Far-Infrared Fine Structure Line Studies of Star Formation in the Early Universe

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Far-IR Fine Structure Lines

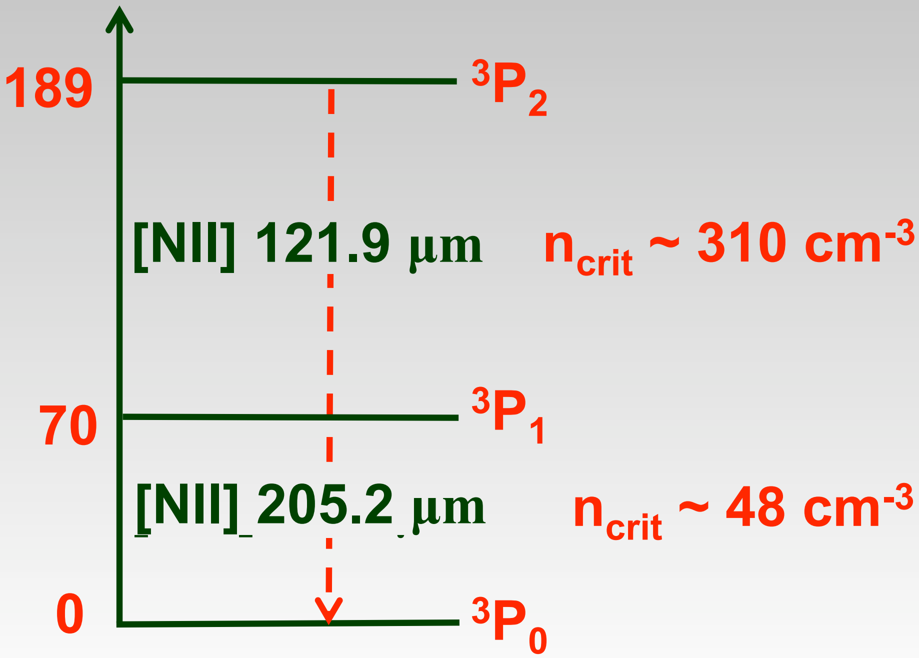
- Most abundant elements are O, C, N
- Species with 1,2,4 or 5 equivalent p electrons will have ground state terms split into fine-structure levels
  - O: O^{+++} (25 um), O^{++} (52 & 88 um), O (146 & 63 um)
  - C: C^{+} (158 um), C^{0} (370 & 610 um)
  - N: N^{++} (57 um), N^{+} (122 & 205 um)
- These lines lie in the far-IR where extinction is not an issue
  - Collisionally excited / optically thin ⇒ cool the gas – trace its physical conditions
  - Reveal the strength and hardness of ambient UV fields – extent and age of the starburst
  - Trace abundances – processing of ISM

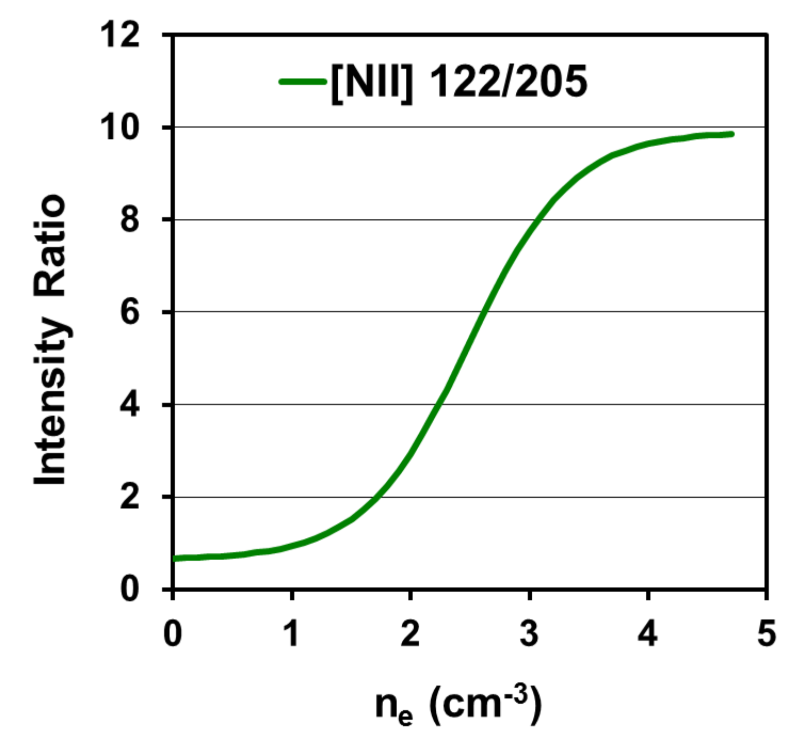
Utility: Ionized Gas Regions

- Density tracers
  - Einstein A coefficients $\propto \nu^3$, collision rates q_{ul} ~ constant

    $\therefore$ since $n_{crit} \sim A/q_{ul}$ we have $n_{crit} \propto \nu^3$
  - Furthermore the emitting levels lie far below T_{gas}

    $\Rightarrow$ line ratios T-insensitive probes of gas density





Utility: Ionized Gas Regions

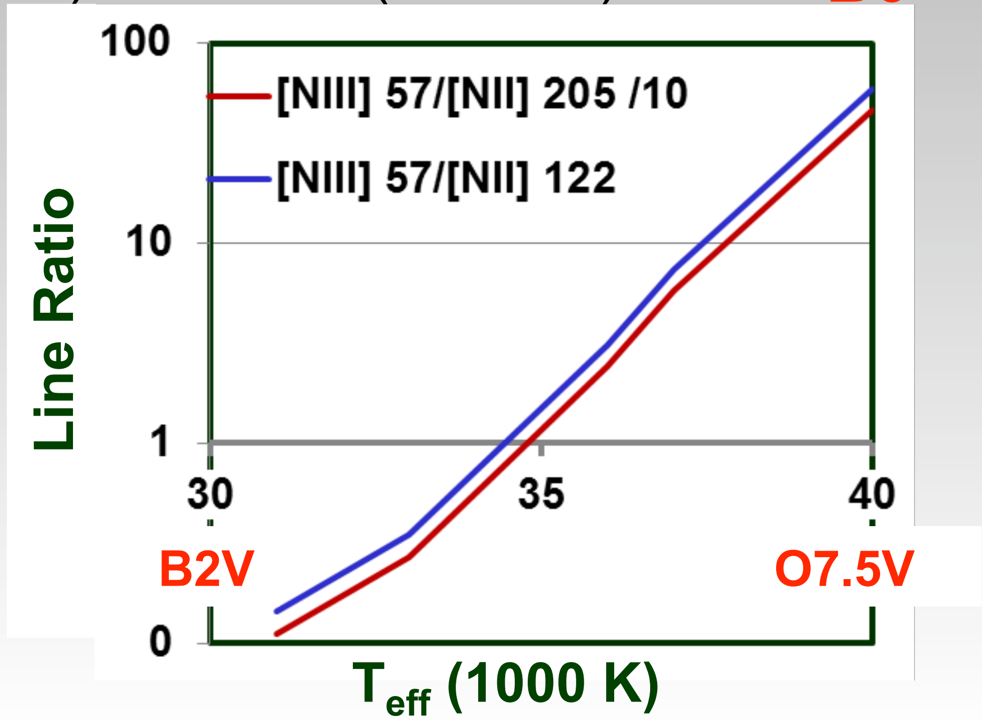
- Hardness of the ambient radiation field
  - Within an HII region, the relative abundance of the ionization states of an element depend on the hardness of the local interstellar radiation field. For exa[mple]

O7.5 Neutral ISM

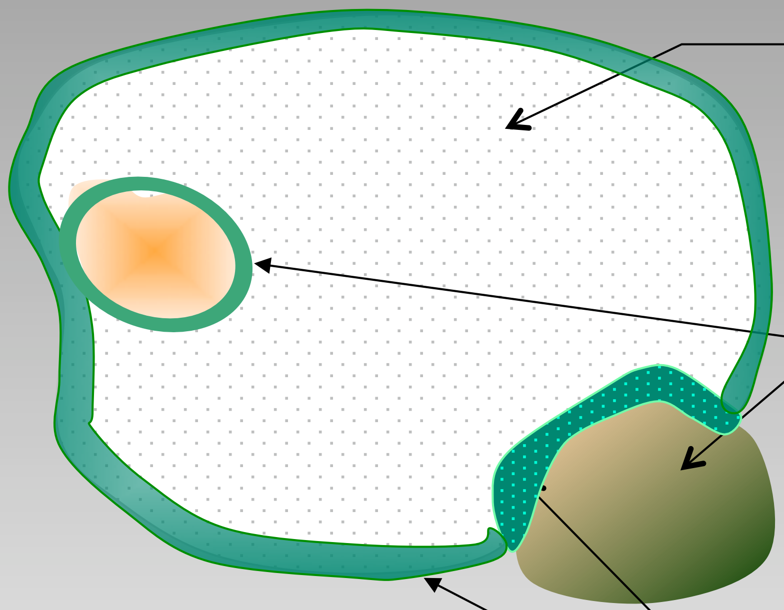
AGN → O^{+++} (54.9 eV), O^{++} (35.1 eV), O^{0} (<13.6 eV)

O8 → N^{++}(29.6 eV), N^{+} (14.5 eV) ← B0

Line ratios between ionization states determine T_{eff}



Neutral Gas Lines: Photodissociation Regions



Molecular cloud collapses, forming stars.

Ionized Hydrogen (HII) regions surrounding newly formed stars.

Photodissociation regions form where far-UV (6-13.6 eV) photons impinge on neutral clouds – penetrate to A_V ~ 3

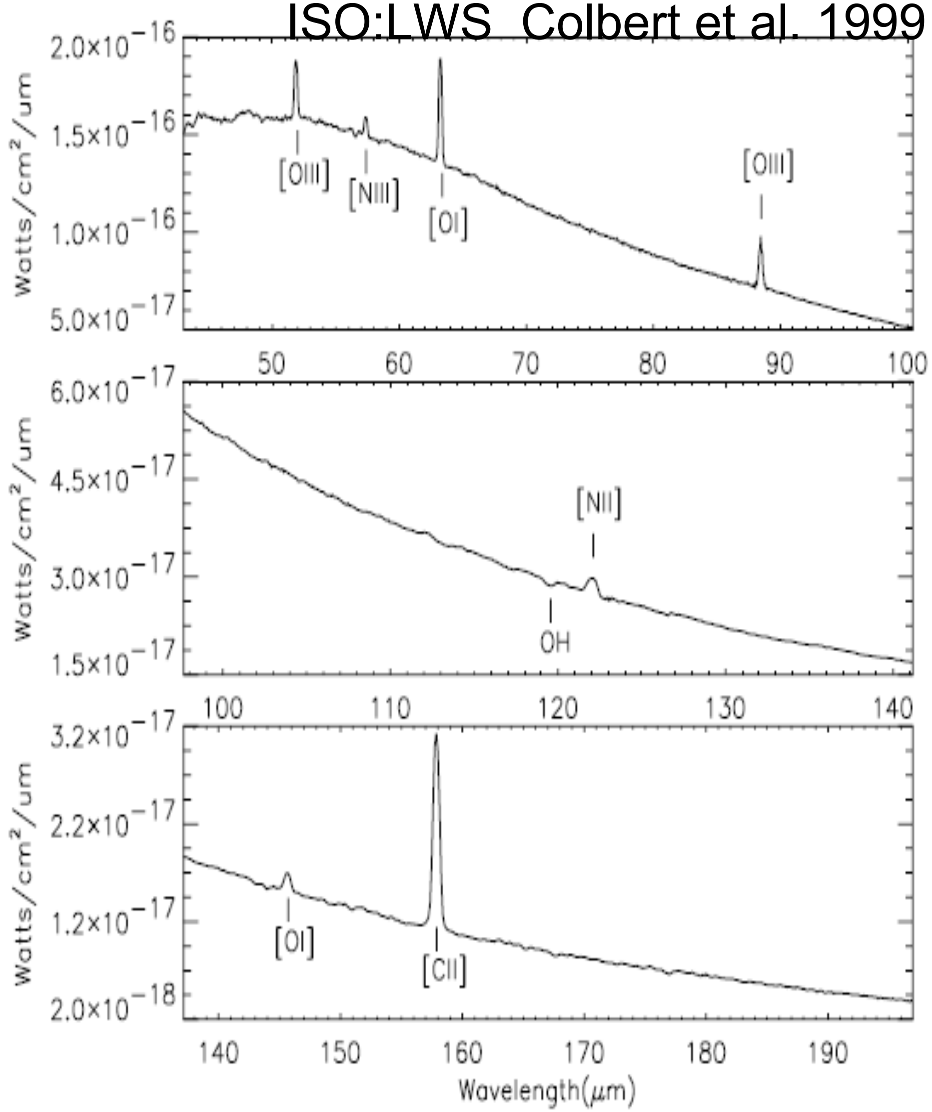
The [CII] and [OI] Line Trace the FUV Radiation Field Strength

- ~0.1 and 1% of the incident far-UV starlight heats the gas through the photoelectric effect, which cools through far-IR line emission of [CII] and [OI] 63 μm
- The efficiency of gas heating is a function of n and FUV field (6 to 13.6 eV) strength, G_0
  - As G_0 rises at constant n, grain charge builds up, lowering the excess KE of the next photo-electron
  - This is mitigated by raising n, enabling more recombinations, so that the efficiency is ~ G_0/n
- Most of the far-UV comes out as FIR continuum down-converted by the dust in the PDRs
- Therefore, the ([CII]+[OI])/FIR ratio measures the efficiency, hence G_0/n. *The combination yields both G and n, since the [CII]/[OI] ratio is density sensitive.*

Air and Spaceborne Platforms: M82

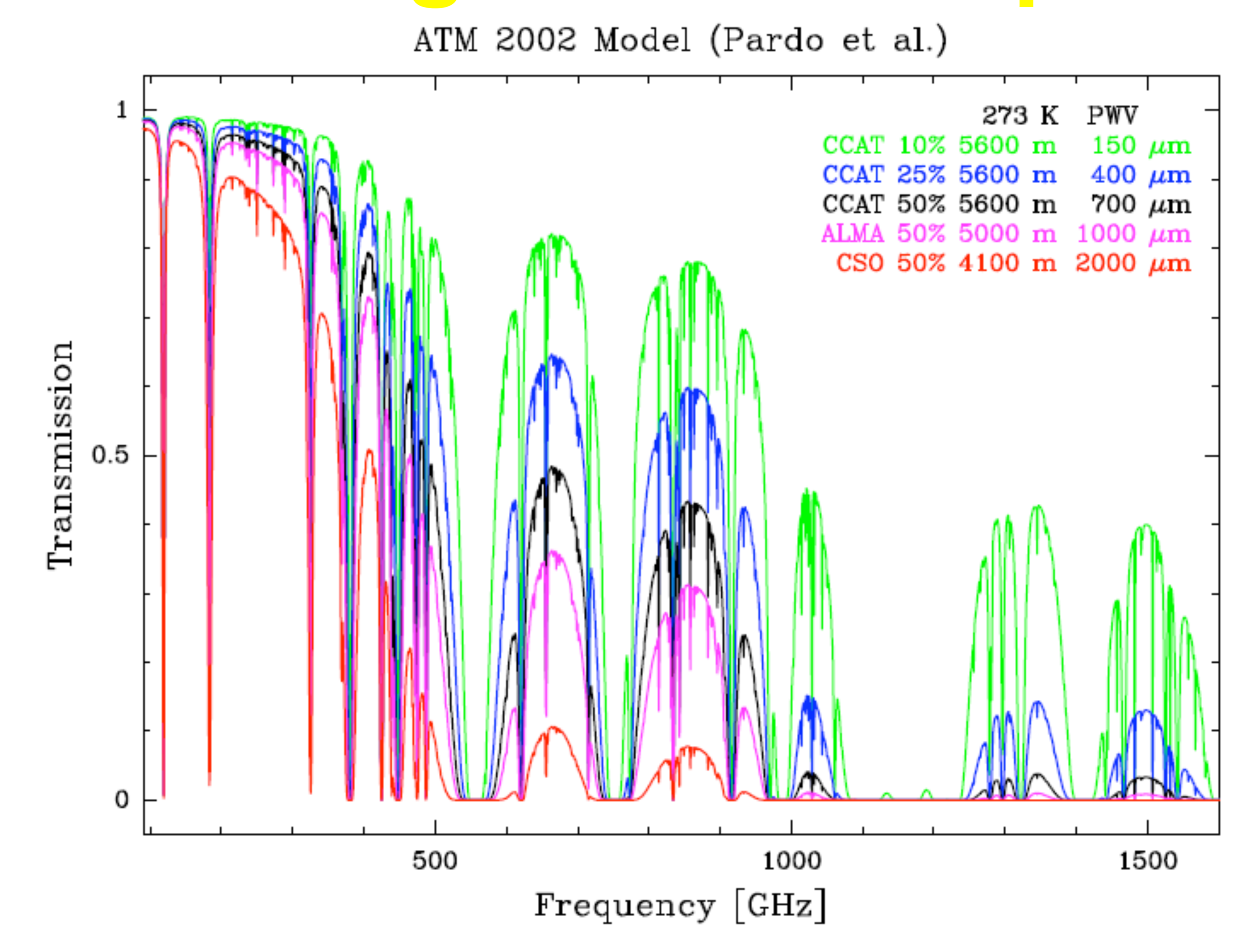
- Lines: [SIII], [SiII], [OIII], [OI], [NII], [CII], [CI]
- Overall Conclusions:
  - Clumpy neutral ISM
    - 50% PDRs, 50% MC cores
    - PDRs: G_0 ~ 700, n~3000 cm^{-3}
  - Ionized ISM
    - Density: 200 cm^{-3}
    - Mass 20% of neutral gas
    - Volume filling factor: 10%
  - Stellar Population:
    - 3 to 5 Myr old instantaneous starburst
    - 100 $M_\odot$ cut-off

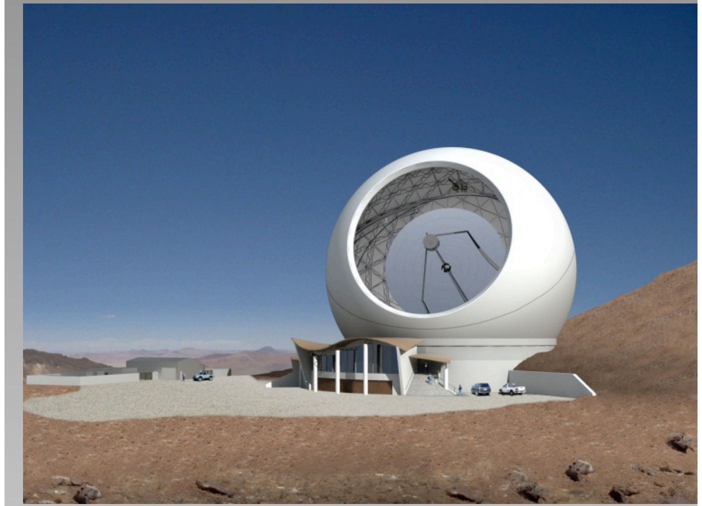
ISO:LWS Colbert et al. 1999



- KAO Study: Lord et al. 1996
- ISO Study: Colbert et al. 1999
- Herschel Study: Contursi et al. 2010

High z Far-IR Spectroscopy





(future) 25 meter CCAT windows on Cerro Chajnantor at 5600 m

- Dust is pervasive even at highest redshifts ⇒ would like to use far-IR lines in early Universe studies. Difficult with small aperture satellites, but enabled with large submm/mm telescopes and arrays
- Unfortunately, telluric windows limit spectral coverage and restrict numbers of lines available for any given source, but still…

The Redshift (z) and Early Universe Spectrometer: ZEUS

S. Hailey-Dunsheath
Cornell PhD 2009

- Submm (650 and 850 GHz) grating spectrometer

◊R ≡ $\lambda/\Delta\lambda$ ~ 1200 ◊ BW ~ 20 GHz ◊ T_{rec}(SSB) < 40 K

⇒ *Limiting flux (5σ in 4 hours) ~ 0.8 to 1.1 ×10^{-18} W m^{-2} (CSO)*

⇒ *Factor of two better on APEX*

- Data here from ZEUS – single beam on the sky
- Upgrade to ZEUS-2 a ◊ 6 color (200, 230, 350, 450, 610, 890 μm bands); ◊ 40 GHz Bandwidth ◊ 10, 9, & 5 beam system

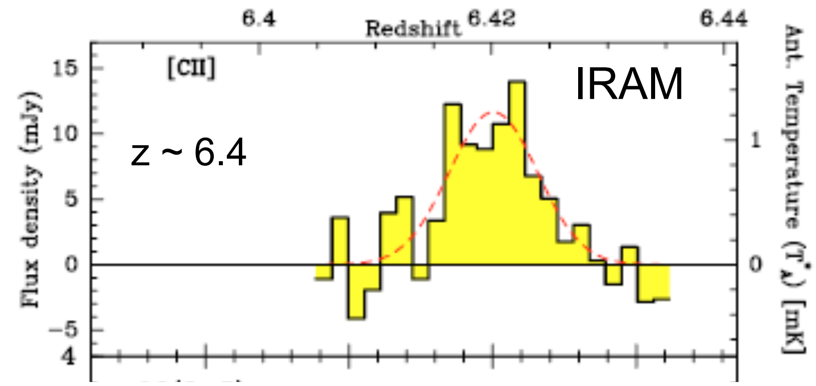
ZEUS/CSO z = 1 to 2 [CII] Survey

Survey investigates star formation near its peak in the history of the Universe

- First survey -- a bit heterogeneous
  - Attempt made to survey both star formation dominated (SF-D) and AGN dominated (AGN-D) systems
  - Motivated by detection – at the time of submission, only 4 high z sources reported elsewhere…
  - L_{FIR} (42.5<λ< 122.5 μm): 4×10^{12} to 2.5×10^{14} $L_{\odot}$
- To date we have reported 13 (now have 22) new detections & 1 strong upper limit

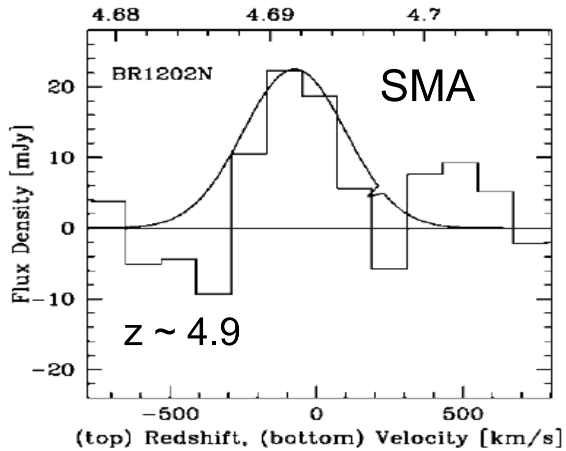
High z [CII]

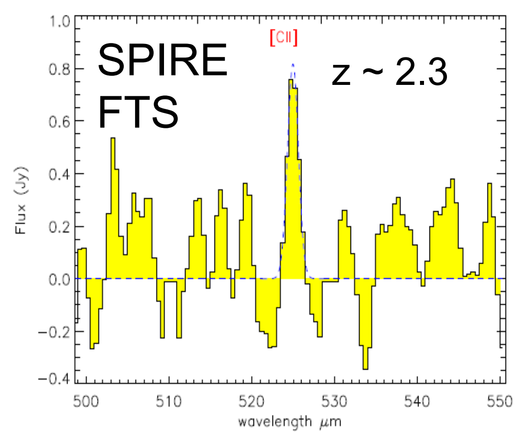
- First detection at high z: J1148+5251 QSO @ z=6.42
- Subsequent detections of other AGN then SB associated systems
  - First detections: [CII]/$L_{far\text{-}IR}$ ≡ R ~ 2-4 × 10^{-4} ~ local ULIRGs
    - PDR Model: High G_o
  - Elevated star-formation rates: 1000 solar masses/yr



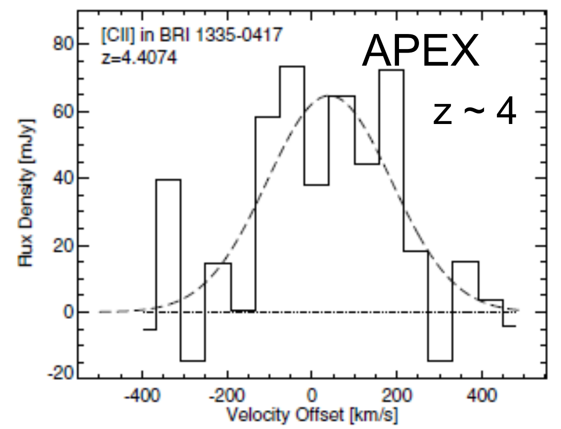
Maiolino et al. 2005

Iono et al. 2006

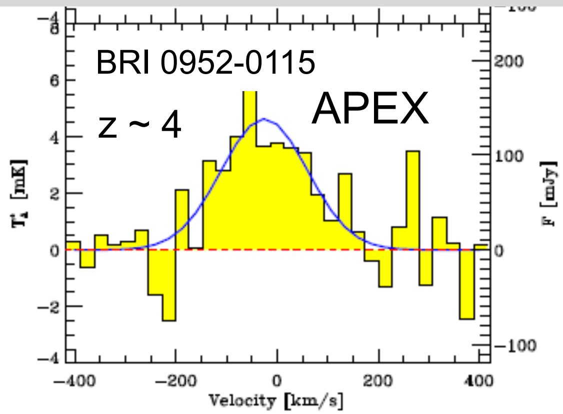




Ivison et al. 2010

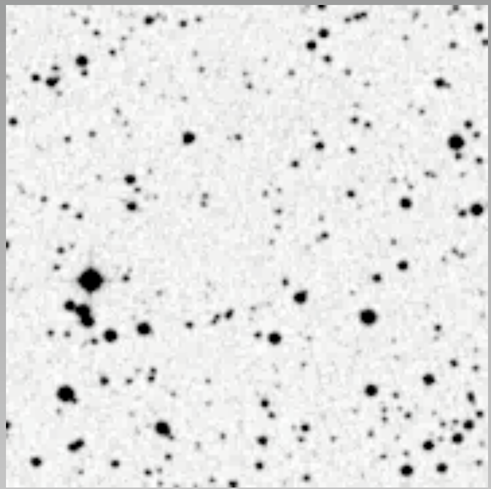
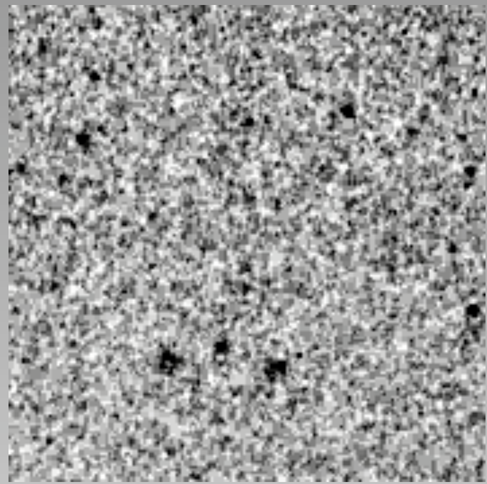
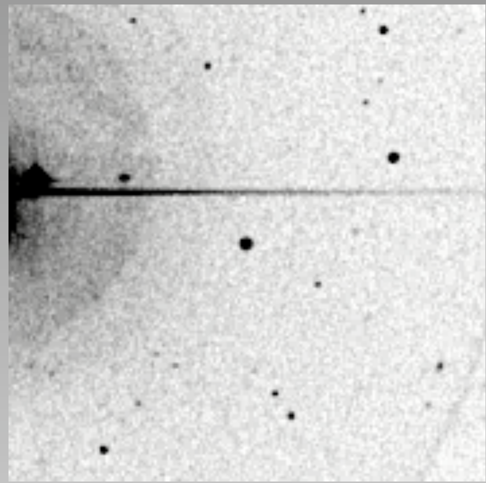
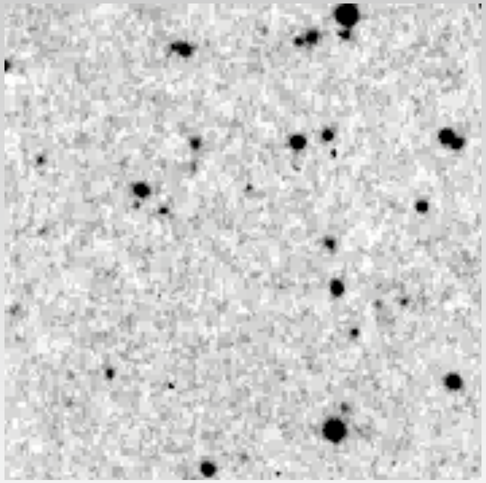
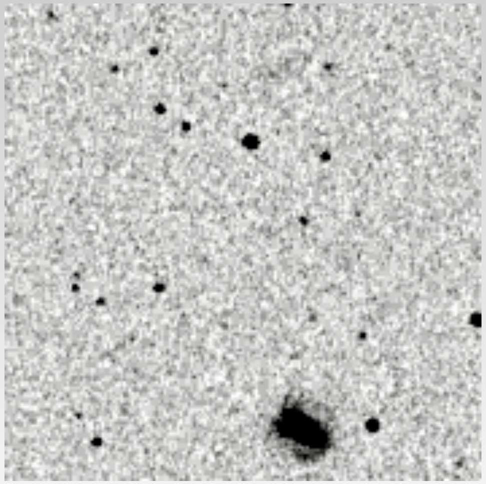
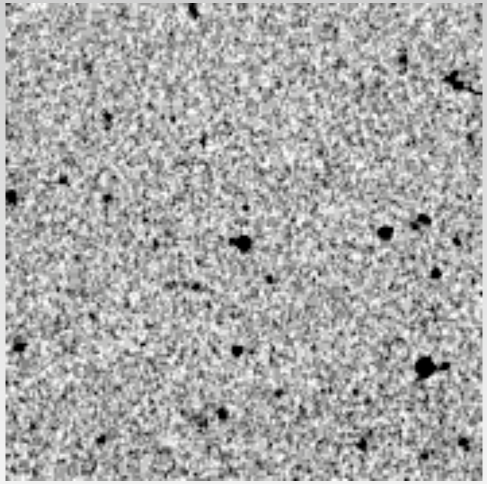


Wagg et al. 2010

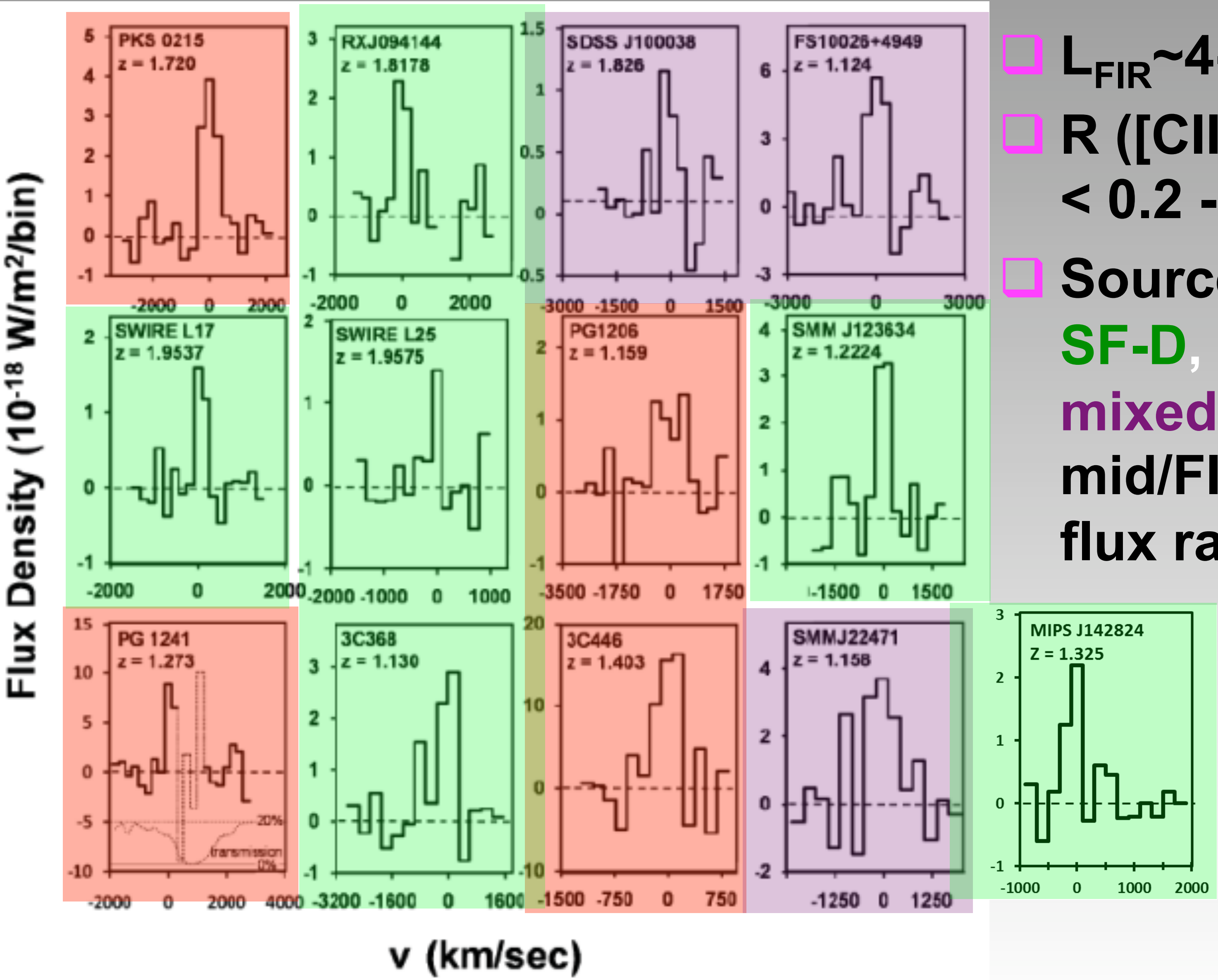


Maiolino et al. 2009

A Few Optical Images…

ZEUS Redshift 1 to 2 [CII] Survey

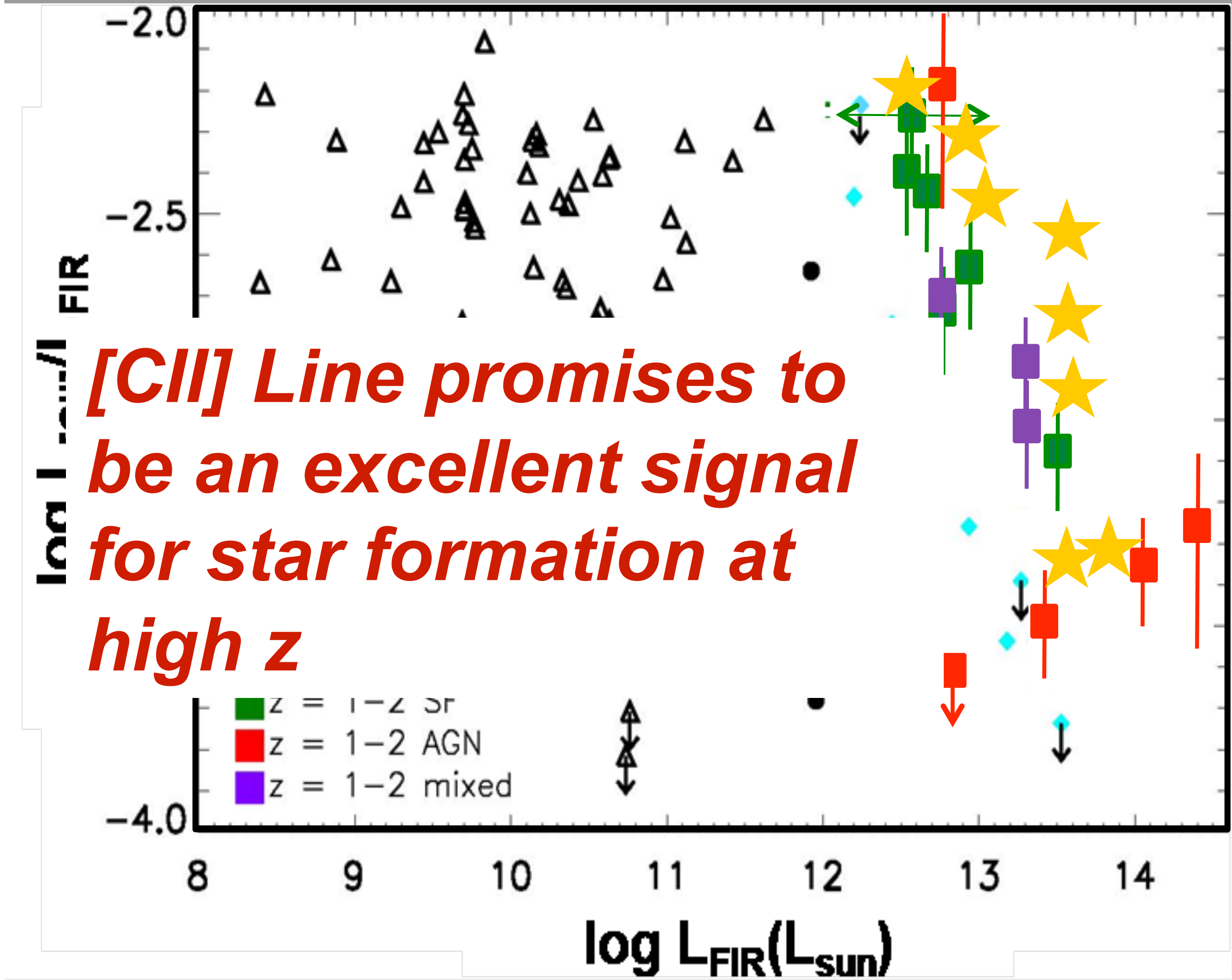


- L_{FIR}~4-240 × 10^{12} $L_{\odot}$
- R ([CII]/$L_{far\text{-}IR}$): < 0.2 - 6 × 10^{-3}
- Sources split into SF-D, AGN-D, mixed – based on mid/FIR continuum flux ratios

Hailey-Dunsheath et al. ApJ 714, L163 (2010)

Stacey et al. ApJ 724, 957 (2010)

Results: The [CII] to FIR Ratio

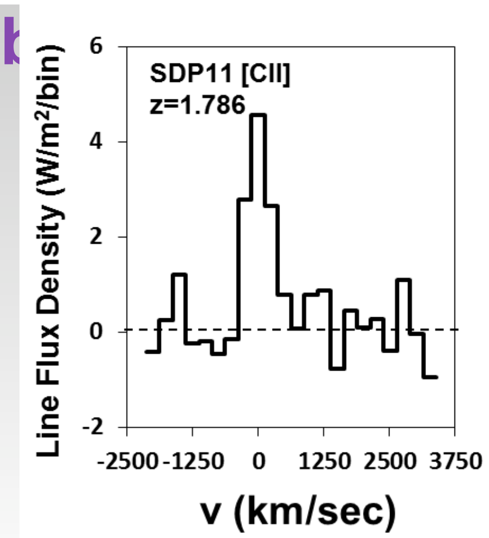


[CII] Line promises to be an excellent signal for star formation at high z

SB-D:

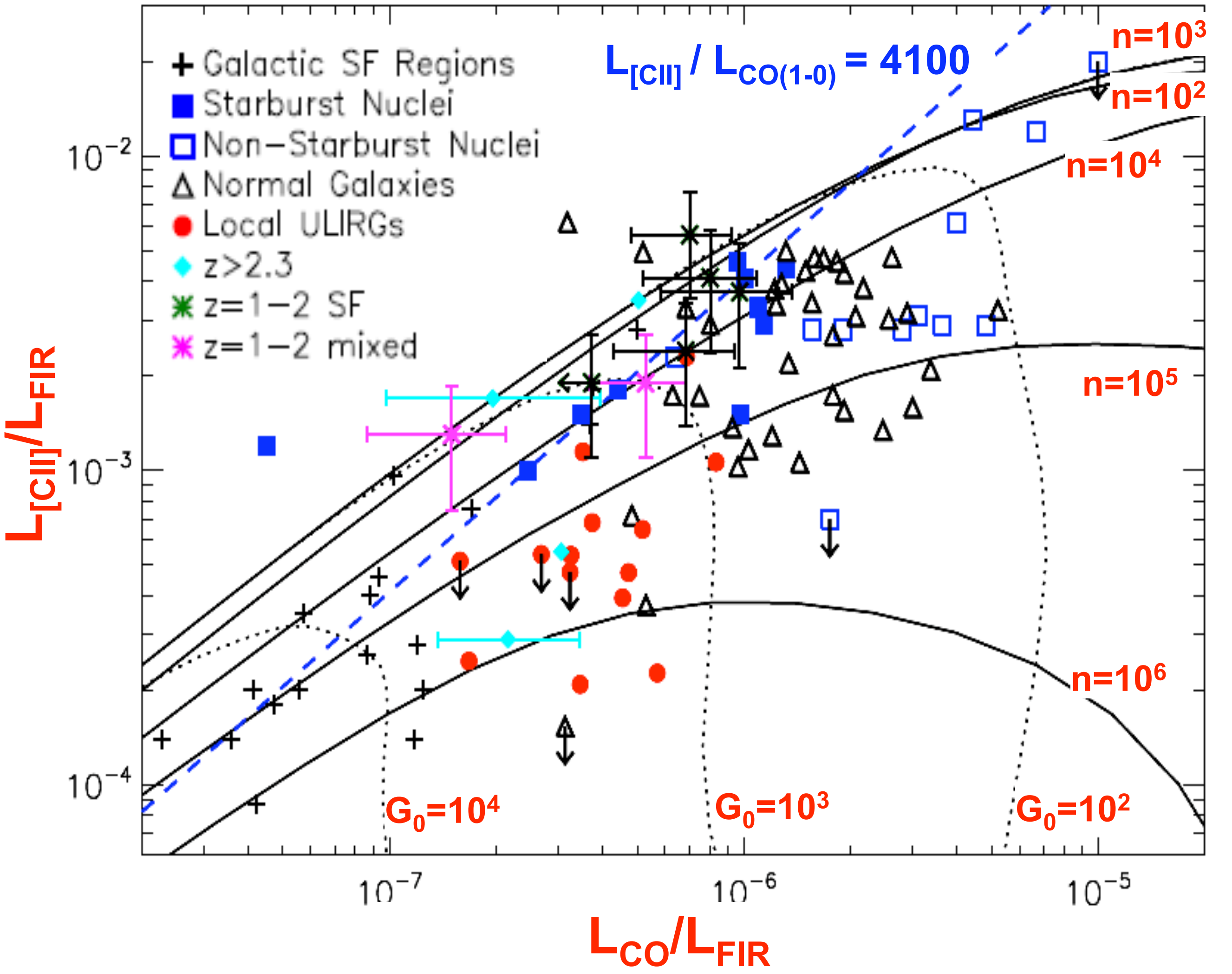
$R = 2.9 \pm 0.5 \times 10^{-3}$

New ZEUS z ~ 1- 2 sources – rough calibration (Brisbin et al 2011)

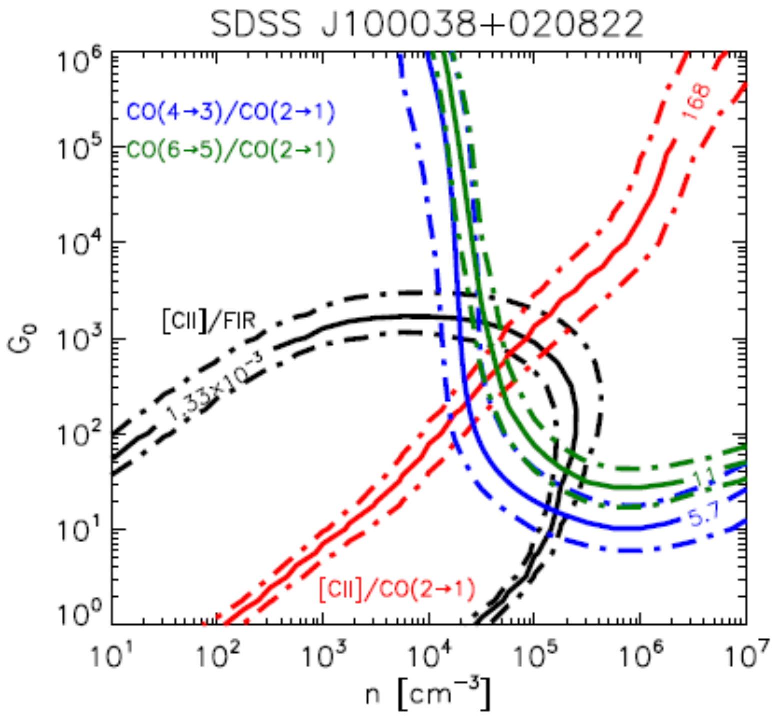


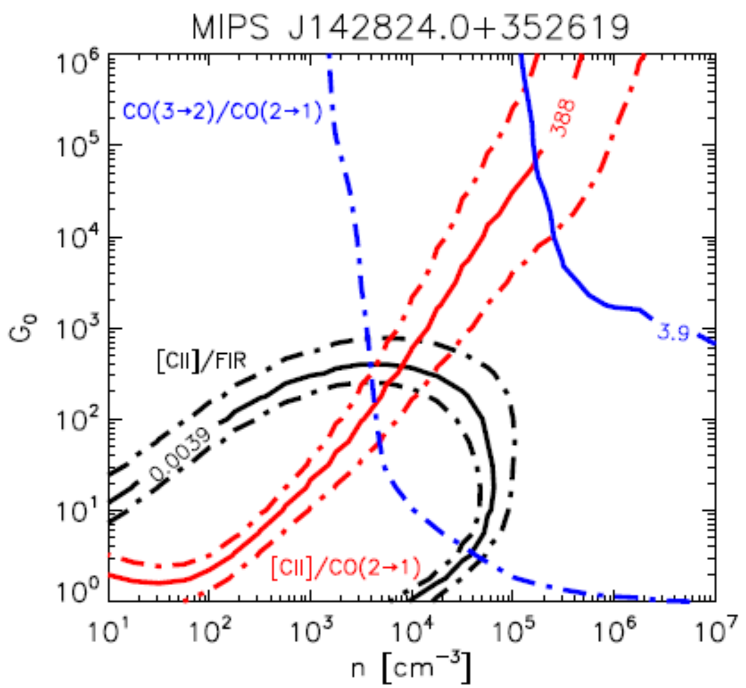
-D

Results: [CII], CO and the FIR ⇒ PDR Emission



- [CII]/CO(1-0) and FIR ratios similar to those of nearby starburst galaxies
- ⇒ emission regions in our SB-D sample have similar FUV and densities as nearby starbursters
  - G ~ 400-5000
  - n ~ 10^3-10^4



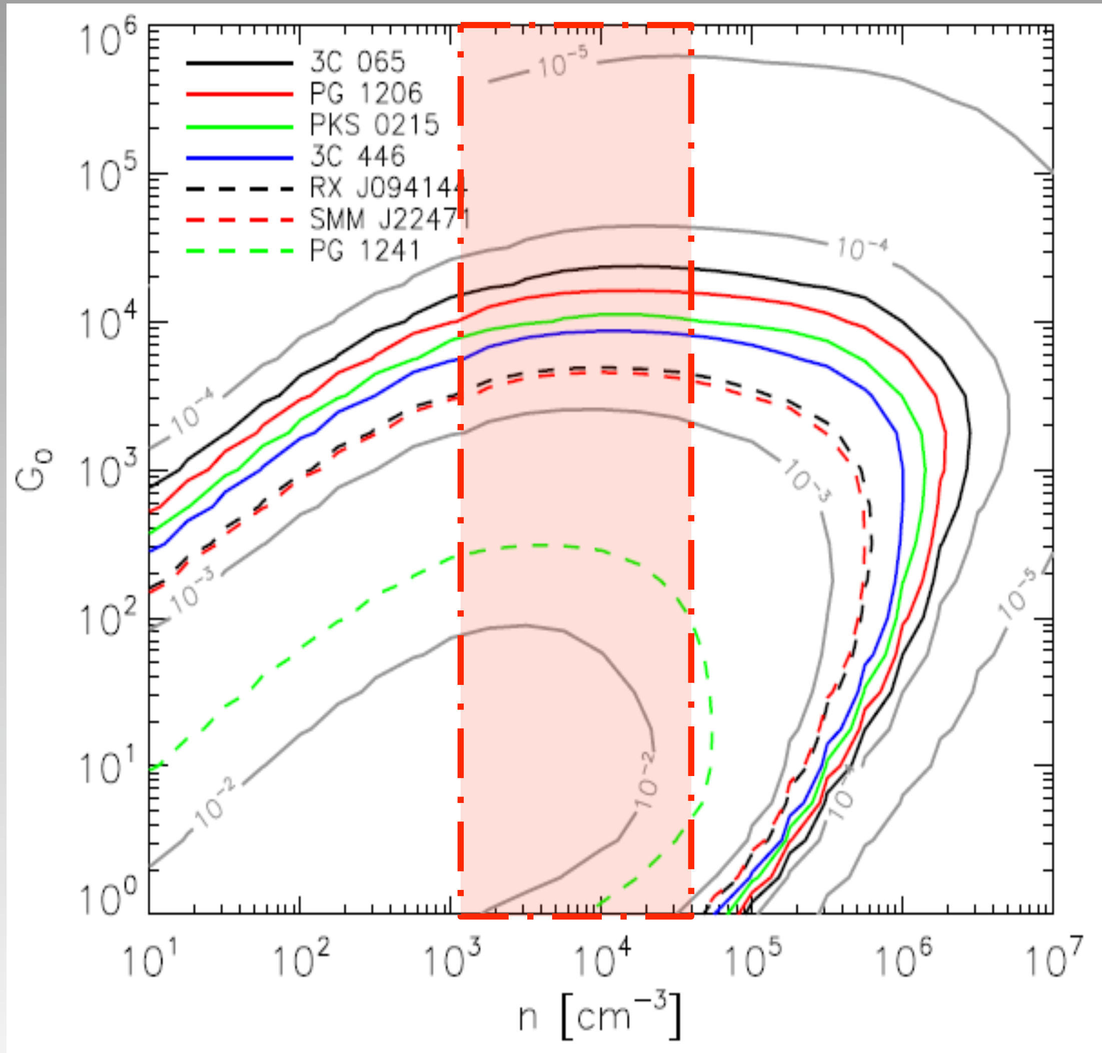


PDR Modeling

- Two sources (SMMJ10038 and MIPS J142824) have multiple CO Lines available, five others just one CO line (SMM J123634, SWIRE J104738, SWIRE J104705, IRAS F10026, 3C 368)
- PDR parameters well constrained
  - G ~ 400-2000
  - n ~ 0.3 to 2×10^4 cm

G_0 from [CII] and FIR

- Seven sources have no CO lines available
- Can still confidently find G_o, from [CII]/FIR ratio since we have learned from above that n ~ 10^3 –few 10^4 cm^{-3}:
  - **3C 065**: G < 23,000
  - **PG 1206**: G ~10,000
  - **PKS 0215**: G ~ 7,000
  - **3C 446**: G ~ 5,000
  - **RX J09414**: G ~ 3,000
  - **SMM J2247:** G ~ 3,000
  - **PG 1241**: G ~ 150



Extended Starbursts at High z

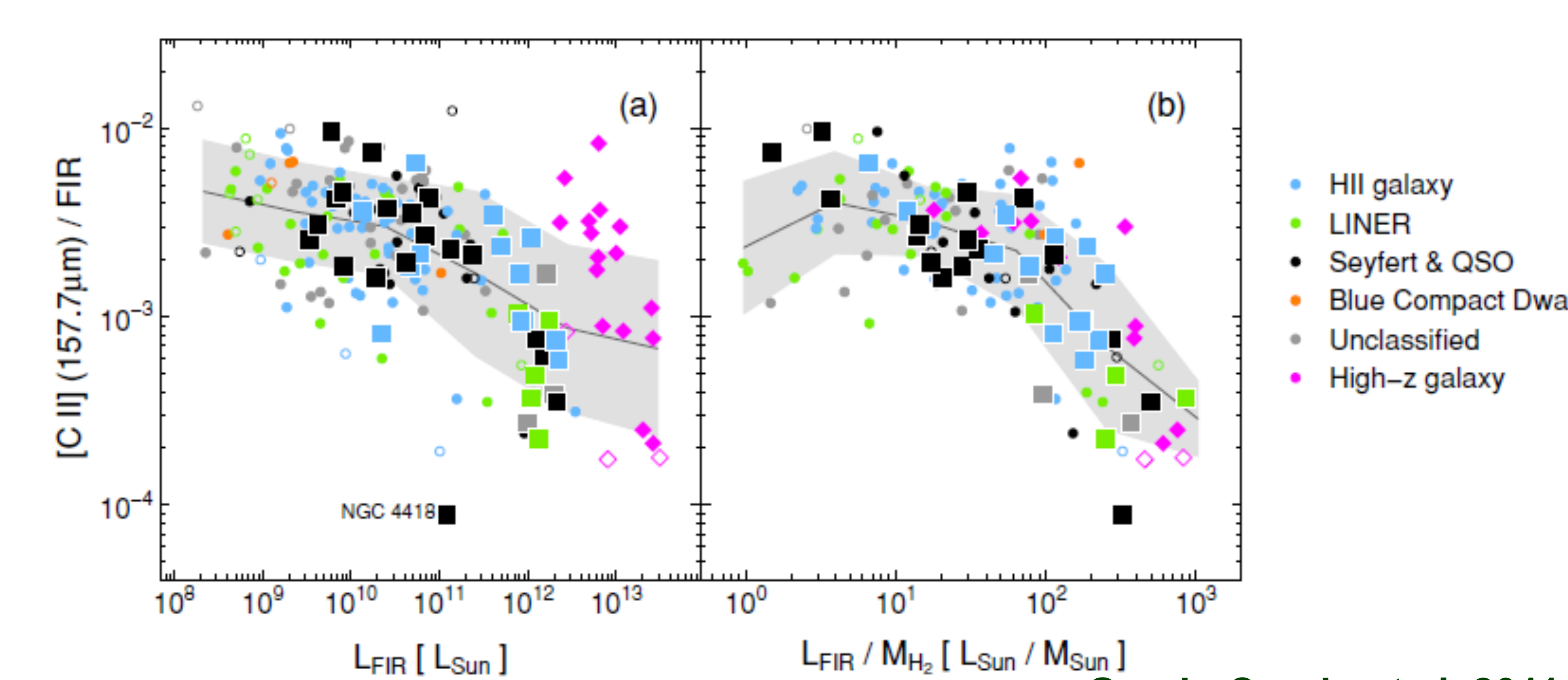
- PDR models constrain G_0 and n – if only [CII]/FIR we have just G_0
  - Since within PDRs, most of the FUV ends up heating the dust, within PDR models, **$G_0 \sim I_{FIR}$**
  - Therefore, a simple ratio I_{FIR}/G_0 yields ϕ_{beam} – which then yields the physical size of the source

Inferred sizes are large – several kpc-scales

- Galaxies are complex ⇒ plane parallel models are only a first cut
- More sophisticated models yield similar results: **size ~ 2 to 6 kpc** depending on assumptions about field distribution

Star formation is extended on kpc scales with physical conditions very similar to M82 – but with 100 to 1000 times the star formation rate!

"Quiescent" Mode of Star Formation



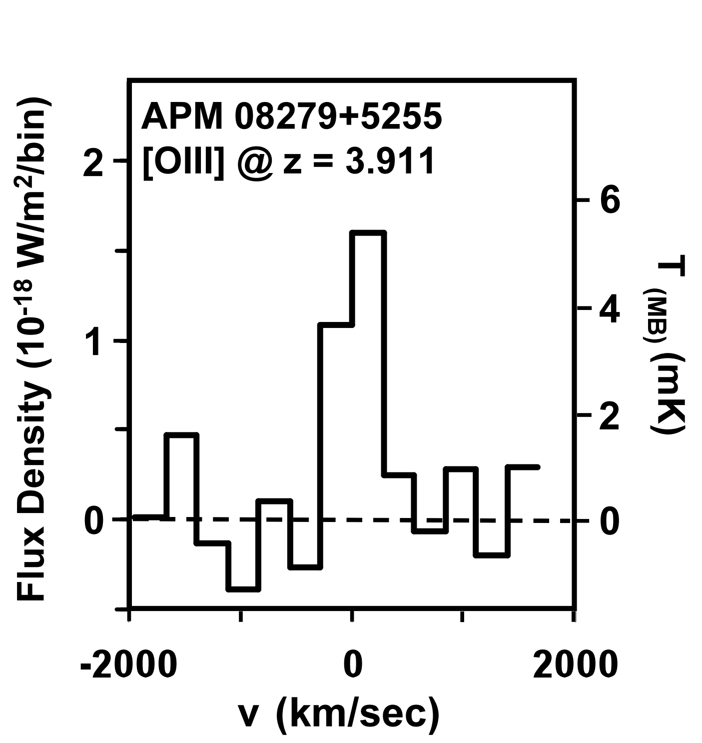
Gracia-Carpio et al. 2011

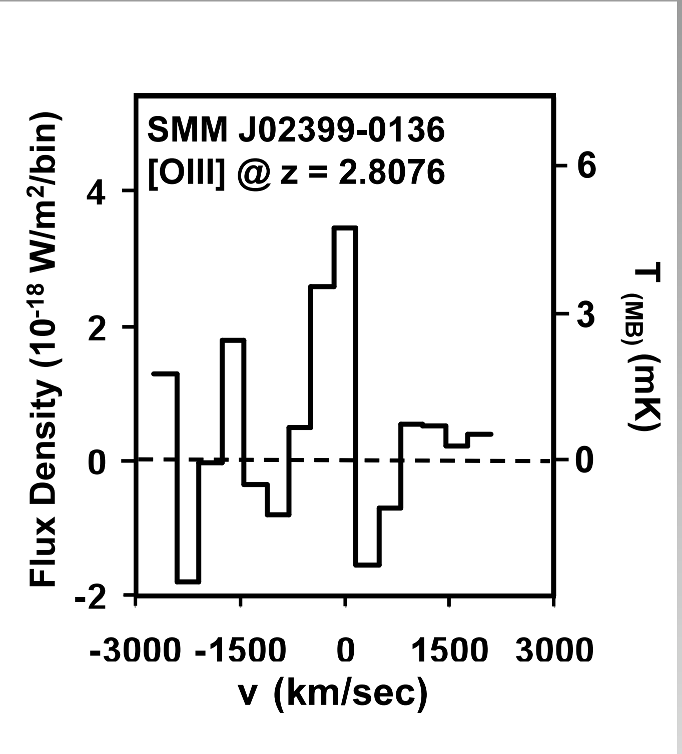
- Our conclusion that star formation is galaxy-wide and less intense than ULIRGs consistent with "quiescent" mode – star formation per unit mass not extreme (Gracia-Carpo et al. 2011)
- Intense, collision-induced star formation results in high ionization parameter, and suppressed FIR lines

ZEUS/CSO [OIII] at High z

- O^{++} takes 35 eV to form, so that [OIII] traces early type stars – or AGN…
- Transmitted through telluric windows at epochs of interests:
  - 88 μm line at z ~ (1.3) 3 and 4 (6) for ZEUS (ZEUS-2)
  - 52 μm line at z ~ (3) 5.7 and 7.7! --- much more challenging
- Detectable in reasonable times for bright sources

ZEUS/CSO Detections





Ferkinhoff et al. 2010 ApJ 714, L147

- Detected in in 1.3 hours of integration time on CSO – differences in sensitivity reflect telluric transmission
- Two composite systems
  - APM 08279 extremely lensed ($\mu \rightarrow$ 4 to 90)
  - SMM J02399 moderately lensed (μ ~ 2.38)

Characterizing the Starburst/AGN

- [OIII]/FIR
  - APM 08279 ~ 5.3×10^{-4}; SMM J02399 ~ 3.6×10^{-3}
  - Straddles the range (2×10^{-3}) found in local galaxies (Malhotra et al. 2001, Negishi et al. 2001, Brauher et al. 2008)
- Origins of [OIII]: APM 08279
  - Very few tracers of star formation available: e.g. H recombination lines clearly from the AGN
  - Spitzer PAH upper limit 10 × $F_{[OIII]}$, and expect ~ unity

⇒ Not clear - build both starburst and AGN model

AGN Origin for APM 08279?

- AGN: NRL $n_e \sim 100 - 10^4$ cm^{-3} $<n_e> \sim 2000$ cm^{-3} (Peterson 1997)
- For this n_e range one can show the expected [OIII] 88 μm line luminosity is:
  - $\sim L_{[OIII]\ 88\ \mu m} \sim 1$ to 100×10^{10} /μ $L_\odot$ (function of n_e)

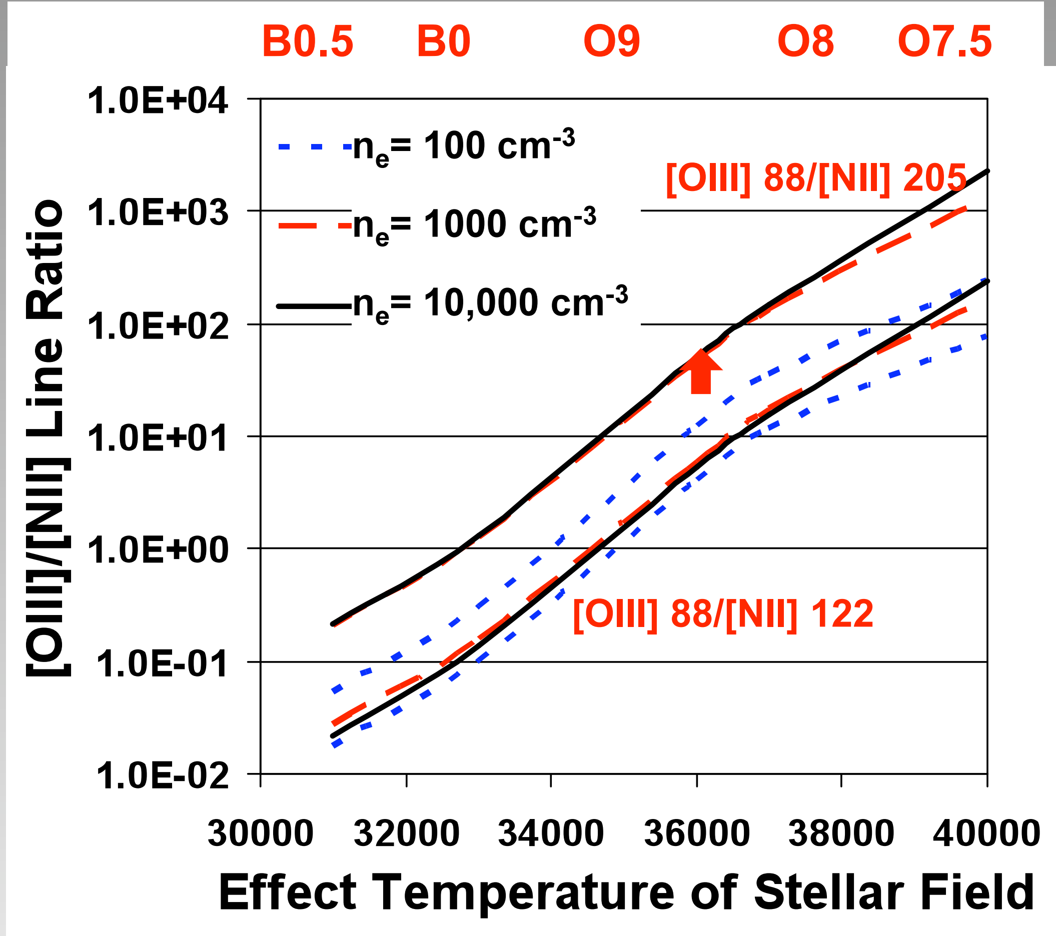
  $\Rightarrow$ all the observed 10^{11} /μ $L_\odot$ [OIII] may arise from NLR if $n_e \sim 2000$ cm^{-3}
- Fit is obtained for $n_e \sim 2000$
- Can test this with the [OIII] 52 μm line since line [OIII] 88/52 μm line ratio is density sensitive

Starburst Origin for APM 08279

- [OIII]/[NII] line ratios insensitive to n_e, but very sensitive to T_{eff}
  - [OIII]/[NII] 122 especially so…
- Ratio in APM 08279 > 17 based on non-detection of 205 μm (Krips et al. 2007)

⇒ T_{eff}> 37,000 K ⇔ O8.5 stars

- FIT: starburst headed by O8.5, 35% of FIR from starburst, SFR ~ 12,000/ μ $M_{\odot}$/year



From Rubin, R. 1985

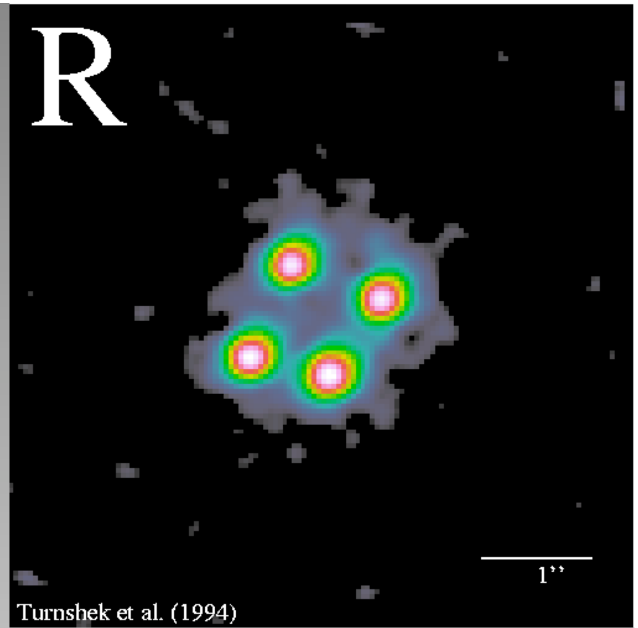
Detections of the [NII] 122 μm Line

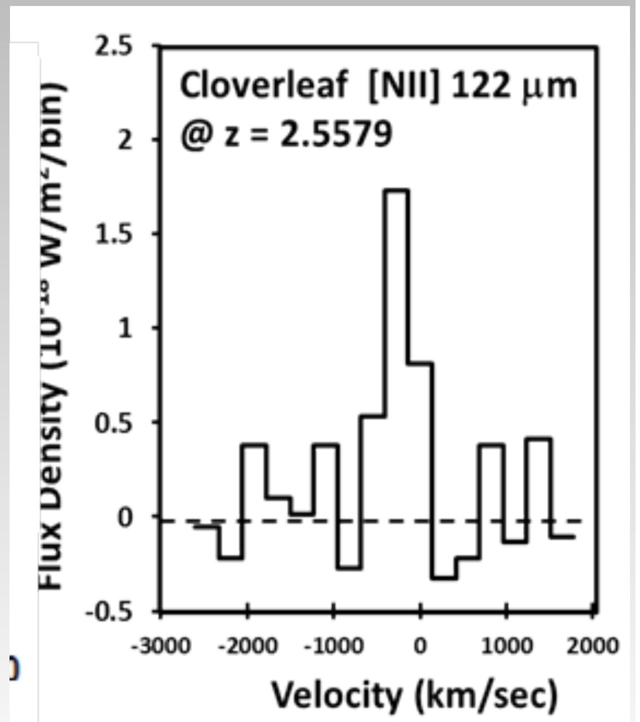
Ferkinhoff et al. 2011 ApJ submitted

- January/March this year detected [NII] 122 μm line from composite systems
  - SMM J02399: $z = 2.808$, $L_{\text{far-IR}} \sim 3 \times 10^{13} / \mu\ L_{\odot}$
  - Cloverleaf quasar: $z = 2.558$, $L_{\text{far-IR}} \sim 6 \times 10^{13} / \mu\ L_{\odot}$
- Line is bright: 0.04 to 0.2% of the far-IR continuum
- Optically thin, high n, high T limit ⇒ Calculate minimum mass of ionized gas:
  - 2 to 16% of molecular ISM
  - Values range from few to 20% (M82, Lord et al. 1996) in star forming galaxies.

[NII] in the Cloverleaf

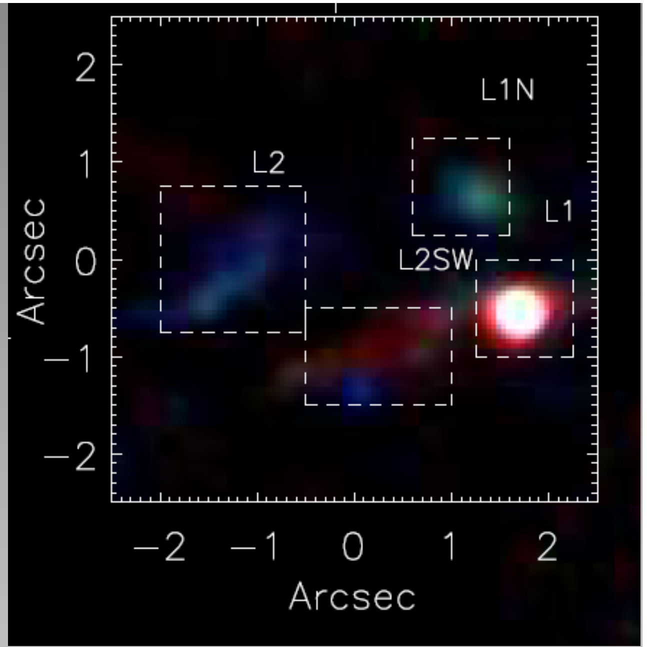
- z = 2.558, lensed by 11, but all components within the 10” beam
- No other far-IR lines, but Hα, Hβ, [OIII] 5007Å (Hill et al. 1993), and 6.2 & 7.7 μm PAH (Lutz et al. 2007)
- Composite model:
  - Star formation: PAH features, half the far-IR, and [NII]
  - Properties similar to M82 – 200 times larger:
    - 1×10^9 – O8.5 stars (T_{eff}~ 36,500 K)
    - ⇒ age ~ 3×10^6 yrs
    - n_e ~ 100 cm^{-3}, M_{HII}~ 3×10^9 $M_\odot$
  - AGN Model: optical lines, half of [NII]
  - Arises from NLR with log(U) = -3.75 to -4
    - n_e ~ 5000 cm^{-3}



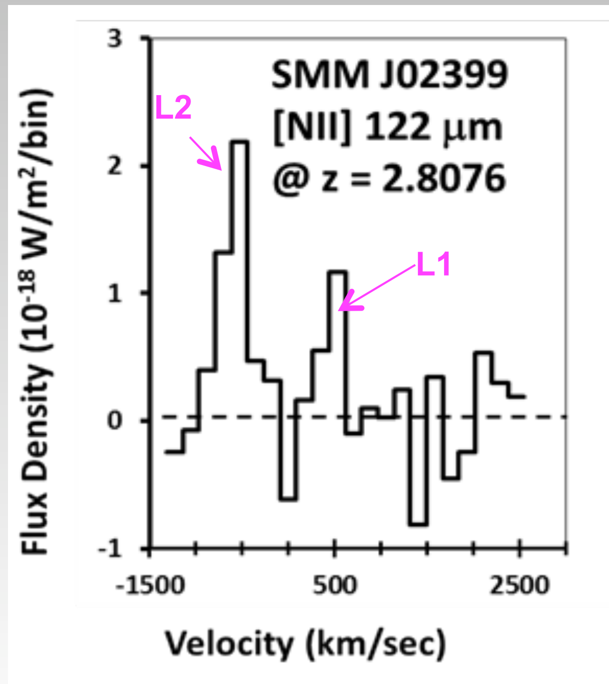


[NII] in SMM J02399

- Strong detection of line at velocity of L2, possible line at velocity of L1
- Velocity information suggests origins for line
  - L2: starburst
  - L1: AGN
- We previously detected the [OIII] 88 μm line (Ferkinhoff et al. 2010)
  - Modeled as a starburst
  - Line was ~ 300 km/sec blue of nominal z – consistent with emission from L2
  - Detection of L1 in [OIII] buried in noise…

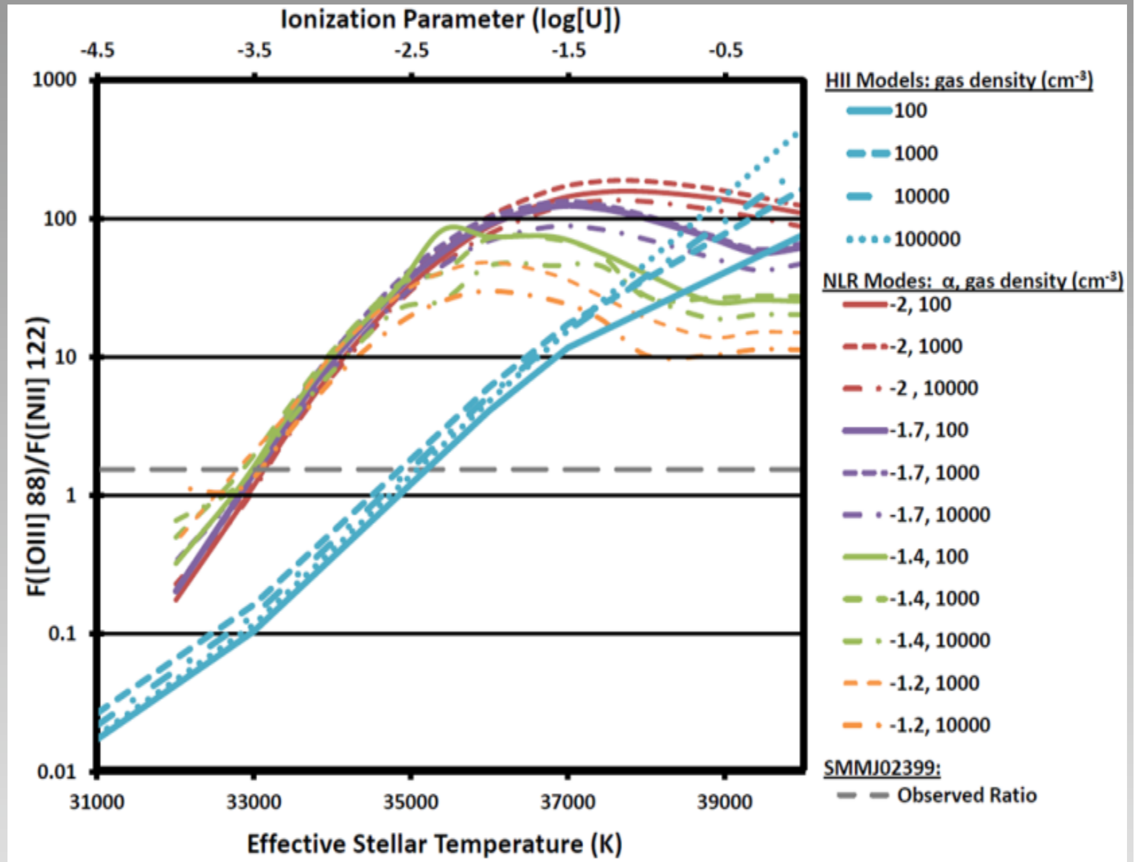


Ivison et al. 2010



[OIII]/[NII]: Yields UV Field Hardness

- 6.2 μm PAH flux ~ [OIII] 88 μm line flux as for starbursts
- ZEUS/CSO [NII] 122 um line
  - [OIII] 88/ [NII] 122 ~ 2 ⇒ starburst headed by O9 stars (T_{eff} ~ 34,000 K)
  - Age of starburst ~ 3×10^6 years
- Composite fit:
  - 70% -- 3 million year old starburst headed by O9 stars, forming stars at a rate ~ 3500/μ per year.
  - 30% -- NLR with log(U) ~ -3.3 to -3.45

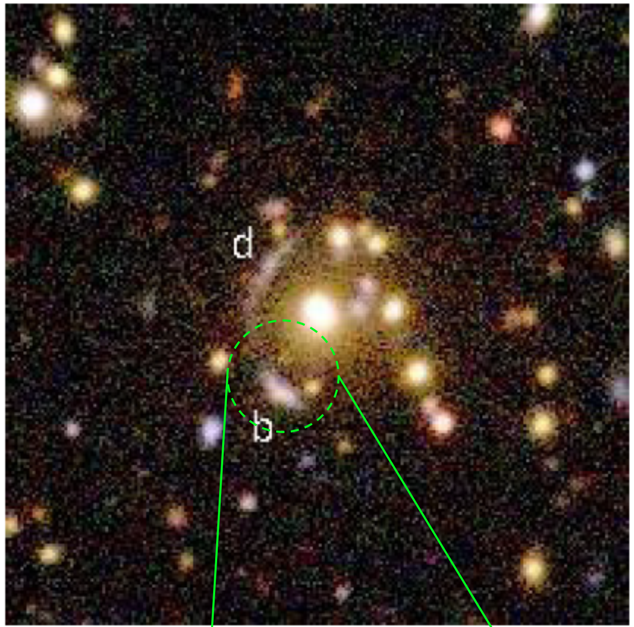


NLR models Groves et al. 2004, HII region models Rubin et al. 1985

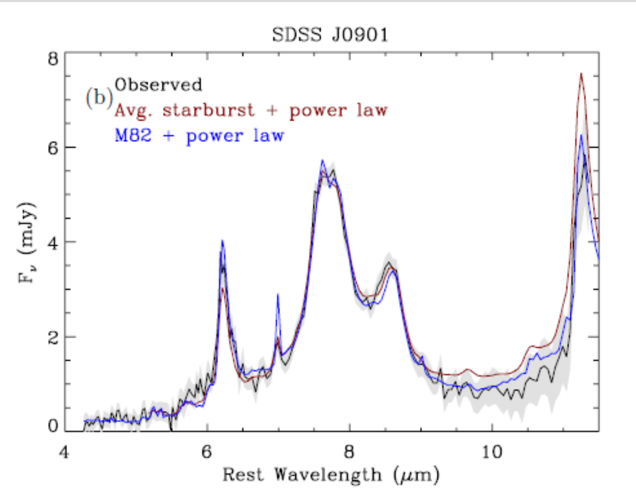
NOTE: T_{eff} derived from [OIII] 88/[NII] 122 ratio is not only insensitive to n_{e}, but also insensitive to O/N abundance ratio

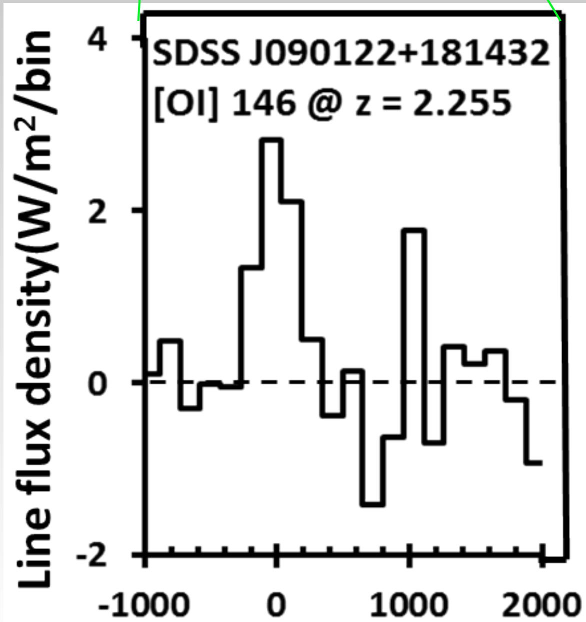
[OI] 146 SDSS J090122

- Lensed (μ ~ 8) galaxy @ z = 2.2558 (Diehl et al. 2009)
- Very strong PAH emitter (Fadely et al. 2010)
  - Fits M82 template quite well
  - L_{far-IR}~3.0× 10^{13} $L_{\odot}/\mu$
  - $L_{[OI]}/L_{FIR}$~0.08%
- Detected in [OI] from component "b" in 1 hour – line flux ~ PAH 6.2 μm/15



Diehl et al. 2009

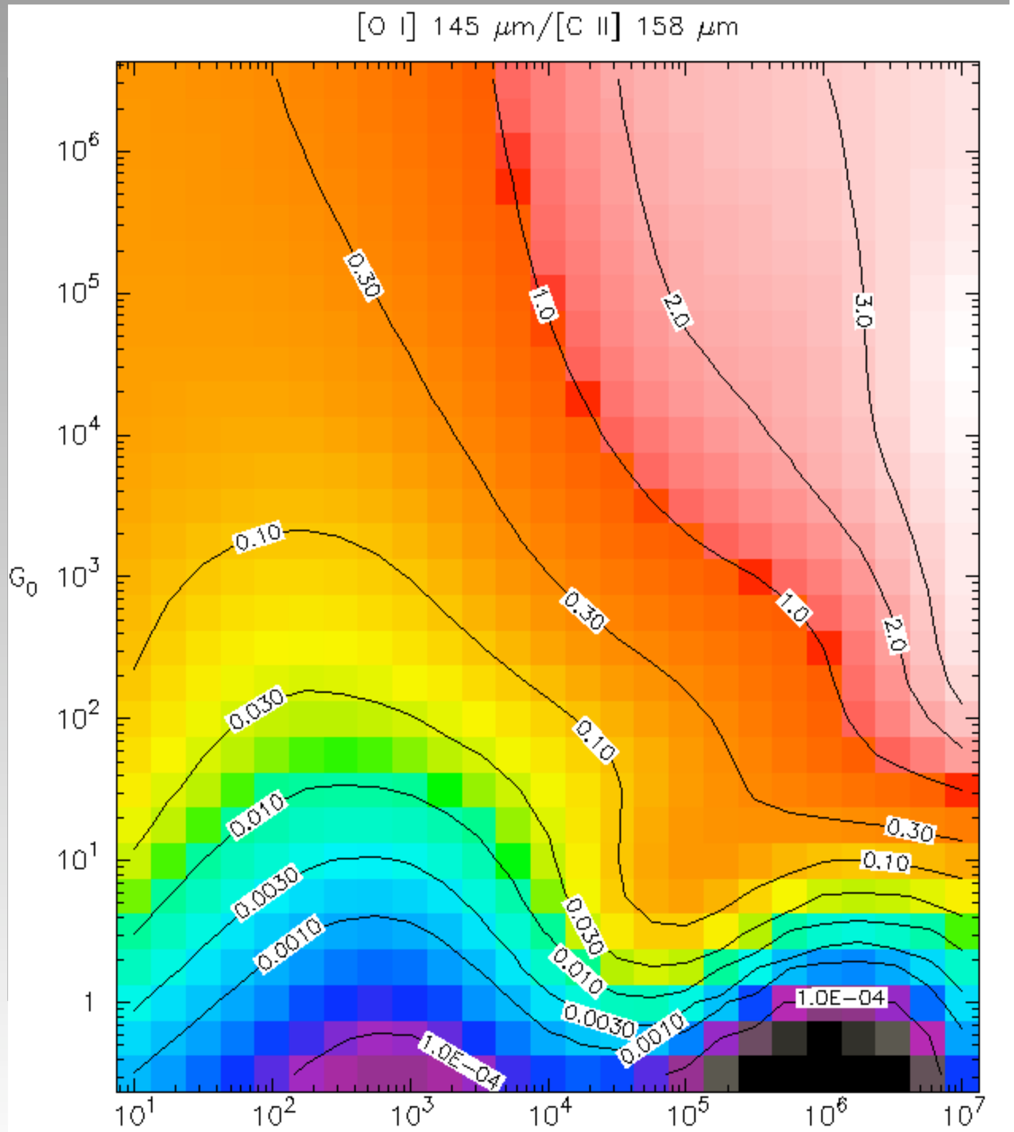




Physics with [OI] 146 μm

- [OI]/[CIII] line ratios trace density, G
- [OI] only arises in PDRs…
- "Typical" line ratios
  - [CII]/[OI] 146 ~ 1/10
  - [CII]/[OI] 63 ~ 1
- Advantage of [OI] 146
  - Near [CII] wavelength ⇒ detectable from same source
  - *Optically thin*
- [OI]/far-IR ~ 0.08% ⇒ G ~ 10^2-10^3, n~ 10^4-10^5 cm^{-3}

Much better constrained by [OI] 146/[CII] ratio…



FS Lines and CCAT

CCAT spectrometers will be ~ 10 times more sensitive than ZEUS on APEX (5σ, 4 hours)

CCAT-ALMA Synergy

- ❑ **ALMA 3 times more sensitive for single line detection**
- ❑ **CCAT:**
  - ➢ **Enormous (> 100 GHz, multi-window) BW – redshifts**
  - ➢ **New THz windows – important for [OI], [OIII], [NII]…**
  - ➢ **Expect *thousands* of sources/sq. degree per window detectable in [CII] line –**

    Our ZEUS source density (5 in Lockman) fits these estimates at high luminosity end

  - ➢ **Multi (10 -100s) object capability – *maybe IFU!***

    $\Rightarrow$ **Find sources, find lines, multi-line science**

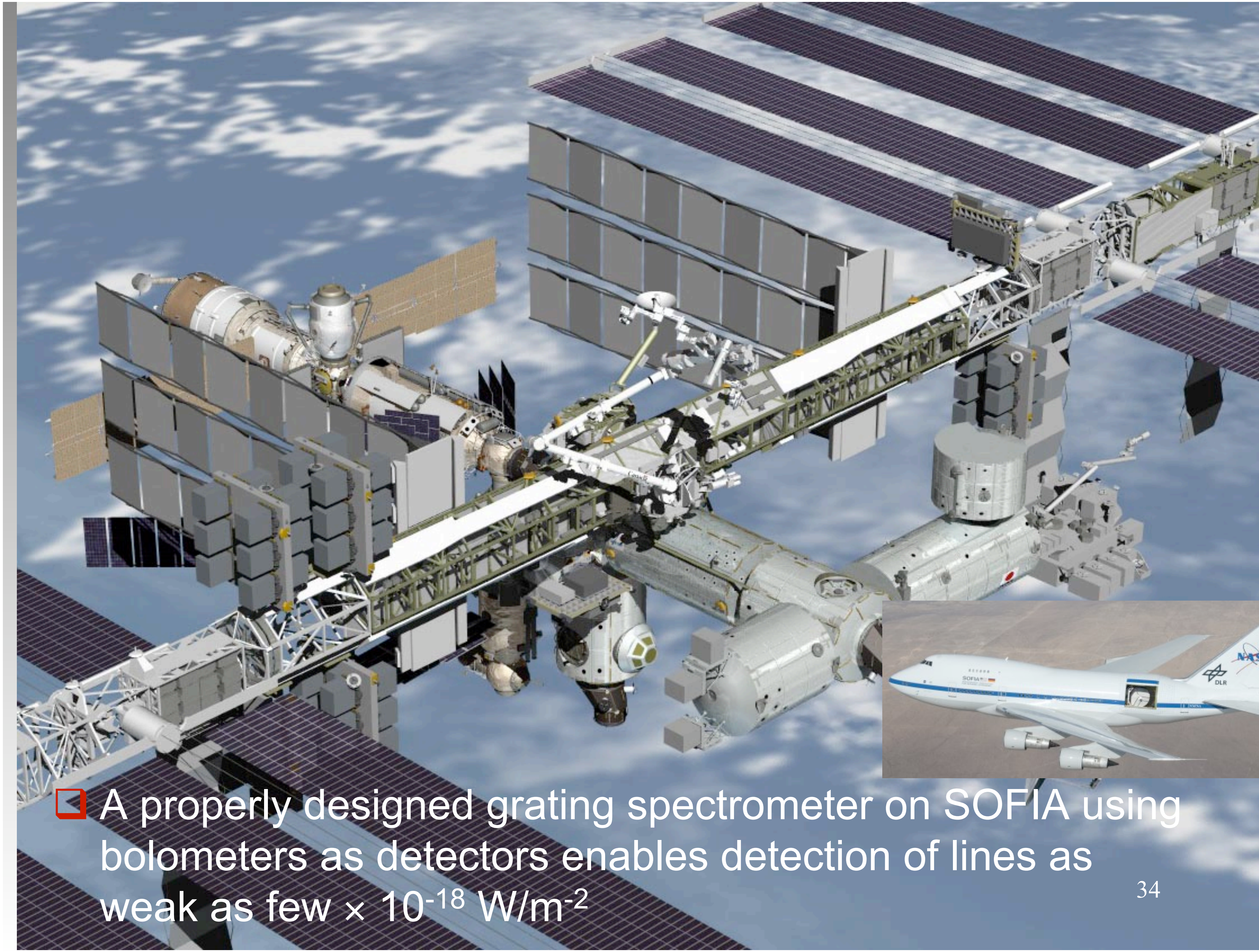
- ❑ **ALMA "zoom-in" on compelling sources**
  - ➢ **Structure**
  - ➢ **Dynamics**

Star-formation Dominated

z

Conclusions

- [CII] line emission detectable at very high z
  - Reveals star forming galaxies
  - Constrains G, and size of star-forming region
  - z ~ 1 to 2 survey *extended starbursts* with local starburst-like physical conditions
- [OI] 146 arises only from PDRs, similar science to [CII]
- [OIII]/[NII] emission at high z
  - Traces current day stellar mass function – age of the starburst: *ratio with [NII] 122 very tight constraints*
  - Also can traces physical conditions of NLR – likely detected NLR emission from composite sources
- Future with CCAT and ALMA exciting – detect and characterize sources that are 50-100 of times fainter – *[CII] from Milky Way at z ~ 3!*



- A properly designed grating spectrometer on SOFIA using bolometers as detectors enables detection of lines as weak as few $\times 10^{-18}$ W/m^{-2}

Complementary Studies

- Clearly much more physics is obtained with multiple line studies: [OI] 63 & 146, [OIII] 88 & 52, [NII] 205 & 122 μm, [NIII] 57 μm
  - Have an Herschel OT1 program to detect the [OI] and [OIII] & [OIV] lines from our [CII] z = 1-2 survey sources
  - We anticipate detecting ~ few dozen sources/year over the lifetime of ZEUS and ZEUS-2 on the submm telescopes – could use more Herschel/PACS time…

But, unfortunately, the plan to bring Herschel back to the International Space Station for "re-heliation" was ***cancelled*** *by Goran Pilbrat*

--- on April 2 ---