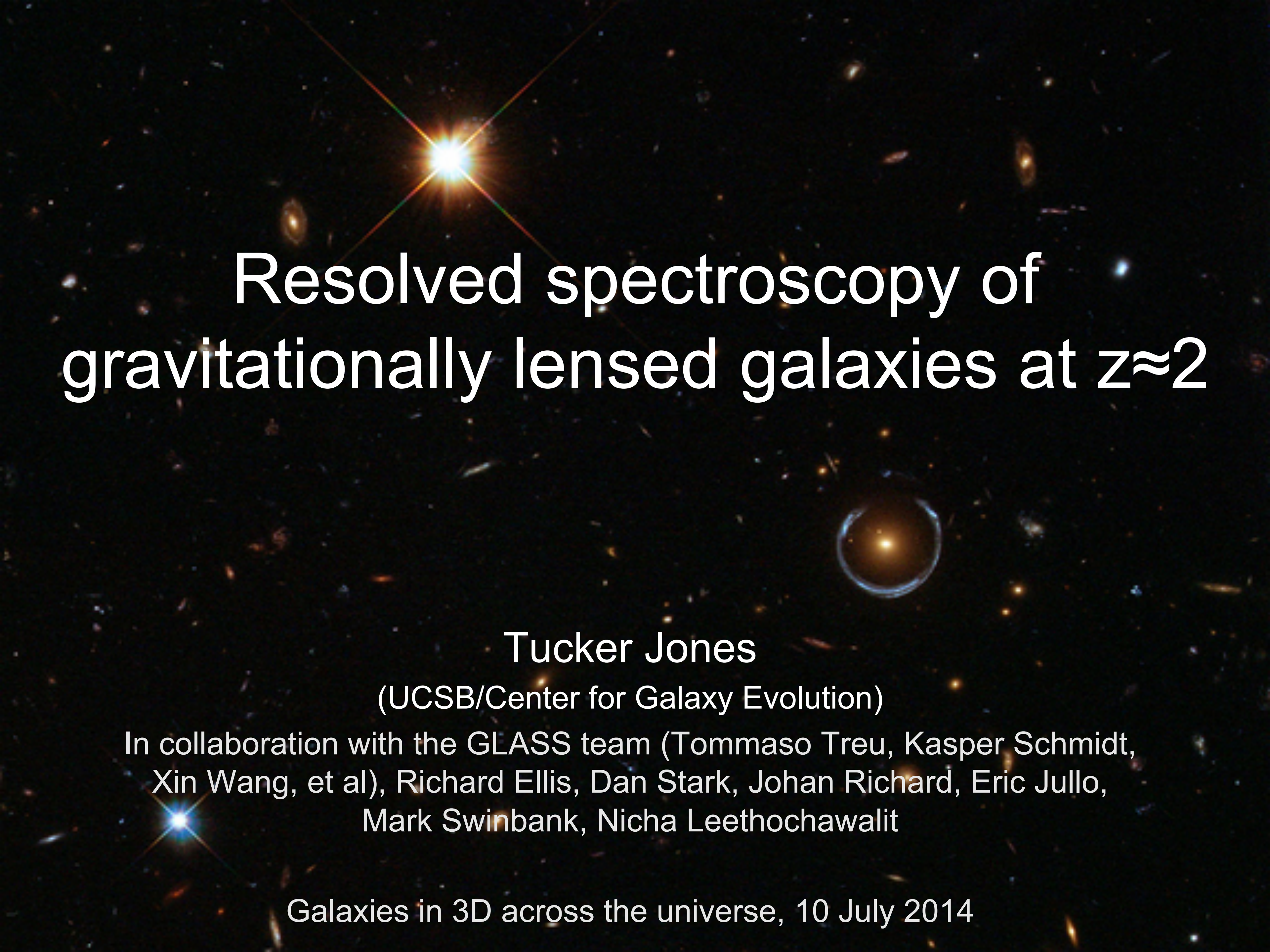


Resolved spectroscopy of gravitationally lensed galaxies at z≈2

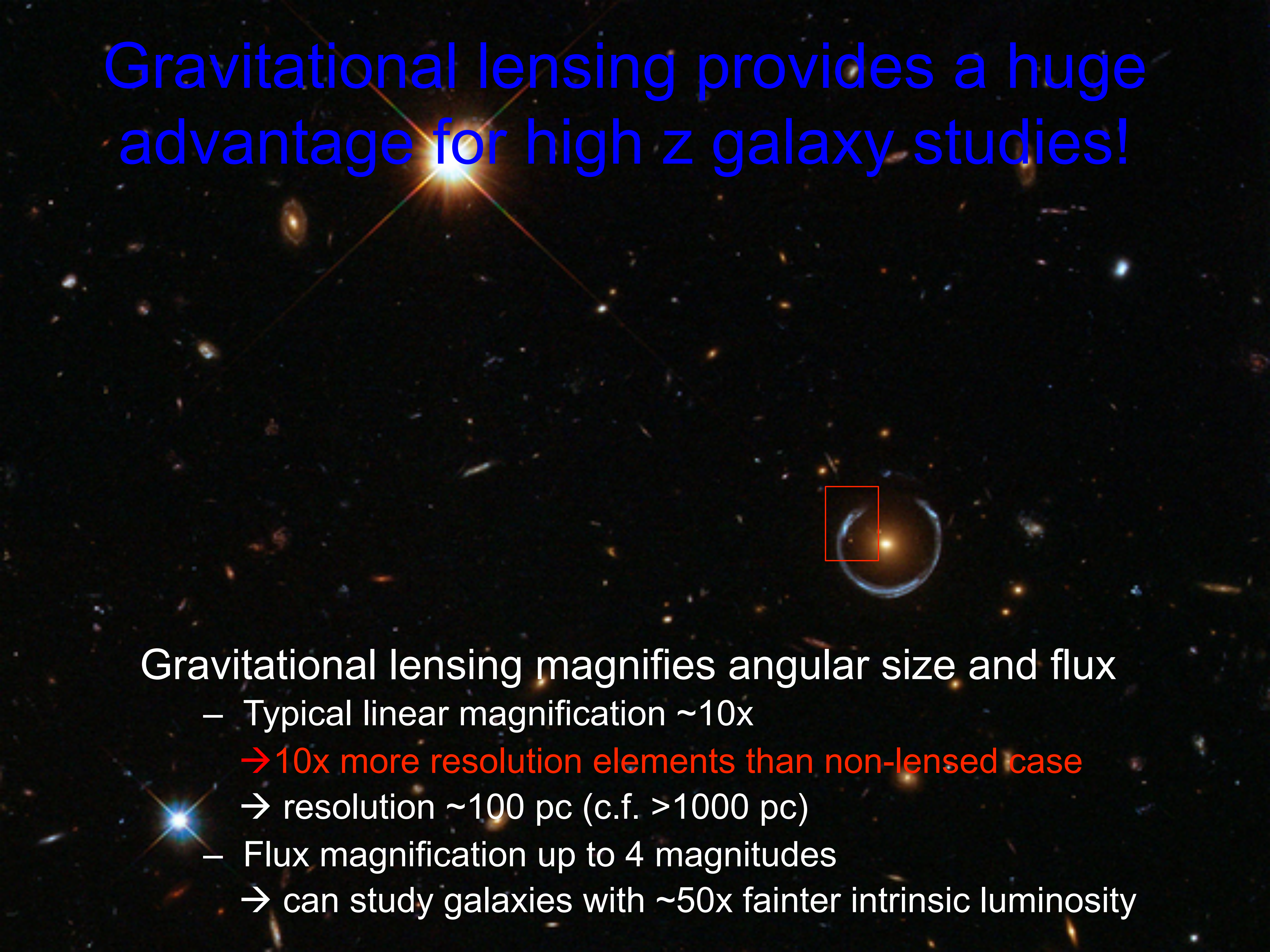
Tucker Jones

(UCSB/Center for Galaxy Evolution)

In collaboration with the GLASS team (Tommaso Treu, Kasper Schmidt, Xin Wang, et al), Richard Ellis, Dan Stark, Johan Richard, Eric Jullo, Mark Swinbank, Nicha Leethochawalit

Galaxies in 3D across the universe, 10 July 2014

Gravitational lensing provides a huge advantage for high z galaxy studies!



Gravitational lensing magnifies angular size and flux

- Typical linear magnification ~10x

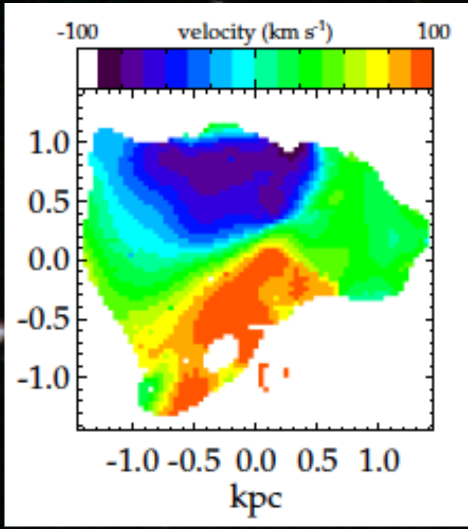
  → 10x more resolution elements than non-lensed case

  → resolution ~100 pc (c.f. >1000 pc)

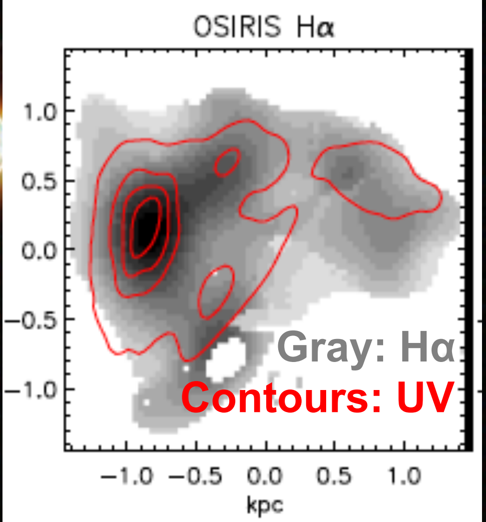
- Flux magnification up to 4 magnitudes

  → can study galaxies with ~50x fainter intrinsic luminosity

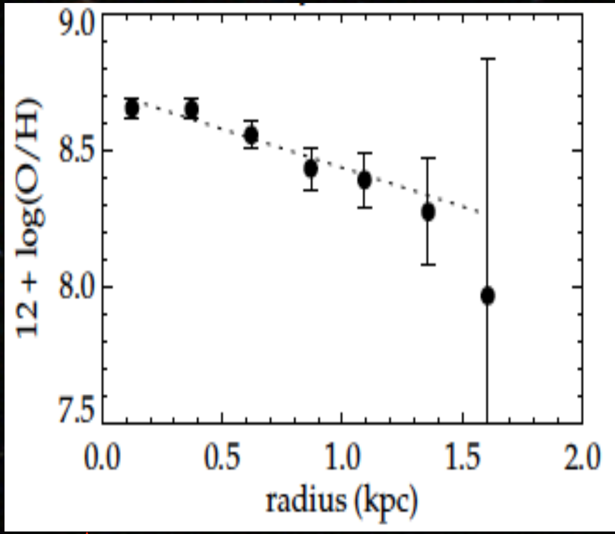
Kinematics



Morphology



Metallicity



- Kinematics: rotating with high velocity dispersion
  - A minority are major mergers
- Gravitationally unstable
  - Toomre parameter $Q = \sigma\kappa/\pi G\Sigma \approx 0.5$-1
- Clumpy star formation driven by gravitational instability
  - Clump sizes, masses agree with expected fragmentation scale

  See talks by Genzel, Förster Schreiber, etc. Lensing data show very similar results for more compact, lower mass galaxies.
- Metallicity: ~0.1-1x solar with negative radial gradients
  - Steeper gradients than in local disk galaxies
  - Indicates no recent major mergers, and consistent with current cosmological simulations with “normal” feedback (e.g. Gibson+2013; Angles-Alcazar+2014)

TJ+2010a,b, 2013; Livermore, TJ+2012; Leethochawalit, TJ+ in prep

Why measure metallicity gradients?

Local disk galaxies have negative radial gas-phase metallicity gradients

– Explained by inside-out disk growth

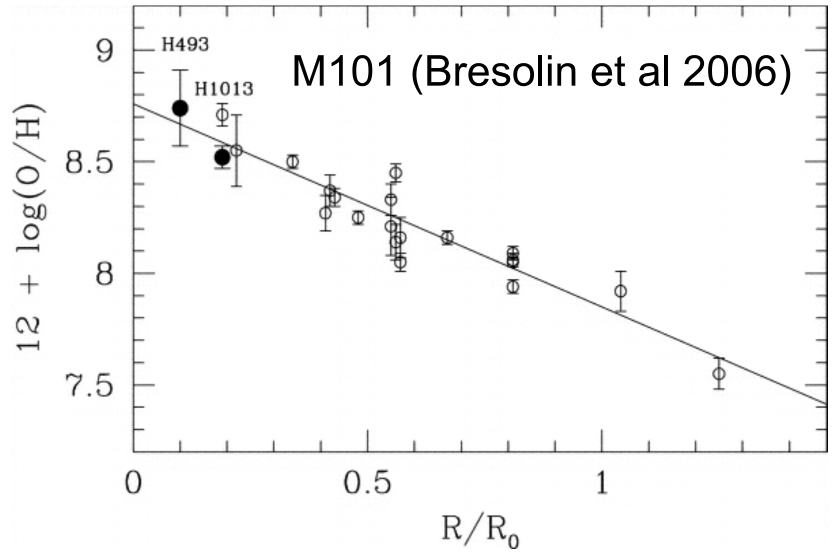
Various models + simulations predict a range of evolutionary behavior for the metallicity gradient slope

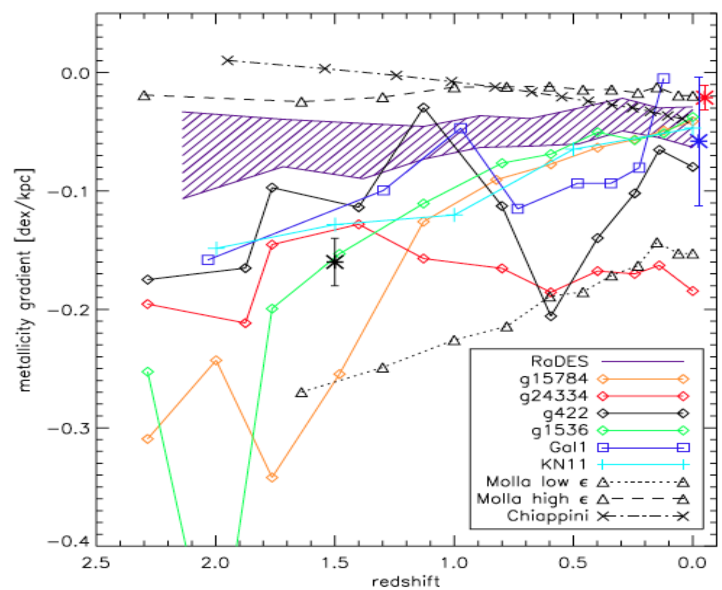
– Gradients may be steeper, flatter, or even inverted at earlier times

– Time evolution is sensitive to kinematics, feedback, accretion history, etc.

– Mergers, interactions cause gradients to flatten on short time scales

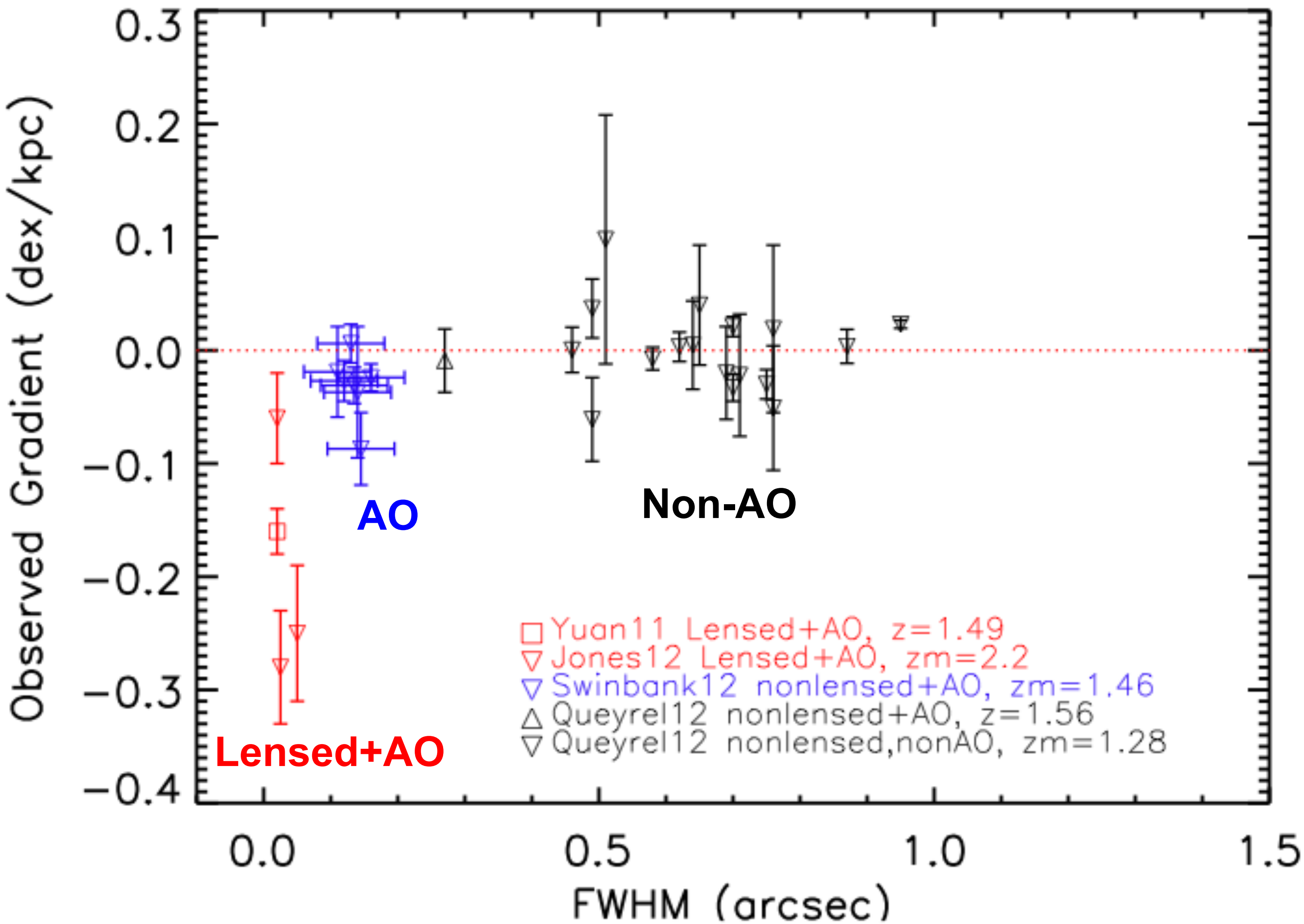
Time evolution of metallicity gradients constrains galaxy assembly history and directly tests models of galaxy formation.





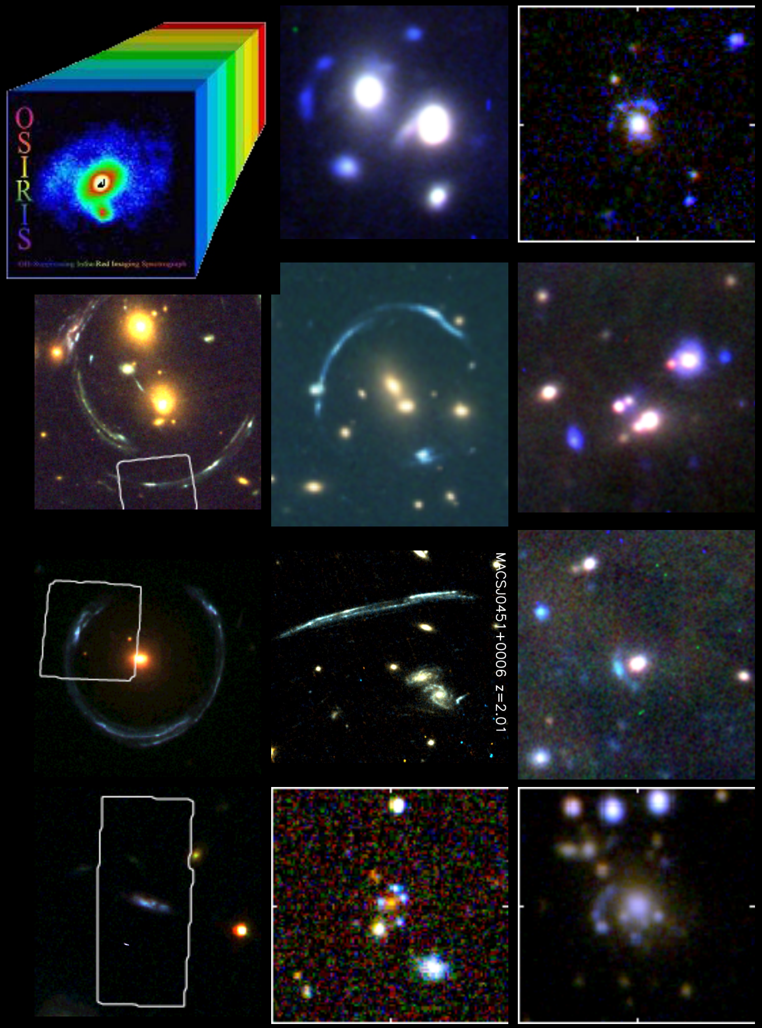
Simulations (Pilkington et al 2012)

High angular resolution is essential for high-z gradient measurements



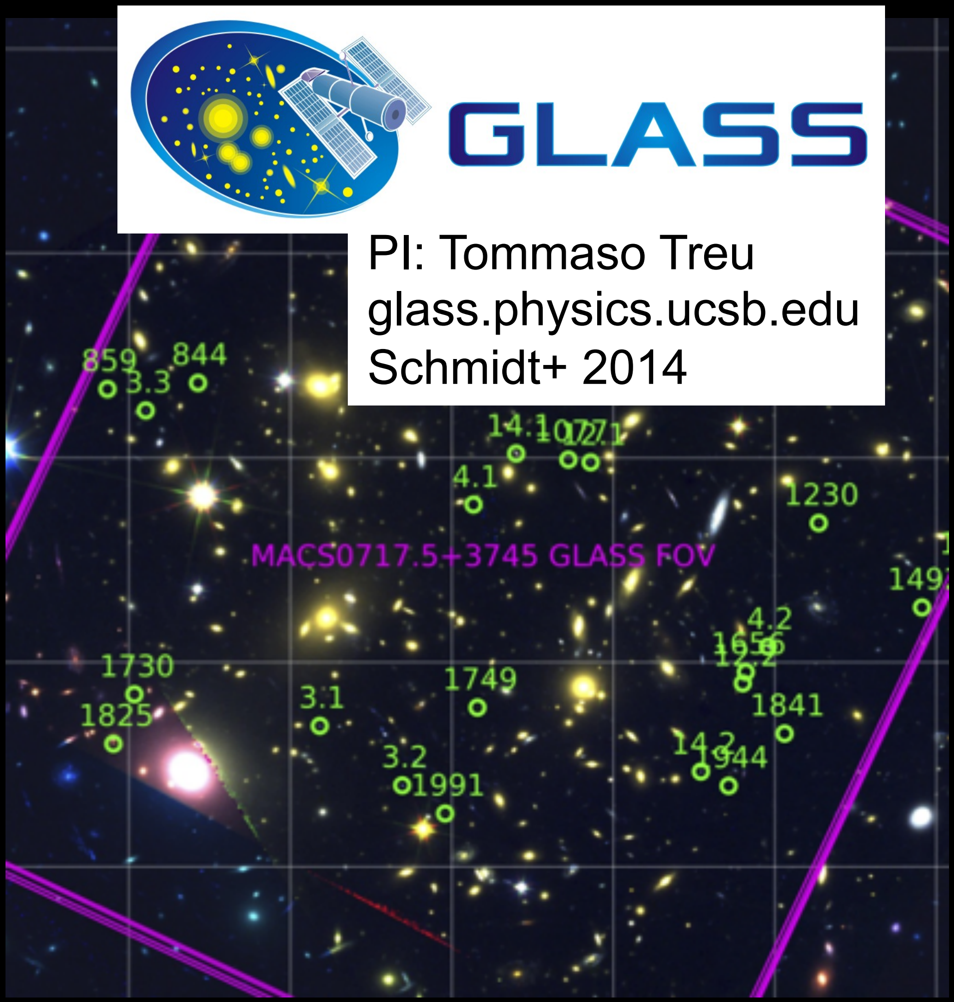
Yuan, Kewley, & Rich 2013

Large samples of lensed galaxies



Ground: Keck/OSIRIS IFU + AO

Advantages: kinematic data, large aperture, sensitivity improved by recent upgrades to grating and AO system

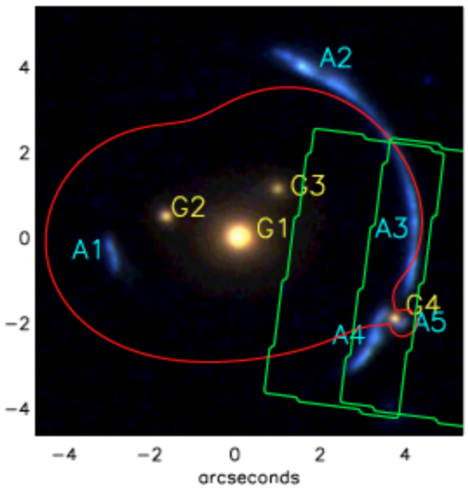


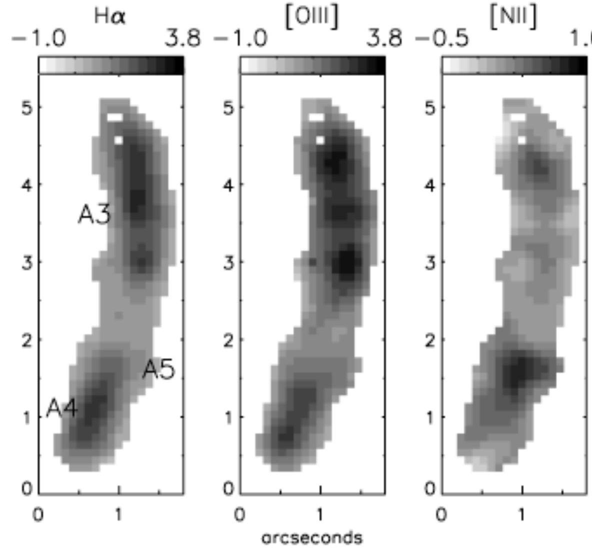
Space: GLASS (HST grism survey of 10 strong lensing galaxy clusters)

Advantages: multiplexing, wavelength range, excellent Strehl, no atmosphere

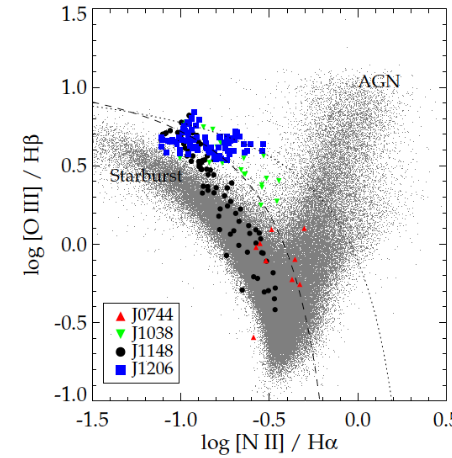
Methods: Keck/OSIRIS+AO data

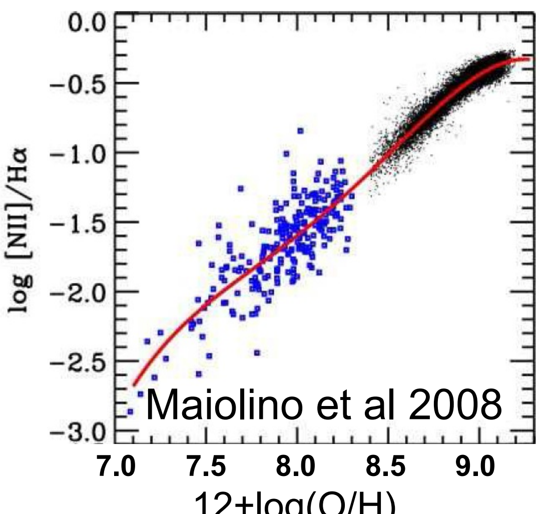
Step 1: take data

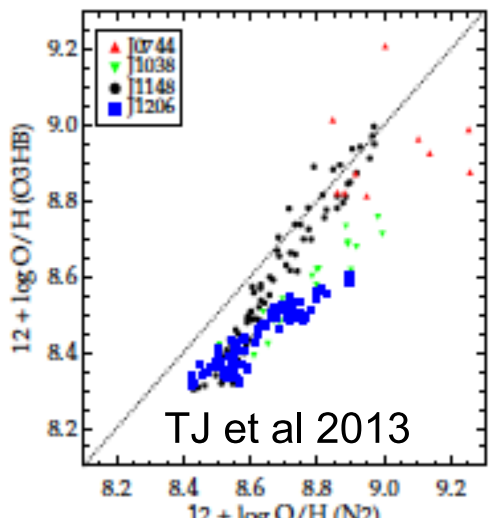




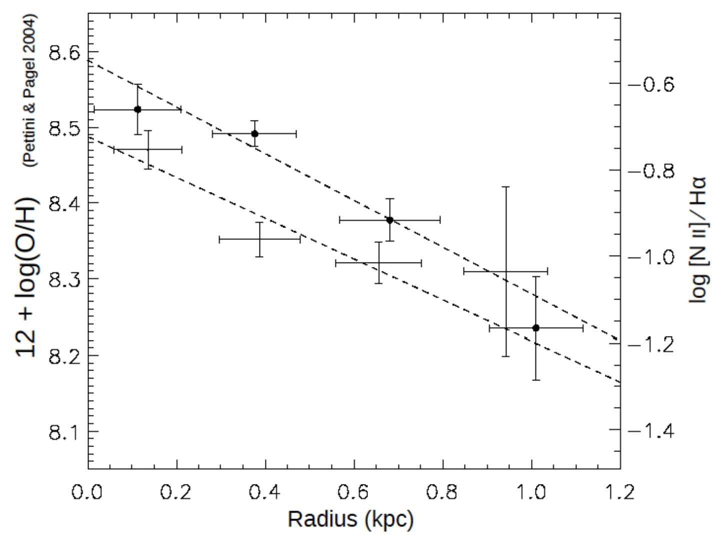
Step 2: confirm that emission is from H II regions (vs. AGN, shocks)





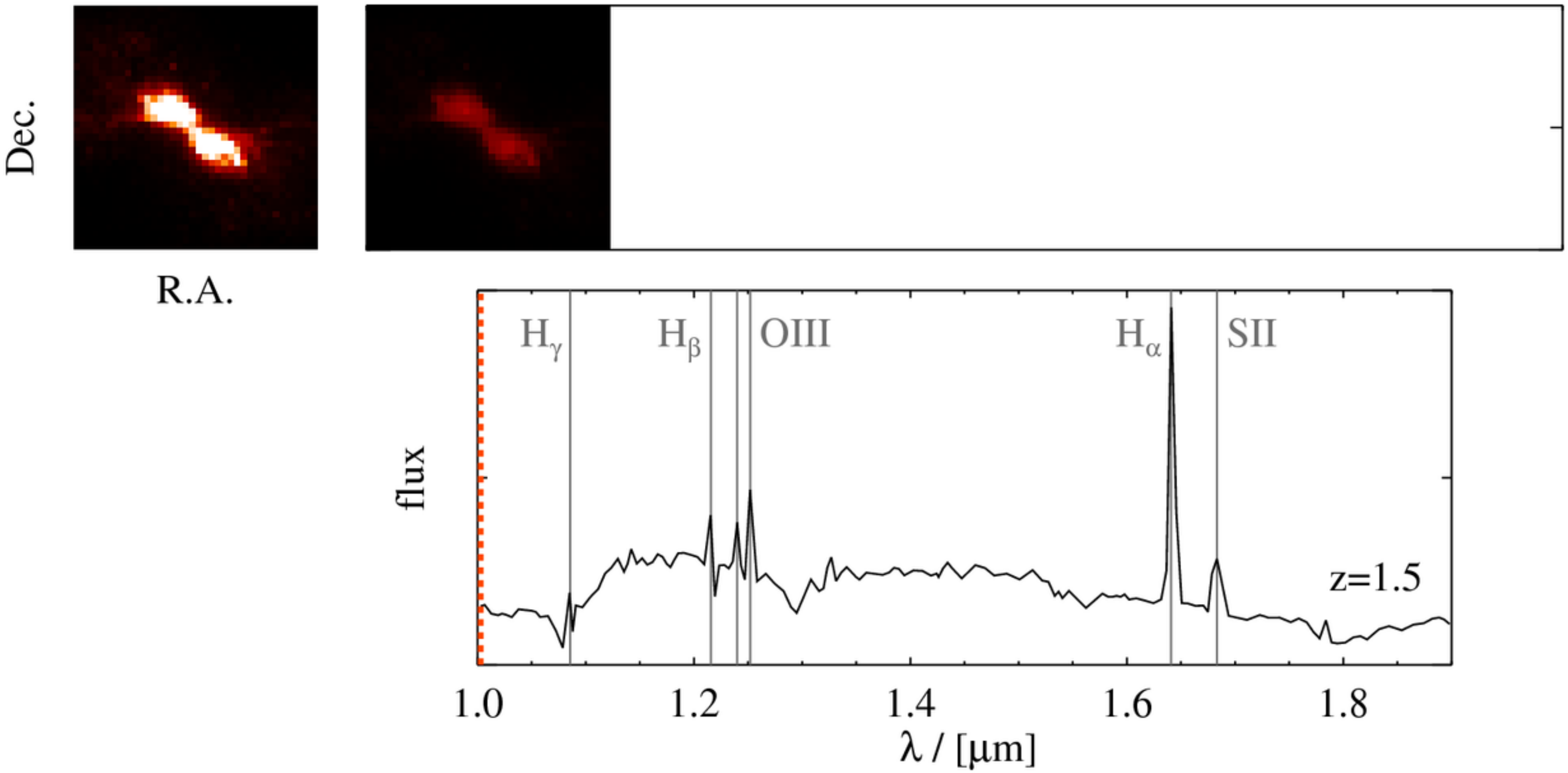


Step 3: use line ratios to infer the metallicity. Check that multiple diagnostics agree.

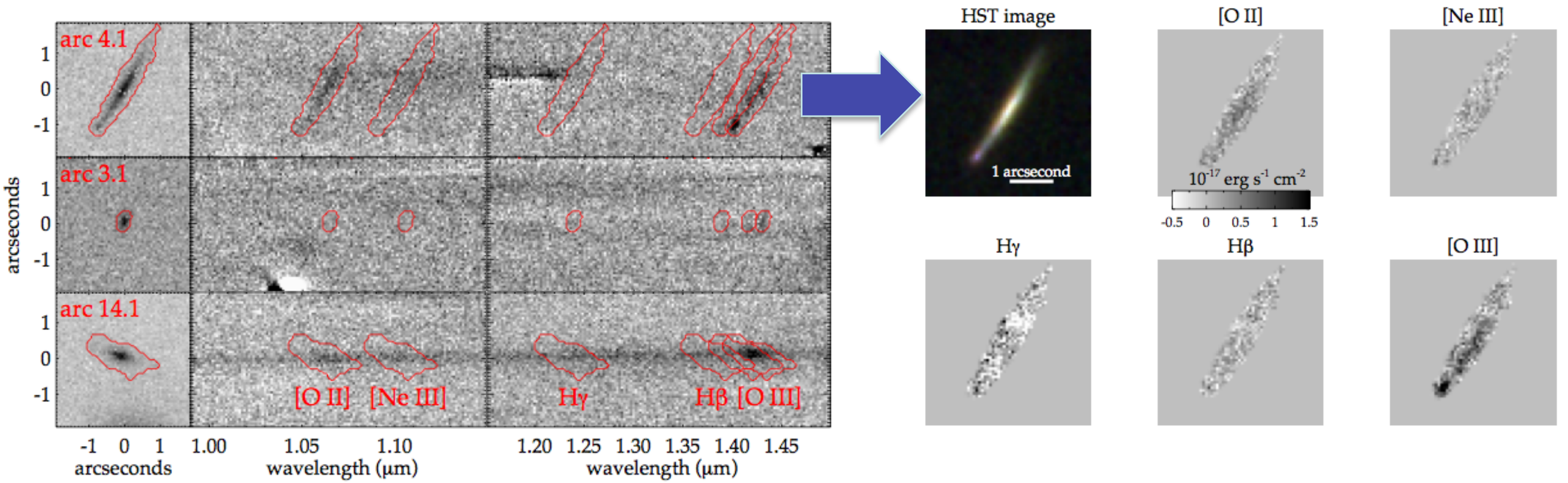


Step 4: profit!

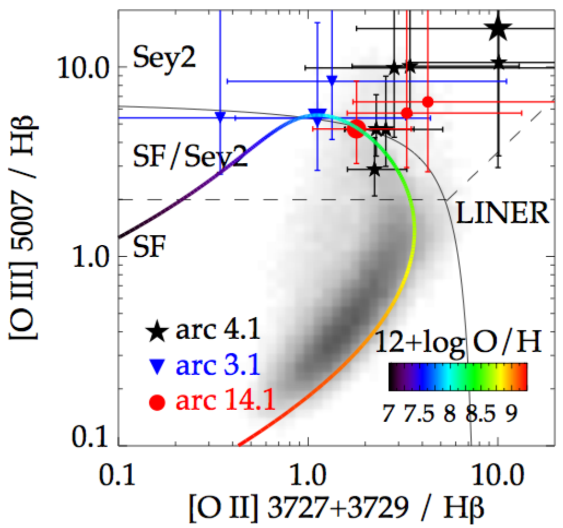
GLASS HST grism survey

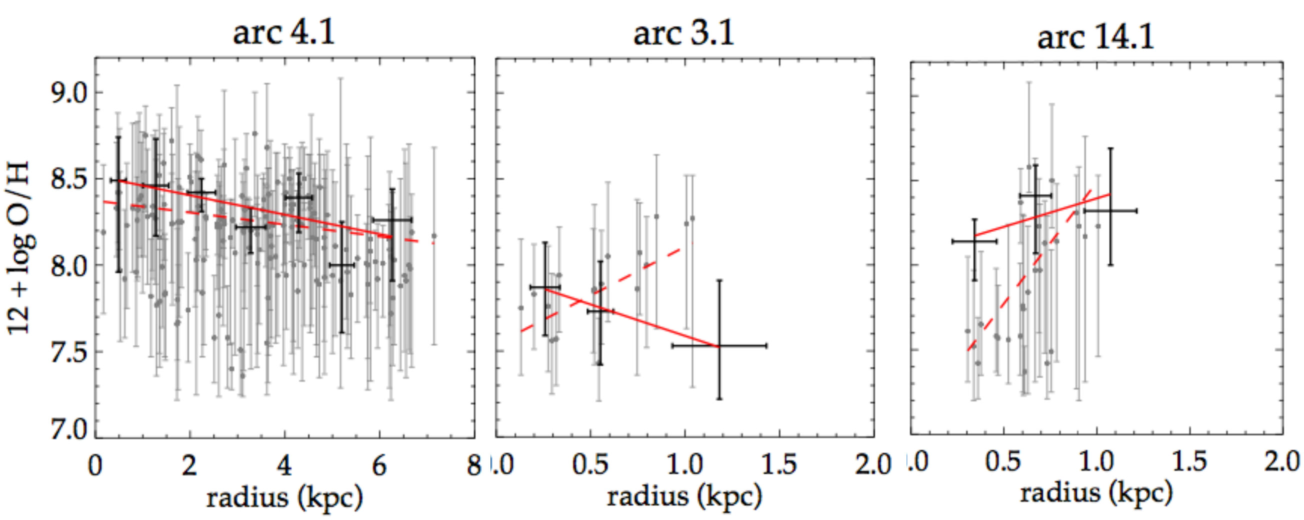


HST/WFC3 grism data

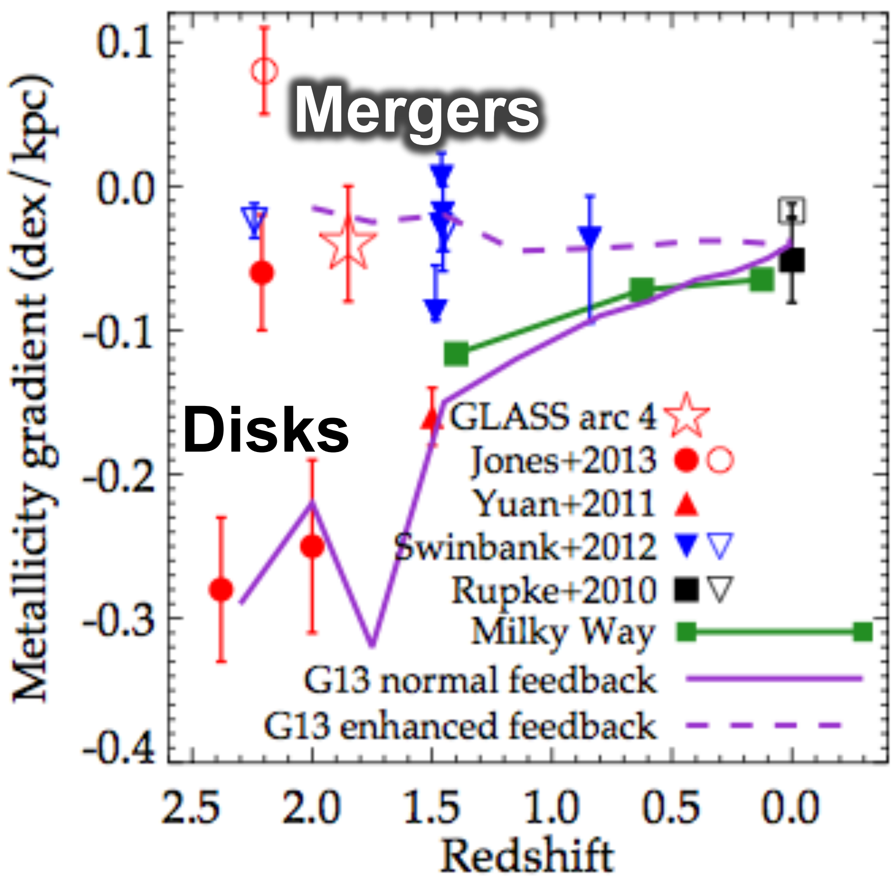


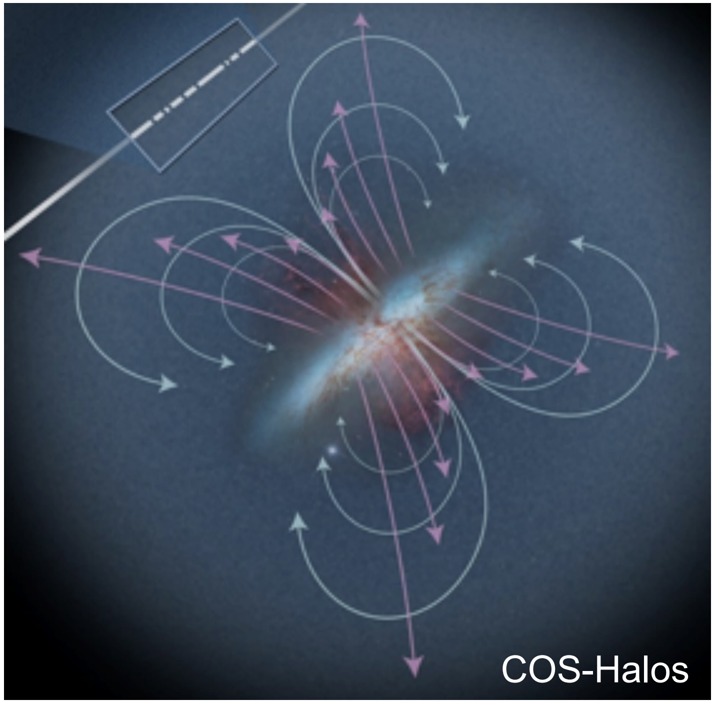
System of 3 interacting galaxies at z=1.855





Gradient evolution: data vs simulations



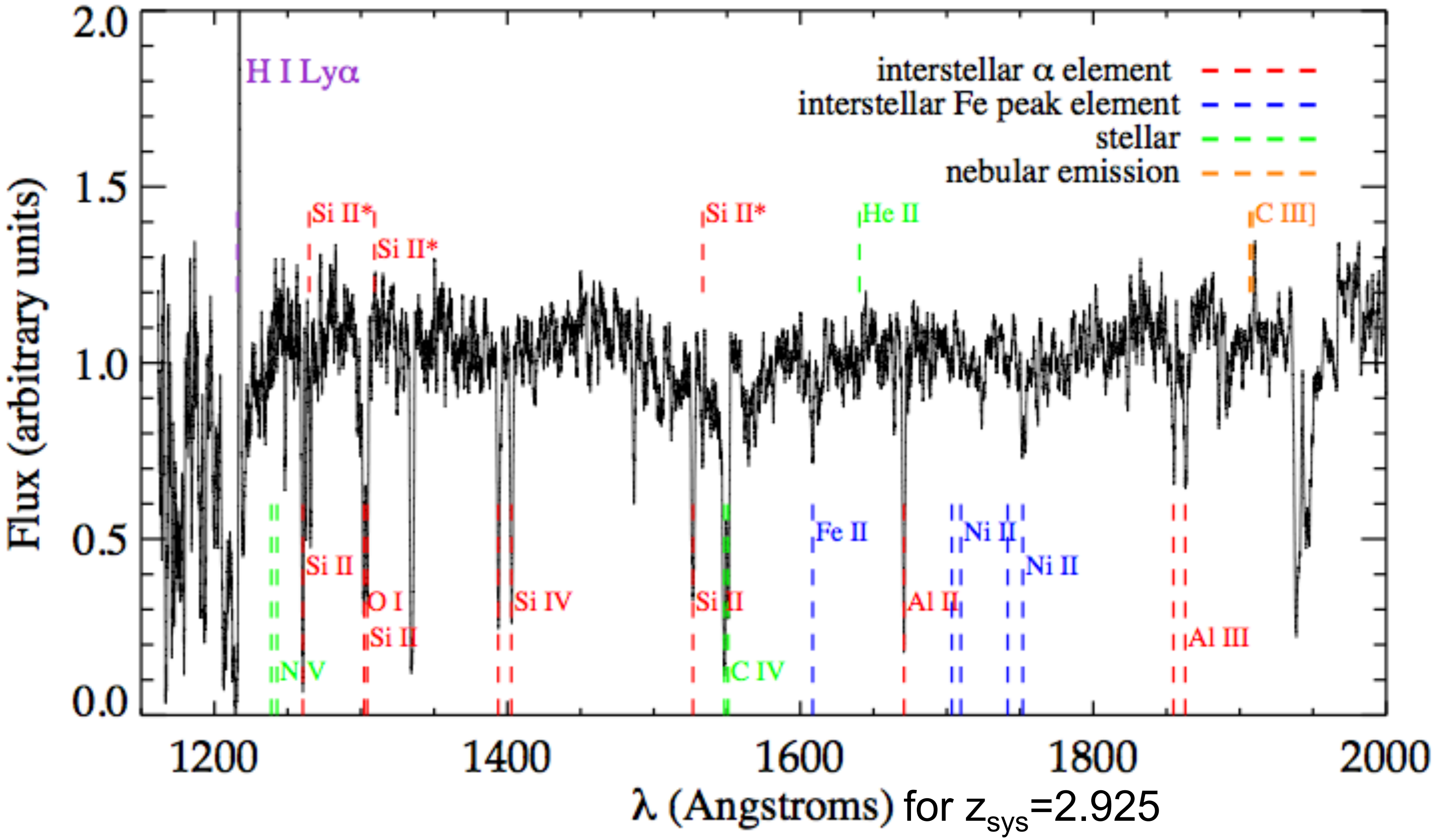


Gibson et al 2013; Angles-Alcazar et al 2014; Torrey et al simulations: stronger feedback removes metals from small radii and re-deposits them at larger radii, resulting in weaker gradients.

→ Current lensing data compatible with “standard” feedback/outflow models.

→ Merging / interacting galaxies have flatter gradients.

Outflow properties from UV absorption lines

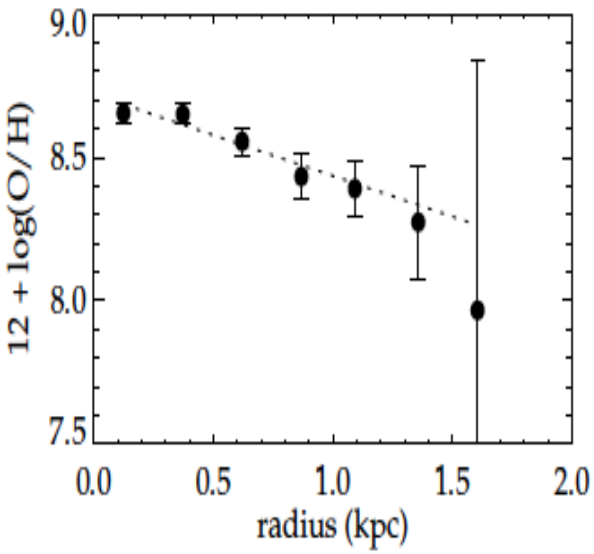


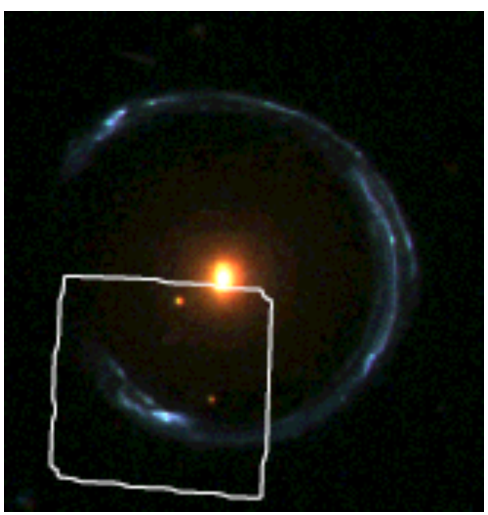
Measure feedback properties, stellar metallicity, ISM metallicity, abundance ratios from optical echelle spectra (Keck/ESI)

High quality data for >10 lensed galaxies

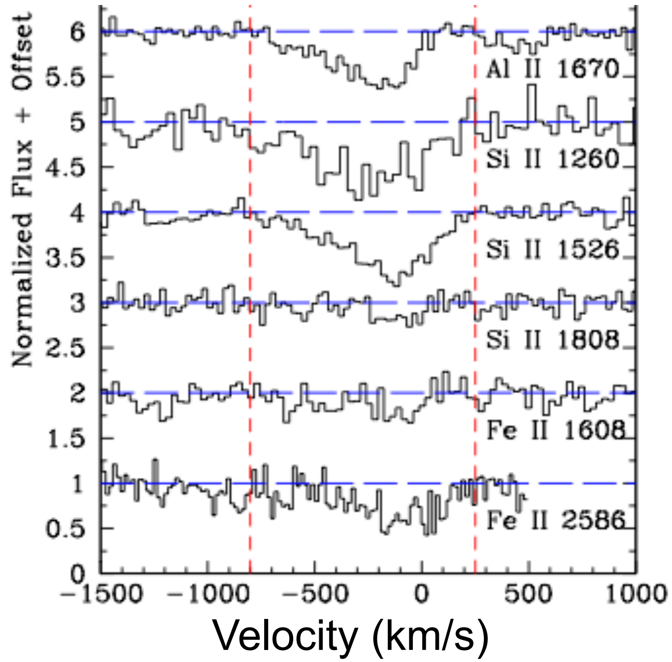
Combining IR and optical spectra

Nebular metallicity

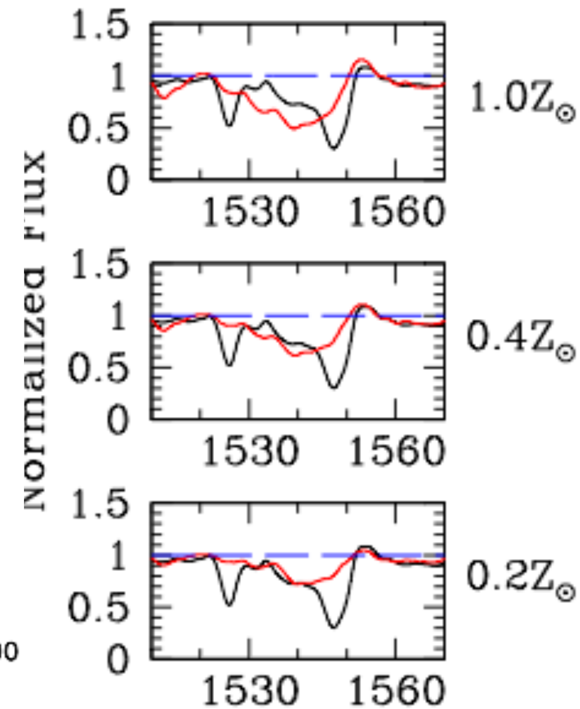




Interstellar metallicity + outflow properties



Stellar metallicity



TJ+ 2013, Quider+ 2009, TJ+ in prep

Average metallicity is [α/H] ≈ −0.3

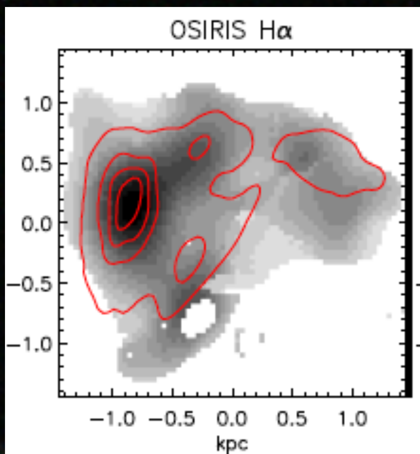
Remarkably good agreement in different phases

ISM abundance ratios [α/Fe] ≈ +0.6

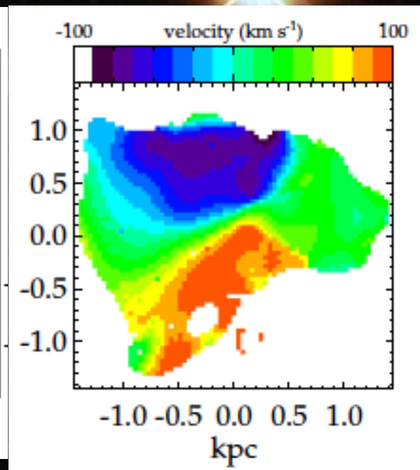
→ Abundances similar to bulge & thick disk of MW

Summary: z=2 galaxies at high resolution

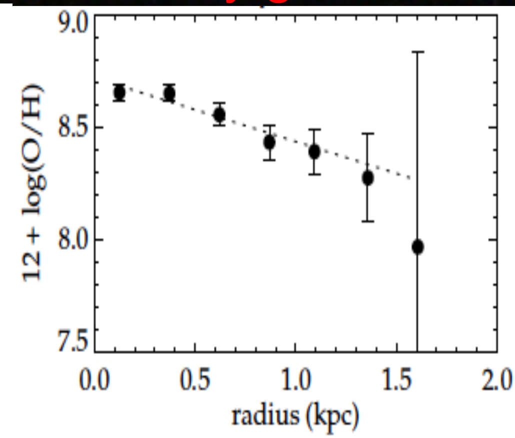
Star formation



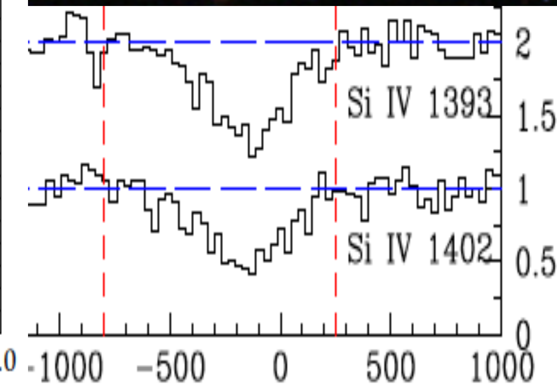
Kinematics



Metallicity gradients



Outflows



Spectroscopy of star-forming galaxies at z=2:

100 pc resolution achieved with gravitational lensing

- 2/3 are thick disks evolving *in situ*
  - High velocity dispersion σ~50-100 km/s, low V/σ < 2
  - Clumpy SF driven by gravitational instability, high gas fraction
  - Negative metallicity gradients, consistent with expectations from feedback
- 1/3 are undergoing major mergers

Lensed galaxy sample size at z~2 is increasing dramatically thanks to OSIRIS instrument upgrades and the GLASS survey