Physics Institute
Univ. of Sao Paulo

COSMOLOGY AND GALAXY EVOLUTION IN THE CROSSROADS

Partly based on 1805.09918, 1809.10321, 1810.02375

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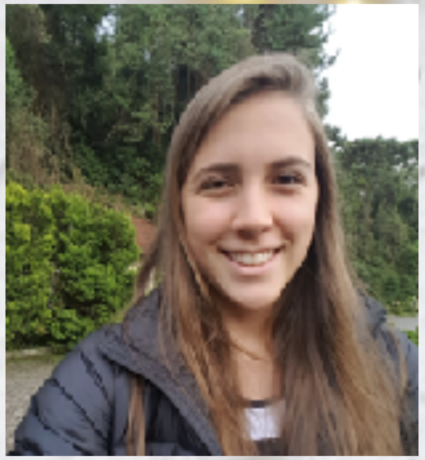
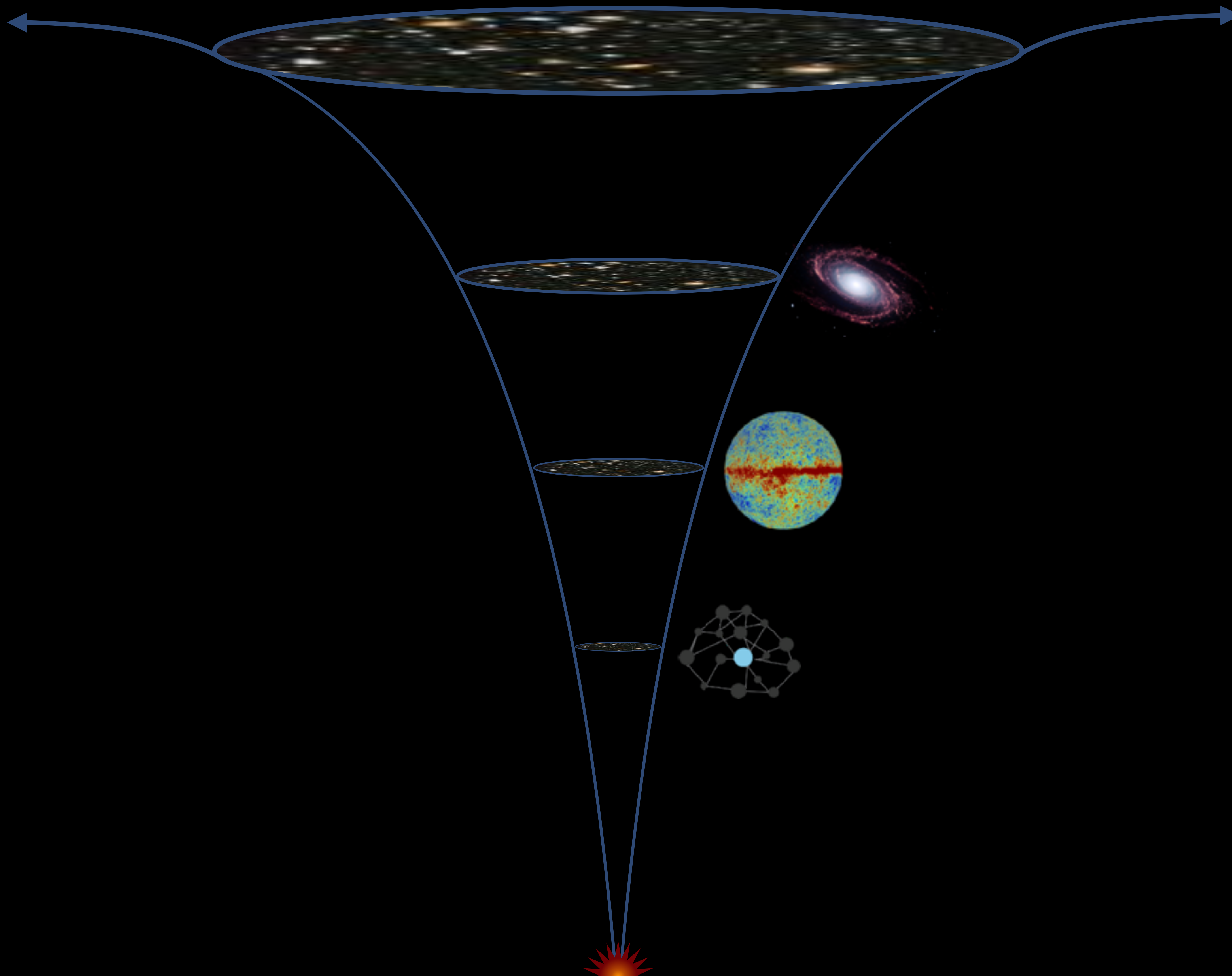


Natalia Vilas-Boas

Gabi Sato-Polito

COSMIC ACCELERATION: DEEPEST MYSTERY OF OUR TIME



Dark energy or modified gravity?

$$G_{\mu\nu} = 8\pi G T_{\mu\nu} + 8\pi G T^{E}_{\mu\nu}$$

$$\Delta G \mu\nu + G_{\mu\nu} = 8\pi G T_{\mu\nu}$$

Modified gravity:

⇒ Change Friedmann's equation

same as dark energy

⇒ Aceleration

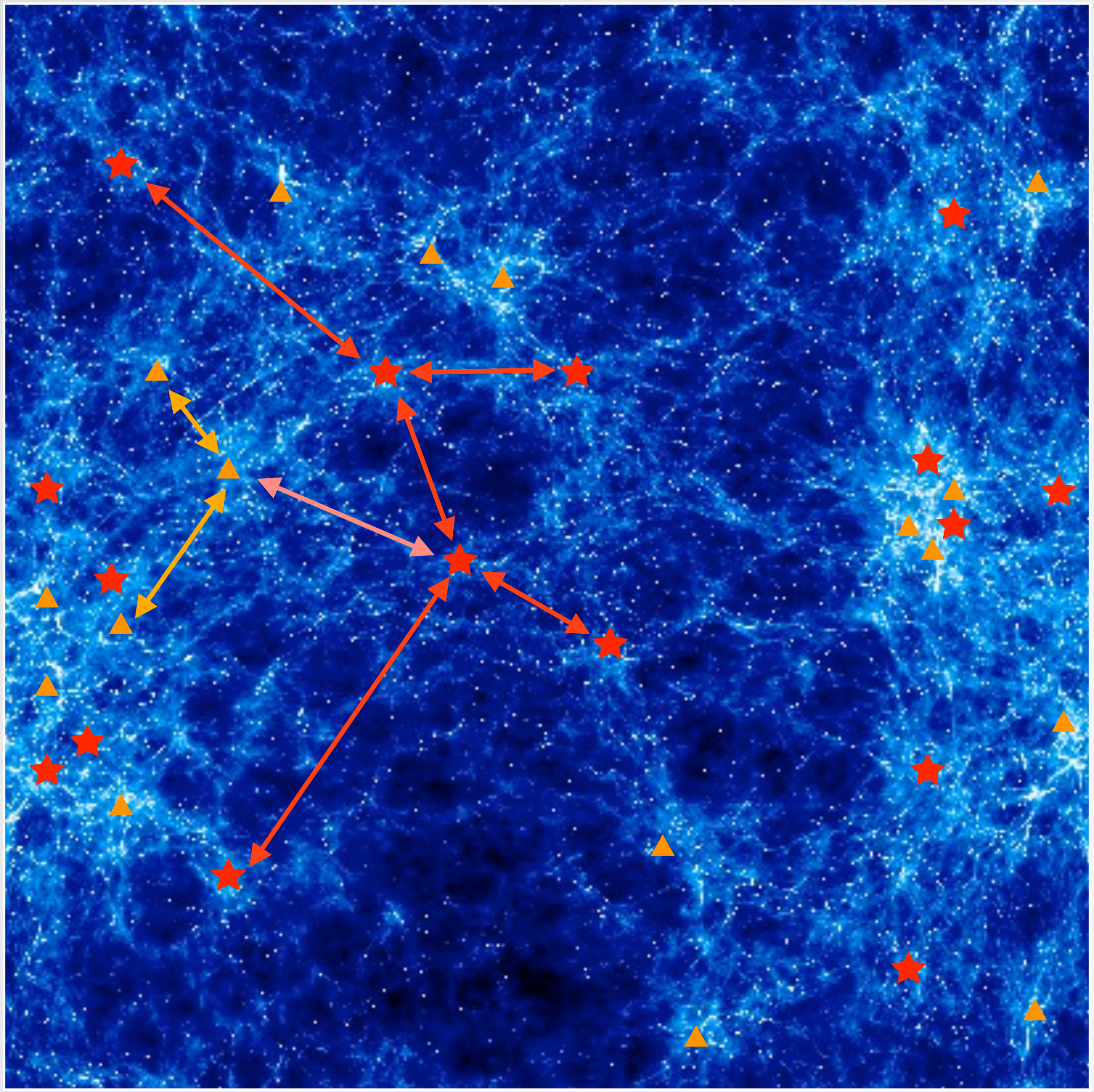
However, modifying gravity leads to changes in the Poisson equation:

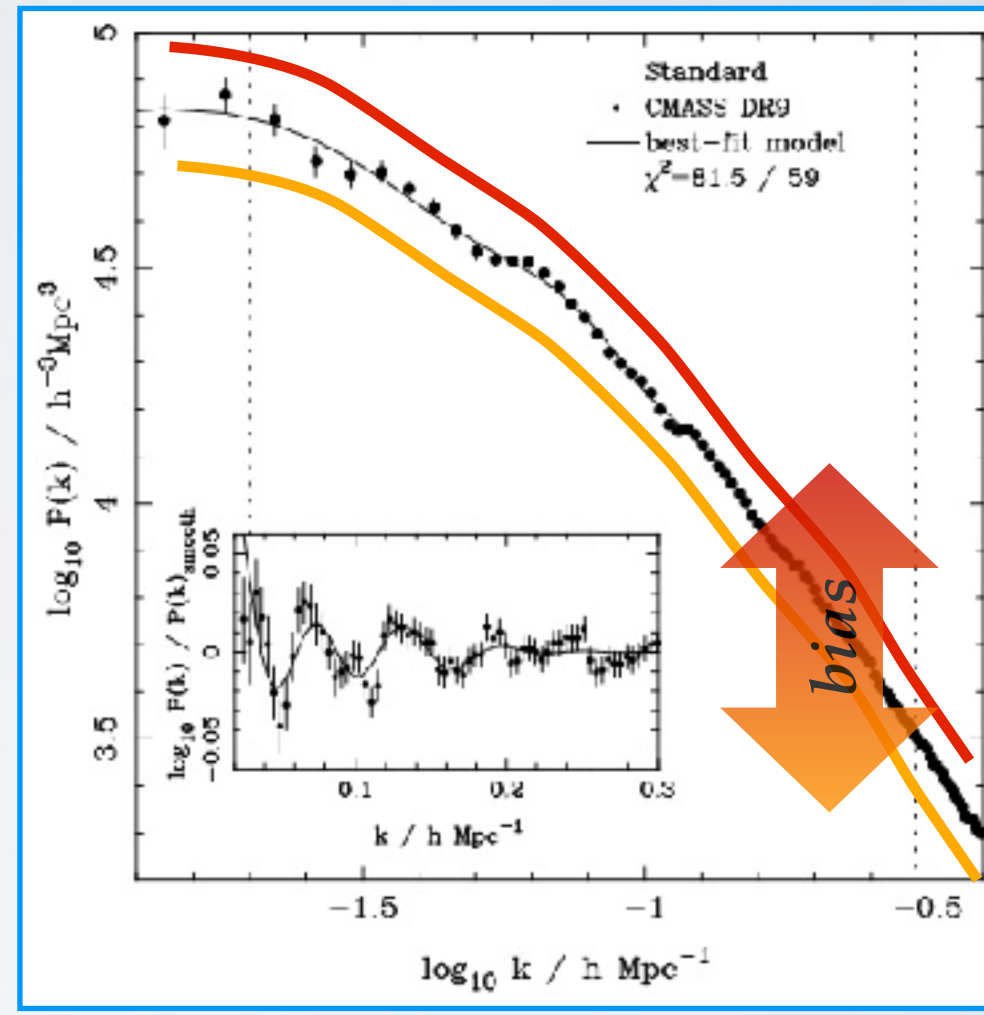
Same matter, different gravity

$$\nabla^2 \Phi = \frac{16\pi G}{3} \delta\rho - \frac{1}{6} \delta R(f_R)$$

⇒ Cosmic structures are more/less attracted compared with GR

LARGE-SCALE STRUCTURES ARE TRACED BY GALAXIES

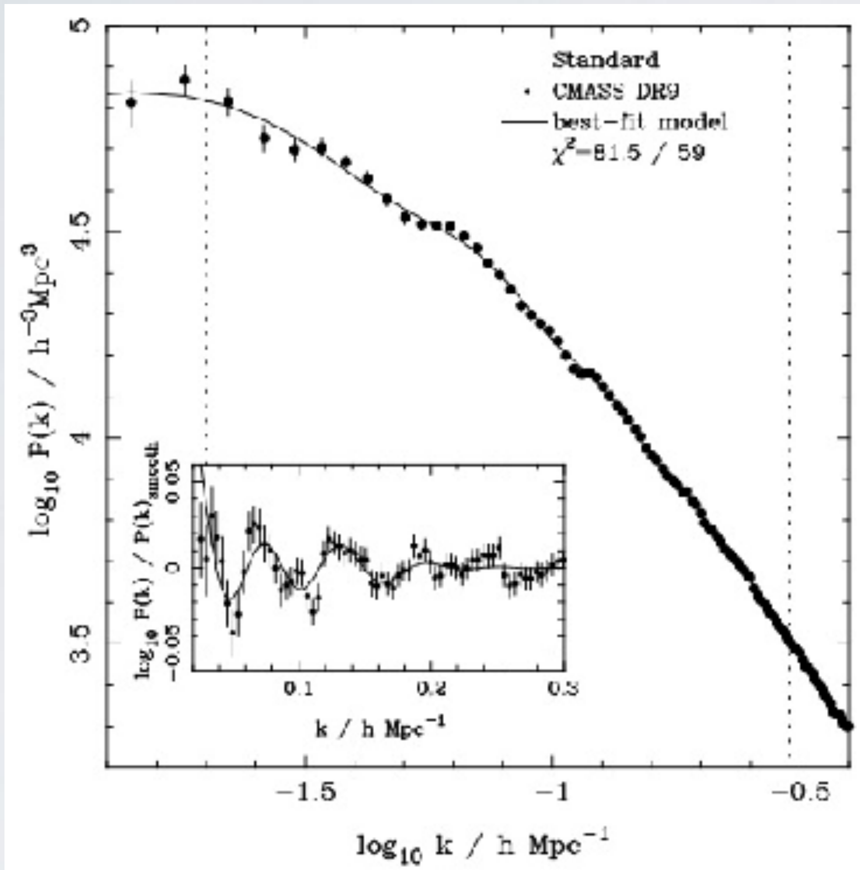


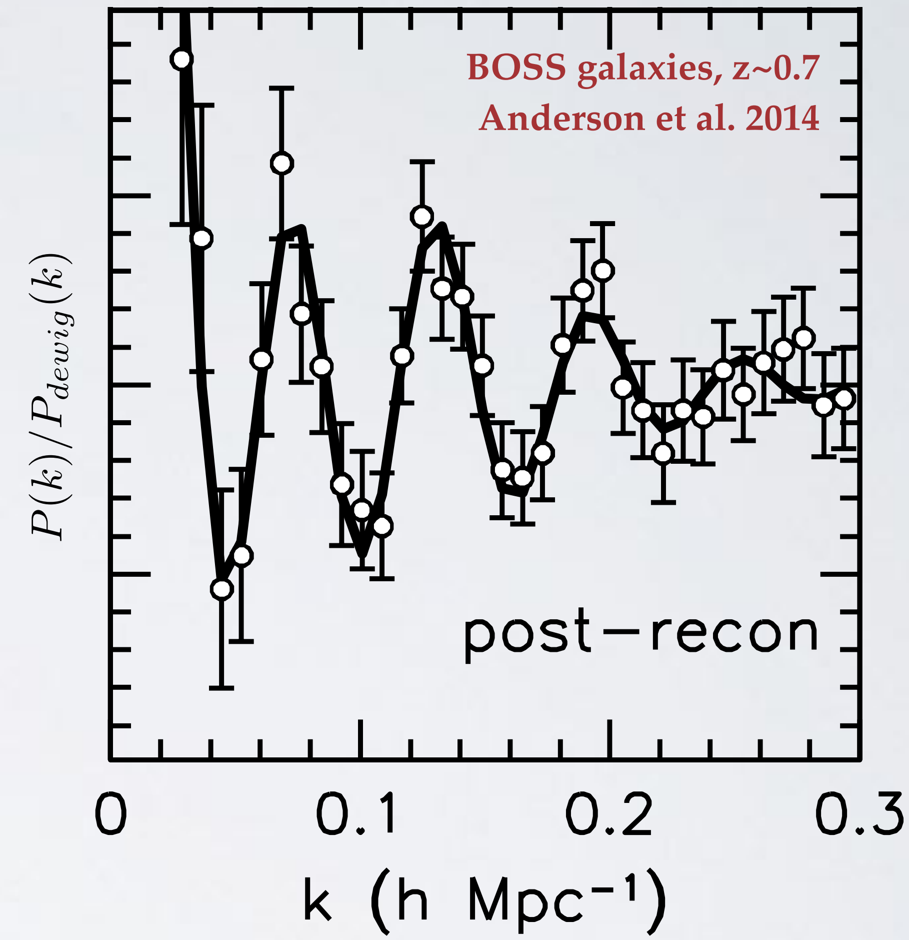


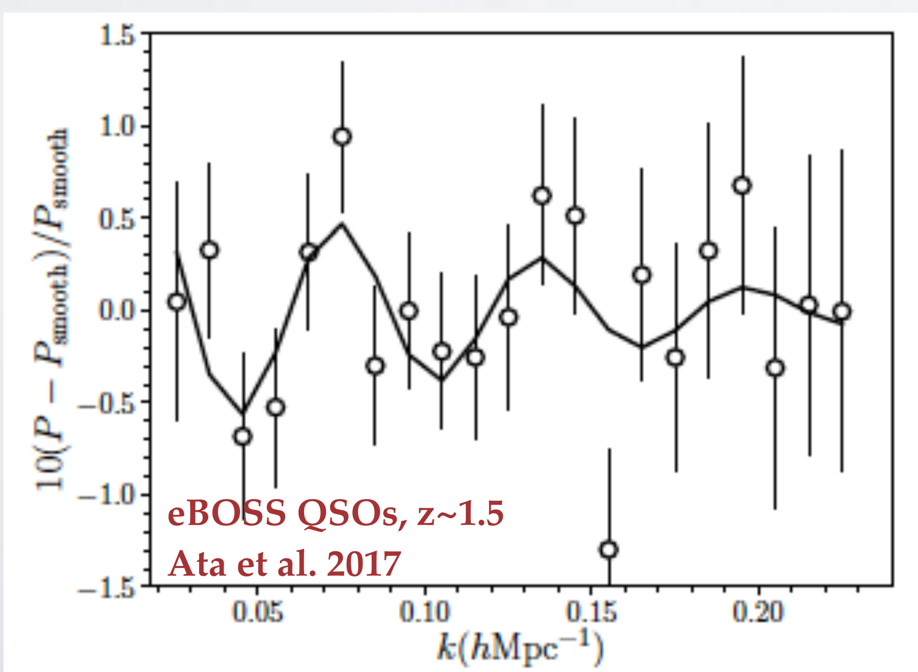
And on small scales, intra-halo effects dominate

DATA

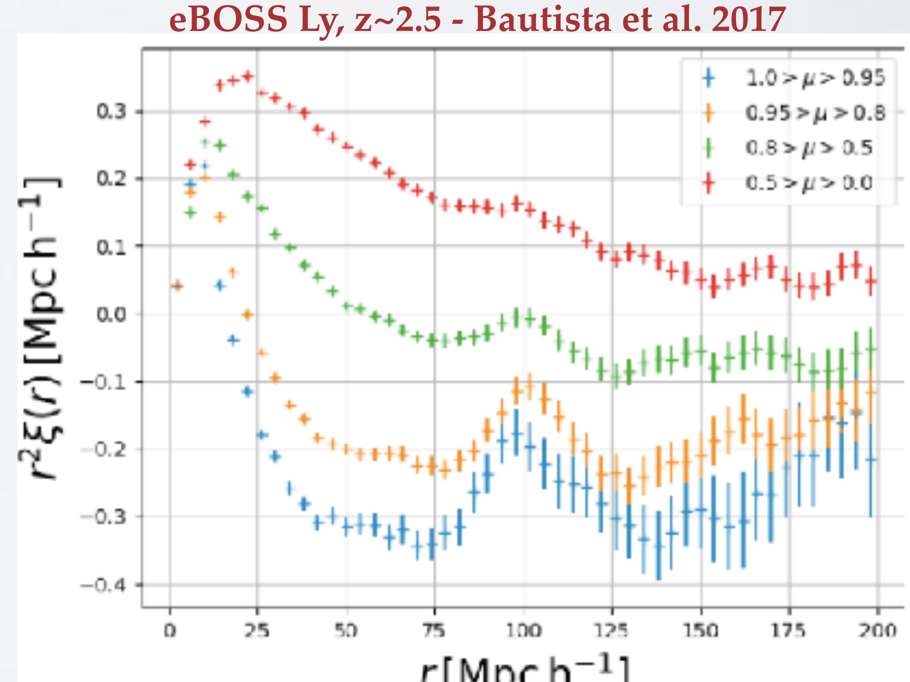
BAOS, ACCELERATION, AND ALL THAT…



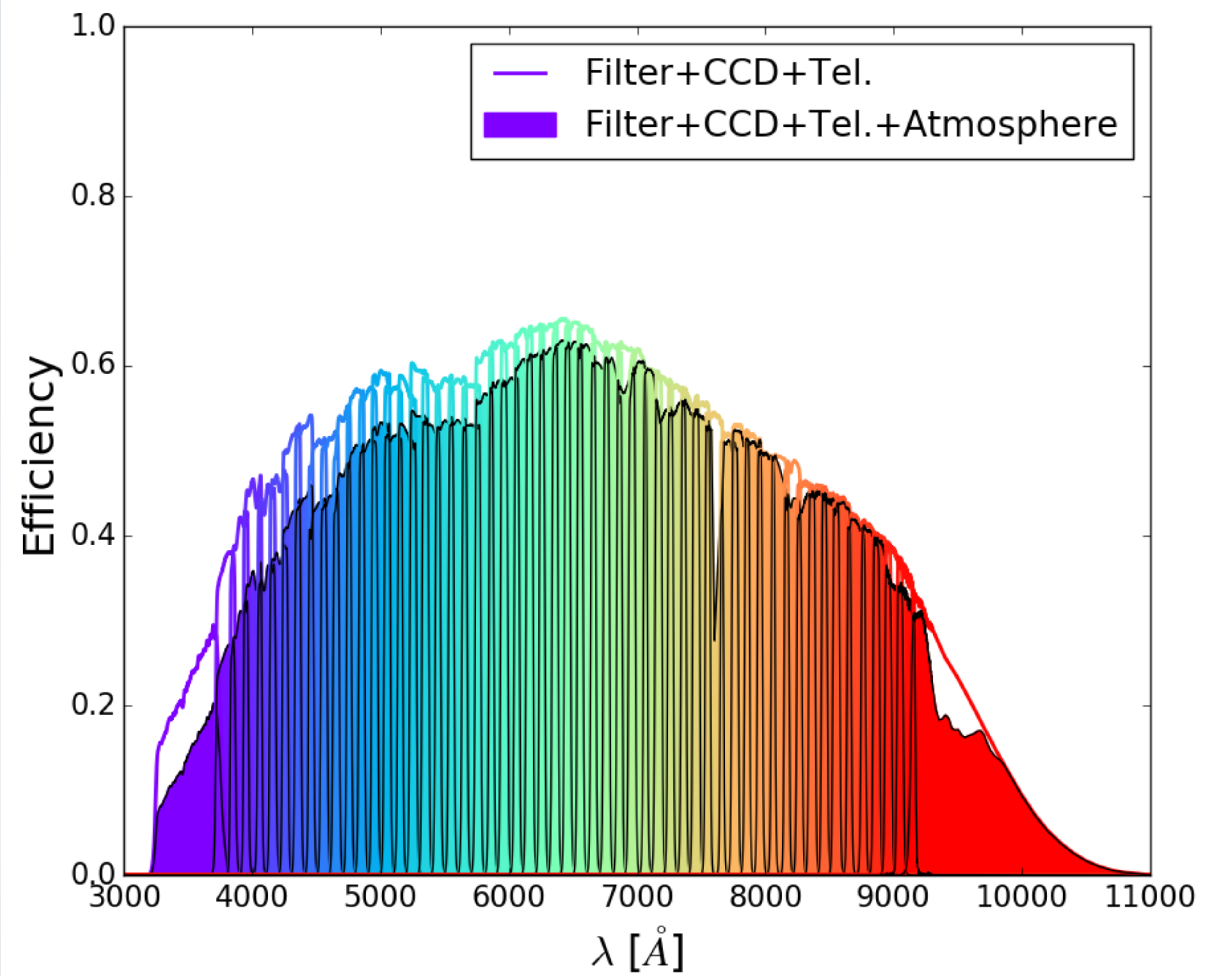




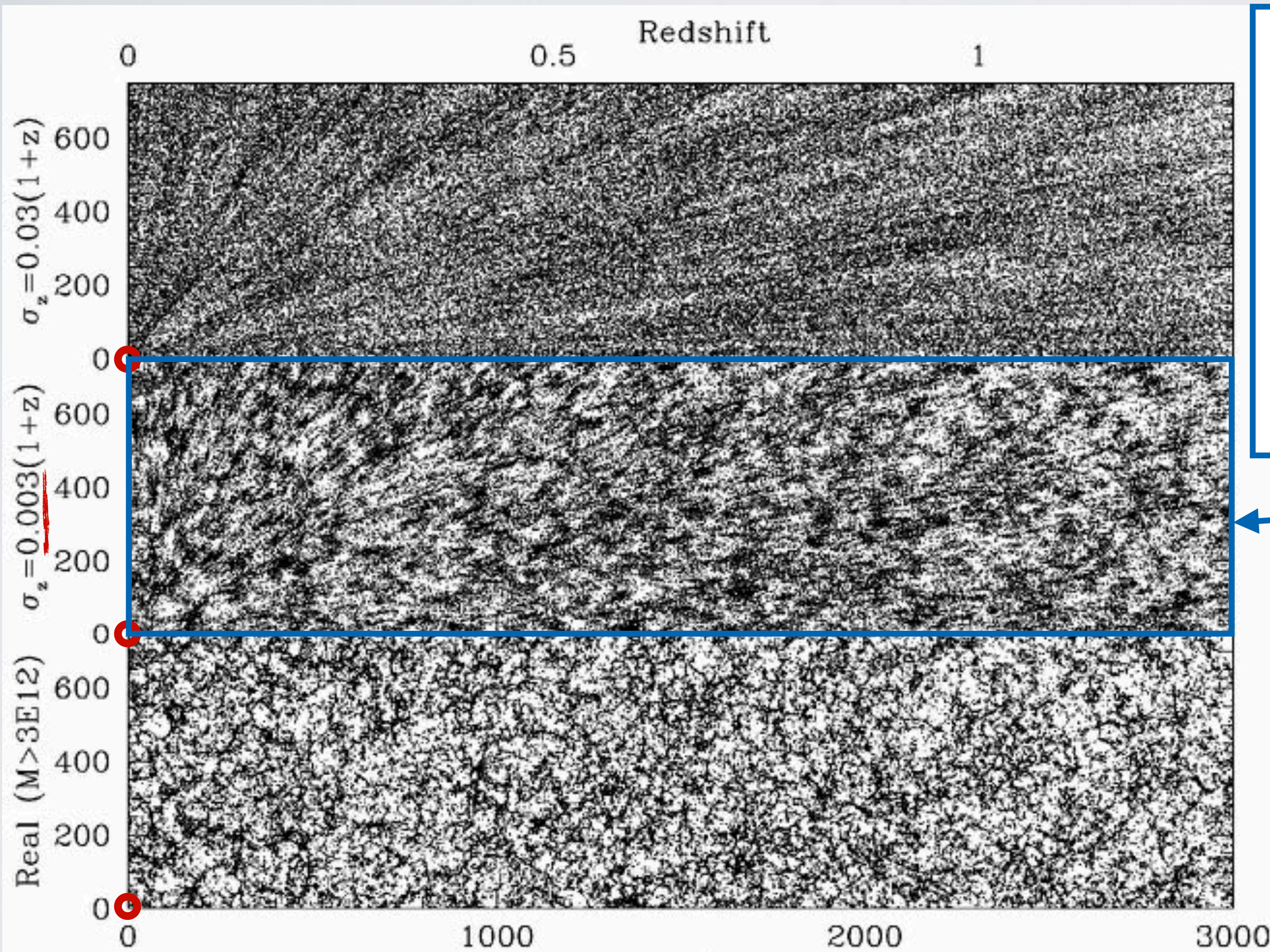
eBOSS Ly, z~2.5 - Bautista et al. 2017



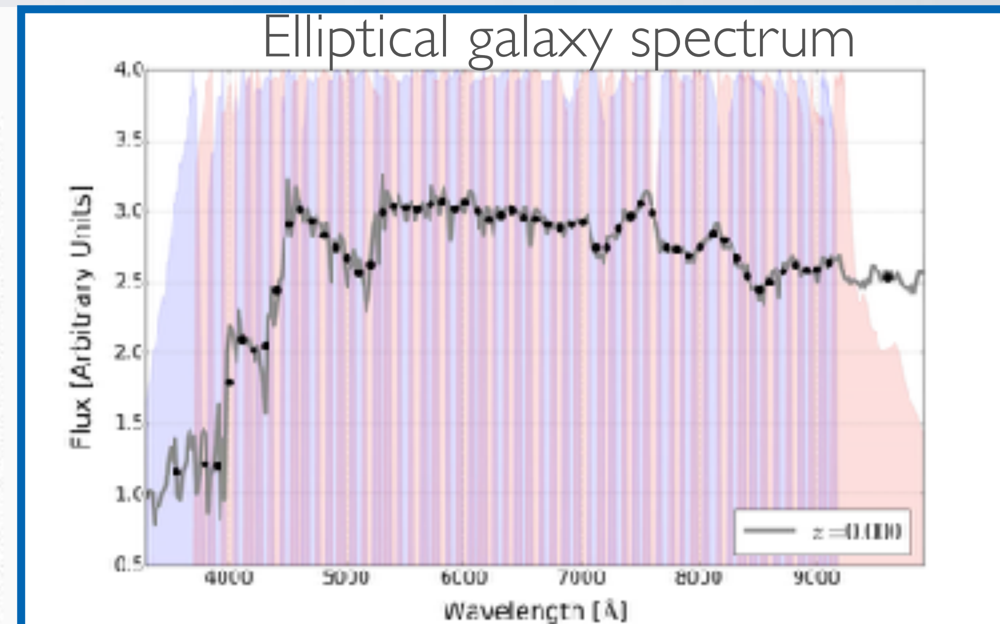
J-PAS

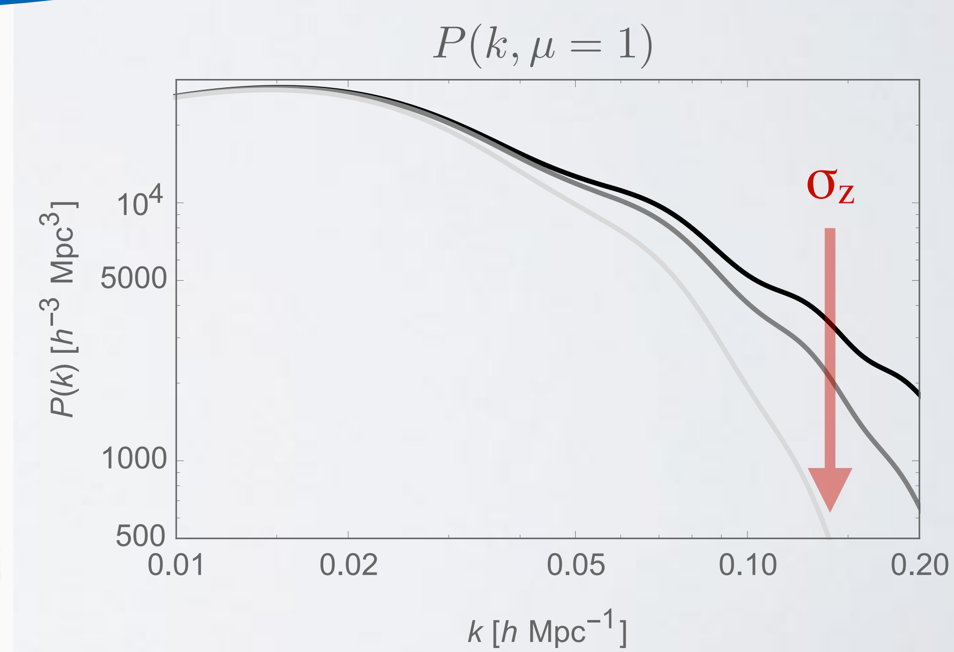

Filter+CCD+Tel.
Filter+CCD+Tel.+Atmosphere
Efficiency
0.0
0.2
0.4
0.6
0.8
1.0
3000
4000
5000
6000
7000
8000
9000
10000
11000
λ [Å]

WHY SO MANY FILTERS?



Benítez et al. 2009

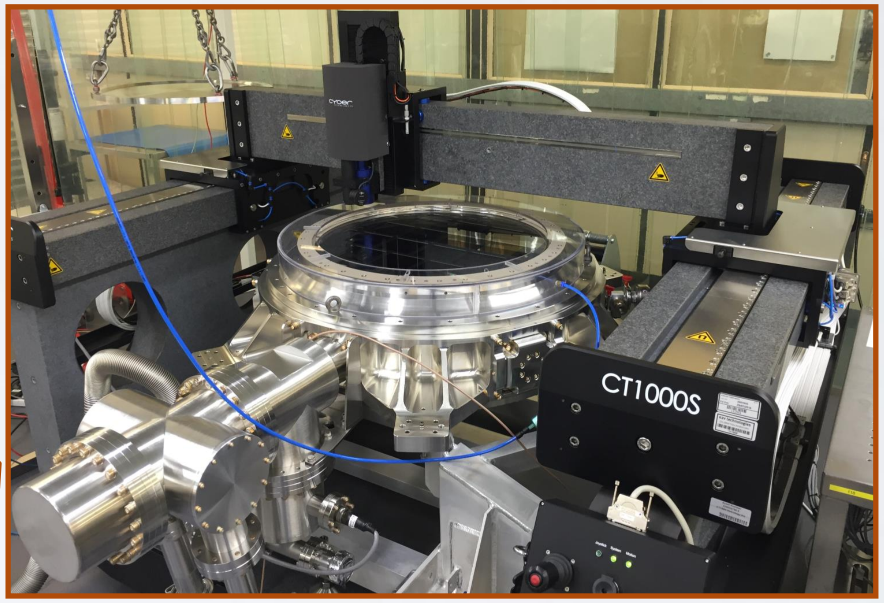




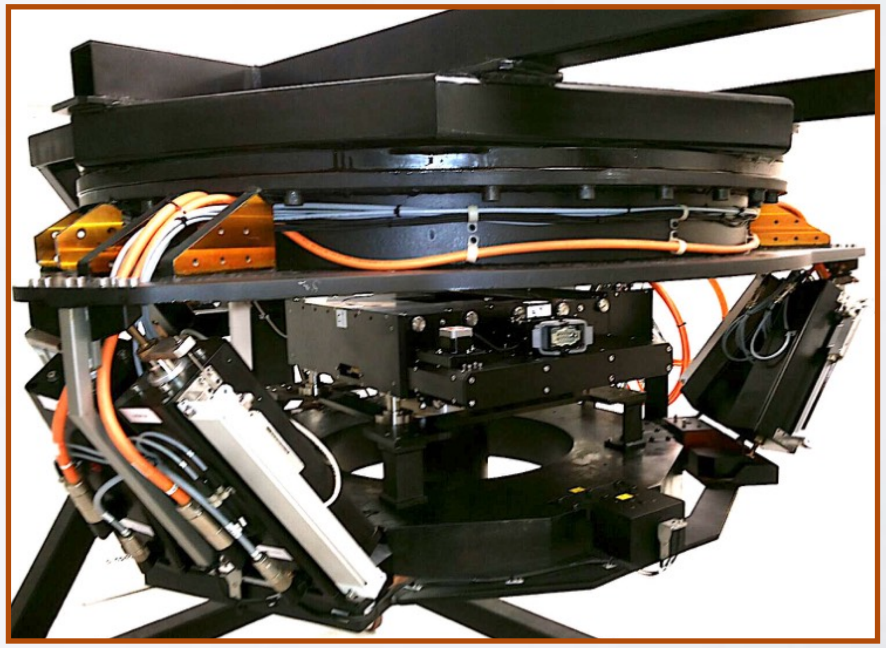
OAJ

Observatorio Astronomico de Javalambre

@ Spain

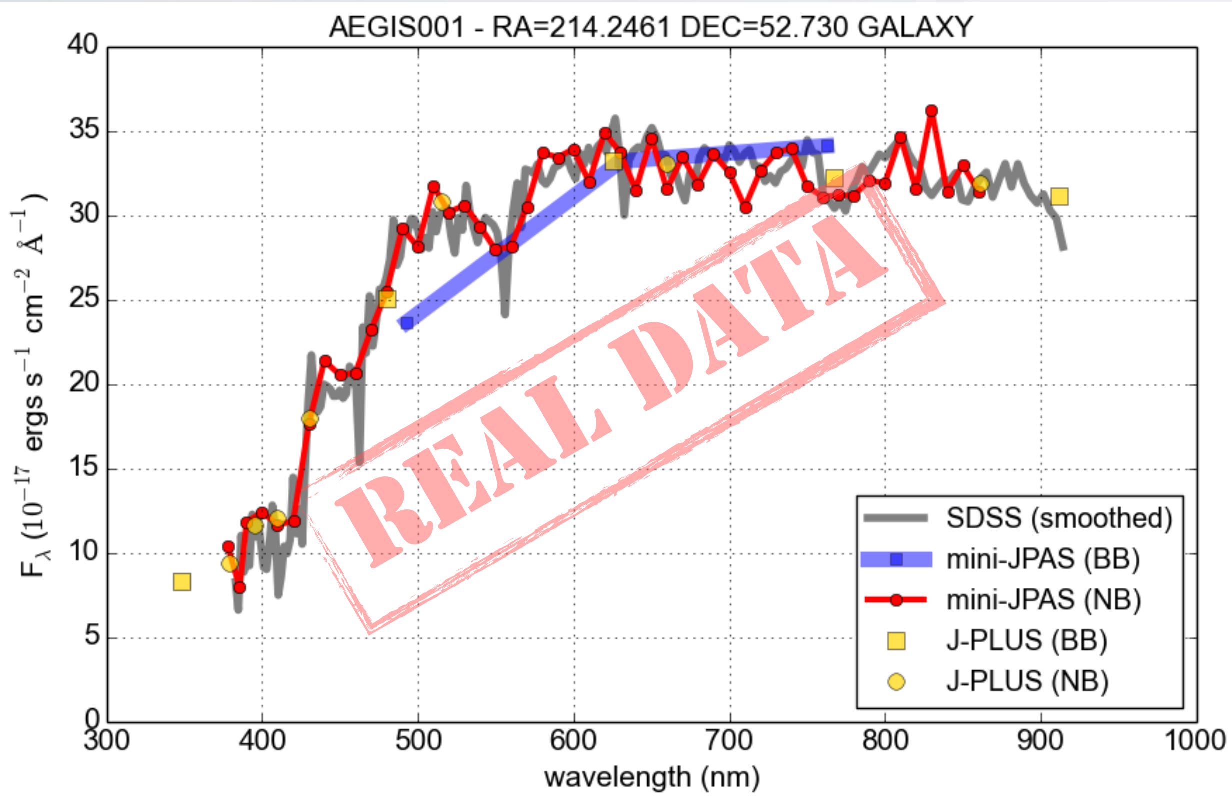


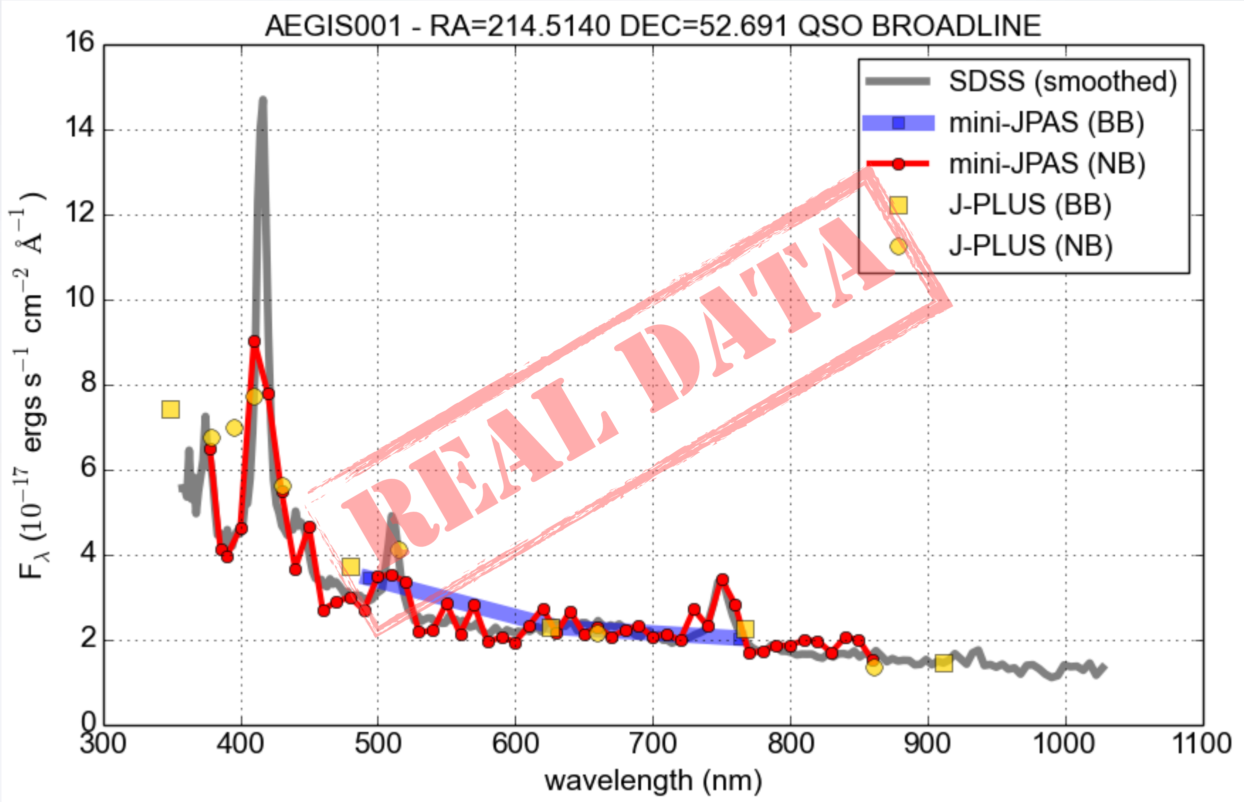
JPCam commissioning Q1/2019



Data verification completed with PathFinder camera

MINI J-PAS





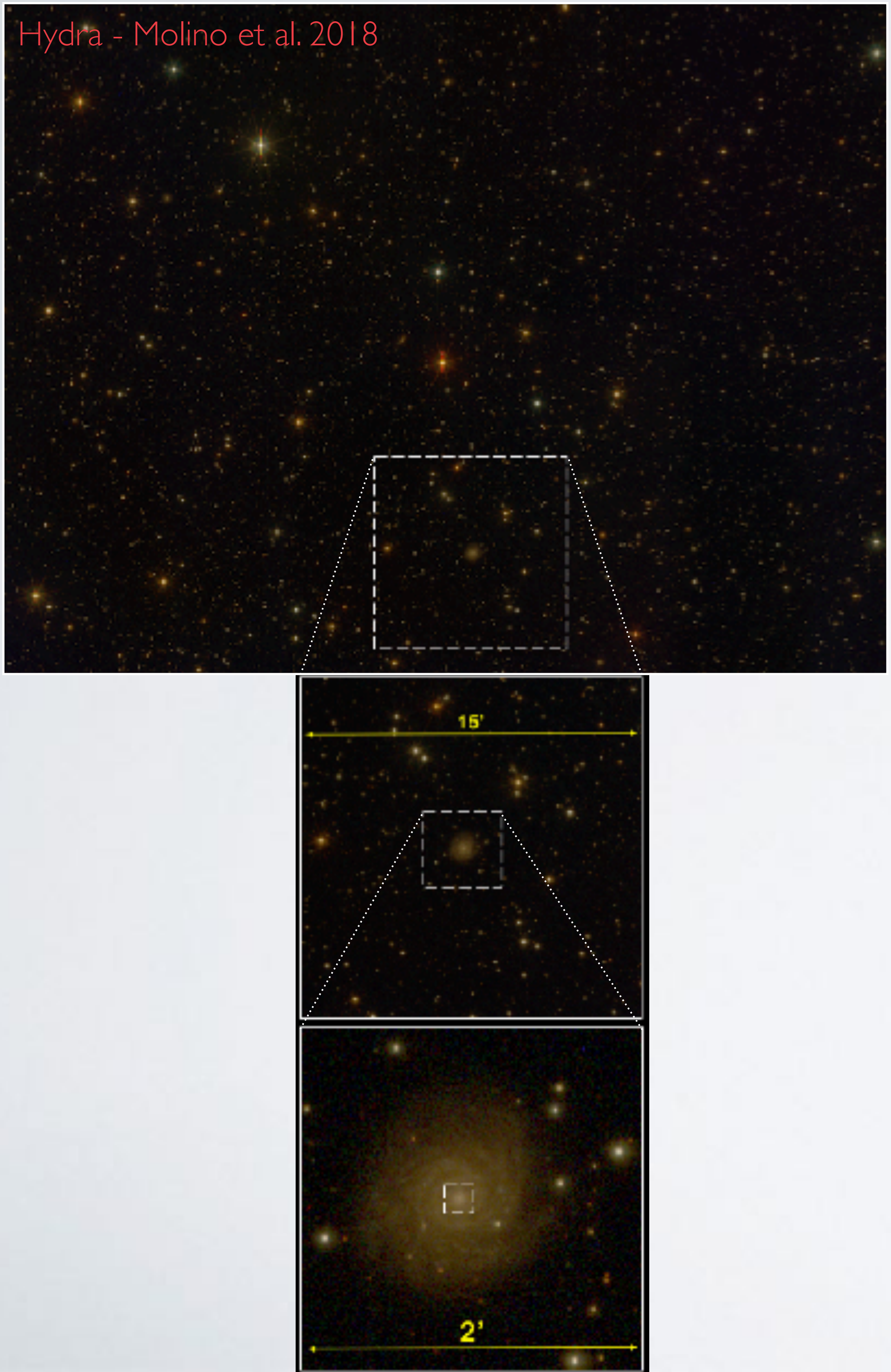
Proof of concept:

photometric redshift accuracies of ~0.2-0.3% !

Molino et al. [J-PAS Collaboration, 2019, to appear]
See also Eriksen et al. 2018 [PAUS]

J-PAS: > 10^5 objects/**deg²**

Billion-object problem: star-galaxy-QSO-junk separation (+ photo-zs!!)



Huge challenge — even with 56 narrow-band filters + g r i

- Classical techniques (e.g., template matching)
- Machine/deep learning (collab. with Comp. Sc. Depts.)

J-PAS: fully probabilistic catalogs:

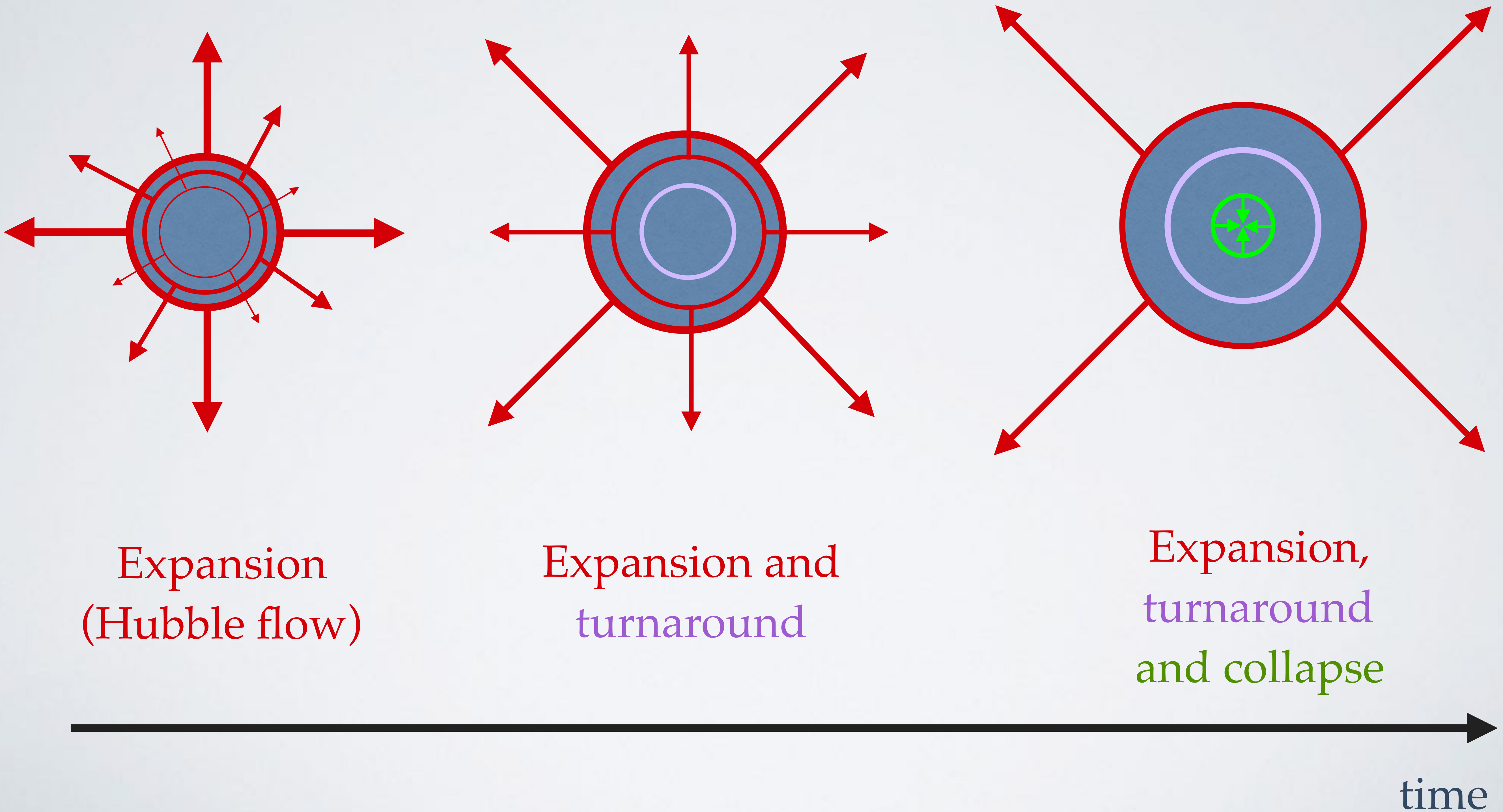
OBJ (RA , DEC):

- p(star)
  - → p(A)
  - → p(B)
  - …
- p(gal)
  - → p(S0) → p(z|S0)
  - → p(E0) → p(z|E0)
  - …
- p(qso)
  - → p(Q) → p(z|Q)
- p(junk)

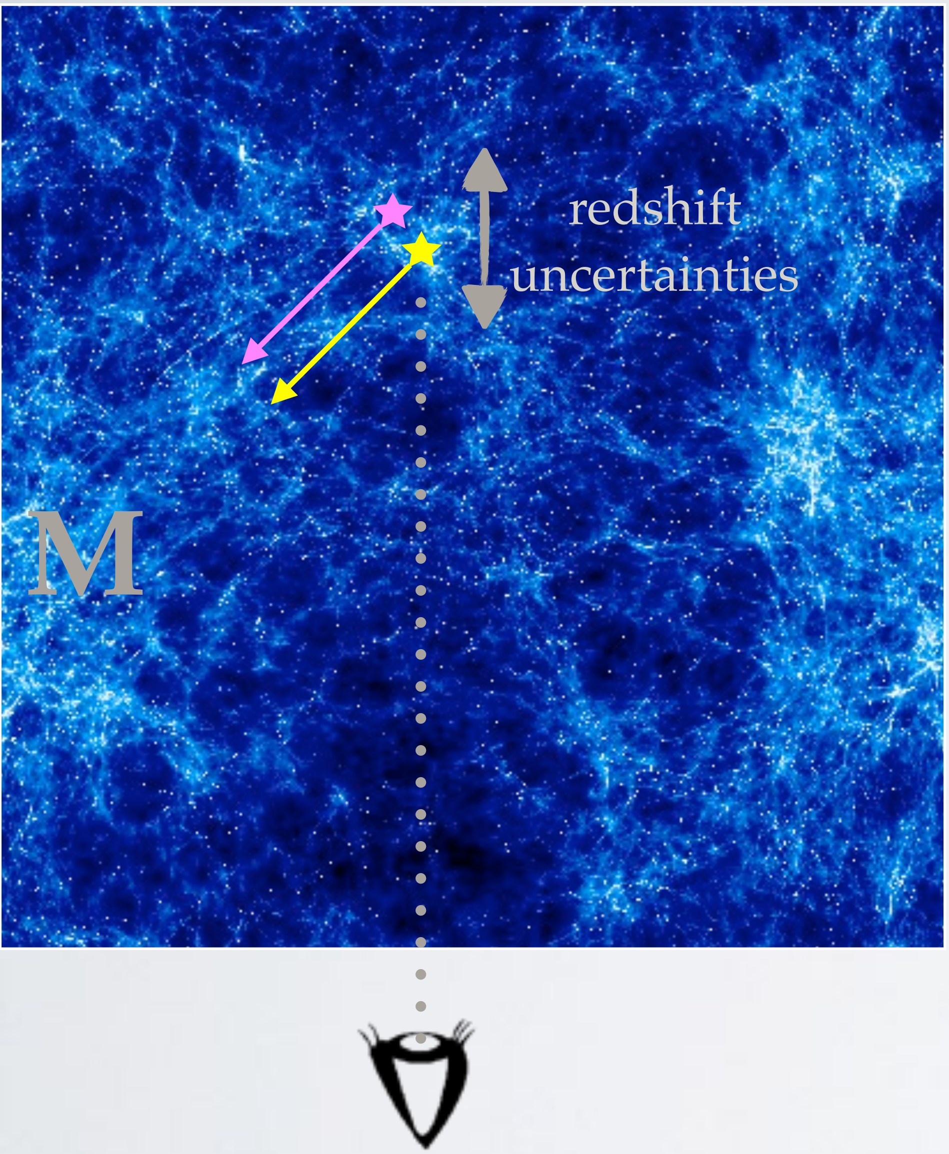
See also Carolina Queiroz's talk!

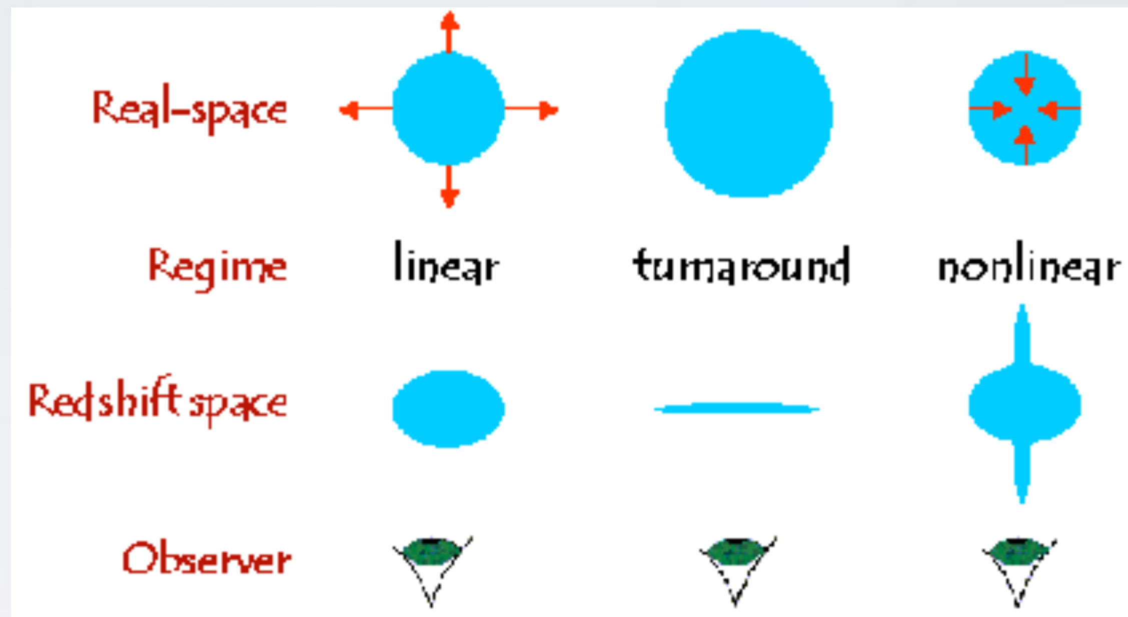
PRECISION COSMOLOGY WITH LARGE-SCALE STRUCTURE?

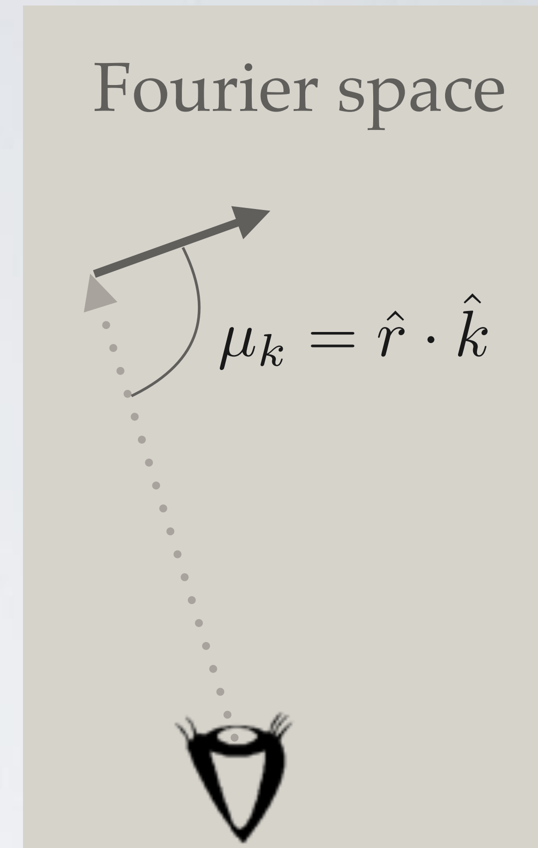
STRUCTURE FORMATION: EXPANSION V. GRAVITATIONAL COLLAPSE



STRUCTURE FORMATION AND THE EQUIVALENCE PRINCIPLE







redshift ⇌ peculiar velocities

In linear regime, $\nabla v = - \nabla^2 \Phi$

Modified gravity?

➪ The **velocity field** reflects the gravitational force in an unbiased way

$$P_g(k) \simeq \left(b_g + f\mu_k^2\right)^2 P_m(k) \quad \left\{ \begin{array}{l} \text{monopole} \\ \text{quadrupole} \\ \ldots \end{array} \right.$$

Kaiser 1987 | Percival & White 2009 | Raccanelli et al. 2013 etc.

THE MULTI-TRACER TECHNIQUE

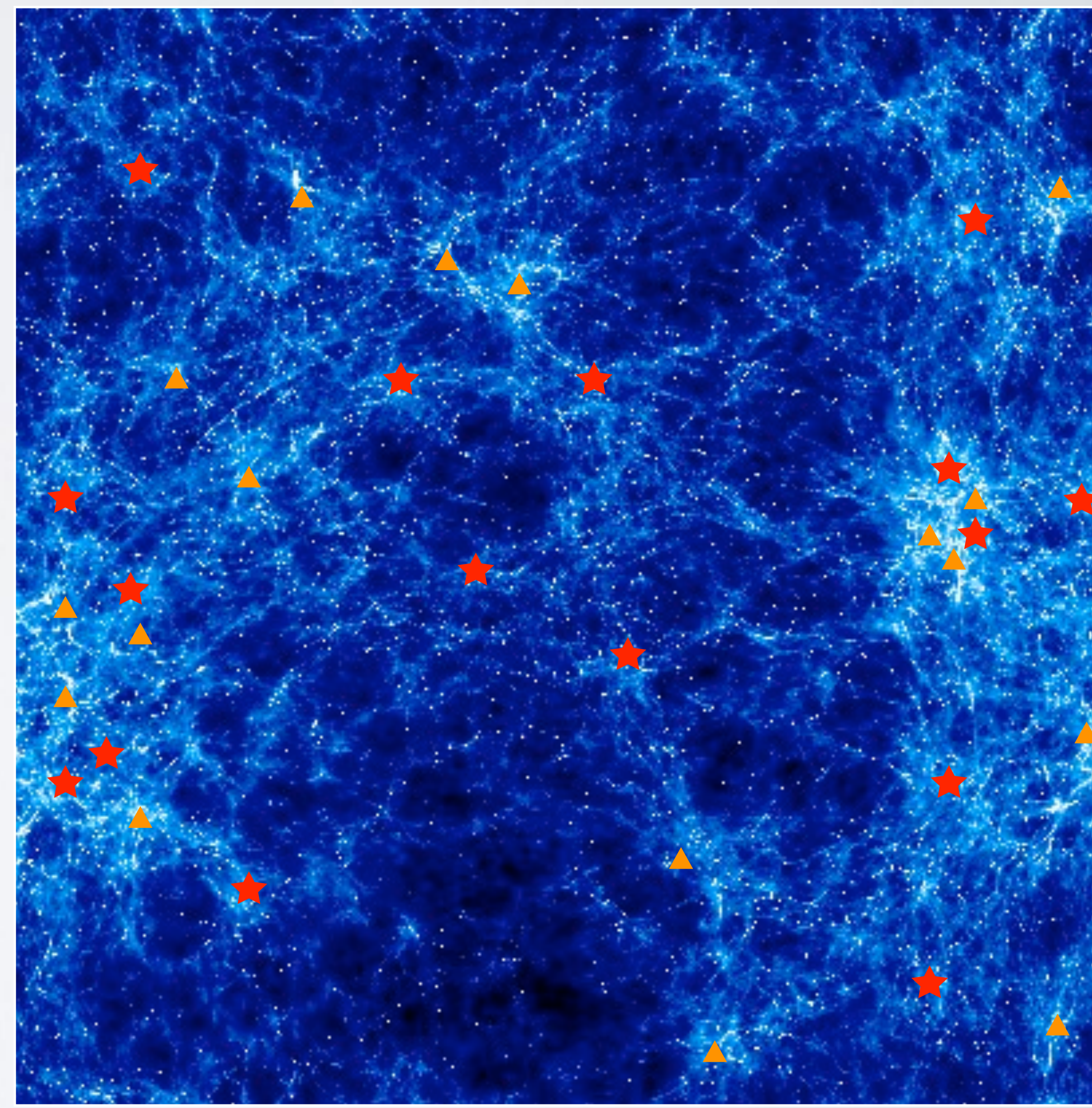
By contrasting the clustering of distinct tracers of large-scale structure, we can measure with "arbitrary" accuracy some physical parameters:

$$\mathcal{P}_1 = n_1\,(b_1 + f\,\mu_k^2)^2\,P(k;z)$$

$$\mathcal{P}_2 = n_2\,(b_2 + f\,\mu_k^2)^2\,P(k;z)$$

$$\frac{\mathcal{P}_1}{\mathcal{P}_2} = \frac{n_1\,(b_1 + f\,\mu_k^2)^2}{n_2\,(b_2 + f\,\mu_k^2)^2}$$

Cosmic variance does not apply:
* bias * RSDs
* NGs * HODs



The key is high numbers of distinct types of tracers: red galaxies, blue galaxies, emission-line galaxies, quasars, neutral H regions (21cm); DM halos; …

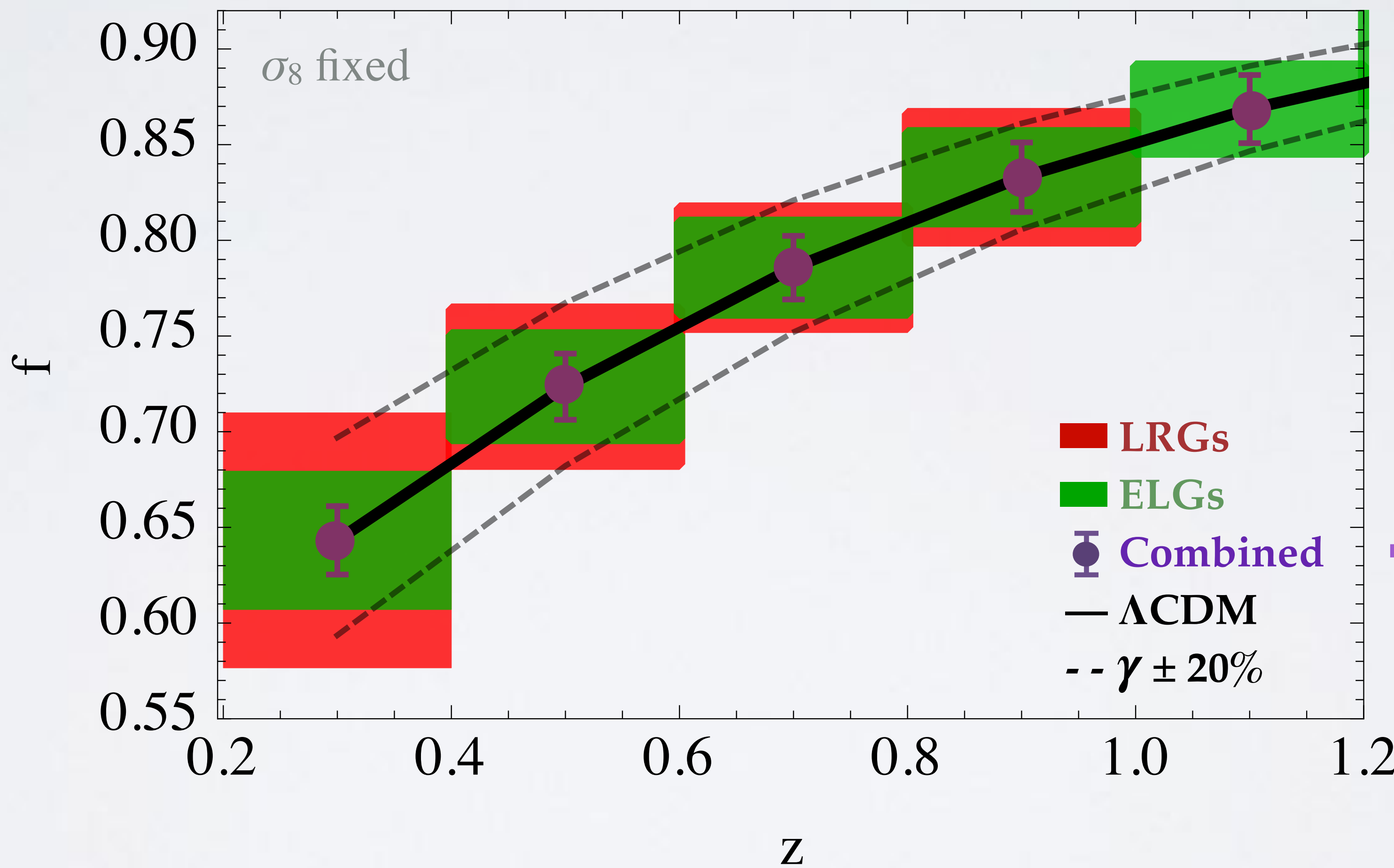
Seljak 2008 ○ McDonald & Seljak 2008 ○ Gil-Marín et al. 2011 ○ Hamaus et al. 2011, 2012 ○ Cai & Bernstein 2011
R.A. 2012 ○ R.A. & K. Leonard 2013 ○ R.A., L. Secco & A. Loureiro 2016 ○ Bull et al. 2018 ○ R.A. & Amendola, to appear

RSD/MODIFIED GRAVITY WITH J-PAS

$$\mathcal{P}_g = n_g\,(b_g + f\,\mu_k^2)^2\,P(k;z)$$

$$f = \frac{d\ln G}{d\ln a} \simeq \Omega_m^{\gamma}$$

modified gravity ($\gamma_{GR} \cong 0.55$)



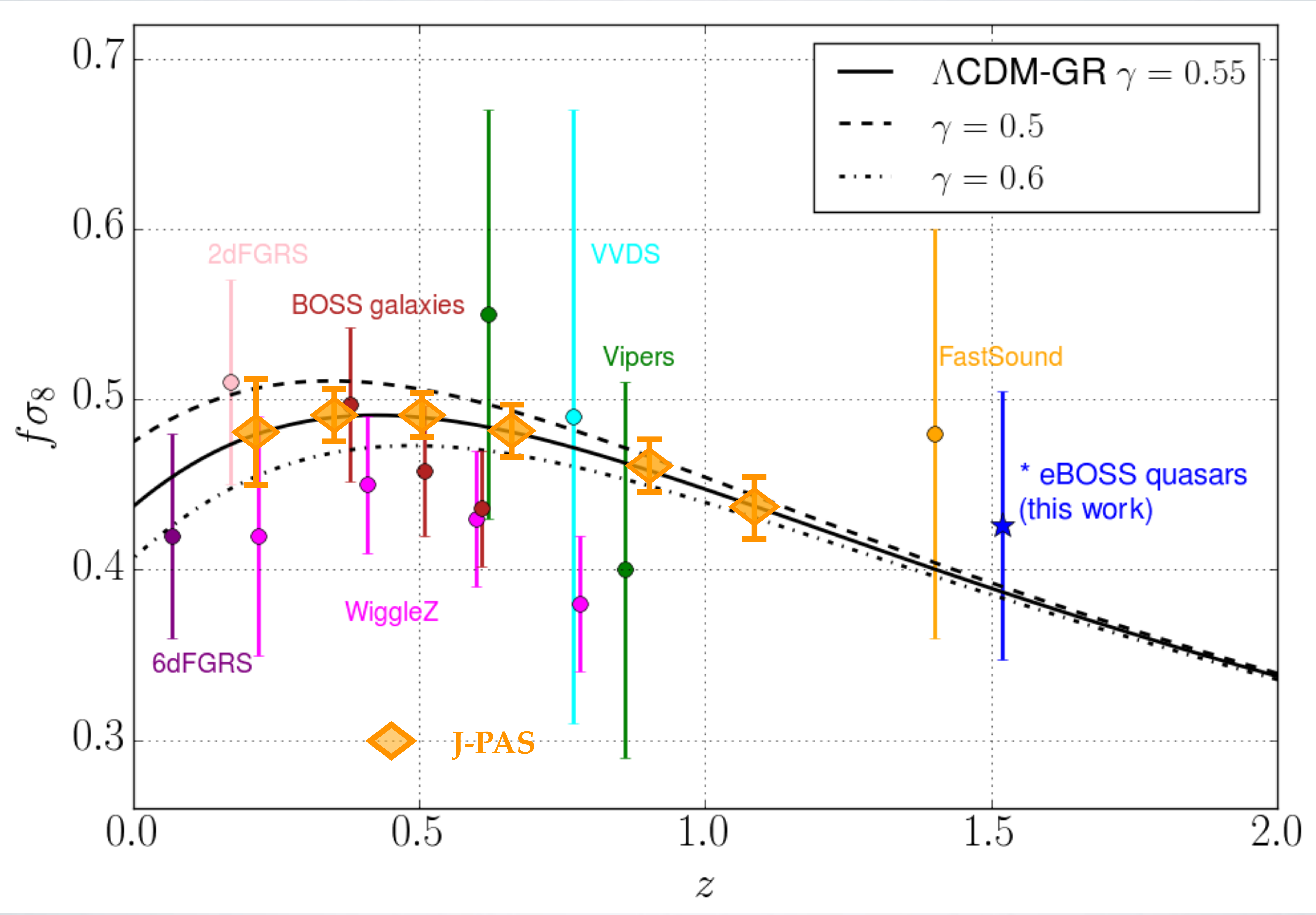
➡Use the multi-tracer technique to combine ELGs, LRGs & QSOs

J-PAS forecast for constraint on γ:

$\sigma(\gamma)$=0.03

R.A. & K. Leonard 2013 ○ Benítez et al. 2014 ○ R.A., L. Secco & A. Loureiro 2016 ○ R.A. & D. Bertacca 2017

RSD/MODIFIED GRAVITY WITH J-PAS

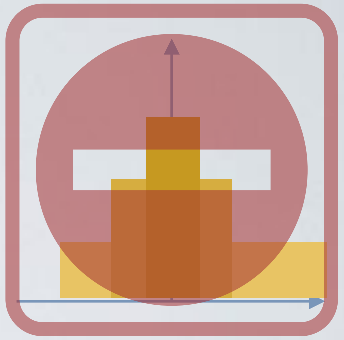


GRAVITATIONAL COLLAPSE AND MODIFIED GRAVITY

STRUCTURE FORMATION: **TURNAROUND**

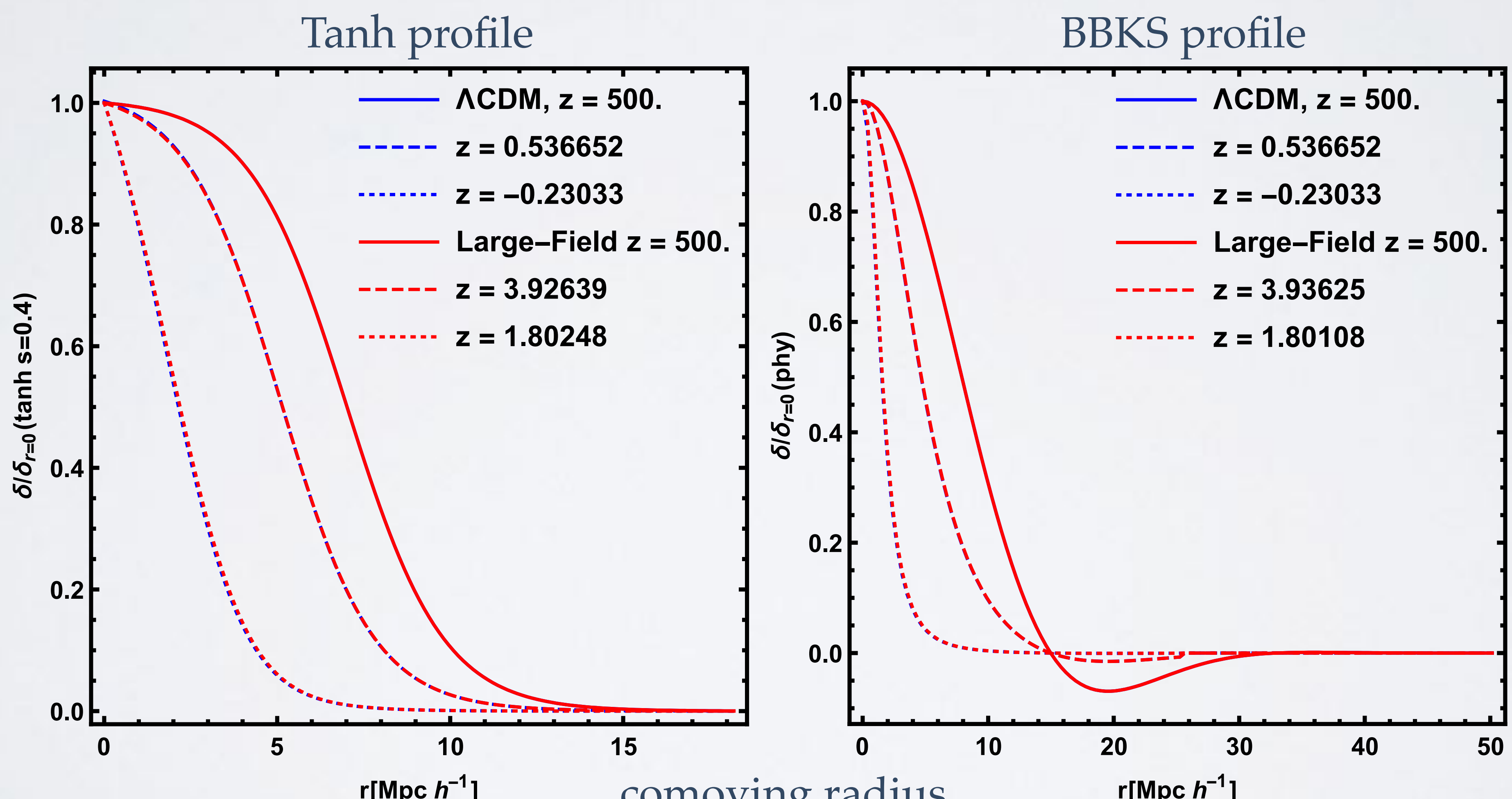
- Turnaround happens in relatively low-density, larger-scale environments
- Top-hat spherical collapse fails in Modified Gravity!
- Screening/chameleon not considered — sparse, low-density environments

➡ Spherical collapse in the Hu-Sawicky f(R) model of modified gravity



Borisov, Jain & Zhang 2012
Cembranos et al. 2012
Kopp et al. 2013

density profile



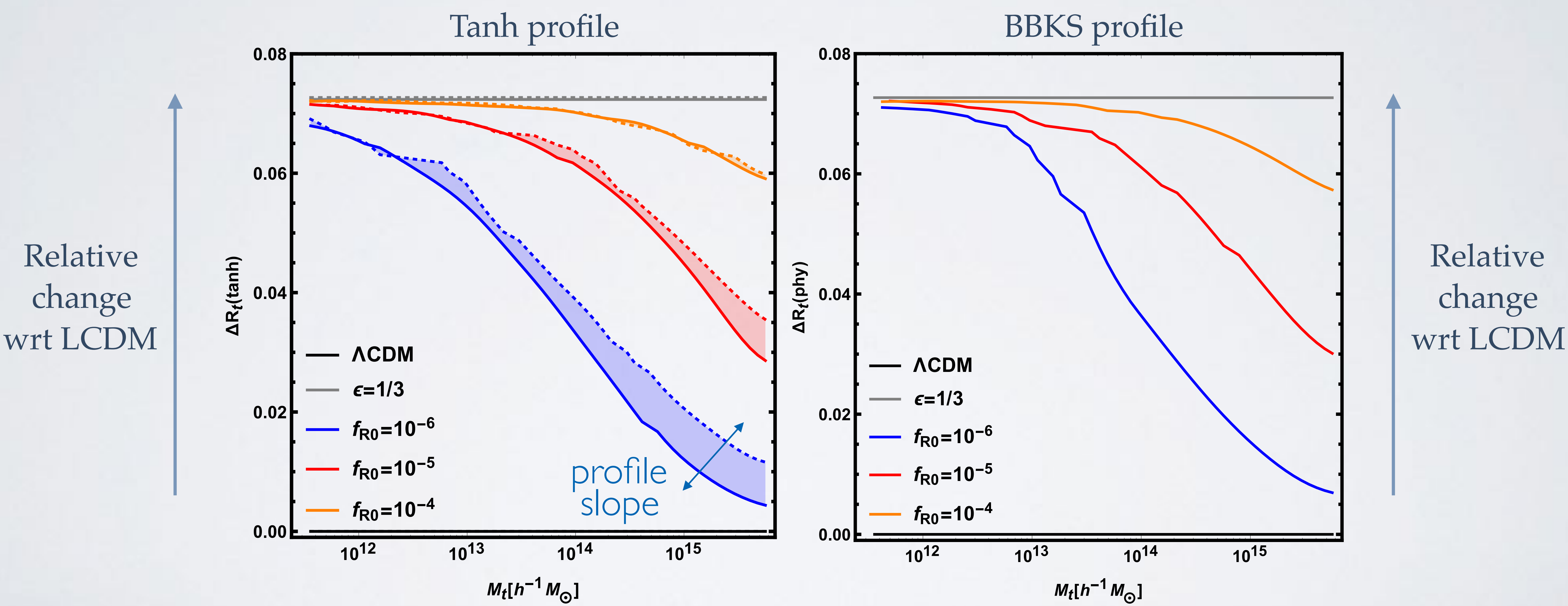
comoving radius

weak & strong: invariance under time reparametrization

Rafael C. Lopes, Rodrigo Voivodic, R.A. & L. Sodré Jr.
JCAP 2018, arXiv: 1805.09918
arXiv: 1809.10321

TURNAROUND AND MODIFIED GRAVITY

- In the strong field regime of Hu-Sawicky MoG the turnaround radius at z=0 is ~7% larger than in LCDM
- At low-mass end, even small parameters of that model lead to an enhancement of the turnaround radius



Rafael C. Lopes, Rodrigo Voivodic, R.A. & L. Sodré Jr.

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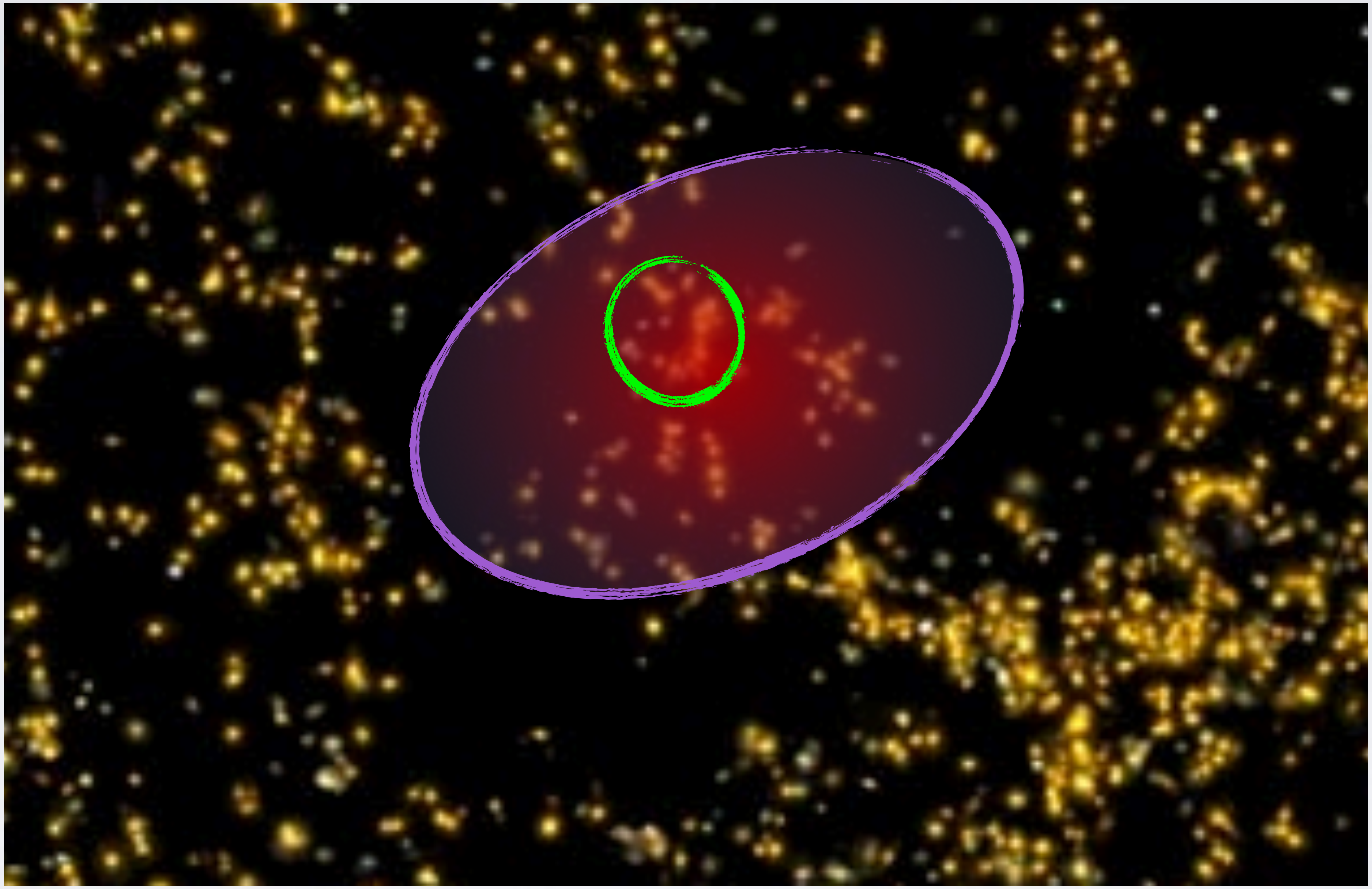
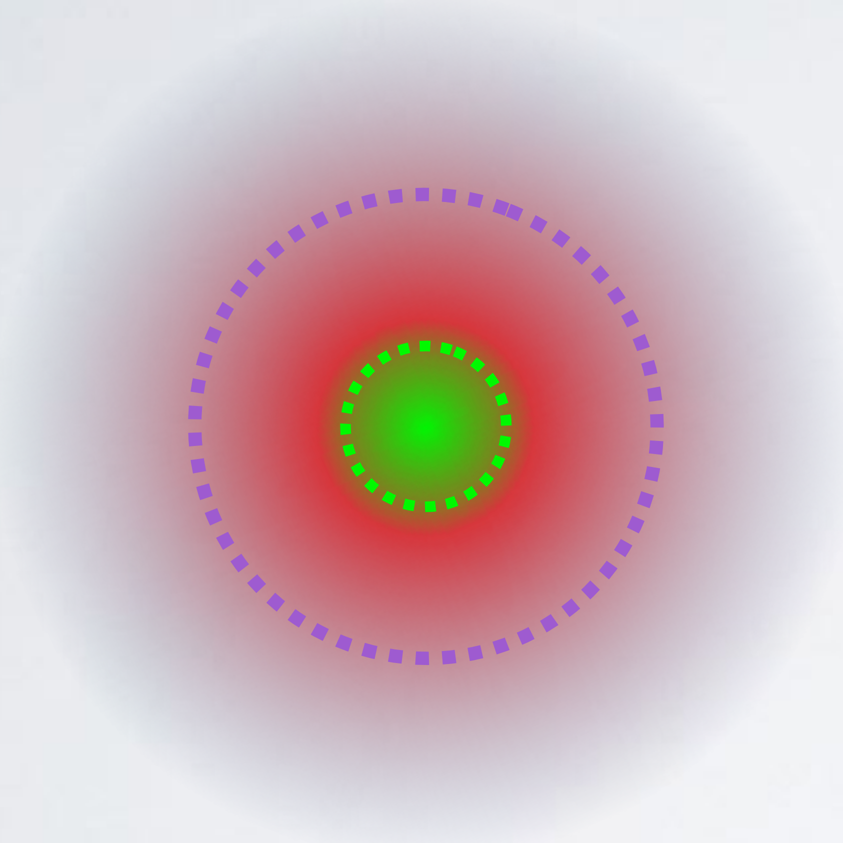
arXiv: 1809.10321

TURNAROUND MASS: HARDER TO OBSERVE…



Turnaround mass and virialized mass

MASS PROFILE: FROM SMALL SCALES TO LARGE SCALES



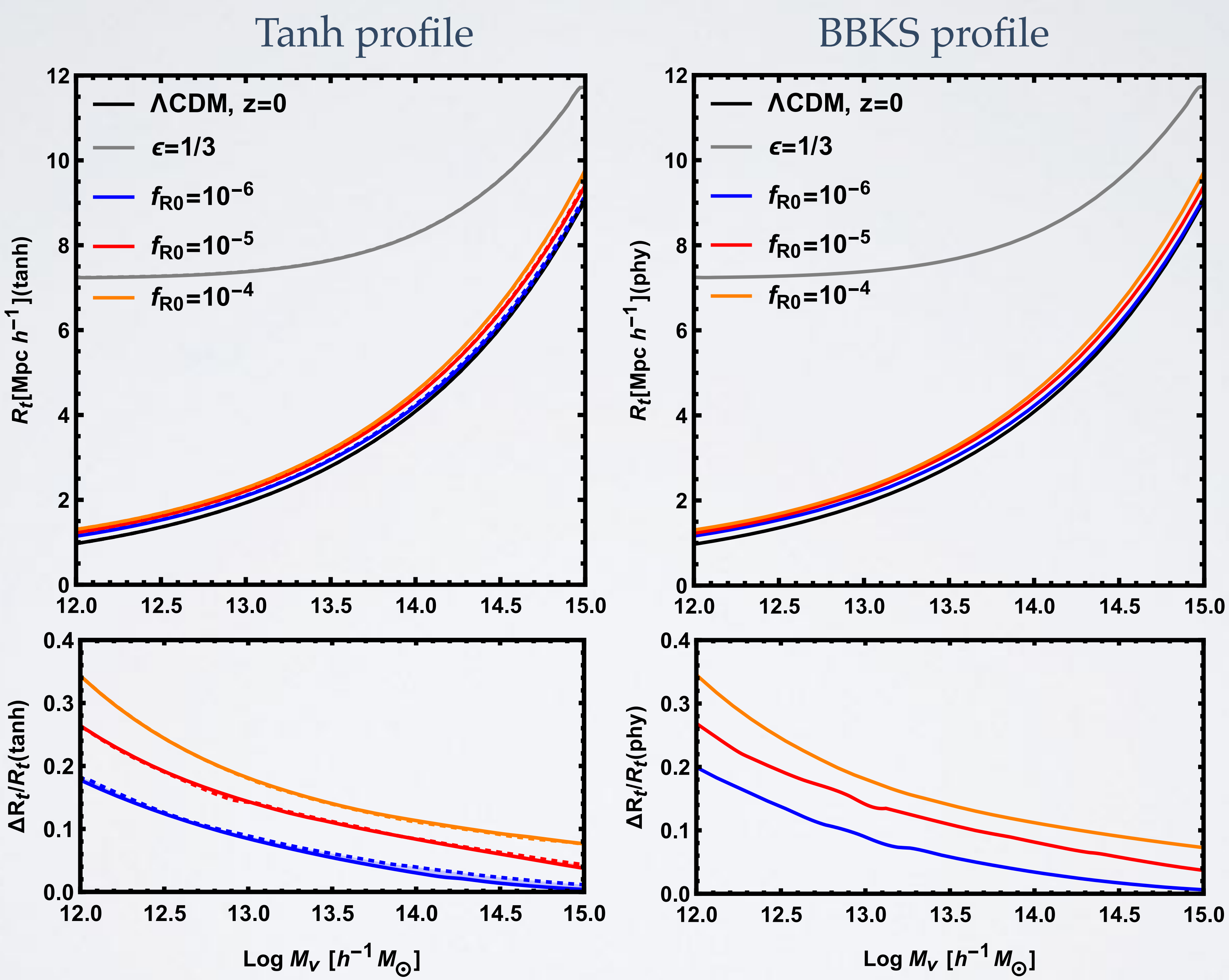
$$\rho_{obs}(r) = \rho_{1h}(r) + \rho_{2h}(r)$$

$$\rho_{2h}(r) = \bar{\rho}_m \, b^{lin}(M_h) \, \xi_m^{lin}(r)$$

Turnaround mass ➠ virialized mass

TURNAROUND AND VIRIAL MASS

- Using the 1-halo + 2-halo description we can link the turnaround radius of the outermost shell with the mass of the virialized central regions of collapsing systems
- Advantage from observational viewpoint: virial mass characterizes the collapsed structures

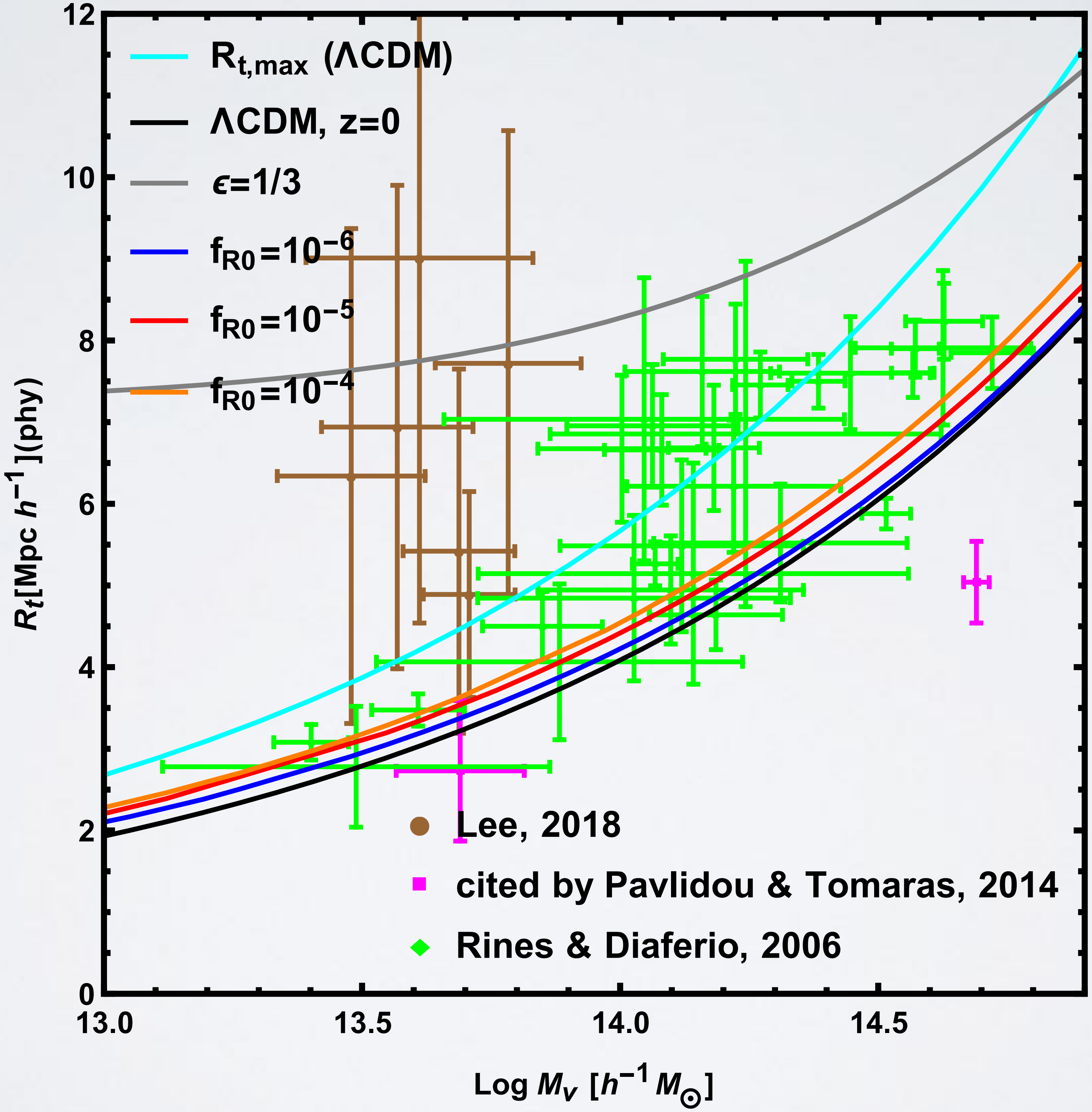


Rafael C. Lopes, Rodrigo Voivodic, R.A. & L. Sodré Jr.
JCAP 2018, arXiv: 1805.09918
arXiv: 1809.10321

virial
mass

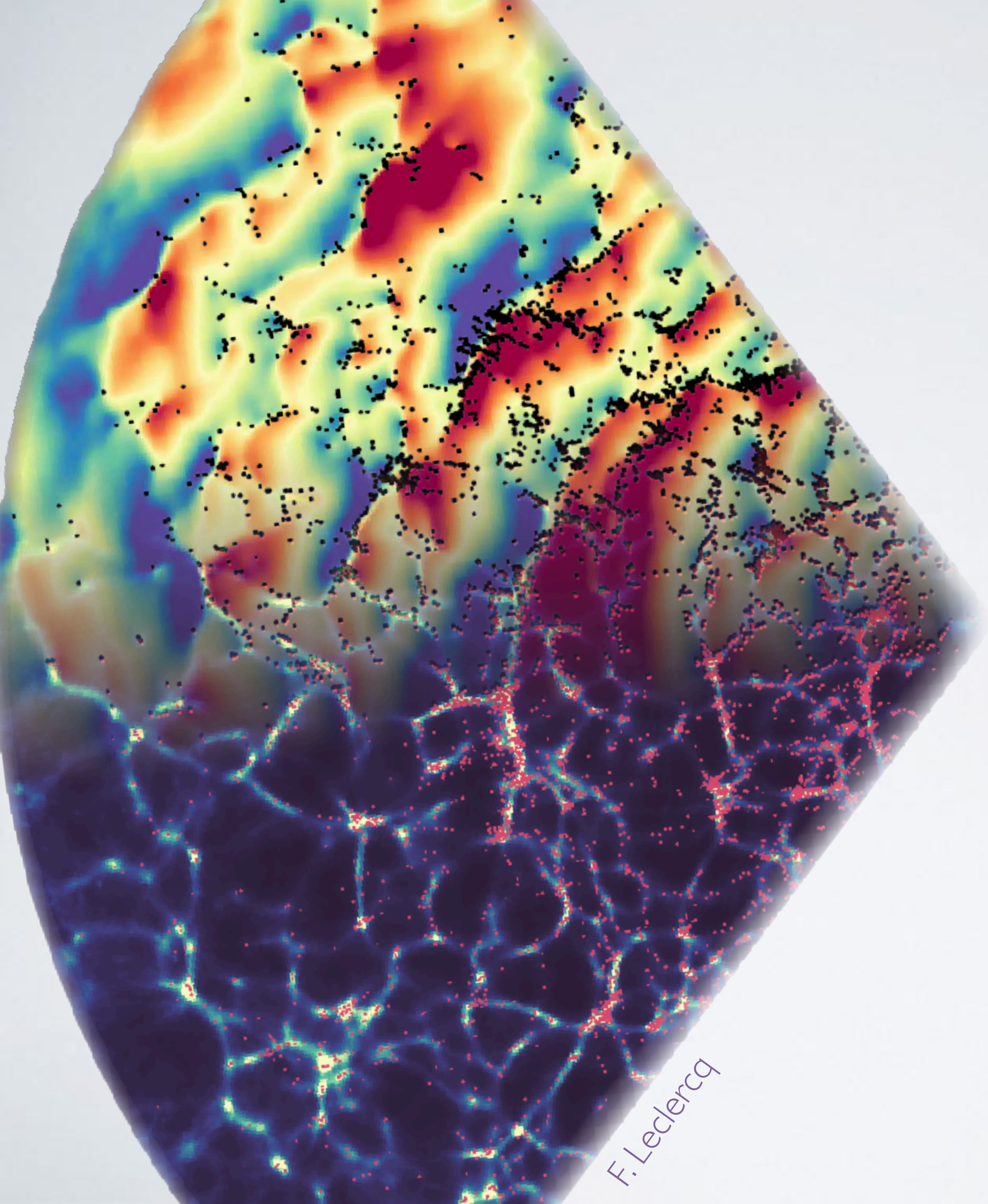
TURNAROUND AND VIRIAL MASS

- Comparison with observations is now straightforward — but challenging



arXiv: 1809.10321

HALOS, THEIR ENVIRONMENTS AND GALAXIES



DARK MATTER
DENSITY FIELD

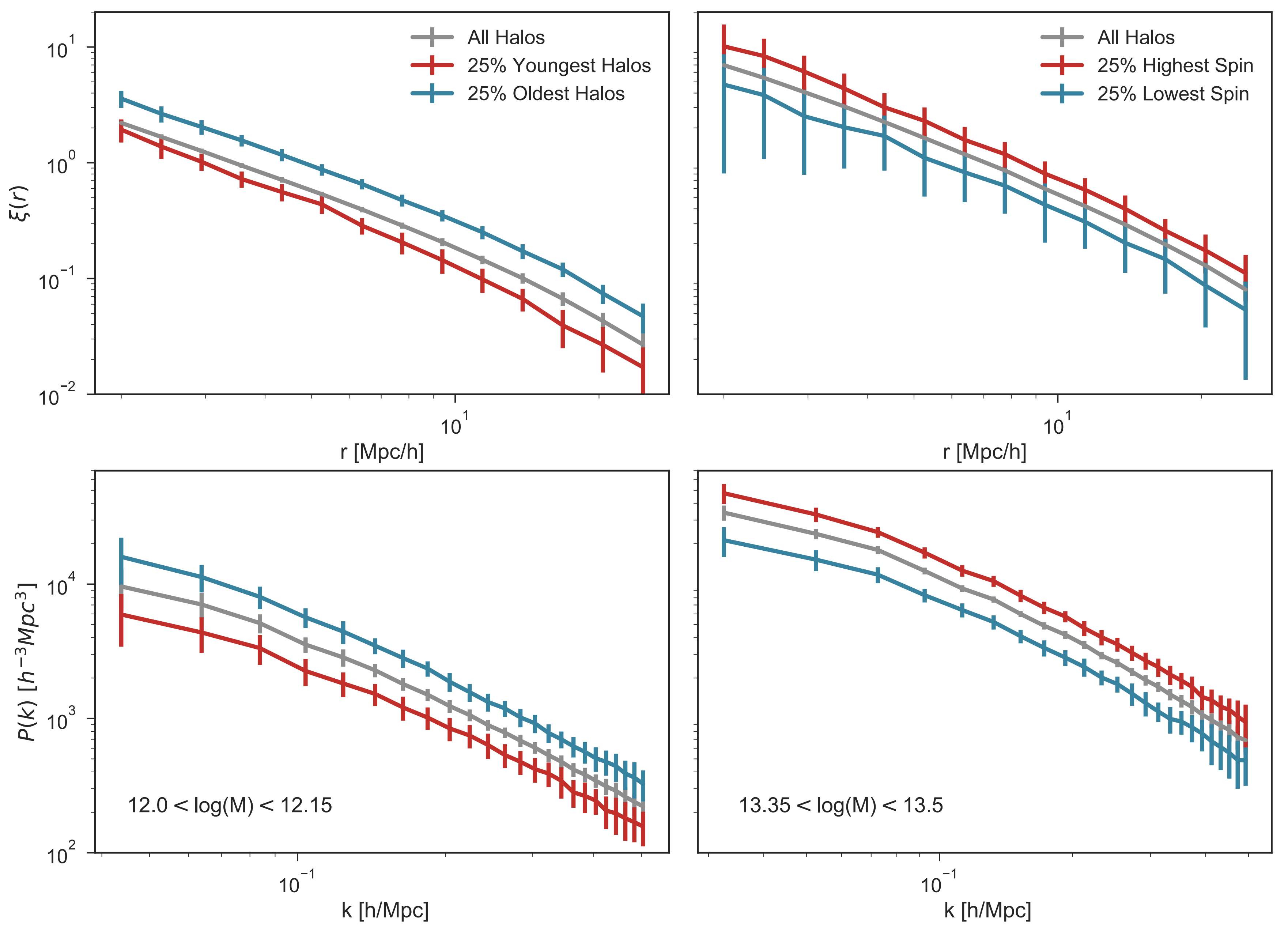
(HALOS)

GALAXIES

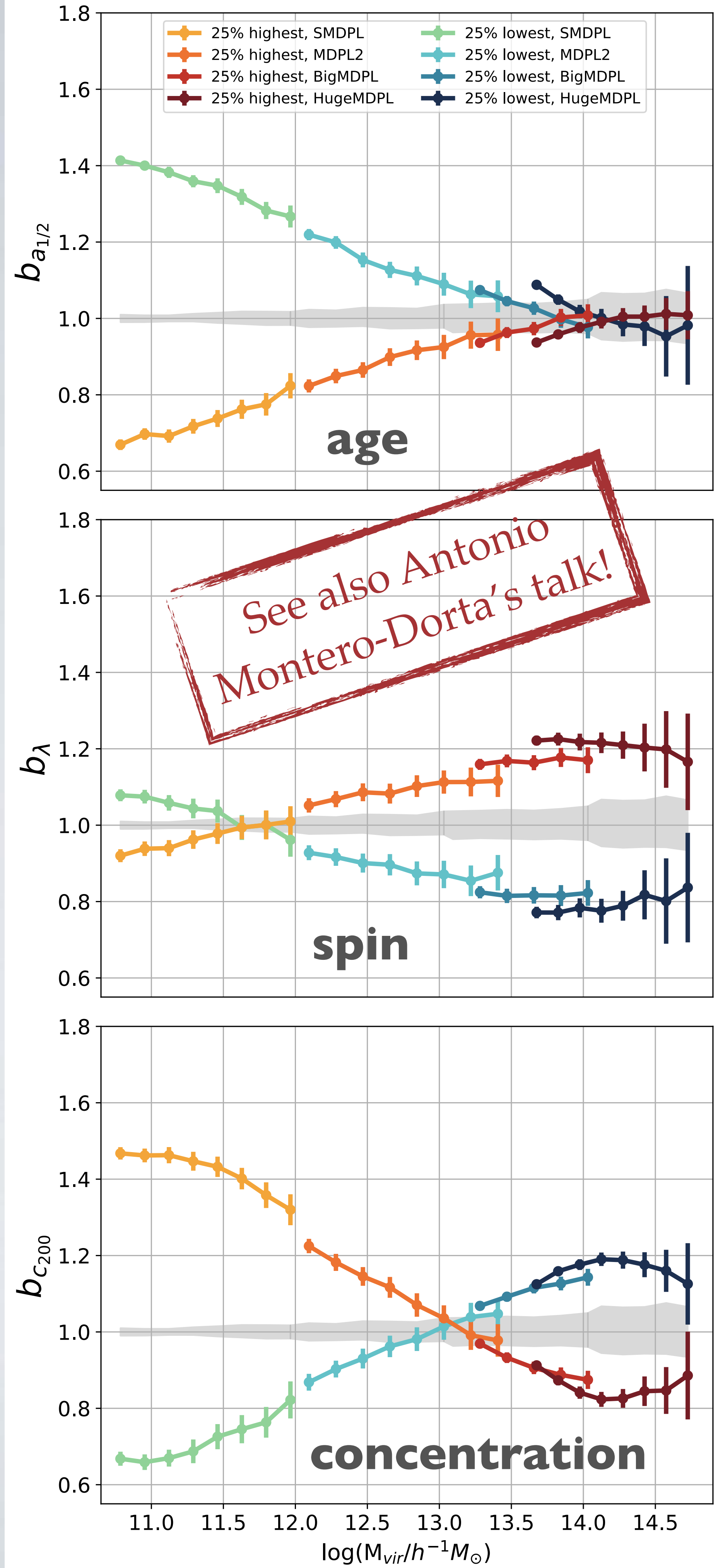
GALAXIES OR HALOS?

- **Halo mass** is the **primary bias** factor
- Other halo properties can also be important: age, spin, concentration, …?
- MultiDARK N-body simulations: 4 boxes: $(400\ h^{-1}\ \mathrm{Mpc})^3$, $(1\ h^{-1}\ \mathrm{Gpc})^3$, $(2.5\ h^{-1}\ \mathrm{Gpc})^3$, $(4\ h^{-1}\ \mathrm{Gpc})^3$

Assembly bias:
Gao et al. 2005
Wechsler et al 2006
Angulo et al. 2008
…
Salcedo et al. 2018
Han et al. 2018



G. Sato-Polito, A. Montero-Dorta, R.A., F. Prada, A. Klypin 1810.02375



ENVIRONMENTS OF HALOS AND GALAXIES ARE CRITICAL FOR LSS!

- Bias can change by up to 50% for the same halo mass
- There is no halo mass range which is preserved
- At low ($<10^{12}$ $M_\odot$) masses, age and concentration are main drivers
- At intermediate (10^{12} $M_\odot$<M<$10^{13.5}$ $M_\odot$) masses, spin is important
- At high (M>$10^{13.5}$ $M_\odot$) masses, spin and concentration dominate

Precision cosmology with galaxies & groups & clusters must cope with a deeper understanding of the physics of halos, their environments, and the galaxies that inhabit these structures

- Relation between galaxy spin, host halo spin, and parent halo spin is not as simple (Mao & White 98; Bullock 2001) as we thought, with subtle baryonic effects (e.g., Jiang et al. 1804.07306)

G. Sato-Polito, A. Montero-Dorta, R.A., F. Prada, A. Klypin 1810.02375

CONCLUSIONS

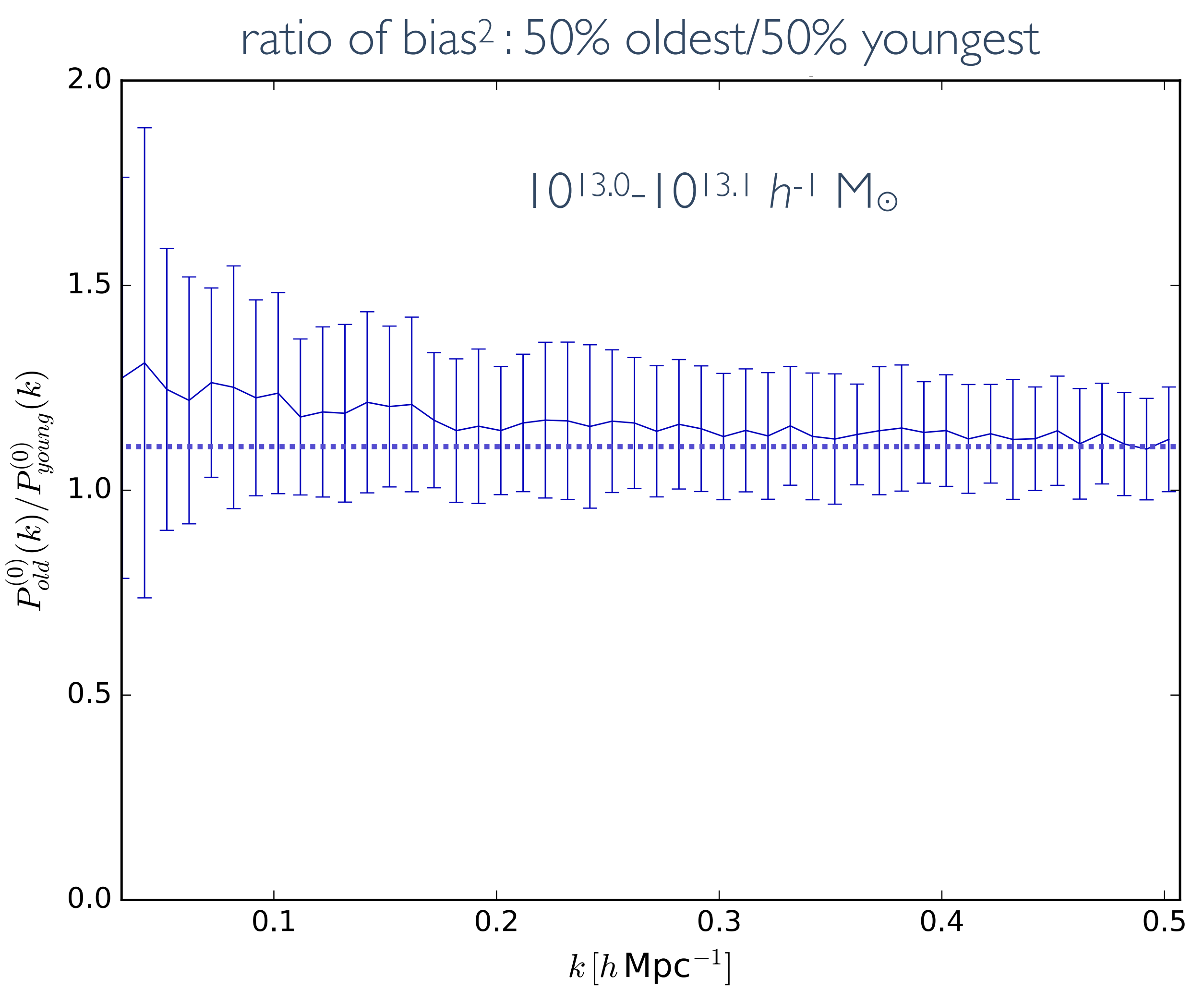
- Cosmological observations of structure growth improving fast, with **many new surveys** and international efforts similar to Particle Physics
- More than BAOs, galaxy surveys allow us to probe **gravity itself**
- We will only achieve **precision cosmology** with LSS if we understand galaxies, halos and their environments. **Galaxy evolution and cosmology will have to evolve together.**

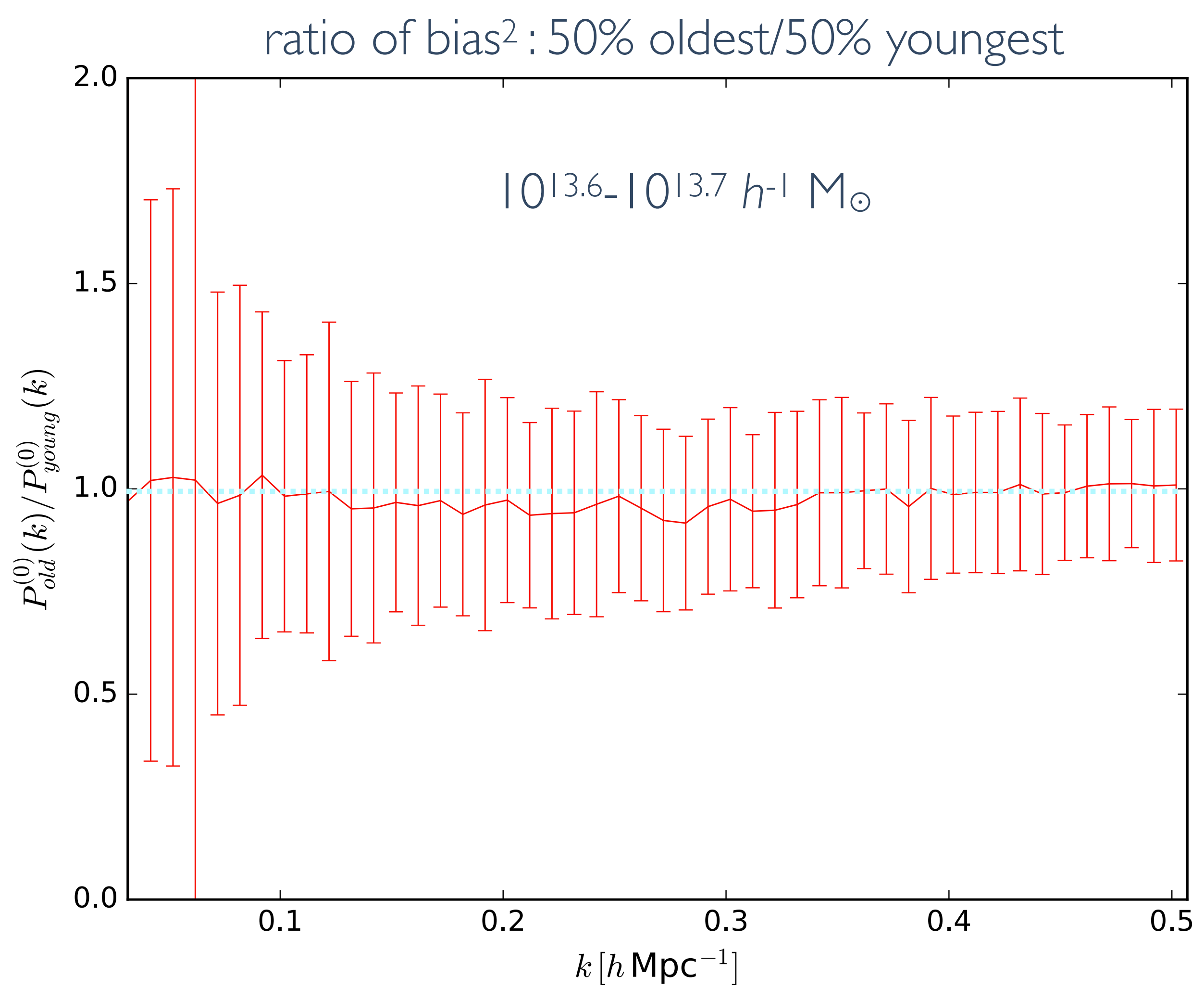

THANK YOU!

EXTRA SLIDES

SCALE-DEPENDENT SECONDARY BIAS PARAMETERS

- Signs of scale-dependence of secondary bias (e.g., Sunayama + 2016)





R.A., G. Sato-Polito, A. Montero-Dorta, F. Prada, 2018, to appear