A Glorious Dawn – Observing the First Galaxies With Hubble

Matt Mechtley – Arizona State University
School of Earth and Space Exploration

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Wik:

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Nimish Hathi (Carnegie Observatories)
Bill Keel (U. Alabama)
Huub Röttgering (Leiden Observatory)
Donald Schneider (Penn. State)
Michael Strauss (Princeton)
HIPPIES Team

Overview

- My Background: Who is this dude?
- Nuts and Bolts: Python and why I use it
- Cosmology: Why study the earliest galaxies?
- HIPPIES: Searching for early galaxies
- My dissertation: Host galaxies of the earliest quasars

My Background

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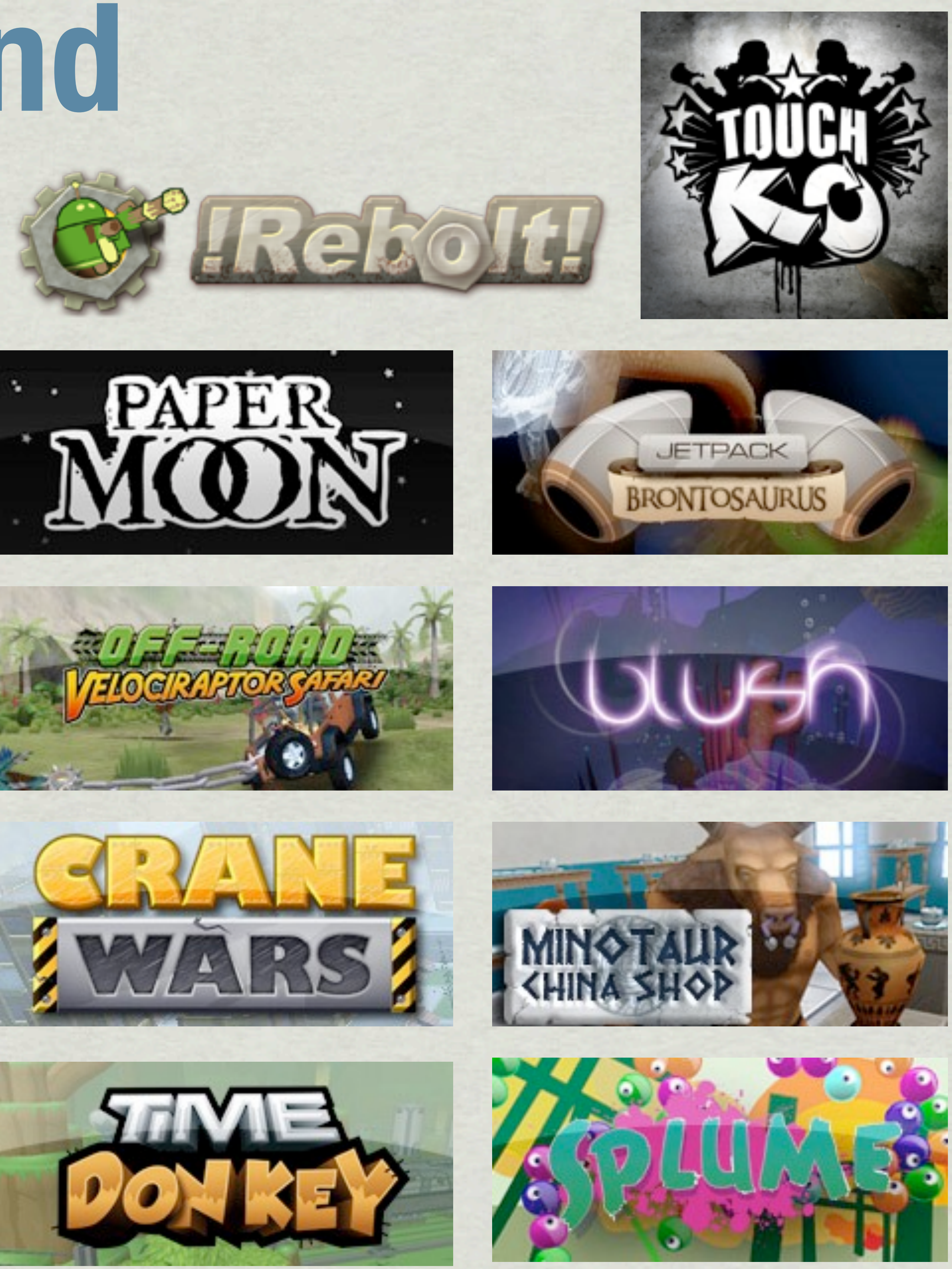
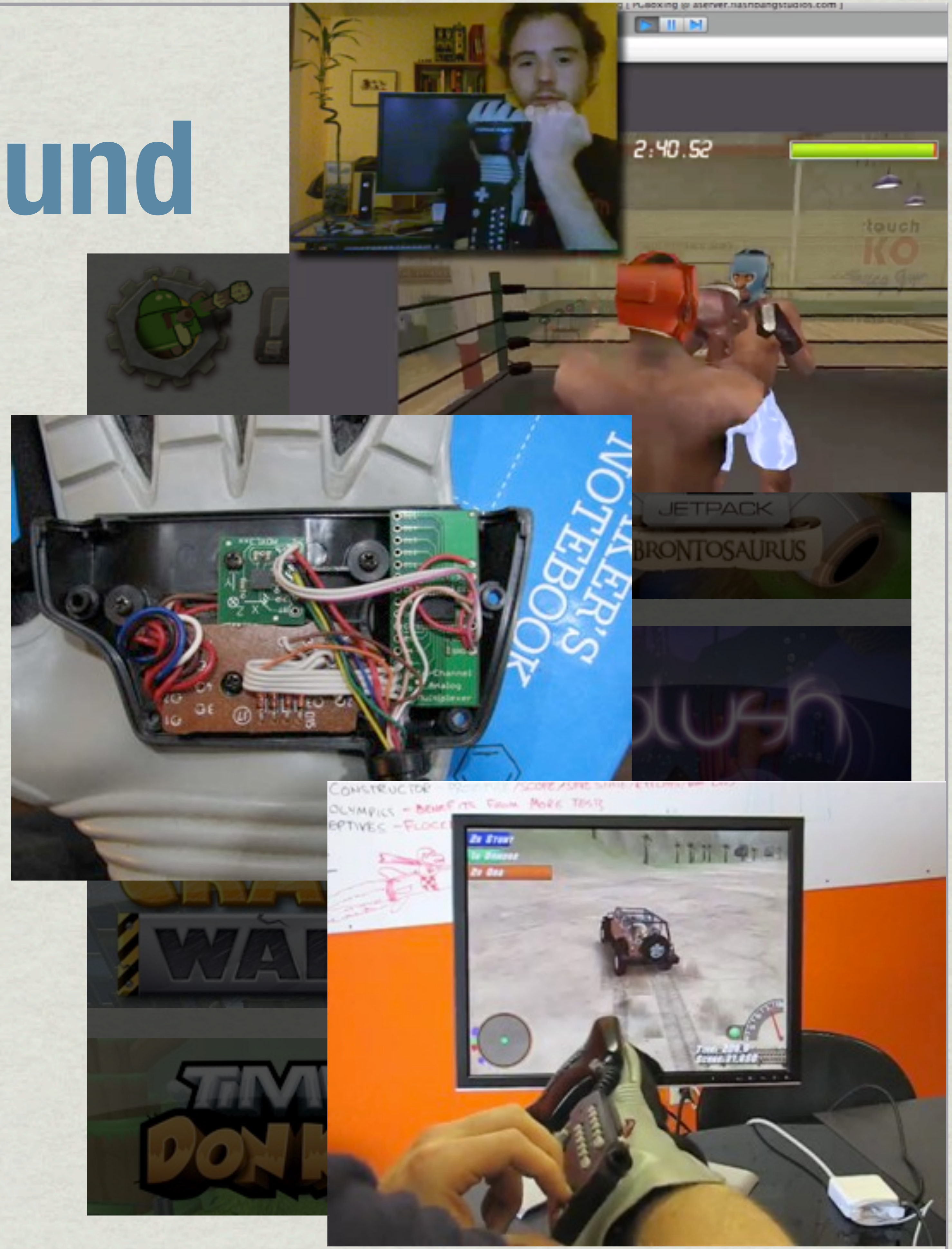


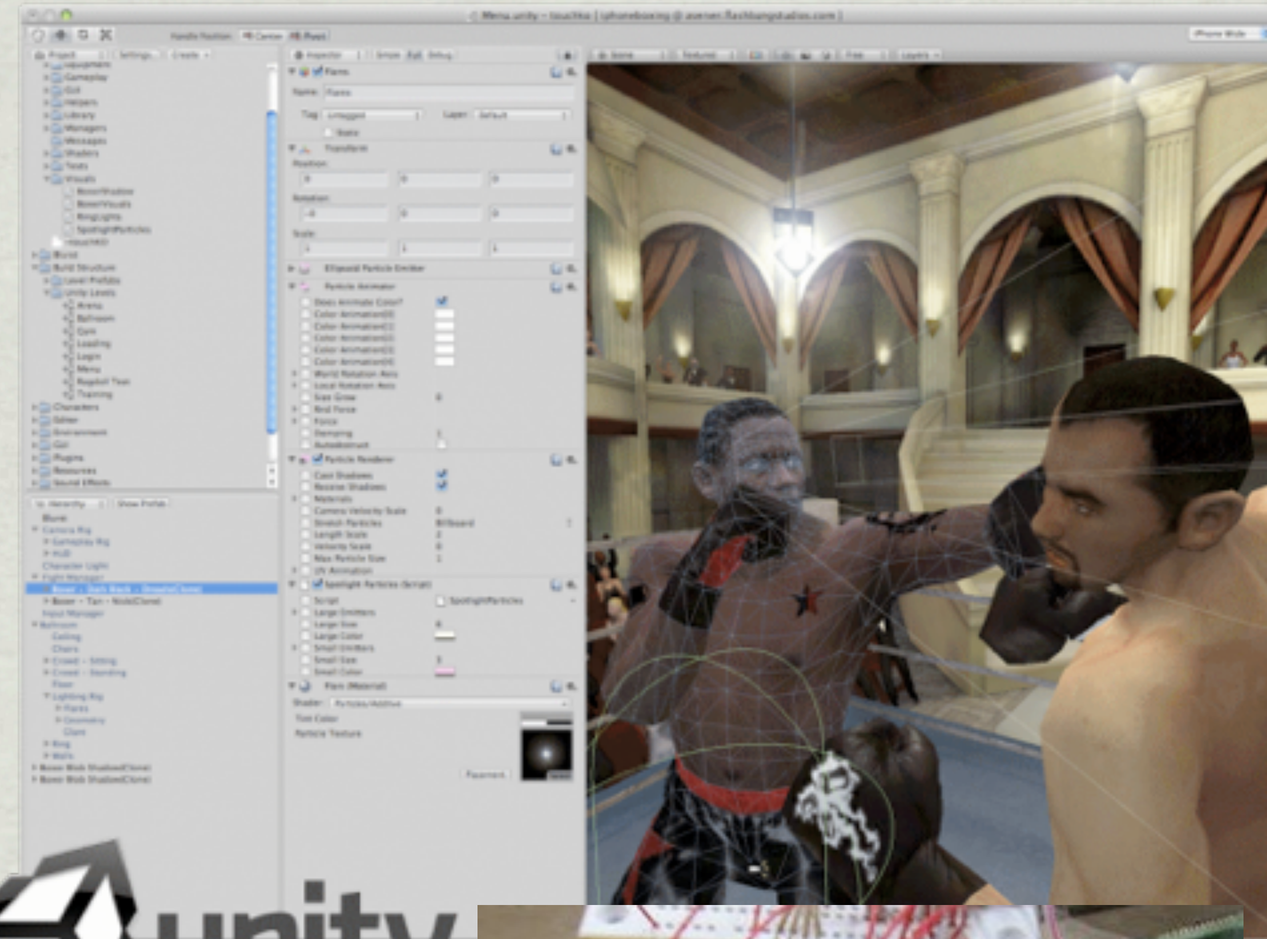
My Background

- B.S. Mathematics (Linear & Abstract Algebra)
- Professional game developer for 2 years
- Lots of games!
- Also some hardware hacking



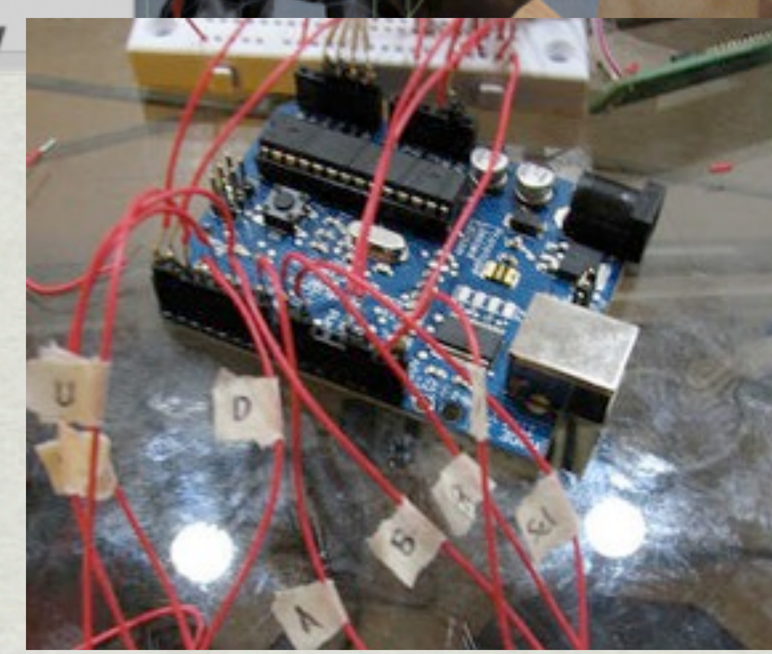
What I Learned From Games

- **PROTOTYPE**
- Good tools make happy developers
- Choose tools that enable rapid iteration (of the modify–build–test loop)
- Lets you fail *early*, avoiding wasted time



unity

ARDUINO



Optimization

* Most programmers learn how to optimize for memory and execution efficiency
* It’s also important to optimize for programmer time
* Saving a day of compute time is great! But what if the optimization took a week to write?
* Computers are constantly getting faster, your day is not constantly getting longer

Rapid Iteration With Python

- Interpreted language – no compiling (modules compiled to bytecode)
- Comprehensive standard library (file system manipulation, strings, subprocesses, sockets, sqlite databases, urls, etc.)
- Installing additional modules/libraries is easy:
  > python setup.py install
- Interactive console – excellent for prototyping
- Vast community/ecosystem – scientists of all flavors, web developers, game developers, robotics folks
  (Search StackOverflow, your problem has likely been solved)

Python's Unique Features

- Readability – "One of Guido [van Rossum]'s key insights is that code is read much more often than it is written." – PEP 8, Python Style Guide
- Iterators – Produce more readable loops, including flattening nested loops
- List Comprehensions – Compact syntax for simple loops

```python
squares = [x**2 for x in range(10)]

# Generally, any functions, nested functions, etc. can occur in the generator
names = ['Snake Plissken', 'Patrick Bateman', 'Dirty Harry', 'Debbie Harry']
lastNames = [name.split()[1] for name in names]
```

Readability: A Sample Program

- Despite only a single comment, most non-Python programmers can tell you what this is doing
- Reduces "WTF was I doing?" time when you have to come back to old code

```python
from math import sin, pi

def sinc(x):
    """Compute the sinc function:
    sin(pi*x)/(pi*x)"""
    try:
        val = (x*pi)
        return sin(val)/val
    except ZeroDivisionError:
        return 1.0

input = [0.0,0.25,0.5,0.75,1.0,
         1.25,1.5,1.75,2.0]
output = [sinc(x) for x in input]
```

From T. Oliphant 2007

“But interpreted languages are too slow”

- Numpy/Scipy are compiled C/Fortran routines with Python bindings. Their algorithms have already been optimized by smart people!

- In many cases, they’re the *same* routines you would have used anyway (e.g. lapack). The only difference in speed comes from the external call.

- Vectorized functions/operations for compact syntax, including common linear algebra operations

- Can also write your own compiled extension modules – Slick tools for this too, like Cython, f2py, etc.

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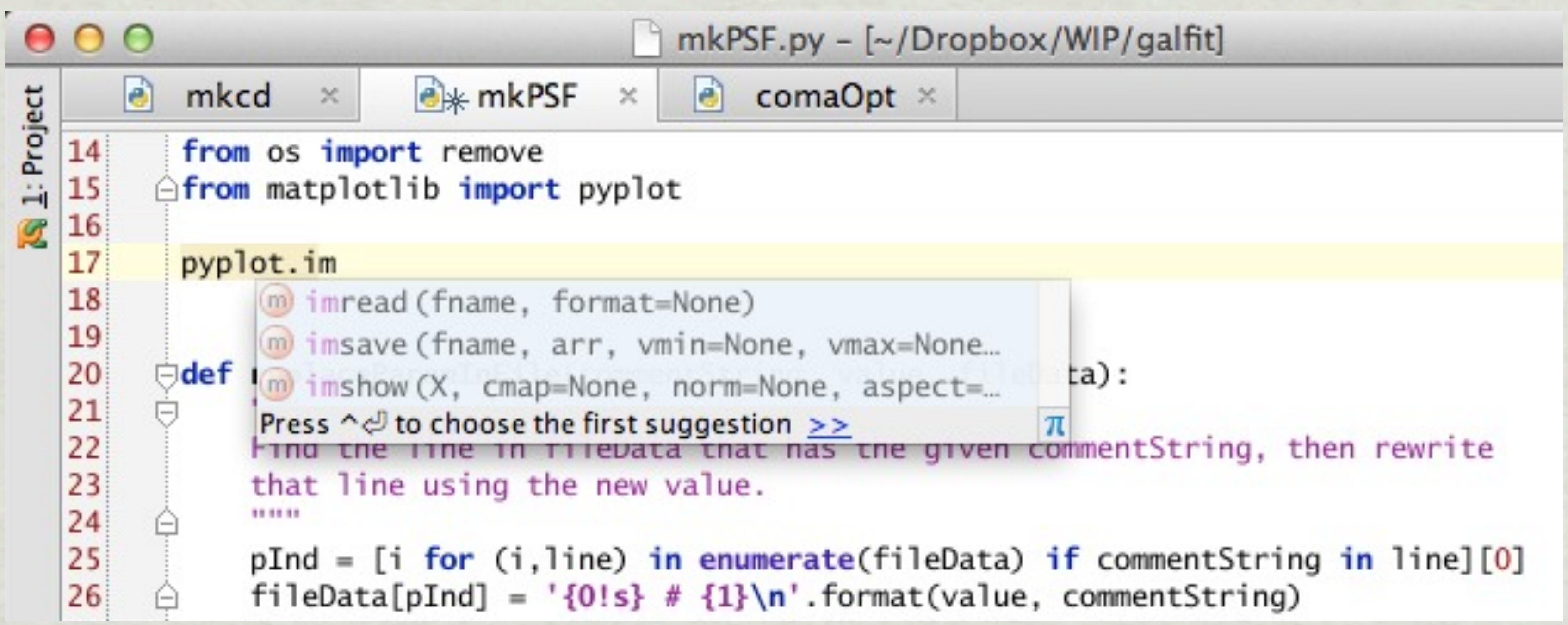
PSA: A Text Editor Can be a Rapid Iteration Tool, Too

- Keep trusty vi/emacs as the hammer in your toolbox, but there are nailguns out there



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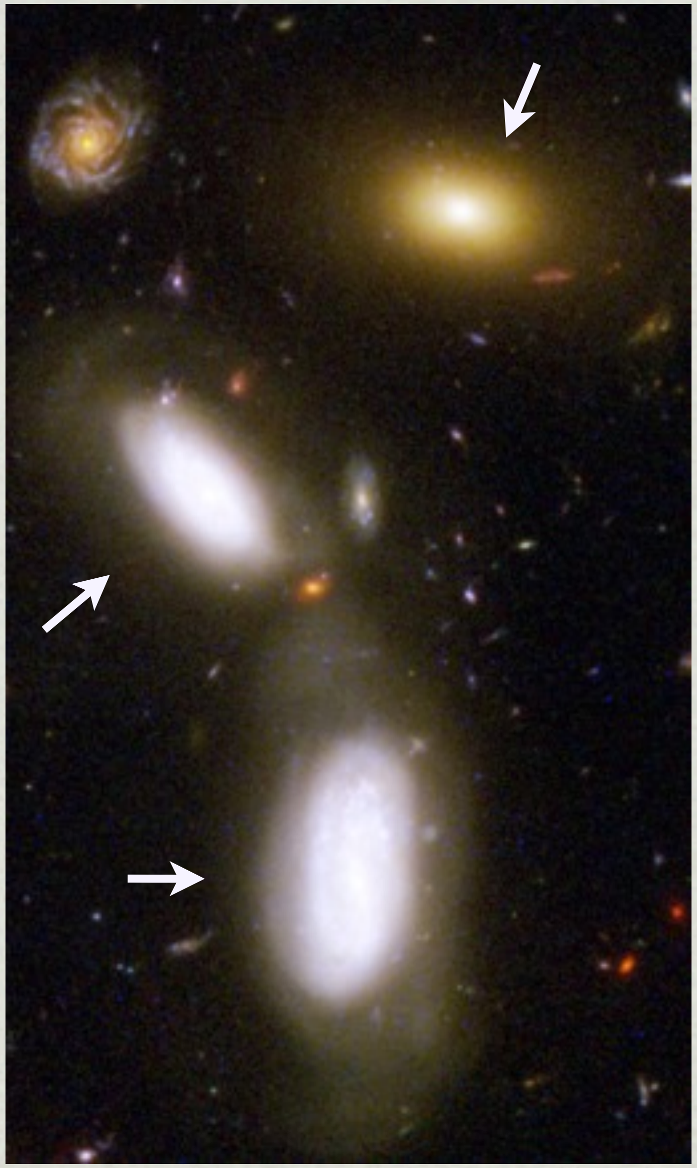
OK, ONTO THE SCIENCE

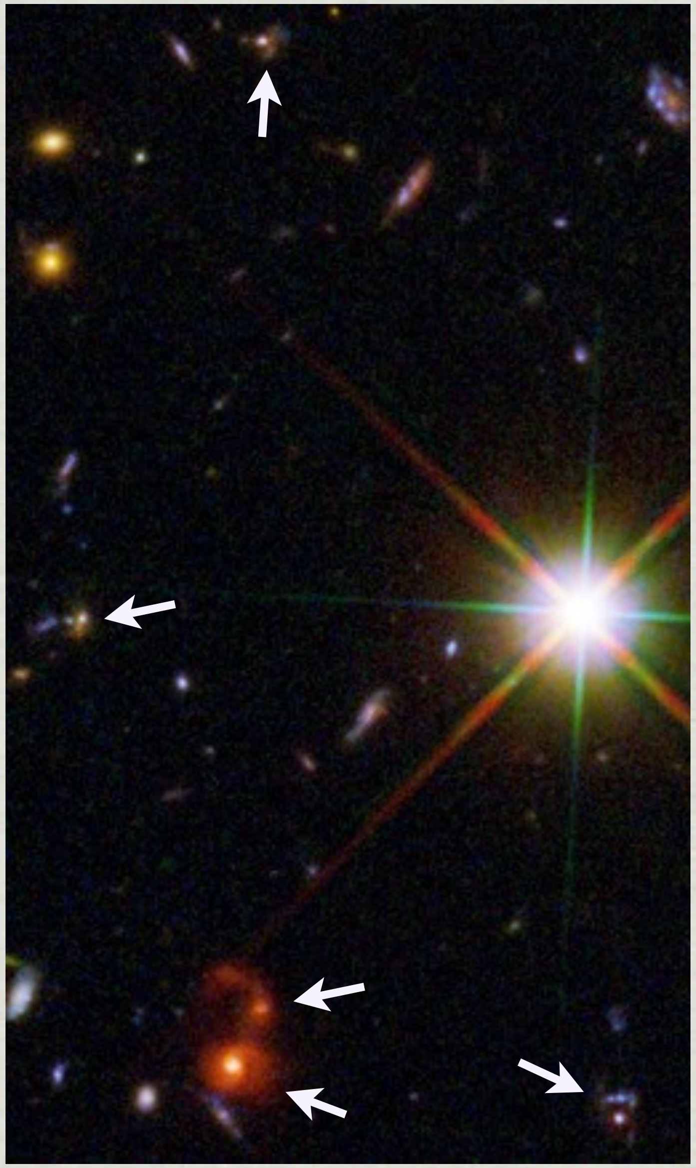
1 Zwicky 18, Extremely Metal-Poor Galaxy – A local analog to galaxies in the early Universe?

Evolution of Galaxy Morphology



Redshift z=0.1
1–2 Gyr Ago

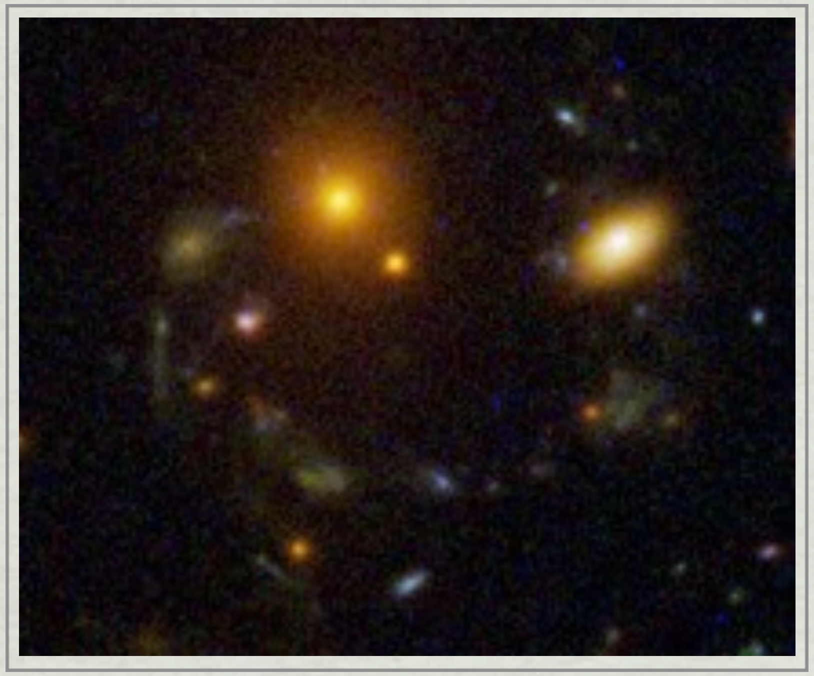
Redshift z=1.0
7–8 Gyr Ago



Redshift z>2
>10 Gyr Ago

13

The Universe Smiles at You



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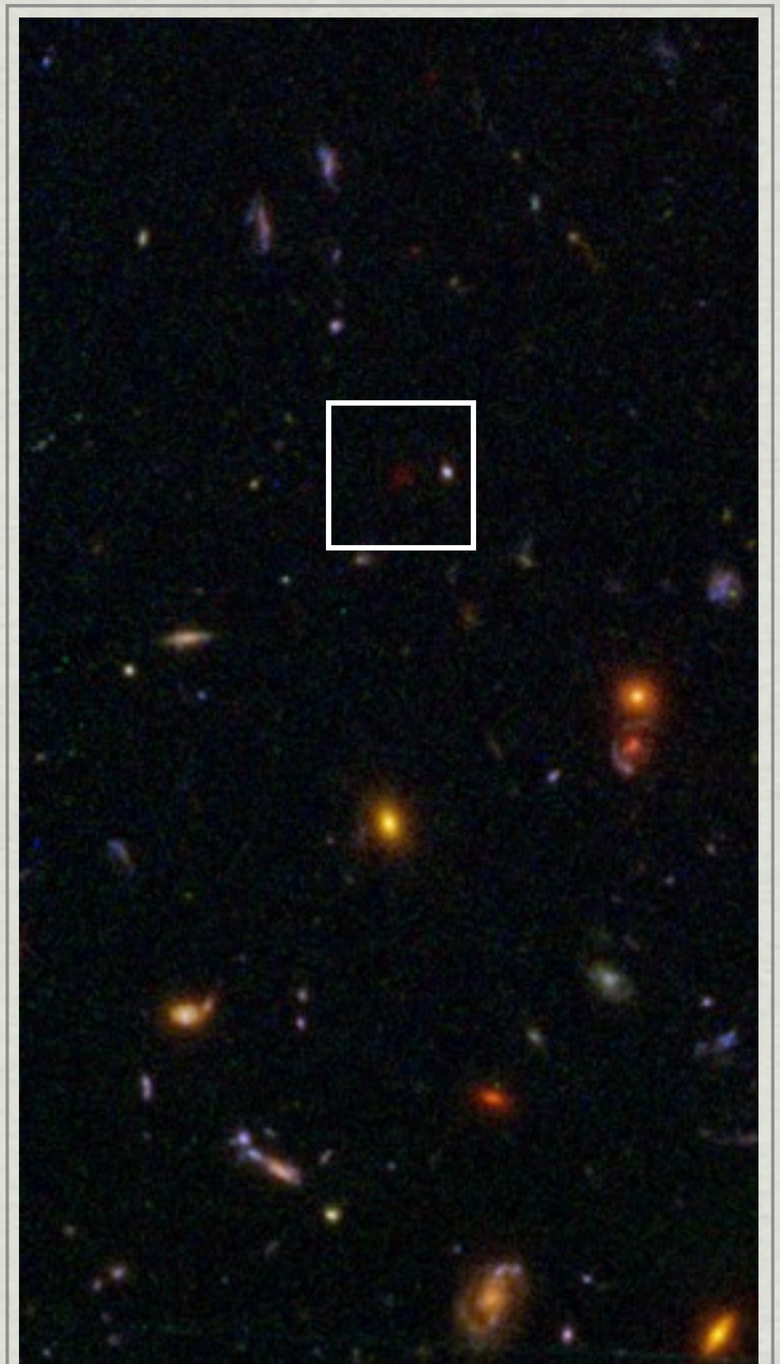
The Most Distant Galaxies



Redshift z~8
12.9 Gyr Ago

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Galaxy Assembly – Growth via Mergers*

*And probably some cold-mode accretion, too

Tadpole Galaxy
(Minor Merger)

Antennae Galaxies
(Major Merger)

Images: Hubblesite

History of the Universe

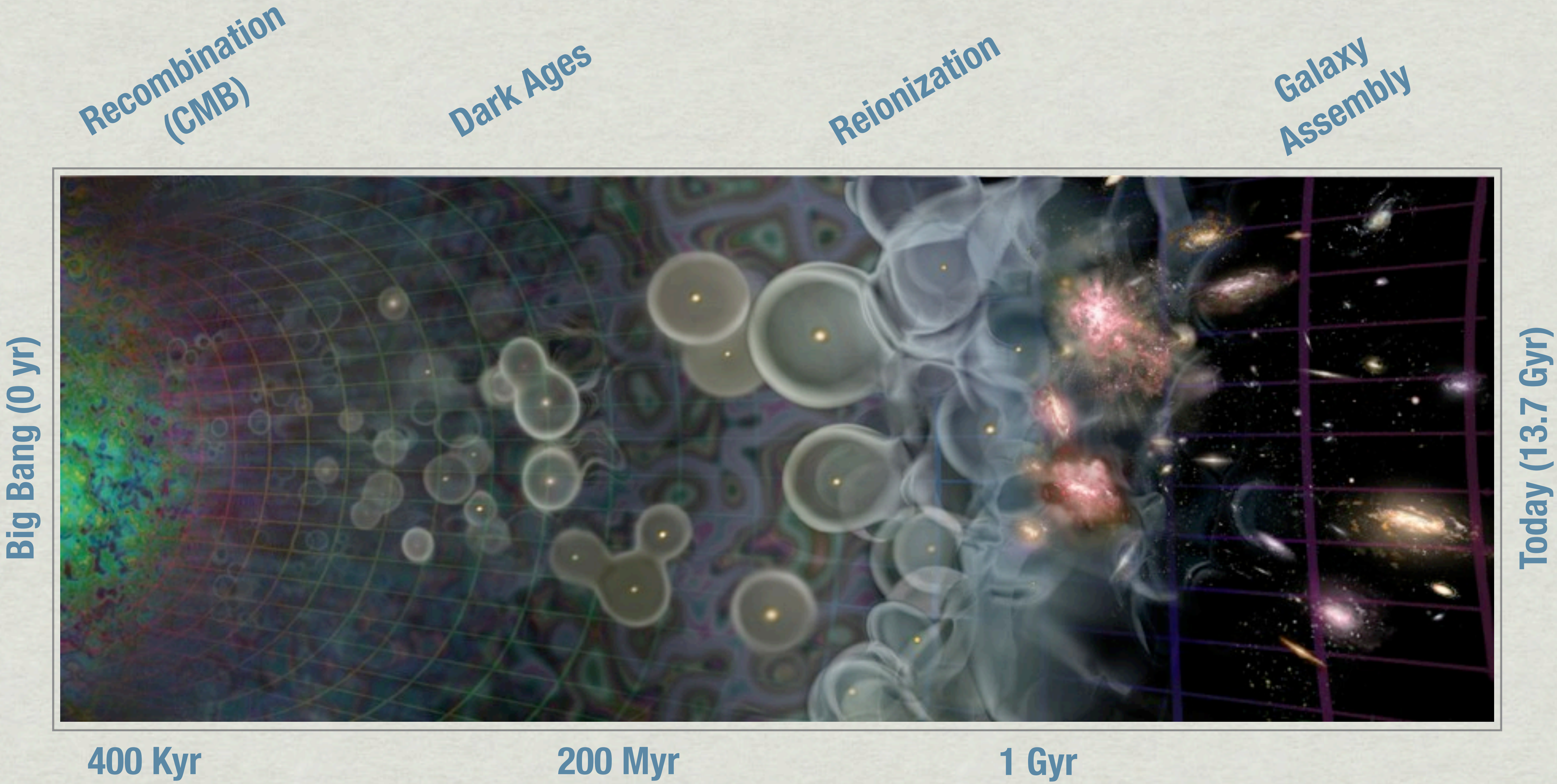
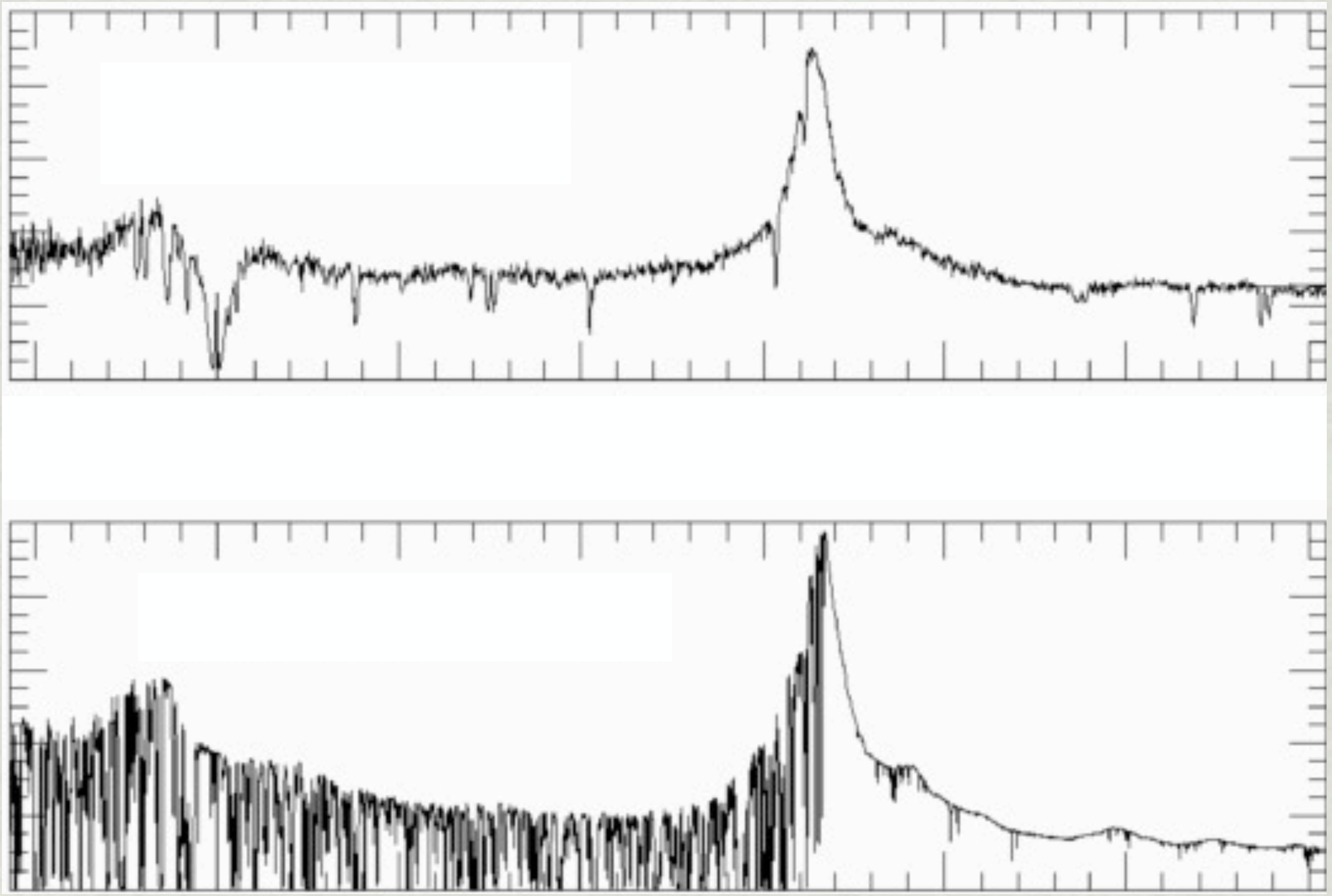


Image: Scientific American

Evidence for Reionization: Lyman Alpha Forest

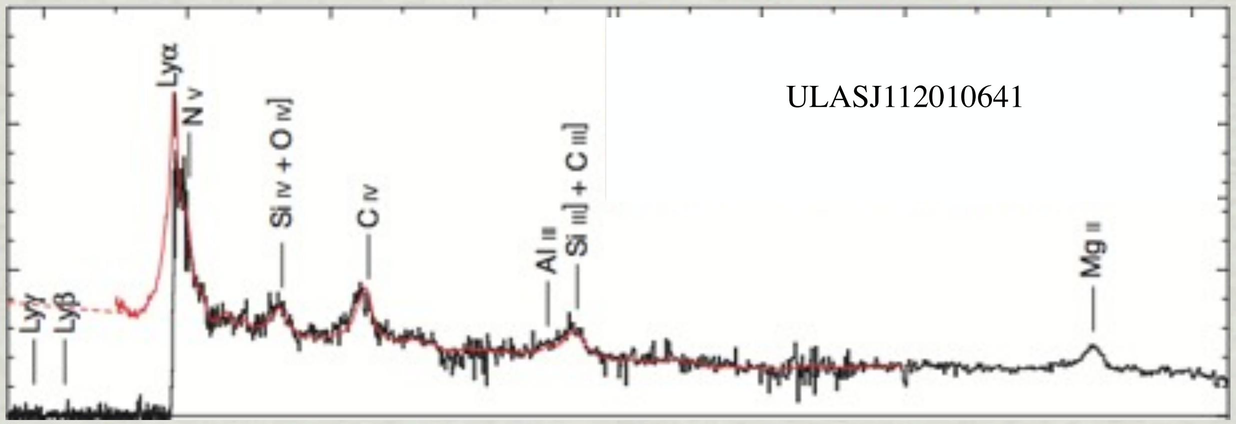
3C 273
z=0.16

Q1422+2309
z=3.6



W. Keel / E.L. Wright

ULAS J1120+0641
z=7.1

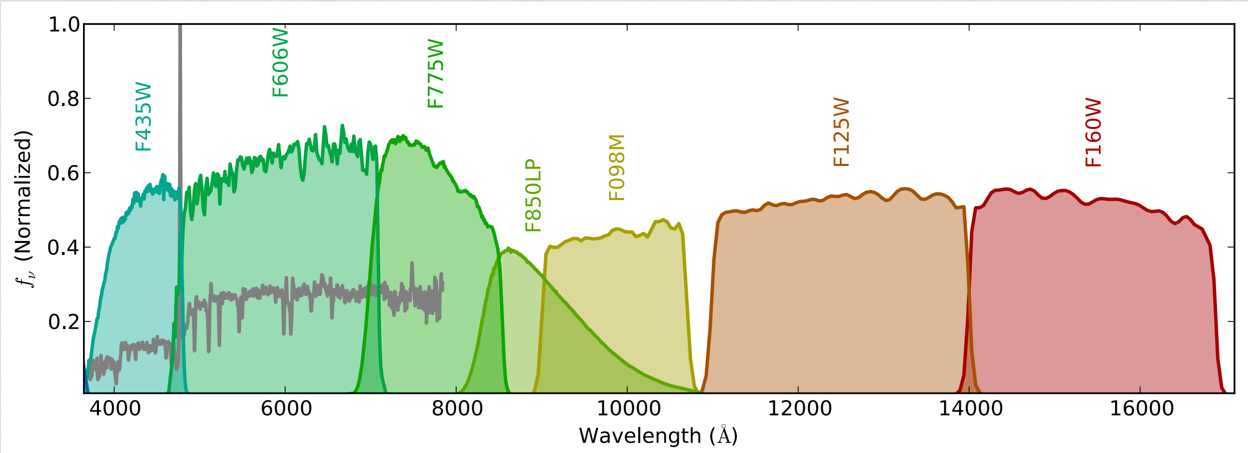


Mortlock et al. 2011

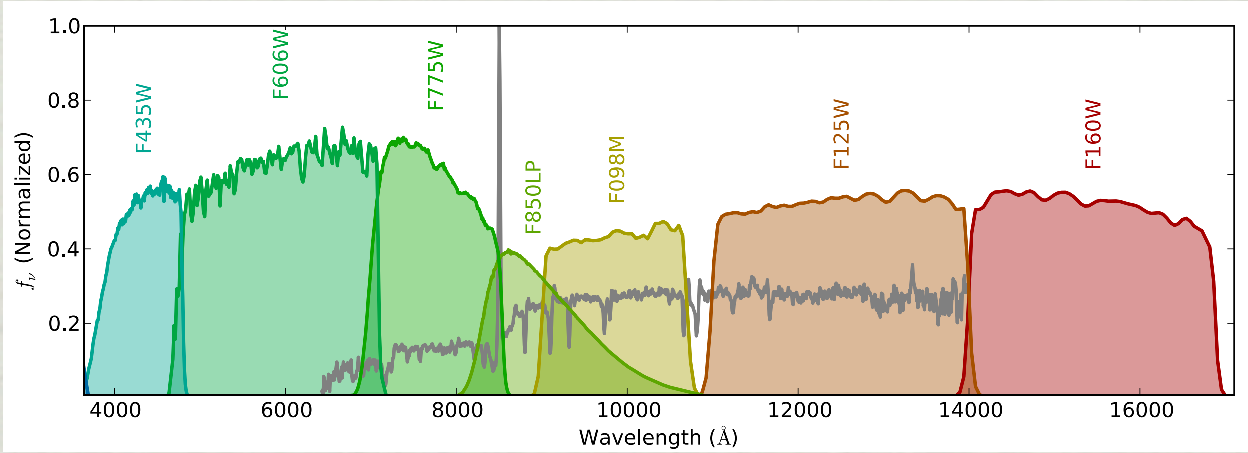
How to find distant galaxies

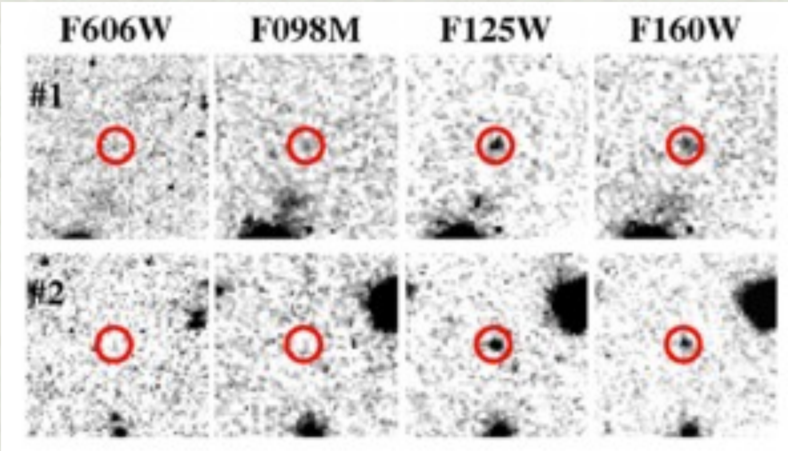
Lyman break or "dropout" technique: Look for objects that are visible in red filters, but not visible in blue ones

Redshift z=3
11.5 Gyr ago



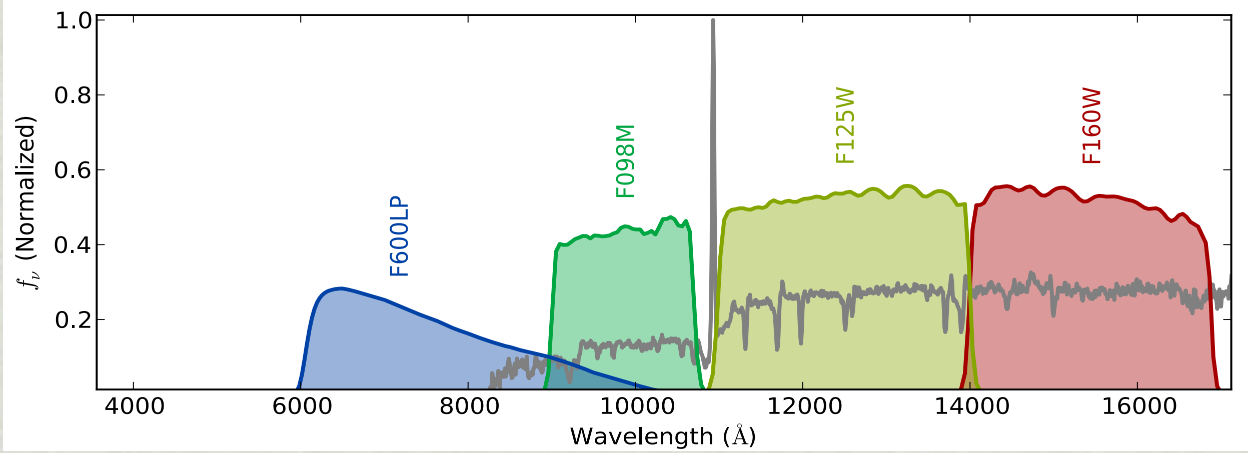
Redshift z=6
12.7 Gyr ago





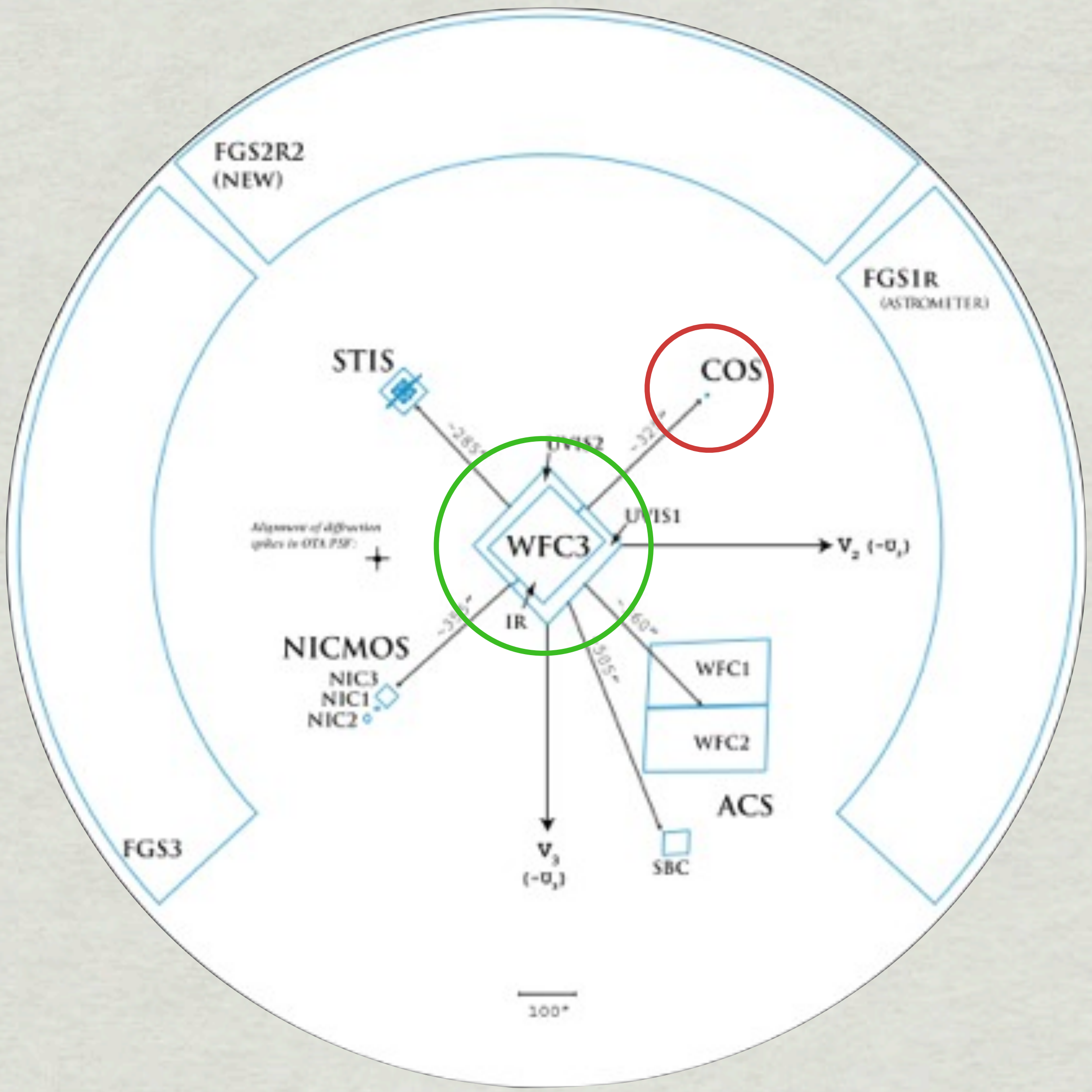
Yan et al. 2011

Redshift z=8
13.0 Gyr ago



Spectrum: Shapley et al. 2003

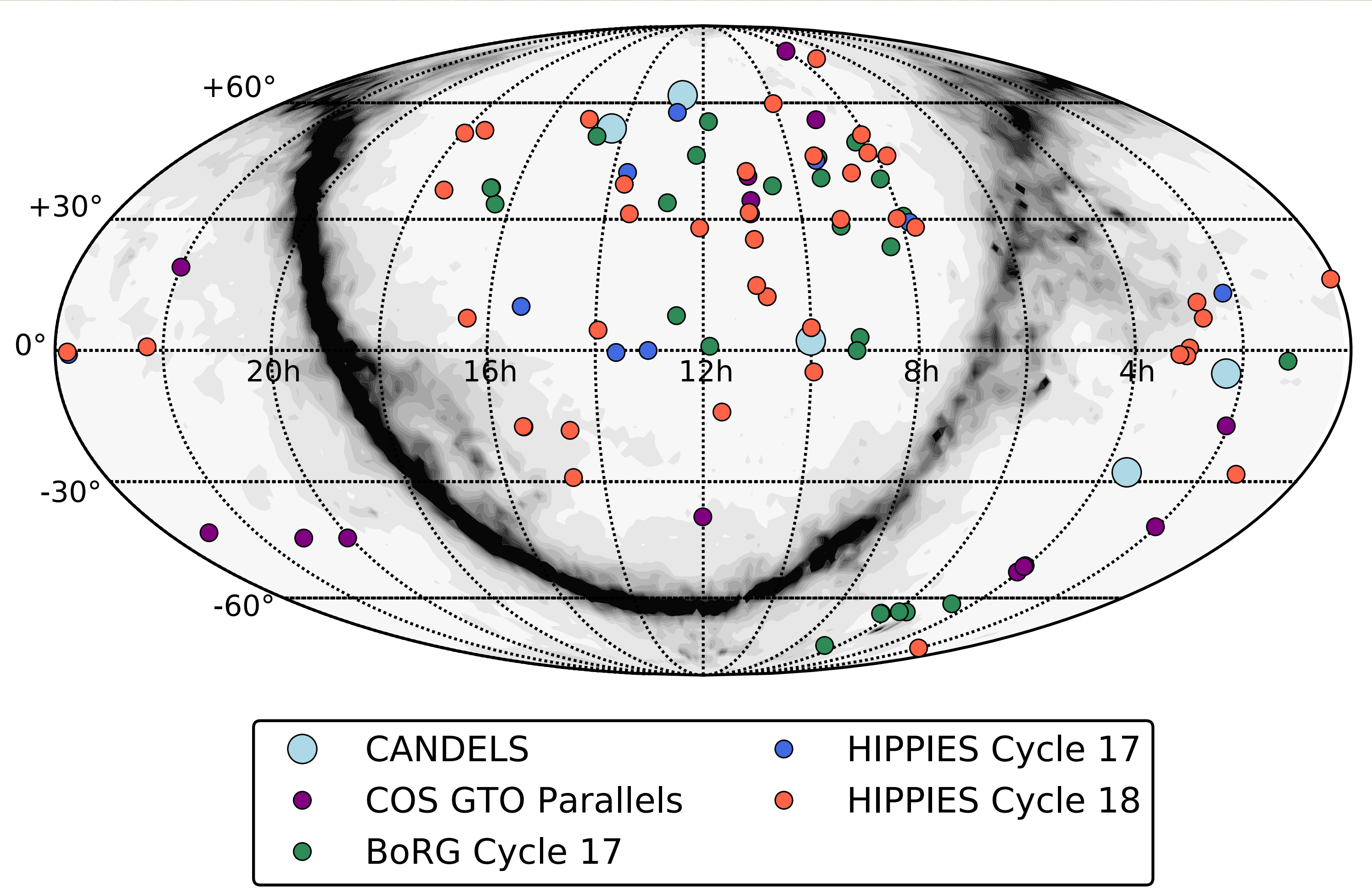
HIPPIES: Hubble Infrared Pure Parallel Imaging Extragalactic Survey



Hubble Space Telescope Focal Plane

- While other observers use the Cosmic Origins Spectrograph, we image a random patch of sky
- “Pure Parallel” since we don’t get to pick where we look
- Bonus data!
- Random fields avoid biases associated with existing well-studied fields

HIPPIES Fields



- 91 random fields
- 4–5 filters each
- 1141 individual exposures

- Need to automate:
  Interpolate over bad pixels
  Resample images
  Align images
  Measure correlated noise
  Detect objects

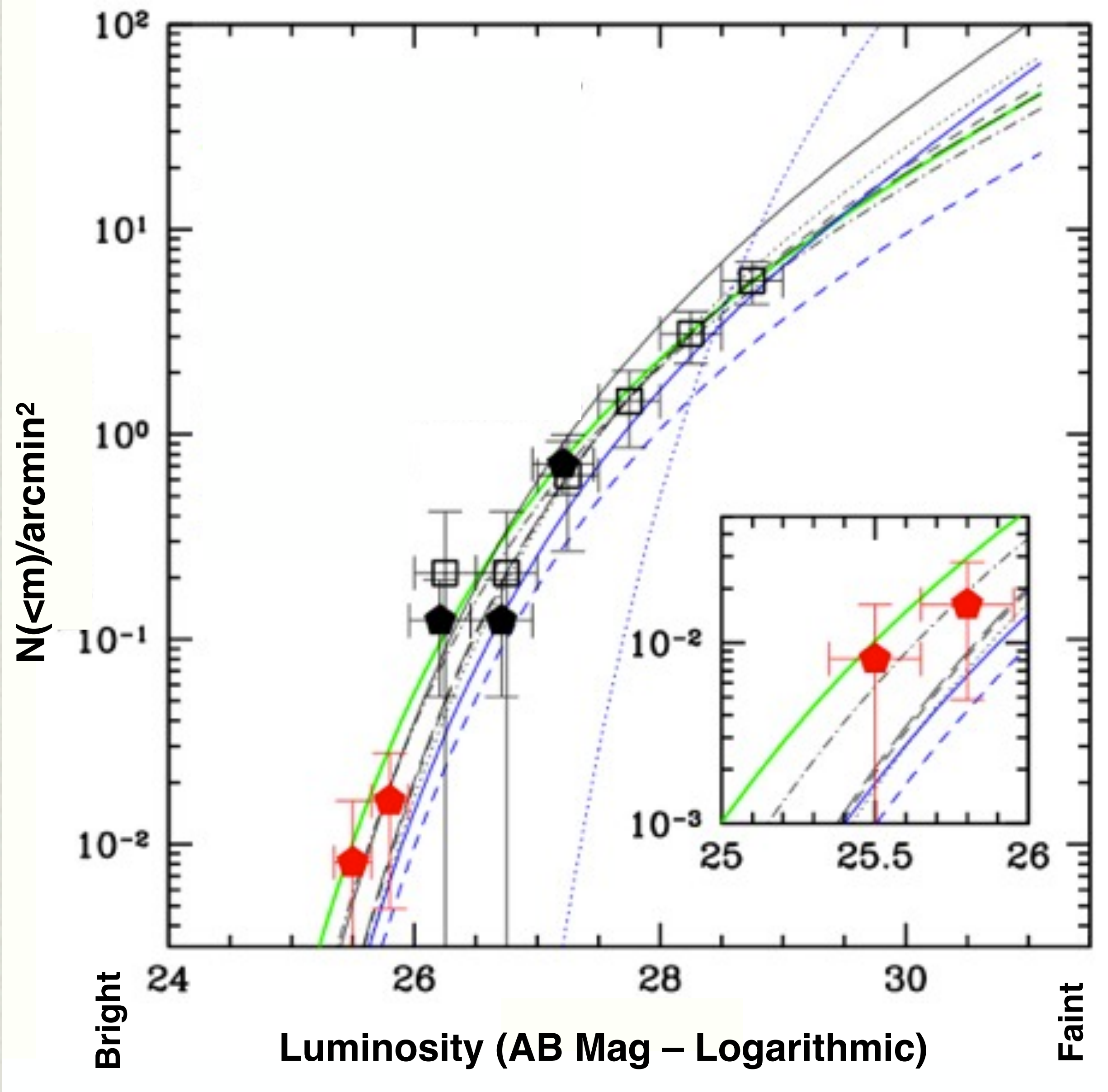
HIPPIES Python Pipeline

* Fully automated (just type go and leave for lunch)
* Replaced an IRAF task for calculating correlated noise and scaling the pixel-to-pixel uncertainty map. IRAF writes all sub-steps to disk, the Python version works in memory.
* Uses Numpy/Scipy for tasks like median filtering and autocorrelation. Speed is actually faster than IRAF.
* ~1300 lines of code and ~1.5 months of work, it's a beast mostly because of error-checking

HIPPIES Primary Science Goal: Measuring the z>7 Luminosity Function

- Essentially a luminosity histogram
- Useful for determining if there are enough galaxies to reionize the Universe
- HIPPIES gets the bright end (needs area)
  HUDF gets fainter bits (needs depth)
- HIPPIES avoids cosmic variance biases

Redshift z=7



Yan et al. 2011

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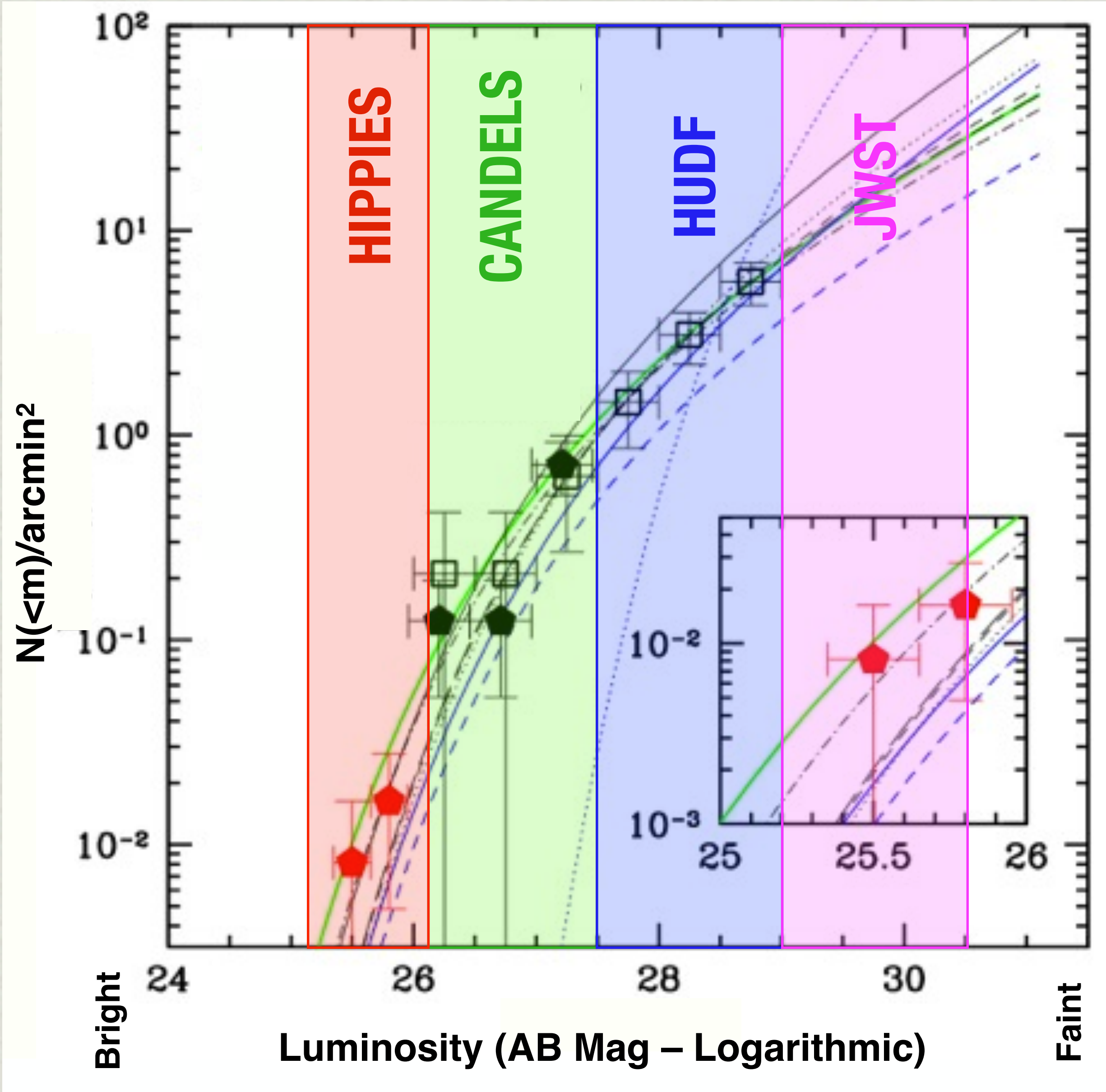


Yan et al. 2011

QUASARS

AGN Unification Model: Quasars are Active Galactic Nuclei (like Centaurus A here), pointed at your face

Quasars

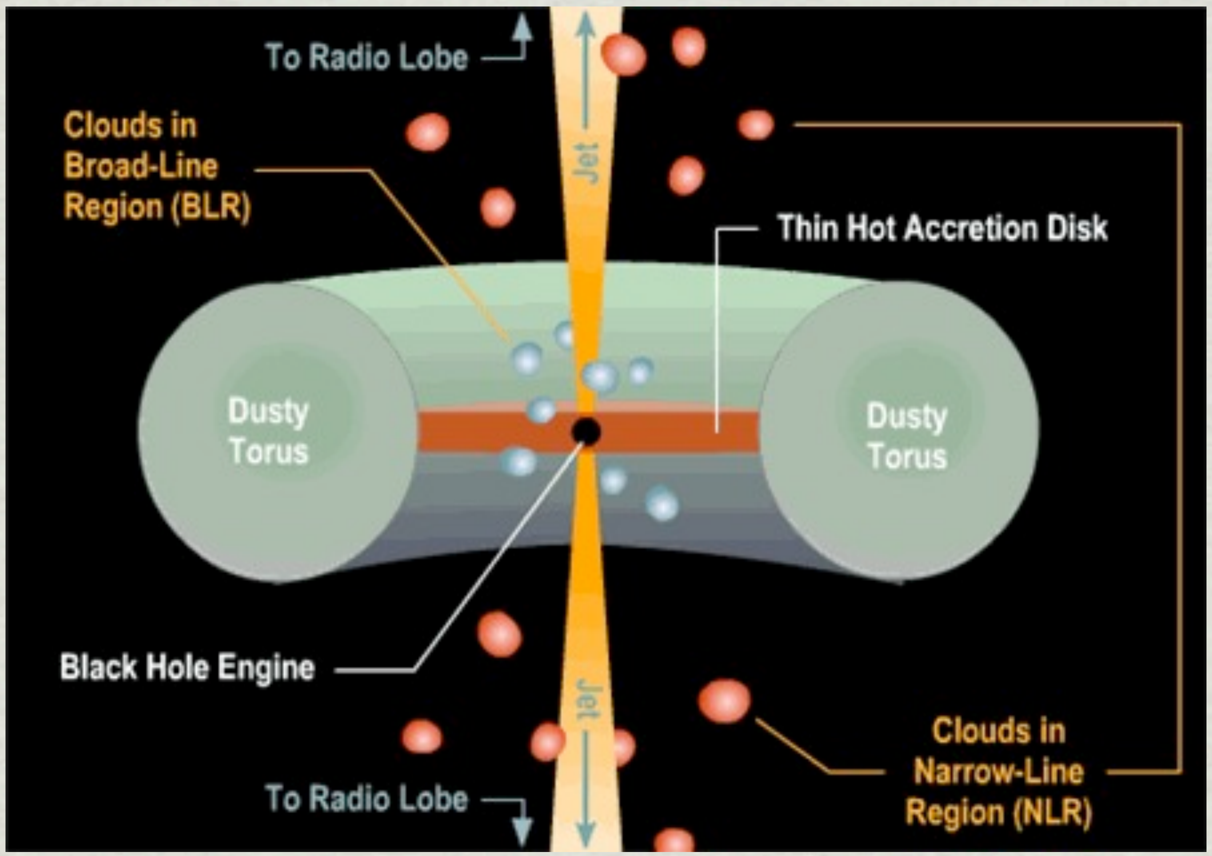


Illustration: Brooks/Cole Thomson Learning

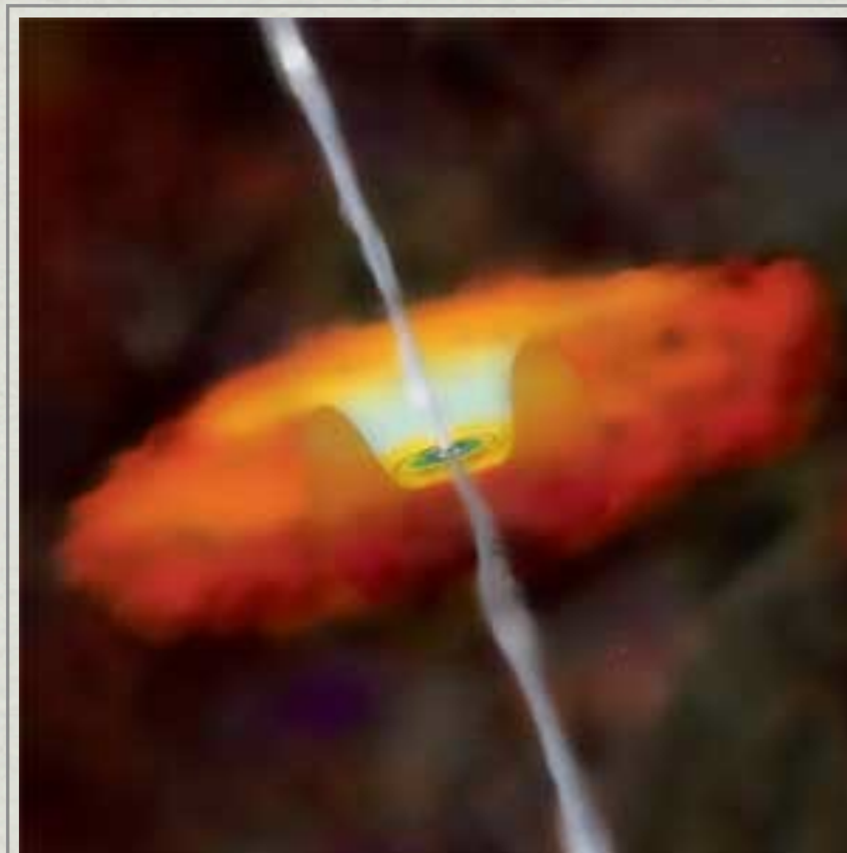
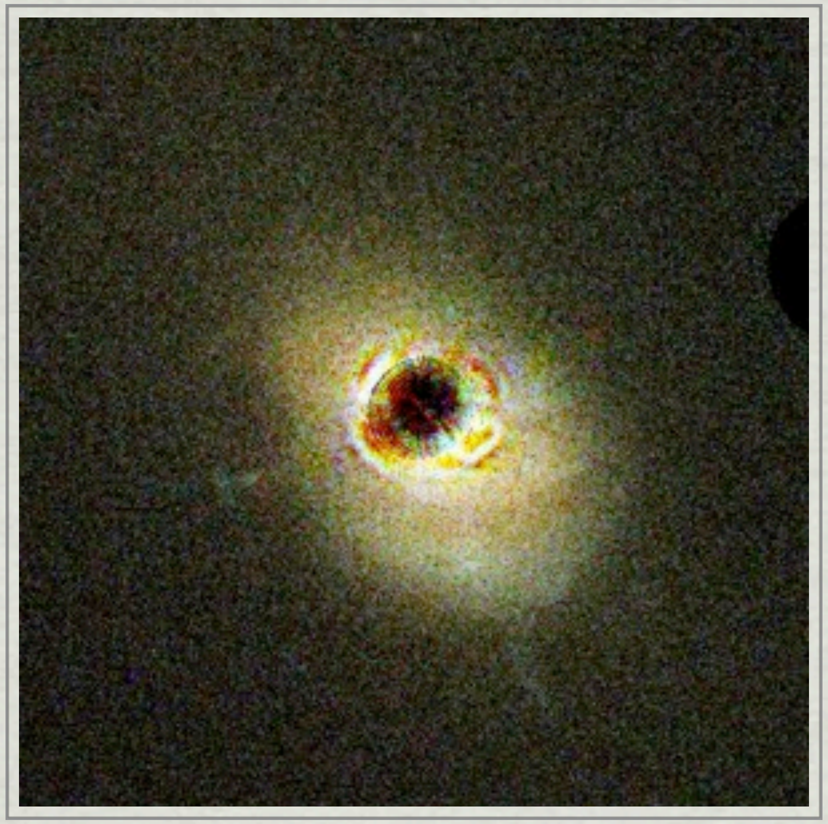


Illustration: Chandra X-Ray Observatory

- Torus is small, several parsecs in diameter. Surrounding galaxy is several *kilo*parsecs
- Can only image this directly for nearby galaxies

Point Source Subtraction

Original Hubble image

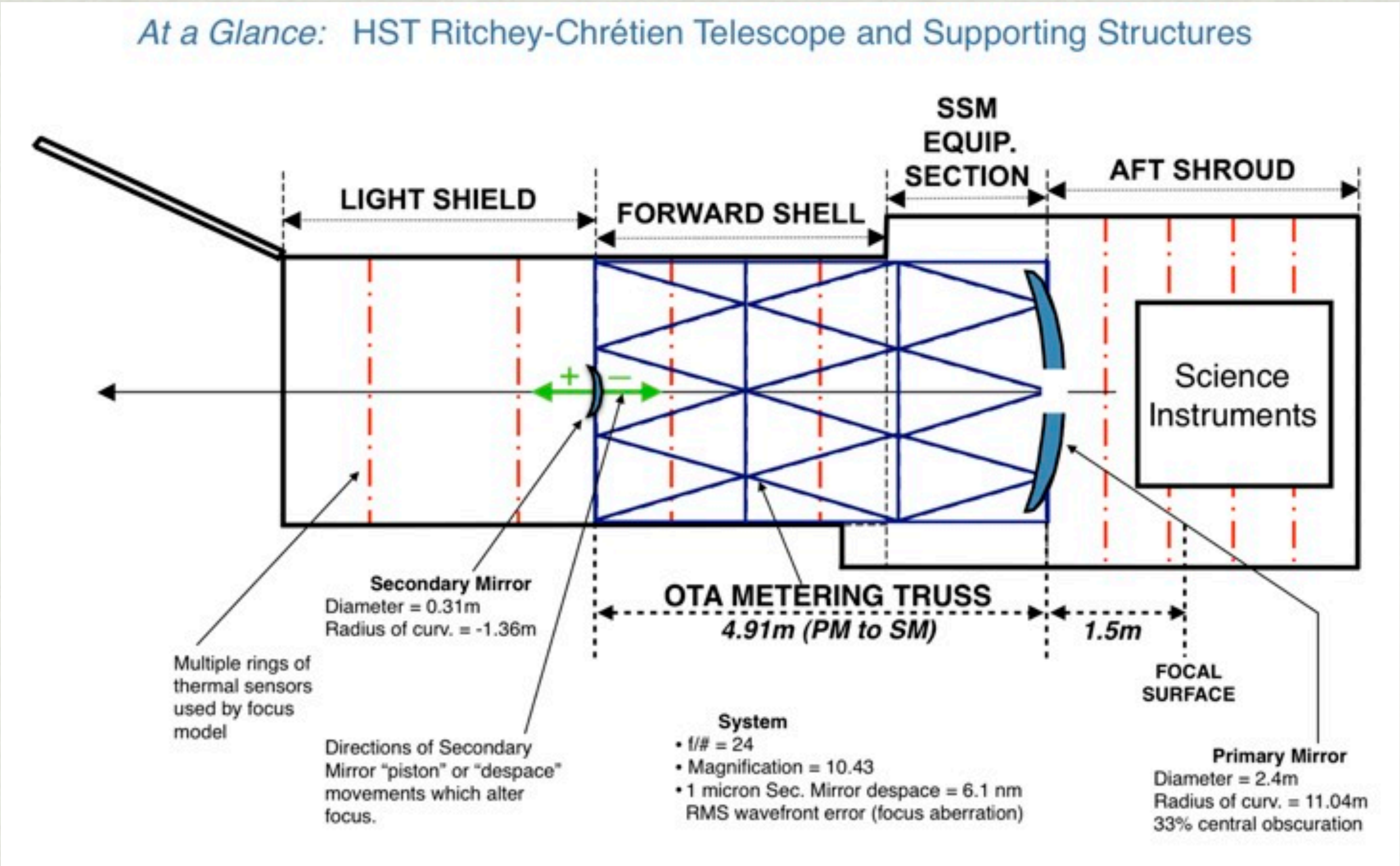


Quasar point source subtracted

Images: Hubblesite

- Lets us disentangle quasar and host galaxy light
- Can use empirical point source (star) or model
- Much harder for distant galaxies! Distant galaxies are small and would fit in the over-subtracted hole

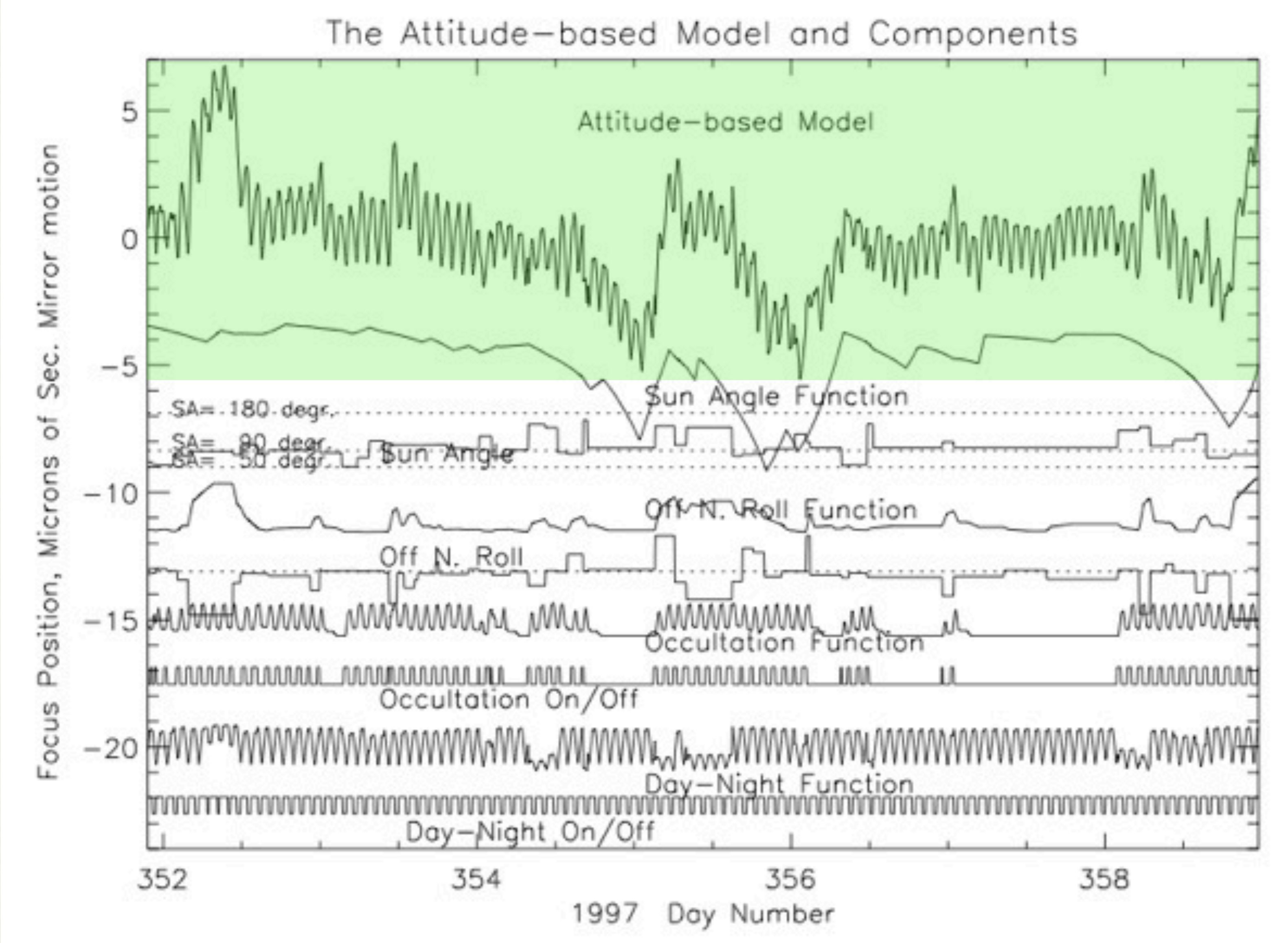
Spacecraft Breathing



- Secondary mirror truss moves, caused by changes in temperature

Spacecraft Breathing

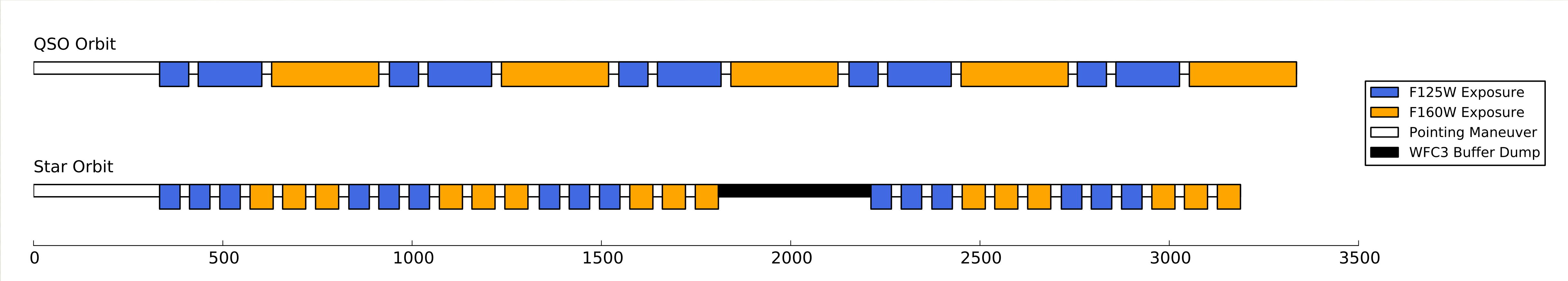
- Telescope focus changes with attitude and orbital day/night cycle
- Hershey (1998) and Cox & Niemi (2011) have modeled this quite well



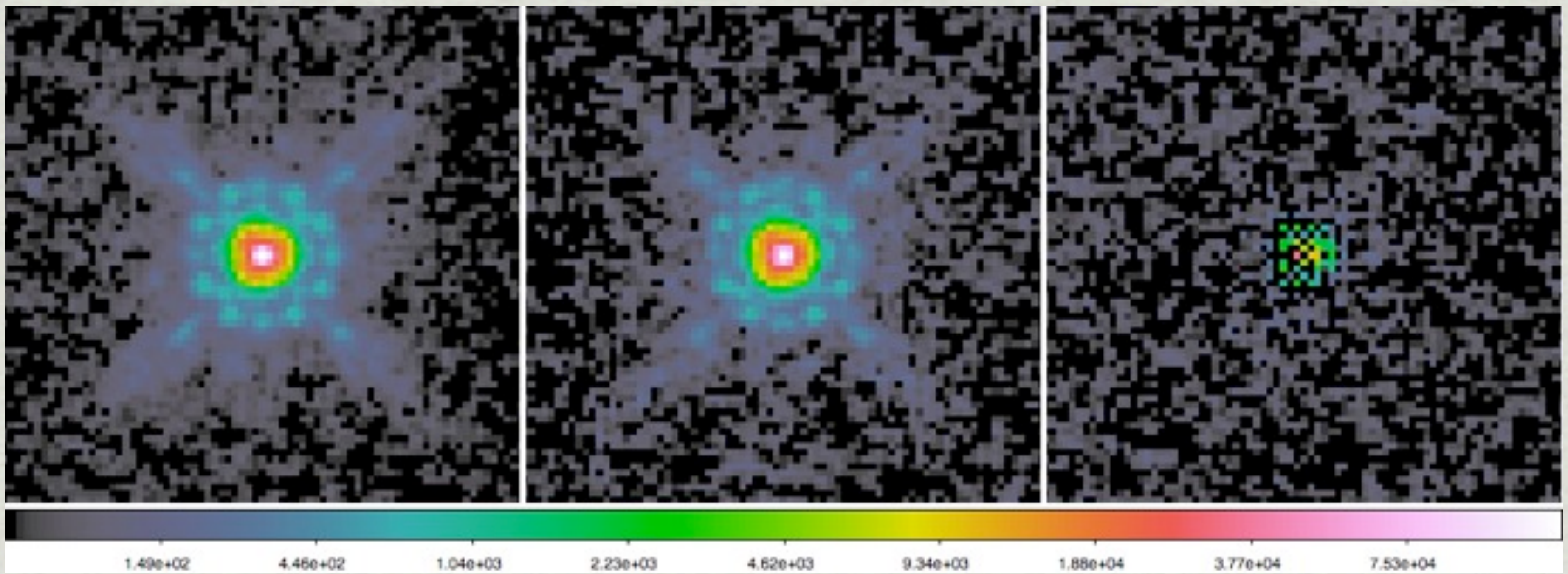
Hershey 1998

Ensuring Thermal Stability: A Solution!

- Pick a star nearby in the sky (to ensure similar telescope attitude)
- Observe in adjacent orbits
- Take matched exposures at the same point in orbital phase, to measure the PSF difference from day/night cycle



Let's Try Subtracting the Empirical PSF (Star)



Quasar **Star** **Residual**

- We used GalFit (Peng et al. 2006) to fit the empirical PSF (x,y shift and normalization)
- Tantalizing numeric residual, but cosmetically hideous
- Would prefer a spatially oversampled PSF, without adding more pixel noise

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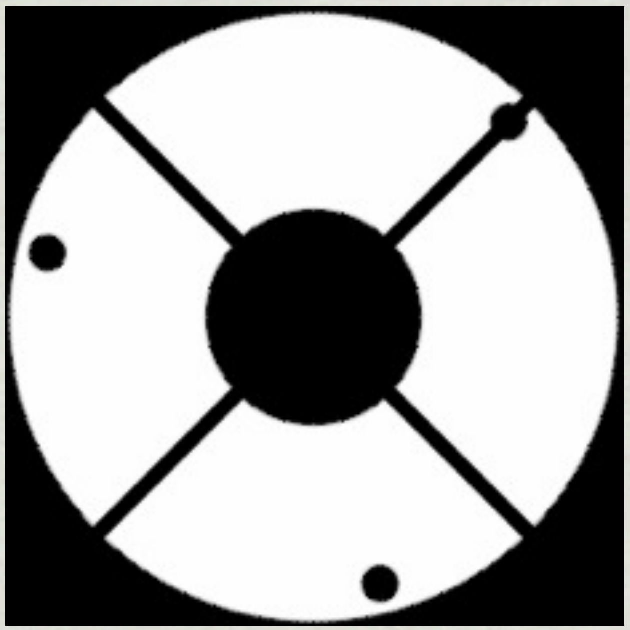
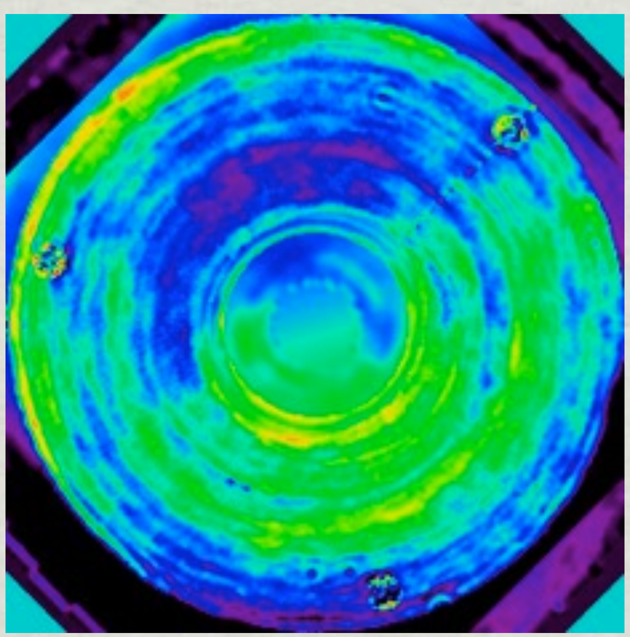
Theory of Fourier Optics (60 Second Version)

Wide Field Camera 3 Entrance Pupil

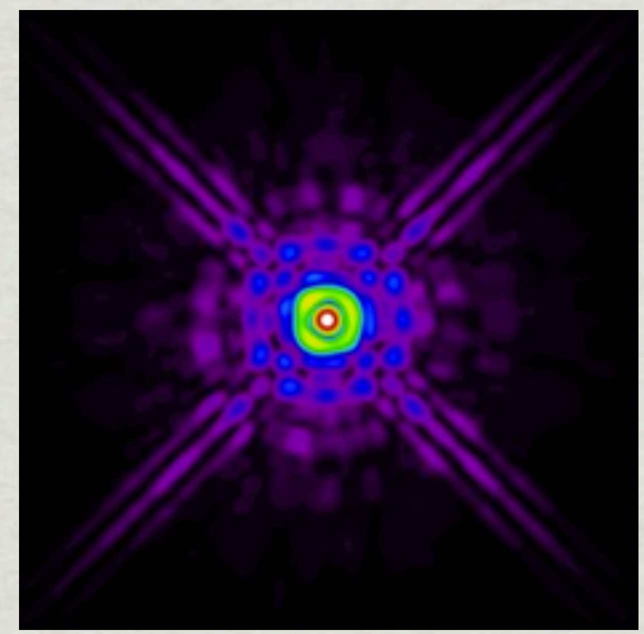
$\Re$ Part – Intensity



$\Im$ Part – Phase



Fourier Transform



$\Re^2$ – Point Spread Function

TinyTim software (Krist et al. 2011) does this to model the Hubble PSF

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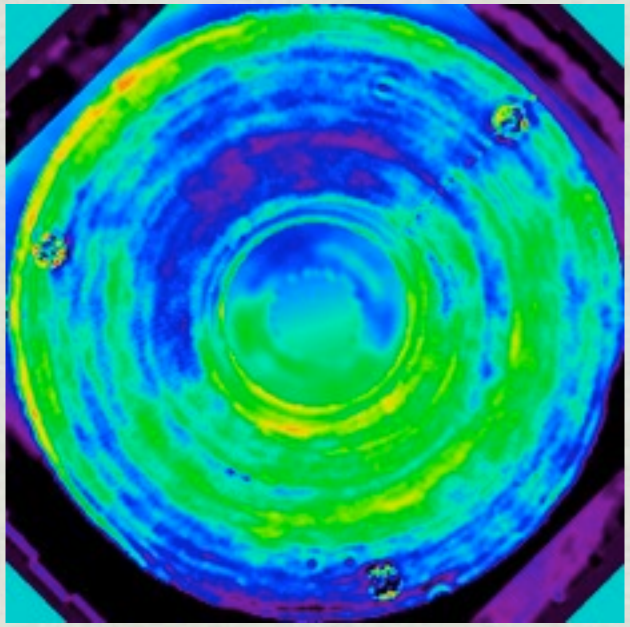
Optimize by Varying Zernike Coefficients



* Wavefront error (phase difference) can be adjusted using these polynomials

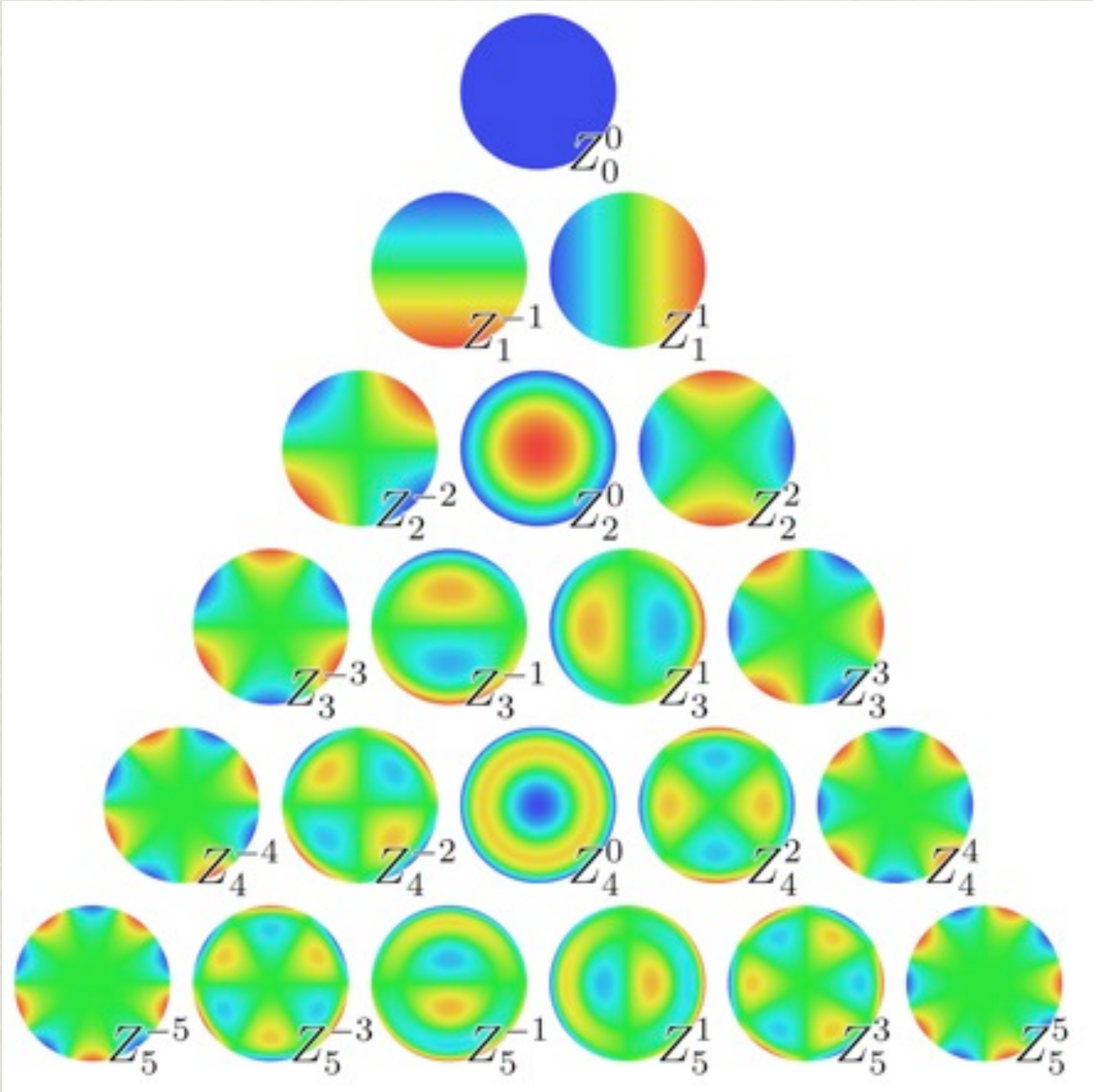


Image: Wikipedia

General Plan

1. Make model PSF that matches star image as well as possible

2. Subtract this model from the quasar

- For step 1, we need to generate many PSF models with varied aberration parameters, and minimize the fit residuals.

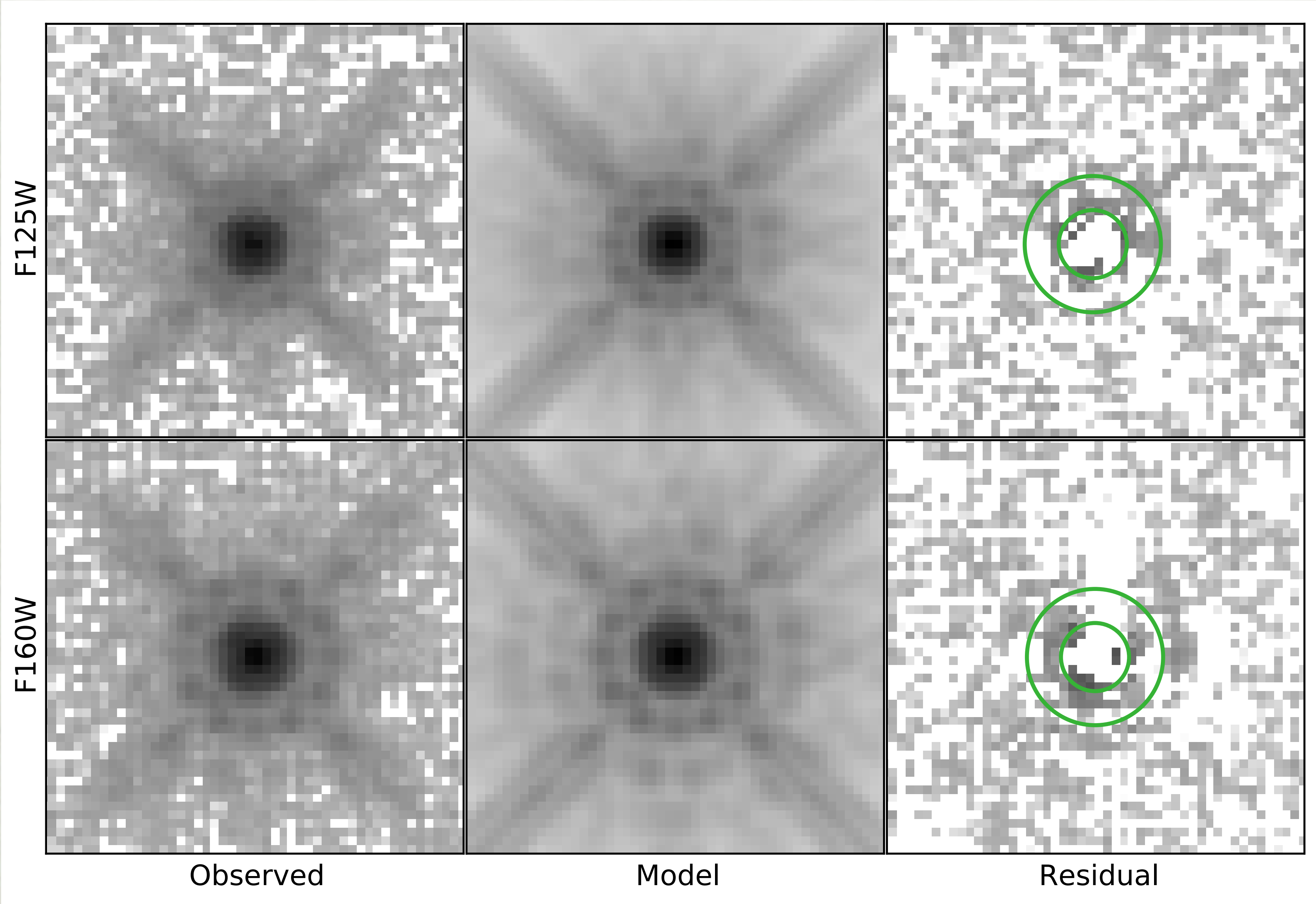
- What is the glue that will hold together TinyTim for modeling and GalFit for fitting? Who could it be...

Could it be... PYTHON?

- Simple grid of parameter space, not at all fancy
- ~10 minutes of programming (including one file not shown)

```
#!/usr/bin/python

import pyfits
import subprocess
from numpy import linspace, abs, zeros
import shutil
import itertools

pDict = dict()
pDict['x_astig'] = linspace(-0.02,0.02,7)
pDict['y_astig'] = linspace(-0.02,0.02,7)
pDict['x_coma'] = linspace(-0.1,0.1,7)
pDict['y_coma'] = linspace(-0.1,0.1,7)
pDict['focus'] = linspace(-8.00,-8.00,7) # Offset from ACS, in microns

bestChi2 = 2e15 # Something way too big

with open('stats.txt','w') as stats:
    stats.write(' '.join(pDict.keys())+ ' cdsigma chi2nu\n')

for params in itertools.product(*pDict.values()):
    stepDict = dict(zip(pDict.keys(),params))
    # Turn dict into k=v string
    clargs = ' '.join(['{0!s}={1!s}'.format(k,v) for k,v in stepDict.items()])
    # Generate PSF for these values
    subprocess.call('python ../TinyTim/mkPSF.py hTempl.par hexpsStar.txt '+clargs, shell=True)
    shutil.move('hPSFStar.fits','psf.fits')

    # Run galfit to determine how well it fits the data
    subprocess.call('galfit fit.feedme', shell=True)

    newChi2 = pyfits.getval('starFit.fits', 'CHI2NU', ext=2)

    with open('stats.txt', 'a') as stats:
        stats.write(' '.join(['%0.4f' % v for v in params])+' %0.4f %0.4f\n' % (sig, newChi2))

    # If it beat the last one, replace best fit/psf files
    if abs(newChi2-1) < abs(bestChi2-1):
        bestChi2 = newChi2
        shutil.move('starFit.fits', 'bestFit.fits')
        shutil.move('psf.fits', 'bestPSF.fits')
```

Optimized PSF



- A marginal detection (upper limit) like the empirical subtraction, but improved S/N (even after accounting for errors in the model)

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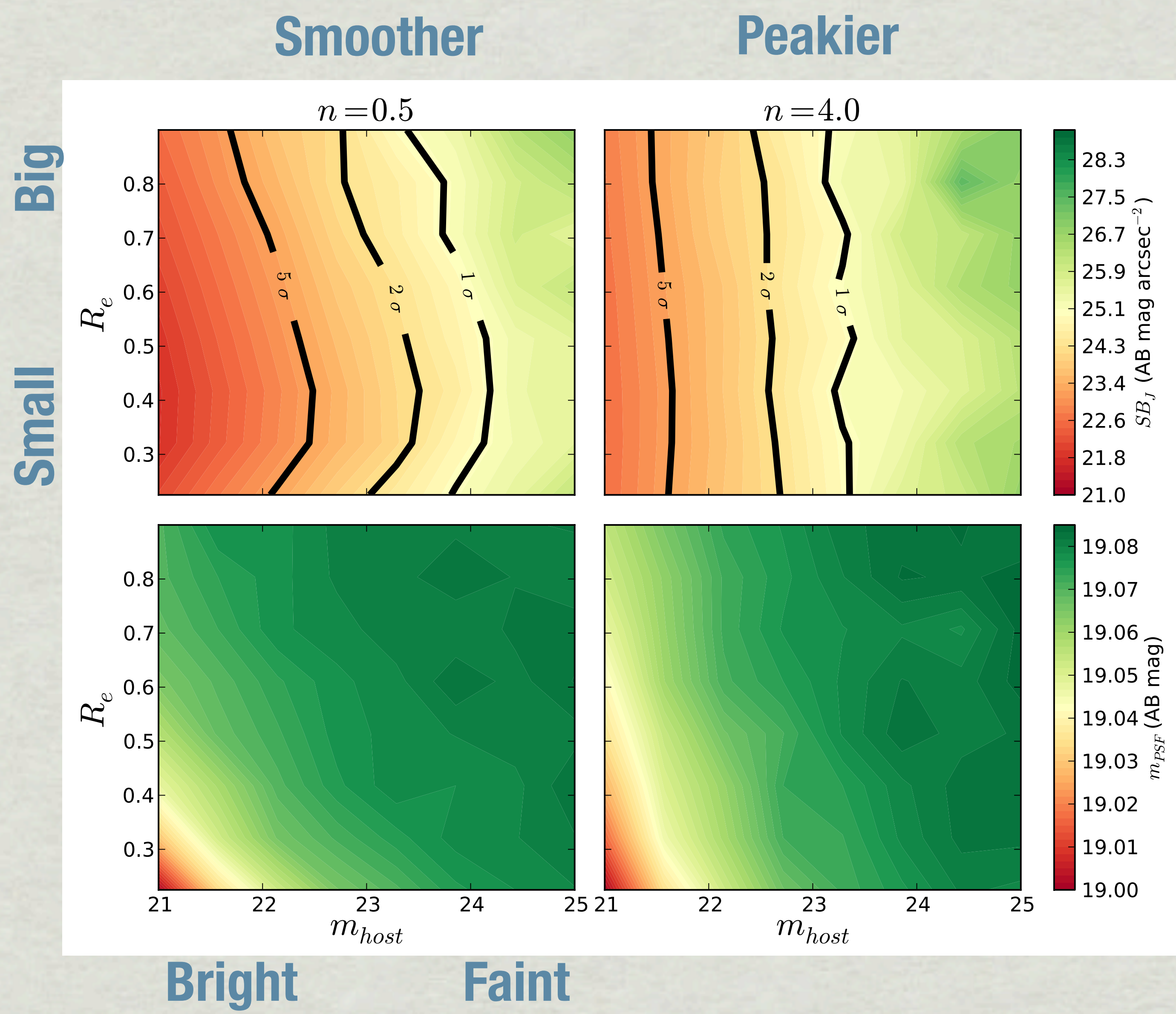
Reliability Modeling

- Make model galaxies + point source, do our subtraction
- Determines our ability to recover host galaxy light, as a function of the host galaxy's parameters
- Varied radius, brightness, Sérsic index ("peakiness")

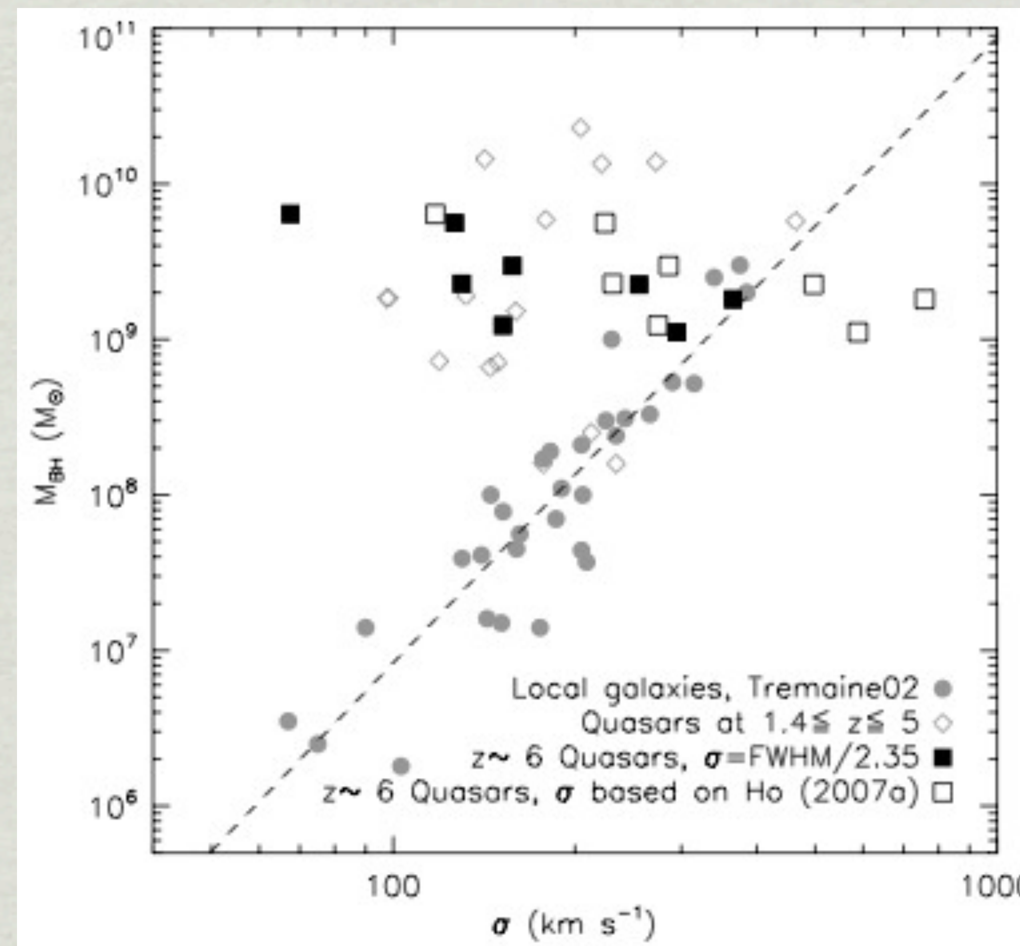


What Does This Tell Us?

- Galaxy seems too small for its black hole, if the local relation holds. Maybe black holes form first?

- Star formation rate consistent with that measured from heated dust – ~2000 M$_\odot$/yr (Milky Way is ~1 M$_\odot$/yr)

Black Hole Mass



Wang et al. 2010

Velocity Dispersion
(Proxy for Galaxy Mass)

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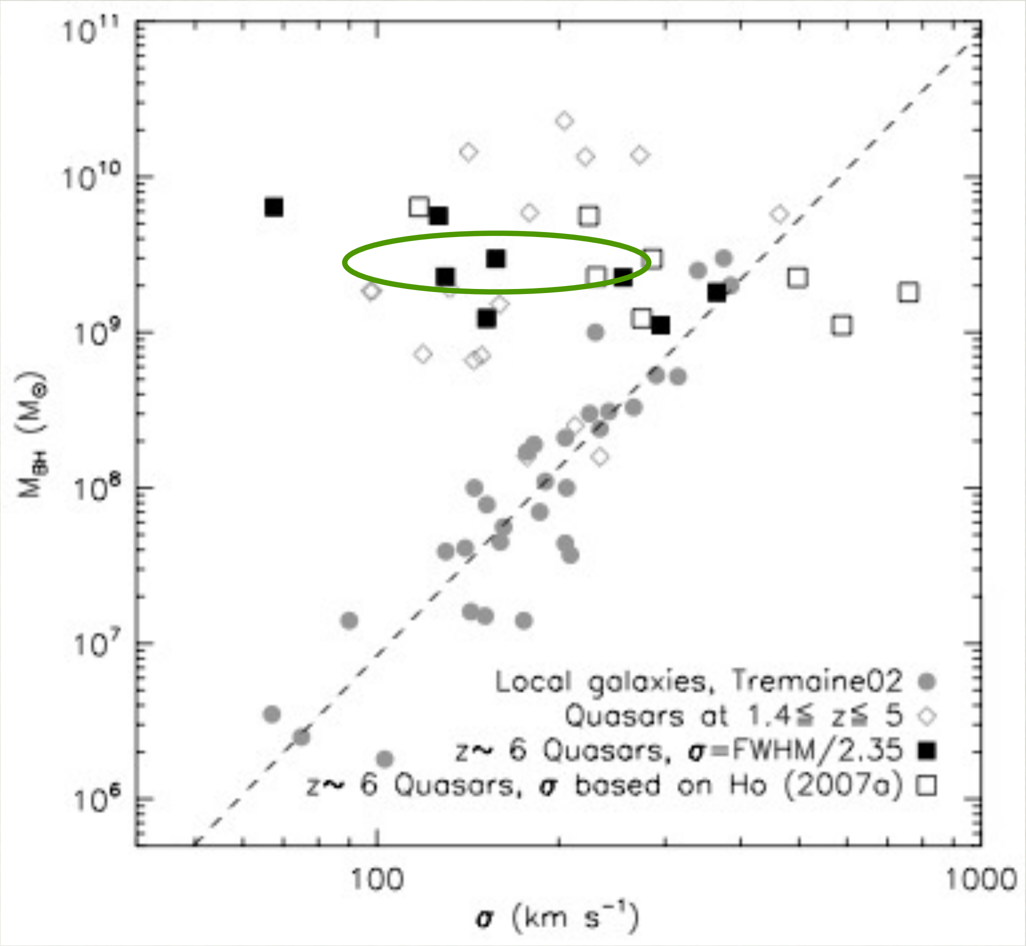
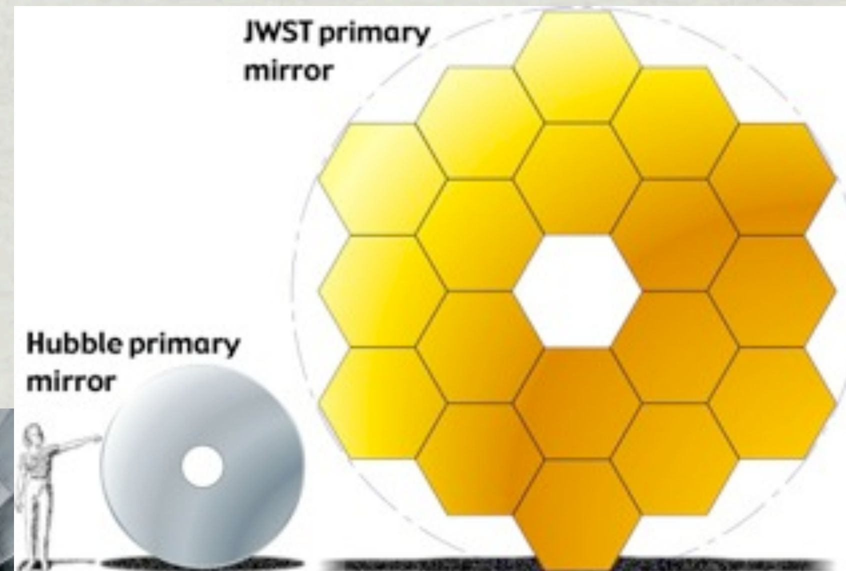
Black Hole Mass

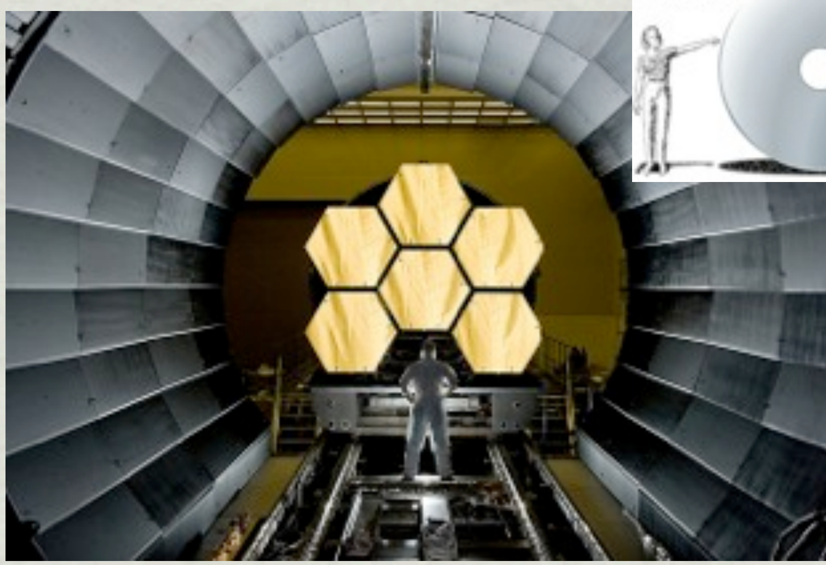


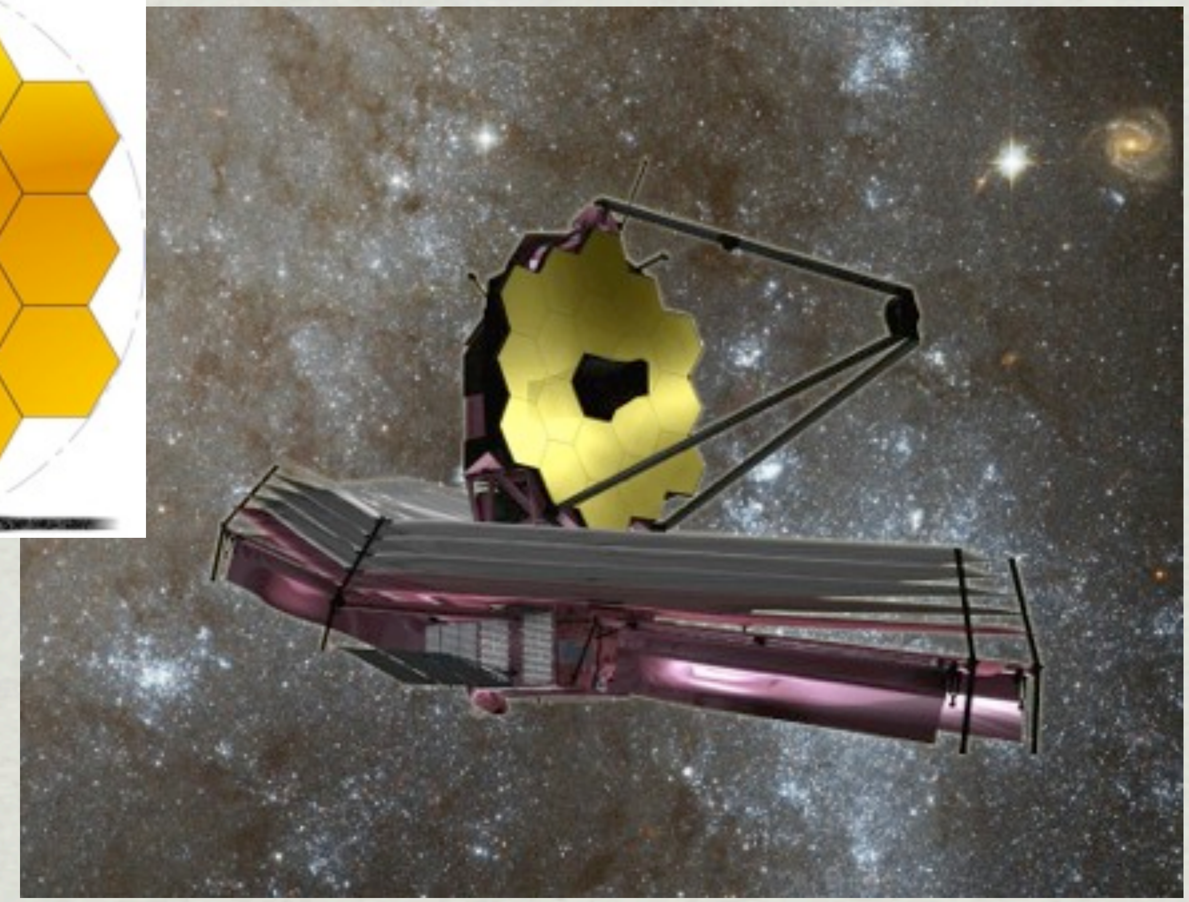
Wang et al. 2010

Velocity Dispersion
(Proxy for Galaxy Mass)

The Future:
James Webb Space Telescope







- 6.5 meter infrared-optimized space telescope
- Launch in ~2018

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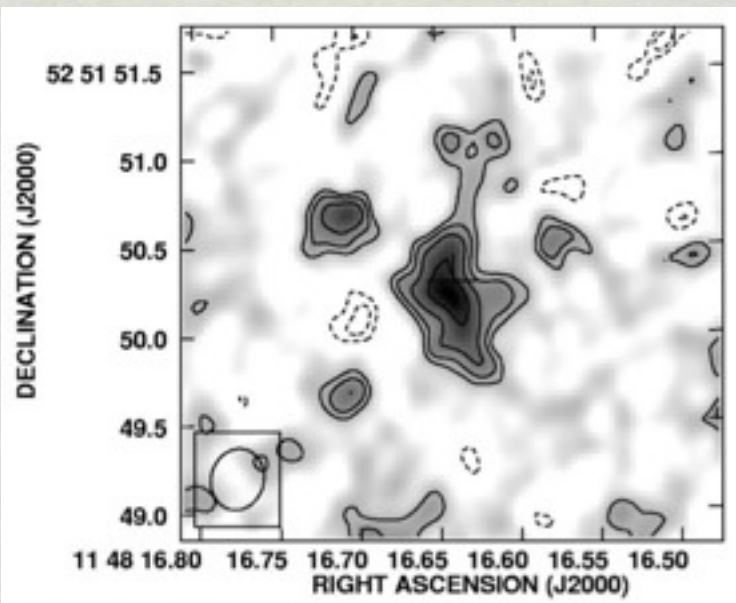
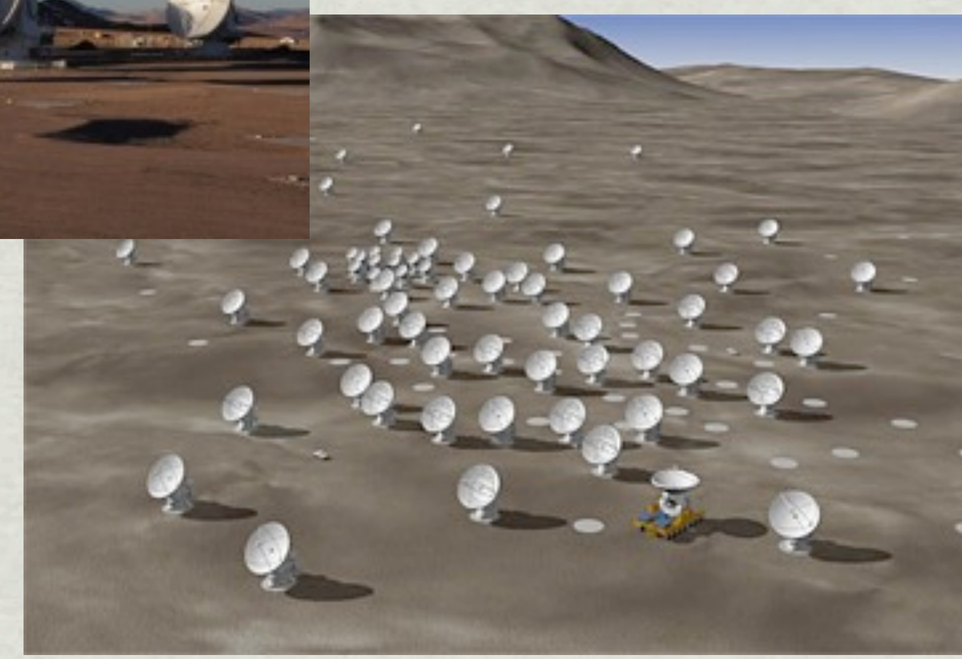
The Future: Atacama Large Millimeter Array



CO emission from quasar host galaxy Walter et al. 2004



- Millimeter-wave radio telescope array in Atacama Desert, Chile. ~50 12-m antennas when complete
- Better sensitivity and site than any other radio telescope

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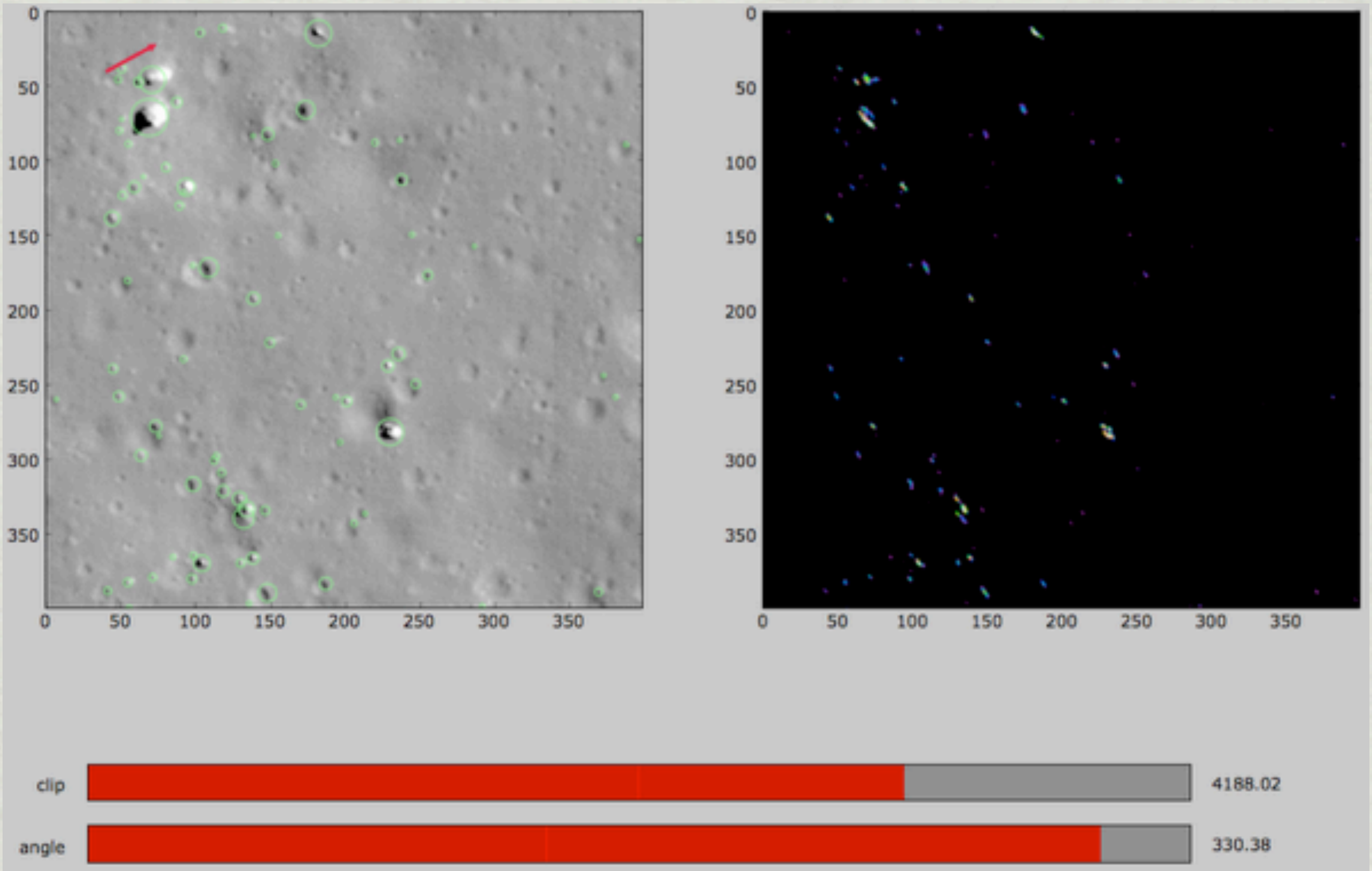
Bonus Pretzel: Finding Rocks on the Moon



- Uses scipy.ndimage for image thresholding and gradients. Matplotlib widgets for interactive parameter tuning!

Conclusions

- Use (or make) tools that enable rapid iteration!
- Optimize for your time programming, as well as the usual things
- HIPPIES: There may be more very bright galaxies than expected at redshifts z>7
- Quasars: The most distant quasar host galaxies may be fainter than expected, or *very* compact. Future observations with JWST and ALMA should tell us for sure!