Constraining the Hubble constant - some lessons learnt from using lensing simulations

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Time-Domain Cosmology with Strong Gravitational Lensing
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Precision cosmology

Goal: Percent-level precision on H_0

Image time-delays

$$t(\vec{\theta}) = \frac{(1+z_d)}{c} \frac{D_d D_s}{D_{ds}} \left[\frac{1}{2}(\vec{\theta} - \vec{\beta})^2 - \psi(\vec{\theta}) \right]$$

Time-delay distance depends on cosmology

Lens mass distribution

Time-delay distance => H_0 (Refsdal 1964)

- **Things that work and things that may work / things that do not work but with caution!**

Outline

- **Lesson-1:** When power-law meets invariance transformation
- **Lesson-2:** Potential drawbacks using cosmology simulations
- **Lesson-3:** Is a kappa map all to a lensing mock? - Truncation

Lesson – 1:

Mass-sheet-transformation (MST, Falco 1985):

Transformed surface density → κ_λ ; Original surface density → κ

$$\kappa_\lambda(\boldsymbol{\theta}) = \lambda\kappa(\boldsymbol{\theta}) + (1-\lambda).$$

Under MST,

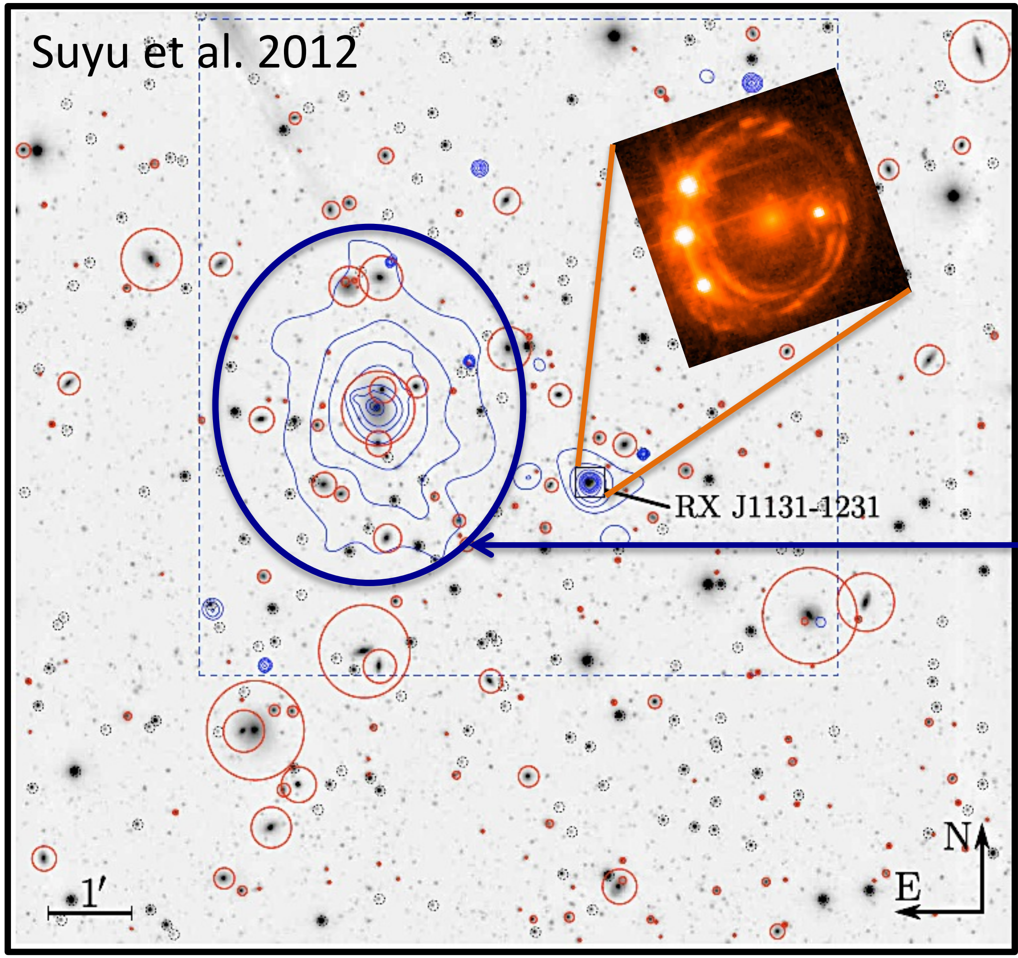
Invariant: image positions and flux ratios ⇨ **Degeneracy**

Changeable: (1) absolute magnification

(2) **multiplication of time delay and H_0**

$H_0 \rightarrow \lambda H_0$

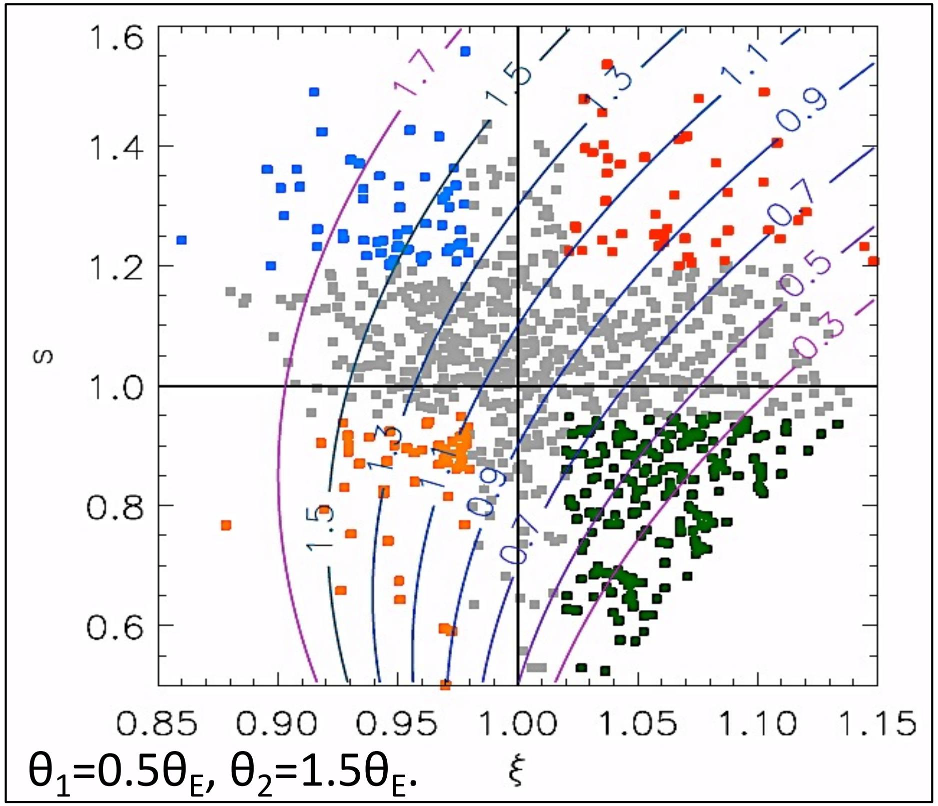
Lesson – 1:



1. A (constant) physical mass sheet (large-scale environment)

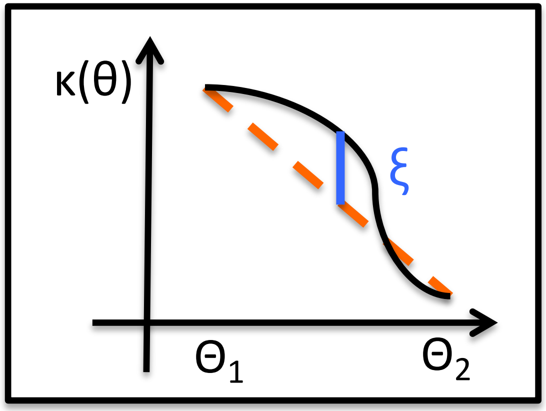
Line of sight structures
(see Li Nan's talk @ #prerecorded_talk_discussion channel)

2. Using too rigid parametric lens mass model, which can artificially breaks the MSD and lead to a purely mathematical MST and thus a factorial bias λ in H_0.



In both Illustris and EAGLE simlations
Xu et al. 2016, Tagore et al. 2017

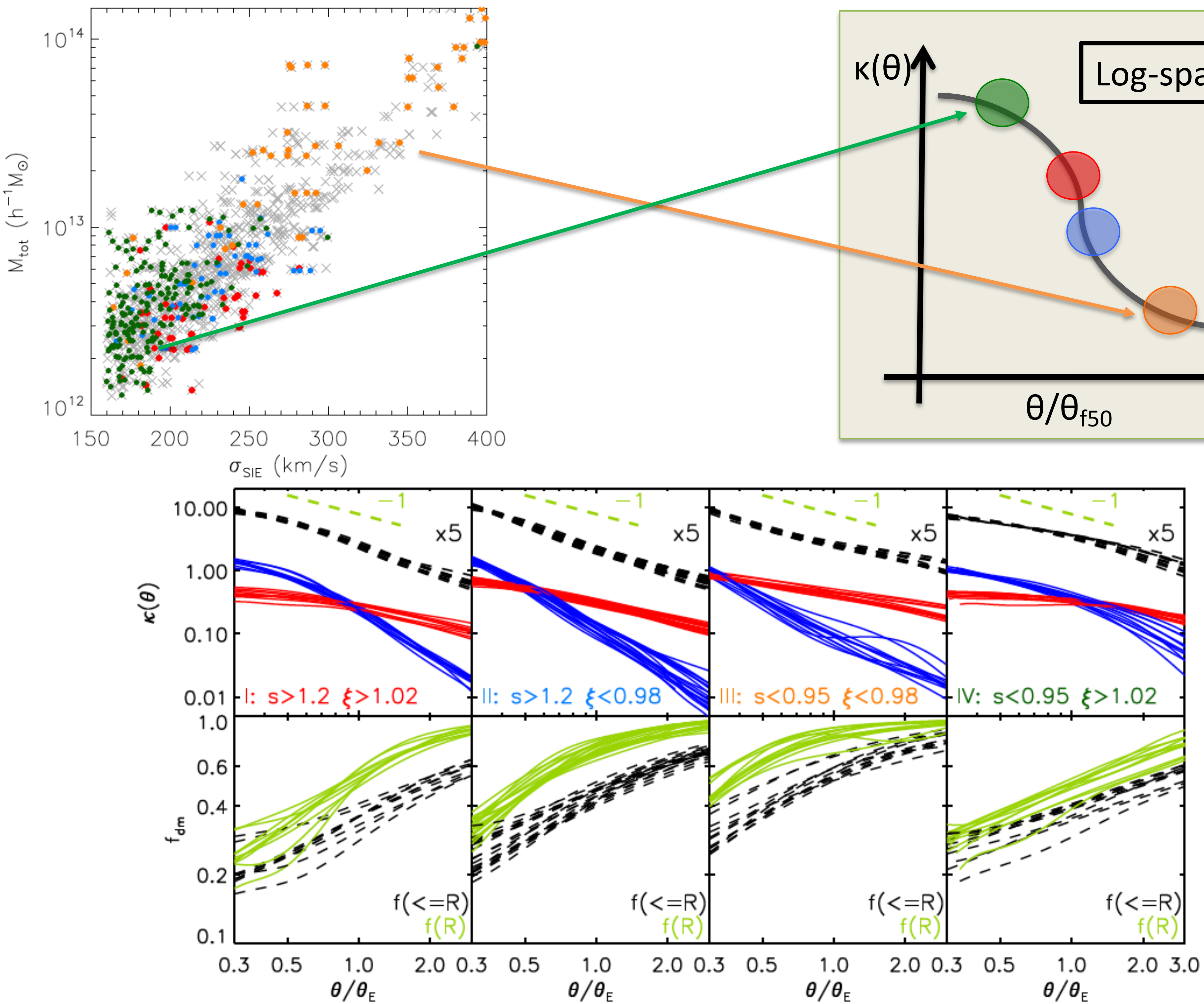
$$\rho(r) \propto r^{-\gamma'}$$



$$s \equiv \frac{\ln(\kappa_2/\kappa_1)}{\ln(\theta_1/\theta_2)},$$

$$\xi \equiv \frac{\kappa(\sqrt{\theta_1\theta_2})}{\sqrt{\kappa_1\kappa_2}},$$

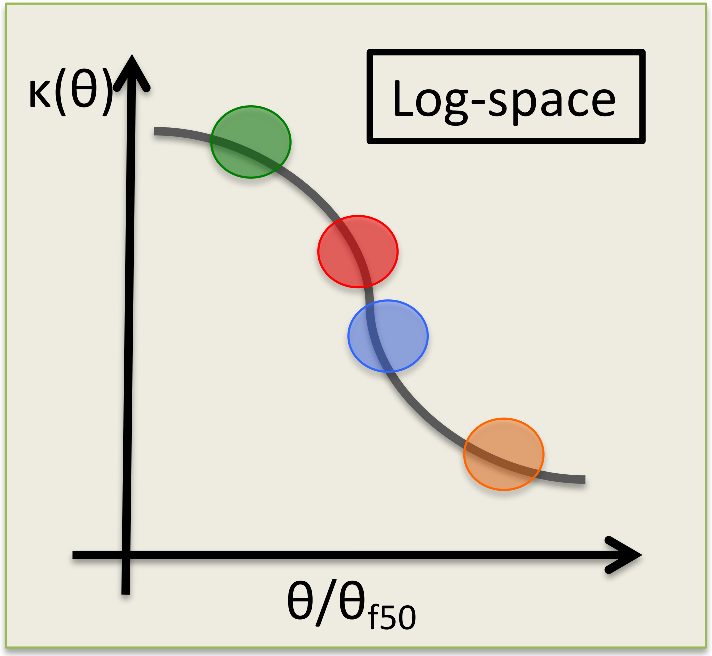
In general galaxies have total density profiles close to power-law and isothermal (γ'~2 or s~1).

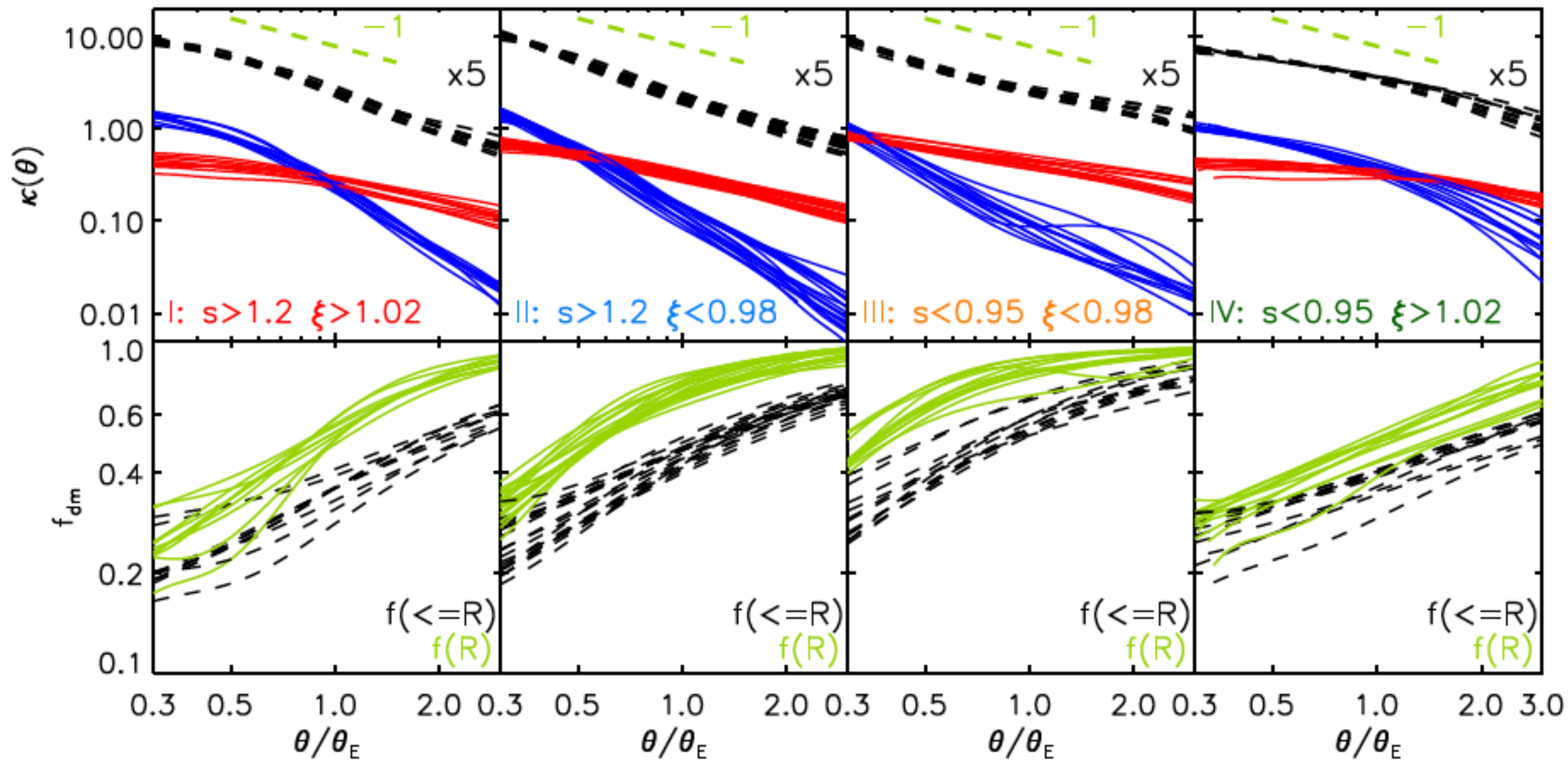


M_{tot} ($h^{-1}M_\odot$)
σ_{SIE} (km/s)
κ(θ)
Log-space
θ/θf50
I: s>1.2 ξ>1.02
II: s>1.2 ξ<0.98
III: s<0.95 ξ<0.98
IV: s<0.95 ξ>1.02
x5
−1
f(<=R)
f(R)
κ(θ)
f_{dm}
θ/θE

Why diverse profile parameters?

Strong lensing probes different parts of the density distribution, depending on the relative contribution of dark and baryonic matter. ***But surely no reason to guarantee a good power-law approximation within a strong lensing zone!***





When the PL assumption meets mass-sheet degeneracy

Mass-sheet degeneracy, power-law models and external convergence: Impact on the determination of the Hubble constant from gravitational lensing (2013)

Peter Schneider[1] & Dominique Sluse[1]

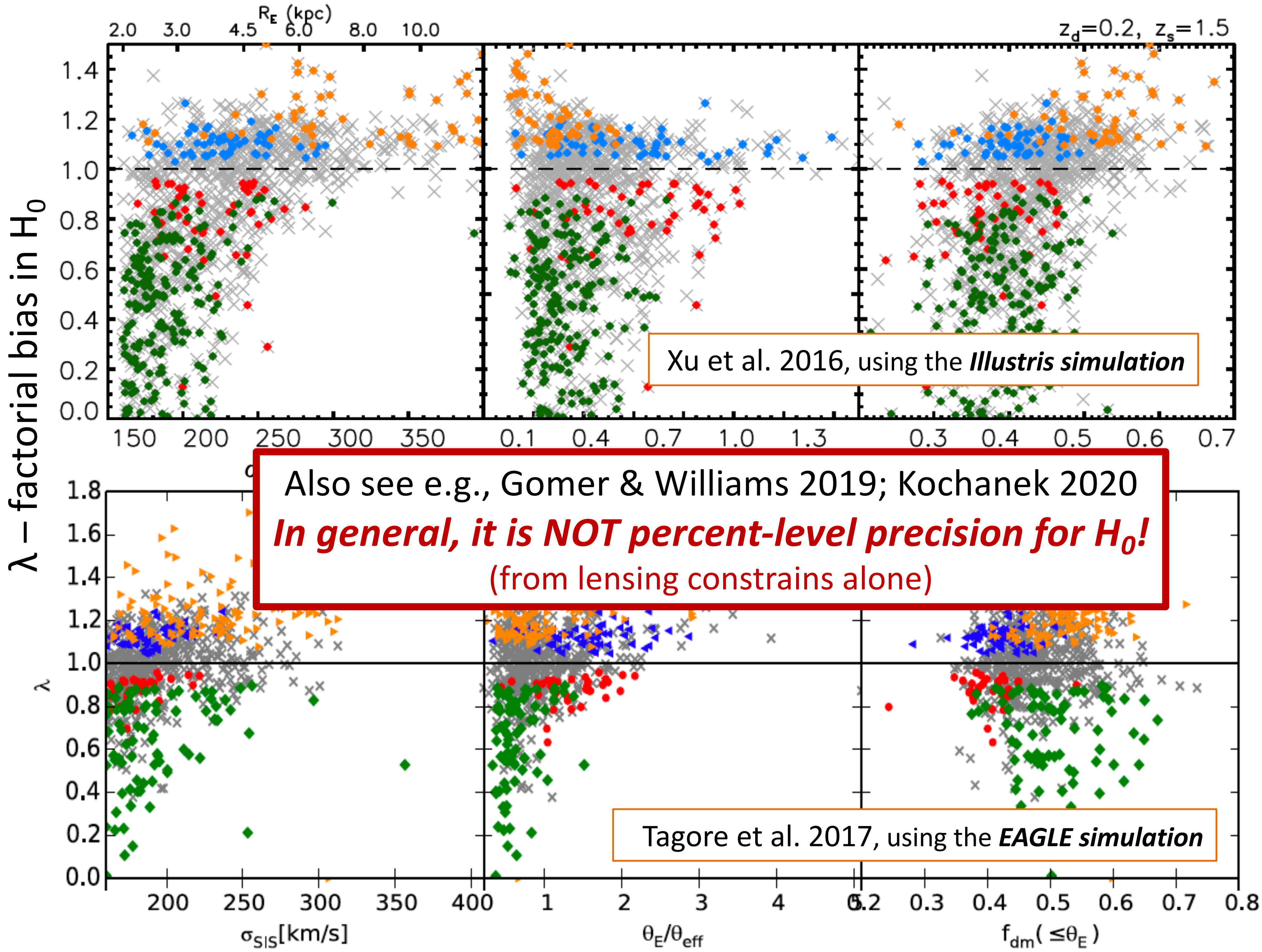
$$\boxed{\lambda} = \frac{\kappa_2 + \kappa_1 - 2\xi\sqrt{\kappa_2\kappa_1}}{\kappa_2 + \kappa_1 - 2\xi\sqrt{\kappa_2\kappa_1} + (\xi^2 - 1)\kappa_2\kappa_1} \Rightarrow \xi_\lambda = \frac{\kappa_\lambda(\sqrt{\theta_1\theta_2})}{\sqrt{\kappa_\lambda(\theta_1)\kappa_\lambda(\theta_2)}} = 1,$$

factorial bias in H_0

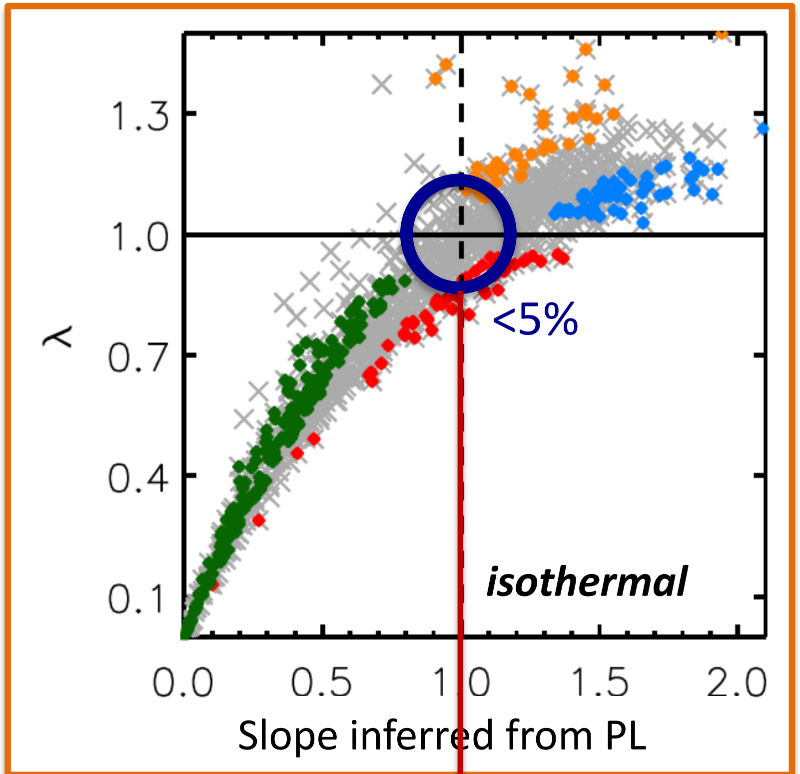
i.e., the transformed local convergence become PL.

Schneider & Sluse (2013): the surface density profile of a realistic two-component galaxy model can be transformed to a power-law with λ ~ 1.2, i.e., a systematic error of 20% on H_0.

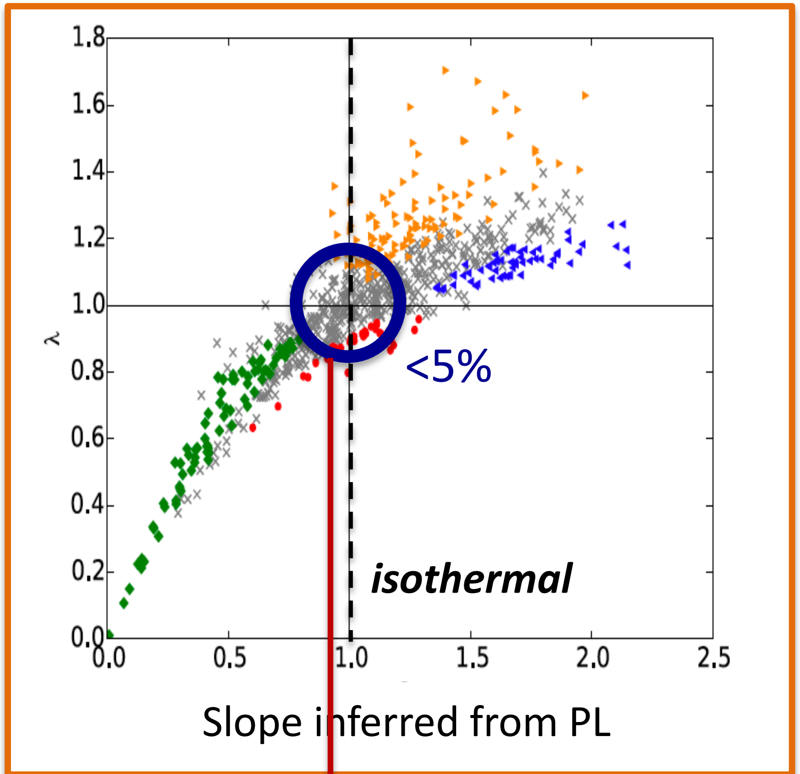
How about galaxies from state-of-the-art cosmological simulations?


R_E (kpc)
2.0 3.0 4.5 6.0 8.0 10.0
z_d=0.2, z_s=1.5
λ – factorial bias in H_0
1.4 1.2 1.0 0.8 0.6 0.4 0.2 0.0
150 200 250 300 350
0.1 0.4 0.7 1.0 1.3
0.3 0.4 0.5 0.6 0.7
Xu et al. 2016, using the Illustris simulation
Also see e.g., Gomer & Williams 2019; Kochanek 2020
In general, it is NOT percent-level precision for H_0!
(from lensing constrains alone)
λ
1.8 1.6 1.4 1.2 1.0 0.8 0.6 0.4 0.2 0.0
200 250 300 350 400
σ_SIS[km/s]
0 1 2 3 4 5
θ_E/θ_eff
0.2 0.3 0.4 0.5 0.6 0.7 0.8
f_dm(≤θ_E)
Tagore et al. 2017, using the EAGLE simulation

Time to panic? No, of course not!

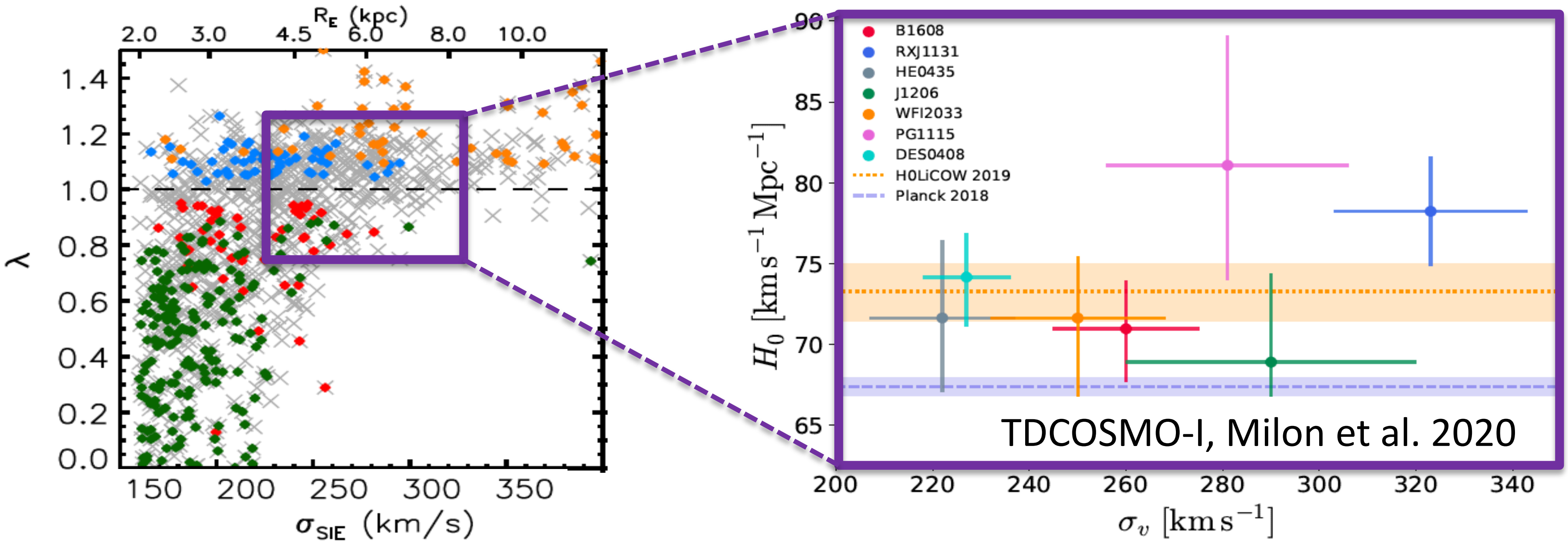


Xu et al. 2016, using the ***Illustris simulation***

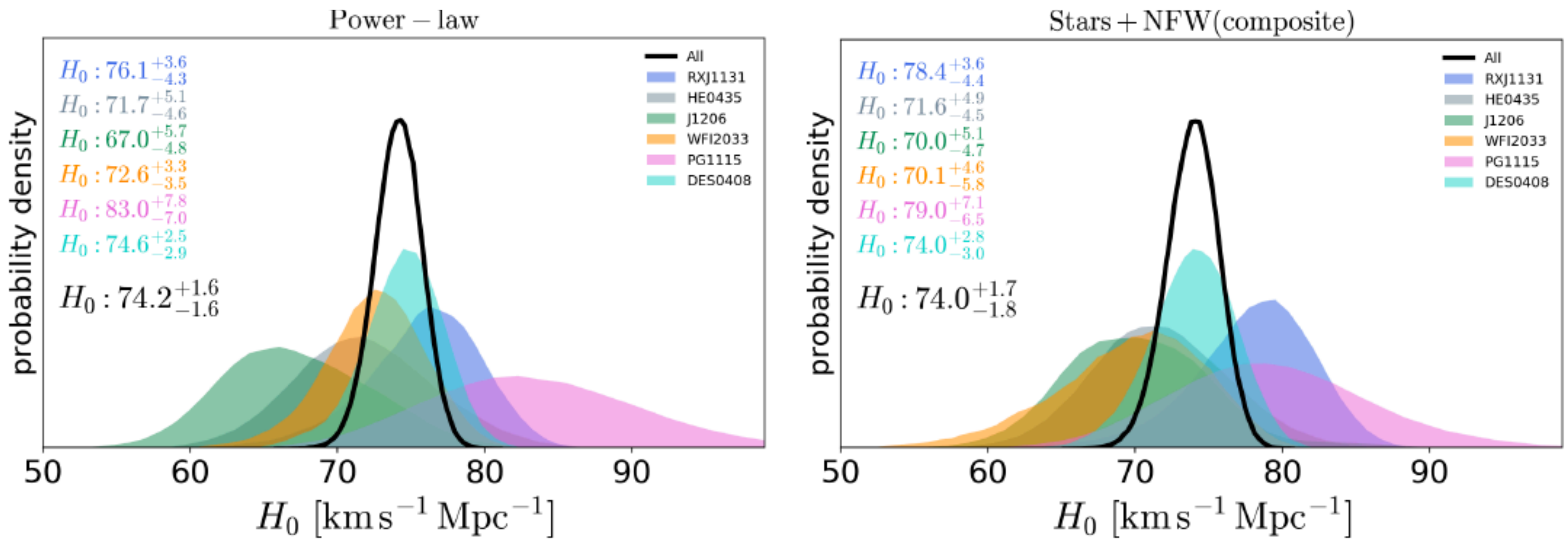


Tagore et al. 2017, using the ***EAGLE simulation***

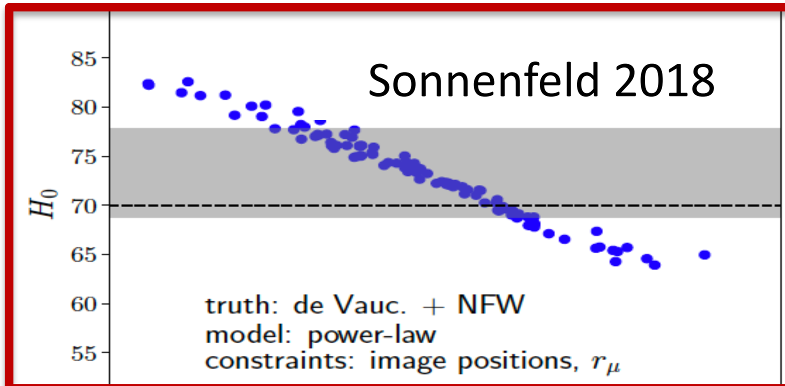
Typical values of the 3D PL-slope measured for time delay lenses are 1.92+/-0.15 [e.g., Suyu et al. 2010; Agnello et al. 2016; Wong et al. 2017]



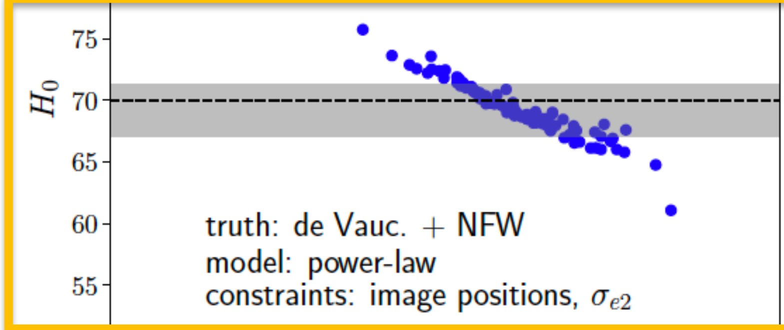
- A bad PL fitting wouldn't go unnoticed for hi-res deep image data



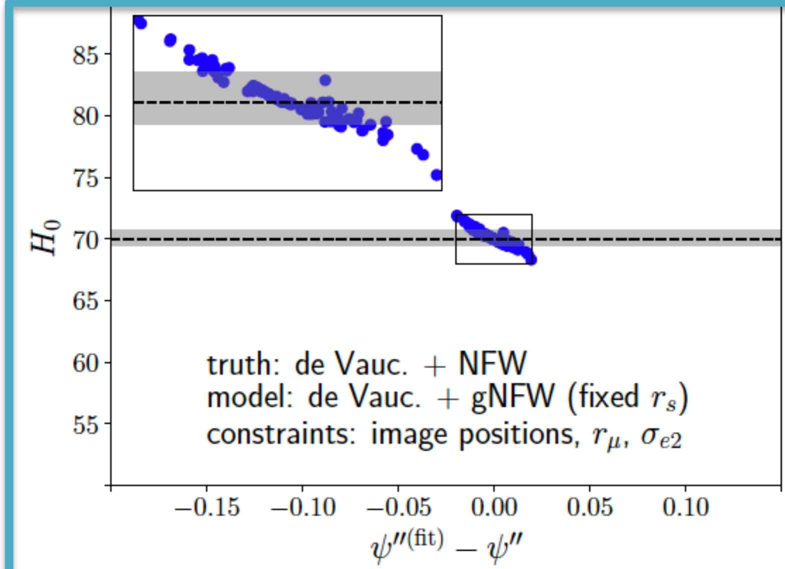
- Consistent results in TDCOSMO between ***PL*** and ***composite*** models also suggest convergence behavior of TD lens (TDCOSMO-I, Milon et al. 2020)



- Using PL model to fit lensing data alone, test lenses with equivalent local PL slopes within a narrower range γ'~ [1.6-2.2] may also have 5% level bias in H_0 and a scatter of 6%.



- Using PL model to fit to combined data of lensing ***+ stellar kinematics***, bias and scatter are largely reduced (3% accuracy)!



- Using ***two-component composite model*** to fit to combined data of lensing ***+ stellar kinematics***, 1% accuracy can be reached!

❖ See @ # prerecorded_talk_discussion: Simon Birrer's talk and Matt Gomer's talk

Where it helps!

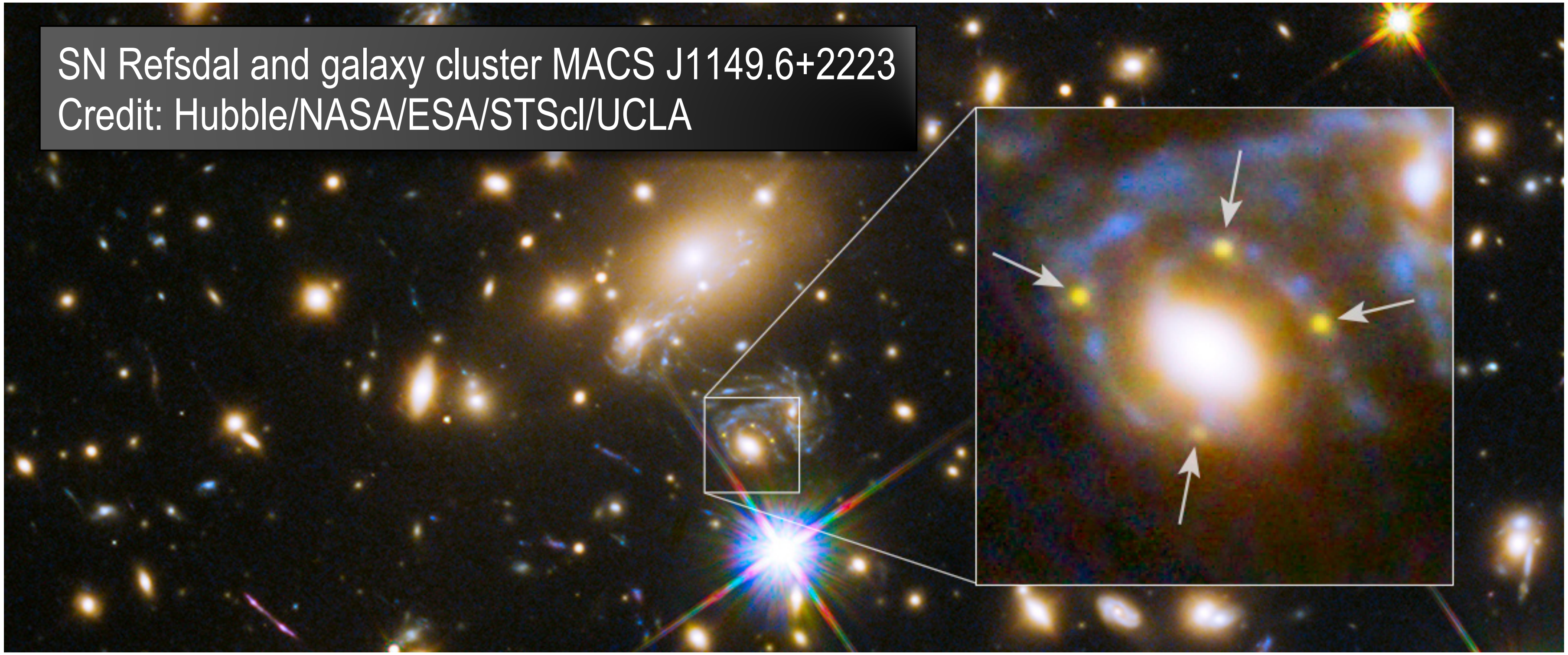
Where it fails!!

See also e.g., Shajib et al. 2018, Milon et al. 2020, Birrer et al. 2020

Another way to break the degeneracy:

$$\mu \to \mu/\lambda^2$$

- *MST changes absolute magnitude!*
- *If intrinsic luminosity is known, then the degeneracy can be correctly broken!*
- *This is why SNIa lensing is interesting!*
- *This is why micro-lensing free and dust-attenuation free SNIa lensing is important!*



In order to test various systematics:

Time Delay Lens Modeling Challenge: I. Experimental Design

Xuheng Ding,[1,2★] Tommaso Treu,[1] Anowar J. Shajib,[1] Dandan Xu,[3] Geoff C.-F. Chen,[4] Anupreeta More,[5] Giulia Despali,[6] Matteo Frigo,[6] Christopher D. Fassnacht,[4] Daniel Gilman,[1] Stefan Hilbert,[7,8] Philip J. Marshall,[9] Dominique Sluse,[10] Simona Vegetti[6]

Time Delay Lens modelling Challenge: II. Results

X. Ding,[1★] T. Treu,[1] S. Birrer,[2] G. C.-F. Chen,[3] J. Coles,[4] P. Denzel,[5,6] M. Frigo,[7] A. Galan,[8] P. J. Marshall,[9] M. Millon,[8] A. More,[10] A. J. Shajib,[1] D. Sluse,[11] H. Tak,[12,13,14,15,16] D. Xu,[17] M. W. Auger,[18] V. Bonvin,[8] H. Chand,[19,20] F. Courbin,[8] G. Despali,[7] C. D. Fassnacht,[3] D. Gilman,[1] S. Hilbert,[21,22] S. R. Kumar,[19] Y.-Y. Lin,[23] J. W. Park,[9] P. Saha,[6,5] S. Vegetti,[7] L. Van de Vyvere,[11] L. L.R. Williams,[24]

- See @ # prerecorded_talk_discussion: Xuheng Ding's talk on the time-delay challenge!

Potential drawbacks of using current cosmological simulation:

Lesson – 2:

- Current state-of-the-art cosmological simulations generally reach a softening scale of 200-700pc; while "lack of central image" observations constrain core size of 5-100pc for typical TD lenses.
  ➔ a cuspy lens mass model would not well fit the mock data where a potentially artificial core is present.

- Removal of subhalos can potentially result in inconsistent lensing convergence maps (subhalo-free) and stellar kinematics data (subhalo-effects included).

➔ Kinematic data may not help to break the degeneracy correctly!

- Halo truncation for lensing maps may potentially introduce negative mass-sheet transformation and artificial shear.

Is a kappa map all to a lensing mock? – The Art of Density Truncation

Lesson – 3:

The impact of mass map truncation on strong lensing simulations

Lyne Van de Vyvere[1,⋆], Dominique Sluse[1], Sampath Mukherjee[1], Dandan Xu[2], and Simon Birrer[3] 2020

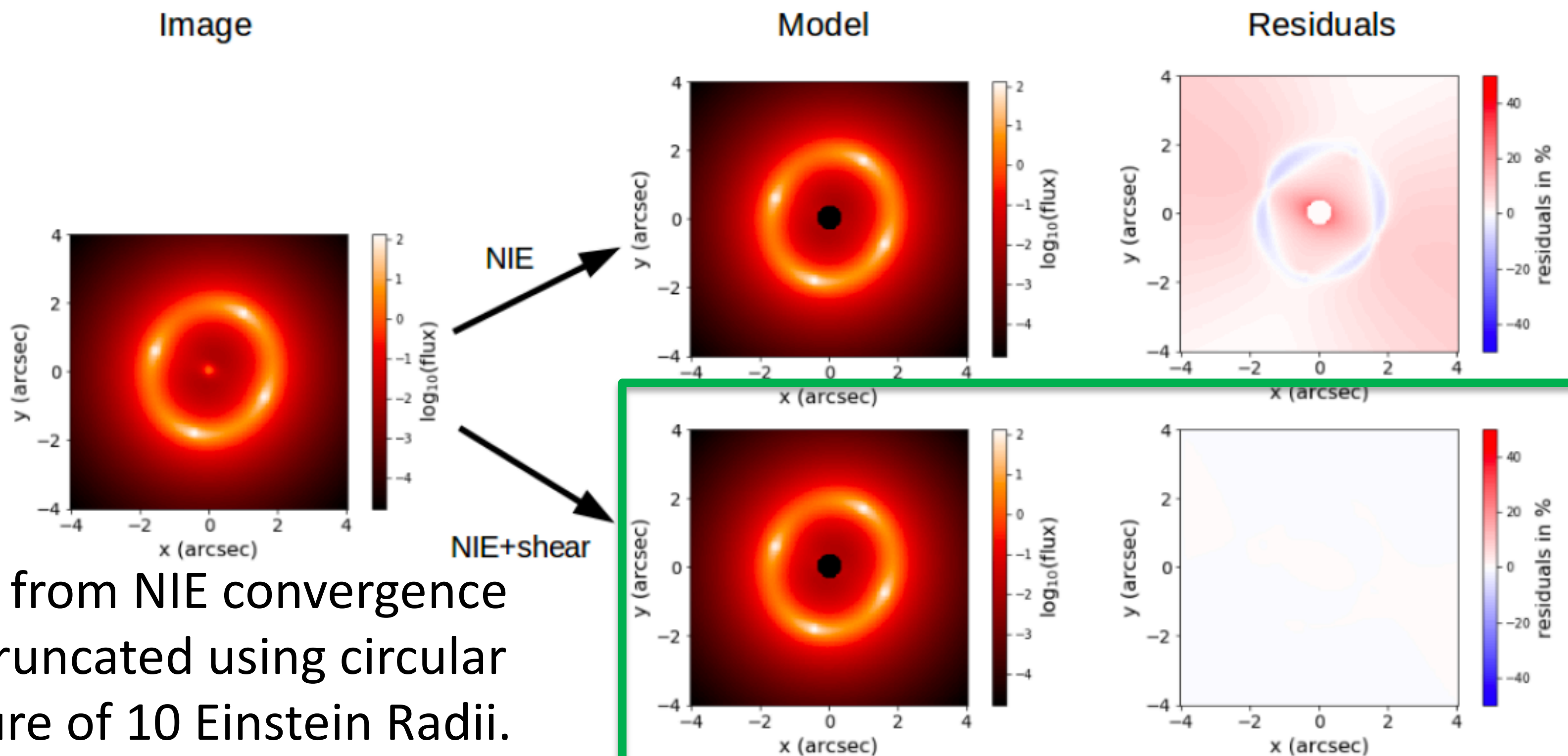


Image from NIE convergence field truncated using circular aperture of 10 Einstein Radii.

A safe circular truncation radius ~ 50 Einstein Radii, corresponding to a maximum shear ~0.001

Introduce artificial shear and result in percent level bias on H_0

Things that work and things that may work but with caution!

- **Lesson-1:** When power-law meets invariance transformation
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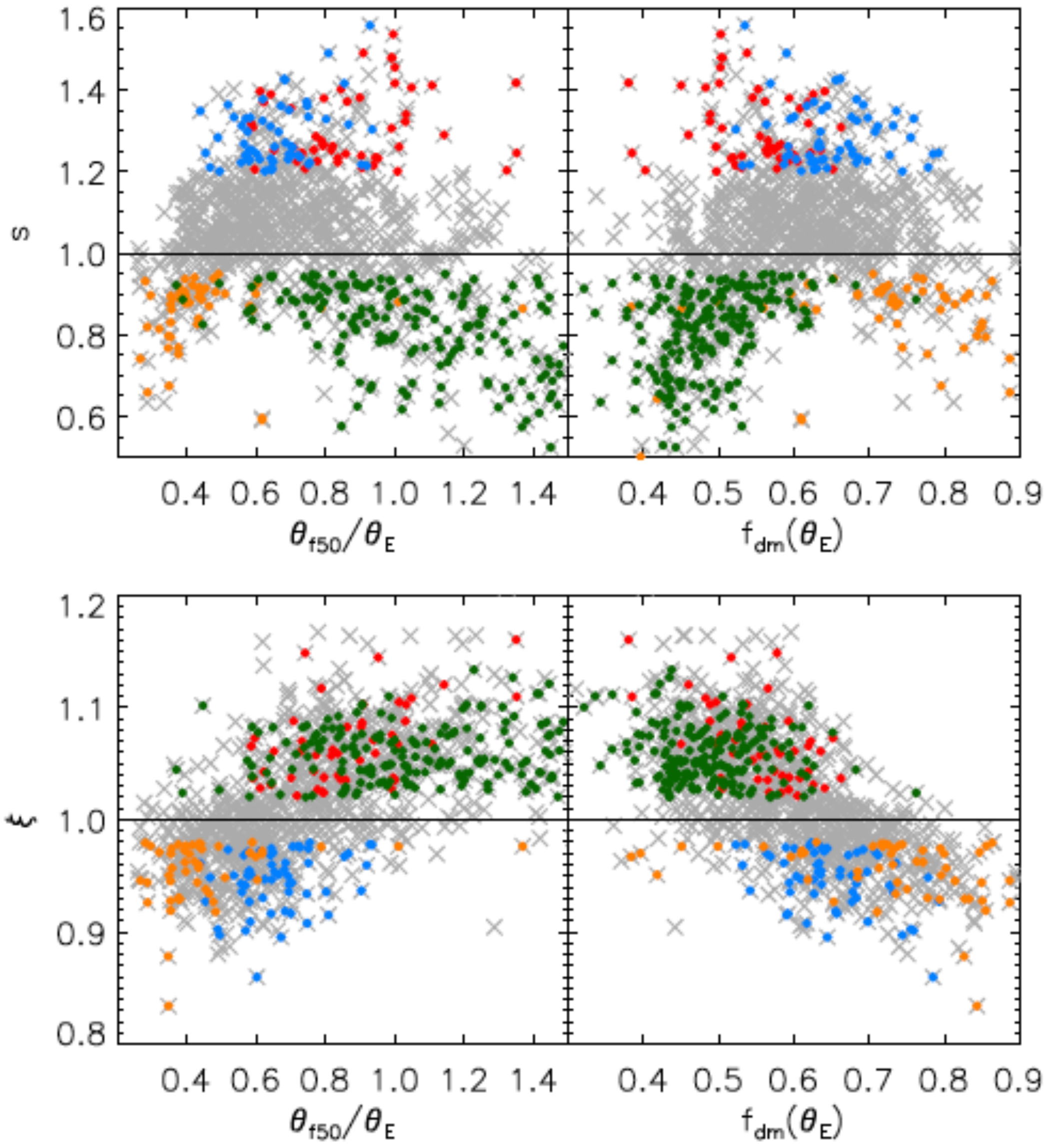
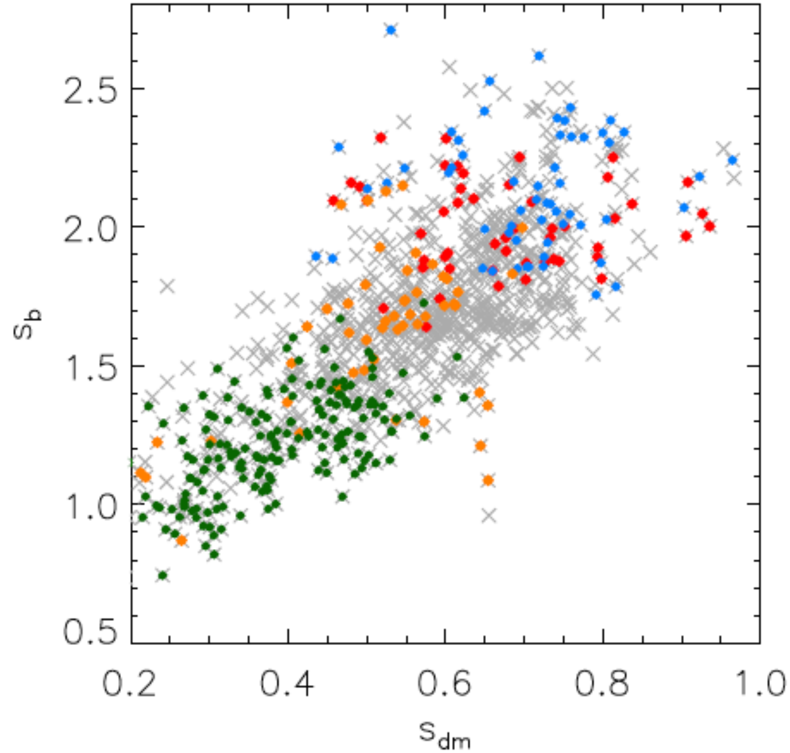
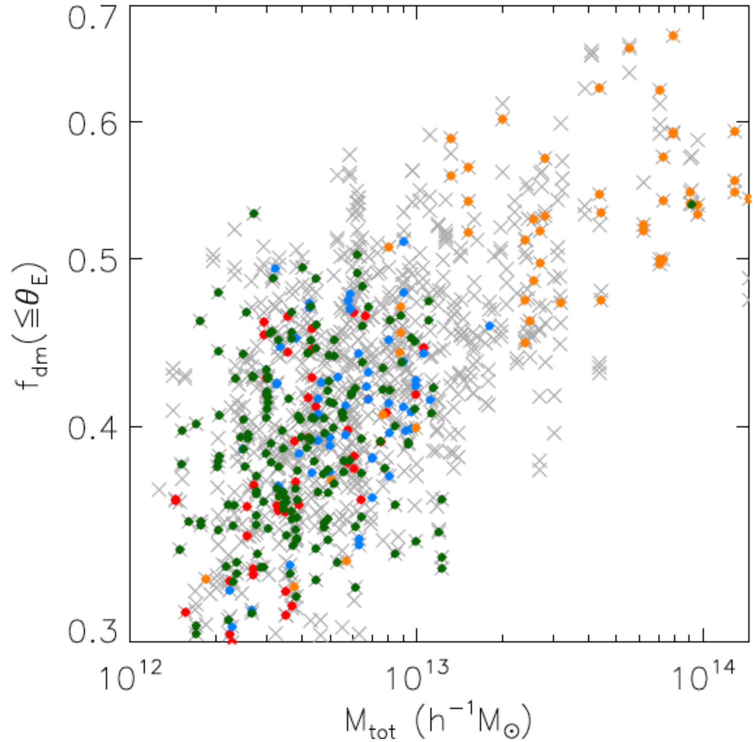
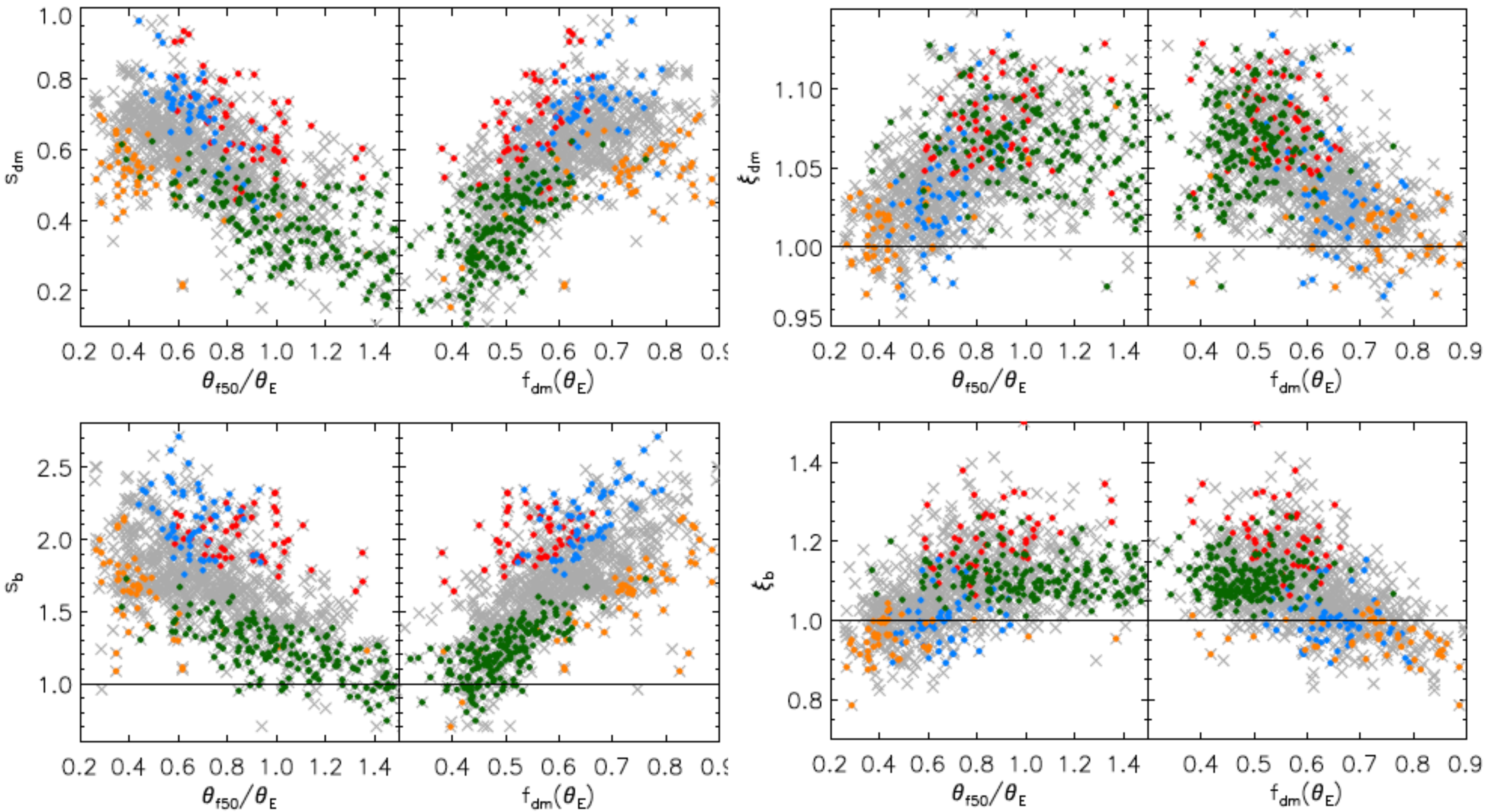
concentrated (and steeper) than the former. Good correlations exist between the dark and baryonic density slopes throughout the projected radii and redshifts studied in this work, indicating the strong interplay between dark matter and baryons in central regions of galaxies.

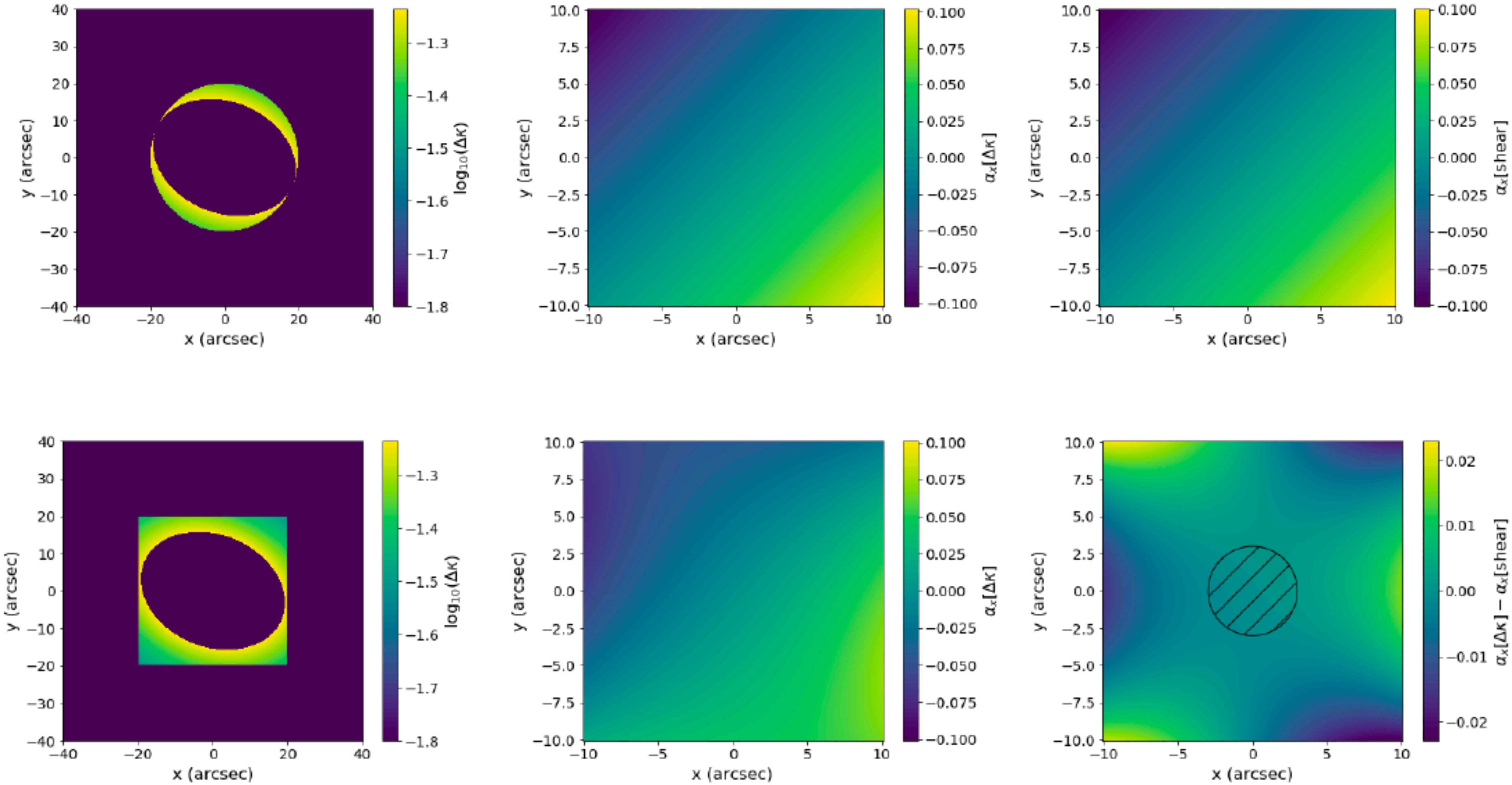








s_{dm}
θ_{f50}/θ_E
$f_{dm}(\theta_E)$
ξ_{dm}
θ_{f50}/θ_E
$f_{dm}(\theta_E)$
s_b
θ_{f50}/θ_E
$f_{dm}(\theta_E)$
ξ_b
θ_{f50}/θ_E
$f_{dm}(\theta_E)$



x (arcsec)
y (arcsec)
log10(Δκ)
αx[Δκ]
αx[shear]
αx[Δκ] − αx[shear]