Pushing to small scales with galaxy and CMB survey cross-correlations

KICC 10th anniversary symposium

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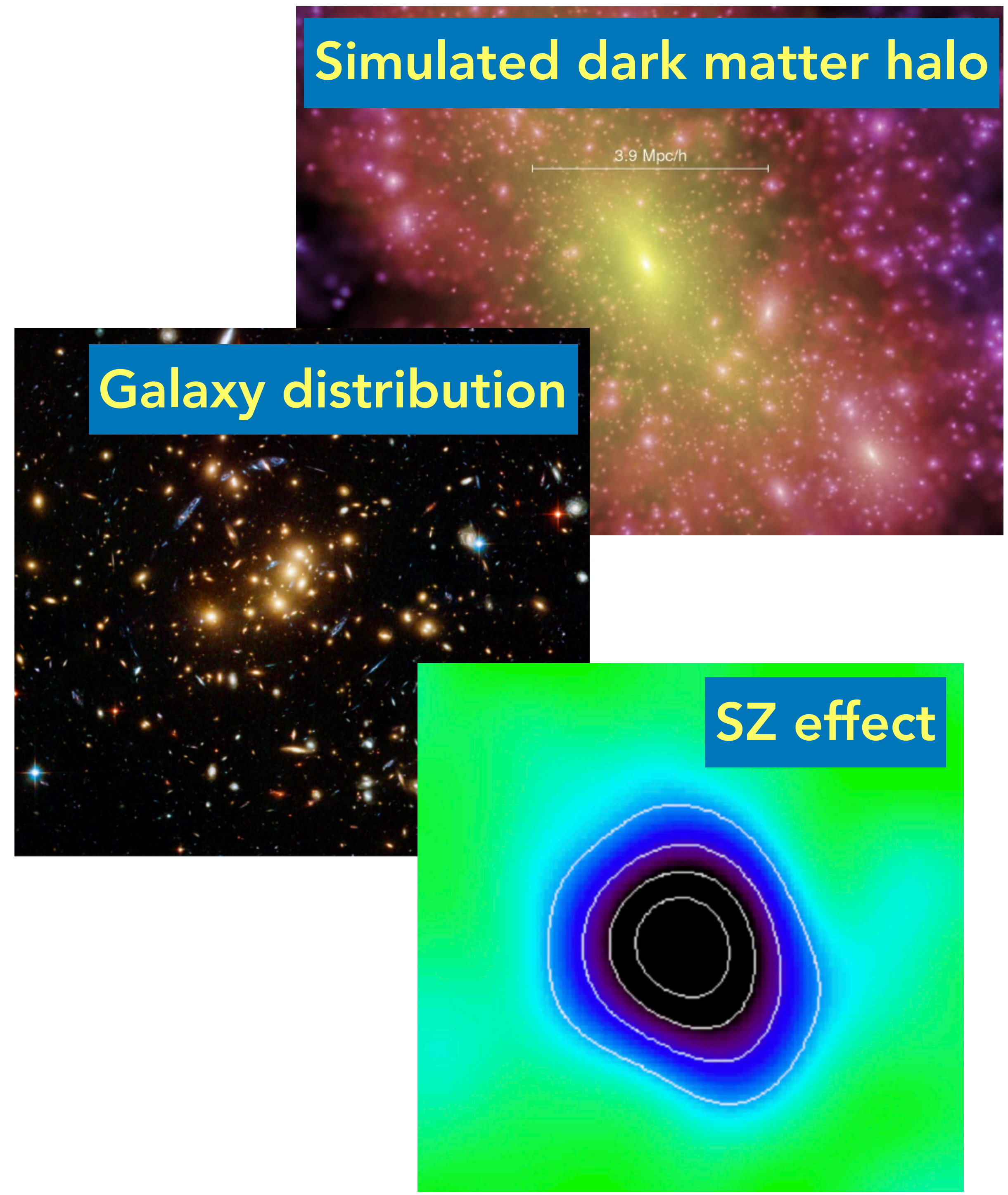
Image: More et al. 2015

Dark matter halos as seen by galaxy and CMB surveys

Galaxy and **CMB** surveys probe halos in different ways:

- **Galaxy survey**:
  distribution of galaxies within the halo, galaxy lensing, …

- **CMB survey**:
  Sunyaev-Zel'dovich effect, gravitational lensing, moving lens, …



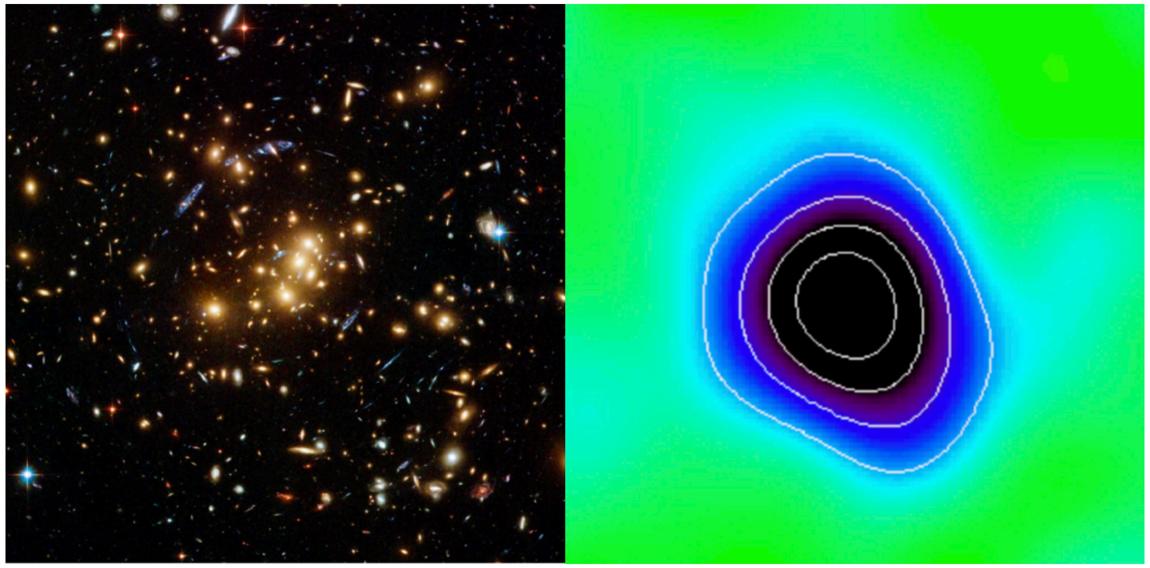
These two views of dark matter halos are synergistic

Probe different physics

Different Redshift sensitivity

Different sources of systematic error

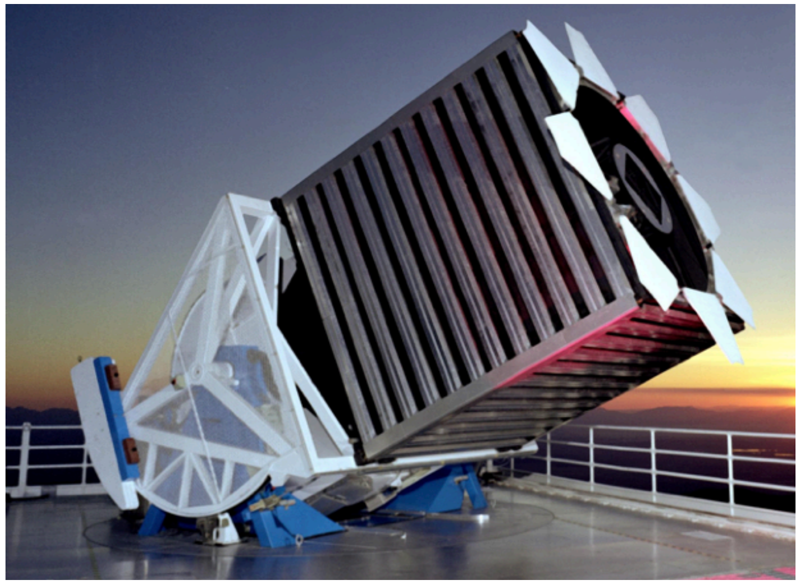
Line of sight information
Galaxy surveys can measure **redshifts**
CMB surveys **measure projected fields**



Cross-correlations of galaxy and CMB surveys exploit these synergies to probe matter and gas distributions inside halos as a function of halo mass and redshift

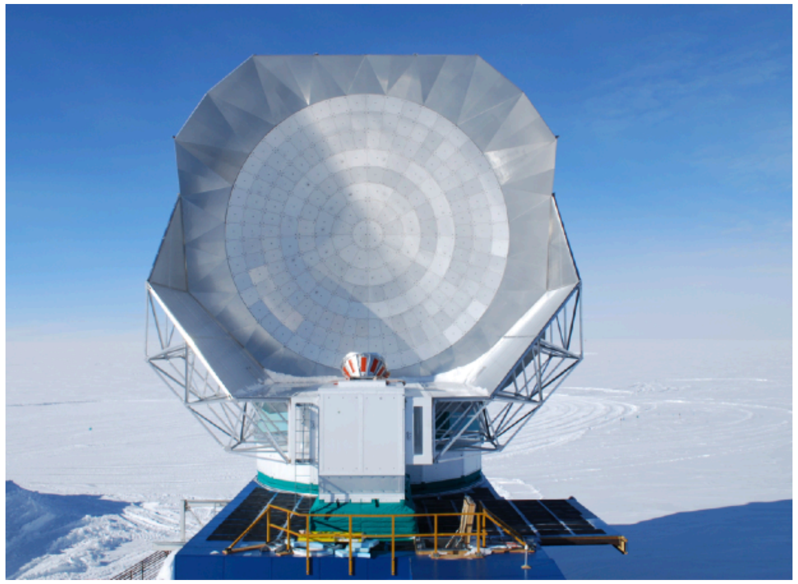
Data from many sources…

Sloan Digital Sky Survey (SDSS)



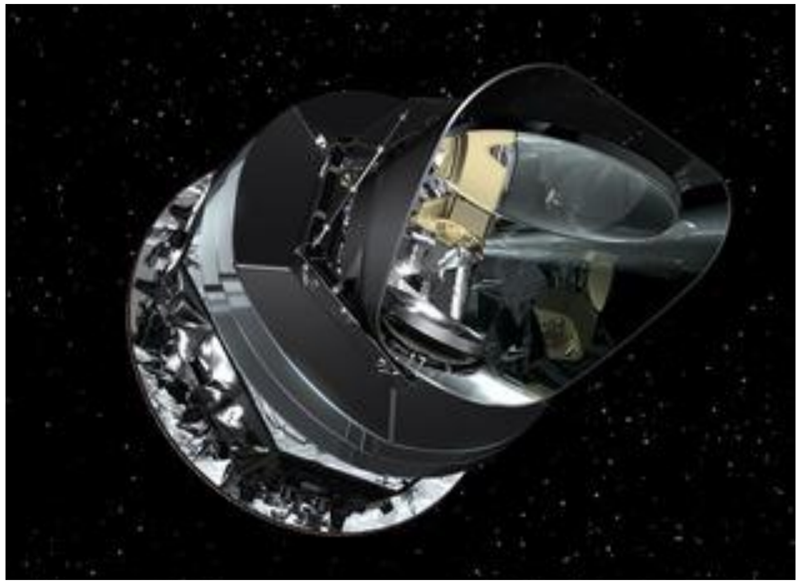
Dark Energy Survey (DES)

South Pole Telescope (SPT)



Atacama Cosmology Telescope (ACT)

Planck



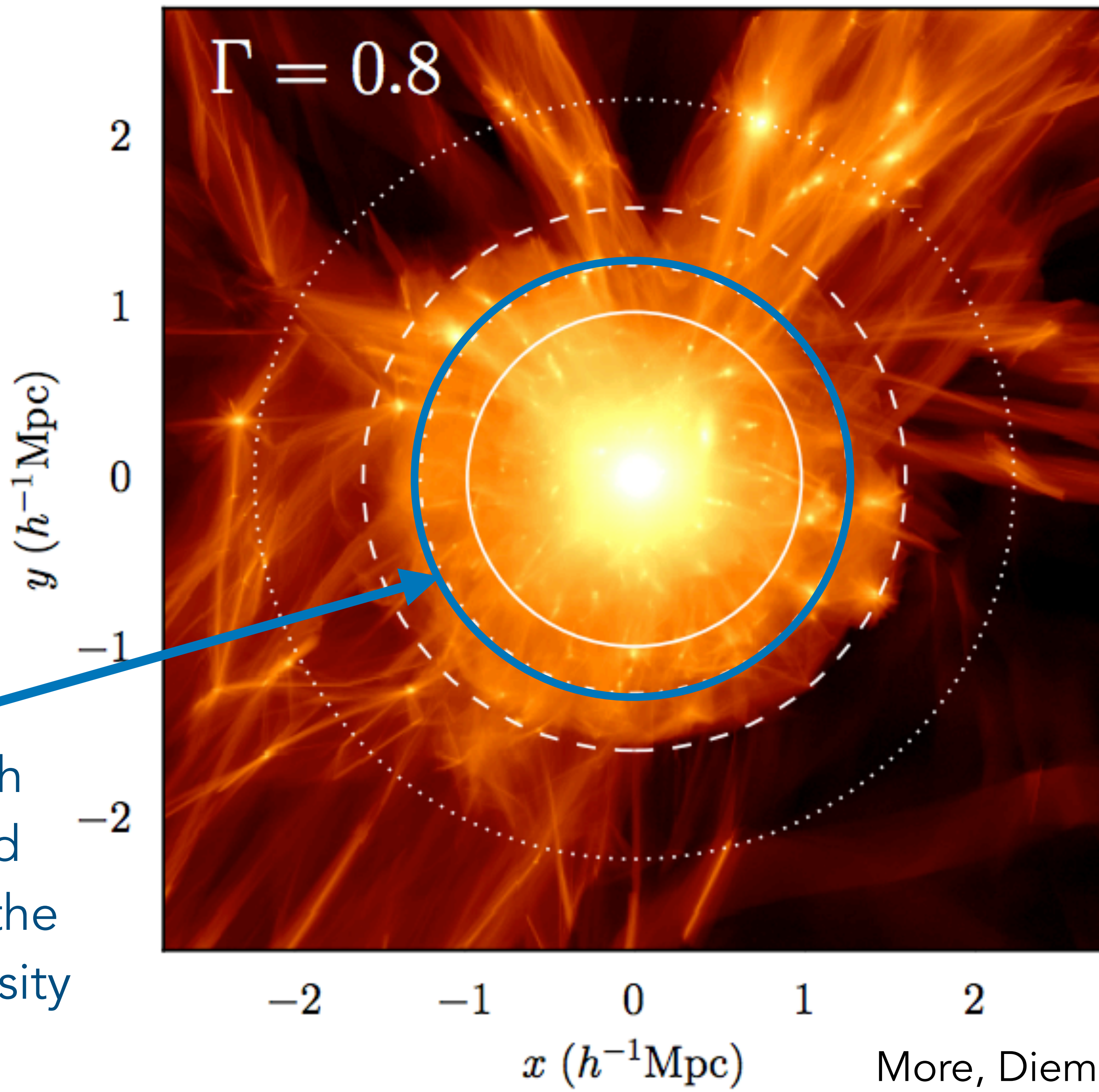
Outline

Two examples of probing the mass and gas profiles of dark matter halos by cross-correlating **galaxy** and **CMB** surveys:

- Measuring the edges of halos with the splashback feature
- Probing the gas inside halos with SZ cross-correlations

Measuring the Edges of Halos with the Splashback Feature

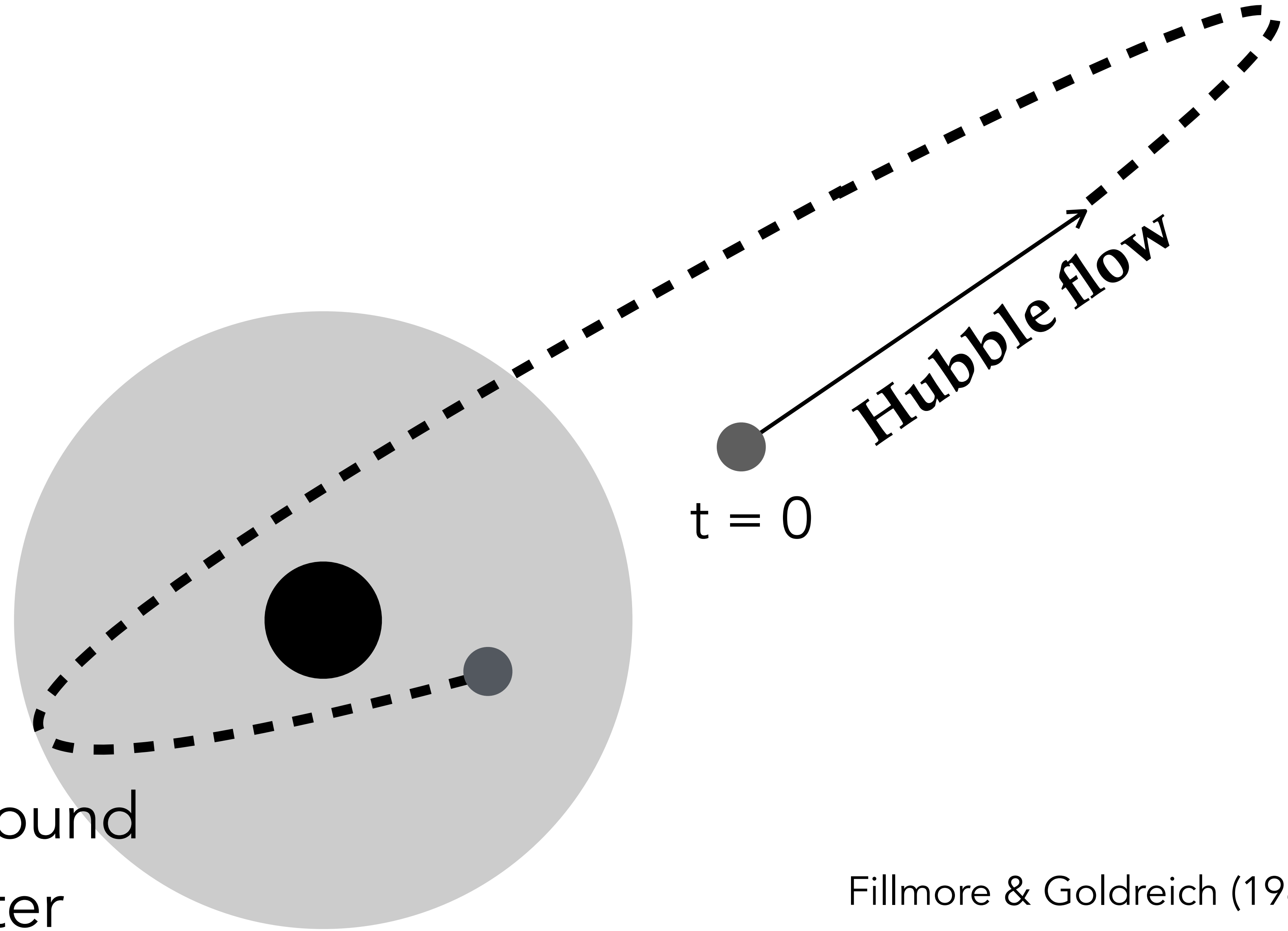
What defines the boundary of a dark matter halo?



R_{200}
Radius at which mean enclosed density is 200x the background density

More, Diemer, Kravtsov 2015

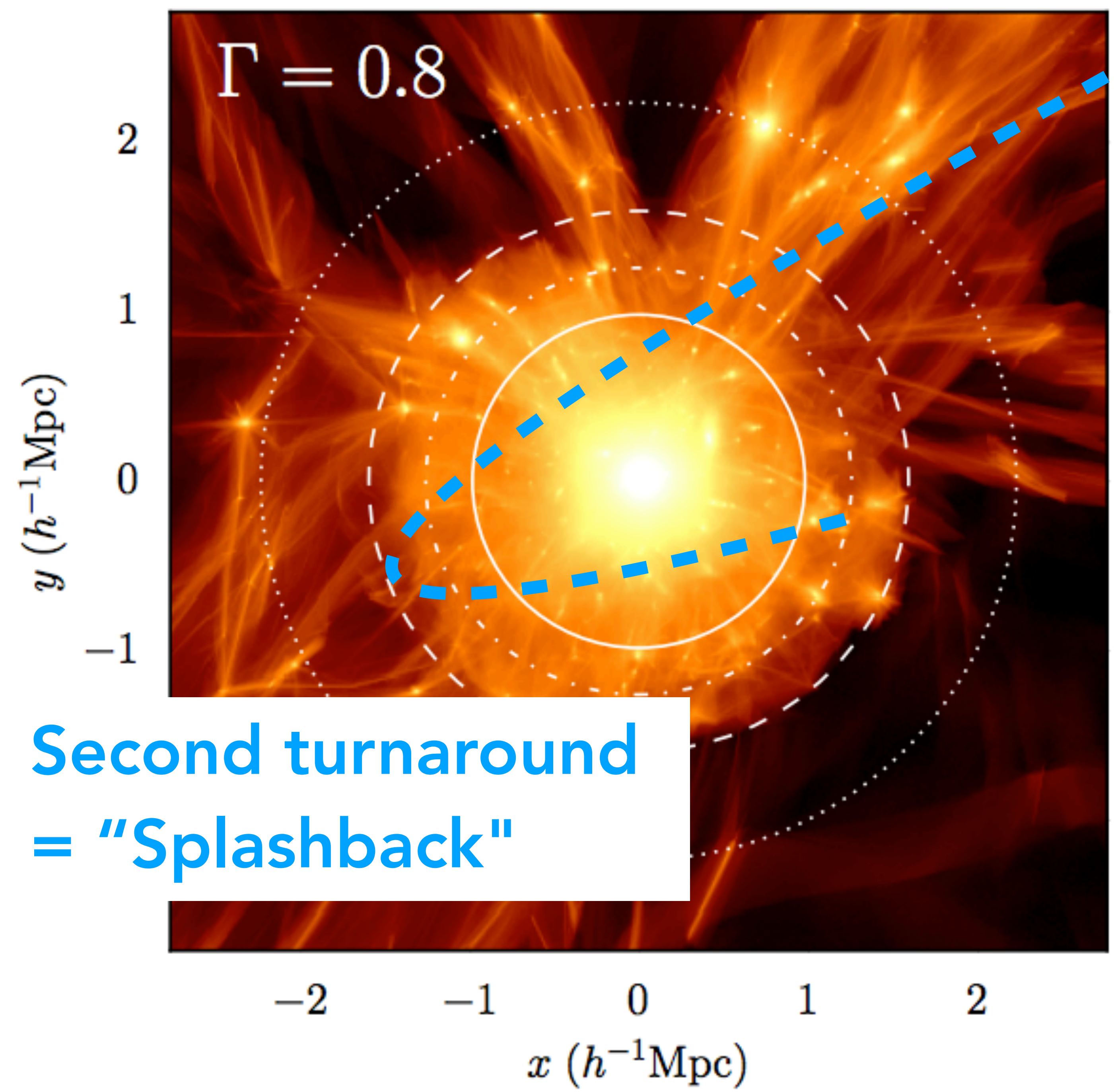
The formation of a dark matter halo



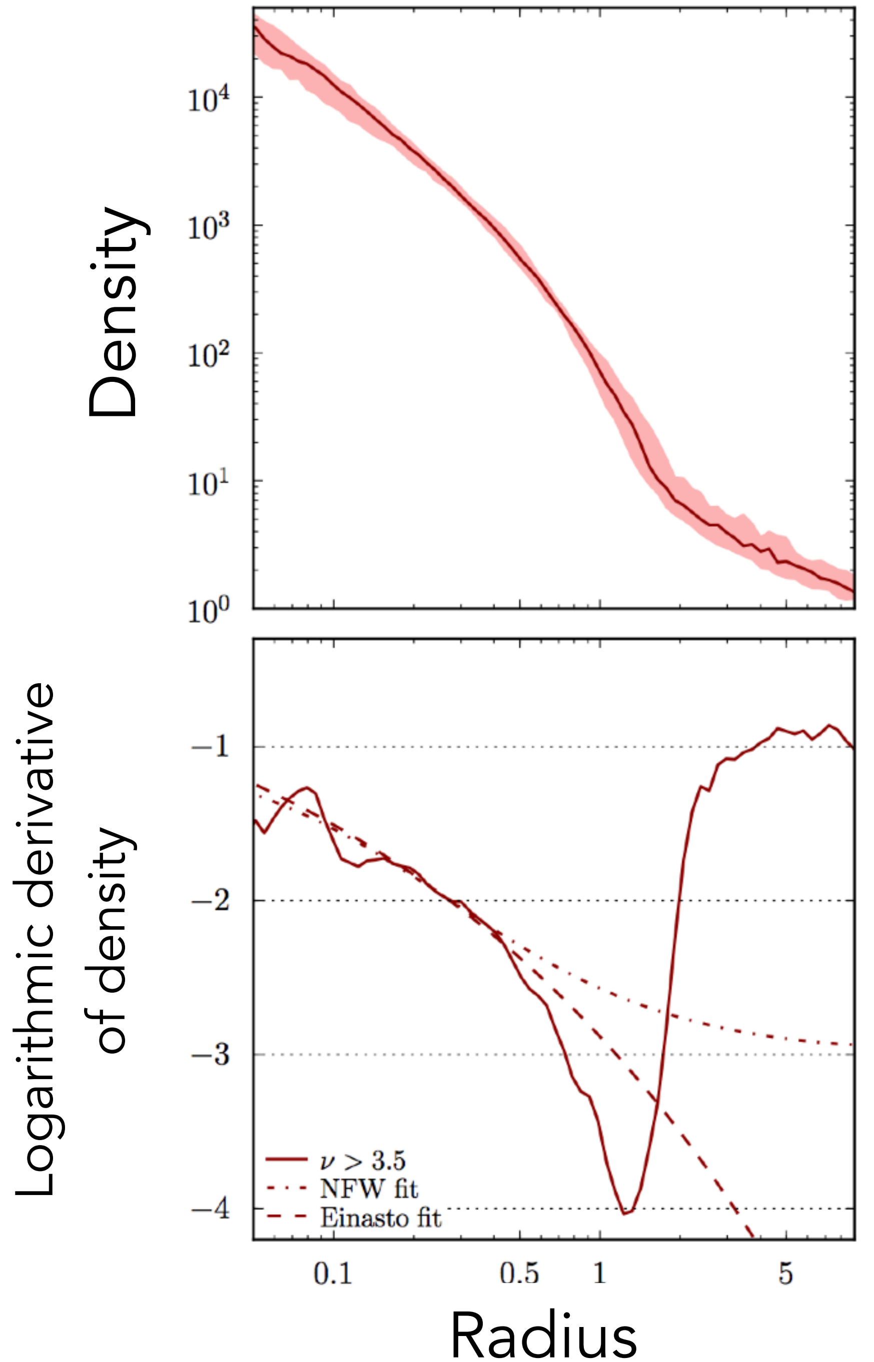
Second turnaround
= first apocenter
= “Splashback"

Fillmore & Goldreich (1984)
Bertschinger (1985)
Diemer & Kravstov (2014)
Adhikari et al. (2014)
Tully (2015)
More et al. (2016)

Splashback



Splashback associated with feature in stacked density profiles



Diemer & Kravstov (2014), More et al. 2016 See also Adhikari et al. (2014), Tully (2015)

Why is splashback interesting?

Splashback feature useful as a tool for probing interesting cluster physics:

High **accretion** dark matter halos should have smaller splashback radii (Diemer & Kravtsov 2014)

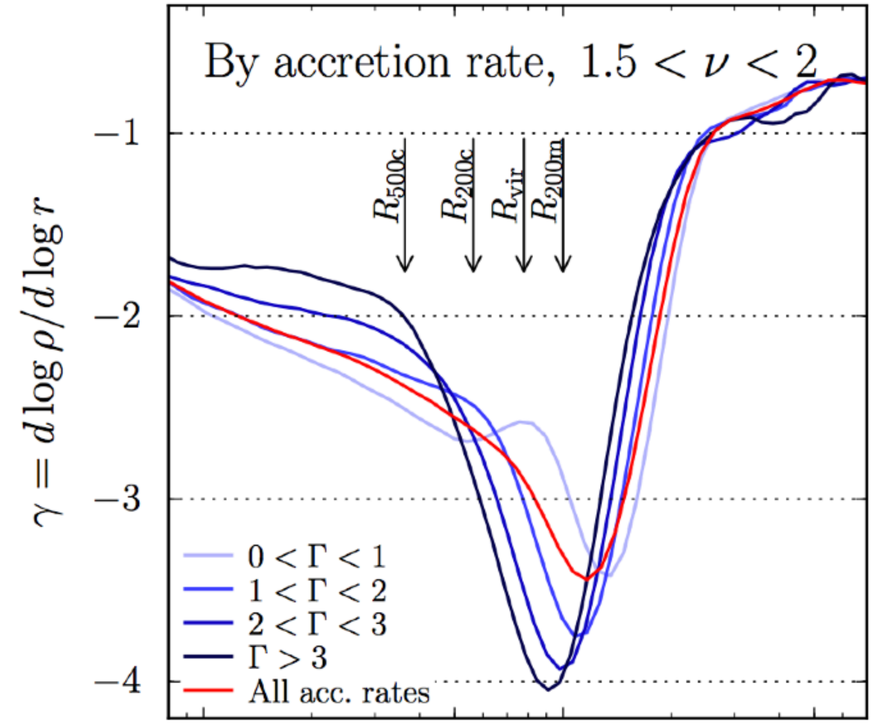
More massive galaxies splashback at smaller radii because of **dynamical friction** (Adhikari, Dalal, Clampitt 2016)

Blue galaxies expected to have less pronounced splashback because many still on first infall, making splashback a probe of **quenching** (EB et al. 2017, Shin, Adhikari, EB et al. 2018)

Self-interacting dark matter can impact galaxy profiles around splashback (Banerjee et al. 2019)

Modified gravity can change dynamics in infall regime, leading to changes in splashback (Adhikari et al. 2018, Contigiani et al. 2018)

Diemer & Kravtsov (2014)



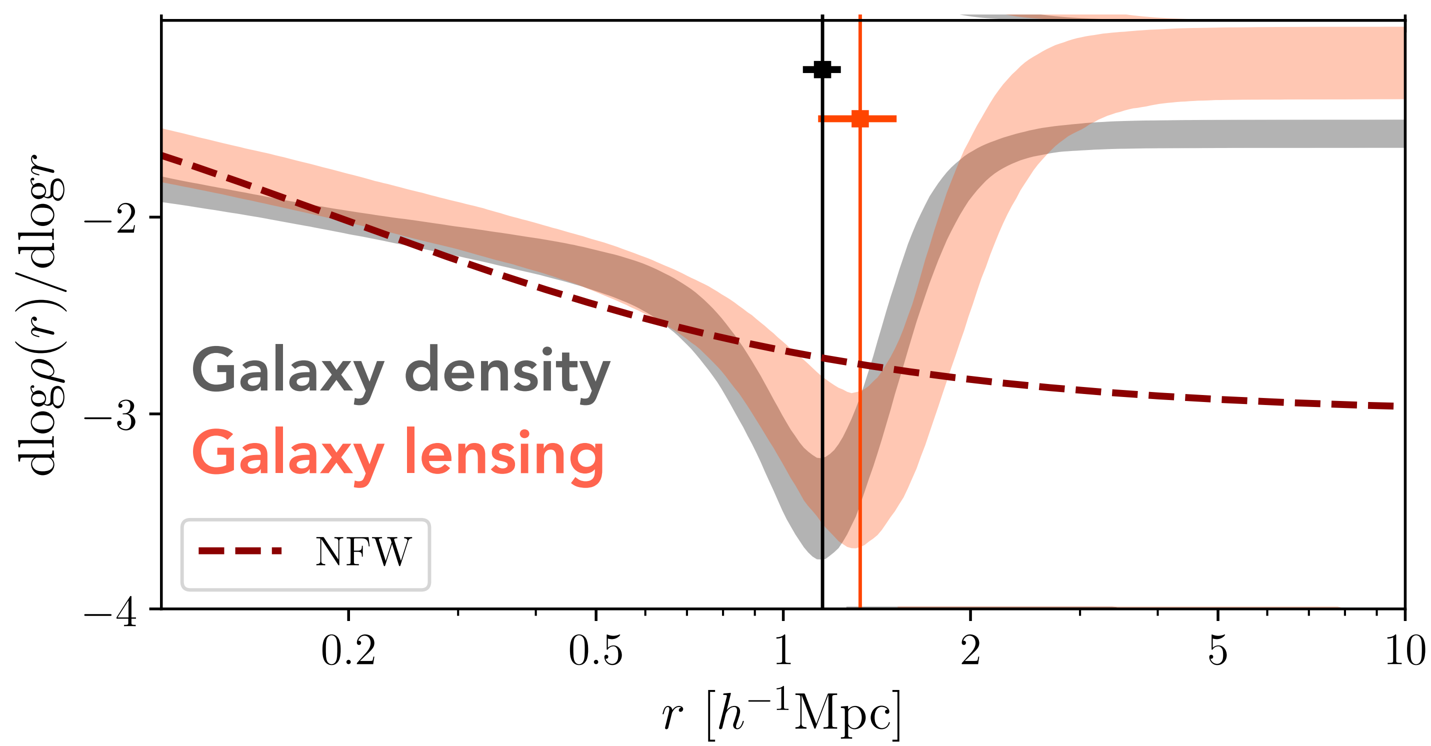
Detecting the splashback feature

Evidence for splashback feature found around optically selected galaxy clusters

Using **galaxies as proxy for mass** with SDSS (More et al. 2016, EB et al. 2017)

And using **gravitational lensing** and galaxies in DES (Chang, EB et al. 2018)

Galaxy and lensing profiles of DES clusters

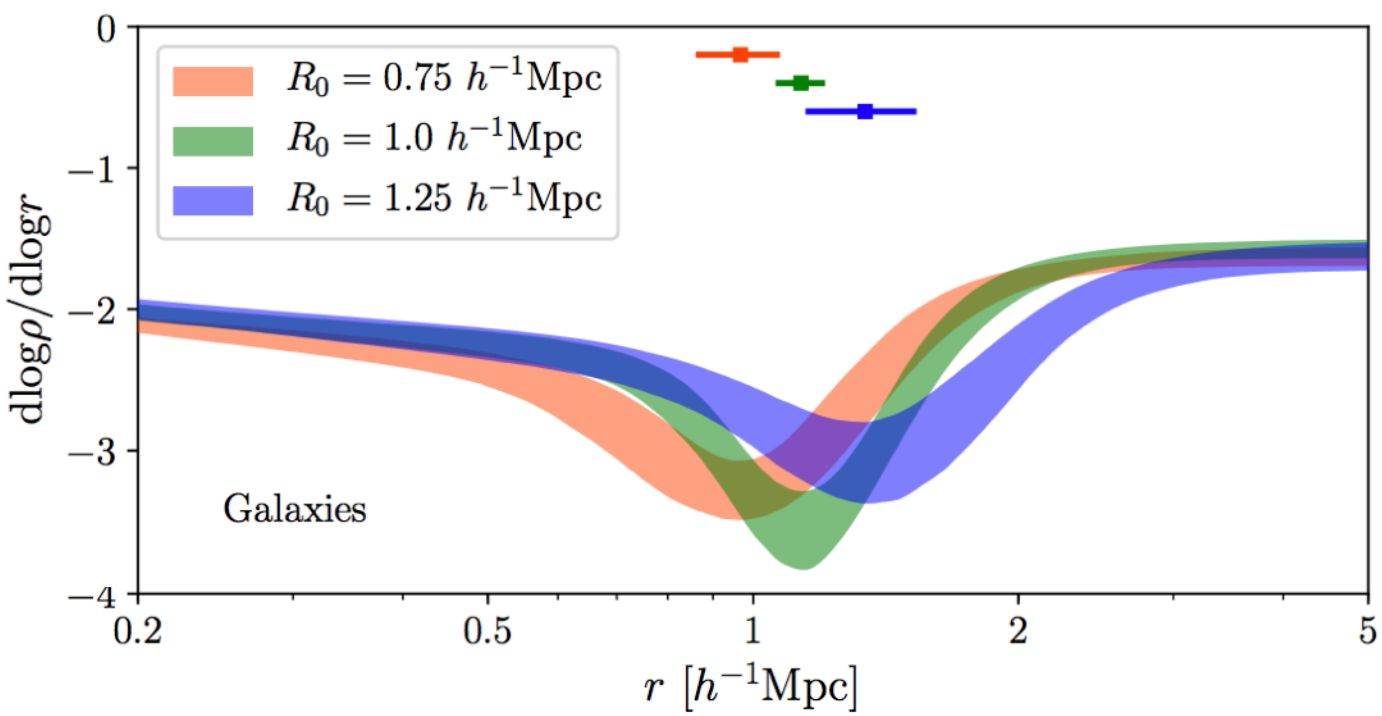


Chang, EB et al. 2018

Evidence for bias in splashback measurement with optically selected clusters

Several hints that splashback measurements with optical clusters may be biased

- Contamination from background galaxies
- Counting galaxies within an aperture to identify clusters

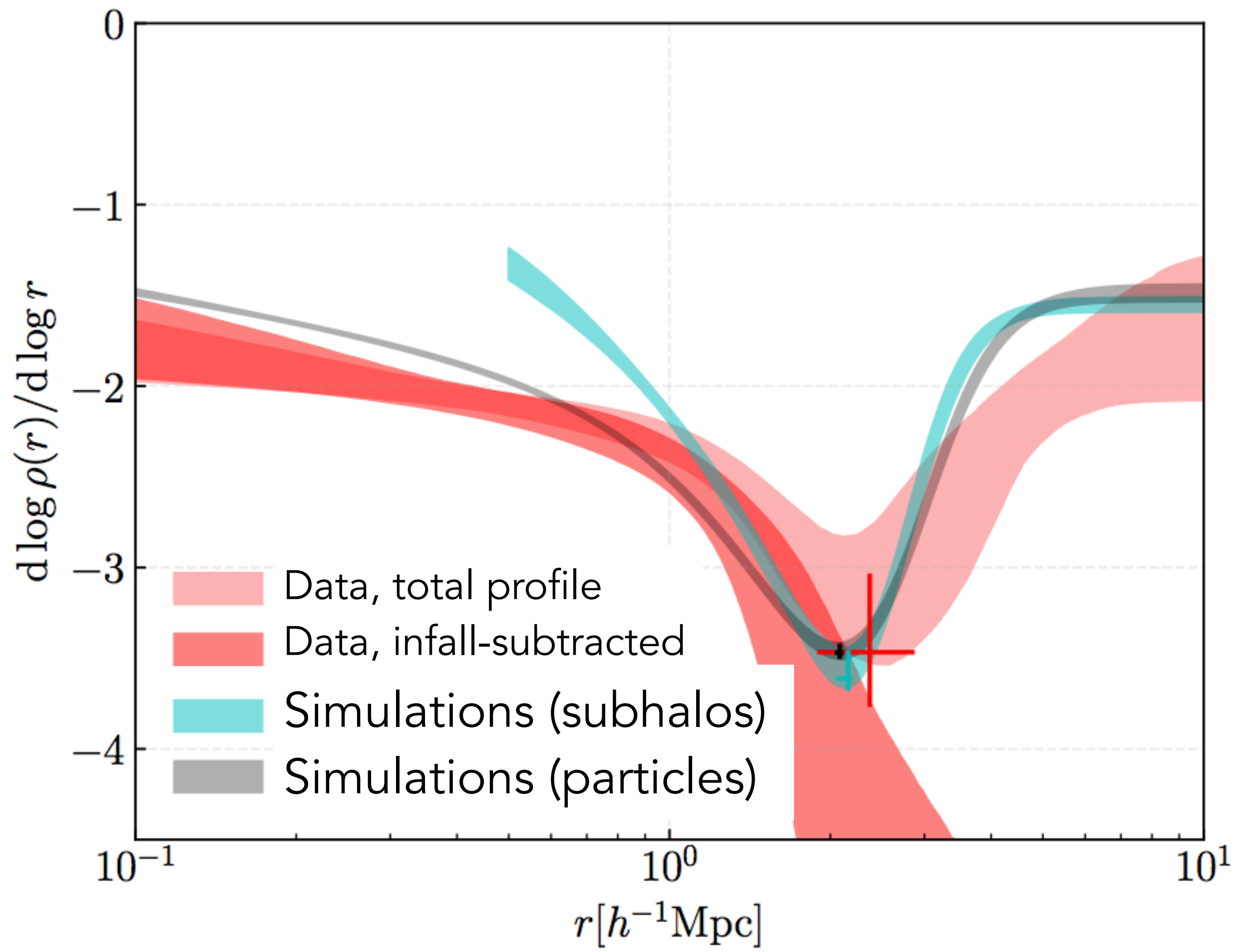


Chang, EB et al. 2017
See also More et al. 2016,
Busch & White 2017, Sunayama & More 2019

Splashback with SZ-selected clusters

Cluster samples selected on Sunyaev-Zel'dovich decrement expected to be immune from these effects

SPT (ACT) clusters x DES galaxies



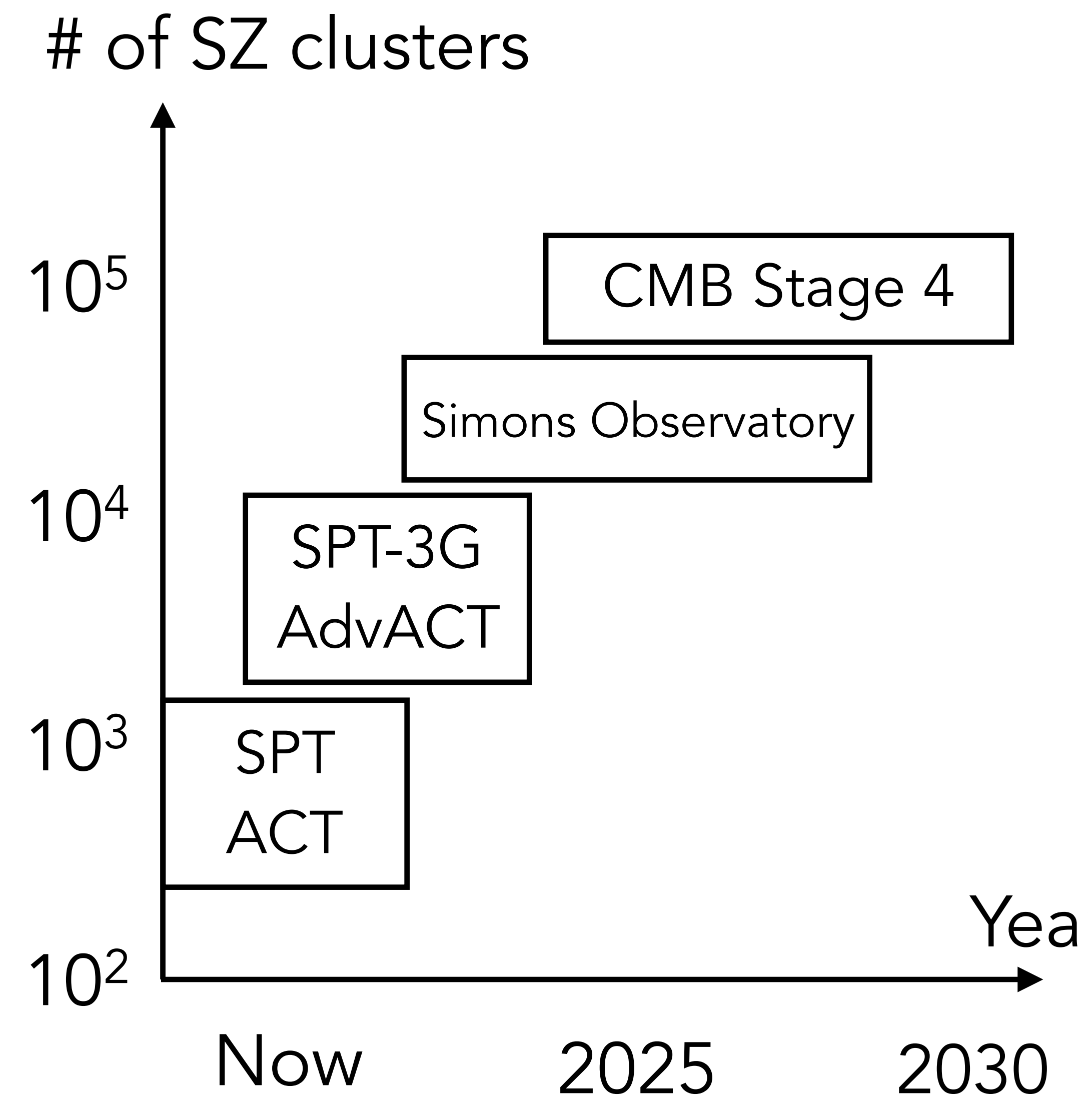
Shin, Adhikari, EB et al. 2018
See also:
Zuercher & More 2018

Should be able to test this expectation more precisely with near-term samples of SZ-selected clusters from e.g. SPT-3G and AdvACT

The future of splashback studies

Significant improvements in signal-to-noise expected soon:

- More SZ clusters from CMB experiments
- Better galaxy density and weak lensing measurements (DES Year 5, LSST, Euclid, WFIRST, …)



SZ-selected clusters cross-correlated with galaxy surveys provide a powerful and robust means of probing splashback

Probing the gas inside halos with Sunyaev-Zel'dovich cross-correlations

Why study the gas profiles of galaxy clusters?

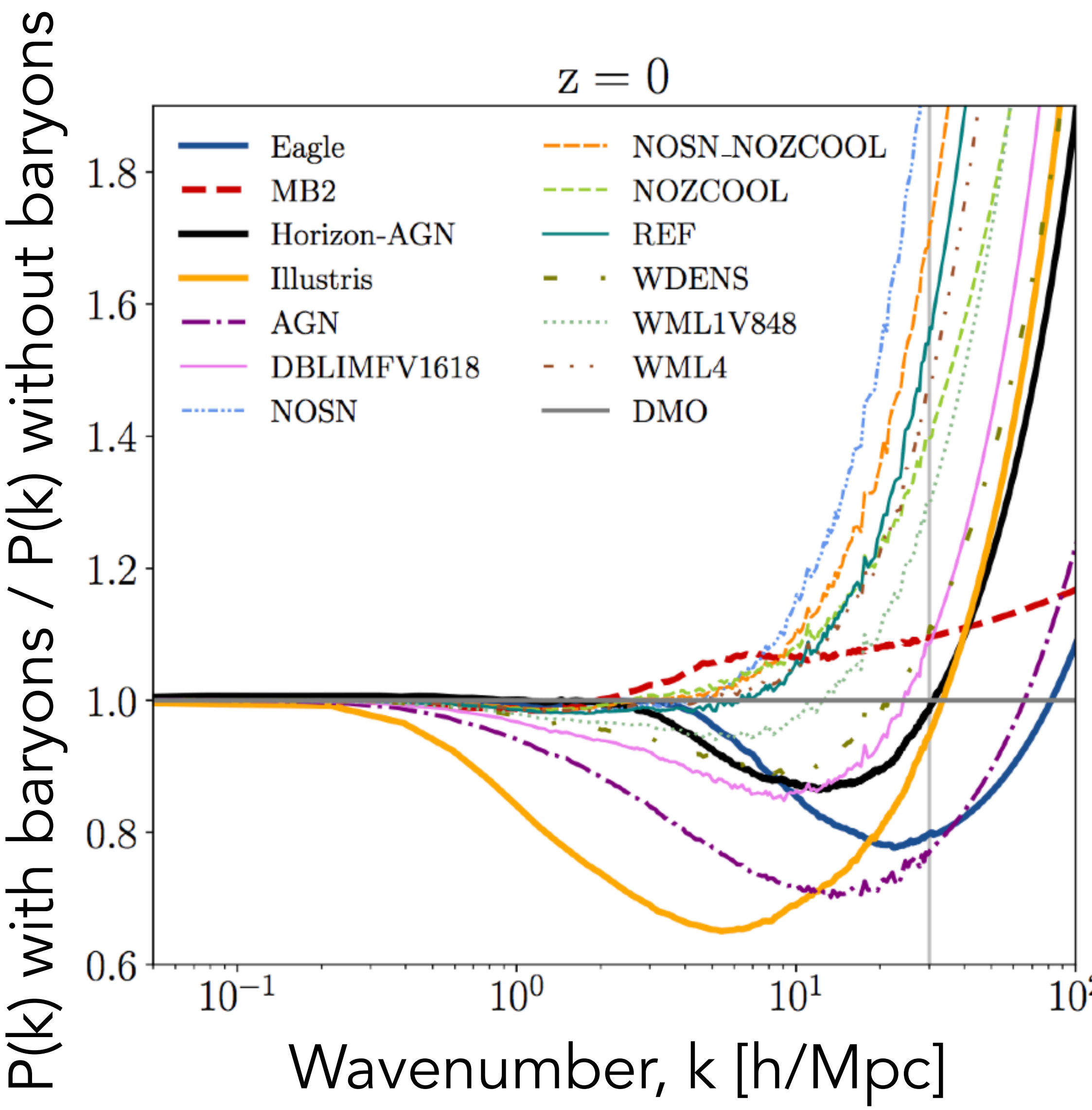
Astrophysics

Gas distribution and energetics connected to galaxy formation and astrophysical feedback

Cosmology

Baryons impact the matter power spectrum at small scales

Constraints on feedback models will lead to improved cosmological constraints



Huang et al. 2018

Measuring pressure profiles with the Sunyaev-Zel'dovich effect

Amplitude of thermal SZ signal is proportional to Compton y-parameter:

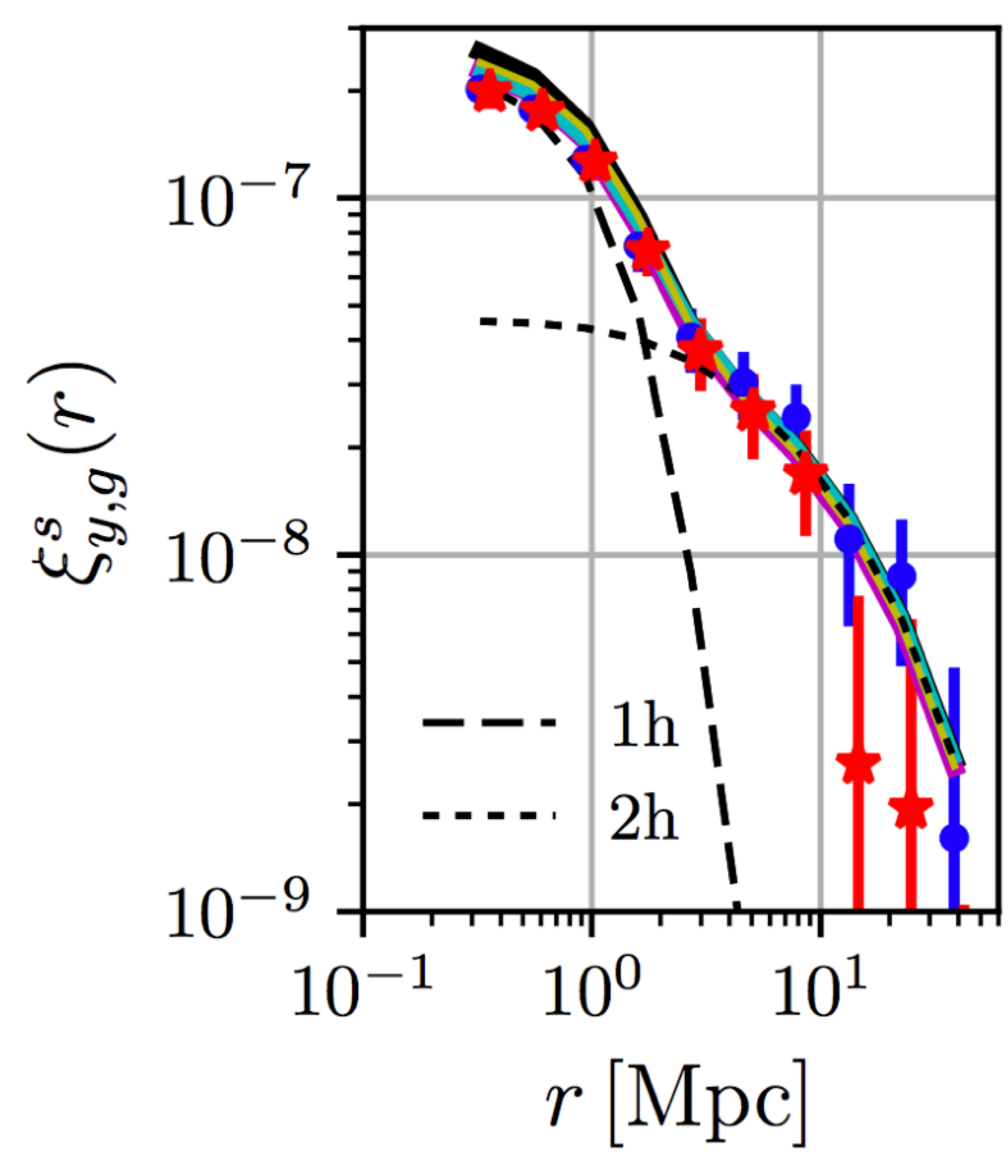
$$y \propto \int dl\, P_e(l)$$

where P_e is the electron pressure

Cross-correlations between galaxies and y isolate contributions to y from particular redshifts and halo masses

SDSS groups x Planck y

$13.5 < \log_{10}(M/(M_\odot h^{-1})) < 14$



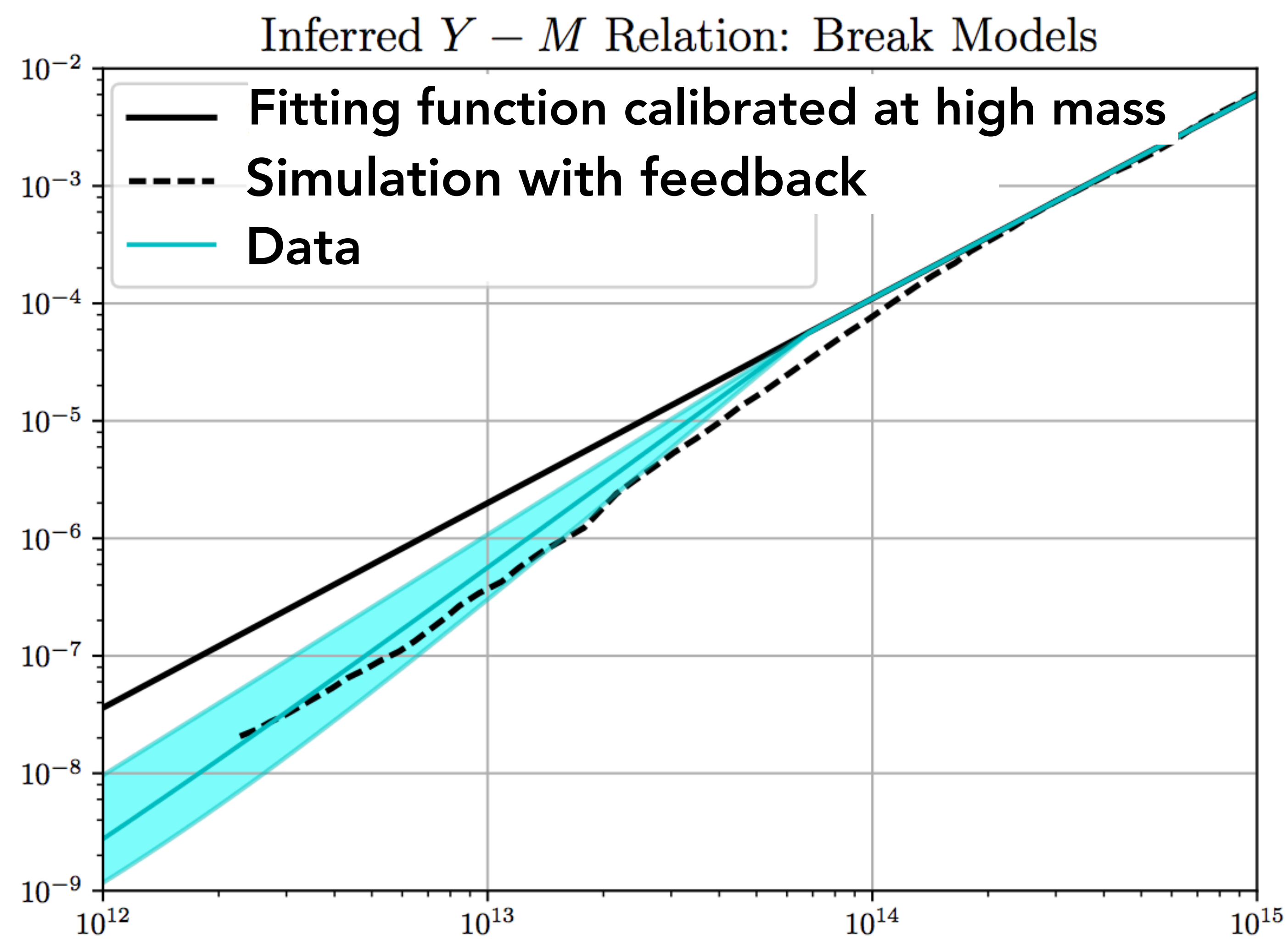
Hill, EB et al. 2018

See also Vikram et al. 2016 and Makiya et al. 2018

Studying feedback with galaxy-SZ cross correlations

Constraints on feedback models from SDSS groups x Planck SZ

Integrated SZ signal from halos of mass M



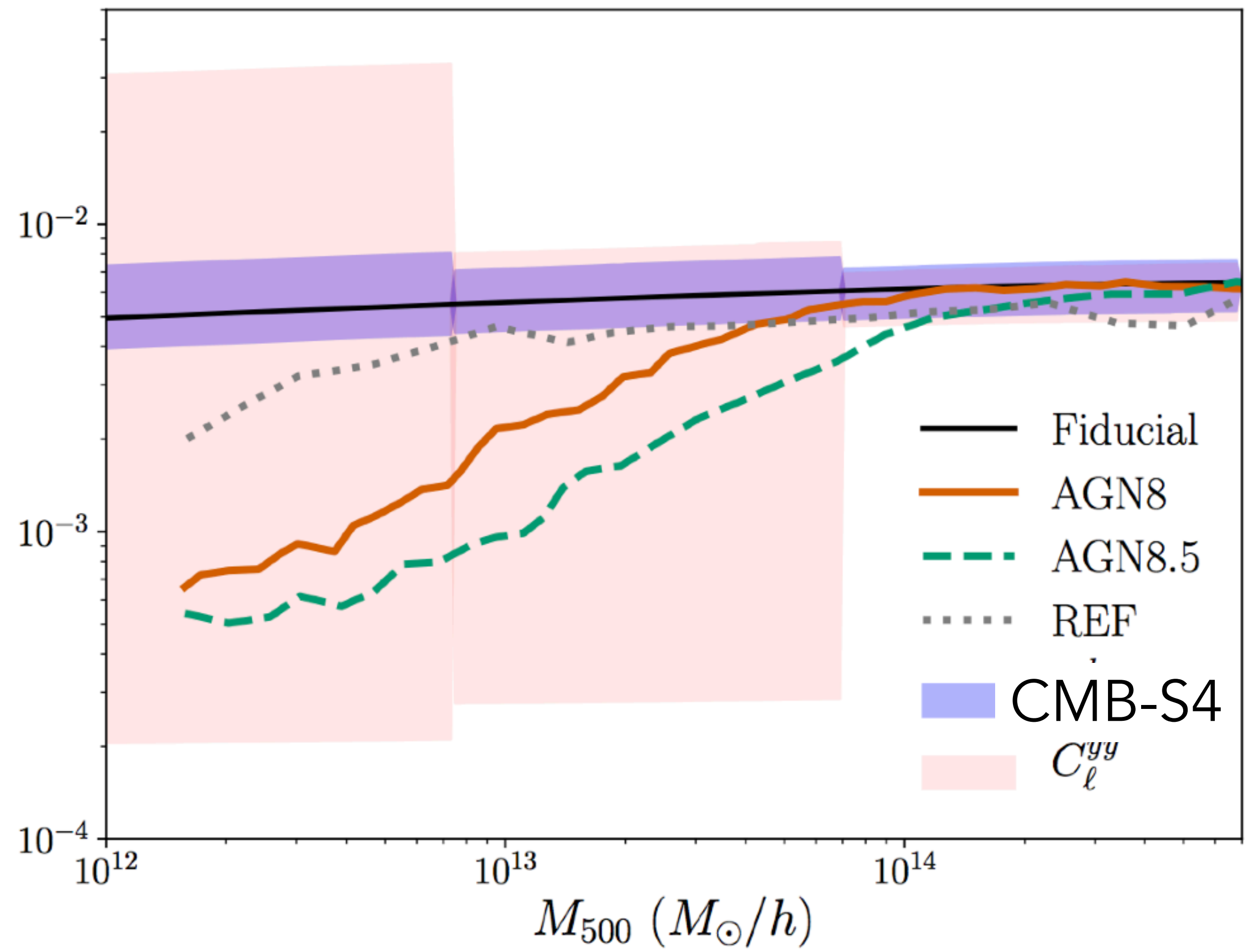
Halo mass ($M_\odot$)

Hill, EB et al. 2018

See also Pandey, EB et al. 2019

Future of SZ cross-correlations

(Normalized) Integrated SZ signal from halos of mass M



Pandey, EB, Hill 2019

- **Improved y-maps**:
  SPT-3G, AdvancedACT, Simons Observatory, CMB Stage IV
- **Improved resolution**:
  necessary for studying low-mass halos, where largest impact of feedback is expected
- **More groups/clusters at high z**:
  DES, HSC, DESI, LSST, Euclid, WFIRST

Probing gas rotation with SZ correlations

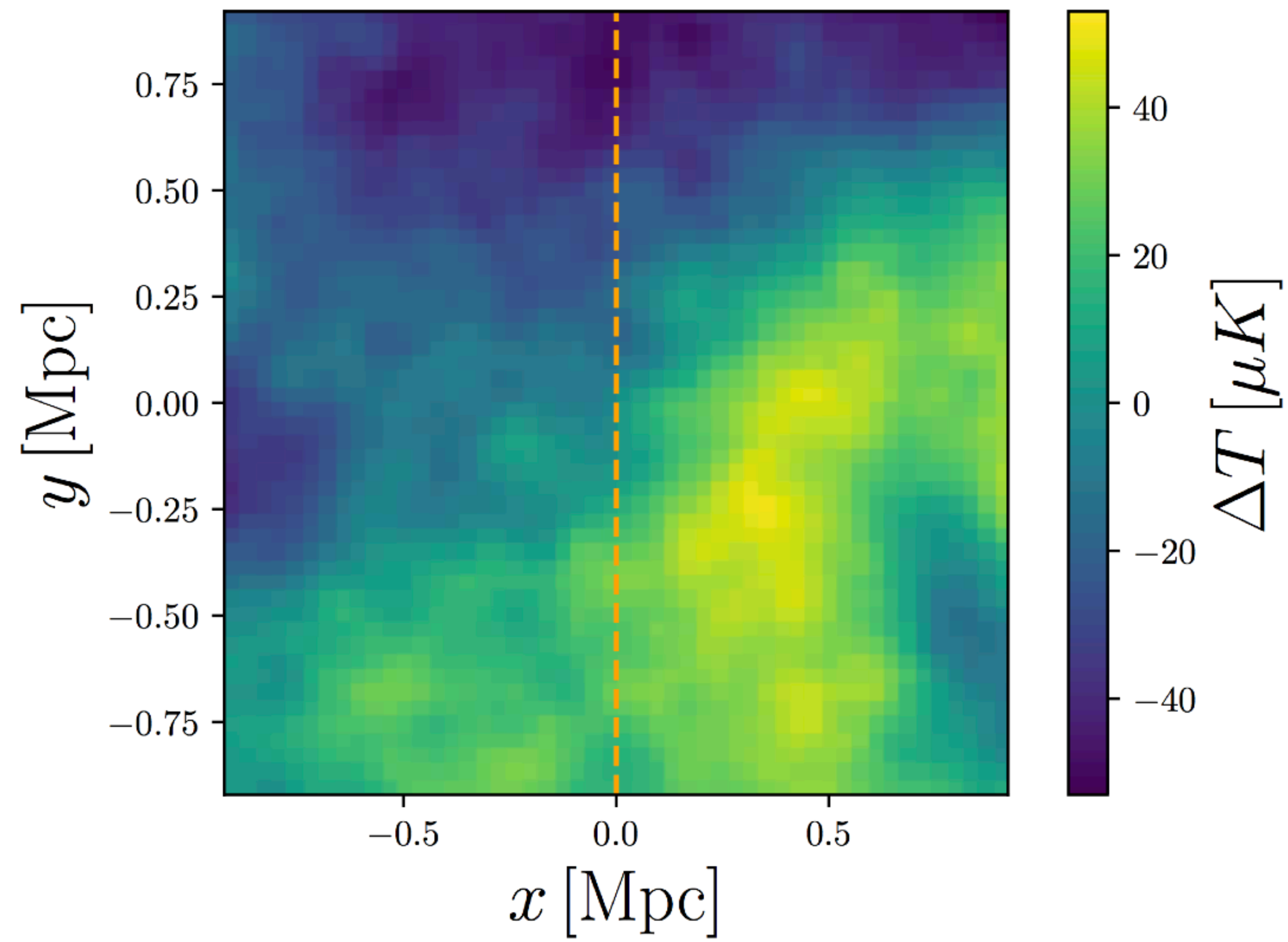
Gas with bulk velocity inverse Compton scattering with CMB photons induces *kinematic* SZ effect

If the cluster gas is rotating, expect to see dipolar signal

Stacking Planck CMB maps (cleaned of *thermal* SZ) on SDSS clusters, oriented along galaxy rotation direction yields >2σ hint of this effect

Future measurements can provide insight into e.g. non-thermal pressure support

Rotation-oriented stack of clusters in *Planck* maps



EB, Sherwin, Raghunathan 2019

Summary

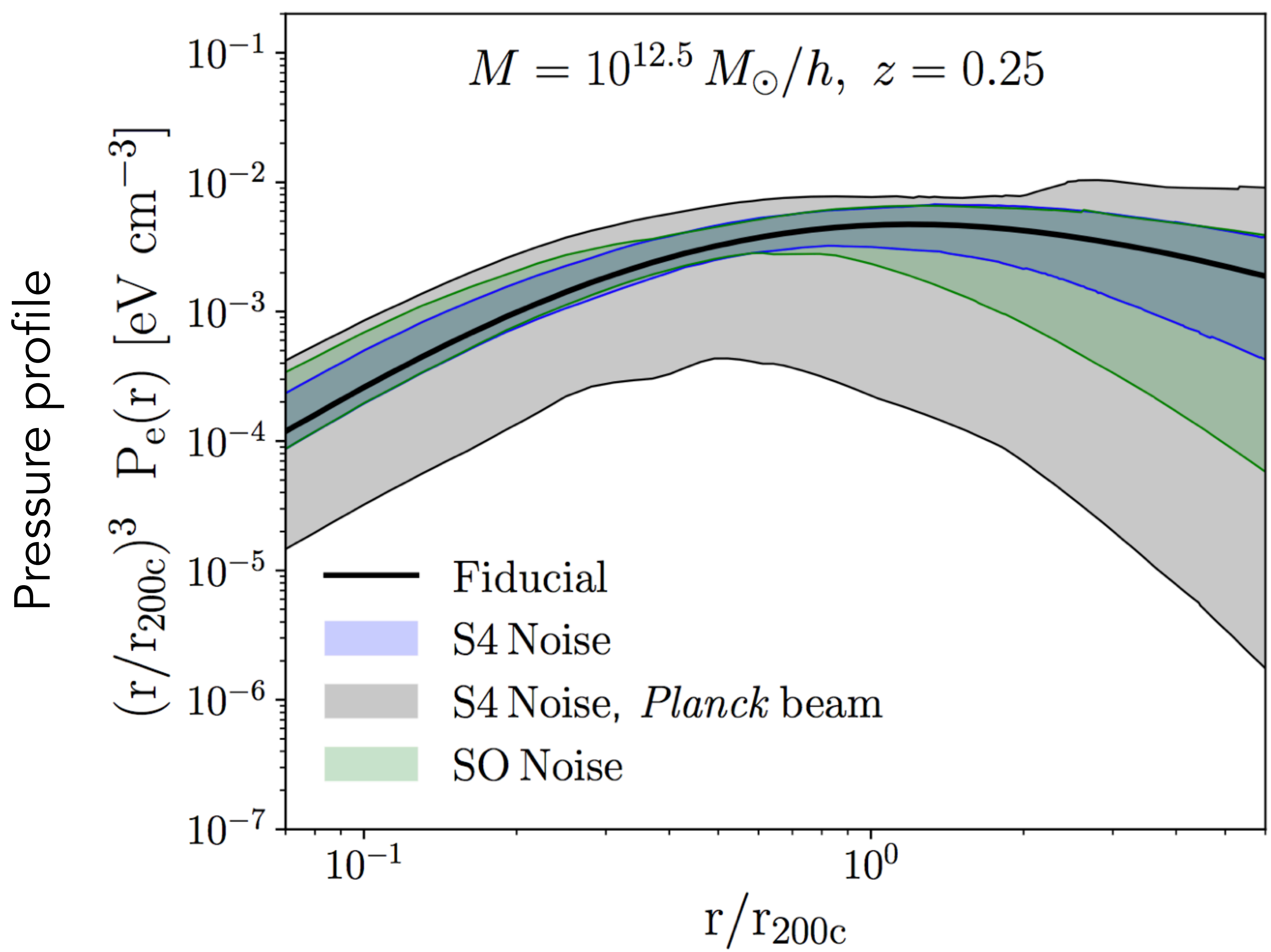
Cross-correlations between galaxy and CMB surveys provide insight into internal structure and physics of dark matter halos

- Splashback: cross-correlations of galaxies and galaxy lensing with SZ-selected clusters will will be interesting as probes of e.g. quenching models, modified gravity, halo accretion

- Gas physics: cross-correlations of galaxies with SZ effect probe feedback in low-mass halos, and properties of gas in clusters

Signal-to-noise of all these measurements will increase dramatically with next generation surveys!

Future of SZ cross-correlations



Pandey, EB, Hill 2019