REVISITING THE LOWER BOUND ON FERMIONIC DM MASS FROM DSPHS

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Phase space mass bound for fermionic dark matter from dwarf spheroidal galaxies

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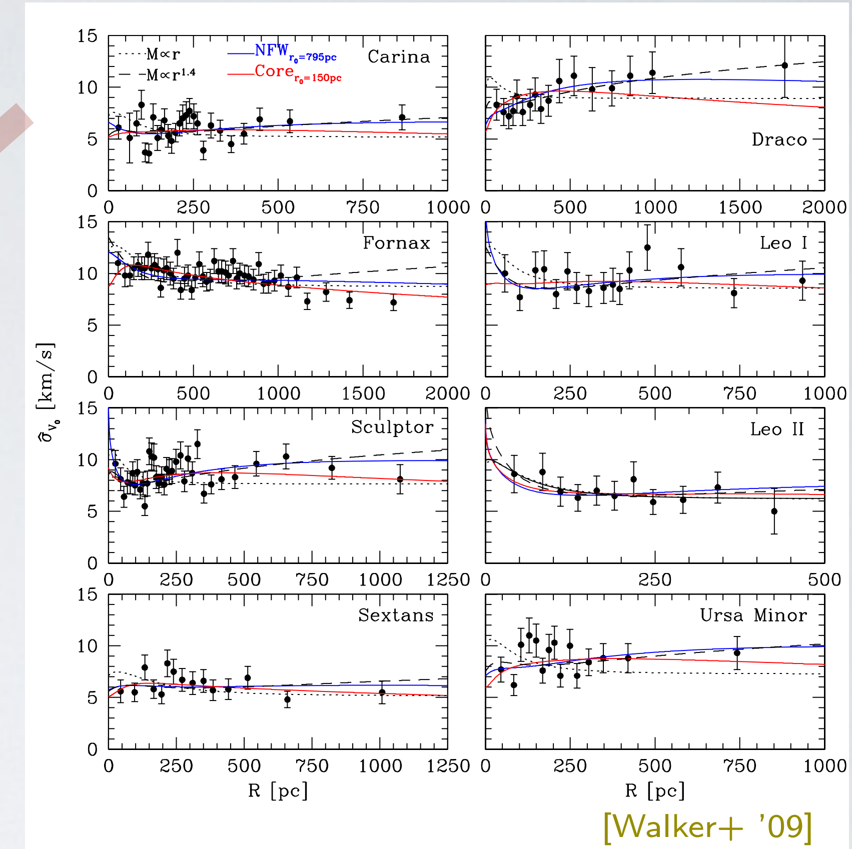
We reconsider the lower bound on the mass of a fermionic dark matter (DM) candidate resulting from the existence of known small Dwarf Spheroidal galaxies, in the hypothesis that their DM halo is constituted by degenerate fermions, with phase-space density limited by the Pauli exclusion

[arXiv:1704.06644]

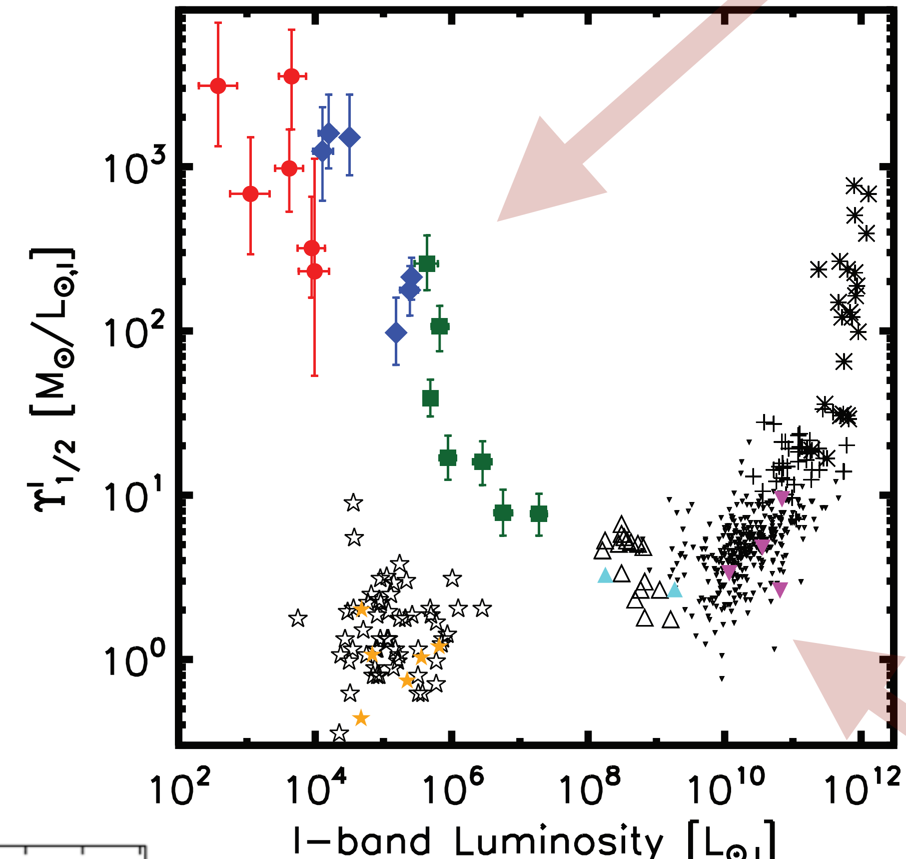
Self-Interacting Dark Matter workshop — NBI, August 4th, 2017

REDUNDANT SLIDE

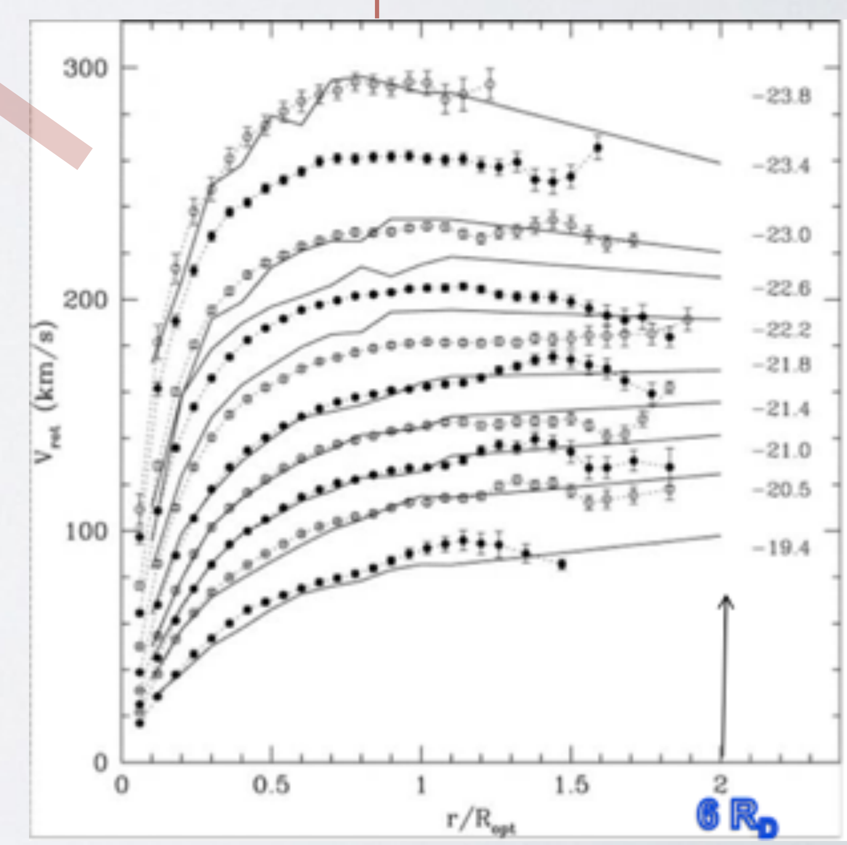
Dwarf Spheroidals

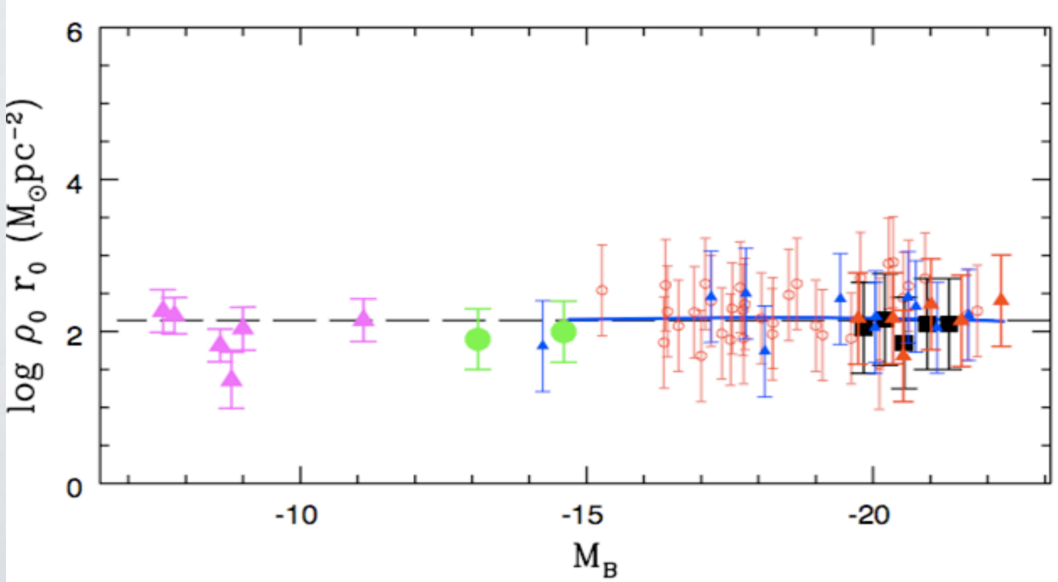


- Mass-to-Light ratio
  striking evidence of DM
- (Globular Clusters likely rule out modifications of gravity for DM)
- Cored profile preferred for small galaxies. . . ?



Spirals





Fits with Burkert:

Constant surface density

$\leftarrow \quad \Sigma_0 = \rho_0 r_0 \simeq 120 M_\odot/\mathrm{pc}^2$

(over many magnitudes !?)

HYPOTHESIS OF DEGENERATE FERMIONS IN DARK MATTER HALOS

- Pauli exclusion can forbid a central density cusp

  …can explain cored profiles

  The largest density is observed in smallest systems, so

  need to focus on the smallest dwarf galaxies

  Dwarf galaxies, dark matter dominated, would be

  quantum degenerate spheres of fermi particles (10^{70} of them)

  The particle mass is bounded from below, *à la* Tremaine-Gunn

[Tremaine-Gunn'79, … Gerhard-Spergel '92,…,Chavanis+ '97, Bilić+ '99, Boyarski+ '09…,Destri DeVega Sanchez '13; Domcke-Urbano '15]

AUTO GRAVITATING FERMION GAS

Spherical symmetry, isothermal. $\phi(r)$: average gravitational potential

Fermi Dirac Statistics:

$$\rho(r) = mn(r) = \frac{gm}{2\pi^2\hbar^3}\int_0^\infty p^2\,dp\,f\left[\frac{p^2}{2m} - \mu(r)\right]$$

$$f_{FD}(E) = \frac{1}{1 + exp(E/T_0)}$$

Poisson equation

$$\begin{cases} \dfrac{d\phi(r)}{dr} = G\dfrac{M(r)}{r^2} \\ \dfrac{dM(r)}{dr} = 4\pi r^2 \rho(r) \end{cases}$$

r-dependent chemical potential:

$$\mu(r) = \mu_0 - m\phi(r)$$

Thomas-Fermi Equation

$$\frac{d^2\mu}{dr^2} + \frac{2}{r}\frac{d\mu}{dr} = -4\pi G m\rho(r) = -\frac{2gGm^2}{\pi\hbar^3}\int_0^\infty dp\,p^2 f\left[\frac{p^2}{2m} - \mu(r)\right]$$

b.c. $\begin{cases} \dfrac{d\mu}{dr}(0) = 0 \\ \mu(0) \end{cases}$ $\mu(0)$ free parameter: degeneracy at origin

THOMAS FERMI - DIMENSIONLESS

$$r = l_0\,\xi \quad , \quad \mu(r) = T_0\,\nu(\xi) \qquad y = p/\sqrt{2mT_0}$$

$$l_0 = \frac{\hbar}{\sqrt{8G}}\left(\frac{2}{g}\right)^{\frac{1}{3}}\left[\frac{9\pi I_2(\nu_0)}{m^8\rho_0}\right]^{\frac{1}{6}} = R_0\left(\frac{2\,keV}{m}\right)^{\frac{4}{3}}\left(\frac{2}{g}\right)^{\frac{1}{3}}\left[\frac{I_2(\nu_0)}{\rho_0}\frac{M_\odot}{pc^3}\right]^{\frac{1}{6}} \qquad R_0 = 7.425\,pc$$

$$\frac{d^2\nu}{d\xi^2} + \frac{2}{\xi}\frac{d\nu}{d\xi} = -I_2(\nu) \qquad I_2(\nu) = 3\int_0^\infty y^2\,dy\,\Psi(y^2-\nu)$$

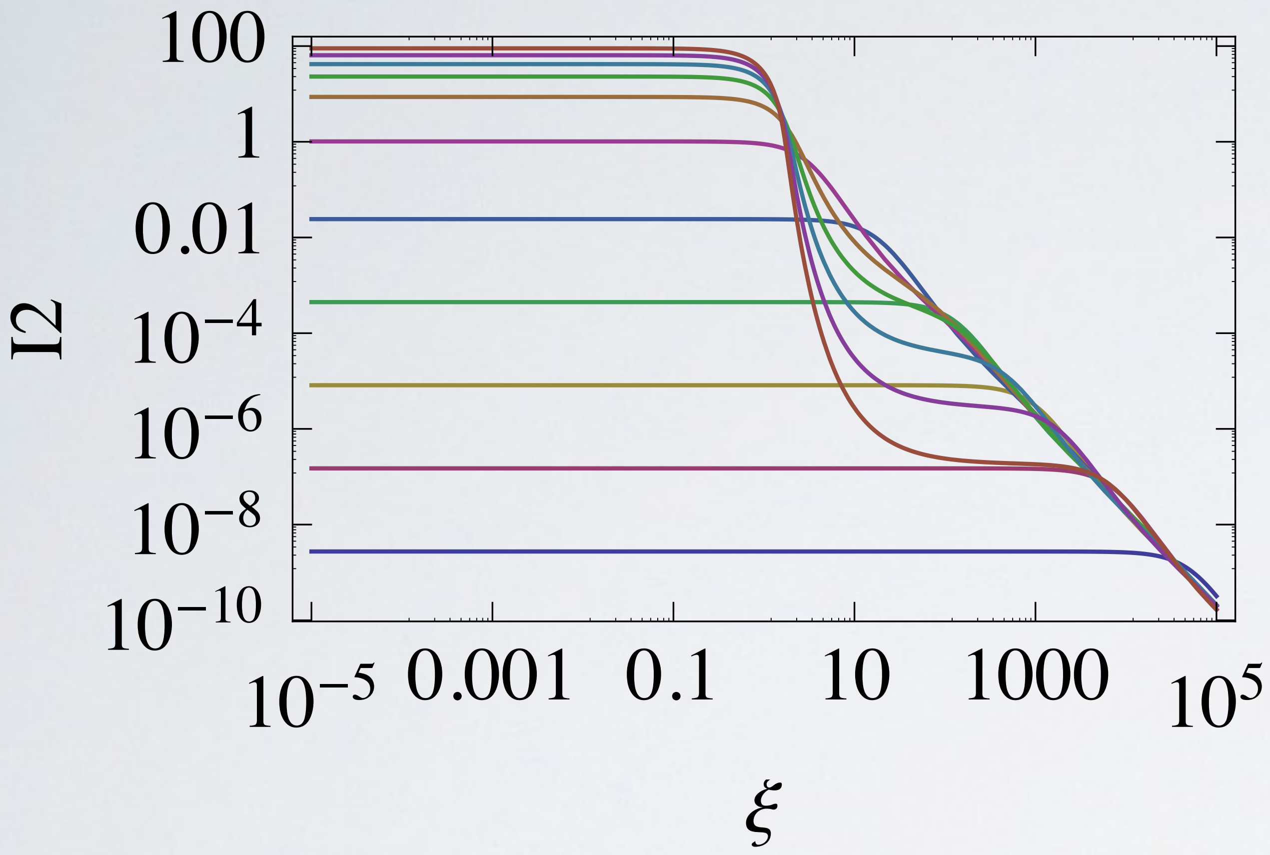
b.c. $\begin{cases} \nu'(0) = 0 \\ \nu_0 \end{cases}$ only one free parameter

determines the dimensionless potential $\nu(\xi)$

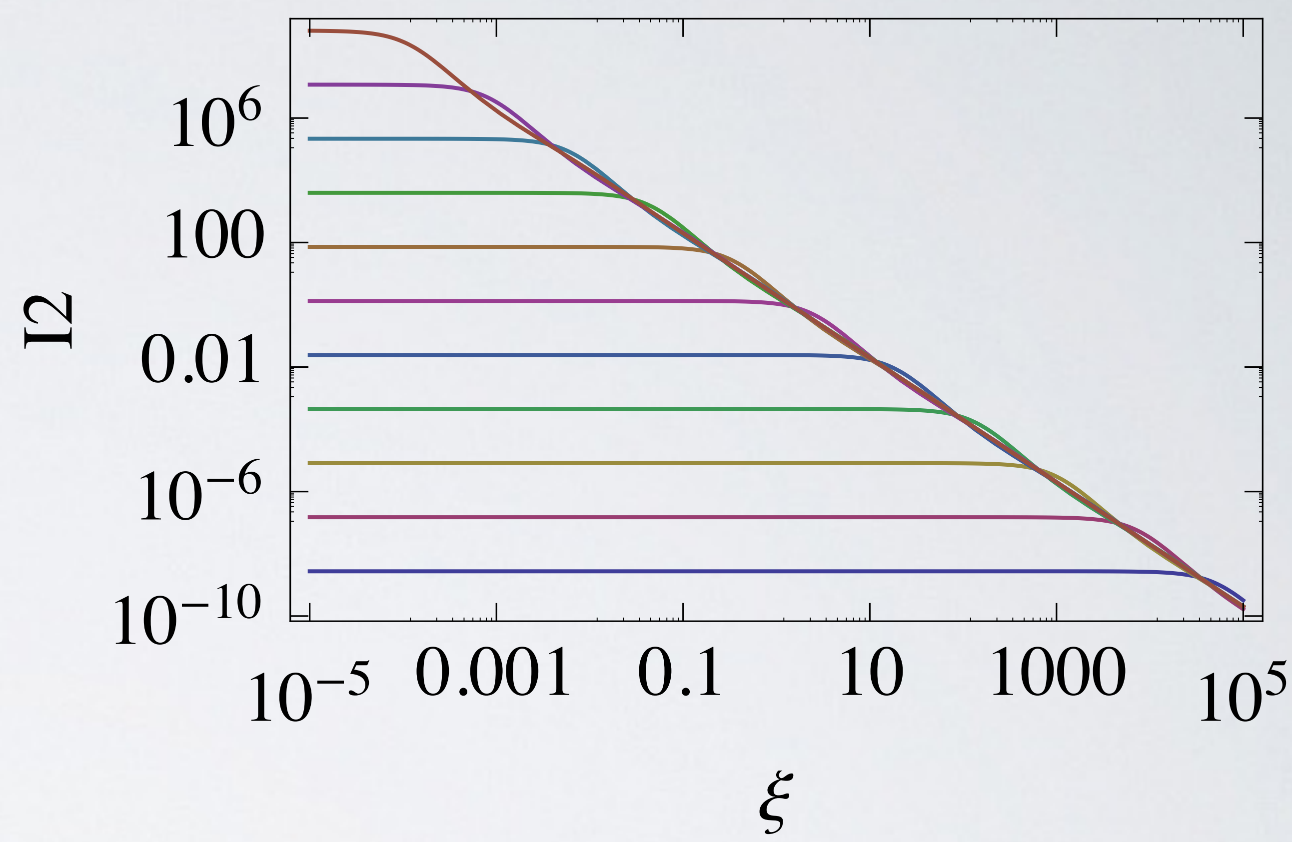
…and all solutions are just rescalings.

MASS DENSITY PROFILE $\rho(r) \sim I_2(\xi)$

Fermi-Dirac



Maxwell-Boltzmann



core for high density

cusp for high density

Fermi-Dirac ► Double feature:
degenerate core plus isothermal tail

Max-Boltzmann ► Classical isothermal halo

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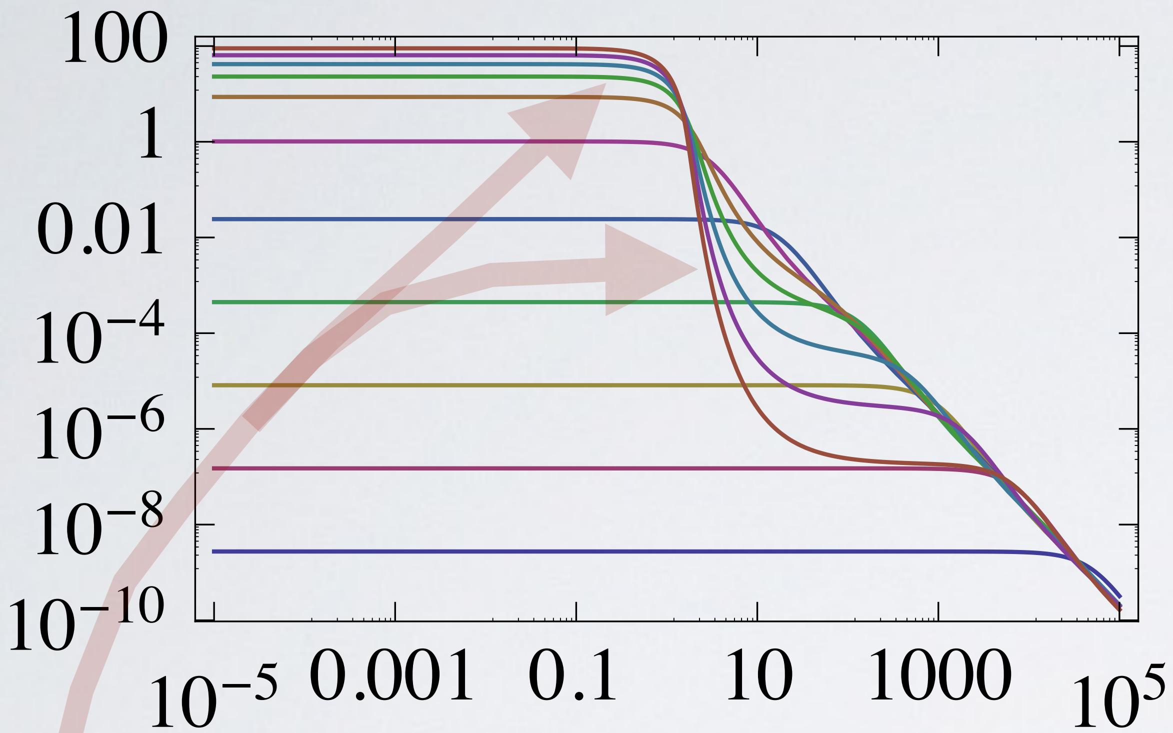

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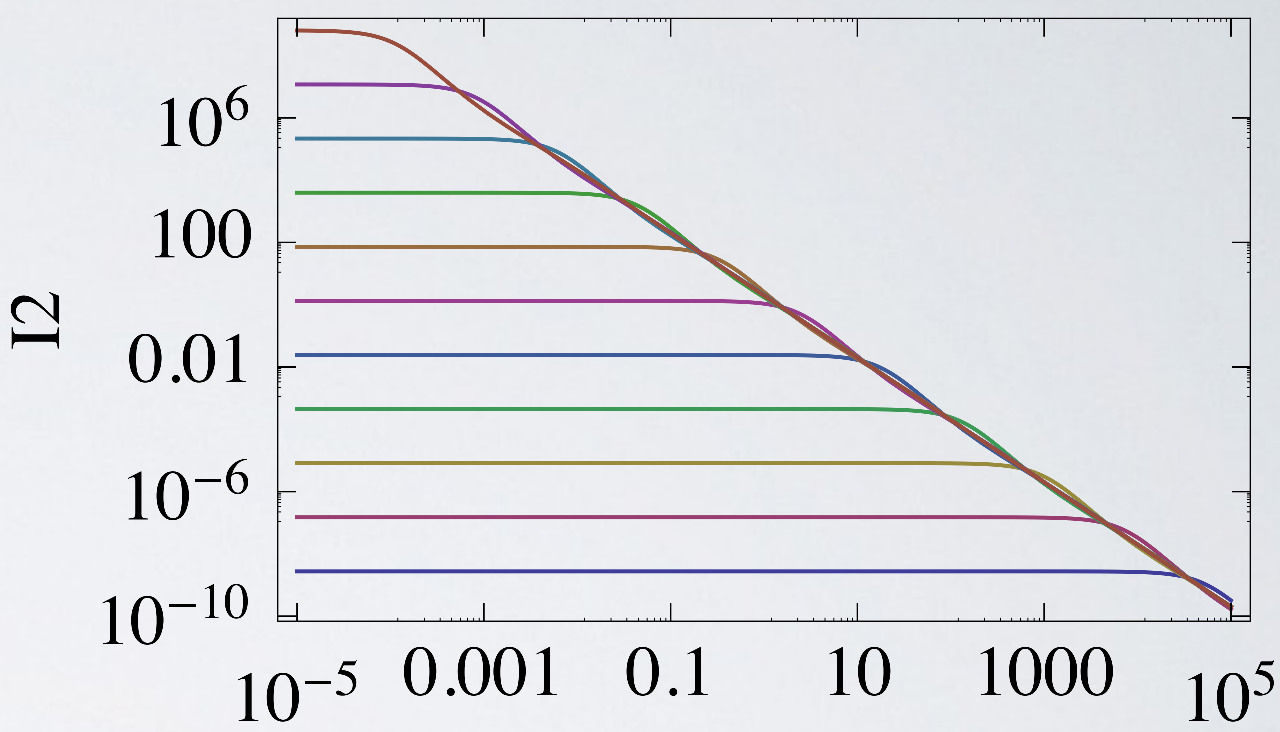

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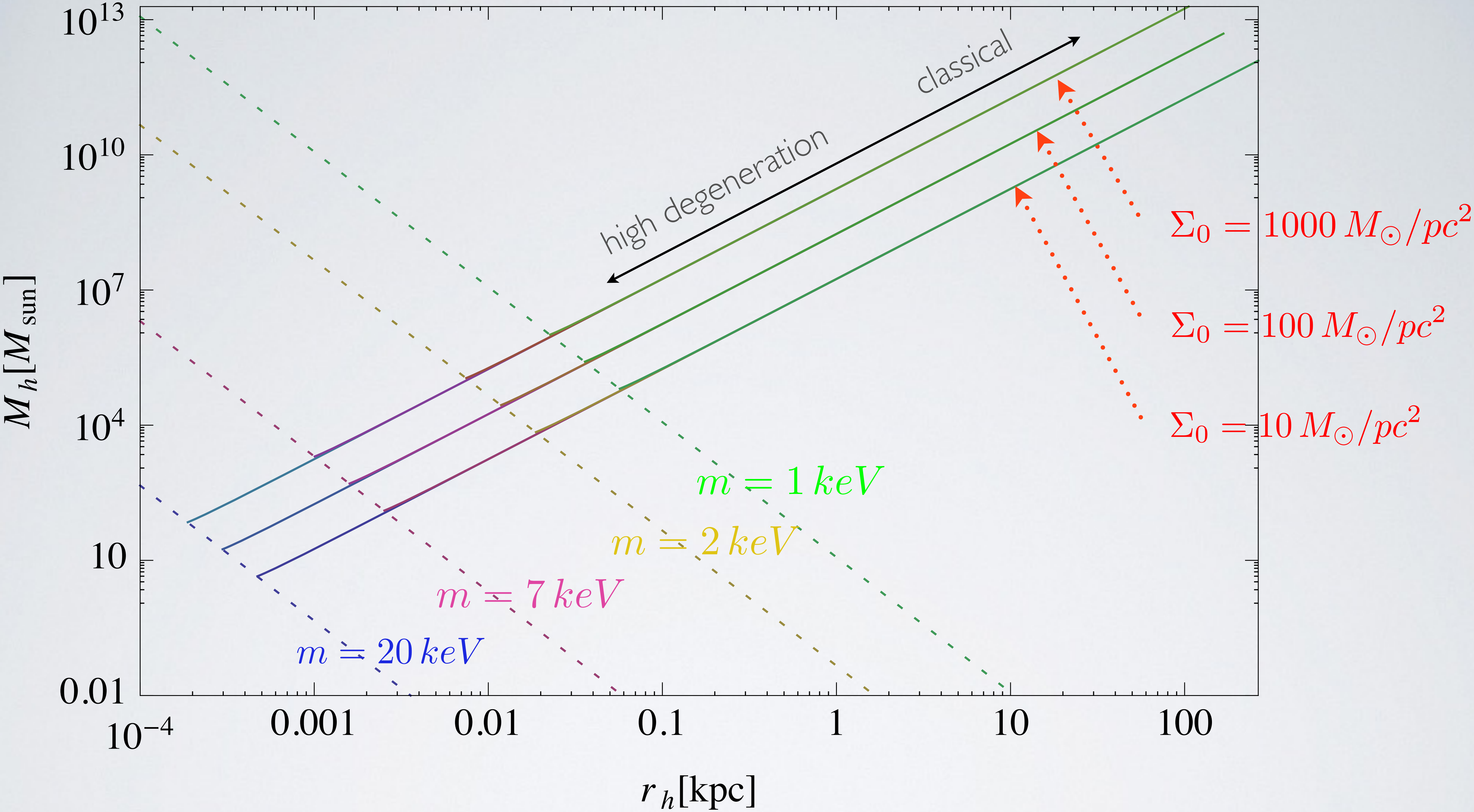
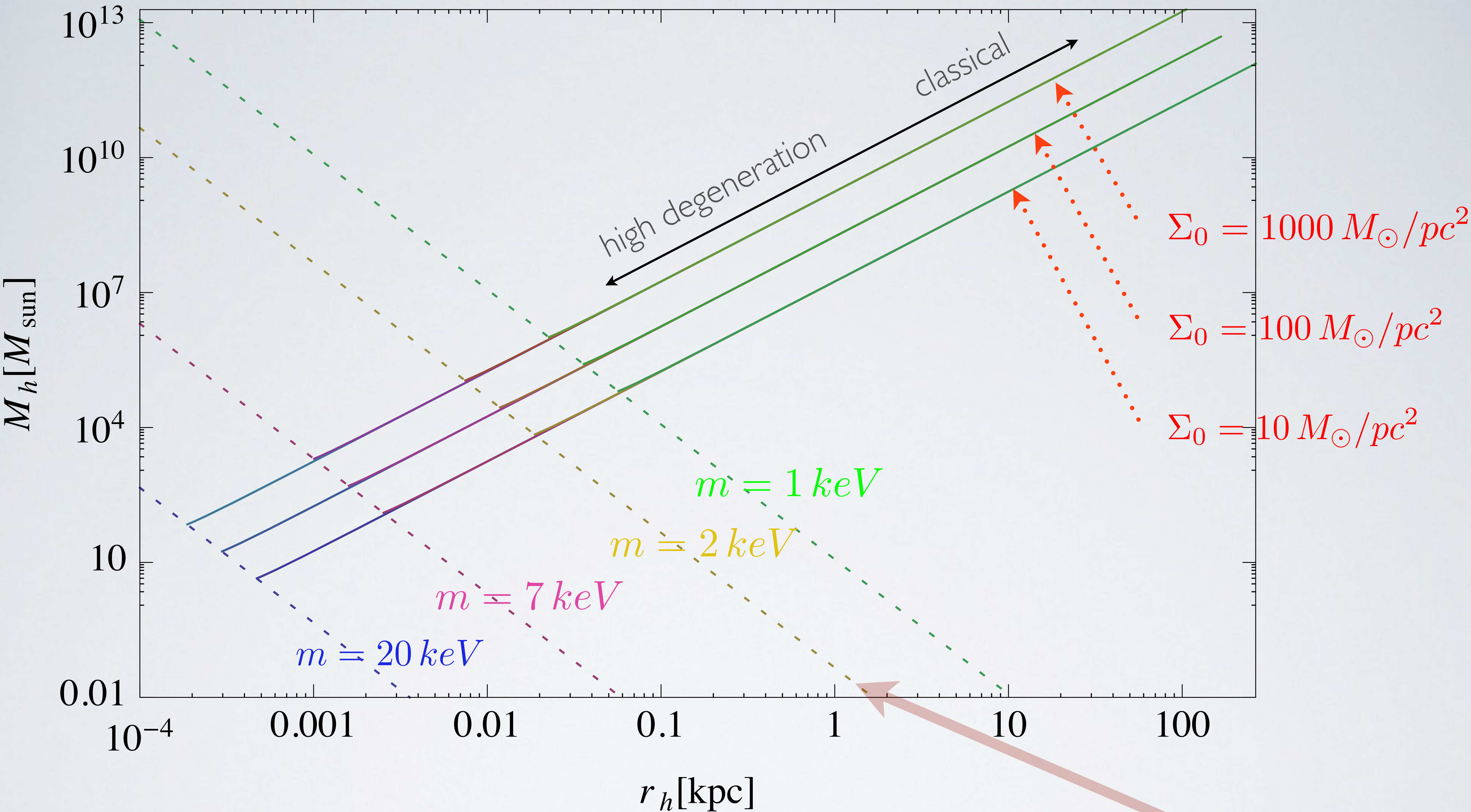


There are lower limits for degenerate: $r_{h,\,min}$ $M_{h,\,min}$

...a minimal galaxy, for given mass $\boldsymbol{m}$



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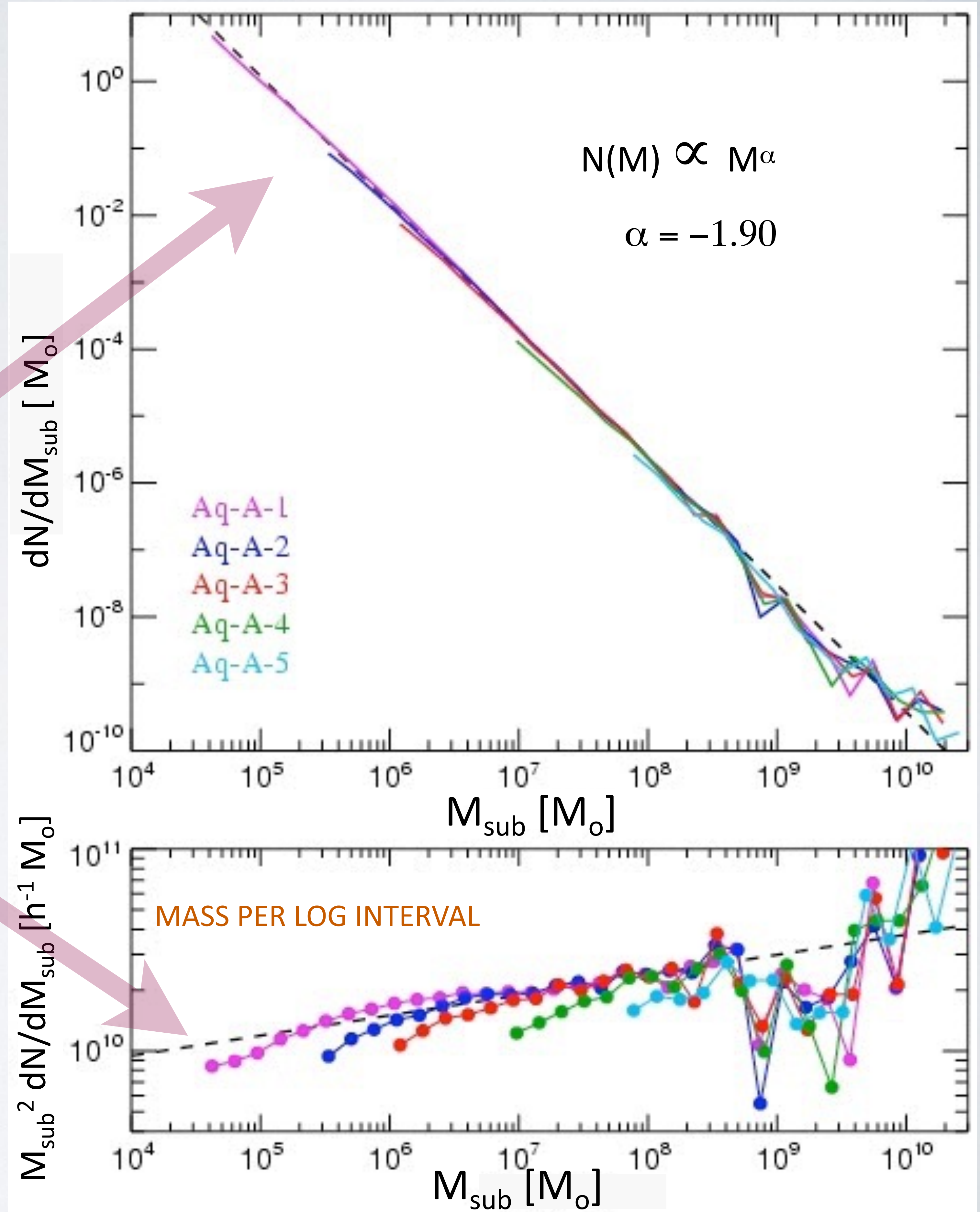
CUT THE SMALL-SCALE EXTRA SATELLITES OF CDM ?

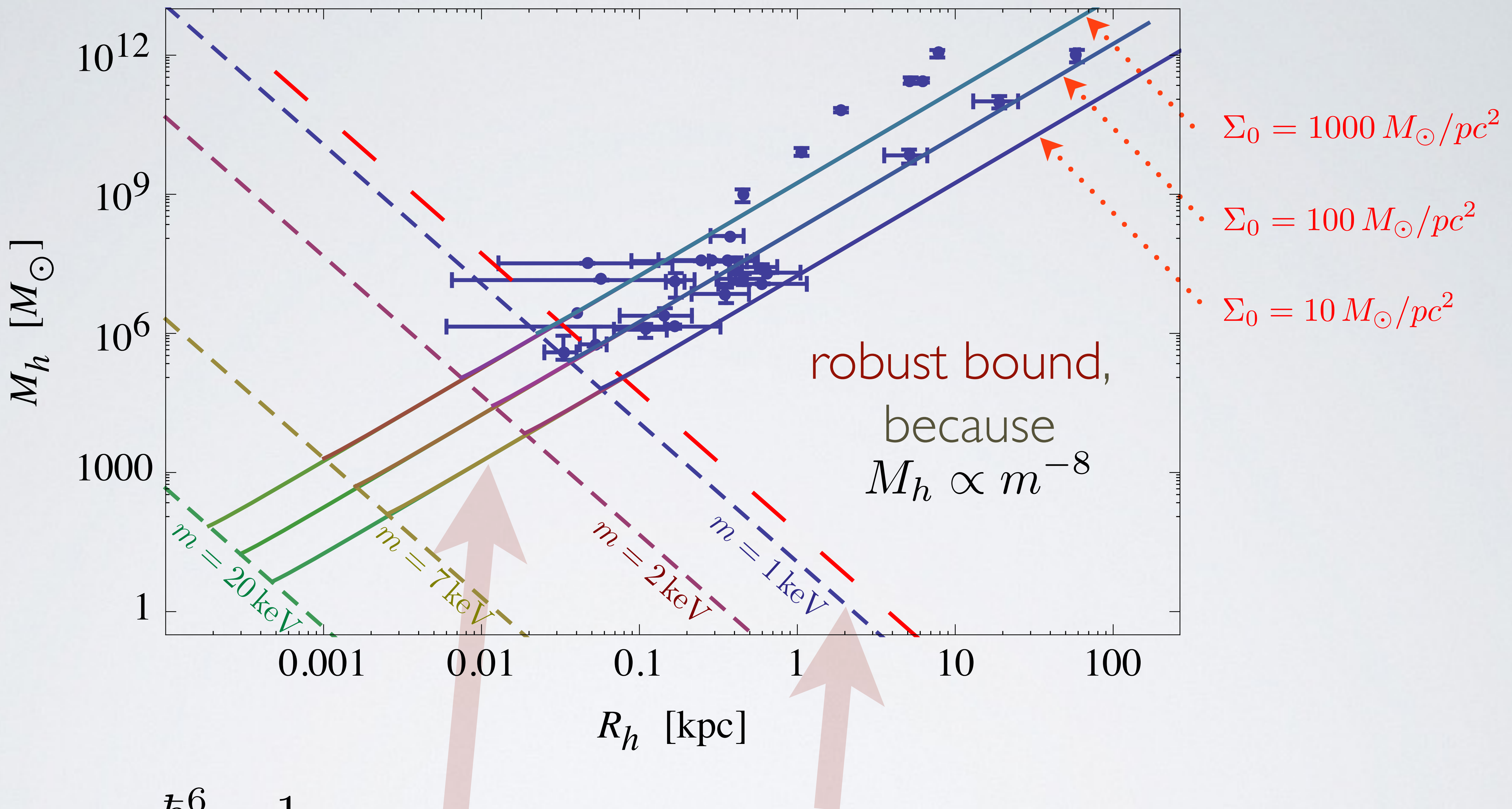
unseen low masses

Dramatic slope, if extrapolated to low masses



[Springel+ '08]

SO : LOWER+UPPER LIMIT ON m ?



$$M_h \sim \frac{\hbar^6}{G^3 m^8} \frac{1}{r_h^3}$$ Degeneration limit (dashed) m fixed

$$M_h \sim \Sigma_0 r_h^2$$ and surface density (solid) Σ_0 fixed

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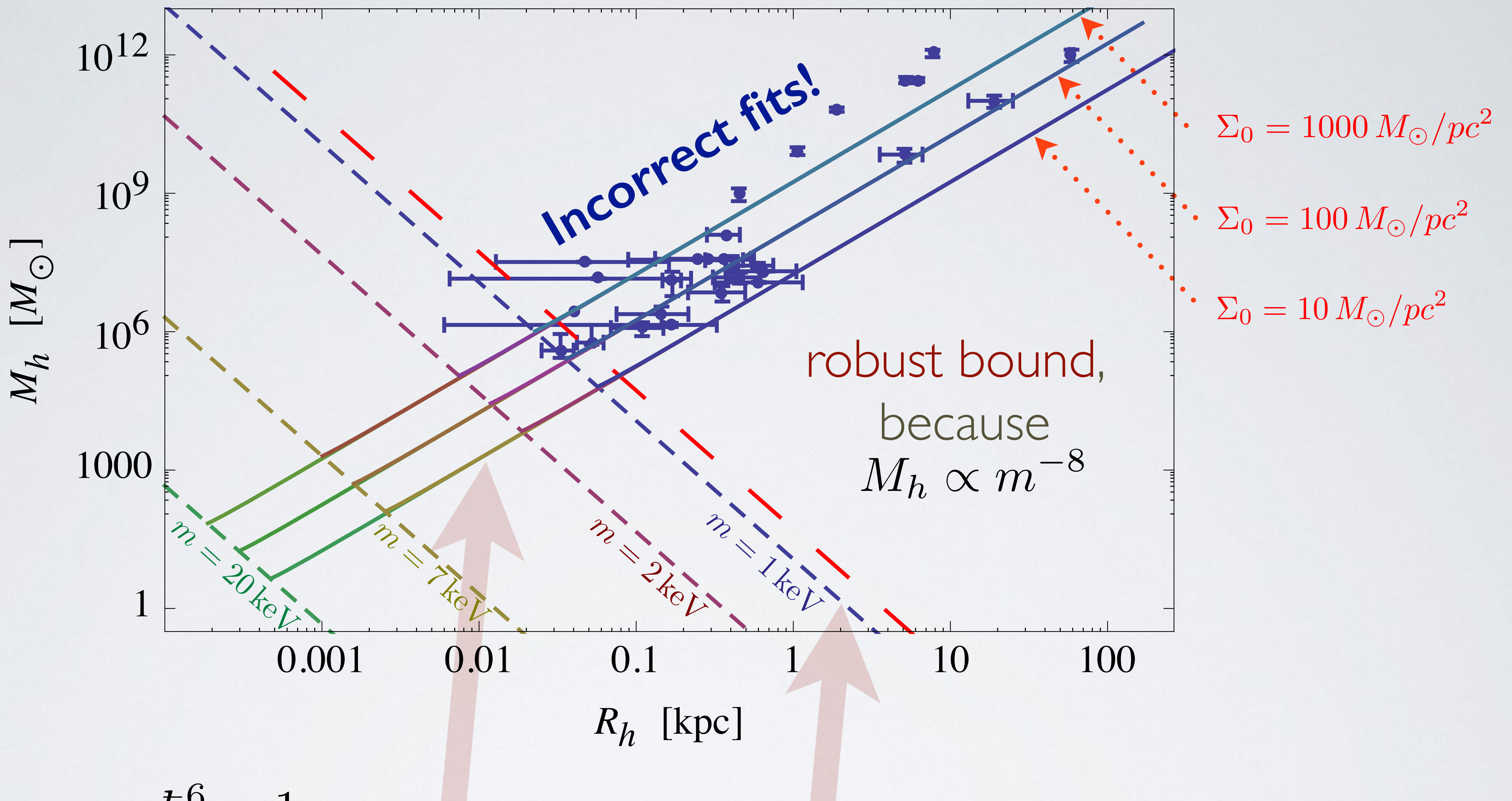

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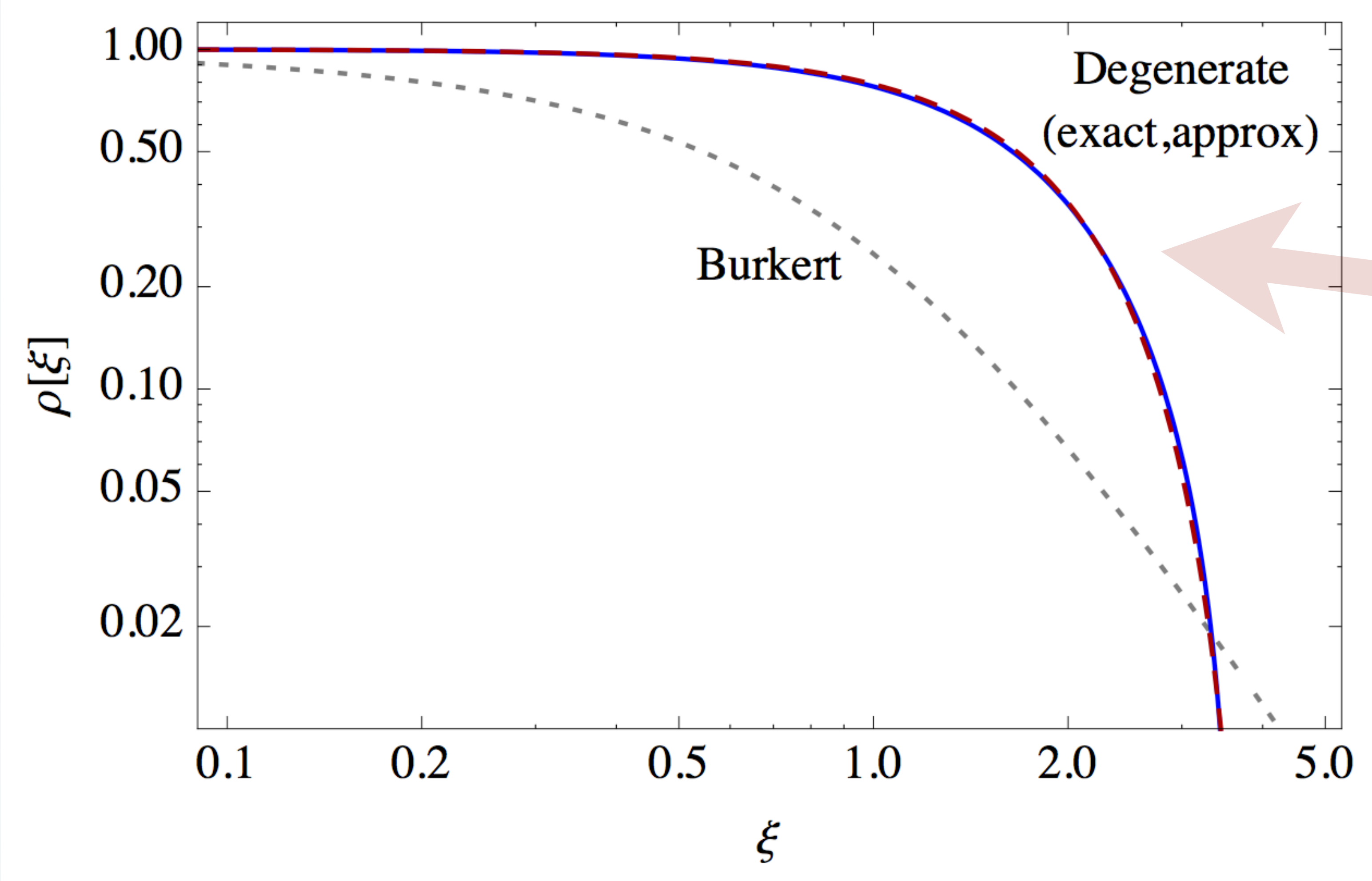
SO, QUANTUM NATURE PREDICTS

- **A minimum for total mass M_h and size R_h**

- **The shape of fully degenerate profile:**



Lane-Emden solution. we **approximate very well by**

$$\rho(\xi) = \rho_0 \cos^3\left[\frac{\pi}{8}\,\xi\right]$$

...can we test this profile?

NO: NONTRIVIAL PROBLEM ALREADY TO ESTIMATE THE HALO SIZE/MASS

- **We observe the STAR velocity DISPERSION (line of sight only, σ_r)**

- Jeans equation predicts it, from given mass model $M(r)$

$$\left(\frac{\partial}{\partial r} + \frac{2\beta}{r}\right)(n_* \sigma_r^2) = -n_* \frac{GM(r)}{r^2}$$

- *Stellar dispersion anisotropy* $\boldsymbol{\beta}$ *unknown* $\beta \equiv 1 - \sigma_\perp^2/\sigma_r^2$

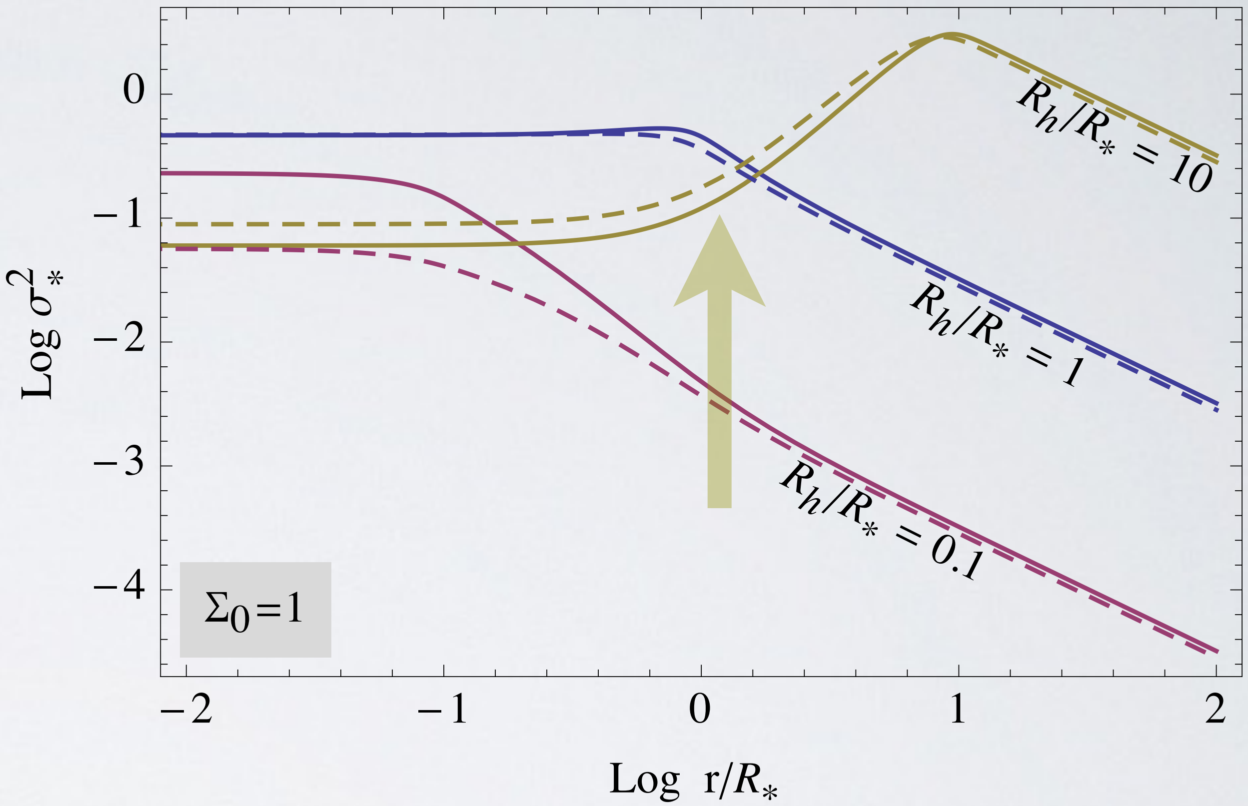
- *and it's hard to measure stars for small galaxies*

PREDICTED STAR VELOCITY DISPERSION

WITH OR WITHOUT ANISOTROPY

- Small or large DM core R_h

  too large cores excluded by constant observed $\sigma_{*,r}$



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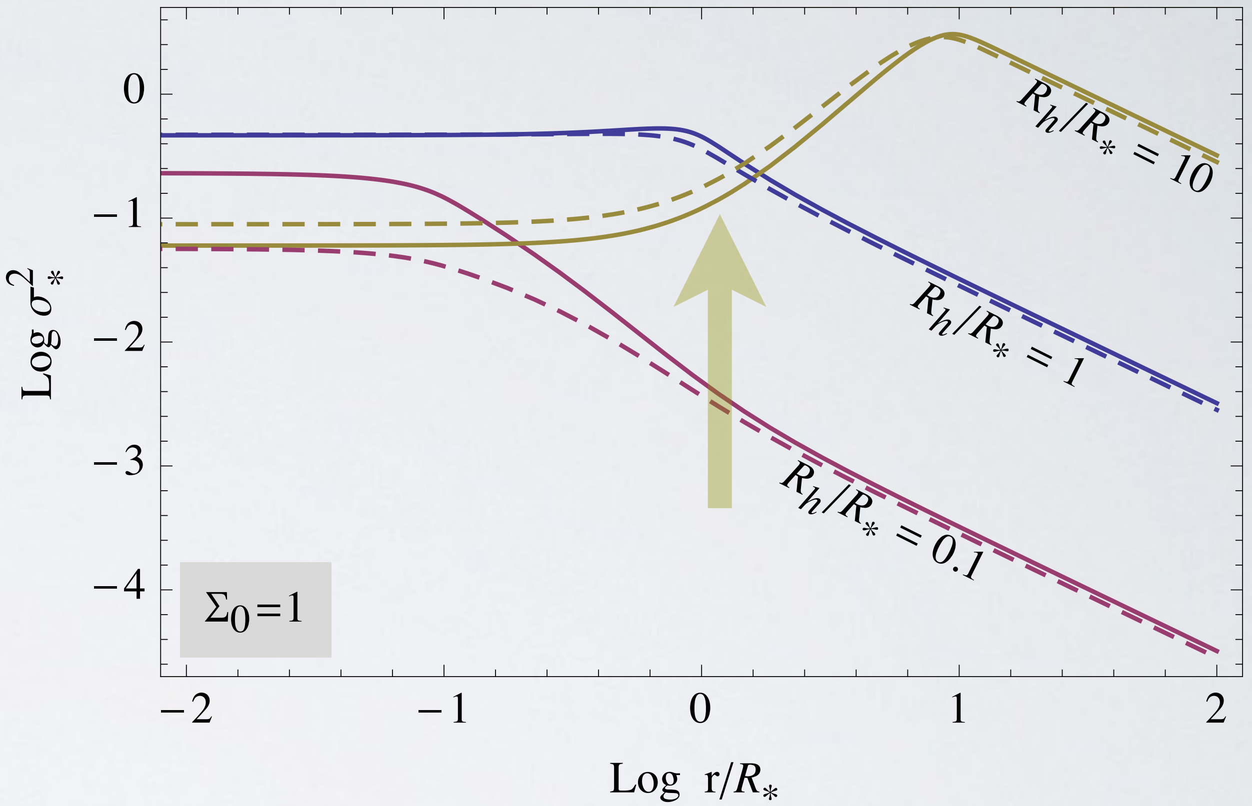
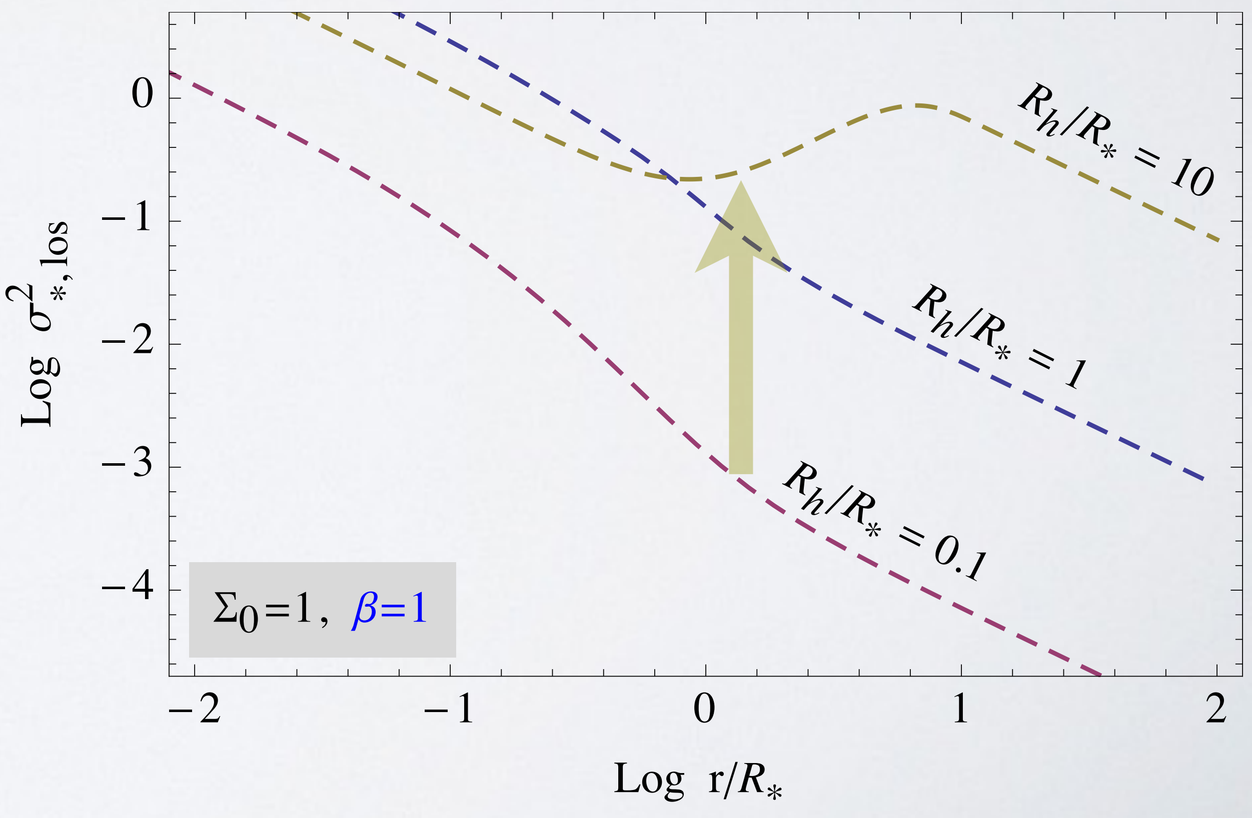


- Effect of anisotropy, e.g. β=1

  large core gives again
  a flattish $\sigma_{*,r}$ … !



TOTAL MASS LIMITED BY DYNAMICAL FRICTION

Satellites would have fallen in the MW halo…
…due to gravitational friction

[Chandrasekar formula, e.g. Binney Tremaine 2008 Read+ '06; Just '11, etc]

- Time:

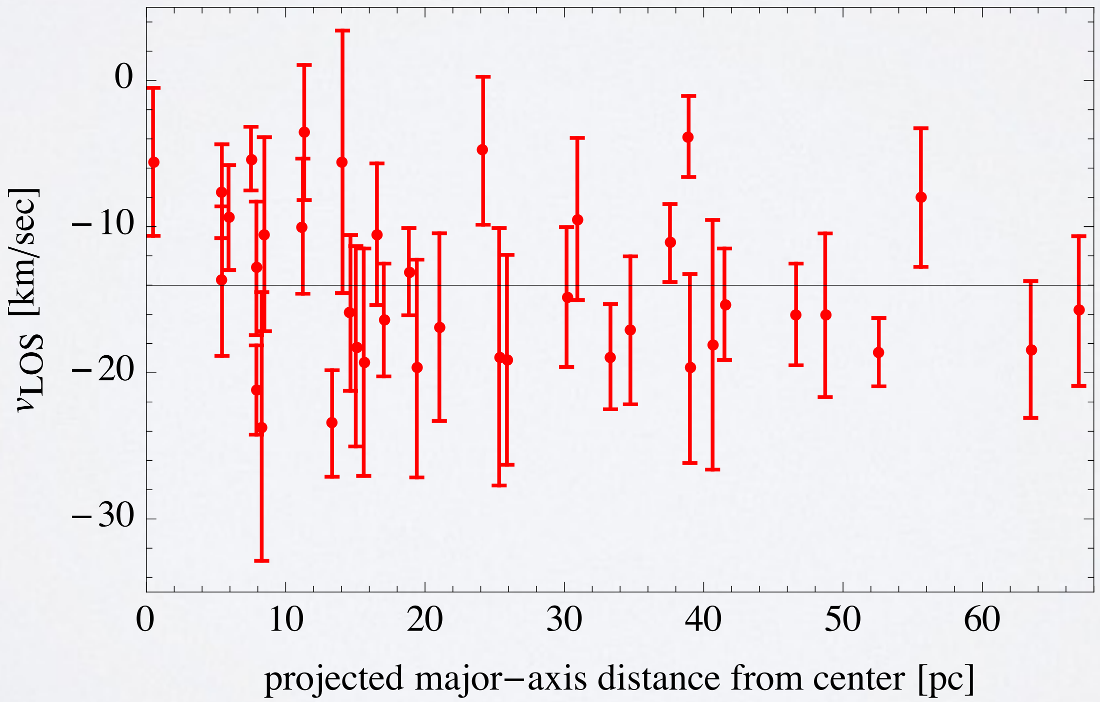
$$t_{\rm fric} = \frac{10^{10}\,{\rm y}}{\ln\Lambda}\left(\frac{D}{60\,{\rm kpc}}\right)^2\left(\frac{v}{220\,{\rm km/s}}\right)\left(\frac{2\cdot 10^{10}\,M_\odot}{M_{\rm h}}\right)$$

should be larger than the age of Galaxy $\sim 10^{10}$ y.

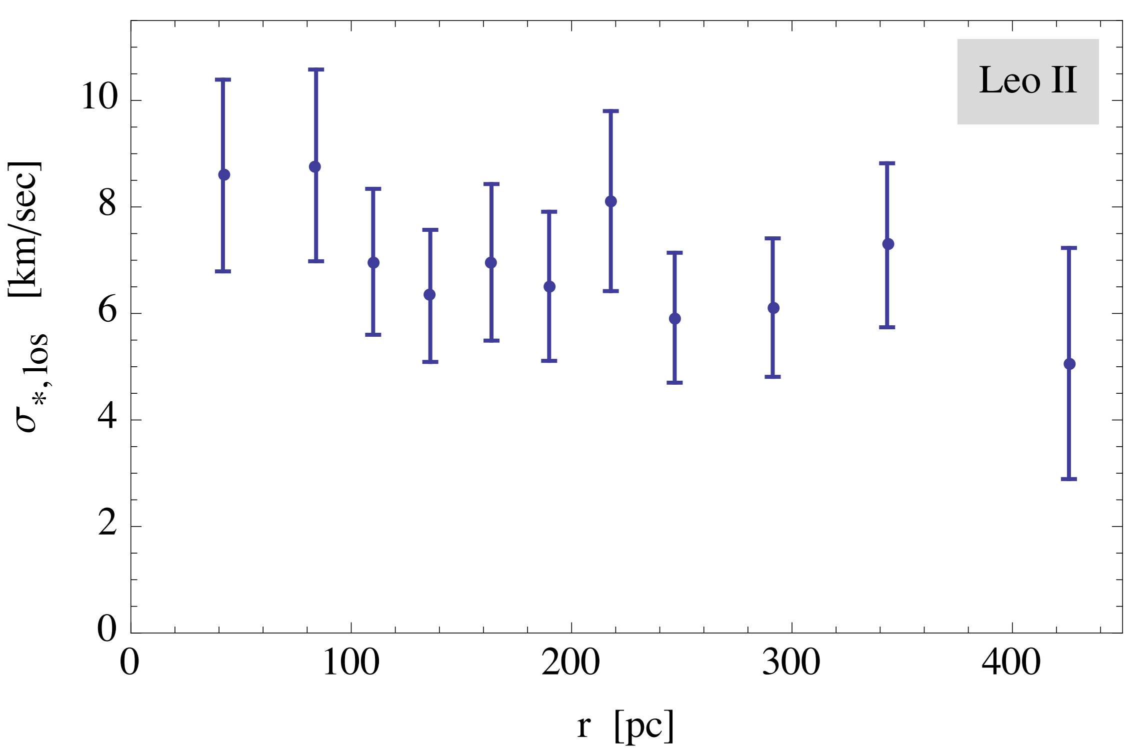
- Puts a limit on halo mass $M_{\rm h}$ [Gerhard Spergel '92]

Are rising velocity dispersion profiles allowed?

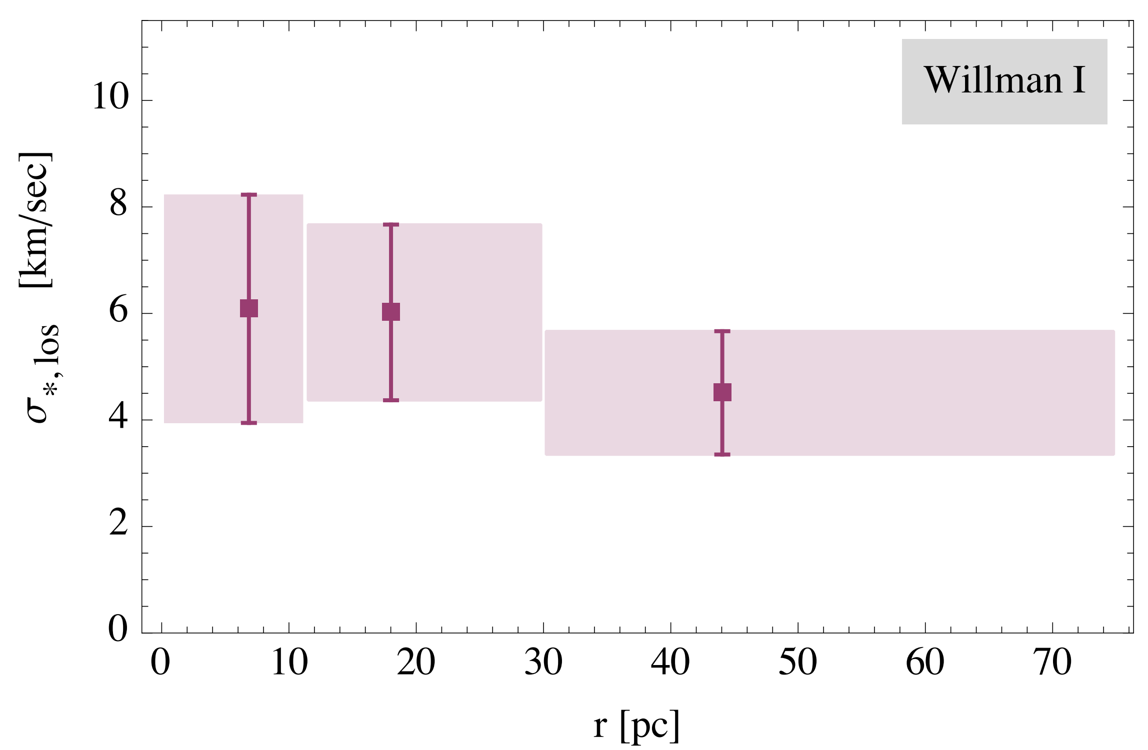
Compare with data



LEO II , WILLMAN I

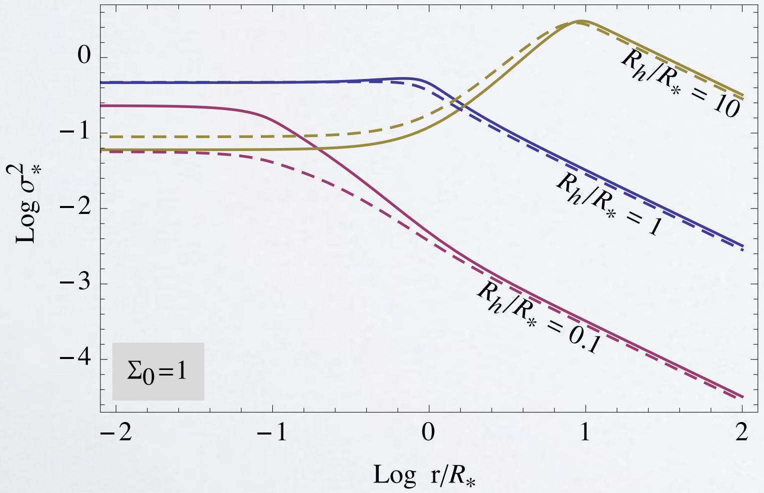


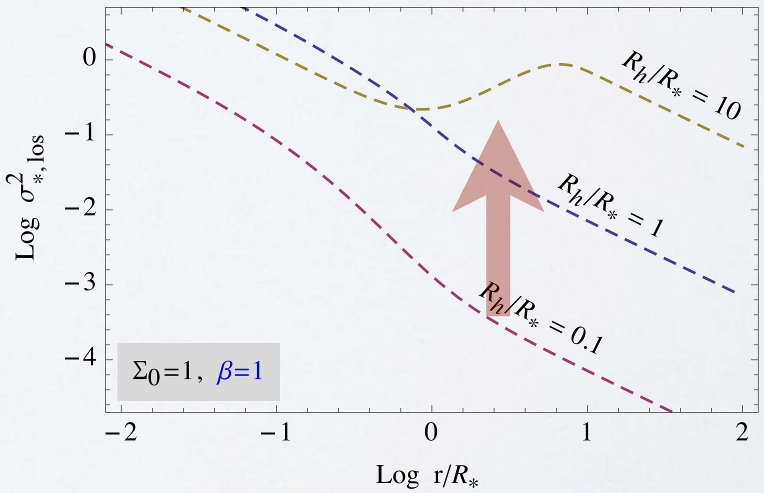
r_*=177pc, distance=205 kpc



r_*=20pc, distance=38 kpc

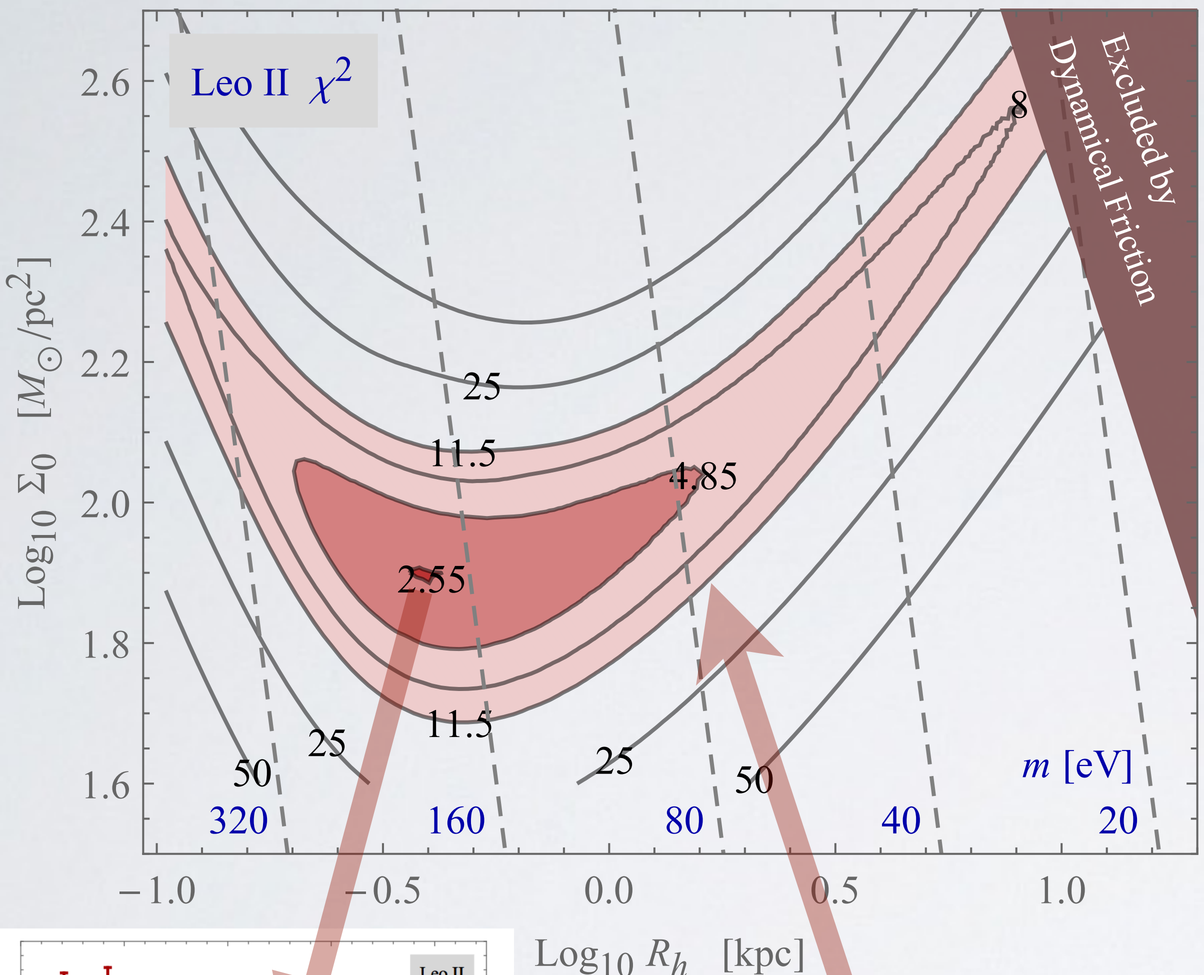
constrain R_h, M_h, m by fitting with predicted profiles





MARGINALIZING BETA β - LEO II

Exclusion by data is not Parameter estimation



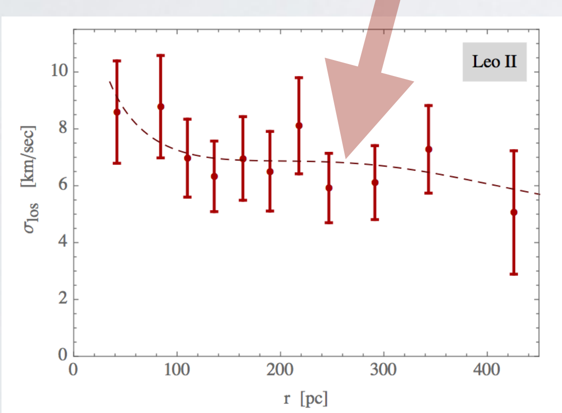
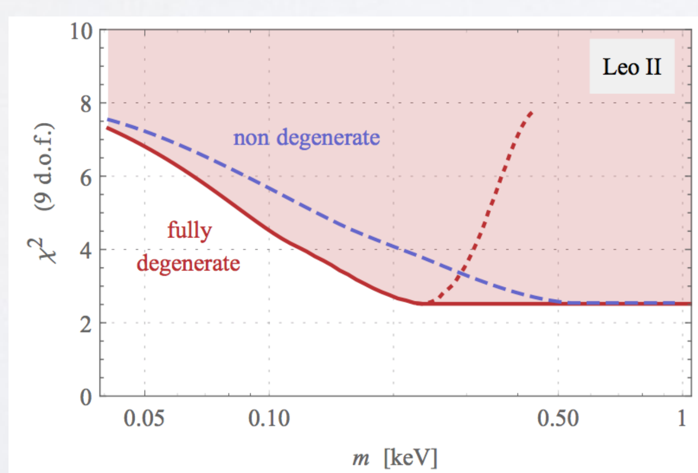


FIG. 4. Stellar line-of-sight velocity dispersions for Leo II. The dashed line represents the best fit, achieved for $\beta = 0.6$.

1σ exclusion



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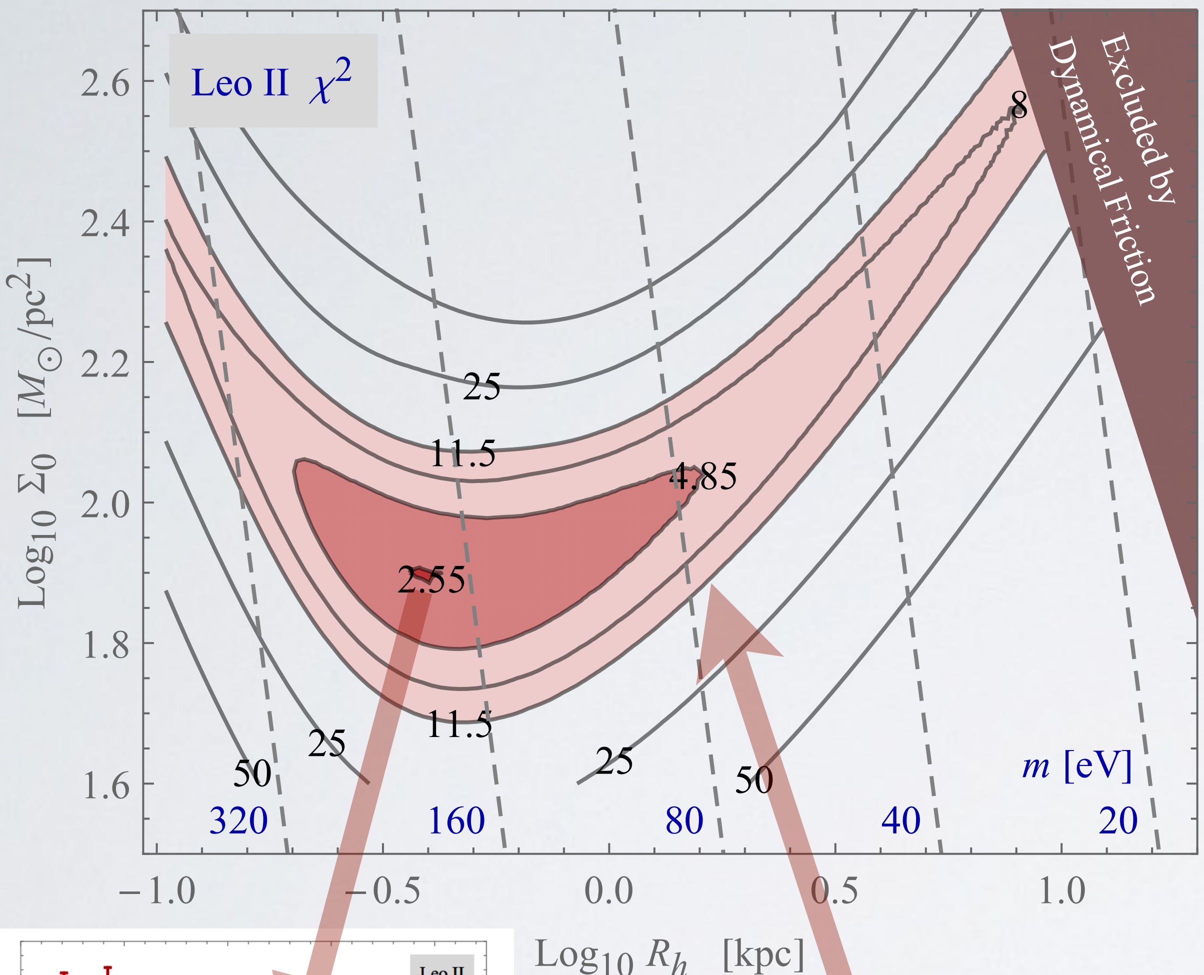
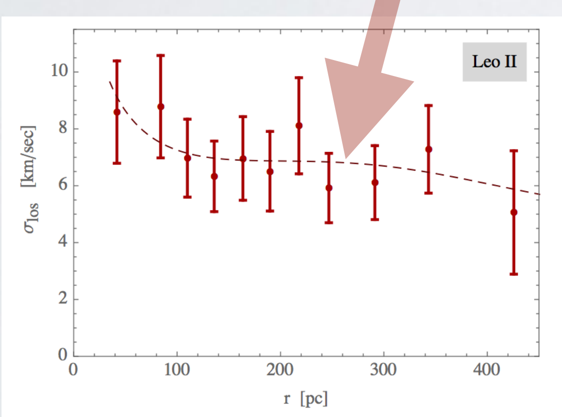


due to $\boldsymbol{\beta} \rightarrow 1$

No upper limit on R_h

No lower limit on m

1σ exclusion



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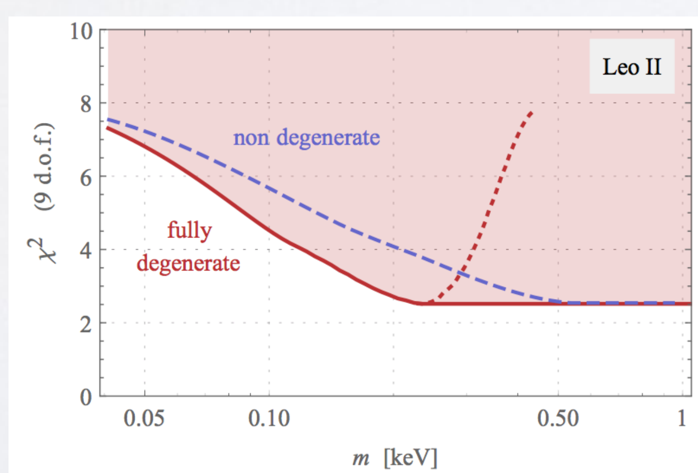
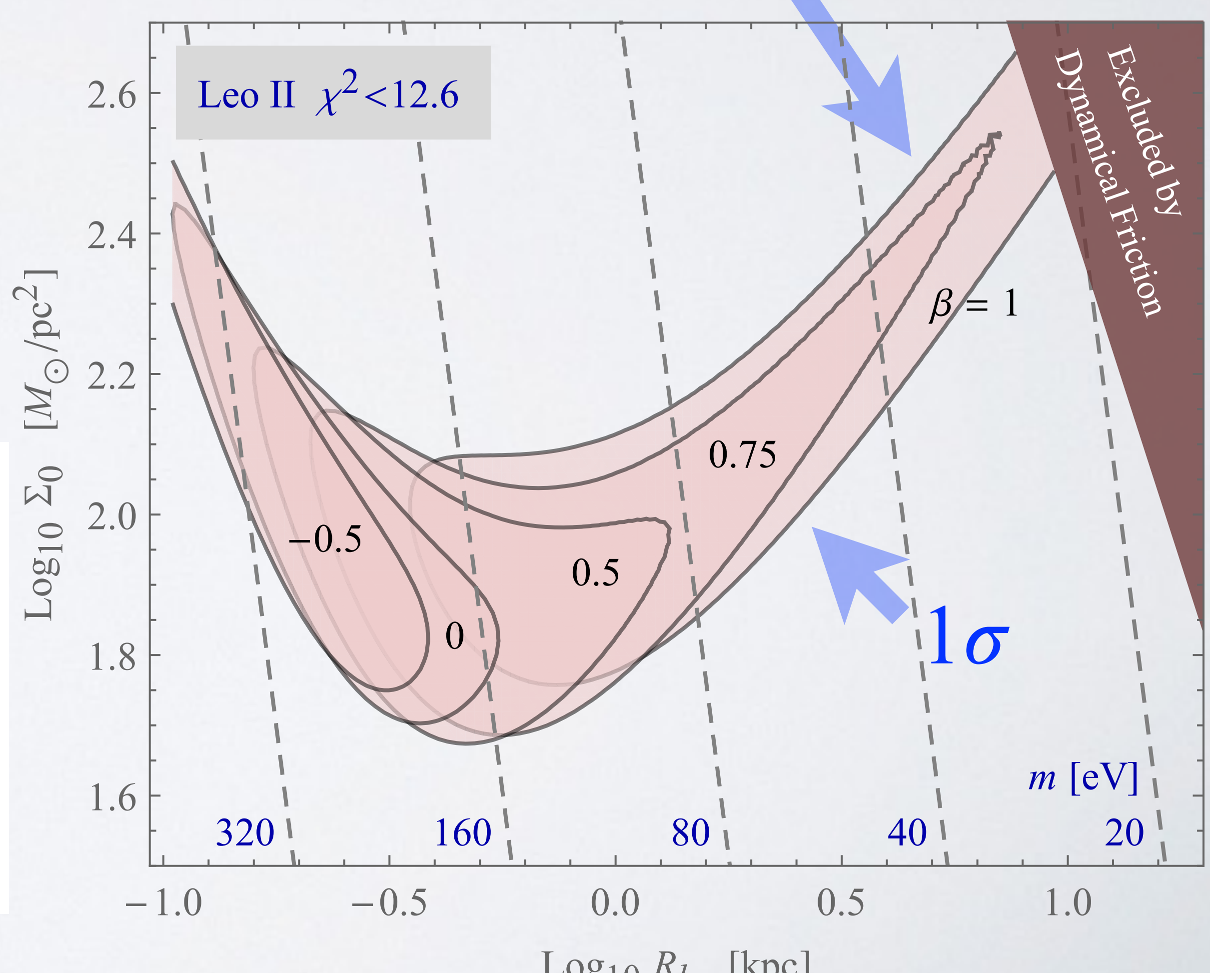
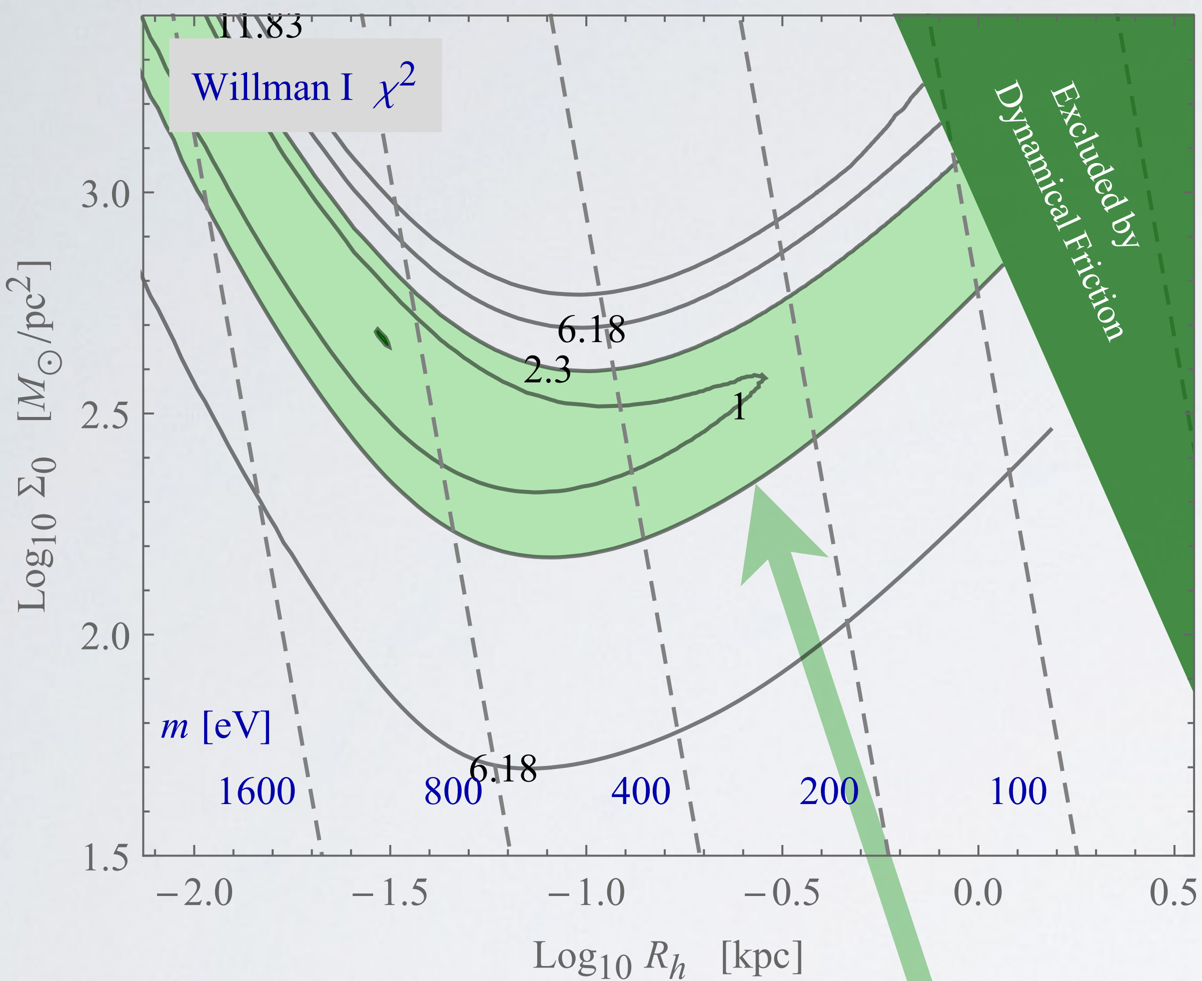




MARGINALIZING BETA β - WILLMAN I

Exclusion by data



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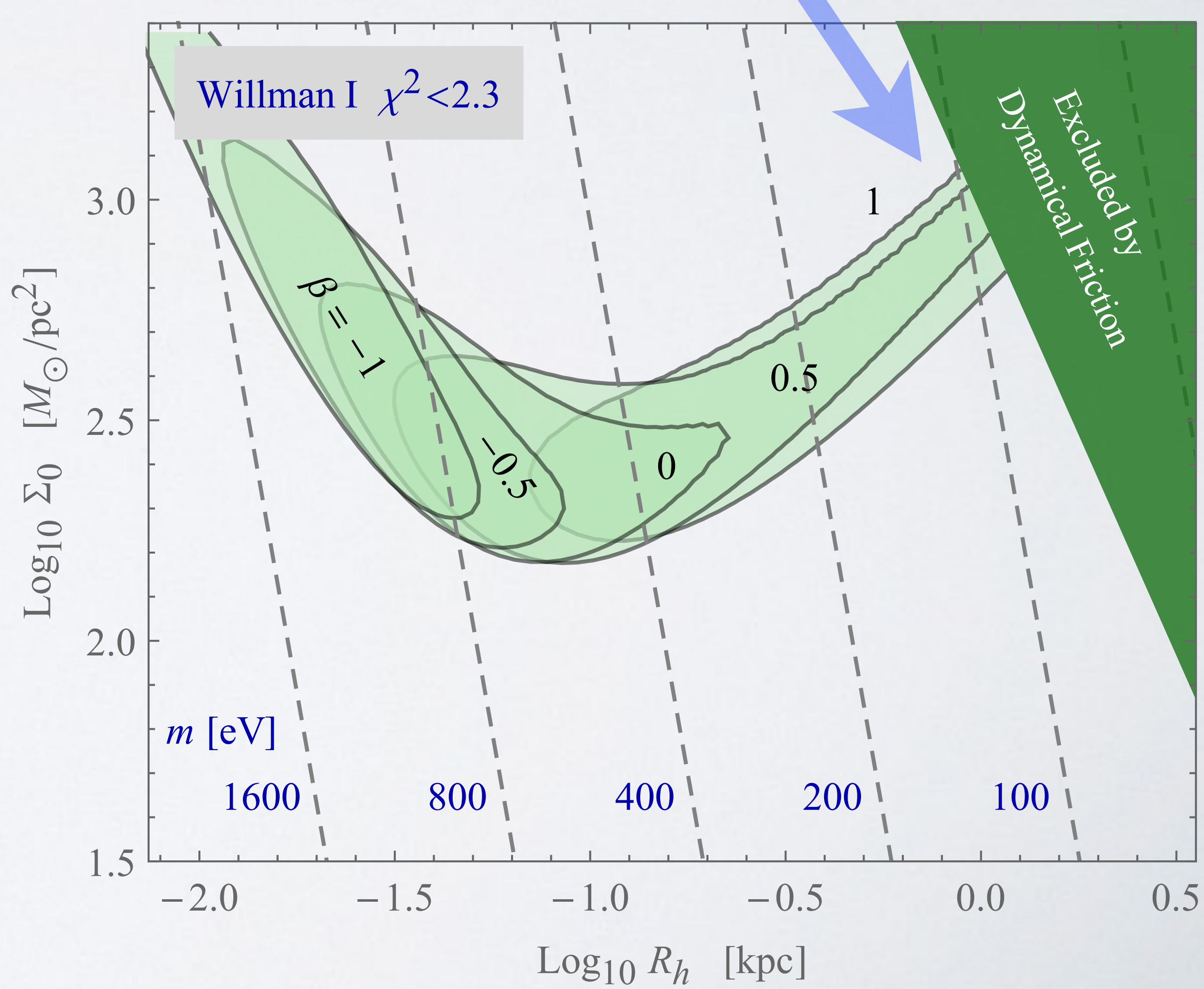
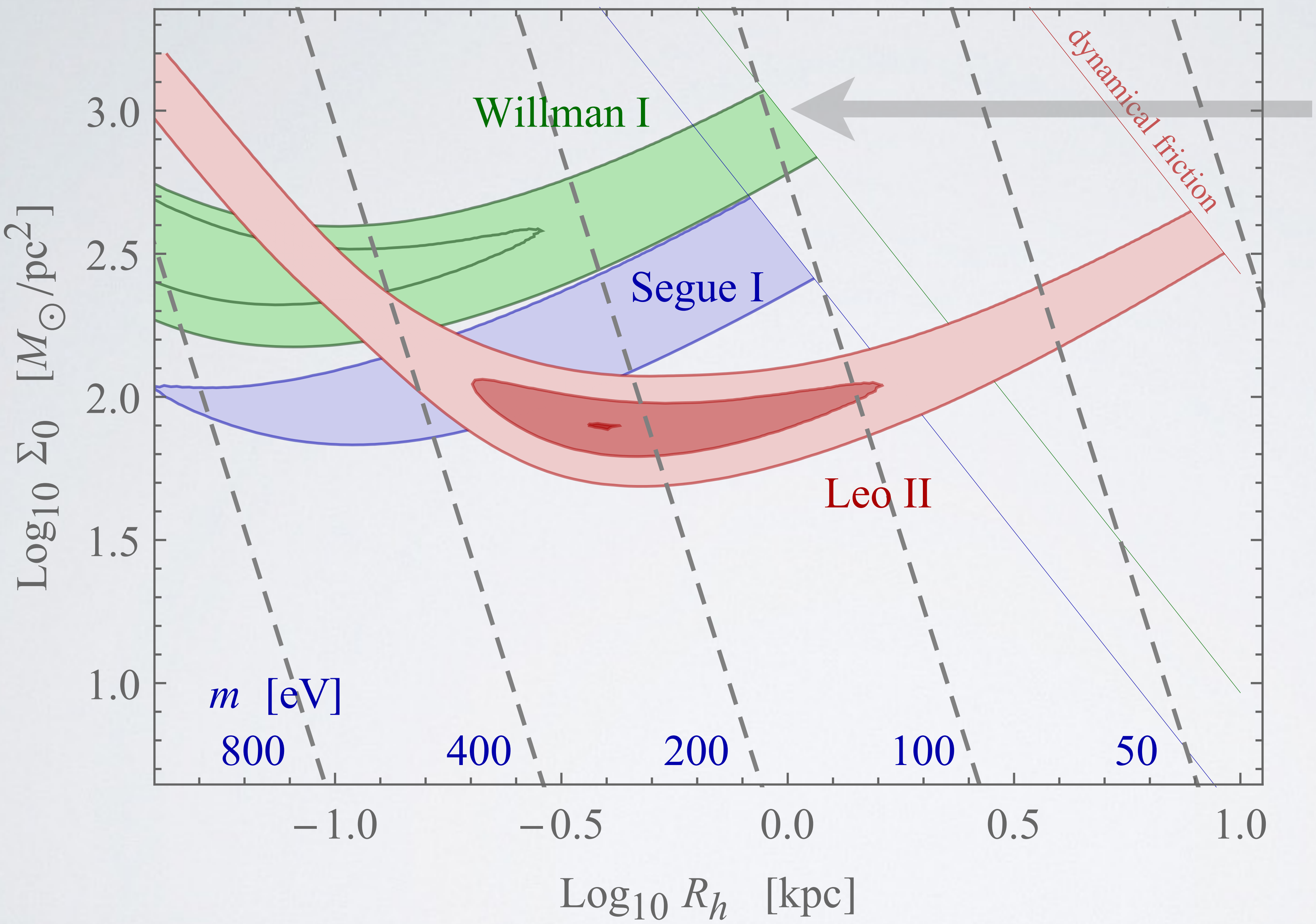


SO, BOUND ON DM MASS *m*



Tremaine Gunn saved by Dynamical Friction

…substantially weakened to $m \gtrsim 100$ eV

dSph may be larger…

(even if one does not want ≳ kpc size)

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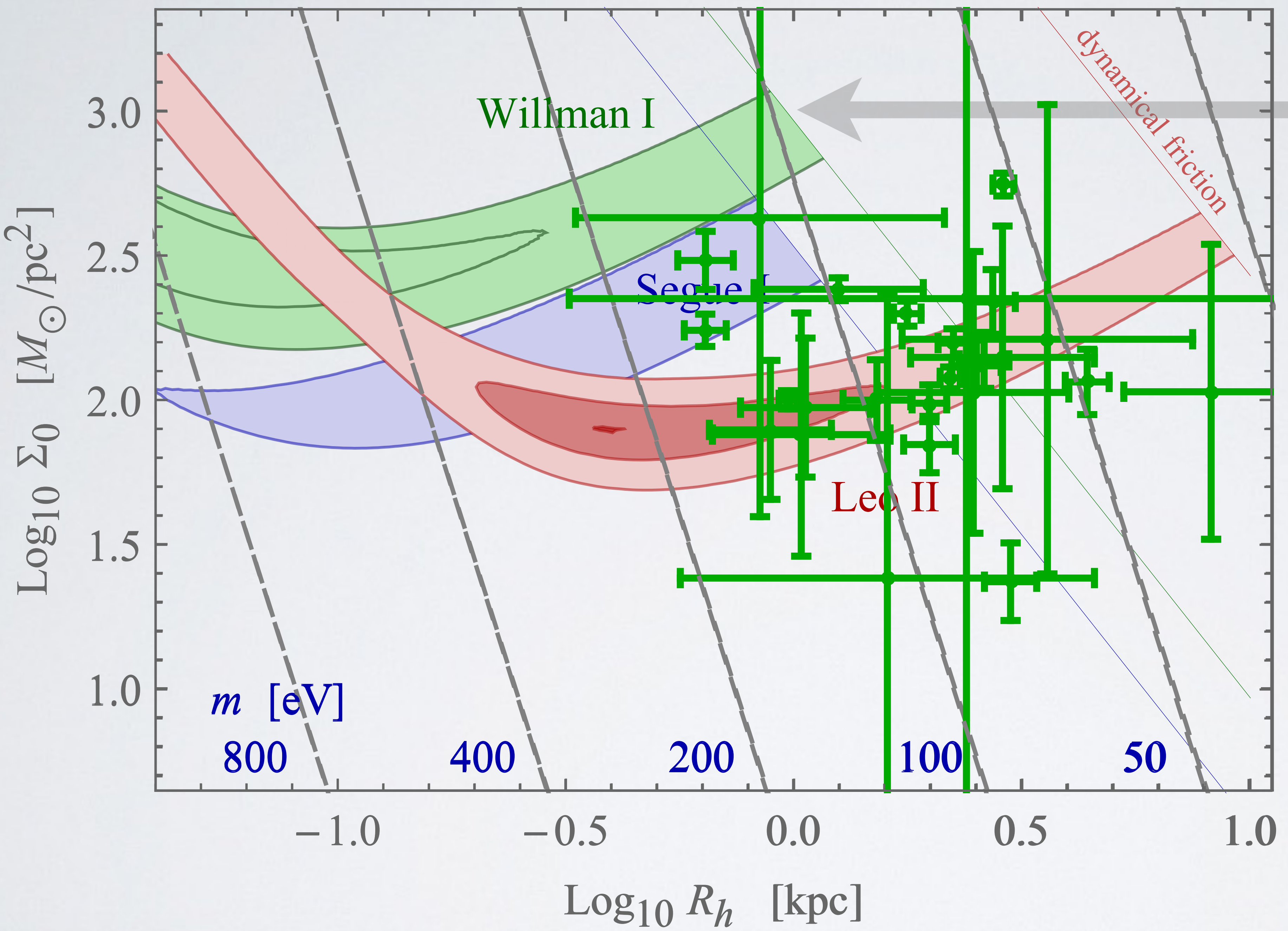

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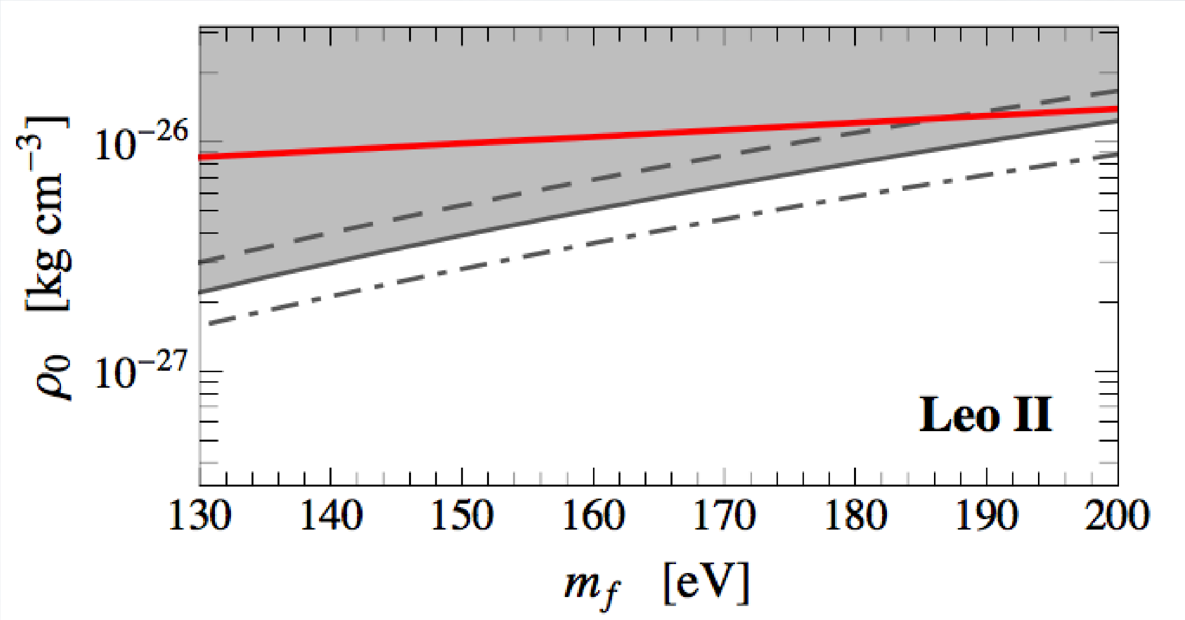
Nothing stronger from Dwarf Disk galaxies [Little Things '15 HI survey]

RECENT WORKS

[Domcke+ JCAP '15]
m>200eV from LeoII (?)



We plot the best-fit value for the central density ρ_0 as a function of the mass m_f, obtained marginalizing over the orbital anisotropy β. The value $m_f = 150\,\mathrm{eV}$ is consistent with the bound $v_F \leqslant v_\infty^{obs}$ for all the analyzed dwarf spheroidal galaxy but Leo II. Note that this result

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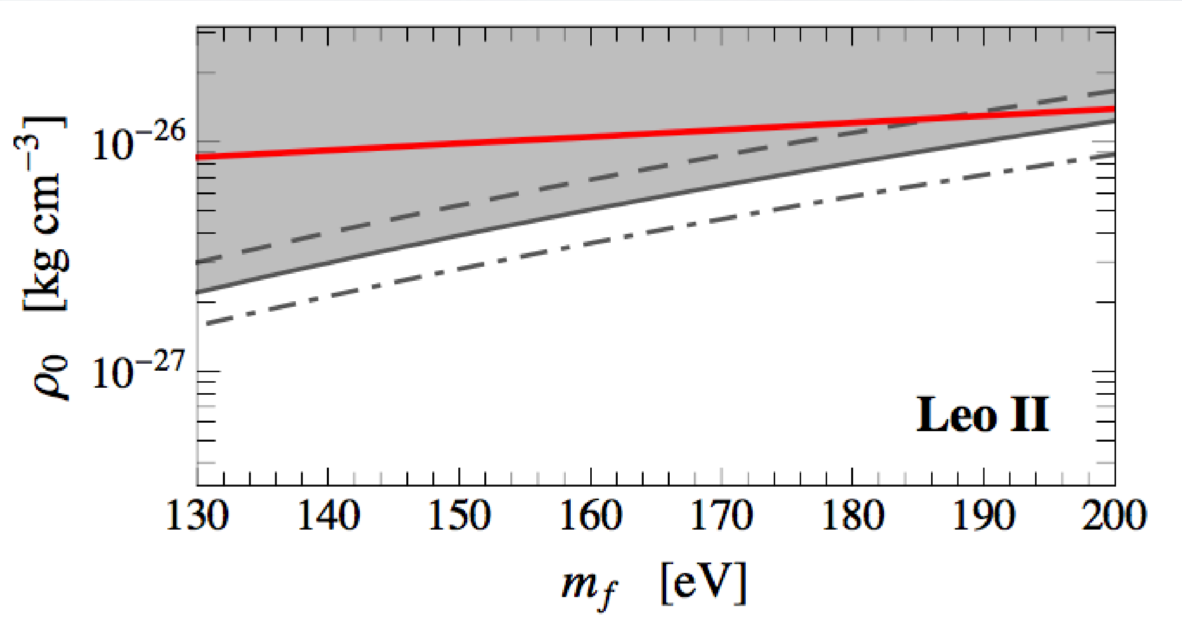

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[Randall+ MNRAS '17]

m>100eV from Fornax (?)

using multi-population

[Amorisco+ '12]

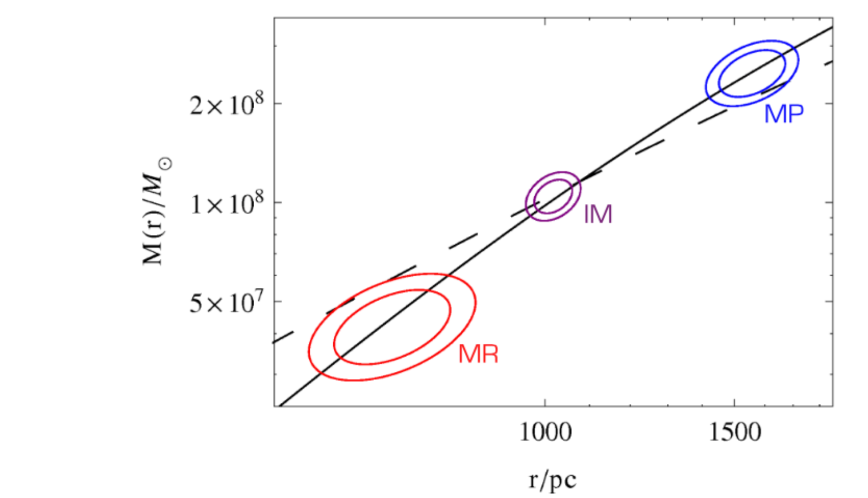

Figure 2. Left panel: estimates of the total enclosed mass $M(r)$ as ob

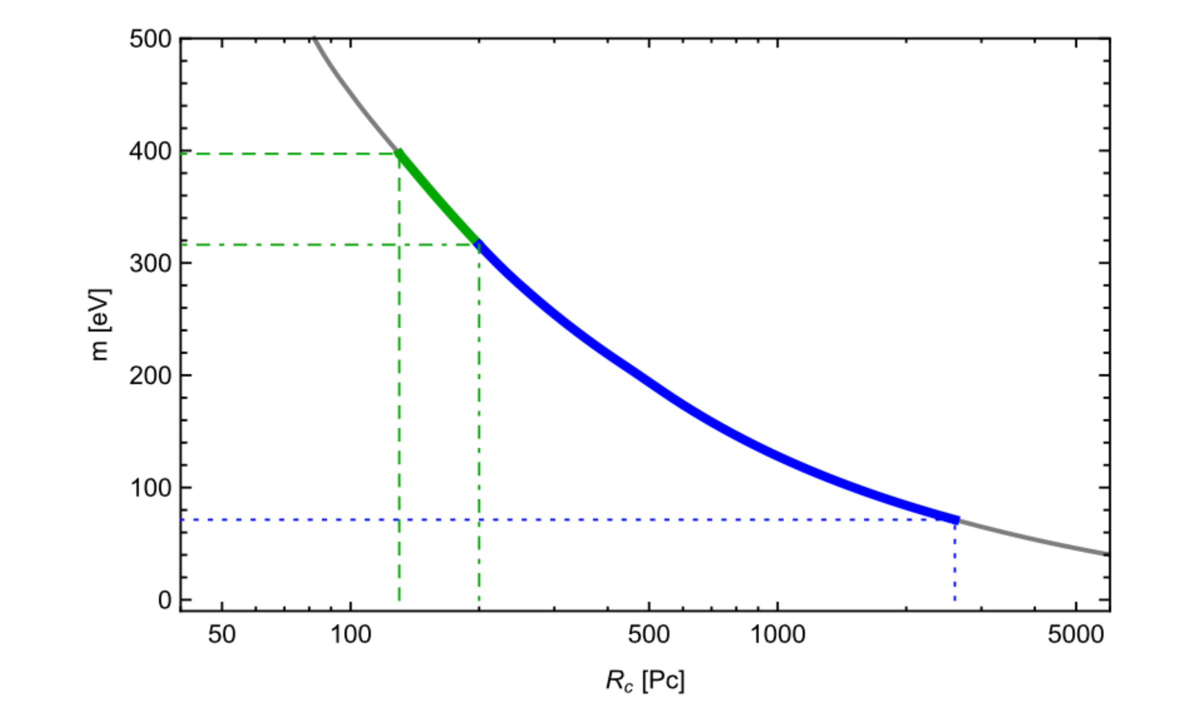

Figure 7. Applying the static solution of Section 2 to the Fornax dwarf galaxy, we show the necessary dark matter mass m as a function of the desired core radius R_c. The blue part of the curve indicates the preferred set of R_c from Walker & Penarrubia (2011). The green portion of the curve shows a weaker condition $R_c > 130\,\text{pc}$.

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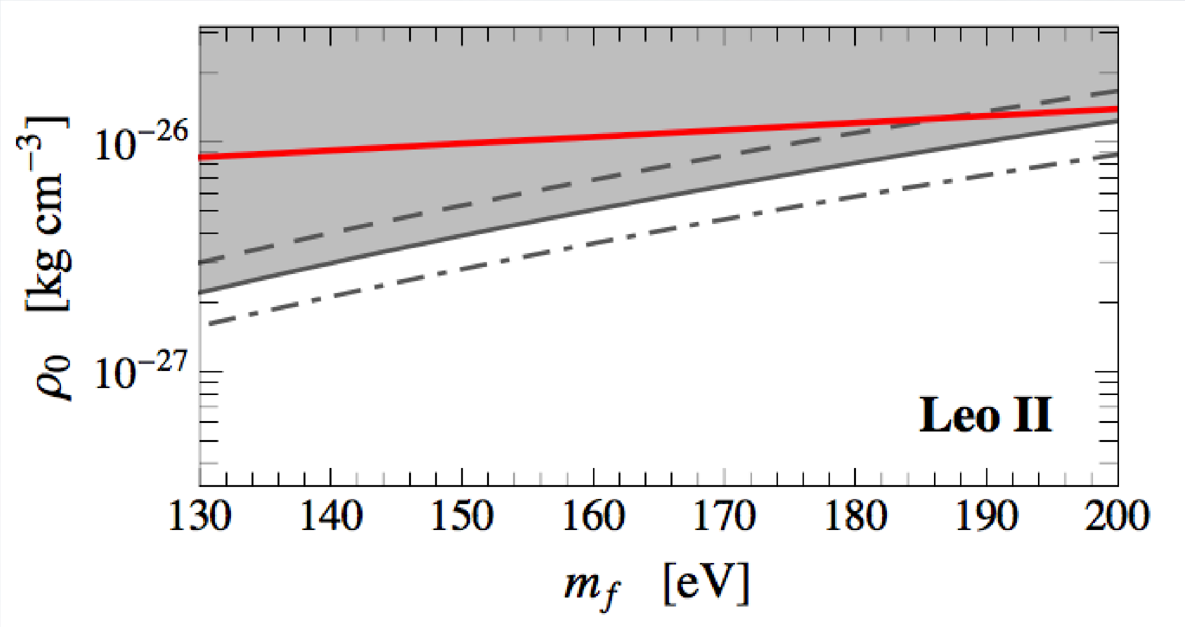

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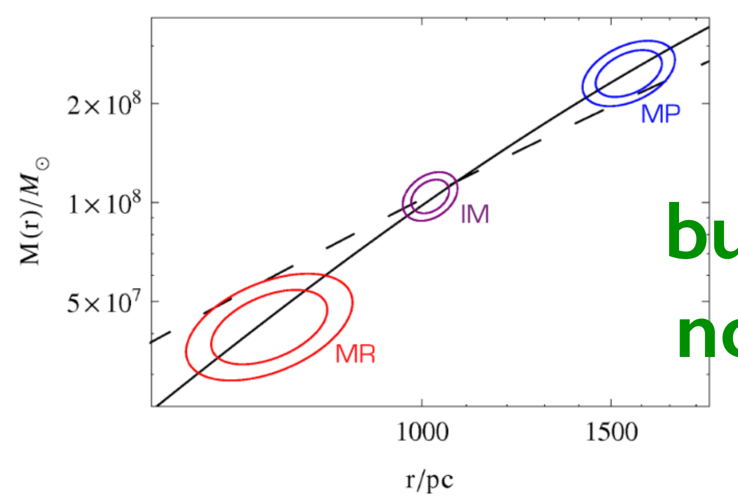
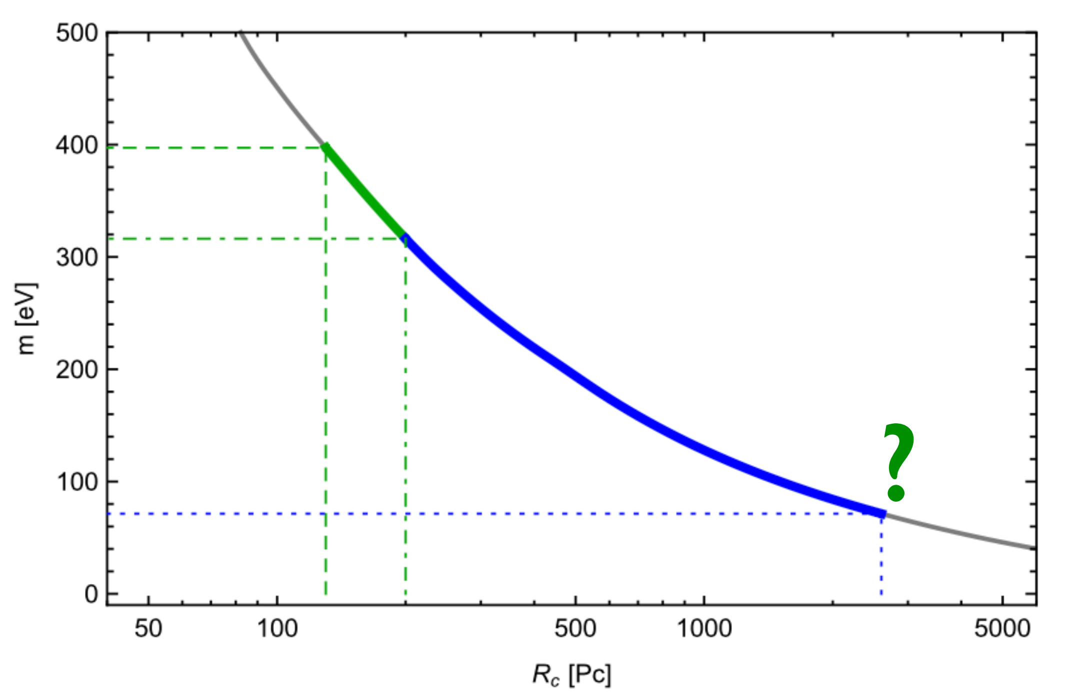


Figure 2. Left panel: estimates of the total enclosed mass $M(r)$ as ob

but large cores not excluded !



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E.G. SEARCHES FOR X-RAY LINES

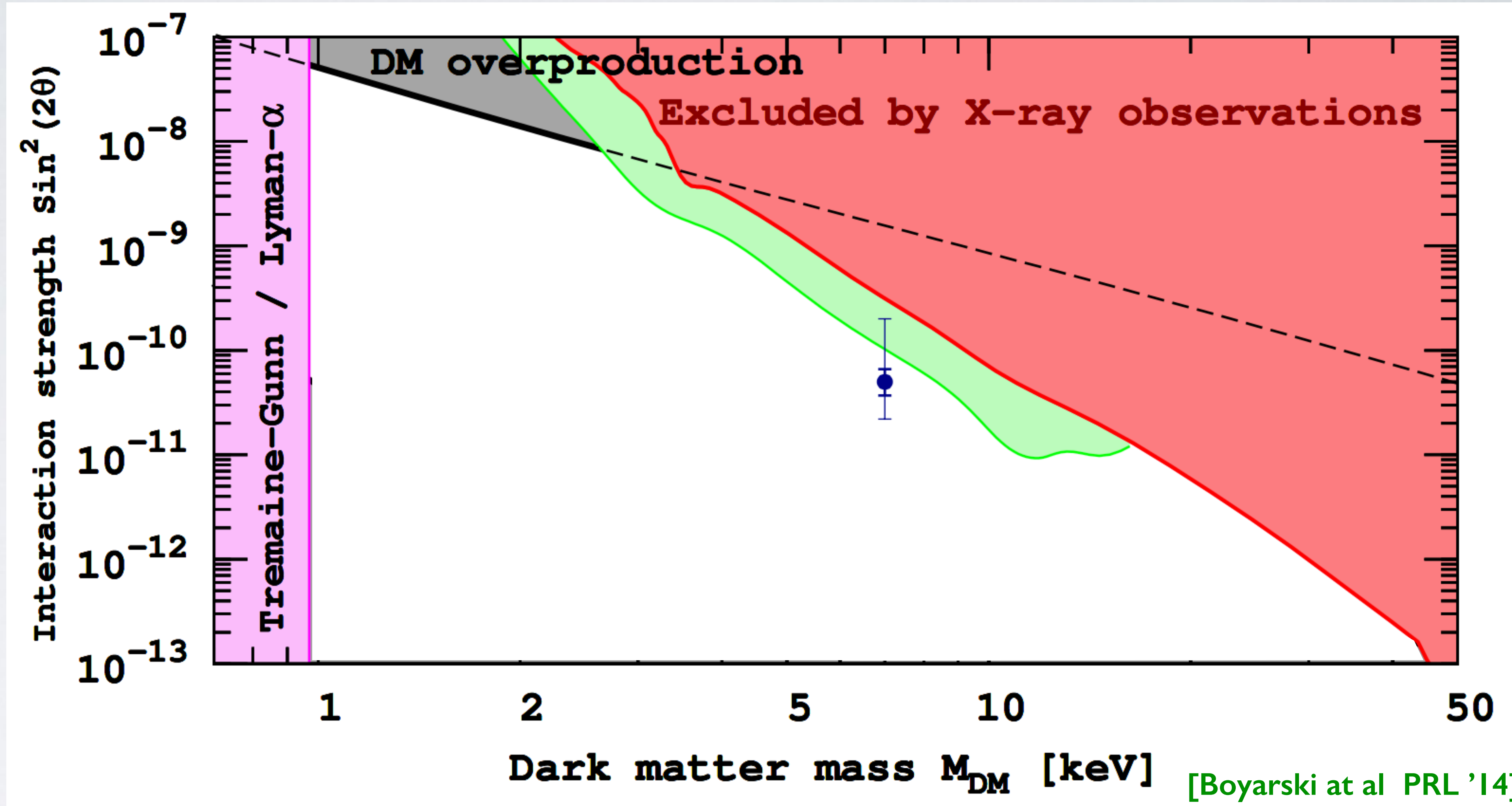

FIG. 4: Constraints on sterile neutrino DM within νMSM [9]. Recent bounds from [16, 17] are shown in green. Similar to older bounds (marked by red) they are smoothed and divided by factor 2 to account for possible DM uncertainties in M31. In every point in the white region sterile neutrino constitute 100% of DM and their properties agree with the existing bounds. Within the gray regions too much (or not enough) DM would be produced in a minimal model like νMSM. At masses below ~ 1 keV dwarf galaxies would not form [4, 48]. The blue point would corresponds to the best-fit value from M31 if the line comes from DM decay. Thick errorbars are $\pm 1\sigma$ limits on the flux. Thin errorbars correspond to the uncertainty in the DM distribution in the center of M31.

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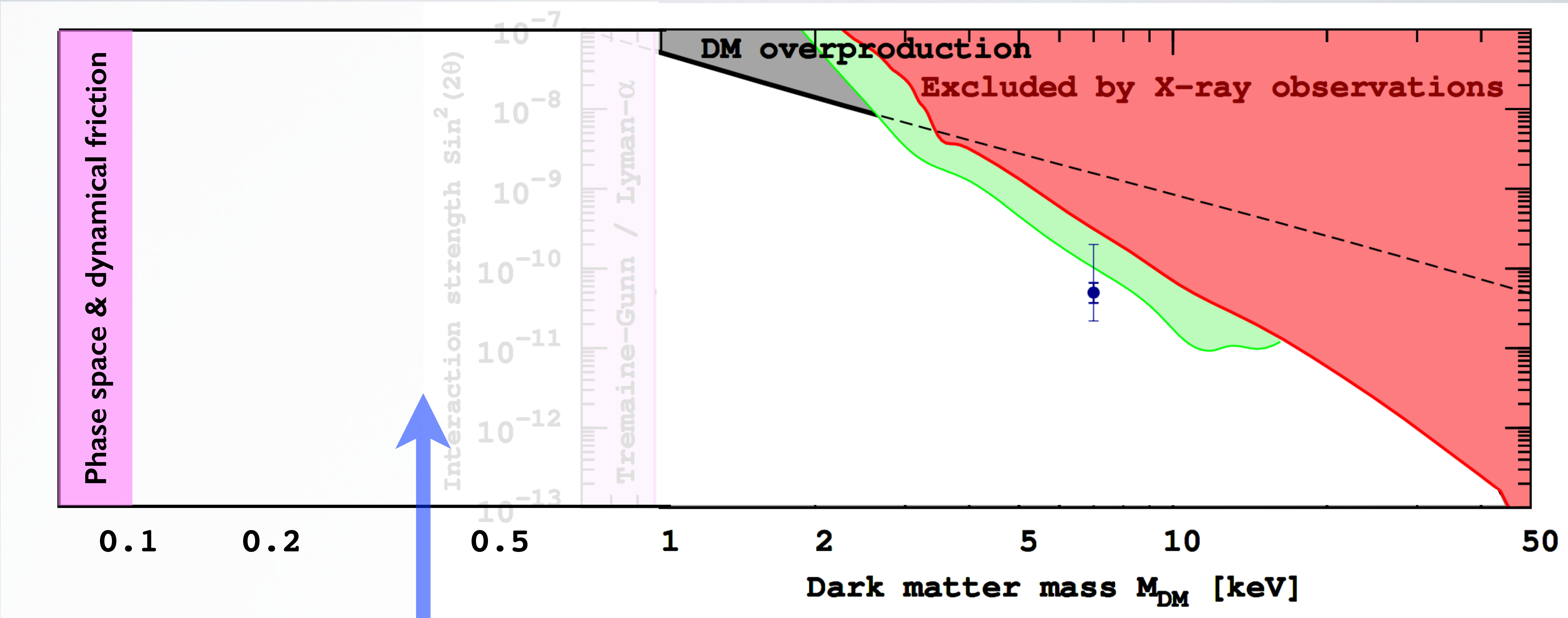


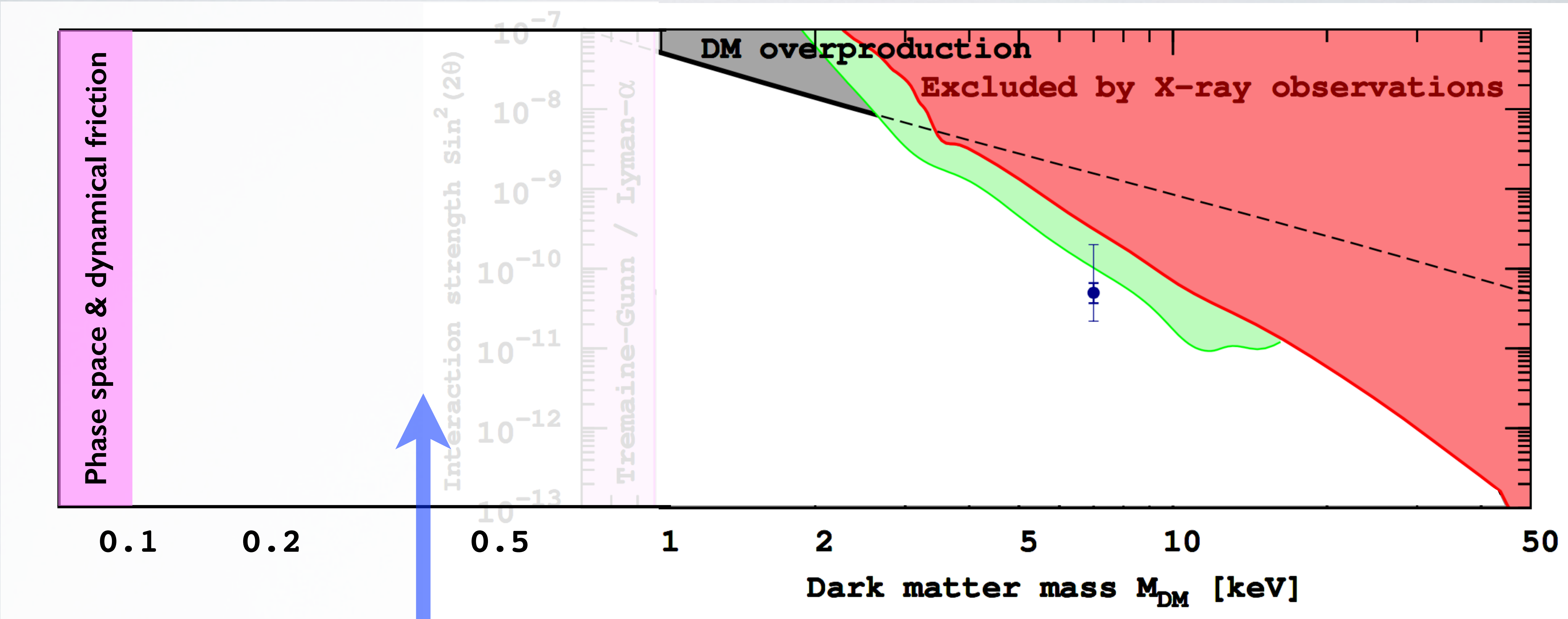
more space for sterile neutrinos

The Lyman-alpha bound $m > 1$–7 keV …

…can be evaded if WDM is cold :) e.g.

- generated via decay [Patraki-Kusenko '08]
- w/ dilution [Bezrukov+ '10] [Nemevsek, Senjanovic, Zhang '12]
- …

E.G. SEARCHES FOR X-RAY LINES



more space
for sterile neutrinos

(and btw how to search for them?)

The Lyman-alpha bound $m > 1\text{–}7$ keV …
…**can be evaded if WDM is cold :)** e.g.

- generated via decay
  [Patraki-Kusenko '08]
- w/ dilution
  [Bezrukov+ '10]
  [Nemevsek, Senjanovic, Zhang '12]
- …

That’s all from data.

Then, a serious question is

Are degenerate fermionic galaxies physical?

PHASE SPACE DISTRIBUTIONS

- For classical models (~maxwellian, intermediate momenta dominate)

- To be compared with degenerate FD

  Lower momenta, Denser.

Will the distribution collapse? How?

[Navarro Eke Frenk ’96]

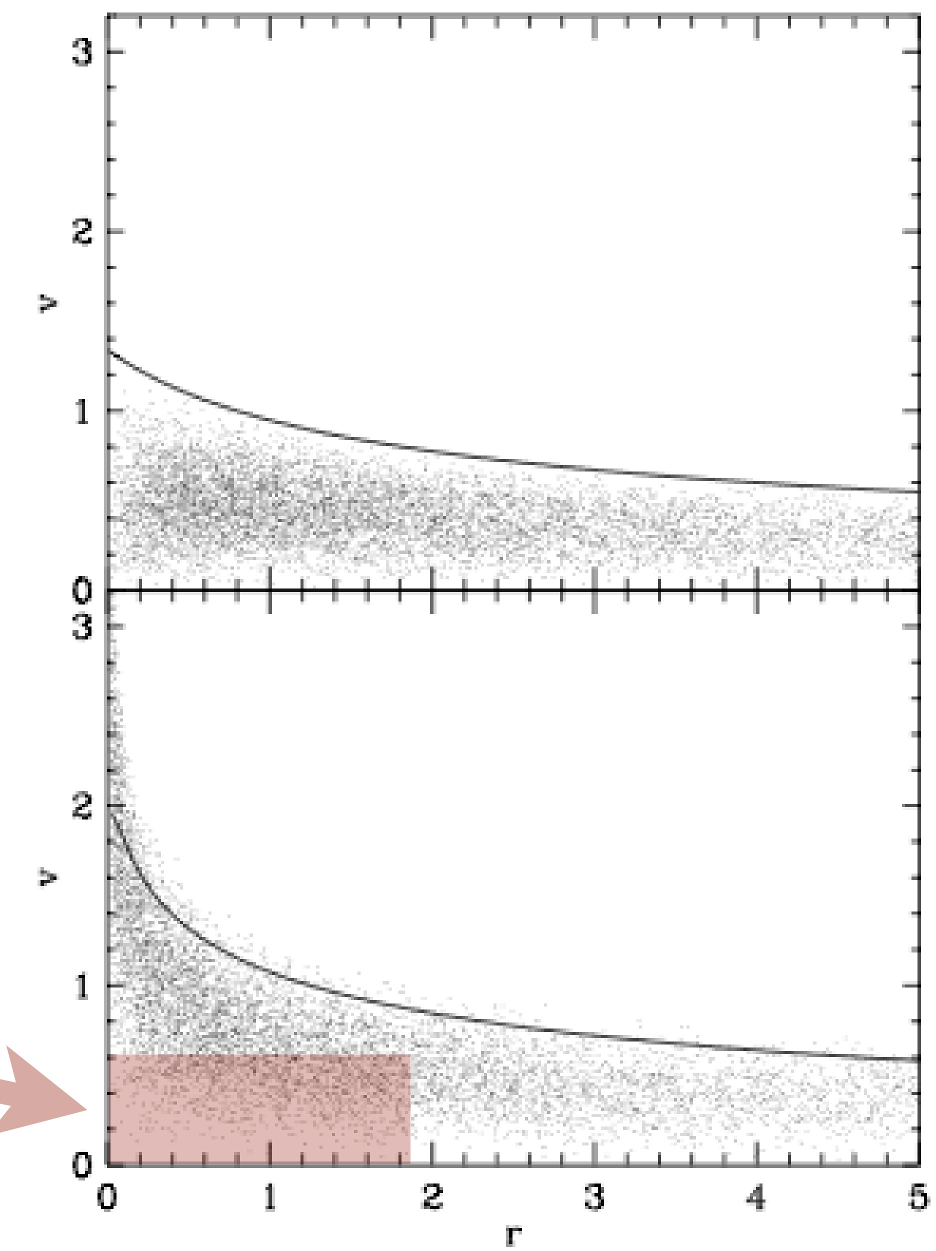
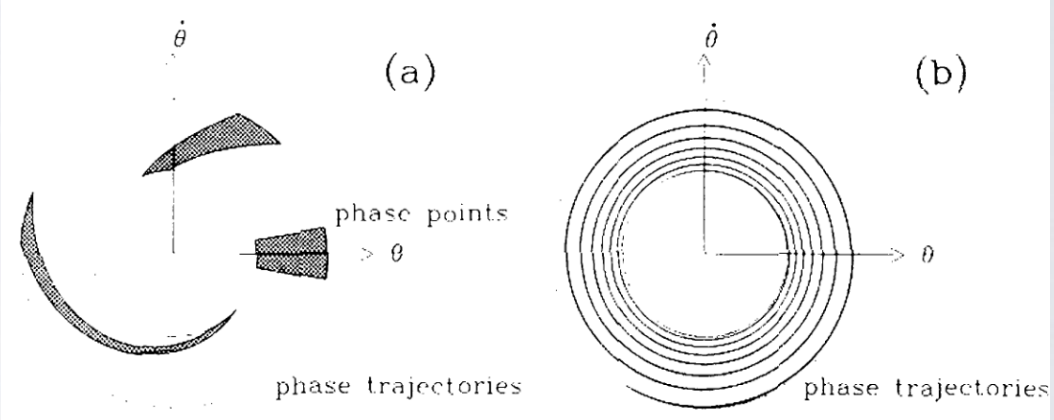


Figure 2. “Phase-space” distribution of halo particles before and after imposing the disk potential (upper and lower panel, repectively). The solid line in each panel shows the escape velocity

RELAXATION IN GALACTIC DYNAMICS

- **Encounters?** No - play a role only for few objects
  ($T = T_{crossing}$ 0.1N/logN, here N~10^70, very large)
  Thus, we are *collisionless*

- **Phase mixing?** *Relaxation for ignorance.*
  Not relevant to get degeneration
  (phase space has to be fully filled)



- **Violent relaxation?**
  changes energy per unit mass (i.e. independent of mass)
  (collision independent - assumes motion in a changing potential)

- **In any case, would need interaction**
  e.g. dissipation, to increase phase-space density (SIMD → fermi cores?)

SO, CONCLUSIONS

- Quantum degenerate fermionic DM may avoid cusps in dwarfs

- Revisiting lower bound from existence of small galaxies:

  Tremaine-Gunn + Dynamical Friction

  $m > 100\mathrm{eV}$

  challenging Direct Search

  - Missing satellite problem (helps SIDM?)

    hint to upper bound $m < \text{few keV}$?

- Smallest galaxies are the frontier - confrontation with data hard dispersion anisotropy the main nuisance.

- Physics of fermionic galaxy formation the outstanding question

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Thanks!

OTHER DSPH

Using triaxial fits from [Hayashi et al. '16]

the huge fit ranges

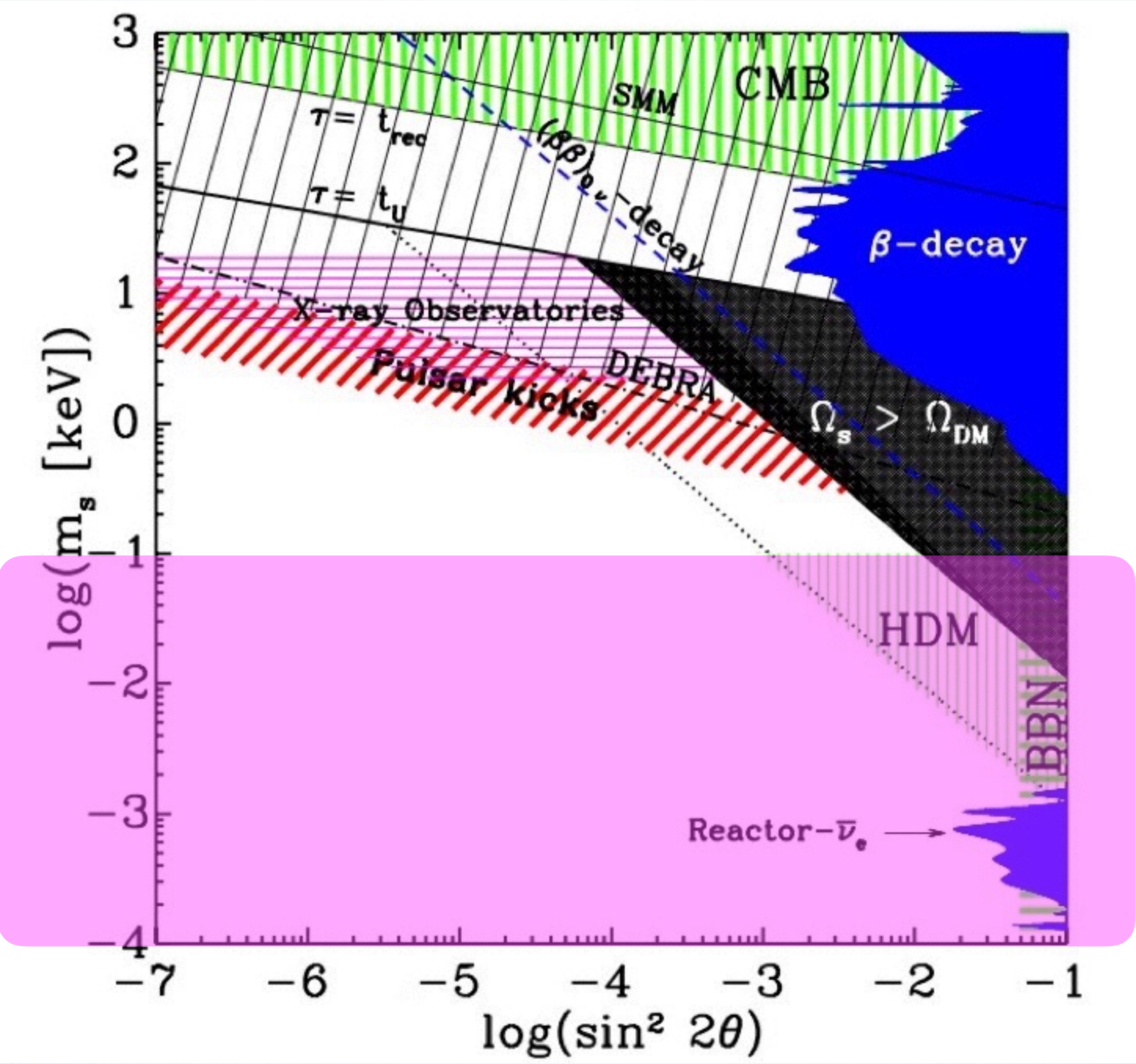
Table 2. Parameter constraints for MW dSph satellites. Errors correspond to the 1σ range of the our analysis.

Object	α	i [deg]
Classical dwarfs		
Carina	$-1.0^{+0.4}_{-0.2}$	71^{+14}_{-15}
Fornax	$-0.2^{+0.1}_{-0.2}$	72^{+12}_{-15}
Sculptor	$-0.3^{+0.2}_{-0.3}$	68^{+16}_{-12}
Sextans	$-0.6^{+0.4}_{-0.5}$	72^{+13}_{-13}
Draco	$-1.0^{+0.2}_{-0.1}$	59^{+15}_{-7}
Leo I	$-1.2^{+0.6}_{-0.4}$	60^{+19}_{-14}
Leo II	$-1.0^{+0.5}_{-0.4}$	62^{+19}_{-17}
Ultra faint dwarfs		
Segue 1	$-2.0^{+0.8}_{-0.6}$	73^{+11}_{-11}
Segue 2	$-1.4^{+1.0}_{-1.0}$	54^{+23}_{-16}
Boötes I	$-0.7^{+0.5}_{-0.6}$	77^{+9}_{-11}

Table 1. Estimated lower bound on the fermionic DM mass m from a number of dwarf spheroidal galaxies, adopting the central densities as determined in Hayashi et al. (2016).

DSph	Log ρ_0 [$M_\odot/pc^3$]	d_0 [kpc]	lower bound on m
Triangulum II	0.3	30	127 eV
Segue 1	−0.4	32	100 eV
Leo T	−0.6	417	26 eV
Reticulum II	−0.8	32	89 eV
Ursa Major I	−0.8	106	49 eV
Coma Berenices	−0.8	44	76 eV
Sculptor	−0.8	86	54 eV
Fornax	−1.1	147	38 eV
Ursa Major II	−1.2	32	80 eV
Leo I	−1.3	254	27 eV
Canes Venatici II	−1.4	151	34 eV
Hercules	−1.4	132	37 eV
Pisces II	−1.5	180	30 eV
Leo IV	−1.7	158	31 eV
Leo II	−1.7	233	25 eV
Draco II	−1.9	20	82 eV
Sextans	−2.	86	38 eV
Canes Venatici I	−2.2	224	22 eV
Carina	−2.2	106	33 eV
Bootes I	−2.4	66	39 eV
Leo V	−2.6	178	22 eV
Draco	−2.7	76	33 eV
Hydra II	−3.1	134	22 eV
Segue 2	−3.2	35	43 eV

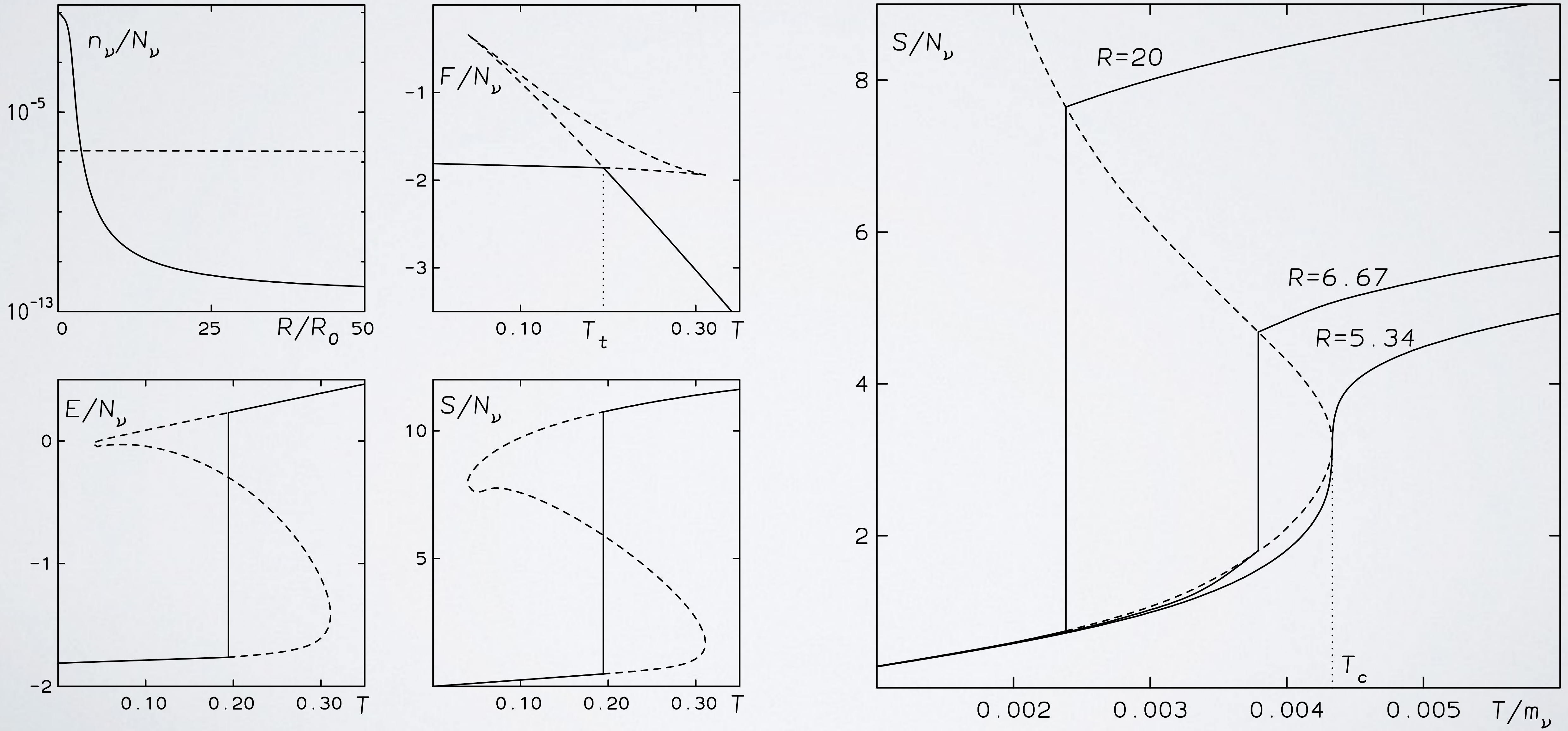
Adding dynamical friction bound



CMB
SMM
τ = t_rec
τ = t_U
(ββ)0ν-decay
β-decay
X-ray Observatories
DEBRA
Pulsar kicks
Ω_s > Ω_DM
HDM
BBN
Reactor-ν̄e
log(m_s [keV])
log(sin² 2θ)
3
2
1
0
−1
−2
−3
−4
−7
−6
−5
−4
−3
−2
−1

PHASE TRANSITION TO DEGENERATE?

possible, because gravity is attractive [Hertel Thirring '71]



[Bilić Viollier '98]

RELAXATION IN GALACTIC DYNAMICS

What about for fermions?

- Fermions interact only with near-fermi-surface states, so even reduced encounters? (and slow ones bounce off)

- Violent relaxation only possibility? (collisionless interaction)
  But are timescales of Potential variation sufficiently long?
  Still an open problem it seems [Chavanis '01-'03]

- BTW: violent relaxation leads to Fermi Dirac - like distribution, even for bosons… [Lynden-Bell '67]
  (thus, we may say it's compatible)

SO IS IT ACTUALLY REALIZED?

Favourable (free)energy budget necessary for phase transition, not sufficient.

Self-gravitating systems like DM halos are **intrinsically non equilibrium…**

So what matter are the timescales... **Relaxation, thermalization, evaporation. ?**

- **Fermionic jeans instability has lower k bound, degeneracy historically relevant** [Chavanis+ 1409xxxx]
- Ideal violent relaxation leads to core plus 1/r^2 [Lynden Bell '67]
  but incomplete violent relaxation can lead to large distance cutoff
  as also evaporation
- Simulations of classical violent relaxation lead to core plus 1/r^4
  [Henon '64;van Albada+ '82; Roy+ '04; Joyce+'09]
  due to thermalization + evaporation after core formation (but it appears to be slow?).

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Looking forward to quantum simulations?