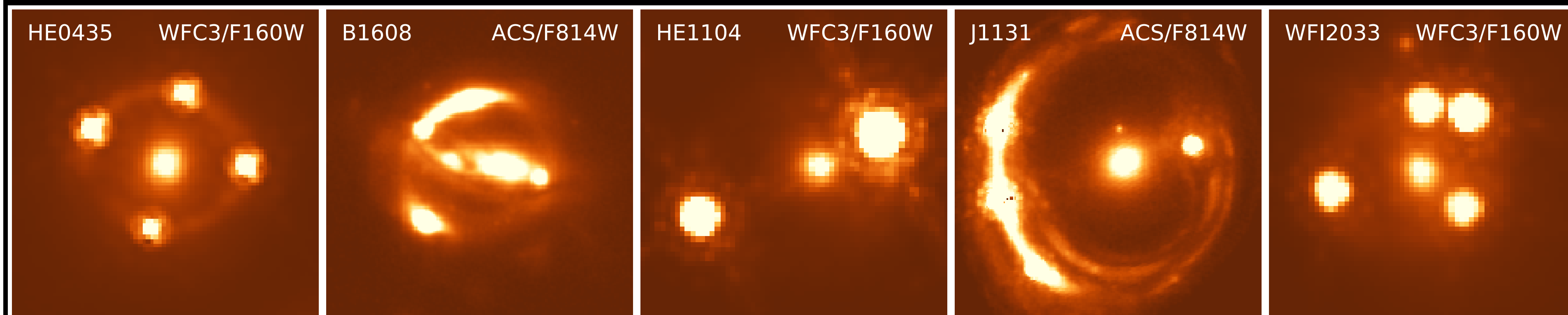
Addressing κ_{ext} for the H0licow time-delay lens systems



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Motivation

- Error budget elements:
  - time delays
  - mass distribution in the lens and its immediate environment
  - line-of-sight mass distribution
- The H0licow sample:
  - five quasar lenses with high-precision time delays
  - All have deep high-resolution imaging (HST, plus AO in some cases) – good for high precision modeling

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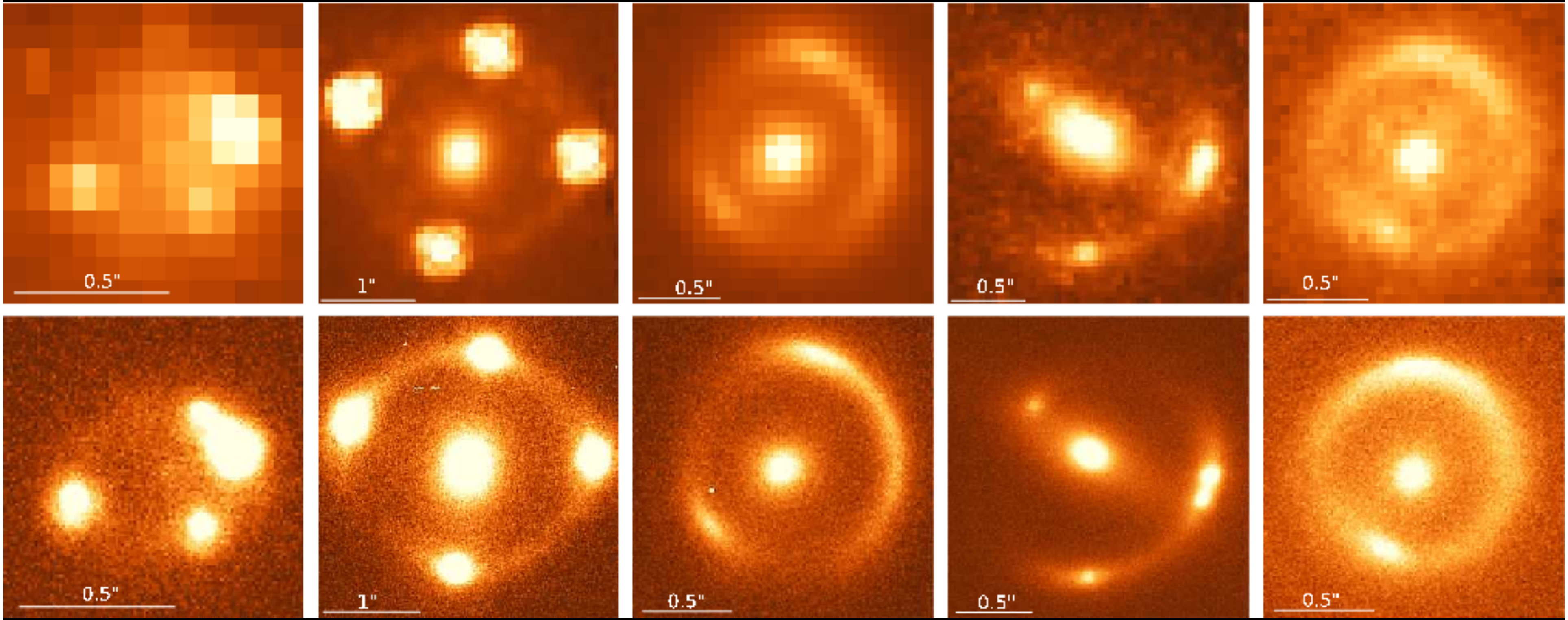
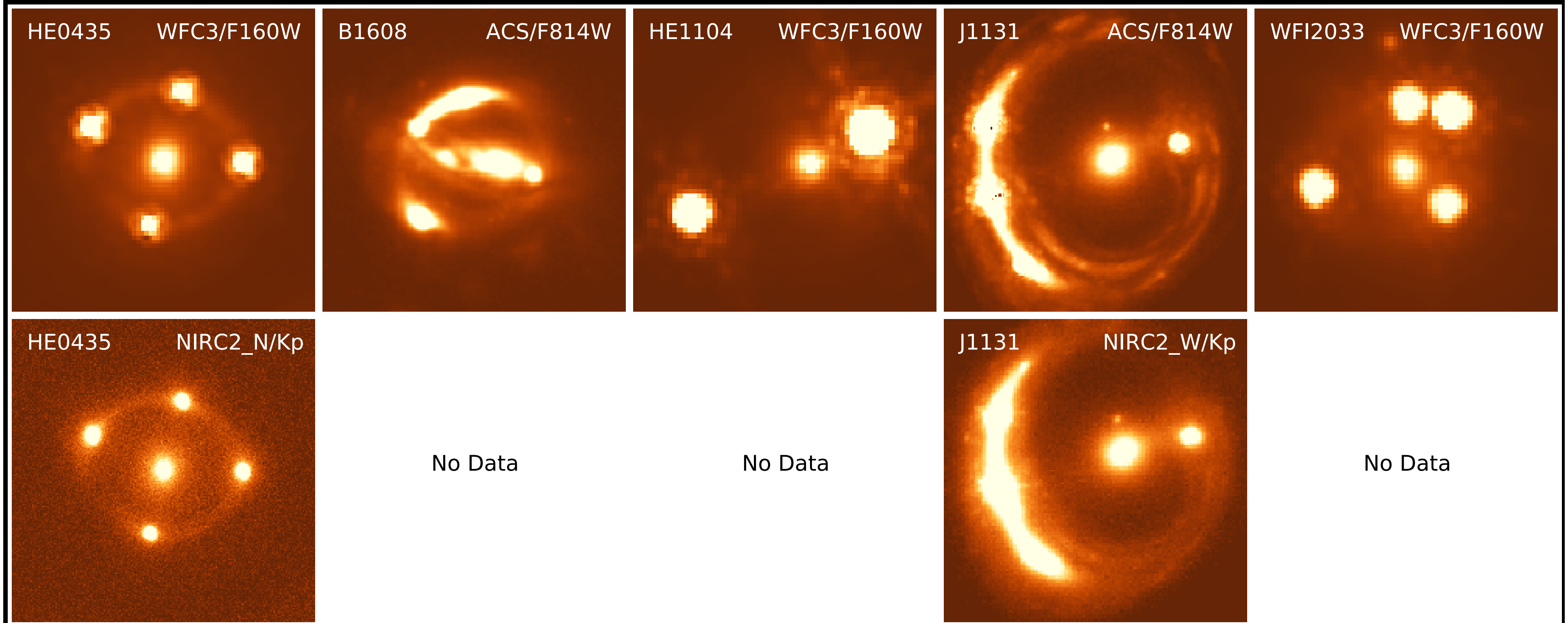
AO vs HST



Top row: Keck adaptive optics, K' band
Bottom row: HST, F160W

Fassnacht et al., in prep

AO Imaging in H0licow



- Pros:
  - Can provide higher resolution than HST
  - Several ground-based facilities provide access
- Cons:
  - Variable PSF
  - Need bright tip-tilt star => limits number of targets

Time-delay lens cosmography and κ_{ext}

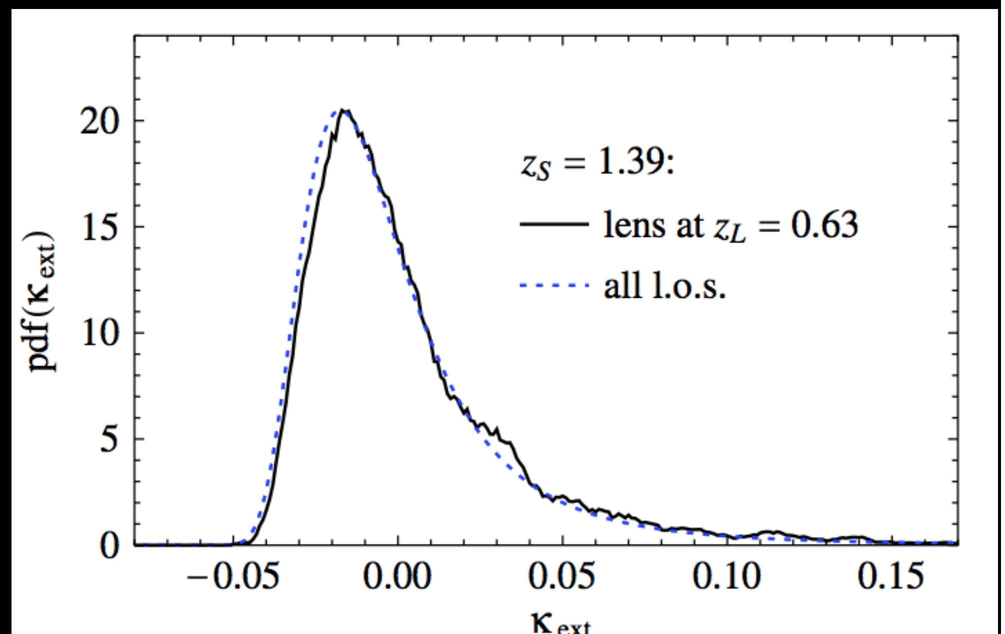
- Assumption that mass is smoothly distributed in Universe is not valid in era of high precision
- κ_{ext} measures relative over/under-density of the line of sight
  - Can be positive or negative
  - Affects measurements at the few percent level
- $H_{0,true} = H_{0,measured}\,(1 - \kappa_{ext})$
- For some lenses (e.g., B1608, RXJ1131), this is now the largest item in the error budget

Incorporating κ_{ext} into the analysis

- Enters as a prior in the Bayesian analysis (e.g. Suyu et al. 2010)

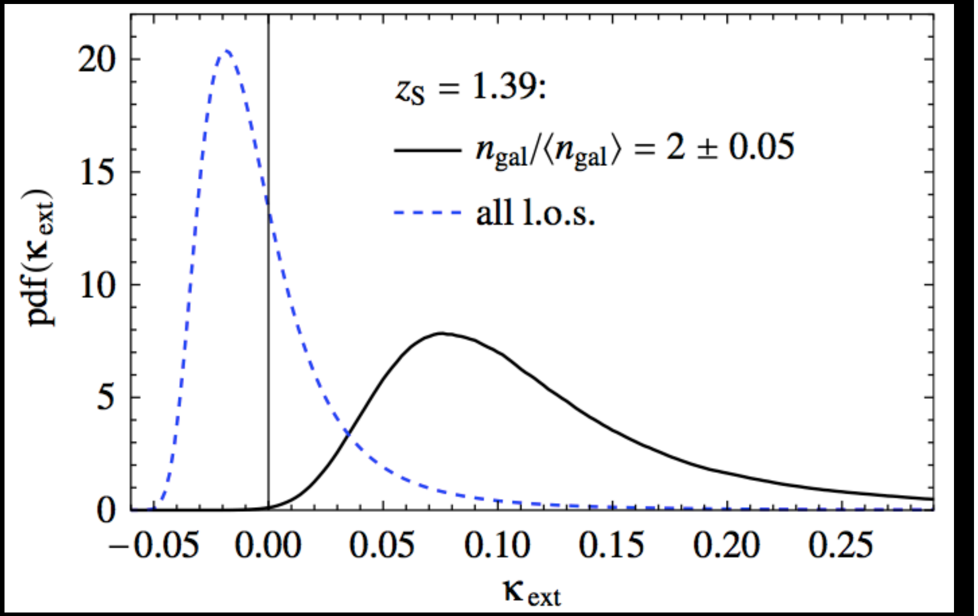
$$\overbrace{P(\pi, \gamma', \kappa_{\mathrm{ext}}, \eta, \delta\psi, s, M_{\mathrm{D}}, r_{\mathrm{ani}})}^{\text{prior}}$$

- The starting point: κ_{ext} from ray tracing along random lines of sight through the Millennium Simulation (Hilbert et al. 2007)



Improving accuracy and precision for individual systems

- Use additional information to improve prior and thus final cosmological parameters
- Look for shifts in peak of κ_{ext} PDF
  - This was important for B1608 (Suyu et al. 2010)
- Try to reduce width of PDF (σ_κ)



Approaches for H0licow

- Approach 1: Galaxy overdensities
- Approach 2: Halo masses from imaging catalogs
- Approach 3: Weak lensing

All require deep high quality multiband imaging
Spectroscopy of galaxies close to the lens is also highly useful

Note: not yet incorporating McCully et al.(2014) approach for H0licow
Still in the data collection, reduction, and analysis stage

Approach 1: Galaxy overdensities

The underlying idea

Less mass.
Lower κ_{ext}

More mass.
Higher κ_{ext}

Fassnacht, Koopmans, & Wong 2011

Approach 1: Galaxy overdensities

Can also include weighting

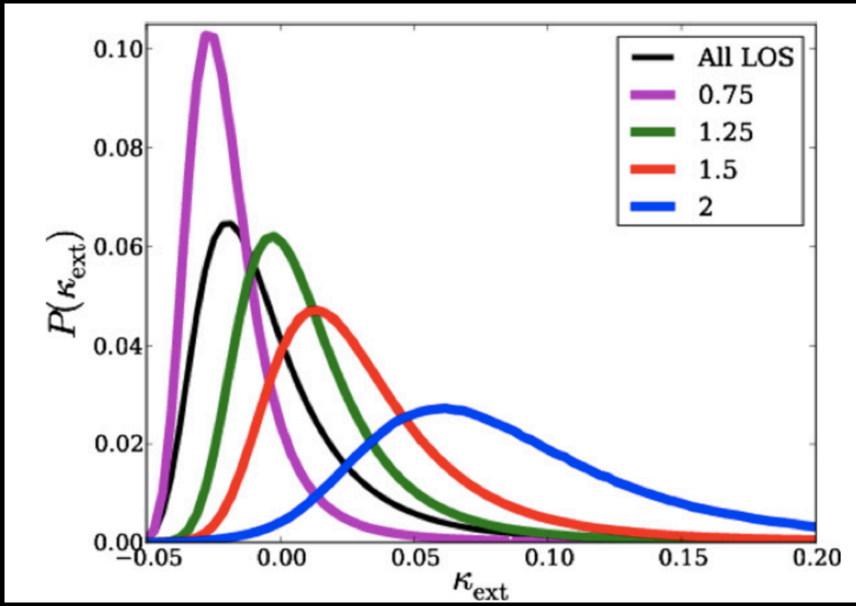
Approach 1: Galaxy overdensities

- For each system compute observed overdensity:
  - ratio of observed (weighted) number counts to average counts in control fields (e.g. Fassnacht et al. 2011)
- Calibrate against the Millennium Simulation
- Ray tracing gives κ_{ext} for each line of sight
- Select lines of sight for which simulated galaxy overdensity matches the observed value
- Gives revised κ_{ext} PDF
  - e.g. Suyu et al. 2010

$$\frac{N}{<N>} = \frac{(\sum w_i)_{\rm lens}}{<\sum w_i>_{\rm random}}$$

Approach 1: Including weighting

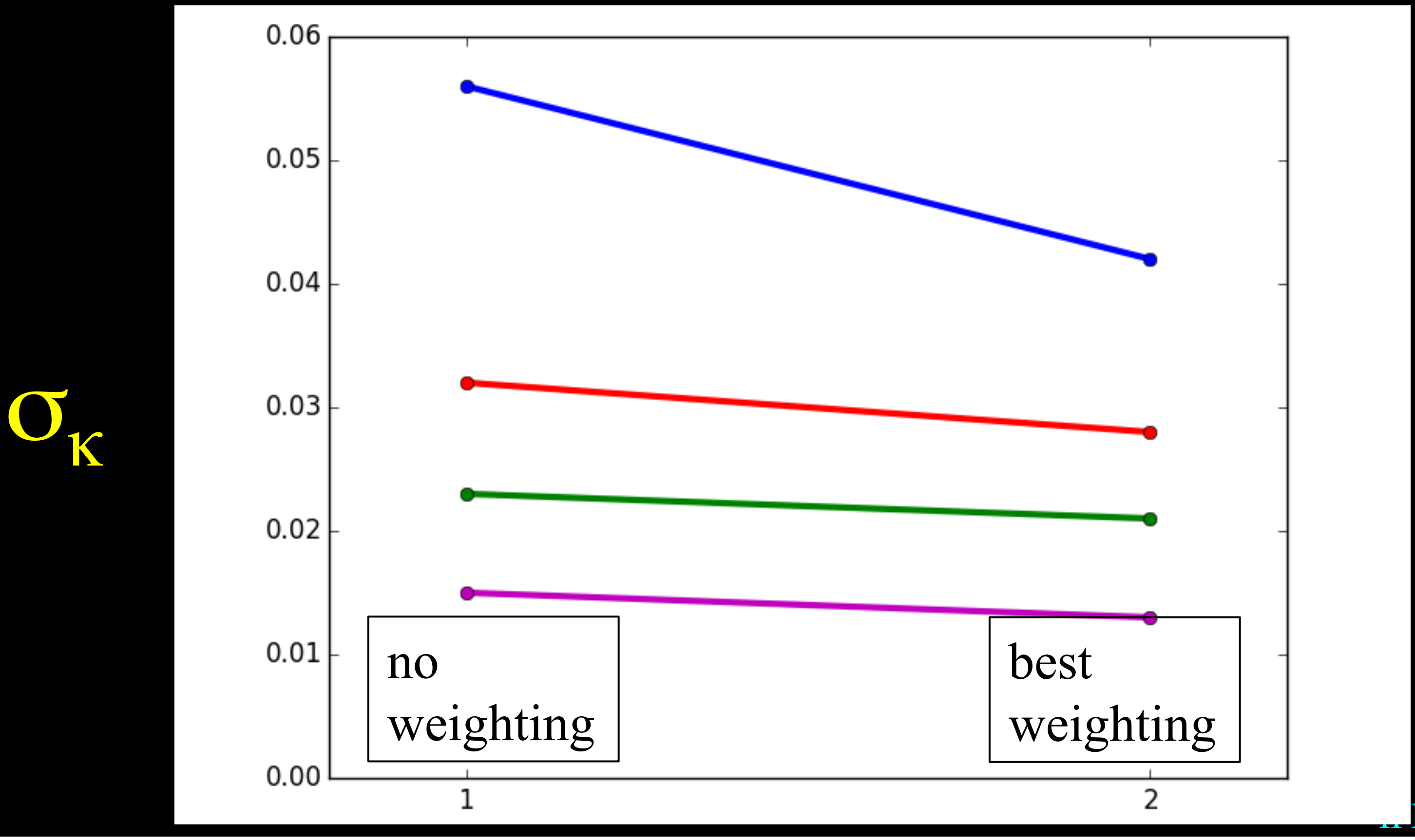
- Weighting by additional observables provides tighter constraints on the κ_{ext} distribution (Greene et al. 2013)
- Properties that could be used for weighting
  - projected distance
  - mass
  - luminosity
  - redshift
  - shear
- Also, underdense lines of sight are better in general
  - width of κ_{ext} distribution is smaller



Greene et al. 2013

Approach 1: Benefits of weighting

- By weighting galaxies by the appropriate quantities, width (σ_κ) of κ_{ext} prior can be reduced (Greene et al. 2013)

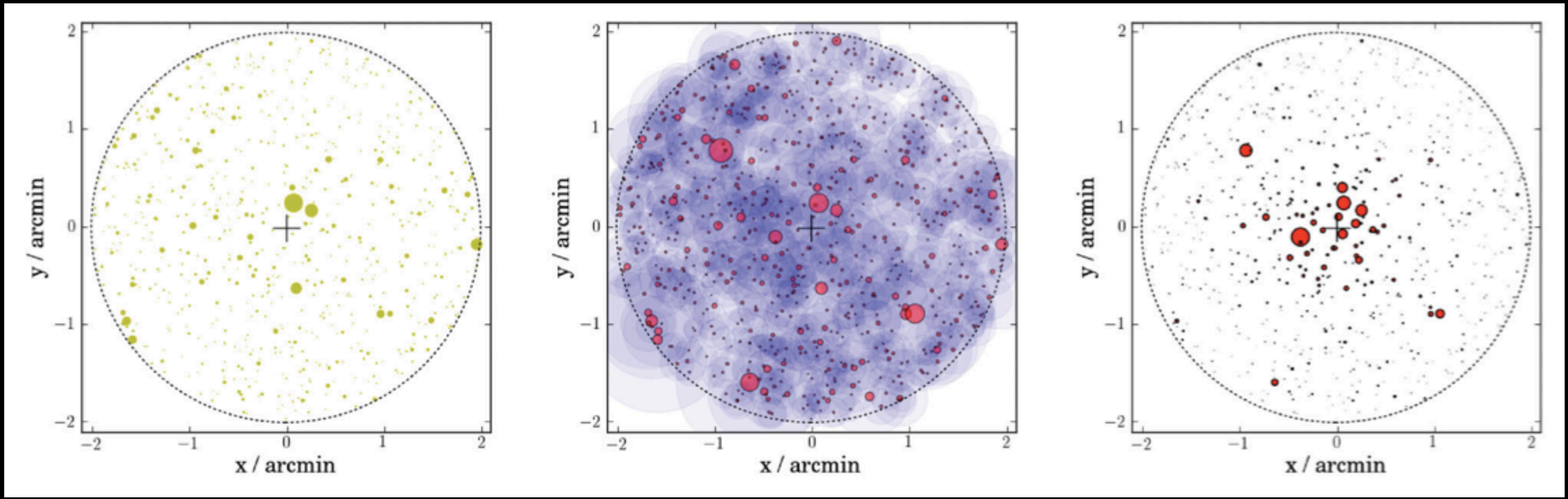


Approach 2: Halo model

- Approach proposed by Collett et al. (2013)
- Assign a halo mass to each galaxy seen in field based on its stellar mass
- Add up convergence at location of lens, using halo masses and redshifts
- Calibrate results with simulations
  - Here, once again, use ray tracing through the Millennium Simulation (Hilbert et al.)

Approach 2: Halo model

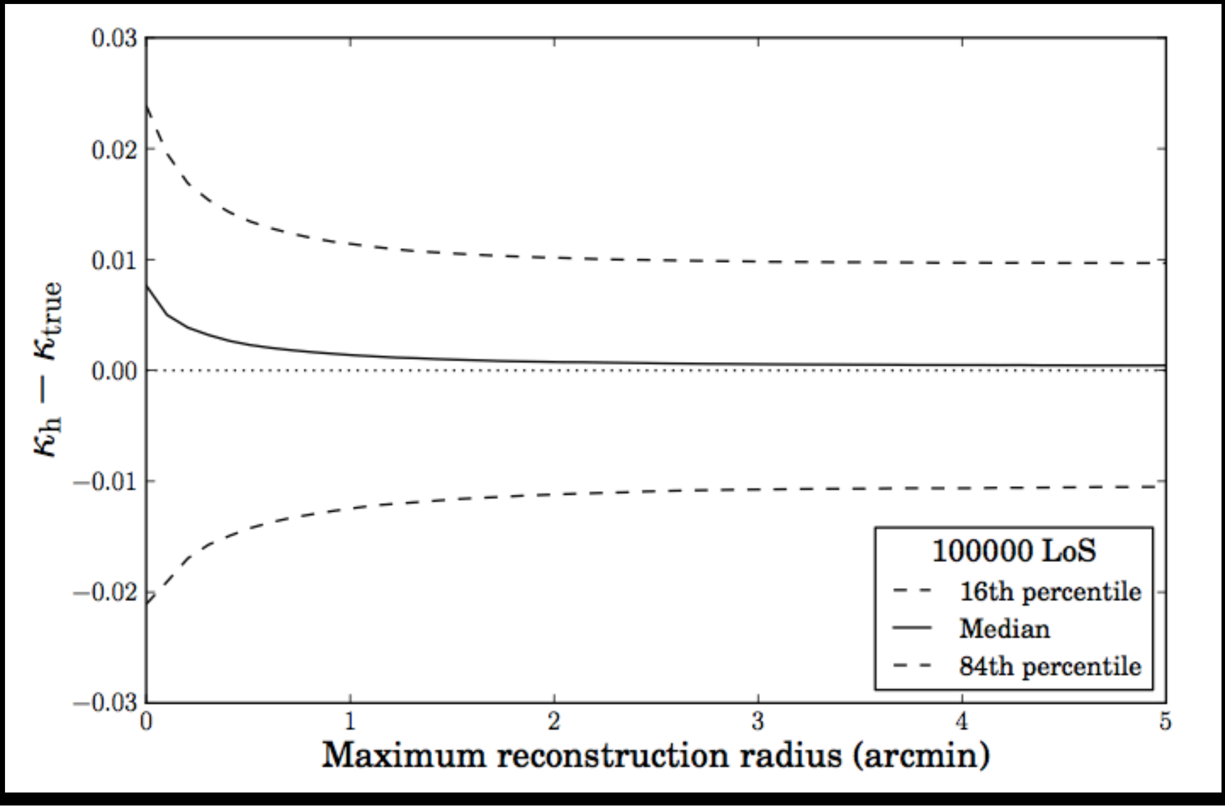
observed i-band flux angular size of halos contributions to κ_{ext}



- Effect of projected distance on contribution to κ_{ext} by halos in the light cone (Collett et al. 2013).
  - middle panel: red circles = r_s, blue = r_{200}

Approach 2: Halo model

- Most important contributions to κ_{ext}, and controlling for bias, comes from halos that are:
  - within ~ 2 arcmin of lens
  - associated with galaxies brighter than i=24



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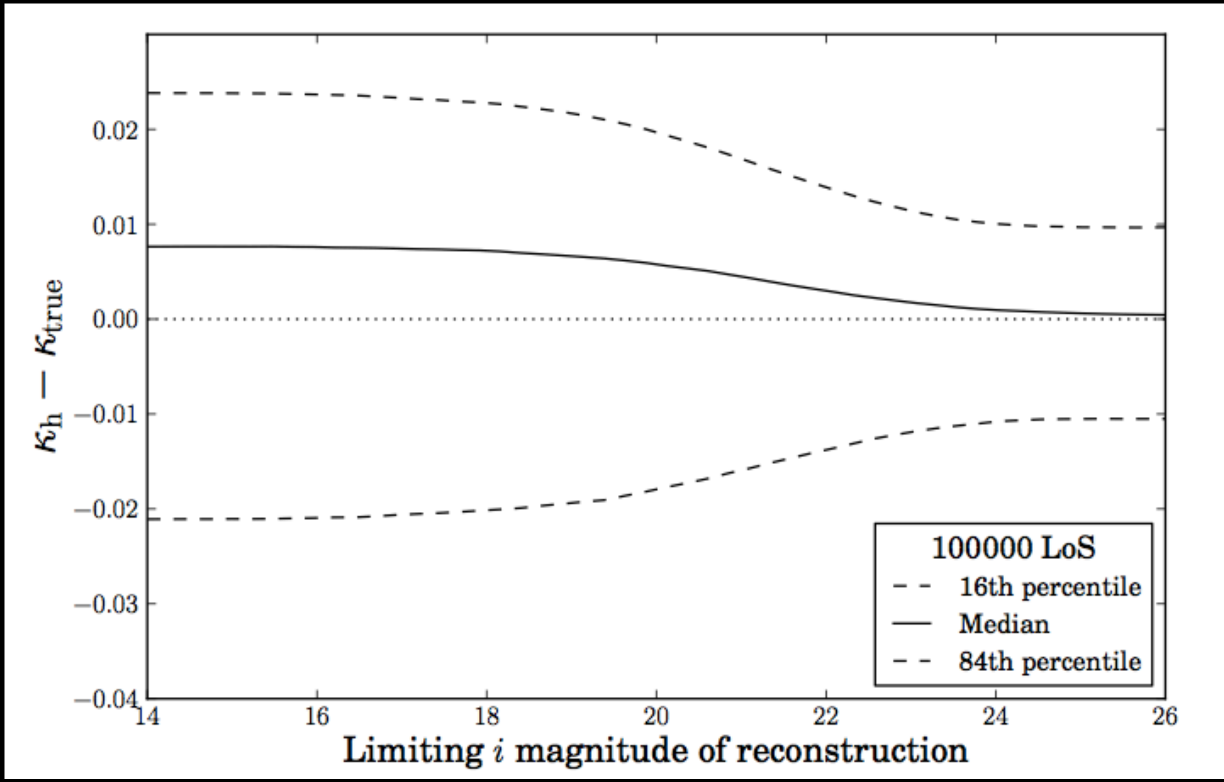


Approach 3: Weak lensing

- Right now neither of the other approaches incorporates the effect of galaxy clusters or groups along the line of sight
- Weak lensing can reveal the presence of large mass concentrations in the fields containing the time-delay lenses

Application to H0licow Sample

Work in progress

Applying the methods: H0licow

- Approaches 1 and 2 need galaxy redshifts and stellar masses
- Spectroscopy is expensive, so primarily focus it on galaxies closest to the lens
  - Effort being led by Sluse (VLT) and Sonnenfeld (Gemini)
- For the remainder, acquire deep multiband imaging
- Deep imaging is also needed for approach 3

Deep imaging: HE0435 gri

Imaging data in hand: H0licow

- Goal: 8-9 band relatively deep imaging for all 5 H0licow systems: ugriJ(H)K_s,3.6, 4.5
- Facilities used:
  - CFHT Megacam u (PI Suyu)
  - DECam u (PI Rusu, plus DES data)
  - Subaru SuprimeCam gri (PI Fassnacht)
  - Gemini NIRI JK_s (PI Fassnacht)
  - VLT HAWK-I JHK_s (PI Fassnacht)
  - Spitzer IRAC 3.6, 4.5 (PI Rusu, plus archival data)

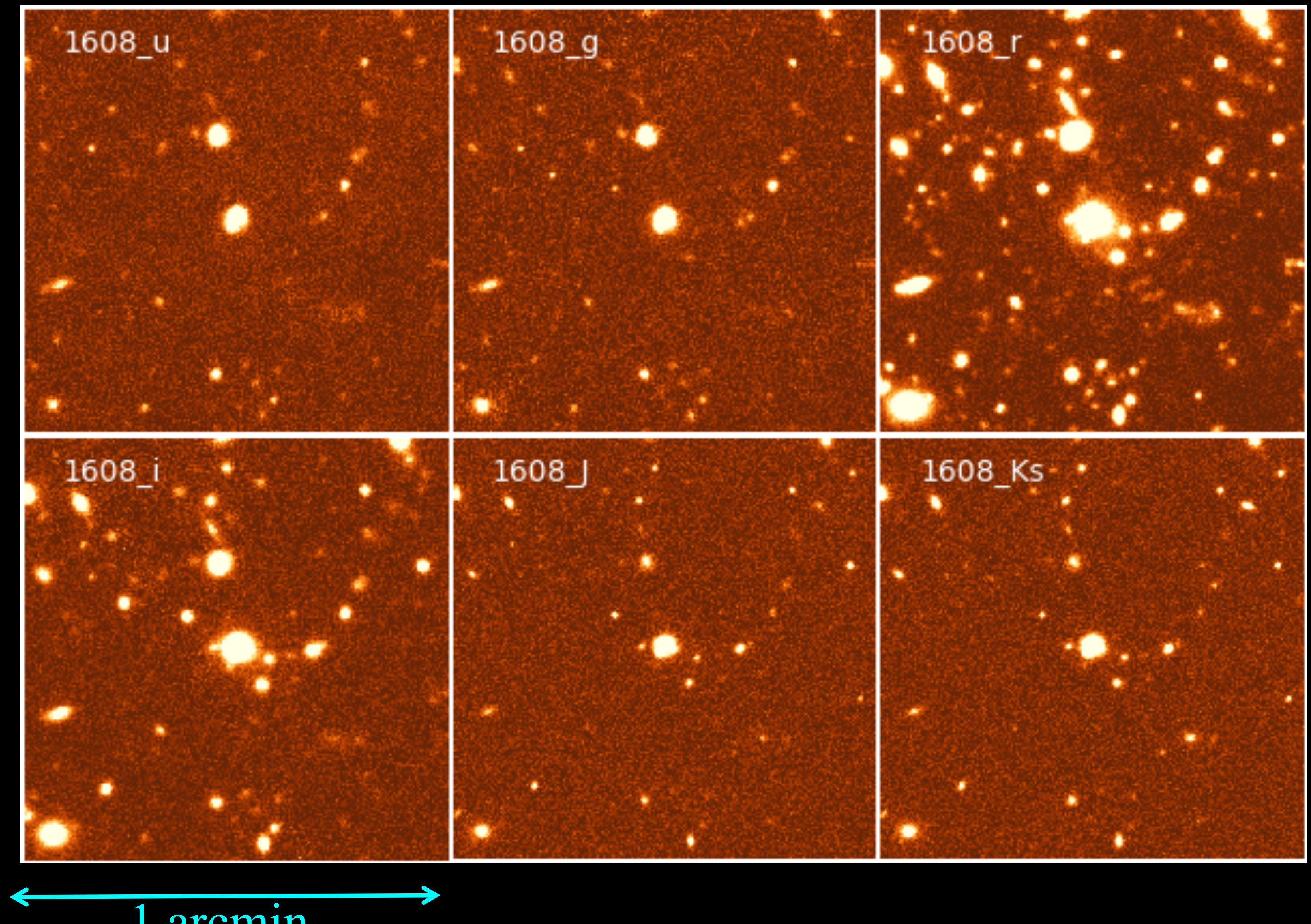
H0licow: Data in hand

Lens	u-band	gri	J(H)K_s	3.6 and 4.5
HE0435	CFHT	Subaru	Gemini	Spitzer
HE1104	CFHT	Subaru	Gemini	Spitzer
RXJ1131	CFHT	Subaru	Gemini	Spitzer
B1608	CFHT	Subaru	Gemini	N/A
WFI2033	N/A	N/A (DES, yr 2)	VLT	Spitzer

Note SuprimeCam r-band data are deep, and can be used for weak lensing (approach 3)

- Completeness depth (AB): r=26
- Courbin et al. are leading the weak lensing analysis

Example: B1608+656



Ongoing analysis

- Work on approaches 1 and 2 being led by Edi Rusu
- Photometric redshift and stellar mass calculations underway using multiband imaging
  - validating against spectroscopic redshifts where available
- Right now: setting up for running approach 2

Exploring the systematics

- Can analysis methods bias the final cosmographic measurements in any way?
- Steps taken to assess systematic effects
  - Three photo-z codes: BPZ, Eazy, M. Auger's code
  - Three stellar mass approaches: K-band magnitudes, FAST, M. Auger's code
  - Three approaches to estimate κ_{ext}
  - Working on using different cosmology in simulations used to calibrate κ_{ext} approaches (Hilbert et al.)

Summary

- Several methods have been developed to do a better job of constraining κ_{ext} over the agnostic approach of using ray tracing of random lines of sight through the simulations
- H0licow is acquiring and analyzing data to better inform κ_{ext} priors for 5 time-delay systems
- Work is ongoing, so stay tuned!