Direct Detection sub-mm Spectroscopy of Galaxies in the Early Universe

Amit Vishwas

June 27, 2017

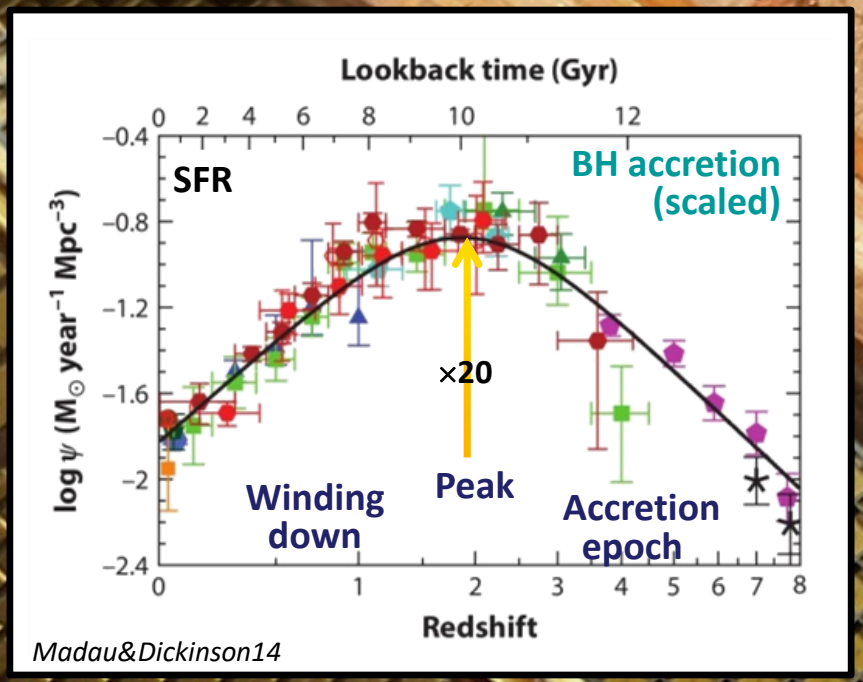
Science Enabled by Novel Infrared Instrumentation

Outline of the talk

1. Far-IR line emission – Unique probes of the ISM
2. Instrumentation: Overview of ZEUS-2
3. ZEUS-2 Survey of [OIII]/[NII] at z ~ 2 - 5

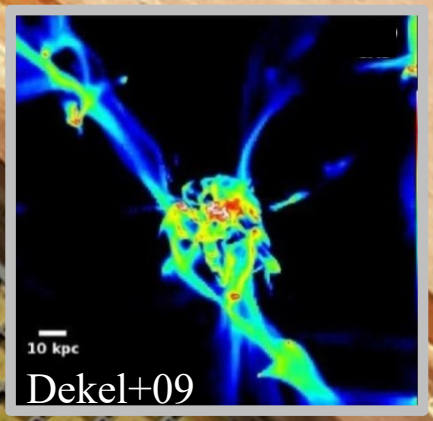
Galaxy Evolution over Cosmic Time

(Major) Mergers and Starbursts



Madau&Dickinson14

Continuous Accretion from Halo and Disk Instabilities



Science Enabled by Novel Infrared Instrumentation

Galaxy Evolution over Cosmic Time

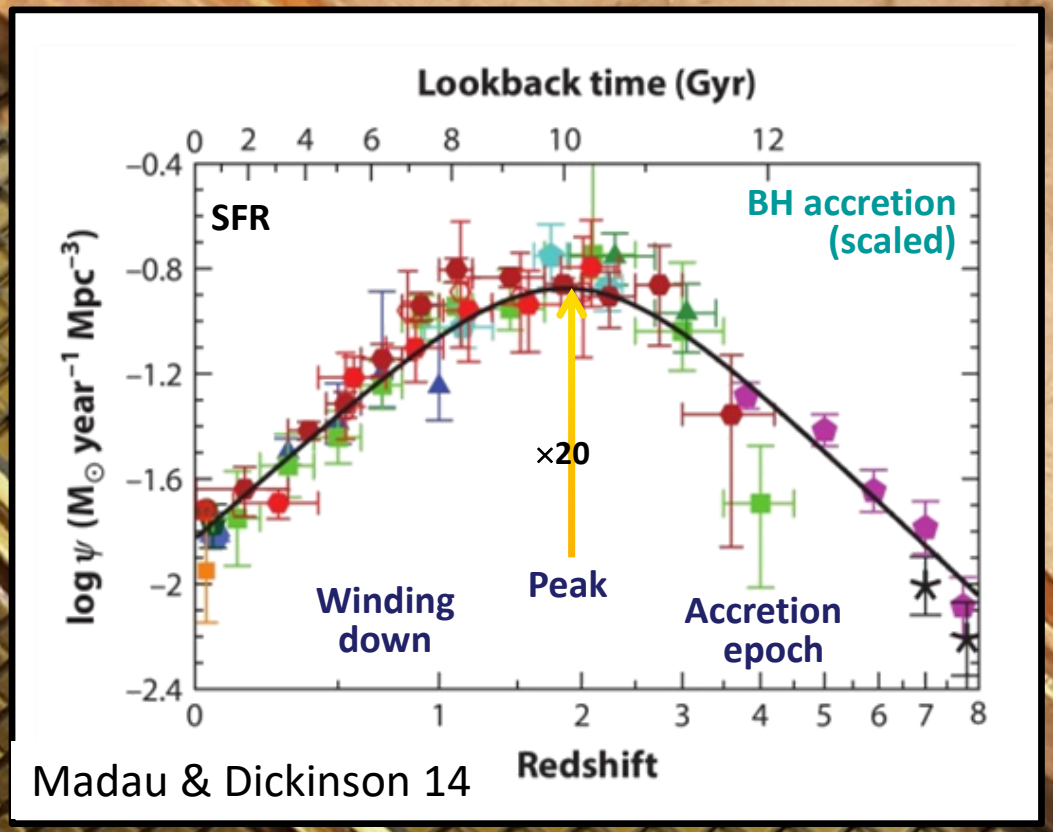
z = 4, ~2kpc disks

z = 0, >30 kpc Galaxies

Science Enabled by Novel Infrared Instrumentation

Dusty Star Forming galaxies

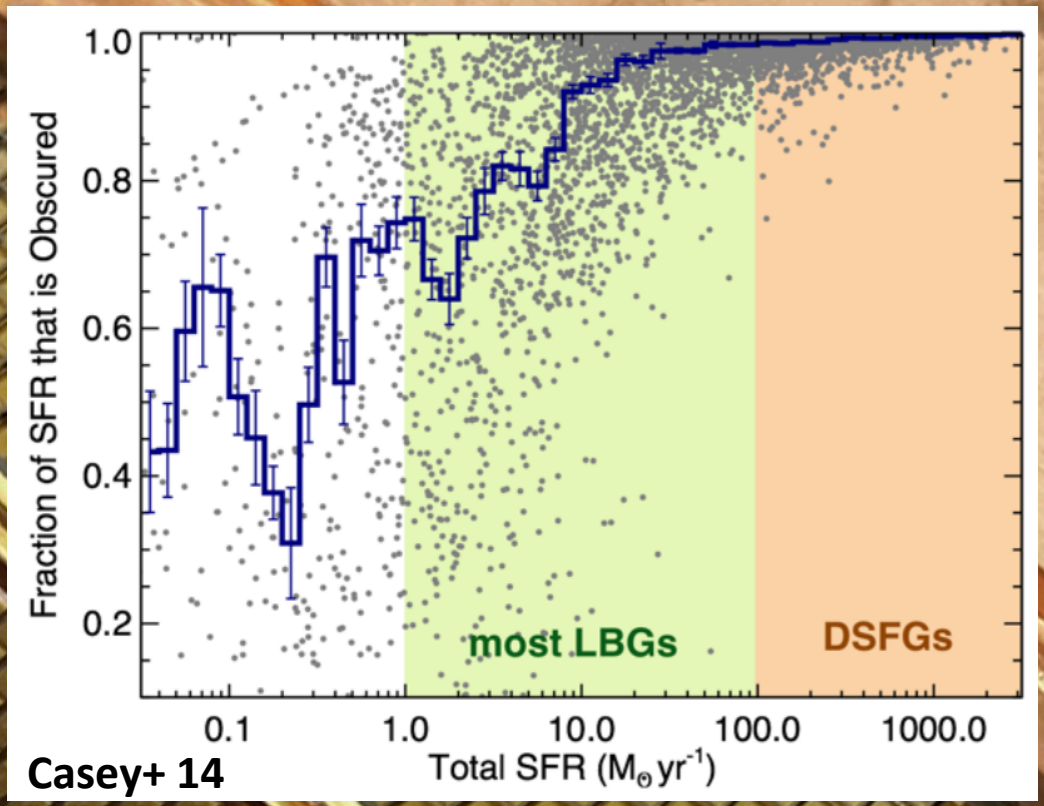
- Contribute Significantly to Cosmic Star Formation



Madau & Dickinson 14

Dusty Star Forming galaxies

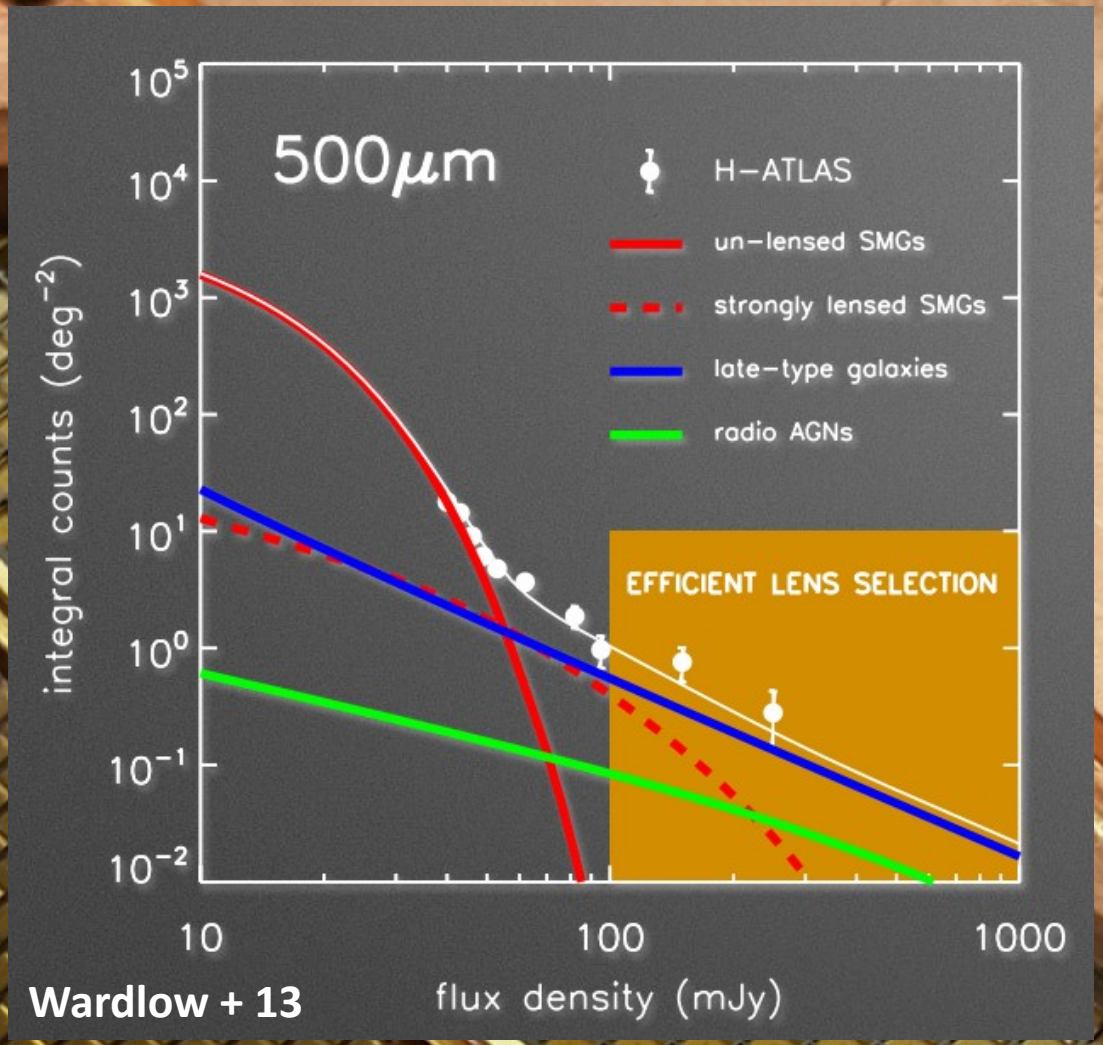
- Contribute Significantly to Cosmic Star Formation
- The Star Formation activity is almost completely obscured



Casey+ 14

Rare beasts!

- Herschel discovered ~10^5 candidates at z>1
- Are rare and short-lived
- Valuable insights to some of the most vital/violent processes for galaxy evolution



Star-formation studies of high-z Galaxies

…should lead to some understanding of the following quantities:

Temperature

Density

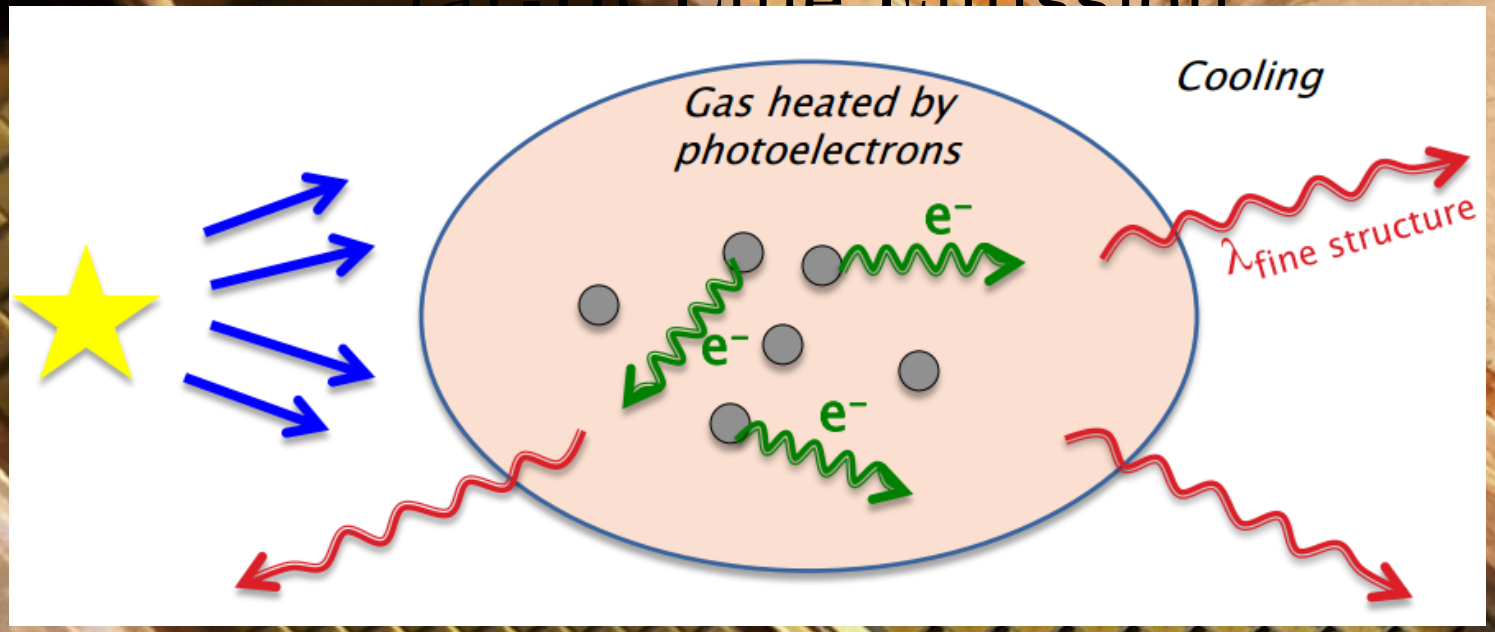
Star formation Rate

Gas Mass

Radiation Field

Metallicity

Star-formation studies of high-z Galaxies with Redshifted far-IR Line Emission

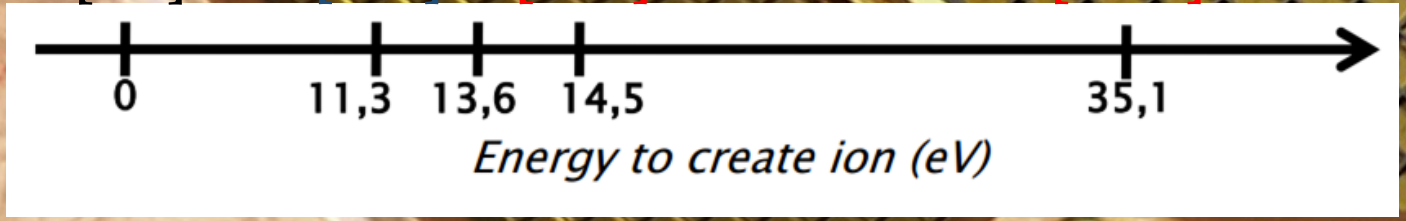


63 μm
145 μm [OI]

158 μm [CII]

[NII] 122 μm 205 μm

[OIII] 52 μm 88 μm



Far-IR probes of Star-formation

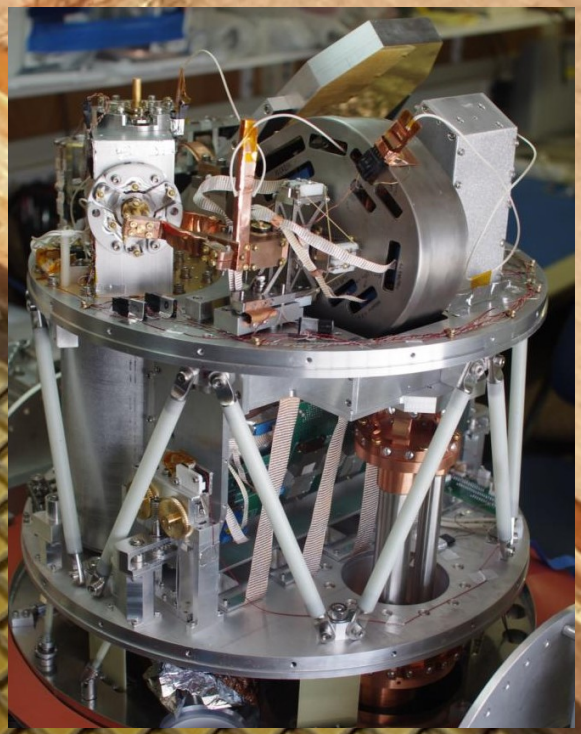
- **(along with FIR) tracks the FUV field strength**
  - # density of late O/early B stars in ISM
- **Far more can be learned by taking advantage of the other FIR fine-structure lines**
  - Neutral gas lines: **[OI] 63 and 145 µm** FUV 6 to 13.6 eV
    decouples density dependence
  - Ionized gas lines:
    [NII] 205 and 122 µm: 14.5 to 28 eV
    [NIII] 57 µm: 28 to 47 eV
    [OIII] 88 and 52 µm: 35 to 54 eV

    } Trace UV field, Density & Abundances

Combination of above lines: Allows us to trace stellar populations, gas properties, C/N/O abundances, SF clock

ZEUS-2 : The 2nd generation Redshift (z) & Early Universe Spectrometer

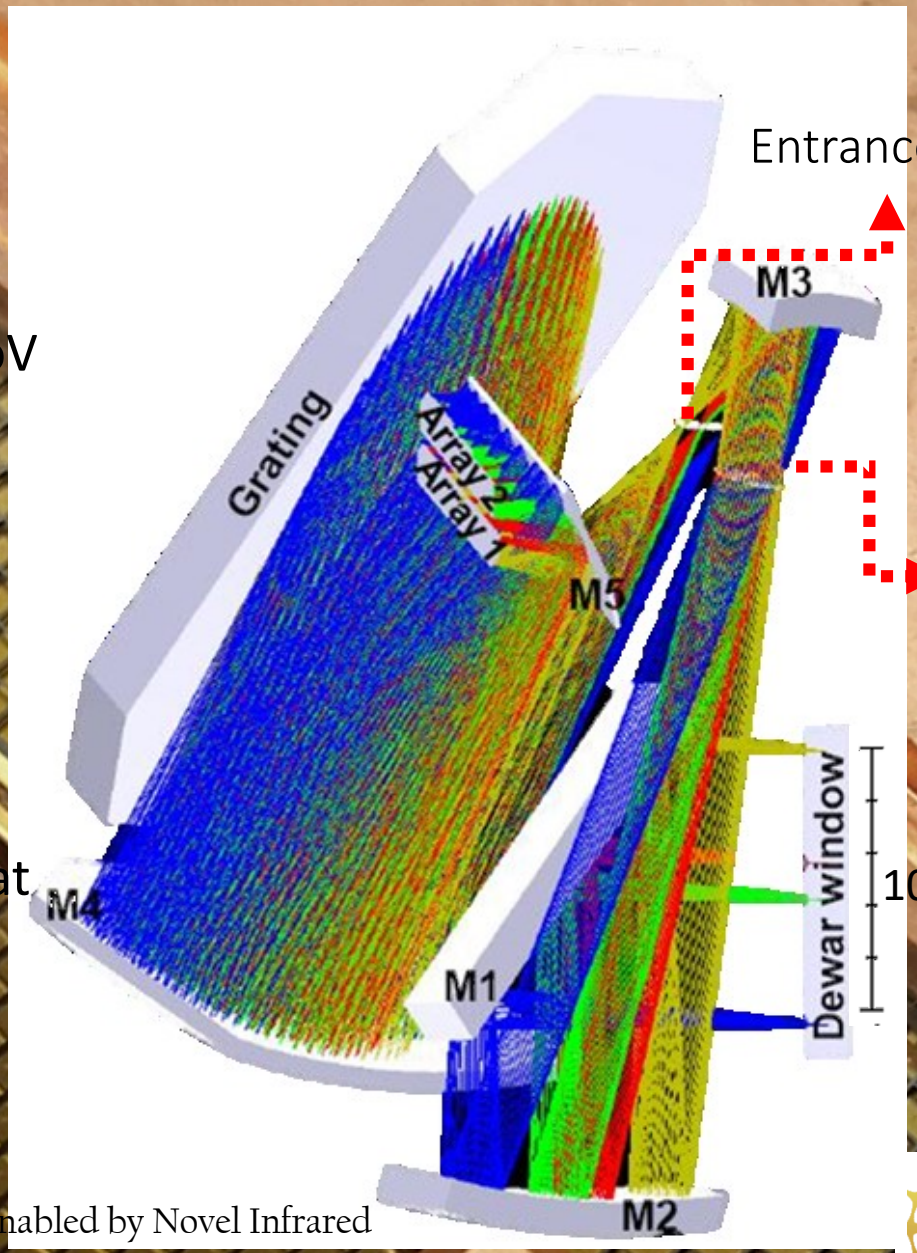
- **Dry Cryostat:** Pulse-tube cooler and two-stage ADR
- **Large focal plane** with an optimized echelle grating
  - 5-10 spatial beams on sky, R ~ 800-1300
- **3 TES Bolometer arrays** : 215, 400 & 645 μm
  - (9x22, 8x35, 5x11 pixels) @ 120 mK
  - 28:1 SQUID multiplexers from NIST.
- Hands-on training for grad students and >20 undergraduates in sub-mm instrumentation



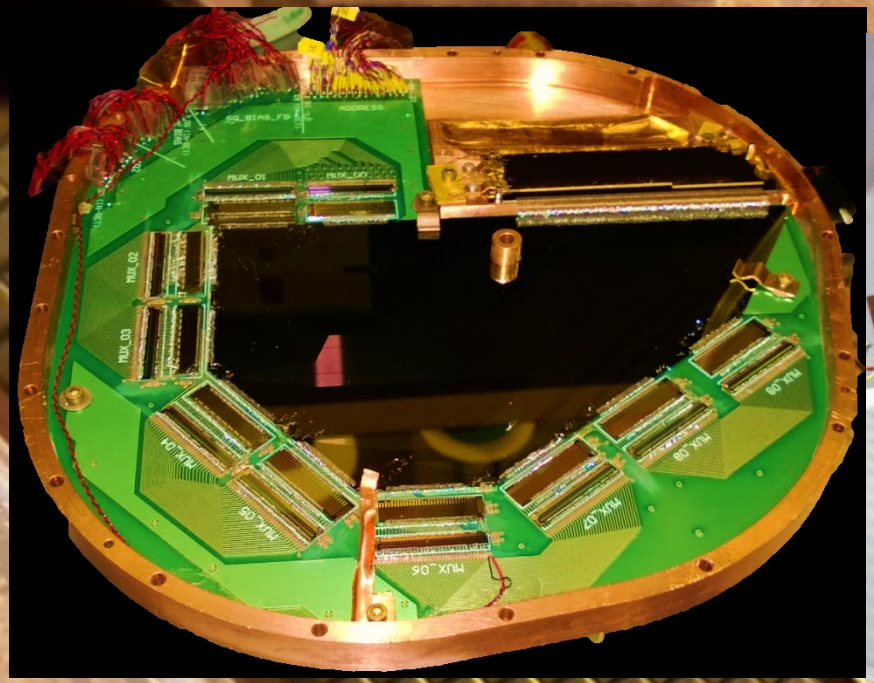
Detector: Ferkinhoff+ SPIE 2012
Opto-Mech-Cryo: Parshley+ SPIE 2012

ZEUS-2 Optics

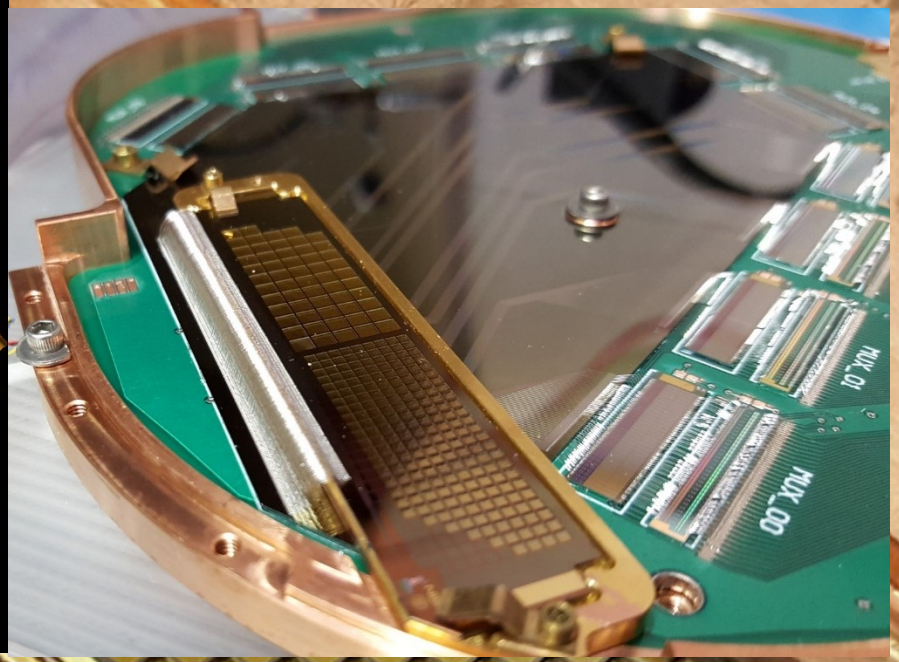
- Multi color, multi beam, large FoV with compact optics
- Blazed-ruled grating operating between 2nd and 9th order
- Diffraction limited Entrance slit at 400 µm to minimize background



ZEUS-2 focal plane Sandwich

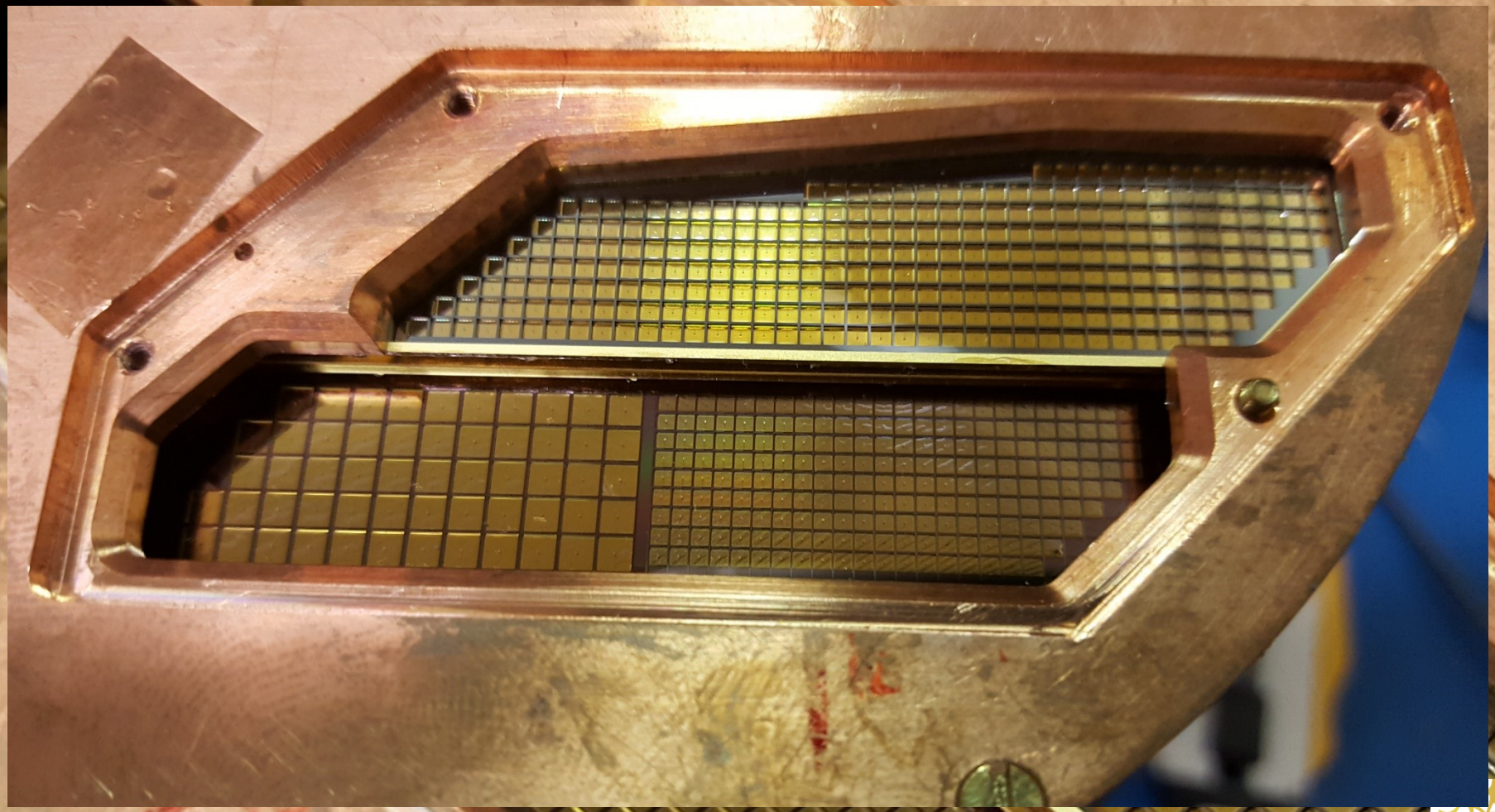


350/450 μm
Back-illuminated Array
with 10 readout columns



Back Half:
Front-illuminated
215/645 μm arrays

Fully populated ZEUS-2 focal plane



The Atacama Pathfinder Experiment (APEX) Telescope

- Llano de Chajnantor, Chile
  - At 5100 mts altitude
- One of the best sub-mm sites on Earth
  - Best PWV ~ 0.2mm, Median PWV ~ 1mm
- Modified ALMA antenna, 12 meters
  - Surface accuracy ~ 17 μm

(surface being upgraded later this year)

ration

ZEUS-2 at APEX

Redshift(z) & Early Universe Spectrometer

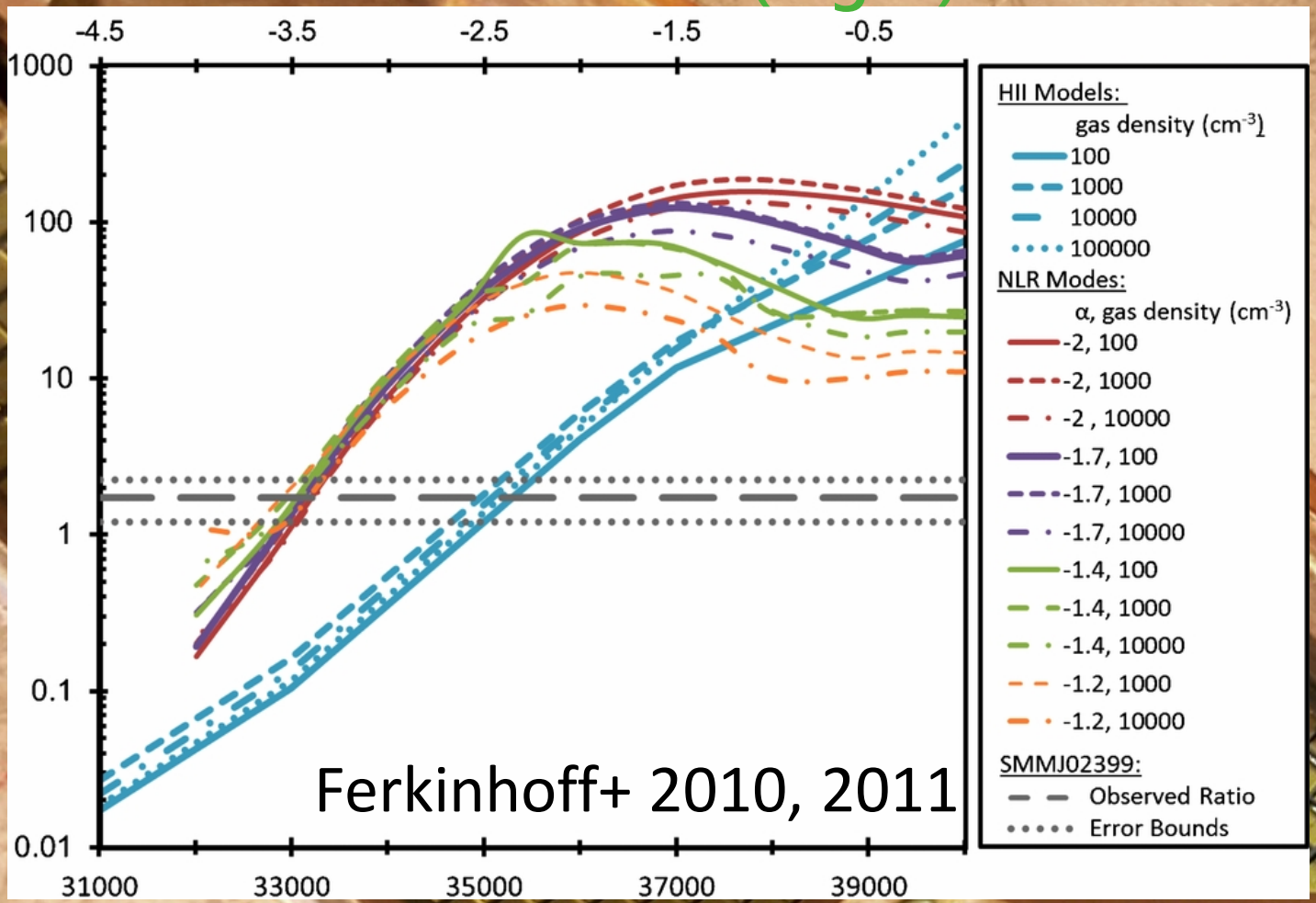
Science Enabled by Novel Infrared Instrumentation

ZEUS-2 at APEX

- ZEUS-2 on APEX offers a very sensitive ground based platform for spectroscopy other wise only possible using airborne or space based observatories
  - 4-successful observing runs to date (2012, 14-16)
- Early Universe: Far-IR probes of starformation
  - Survey of [CII], [OI] [OIII], [NII] lines from $z \sim 1 - 5$
- Local Universe: Map multiple spectral lines
  - Studies of the ionized, atomic and molecular phases of MW & nearby galaxies: [NII], mid-J CO, [CI]

Utility of Oxygen

- Comparing [OIII]/[NII]
  - Ionization state of the medium
  - Hardness of the UV field
- In NLR: UV Hardness varies little with power law index.
  - OIII/NII: ratio of ionizing photons to hydrogen nuclei. (Ionization Parameter)
- In Stellar HII Regions: Measures the effective Temperature of the Stars
  - Constrains Spectral Type, Starburst age & # such stars



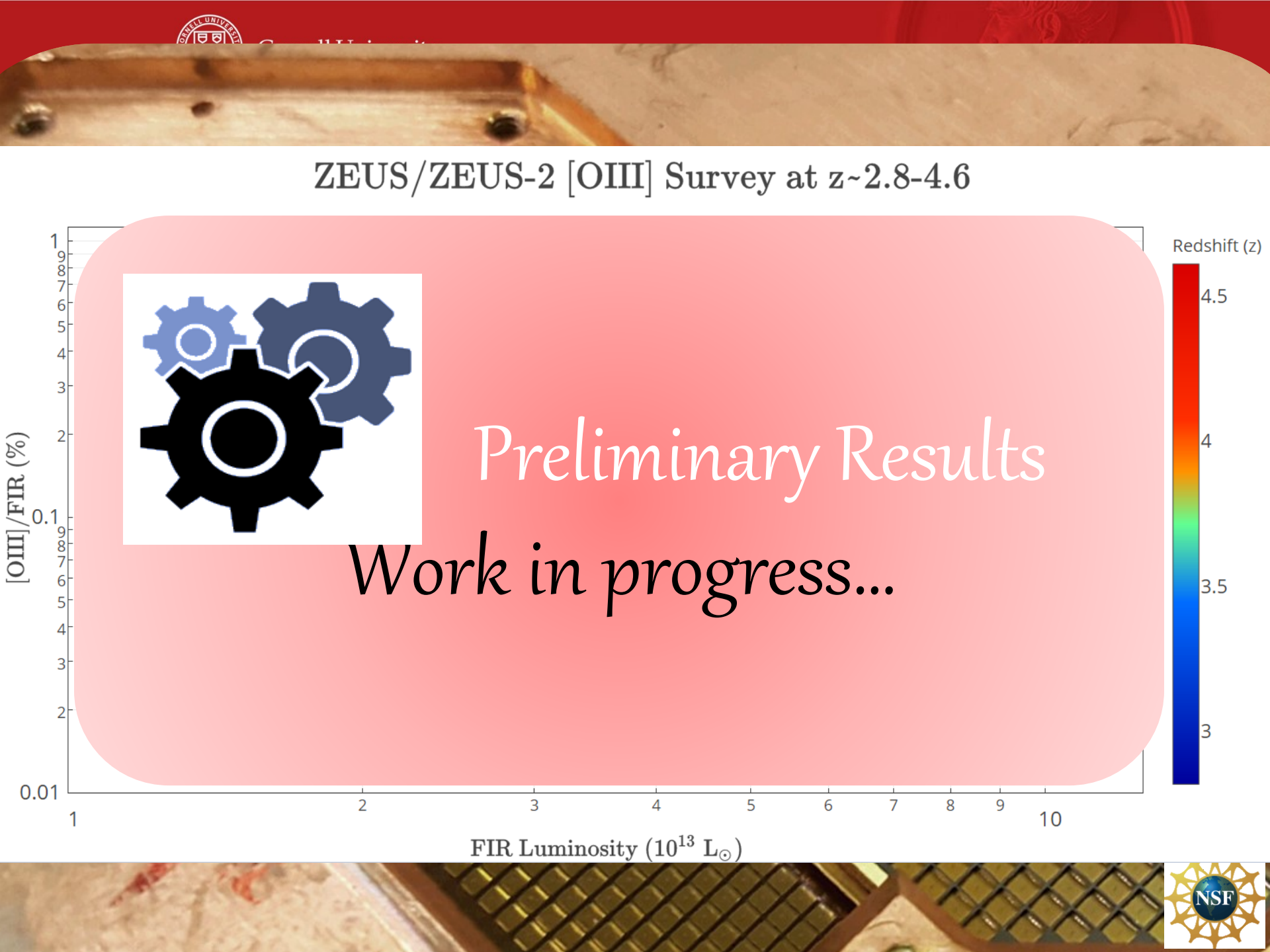
Science Enabled by Novel Infrared Instrumentation

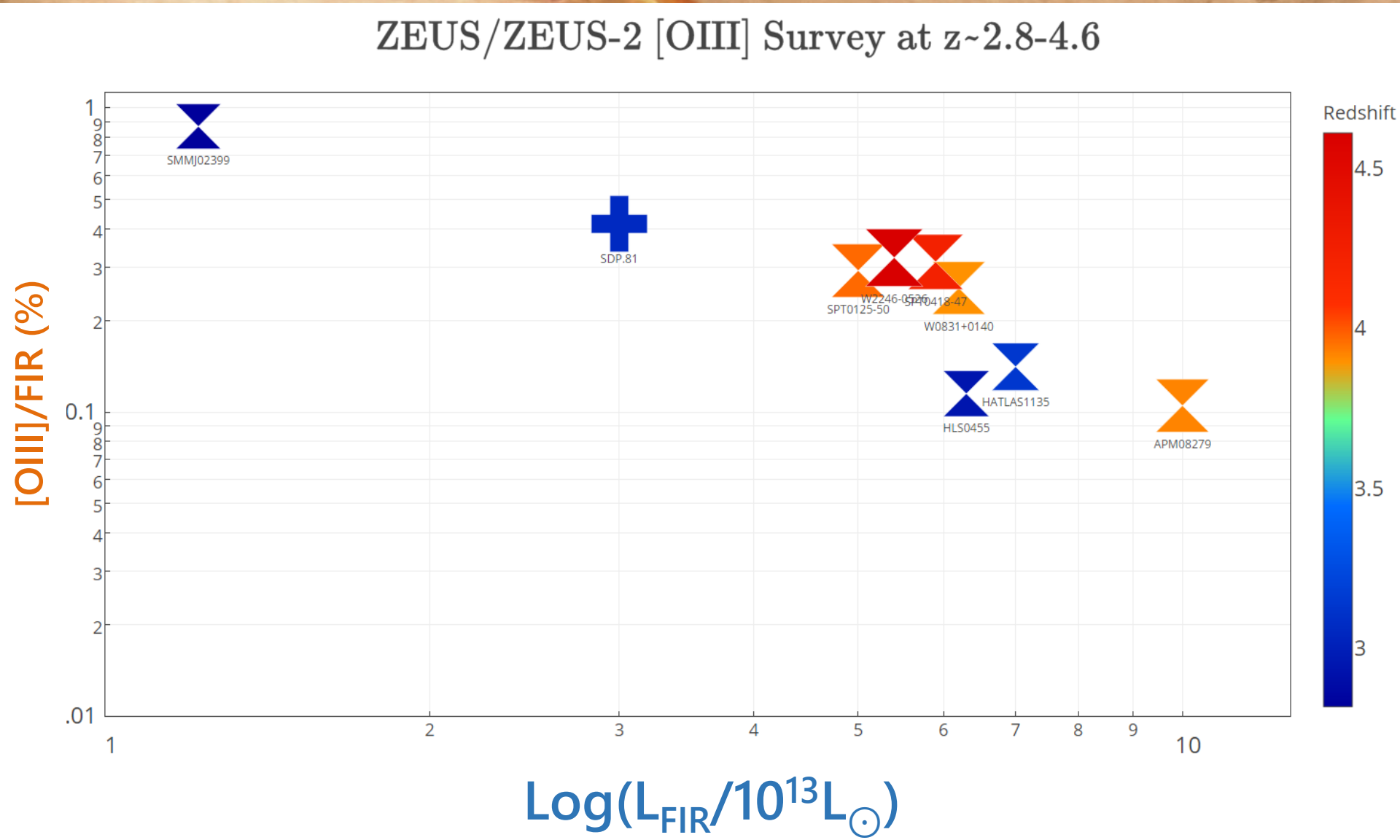
ZEUS/ZEUS2 Survey of [OIII]/[NII]

- First high-z detections of the [OIII] and [NII] lines reported by Ferkinhoff et al. 2010, 2011 using ZEUS on CSO
- We are continuing this survey of ionized far-IR lines to probe stellar populations in the early Universe with ZEUS-2.
  - 6 (1) Tentative high-z [OIII] (NII 122) detections
  - 2 upper limits (~10^{-18} W/m^2 , few $\times$ 10^{10} $L_\odot$)
  - Literature high-z [OIII]: (1 Herschel/SPIRE, 3 ALMA z>7)

ZEUS/ZEUS2 Survey of [OIII]/[NII]

- First high-z detections of the [OIII] and [NII] lines reported by Ferkinhoff et al. 2010, 2011 using ZEUS on CSO
- We are continuing this survey of ionized far-IR lines to probe stellar populations in the early Universe with ZEUS-2.
  - 6 (1) Tentative high-z [OIII] (NII 122) detections
  - 2 upper limits (~10^{-18} W/m^2 , few $\times$ 10^{10} $L_\odot$)
  - Literature high-z [OIII]: (1 Herschel/SPIRE, 3 ALMA z>7)


ZEUS/ZEUS-2 [OIII] Survey at z~2.8-4.6
Preliminary Results
Work in progress...
[OIII]/FIR (%)
FIR Luminosity (10^{13} $L_\odot$)
Redshift (z)
4.5
4
3.5
3
1
0.1
0.01
1
2
3
4
5
6
7
8
9
10

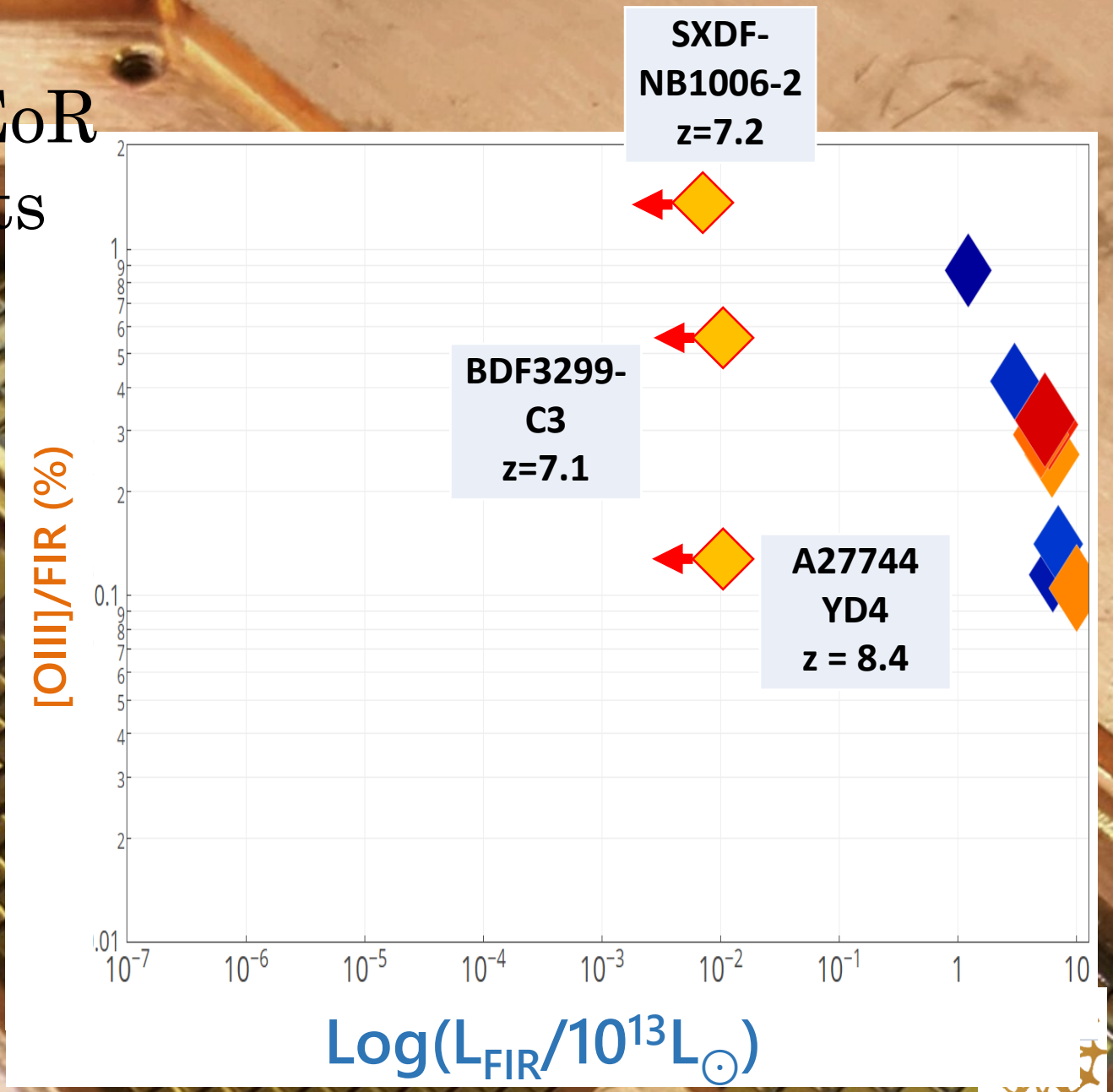

ZEUS/ZEUS-2 [OIII] Survey at z~2.8-4.6
[OIII]/FIR (%)
1
.1
.01
1
2
3
4
5
6
7
8
9
10
Log(L_FIR/10^13 L_⊙)
Redshift
4.5
4
3.5
3
SMMJ02399
SDP.81
SPT0125-50
W2246-0526
SPT0418-47
W0831+0140
HLS0455
HATLAS1135
APM08279

[OIII]/FIR : EoR ALMA Results

SXDG-NB1006-2
z=7.21
Inoue+ 16

A27744-YD4
z=8.38
Laporte+ 17

BDF3299 Clump-C
z=7.11
Carniani+ 17



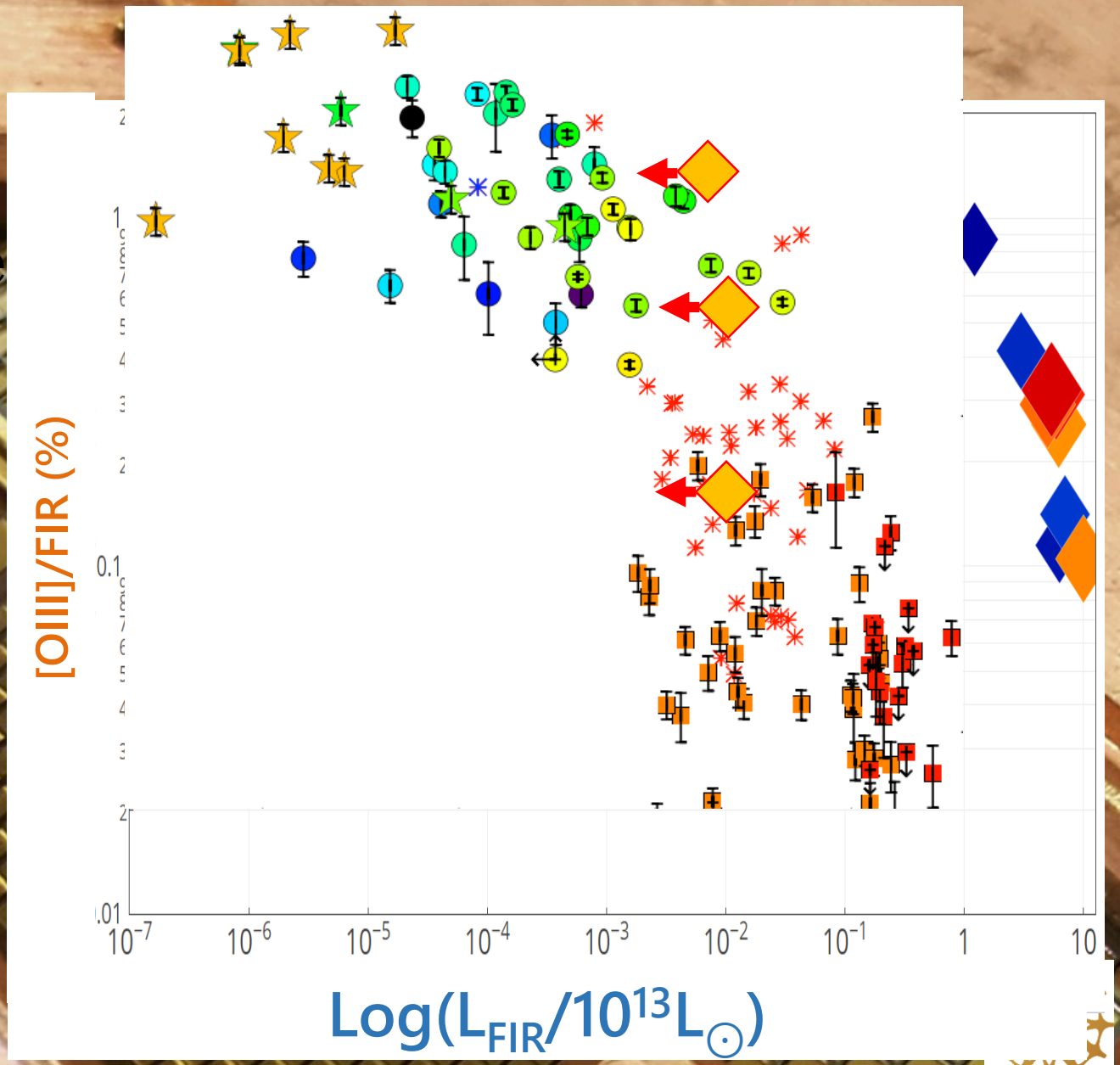
[OIII]/FIR : Compared to Local Sample

(ISO, Red *)
Brauher 08

(HERUS, Orange □)
Farrah+ 13

(SHINING, Red □)
Gracia-Carpio+ 11

(DGS, ○ , ★)
Cormier+15



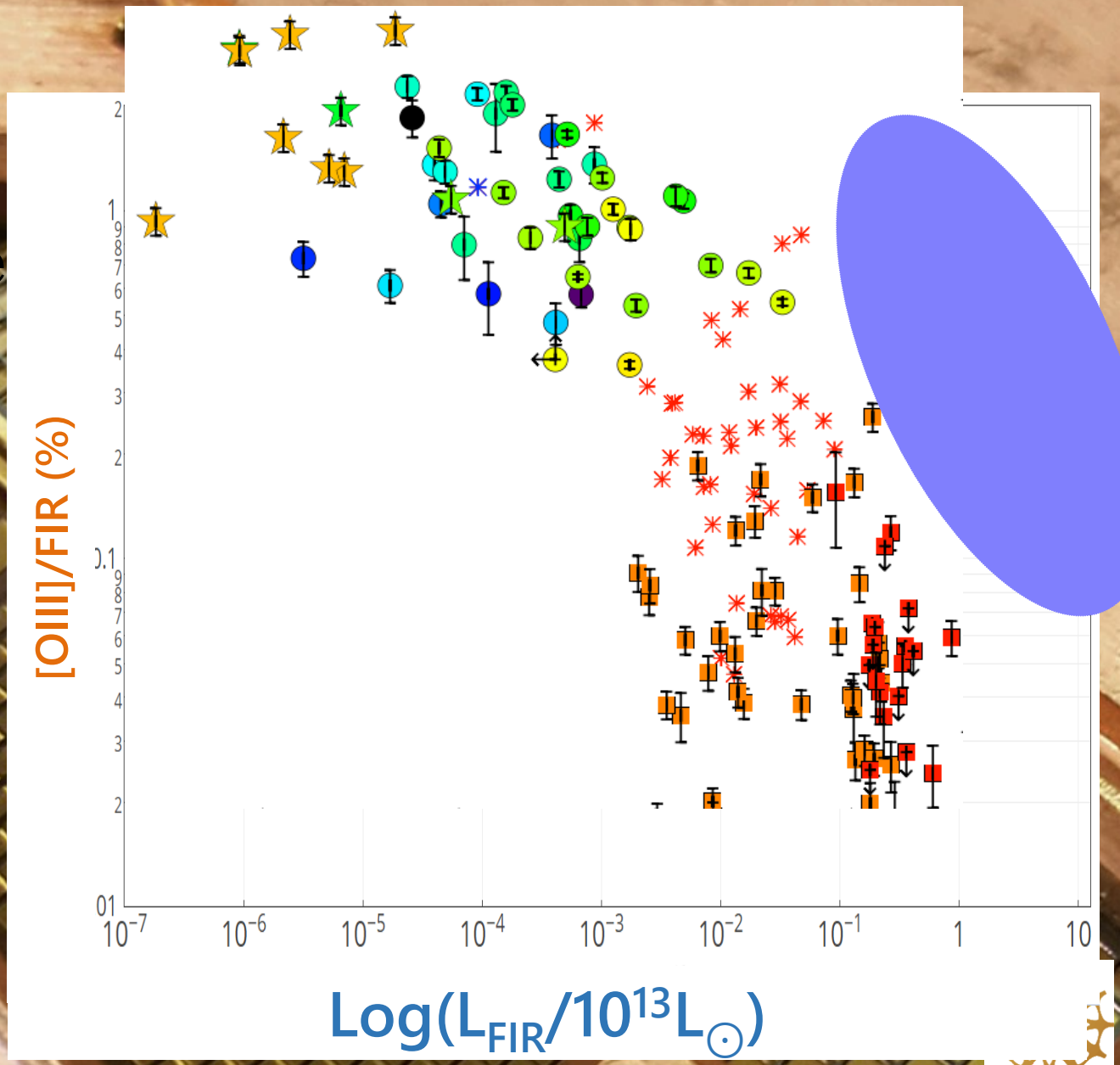
[OIII]/FIR : Compared to Local Sample

(ISO, Red *)
Brauher 08

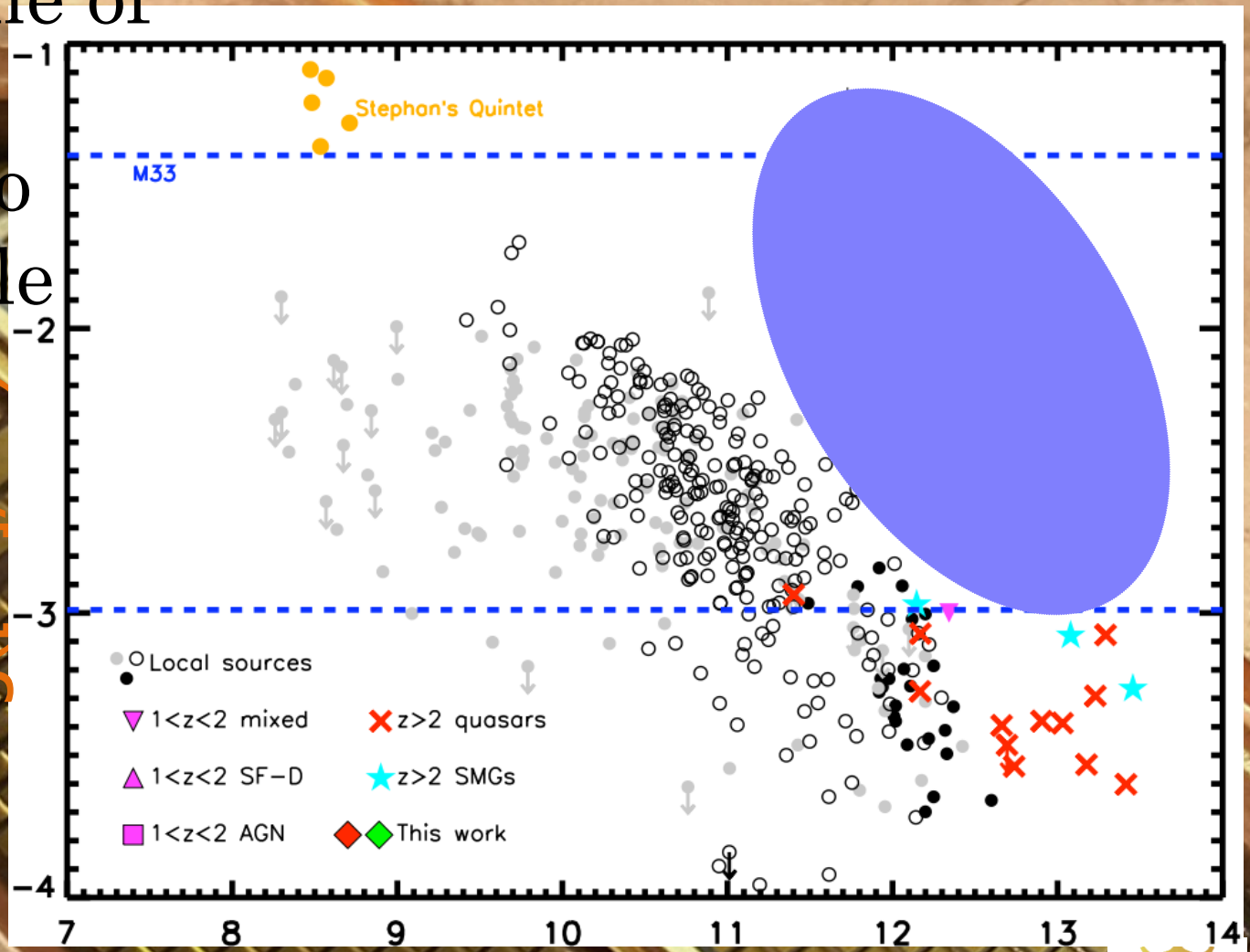
(HERUS, Orange □)
Farrah+ 13

(SHINING, Red □)
Gracia-Carpio+ 11

(DGS, ○ , ★)
Cormier+15

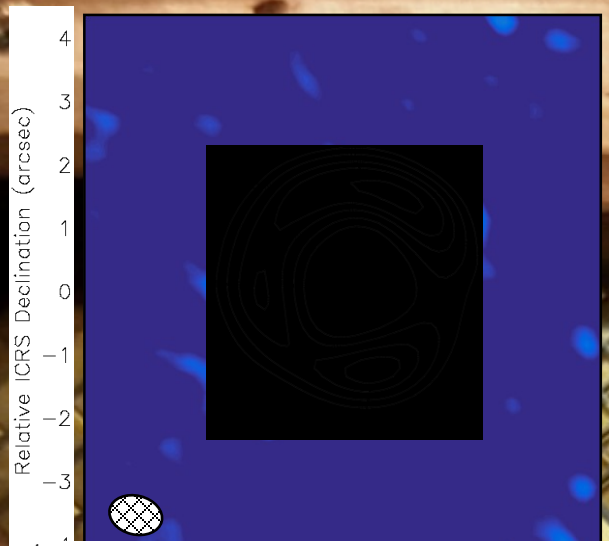


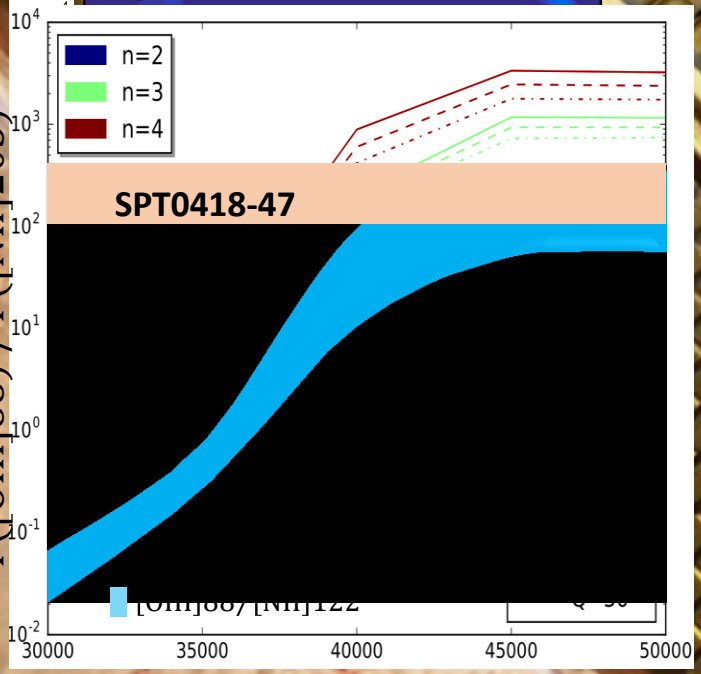
Reminded me of [CII]/FIR : Compared to Local Sample



Stacey+ 10
Hailey-Dunsheath+ 10
Ferkinhoff+ 14,
Brisbin+ 15

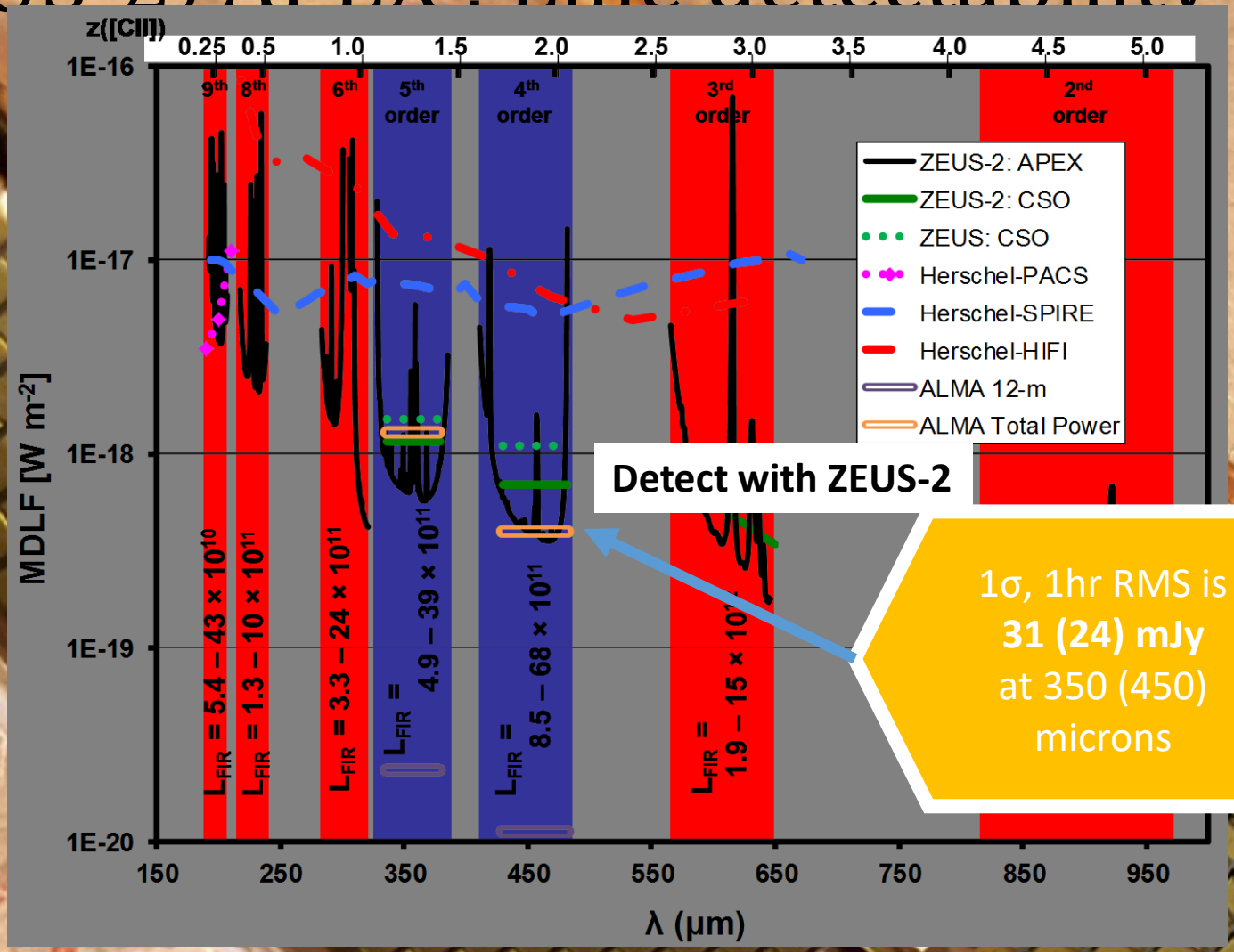
Mapping ZEUS sources



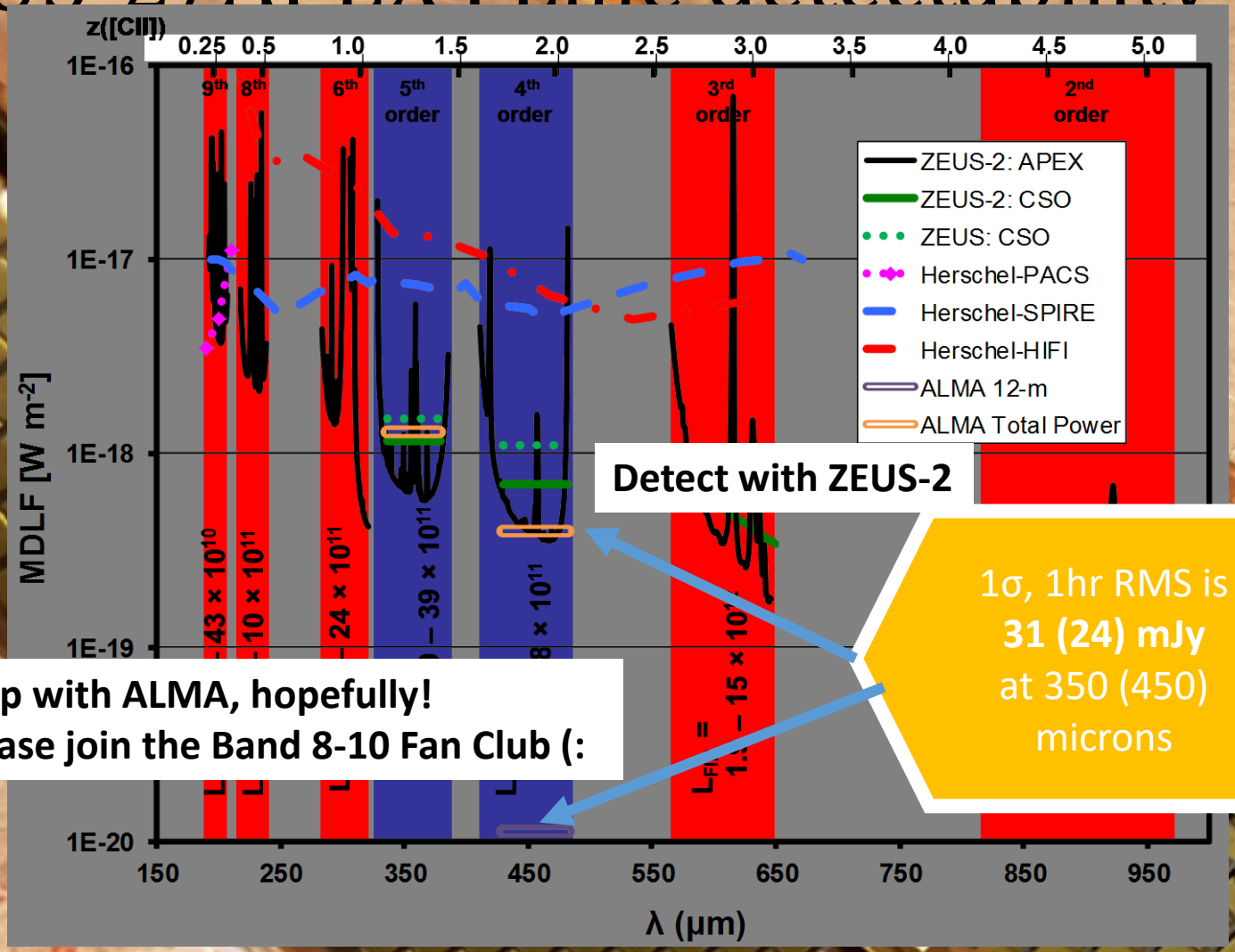


- Any line detected with ZEUS-2 can be mapped with ALMA across 40 beams
- Continuum sizes can be misleading
- Some sources are gravitationally lensed – enabling sampling of a broader range for intrinsic L_{IR}
- 8 ALMA Cy3/4 programs, over 30 hours.
- VLA program, ZINGRS!

ZEUS-2 / APEX : Line detectability



ZEUS-2 / APEX : Line detectability



Detect with ZEUS-2

1σ, 1hr RMS is **31 (24) mJy** at 350 (450) microns

Map with ALMA, hopefully!
Please join the Band 8-10 Fan Club (:

Thank You!