# BREAKING COSMIC DAWN: STUDYING Z\_7 GALAXIES WITH CLUSTER LENSES AS COSMIC TELESCOPES

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# Study EoR

- \* We want to answer important questions (now!):
  - $\rightarrow$  Who did it?
  - → How did it happen?
  - → When did it happen?

### Detect and study high-z galaxies

- ★ Detecting and measuring their UV SFR (instantaneous SFR) → Hubble, JWST
- \* Lyman- $\alpha$  emission (very sensitive to the topology)  $\rightarrow$  Keck, TMT
- ★ Measuring their older stellar population → Spitzer
- \* Gas reservoir for star formation  $\rightarrow$  ALMA

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### Detecting these galaxies is hard....

Need assistance....

Lensing is fantastic<sup>™</sup>





#### **DETECT + YOUNG STELLAR POPULATION**

### INCREASED FLUX AND SIZE (TEAH!!)

galaxy

#### **OLD STELLAR POPULATION**



lensed galaxy images

galaxy cluster

#### TOPOLOGY OF REIONIZATION,Z CONFIRMATION





distorted light-rays

#### GAS RESERVOIR, Z CONFIRMATION

Earth



# **The Frontier Fields**

PI Jen Lotz Matt Mountain Hubble + Spitzer directors' program Deepest views of the universe to date (nJy sources: intrinsic AB mag > 31)



http://www.stsci.edu/hst/campaigns/frontier-fields/

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galaxy

# TOPOLOGY OF REIONIZATION Z CONFIRMATION

VLA

Astro-H

SPICA

eROSITA



, lensed galaxy images

THE REPORT OF TH

DESI

HSC

E-ELT

**725** 

PFS

GMT

#### How do we capitalize on deep cluster imaging?

- \* CLASH, Frontier Fields, SURFS UP, etc. give us great imaging.
- Need spectra:
  - → Ultimate redshift determination.
  - $\rightarrow$  Reionization.
  - → Study SFR

THE GOOD

#### How do we capitalize on deep cluster imaging?

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### Have we reached the limit?



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THE BAD

### Spectroscopy at z > 7 is hard

MOSFIRE



~ 3 hour exposure on MOSFIRE

#### TMT SCIENCE FORUM

Treu et al. 2013

### Spectroscopy at z > 7 is hard



- BoRG follow-up with MOSFIRE (Keck MOS in NIR) looking for Lyα emission (Treu, Schmidt et al. 2013) - only non-detections
- No detections at z>7.51 (Finkelstein+13) [z>7.62 (Schenker+14)]
- Treu et al. 2012 formalism can put constraints on EoR e.g., p(Lyαl LBG) and the EoR model (patchy vs. smooth) (see e.g. Treu+12, Treu, Schmidt+13, Pentericci+14)

# Spectroscopy at z > 7 is hard



A 52 hours VLT/FORS2 spectrum of a bright z ~ 7 HUDF galaxy

z-band dropout HUDF-J033242.56-274656.6



Vanzella et al. 2014





- \* For spectroscopy we need lensing even in the TMT era!!
- Spectrum of everything in the field of view
- High sensitivity owing to lensing magnification
- Uninterrupted wavelength coverage, potentially able to detect weaker and redder nebular lines



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

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### High Redshift Measurements without Lyα?





The faintest high-z galaxy ever detected spectroscopically - 16 hours on VLT

z=6.740 LAE (0.5L\* LBG) Faint LAEs are very important beacon for

reionization

Bradač et al. 2012

### INCREASED FLUX AND SIZE (TEAH!!)

# galaxy YOUNG STELLAR POPULATION

alaxy images

#### OLD STELLAR POPULATION distorted light-rays



Earth



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# SURFS UP: Spitzer UltRa Faint SUrvey Program

- Exploration Science Spitzer Program for Cycle 9 (PI Bradač)
- A Over 550 hours with Spitzer for 10 clusters
- Think Spitzer-UDF depth, but assisted by lensing!
- Star formation rates and stellar masses of a large number of galaxies (50 at z~7 and 10 at z~8)
- Presence (or absence) of established stellar population.

http://www.physics.ucdavis.edu/~marusa/SurfsUp.html TMT SCIENCE FORUM



Bradač et al. 2014 (ApJ), Ryan et al. 2014 (ApJL)

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### SURFS UP: Spitzer UltRa Faint SUrvey Program

**Bullet Cluster** 

MACS 1149 Cluster



Foreground Clusters Magnify Distant Galaxies NASA / JPL-Caltech / R. E. Ryan, Jr. (STScl) Spitzer Space Telescope • IRAC sig14-015

http://www.spitzer.caltech.edu/news/1669-feature14-13-Catching-a-Wave-of-Galaxies-Ending-the-Dark-Ages

Bradač et al. 2014 (ApJ), Ryan et al. 2014 (ApJL)



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# MACS1149-zD



Zheng et al. 2012, Bradač et al. 2014

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### "Distinguished" stellar populations



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LePhare + Monte Carlo

# "Distinguished" stellar populations

$z_{ m phot}$	$9.5\pm0.2$
SFR	$1.0^{+5.0}_{-0.4} (\mu/14.5)^{-1} M_{\odot} \mathrm{yr}^{-1}$
$M^*$	$7^{+1}_{-5} \times 10^8 (\mu/14.5)^{-1} M_{\odot}$
Age	$450^{+30}_{-360}$
$\mu$	$14.5^{+4.2}_{-1.0}$ (c)
$[3.6  \mu \mathrm{m}]_{\mathrm{int}}$	$28.6_{-0.8}^{+0.9}$
$[4.5\mu\mathrm{m}]_\mathrm{int}$	$27.9^{+0.6}_{0.4}$

The age of the universe at  $z \sim 9.5$  is  $\sim 520$  Myr.



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# Summary

- Something is happening at z > 7: exciting opportunities ahead!
- There seem to exist evolved stellar population at z>7
- Future is bright, magnified by lensing!
- \* Lot of time investments (HST, Spitzer, Keck) on the way to use clusters as cosmic telescopes:
  - → Frontier Fields , GLASS, SURFS UP: Study stellar masses, ages and SFR at the EoR







For the Frontier fields TMT is needed, for spectroscopy at z>7 we need lensing!



