Leading constraints on $f(R)$ gravity from SPT galaxy clusters with DES/HST mass information and primary CMB

Sophie M. L. Vogt

January 10th 2025

21st Rencontres du Vietnam, TMEX-2025, Quy Nhon

with S. Bocquet, C. Davies, J. Mohr, F. Schmidt, B. Li, C.-Z. Ruan, C. Hernández-Aguayo, S. Grandis, T. Schrabback (SPT+DES collaboration)

Paper: arXiv:2409.13556 (Vogt+24b)

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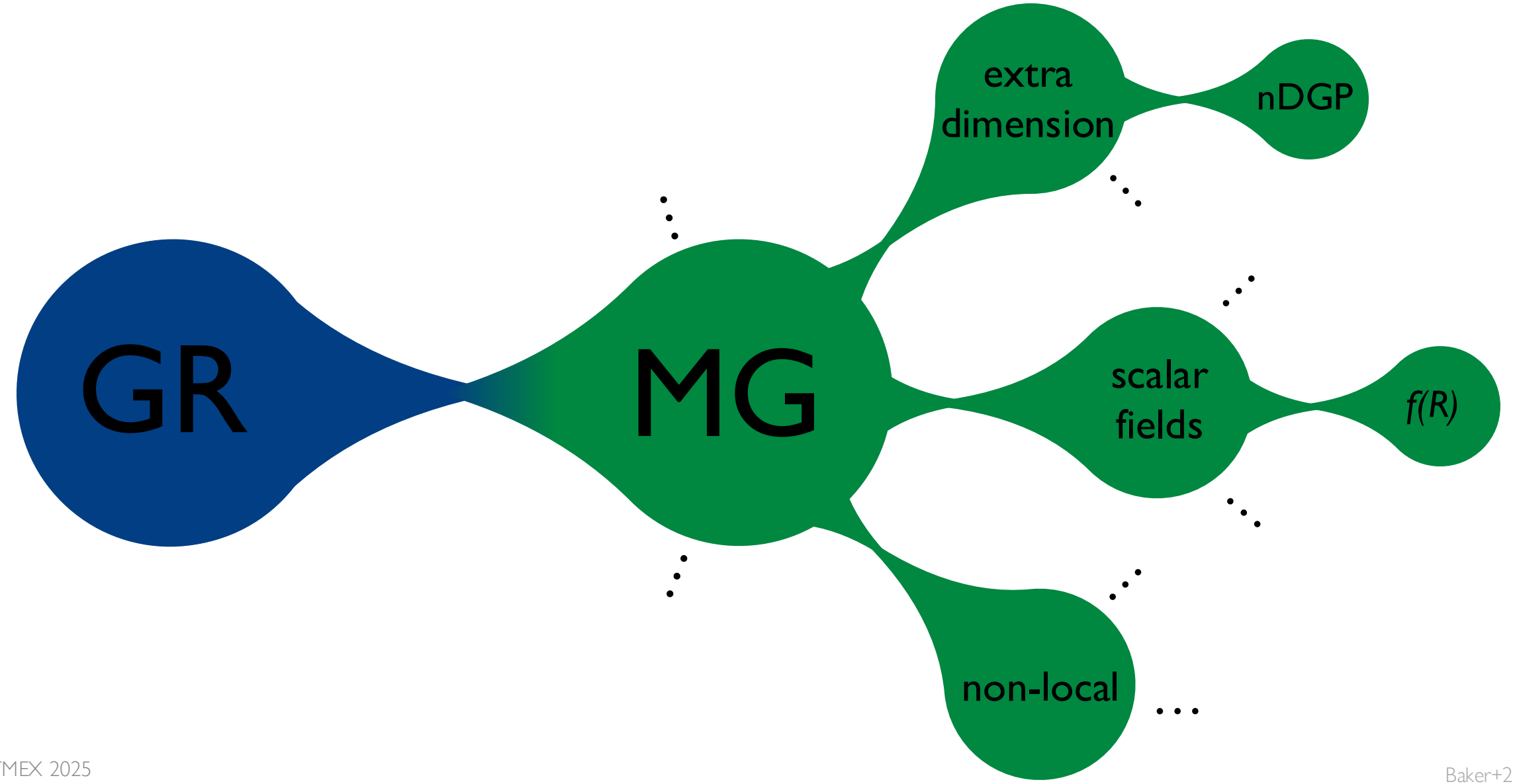
LMU LUDWIG-MAXIMILIANS-UNIVERSITÄT MÜNCHEN

ORIGINS Excellence Cluster

MAX-PLANCK-INSTITUT FÜR ASTROPHYSIK

What is the underlying theory of gravity?



Baker+21

$f(R)$ Modified Gravity

https://ned.ipac.caltech.edu/level5/Sept05/Carlstrom/Carlstrom2.html

Buchdahl 1970, Schmidt+09, He+13

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$$S = \int \mathrm{d}^4x \sqrt{-g} \left[\frac{R - 2\Lambda}{16\pi G} + \mathcal{L} \right]$$

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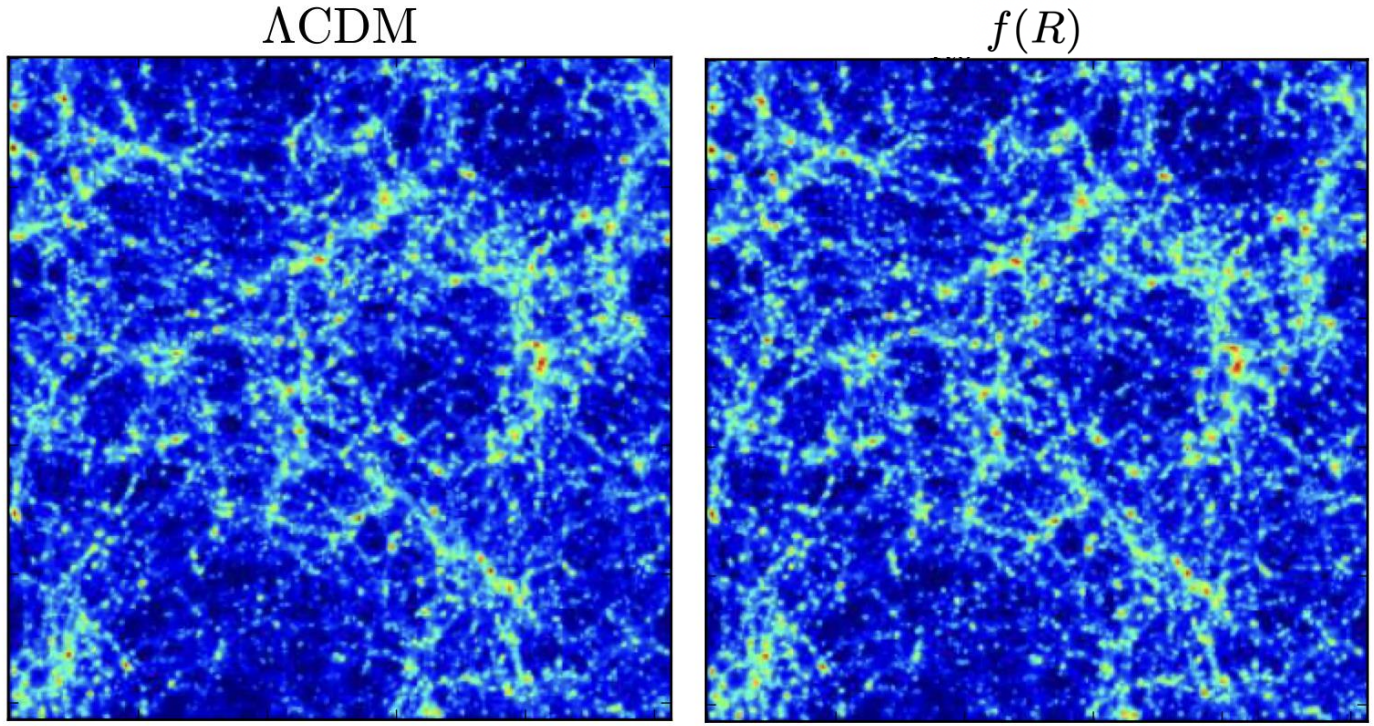

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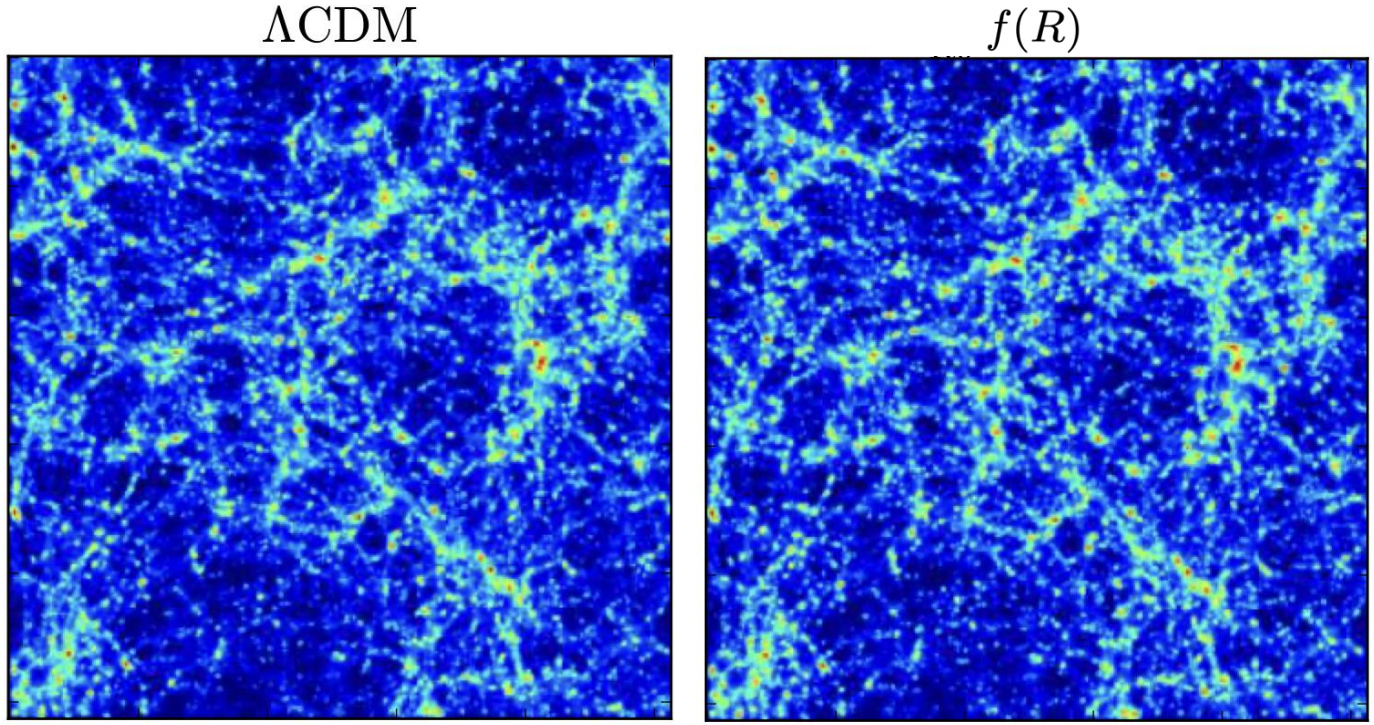

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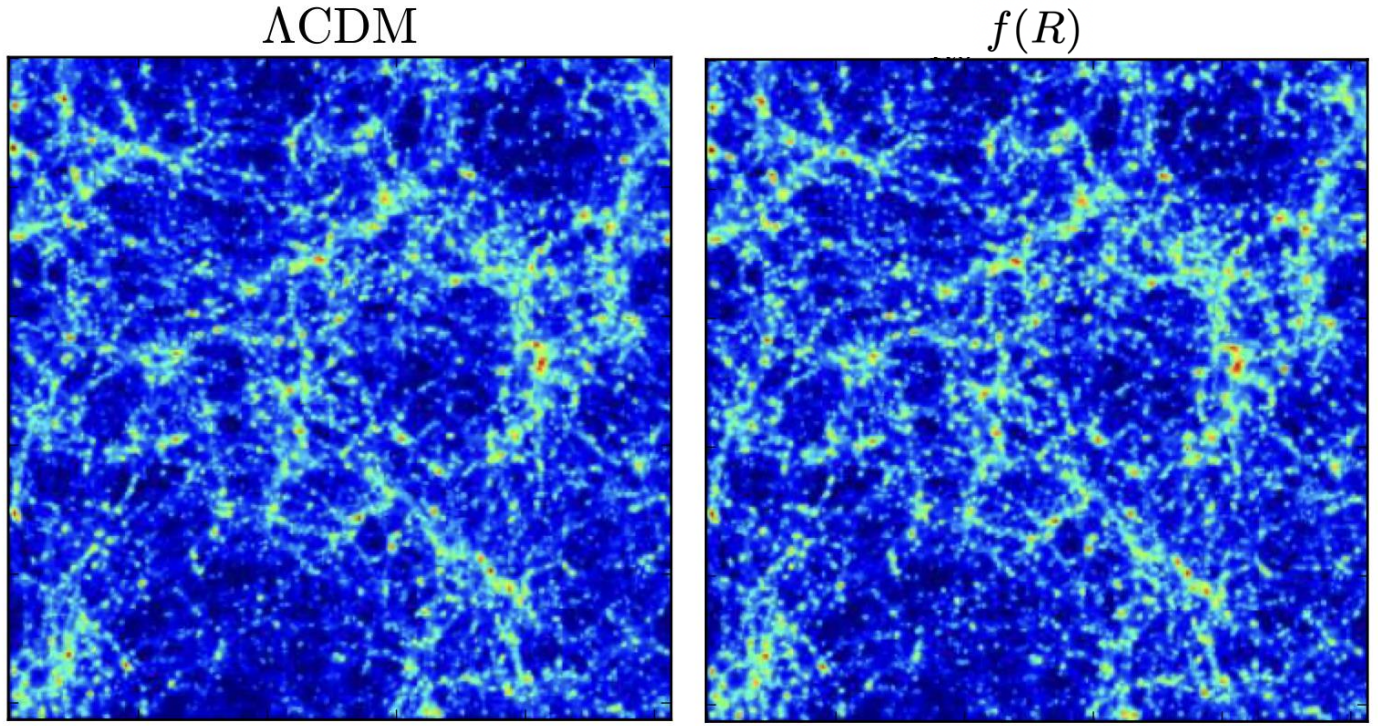
$$\longrightarrow H(z) = H_0\sqrt{\Omega_m(1+z)^3+\Omega_\Lambda}$$



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- Affects the distribution of massive galaxy clusters in mass and redshift.
  - New (scale dependent) halo mass function (HMF).

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$f(R)$ Gravity Impact on Halo Abundance

Hu&Sawicki07, Li+11, Lombriser+13, , Cataneo+16

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Hu & Sawicki $f(R)$ gravity model

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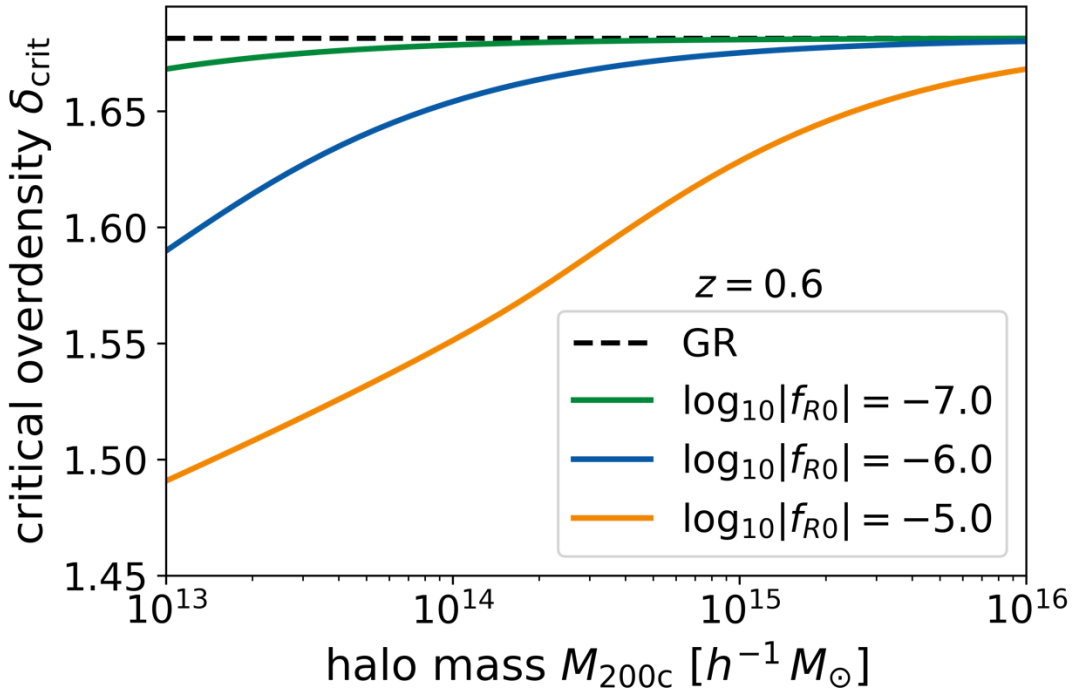

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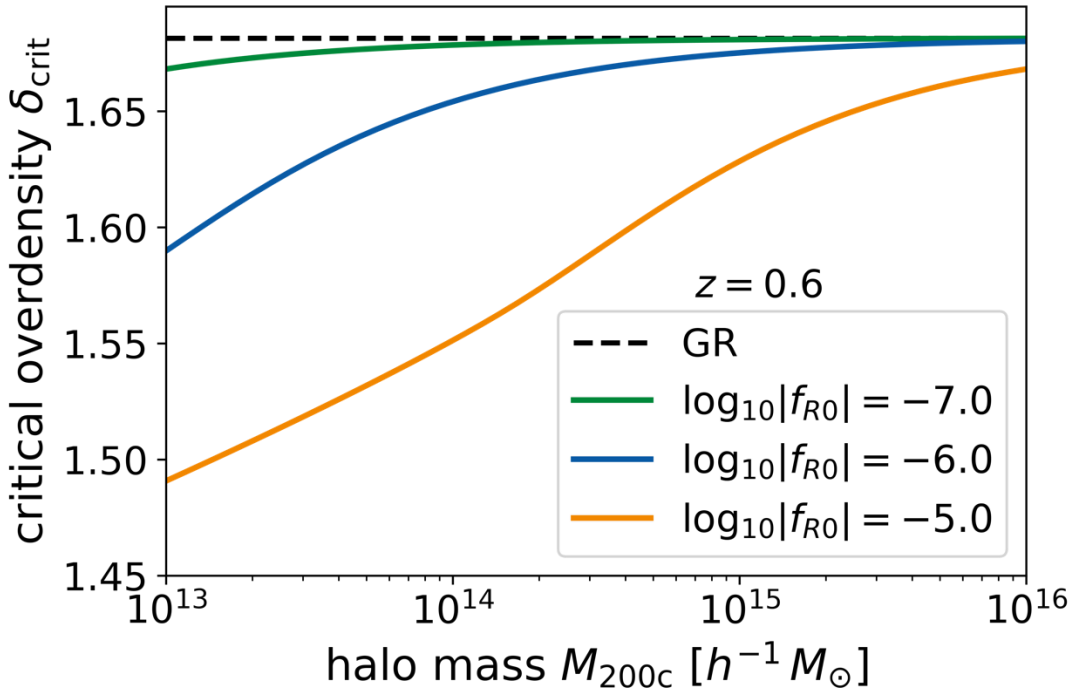
- Use δ_c for a modified Sheth-Tormen HMF



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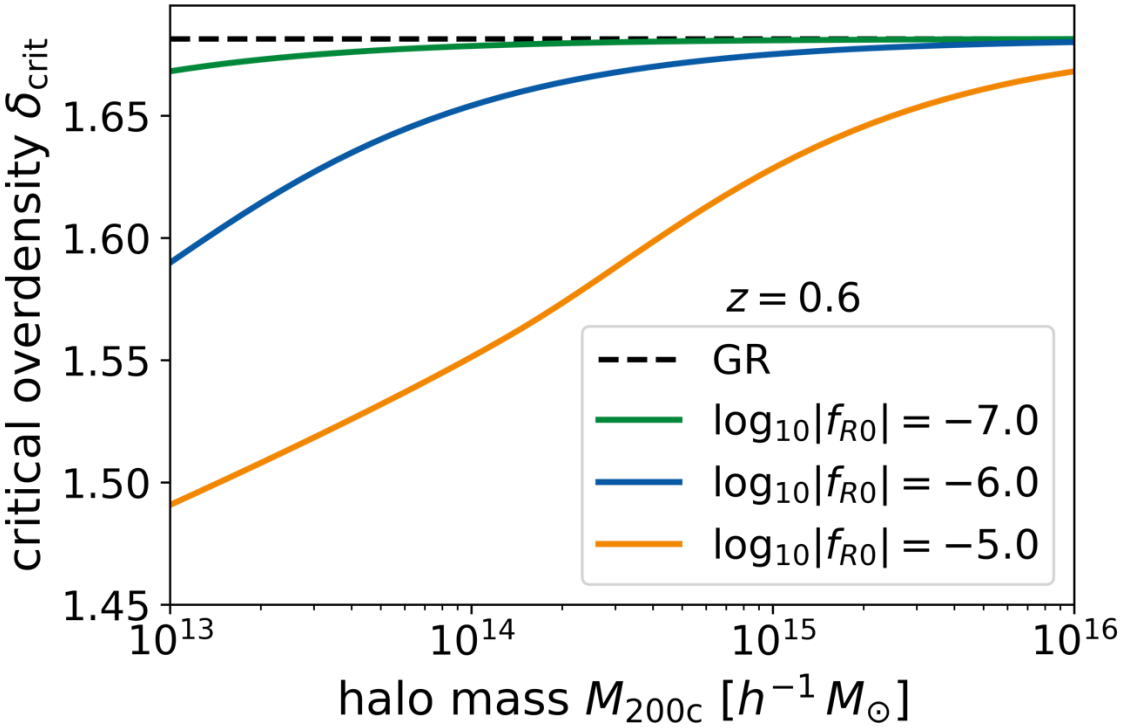

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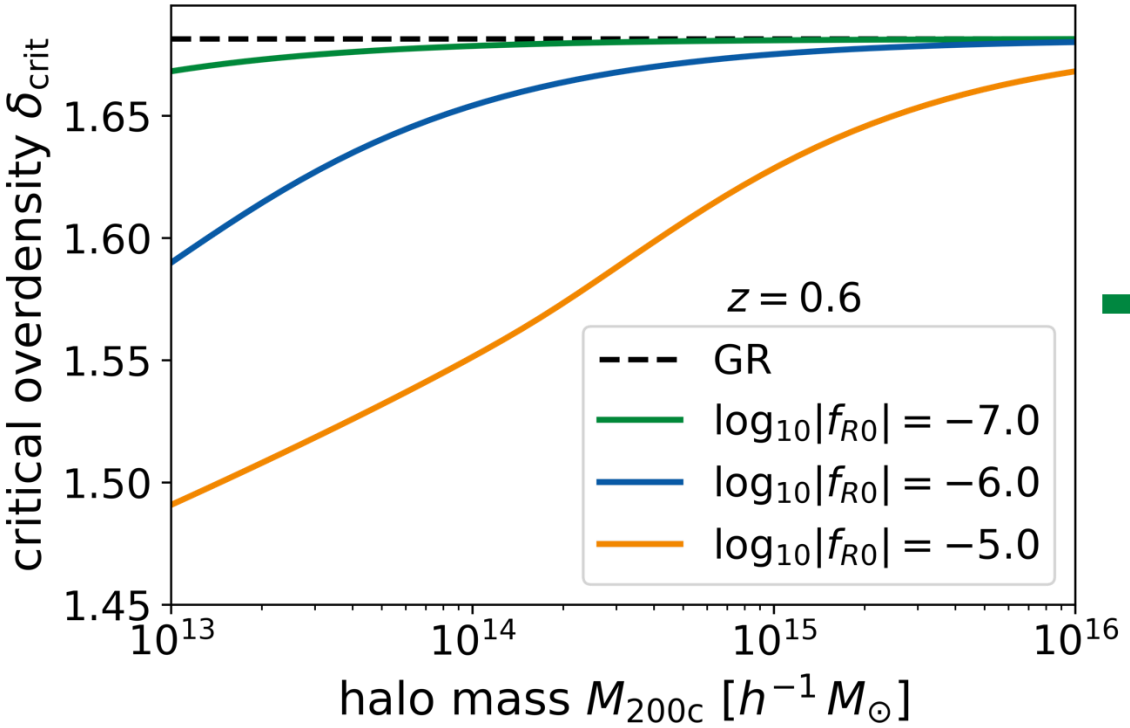

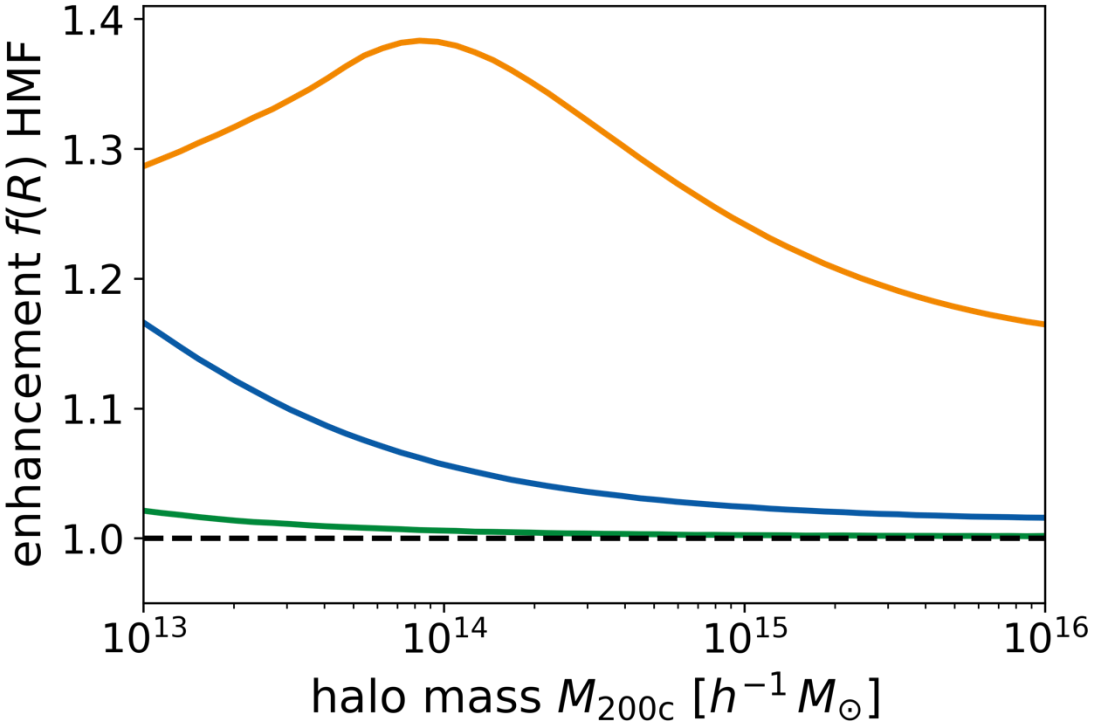

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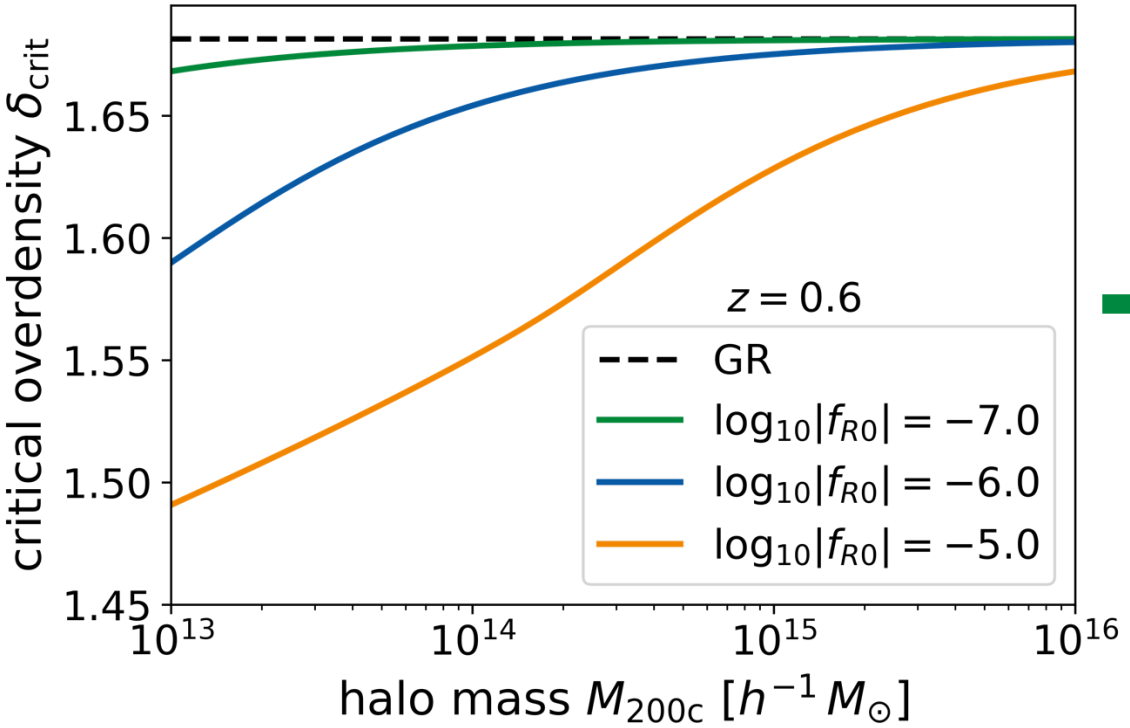

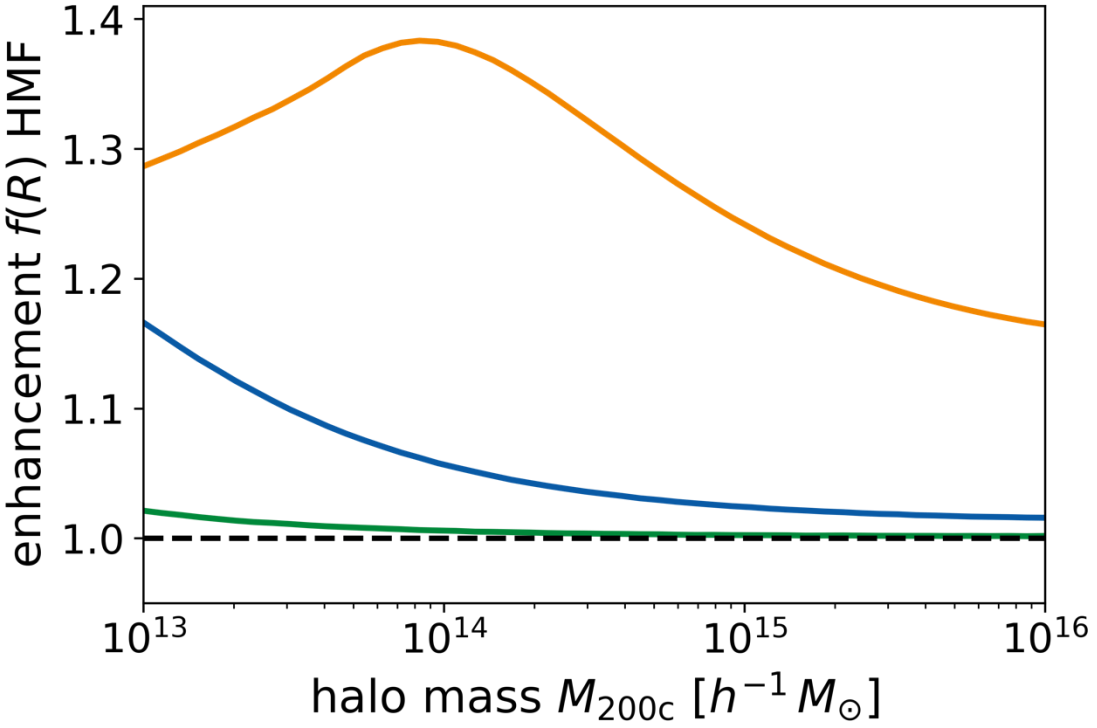

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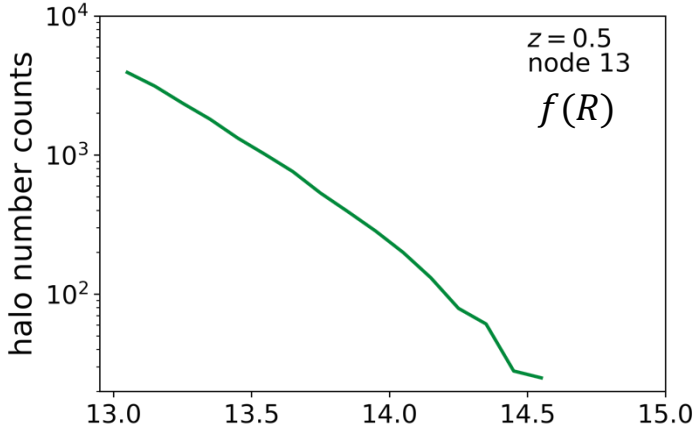

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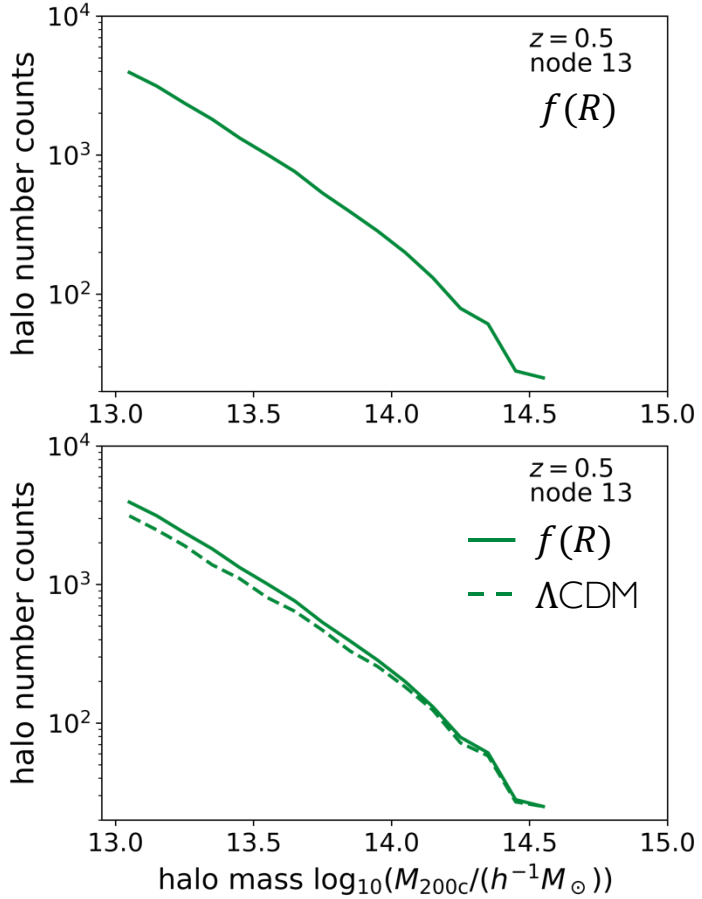

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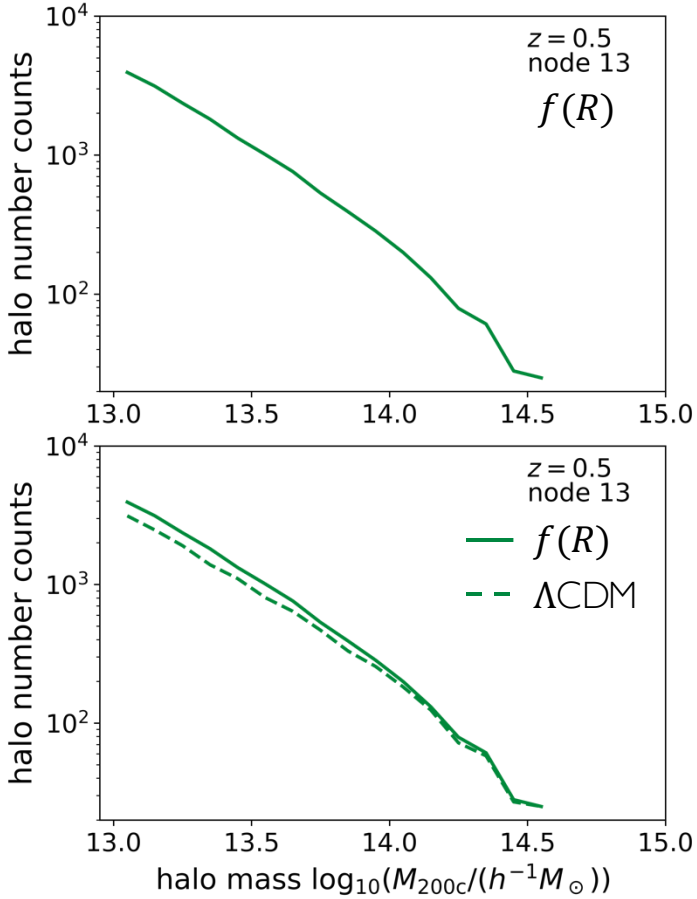

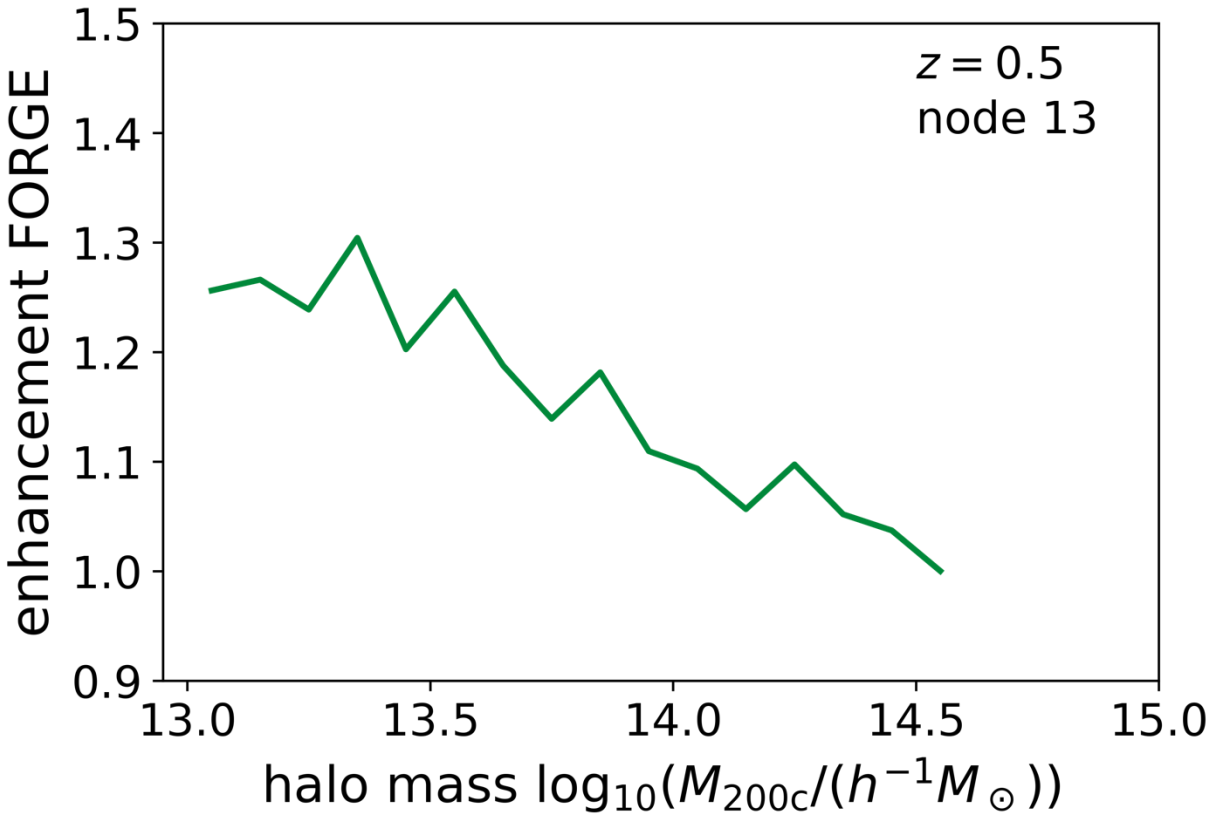

HMF Calibration from FORGE Simulations

Vogt+24b, Arnold+22

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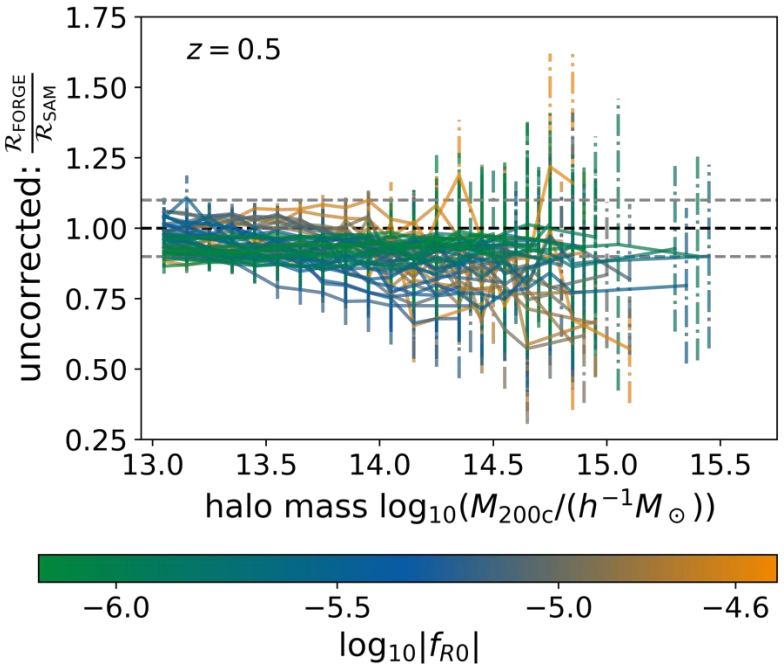

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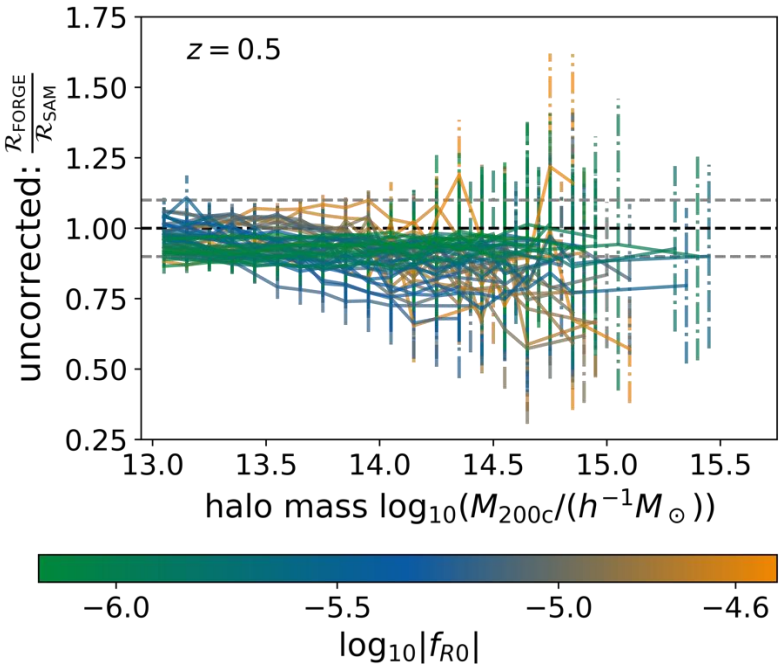

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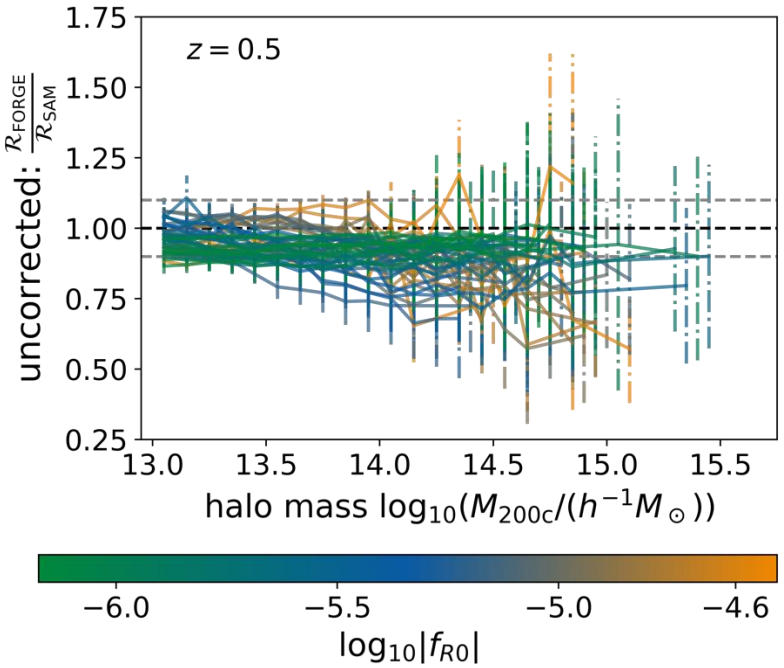

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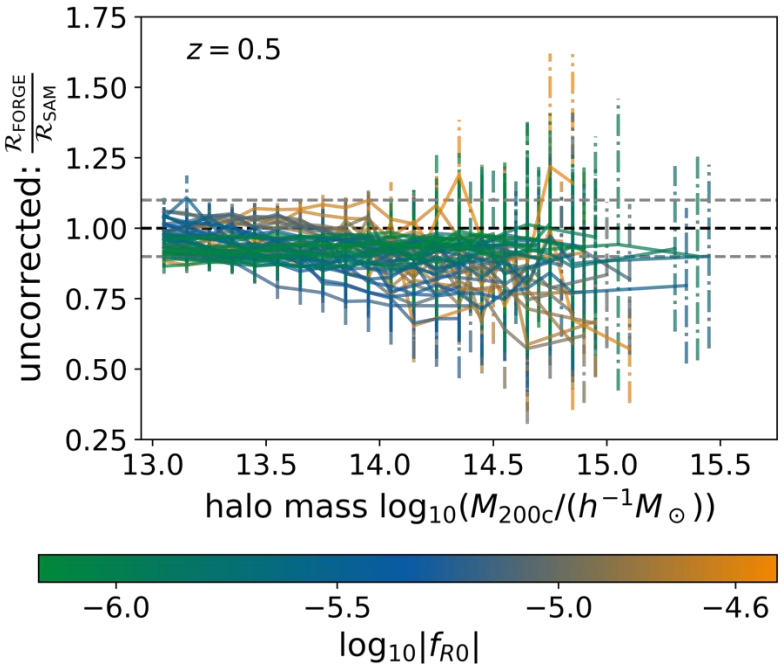

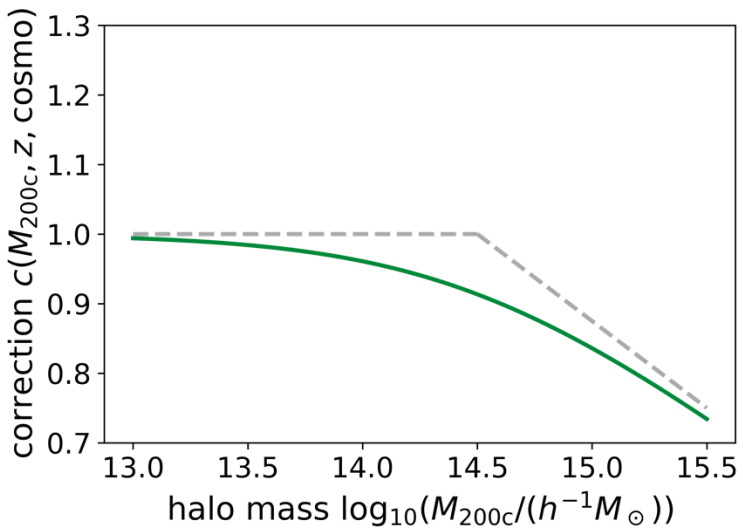

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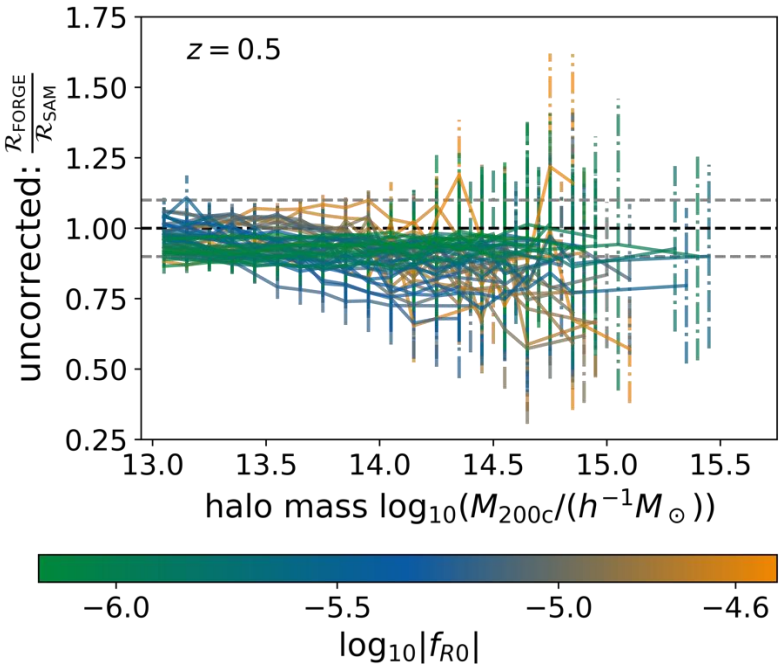

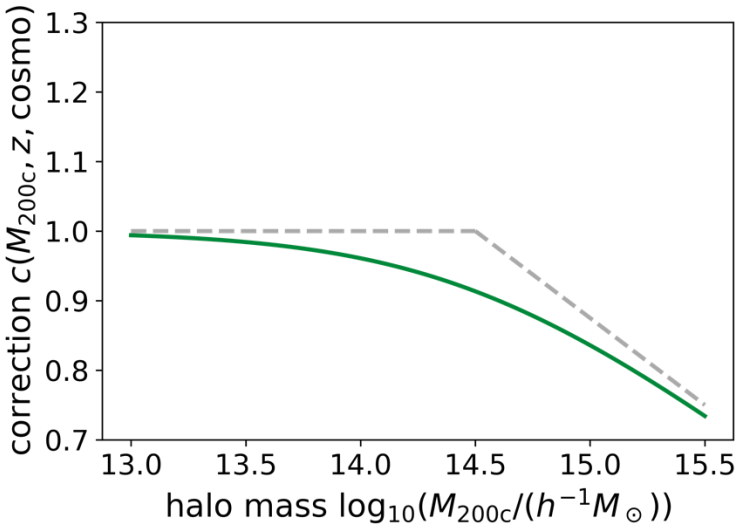

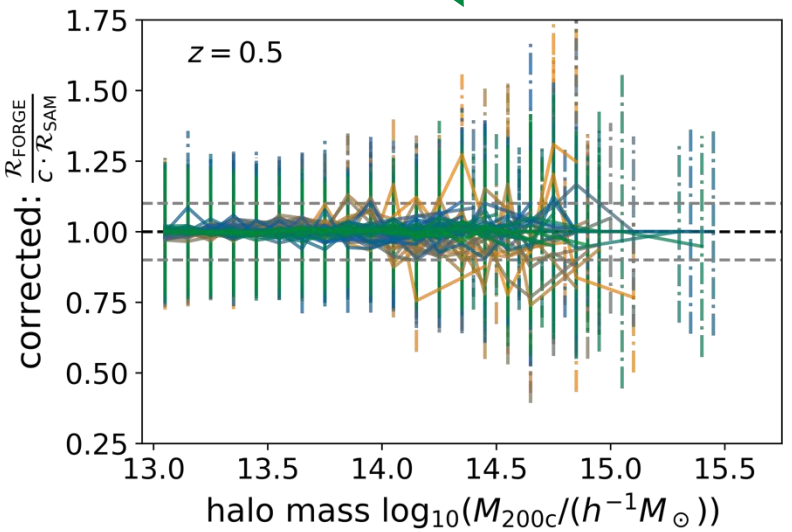

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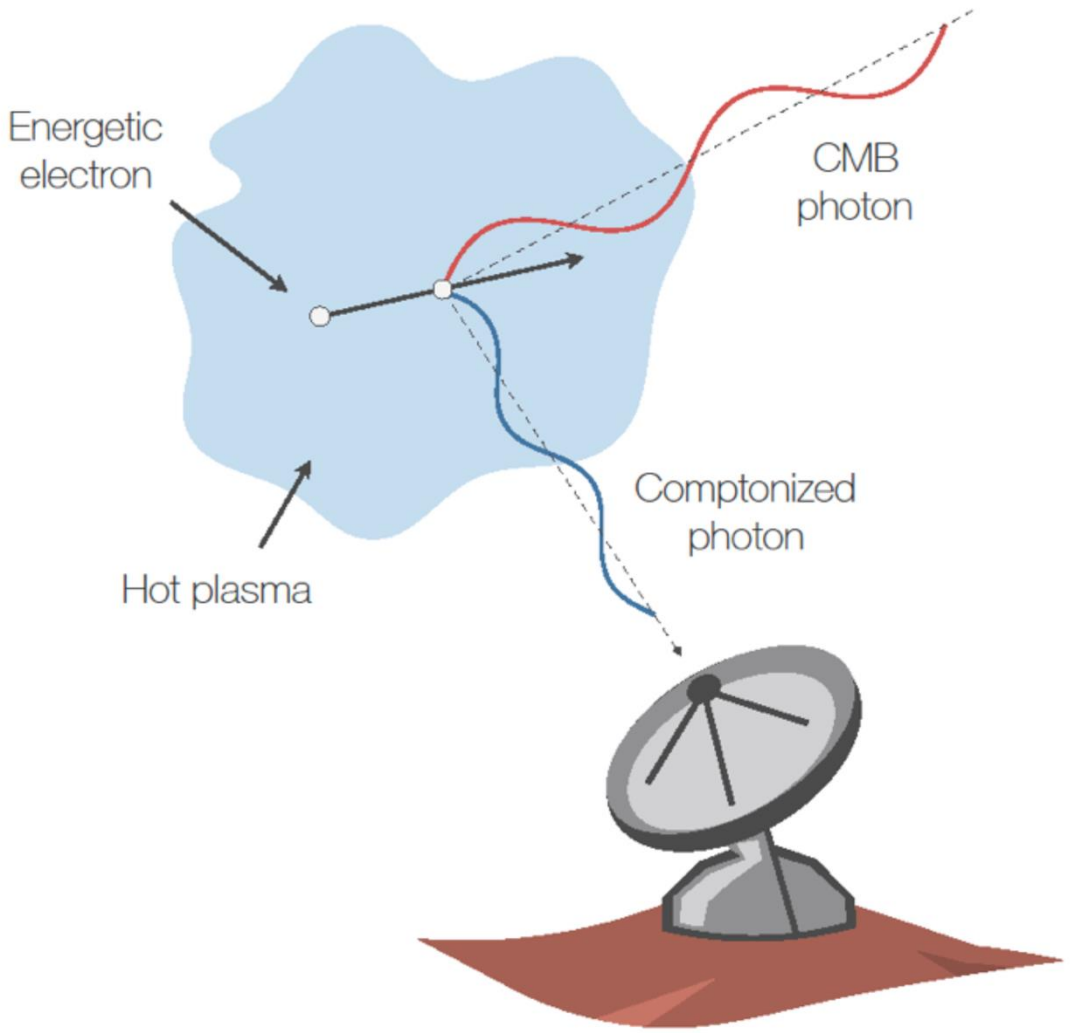
  - Weak-lensing data from the Dark Energy Survey (DES) and the Hubble Space Telescope (HST).

Thermal Sunyaev-Zel'dovich Effect

https://sci.esa.int/s/wN414B8

Sunyaev&Zel'dovich+72

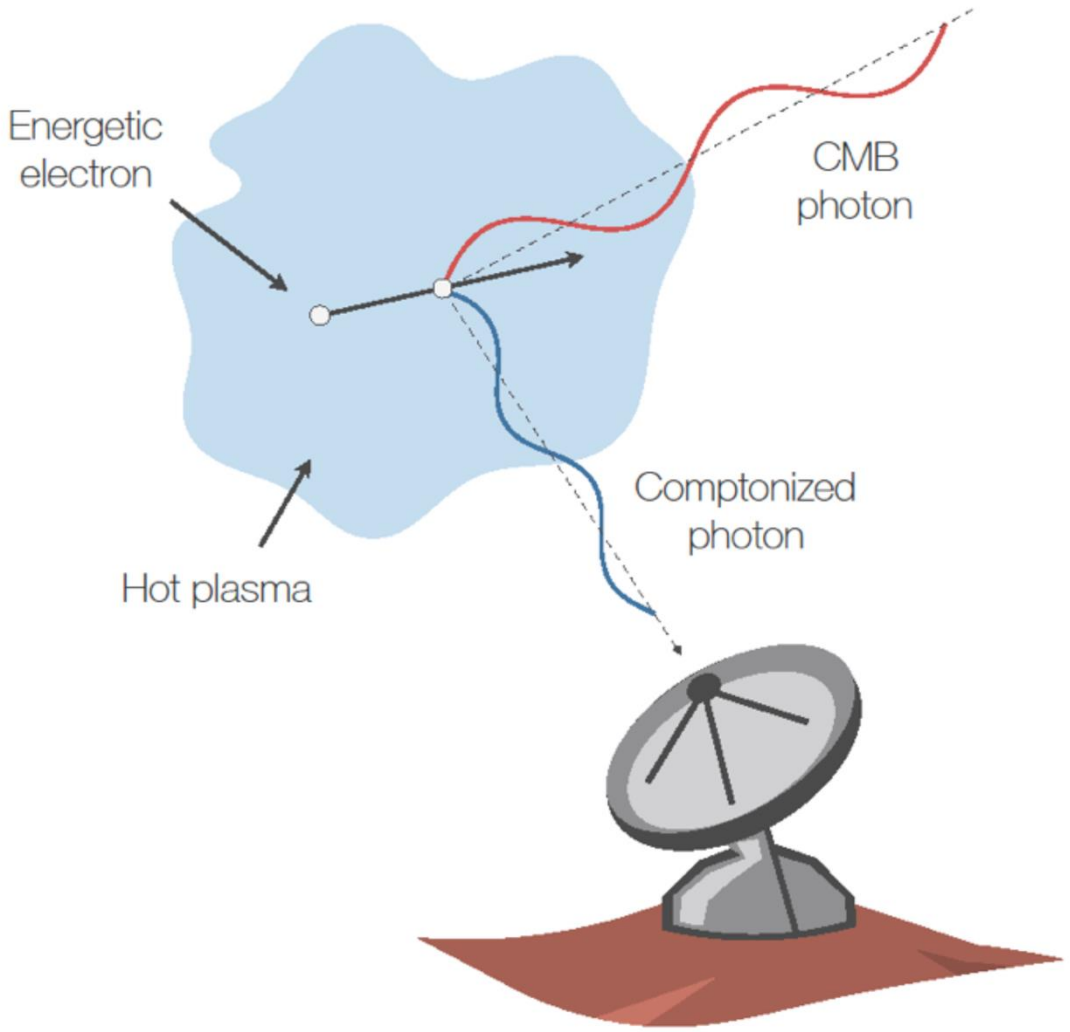
Thermal Sunyaev-Zel'dovich Effect



https://astro.uni-bonn.de/en/research/mm-submm-astronomy/projects-1/sz-effect-and-cosmology

https://sci.esa.int/s/wN414B8

Thermal Sunyaev-Zel'dovich Effect



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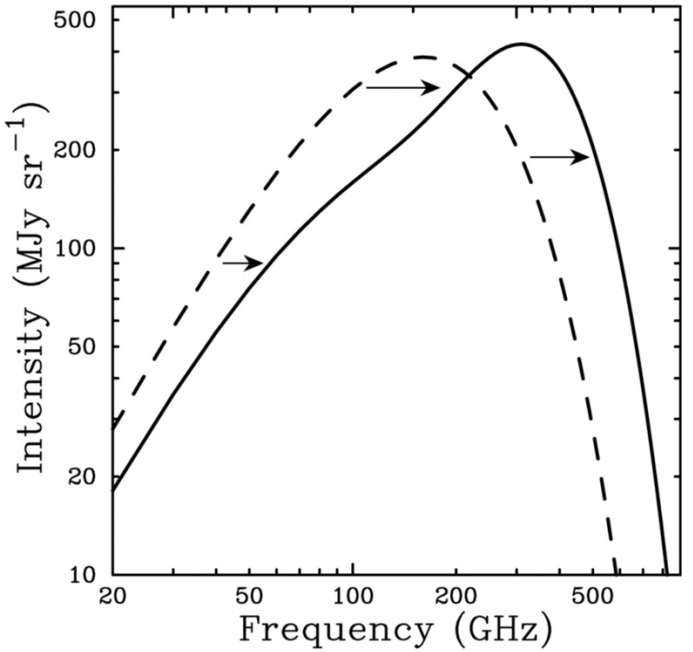

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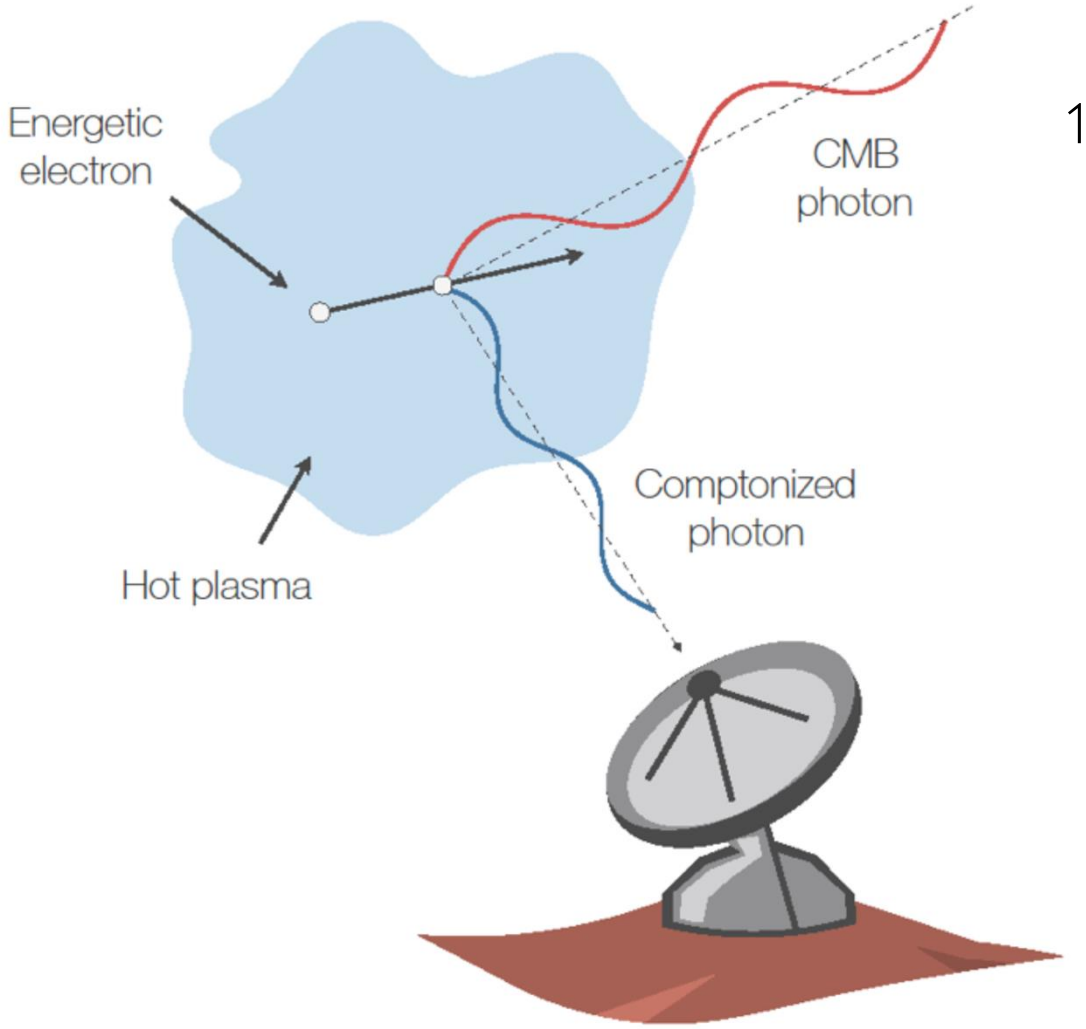

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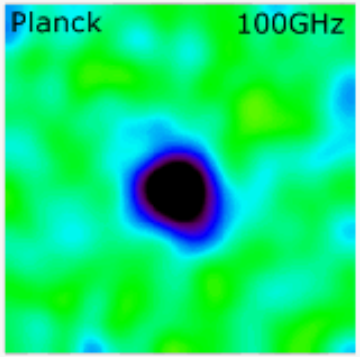

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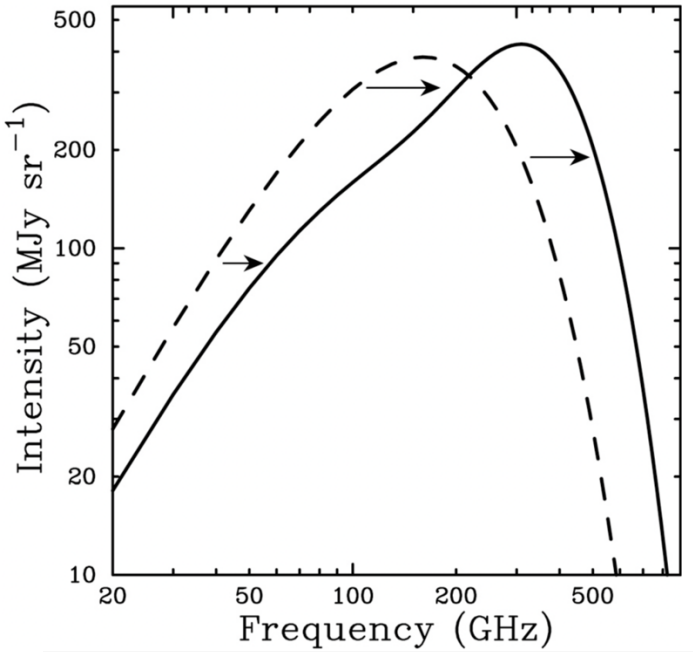

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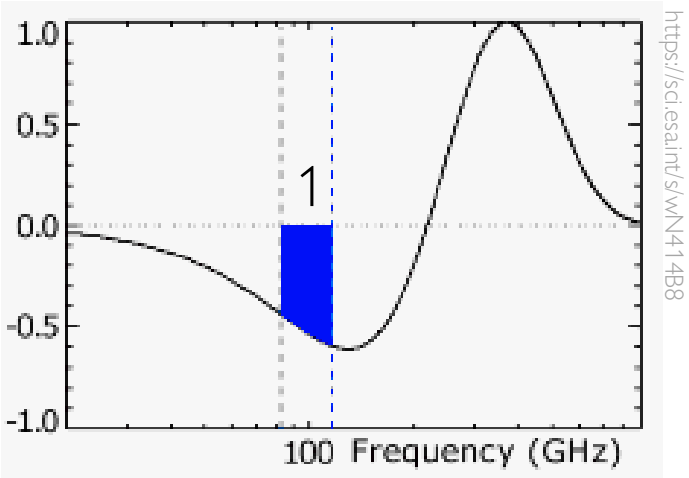

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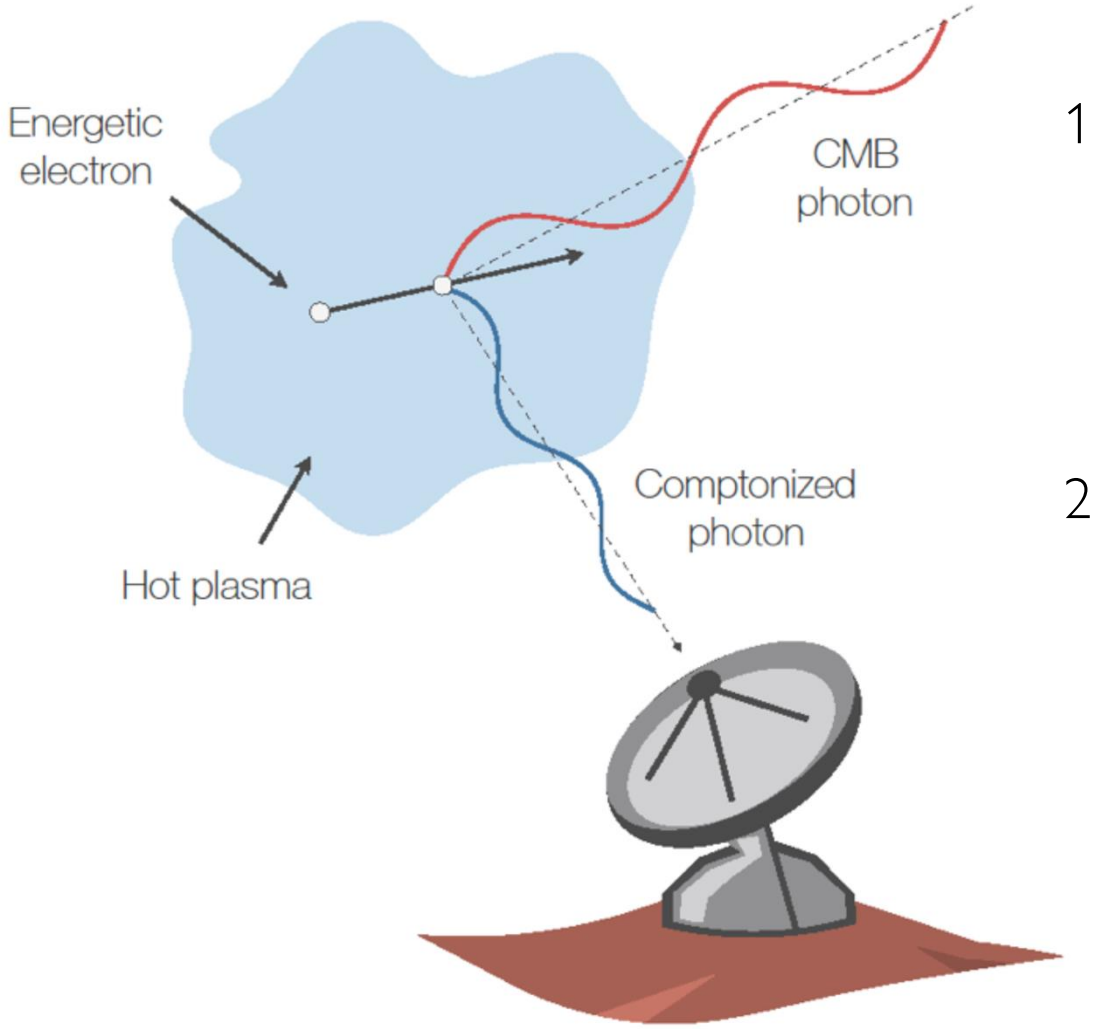

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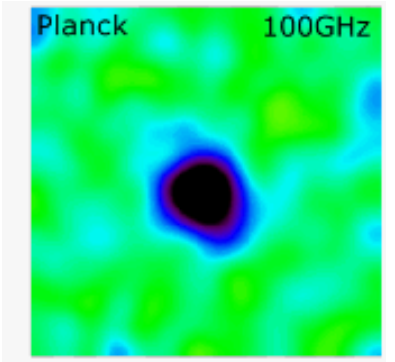

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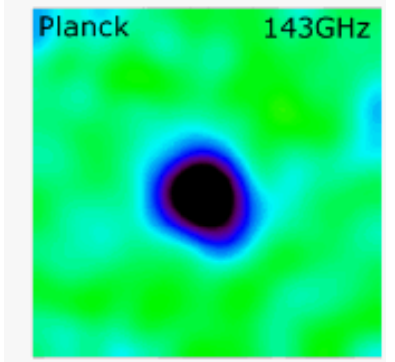

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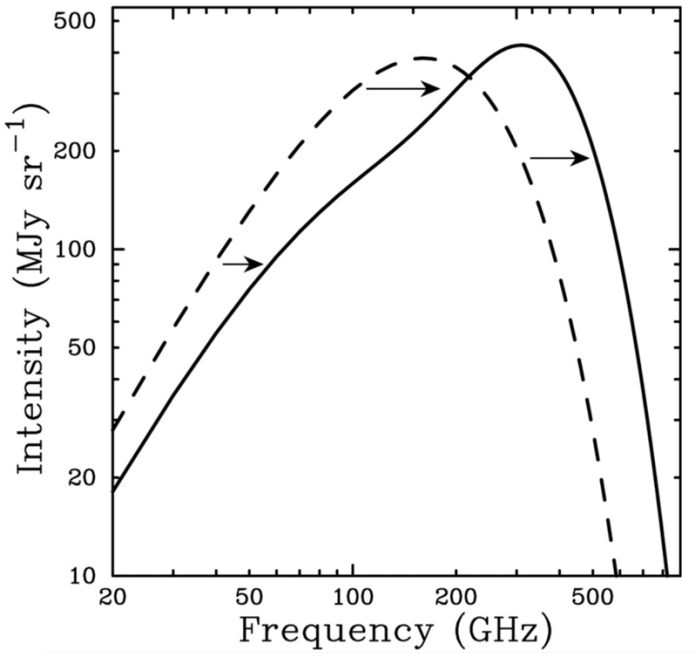

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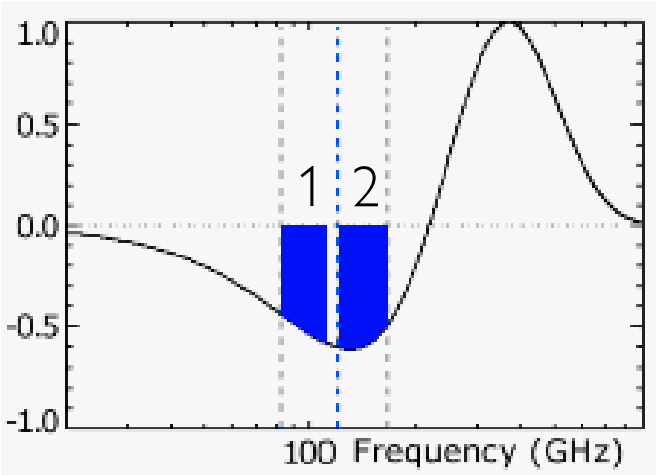

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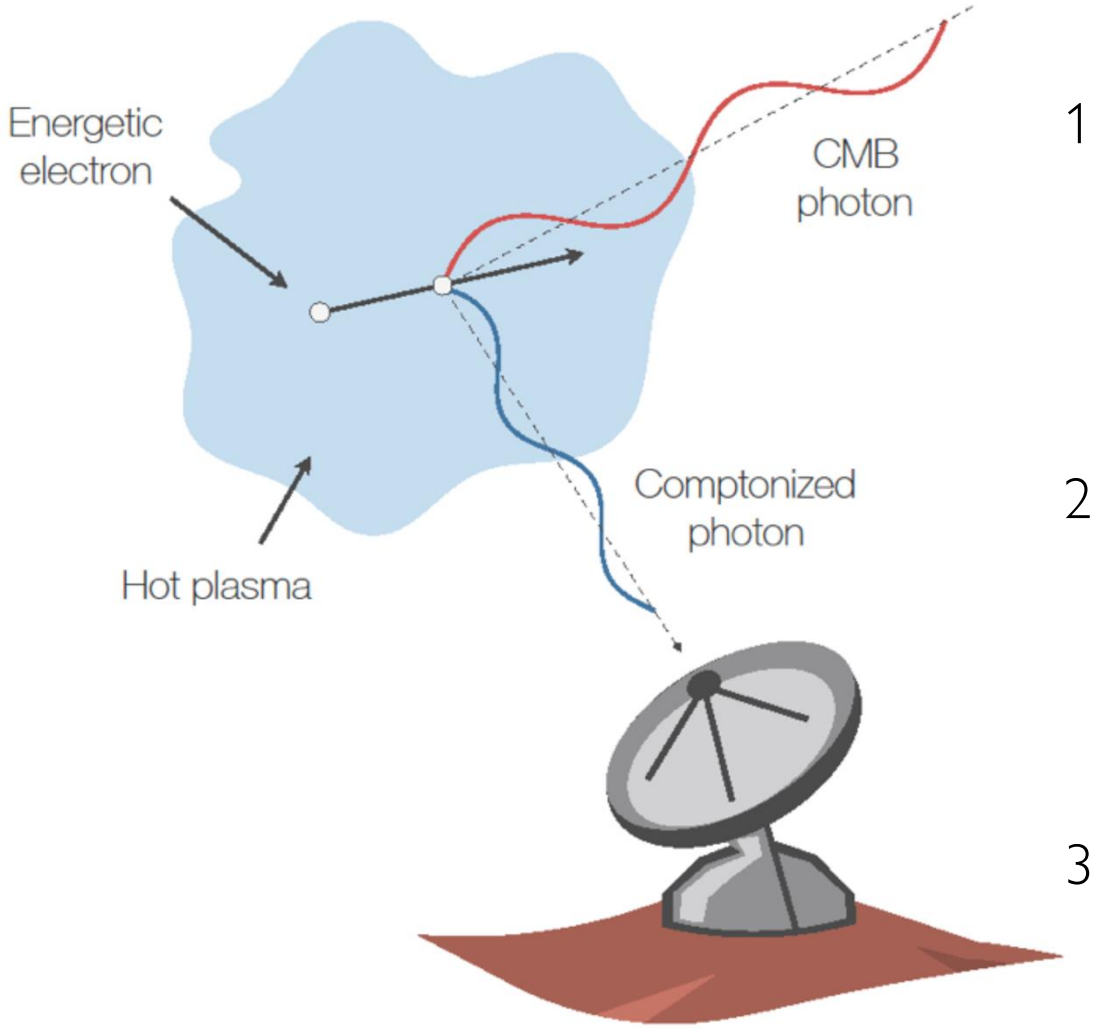

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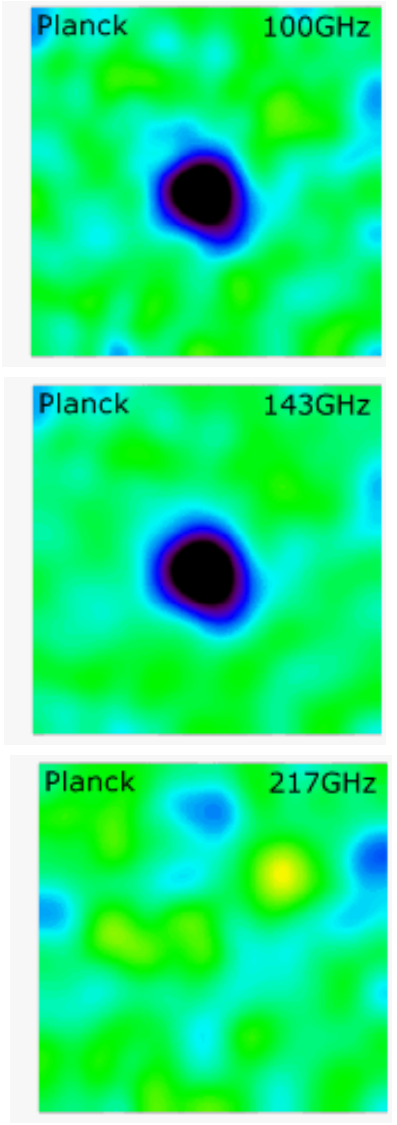

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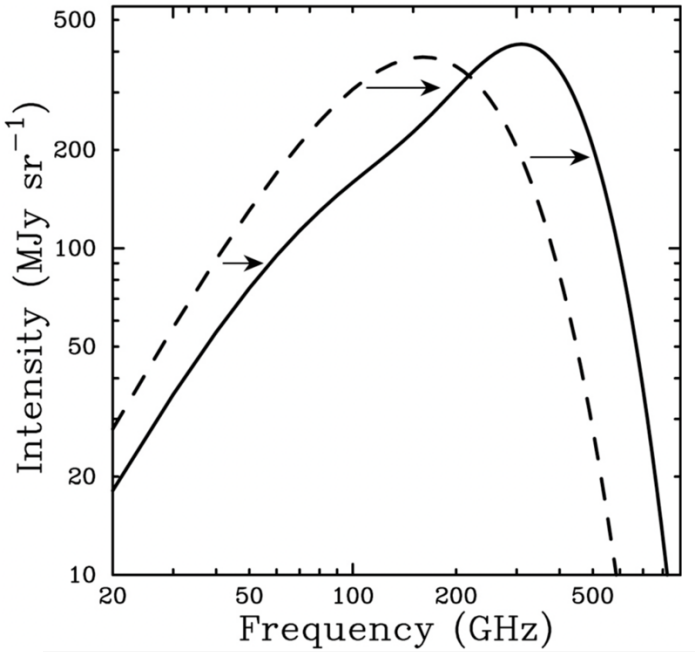

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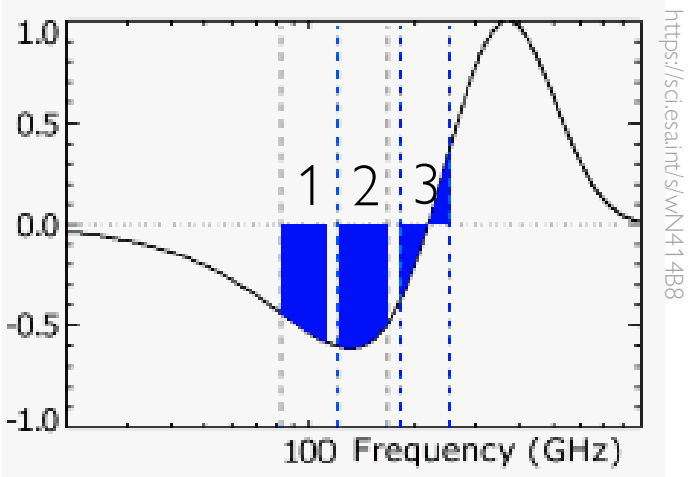

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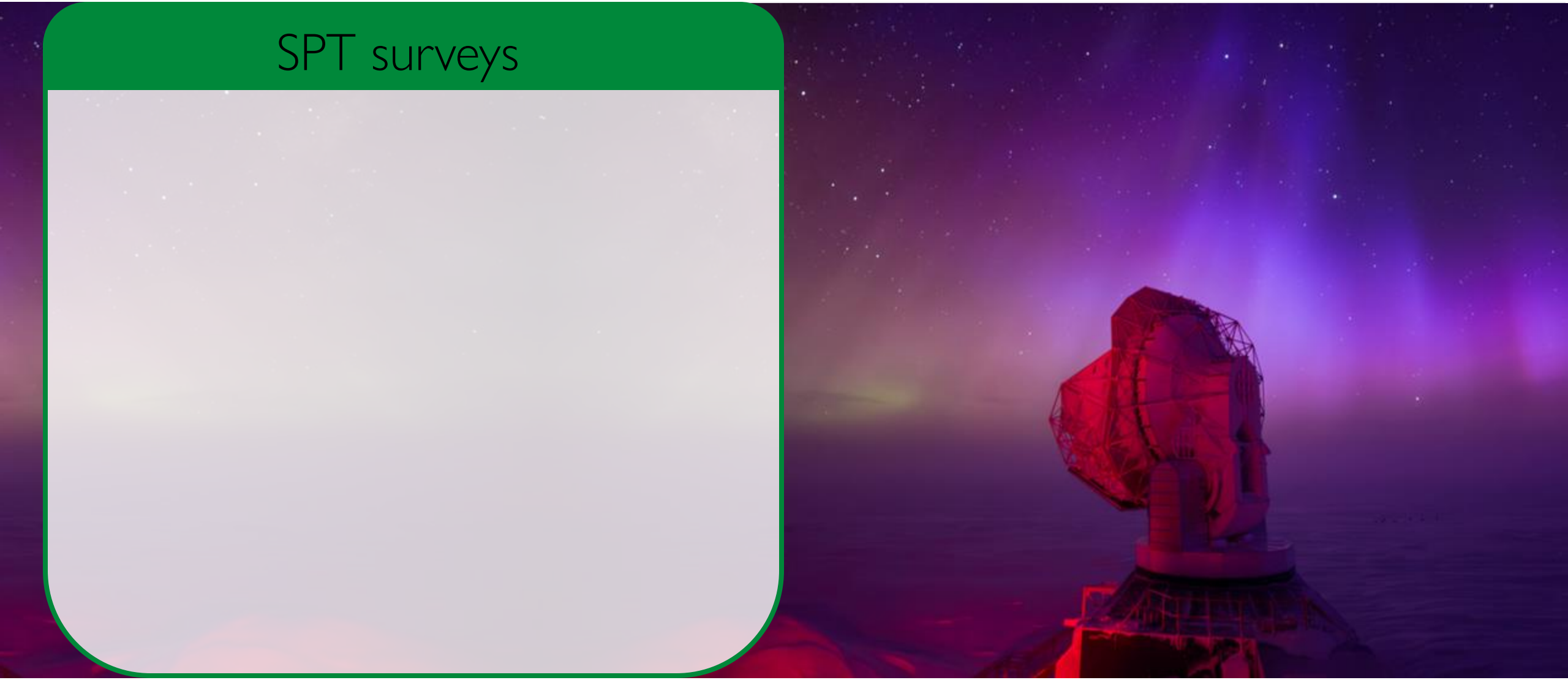
Sunyaev&Zel'dovich+72

SPT Cluster Surveys

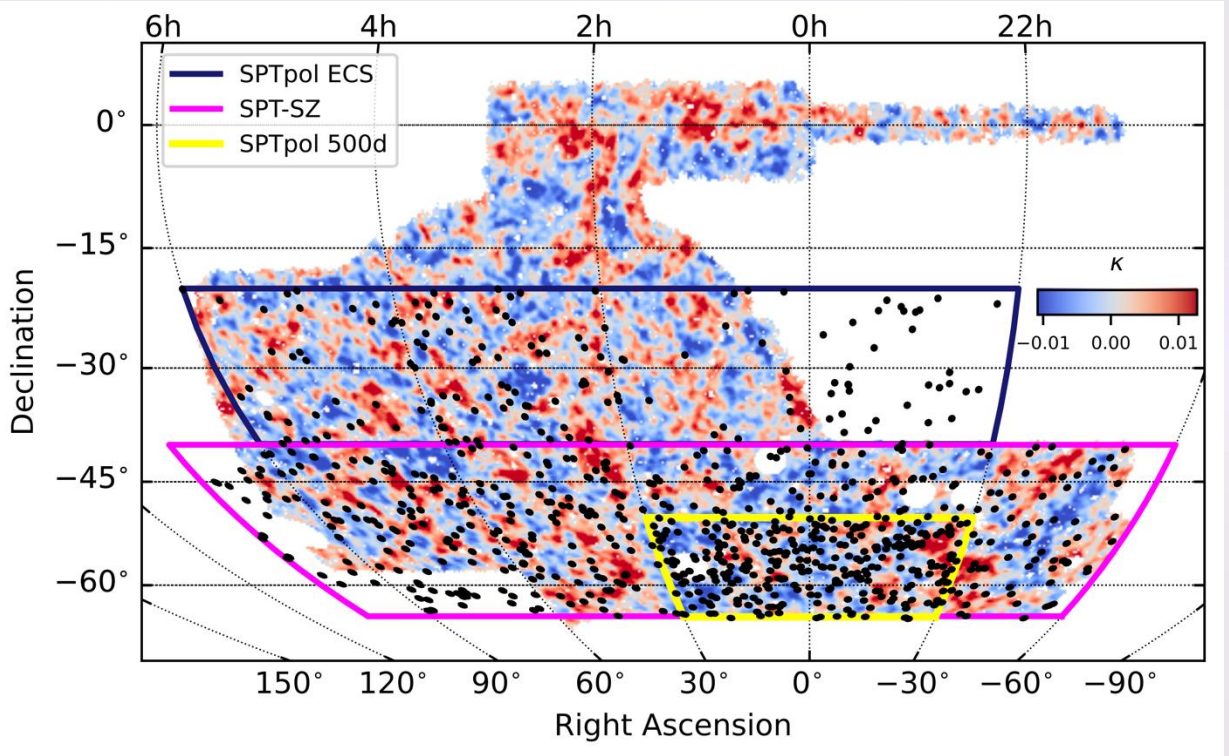
SPT surveys



SPT Cluster Surveys

SPT surveys

- Area: 5,270 deg^2
  - 75% covered by DES footprint



Bleem+15, Bleem19+, Bleem23+, Bocquet+23, Bocquet+24, Klein+19

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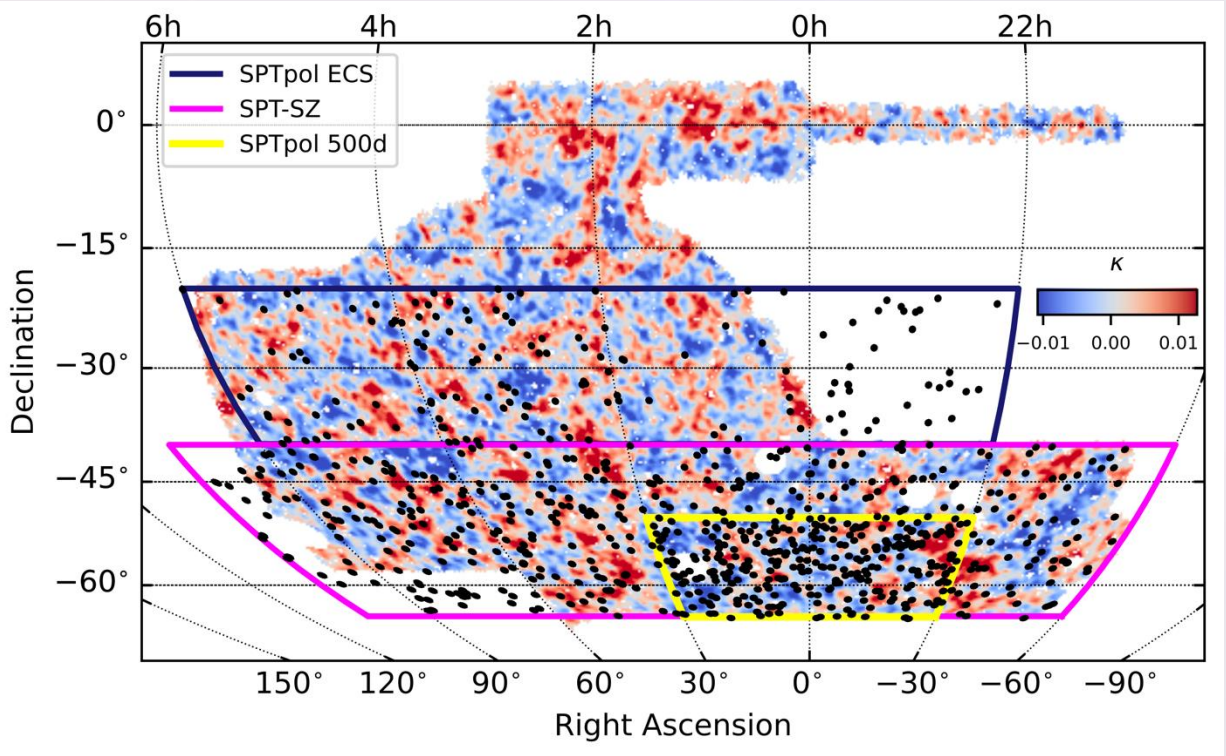
covered by DES Outside DES



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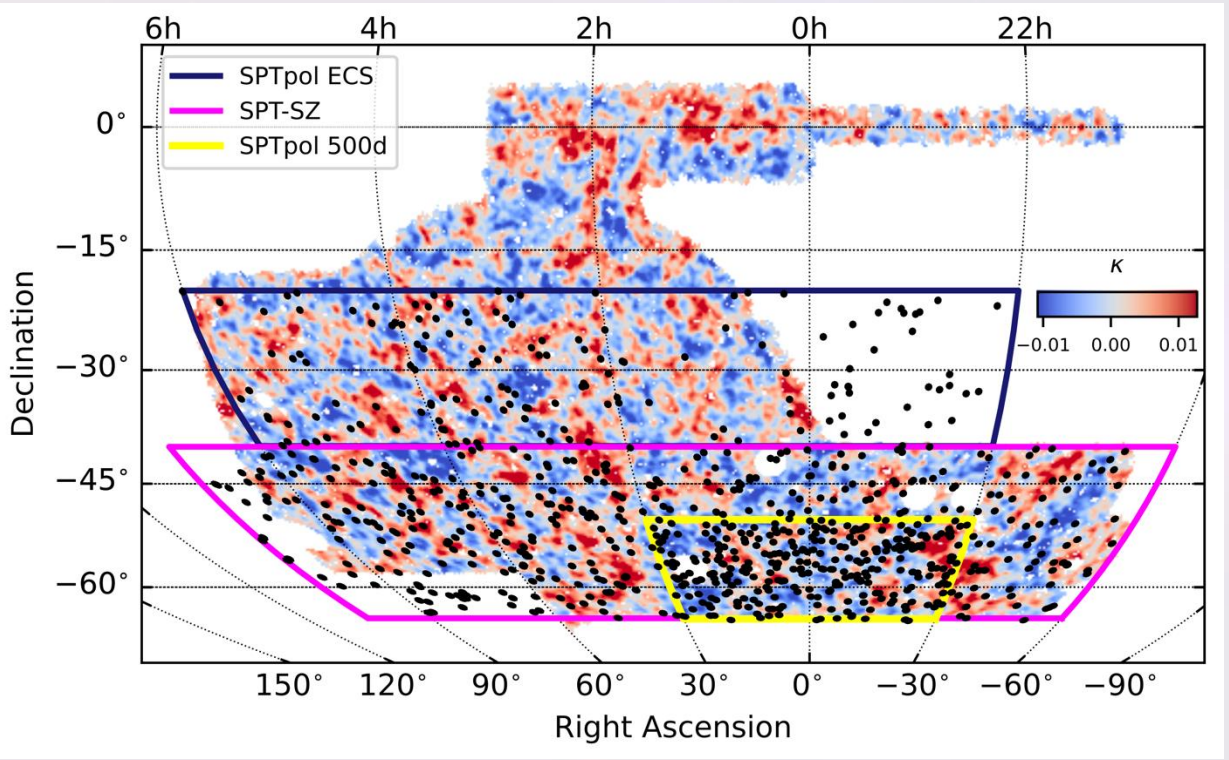

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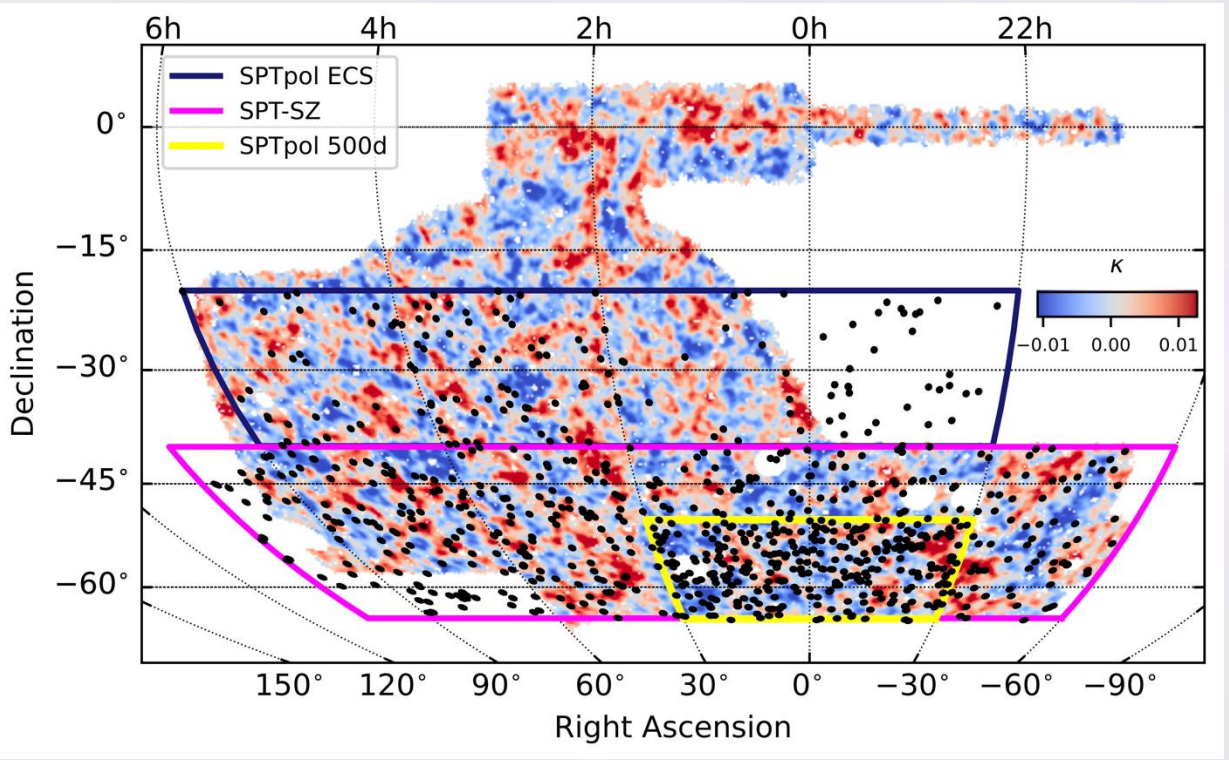

Bleem+15, Bleem19+, Bleem23+, Bocquet+23, Bocquet+24, Klein+19 11

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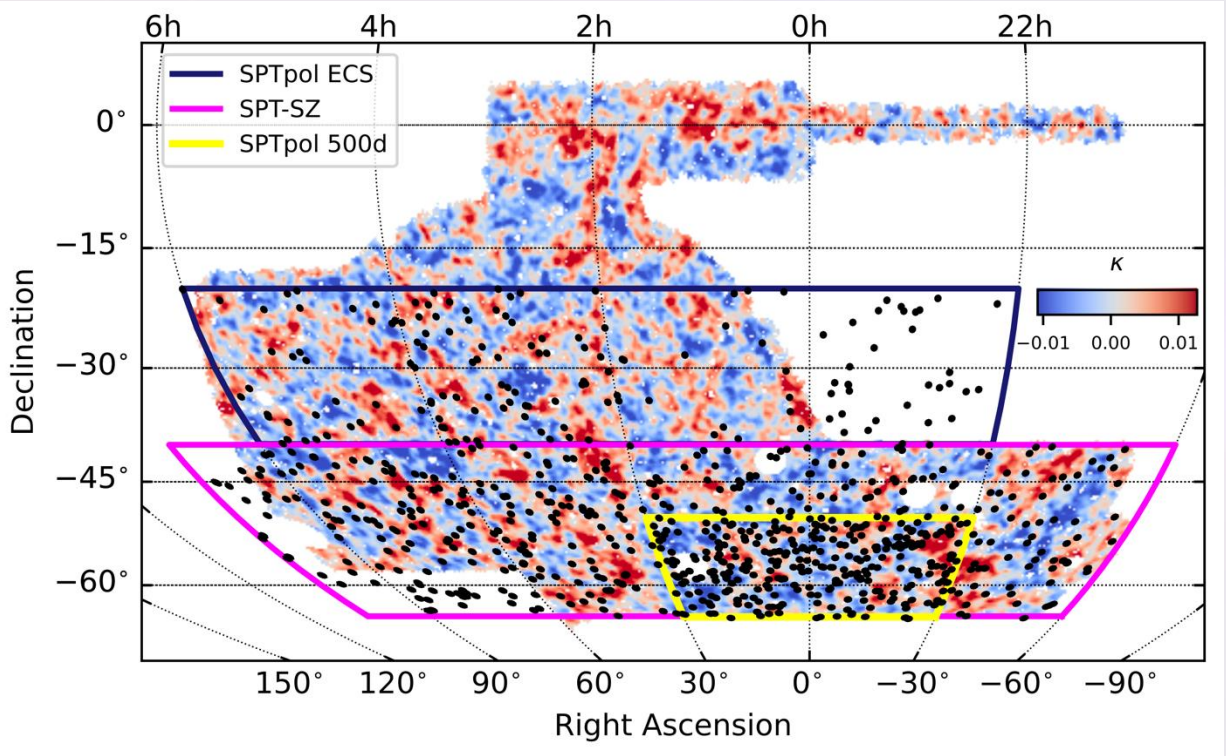

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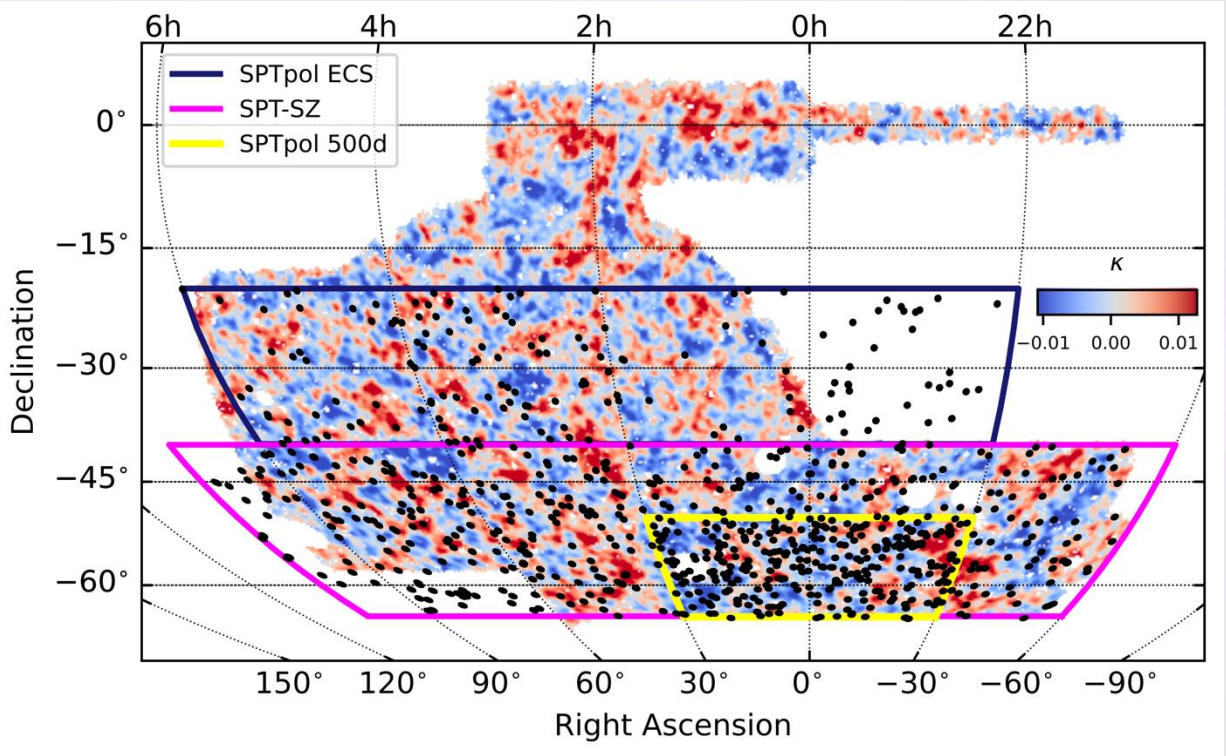

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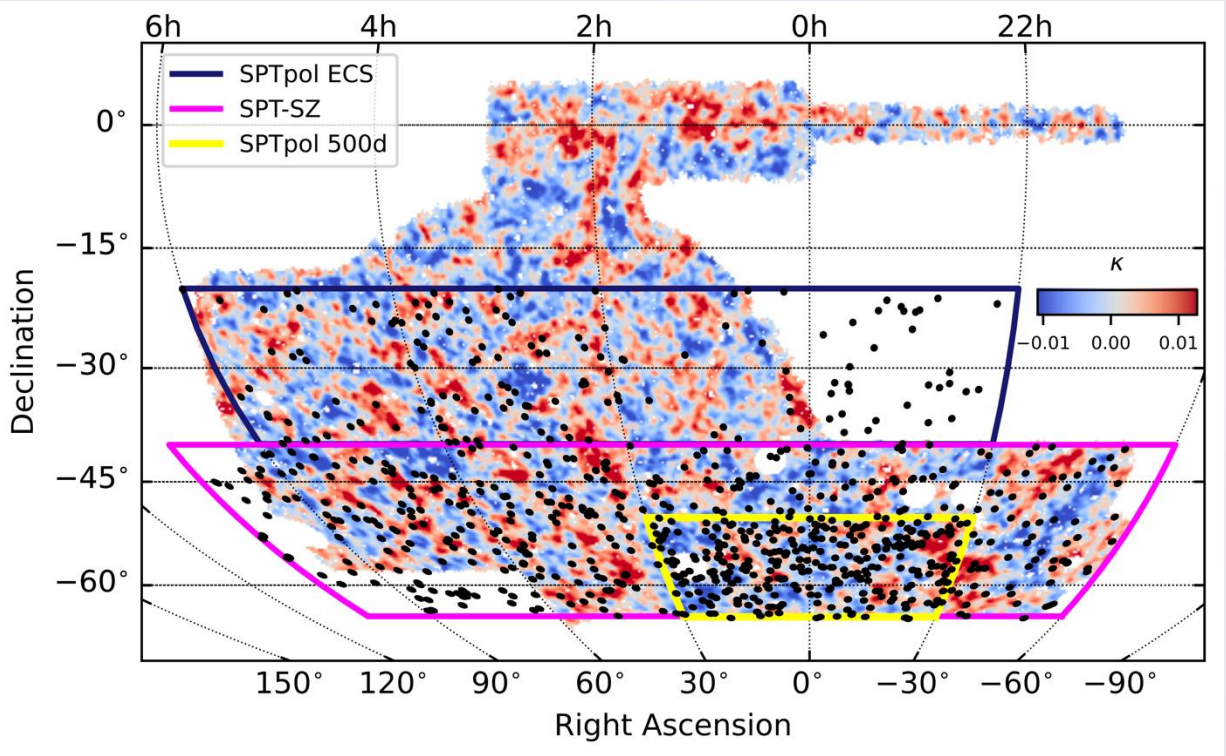
Cluster sample of 1,005 clusters



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$$\langle \ln \mathrm{obs} \rangle = \ln A_{\mathrm{obs}} + B_{\mathrm{obs}} \ln \left(\frac{M_{200c}}{M_{\mathrm{piv}}} \right) + C_{\mathrm{obs}} g(z)$$

Image credit: SPT 2024 winter-overs Josh + Kevin

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Informations about this parameters?
→ WL data

Image credit: SPT 2024 winter-overs Josh + Kevin

Weak-Lensing Mass Estimation

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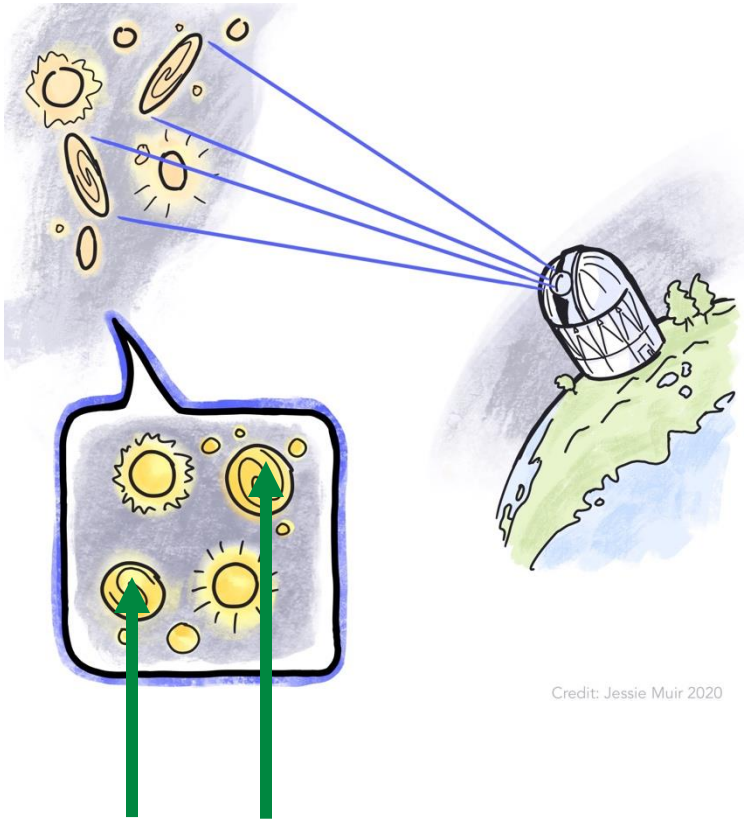
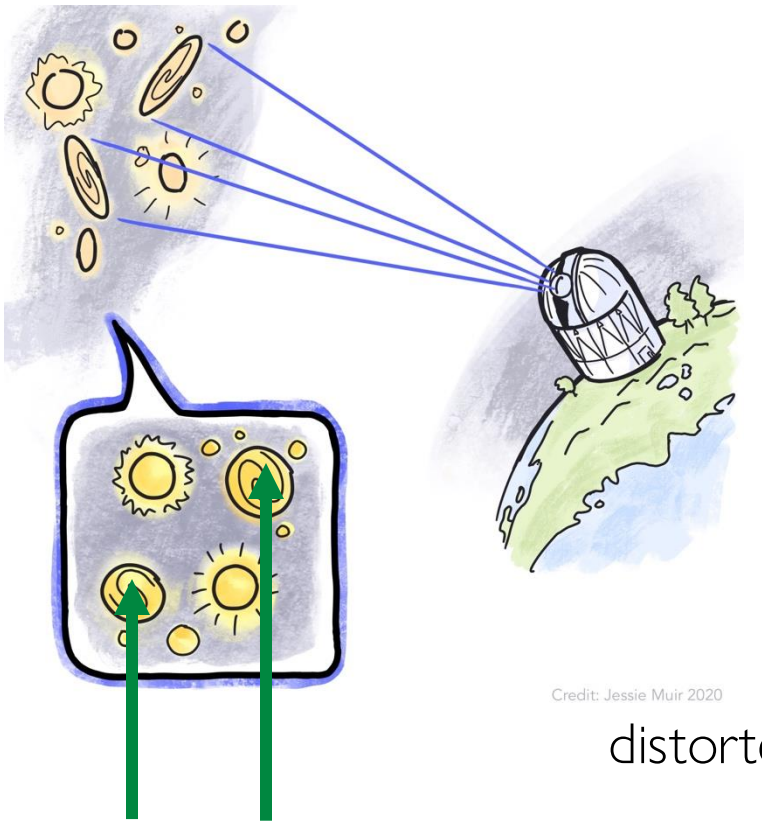
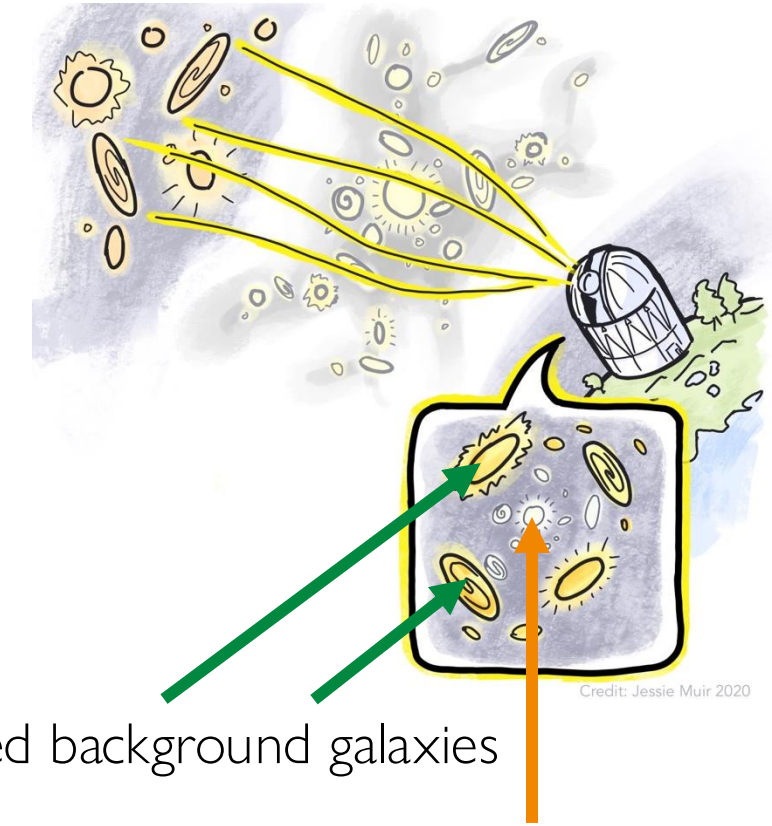


(background) galaxies

Weak-Lensing Mass Estimation

https://www.jessiemuir.com/2021-08-13-3x2pt/





(background) galaxies

distorted background galaxies

massive galaxy cluster

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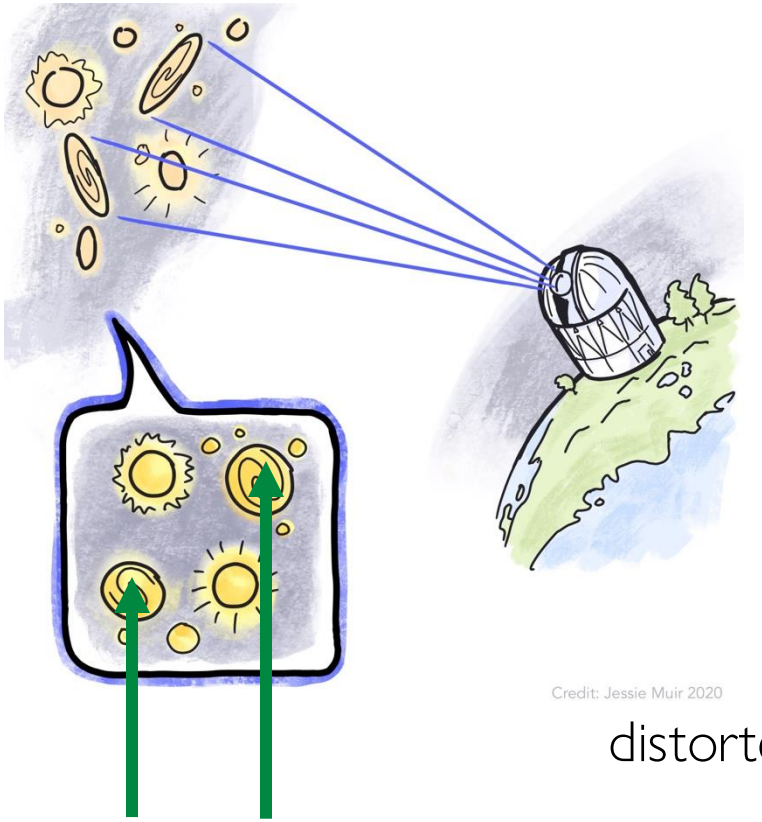
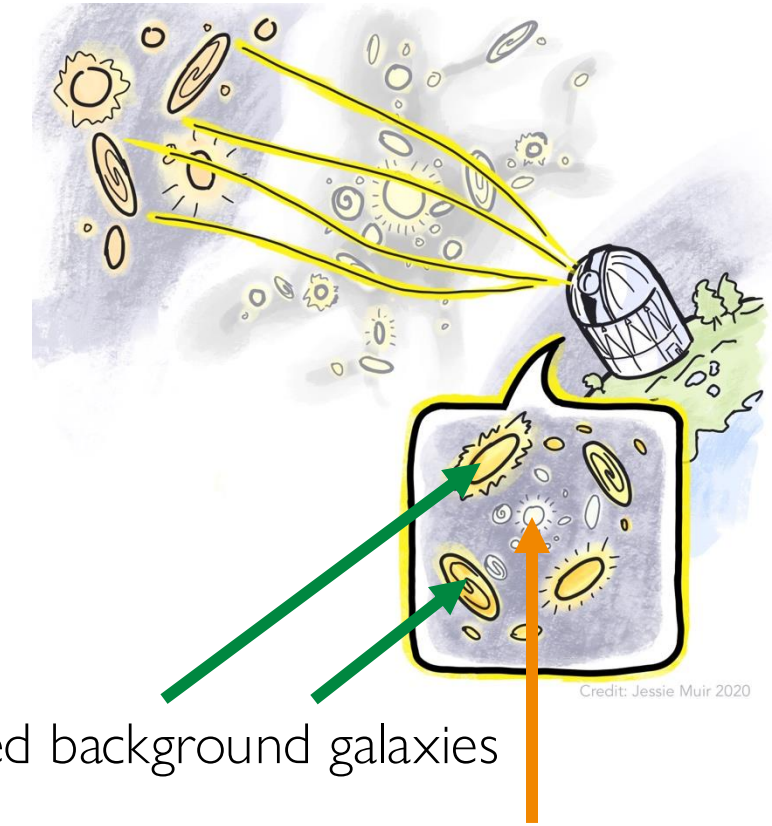


Credit: Jessie Muir 2020



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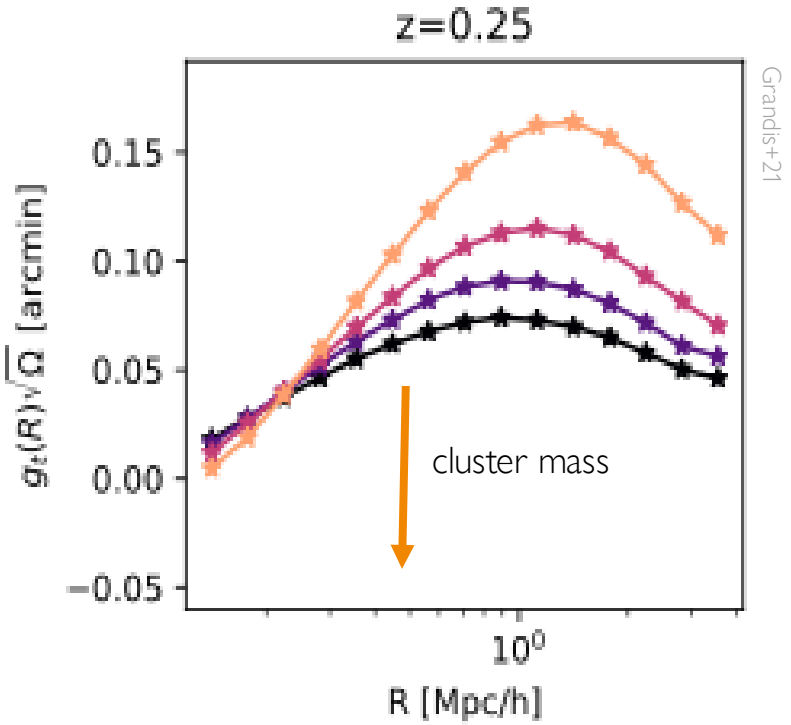

Grandis+21

distorted background galaxies

(background) galaxies

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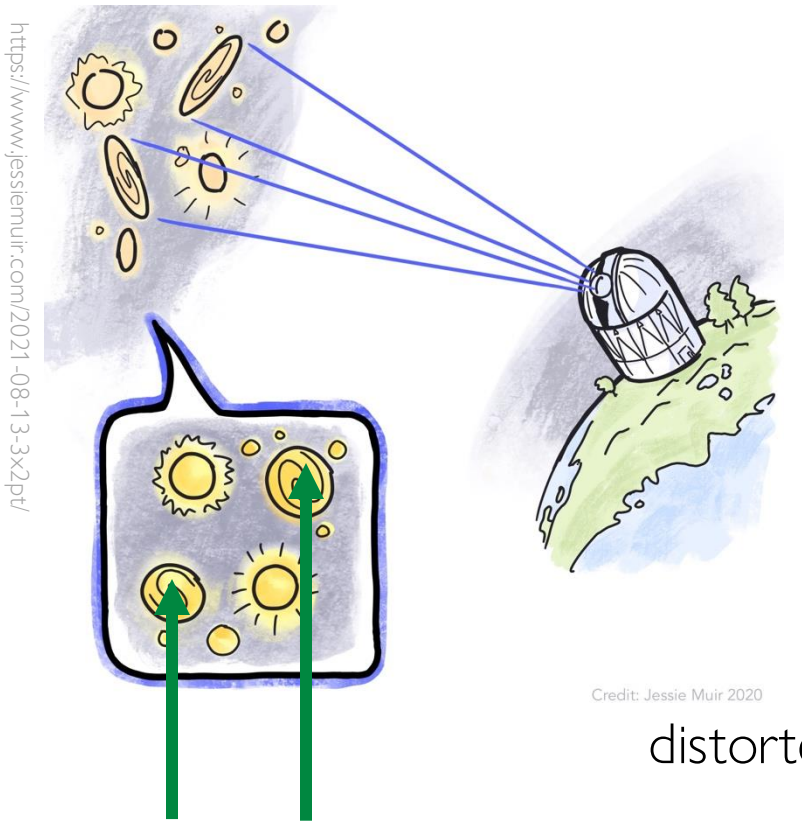
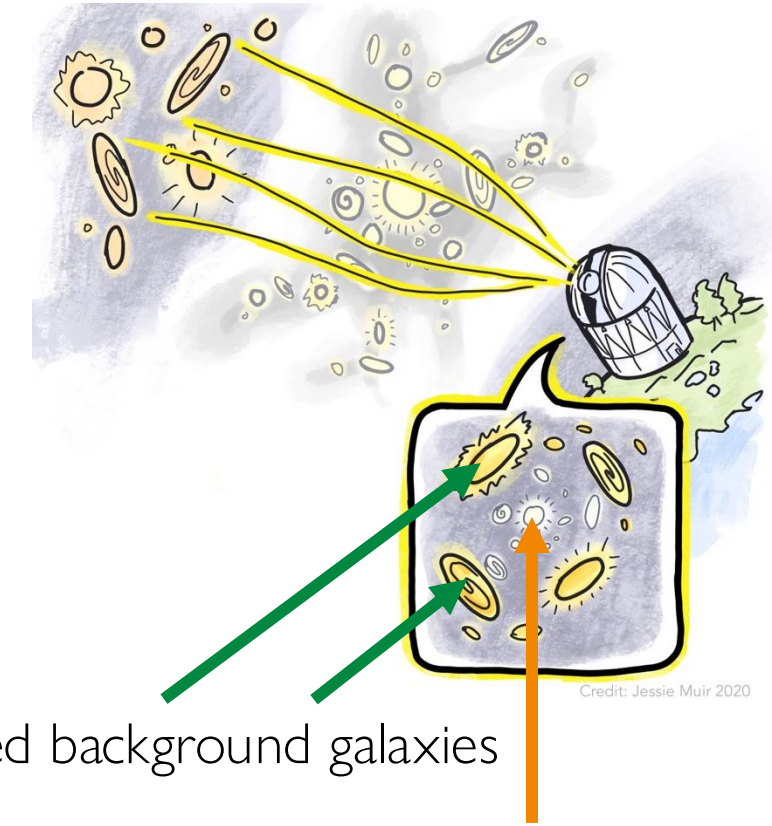


(background) galaxies



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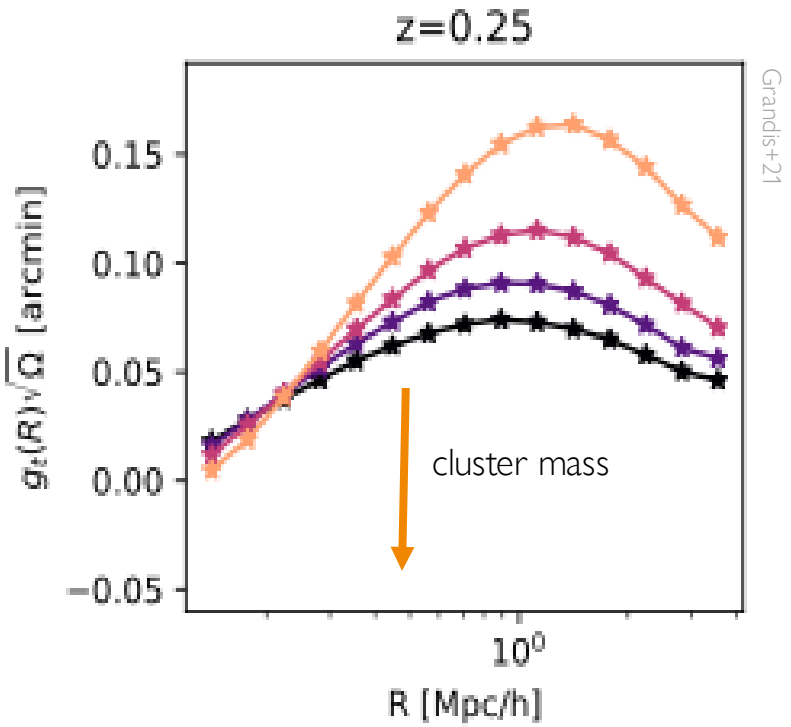

tangential shear → NFW profile → cluster mass M_{WL}

DES and HST Weak-lensing Data

Weak-lensing model and surveys

DES and HST Weak-lensing Data

Weak-lensing model and surveys

- M_{WL} measured from the tangential shear profiles

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$$\left\langle \ln \frac{M_{\mathrm{WL}}}{M_0} \right\rangle = b_{\mathrm{WL}}(z) + b_M \ln \left(\frac{M_{200c}}{M_0} \right)$$

  - Relation calibrated by (ΛCDM) simulations

DES and HST Weak-lensing Data

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DES ($z < 0.9$)

- Shear profiles and M_{WL}

for 688 SPT clusters

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  - Relation calibrated by (ΛCDM) simulations

DES ($z < 0.9$)

- Shear profiles and M_{WL} for 688 SPT clusters

HST ($0.6 < z < 1.7$)

- Target observations for 39 SPT clusters

Analysis Method

Bocquet+23, Bocquet+24, Vogt+24a, Vogt+24b

Analysis Method

Cluster likelihood
(constrains f(R) parameter)

Bocquet+23, Bocquet+24, Vogt+24a, Vogt+24b

Analysis Method

Cluster likelihood
(constrains f(R) parameter)

$$\frac{\mathrm{d}^3 N(p)}{\mathrm{d}M\mathrm{d}z\mathrm{d}V}\frac{\mathrm{d}V(p)}{\mathrm{d}\Omega_s}$$

Cosmology dependent (differential) HMF

Bocquet+23, Bocquet+24, Vogt+24a, Vogt+24b

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(constrains f(R) parameter)

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Cosmology dependent (differential) HMF

$$\langle \ln \mathrm{obs} \rangle = \ln A + B \ln\left(\frac{M}{M_0}\right) + Cg(z)$$

Observable-mass relations

Bocquet+23, Bocquet+24, Vogt+24a, Vogt+24b

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$$\frac{\mathrm{d}^3N(p)}{\mathrm{d}\xi\mathrm{d}\lambda\mathrm{d}z}$$

(Differential) observable cluster abundance

Bocquet+23, Bocquet+24, Vogt+24a, Vogt+24b

Analysis Method

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$\frac{\mathrm{d}^3N(p)}{\mathrm{d}M\mathrm{d}z\mathrm{d}V}\frac{\mathrm{d}V(p)}{\mathrm{d}\Omega_s}$

Cosmology dependent (differential) HMF

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(Differential) observable cluster abundance

$\ln \mathcal{L}(p)$

Poisson cluster likelihood

Bocquet+23, Bocquet+24, Vogt+24a, Vogt+24b

Analysis Method

Cluster likelihood
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+

Planck2018 data
(for breaking degeneracies and to constrain standard cosmo params)

$$\frac{\mathrm{d}^3N(p)}{\mathrm{d}M\mathrm{d}z\mathrm{d}V}\frac{\mathrm{d}V(p)}{\mathrm{d}\Omega_s}$$

Cosmology dependent (differential) HMF

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Observable-mass relations

$$\frac{\mathrm{d}^3N(p)}{\mathrm{d}\xi\mathrm{d}\lambda\mathrm{d}z}$$

(Differential) observable cluster abundance

$$\ln \mathcal{L}(p)$$

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Bocquet+23, Bocquet+24, Vogt+24a, Vogt+24b

Analysis Method

Cluster likelihood (constrains f(R) parameter) + Planck2018 data (for breaking degeneracies and to constrain standard cosmo params) → Cosmological constraints

$$\frac{\mathrm{d}^3N(p)}{\mathrm{d}M\mathrm{d}z\mathrm{d}V}\frac{\mathrm{d}V(p)}{\mathrm{d}\Omega_s}$$

Cosmology dependent (differential) HMF

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Observable-mass relations

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Results from clustersxWL+Planck18 (Vogt+24b)

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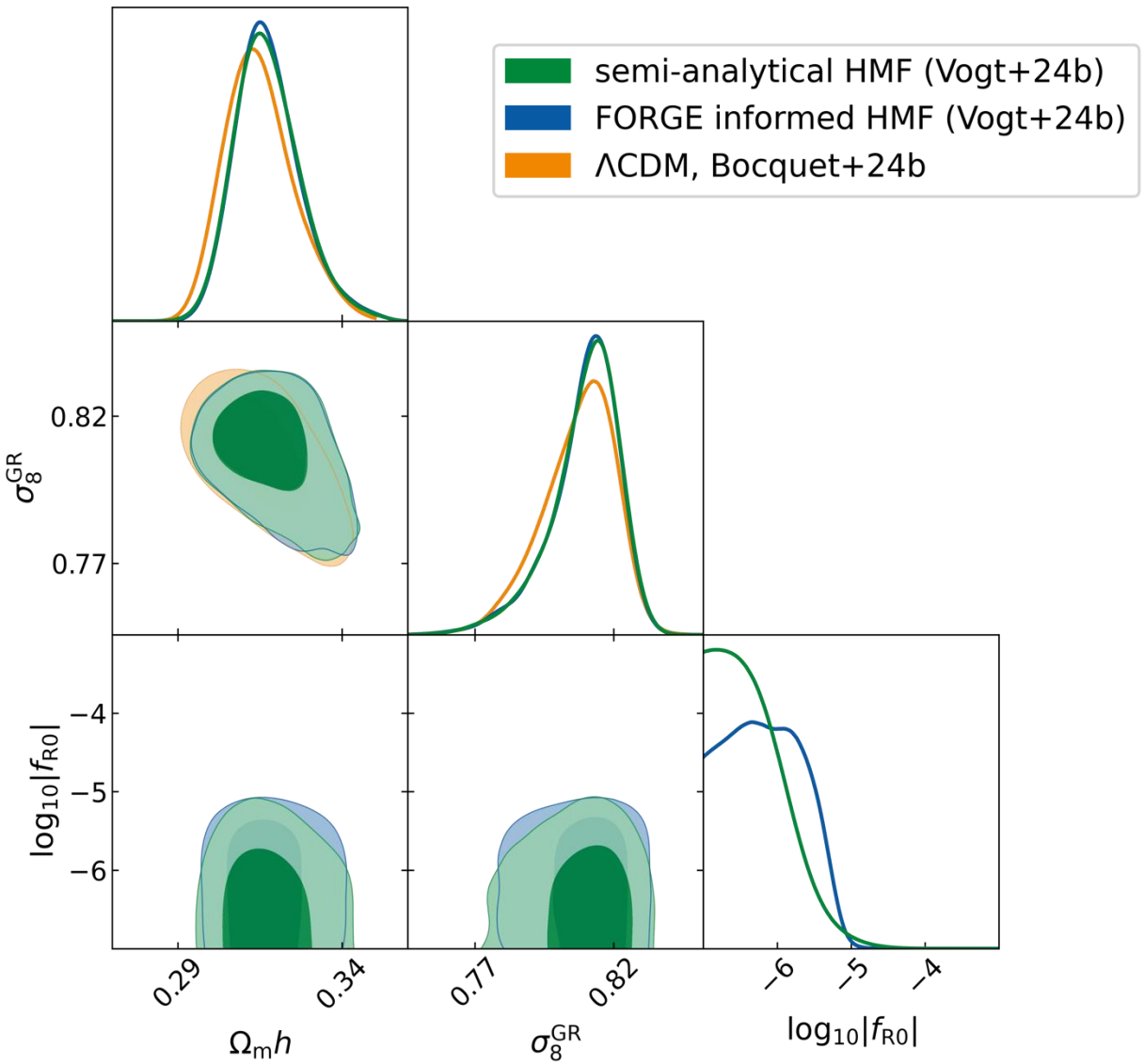

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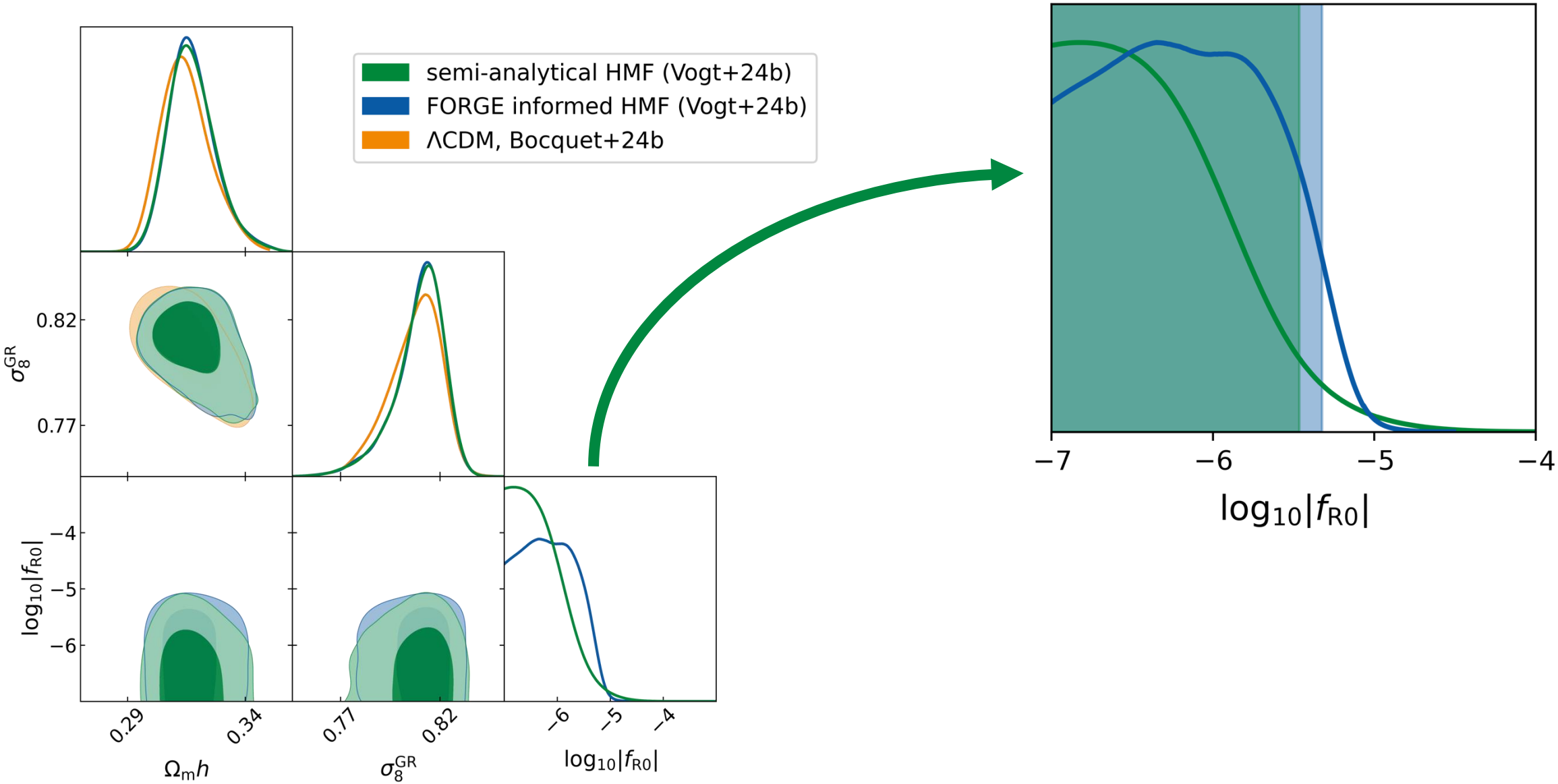

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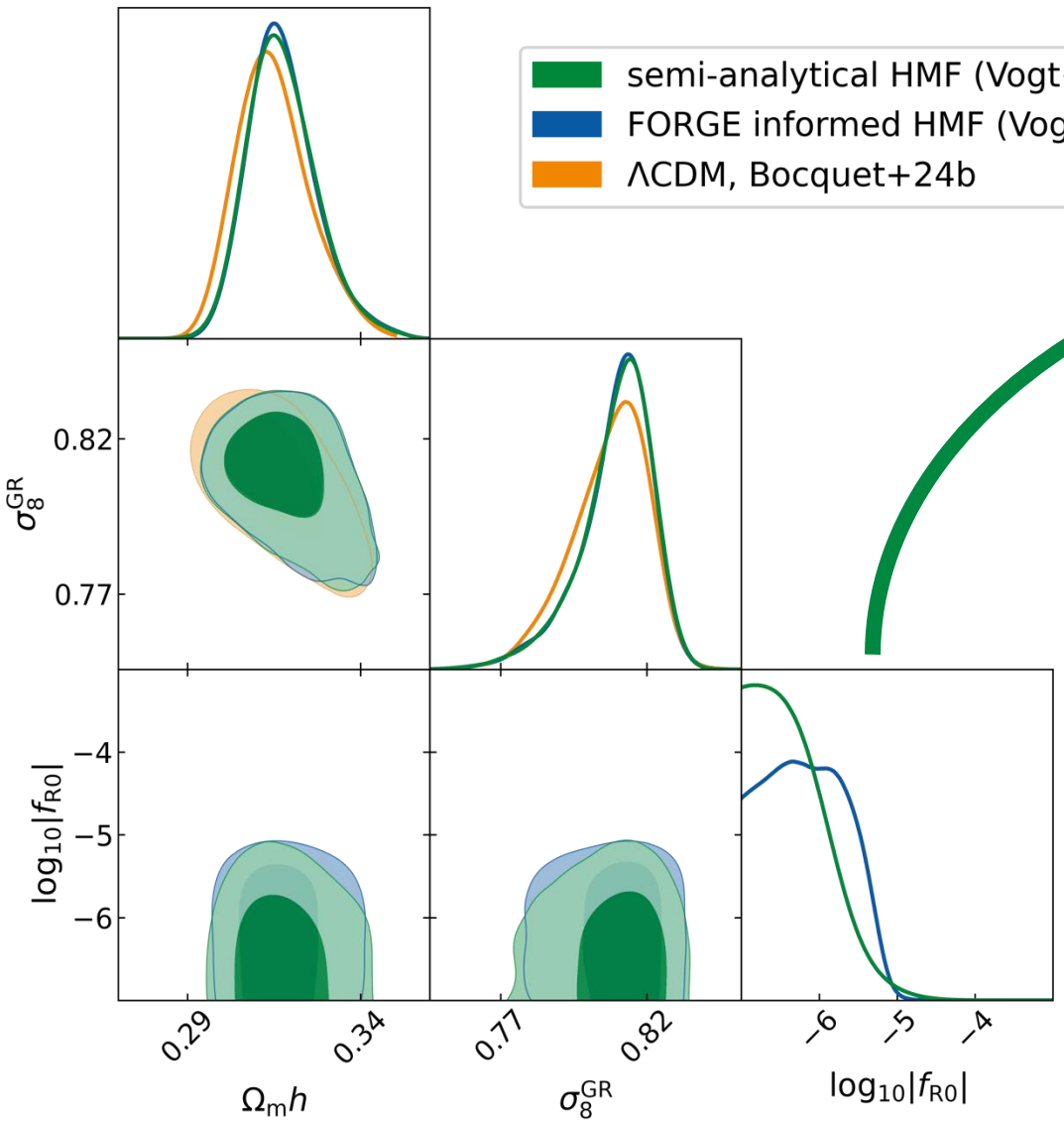

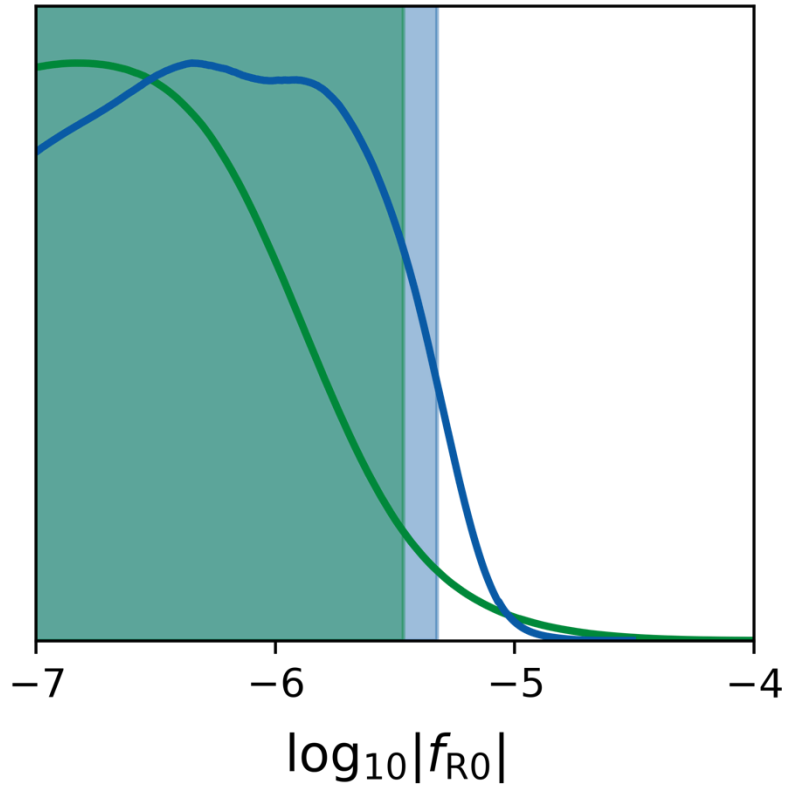

95% upper bound constraints

Semi-analytical HMF: $\log_{10}|f_{R0}| < -5.46$

FORGE informed HMF: $\log_{10}|f_{R0}| < -5.32$

Comparison to Other Results

SPTclusters+CMB (FORGE informed HMF)

SPTclusters+CMB (semi-analytical HMF)

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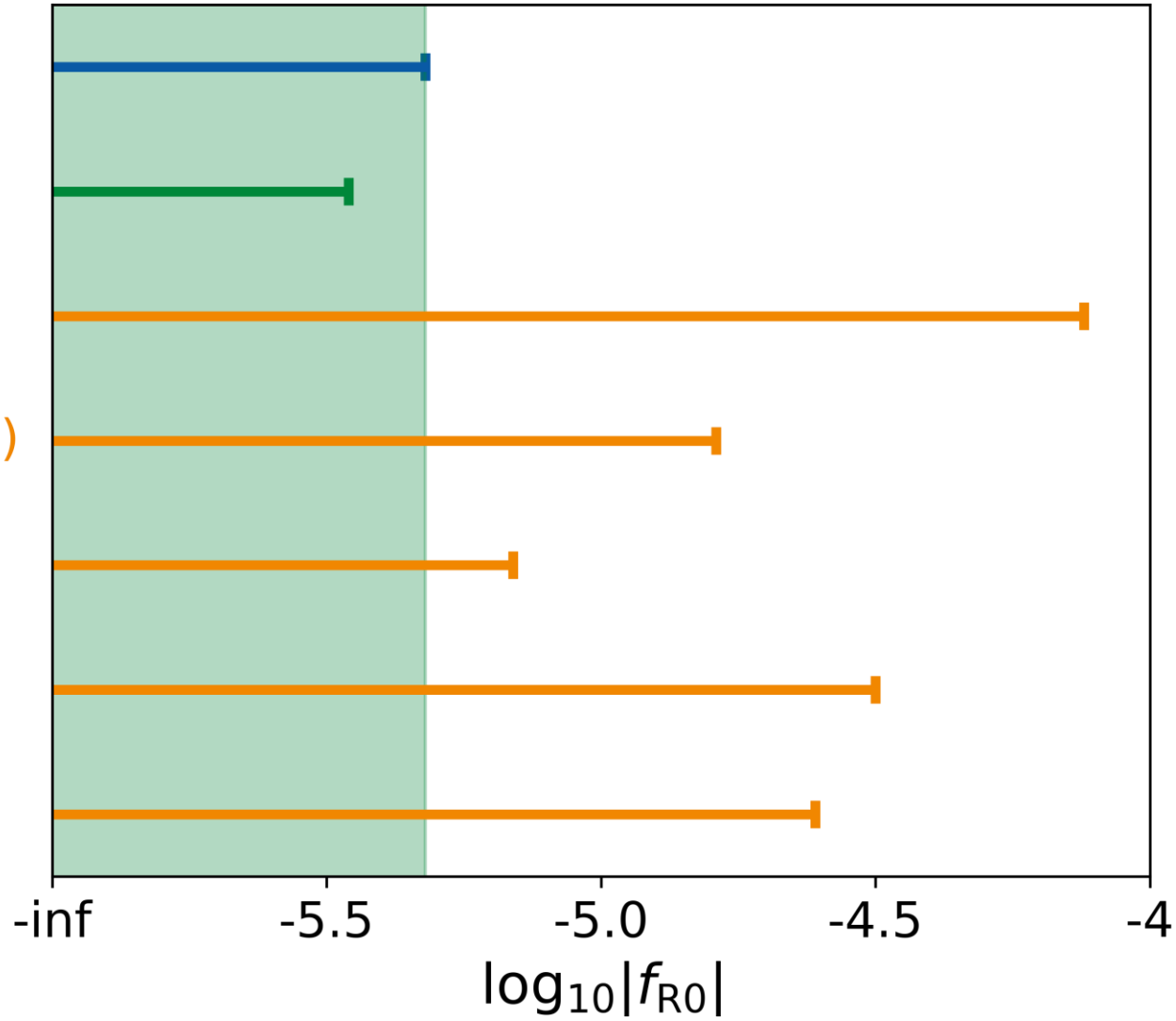

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- Same area: ~5,000 deg^2
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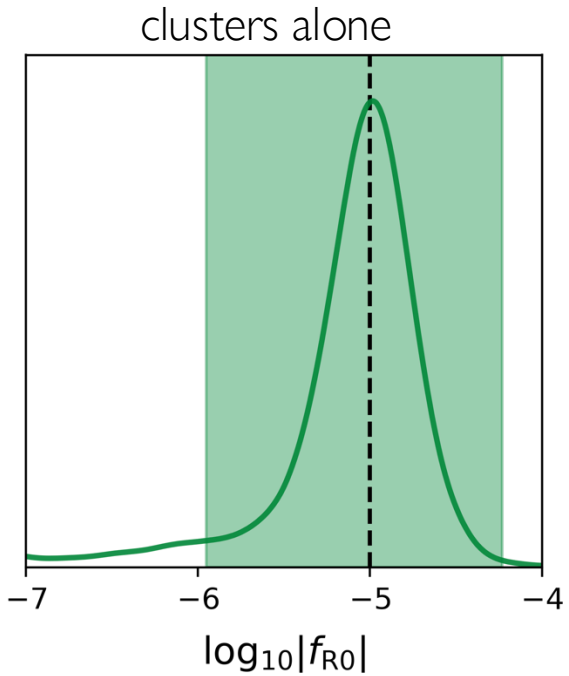

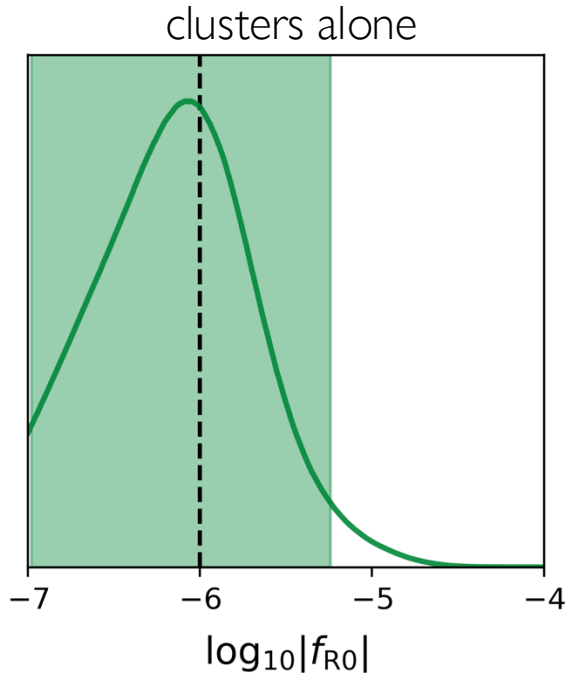

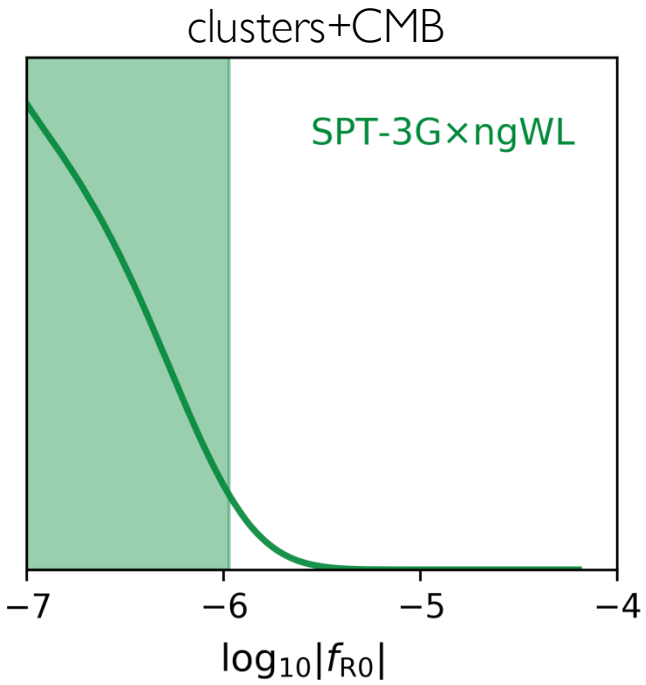

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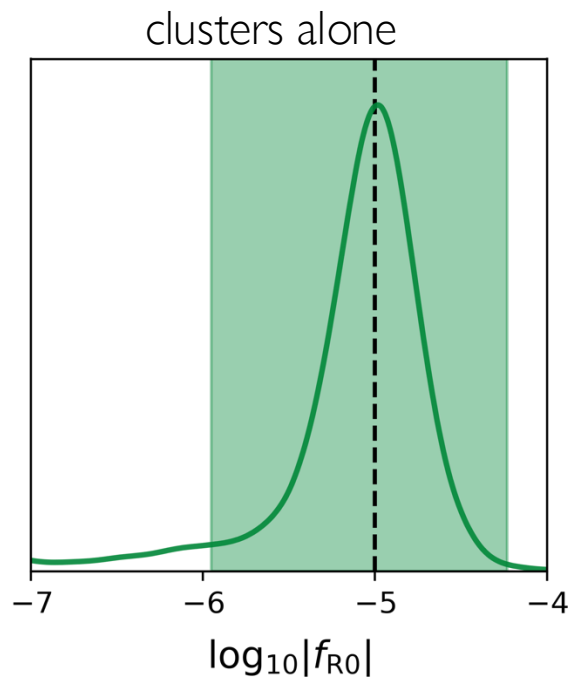

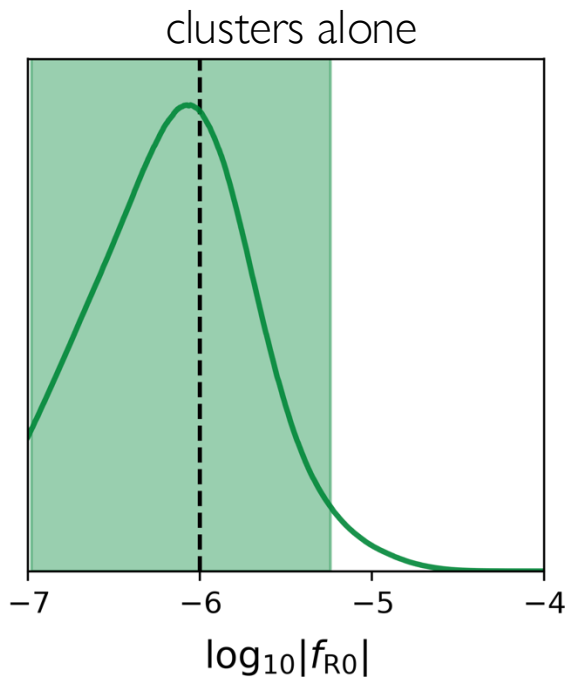

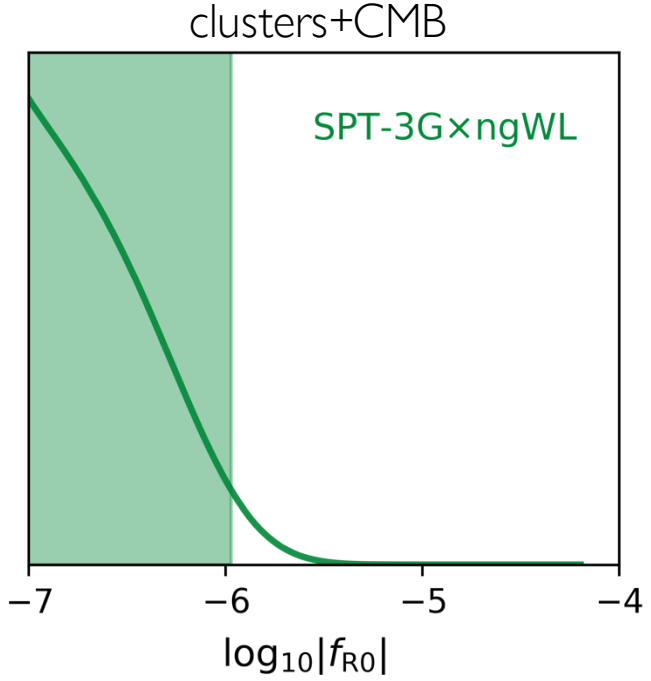

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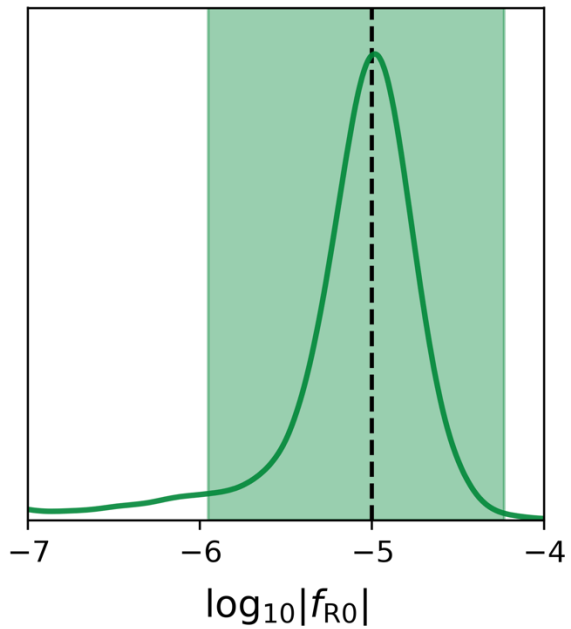
- Expect ~32,000 clusters (~10,000 deg^2)
- Broader redshift range: 0.1 < z < 2

clusters alone



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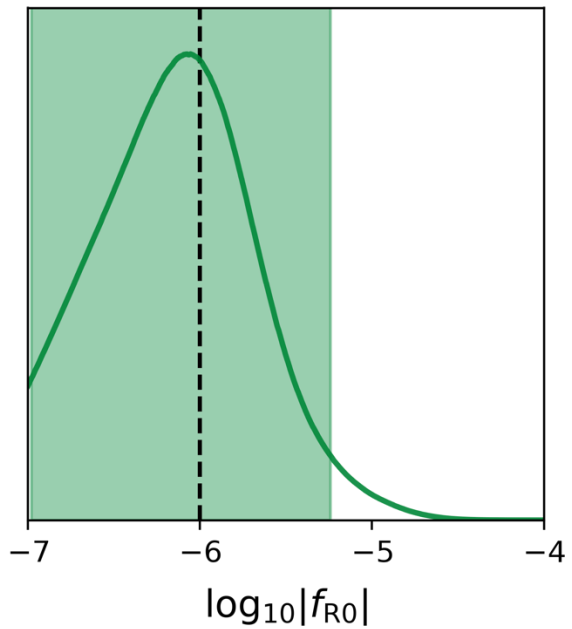
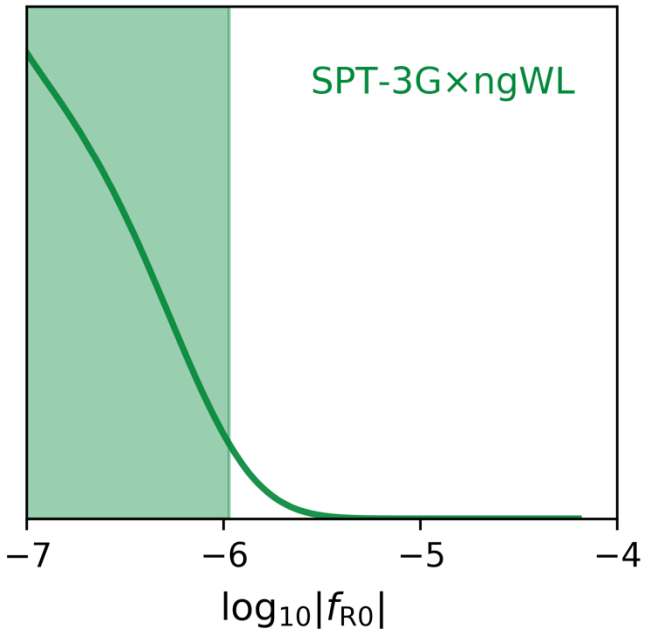


clusters+CMB



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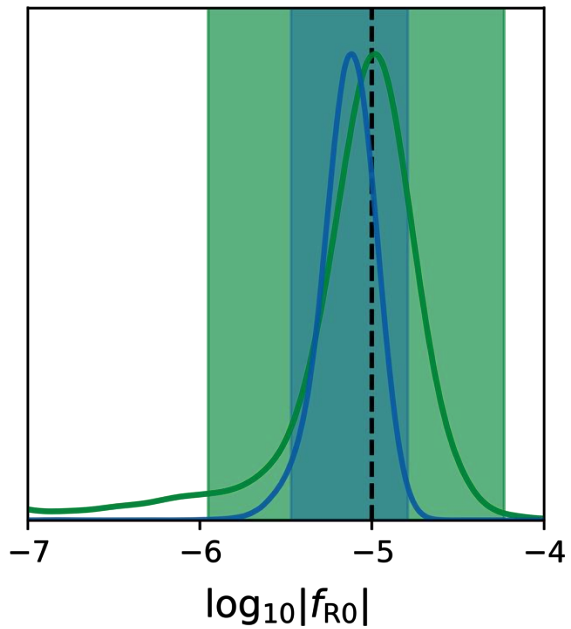

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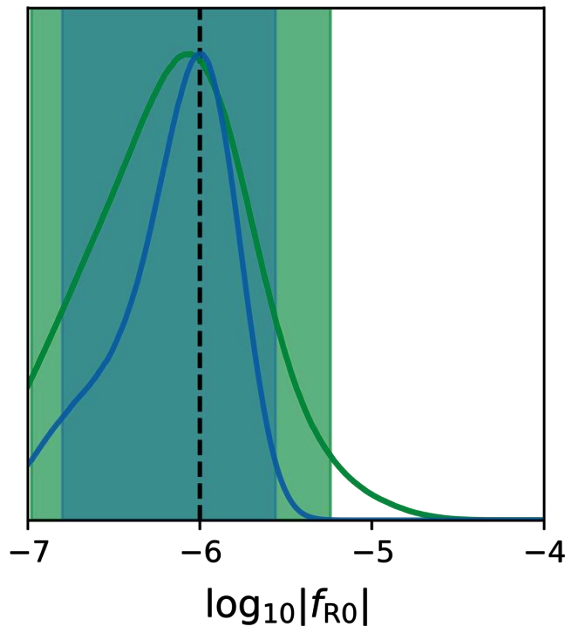

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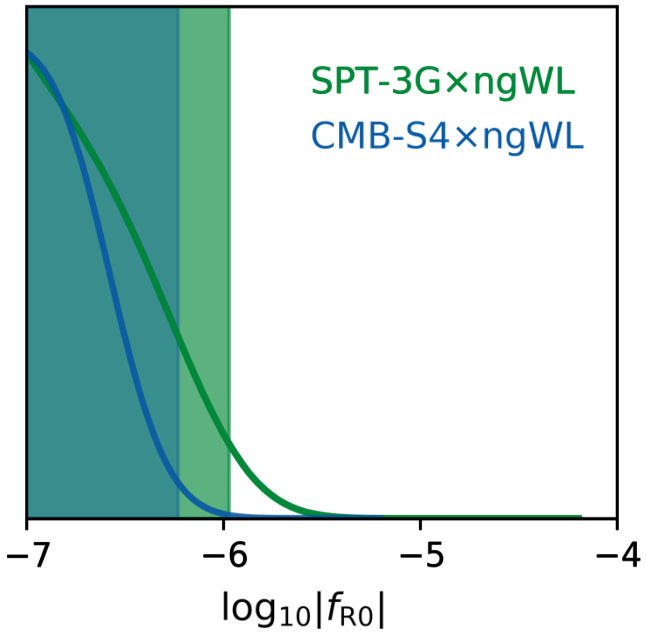

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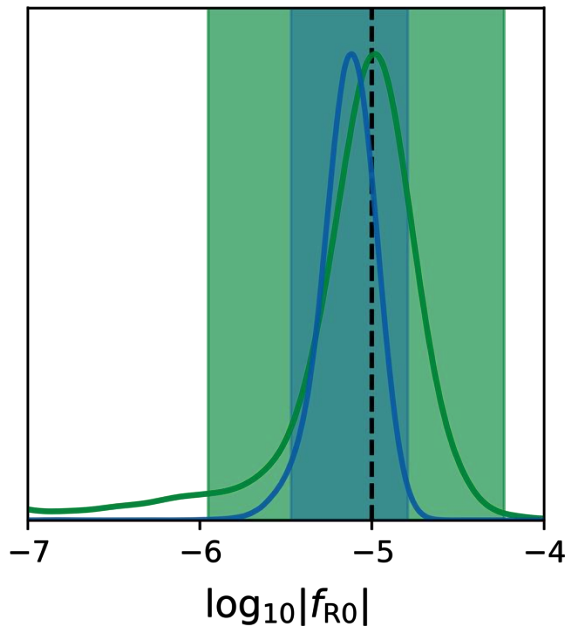

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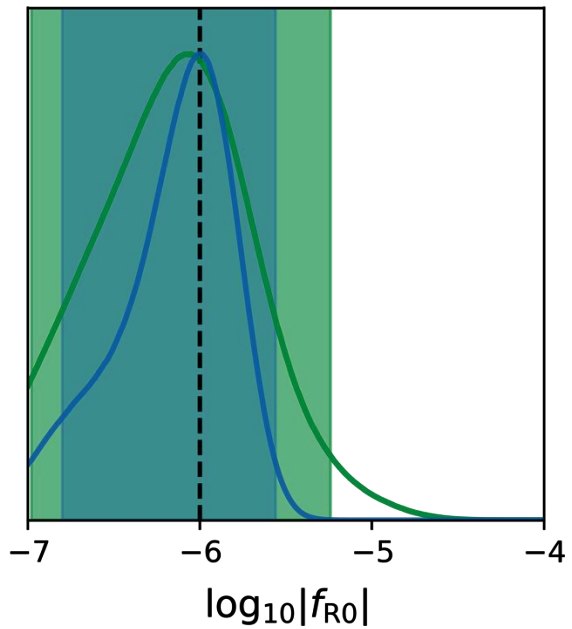

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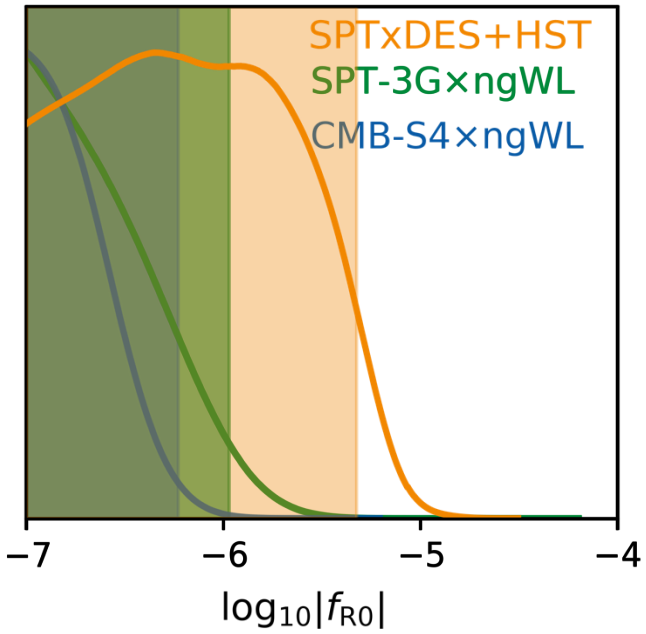

What else can we do with SPT clusters?

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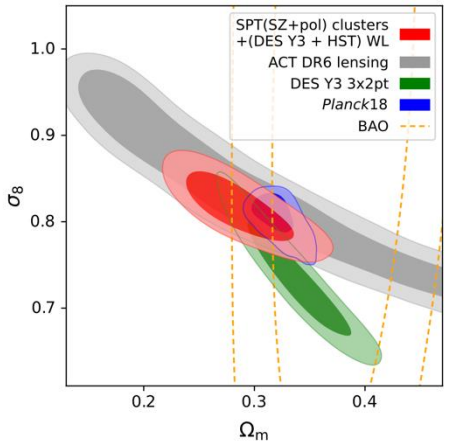
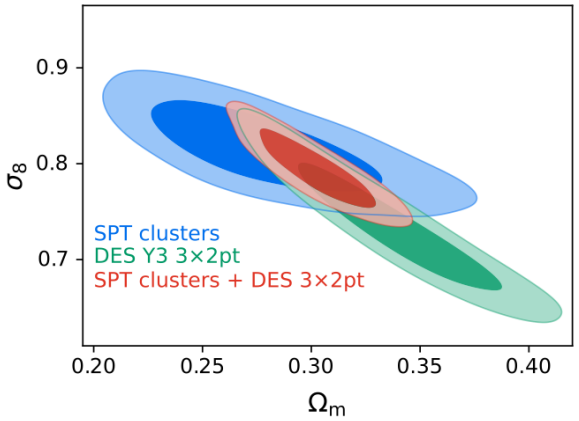
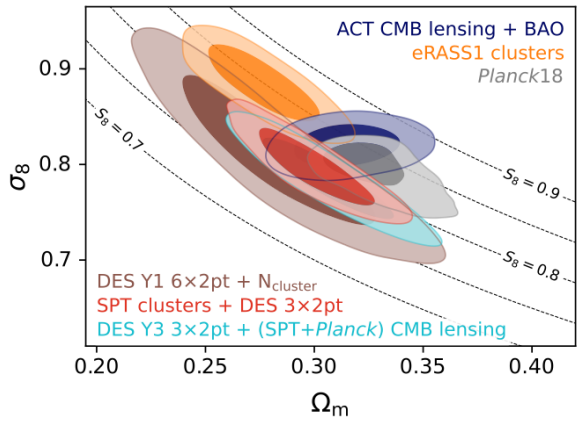
ΛCDM, wCDM, $\nu\Lambda$CDM (Sebastian Bocquet)

- Key cosmological project (Bocquxet+24b)



- Combination with DES 3x2pt (Bocquet+24c)





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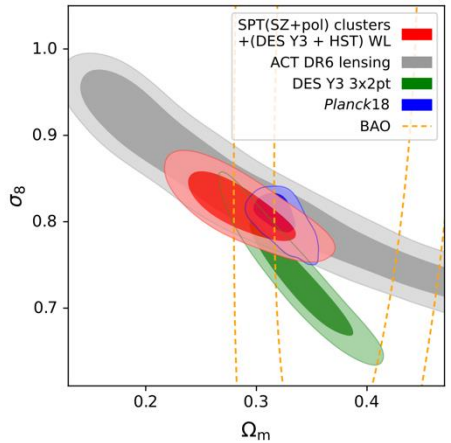

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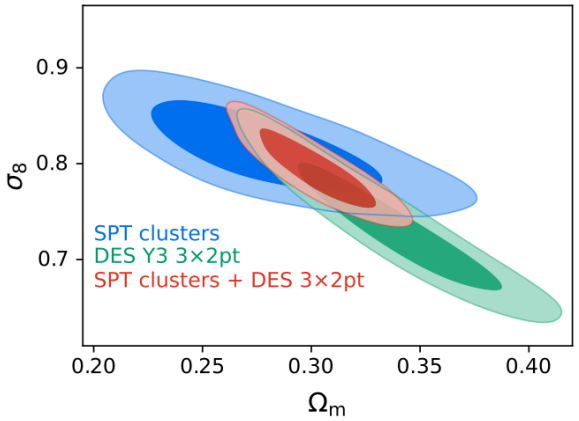
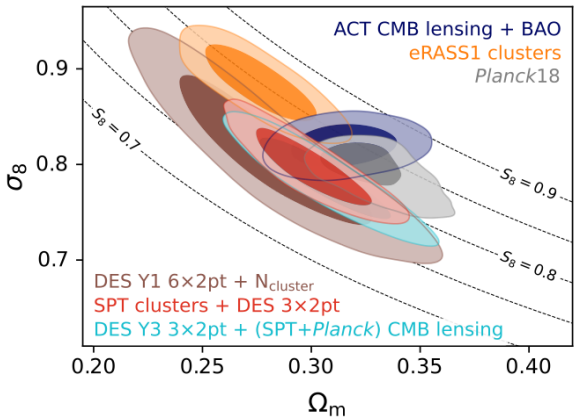
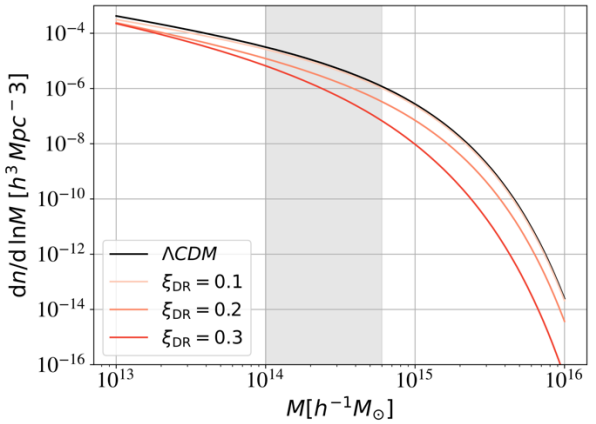
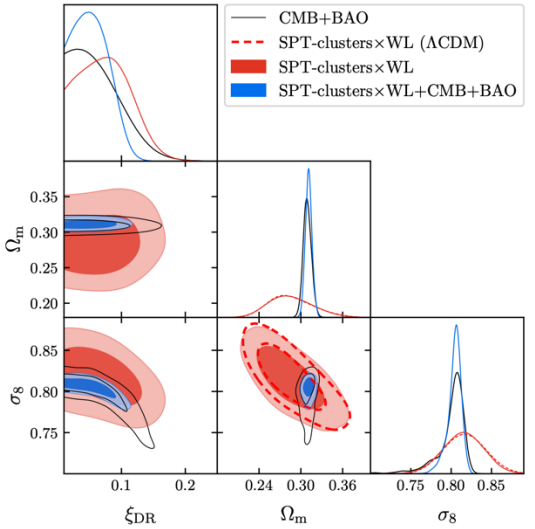




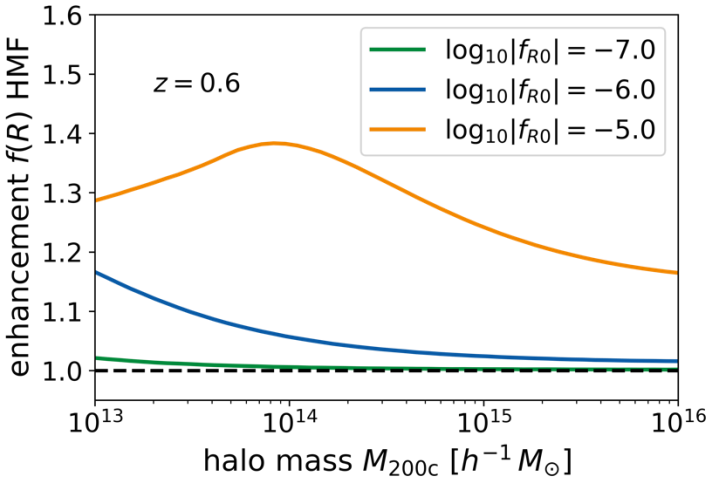
Interacting Dark Matter (Asmaa Mazoun)

- Beyond CDM model with self-interacting DM component
- Mazoun+24 (arXiv:2411.19911)





$f(R)$-gravity: scale dependent growth



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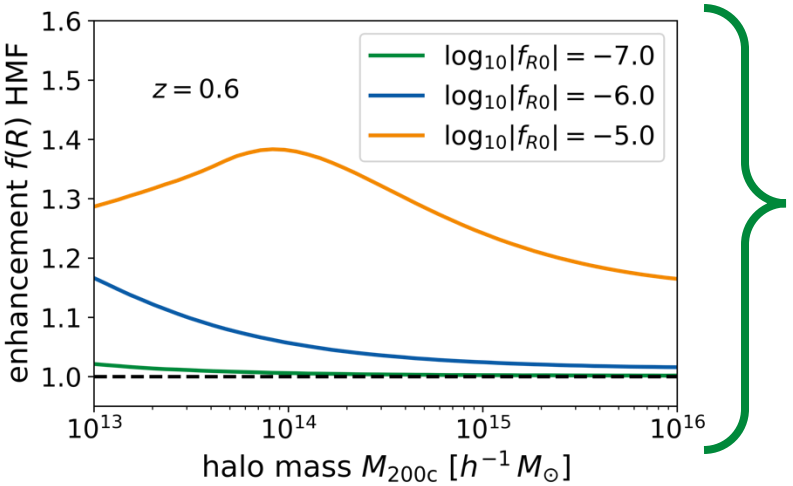
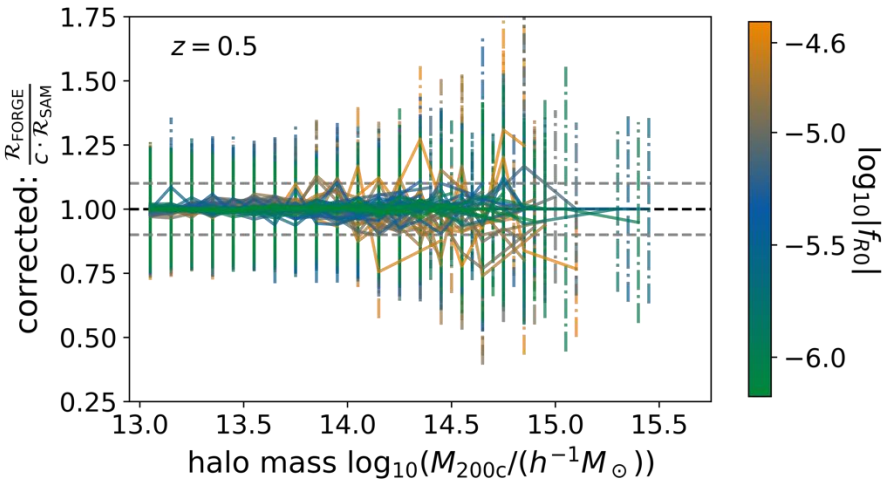


HMF calibrated to FORGE simulations



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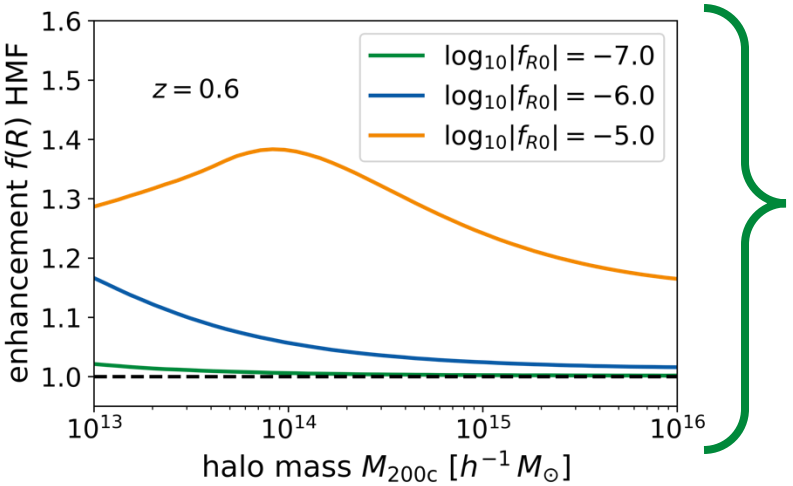

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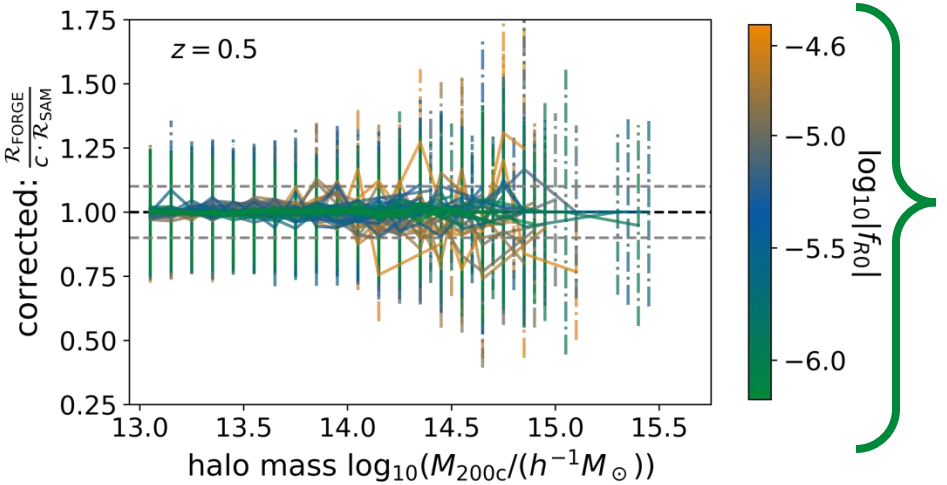

Apply to SPT clusters with DES/HST WL

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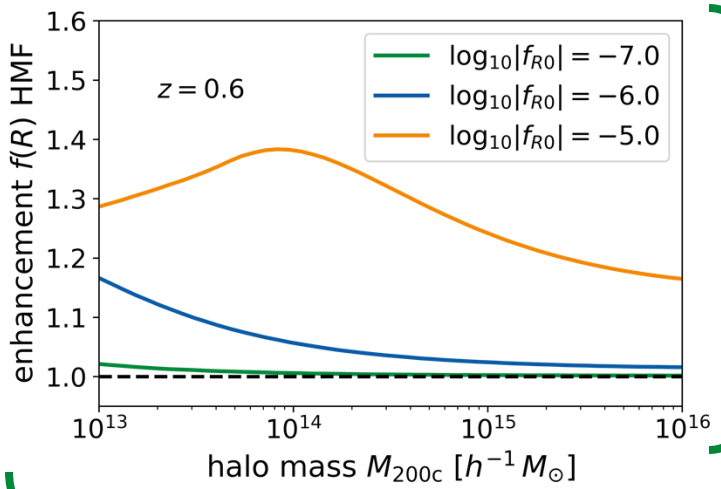

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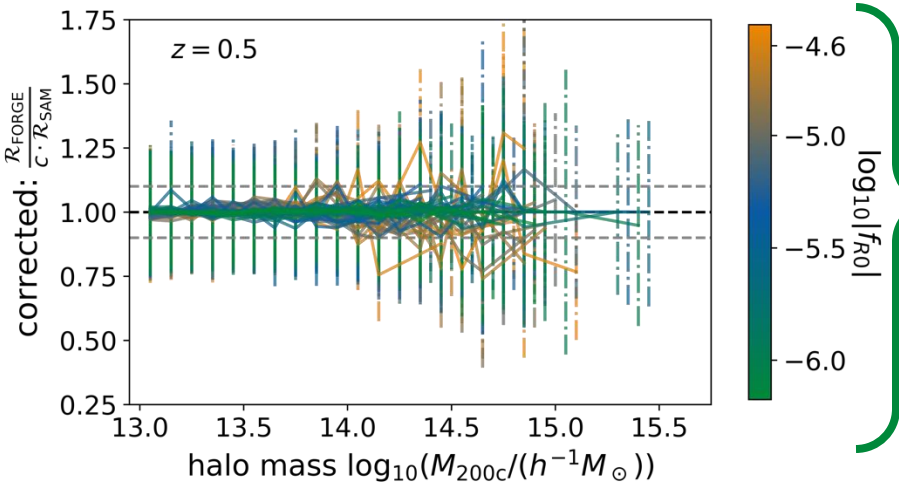

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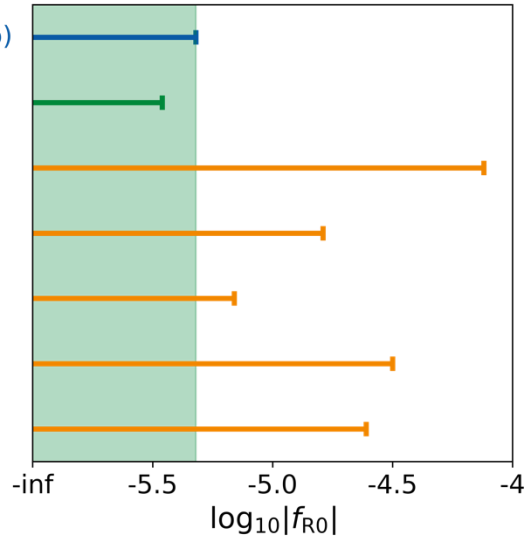

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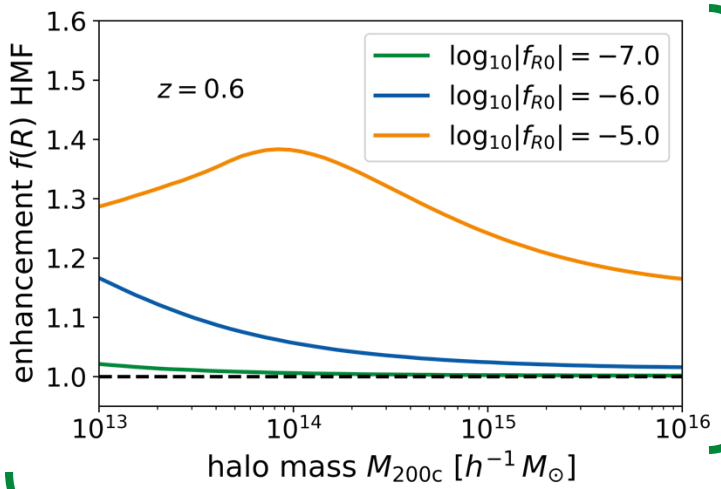

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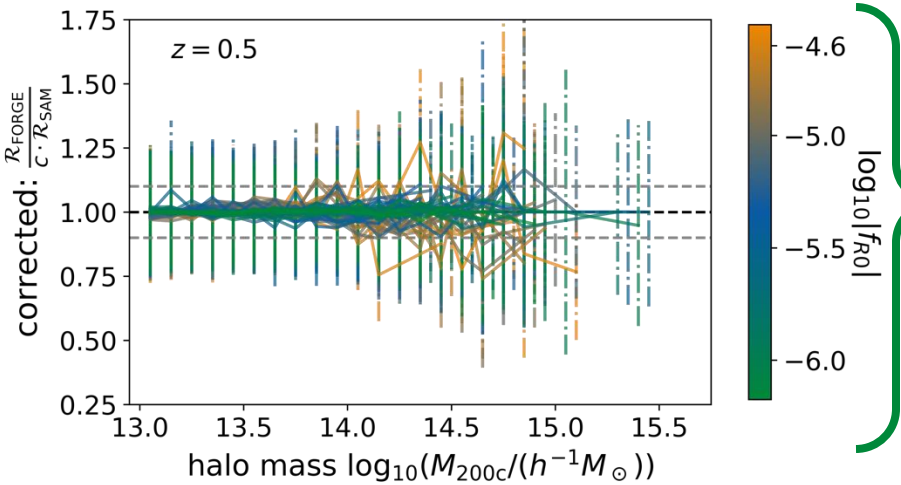

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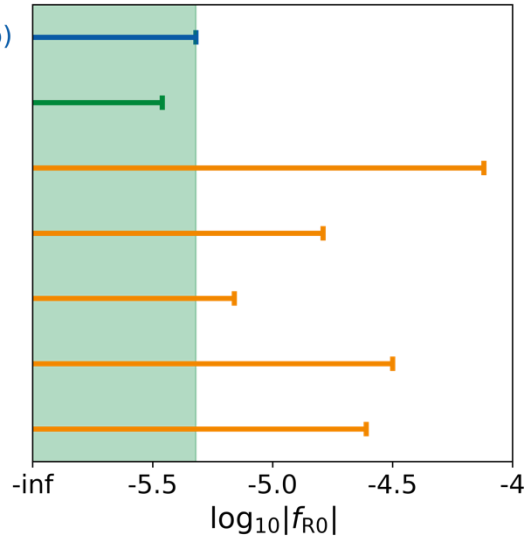

Future work: Apply this to nDGP gravity