Discovery of a Strong Lensing Galaxy Embedded in a Cluster at z = 1.62

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Galaxies and Cosmology in Light of Strong Lensing
Kavli IPMU
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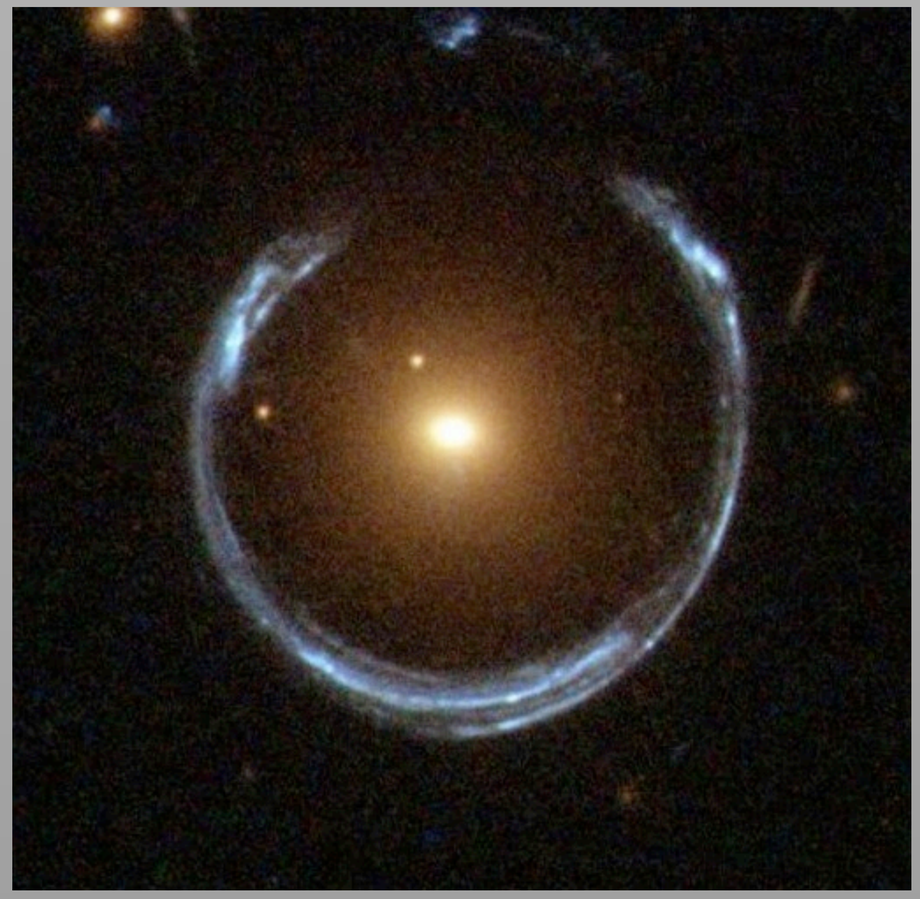
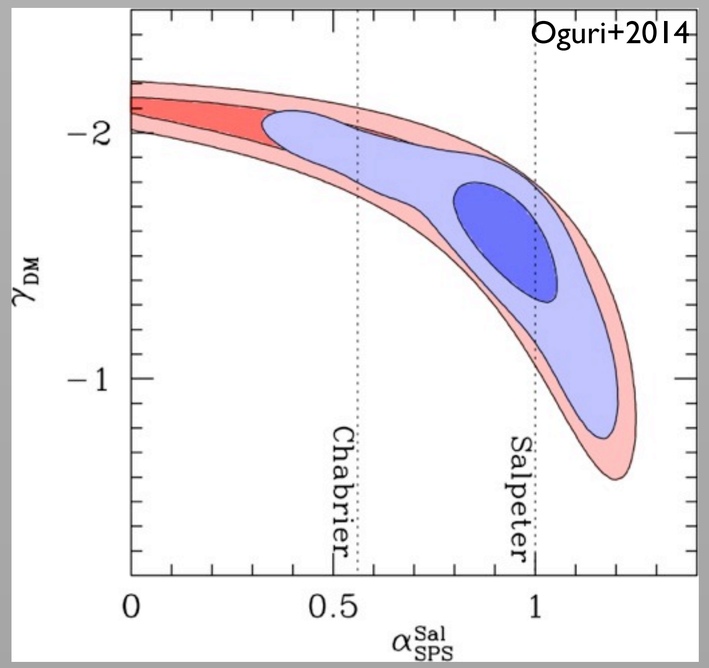
Strong Gravitational Lensing

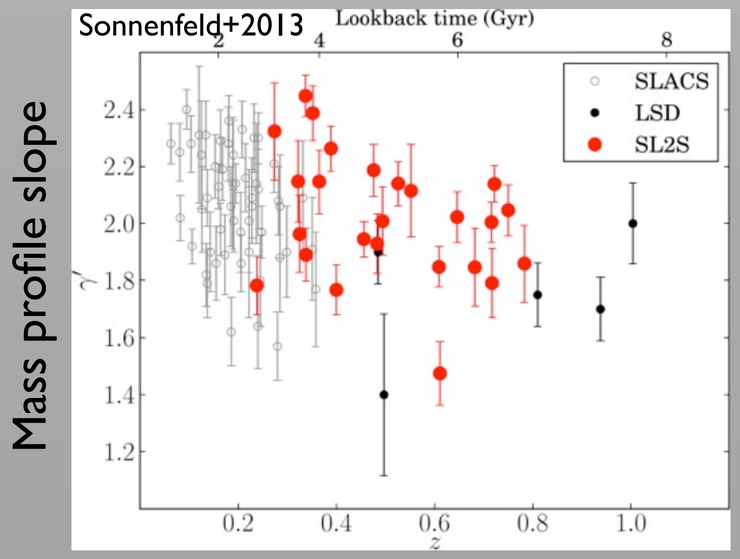
- What can we learn about lens galaxies?
  - Total mass (within Einstein radius θ_E)
  - Mass profile slope
  - Ellipticity/orientation
  - Substructure
- Typical lens galaxies
  - massive early-type (elliptical) galaxies
  - tend to lie in overdense environments
- Surveys to build statistical samples of lenses (e.g., SLACS, SL2S, BELLS)
  - Mostly $z \lesssim 0.4$, up to $z \lesssim 0.8$

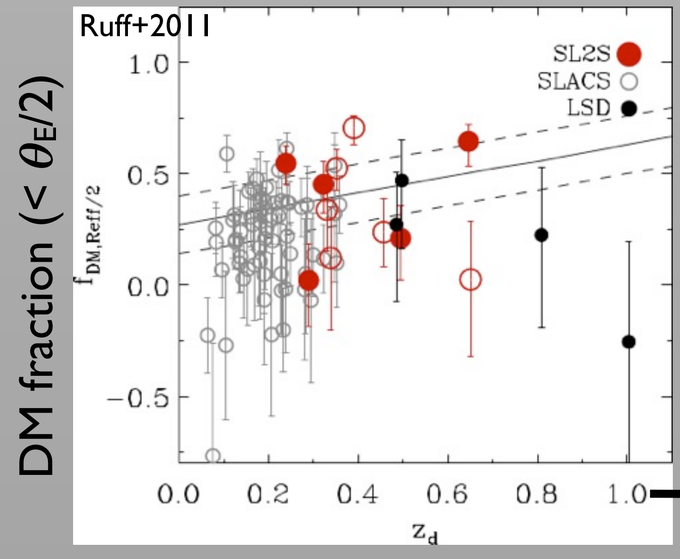


Lensing Constraints on ETGs at z < 1



Early-type galaxies
prefer Salpeter IMF





z > 1 → ???

Redshift ⟶

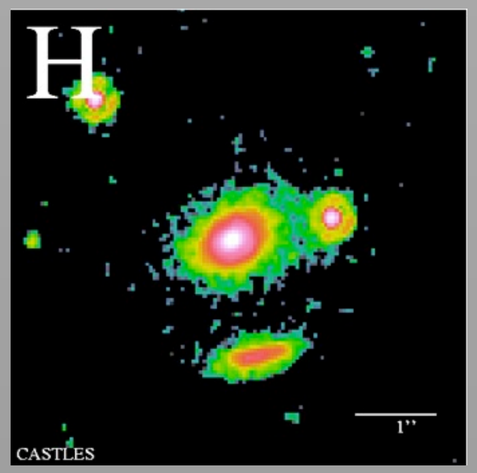
Few constraints at higher redshift: **z > 1 lenses are rare**

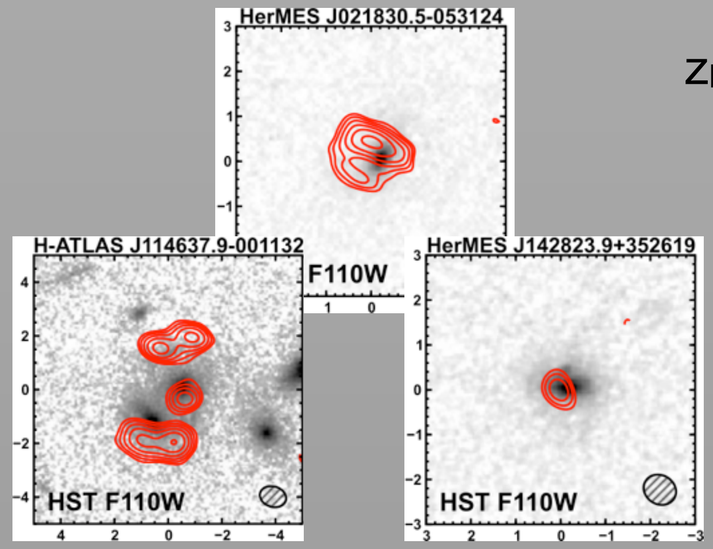
Why are z > 1 lenses rare?

- Evolution of galaxy mass function (fewer potential lenses)
- Less cosmological volume behind potential lenses (fewer potential sources)
- Lensing most “efficient” when lens is ~halfway between observer and source (efficiency drops at $z_L > 1$ for any reasonable cosmology and source redshift)
- More distant lenses are fainter and harder to resolve (need deep high-resolution imaging)
- Spectroscopic confirmation difficult (need deep NIR spectroscopy)

H-ATLAS/HERMES lenses
z_L = 1.03-1.35 (Bussmann+2013)

MG2016+112
z_L = 1.01 (Lawrence+1984)



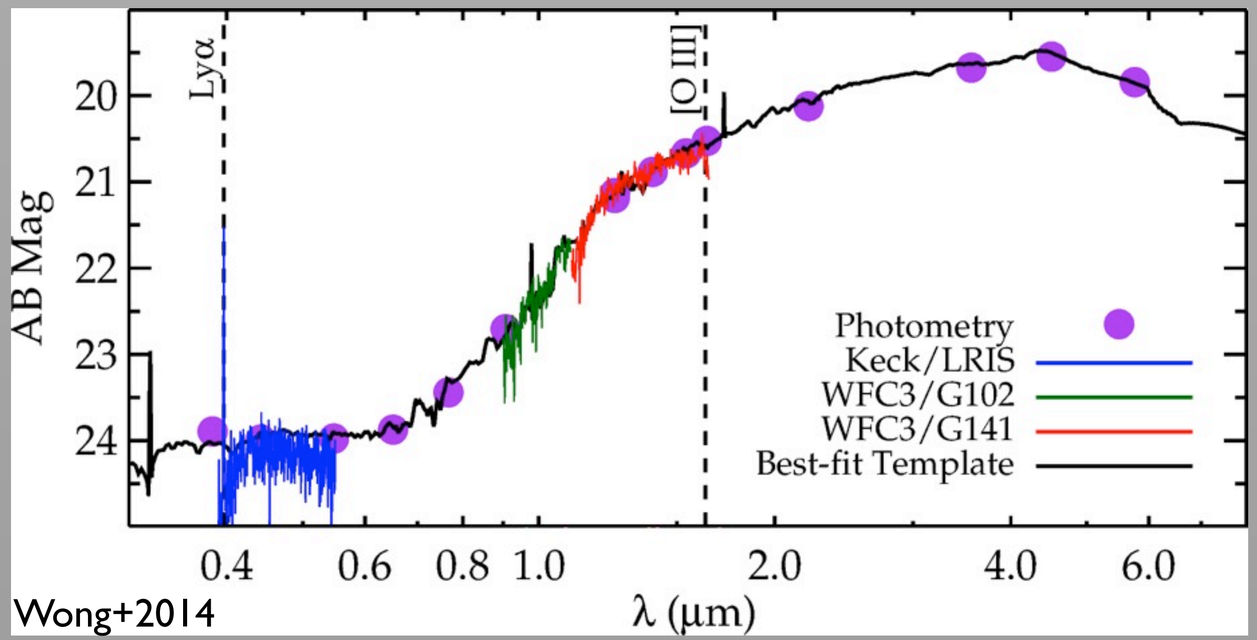


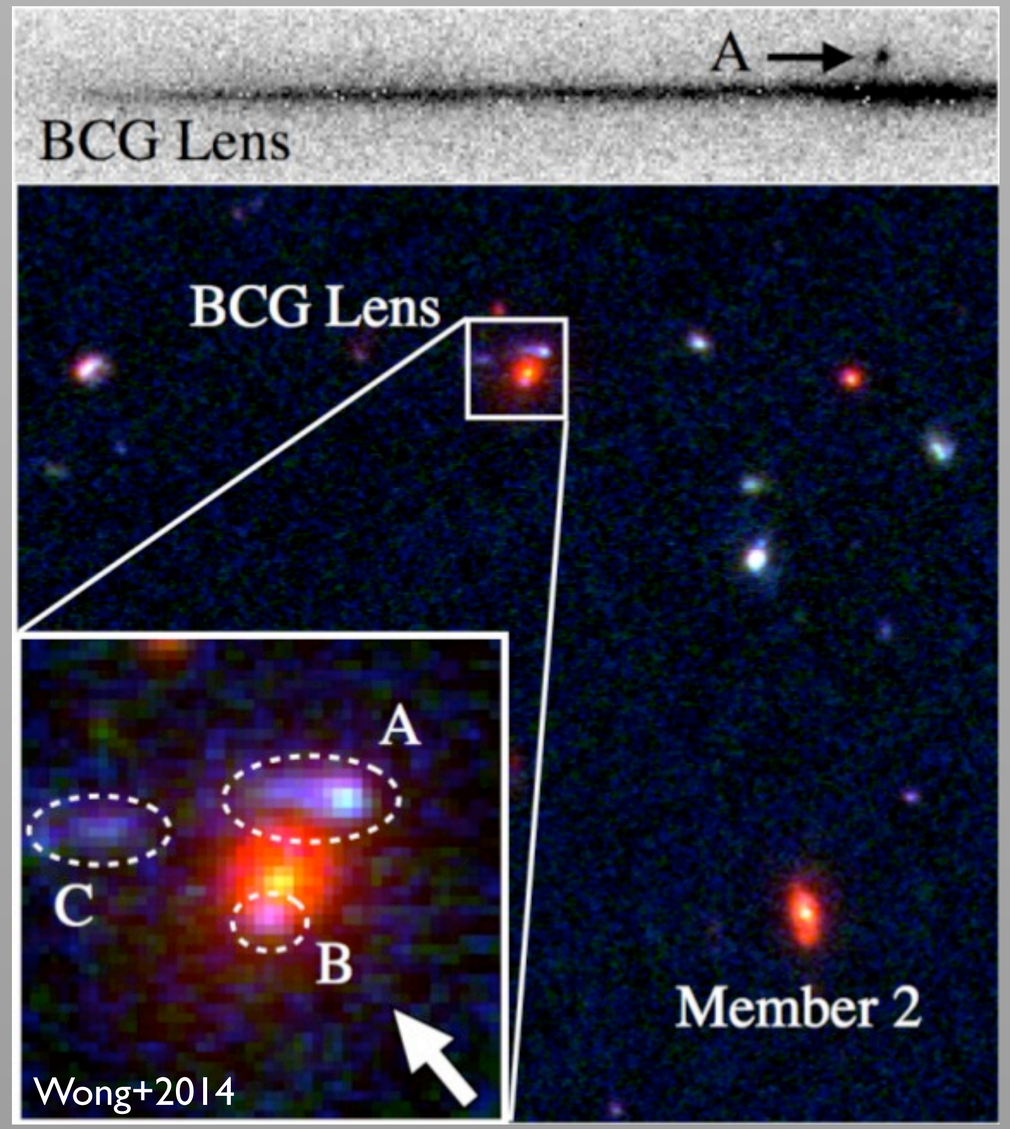
J1000+0221
z_L = 1.53 (van der Wel+2013)

...plus a handful of other candidates at 1.0 ≲ z ≲ 1.3 based on photo-zs or uncertain interpretation (e.g., Faure+2008, Lagattuta+2010)

Discovery of Lens Galaxy at z = 1.62

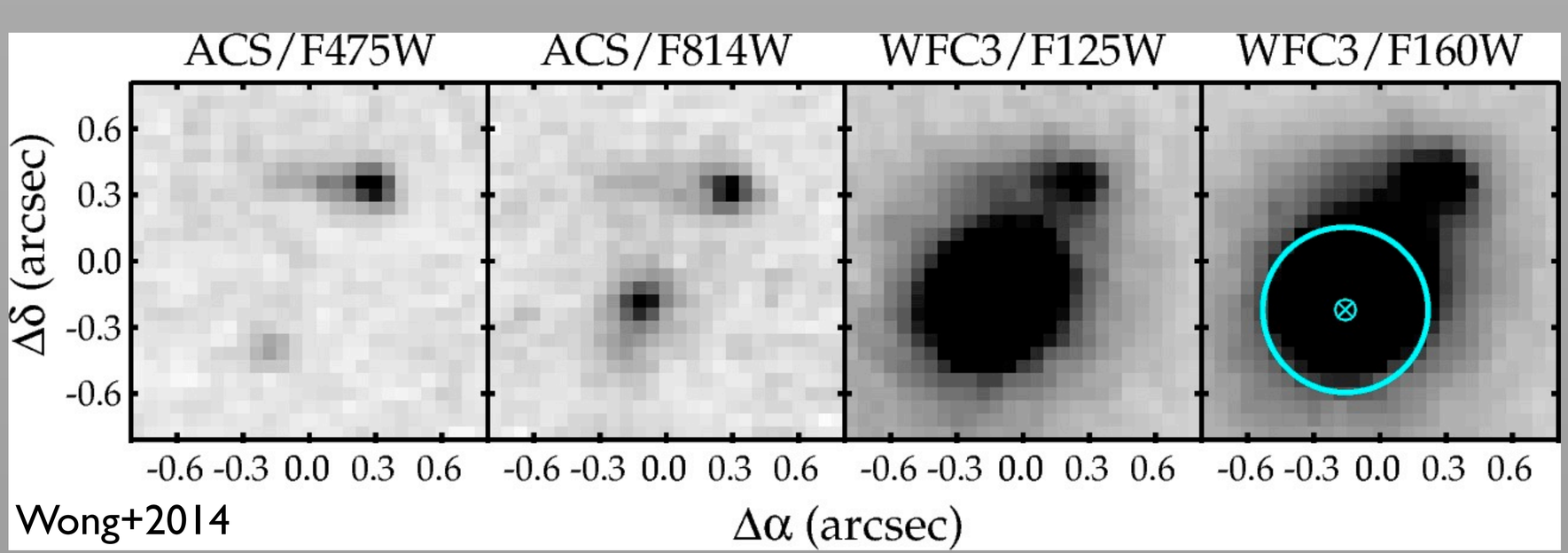
- Strong lens galaxy in IRC 0218 cluster (Papovich+2010)
- **z = 1.62 → most distant strong lensing galaxy known!**
- Large amount of data (including UKIDSS, CANDELS, 3D-HST)
  - 18-band photometry (0.4 - 8 μm)
  - HST/G102+G141 spectroscopy
  - Keck/LRIS spectroscopy
- Lyα, [O III] emission from source at z = 2.26
- Stellar mass ≈ 2×10^{11} $M_\odot$ (Papovich+2012)





Lens Modeling

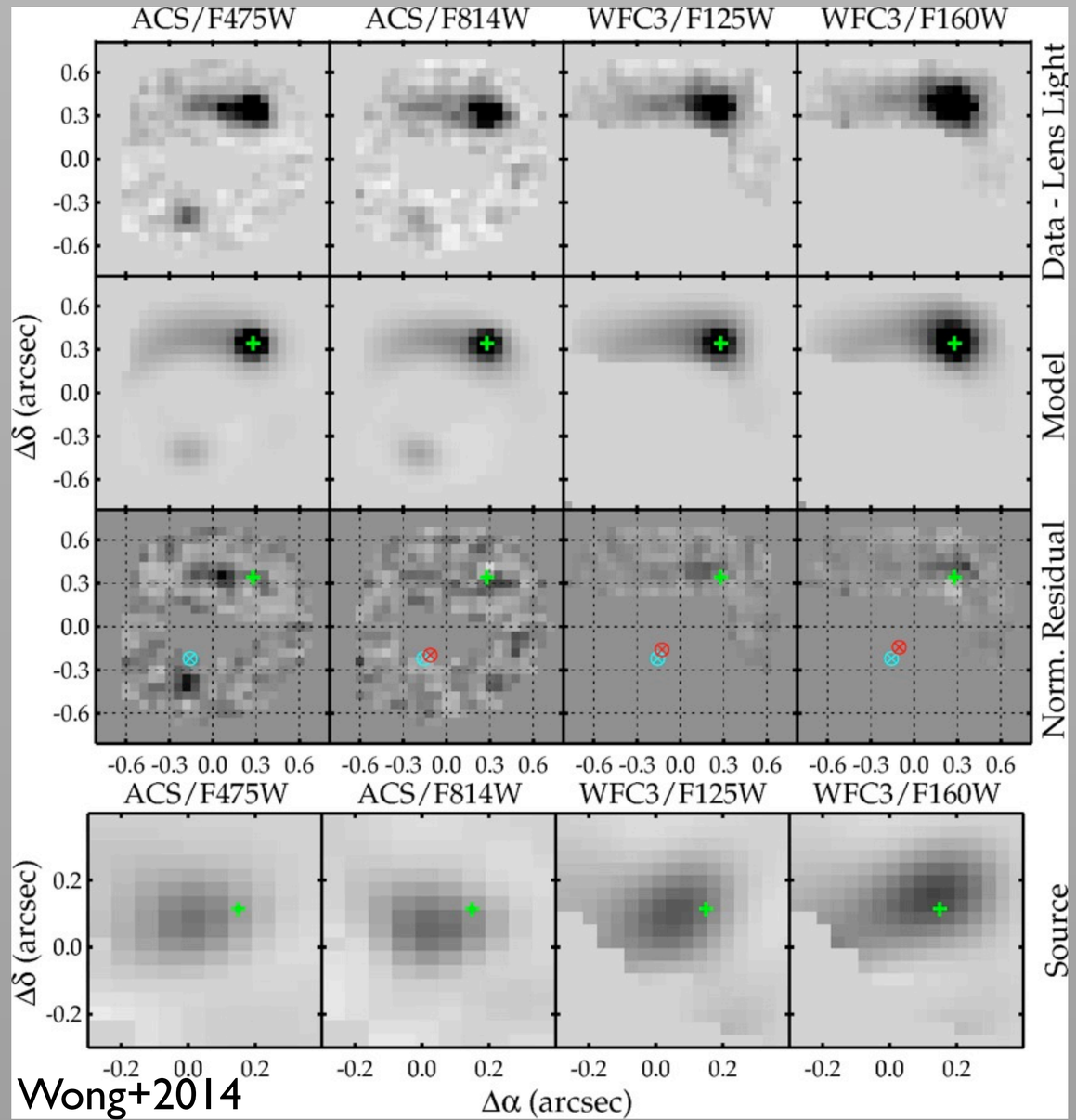
- Model lens using GLEE (Suyu & Halkola 2010)
- Simultaneously fit singular power-law elliptical model to four HST bands
- Lens environment included in model
  - Cluster NFW halo properties from X-ray constraints (Pierre+2012)
  - Cluster + LOS galaxies have little effect on lens galaxy properties
  - Estimate ~10% of mass within θ_E from environment
- Source modeled as extended component + compact point source



Wong+2014

Results

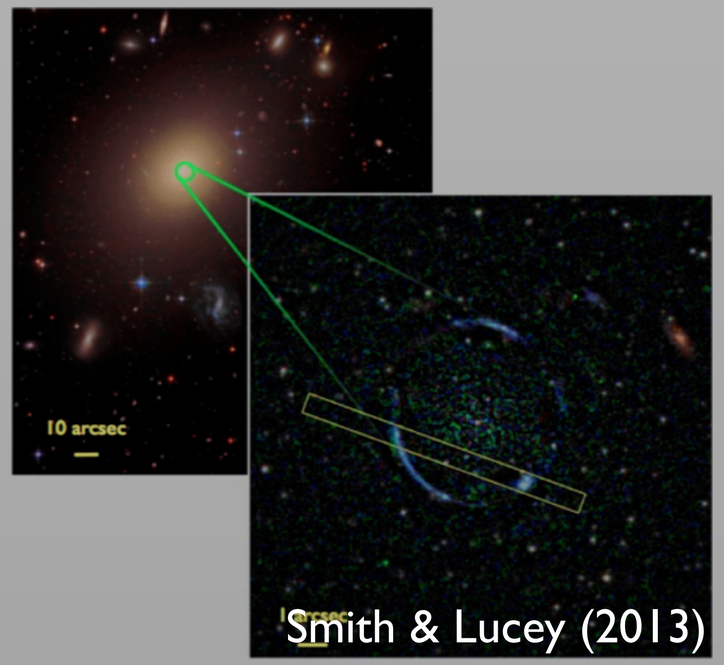
- Lens galaxy
  - Low ellipticity (b/a = 0.8)
  - θ_E = 0.38” (~3.2 kpc at z = 1.62)
  - M_{tot} (< θ_E) = 1.8 × 10^{11} $M_\odot$
  - f_{DM} ~ $0.3^{+0.1}_{-0.3}$ (Chabrier IMF)
  - f_{DM} ~ $-0.3^{+0.2}_{-0.5}$ (Salpeter IMF)
- Source
  - Compact emission offset from peak of extended component
  - Residuals in image - compact emission line regions?



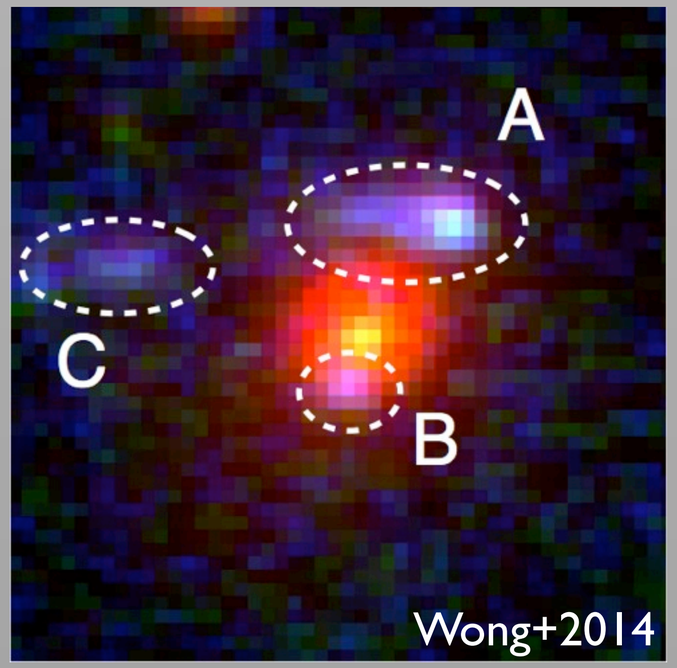
Wong+2014

An Interesting Comparison...

z_L = 0.035



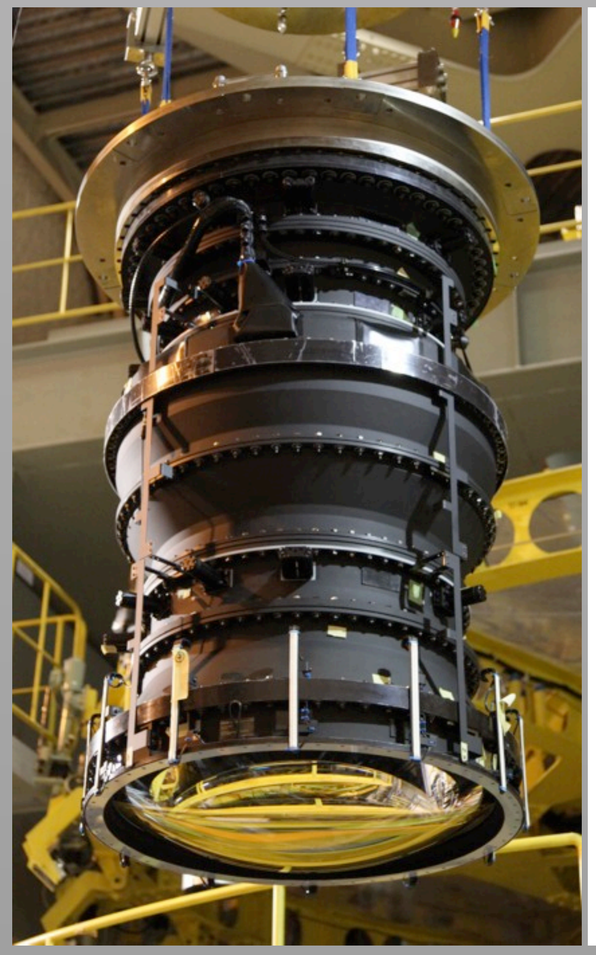
z_L = 1.62



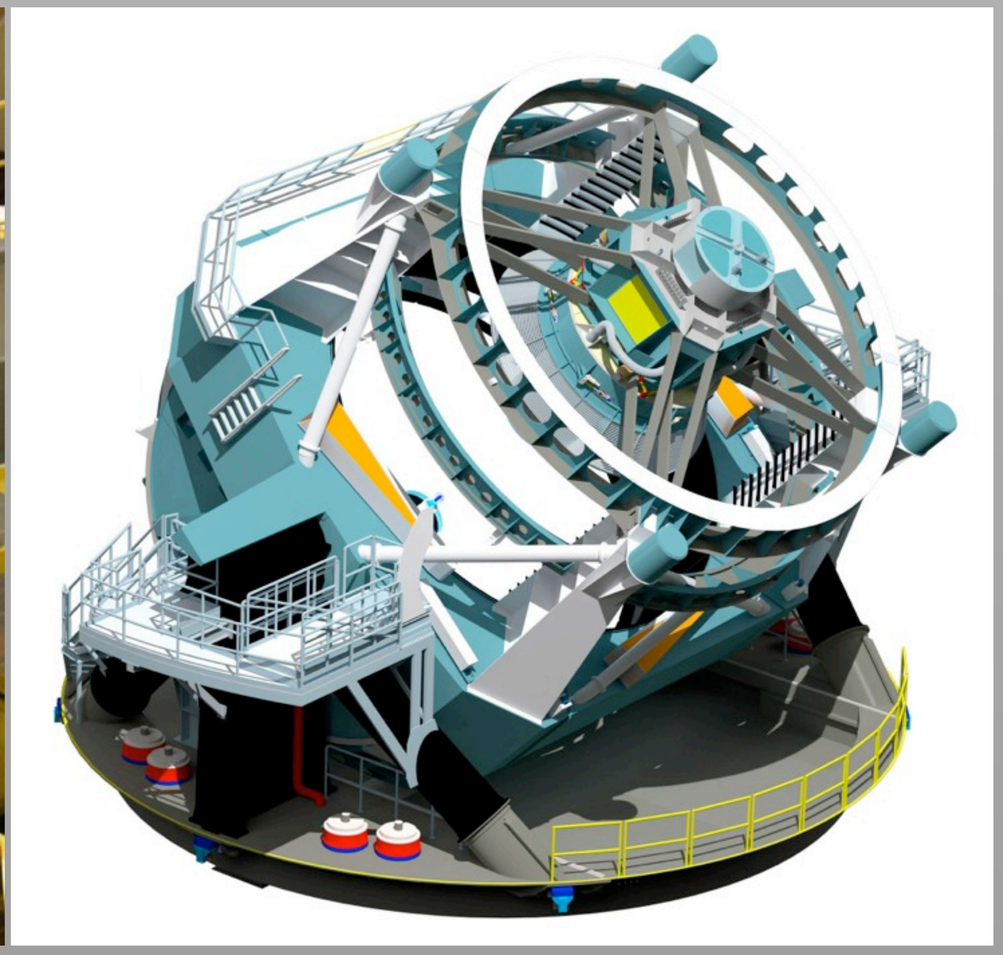
- ESO325−G004 (Smith & Lucey 2013), lowest-redshift strong lens galaxy
- Very low dark matter content within θ_E but also has lightweight IMF - Salpeter ruled out
- IMF depends on conditions under which bulk of stars were formed?
- Gargiulo+2014 suggest high Σ* galaxies have higher ratio of high-to-low mass stars
- Although Chabrier+2014 suggest the exact opposite...
- ???

Discovering More High-z Lenses

- z > 1 lenses are rare, faint, hard to resolve
- Need deep, wide-field survey - HSC, DES, LSST
- Ways to search for lenses in big imaging surveys?
  - Close pairs of red (lens) galaxy and blue (source) galaxy
  - Objects with negative color gradients - redder in core regions
  - Look in overdense regions (e.g. high-z clusters)
- Spectroscopic follow-up?
- High-resolution follow-up?



HSC



LSST

Summary

- Discovery of lens in z = 1.62 cluster
  - **highest-redshift lens galaxy known**
- Lens model constrains total mass within θ_E
  - Environment contributes ~10%
- f_{DM} ~ 0.3 for Chabrier IMF; Salpeter IMF disfavored
  - **Possible tension with low-z ETGs**
- Source has compact emission - offset emission line regions?
- More z > 1 lenses will improve constraints on evolution of ETG properties
  - Wide-field surveys (HSC, DES, LSST, etc.) will hopefully discover more