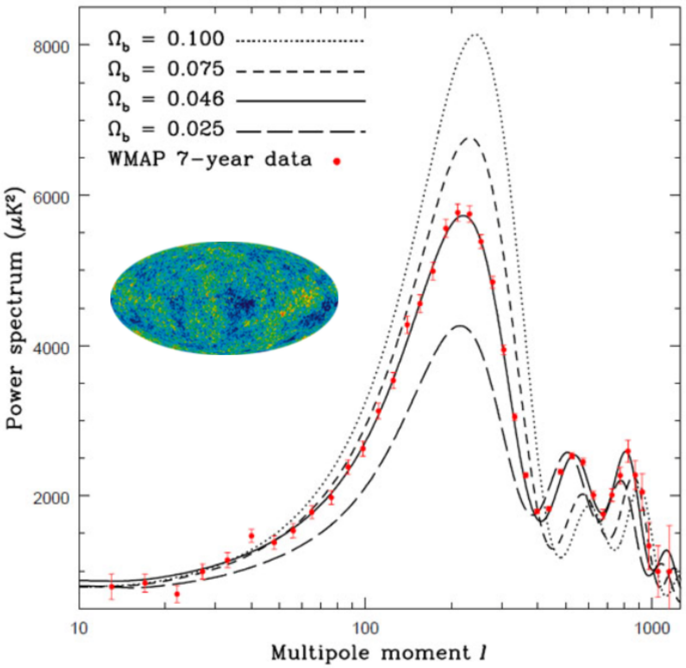
Galactic Rotation Curves
vs.
Ultra-Light Dark Matter

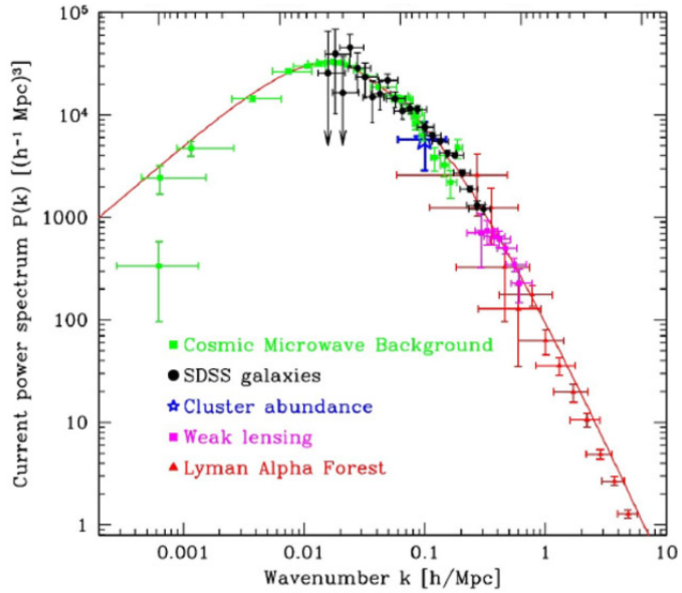
Kfir Blum

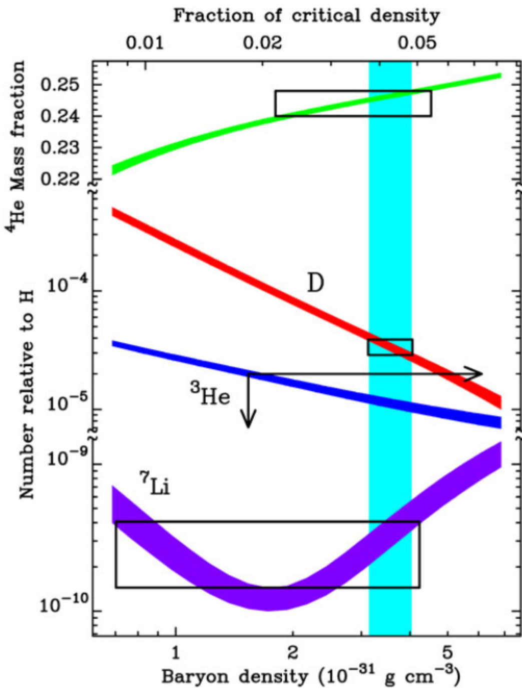
1805.00122: **Bar**, Blas, KB, Sibiryakov
1903.03402: **Bar**, KB, Sato, Eby

La Thuile / 12/3/2019

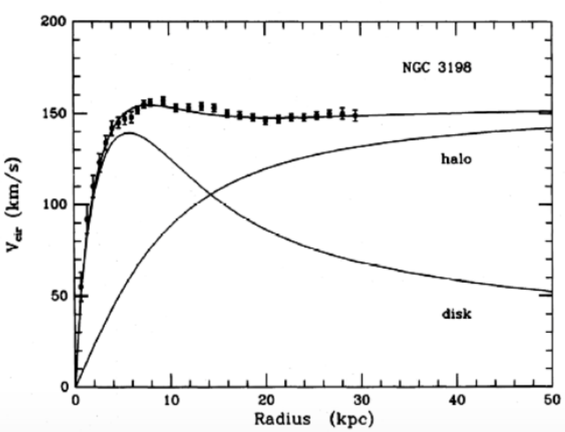
What is dark matter?

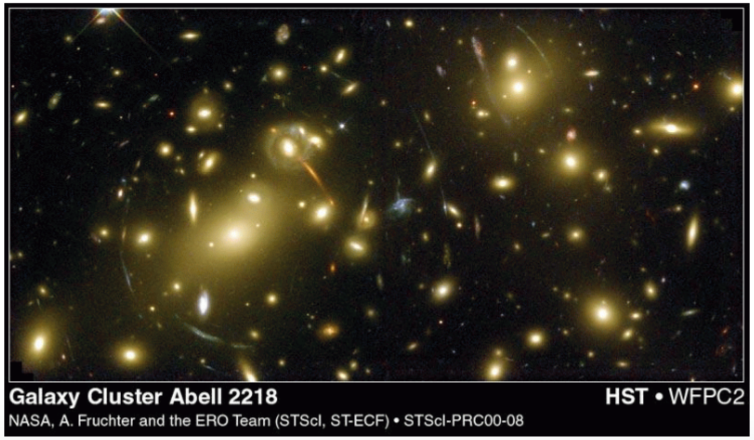






DISTRIBUTION OF DARK MATTER IN NGC 3198



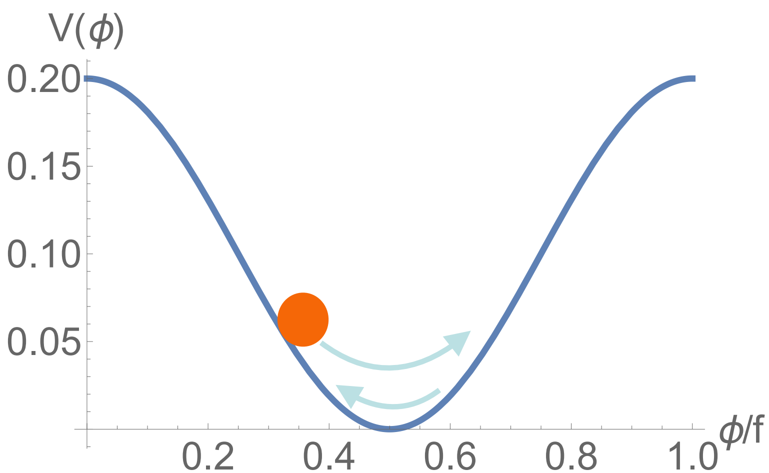


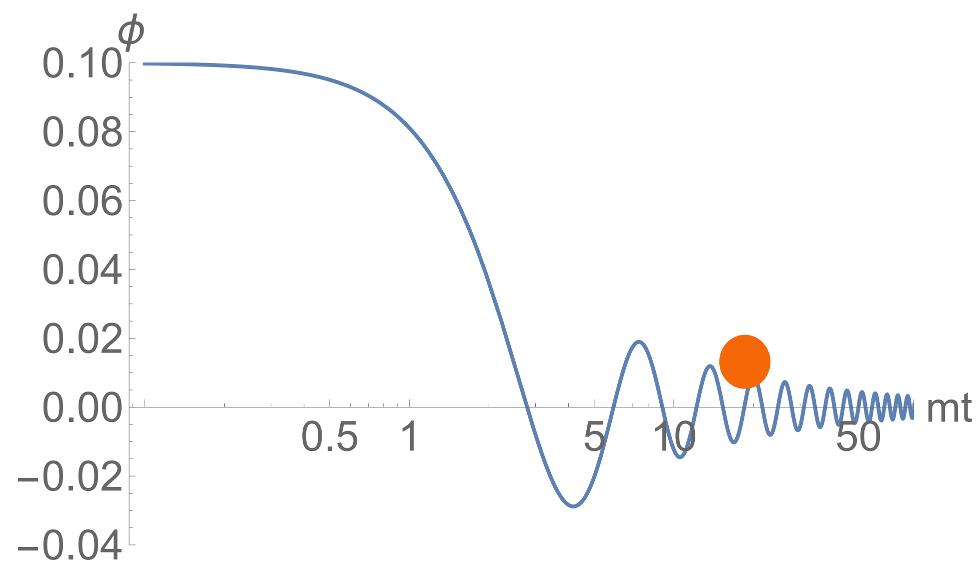
Light (pseudo-)scalar fields are featured in many UV models,
where they arise as PNGBs of spontaneously broken symmetries.

The PQ- or QCD-axion is an example.

Such scalar field, initially displaced from a minimum of its potential during the early cosmological history, begins to oscillate around the minimum when H~m.

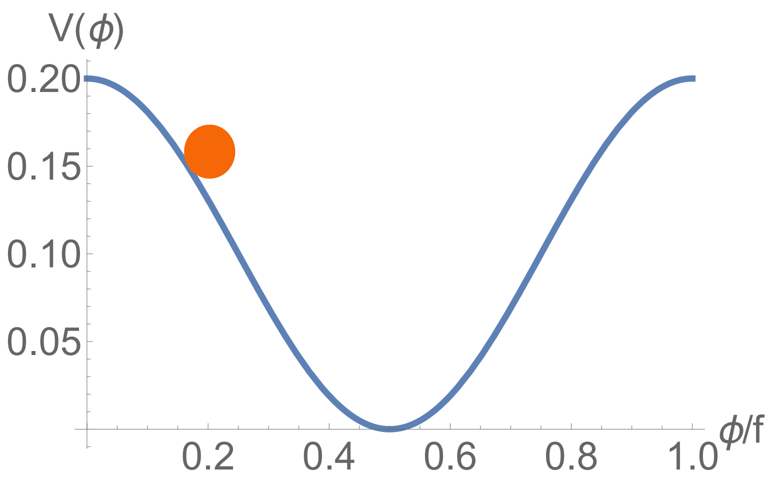
Correct cosmological equation of state for dark matter.





Natural initial condition: $\boxed{\phi \sim f}$ = range of Goldstone boson.

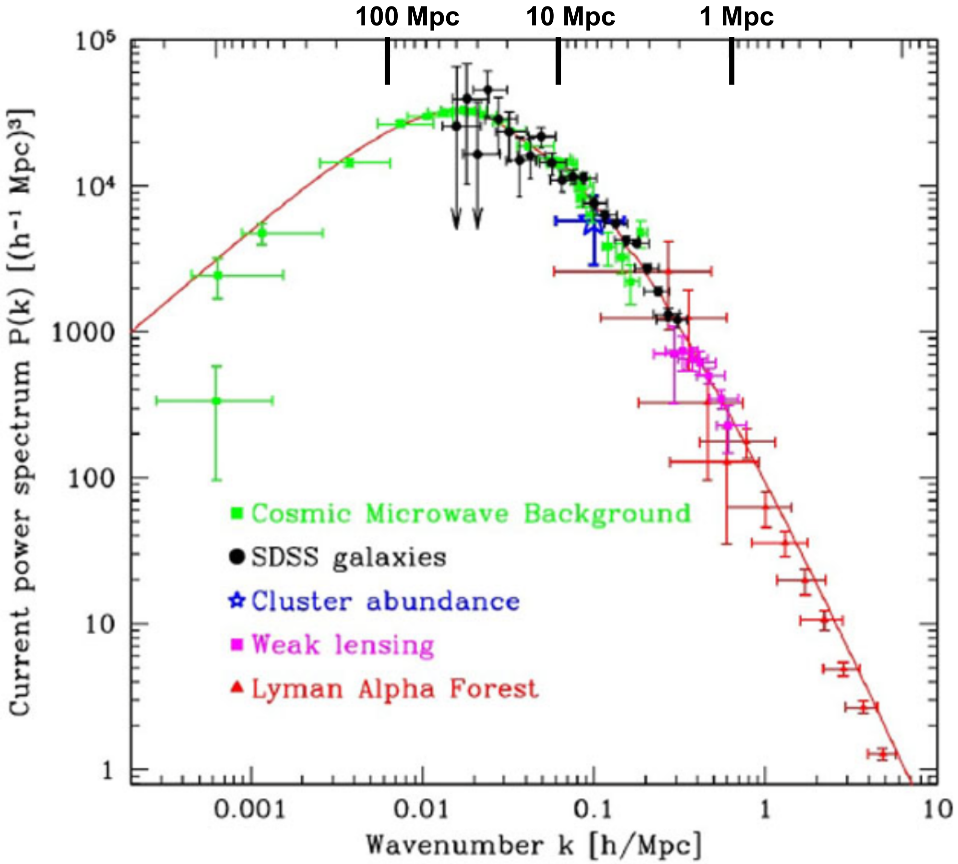
Assuming SSB before end of inflation, contribution to energy density today: $\boxed{\Omega_m \sim 0.1 \left(\frac{m}{10^{-22}\ \mathrm{eV}}\right)^{\frac{1}{2}} \left(\frac{f}{10^{17}\ \mathrm{GeV}}\right)^2}$



Ultra-light dark matter (ULDM)

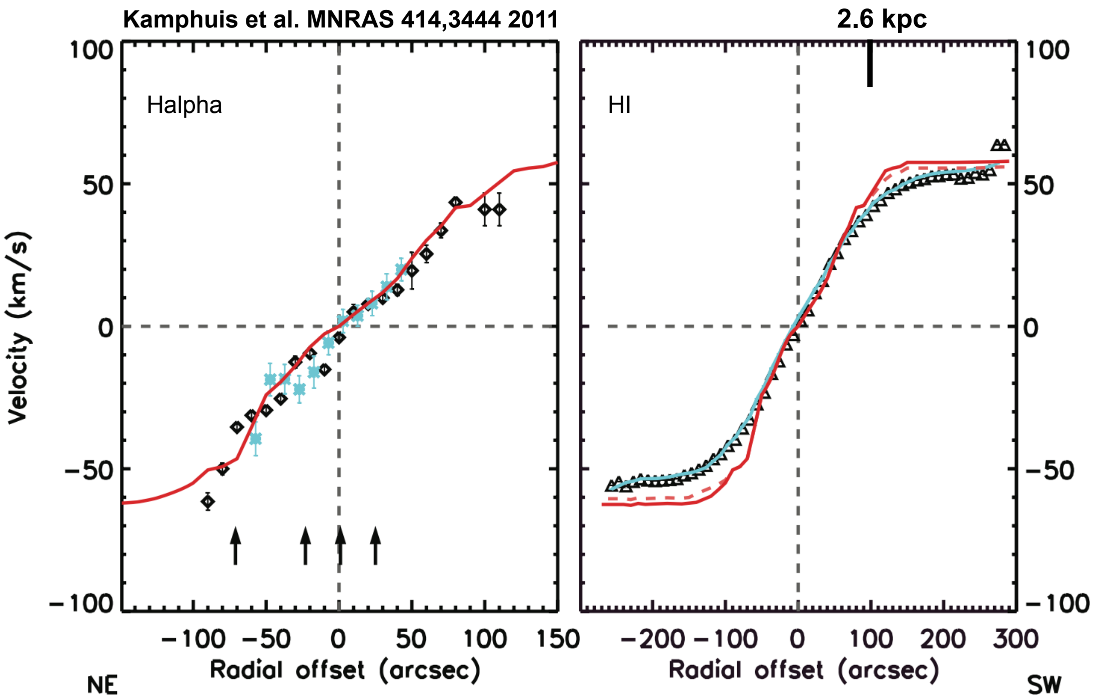
On scales much larger than de Broglie wavelength, **ULDM** behaves like WIMP DM.

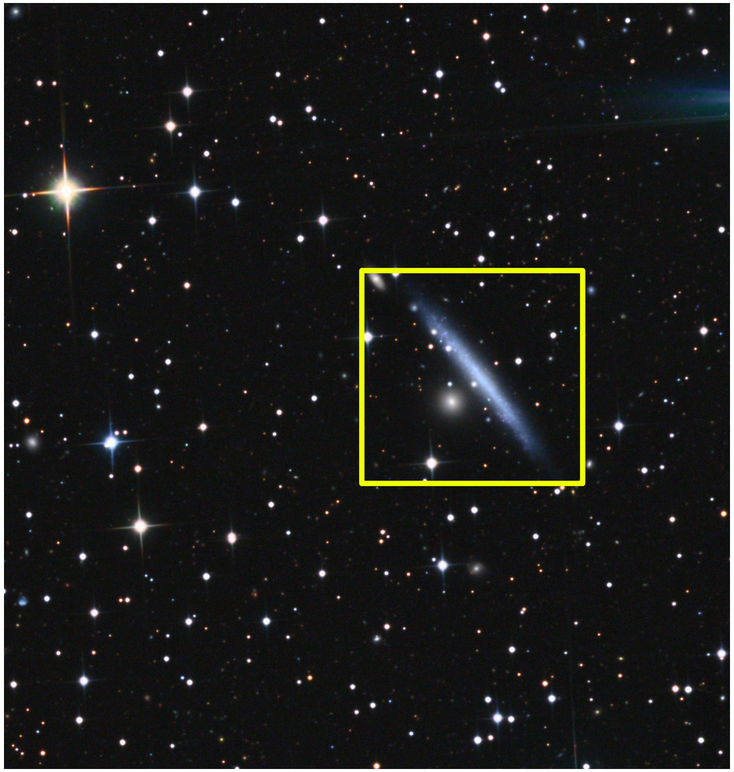
dB length ~ 100 pc for m~10^-22 eV



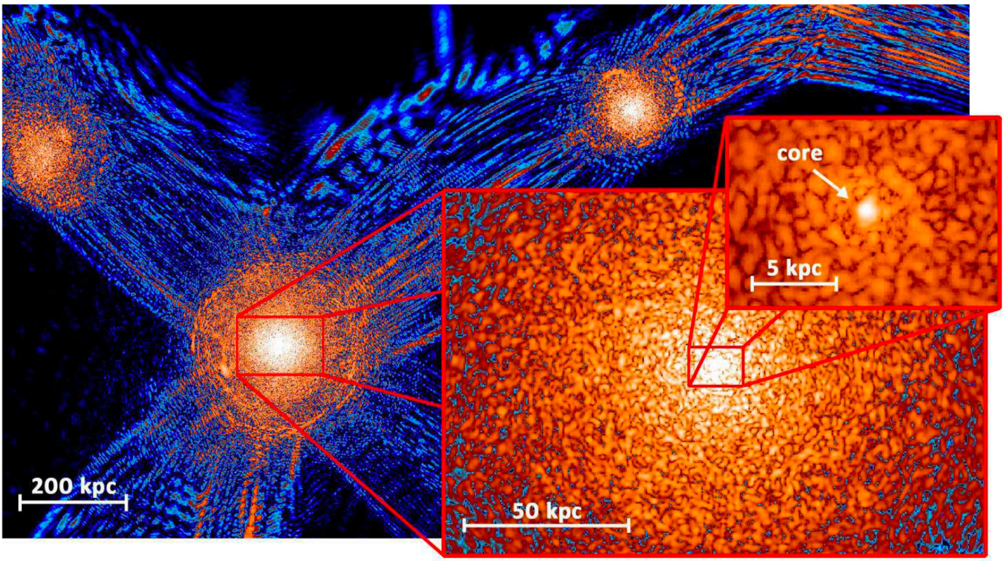
On scales of order de Broglie wavelength, **ULDM is markedly different than WIMPs.**

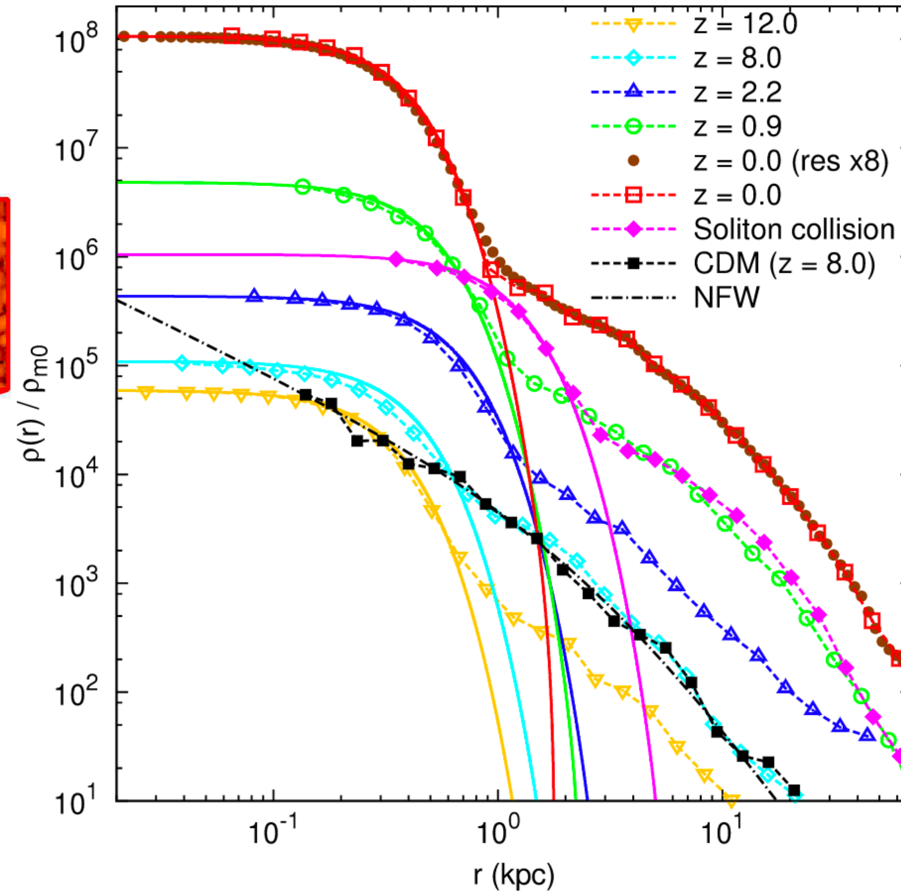
dB length ~ 100 pc for m~10^-22 eV





Numerical simulations: inner part of galaxies develops a core ("soliton")





Schive et al 1406.6586
Schive et al 1407.7762
Veltmaat et al 1804.09647
Mocz 1705.05845

On scales of order de Broglie wavelength, equations of motion of ULDM are simple enough to solve

$$\partial_r^2 \left(r\chi\right) = 2r\left(\Phi - \gamma\right)\chi,$$
$$\partial_r^2 \left(r\Phi\right) = r\chi^2.$$

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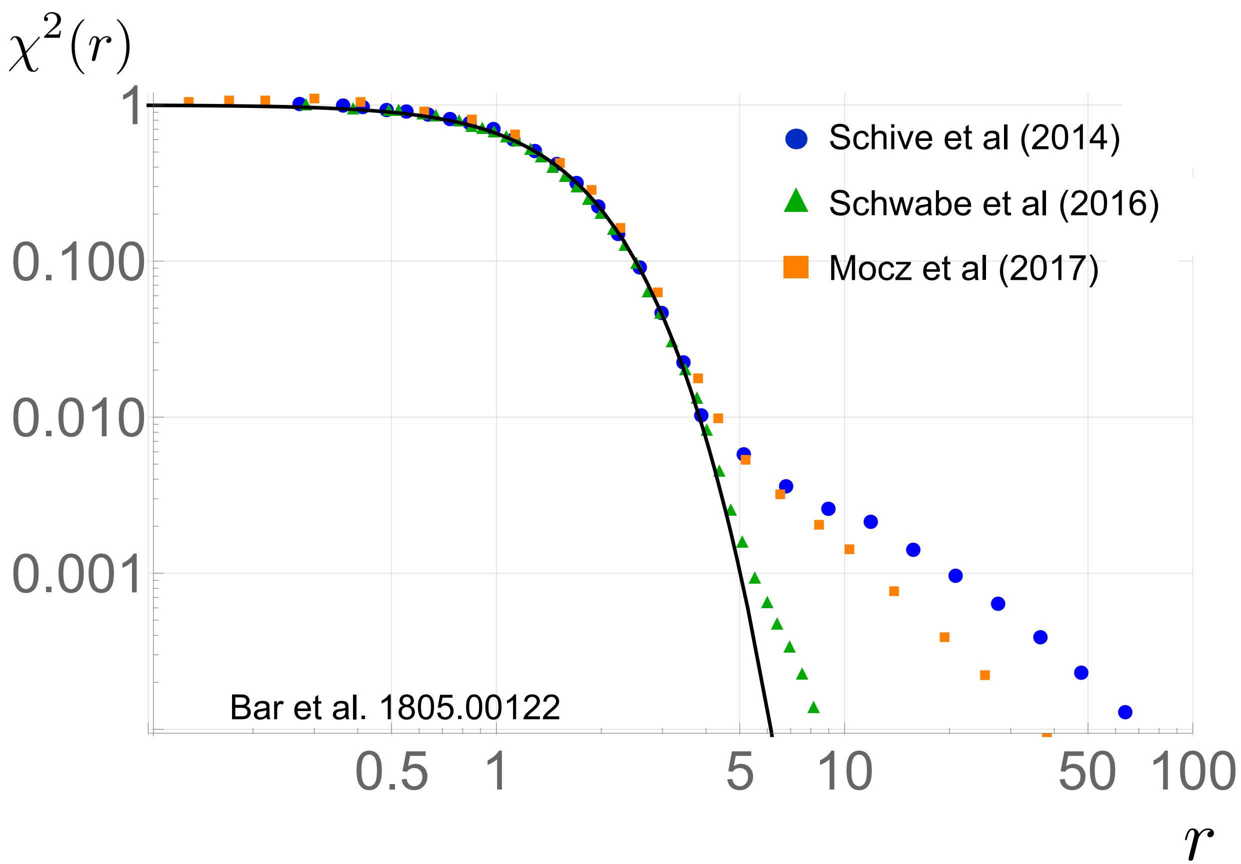

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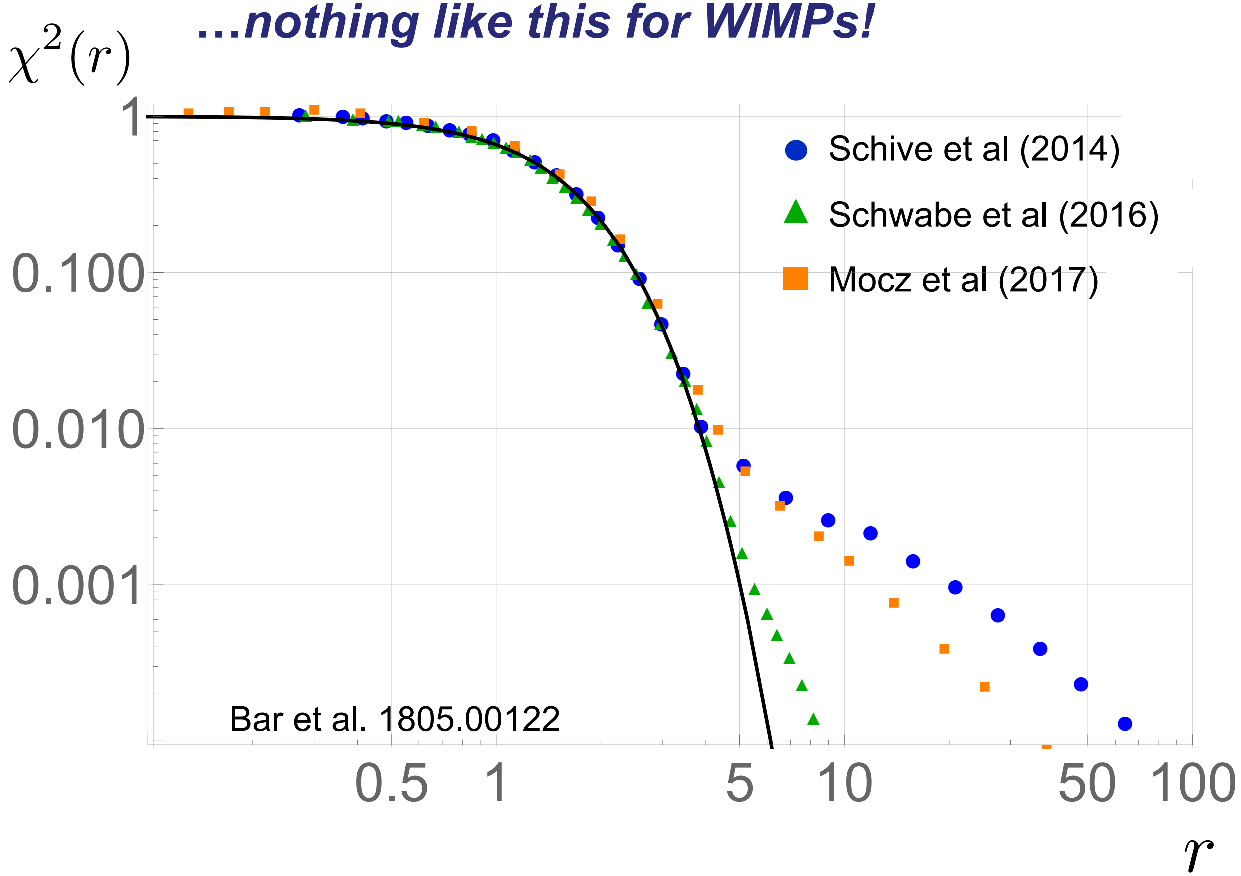
…nothing like this for WIMPs!



Numerical simulations: soliton — halo relation

Schive et al 1406.6586
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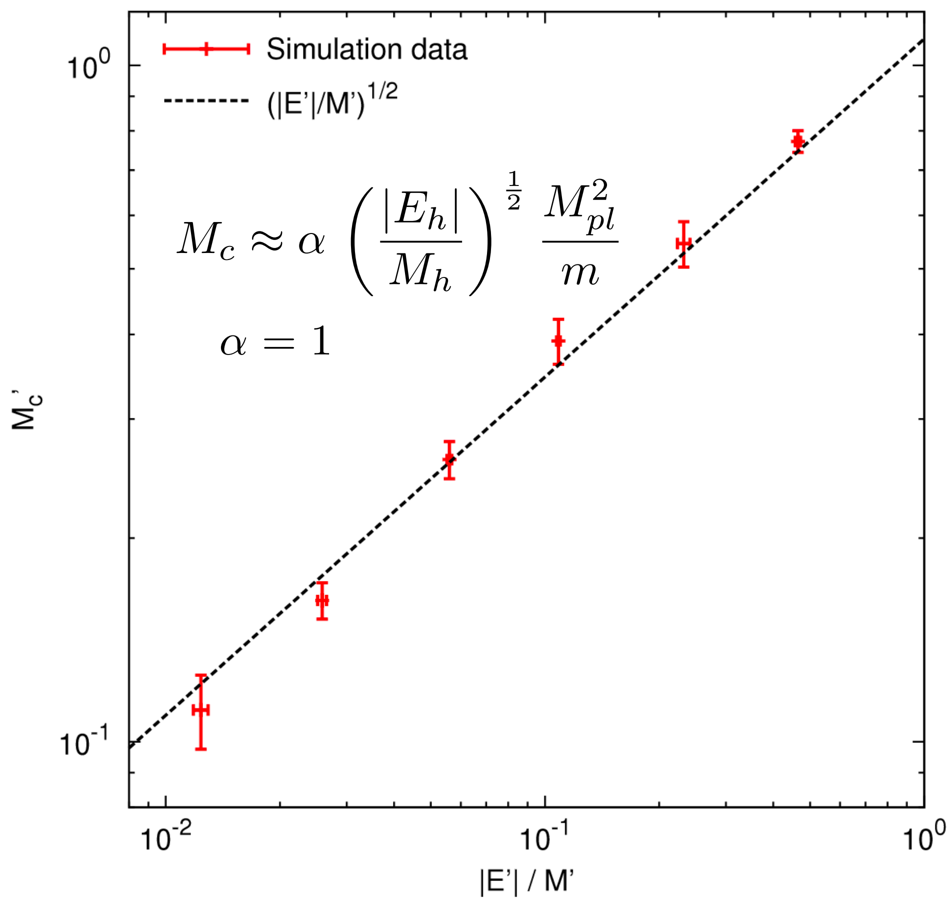

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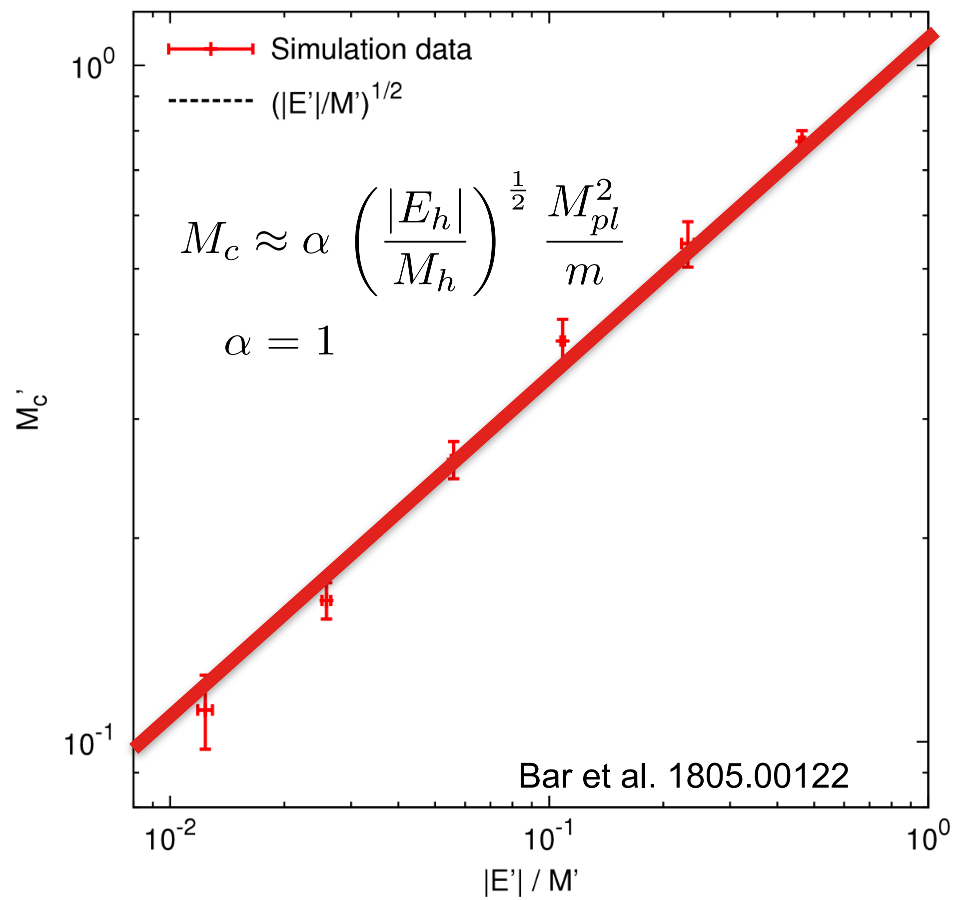
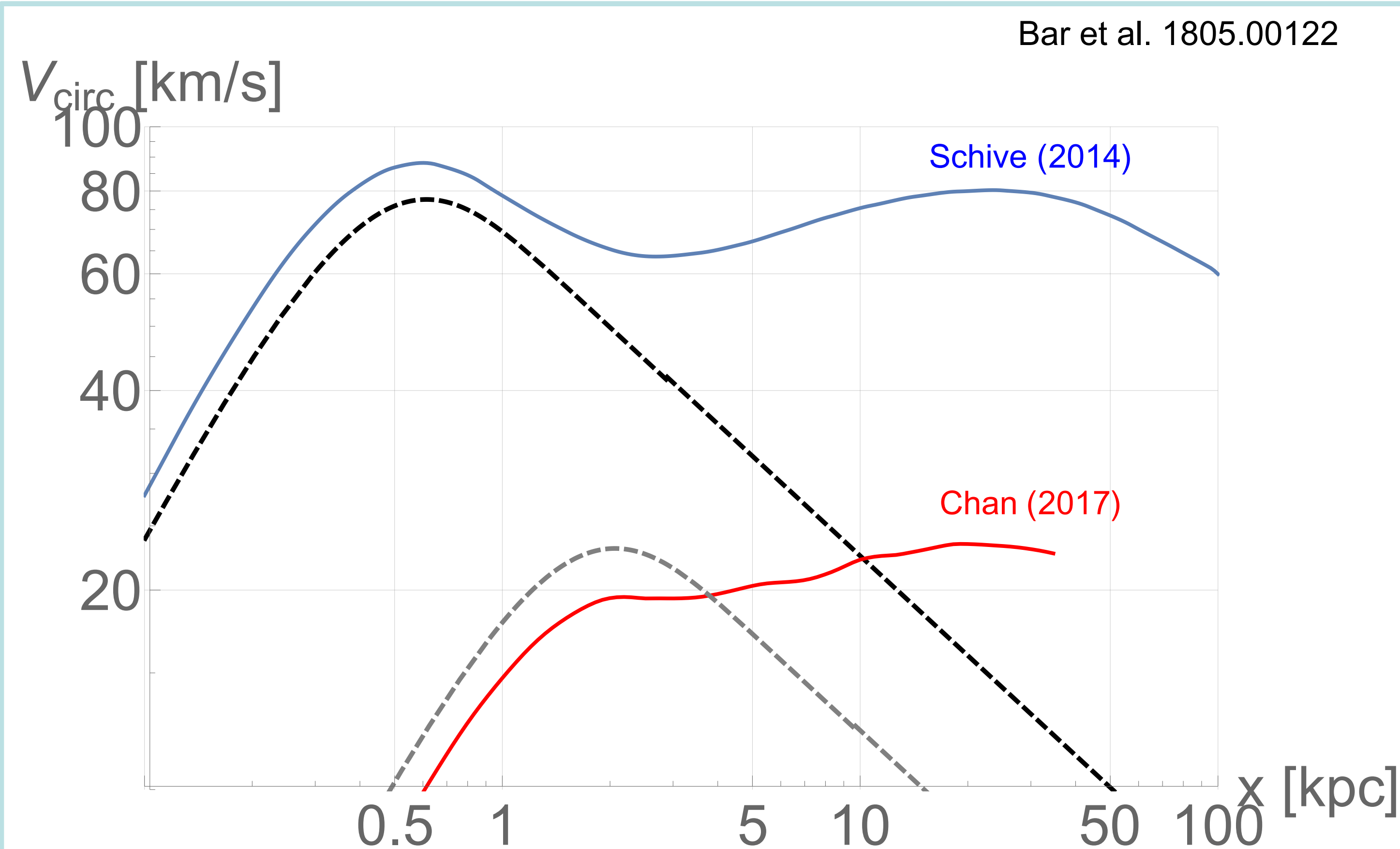
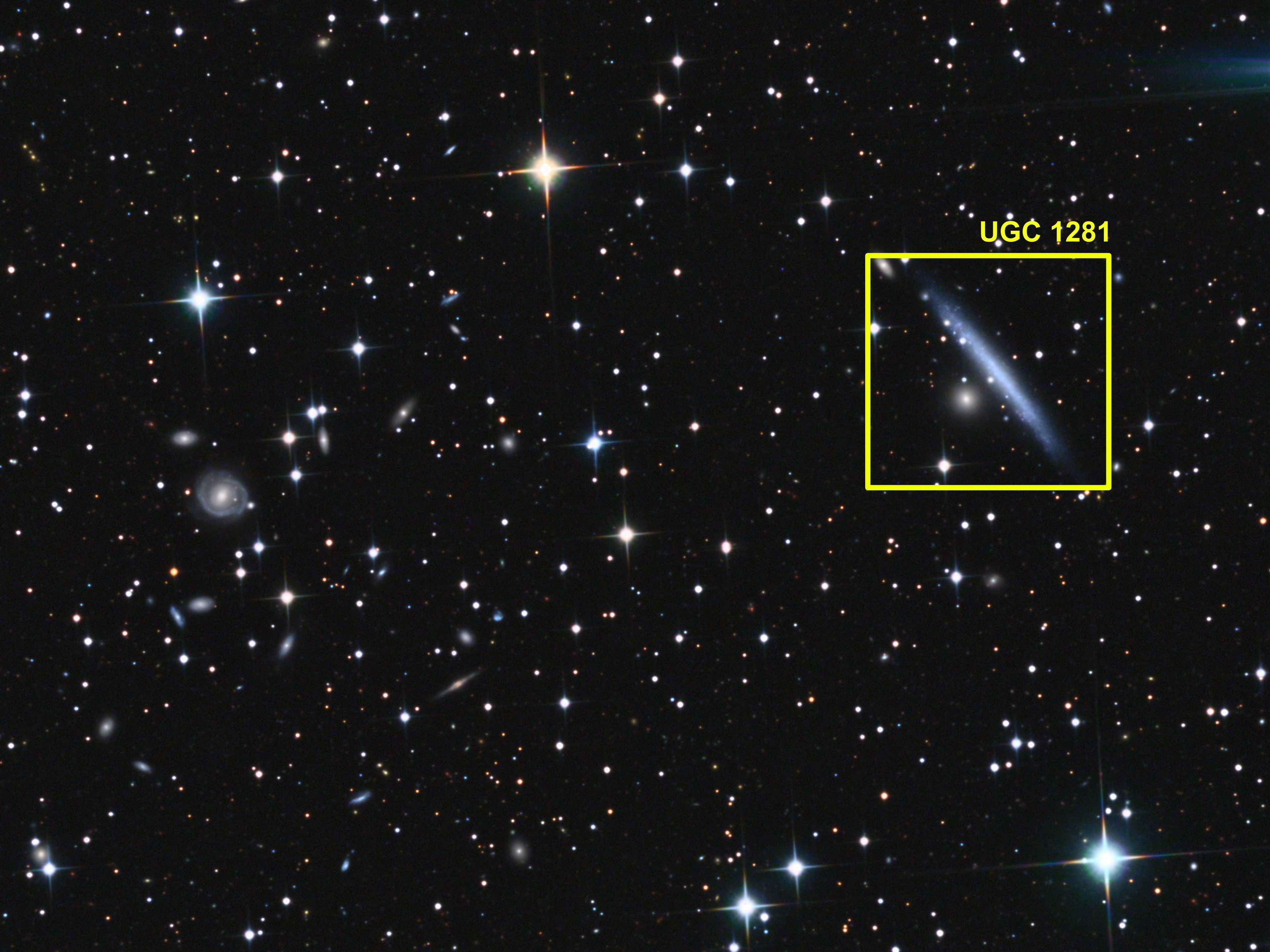
What it says:

$$\boxed{\left.\frac{K}{M}\right|_{\text{soliton}} = \left.\frac{K}{M}\right|_{\text{halo}}}$$

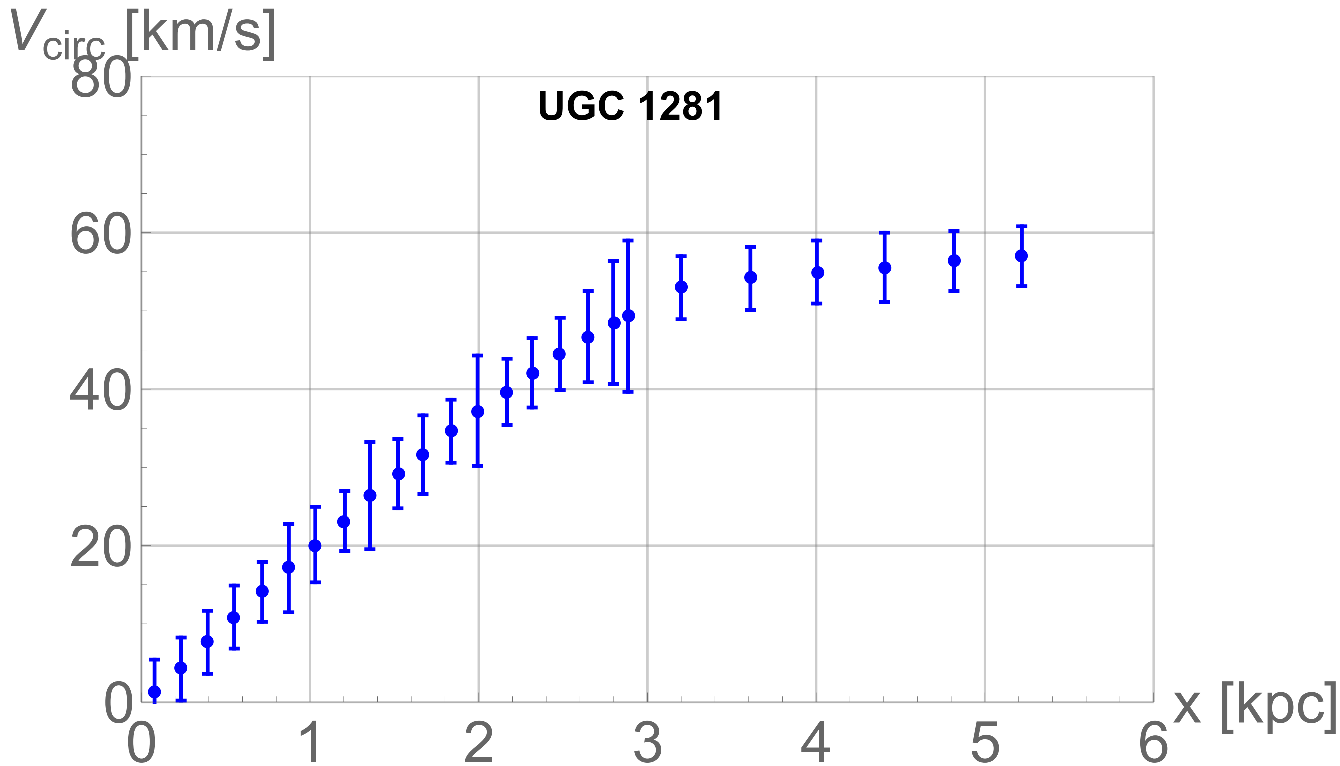


Rotation curves from simulations: velocity bump in inner galaxy




UGC 1281

m=1e-22 eV



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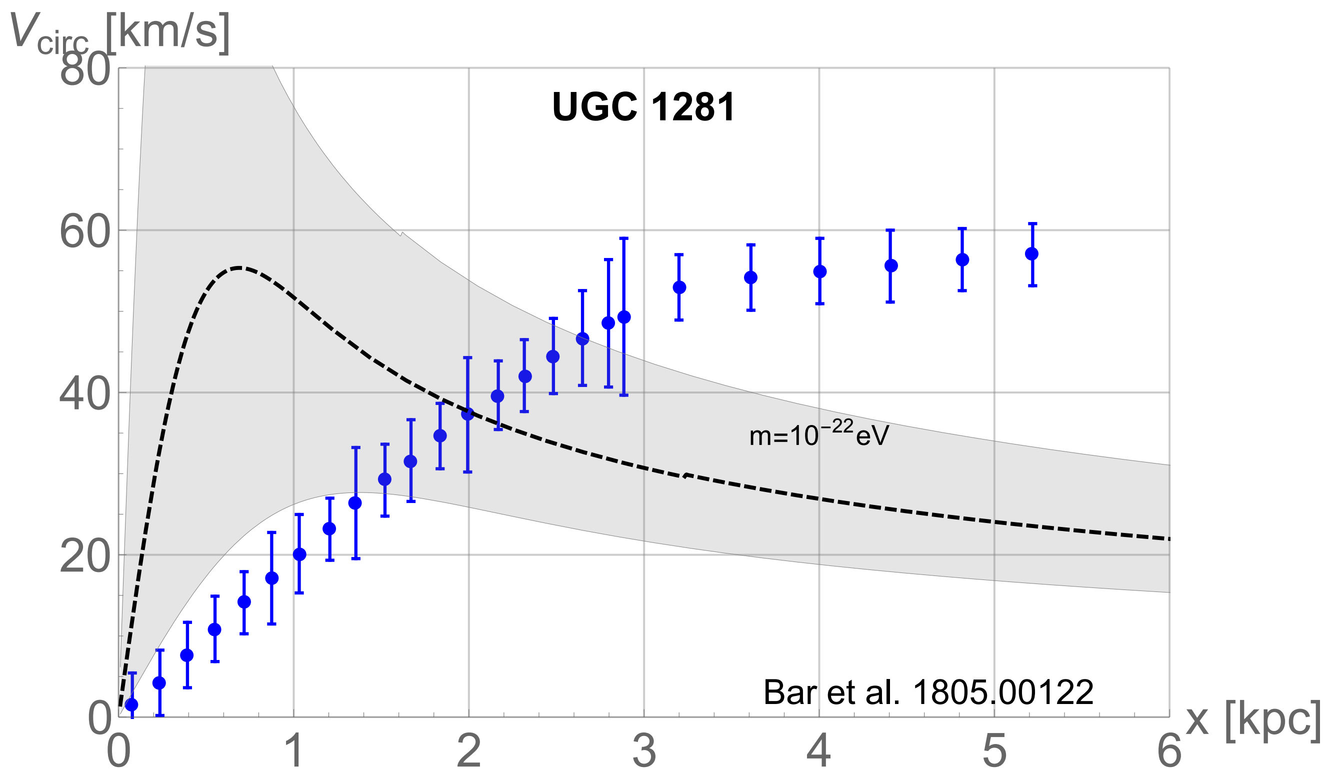
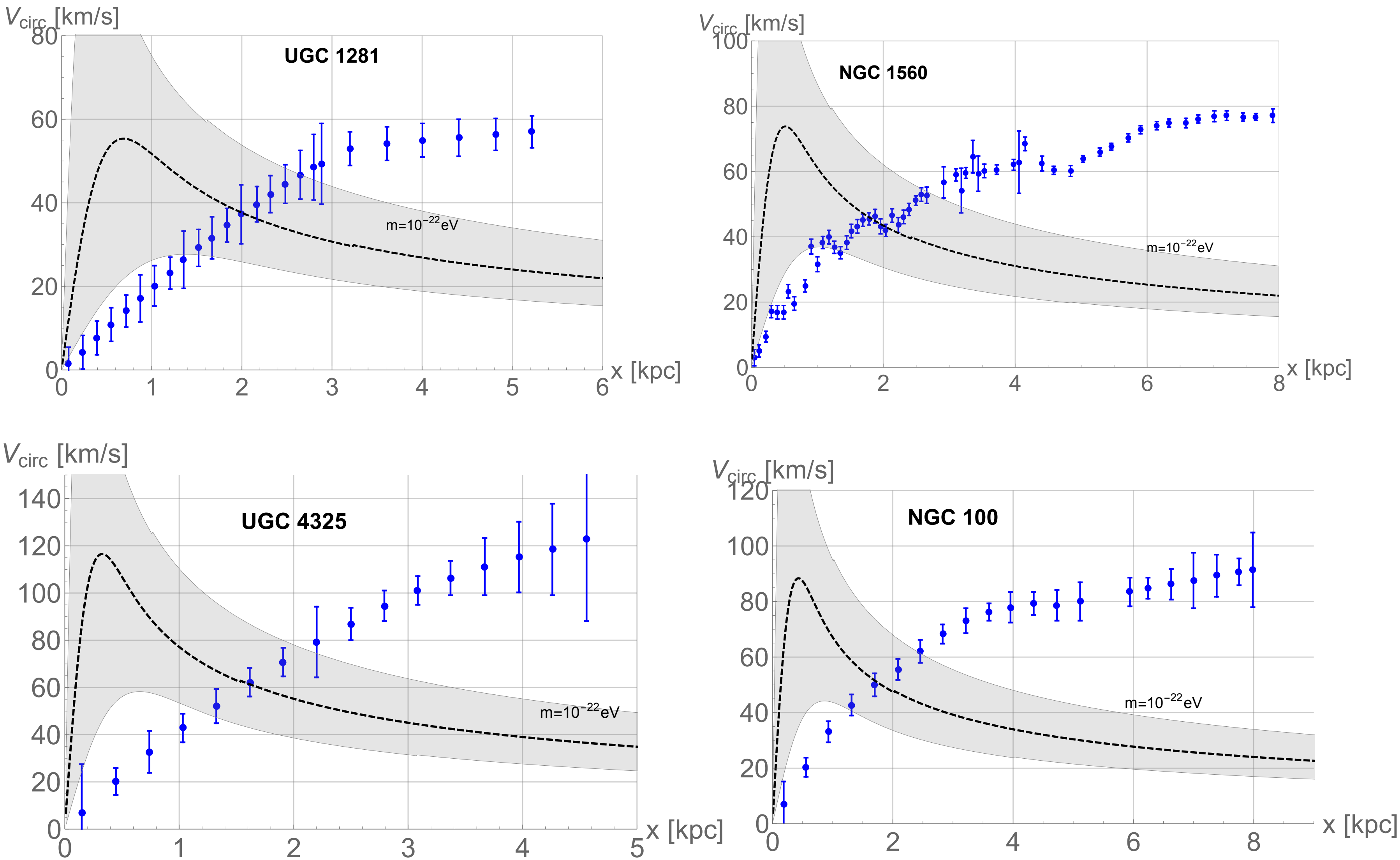


V_{circ} [km/s]
80
60
40
20
0
UGC 1281
m=10^{-22}eV
Bar et al. 1805.00122
0
1
2
3
4
5
6
x [kpc]

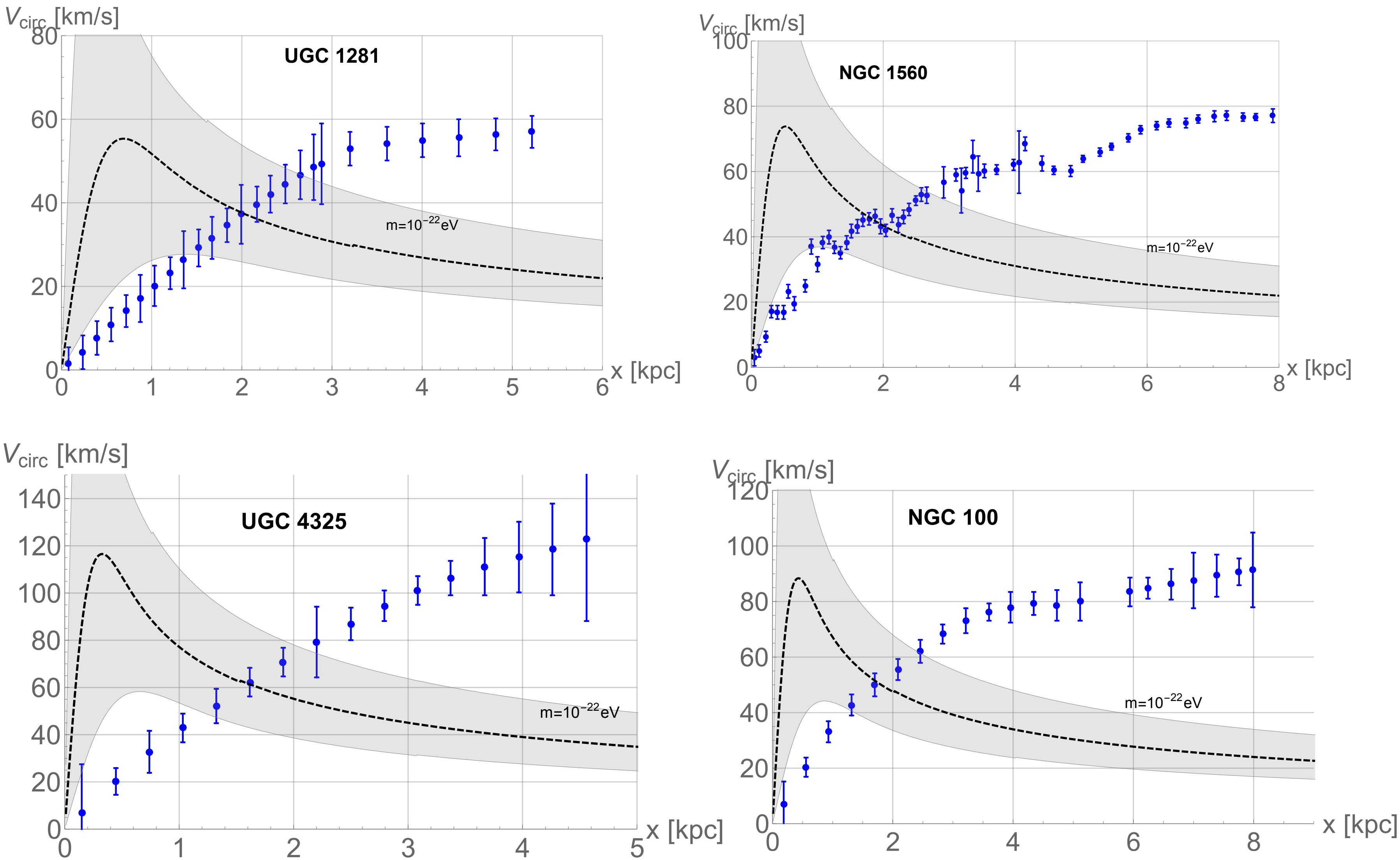
m=1e-22 eV



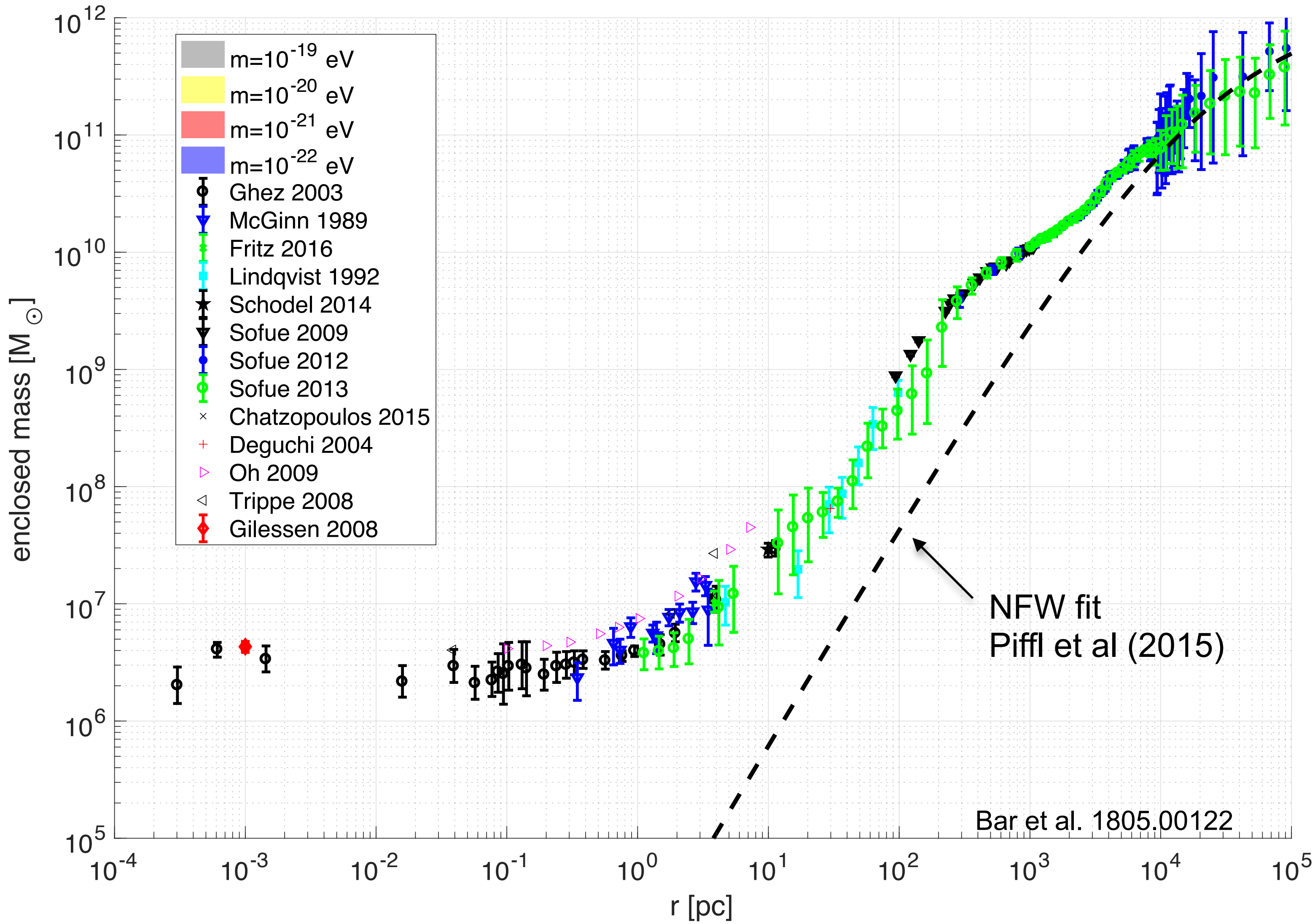
Bar et al. 1805.00122 analysed dozens of rotation curves: the feature isn’t there.

m < 1e-21 eV   in tension with observations.

(excludes ULDM from addressing small-scale puzzles of DM.)



Future prospects: e.g., Milky Way



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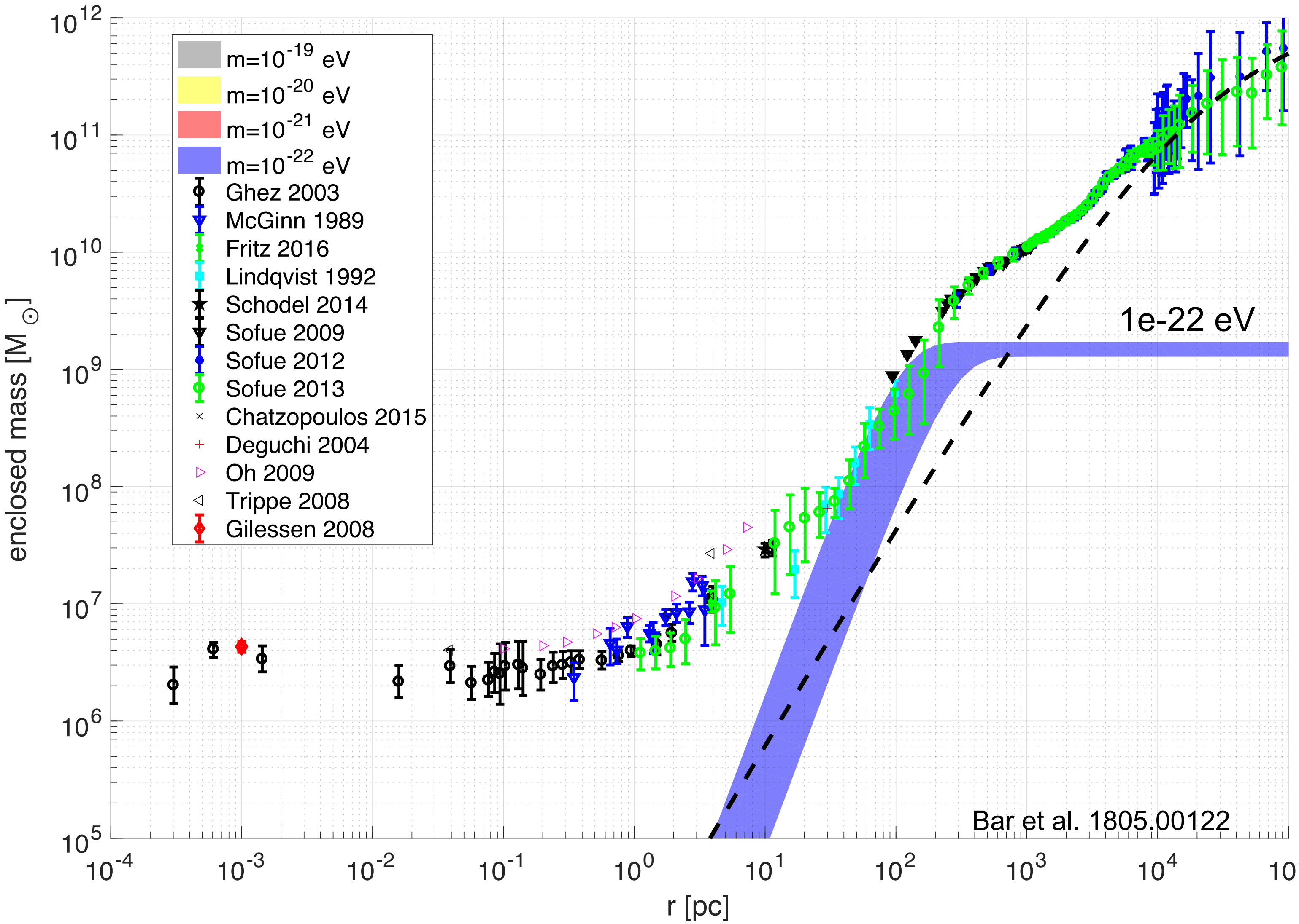

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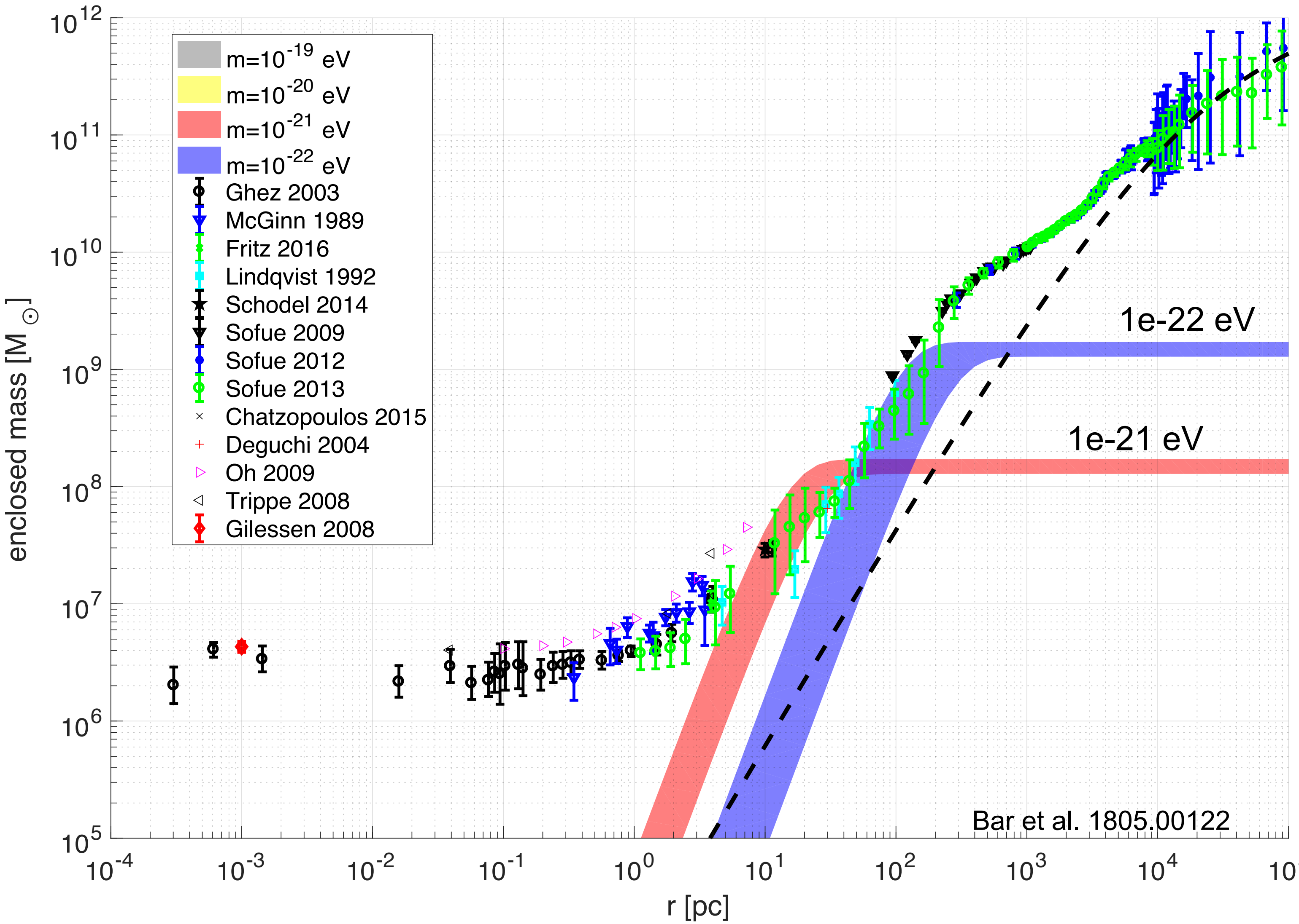

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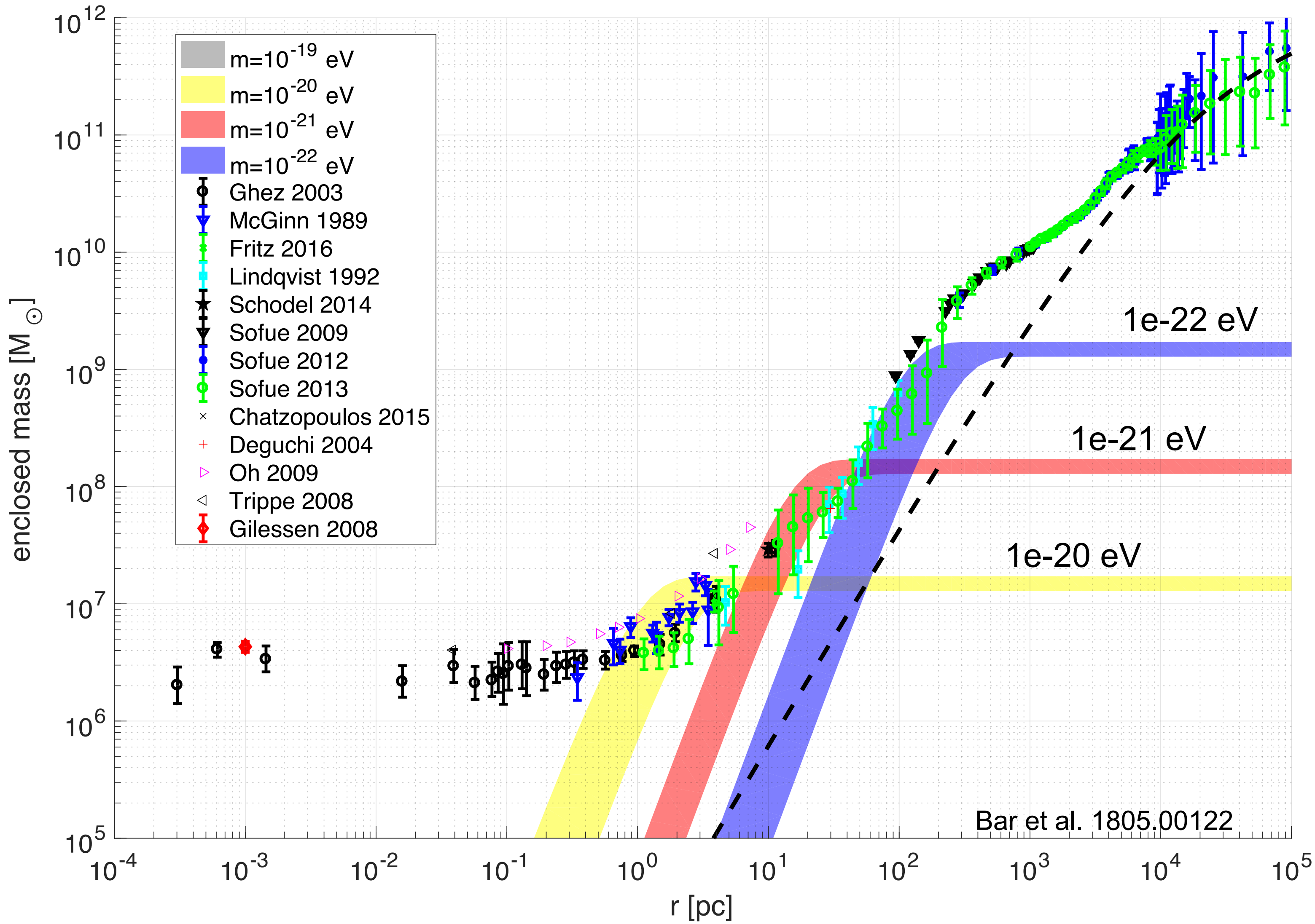

Summary

* ULDM exhibits wave dynamics on scales ~ de Broglie wavelength.
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* Predicts features in inner kinematics of galaxies.

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Comparable independent constraints from Ly-alpha Forest
Armengaud (1703.09126), Irsic (1703.04683), Zhang (1708.04389), Kobayashi (1708.00015)

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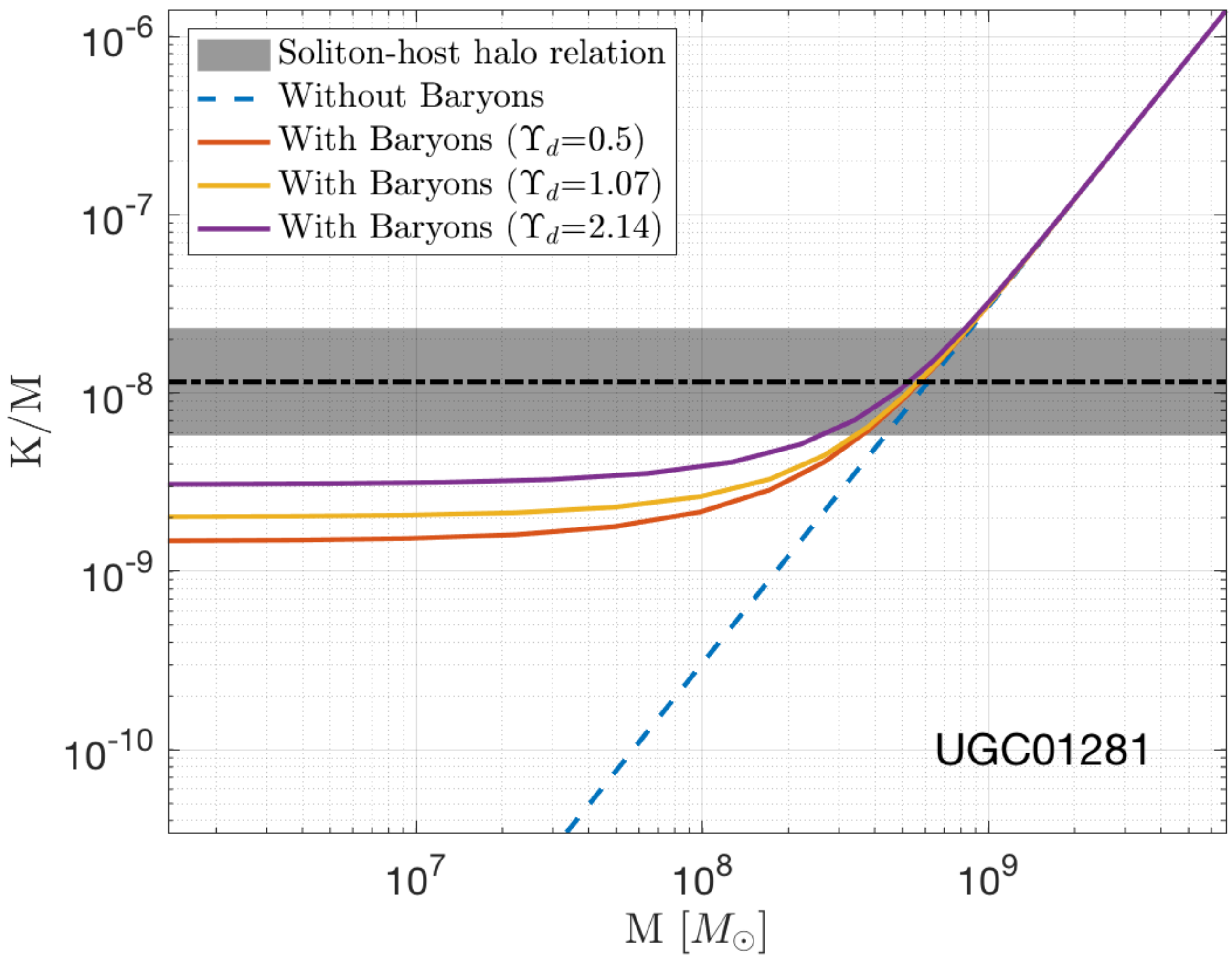
<u>Open questions / work in progress:</u>
Is the soliton—host halo relation correct? (or artefact of numerical simulations?)
If yes, what is the dynamical reason for it?

More observational tests of particle nature of dark matter, based on gravity alone?

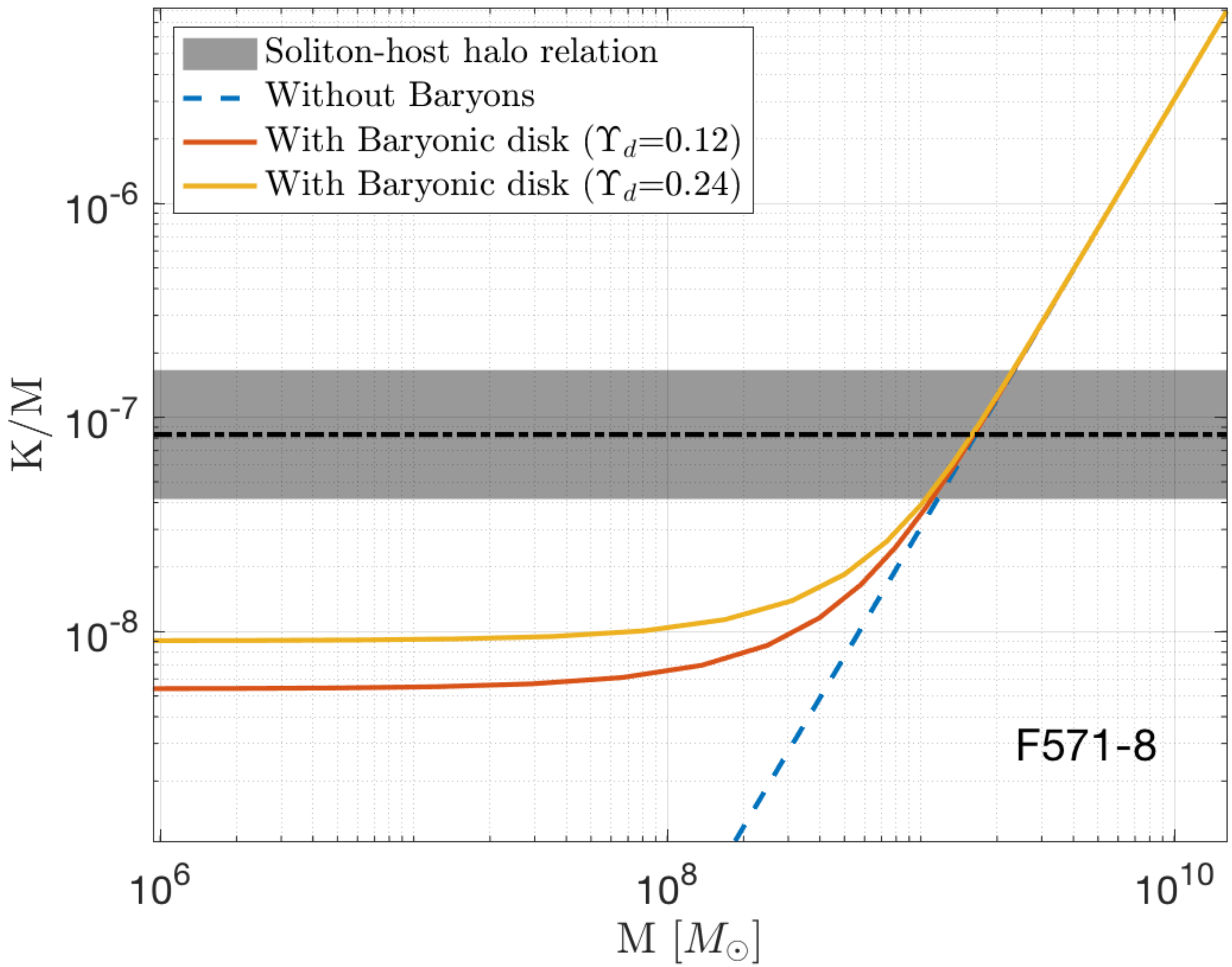
Xtra

m=1e-22 eV



Soliton-host halo relation
Without Baryons
With Baryons (Υ_d=0.5)
With Baryons (Υ_d=1.07)
With Baryons (Υ_d=2.14)
UGC01281
K/M
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{7}
10^{8}
10^{9}
M $[M_\odot]$

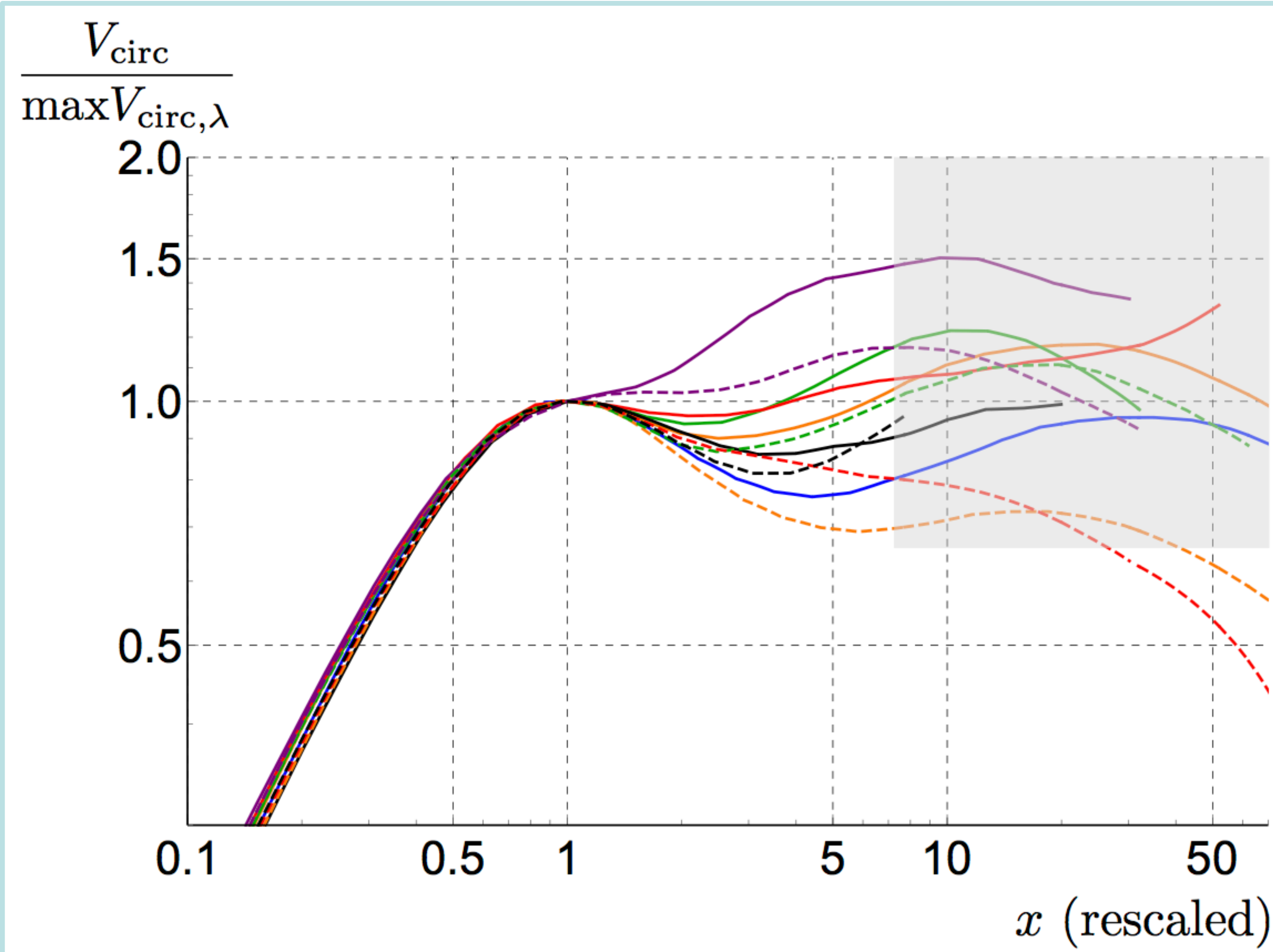
m=1e-22 eV



Soliton-host halo relation
Without Baryons
With Baryonic disk (Υ_d=0.12)
With Baryonic disk (Υ_d=0.24)
10^{-6}
10^{-7}
10^{-8}
K/M
F571-8
10^{6}
10^{8}
10^{10}
M $[M_\odot]$

Rotation curves from simulations

Velocity bump in inner galaxy: implied by soliton—halo relation



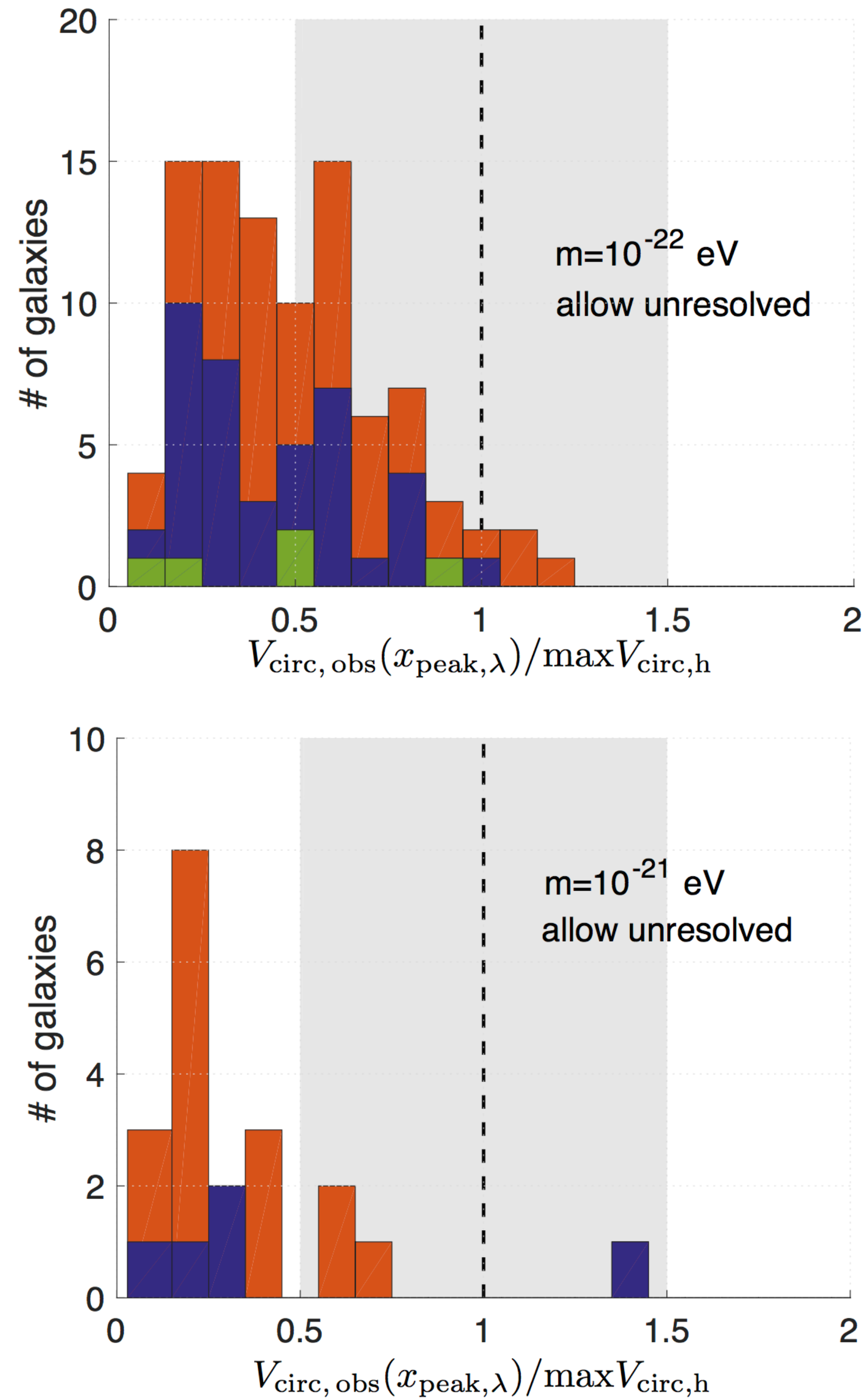
SPARC Lelli et al, 1606.09251
175 rotation curves

* 3.6um
* HI + Halpha rotation curves

max $V_{bar}/V_{DM} < 1$

max $V_{bar}/V_{DM} < 0.5$

max $V_{bar}/V_{DM} < 0.3$



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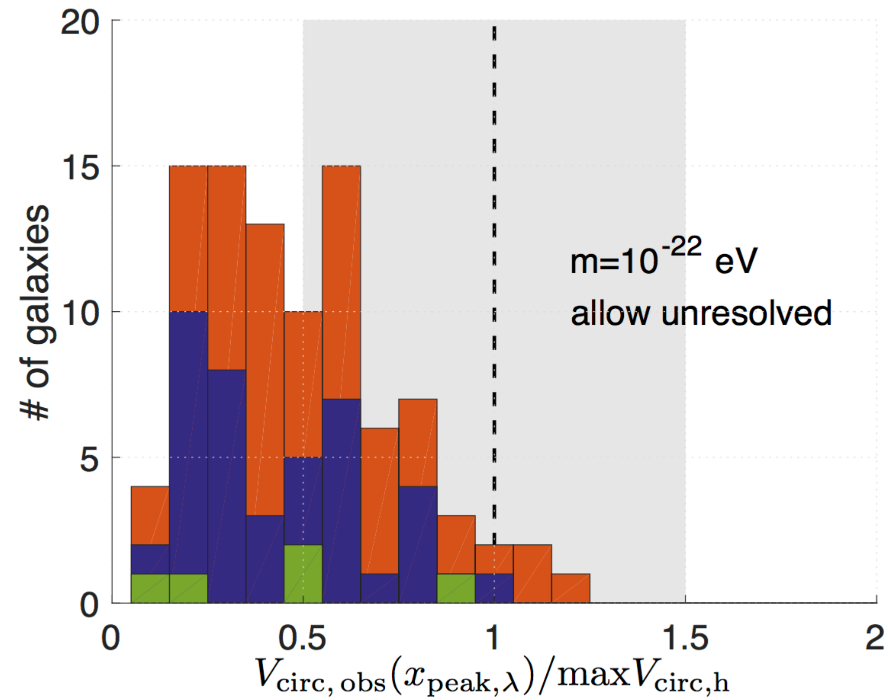

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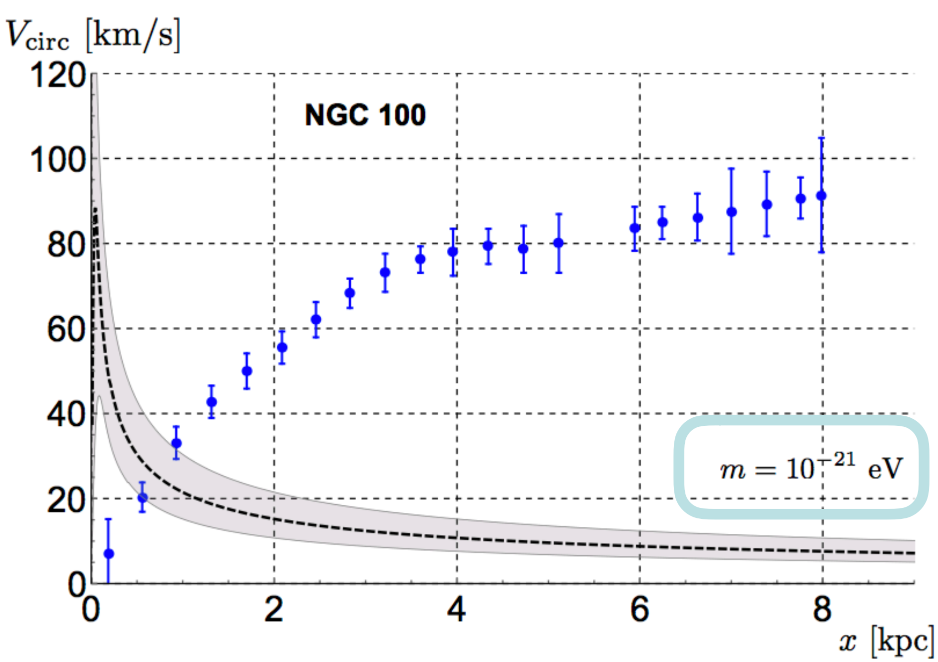
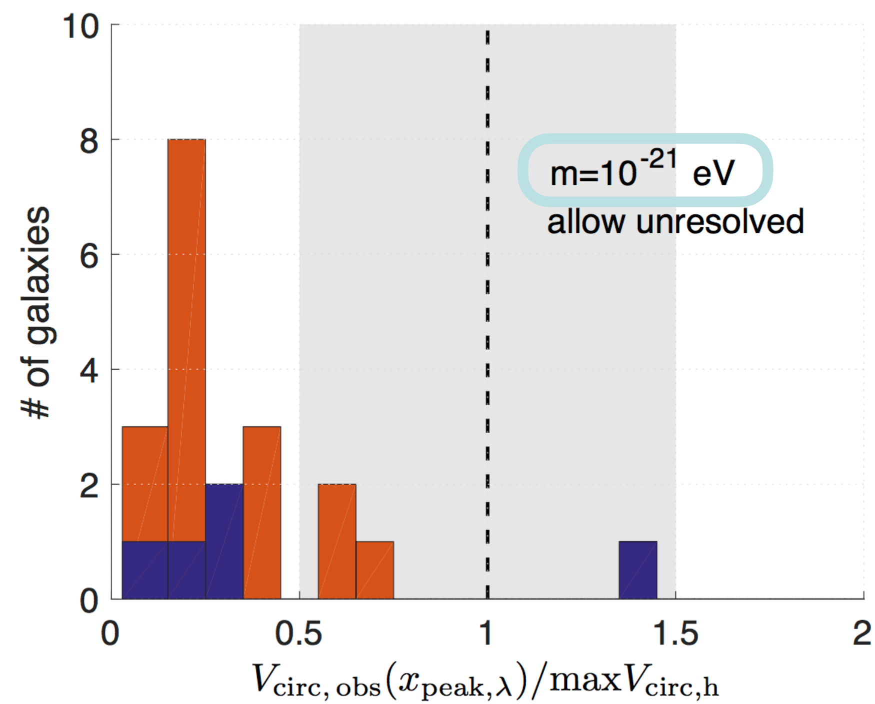
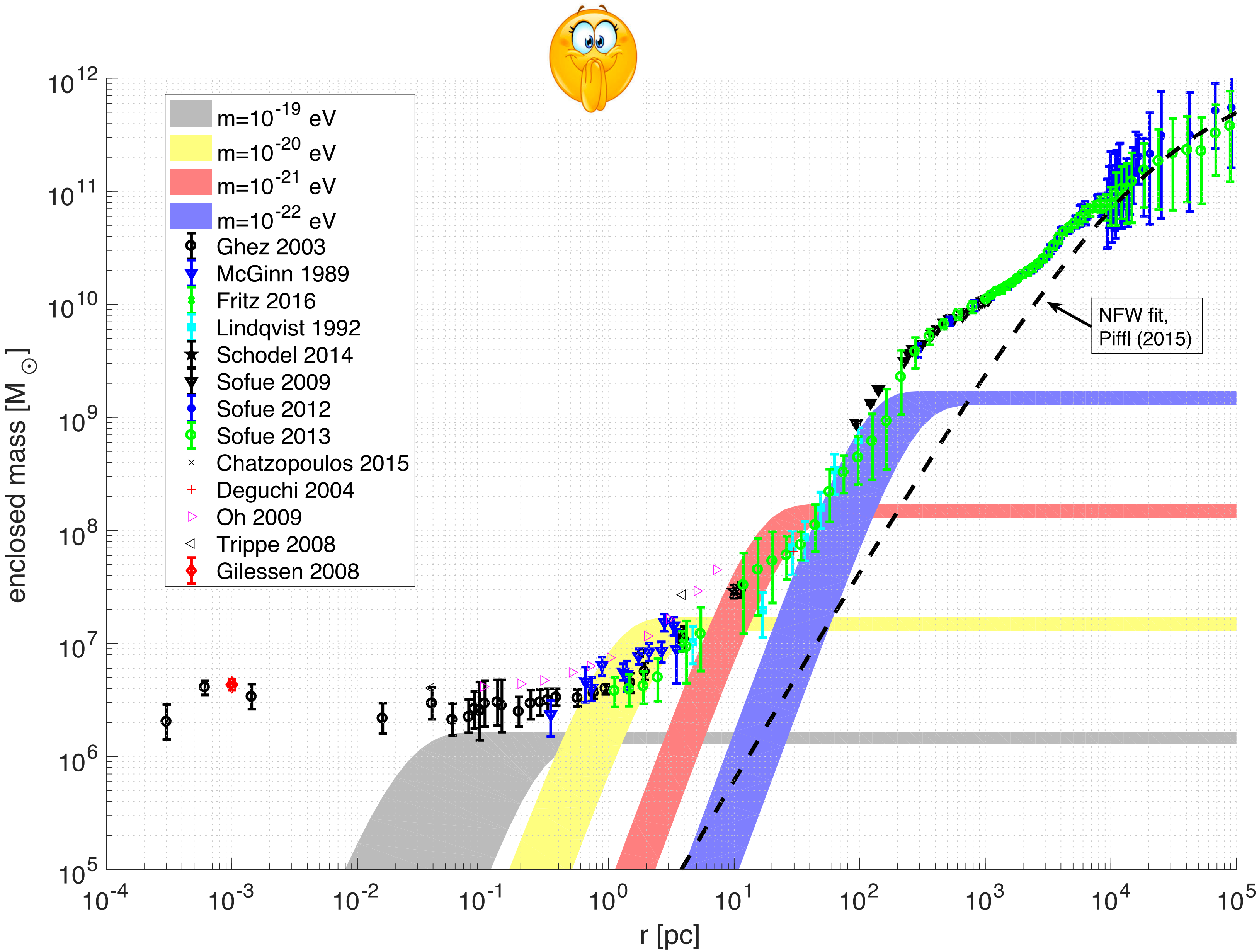




The Milky Way: nuclear bulge vs. soliton



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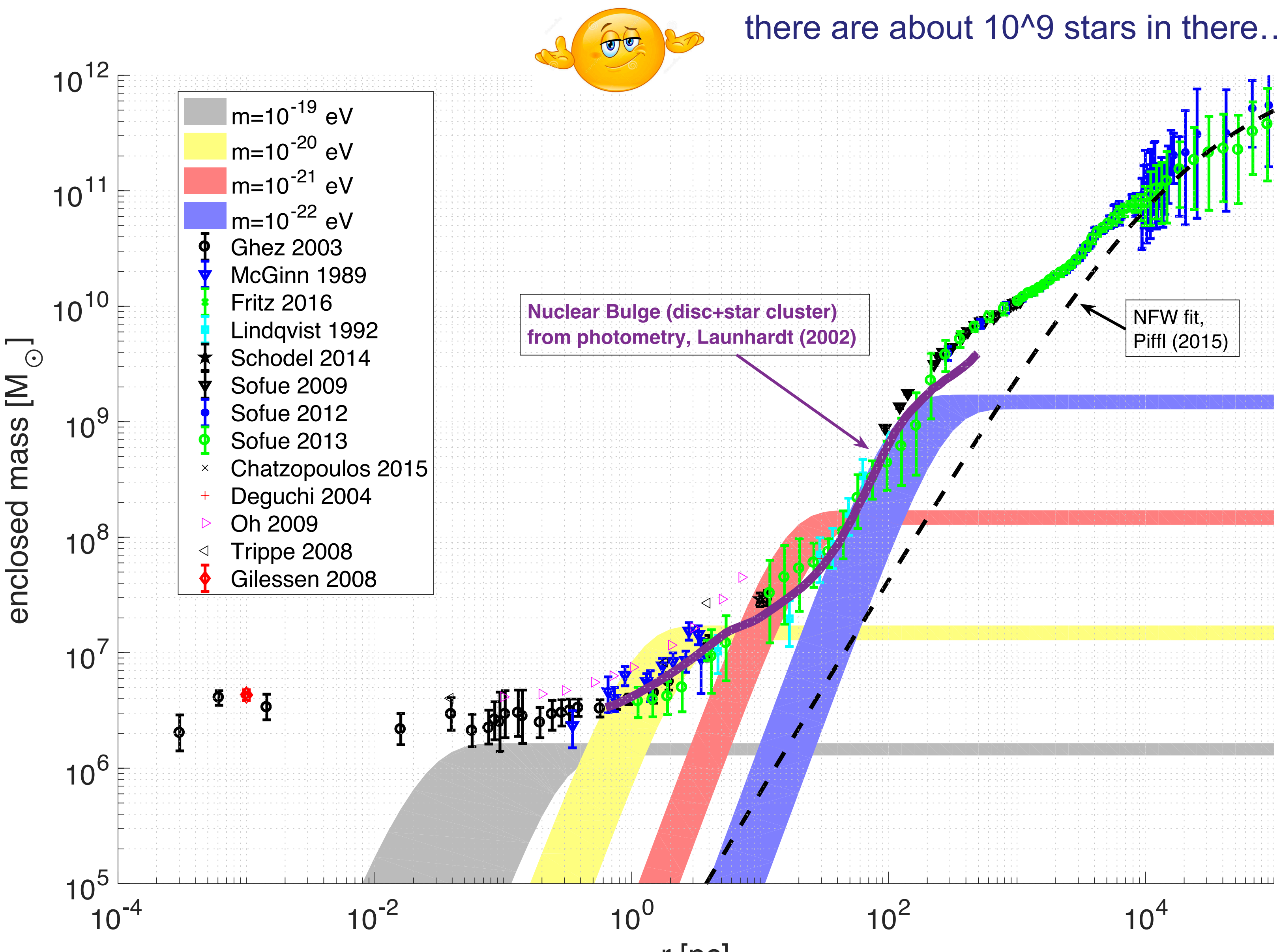
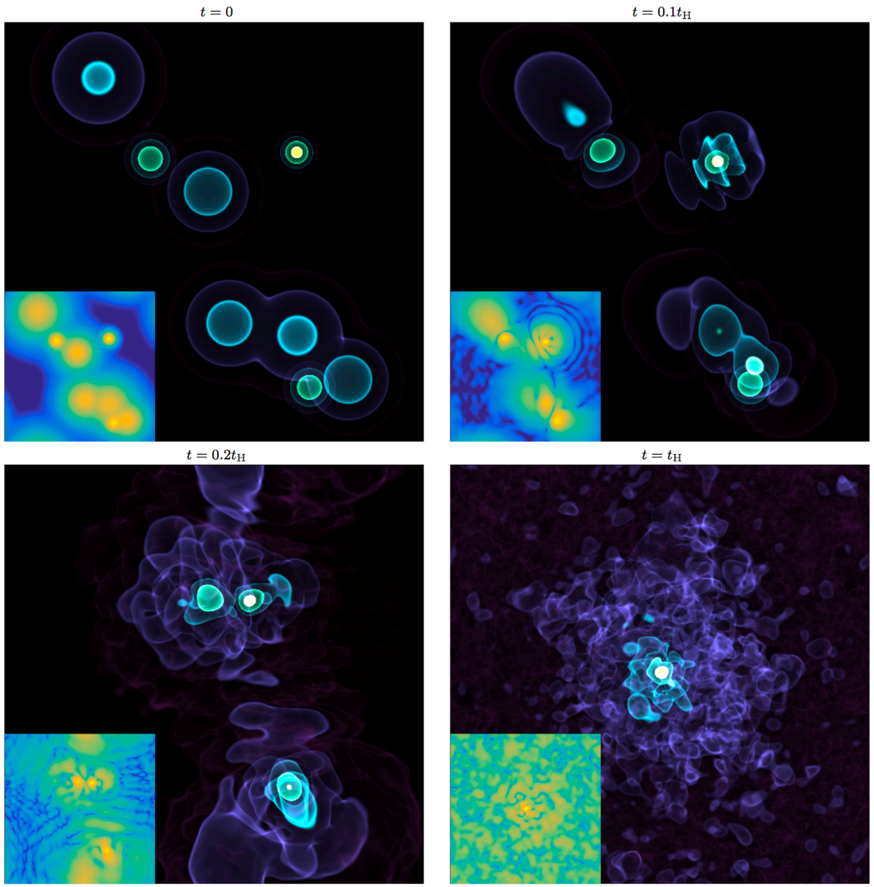
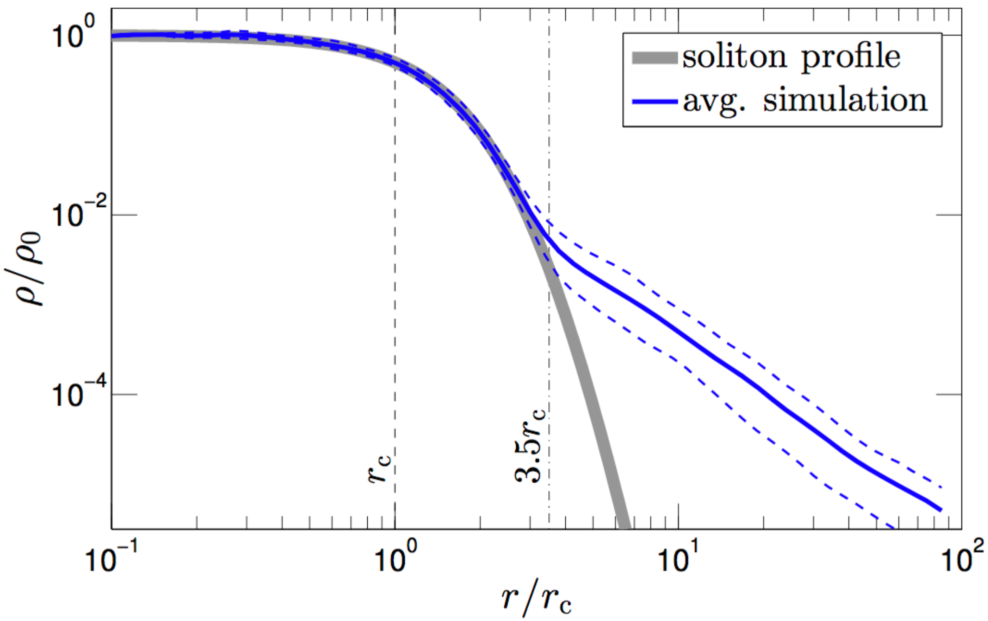


Mocz et al 1705.05845





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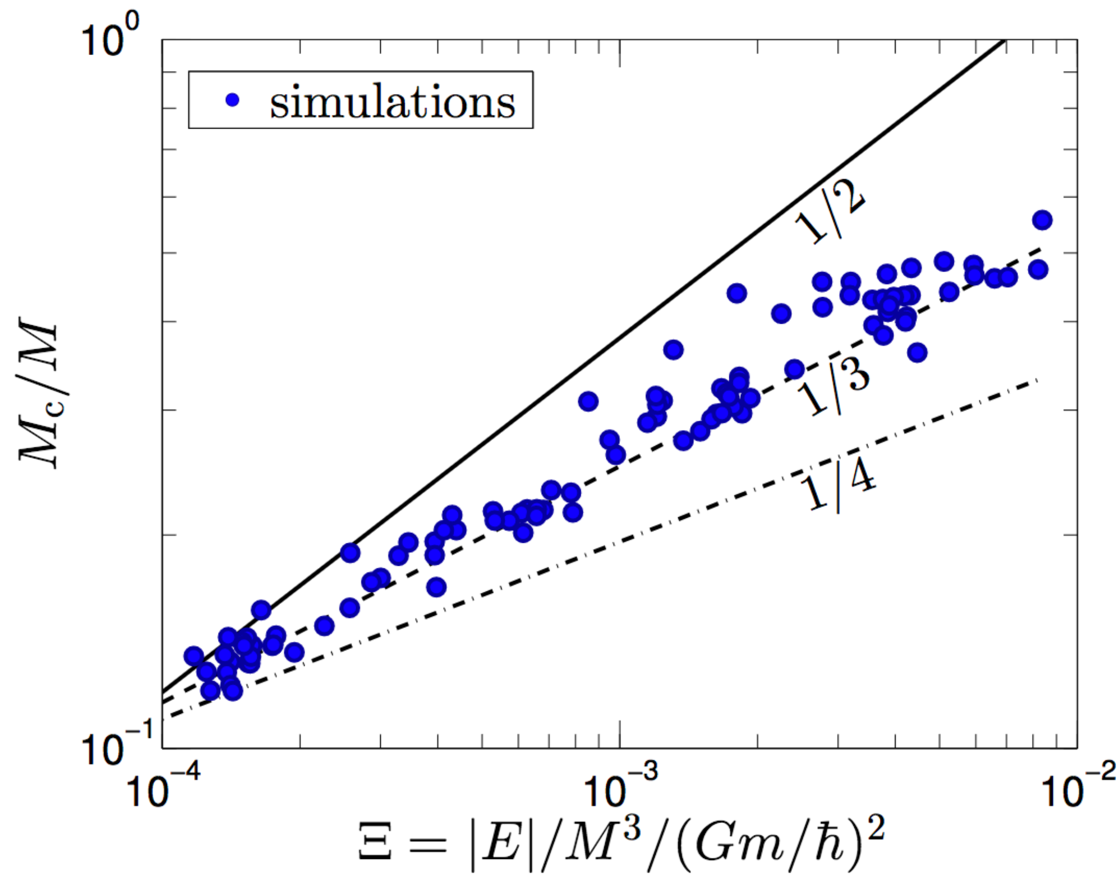
In our 100 simulations of virialized multi-body mergers, essentially characterised by a single parameter $\Xi \equiv |E|/M^3/(Gm/\hbar)^2$ set by the initial mass and energy (we have assumed no net angular momentum), we do find a fundamental relation between core mass M_c and Ξ.

$$M_c/M \simeq 2.6\Xi^{1/3} = 2.6\left(\frac{|E|}{M^3(Gm/\hbar)^2}\right)^{1/3}, \qquad (32)$$

which reproduces our simulations spanning two orders of magnitude in E, as shown in Fig. 4. More precisely, a nu-



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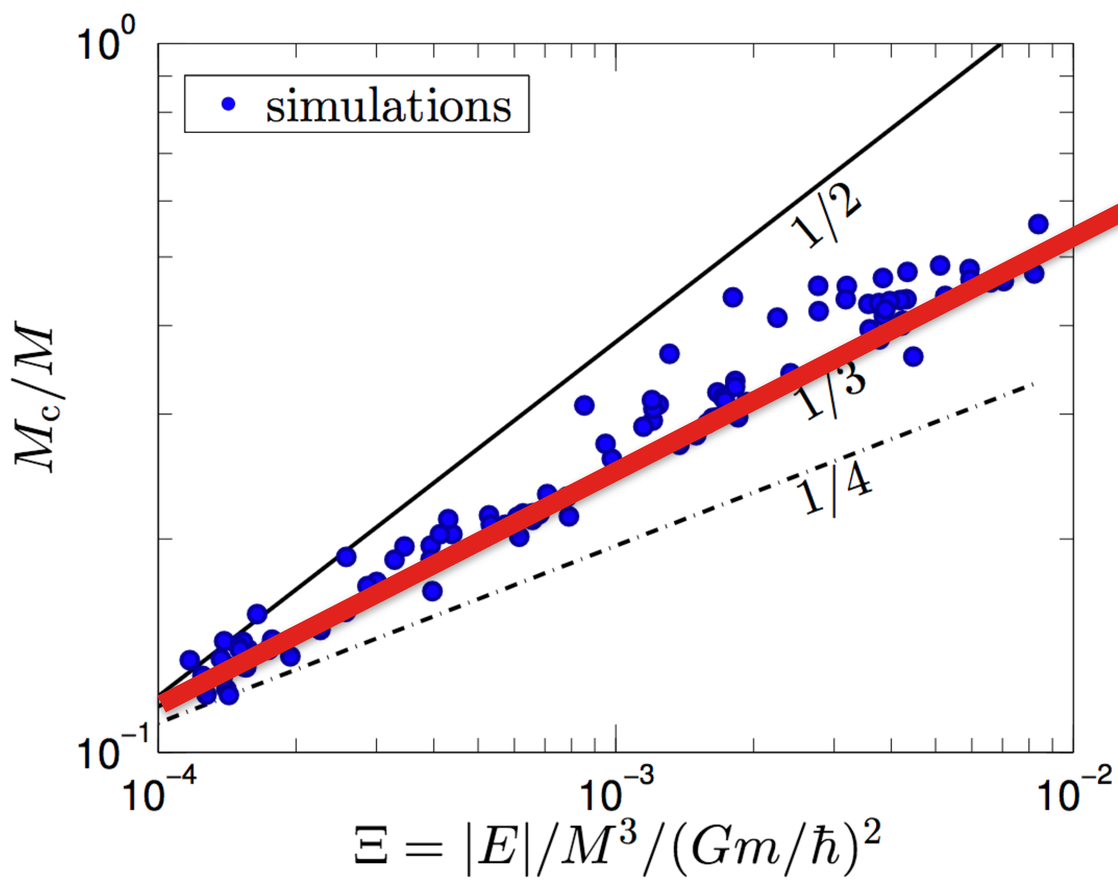
Analytic soliton:

$$E = \frac{1}{2}\int d^3x \left(\frac{1}{m^2}\left|\nabla\psi\right|^2 + \Phi\left|\psi\right|^2\right)$$

$$E_\lambda \approx -0.476\,\lambda^3\frac{M_{pl}^2}{m},$$

$$M_\lambda \approx 2.06\,\lambda\frac{M_{pl}^2}{m}.$$

$$\boxed{\frac{M_\lambda}{(M_{pl}^2/m)} \approx 2.64\left|\frac{E_\lambda}{(M_{pl}^2/m)}\right|^{\frac{1}{3}}}$$



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This means that the total energy in the simulation box was eaten up by 1 soliton.

Should not apply to real galaxies above ~1e8 Msol

(initial conditions?)

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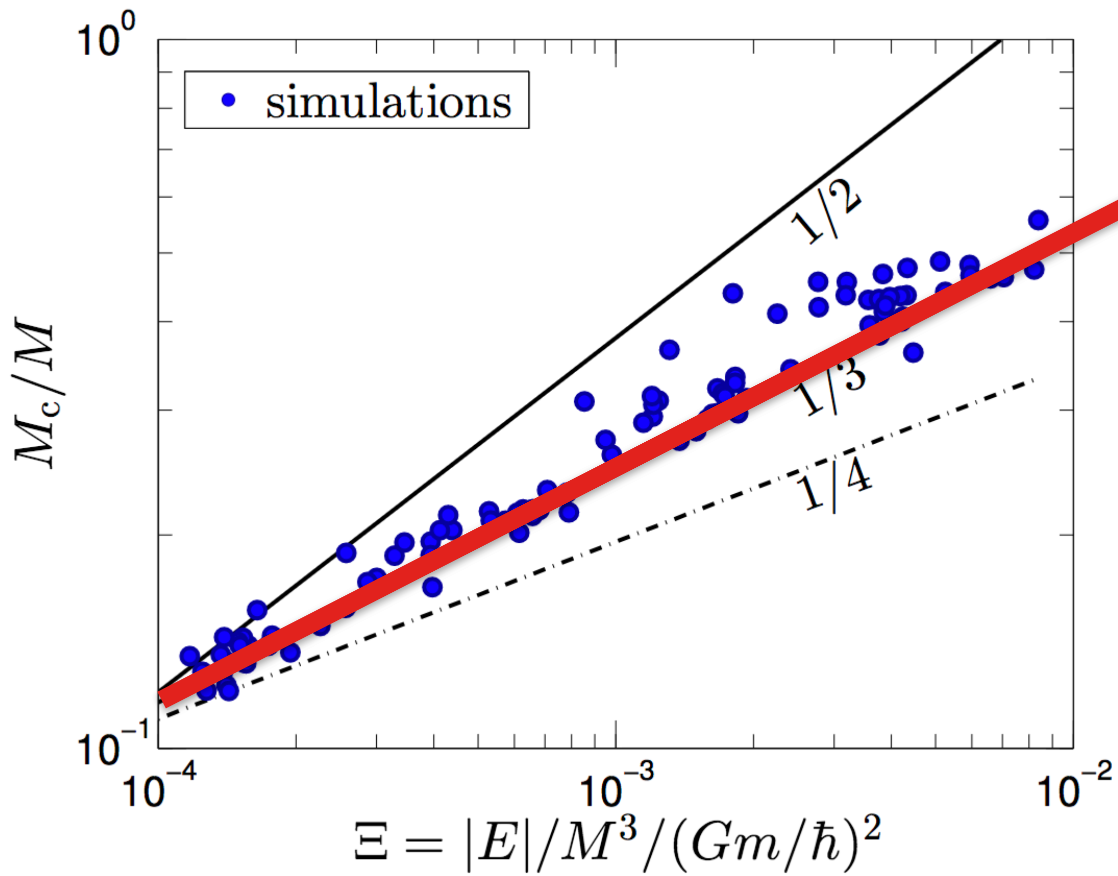

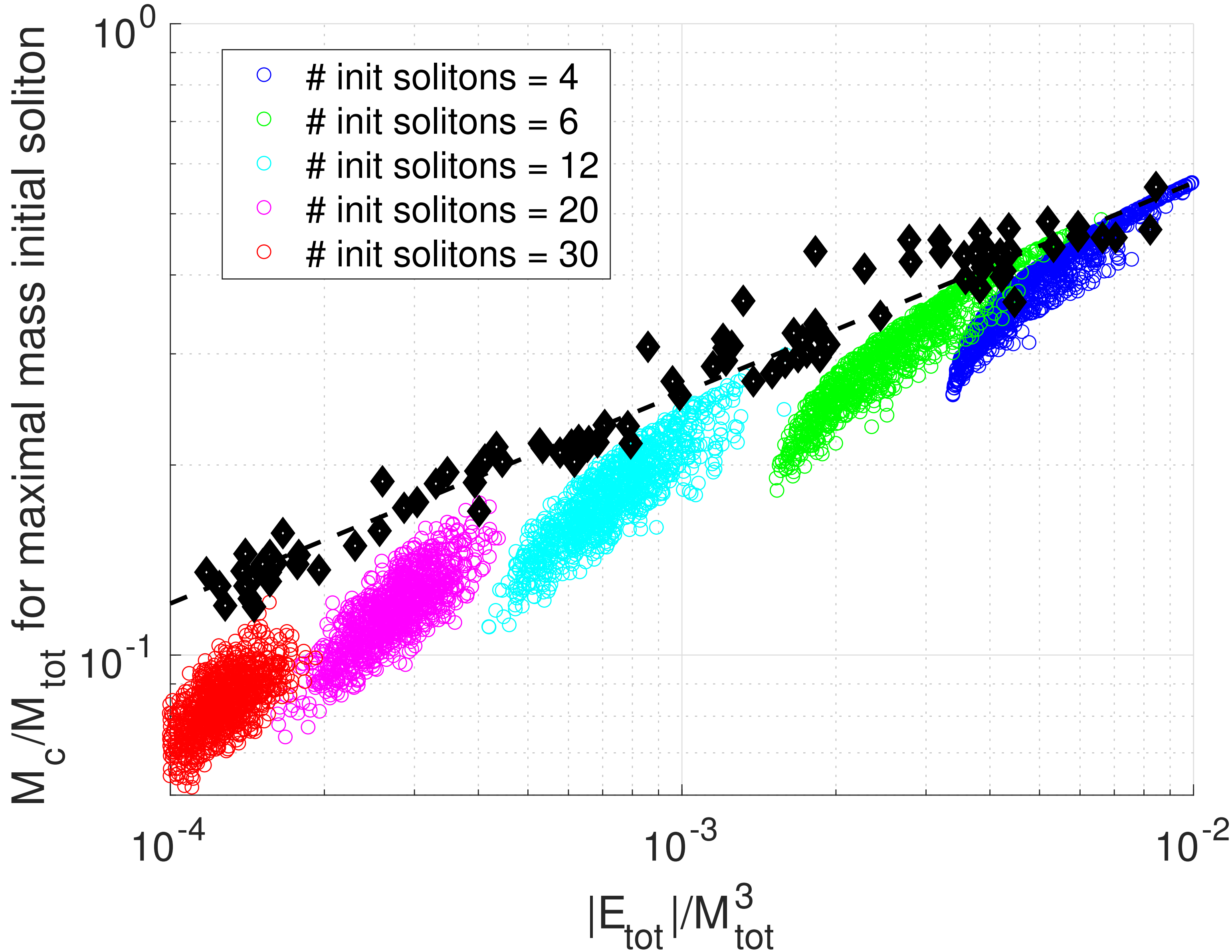

init solitons = 4
init solitons = 6
init solitons = 12
init solitons = 20
init solitons = 30
10^0
10^{-1}
10^{-4}
10^{-3}
10^{-2}
M_c/M_{tot} for maximal mass initial soliton
$|E_{tot}|/M^3_{tot}$

Non-gravitational interactions

$$\delta V(\phi) = \frac{\kappa\phi^4}{4}$$

$$|\kappa| < \frac{2m^2}{x_{c\lambda}^2 \rho_{c\lambda}} \quad \Rightarrow \quad |\kappa| < 4 \times 10^{-93} \left(\frac{m}{10^{-22}\mathrm{eV}}\right)^2 \left(\frac{M_h}{10^{12} M_\odot}\right)^{-\frac{2}{3}}$$

$$V(\phi) = m^2 f^2 (1 - \cos(\phi/f))$$

$$\Rightarrow \quad \kappa = -\frac{m^2}{6f^2}$$

$$\approx -1.7 \times 10^{-97} \left(\frac{m}{10^{-22}\mathrm{eV}}\right)^2 \left(\frac{f}{10^{17}\mathrm{GeV}}\right)^{-2}$$

Some facts about solitons

Real, free, KG field doing the job of DM

$$\phi(x,t) = \frac{1}{\sqrt{2m}} e^{-imt}\psi(x,t) + cc$$

$$i\partial_t \psi = -\frac{1}{2m}\nabla^2\psi + m\Phi\psi,$$
$$\nabla^2\Phi = 4\pi G|\psi|^2.$$

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On scales of order de Broglie wavelength:

$$\psi(x,t) = \left(\frac{m M_{pl}}{\sqrt{4\pi}}\right) e^{-i\gamma m t} \chi(x)$$

$$\Rightarrow \quad \partial_r^2 (r\chi) = 2r\,(\Phi - \gamma)\,\chi,$$
$$\partial_r^2 (r\Phi) = r\chi^2.$$

Some facts about solitons

Continuous family of ground state solutions, characterised by one parameter

Let $\chi_1(r)$ be defined to satisfy $\chi(0) = 1$, vanishing at infinity w/ no nodes.

$$M_1 = \frac{M_{pl}^2}{m} \int_0^\infty dr r^2 \chi_1^2(r)$$

$$\approx 2.79 \times 10^{12} \left(\frac{m}{10^{-22}\ \mathrm{eV}} \right)^{-1}\ \mathrm{M}_\odot$$

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Other solutions obtained by scaling

$$\chi_\lambda(r) = \lambda^2 \chi_1(\lambda r),$$
$$\Phi_\lambda(r) = \lambda^2 \Phi_1(\lambda r),$$
$$\gamma_\lambda = \lambda^2 \gamma_1,$$

$$M_\lambda = \lambda M_1,$$
$$x_{c\lambda} = \lambda^{-1} x_{c1}$$

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What it says:

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$$E = \int d^3x \left(\frac{|\nabla\psi|^2}{2m^2} + \frac{\Phi\,|\psi|^2}{2} \right)$$

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