Ultra light axion dark matter and small scale problems

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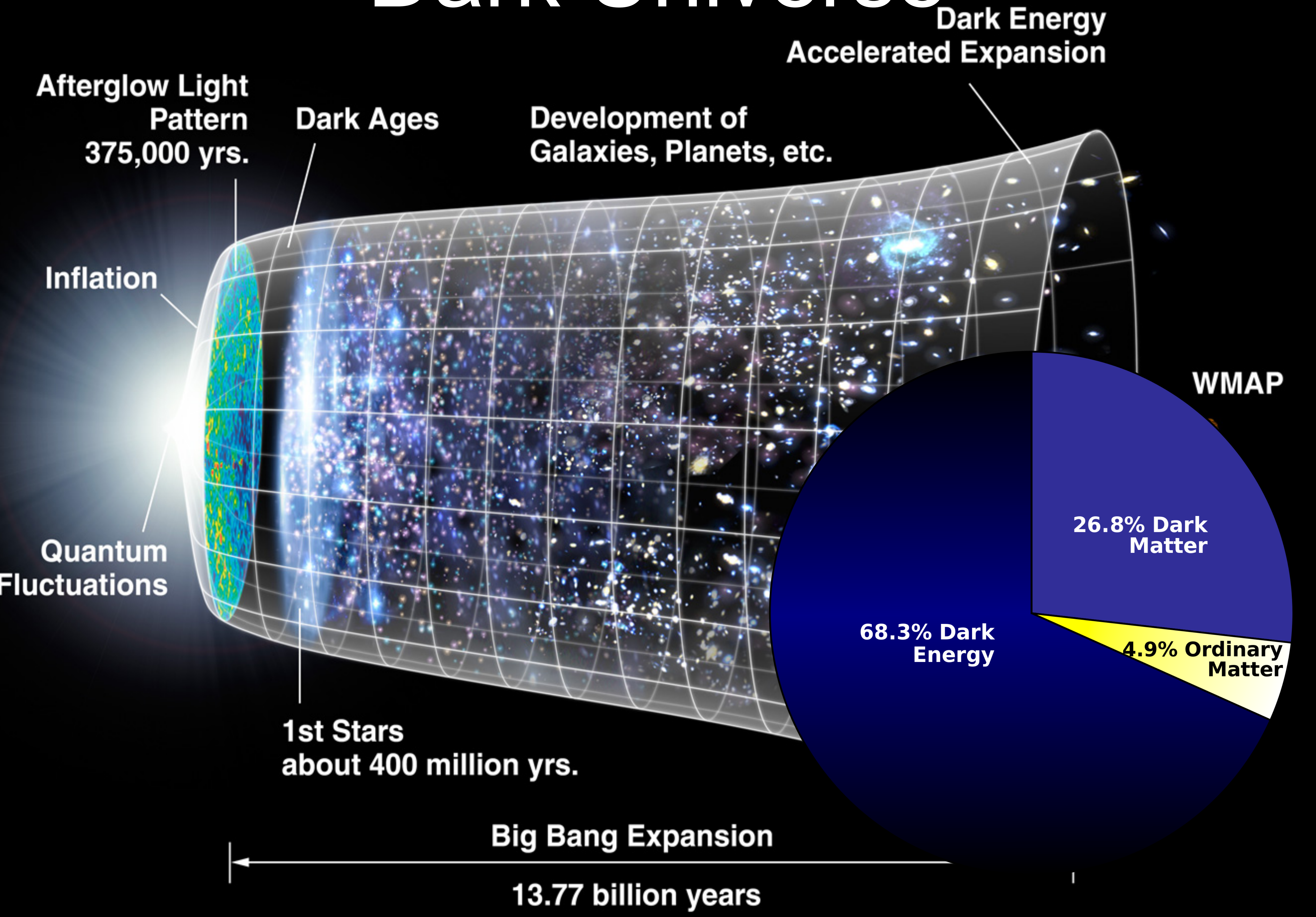
Contents

Introduction

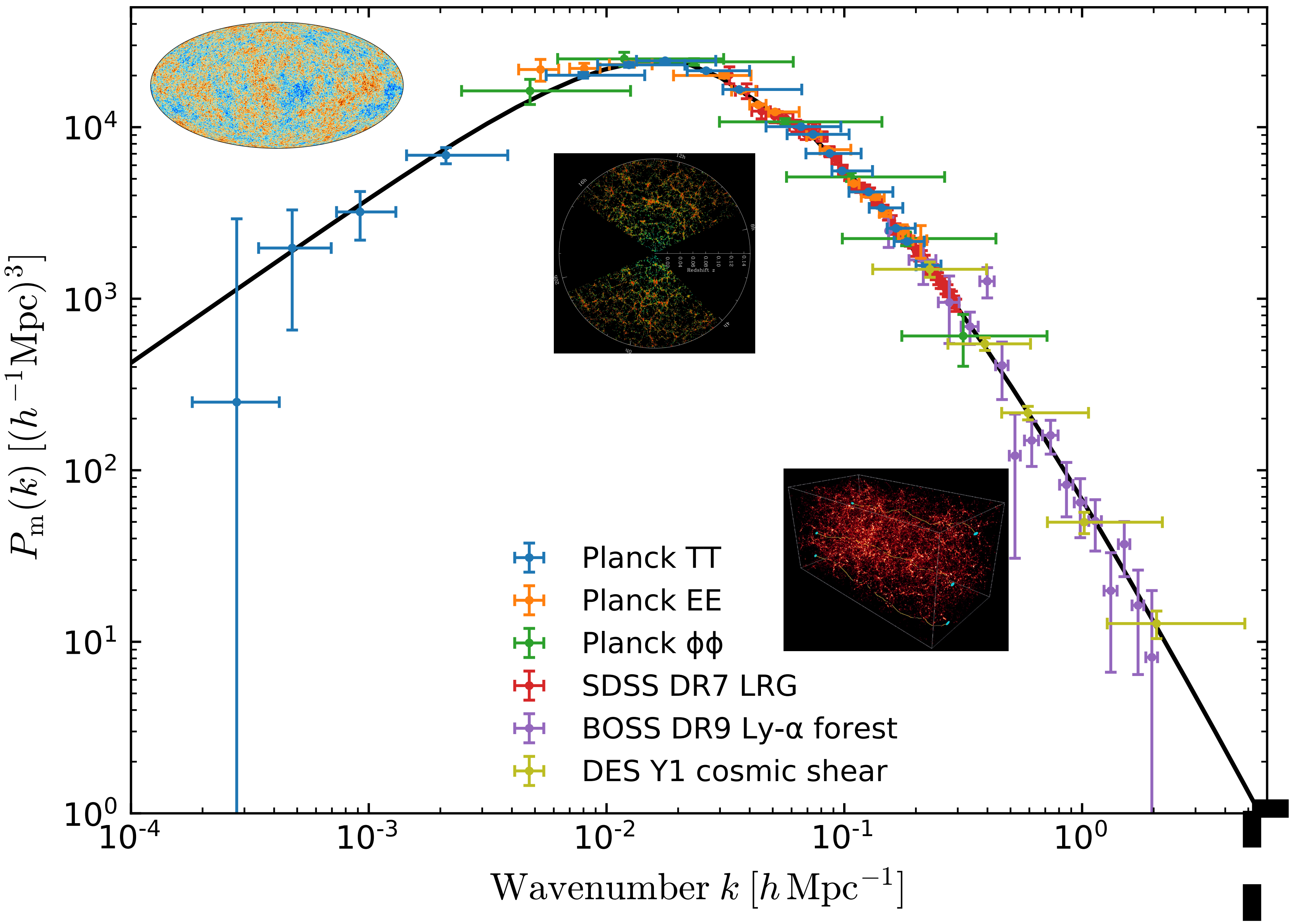
Cold dark matter theory
and
dwarf spheroidal galaxies

Dark Universe



Λ Cold Dark Matter model

ESA and the Planck Collaboration

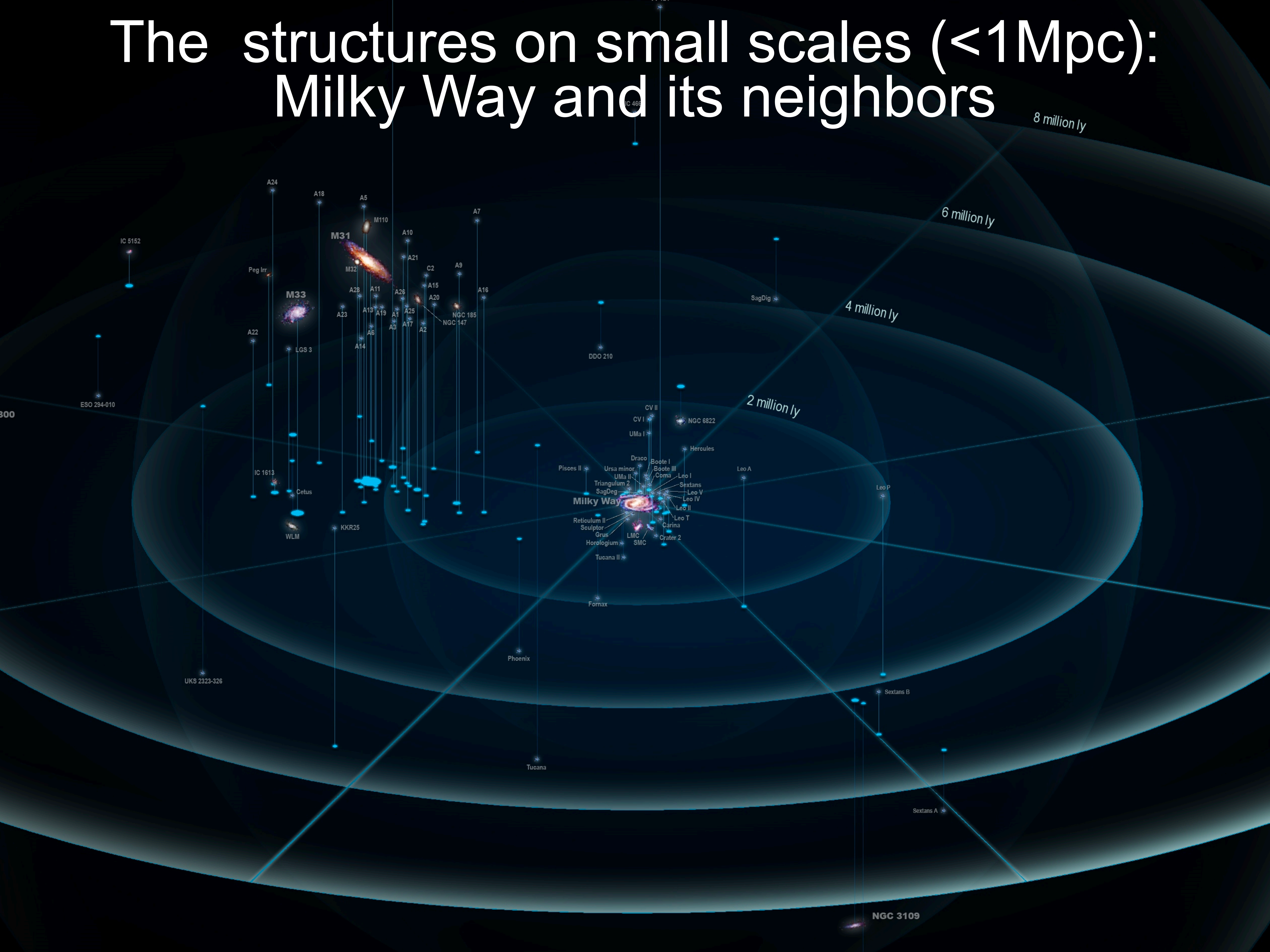


Large scale (> 1Mpc)
⇒ Remarkable success!

Small scale (<1 Mpc)
⇒ What's going on?

?

The structures on small scales (<1Mpc): Milky Way and its neighbors



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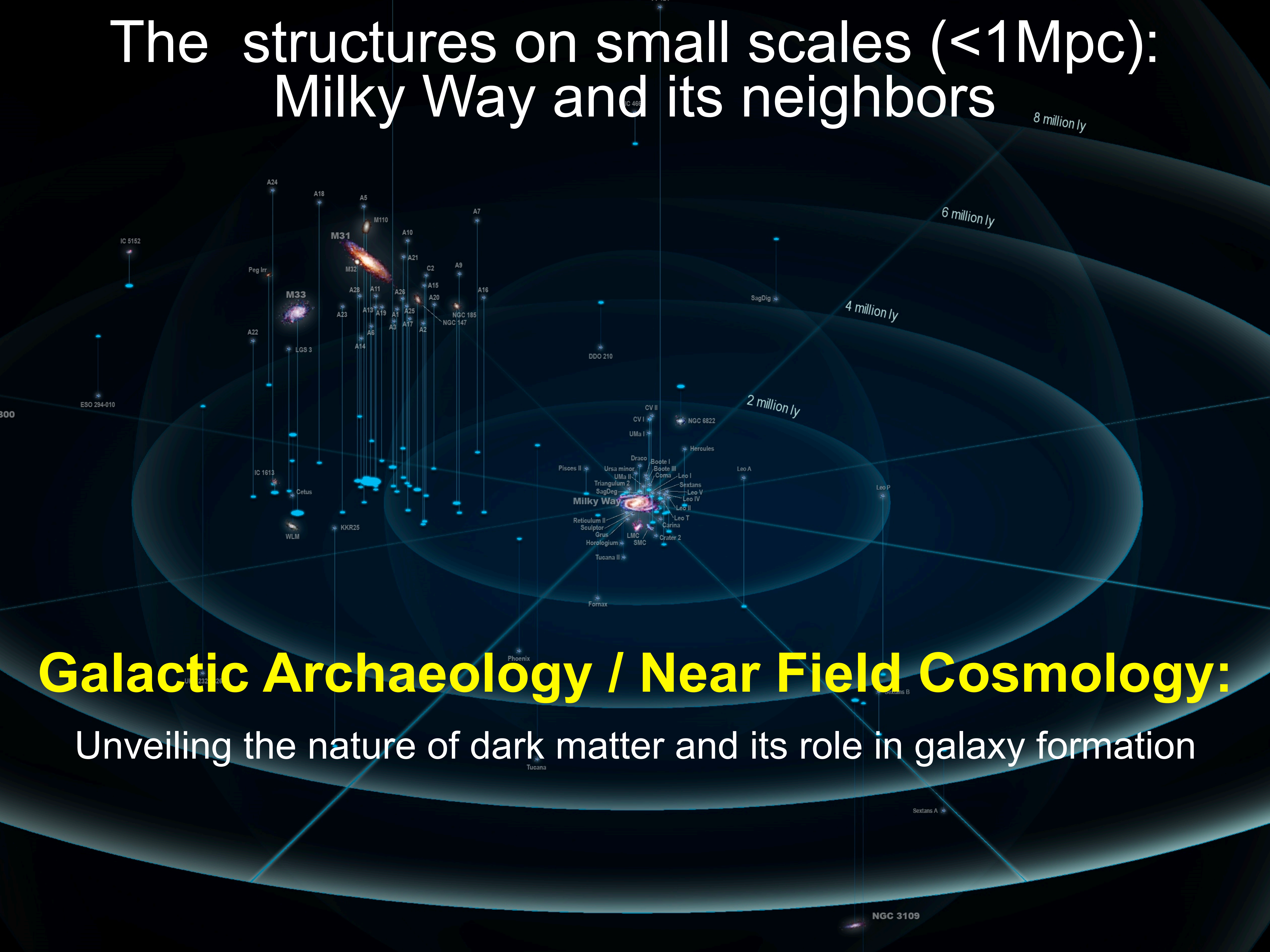
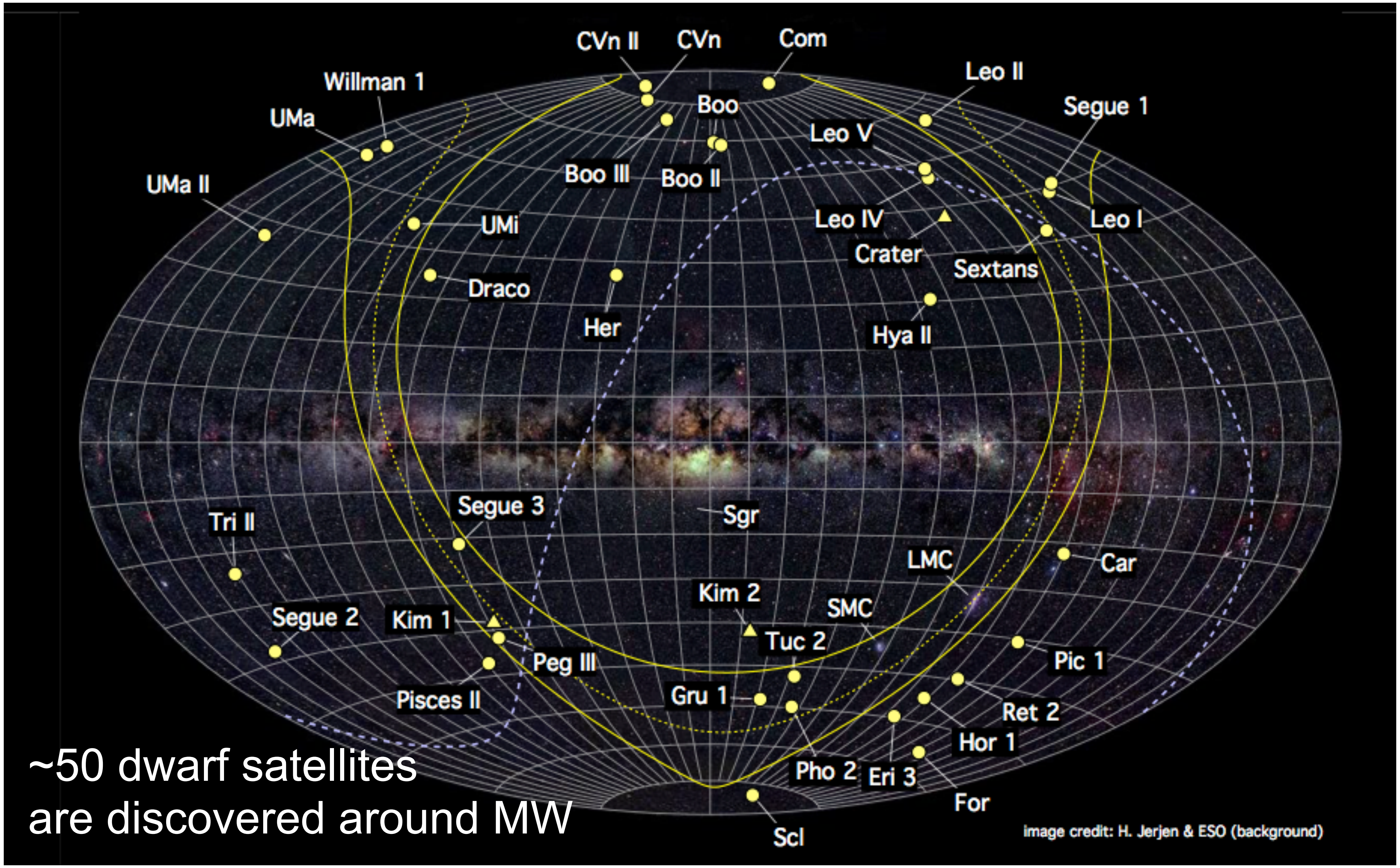


Galactic Archaeology / Near Field Cosmology:

Unveiling the nature of dark matter and its role in galaxy formation

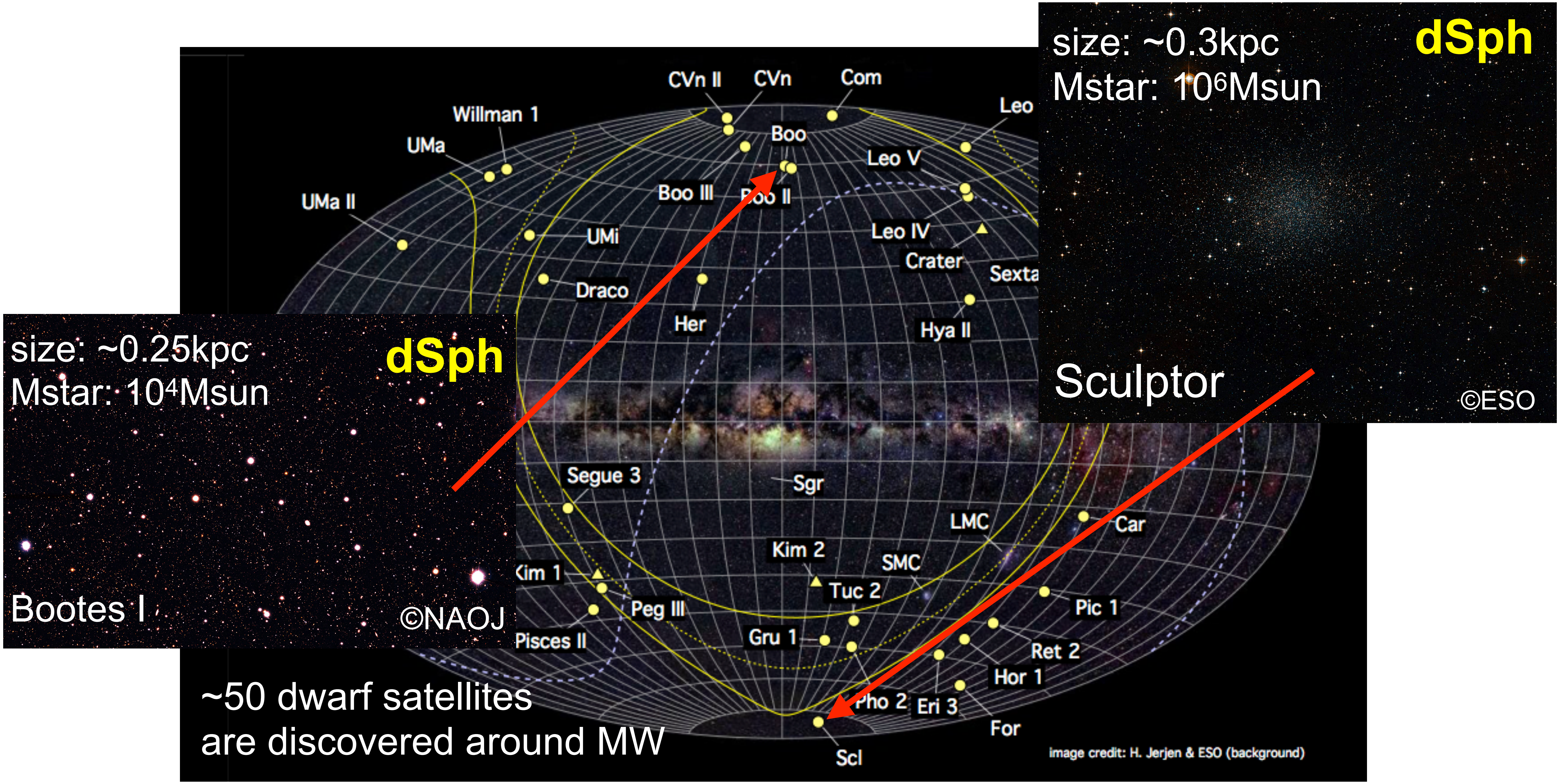
Dwarf Spheroidal Galaxy (dSph): basic properties



~50 dwarf satellites
are discovered around MW

image credit: H. Jerjen & ESO (background)

Dwarf Spheroidal Galaxy (dSph): basic properties



size: ~0.25kpc
Mstar: 10^4Msun

©NAOJ

size: ~0.3kpc
Mstar: 10^6Msun

©ESO

~50 dwarf satellites
are discovered around MW

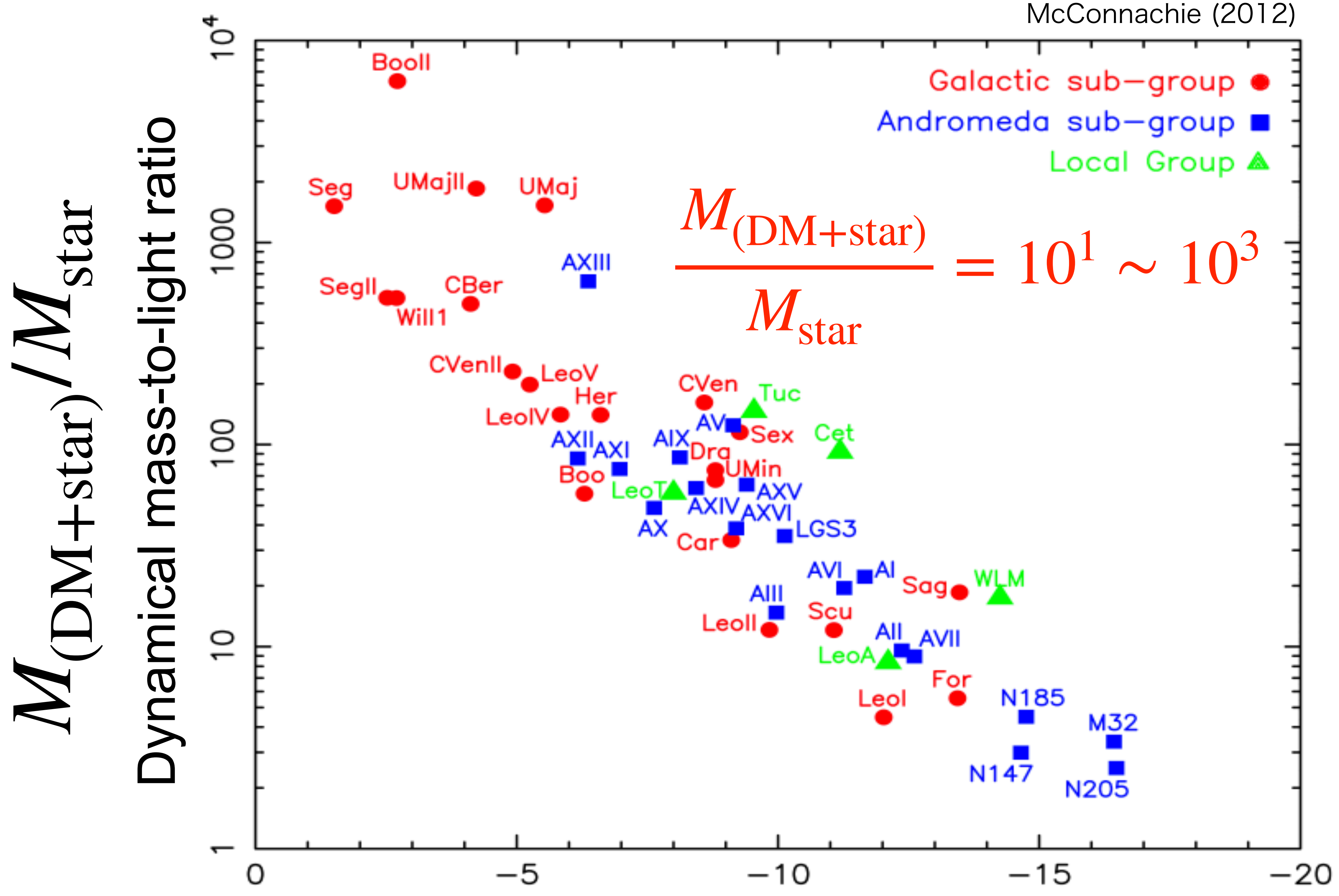
image credit: H. Jerjen & ESO (background)

- ✤ no gas, no current SF
- ✤ smallest and oldest galaxy

➜ **Fossil records of galaxy formation**

dSphs: dark-matter dominated system

McConnachie (2012)



$$\frac{M_{(\mathrm{DM+star})}}{M_{\mathrm{star}}} = 10^1 \sim 10^3$$

DSphs are ideal sites for studying the nature of DM!

Small scale problems in ΛCDM models

Small-scale challenges to ΛCDM paradigm

Definition of "small scales"

$$M_{\rm virial} < 10^{11} M_\odot, k > 3{\rm Mpc}^{-1}, r < 1{\rm Mpc}$$

$$\Longrightarrow r_{\rm vir} < 150{\rm kpc}, V_{\rm virial} < 50{\rm km/s}$$

i.e., galaxy and dwarf-galaxy scales

Bullock &
Boylan-Kolchin (2017)

✦ **Missing satellite problem (Moore+99, Klypin+99)**

- Overabundance of dark subhalos

✦ **Core-cusp problem (de Blok 2002, Gilmore+ 07)**

- Cuspy central density in CDM halos vs. cores in observed galaxies

✦ **Too-big-to-fail problem (Boylan-Kolchin+ 11)**

- Most massive subhalos are more concentrated than observed luminous satellites

+ the other problems (Pawlowski+ 12, KH & Chiba 12)

(satellite planes, shapes of dark halo, etc…)

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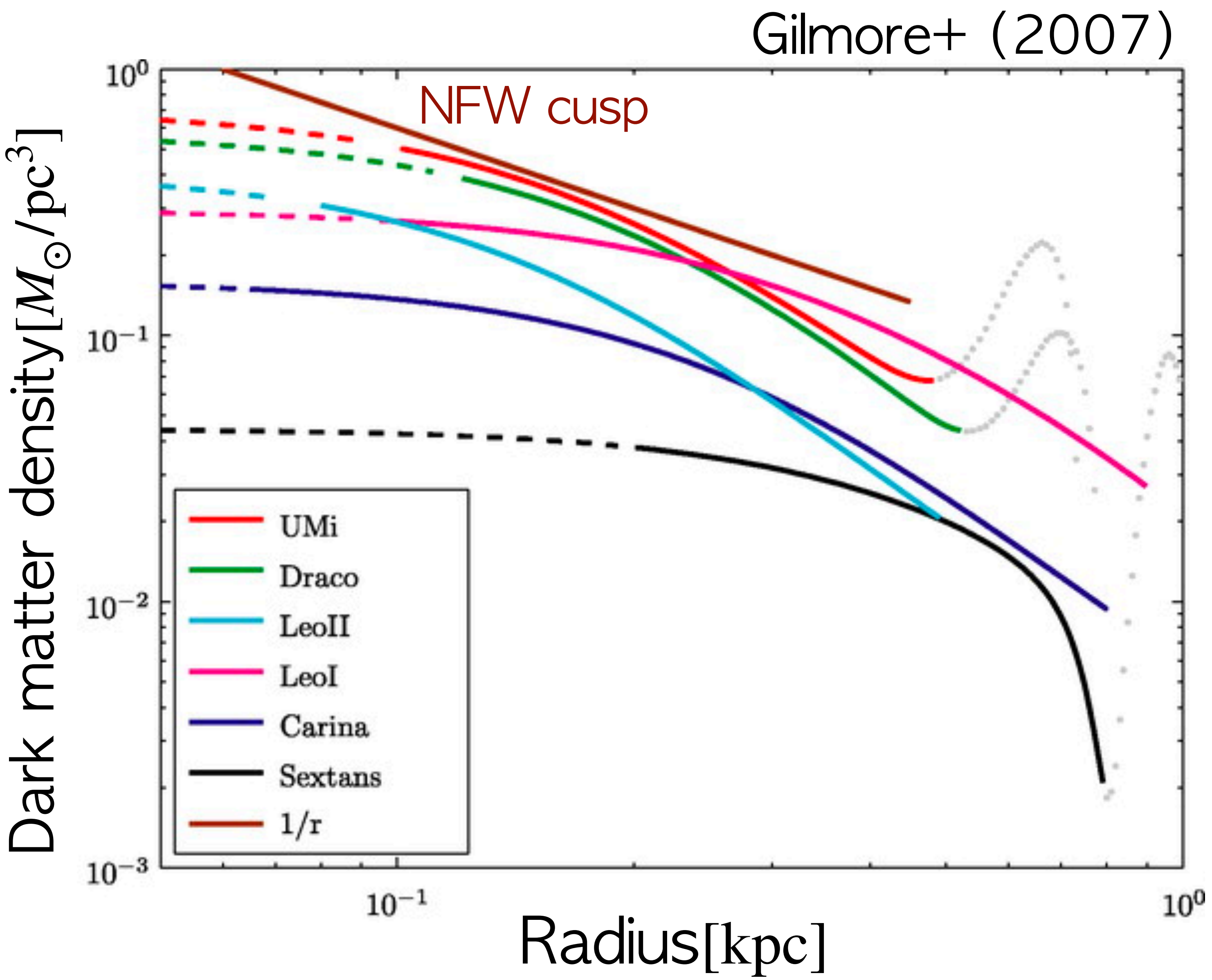
Solution to core-cusp problem

✦ Core-cusp problem

- Cuspy central density in CDM halos vs. cores in observed galaxies



Possible solutions:

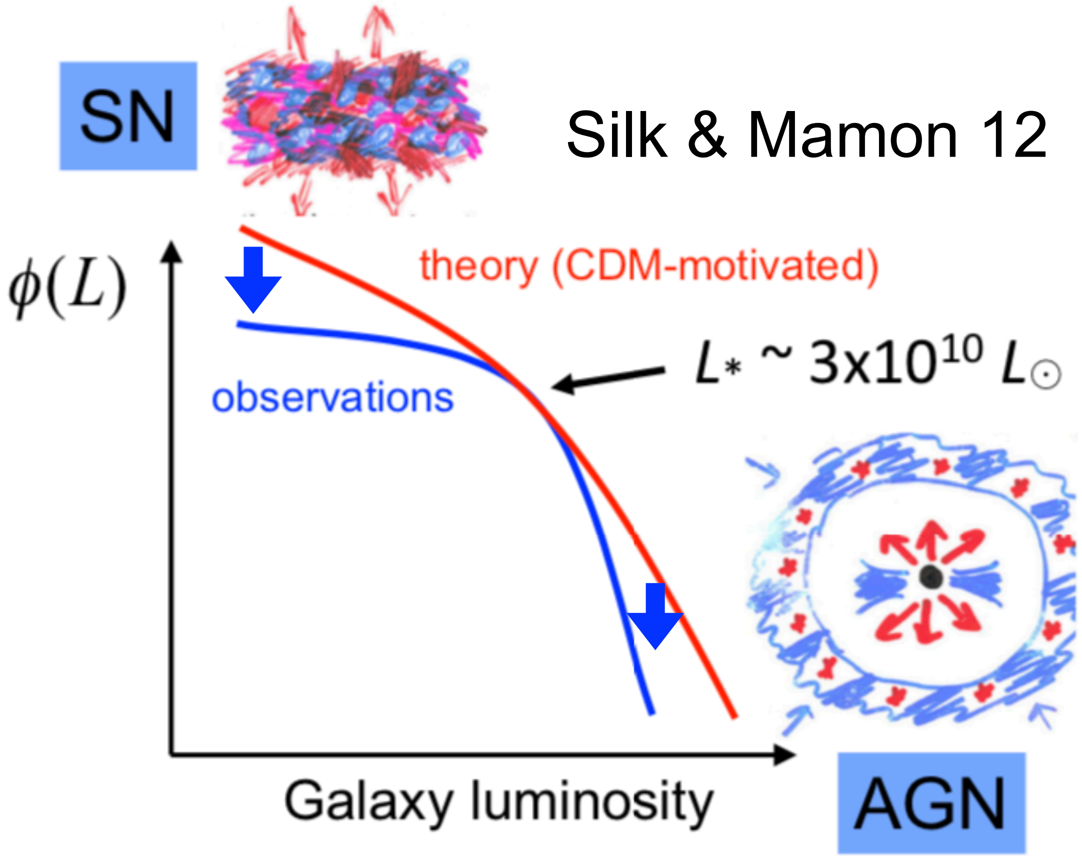
- **Baryonic feedback**
  Stellar feedbacks such as SNe can transform central cusp into cored dark matter profiles.
- **Alternative dark matter models**
  The other dark matter models motivated by particle physics (SIDM, SIMP, Axion..) can create a cored density profiles without relying on any baryon effects.

Caveats:

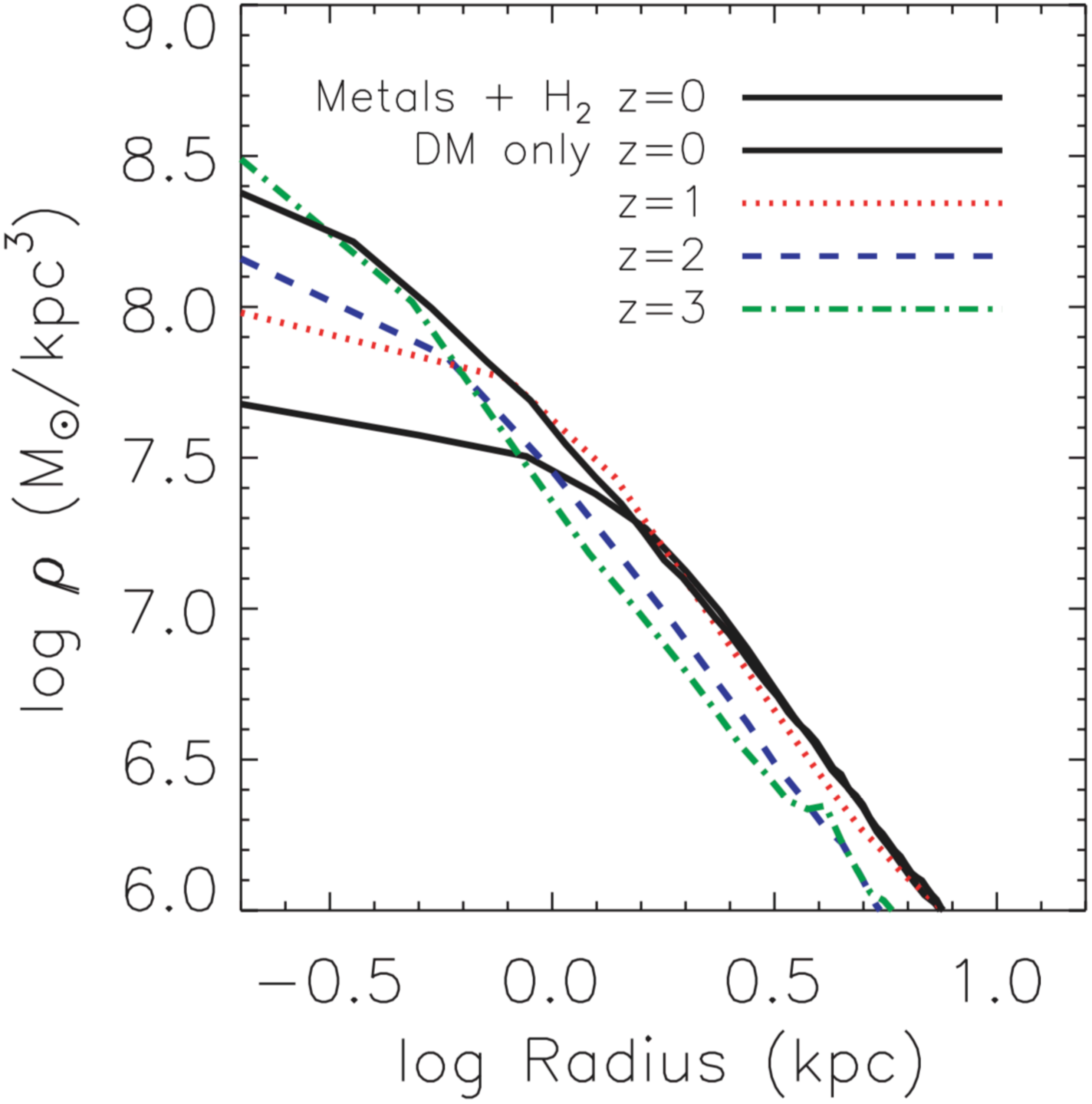
- **Incomplete observed data**
- **Uncertainties on dynamical analysis**

Solution to core-cusp problem

- Baryonic feedback



Silk & Mamon 12



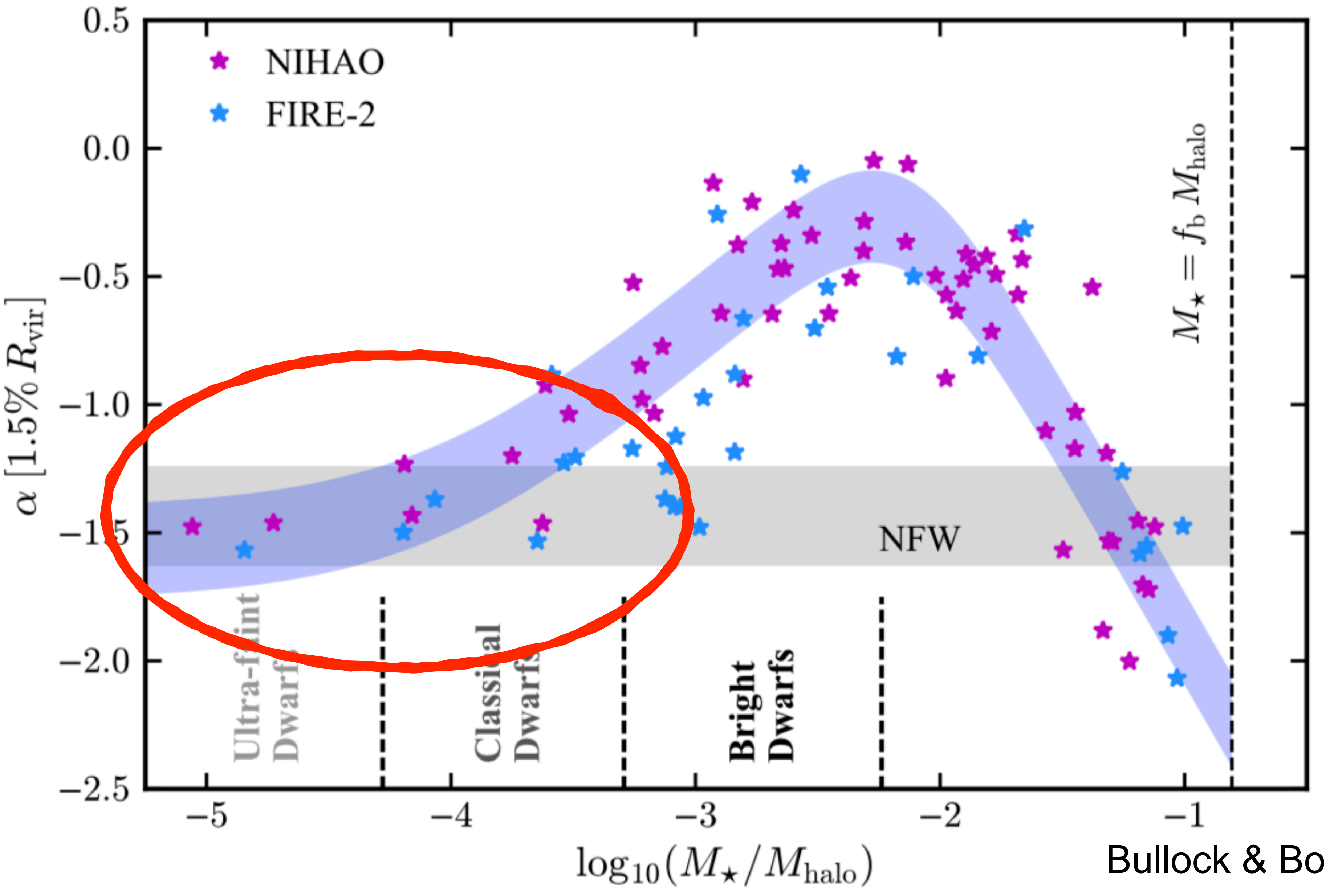
Governato+ 12

- Supernova feedback is dominated in less-massive galaxies.
- Numerical simulations have predicted that this feedback process can transform central cusp into cored dark matter profiles.

Solution to core-cusp problem

- Baryonic feedback

Recent high resolution simulations argue that **the impact of baryonic feedback is negligible on classical and ultra faint dwarf galaxy mass scales**.

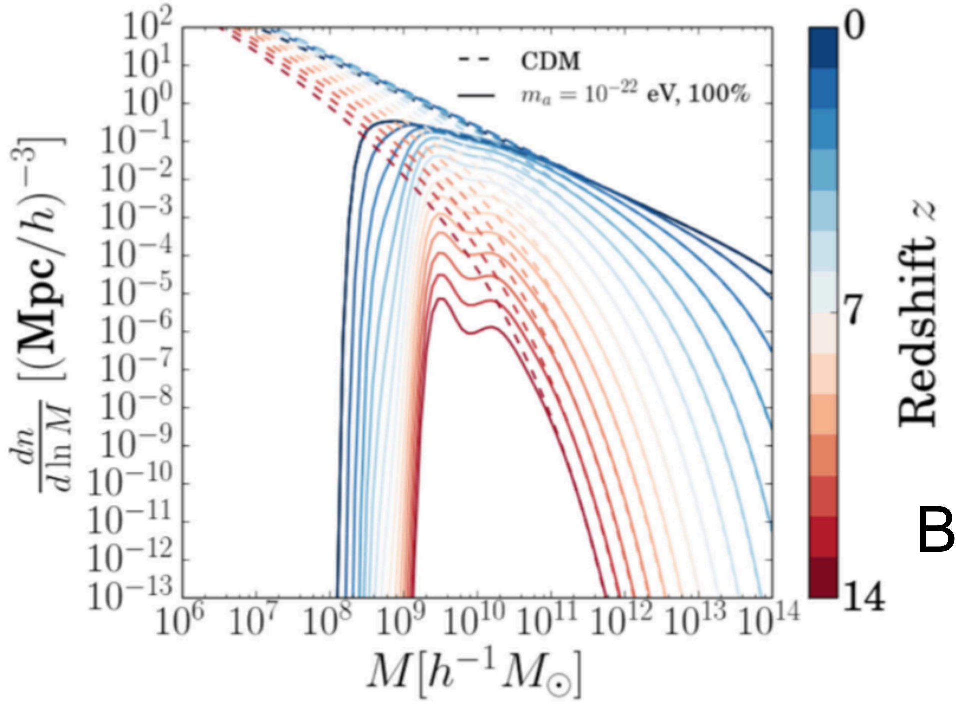


Bullock & Boylan-Kolchin (2017)

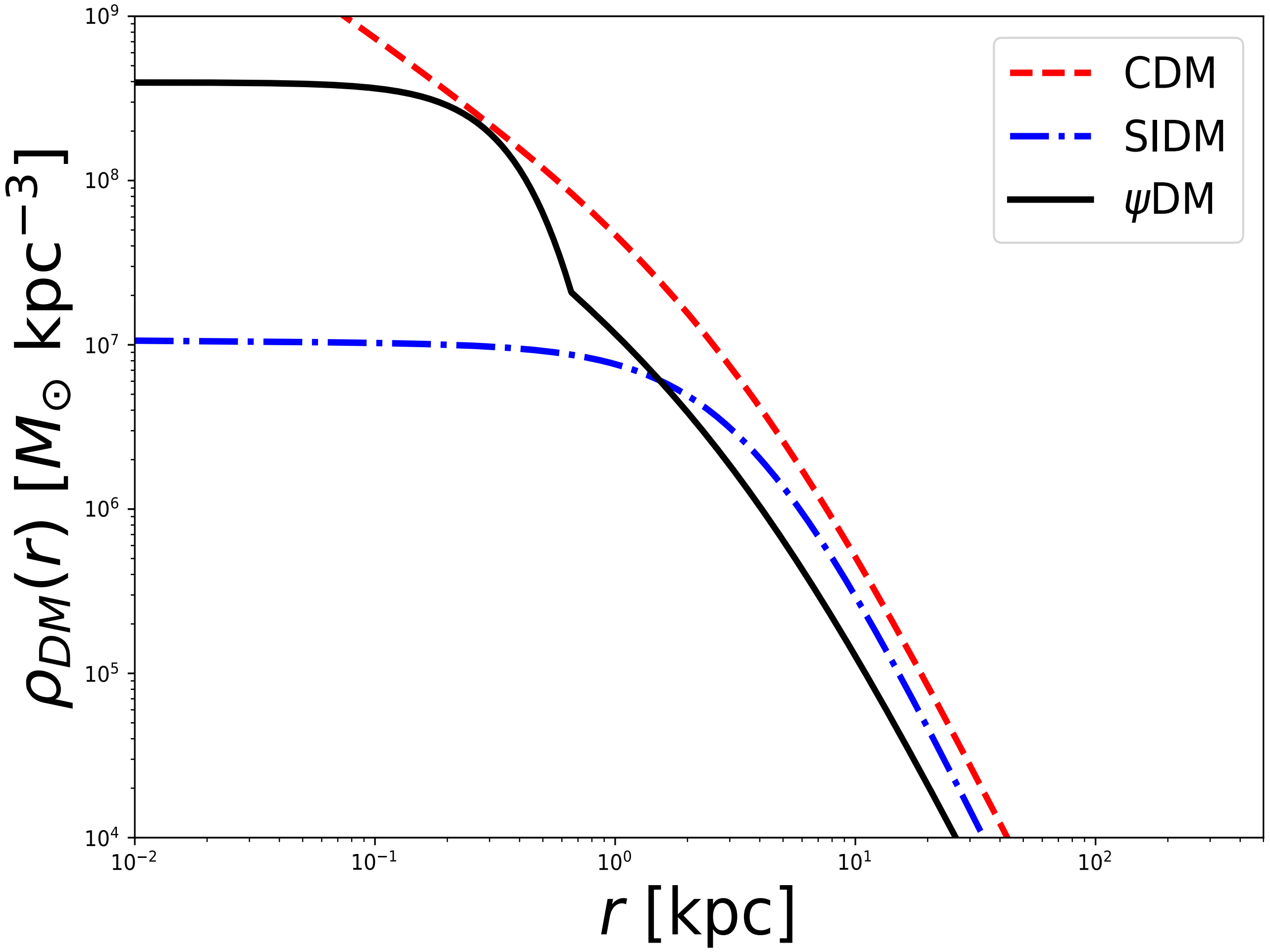
Solution to core-cusp problem

- Alternative DM models (WDM, SIDM, SIMP, Ultra light axion,…)

- Suppress the matter power spectrum on small scales.
- Dark matter cannot be concentrated on smaller spatial scales.
- Create a cored dark matter density profiles without relying on any baryon physics.



Bozek+ 15



Ultra light Axion Dark Matter

as a solution to small scale problems

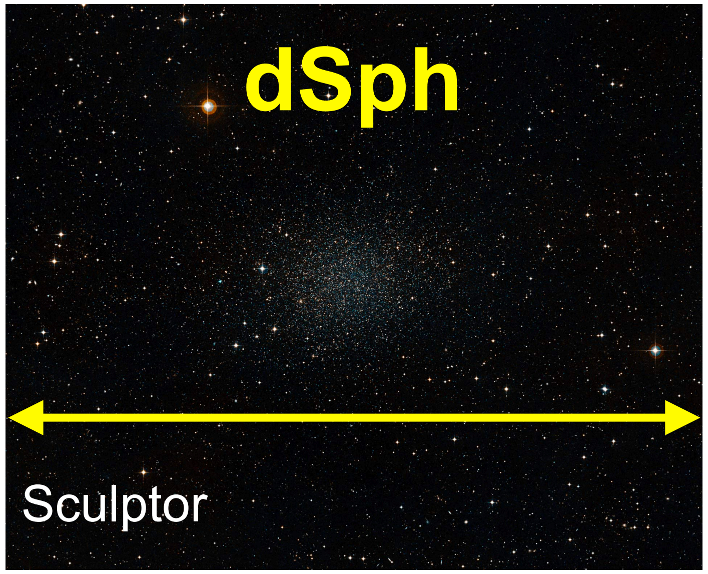
Ultralight axion dark matter (ULADM)

- The lightest particle among dark matter candidates ($m_\psi \sim 10^{-22}$ eV)

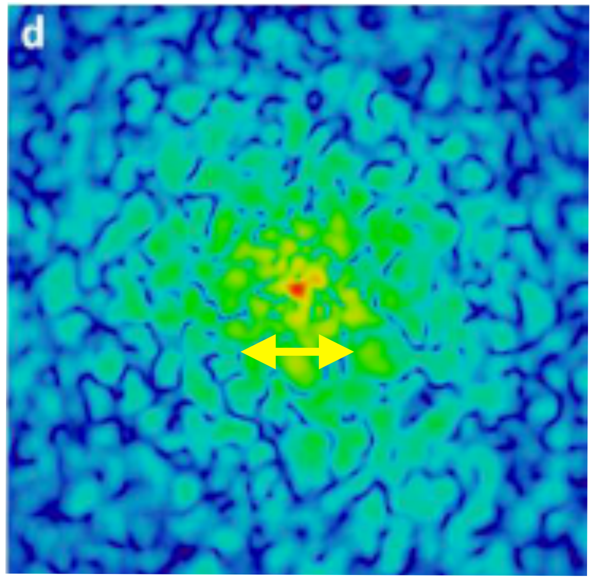
- Create a core (~kpc) comes from quantum pressure

$$r_{\rm core} \sim \lambda_{\rm dB} \equiv \frac{h}{m_\psi v}$$

- central soliton core + outer NFW DM profile



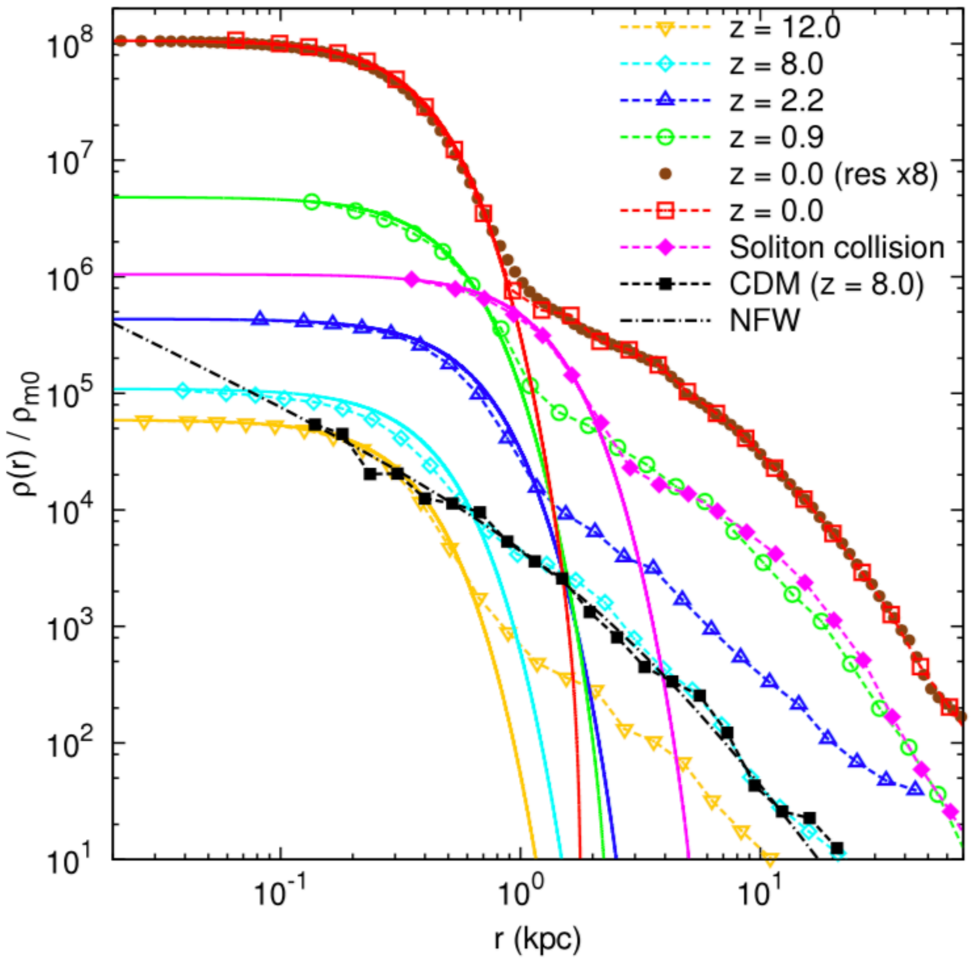
Schive et al. (2014)



Soliton-core dark matter density profile

$$\rho_{\rm soliton}(r) = \frac{\rho_{\rm c}}{[1 + 0.091(r/r_c)^2]^8}$$

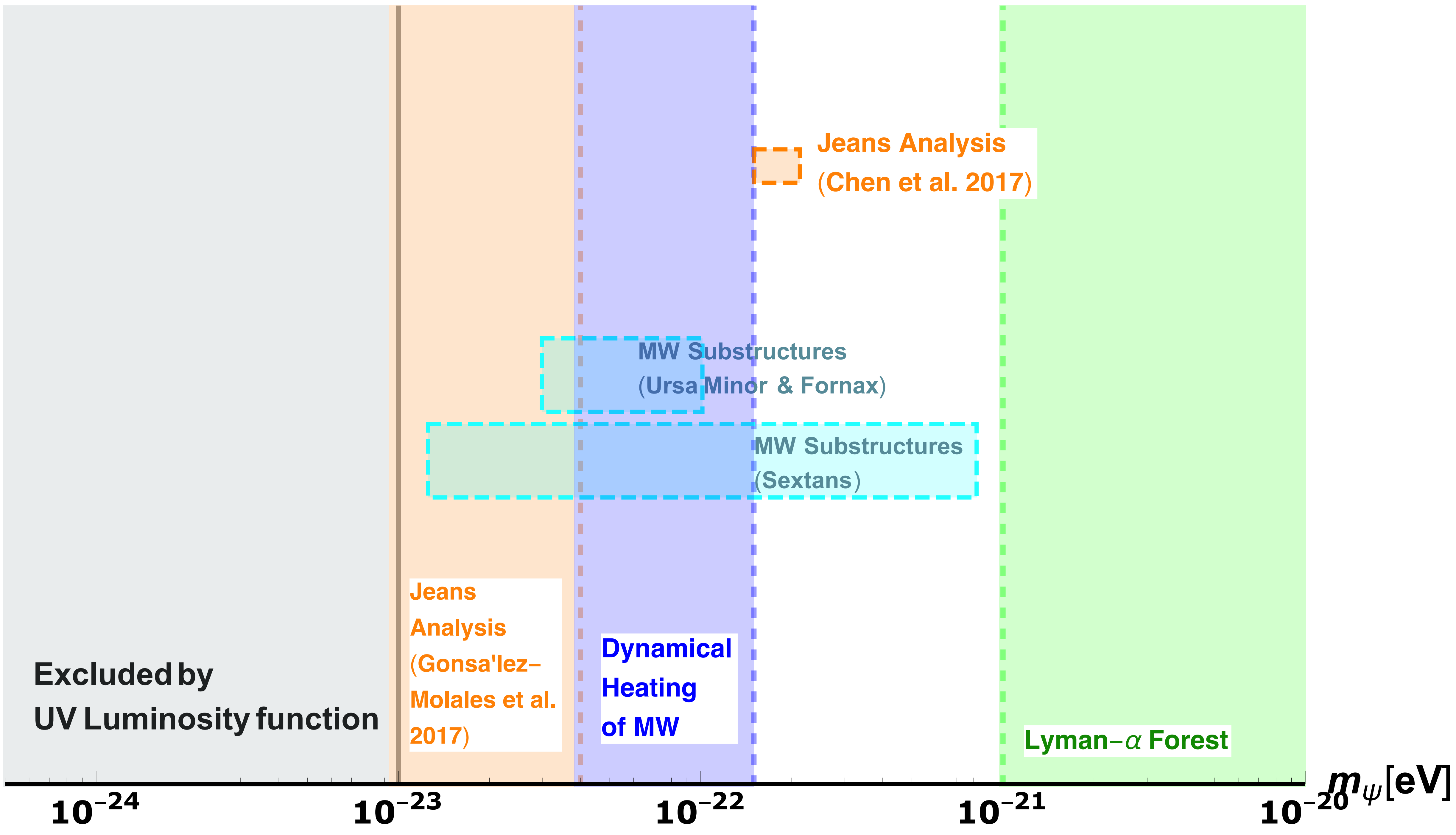
$$\rho_c = 1.9 \times 10^{12} \left(\frac{m_\psi}{10^{-23}\ {\rm eV}}\right)^{-2} \left(\frac{r_c}{\rm pc}\right)^{-4} \ [M_\odot\ {\rm pc}^{-3}]$$



Ultralight axion dark matter (ULADM)

- Current constraints on particle mass of ULADM

KH & Obata 19



Constraining particle mass of ULADM

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Dynamical models for stars
ex) Spherical Jeans equation

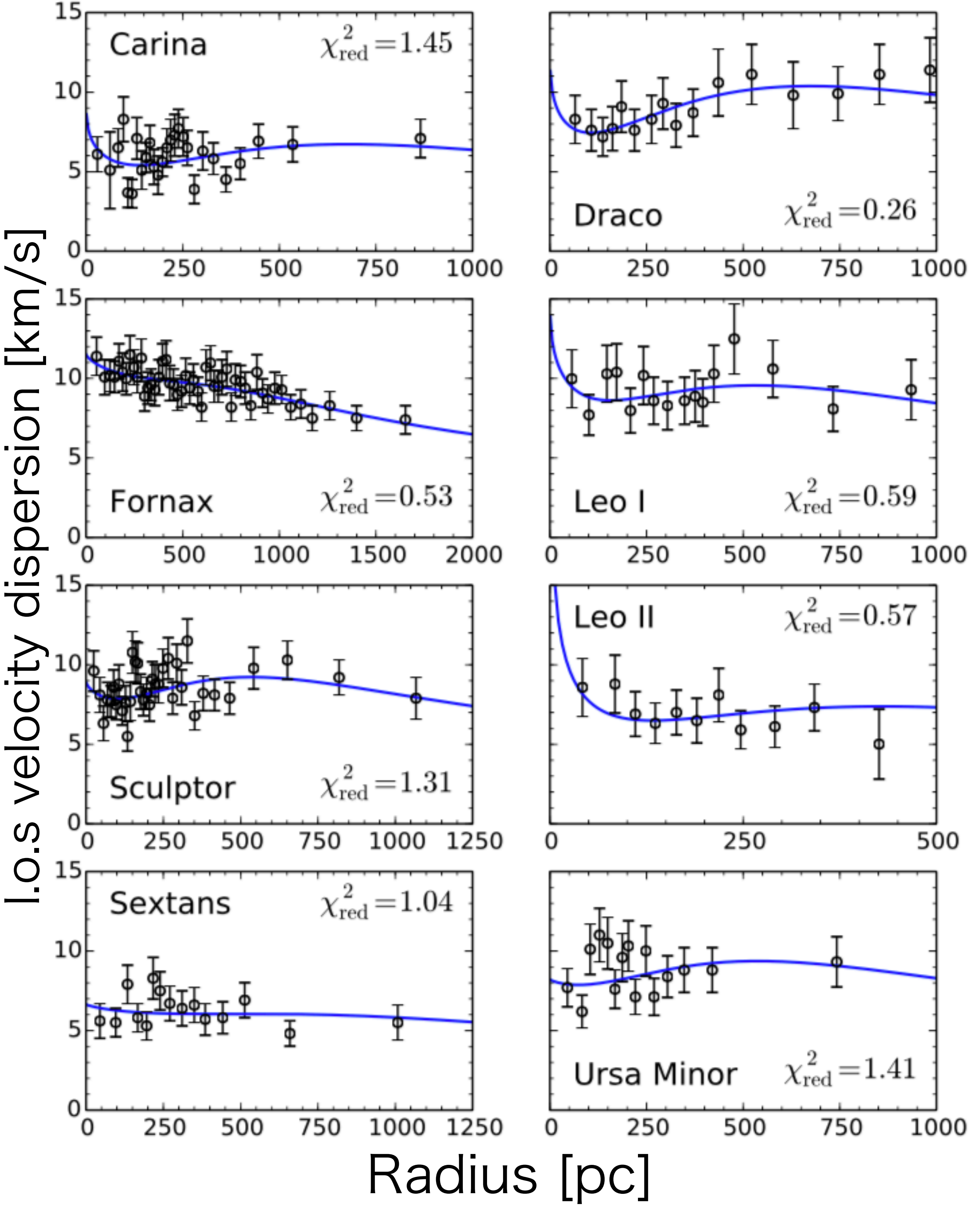
$\sigma_{\mathrm{l.o.s}}^{(\mathrm{Theory})}$ **FIT** $\sigma_{\mathrm{l.o.s}}^{(\mathrm{obsrved})}$

$$\sigma^2_{\mathrm{l.o.s}}(R) = \frac{2}{I(R)}\int_R^\infty \left(1-\beta_a\frac{R^2}{r^2}\right)\frac{\nu(r)v_r^2}{\sqrt{r^2-R^2}}dr$$

- Current constraint from Spherical mass models

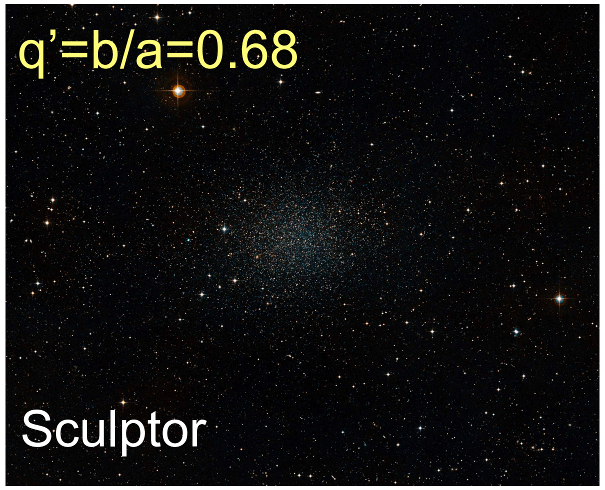
$$m_\psi = 1.79^{+0.35}_{-0.33}\times 10^{-22}\ \mathrm{eV}\ (2\sigma)$$

Chen et al. (2017)

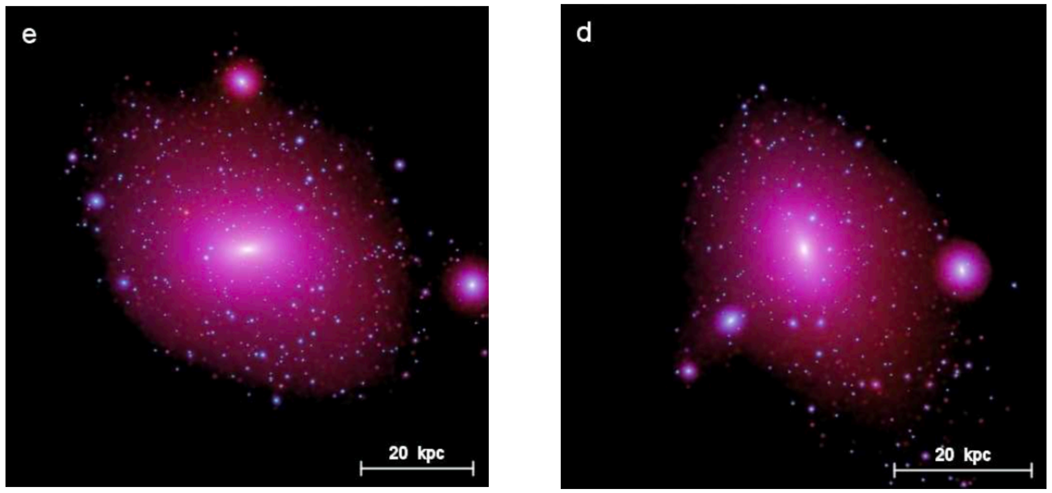


Major systematic uncertainty: Spherical Symmetry

1. Observed dSphs are **NOT** spherical shape

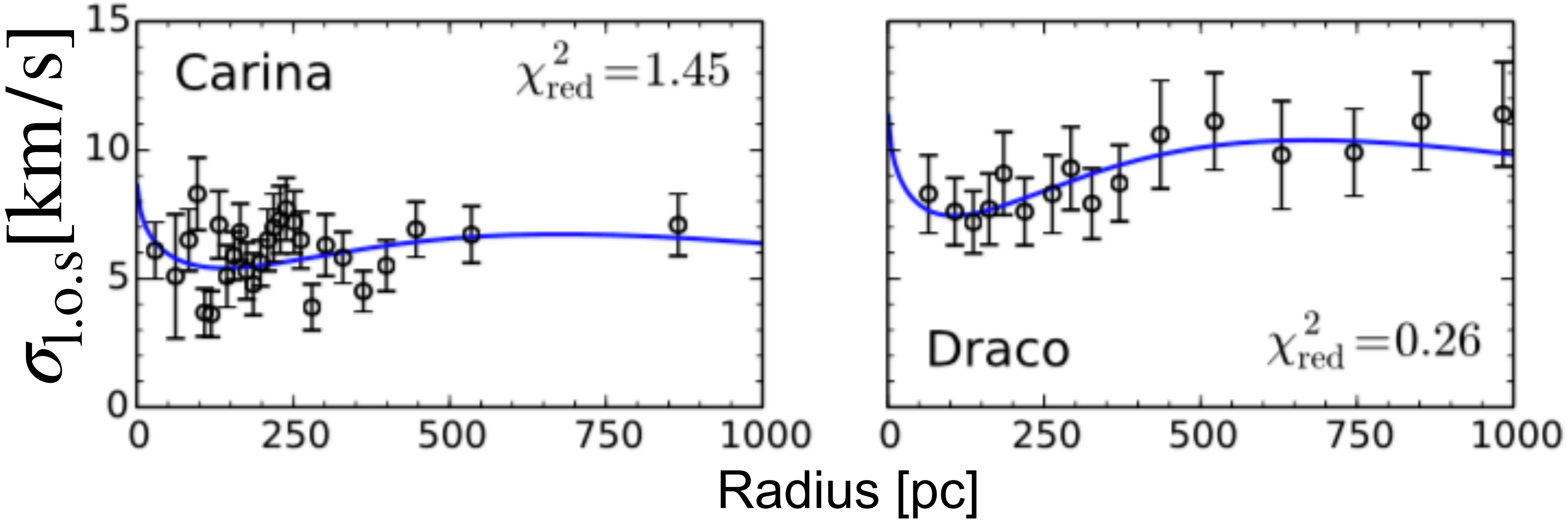


2. DM models predict **NON-spherical** DM halo



credit: Aquarius project

3. 1D spatial information



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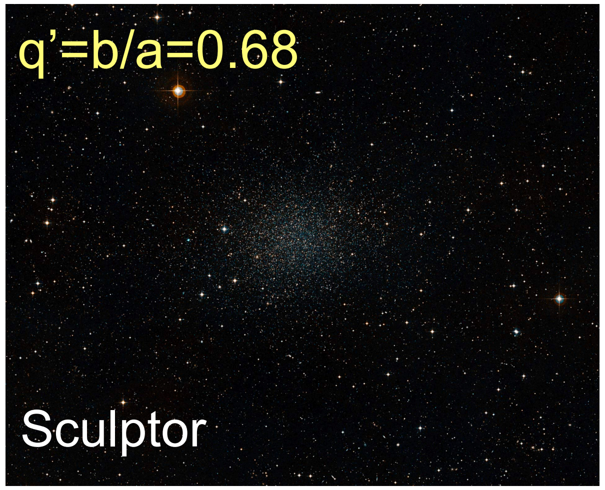

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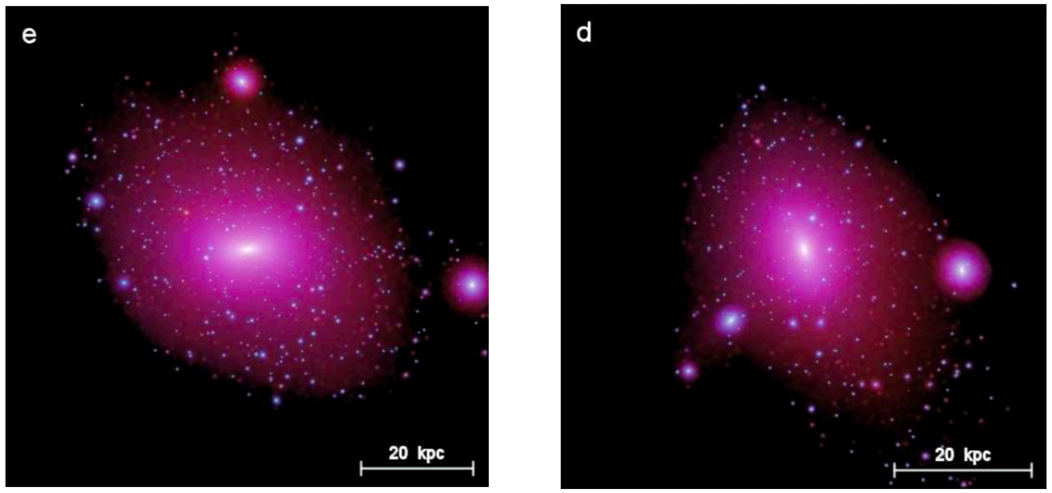

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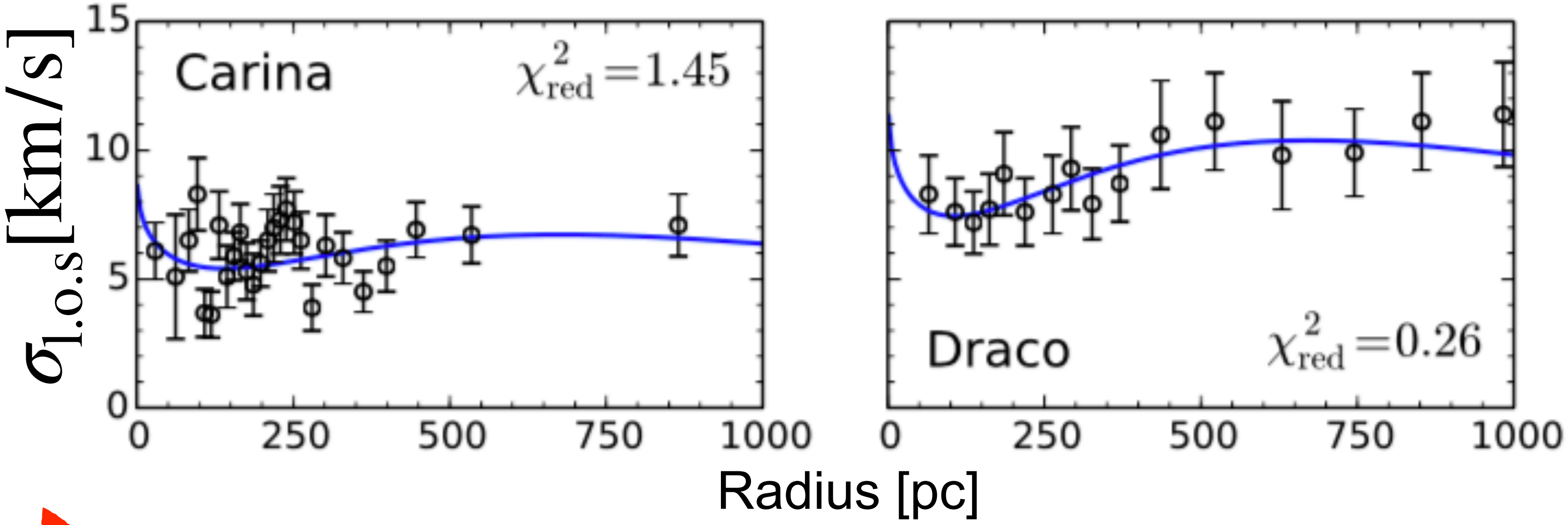

Non-spherical mass model

Non-sphericity of ultralight axion dark matter halos in the Galactic dwarf satellites

Hayashi and Obata (2019), arXiv: 190203054

Non-spherical dynamical mass models

Unobservable

Non-spherical dark matter density profile

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$$\rho_c = 1.9\times 10^{12}\left(\frac{\boxed{m_\psi}}{10^{-23}\ {\rm eV}}\right)^{-2}\left(\frac{\boxed{r_c}}{\rm pc}\right)^{-4}\ [M_\odot\ {\rm pc}^{-3}]$$

$$r^2 = R^2 + \frac{z^2}{\boxed{Q^2}}$$

DM halo axial ratio

Non-spherical stellar profile

$$\rho_*(r_*) = \frac{3L}{4\pi r_p^3}\left[1+\frac{r_*^2}{r_p^2}\right]^{-5/2}$$

$$r_*^2 = R^2 + \frac{z^2}{q^2}$$

stellar axial ratio

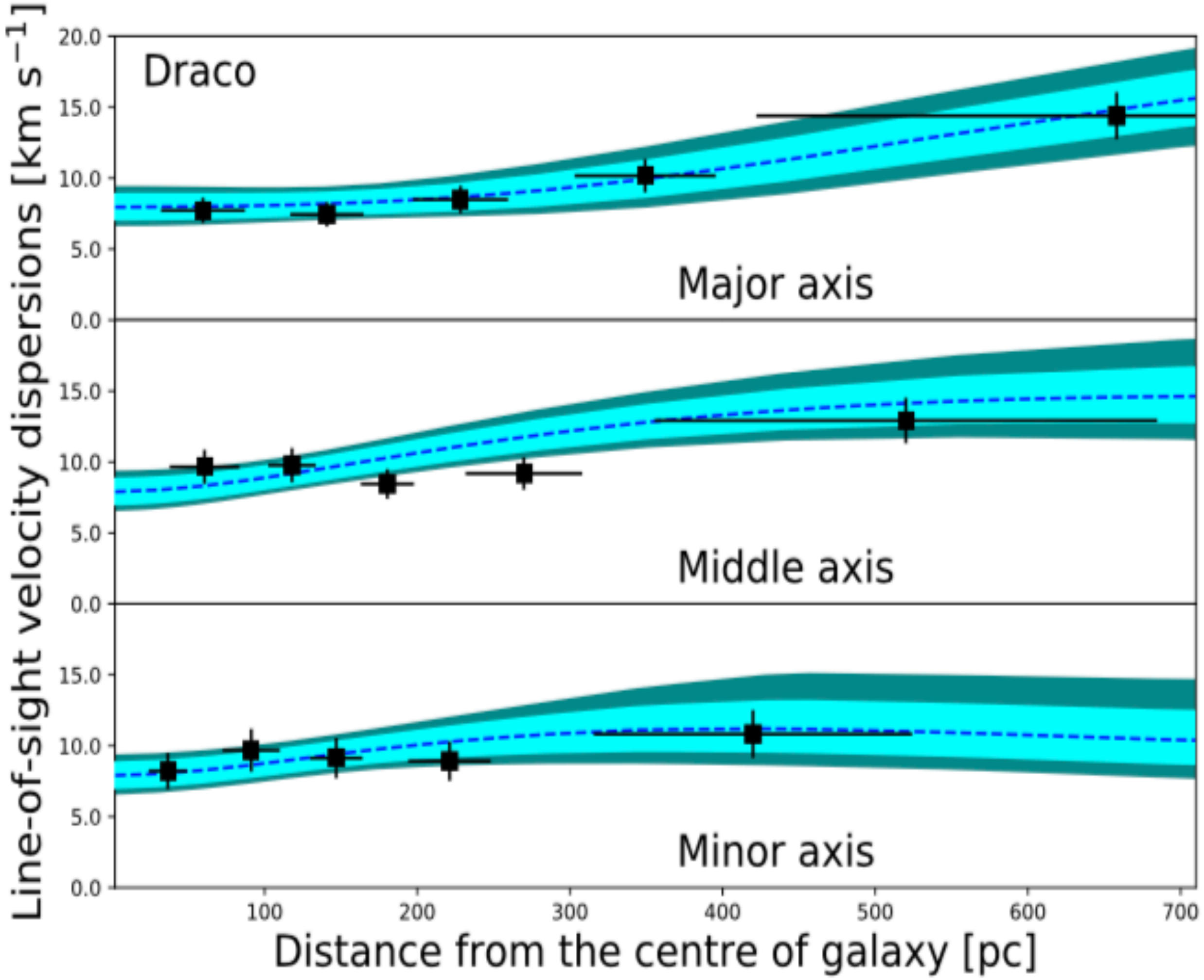
Axisymmetric Jeans equations

$$\Rightarrow (\overline{v_z^2}, \overline{v_\phi^2})$$

$\overline{v_R^2}$ is unknown parameter as $\boxed{\beta_z} = 1 - \overline{v_z^2}/\overline{v_R^2}$

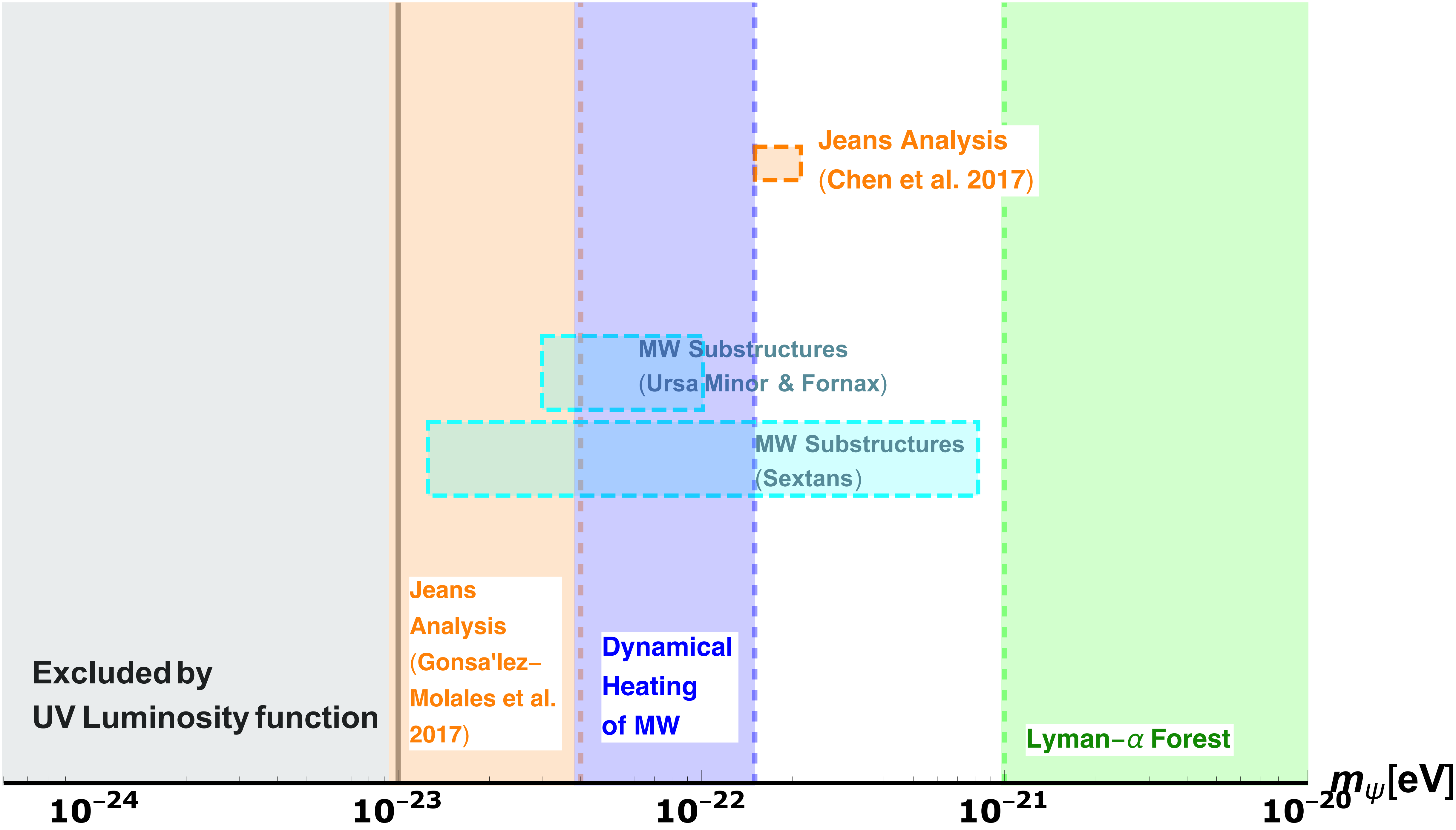
$$\sigma_{\rm l.o.s}^{\rm (theory)} \Longleftrightarrow \sigma_{\rm l.o.s}^{\rm (obsrved)}$$

FIT



Constraints on ULADM via non-spherical analysis

Hayashi & Obata (2019), 1902.03054



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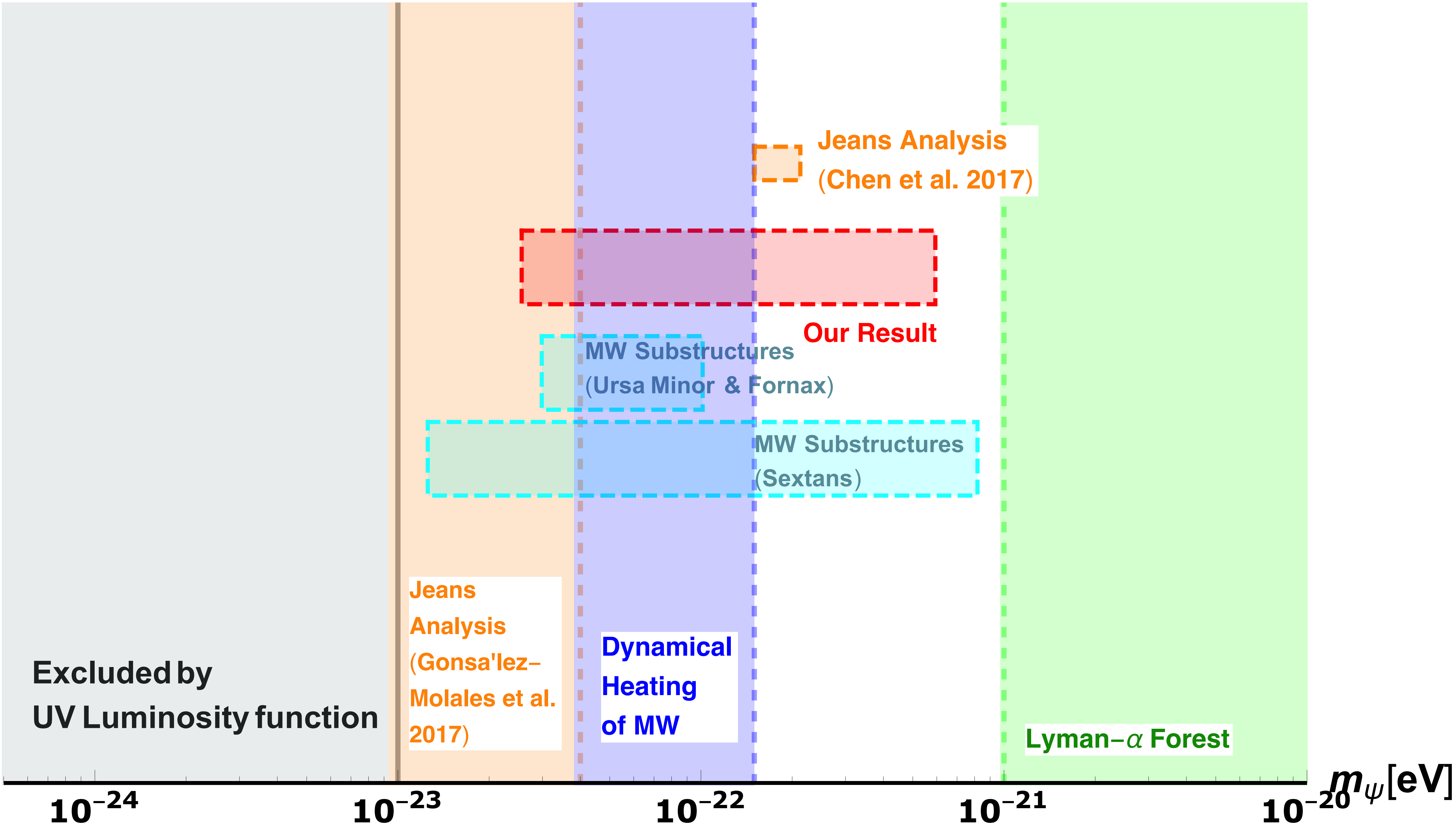

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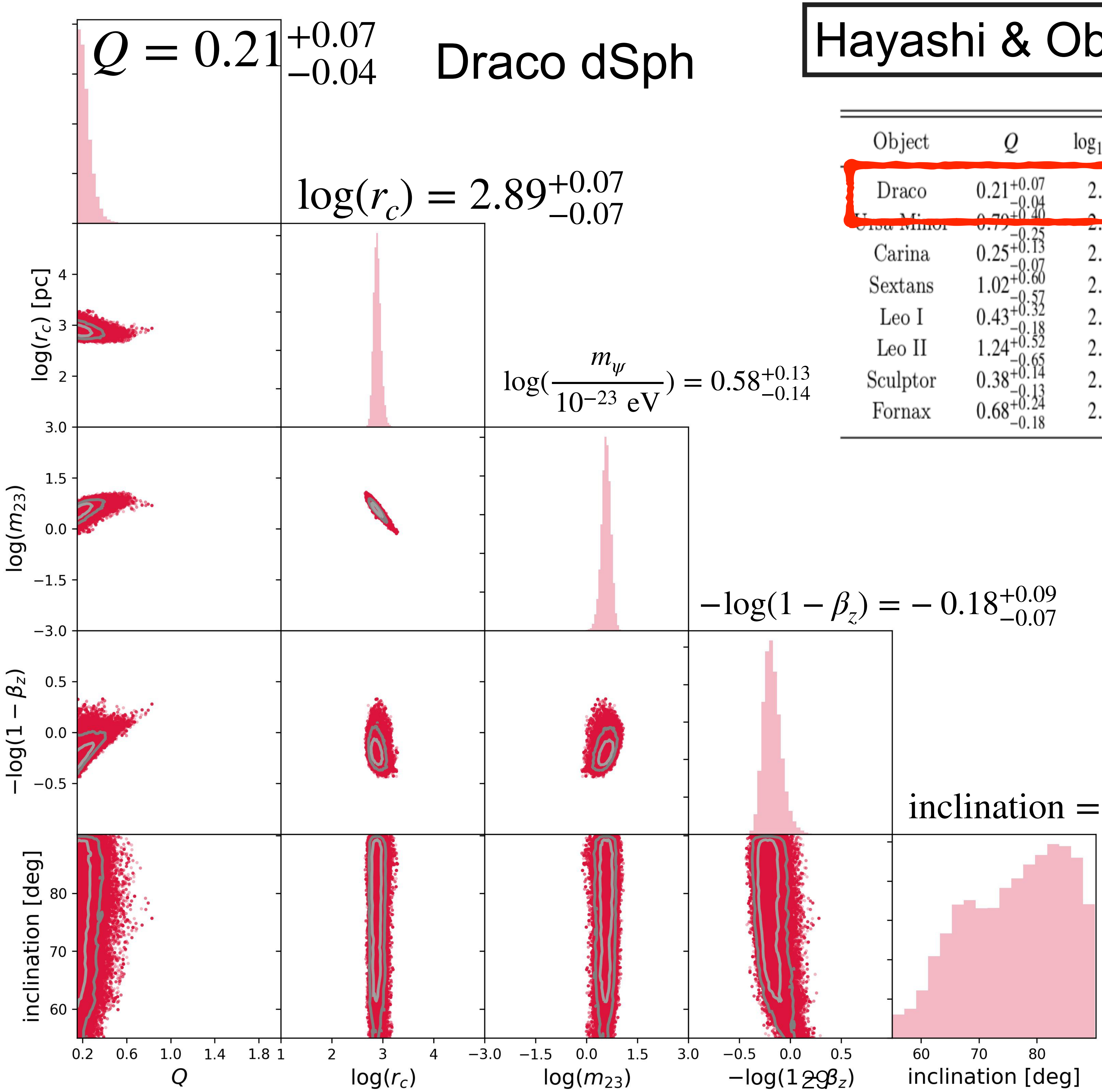


$Q = 0.21^{+0.07}_{-0.04}$

Draco dSph

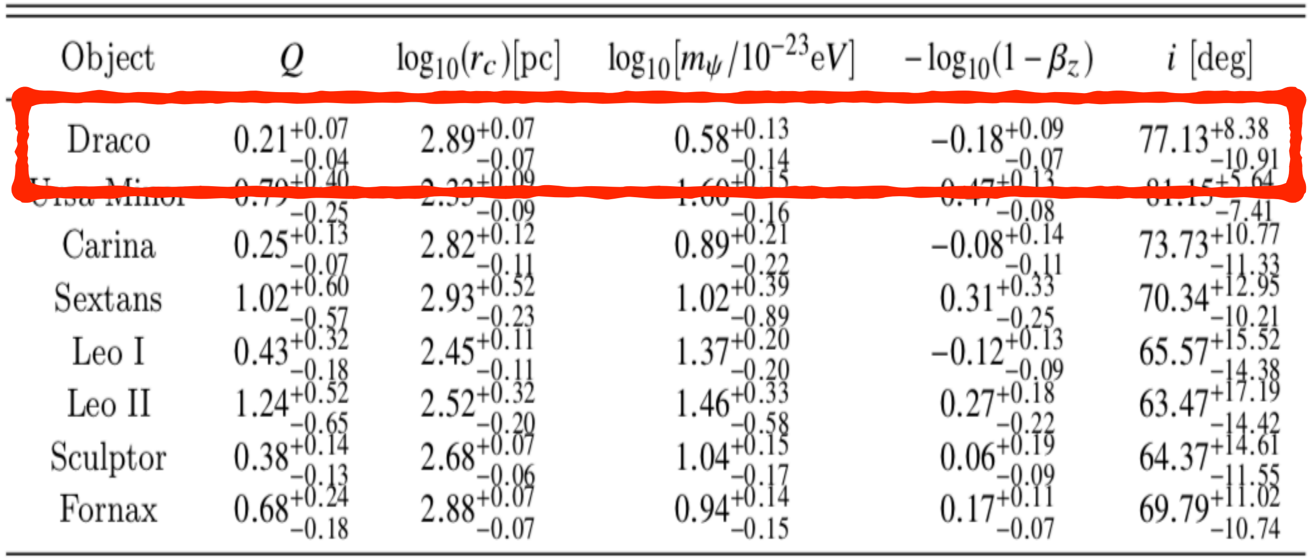
$\log(r_c) = 2.89^{+0.07}_{-0.07}$

$\log(\frac{m_\psi}{10^{-23}\ \mathrm{eV}}) = 0.58^{+0.13}_{-0.14}$

$-\log(1-\beta_z) = -0.18^{+0.09}_{-0.07}$

$\mathrm{inclination} = 77.13^{+8.38}_{-10.91}$

Hayashi & Obata (2019), 1902.03054



Object	Q	$\log_{10}(r_c)$[pc]	$\log_{10}[m_\psi/10^{-23}\mathrm{eV}]$	$-\log_{10}(1-\beta_z)$	i [deg]
Draco	$0.21^{+0.07}_{-0.04}$	$2.89^{+0.07}_{-0.07}$	$0.58^{+0.13}_{-0.14}$	$-0.18^{+0.09}_{-0.07}$	$77.13^{+8.38}_{-10.91}$
Ursa Minor	$0.79^{+0.40}_{-0.25}$	$2.33^{+0.09}_{-0.09}$	$1.60^{+0.15}_{-0.16}$	$0.47^{+0.13}_{-0.08}$	$81.15^{+5.64}_{-7.41}$
Carina	$0.25^{+0.13}_{-0.07}$	$2.82^{+0.12}_{-0.11}$	$0.89^{+0.21}_{-0.22}$	$-0.08^{+0.14}_{-0.11}$	$73.73^{+10.77}_{-11.33}$
Sextans	$1.02^{+0.60}_{-0.57}$	$2.93^{+0.52}_{-0.23}$	$1.02^{+0.39}_{-0.89}$	$0.31^{+0.33}_{-0.25}$	$70.34^{+12.95}_{-10.21}$
Leo I	$0.43^{+0.32}_{-0.18}$	$2.45^{+0.11}_{-0.11}$	$1.37^{+0.20}_{-0.20}$	$-0.12^{+0.13}_{-0.09}$	$65.57^{+15.52}_{-14.38}$
Leo II	$1.24^{+0.52}_{-0.65}$	$2.52^{+0.32}_{-0.20}$	$1.46^{+0.33}_{-0.58}$	$0.27^{+0.18}_{-0.22}$	$63.47^{+17.19}_{-14.42}$
Sculptor	$0.38^{+0.14}_{-0.13}$	$2.68^{+0.07}_{-0.06}$	$1.04^{+0.15}_{-0.17}$	$0.06^{+0.19}_{-0.09}$	$64.37^{+14.61}_{-11.55}$
Fornax	$0.68^{+0.24}_{-0.18}$	$2.88^{+0.07}_{-0.07}$	$0.94^{+0.14}_{-0.15}$	$0.17^{+0.11}_{-0.07}$	$69.79^{+11.02}_{-10.74}$

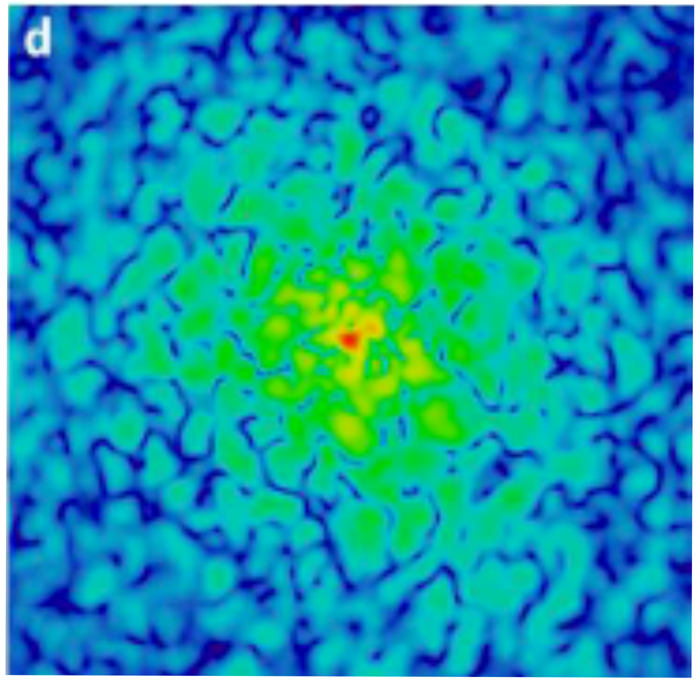
Constraints on ULADM via non-spherical analysis

Hayashi & Obata (2019), 1902.03054

Stellar & DM halo axial ratio of Draco

$$q = (b/a)_{\rm star} = 0.69$$

$$Q = (b/a)_{\rm DM} = 0.21$$



$Q \sim 1.0$

Schive et al. (2014)

- Draco has strongly elongated dark halo, **Q~0.2**.
- Draco's ULADM halo is **much more flattened** than N-body predictions and stellar distributions.
- Further understanding of baryonic and DM physics should be needed.

Summary

- ΛCDM theory faces the serious challenges on dwarf galaxy scales.
- Ultralight axion dark matter is one of the dark matter candidates, because it can resolve small scale problems.
- The MW dSphs are ideal sites for studying the nature of dark matter because these are DM-dominated systems.
- To obtain realistic limits on DM models, we construct new dynamical modeling with taking into account non-sphericity.
- Our mass models place less stringent constraints on ULADM mass but require unphysically elongated ULADM halos.
- We revisit core-cusp problem and find that the diversity of inner slopes of DM profiles in the classical dwarfs.