Ultralight dark matter

Kfir Blum (CERN, Weizmann)

Bar, Blas, KB, Sibiryakov, 1805.00122
Bar, KB, Sato, Eby, 1903.03402
Bar, KB, Lacroix, Panci, 1905.11745

Benasque 2019

dark matter mass

10^{-22} eV — 1 MeV — 1 GeV — 1 TeV — 100 $M_\odot \sim 10^{68}$ eV

Ultralight ("fuzzy") DM — **WIMPs** — **Primordial black holes**

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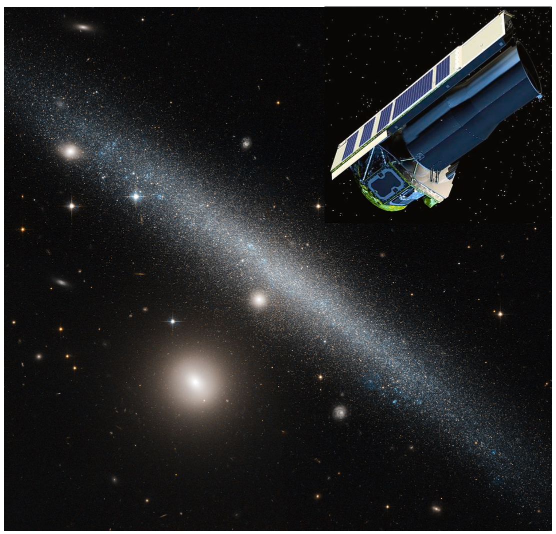
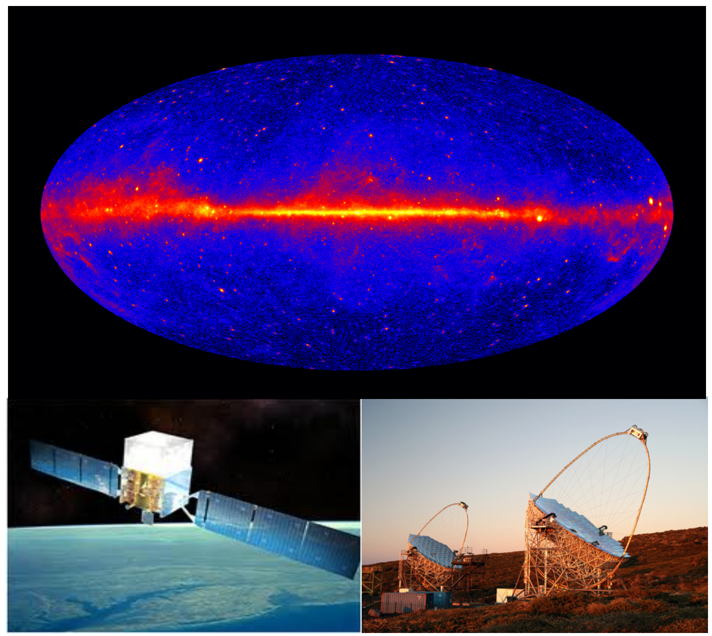
10^{-22} eV — 1 MeV — 1 GeV — 1 TeV — $100\ \mathrm{M}_\odot \sim 10^{68}$ eV

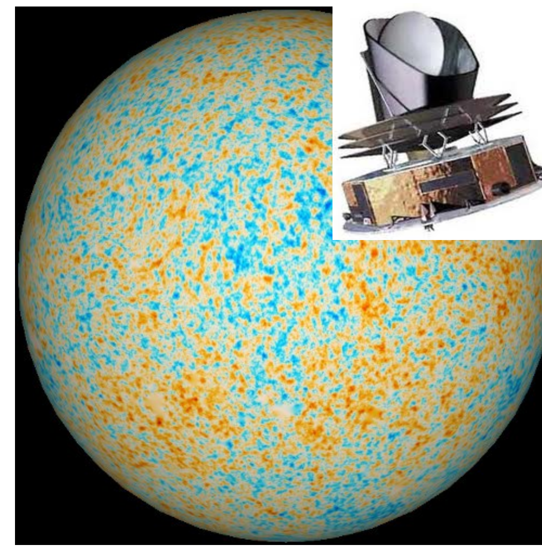
Ultralight ("fuzzy") DM



WIMPs



Primordial black holes



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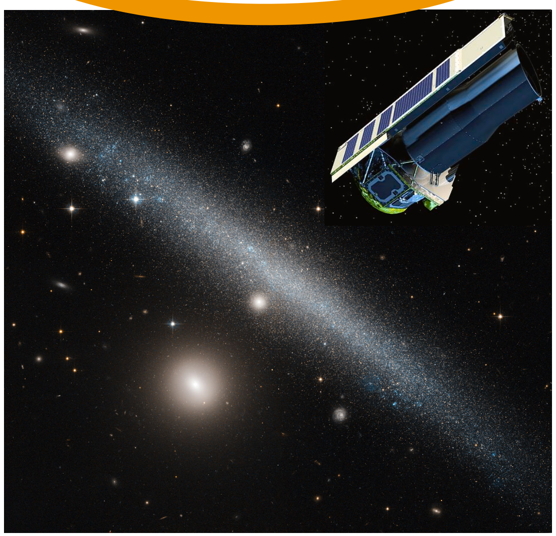
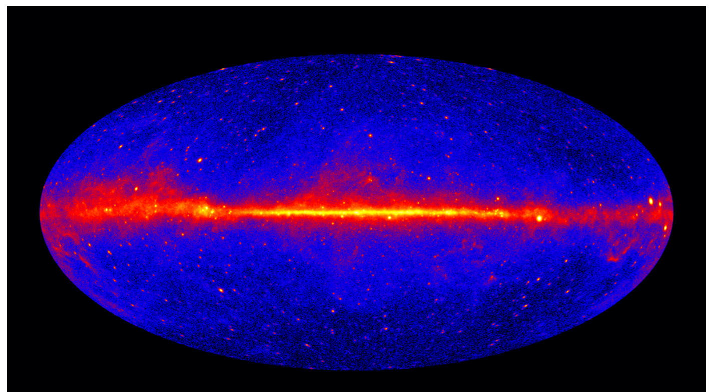
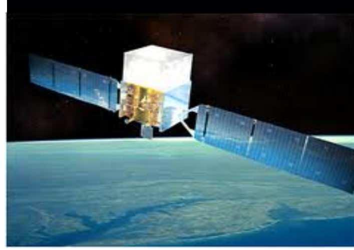
10^{-22} eV $\qquad$ 1 MeV $\qquad$ 1 GeV $\qquad$ 1 TeV $\qquad$ $100\ M_\odot \sim 10^{68}$ eV

Ultralight (“fuzzy”) DM

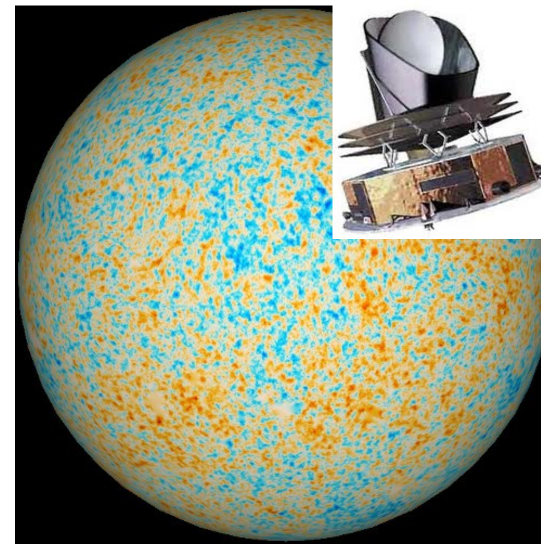


WIMPs





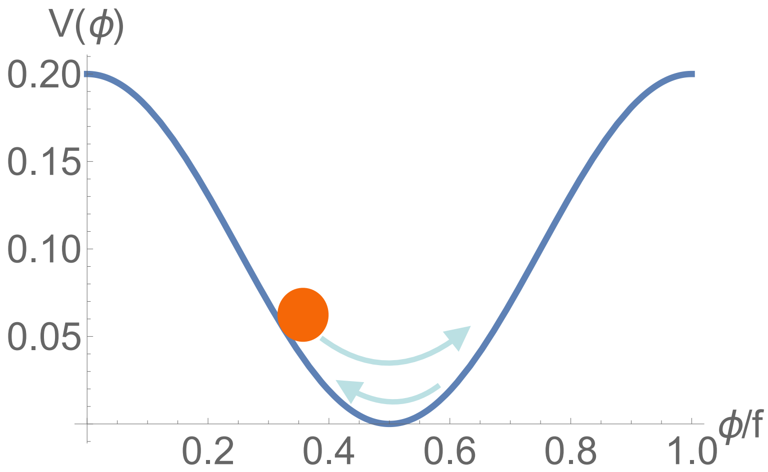
Primordial black holes

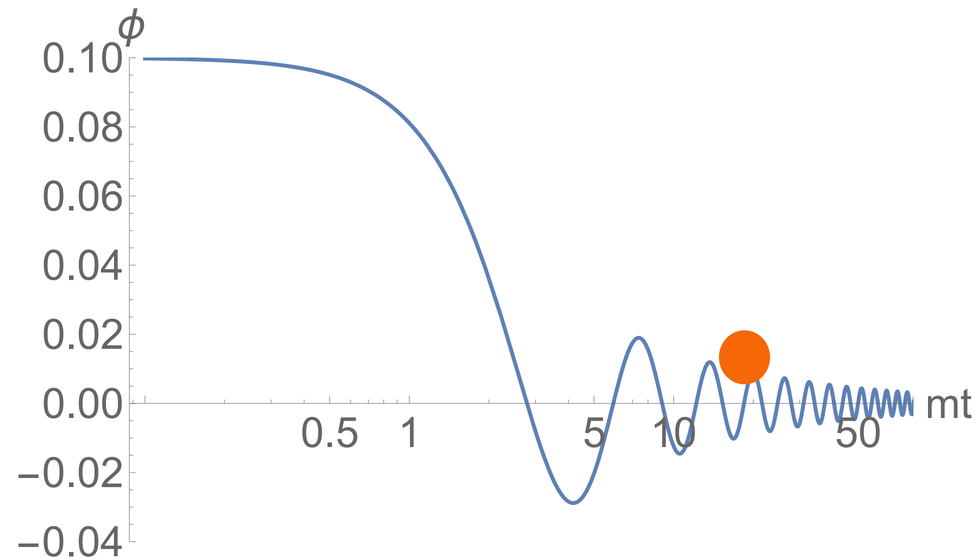


Light (pseudo-)scalar fields featured in many UV models,
as PNGBs of spontaneously broken symmetries.

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

Correct cosmological equation of state for dark matter.



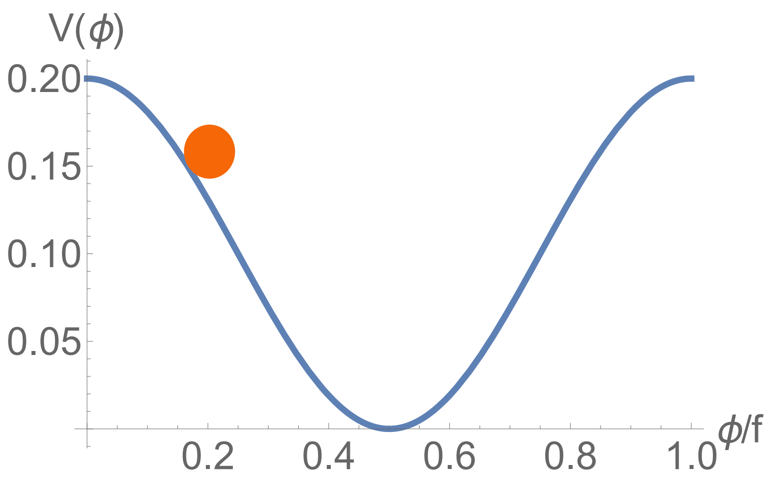


Relic abundance set by initial conditions.

Natural initial condition: $\phi \sim f$

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

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



Ultra-light dark matter (ULDM)

[1] W. Hu, R. Barkana, and A. Gruzinov, "Cold and fuzzy dark matter," Phys. Rev. Lett. **85** (2000) 1158–1161, arXiv:astro-ph/0003365 [astro-ph].
[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].
[6] D. J. E. Marsh and A.-R. Pop, "Axion dark matter, solitons and the cusp-core problem," Mon. Not. Roy. Astron. Soc. **451** no. 3, (2015) 2479–2492, arXiv:1502.03456 [astro-ph.CO].
[7] S.-R. Chen, H.-Y. Schive, and T. Chiueh, "Jeans Analysis for Dwarf Spheroidal Galaxies in Wave Dark Matter," Mon. Not. Roy. Astron. Soc. **468** no. 2, (2017) 1338–1348, arXiv:1606.09030 [astro-ph.GA].
[8] L. Hui, J. P. Ostriker, S. Tremaine, and E. Witten, "Ultralight scalars as cosmological dark matter," Phys. Rev. **D95** no. 4, (2017) 043541, arXiv:1610.08297 [astro-ph.CO].
[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].
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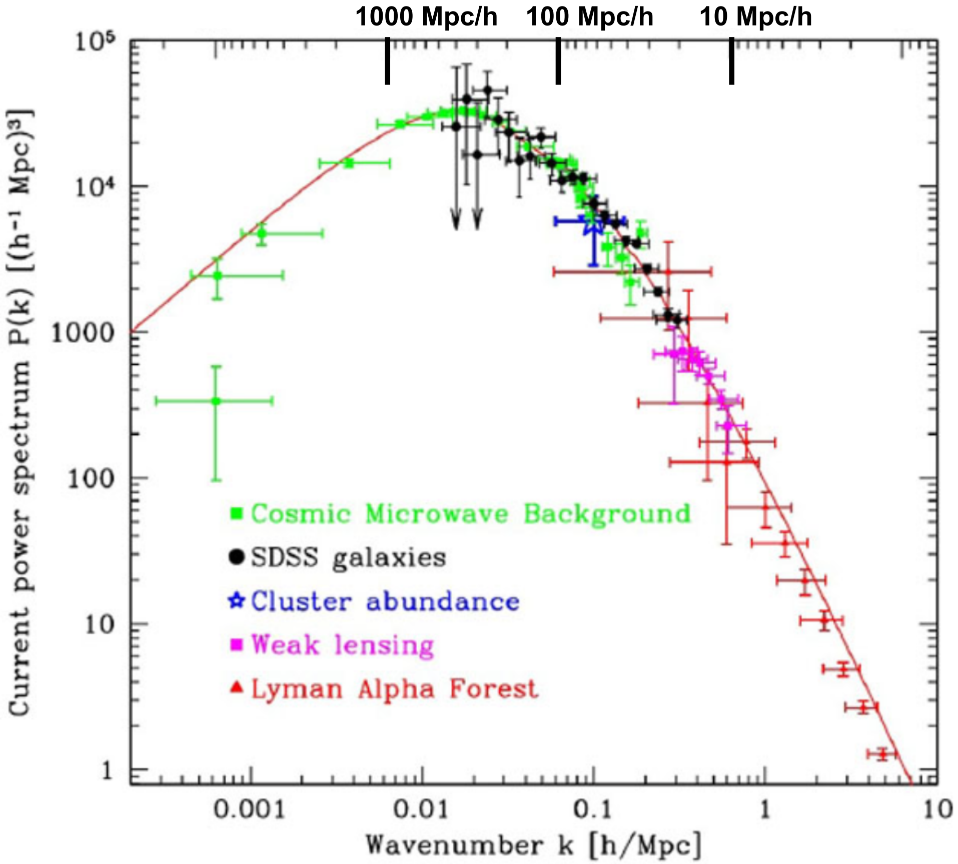
Ultra-light dark matter (ULDM)

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



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

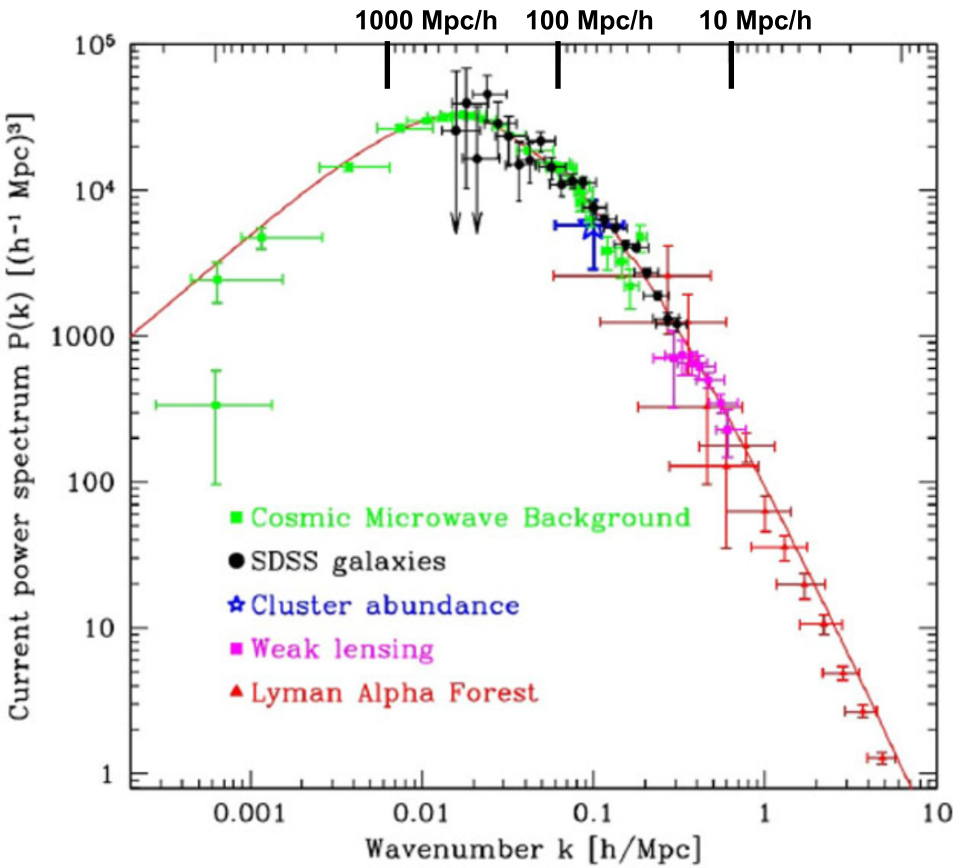
Early structure formation:

DM EoS achieved when H ~ m:

$$T \sim (m\, M_{pl})^{\frac{1}{2}} \sim \left(\frac{m}{10^{-22}\ \mathrm{eV}}\right)^{\frac{1}{2}}\ \mathrm{keV}$$

$$z \sim 10^6 \left(\frac{m}{10^{-22}\ \mathrm{eV}}\right)^{\frac{1}{2}}$$

Mpc scales enter the horizon.

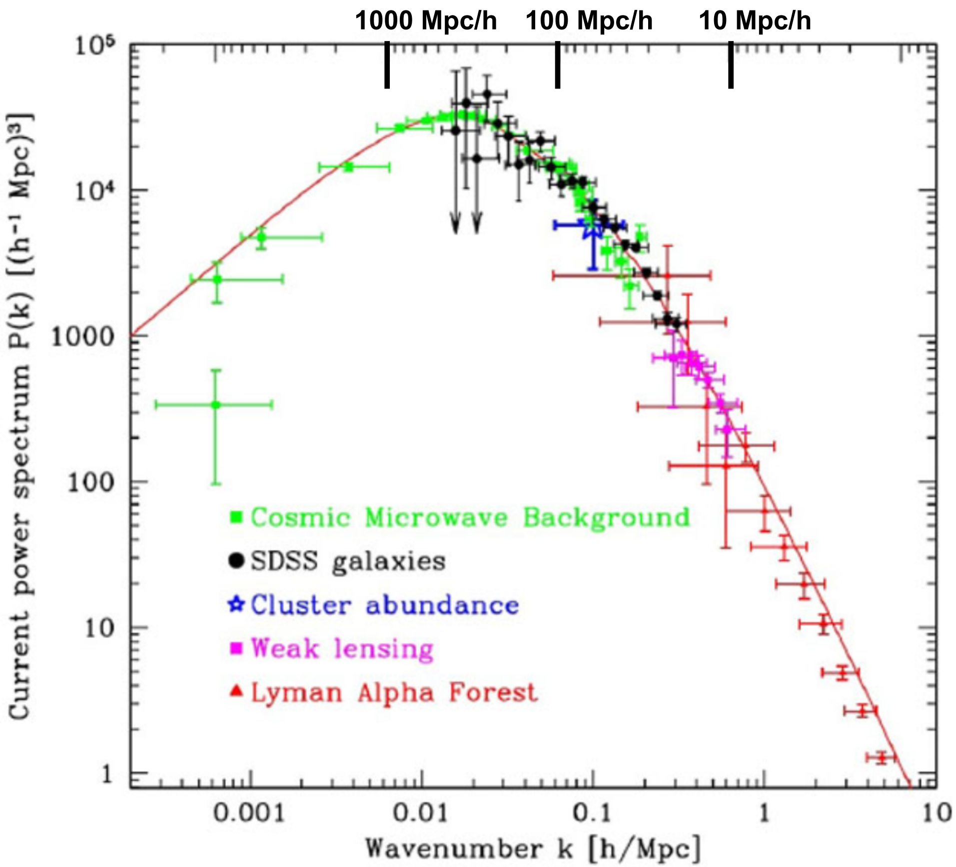


On scales of order de Broglie wavelength, **ULDM is markedly different than WIMPs.**

dB length for self-gravitating perturbation ("Jeans scale"):

$$v^2 = \frac{G\,M}{R} = \frac{4\pi}{3} G\,\delta\rho \left(\frac{\lambda_{dB}}{2}\right)^2$$

$$\lambda_{dB} = \frac{2\pi}{m\,v}$$



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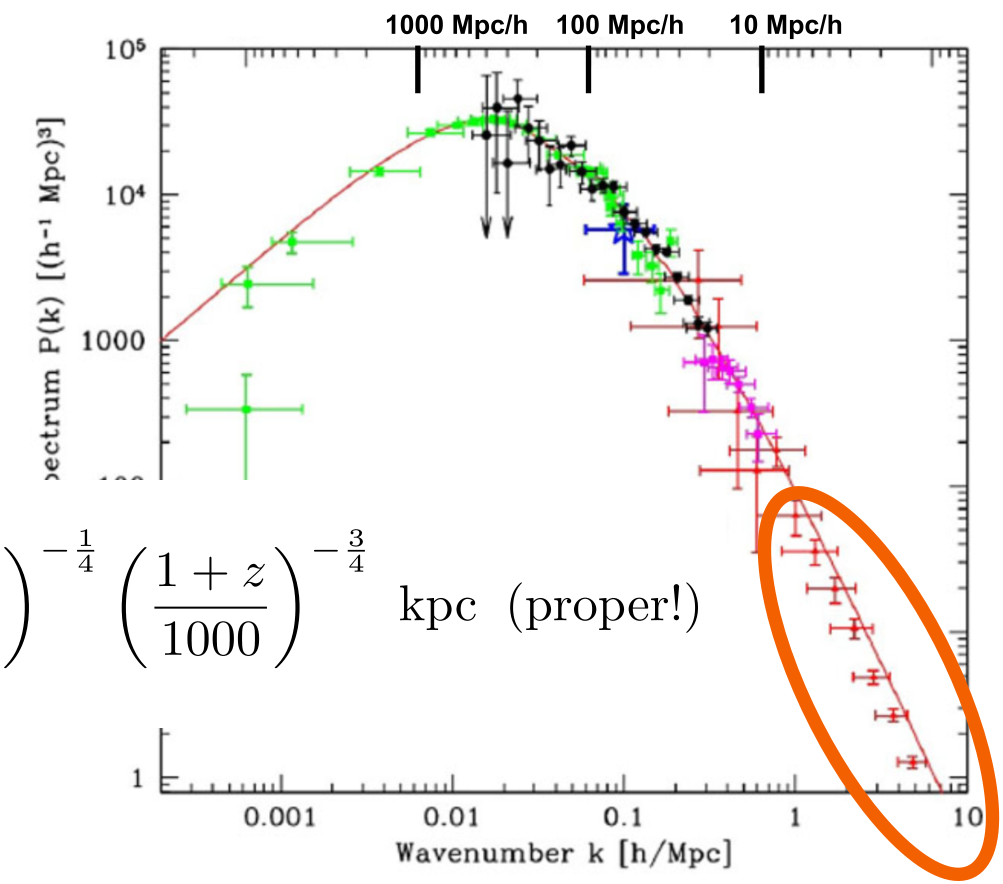
$$= \left(\frac{G\,\delta\rho\,m^2}{12\pi}\right)^{-\frac{1}{4}}$$

$$\approx 5.8 \left(\frac{m}{10^{-22}\ \mathrm{eV}}\right)^{-\frac{1}{2}} \left(\frac{\delta\rho/\rho}{10^{-5}}\right)^{-\frac{1}{4}} \left(\frac{1+z}{1000}\right)^{-\frac{3}{4}} \ \mathrm{kpc}\ \ \text{(proper!)}$$



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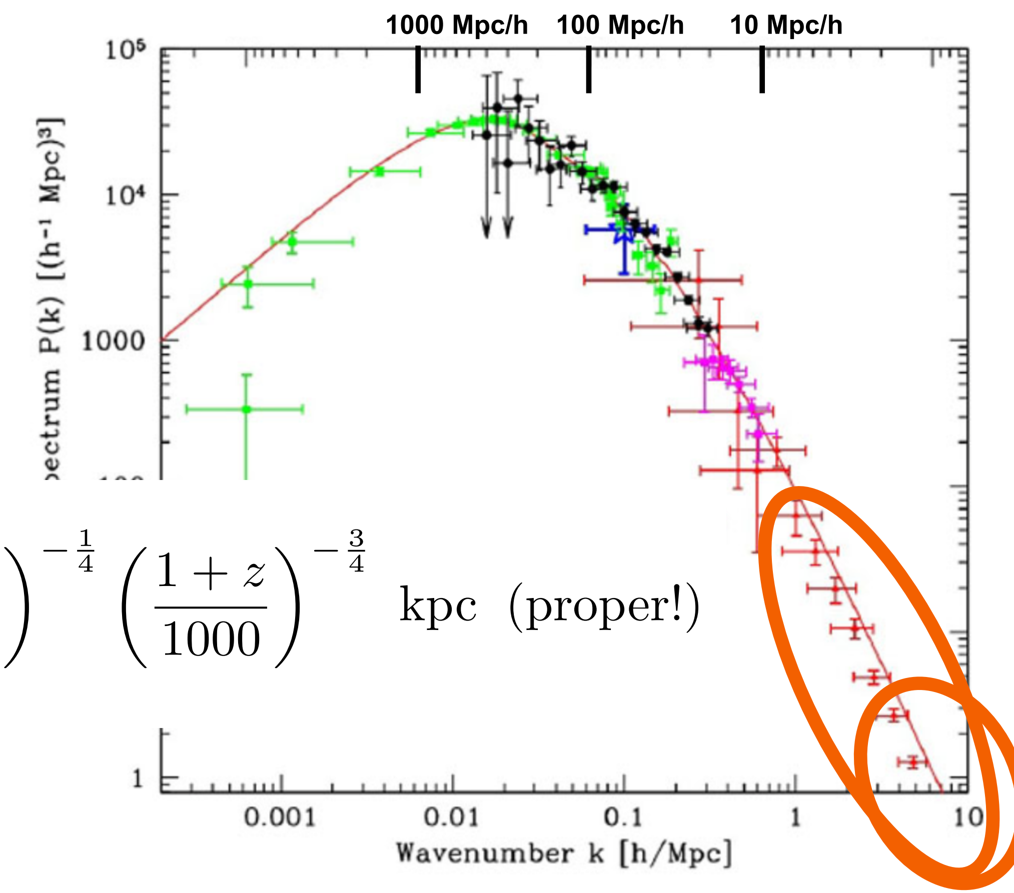
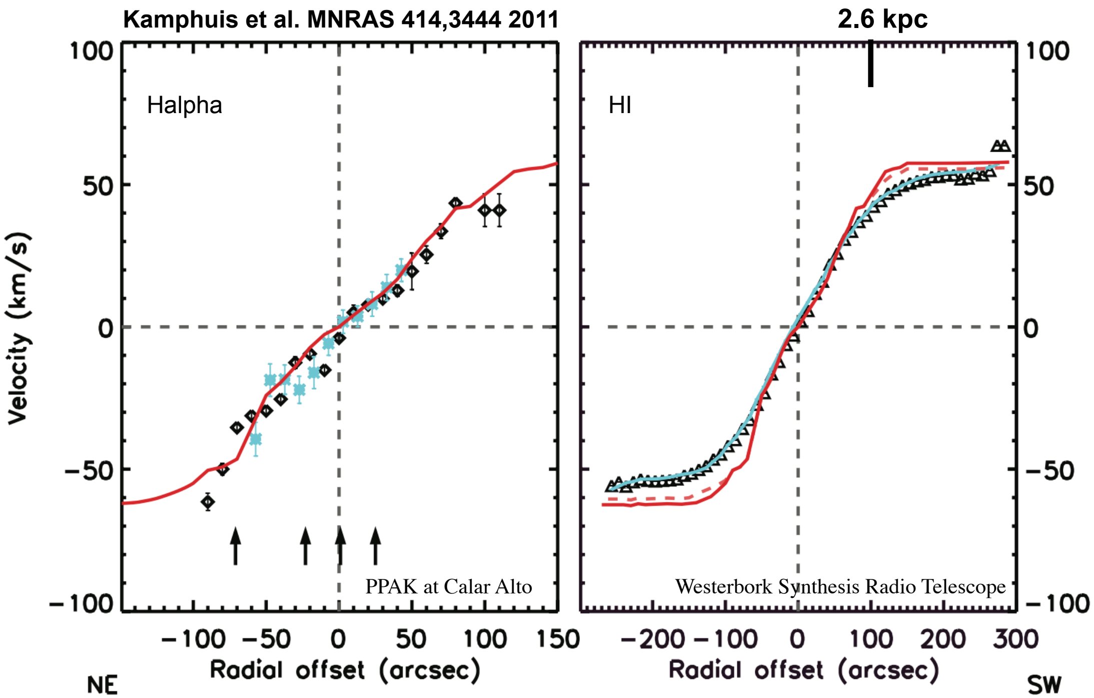


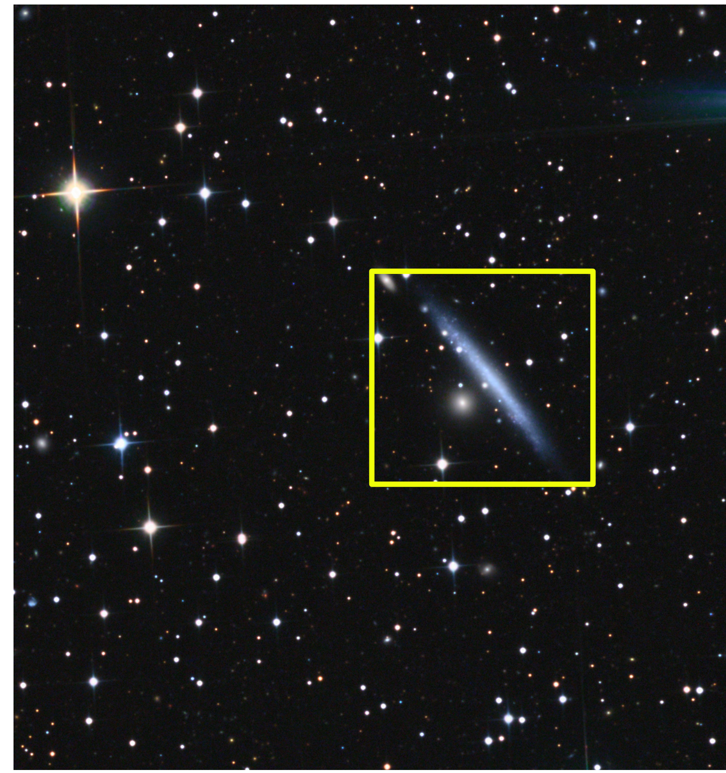
Ly-alpha Forest: $m \gtrsim 10^{-21}\ \mathrm{eV}$

Armengaud (1703.09126),
Irsic (1703.04683),
Zhang (1708.04389),
Kobayashi (1708.00015)
…

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

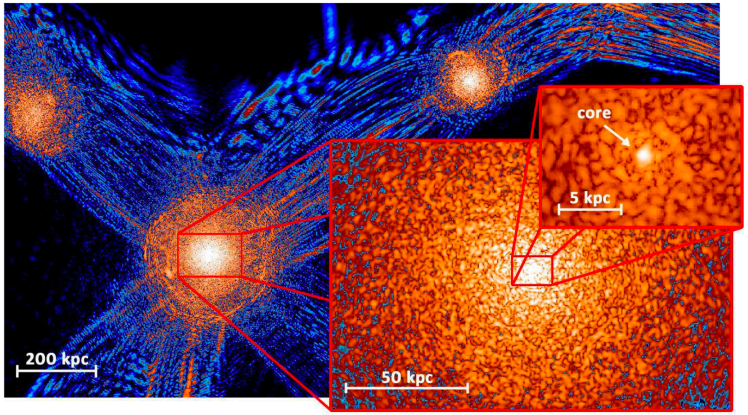
dB length ~ kpc for $m \sim 10^{-22}\ \mathrm{eV}$



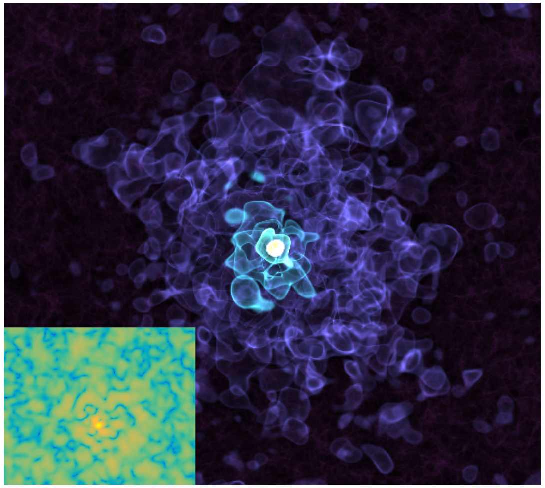


ULDM in galaxies

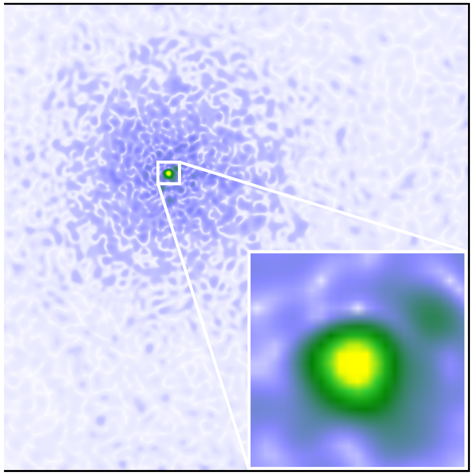
Progress in numerical simulations



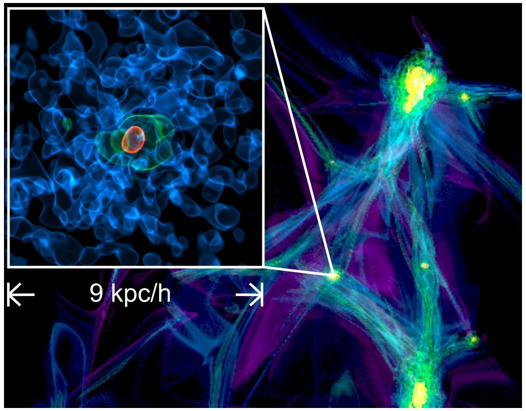
Schive et al, Nature Phys. 10 (2014) 496-499



Mocz et al, MNRAS. 471 (2017) 4559-4570



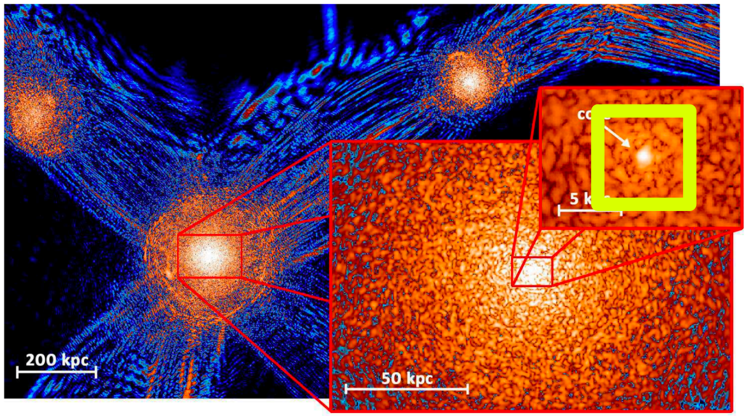
Levkov, Panin, Tkachev,
Phys.Rev.Lett. 121 (2018) 151301



Veltmaat, Niemeyer, Schwabe,
Phys.Rev. D98 (2018) 043509

ULDM in galaxies

Inner part of simulated galaxies forms a core



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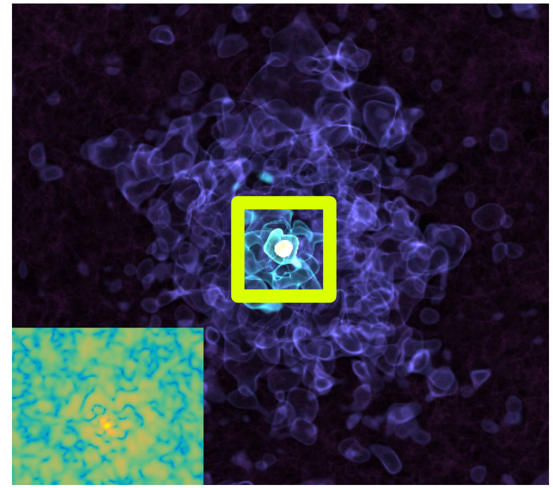

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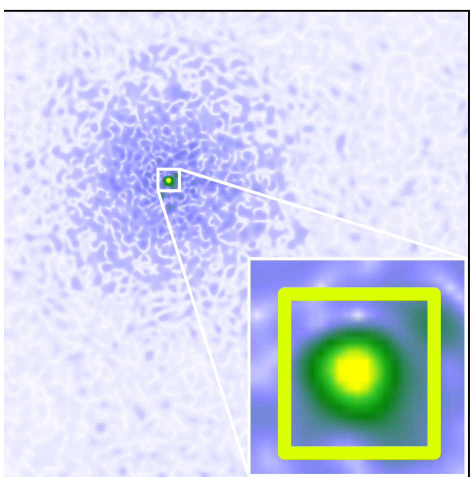

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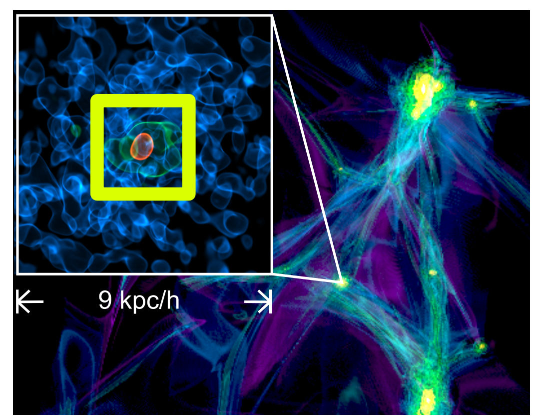

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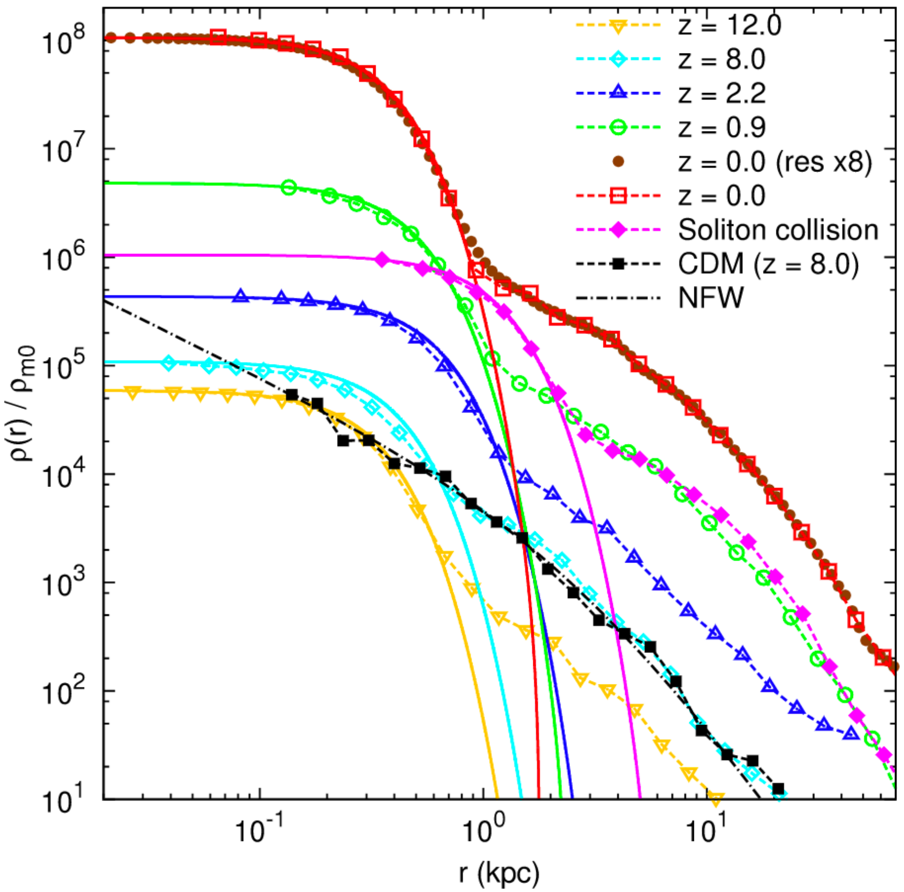
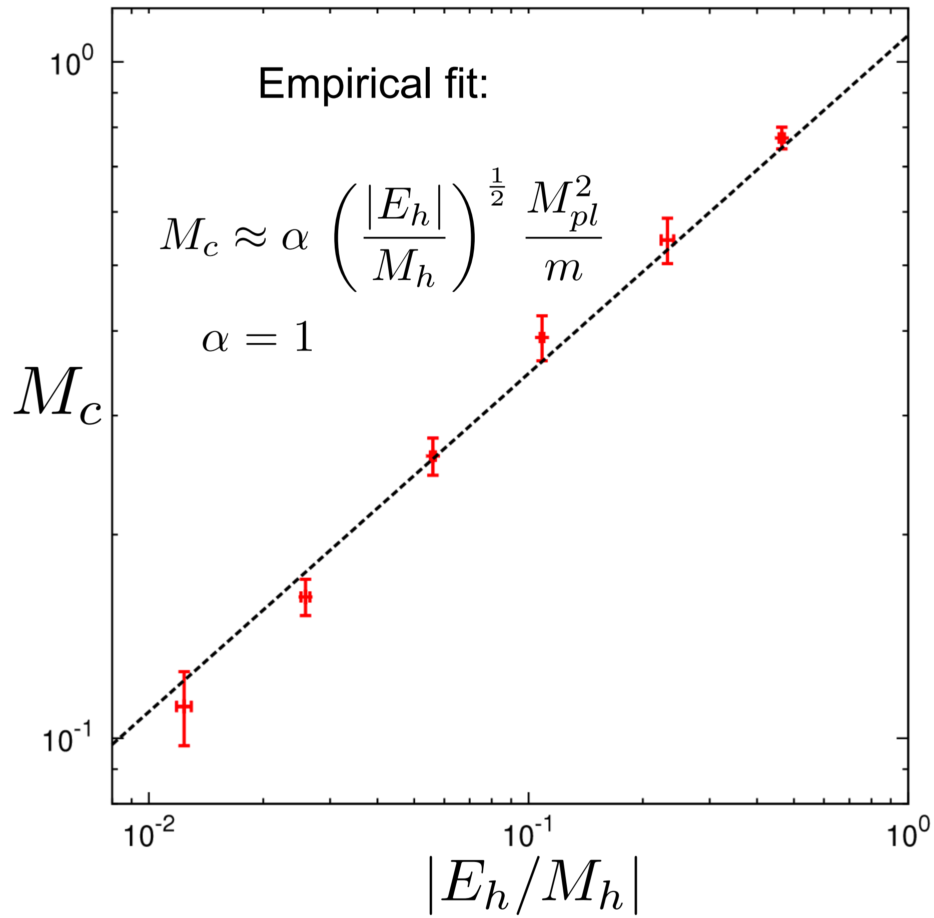
A soliton — host halo relation?



Schive et al 1406.6586
Schive et al 1407.7762
Veltmaat et al 1804.09647



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

Some facts about solitons

Real, free, KG field

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

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

<u>Some facts about solitons</u>

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

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.

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

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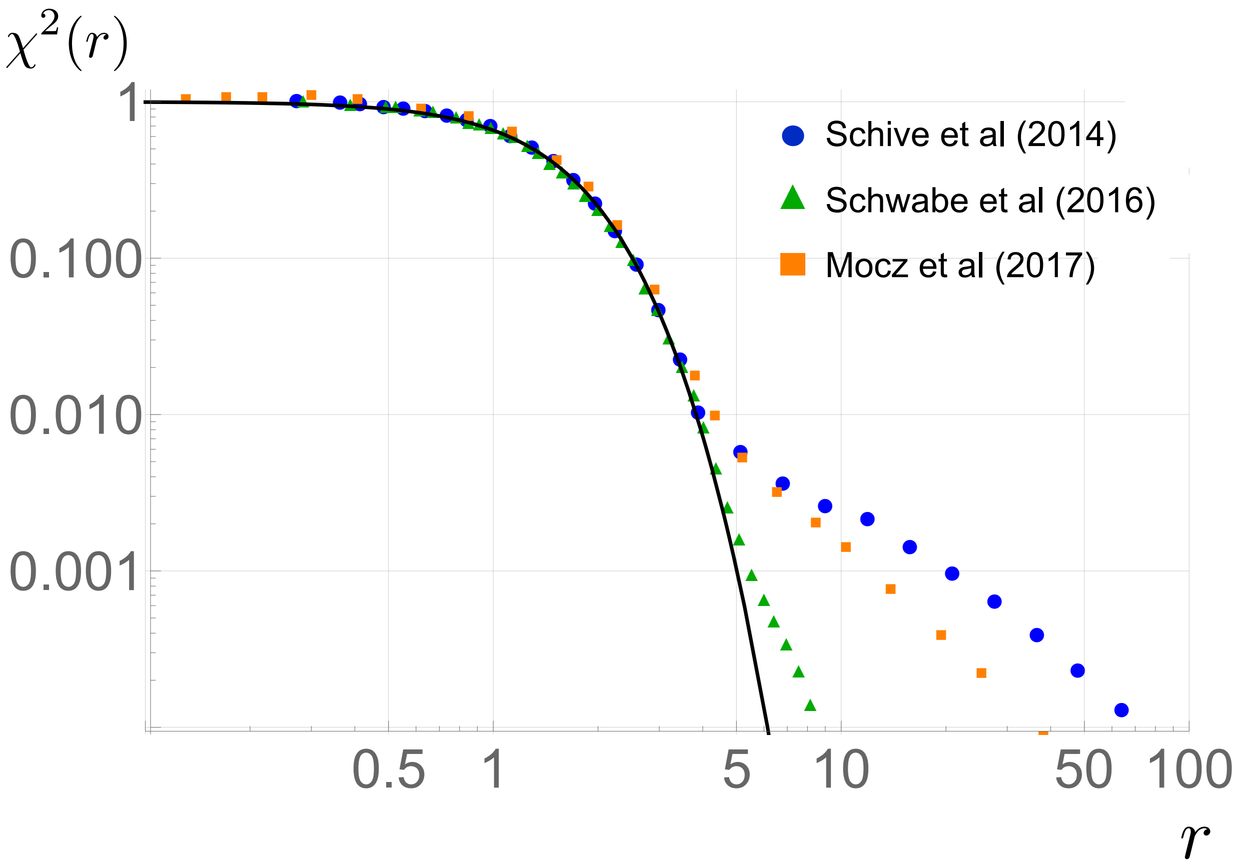
$$\approx 2.79 \times 10^{12} \left(\frac{m}{10^{-22}\ \mathrm{eV}}\right)^{-1}\ \mathrm{M}_\odot$$

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



Bar, Blas, KB, Sibiryakov; 1805.00122

* Oscillatons? oscillons?

A soliton — host halo relation?

Schive et al 1406.6586
Schive et al 1407.7762
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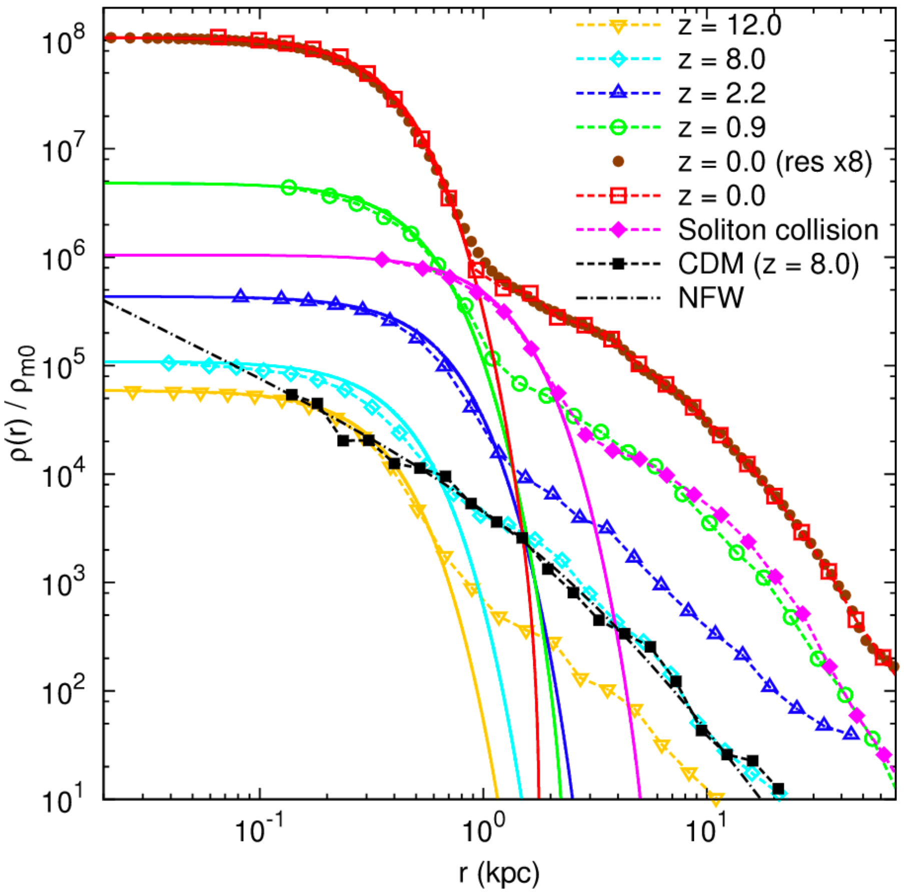

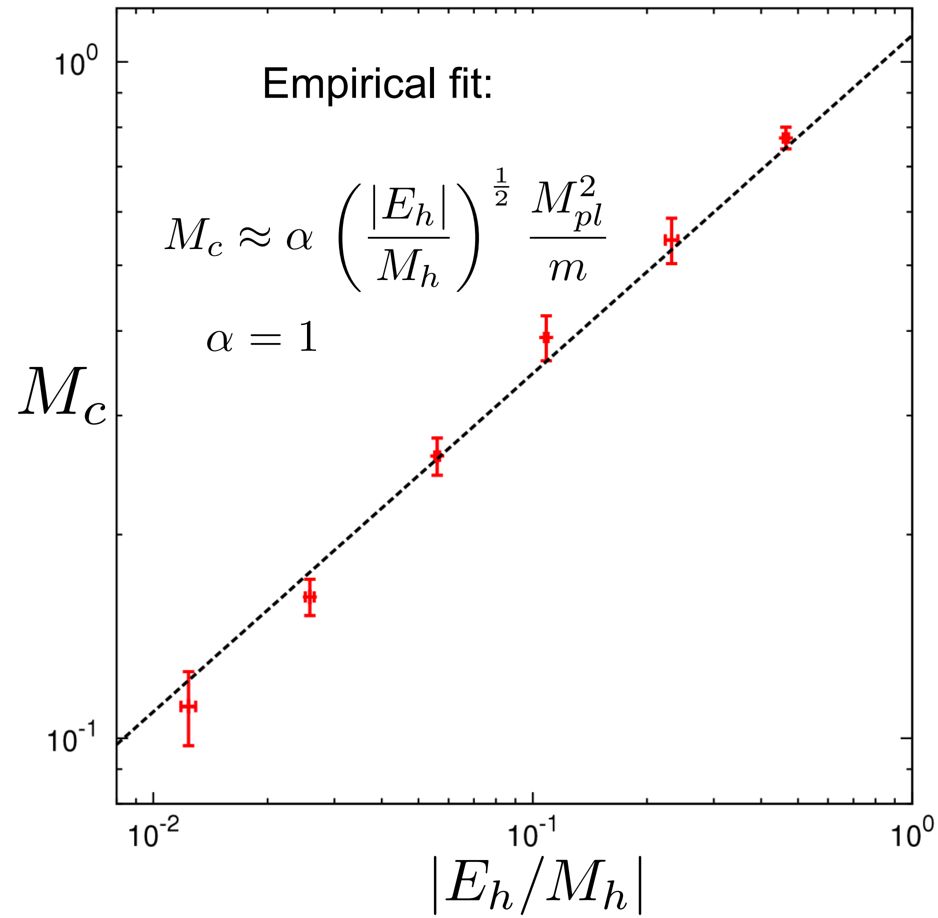

Mocz 1705.05845 find a different relation?
(Xtra material in this talk)

A soliton — host halo relation?

soliton—halo relation equivalent to:

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

Bar, Blas, KB, Sibiryakov; 1805.00122

Bar, KB, Sato, Eby; 1903.03402

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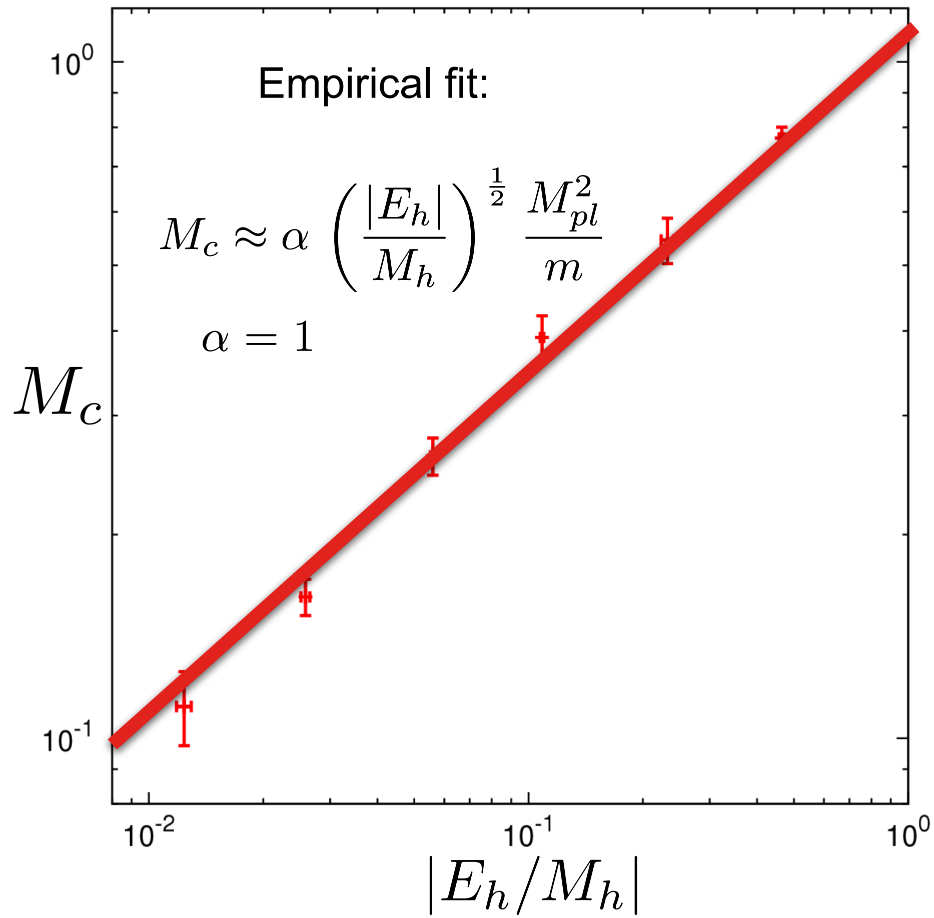
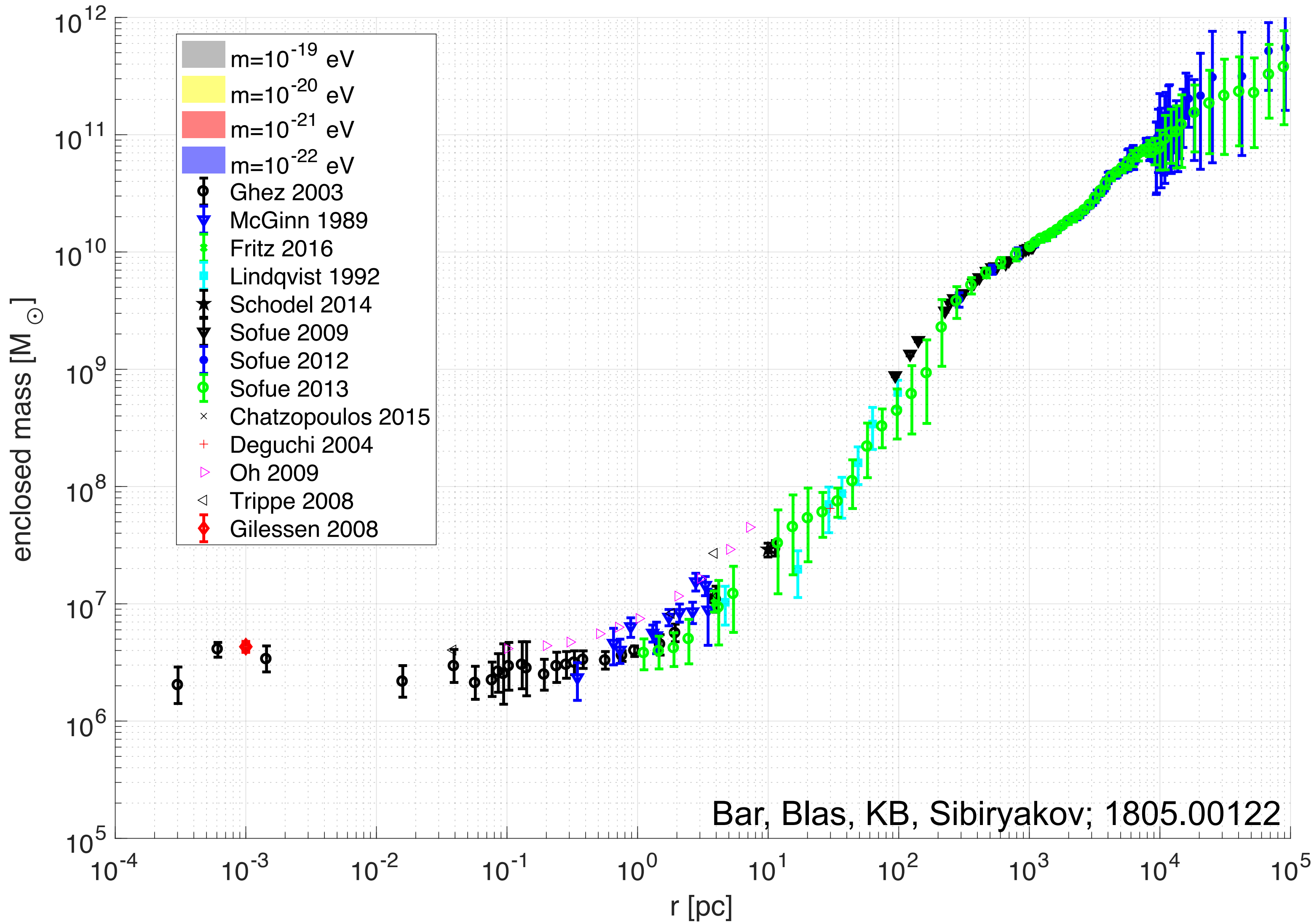


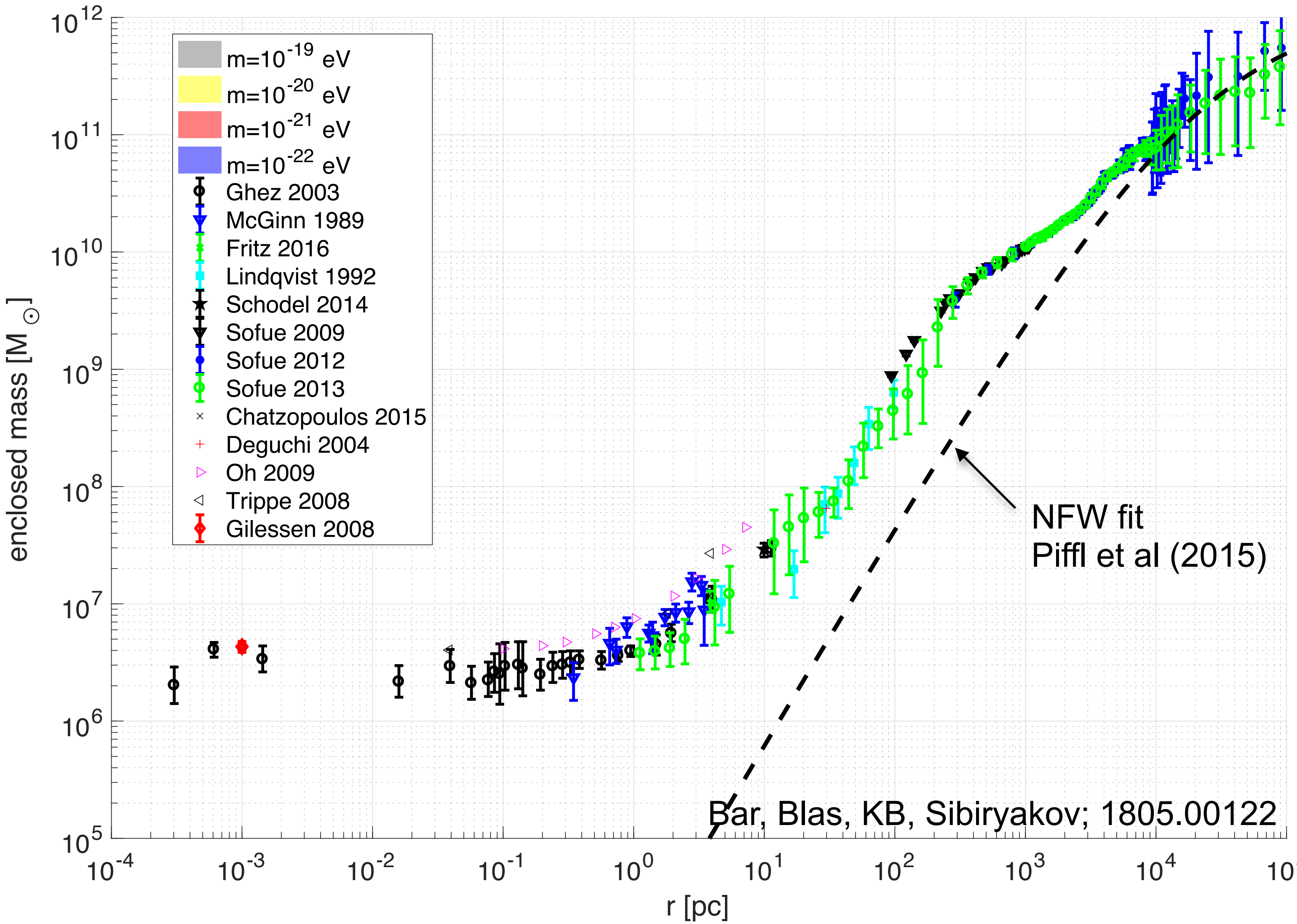
Mocz 1705.05845 find a different relation?
(Xtra material in this talk)

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



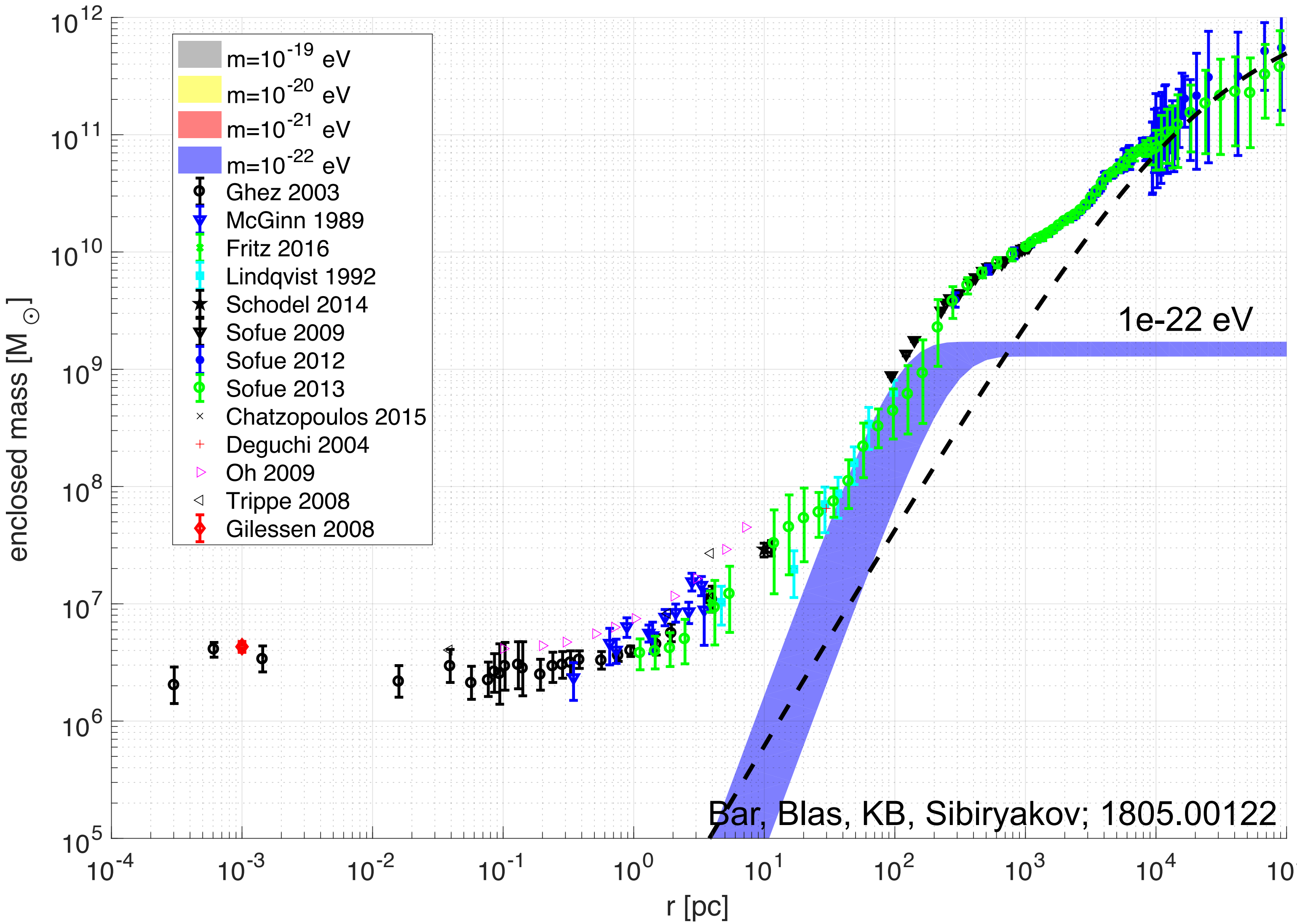
WIMP dark matter:

thought to affect outer part of rotation curve



ULDM:

Affects the inner part of rotation curve



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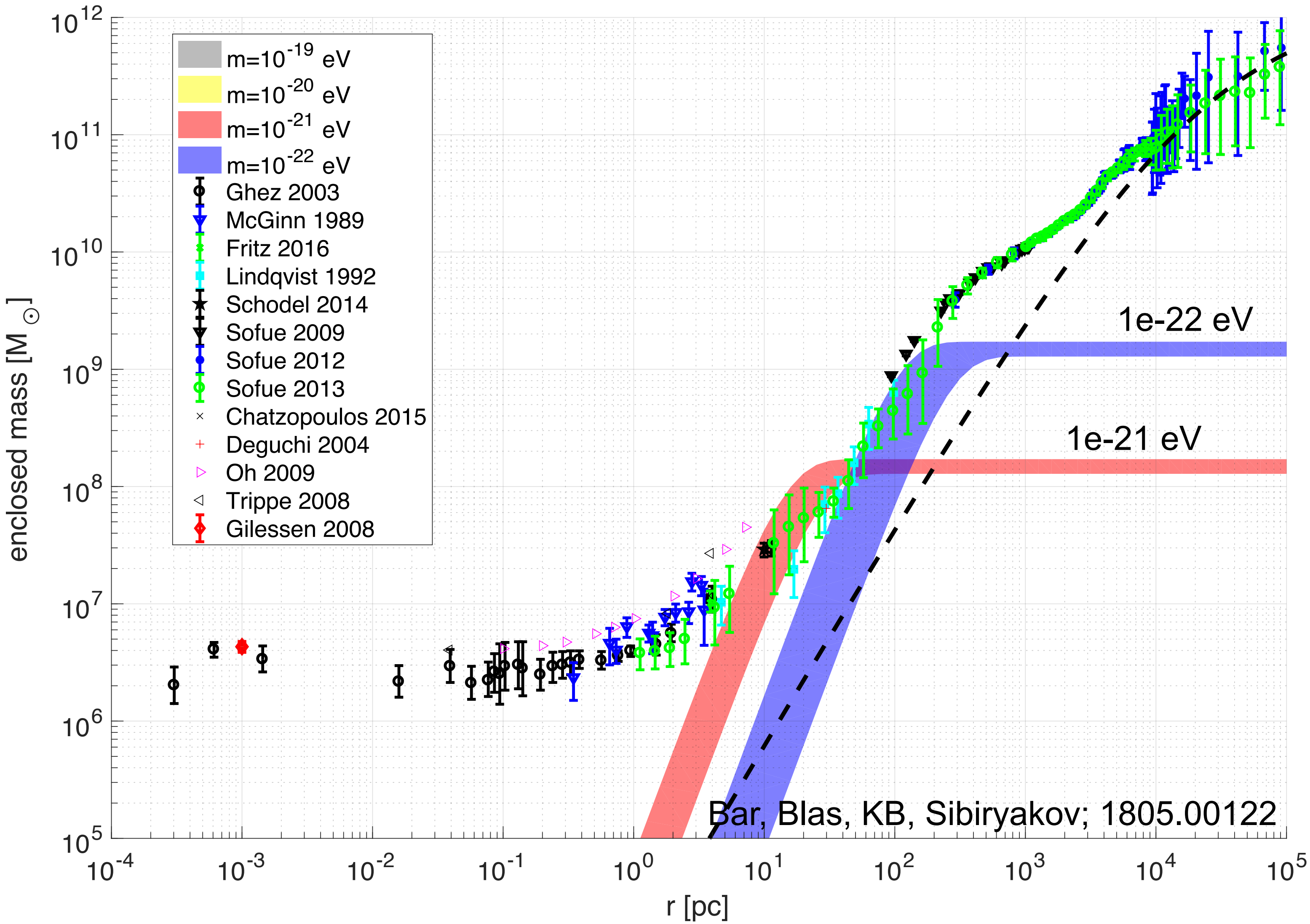

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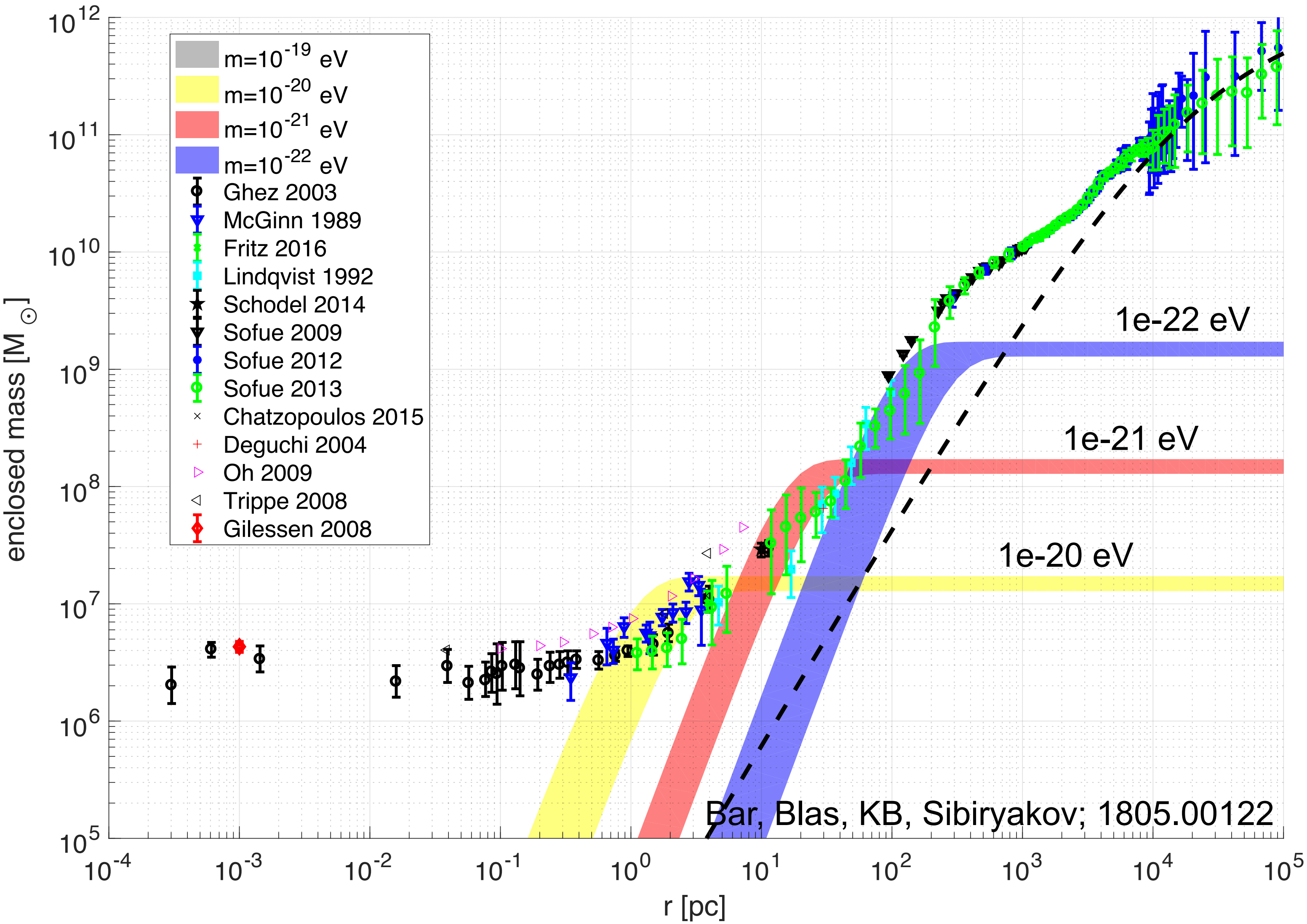

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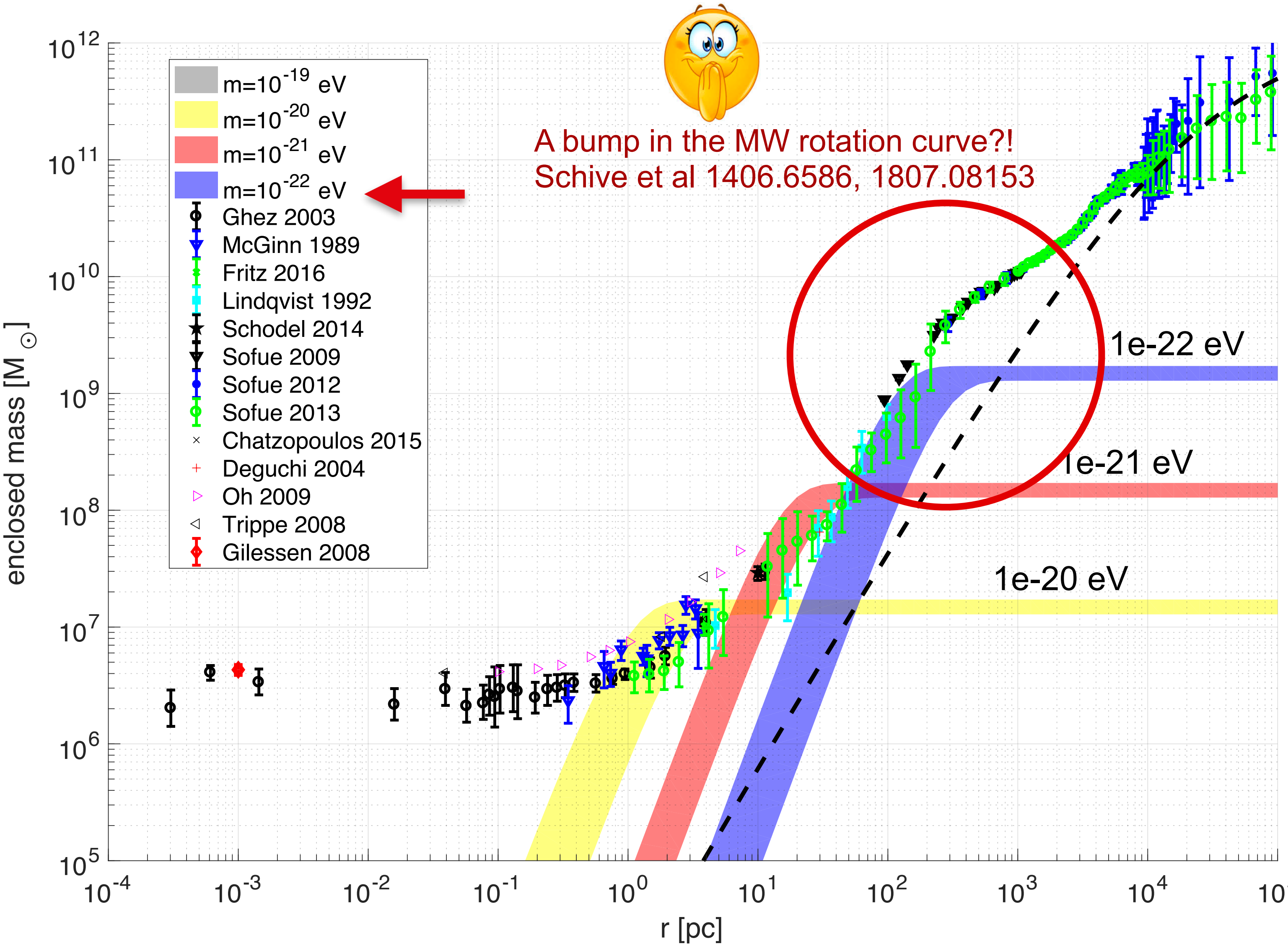
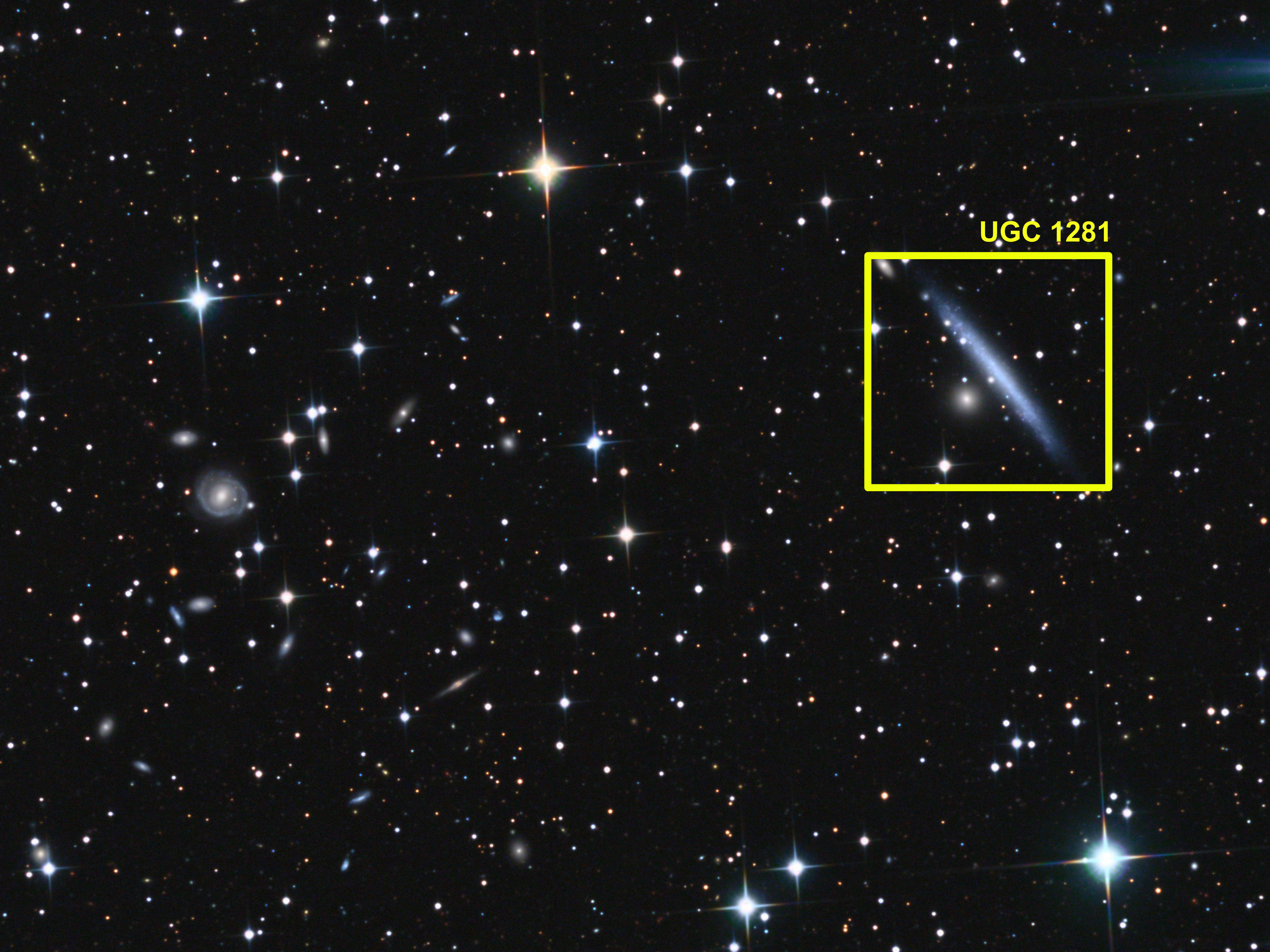
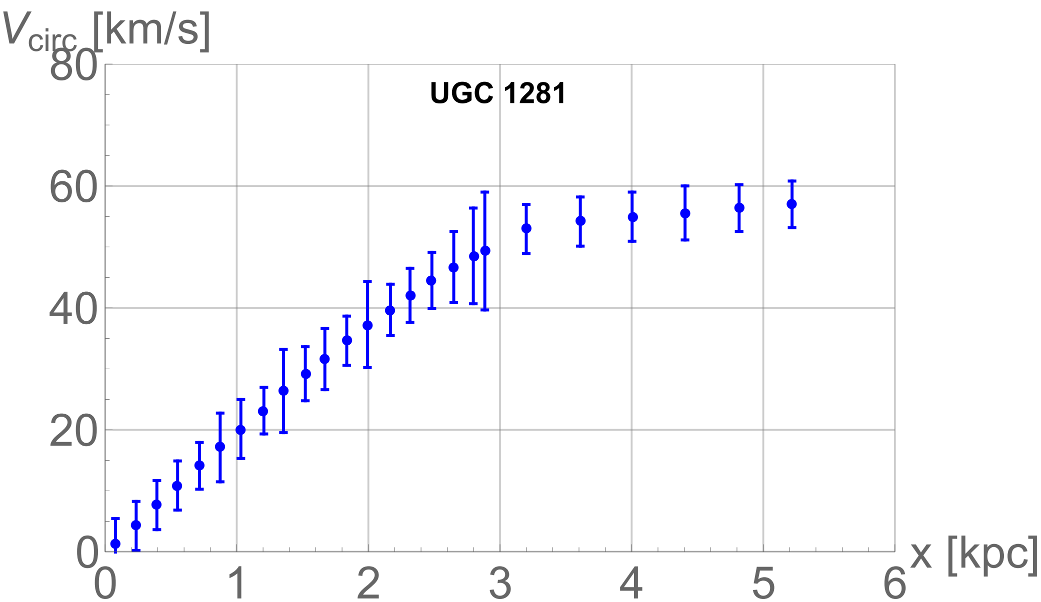



UGC 1281


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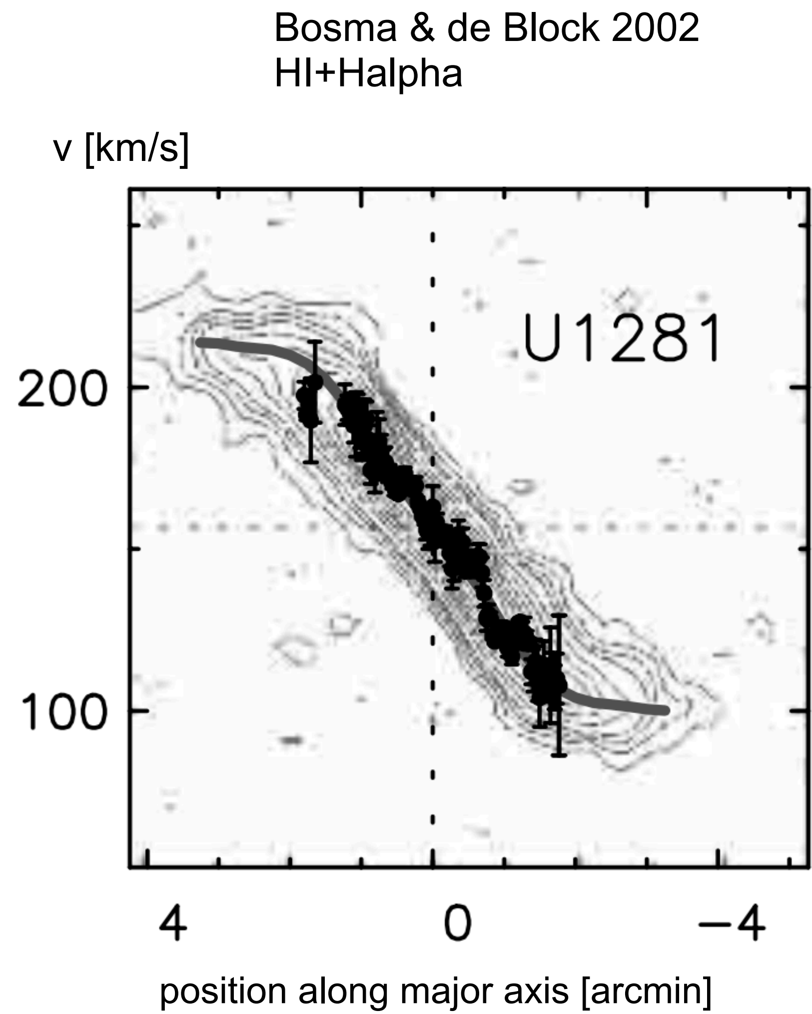
UGC 1281
0
1
2
3
4
5
6
x [kpc]


Bosma & de Block 2002
HI+Halpha
v [km/s]
U1281
200
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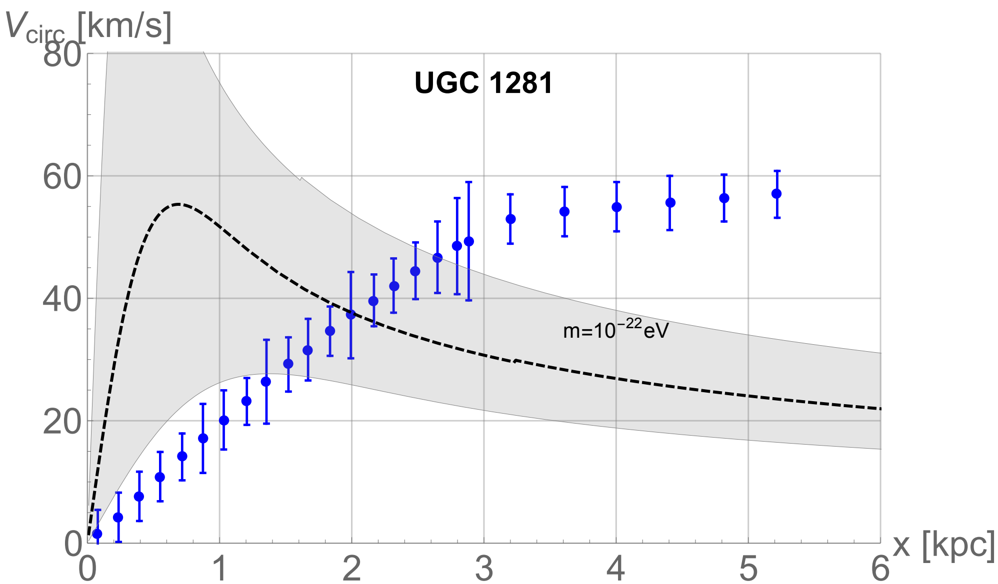
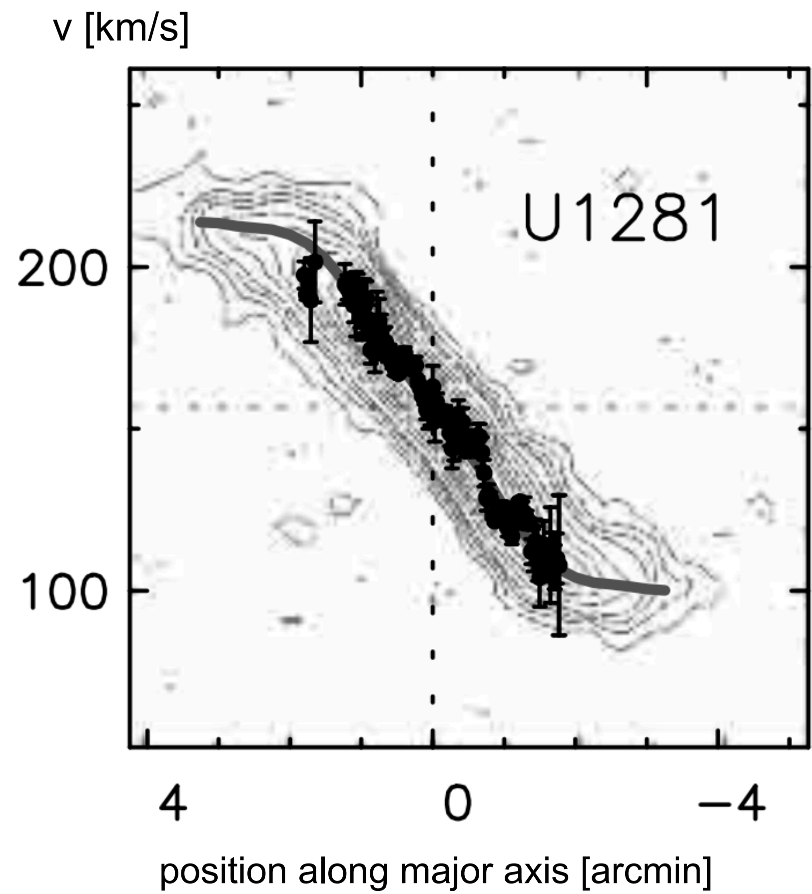
4
0
−4
position along major axis [arcmin]

$$m = 10^{-22}\ \text{eV}$$

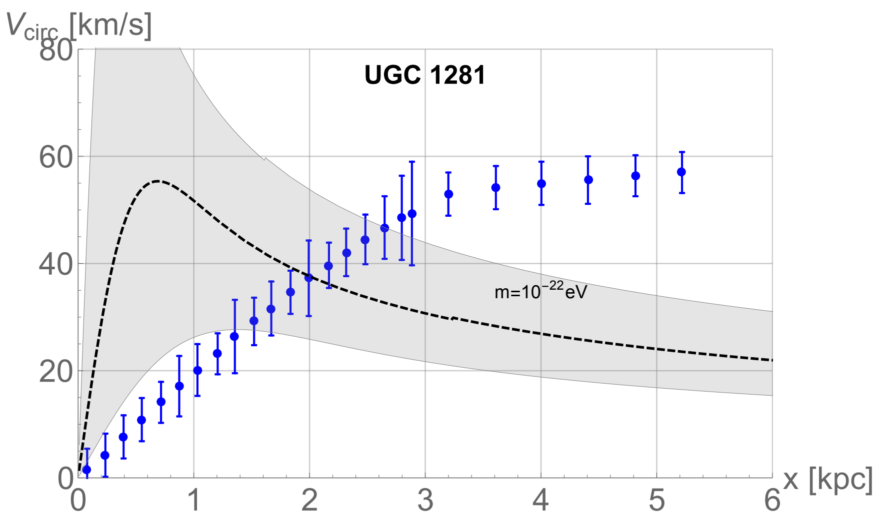


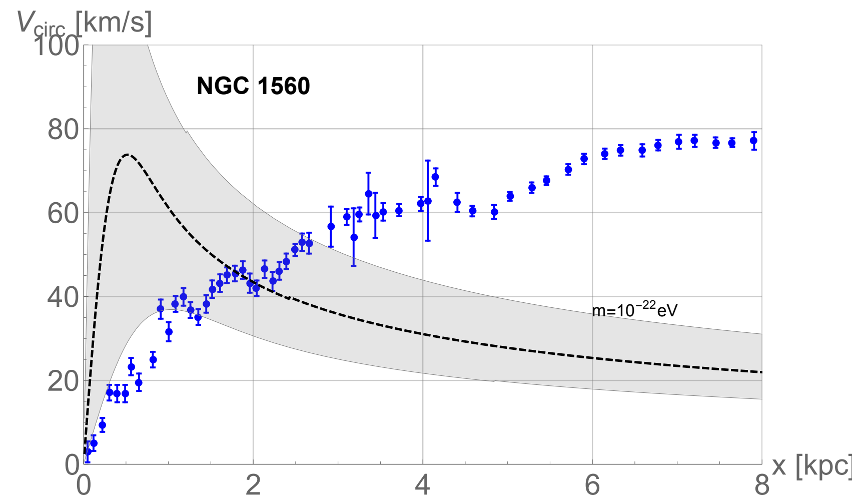
Bosma & de Block 2002
HI+Halpha

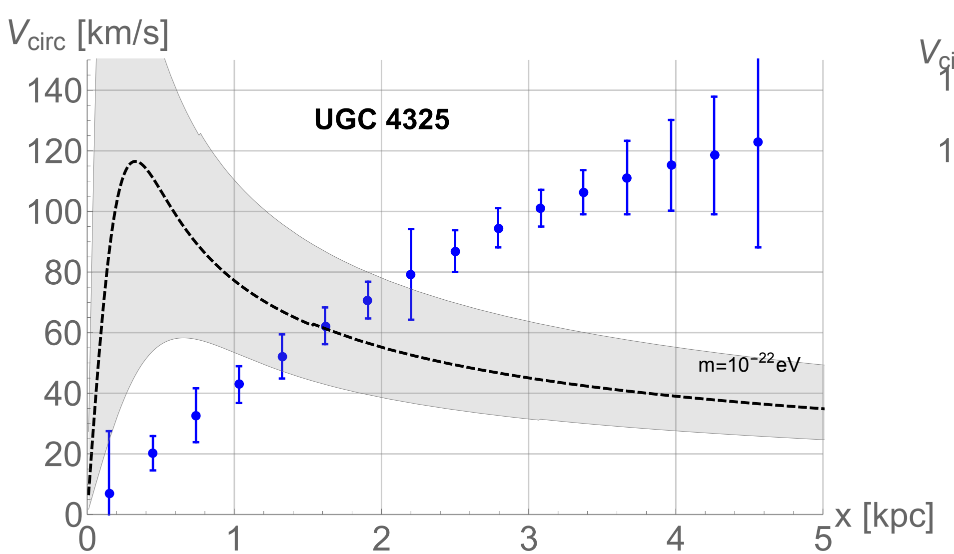


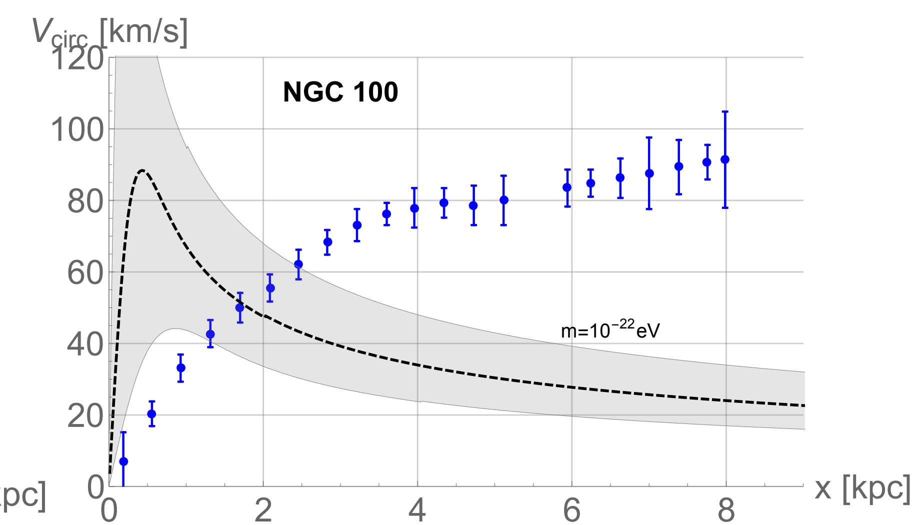
$m = 10^{-22}$ eV

(dozens of other galaxies look similar)

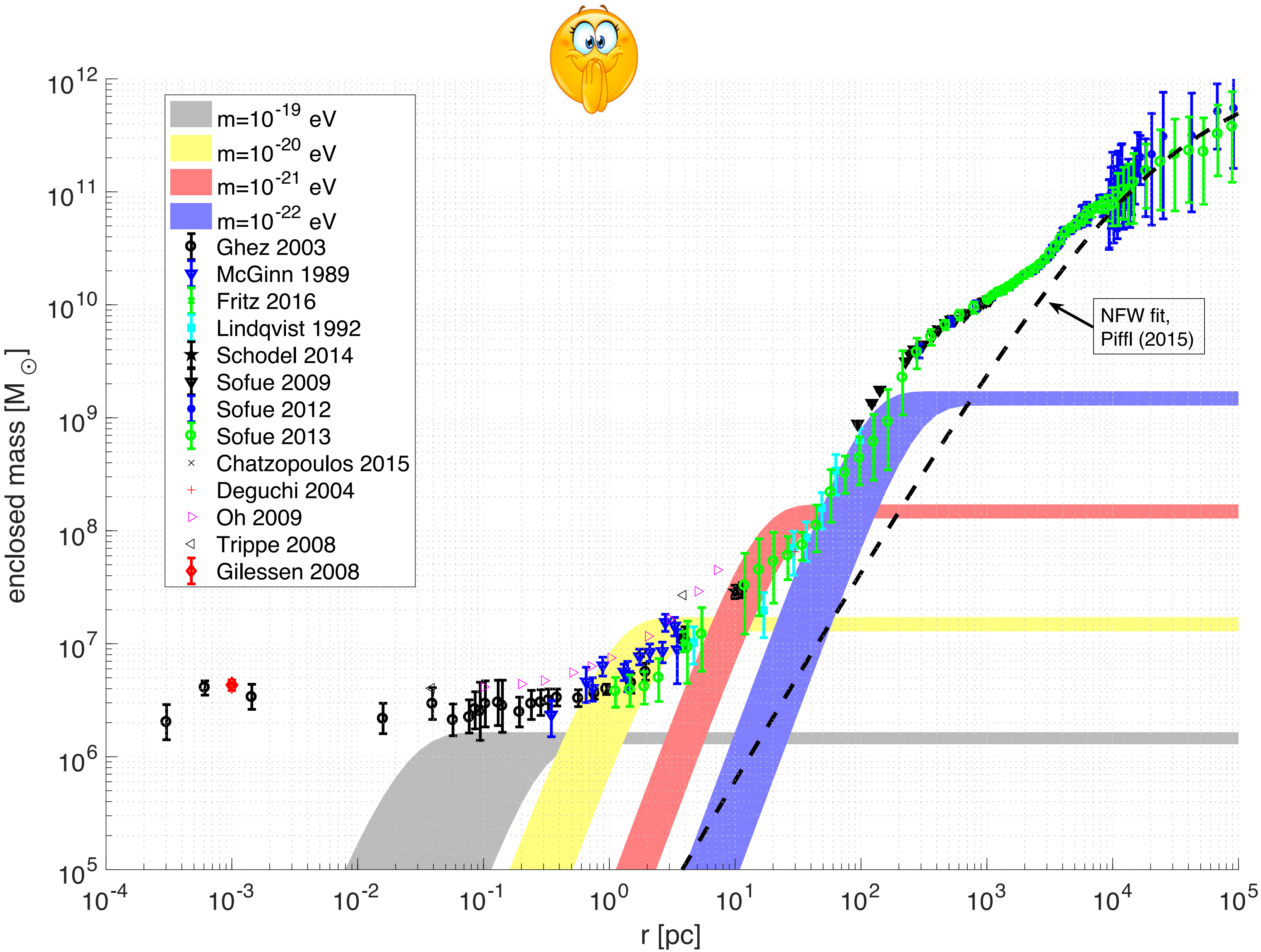






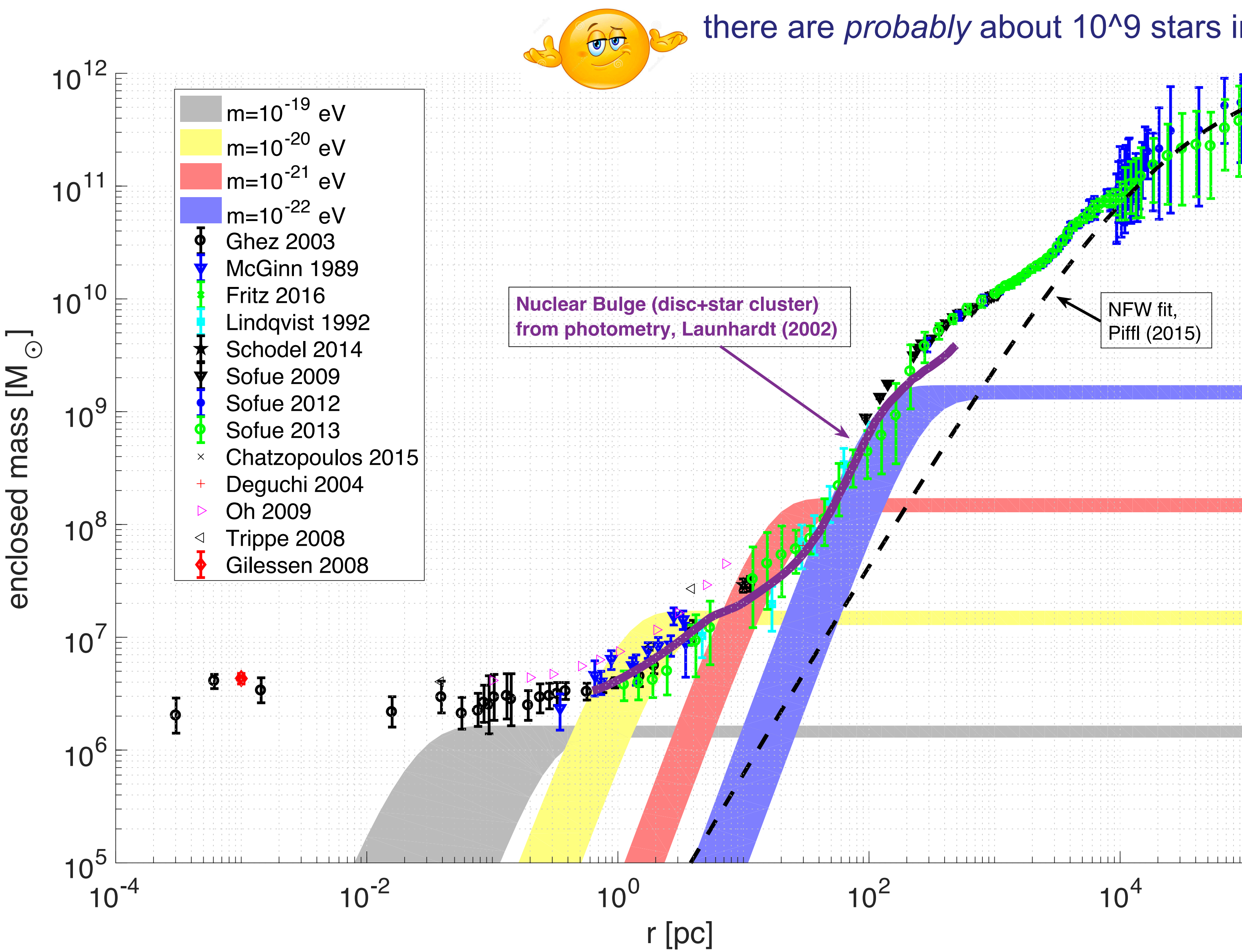


The Milky Way: nuclear bulge vs. soliton



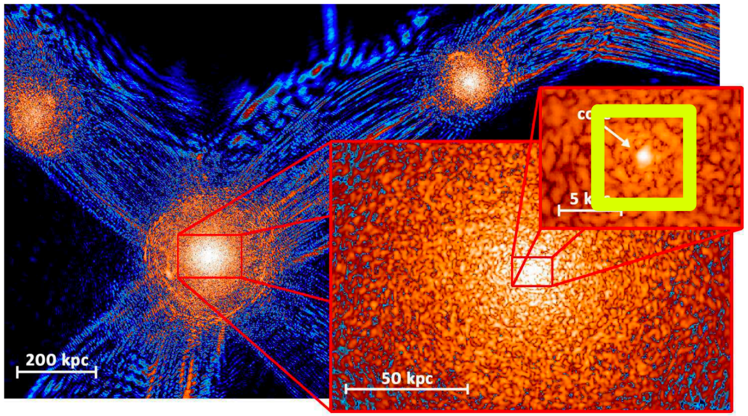
The Milky Way: nuclear bulge vs. soliton

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

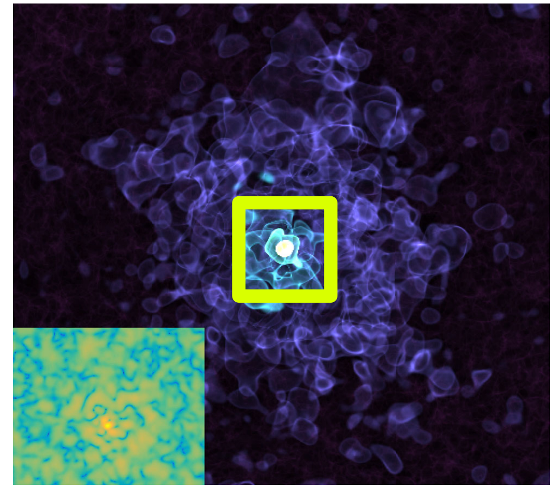


ULDM in galaxies

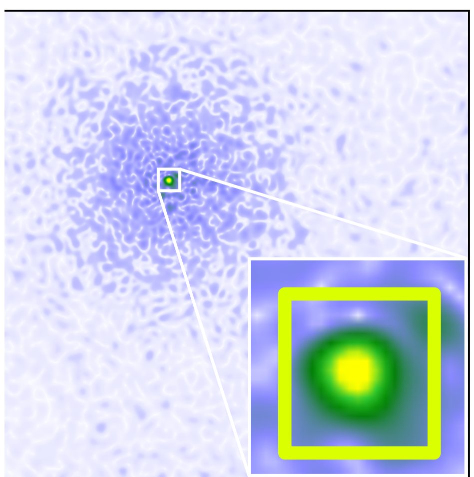
Inner part of simulated galaxies forms a core



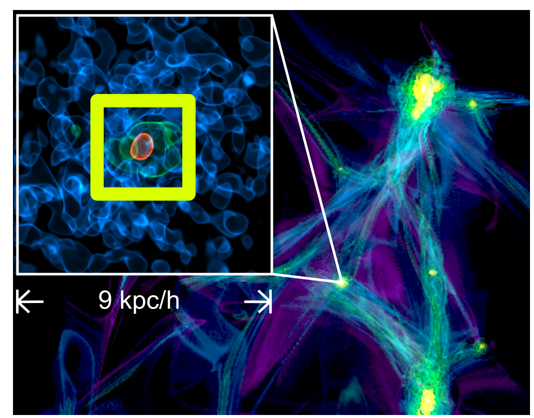
Schive et al, Nature Phys. 10 (2014) 496-499



Mocz et al, MNRAS. 471 (2017) 4559-4570



Levkov, Panin, Tkachev,
Phys.Rev.Lett. 121 (2018) 151301

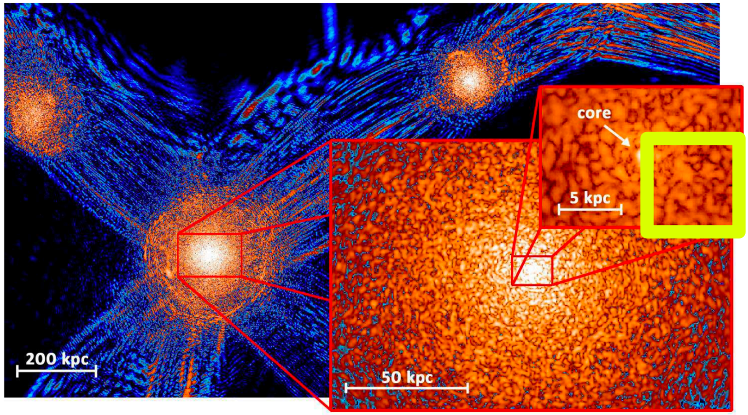


Veltmaat, Niemeyer, Schwabe,
Phys.Rev. D98 (2018) 043509

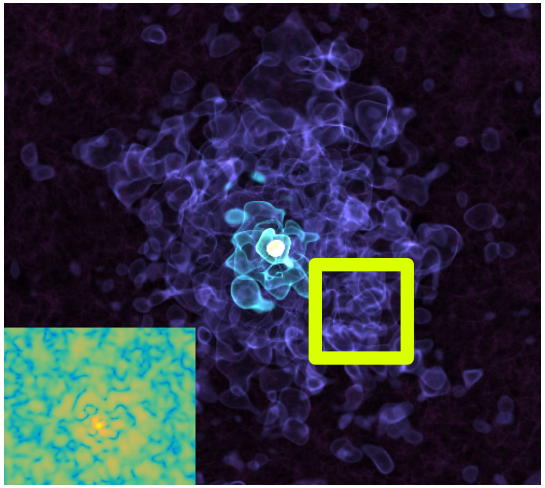
ULDM in galaxies

Hui et al, PRD95 (2017) no.4, 043541
Bar-Or, Fouvry, Tremaine, Astrophys.J. 871 (2019) no.1, 28

ULDM has more (unbound) substructure than CDM



Schive et al, Nature Phys. 10 (2014) 496-499



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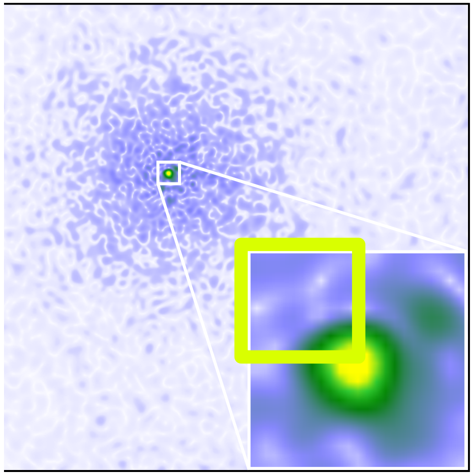

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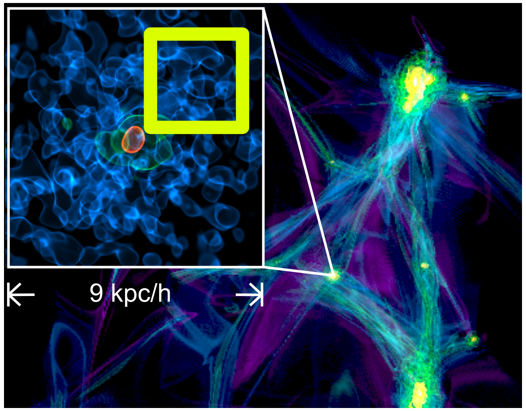

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➡ ULDM has more (unbound) substructure than CDM

Orbital decay times for the globular clusters in Fornax for cold dark matter (CDM) and fuzzy dark matter (FDM)

	projected radius	cluster mass	CDM		FDM		
n	$r_\perp$ (kpc)	$m_{\rm cl}$ ($M_\odot$)	C	τ (Gyr)	kr	C	τ (Gyr)
1	1.6	3.7×10^4	4.29	112	8.90	2.46	215
2	1.05	1.82×10^5	3.32	9.7	5.04	1.88	12
3	0.43	3.63×10^5	2.45	0.62	0.97	0.29	2.2
4	0.24	1.32×10^5	2.50	0.37	0.31	0.033	10
5	1.43	1.78×10^5	3.46	21.3	7.79	2.32	31

FORNAX 2 FORNAX 3 FORNAX 5
NASA, ESA, S. Larsen (Radboud University, the Netherlands)

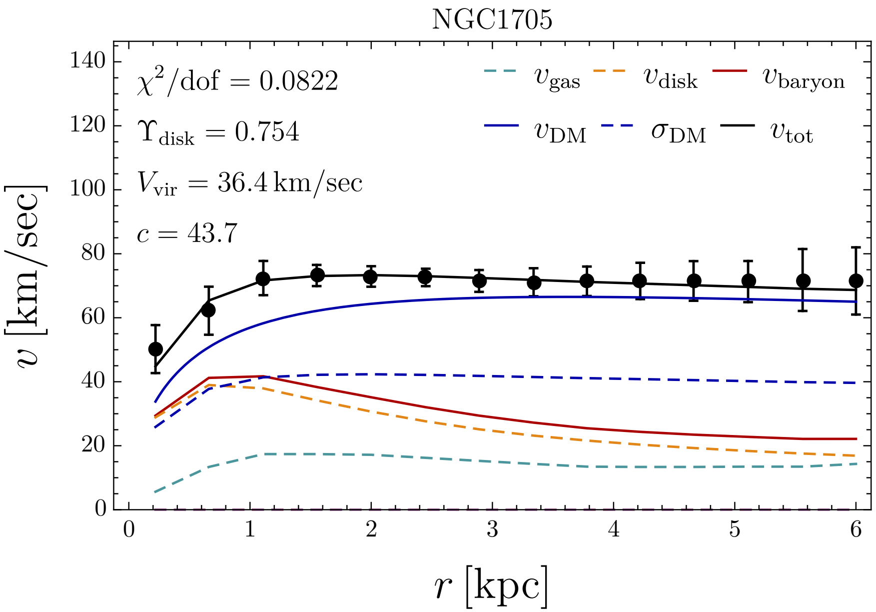
ULDM in galaxies

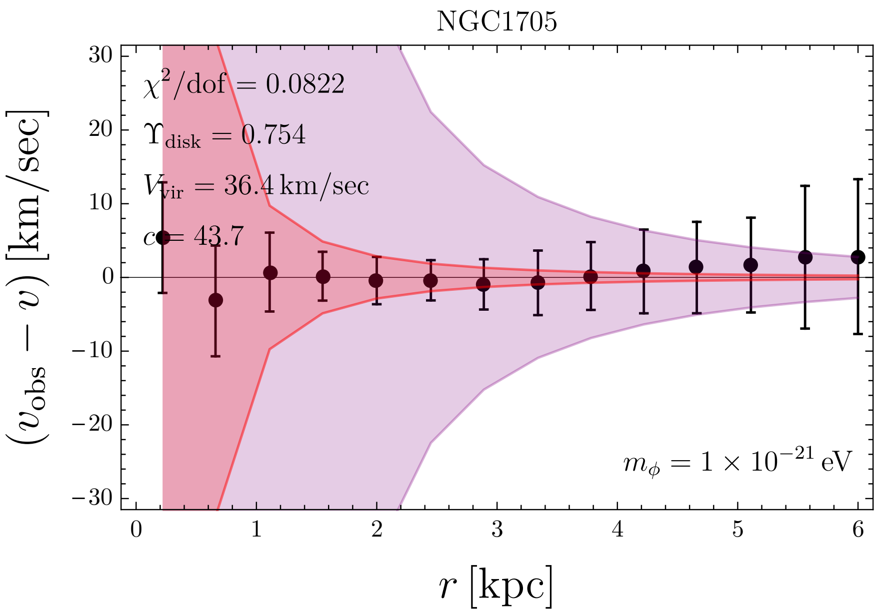
ULDM has more (unbound) substructure than CDM

Hui et al, PRD95 (2017) no.4, 043541
Bar-Or, Fouvry, Tremaine, Astrophys.J. 871 (2019) no.1, 28

In progress: ULDM vs. velocity dispersion in DSph and LSB galaxies

KB, Josh Eby, Hyungjin Kim, *in prep*





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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Bar et al. 1805.00122, 1903.03402 analysed dozens of LSB rotation curves.
As far as we could see, the core isn’t there:

m < 1e-21 eV in tension with observations.
(disfavours 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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<u>Questions / work in progress:</u>
Is the soliton—host halo relation correct? (or spurious effect 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

Hui et al, Phys.Rev. D95 (2017) no.4, 043541
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ESO and NASA/Canada-France-Hawaii Telescope, J.-C. Cuillandre (CFHT)

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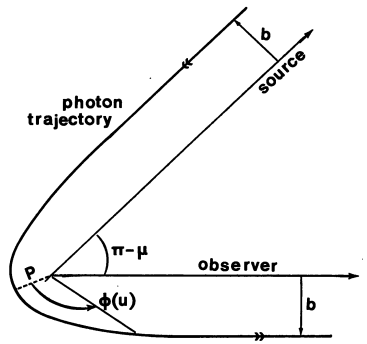
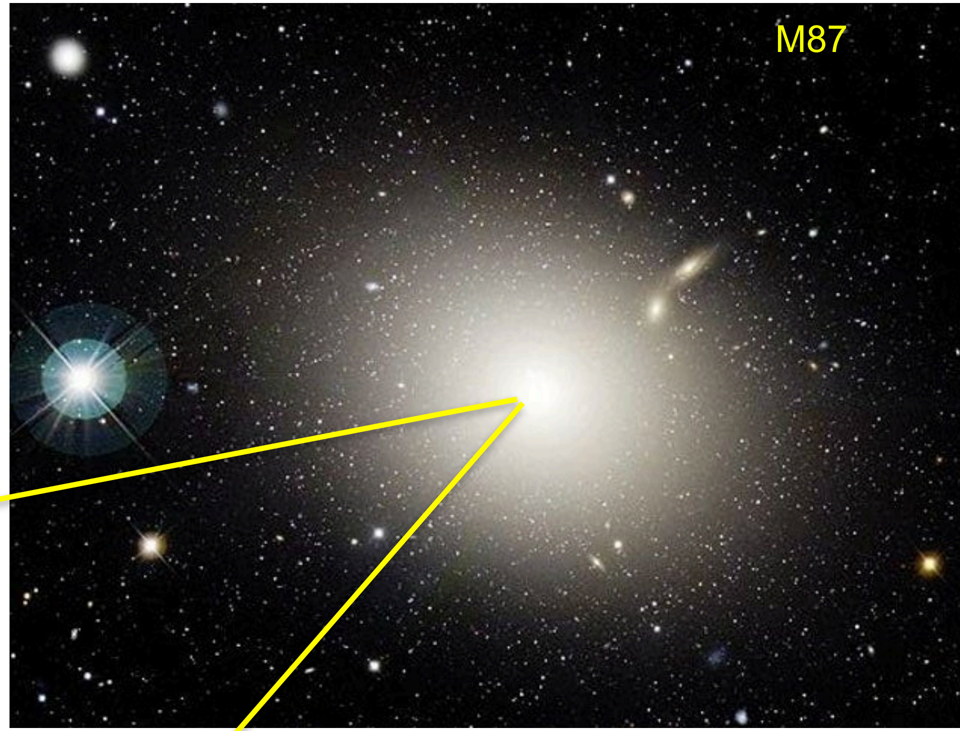


J.-P. Luminet, Astron.Astrophys. 75 (1979) 228-235



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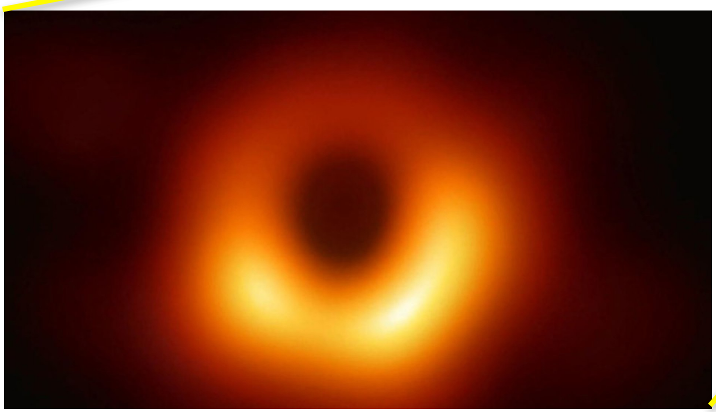

Event Horizon Telescope, Astrophys.J. 875 (2019) no.1, L6

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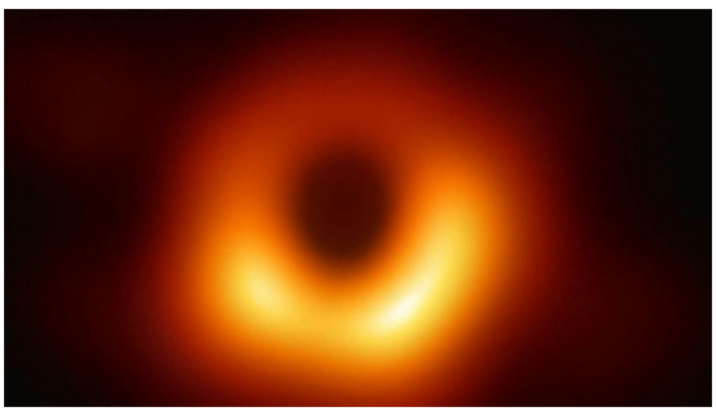
BH shadow **~0.00062 pc**

$$\frac{GM_{\rm BH}}{c^2 D} = 3.8 \pm 0.4\ \mu\text{arcsec}$$



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With EHT 2019, that's no longer plausible

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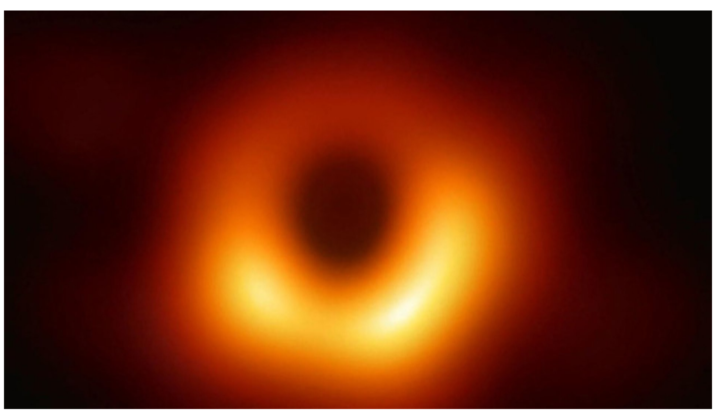
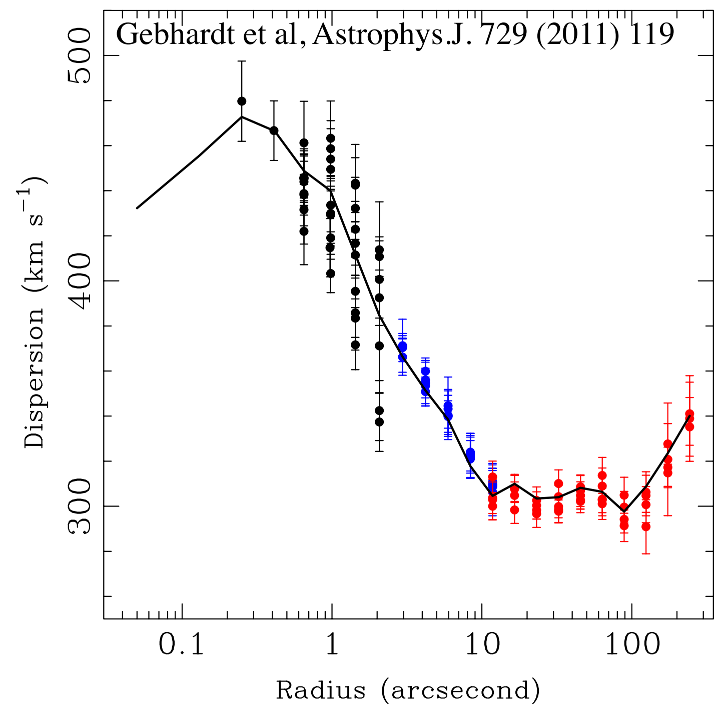


Event Horizon Telescope, Astrophys.J. 875 (2019) no.1, L6

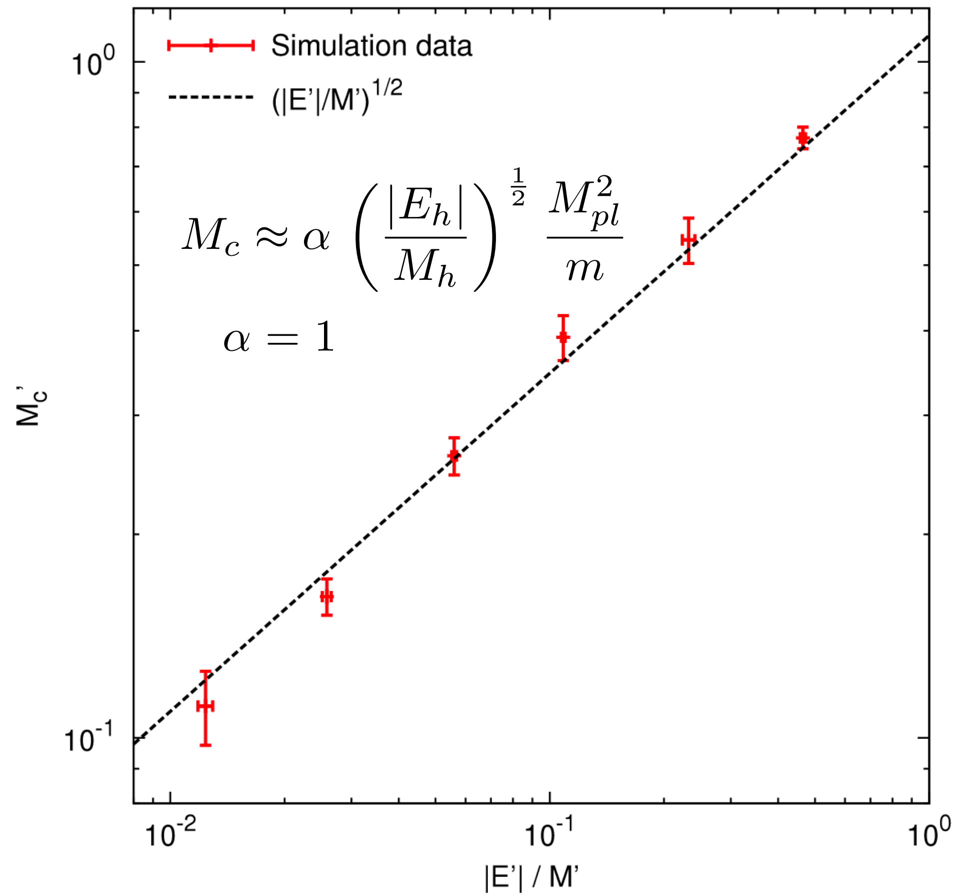
Stellar velocity dispersion **~500 pc**

$$\frac{GM(\theta_*)}{c^2 D} = 3.6 \pm 0.2\ \mu\text{arcsec}$$



Let's consider
numerical simulation results

Schive et al 1406.6586
Schive et al 1407.7762



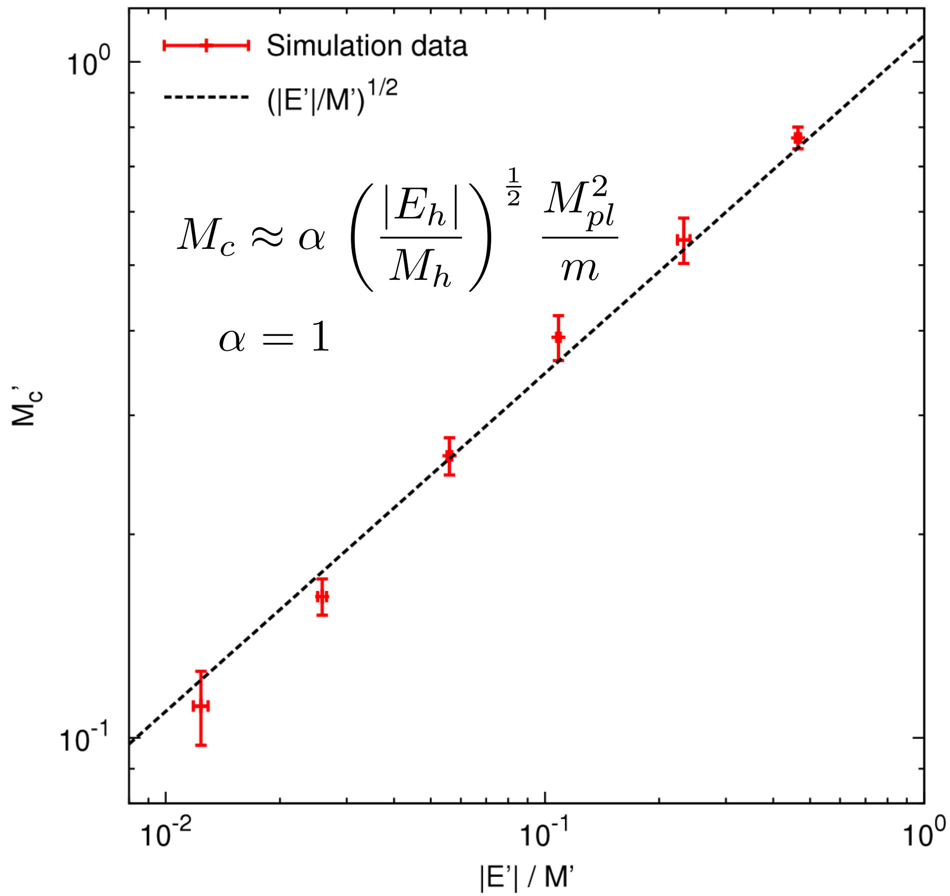
$$E = \int d^3x \left(\frac{|\nabla \psi|^2}{2m^2} + \frac{\Phi\, |\psi|^2}{2} \right)$$

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

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

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

Schive et al 1406.6586
Schive et al 1407.7762



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

Schive et al 1406.6586
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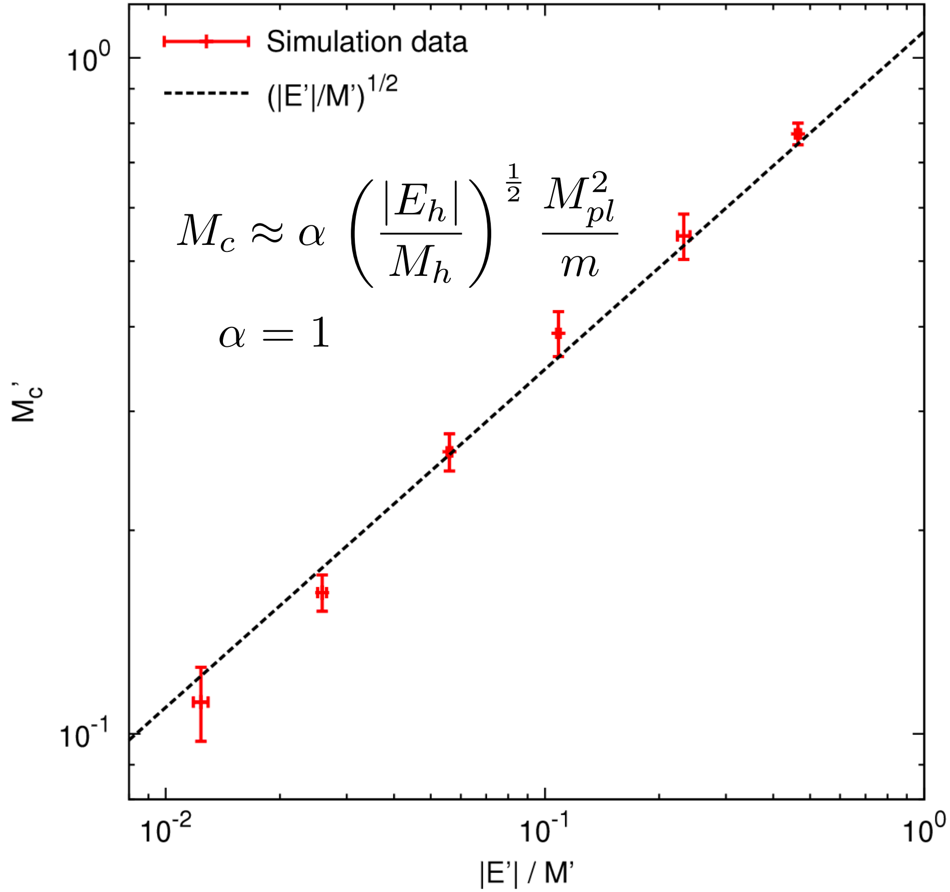

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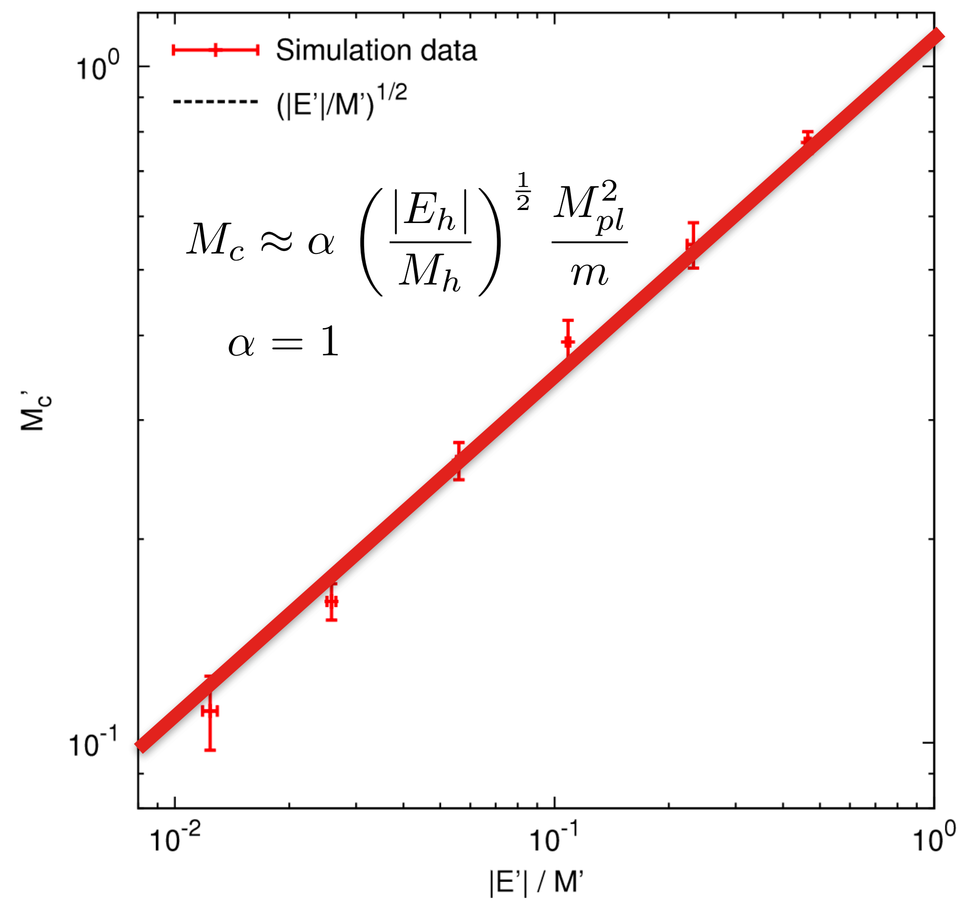
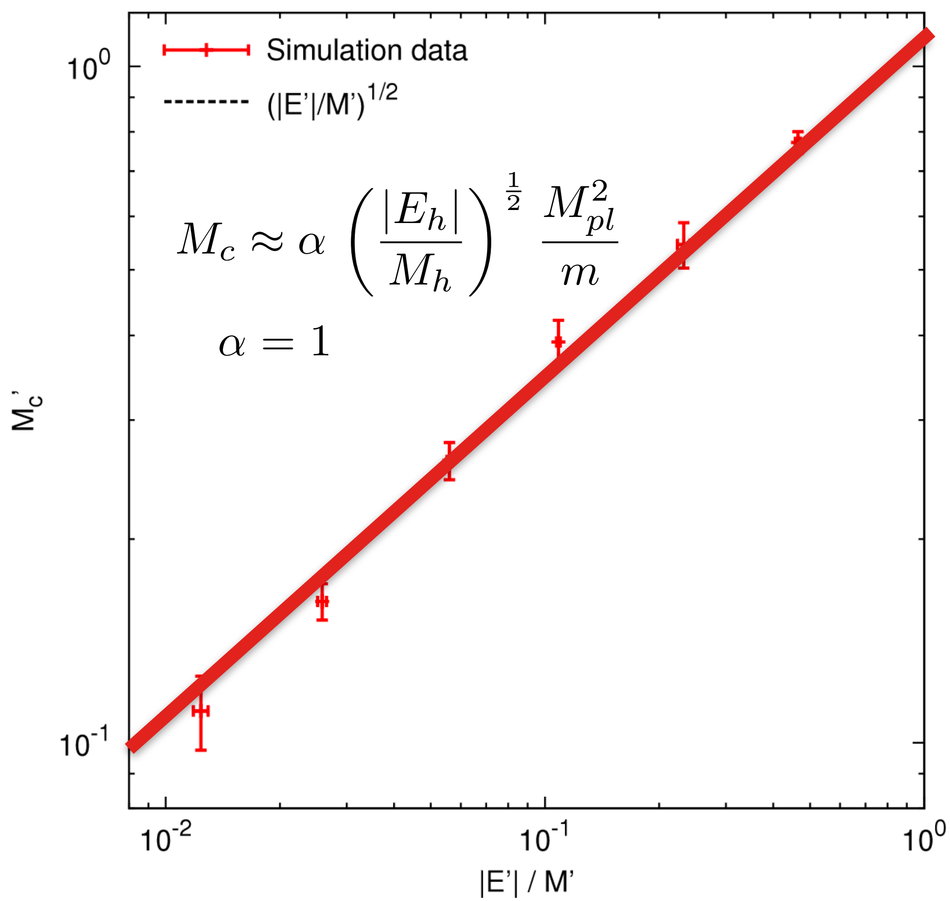


This is equivalent to:

$$\frac{E}{M}\Big|_{\text{soliton}} \approx \frac{E}{M}\Big|_{\text{halo}}$$

Bar, Blas, KB, Sibiryakov; 1805.00122

Schive et al 1406.6586
Schive et al 1407.7762



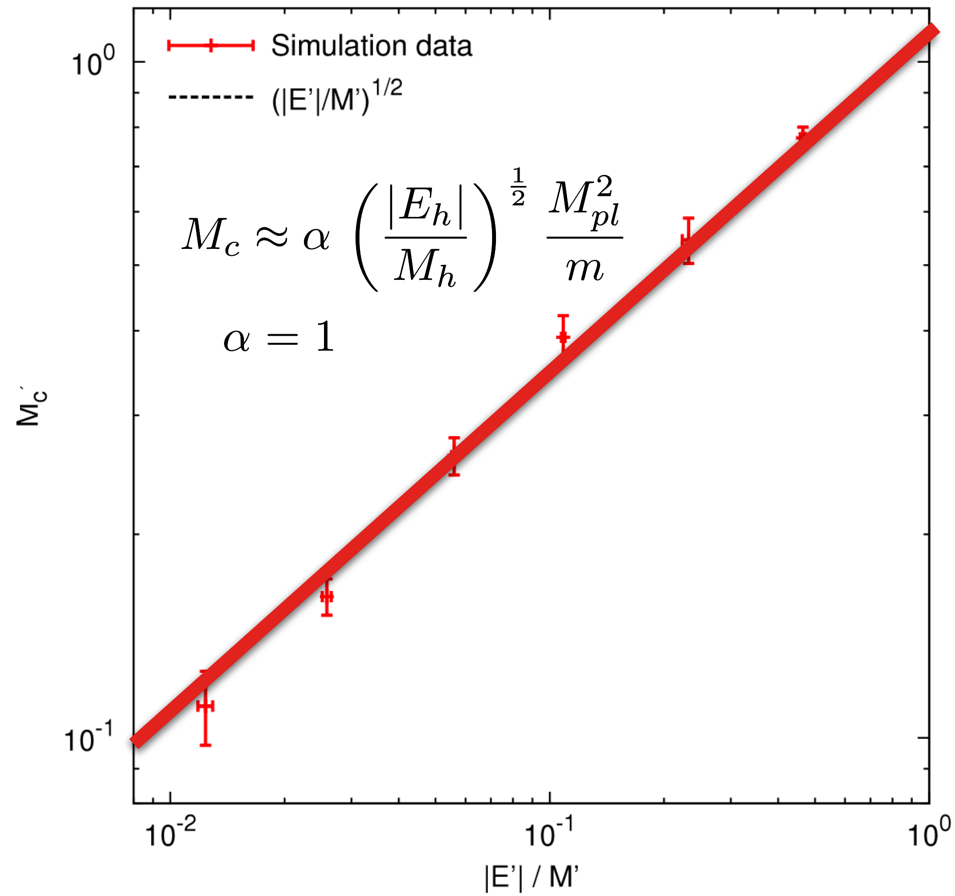
This is equivalent to:

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

Bar, KB, Sato, Eby; 1903.03402

K/M: kinetic energy/mass.

Schive et al 1406.6586
Schive et al 1407.7762



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Bar, KB, Sato, Eby; 1903.03402

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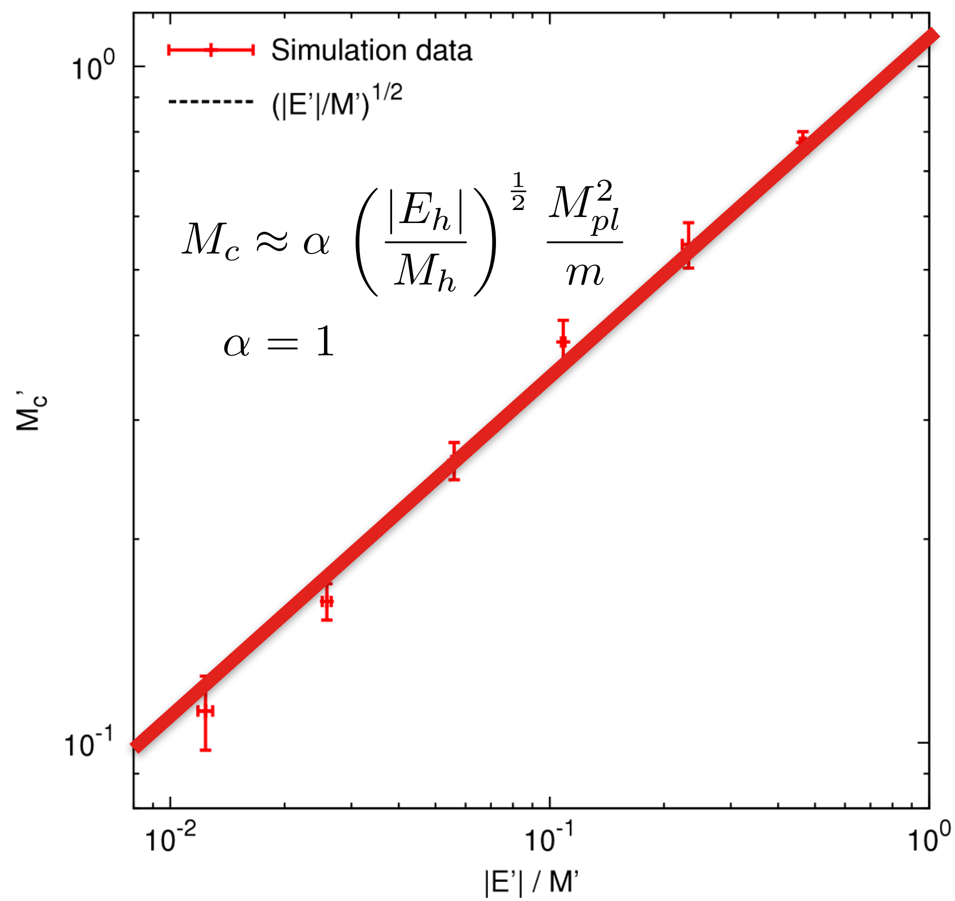
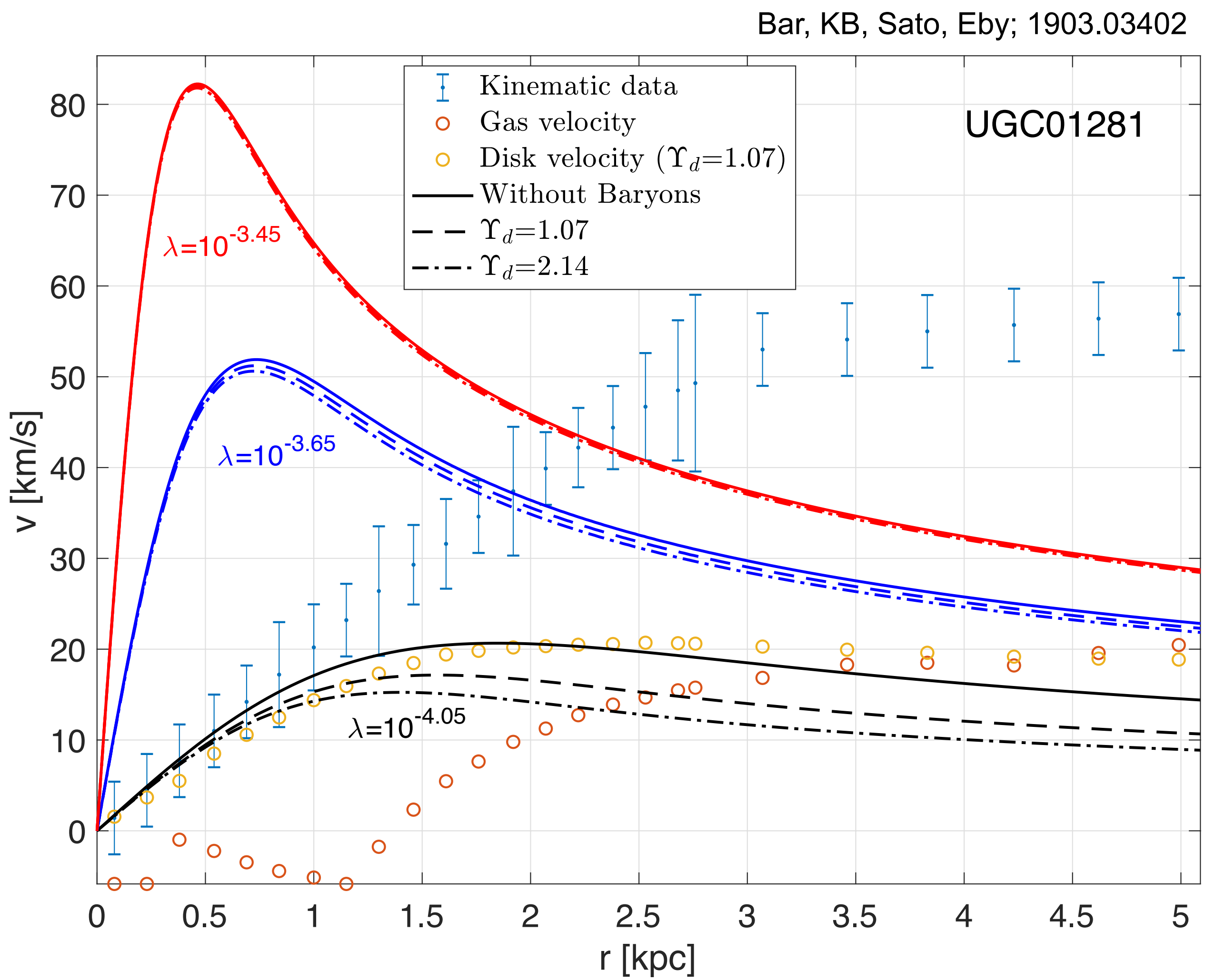
Open questions

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

Schive et al 1406.6586
Schive et al 1407.7762



This galaxy is a relatively clean, low surface-brightness object.
From photometric+kinematic data, we can bound stellar+gas effects on K/M



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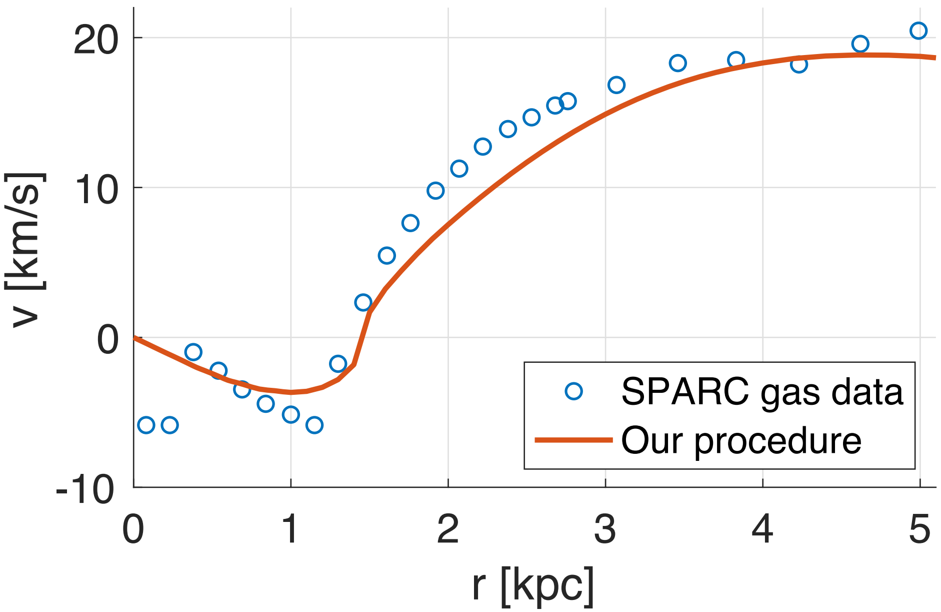
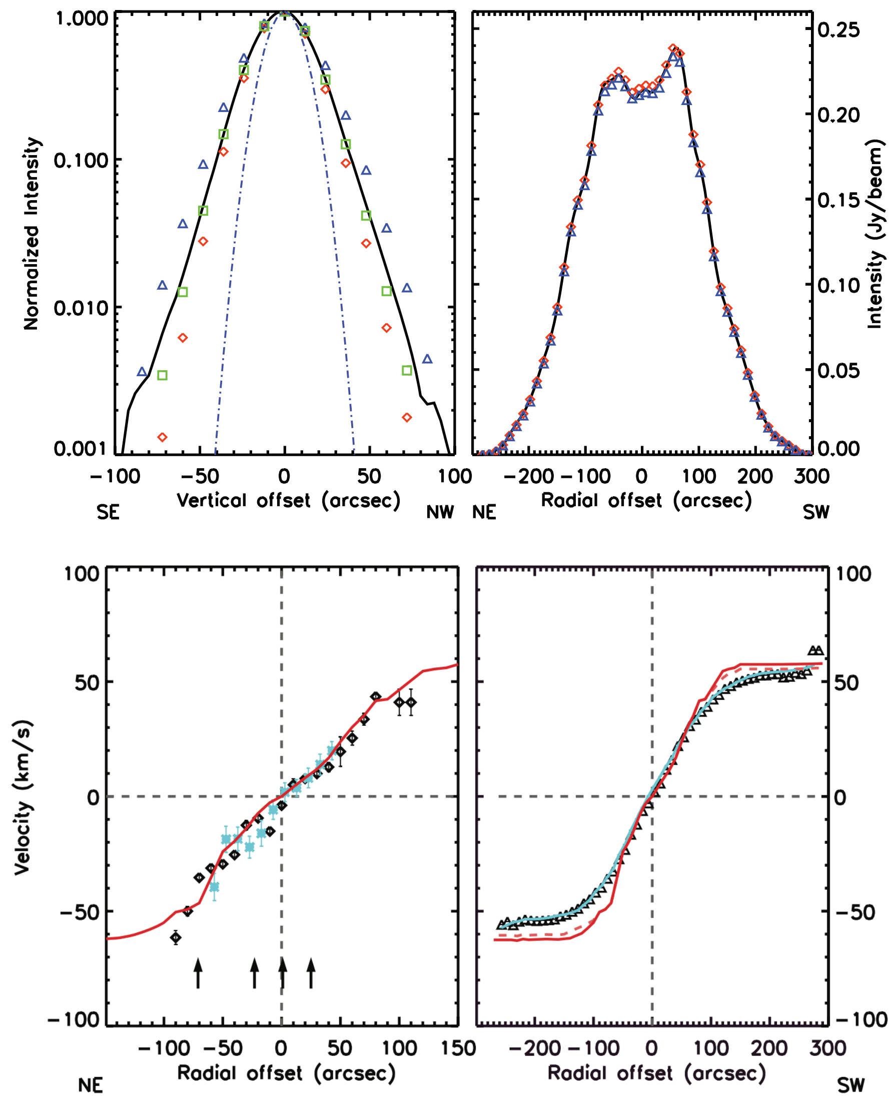
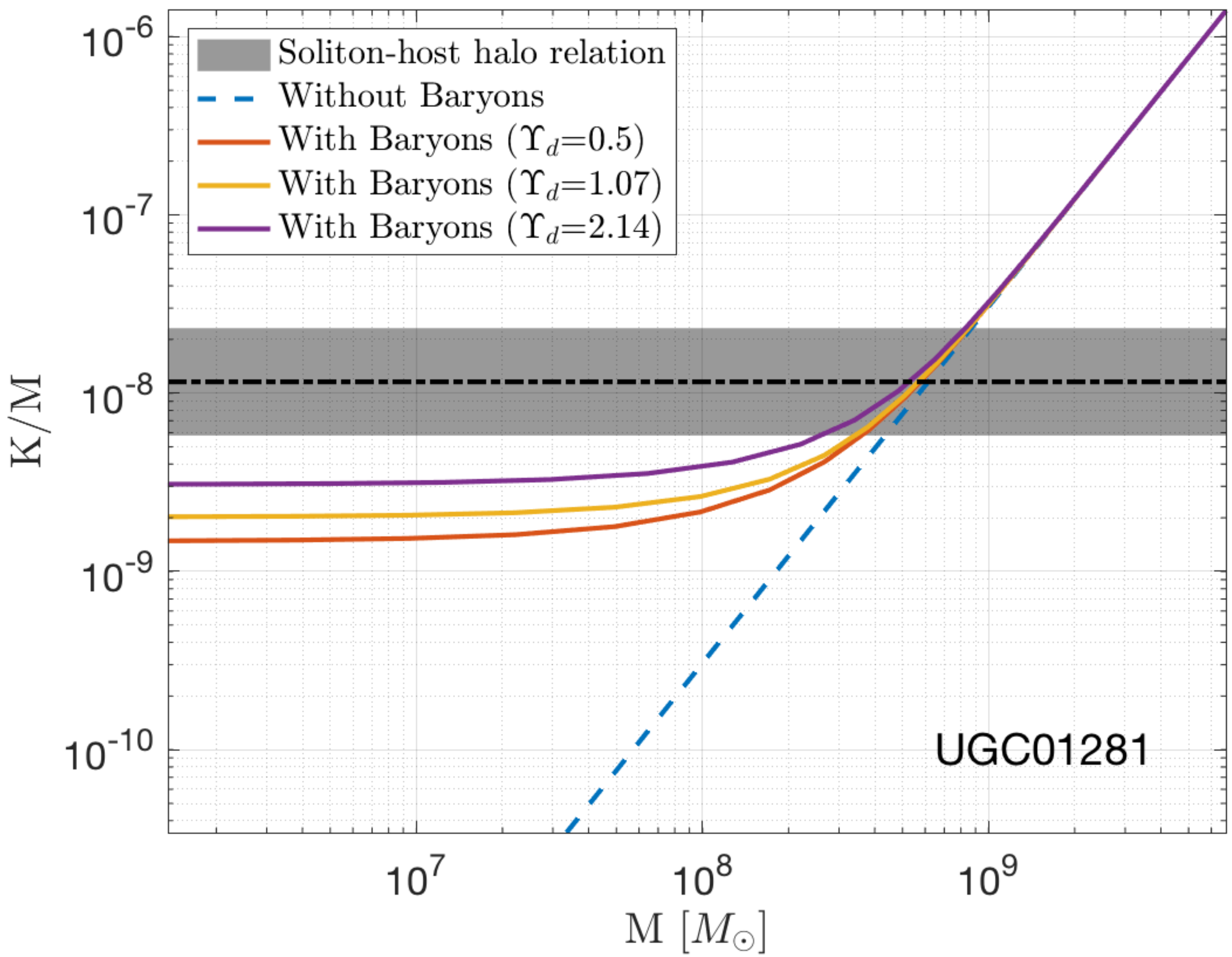


Kamphuis et al. MNRAS 414,3444 2011

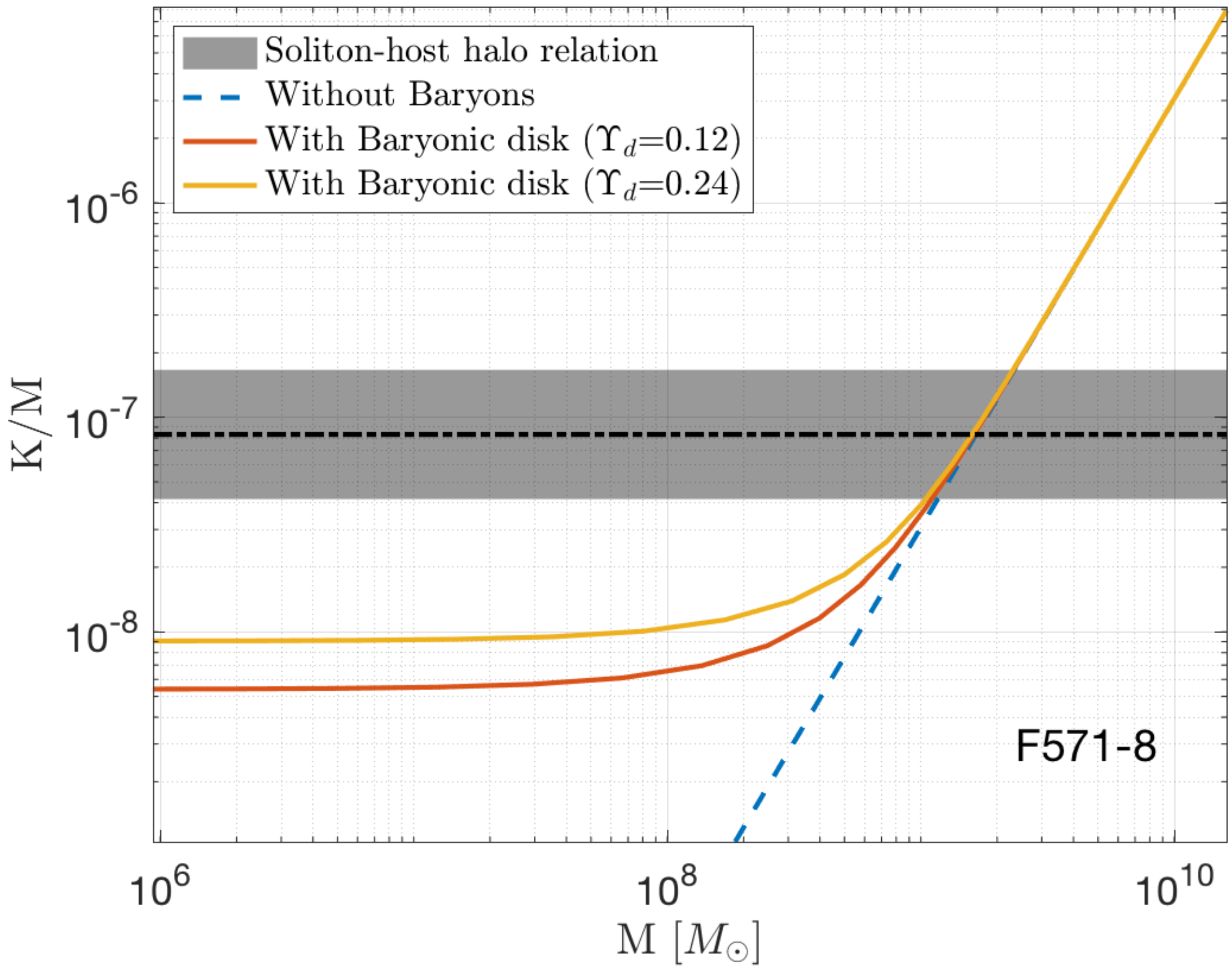


m=1e-22 eV



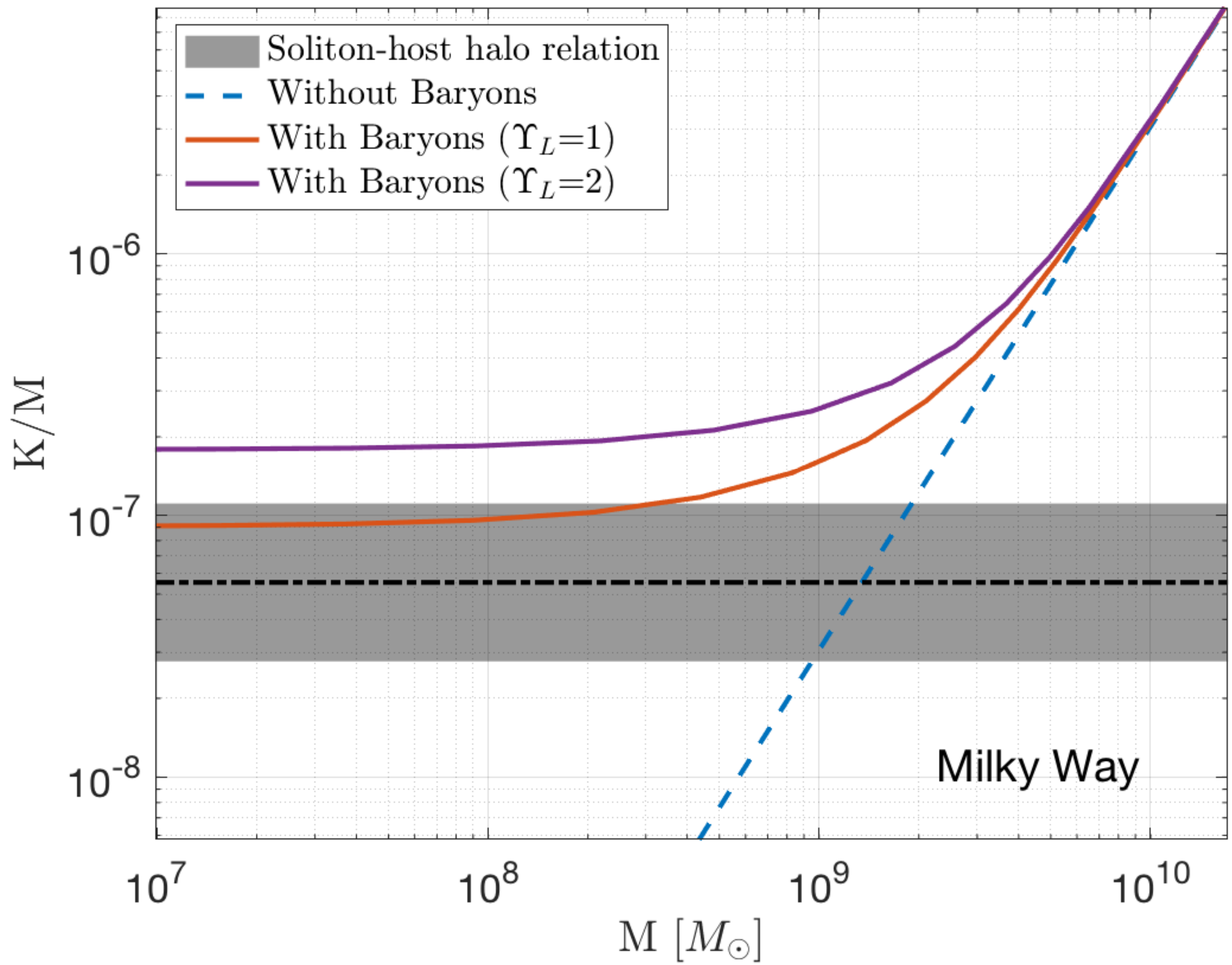
Soliton-host halo relation
Without Baryons
With Baryons (Υ_d=0.5)
With Baryons (Υ_d=1.07)
With Baryons (Υ_d=2.14)
UGC01281
K/M
M [$M_\odot$]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{7}
10^{8}
10^{9}

m=1e-22 eV

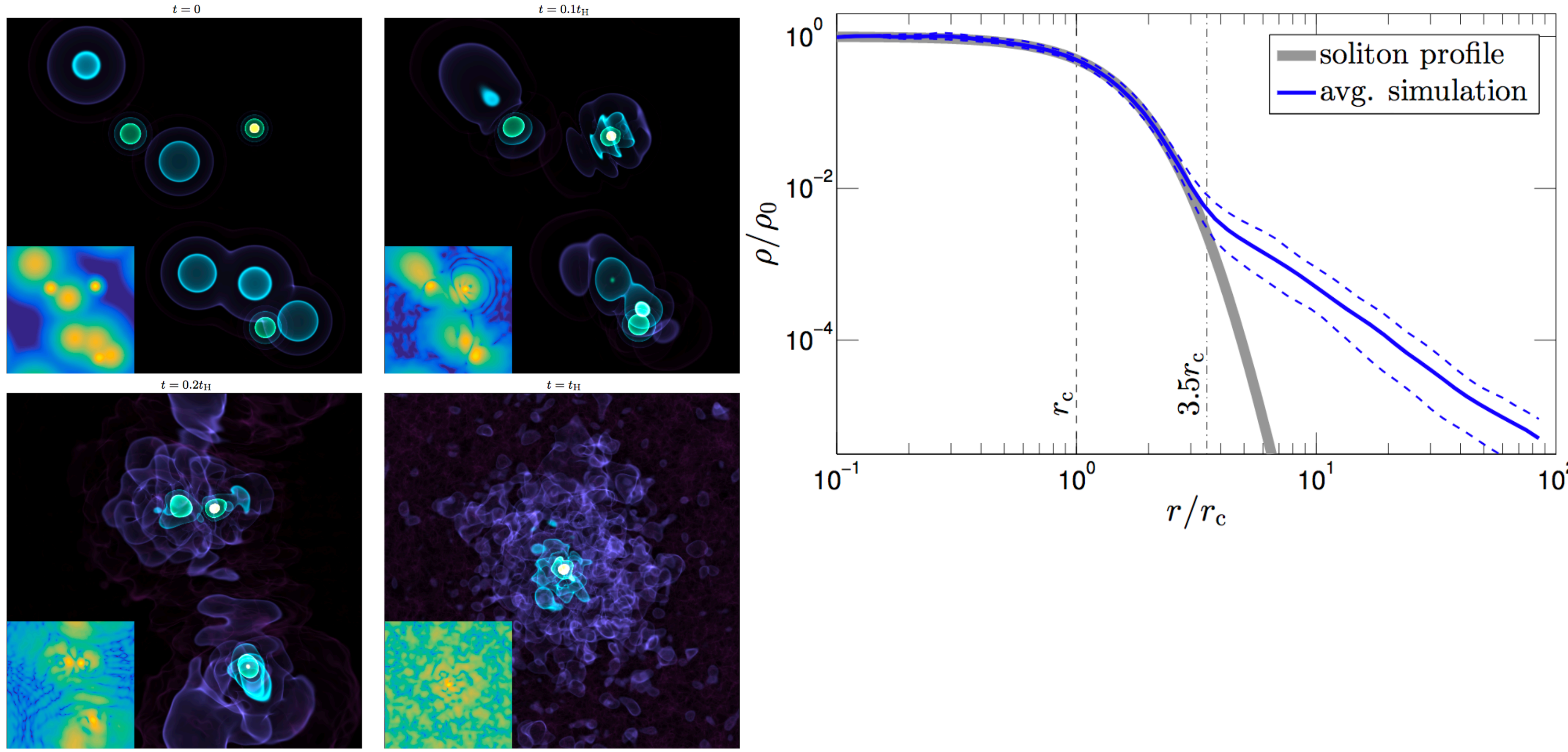


Soliton-host halo relation
Without Baryons
With Baryonic disk (Υ_d=0.12)
With Baryonic disk (Υ_d=0.24)
10^{-6}
10^{-7}
10^{-8}
K/M
F571-8
10^{6}
10^{8}
10^{10}
M $[M_\odot]$

The Milky Way is much more difficult



Mocz et al 1705.05845

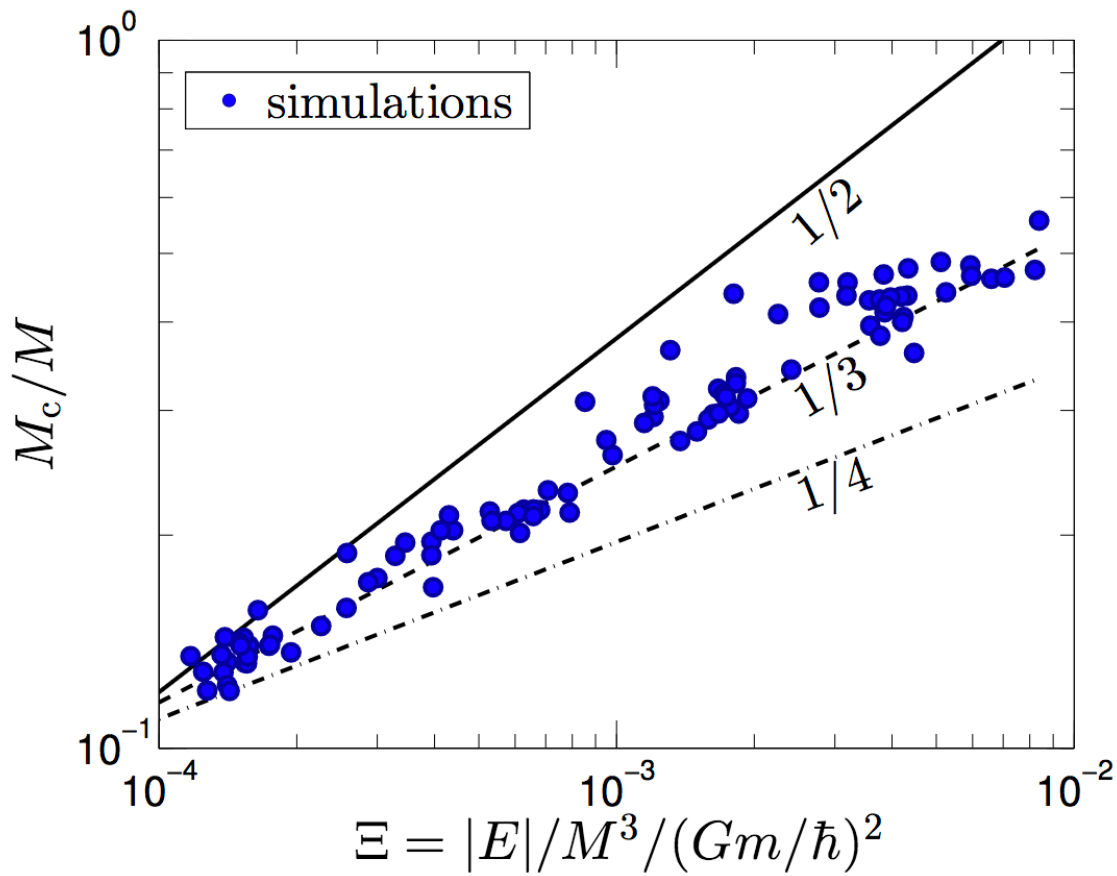


Mocz et al 1705.05845

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:

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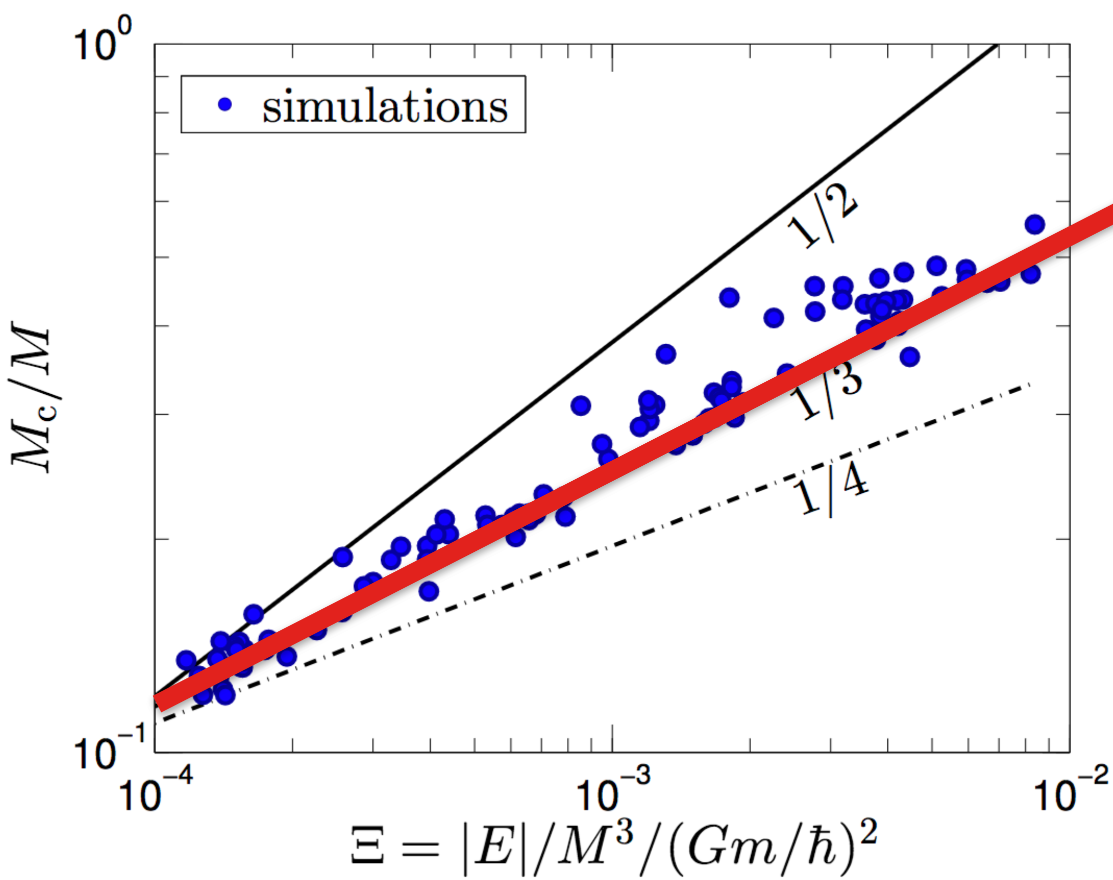

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This means that the total energy in the simulation box was eaten up by 1 soliton.

Should not apply to real galaxies above ~1e8 Msol

(initial conditions?)

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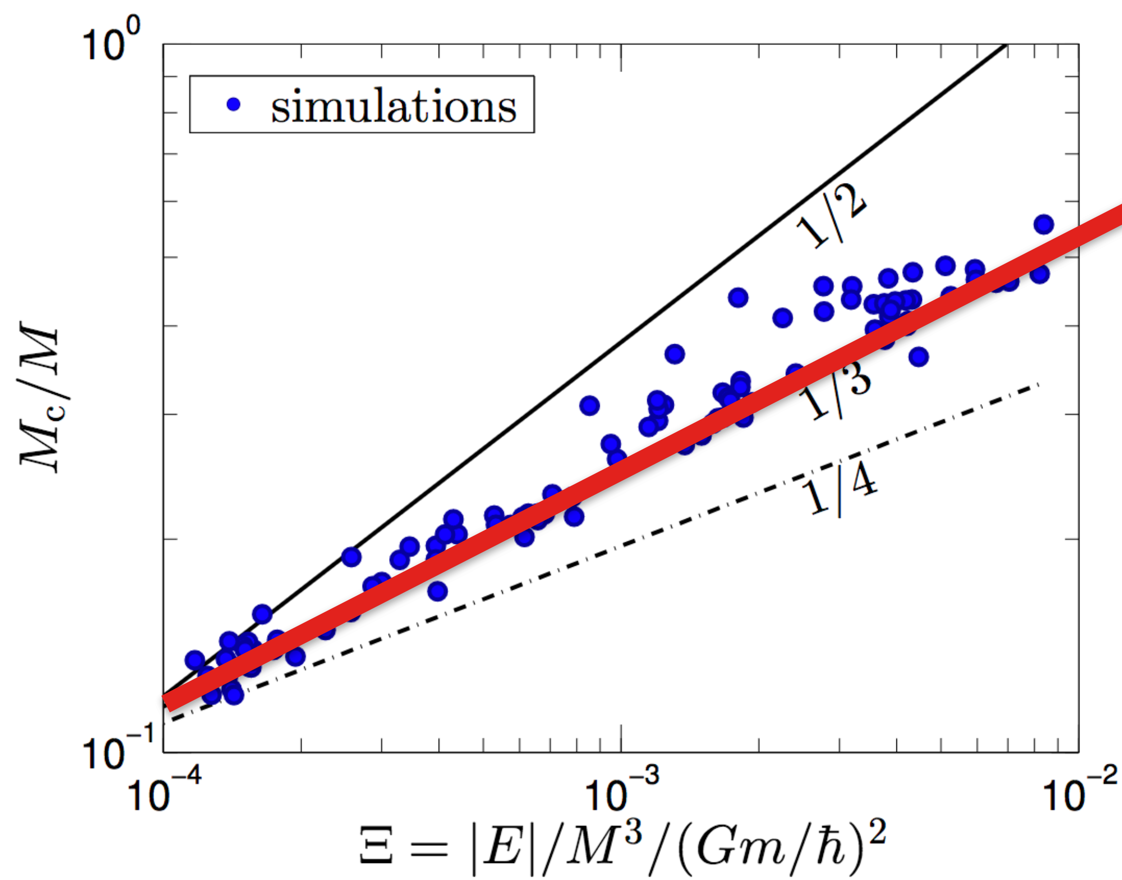
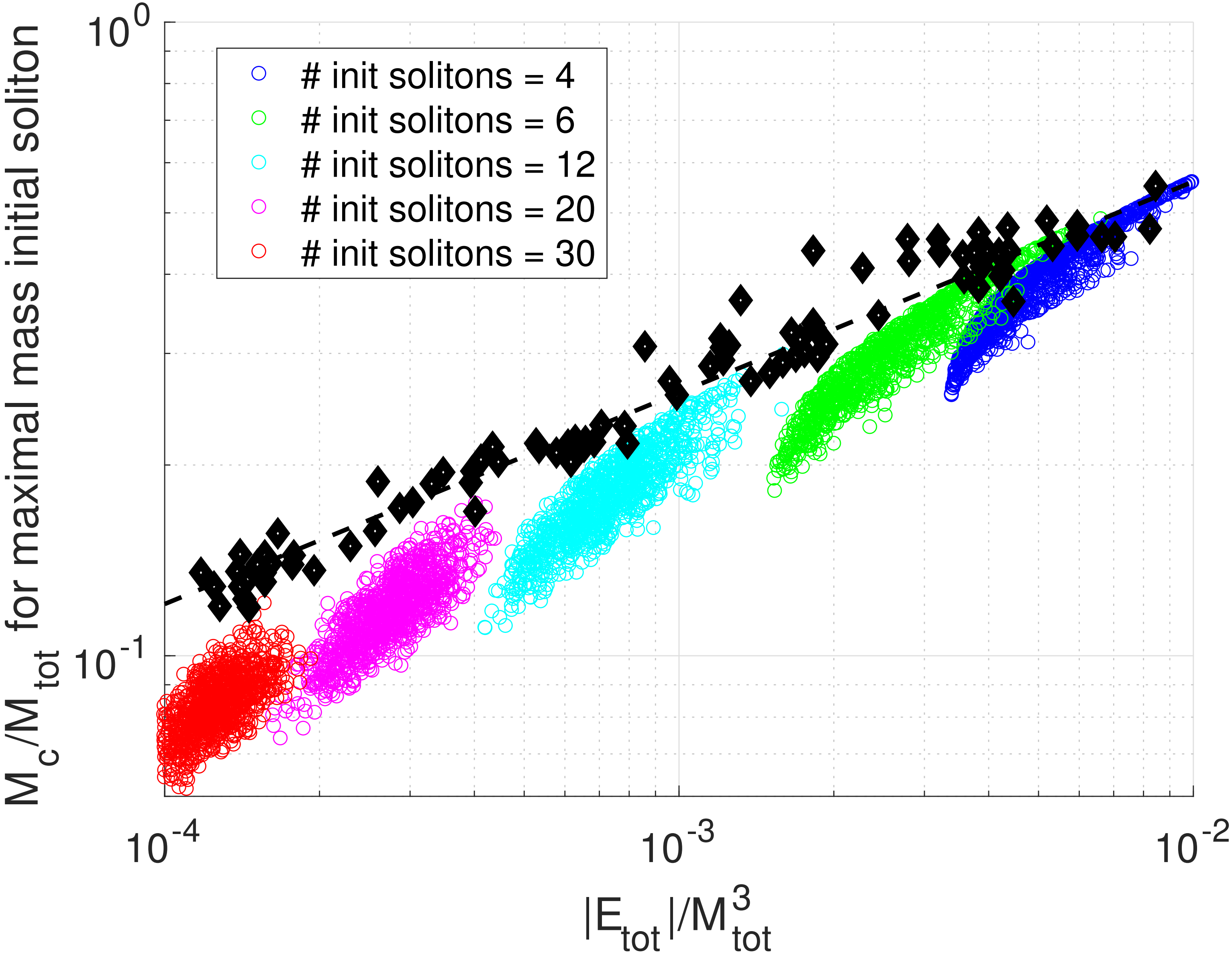
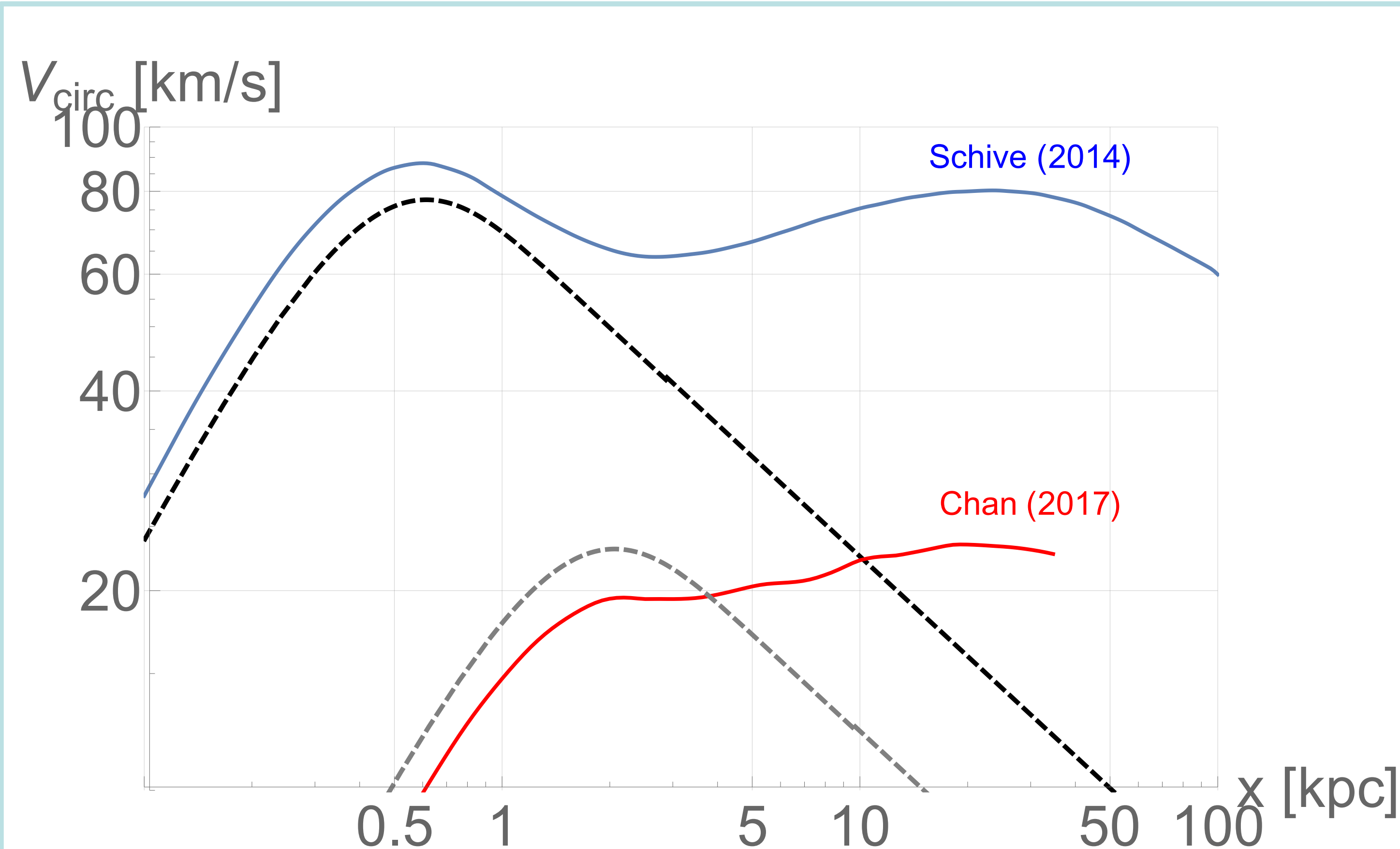




10^0
10^{-1}
10^{-4}
10^{-3}
10^{-2}
init solitons = 4
init solitons = 6
init solitons = 12
init solitons = 20
init solitons = 30
M_c/M_{tot} for maximal mass initial soliton
$|E_{tot}|/M_{tot}^3$

Rotation curves from simulations:

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



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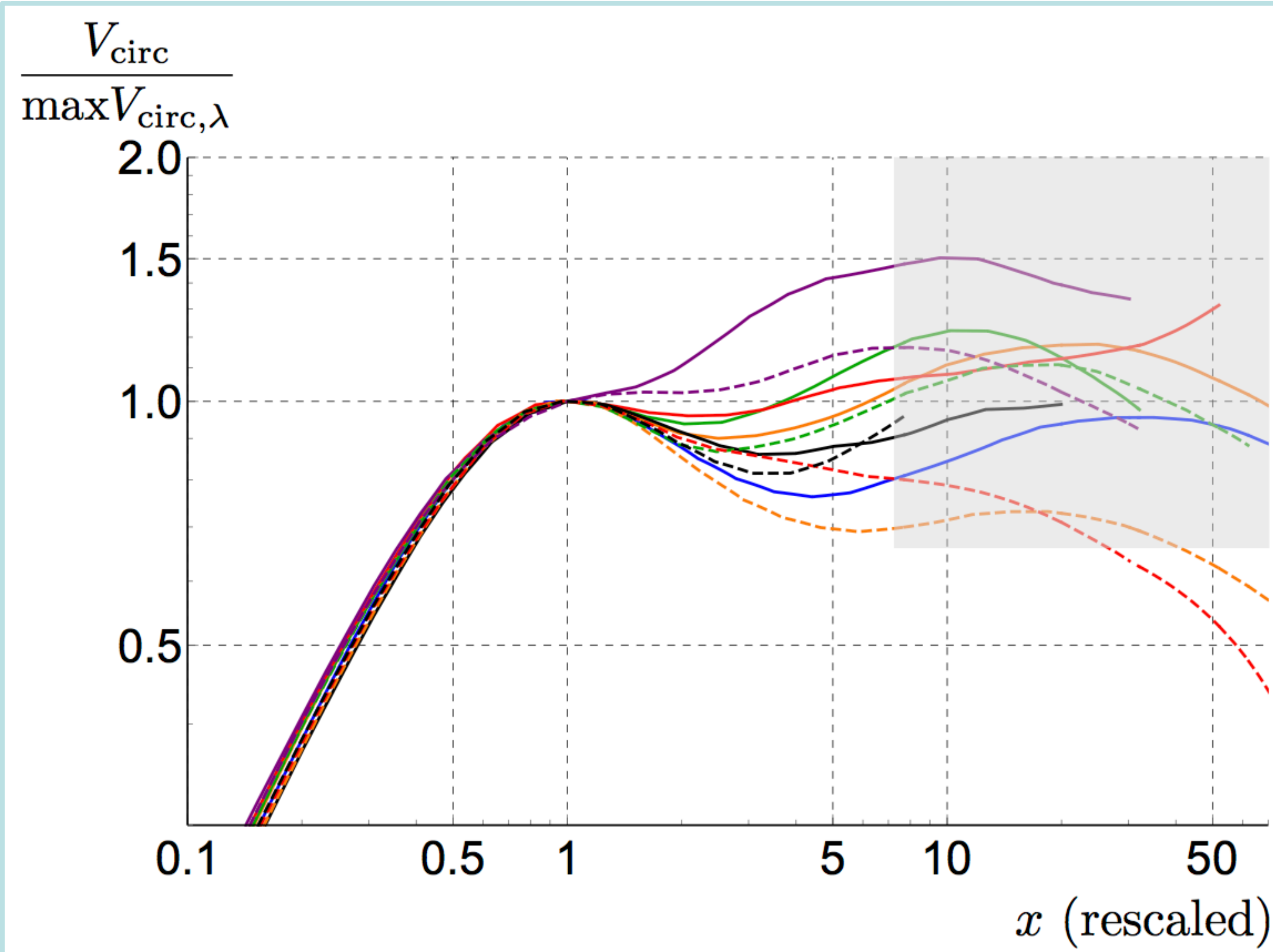


Non-gravitational interactions

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

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

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

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

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

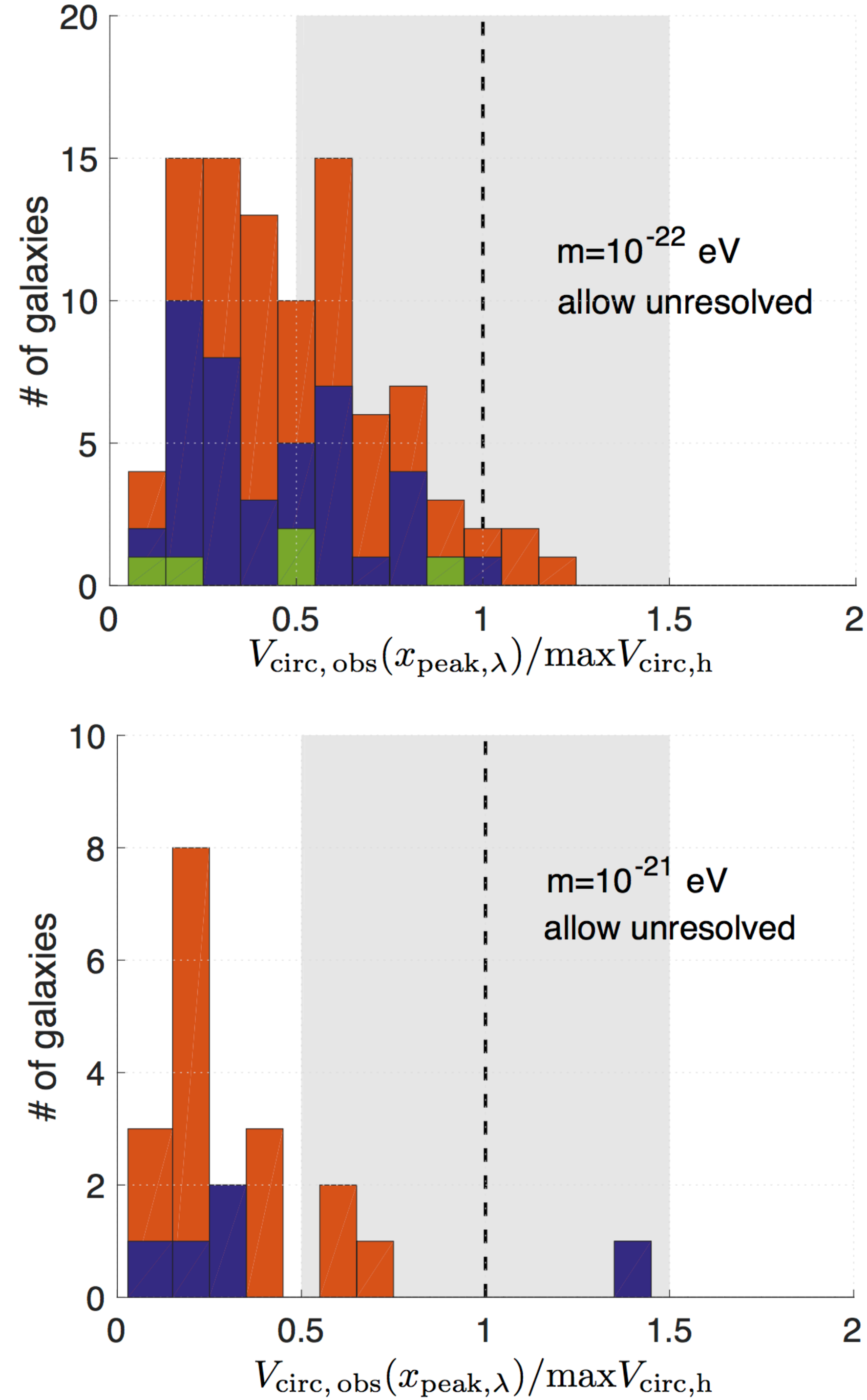
SPARC Lelli et al, 1606.09251
175 rotation curves

* 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



SPARC Lelli et al, 1606.09251
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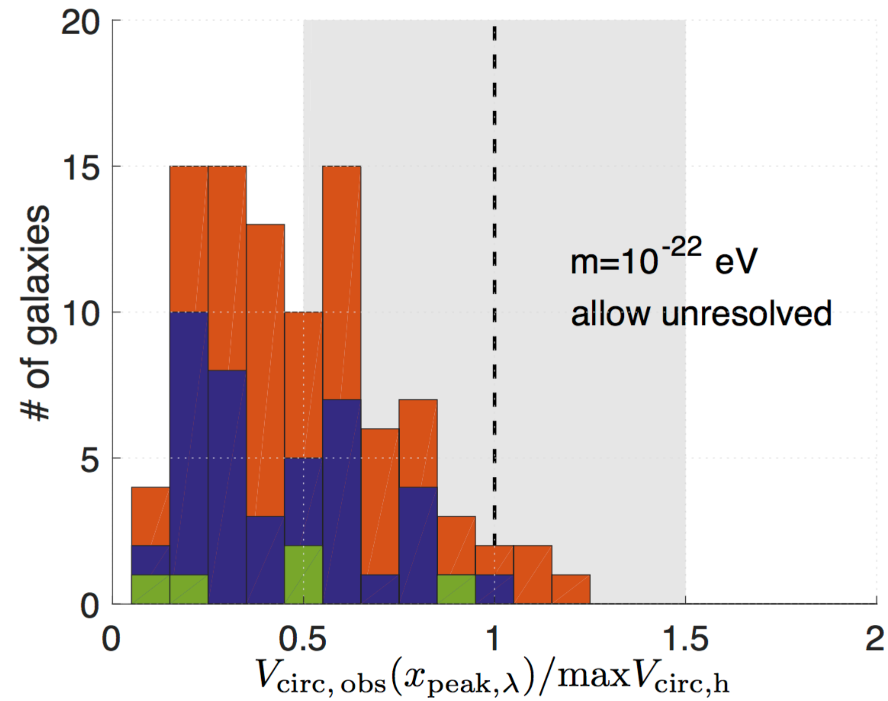
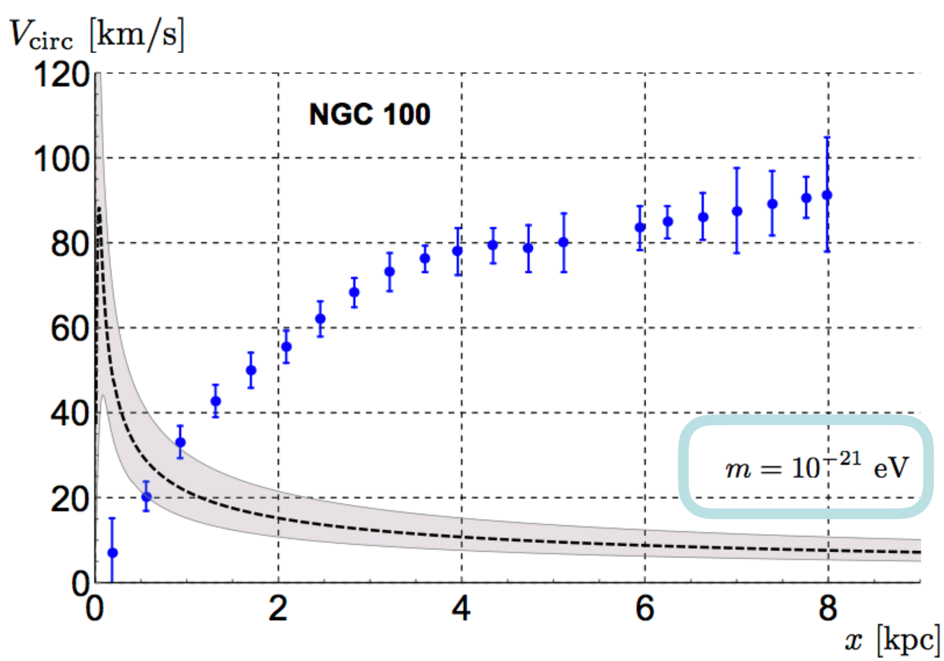
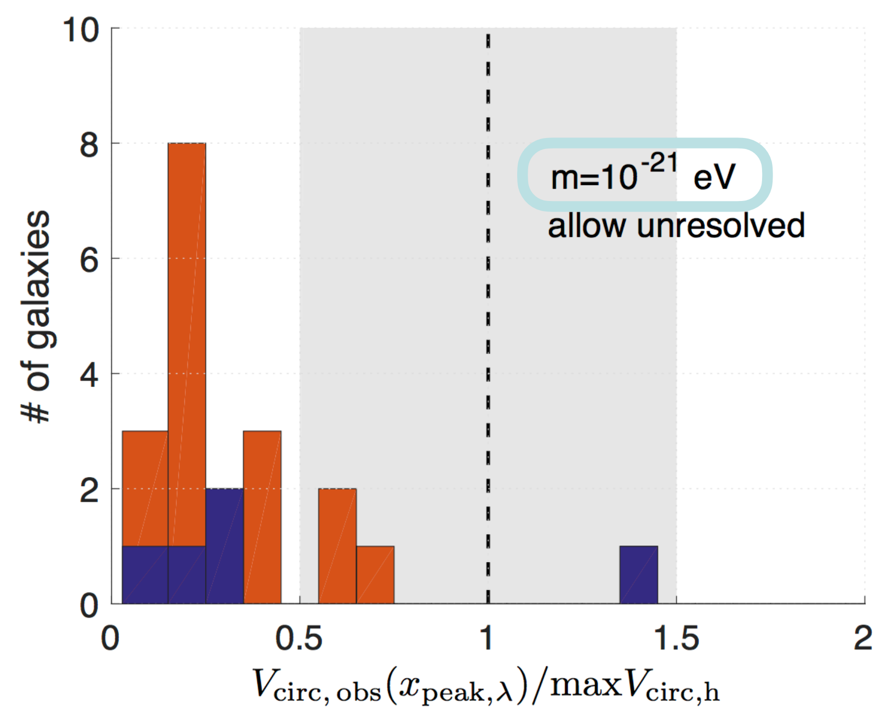
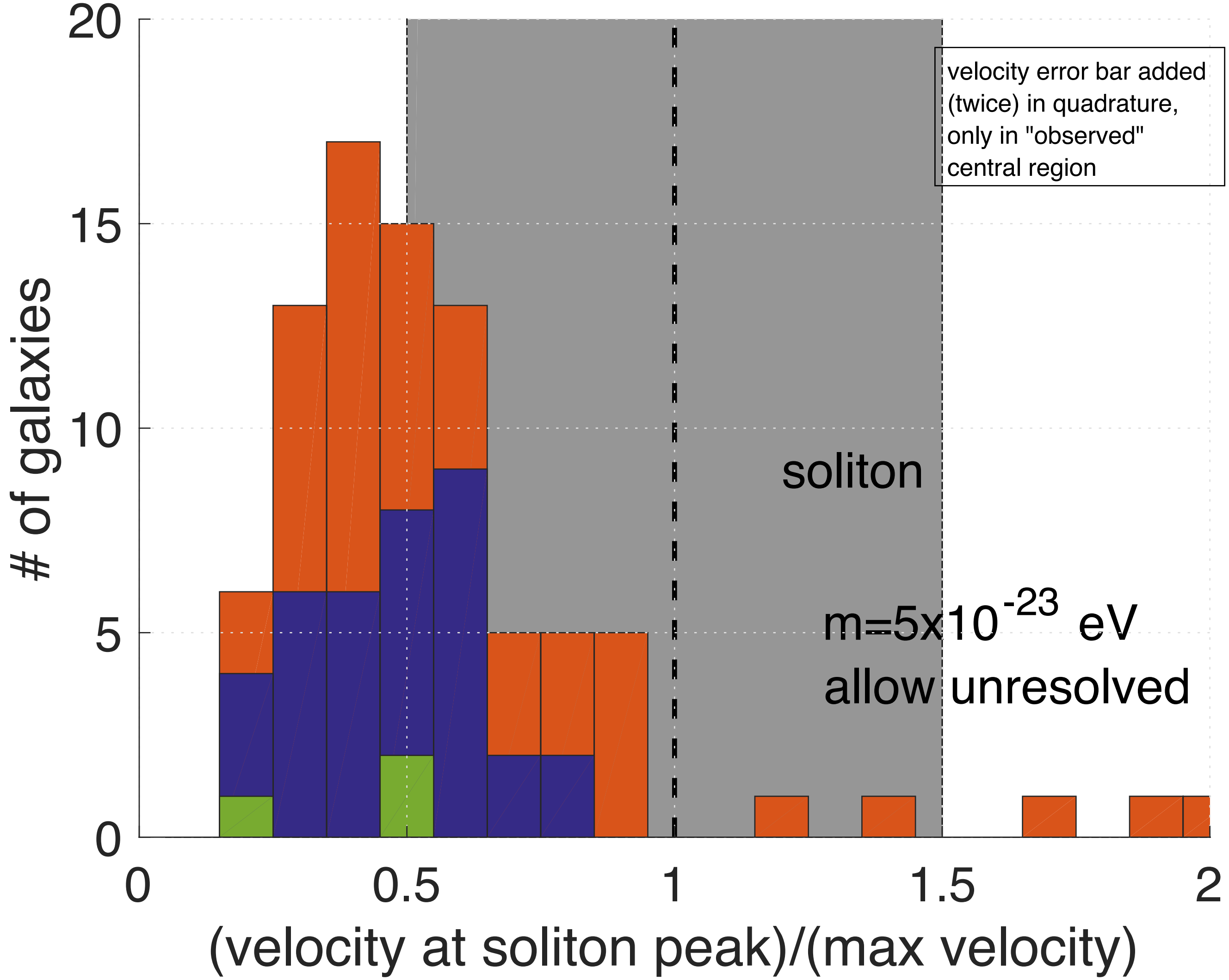






m = 5x10^-23 eV



20
15
10
5
0
# of galaxies
0
0.5
1
1.5
2
(velocity at soliton peak)/(max velocity)
velocity error bar added (twice) in quadrature, only in "observed" central region
soliton
m=5x10^-23 eV
allow unresolved

Consider a halo with an NFW density profile

$$\rho_{NFW}(x) = \frac{\rho_c \delta_c}{\frac{x}{R_s}\left(1 + \frac{x}{R_s}\right)^2},$$

where

$$\rho_c(z) = \frac{3H^2(z)}{8\pi G}, \quad \delta_c = \frac{200}{3} \frac{c^3}{\ln(1+c) - \frac{c}{1+c}}.$$

$$\frac{E}{M}\Big|_{\text{halo}} \approx \frac{\tilde{c}}{4} \Phi_h,$$

$$\tilde{c} = \frac{c - \ln(1+c)}{(1+c)\ln(1+c) - c}$$

NFW halo gravitational potential:

$$\Phi_{NFW}(x) = -\frac{4\pi G \rho_c \delta_c R_s^3}{x} \ln\left(1 + \frac{x}{R_s}\right)$$

$$\Phi_{NFW}(x \ll R_s) \approx \Phi_h$$

soliton—host halo relation says:

$$\frac{E_\lambda}{M_\lambda} \approx \frac{\tilde{c}}{4}\Phi_h$$

$$\frac{E}{M}\Big|_{\rm halo} \approx \frac{\tilde{c}}{4}\,\Phi_h,$$

$$\tilde{c} = \frac{c - \ln(1+c)}{(1+c)\ln(1+c) - c}$$

soliton—host halo relation says:

$$-0.23\,\lambda^2 \approx \frac{E_\lambda}{M_\lambda} \approx \frac{\tilde{c}}{4}\Phi_h$$

Which fixes the soliton scale parameter.

$$\frac{E}{M}\Big|_{\rm halo} \approx \frac{\tilde{c}}{4}\,\Phi_h,$$

$$\tilde{c} = \frac{c - \ln(1+c)}{(1+c)\ln(1+c) - c}$$

soliton—host halo relation says:

$$-0.23\,\lambda^2 \approx \frac{E_\lambda}{M_\lambda} \approx \frac{\tilde{c}}{4}\Phi_h$$

$$\frac{E}{M}\Big|_{\rm halo} \approx \frac{\tilde{c}}{4}\,\Phi_h,$$

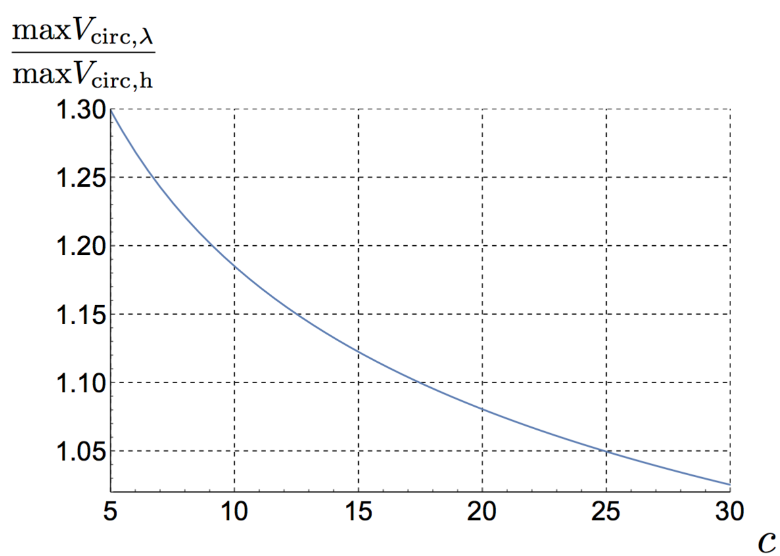
$$\tilde{c} = \frac{c - \ln(1+c)}{(1+c)\ln(1+c) - c}$$

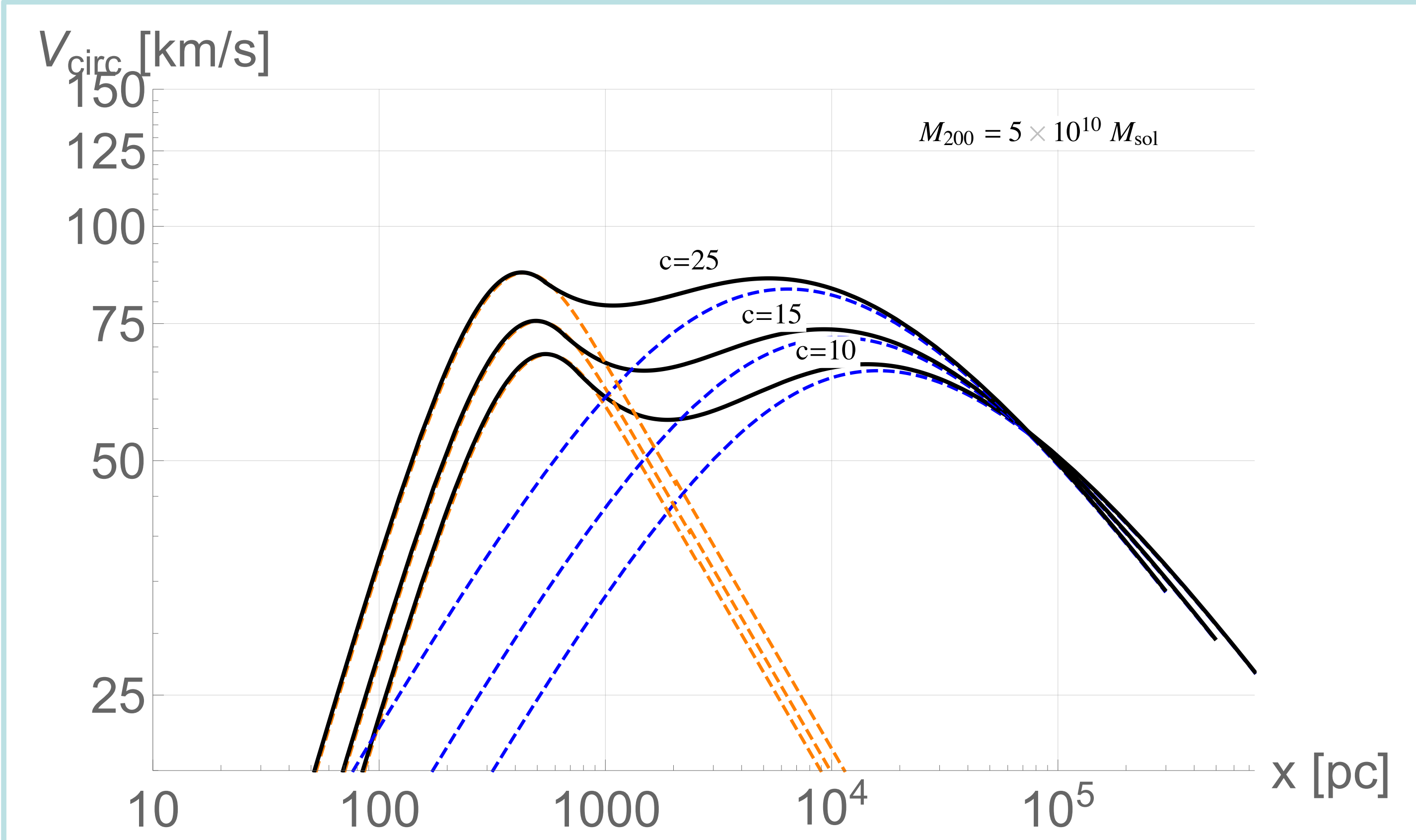
Which fixes the soliton scale parameter.

Equal specific energy ==> equal specific kinetic energy

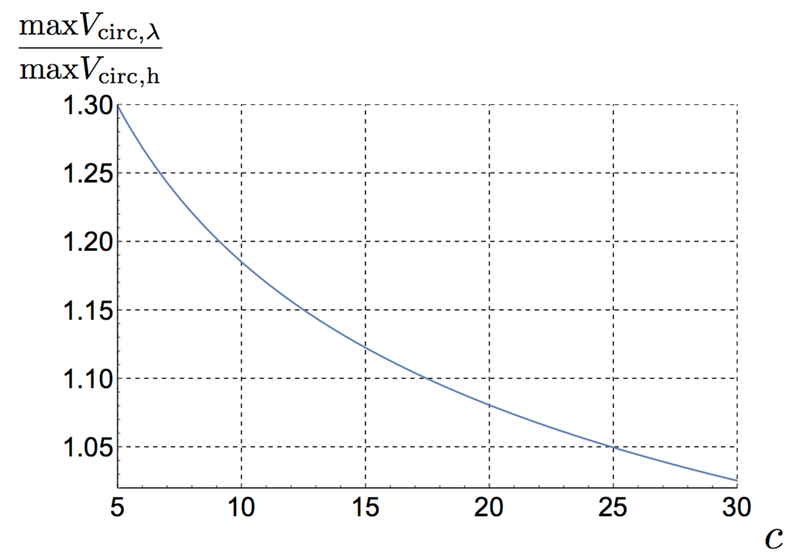
==> ~equal peak rotation velocity

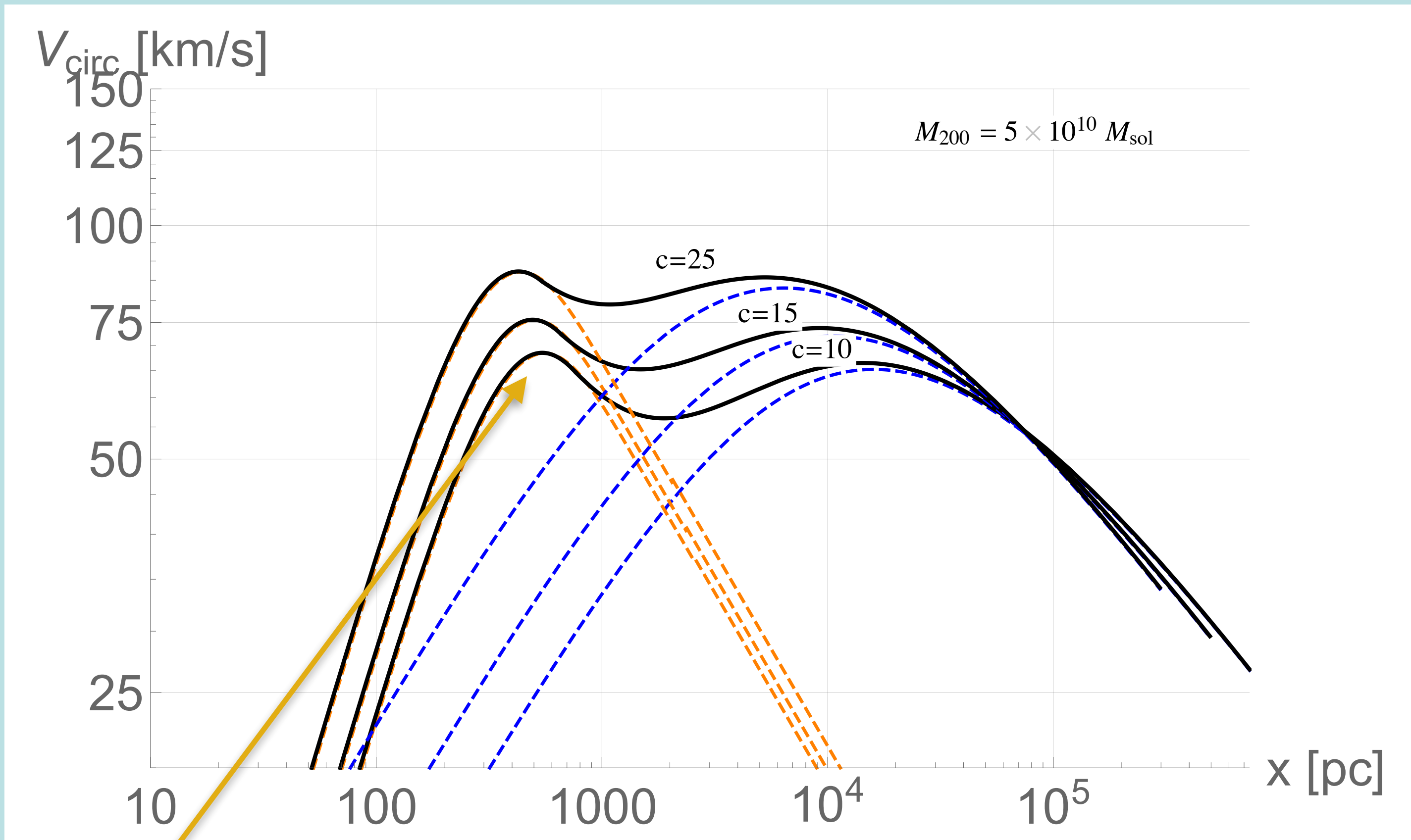
$$\frac{\max V_{\rm circ,\lambda}}{\max V_{\rm circ,h}} \approx 1.1\left(\frac{\tilde{c}}{0.4}\right)^{\frac{1}{2}}$$



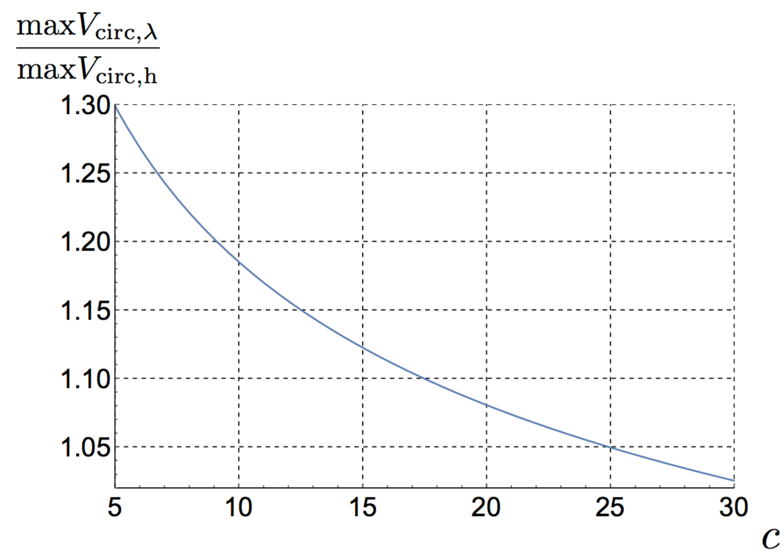


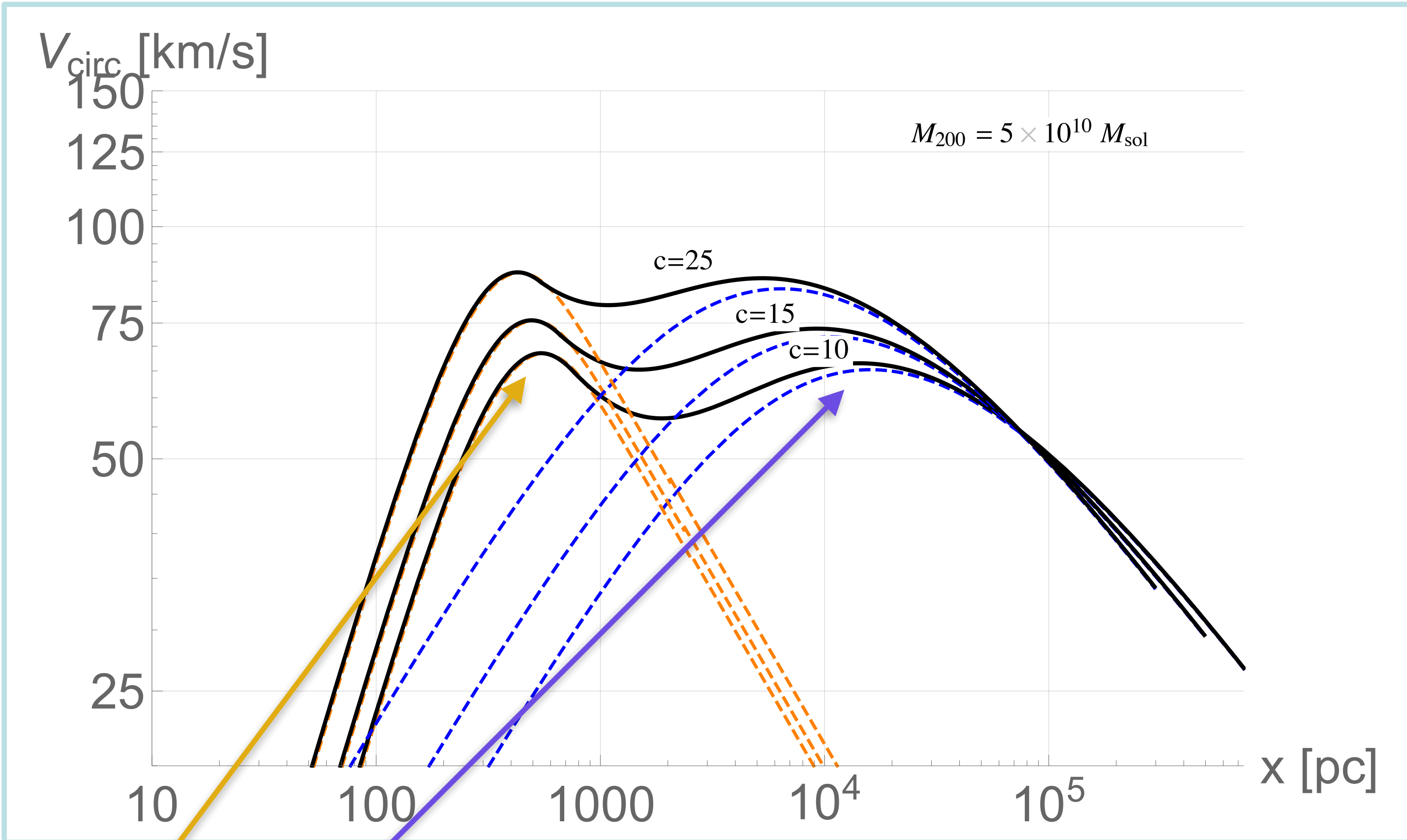
$$\frac{\max V_{\mathrm{circ},\lambda}}{\max V_{\mathrm{circ,h}}} \approx 1.1 \left(\frac{\tilde{c}}{0.4} \right)^{\frac{1}{2}}$$



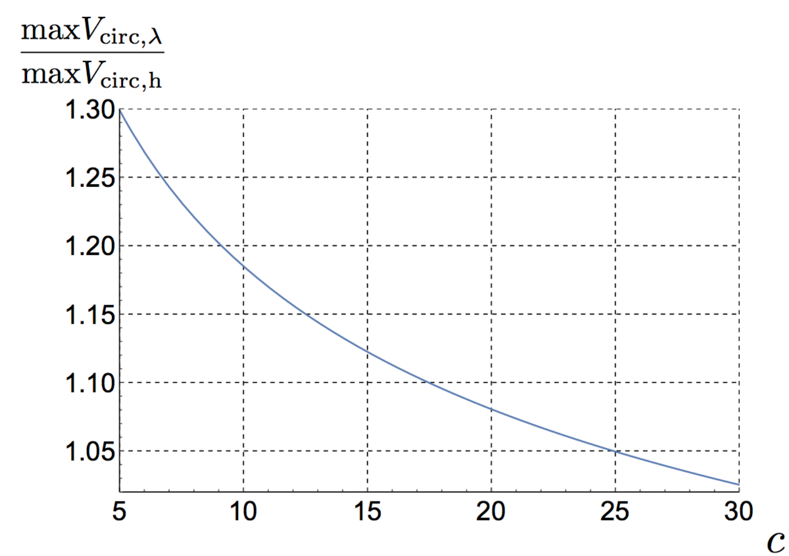


$$\frac{\max V_{\mathrm{circ},\lambda}}{\max V_{\mathrm{circ,h}}} \approx 1.1 \left(\frac{\tilde{c}}{0.4}\right)^{\frac{1}{2}}$$

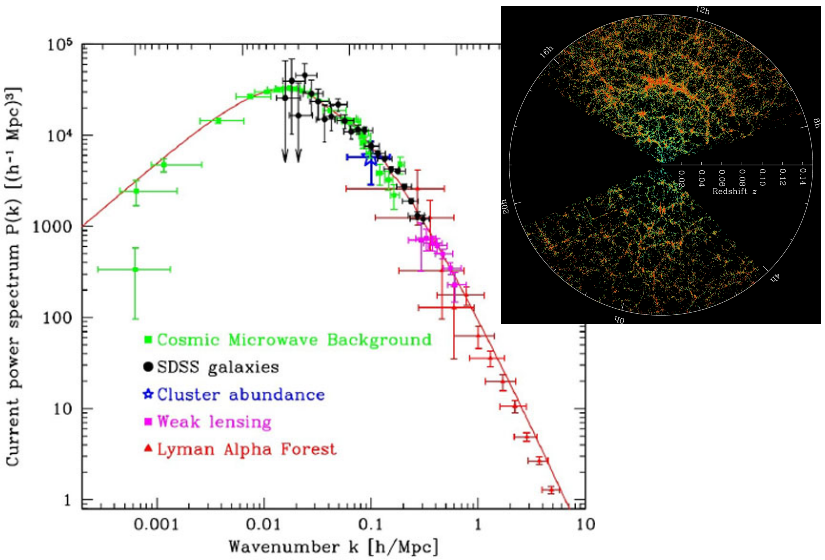


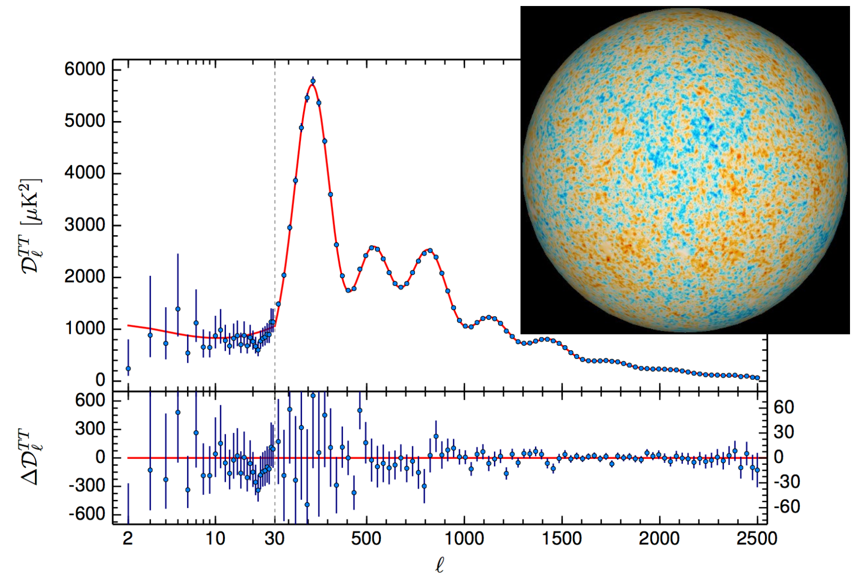


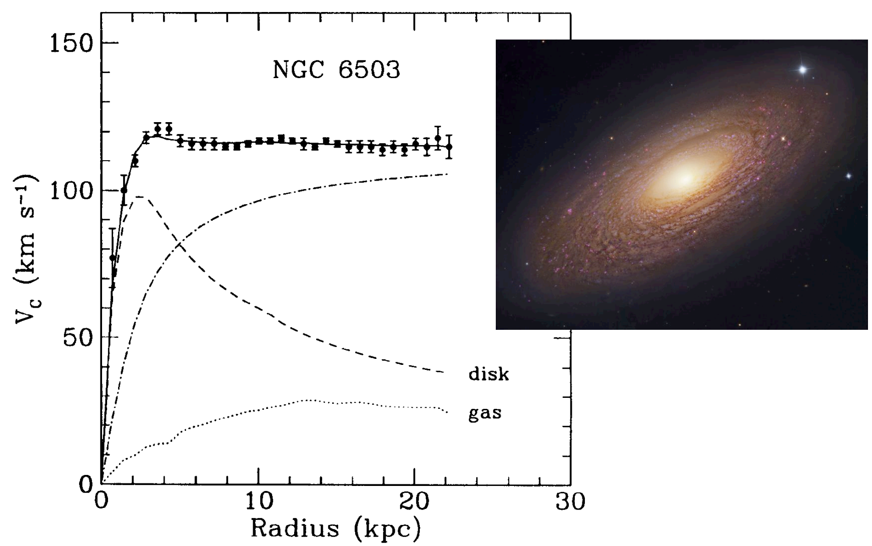
$$\frac{\max V_{\mathrm{circ},\lambda}}{\max V_{\mathrm{circ,h}}} \approx 1.1 \left(\frac{\tilde{c}}{0.4}\right)^{\frac{1}{2}}$$

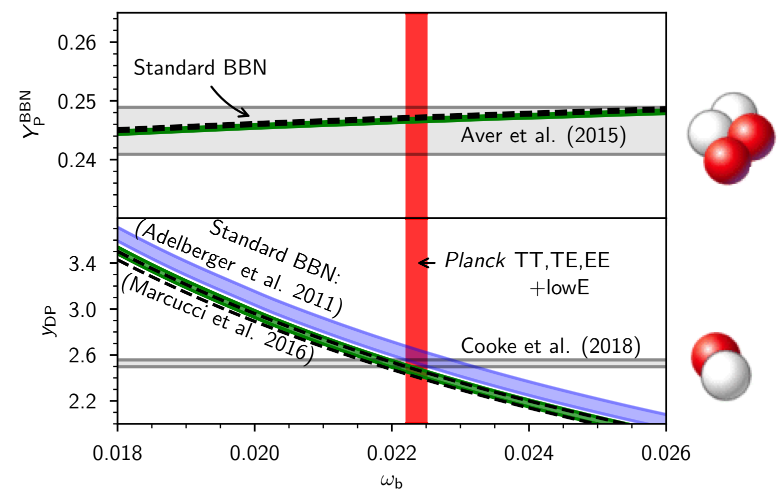


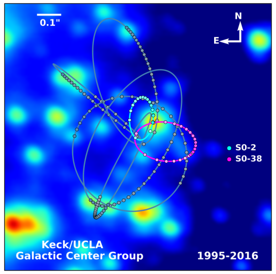
Evidence for DM is gravitational: a huge problem. Naturally, our efforts are diverging.

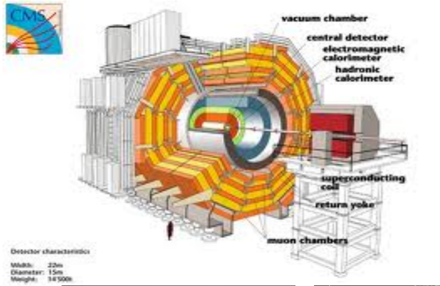


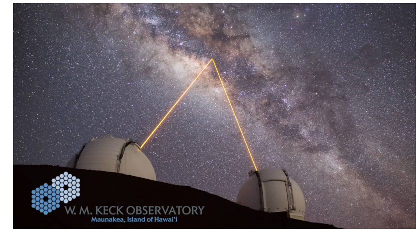


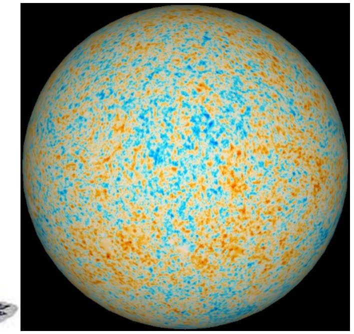


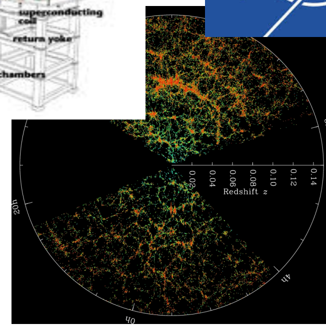


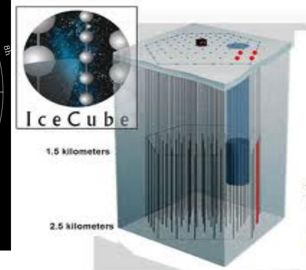

0.1"
N
E
S0-2
S0-38
Keck/UCLA
Galactic Center Group
1995-2016

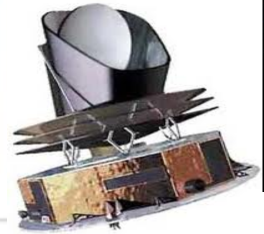

CMS
vacuum chamber
central detector
electromagnetic calorimeter
hadronic calorimeter
superconducting coil
return yoke
muon chambers
Detector characteristics

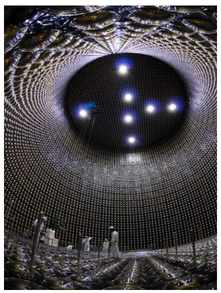

W. M. KECK OBSERVATORY
Maunakea, Island of Hawai'i



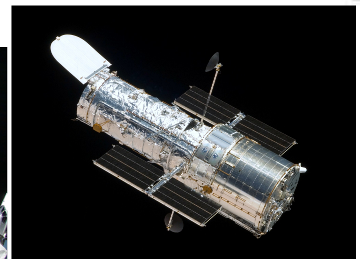

Redshift z
0.02
0.04
0.06
0.08
0.10
0.12
0.14

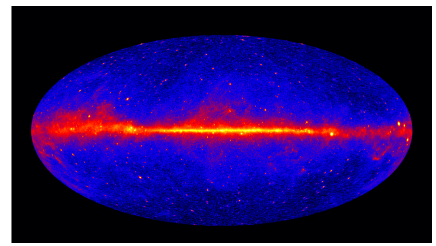

IceCube
1.5 kilometers
2.5 kilometers

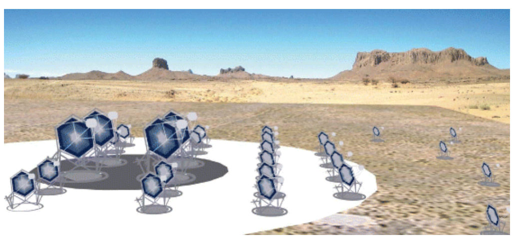


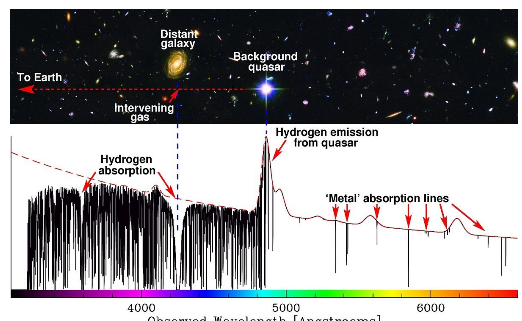


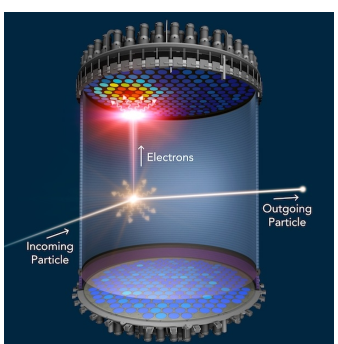

AMS

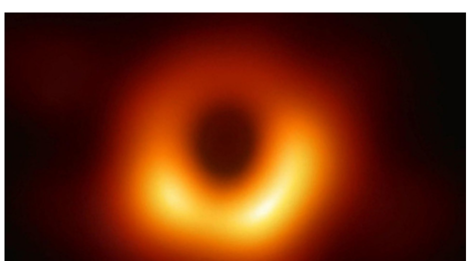


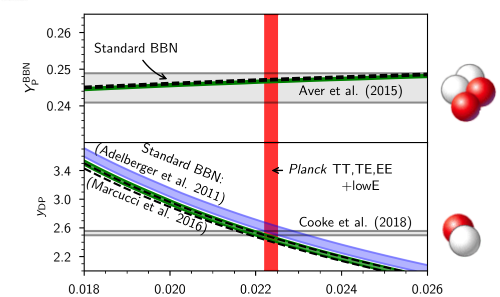


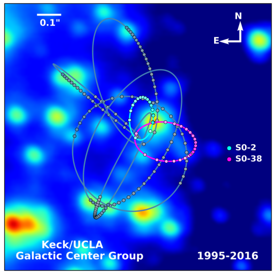


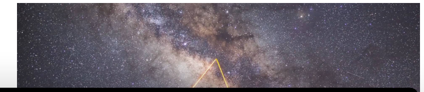

To Earth
Distant galaxy
Background quasar
Intervening gas
Hydrogen emission from quasar
Hydrogen absorption
'Metal' absorption lines
4000
5000
6000
Observed Wavelength [Angstroems]

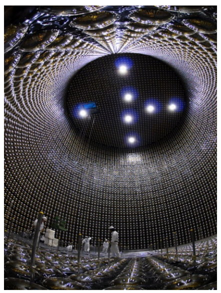

Electrons
Outgoing Particle
Incoming Particle

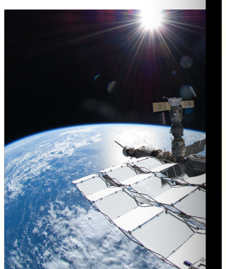


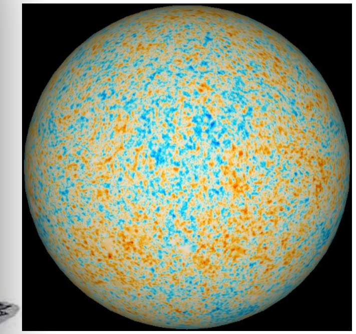

Standard BBN
Aver et al. (2015)
Standard BBN:
(Adelberger et al. 2011)
(Marcucci et al. 2016)
Planck TT,TE,EE +lowE
Cooke et al. (2018)
0.26
0.25
0.24
3.4
3.0
2.6
2.2
0.018
0.020
0.022
0.024
0.026

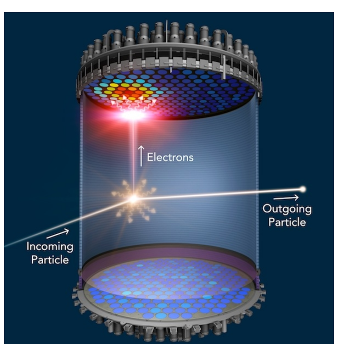


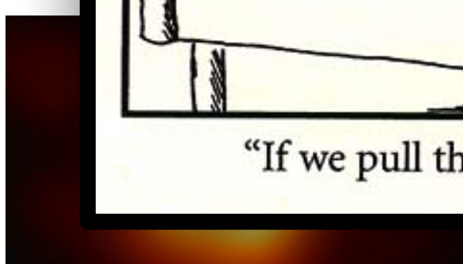


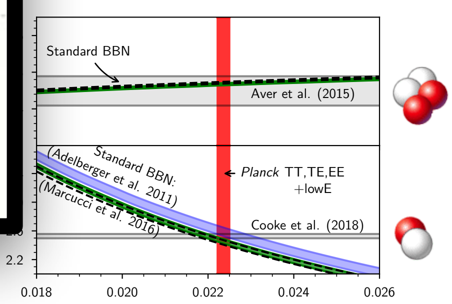


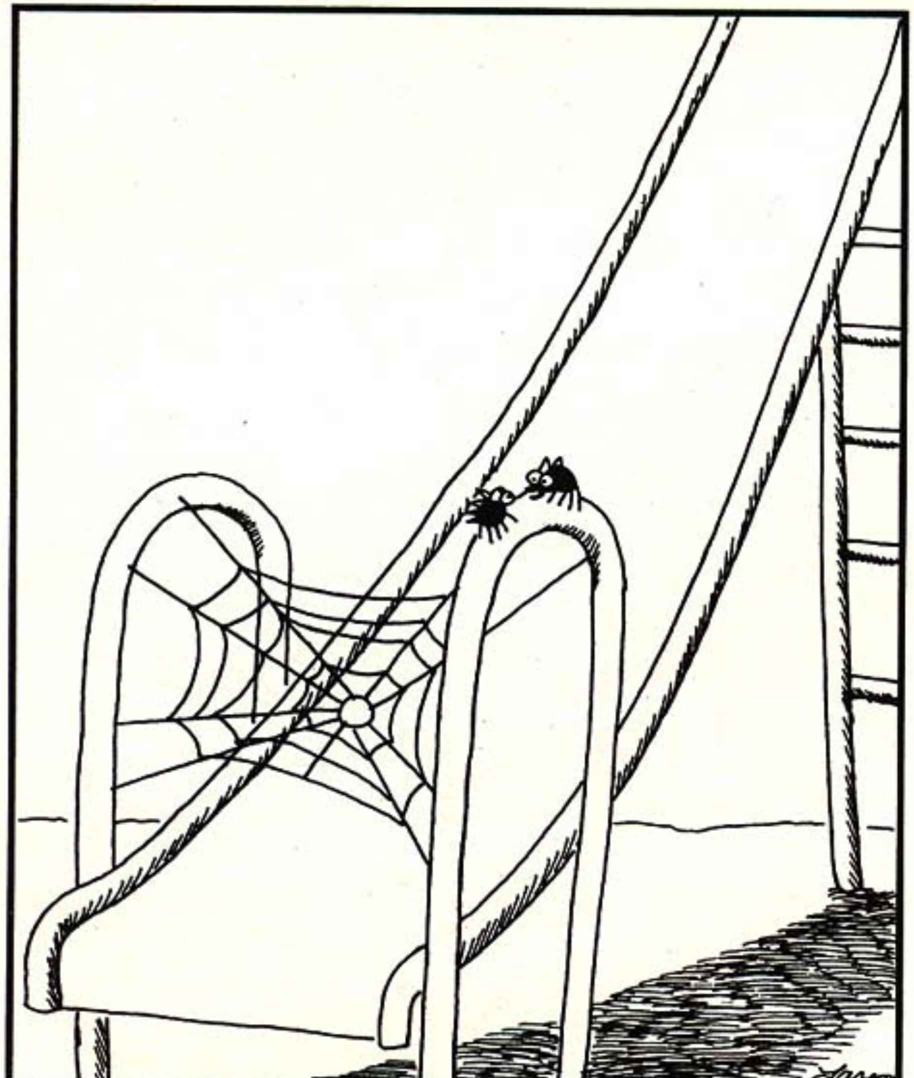












"If we pull this off, we'll eat like kings."