HAGGLeS

The HST Archive Galaxy-scale Gravitational Lens Search

Phil Marshall

with Tim Schrabback, Eric Morganson, David Hogg, Chris Fassnacht, Lexi Moustakas, Marusa Bradac and Roger Blandford

UCSB ASTROPHYSICS

KIPAC

Overview

- Introduction and motivation

- The survey definition – and the image processing performed so far. We are an HST Archive Legacy Project(TM)...

- Automated lens detection: the HAGGLeS robot

- Preliminary results from the GO archive

Strong lensing science

Current sample: c. 200 lenses

We can aim to enlarge this by at least 2 orders of magnitude with future facilities like Dune and SNAP...

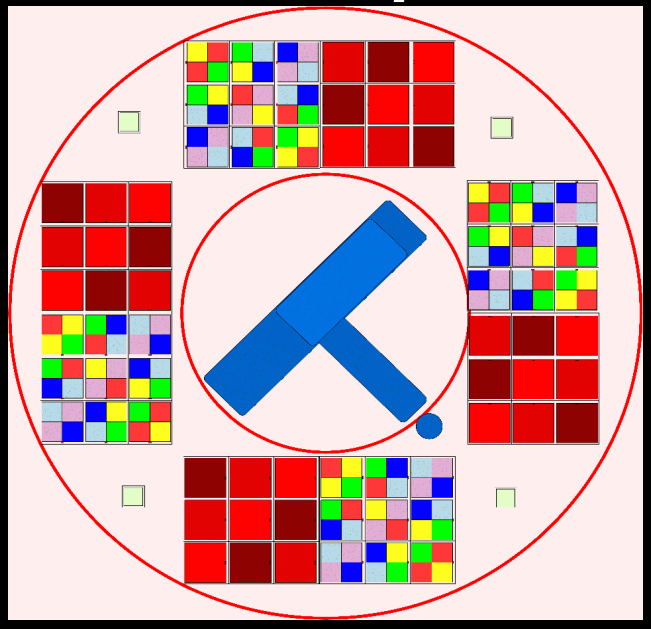
An INCOMPLETE list of projects possible with ENORMOUS statistical samples:

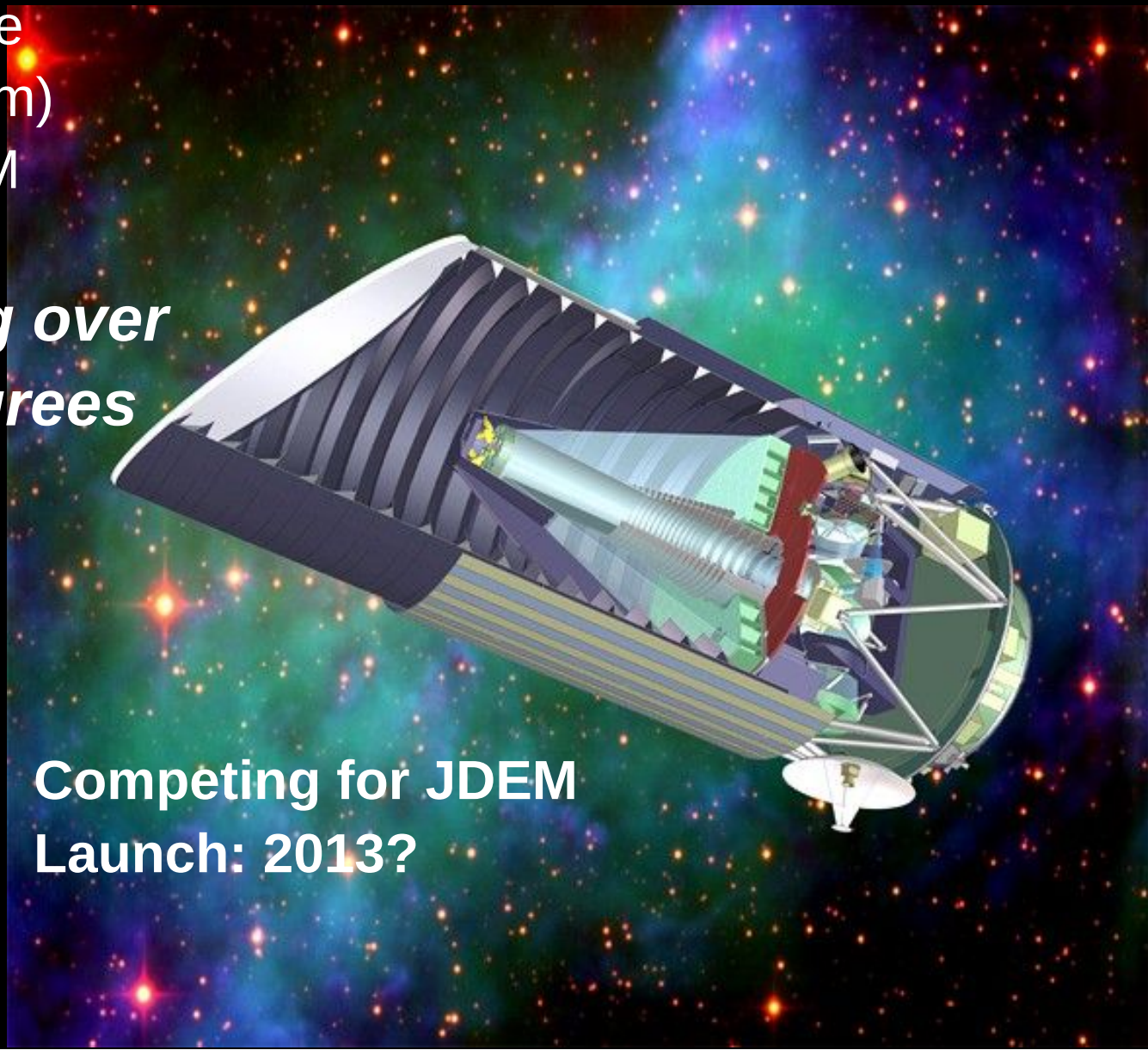
- **Lens statistics**: galaxy mass profiles and their evolution with high precision, simultaneous inference of cosmological parameters?
- **Image separations**: galaxy mass profiles and their evolution with high precision, simultaneous inference of cosmological parameters?
- **Time delays**: lensed AGN, supernovae – simultaneous inference of H0, microlensing statistics, lens environments, galaxy mass profiles etc
- **Sub-galaxy scale substructure**: anomalous magnification ratios (best in radio), extended source deformations
- **Redshift distribution** of the faintest galaxies
- **Rare events**: higher order catastrophes, lensed exotica...

SNAP

- 2m class telescope, 0.7 sq degree field of view
- IF Spectrograph for SNe
- 9 filters (350nm–1700nm)
- PSF 0.13 arcsec FWHM
- 0.1 arcsec pixels,

HST-quality imaging over 1000 square degrees



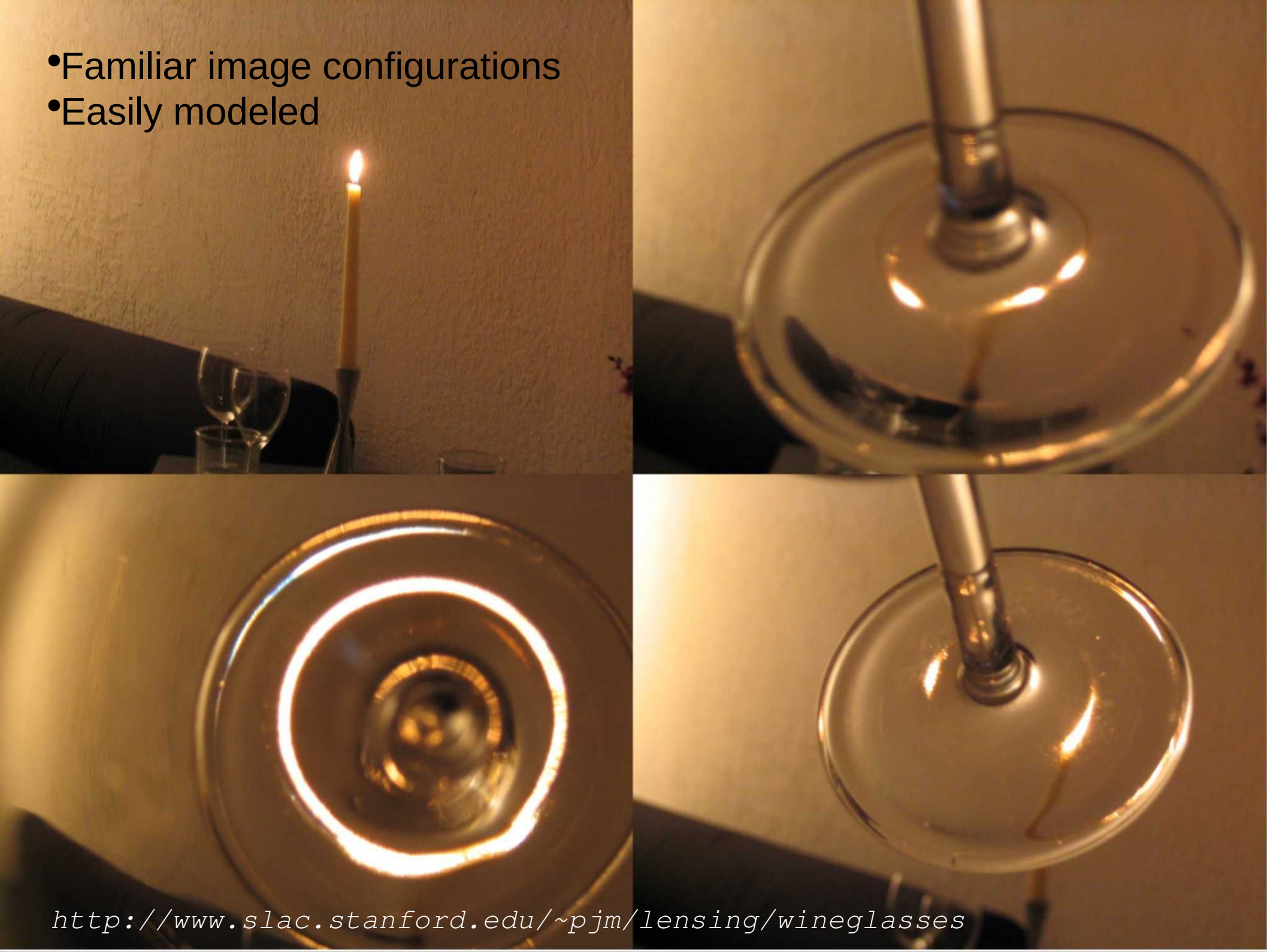


Competing for JDEM
Launch: 2013?

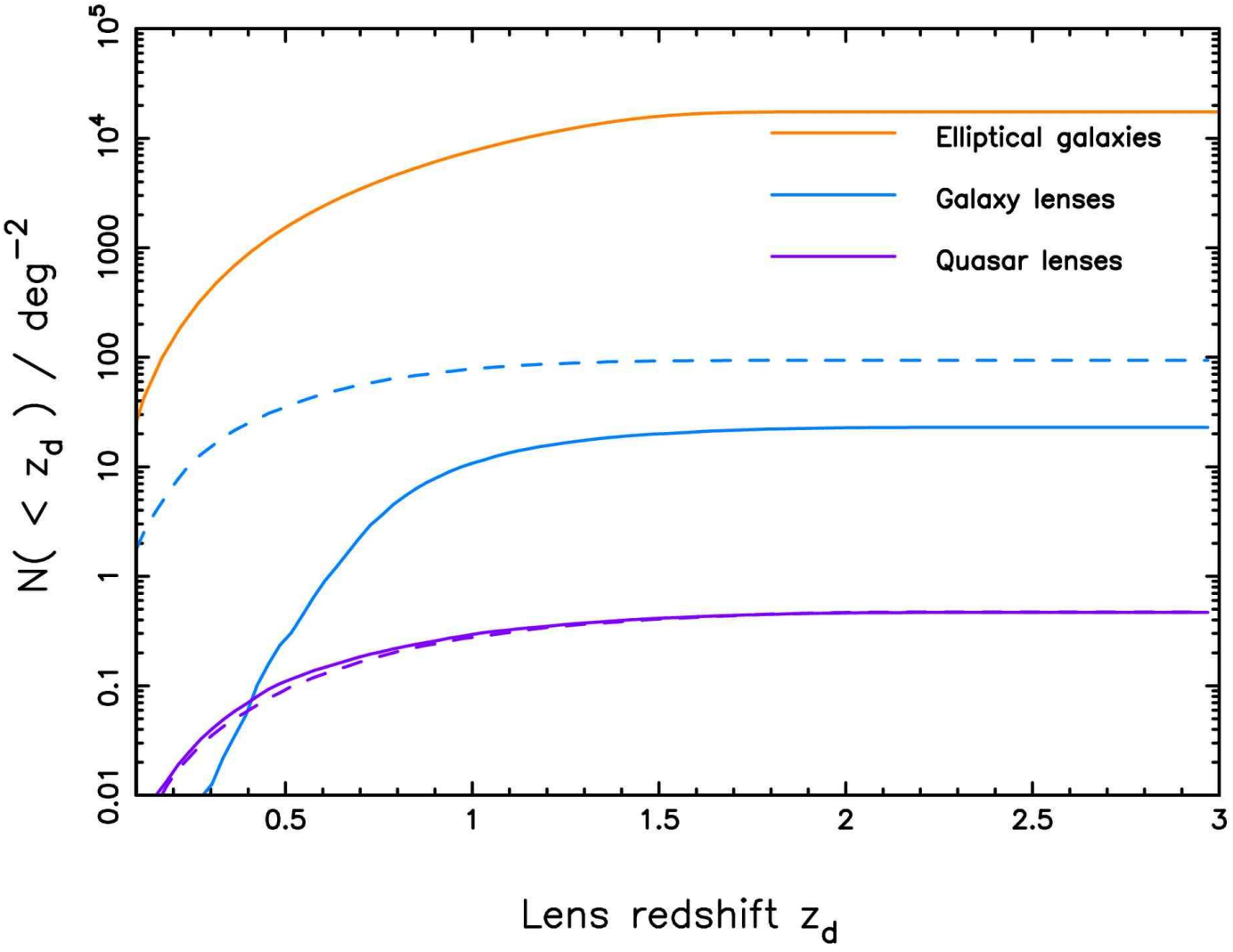
Examining elliptical galaxies

Most of the lensing cross-section in the universe is in massive elliptical galaxies; most of the sources are faint blue galaxies

- Optimise search for these “typical” lenses


•Familiar image configurations
•Easily modeled
http://www.slac.stanford.edu/~pjm/lensing/wineglasses

Examining elliptical galaxies



1 in 40000 elliptical galaxies is lensing a quasar,

1 in 200 is lensing a normal galaxy (but you may only realise it once every 5 times)

Predict:

c. 20 lenses per square degree with SNAP

HAGGLeS

We are searching the entire HST/ACS imaging archive for galaxy-scale gravitational lenses

- Exposure time > 2000s in each of at least 2 filters – register and stack to maximise depth and fidelity
- Parallel fields, individual galaxies, clusters, GRBs, large surveys etc etc - *a range of lens environments*
- Predict ~10 strong gravitational lenses per sq degree - some will already be known...
- With an eye on the bigger picture – automate the search

`http://www.slac.stanford.edu/~pjm/HAGGLeS`

Image processing

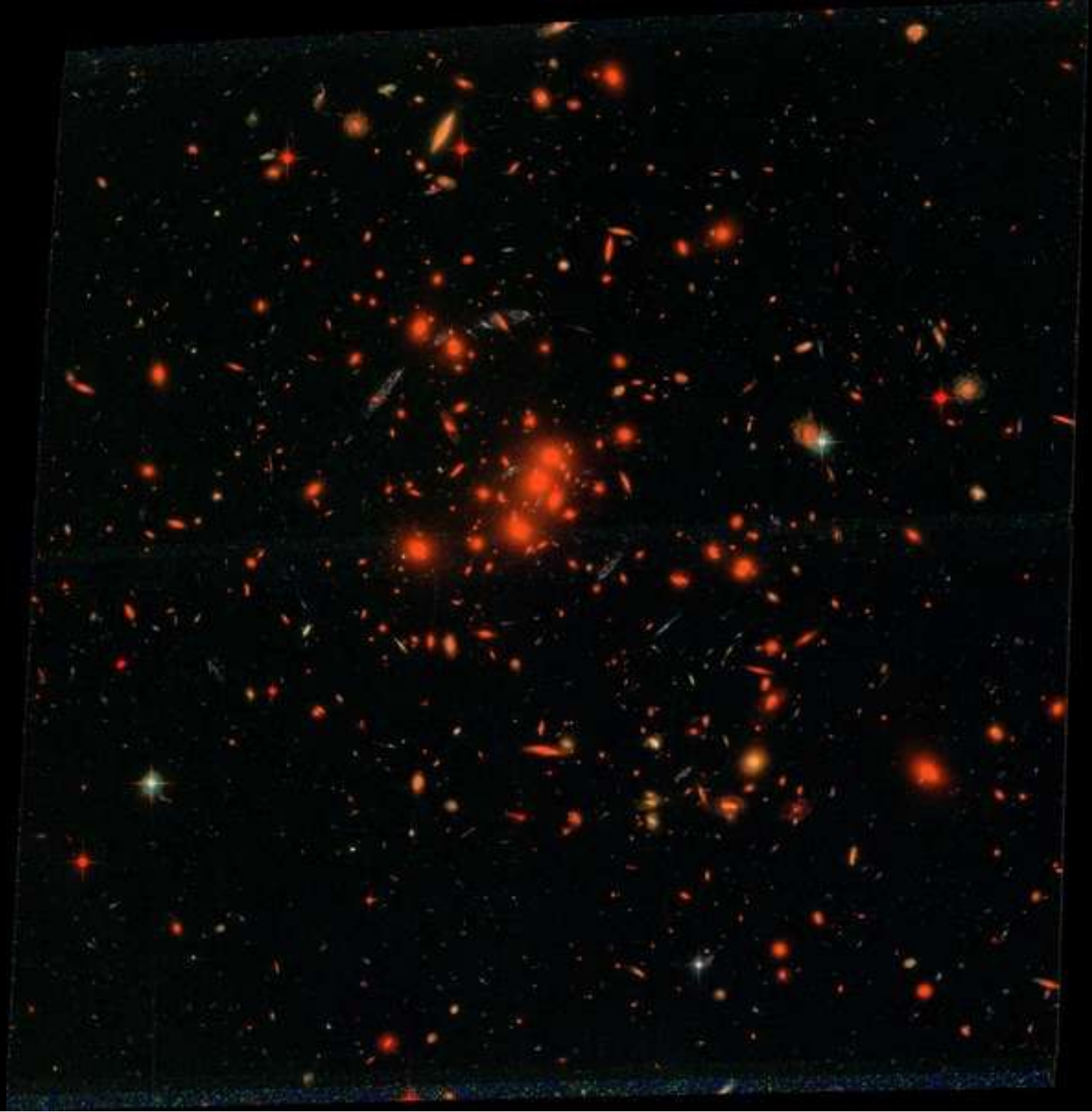
Lens searching requires deep, high quality stacked images: this is one of the project's legacies to the community

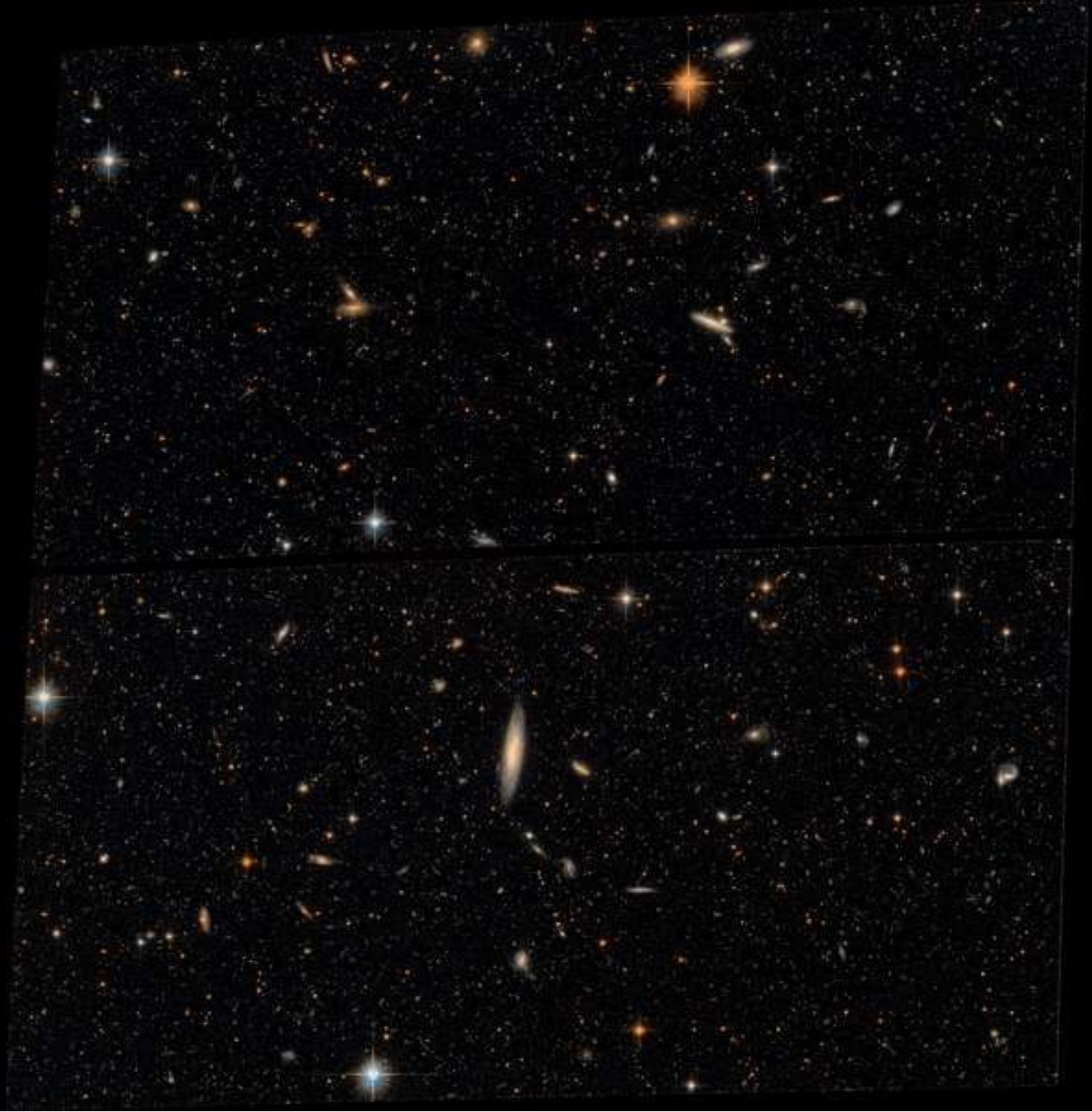
- We are aggressively combining ACS exposures from many proposals and epochs, to make the “ultimate” image
- Tim Schrabback is leading the weak lensing effort – and enforcing high standards!
- The high level science product images will be returned to MAST later this year for public use
- Aim to show the status of the image processing here

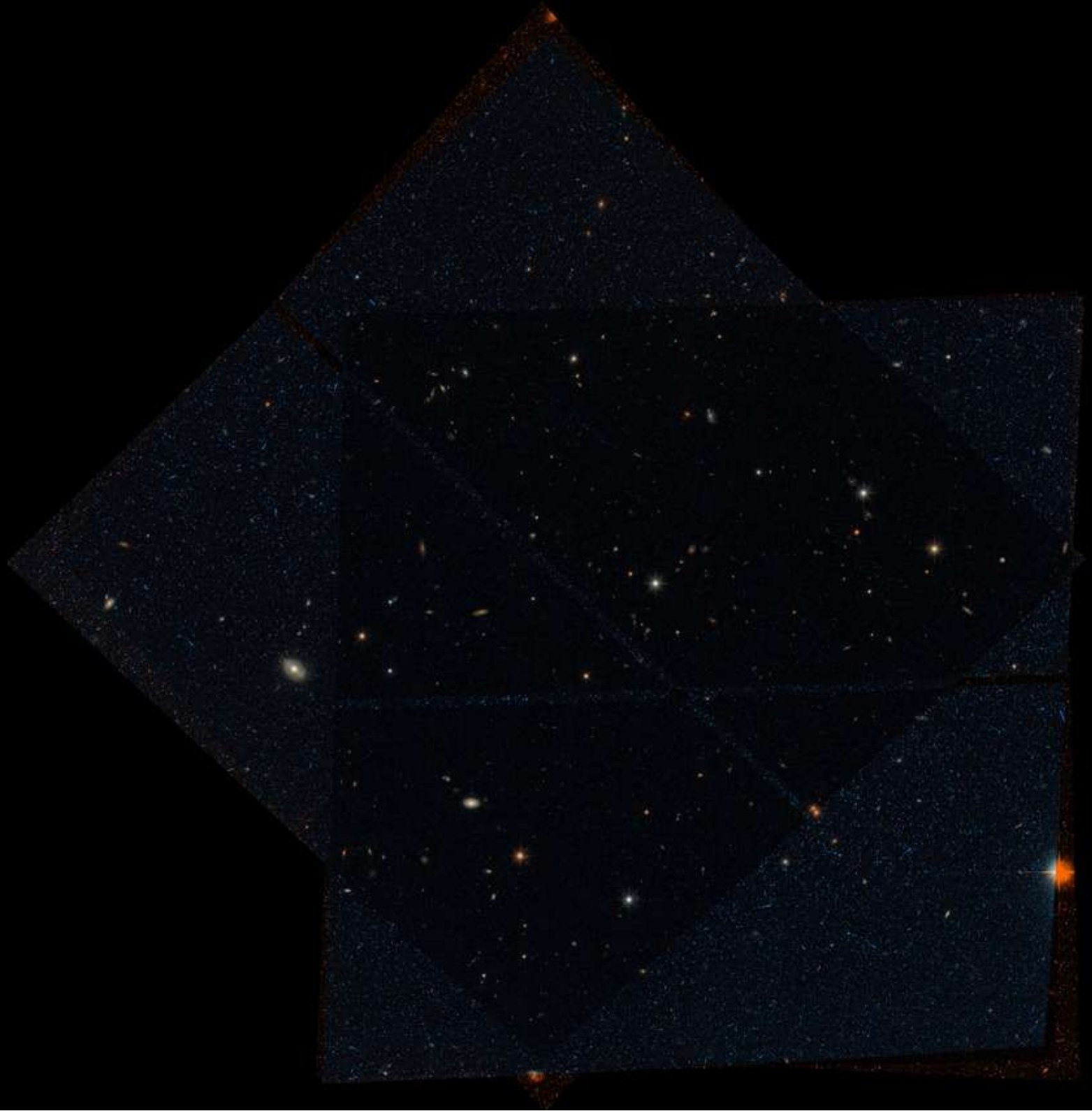
- Keep an eye open for lenses!

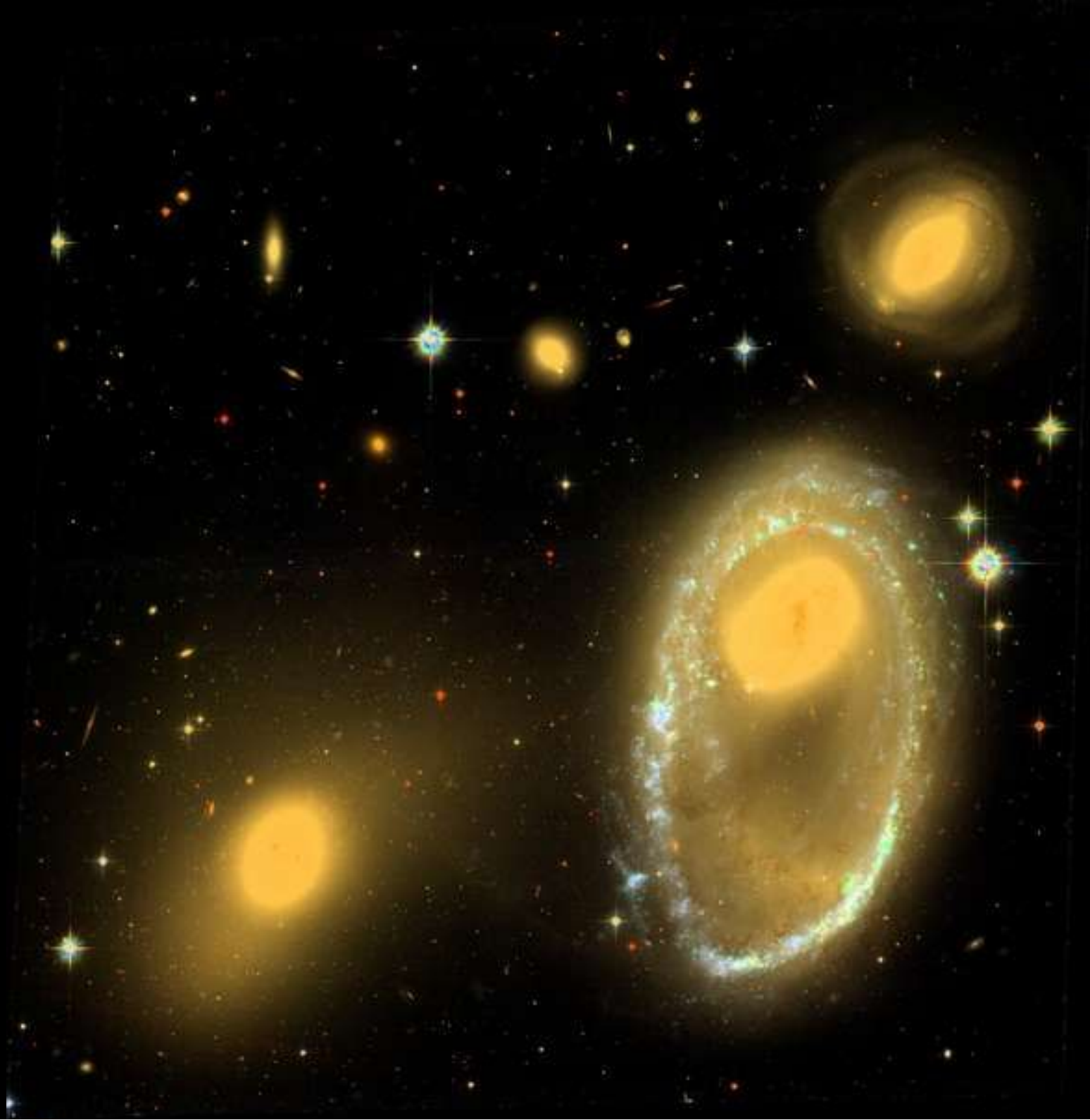
HAGGLeS: 224 fields (0.690 square degrees)

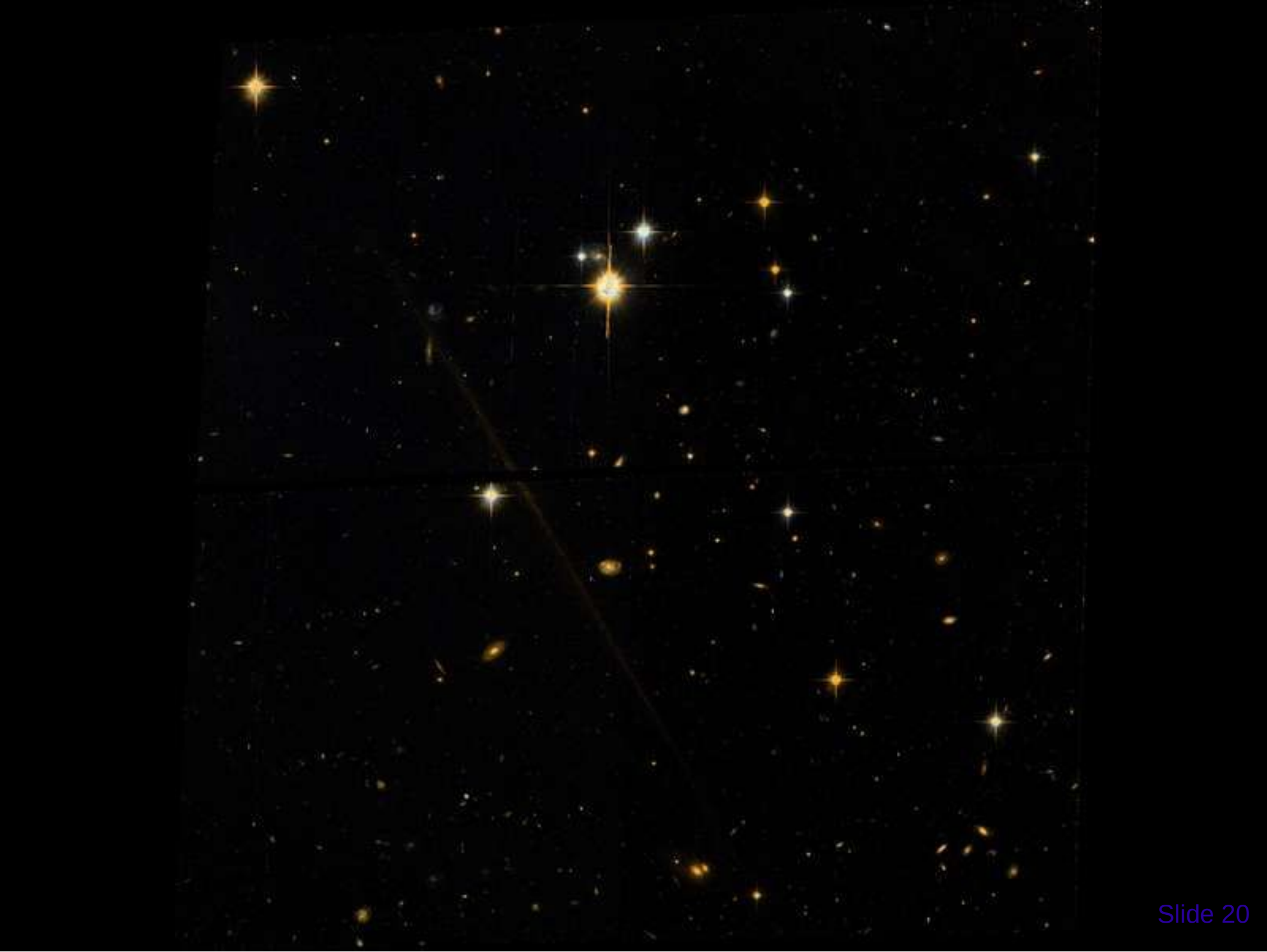
Baking situation	No. of fields
All processing complete	73
No workspace set up	3
CALACS failed	43
Background subtraction failed	3
FLT checking not done	72
Shift refinement failed	13
Multidrizzle failed	11
WCS correction failed	4
Colour JPG creation failed	2

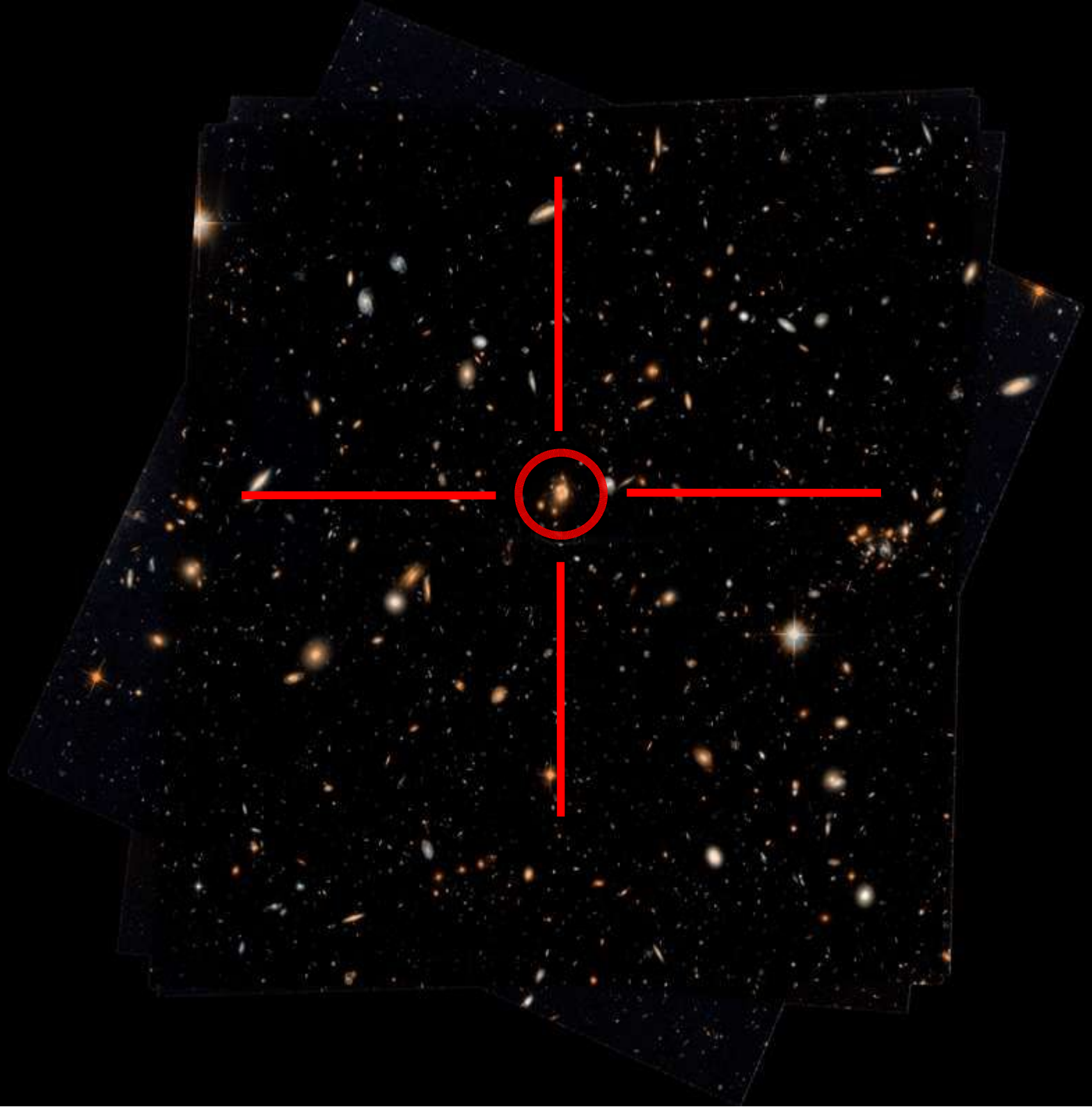












Preparing for the future

Moustakas et al (2007) searched 63 ACS fields by eye for elliptical galaxy lenses

Each field took about 15 minutes – that's 2.25 working weeks per square degree, or

45 Lexi-years to look at the SNAP wide survey

Better to look at postage stamps of elliptical galaxies

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Better to look at postage stamps of elliptical galaxies

At 10,000 elliptical galaxies per sq deg, a trained human needs ~1 week to inspect 2 sq deg of sky: that's *~10 Lexi-years for SNAP*. Automated methods are needed in the wide field era!

Preparing for the future

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45 Lexi-years to look at the SNAP wide survey

Better to look at postage stamps of elliptical galaxies

At 10,000 elliptical galaxies per sq deg, a trained human needs ~1 week to inspect 2 sq deg of sky:

that's *9.6 Lexi-years for SNAP*.

Even better to have a robot do it for you

A robot for finding lenses

- Detect bright, red, extended objects (LRGs): massive elliptical galaxies
- Make small cutout images
- Subtract off smooth flux from bright galaxy
- Examine (blue) residuals for signs of lensing

A robot for finding lenses

- Detect bright, red, extended objects (LRGs): massive elliptical galaxies
- Make small cutout images
- Subtract off smooth flux from bright galaxy
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IDEA:

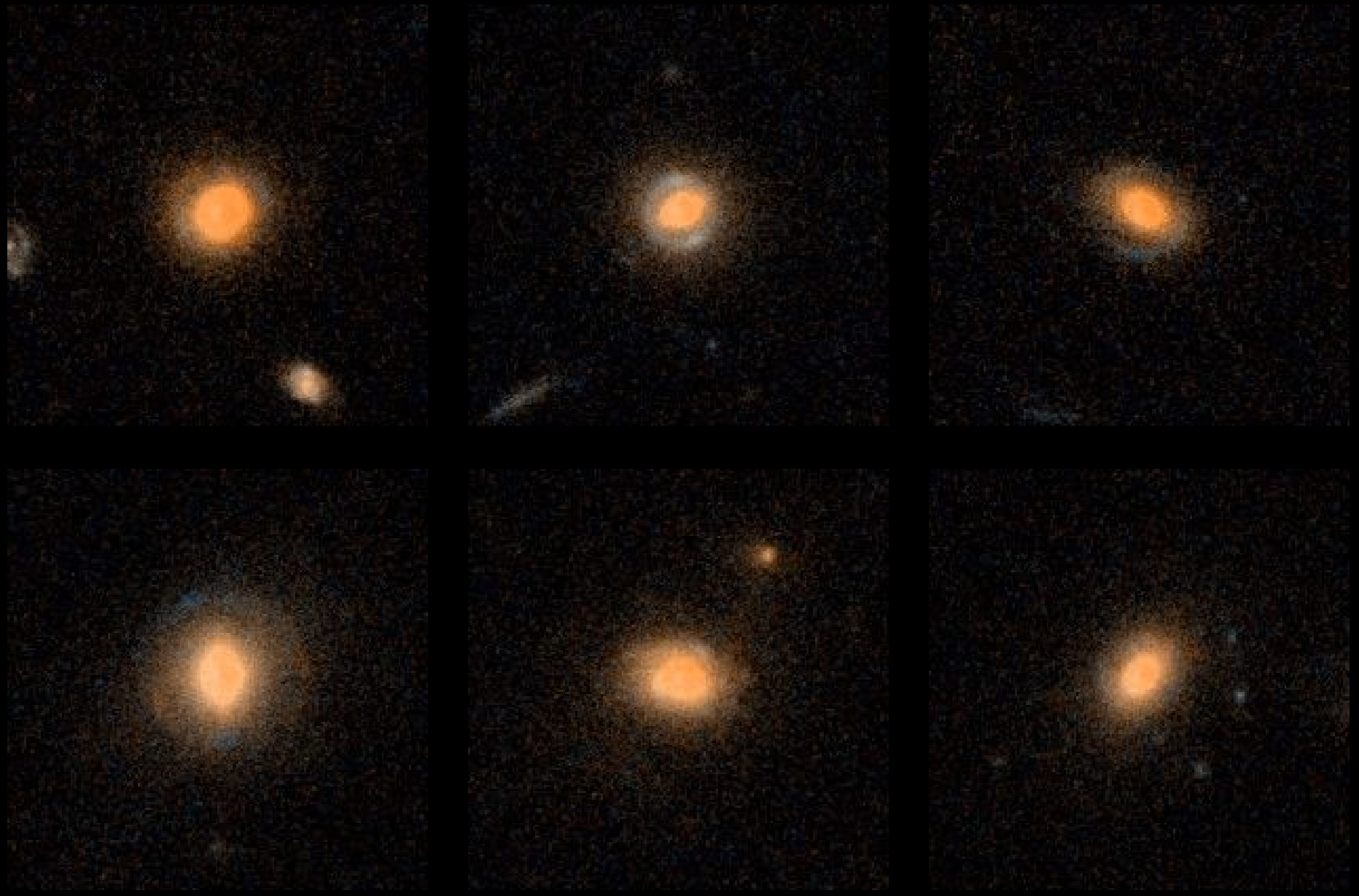
MODEL EVERY OBJECT AS IF IT WERE A LENS

Trace flux back to source plane using assumed model, measure mean brightness of *minimum* image, vary model parameters (mass, shear) to maximise flux of source, rank and present to human QC...

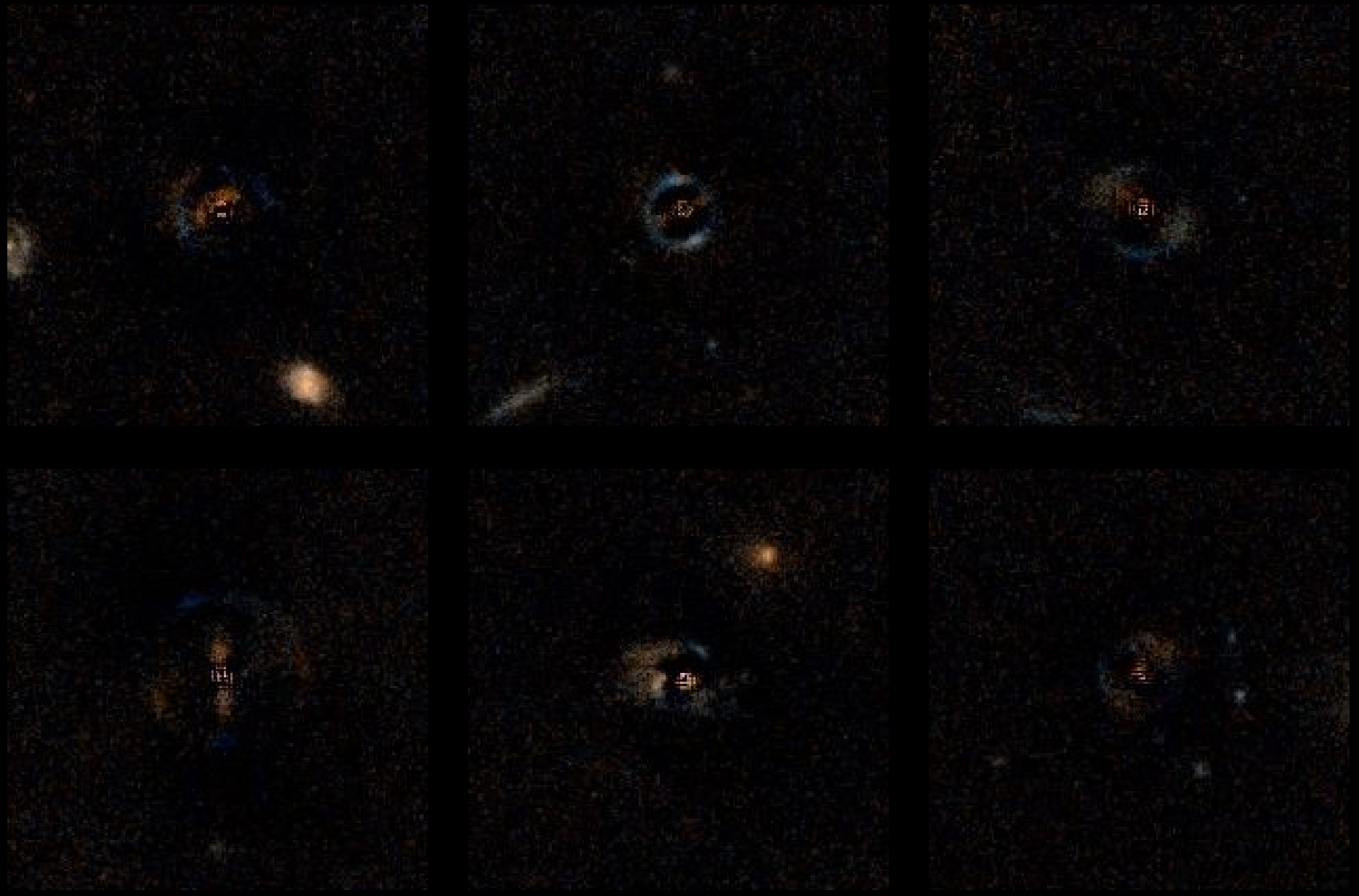
Demonstration 1: simulated lenses

- Morphologically selected spheroids from the Extended Groth Strip survey as model lens galaxies
- Faint blue galaxies drawn from the same, and placed behind the lenses
- Model with robot, learn from results...

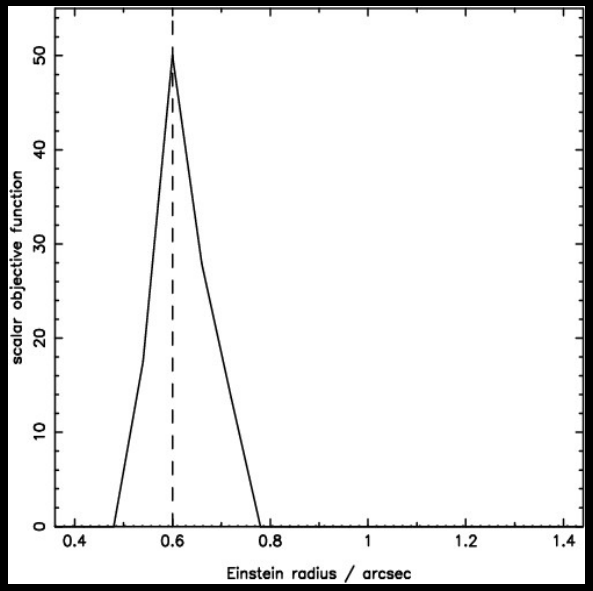
Demonstration 1: simulated EGS data

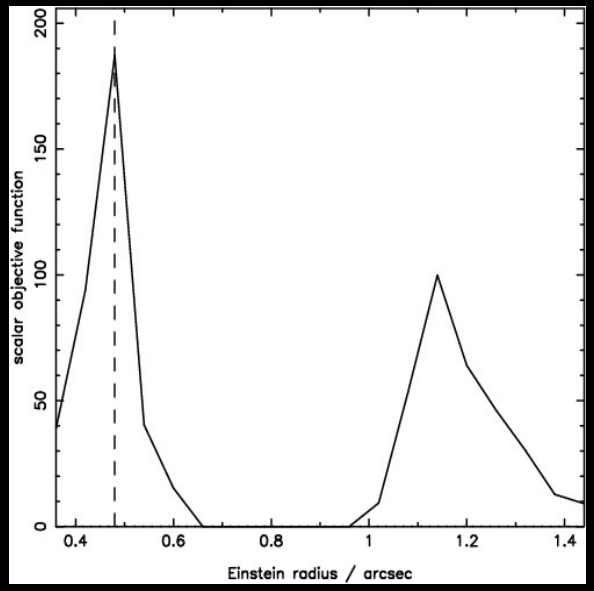


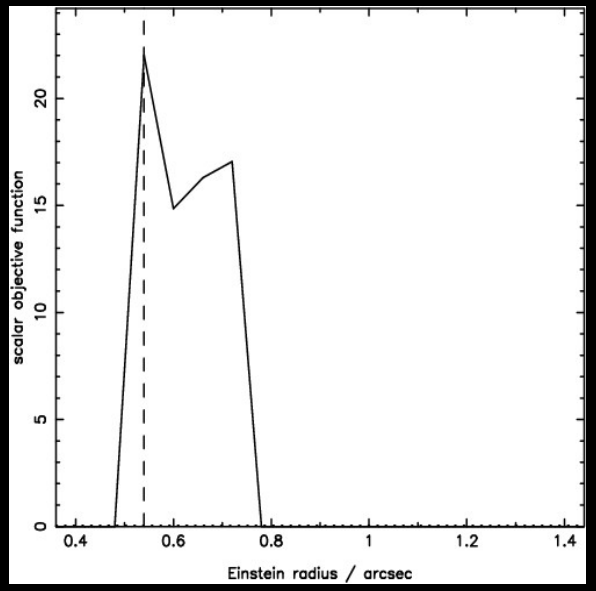
Demonstration 1: after LRG profile subtraction

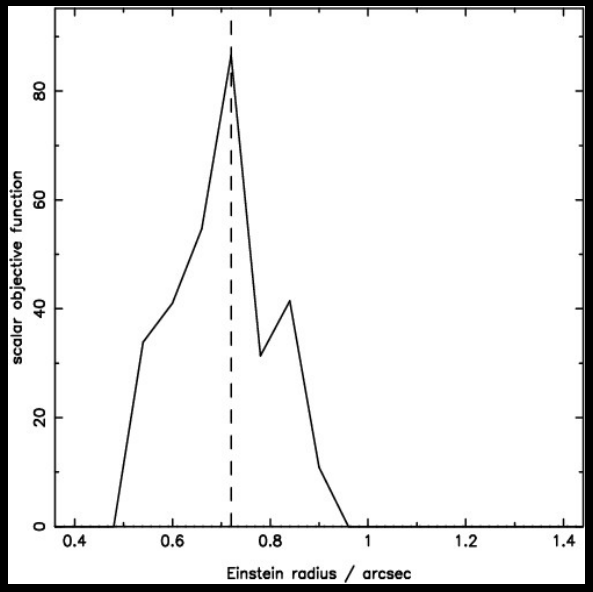


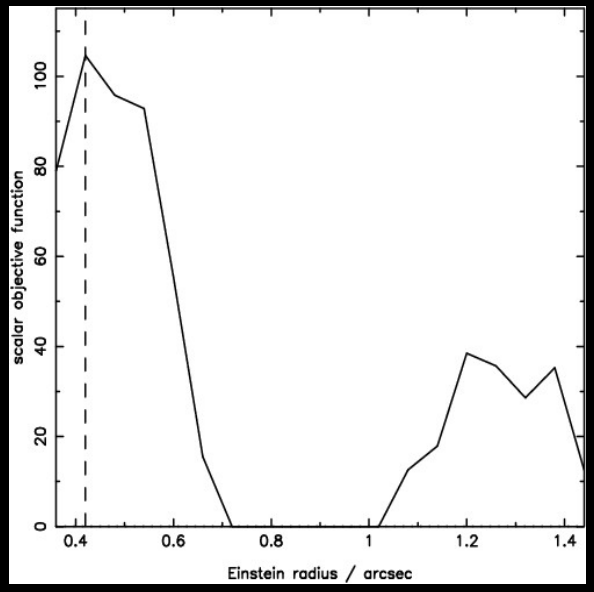
Demonstration 1: Einstein radius optimisation

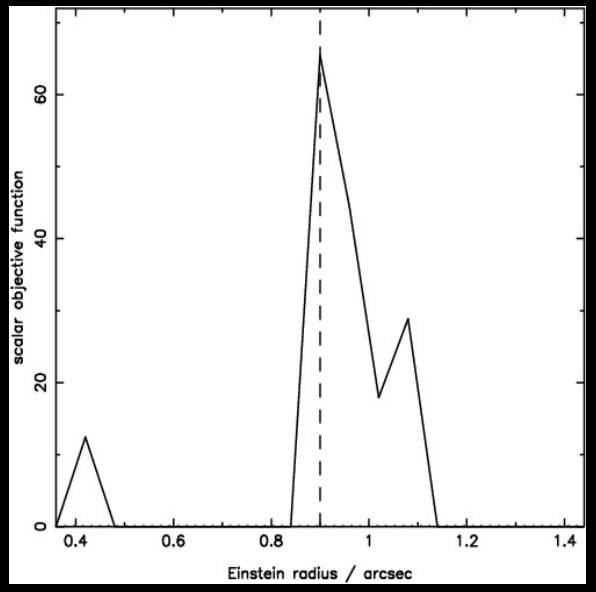




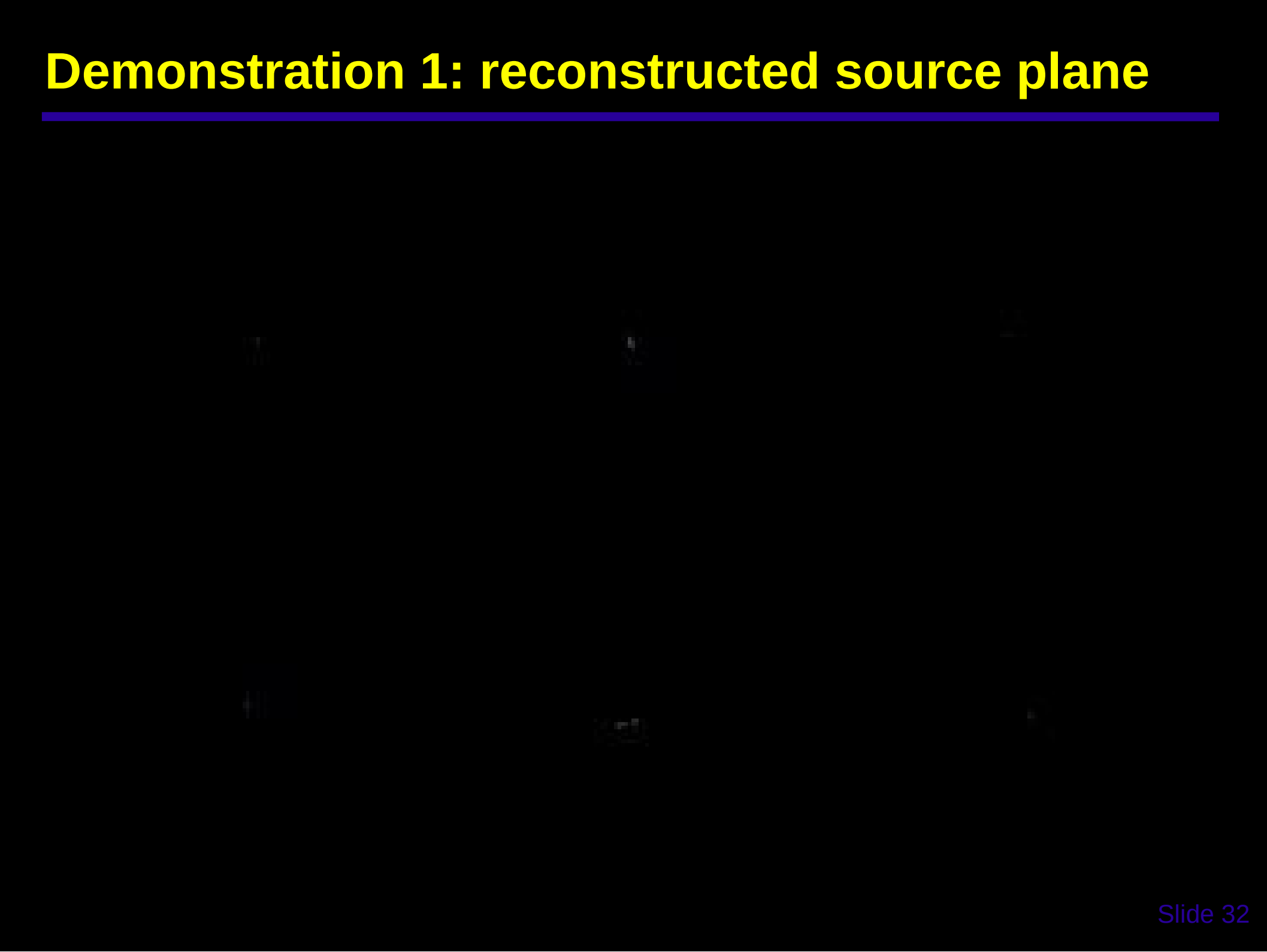








Demonstration 1: reconstructed source plane



Demonstration 1: predicted image plane

Demonstration 1: masked data for comparison

Demonstration 1: simulated lenses

- Morphologically selected spheroids from the Extended Groth Strip survey as model lens galaxies
- Faint blue galaxies drawn from the same, and placed behind the lenses
- Model with robot, learn from results...

- Robot accurately recovers realistic lensed features when the lens galaxy is simple
- Preliminary results suggest that up to 50% of lenses have morphology (disks, satellites) that is confusing enough to cause a false negative – the robot can be improved! Eventually this study will give us the robot selection function...

Demonstration 2: the EGS survey

- 63 ACS pointings, 0.19 sq deg, F606W+F814W
- Moustakas et al (2007) inspected all the frames by eye and identified 3 “A-list” lenses (2 not previously known), and 4 “B-list” candidates
- A useful testing ground! Calibrate the robot on Lexi's A-list, and see what else we get...

- The HAGGLeS robot finds, from 1032 bright red objects, 310 “class-2” candidates, and 11 “class-3” candidates

HAGGLeS robotic lens detection: EGS-08-01 - Mozilla Firefox

File Edit View Go Bookmarks Tools Help

http://www.slac.stanford.edu/~pjm/HAGGLeS/hlsp/EGS/EGS-

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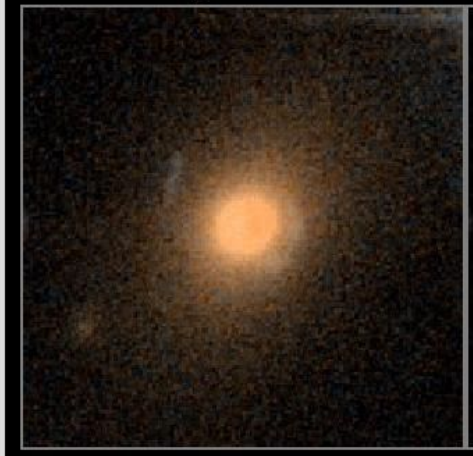
HSTJ141833.11+524352.5

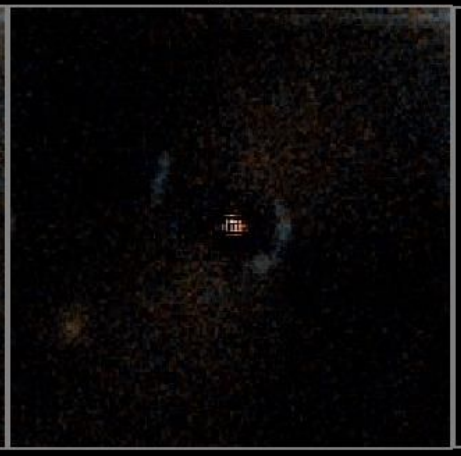
thetaE = 0.9 arcsec, xgamma = 0.1, xtheta = 2.44346 rad

scalar = 181.461, source F606W mag = 29.224703, goodness of fit (sigmas) = 5.144539

Basic color image

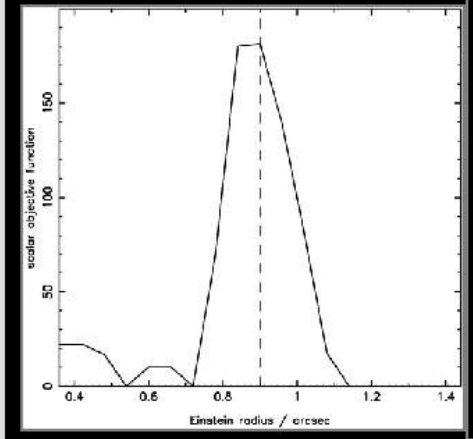


Color residual image



Masked input image

Scalar objective (min)



Corresponding (min) source

Reconstructed (min) image

BACK TOP NEXT

Done

HAGGLeS robotic lens detection: EGS-06-03 - Mozilla Firefox

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http://www.slac.stanford.edu/~pjm/HAGGLeS/hlsp/EGS/EGS-

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astrometry.net | HAGGLeS robotic l... | xkcd - A webcomic of... | Arsenal.com | David MacKay: Infor...

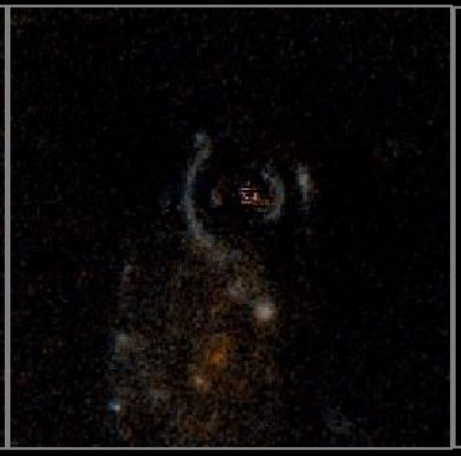
HSTJ141820.84+523611.2

thetaE = 0.6 arcsec, xgamma = 0, xtheta = 0 rad

scalar = 617.751, source F606W mag = 28.311286, goodness of fit (sigmas) = 13.002473

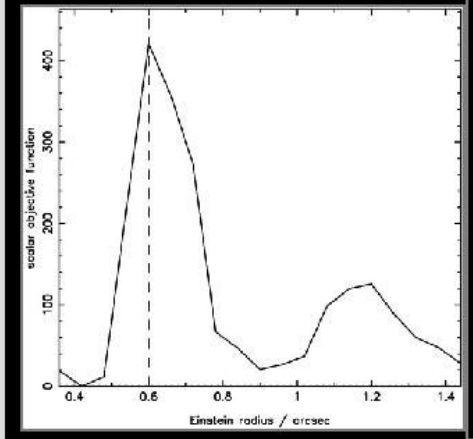
Basic color image

Color residual image



Masked input image

Scalar objective (min)



Corresponding (min) source

Reconstructed (min) image

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http://www.slac.stanford.edu/~pjm/HAGGLeS/hlsp/EGS/EGS-06-03/www/HSTJ141820.84+523611.2_sci_moffatdiff.jpg

Demonstration 2: the EGS survey

- The HAGGLeS robot finds, from 1032 bright red objects, 310 “class-2” candidates, and 11 “class-3” candidates
- class>2 has purity ~20% and is ~70% complete
- class>1 has purity ~1% but is ~90% complete (and contains all 3 Moustakas et al confirmed lenses)

- Human classification of the class>1 sample (321 objects) picked out all the Moustakas et al candidate lenses therein – and one new object:

HAGGLeS robotic lens detection: EGS-02-02 - Mozilla Firefox

File Edit View Go Bookmarks Tools Help

http://www.slac.stanford.edu/~pjm/HAGGLeS/hlsp/EGS/EGS-02-(

Go

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HAGGLeS image flagging | HAGGLeS robotic lens detect... | HAGGLeS robotic lens det... | http://www.sla...entory/WL.html

HSTJ141719.80+522824.3

thetaE = 0.66 arcsec, xgamma = 0, xtheta = 0 rad

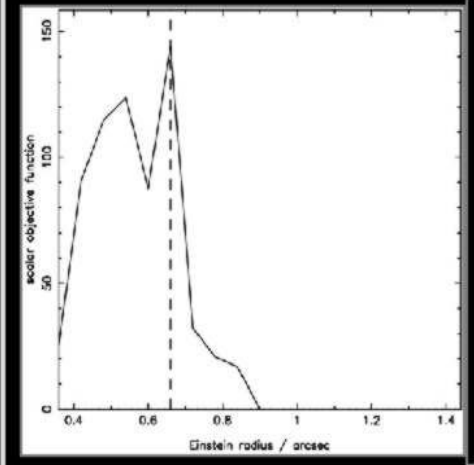
scalar = 430.111, source F606W mag = 29.474792, goodness of fit (sigmas) = 28.420794

Basic color image

Color residual image

Masked input image

Scalar objective (min)



Corresponding (min) source

Reconstructed (min) image

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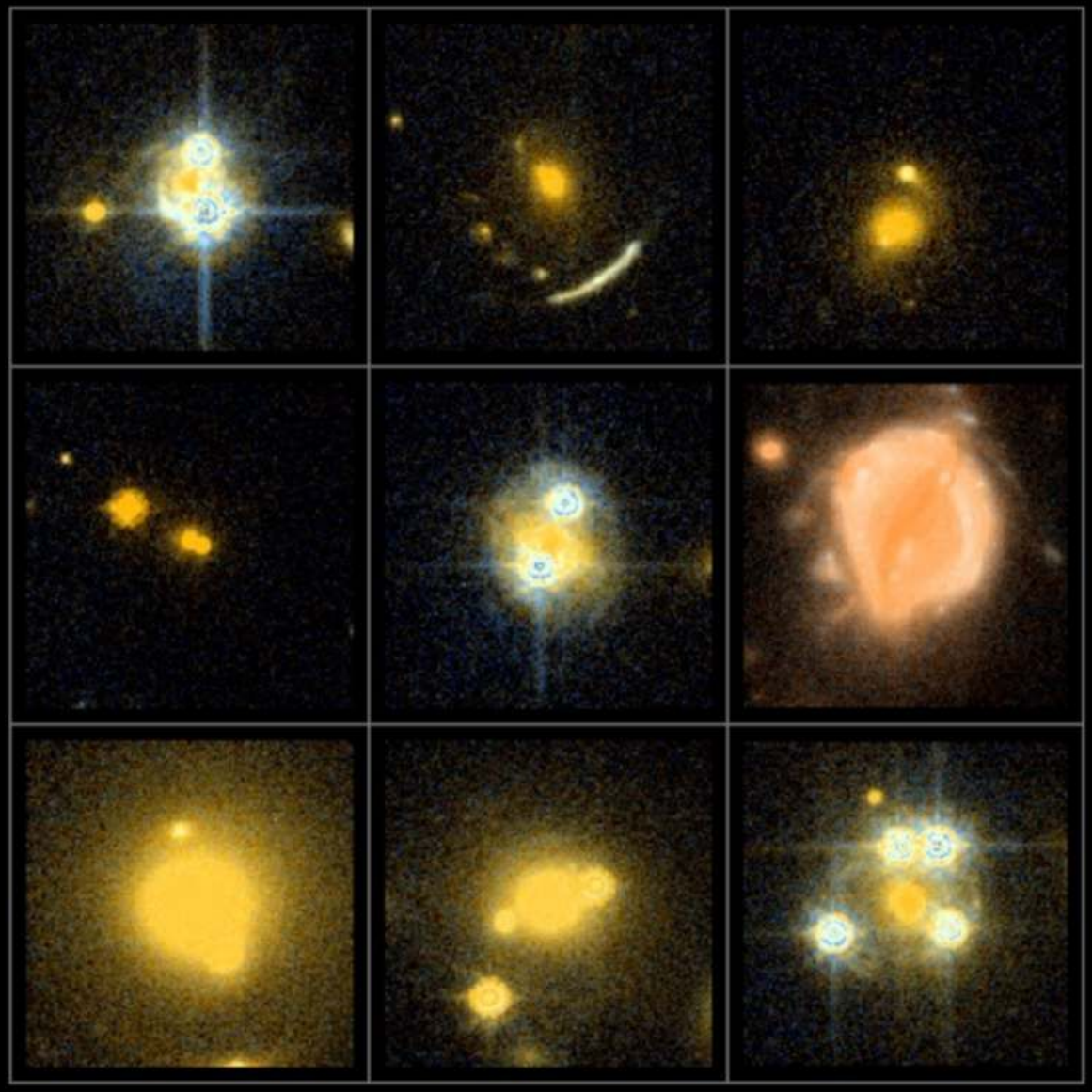
http://www.slac.stanford.edu/~pjm/HAGGLeS/hlsp/EGS/EGS-02-02/www/HSTJ141719.80+522824.3_sci_moffatdiff.minsrc.jpg

Robots make classification fast

- 2 square degrees is covered by
- 650 ACS pointings
- containing 700,000 galaxies
- of which 20,000 are bright and red
- but only ~20 of those are actually lenses;
- the robot thinks 30% = ~6000 might be lenses, is “sure” about ~200 of them, and is right about ~14 of those.
- Robot-aided human classification is fast (~few seconds per object via a cgi-bin interface): only looking at the class>1 robot output, the whole HAGGLeS survey will take 6 Lexi-hours
- At the same rate, SNAP-wide would take 75 Lexi-weeks – becoming feasible, but some way to go yet...

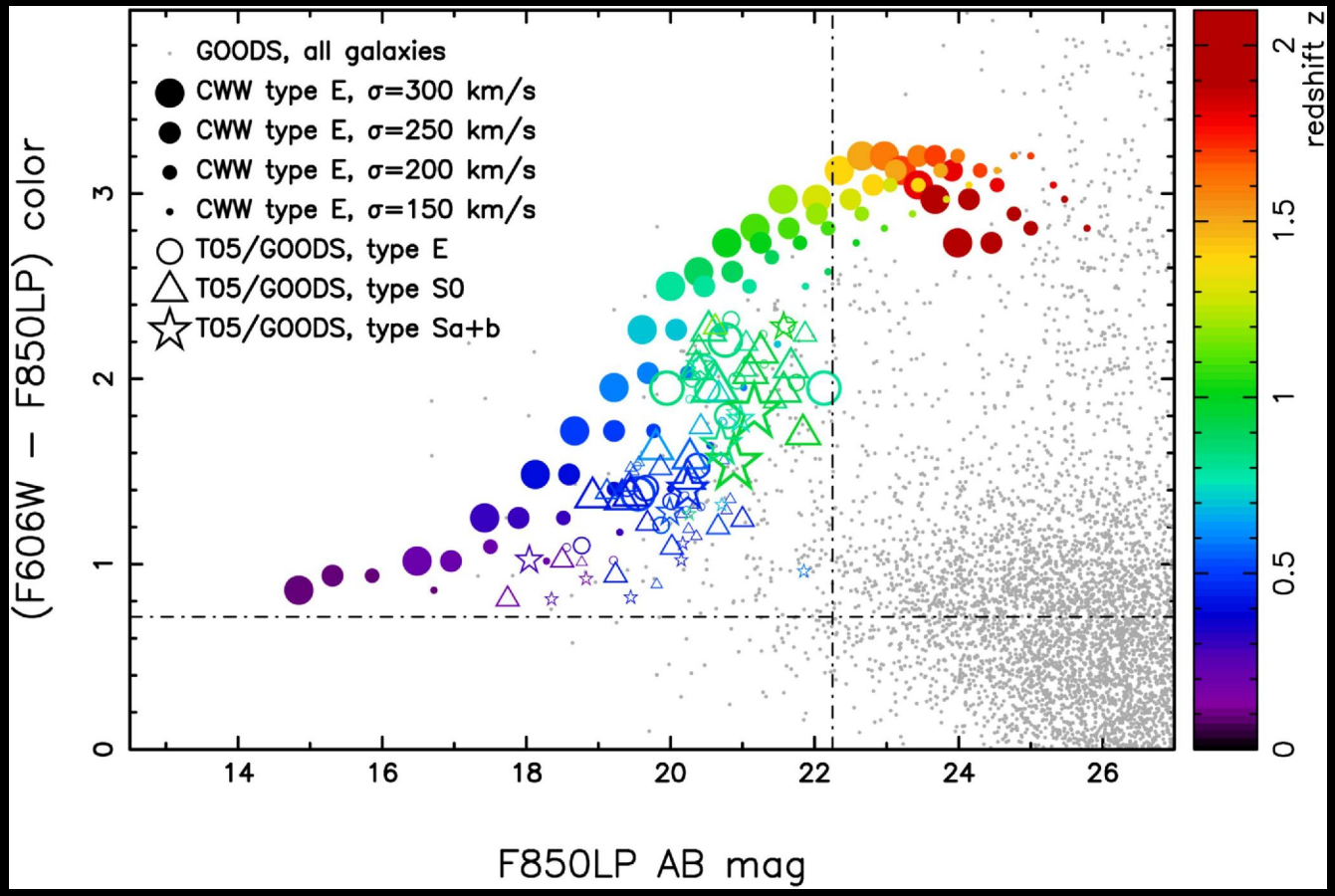
Demonstration 3: CASTLeS lenses

- 9 CASTLeS lens fields processed to date
- Note the different appearance...
- The HAGGLeS robot fails to identify ANY of these as lenses!
- It is blinded by the quasars: the high S/N ratio demands a better lens model than the robot can provide
- The CASTLeS objects are ***atypical lenses*** – our starting aim was to find ***typical lenses***



The GO archive: preliminary results

- Search first 0.23 sq deg of GO archive: 75 ACS frames
- Attempt to select elliptical galaxies by magnitude and colour (typically have 2 filters):



The GO archive: preliminary results

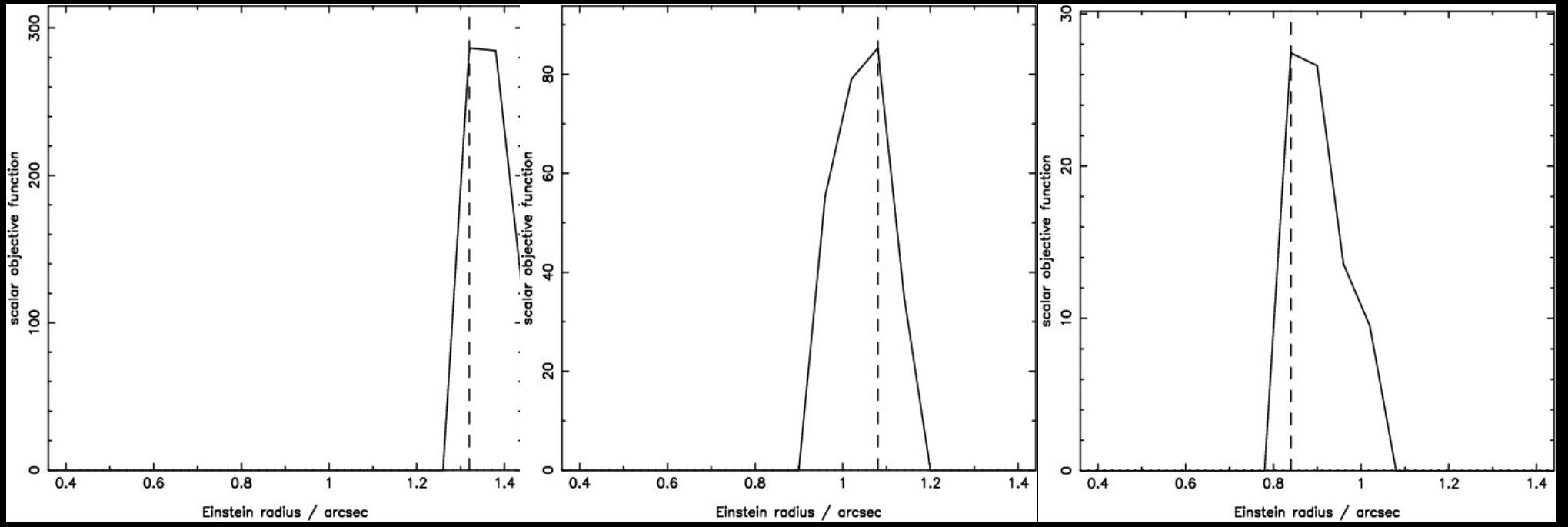
- Search first 0.23 sq deg of GO archive: 75 ACS frames
- Select elliptical galaxies by magnitude and colour (typically 2 filters)
- Run robot on resulting 8744 LRGs:

  889 class>1 candidates (10% again)
- Human classification gives 3 “B-list” candidates:

The GO archive: new lens candidates

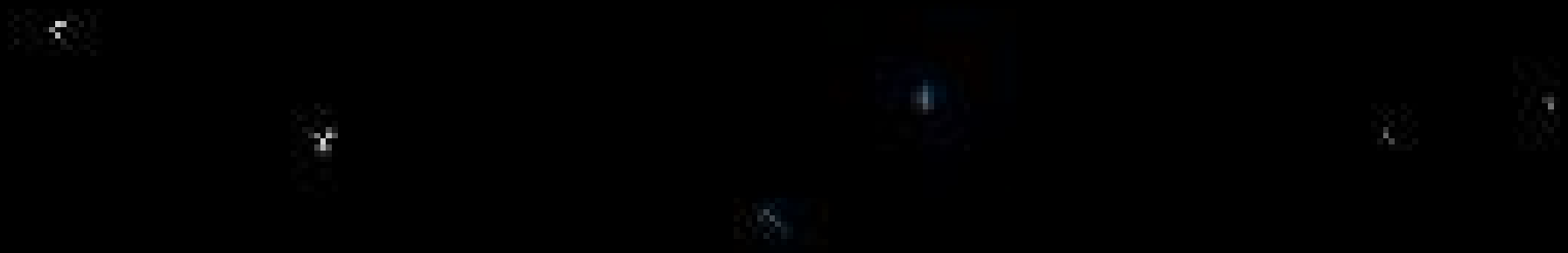
The GO archive: after LRG profile subtraction

The GO archive: Einstein radius optimisation

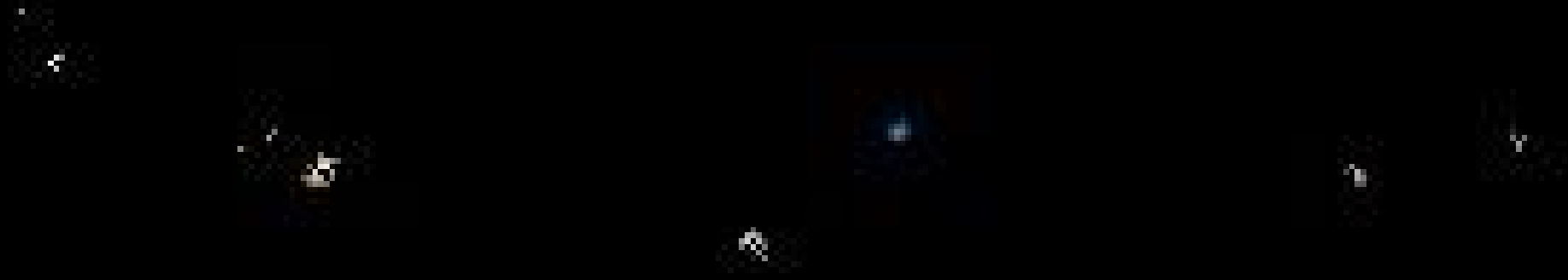


The GO archive: reconstructed source plane

The GO archive: predicted image plane



The GO archive: masked data for comparison



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- Select elliptical galaxies by magnitude and colour (typically 2 filters)
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  889 class>1 candidates (10% again)
- Human classification gives 3 “B-list” candidates – but no new A-list lenses...
- But what do YOU think?!
- Having mult-ifilter high resolution imaging but no spectroscopy *may* be a situation we have to get used to – then the lens model is all we have!

Conclusions

- We have reprocessed ~20% of the deep, multi-filter, GO HST-ACS archive, aggressively combining exposures to make deep, high quality images – the rest are being processed as we speak
- Calibrating our lens-detection robot to simulations and the EGS eyeball survey of Moustakas et al (2007), we expect completeness of ~70% but purity of 1% - these numbers can be improved upon!
- By automated searching of the HST archive data we have, to date, discovered 4 new lens candidates
- In future, higher purity (through better elliptical galaxy selection and lens light modelling) and completeness (through more powerful lens modelling) will make identifying and classifying the SNAP wide lens survey candidates feasible on timescales ~ few days

WL: 628 fields (1.93 square degrees)

Baking situation	No. of fields
All processing complete	18
No workspace set up	3
CALACS failed	37
Background subtraction failed	5
FLT checking not done	556
Shift refinement failed	6
Multidrizzle failed	1
WCS correction failed	0
Colour JPG creation failed	2