# Pseudo phase space density of dark matter halos in the dwarf spheroidals

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# Dark Universe

Dark Energy
Accelerated Expansion

Afterglow Light
Pattern
375,000 yrs.

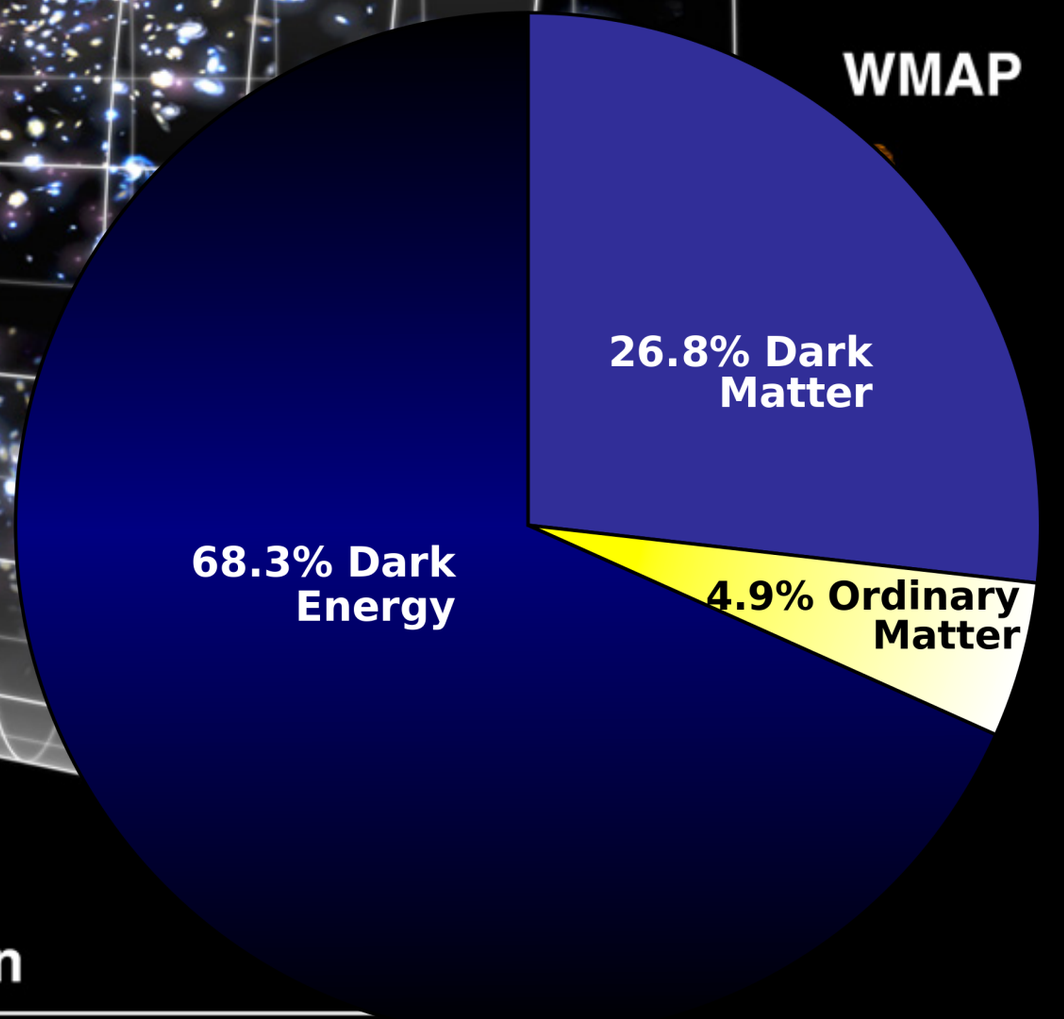
Dark Ages

Development of
Galaxies, Planets, etc.

Inflation

Quantum
Fluctuations

1st Stars
about 400 million yrs.

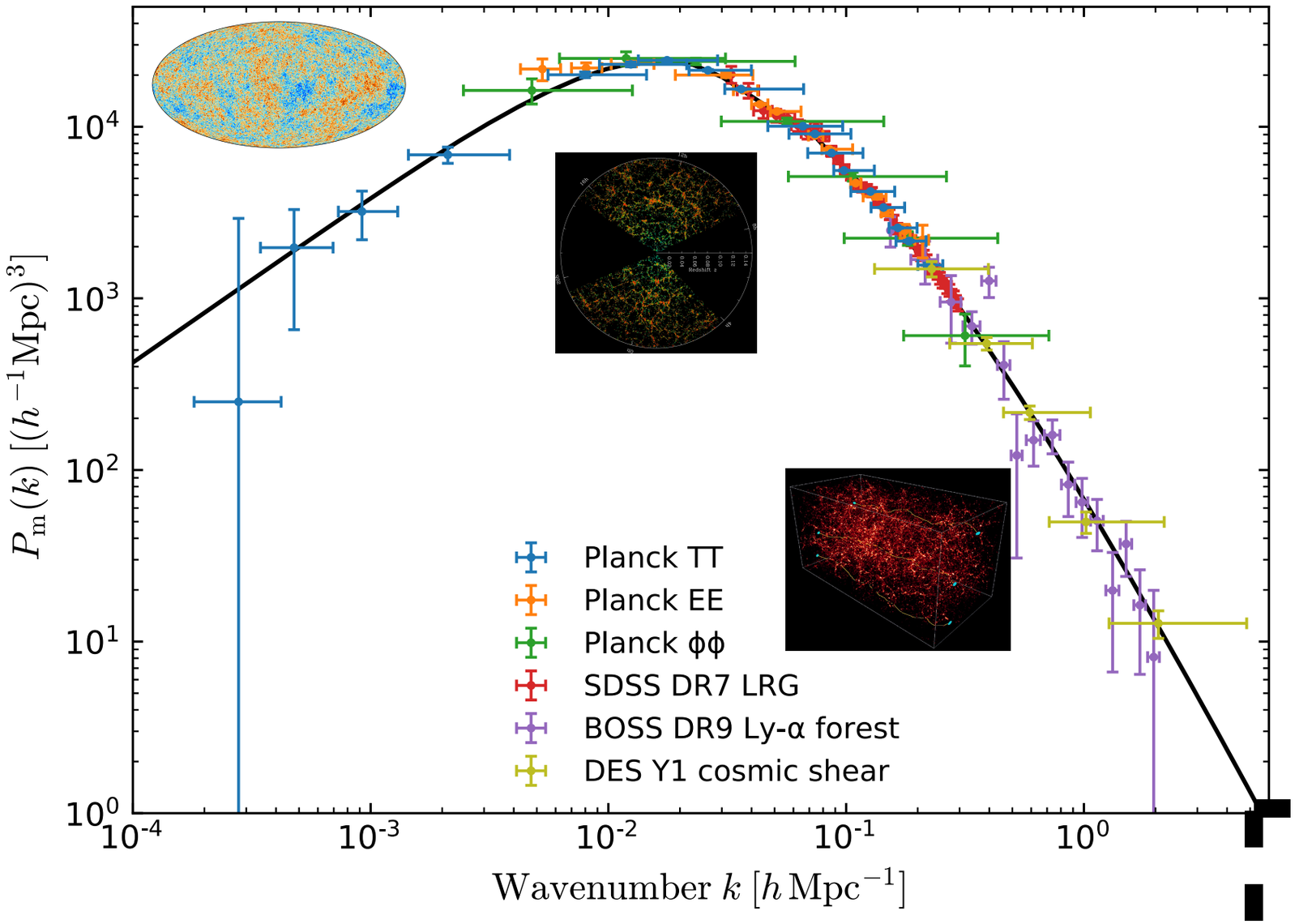



Big Bang Expansion

13.77 billion years

# Λ Cold Dark Matter model

ESA and the Planck Collaboration




Large scale (> 1Mpc)

⇒ Remarkable success!

Small scale (<1 Mpc)

⇒ What's going on?

?

# Dark matter halo structure

THE STRUCTURE OF COLD DARK MATTER HALOS

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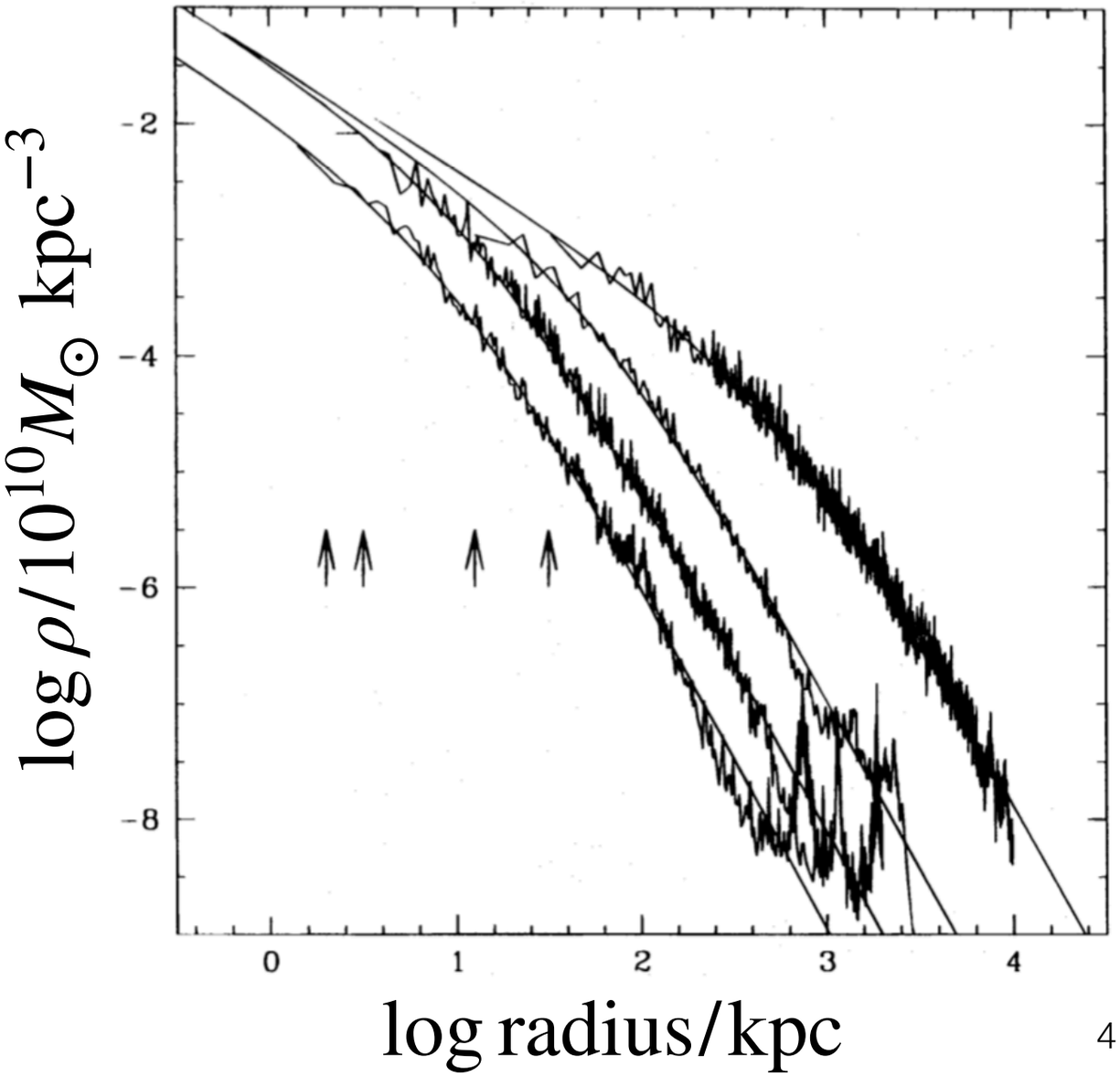



**NFW profile:**

$$\frac{\rho(r)}{\rho_{\rm crit}} = \frac{\delta_c}{(r/r_s)(1+r/r_s)^2}$$

$$\delta_c = \frac{200}{3}\frac{c^3}{[\ln(1+c) - c/(1+c)]}$$

➡ **Universal profile**

# Pseudo phase space density (PPSD) profile

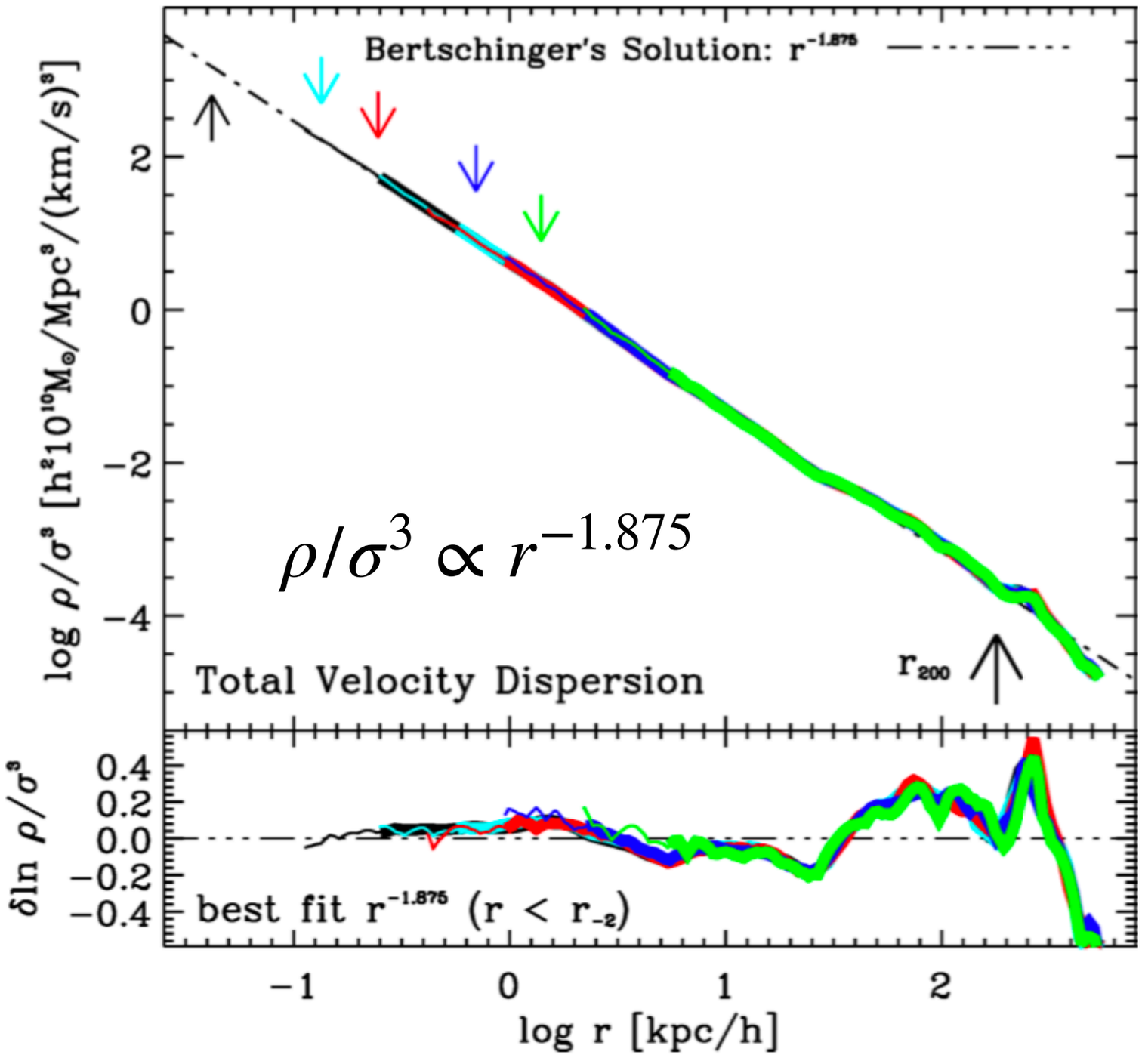
Navarro et al. (2010)

1. Universal profile (Taylor & Navarro 2001)

$$\rho/\sigma^3 \propto r^{-1.875}$$

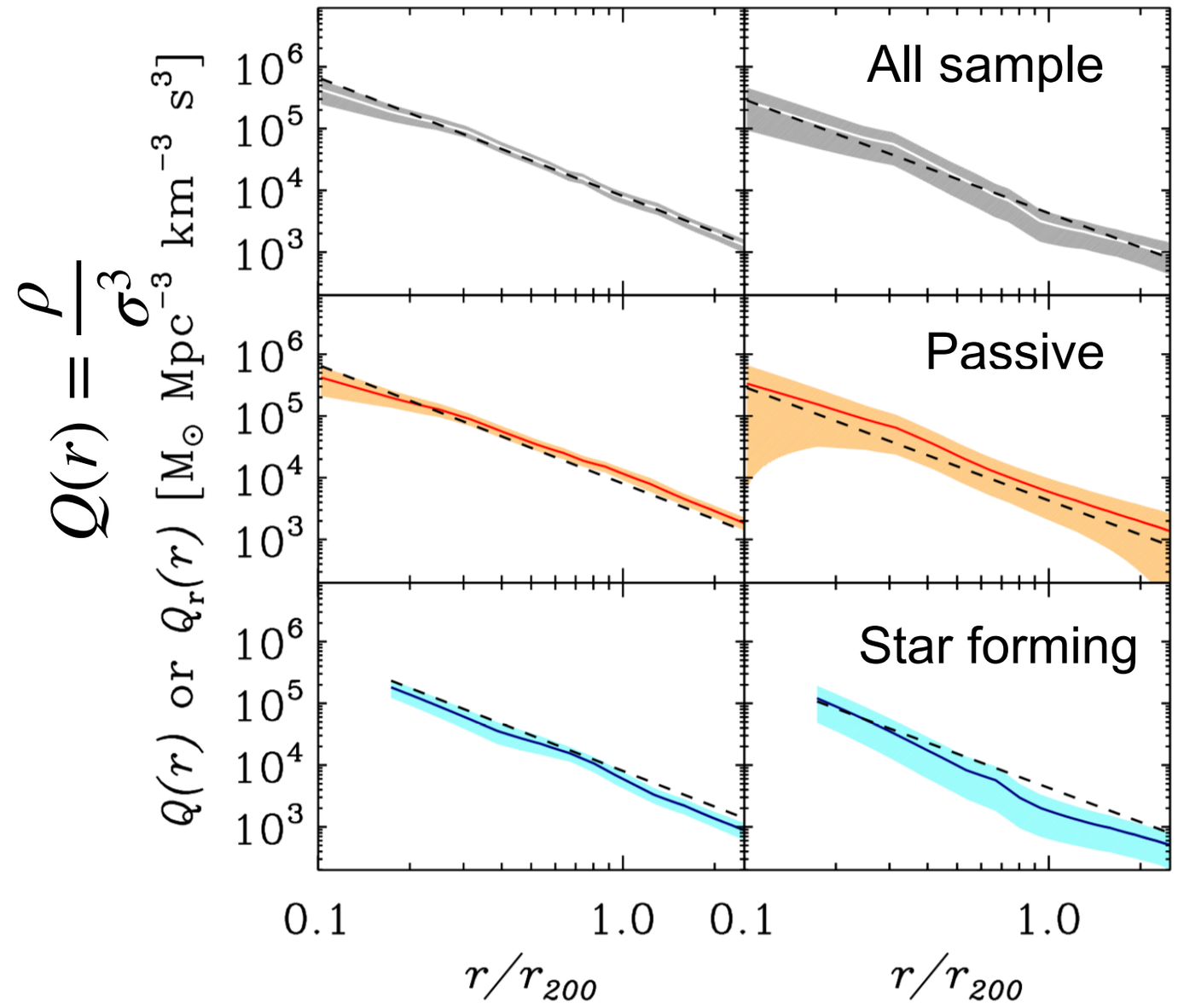
2. The power-law is not largely dependent upon “cosmology” and slopes of dark matter density profiles (e.g., Navarro+09; Ludlow+12).

3. Identical to self-similar secondary infall solution in an Einstein-de Sitter universe (Fillmore & Goldreich 84; Bertschinger 85).



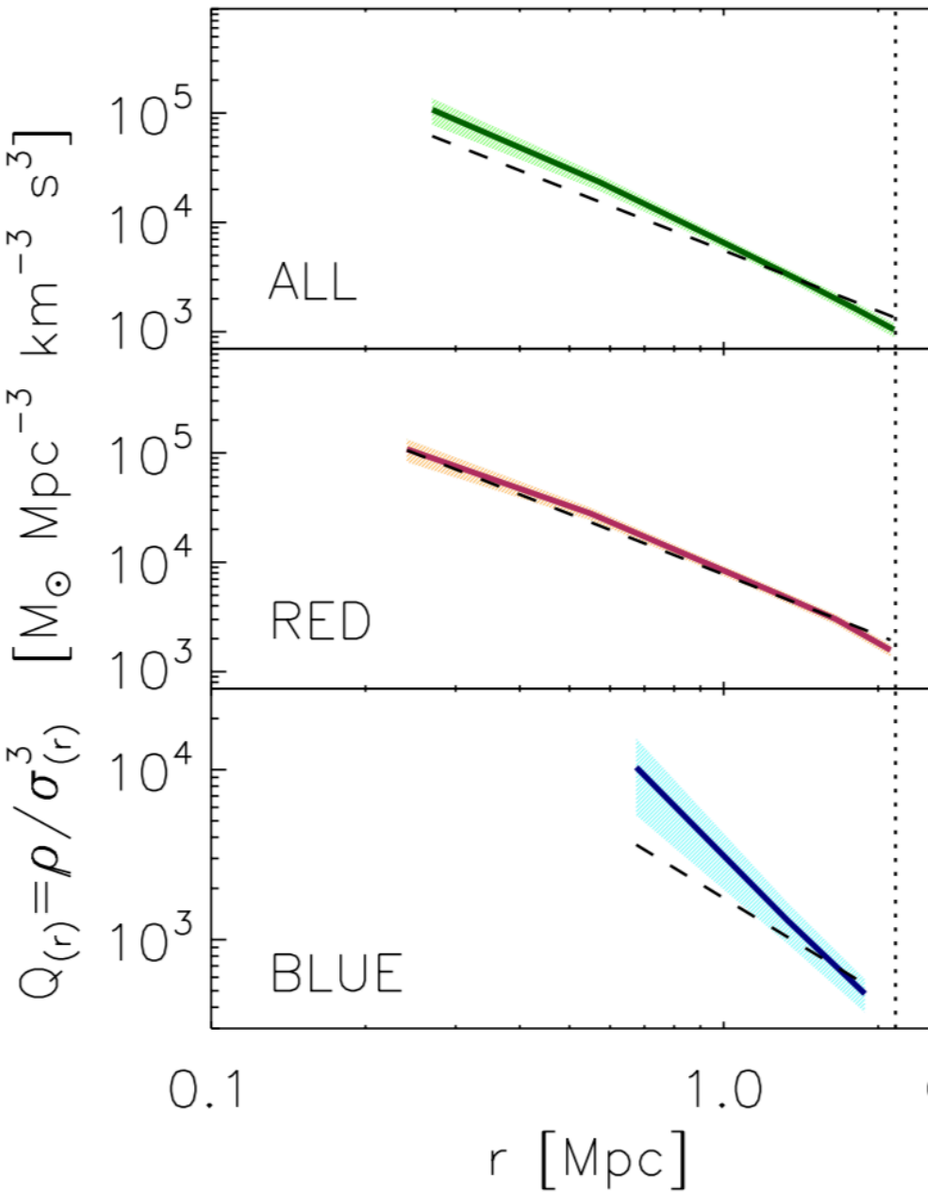
# PPSD profile for galaxy cluster

MACS J1206.2-0847 (z=0.44)




Biviano+ (2013)

Abell 2142 (z~0.09)




Munari+ (2014)

# PPSD profile for dwarf galaxy?

# Non-spherical dynamical mass models

**Unobservable**

## Non-spherical dark matter density profile

$$\rho_{\rm DM}(r) = \frac{\rho_s}{(r/r_s)^{\gamma}[1+(r/r_s)^{\alpha}]^{(\beta-\gamma)/\alpha}}$$

$$r^2 = R^2 + \frac{z^2}{Q^2}$$ ← **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

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

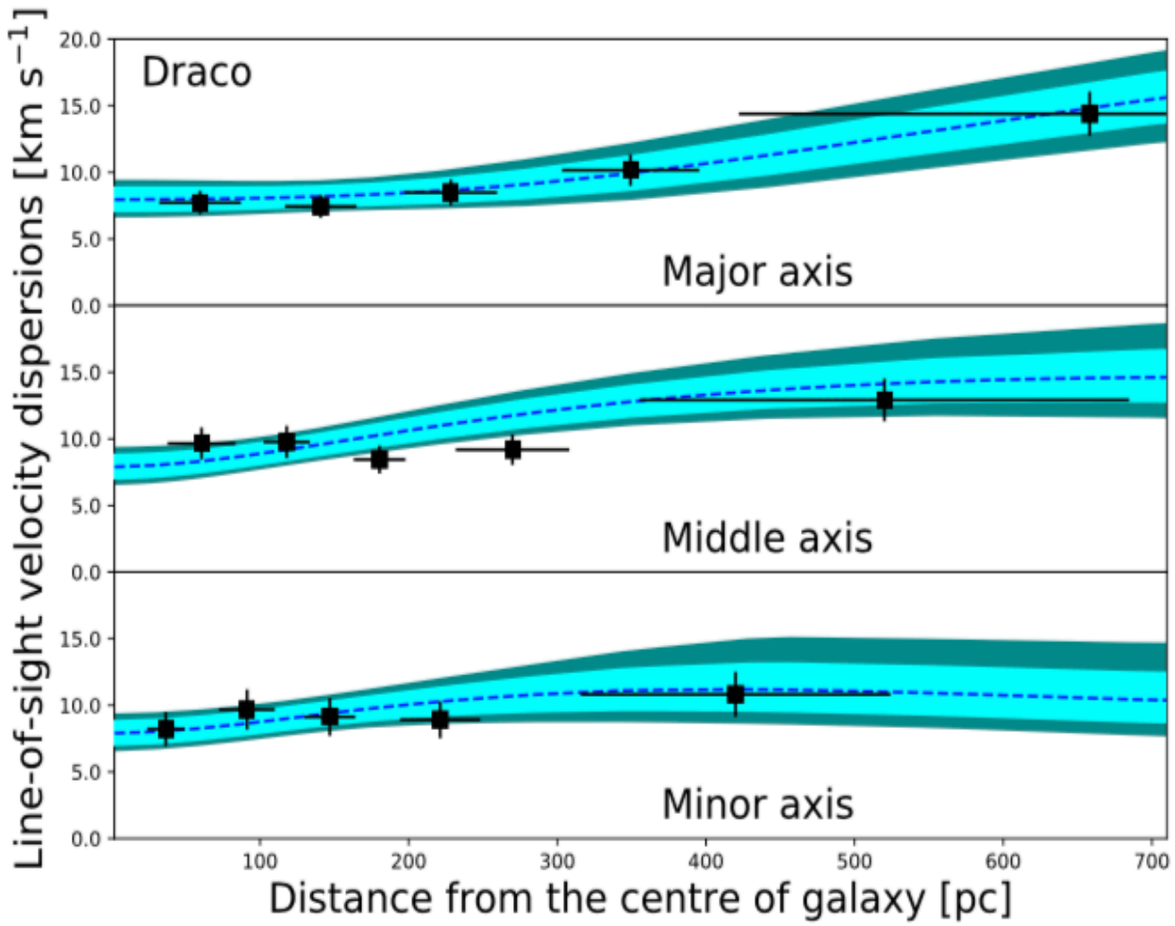
$\overline{v_R^2}$ is unknown parameter as

$$\beta_z = 1 - \overline{v_z^2}/\overline{v_R^2}$$

**FIT**

$\sigma_{\rm l.o.s}^{\rm (Theory)}$ ⟷ $\sigma_{\rm l.o.s}^{\rm (obsrved)}$

Draco dSph

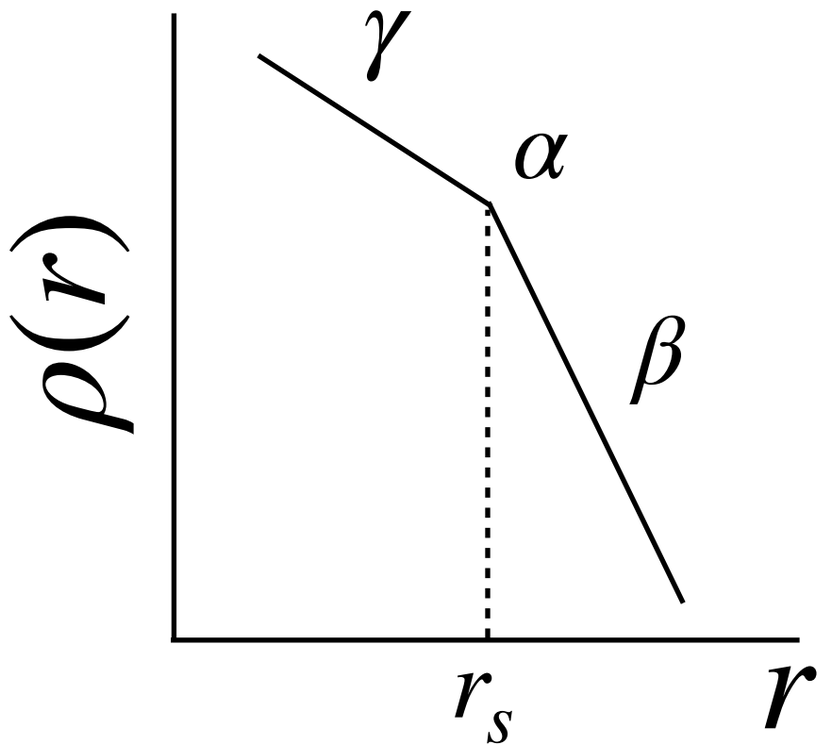


# DM profiles of the classical dwarfs

- Parameterized dark matter density profile

$$\rho_{\mathrm{DM}}(r) = \frac{\rho_s}{(r/r_s)^{\gamma}[1+(r/r_s)^{\alpha}]^{(\beta-\gamma)/\alpha}}$$

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



# DM profiles of the classical dwarfs

**KH+ (in prep.)**

**Preliminary**

**Cuspy profile**

**Less cuspy profile**

**Dark matter density [Msun/kpc$^3$]**

Sorry…

Sorry…

Sorry…

**Major axis [kpc]**

# PPSD profiles for dSphs

KH+ (in prep.)

$$Q(r) = \frac{\rho}{\sigma^3} \qquad \sigma^3 = \sigma_R \sigma_z \sigma_\phi$$

**Preliminary**

Sorry…

**Pseudo phase space density [Msun/kpc³/(km/s)³]**

**Major axis [kpc]**

# Draco dSphs

# Sorry…

What's an origin of this deviation of PPSD profile?

# What's an origin of this deviation of PPSD profile?

- **Systematics?**

  Velocity dispersion is derived by not dark matters but star kinematics.

- **Baryonic feedback?**
  but, Draco prefers to have cusped DM halo. SF feedback might be not efficient…

- **Alternative DM models?**
  (WDM, Axion, SIDM,…)

- still ongoing discussion …

Sorry…

# Summary

- Pseudo phase space density profile is universal within the framework of ΛCDM universe.
- The slope of PPSD profile is identical to self-similar secondary infall solution in an Einstein-de Sitter universe.
- We look into PPSD profiles on dwarf-galaxy scales for the first time.
- We find **the diversity of inner slopes of DM density profiles** in the classical dSphs and **their PPSD profiles deviate from ΛCDM models**.