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

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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

Continuous Accretion from Halo and Disk Instabilities

(Major) Mergers and Starbursts

Science Enabled by Novel Infrared Instrumentation

Hopkins+12

Dekel+09

SFR

BH accretion (scaled)

Winding down

Peak

Accretion epoch

Madau&Dickinson14
Galaxy Evolution over Cosmic Time

$z = 4, \sim 2\text{kpc disks}$

$z = 0, >30\text{kpc Galaxies}$

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Dusty Star Forming galaxies

- Contribute Significantly to Cosmic Star Formation

Science Enabled by Novel Infrared Instrumentation
Dusty Star Forming galaxies

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

Science Enabled by Novel Infrared Instrumentation
Rare beasts!

Herschel discovered \( \sim 10^5 \) candidates at \( z \geq 1 \)

- Are rare and short-lived
- Valuable insights to some of the most vital/violent processes for galaxy evolution

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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

Gas heated by photoelectrons

 Cooling

\[ \lambda_{\text{fine structure}} \]

63 \( \mu m \)
145 \( \mu m \)

[OI]

158 \( \mu m \)

[CI]

122 \( \mu m \)

205 \( \mu m \)

52 \( \mu m \)

88 \( \mu m \)

[OIII]

Energy to create ion (eV)
Far-IR probes of Star-formation

[CII] (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: \([\text{OI}]\) 63 and 145 µm FUV 6 to 13.6 eV
decouples density dependence
  - Ionized gas lines:
    - \([\text{NII}]\) 205 and 122 µm: 14.5 to 28 eV
    - \([\text{NIII}]\) 57 µm: 28 to 47 eV
    - \([\text{OIII}]\) 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 $\mu$m
Back-illuminated Array
with 10 readout columns.

Back Half:
Front-illuminated
215/645 $\mu$m arrays

Science Enabled by Novel Infrared Instrumentation
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)
2nd Generation

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 otherwise 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
Effective Stellar Temperature (K)

Ionization Parameter (log U)

F([OIII]88) / F([NII]122)

Ferkinhoff+ 2010, 2011

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 ($\sim 10^{-18} \text{ W/m}^2$, few $\times 10^{10} L_\odot$)
  - Literature high-z [OIII]: (1 Herschel/SPIRE, 3 ALMA z>7)
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ZEUS/ZEUS-2 [OIII] Survey at z~2.8-4.6

Preliminary Results

Work in progress...
ZEUS/ZEUS-2 [OIII] Survey at z~2.8-4.6

\[
\log \left( \frac{L_{\text{FIR}}}{10^{13} L_\odot} \right)
\]
[OIII]/FIR : EoR
ALMA Results

SXDF-NB1006-2
z=7.21
Inoue+ 16

A27744-YD4
z=8.38
Laporte+ 17

BDF3299 Clump-C
z=7.11
Carniani+ 17

Log(L_{FIR}/10^{13}L_\odot)
[OIII]/FIR : Compared to Local Sample

(ISO, Red *)
Brauher 08

(HERUS, Orange □)
Farrah+ 13

(SHINING, Red □)
Gracia-Carpio+ 11

(DGS, O , ★)
Cormier+15

\[
\log(L_{\text{FIR}}/10^{13}L_{\odot})
\]
[OIII]/FIR:
Compared to Local Sample

(ISO, Red *)
Brauher 08

(HERUS, Orange □)
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(DGS, O , ★)
Cormier+15

Log(L_{FIR}/10^{13}L_{⊙})
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 $L_{\text{IR}}$
• 8 ALMA Cy3/4 programs, over 30 hours.
• VLA program, ZINGRS!
ZEUS-2/APEX: Line detectability

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

Detect with ZEUS-2
ZEUS-2/APEX: Line detectability

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

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

Detect with ZEUS-2

Map with ALMA, hopefully!
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Thank You!