Cluster mass distributions (lessons from HFF)

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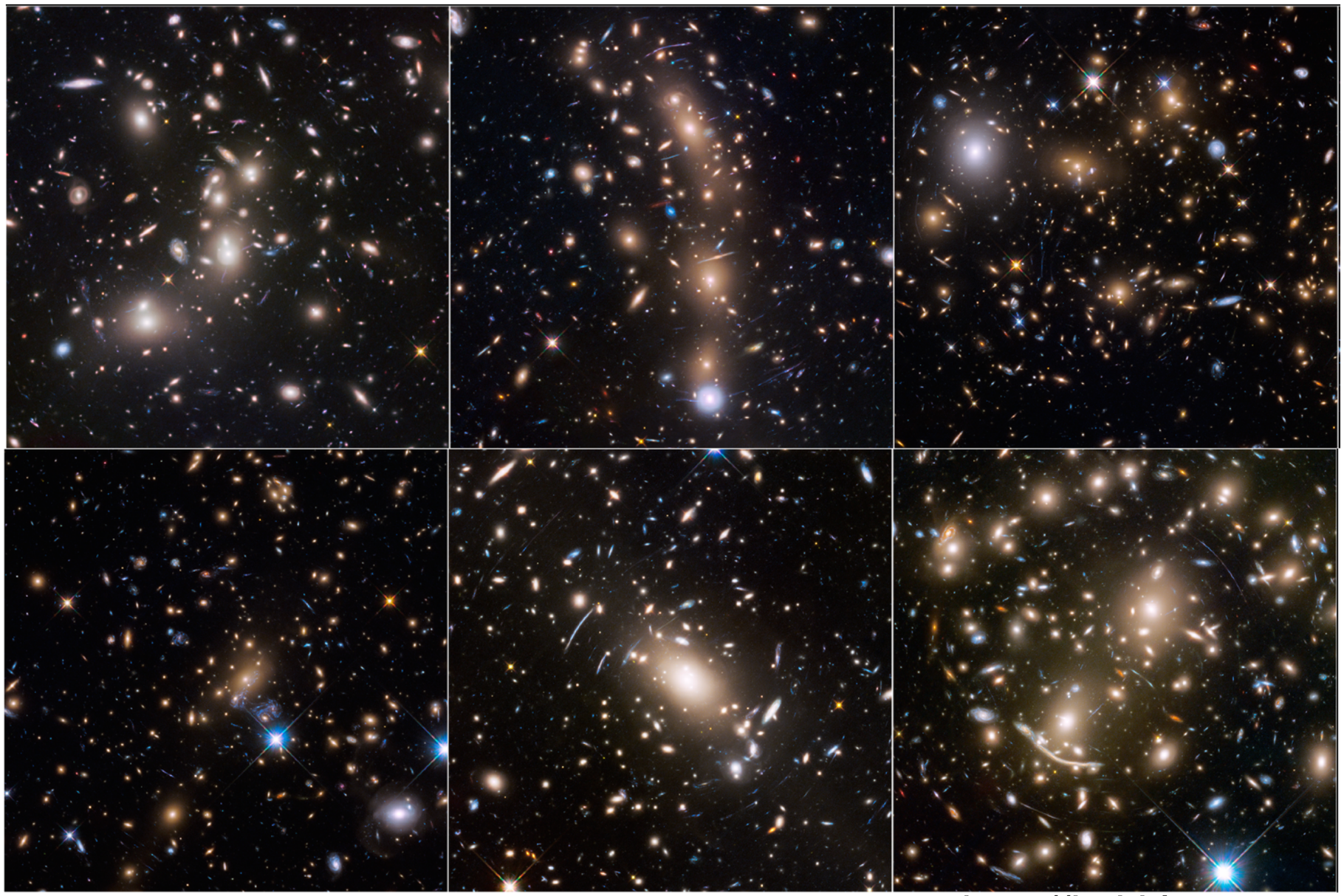
Lotz, Koekemoer, Coe+ ApJ **837**(2017)97

HST Frontier Fields (HFF)

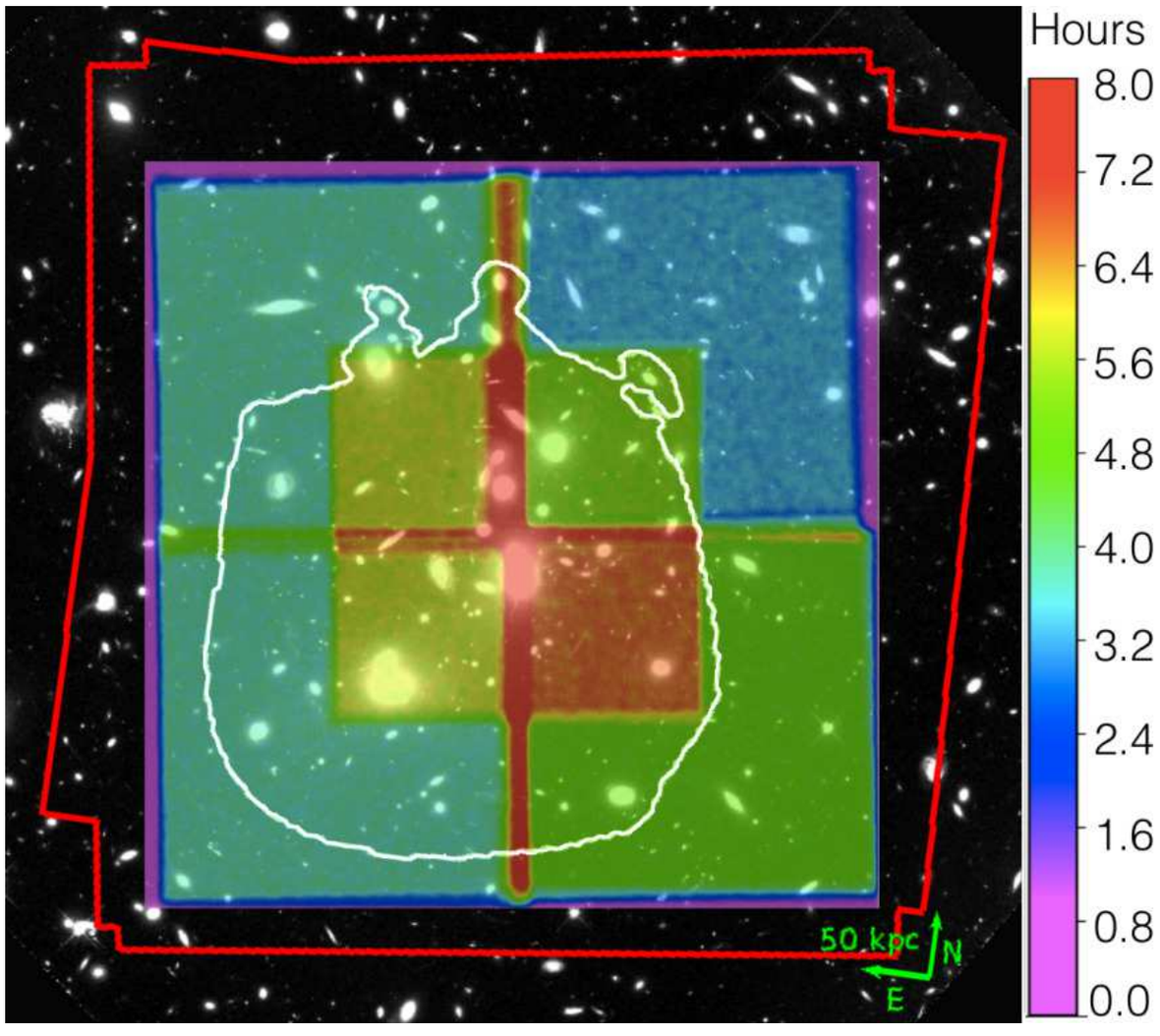
- >100 multiple images for each cluster led to significant progress in cluster strong lens study!



http://hubblesite.org

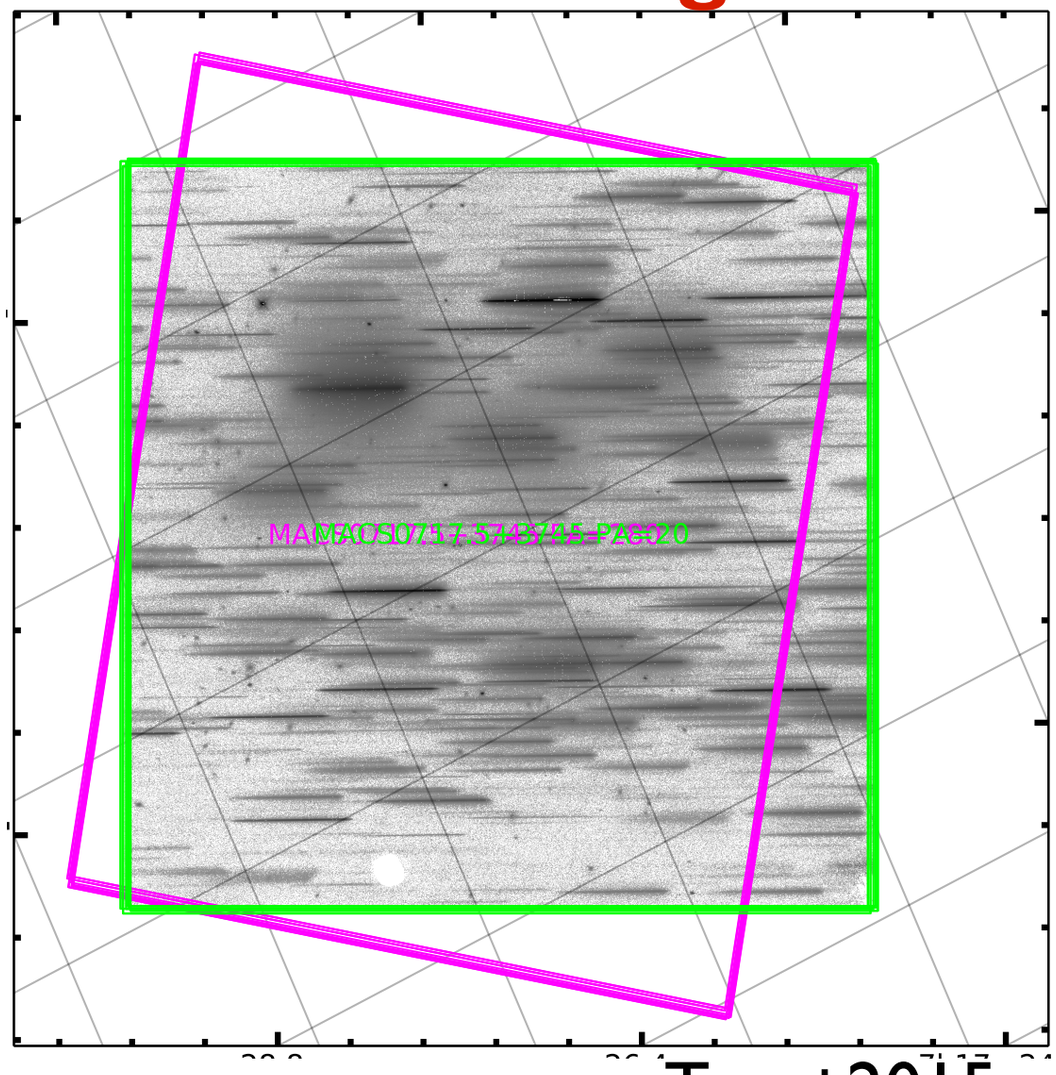
Spec-z revolutions

VLT MUSE



Mahler+2018

HST WFC3 grism



Treu+2015

- spec-z's for many multiple images
  → secure identifications & more constraints!

https://archive.stsci.edu/prepds/frontier/lensmodels/

HFF mass models (v3, v4)

Parametric

LENSTOOL

CATS

Sharon

Caminha

GLAFIC

GLAFIC

LENSMODEL

Keeton

(also GLEE by Grillo, Suyu+)

LTM

Zitrin

WSLAP+

Diego Bernstein

Grale

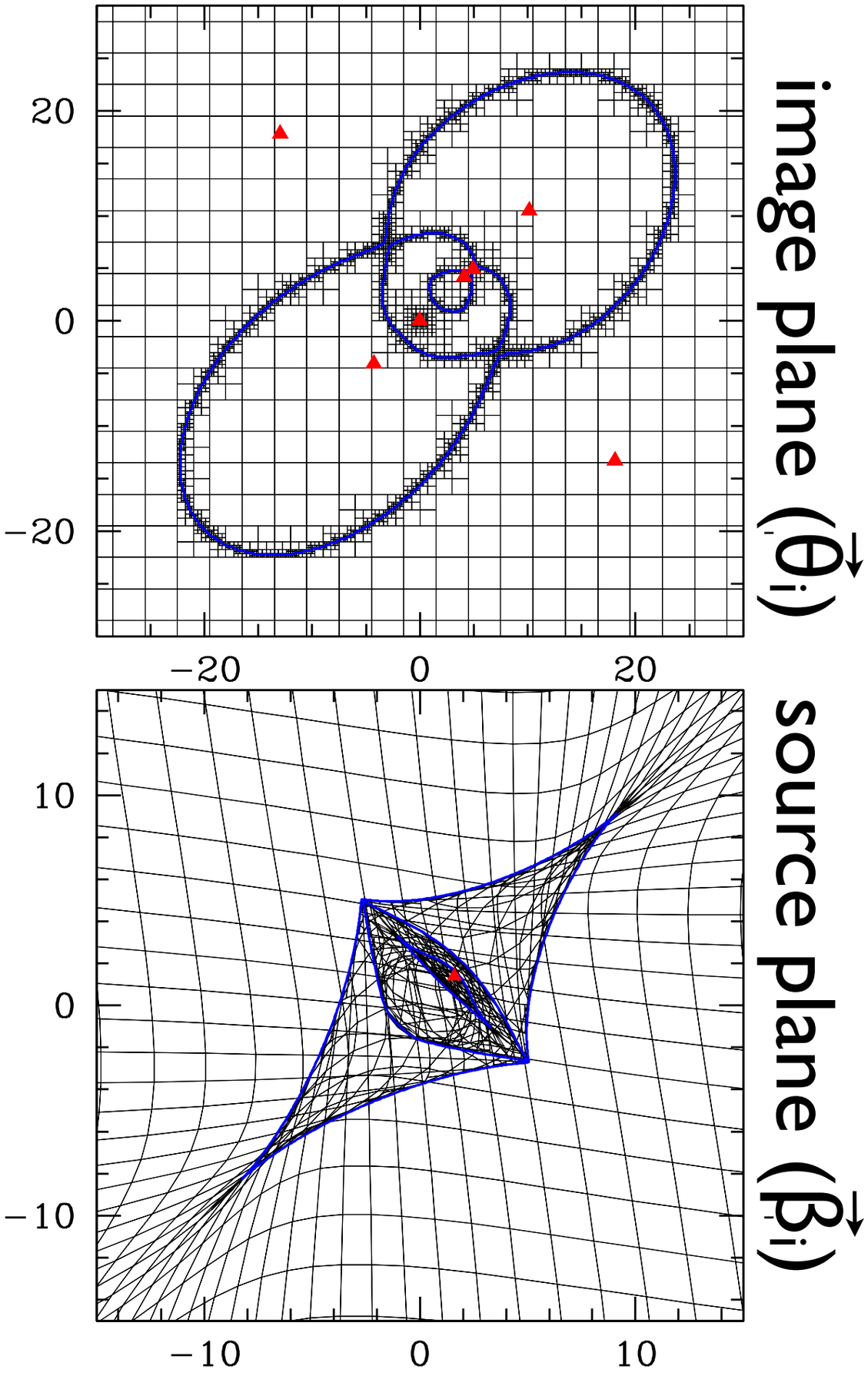
Williams

SWUnited

Bradac

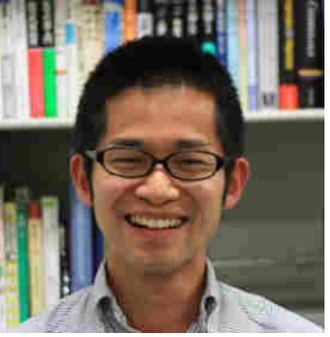
Non-Parametric

http://www.slac.stanford.edu/~oguri/glafic/



GLAFIC

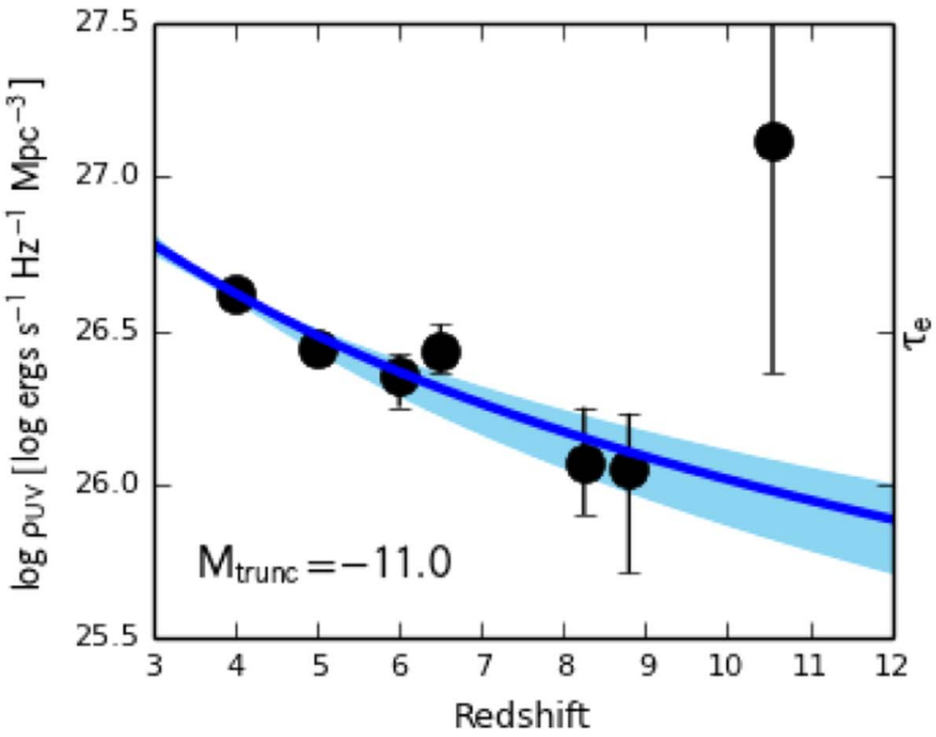
- public software for strong lensing analysis ("parametric" modeling)
- adaptive grid to solve lens equation efficiently
- support many kind of lens potentials
- see Kawamata, MO+ ApJ **819**(2016)114 for details of our HFF mass modeling

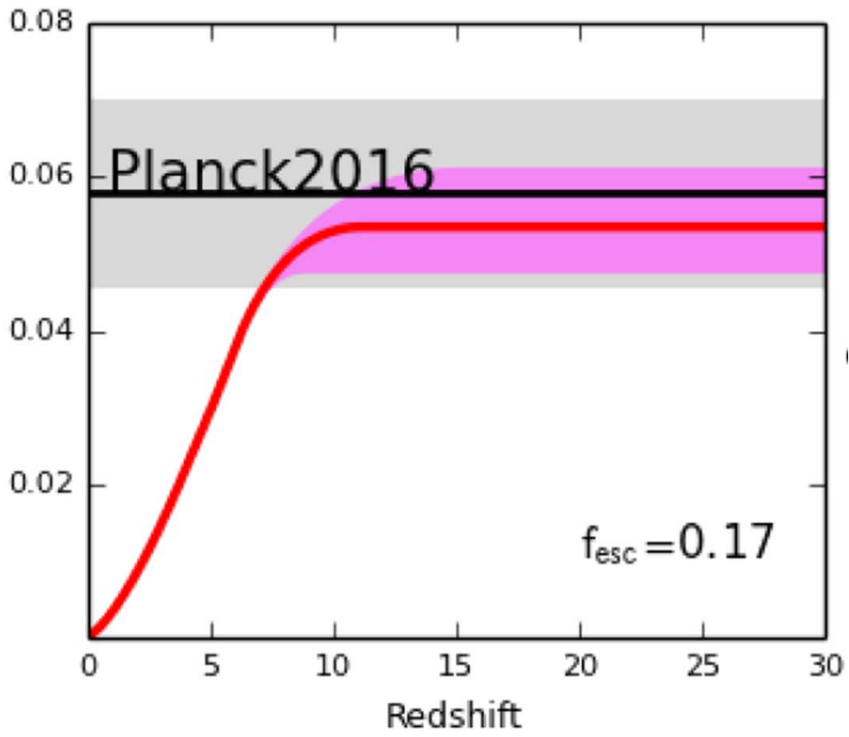


Ishigaki, Kawamata, Ouchi, MO+ ApJ **854**(2018)73

Some high-z galaxy results

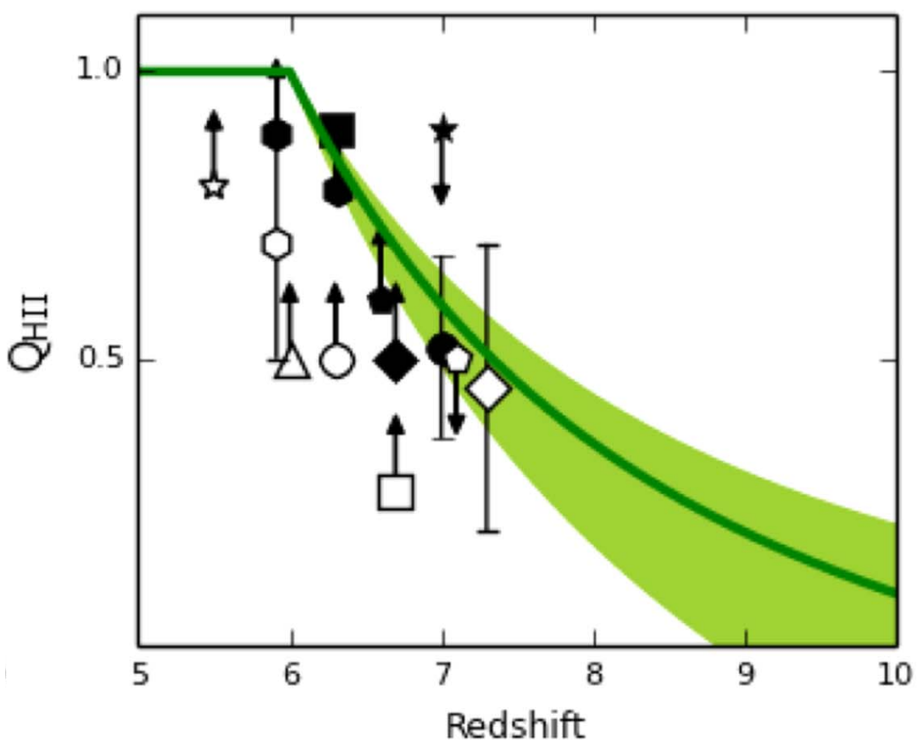
UV luminosity density





Thomson scattering optical depth

ionized hydrogen fraction



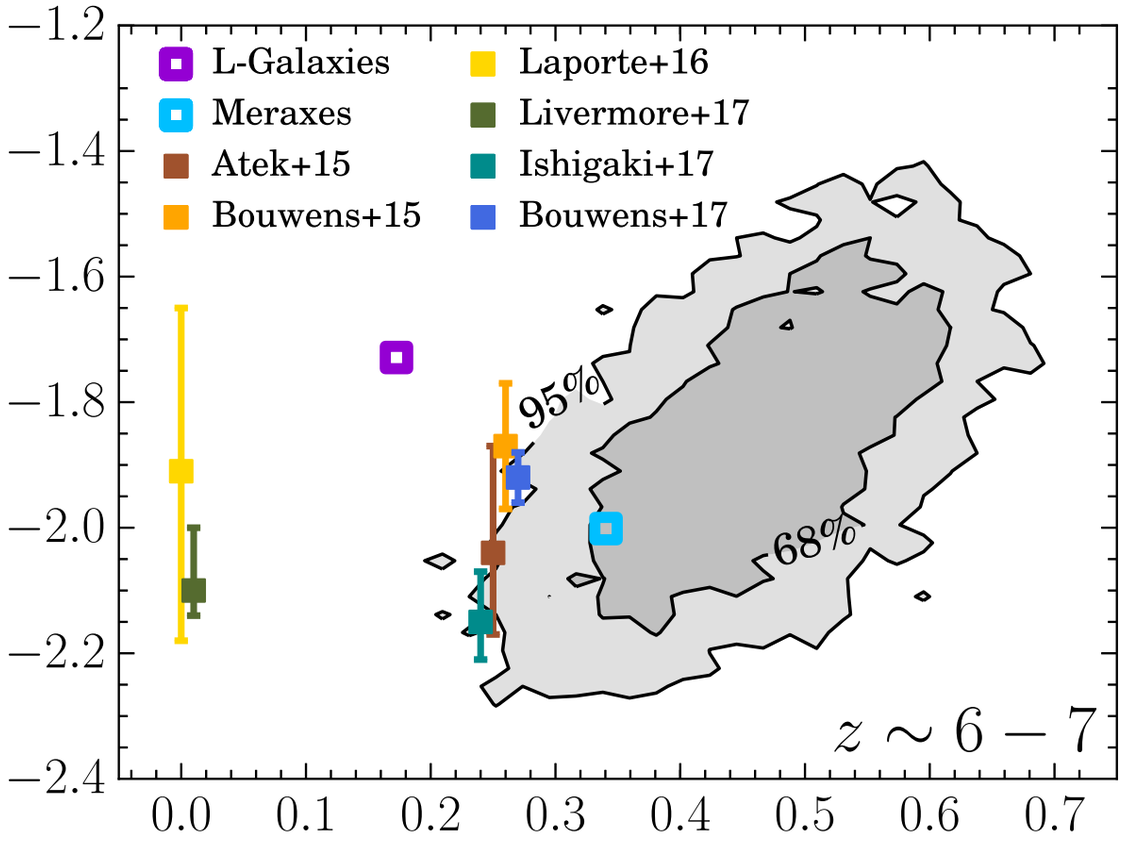
- analysis of all 6 HFF clusters
- a simple galaxy reion model can explain all observations

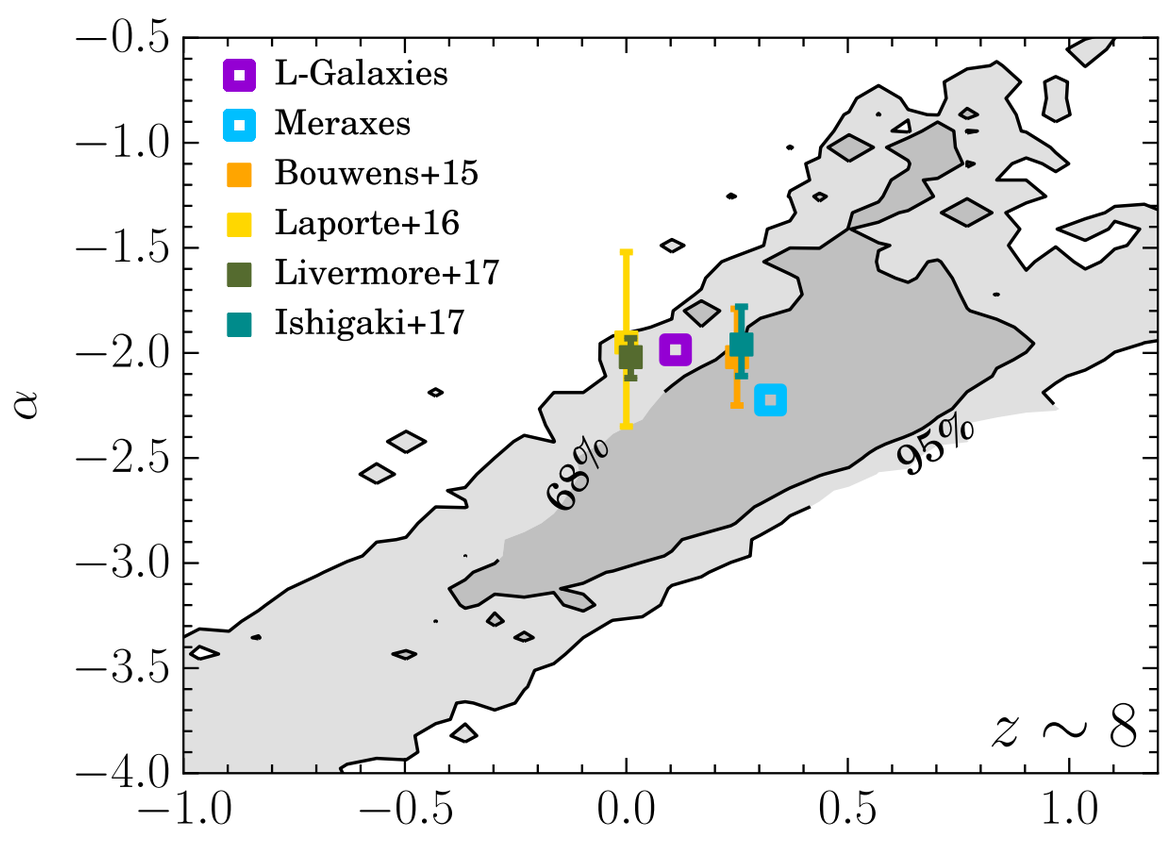
[also talks by D. Coe, R. Bouwens]

Kawamata, Ishigaki, Shimasaku, MO+ ApJ **855**(2018)4

Some high-z galaxy results

LF faint end slope





galaxy size $r_e \propto L^{\beta}$

- galaxy size important for galaxy LF measurements!
- degeneracy between LF and size parameters

[also talks by D. Coe, R. Bouwens]

Quantify goodness of mass models

- blind test from mass modeling of simulated strong lensing clusters (e.g., Meneghetti+2017)

  [talks by M. Meneghetti, C. Giocoli]

- blind test from magnifications and time delays of lensed SNe (e.g., Rodney+2015; Kelly+2015, 2016)

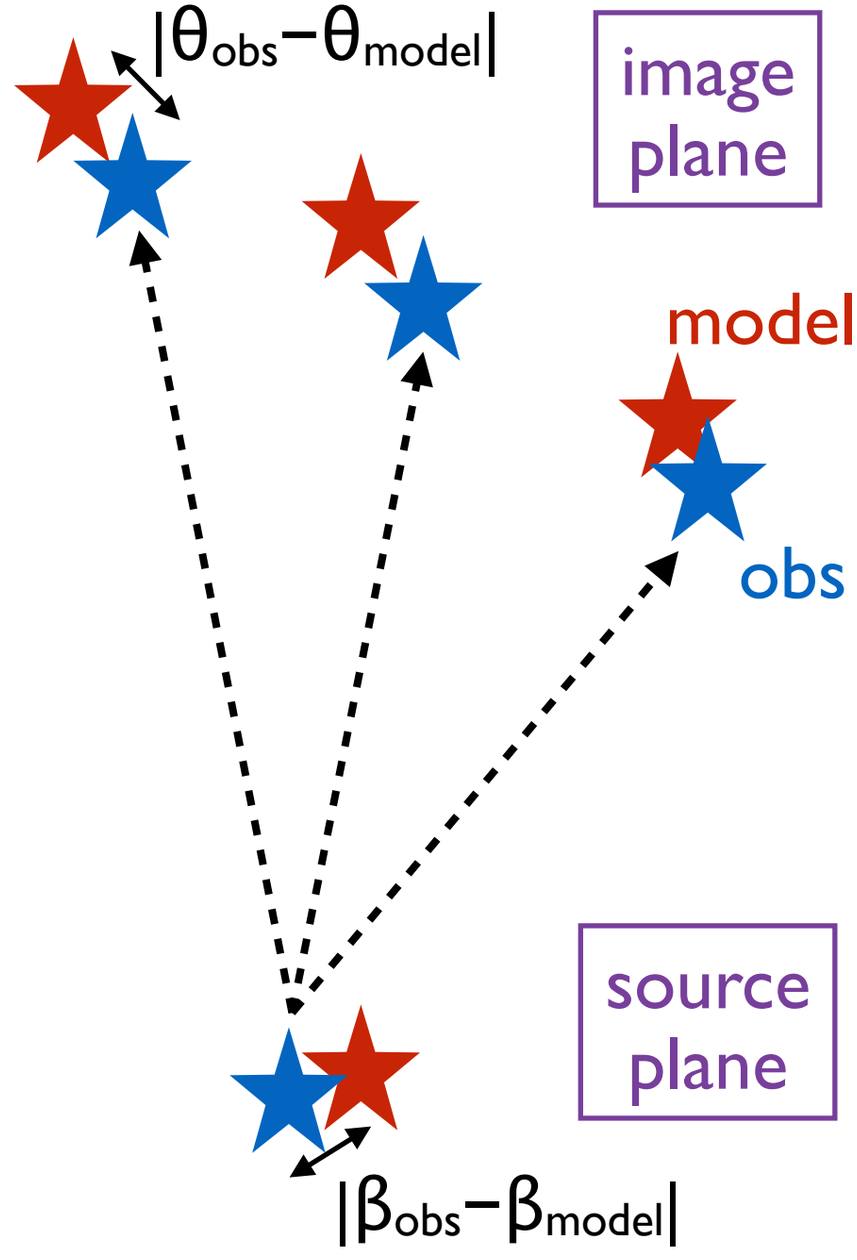
  [talks by N. Lyskova, P. Kelly, S. Rodney, T. Petrushevska]

- root-mean-square (RMS) of differences of multiple image positions btw obs and model

  [talks by G. Caminha, L. Williams]

RMS of multiple image positions

- typically 0.3″–0.7″ for HFF cluster mass modeling (worse than meas. error)
- many caveats:
  - smaller RMS does not necessarily mean better
  - overfitting? use training and test samples
    (e.g., Remolina Gonzalez+2018)
  - beware of misidentification of multiple images



How should we define RMS or χ^2?

(1) $\sum \frac{|\vec{\theta}_{\rm obs} - \vec{\theta}_{\rm model}|^2}{\sigma^2}$

estimate RMS in the image plane, robust but time-consuming

$\mathbf{M}^{-1} = \frac{\partial \vec{\beta}}{\partial \vec{\theta}}$

(2) $\sum \frac{|\mathbf{M}(\vec{\beta}_{\rm obs} - \vec{\beta}_{\rm model})|^2}{\sigma^2}$

estimate RMS in the source plane with mag tensor, very similar to (1) (see MO PASJ **62**(2010)1017)

(3) $\sum \frac{|\vec{\beta}_{\rm obs} - \vec{\beta}_{\rm model}|^2}{\mu^{-1}\sigma^2}$

approximated version of (2)

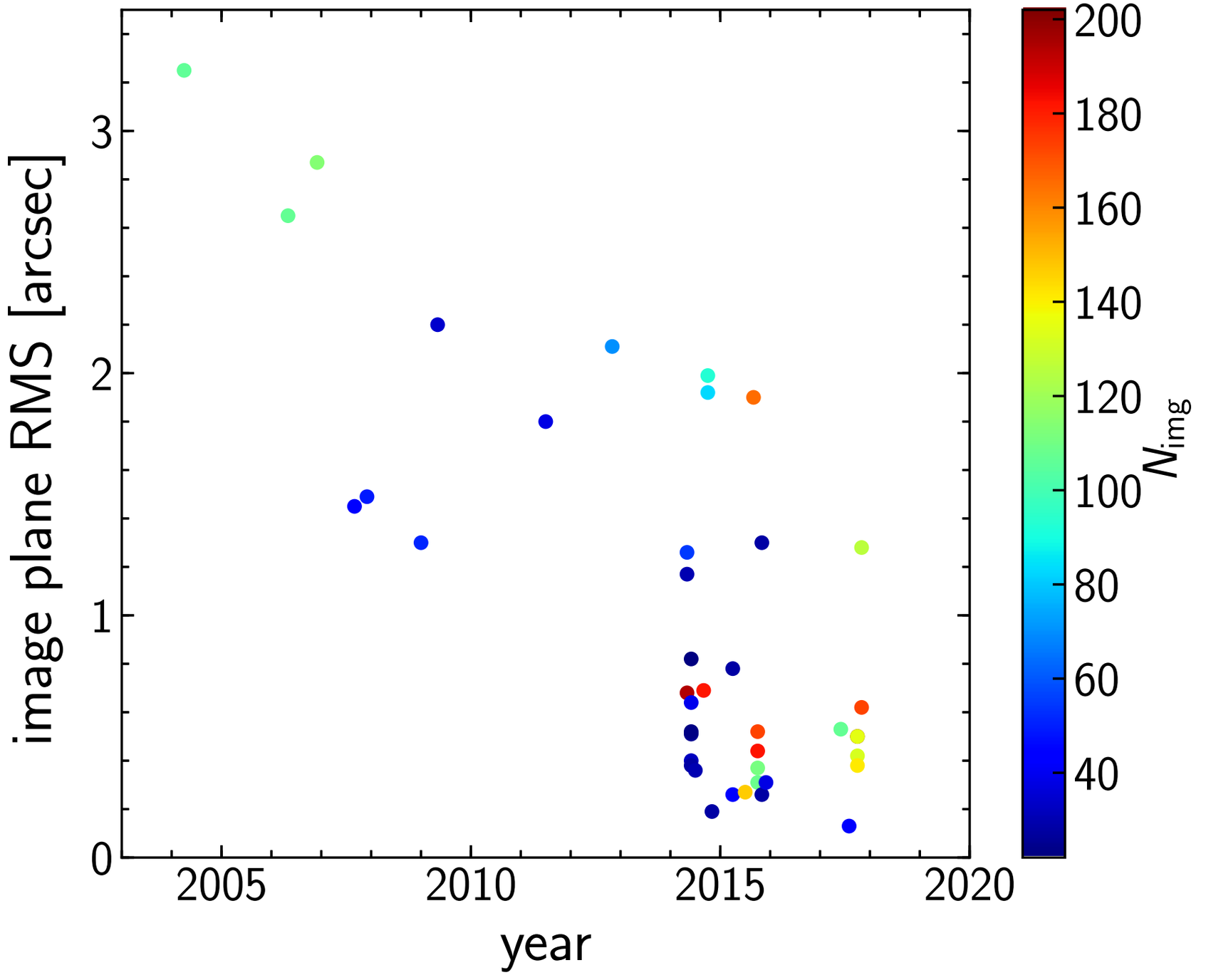
(4) $\sum \frac{|\vec{\beta}_{\rm obs} - \vec{\beta}_{\rm model}|^2}{\sigma^2}$

can be biased toward higher magnifications (flatter profiles)

choose proper one!

Improvements of RMS

- mass modeling of clusters w/ ≳50 multiple images
- plotted data not complete
- RMS getting better….



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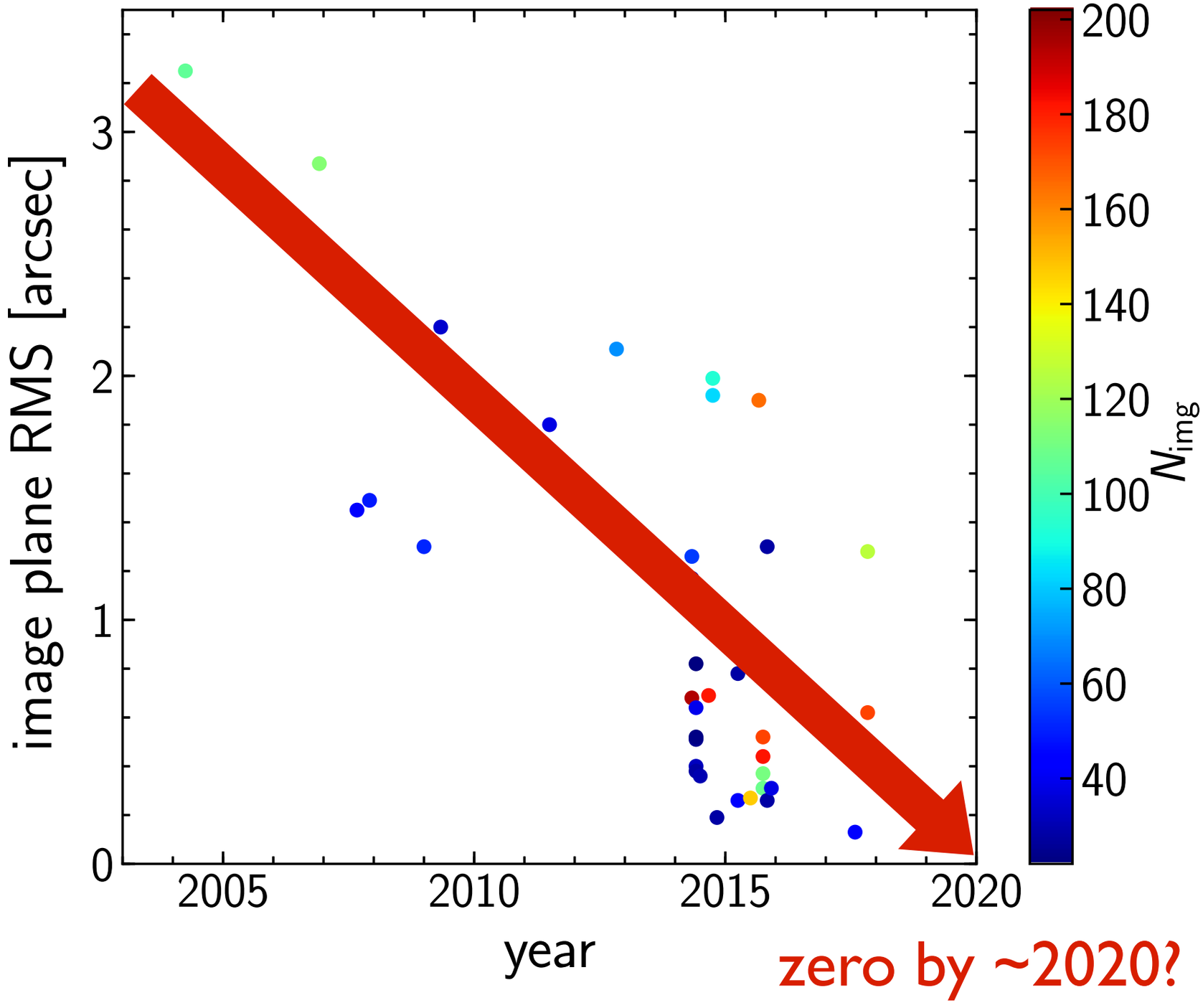


Open (?) questions

- can we improve (no-overfitting) RMS further, and if yes, down to what value?
- does RMS contain any useful cosmological information such as small scale power of density fluctuations?
- how well can we understand/model line-of-sight contributions?

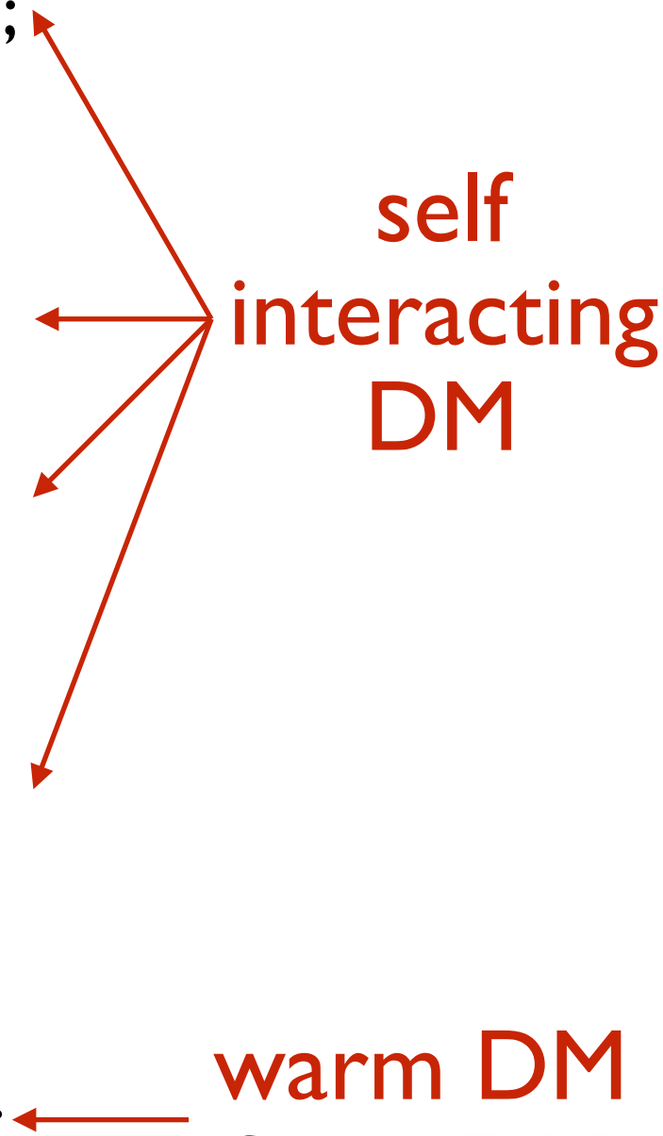
Cluster lensing and dark matter

- strong lensing allows us to accurately measure dark matter (DM) distribution near the cluster center

- it provides useful constraints on DM models!

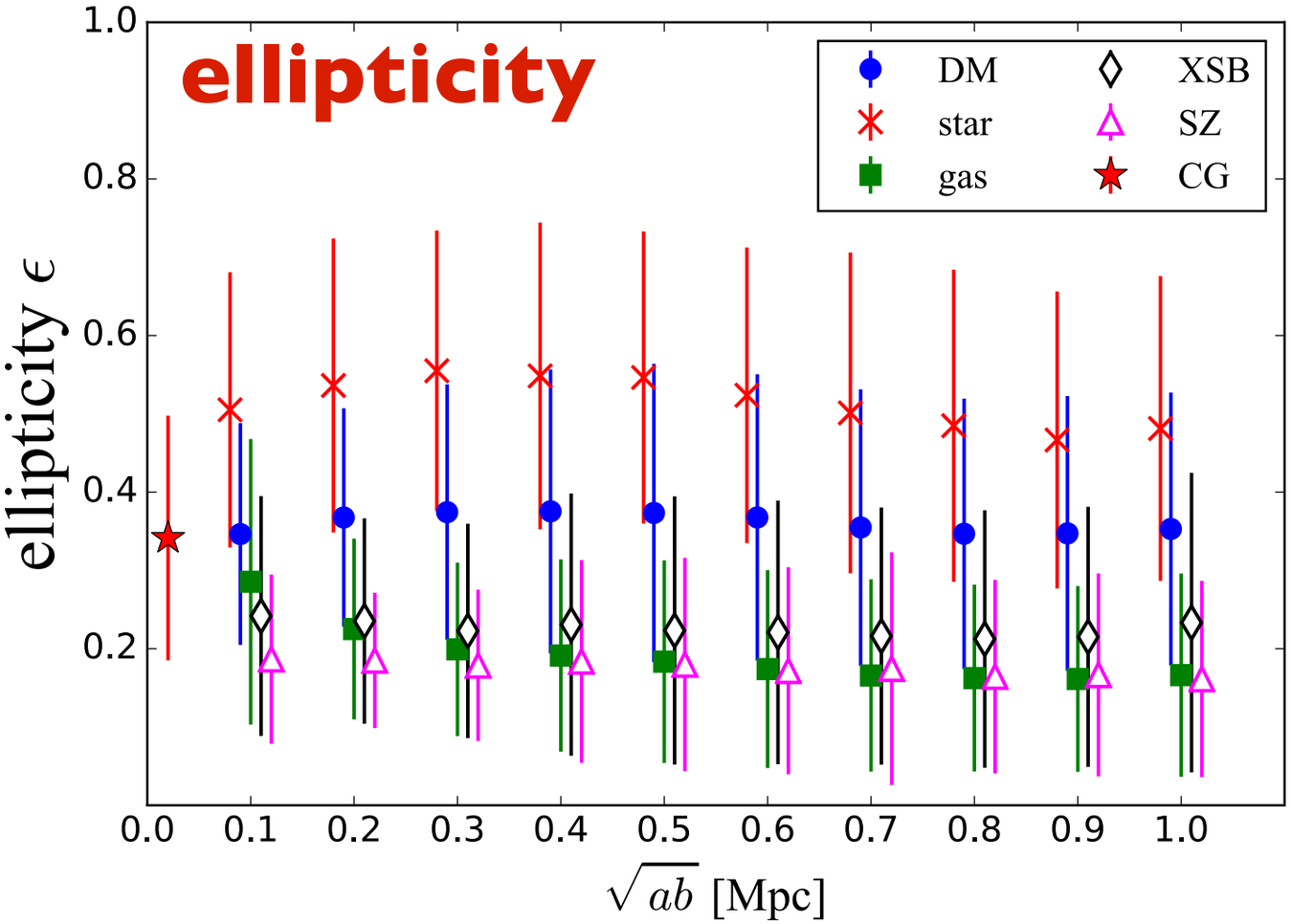
Things to check

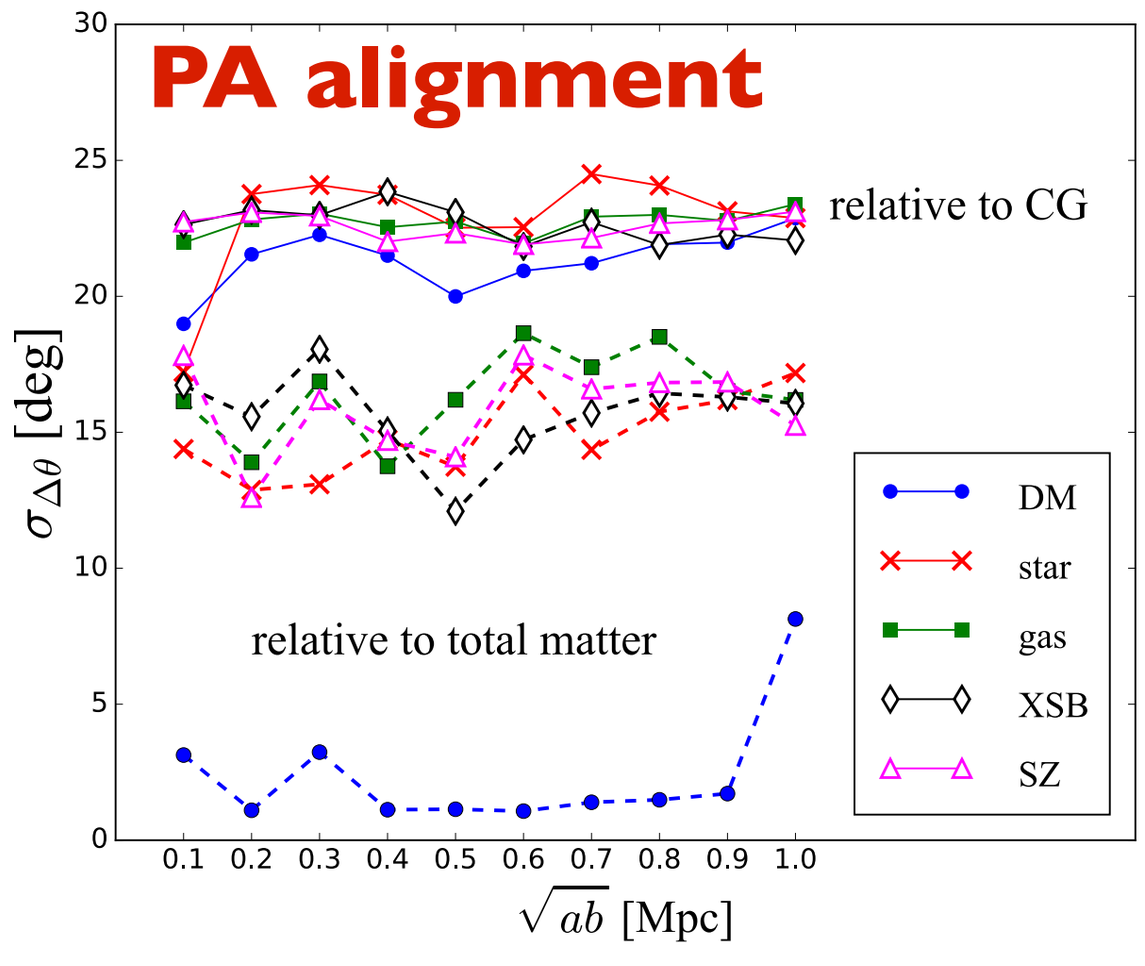
- central density profile (e.g., Newman+2013; Caminha+2017)
- ellipticity (e.g., Richard+2009; MO+2012)
- (mis-)alignment between DM and stellar dist. (e.g., Donahue+2016; Jauzac+2018)
- offset between centroids of DM and stellar dist. (e.g., Harvey+2017; Massey+2018)
- subhalos/substructures (e.g., Jauzac+2016; Mohammed+2016; Natarajan+2017)



Okabe, Nishimichi, MO+ MNRAS **478**(2018)1141

Prediction based on ΛCDM





- detailed prediction based on the Horizon-AGN cosmological hydrodynamical simulation
- star, gas and DM reasonably well aligned

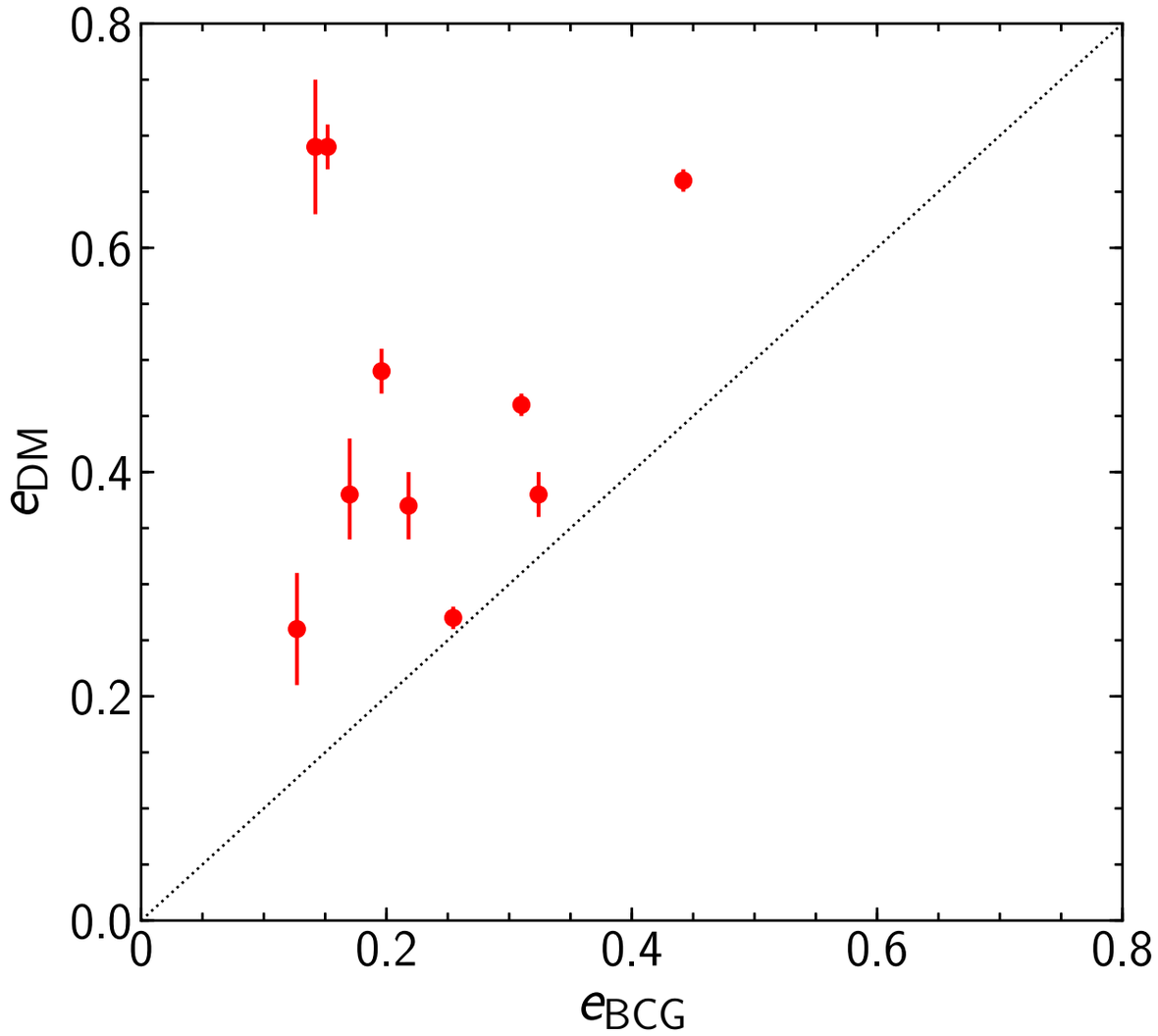
everything is very preliminary

Quick check with HFF+

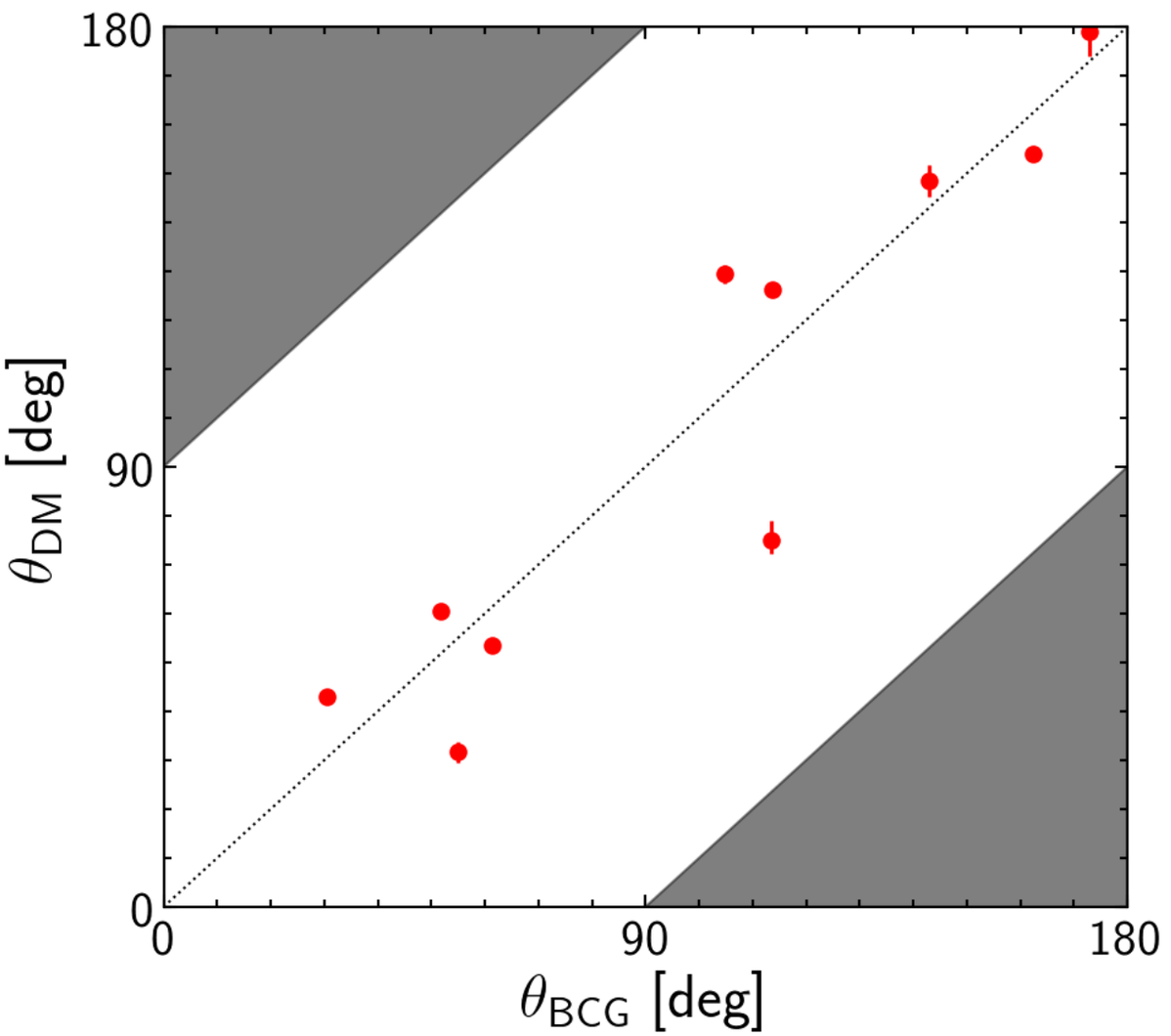
- HFF clusters and some other clusters with accurate GLAFIC mass models
- compare halo ellipticity from strong lens modeling with ellipticity of BCG light profile
- also check the alignment of position angles

everything is very preliminary

Quick check with HFF+



DM distribution is more elongated than BCG

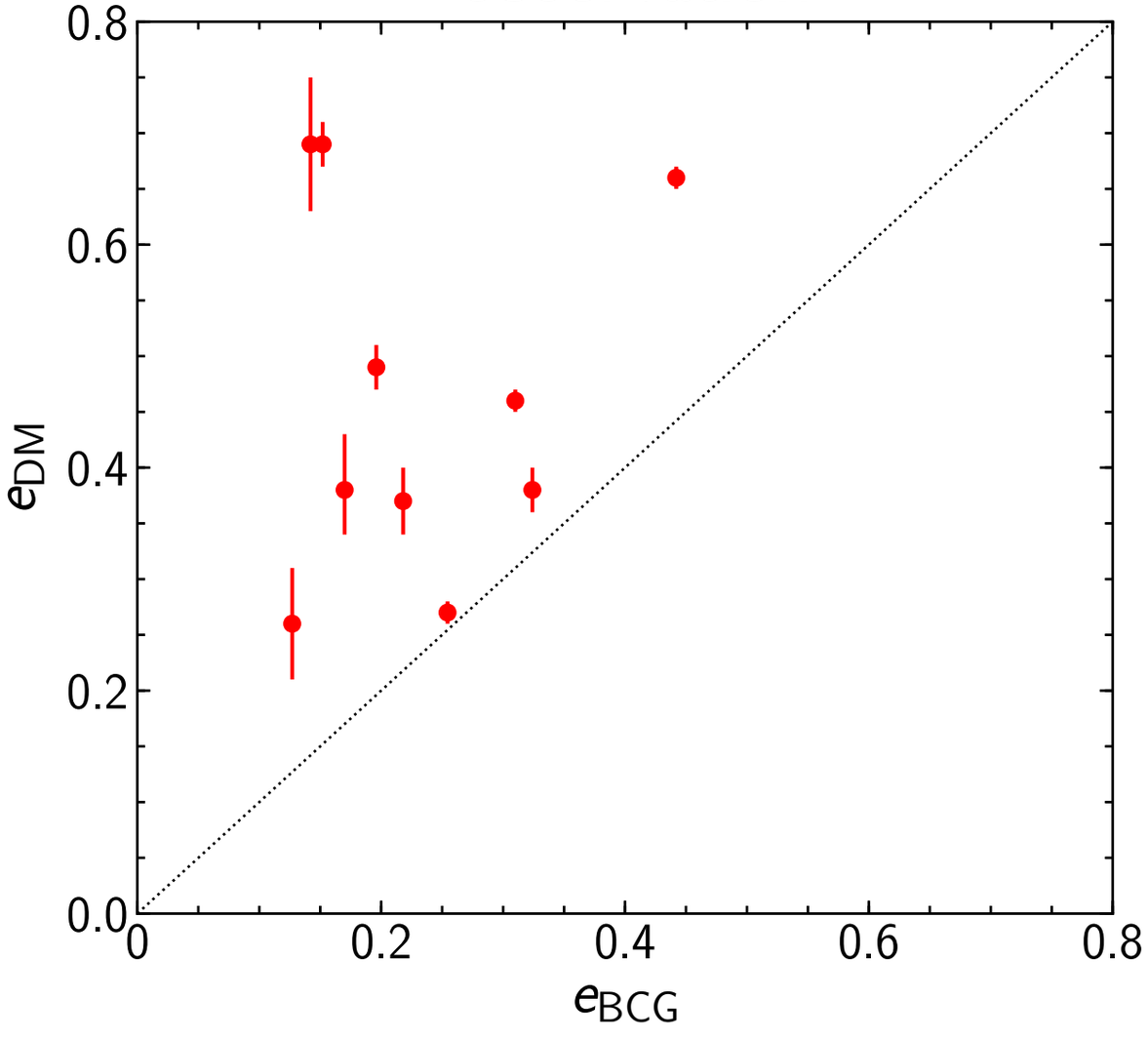


position angles are aligned well

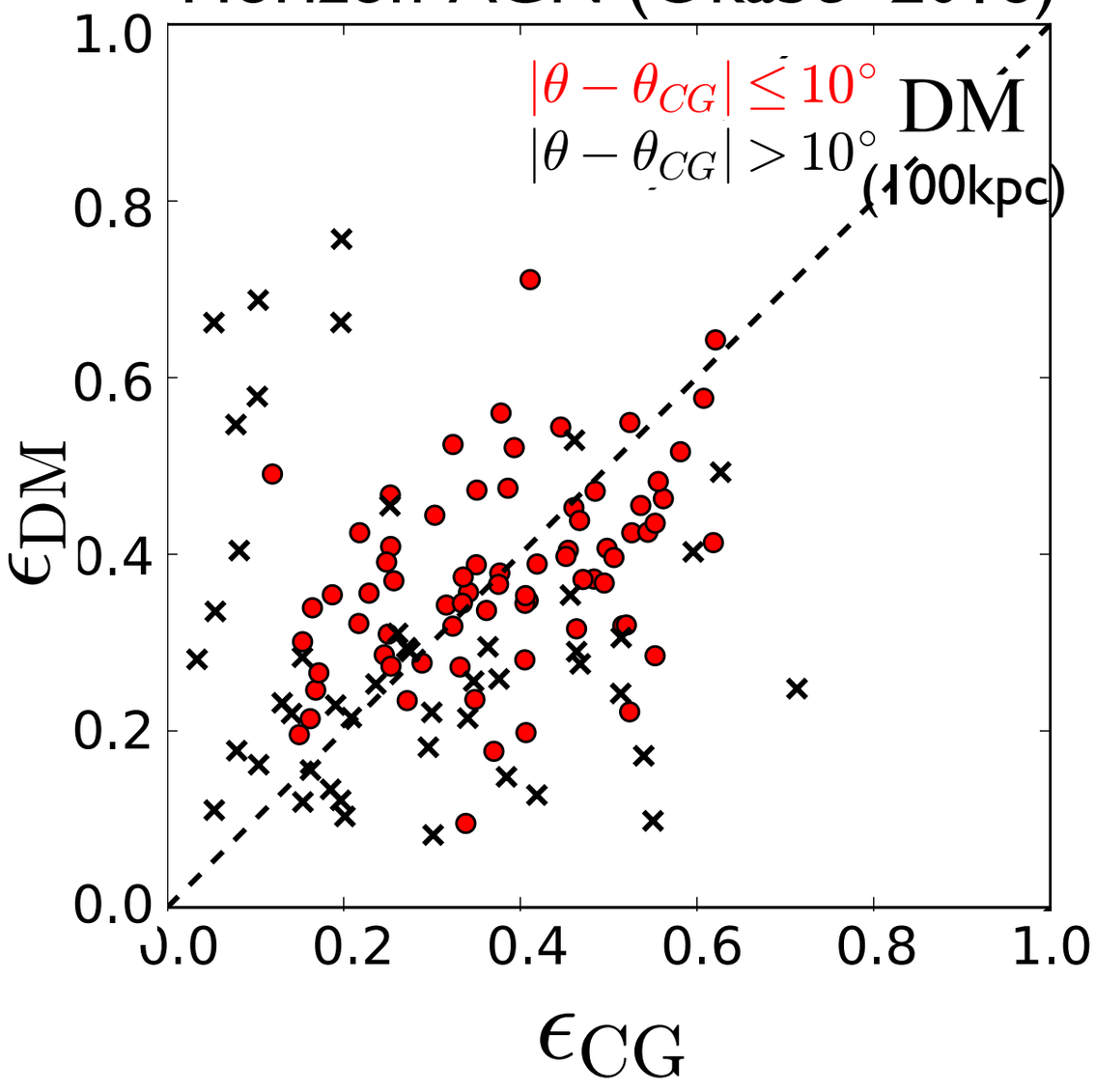
everything is very preliminary

Comparison with Horizon-AGN

observation



Horizon-AGN (Okabe+2018)

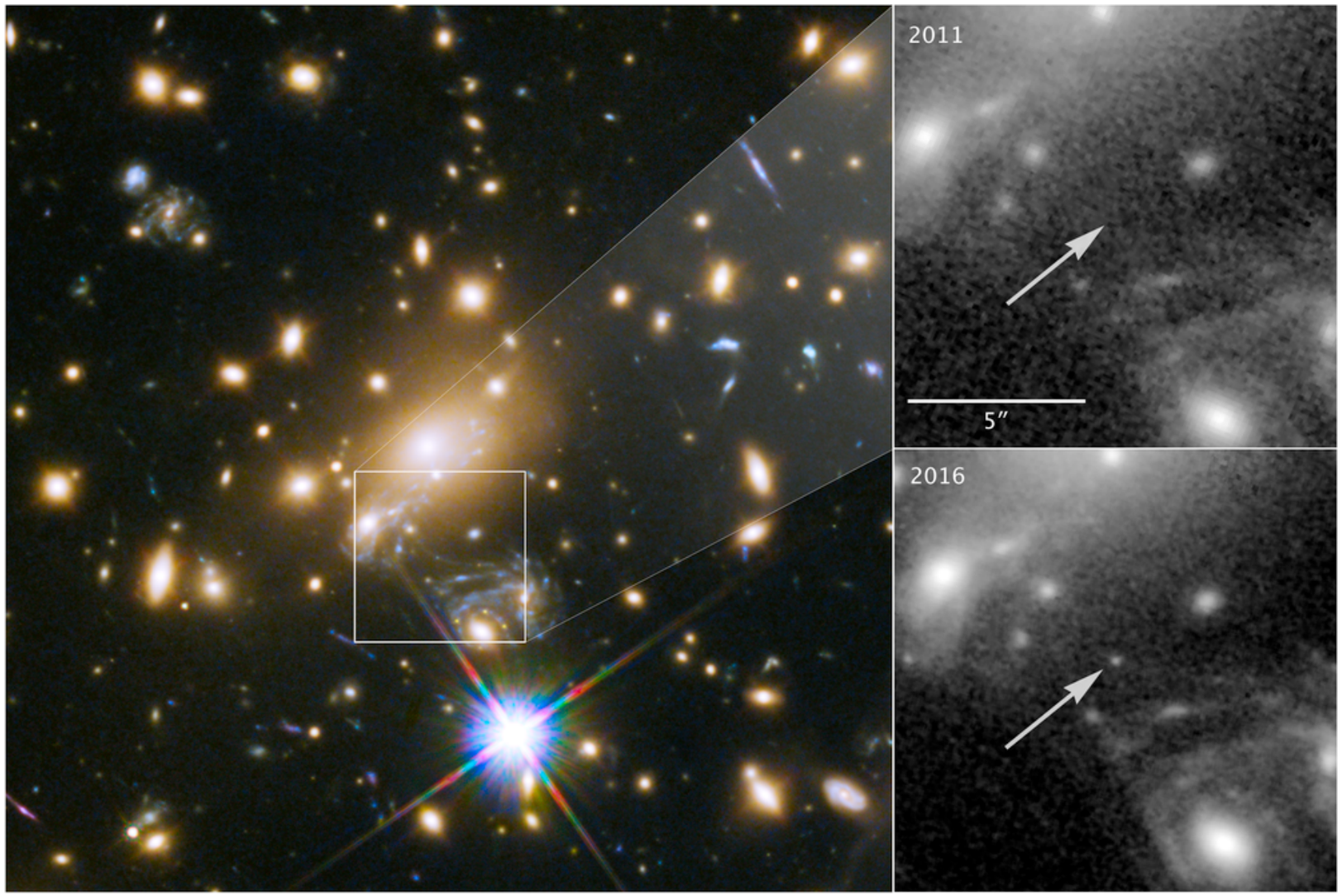


- ellipticities of DM and BCG are similar in Horizon-AGN, but different in observation (?)

More dark matter studies

- caustic crossing near the critical curve can constrain compact DM (primordial black holes)

  (Kelly+2018; Diego+2018; Venumadhav+2018; MO+2018)



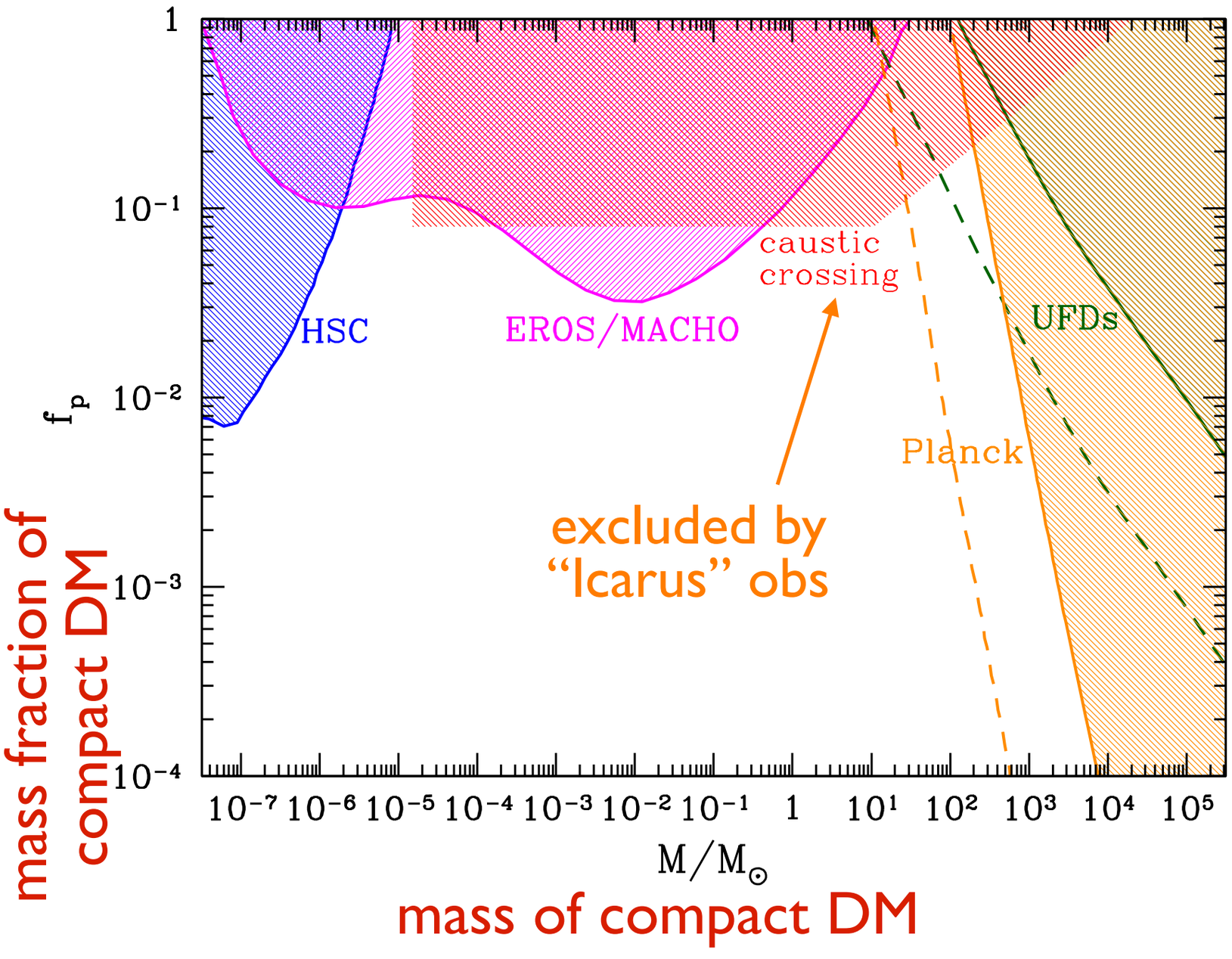
(NASA/ESA/P. Kelly)

"Icarus" found in MACS1149

see P. Kelly's talk!

MO, Diego, Kaiser+ PRD **97**(2018)023518

Constraint on compact DM



- due to saturation high μ found in Icarus cannot be explained in compact DM scenario
- close window at 10-100 M_{sun}

Summary

- significant advance of cluster strong lensing mass modeling after HFF
- further improvement possible? note that we want to get "accurate" mass models rather than "precise" ones
- a lot of room to explore dark matter from cluster strong lensing