The Rise of Metals across Time and Space, and High-Redshift Perspectives on SOFIA

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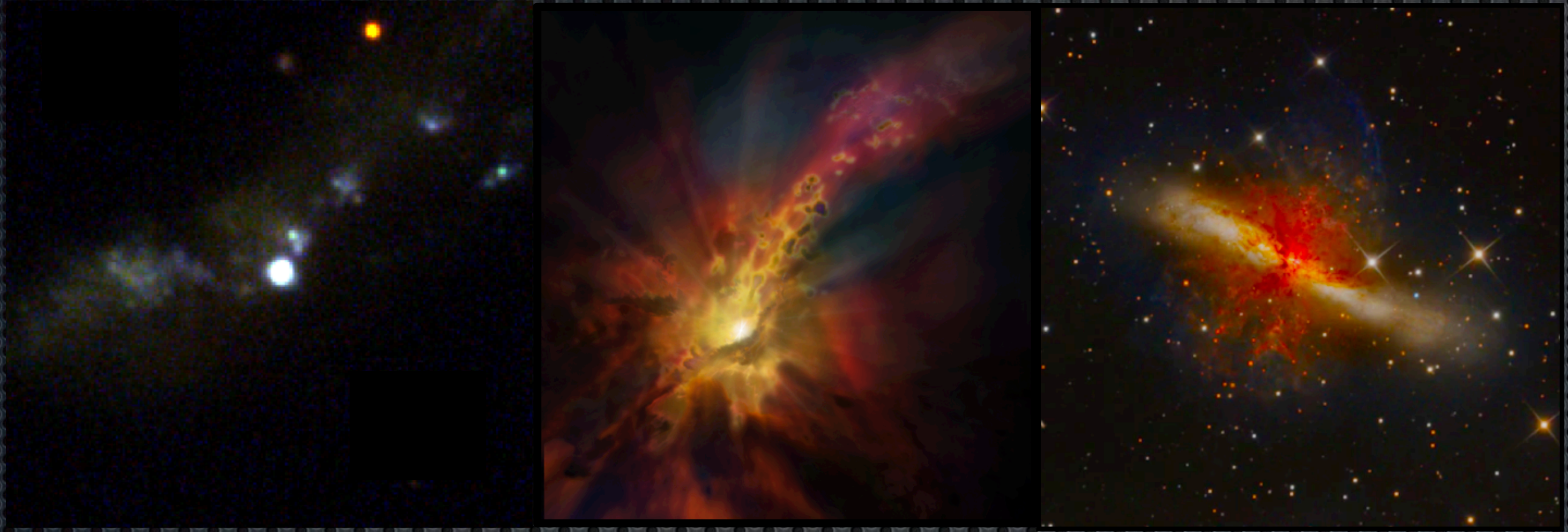
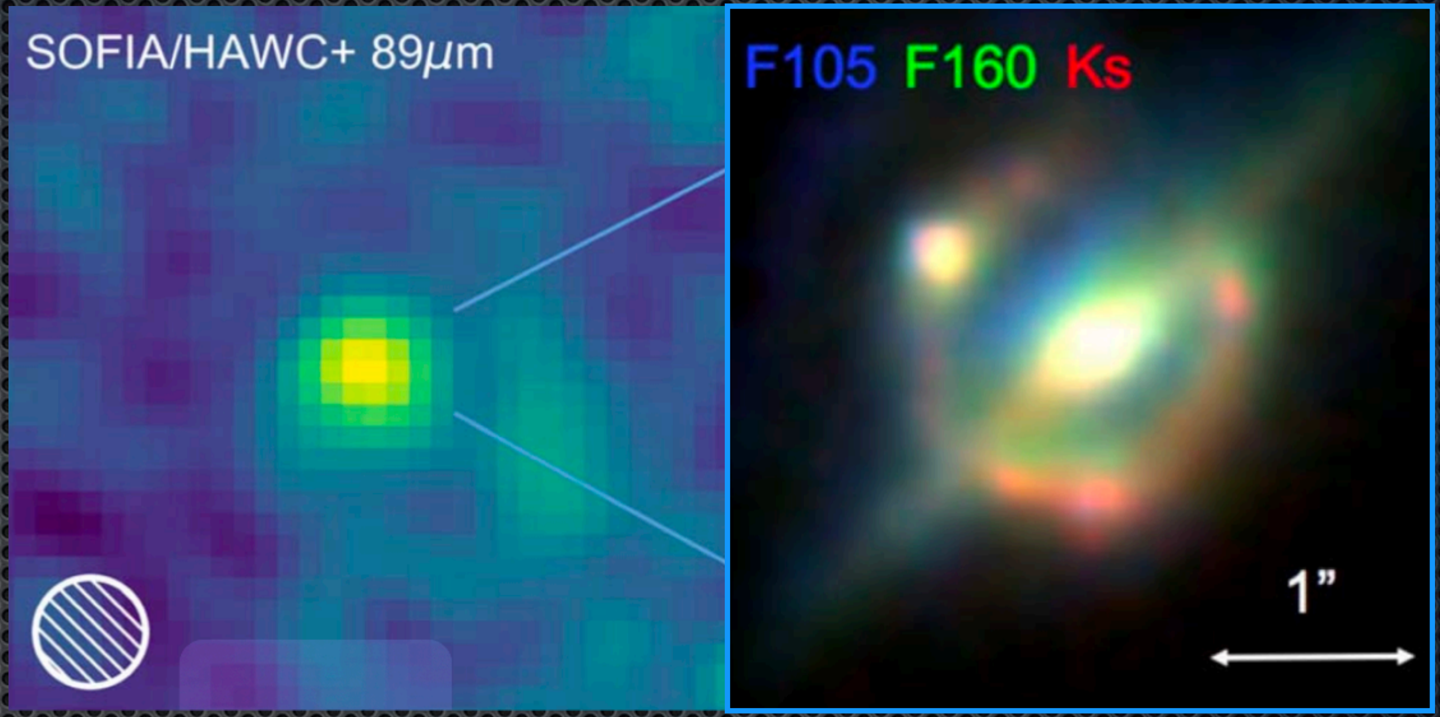


Students: Rebecca Levy (Maryland), *Jack Saha (Texas), Gabriella Sanchez (UH-Manoa)*, Peter Senchyna (Arizona), Liz Tarantino (Maryland)

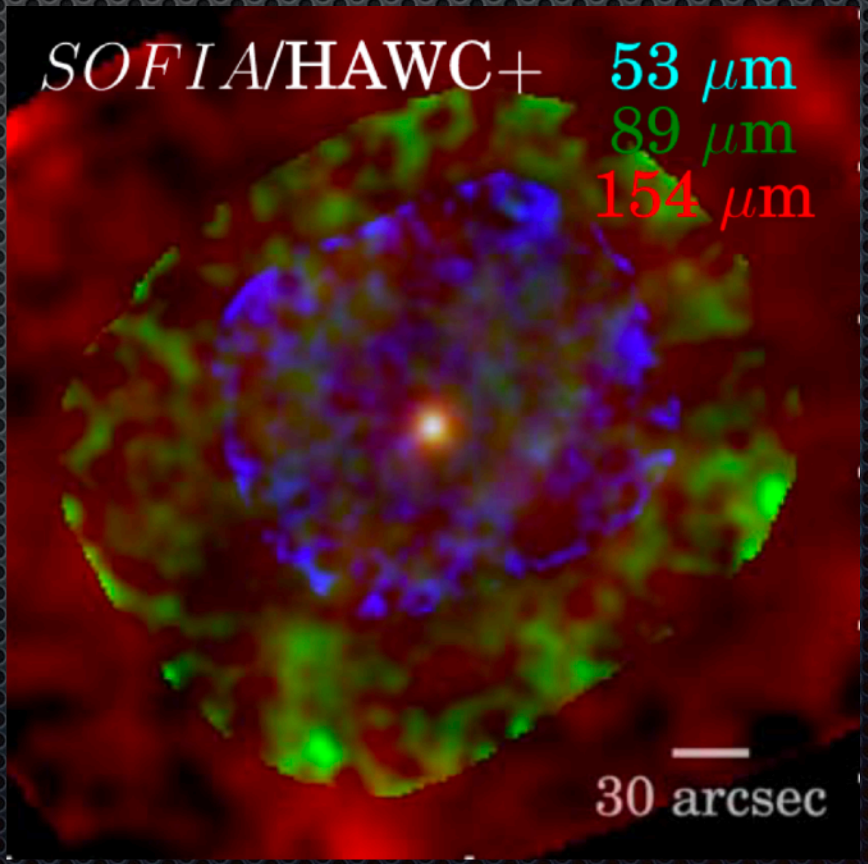
Also with Alberto Bolatto, Adam Leroy, Tucker Jones, Dan Marrone, Karin Sandstrom, Dan Stark, Ben Weiner

Sensitivity is the key limiting factor for *real* high-redshift work with SOFIA

- HAWC+ observations of rest-frame mid-IR in z~1 and z~4 lensed quasars
- Constrain buried AGN by detecting the hot dusty torus
- Both these targets have $L_{IR} \sim 10^{15} L_{sun}$
  - There just aren't that many targets amenable to these observations!



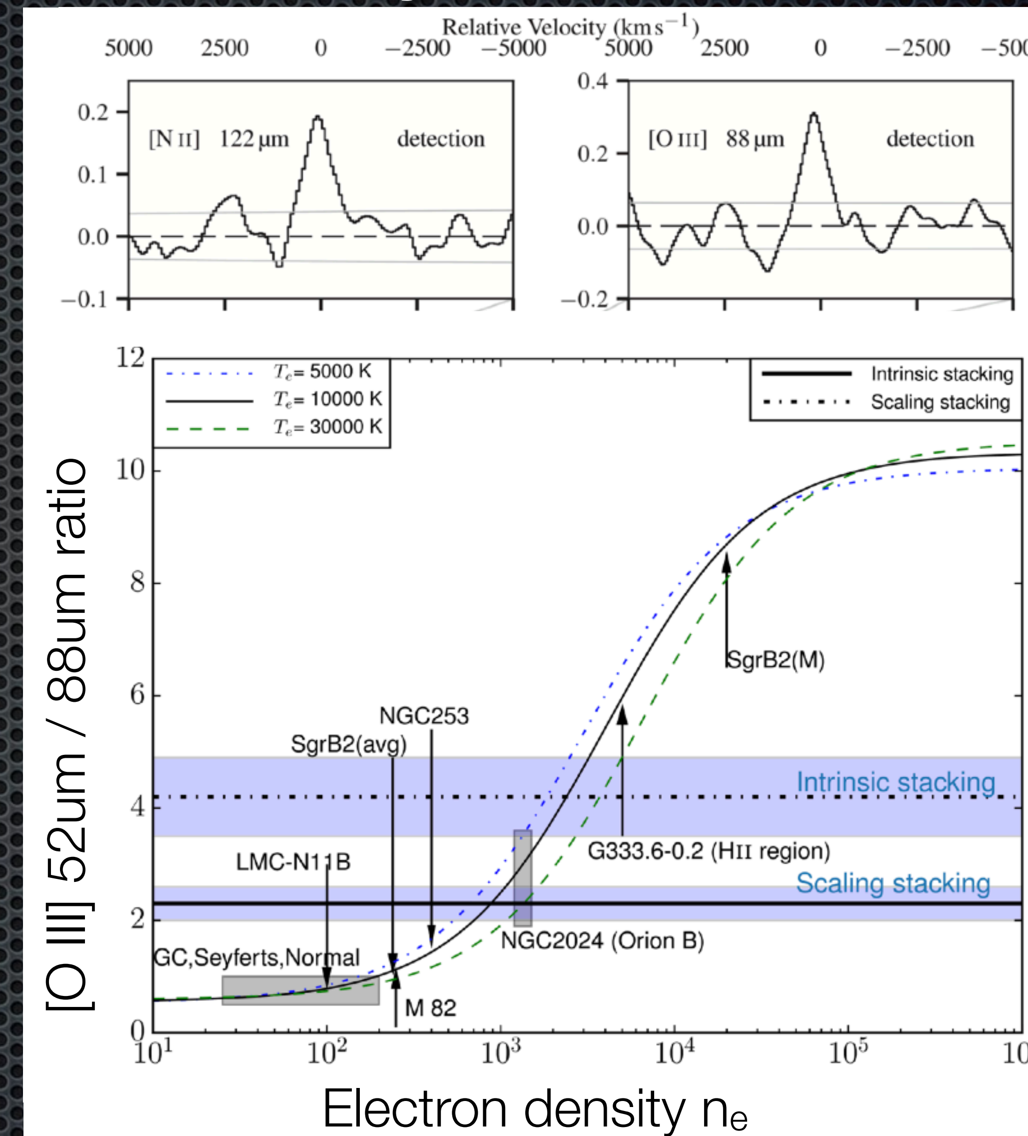
J. Ma + 2018
z=1 lensed quasar



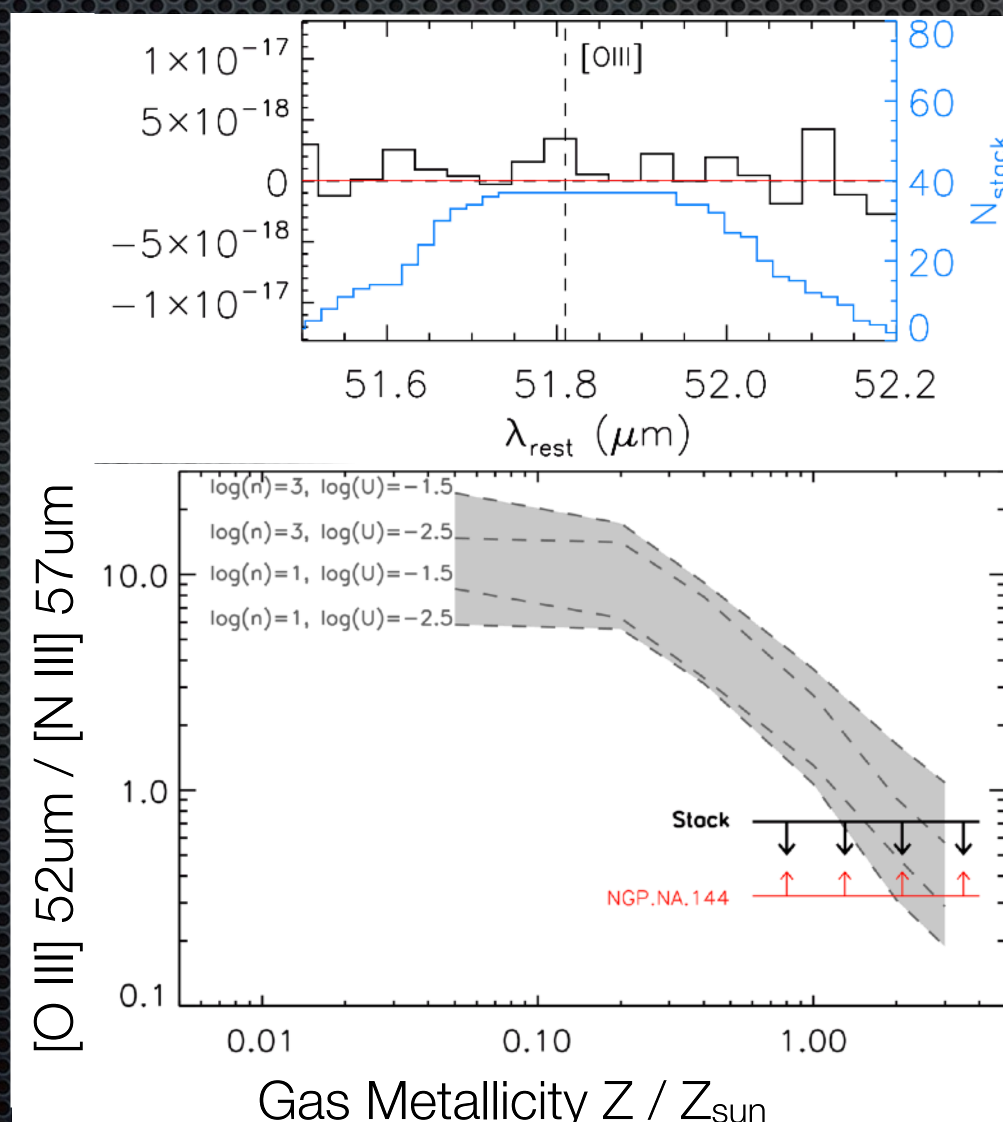
Leung + 2019
z=3.9 lensed quasar

High-z spectroscopy is virtually impossible without order-of-magnitude gains in raw sensitivity

- Even *Herschel* did fairly little far-IR spectroscopy
  - Again concentrated on lensed starbursts & quasars, stacked spectra



Zhang+2018
Stack of 45 SPIRE spectra
towards dusty starbursts
ISM more dense than local starbursts



Wardlow+2017
Stack of 45 PACS spectra
towards dusty starbursts
Consistent with solar metallicity ISM

Instead we must rely on *local analogs* of high-redshift systems

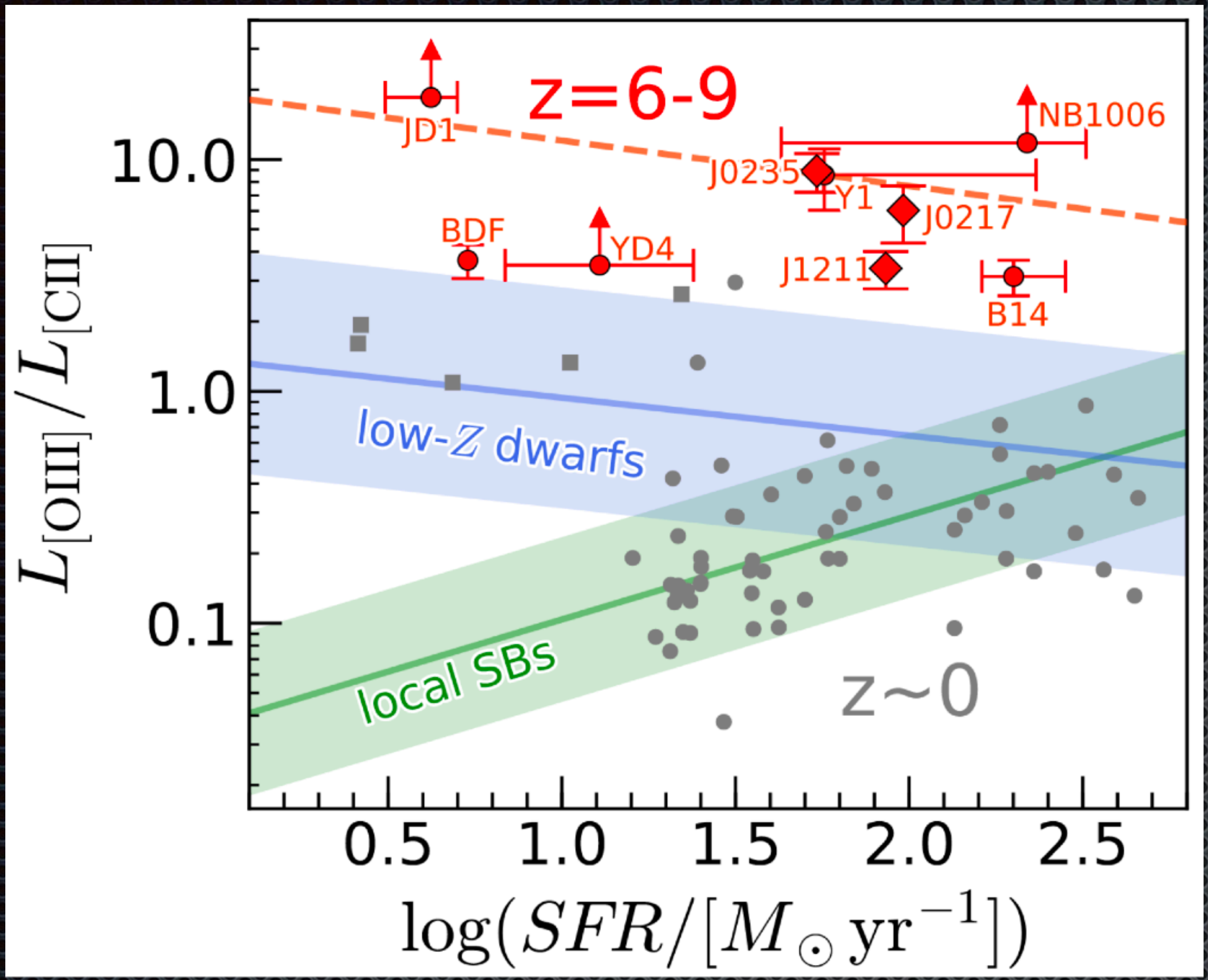
- Pick nearby galaxies with some property/properties similar to those seen at high redshift
- Typical choices: mass, UV/optical colors, optical nebular line strengths & ratios, ionizing radiation field strength, …
- Often these are motivated by puzzling / difficult observations from other facilities

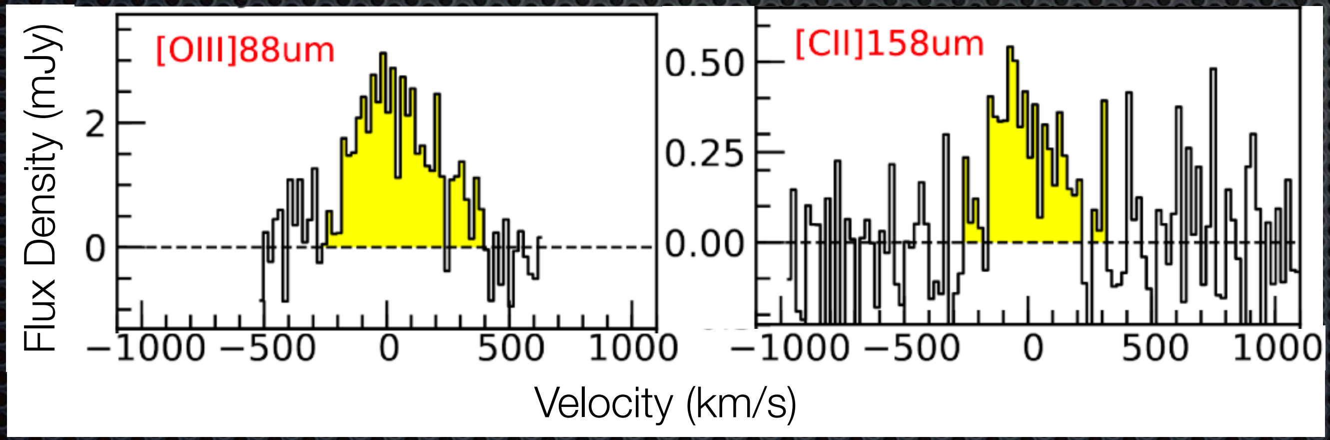
Two Case Studies of High-z Applications of SOFIA Observations

Understanding unusual [O III] / [C II] line ratios in the reionization epoch

Tracing the rise of metals with powerful extinction-immune metallicity indicators

ALMA Finds Bright [O III]88 and Faint [C II]158 at z > 6

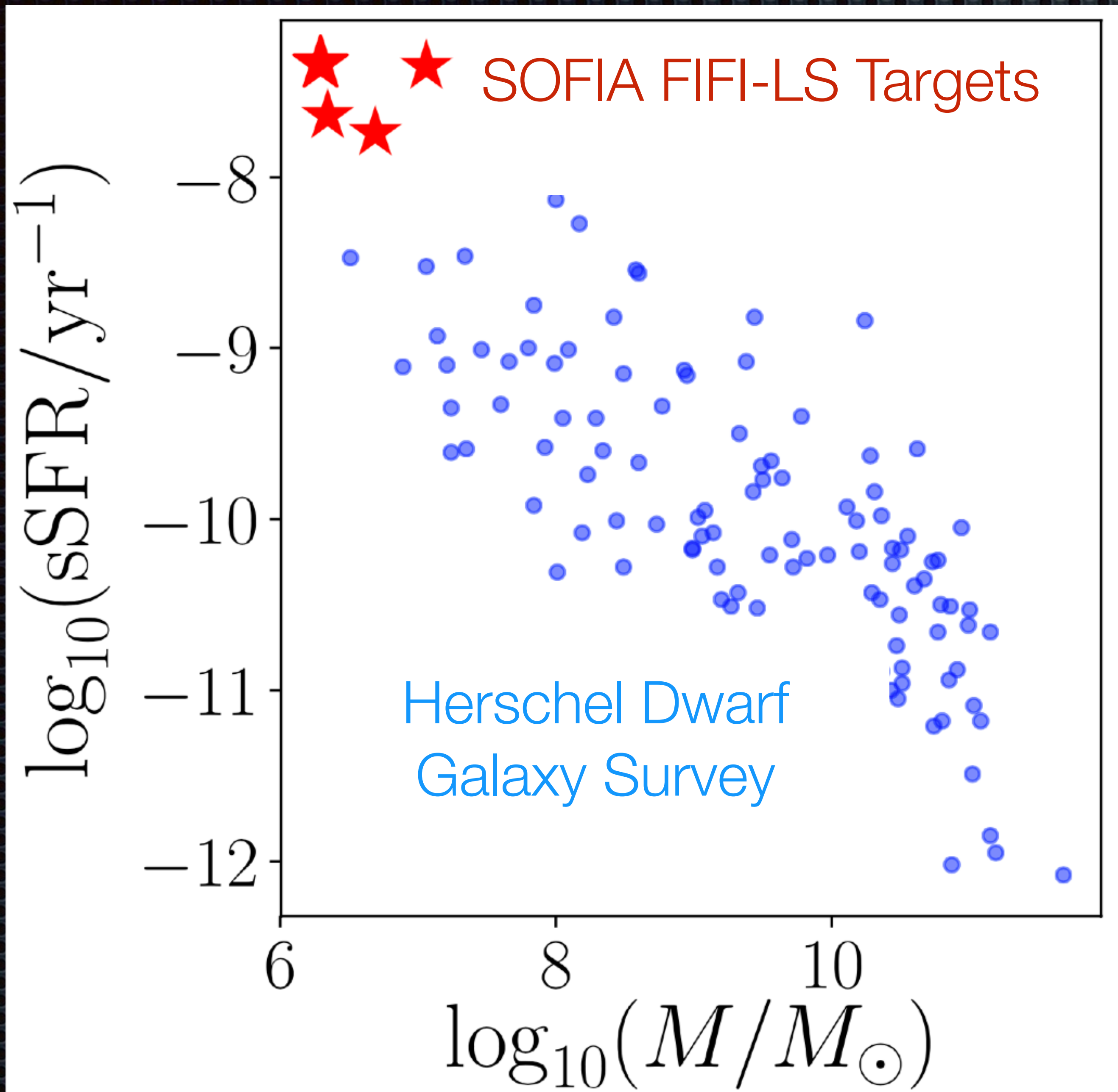




- While [C II] is typically the brightest far-IR line in nearby galaxies, the galaxies responsible for reionizing the universe show very weak [C II], but very bright [O III]88um instead
  - This is true even in comparison to the dwarf galaxies observed by Herschel
- The galaxies that reionized the universe were lower-mass, more metal-poor, and had harder UV radiation fields even than most nearby dwarf galaxies

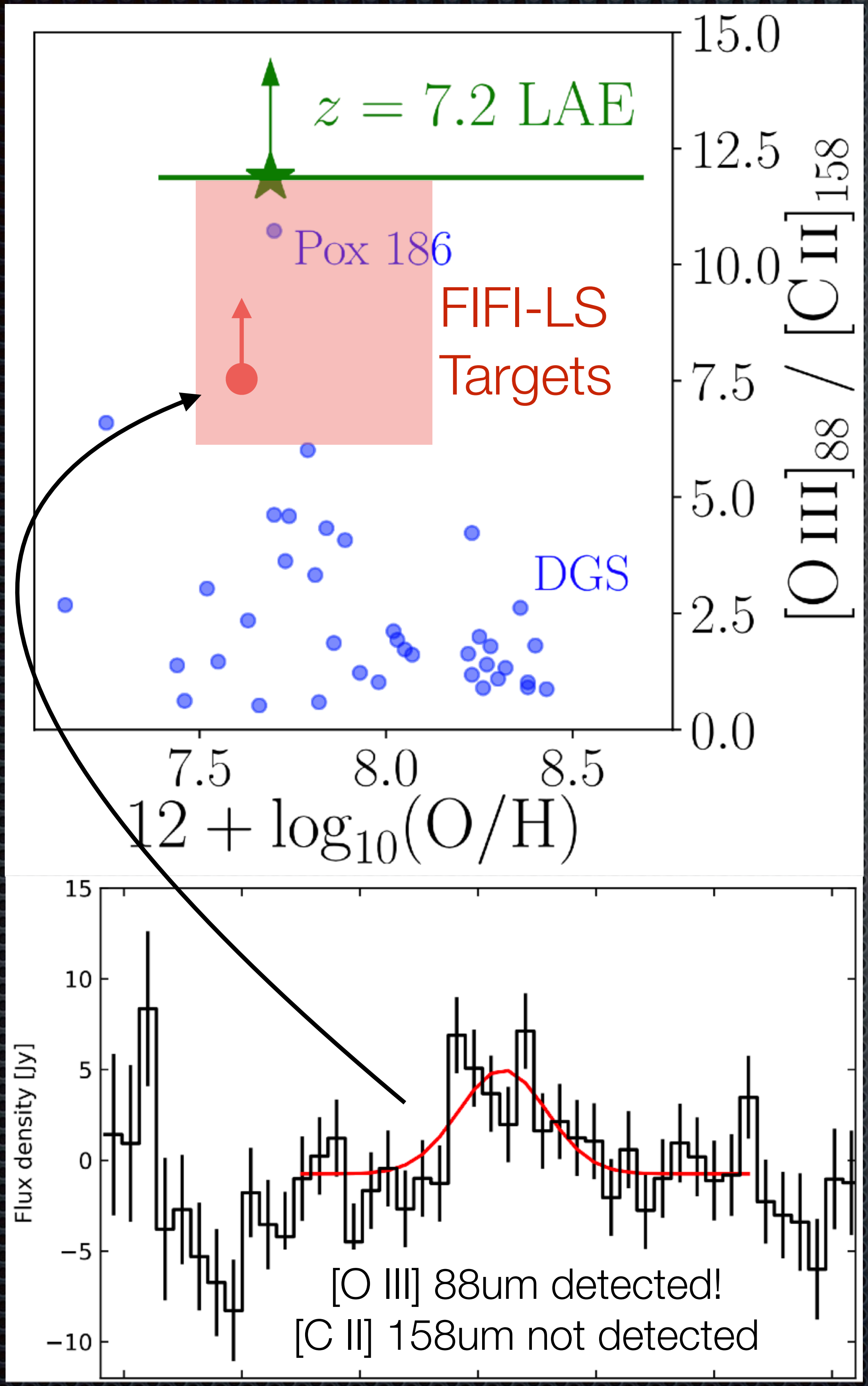
Harikane+2020

Establishing (one possible) local analog SOFIA sample



- Select local galaxies with (locally) extreme UV properties, very low stellar mass, and *HST*/COS spectra
- We want objects with ionizing spectra similar to the reionization era
- Cycle 7 program, PI: B. Weiner (analysis from new-PhD Peter Senchyna)
- FIFI-LS can observe [OIII]88um and [CII]158um simultaneously

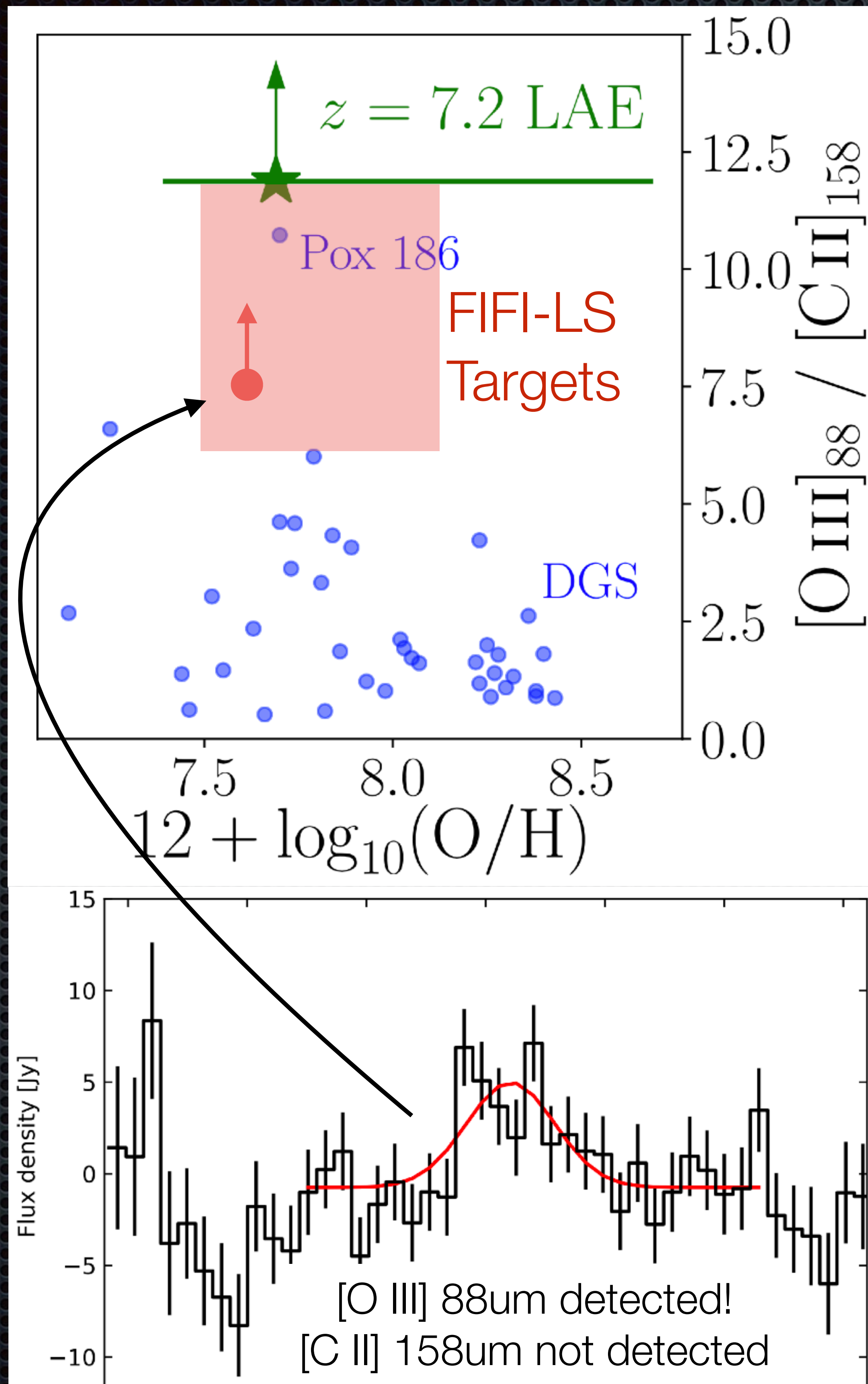
Local objects with extreme [OIII]/[CII] ratios



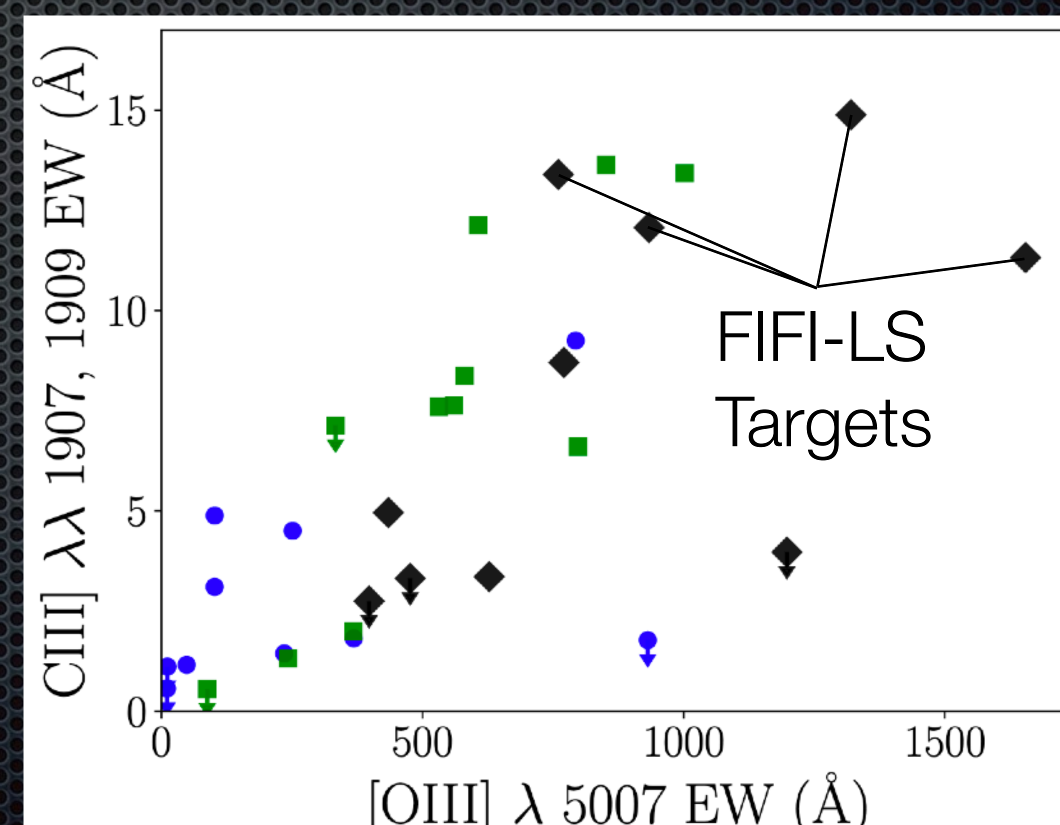
- We find ubiquitously high [OIII]88 / [CII]158 ratios, with values & limits consistent with z > 6 reionization-era galaxies

Senchyna, Weiner, JS + in prep.

Local objects with extreme [OIII]/[CII] ratios



- We find ubiquitously high [OIII]88 / [CII]158 ratios, with values & limits consistent with z > 6 reionization-era galaxies
- All have very strong C III] emission in the UV
  - Perhaps C^+ is not the dominant ionization state of carbon?



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Two Case Studies of High-z Applications of SOFIA Observations

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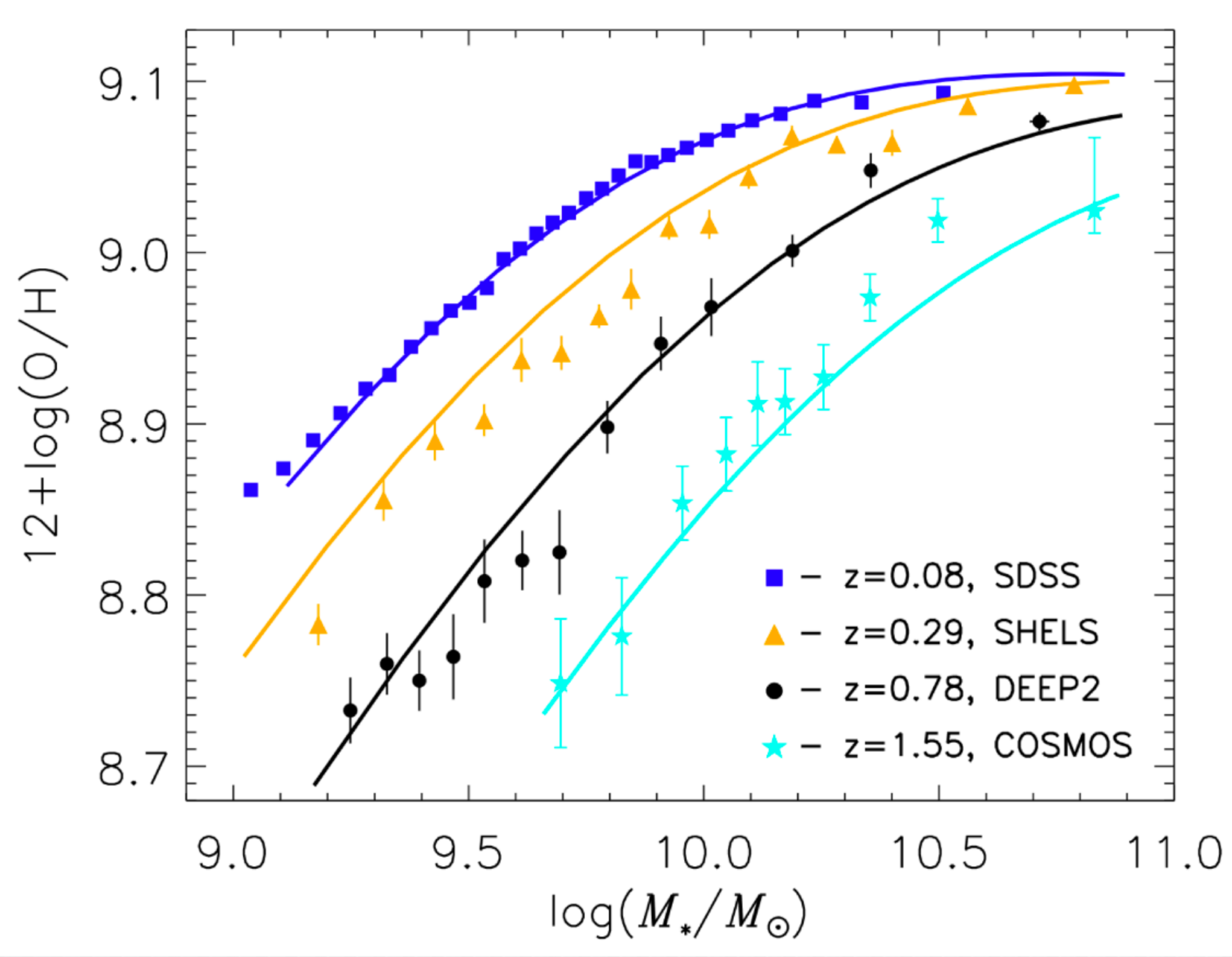
The Rise and of Metals Across Time and Space

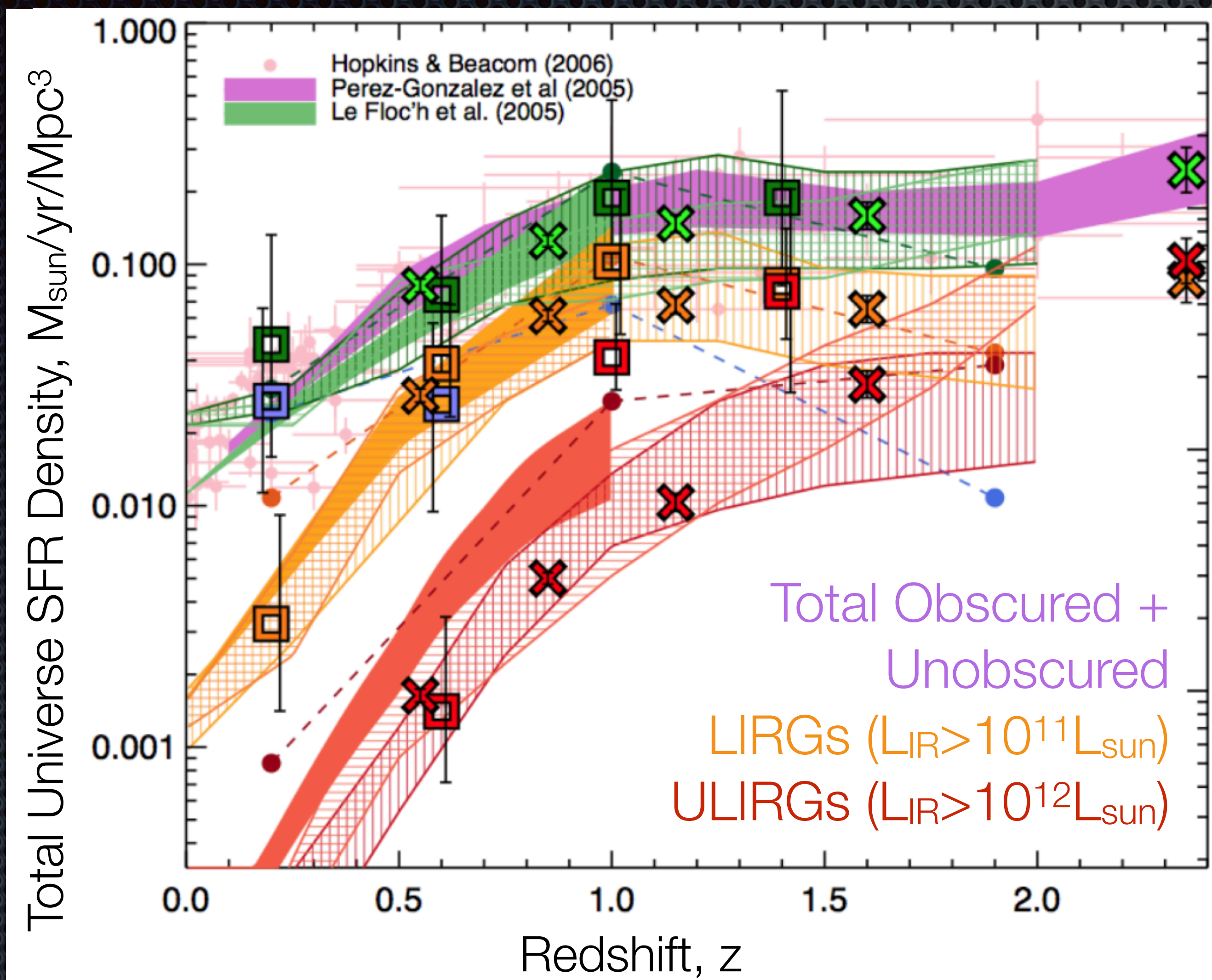


Zahid+2014

- Galaxy metallicities are the end result of a huge range of physical processes:
  - Metal-poor inflow
  - Enrichment via star formation
  - Metal-enriched outflows
- Amazingly, there's a tight mass-metallicity relation that evolves with redshift
- *However…*

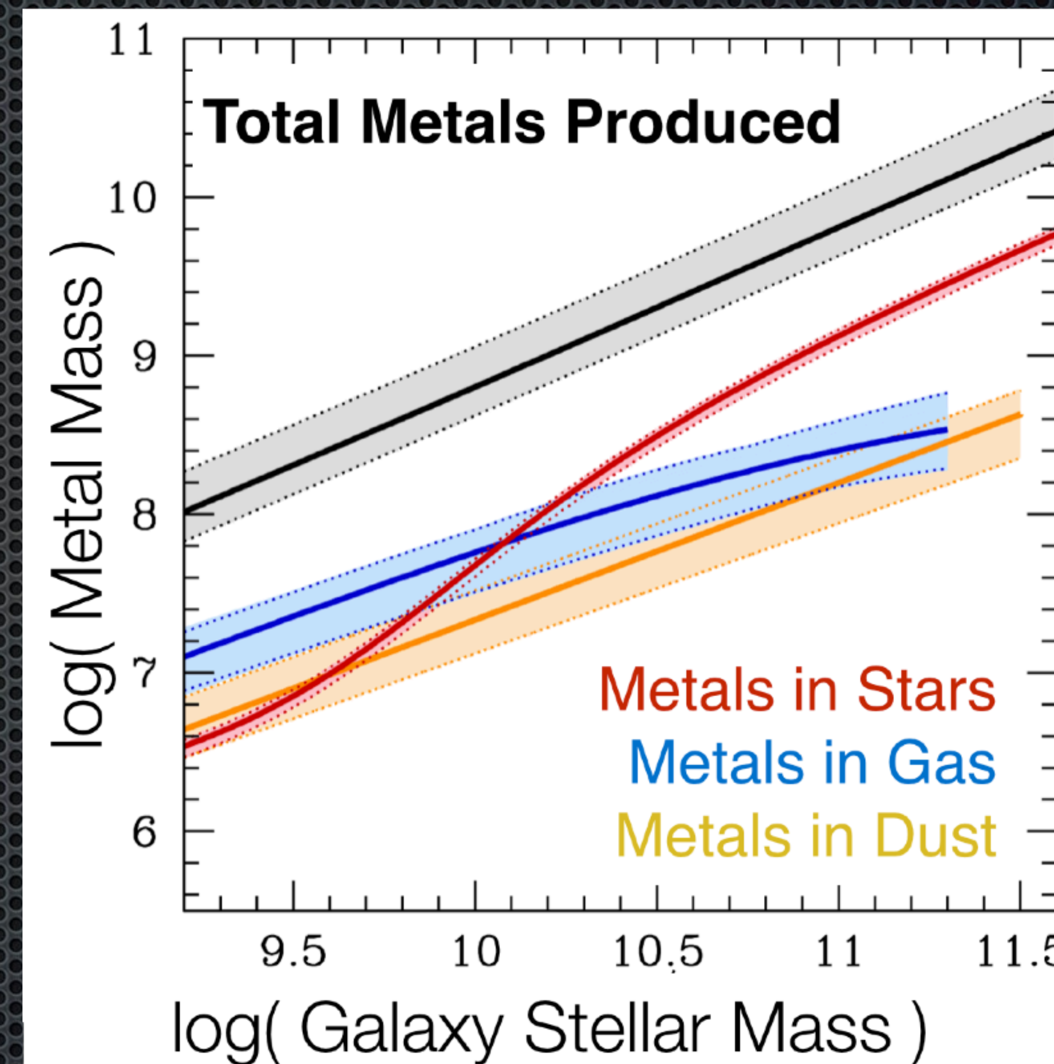
The Rise and of Metals Across Time and Space

Highly-obscured dusty galaxies dominate star formation in the universe at z >~ 1



Casey+2014 compilation

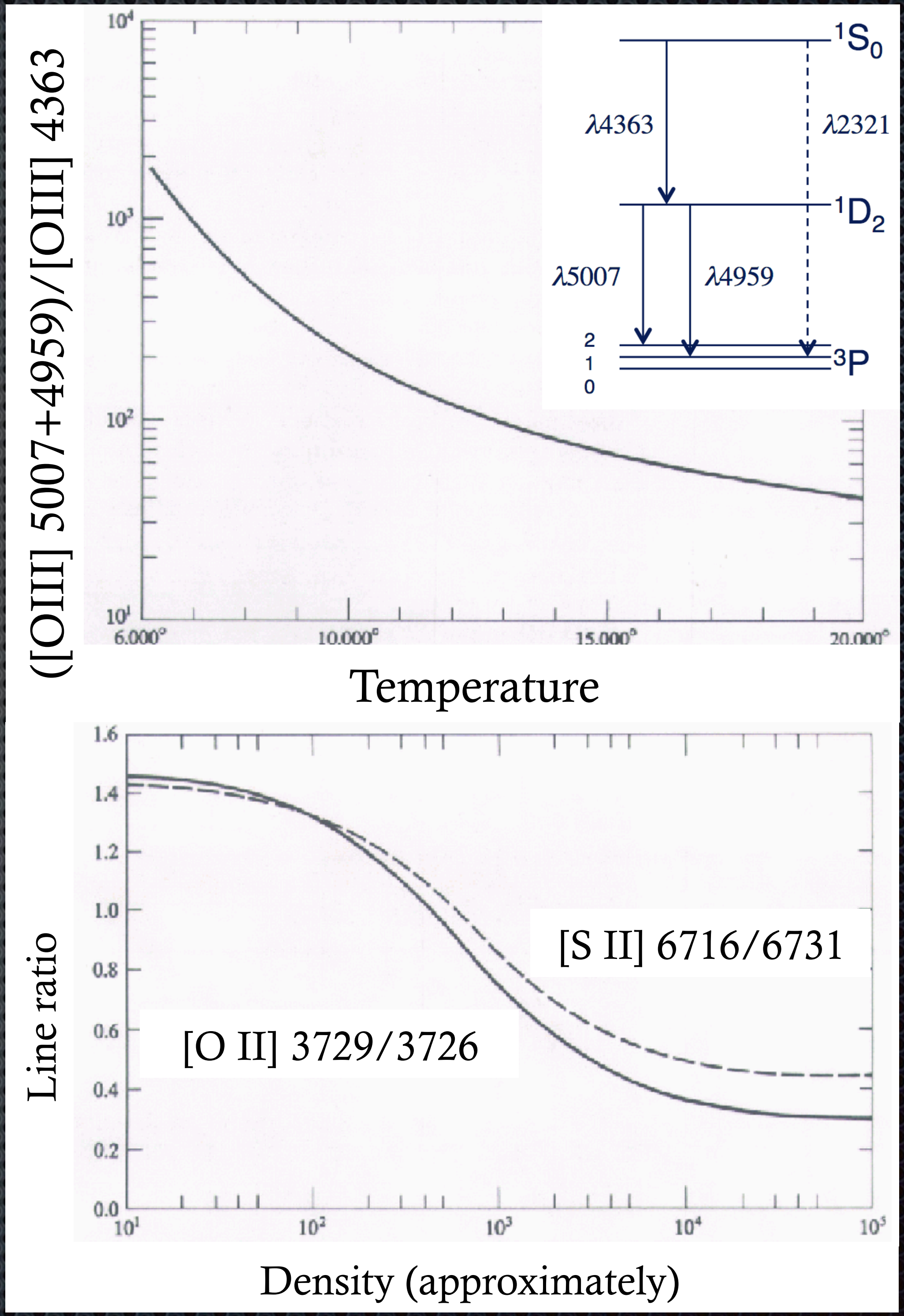
90% (!!) of metals from stellar evolution don't stay in the galaxies that produced them



Werk+2014, many others

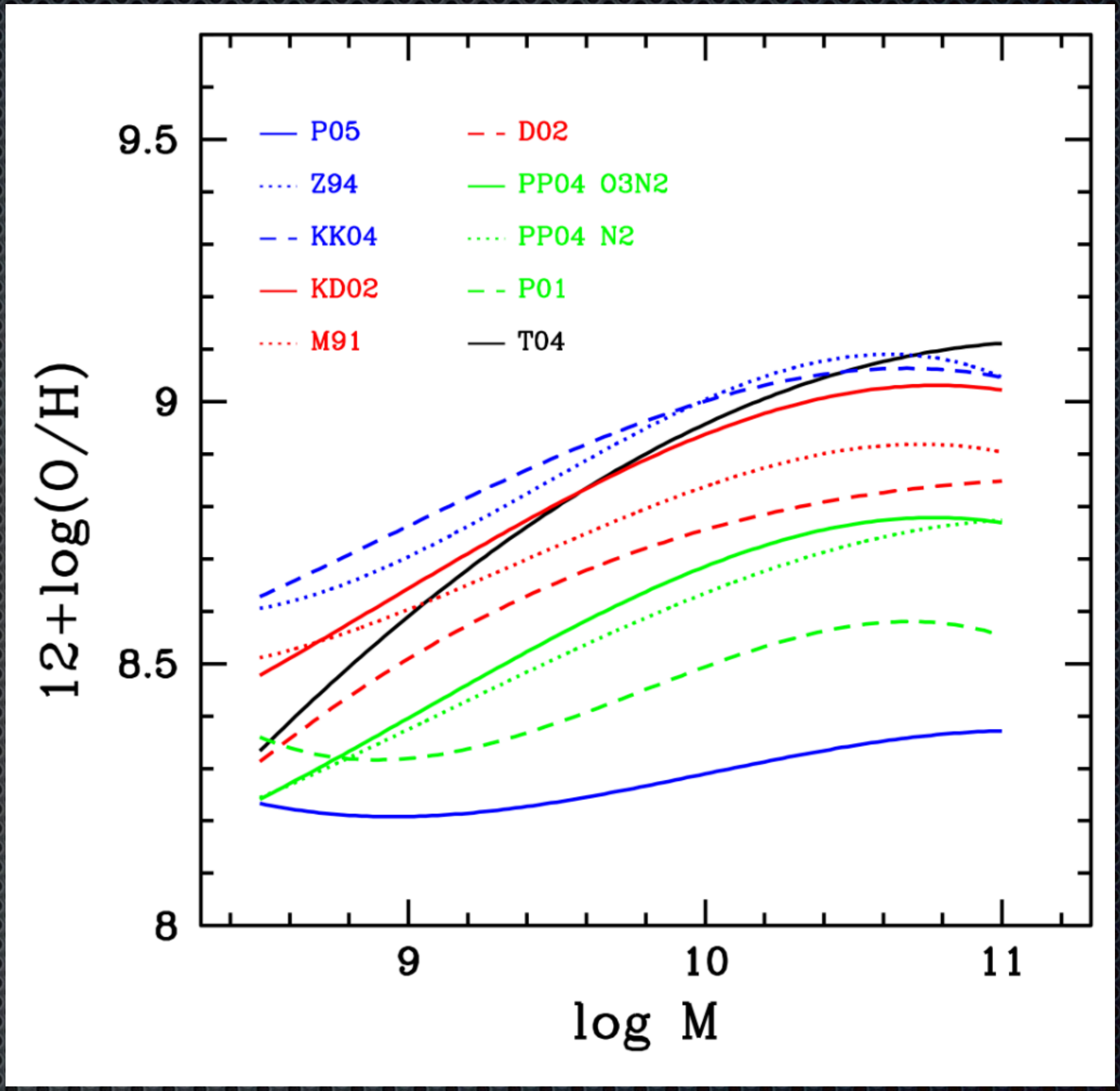
How to measure galaxy metallicities

- Measure multiple spectral lines, of C/N/O etc.
- Relative line ratio depends on:
  - Temperature
  - Density
  - Ionization state
  - Elemental abundances
- Measure or assume 3 of these to get the other



How to measure galaxy metallicities

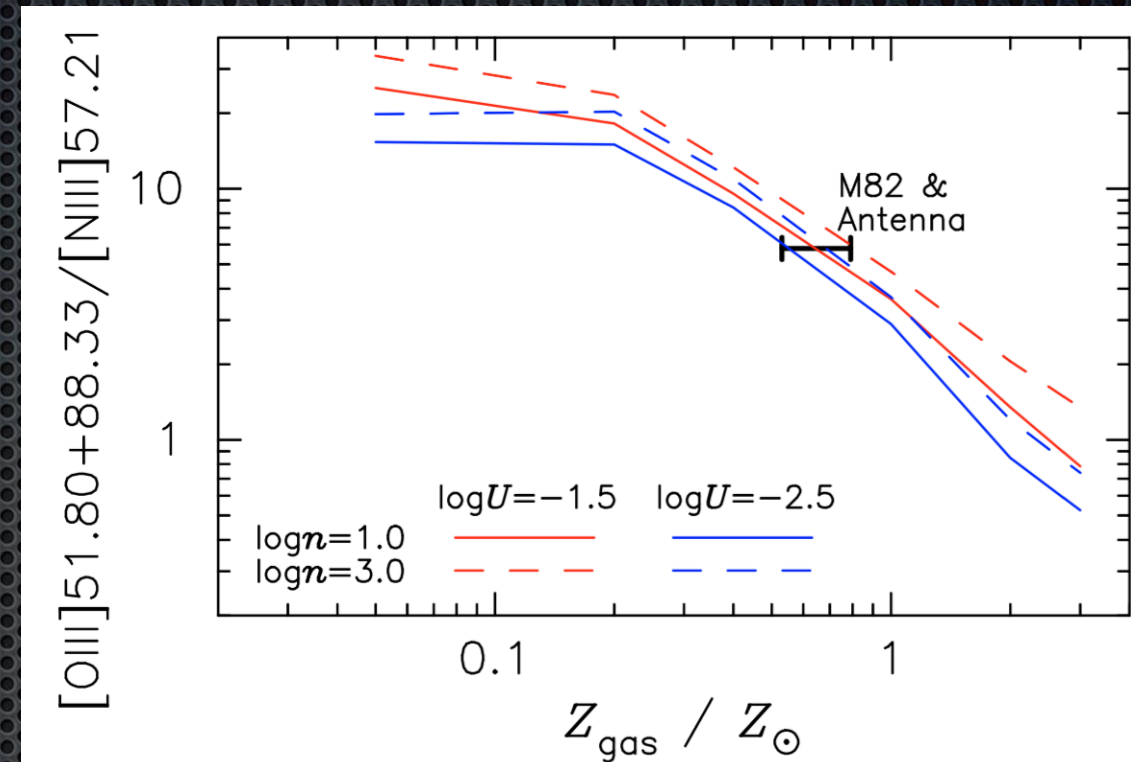
- There are many metallicity calibrations. How well do they agree?
- … very poorly.
- Problems lie in:
  - Assumptions (T_e in particular)
  - Dust along sightline

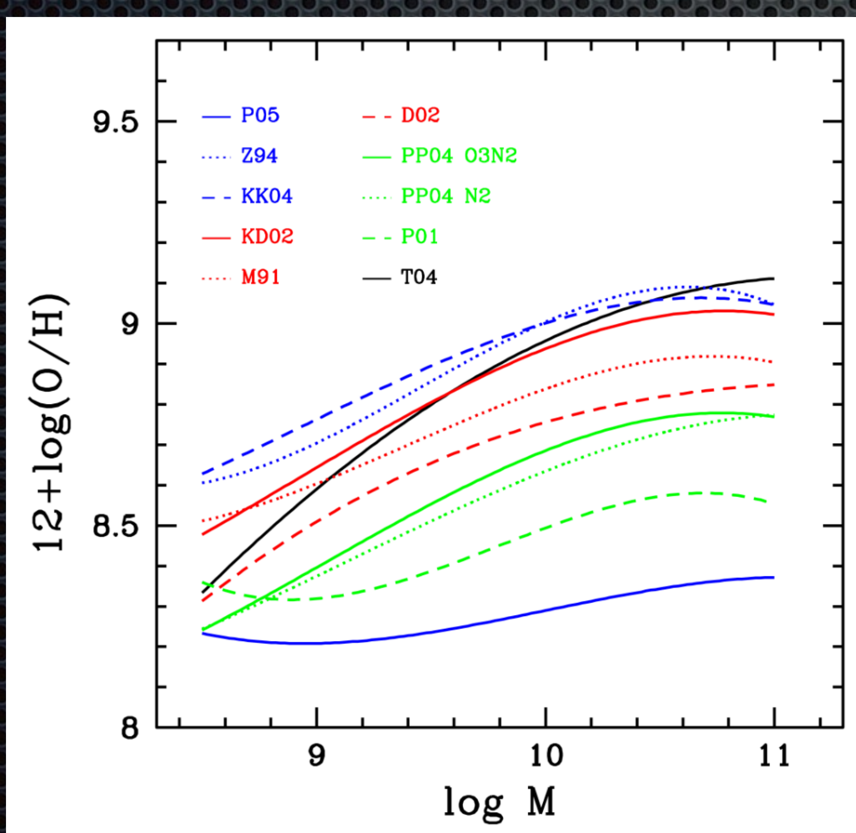


Kewley & Ellison 2008

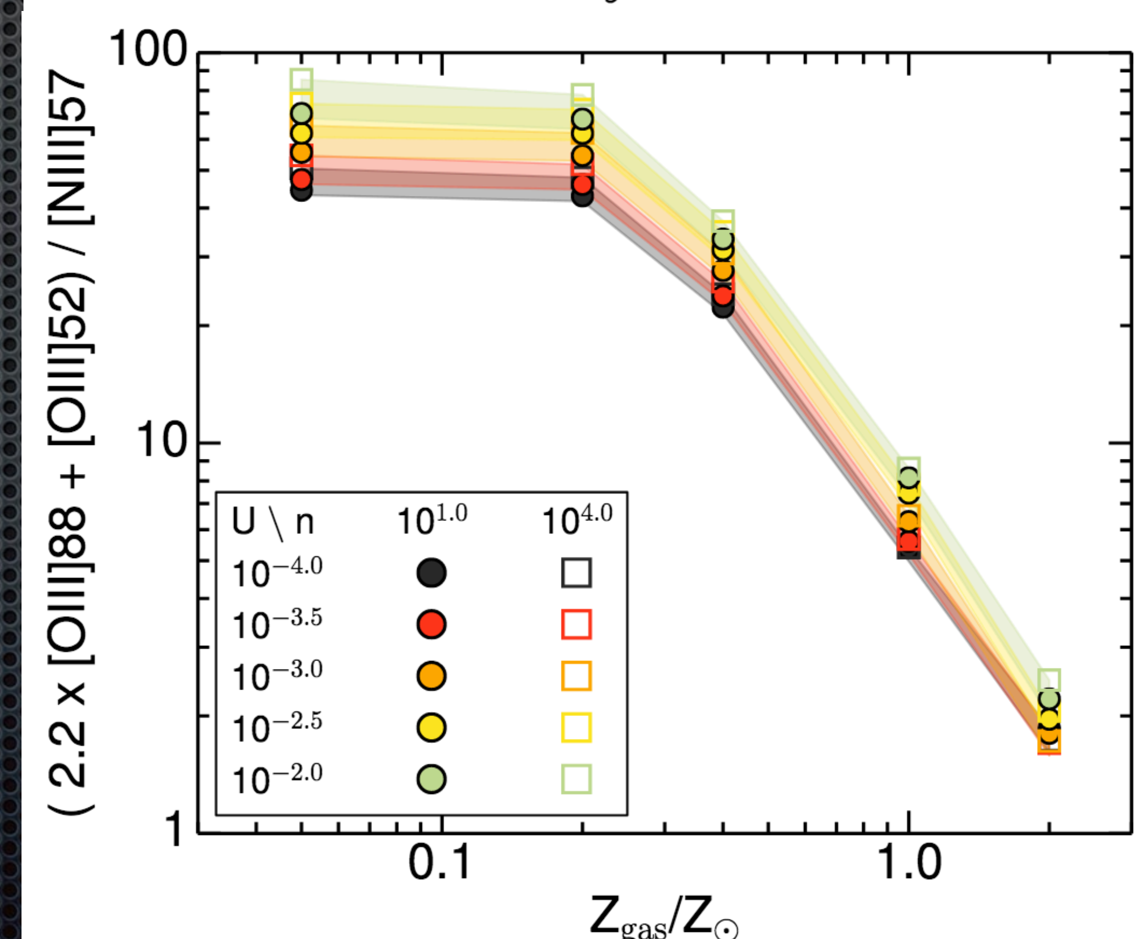
Can we win in the far infrared?

- The far-IR has multiple advantages:
  - Temperature mostly irrelevant
  - Dust mostly irrelevant
  - Other parameters (e.g. density) easily constrained

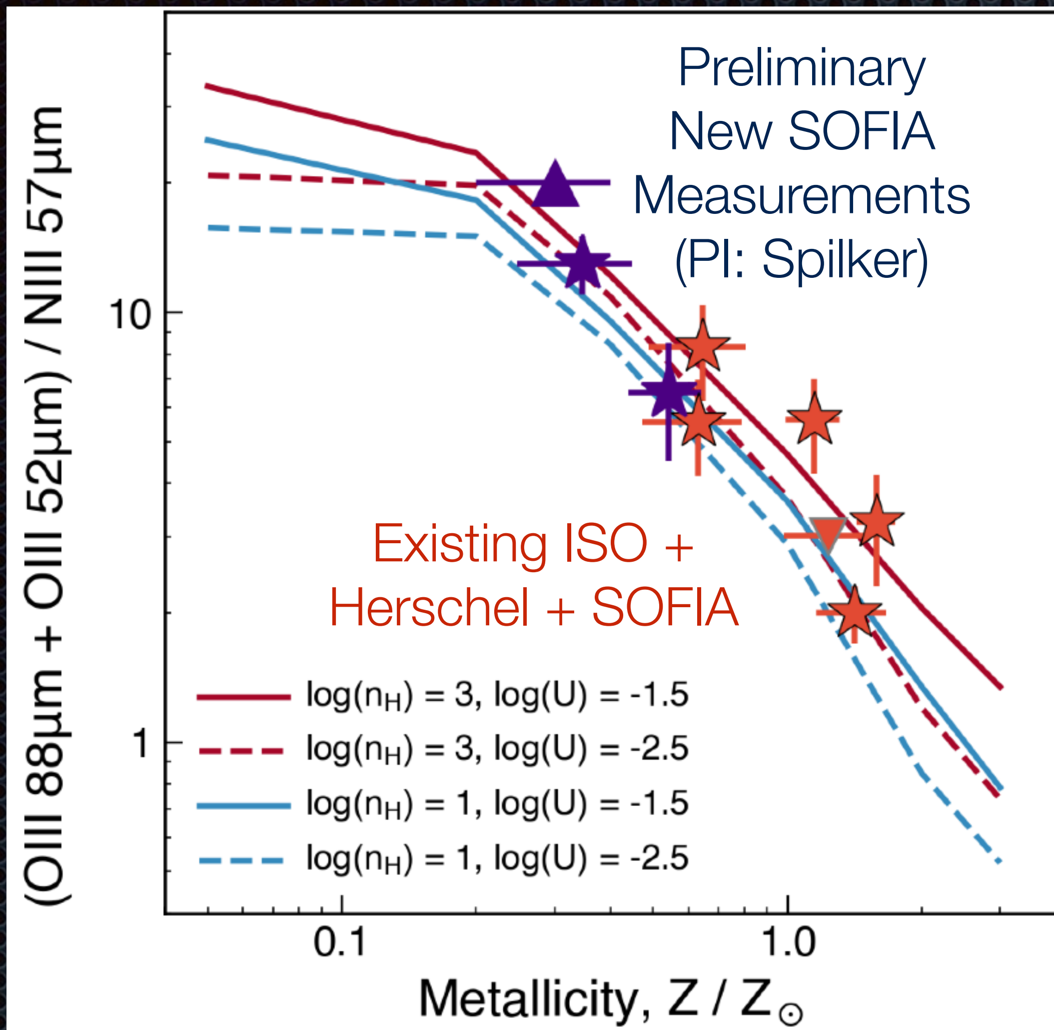


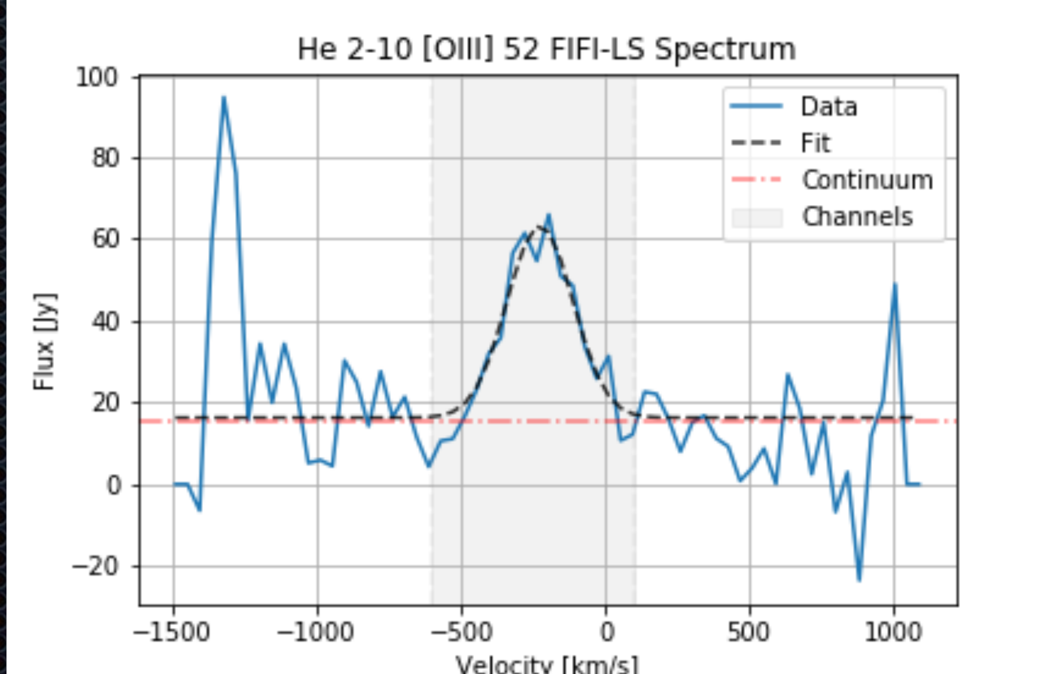


Nagao+2011, Pereira-Santaella+2017



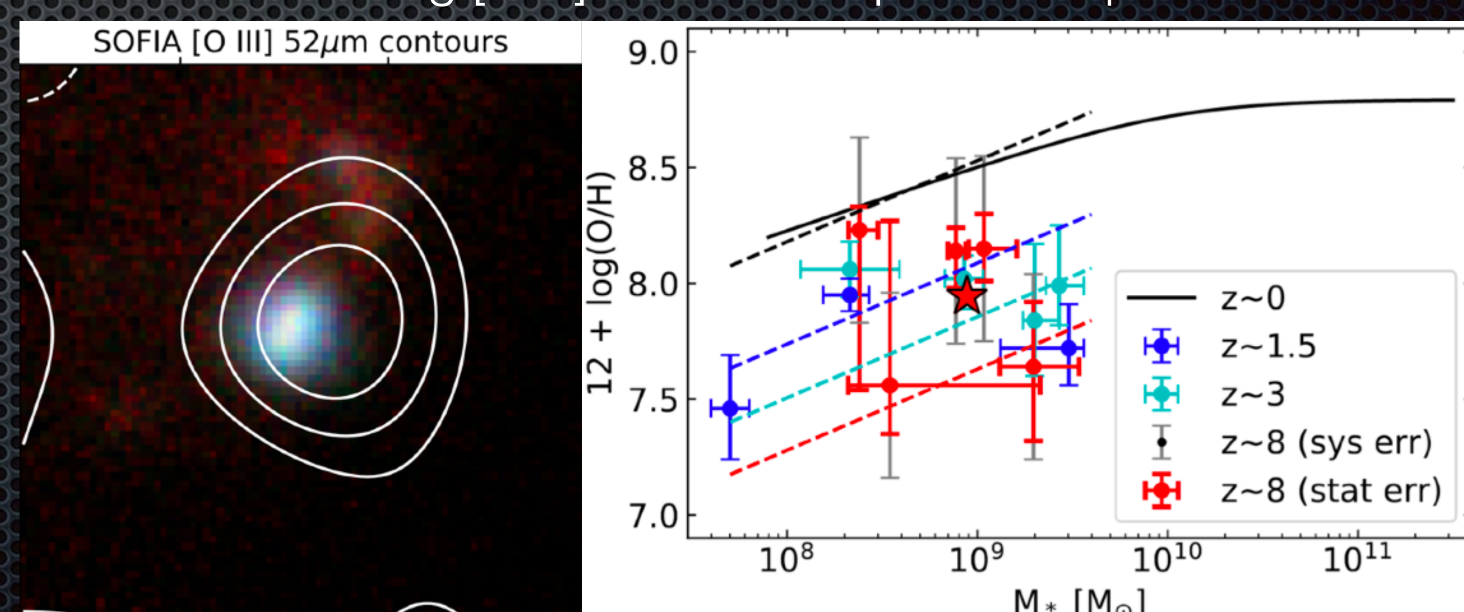
Developing Extinction-Free Metallicity Indicators



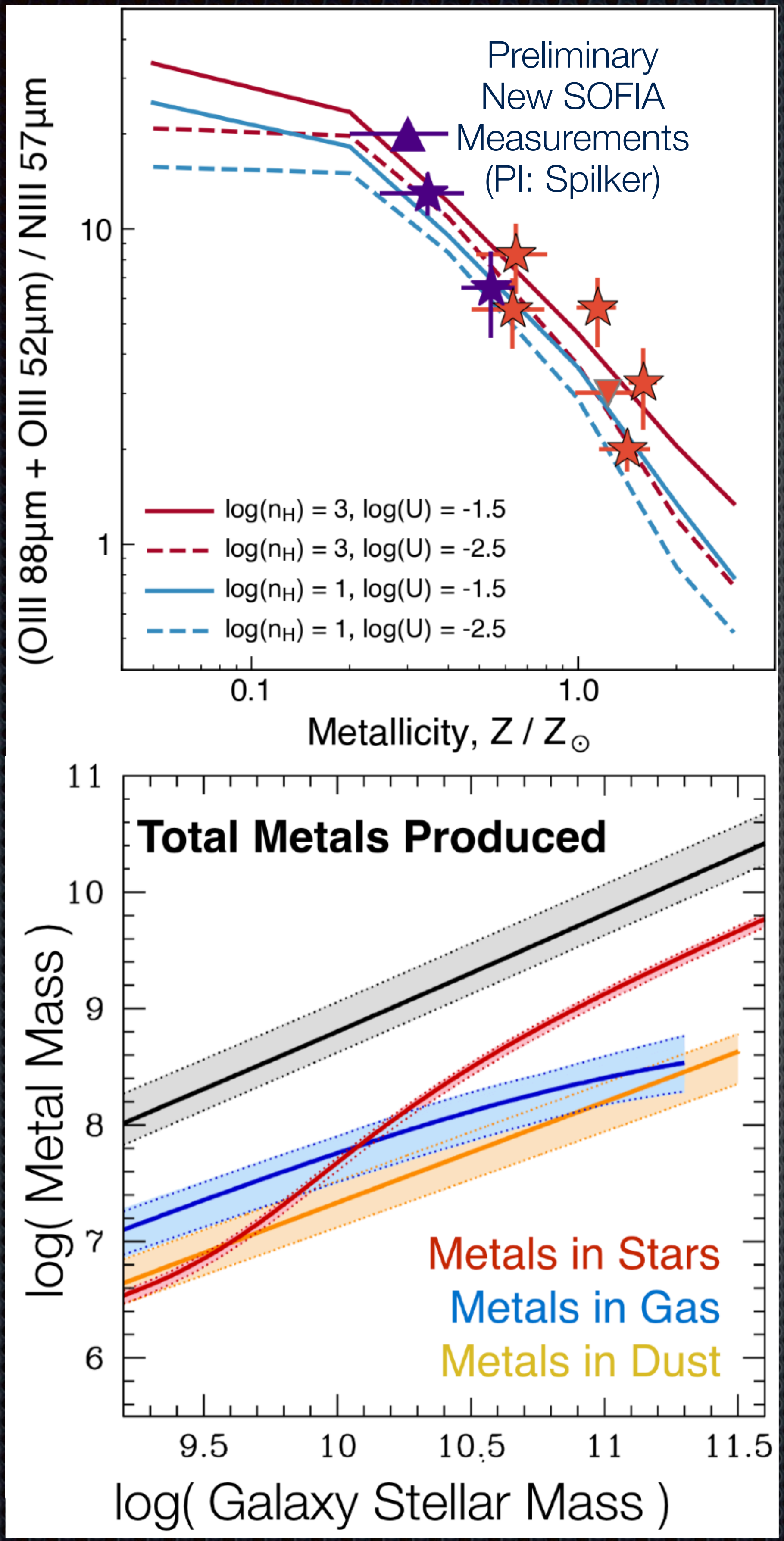


- We now have an indicator calibrated over ~1dex in metallicity that relies *only* on far-IR fine structure lines
- We recover a mass-metallicity relationship in agreement with SDSS work (independent check on the method)
- Only possible because FIFI-LS can get [O III] 52um, unlike PACS

See also T. Jones + 2020, arXiv:2006.02447
for a method using [O III]52um with optical H-alpha or H-beta



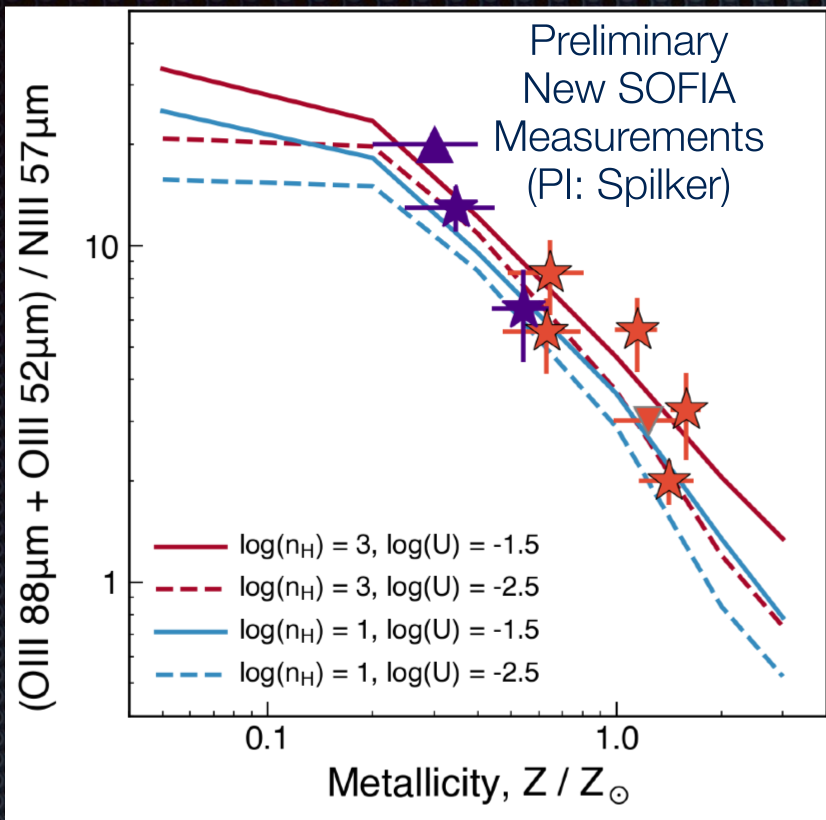
Tracking the dispersal of metals



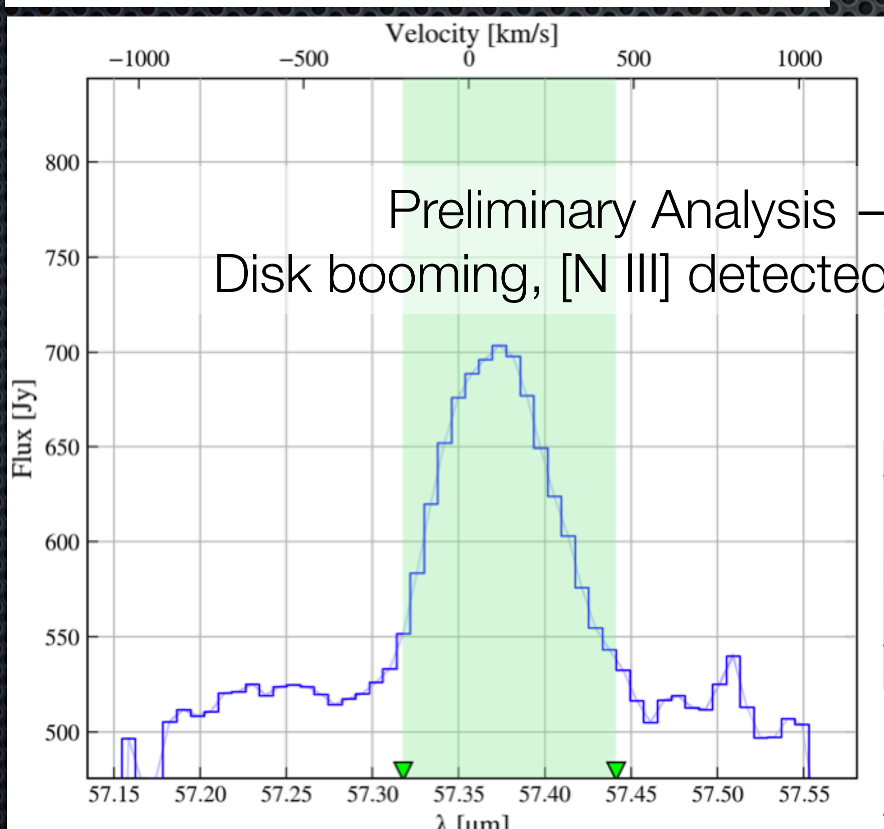
- ~90% of all metals produced by stellar evolution don't remain in the galaxies where they were produced
- The get transported into the circumgalactic medium, primarily by metal-enriched galactic outflows

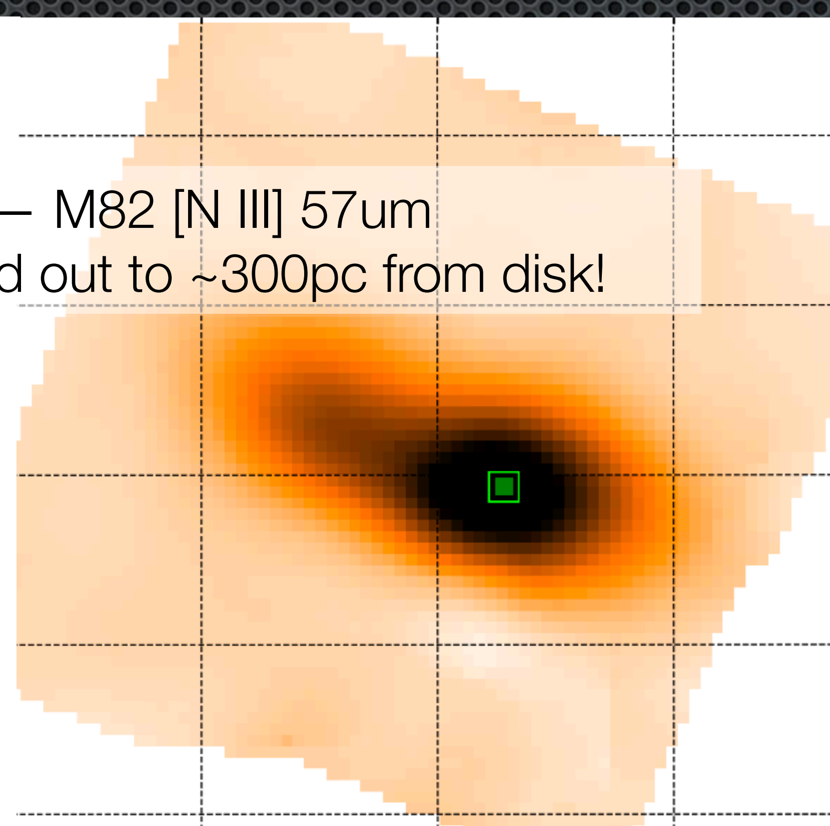
- Problem: Starbursts that drive these outflows are in heavily obscured regions
- Solution: Use our new far-IR metallicity diagnostics on spatially-resolved scales!

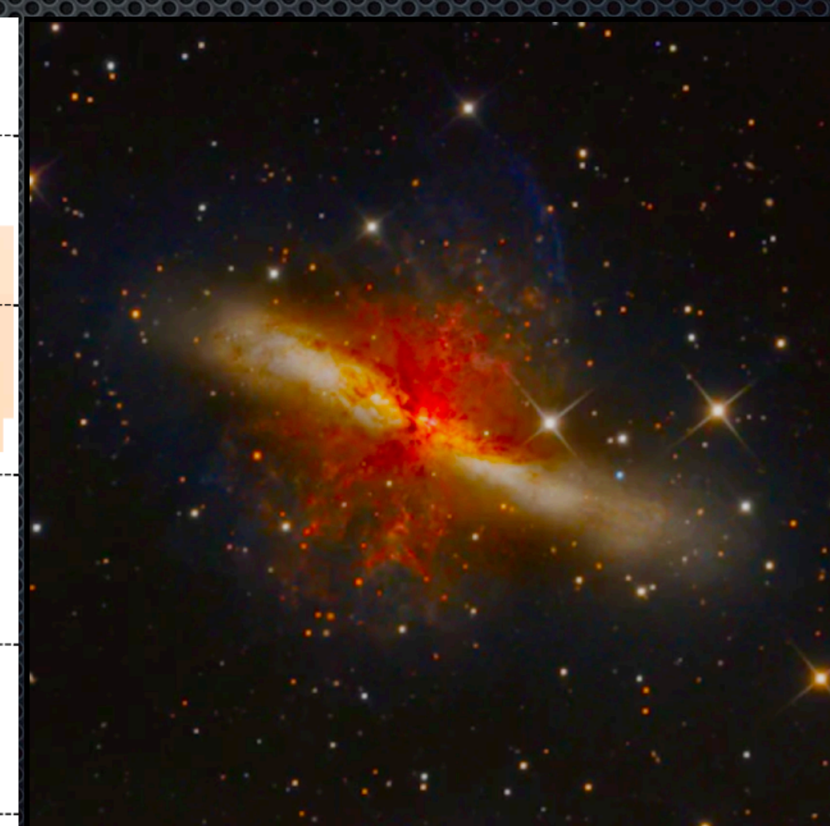
Tracking the dispersal of metals



- Are galactic winds really metal-enriched compared to their host galaxies?
- Combine new and archival FIFI-LS data to answer fundamental questions about the cycle of metals in and out of galaxies
- SPICA/Origins will do this across cosmic time







Preliminary Analysis — M82 [N III] 57um
Disk booming, [N III] detected out to ~300pc from disk!

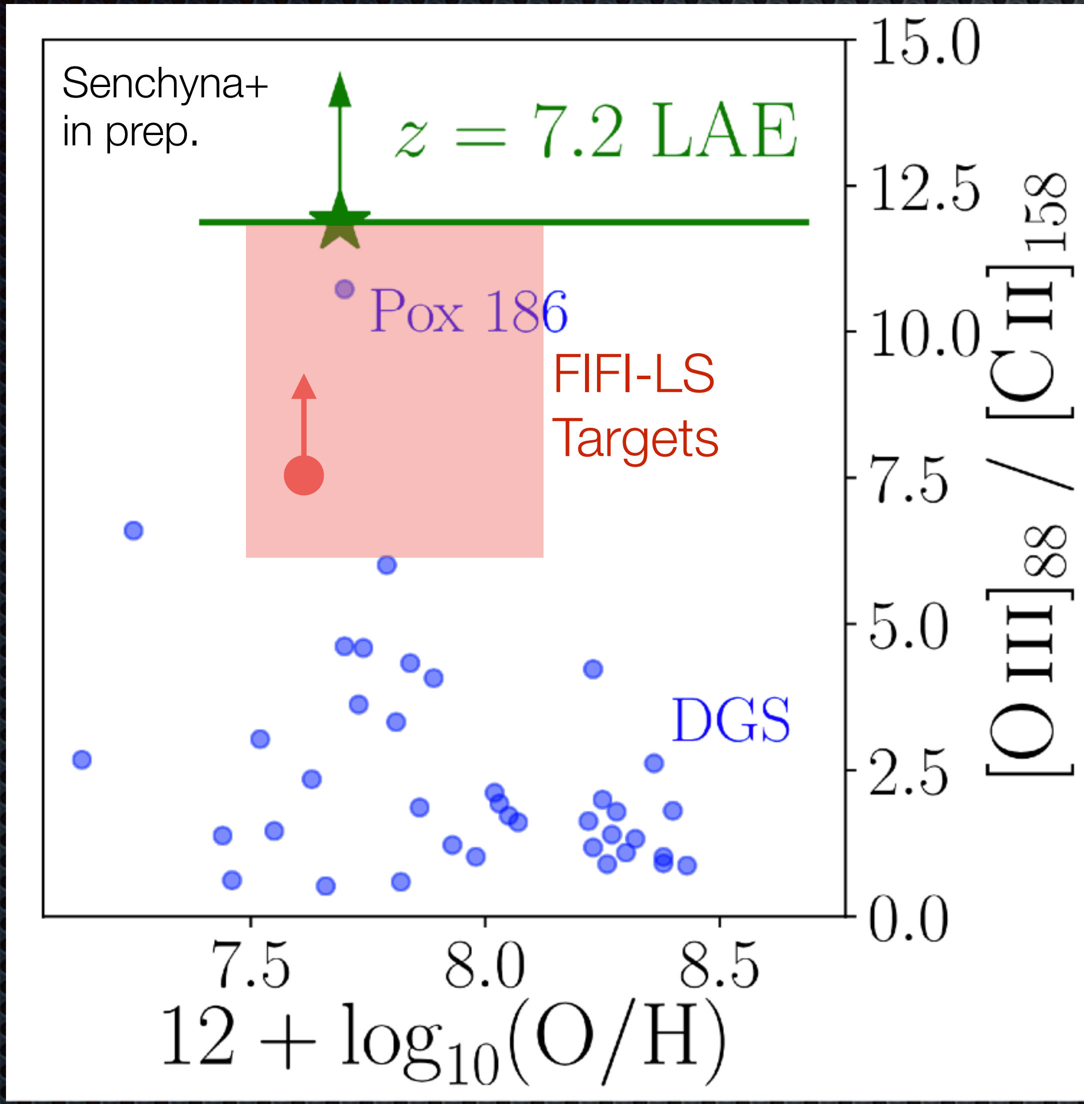
“What the high-redshift community needs”

(a biased view)

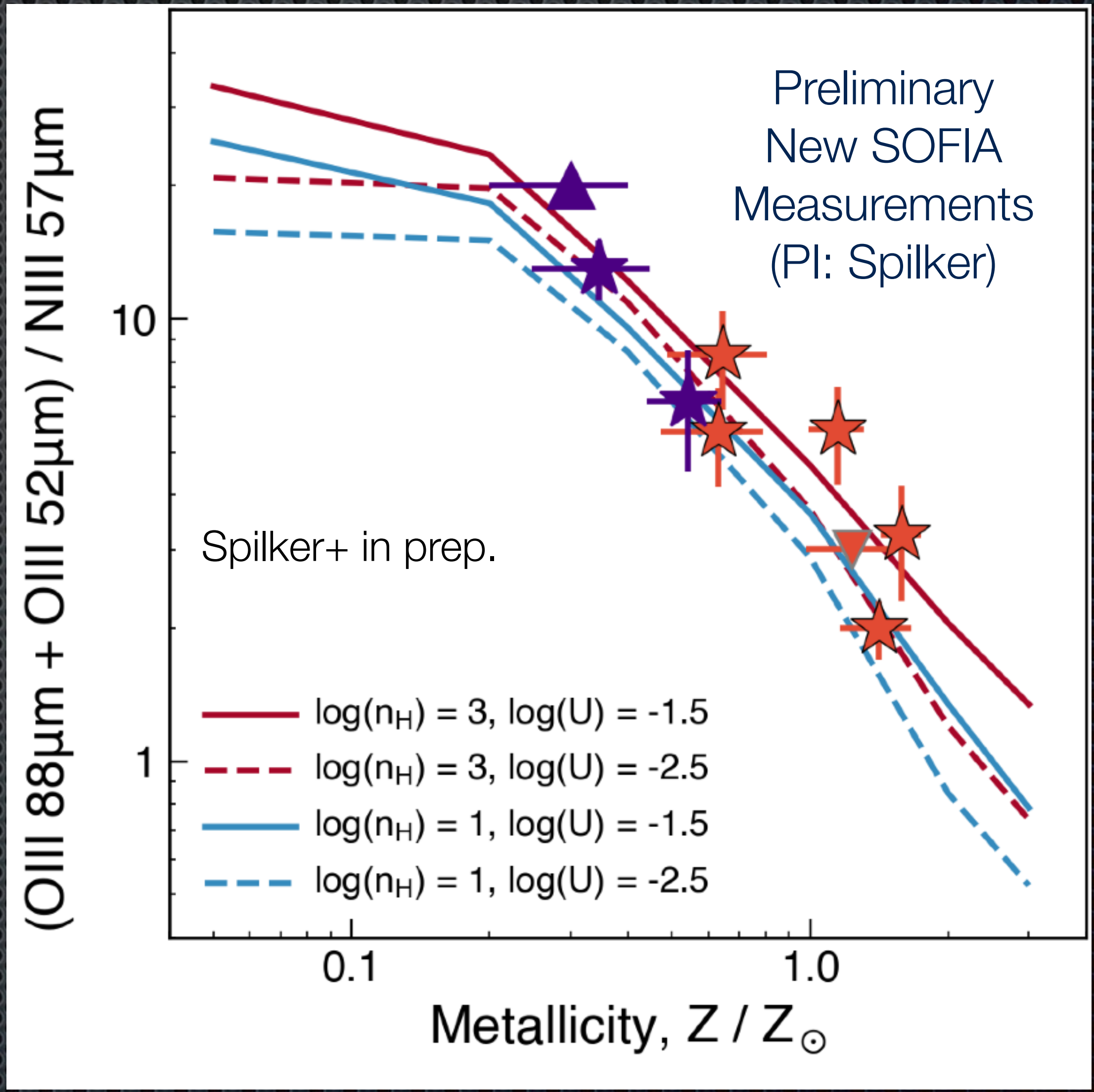
- Sensitivity will always be key
  - Even ‘small’ ~2x gains let us access a more diverse and more distant set of (still-nearby) analogs — HIRMES-like sensitivity is very powerful
  - True far-IR high-z spectroscopy will require SPICA/Origins (~10x PACS sensitivity)
- Improved far-IR spectral resolution would be great
  - Enables dynamics / velocity-resolved observations. Need some middle-ground between FIFI±LS and upGREAT — HIRMES-like resolution supports many cases
- Need to encourage the community to be creative
  - “How can SOFIA make progress in my science area?” is a much harder question than “How can I make progress in my science area?”
  - High-z science is not a core strength of SOFIA. It is non-trivial to develop science programs that can compellingly address high-z science cases with SOFIA. Knowing that, how can we develop intuition and support creativity in the high-z community?

Conclusions

Large [OIII]/[CII] ratios at reionization can be found in the local universe. Possibly the result of very hard ionizing spectra.



We now have a far-IR only metallicity indicator that can be used in dust-obscured systems. We can use this to trace metal enrichment on large scales.



- SOFIA can make valuable contributions to high-redshift science!
- Requires community effort and creativity to make the most of it