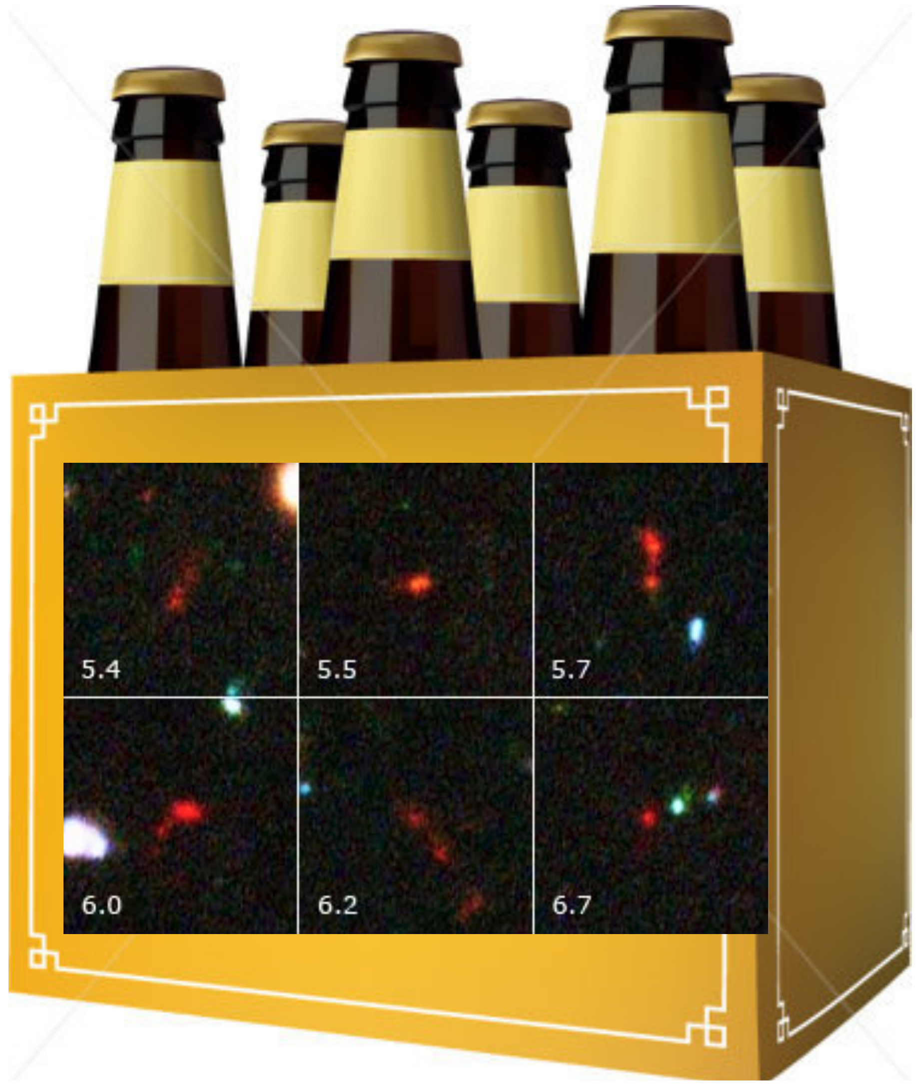
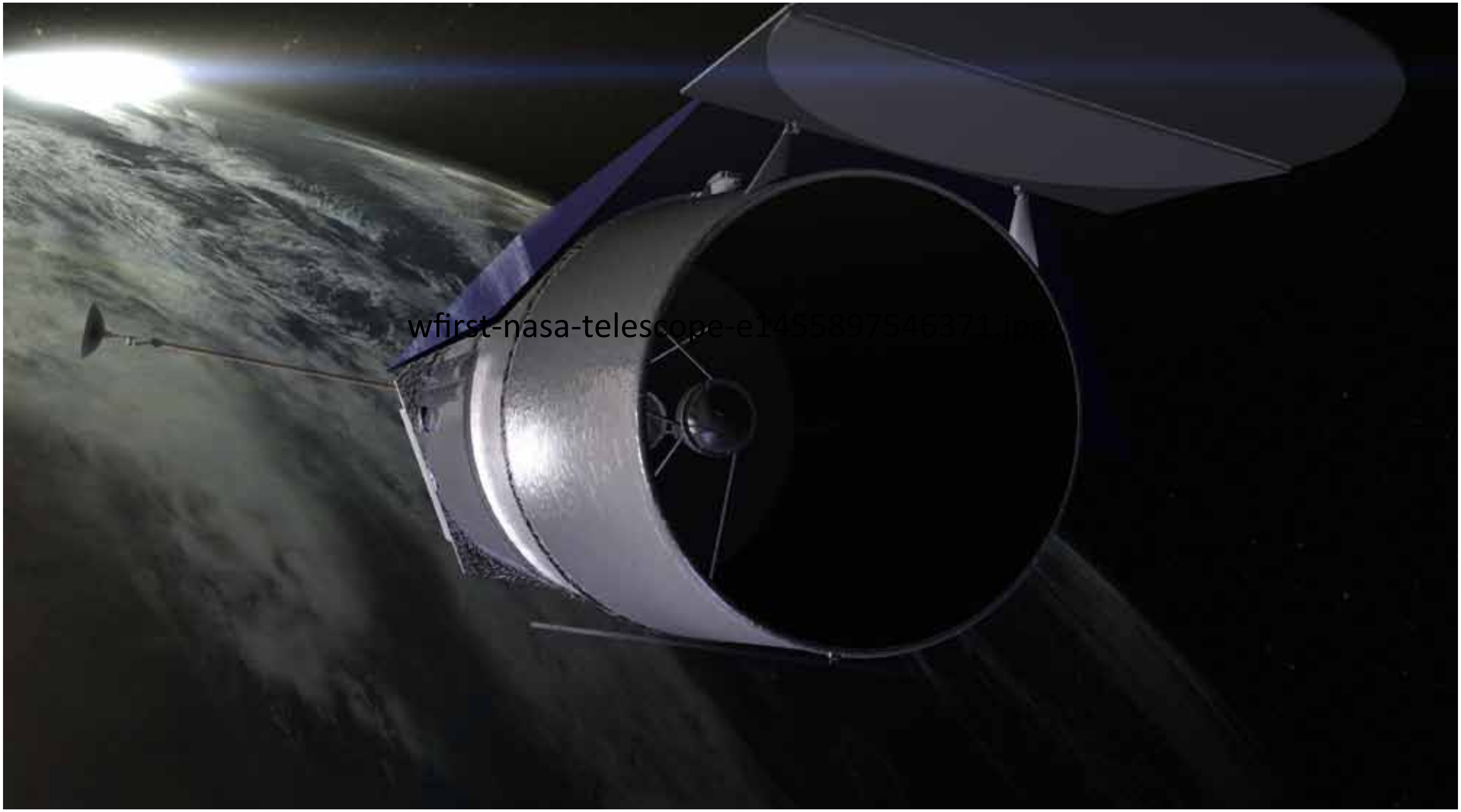
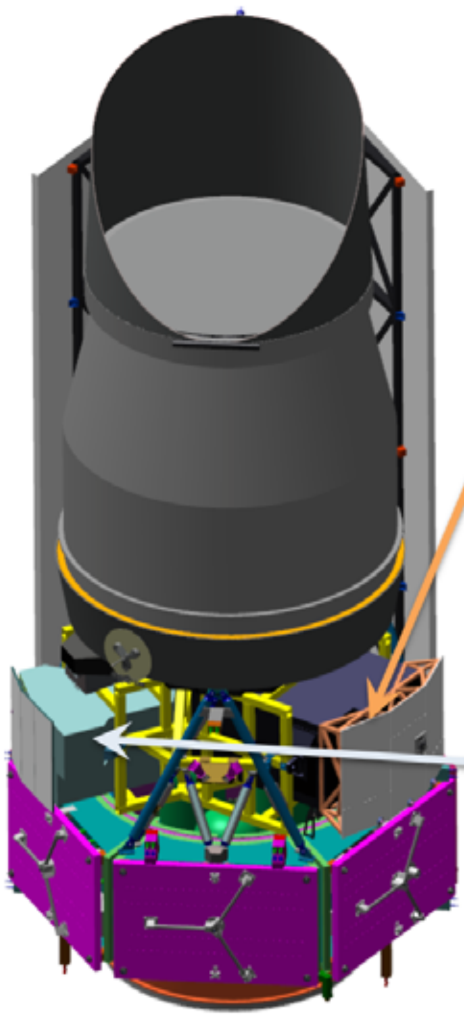
Beyond the six-pack statistics quasars and galaxies at high-z



WFIRST



WFIRST Instruments



Wide-Field Instrument

- *Imaging & spectroscopy over 1000s of sq. deg.*
- *Monitoring of SN and microlensing fields*
- 0.7-2.0 μm (imaging), 1.1?-1.89 μm (spec.), 0.45-2.0 μm (IFU)
- 0.28 deg^2 FoV (100x JWST FoV), 9 $asec^2$ & 36 $asec^2$ (IFU)
- 18 H4RG detectors (288 Mpixels), 2 H1RG detectors (IFU)
- 6 filter imaging, grism + IFU spectroscopy

Coronagraph

- *Image and spectra of exoplanets from super-Earths to giants*
- *Images of debris disks*
- 430 – 970 nm (imaging) & 600 – 970 nm (spec.)
- Final contrast of 10^{-9} or better
- Exoplanet images from 0.1 to 1.0 arcsec

Hubble - A Spectacular Start

The Hubble Ultra Deep Field
seeing the Universe, 10,000
galaxies at a time

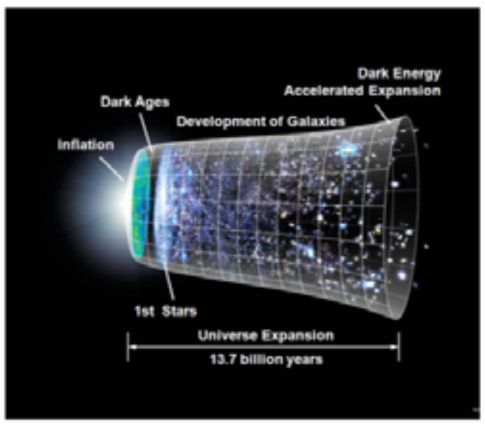
WFIRST-AFTA - Hubble X 100

An AFTA/WFIRST Deep Field
A New Window on the Universe - **1,000,000** galaxies at a time

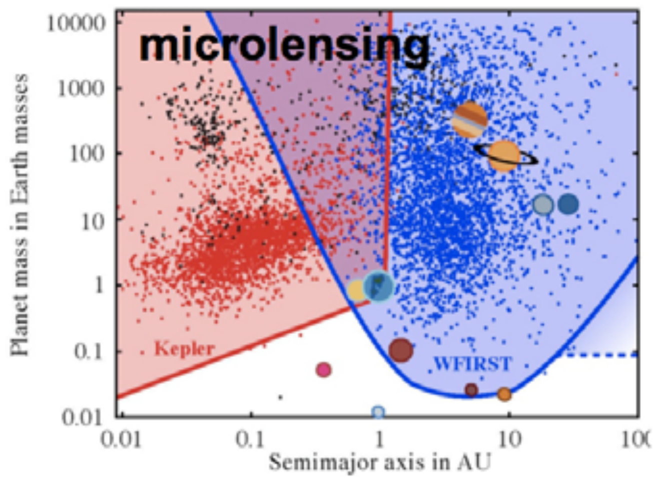
Discovery Science

- WFIRST was highest ranked large space mission in 2010 Decadal Survey
- Use of 2.4m telescope enables
  - Hubble quality imaging over 100x more sky
  - Imaging of exoplanets with 10^{-9} contrast with a coronagraph

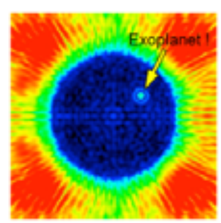
Dark Energy



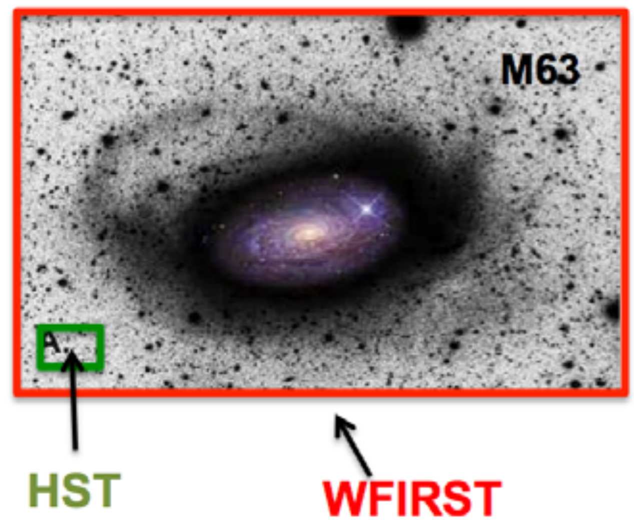
Exoplanets



coronagraph



Astrophysics



Yields

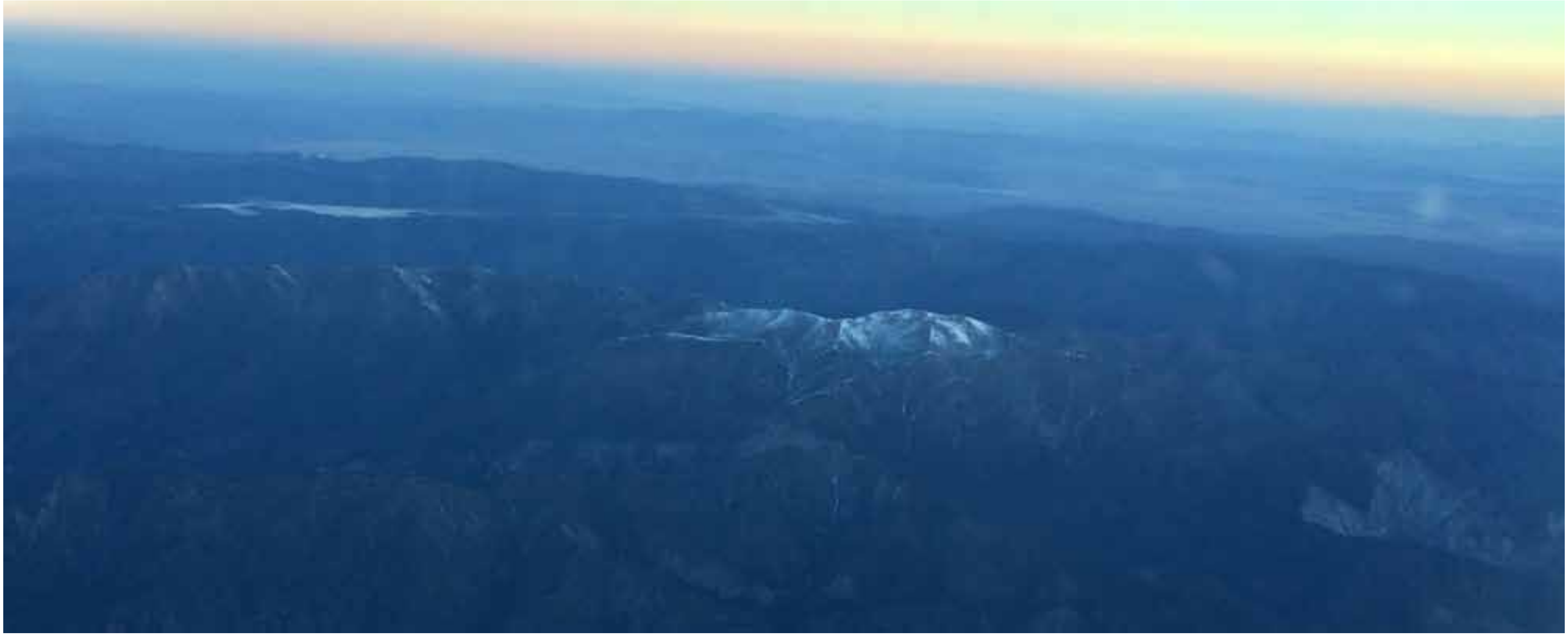
Attributes	WFIRST Yields
Imaging survey	J ~ 26.7 AB over 2200 sq deg
	J ~ 29 AB over 3 sq deg deep fields
Slitless spectroscopy	R ~ 461λ over 2200 sq deg
Number of SN Ia SNe	2700 to z~1.7
Number galaxies with spectra	2×10^7
Number galaxies with shapes	4×10^8
Number of galaxies detected	few x 10^9
Number of massive clusters	4×10^4
Number of microlens exoplanets	2600
Number of imaged exoplanets	10s

Cosmic Dawn and Reionization

A. Properties of first stars, galaxies, quasars
B. Reionization
    When: and how long?
    Who: quasars, galaxies – big, small?
    Where: how inhomogeneous?

Cosmic Dawn with WFIRST

James Rhoads, **Sangeeta Malhotra**, Xiaohui Fan, Steven Finkelstein, Rolf Jansen, Hannes Jensen, Garrelt Mellema, Casey Papovich, Vithal S. Tilvi, Rogier Windhorst,
Isak Wold, Erik Zackrisson.
(malhotra@asu.edu)



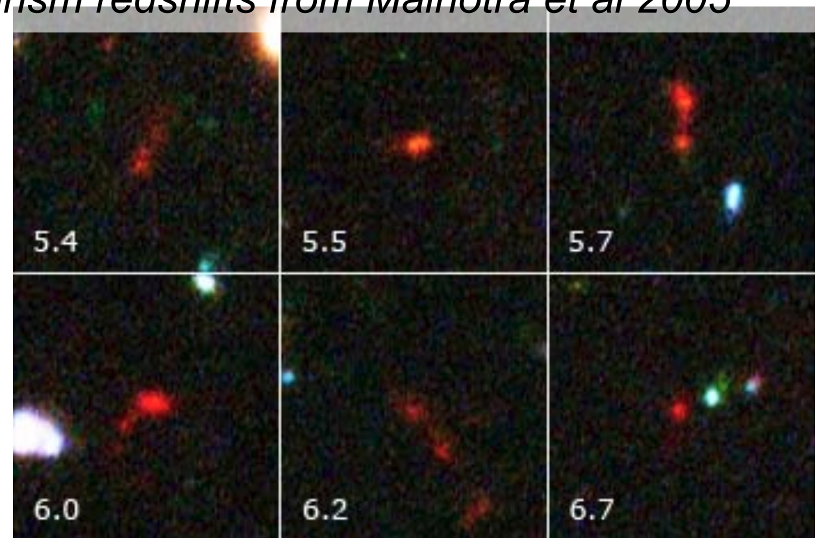
Ways to Study Reionization

- Look for the ionizing sources, estimate ionizing photon production, and compare to requirements for (re)ionization.
  - Galaxies
  - Quasars [or AGN more generally]

- Look for evidence of neutral gas and/or evidence of free electrons.
  - Lyman alpha galaxy statistics
  - Quasar spectroscopy

- We will explore all of these in detail for WFIRST capabilities.

Lyman break galaxies with HST slitless grism redshifts from Malhotra et al 2005



Mellema, Iliev, Pen, Merz, Shapiro, & Alvarez: reionization simulation

Results from deep HST grism

Sangeeta Malhotra (malhotra@asu.edu)

GRAPES: HUDF, G800 10 orbits x 4 PAs

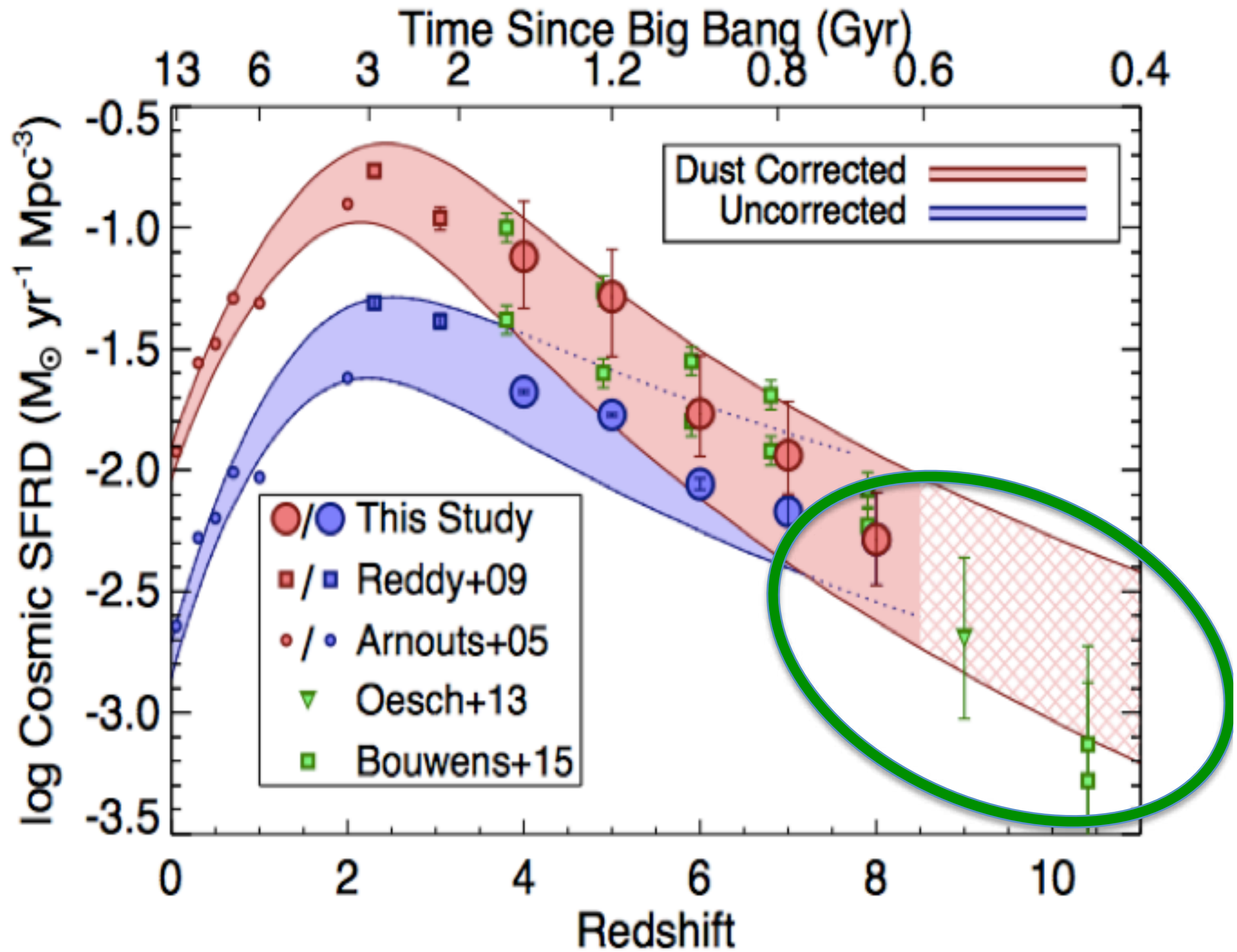
PEARS: G800, 8 fields to 5 x 4 PAs

FIGS: G102, 4 fields 8x5PAs

(Deep Imaging data from HST)

Hunting the Sources of Reionization: Star Forming Galaxies

- Star formation rate density history from Finkelstein et al 2015.
- WFIRST GO/GI surveys will help fill out the high-*z* end of this with incredible sample sizes.
- Will complement small but deeper JWST fields.

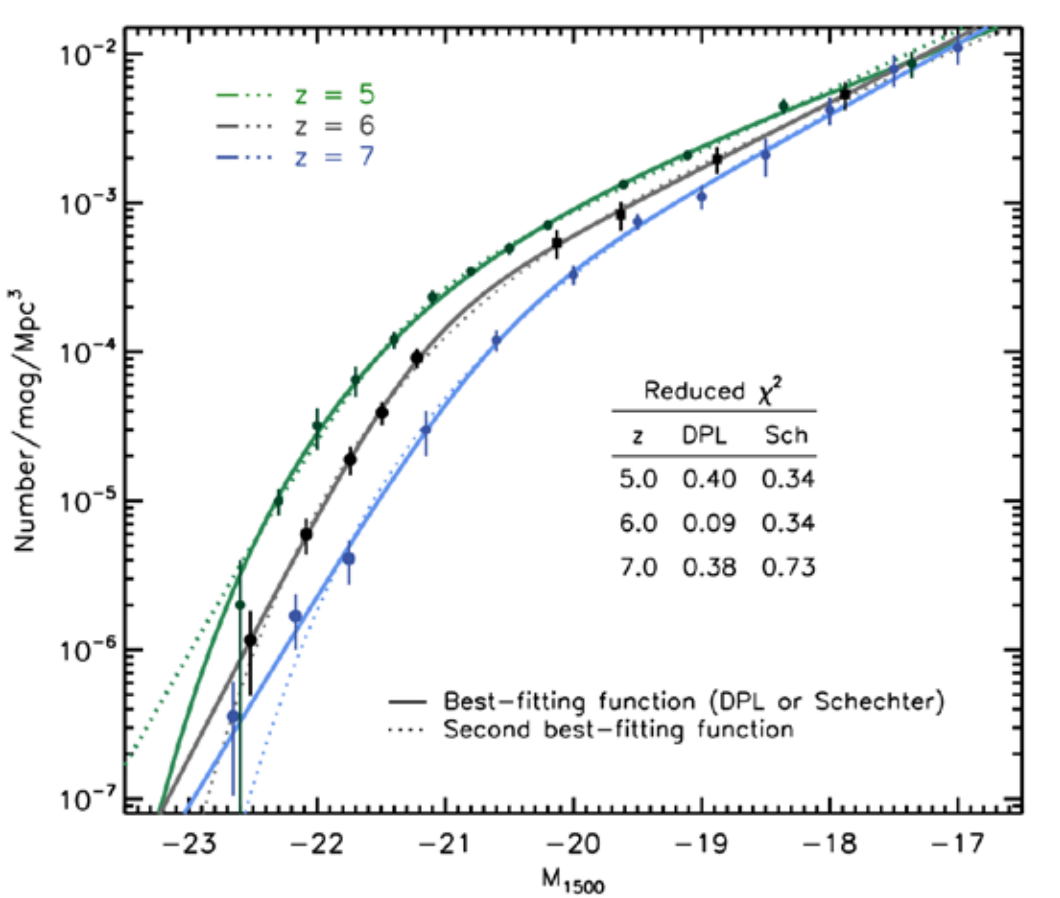


Hunting the Sources of Reionization: Star Forming Galaxies

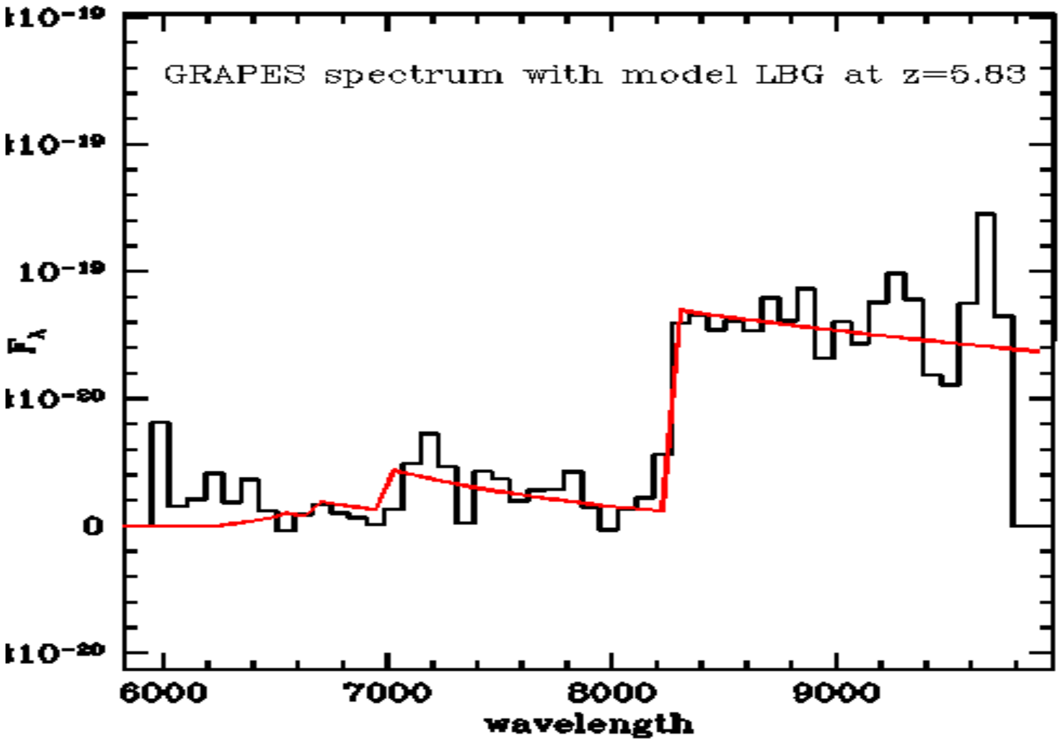
- When you have this many objects, you can do new things:
- E.g.: Test recent suggestions that the z ~ 7 galaxy luminosity function has an excess of bright sources (Bowler et al 2013)
- With WFIRST, we can look for deviations from Schechter functions with high statistical significance.
- Physical implications: Testing feedback...

Luminosity functions at z ~7

Bowler et al. 2015

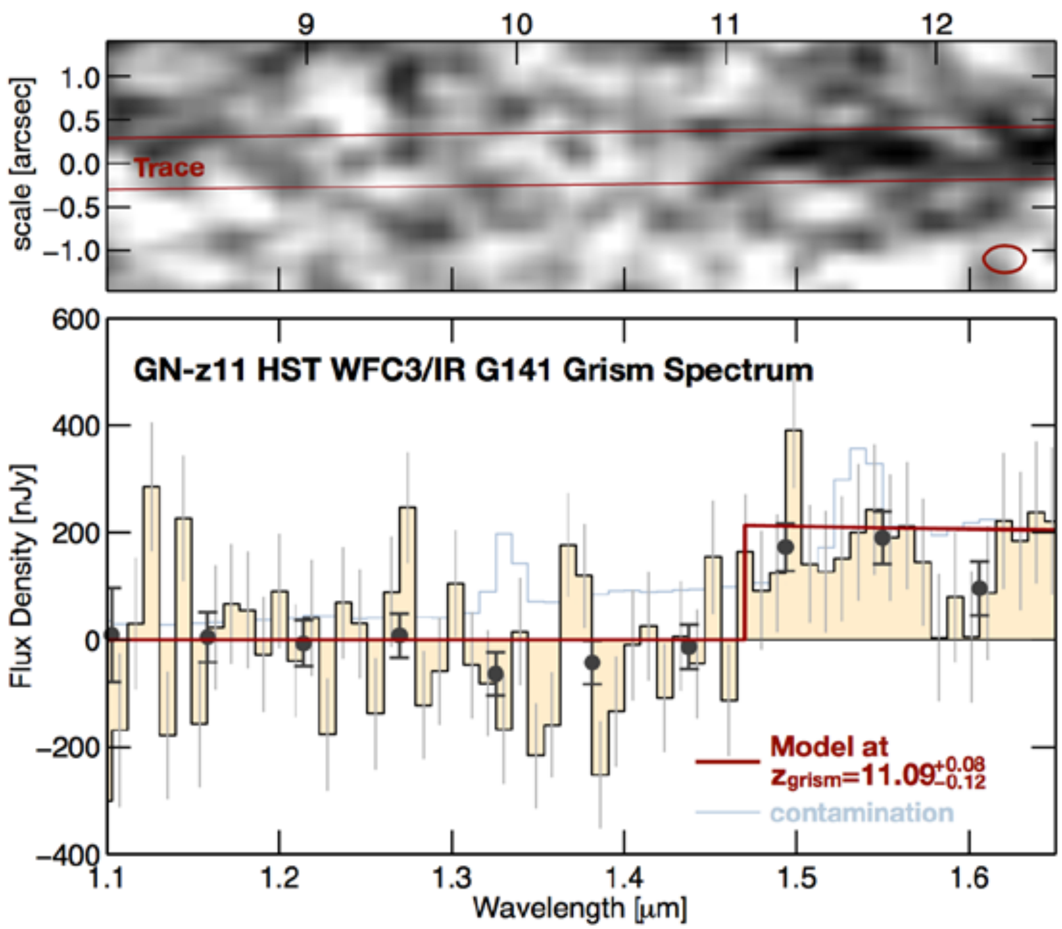


Deep HST slitless grism data



Malhotra et al. 2005

Z=11 galaxy (Oesch et al. 2016)



Hunting the Sources of Reionization: Quasars and AGN

- Accretion onto black holes → hot accretion disks → ionizing photon production.
- Census of AGN used to say, not enough for reionization. Recent changes:
  - Lower redshift of reionization from Planck;
  - New census of AGN from GOODS + CANDELS + 4 Msec CXO observations (Giallongo et al 2015)

AGN and Reionization with WFIRST

- Red: Ionizing photons needed for IGM ionization
- Black: Produced by AGN (Giallongo et al 2015)
- The Willott et al (2010) LF
  - 2500 z ~ 7 QSOs,
  - 600 z ~ 8 QSOs,
  - 130 z ~ 9 QSOs, and
  - A handful up to z ~ 12.
- ***Number of z>7 QSOs today: One!***

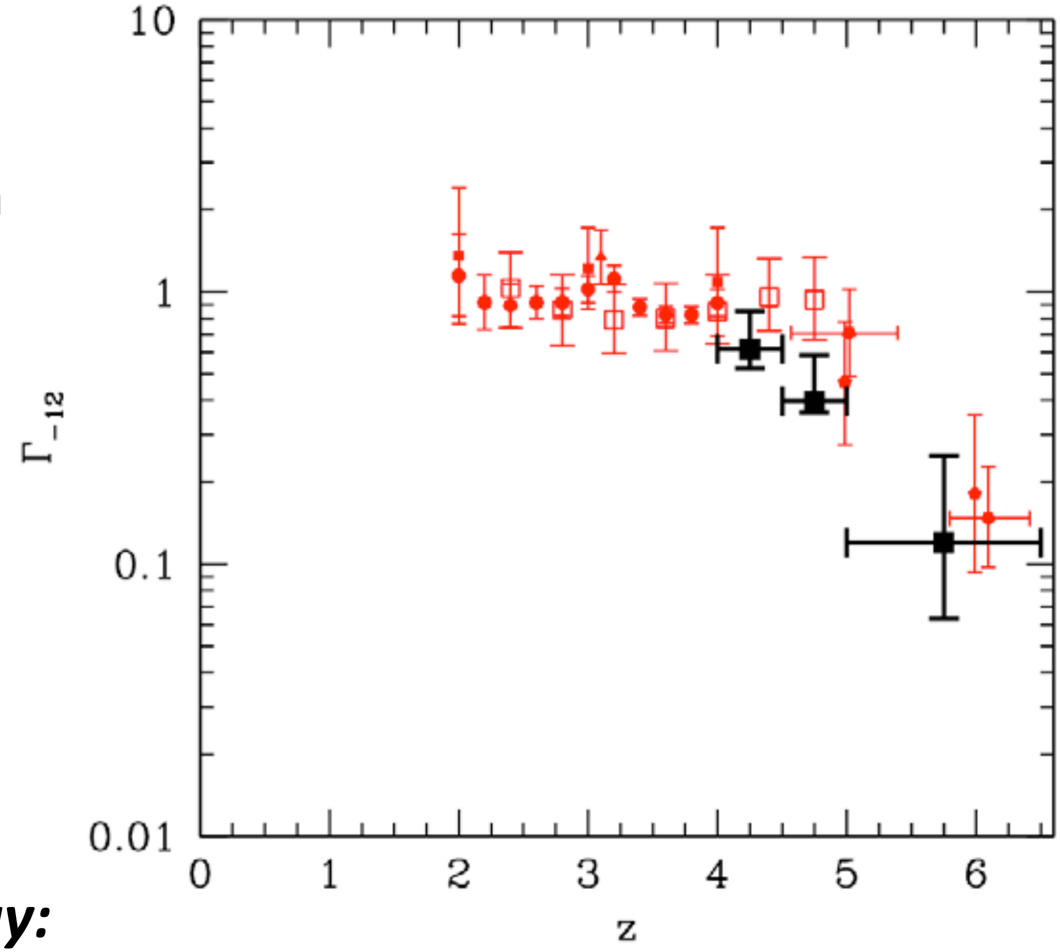
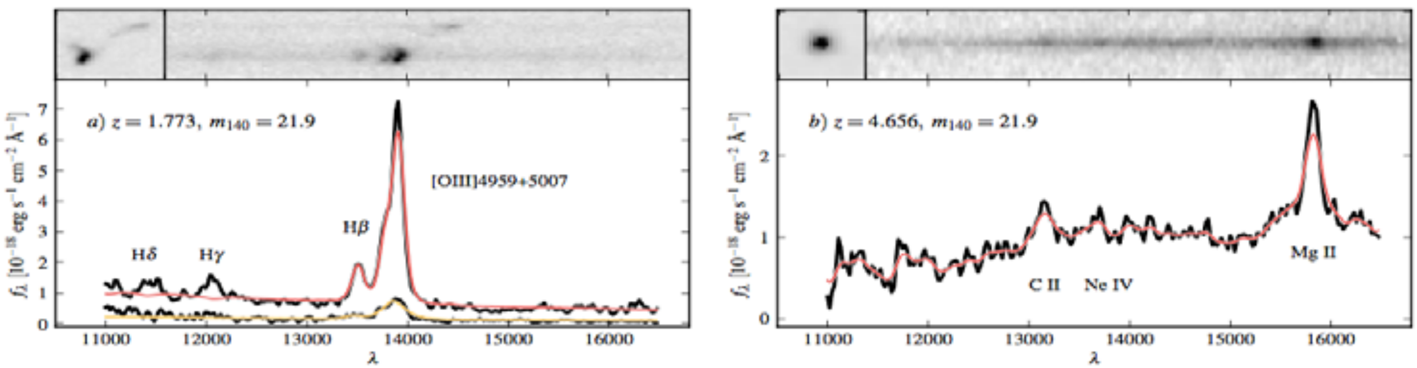


Figure from Giallongo et al 2015

WFIRST Grism is a valuable tool for quasar hunting.



Brammer et al. 2012

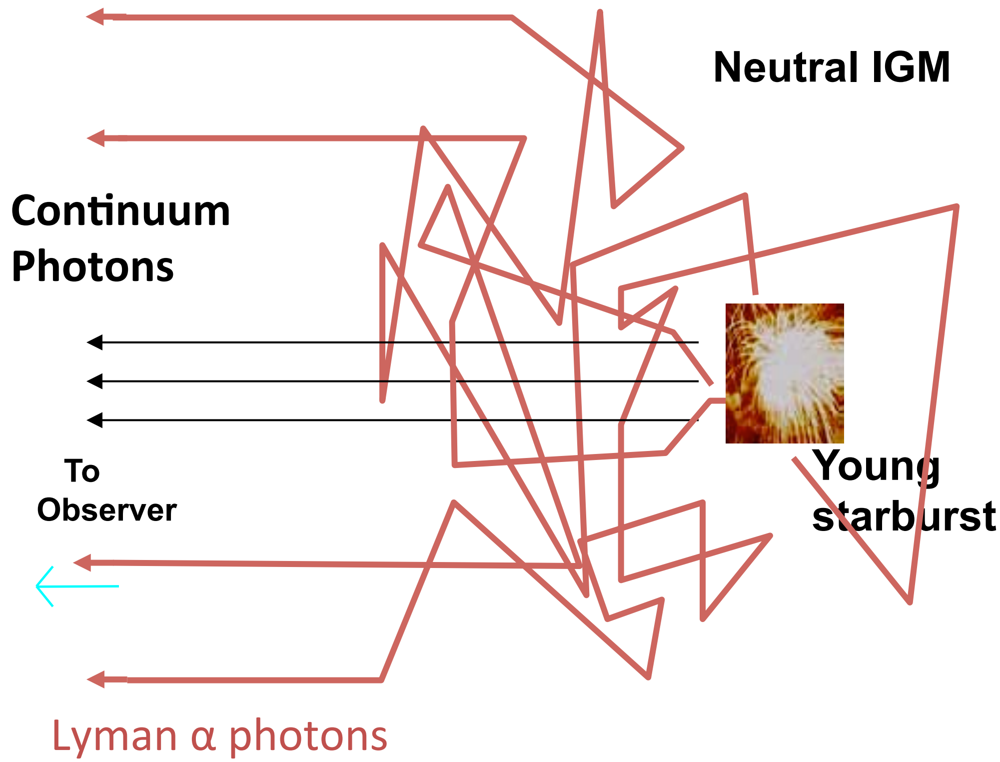
- Powerful redshift machine:
  - quasar broad line resolved
  - measure both flux and width
  - for z>5, reaches AB ~24 for detection of average CIV lines

Survey	wavelength	resolution	depth
3d-HST	1.1-1.6	150	5E-17
EUCLID	1.0 -2.0	250	3E-16
WFIRST	**1.35 - 1.95**	**600**	**5E-17**
PFS	0.38-1.26	1900-3500	5E-17
DESI	0.36-0.98	2000-5500	1E-16

Neutral fraction test: Quasar Spectra

- The ionized "near zones" of quasars have a size that depends critically on ambient neutral fraction.
- Given a statistical sample of high-z quasars, we can use this to learn about neutral fraction evolution.
- These will be bright targets for high resolution follow-up with large ground based telescopes or JWST.

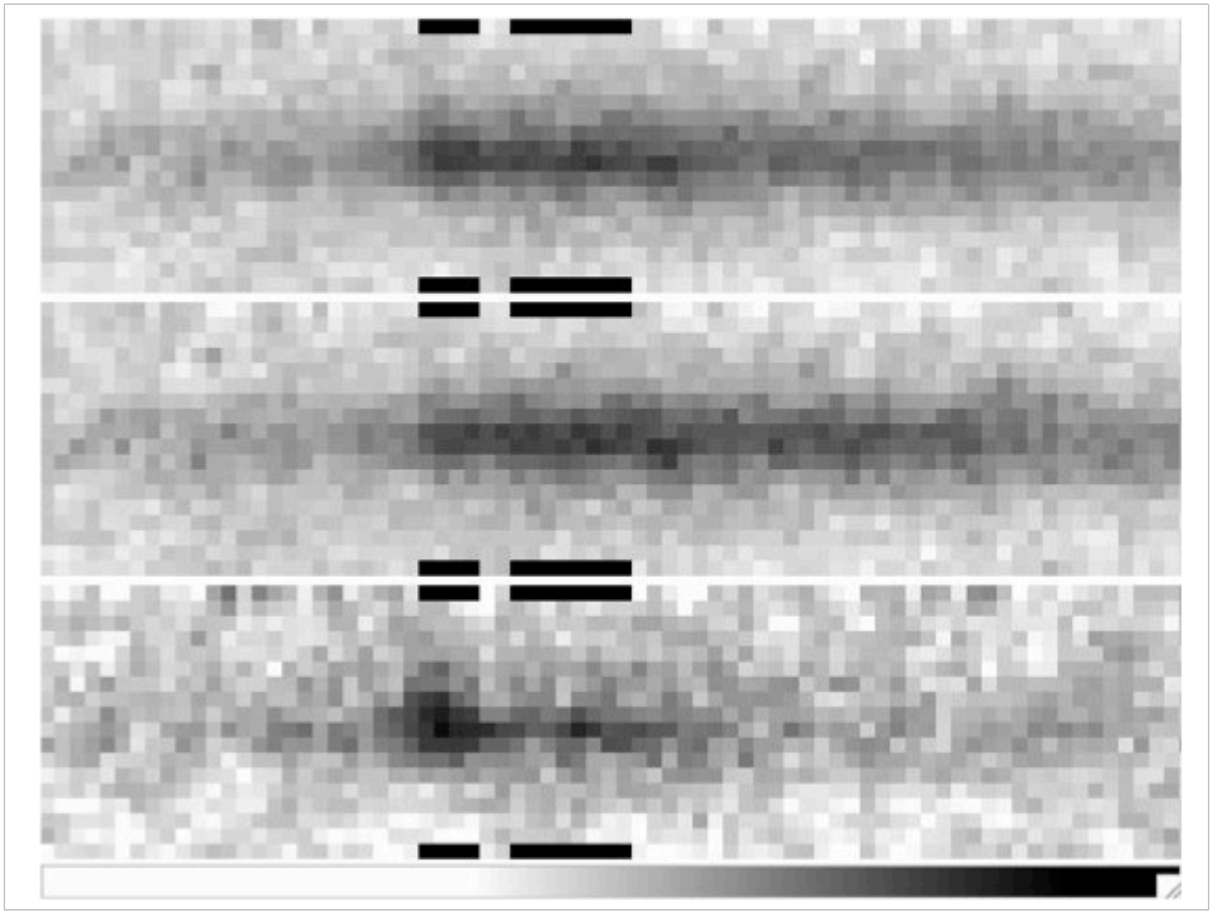
Neutral Fraction Test: Lyman α Galaxies



- Scattering by neutral intergalactic gas hides Lyα from view.
- This affects Lyα luminosity functions and clustering in detectable ways.

Luminosity function test references: Miralda-Escude 1998; Miralda-Escude & Rees 1998; Haiman & Spaans 1999; Loeb & Rybicki 1999; Santos 2004; Malhotra & Rhoads 2004; Stern et al 2005.

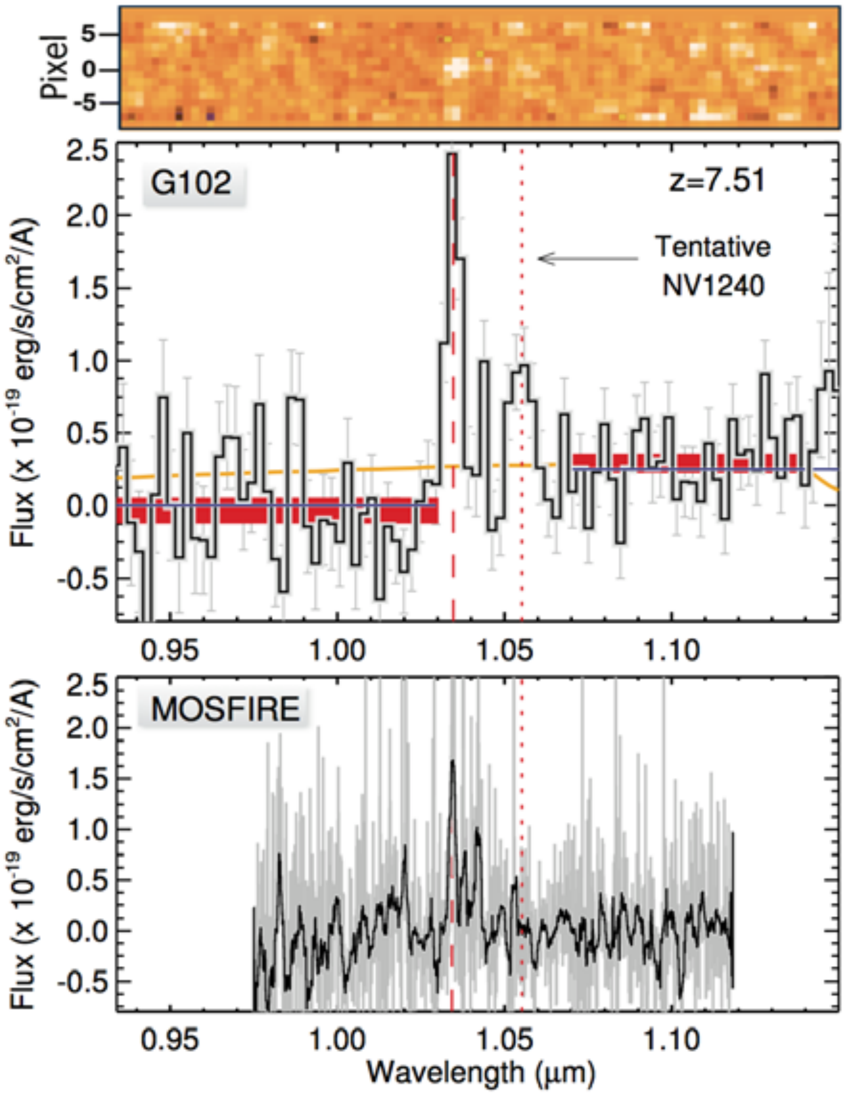
Spectroscopy unbiased to Lyman α:



Real HST grism spectra from the GRAPES and PEARS projects. Composite z ~ 5 LBG spectra for the full GRAPES sample (top), and those without LyA (middle) and with LyA (Bottom).

[Rhoads et al 2009].

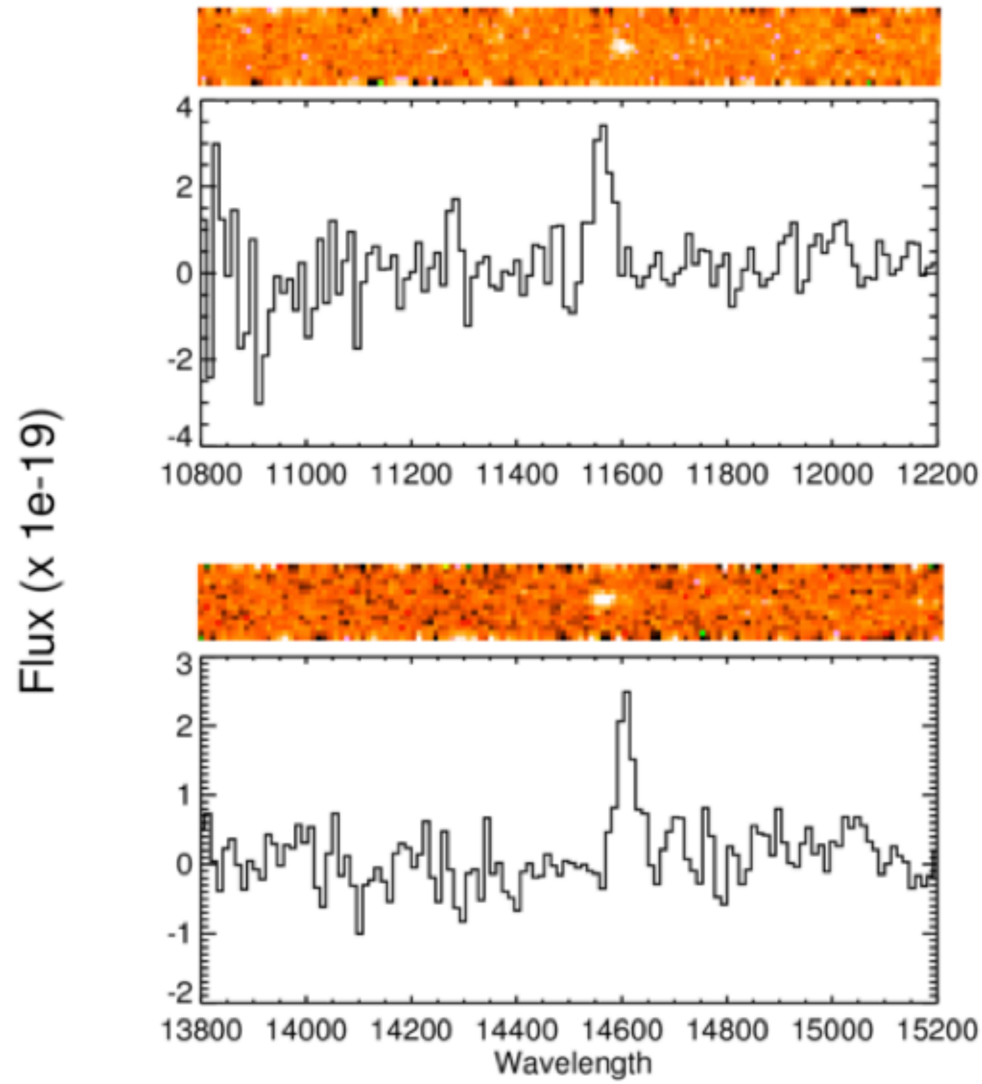
Faint Infrared Grism Survey (FIGS)



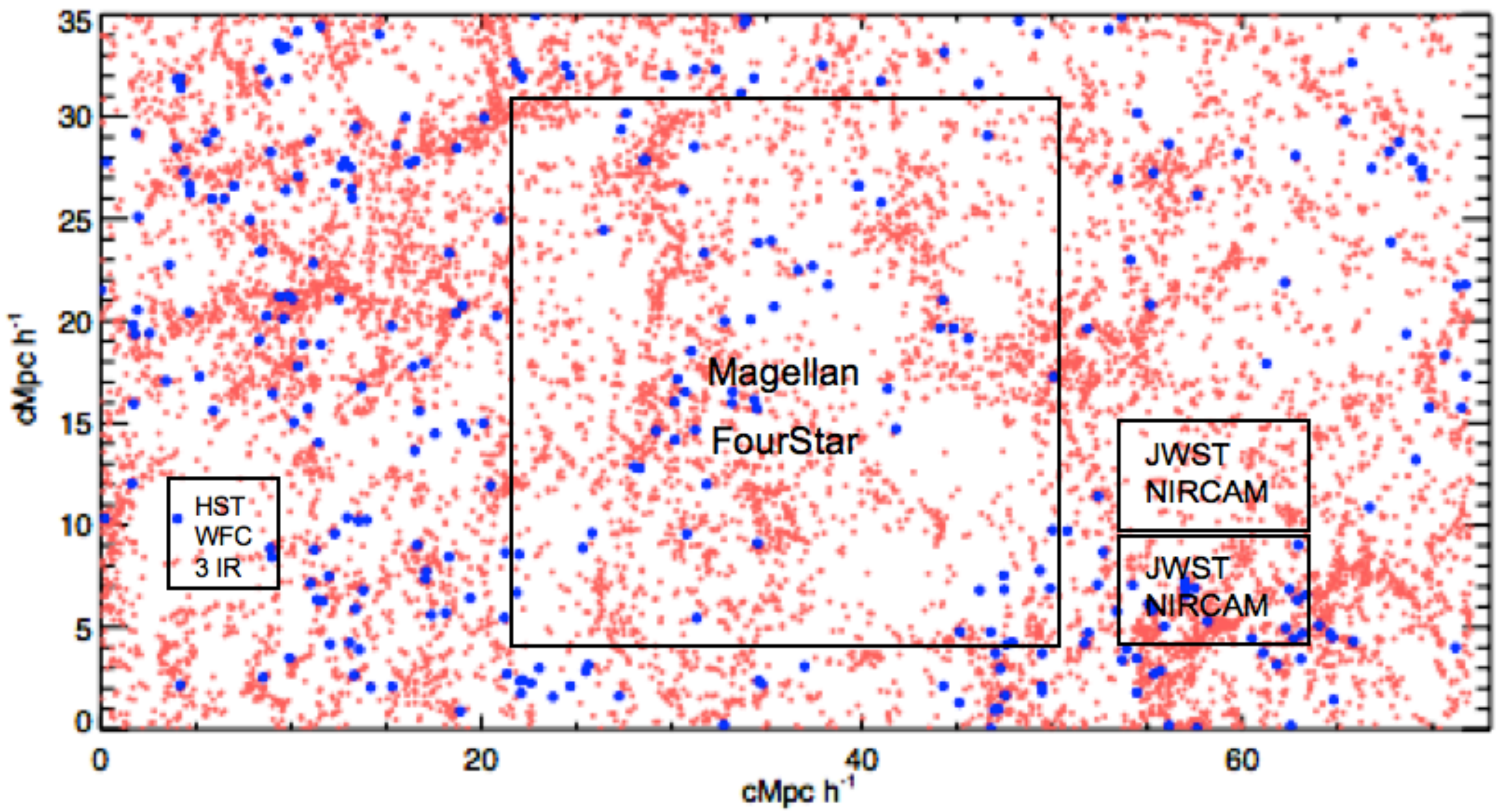
Z=7.51 (Tilvi et al. 2016, **arXiv:1605.06519)**

Finding Ly-α with WFIRST:

- Right: **Simulated** 30 hour WFIRST spectra for a source with AB=26.0 and f=1.3e-17 erg / cm2 / s at z=8.5 (top) and z=11 (bottom).

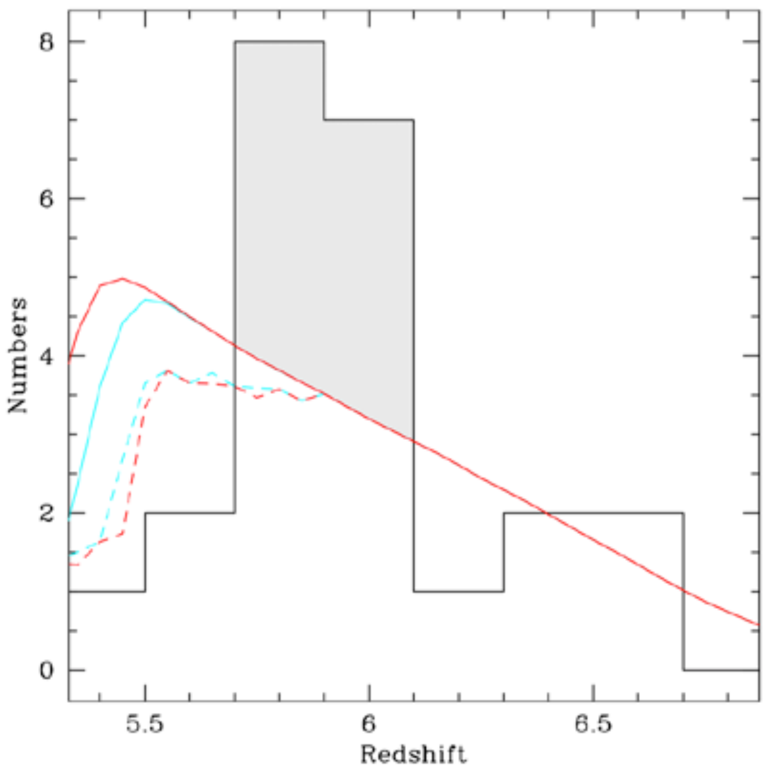


WFIRST can handle "Cosmic Variance":

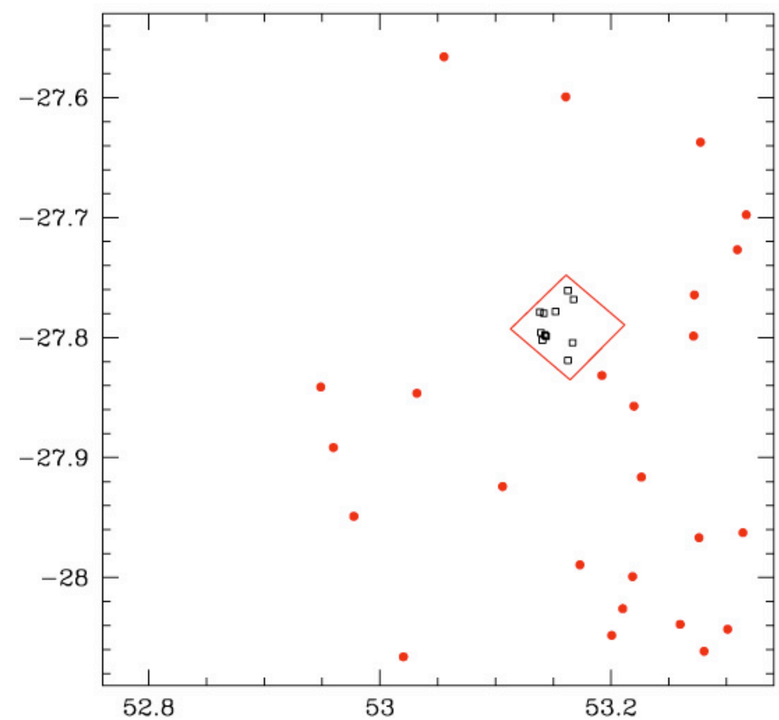


Simulation of dark matter halos (red dots) and Lyman alpha galaxies (blue dots) from Tilvi et al (2009). Two adjacent NIRCAM fields are shown to illustrate the potential impact of field-to-field variations. The WFIRST field of view exceeds the entire plotted area (23'x45'; the FourStar field is 11'x11'.)
Aside: We do not have IGM obscuration of Lyα here; it's just galaxy clustering.

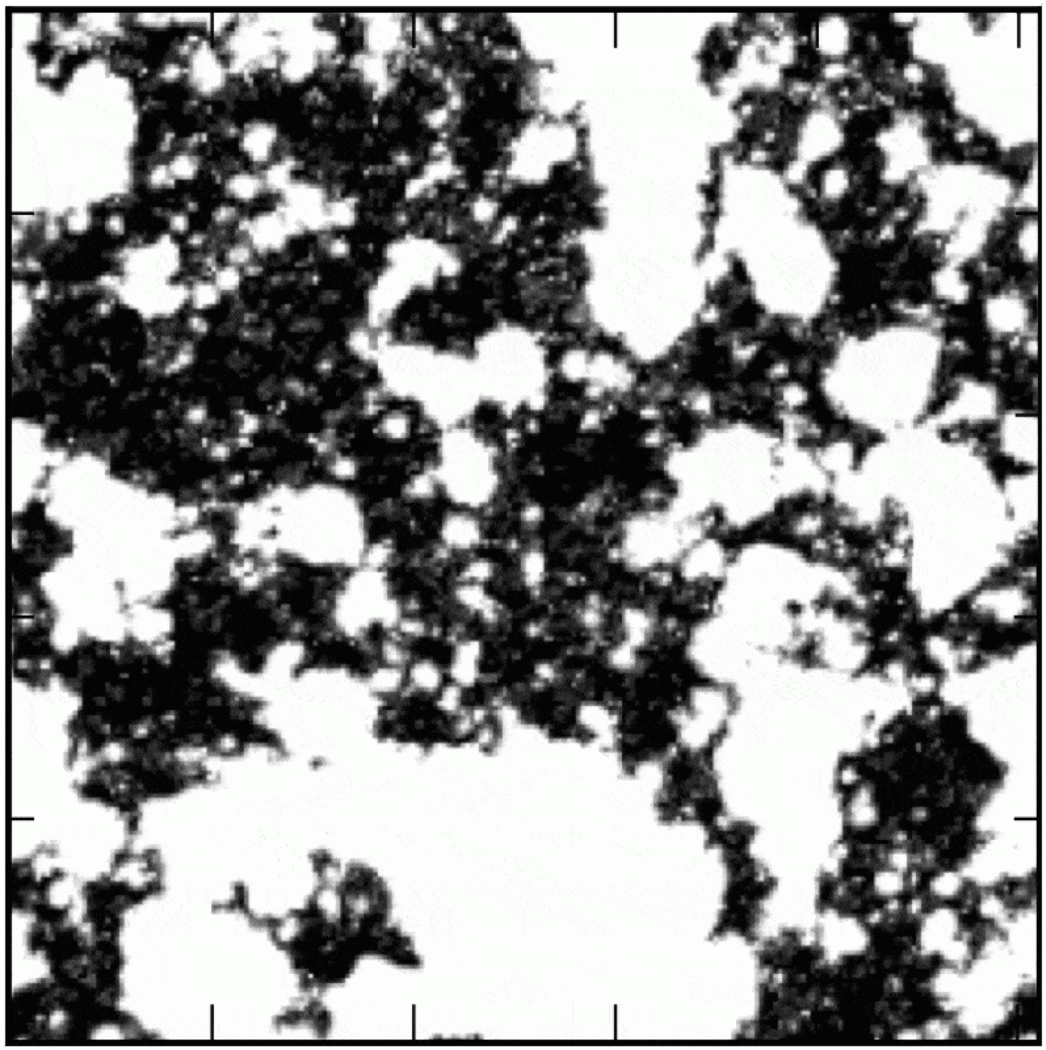
Ionizing sources (Malhotra 2005)



Overdensity > 4 at z=5.8



Neutral Fraction Test: Lyman α Galaxies



Neutral and ionized regions / observed Lyα galaxies.

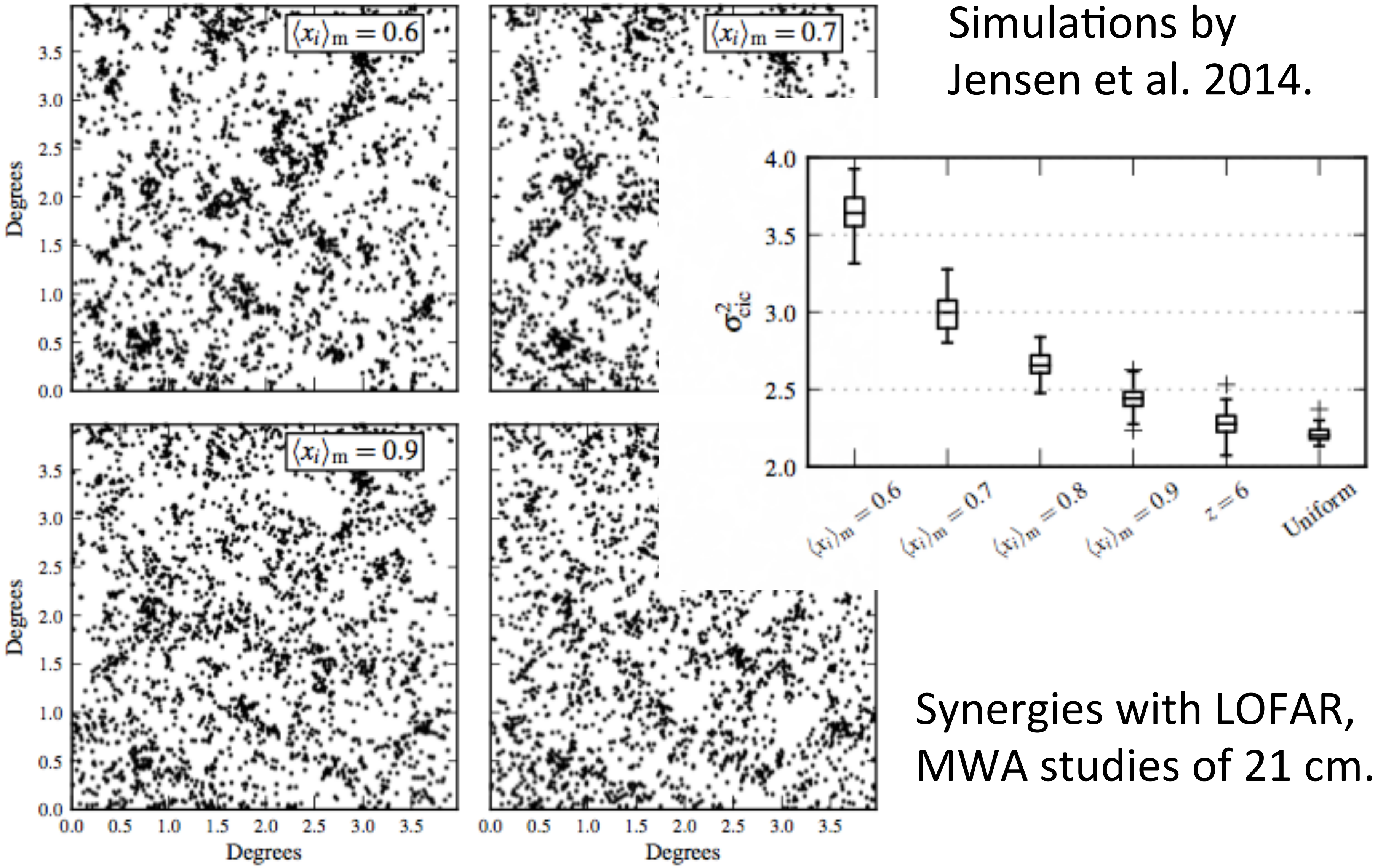
WFIRST can map Lyα galaxies over a field this size.
(163 cMpc, ~ 1 deg.)

Figures from Jensen et al 2012.

Ionized bubbles modulate visibility of Lyα.
This is used to infer properties of the bubbles.

Clustering test references: Furlanetto et al 2005, McQuinn et al 2007; Jensen et al 2012, 2014.

Topology of Reionization:



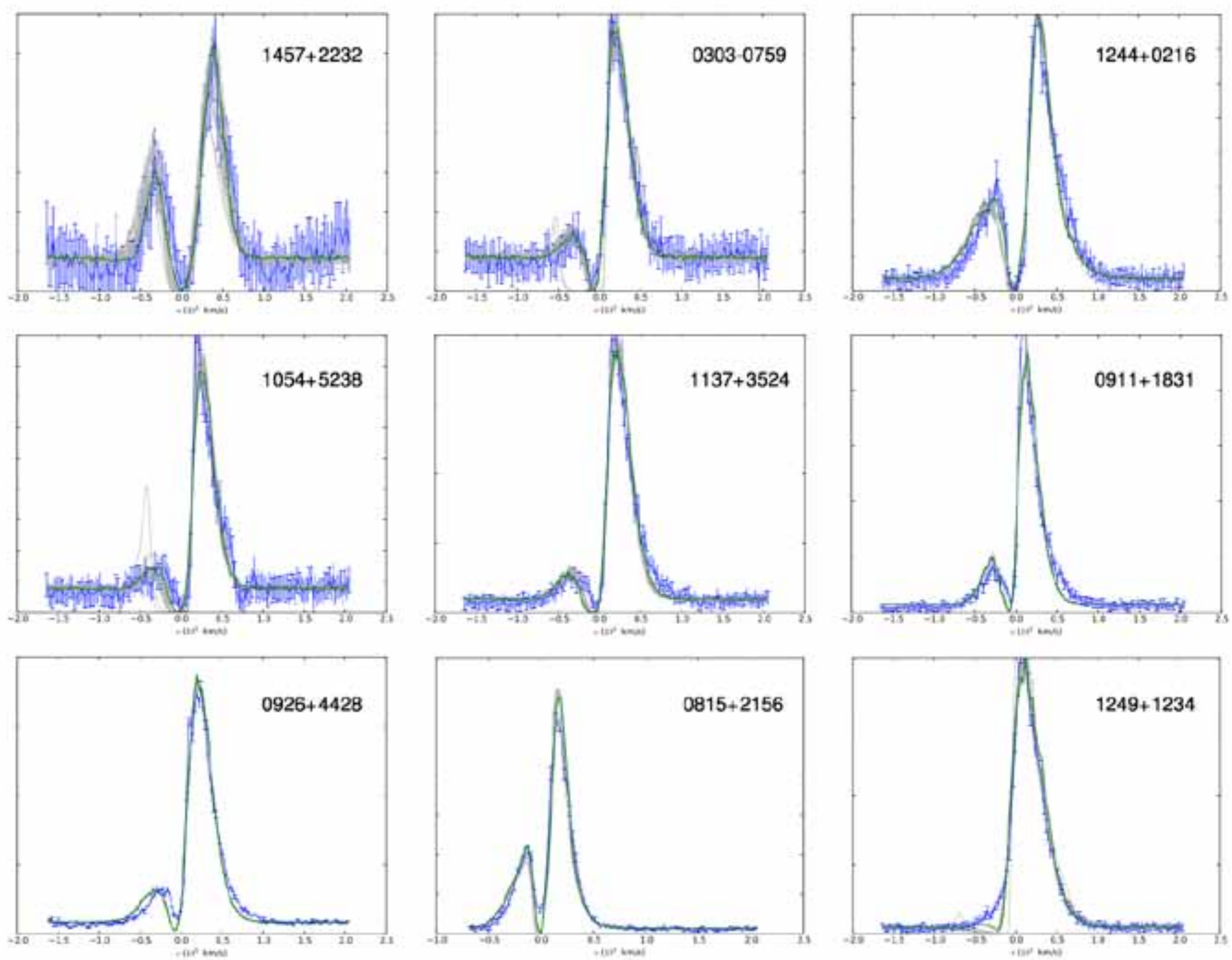
Simulations by Jensen et al. 2014.

Synergies with LOFAR, MWA studies of 21 cm.

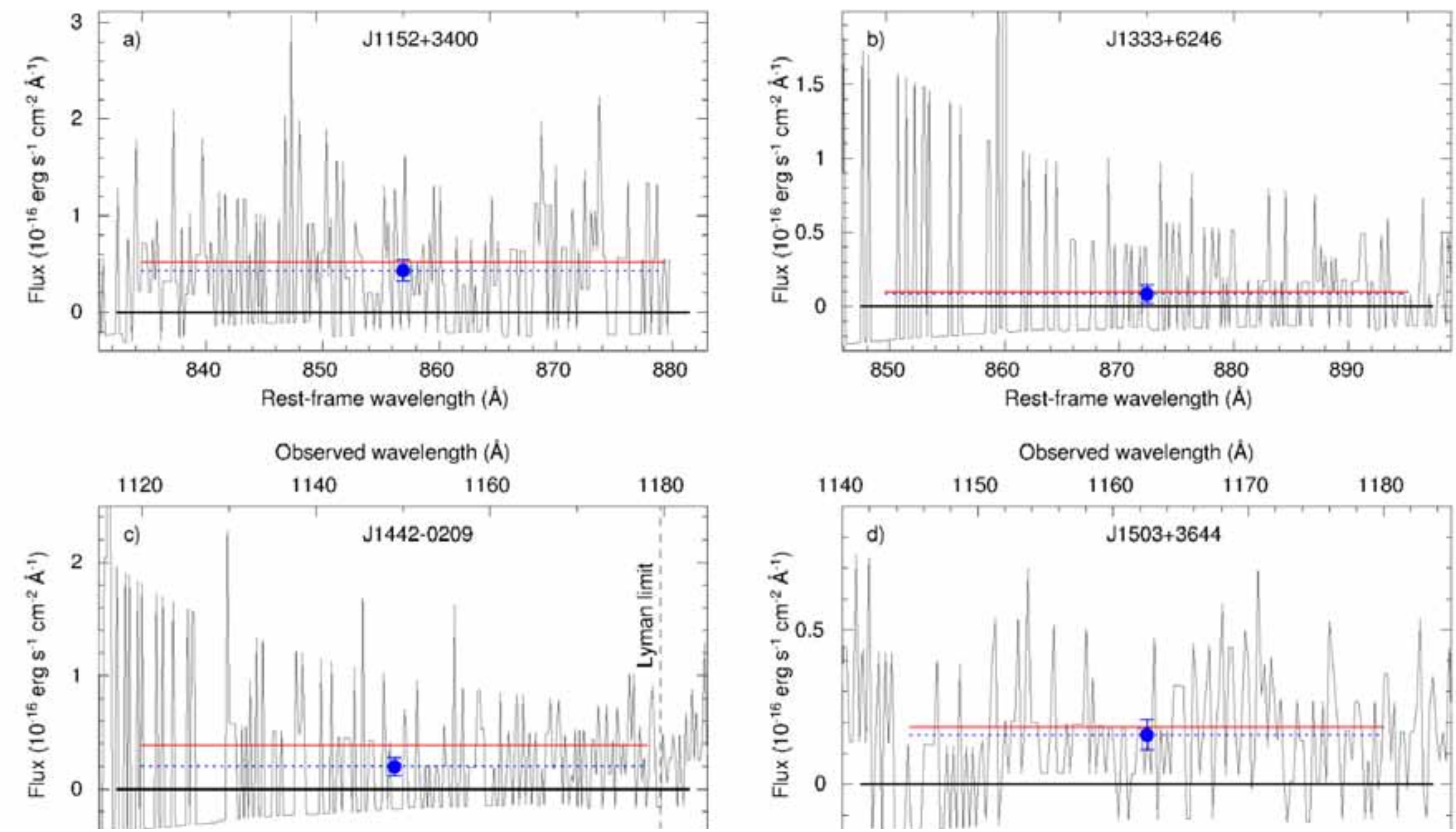
Galaxy Environment and Reionization

- Environment may affect galaxy properties.
- WFIRST will be our first opportunity to test this in the epoch of reionization, offering galaxy samples in Coma-cluster-progenitor environments and in void environments.
- Studying clumpiness of ionizing photon production will help understand inhomogeneity of reioinization (which we may see directly with Lyα and quasar tests.)

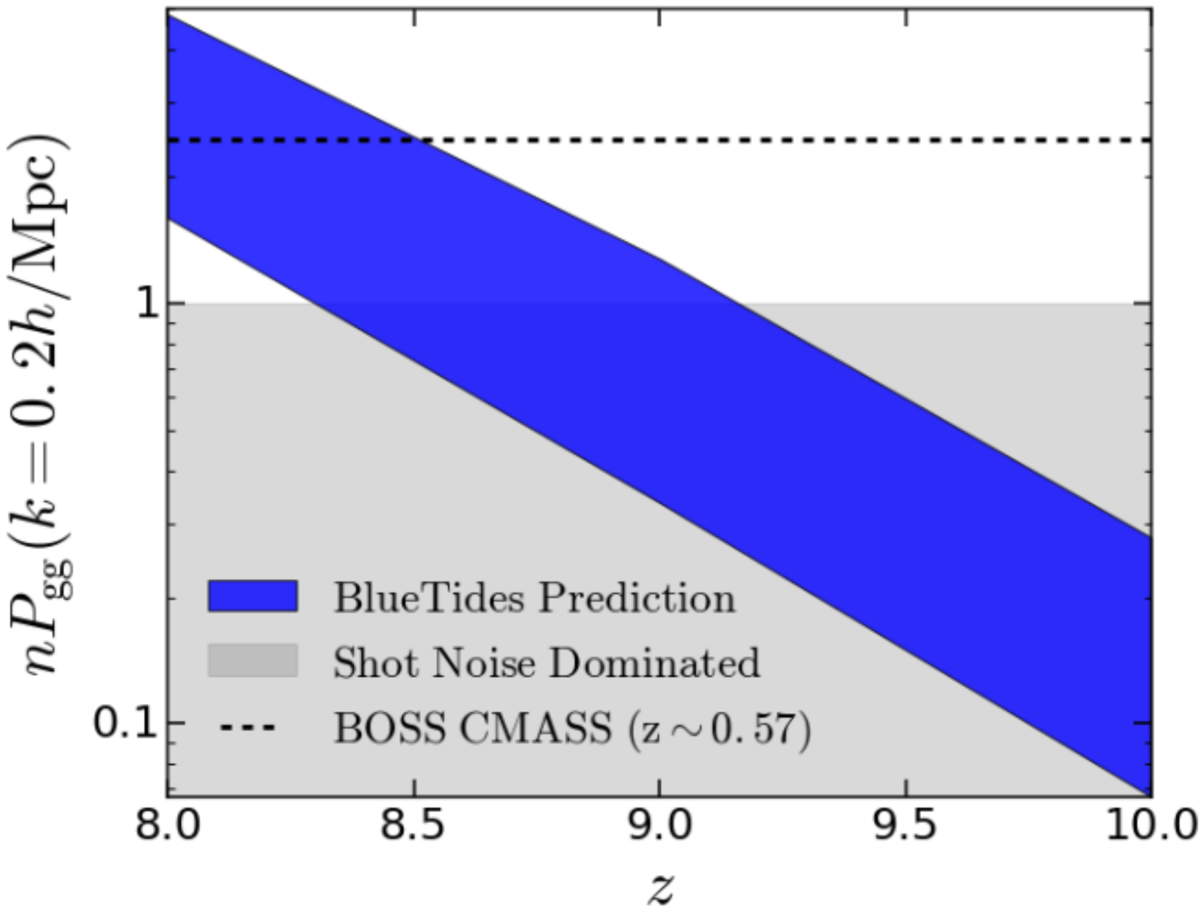
[OIII] intense objects at z=0.1-0.3 (Yang, malhotra et al. 2015)



Izotov et al. 2016



BAO at z~8?



Waters et al. 2016
4.7 − 6.3σ detection of the BAO signal at z = 8
(Bluetide)

Science Summary

- WFIRST will find unprecedented samples of Lyman break galaxies, Lyα galaxies, and quasars in the epoch of reionization.
  - This will test luminosity function evolution and provide key data on the ionizing photon budget at $z>7$.
- Both quasars and Lyα galaxies from WFIRST can be used to directly study the neutral fraction during reionization.

WFIRST and Euclid are Complementary

- Understanding dark energy will require tight control of systematics and multiple cross checks
- **WFIRST-AFTA**
  - Is deep, infrared over 2000 square degrees
  - Multiple shape measurements in 2-3 well–sampled bands
  - Higher resolution and source density (2.5 times as many as Euclid)
  - High quality survey of >2000 SN using a dedicated IFU
  - Redshift survey for galaxy clustering extends to z=3
- **Euclid**
  - Measures shapes in single optical band but with CCD detectors very well known for WL. Different systematics than WFIRST-AFTA, lower redundancy and internal cross-checks.
  - Much wider (15,000 deg^2) but shallower
  - No SN
  - Lower redshift range for galaxy clustering
  - Launch in 2020, survey completed by 2026: 2500 deg^2 public in 2023, 7500 deg^2 in 2025, final 2027.
- **Euclid-WFIRST data processing synergy:** lessons learned from Euclid (H2RG detectors, Grisms), tens of scientists and engineers involved in both surveys

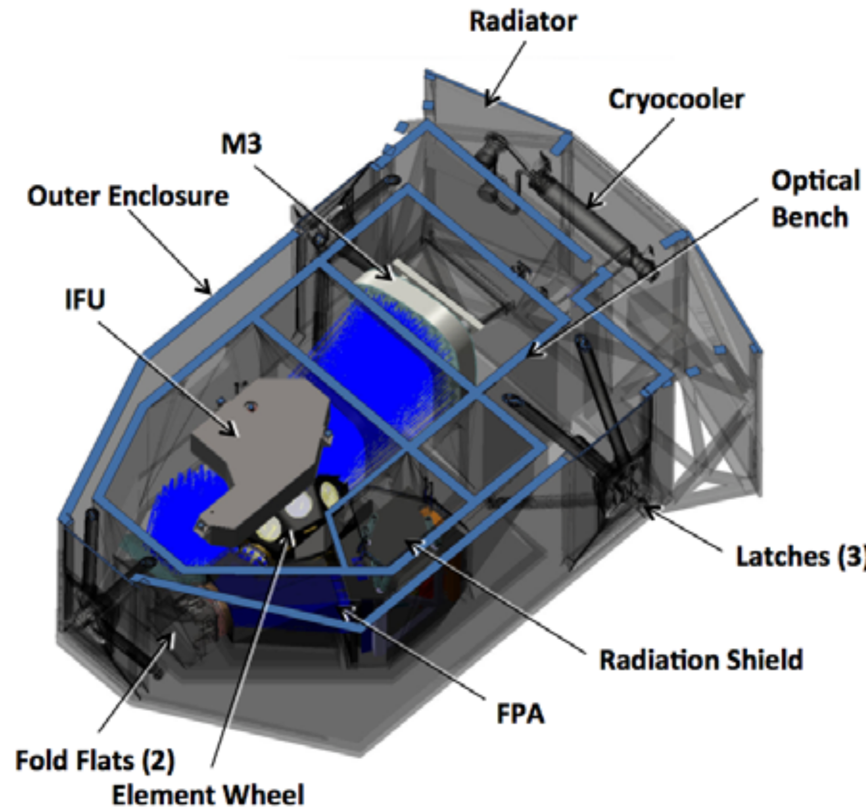
The best constraints on DE and Legacy in the 2020s will come from a combination of Euclid, WFIRST and ground-based (LSST, Subaru) data

J Rhodes at WFIRST 2016 meeting.

WFIRST
Wide-Field Infrared Survey Telescope
Astrophysics • Dark Energy • Exoplanets

Wide Field Instrument

- 0.281 deg^2 (28 H4RG detectors (4k x 4k pixels per detector)
- GRS Spectroscopy (135-1.89) R=461 λ
- Filter wheel enables 6 filters from 0.76 to 2 microns, a grism, and a dark [ACTIVE DISCUSSION OF OPTIMAL FILTERS: SHOULD WE GO BLUE?]
- Integral Field Unit for slit spectroscopy (0.6-2.0 microns, R~100)



High Latitude Survey: Optimized to study dark energy

- 2227 deg^2 area YJHF184
  - 7 σ line flux of 1.2 x 10^{-16} $erg/cm^2/s$ (R=600)
  - 26.7 AB mag YJH (4-5 dithers at each of two roll angles/174 s integration)
- SN surveys: 27.44/8.96/5.04 deg^2 with depths increasing to J=29.3/H=29.4
  - LSST deep drilling fields + Subaru fields

Bulge Survey: Optimized for exoplanet discussion

- 6 season of 72 days
- 10 contiguous field (2.8 degrees) each observed every 15 minutes in W149 and once every
- 52 seconds in W149 (33000 epochs) and 290 seconds in Z087 (7000)
- Fields are "confusion-limited"
- Potential for high precision astrometry (50-700 mas/epoch) and seismology
  - 2.6 billion photons from a H=19.6 mag star!

WFIRST
WIDE-FIELD INFRARED SURVEY TELESCOPE
ASTROPHYSICS • DARK ENERGY • EXOPLANETS

Wide Field IR Telescope