Small scales, big differences: nonlinear structures beyond CDM

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The standard model of cosmology: ΛCDM + vanilla inflation

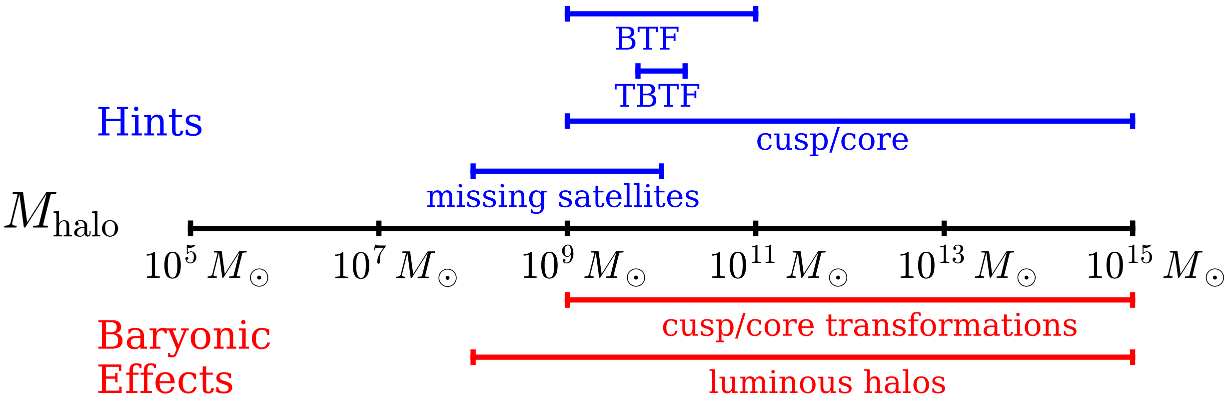
- Λ:
  - no time dependence
  - no couplings to DM or baryons
  - gravity = GR

- CDM:
  - nonrelativistic; no non-gravitational interactions
  - nearly self-similar hierarchy of bound structures (halos) with $dn/dM \sim M^{-1.9}$ at small masses
  - halo substructure down to free-streaming scale with $dN/dm \sim m^{-1.8}$
  - without baryons: near-universal density profiles („NFW“) with central 1/r-cusps

- slow-roll, single field inflation:
  - nearly scale-invariant perturbation spectrum on scales relevant for structure formation
  - negligible isocurvature perturbations
  - negligible primordial non-Gaussianties

- physics beyond CDM (bCDM):
  - differences most pronounced on small, nonlinear scales
  - challenges for both observations and theory

Small-scale structure and ΛCDM: Is it a bug or a feature?



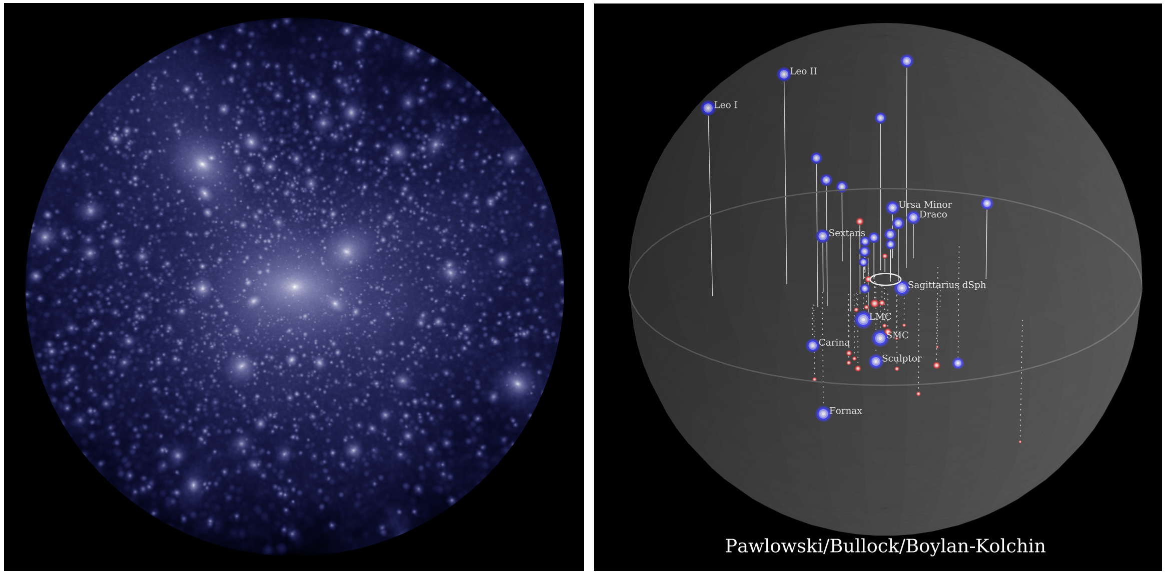
Buckley & Peter ’18

Please consult these reviews for details and references to original work…

- Weinberg et al. 2015, PNAS, arXiv:1306.0913
- Bullock & Boylan-Kolchin 2017, ARAA, arXiv:1707.04256
- Buckley & Peter 2018, arXiv:1712.06615

…and of course Carlos Frenk’s talk this afternoon.

Missing satellites

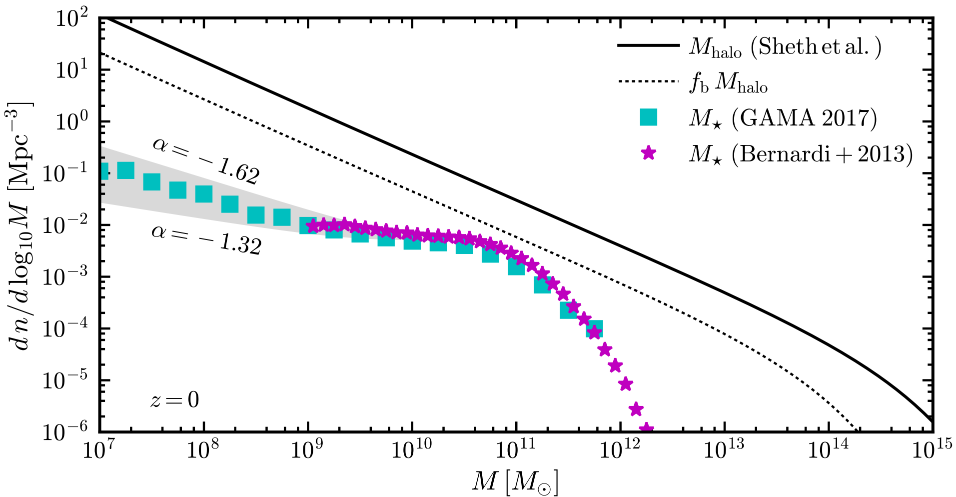


Bullock & Boylan-Kolchin '18

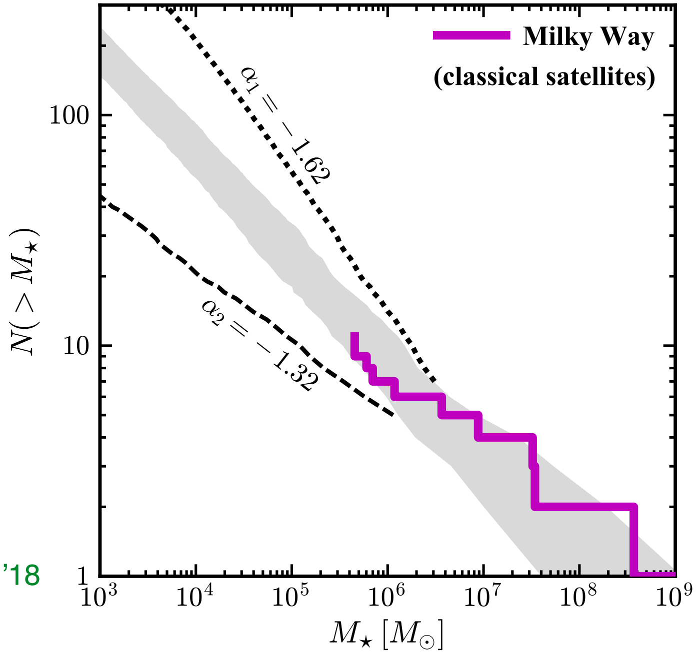
- N-body simulations show structure on all scales down to resolution limit

- Only ~ 50 observed satellites with $M_\star > 300\ M_\odot$ within 300 kpc of MW vs. ~ 1000 predicted DM subhalos $> 10^7\ M_\odot$ (Moore+ '99, Klypin+ '99)

Baryons: galaxy formation (in)efficiency



Bullock & Boylan-Kolchin ’18

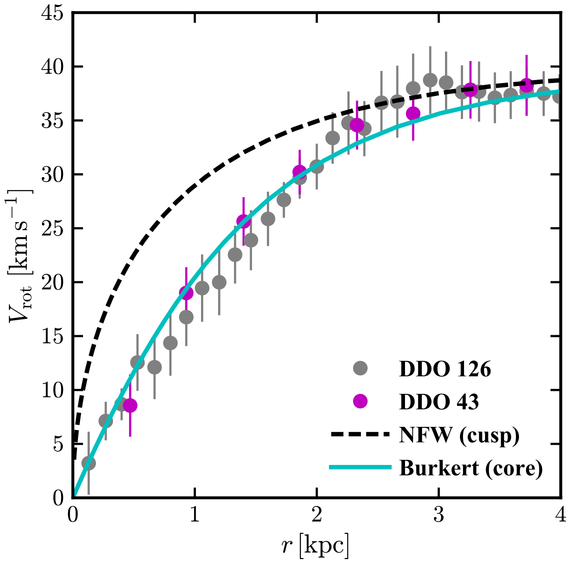


- Observed stellar mass functions are much flatter at low masses than DM halo mass functions (~ -1.5 vs. -1.9)

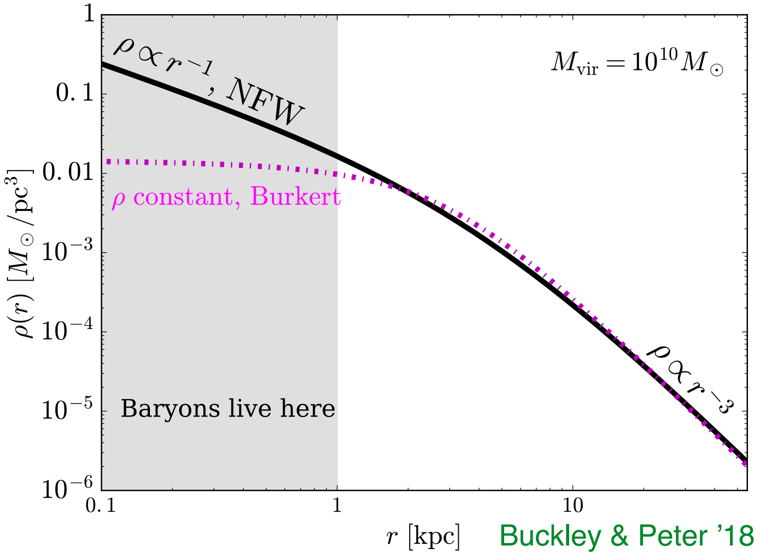
- Galaxy formation efficiency varies nonlinearly with halo mass, differences grow at both large and small masses (consistent with photoionization from UV background and stellar feedback)

- Abundance matching and simulations suggest that the number of classical satellites in the Milky Way is consistent with ΛCDM ⇒ missing satellite problem solved?

Low-density cores vs. high-density cusps



Bullock & Boylan-Kolchin ’18

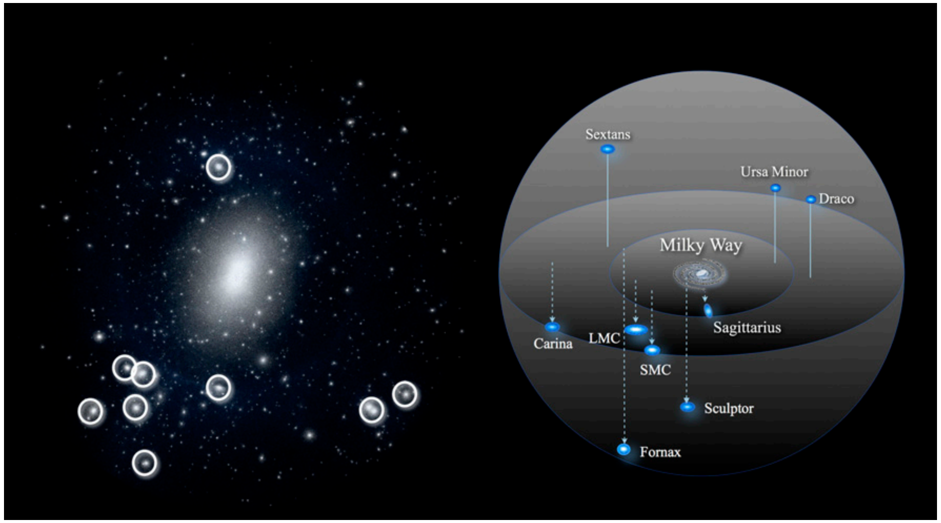


Buckley & Peter ’18

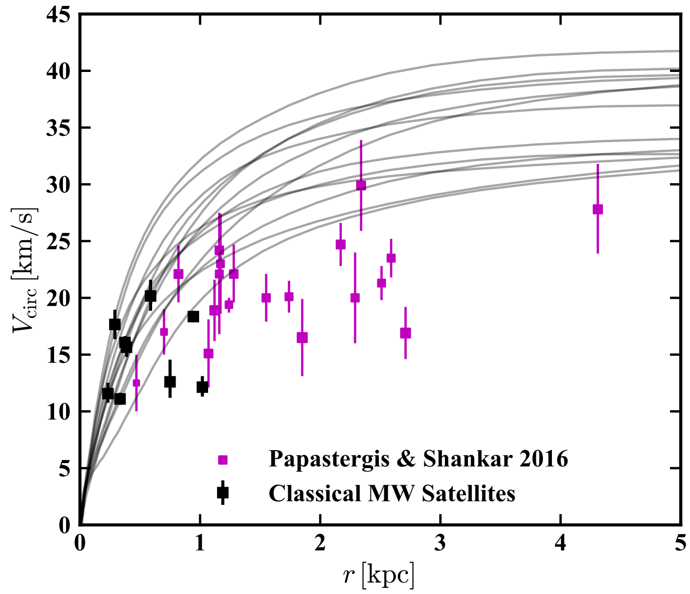
- Rotation curves show that galaxy centers are less dense and less cuspy than predicted by N-body simulations (~ few % of virial radius)

- In principle two distinct problems, but possibly single underlying cause

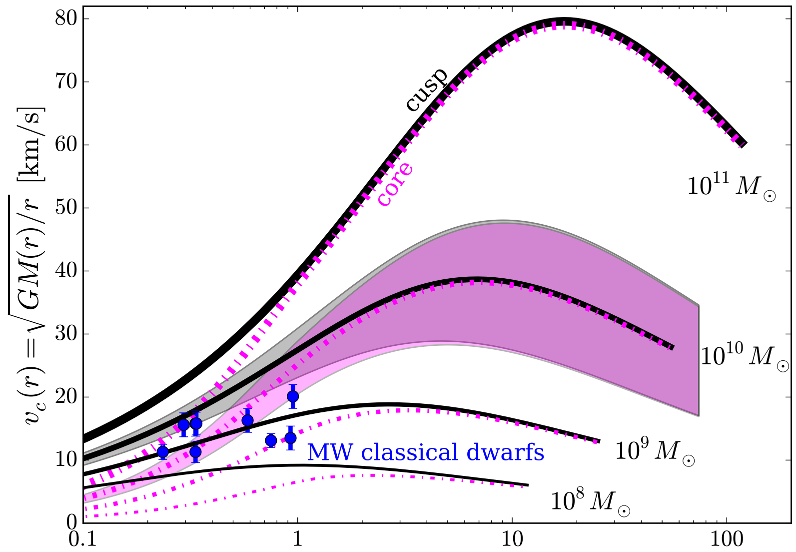
„Too big to fail“



Weinberg+ ’15



- Most massive CDM subhalos are too dense to host the bright MW satellites
- These subhalos should form stars if less massive ones do ⇒ TBTF (Boylan-Kolchin+ ’11)
- Numbers of massive subhalos match, but central densities are ~50 % lower than predicted from CDM ⇒ TBTF may be a variant of the cusp-core problem (excess central mass)



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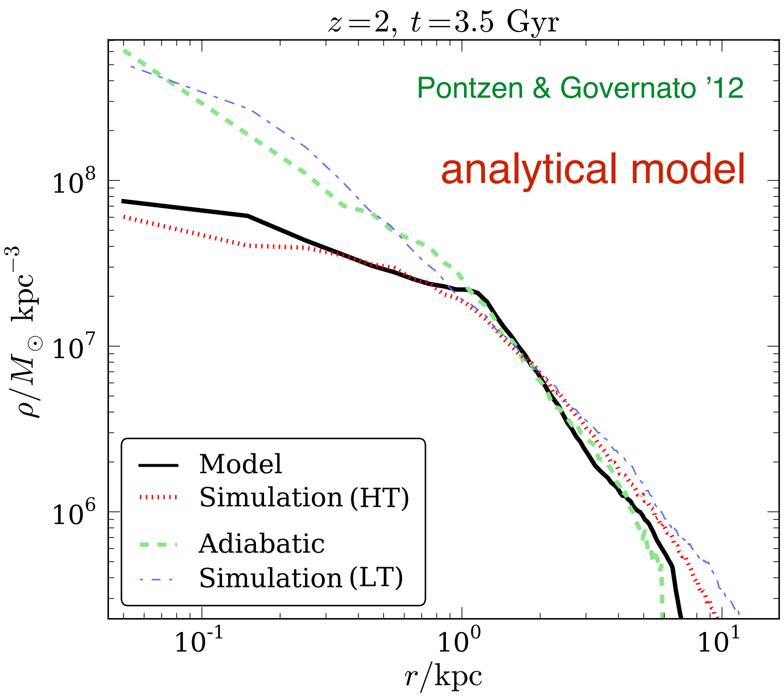
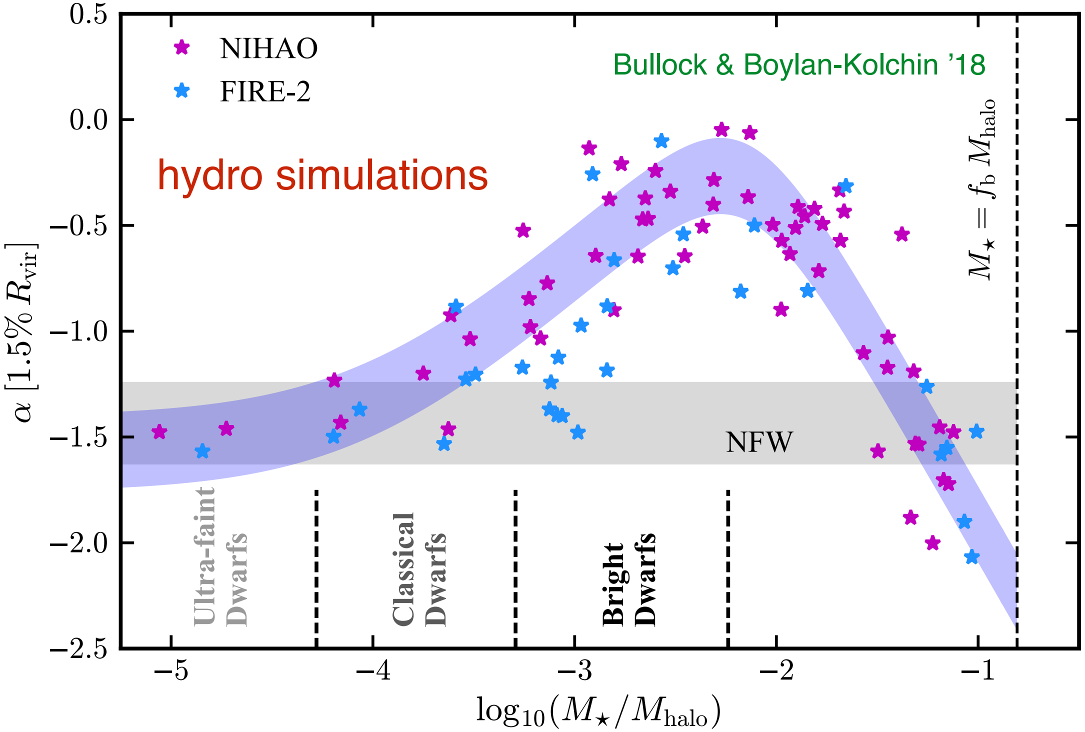
Baryons: cores from gravitational relaxation





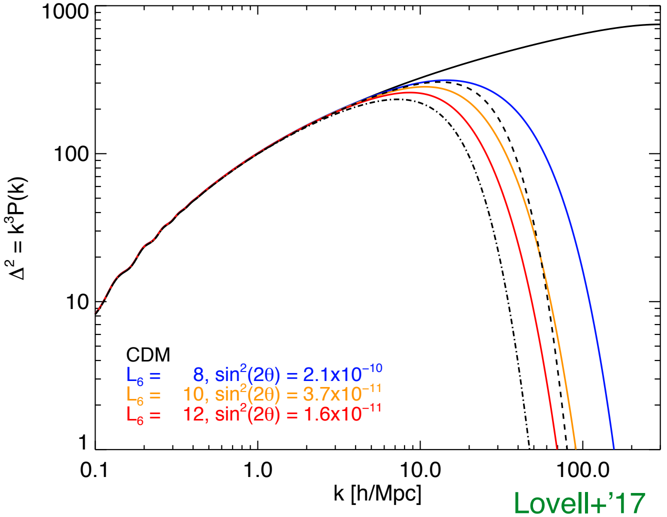
- Even low-level star formation over extended period can produce cores by gravitational fluctuations (Navarro+ '96)
- Star-formation driven core formation most efficient for bright dwarfs, becomes inefficient for classical dwarfs (near TBTF scales; explains ~ half of the problem)
- Additional feedback from tidal interactions with MW ⇒ only for MW satellites, field galaxies should differ (feedback from cosmic web?)

bCDM physics: „WDM-like“ suppression of small-scale power

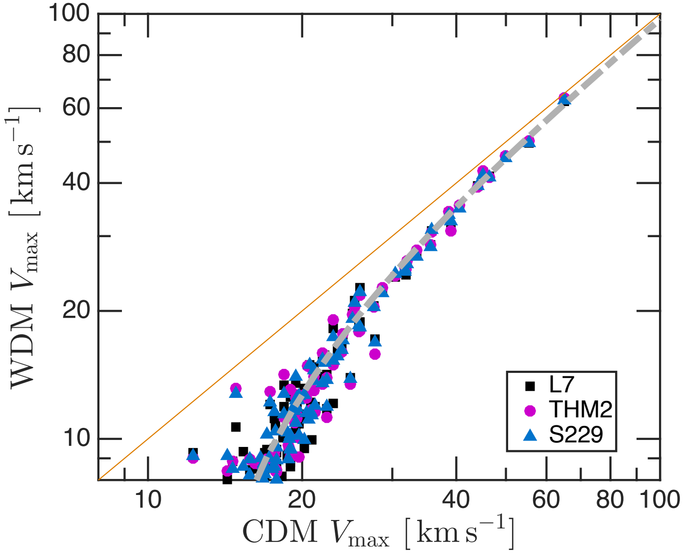
- Warm dark matter suppression of matter power spectrum by free-streaming out of small perturbations while DM is relativistic
- Half-mode mass for thermal WDM:

$$M_{\rm hm} = 5.5 \times 10^{10} \left(\frac{m_{\rm WDM}}{1\,{\rm keV}}\right)^{-3.33} M_\odot$$

- No unique m-k_{fs} relation for resonantly produced sterile neutrinos; effects depend on non-thermal momentum distribution.
- UV luminosity function at z=6 ⇒ $m_x \gtrsim 2.1$ keV, $m(\nu_s) \gtrsim 6.1$ keV (resonant) (Menci+ ’16)
- WDM delays formation of halos near M_{hm} relative to CDM ⇒ lower concentration ⇒ reduced V_{max} for given halo ⇒ possible solution for TBTF

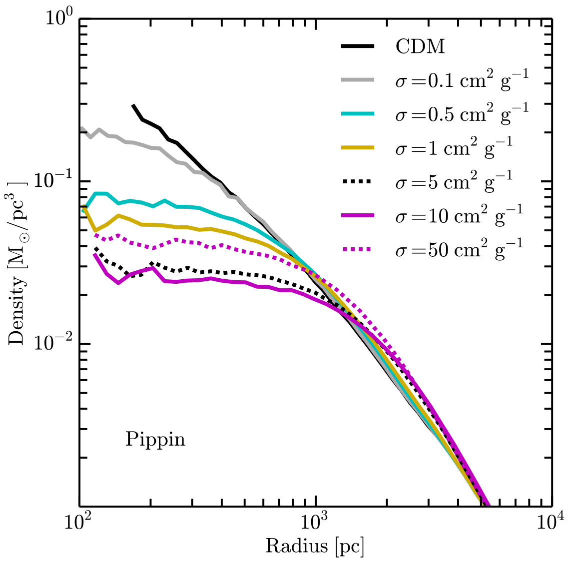


Lovell+’17

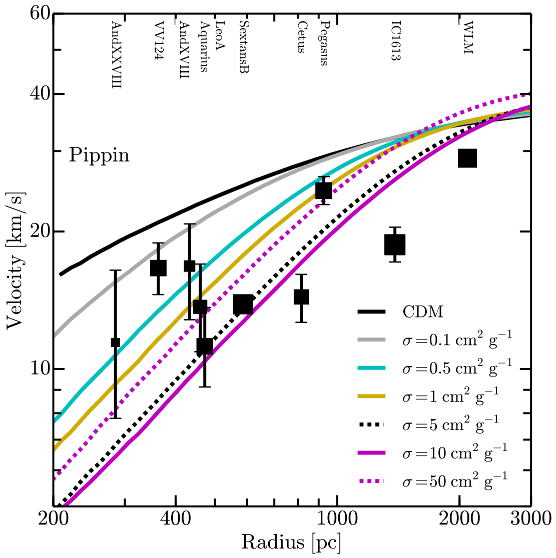


Bozek+’16

bCDM physics: „SIDM-like“ enhanced thermalization / relaxation



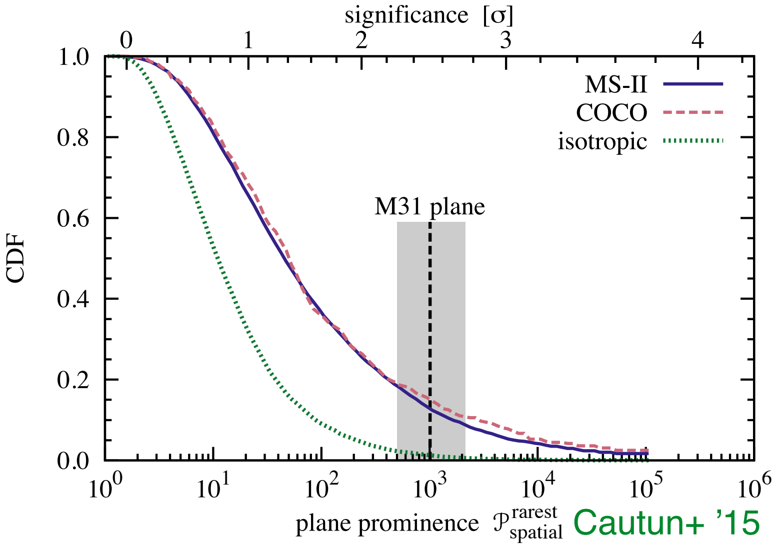
Elbert+’15



- Self-interacting dark matter (Spergel & Steinhardt ’00; recent review: Tulin & Yu, arXiv:1705.02358)
- Interactions thermalize the inner halo, reduce its density, and make it more spherical; possible solution to cusp-core and TBTF problems
- Need $\sigma \gtrsim 1$ cm^2 g^{-1} to form cores in spiral galaxies, while Bullet Cluster and halo shapes require $\sigma \lesssim 0.7$ cm^2 g^{-1} ⇒ velocity dependent cross section (e.g. from ADM)
- Doesn’t strongly affect the missing satellite problem

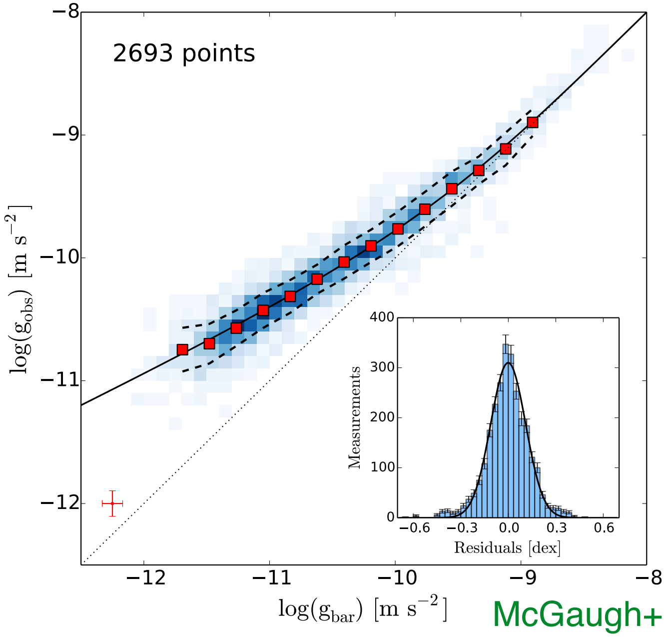
Other potential problems with no obvious relation to bCDM physics

- Satellite planes:
  - Satellite galaxies appear to lie in a polar plane for MW, M31, and Centaurus A
  - May not be in strong conflict with CDM (Cautun+ ’15)
  - Dependence on LSS environment suggests connection to accretion history (Wang+ ’18)



Cautun+ ’15

- Regularity vs. diversity
  - Baryonic Tully-Fisher Relation: tight correlation between baryonic mass and rotation velocity, independent of other galaxy properties: $M_{\rm bar} \sim V^4$
  - Radial Acceleration Relation: observed radial acceleration strongly correlated with that due to baryons (generalization of BTF) (McGaugh+ ’16)
  - Observed scatter in $V_{\rm max}$ much greater than predicted by simulations but correlation with baryons nearly exact
  - ΛCDM robustly predicts RAR in high acceleration region including turn-over, but lower part more difficult (Navarro+ ’16)



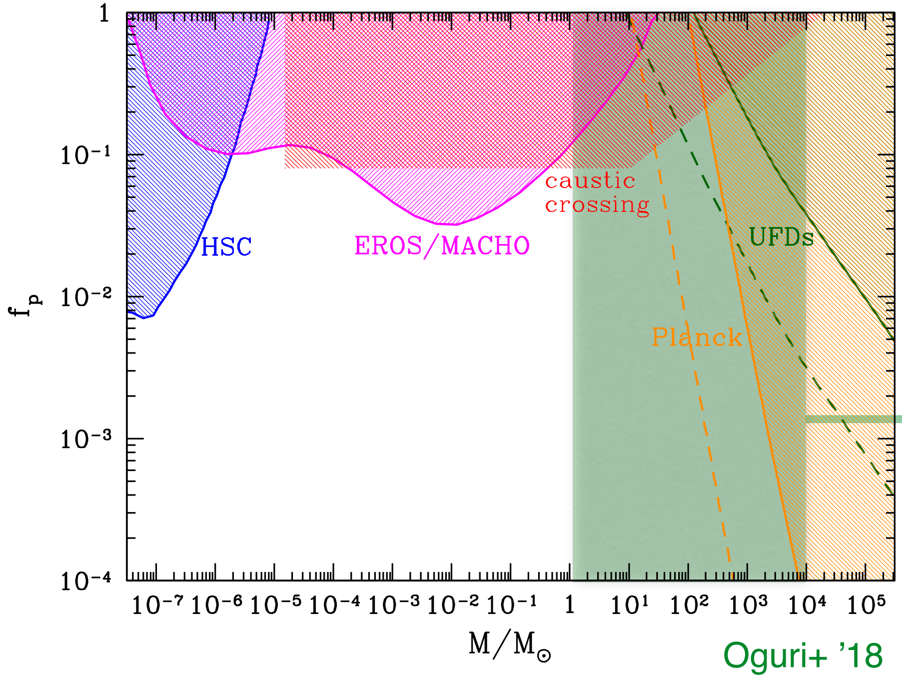
McGaugh+ ’16

Classic small-scale problems and solutions

problem: *solution:*	missing satellites	cusp-core	too big to fail
baryons: SF efficiency	✓	✗	✗
baryons: gravitational relaxation	✗	✓	?
bCDM WDM-like	✓	✗	✓
bCDM SIDM-like	✗	✓	✓

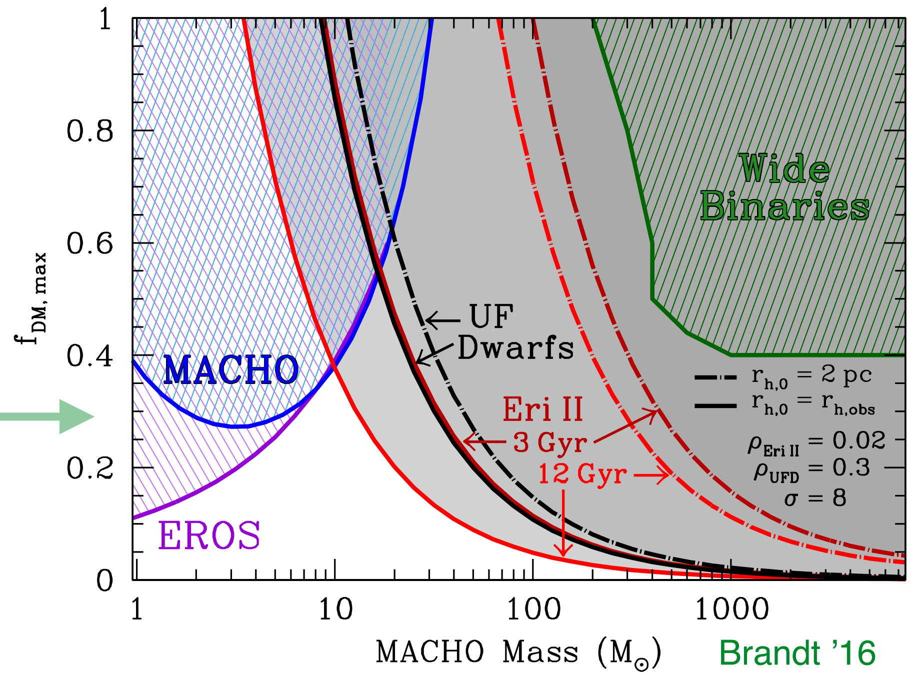
bCDM physics: „PBH-like“ formation of compact objects

lensing



Oguri+ '18

dynamical



Brandt '16

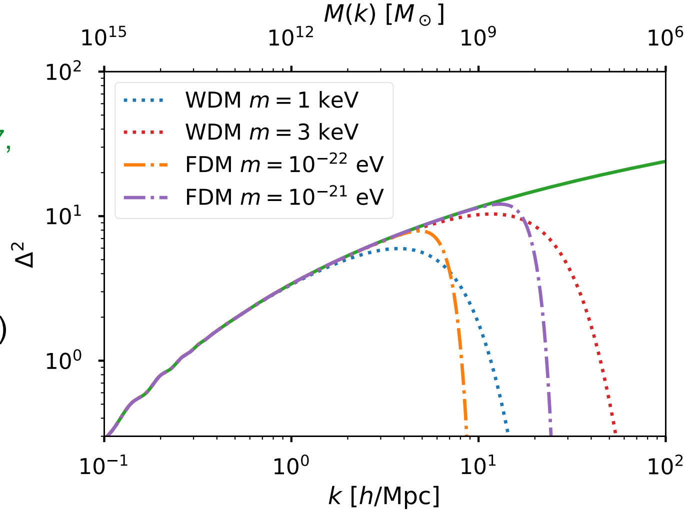
- Formation of primordial black holes in theories with non-vanilla inflation and/or particle content
- Micro- etc. lensing sensitive to masses below ~10 M⊙
- Dynamical heating of stars in dwarf galaxies constrains MACHO dark matter for masses above ~10 M⊙ (Brandt '16, Koushiappas & Loeb '17)
- Purely gravitational probes, apply equally to other compact objects or substructure

bCDM physics: „axion-like“ all of the above!

Ultralight axions

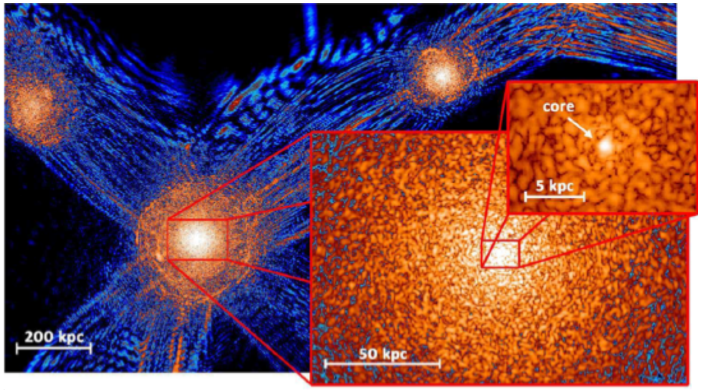
- Suppression of small-scale perturbations *(„WDM-like“)*
  - high-z luminosity functions (Bozek+ ’15, Schive+ ’16, Corasaniti+ ’17, Menci+ ’17)
  - Lyman-α forest (Iršič+ ’17, Armengaud+ ’17) → $m \gtrsim 10^{-21}$ eV
  - reionization (Bozek+ ’15; Schneider ’18; Lidz, Hui ’18)

  (N.B. most simulations use standard N-body with modified transfer function)



- Incoherent interference patterns and granularity on scales of $\lambda_{dB} \sim 1 \ldots 100$ kpc
  - „quasi-particle relaxation“ → subhalo orbit decay, dark disk, … (Hui+ ’17) *(„SIDM-like“)*
  - halo substructure evolution (Du+ ’18)

- Formation of coherent solitonic halo cores
  - cusp-core etc., halo substructure (Marsh,Silk ’13, Schive+ ’14, Marsh,Pop ’15, Calabrese,Spergel ’16, Du+ ’16)



Schive+ ’14

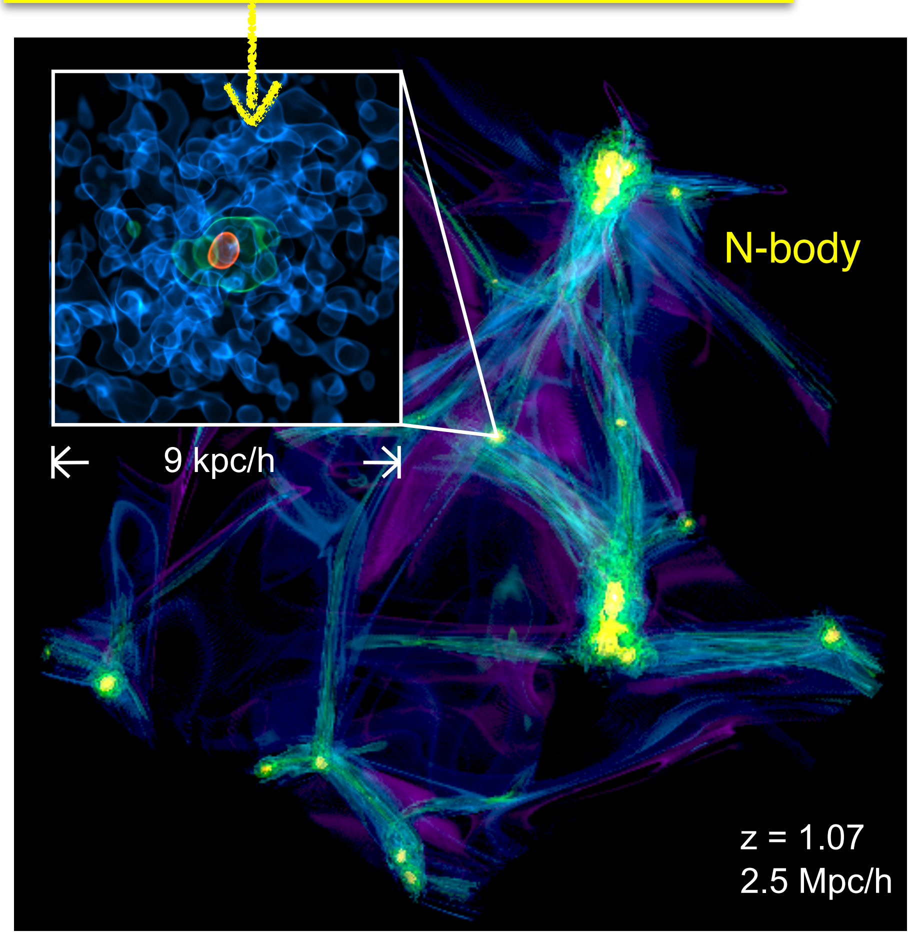
QCD axions

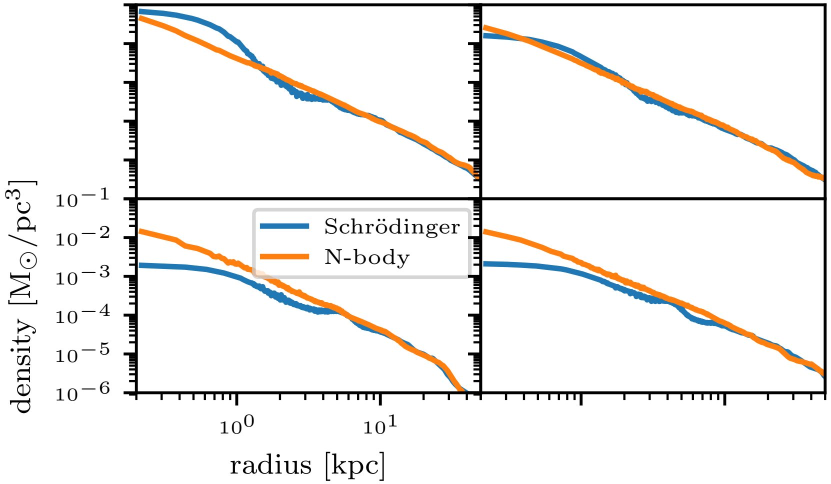
- Formation of axion miniclusters (Tkachev ’86; Hogan,Rees ’88; Kolb,Tkachev ’93/94; Zurek+ ’07)
  - relevant for direct detection experiments
  - potentially observable in fast radio bursts, tidal streams, microlensing (Tkachev ’15, Tinyakov+ ’16, Fairbairn+ ’17)
- Formation of axion stars (e.g. Levkov+ ’18) *(„PBH-like“)*

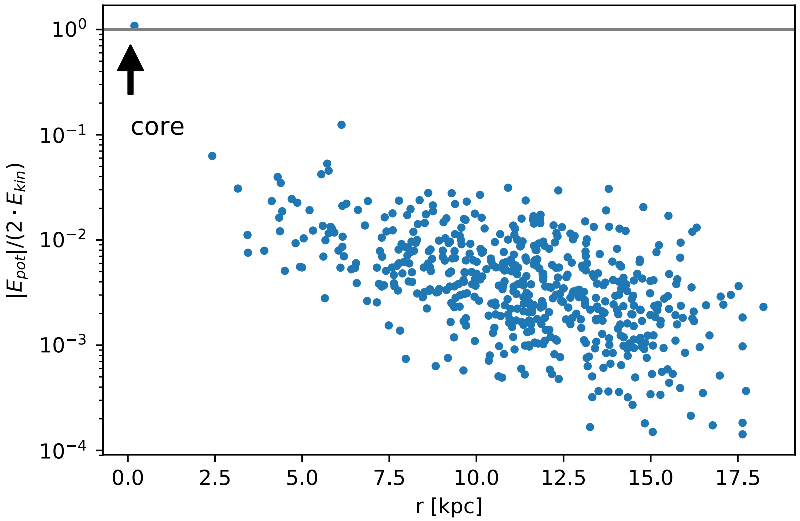
Simulations of halo formation with ultralight axion dark matter

(Veltmaat, JN, Schwabe ’18, arXiv:1804.09647)

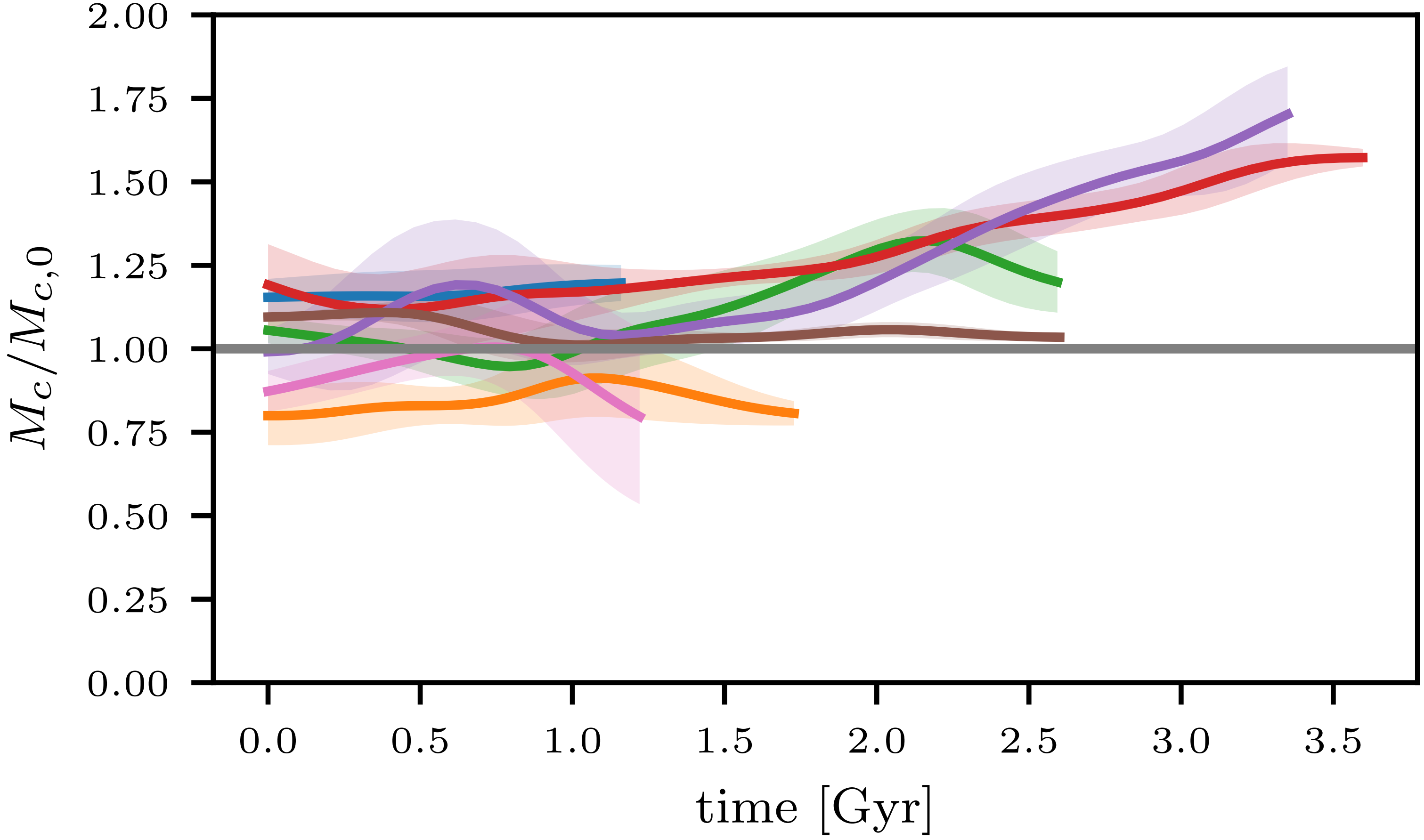
$$i\hbar\frac{\partial\psi}{\partial t} = -\frac{\hbar^2}{2a^2m}\nabla^2\psi + mV\psi$$







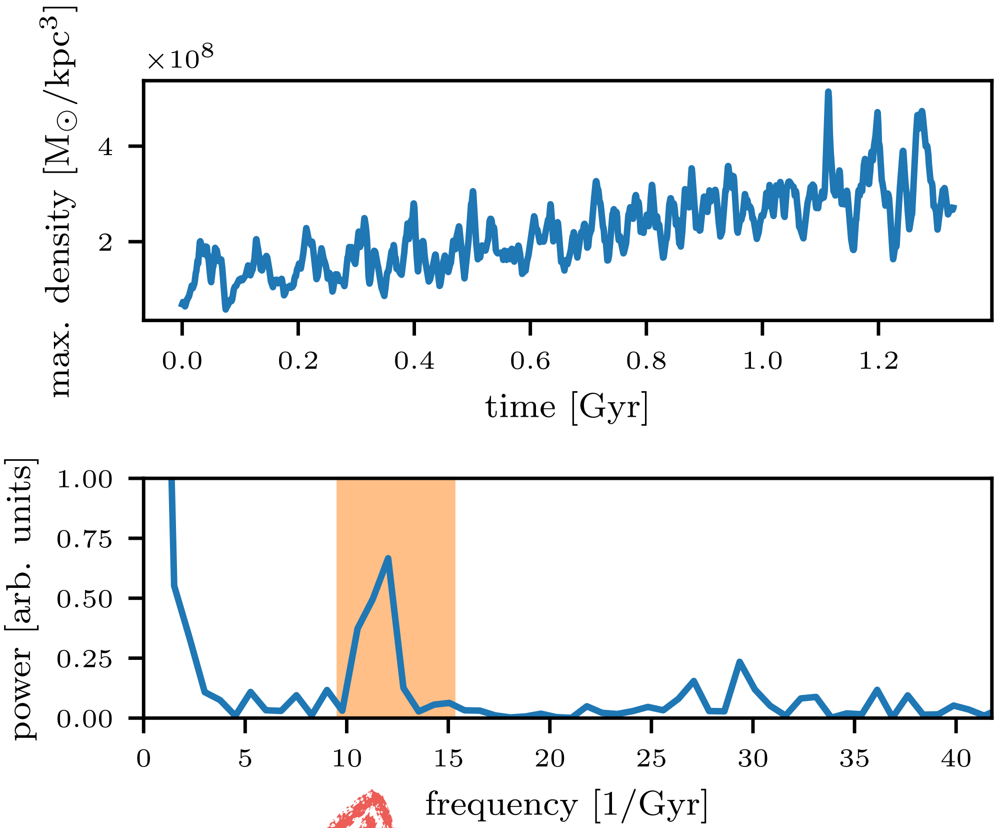
Core mass evolution



$$M_{\rm c} = \frac{1}{4} a_{\rm vir}^{-1/2} \left(\frac{\zeta(a_{\rm vir})}{\zeta(0)} \right)^{1/6} \left(\frac{M_{\rm h}(a_{\rm vir})}{M_0} \right)^{1/3} M_0$$

$$M_0 \sim 4.4 \times 10^7 m_{22}^{-3/2} M_\odot$$

Core oscillations



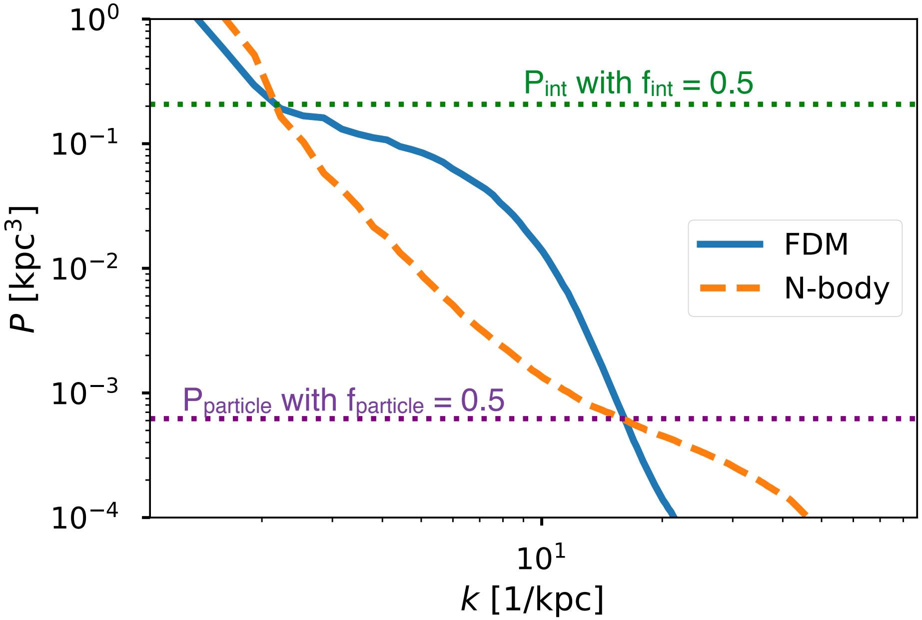
quasinormal soliton mode

Gravitational relaxation from wave interference noise

- Wave interference produces white noise with power

$$P_{\rm int} \sim \frac{f_{\rm int}}{n_{\rm int}} \sim f_{\rm int}\left(\frac{\lambda_{\rm dB}}{2}\right)^3 \sim f_{\rm int}\left(\frac{h}{2mv}\right)^3 ,$$

- From simulations, we get $f_{\rm int} \sim 0.5$



- Gravitational fluctuations produce dynamical relaxation on the time scale (El-Zant+ '16)

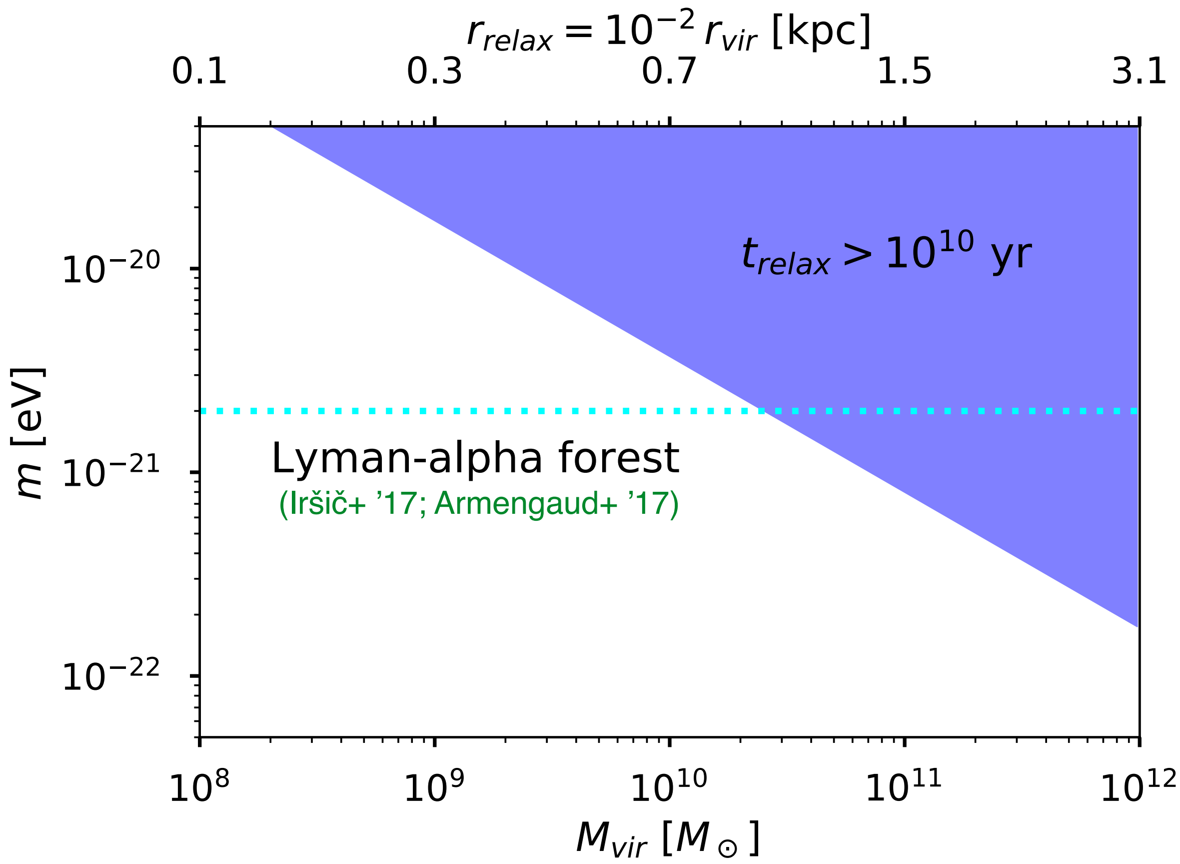
$$t_{\rm relax} \sim \frac{1}{8\pi\langle\delta^2\rangle}\,\frac{r}{v} \sim \frac{r^3}{6P_{\rm int}}\,\frac{r}{v}$$

- Together, this gives $\boxed{t_{\rm relax} \sim \frac{1}{6\pi^3}\,\frac{m^3v^2r^4}{f_{\rm int}\hbar^3}}$

- Hui et al. (2017) find $t_{\rm relax} \sim \frac{0.4}{f_{\rm relax}}\,\frac{m^3v^2r^4}{\pi^3\hbar^3}$

from 2-body relaxation with granular quasi-particles

Gravitational relaxation from wave interference noise



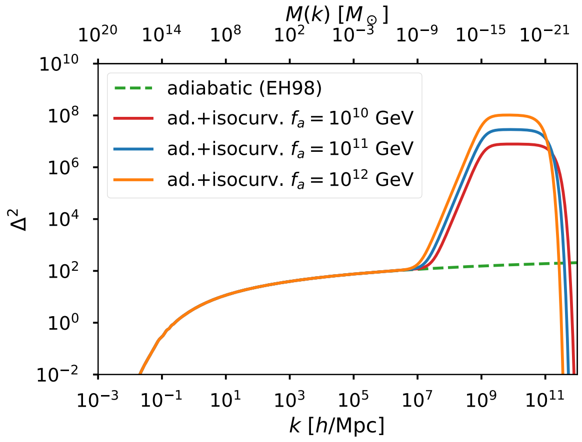
Dynamical relaxation from wave noise may be relevant for dwarf cores, independent of the solitonic core itself.

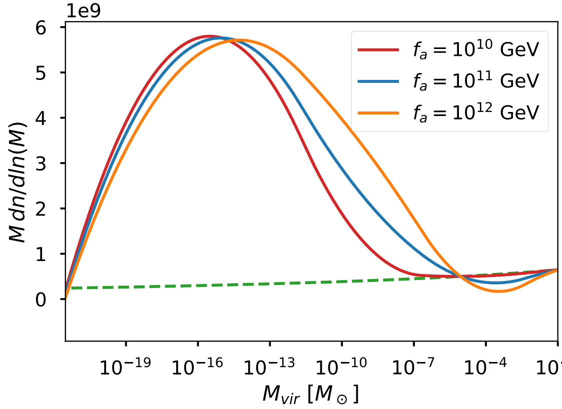
Formation of QCD axion miniclusters

N-body simulations of nonlinear density perturbations during radiation-dominated epoch:

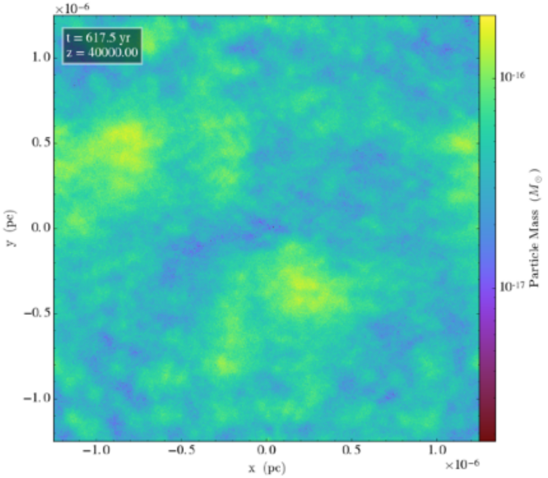
- Initial conditions from simulations of complex axion field (Redondo, Vaquero, Stadler)
- Questions: minicluster mass function, total mass bound in miniclusters, …
- Paper: coming soon…

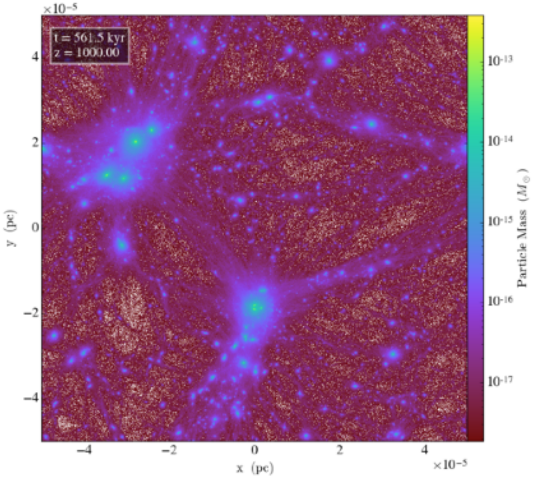
Simple estimates of power spectrum and HMF:





Simulations:





Wiebe, Redondo, JN+ , in preparation

Summary

- The confrontation of ΛCDM (+ inflation) predictions for small-scale structure with observations provides ongoing motivation for studying physics beyond CDM

- Prominent classes of modifications predict suppression of small-scale power (*WDM-like*), enhanced transport effects (*SIDM-like*), and the production of compact objects (*PBH-like*)

- Axion cosmology has a little bit of all:
  - Primordial suppression of high-k power (ultralight axions)

    probes: Lyman-alpha forest, high-z luminosity functions, reionization, galactic streams, substructure lensing,…
  - Dynamical enhancement of gravitational relaxation

    probes: morphology of inner parts of disk galaxies, orbital stability of SMBHs and globular clusters (Hui+ ’17)
  - Production of axion miniclusters / axion stars / solitonic cores

    probes (QCD axion miniclusters and axion stars): micro-, nano-, pico-, femto-, attolensing; non-gravitational probes

    probes (FDM cores): dwarf galaxy rotation curves, core oscillations?