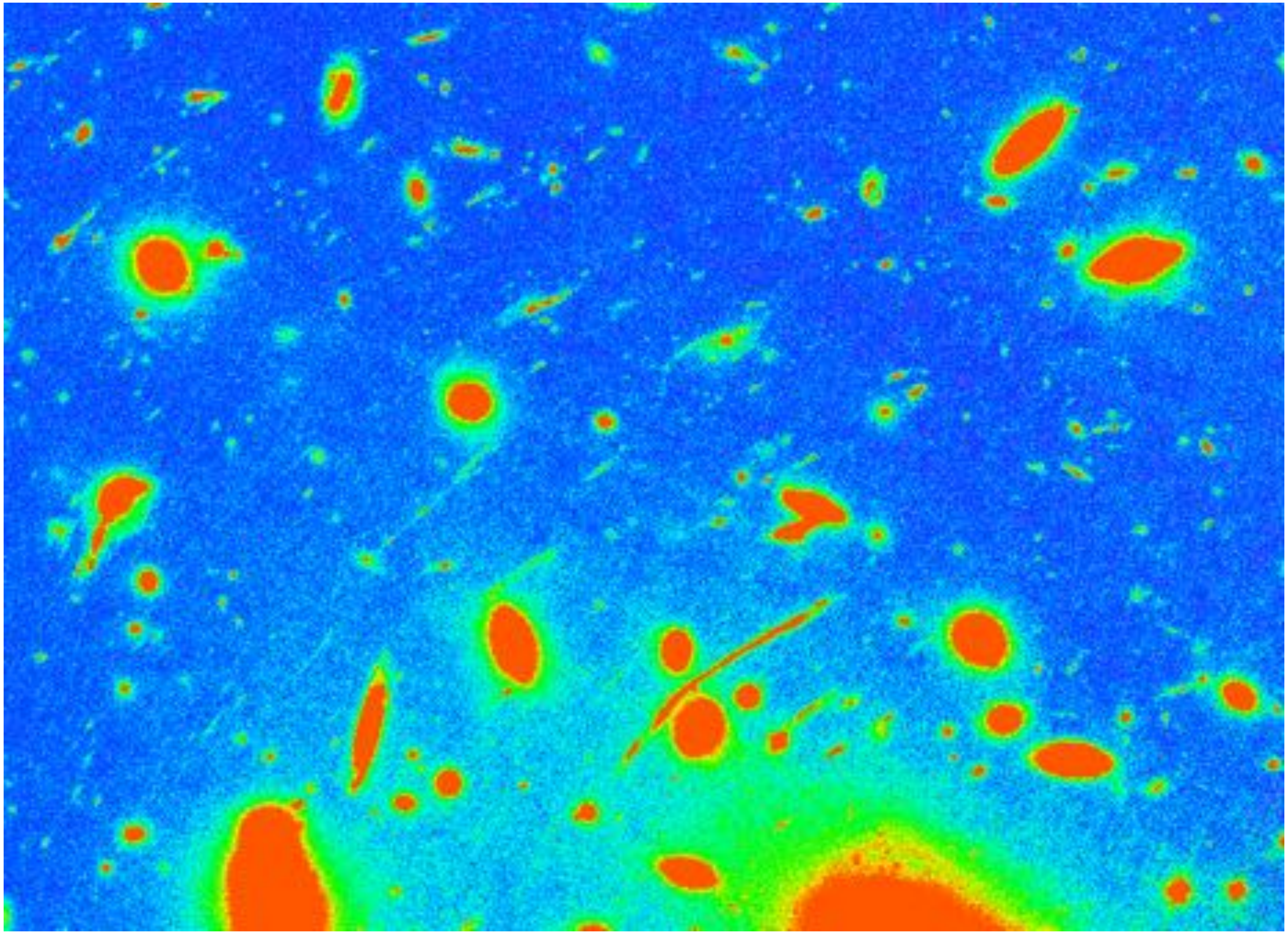
NIRISS GTO Program Extragalactic Science



Chris Willott, NRC + NIRISS Science Team

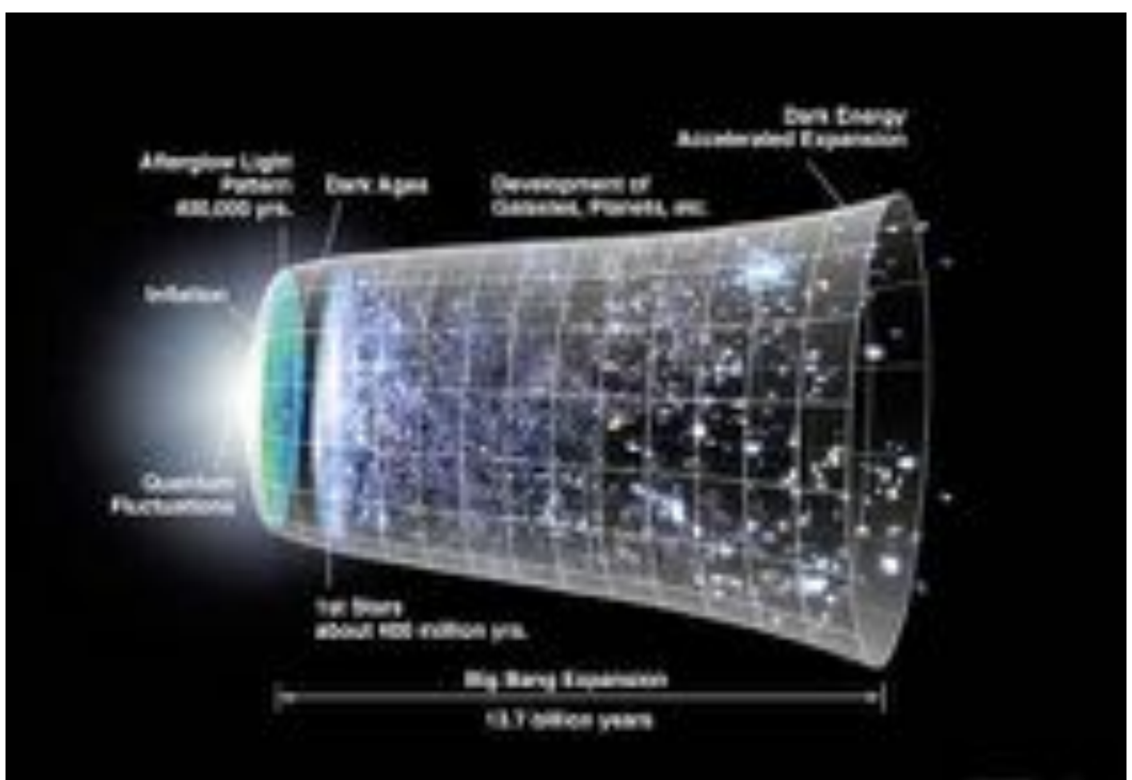
Outline

1. Science Motivation
2. The WFSS Advantage
3. Simulations
4. Major Unresolved Questions for GTO Program
5. Future Work Plan

Science Motivation

The End of the Dark Ages: First Light and Reionization

- When did the first stars, galaxies and black holes form?
- What are the properties of the first galaxies?
- When and how did reionization occur?



The Assembly of Galaxies

- How do galaxies change as the universe evolves?
- How do galaxies interact with their surroundings?
- What effect do black holes and stars have on galaxies?

Science Motivation

Galaxy Assembly (1<z<7)

Theme is low-mass/dwarf galaxies, low-z analogues of reionizing galaxies

- Search for extreme stellar pop spectra (Pop III, top-heavy IMF), UV slope at z>4 + HeII line at z>5
- Spatially-resolved emission lines:
  - ✦ H alpha for SFR maps
    - ✳ vs stellar mass (NIRCam) - where is SF distributed,
    - ✳ vs UV - where is dust located/SFH?,
    - ✳ vs ALMA/radio, diff indicator of SF.
  - ✦ H alpha / H beta - where is dust located
  - ✦ Metallicity - resolved
- Halpha LF at 1<z<2 - low lum SF LF - feedback in low-mass DM halos
- Mass-metallicity relation at 1<z<3
- Quenching - environment (concordance - quenched gals have quenched satellites?) - E+A gals - can we do Hdelta? maybe only by stacking
- Merger rate from physical pairs - if need more volume could add in archival
- Clumps in strongly-lensed resolved galaxies - globular clusters, SF clumps
- High SFR galaxies from ALMA
- AGN - X-ray, radio, heavily obscured
- Transients at all redshifts - SNe identified either by photometric variation or unusual spectra

Science Motivation

First Light (z>7)

- Redshifts and confirmation of high-z photo-z candidates
- Lya disappearance and the IGM - NIRSpec can likely do a better job of this, but we may be able to make a start
- Lya sizes
- UV spectral slopes of high-z galaxies (evolution, inc data at 4<z<7)
- Small-scale clustering of high-z galaxies - groups, filaments
- Direct imaging - sizes and shapes

Cosmology (Strong Lensing)

- Hundreds of redshifts of lensed galaxies
- Identification/confirmation of multiple images
- Cosmological parameter constraints from lens modelling
- Dark matter substructure (and cluster merger history?) from detailed lens modelling

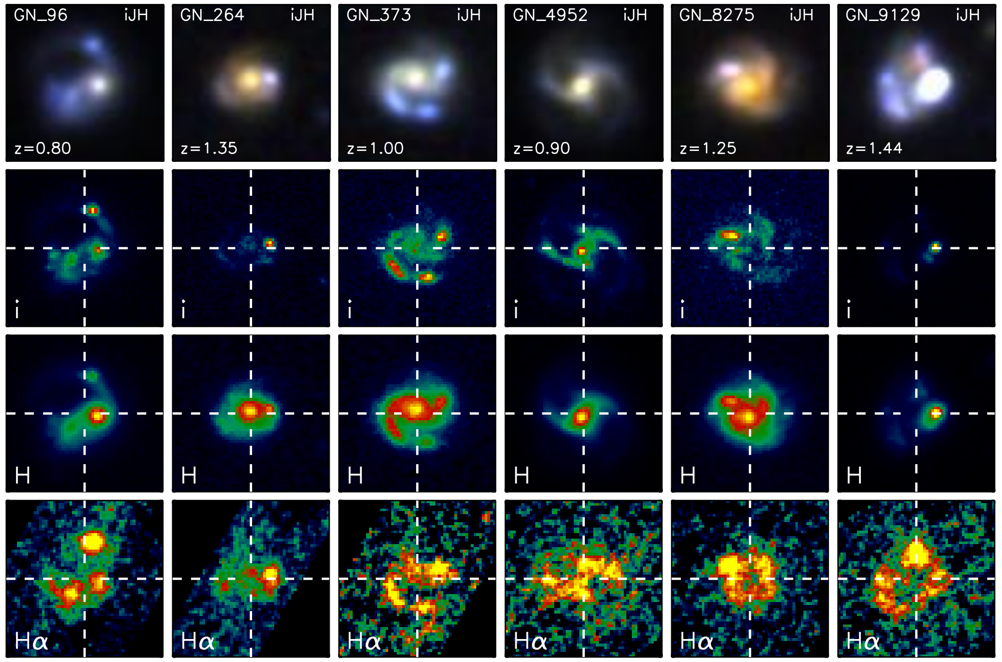
Massive clusters

- What are strongest emission lines at cluster redshift (Halpha in F115W or not?)?
- Stack low mass cluster galaxy spectra by type/location etc.
- Stripped remnants in cluster - GCs, streams, ICL

What is NIRISS Wide-Field Slitless Spectroscopy capable of?

Observables:

- Redshift -> distance, geometry, mergers, environment
- Emission line luminosity -> star formation rate, IGM absorption
- Absorption line strength -> age, SFH - more difficult, can be done if bright or in a stack.
- Emission line map -> star formation map
- Emission line ratios -> ionization, metallicity, dust
- Continuum spectral shape -> stellar population

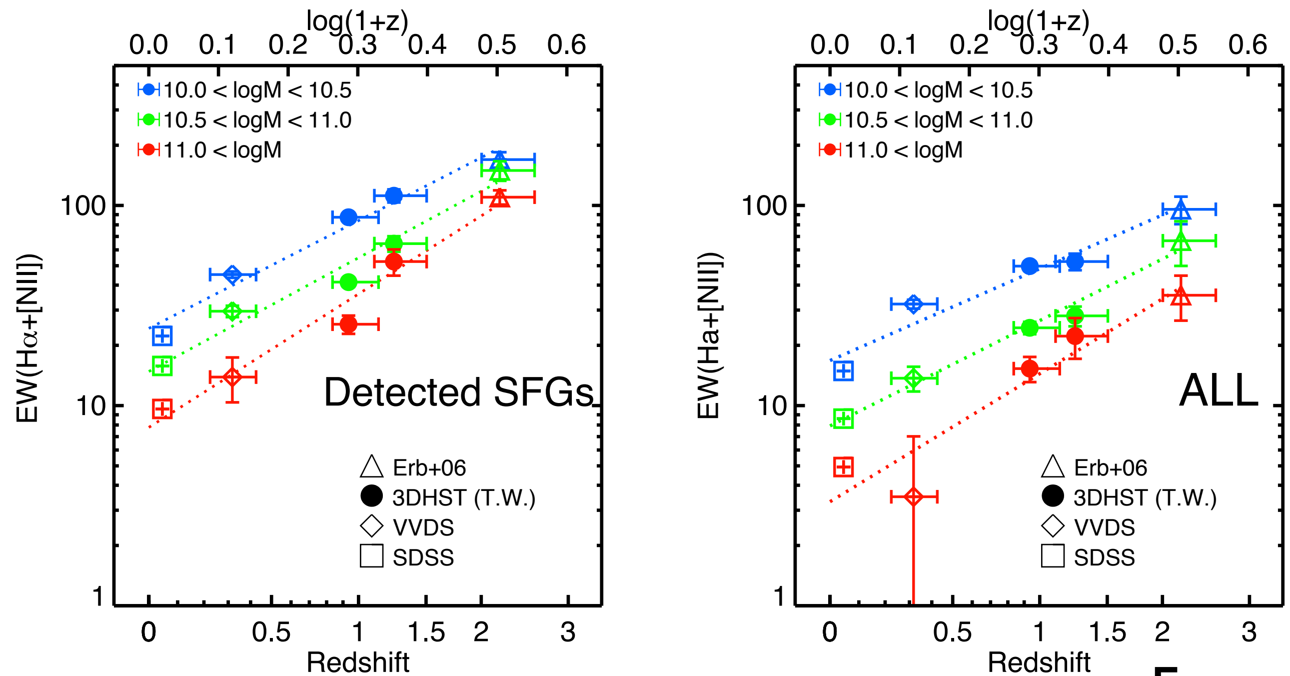


Wuyts et al. 2013

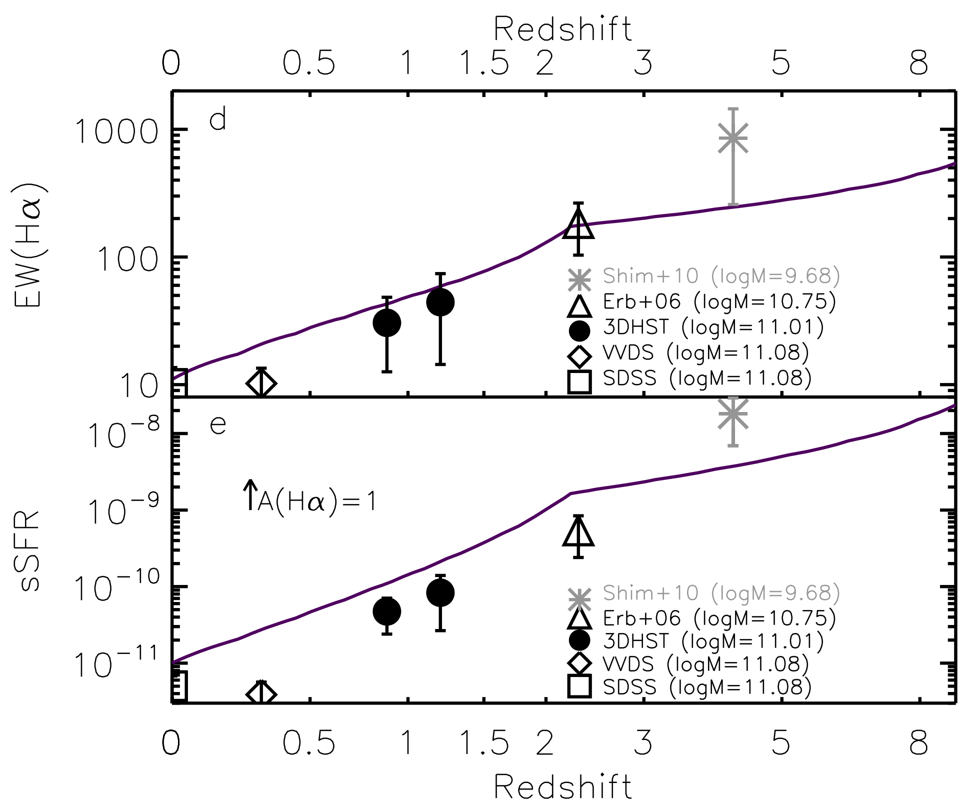
The WFSS Advantage

What is NIRISS Wide-Field Slitless Spectroscopy capable of?

Rest-frame equivalent width of emission lines increases rapidly at higher redshift due to higher specific star formation rate



Fumagalli et al. 2012



[OIII] lines increase with decreased metallicity.

Our simulated NIRISS observations show emission lines in a large fraction of galaxies.

Potentially thousands of redshifts per field - huge multiplexing.

The WFSS Advantage

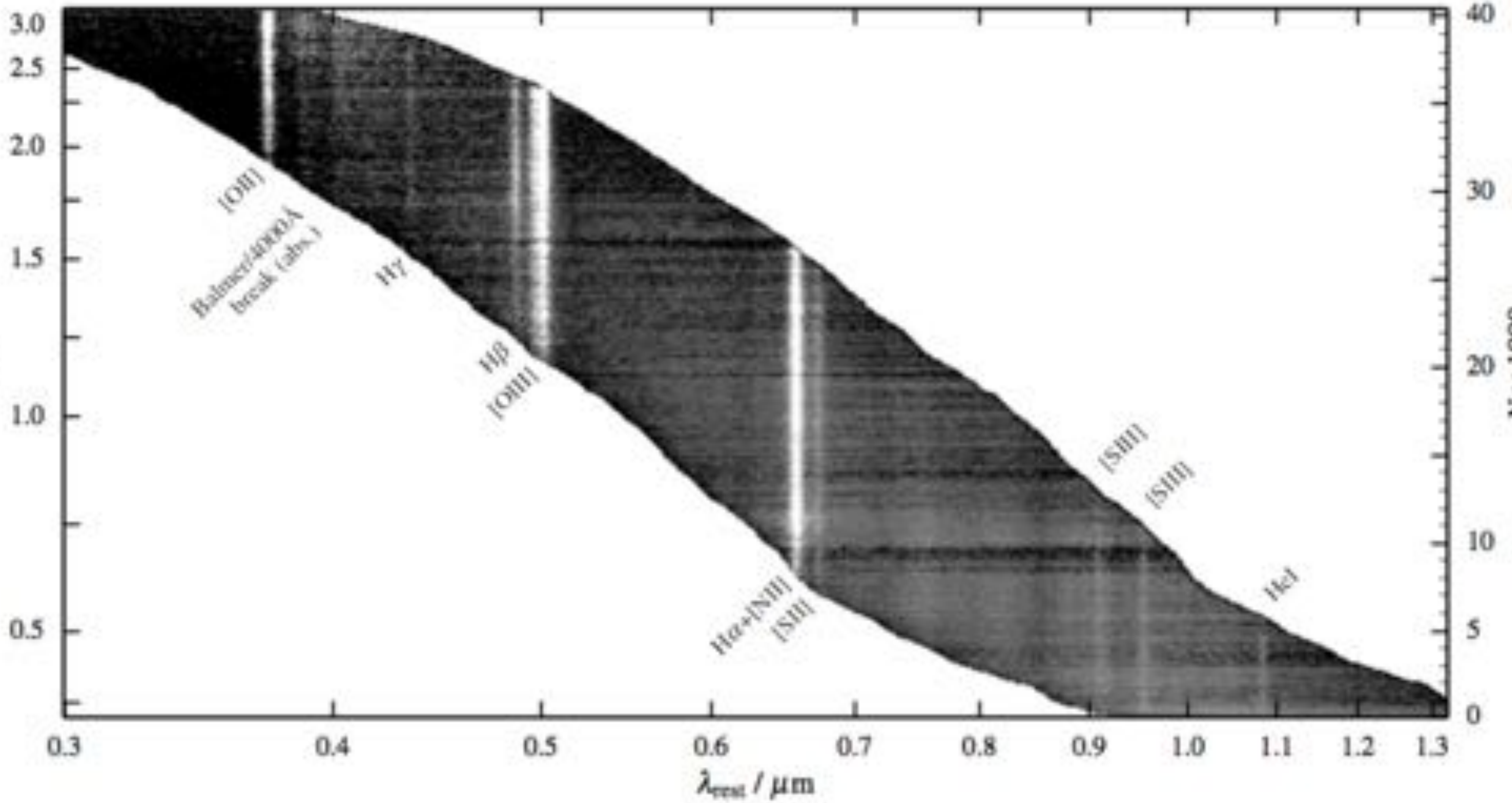
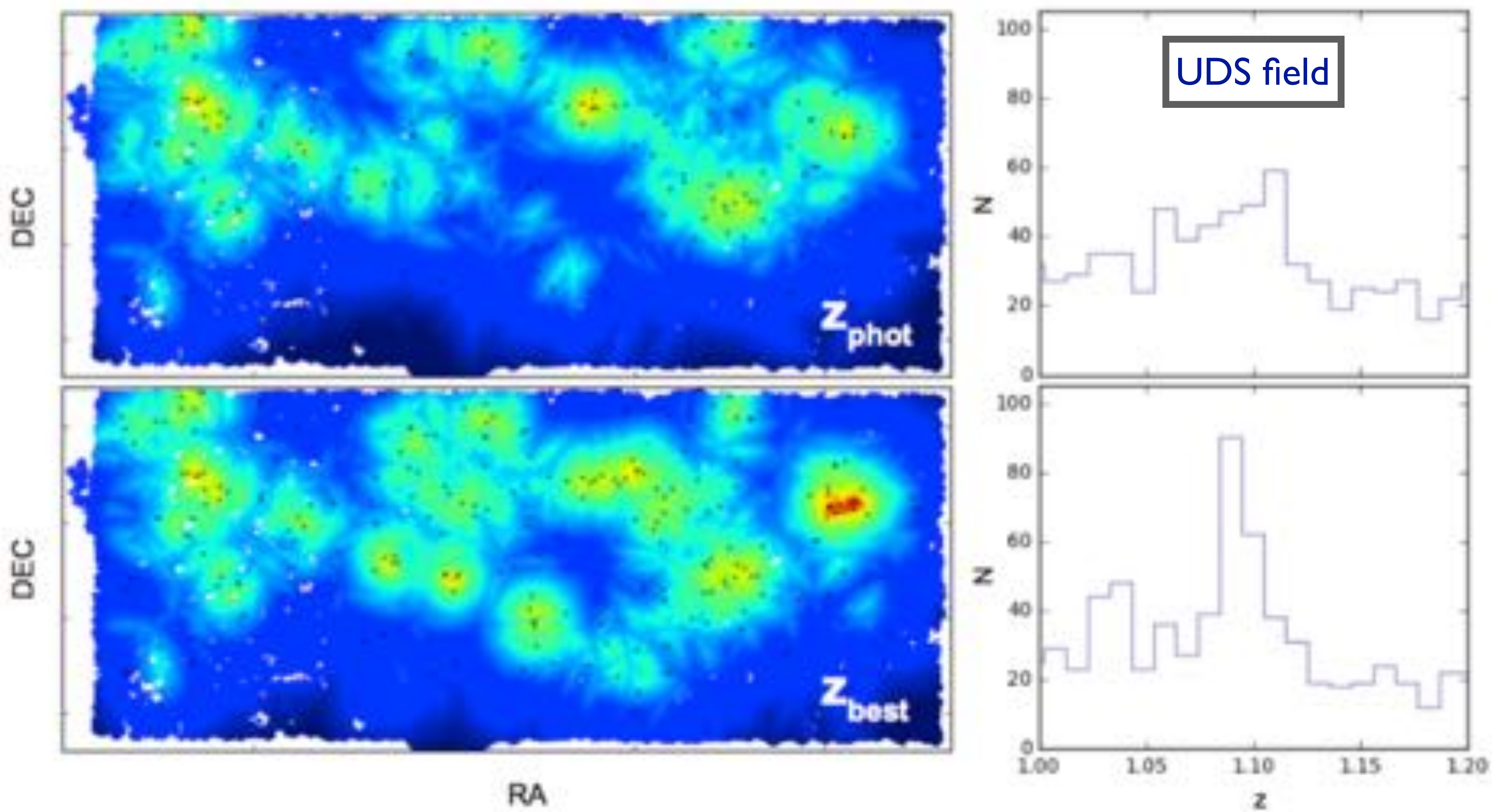


Figure 25. Overview of ~ 40,000 3D-HST G141 grism spectra with $H_{160} < 25$. Each pixel row shown is the median of 100 individual 1D spectra sorted by redshift and shifted to the rest frame; ticks on the right axis mark every 1000 galaxies, and tick labels on the left axis indicate the corresponding redshift. Each spectrum is normalized by the object's JH_{140} flux. Absorption and emission lines that move through the G141 passband at different redshifts are indicated.

3D-HST, Momcheva+15

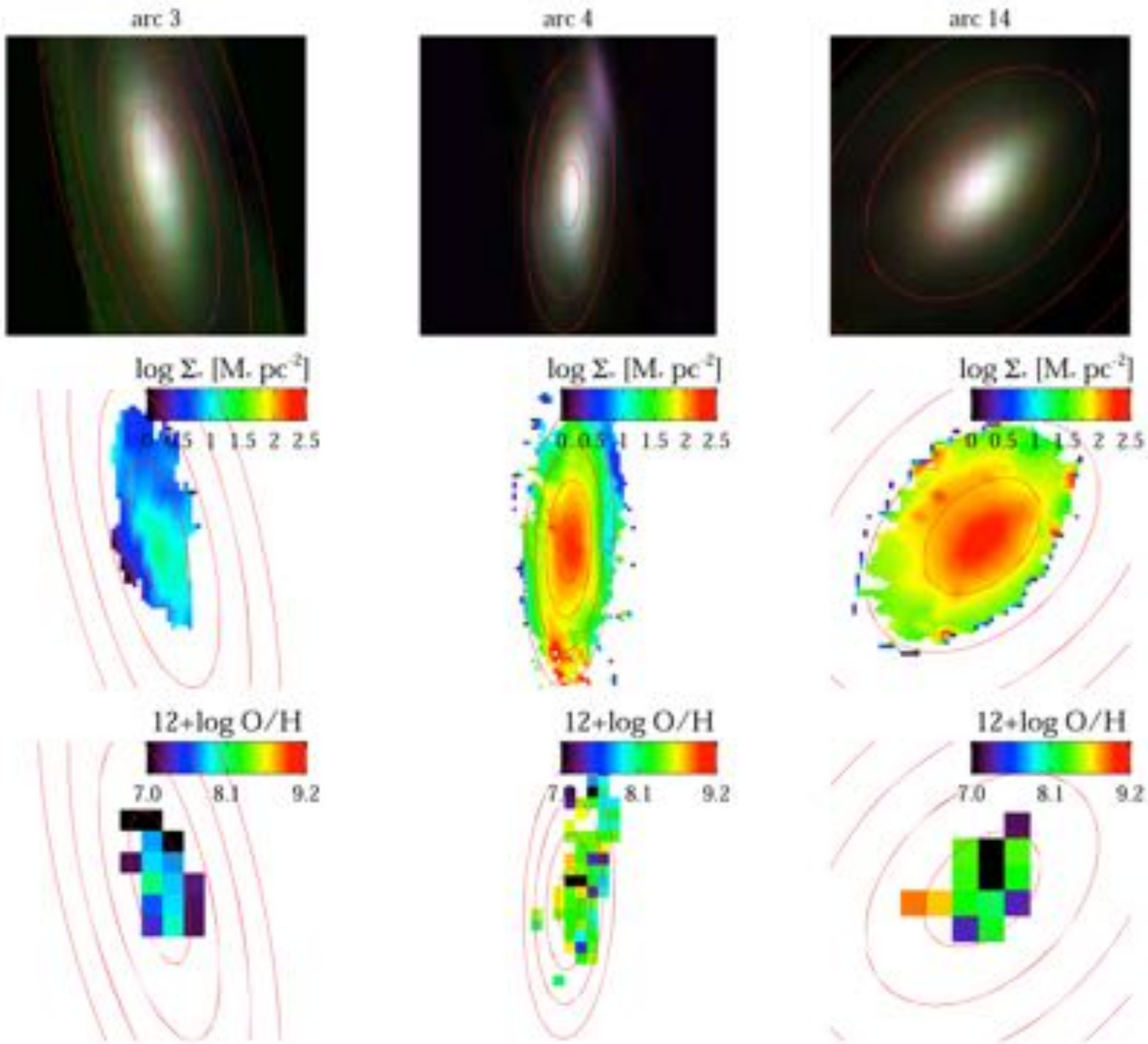
The WFSS Advantage

Grism redshifts accurate to ~0.003×(1+z) ➤ Environment



3D-HST, Momcheva+15

The WFSS Advantage



Use gravitational lensing to determine spatially-resolved metallicity distribution in low-mass dwarf galaxies

GLASS, Jones+15

Simulations

Simulations of WFSS in Frontier Field MACS0416 now complete

Aims of simulations:

- Verify choice of integration times (direct and grism) per filter
- Finalize choice of filters - F115W, F140M, F150W, F158M and F200W
- Identify complementary data essential or helpful
- Determine redshift accuracy, line and continuum break
- Determine contamination rates - is blank field better option?
- Sample quality of spectra
- Plan data analysis - prep in advance for GTO data
- Define science projects

Simulations

GR150R/GR150C simulations done in all filters

Details of simulations:

- Based on HFF F814W images and ACS/WFC3IR photometry
- Detected objects assigned likely redshifts and SEDs
- Emission lines included based on correlations with z, M_*
- No spatial variation of continuum/emission lines per object
- Extra z>6 objects added and extra faint objects to match F160W number counts.
- IntraCluster Light (ICL) added based on F814W image.
- Zodiacal background + (white) detector noise added.
- No dithering, bad pixels, non-Gaussian noise, cosmic rays, crosstalk, flat fielding, non-linearity, stray light, …

Simulations

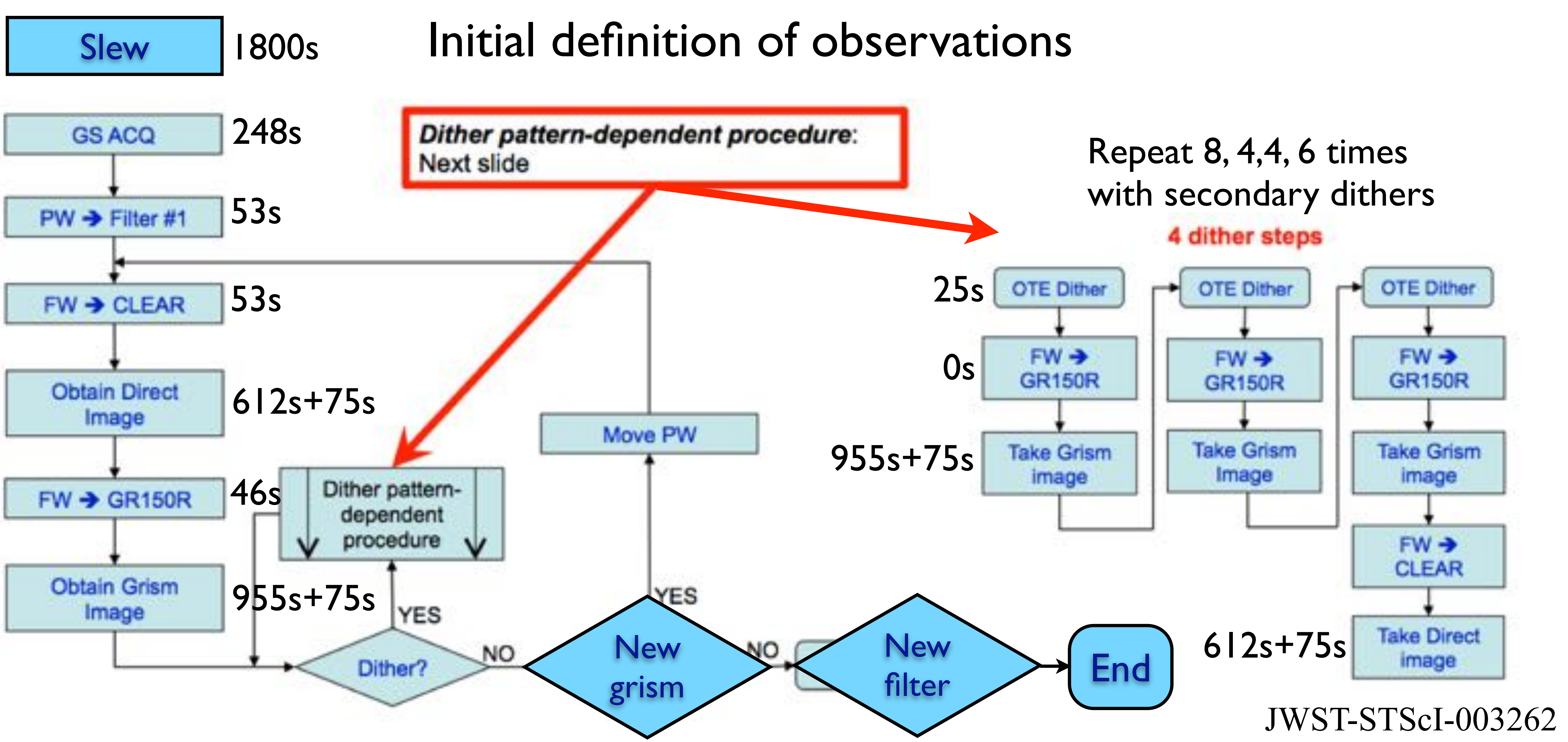
Initial definition of observations

Targets: best 3 clusters or blank fields based on latest HST data available in late 2016.
Total integration times per filter (4) per grism (2):

- F115W ~8 hrs (30,560s)
- F140M ~4 hrs (15,280s)
- F158M ~4 hrs (15,280s)
- F200W ~6 hrs (22,920s)
- Total 46 hrs grism integration per cluster
- Each filter total direct image for 2448 seconds (4% - 8% of grism exposure time).

Add overheads (direct and indirect) makes ~200 hrs total.

Simulations



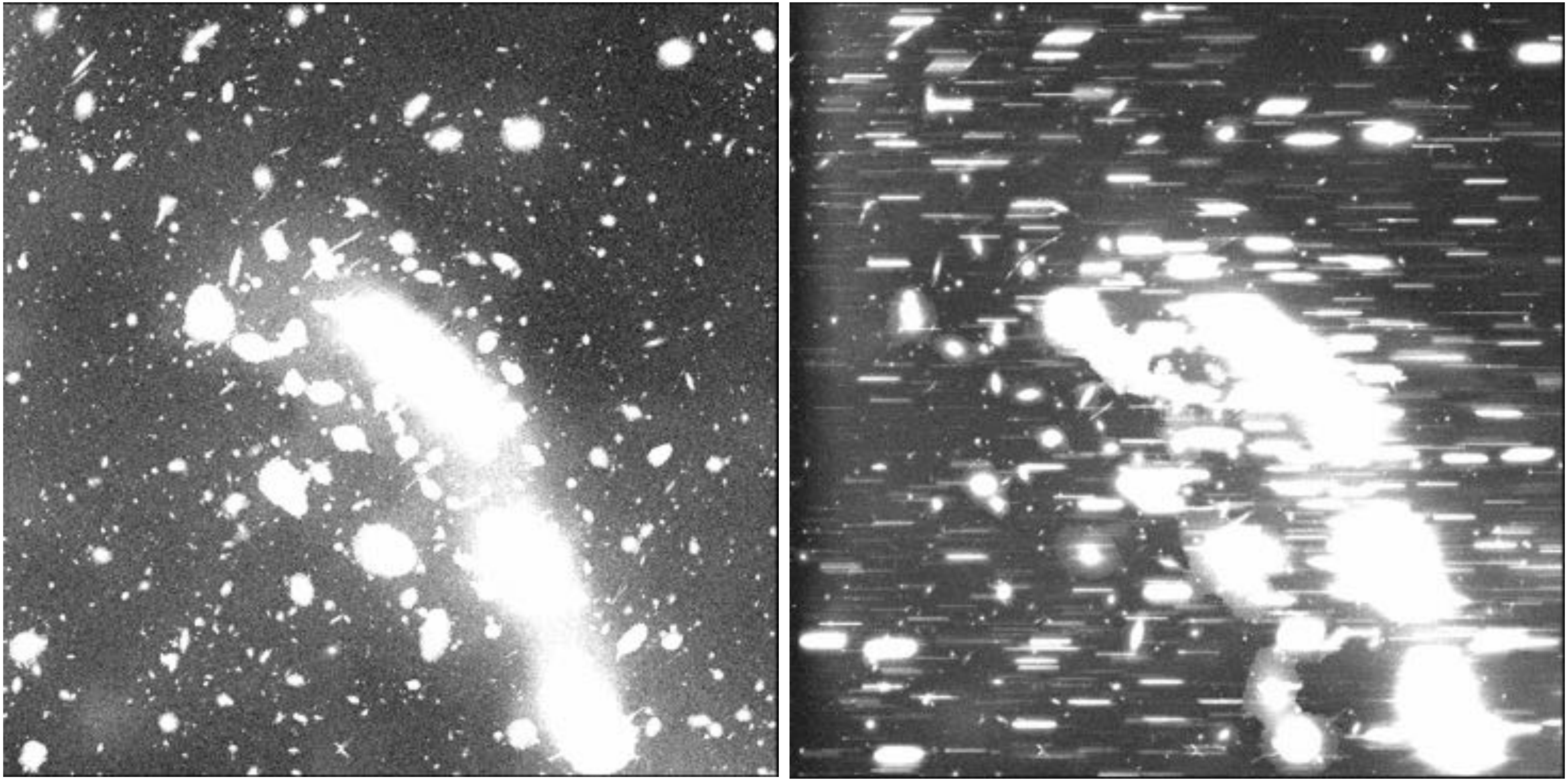
JWST-STScI-003262

Observe all **dithers**, then both **grisms**, then all **filters** (better because direct images to be combined observed in same sequence - accuracy of sub-pixel dithers).
Alternative is all **dithers**, then all **filters**, then both **grisms**.

Simulations

We are using the threedhst and aXe software to simulate NIRISS observations

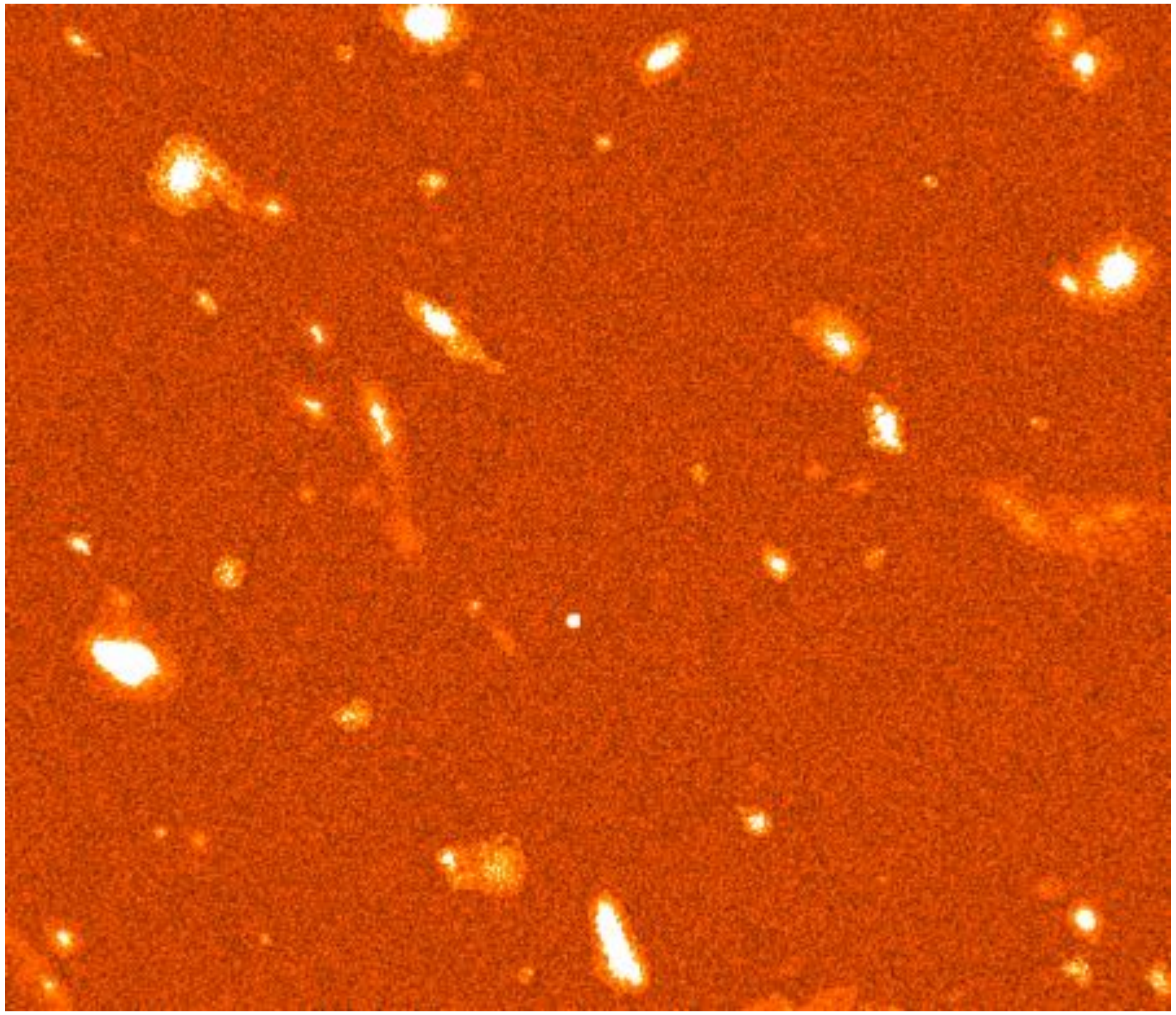
F200W + CLEAR → F200W + GR150R

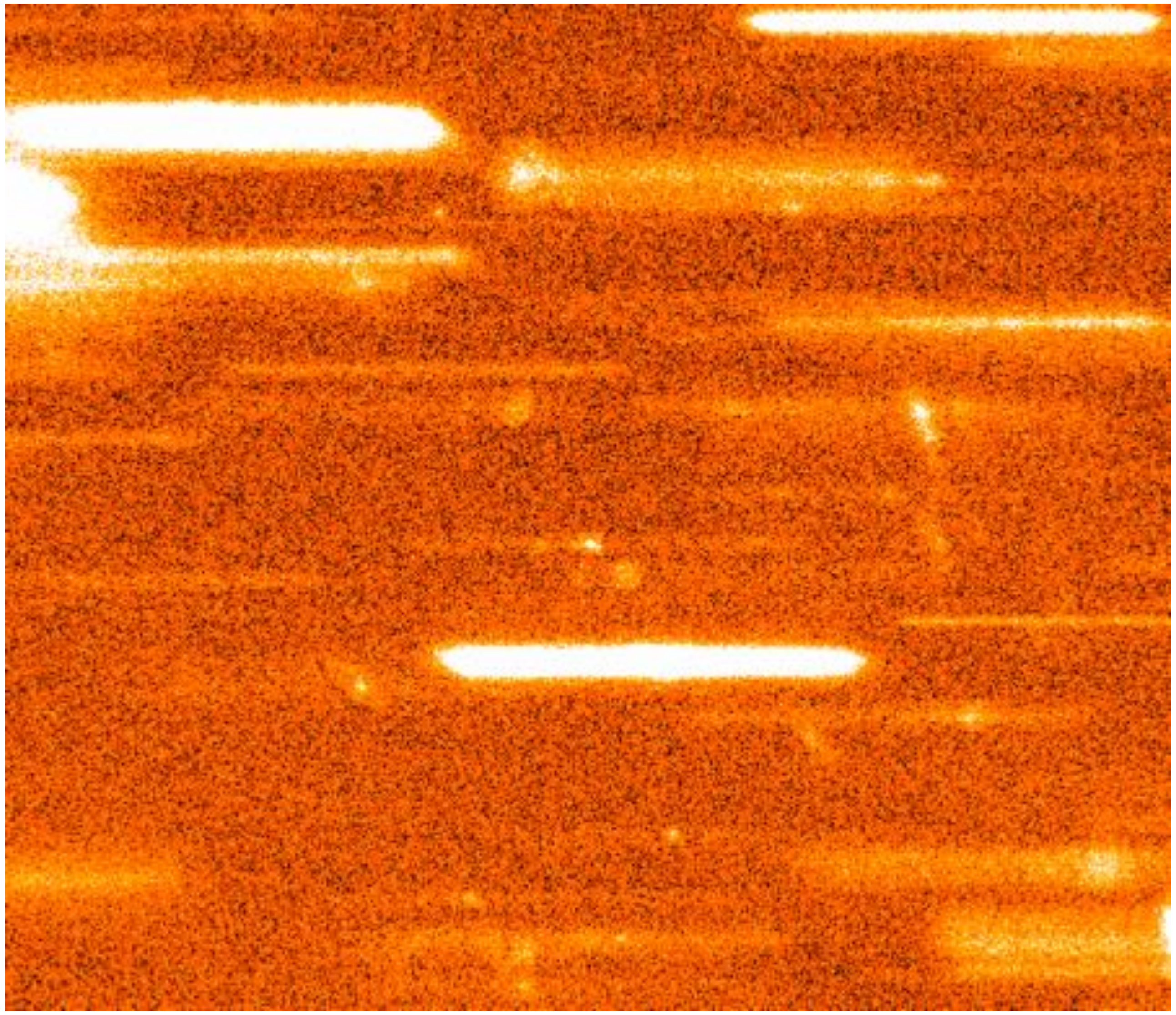


Simulations

Zoom-in to 1% of the field shows many faint galaxies with emission lines

F150W + CLEAR → F150W + GR150C

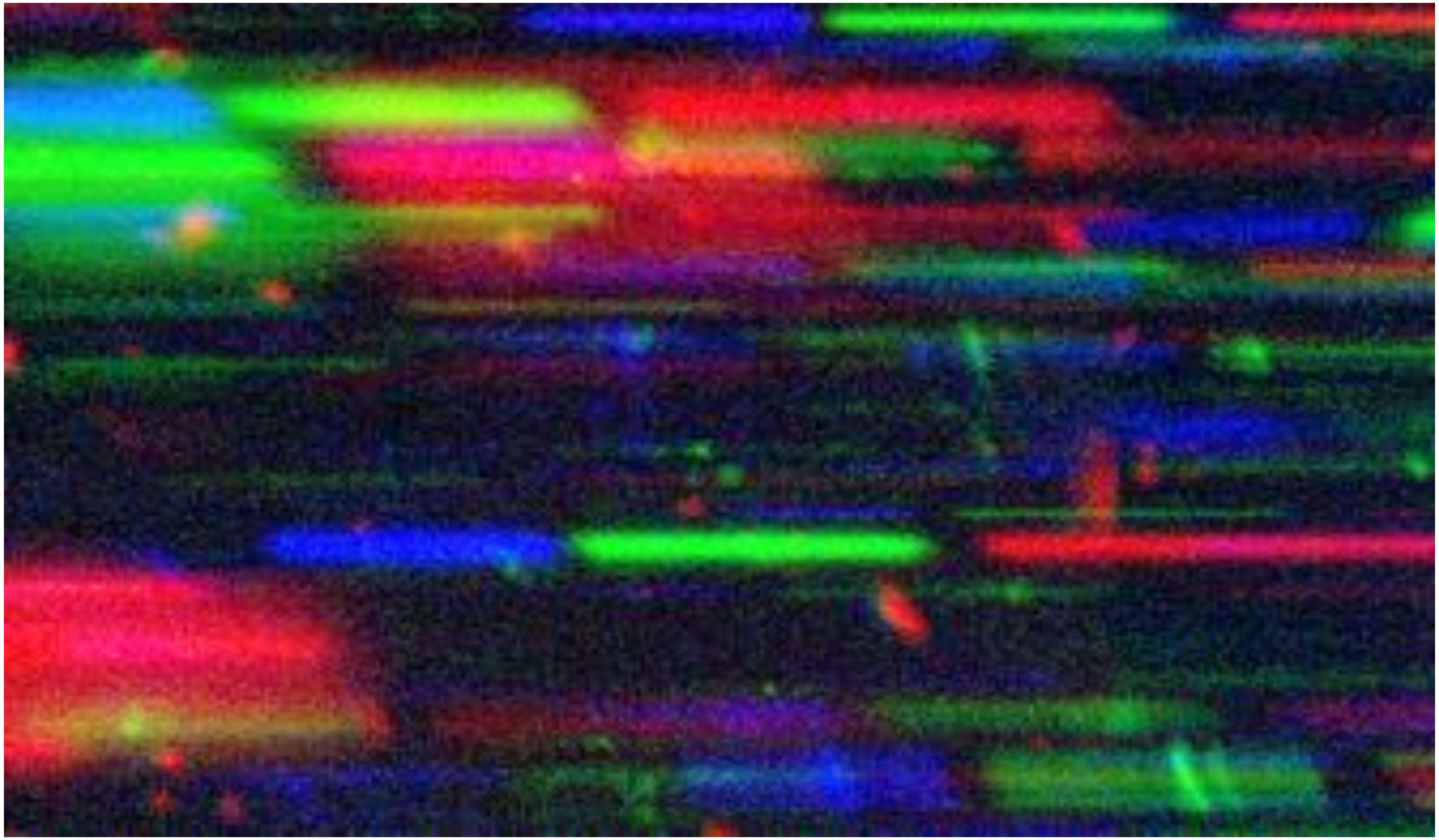




Simulations

Zoom-in to 1% of the field shows many faint galaxies with emission lines

F115W, F150W, F200W + GR150C



z=1.594
z=2.976
z=1.673
z=1.745
z=1.778
z=8.132
z=1.295
z=2.162
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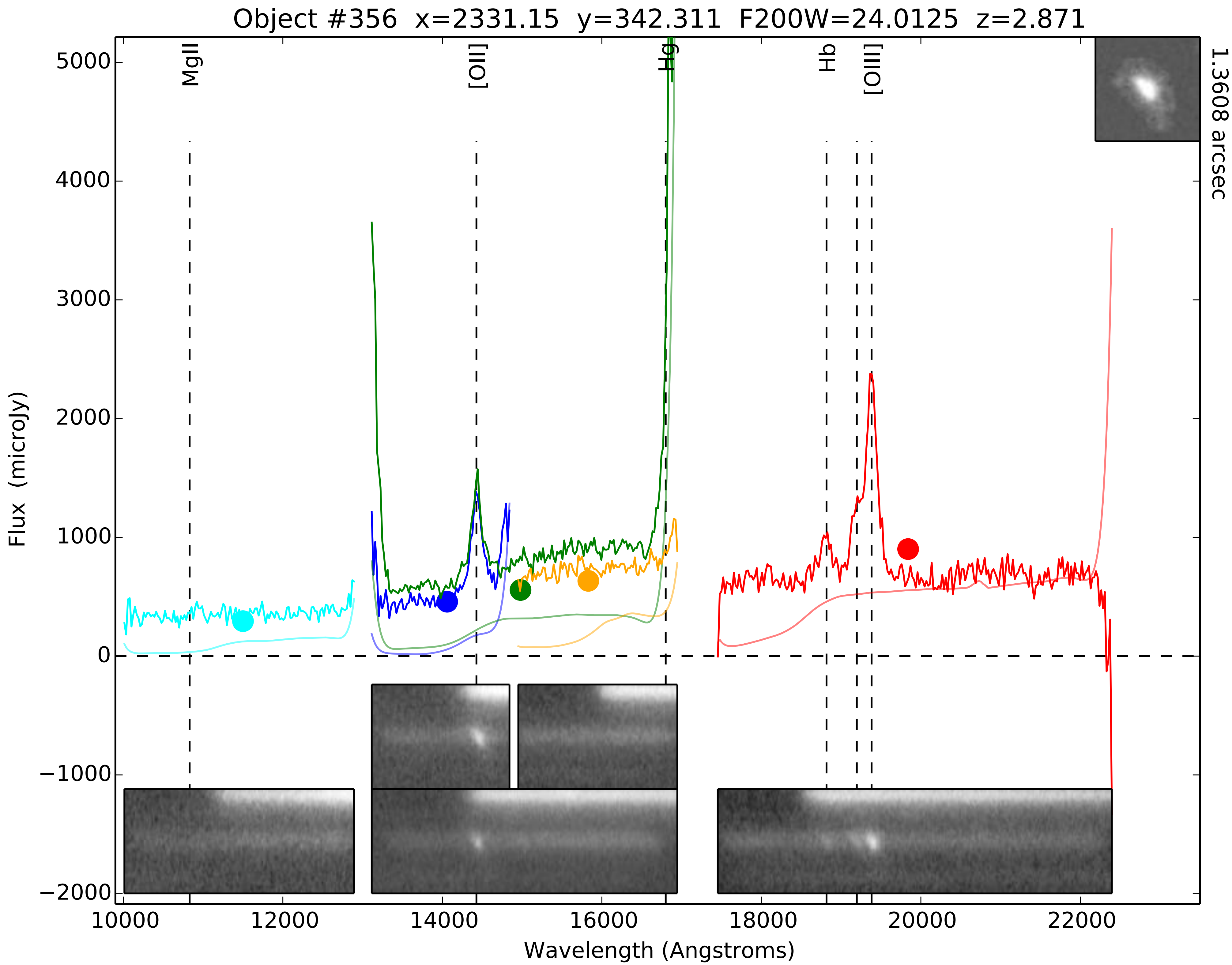
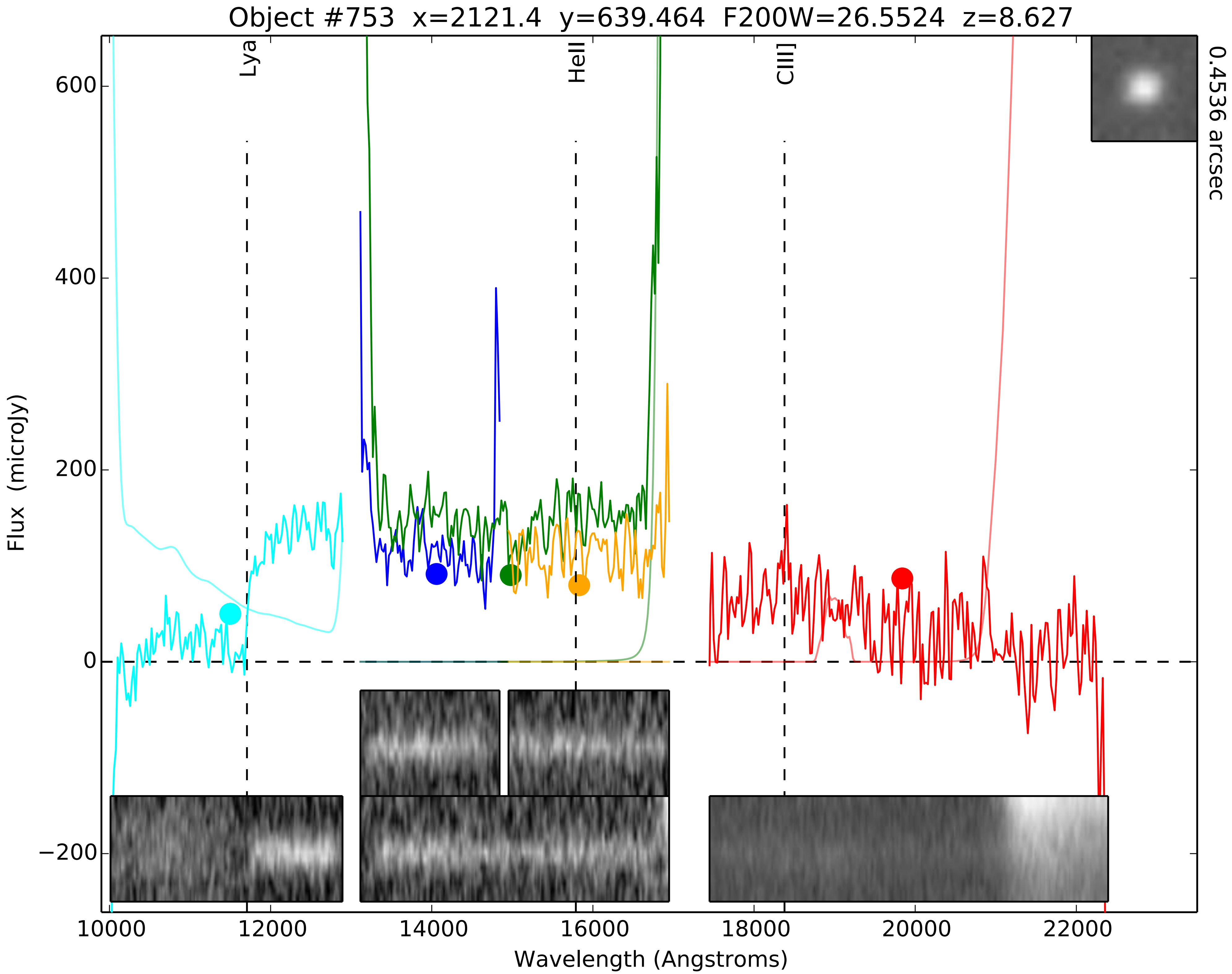
z=1.331

Simulations



Simulations



Major Unresolved Questions for GTO

1. Decide on top science priorities - where will we have greatest impact?
2. Flow down from science to survey plan
    - depth vs area
    - filters
    - fields.
3. Consider collaboration with other GTOs, more HST data required?
4. Effective use of parallels (or not).
5. How well can we subtract contamination?
6. Publication (data+papers) timeline and policy.

Major Unresolved Questions for GTO

Depth vs Area

Baseline GTO plan is 3 fields with depth of 46 hrs grism integration per cluster

What is the widest area we could cover with our observing sequence?

Total integration times per filter (3, F150W instead of F140M&F158M) per grism (2):

- F115W ~1.06 hrs (3,820s)
- F150W ~1.06 hrs (3,820s)
- F200W ~1.06 hrs (3,820s)

- Total 6.6 hrs grism integration per cluster (1 mag brighter than baseline and simulations).

- Each filter total direct image for 1500 seconds (20% of grism exposure time). Imaging sensitivity, 10 sigma: F115W 28.2, F150W 28.5, F200W 28.7.

- Direct overheads per field are 4900s.

- Total time per field is 9hrs, so after indirect overheads of 16% could observe 19 fields (80 sq arcmin) in ~200 hrs. c.f. one full GOODS field is 160 sq arcmin and CANDELS-Deep is 120 sq arcmin (60 in each GOODS field).

Major Unresolved Questions for GTO

Depth vs Area

Deep

- Lower luminosity/mass of galaxies
- Further from HST depth, more unique
- More detailed data at given depth
- Good for steep luminosity function, $\alpha<-2$
- Higher median redshift
- Better for eliminating detector cosmetics
- Slightly more efficient

Wide

- Rarer, high luminosity/mass galaxies
- Good for flat luminosity function, $\alpha>-2$
- Higher yield of objects (most have $\alpha>-2$)
- More chance for parallel data overlap
- Contiguous survey gives edge contam model
- Lower spectral contamination

Could do some Deep and Wide (mini Wedding cake).

Blank vs Clusters

Blank

- Good for flat luminosity function, $\alpha > -2$
- Less contamination from bright galaxies
- Less ICL (varying background)
- Better observability and lower zodi/background
- Better, more homogeneous, multi-wavelength data (X-ray, radio)
- Collaboration with other GTOs

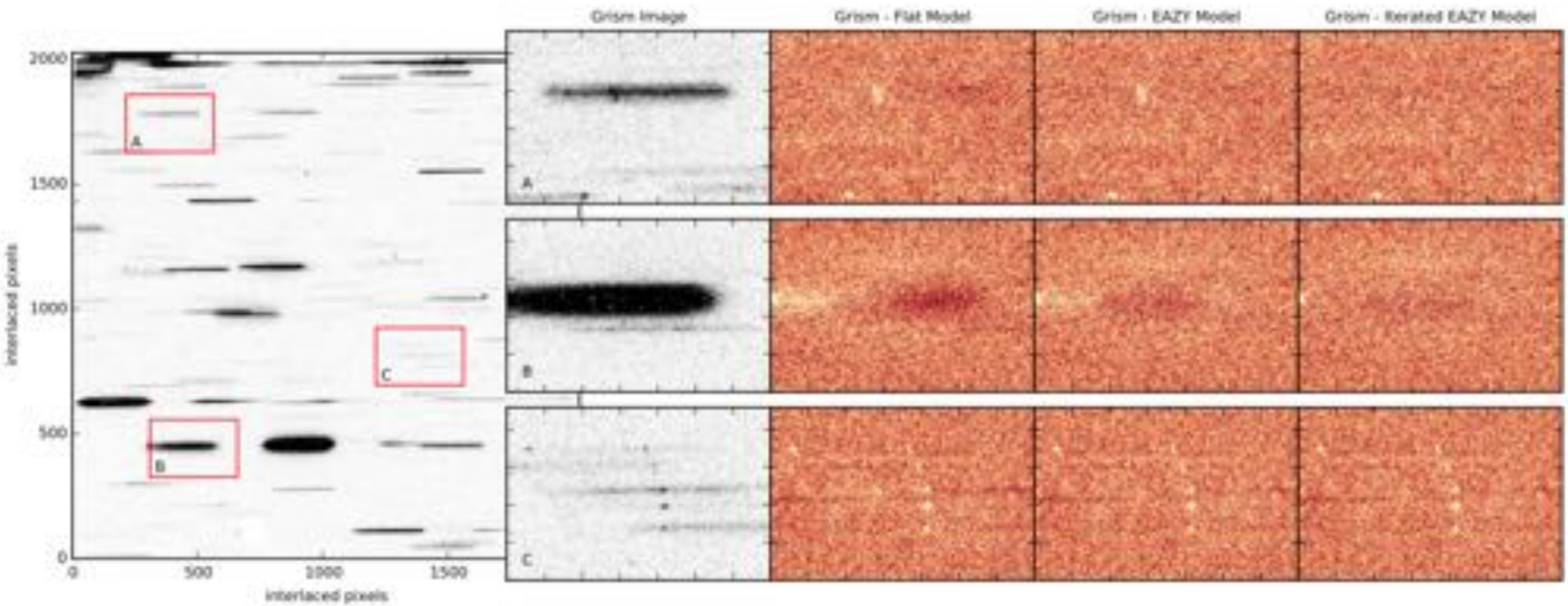
Clusters

- Good for steep luminosity function, $\alpha < -2$
- Gravitational lensing science - cosmology
- Lensing assist to lower mass, maybe higher z
- Lensing assist of spatial resolution

Major Unresolved Questions for GTO

Contamination

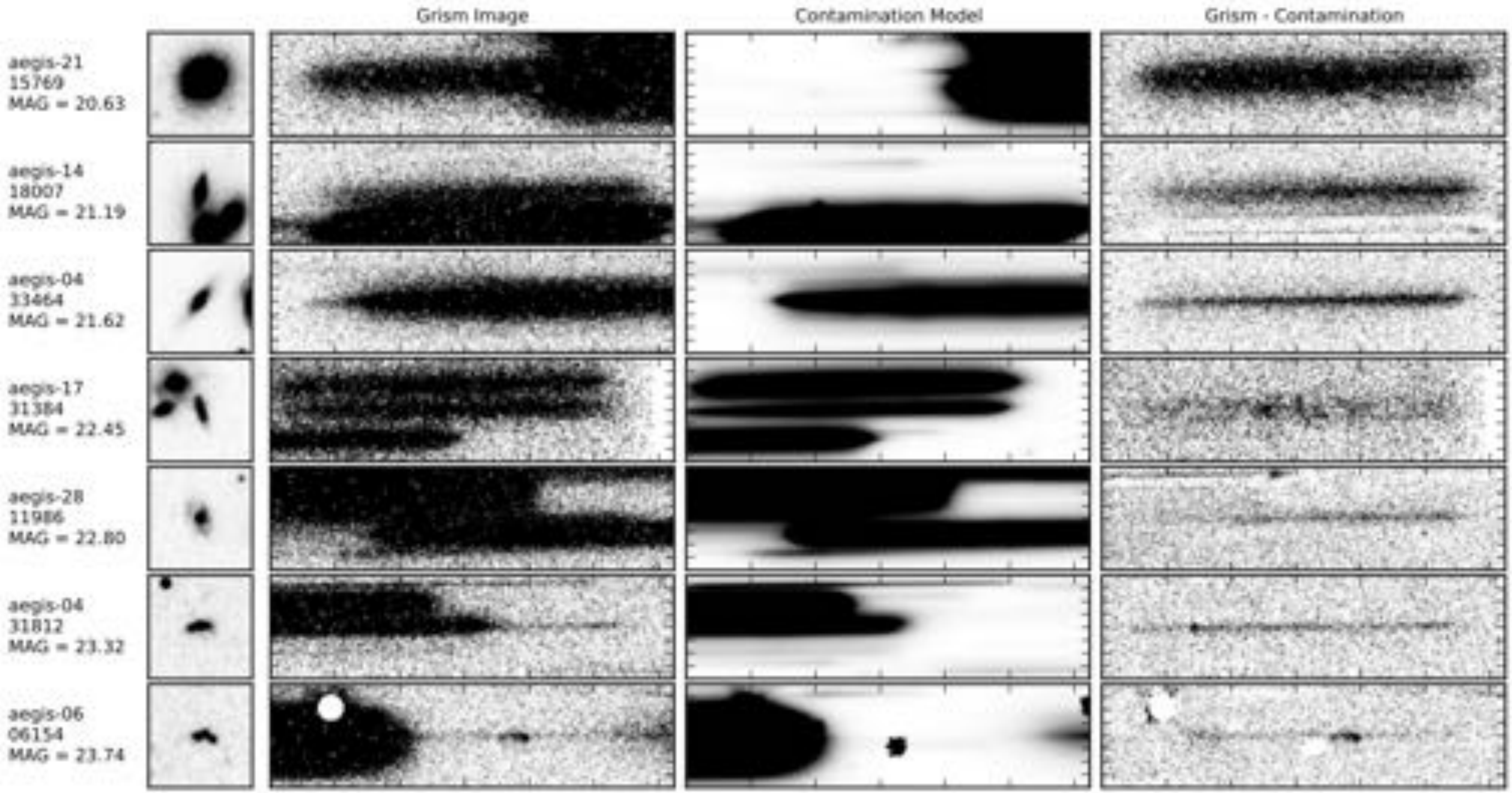
Need to build 2D model of target and contaminating objects and fit to data.
Multiple iterations to fit more complex spectra where appropriate.



3D-HST, Momcheva+15

Major Unresolved Questions for GTO

Contamination subtraction can be very effective if done properly.



3D-HST, Momcheva+15

Major Unresolved Questions for GTO

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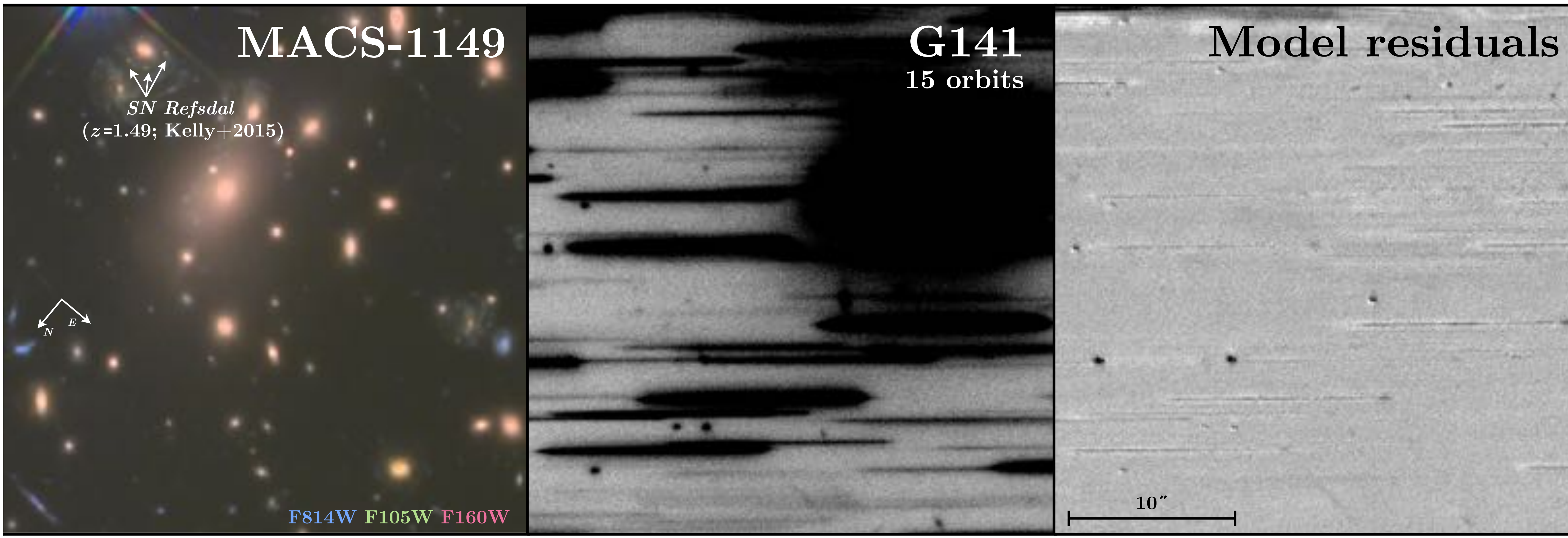
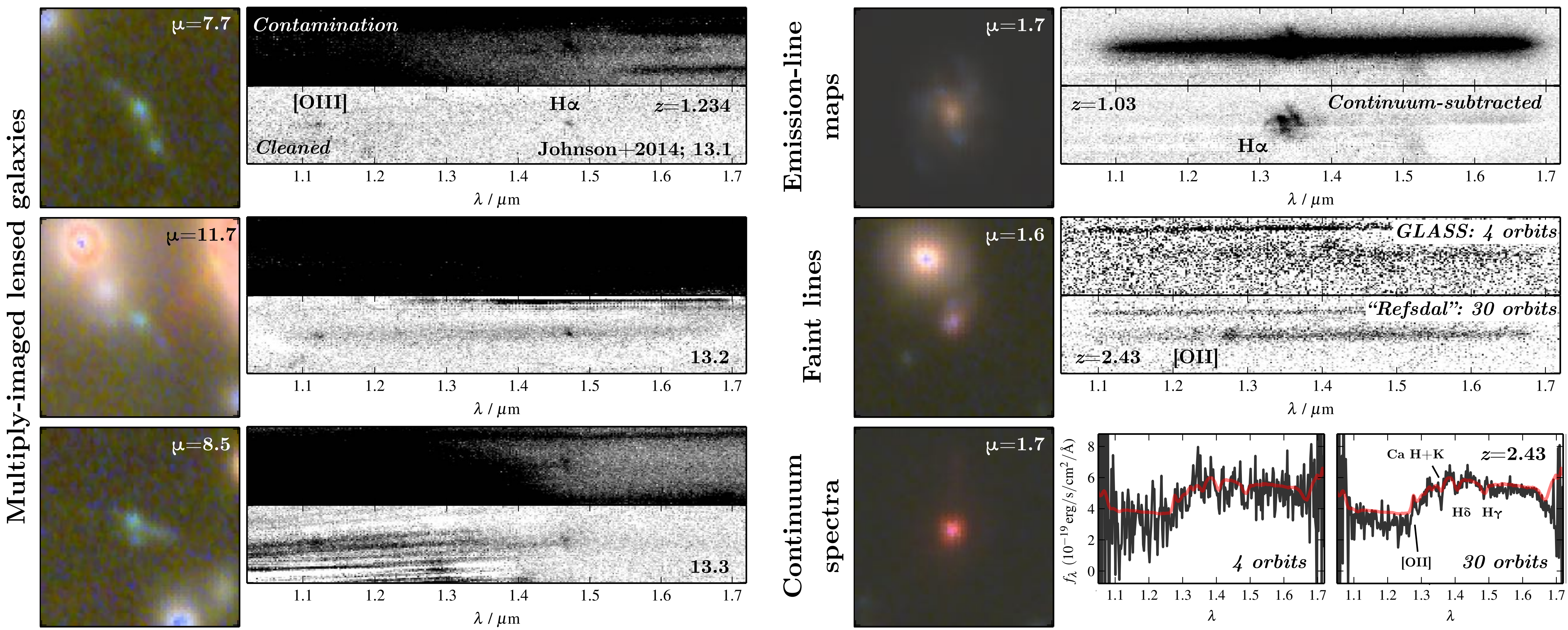


GLASS (Deep), Brammer

Major Unresolved Questions for GTO

Contamination subtraction can be very effective if done properly.



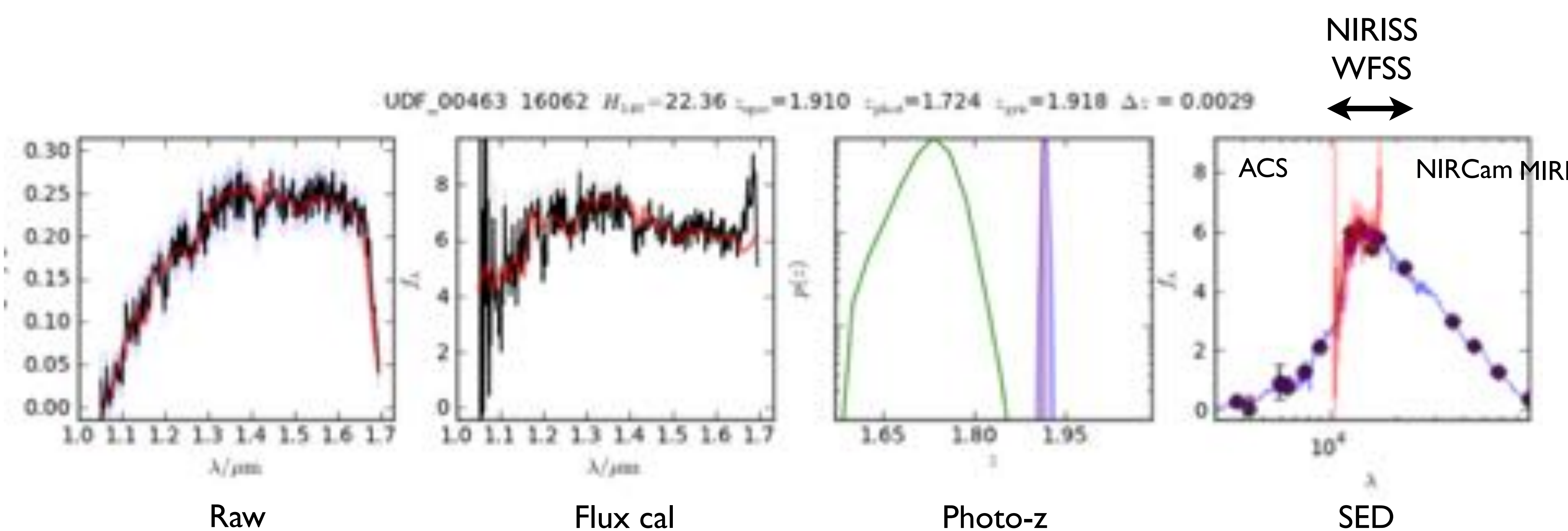
GLASS (Deep), Brammer

Major Unresolved Questions for GTO

Data Analysis

Need to incorporate other information into analysis, e.g. HST, Spitzer, NIRCam photometry.

Extended wavelength range with NIRISS (c.f. WFC3IR) means more likely to find two emission lines, but gaps remain and some galaxies have weak or absent lines.



3D-HST, Brammer+12

Major Unresolved Questions for GTO

Urgent issues (finalise by Apr 2017):

1. Decide on top science priorities - where will we have greatest impact?
2. Flow down from science to survey plan
   - depth
   - filters
   - fields.
3. Consider collaboration with other GTOs, more HST data required?
4. Effective use of parallels (or not).
5. Publication (data+papers) timeline and policy.

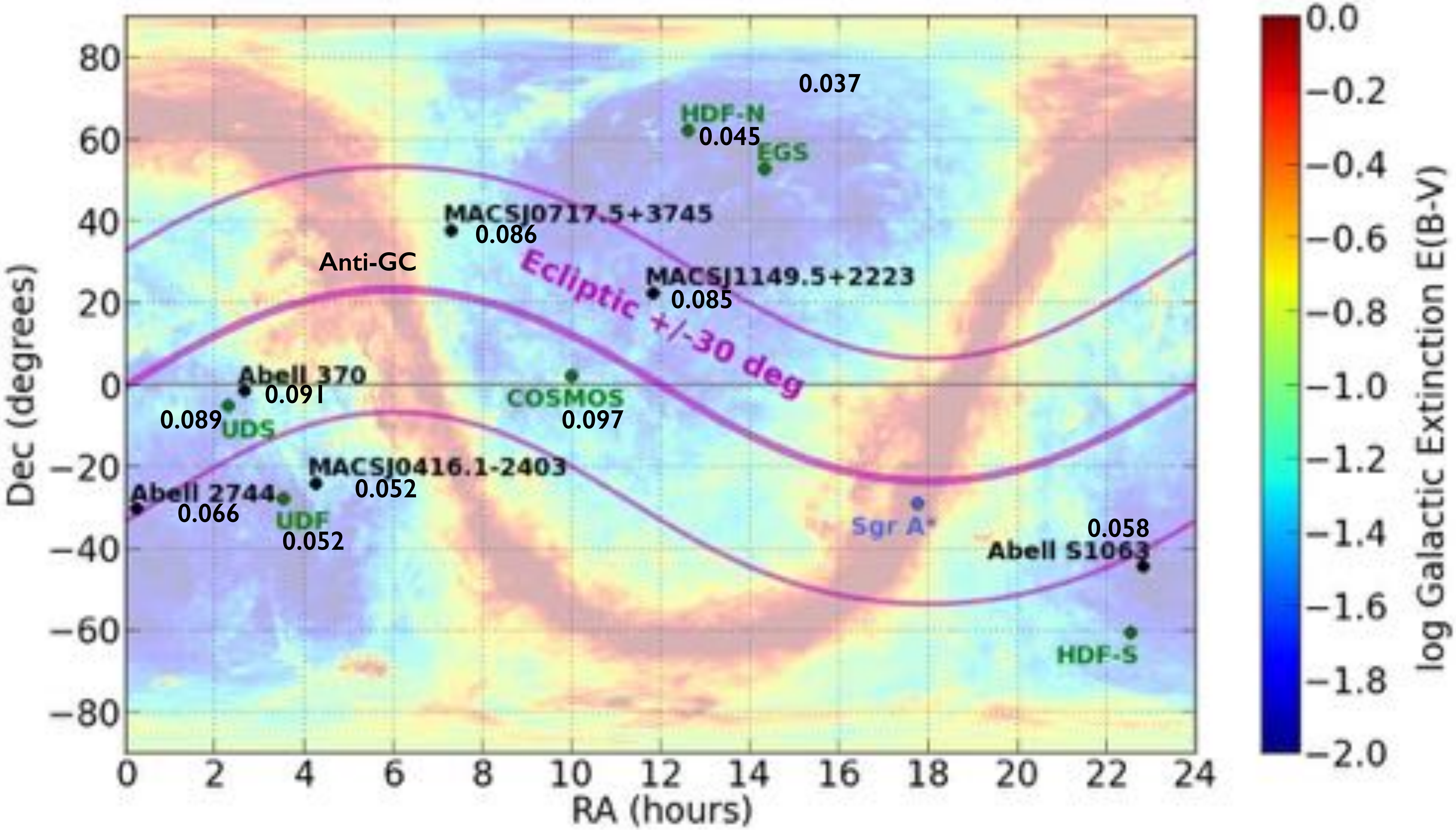
Other issues:

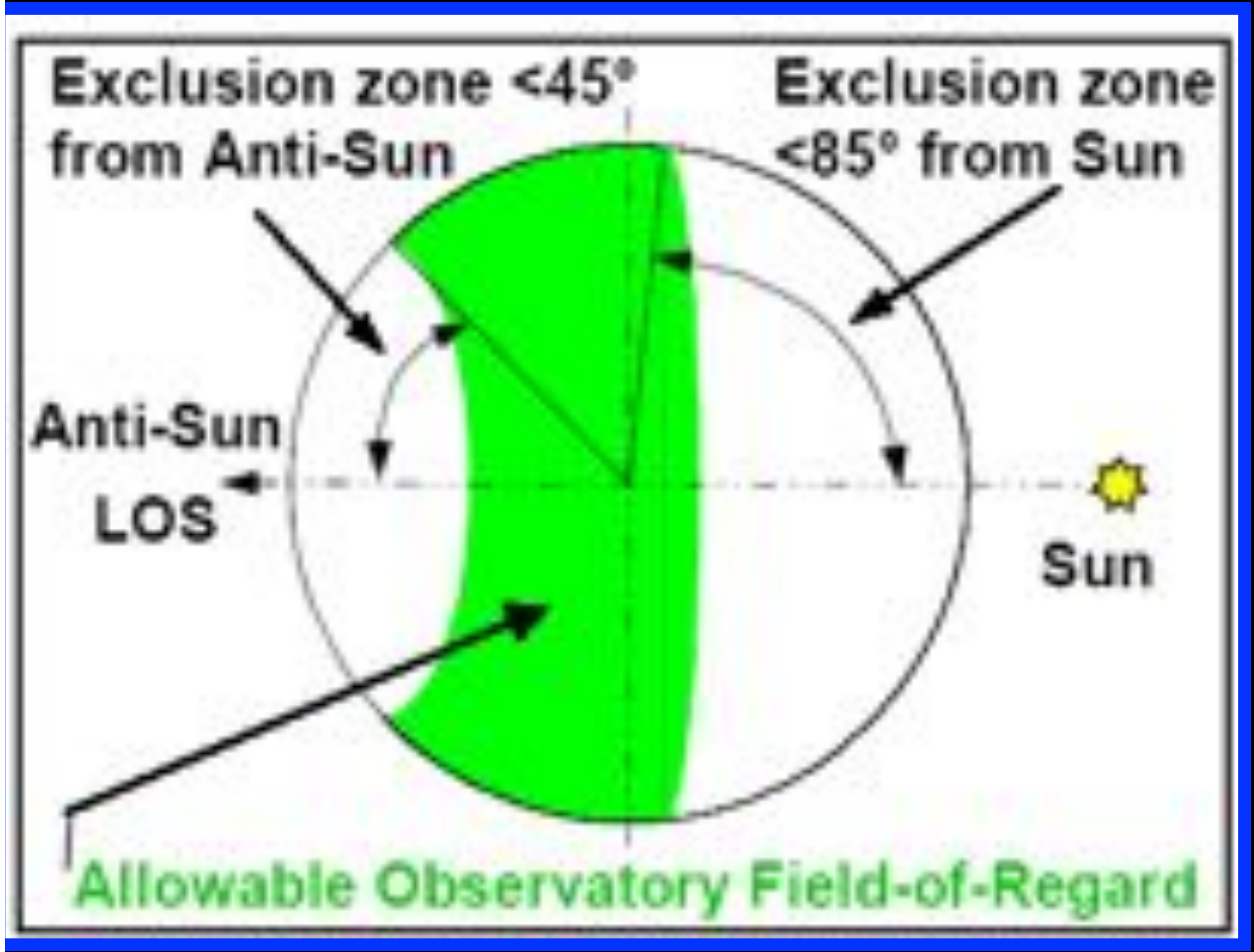
1. Begin to think about tools required to be put in place between now and 2019
2. Begin to think about human resources required for now and the future

Backup slides

Fields, Observability and Backgrounds

Minimum zodiacal background (at 3.6 microns in MJy/sr). Scattered light worst towards GC and anti-GC.





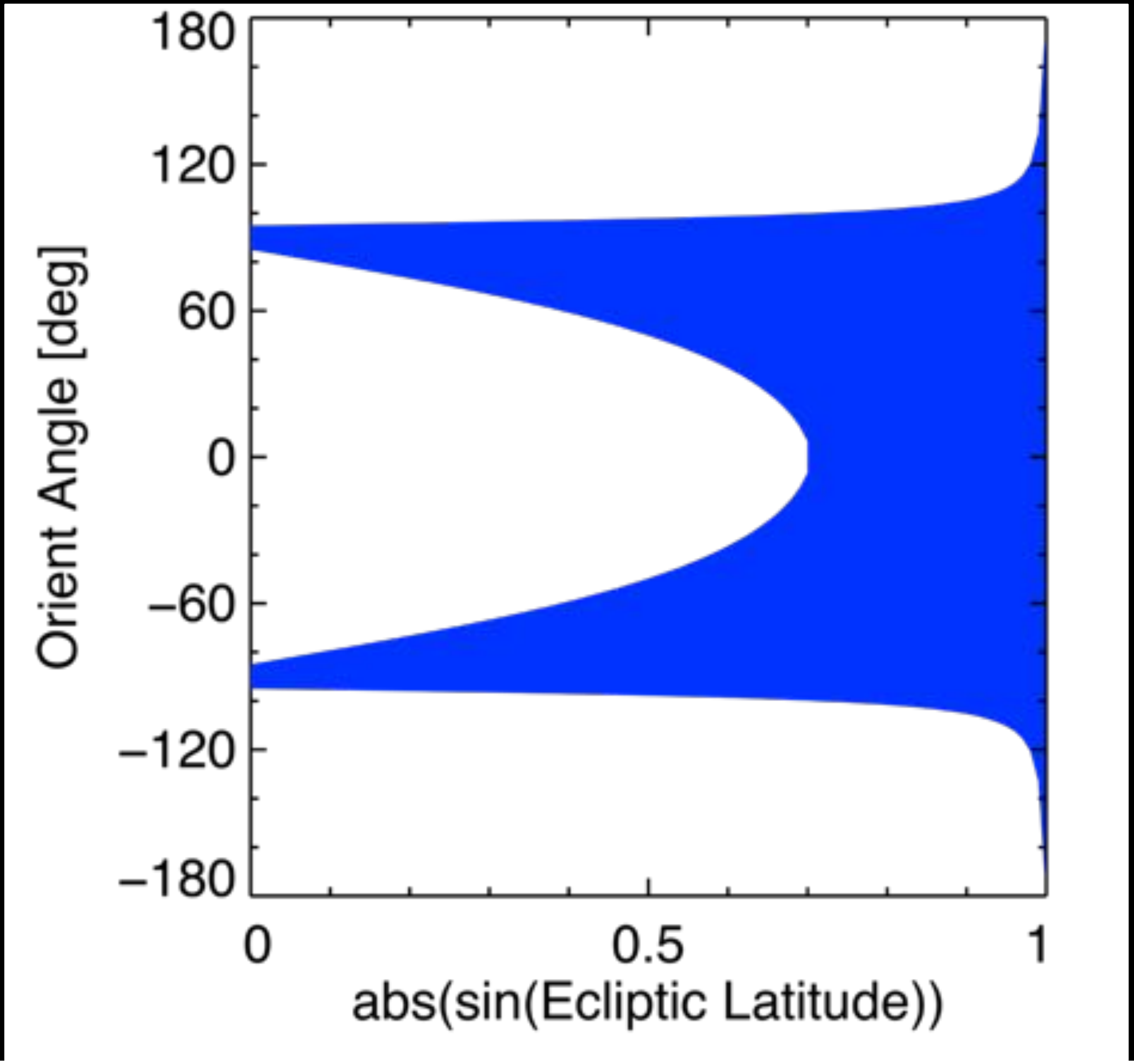
Observing with JWST – Spacecraft Pointing

JWST's Field Of Regard is 45 degrees wide, it can't point anti-sunward!

Observing with JWST – Sky Viewing Coverage

JWST has 100% coverage of the sky for at least 51 days, but only a very small region (the CVZ) is viewable all the time

Observing with JWST – Spacecraft Pointing

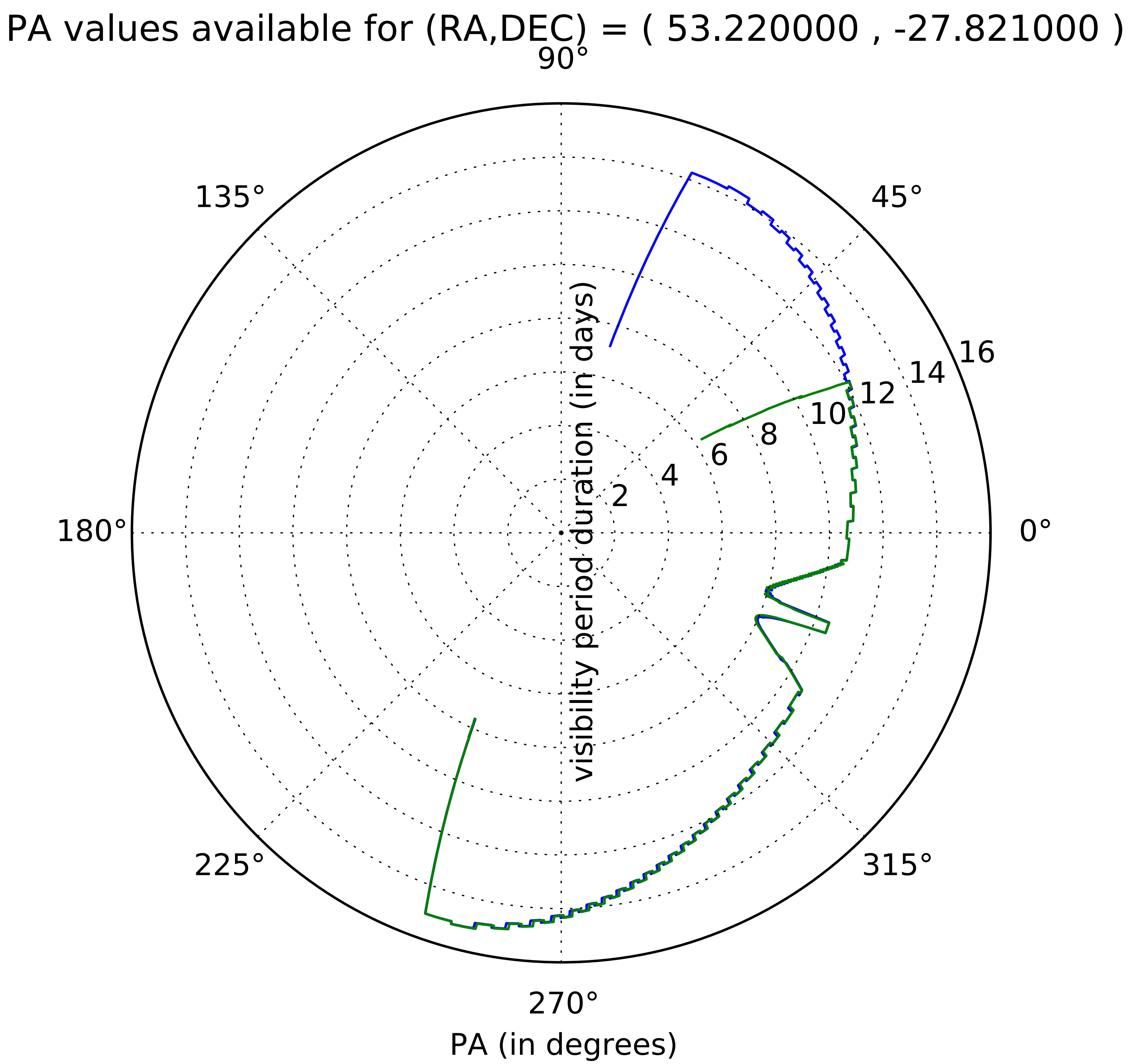


- & As a result, MANY pointings with JWST will have restricted Orient availability

- The Two extremes:
- At the ecliptic poles (0.4% of the sky), ALL orients are available, but a specific orient is schedulable for only ~10 days.
- In the ecliptic plane, only specific orient ranges are possible, those are available for ~50 day windows.

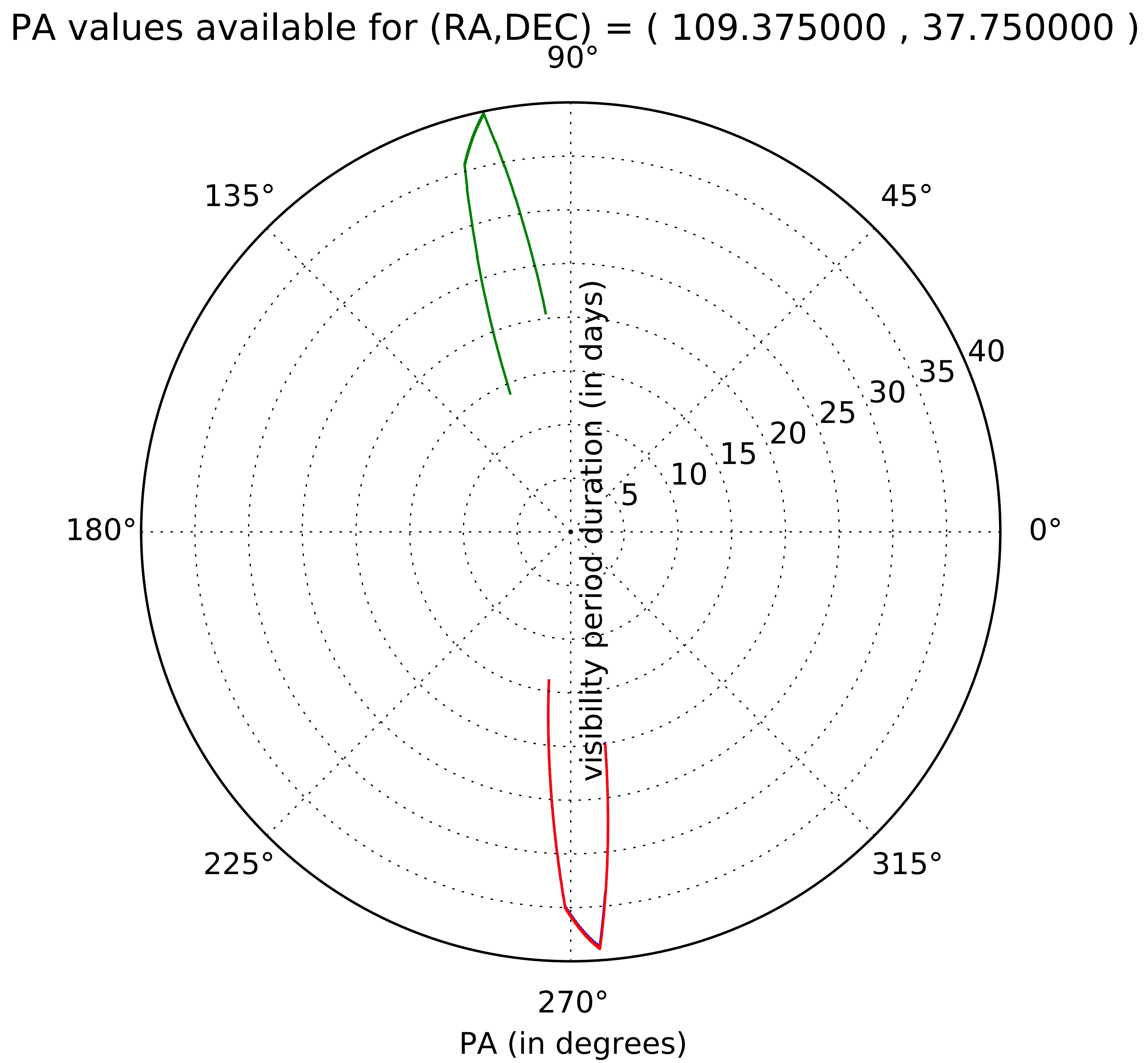
Fields, Observability and Backgrounds

GOODS-S



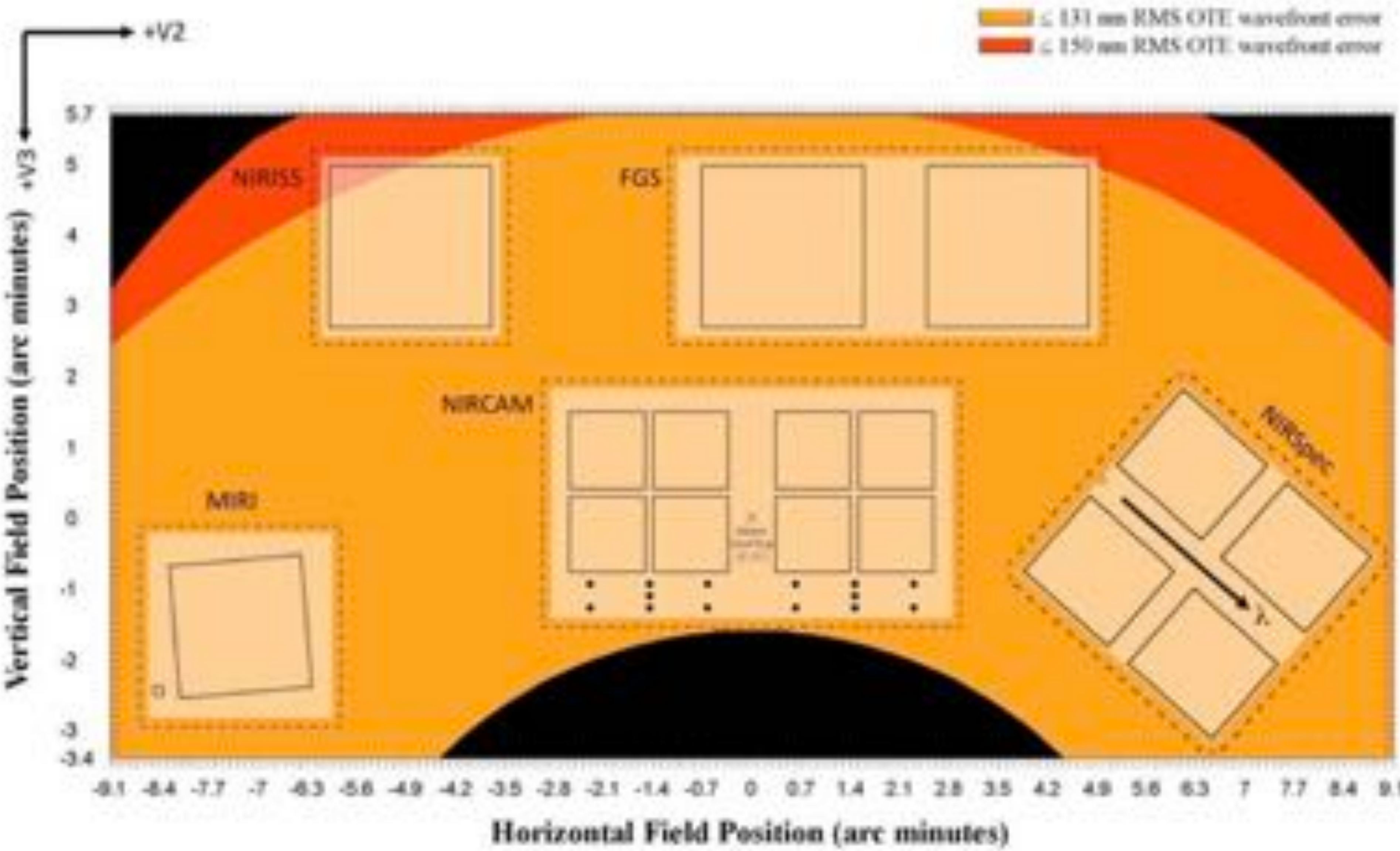
Fields, Observability and Backgrounds

MACSJ0717.5+3745



Parallels

Observing with JWST – JWST Instruments in the Focal Plane

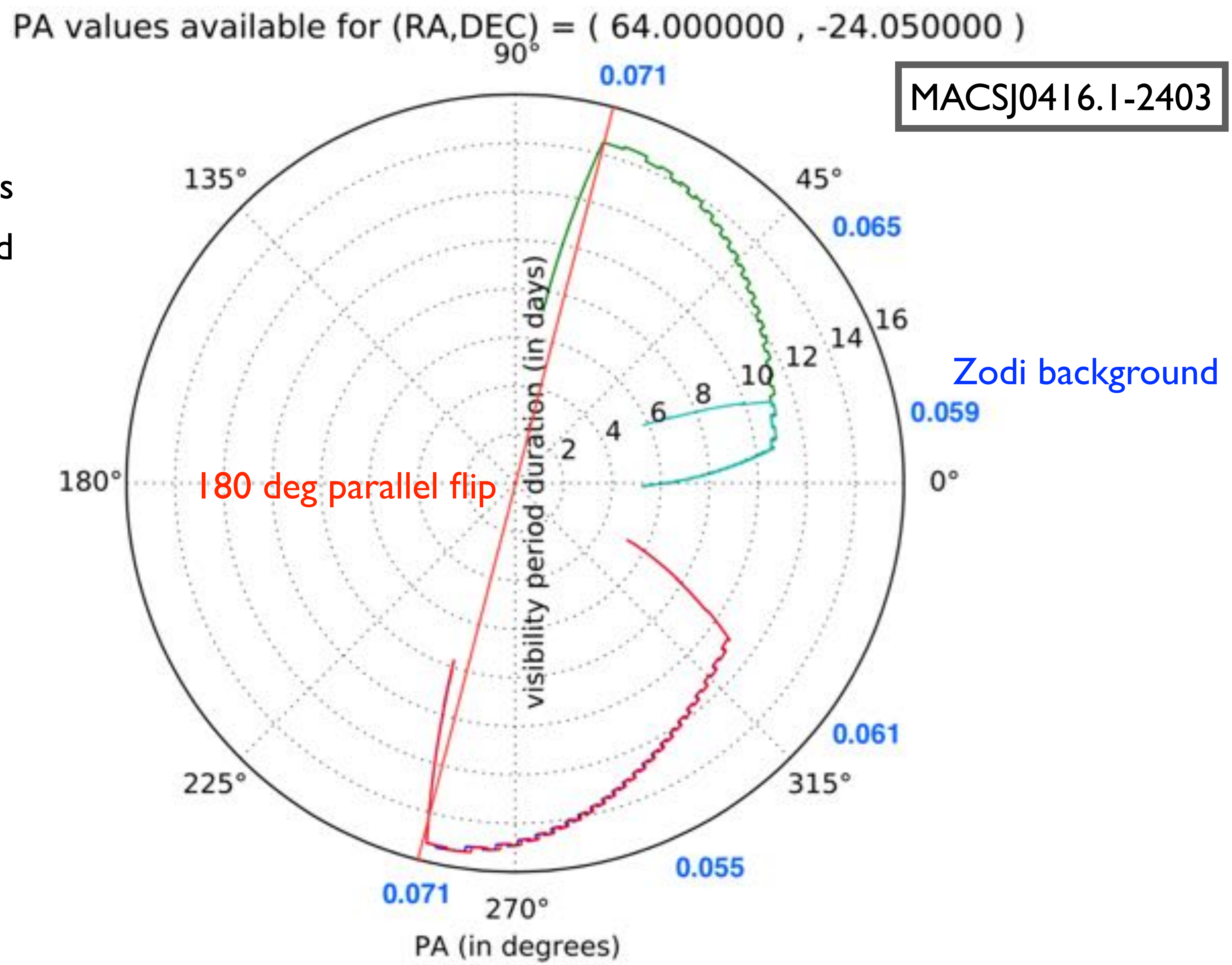


Parallels

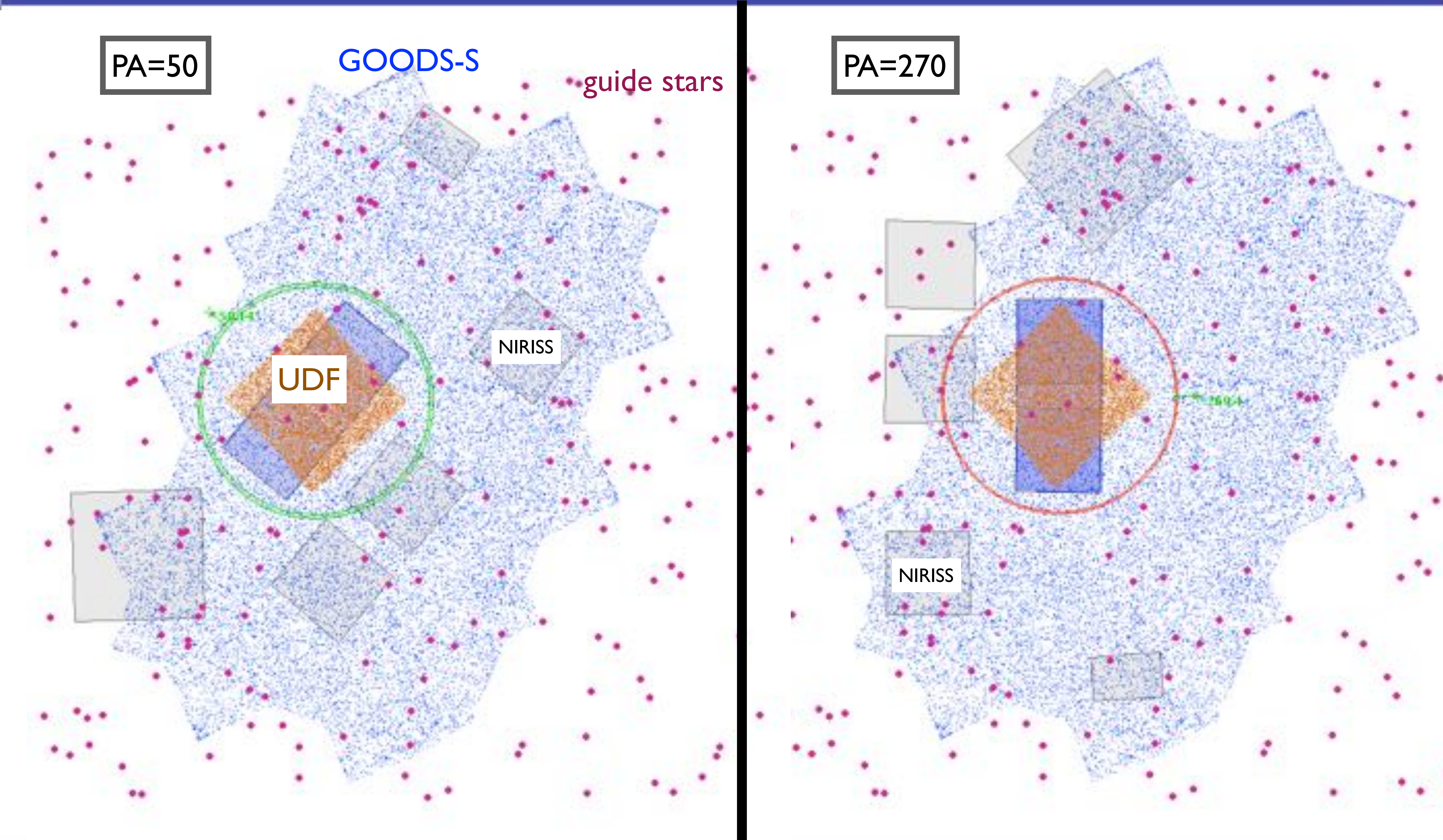
180 degree flip parallels hard to schedule and have higher background

Fields at low ecliptic latitude have much higher worst/best zodi background ratios.

Observing at edges of observability period gives 40-100% higher zodi



Parallels



Tools

GLASS Inspection GUI

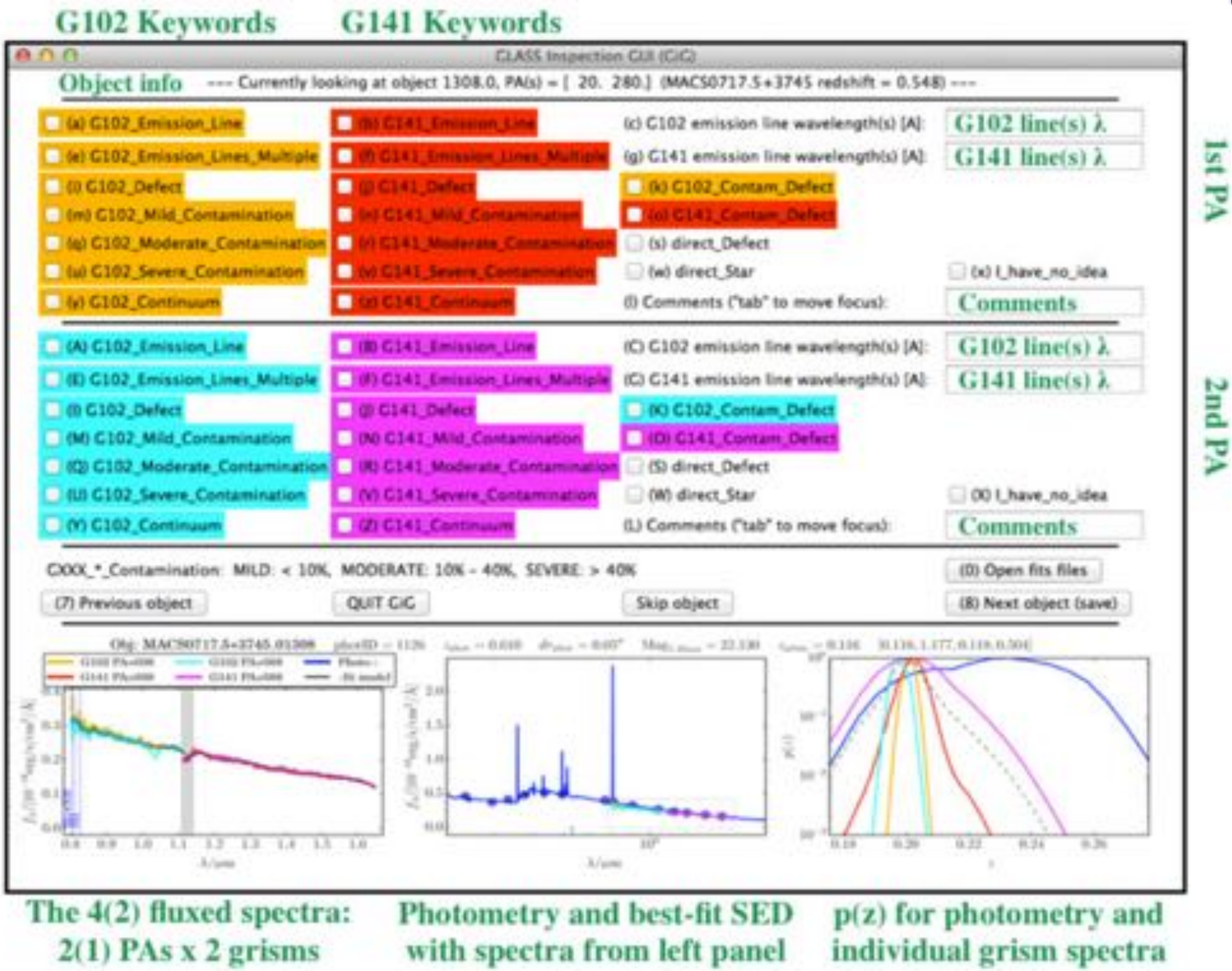
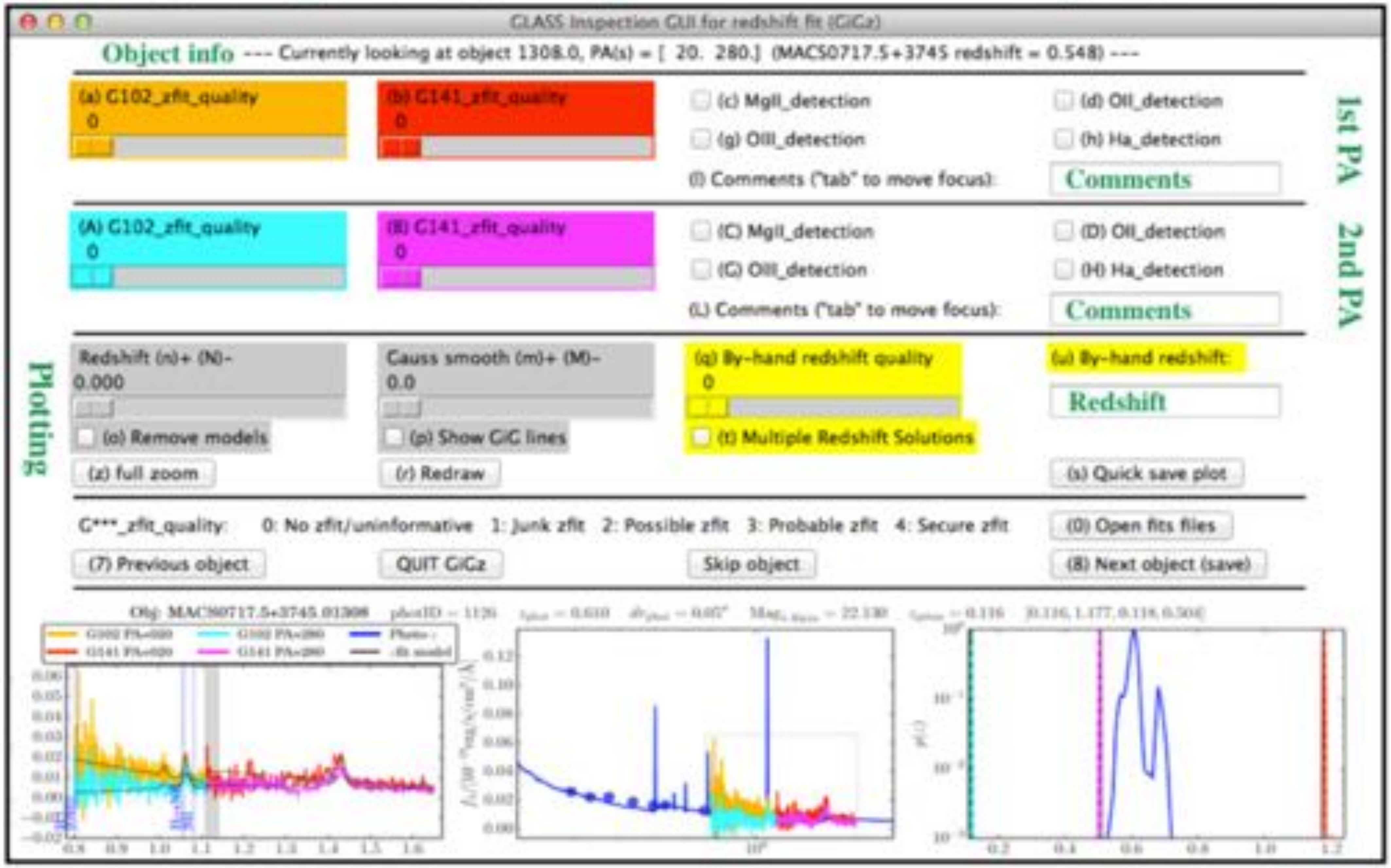


FIG. 16.— Overview of the GiG interface. The green text comments on the individual parts of the GUI. The software is publicly available for download at https://github.com/kasperschmidt/GLASSinspectionGUIs

Tools

GLASS Inspection GUI

G102 z-fit rating G141 z-fit rating Emission Line Keywords



The 4(2) fluxed spectra: 2(1) PAs x 2 grisms

Photometry and best-fit SED with spectra from left panel

p(z) for photometry and individual grism spectra

Major Unresolved Questions for GTO

Questions for science team (June 2014)

What are the top science goals of the observations? How do these drive the data requirements?

Blank fields vs lensing fields as targets.

Which filters are optimal for the science?

Is the total integration time appropriate?

What is the niche for NIRISS compared to NIRCam and NIRSpec?

What supporting/followup observations are essential or useful?

Should supporting observations be done ourselves or in collaboration?

Can we identify parallel observing opportunities in GTO time?

Are we interested in coordinating a large pure parallel NIRISS WFSS program?

When should we allow the data to become public? When do we provide a reduced data release?

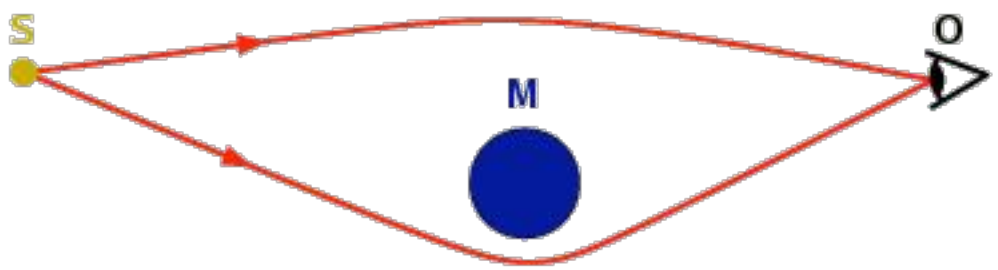
How do we get enough manpower for data analysis, science and publishing in a short time frame?

What is NIRISS Wide-Field Slitless Spectroscopy capable of?

- Spectra of all objects in the field. In a “blank” field there are ~3000 galaxies brighter than mag=28.
- Almost complete wavelength coverage from 0.9 to 2.2 microns.
- At least one strong emission line from z=0.5 to z=4.9. Lyman alpha if present at 6<z<17.
- Resolving power of 100 to 200. Most lines spectrally unresolved, so a map of line emission.
- Spatial resolution of 0.06” ~ 0.5 kpc.
- Cross-dispersed grisms to mitigate contamination.
- Point-and-shoot observing - no target acquisition.

Major Unresolved Questions for GTO

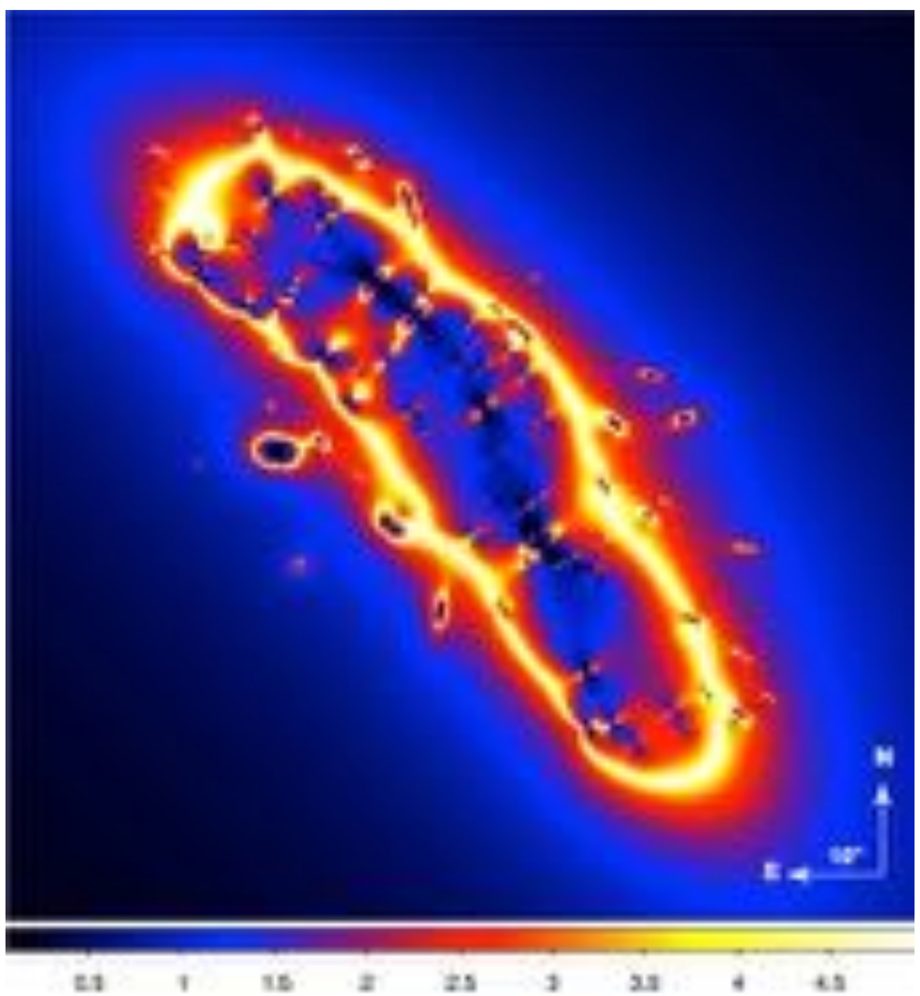
Gravitational lensing



- Light rays bent by gravitational fields

- Effects
  - ✳ Magnification
  - ✳ Stretching
  - ✳ Multiple images
  - ✳ Reduction in search area

- Frontier Fields - six clusters selected to have large areas with high magnification to search for very high-redshift galaxies.

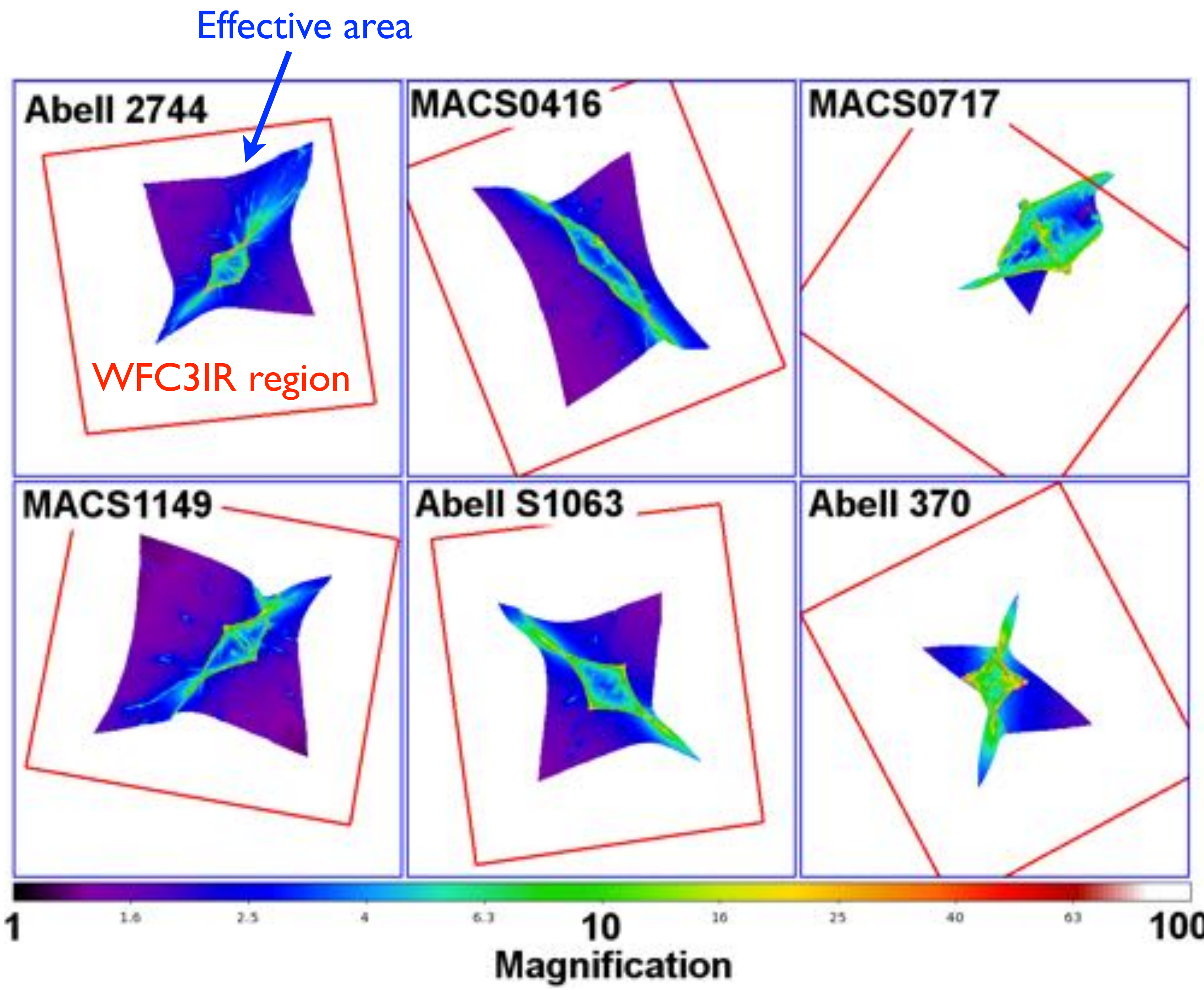


MACSJ0416

Jauzac et al. 2014

Major Unresolved Questions for GTO

Frontier Fields



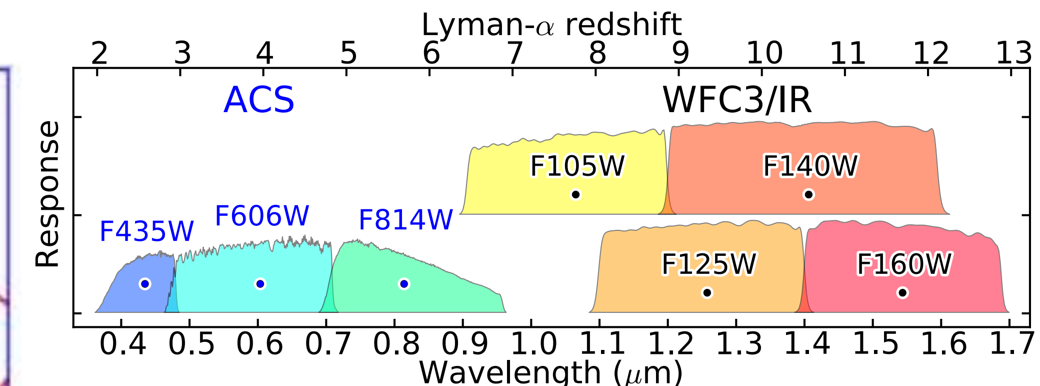


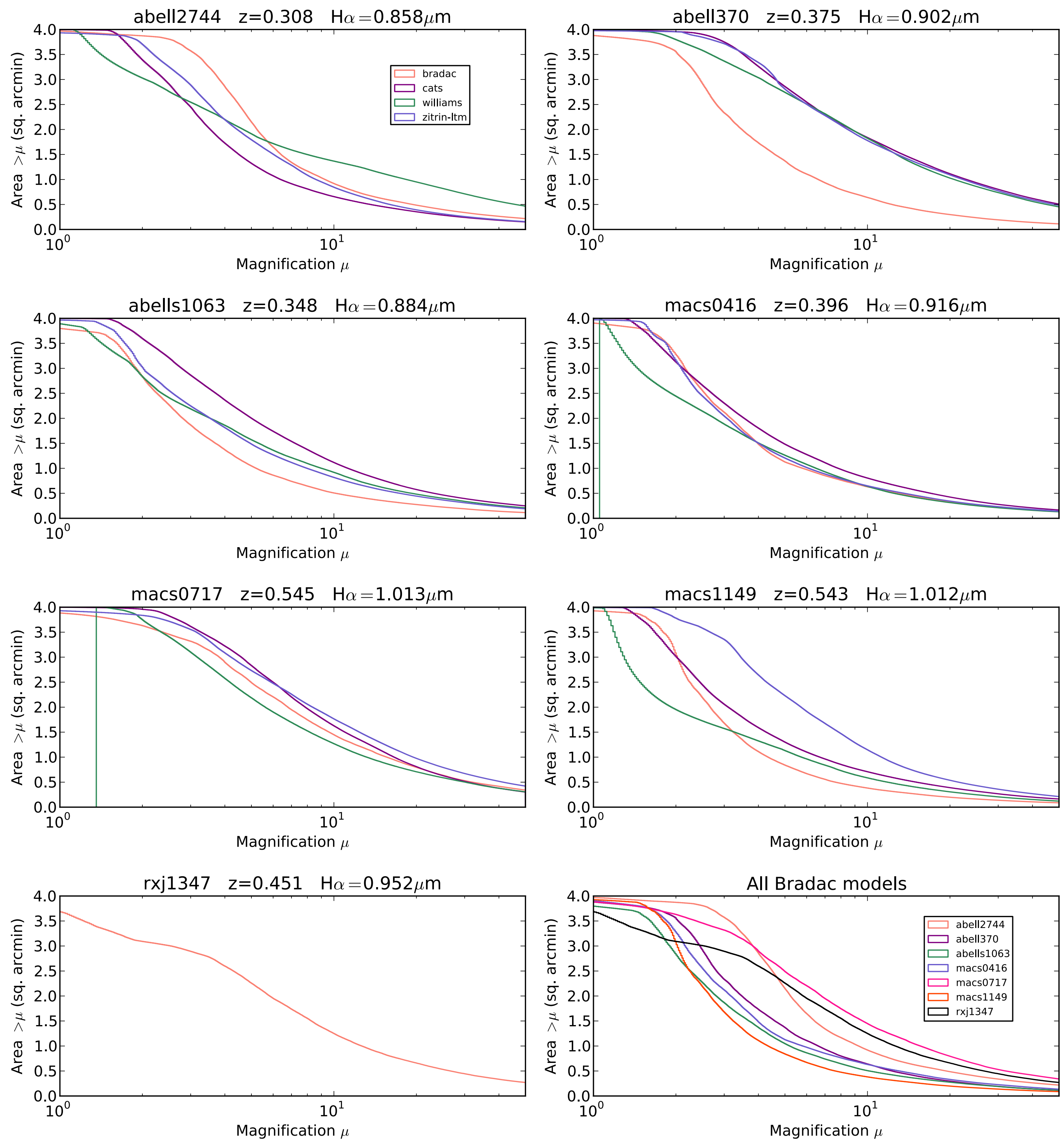
Table 1
Exposure Times and Expected Depths

Camera	Filter	λ^{a} (μm)	Exposure	Depth^{b} (AB)	Sens.^{c} (nJy)
HST ACS/WFC	F435W	0.43	18 orbits	28.8	2.2
HST ACS/WFC	F606W	0.59	10 orbits	28.8	2.2
HST ACS/WFC	F814W	0.81	42 orbits	29.1	1.7
HST WFC3/IR	F105W	1.06	24 orbits	28.9	2.0
HST WFC3/IR	F125W	1.25	12 orbits	28.6	2.6
HST WFC3/IR	F140W	1.39	10 orbits	28.6	2.6
HST WFC3/IR	F160W	1.54	24 orbits	28.7	2.4
SST IRAC	ch1	3.6	50 hours	26.6	16.6
SST IRAC	ch2	4.5	50 hours	26.0	28.9

[1] Effective "pivot" wavelength (Tokunaga & Vacca 2005)
[2] 5σ point source AB magnitude limit (within a $0.4''$ diameter aperture for *HST*)
[3] 1σ point source sensitivity (nJy) within the same apertures

Coe et al. 2014

Major Unresolved Questions for GTO



Frontier Fields

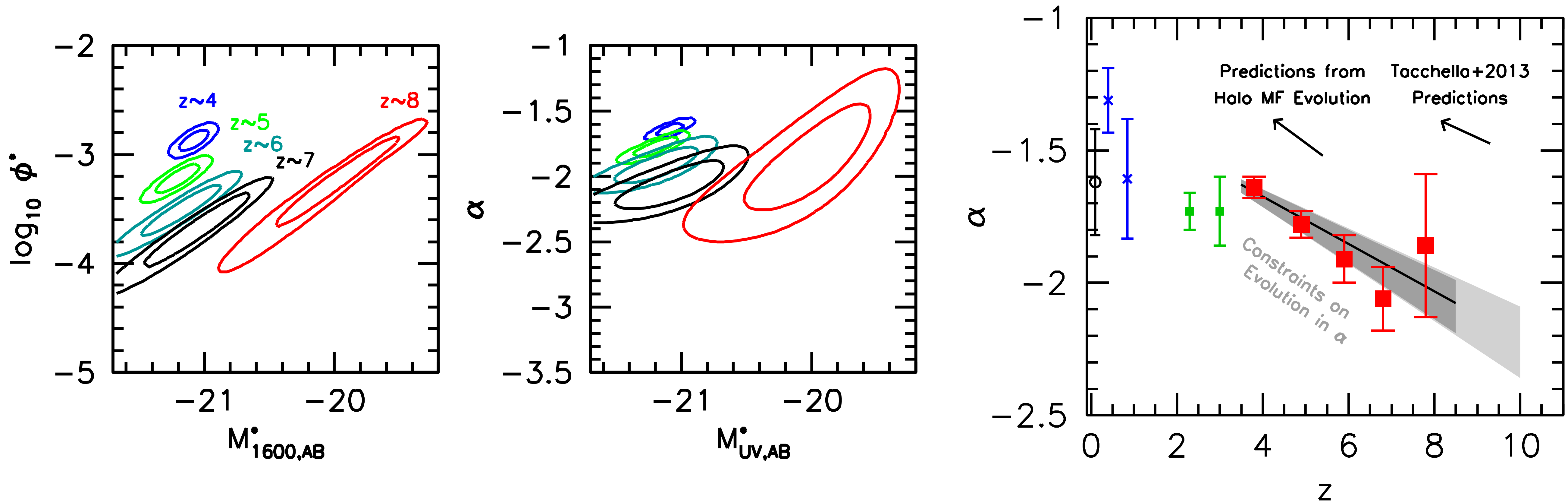
Lensing magnification
vs area in the image plane.

Major Unresolved Questions for GTO

Relative merits of lensed or blank fields depend on unknown luminosity function.

For density evolution the effect is less important.

Faint end slope α ~ -2 at high redshift.



Use Bouwens et al. 2014 evolving luminosity function, with a cutoff in α evolution.

$$M^*_{UV} = (-20.89 \pm 0.09) + (0.12 \pm 0.05)(z-6)$$
$$\phi^* = (0.48^{+0.10}_{-0.08}) 10^{(-0.19\pm0.04)(z-6)} 10^{-3}\mathrm{Mpc}^{-3}$$
$$\alpha = (-1.85 \pm 0.04) + (-0.09 \pm 0.02)(z-6)$$

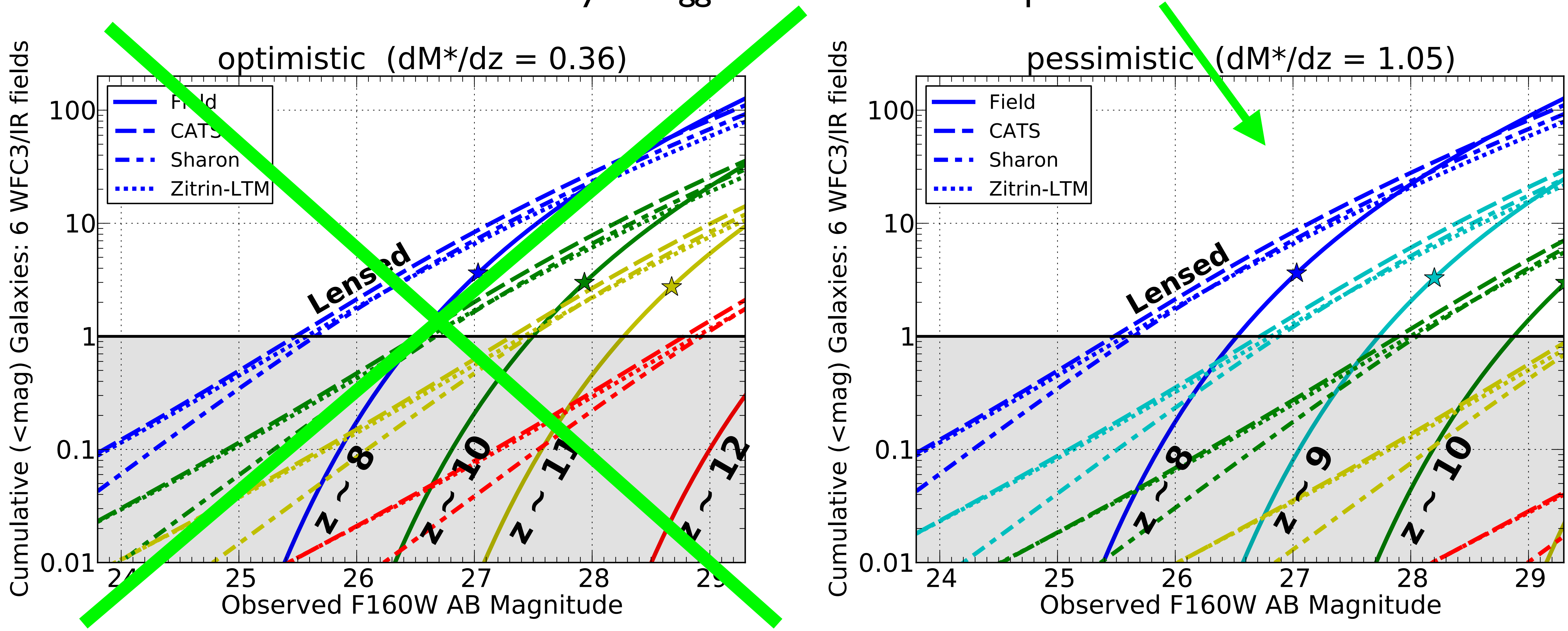
Bouwens et al. 2014

Major Unresolved Questions for GTO

Relative merits of lensed or blank fields depend on unknown luminosity function.

For slopes of α<-2 get increase in counts, for slopes of α>-2 get decrease in counts.

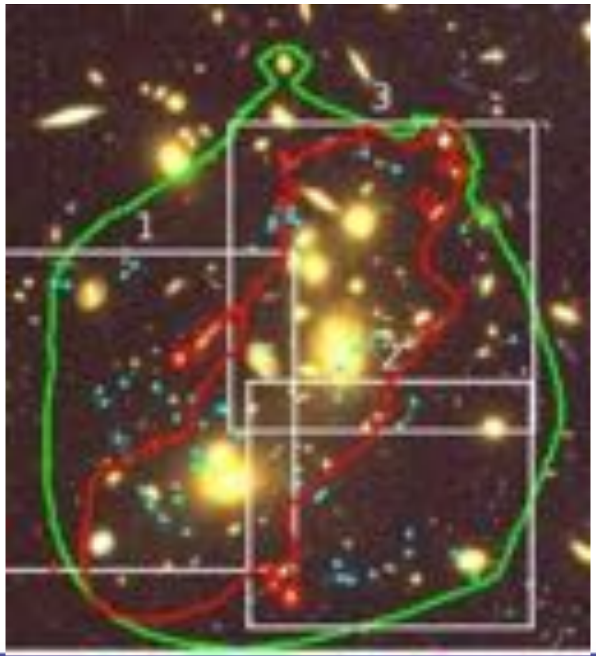
Current FF analysis suggests real LF close to pessimistic case



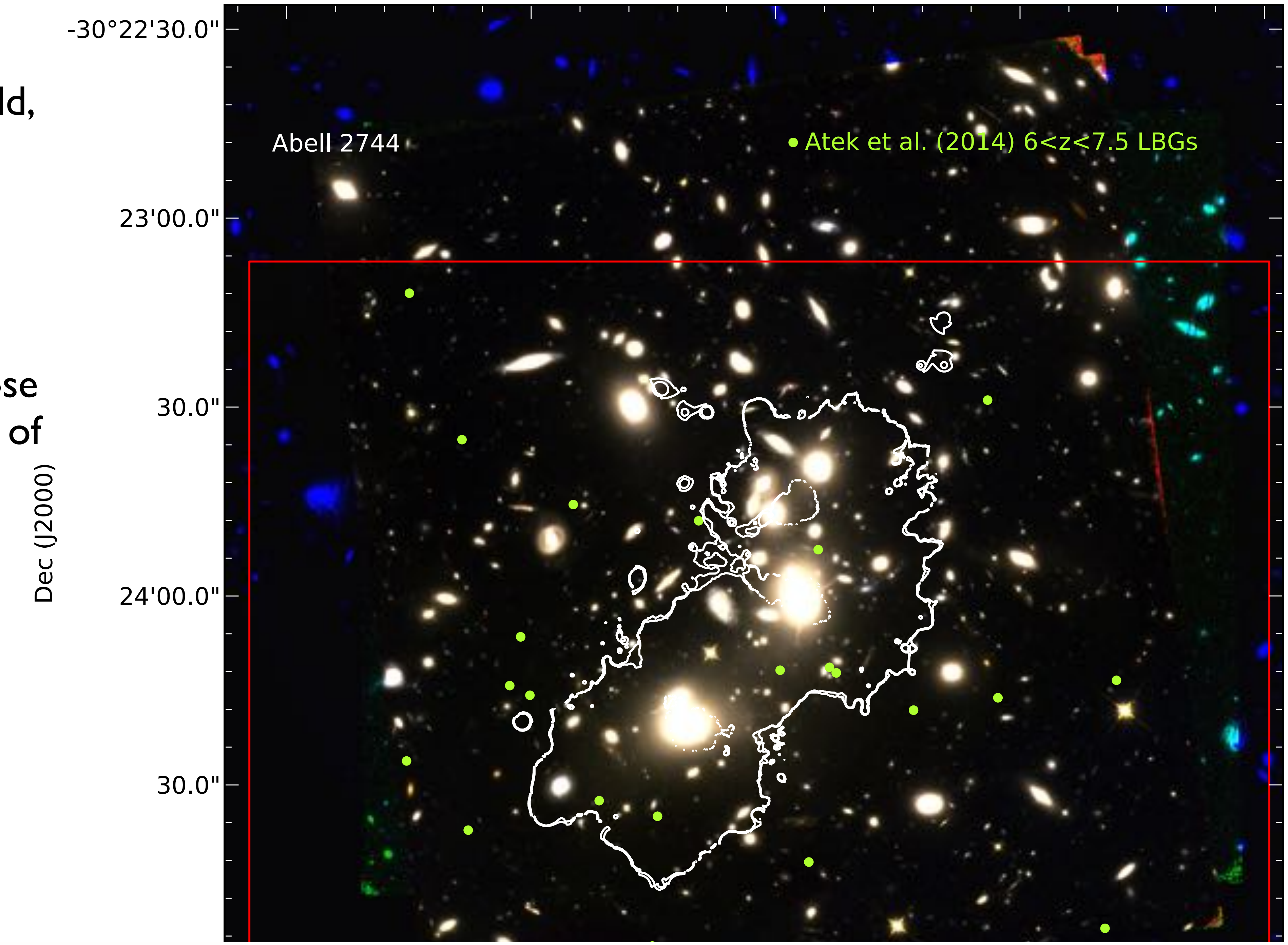
Coe et al. 2014

Major Unresolved Questions for GTO

- Green circles show likely high-z galaxies.
- Note distributed around field, not all on the critical lines.
- Most have moderate magnifications.
- Multiple images only for those in central region (~20 to 30% of galaxies).



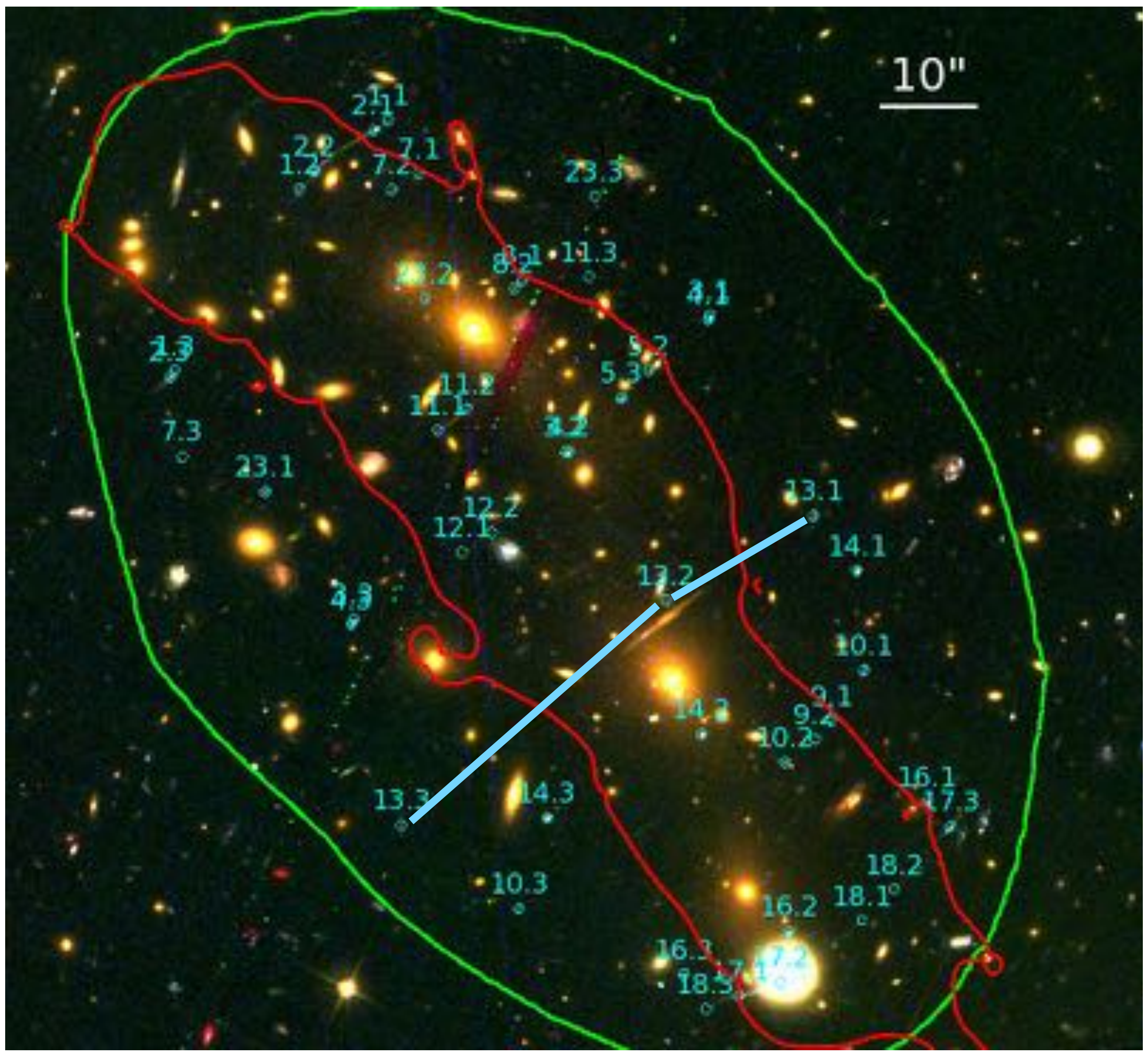
Frontier Fields



Frontier Fields - MACSJ0416

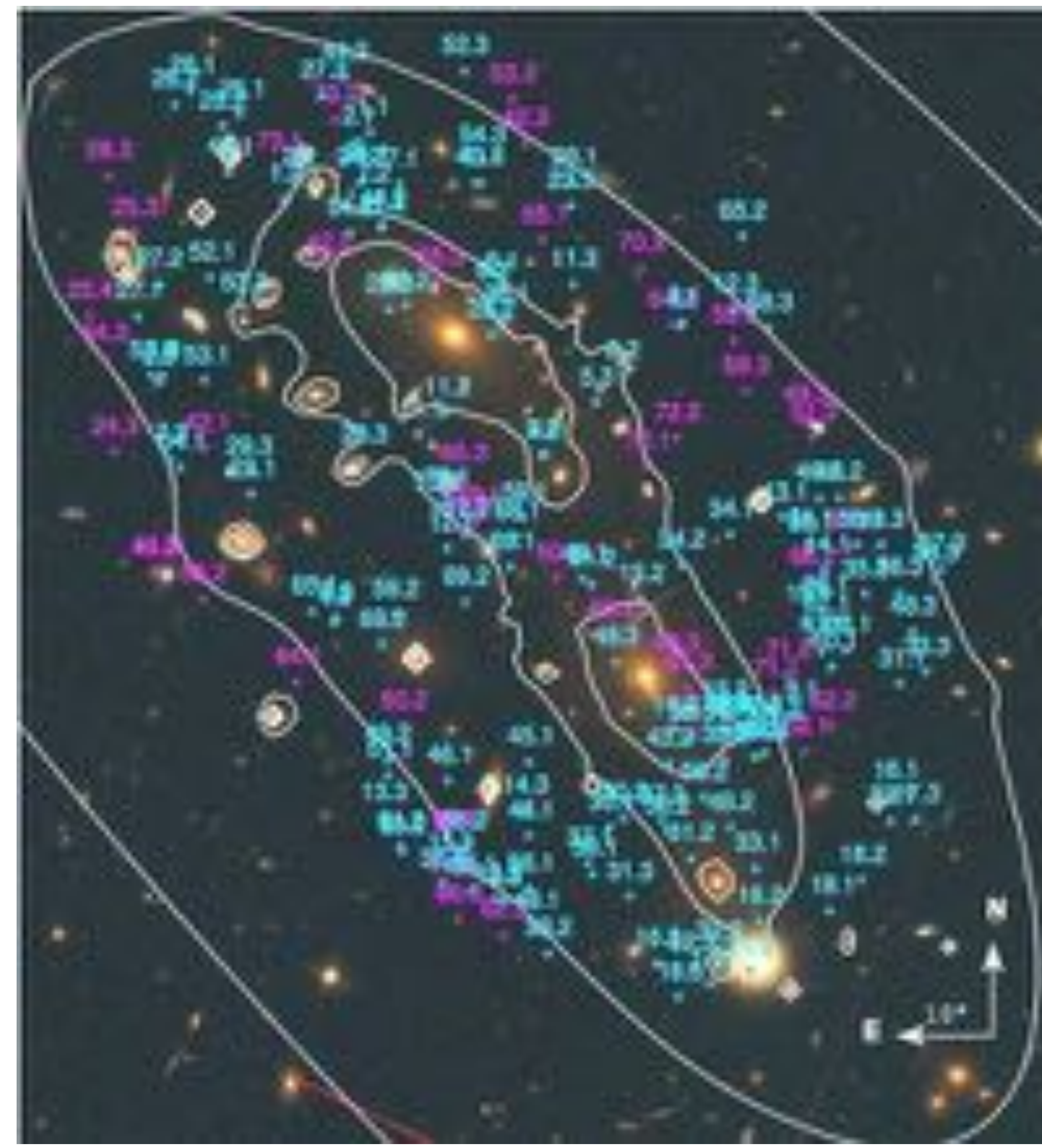
Cyan are known multiply imaged

Green line: Multiple image region at z=7.



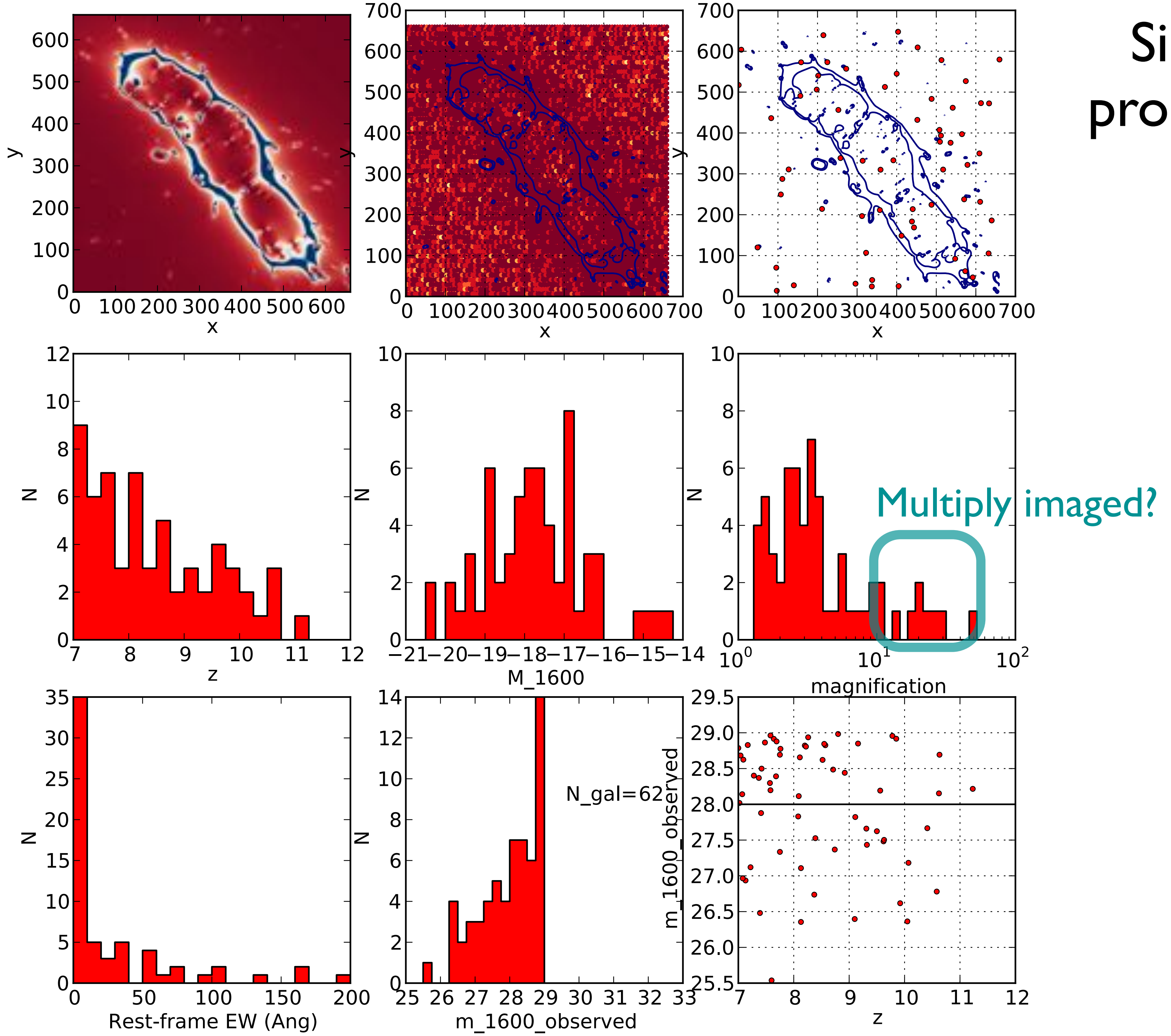
Richard et al. 2014

Early FF data: ~200 images of 73 galaxies.
Most have no known redshift.

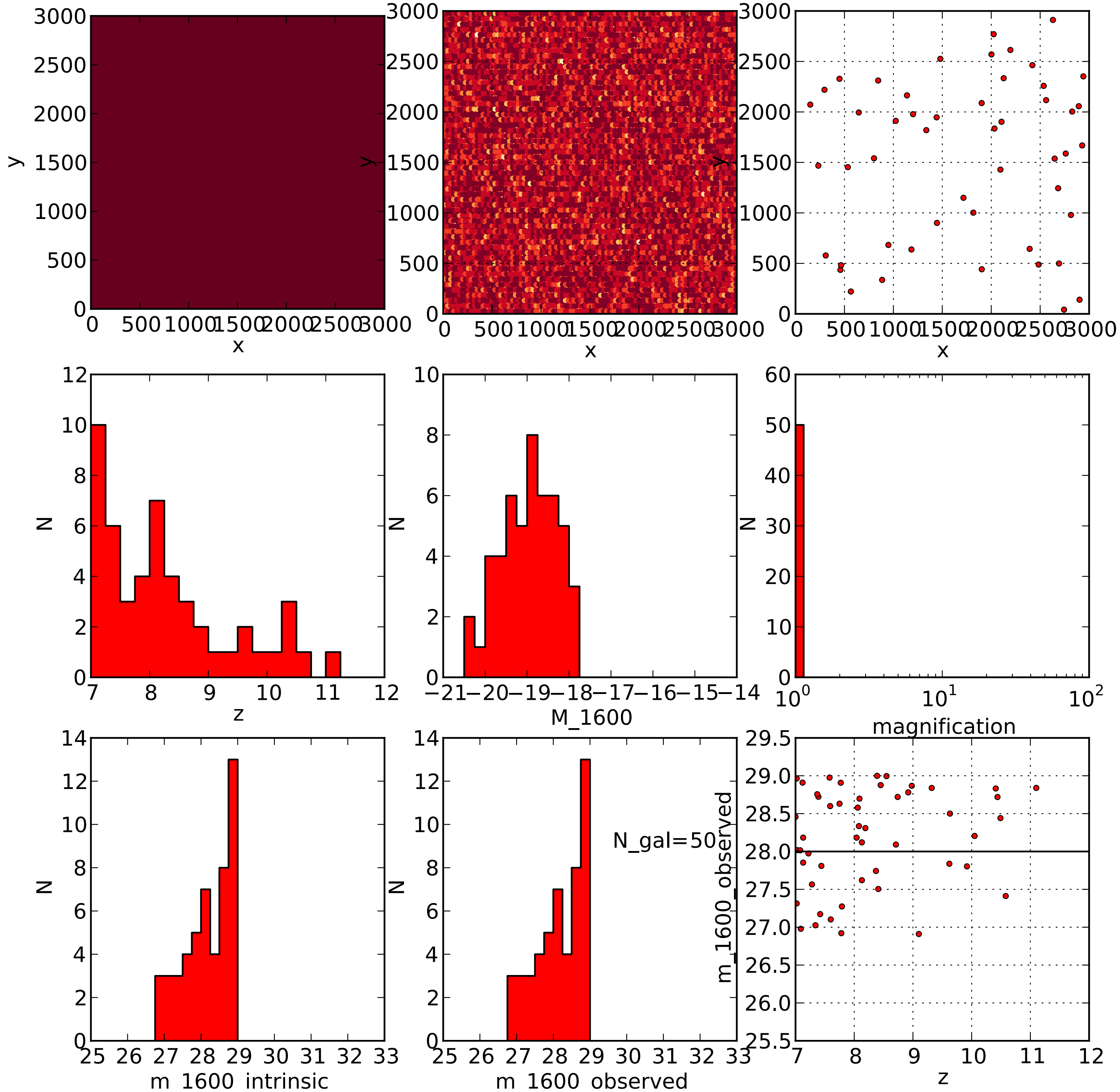


Jauzac et al. 2014

Major Unresolved Questions for GTO



Simulated z>7 galaxy properties in the field of MACSJ0416



Blank field comparison

Optimal strategy for high-redshift galaxies.

3. The choice of filters to use for WFSS of high-redshift galaxies depends upon the expected redshift range of galaxies to be detected (Table 1). As shown previously M*, gets fainter at higher redshift, so the high-redshift limit will be set by sensitivity rather than the upper redshift range of NIRISS. Note that in a fixed integration time the sensitivity reached using F140M + F158M equals that using F150W. It is preferable to use F140M and F158M due to decreased spectral contamination from bright objects.

A baseline high-redshift galaxy search would use F115W, F140M and F158M to probe redshifts from 7.4 to 12.8. Equal integration time in each filter is assumed because the higher redshift galaxies are fainter.

Filter	z Lyα min	z Lyα max
F090W	6.2	7.2
F115W	7.4	9.5
F140M	10	11
F158M	11.3	12.8
F150W	9.9	12.9
F200W	13.5	17.4

Observing time

Assumption is that deep blank fields are observed with 30 hours (not including overheads) per field per filter, split equally between GR150R and GR150C. Cluster lensing fields are observed with 15 hours (not including overheads) per field per filter, split equally between GR150R and GR150C.

S/N calculations

Galaxy redshifts can be determined from either continuum breaks or emission lines. Simulations by C. Willott show that for typical z~6 galaxy properties redshifts are more frequently determined from continuum breaks (Fig.3). The main reason is that the low spectral resolution of ~130 for Lyα at z~8 sets a lower limit of EW_{obs} >~ 100 Angstroms in order that the line be observed above the Lyman break. More detailed simulations are required to define the line detection efficiency as a function of EW and where it falls on the detector pixels (including sub-pixel dithering).

The result of the simulations in Fig. 3 shows a 50% success rate of redshift determination at AB=28.3, so this is the assumed magnitude limit for 30hrs in F115W. Some fainter sources will be detected, especially if they have strong emission lines. F140M is 0.4 mag deeper in same integ time (so limit is AB=28.7) and F158M is 0.1 mag deeper in same integ time (so limit is AB=28.4). For 15 hours integration these sensitivities are all reduced by 0.4 mag giving limits of AB=27.9, 28.3 and 28.0 in the three filters.

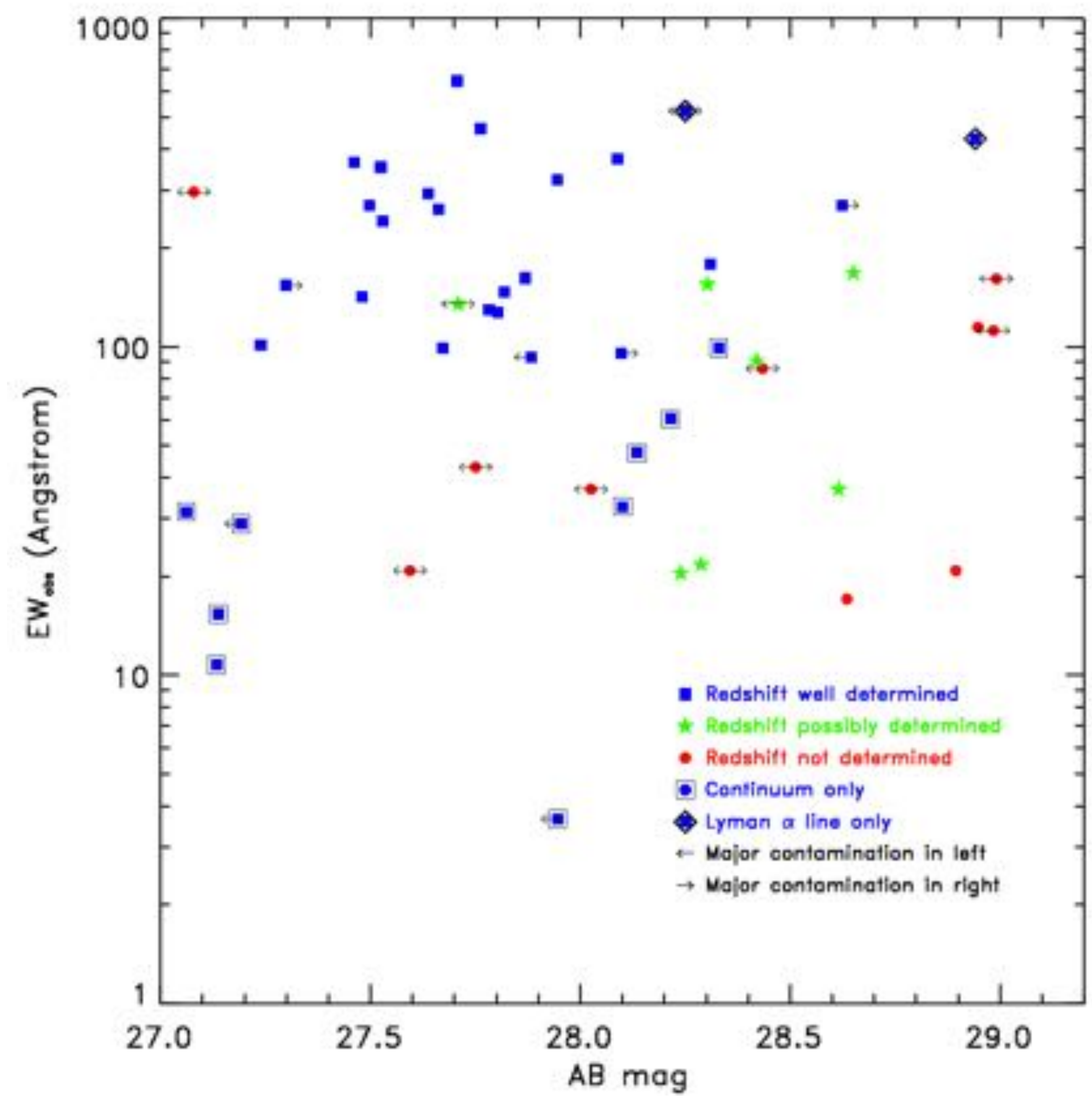


Fig. 3. F115W simulation of 30 hrs on HUDF