Early disk galaxies revealed by gravitational lensing:

What did the Milky Way look like at z~2?

Tucker Jones
University of Hawaii / University of California, Davis

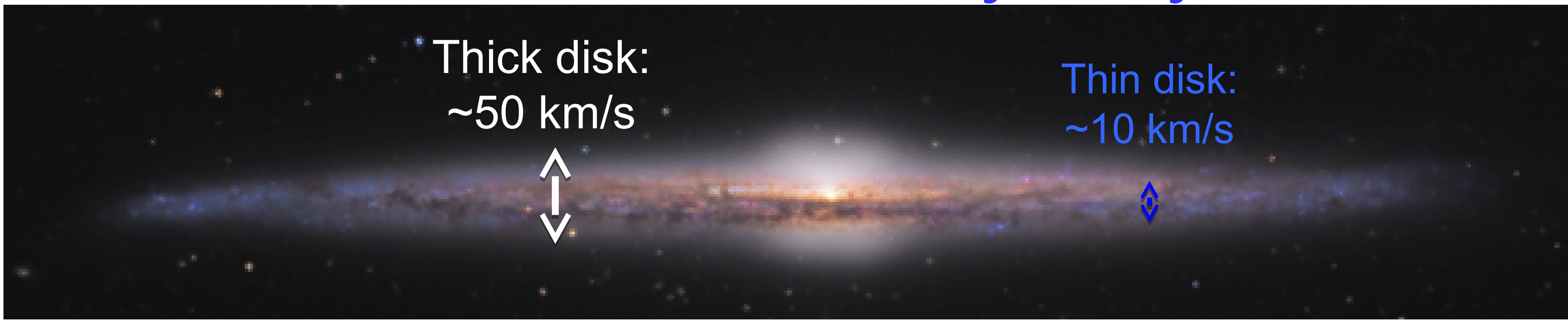
Discs in Galaxies ★ Munich Joint Conference ★ 12 July 2016

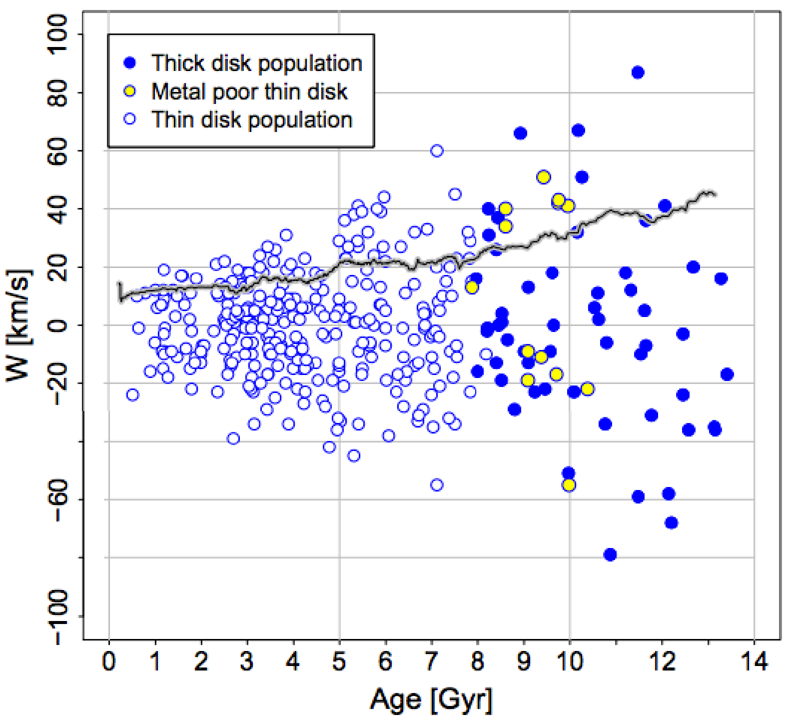
With Richard Ellis, Nicha Leethochawalit, Dan Stark, Tommaso Treu, Kasper Schmidt, Xin Wang, & the GLASS team

Outline

- Resolved spectroscopy of Milky Way-like progenitors at high redshifts (z~2)
- Kinematics
  - Rotation; merging; velocity dispersion
- Chemistry
  - Metallicity; radial gradients; abundance ratios

Formation of the Milky Way disk



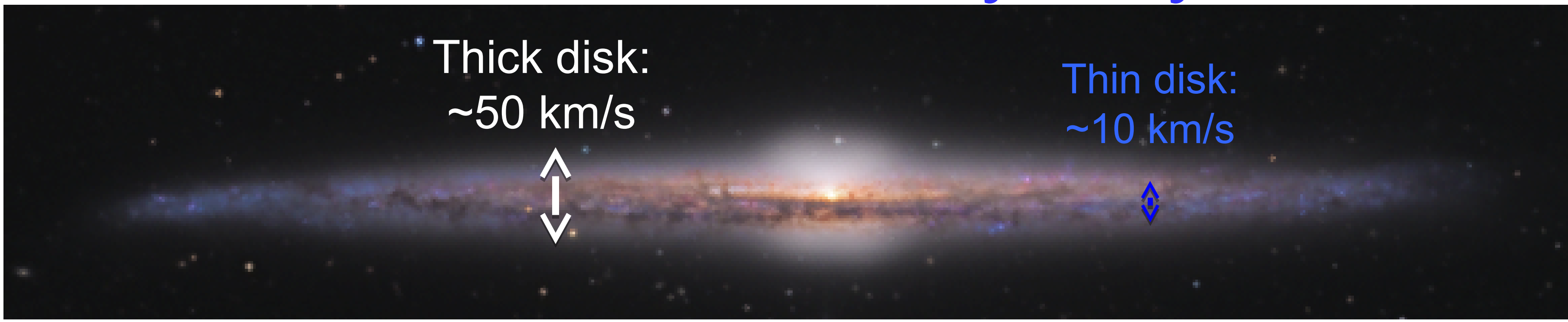


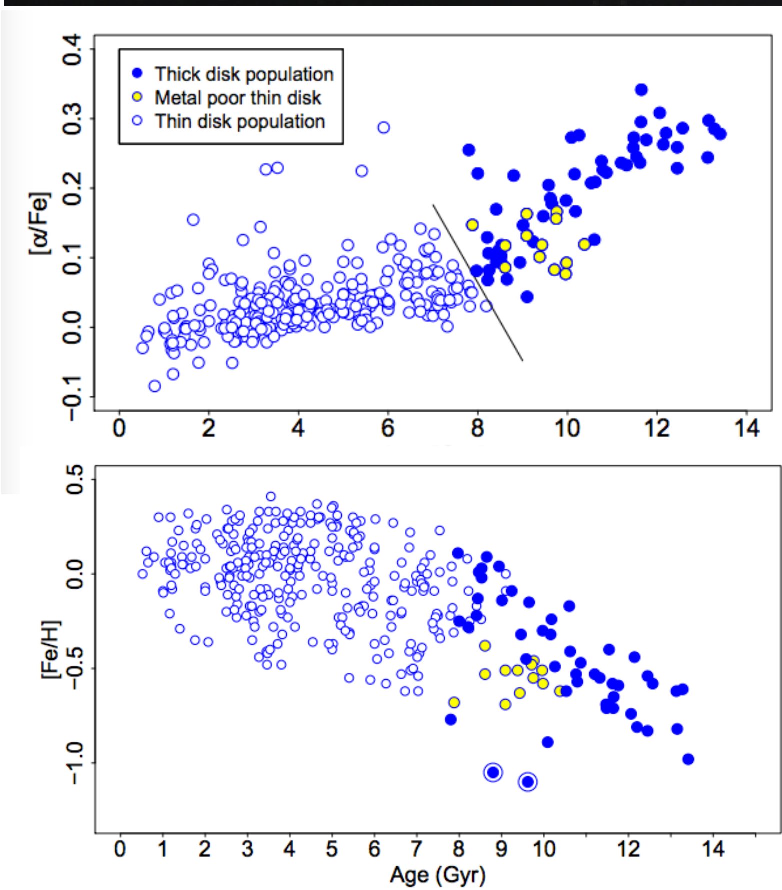
Kinematics vs. age

- Older stellar populations have larger vertical velocity dispersion, and larger scale height
- ~10 km/s for stars formed at z=0
- ~40 km/s for stars formed at z=2 (in solar neighborhood)

Haywood et al 2013

Formation of the Milky Way disk



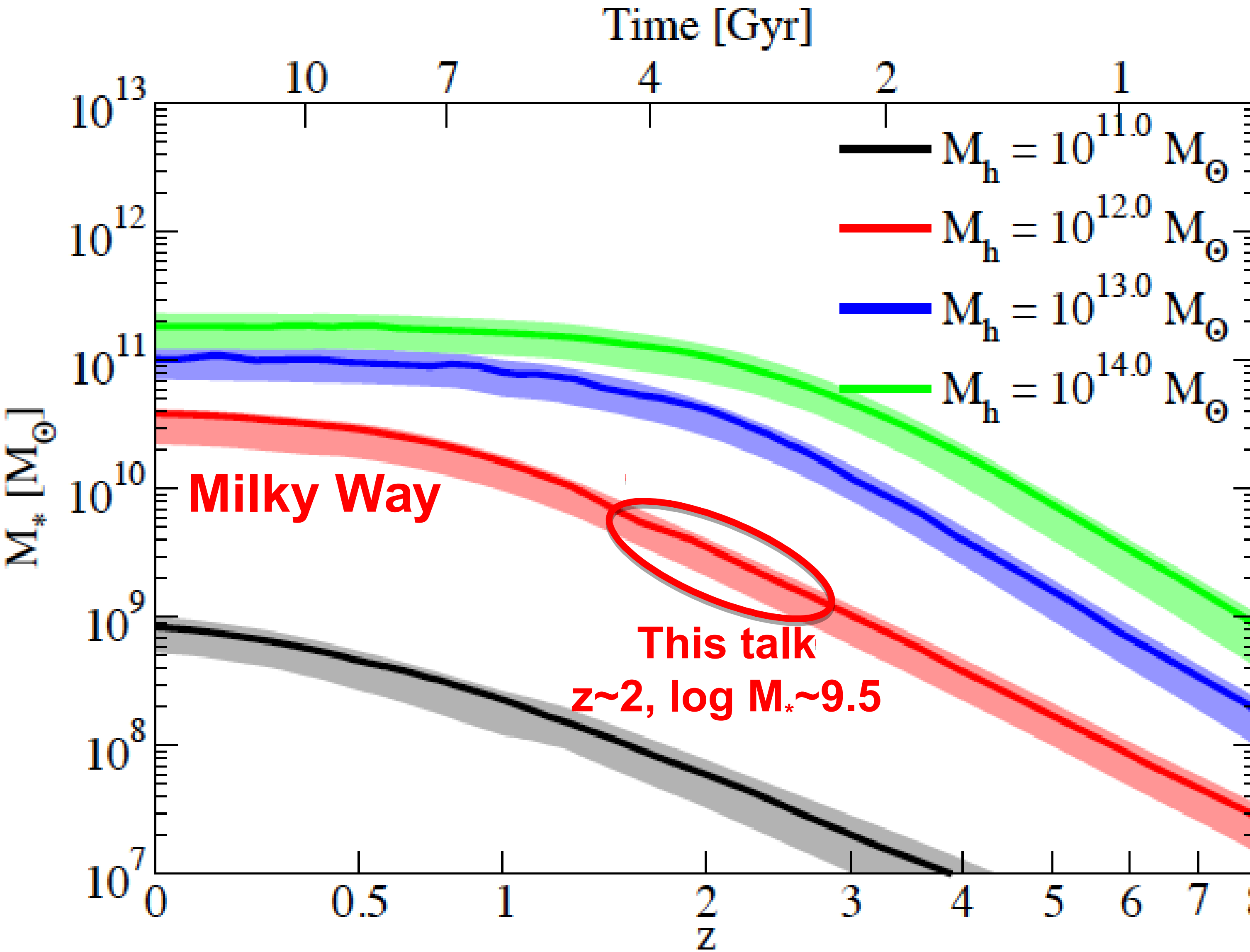


Chemistry vs. age

- Older stellar populations have higher alpha/Fe abundance, and lower overall metallicity
- Range of overall metallicity at a given age, partly due to radial gradients

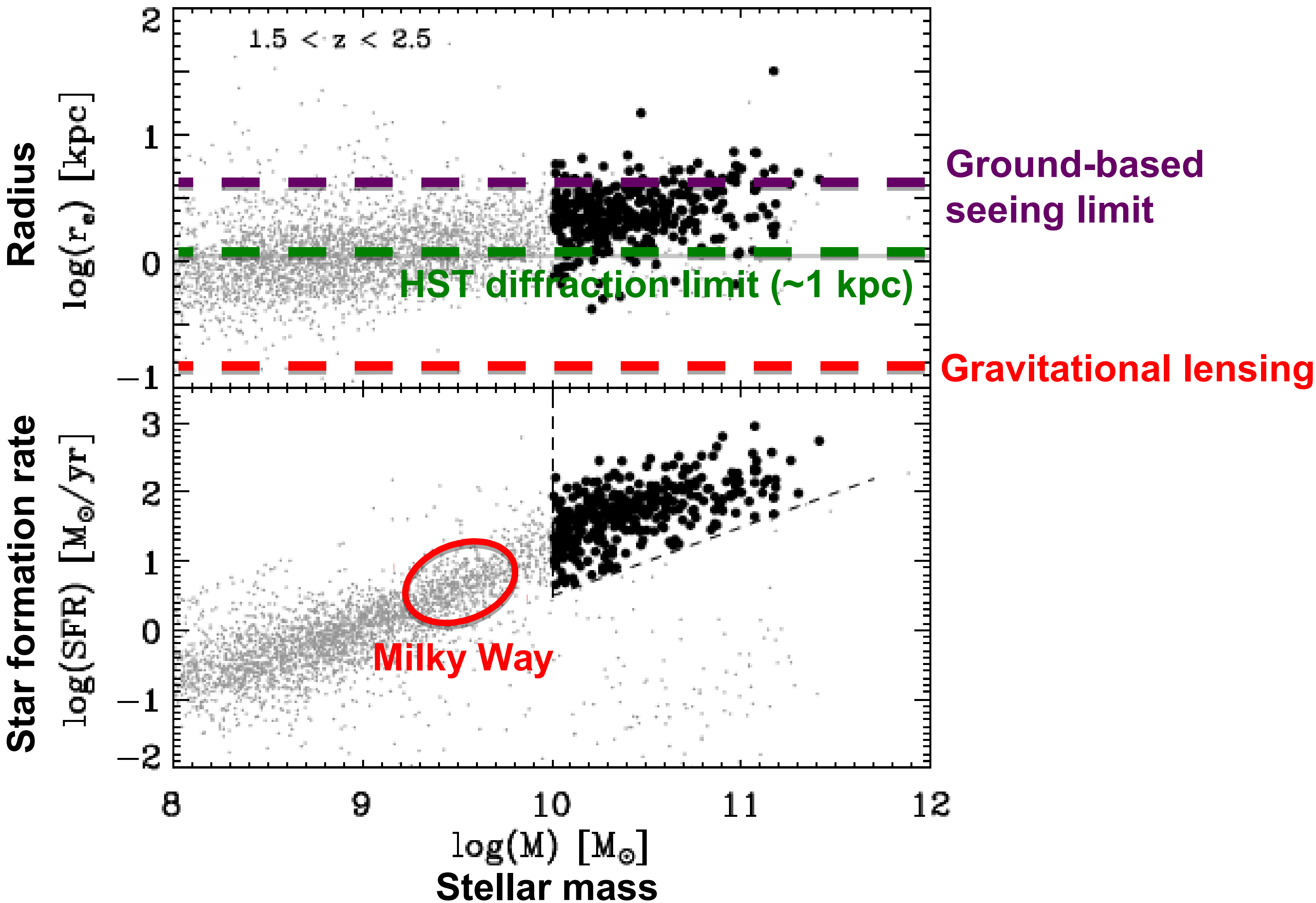
Haywood et al 2013

Identifying Milky Way progenitors at high z: abundance matching



Behroozi et al 2013

The galaxy population at z=2



CANDELS: Wuyts et al. 2012

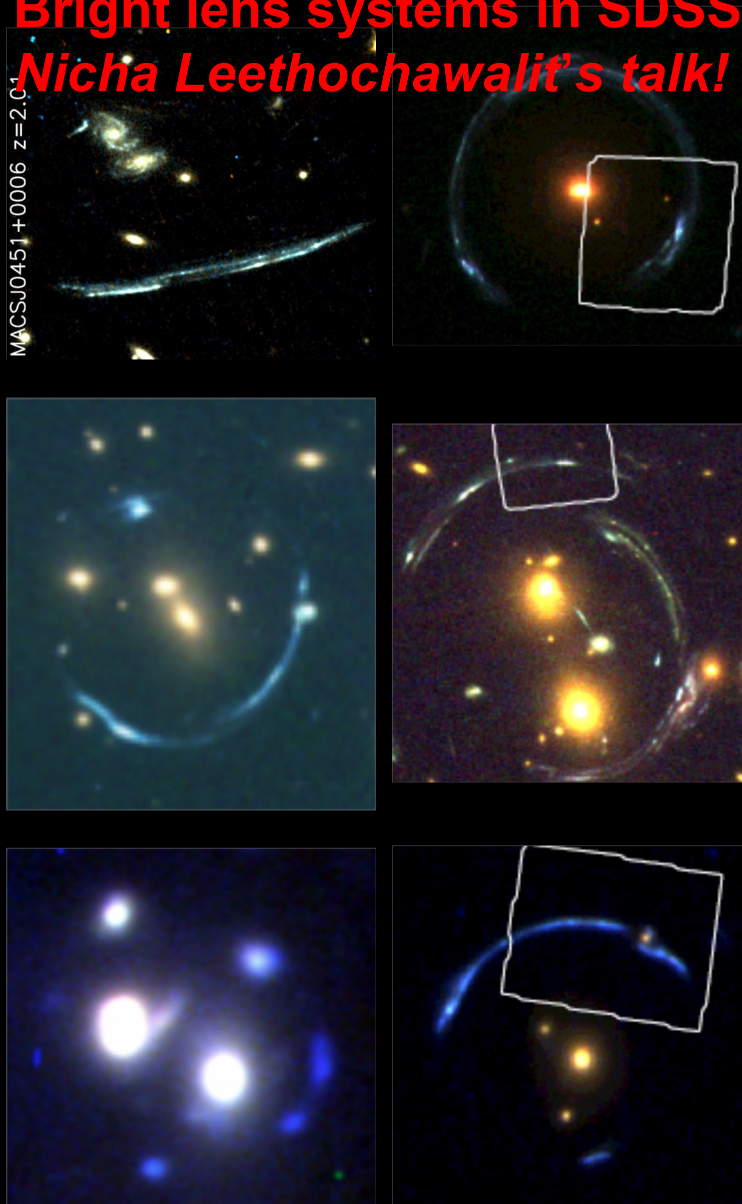
How to beat the diffraction limit

Magnified by ~30x

Lensed galaxy samples

Bright lens systems in SDSS

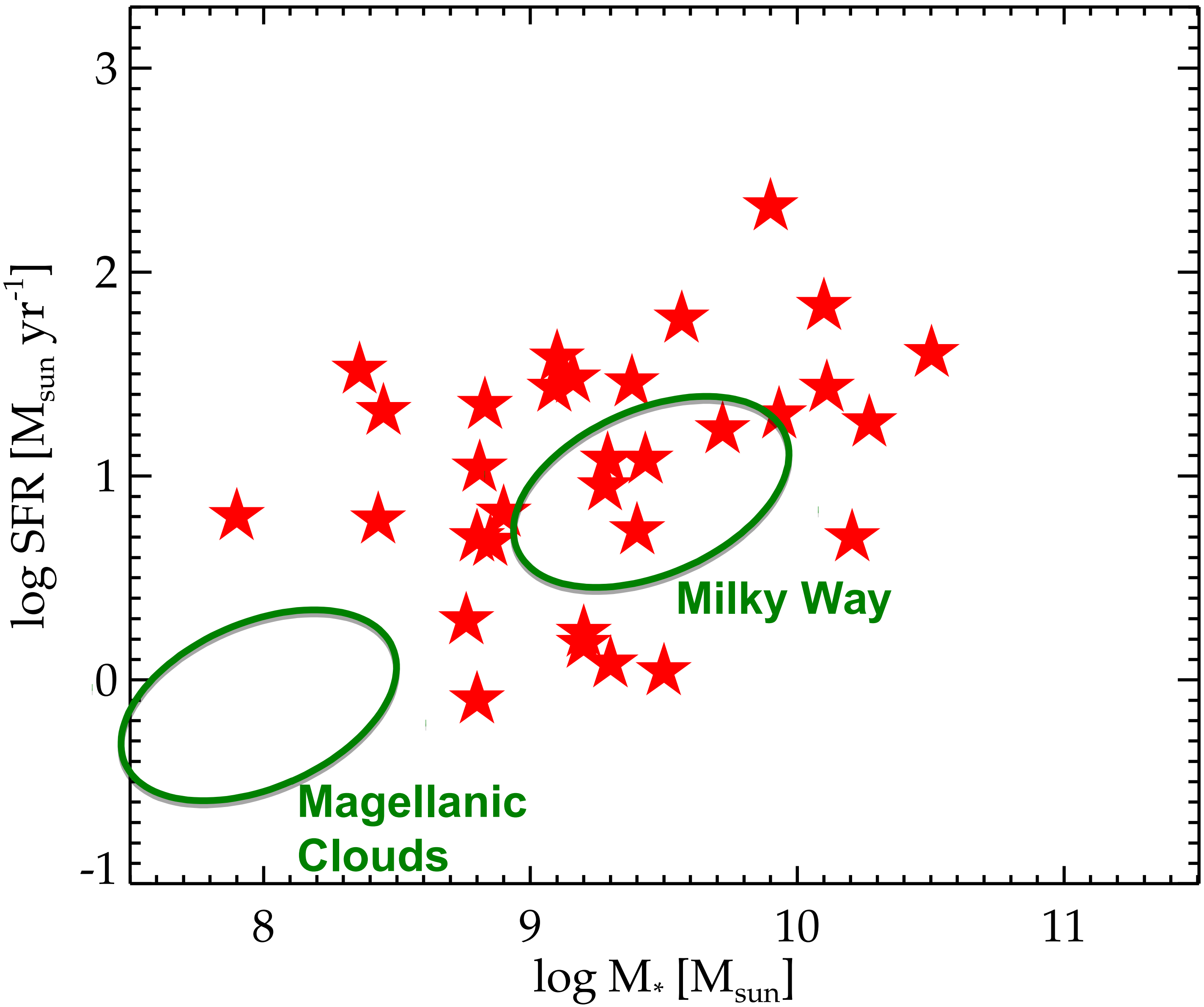
Nicha Leethochawalit's talk!



Strong lensing galaxy clusters:

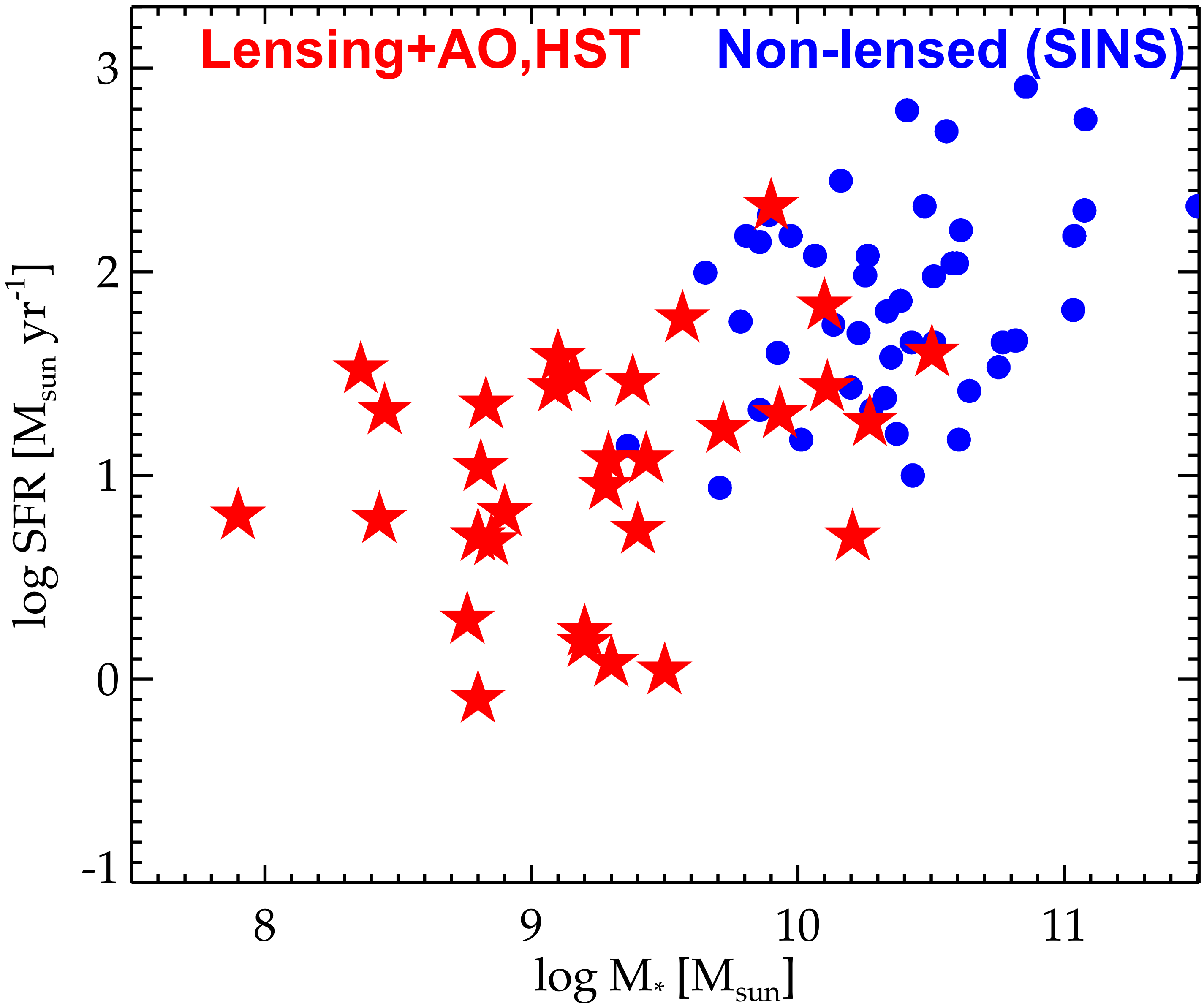
Frontier Fields, GLASS, RELICS, …

Lensed z~2 sample properties



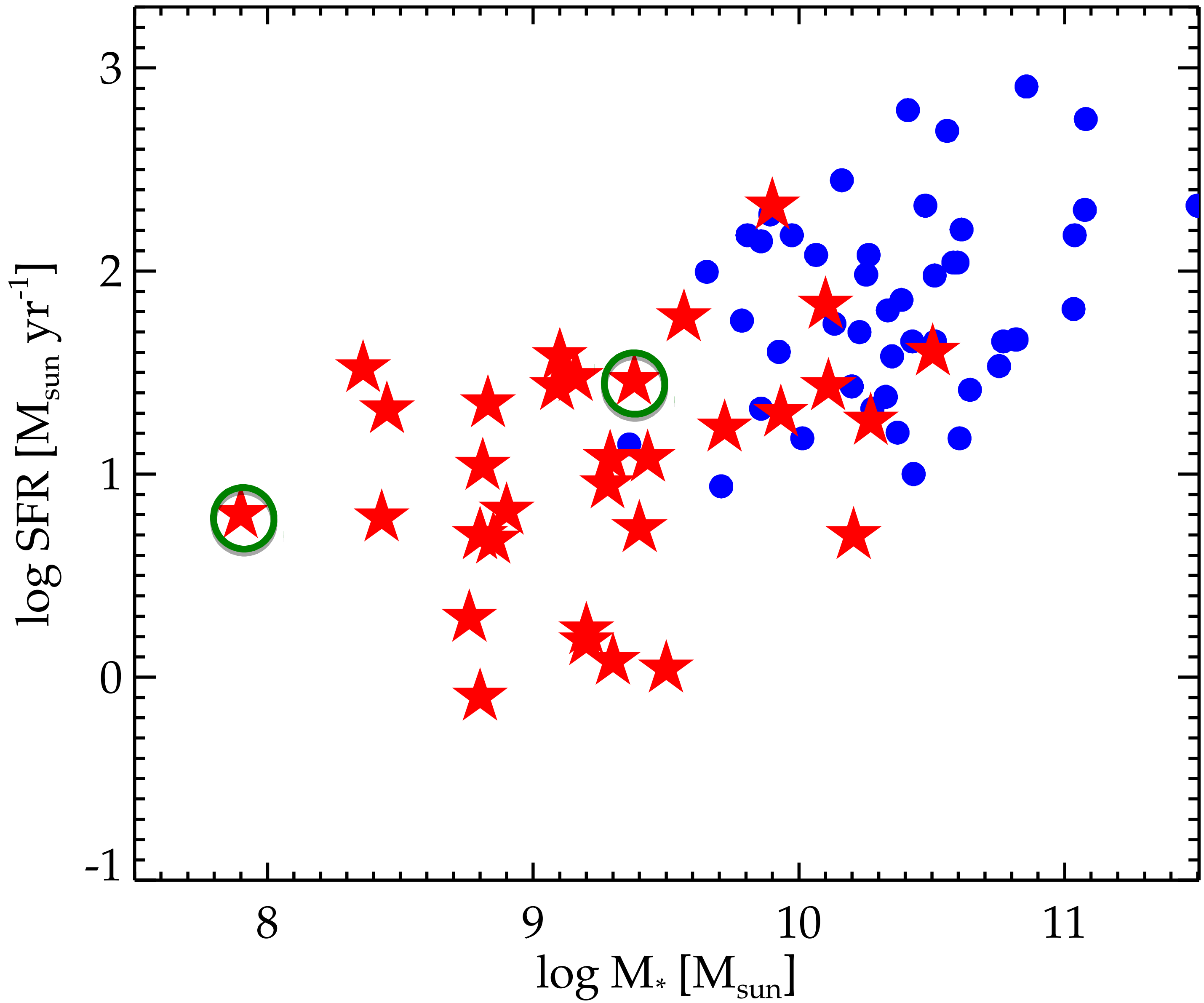
Jones et al. 2010a, 2013a, 2015a; Livermore, Jones et al. 2015; Leethochawalit, Jones et al. 2016; Wang, Jones et al. 2016 in prep

Lensed z~2 sample properties



Jones et al. 2010a, 2013a, 2015a; Livermore, Jones et al. 2015; Leethochawalit, Jones et al. 2016; Wang, Jones et al. 2016 in prep

Examples of individual objects



Jones et al. 2010a, 2013a, 2015a; Livermore, Jones et al. 2015; Leethochawalit, Jones et al. 2016; Wang, Jones et al. 2016 in prep

GLASS

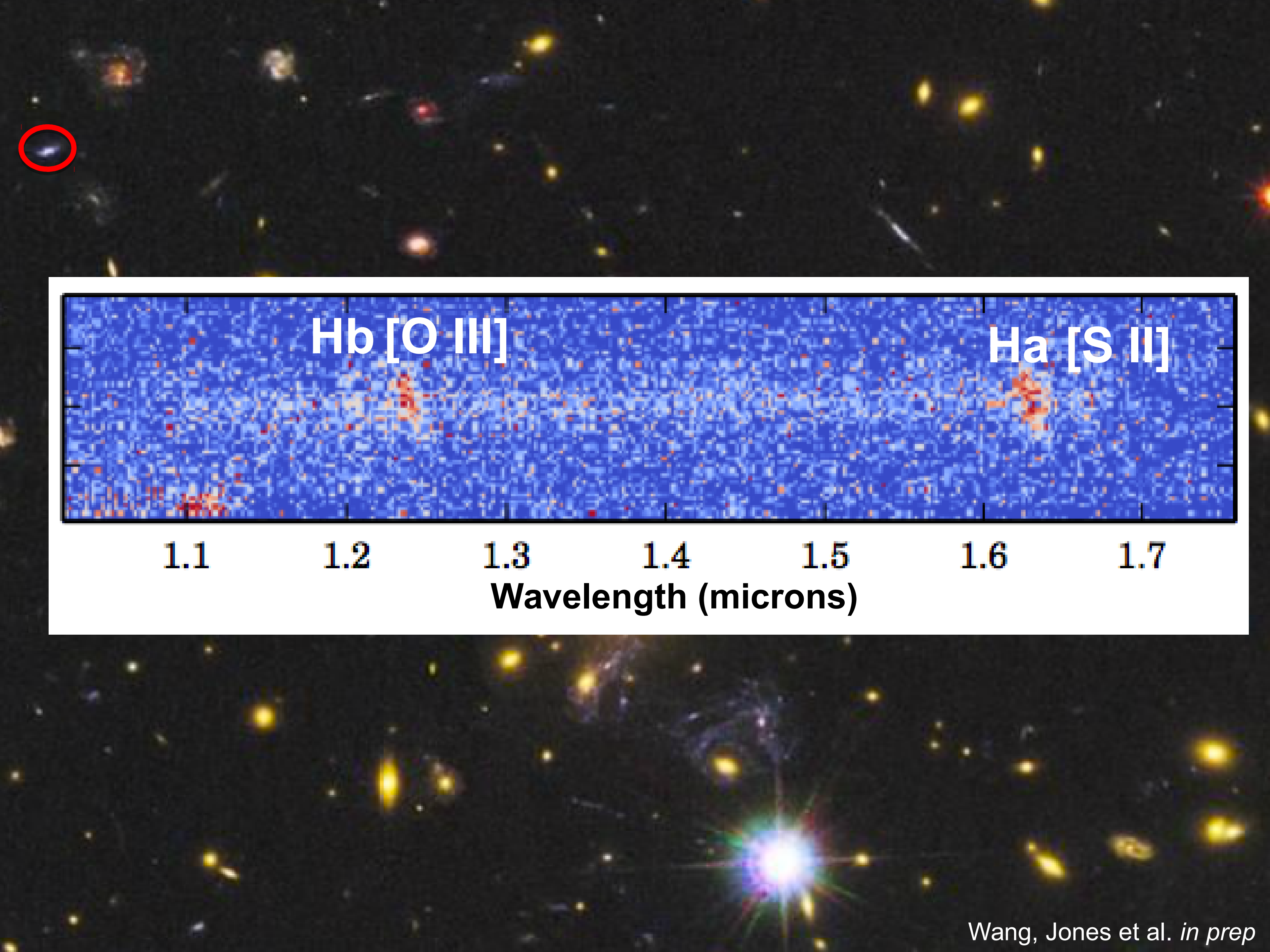
The Grism Lens-Amplified Survey from Space

2-D Hubble grism spectroscopy of 10 strong-lensing galaxy clusters

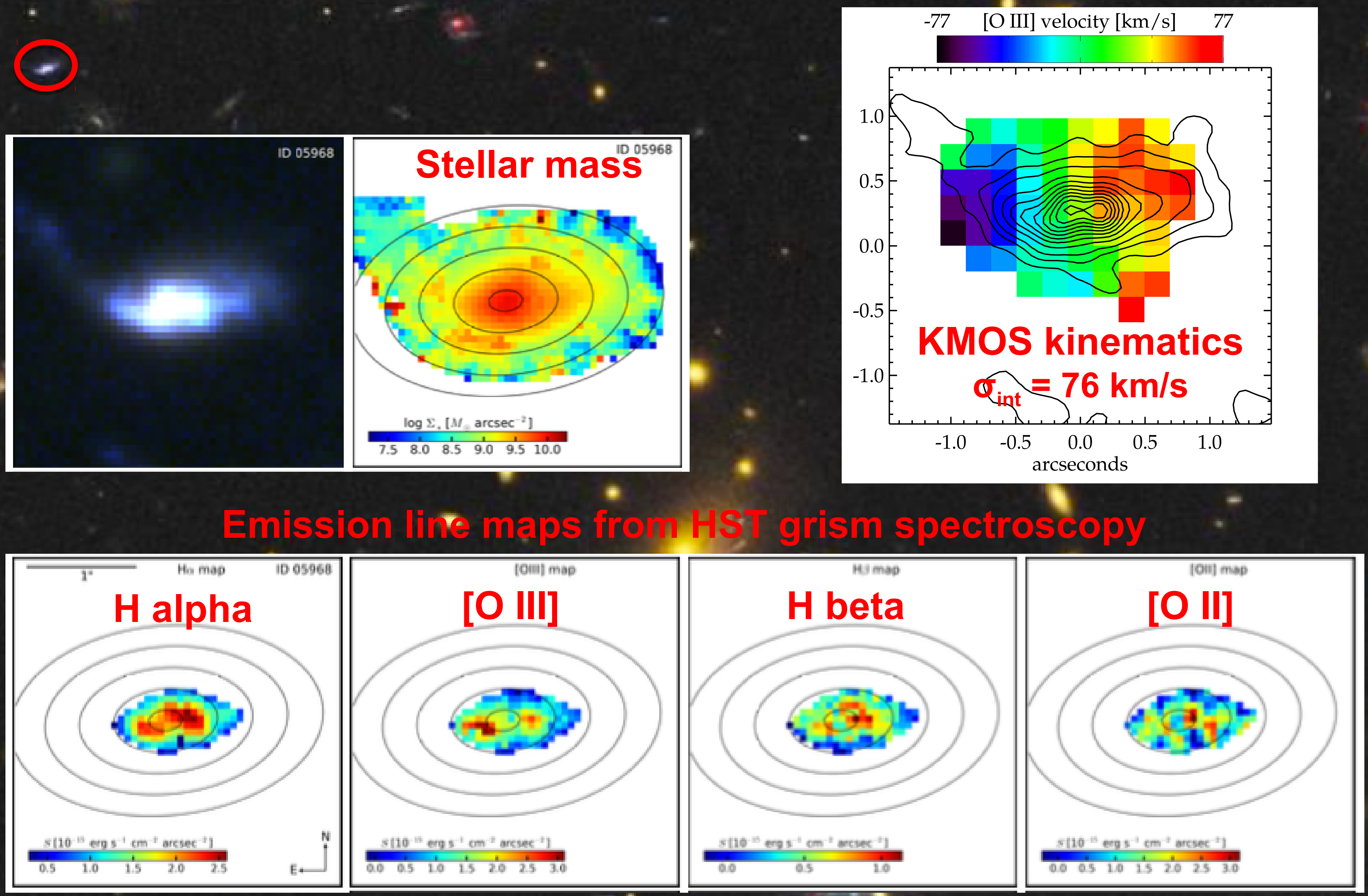
Treu et al. 2015 (survey overview)

Jones et al. 2015 (first results)

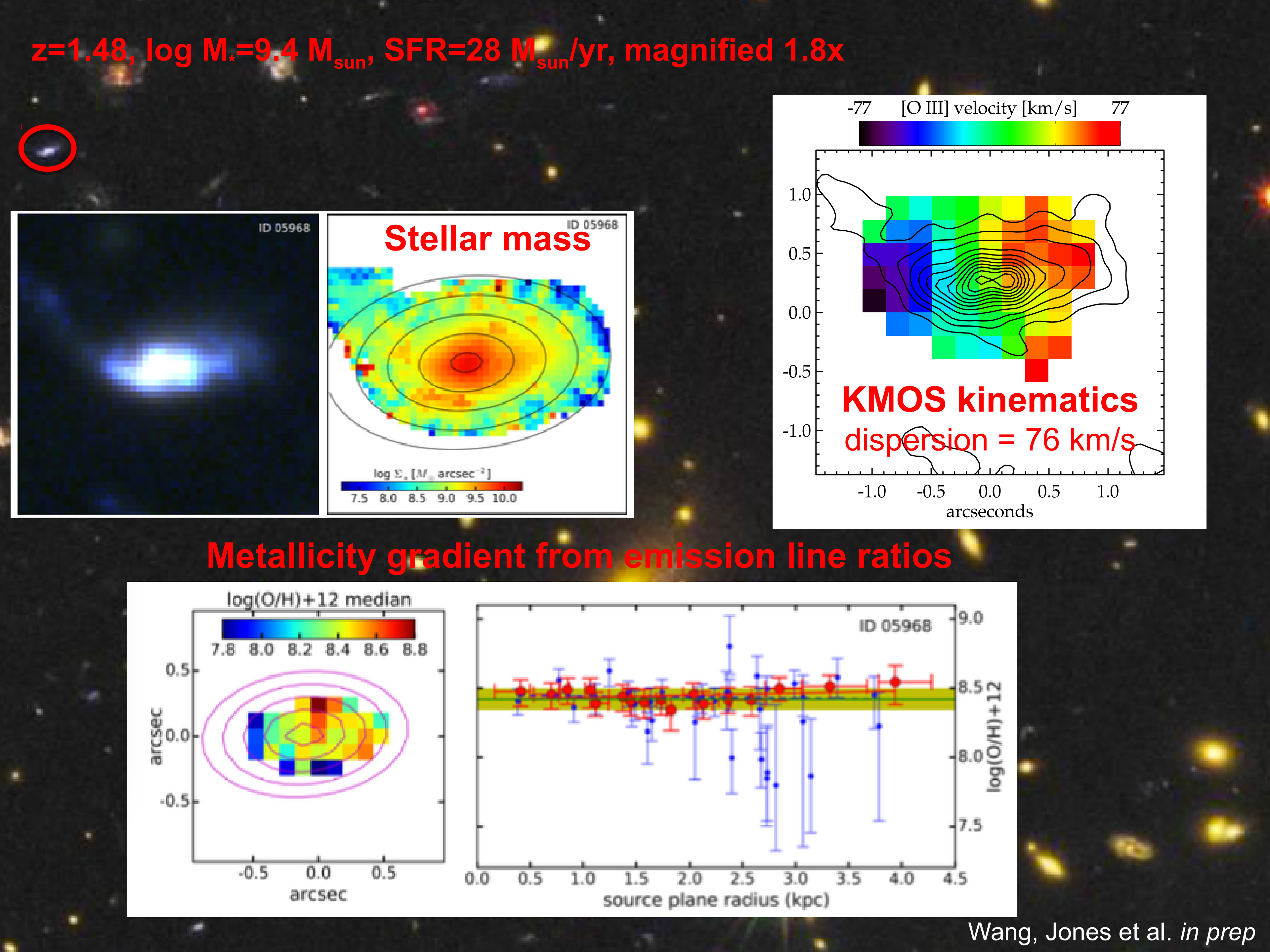
Wang et al. *in prep* (expanded sample)

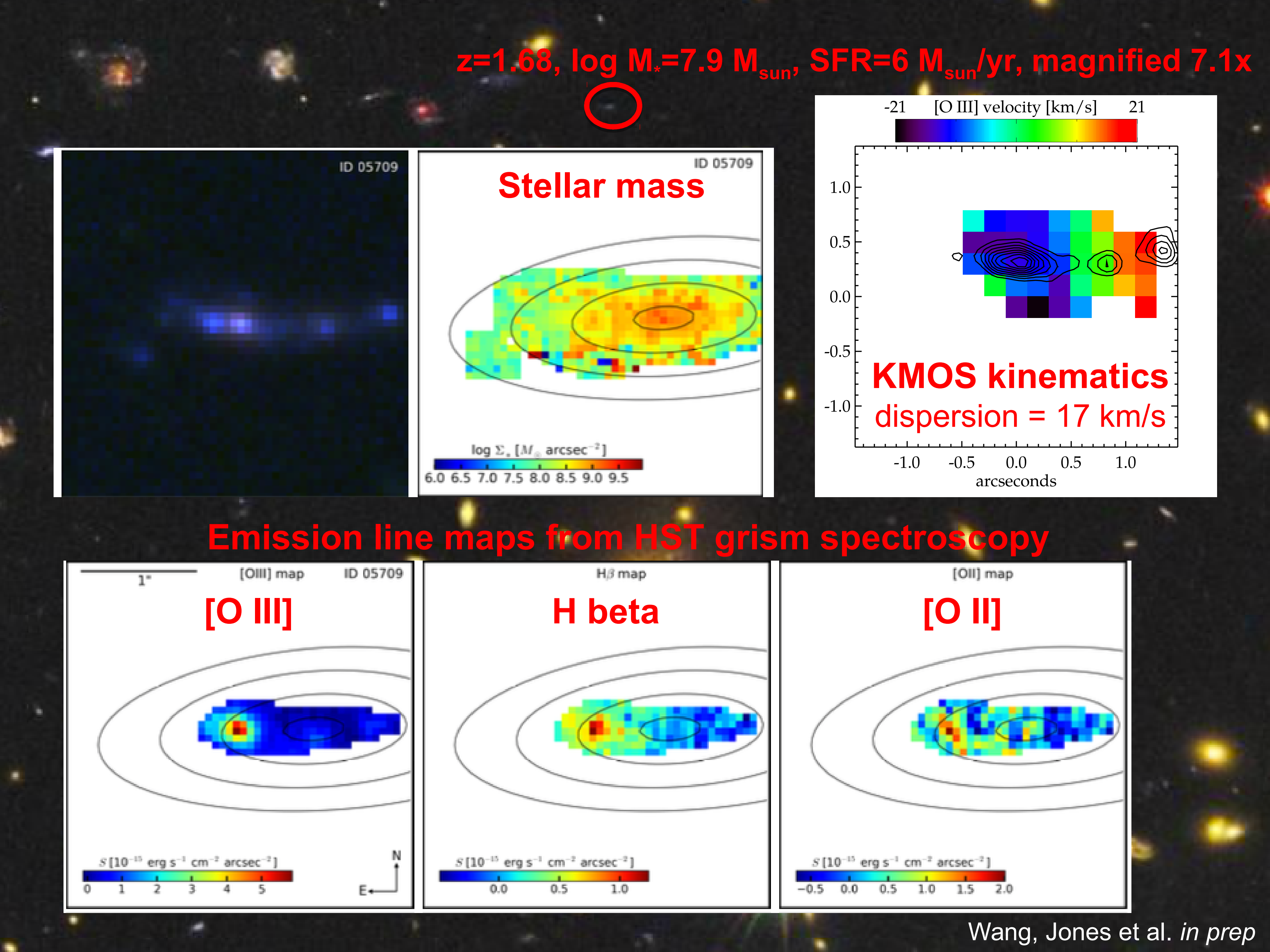

Hb [O III]
Ha [S II]
1.1
1.2
1.3
1.4
1.5
1.6
1.7
Wavelength (microns)
Wang, Jones et al. *in prep*

z=1.48, log M_*=9.4 M_{sun}, SFR=28 M_{sun}/yr, magnified 1.8x

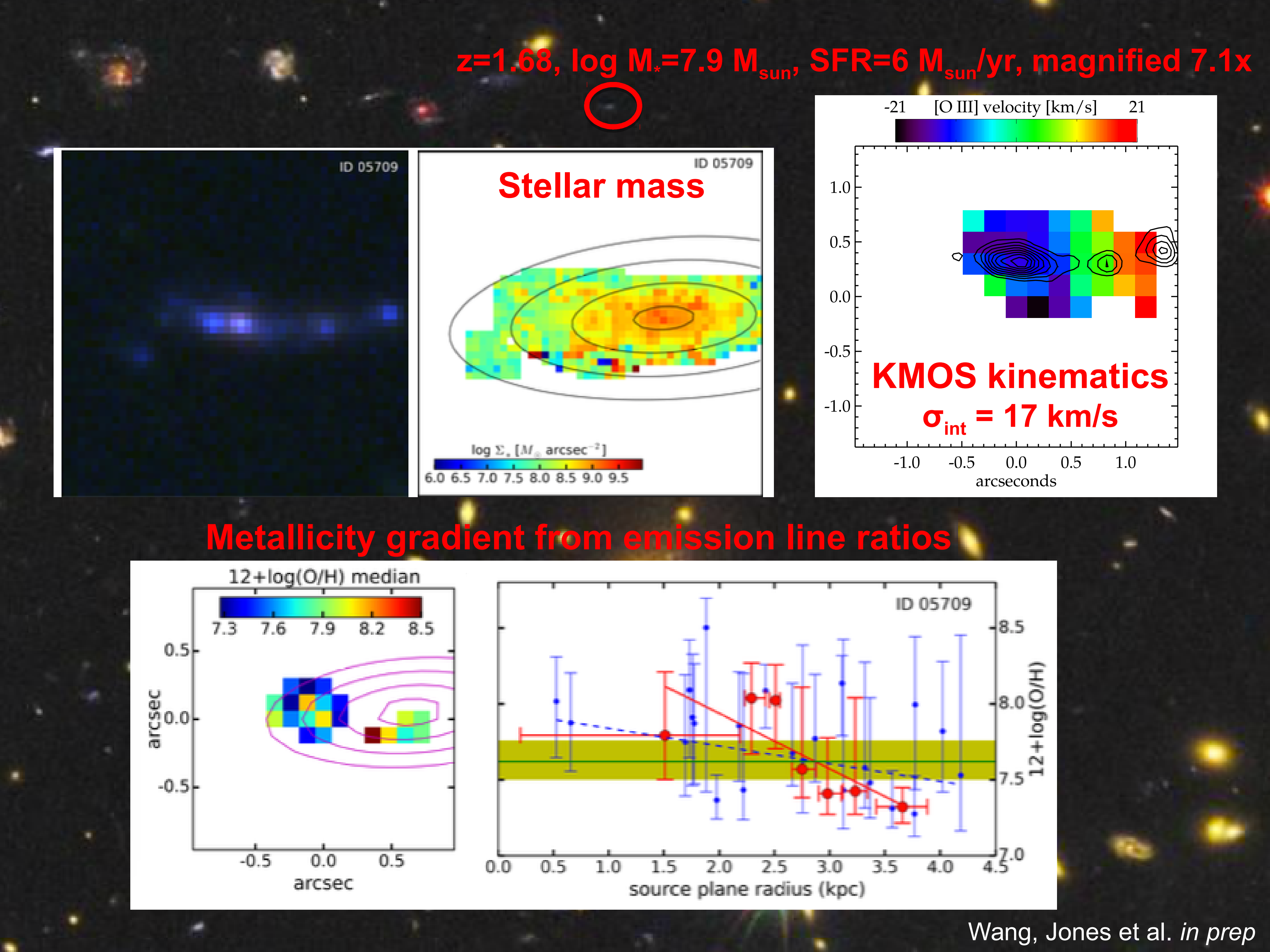


Wang, Jones et al. *in prep*


z=1.48, log M* =9.4 Msun, SFR=28 Msun/yr, magnified 1.8x
ID 05968
ID 05968
Stellar mass
log Σ* [M☉ arcsec⁻²]
7.5 8.0 8.5 9.0 9.5 10.0
-77 [O III] velocity [km/s] 77
1.0
0.5
0.0
-0.5
-1.0
-1.0 -0.5 0.0 0.5 1.0
arcseconds
KMOS kinematics
dispersion = 76 km/s
Metallicity gradient from emission line ratios
log(O/H)+12 median
7.8 8.0 8.2 8.4 8.6 8.8
arcsec
0.5
0.0
-0.5
-0.5 0.0 0.5
arcsec
ID 05968
9.0
8.5
8.0
7.5
log(O/H)+12
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5
source plane radius (kpc)
Wang, Jones et al. in prep

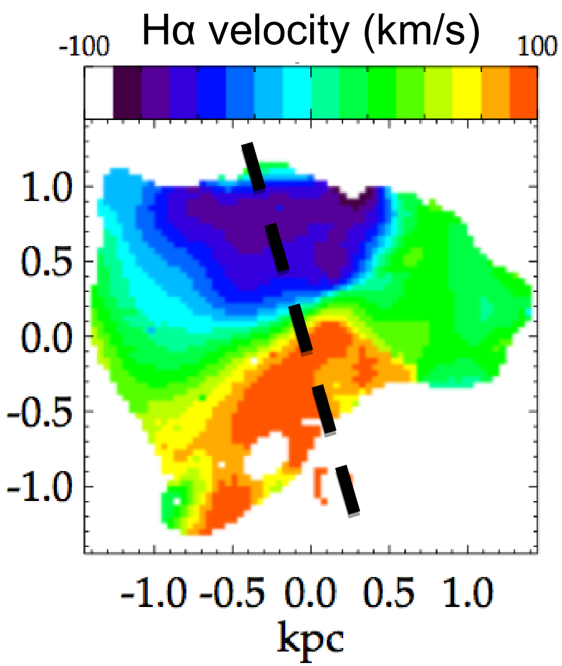


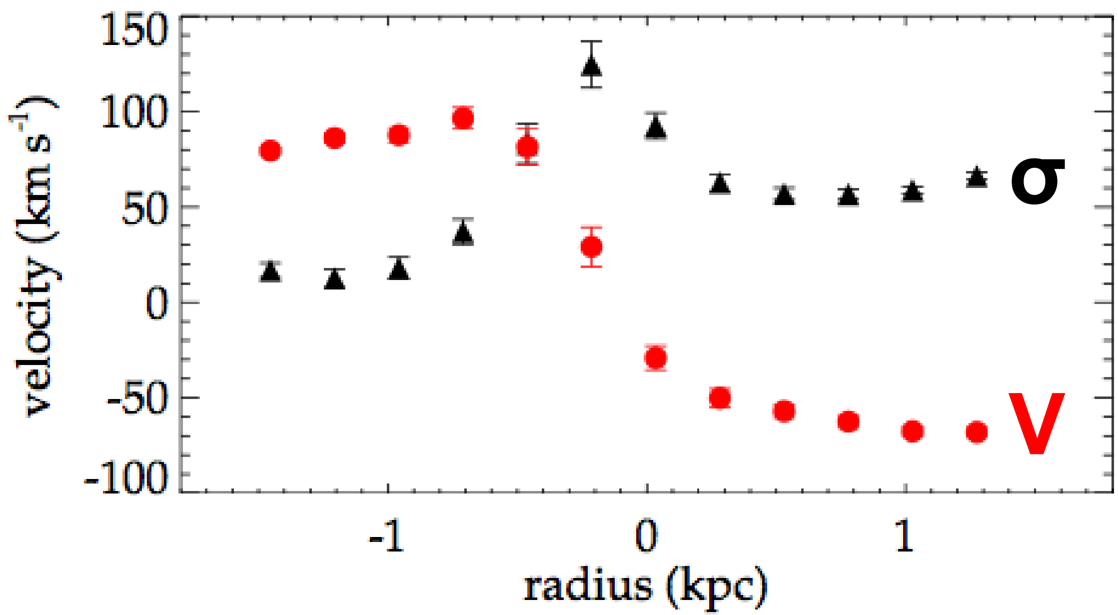
z=1.68, log M*=7.9 Msun, SFR=6 Msun/yr, magnified 7.1x
ID 05709
Stellar mass
ID 05709
log Σ* [M⊙ arcsec⁻²]
6.0 6.5 7.0 7.5 8.0 8.5 9.0 9.5
-21 [O III] velocity [km/s] 21
1.0
0.5
0.0
-0.5
-1.0
-1.0 -0.5 0.0 0.5 1.0
arcseconds
KMOS kinematics
dispersion = 17 km/s
Emission line maps from HST grism spectroscopy
1"
[OIII] map
ID 05709
[O III]
S [10⁻¹⁵ erg s⁻¹ cm⁻² arcsec⁻²]
0 1 2 3 4 5
N
E
Hβ map
H beta
S [10⁻¹⁵ erg s⁻¹ cm⁻² arcsec⁻²]
0.0 0.5 1.0
[OII] map
[O II]
S [10⁻¹⁵ erg s⁻¹ cm⁻² arcsec⁻²]
−0.5 0.0 0.5 1.0 1.5 2.0
Wang, Jones et al. in prep



z=1.68, log M*=7.9 Msun, SFR=6 Msun/yr, magnified 7.1x
ID 05709
ID 05709
Stellar mass
log Σ* [M⊙ arcsec⁻²]
6.0 6.5 7.0 7.5 8.0 8.5 9.0 9.5
-21 [O III] velocity [km/s] 21
1.0
0.5
0.0
-0.5
-1.0
-1.0 -0.5 0.0 0.5 1.0
arcseconds
KMOS kinematics
σint = 17 km/s
Metallicity gradient from emission line ratios
12+log(O/H) median
7.3 7.6 7.9 8.2 8.5
0.5
0.0
-0.5
arcsec
-0.5 0.0 0.5
arcsec
ID 05709
8.5
8.0
7.5
7.0
12+log(O/H)
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5
source plane radius (kpc)
Wang, Jones et al. in prep

Sample properties: kinematics at z=2

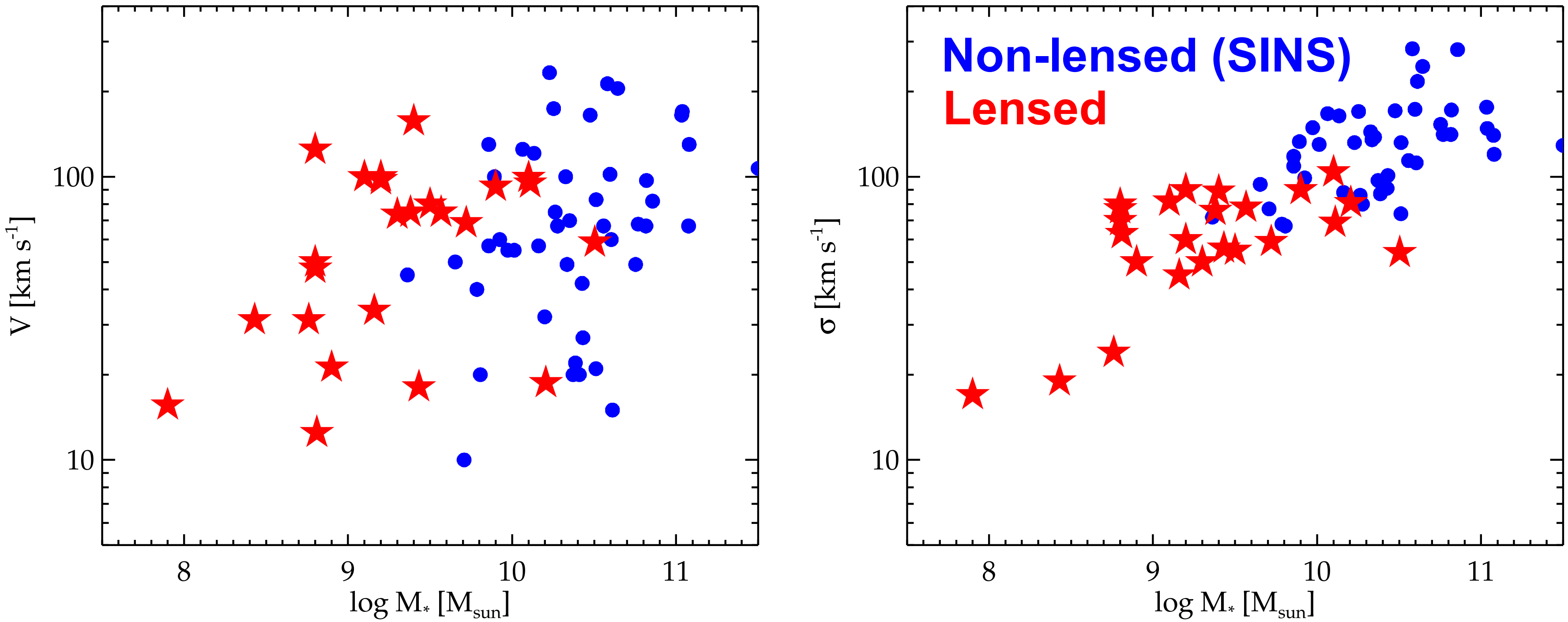




Rotation, high local velocity dispersion characteristic of thick disk

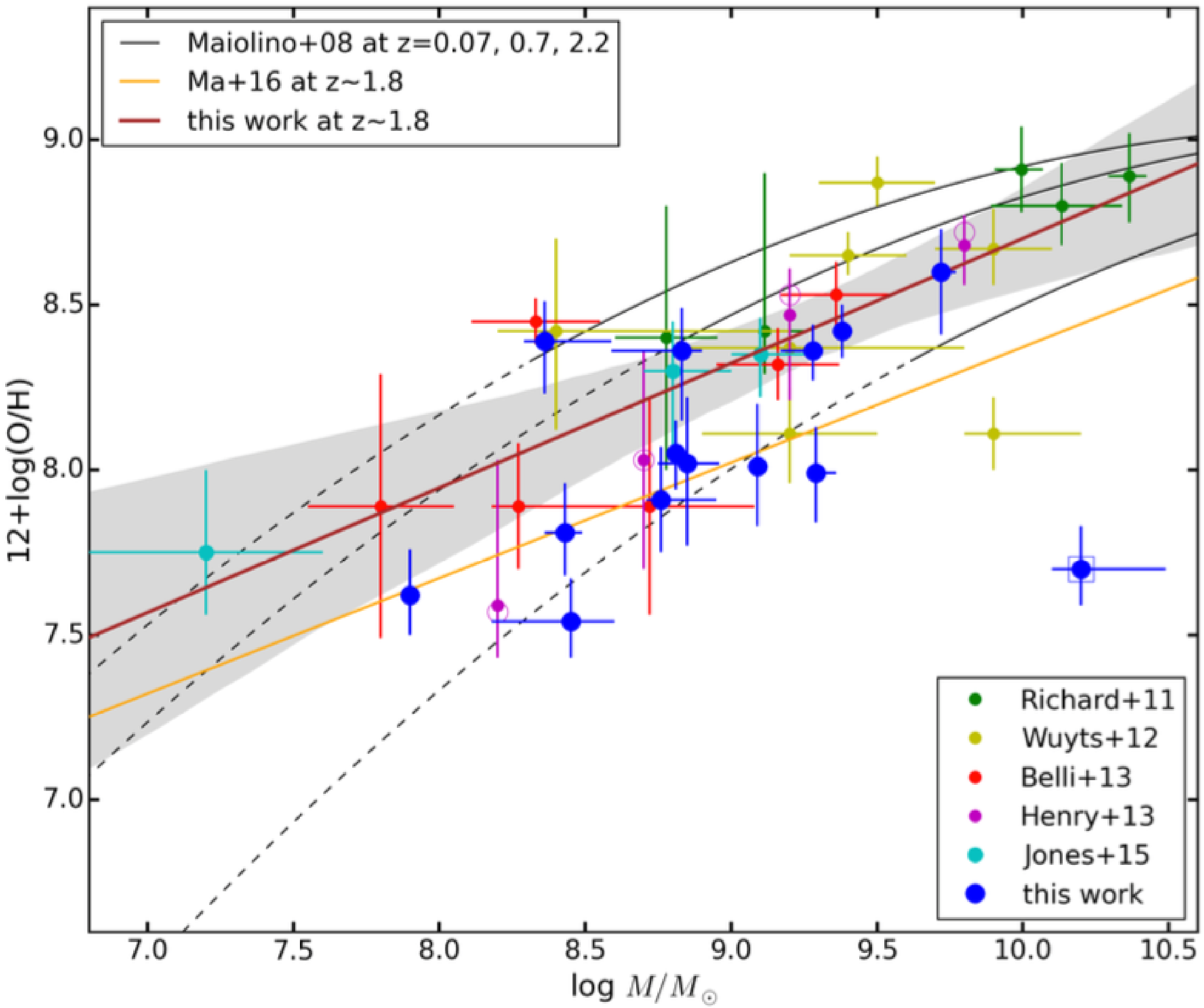
Jones et al. 2010a, 2013a

Sample properties: kinematics at z=2



~2/3 are thick disks, ~1/3 are mergers
Rotation is clearly resolved in low-mass lensed galaxies

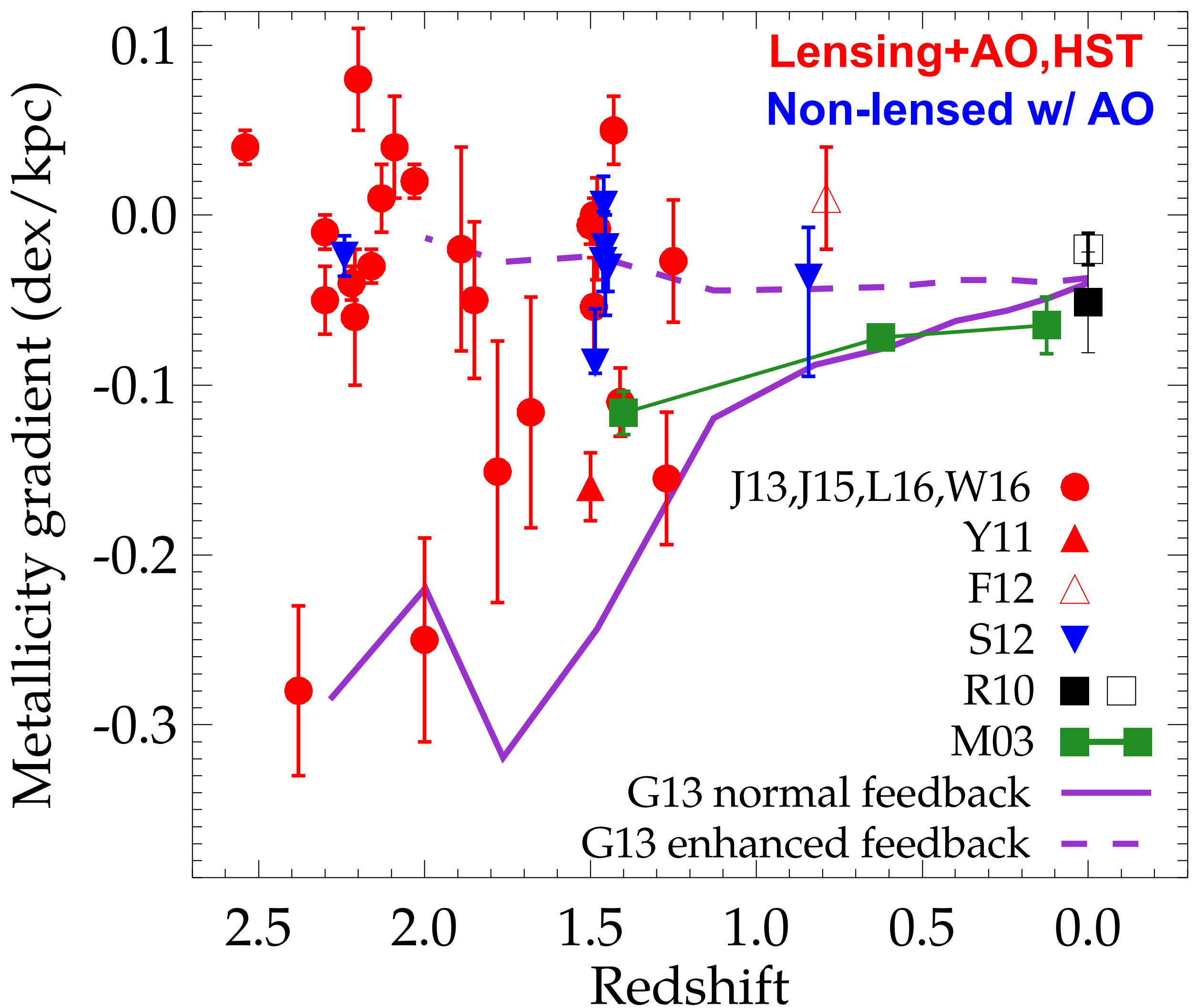
Sample properties: metallicity at z=2



[O/H] ~ −0.2 for stars forming in MW progenitors at z~2

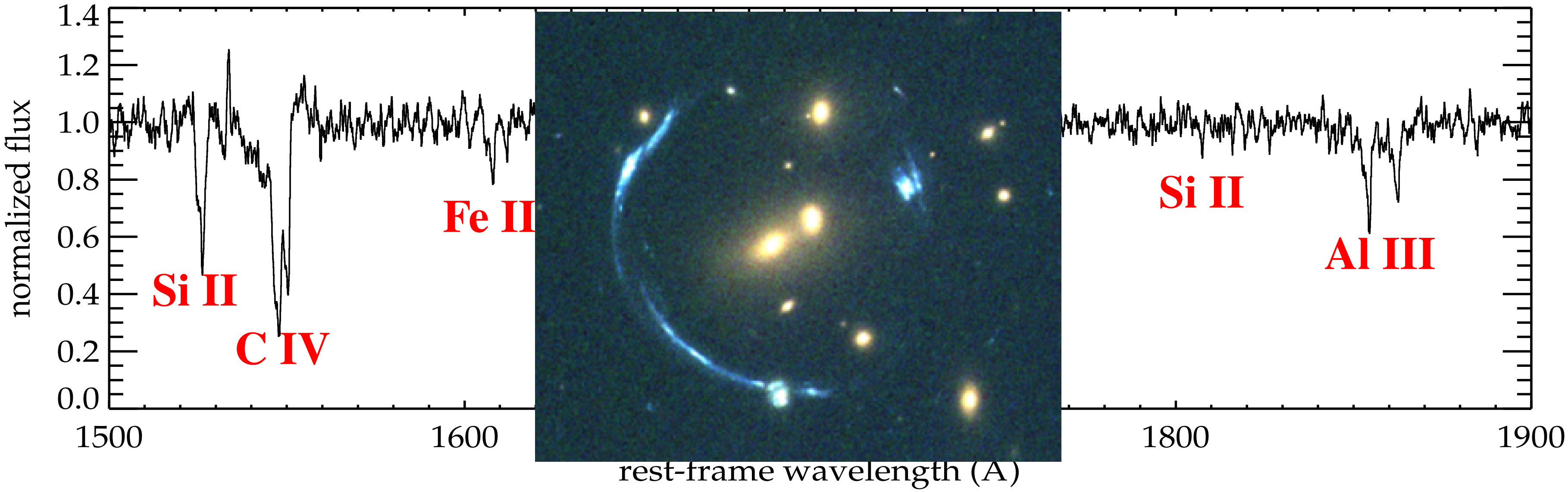
Wang, Jones et al. *in prep*

Sample properties: metallicity gradients

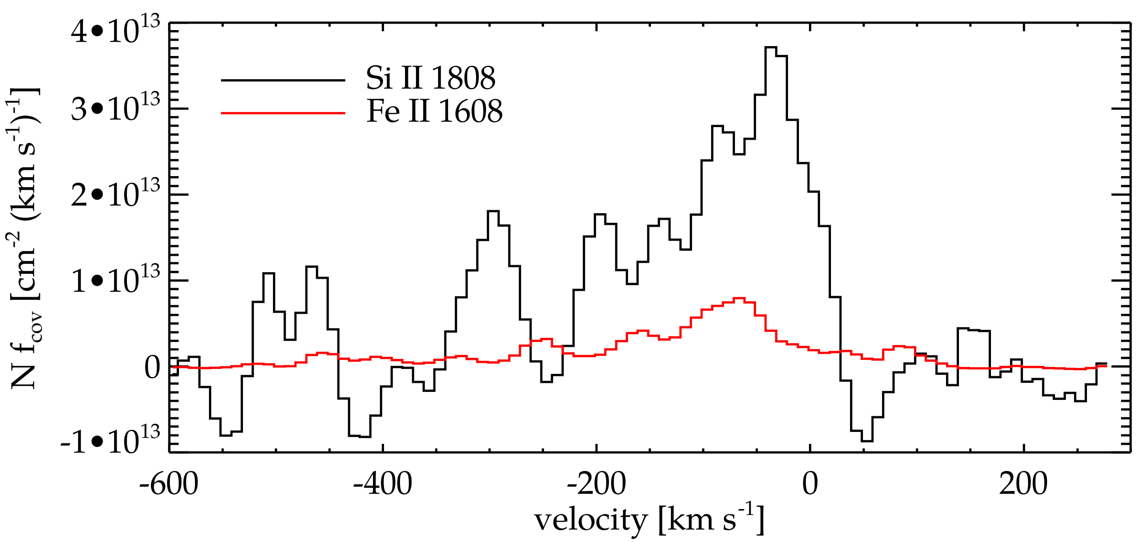


Variety of gradients seen at z~2, typically with negative slope
Gas mixing suggests strong feedback

Sample properties: abundance ratios at z=2



Near-UV absorption spectroscopy of several elements

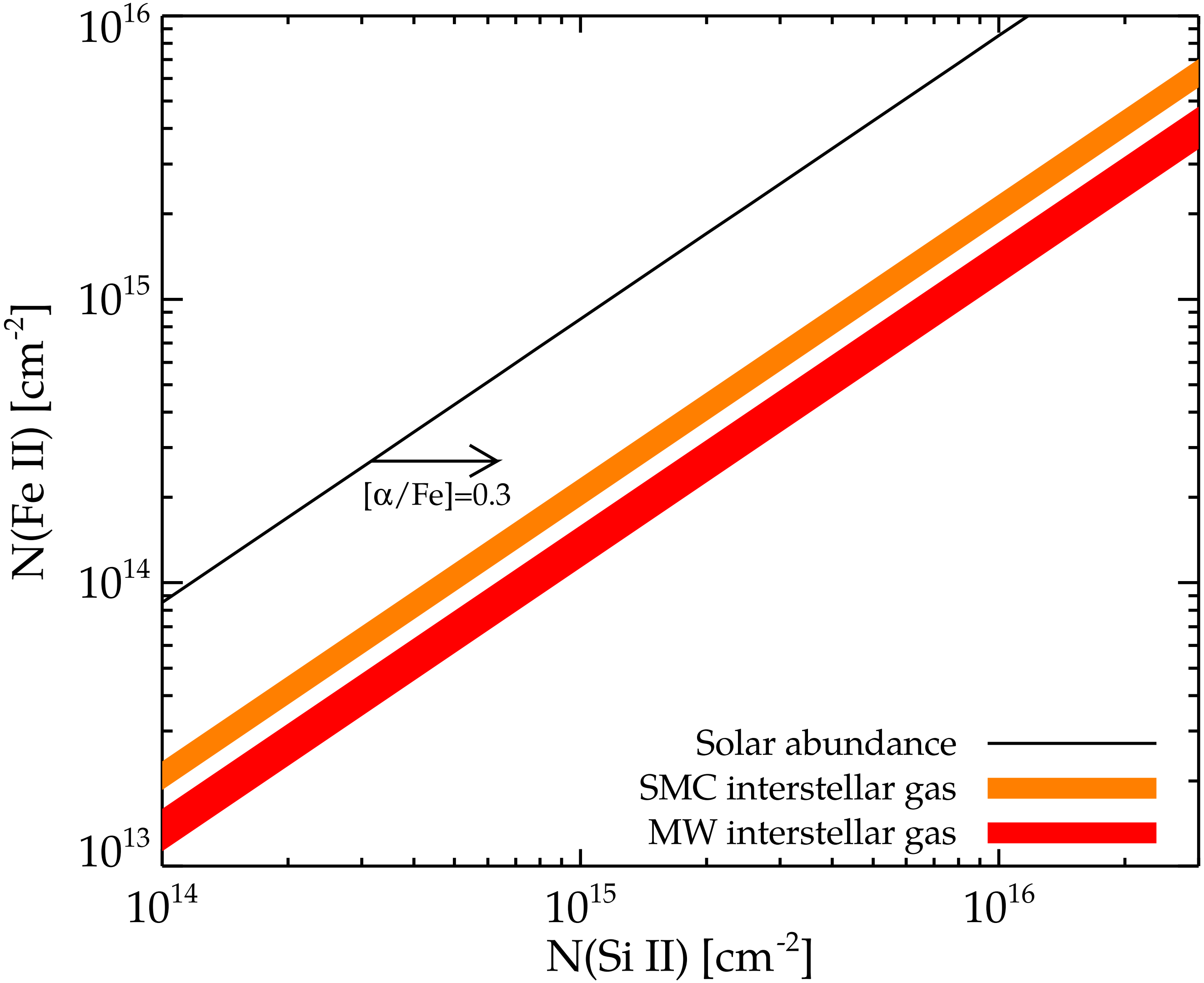


Fe II, Si II:
Column densities are well-constrained over 3 orders of magnitude from multiple transitions

Fe II, Si II have essentially identical ionization potentials

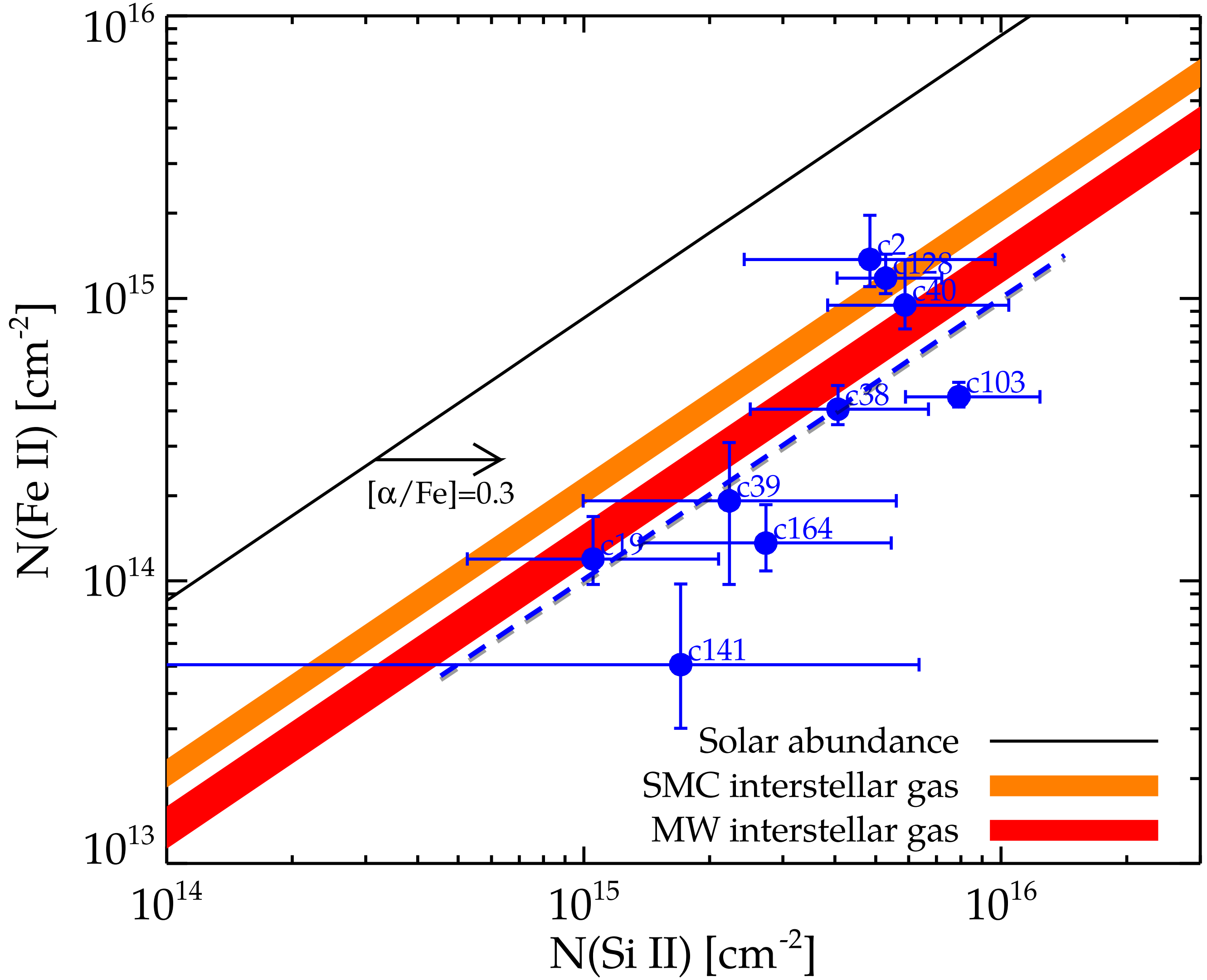
Jones et al. *in prep*

Sample properties: abundance ratios at z=2



Intrinsic [Si/Fe] is redundant with dust depletion factors

Sample properties: abundance ratios at z=2



Median [α/Fe] ≈ 0.1−0.3, assuming dust depletion patterns from local galaxies of similar overall metallicity

Summary: early disks at z=2 revealed by resolved spectroscopy

Typical properties of Milky Way progenitors at z≈2

- Thick disk kinematics: local **$\sigma \approx 50$** km/s≈≈
- Metallicity **[O/H] ≈ −0.2**, and likely **[α/Fe] ≈ +0.2**
- Radial metallicity gradients with median **Δ[O/H]/ΔR ≈ −0.05** dex/kpc

Scaling relations established spanning 3 orders of magnitude in M_*