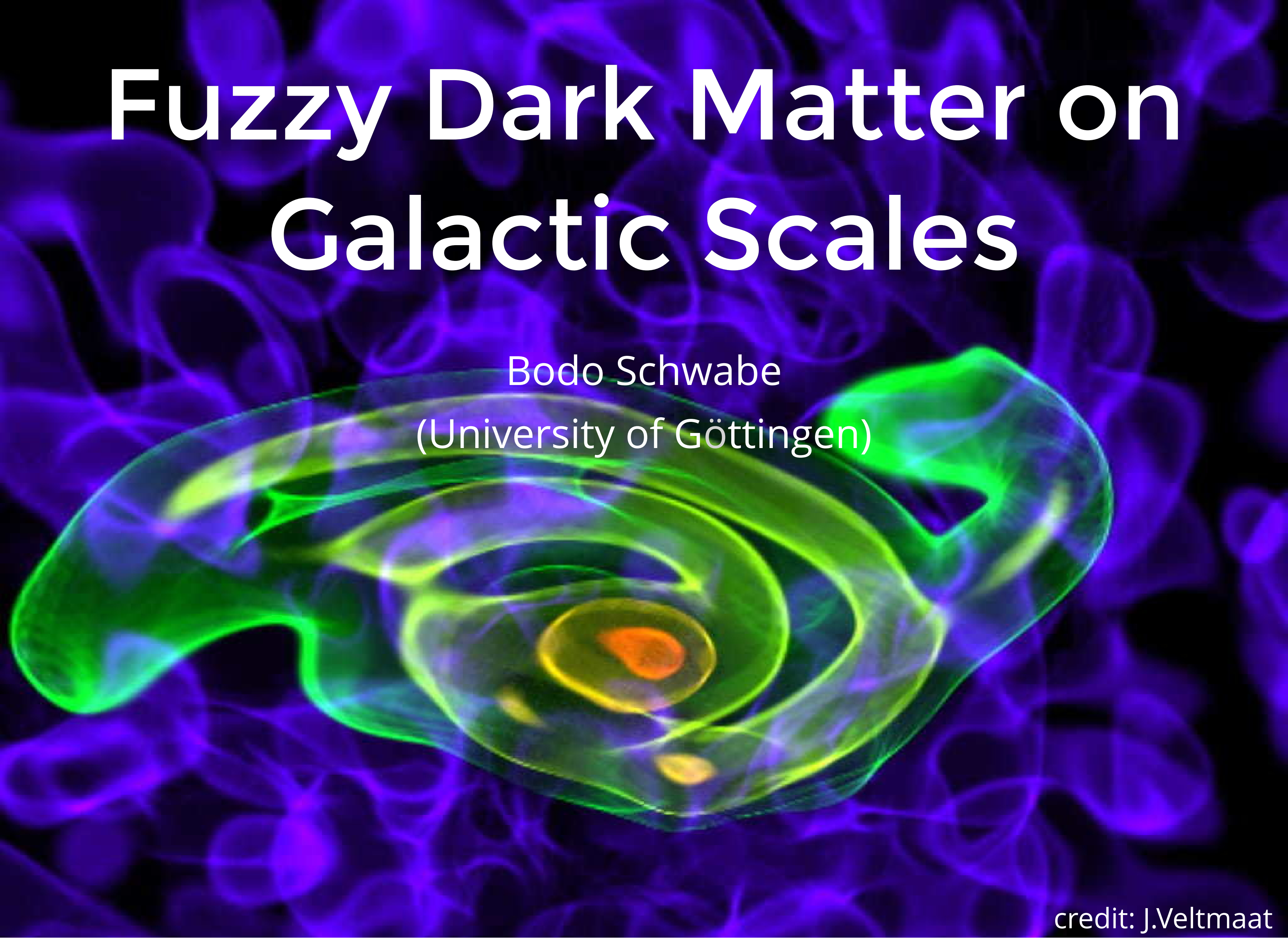


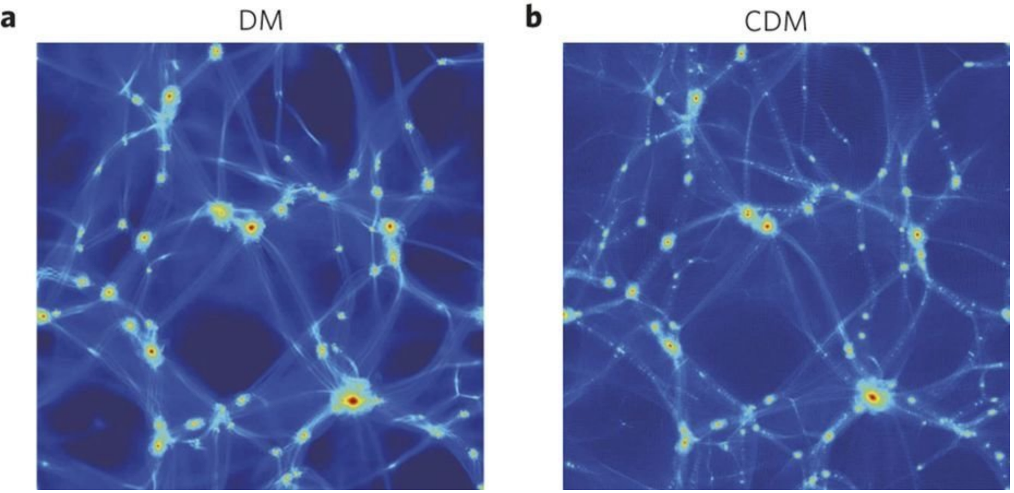
Fuzzy Dark Matter on Galactic Scales

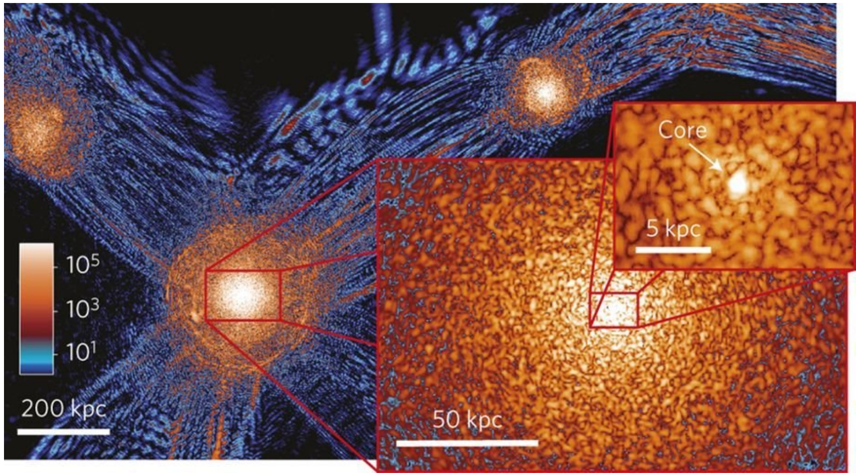
Bodo Schwabe
(University of Göttingen)

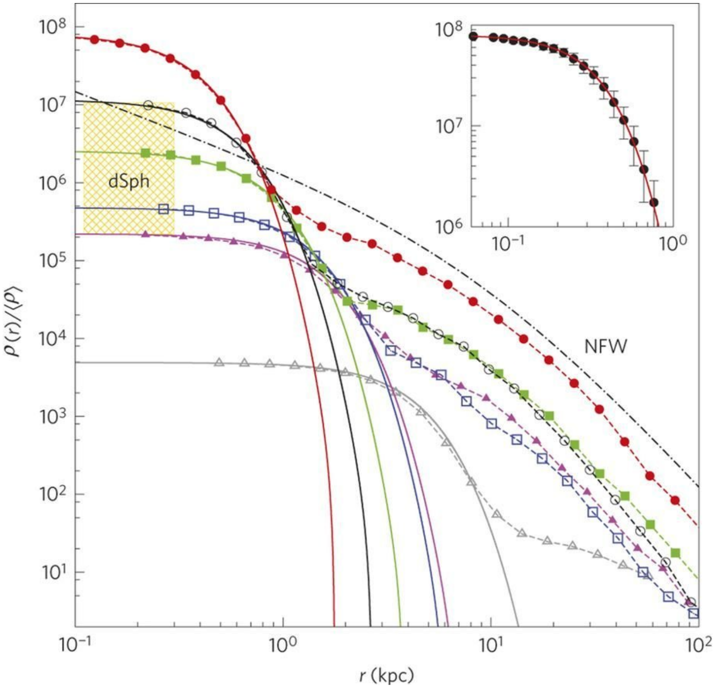
credit: J.Veltmaat

FDM Structure Formation

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







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

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

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

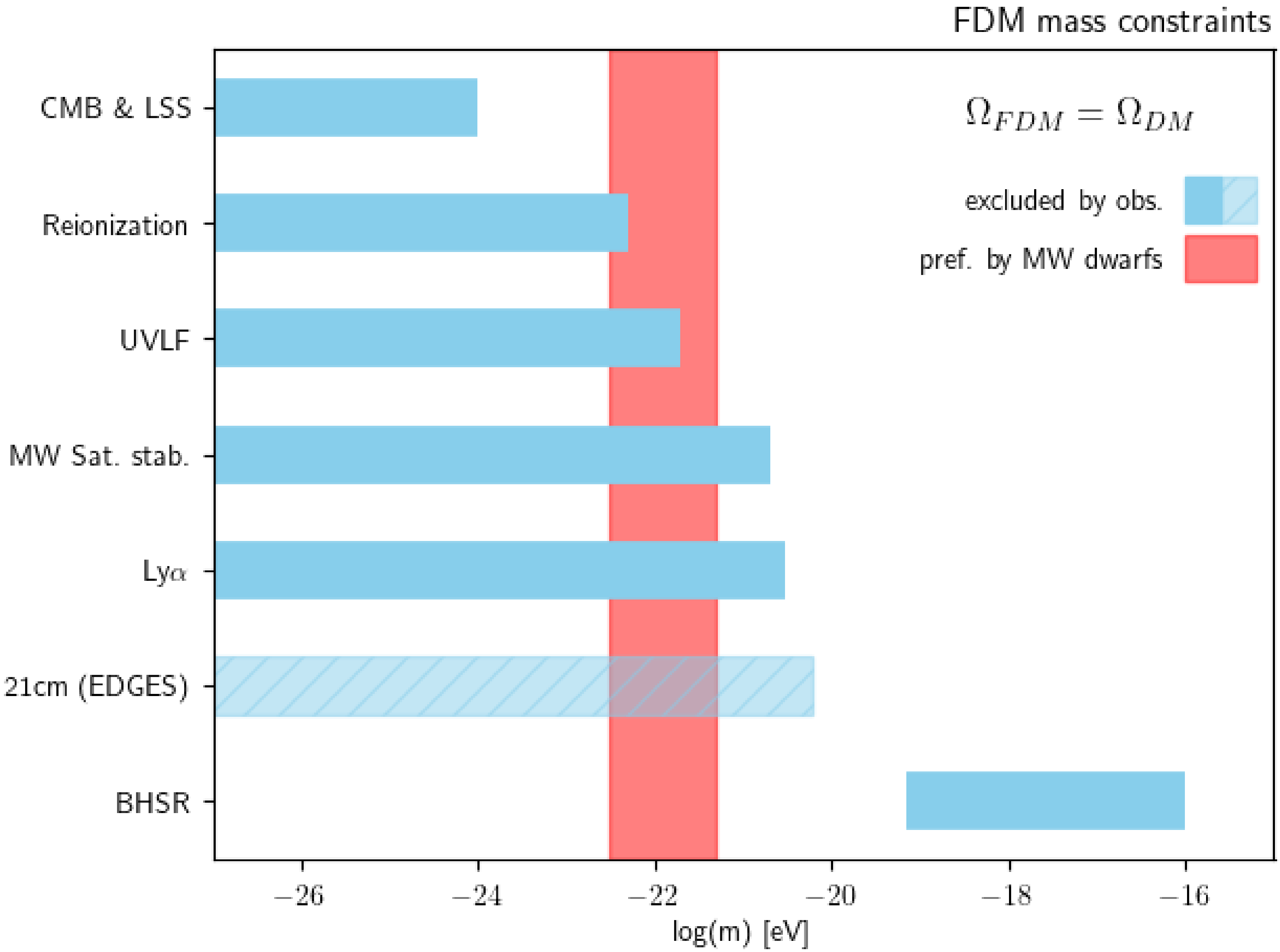
$$\tau_{\mathrm{dB}} \sim \hbar/mv_{\mathrm{vir}}^2$$

FDM Solitonic core dynamics

- Formation
- Merger history
- Tidal disruption
- Equilibration in halo

FDM halo dynamics

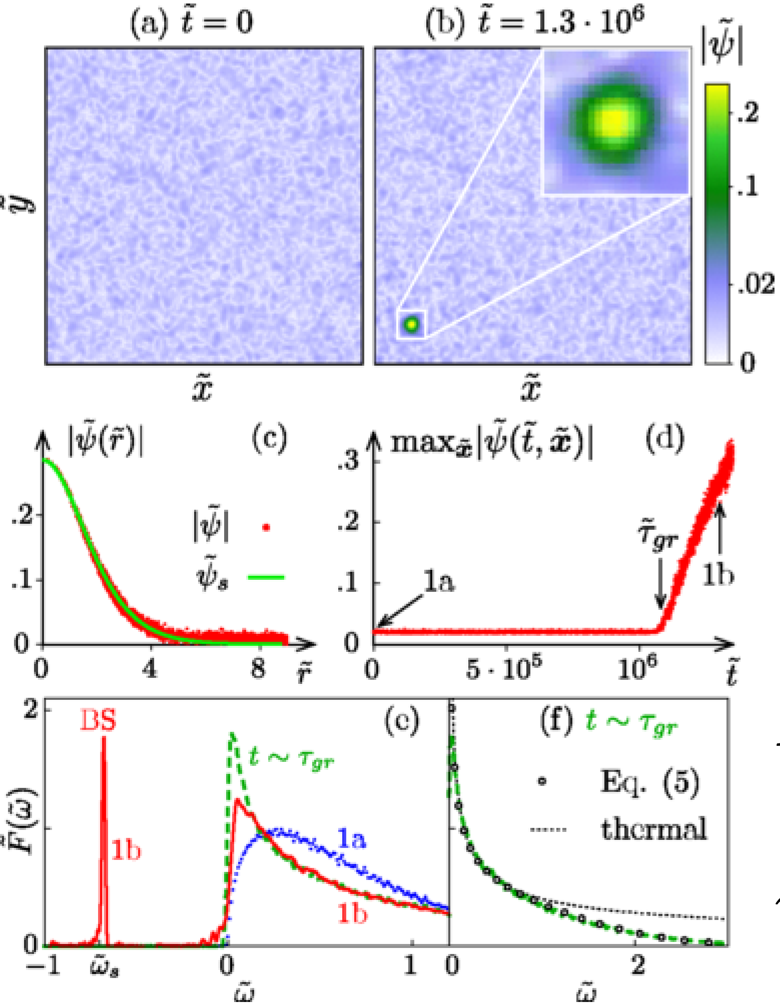
- CDM velocity dispersion vs. FDM granular structure

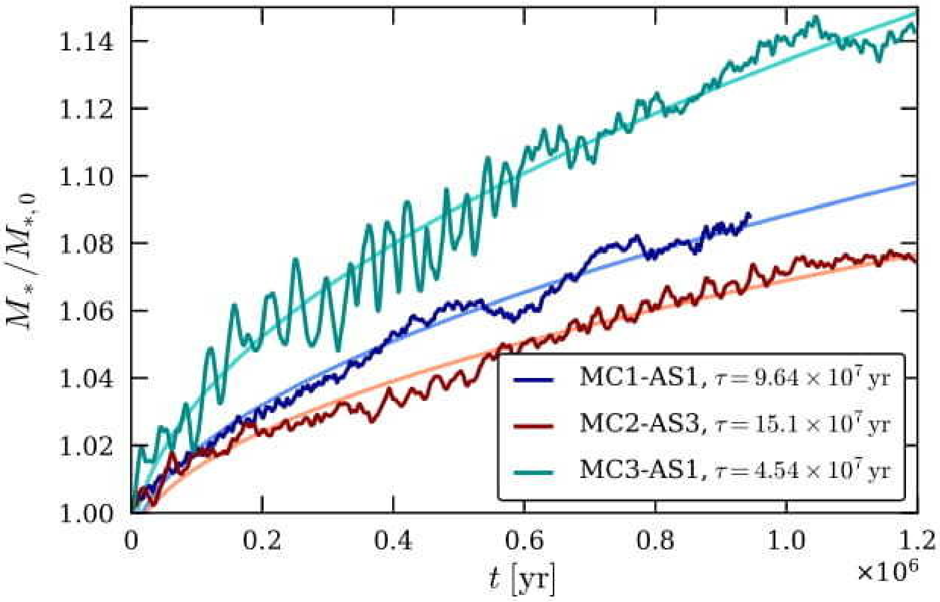

FDM mass constraints
$\Omega_{FDM} = \Omega_{DM}$
excluded by obs.
pref. by MW dwarfs
CMB & LSS
Reionization
UVLF
MW Sat. stab.
Lyα
21cm (EDGES)
BHSR
−26
−24
−22
−20
−18
−16
log(m) [eV]

Formation and Mass Growth of Axion Stars in Axion Miniclusters

D.G. Levkov, A.G. Panin, I.I. Tkachev, *Phys. Rev. Lett.*, October 2018

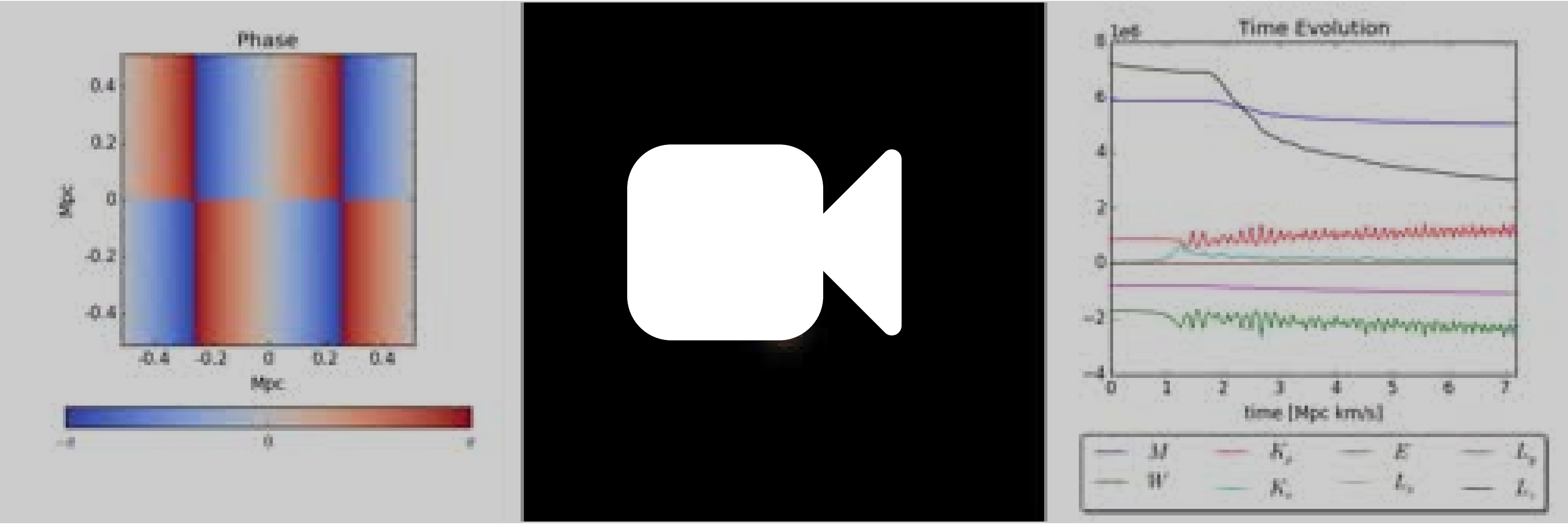
B. Eggemeier, J.C. Niemeyer, *Phys. Rev. D,* September 2019





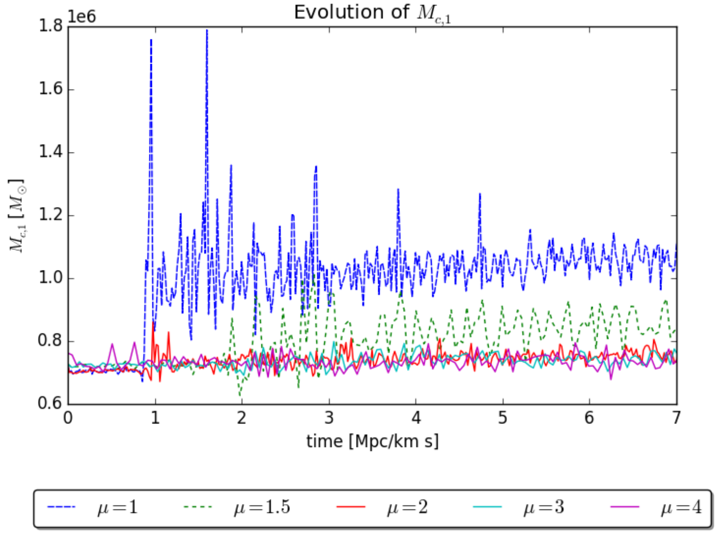
$$M_*(t) \simeq M_{*,0}\left(\frac{t}{\tau}\right)^{1/2} \to M_*(t) \simeq M_{*,\mathrm{sat}}\left(\frac{t}{\tau_{\mathrm{sat}}}\right)^{1/8}$$

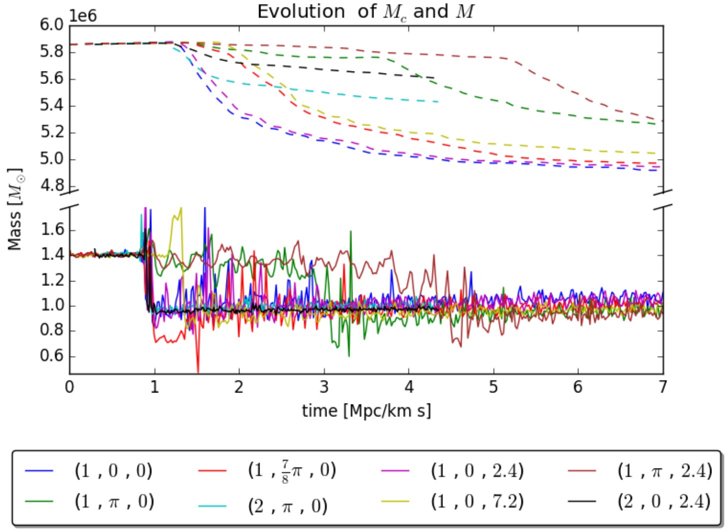
$$\tau \simeq \frac{1}{20}\frac{R}{v}(R/\lambda_{\mathrm{dB}})^3/\log(R/\lambda_{\mathrm{dB}}) \qquad M_{*,\mathrm{sat}} \sim M_h^{1/3}$$

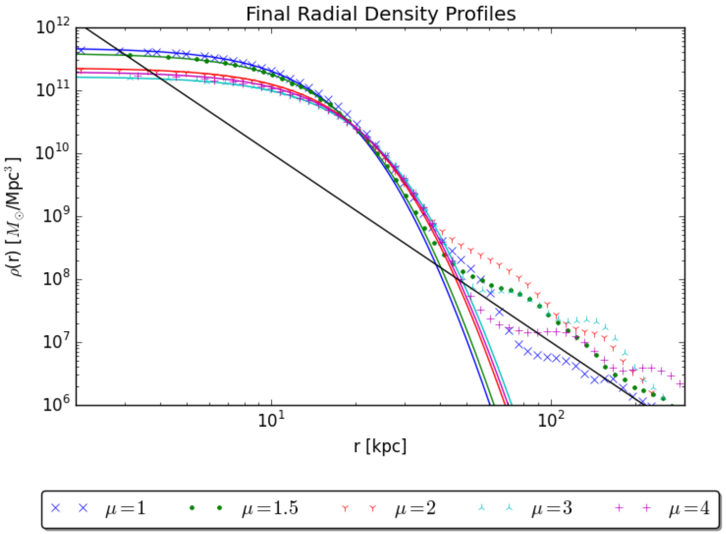

Phase
0.4
0.2
0
-0.2
-0.4
Mpc
-0.4
-0.2
0
0.2
0.4
Mpc
$-\pi$
0
π
Time Evolution
1e6
8
6
4
2
0
-2
-4
0
1
2
3
4
5
6
7
time [Mpc km/s]
M
K_ρ
E
L_y
W
K_v
L_x
L_z

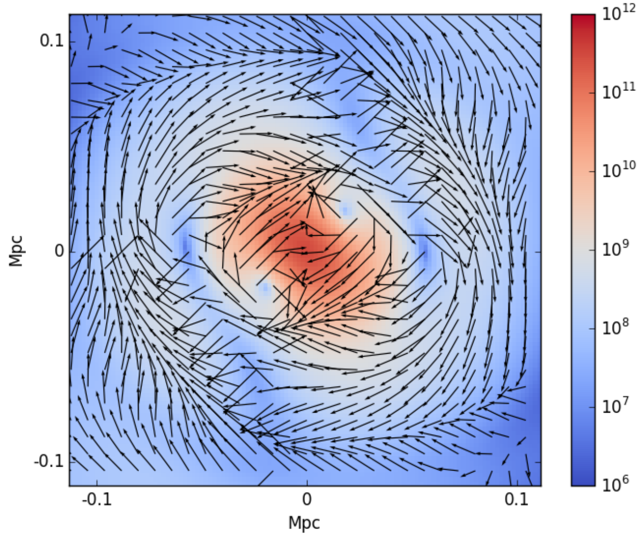
Solitonic Core Mergers

BS, J. C. Niemeyer, and J. F. Engels, *Physical Review D*, August 2016.





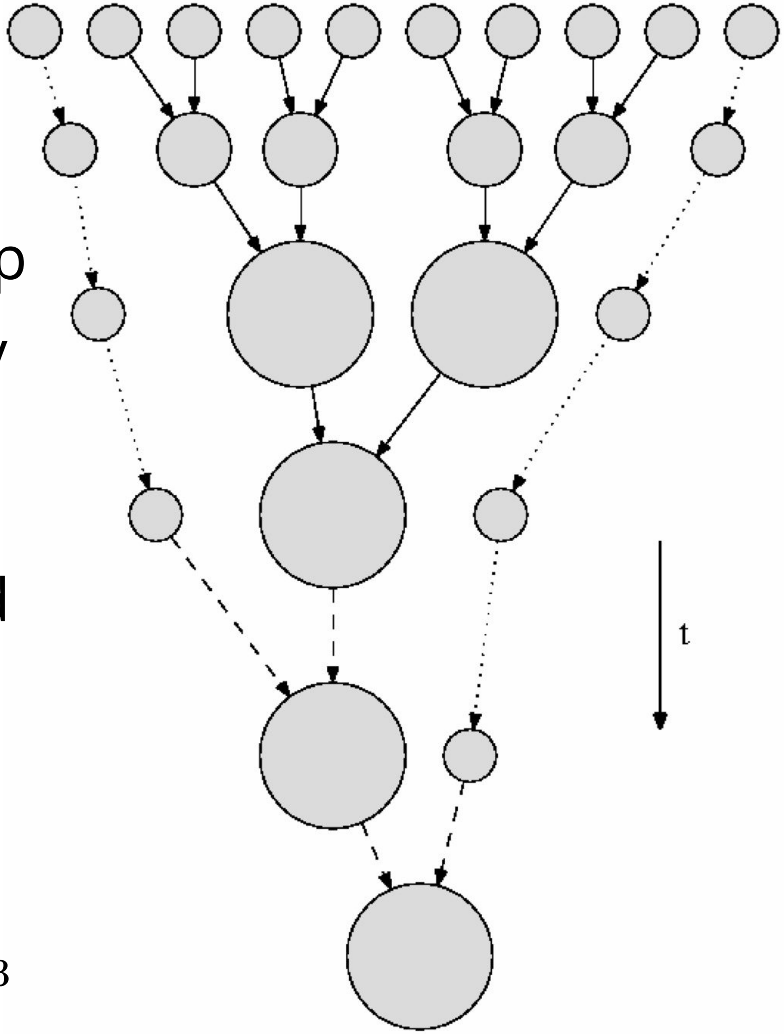




Recipe for Core Evolution

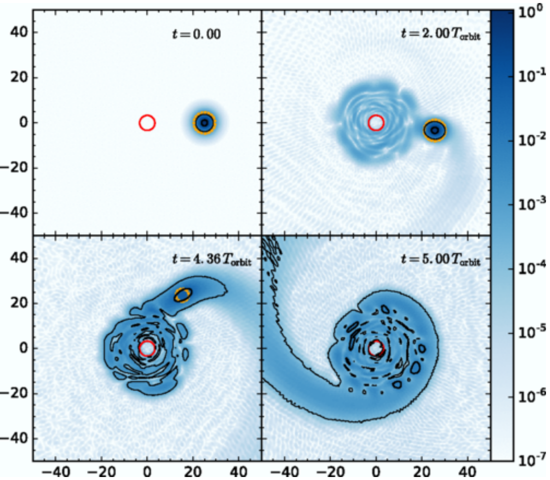
BS, J. C. Niemeyer, and J. F. Engels, *Physical Review D*, August 2016.
X. Du, C. Behrens, J. C. Niemeyer, and BS, *Physical Review D*, February 2017.

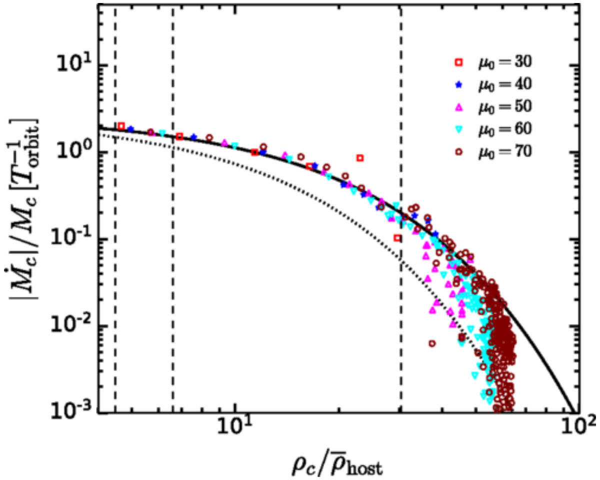
- Bound core mergers result in new solitonic core
- Cores merge rapidly once they overlap
  - Merger history is a series of binary mergers
- Only major mergers with mass ratio $\mu = M_{c1}/M_{c2} < \beta/(1-\beta)$yield increased core mass $M_c = \beta(M_{c1} + M_{c2})$
- Minor mergers and smooth accretion leave heavier core unchanged
- Numerically find $\beta \simeq 0.7$
- Recover the scaling relation $M_c \sim M_h^{1/3}$ found in cosmological simulations

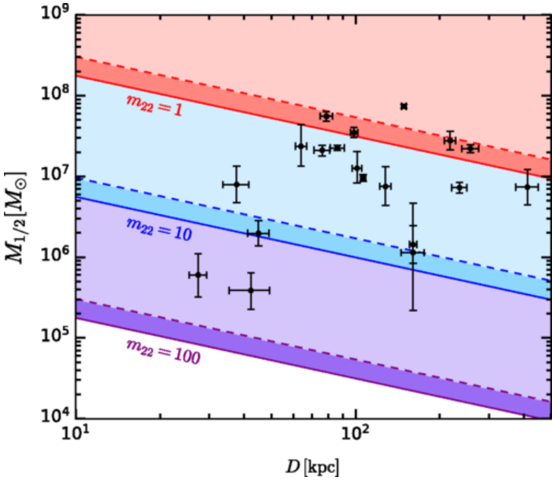


Tidal Disruption of Subhalo Cores

X. Du, BS, J. C. Niemeyer, and D. Bürger, *Physical Review D*, March 2018.





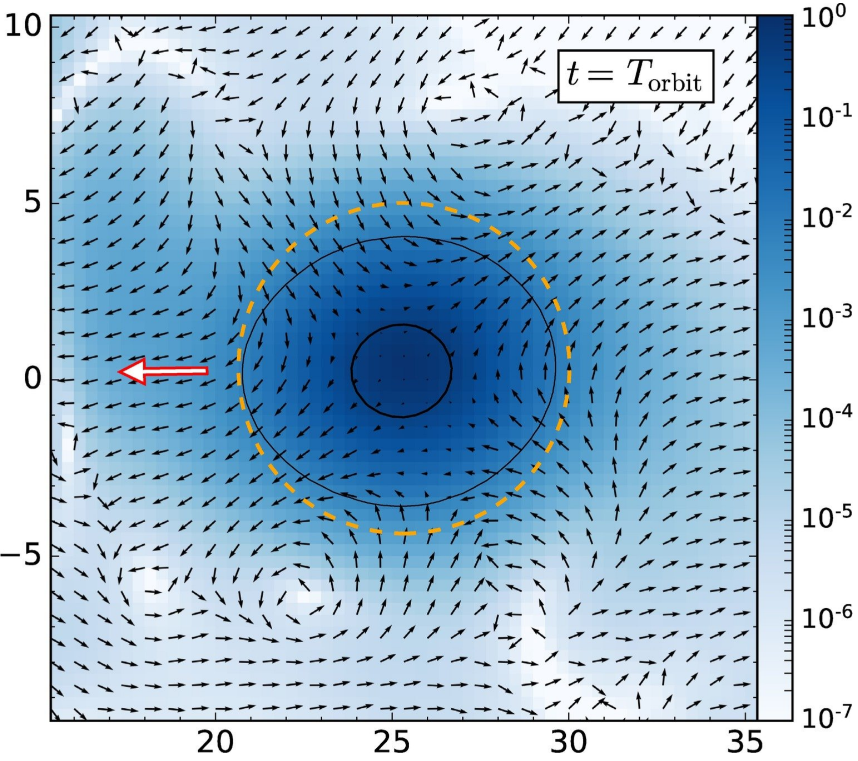


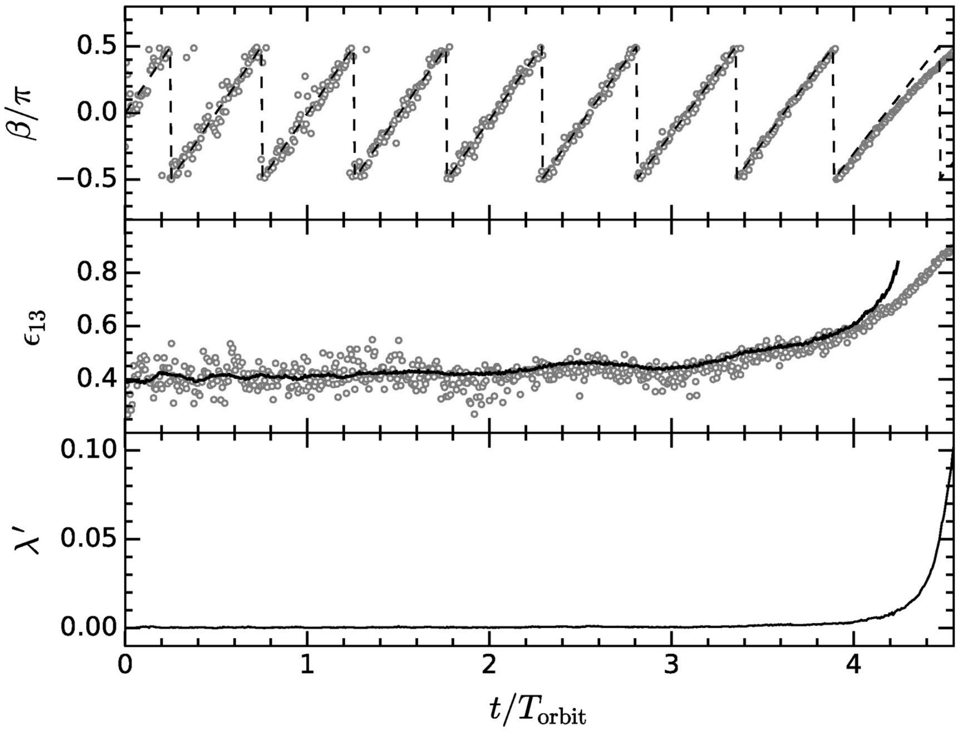
$$M_c > 5.82 \times 10^8 \, [\mu_{\min}(N_{\rm sur})]^{1/4} \, m_{22}^{-3/2} \left(\frac{D}{\rm kpc}\right)^{-3/4} \left(\frac{M_h}{10^{12}\,M_\odot}\right)^{1/4} M_\odot$$

- Lightest satellites close to the Galactic center will only survive for more than one orbital time if the particle is as heavy as $m_{22} \simeq 20$.

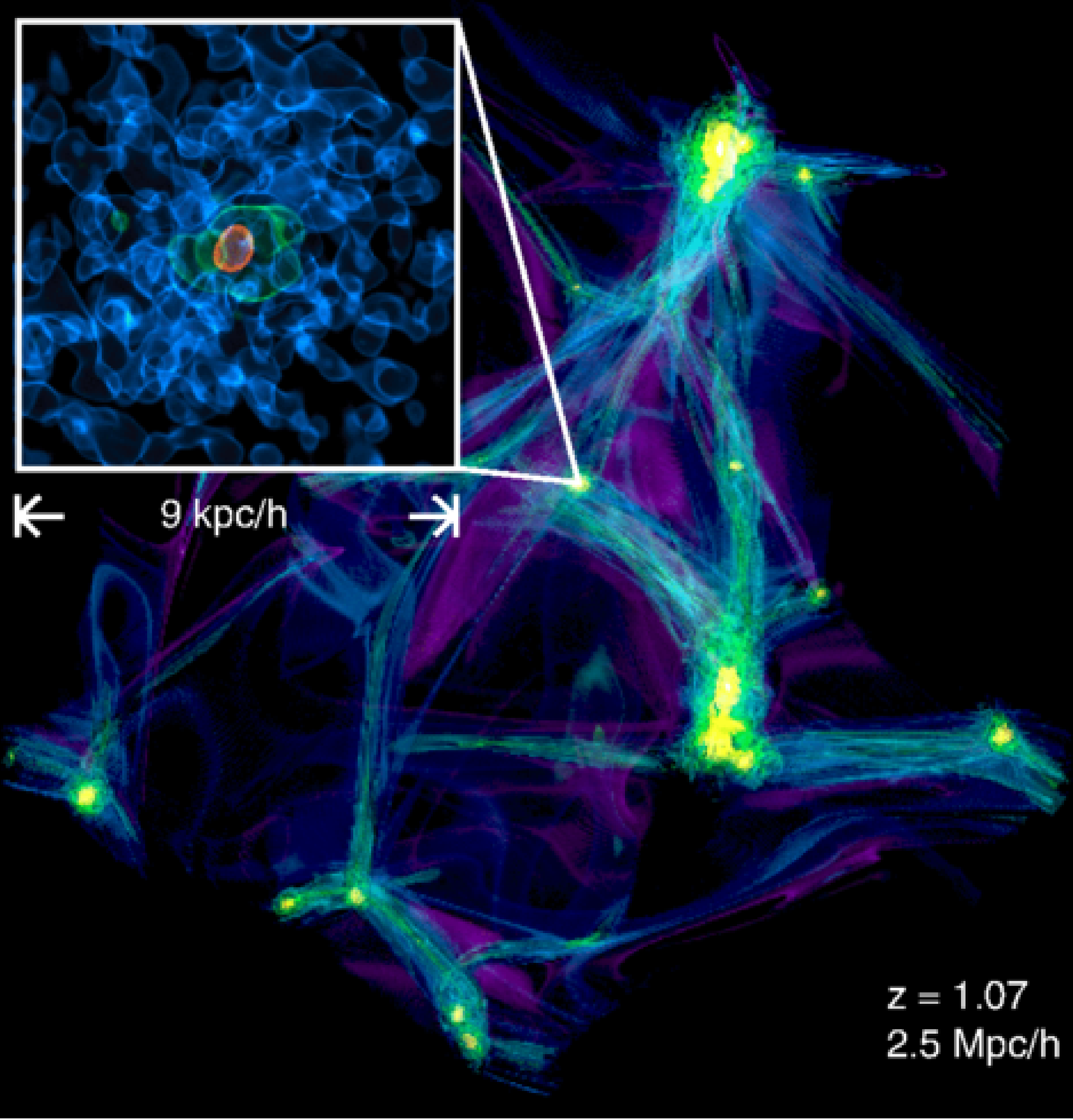
Tidal core deformation

X. Du, BS, J. C. Niemeyer, and D. Bürger, *Physical Review D*, March 2018.



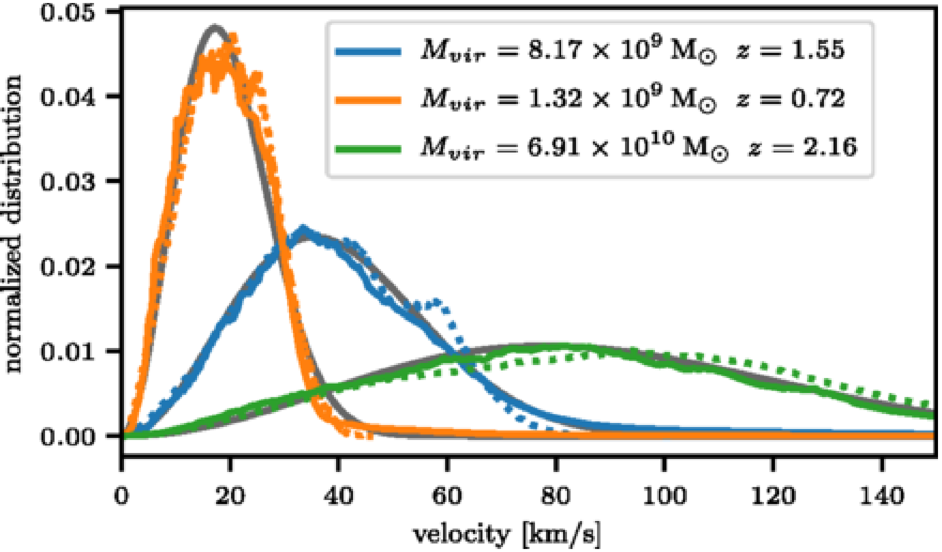


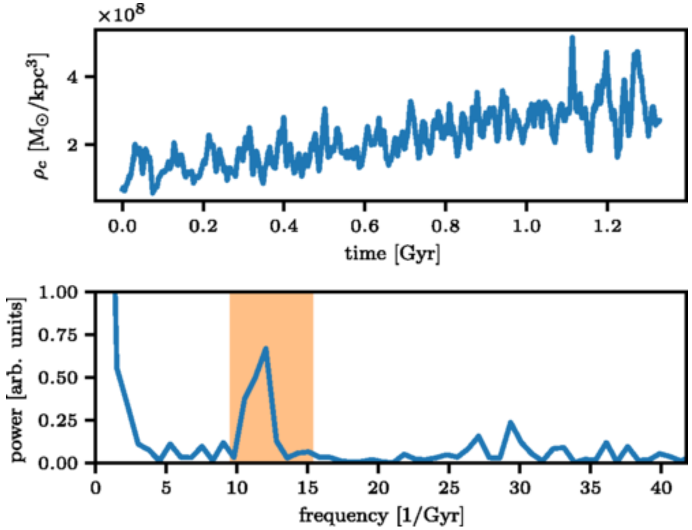
Tidally locked ellipsoid with decreasing mass and central density (-> smaller tidal radius) and increasing core radius and eccentricity

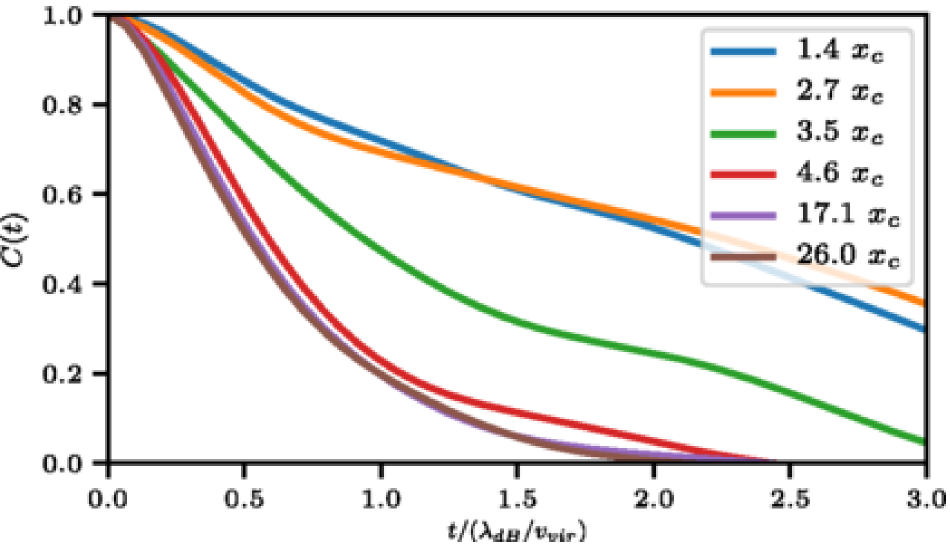

9 kpc/h
z = 1.07
2.5 Mpc/h

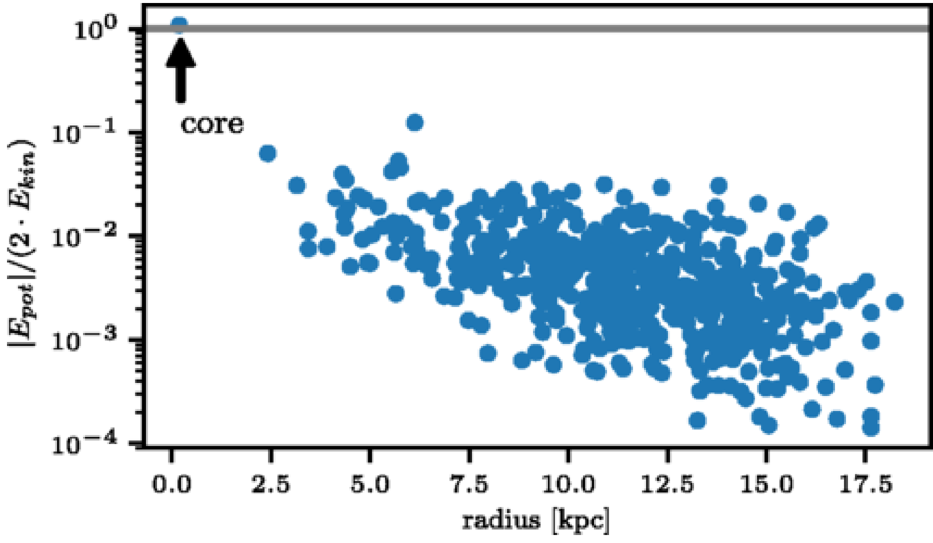
Structure of FDM halos

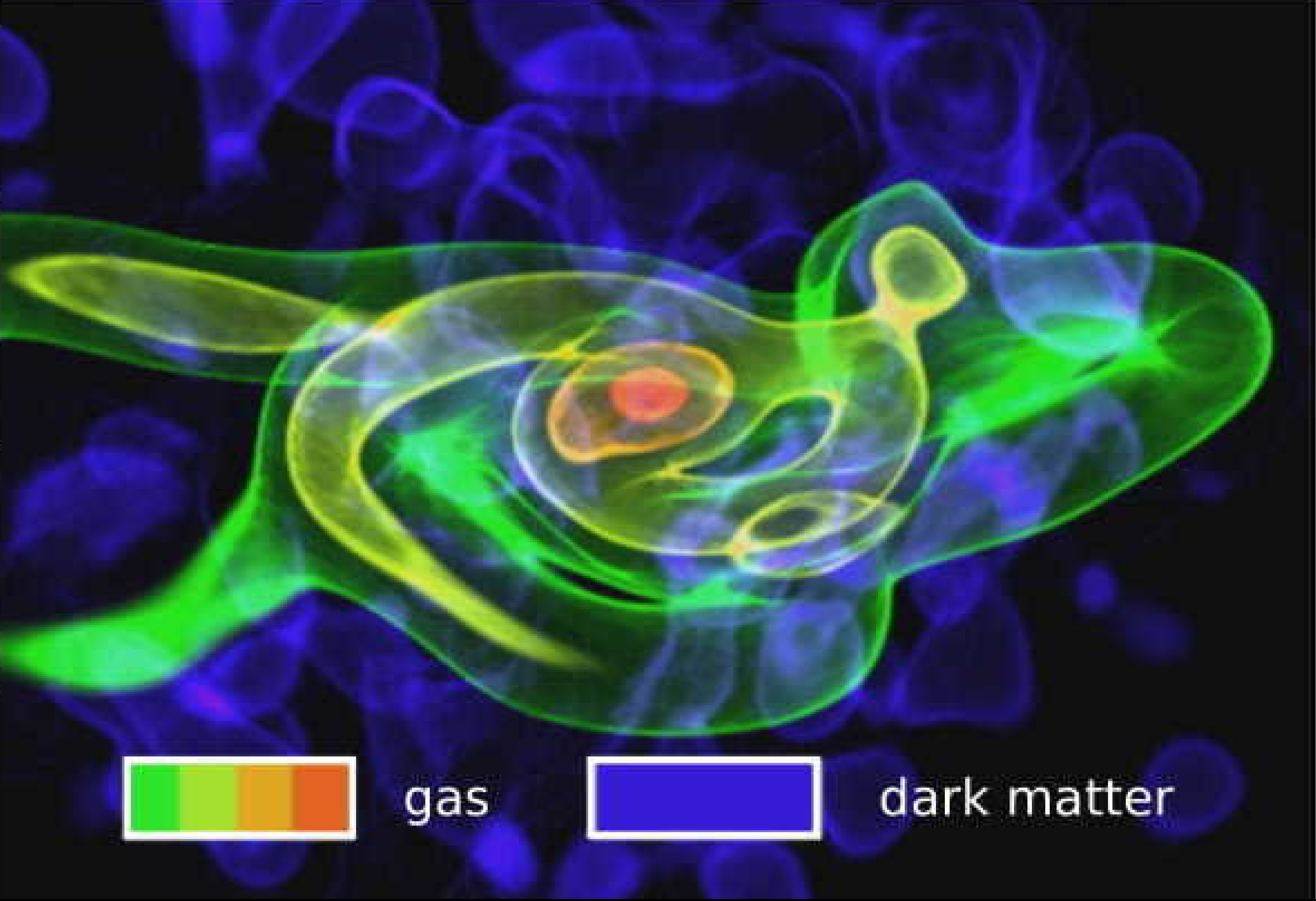
J. Veltmaat, J. C. Niemeyer, and BS, *Physical Review D*, August 2018.





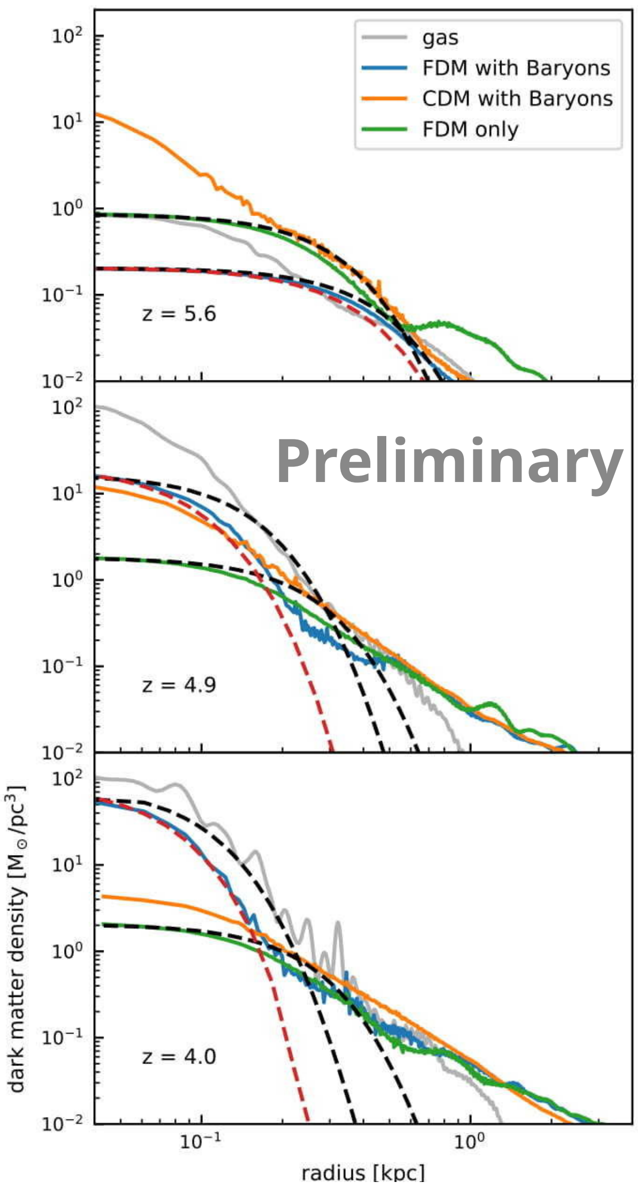


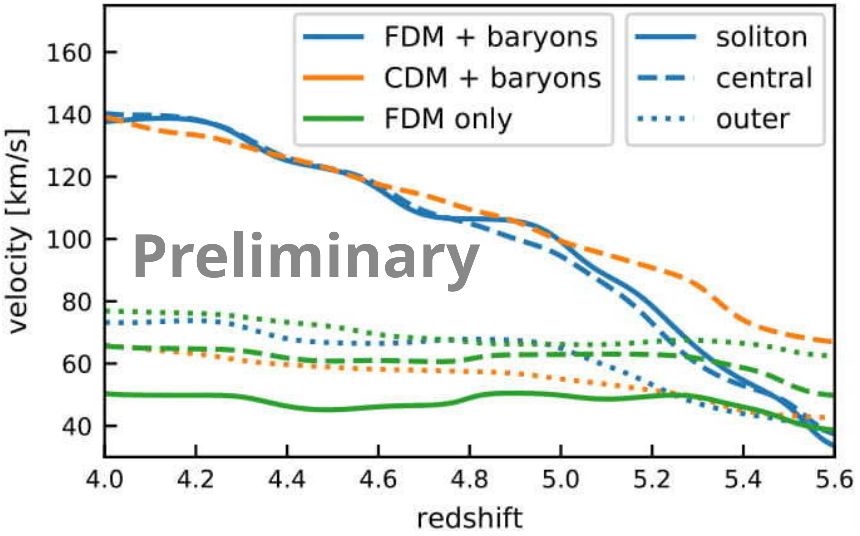


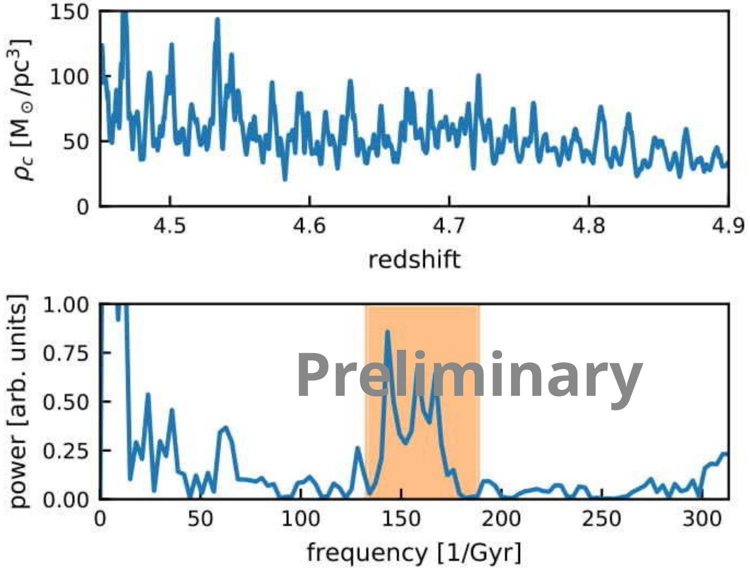

gas
dark matter

FDM dwarf galaxy with baryons

J. Veltmaat, J. C. Niemeyer, and BS, *to be published*, October 2018.







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
  - Heavier FDM mass can be best constrained on non-linear, galactic scales (soliton osc., soliton mergers, gravitational heating/cooling, tidal disruption,...)
  - Local FDM density important for experiments but not well constraint yet

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