Fuzzy Dark Matter on Galactic Scales

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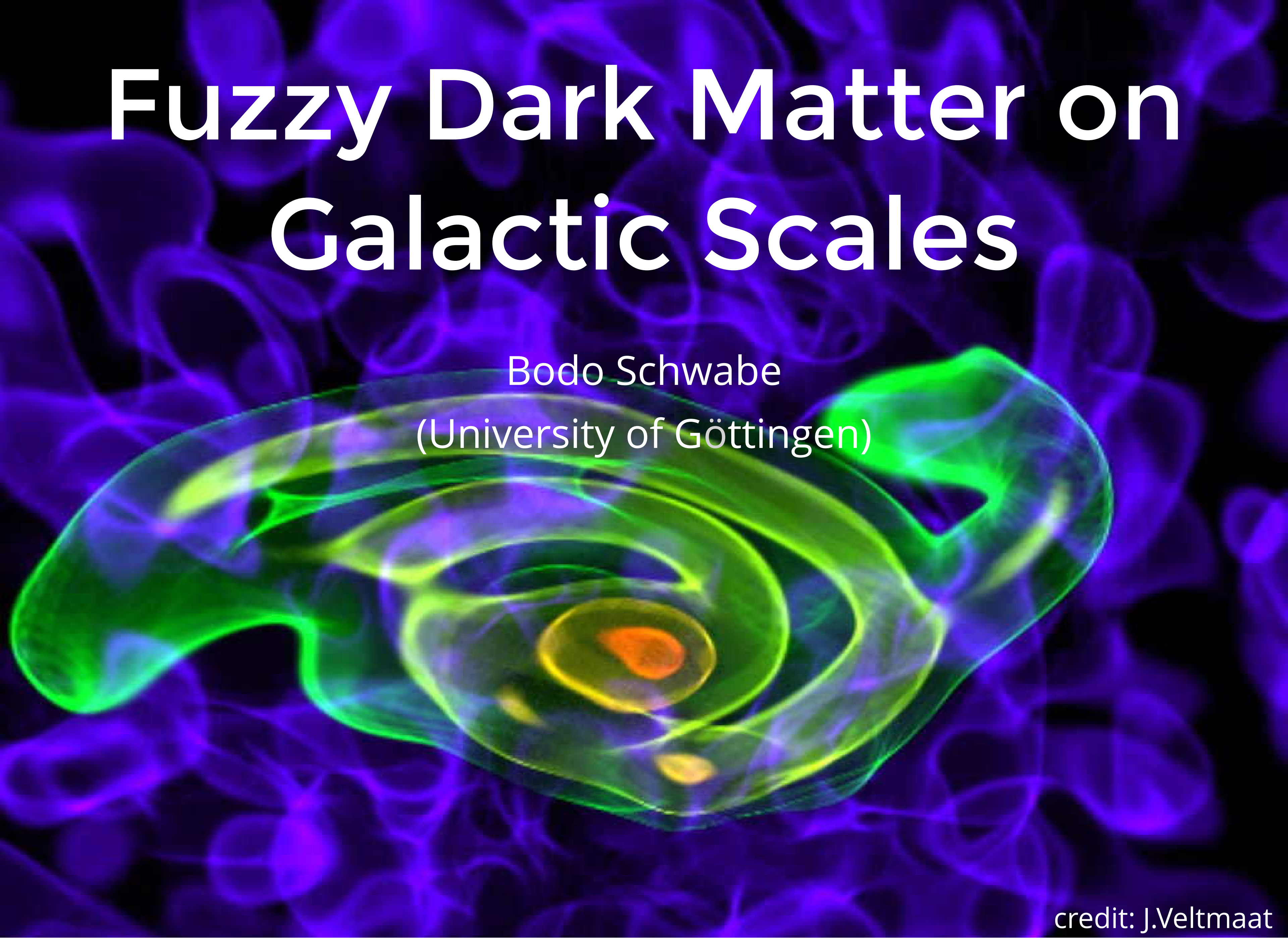
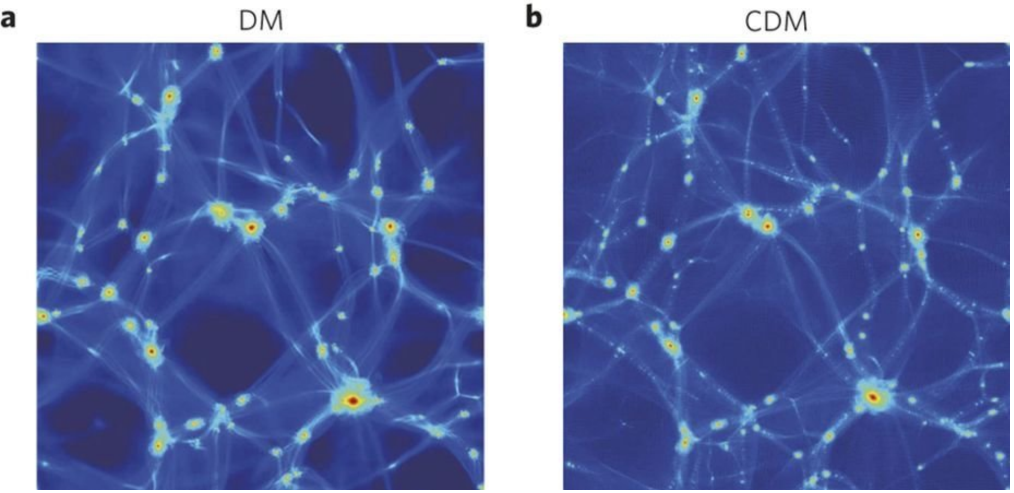
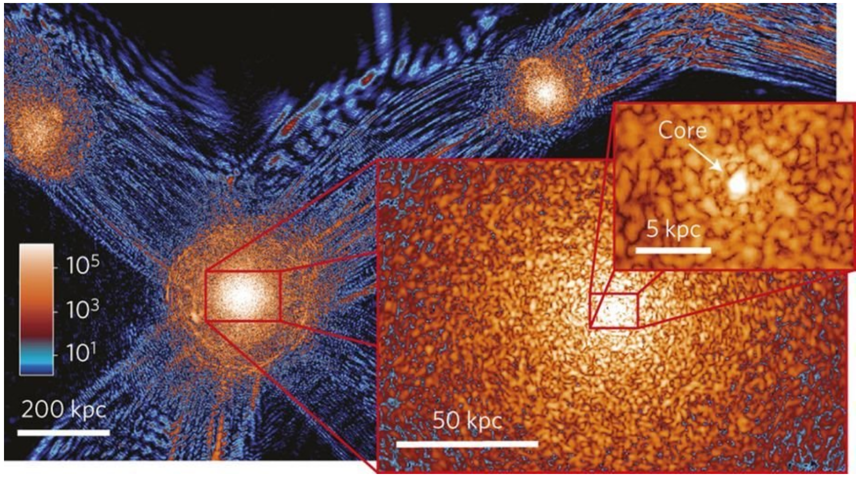


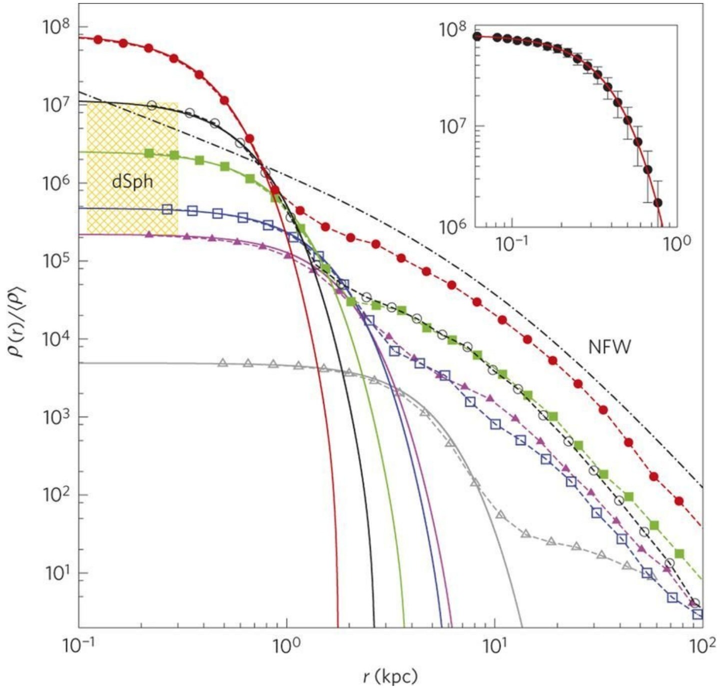
credit: J.Veltmaat

FDM Structure Formation

H.-Y. Schive, T. Chiueh, and T. Broadhurst, *Nature Physics*, 2014





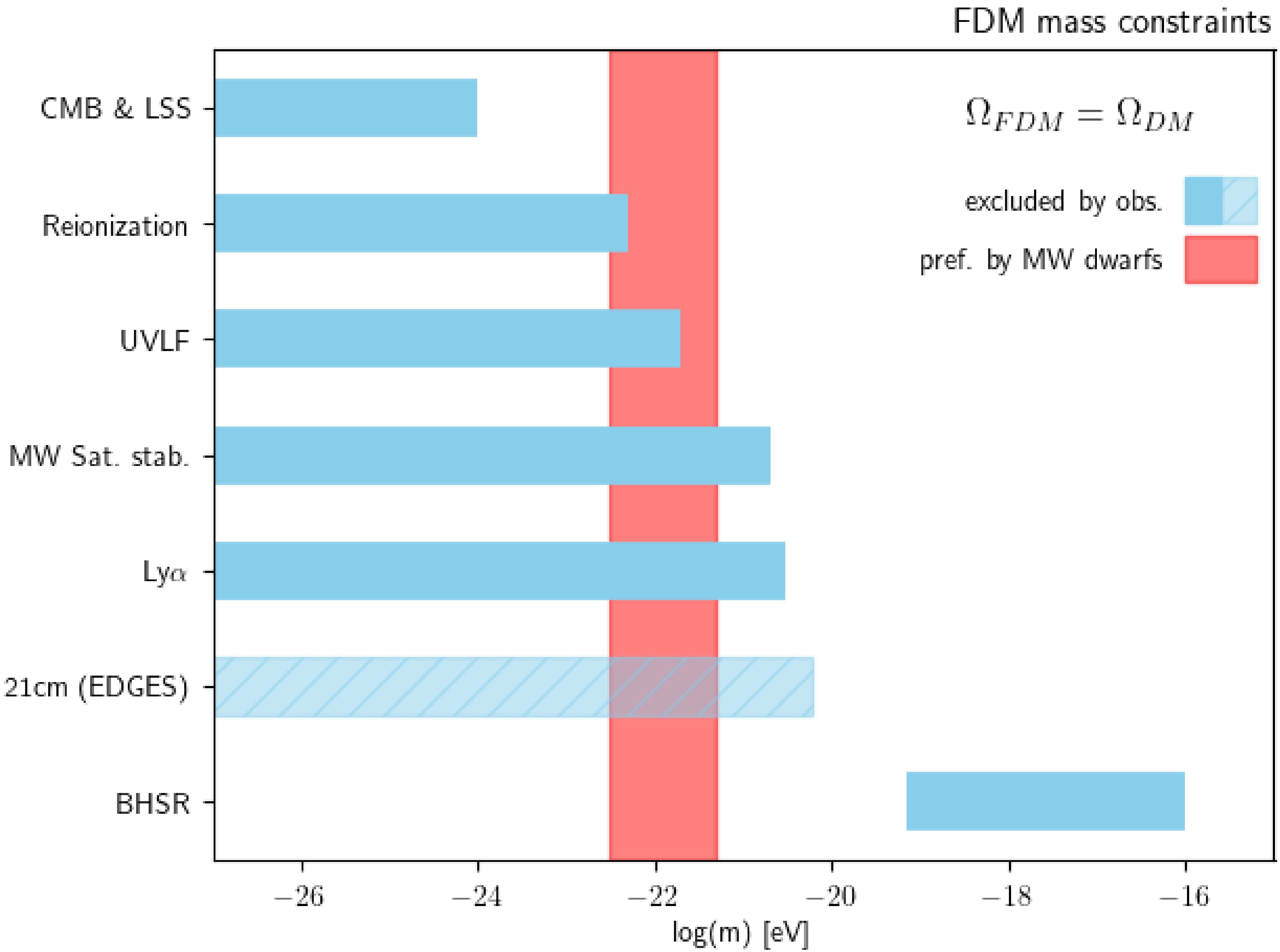


$$i\hbar\frac{\partial\psi}{\partial t} = -\frac{\hbar^2}{2ma^2}\nabla^2\psi + mV\psi$$

$$\nabla^2 V = \frac{4\pi G}{a}\delta\rho \qquad \delta\rho = |\psi|^2$$

$$\lambda_{\mathrm{dB}} \sim \hbar/mv_{\mathrm{vir}} \sim (\hbar/m)(G\rho)^{-1/2}r^{-1}$$

$$\tau_{\mathrm{dB}} \sim \hbar/mv_{\mathrm{vir}}^2$$



FDM mass constraints
$\Omega_{FDM} = \Omega_{DM}$
excluded by obs.
pref. by MW dwarfs
CMB & LSS
Reionization
UVLF
MW Sat. stab.
Lyα
21cm (EDGES)
BHSR
−26
−24
−22
−20
−18
−16
log(m) [eV]

Quantifying FDM Halo Dynamics

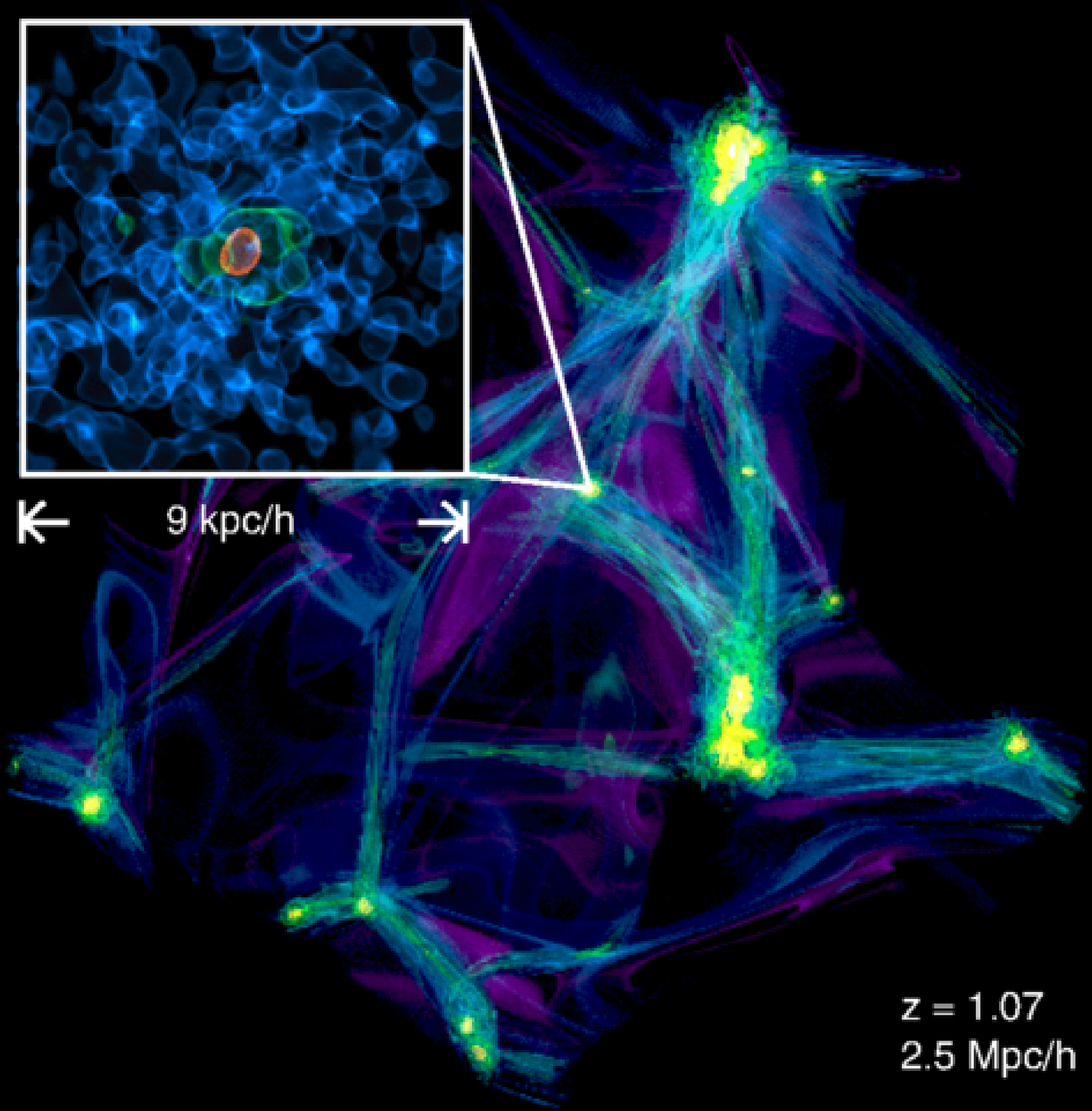
- Radial density profiles
- CDM velocity dispersion vs. FDM granular structure
- Solitonic core dynamics

in three different scenarios

- Pure FDM
- FDM + Baryons
- FDM + CDM

using

- AMR grid structures
- Hybrid particle+grid Methods
- Finite differencing
- Spectral codes
- N-body algorithms


9 kpc/h
z = 1.07
2.5 Mpc/h

Hybrid Method

Goal:

- AMR simulation
- Particle method on low resolution levels
- Finite-difference method on finest level
- Important: Boundary conditions between methods

Madelung transformation: $\Psi = A \exp[-iSm/\hbar]$

Initial phase: $\nabla \cdot v_0 = a^{-1} \nabla^2 S_0$

Phase evolution: $\frac{\mathrm{d}S_i}{\mathrm{d}t} = \frac{1}{2} {v_i}^2 - V(x_i)$

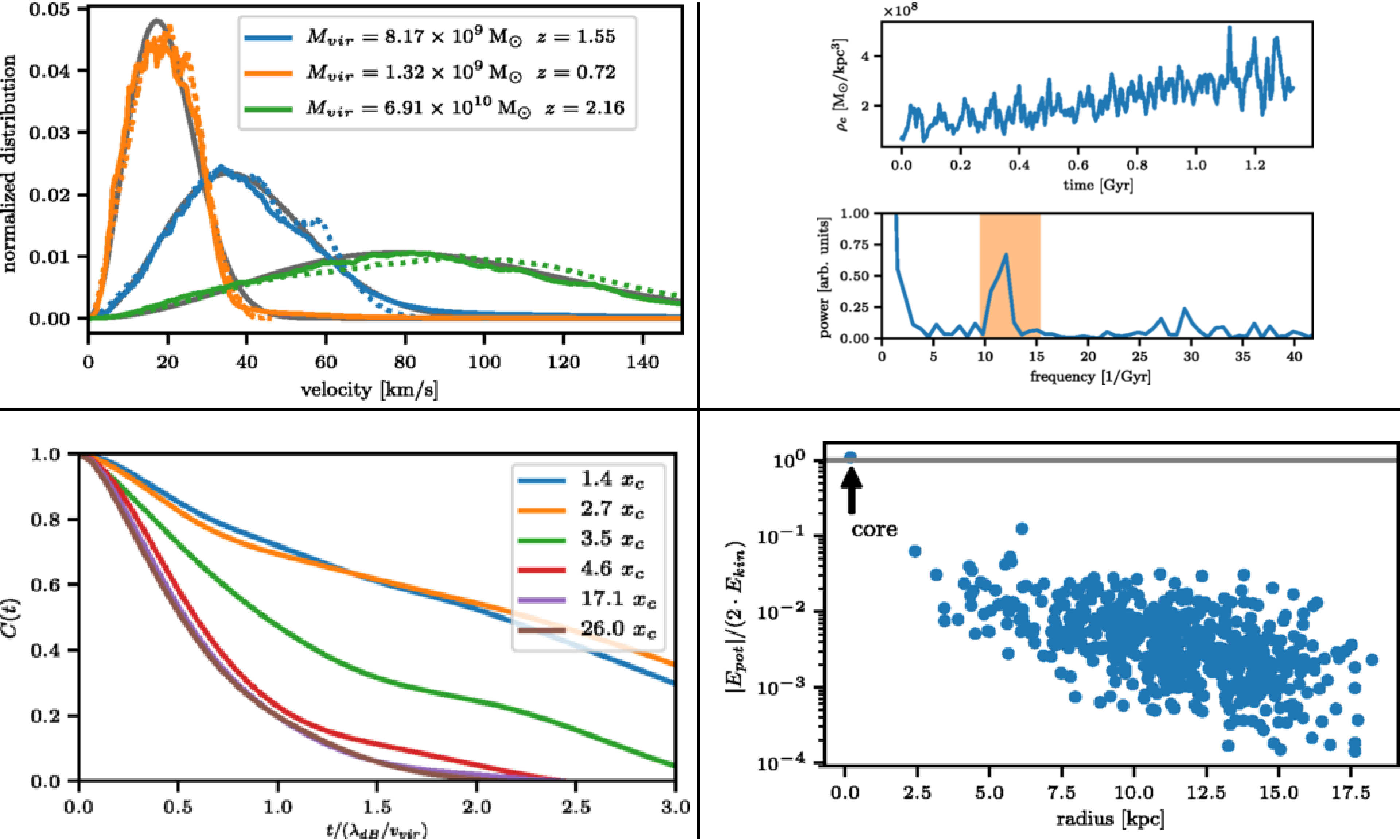
Construction of wavefunction: $A(x) = \sqrt{\sum_i W(x - x_i)}$

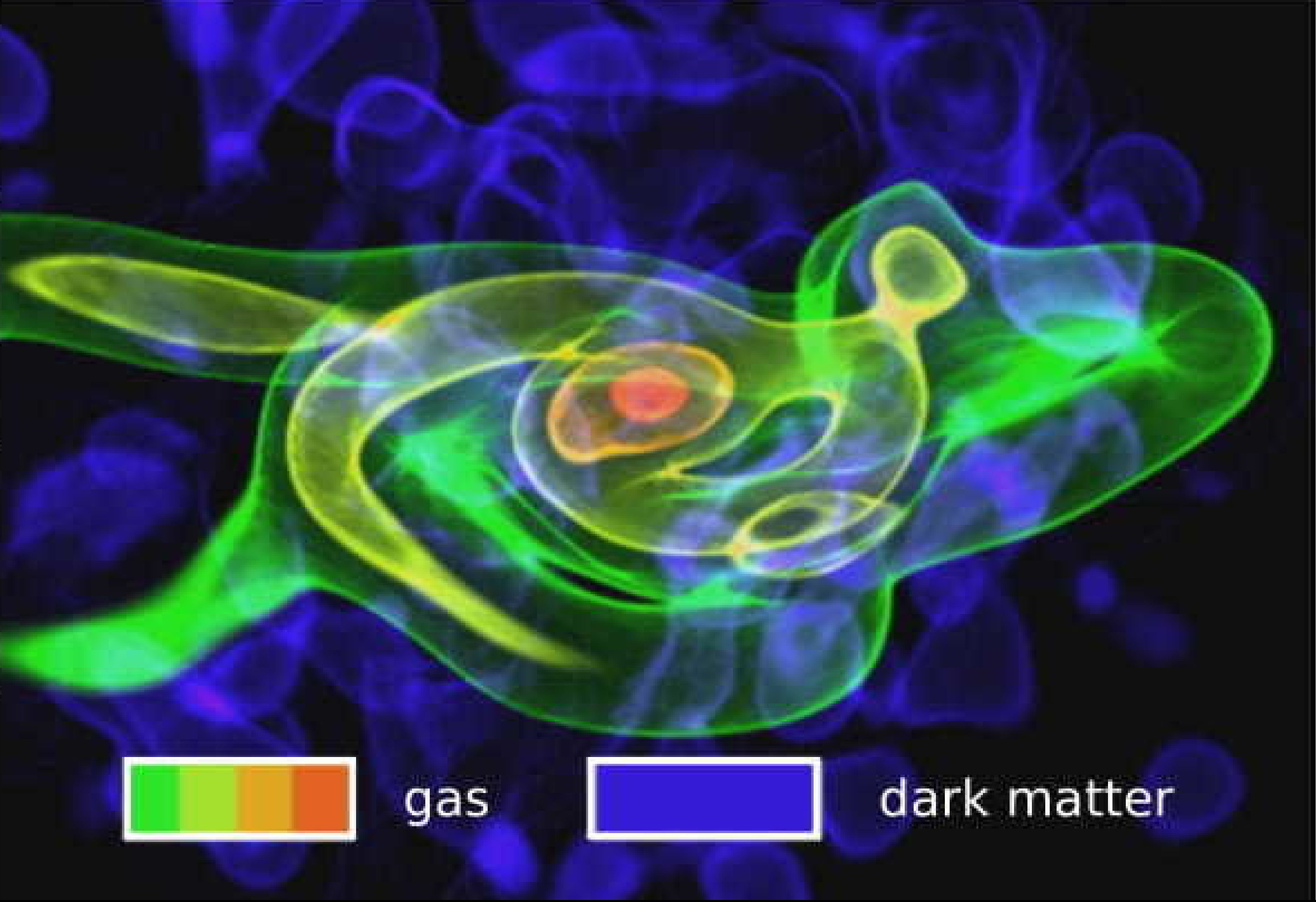
$$S(x) = \frac{\hbar}{m} \arg \left[\sum_i \sqrt{W(x - x_i)} e^{i(S_i + v_i \cdot a(x - x_i))m/\hbar} \right]$$

Note: Classical density -> no gradient energy and interference effects

Structure of FDM Halos

J. Veltmaat, J. C. Niemeyer, and BS, *Physical Review D*, August 2018.

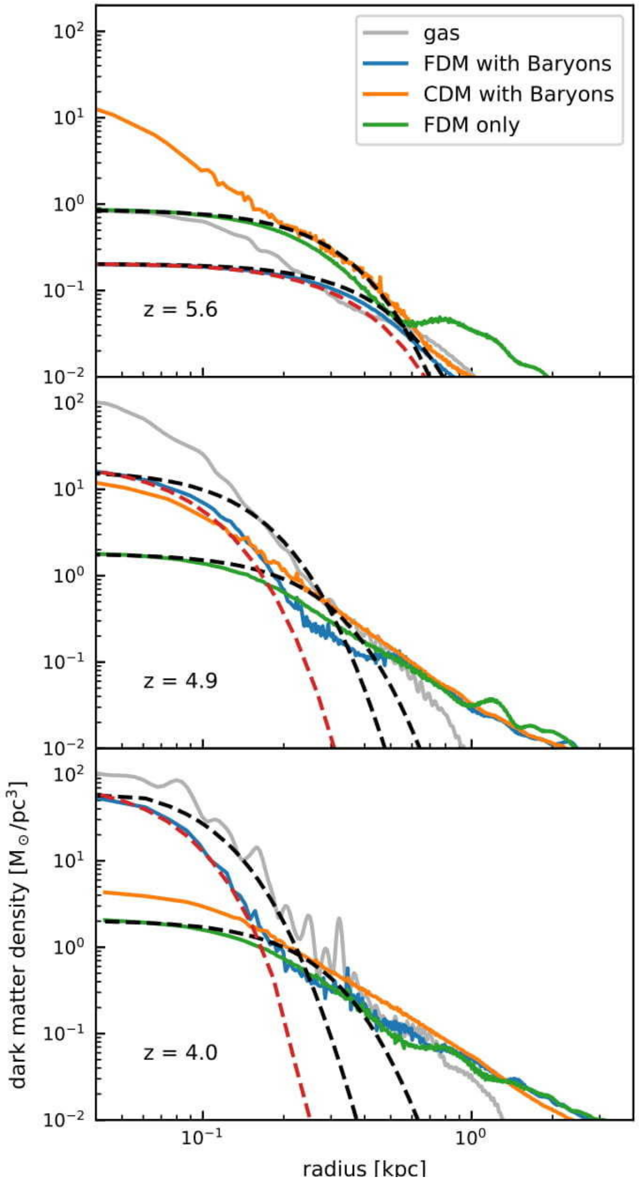


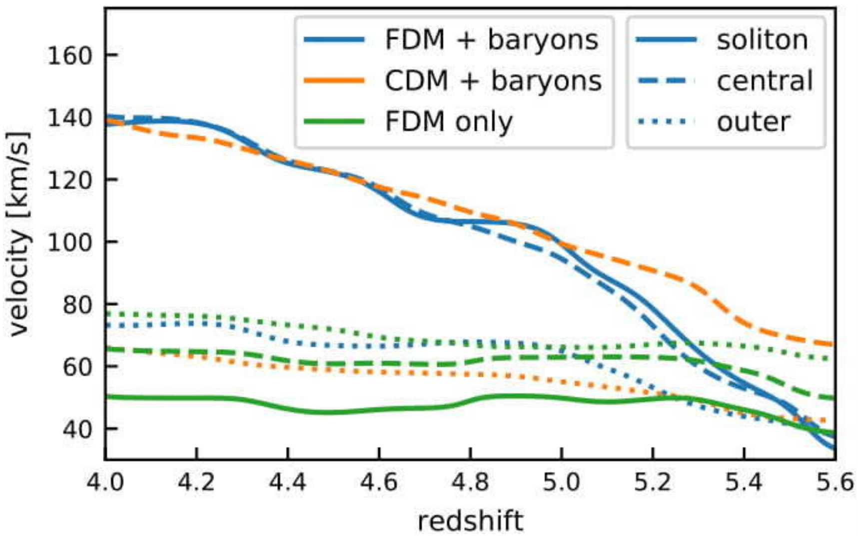


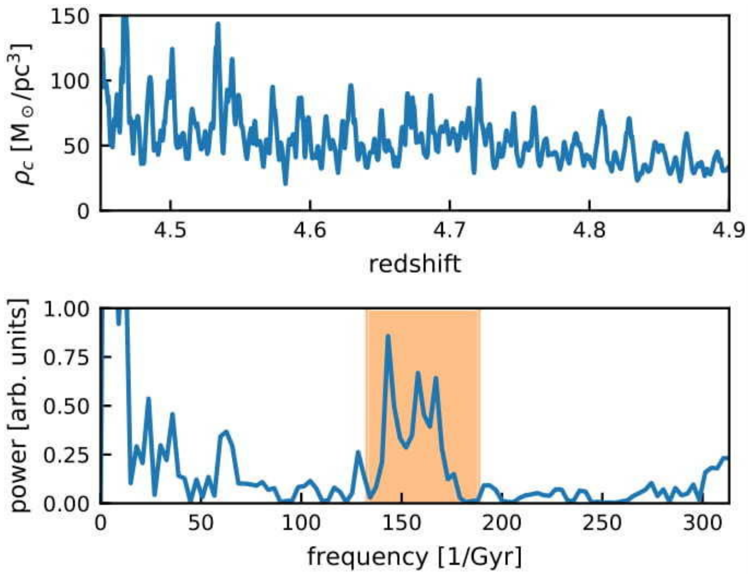
gas
dark matter

FDM Dwarf Galaxy with Baryons

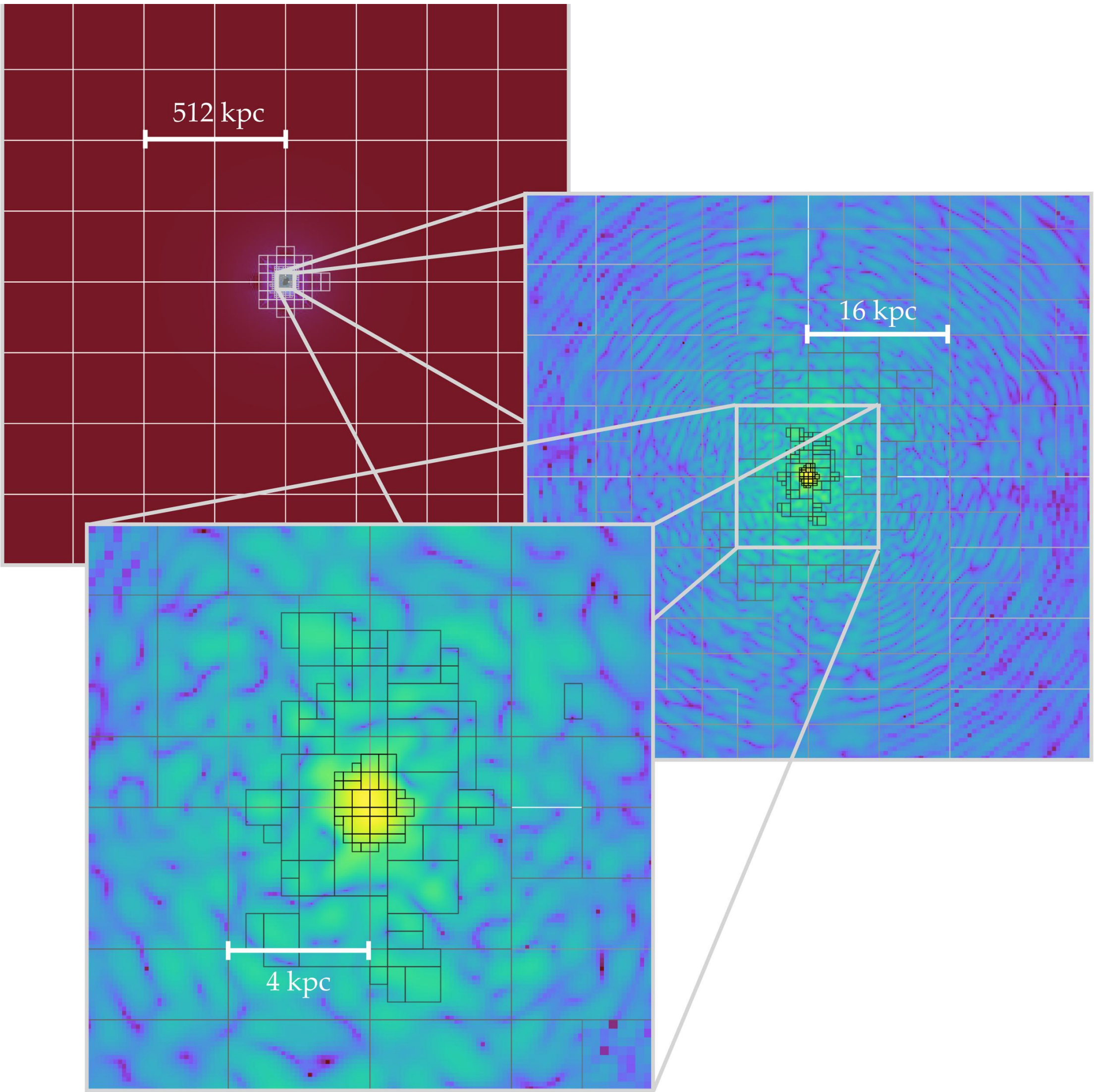
J. Veltmaat, BS, and J. C. Niemeyer, *Physical Review D*, April 2020.







AxioNyx: Simulating Mixed Fuzzy and Cold Dark Matter



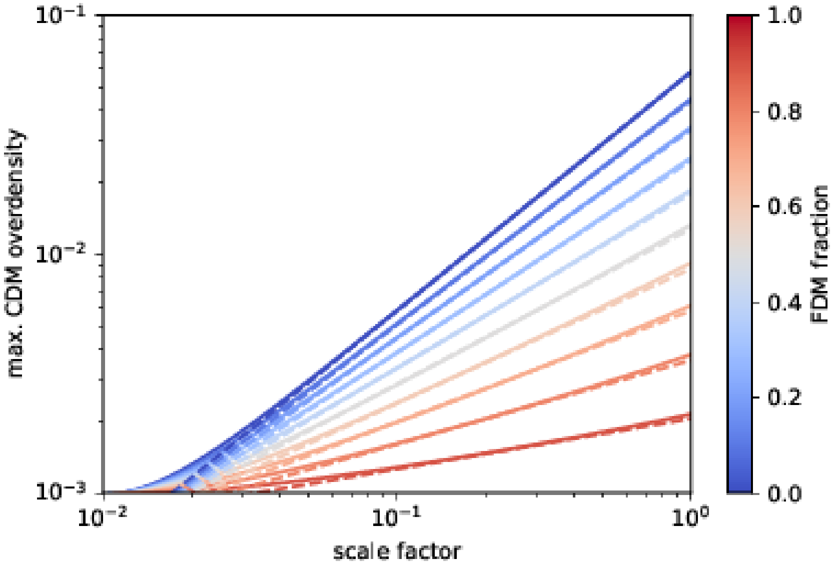
BS, Mateja Gosenca, Christoph Behrens, Jens C. Niemeyer, and Richard Easther, *in prep.*

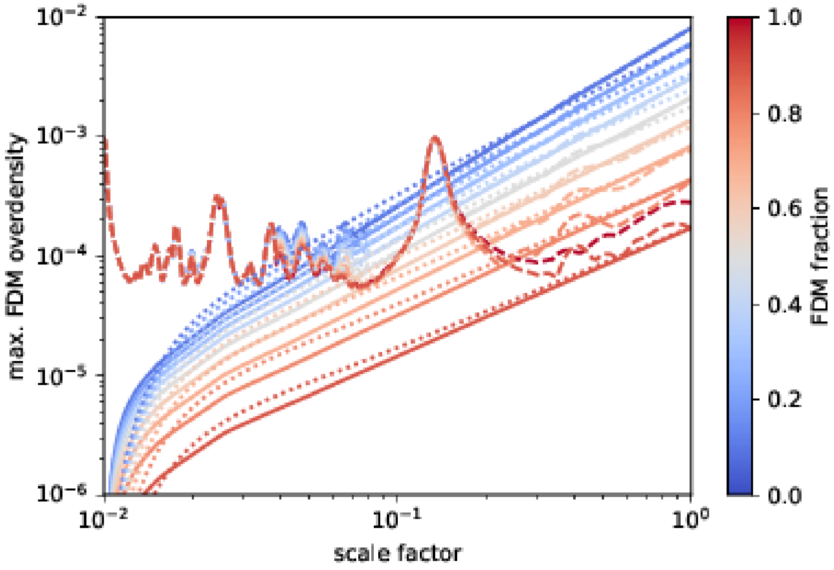
Goal:

- AMR simulations for Mixed Dark Matter
- CDM -> N-body scheme
- FDM -> Spectral/Finite-difference method
- Baryonic physics -> Nyx modules for hydrodynamics and feedback

Spherical Collapse - linear

$$\ddot{\delta}_{\rm FDM} + 2H\dot{\delta}_{\rm FDM} + \left(\frac{k^4\hbar^2}{4m^2a^4} - 4\pi G f\overline{\rho}\right)\delta_{\rm FDM} = 4\pi G(1-f)\overline{\rho}\delta_{\rm CDM}$$
$$\ddot{\delta}_{\rm CDM} + 2H\dot{\delta}_{\rm CDM} - 4\pi G(1-f)\overline{\rho}\delta_{\rm CDM} = 4\pi G f\overline{\rho}\delta_{\rm FDM}$$

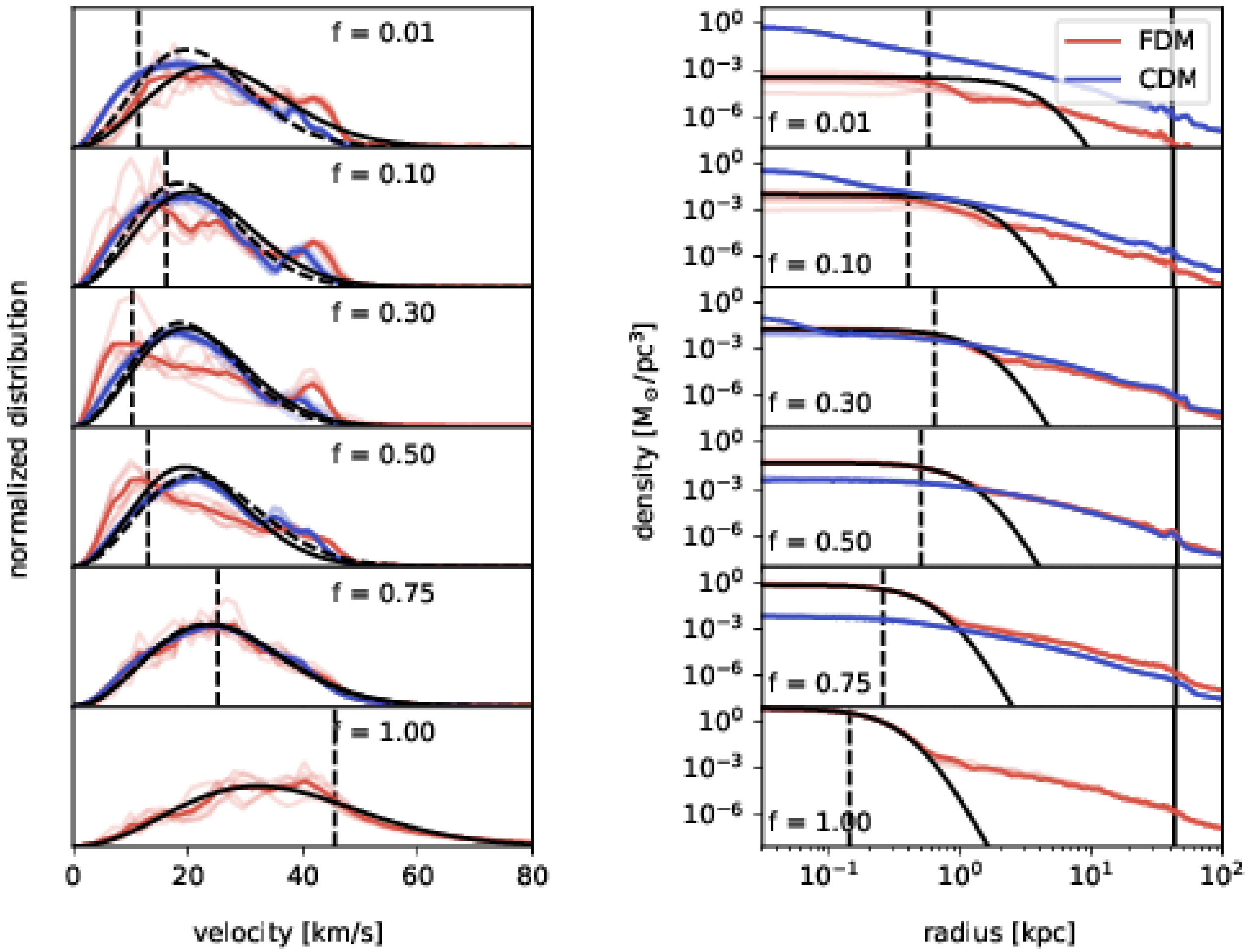




$$\delta_{\rm CDM}(a) \propto a^{(\sqrt{1+24(1-f)}-1)/4}$$

$$\delta_{\rm FDM}(a) \propto a^{(\sqrt{1+24(1-f)}+3)/4}$$

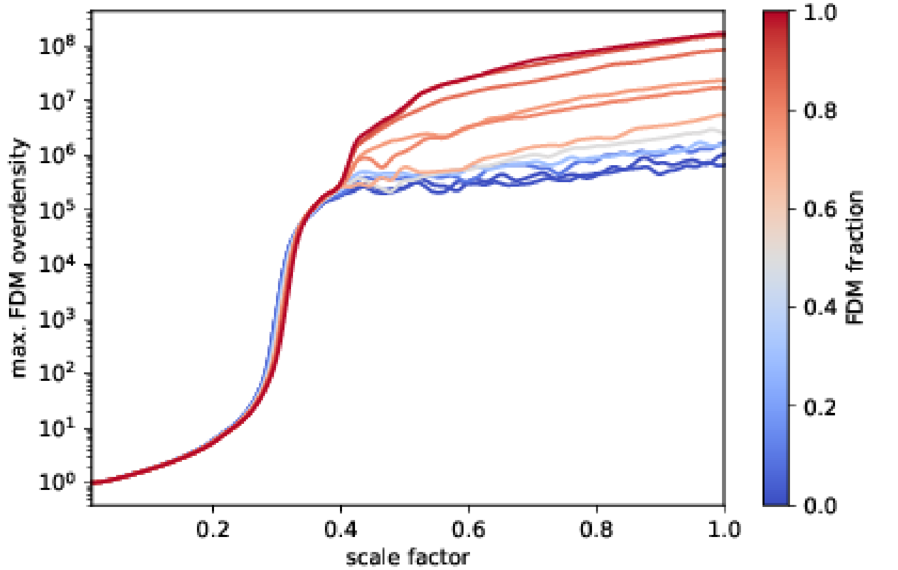
Spherical Collapse - Non-linear

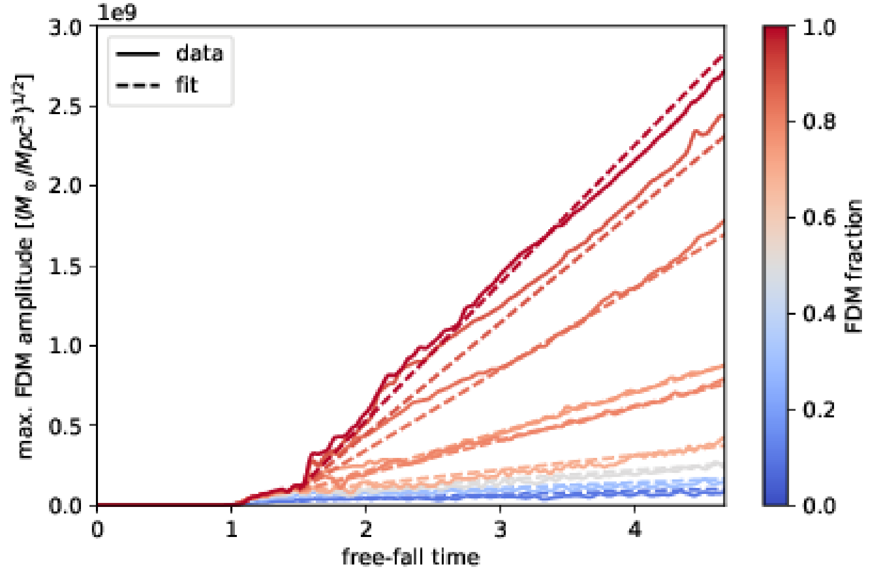


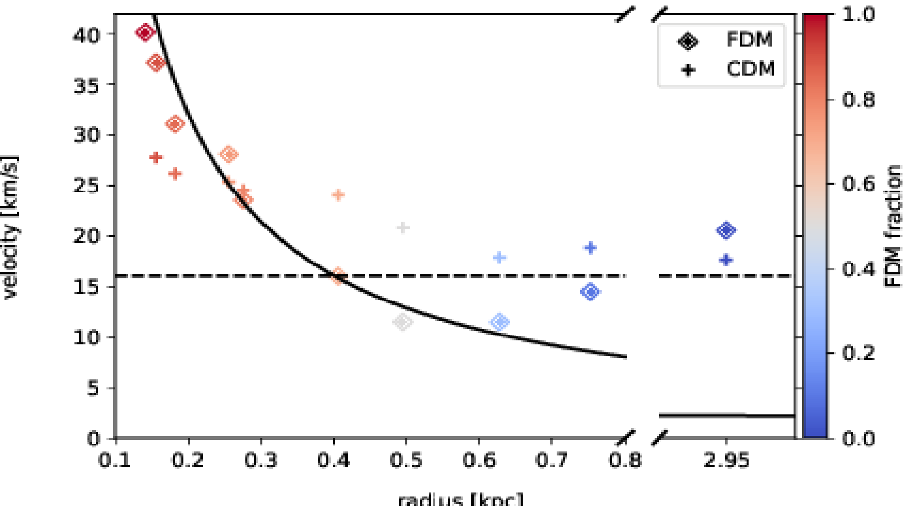
$$f(\mathbf{v}) = \frac{1}{N}\left|\int \mathrm{d}^3x \exp\left[-im\mathbf{v}\cdot\mathbf{x}/\hbar\right]\psi(\mathrm{x})\right|^2$$

$$v_c = \frac{2\pi}{7.5}\frac{\hbar}{mr_c}$$

Spherical Collapse - Non-linear







$$A(t) = A_1 \cdot (t - t_0)/\tau_{\rm gr} + A_0 f^{1/2}$$

$$\tau_{\rm gr} = \frac{0.7\sqrt{2}}{12\pi^3}\,\frac{m^3 v_c^6}{G^2 \rho_c^2 \Lambda} \simeq 0.015\,\frac{t_c}{\Lambda}$$

Conclusions

- FDM structure formation similar to CDM on super deBroglie scales (except cut-off in initial power spectrum as for WDM)
  - Weakly non-linear probes like Lyman-alpha exclude $m < 10^{-21}\,\mathrm{eV}$
- **Distinguishing features of FDM:** Strong stochastic density fluctuations in halos on deBroglie length and time scales and formation of stable, oscillating soliton cores in center of halos
  - Local FDM density important for experiments but not well constraint yet
  - Heavier FDM mass can be best constrained on non-linear, galactic scales (soliton osc., soliton mergers, gravitational heating/cooling, tidal disruption,...)

-- Need further dedicated FDM simulations on galactic scales --