Title: Galactic rotation curves vs. ultralight dark matter

Speakers: Kfir Blum

Series: Particle Physics

Date: March 26, 2019 - 1:00 PM

URL: http://pirsa.org/19030122

Abstract: Bosonic ultra-light dark matter (ULDM) would form cored density distributions at the centres of galaxies. These cores admit analytic description as the lowest energy bound state solution ("soliton") of the SchrÃ¶dinger-Poisson equations. Numerical simulations of ULDM galactic halos found empirical scaling relations between the mass of the large-scale host halo and the mass of the central soliton.
We connect the simulation results of different groups to basic properties of the soliton. Importantly, simulations imply that the specific kinetic energy in the soliton and in the host halo should be approximately equal. This relation predicts that the peak circular velocity, measured for the host halo in the outskirts of the galaxy, should repeat itself in the central region. Contrasting this prediction to the measured rotation curves of low surface-brightness galaxies, we show that ULDM in the mass range m ~ 10â•»Â²Â²-10â•»Â²Â¹ eV, which has been invoked as a possible solution of small-scale puzzles of Î›CDM, is in tension with the data. We discuss the potential of detailed dynamical modelling of the Milky Way and other well-resolved galaxies to probe ULDM up to m ~ 10â•»Â¹â•¹ eV.

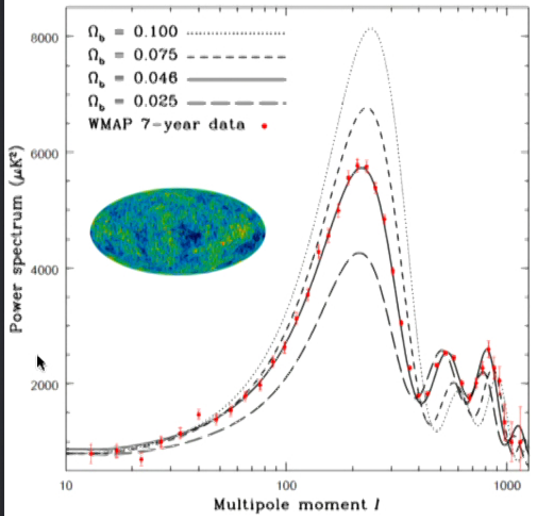
Galactic rotation curves vs. ultra-light dark matter

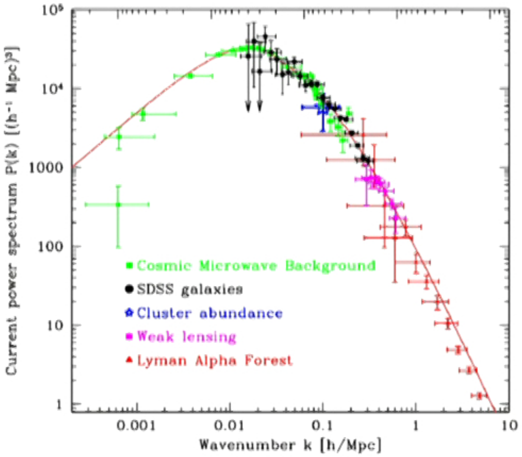
Kfir Blum

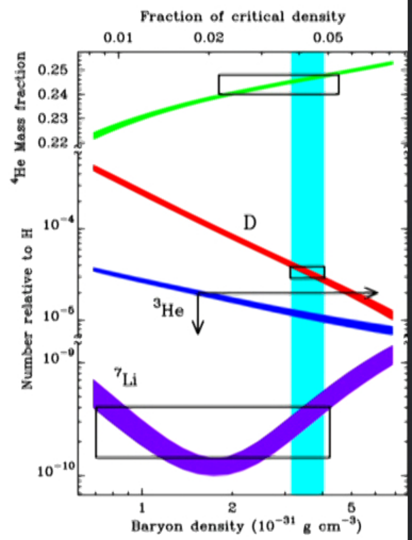
Bar, Blas, KB, Sibiryakov; 1805.00122
Bar, KB, Sato, Eby; 1903.03402

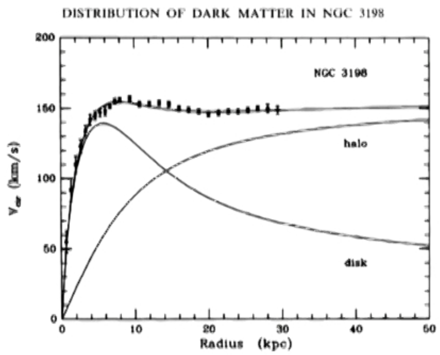
PI 2019

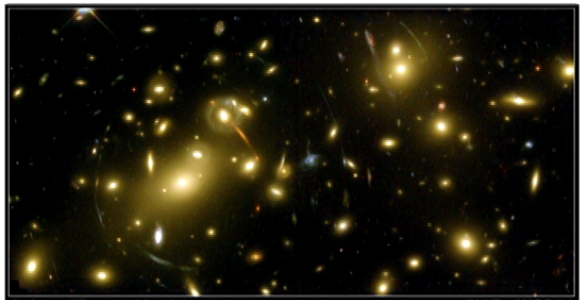
What is dark matter?










Galaxy Cluster Abell 2218 HST • WFPC2
NASA, A. Fruchter and the ERO Team (STScI, ST-ECF) • STScI-PRC00-08

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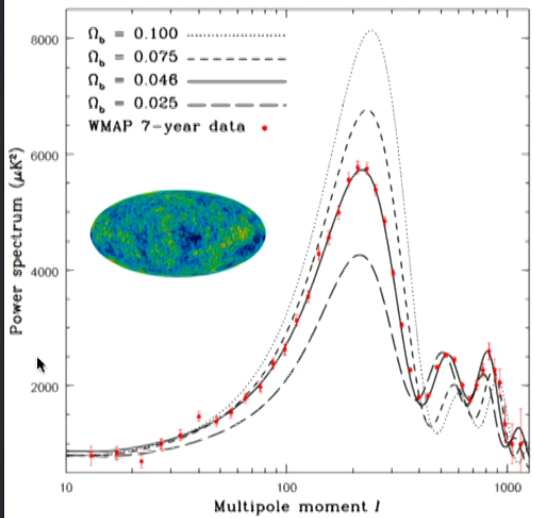
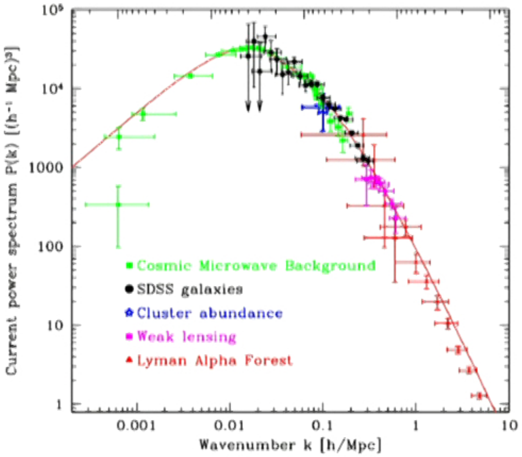
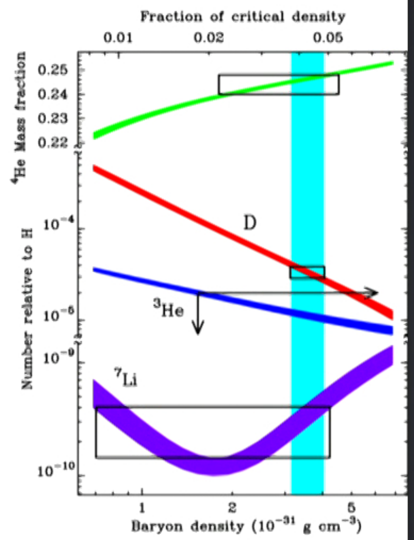
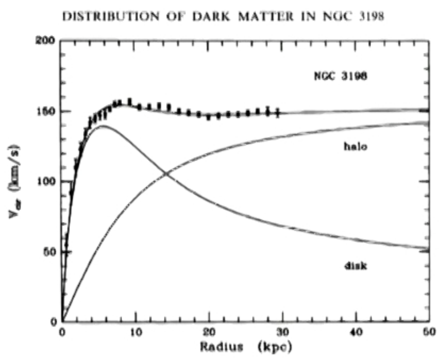
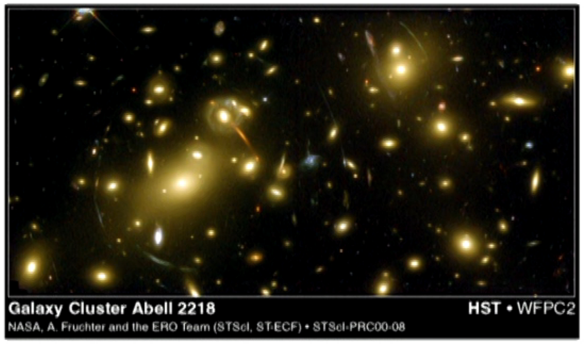






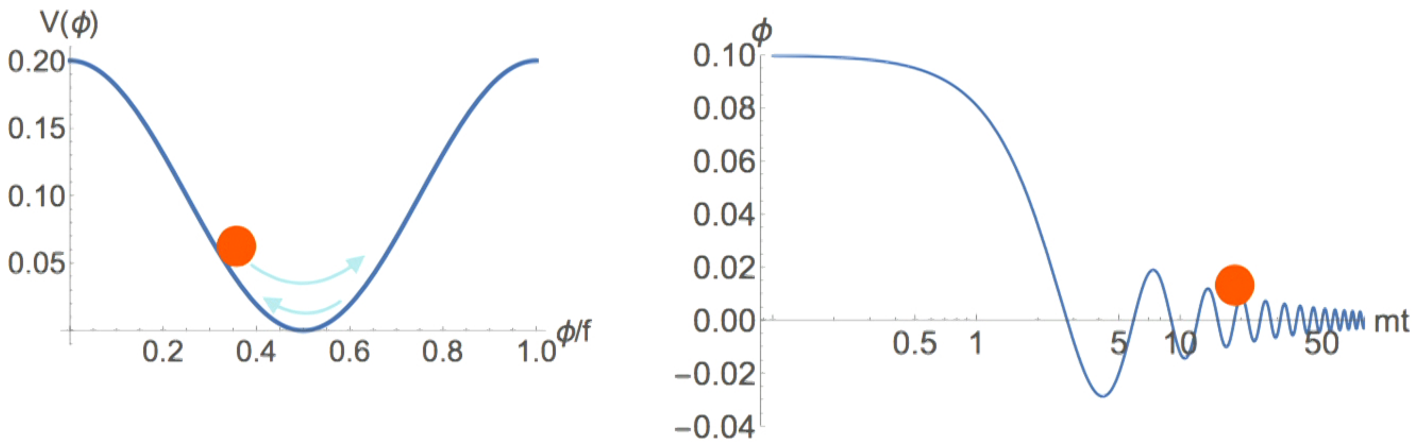




Light (pseudo-)scalar fields are featured in many UV models, where they arise as PNGBs of spontaneously broken symmetries.

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.



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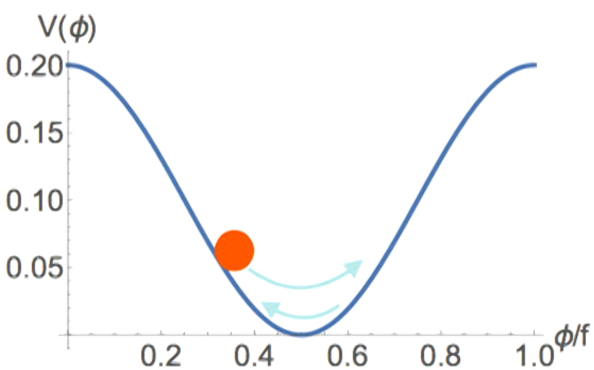

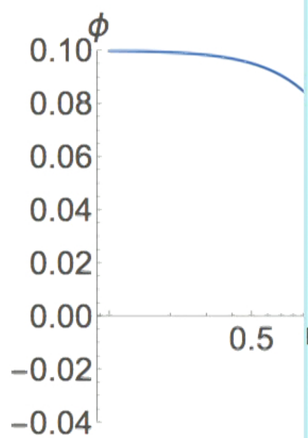

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[2] A. Arbey, J. Lesgourgues, and P. Salati, "Quintessential haloes around galaxies," Phys. Rev. **D64** (2001) 123528, arXiv:astro-ph/0105564 [astro-ph].
[3] J. Lesgourgues, A. Arbey, and P. Salati, "A light scalar field at the origin of galaxy rotation curves," New Astron. Rev. **46** (2002) 791–799.
[4] P.-H. Chavanis, "Mass-radius relation of Newtonian self-gravitating Bose-Einstein condensates with short-range interactions: I. Analytical results," Phys. Rev. **D84** (2011) 043531, arXiv:1103.2050 [astro-ph.CO].
[5] P. H. Chavanis and L. Delfini, "Mass-radius relation of Newtonian self-gravitating Bose-Einstein condensates with short-range interactions: II. Numerical results," Phys. Rev. **D84** (2011) 043532, arXiv:1103.2054 [astro-ph.CO].
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[9] H.-Y. Schive, T. Chiueh, and T. Broadhurst, "Cosmic Structure as the Quantum Interference of a Coherent Dark Wave," Nature Phys. **10** (2014) 496–499, arXiv:1406.6586 [astro-ph.GA].
[10] H.-Y. Schive, M.-H. Liao, T.-P. Woo, S.-K. Wong, T. Chiueh, T. Broadhurst, and W. Y. P. Hwang, "Understanding the Core-Halo Relation of Quantum Wave Dark Matter from 3D Simulations," Phys. Rev. Lett. **113** no. 26, (2014) 261302, arXiv:1407.7762 [astro-ph.GA].
...

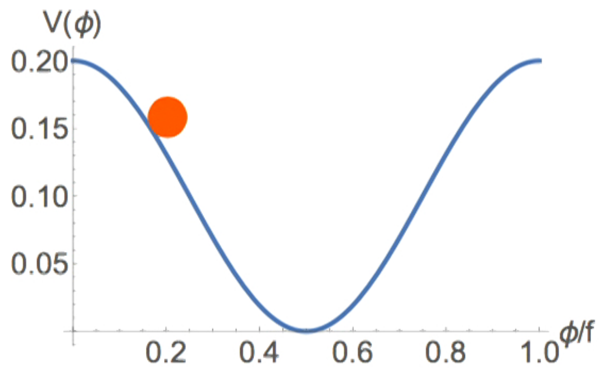
Light (pseudo-)scalar fields are featured in many UV models, where they arise as PNGBs of spontaneously broken symmetries.

Relic abundance set by initial conditions.

Natural initial condition: $\phi \sim f$

Assuming potential exists before end of inflation, contribution to energy density today:

$$\Omega_m \sim 0.1 \left(\frac{m}{10^{-22}\ \mathrm{eV}}\right)^{\frac{1}{2}} \left(\frac{f}{10^{17}\ \mathrm{GeV}}\right)^2$$



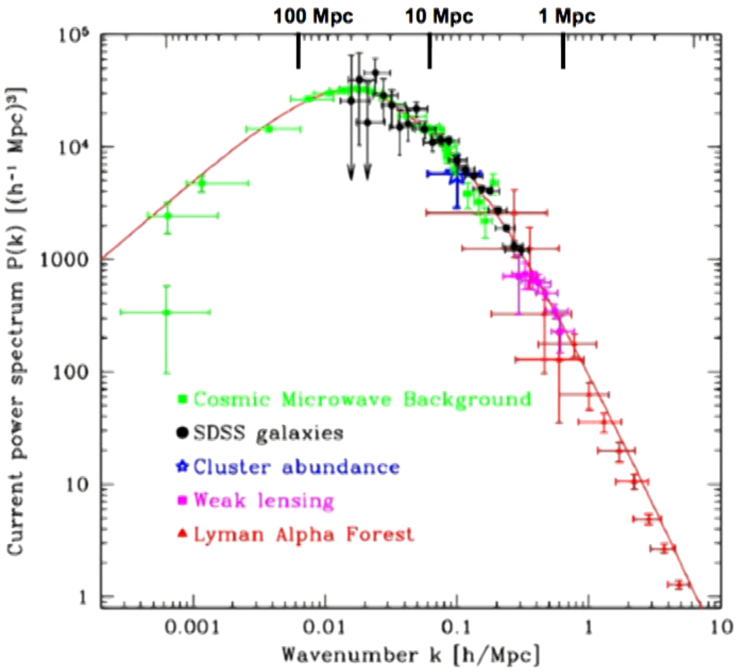
Ultra-light dark matter (ULDM)

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

dB length for self-gravitating perturbation ("Jeans scale"):
v^2 ~ G\rho(1/mv)^3(mv)
kdB ~ (mv) ~ (G\rho m^2)^1/4.

pert' can't grow for k>kdB.
ldB ~ 0.1Mpc (m/10^-22 eV)^-1/2

Ly-alpha Forest: m >~ 10^-21 eV
Armengaud (1703.09126),
Irsic (1703.04683),
Zhang (1708.04389),
Kobayashi (1708.00015)
…



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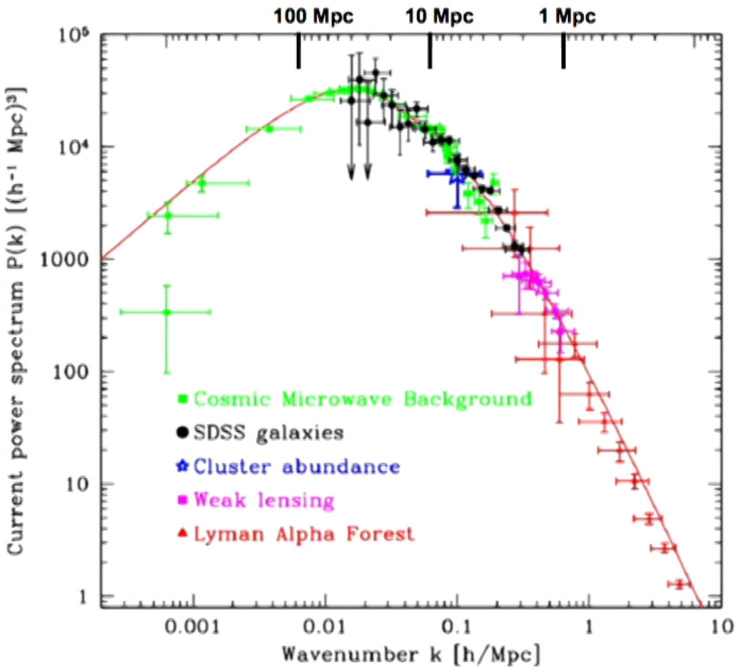

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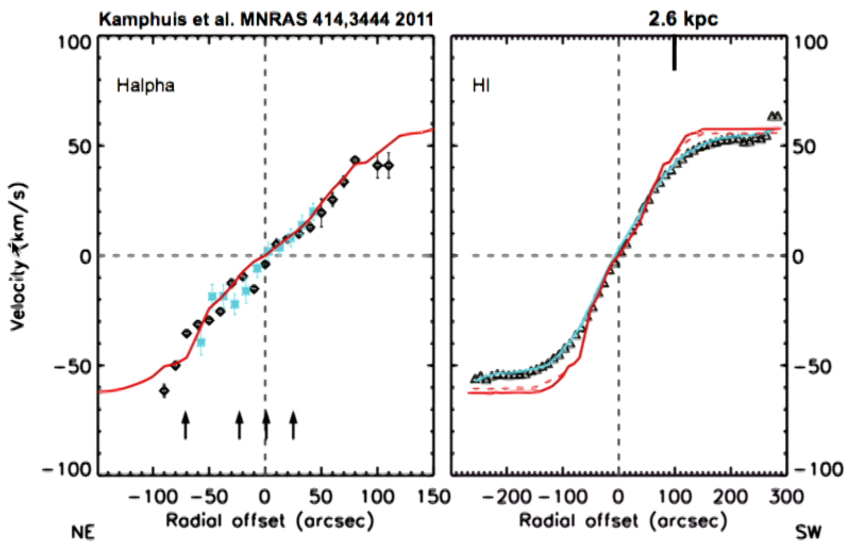
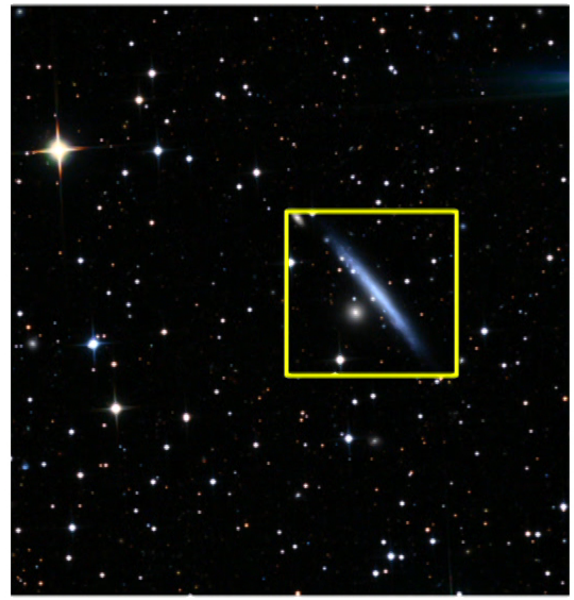
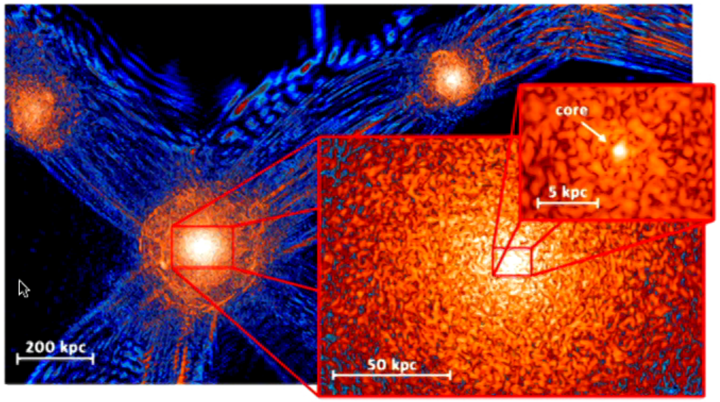
On scales of order de Broglie wavelength, **ULDM is markedly different than WIMPs.**

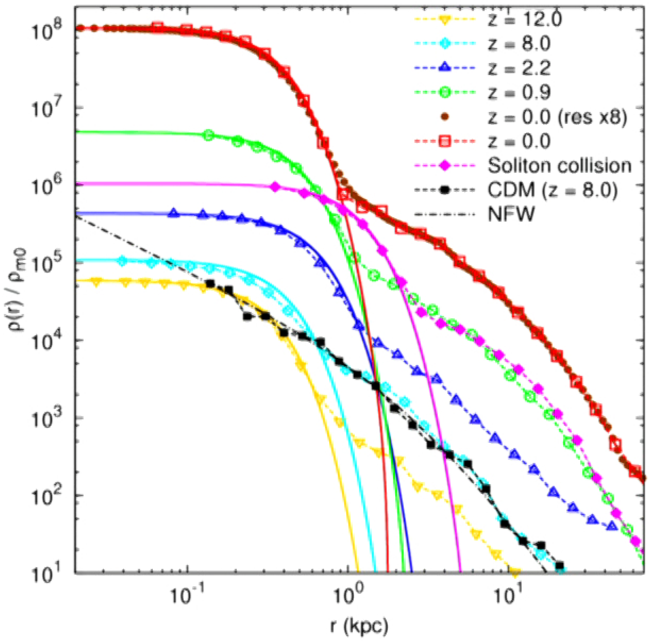
dB length ~ kpc for m~10^-22 eV





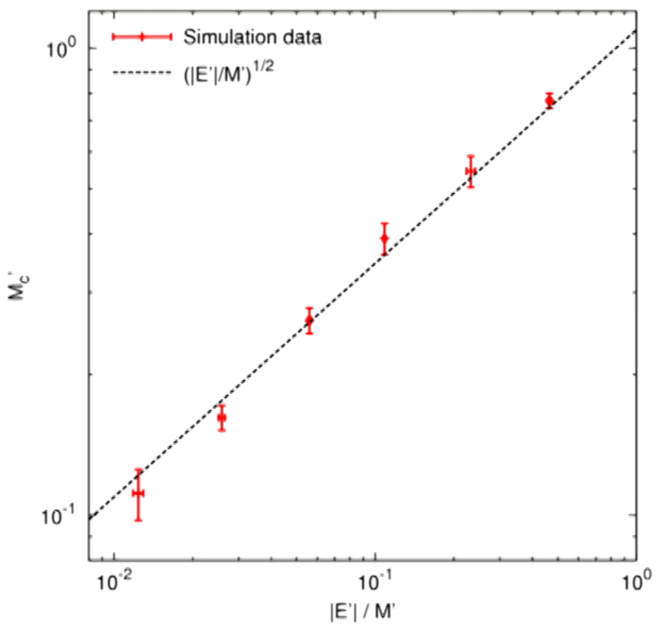
soliton core in simulated ULDM galaxies

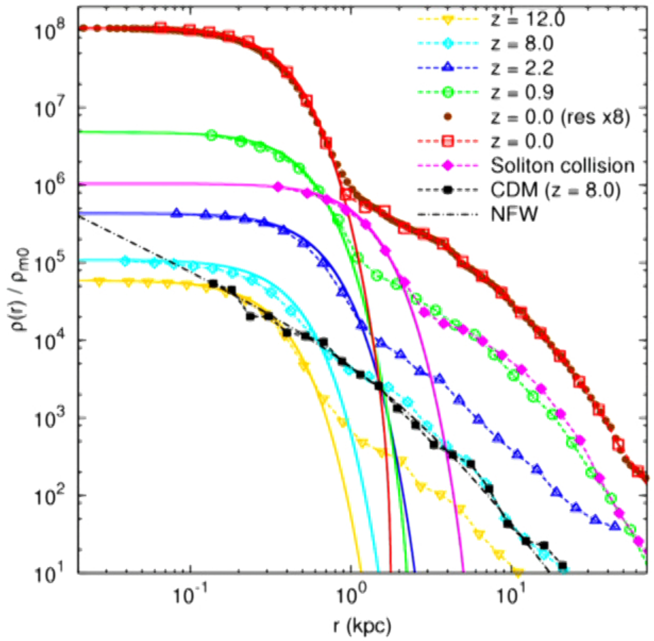




Schive et al 1406.6586

A soliton — host halo relation?





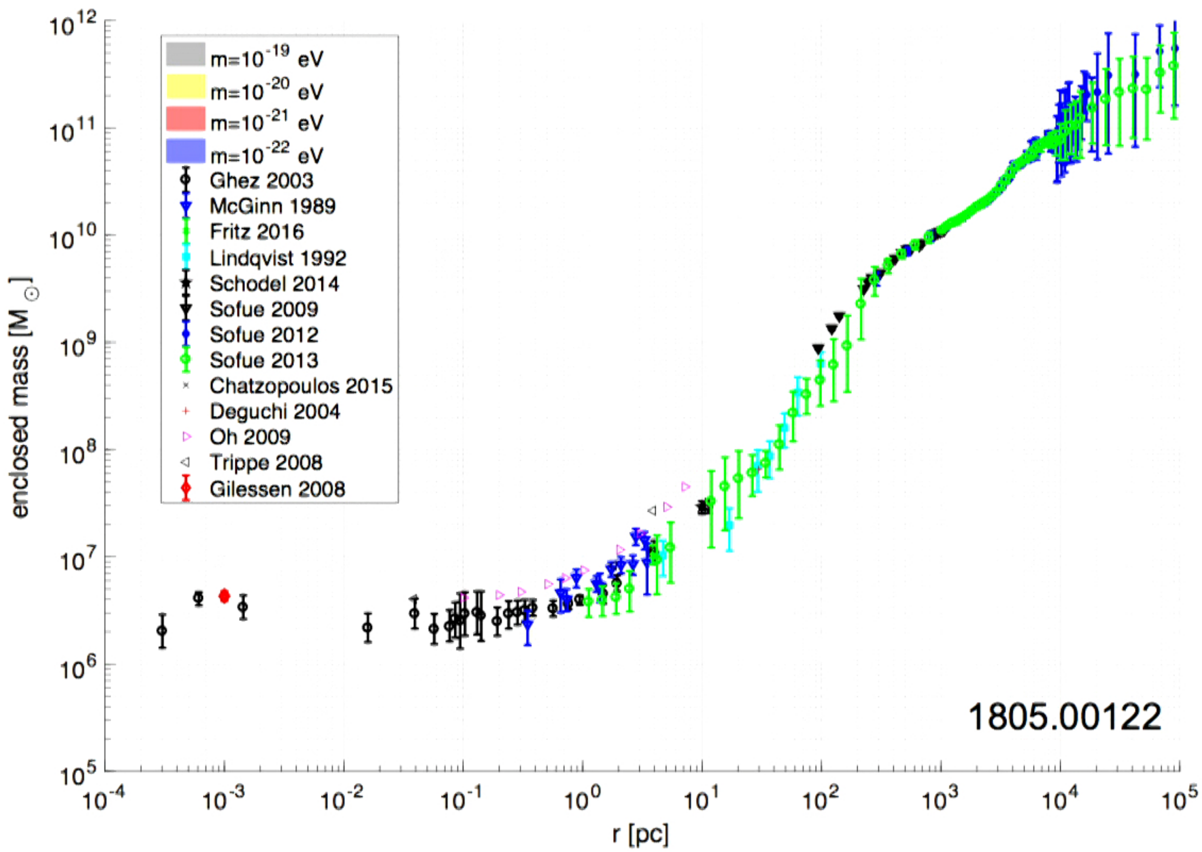
Empirical fit: $M_c \approx \alpha \left(\frac{|E_h|}{M_h}\right)^{\frac{1}{2}} \frac{M_{pl}^2}{m}$

$\alpha = 1$

Schive et al 1406.6586
Schive et al 1407.7762
also: Veltmaat et al 1804.09647

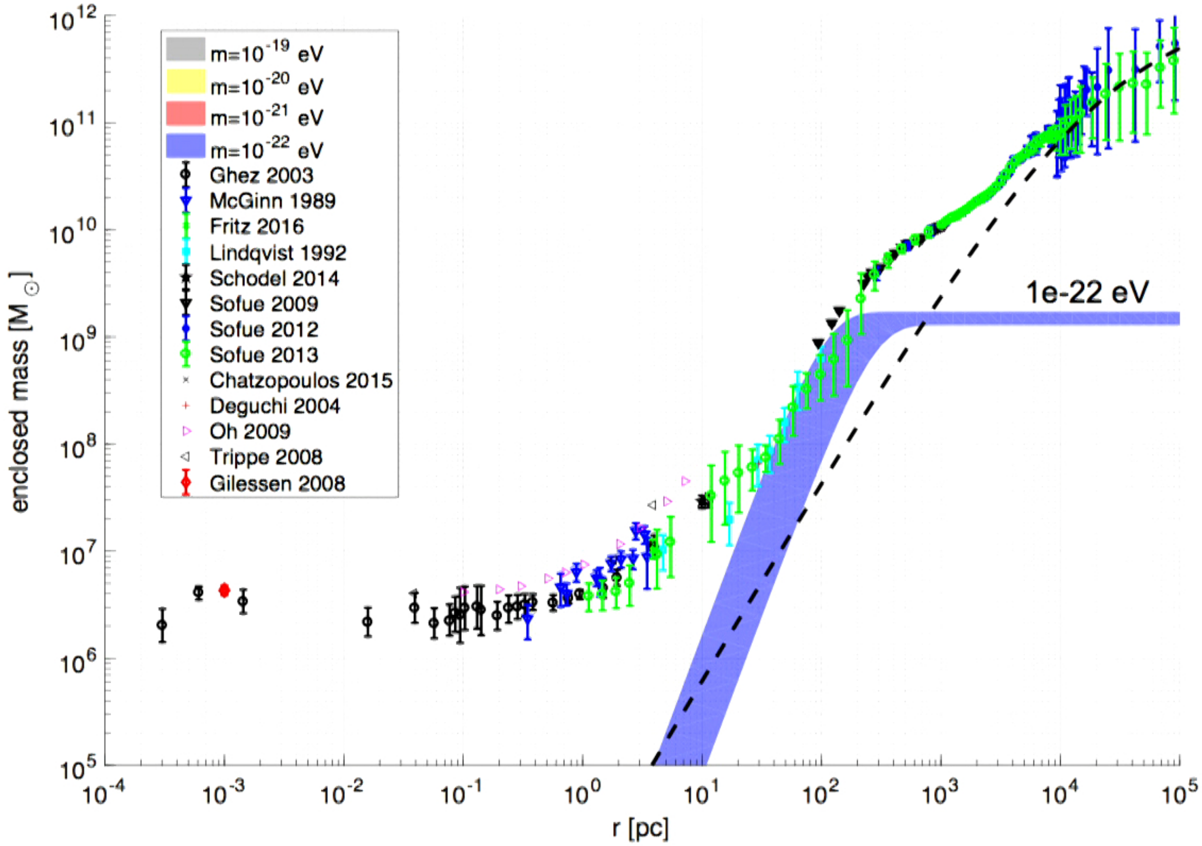
Mocz 1705.05845 find a different relation?
(Xtra material in this talk)

(estimated) radially-averaged mass profile of the Milky Way



Ultra-Light Dark Matter (ULDM):

Affects the inner part of rotation curve



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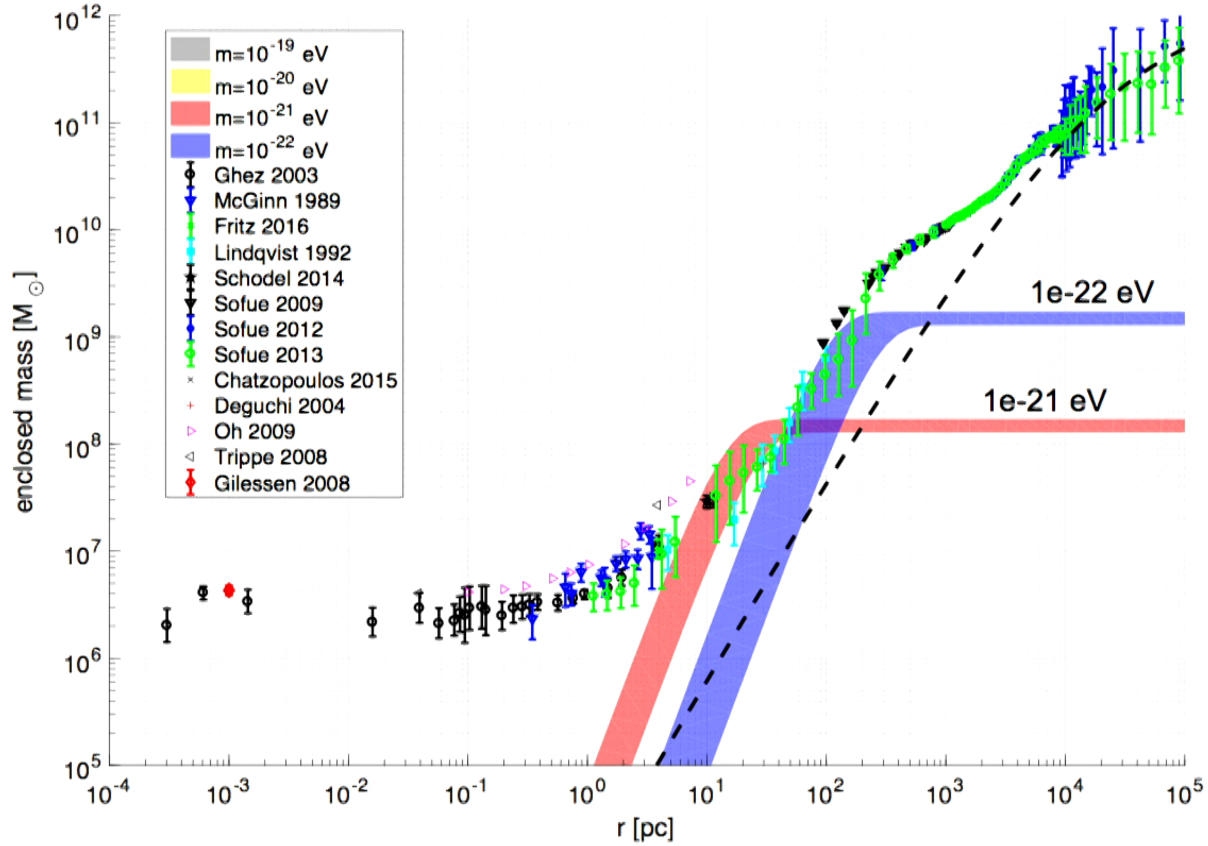

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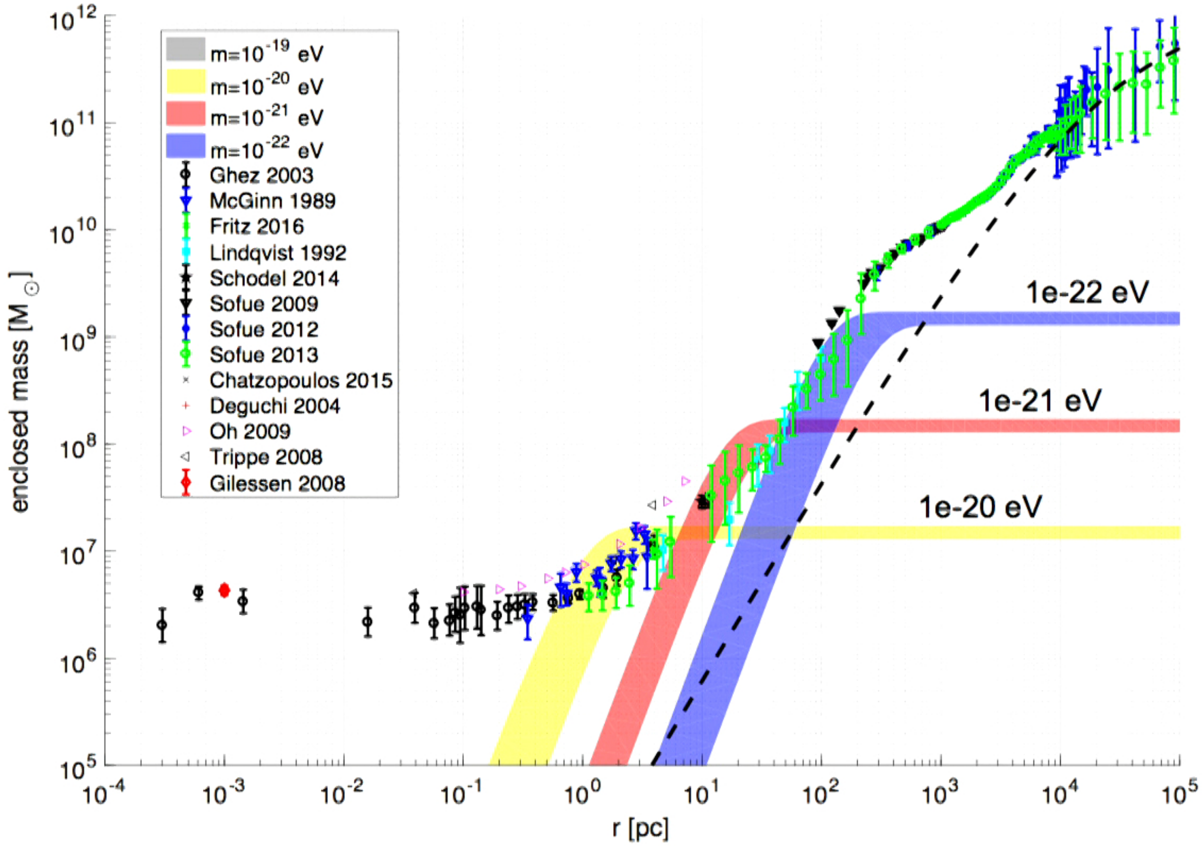

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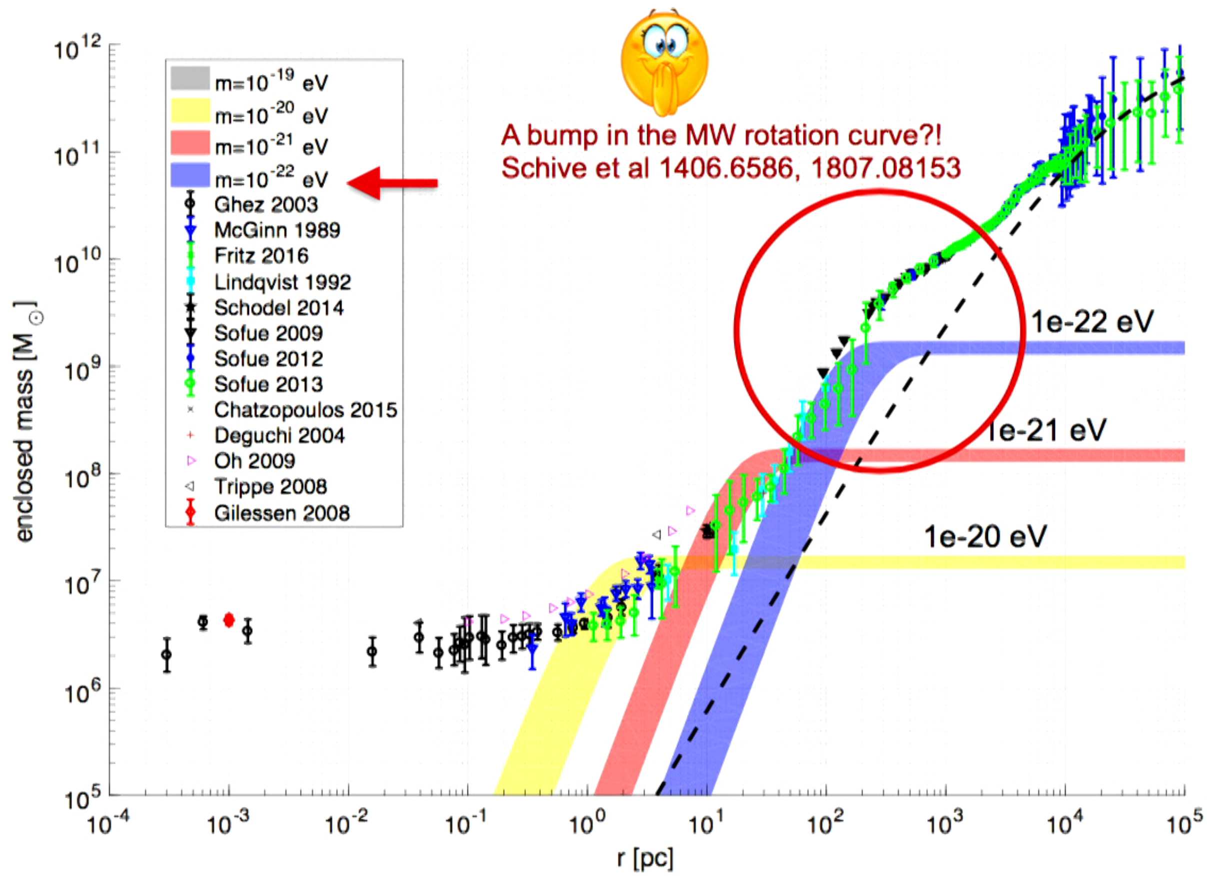


Some facts about solitons

Real, free, KG field doing the job of DM

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

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

On scales of order de Broglie wavelength:

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

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

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.

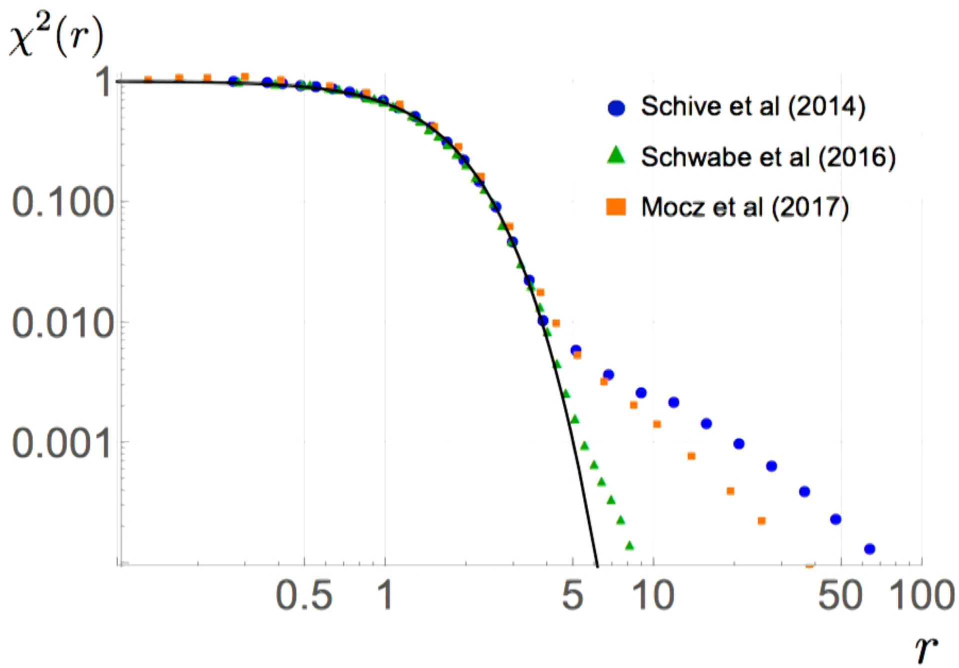
$$M_1 = \frac{M_{pl}^2}{m}\int_0^\infty dr r^2 \chi_1^2(r)$$
$$\approx 2.79 \times 10^{12} \left(\frac{m}{10^{-22}\ \mathrm{eV}}\right)^{-1} \mathrm{M}_\odot$$

Other solutions obtained by scaling

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

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

Numerical simulations of galaxy formation w/ ULDM find proper solitons* in the centre of galactic halos



* Oscillatons? oscillons?

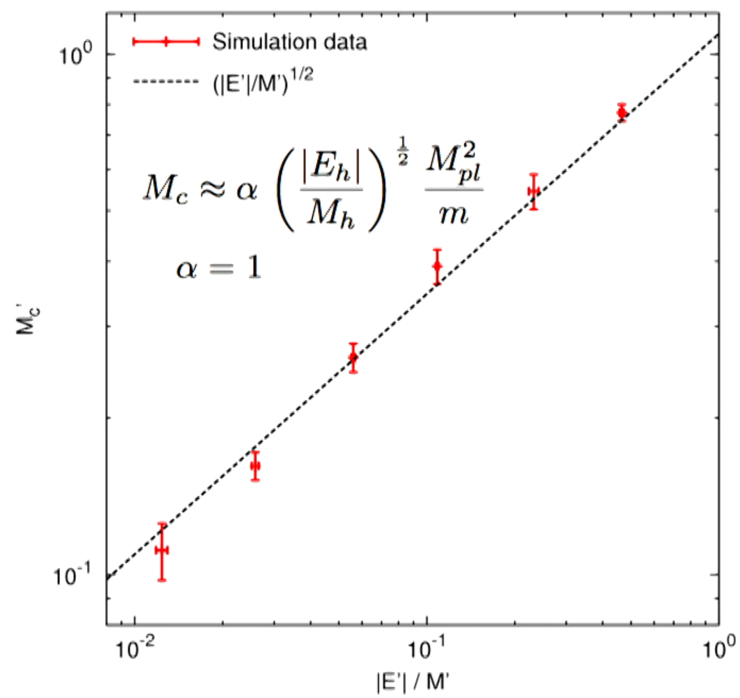
$$E = \int d^3x \left(\frac{|\nabla \psi|^2}{2m^2} + \frac{\Phi\,|\psi|^2}{2} \right)$$

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

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

$$\Rightarrow \quad M_\lambda \approx 4.3 \left(\frac{|E_\lambda|}{M_\lambda} \right)^{\frac{1}{2}} \frac{M_{pl}^2}{m}$$

Schive et al 1406.6586
Schive et al 1407.7762



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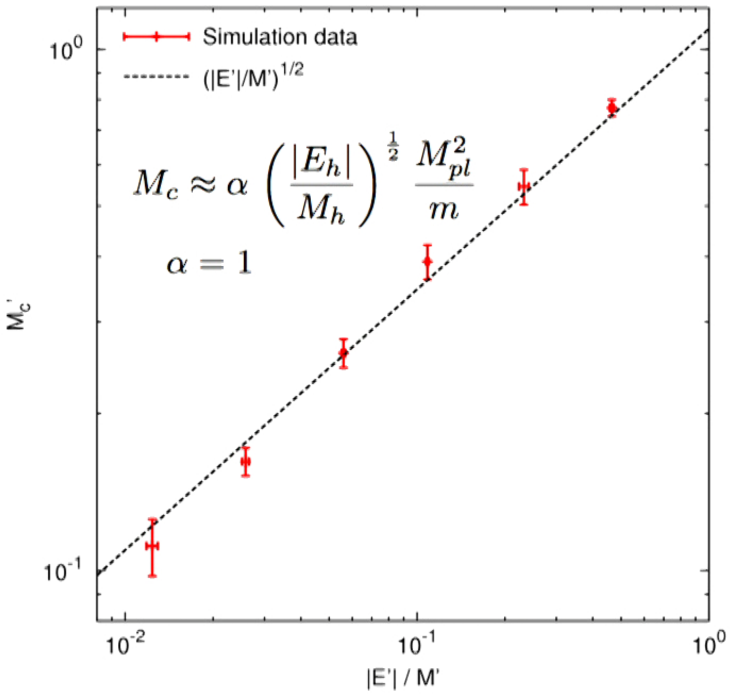
$$E_\lambda \approx -0.476\,\lambda^3 \frac{M_{pl}^2}{m},$$

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

$$M_{c\lambda} \approx 0.236 M_\lambda$$

$$\Rightarrow \quad M_{c\lambda} \approx 1.02 \left(\frac{|E_\lambda|}{M_\lambda} \right)^{\frac{1}{2}} \frac{M_{pl}^2}{m}$$

Schive et al 1406.6586
Schive et al 1407.7762



This is equivalent to:

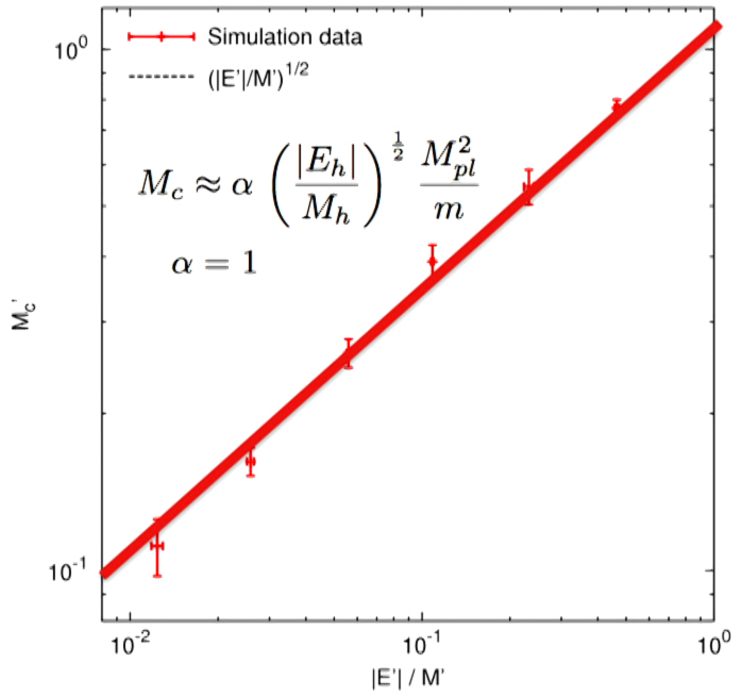
$$\left.\frac{K}{M}\right|_{\rm soliton} = \left.\frac{K}{M}\right|_{\rm halo}$$

Bar, KB, Sato, Eby; 1903.03402

K/M: kinetic energy/mass.

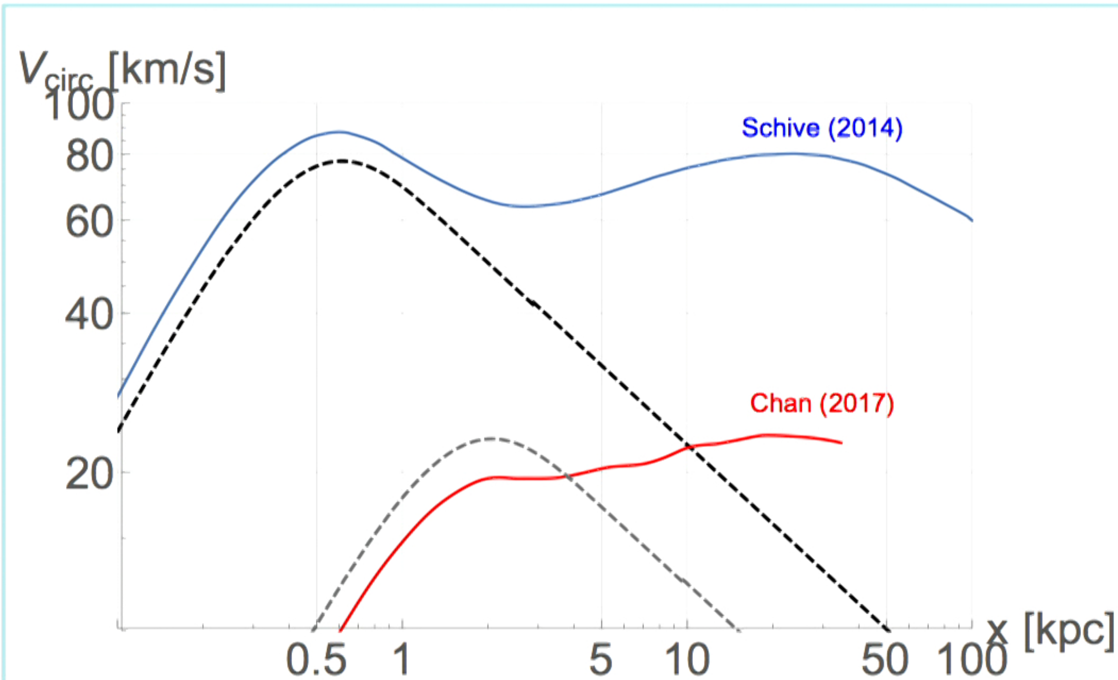
Open questions
1. Is this actually true? (more simulations?)
2. If it is true, why?

Schive et al 1406.6586
Schive et al 1407.7762



Rotation curves from simulations:

Soliton/halo equal specific kinetic energy ==> equal characteristic velocity



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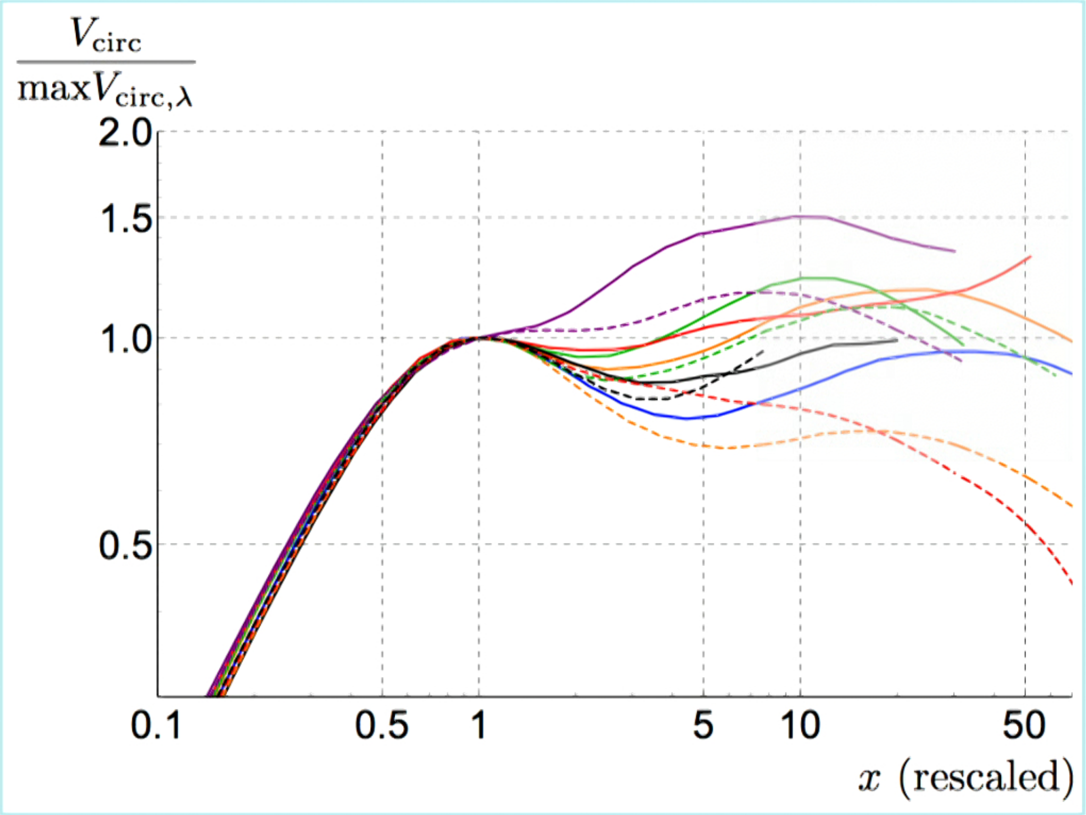
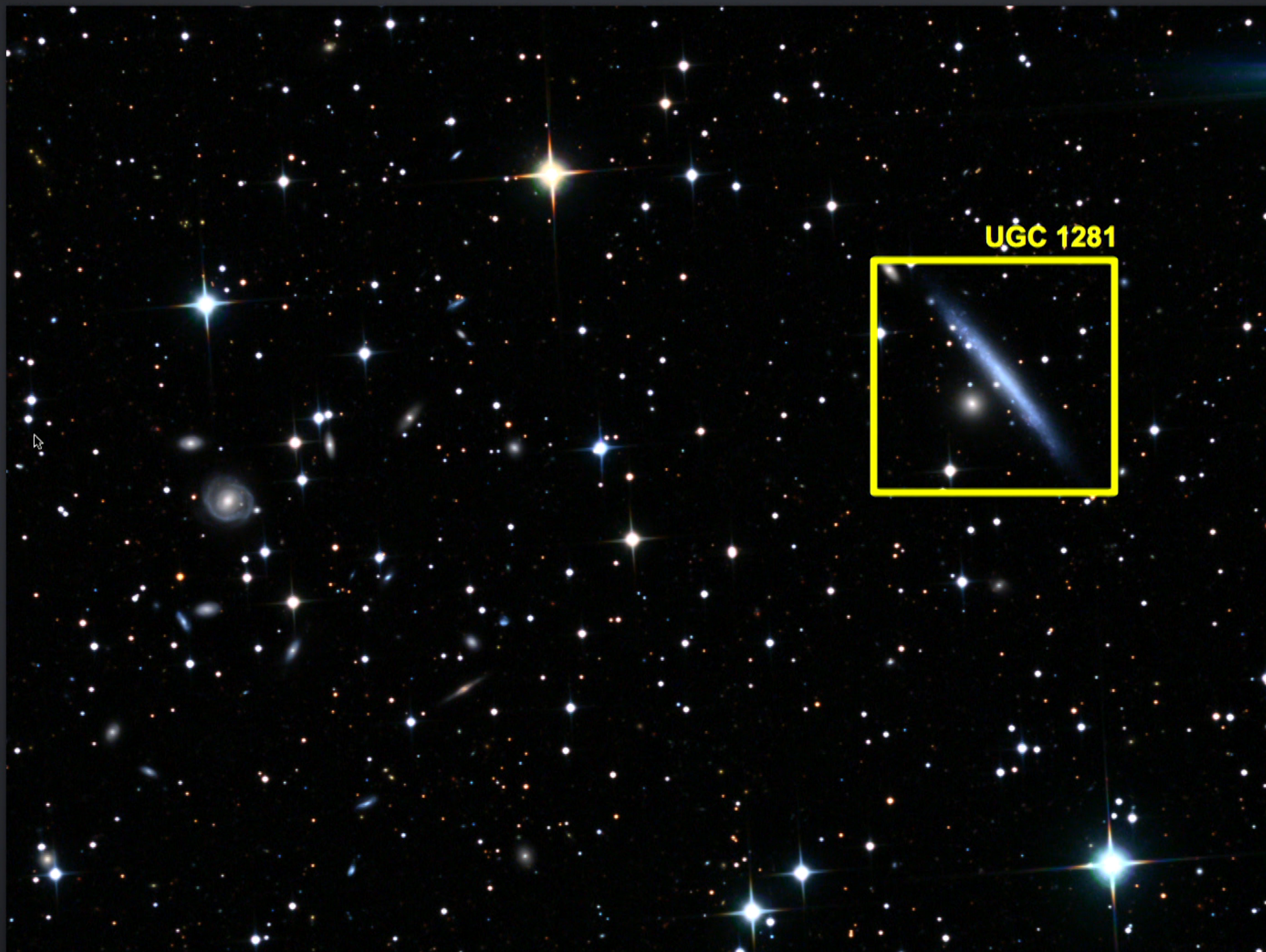
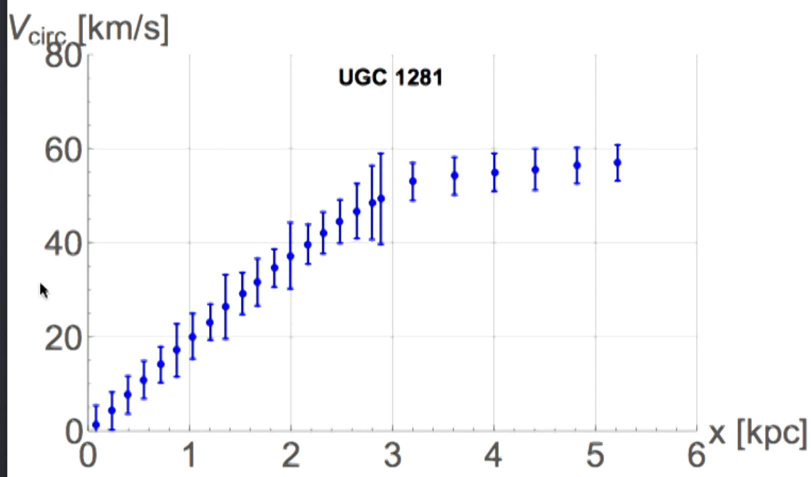
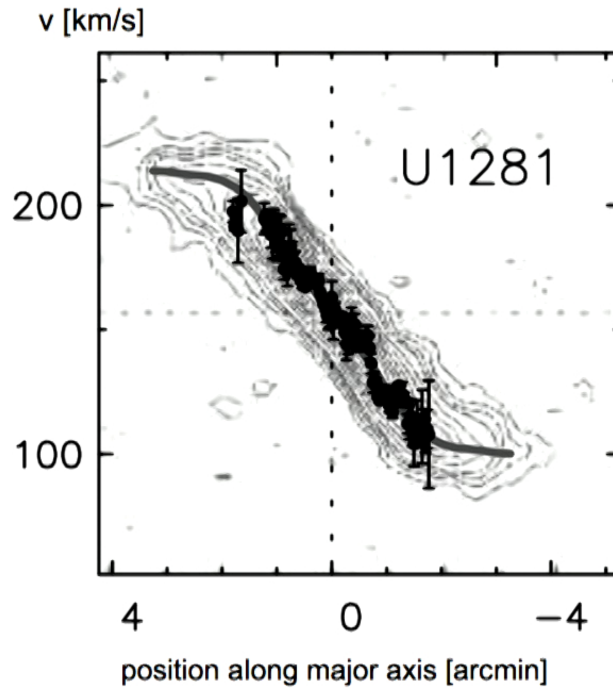
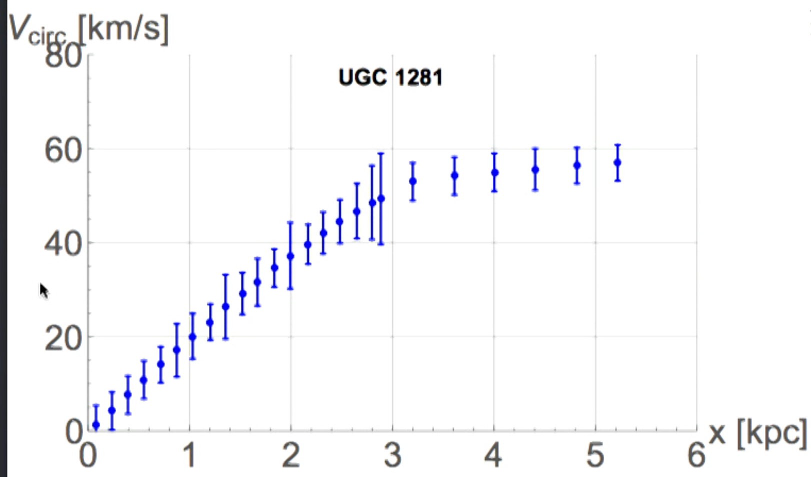


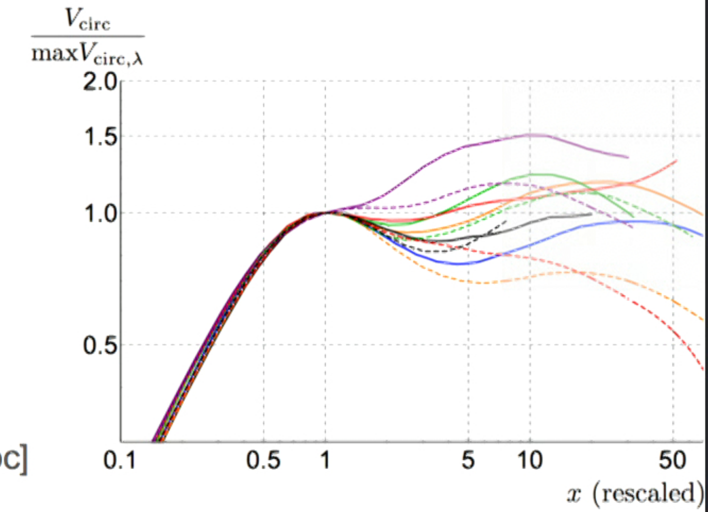

UGC 1281



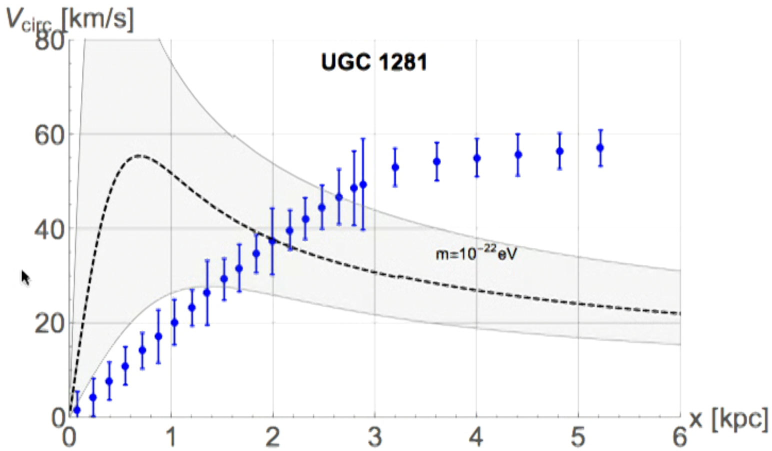
Bosma & de Block 2002
HI+Halpha



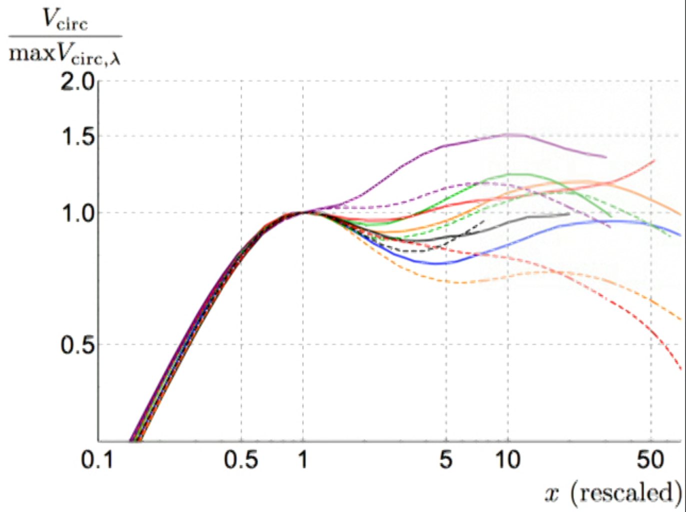

V_{circ} [km/s]
UGC 1281
80
60
40
20
0
0 1 2 3 4 5 6
x [kpc]


$\frac{V_{circ}}{\max V_{circ,\lambda}}$
2.0
1.5
1.0
0.5
0.1 0.5 1 5 10 50
x (rescaled)

m=1e-22 eV

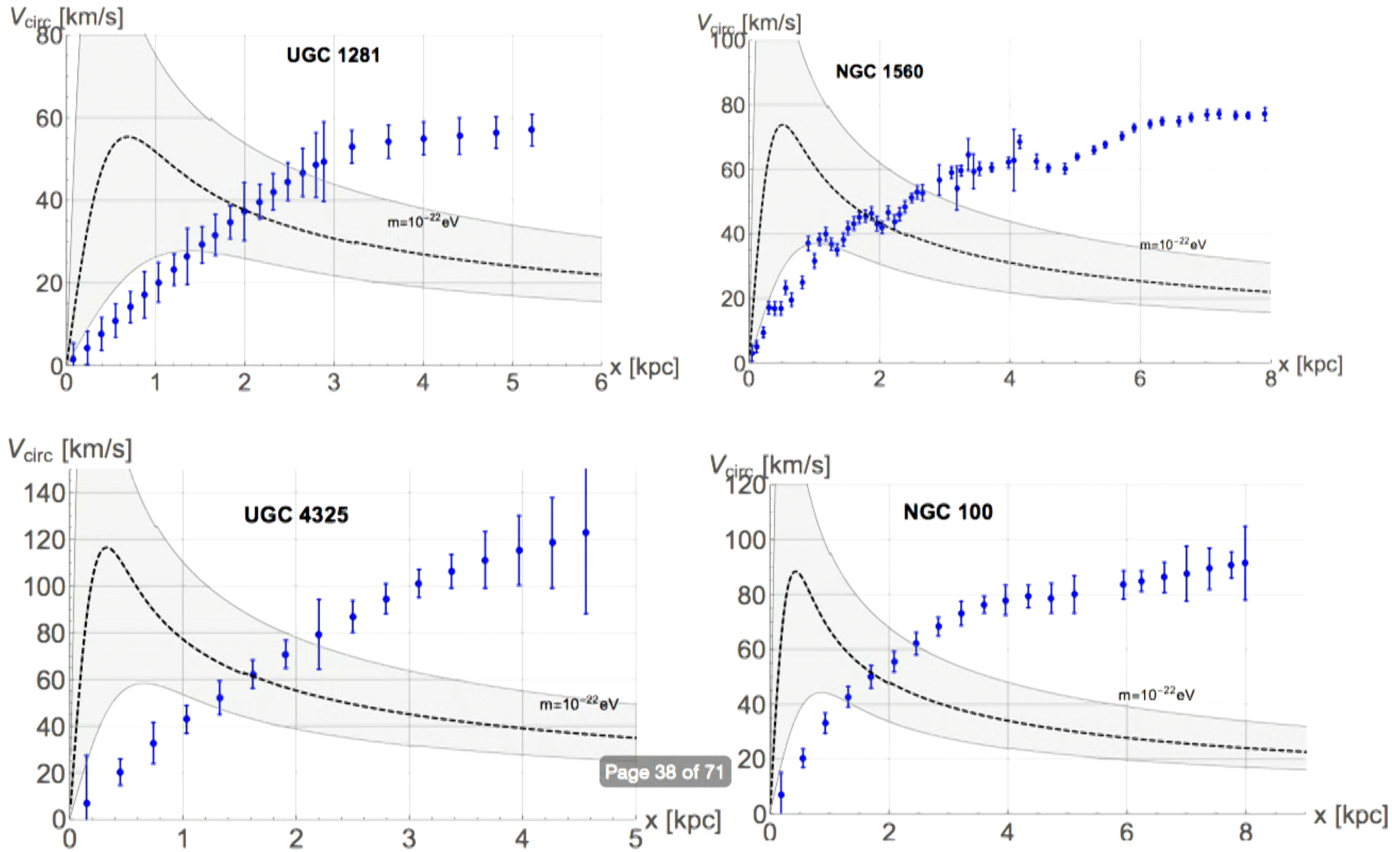


V_{circ} [km/s]
UGC 1281
m=10^{-22}eV
x [kpc]
0
1
2
3
4
5
6
20
40
60
80



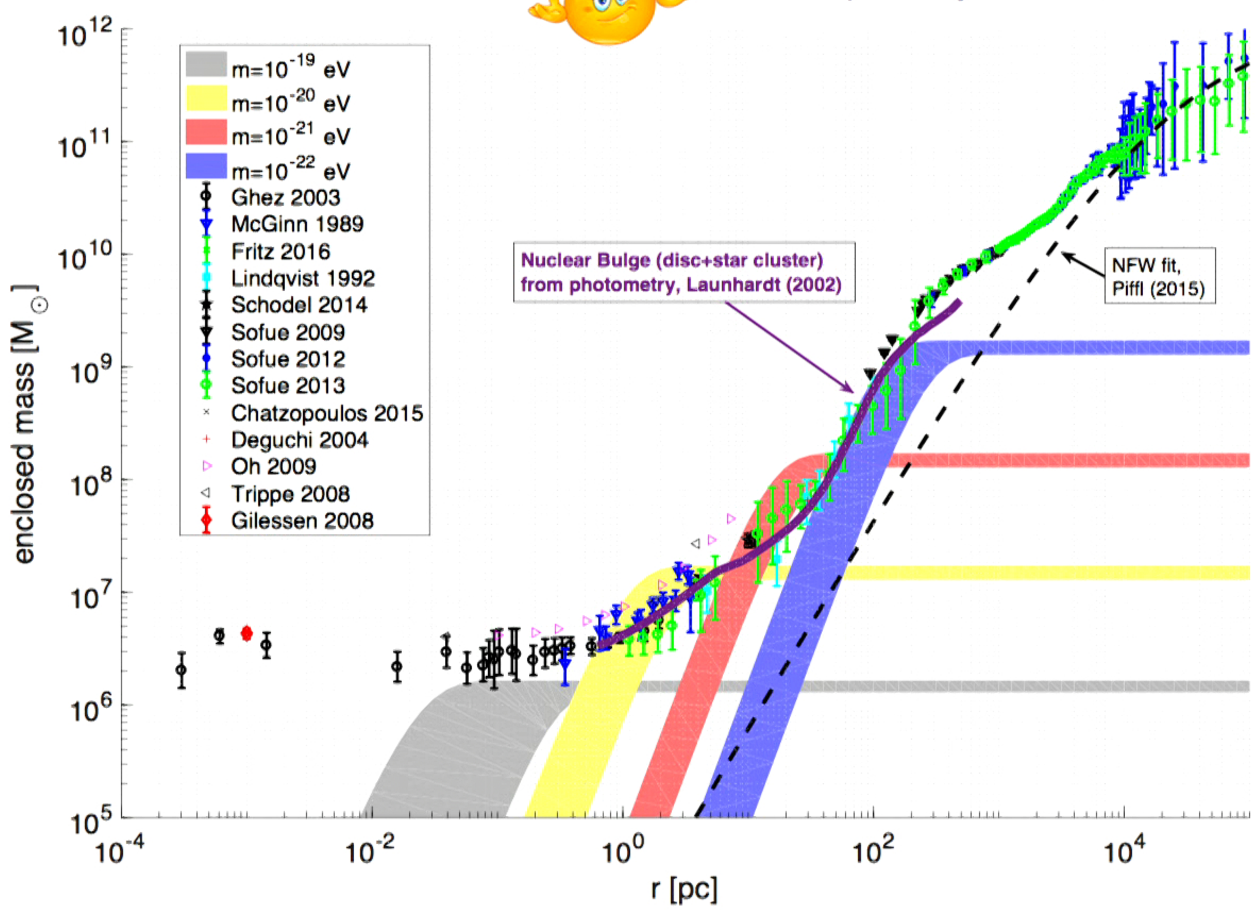
$\frac{V_{circ}}{\max V_{circ,\lambda}}$
2.0
1.5
1.0
0.5
0.1
0.5
1
5
10
50
x (rescaled)

m=1e-22 eV (dozens of other galaxies look similar)



The Milky Way: nuclear bulge vs. soliton

there are *probably* about 10^9 stars in there…



Summary

* ULDM exhibits wave dynamics on scales ~ de Broglie wavelength.
* Lends itself to analytic understanding (*nothing like this for WIMPs*).
* Predicts features in inner kinematics of galaxies.

Bar et al. 1805.00122, 1903.03402 analysed dozens of clean rotation curves.
Clarifies what the simulations show (=!validate them).
As far as we could see, the feature isn't there:

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

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

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

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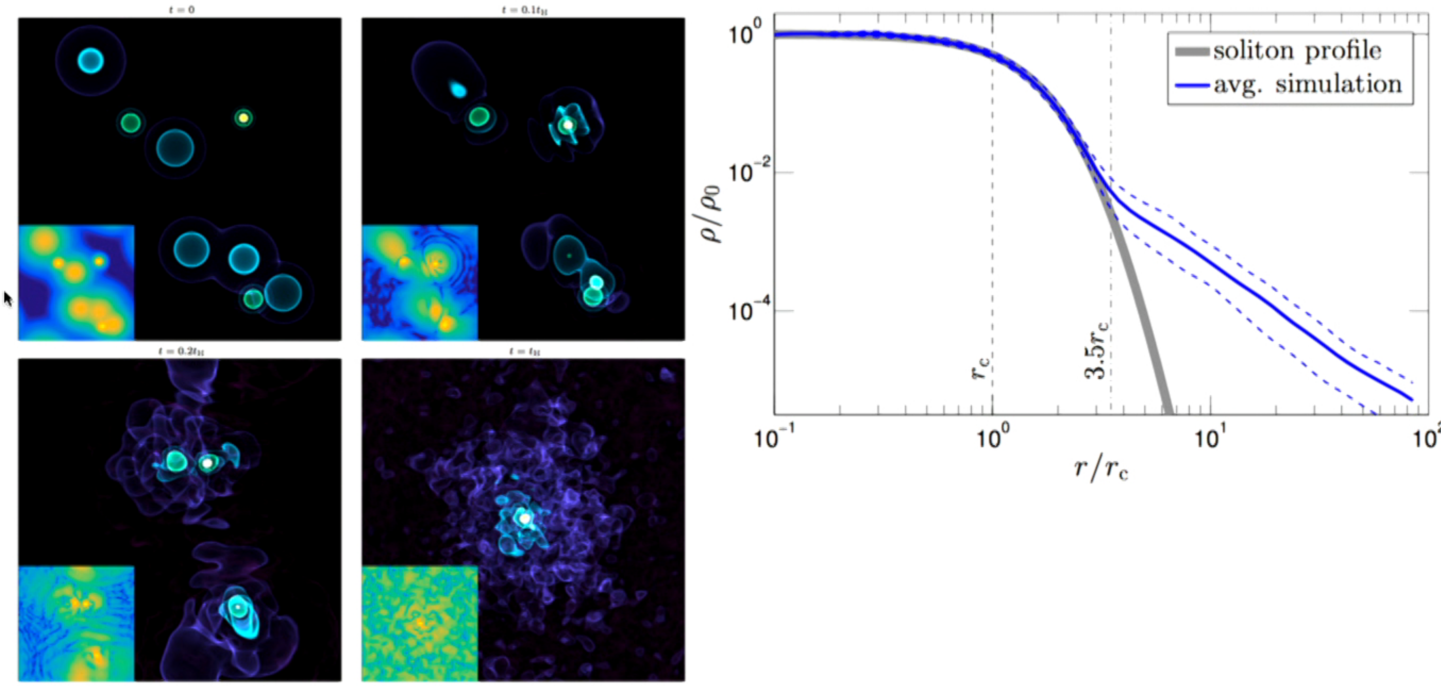
Open questions / work in progress:
Is the soliton—host halo relation correct? (or artefact of numerical simulations?)
If yes, what is the dynamical reason for it?

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

Mocz et al 1705.05845

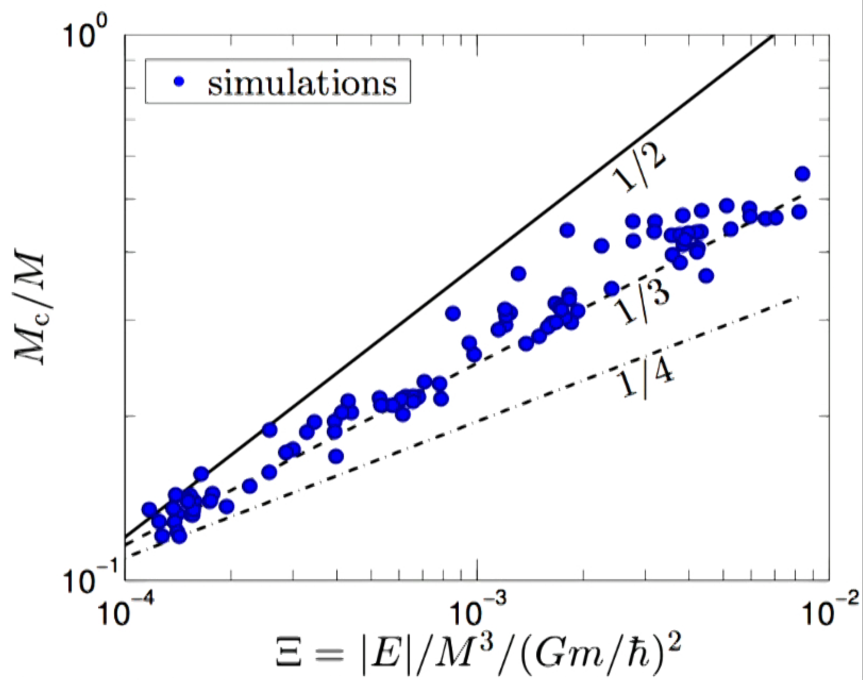


Mocz et al 1705.05845

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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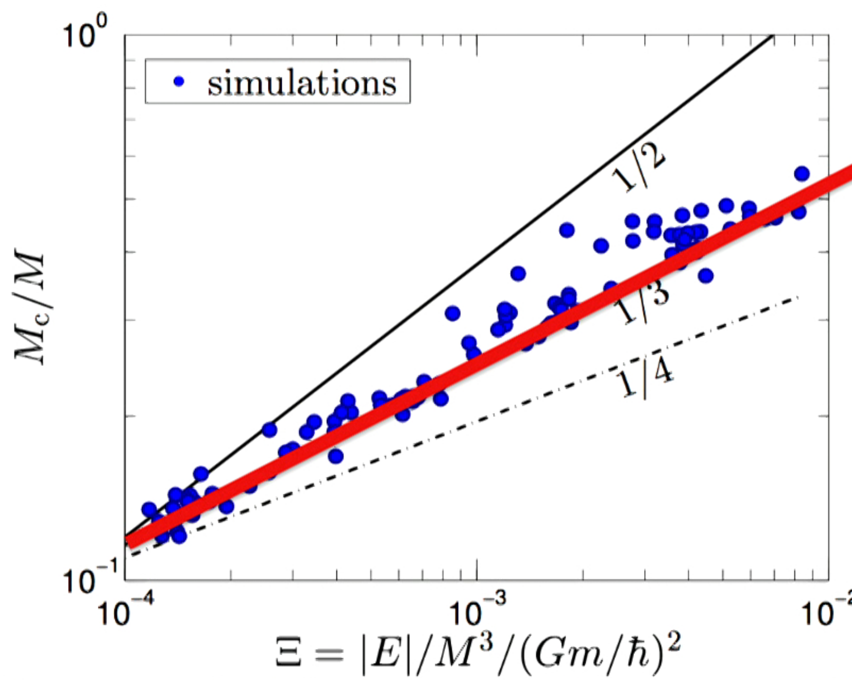
Analytic soliton:

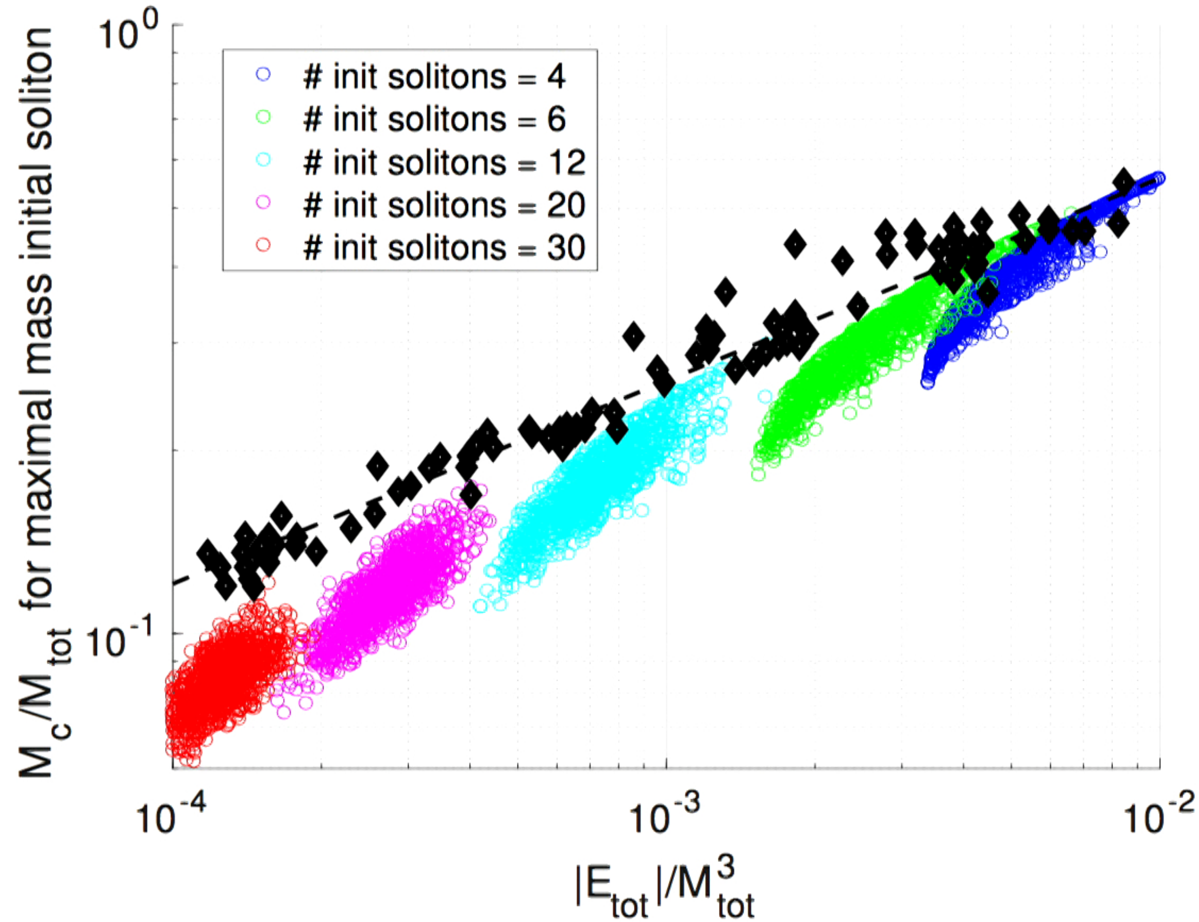
$$E = \frac{1}{2}\int d^3x\left(\frac{1}{m^2}|\nabla\psi|^2 + \Phi|\psi|^2\right)$$

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

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

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





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