The Chemical Evolution of Galaxies Across Cosmic Time

Tucker Jones
University of California, Davis

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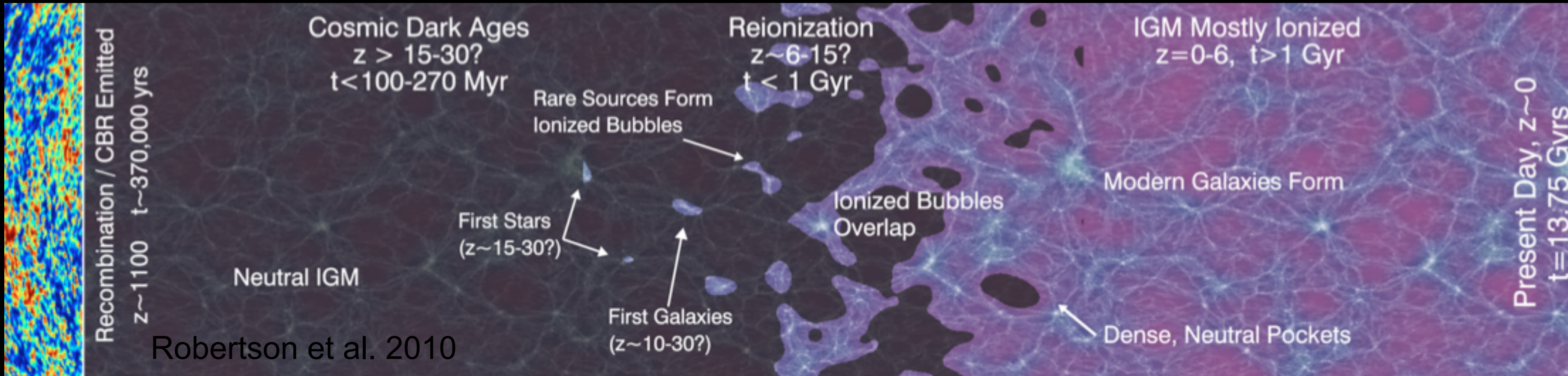
Image credit: the DEEP2 team

Ryan Sanders
Hubble Fellow @ UC Davis

Erin Huntzinger
grad student @ UC Davis

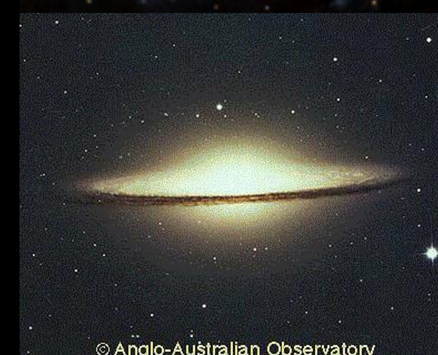
Yuguang Chen
postdoc @ UC Davis

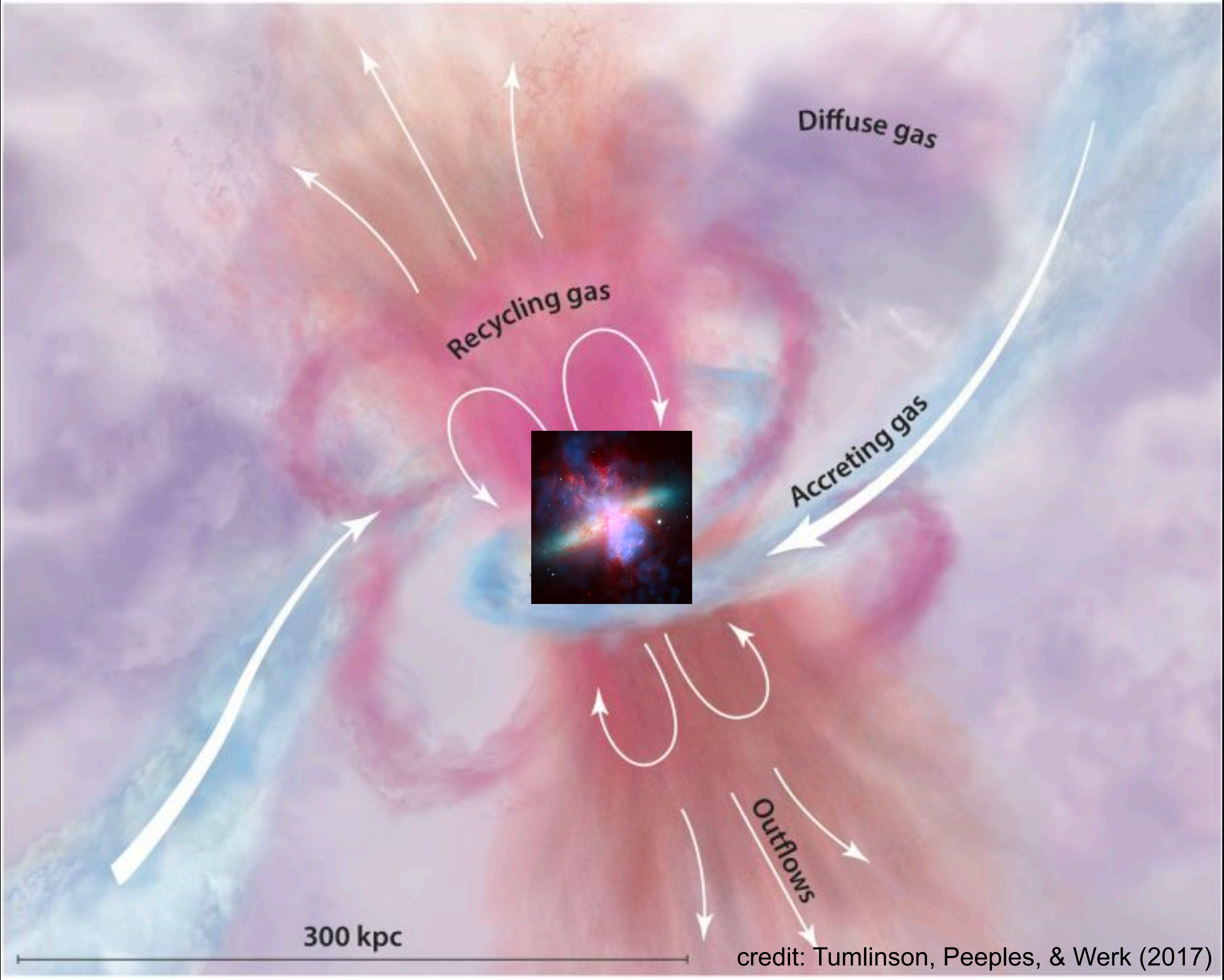
in collaboration with Ryan Sanders, Erin Huntzinger, Yuguang Chen (UC Davis), Guido Roberts-Borsani (UCLA), Richard Ellis (UCL), Yuichi Harikane (NAOJ), Tommaso Treu (UCLA), Nicolas Laporte (Cambridge), Mike Cooper (UCI), Crystal Martin (UCSB), Fabio Bresolin (Hawaii), Dan Stark (Arizona), Robert Minchin (USRA), and other wonderful colleagues



How do galaxies form?

z≈11





credit: Tumlinson, Peeples, & Werk (2017)

including heavy elements!

Baryons ^ cycle in and out of galaxies through accretion, star formation, and outflows

… but the gas flows are difficult to observe

… especially at high redshifts, when gas flow rates and gas fractions were much higher

Preferred heavy element: oxygen

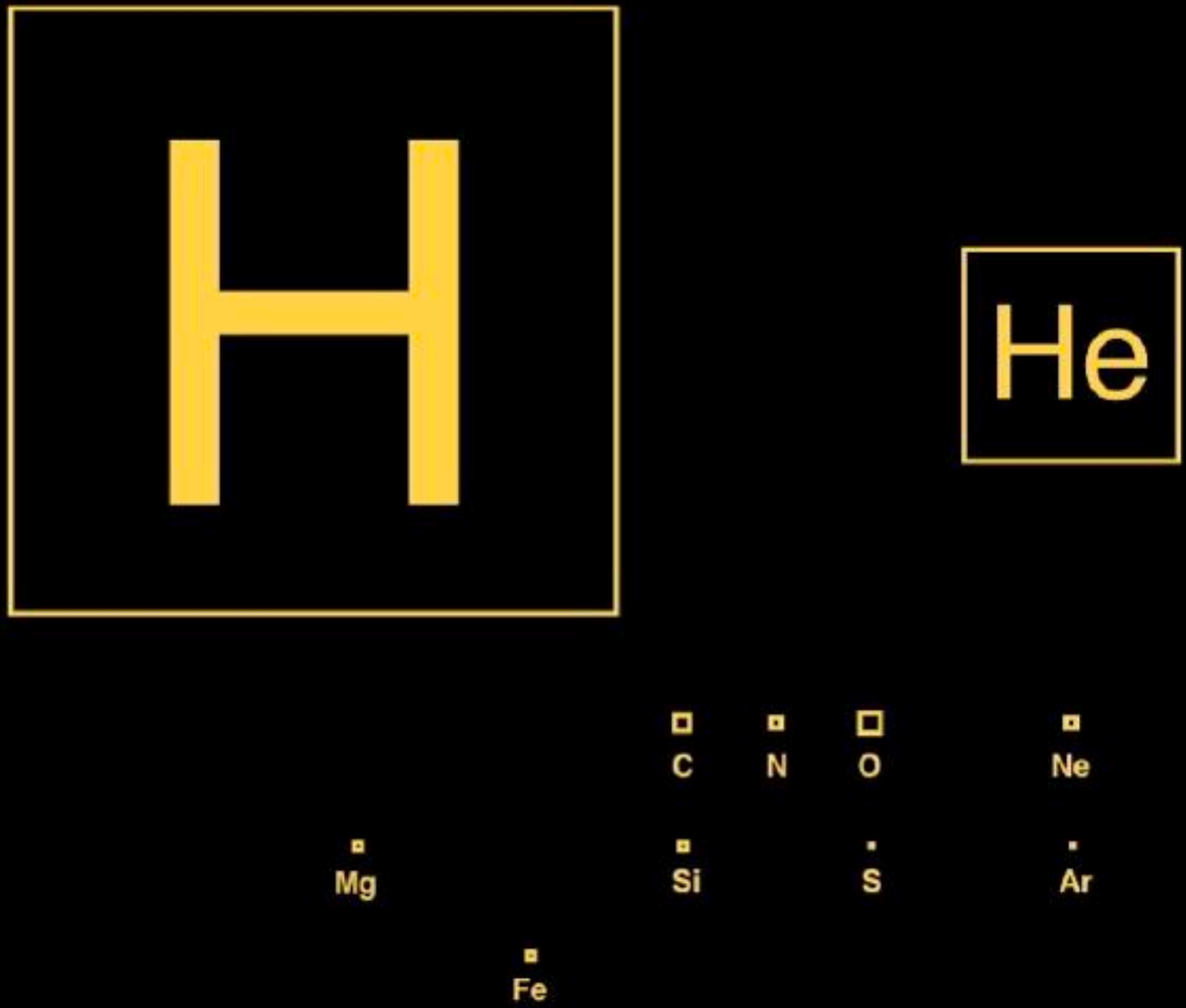
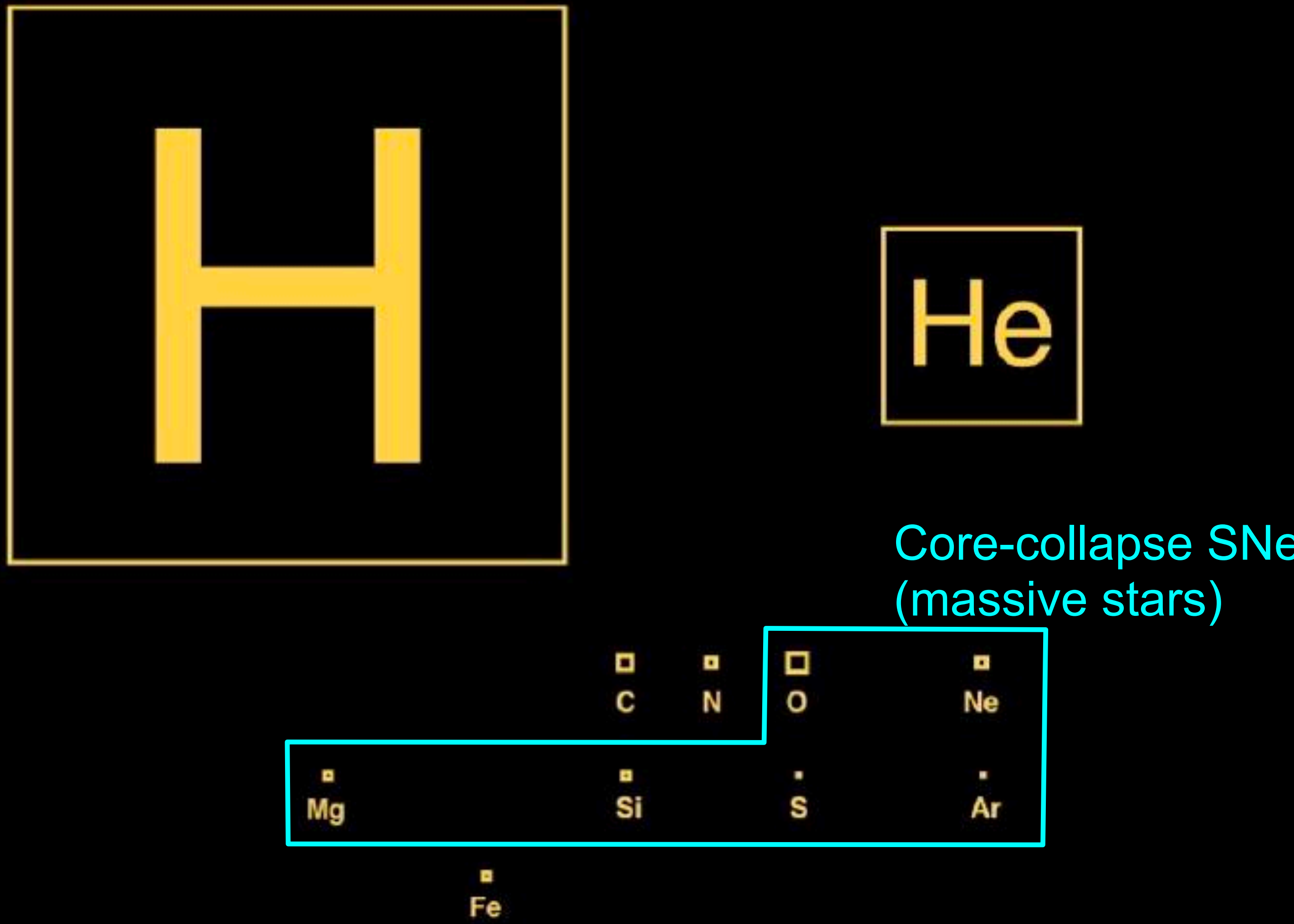


Image credit: Paul Wallace

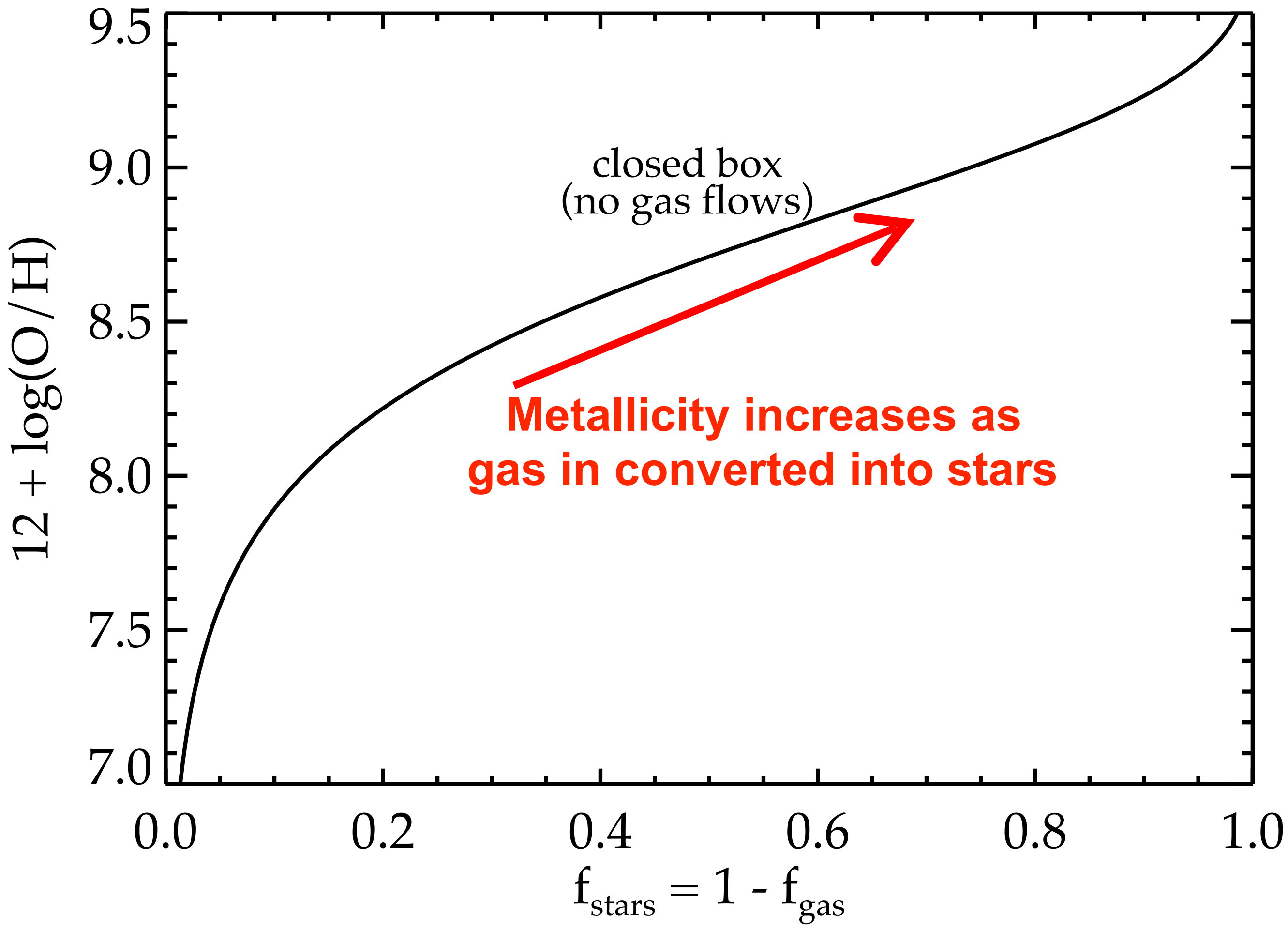
Preferred heavy element: oxygen



1. Oxygen is relatively abundant & undepleted
2. Traces short-timescale enrichment from stars
3. Easiest to measure with emission line spectra

Image credit: Paul Wallace

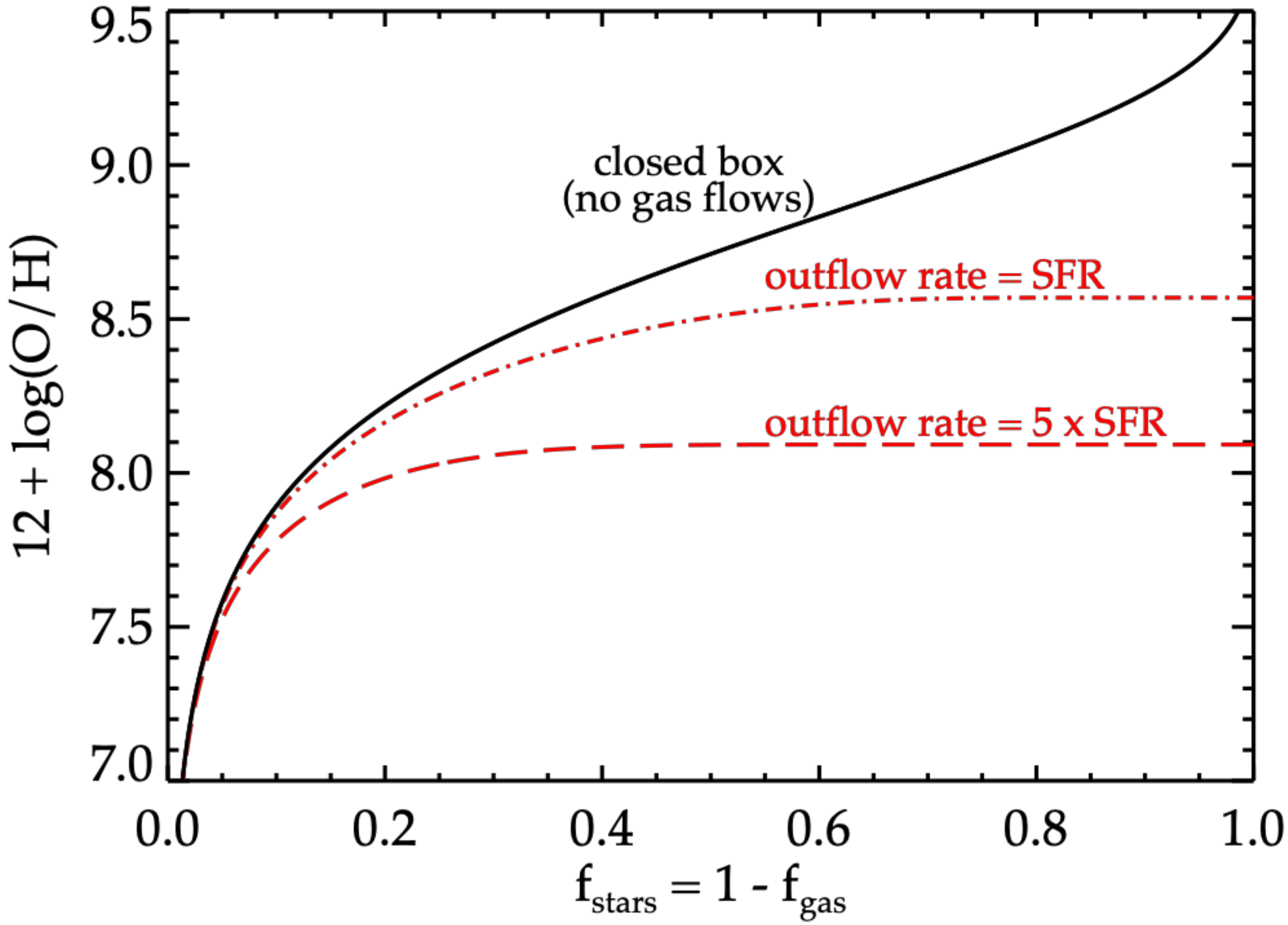
Metallicity as a probe of gas flows & galaxy formation



"Metallicity" = gas-phase oxygen abundance

Solar value: $12 + \log(O/H)_\odot = 8.69$

Metallicity as a probe of gas flows & galaxy formation



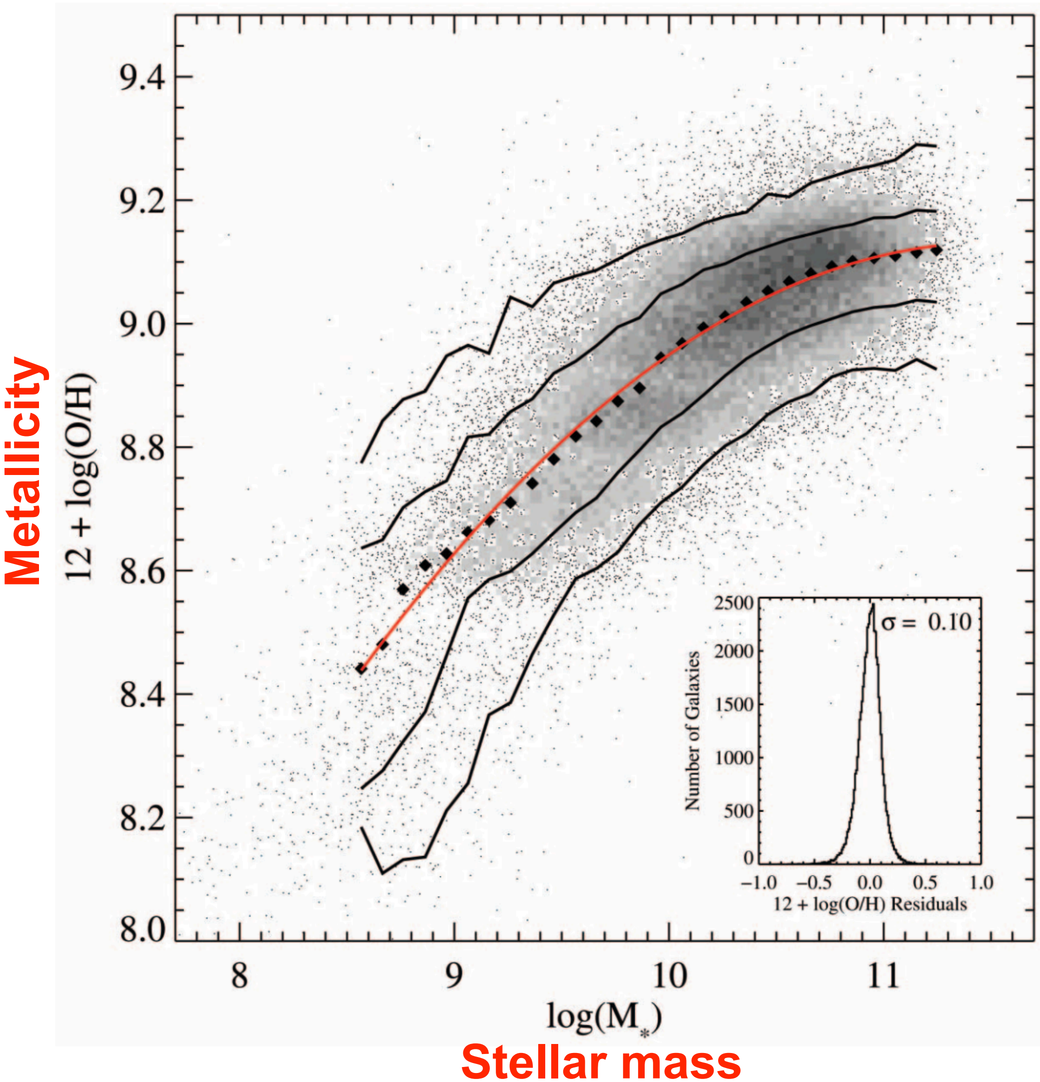
Assume: (inflow rate) = SFR + (outflow rate)

$$Z_g = \frac{y}{1+f_0'}\left[1 - \exp\left(-(1+f_0')\frac{1-f_{gas}}{f_{gas}}\right)\right]$$

f_0' = (metals ejected) / (metals retained in ISM)

Jones et al. 2013a

The mass-metallicity relation



Galaxies with lower mass have lower gas-phase metallicity

- At lower mass, a larger fraction of heavy elements are ejected in outflows
- Shape of the relation is set by outflow mass loading factor

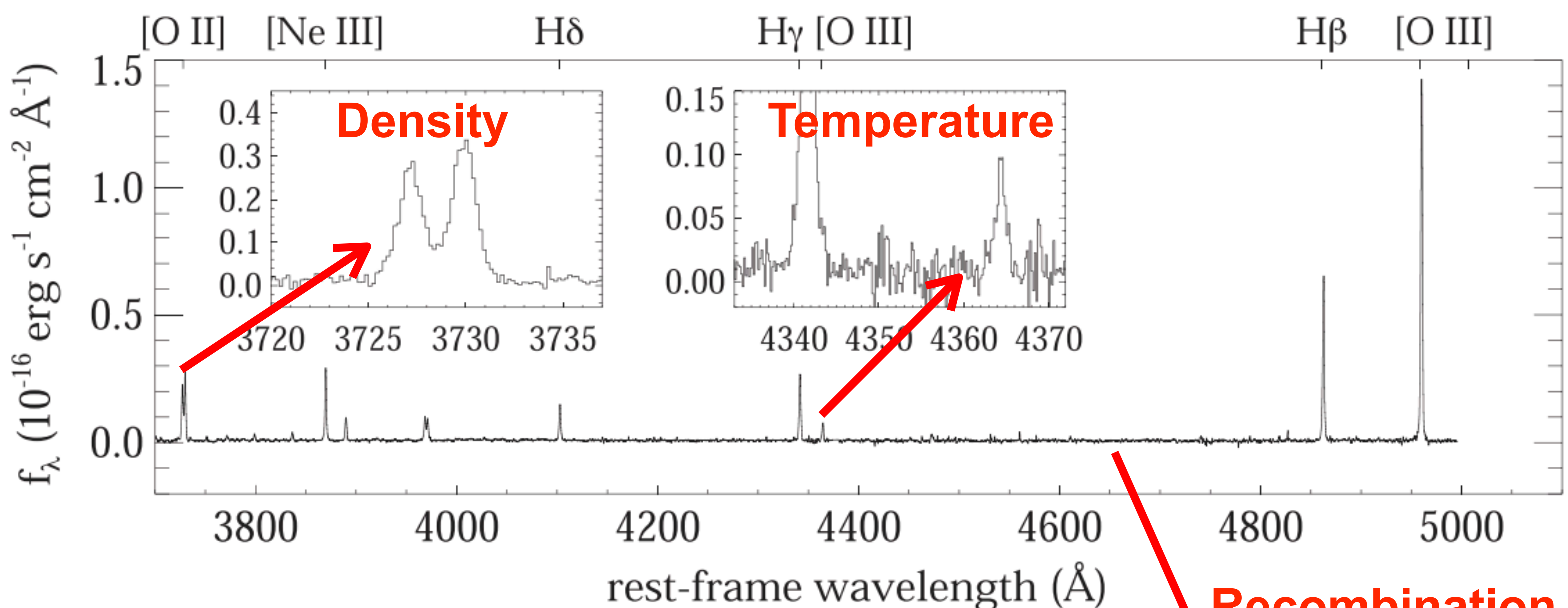
At higher redshift: generally expect lower metallicity (at fixed mass) due to increased gas fractions, & large outflow mass loss rates

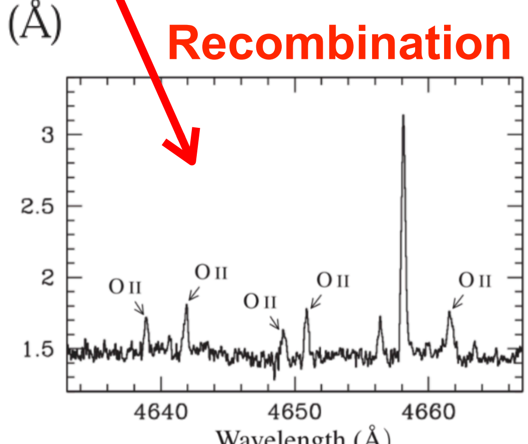
Tremonti et al. 2004

How do we measure gas-phase metallicities?

1. Direct T_e method

- Calculate abundances from measurements of gas density and temperature
- Relies on weak auroral emission lines (usually [O III] 4363)





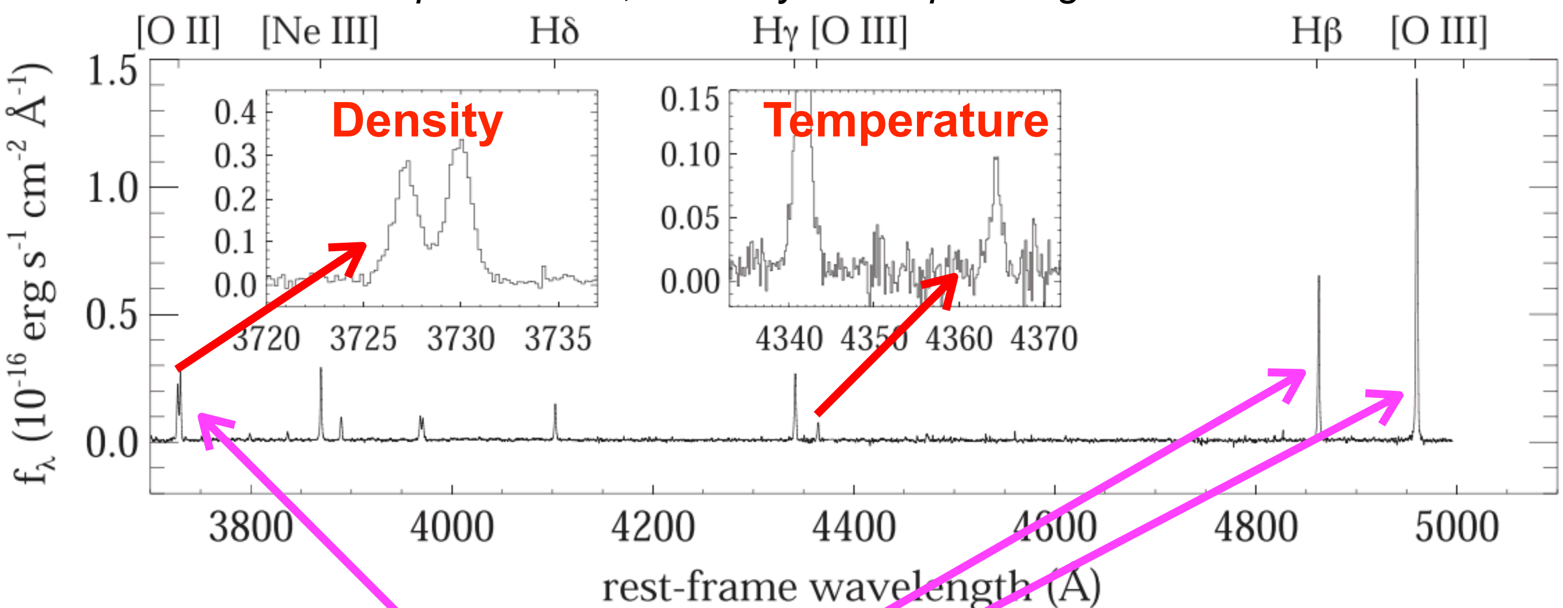
2. Recombination line method

- Relatively insensitive to temperature & density
  - Mostly sensitive to abundances!
- But, lines are 100x weaker than auroral emission!

How do we measure gas-phase metallicities… at high redshifts?

1. Direct T_e method

- Calculate abundances from measurements of gas density and temperature
- Relies on weak auroral emission lines (usually [O III] 4363)
- *Limited samples at z>1, but they are expanding…*

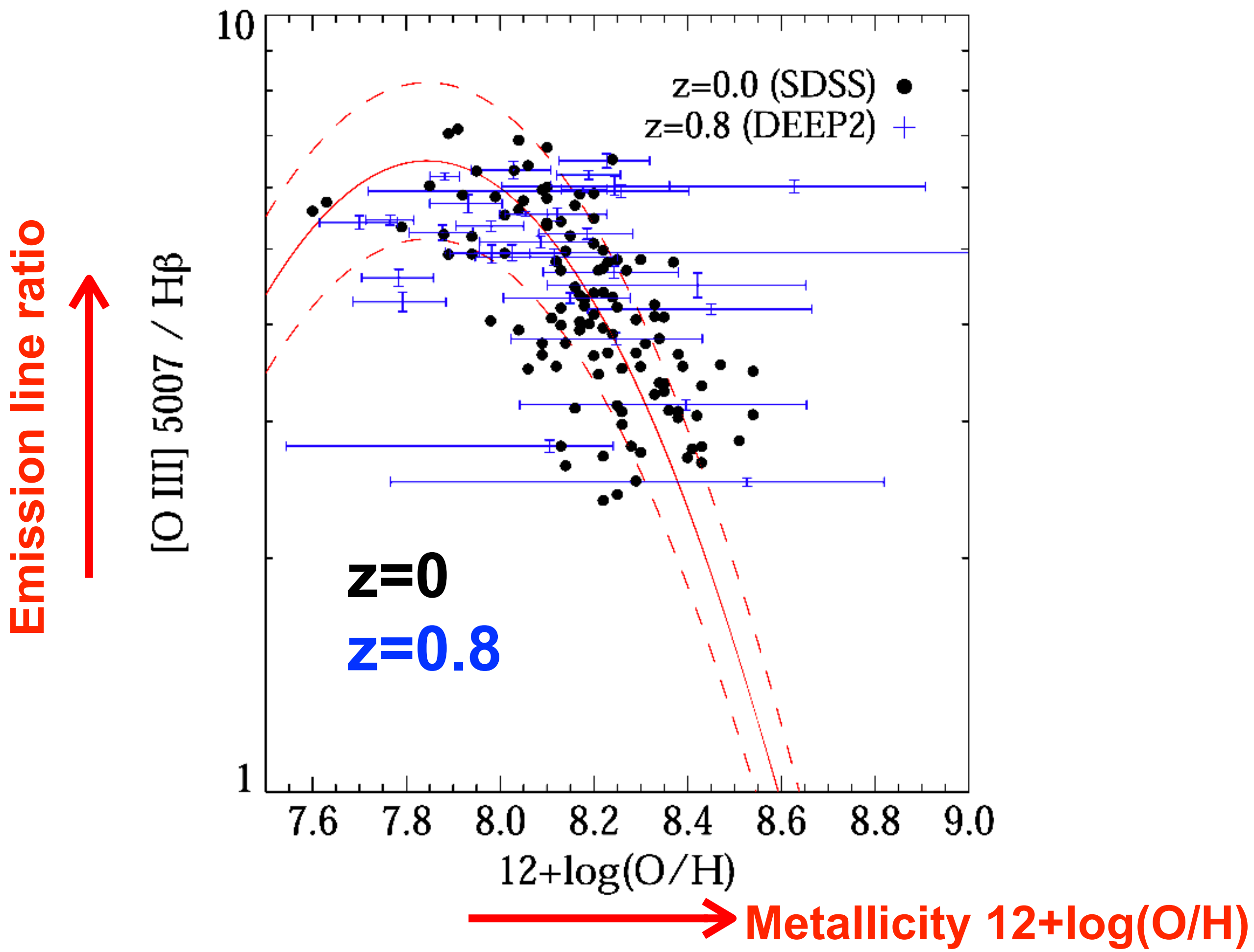


2. Indirect "strong line" method

- Use ratios of strongest emission lines (100x brighter than auroral lines)
- Calibrated to direct measurements at z=0

NB: this method must be carefully calibrated for high z!
Physical conditions are different than at z~0.

Strong-line metallicity calibrations at z=0.8

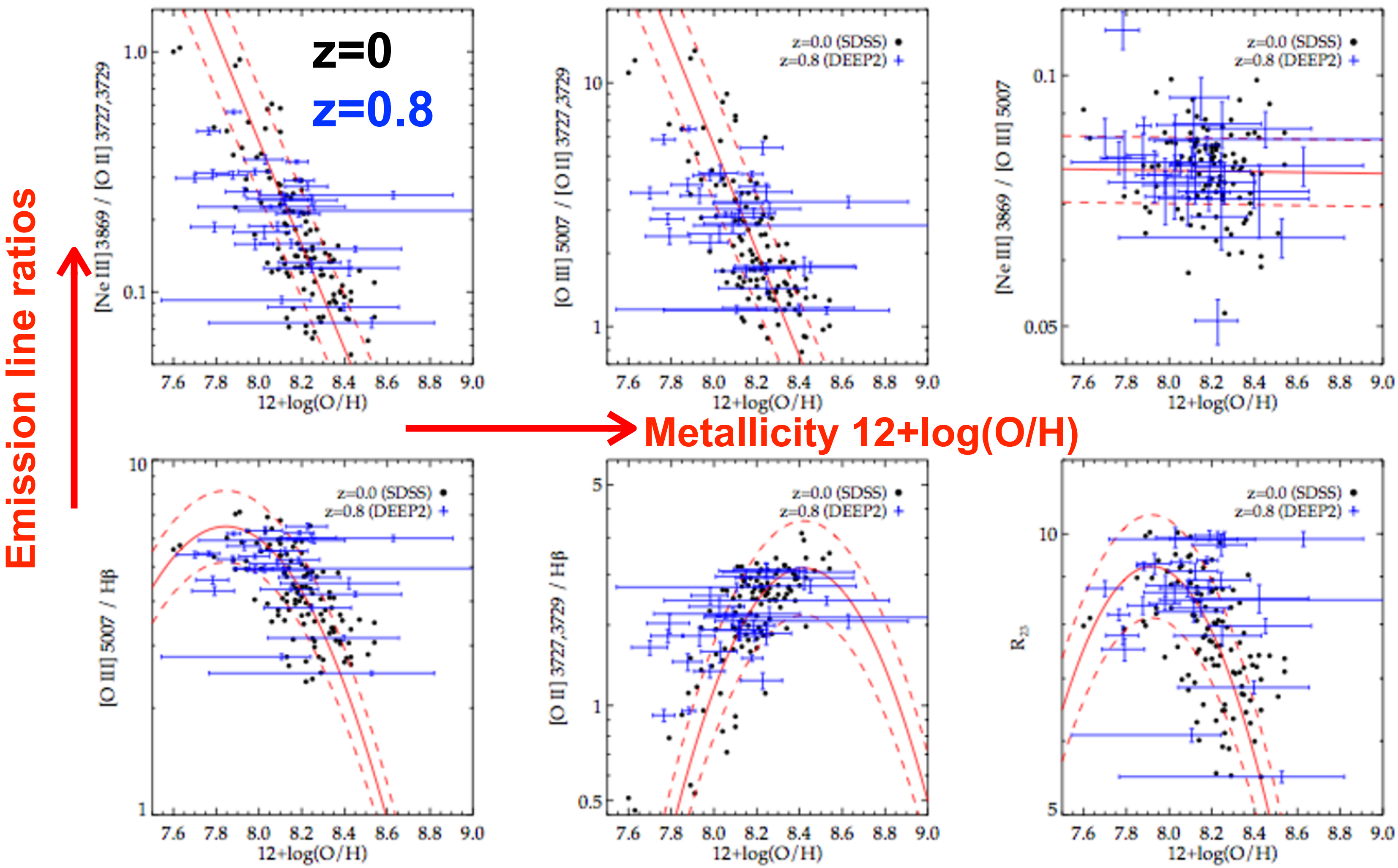


T_e metallicity vs. various emission line ratios

- Consistent with a local z=0 sample of similar excitation properties

Jones et al. 2015, ApJ, 813, 126

Strong-line metallicity calibrations at z=0.8

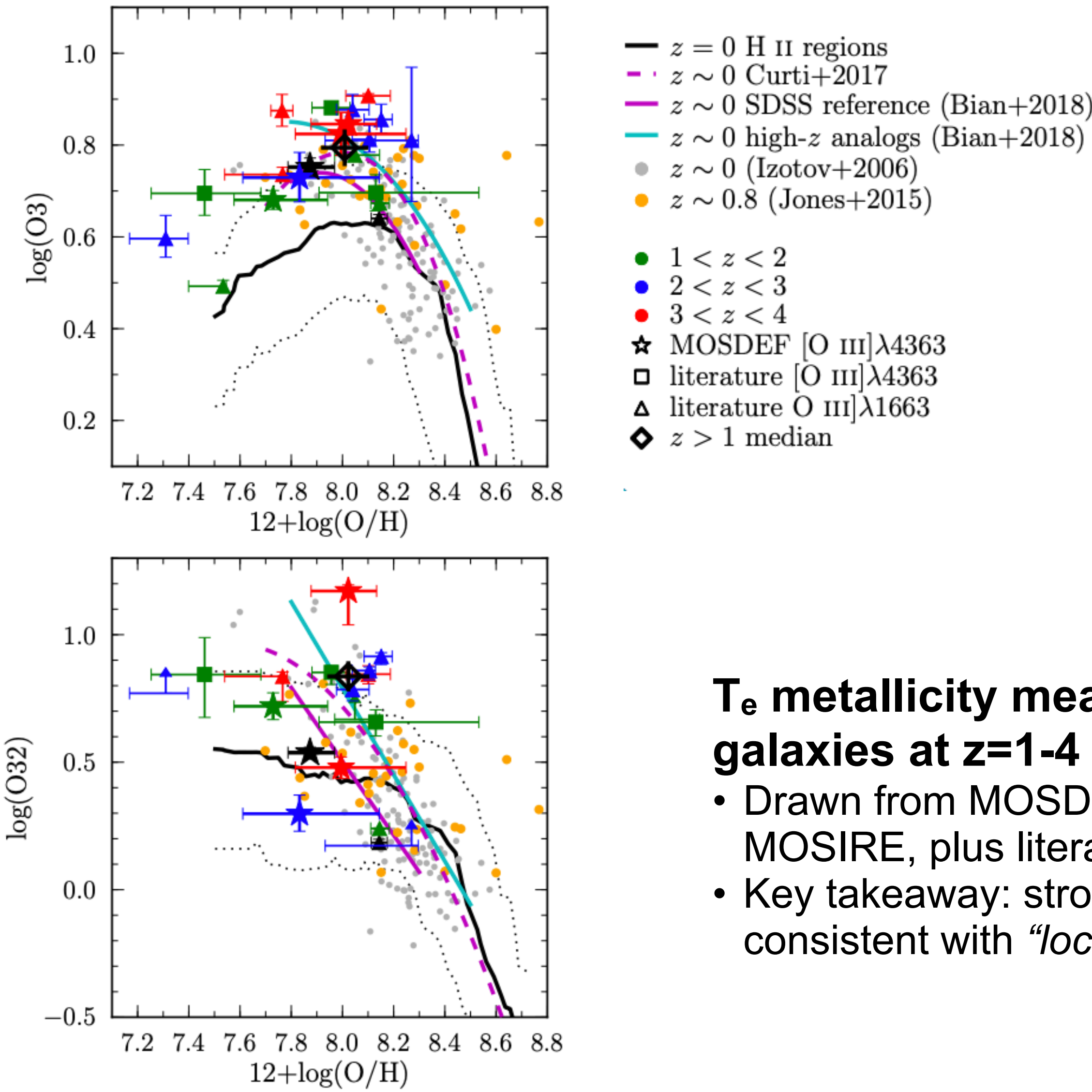


T_e metallicity vs. various emission line ratios

- Consistent with a local z=0 sample of similar excitation properties
- $\Delta\log(O/H) = 0.01 \pm 0.03$

Jones et al. 2015, ApJ, 813, 126

Direct metallicity measurements at z>1



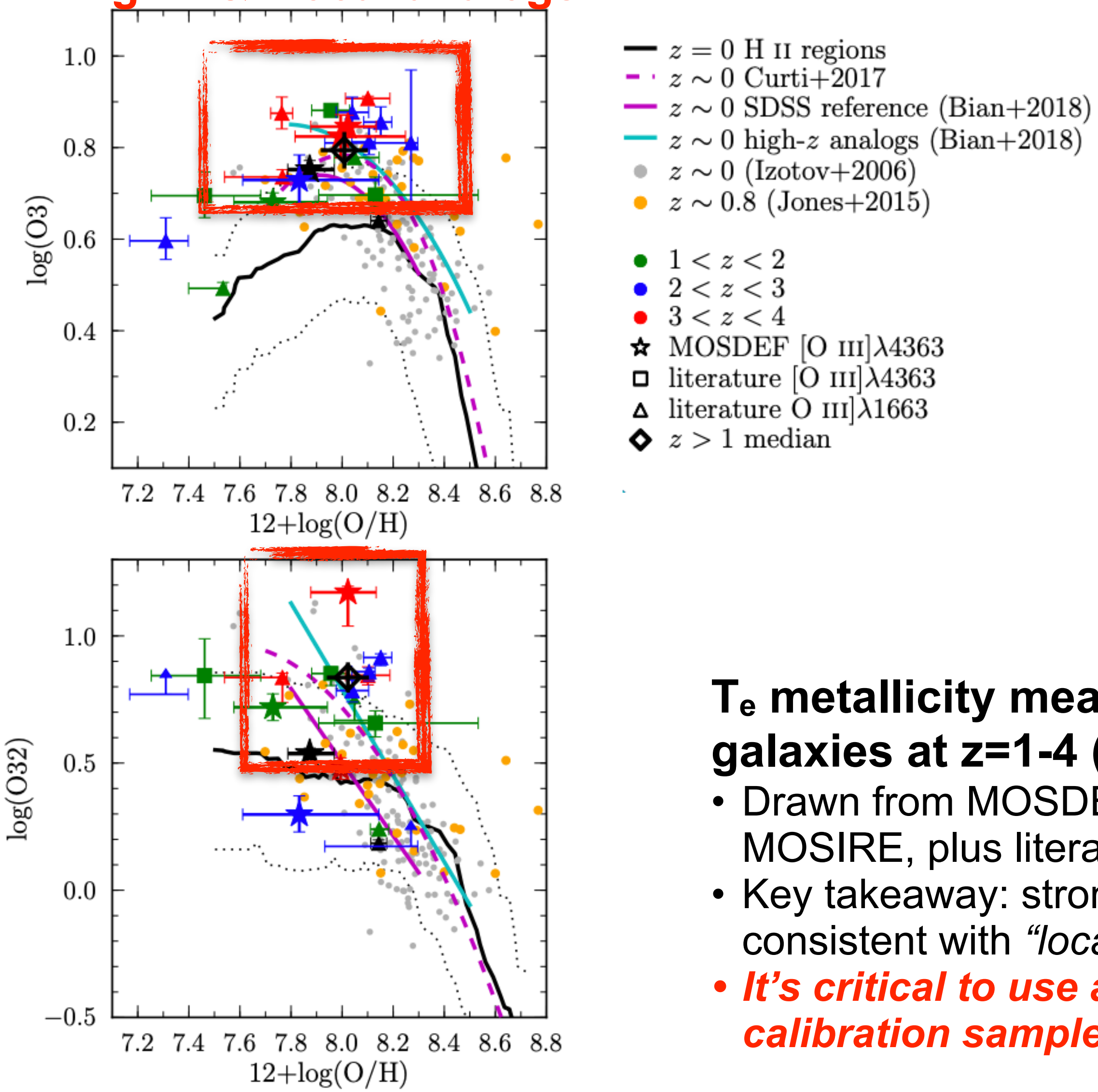
T_e metallicity measurements of 19 galaxies at z=1-4 (Sanders+2020a)

- Drawn from MOSDEF survey with Keck/MOSIRE, plus literature
- Key takeaway: strong-line metallicities are consistent with *"local high-z analog" samples*

Sanders et al. 2020, MNRAS, 491, 1427

Direct metallicity measurements at z>1

High z & "local analogs"



T_e metallicity measurements of 19 galaxies at z=1-4 (Sanders+2020a)

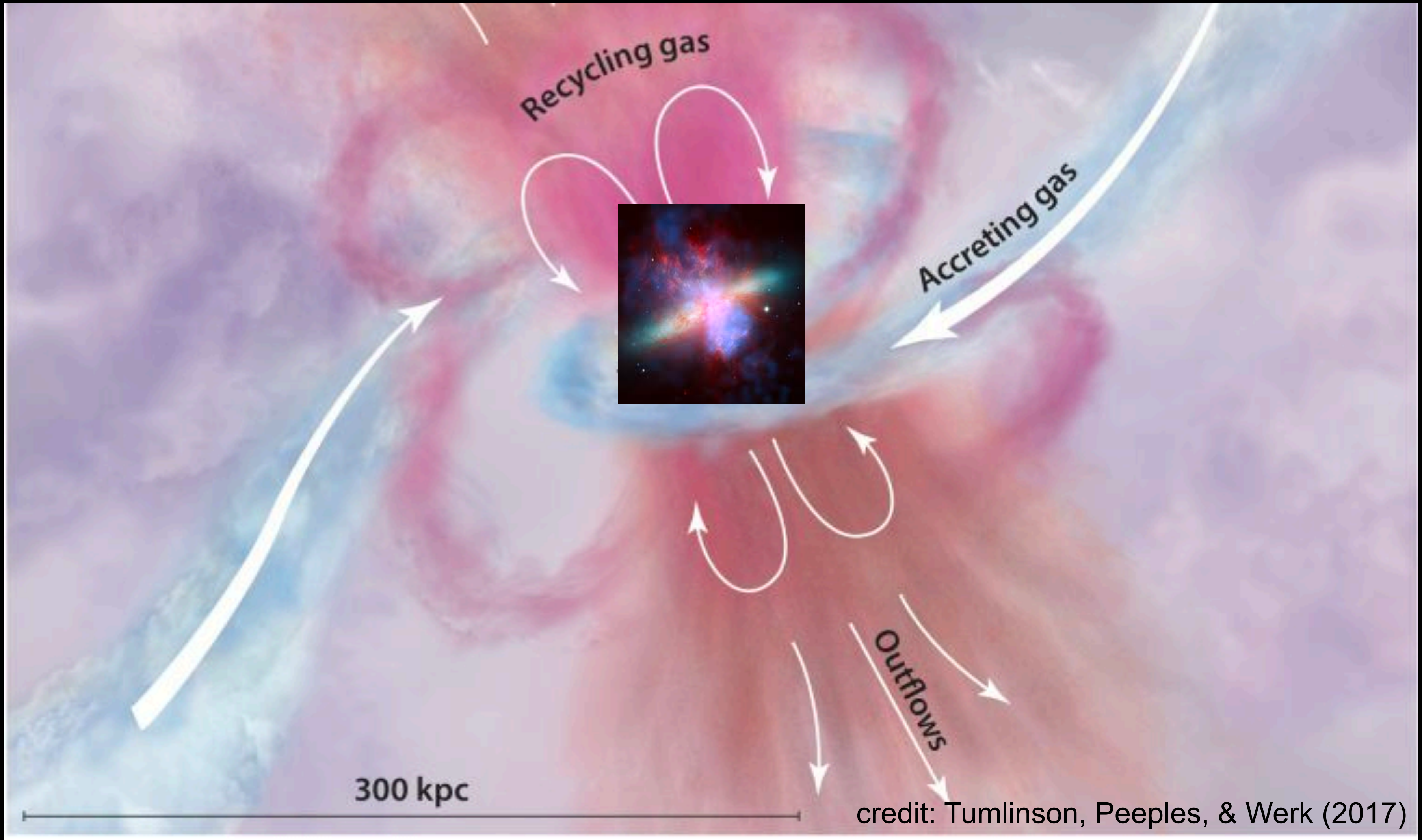
- Drawn from MOSDEF survey with Keck/MOSIRE, plus literature
- Key takeaway: strong-line metallicities are consistent with *"local high-z analog" samples*
- ***It's critical to use an appropriate calibration sample***

Sanders et al. 2020, MNRAS, 491, 1427

Baryons cycle in and out of galaxies through accretion, star formation, and outflows

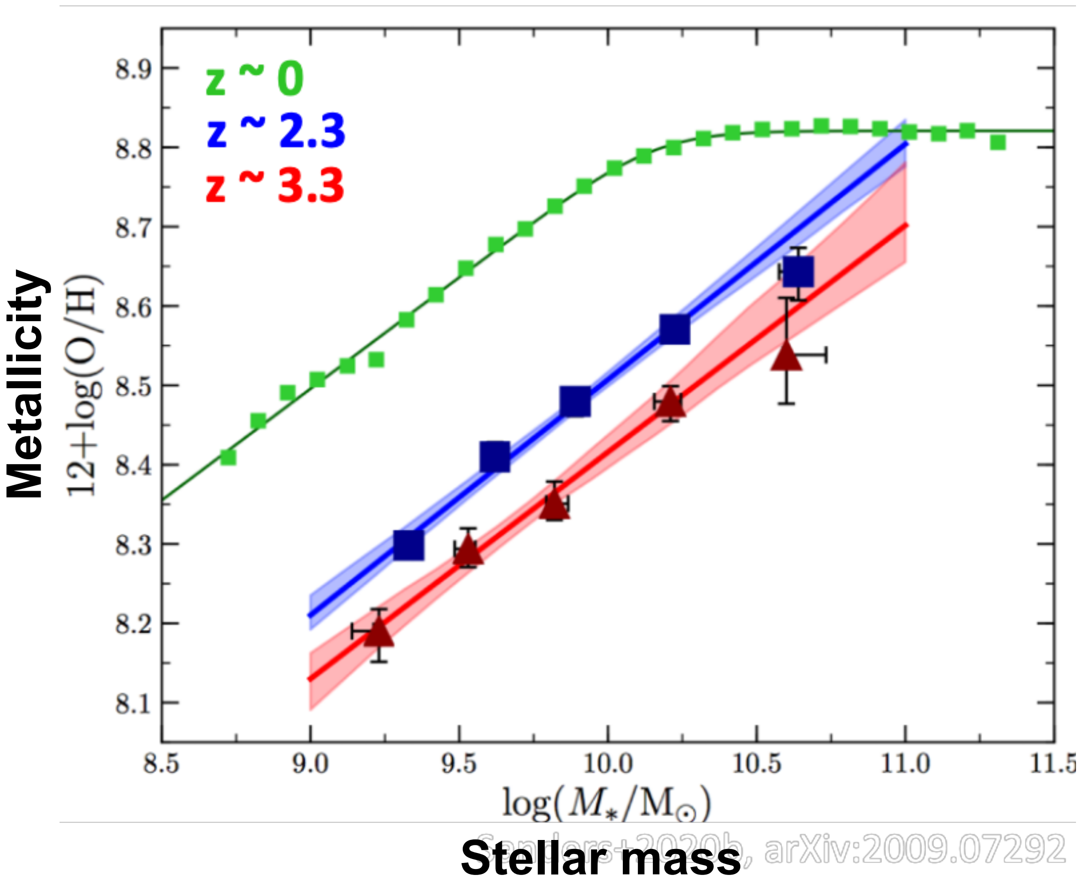
… but the gas flows are difficult to observe

… so we use metallicity to trace these processes!



credit: Tumlinson, Peeples, & Werk (2017)

Evolution in the mass-metallicity relation



Sanders+2020b, arXiv:2009.07292

Galaxies with lower mass have lower gas-phase metallicity

- At lower mass, a larger fraction of heavy elements are ejected in outflows
- Shape of the relation is set by outflow mass loading factor

Galaxies at higher redshift have lower gas-phase metallicity

- Slope of the relation is constant out to z~3.3 (12 Gyr ago)
- Modest evolution at fixed stellar mass:

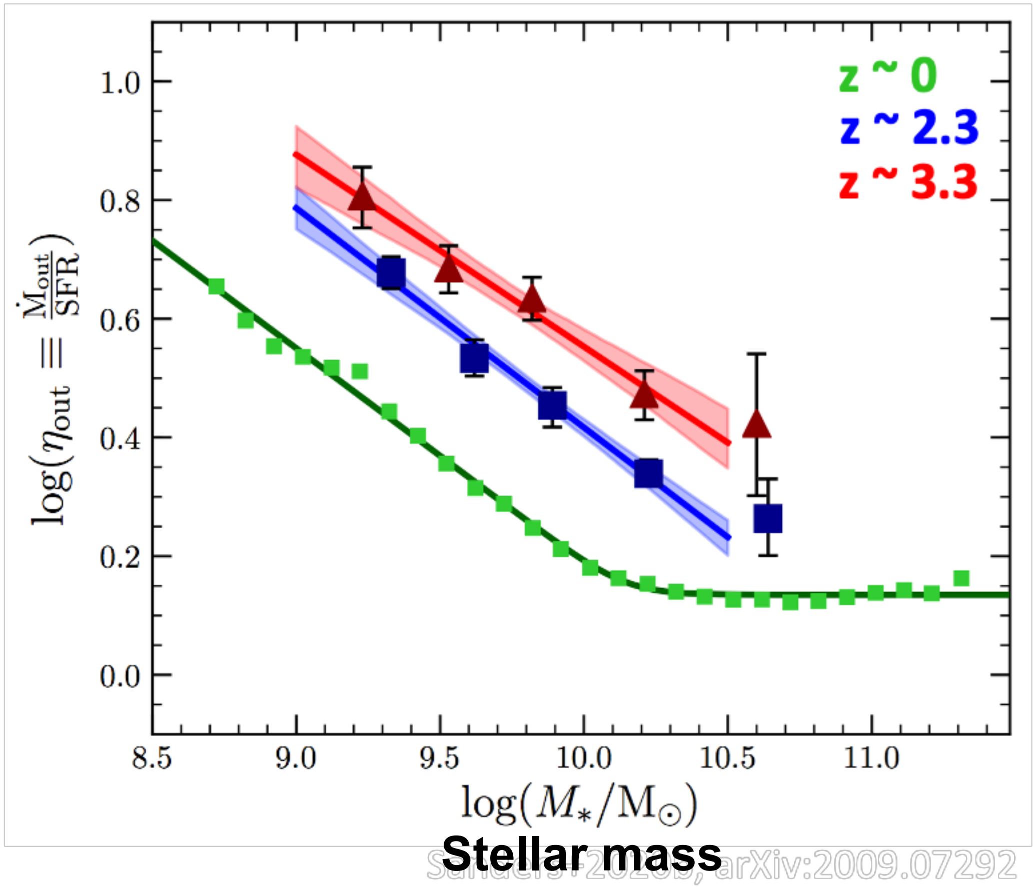
$$\frac{d\log(\mathrm{O/H})}{dz} = -0.11 \pm 0.02$$

NB: Careful metallicity calibrations are essential!

- 1000s of galaxies at z>1 with strong lines, but only ~10 with direct measurements

Sanders et al. 2021, ApJ, 914, 19

Evolution in the outflow properties



Mass loading factor η_{out}

- Ratio of outflow mass loss rate to star formation rate:

$$\eta_{out} = \frac{\dot{M}_{out}}{\mathrm{SFR}}$$

Mass loading factor increases with redshift (at fixed stellar mass)

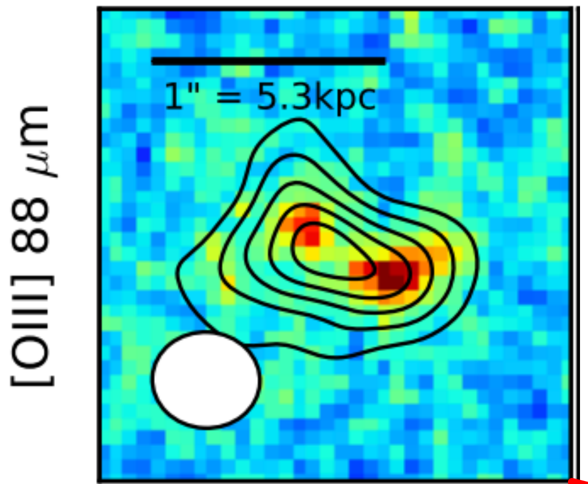
- Gas and heavy elements are removed more efficiently at higher z

Lower metallicities at high redshift are driven by:

- Larger gas fractions (less production of metals by stars)
- Larger mass loading factors (removal of heavy elements)

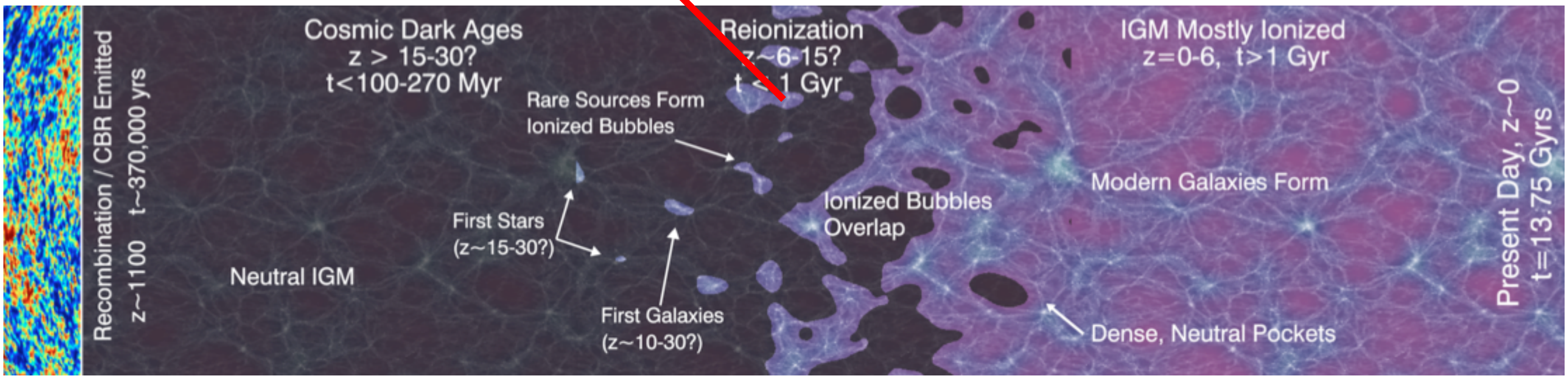
Sanders et al. 2021, ApJ, 914, 19

Buildup of heavy elements in the first billion years



Hashimoto et al. 2019

z = 7.15
t = 750 Myr



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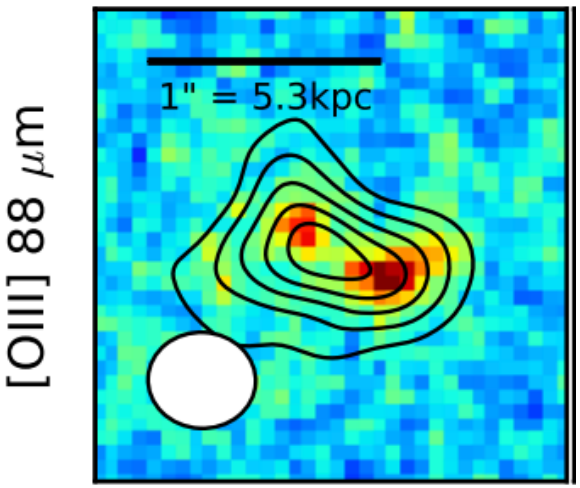
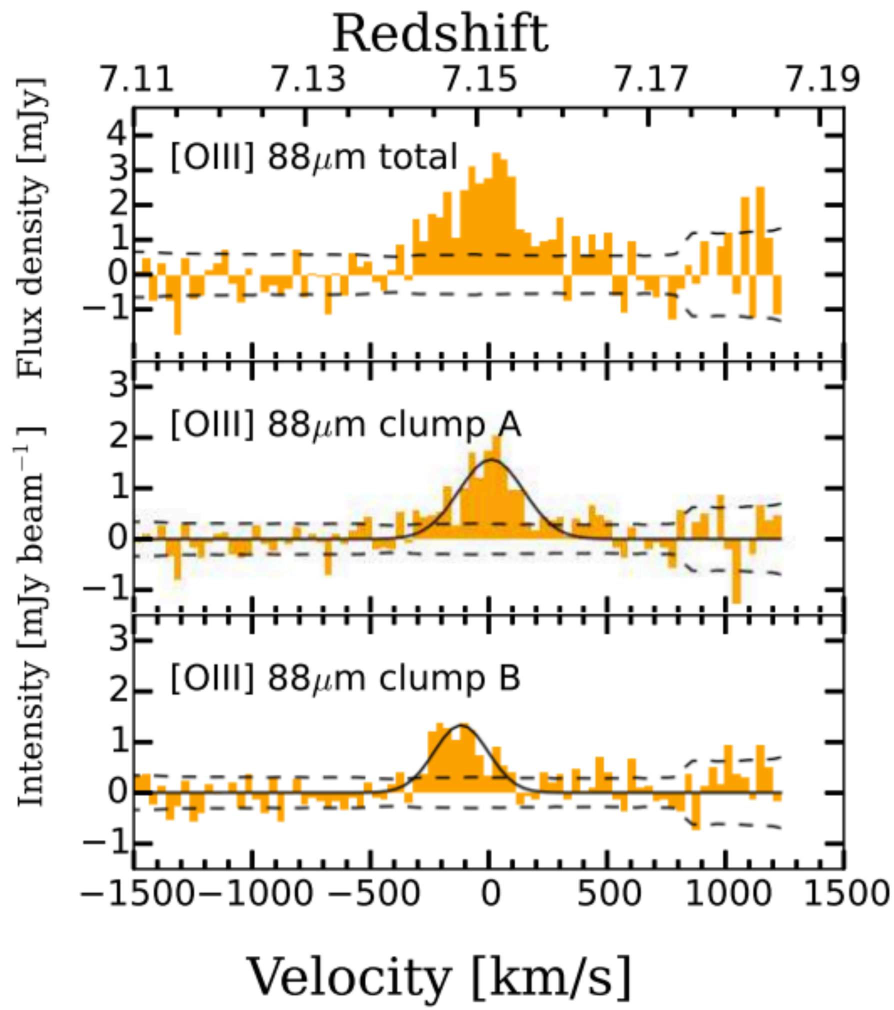
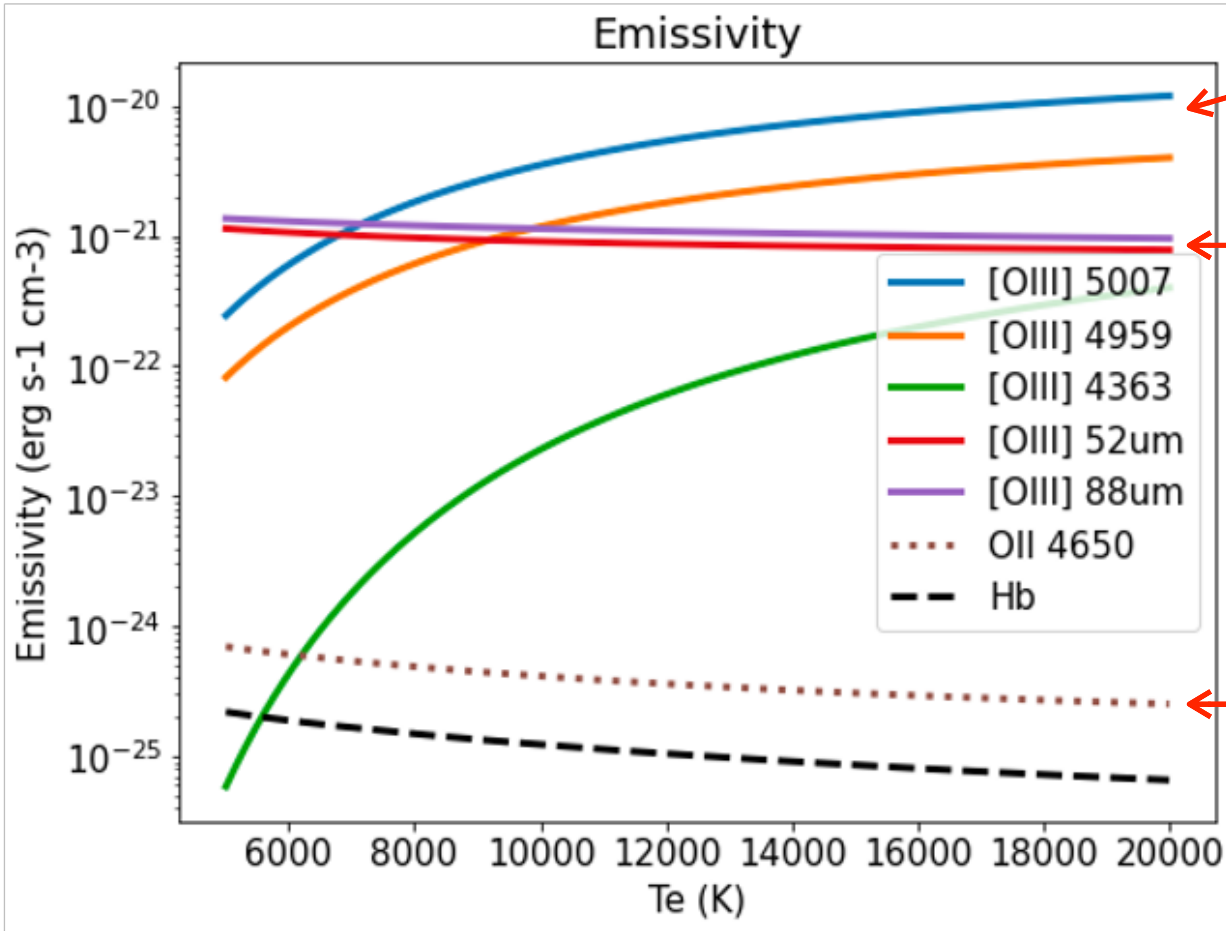




Hashimoto et al (2019): Strong [O III] emission from a galaxy at z=7.15 (only 750 Myr after the Big Bang)!

Hashimoto et al. 2019

Metallicity with infrared [O III] lines

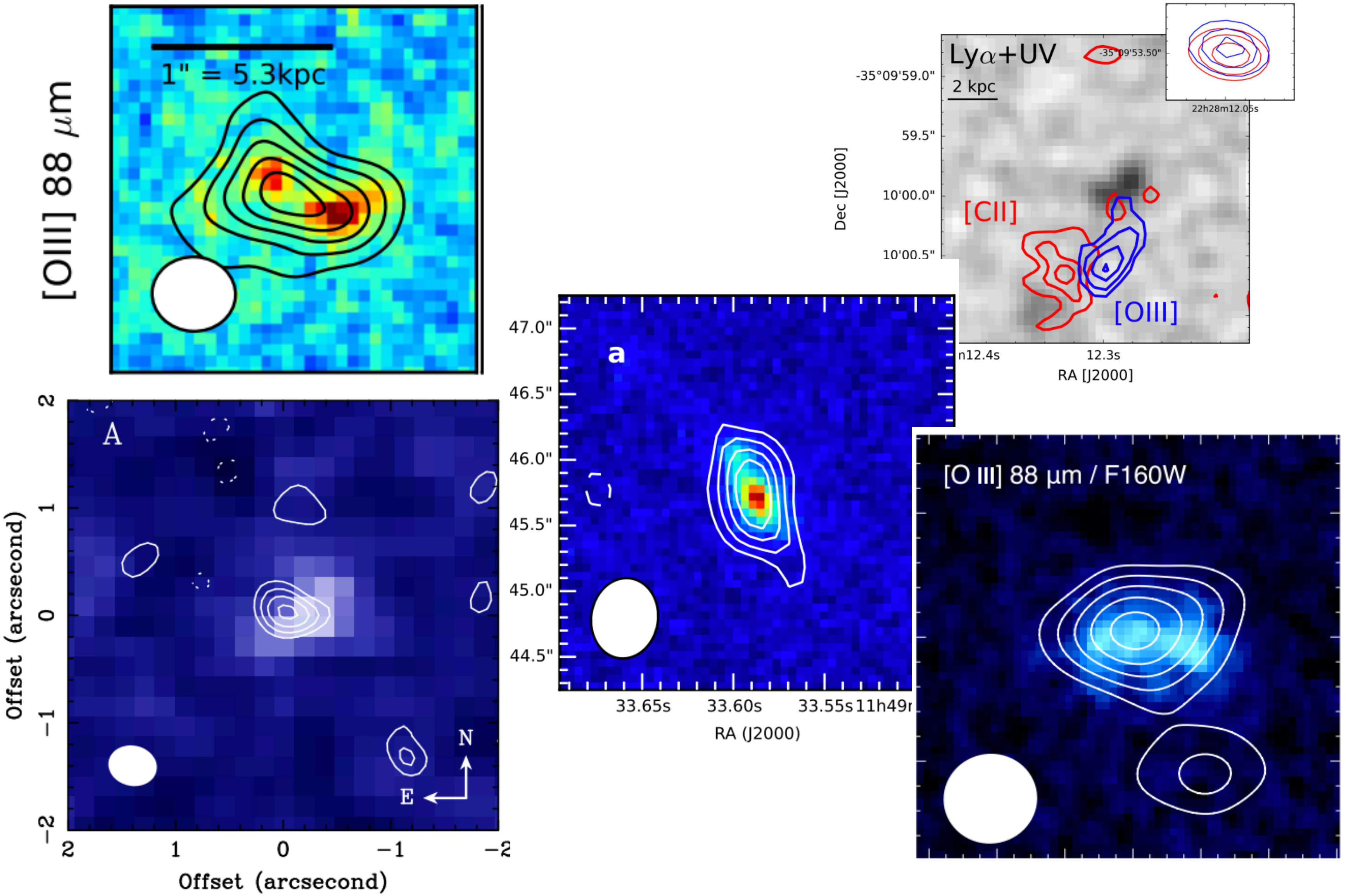


Optical strong lines:
highly sensitive to Temperature

IR lines:
scale with abundance!
(insensitive to T)

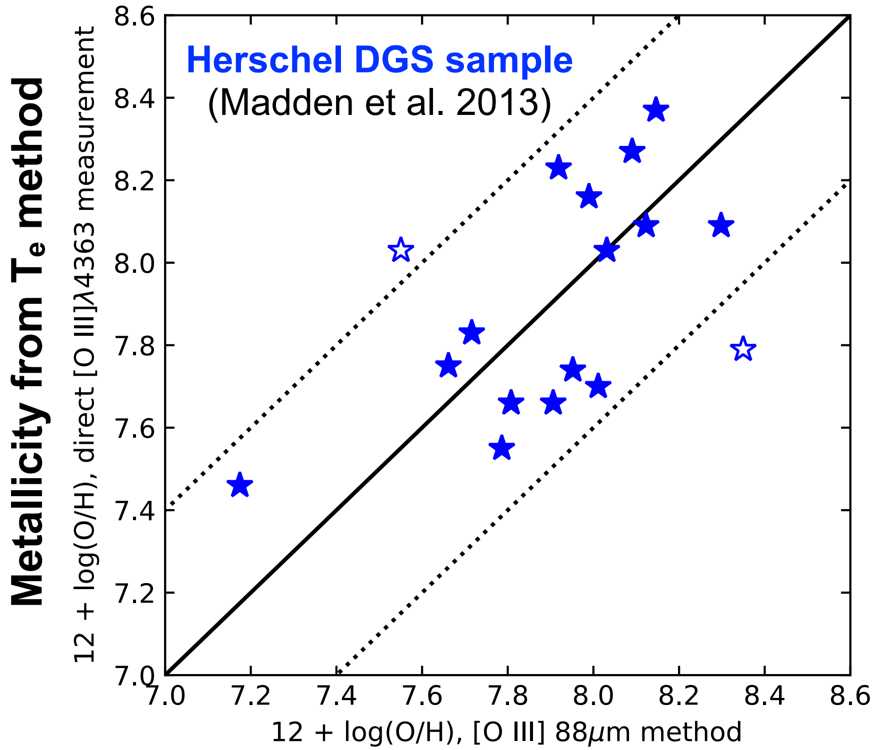
Recombination lines:
insensitive to T, but weak

ALMA detections of [O III] lines at z>7



Inoue et al. (2016); Carniani et al. (2017); Hashimoto et al. (2018, 2019); Tamura et al. (2019)

Aside: verifying the method with a z=0 sample



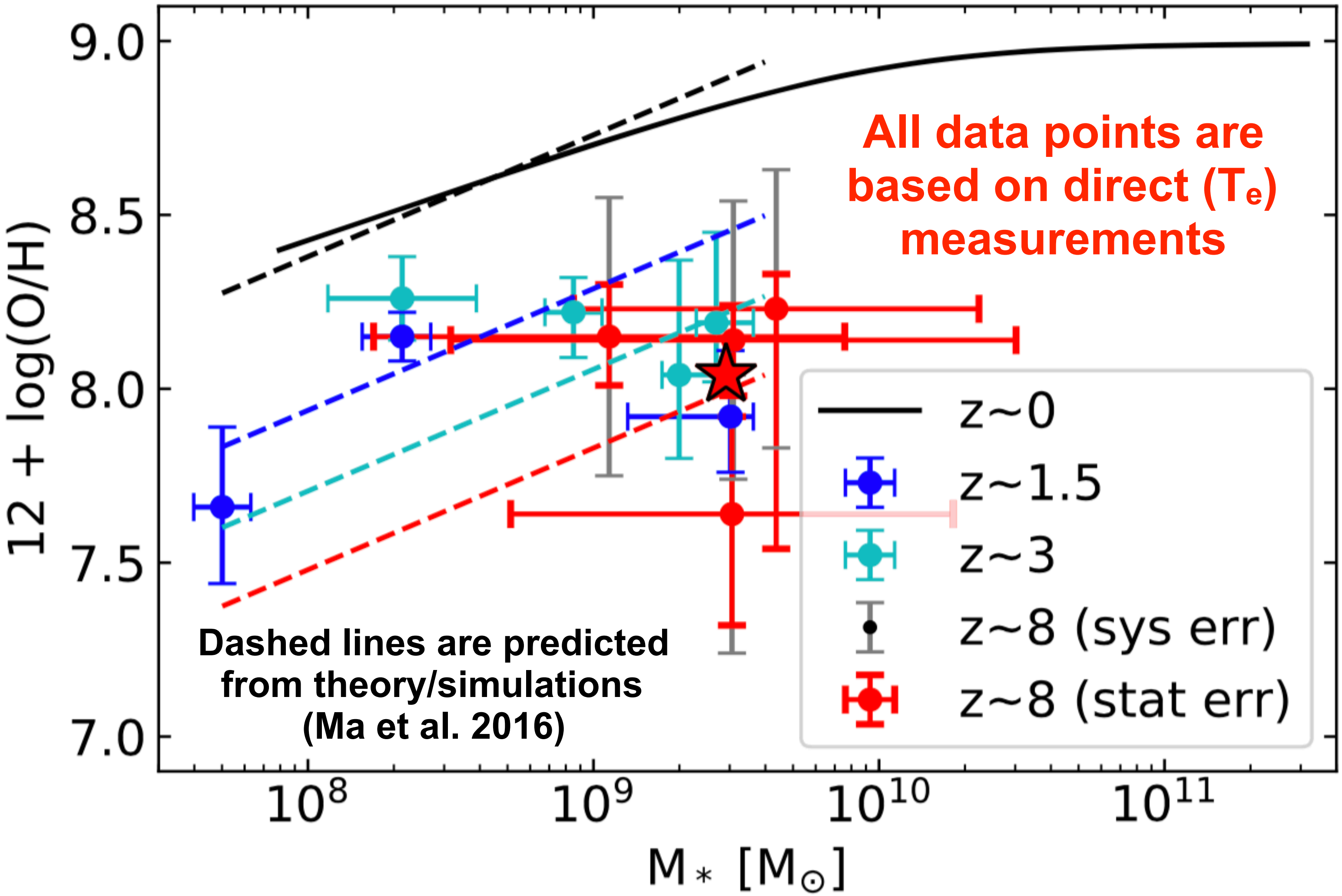
Good agreement!
0.2 dex scatter (1σ)
10% outliers

Methodology: combine [O III] 88 μm flux and SFR

- O^{++} abundance from [O III] emission
- H^{+} abundance estimated from SFR (proxy for H I recombination flux)
- Range of values considered for density, temperature, ionization, etc
  - Conservative range results in ~0.4 dex systematic uncertainty in O/H
  - Validated with z~0 galaxy samples which show only 0.2 dex scatter!
- *JWST will provide ~0.1 dex precision at z>6!! (Cycle 1 program ID 01657, PIs: Harikane & Sanders)*

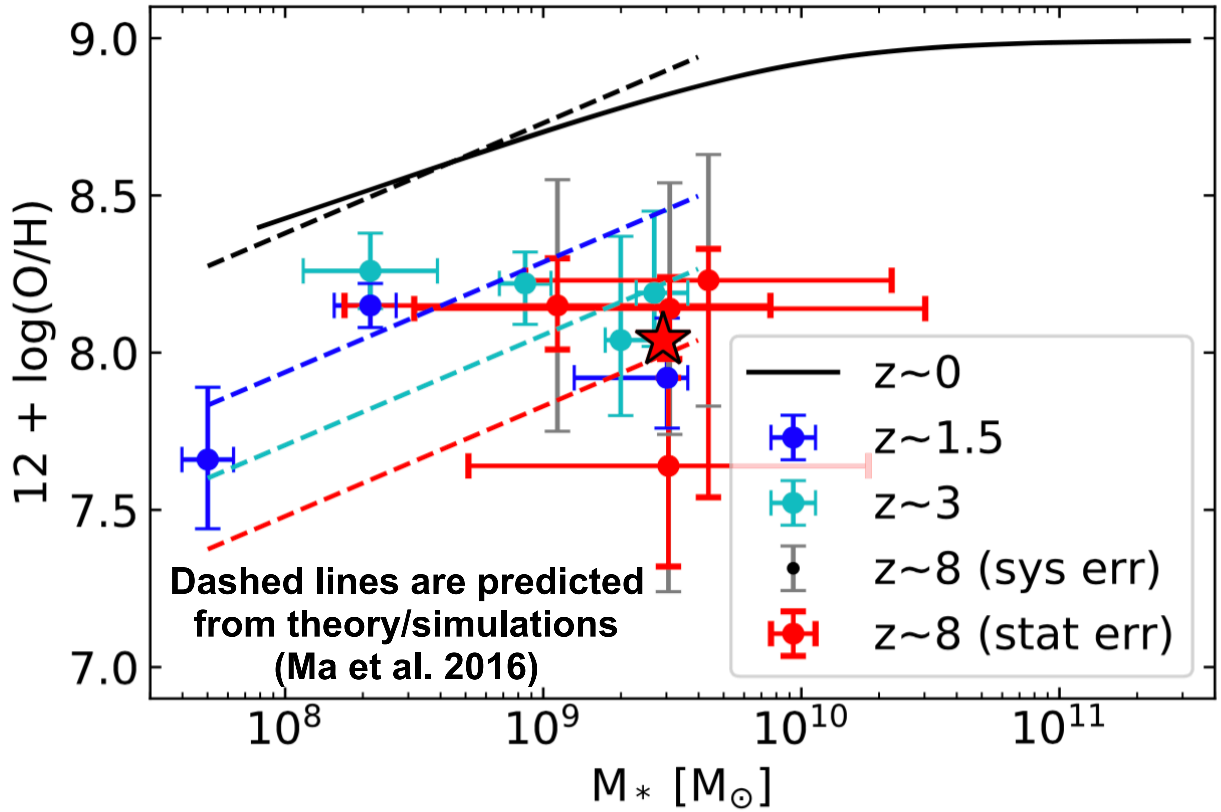
Jones et al. 2020, ApJ, 903, 150

Chemical evolution up to z=8 !!



Jones et al. 2020, ApJ, 903, 150

Chemical evolution up to z=8 !!



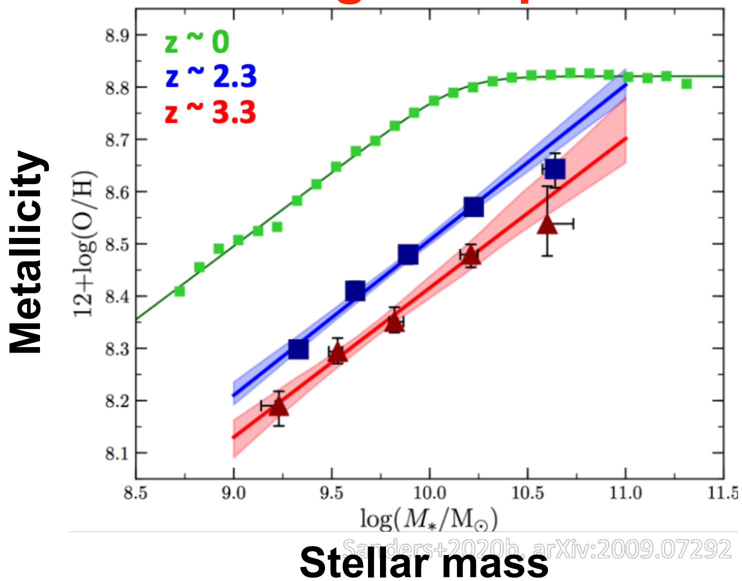
T_e metallicity measurements of 6 galaxies at z = 7 - 9

- Metallicity shows little evolution at z>3, at fixed mass
  - (but currently there is considerable systematic uncertainty)
  - (some do not have reliable stellar masses — awaiting JWST)
- In agreement with simulations, where small evolution results from relatively constant gas fractions
- Metallicities > 10% solar imply previous enrichment over ~100 Myr or more

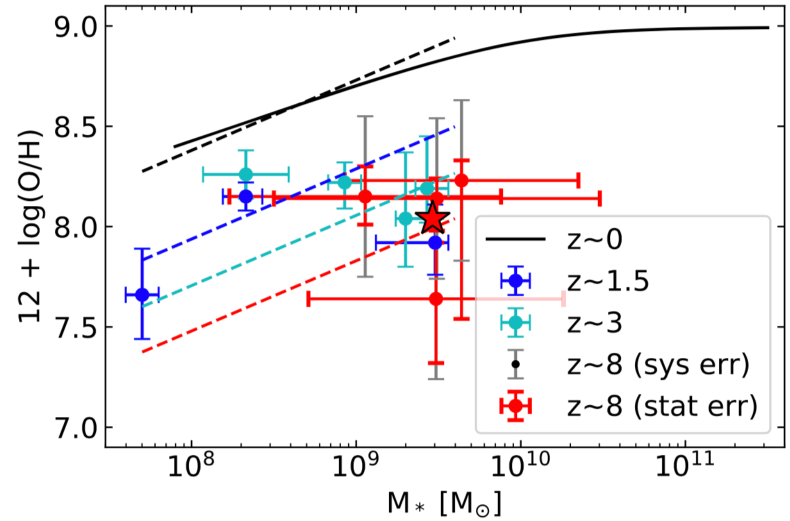
Jones et al. 2020, ApJ, 903, 150

Recap: chemical evolution up to z=8

Large samples



Direct measurements



Chemical evolution probes galaxy assembly & baryon cycle

- Scaling of gas inflows & outflows, with large samples up to z<4

Growing sample of direct T_e metallicity measurements at z=1-4

- Challenging, but essential for reliable chemical evolution results!
  - JWST Cycle 1 programs will dramatically enlarge current samples

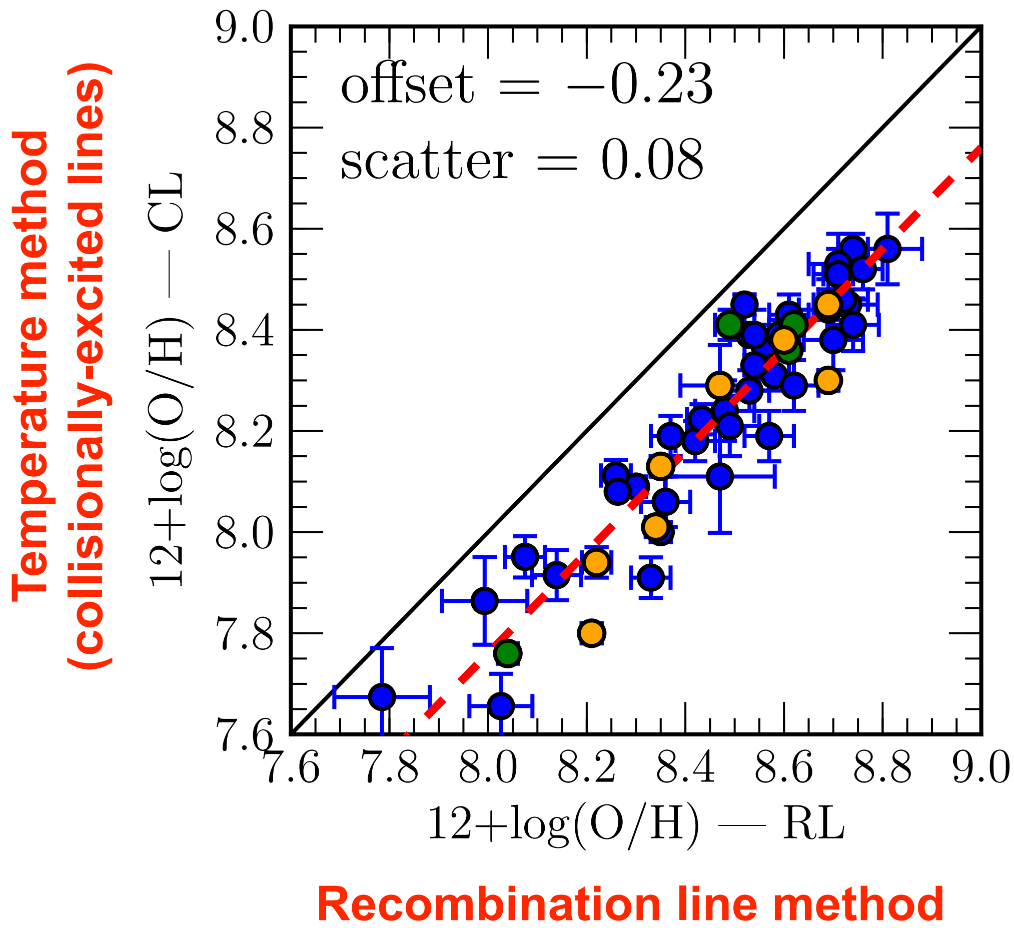
First glimpse of metallicity (with direct T_e method!) at z>7

- Metallicity from IR [O III] lines from ALMA; little evolution from z=3 to 8
- Chemical enrichment suggests significant past star formation (z>10)

What is the true metallicity scale?

How many heavy elements are there in the universe?

The Abundance Discrepancy Factor (ADF)



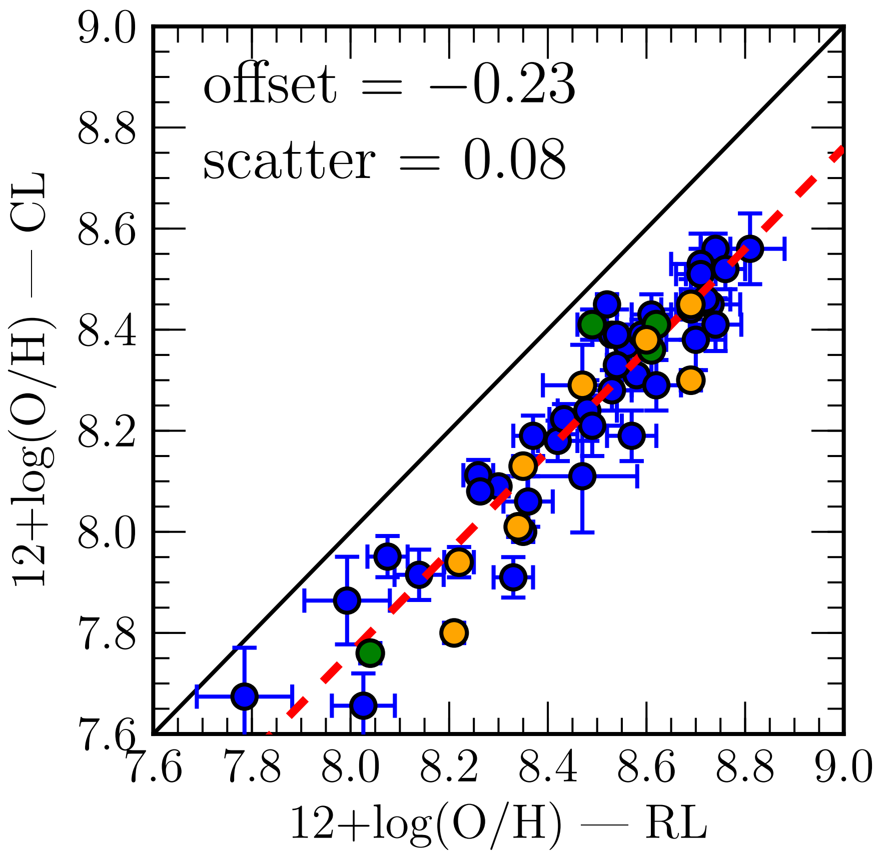
Direct measurements of metallicity with different methods give different results

- This is the ADF = abundance discrepancy factor
- RL metallicities are higher by a factor of nearly 2!
- Relatively small scatter, but large systematic offset

NB: relative measurements are still reliable. Chemical evolution results shown previously are still valid!

The Abundance Discrepancy Factor (ADF)

Temperature method (collisionally-excited lines)

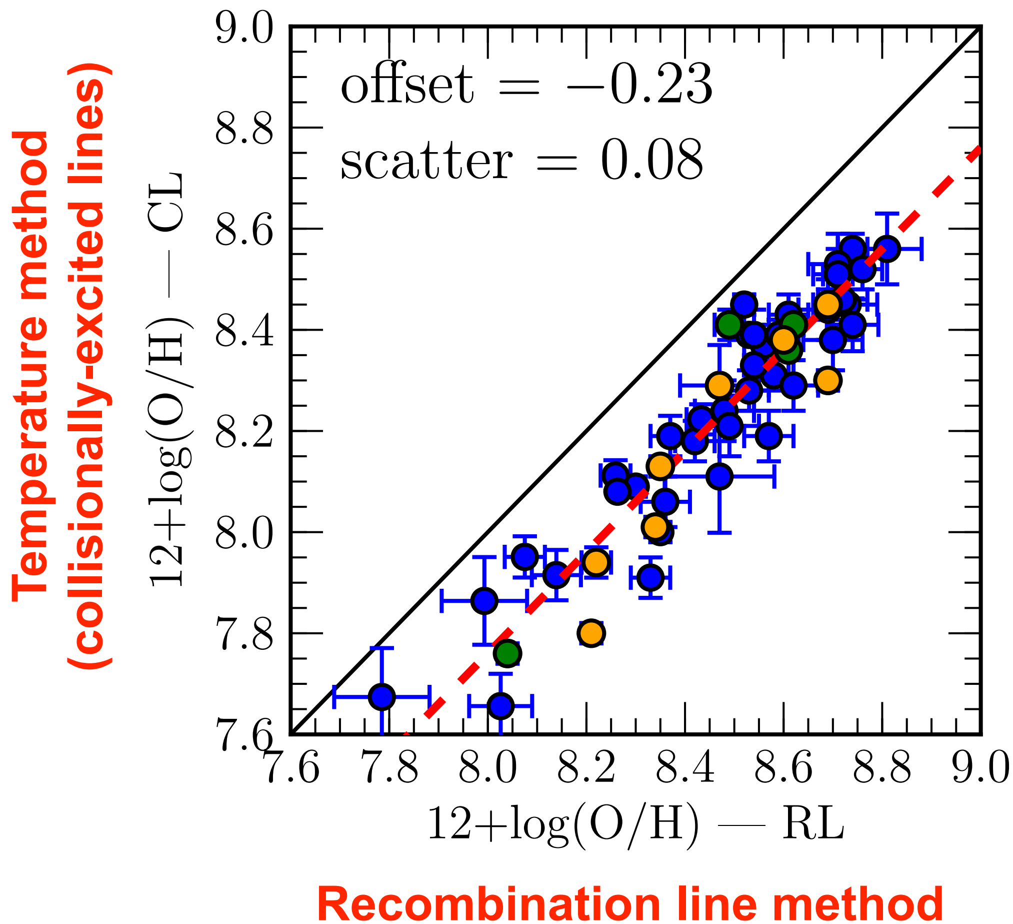


Recombination line method

NB: relative measurements are still reliable. Chemical evolution results shown previously are still valid!

Key test: [O III] infrared lines are *insensitive to temperature*.
These enable a "T_e" measurement, but without the potential bias from temperature fluctuations. *[O III] 52 μm line is the best tracer of metallicity!*

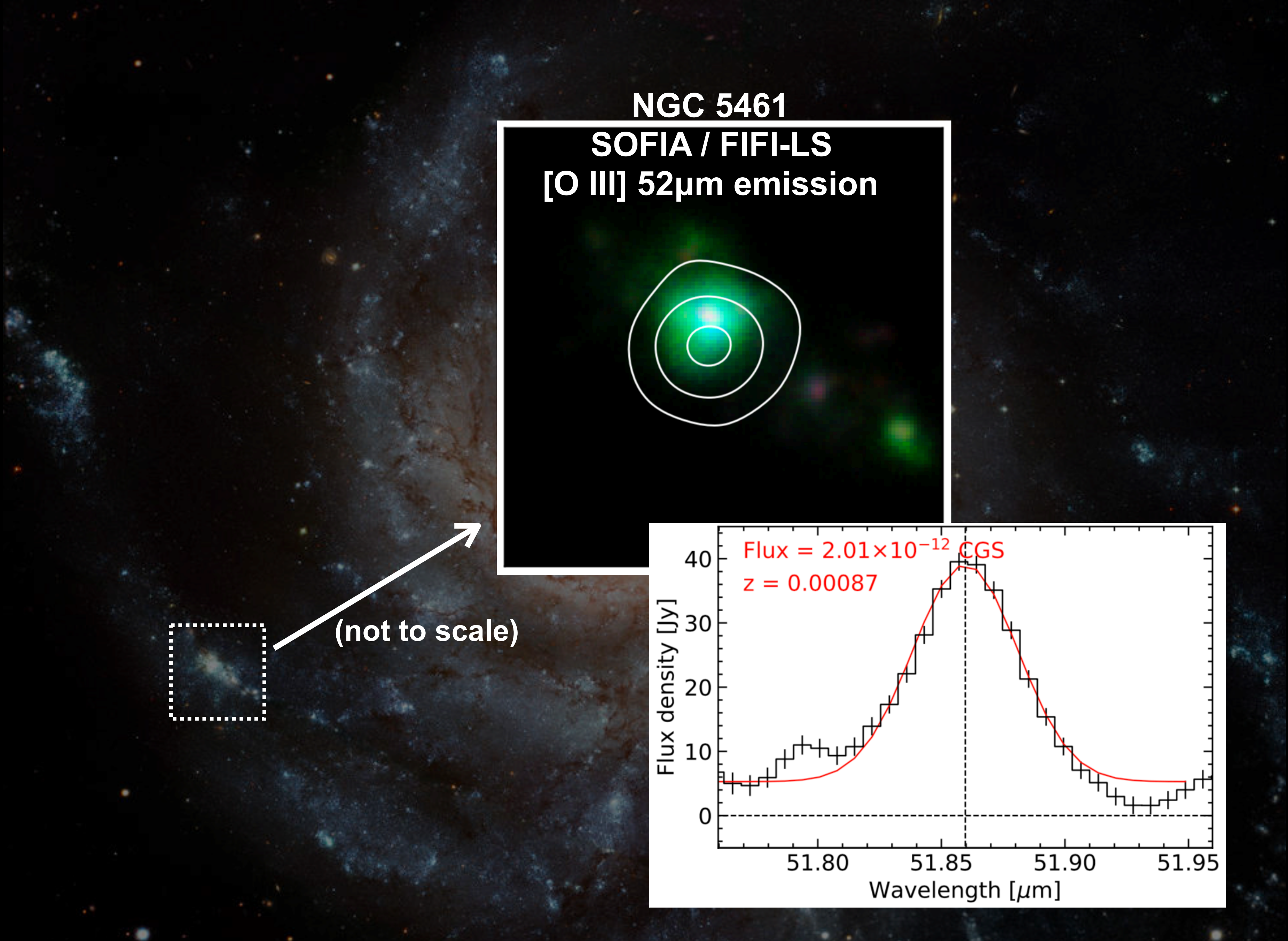
The Abundance Discrepancy Factor (ADF)



Hypothesis

- If temperature fluctuations cause the ADF, then far-IR based measurements should be *higher than Te method* (from optical), and *in agreement with RL result*
  - RL measurements would be correct, and CEL biased low
- Far-IR lines should accurately trace the true gas-phase metallicity

Credits: NASA, ESA, K. Kuntz (JHU), F. Bresolin (University of Hawaii), J. Trauger (Jet Propulsion Lab), J. Mould (NOAO), Y.-H. Chu (University of Illinois, Urbana) and STScI



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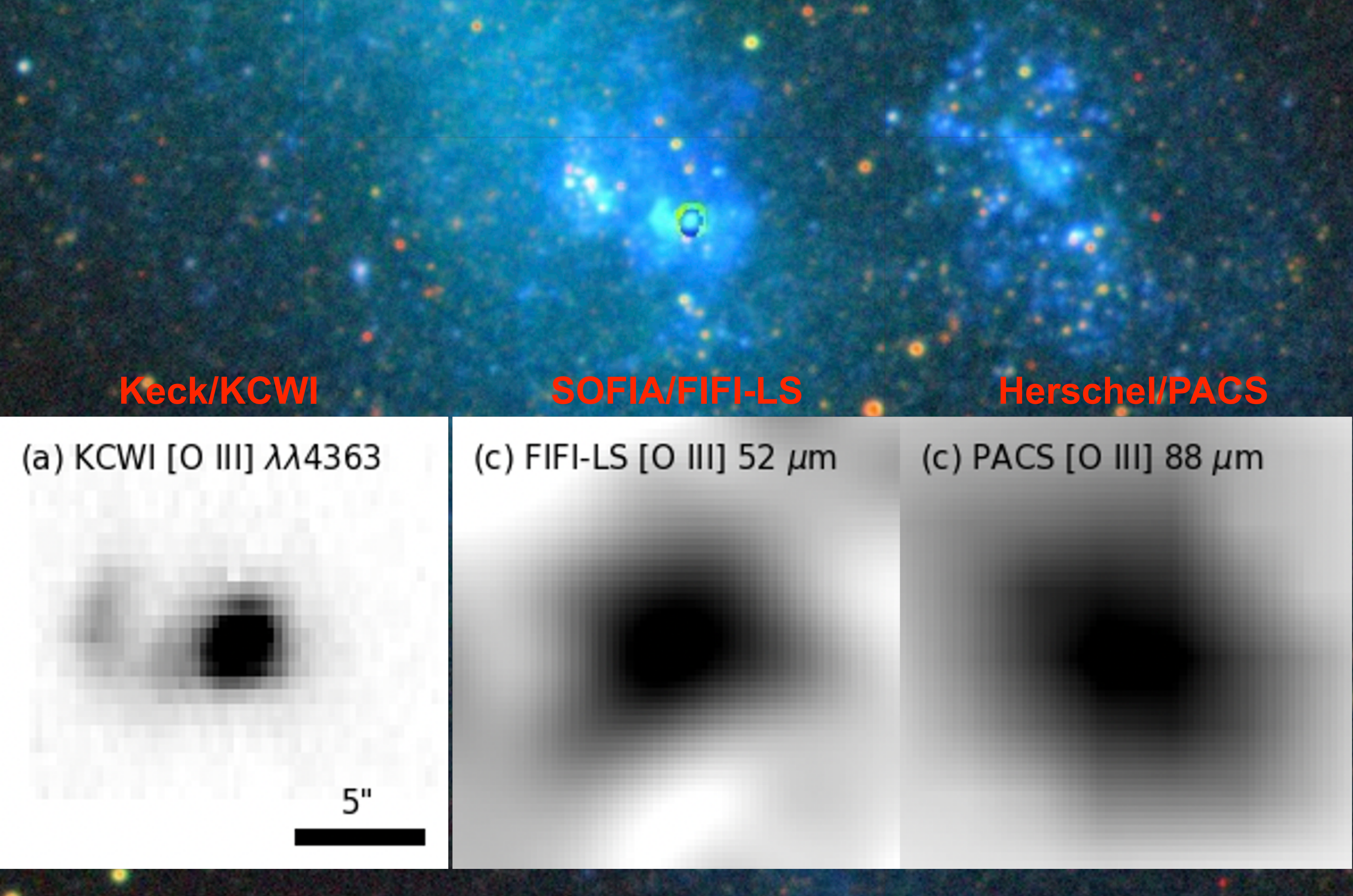
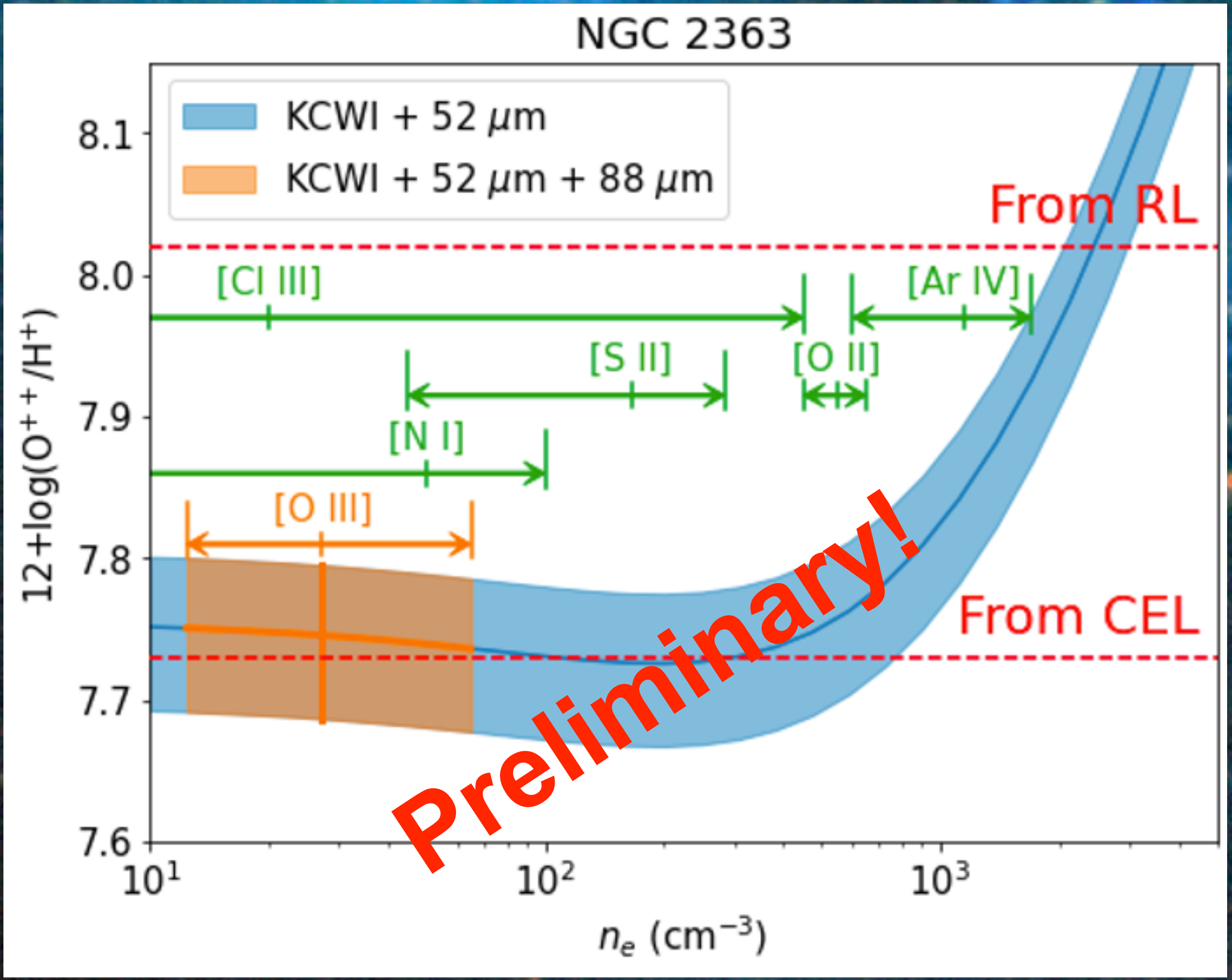
Example target: NGC 2363



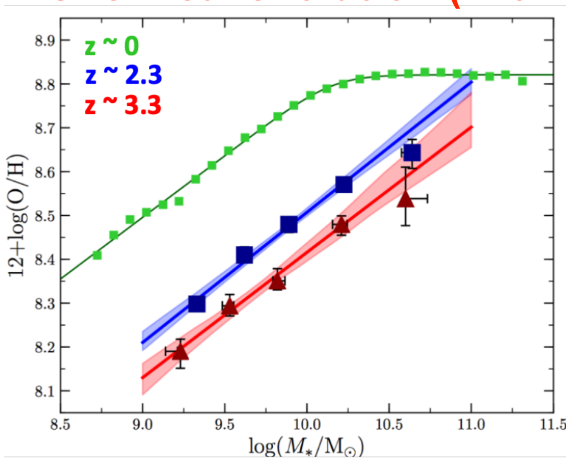
Example target: NGC 2363



Initial results do not reconcile the different methods.
We are looking into further possible systematics…

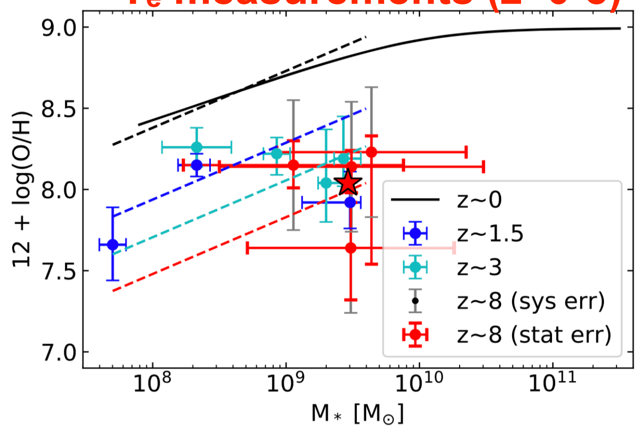
Summary

Chemical evolution (z=0-4)

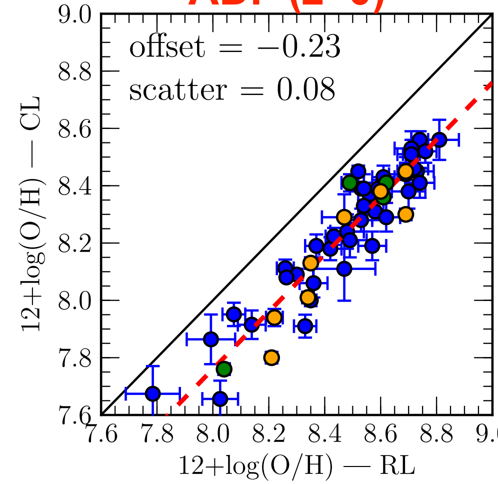


Sanders+2020b, arXiv:2009.07292

T_e measurements (z=0-8)



ADF (z=0)



Galaxy assembly revealed by chemical evolution at high z

- Gas content, inflow and outflow rates with large samples
  - … including the first glimpse at z=8
- Modest and growing samples of direct (T_e) measurements at z = 0.8 - 4
- Appropriate strong-line calibrations validated for use at high z

Prospects for establishing the absolute abundance scale

- Far-IR lines enable a critical test of systematic uncertainties
- Distinguish between the T_e vs recombination line methods
  - … and use results to calibrate all methods to same absolute scale