Strong Lensing

Sloan Giant Arcs Survey: *Michael Florian(Chicago), Traci Johnson(UMich), Matt Bayliss(Harvard/CfA), Eva Wuyts(MPE), Kate Whitaker(GSFC),* Keren Sharon (UMich), Jane Rigby(GSFC), Hakon Dahle(Oslo)

Chicago/Argonne SL Sims: *Steve Rangel(Northwestern), Nan Li(Chicago), Lindsey Bleem(ANL)*, Katrin Heitmann(ANL), Salman Habib (ANL)

Mike Gladders

The University of Chicago
Department of Astronomy and Astrophysics
Kavli Institute for Cosmological Physics

WFIRST2014

Preparation, Sample Definition, Follow-up

- Current landscape for galaxy-mass lenses, group and cluster scale lenses: **science impact**, search techniques
- What will WFIRST find and how do we define samples of strong lenses from it? The need for simulations.
- How do we exploit these samples most effectively? Strong lensing in a resource-constrained regime...

Strong Lensing: Why bother?

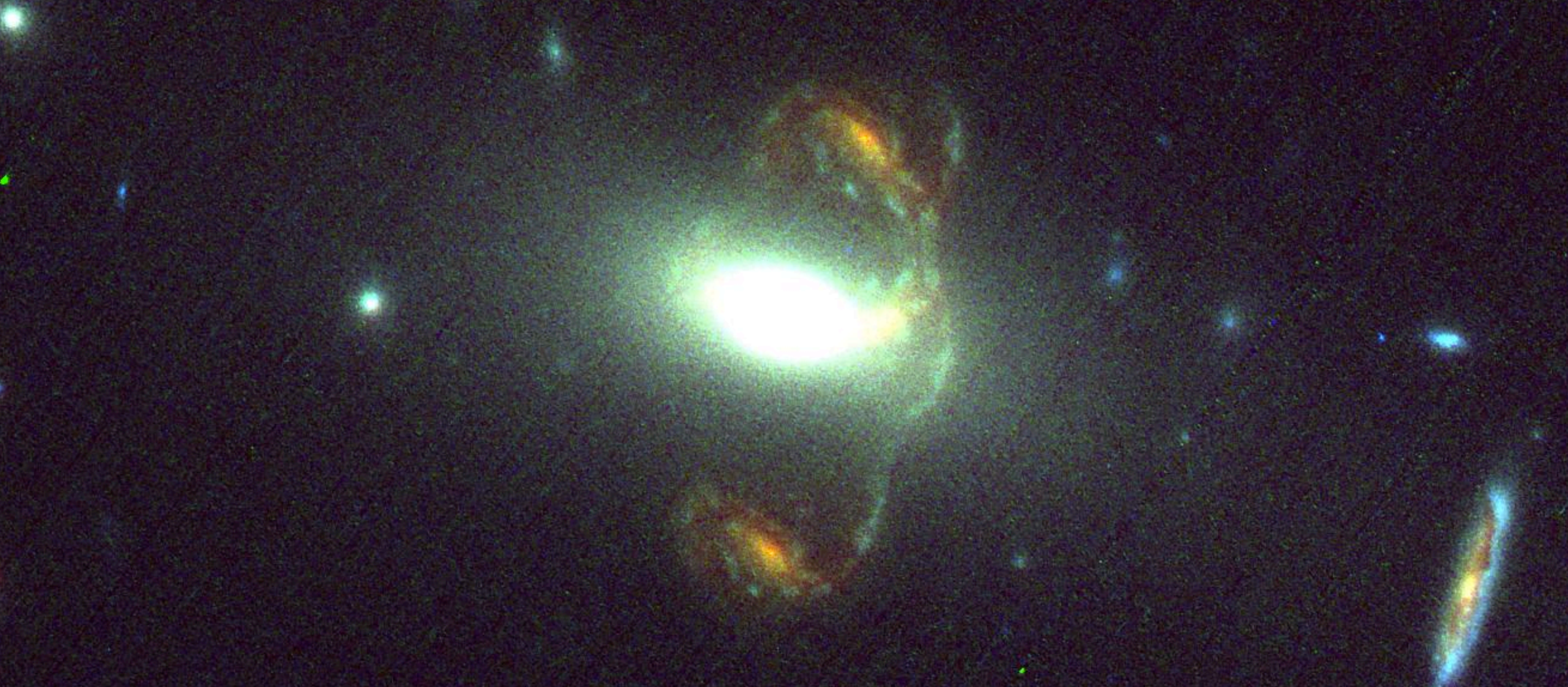
Jane Rigby's talk

- Studying sources:
  - better S/N (broader λ coverage, better spectra)
  - better spatial resolution
- Studying lenses:
  - Details of internal structure
  - Statistics of lensing
- Cosmology :
  - e.g. time delays for H_0

HST: F140 + F814 + F606

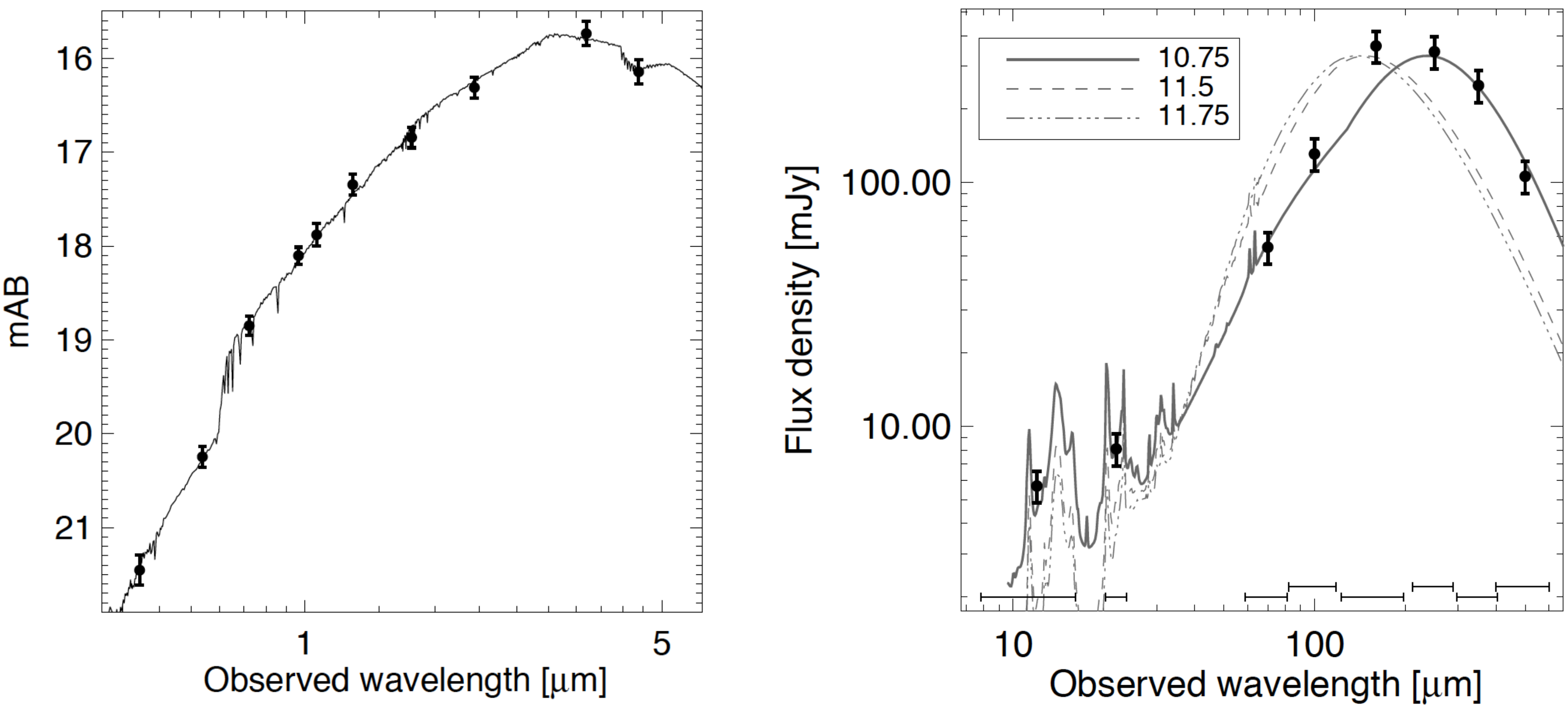
SGAS1438+1454

- z=0.82 LIRG - a typical Spitzer 24um source, SFR ~ 28 M_{sun}/yr
- Appears to be a well-developed disk with star formation everywhere

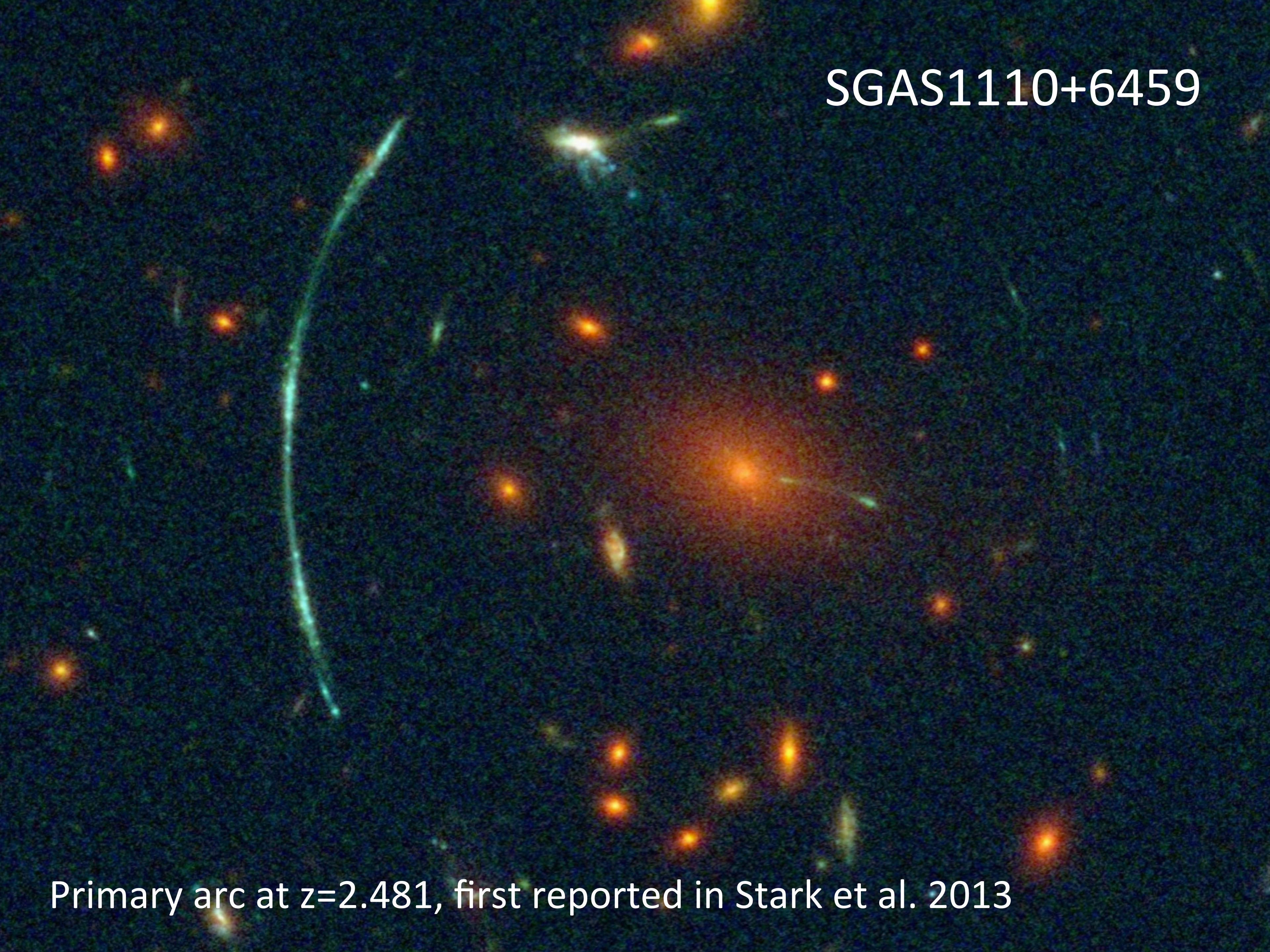


- one mag brighter and you could see this in 2MASS…

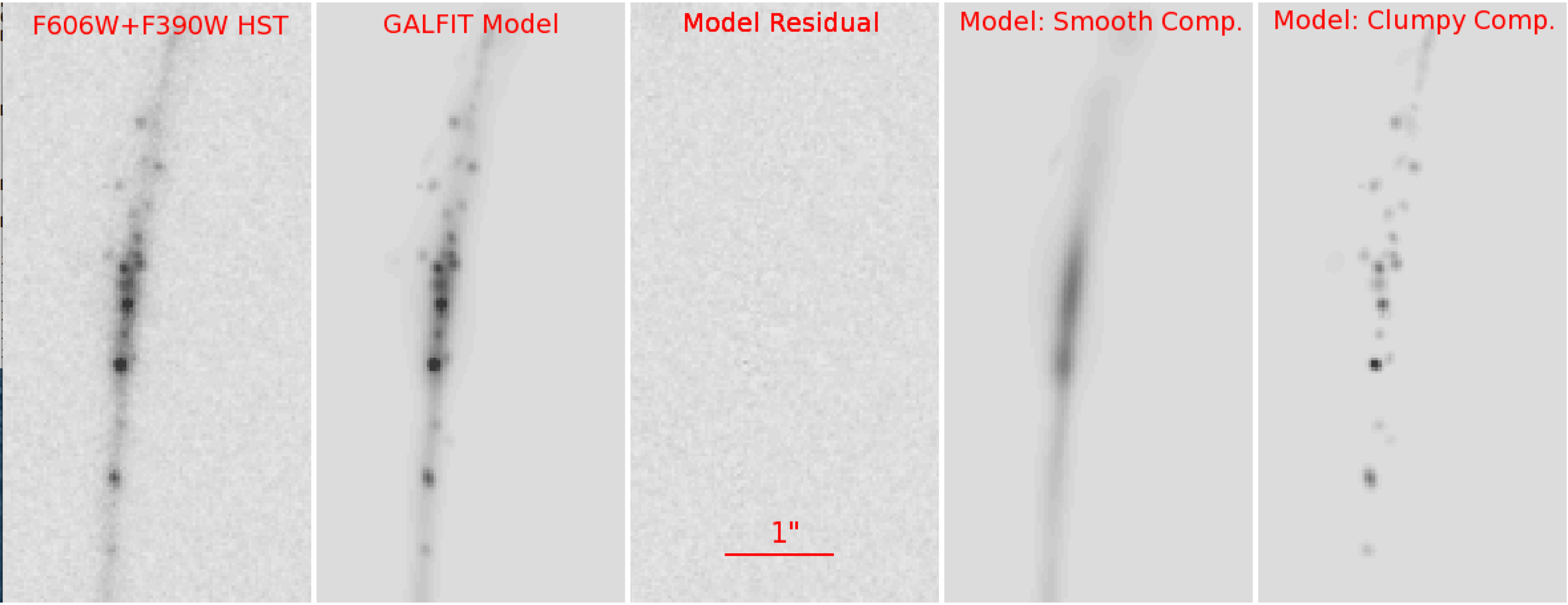
Hence – the SED of a typical (in the sense of being where the bulk of the star formation is) galaxy at z~1, from 300nm to 1mm.



Gladders et al. (2013)


SGAS1110+6459
Primary arc at z=2.481, first reported in Stark et al. 2013

Structural Components, Image Plane Modeling

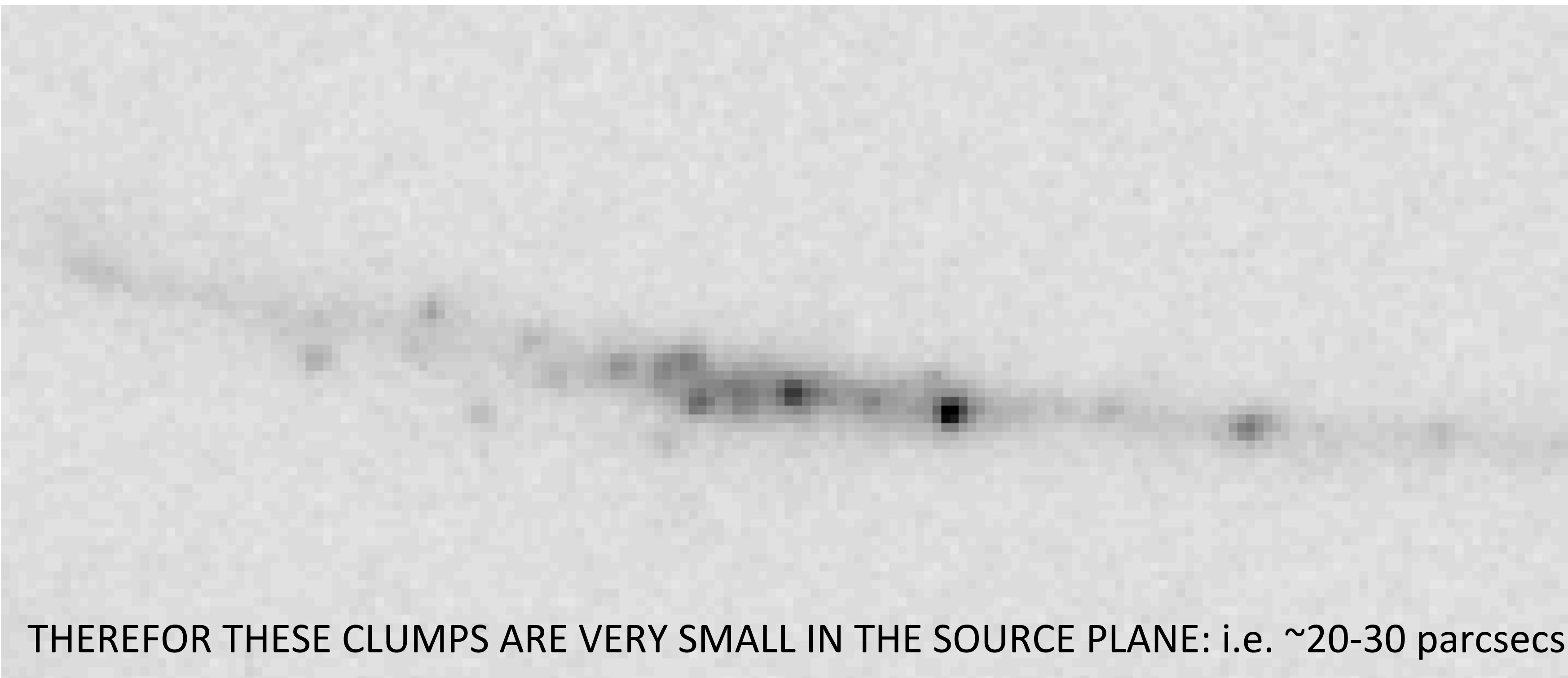


Structural Components, What is Means

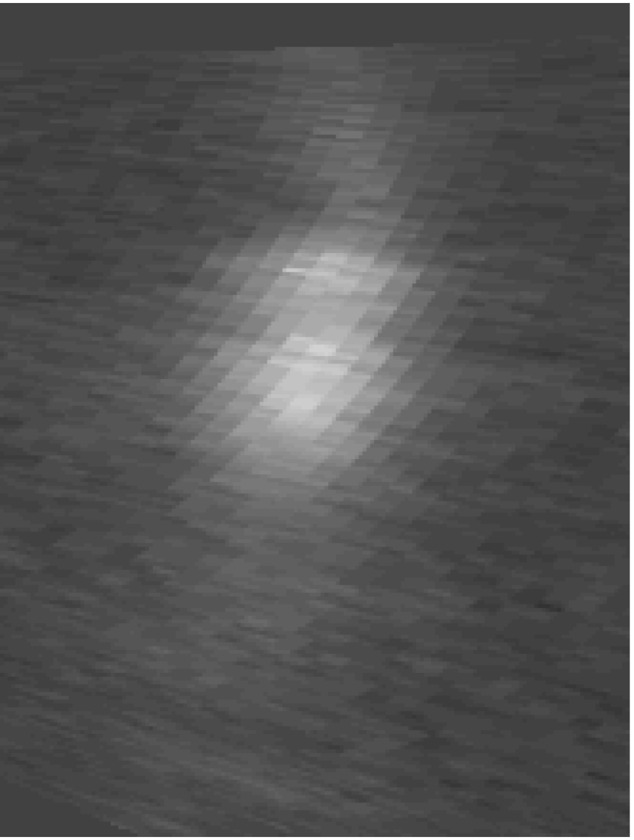
Building a GALFIT model in this context is basically doing a parametric de-convolution in the image plane. Consider a single clump:

- presume it is round in the source plane
- lens it, and observe it with HST: if the tangential extent of lensed image is as-large/ larger than the HST PSF then the clump appears tangentially elongated

THESE CLUMPS ARE NOT!!

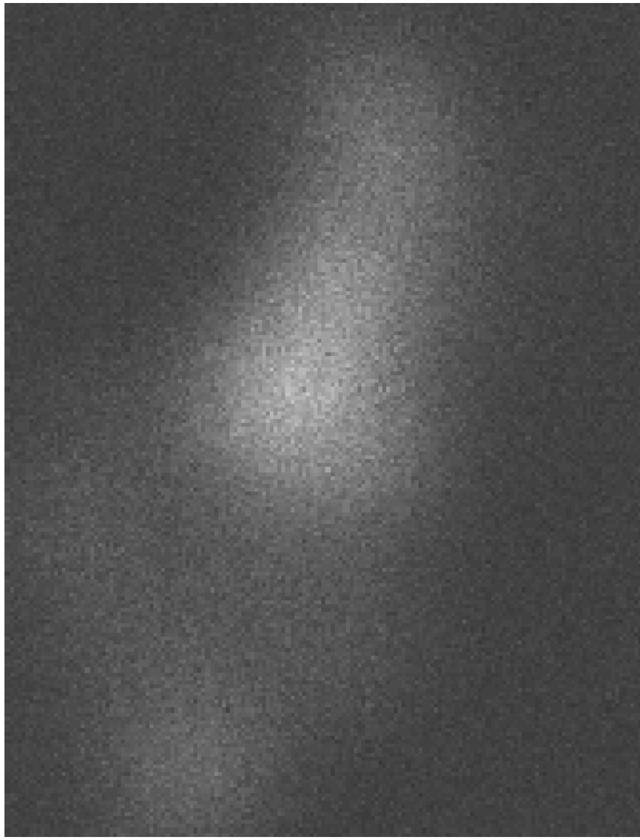


Structural Components, Source Plane



Actual Smooth Component Data, De-lensed to Source Plane

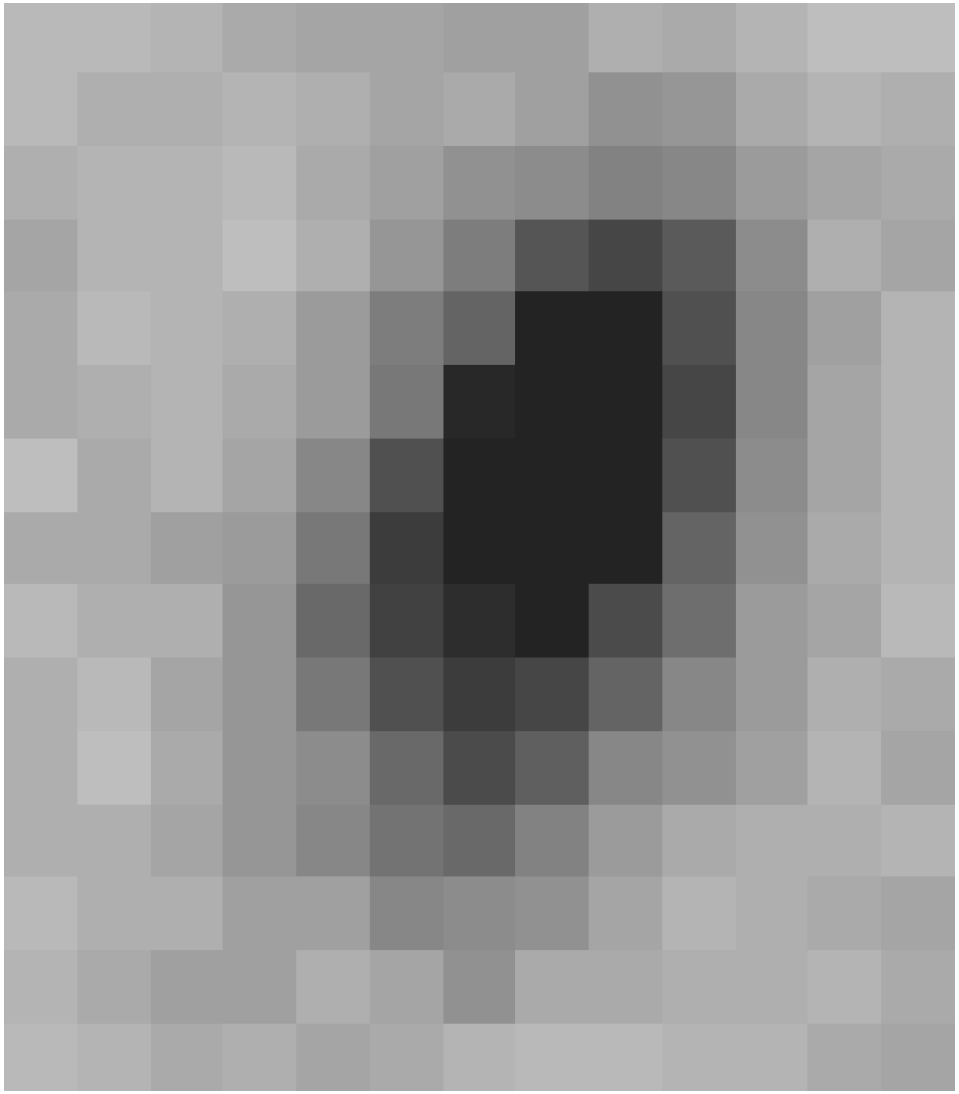
Clump Component Model, Re-built in Source Plane



Simple Source plane model, just from smoothing the clumps!

There is little evidence that the smooth component is anything but intimately connected to the clumps

Without Lensing...



Without strong lensing, at reasonable S/N, this is what this galaxy would look like to WFIRST. Just another undistinguished fuzzy blob! The only way we can learn these details about the interiors of distant galaxies is through strong lensing .

Strong Lensing: Why bother?

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  - better spatial resolution
- Studying lenses:
  - Details of internal structure
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- Cosmology :
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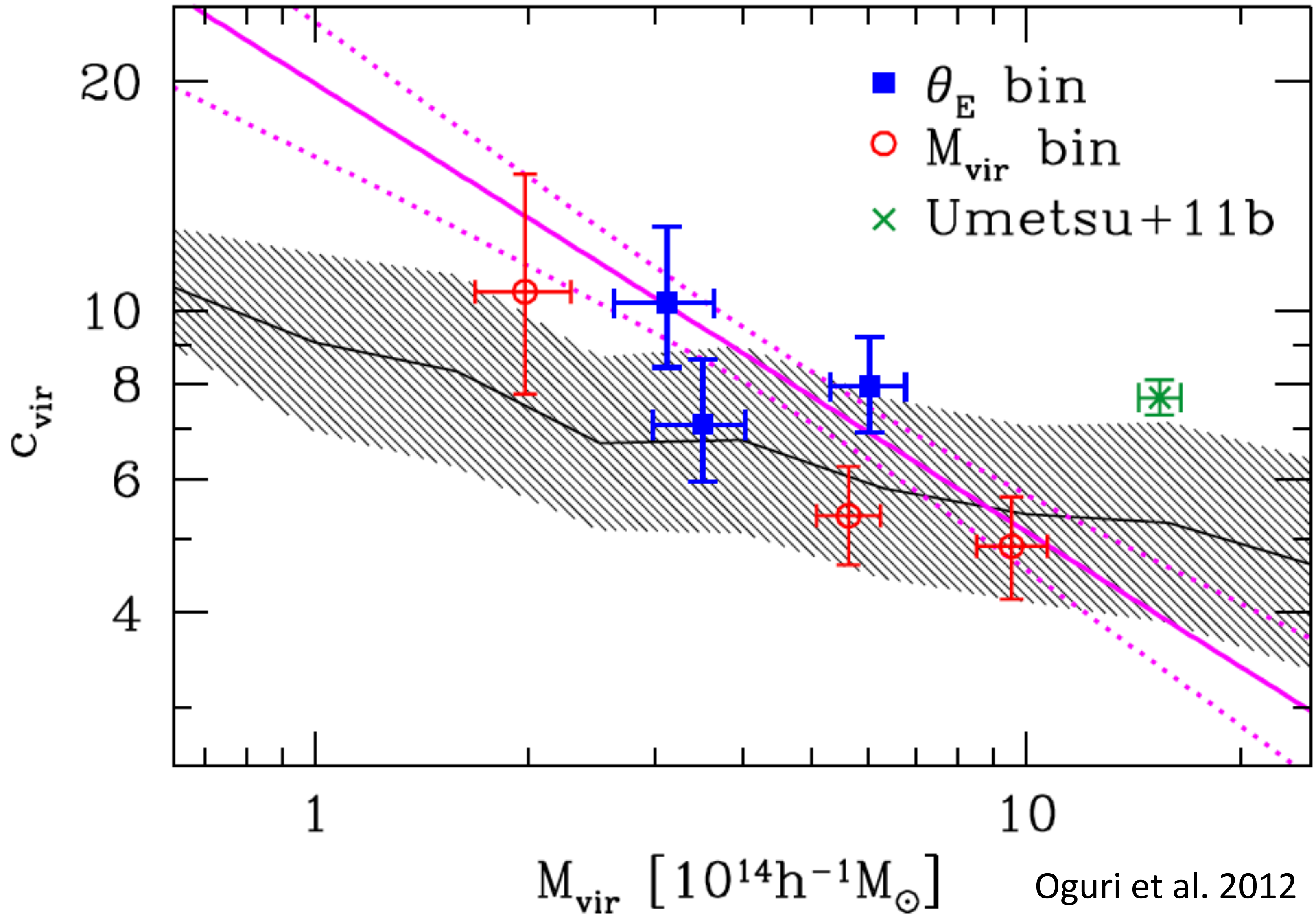
Lensing Cluster Mass-Concentration



Oguri et al. 2012

See also Merten et al. 2014

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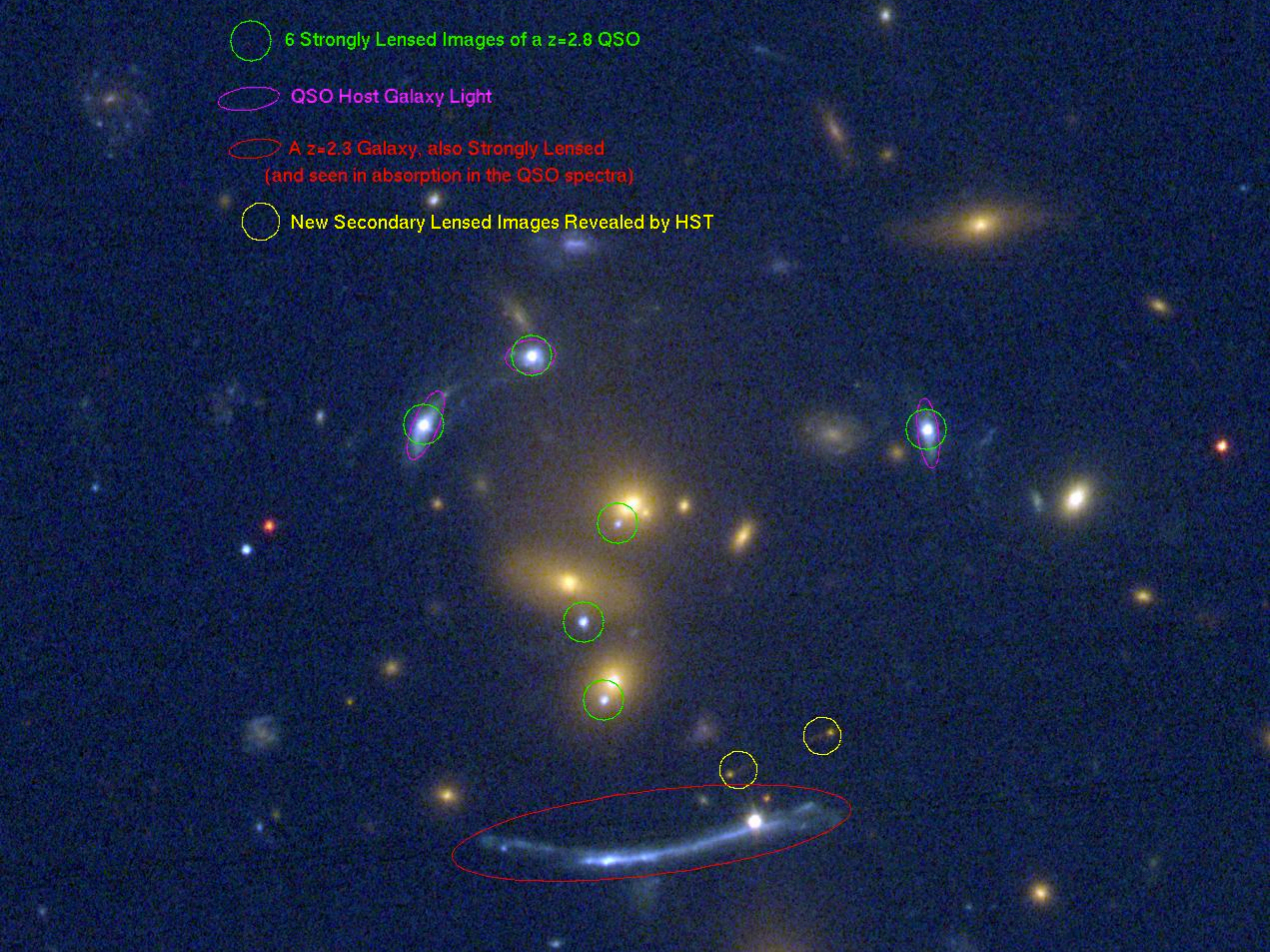
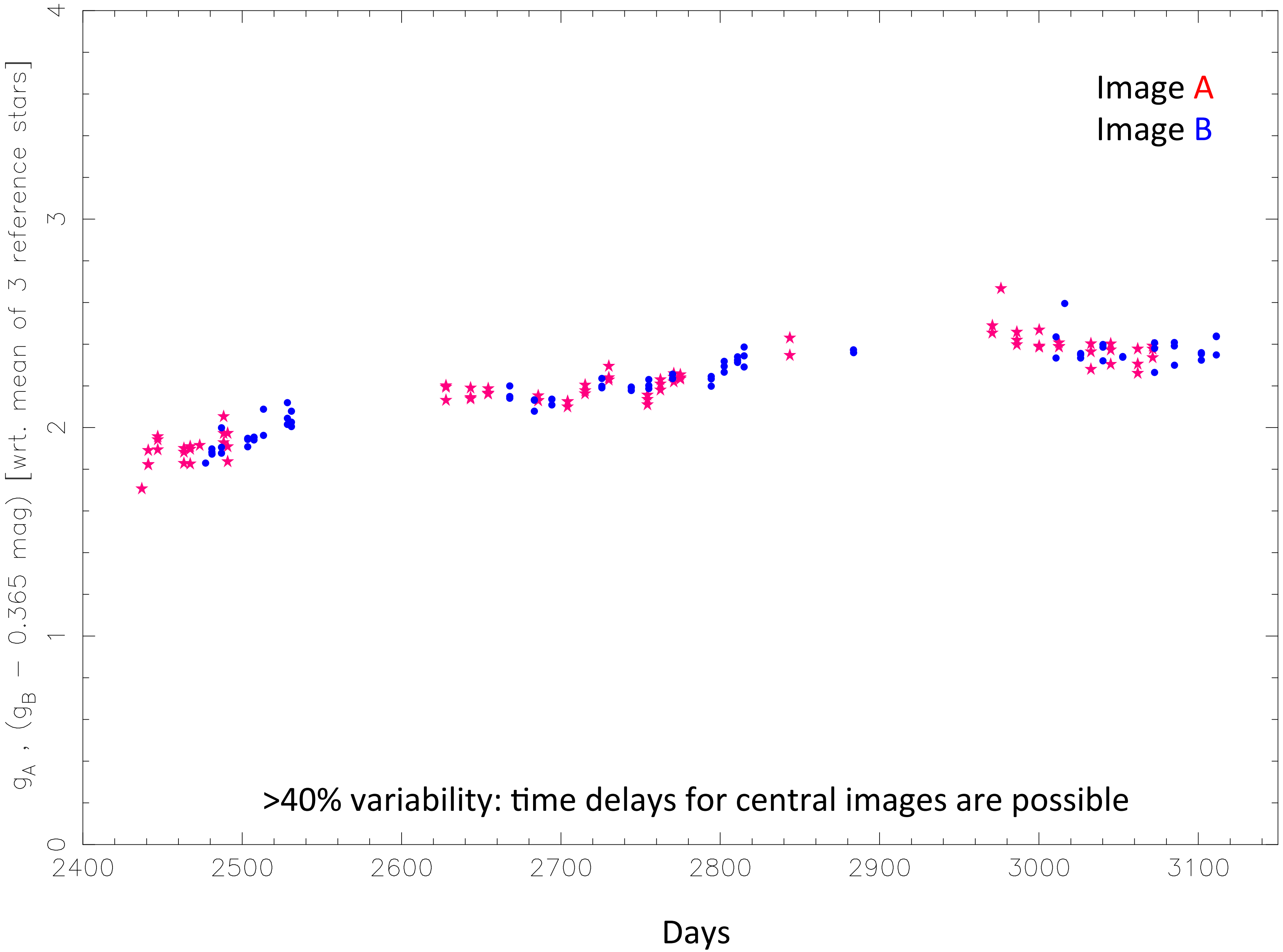

6 Strongly Lensed Images of a z=2.8 QSO
QSO Host Galaxy Light
A z=2.3 Galaxy, also Strongly Lensed
(and seen in absorption in the QSO spectra)
New Secondary Lensed Images Revealed by HST

A Measured Time Delay!



Preparation, Sample Definition, Follow-up

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- What will WFIRST find and how do we define samples of strong lenses from it? The need for simulations.
- How do we exploit these samples most effectively? Strong lensing in a resource-constrained regime…

Finding Strong Lenses: History

- General Relativity – Einstein (1916)
- Dark Matter, oh yeah and lensing too… Zwicky (1937)
- Twiddling of thumbs – many (1937-1979)
- The Double Quasar – Walsh et al. (1979)
- Abell 370, CL2242 – Soucail et al. (1987), Lynds & Petrosian (1986

Strong Lens Samples Now

- Lensed quasars ~120
- lensed galaxies >400

By source

- galaxy scale lenses ~400
- Group+cluster scale lenses >200

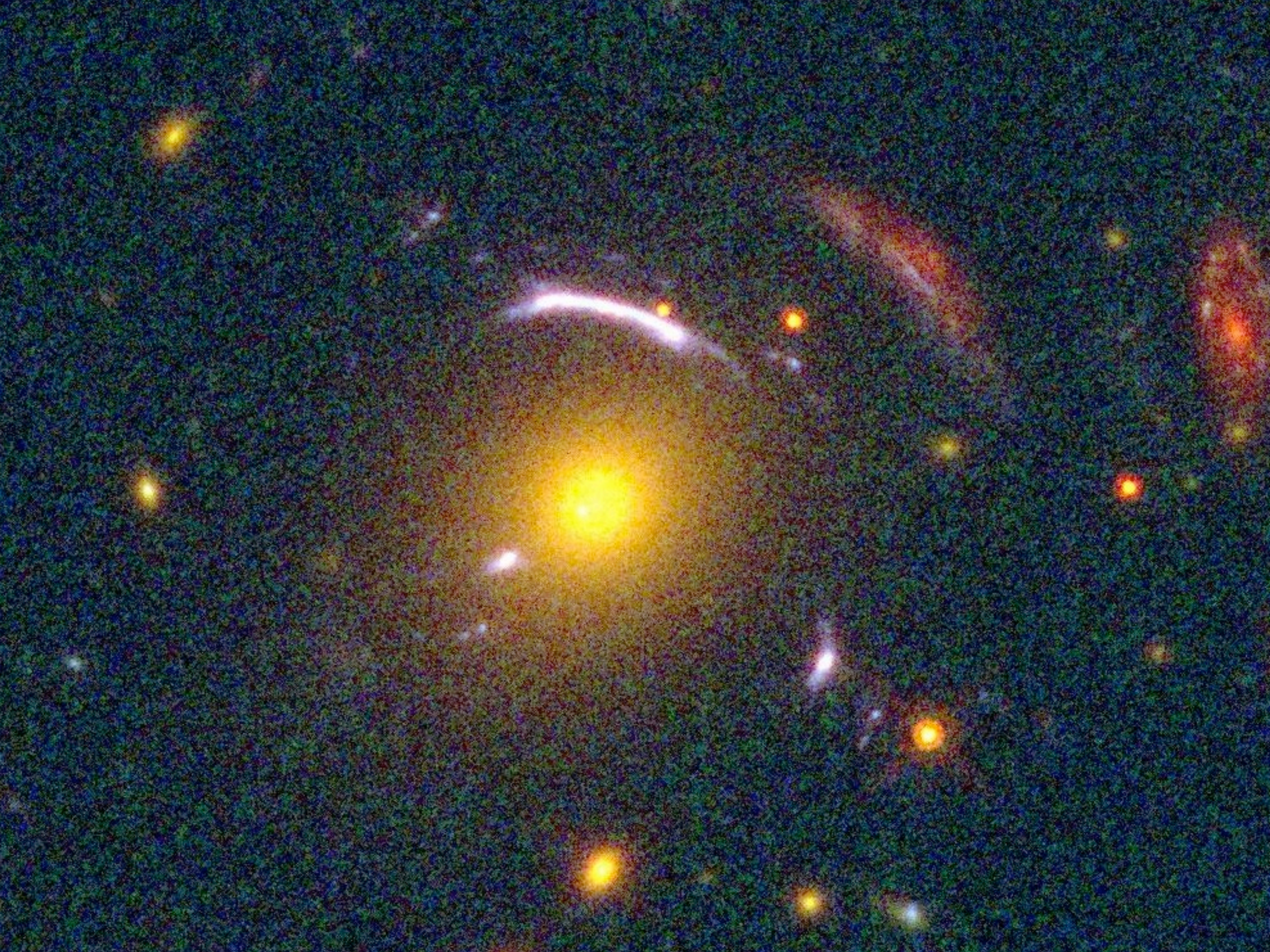
By lens

(Master Lens Database: Moustakis et al.)

How to Find Strong Lenses

The Sloan Giant Arcs Survey (SGAS) example:

- Strong lensing defined morphologically
  - Sensible(?) since strong lensing manifests geometrically; with sufficiently high-quality data, it is simply unambiguous
- Searched performed visually
  - Sensible(?) since the human eye and brain are remarkably good at spotting faint signals in complex visual fields



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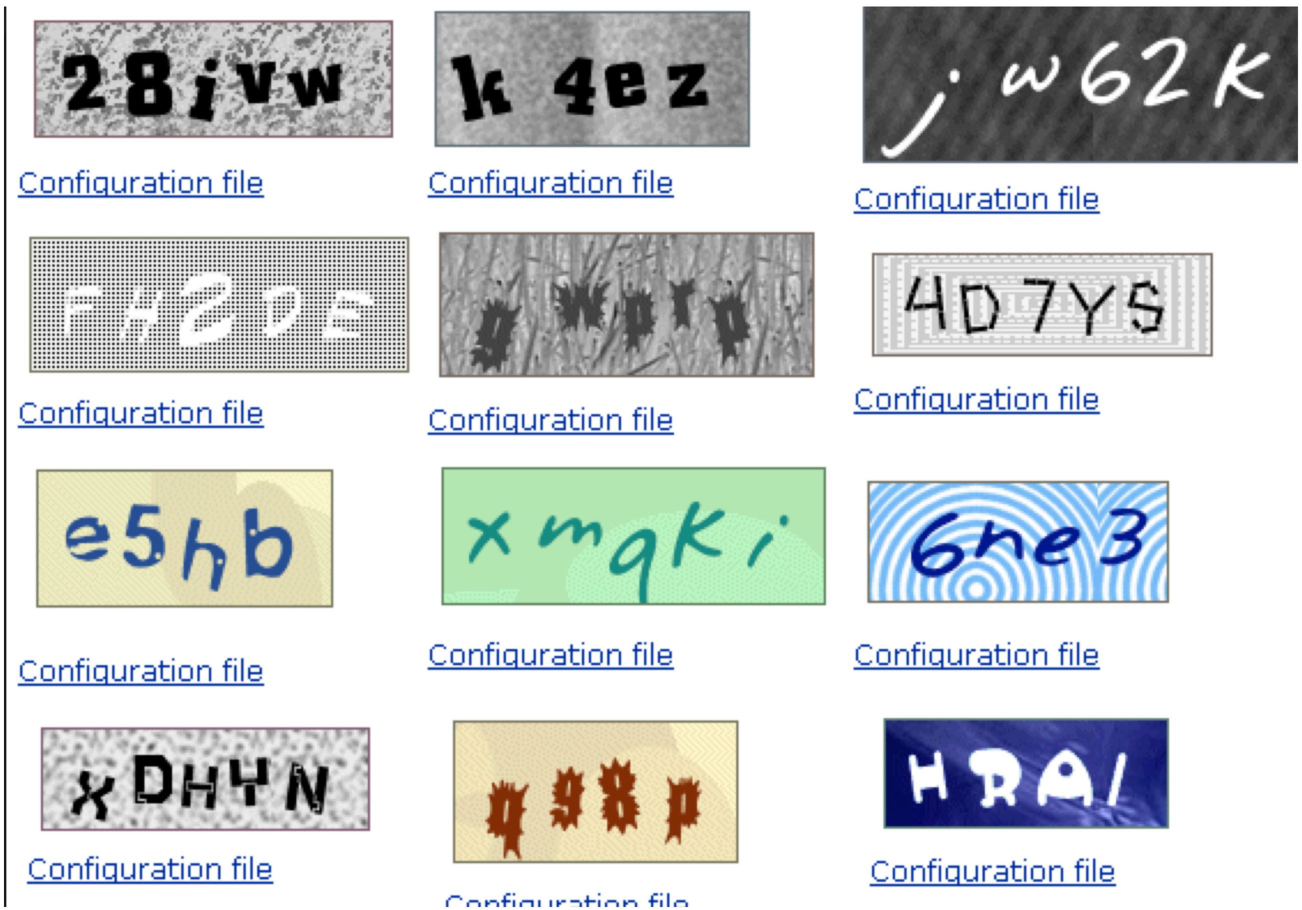
SGAS: Humans versus Computers…

Plan: Find candidate lens systems – a needle in the haystack problem
Execution: look by eye at ~300,000 images…

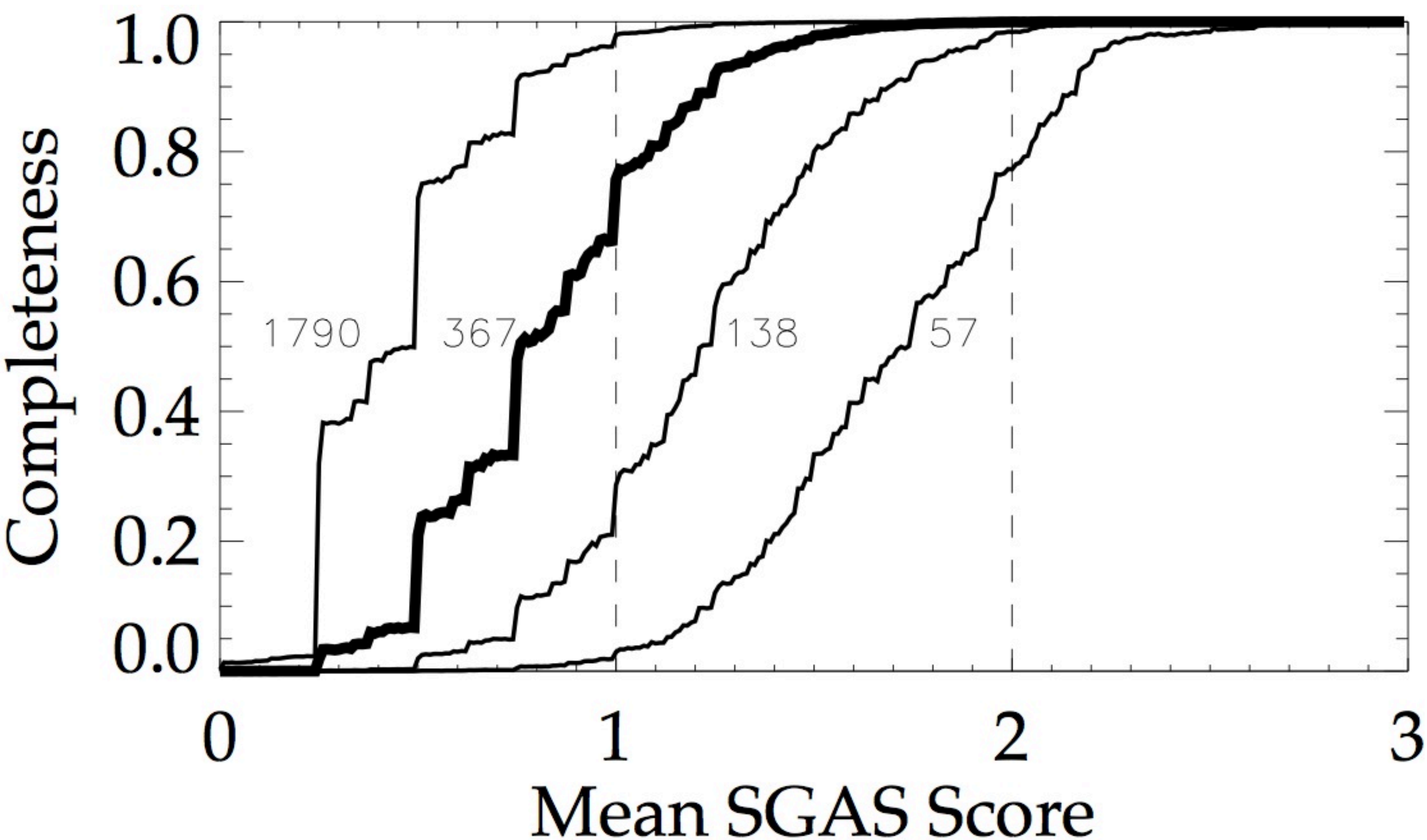


CAPTCHA: **C**ompletely **A**utomated **P**ublic **T**uring test to tell **C**omputers and **H**umans **A**part

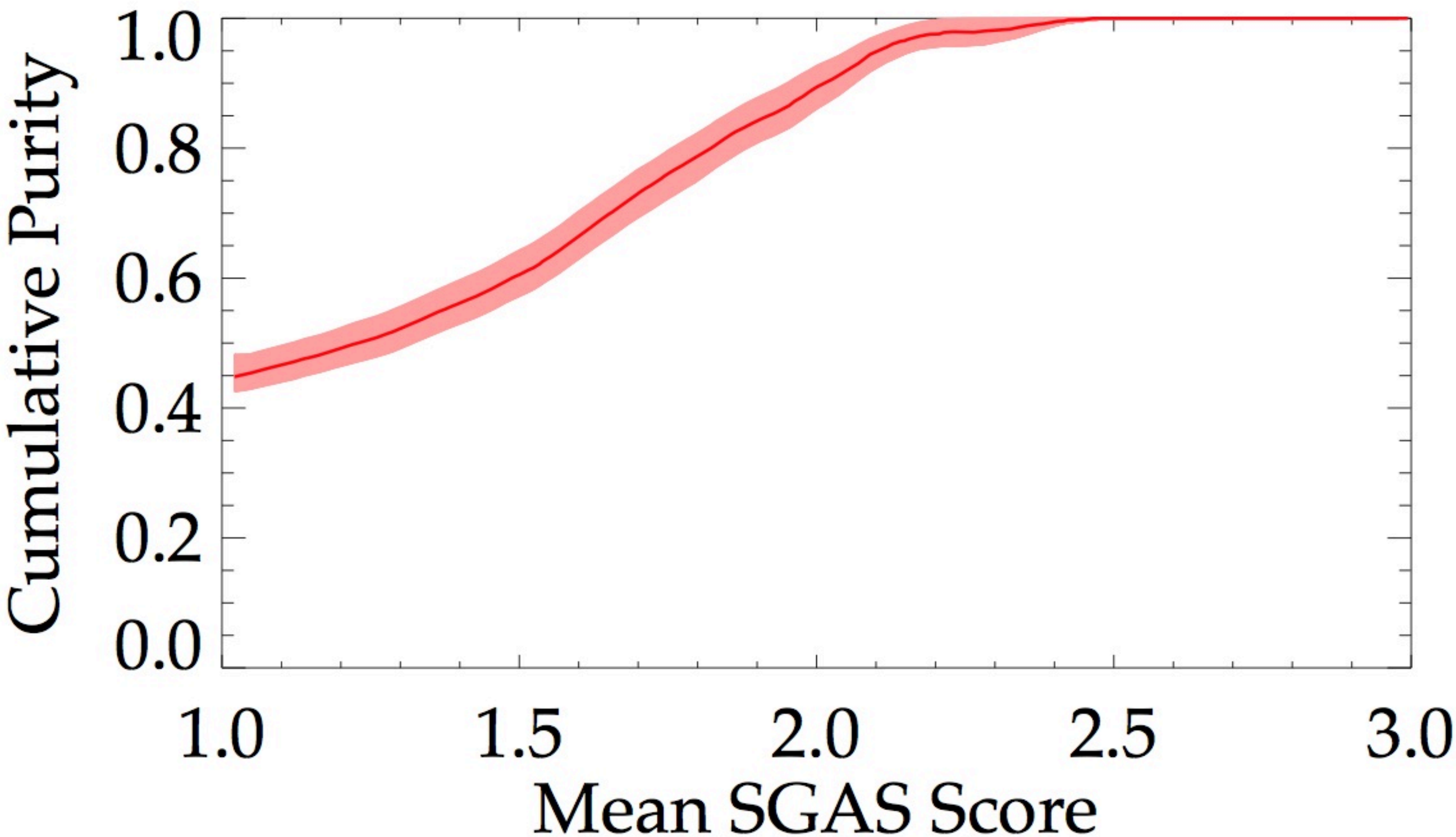
Why are we good at this?

Answer: Evolution, probably?

Candidate Completeness is Internally Defined



Pure Sample by Follow-up
(establishes purity of search approach)



WFIRST Implications

- We CAN – and will! - do a visual definition of strong lensing in WFIRST images. A great opportunity for 'citizen science'.
- We CANNOT follow-up all of these lensing systems in a manner that echoes current work.
- New approaches are needed:
  - 'Golden' Lenses
  - Simulation backed statistics

WFIRST Strong Lensing Numbers

COSMOS: HST - 2 square degrees imaged to an F814W 5-sigma point source depth of ~26.5: comparable to WFIRST

- 67 strong lenses, rather broadly defined
- 'useful' strong lenses are ~10-20% of that total : say 3-6 per square degree

Ground-based 4m-class efforts (RCS2, S2LS): interesting lens sky densities of 1 per 10 to 1 per few square degrees

WFIRST 'interesting' strong lens numbers:

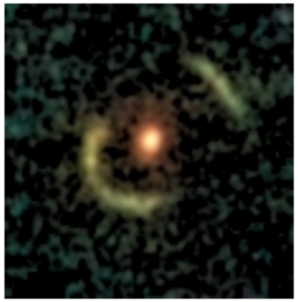
1000-20000 systems

Spectroscopic ←→ Photometric

COSMOS5921+0638

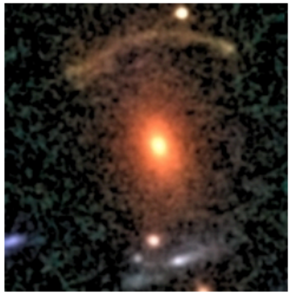
ID: #3566
RA (deg): 149.84068
Dec (deg): 2.11067
zl: 0.551
zs: unknown
Arc radius: 0.80"

COSMOS0018+3845



ID:
RA (deg):150.07666
Dec (deg):2.64580
zl: 0.71(+0.02,-0.13)
zs: unknown
Arc radius: 0.40"

COSMOS0211+1139

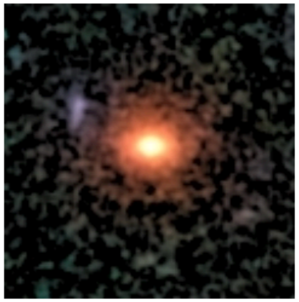


ID: #24769
RA (deg): 150.54673
Dec (deg): 2.19430
zl: 0.90 (+0.06, -0.04)
zs: unknown
Arc radius: 3.20"

YES

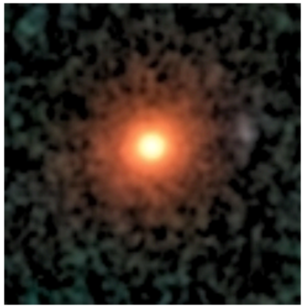
NO

COSMOS0227+0451



ID: #11051
RA (deg): 150.61457
Dec (deg): 2.08104
zl: 0.89 (+0.03, -0.05)
zs: unknown
Arc radius: 1.62"

COSMOS0107+0533



ID: #8169
RA (deg): 150.28312
Dec (deg): 2.09260
zl: 0.90 (+0.06, -0.06)
zs: unknown
Arc radius: 1.71"

COSMOS0148+2325

ID: #14940
RA (deg): 150.45053
Dec (deg): 2.39035
zl: 0.40 (+0.04, -0.04)
zs: unknown
Arc radius: 1.43"

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1000-20000 systems

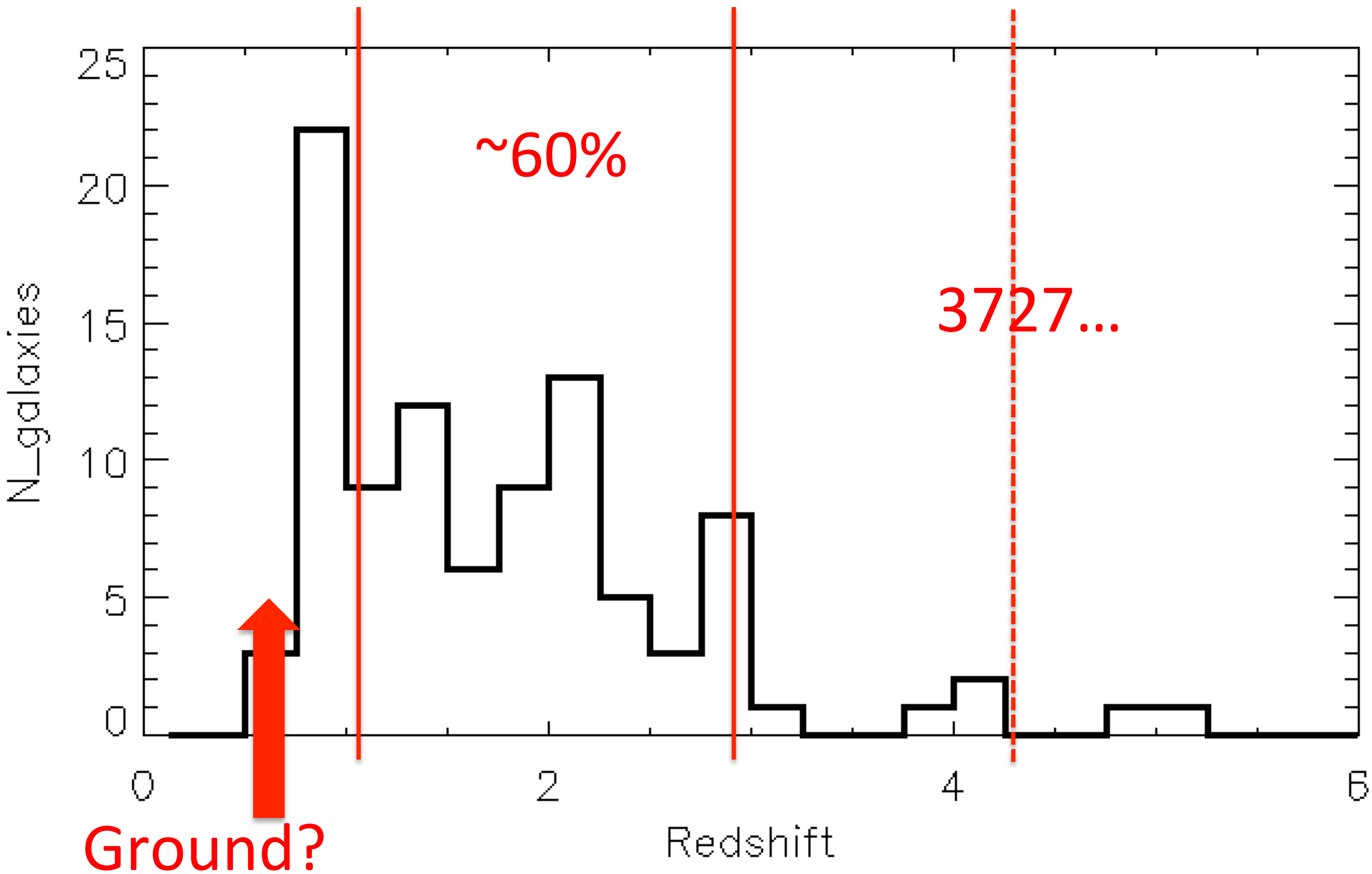
Spectroscopic ←→ Photometric

WFIRST Strong Lensing Follow-up

Likely at most <10% percent of the sample will receive devoted follow-up. `Interesting' lenses will STILL have sky surface densities of a few per square degree, and so there is little multiplex advantage from typical instruments. It will be a one-by-one game. (But still worthwhile!)

The bright end of the strong lens sample from the HLS will have many redshifts of lensed sources from the grism survey. The lensed source redshift distribution peaks at z~2, and the fiducial 1<z<3 range of the grism (for one of 5007 or H-alpha) encompasses ~60% of typical lensed source redshifts.

CASSOWARY (Stark et al. 2013) + SGAS (Bayliss et al. 2011)
Lensed Source Spectroscopy



WFIRST `Golden' Lenses

(or even Bronzy or Brassy lenses…)

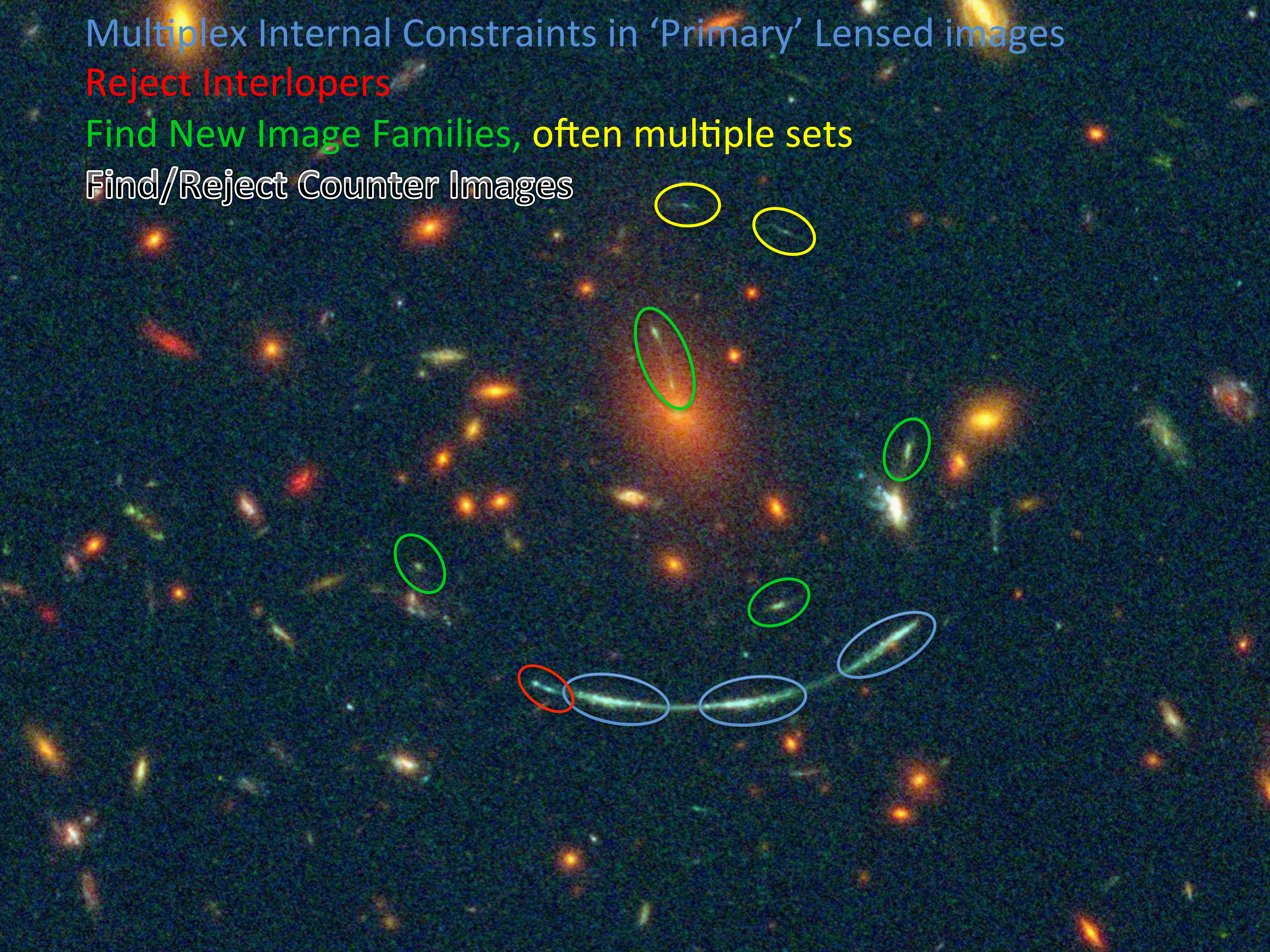
The history of strong lensing suggests that drilling down on a small subset of lenses – be it to study exceptional sources, or exceptional lenses – pays off scientifically. How does WFIRST sit in this game?

z<4 sources: **Meh**. Ground based effort will find / have found the brightest things.

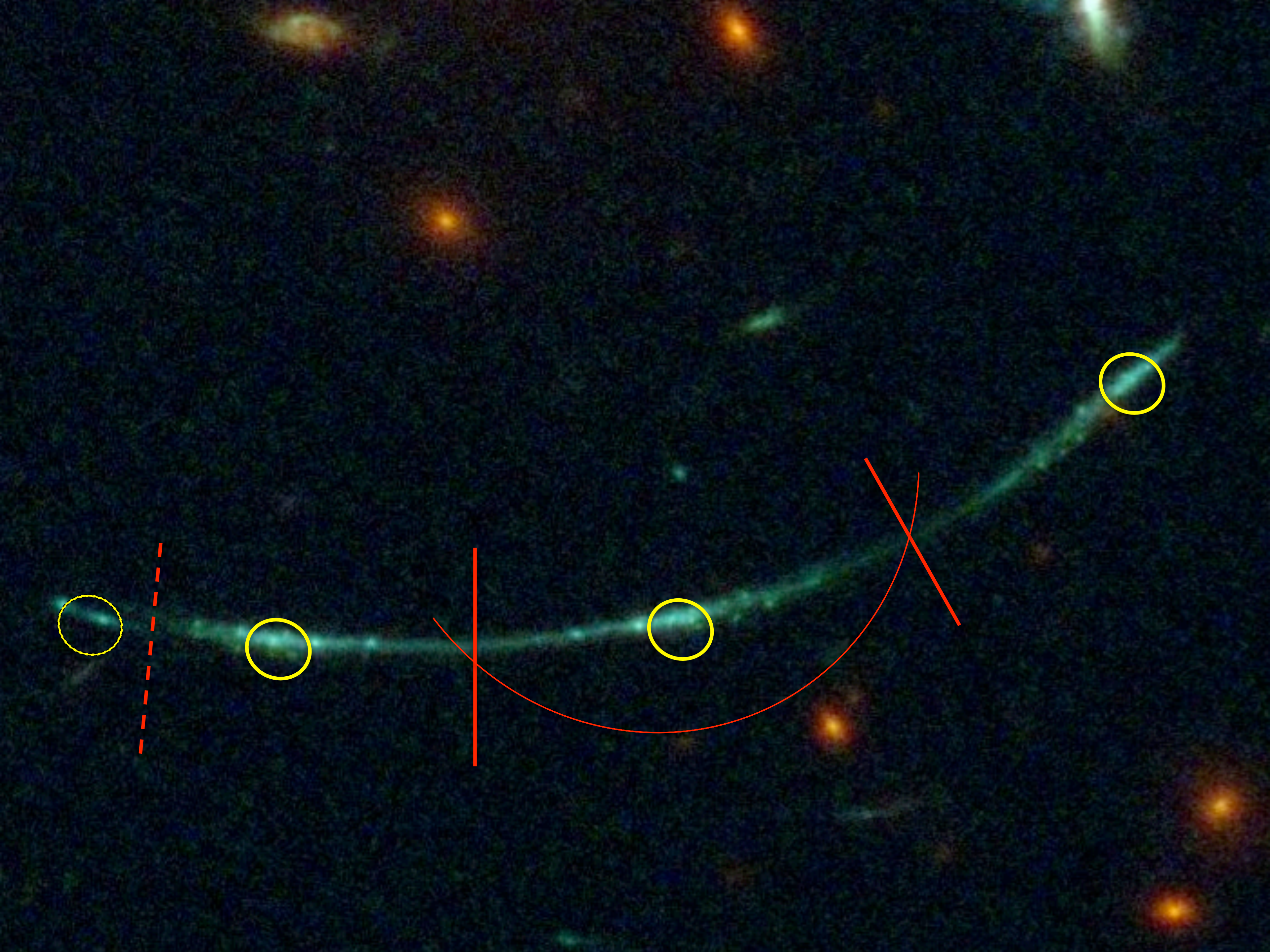
z>4 sources: **Woohoo!** Sensitivity + area means a new regime. Find the brightest lensed sources into the reionization epoch. (But Euclid will do this better due to area.) Crawl down the LF to very faint limits (WFIRST does this well, but JWST will rule.)

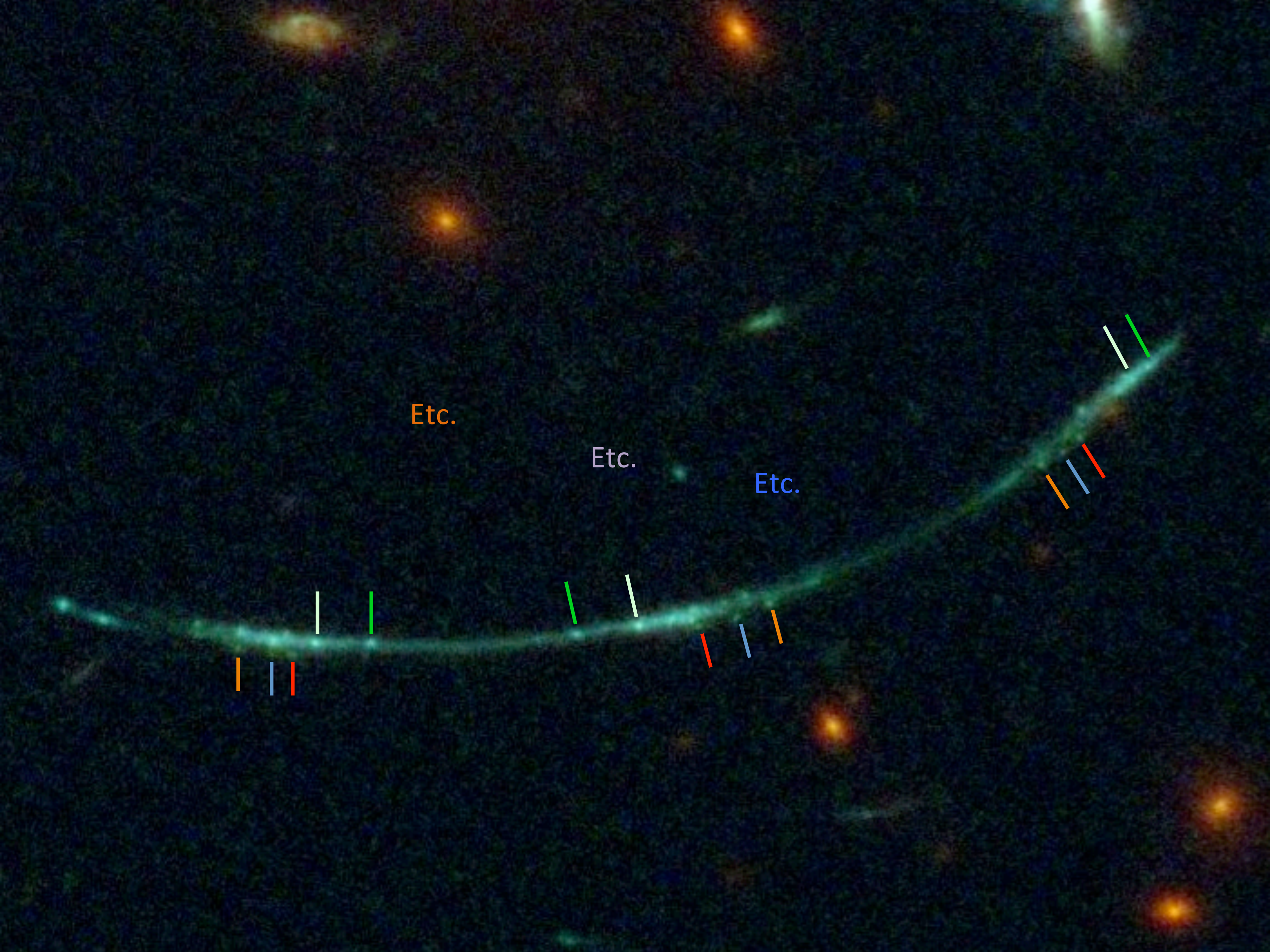
Variable Sources: **Yes!** Quasar timing and flux ratios tests will be exciting for cosmology and lens astrophysics, with ~1000 quads expected. (c.f. Bob A's talk). NOT all of these are golden…

Exceptional Lenses: **??** I think we're waiting for surprises here.



Multiplex Internal Constraints in 'Primary' Lensed images
Reject Interlopers
Find New Image Families, often multiple sets
Find/Reject Counter Images




Etc.
Etc.
Etc.

Golden Lenses require Golden Analysis

- The richness of constraints on lens models that results from multi-band space imaging allows the construction of detailed mass models for strong lensing systems
- However, consider the Hubble Frontier Fields… 6 clusters only:
  - 840 orbits
  - Suite of 6 mass models , from 6 teams, funded at the few $100K level – for PRELIMINARY pre-execution models.
- This is **an unsustainable approach** in the WFIRST era

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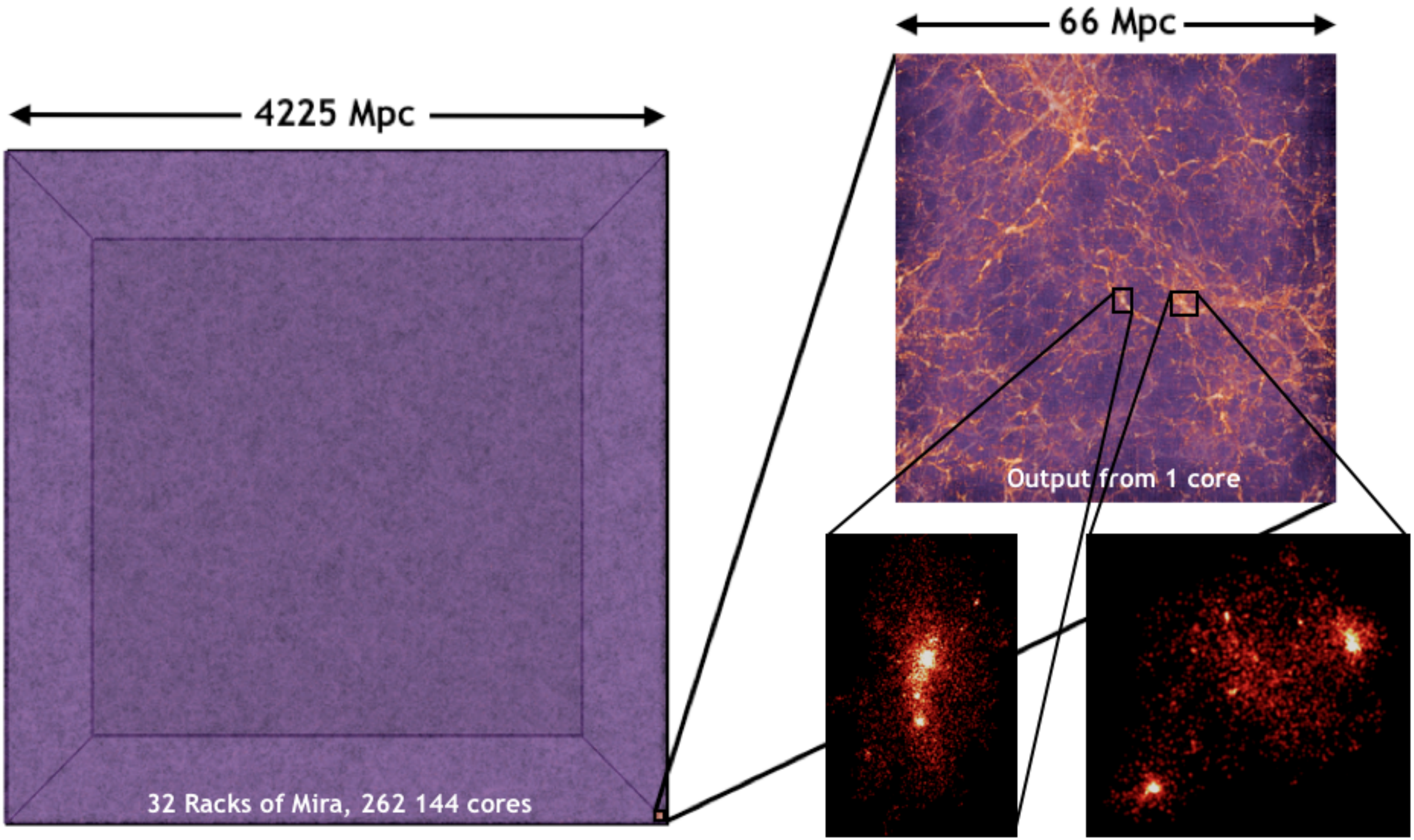
Spectroscopic ← → Photometric

WFIRST Strong Lensing - Understanding Samples…

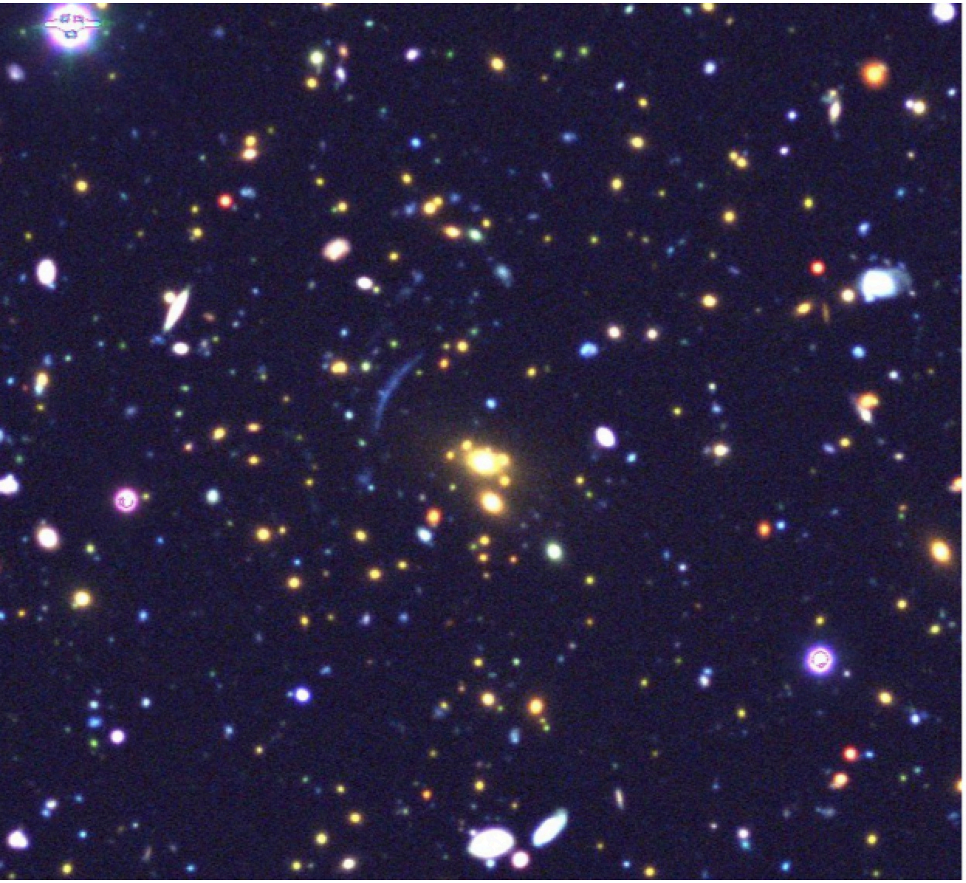
The bulk of the strong lensed sample will not have spectroscopic redshifts. Those that do will be powerful set of objects to study for the background Universe. Those that do not will mostly inform studies of the lenses themselves.

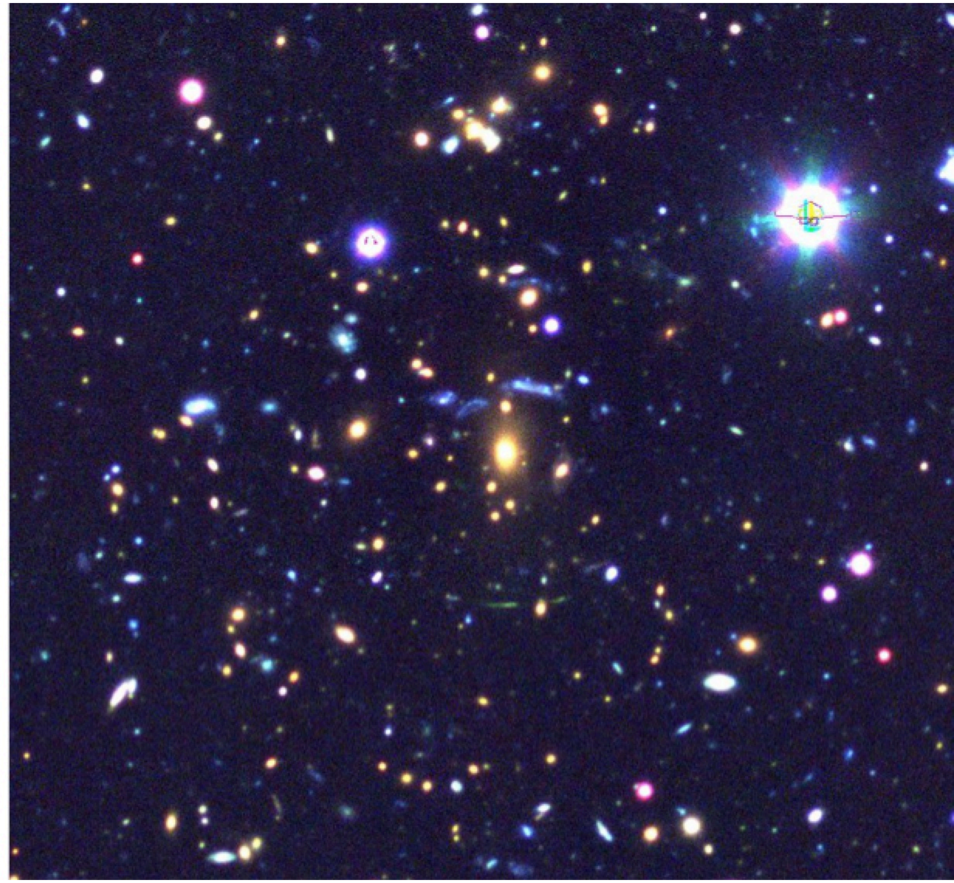
Some choices will have to be made when defining and using a sample: full image simulations will be key here. Several groups are developing the required framework…

Chicago/ANL Simulated Strong Lensing:
Ray-tracing the ‘Outer Rim’ Simulation
1.1 trillion particles $(4225\ \mathrm{Mpc})^3$



Chicago/ANL Simulated Strong Lensing: Ray-tracing the 'Outer Rim' Simulation

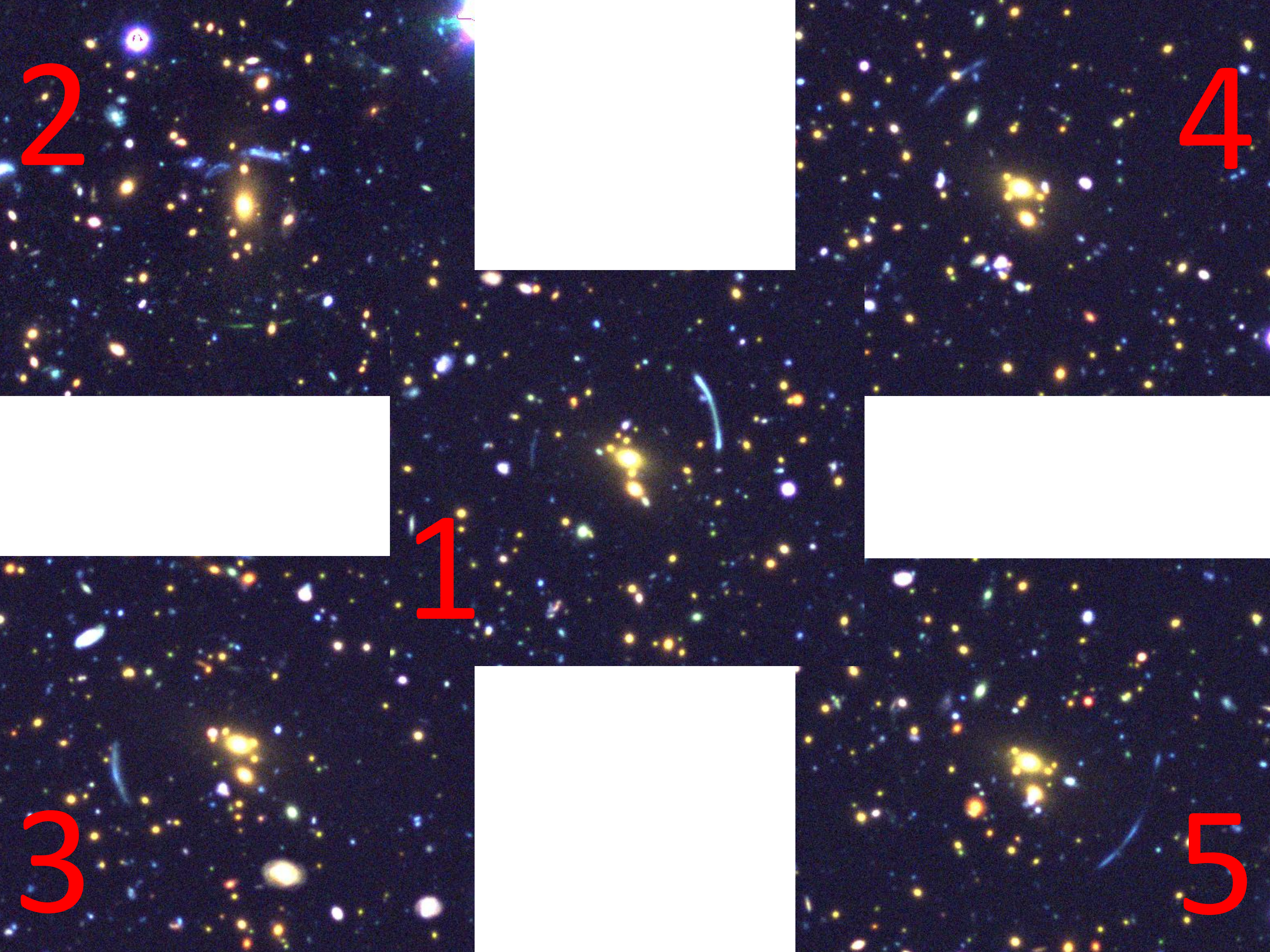


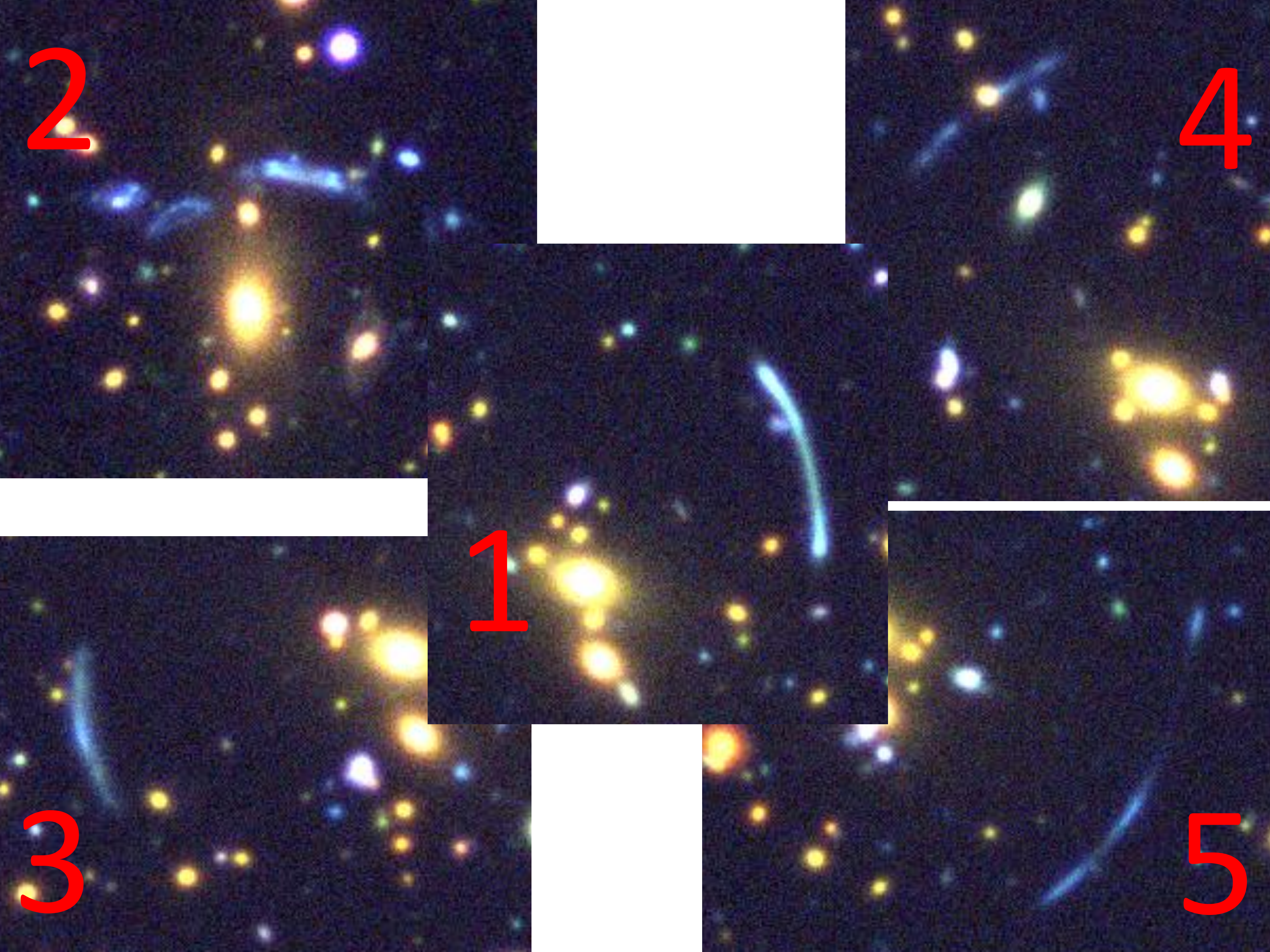


Simulated Magellan Megacam
gri imaging

? ?

Real Magellan Megacam
gri imaging of a $z=0.55$ SPT strong lens


2
4
1
3
5


2
4
1
3
5

Challenges Going Forward into the WFIRST era:

- We must automate lens modeling to a much greater extent
  - Throw the computer at it, taking advantage of all possible measurements to constrain the problem (positions, colors, surface brightnesses, morphologies – see M. Florian’s poster)
- Simulations will be KEY to understanding and exploiting these samples – both individual ‘golden lenses’ and the broadest statistical samples.
  - N-body+ simulations exist, and continue to grow
  - Sources will become a problem. No current data are sufficient. We need to ‘complexify’.

INTRODUCING GAMER: A FAST AND ACCURATE METHOD FOR RAYTRACING GALAXIES USING PROCEDURAL NOISE

N. E. Groeneboom[1], H. Dahle, [1]