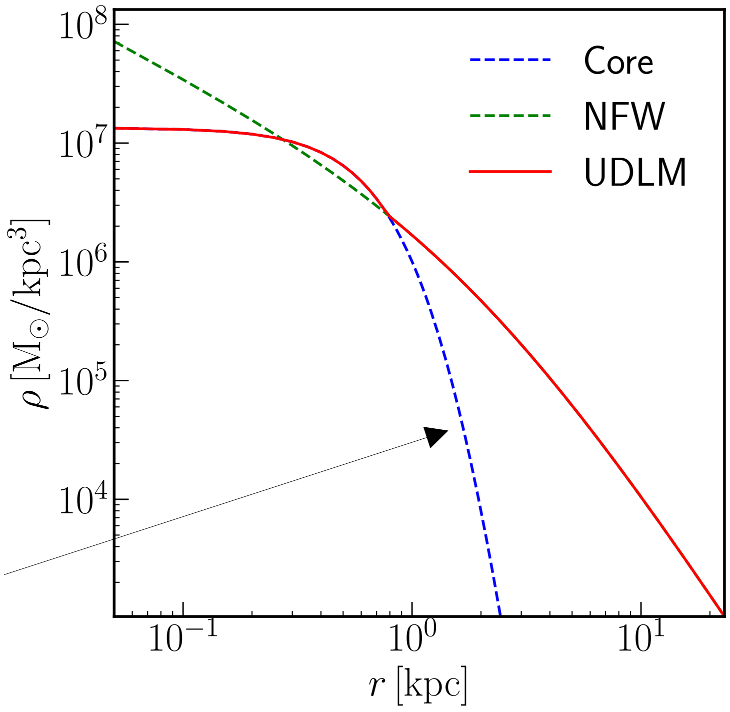

$$\left(-\frac{\hbar^2}{2m_i}\nabla_r^2 + m_i V(r) + \frac{\hbar^2}{2m}\frac{(l+l)l}{r^2}\right)\phi_0(r) = E_0\phi_0(r)$$

$$\nabla_r^2 V(r) = 4\pi G\,\rho(r)$$

Pheno

- "Quantum" pressure
- Solitons
  - At the center of fdm halos
  - Ground state of the halo potential
  - Mass and radius are the focus of a larger body of work

$$M_c \approx \frac{5.5 \times 10^9}{(m_B/10^{-23}\ \mathrm{eV})^2 (\mathrm{r_c}/\mathrm{kpc})} M_\odot .$$

$$r_c = 1.6\ m_{22}^{-1} a^{1/2} \left(\frac{\zeta(z)}{\zeta(0)}\right)^{-1/6} \left(\frac{M_h}{10^9\ M_\odot}\right)^{-1/3}\ \mathrm{kpc}.$$

Schive et al, Nature (2014)

Schive et al, PRL (2014)

Pheno

- “Quantum” pressure
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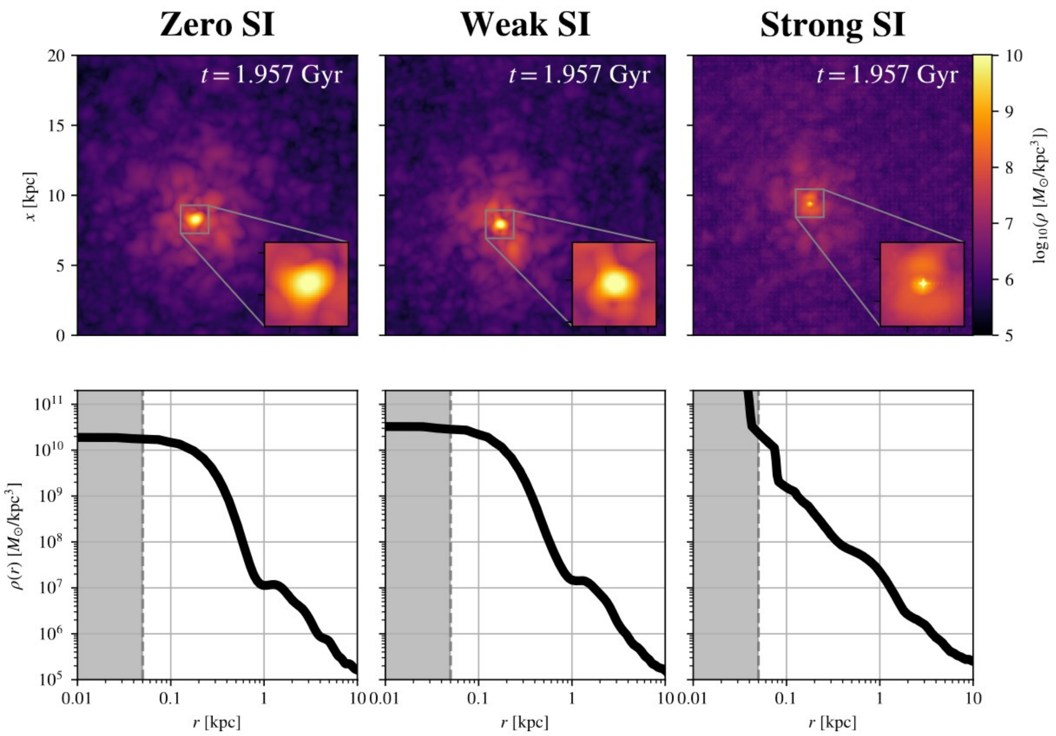
  - At the center of fdm halos
  - Ground state of the halo potential
  - Mass and radius are the focus of a larger body of work
  - Extended work also focuses on the impact on solitons

Self interactions



Painter et al, MNRAS (2023)

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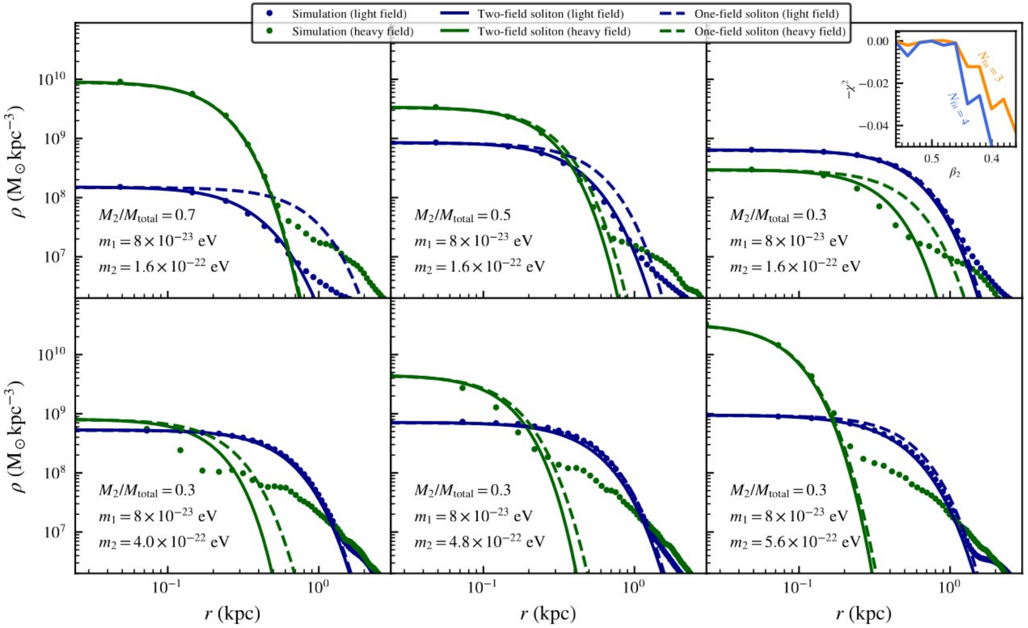
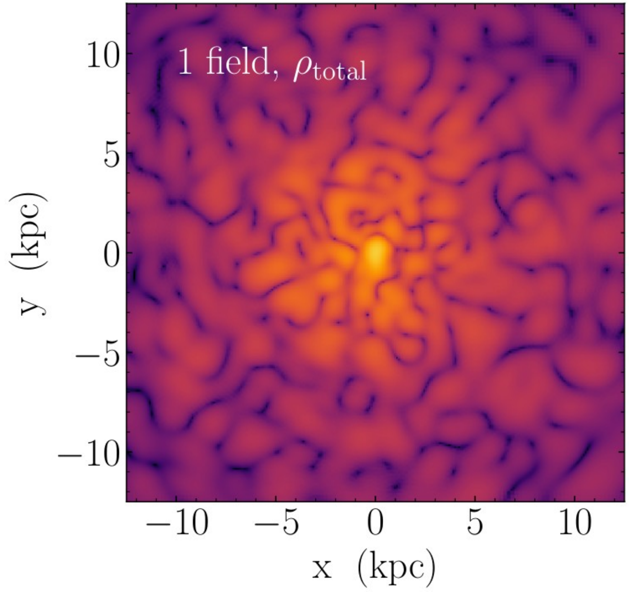
Multi-field



Luu et al, MNRAS (2024)

Pheno

- "Quantum" pressure
- Solitons
- Density granules
  - Halos exhibit ~O(1) fluctuations in the density



Gosenca [, Eberhardt] et al., PRD (2023)

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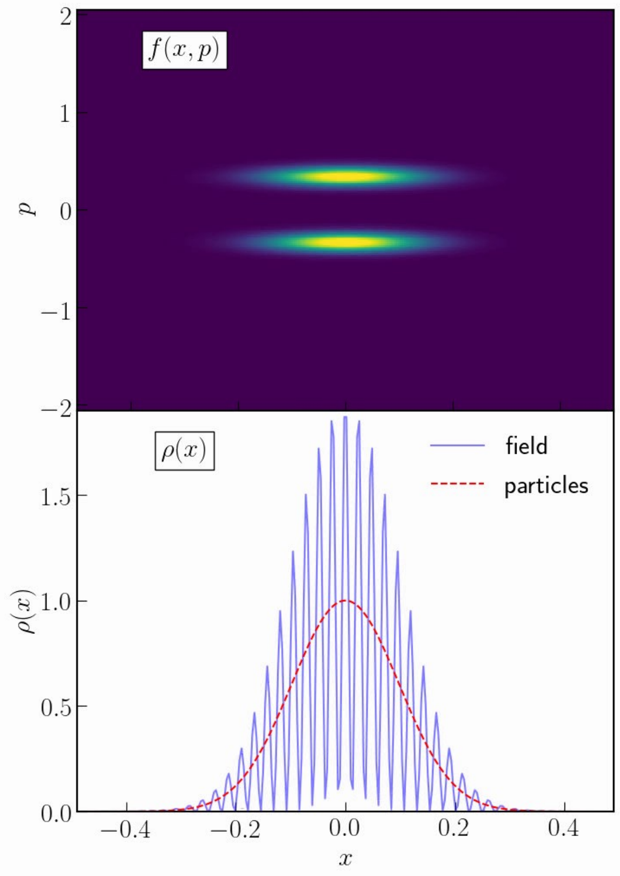

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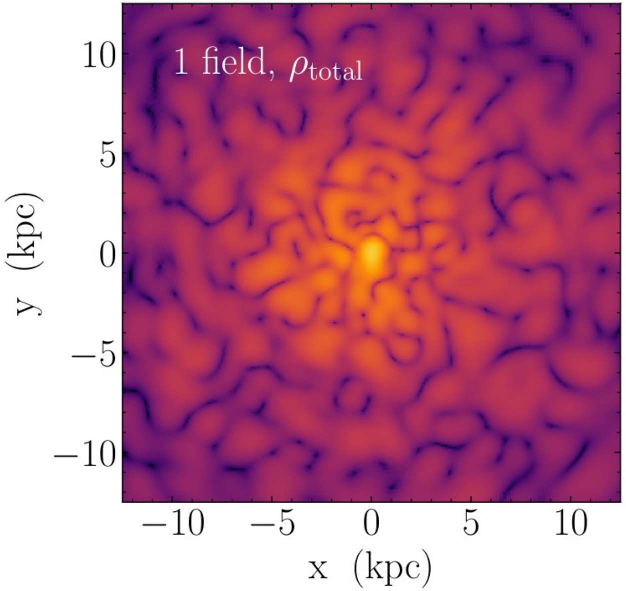

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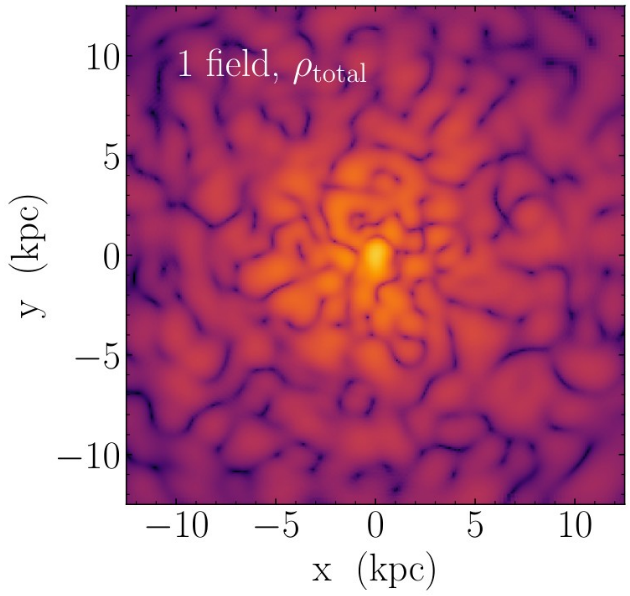

$$\psi(t) = \sum_n w_n \, e^{-i\,E_n\,t} \phi_n$$

Pheno

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  - Interfere moment
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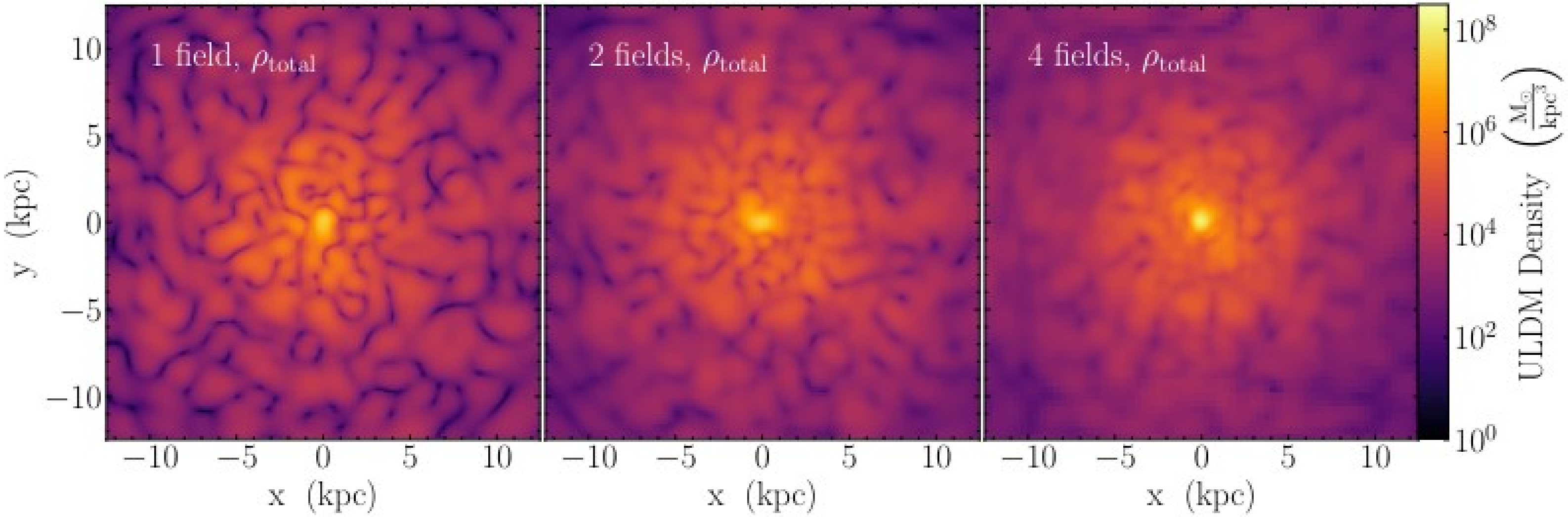
  - Granules have been another focus of extended work

Multifield



Gosenca [, Eberhardt] et al., PRD (2023)

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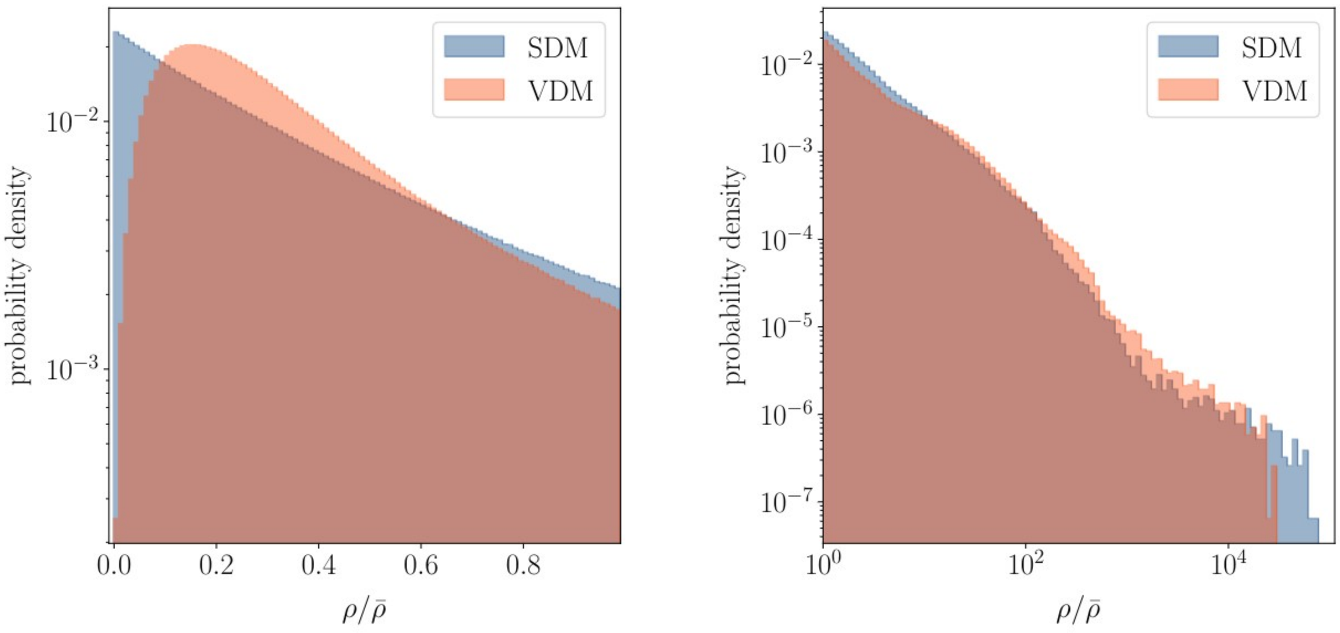
  - Halos exhibit ~O(1) f density
  - Interference betweer momentum streams i
  - Higher energy mode: granules
  - Granules have been extended work

Vector



Amin et al, JCAP (2022)

Pheno

- “Quantum” pressure
- Solitons
- Density granules
- Relativistic pressure

$$\Psi(\mathbf{x},t) \simeq \Psi_0(\mathbf{x}) + \Psi_c(\mathbf{x})\cos\left(\omega t + 2\alpha(\mathbf{x})\right)$$

$$\Psi_c(\mathbf{x}) = \frac{1}{2}\pi G A(\mathbf{x})^2 = \pi \frac{G\rho_{\rm DM}(\mathbf{x})}{m^2}$$

Khmelnitsky and Rubakov, JCAP (2014)

Pheno

- "Quantum" pressure
- Solitons
- Density granules
- Relativistic pressure

$$\tau_c \sim \hbar/mc^2$$

$$\lambda_c \sim \hbar/mc$$

$$\Phi = \Phi_0 + \Phi_c$$

$$\Phi_c \sim \frac{v^2}{c^2}\Phi_0$$

$$\Psi(\mathbf{x},t) \simeq \Psi_0(\mathbf{x}) + \Psi_c(\mathbf{x})\cos\left(\omega t + 2\alpha(\mathbf{x})\right)$$

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Numerics

Numerics

- N-body simulations with altered transfer function

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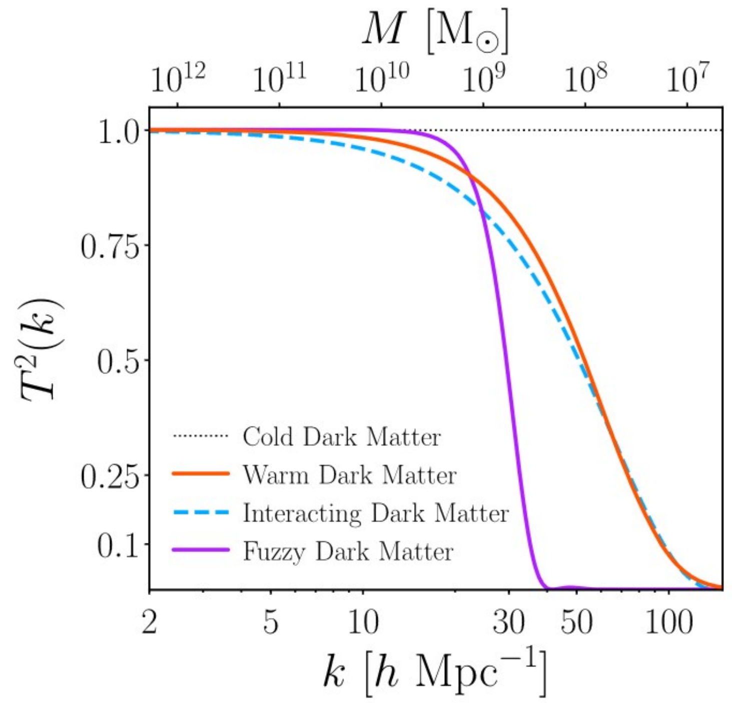

Nadler et al, PRL (2021)

Numerics

- N-body simulations with altered transfer function
- Eigenvalue decomposition methods

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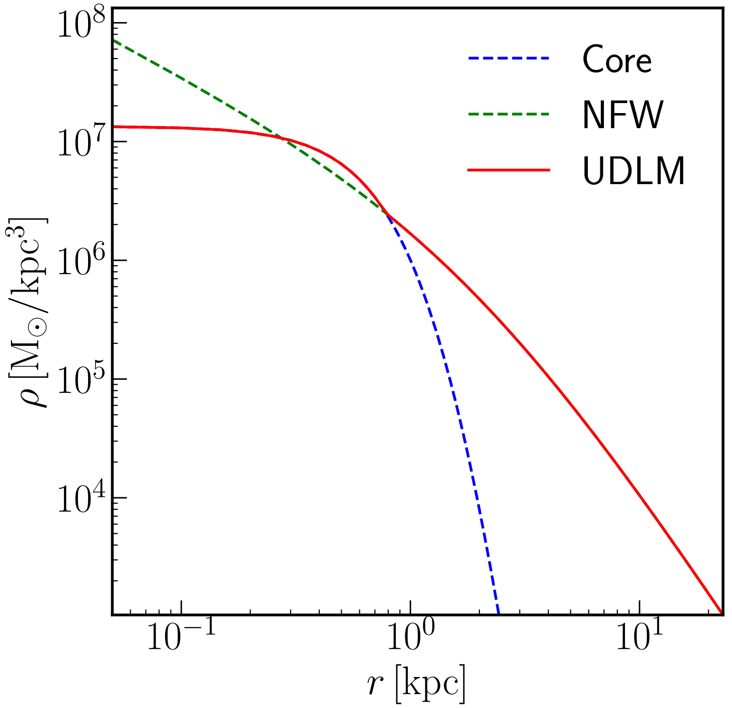

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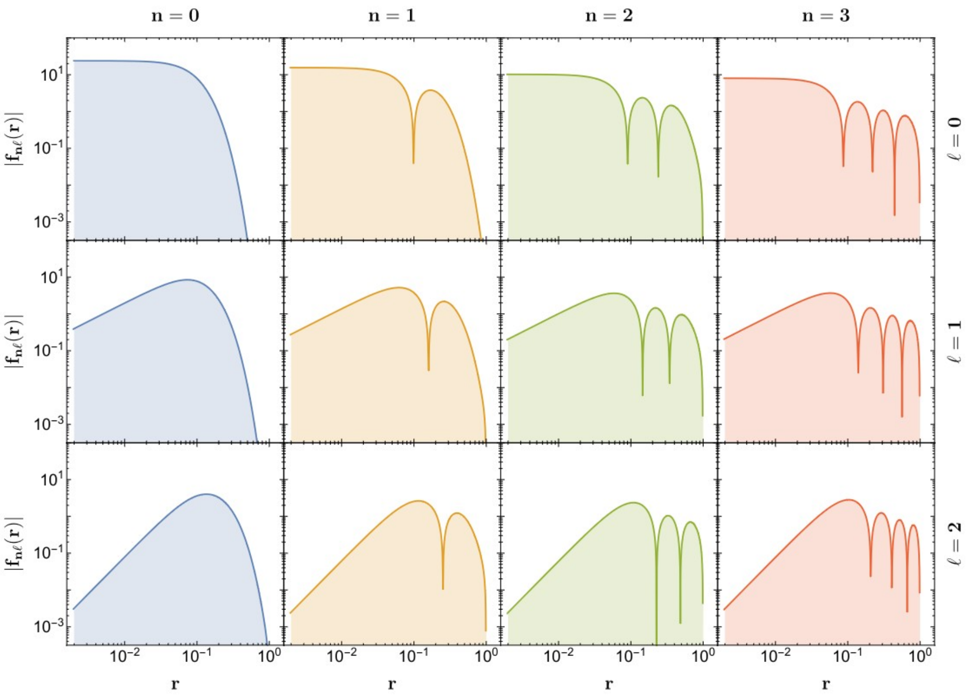
Numerics

- N-body simulations with altered transfer function
- Eigenvalue decomposition methods
  - Solve eigenvalue problem of Hamiltonian

Zagorac et al., PRD (2022)



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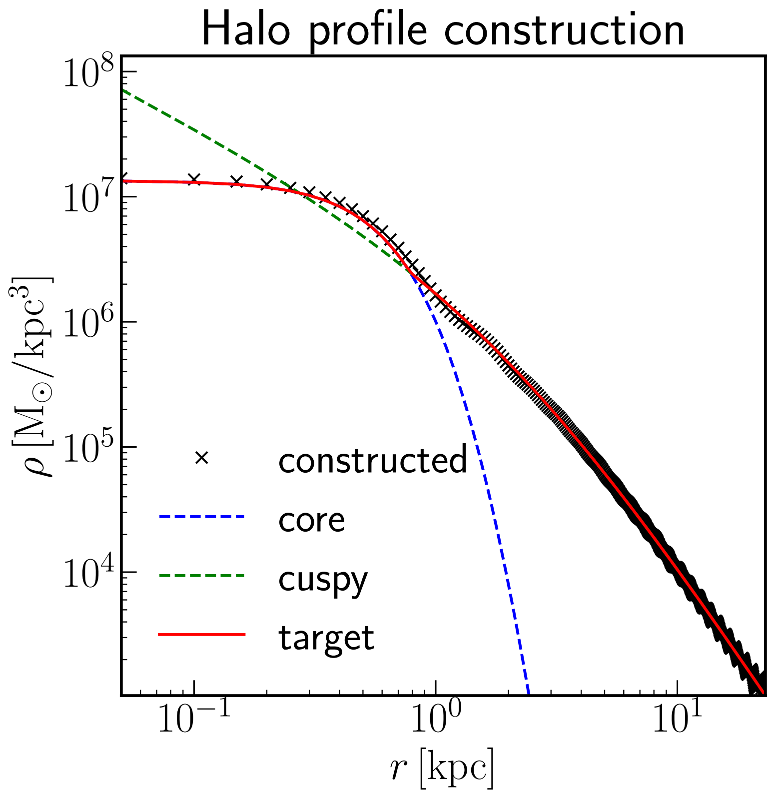
Numerics

- N-body simulations with altered transfer function
- Eigenvalue decomposition methods
  - Solve eigenvalue problem of Hamiltonian
  - Solve for weights in eigenvalue sum

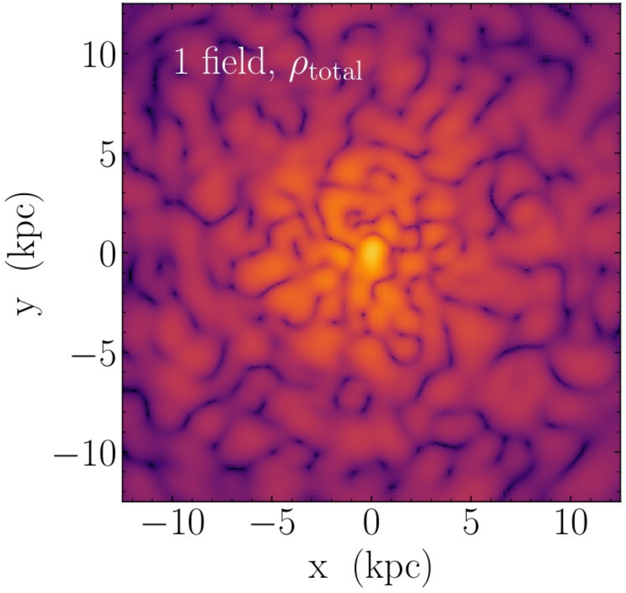


$$\psi(r,\theta,\varphi) = \sum_{l}^{l_{max}} \sum_{m=-l}^{l} \sum_{n}^{e_{max}} w_j\, Y_l^m(\theta,\varphi)\, \phi_n^l(r)\, e^{-i\,\omega_{lmj}}$$

Numerics

Gosenca [, Eberhardt] et al., PRD (2023)

- N-body simulations with altered transfer function
- Eigenvalue decomposition methods
  - Solve eigenvalue problem of Hamiltonian
  - Solve for weights in eigenvalue sum
  - Sum eigenvectors with random phase



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Numerics

- N-body simulations with altered transfer function
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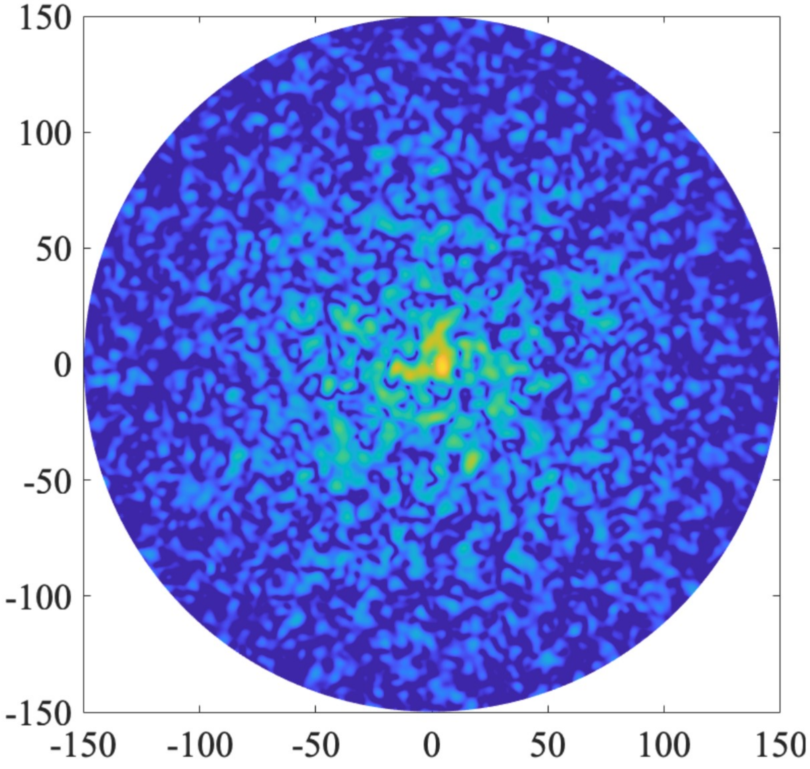
  - Sum can be used for approximate simulations

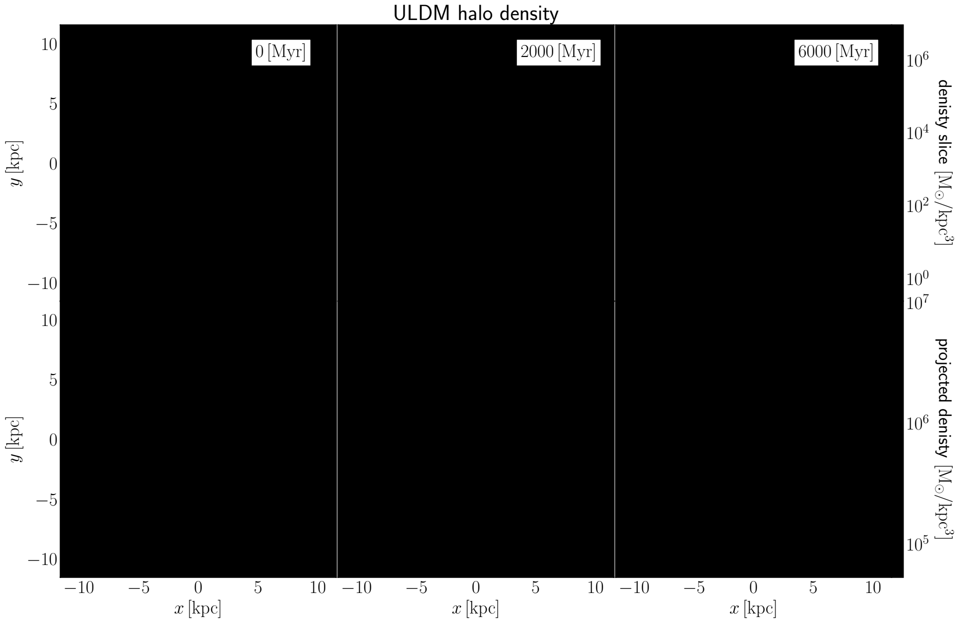
$$\psi(t) = \sum_n w_n \, e^{-i\,E_n\,t} \phi_n$$



Dalal and Krastov, PRD (2022)

Numerics

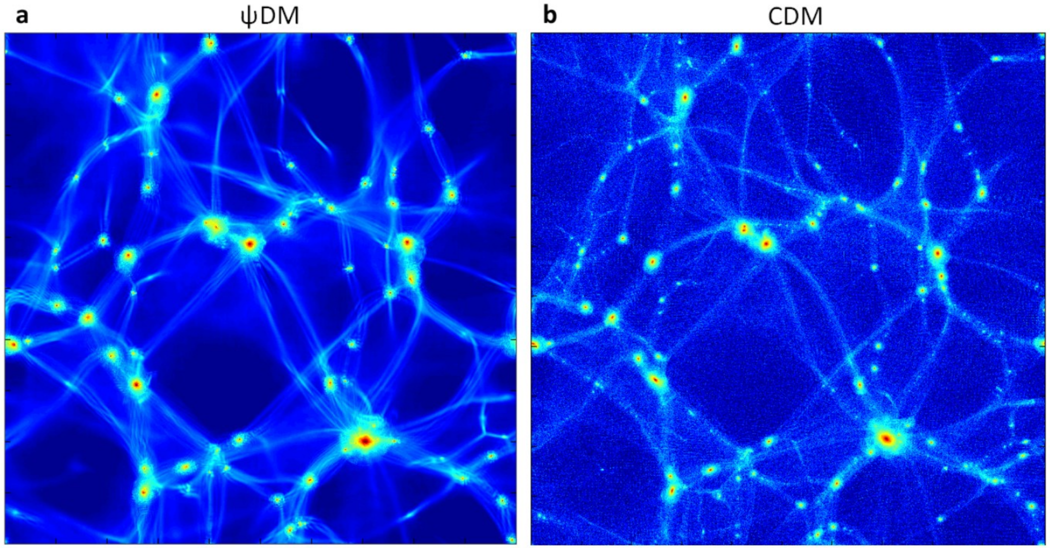
- N-body simulations with altered transfer function
- Eigenvalue decomposition methods
  - Solve eigenvalue problem of Hamiltonian
  - Solve for weights in eigenvalue sum
  - Sum eigenvectors with random phase
  - Sum can be used for approximate simulations
  - Can give initial conditions for full simulations



Numerics

- N-body simulations with altered transfer function
- Eigenvalue decomposition methods
- Full nonlinear simulations

Schive et al (Nature 2014)



Full field simulations

Full field simulations

- Fixed and dynamic resolution simulations exist

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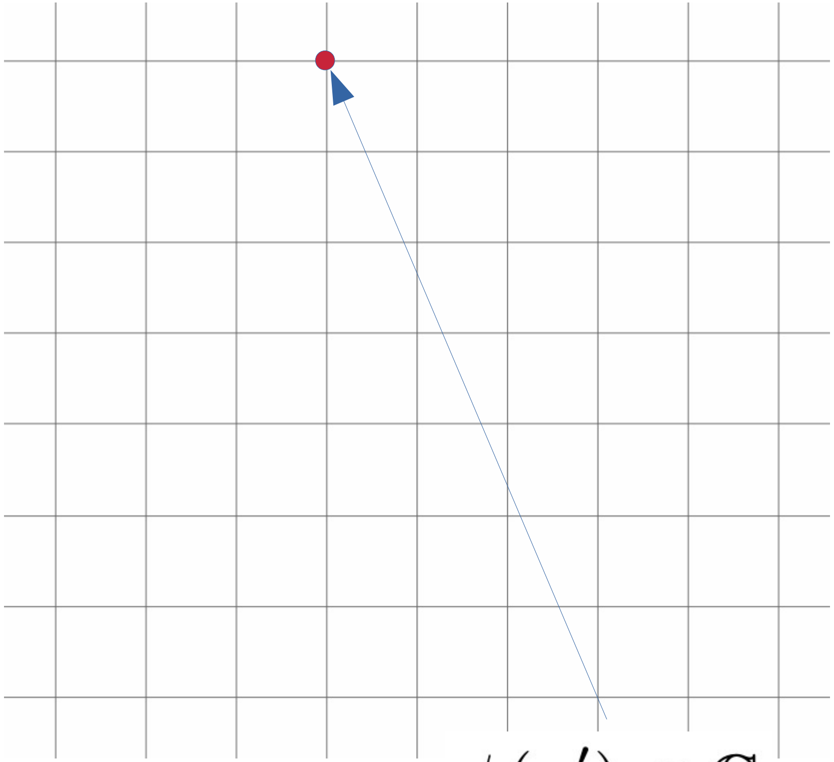
    pyUltralight

Full field simulations

- Complex field on a grid

$$\psi(x) = A(x)\, e^{i\phi(x)}$$



$\psi(x') \in \mathbb{C}$

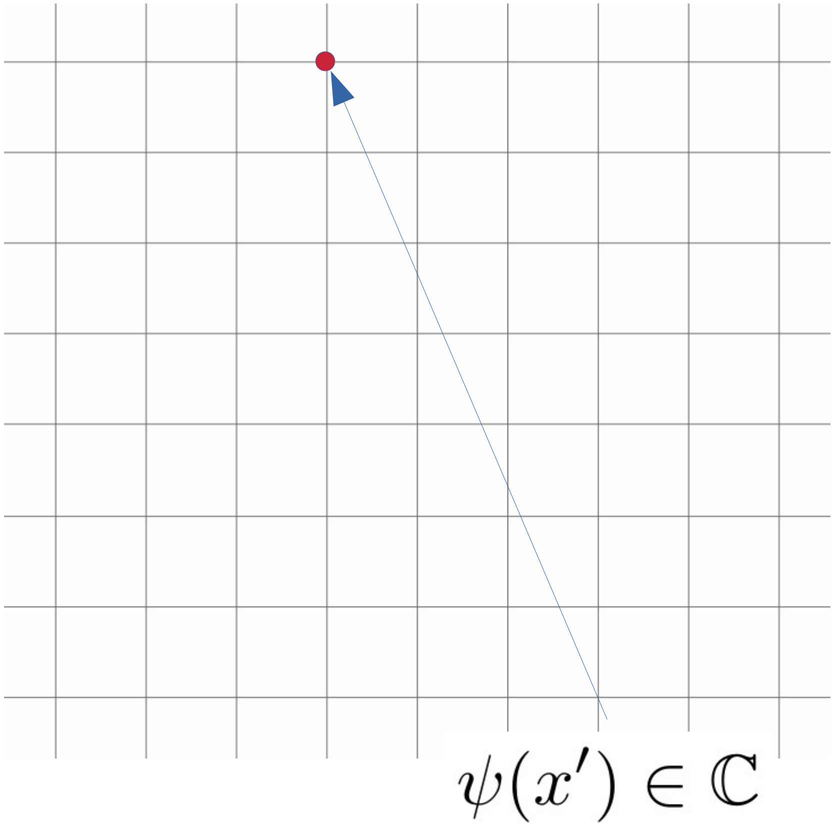
Full field simulations

- Complex field on a grid
- Amplitude and phase have information about spatial density and velocity

$$\psi(x) = A(x)\, e^{i\phi(x)}$$

$$\rho(x) = |A(x)|^2$$

$$v(x) = \frac{\hbar}{m} \nabla \phi(x)$$



Full field simulations

$$\partial_t \psi(x,t) = \frac{-i}{\hbar}\left(\frac{\hat{p}^2}{2m} + mV\right)\psi(x,t)$$

- Complex field on a grid
- Amplitude and phase have information about spatial density and velocity
- Update the field using unitary operators in kick-drift-kick scheme

Full field simulations

- Complex field on a grid
- Amplitude and phase have information about spatial density and velocity
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↓

$$\psi(x,t) = e^{-i\left(\frac{\hat{p}^2}{2m}+mV\right)t/\hbar}\psi(t=0)$$

Full field simulations

- Complex field on a grid
- Amplitude and phase have information about spatial density and velocity
- Update the field using unitary operators in kick-drift-kick scheme

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$$\psi(x,t) = e^{-i\left(\frac{\hat{p}^2}{2m} + mV\right)t/\hbar}\psi(t=0)$$

$$\psi(x, t+\Delta t/2) = e^{-imV\Delta t/2\hbar}\psi(x,t)$$

$$\psi(p, t+\Delta t) = e^{-i\frac{\hat{p}^2}{2m}\Delta t/\hbar}\psi(p)$$

$$\psi(x, t+\Delta t) = e^{-imV\Delta t/2\hbar}\psi(x, t+\Delta t/2)$$

Full field simulations

- Complex field on a grid
- Amplitude and phase have information about spatial density and velocity
- Update the field using unitary operators in kick-drift-kick scheme

$$\partial_t \psi(x,t) = \frac{-i}{\hbar}\left(\frac{\hat{p}^2}{2m} + mV\right)\psi(x,t)$$

$$\psi(x,t) = e^{-i\left(\frac{\hat{p}^2}{2m}+mV\right)t/\hbar}\psi(t=0)$$

Momentum half step

Position full step

$$\psi(x,t+\Delta t/2) = e^{-imV\Delta t/2\hbar}\psi(x,t)$$

$$\psi(p,t+\Delta t) = e^{-i\frac{\hat{p}^2}{2m}\Delta t/\hbar}\psi(p)$$

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Full field simulations

- Ultralight dark matter approaches cold dark matter on large scales

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Full field simulations

- Ultralight dark matter approaches cold dark matter on large scales

$$\psi(x, t+\Delta t/2) = e^{-imV\Delta t/2\hbar}\psi(x,t)$$

$$\psi(p, t+\Delta t) = e^{-i\frac{\hat{p}^2}{2m}\Delta t/\hbar}\psi(p)$$

$$v(x) = \frac{\hbar}{m}\nabla\phi(x)$$

$$x(p) = \hbar\nabla_p\phi(p)$$

$$\psi(x) = A(x)\, e^{i\phi(x)}$$

Full field simulations

- Ultralight dark matter approaches cold dark matter on large scales

$$\psi(x, t + \Delta t/2) = e^{-imV\Delta t/2\hbar}\psi(x,t) \qquad \psi(p, t+\Delta t) = e^{-i\frac{\hat{p}^2}{2m}\Delta t/\hbar}\psi(p)$$

$$v(x) = \frac{\hbar}{m}\nabla\phi(x)$$

$$x(p) = \hbar\nabla_p\phi(p)$$

$$\psi(x) = A(x)\,e^{i\phi(x)}$$

$$\partial_t v(x) = \frac{\hbar}{m}\nabla\partial_t\phi(x)$$

$$\partial_t v(x) = \frac{\hbar}{m}\nabla(-mV/\hbar)$$

$$\partial_t v(x) = -\nabla V$$

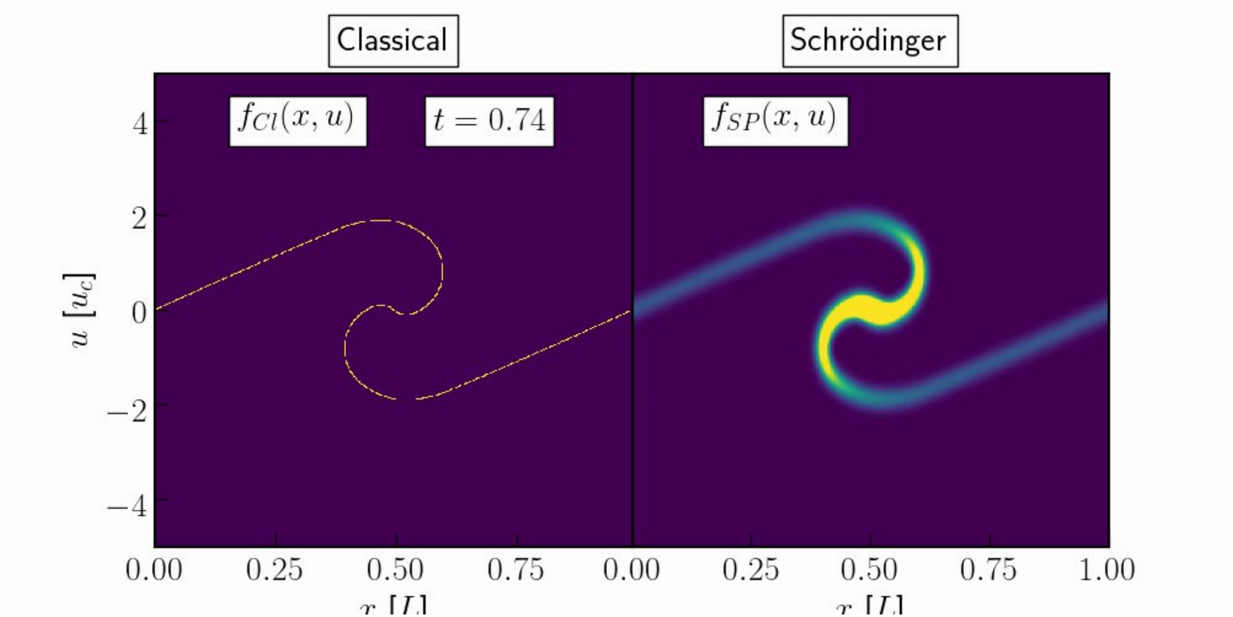
$$\partial_t x(v) = \hbar\nabla_p\partial_t\phi(p)$$

$$\partial_t x(v) = \hbar\nabla_p\frac{\hat{p}^2}{2m}/\hbar$$

$$\partial_t x(v) = \frac{p}{m} = v$$

Full field simulations

- Ultralight dark matter approaches cold dark matter on large scales



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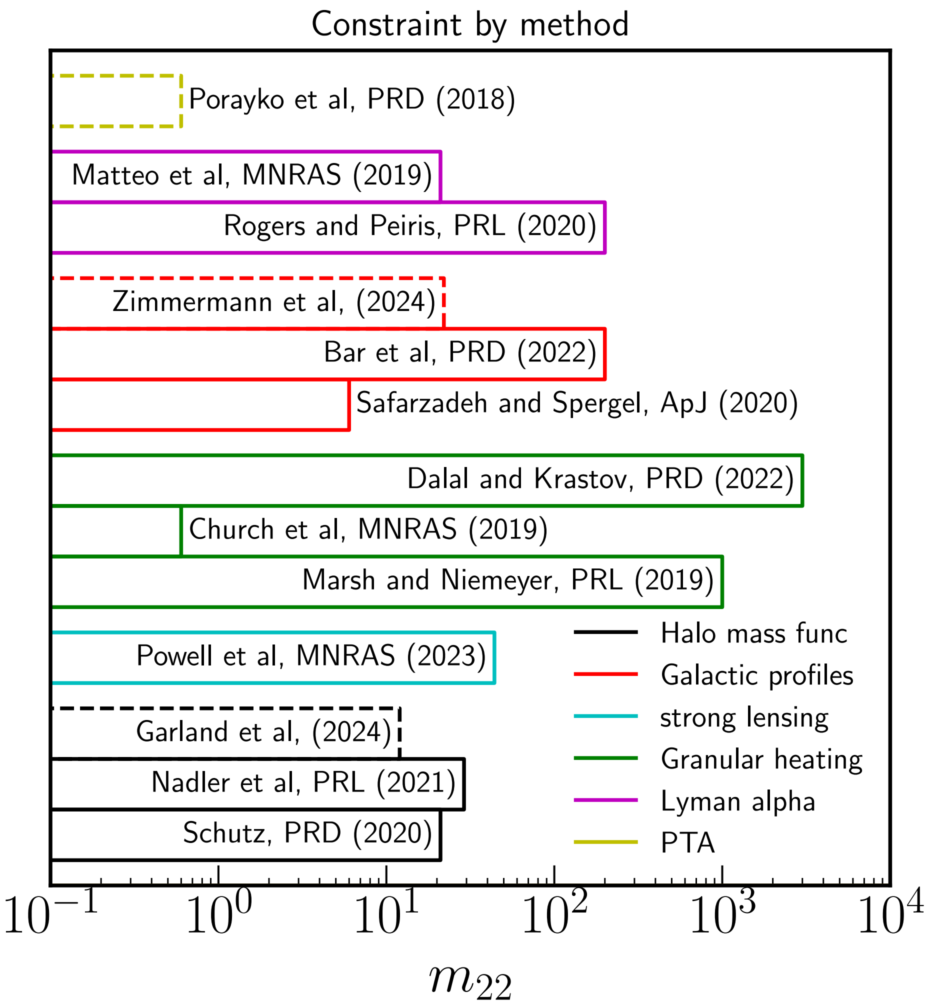


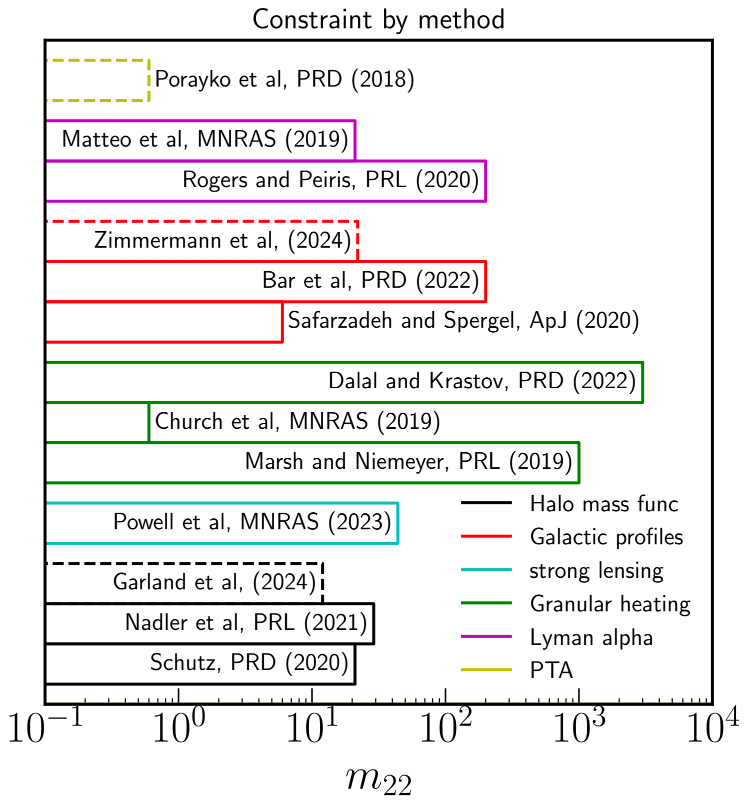
Constraints

- Halo mass functions

$m > 2.1 \times 10^{-21}$ eV **Schutz, PRD (2020)**

$m > 2.9 \times 10^{-21}$ eV **Nadler et al, PRL (2021)**

$m > 1.2 \times 10^{-21}$ eV *Garland et al, MNRAS (2024)*



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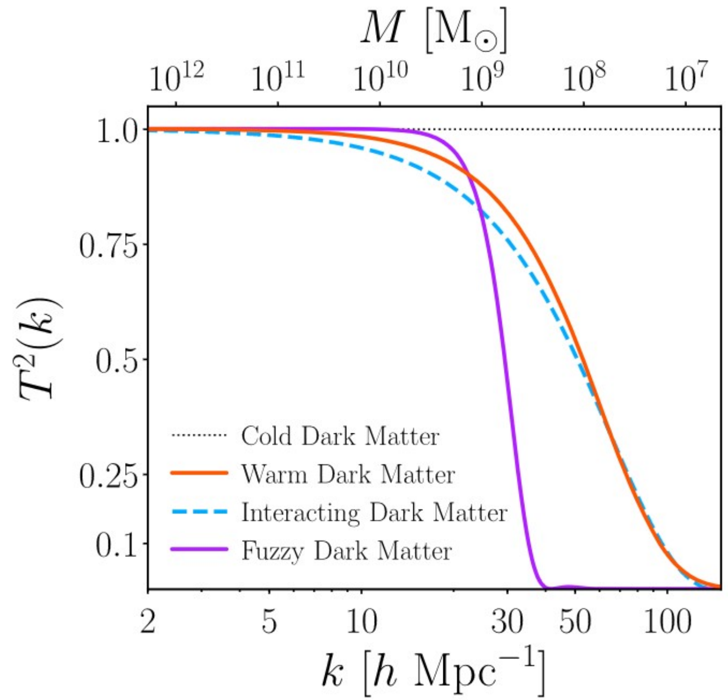
- Halo mass functions
  - Estimate halo mass function from cosmological N-body simulations with FDM transfer function



Nadler et al, PRL (2021)

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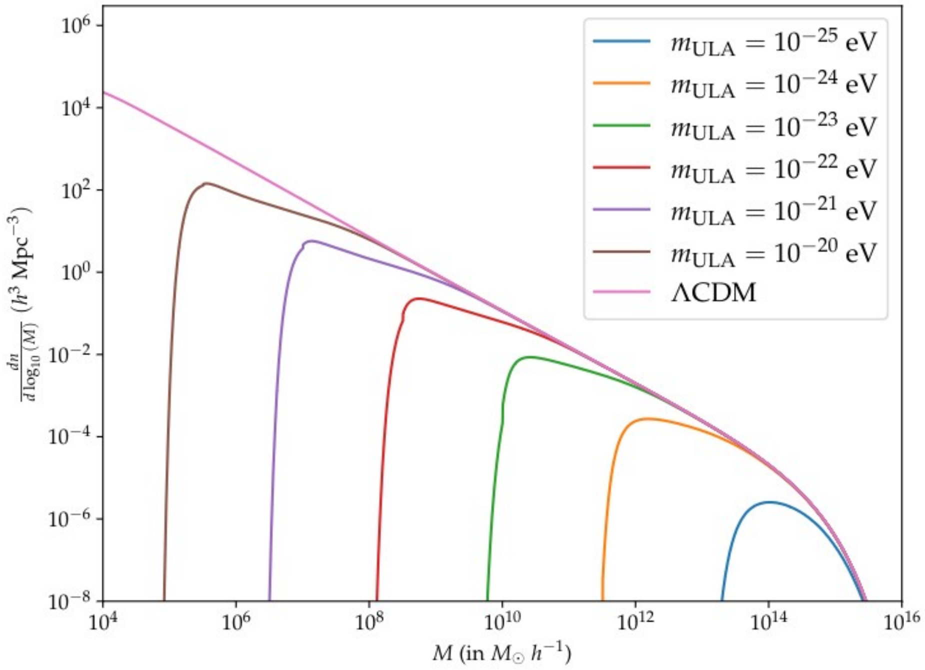

Garland et al, (2024)

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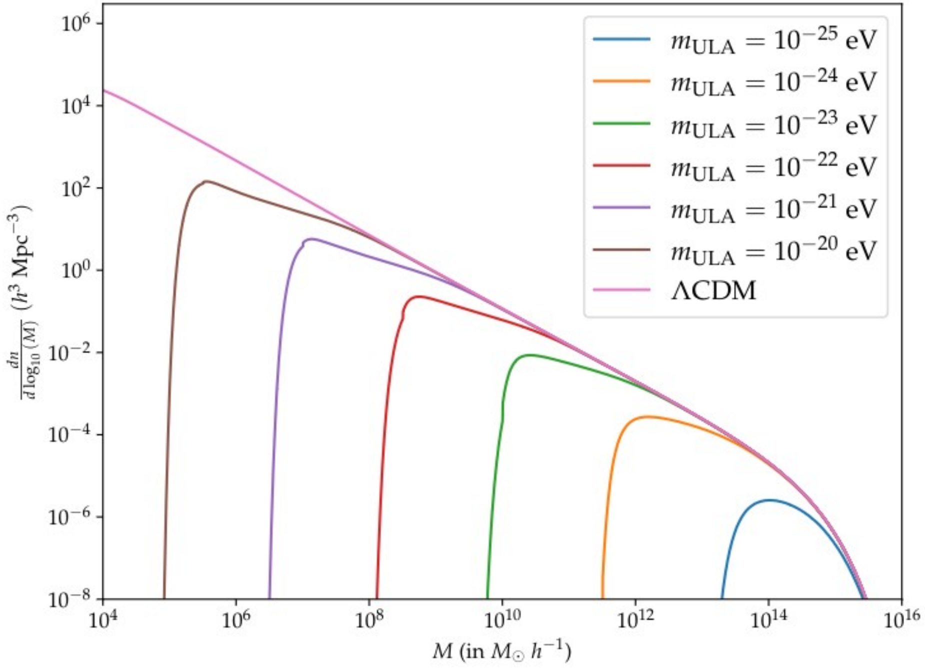
$m > 1.2 \times 10^{-21}\,\text{eV}$ *Garland et al, MNRAS (2024)*

- Halo mass functions
  - Estimate halo mass function from cosmological N-body simulations with FDM transfer function
  - Compare predicted number of satellites with observations



Garland et al, (2024)

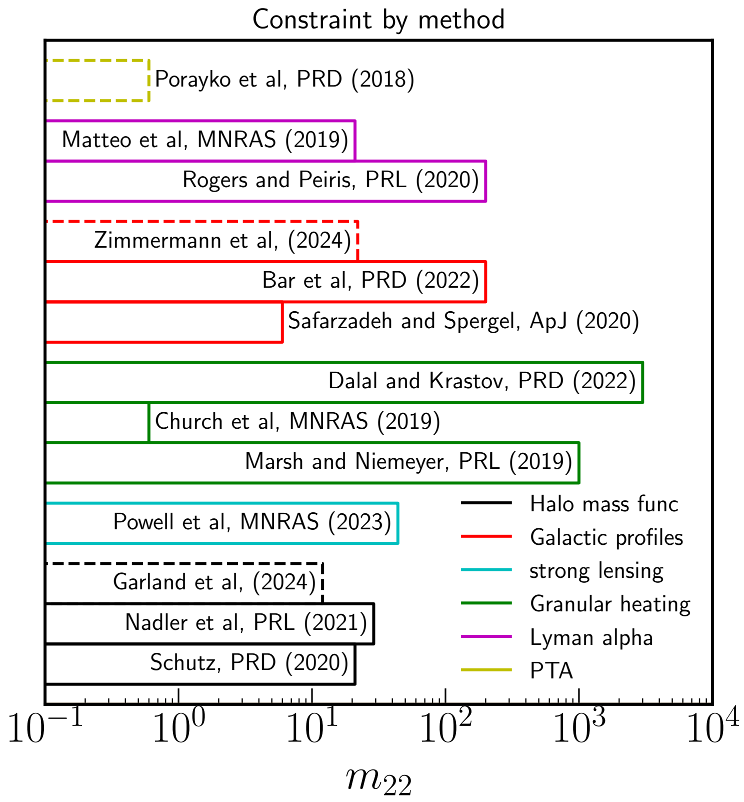
Constraints

$$m > 6 \times 10^{-22}\,\text{eV}$$ **Safarzadeh and Spergetl, ApJ (2020)**

$$m > 2 \times 10^{-20}\,\text{eV}$$ **Bar et al, PRD (2022)**

$$m > 2.2 \times 10^{-21}\,\text{eV}$$ *Zimmermann et al, (2024)*

- Halo mass functions
- Cores



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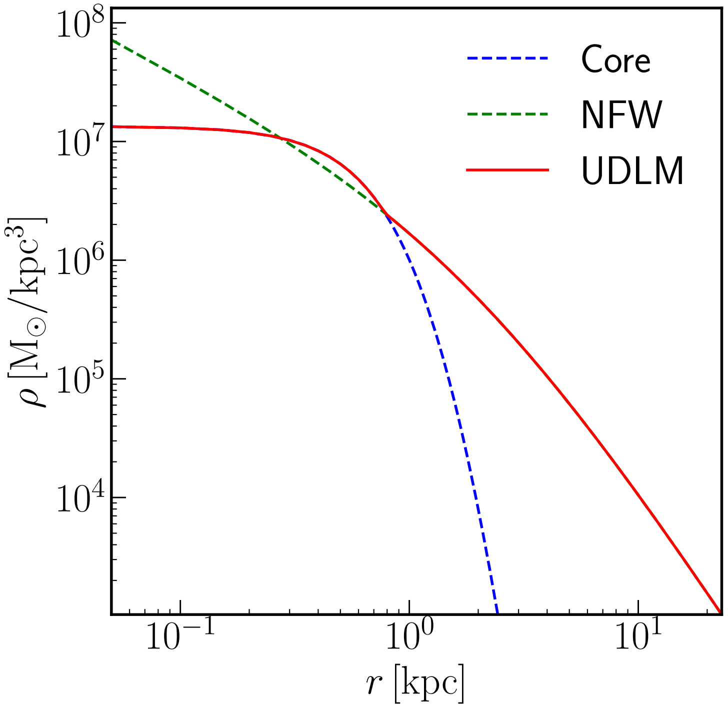
- Halo mass functions
- Cores
  - FDM predicts a soliton core instead of a cusp



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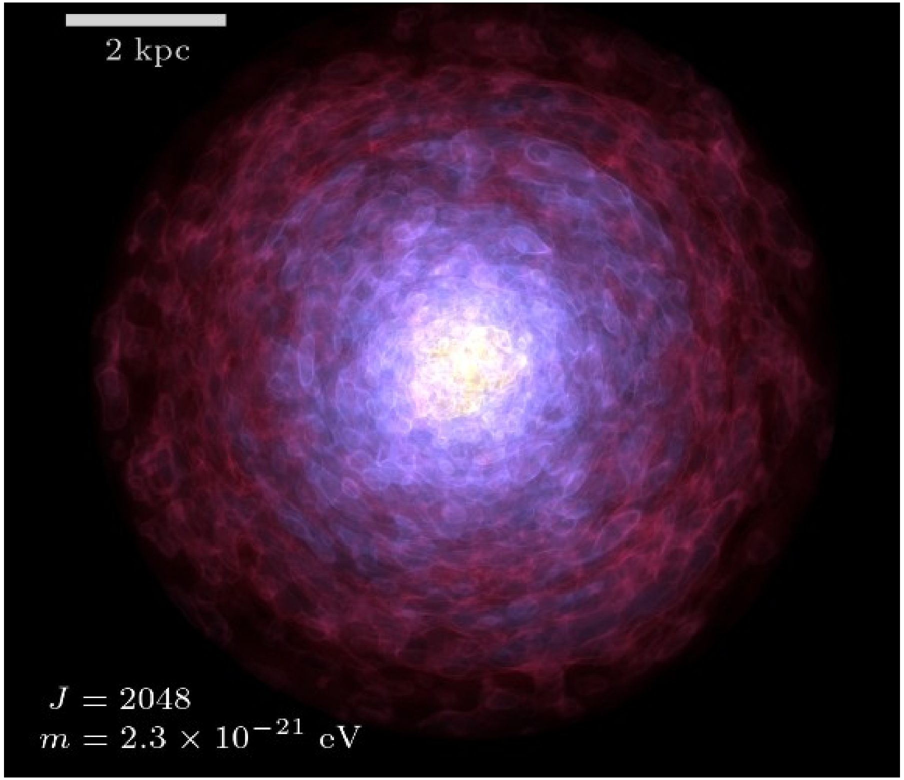
- Halo mass functions
- Cores
  - FDM predicts a soliton core instead of a cusp
  - Semi-analytic (informed by full FDM sims), or eigenvalue constructions of these cores predict rotation curves which can be compared to data



Zimmermann et al, (2024)

Constraints

- Halo mass functions
- Cores
- Granules

$m > 1 \times 10^{-19}\,\mathrm{eV}$ **Marsh and Niemeyer, PRL (2019)**

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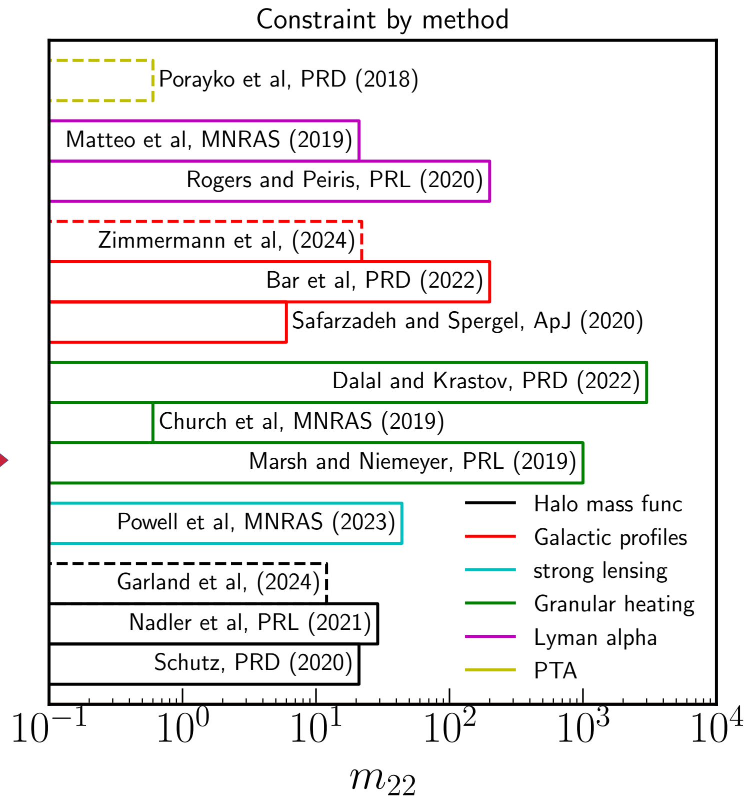
$m > 3 \times 10^{-19}\,\mathrm{eV}$ **Dalal and Krastov, PRD (2022)**



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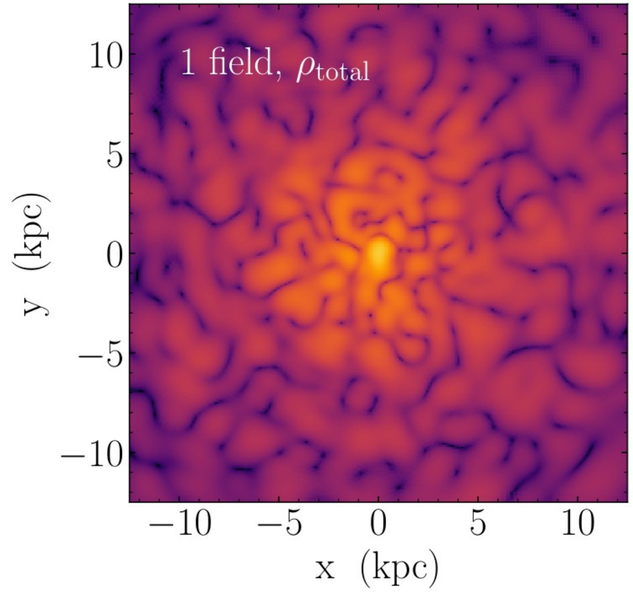
- Halo mass functions
- Cores
- Granules
  - FDM halos have density granules due to inferring modes



Gosenca [, Eberhardt] et al., PRD (2023)

Constraints

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$m > 4.4 \times 10^{-21}$ eV **Powell et al, MNRAS (2023)**
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- Halo mass functions
- Cores
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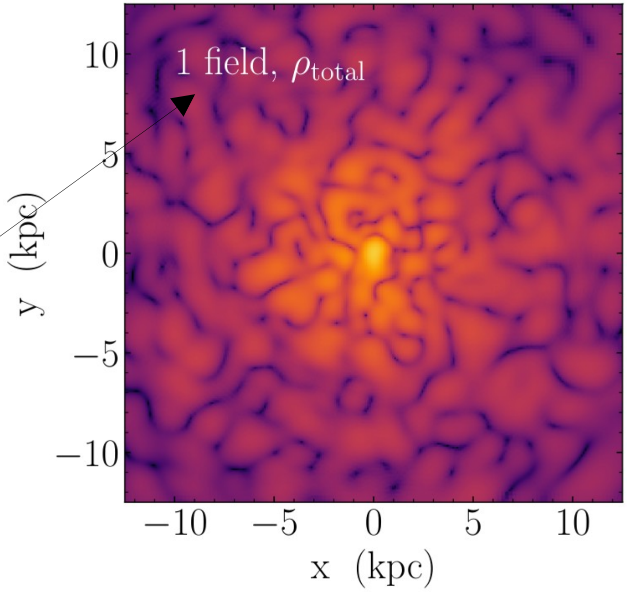
  - FDM halos have density granules due to inferring modes

Effects of granules are sensitive to field spin, number of fields, quantum corrections



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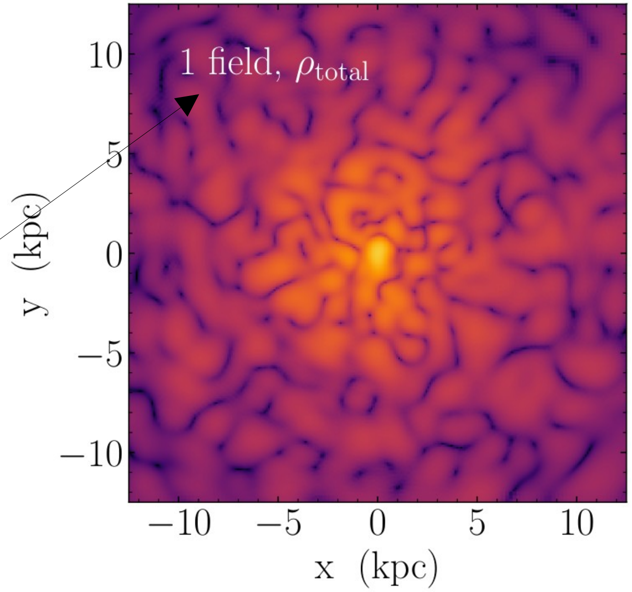


Gosenca [, Eberhardt] et al., PRD (2023)

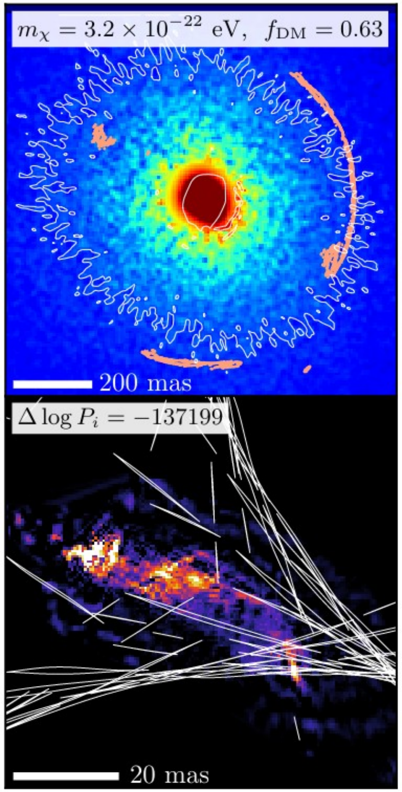
Spin – Amin et al, JCAP (2022)
Number – Gosenca [,Eberhardt] et al, PRD (2023)
Quantum corrections – Eberhardt et al, PRD (2024)

Constraints

$m > 1 \times 10^{-19}\,\mathrm{eV}$ **Marsh and Niemeyer, PRL (2019)**
→ $m > 4.4 \times 10^{-21}\,\mathrm{eV}$ **Powell et al, MNRAS (2023)**
$m > 3 \times 10^{-19}\,\mathrm{eV}$ **Dalal and Krastov, PRD (2022)**

- Halo mass functions
- Cores
- Granules
  - Strong lensing

Power et al, MNRAS (2023)



Constraints

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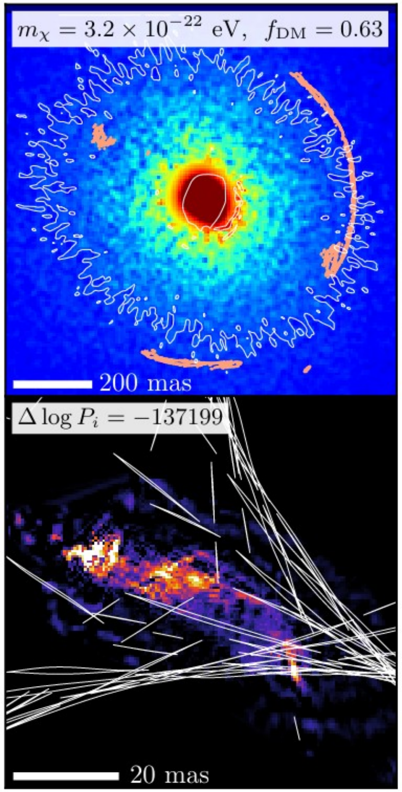
→ $m > 4.4 \times 10^{-21}\,\text{eV}$ **Powell et al, MNRAS (2023)**

$m > 3 \times 10^{-19}\,\text{eV}$ **Dalal and Krastov, PRD (2022)**

- Halo mass functions
- Cores
- Granules
  - Strong lensing
    - Granular over densities prevent image from forming observed sharpness

Power et al, MNRAS (2023)



Constraints

- Halo mass functions
- Cores
- Granules
  - Strong lensing
  - Heating of stellar dispersions

$m > 1 \times 10^{-19}\,\mathrm{eV}$ **Marsh and Niemeyer, PRL (2019)**

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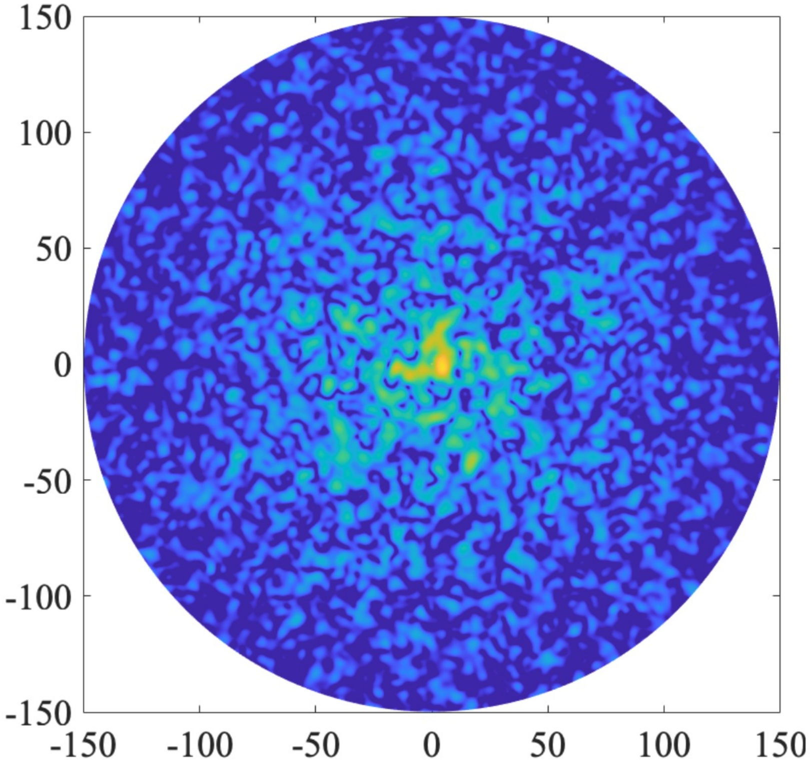

Dalal and Krastov, PRD (2022)

Constraints

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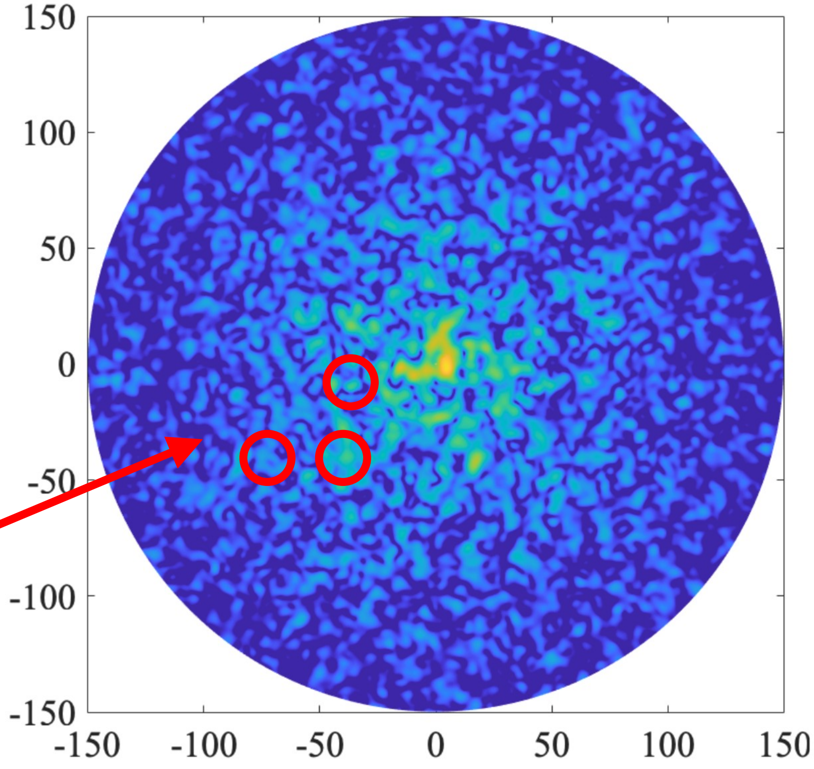
- Halo mass functions
- Cores
- Granules
  - Strong lensing
  - Heating of stellar dispersions
    - Density fluctuations act as quasi-particles



quasi-particles

Dalal and Krastov, PRD (2022)

Constraints

$m > 1 \times 10^{-19}\,\mathrm{eV}$ **Marsh and Niemeyer, PRL (2019)**
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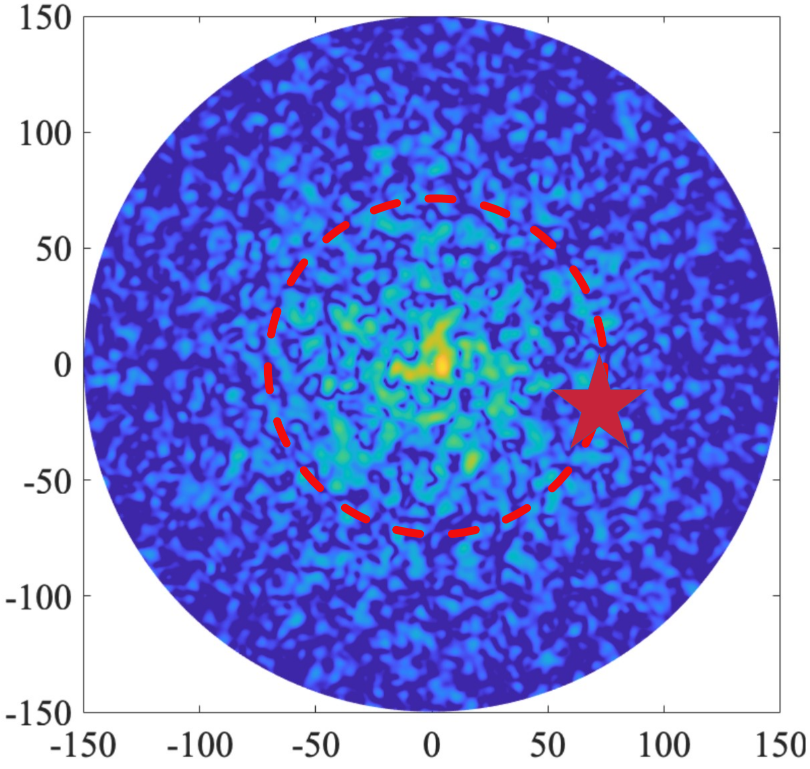
- Halo mass functions
- Cores
- Granules
  - Strong lensing
  - Heating of stellar dispersions
    - Density fluctuations act as quasi-particles
    - Stars in orbit are kicked by the granules



Dalal and Krastov, PRD (2022)

Constraints

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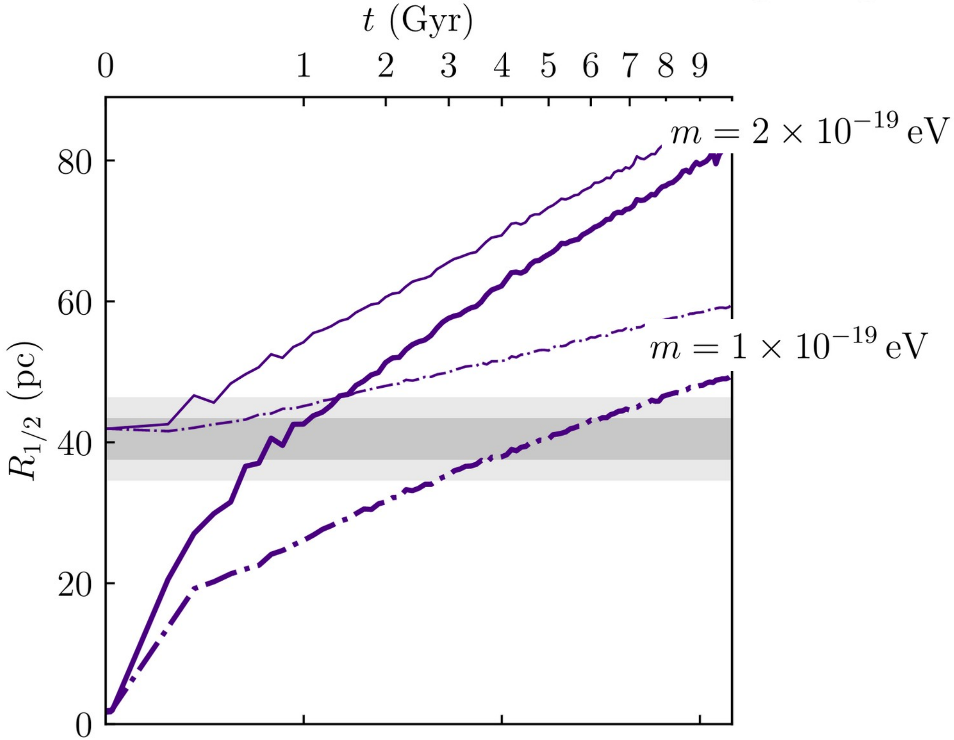
$m > 4.4 \times 10^{-21}$ eV **Powell et al, MNRAS (2023)**
$m > 3 \times 10^{-19}$ eV **Dalal and Krastov, PRD (2022)**

- Halo mass functions
- Cores
- Granules
  - Strong lensing
  - Heating of stellar dispersions
    - Density fluctuations act as quasi-particles
    - Stars in orbit are kicked by the granules
    - Overtime this heats the dispersion and results in larger half-light radii than is observed



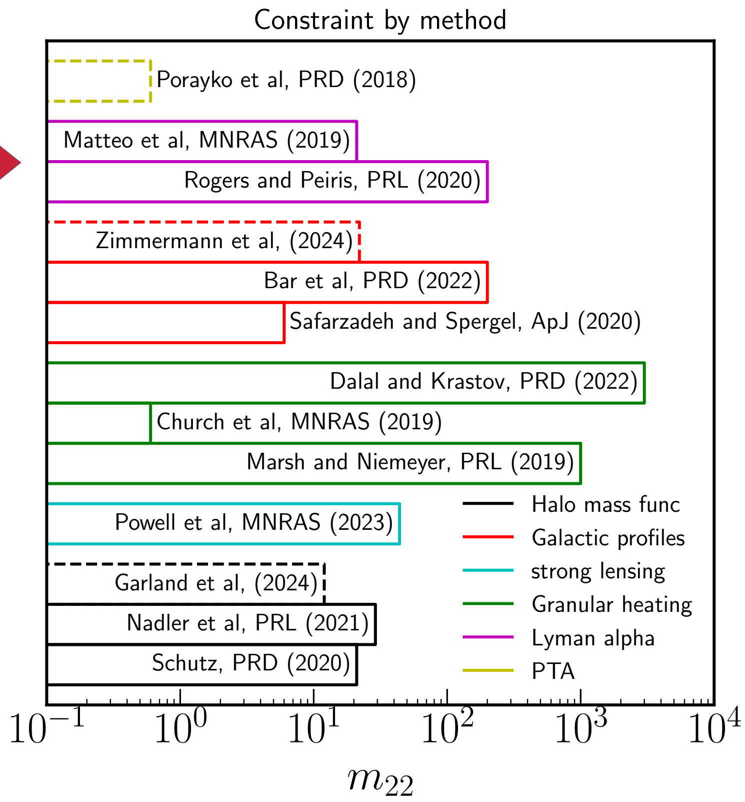
Dalal and Krastov, PRD (2022)

$m > 2 \times 10^{-20}$ eV **Rogers and Peiris, PRL (2020)**

$m > 2.1 \times 10^{-21}$ eV **Matteo et al, MNRAS (2019)**

Constraints

- Halo mass functions
- Cores
- Granules
  - Strong lensing
  - Heating of stellar dispersions
- Lyman alpha



Constraints

$m > 2 \times 10^{-20}$ eV **Rogers and Peiris, PRL (2020)**

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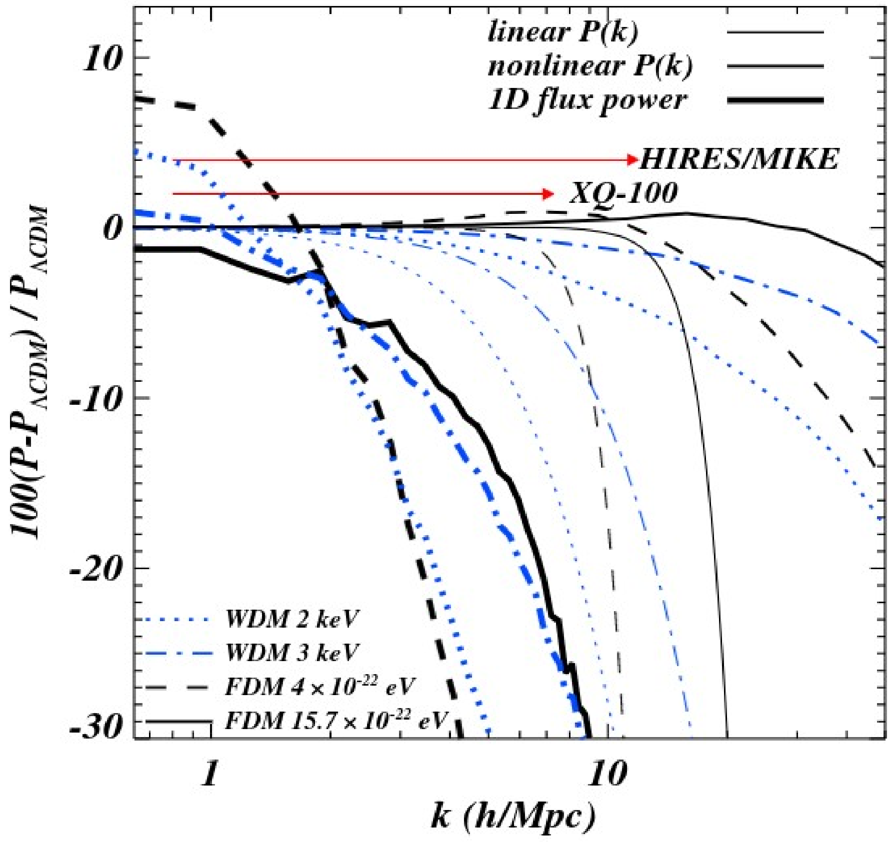
- Halo mass functions
- Cores
- Granules
  - Strong lensing
  - Heating of stellar dispersions
- Lyman alpha
  - Prevents formation of structure on the small scales observed in the Lyman alpha forest



Irsic et al, PRL (2017)

Constraints

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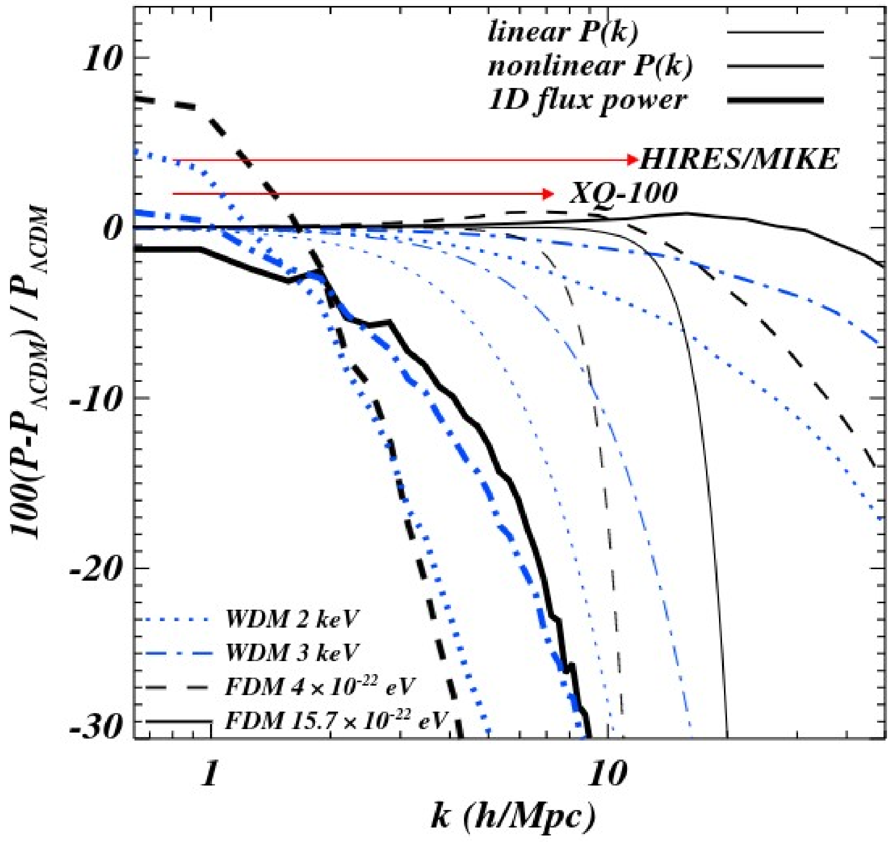
- Halo mass functions
- Cores
- Granules
  - Strong lensing
  - Heating of stellar dispersions
- Lyman alpha
  - Prevents formation of structure on the small scales observed in the Lyman alpha forest
  - Compare with predictions of Cdm simulations with altered transfer function

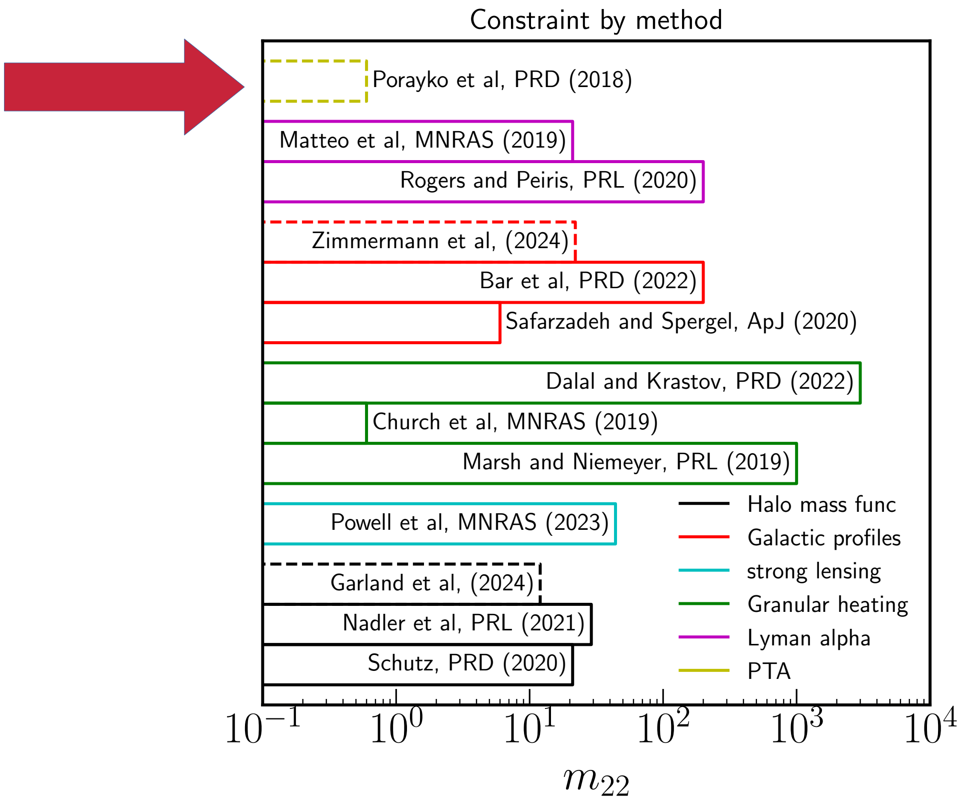


Irsic et al, PRL (2017)

$m > 6 \times 10^{-23}\,\mathrm{eV}$ **Porayko, PRD (2018)**

Constraints

- Halo mass functions
- Cores
- Granules
  - Strong lensing
  - Heating of stellar dispersions
- Lyman alpha
- Pulsar timing arrays



$m > 6 \times 10^{-23}\,\mathrm{eV}$ **Porayko, PRD (2018)**

Constraints

- Halo mass functions
- Cores
- Granules
  - Strong lensing
  - Heating of stellar dispersions
- Lyman alpha
- Pulsar timing arrays
  - Relativistic fluctuating pressure

$$\Phi = \Phi_0 + \Phi_c$$

$$\Phi_c \sim \frac{v^2}{c^2}\Phi_0$$

$m > 6 \times 10^{-23}\,\mathrm{eV}$ **Porayko, PRD (2018)**

Constraints

- Halo mass functions
- Cores
- Granules
  - Strong lensing
  - Heating of stellar dispersions
- Lyman alpha
- Pulsar timing arrays
  - Relativistic fluctuating pressure
  - Produces signal that fluctuates on Compton timescale

$$\Phi = \Phi_0 + \Phi_c$$

$$\Phi_c \sim \frac{v^2}{c^2}\Phi_0$$

$$\tau_\mathrm{c} \sim \hbar/mc^2$$

$$\lambda_\mathrm{c} \sim \hbar/mc$$

$m > 6 \times 10^{-23}\,\mathrm{eV}$ **Porayko, PRD (2018)**

Constraints

- Halo mass functions
- Cores
- Granules
  - Strong lensing
  - Heating of stellar dispersions
- Lyman alpha
- Pulsar timing arrays
  - Relativistic fluctuating pressure
  - Produces signal that fluctuates on Compton timescale

$$\frac{\Delta\Omega}{\Omega_0} = \frac{\Phi_c(x_\oplus) - \Phi_c(x_p)}{c^2}$$

$m > 6 \times 10^{-23}$ eV **Porayko, PRD (2018)**

Constraints

- Halo mass functions
- Cores
- Granules
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  - Heating of stellar dispersions
- Lyman alpha
- Pulsar timing arrays
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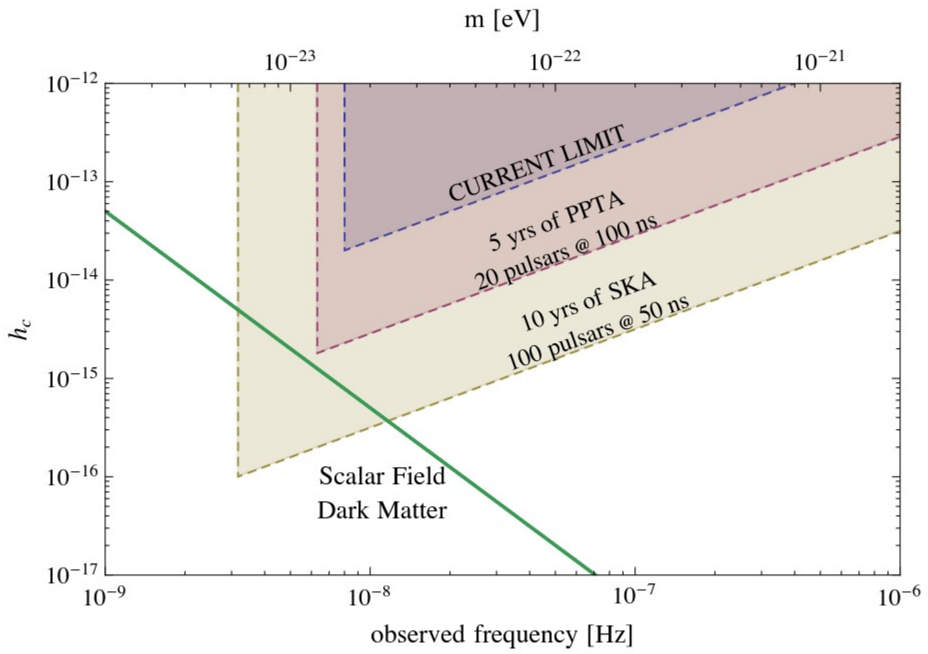

Khmelnitsky and Rubakov, JCAP (2014)

$m > 6 \times 10^{-23}\,\mathrm{eV}$ **Porayko, PRD (2018)**

Constraints

- Halo mass functions
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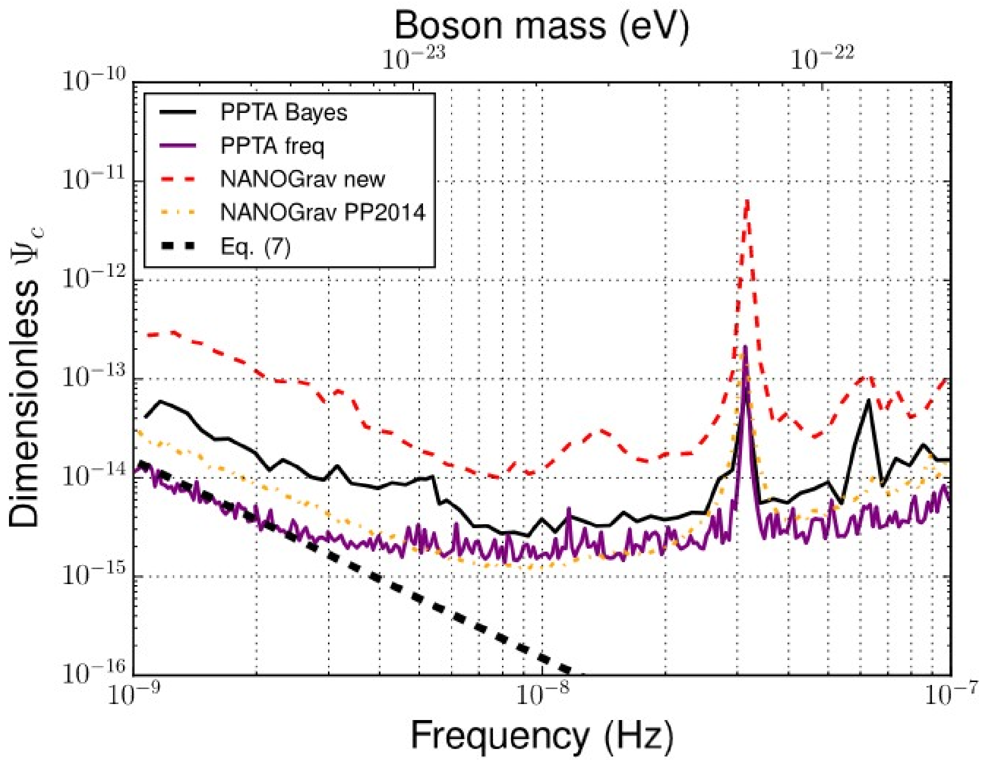
  - Strong lensing
  - Heating of stellar dispersions
- Lyman alpha
- Pulsar timing arrays
  - Relativistic fluctuating pressure
  - Produces signal that fluctuates on Compton timescale

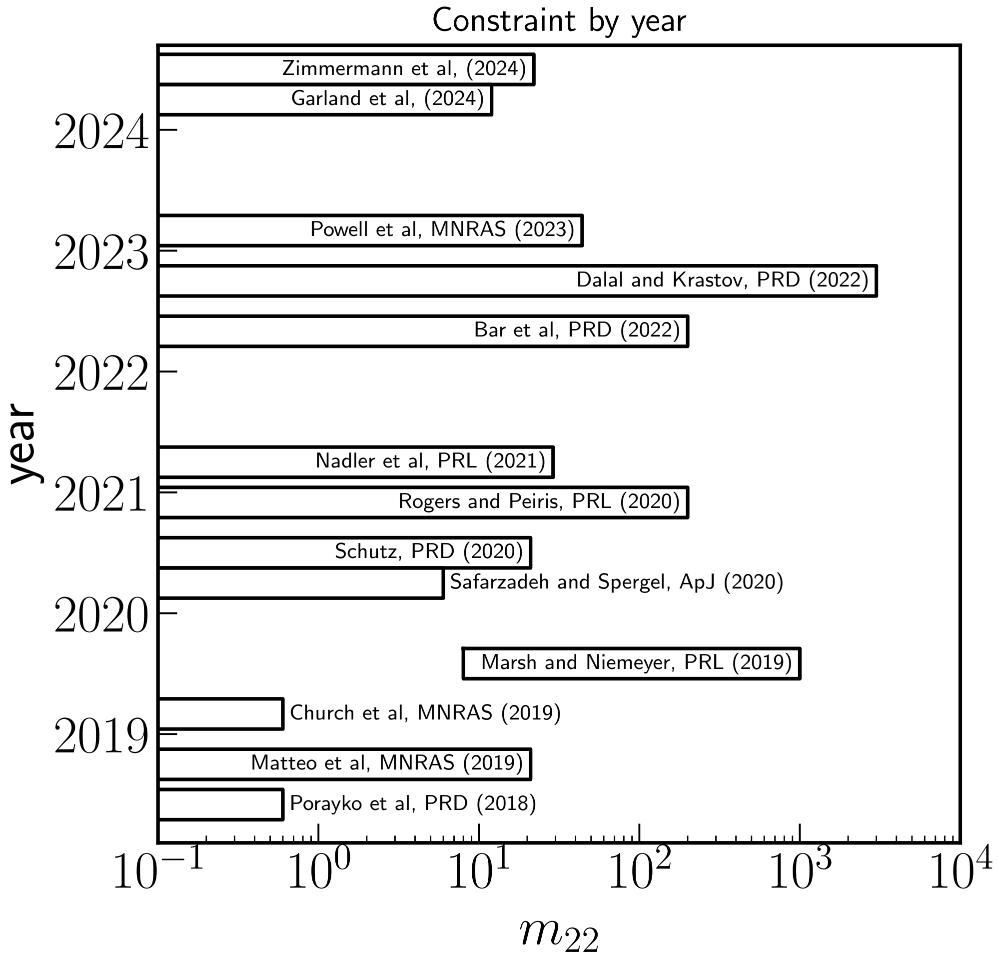


Porayko et al, PRD (2018)

Outlook

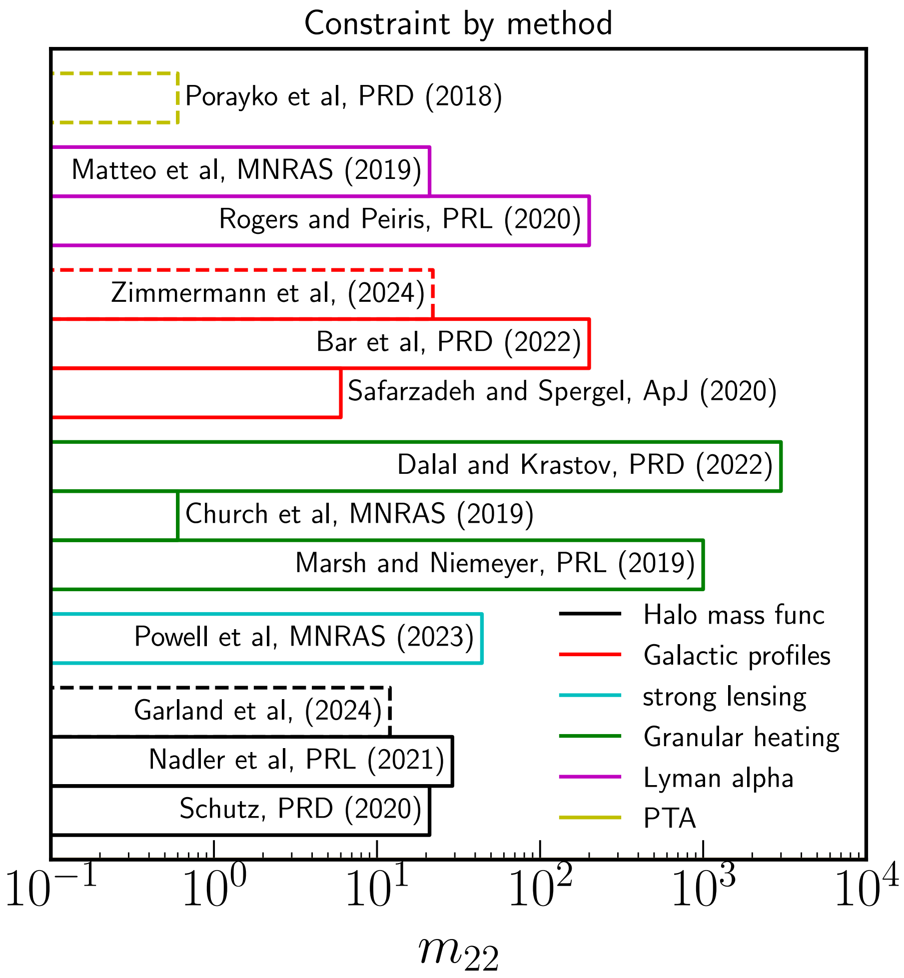
Outlook

- Vanilla FDM model is dead



Outlook

- Vanilla FDM model is dead
  - Multiple observational probes, numerical methods, phenomenology rule it out



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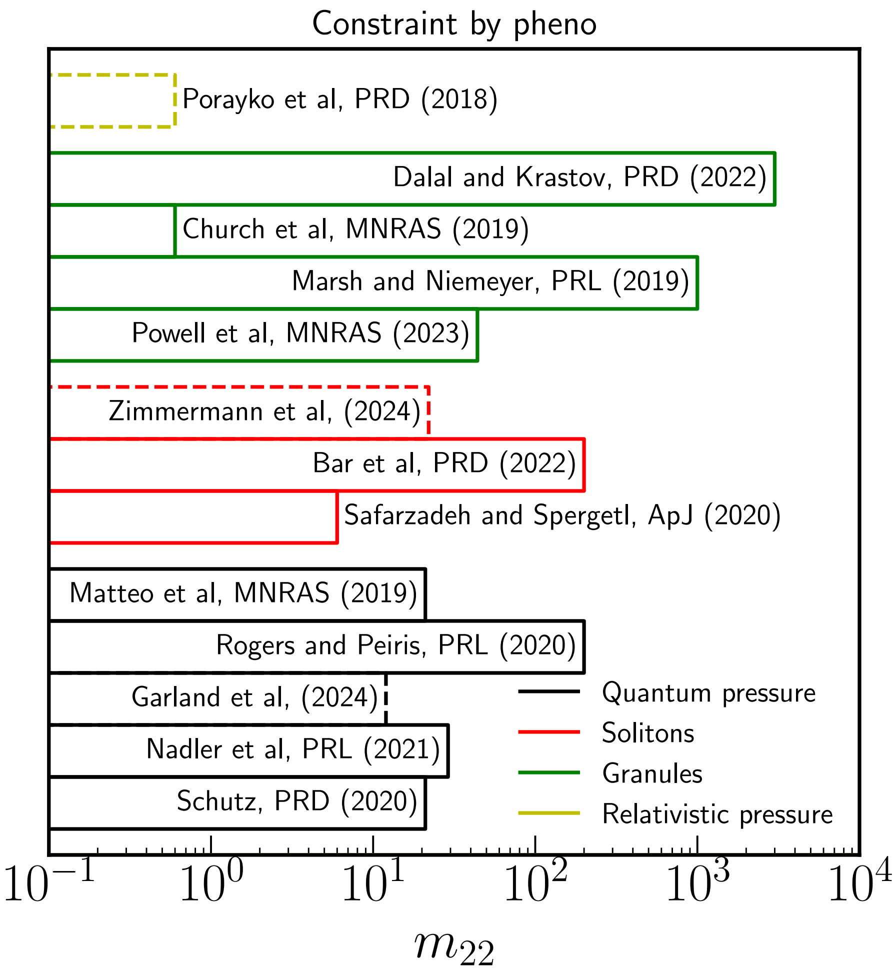

Outlook

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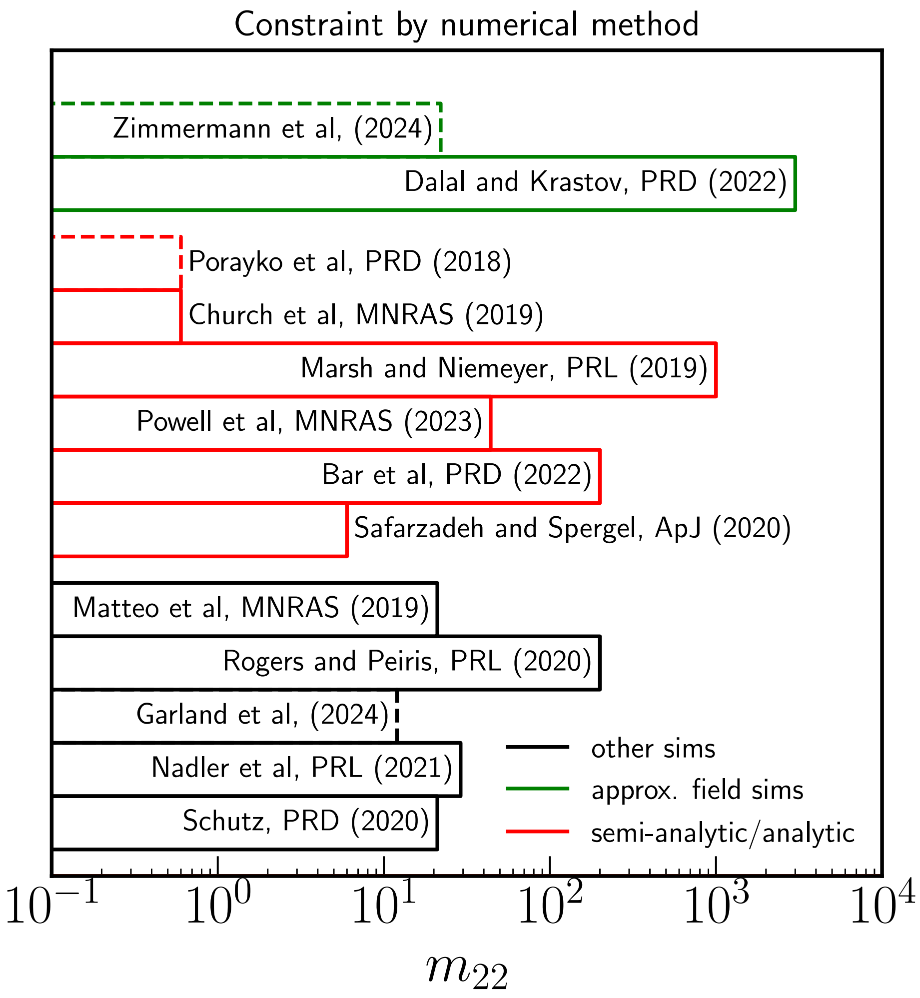
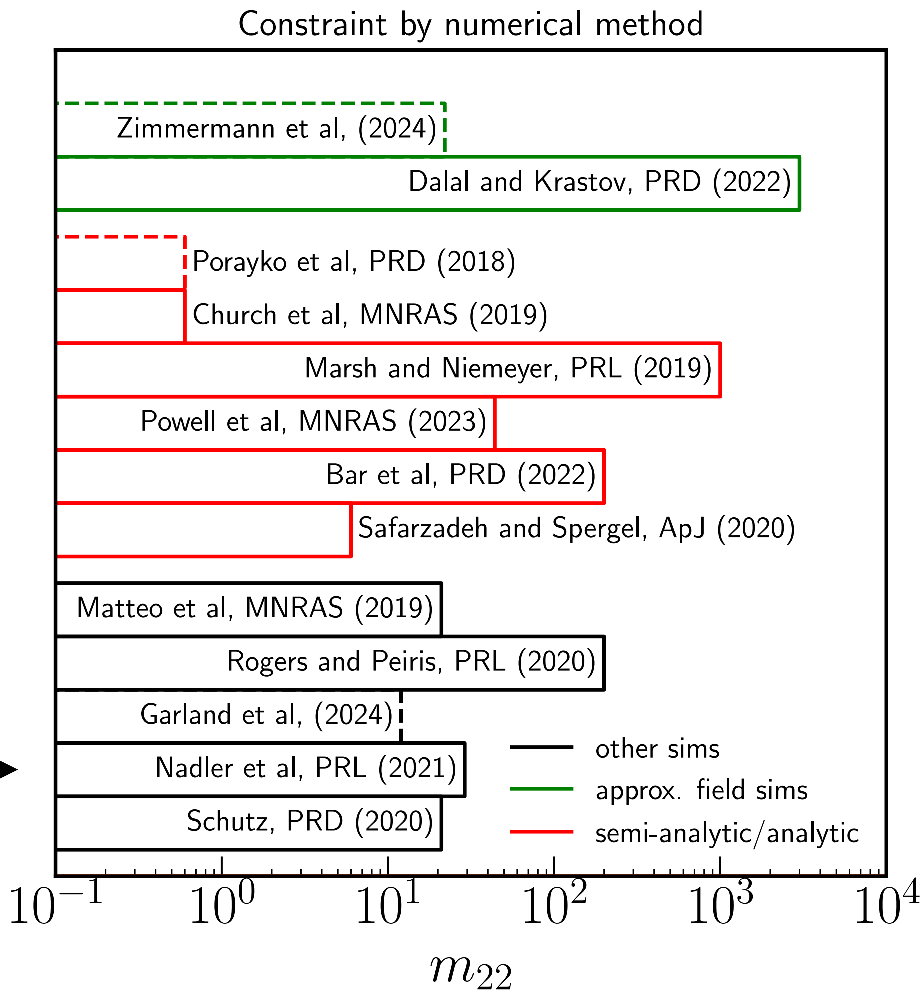


Outlook

- Vanilla FDM model is dead
  - Multiple observational probes, numerical methods, phenomenology rule it out

Simulations with altered transfer function at correct mass but not direct FDM sims

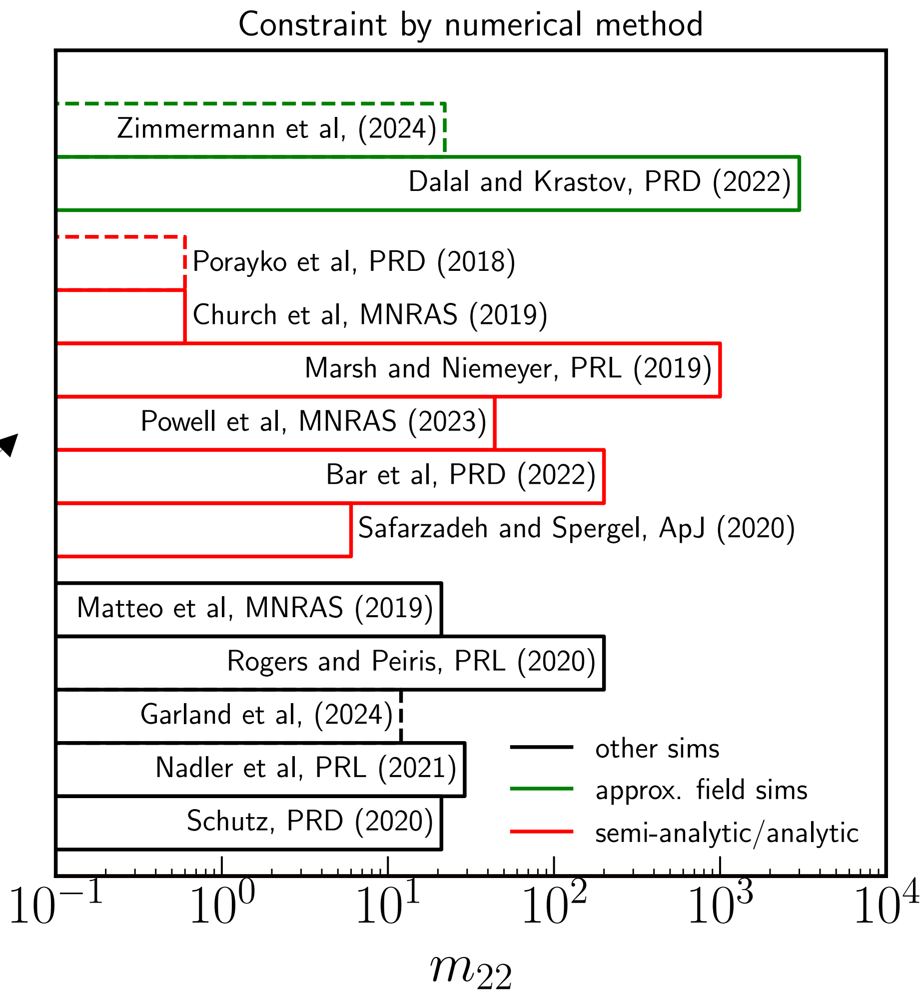


Outlook

- Vanilla FDM model is dead
  - Multiple observational probes, numerical methods, phenomenology rule it out

Use derived relations from full FDM sims at low mass

Schive et al (Nature 2014)



Outlook

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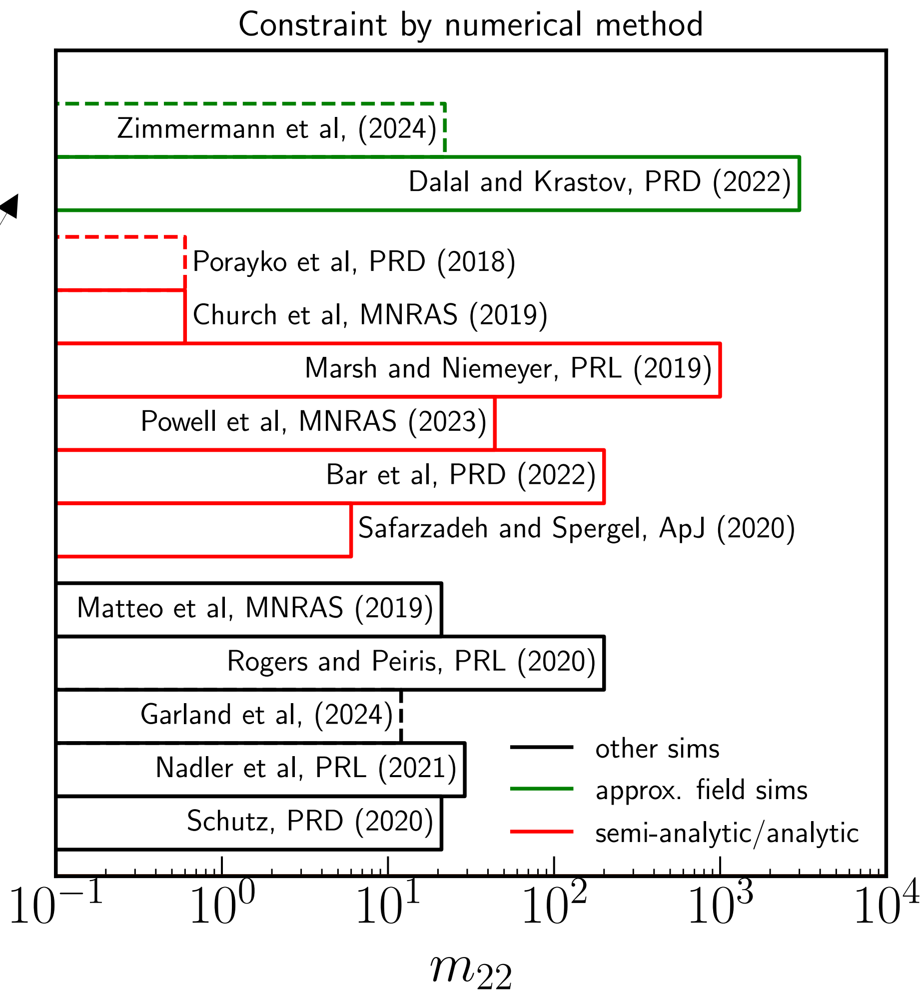
FDM simulations at correct mass but with some dynamical approximation



Outlook

- Vanilla FDM model is dead
- Wide range of work looking into extensions of the model

Outlook

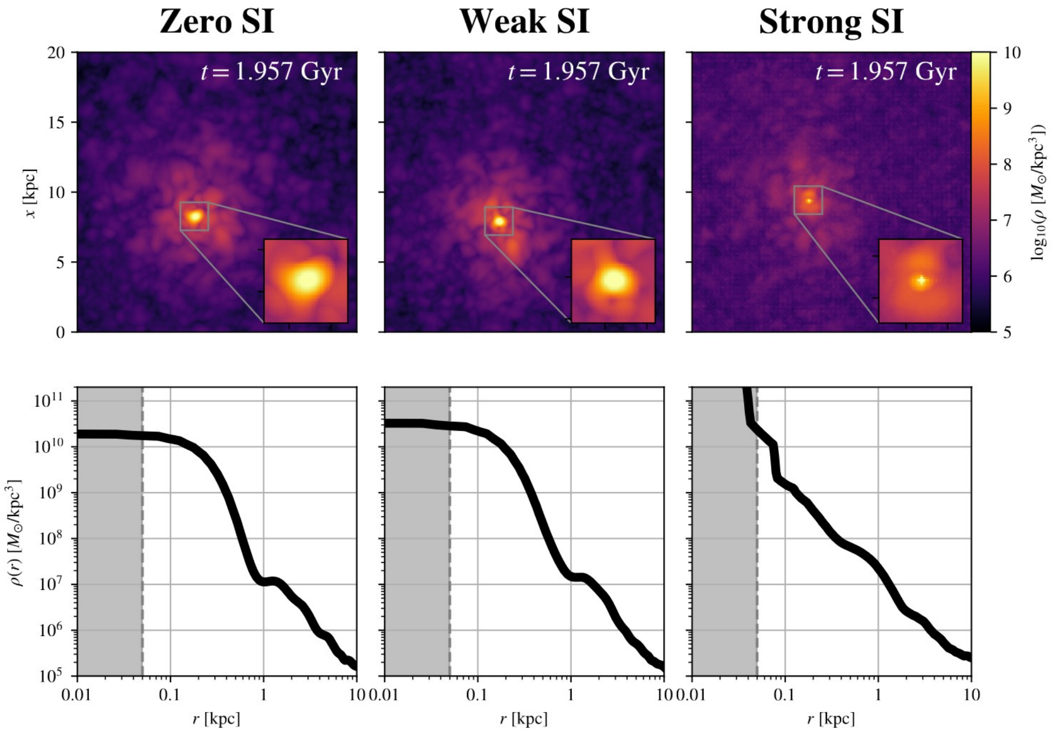
- VanillaFDM model is dead
- Wide range of work looking into extensions of the model

Model in which we describe the dark matter a single, spin-zero, non-relativistic, classical field

Outlook

- Vanilla FDM model is dead
- Wide range of work looking into extensions of the model
  - Self interactions

Soliton effects



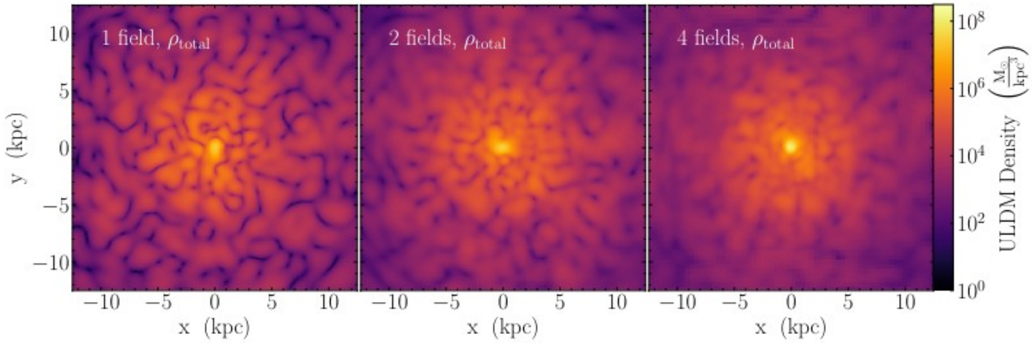
Painter et al, (2024)

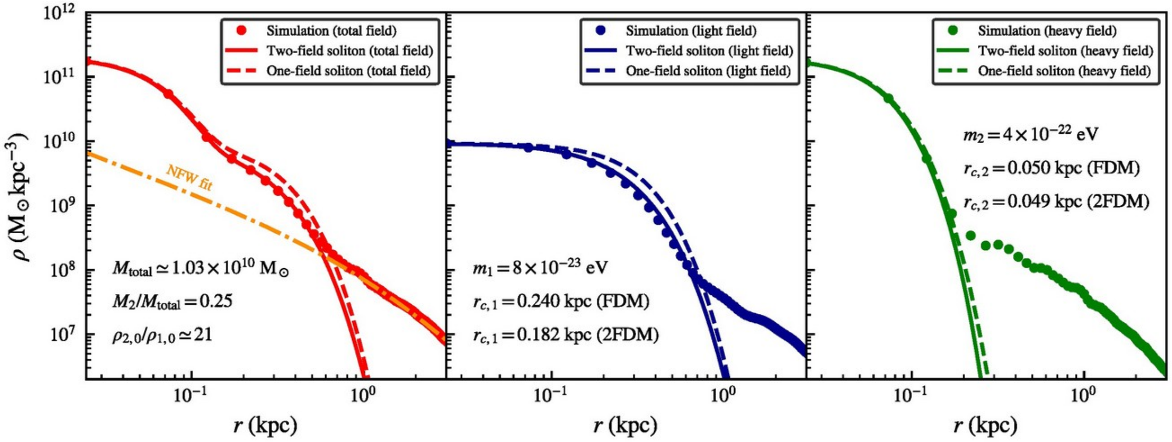
Gosenca [, Eberhardt] et al., PRD (2023)

Outlook

- Vanilla FDM model is dead
- Wide range of work looking into extensions of the model
  - Self interactions
  - Multiple fields/mixed

Granule effects





Luu et al, MNRAS 2023

Soliton effects

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Future constraint plots will look like this

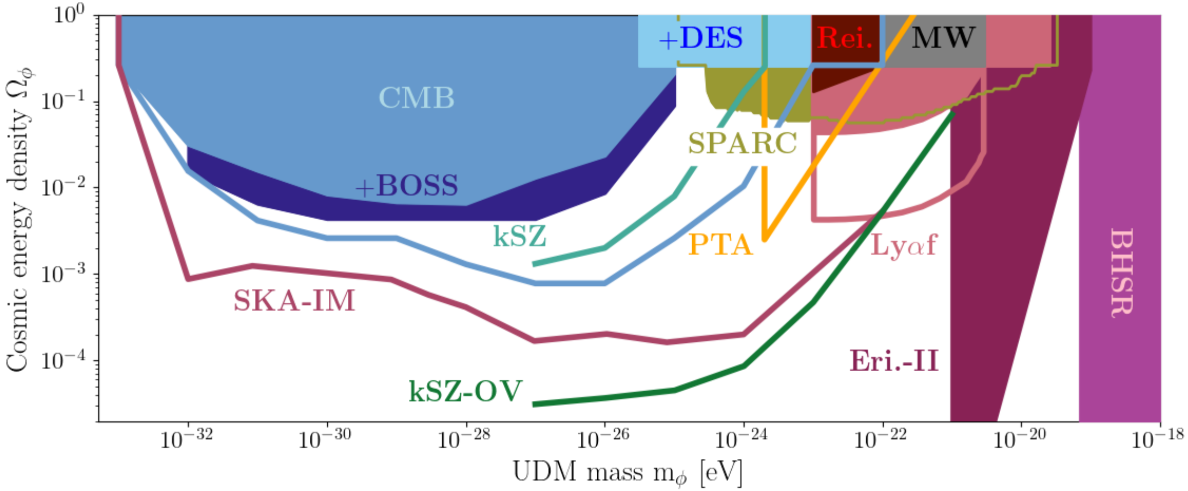

Image credit: Kier Rogers

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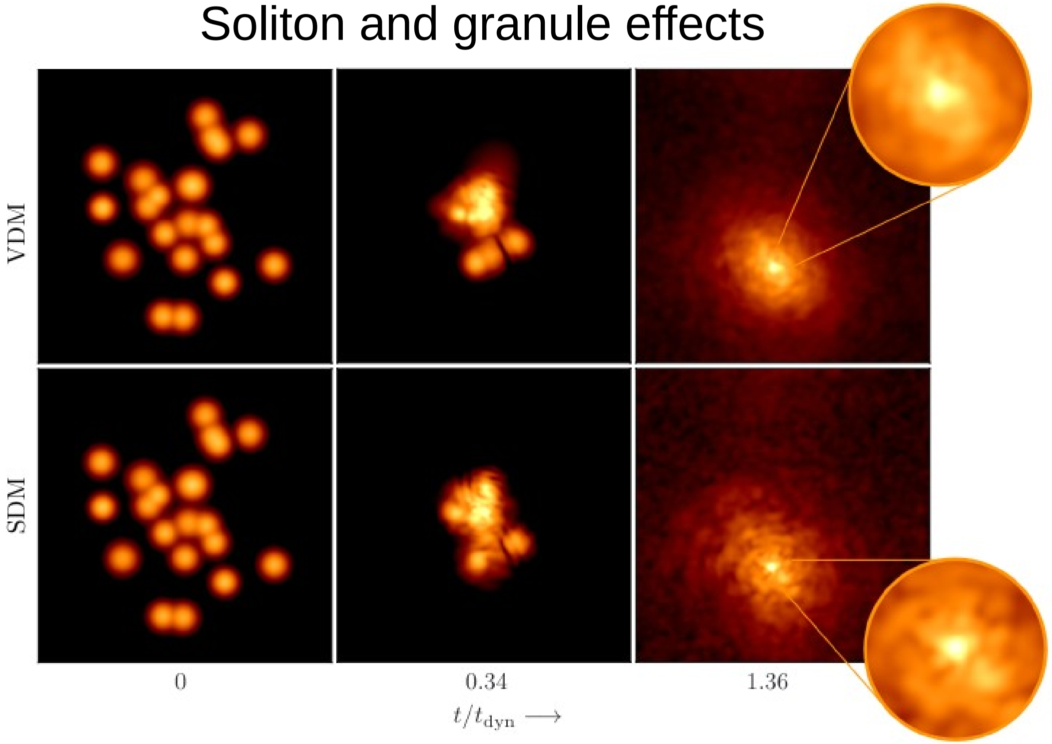
Soliton and granule effects



Amin et al, JCAP (2022)

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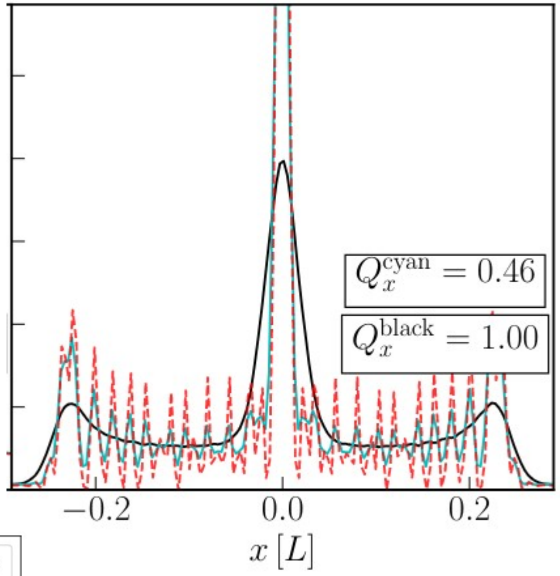
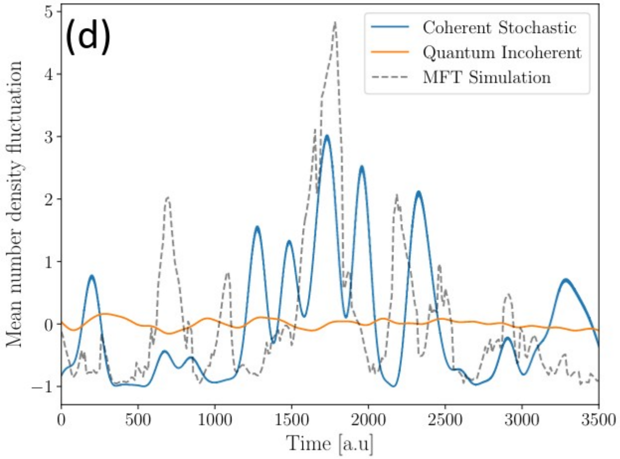
Eberhardt et al, PRD (2024)





Marsh, Annalen Phys. (2024)

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Each alleviate some tensions and introduce new pheno

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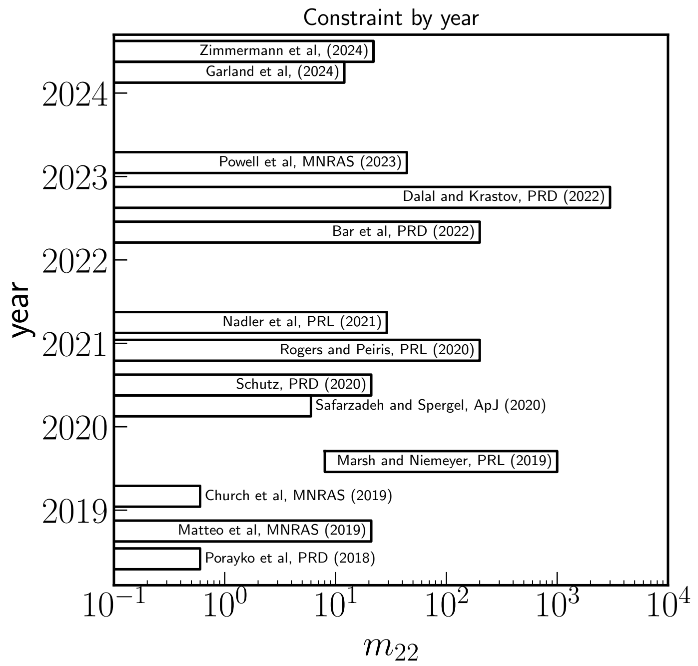
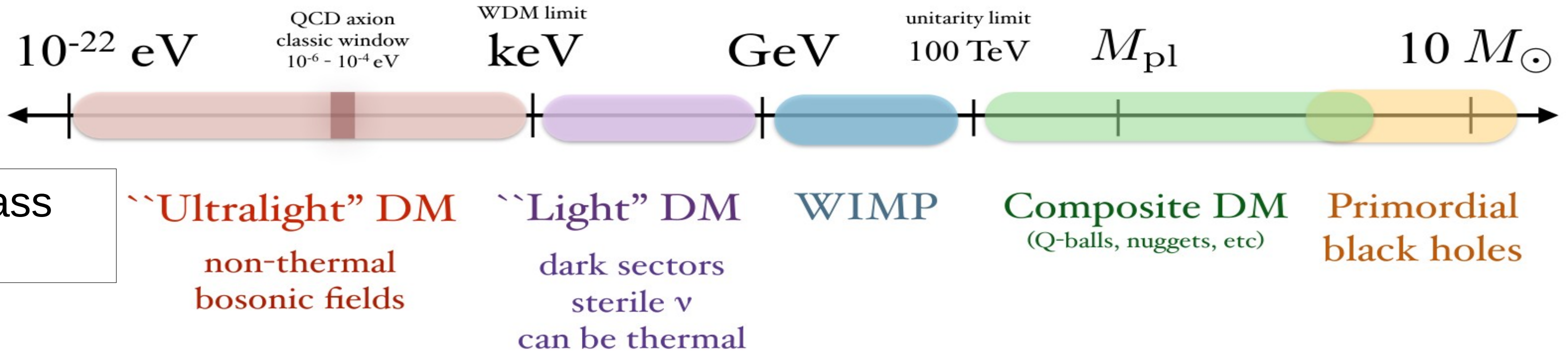
- Wide range of work looking into extensions of the model
- Increasingly powerful constraint on the lower bound of dark matter models





Lower mass bound

Lin arXiv 1904.07915

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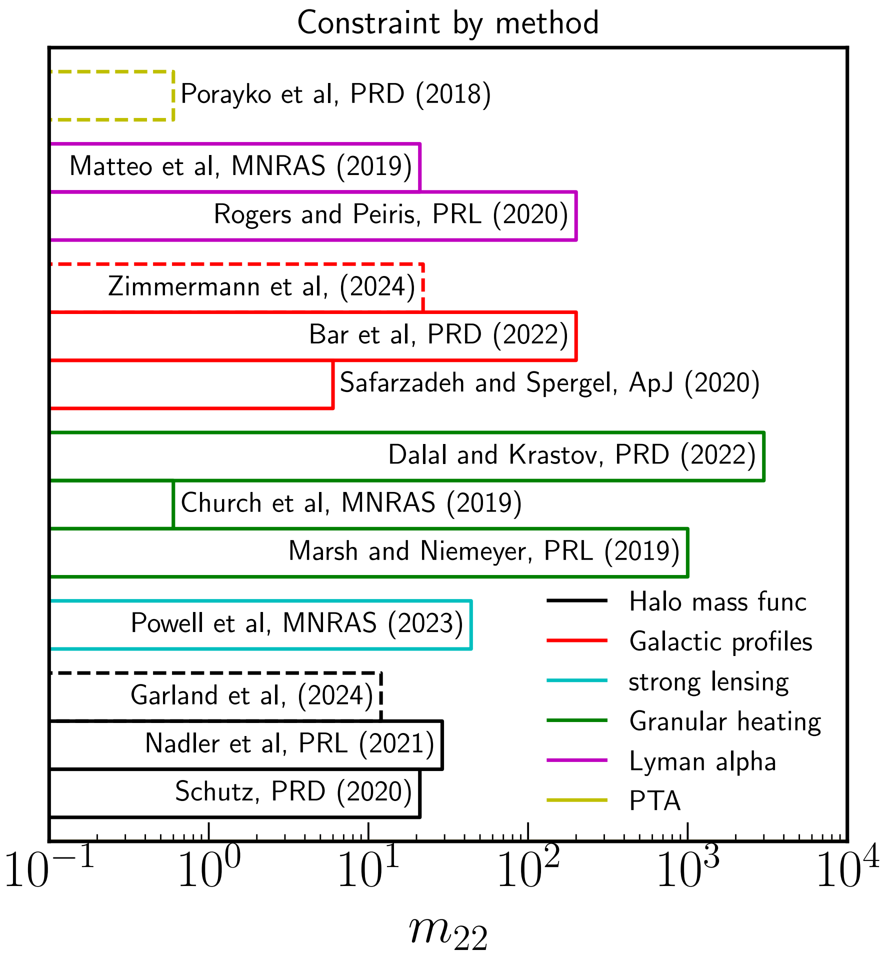
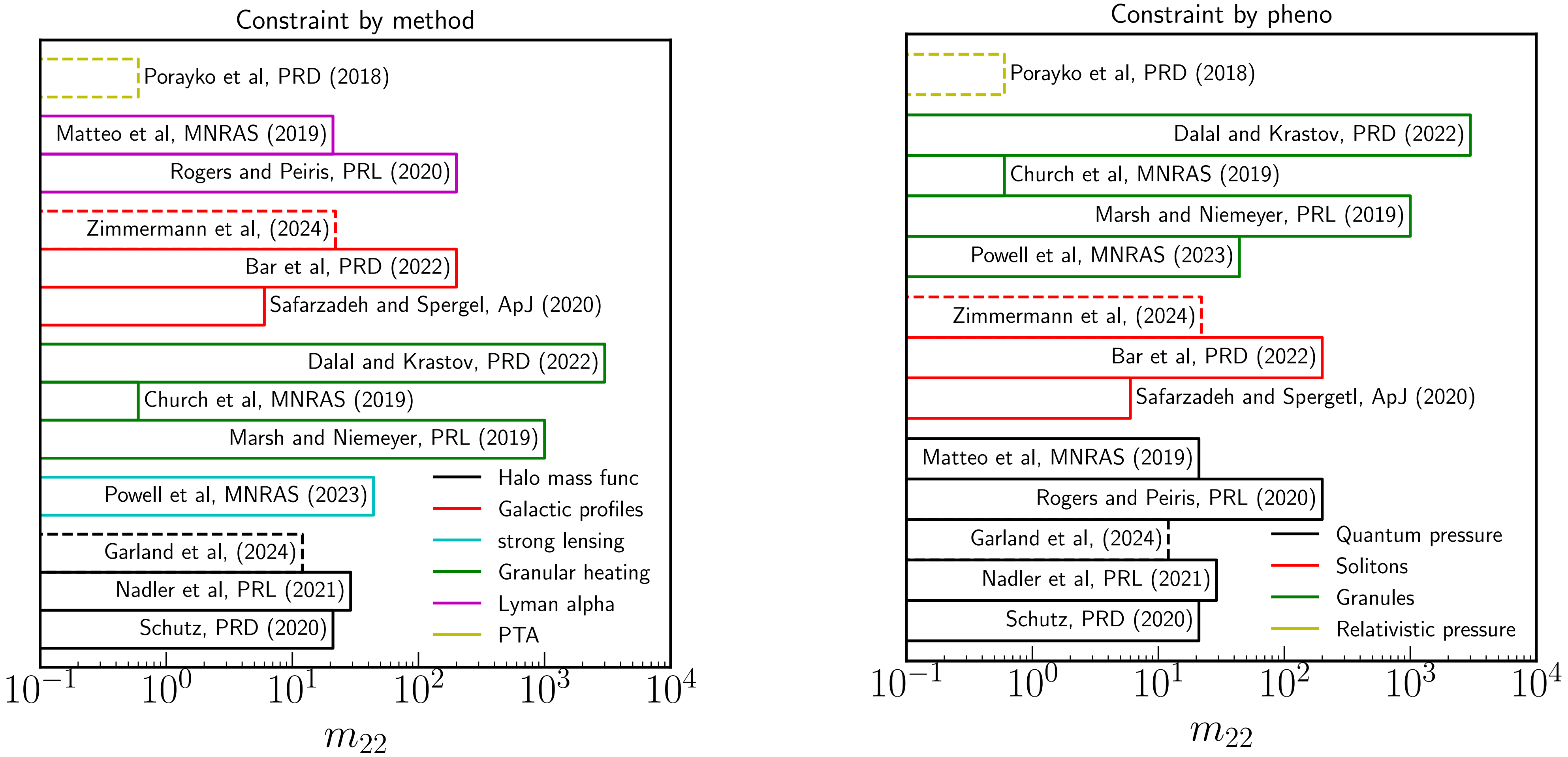
  - No direct detections, ultralight dark matter work is prepared for the worst case minimally coupled scenario
  - Future surveys will probe smaller scales and earlier times making ultralight dark matter constraints at higher masses



Questions?


Constraint by method
Porayko et al, PRD (2018)
Matteo et al, MNRAS (2019)
Rogers and Peiris, PRL (2020)
Zimmermann et al, (2024)
Bar et al, PRD (2022)
Safarzadeh and Spergel, ApJ (2020)
Dalal and Krastov, PRD (2022)
Church et al, MNRAS (2019)
Marsh and Niemeyer, PRL (2019)
Powell et al, MNRAS (2023)
Garland et al, (2024)
Nadler et al, PRL (2021)
Schutz, PRD (2020)
Halo mass func
Galactic profiles
strong lensing
Granular heating
Lyman alpha
PTA
10^{-1} 10^{0} 10^{1} 10^{2} 10^{3} 10^{4}
m_{22}
Constraint by pheno
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Granules
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Resolution

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$$v_{max} = \hbar/dx/m = \hbar N/L/m$$

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