GLASS

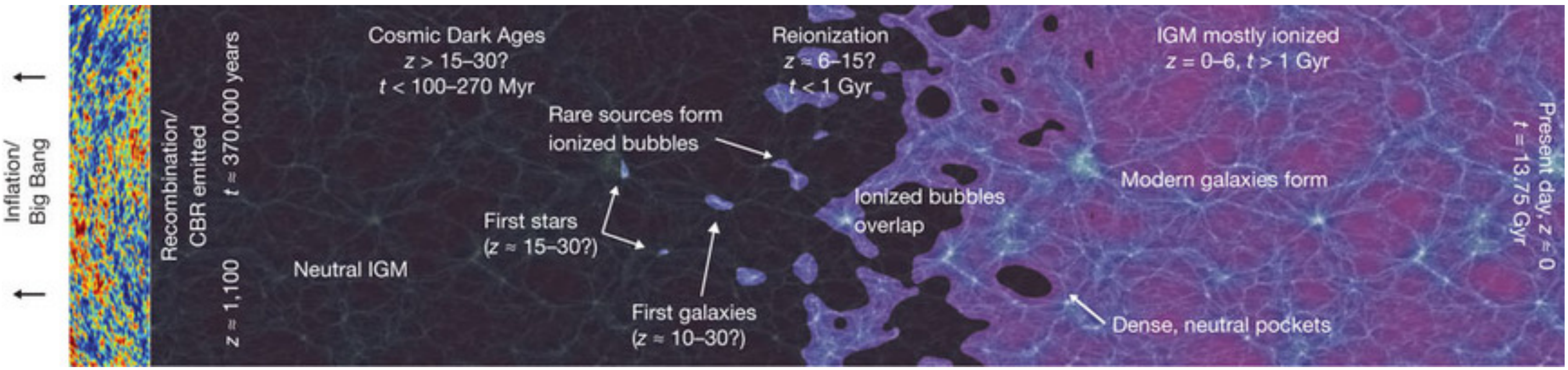
Finding the first galaxies with a magnifying GLASS

TOMMASO TREU (UCLA)

Outline

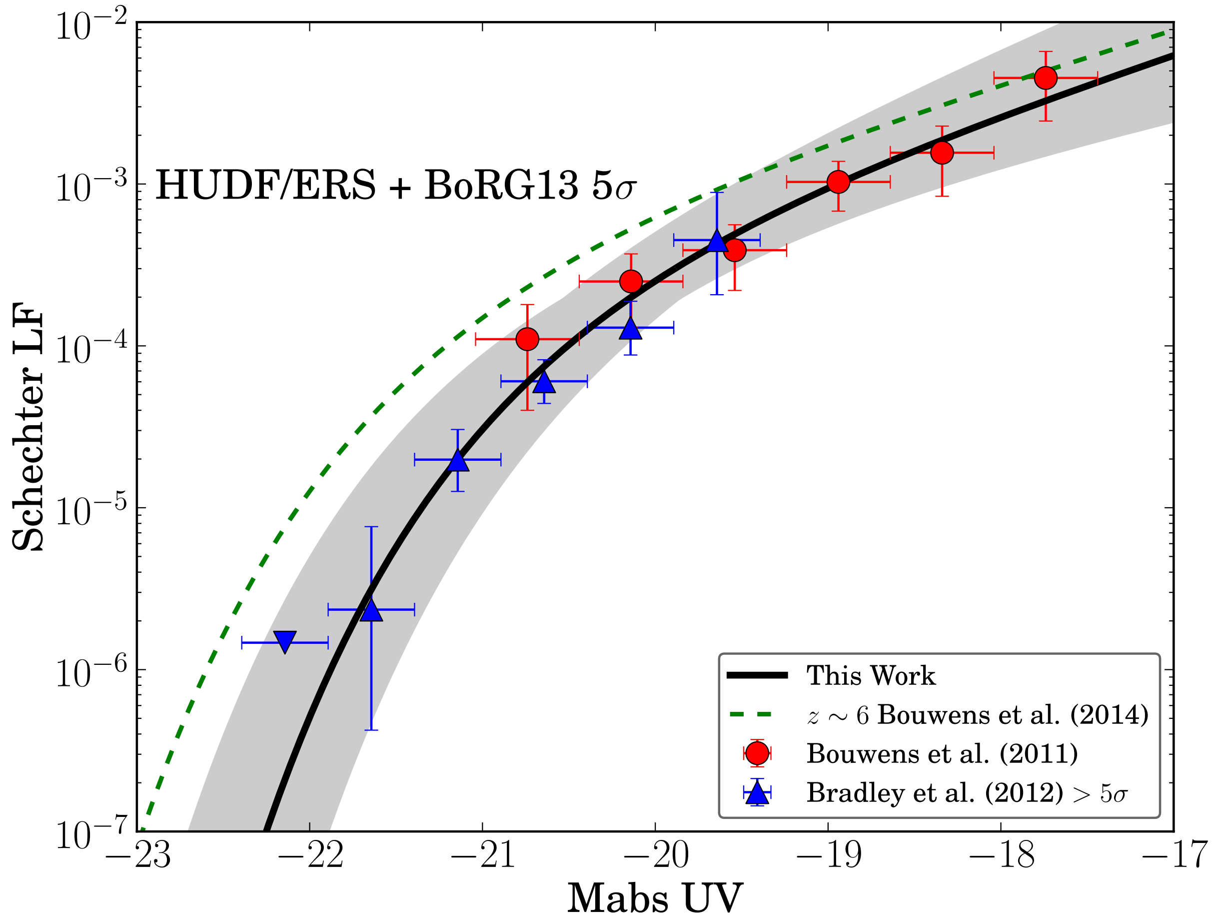
- When did cosmic re-ionization occur? Who did it?
- Results from imaging
- Results from spectroscopy
- The importance of gravitational lensing
- The Grism Lens Amplified Survey from Space (GLASS)
- How about black holes? Measuring black holes masses at high-z with reverberation mapping

Cosmic reionization



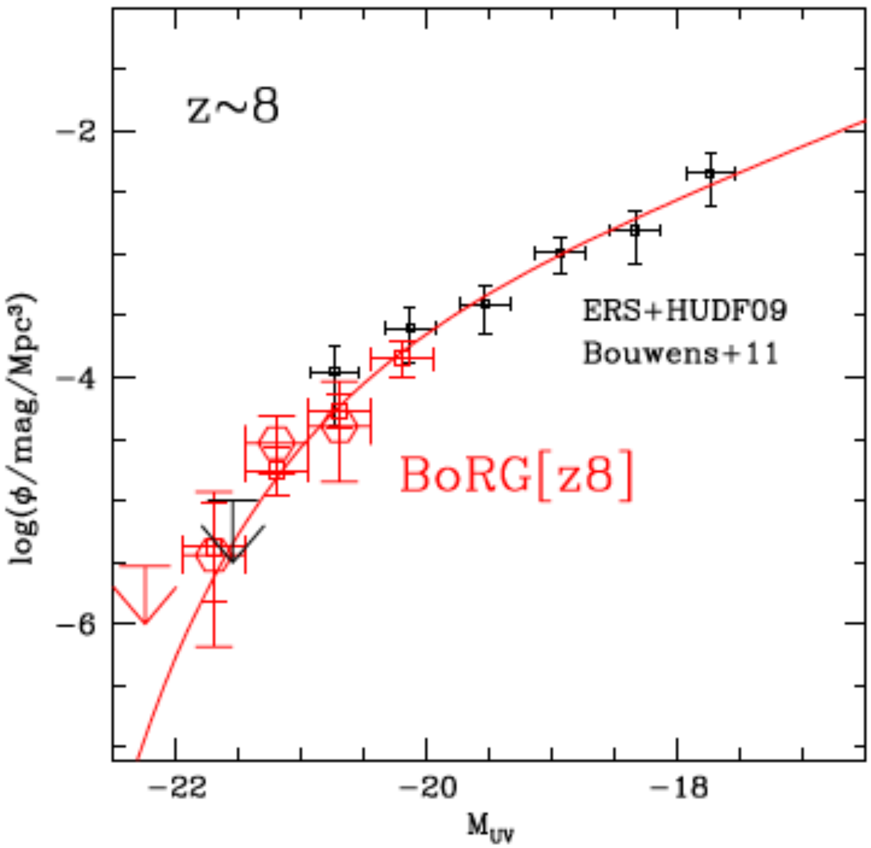
Whodunit?

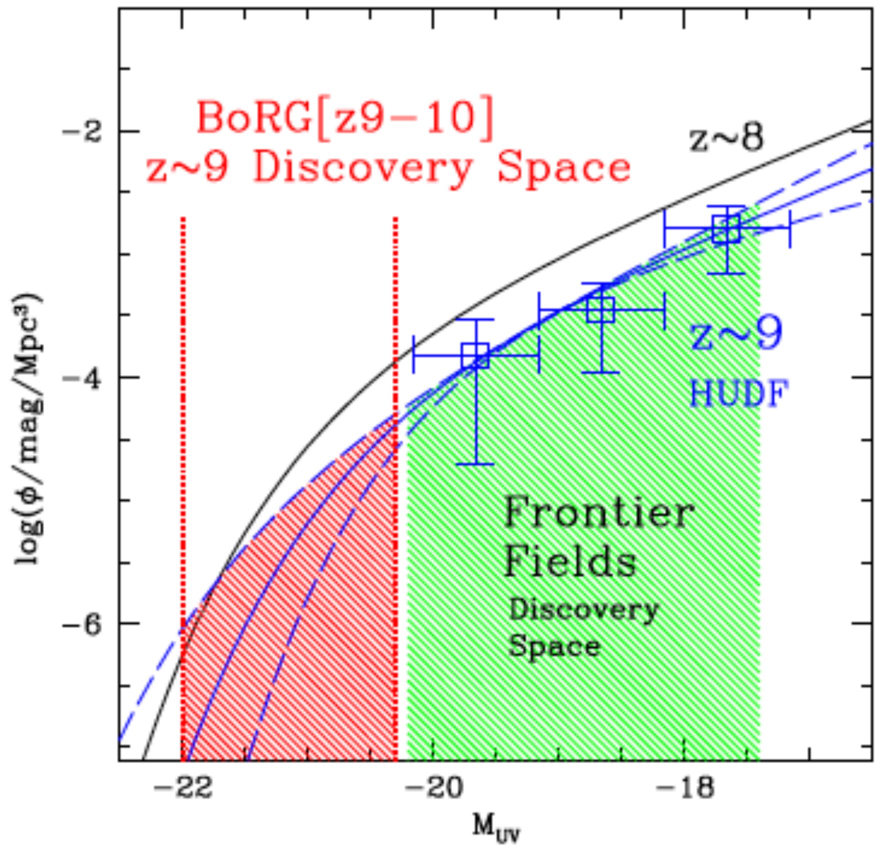
We know there are LBGs



Schmidt et al. 2014b

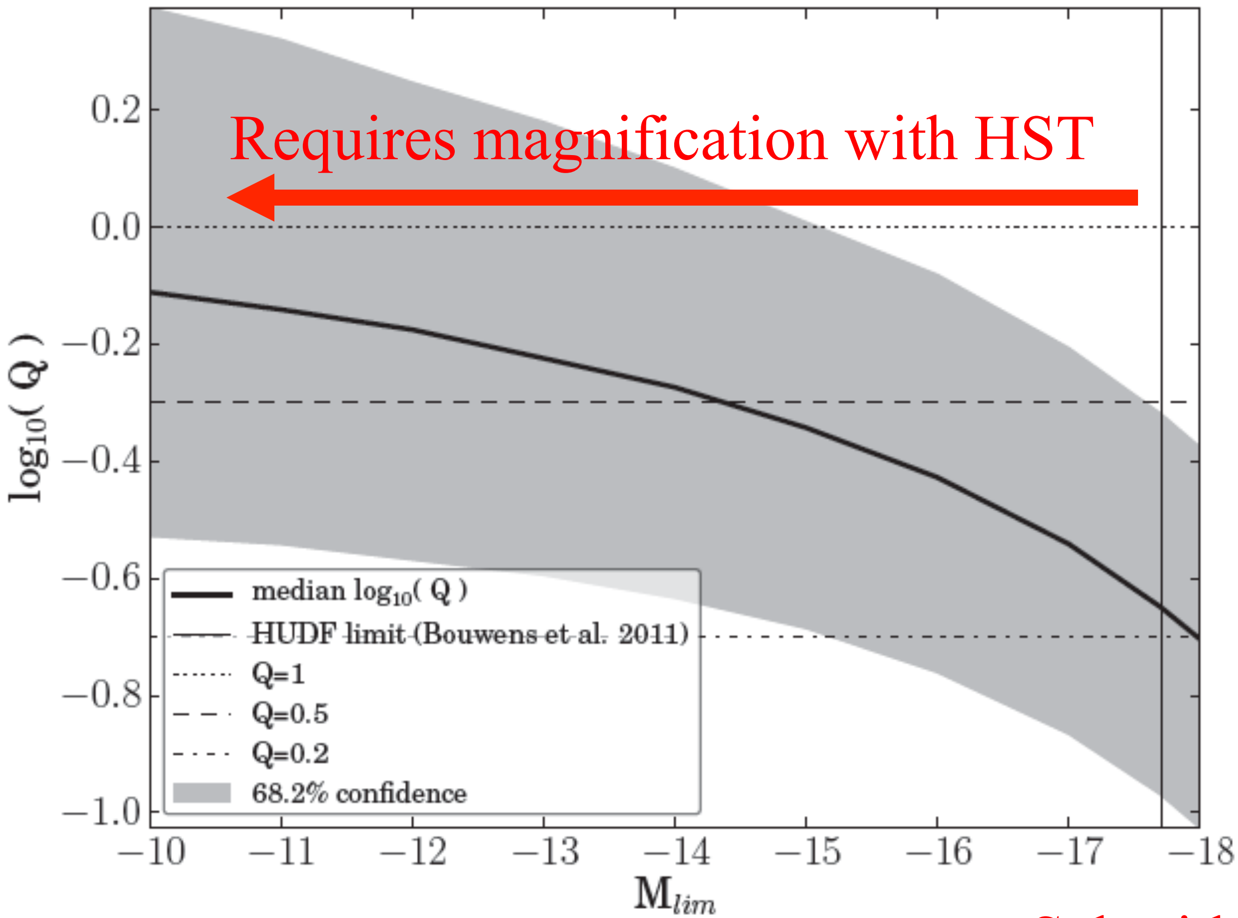
And we will find more!





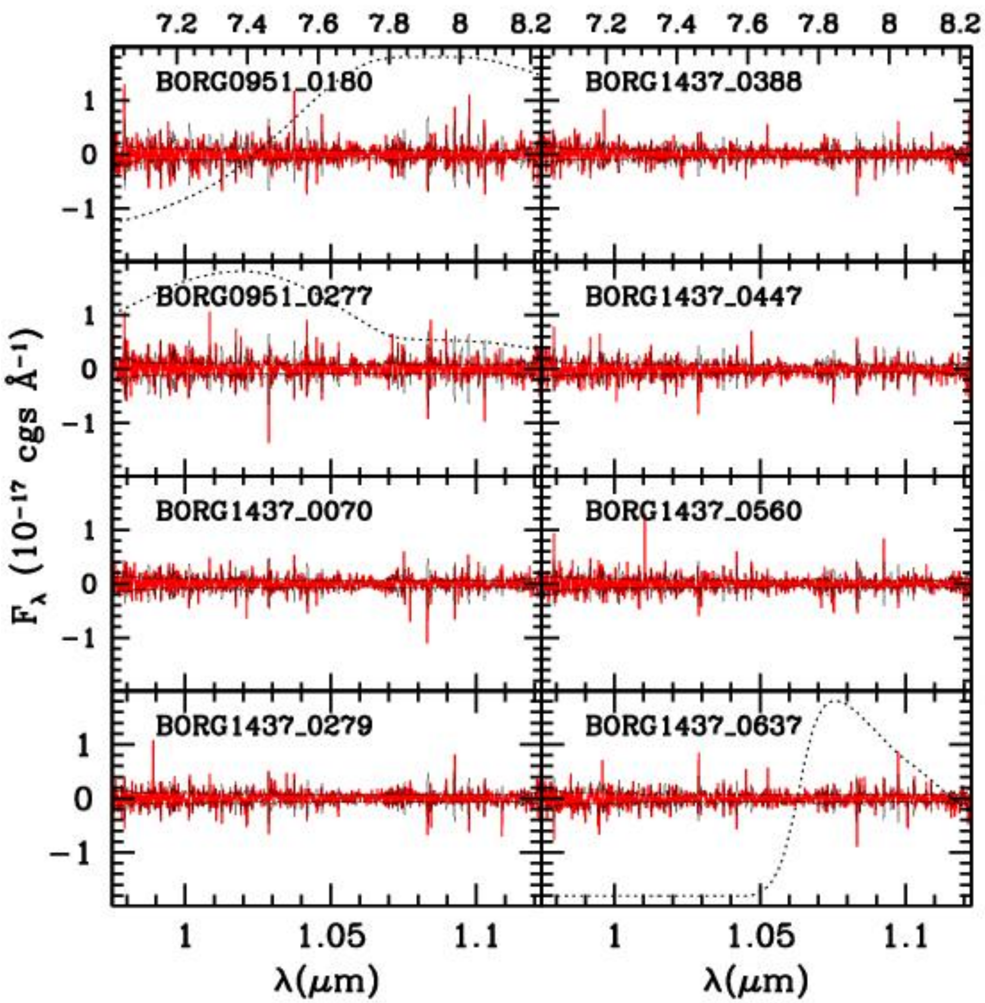
BORG cycle 22 approved; PI: Trenti

Not clear if they are sufficient for reionization



Schmidt et al 2014b

…but we have not been able to confirm them!



Treu et al. 2013

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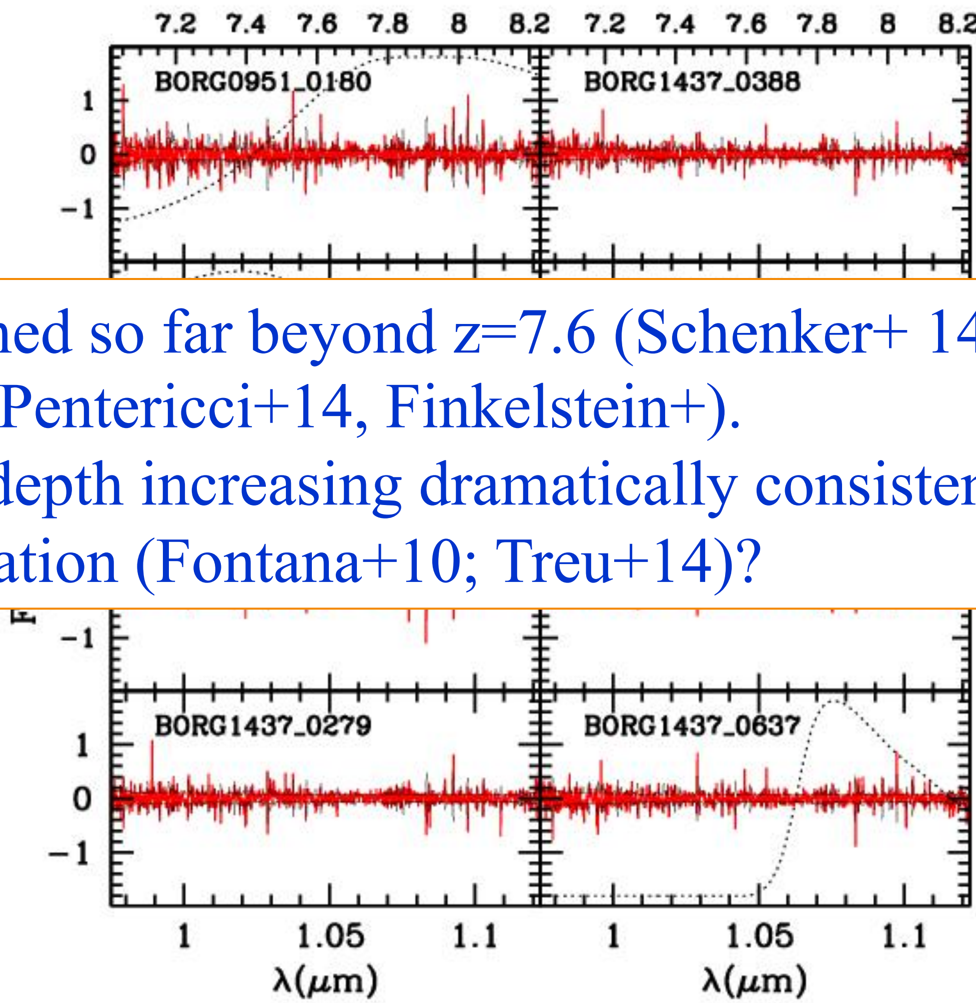
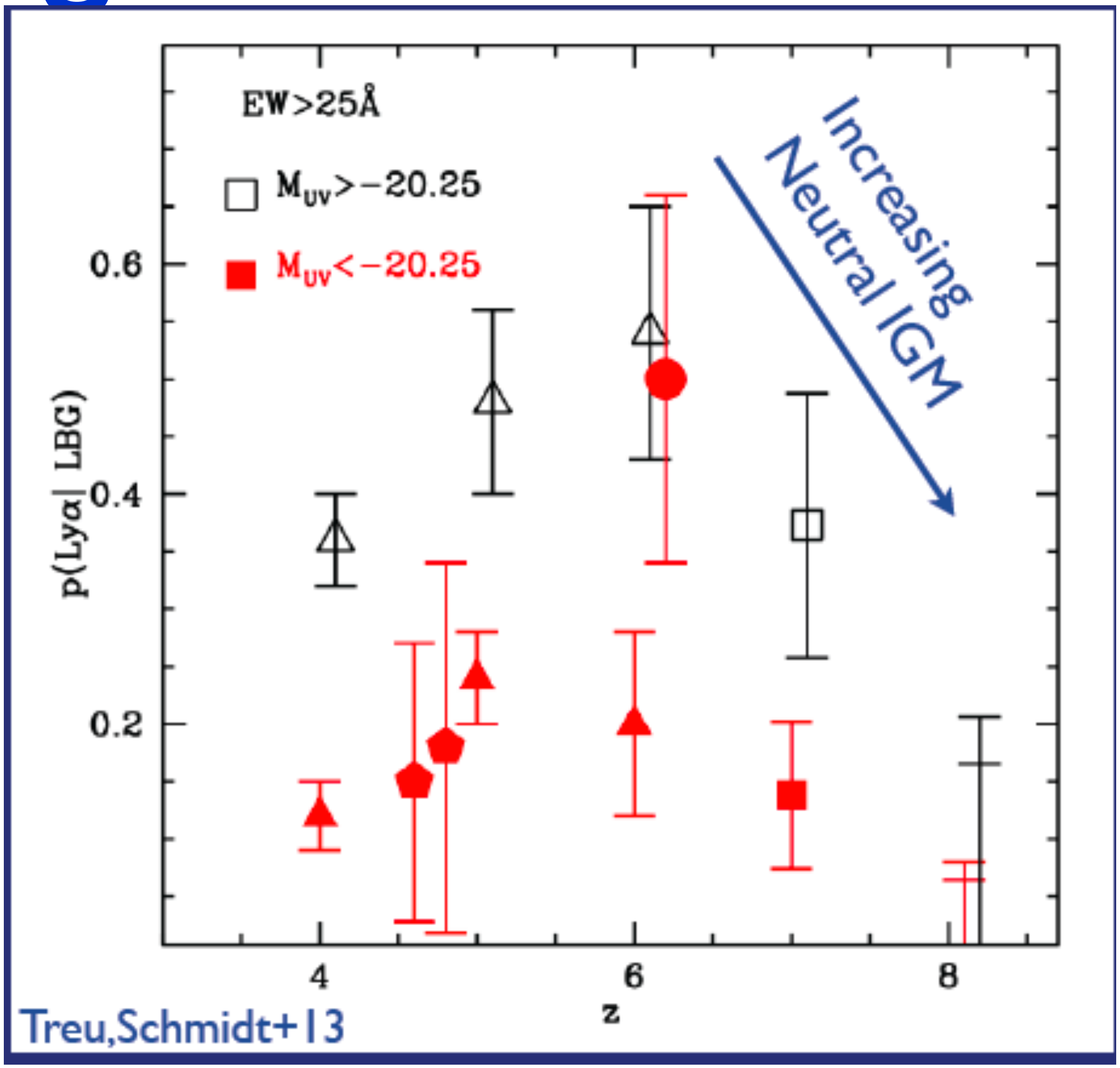


No lya published so far beyond z=7.6 (Schenker+ 14) despite many attempts (e.g. Pentericci+14, Finkelstein+).
Is the optical depth increasing dramatically consistent with the tail-end of reionization (Fontana+10; Treu+14)?

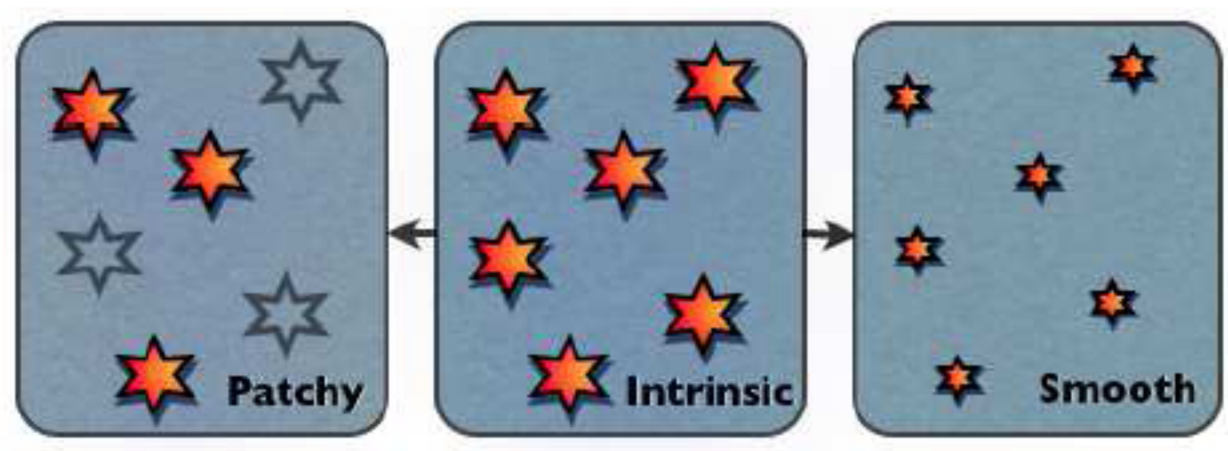
Treu et al. 2013

Is decline in lya a smoking gun of reionization?



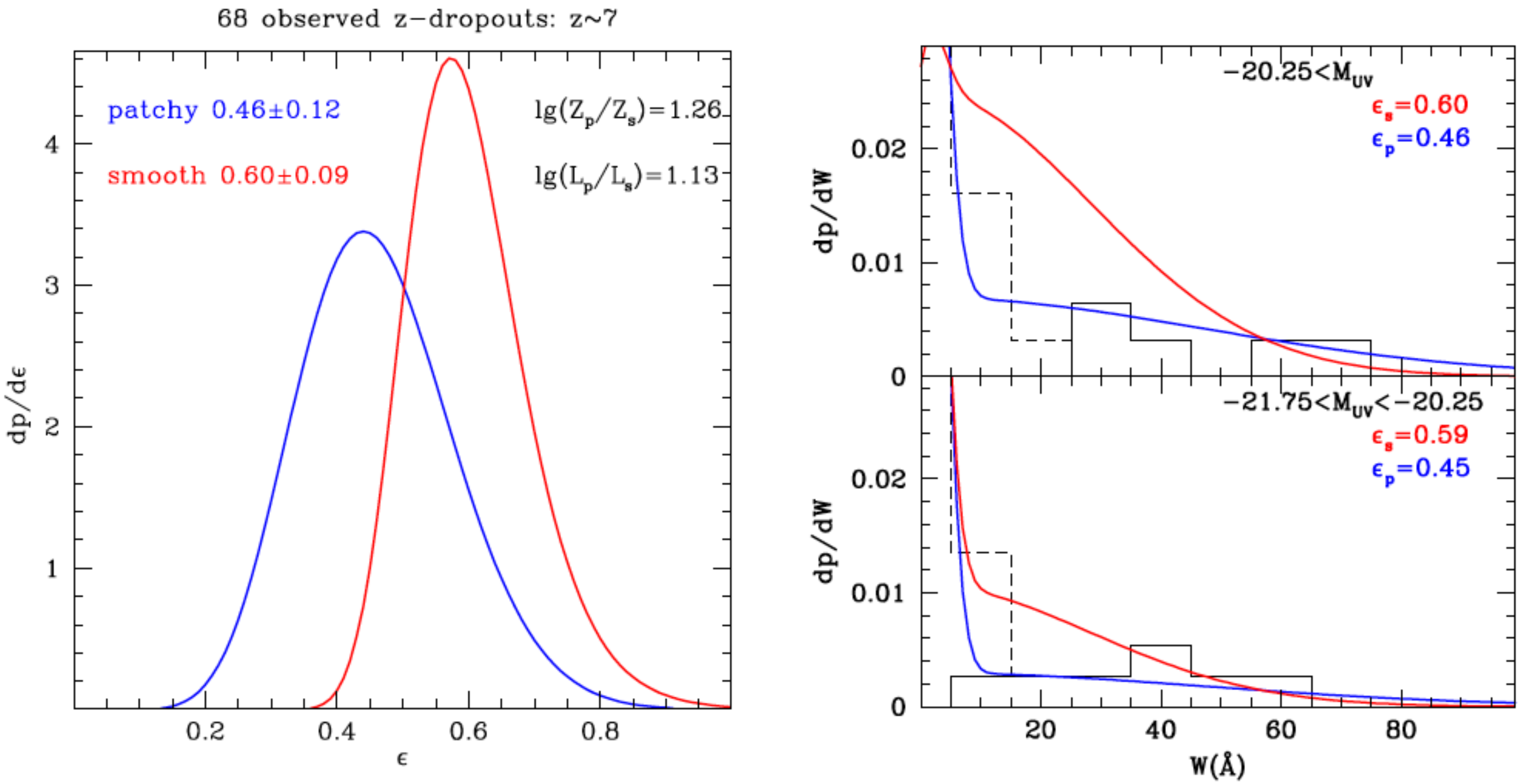
A simple model. Smooth or patchy lya optical depth?

Bayesian inference from observations (Treu et al. 2012, 2013)



Tilvi et al. 2014

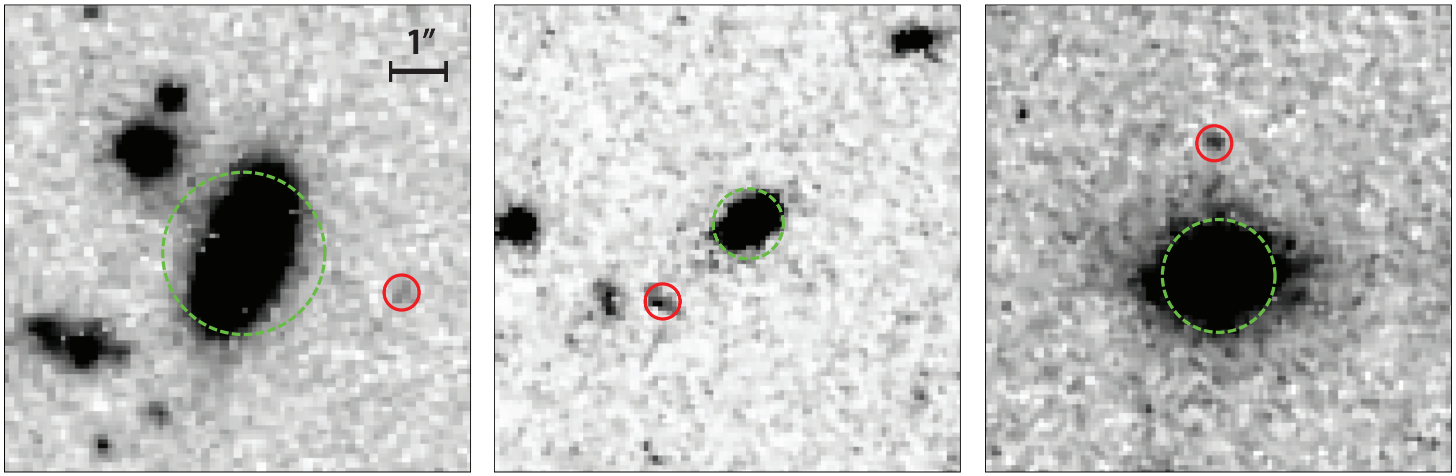
Patchy!



Penterricci et al. 2014 (models by TT); See also Tilvi et al. 2014

The importance of gravitational lensing

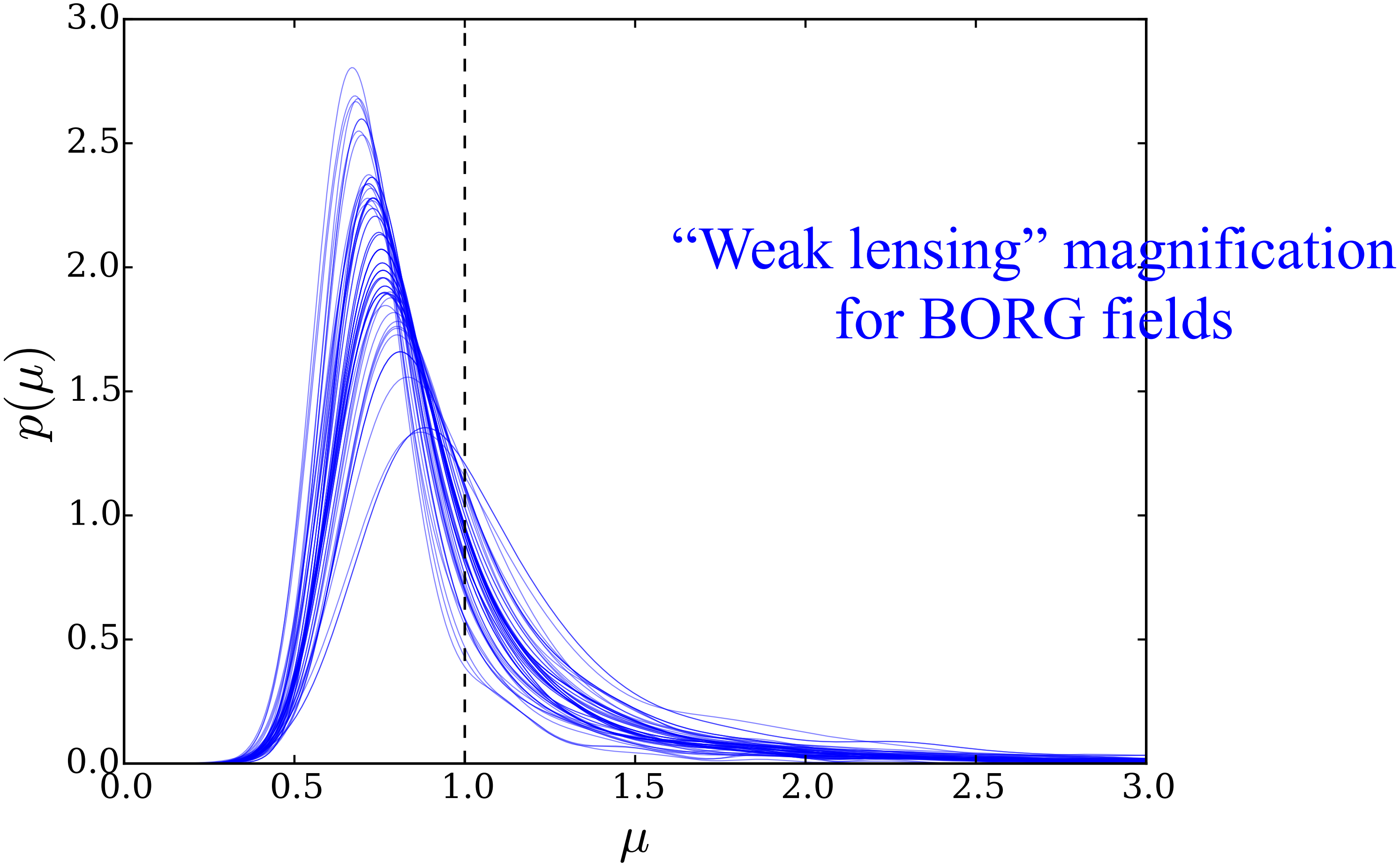
Lensing magnification effects in "blank fields"



Strong and intermediate lensing

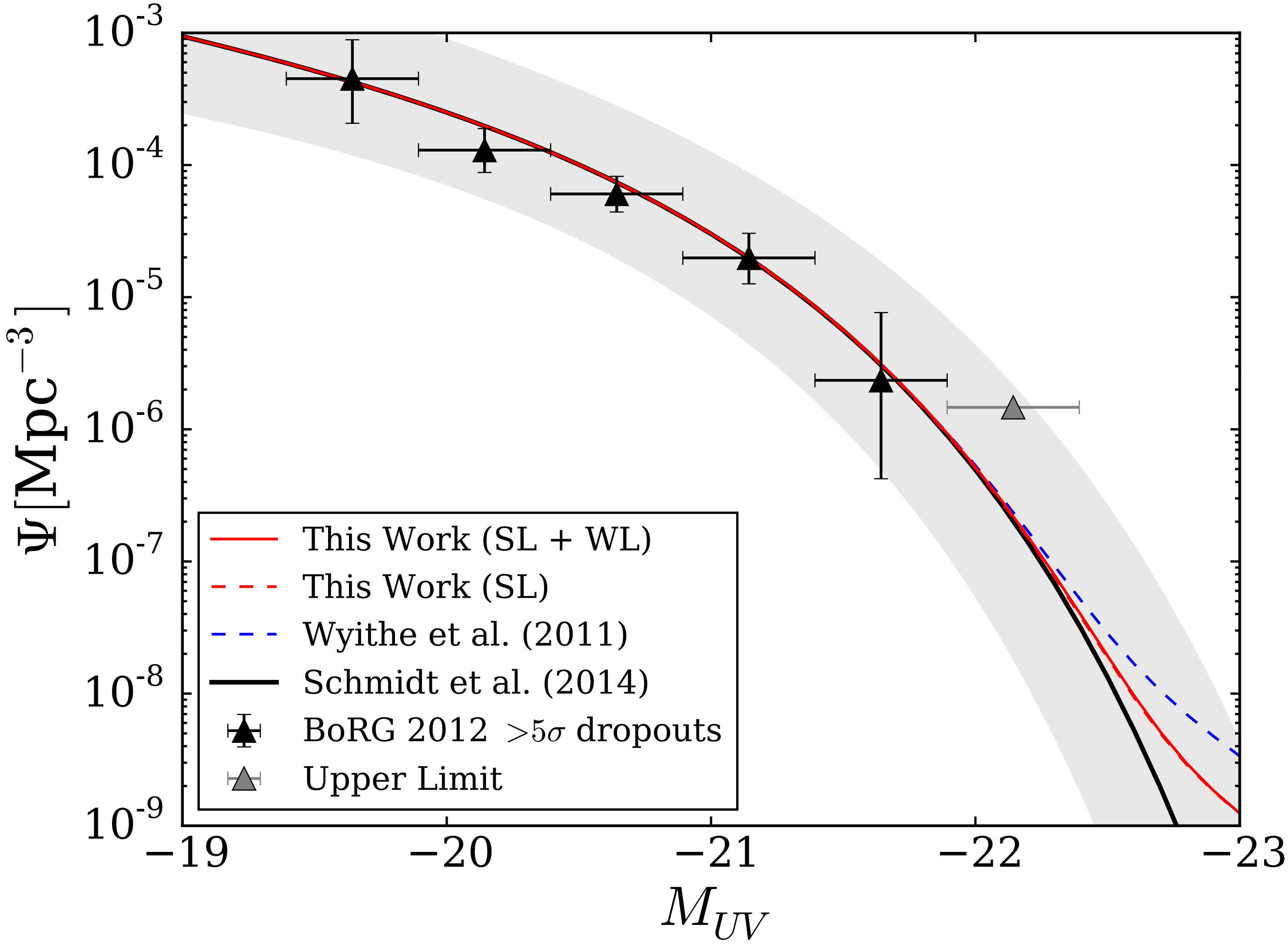
Mason et al. 2014; see also Wyithe et al. 2011

Lensing magnification effects in "blank fields"



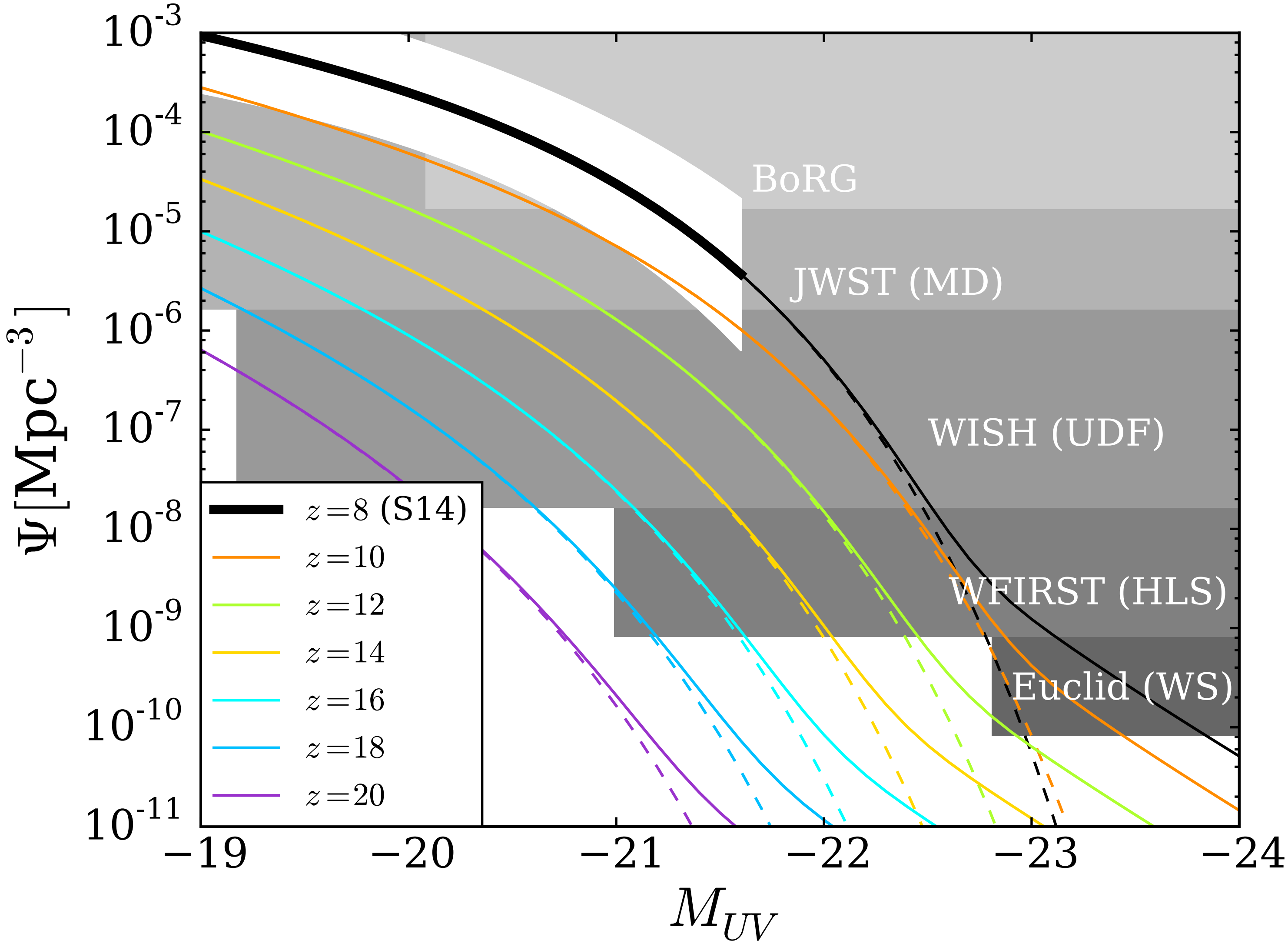
Mason et al. 2014; using pangloss by Collett et al. 2013

The effect is small now…



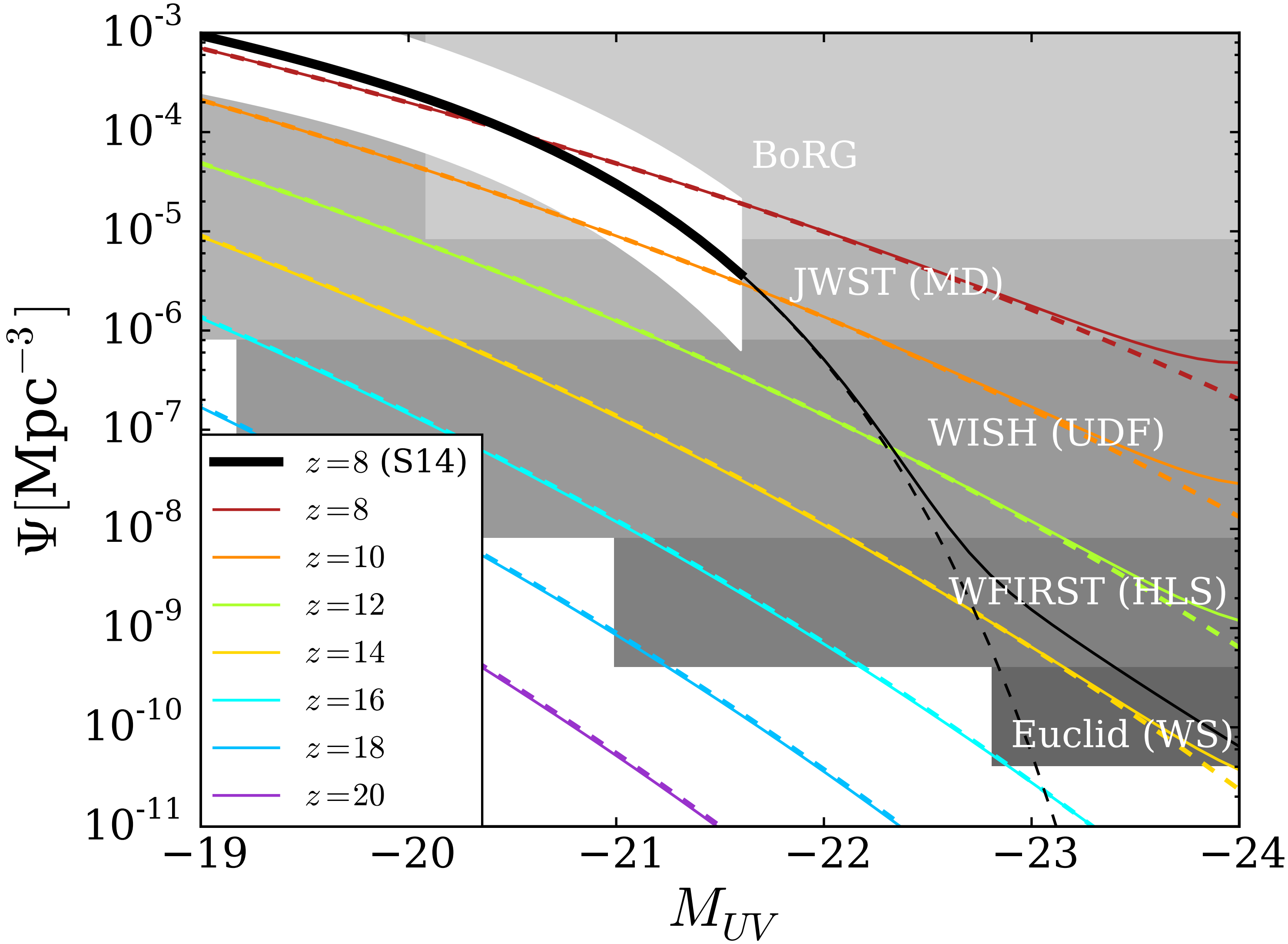
Mason et al. 2014

... but it will be important..



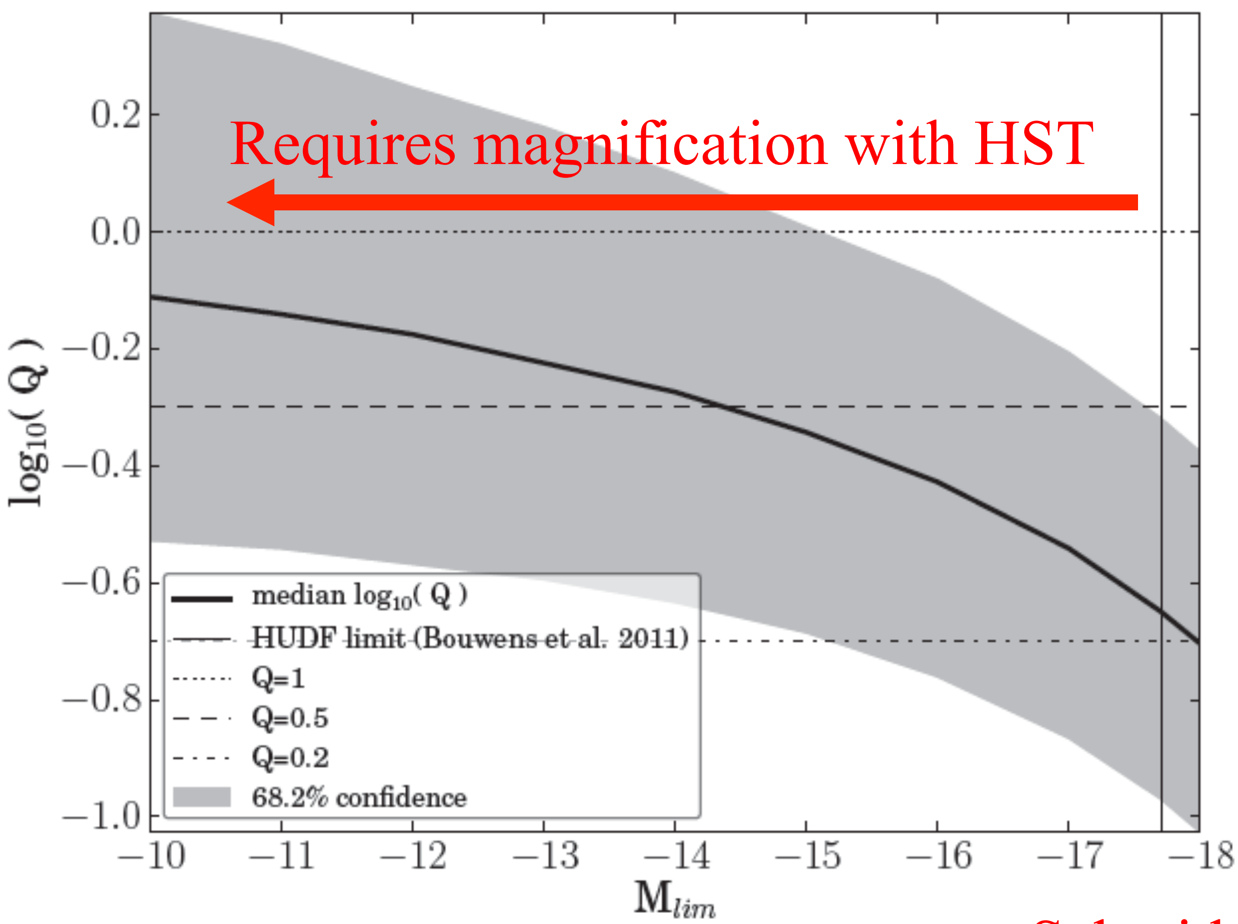
Mason+ 2014; LF from Schmidt+2014b and Bouwens+2014

… to infer the bright end



Mason+14; LF from Schmidt+14b, Munoz+12

Of course, lensing is the only way to probe the faint end



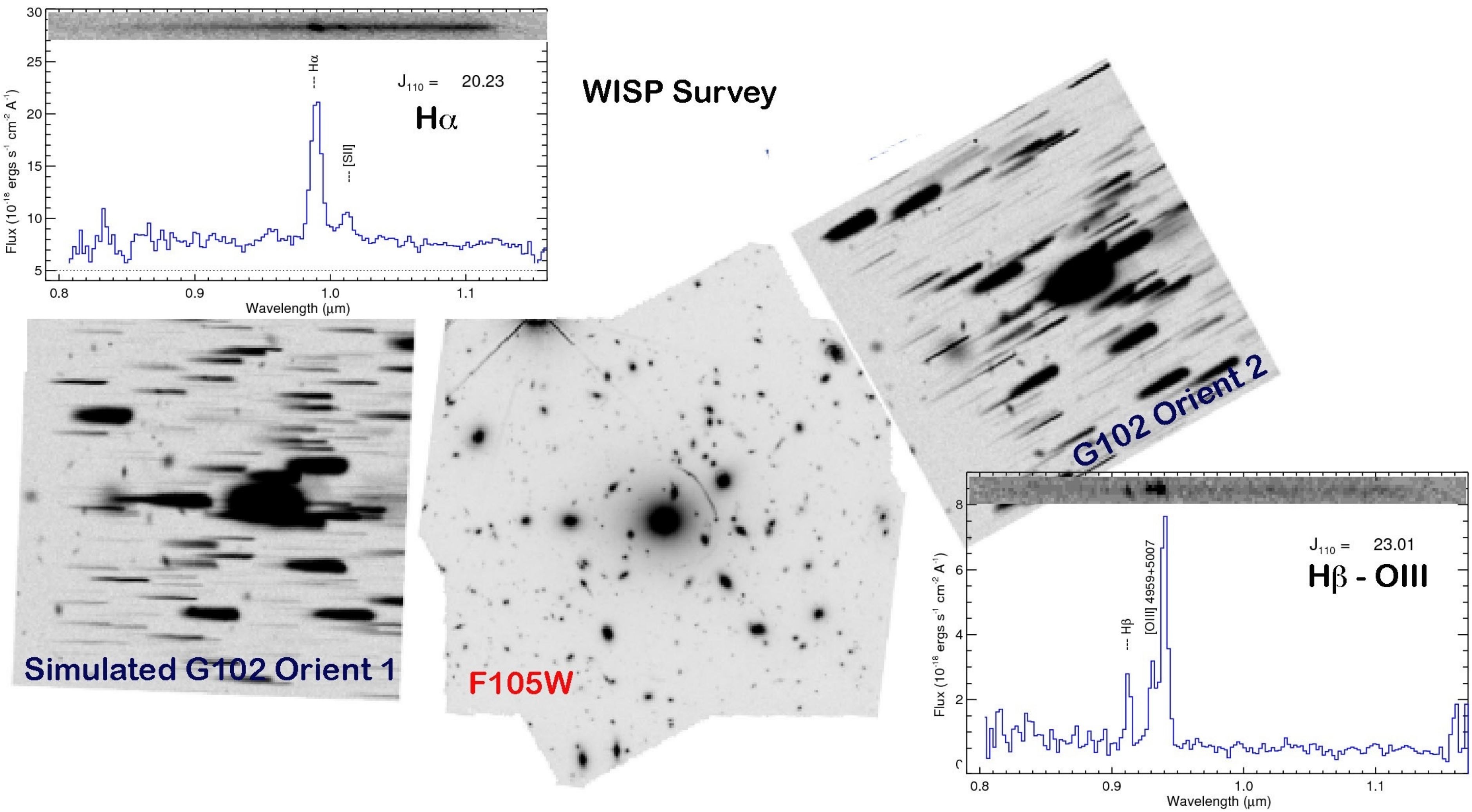
Schmidt et al 2014

GLASS

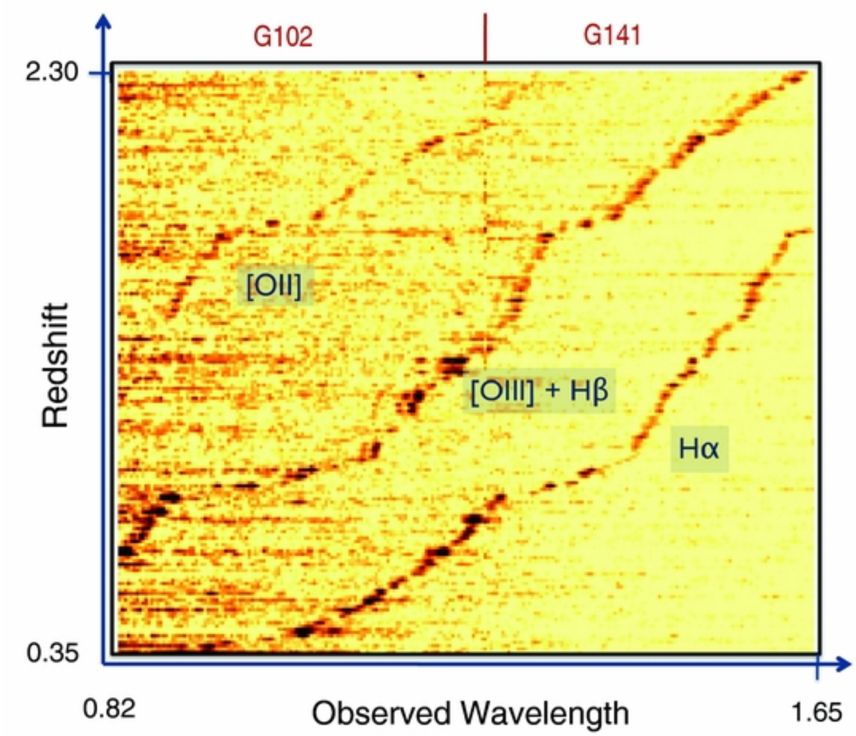
Key science drivers

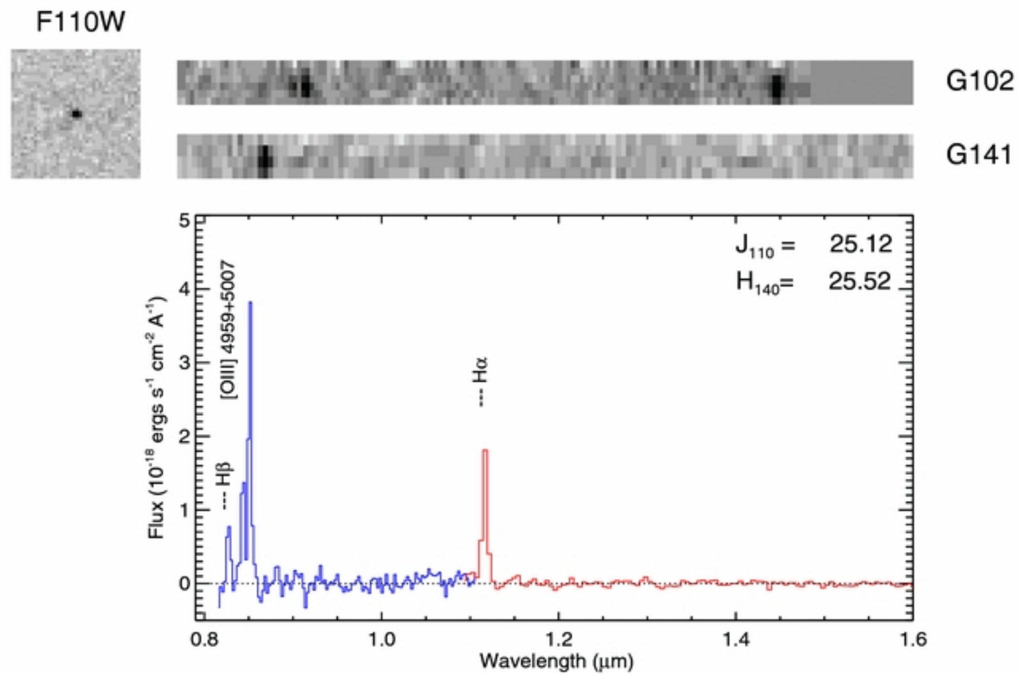
- **When did cosmic re-ionization occur? Who did it?**
  - Observing Lya at z=5.5-13.0
- **How do gas and metals cycle in and out of galaxies?**
  - Spatially resolved metallicity of galaxies
- How does environment affect galaxy evolution?
  - Maps of star formation in cluster galaxies at z~0.5
- How are luminous and dark matter distributed in clusters?
  - Cluster mass models
- **Supernovae cosmology**
  - **Discovery of high-z magnified supernovae Ia**

The tool: HST grisms



Wavelength coverage and observational strategy





- Spectroscopy of 10 clusters, including HFF and CLASH
- 140 orbits cycle 21 (PI Treu) glass.physics.ucsb.edu

GLASS in context

SPACE

GLASS

HST spectroscopy of clusters.

No atmosphere
No skylines

SPACE

CLASH

FRONTIER FIELDS

Extensive HST imaging of clusters

GROUND

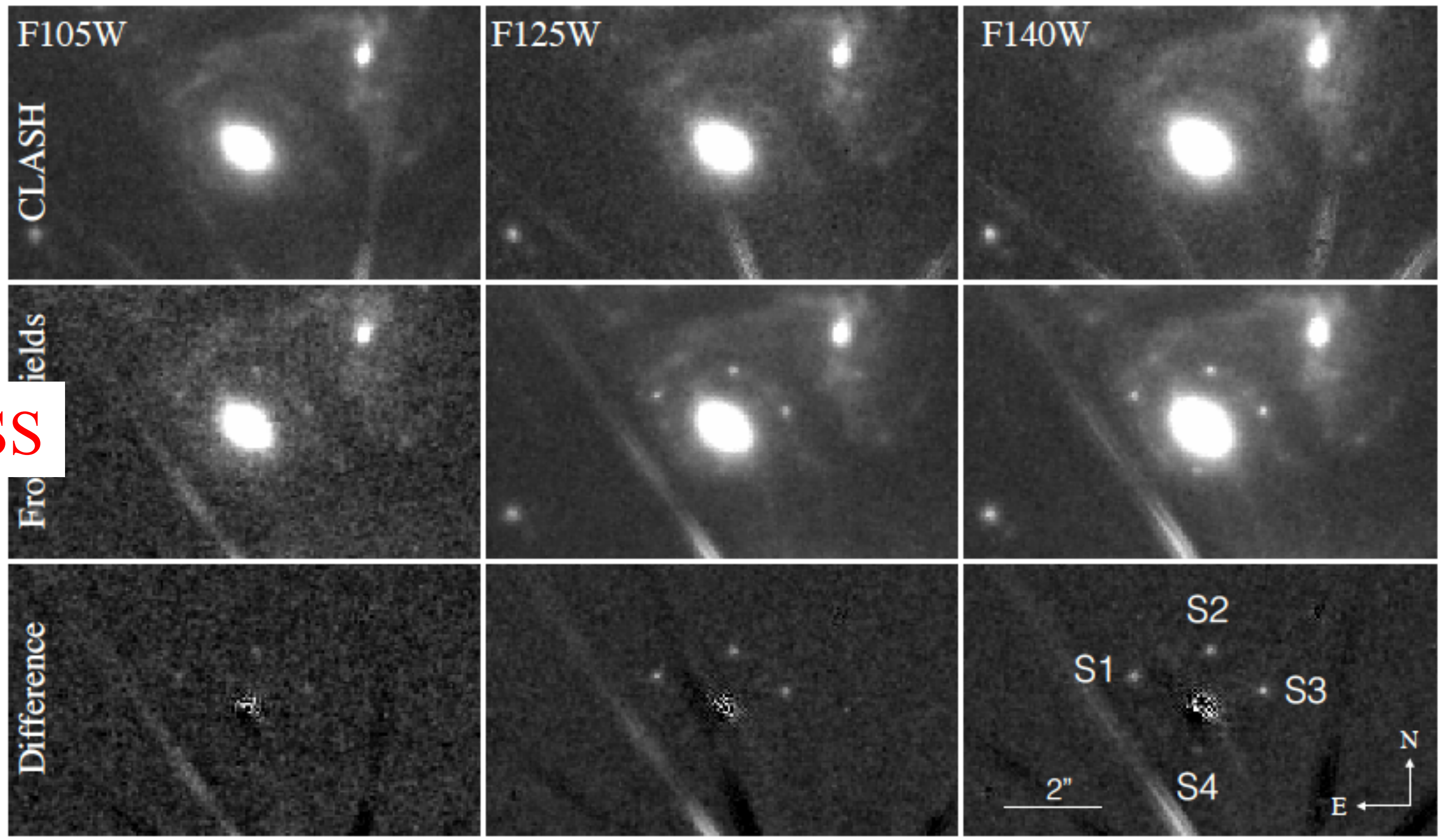
Atmospheric absorption and skylines

European Southern Observatory
www.eso.org

W. M. KECK OBSERVATORY

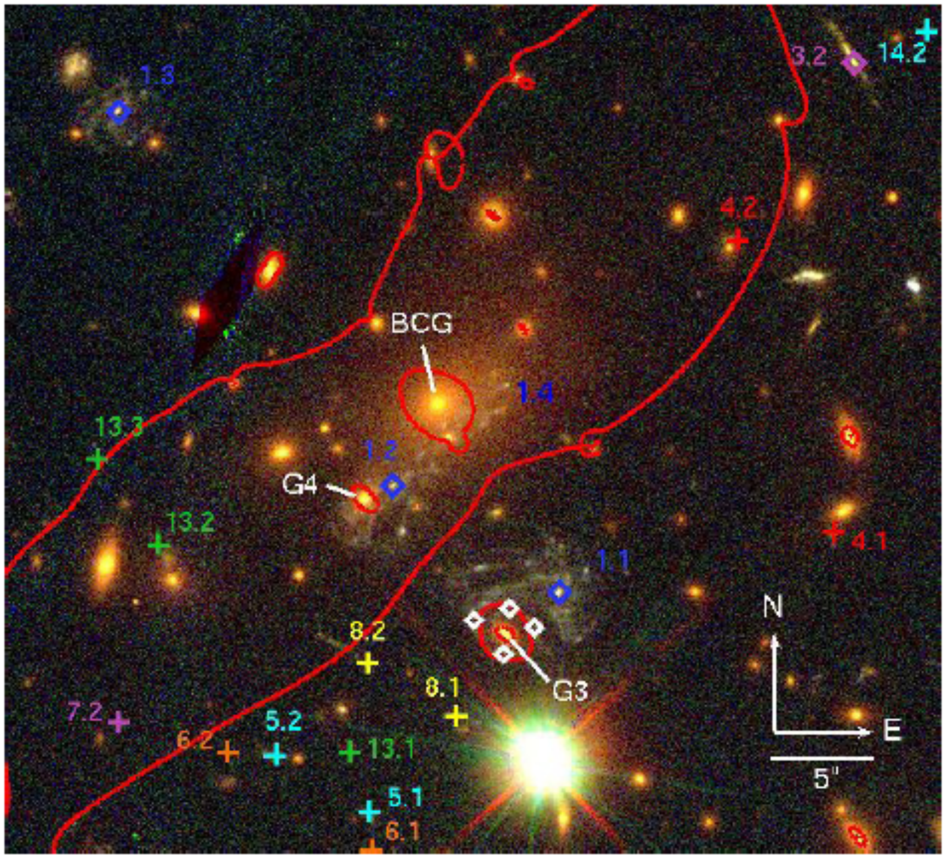
Similar to synergy between
3D-HST and CANDELS in the field

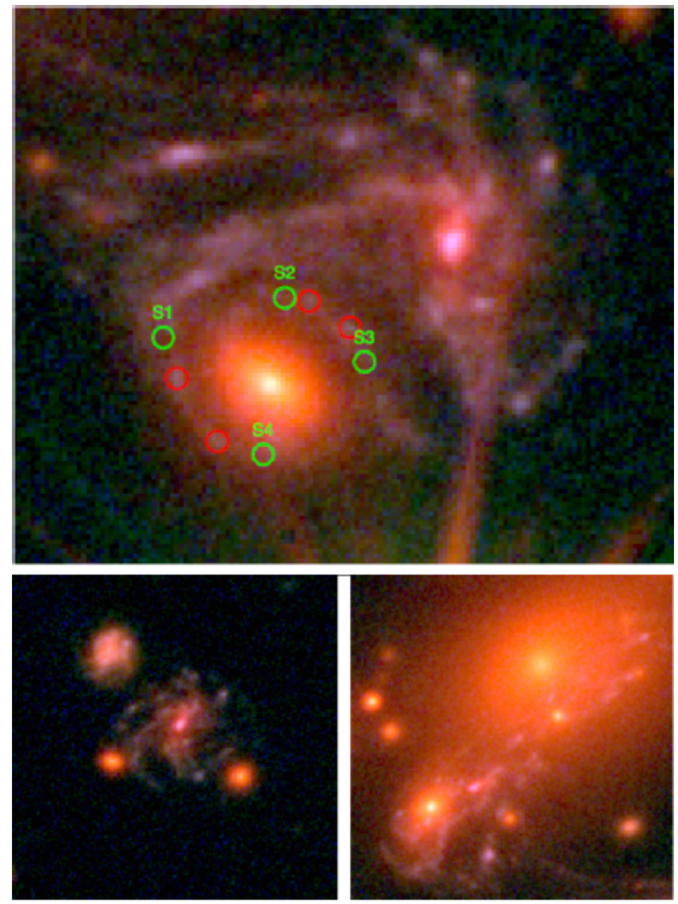
A long awaited discovery
Supernova "Refsdal"



Kelly, Rodney,Treu et al. 2014

A long awaited discovery
Supernova "Refsdal"





Sharon & Johnson 2014

Kelly, Rodney,Treu et al. 2014

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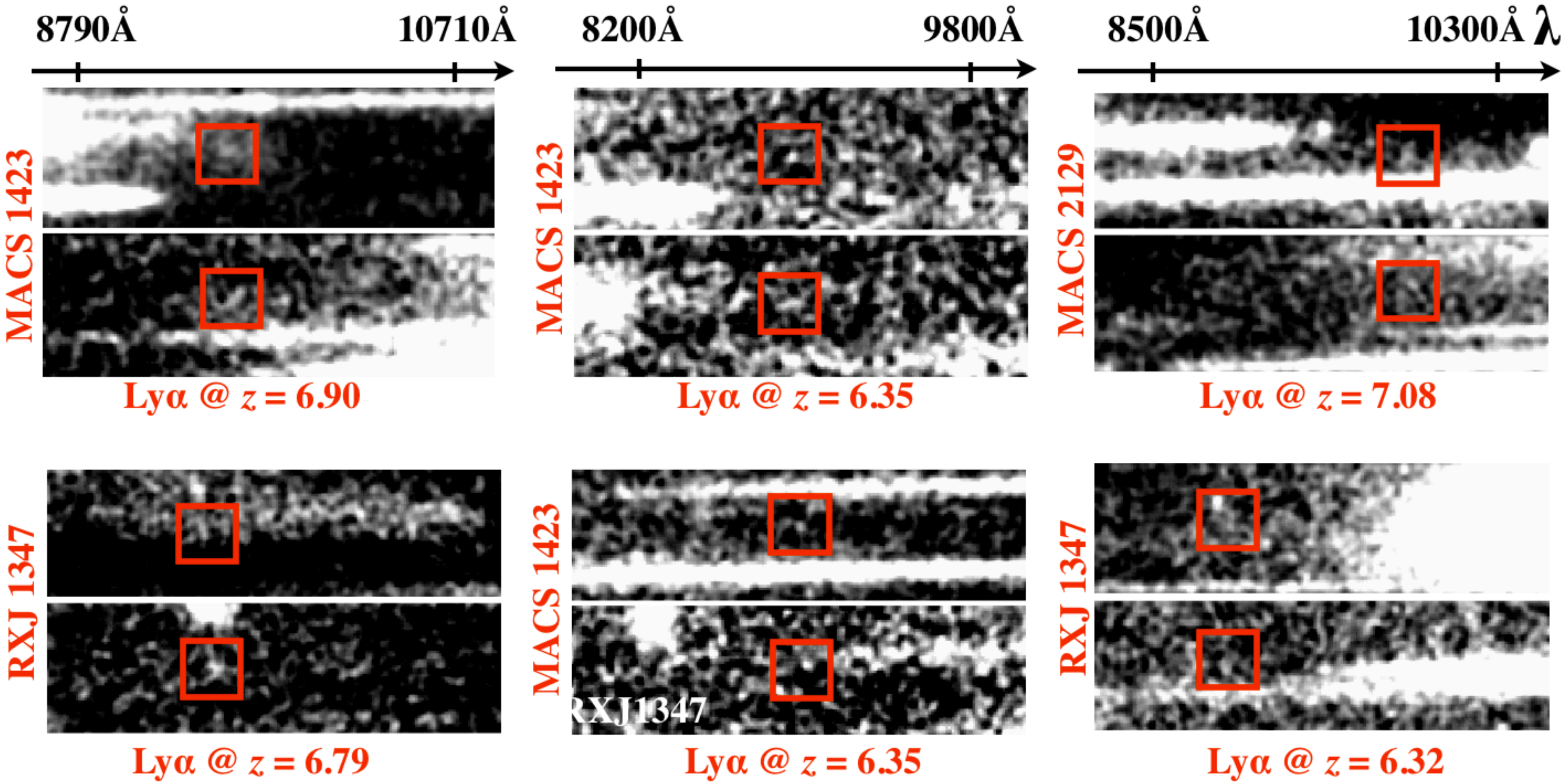
GLASS Strengths

- Spectrum of everything in the field of view
- High sensitivity owing to lensing magnification
- Excellent photometric redshift owing to HFF/ CLASH photometry
- Uninterrupted wavelength coverage, potentially able to detect weaker and redder nebular lines
- Many l.o.s reduce cosmic variance and lya patchiness effects (c.f. Robertson et al. 2014)

WFC3 G102 Spectra from GLASS



Confirmed lya in multiply imaged sources at z=6.1 and 6.4 (Boone+13, Balestra+13, Vanzella+14)

Key science drivers

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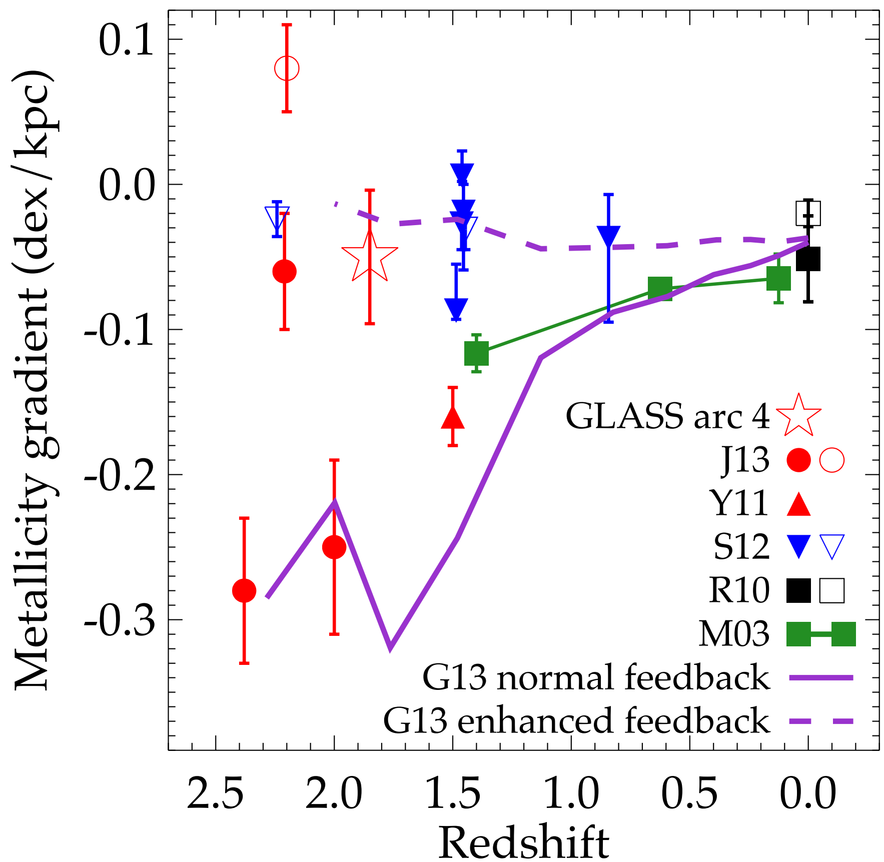
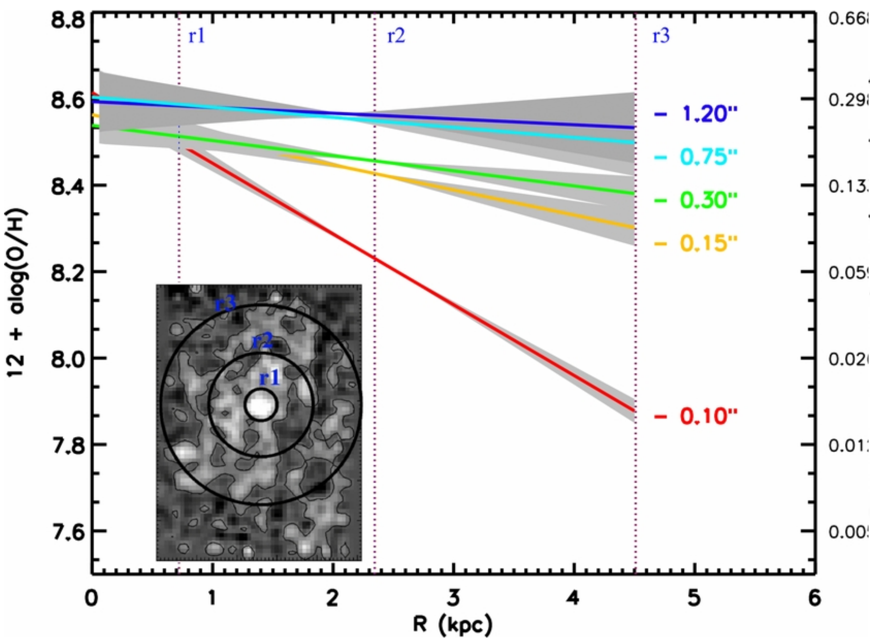
GLASS

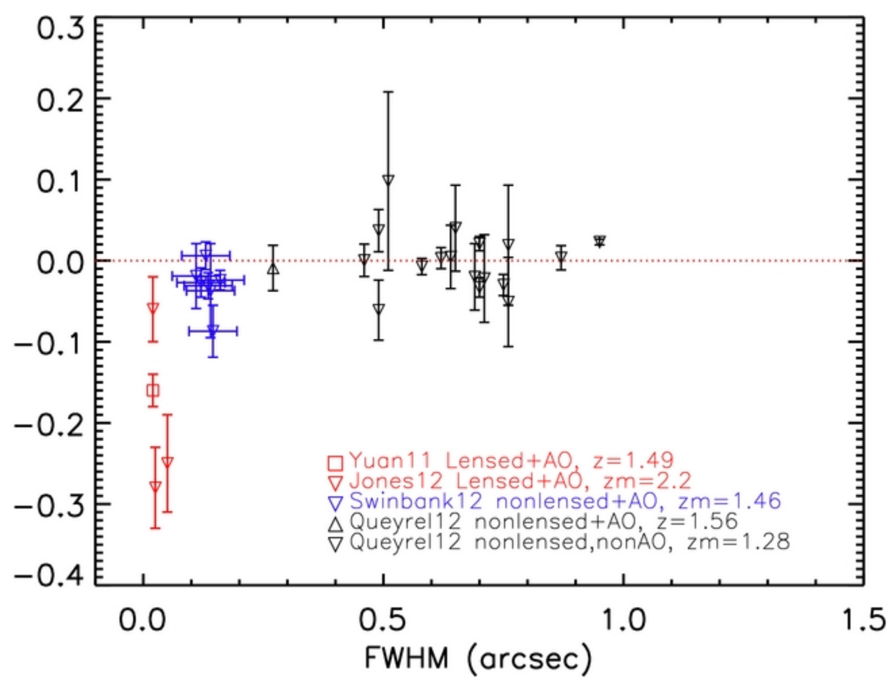
Metallicity gradients as a test of feedback models



Jones+14

Metallicity gradients: resolution effects



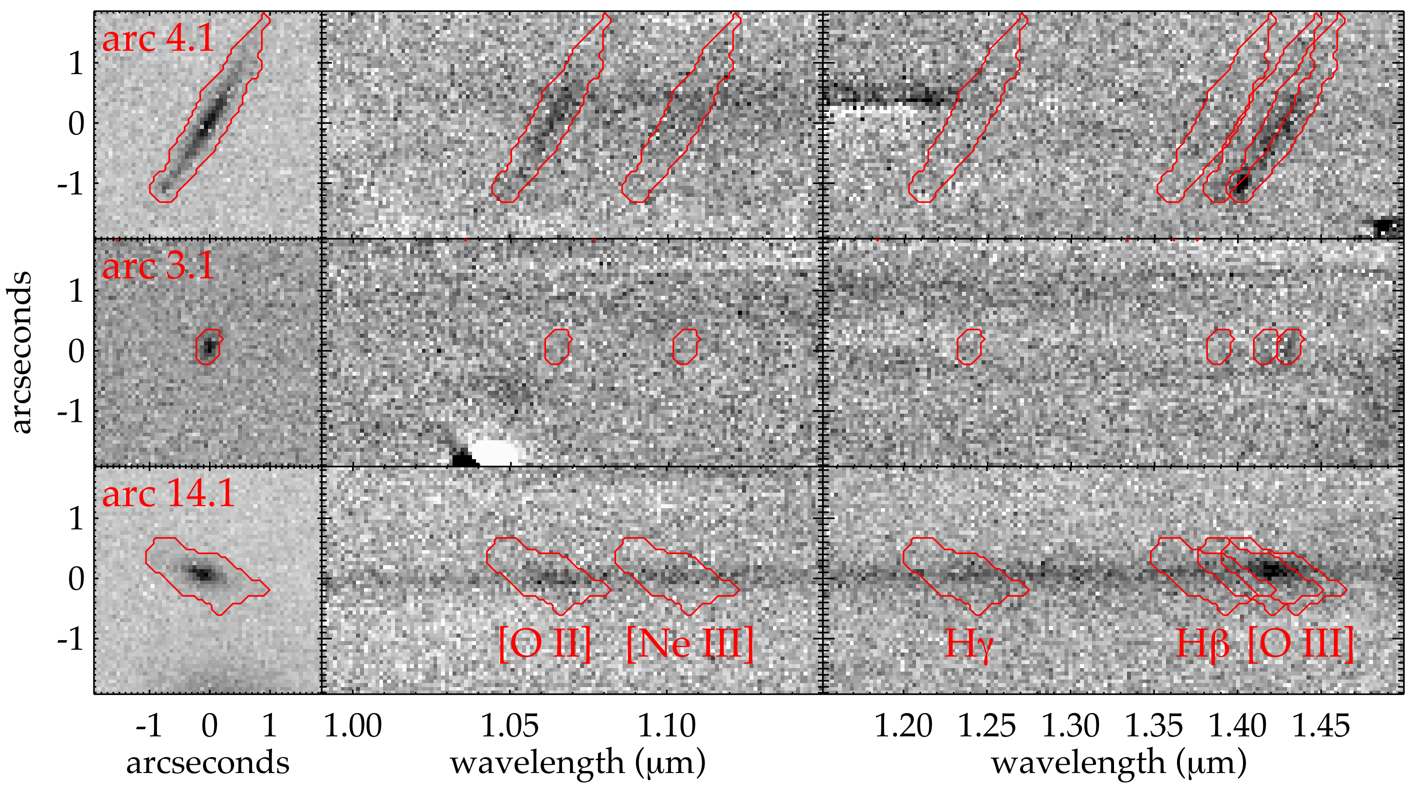


Yuan+13

Metallicity gradients: current state of affairs

- Only a handful of measurement achieve sufficient resolution by combining AO resolution with lensing
  - They seem to prefer steep gradients (hence normal feedback)
- Lower resolution measurement seem to point at shallower profiles
  - Instrumental effect or evidence for enhanced feedback or different modes of metal enrichment?

Superb resolution, sensitivity and wavelength coverage

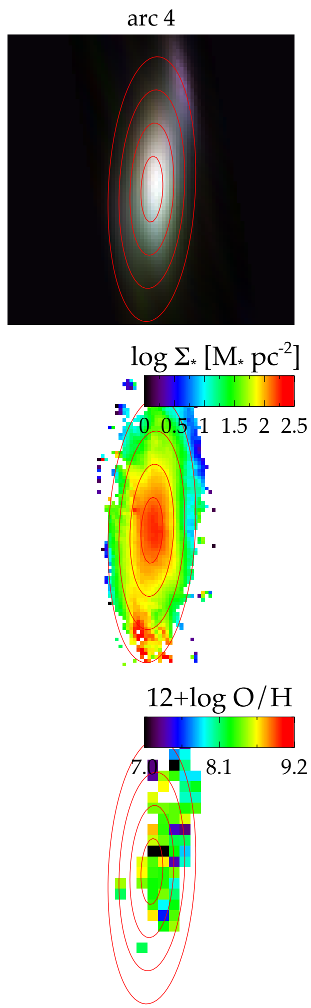


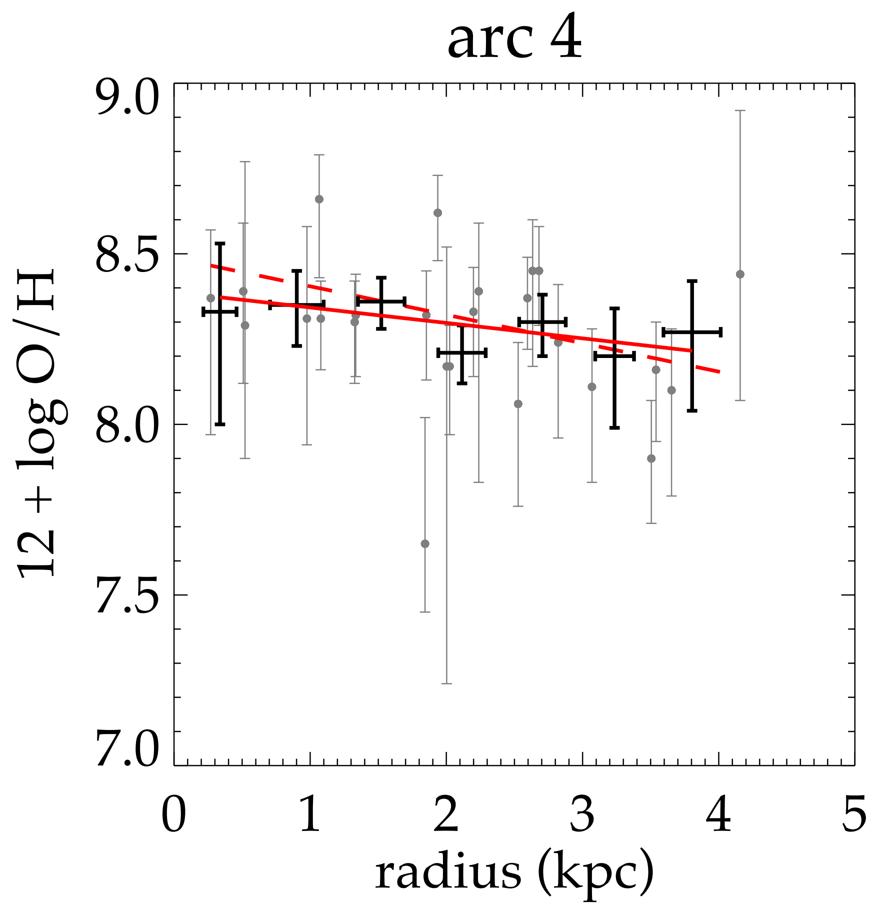
Jones+14

GLASS

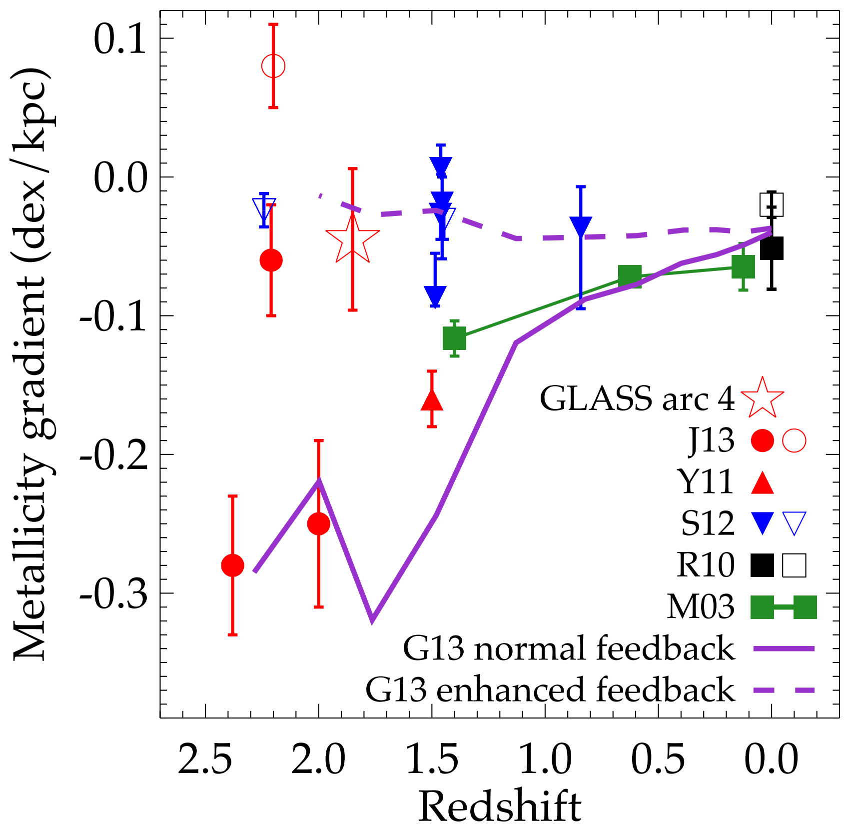
Metallicity maps and gradients

Jones+14





An intriguing result

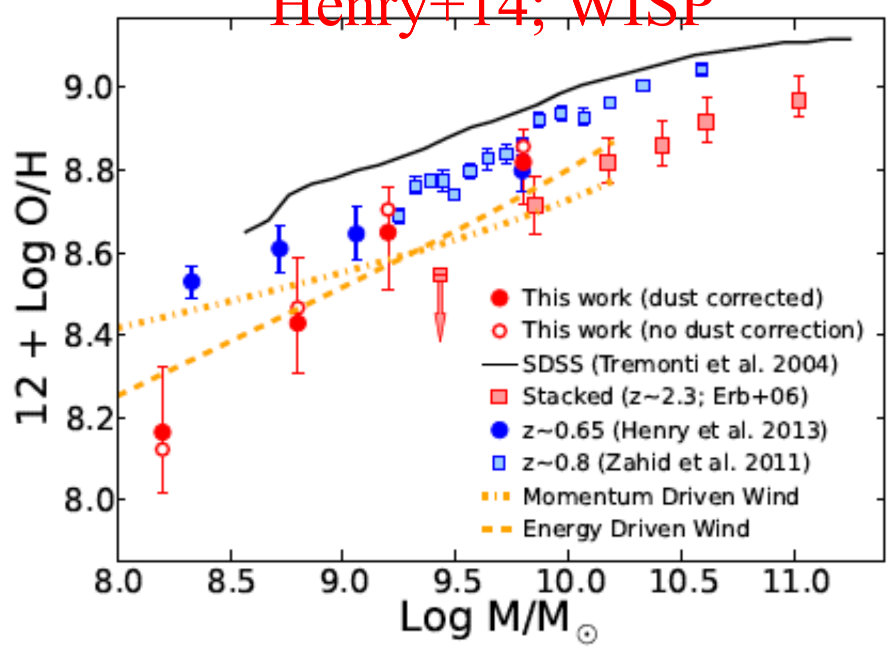


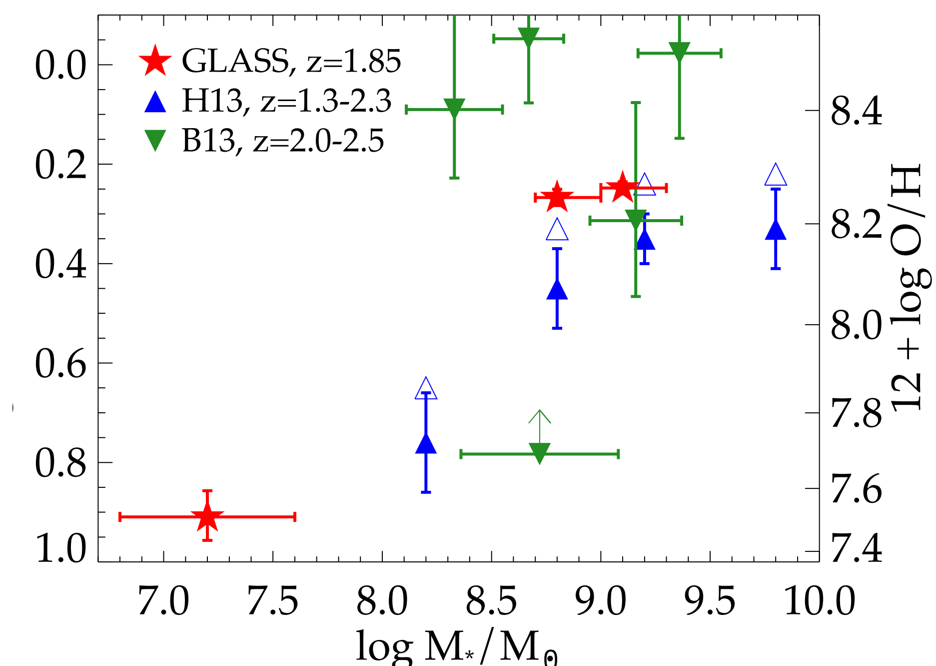
- The shallow gradients measured by GLASS are real
- Consistent with enhanced feedback, or perhaps gas has been stirred by the interaction with the two companion galaxies?
- Analysis of 20 systems in GLASS will provide the answer

Jones+14

The faint end of the mass-metallicity relation

Henry+14; WISP





Jones+14

GLASS will measure it for 100s of objects down to 10^7 M_{sun}!

Summary

- Something very interesting is happening at $z>8$:
  - The IGM is becoming neutral
  - Or galaxies are changing rapidly
- We have not detected the sources of ionizing photons, but great progress will come with GLASS and the Frontier fields
- The evolution of metallicity gradients is still very much an open question. GLASS will be a major step forward and test feedback and outflows models

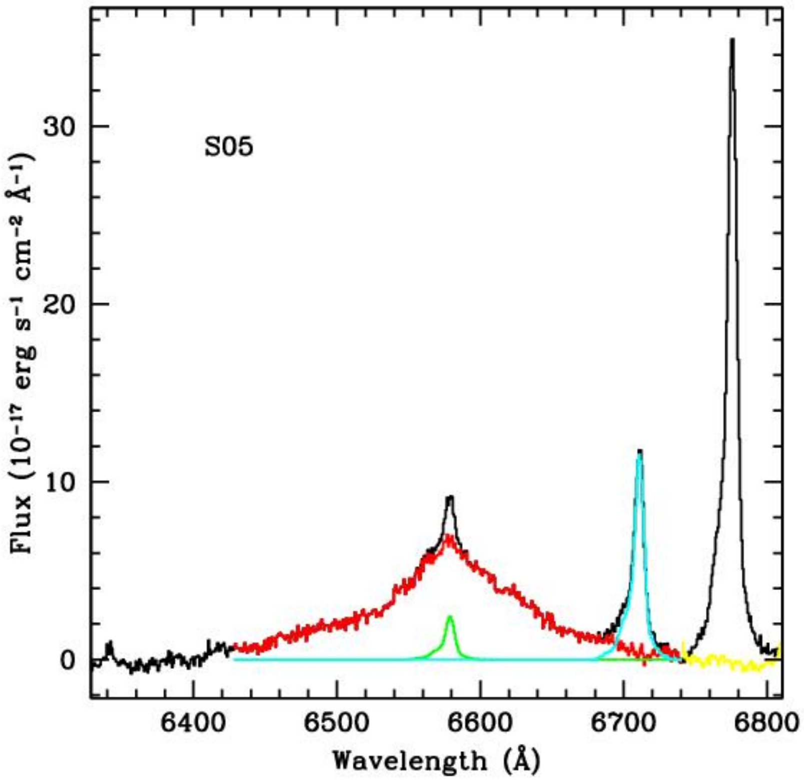
Coda:

what about quasars?

Measuring black hole masses at z>0

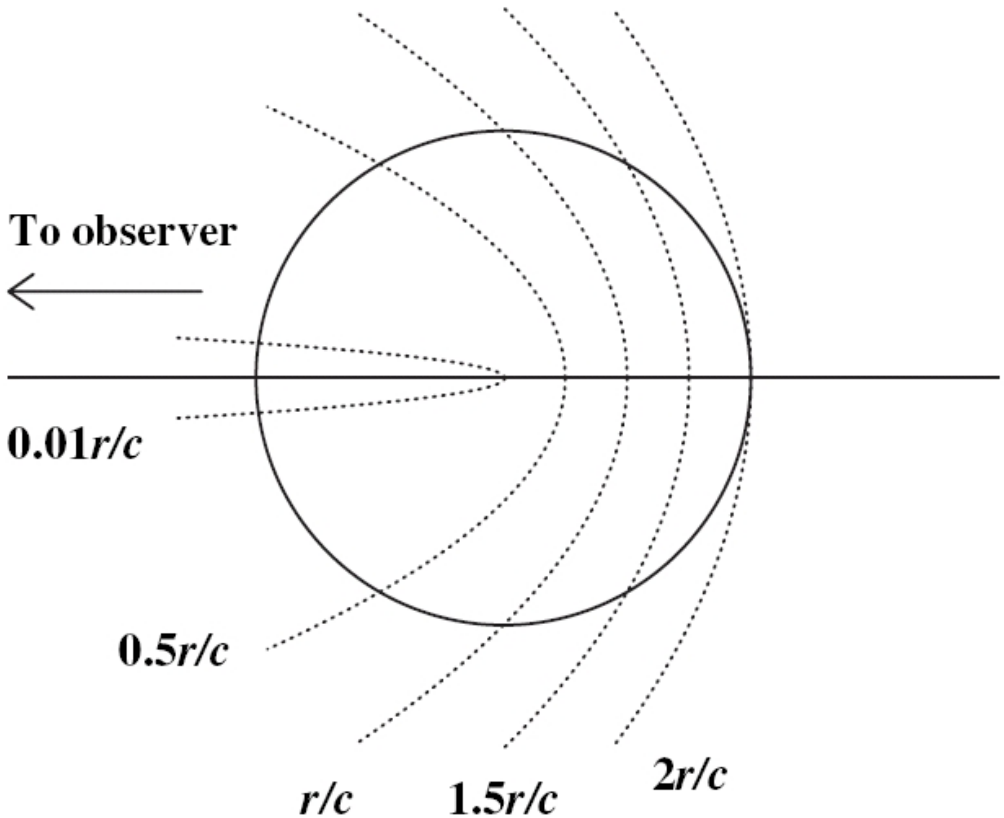
- Broad Hβ width measures the kinematics of the gas orbiting the black hole
- Size from L
- **Overall uncertainty on BH mass ~0.4-0.5 dex**

Treu et al. 2014



$$M_{BH} = 10^{8.58} \left(\frac{\sigma_{H\beta}}{3000 \mathrm{km\,s^{-1}}} \right)^2 \left(\frac{\lambda L_{5100}}{10^{44} \mathrm{erg\,s^{-1}}} \right)^{0.518}$$

Reverberation Mapping



Ring of gas with radius *r*

Gas along line of sight to observer will appear to respond with no delay

Gas that is furthest from observer will appear to have response delayed by 2*r*/*c*

Mean lag time is *r*/*c*

Blandford & McKee 1982

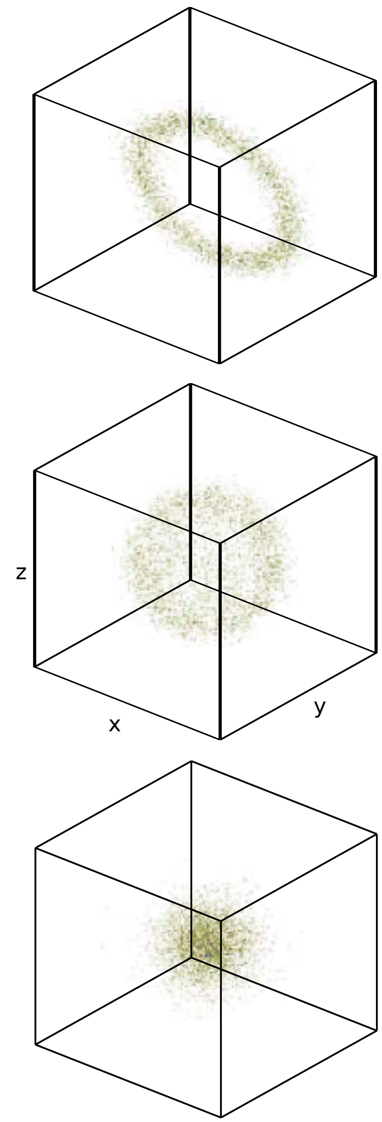
Example of traditional results

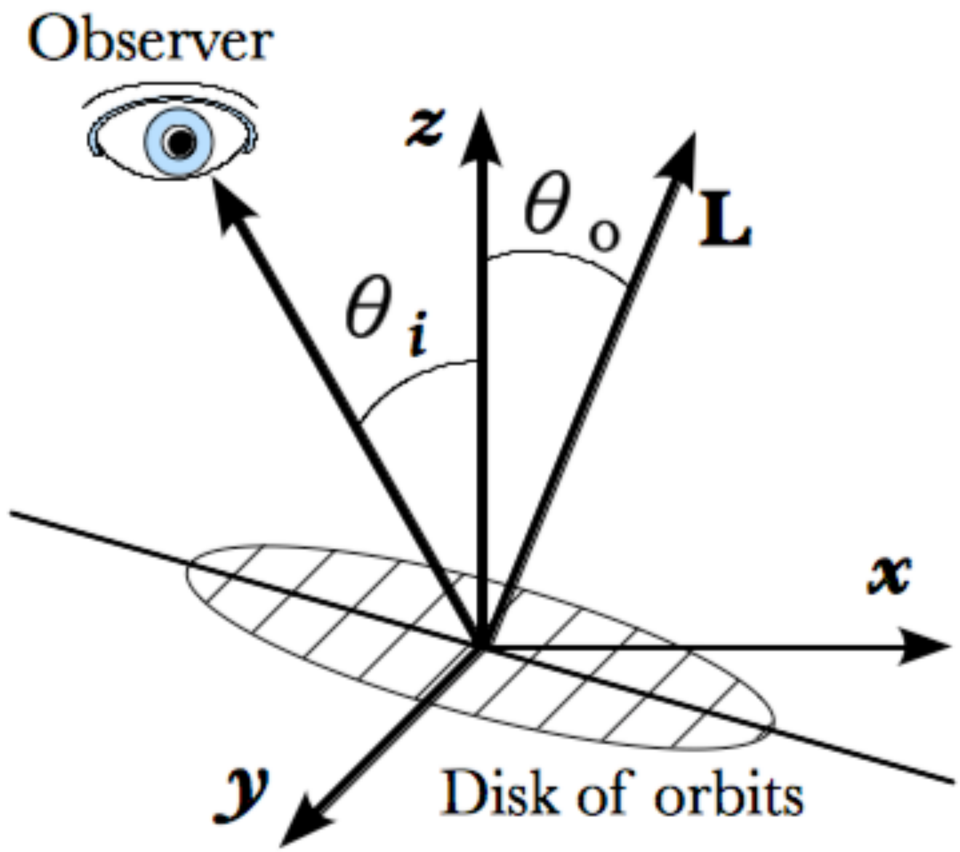
Table 13. Virial Products and Derived Black Hole Masses

Object	$c\tau_{\rm cent}\sigma^2_{\rm line}/G$ (10^6 M$_\odot$)	$M_{\rm BH}$[a] (10^6 M$_\odot$)
Mrk 142	$0.40^{+0.12}_{-0.14}$	$2.17^{+0.68}_{-0.75}$
SBS 1116+583A	$1.05^{+0.33}_{-0.29}$	$5.80^{+1.84}_{-1.58}$
Arp 151	$1.22^{+0.16}_{-0.22}$	$6.72^{+0.89}_{-1.19}$
Mrk 1310	$0.41^{+0.12}_{-0.13}$	$2.24^{+0.68}_{-0.69}$
Mrk 202	$0.26^{+0.15}_{-0.10}$	$1.42^{+0.83}_{-0.56}$
NGC 4253	$0.32^{+0.21}_{-0.20}$	$1.76^{+1.15}_{-1.11}$
NGC 4748	$0.47^{+0.16}_{-0.21}$	$2.57^{+0.90}_{-1.14}$
NGC 5548	$14.9^{+3.4}_{-4.9}$	82^{+19}_{-27}
NGC 6814	$3.36^{+0.54}_{-0.56}$	$18.5^{+3.0}_{-3.1}$

[a] Assuming $f = 5.5$.

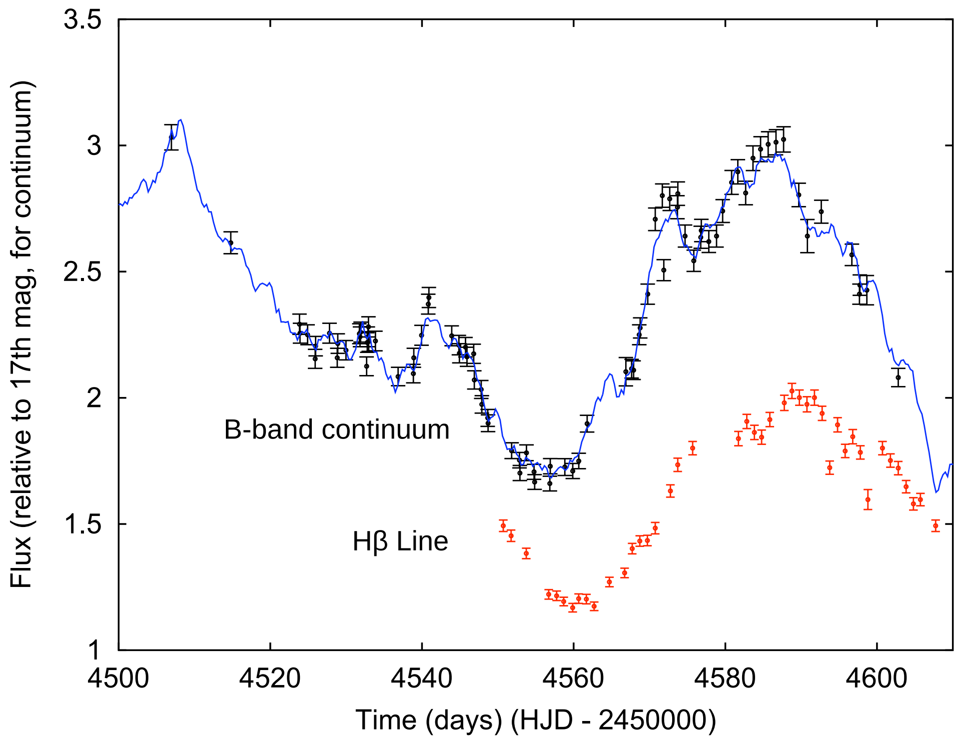
A new approach: Geometric and dynamical models

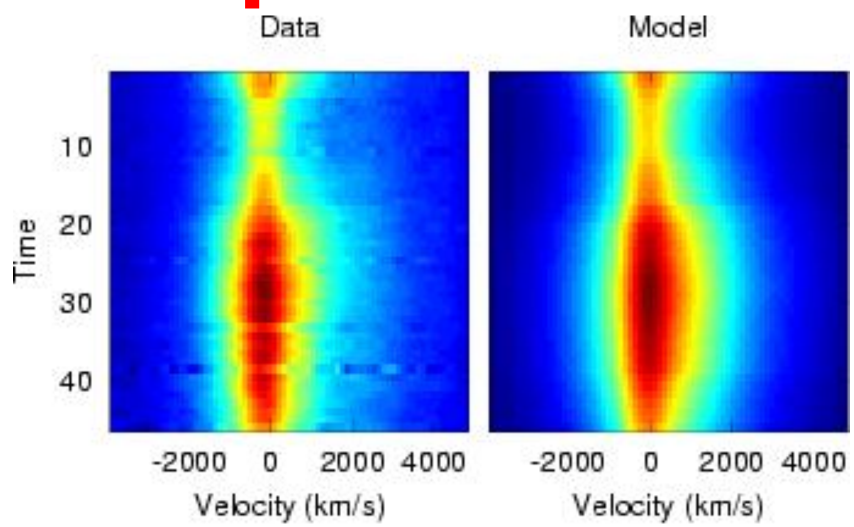


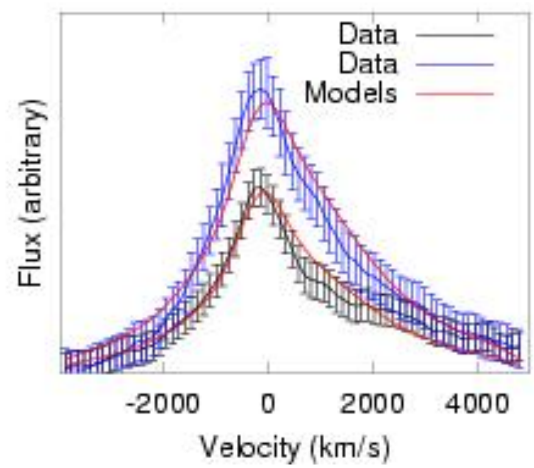


Pancoast, Brewer & Treu, 2011, 2014

Geometric and dynamical models: Application to Arp 151

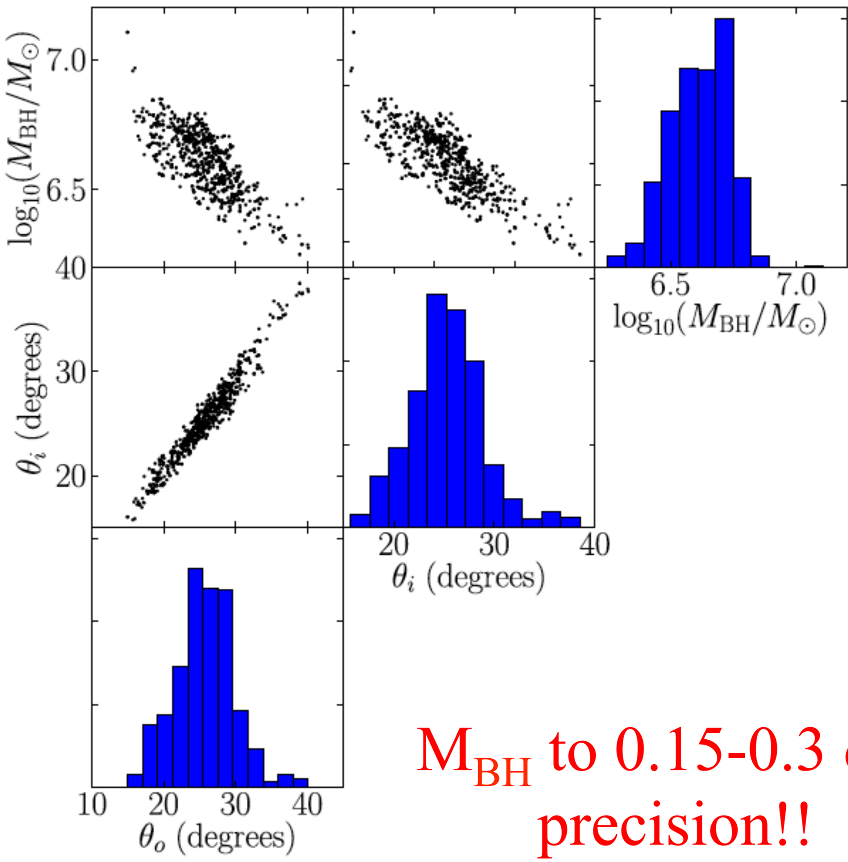






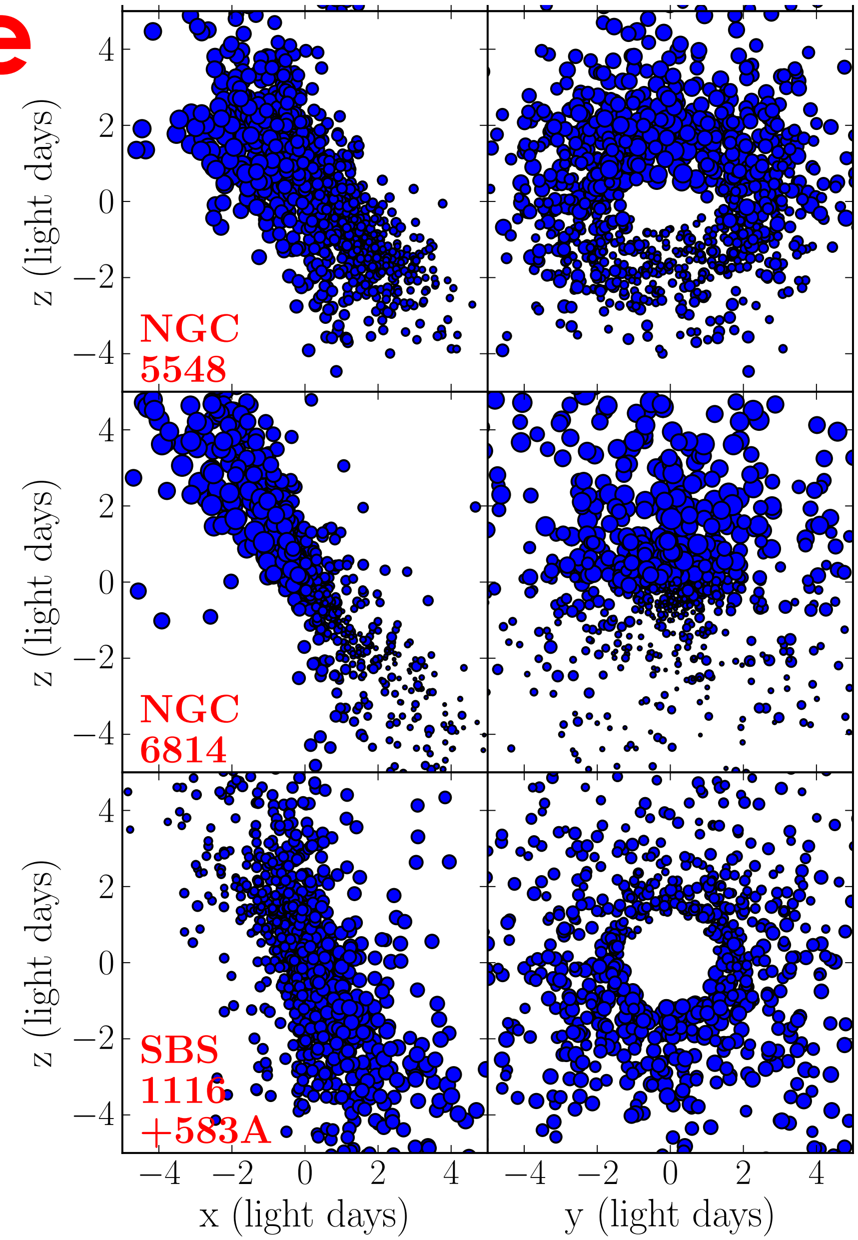
Brewer, Treu, Pancoast et al 2011

Inferences about M_{BH} and BLR structure



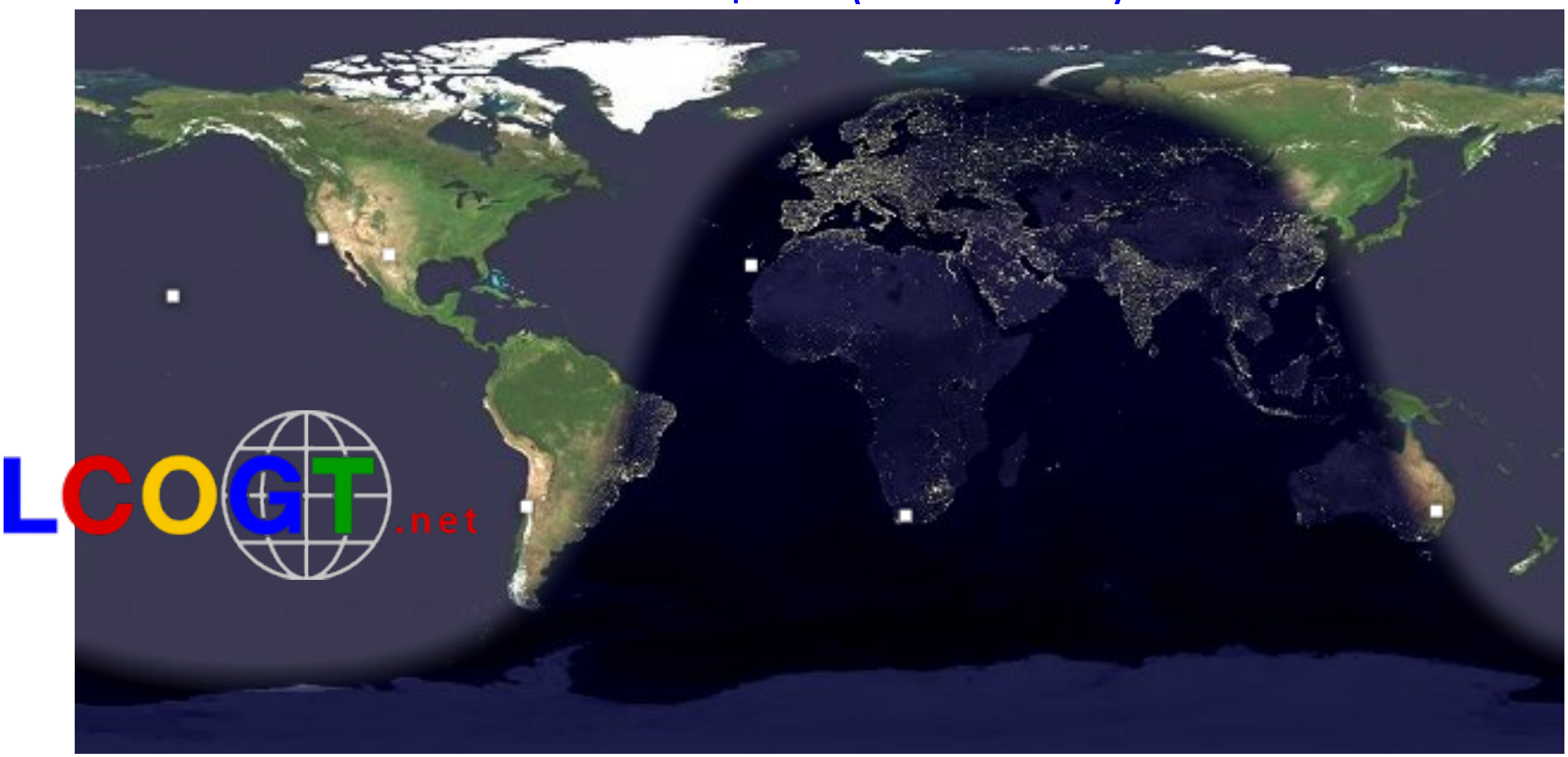
M_{BH} to 0.15-0.3 dex precision!!

Pancoast et al. 2014b



Reverberation mapping

- At z~0, several objects have been studied with sufficient quality (LAMP08/11 and Peterson Group)
- At z>0, very hard with traditional telescopes (e.g. Woo et al. 2007). Large program under way with LCOGT robotic telescopes (PI: Horne).



The end

Credits

- K.Schmidt (UCSB)
- R.Barone (Melbourne)
- M.Bradac (UCD)
- L.Bradley (STScI)
- G.Brammer (STScI)
- B.Brewer (Auckland)
- *T.Collett (IoA)*
- M.Dijkstra (UoO)
- A.Dressler (OCIW)
- A.Fontana (Roma)
- R.Gavazzi (IAP)
- A.Henry (NASA)
- *A.Hoag (UCD)*
- T.Jones (UCSB)
- P.Kelly (UCB)
- K.Huang (UCD)
- M.Malkan (UCLA)
- P.Marshall (Stanford)
- *C.Mason (UCSB)*
- *A.Pancoast (UCSB)*
- L.Pentericci (Roma)
- B.Poggianti (Padova)
- M.Stiavelli (STScI)
- M.Trenti (IoA)
- A.vdLinden (Stanford/Dark)
- B.Vulcani (IPMU)
- *X.Wang (UCSB)*
- S.Wyithe (Melbourne)

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