HAGGLeS

The HST Archive Galaxy-scale Gravitational Lens Search

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and encouraged by Raphael Gavazzi, Tommaso Treu, Jean-Paul Kneib and Cecile Faure

UCSB ASTROPHYSICS

KIPAC

Overview

- Introduction and motivation:
  strong lens survey science in the wide-field era

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

- Automated lens detection: the HAGGLeS robot
  Testing on :
  1) simulated data
  2) the EGS survey fields
  3) known CASTLeS lenses

- Preliminary results from the GO archive

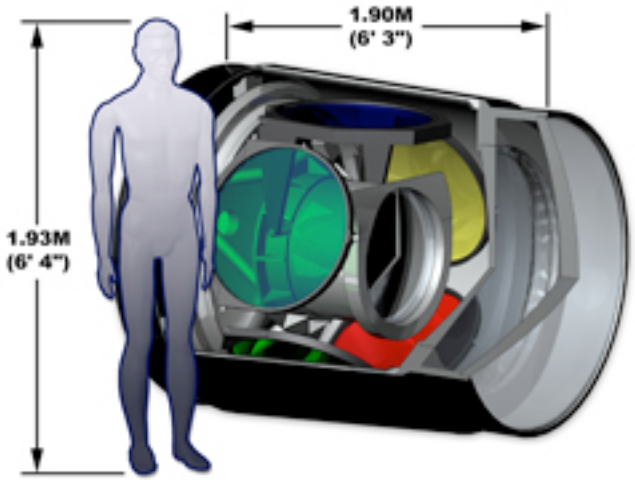
Strong lensing survey science

Current sample: c. 200 lenses
We can aim to enlarge this by at least 2 orders of magnitude with future facilities like LSST, Dune and SNAP...

An INCOMPLETE list of projects possible with ENORMOUS statistical samples:

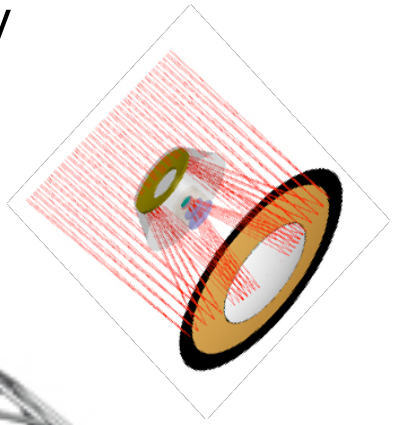
- **Lens statistics**: galaxy mass profiles and their evolution with high precision, simultaneous inference of cosmological parameters?
- **Image separations**: galaxy mass profiles and their evolution with high precision, simultaneous inference of cosmological parameters?
- **Time delays**: lensed AGN, 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, sizes and structure
- **Rare events**: higher order catastrophes, lensed exotica, the unexpected...

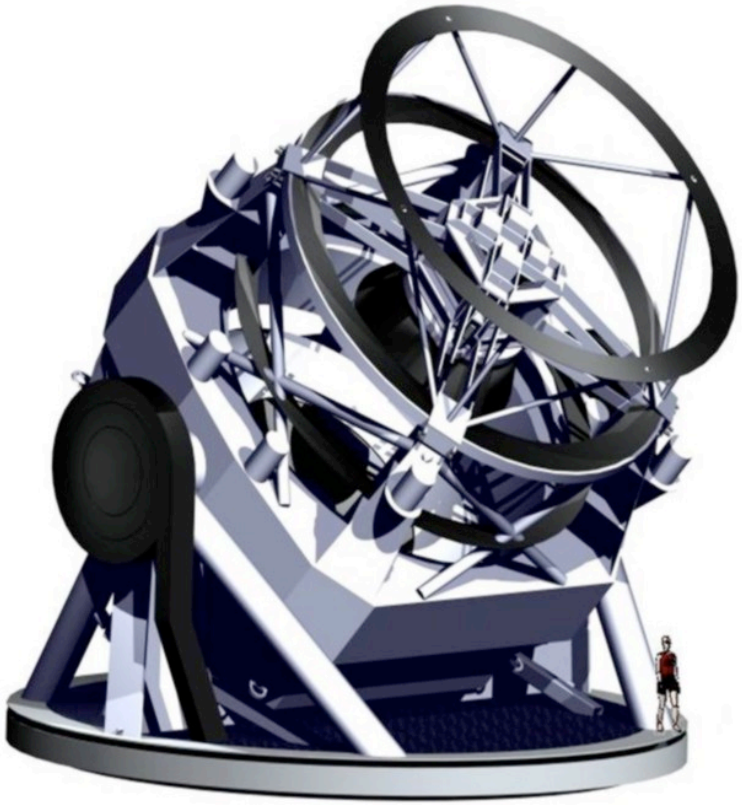
Strong lensing with LSST

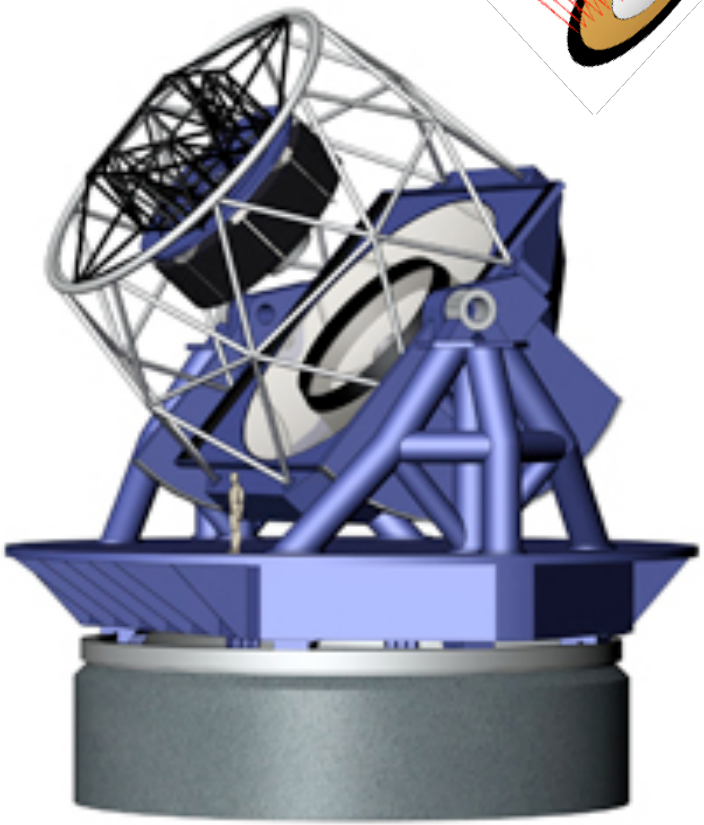


High etendue survey telescope

- 6m effective aperture
- 10 sq deg field, 20,000 sq deg survey
- 24.5 mag in 30 seconds, ugrizY
- Visible sky mapped every four nights
- Ten year ***movie*** of the sky
- ~10^5 lenses



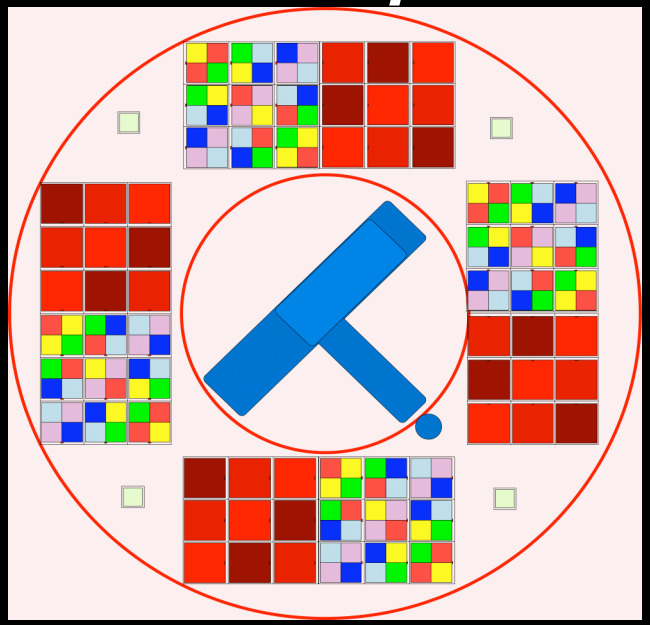


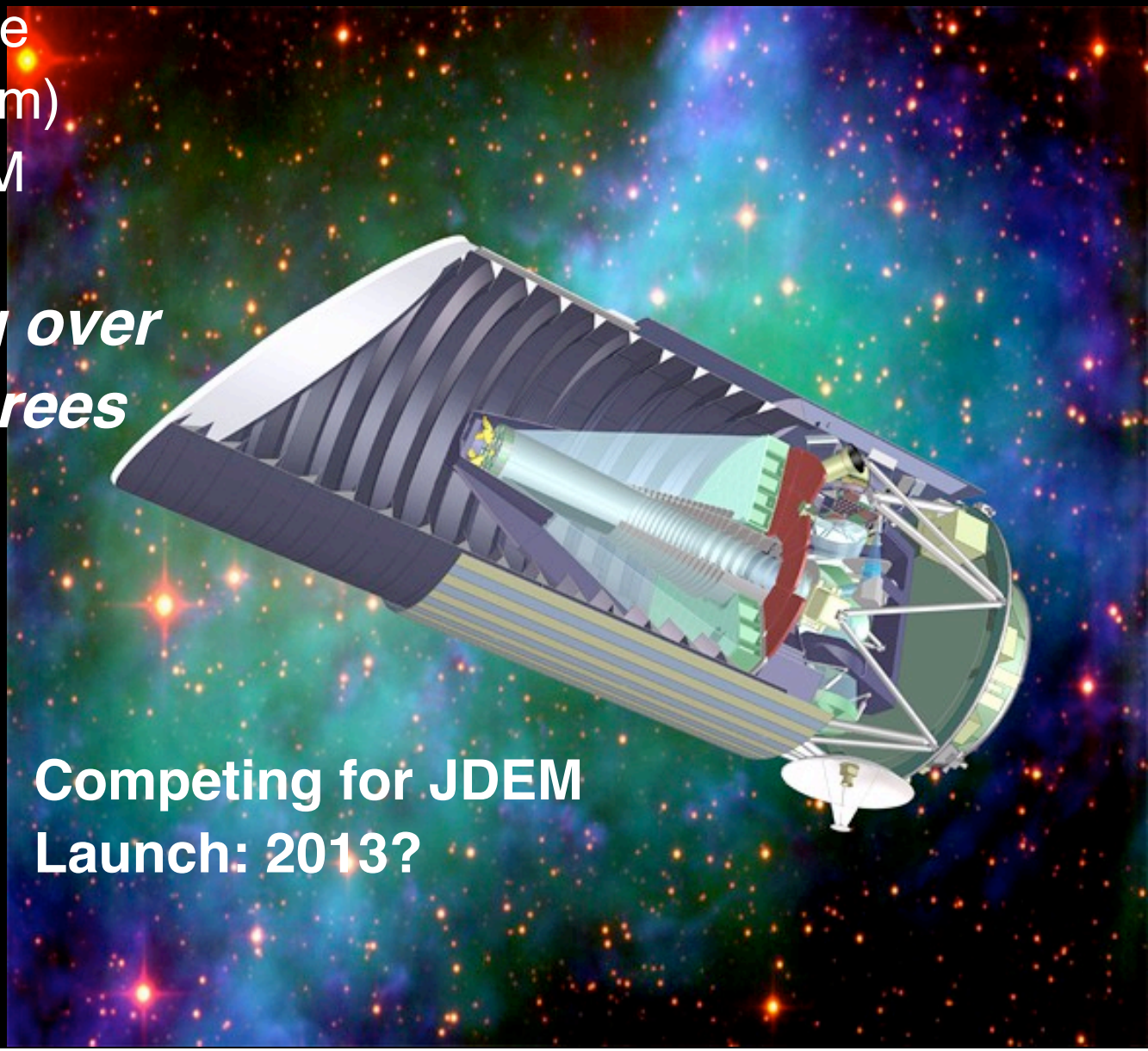


SNAP

- 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



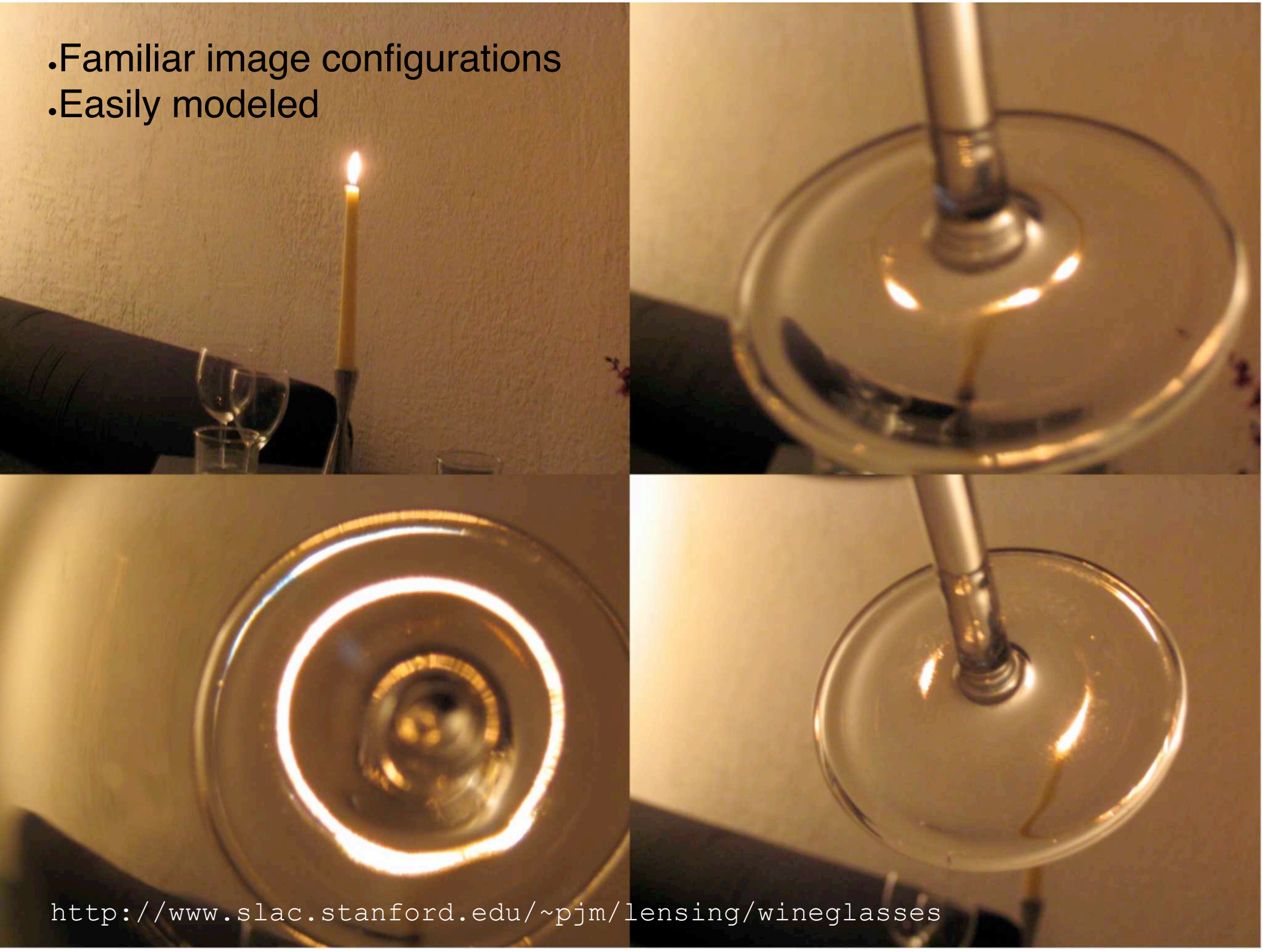


Competing for JDEM
Launch: 2013?

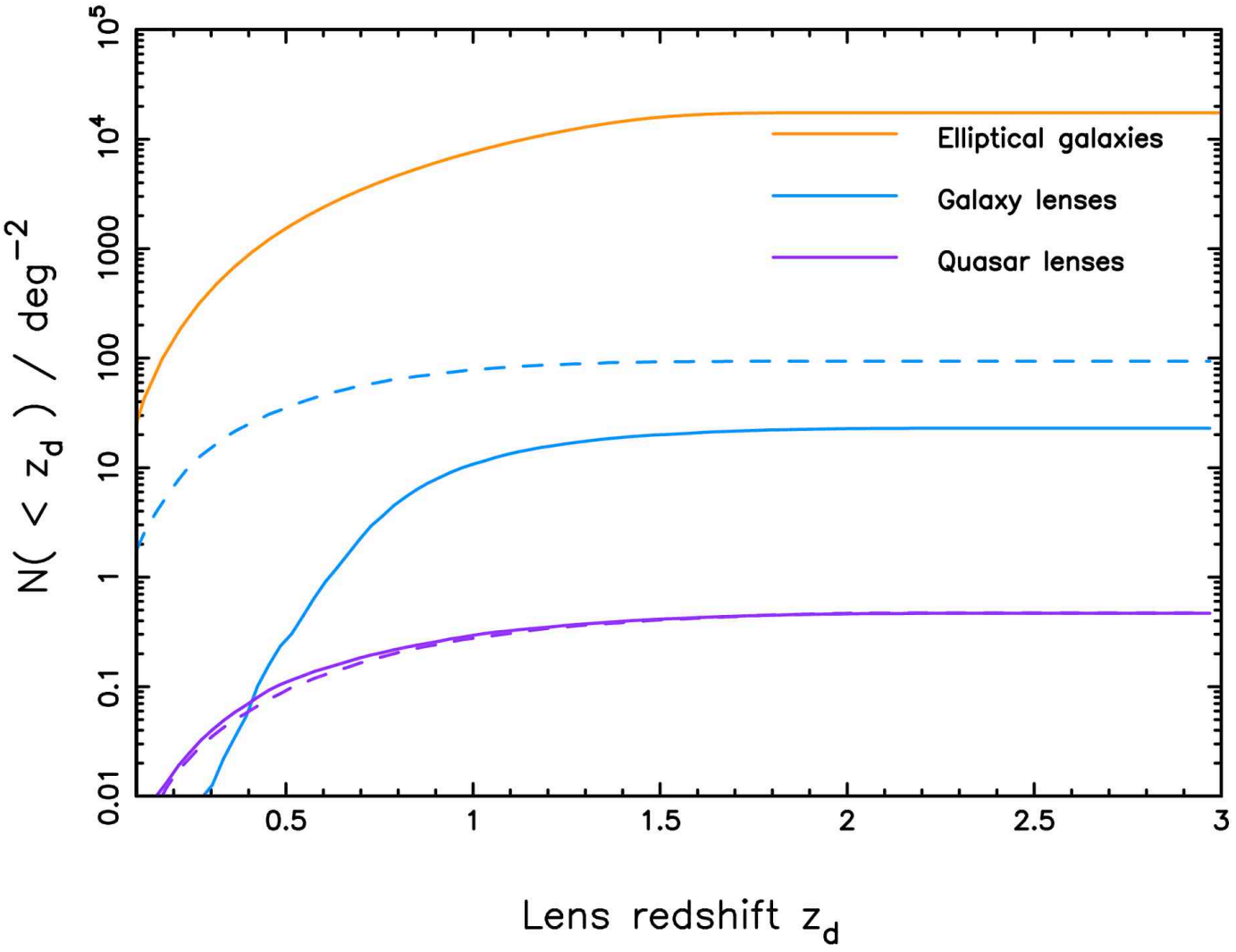
Examining elliptical galaxies

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 one eye on the bigger picture – automate the search
- This is the ONLY precursor dataset for SNAP

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

Image processing

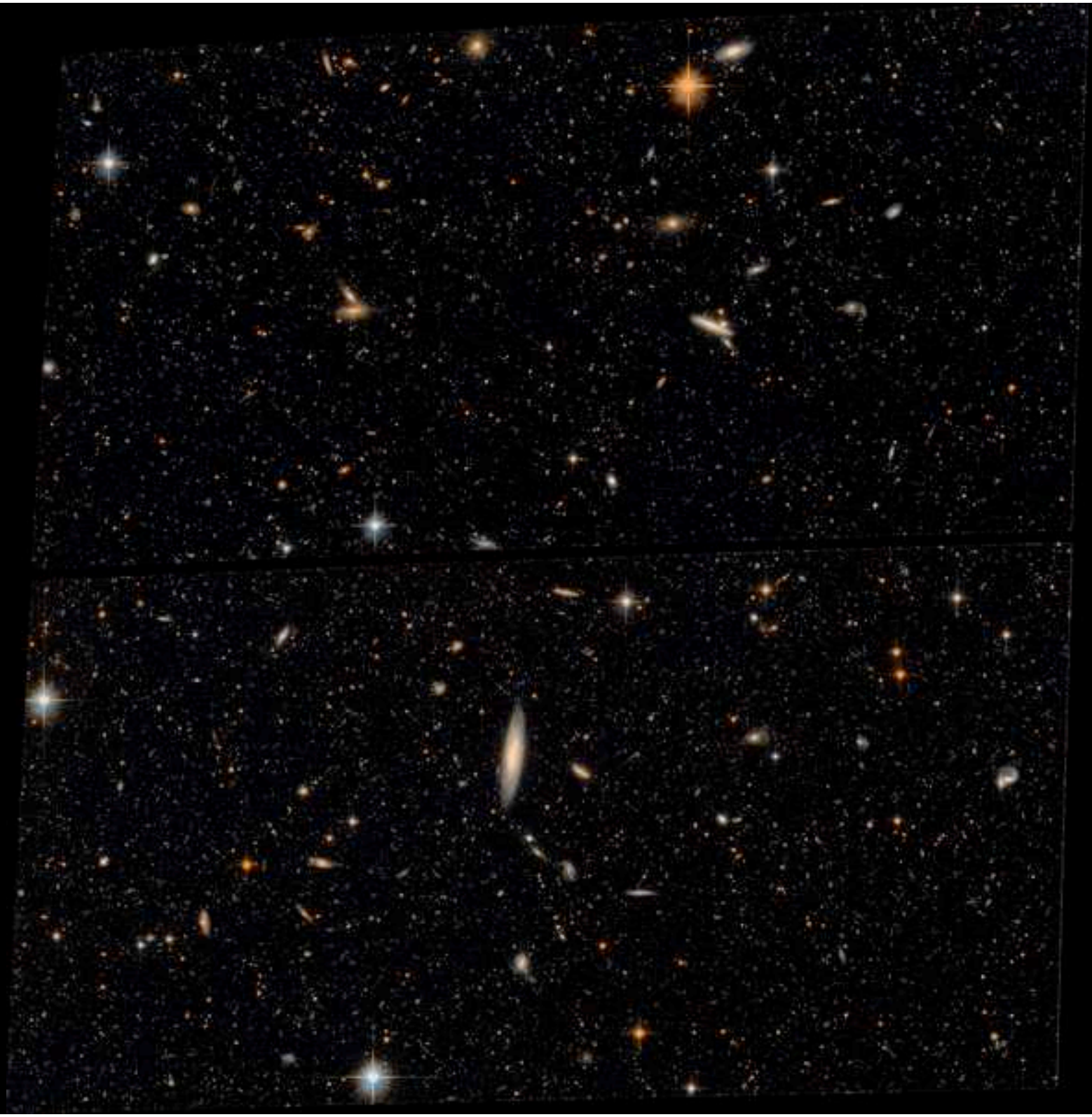
Lens searching requires deep, high quality stacked images:
this is one of the project's legacies to the community

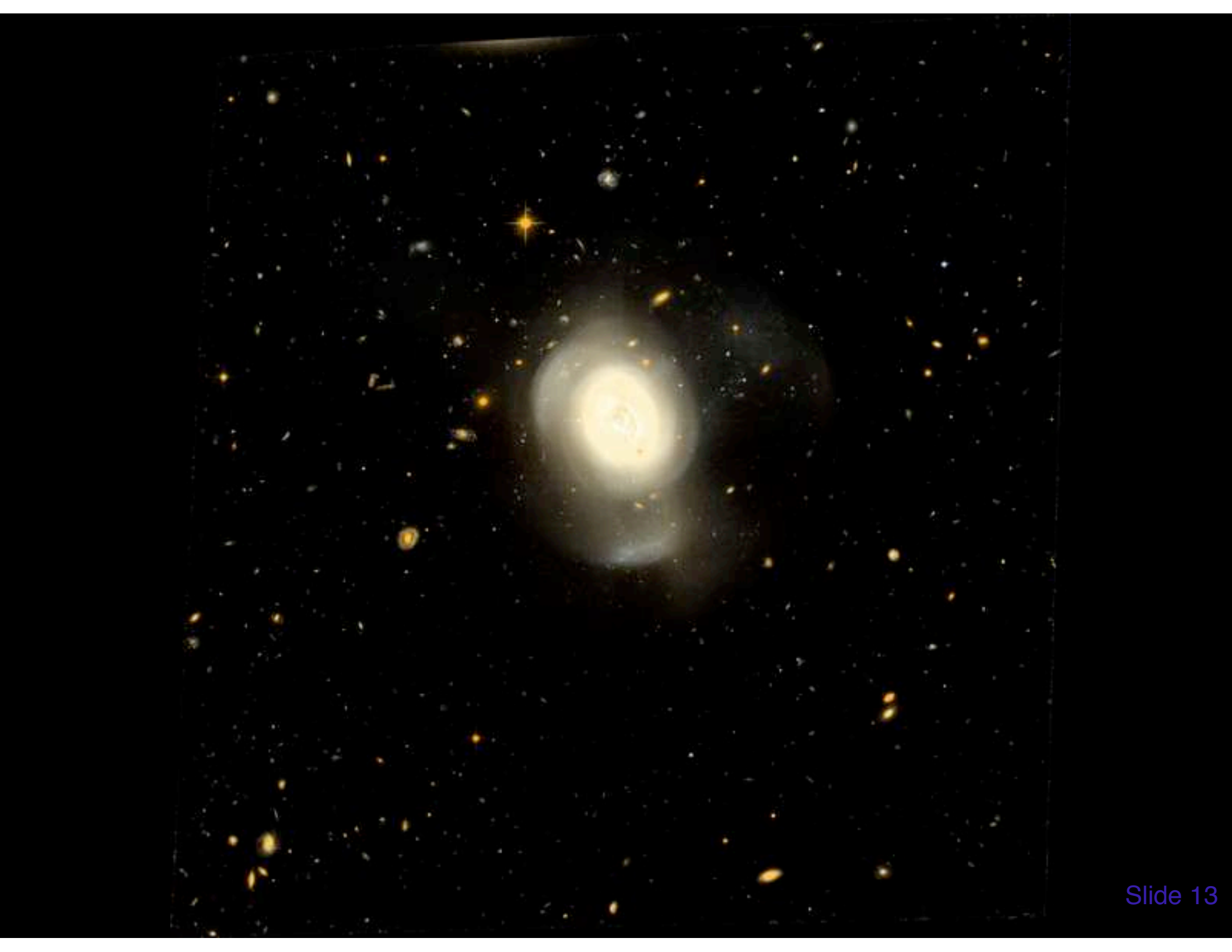
- We are aggressively combining ACS exposures from many proposals and epochs, to make the “ultimate” image
- Tim Schrabback is leading the weak lensing effort – and enforcing high standards!
- Extension to single filter data to follow: see Cecile Faure’s talk on the COSMOS candidates
- The high level science product images will be returned to MAST later this year for public use
- Aim to show the status of the image processing here

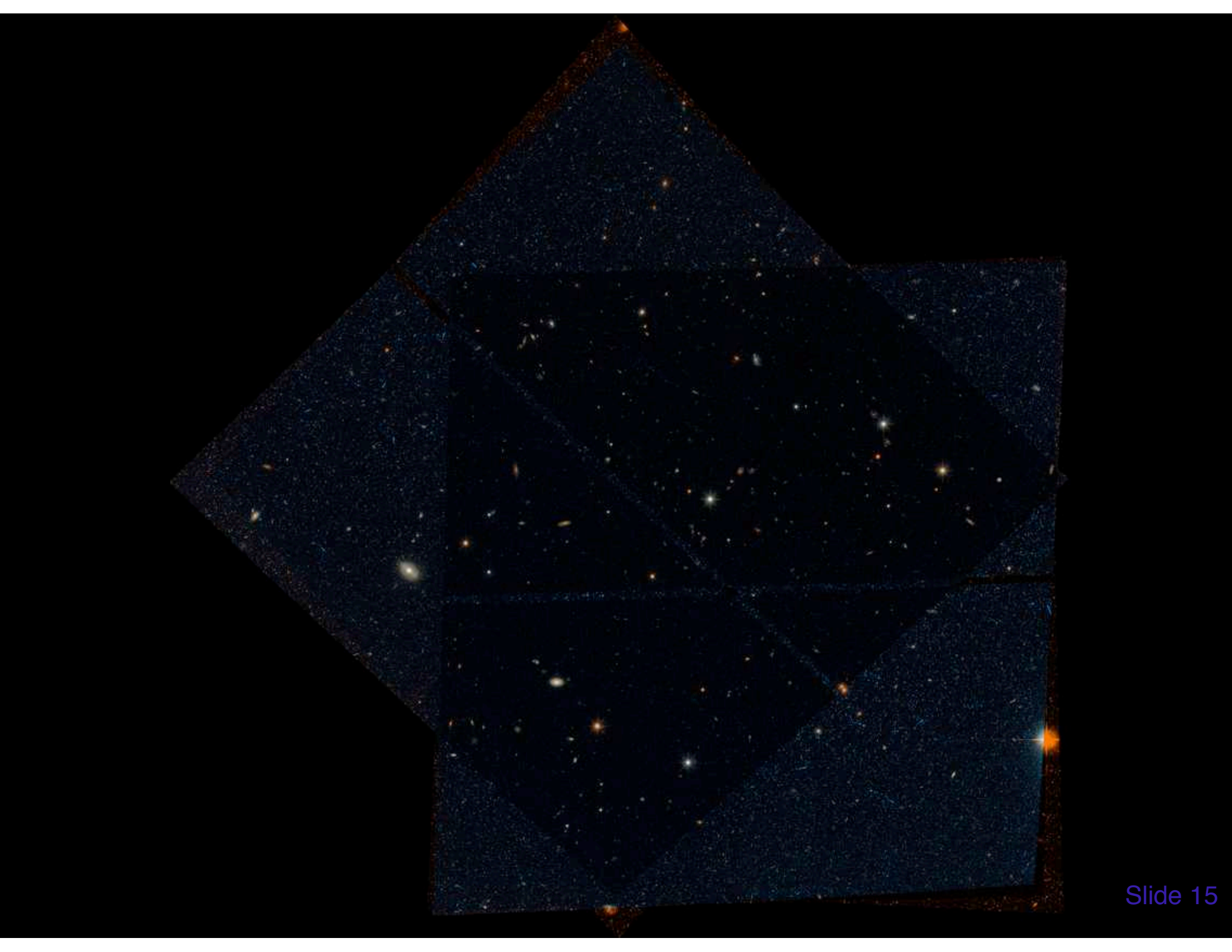
- Keep an eye open for lenses!

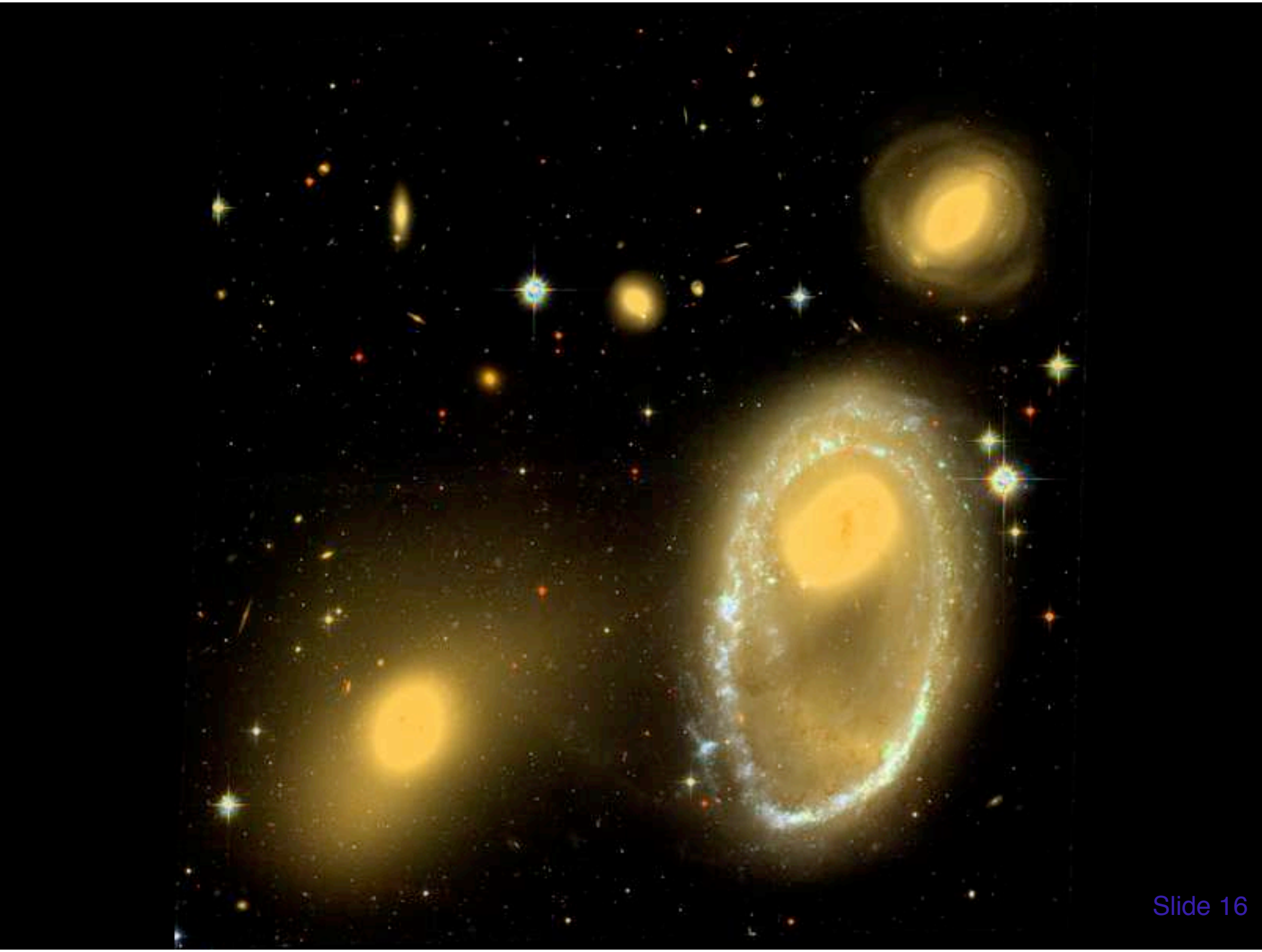
HAGGLeS: 224 fields (0.690 square degrees)

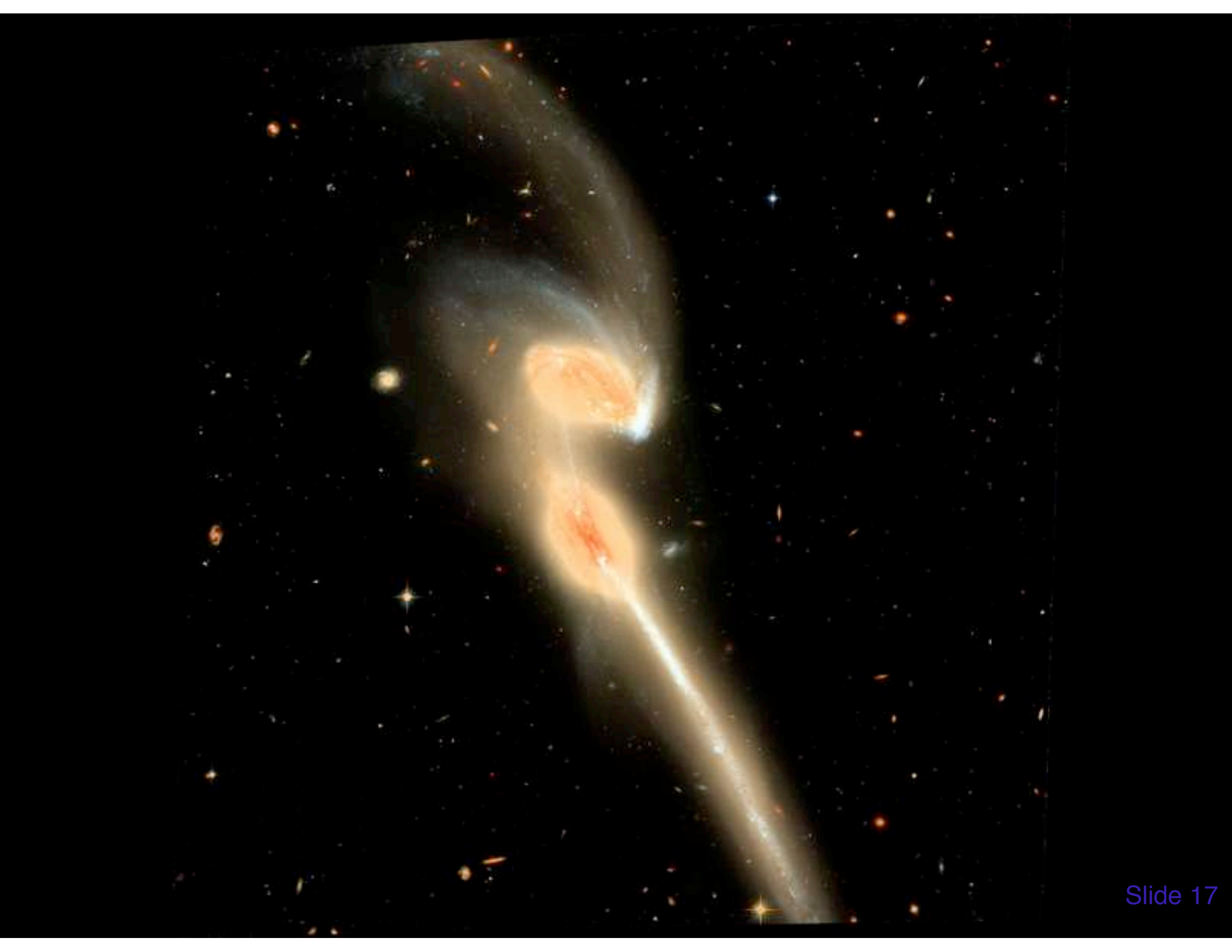
Baking situation	No. of fields
All processing complete	73
No workspace set up	3
CALACS failed	43
Background subtraction failed	3
FLT checking not done	72
Shift refinement failed	13
Multidrizzle failed	11
WCS correction failed	4
Colour JPG creation failed	2

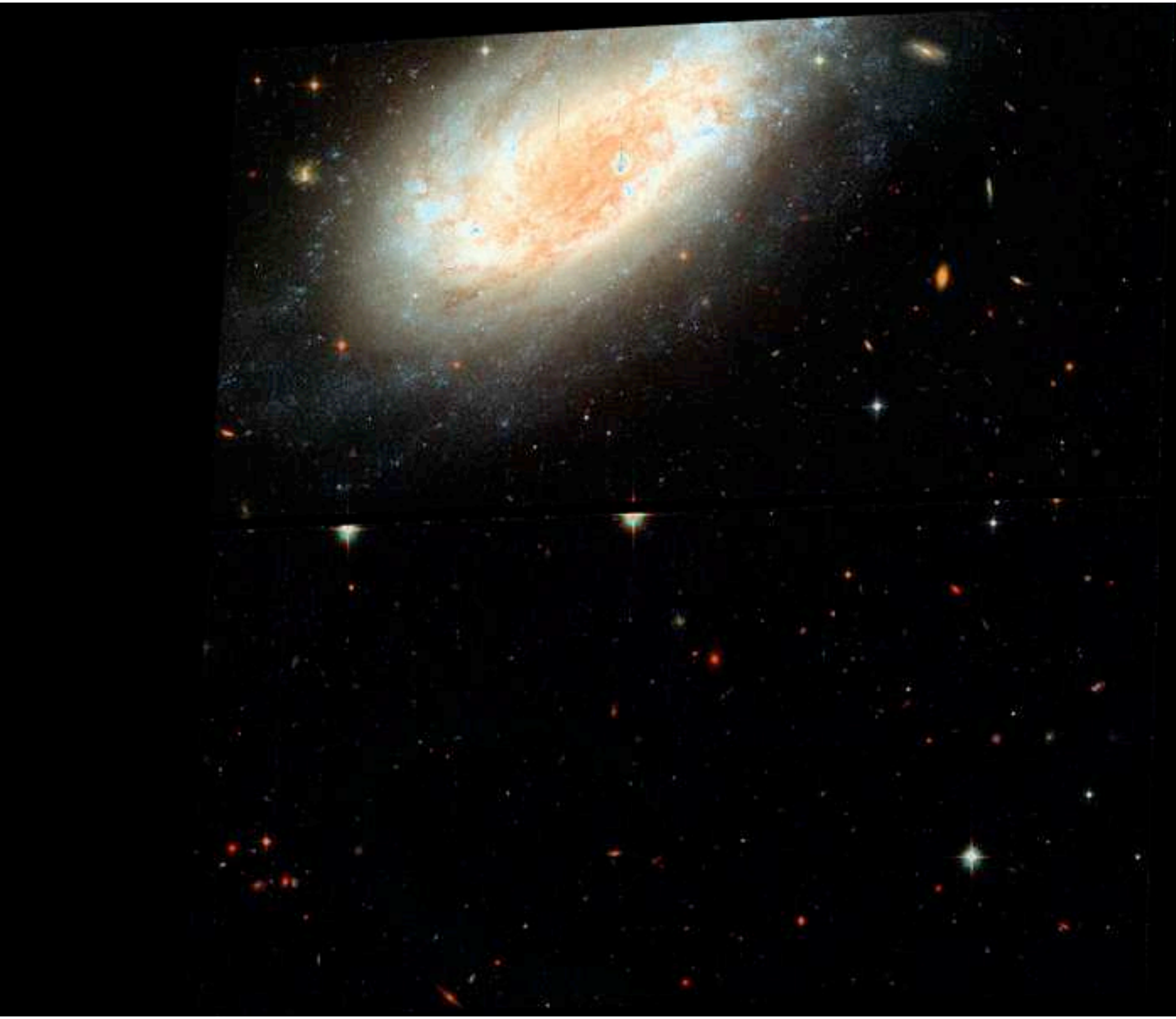


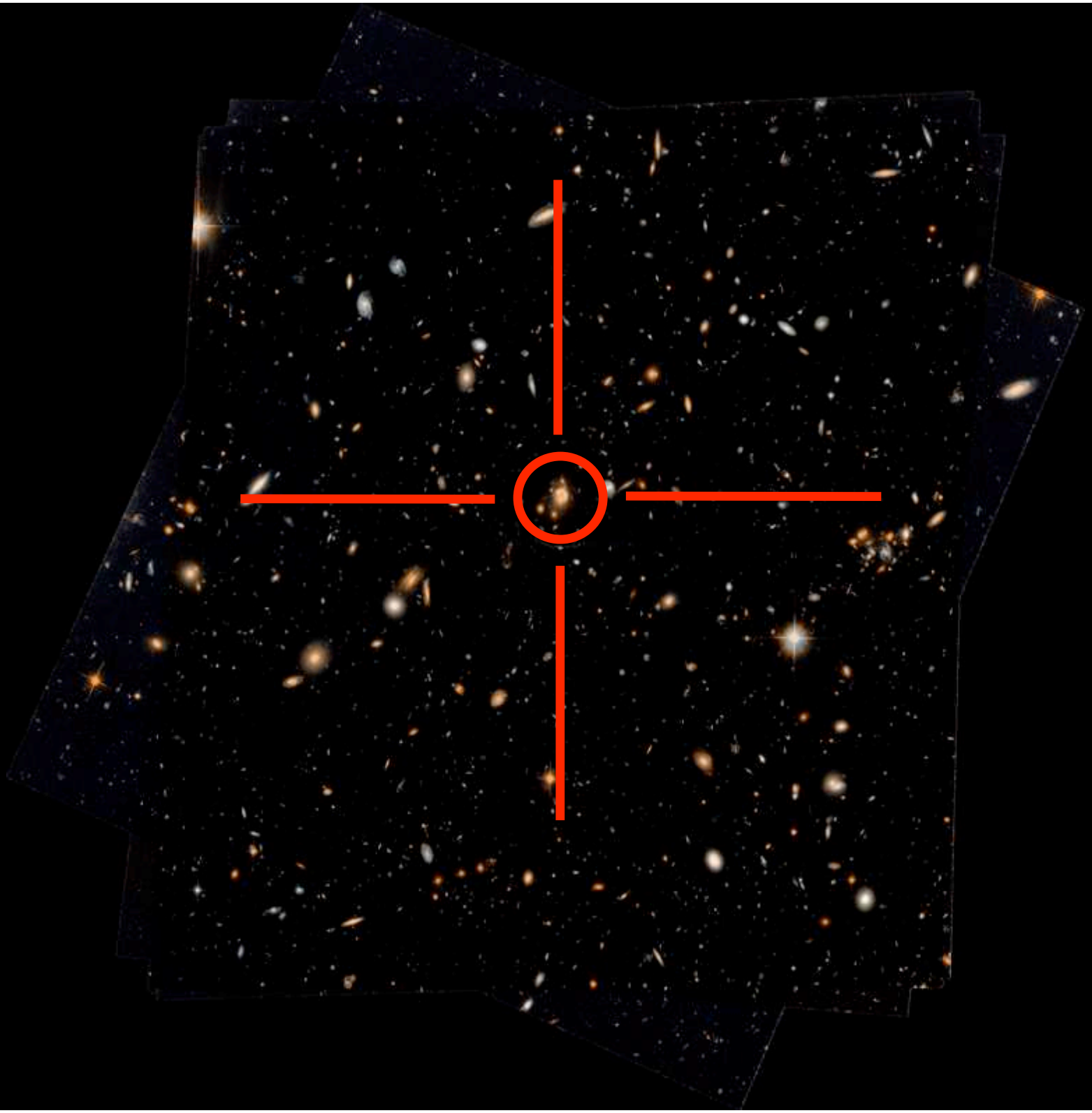












Preparing for the future

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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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!

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Even better to have a robot do it for you

A robot for finding lenses

- Select 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

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- Subtract off smooth flux from bright galaxy
- Examine (blue) residuals for signs of lensing

IDEA:

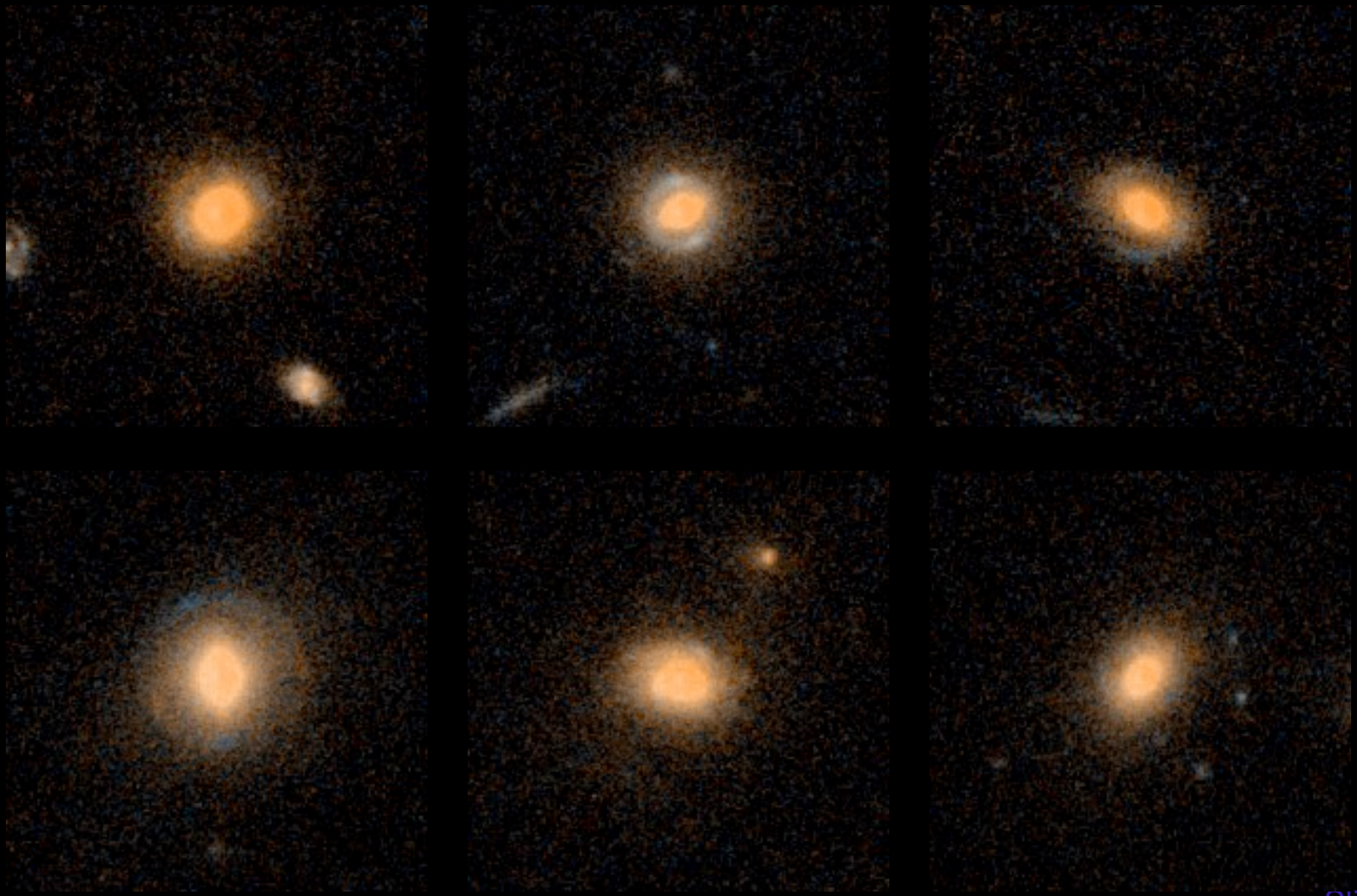
MODEL EVERY OBJECT AS IF IT WERE A LENS

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...

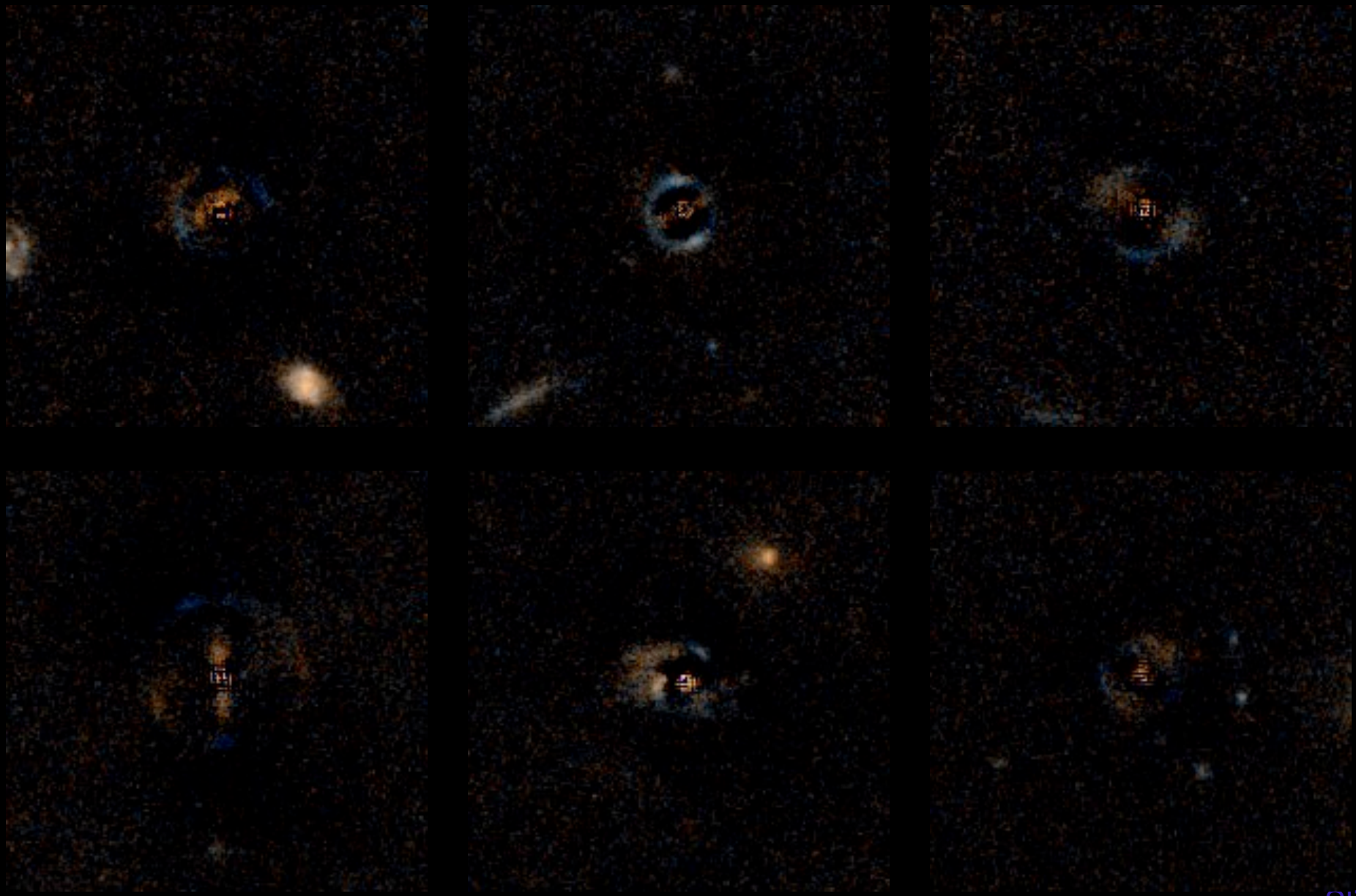
Demonstration 1: simulated lenses

- Morphologically selected spheroids from the Extended Groth Strip survey as model lens galaxies
- Faint blue galaxies drawn from EGS (with magnitudes to the detection limit), and placed behind the lenses
- Model with robot, learn from results...

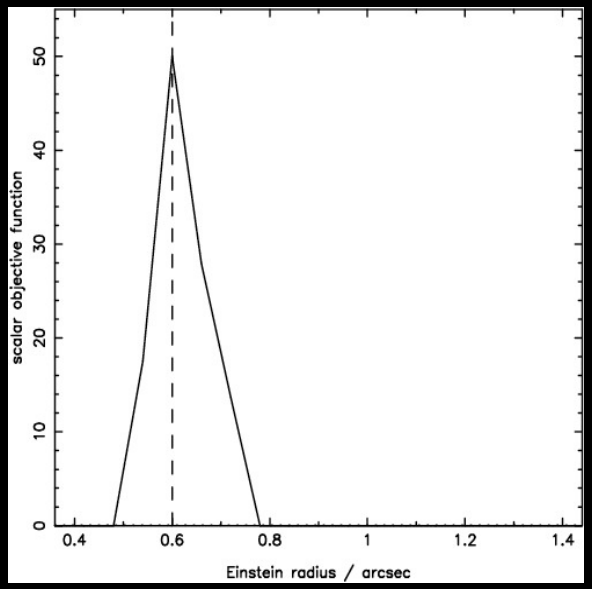
Demonstration 1: simulated EGS data

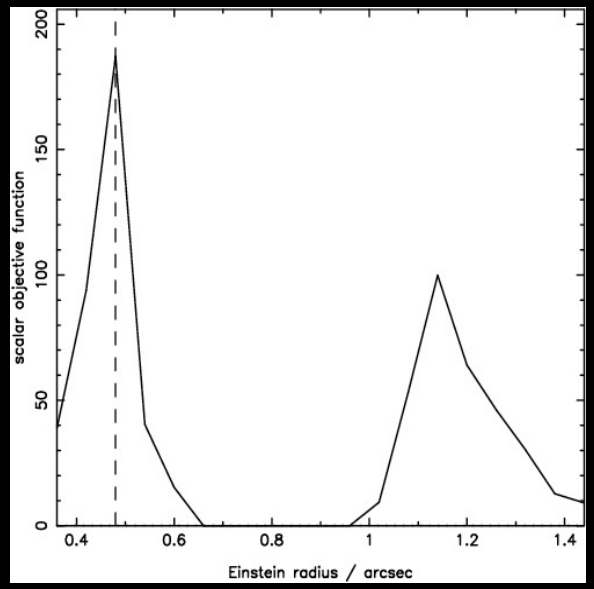


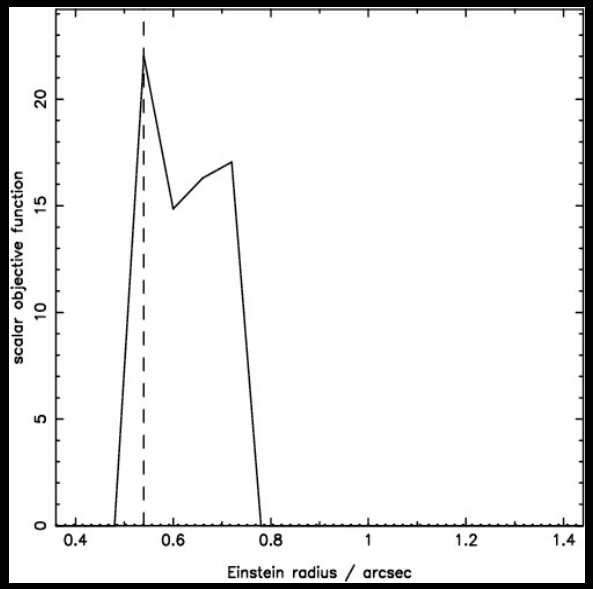
Demonstration 1: after LRG profile subtraction

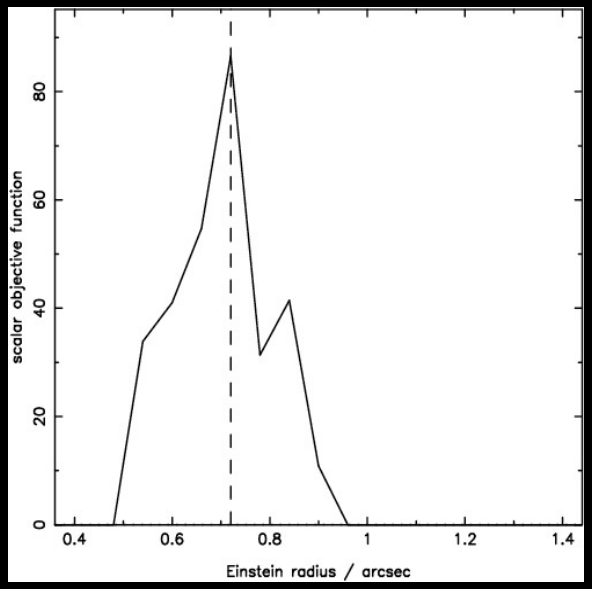


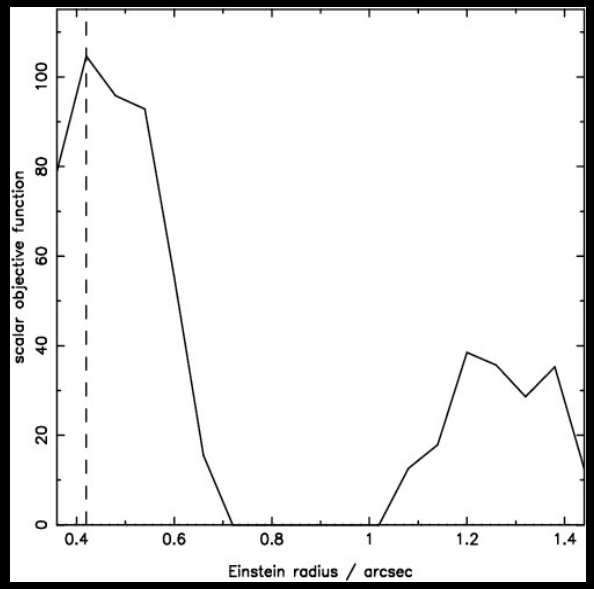
Demonstration 1: Einstein radius optimisation

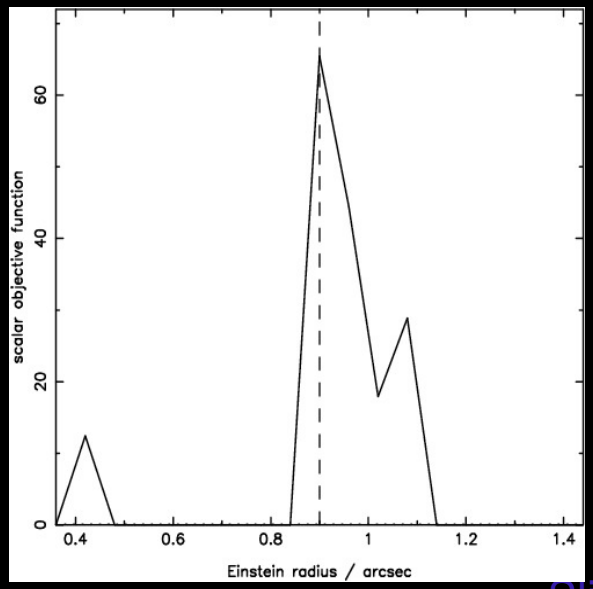






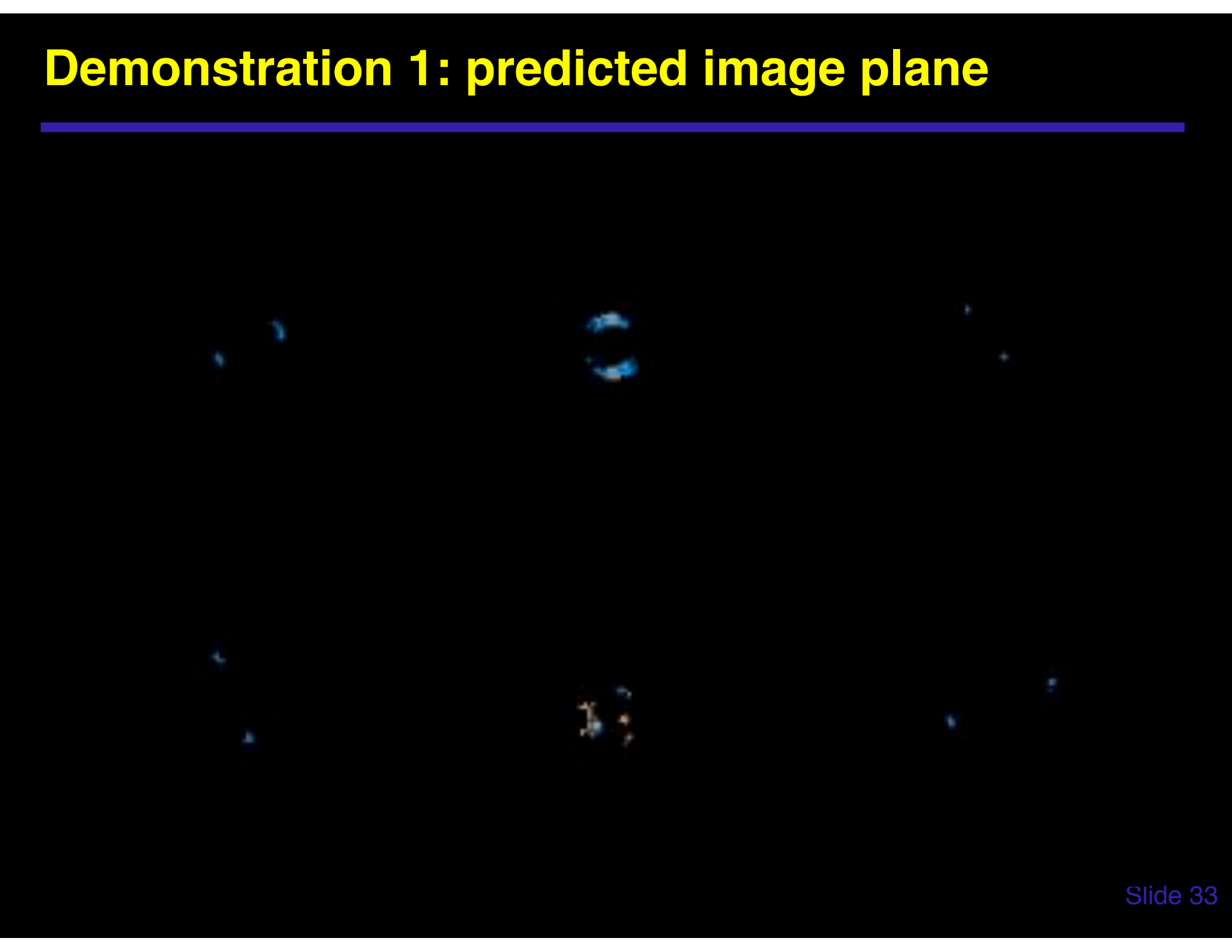






Demonstration 1: reconstructed source plane

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 EGS (with magnitudes to the detection limit), and placed behind the lenses

- 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 - but how does it compare with Lexi?

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 “B-list” candidates, and 11 “A-list” candidates

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

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

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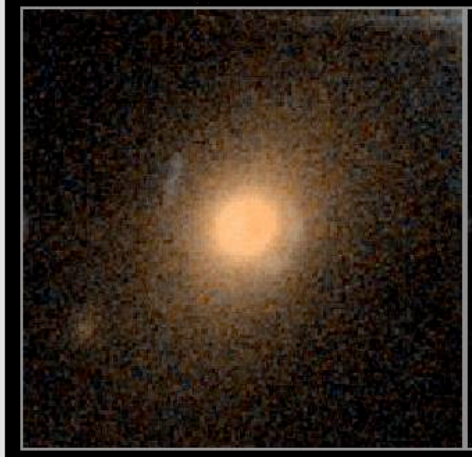
HSTJ141833.11+524352.5

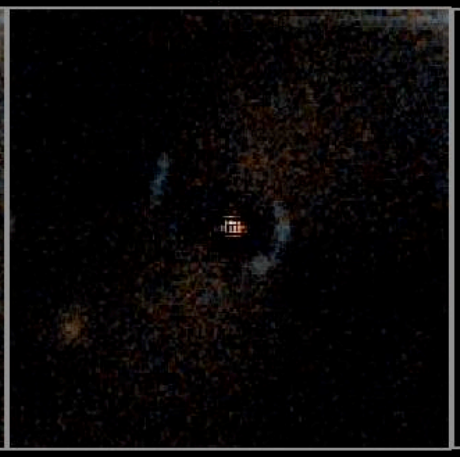
thetaE = 0.9 arcsec, xgamma = 0.1, xtheta = 2.44346 rad

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

Basic color image

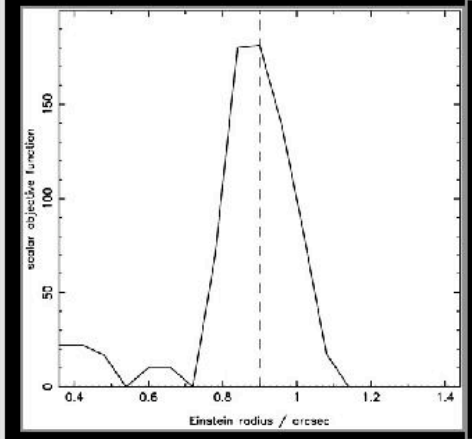


Color residual image



Masked input image

Scalar objective (min)



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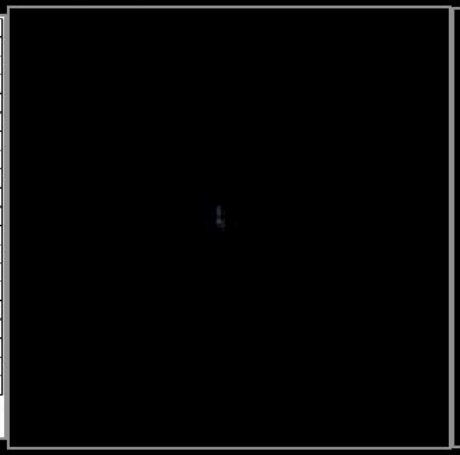
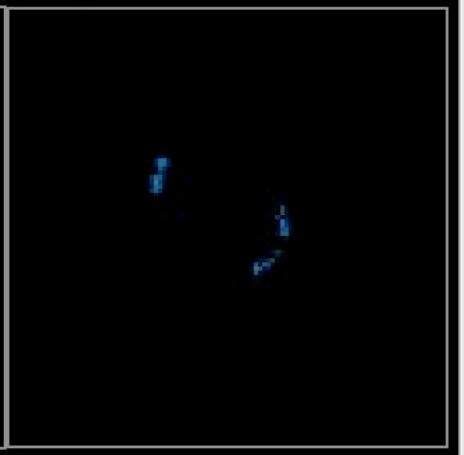


Reconstructed (min) image



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Done

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

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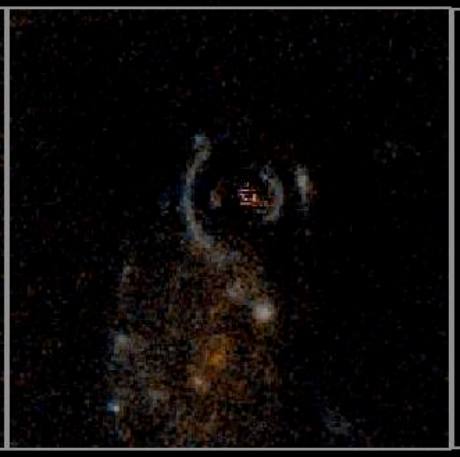
HSTJ141820.84+523611.2

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

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

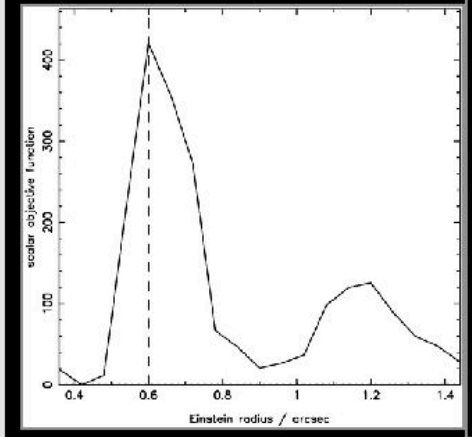
Basic color image

Color residual image

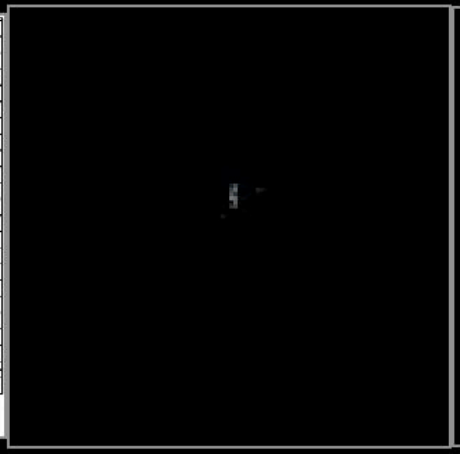


Masked input image

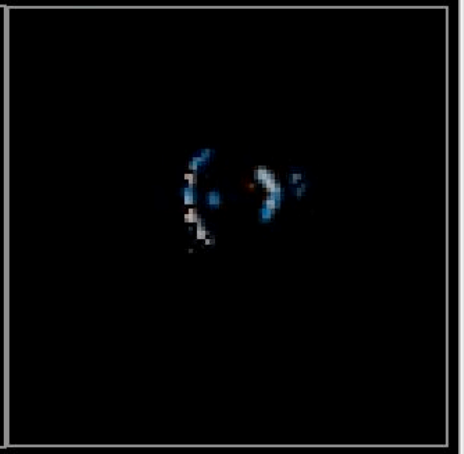
Scalar objective (min)



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 “B-list” candidates, and 11 “A-list” candidates
- A-list has purity ~20% and is ~70% complete
- A+B-list has purity ~1% but is ~90% complete (and contains all 3 Moustakas et al confirmed lenses by design)

- Human classification of the A+B 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

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

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

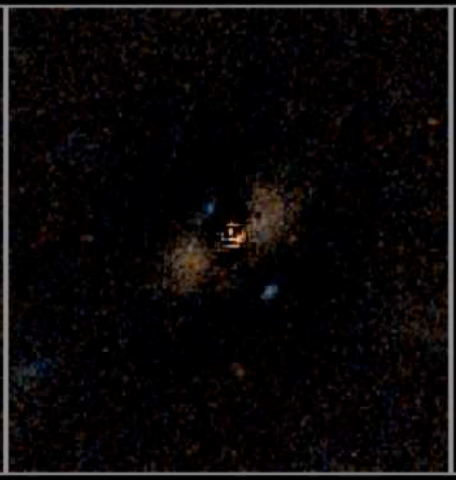
HSTJ141719.80+522824.3

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

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

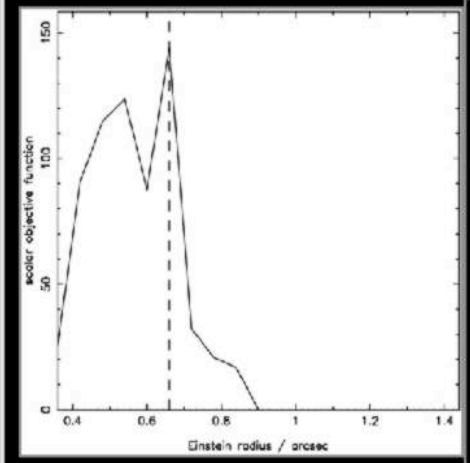
Basic color image

Color residual image

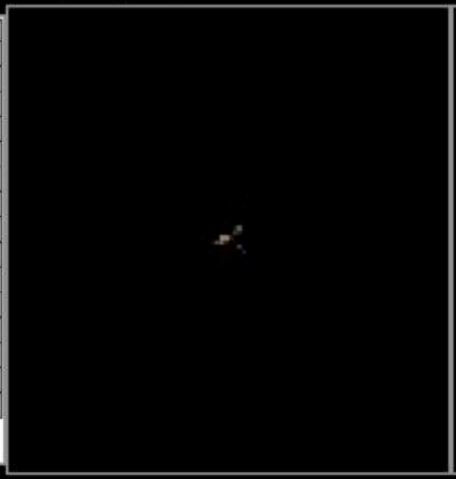


Masked input image

Scalar objective (min)



Corresponding (min) source



Reconstructed (min) image

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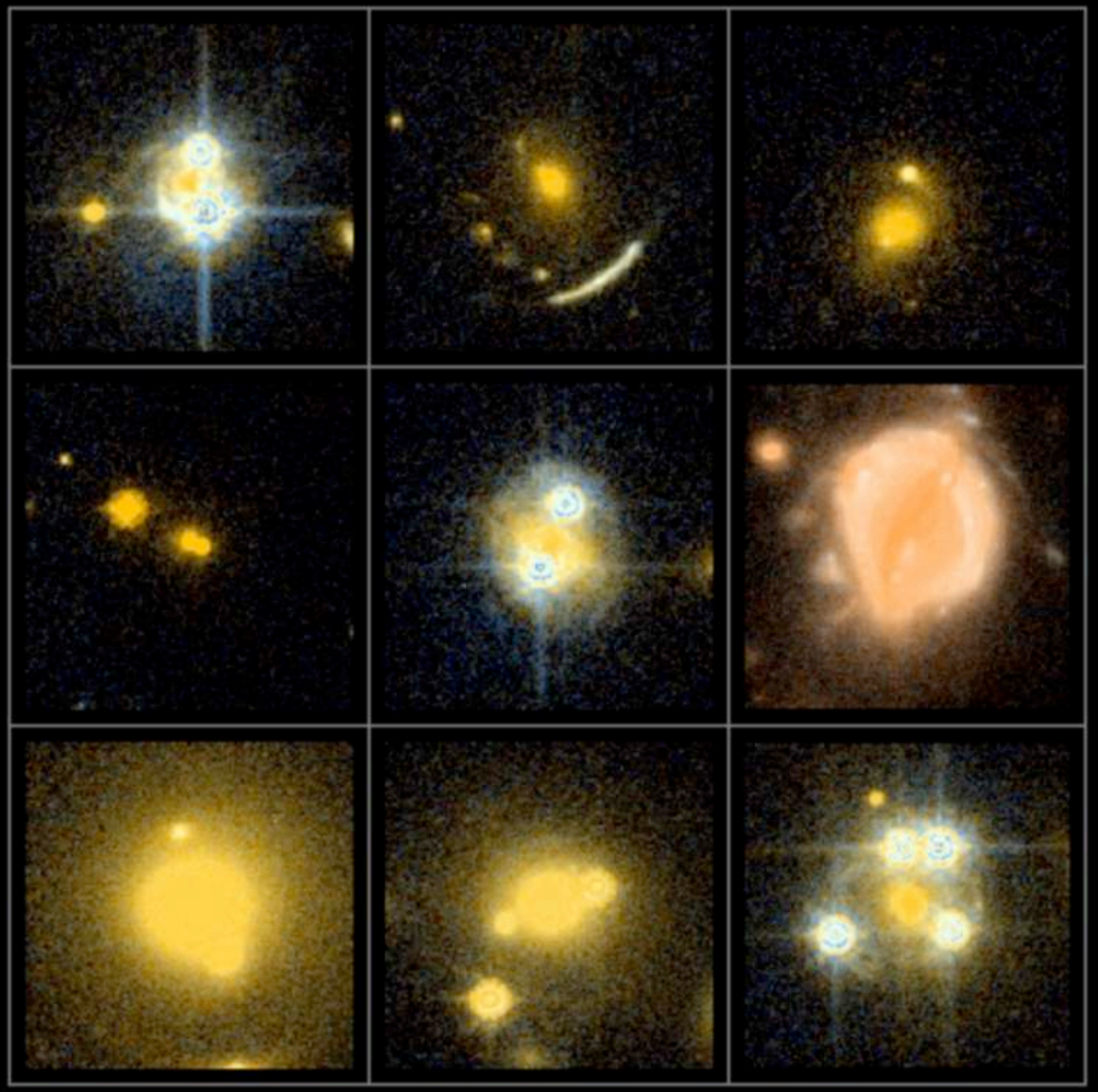
http://www.slac.stanford.edu/~pjm/HAGGLeS/hlsp/EGS/EGS-02-02/www/HSTJ141719.80+522824.3_sci_moffatdiff.minsrc.jpg

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 A+B-list 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...

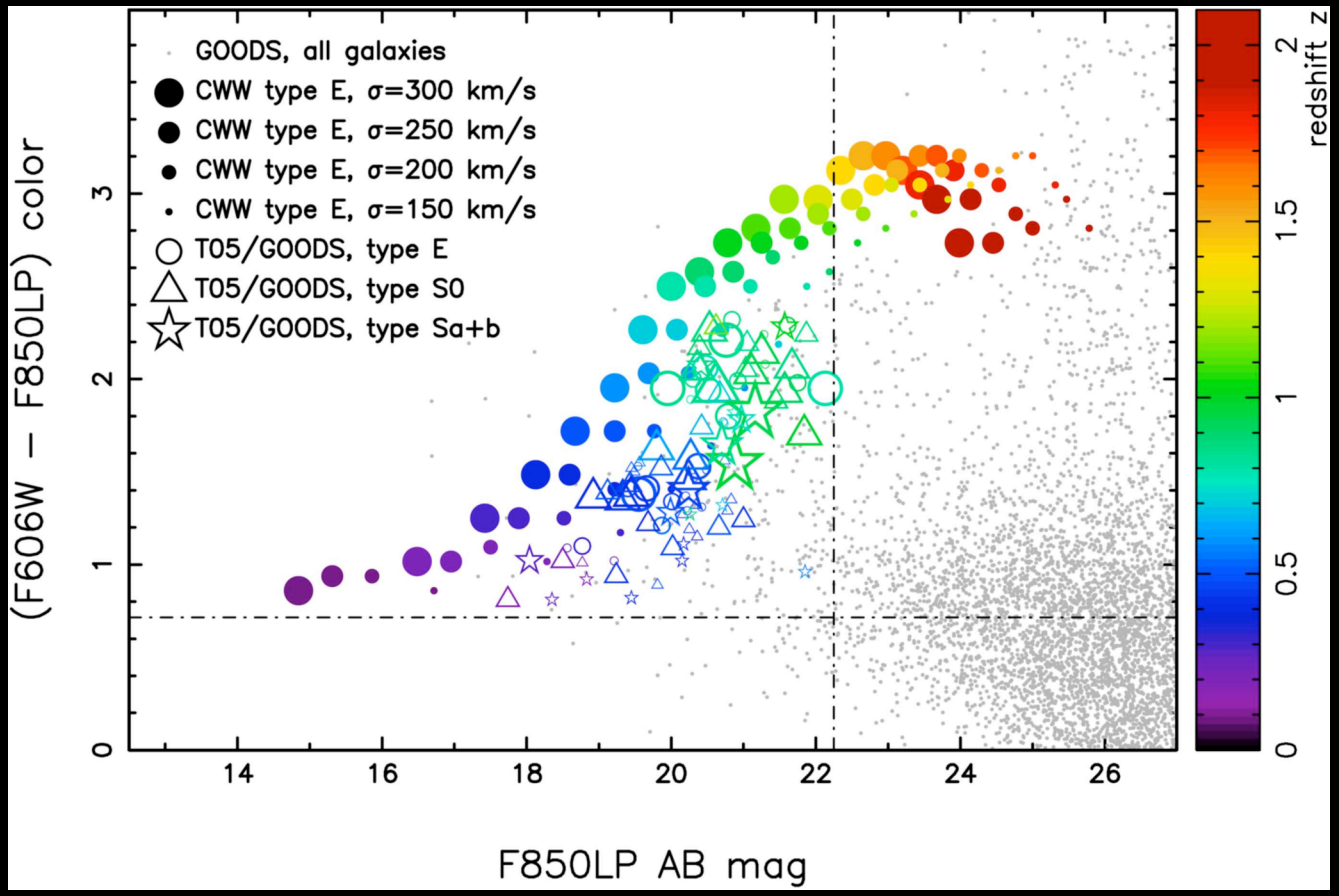
Demonstration 3: CASTLeS lenses

- 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):



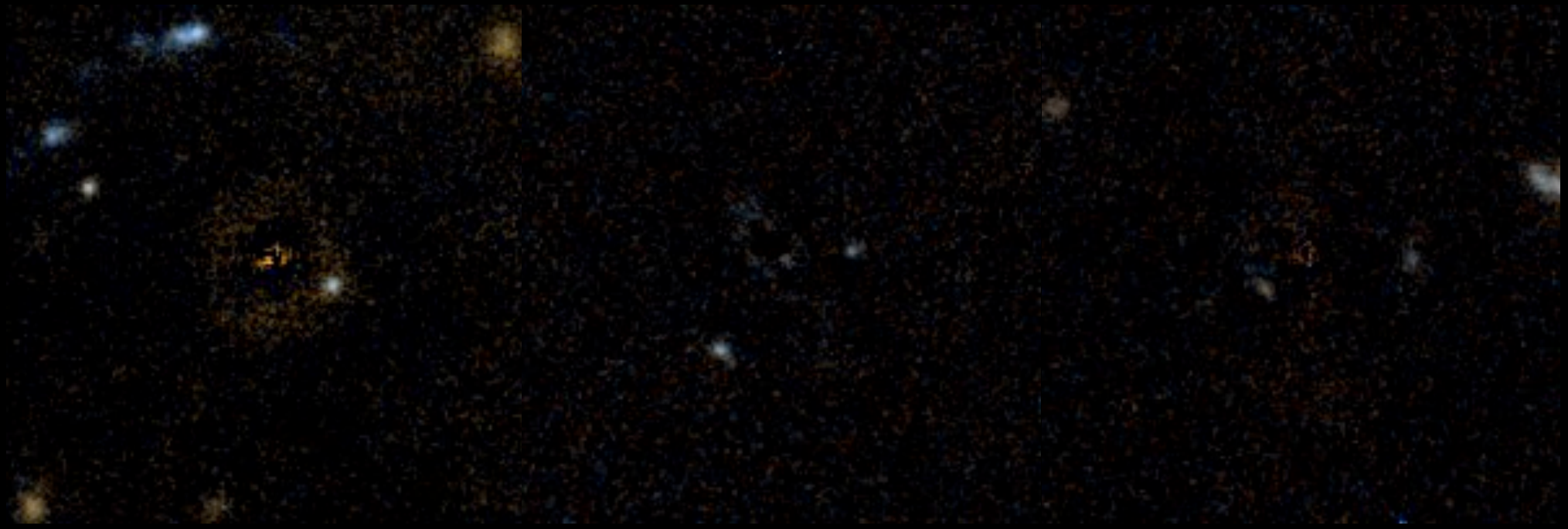
The GO archive: preliminary results

- 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:

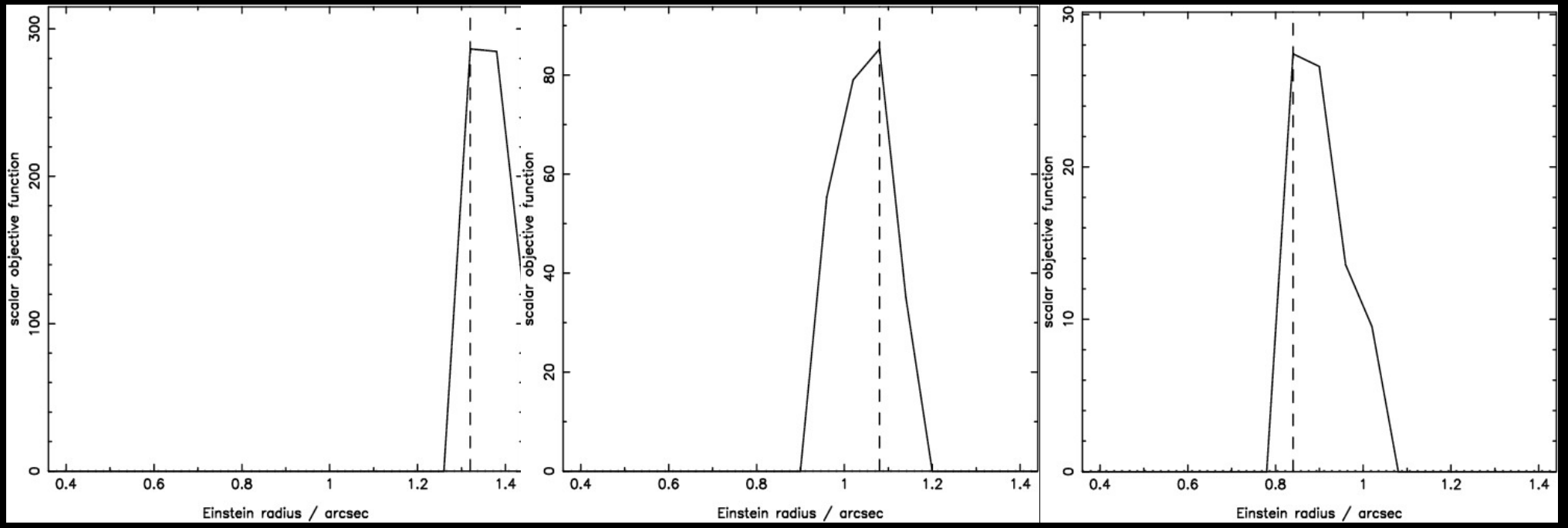
  889 A+B-list candidates (10%)
- Human classification of the robot candidates gives 3 “B-list” candidates:

The GO archive: new lens candidates

The GO archive: after LRG profile subtraction

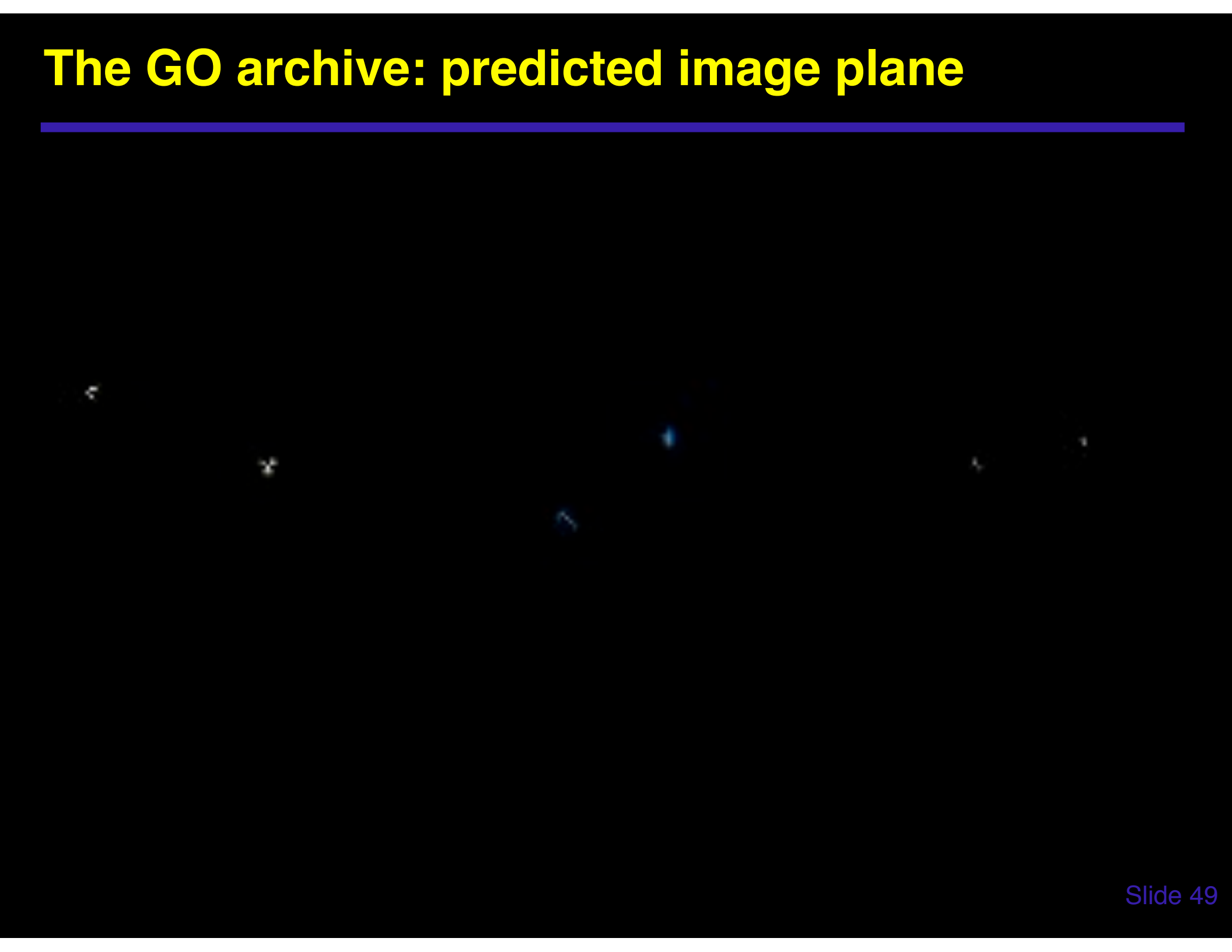


The GO archive: Einstein radius optimisation

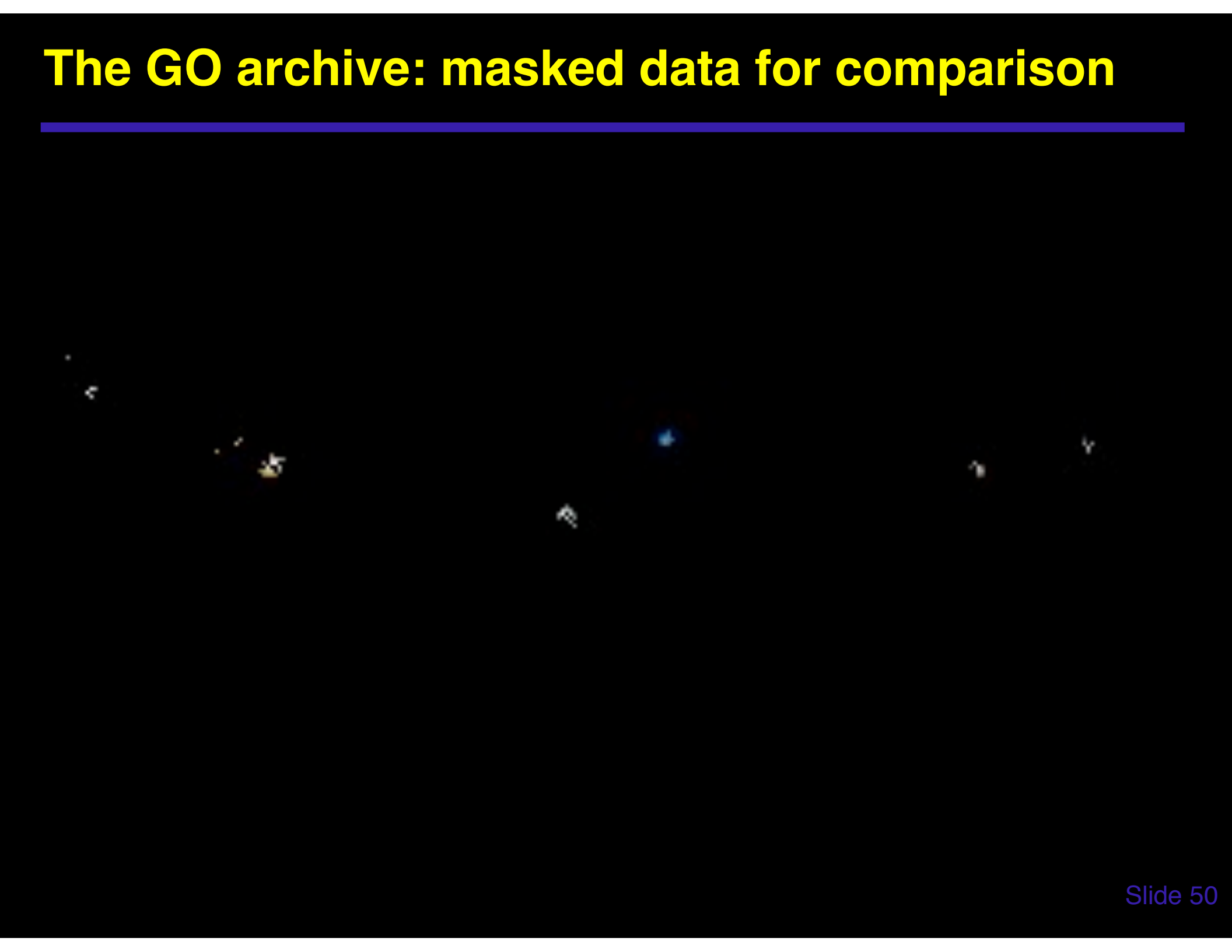


The GO archive: reconstructed source plane

The GO archive: predicted image plane



The GO archive: masked data for comparison



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 A+B-list candidates (10%)
- Human classification gives 3 “B-list” candidates – but no new A-list lenses...
- But what do YOU think?!
- Having multi-filter 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
- The appropriateness of the model for the data will be our only "confirmation" in the absence of massive spectroscopic follow-up
- *It is already possible to model every single lens candidate as part of the survey process*: classifying the SNAP wide lenses should eventually be 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