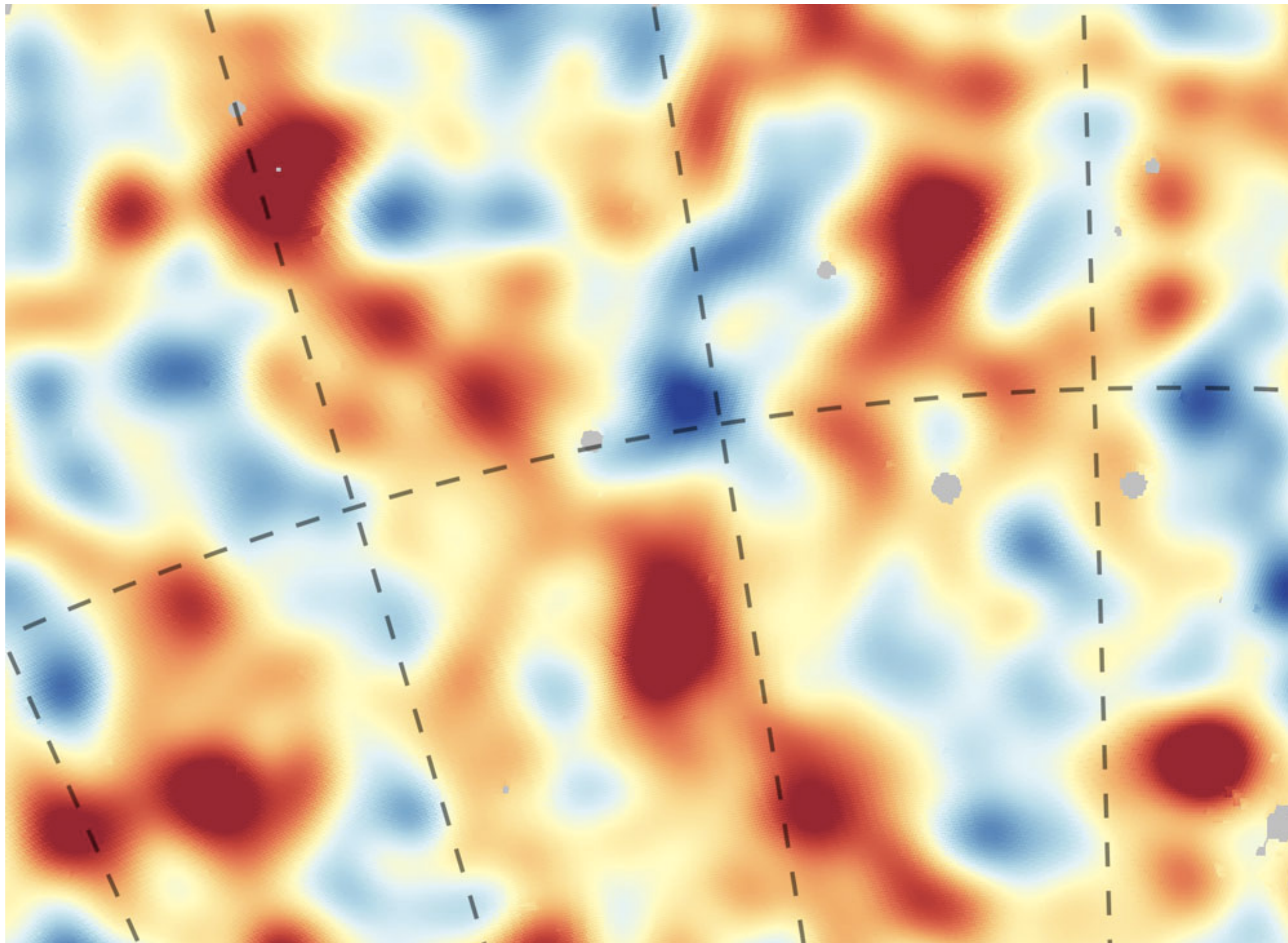
LSST Dark Matter Workshop Aug 5, 2019

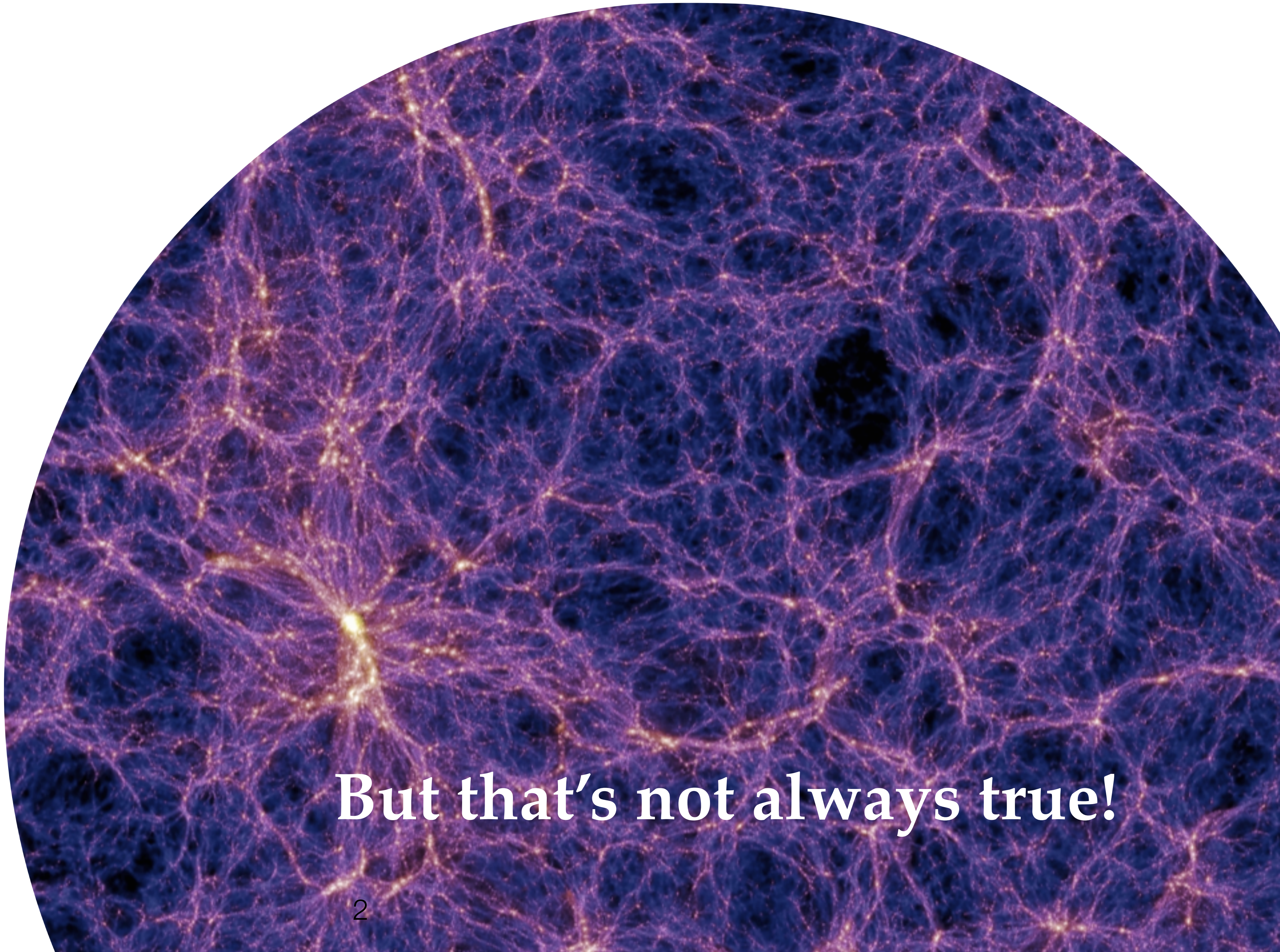
Weak Lensing as a Tool for Dark Matter Physics

Chihway Chang (UChicago)

with the DES & LSST DESC Collaborations

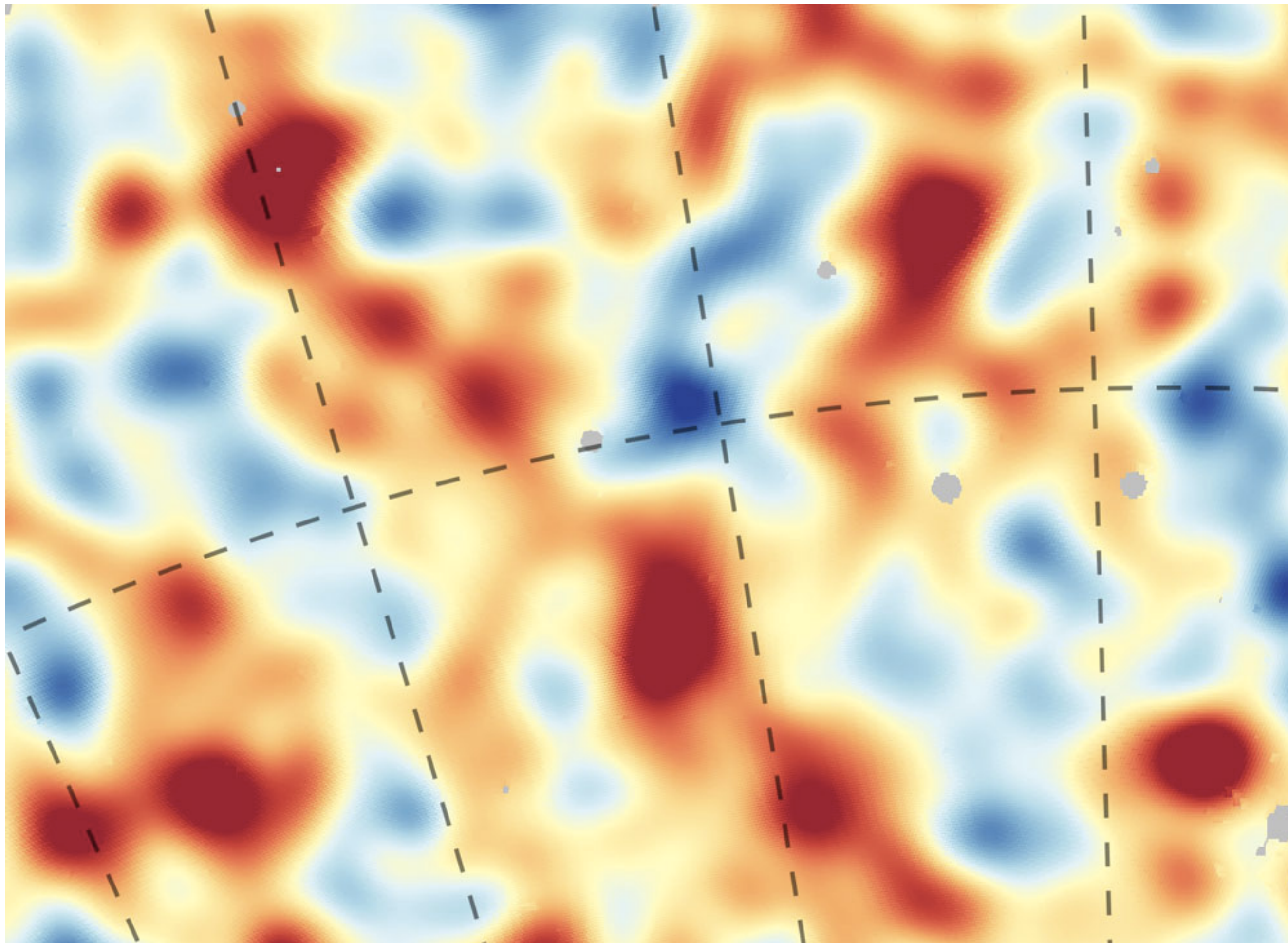


In Weak Lensing (WL), we typically care about **WHERE** Dark Matter is, not **WHAT** it is…

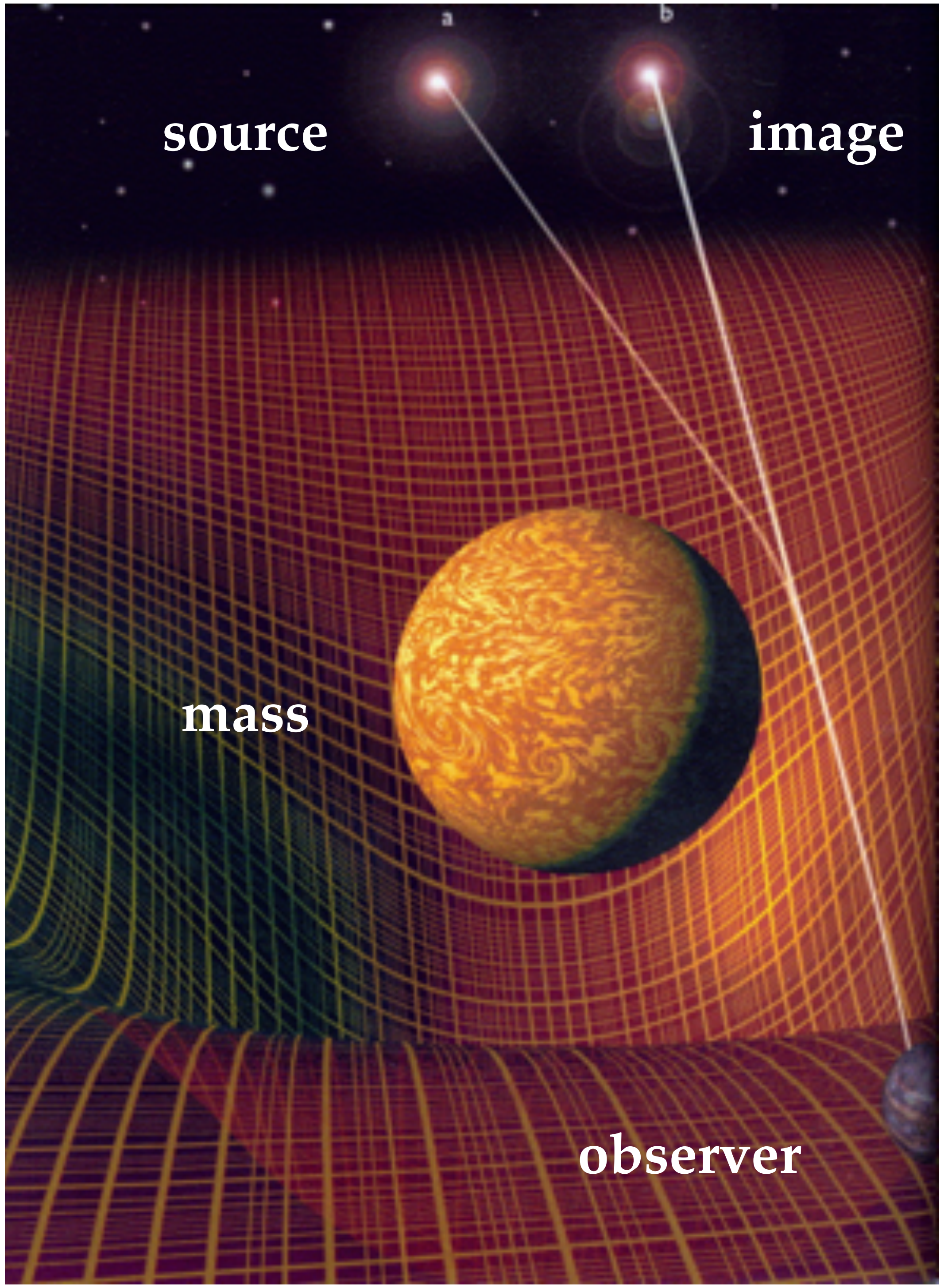


Outline

- WL and state-of-the-art (DES-centric)
- WL applications for Dark Matter physics:
  - Mass maps
  - Towards the smallest halos
  - Cluster profiles



Gravitational Lensing



According to **GR**, light is bent when traveling through spacetime perturbed by **mass** distributions.

$$\text{deflection} \propto \frac{GM}{c^2 b} \frac{D_{LS}}{D_S}$$

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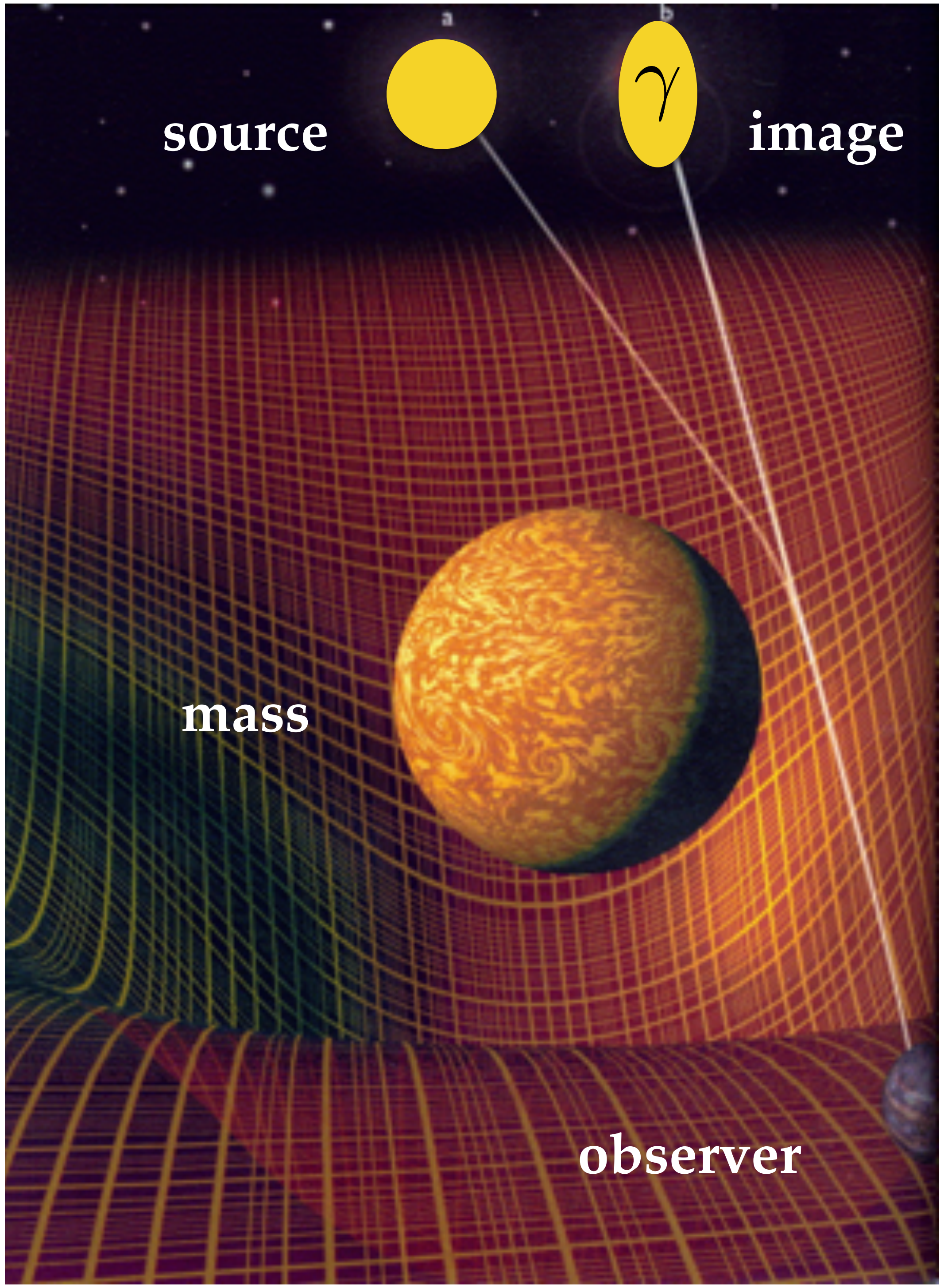

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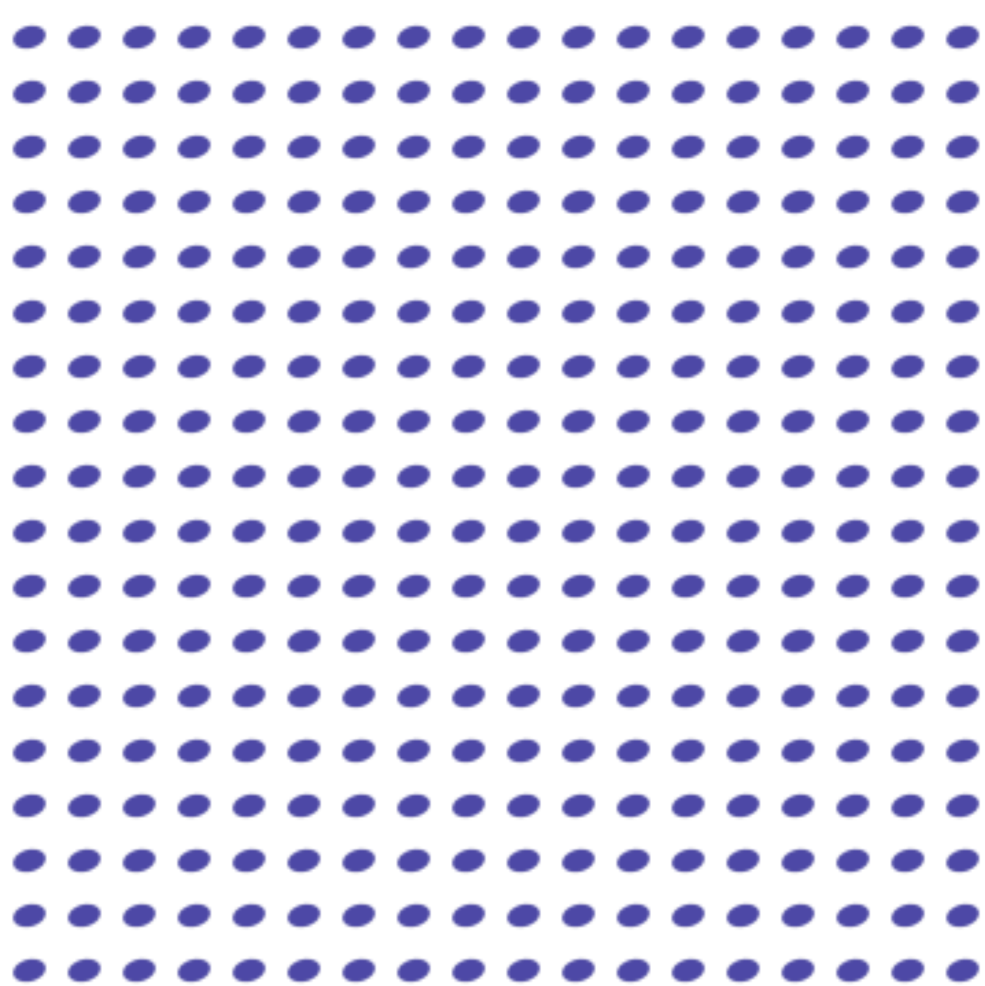
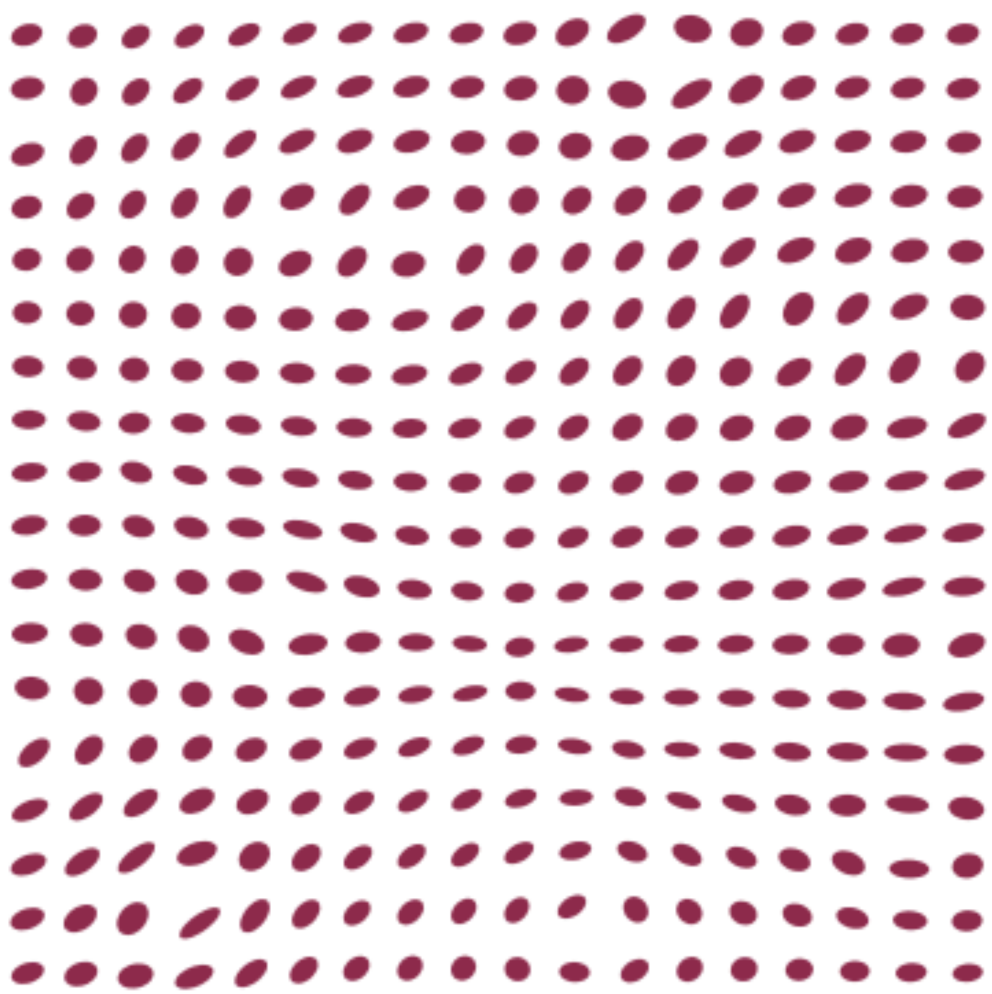
Weak Lensing

Weak lensing is the lensing from the **large-scale structure**, and refers to the regime where you need to **statistically** extract the lensing signal from **averaging** over a very large number of galaxies.



Unlensed sources



Weak lensing

Weak Lensing Formalism

Lensing potential	$\psi(\boldsymbol{\theta}, r) = 2\int_0^r \mathrm{d}r' \frac{r - r'}{rr'} \Phi(\boldsymbol{\theta}, r')$
Deflection	$\alpha = \nabla\psi$
Convergence	$\kappa = \frac{1}{2}\nabla^2\psi = \frac{1}{2}(\psi_{,11} + \psi_{,22})$
Shear	$\gamma = \gamma_1 + i\gamma_2 = \frac{1}{2}\left(\psi_{,11} - \psi_{,22}\right) + i\psi_{,12}$

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"mass" (spin-0) ← Convergence

observable: distortion of galaxy shapes (spin-2) ← Shear

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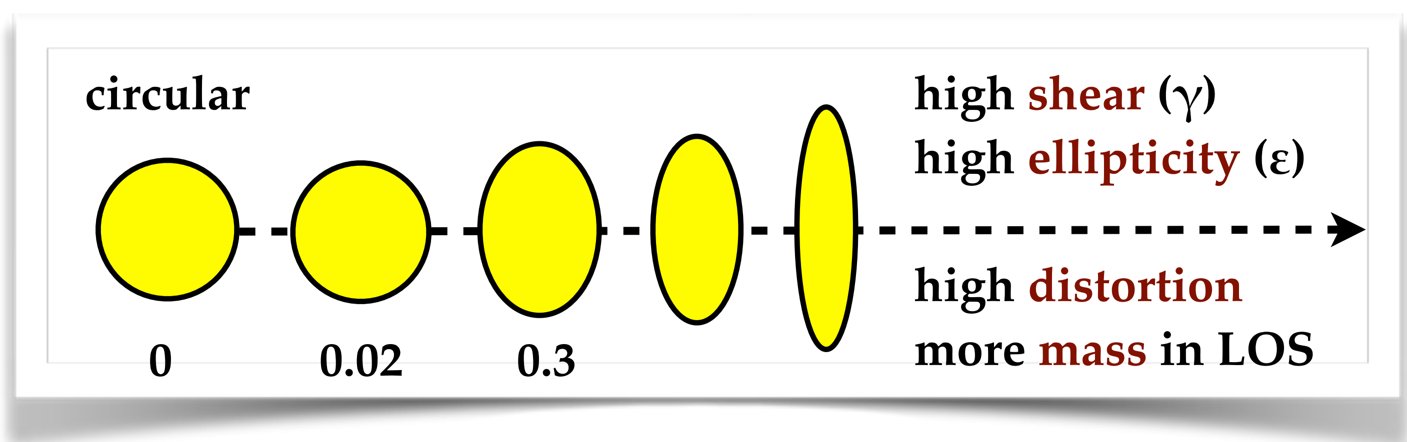
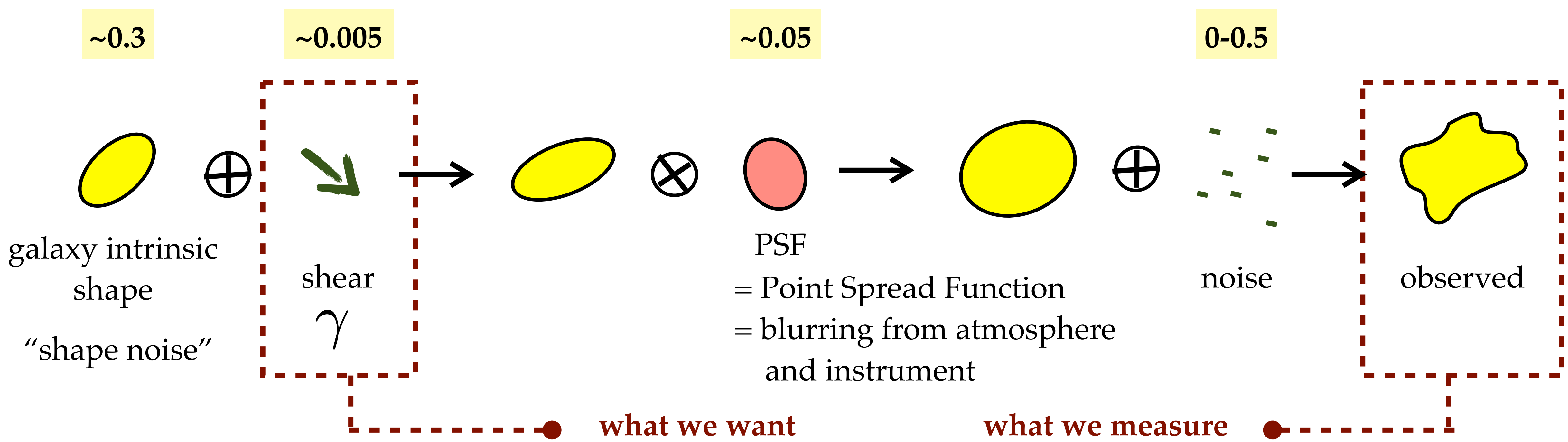


Weak Lensing is Challenging



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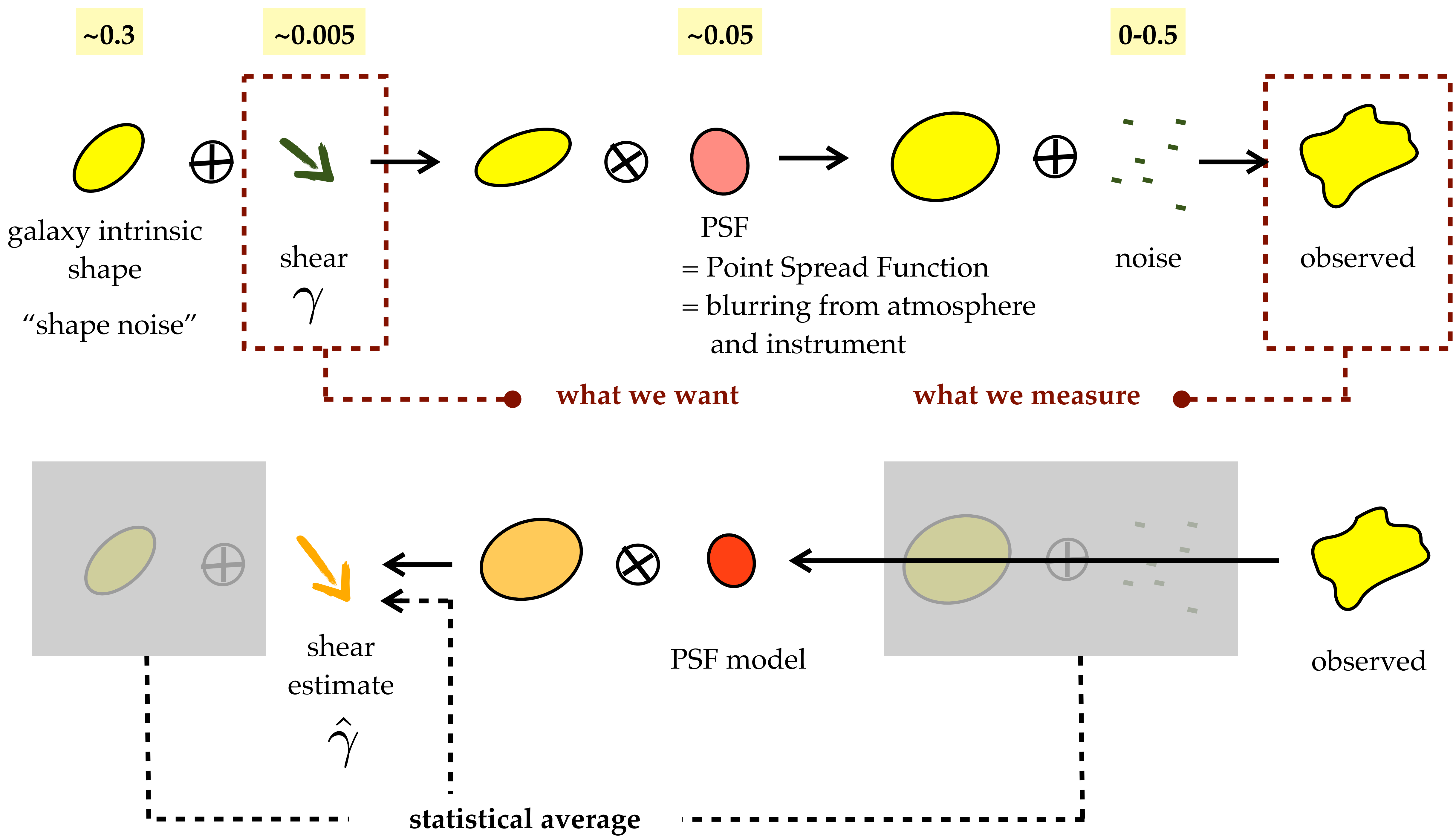

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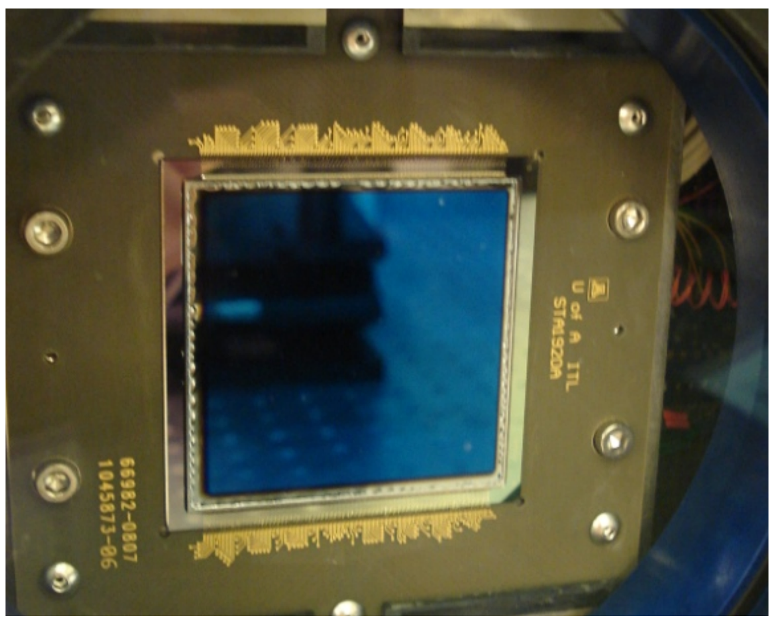
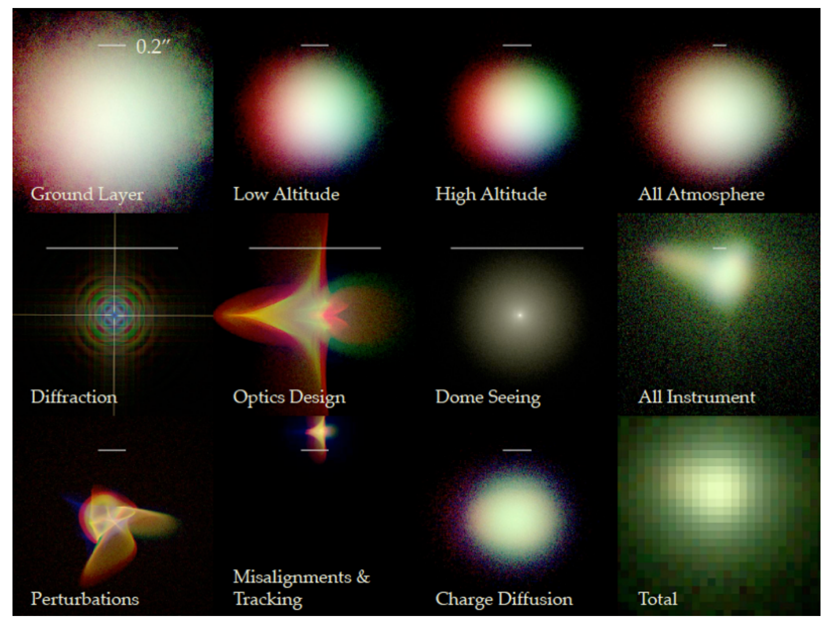
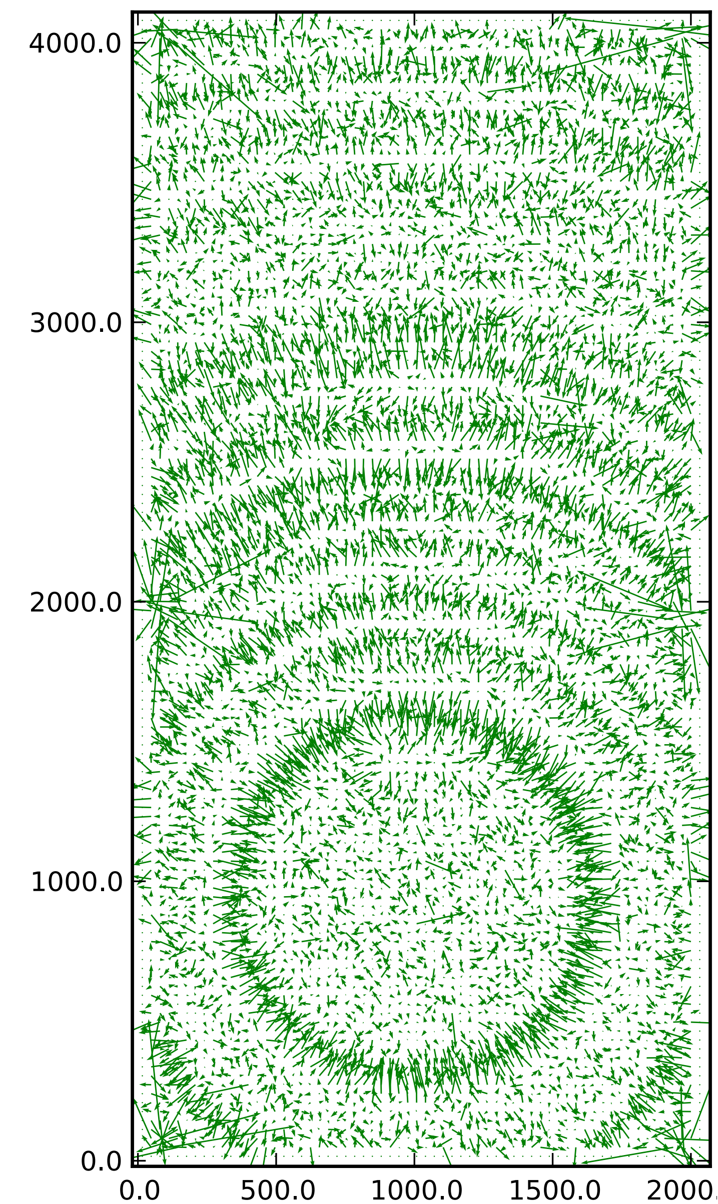


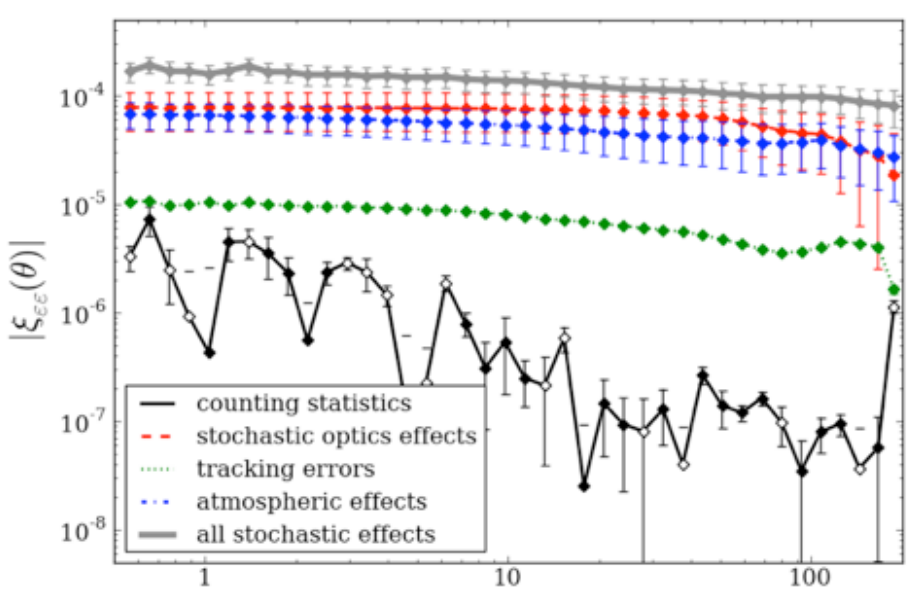
study-type LSST CCDs



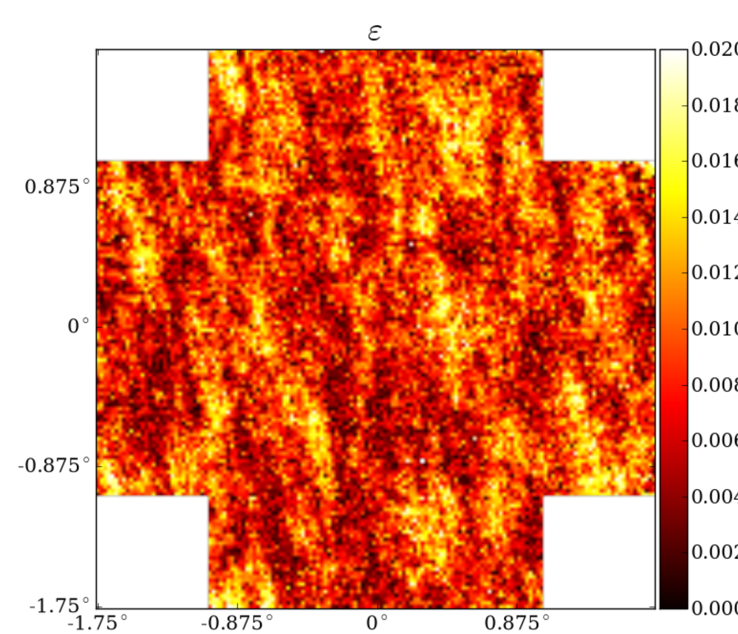
PhoSim: *Peterson et al. (2015)*

Plazas et al. (2014)



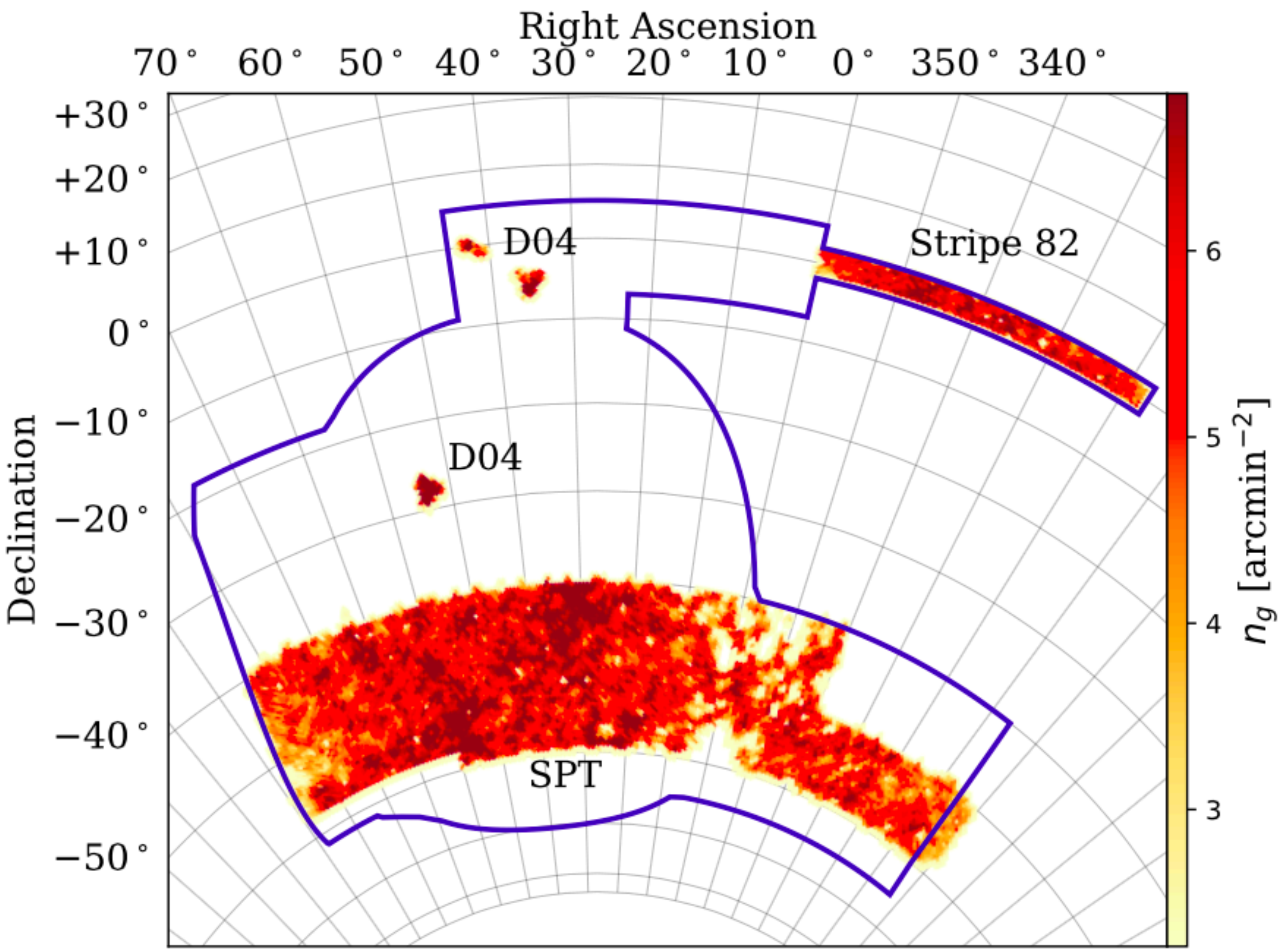


Chang et al. (2013)



Chang et al. (2012)

Weak Lensing State-of-the-Art



Zuntz et al. (2017)

- The Dark Energy Survey (DES) Y1 data
- **30 M** galaxies with accurate shape measurements @ m~2%
- Two independent shear catalogs
- **Metacalibration** (Sheldon & Huff, 2017): innovative shape measurement algorithm

DES Y3, coming soon, 100 M WL galaxies over 5000 sq. degree…

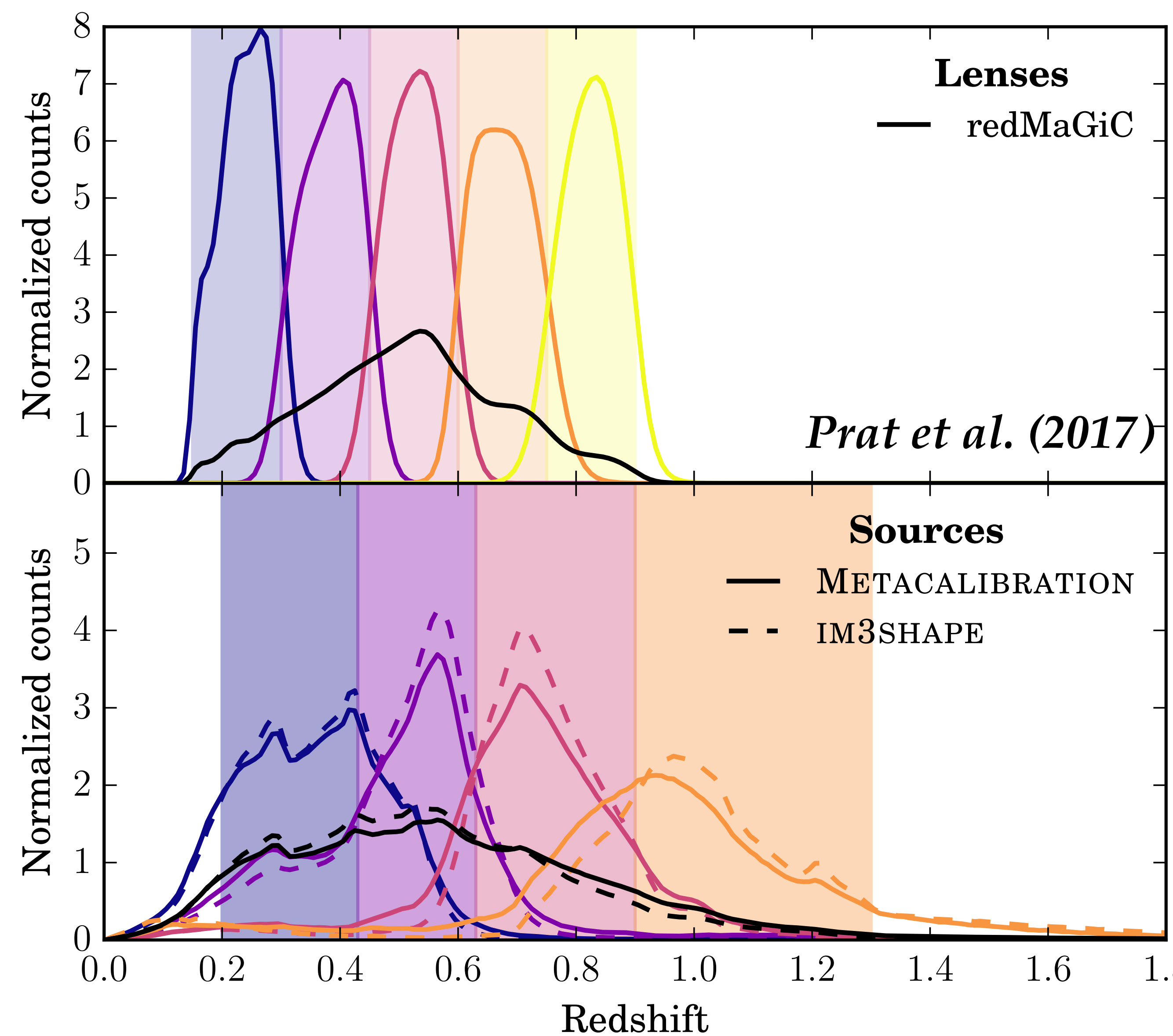
Weak Lensing State-of-the-Art

DES Y1: **clustering redshfit, COSMOS**

- Photometric redshift (photo-z) is an inseparable part of the WL story. Recall

$$\text{deflection} \propto \frac{GM}{c^2 b}\frac{D_{LS}}{D_S}$$

- **Calibration** and **validation** methods for the photo-z's is ongoing a lot of development these days



DES Y3: **Self-Organizing Map (SOM)**

LSST DESC Weak Lensing

Shear Measurement

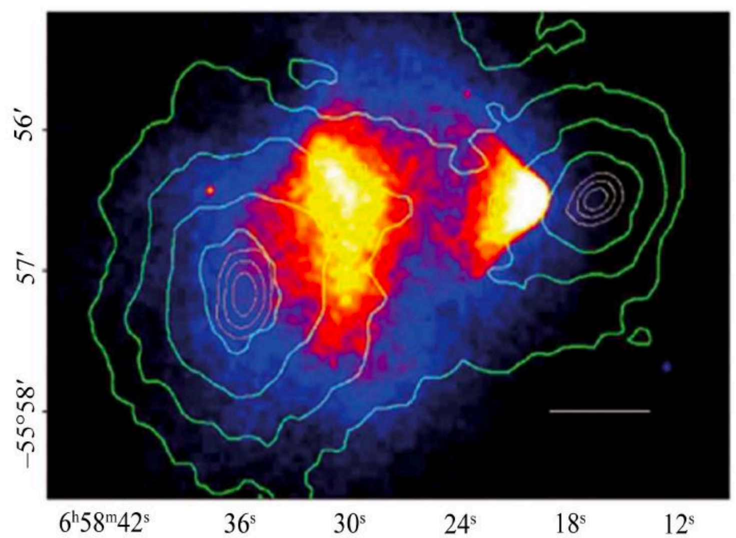
PSF Modeling

TXPipe (3x2pt)

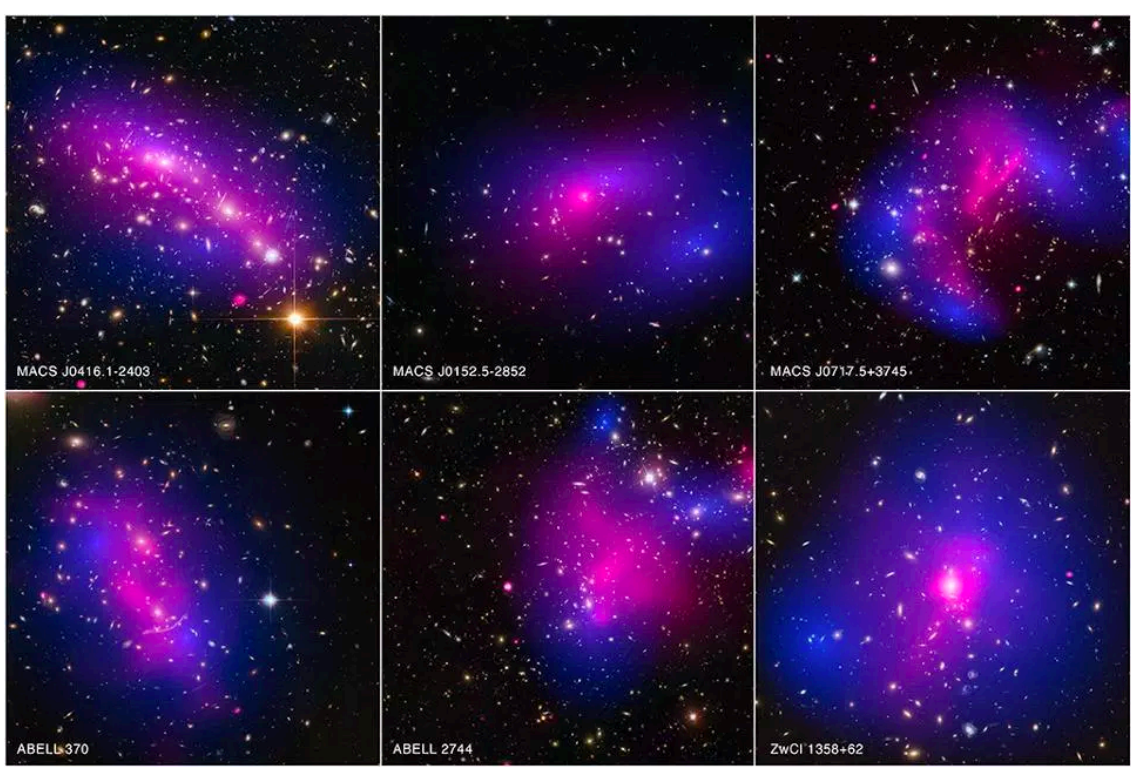
Mass Mapping and Higher Order Statistics

Blending

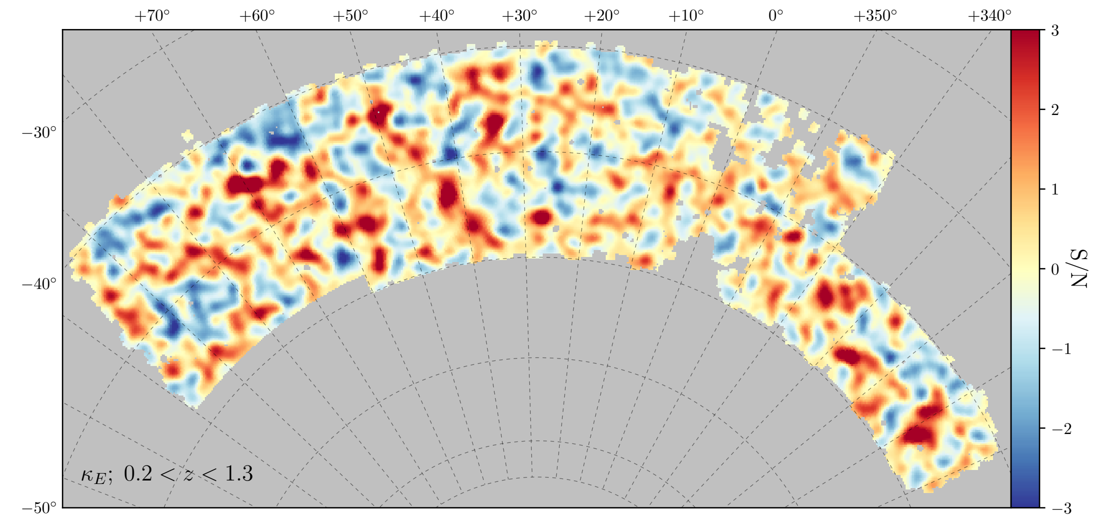
Mass Maps



Clowe et al. (2006)

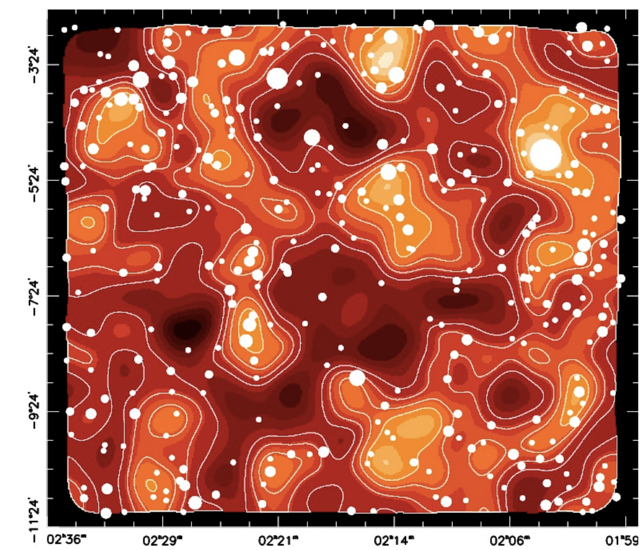


Harvy et al. (2015)

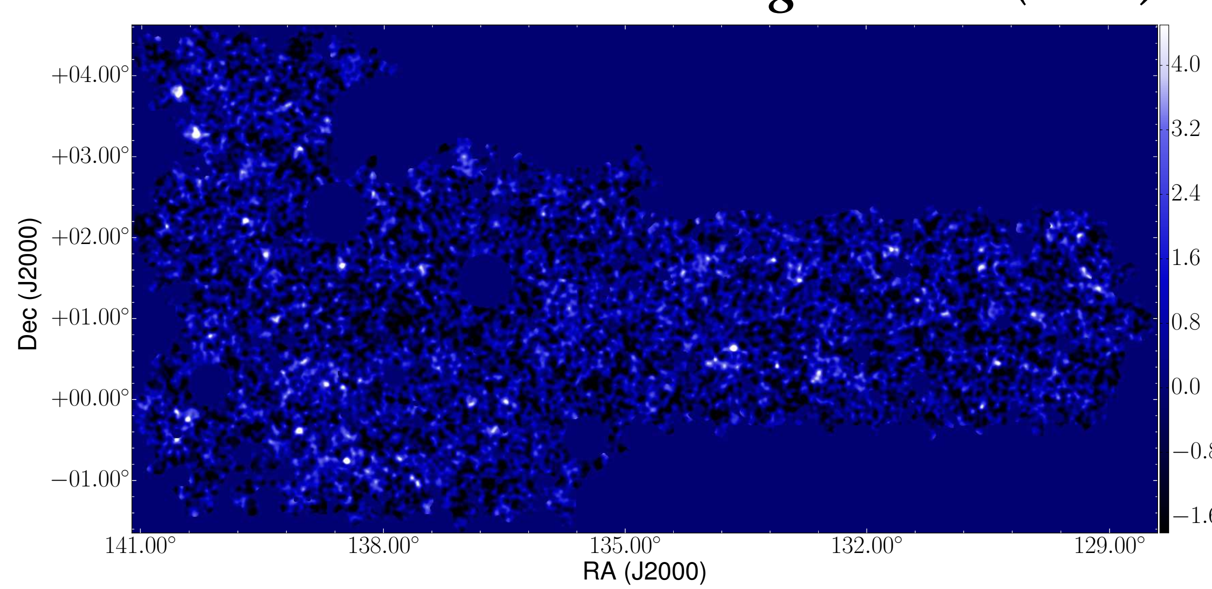


Chang et al. (2017a)

Van Waerbeke (2013)



Oguri et al. (2017)



Recall: Convergence vs. Shear

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The Kaiser-Squires (KS 1993) method:

$$\hat{\kappa}_{\boldsymbol{\ell}} = D^*_{\boldsymbol{\ell}}\hat{\gamma}_{\boldsymbol{\ell}} \qquad D_{\boldsymbol{\ell}} = \frac{\ell_1^2 - \ell_2^2 + 2i\ell_1\ell_2}{|\boldsymbol{\ell}|^2}$$

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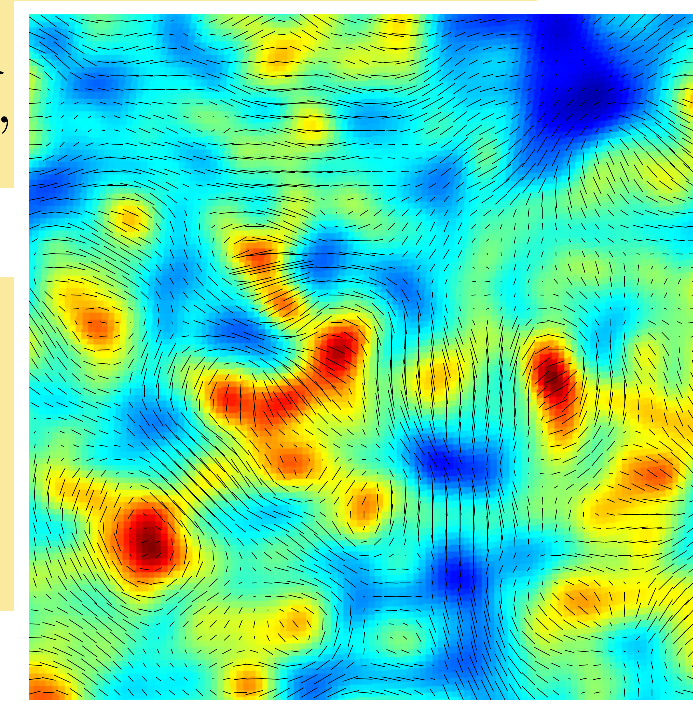

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Curl-free: signal

 $\hat{\kappa}_E + i\hat{\kappa}_B$ 

Divergent-free: noise

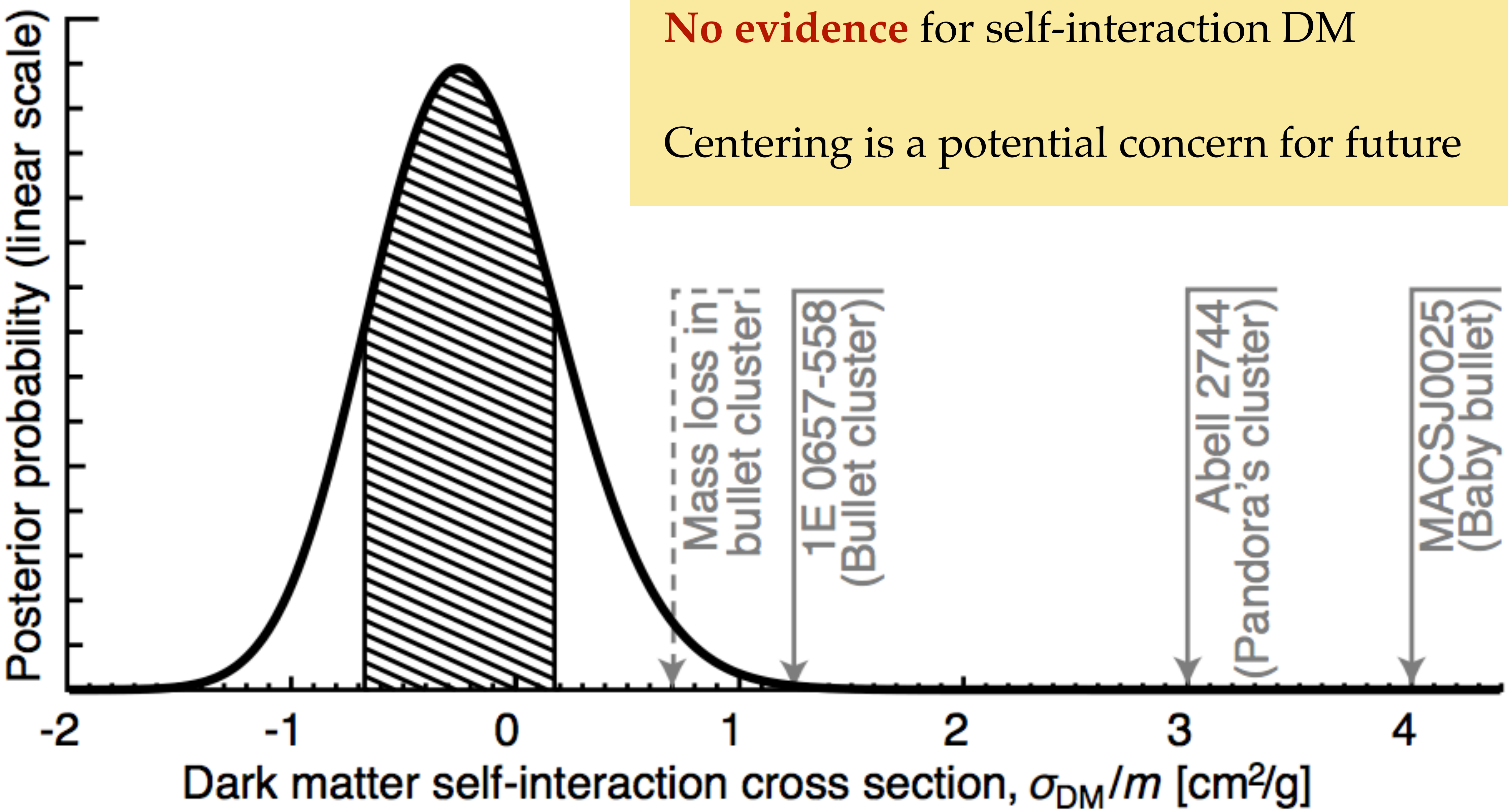
Bullet Clusters

Use distance between **stars (optical)** and **mass (WL)** for 72 systems to infer DM self-interaction cross-section

Detection of DM at **7.6 sigma**

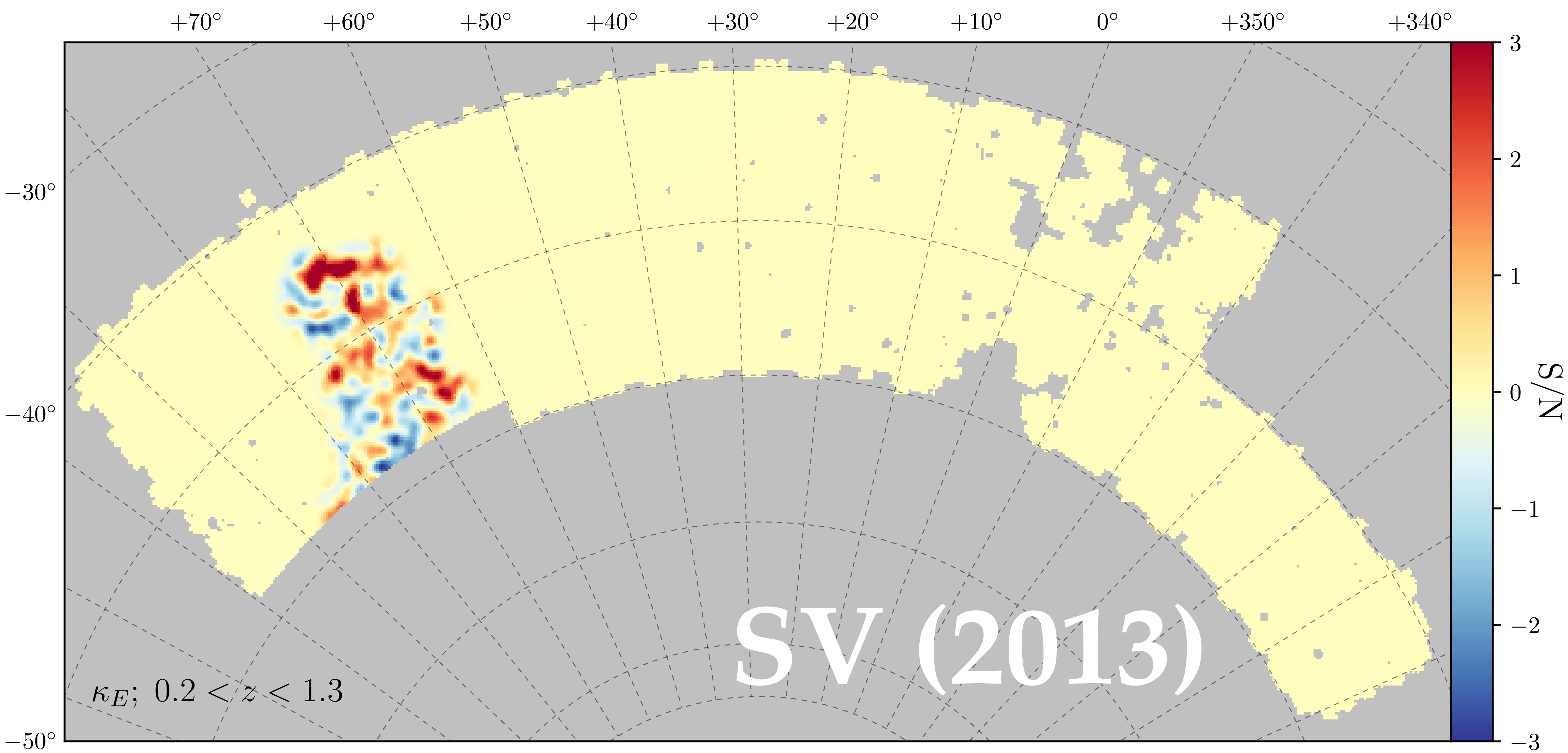
No evidence for self-interaction DM

Centering is a potential concern for future



Harvy et al. (2015)

Wide Field Mass Maps



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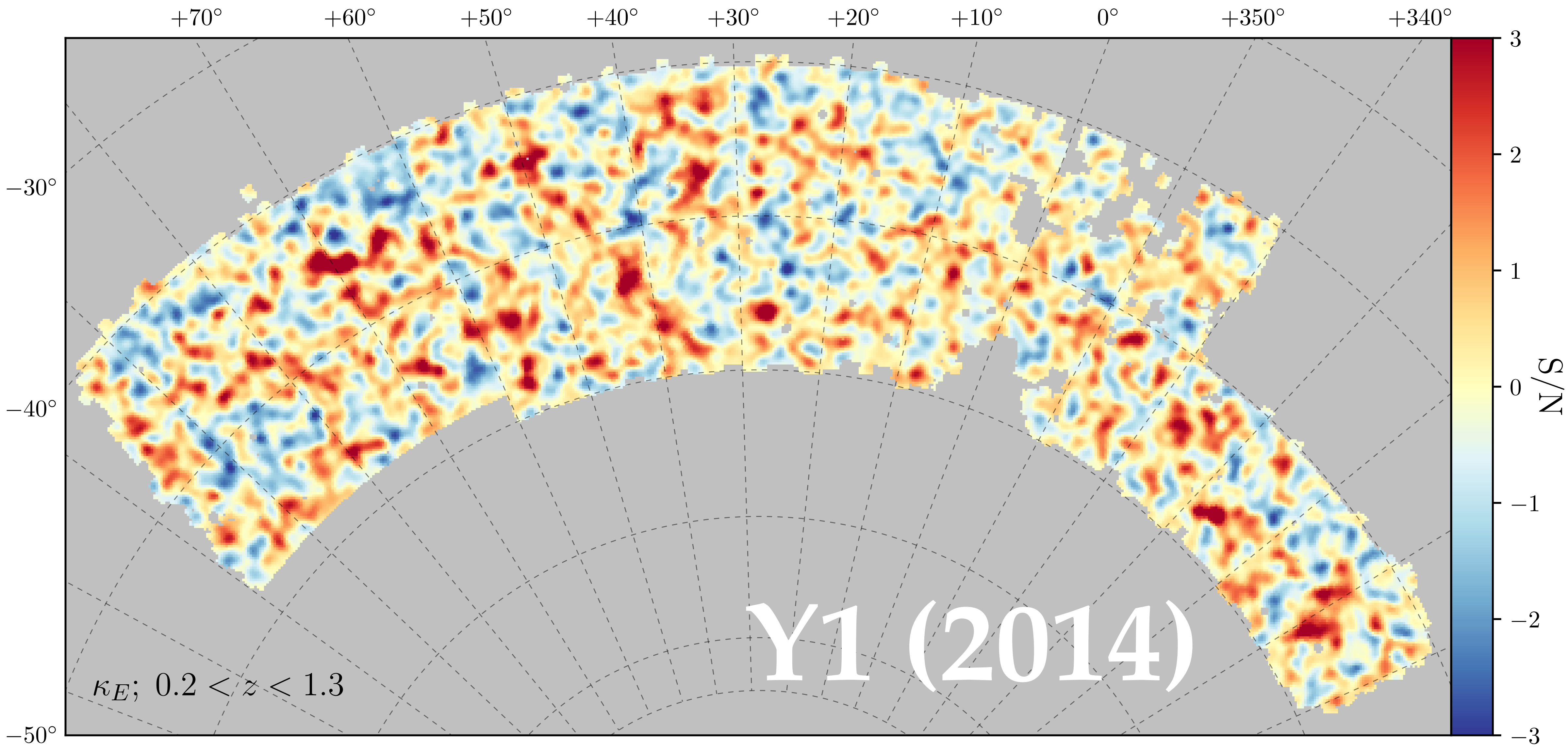
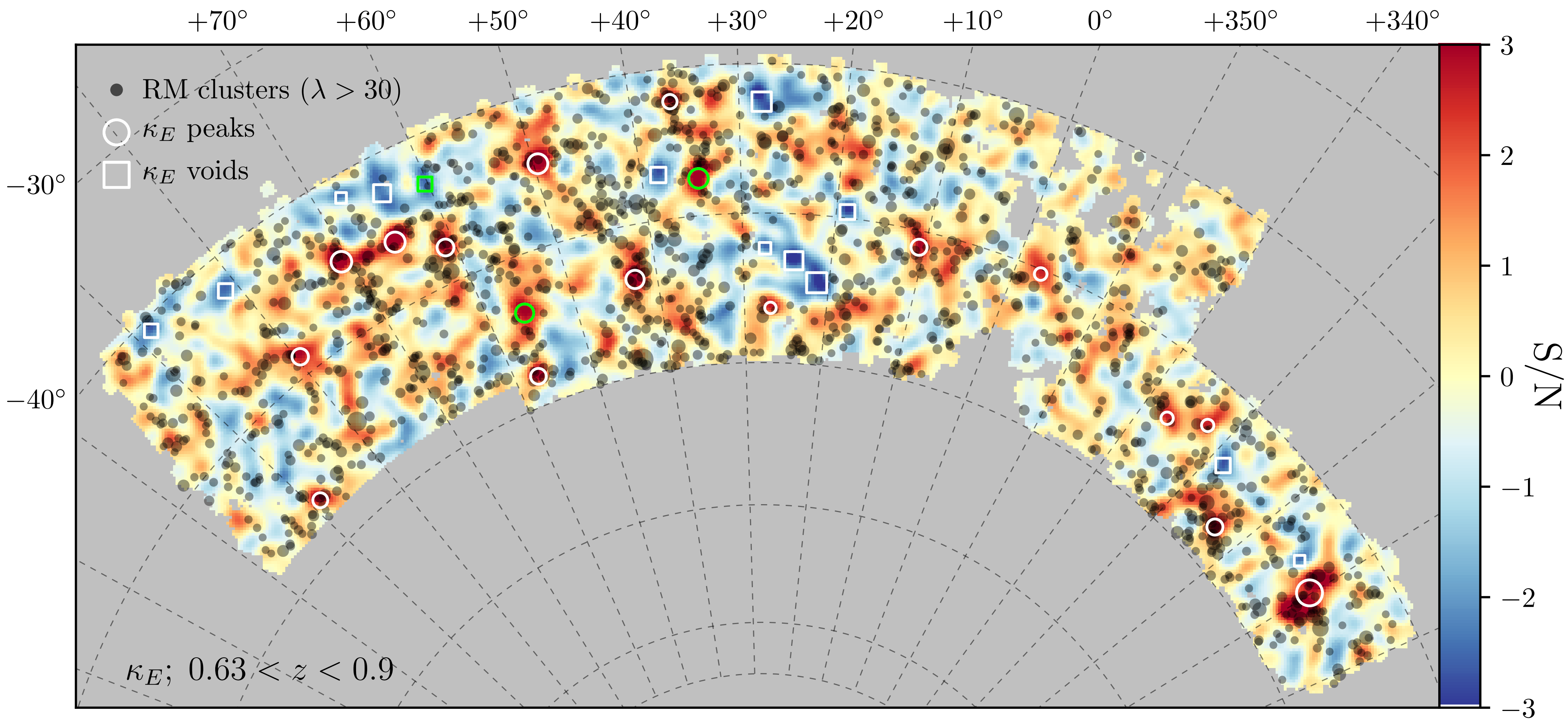
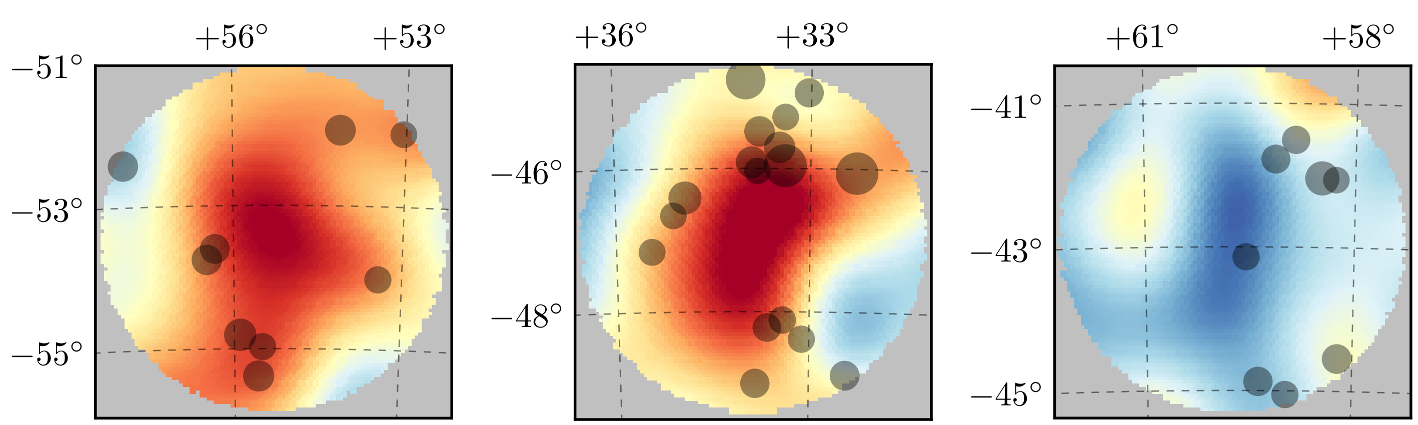


Anomalies in WL Mass Maps?!

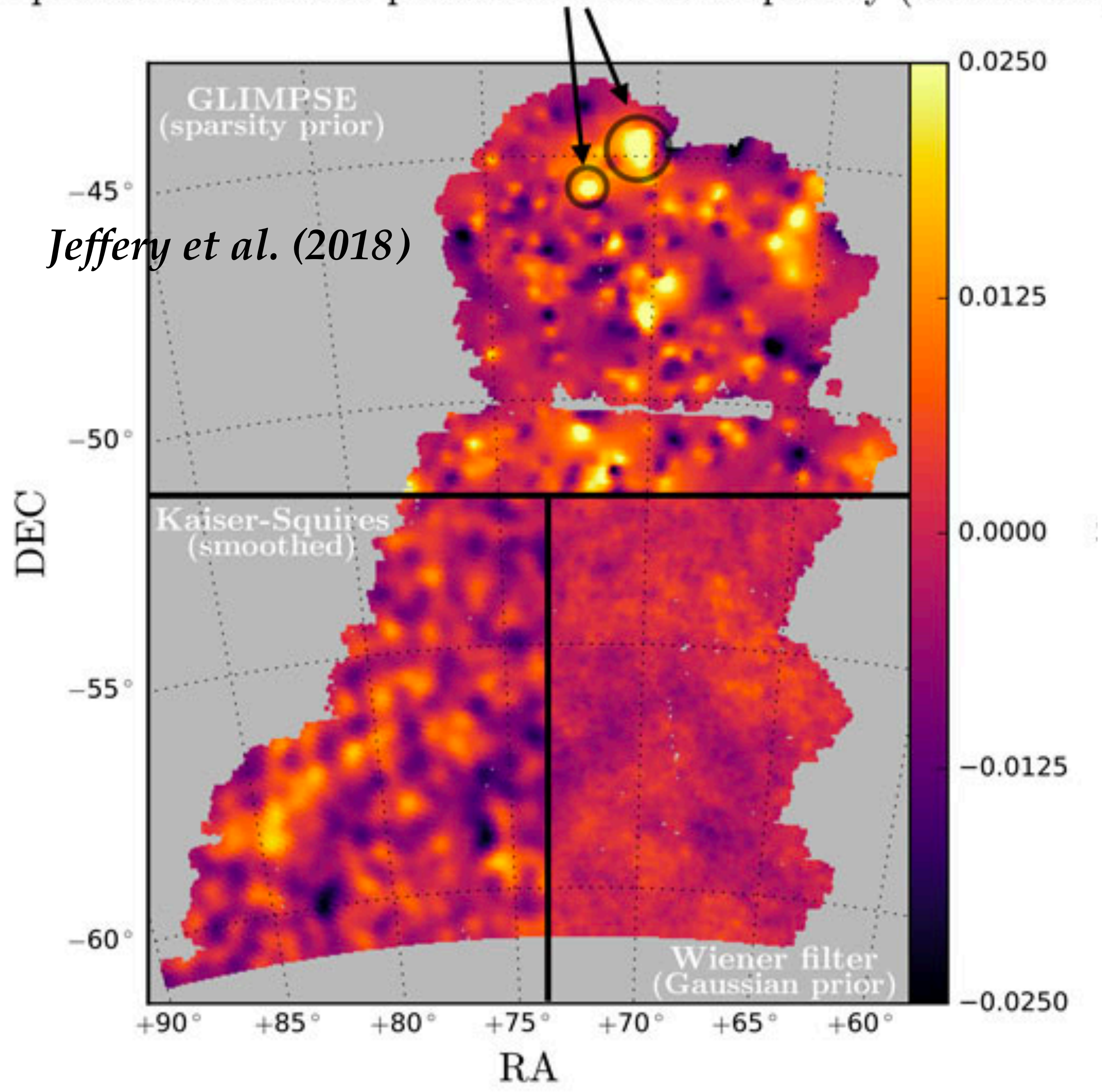




Or maybe just noise?

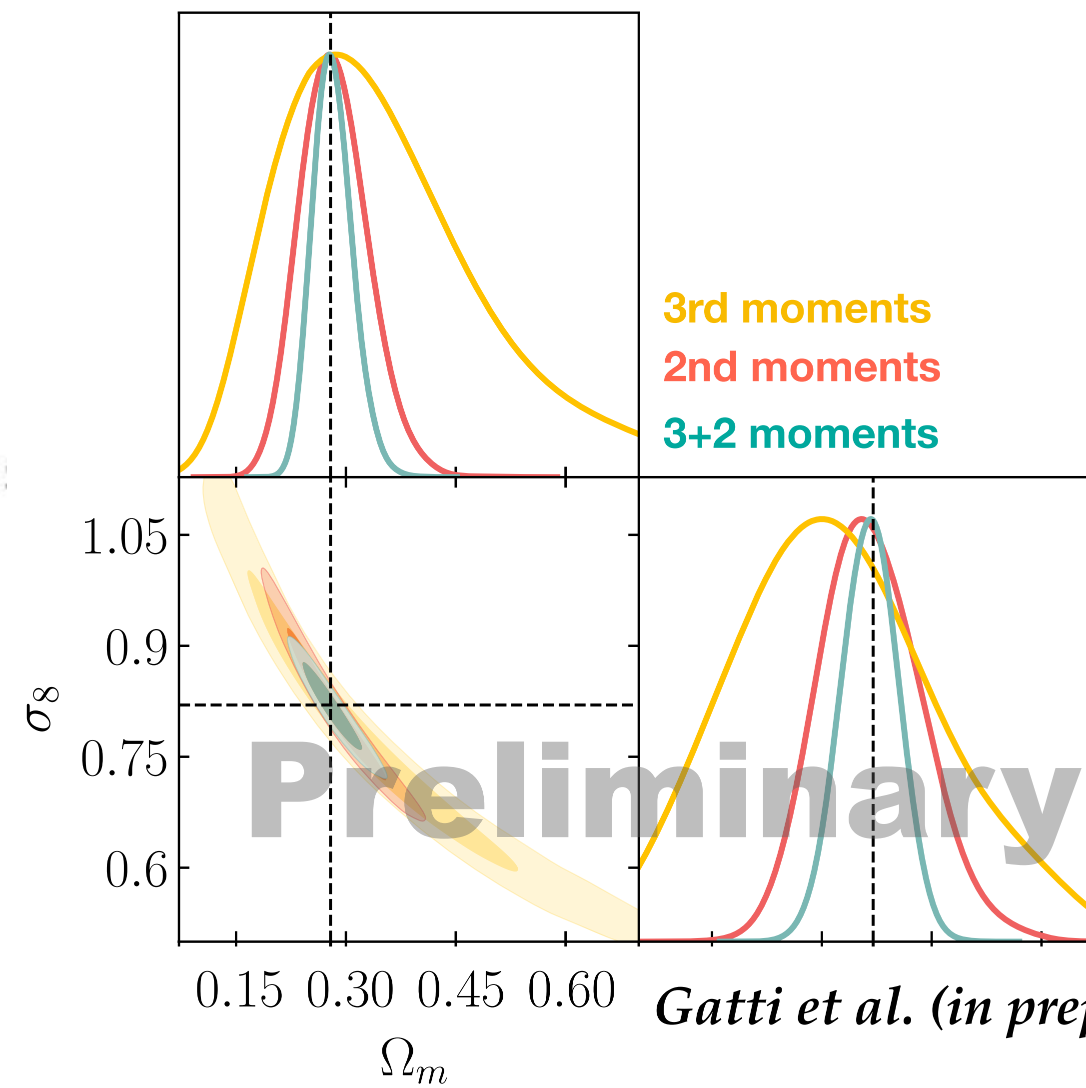
Developments in Mass Mapping

Improved dark matter peak detection with sparsity (GLIMPSE)



Jeffery et al. (2018)

Dark Matter Map with 3 Methods



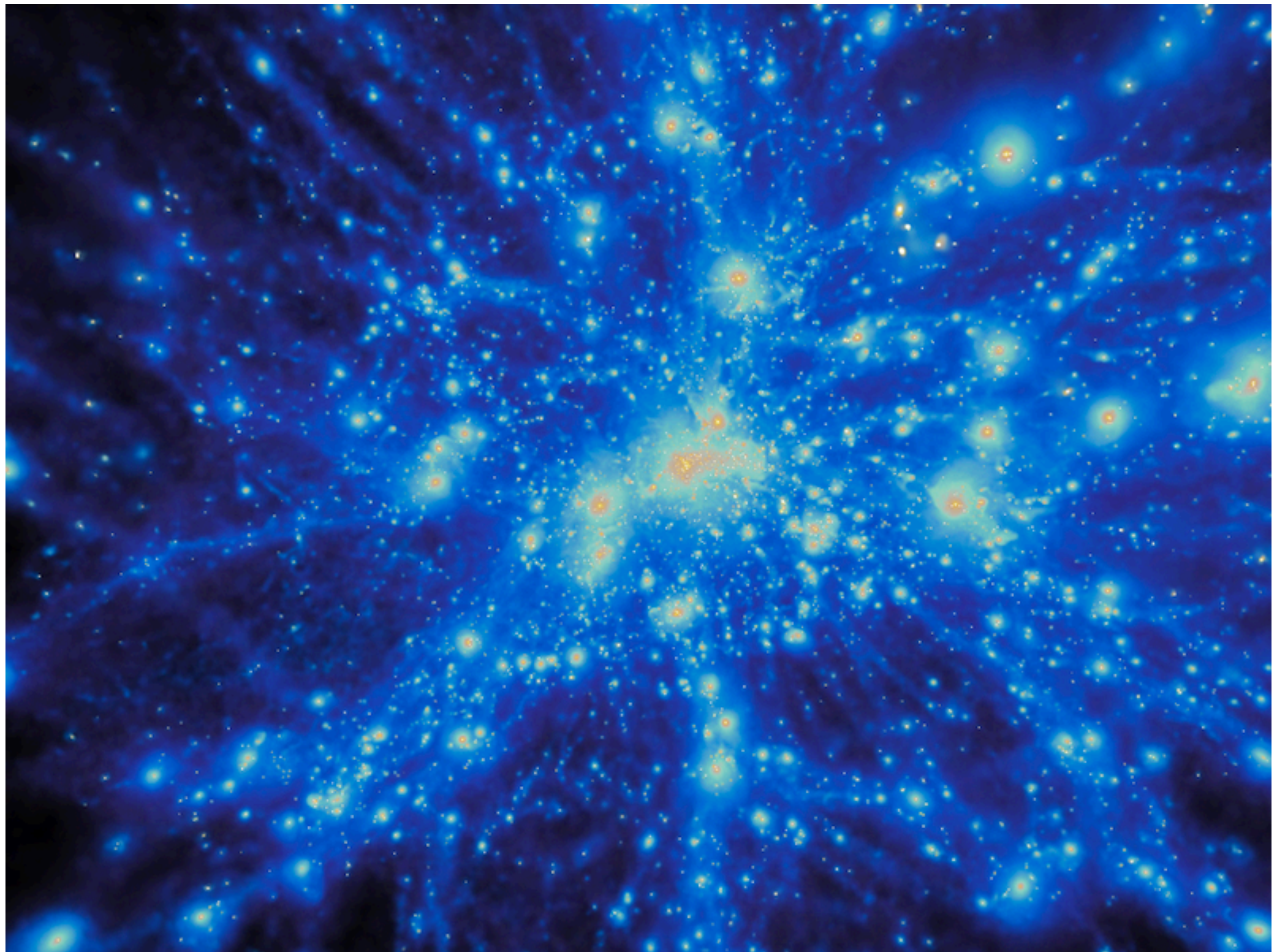
Gatti et al. (in prep)

Towards the Smallest Halos

Standard CDM predicts dark matter halos should exist down to at least **Earth mass**. Alternative DM models would predict a low mass cutoff.

We can robustly measure halo mass of **$\sim 10^{10}$ $M_\odot$**; there exist evidence for the existence of **$\sim 10^{8}$ $M_\odot$** halos. Pushing to lower mass is important to probing potential breakdown of CDM.

Low mass —> hard to measure!

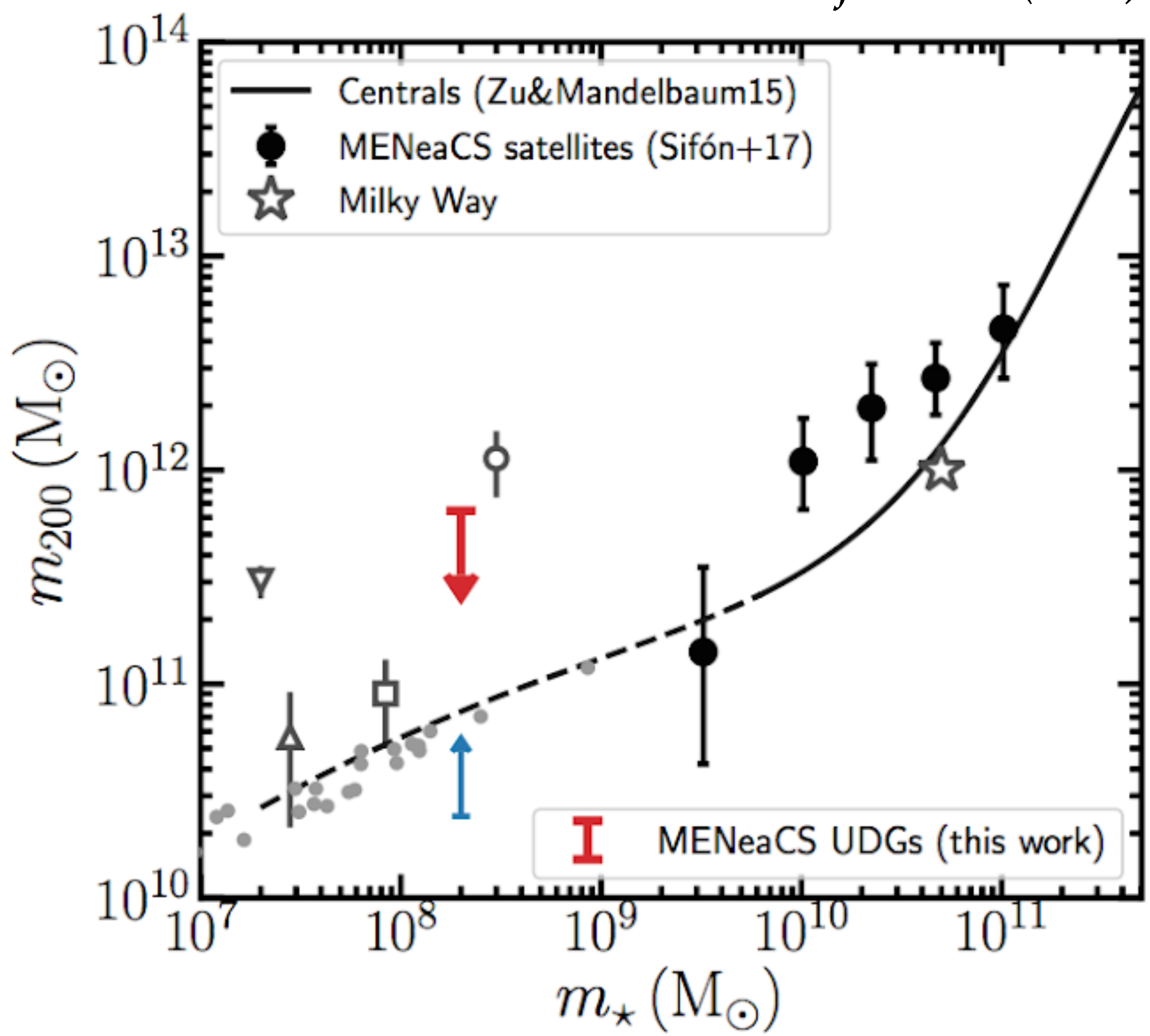


Credit: Bolshoi Simulations

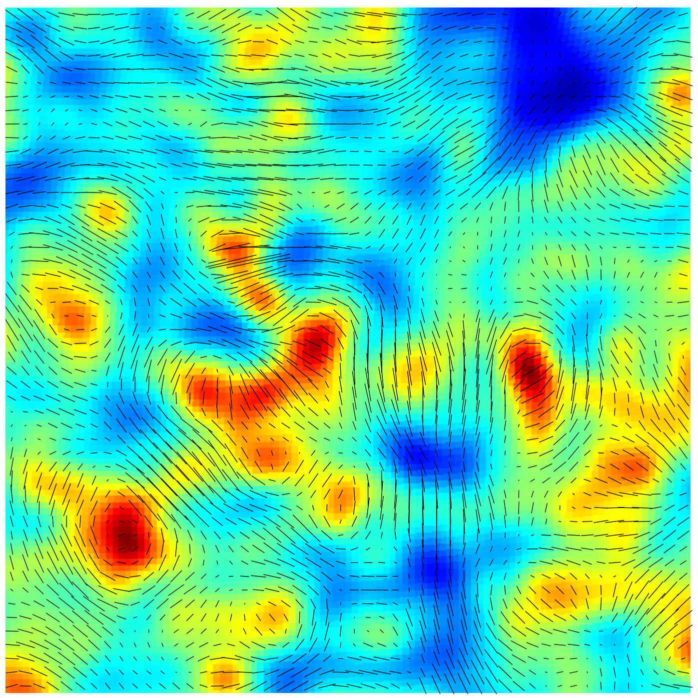
Towards the Smallest Halos

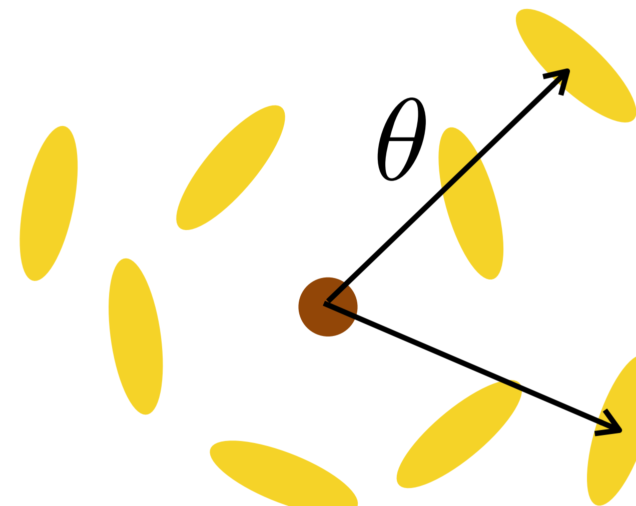
The **luminosity function** and the **stellar to halo mass relation** at the low mass end inform us about Dark Matter models as well as astrophysics (galaxy formation)

Sifon et al. (2017)



Galaxy-galaxy Lensing



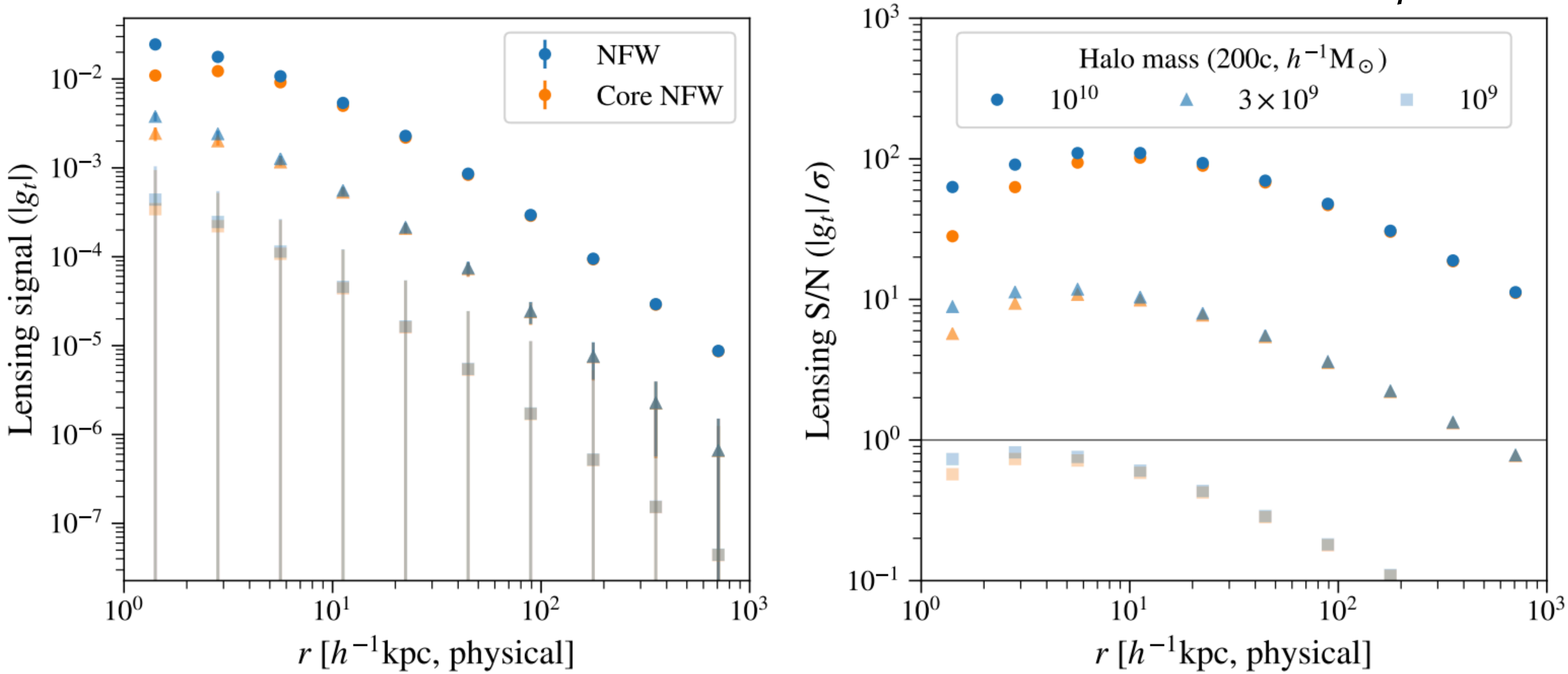


"Galaxy-galaxy lensing" measures the average mass profile of halos that host the galaxy sample of interest.

The precision of the measurement depends on: 1) number of lens galaxies 2) number of source galaxies 3) how well we know the redshifts

Prediction for Detection

LSST DESC DM White Paper (2019)



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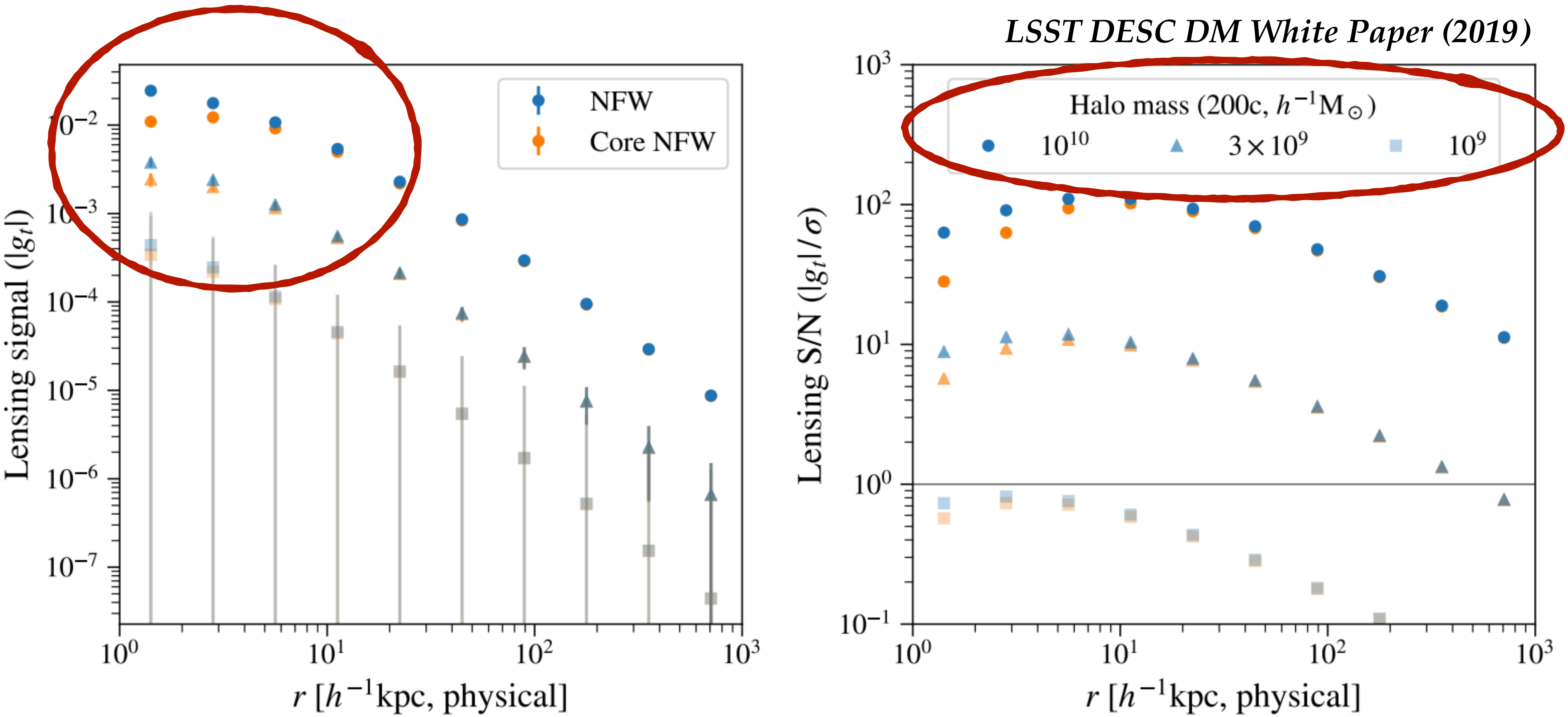

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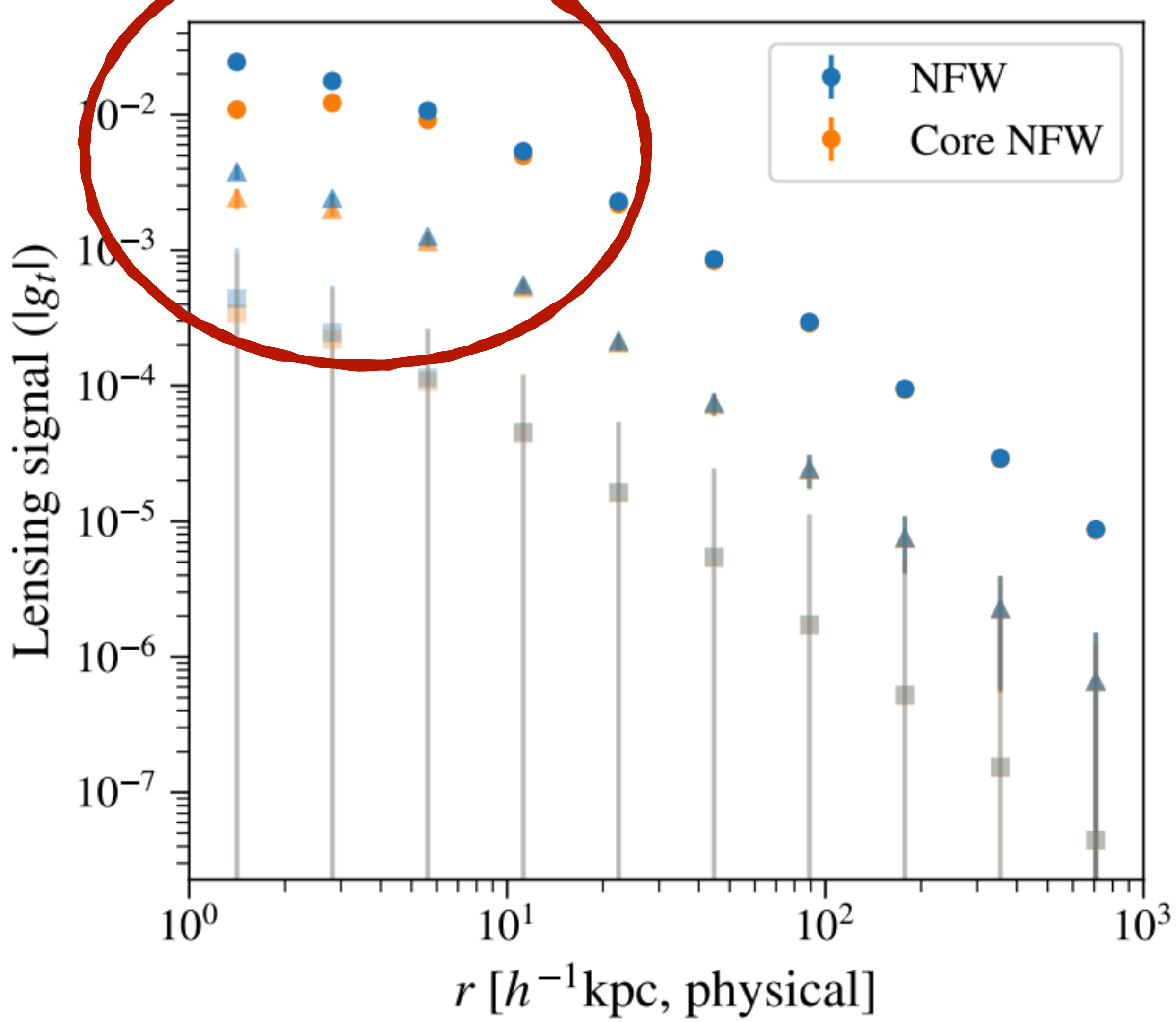

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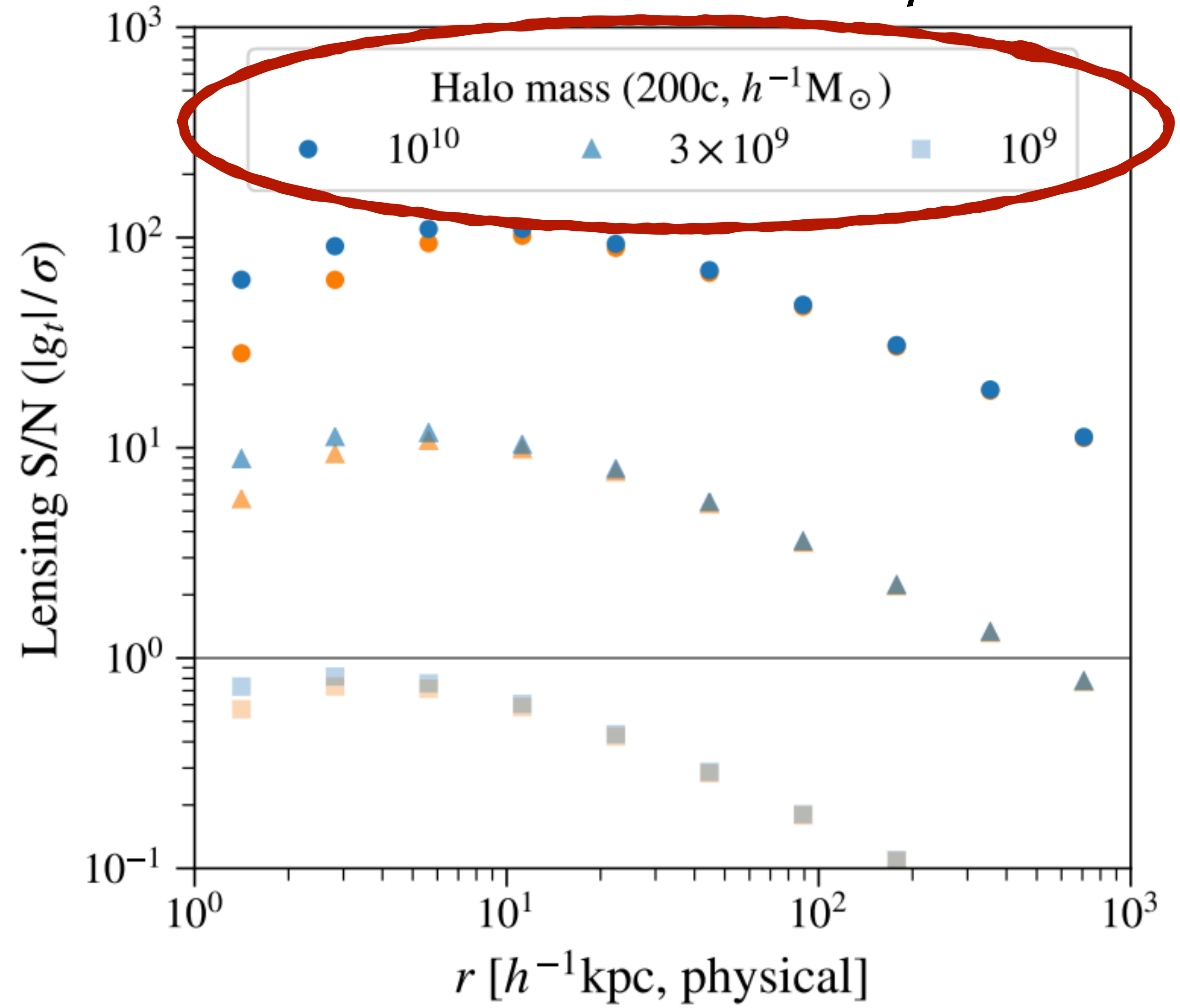
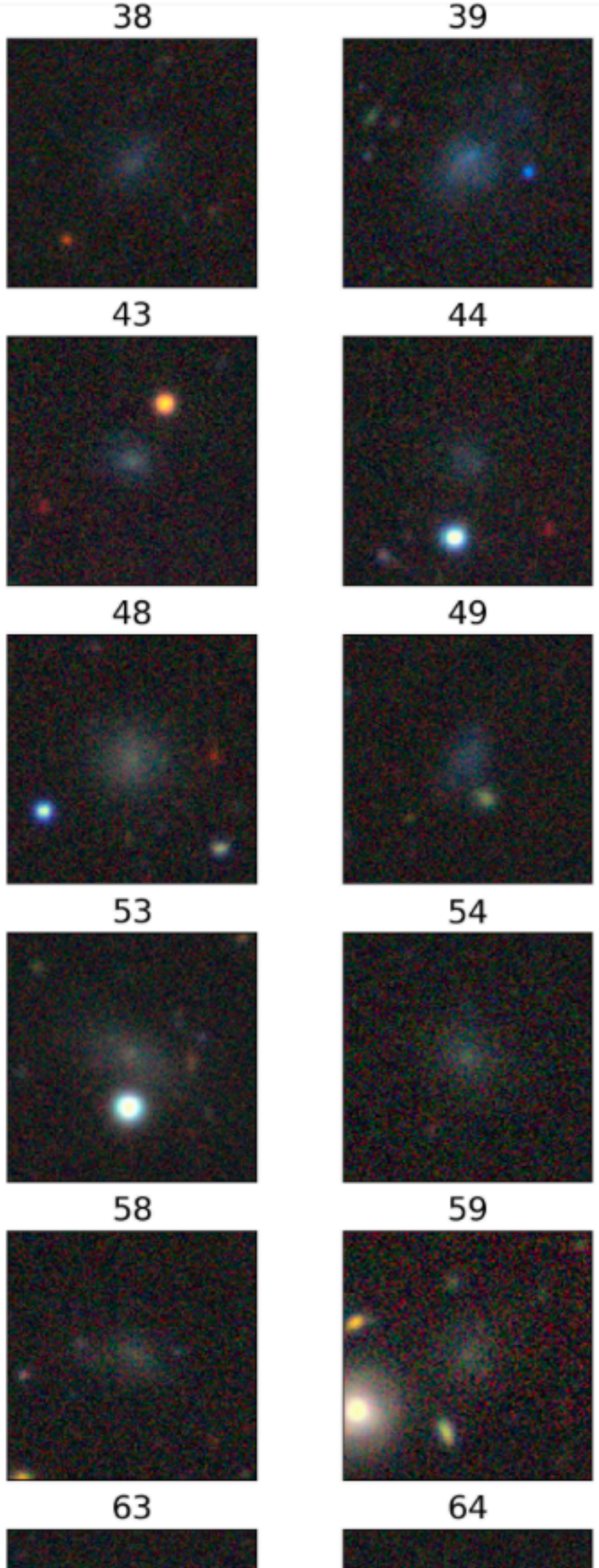


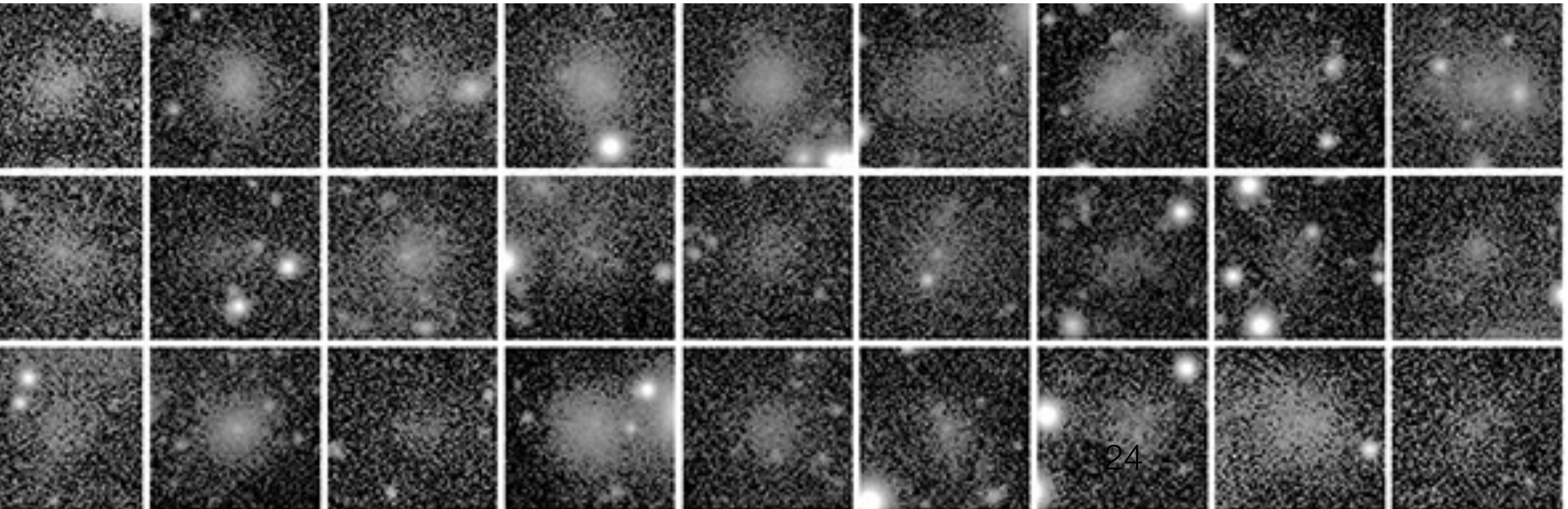
See also Alexie Leauthaud & Malin Renneby's talk Tuesday



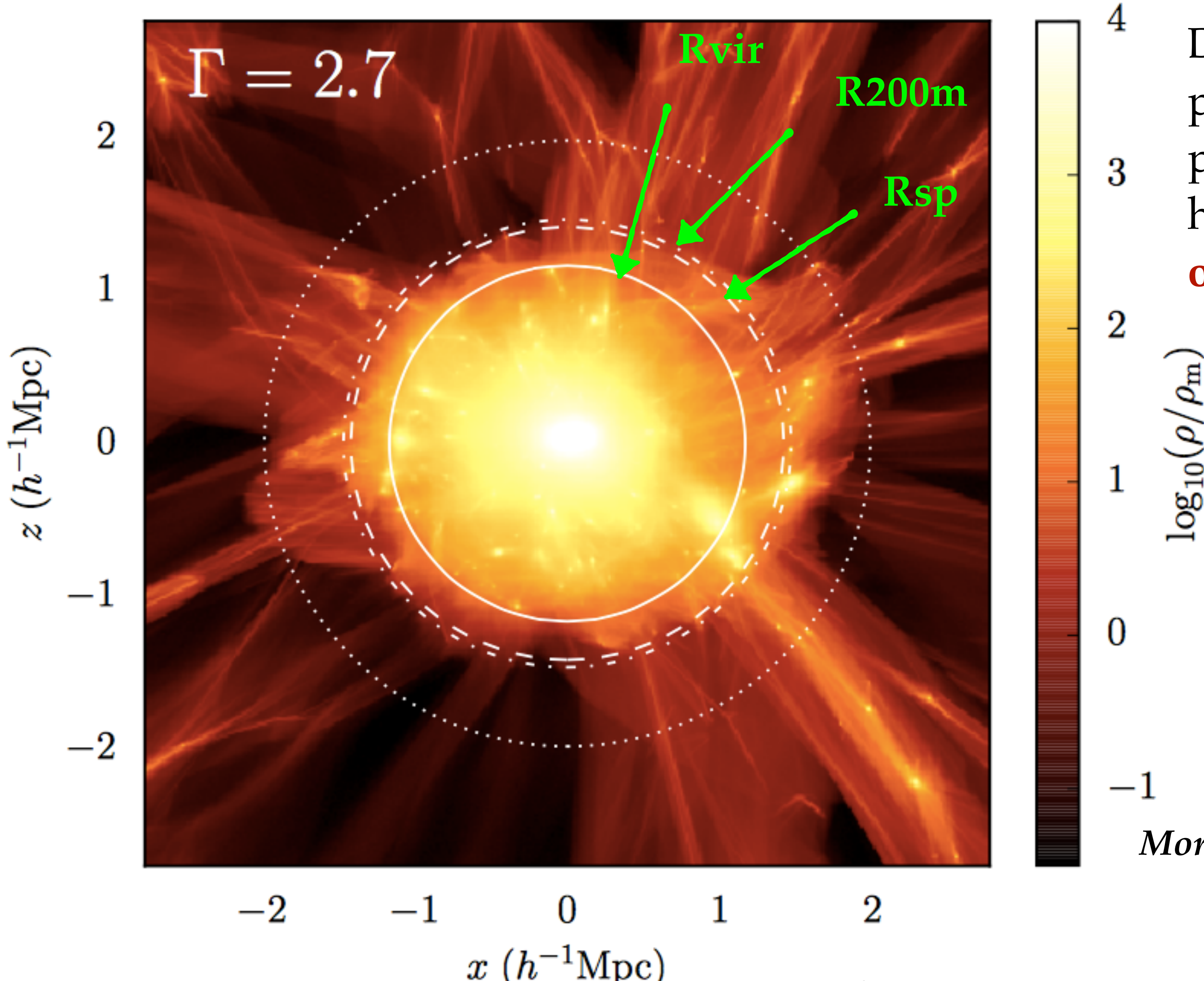
Ultra Diffused Galaxies

- Ultra Diffuse Galaxies (UDGs) are large, faint galaxies, often found in **galaxy clusters**
- The existence and formation of UDGs are not well understood. Quantifying the **mass** and **environment characteristics** of UDGs will help — they could hold a lot of Dark Matter

Credit: Carolin Wittmann (WHT)



Cluster Profiles



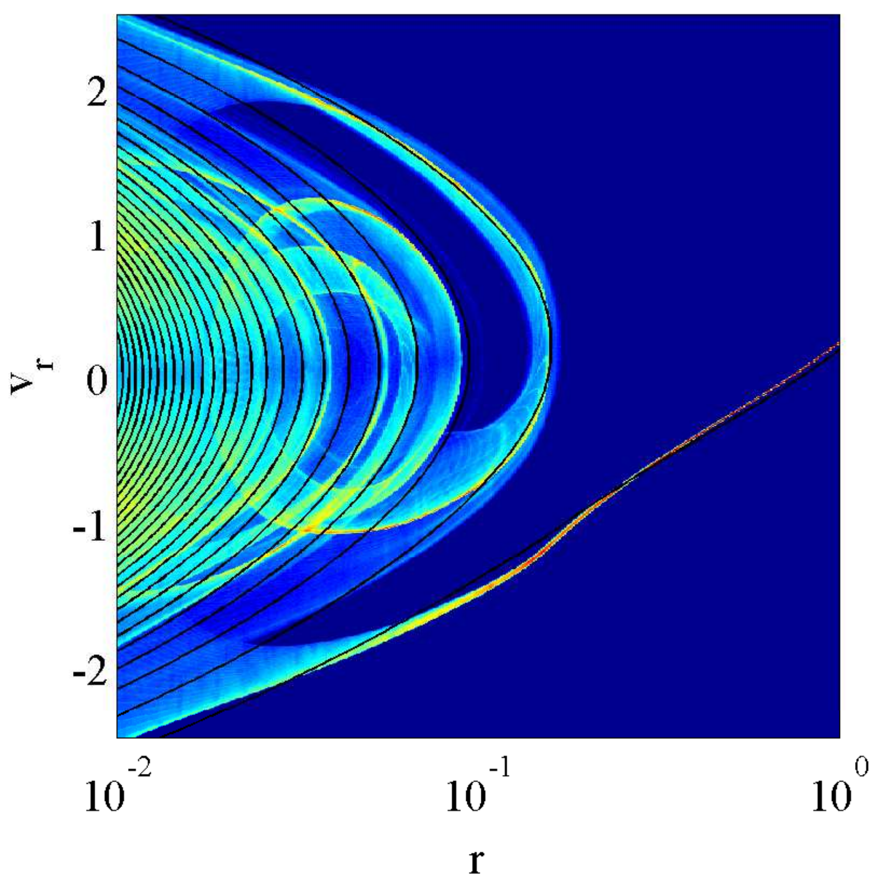
Different Dark Matter model predicts different mass profiles for massive clusters, here we focus on the **outskirts of galaxy clusters**

More, Diemer & Kravstov (2015)

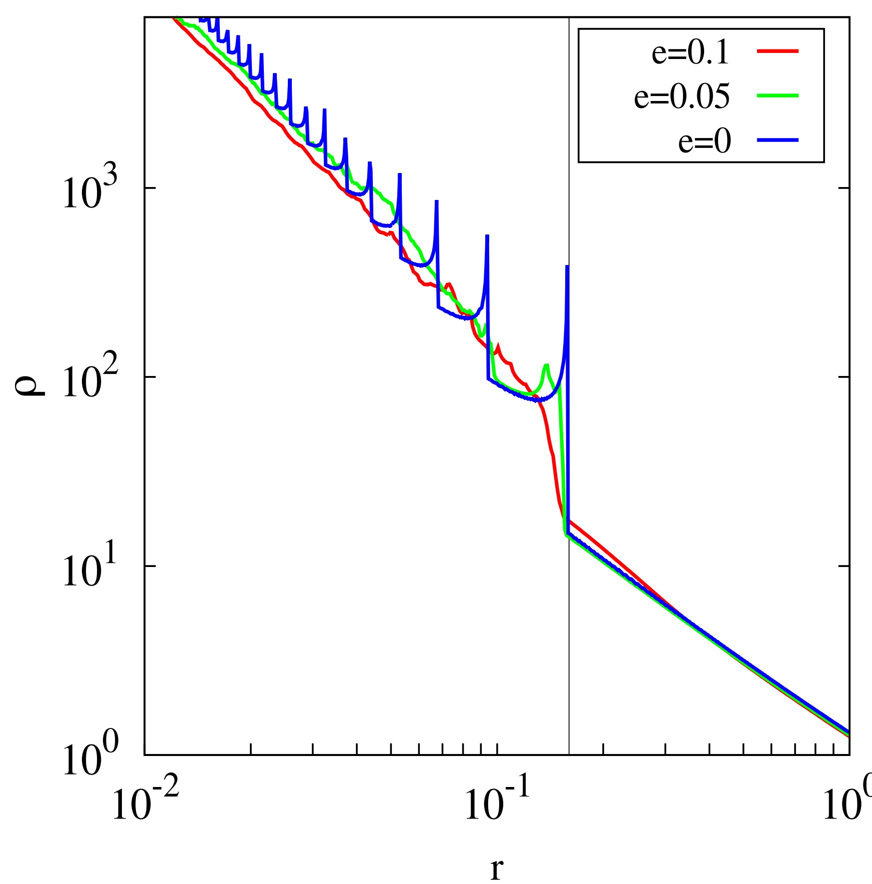
Cluster Profiles & Splashback

- Boundary of the **1-stream** vs. **multi-stream** region for infalling particles.
- Probe for **assembly bias**, **dynamical friction, SIDM, modified gravity**

Phase-space Diagram



Density Profiles



Adhakari et al. (2014)

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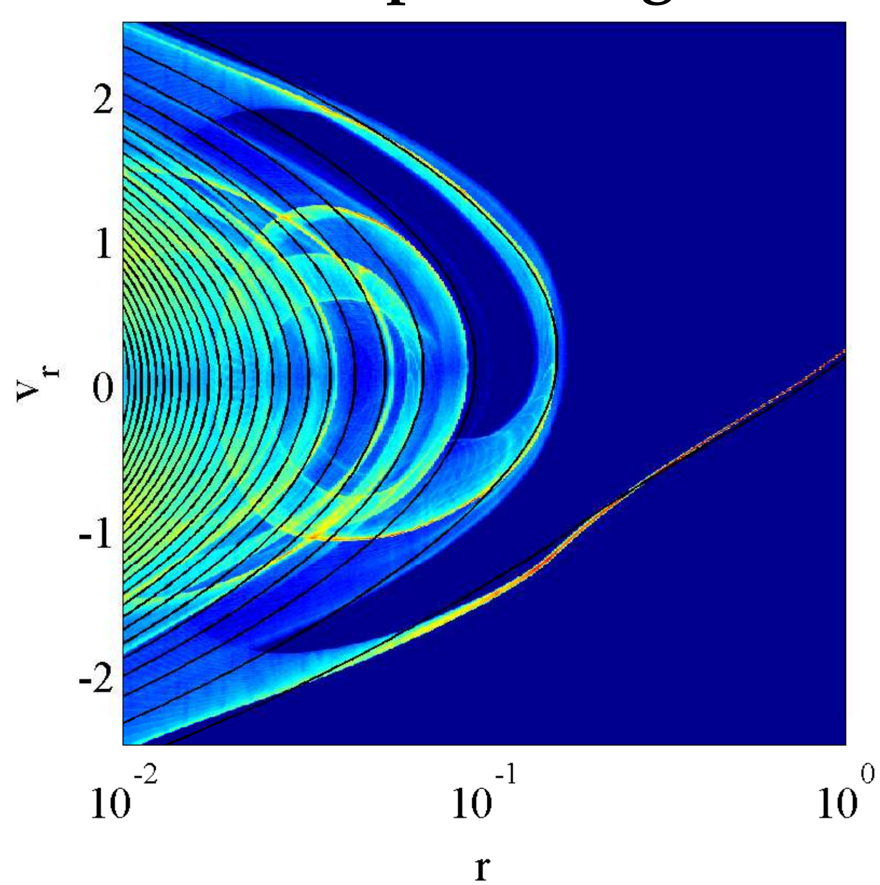

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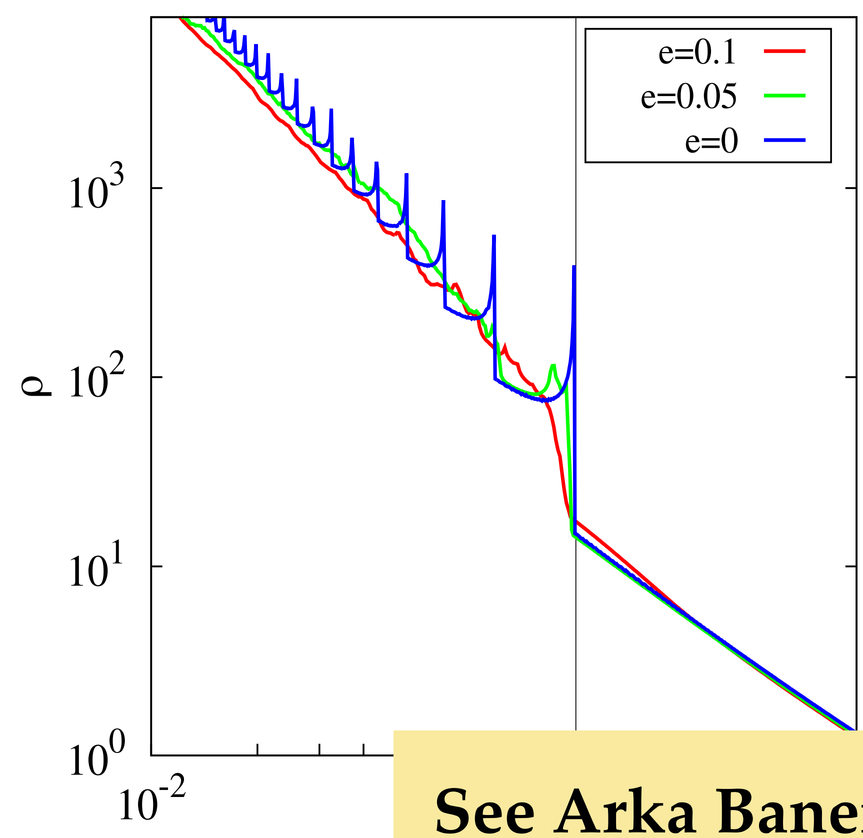

Adhakari et al. (2014)

See Arka Banerjee's talk Tuesday

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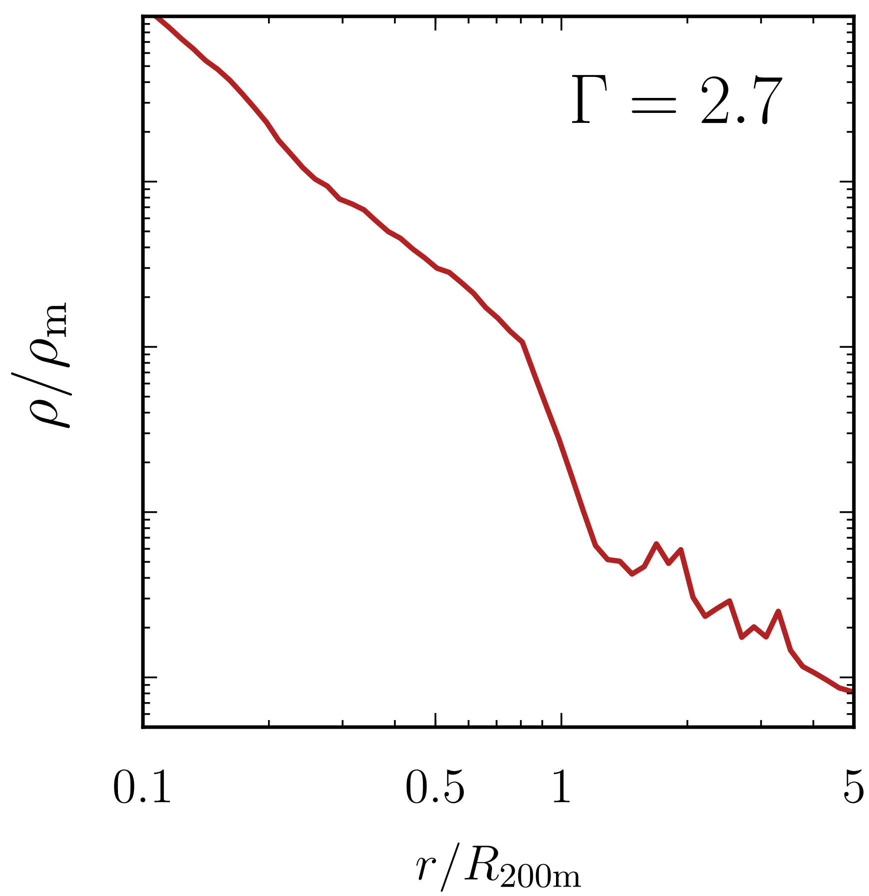
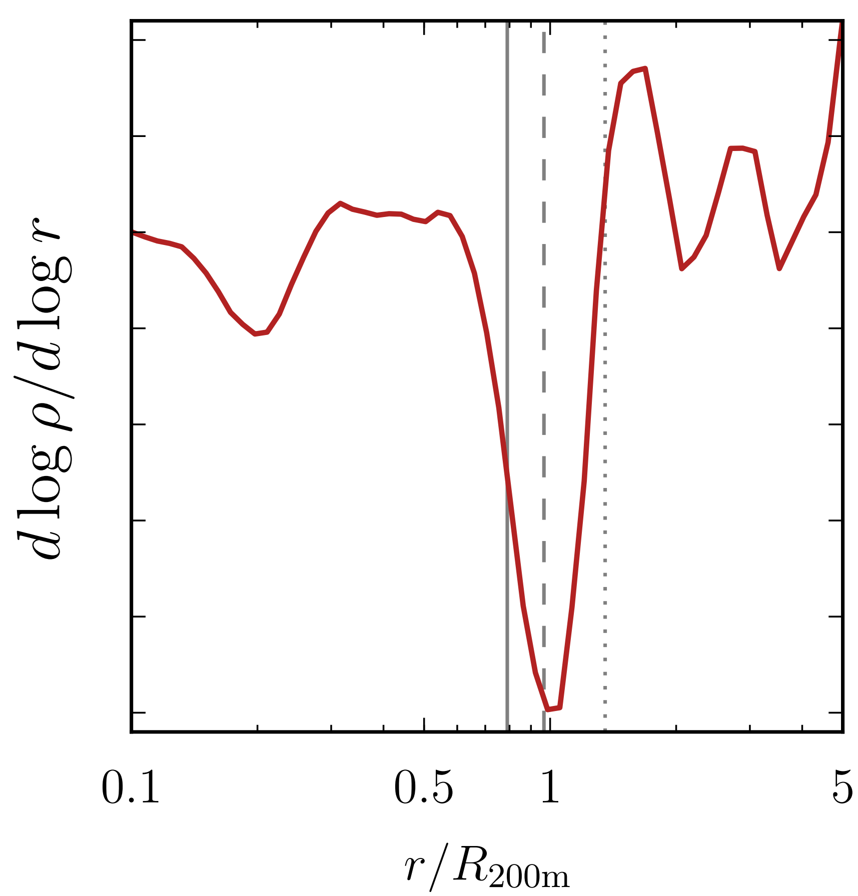
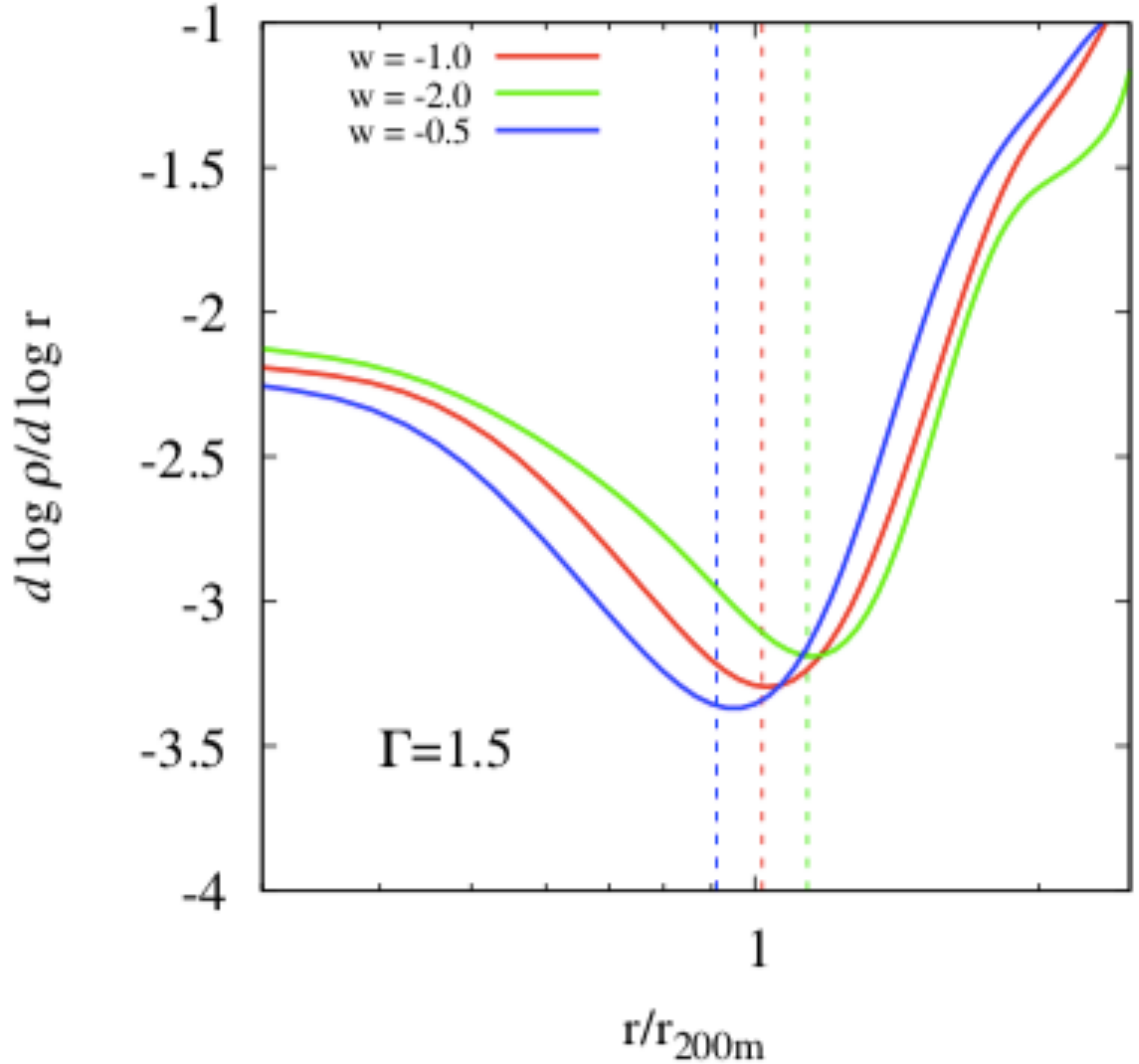
-





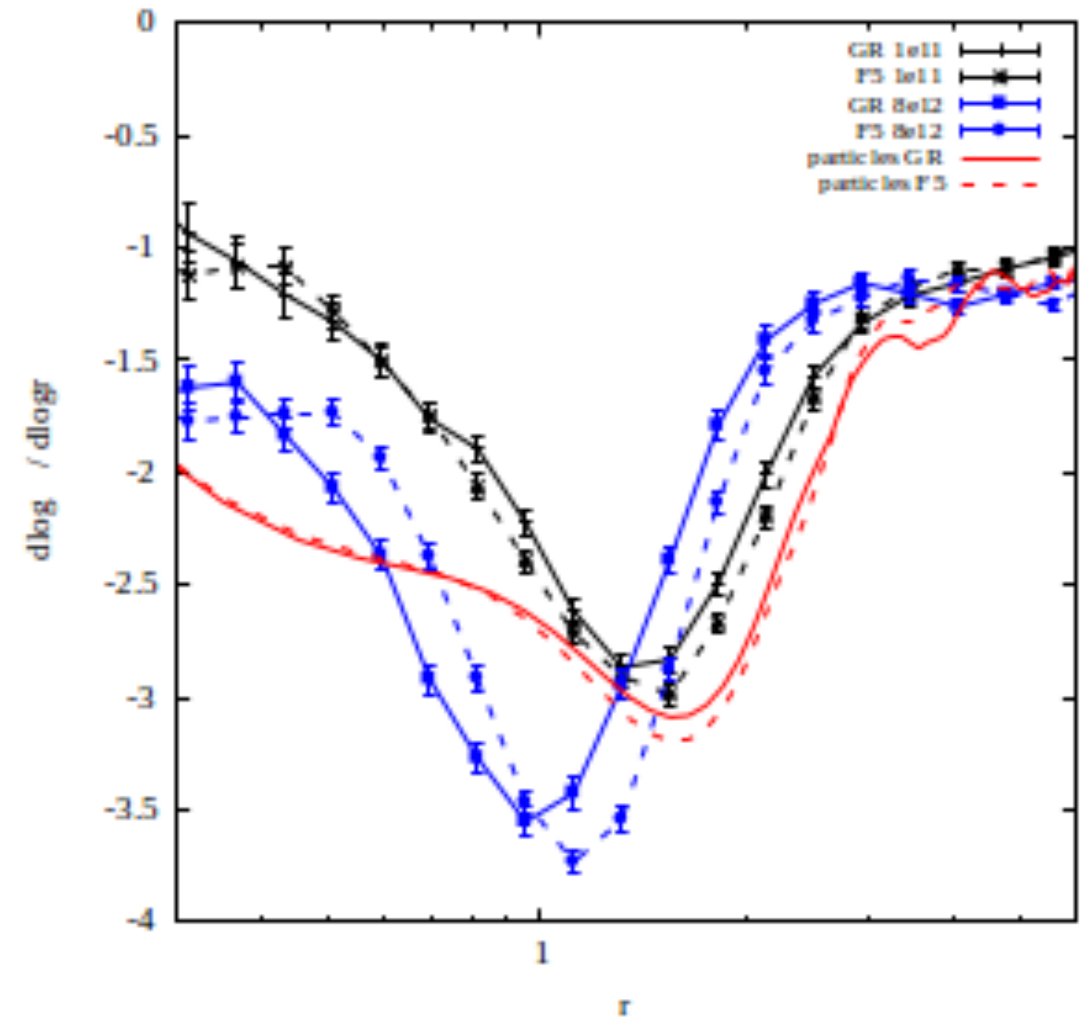
Diemer & Kravstov (2014)

Novel Probe for New Physics



Dark energy dependence: weak

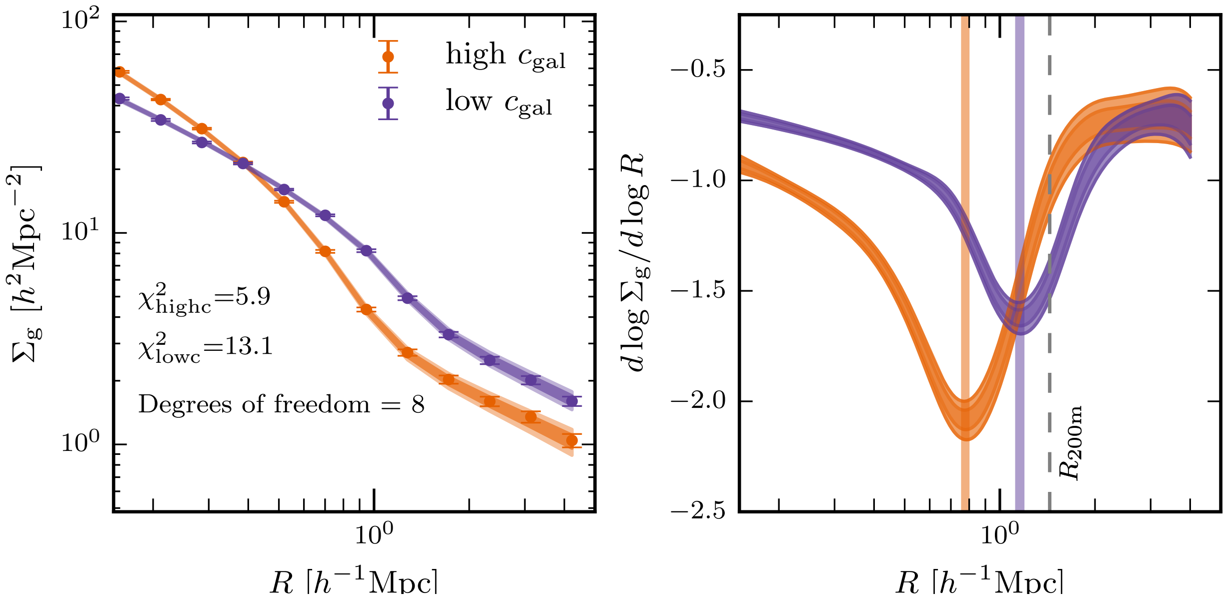
Adhikari et al. (2018)



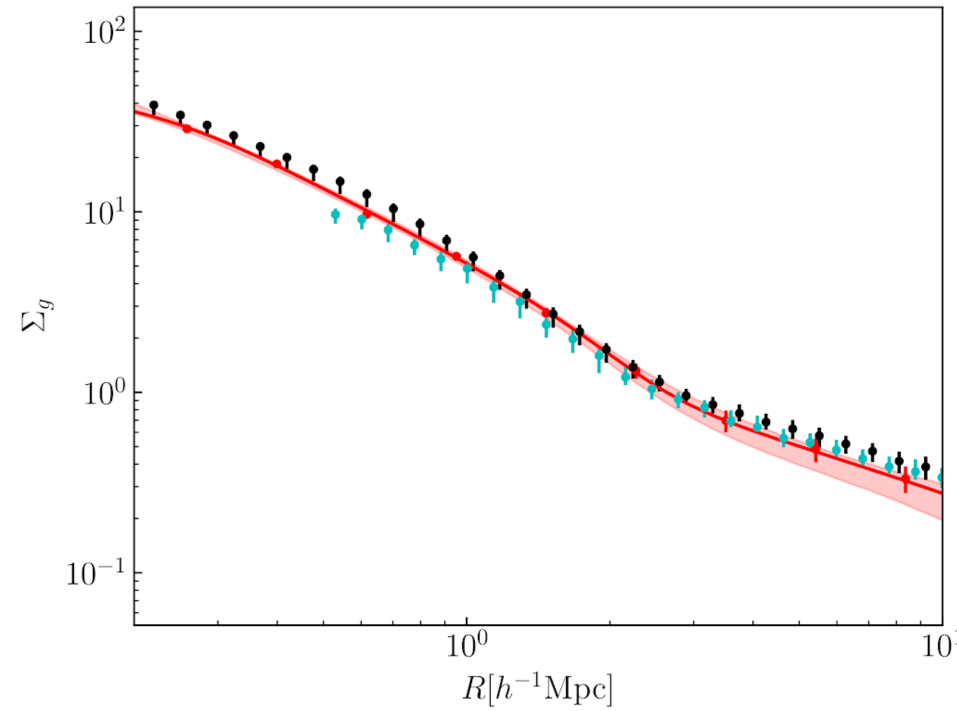
SIDM: complicated, but promising

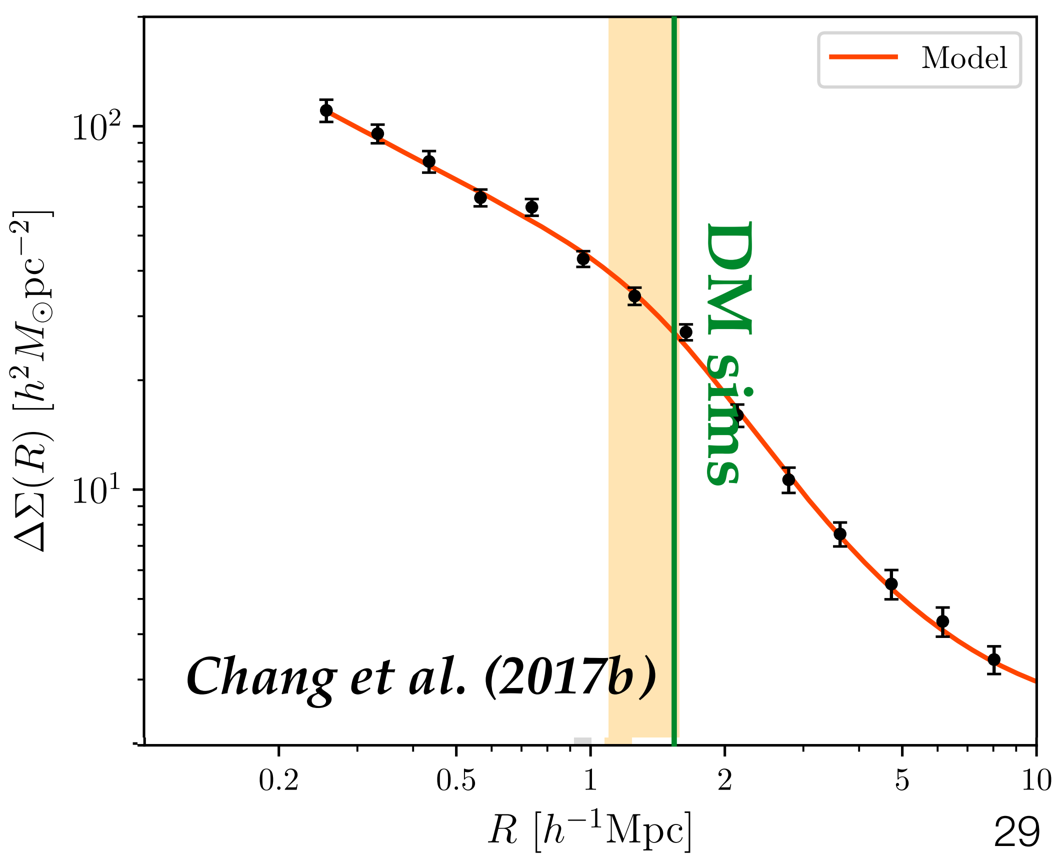
Systematics, Systematics, Systematics

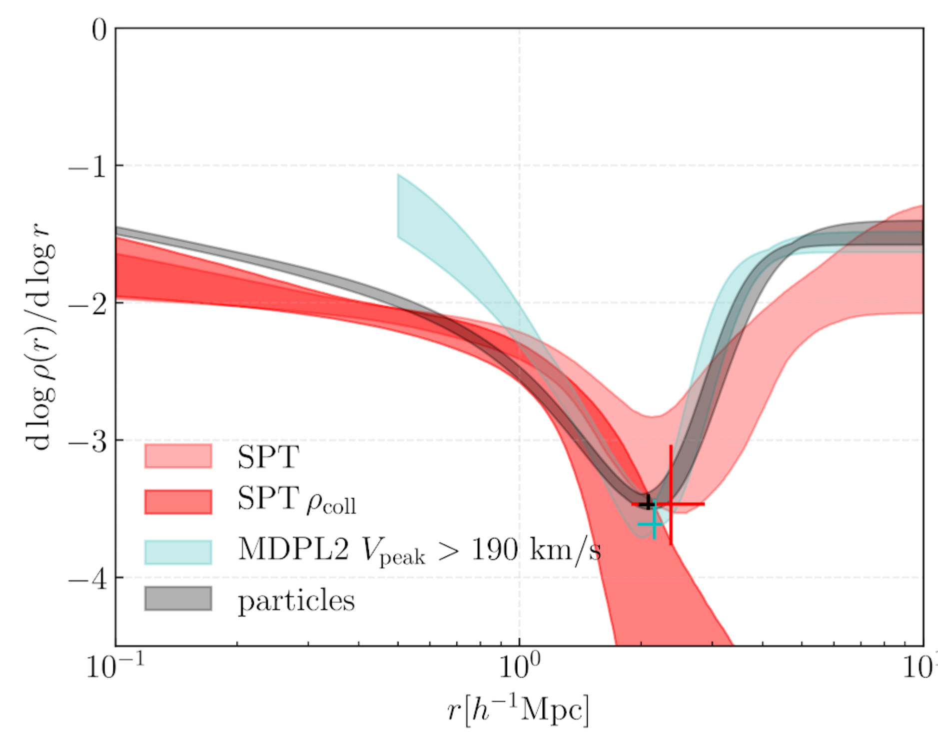
More et al. (2016)



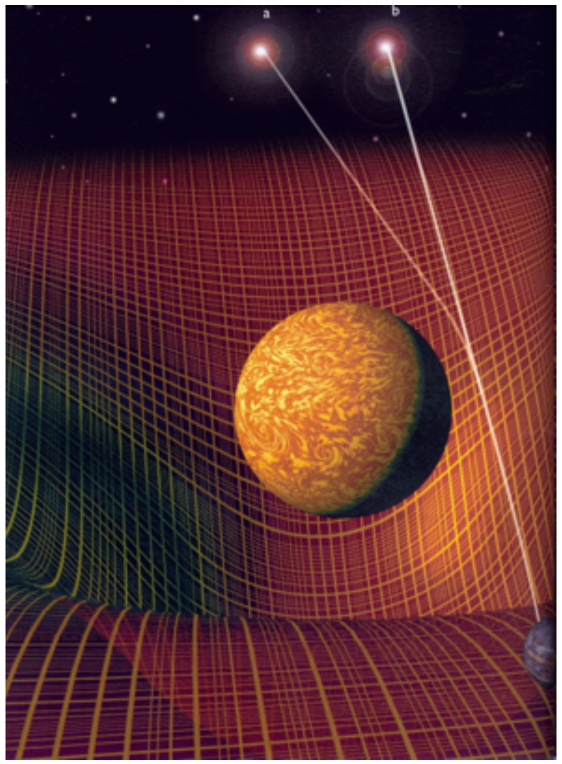
Shin et al. (2019)

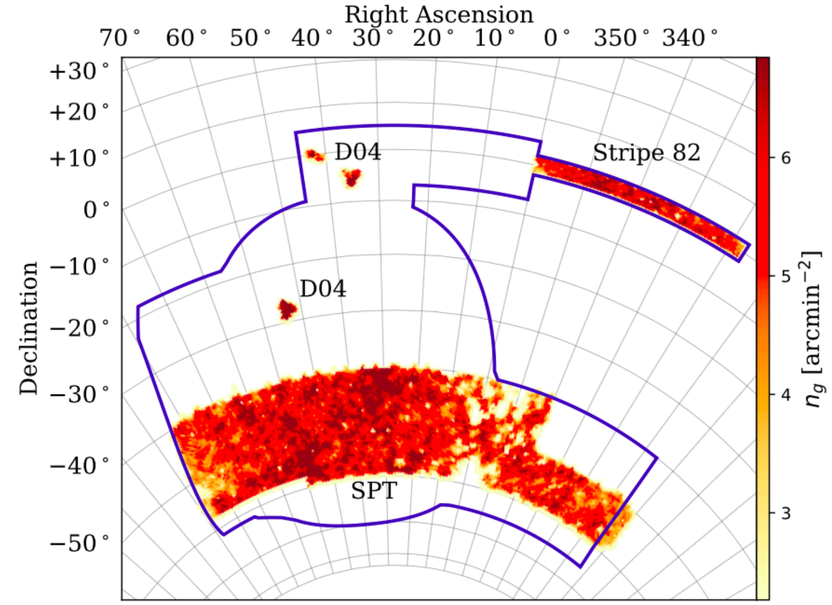


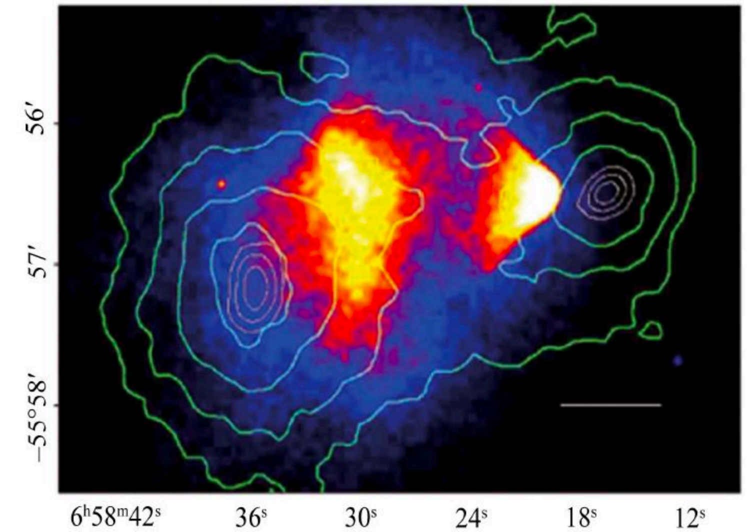


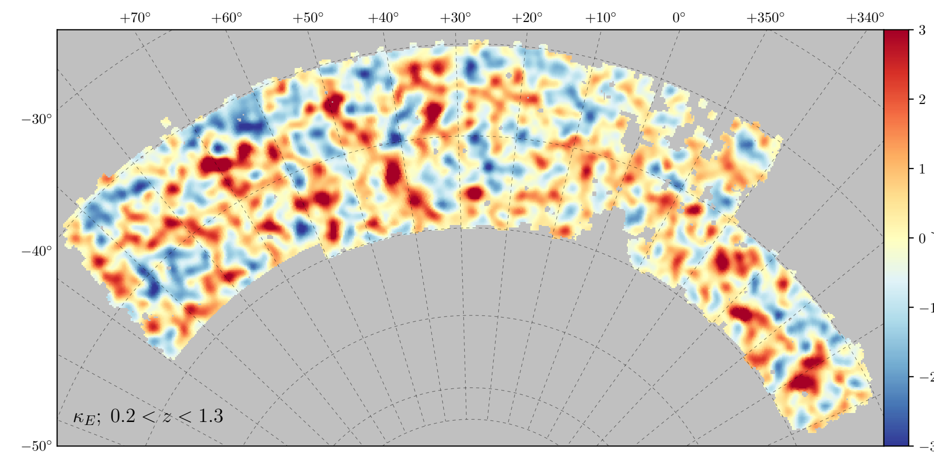


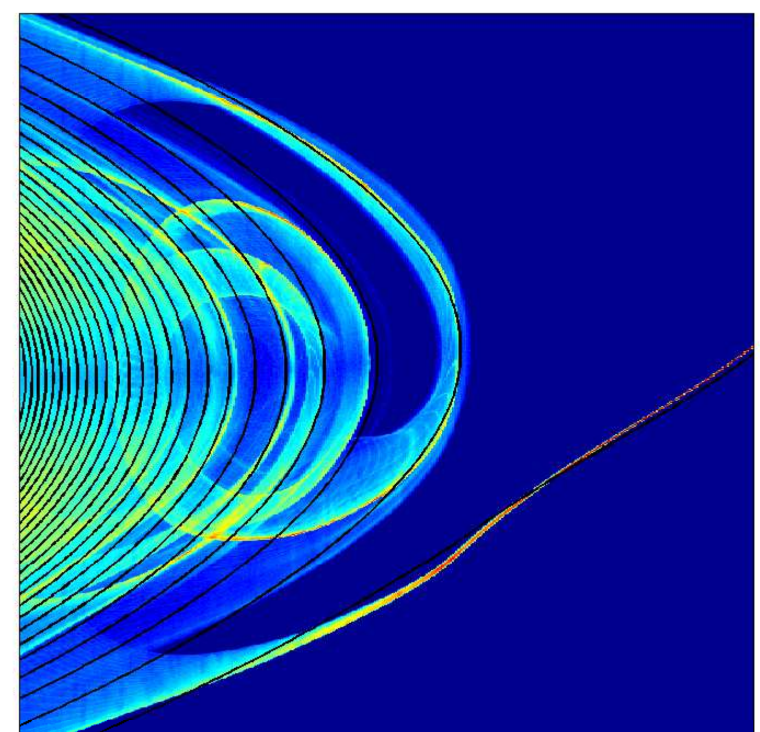
Summary

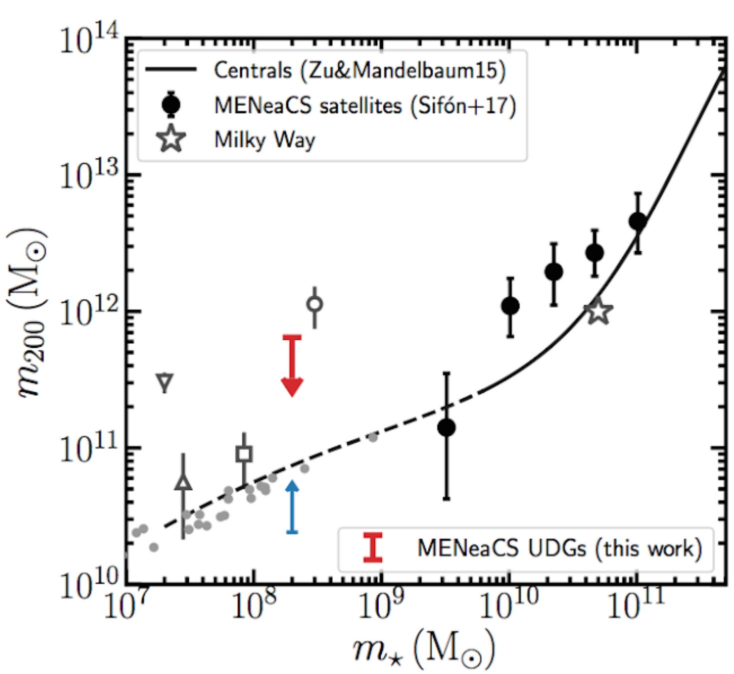


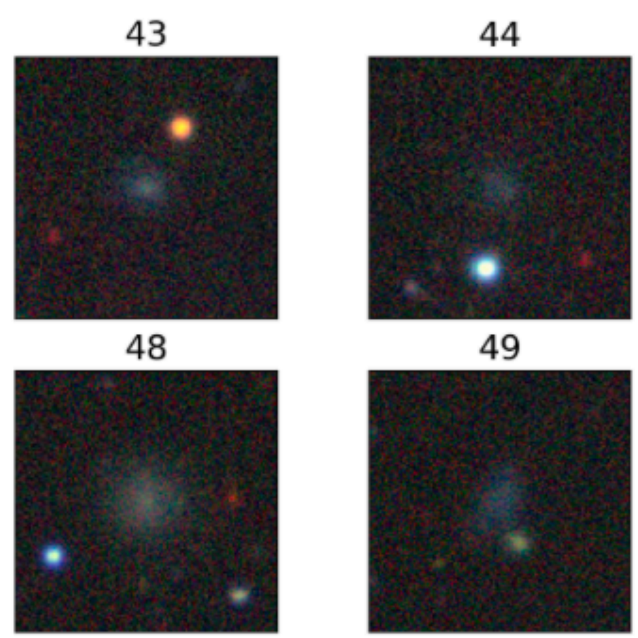

Right Ascension
70° 60° 50° 40° 30° 20° 10° 0° 350° 340°
+30° +20° +10° 0° −10° −20° −30° −40° −50°
Declination
D04
D04
Stripe 82
SPT
n_g [arcmin^{-2}]
3 4 5 6


56′
57′
−55°58′
6h58m42s 36s 30s 24s 18s 12s


κ_E: $0.2 < z < 1.3$
S/N




Centrals (Zu&Mandelbaum15)
MENeaCS satellites (Sifón+17)
Milky Way
MENeaCS UDGs (this work)
$m_{200}\,(\mathrm{M}_\odot)$
$m_\star\,(\mathrm{M}_\odot)$
10^{10} 10^{11} 10^{12} 10^{13} 10^{14}
10^{7} 10^{8} 10^{9} 10^{10} 10^{11}


43
44
48
49