Submm Spectroscopy of Far-Infrared Fine Structure Lines from High-z Galaxies

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Collaborators

- Gordon Stacey (PI, Cornell)
- Carl Ferkinhoff (Cornell)
- Stephen Parshley (Cornell)
- Drew Brisbin (Cornell)
- Many undergraduate students
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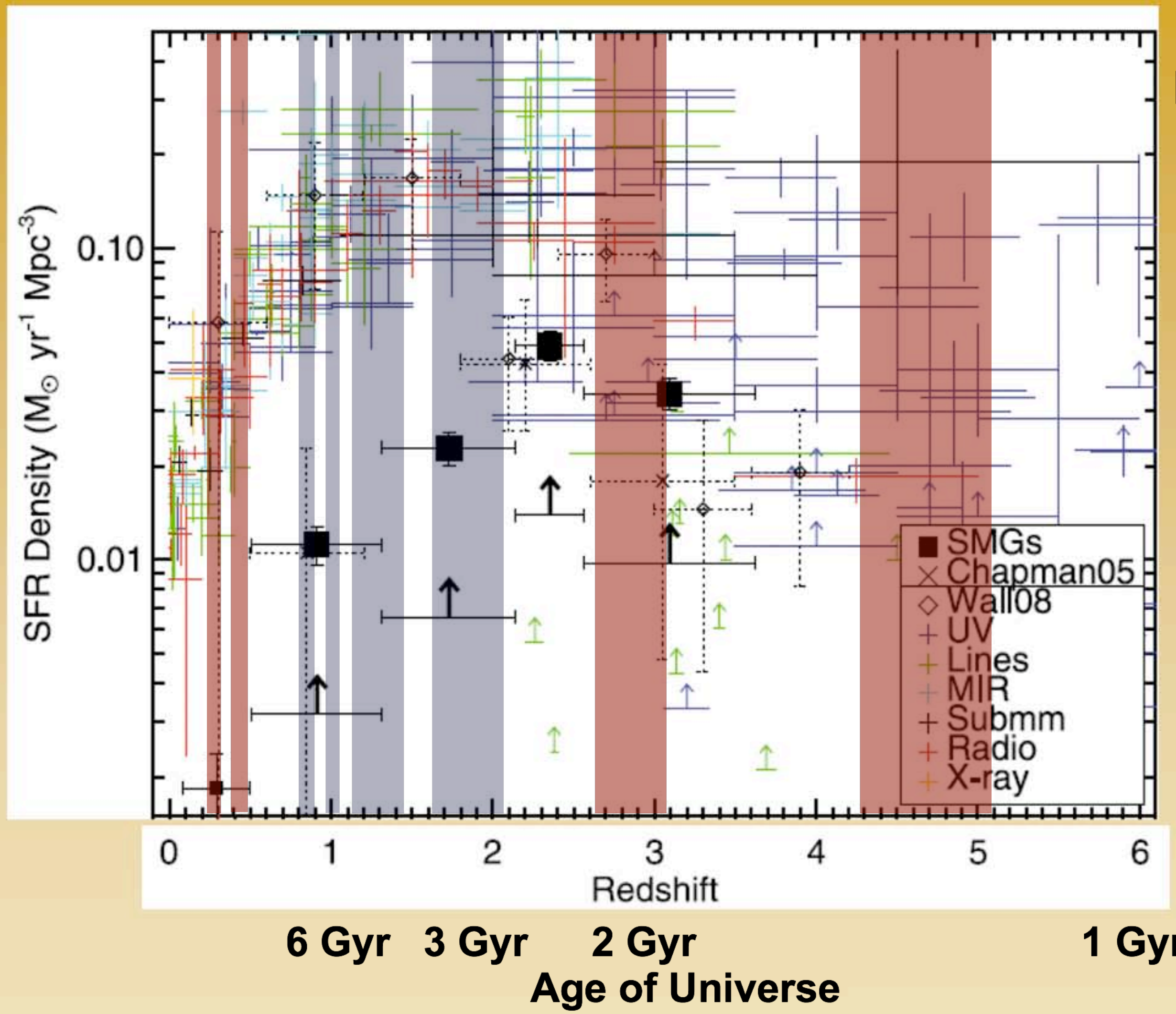
- Dominic Benford (GSFC)
- Mark Halpern (UBC)
- Alain Omont (IAP)
- Nicolas Fiolet (IAP)

Star Formation History of the Universe

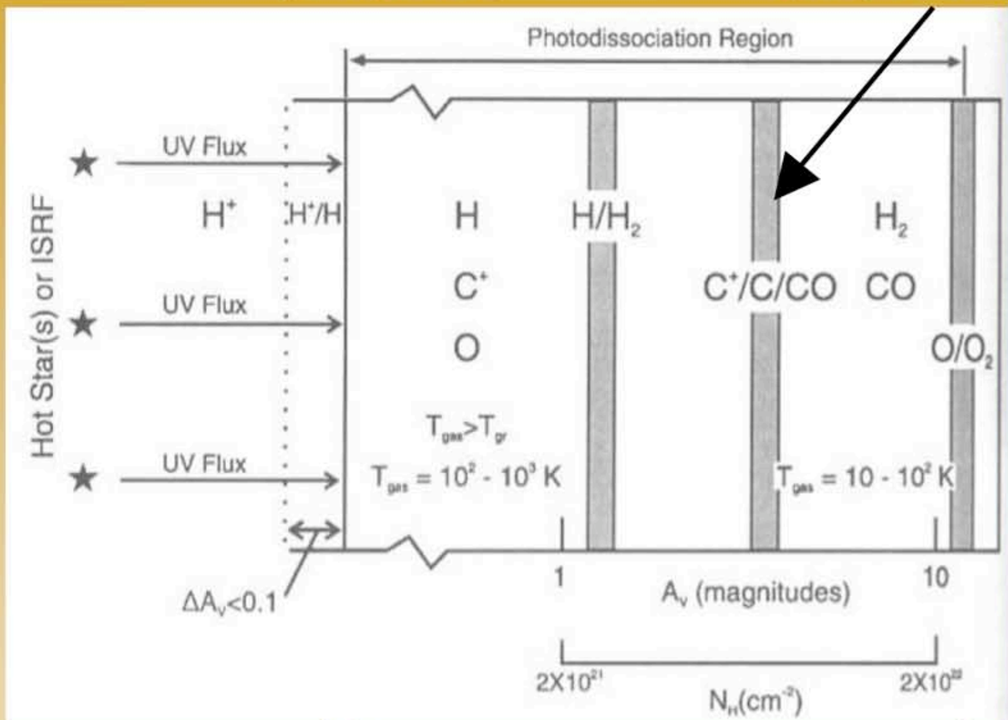


Michalowski, Hjorth, & Watson 2010, A&A, 514, A67

Structure of the PDR

[C II] 158 μm

[C I] 609, 370 μm



Structure depends on G/n:

- $G_0 \sim 1$ (local) to 10^5 (Orion)
- $n \sim 0.5$ (WNM); 30 (CNM); 10^3-10^7 (GMCs)

[O I]/[C II] :	6 -13.6 eV
[N II] :	14.5 - 29.6 eV
[S III] :	23.5 - 40 eV
[N III] :	29.6 - 47.4 eV
[O III] :	35.1 - 54.9 eV

[N II] 205, 122 μm

[O I] 63, 146 μm

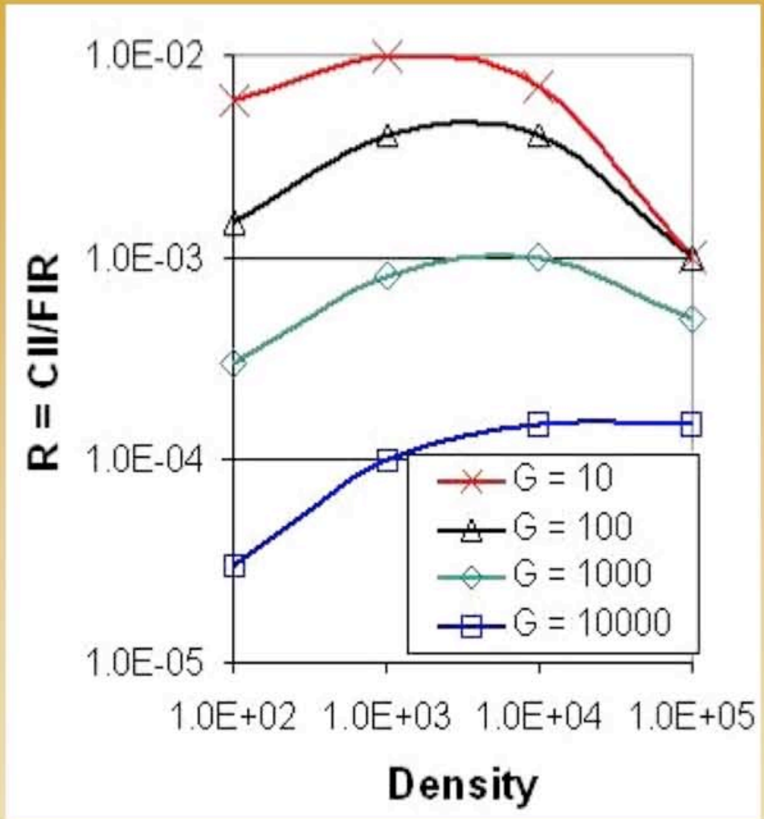
[O III] 88, 52 μm

[N III] 57 μm

Hollenbach and Tielens, Rev. Mod. Physics 71, 173 (1999)

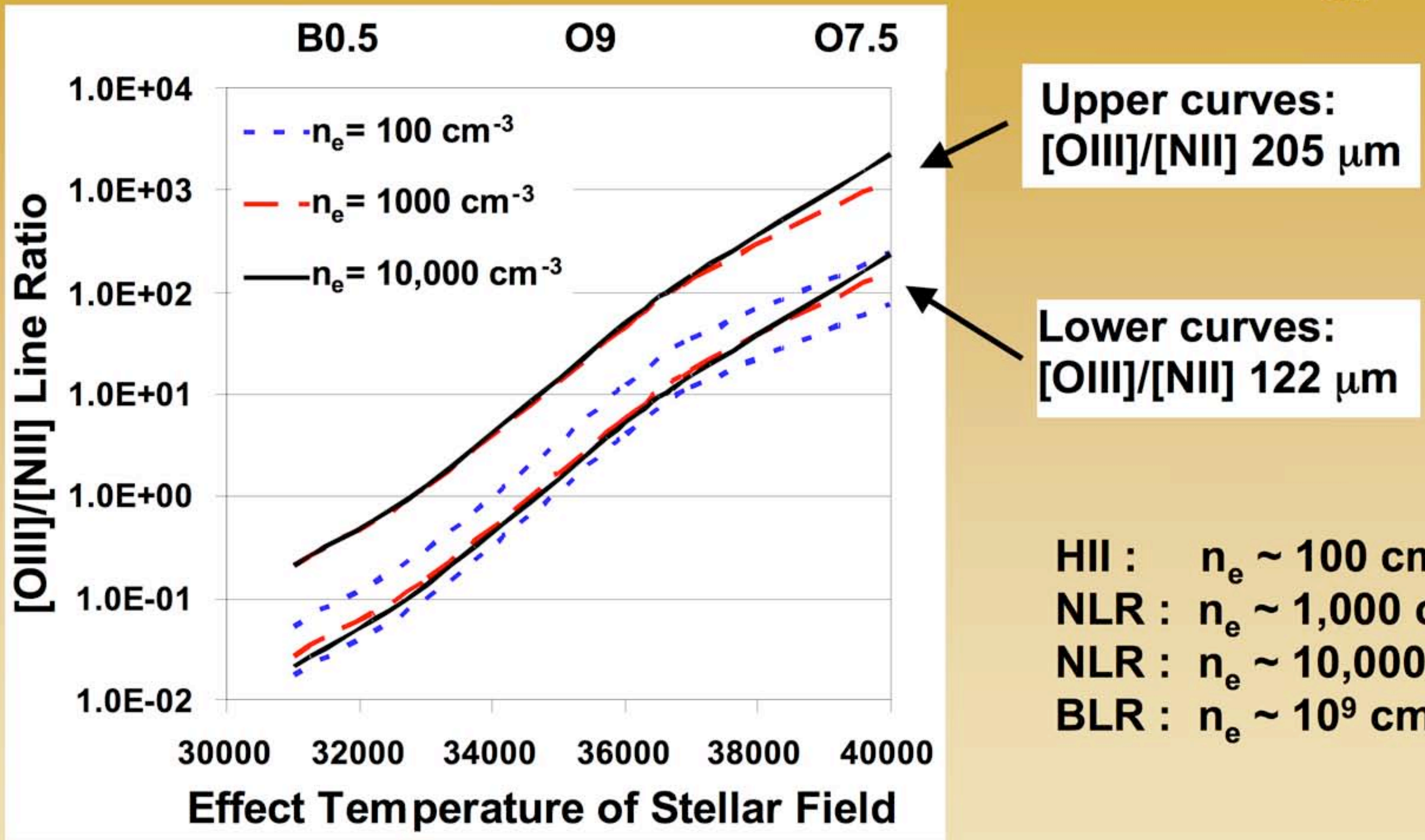
The [CII] and [OI] Line Trace the FUV Radiation Field Strength

- ***At a given density, the ratio R ≡ [CII]/FIR uniquely yields G***
- **This single-line utility holds until G/n gets small and column of [CII] determined by ion-eq.**
  - **Range ~ 10^2 to 10^4 cm^{-3}**
- **Notice the inverse relationship due to saturation of [CII] line emission:**
  - **R is smaller for larger G (e.g. Orion HII region/GMC interface, ULIRGs)**



Ionized Gas Lines: Ionization

[O III]88/[N II] line ratios as a function of T_{eff}.



HII : $n_e \sim 100$ cm^{-3}
NLR : $n_e \sim 1{,}000$ cm^{-3}
NLR : $n_e \sim 10{,}000$ cm^{-3}
BLR : $n_e \sim 10^9$ cm^{-3}

Vacca, Garmany, Shull 1996 ApJ, 460, 914
Rubin 1985, ApJS, 57, 349

ZEUS/CSO z = 1–2 [CII] Survey

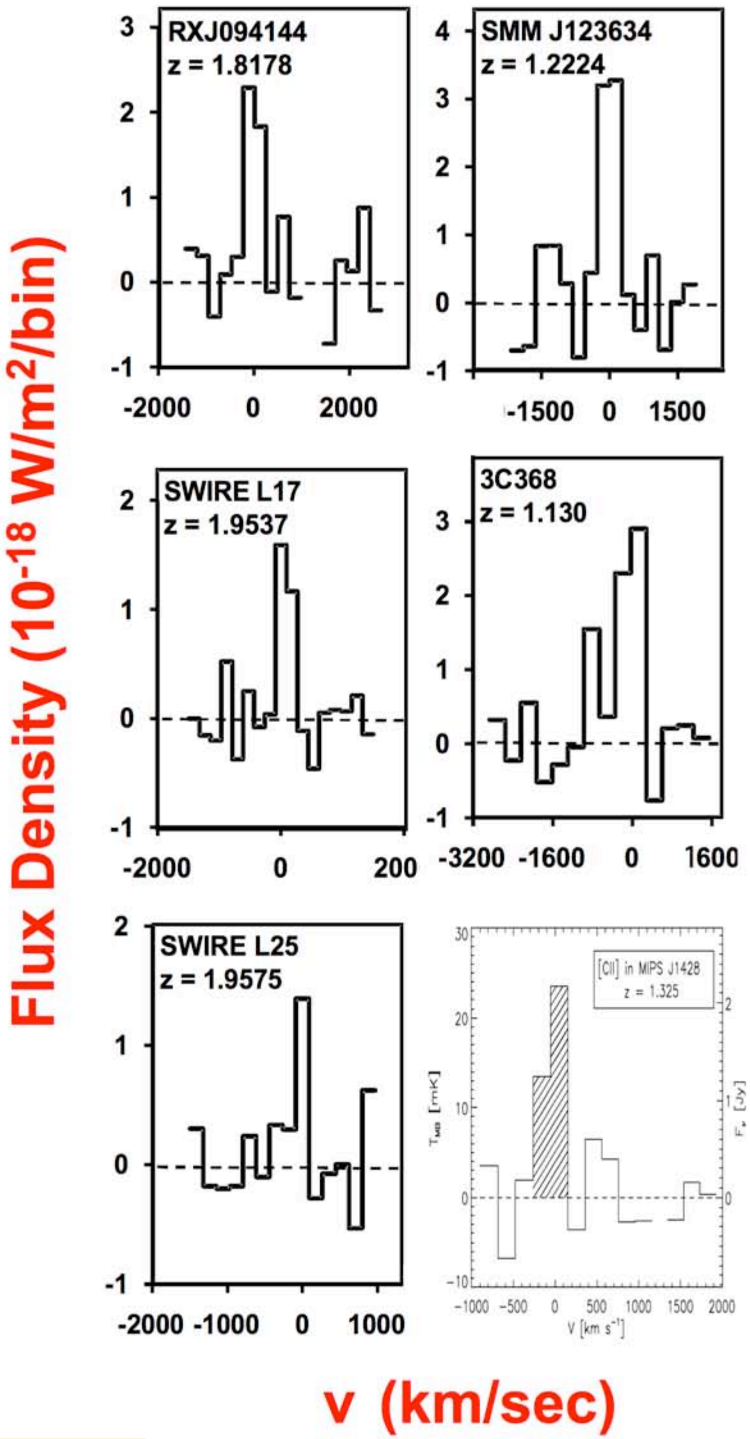
Stacey et al. 2010, ApJ, 724, 957

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**
  - **A star formation tracer, but previously only detected in 4 (now 5) high z sources reported elsewhere…**
  - **L_{FIR} ($42.5<\lambda< 122.5$ μm): 4×10^{12} to 2.5×10^{14} $L_{\odot}$ (no lensing correction)**

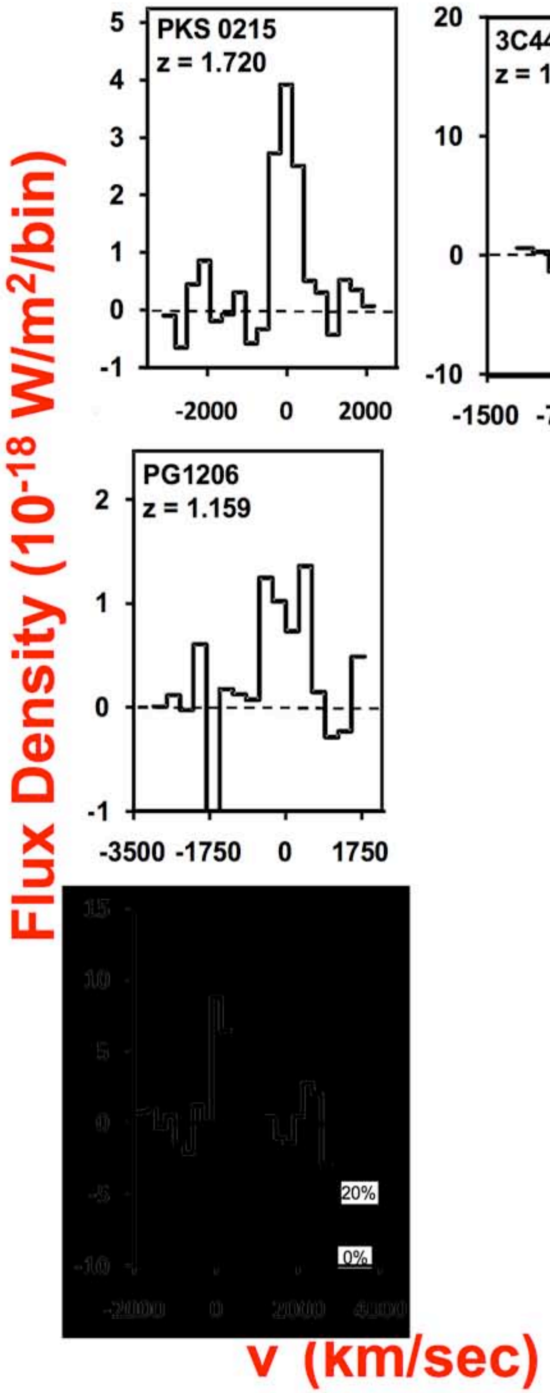
ZEUS/CSO z = 1–2 [CII] Survey (2)

- Report 12 new detections & 1 strong upper limit
  - Split survey into SF-D, AGN-D and mixed (or poorly characterized) literature based characterization of TIR (3 to 1000 μm) luminosity – typically dominated by MIR for AGN systems
  - 12 new detections, 1 strong upper limit
    - ◊ 6 SF-D ◊ 5 AGN-D ◊ 3 mixed



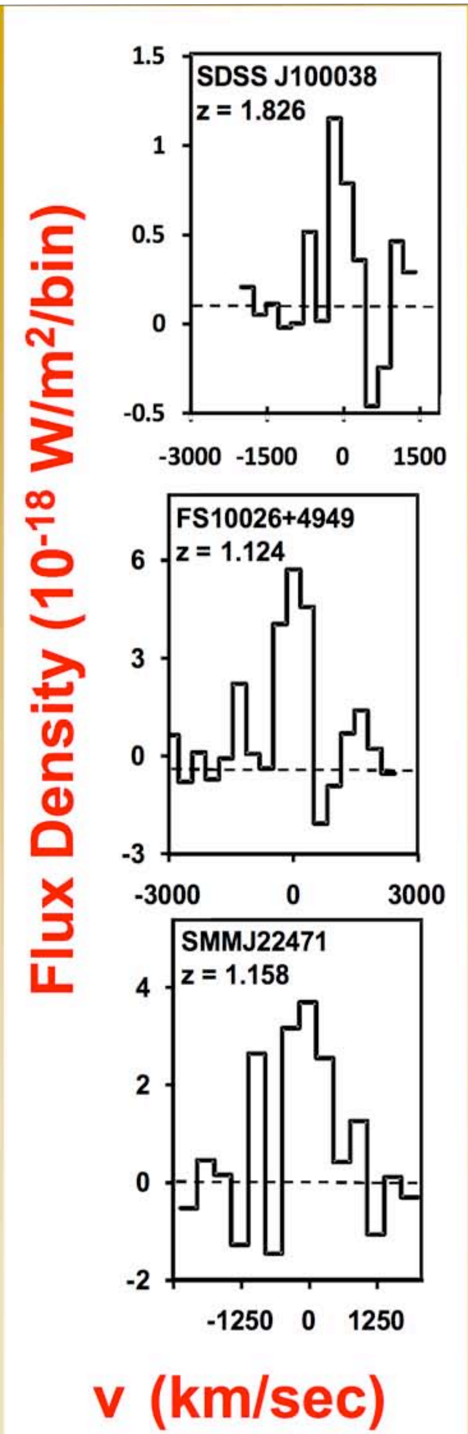
Star Formation-Dominated Sample

Source	z	L_{FIR} ($L_{\odot}$)	$F_{[CII]}$ (10^{-18} W/m^2)
RXJ094144	1.819	2.7E13	3.8±0.52
SWIRE			
J104738+59	1.954	7.5E12	2.8±0.36
J104705+59	1.958	5.7E12	1.7±0.45
SMM J1236	1.222	4.0E12	6.5±0.90
3C 368	1.130	5.1E12	5.1±0.80
MIPS 14282	1.325	1.3E13	19.8±3.0



AGN-Dominated Sample

Source	z	L_{FIR} ($L_{\odot}$)	$F_{[CII]}$ (10^{-18} W-m^{-2})
PKS 0215	1.720	1.1E14	9.4±0.82
3C065	1.176	6.7E12	<0.8
PG1206	1.159	2.6E13	4.2±0.60
PG1241	1.273	5.9E12	15.3±2.2
3C446	1.403	2.5E14	42.8±6.5

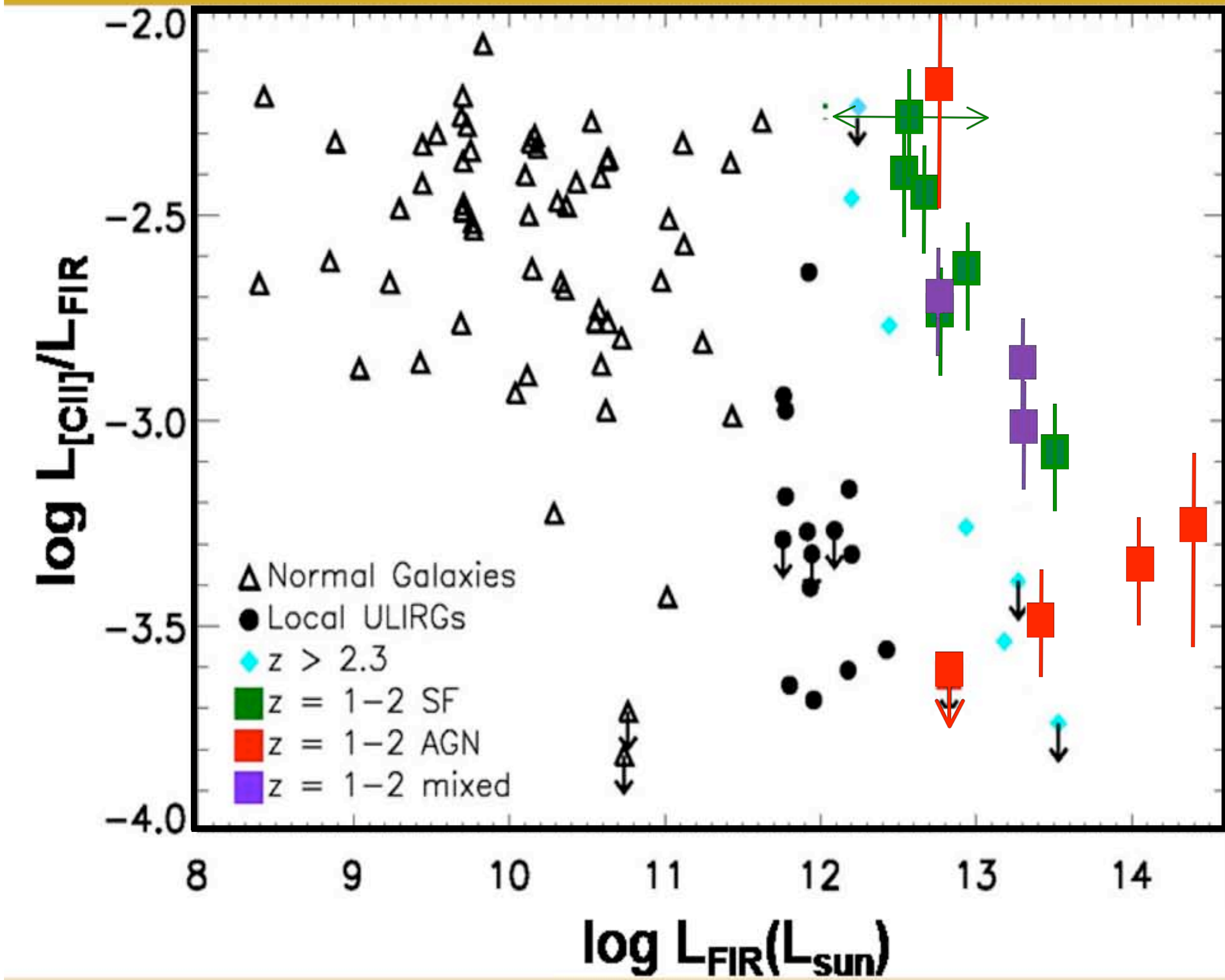


Mixed or Poorly Characterized Sample

Source	z	L_{FIR} ($L_{\odot}$)	$F_{[CII]}$ (10^{-18} W-m^{-2})
SDSS100038	1.720	5.7E12	1.74±0.40
IRAS F10026	1.176	2.0E13	14.4 ±1.1
SMM J22471	1.159	1.0E13	9.3 ±2.1

Need Very Good Sensitivity To Detect The Lines!

Results: The [CII] to FIR Ratio



SF-D:

R = 2.9±0.5 $\times 10^{-3}$

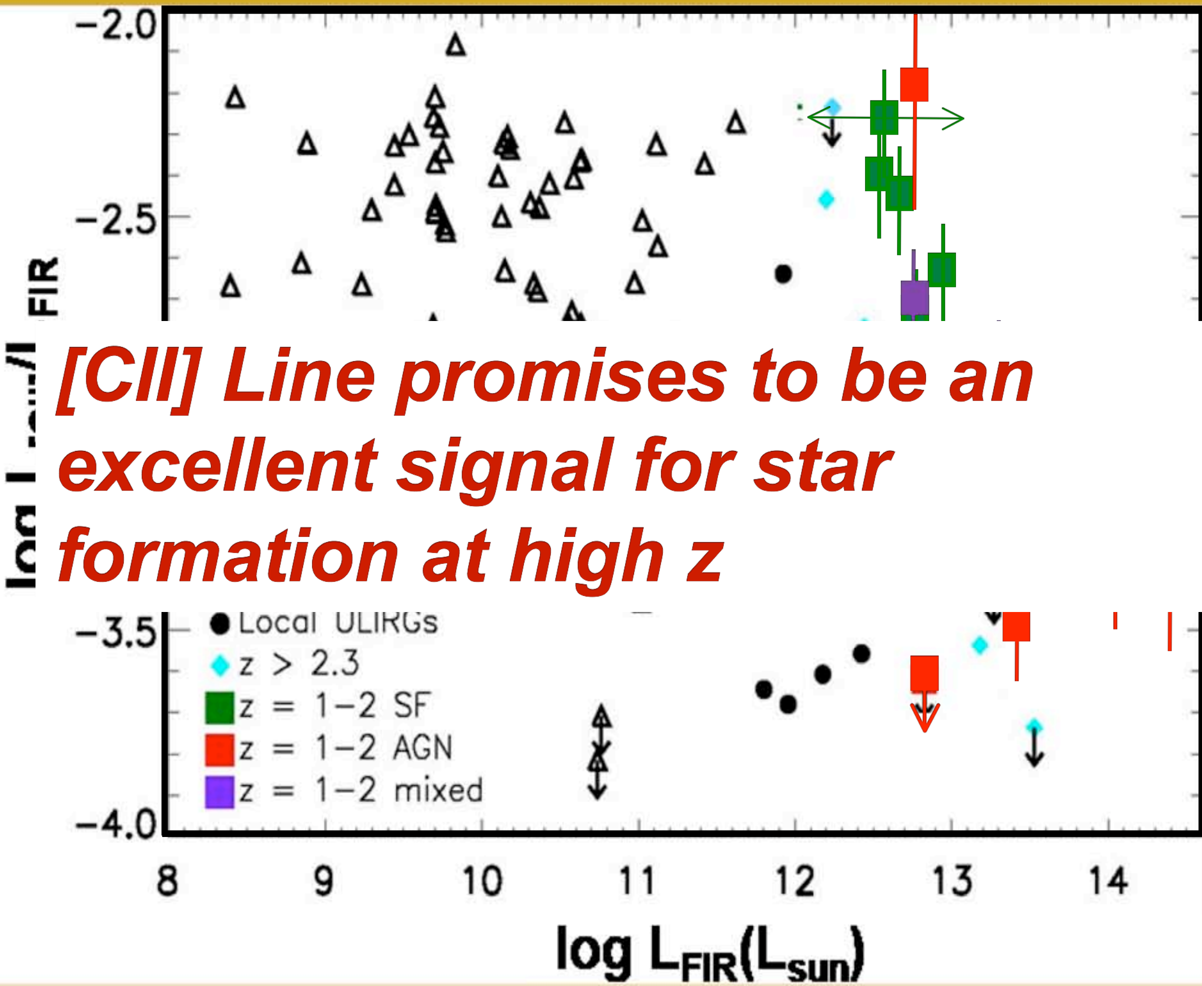
AGN-D:

R = 3.8±0.7$\times 10^{-4}$

Mixed – in between

SF-D to AGN-D ratio is ~ 8:1

Results: The [CII] to FIR Ratio



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

SF-D:

R = 2.9±0.5 $\times 10^{-3}$

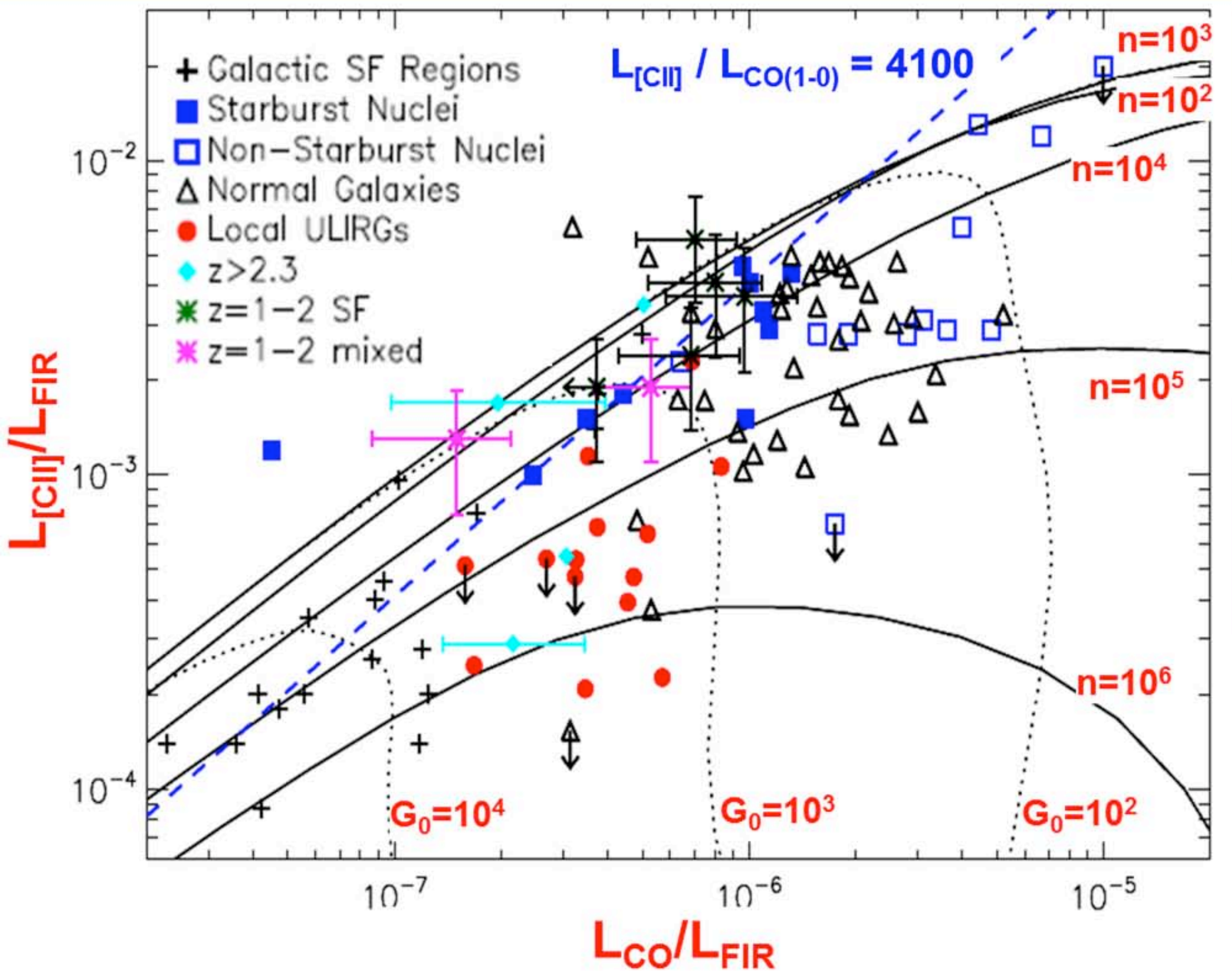
AGN-D:

R = 3.8±0.7$\times 10^{-4}$

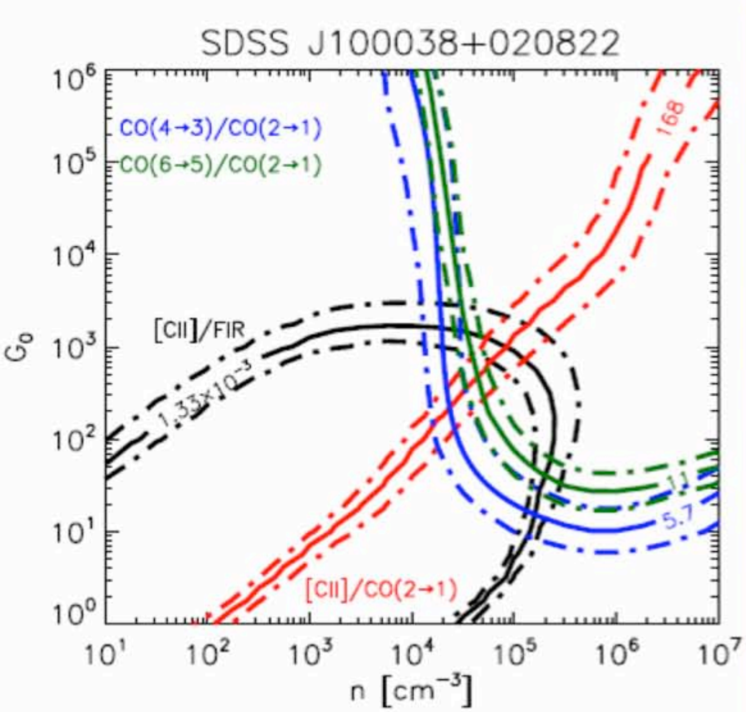
Mixed – in between

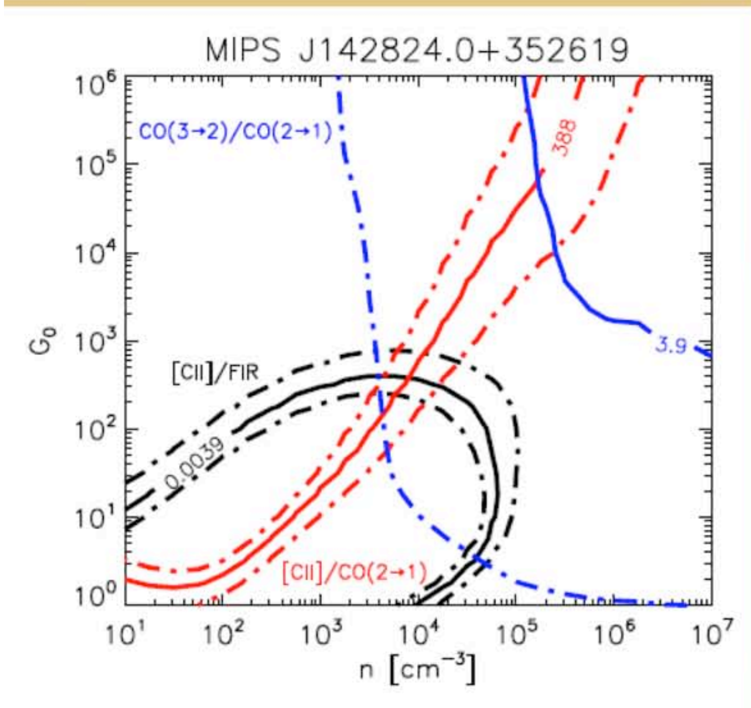
SF-D to AGN-D ratio is ~ 8:1

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



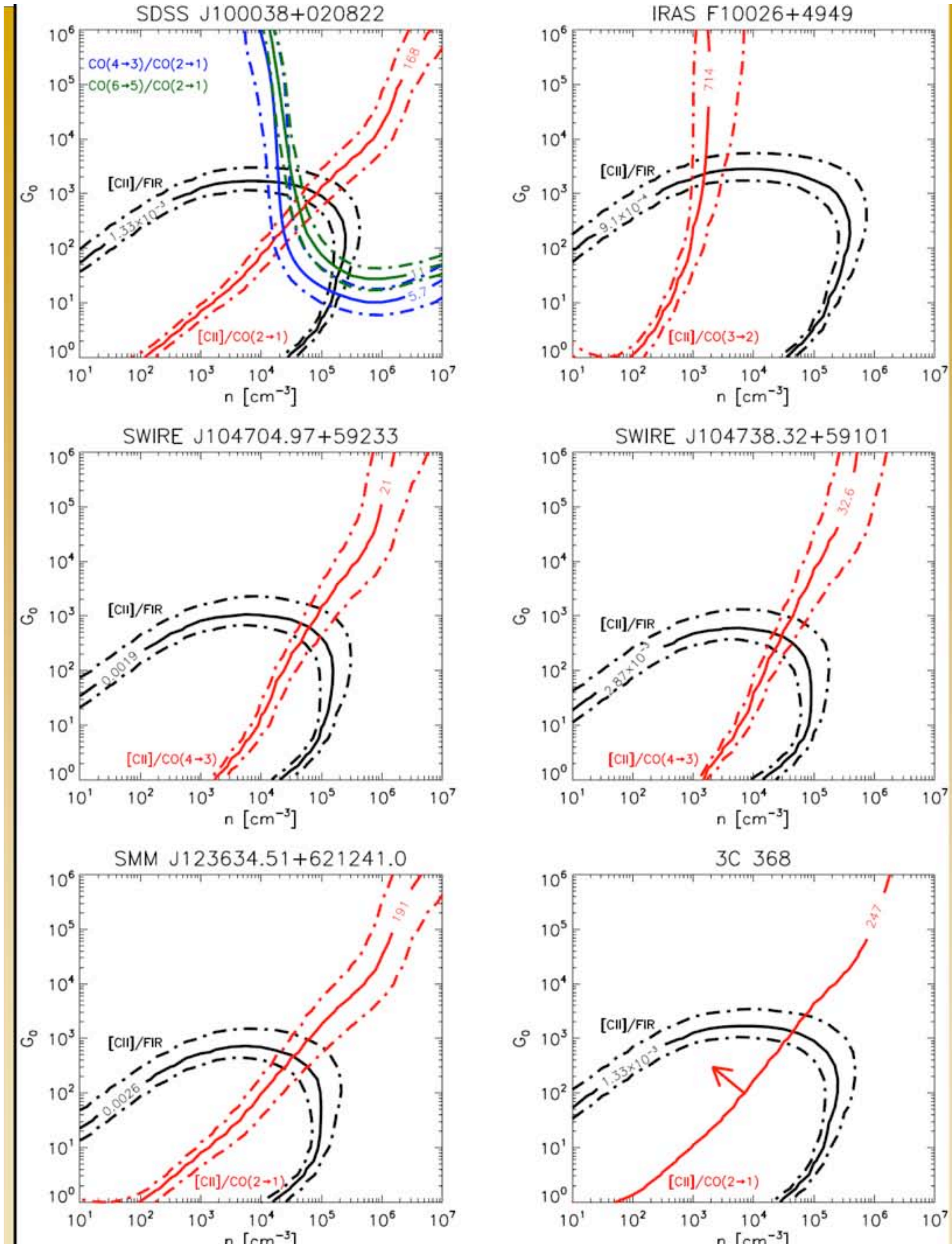
- **[CII]/CO(1-0) and FIR ratios similar to those of nearby starburst galaxies**
- **⇒ emission regions in our SF-D sample have similar FUV and densities as nearby starbursters**
  - **G ~ 400-5000**
  - **$n \sim 10^3$-10^4**





PDR Modeling

- **Two sources multiple CO Lines available**
- **PDR parameters well constrained**
  - **SDSS J100038 ("mixed")**
    - **G ~ 800**
    - **n ~ 4×10^4 cm**
  - **MIPS J1428 (SF-D)**
    - **G ~ 400**
    - **n ~ 8×10^3 cm^{-3}**



PDR Modeling

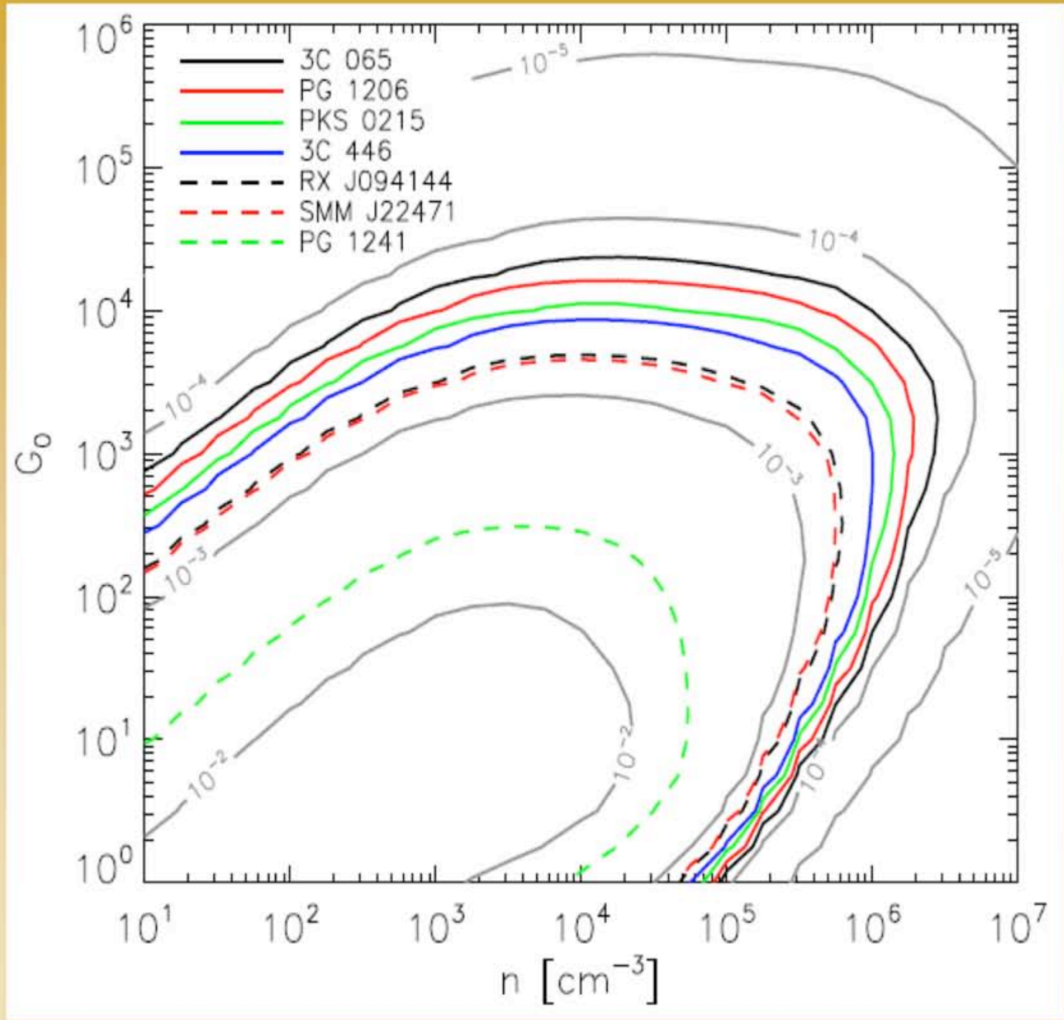
Five w/ one CO line available

PDR parameters well constrained

- **SMM J123634 (SF-D)**
  - **G ~ 500**
  - **n ~ 3 ×10^4 cm**
- **SWIRE J104738 (SF-D)**
  - **G ~ 400**
  - **n ~ 3 ×10^4 cm^{-3}**
- **SWIRE J104705 (SF-D)**
  - **G ~ 600**
  - **n ~ 6 ×10^4 cm**
- **IRAS F10026 ("mixed")**
  - **G ~ 2300**
  - **n ~ 1.6 ×10^3 cm^{-3}**
- **3C 368 (SF-D)**
  - **G ~ 1000**
  - **n < 5 ×10^4 cm^{-3}**

G_0 from [CII] and FIR

- **Seven sources have no CO lines available**
- **Can still confidently find G_o, since we have learned n ~ 10^3 -10^5 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**



How Extended are the Starbursts?

- 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-scale

- Galaxies are complex ⇒ plane parallel models are only a first cut
- Better to model distributed FUV fields (Wolfire 1990):

$$G_0 \sim \lambda L_{FIR} / D^3 \quad \lambda << D$$

$$G_0 \sim L_{FIR} / D^2 \quad \lambda >> D$$

  - λ is the mean free path of a FUV photon
  - D = size of the emitting region

Extended Starbursts in the z = 1–2 Survey

- We use this technique to estimate source sizes based on scaling from M82:
  - Star formation dominated systems:
    - D ~ 2 kpc for $\lambda \ll D$
    - D ~ 6 kpc for $\lambda \gg D$
  - Walter et al. (2009) resolved the [CII] emission from SDSS J1148 +5251 – scaling from this source for high G_0 sources (e.g. PG1206) we arrive at much the same answer
  - For cases where other tracers of star formation are available, our derived source sizes are typically somewhat smaller
- ***Star formation is extended on kpc scales with physical conditions very similar to M82 – with 100 to 1000 times the star formation rate!***

Star Formation Evolves

- Our derived physical conditions and source size contrast markedly with local ULIRGS where:
  - Star formation is relatively confined (< few hundred pc)
  - Star formation has relatively high FUV fields – 10 times larger than those derived here.
- Growing evidence for extended starbursts at high z
  - SMGs radio emission extends over kpc scales (Chapman et al. 2004), with median size ~ 5 kpc (Biggs & Ivison 2008)
  - CO interferometry of SMGs shows emission over ~ 4 kpc scales (Tacconi et al. 2006, 2008)
  - CO(3-2) survey of z > 1 sources suggests size scales between 3 and 16 kpc (Iono et al. 2009)
  - PdBI CO interferometry of MIPS 142824 and SMM 123634: 6.3 × 4.2 & 4.3 kpc scales (Hailey-Dunsheath et al., Engle et al. in prep.
- Likely the effect of much more massive molecular disks in the early Universe.

A Curious Situation in AGN-D

- If [CII] and FIR from starburst why is R different from SF-D sources?
- R is significantly smaller for AGN-D systems ⇒ FUV fields significantly larger
  - For the same source luminosity, one would therefore derive a smaller beam filling factor, hence smaller size
  - But, the AGNs are significantly more luminous ⇒ derive similar source size:
    - D ~ 1-3 kpc for $\lambda << D$
    - D ~ 3-12 kpc for $\lambda >> D$
    - Exception is 3C065 with D < 0.6-0.9 kpc
- *The AGN-D sources have much more intense, but similar sized starbursts as the SF-D sample.*

What Causes this Dichotomy?

1. What if the FIR in AGN comes from another source?

- PAH and [NeII] line studies suggest most of the FIR from both local AGN, and z ~ 2 AGN has its origins in star formation (Schweitzer et al. 2006, Shi et al. 2007, Lutz et al. 2008)
- Relationship between the 2-10 KeV X-ray and IR luminosity from AGN: pure systems, $L_{X\text{-}ray}/L_{FIR}\sim 0.45$ (Ruiz et al. 2007)
  - Using this scaling, for all but one source (PKS 0215) we find < 5% of the FIR is associated with the AGN.
    - For PKS 0215 we also show the [CII] emission might arise from an XDR (torus) associated with the engine
    - For other sources, we expect little [CII] from the BLR, NLR or XDR
- Conceivable that the FIR from our two blazars (PKS 0215 and 3C446) is relativistically boosted synchrotron radiation

What Causes this Dichotomy?

2. It could simply be that the $z = 1$ to 2 SF-D and AGN-D systems are distinct populations tracing different evolutionary paths

What Causes this Dichotomy?

3. May be there is a temporal link between the SF-D and AGN-D sources:

- Can AGN activity stimulate a kpc-scale starburst?
- The starburst ages as AGN activity shuts down
  - Young, intense starburst associated with AGN-D system evolves into less intense, but still extended SF-D systems
  - Observational support: [OIII] emission traces O stars. With ZEUS/CSO we detected [OIII] 88 um from two high z (2.8 & 3.9) composites (Ferkinhoff et al. 2010), and PACS/Herschel [OIII] 52 um from MIPS 1428 and the composite FSC 10214 (Sturm et al. 2010)
    - Ranked in order of high to low [OIII]/FIR ratio, the AGN-D systems tend to have strong lines ⇒ with younger starburst

What Causes this Dichotomy?

3. May be there is a temporal link between the SF-D and AGN-D sources:

- Can AGN activity stimulate a kpc-scale starburst?
- The starburst ages as AGN activity shuts down

Preferred, and testable solution: [OIII] ratio is density sensitive – how extended is [OIII] region?

If AGN generated [OIII], can test with [OIV] 24 um line.

m

ms

z

GN-

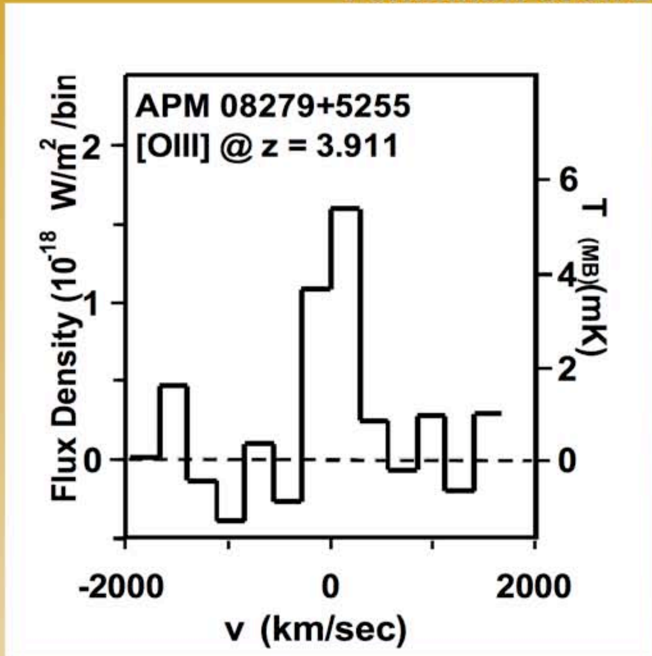
D systems tend to have strong lines ⇒ with younger starburst

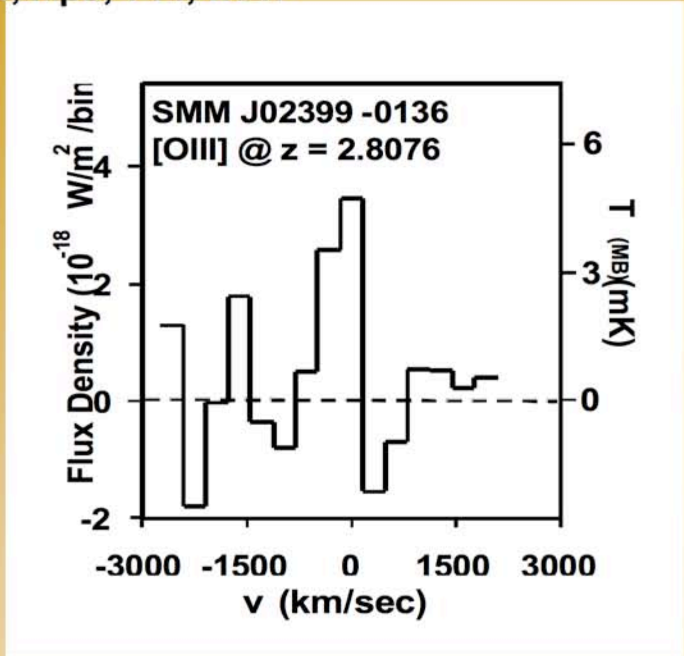
ZEUS/CSO [OIII] at High z

- O^{++} takes 35 eV to form, so that [O III] traces early type stars
- Transmitted through telluric windows at epochs of interests:
  - 88 μm line at z~ (1.5) 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 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 ($\mu \sim$ 2.38)**

Characterizing the Starburst/AGN

- [O III]/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)
- APM 08279
  - [OIII]/[NII] ⇒ Starburst dominated by stars with T_{eff} > 36,000 K (O9)
  - 35% of observed FIR comes from this starburst: 12,000/μ $M_{\odot}$/year
  - Can also be generated in the narrow-line region of AGN if n > 1000 cm^{-3}
- SMM J02399
  - Starburst most likely: with T_{eff} > 40,000 K (O7.5)
  - Most of the FIR comes from this starburst 5,000/μ $M_{\odot}$/year

The Redshift (z) and Early Universe Spectrometer: ZEUS

S. Hailey-Dunsheath Cornell PhD 2009

- **Submm (650 and 850 GHz) grating spectrometer**

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

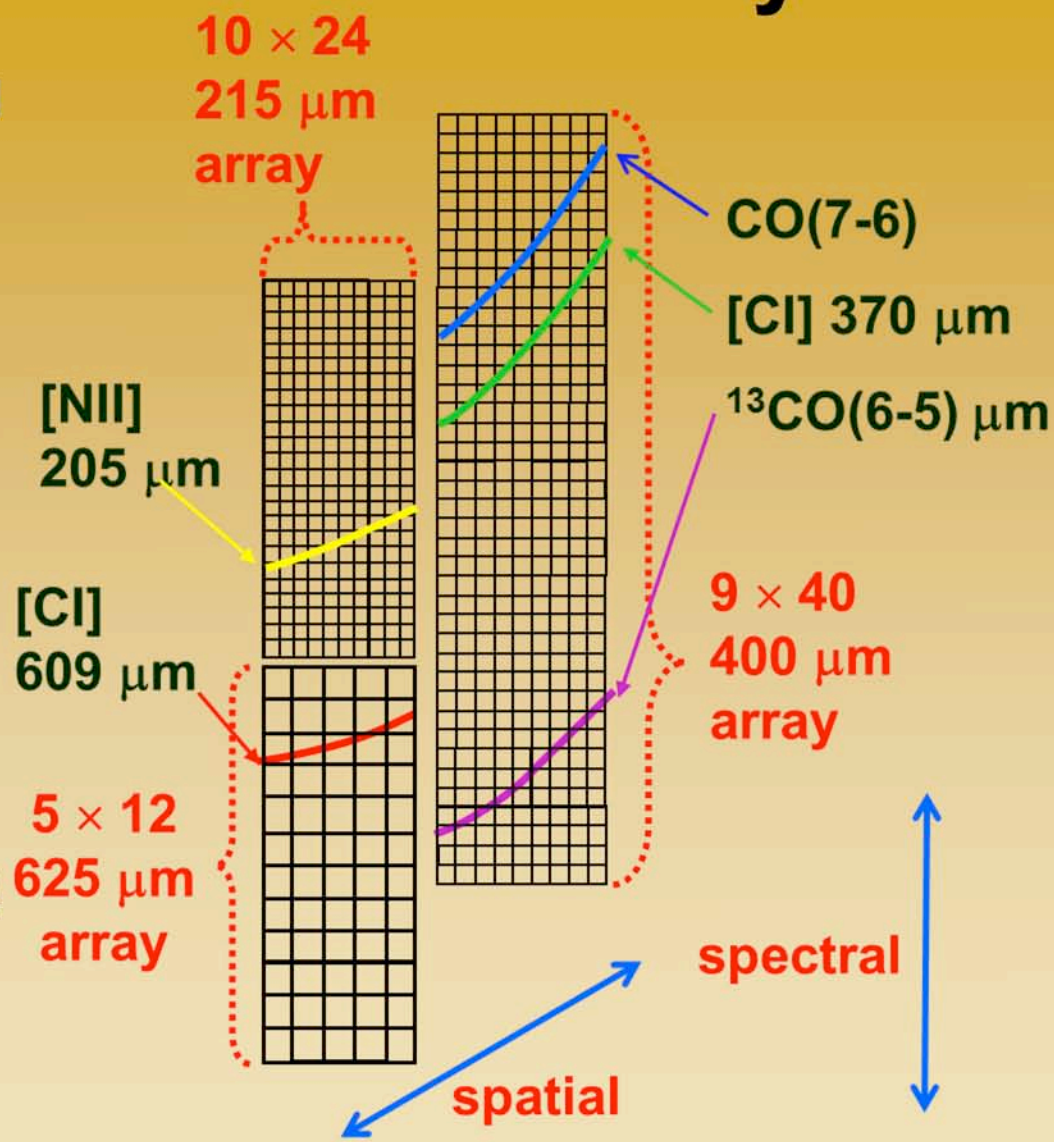
  ⇒Limiting flux (5σ in 4 hours) ~ 0.8 to 1.1 $\times 10^{-18}$ W m^{-2} (CSO)

  ⇒Factor of two better on APEX

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

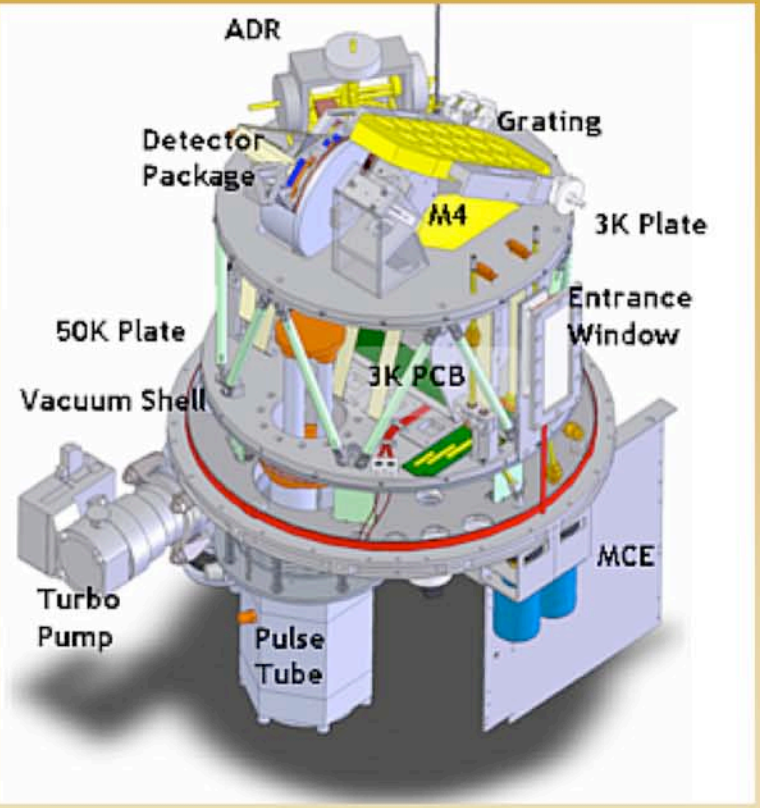
ZEUS-2 Focal Plane Array

- **Upgrading to (3) NIST 2-d TES bolometer arrays**
- **Backshort tuned**
- **5 lines in 4 bands *simultaneously***
  - **215 μm (1.5 THz)**
  - **350 μm (850 GHz)**
  - **450 μm (650 GHz)**
  - **625 μm (475 GHz)**
- **Imaging capability (9-10 beams)**
- **Simultaneous detection of [CII] and [NII] in z ~ 1-2 range**



ZEUS-2

- Al dewar designed and manufactured locally
- Extensive light-weighting and compact design
- Cryomech model PT407 pulse-tube cooler (55k and 3K)
- dual stage ADR from Janis (1K and 100mK)
- Detector package held in Kevlar mount; a 100 mK housing with 1 K shield



Stephen Parshley

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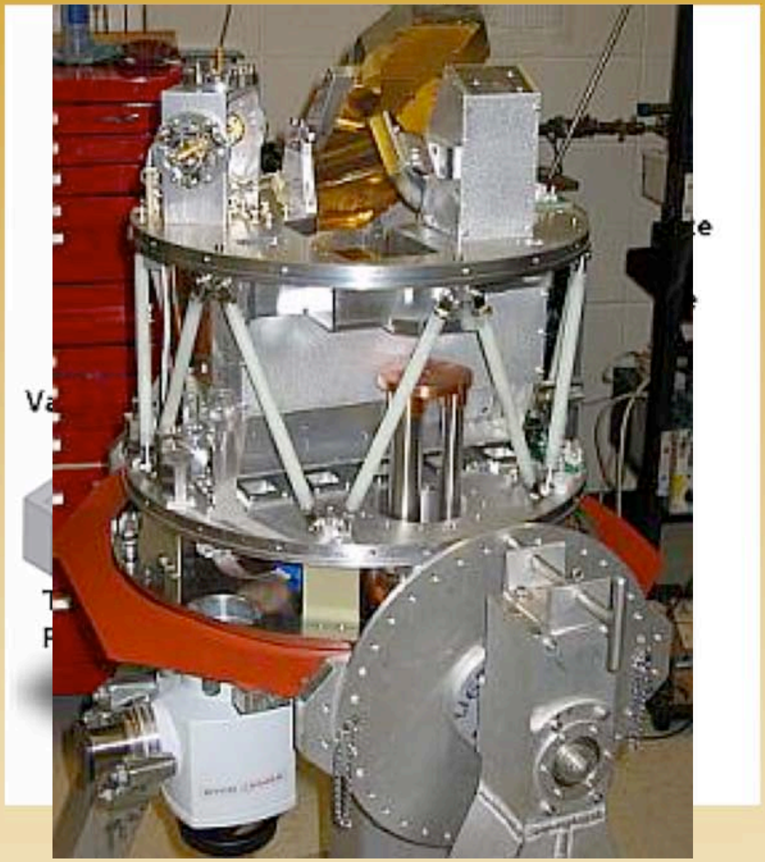


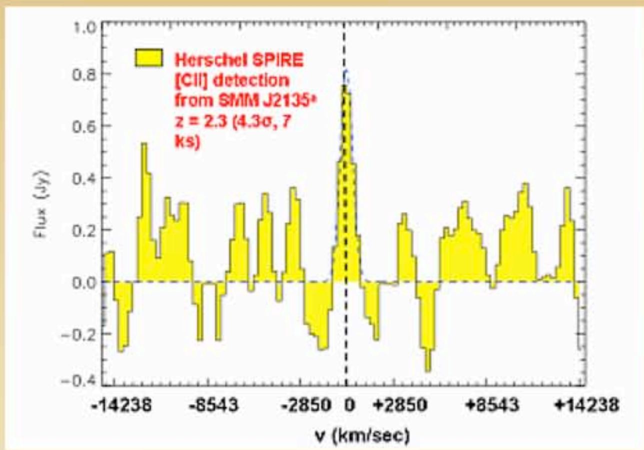
Stephen Parshley

ZEUS/ZEUS-2 Optimized For High-z Spectroscopy

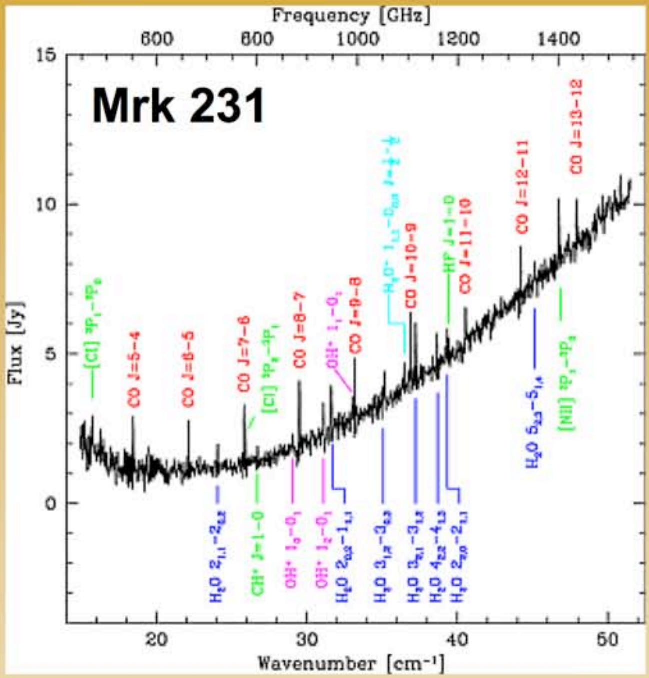
- **Resolution matched to line width**
- **Simple optics (mirrors): maximum throughput**
- **High through-put (30%) in *both polarizations***
- **ZEUS is nearly background limited (within ~1.1 BLIP)**
- **ZEUS-2 expected to be BLIP:**
  - **T_{rec}(SSB) < 25K in all bands**
- **Multi-beam (slit) enables serendipitous detection of high-z sources**

Herschel Spectroscopy

- **Herschel/SPIRE provides huge wavelength range**
- **No atmospheric restrictions**
- **Great for spectral multiplexing**



Ivison et al. 2010, A&A, 518, L35



van der Werf et al. 2010, A&A, 515, L43

Herschel Spectroscopy

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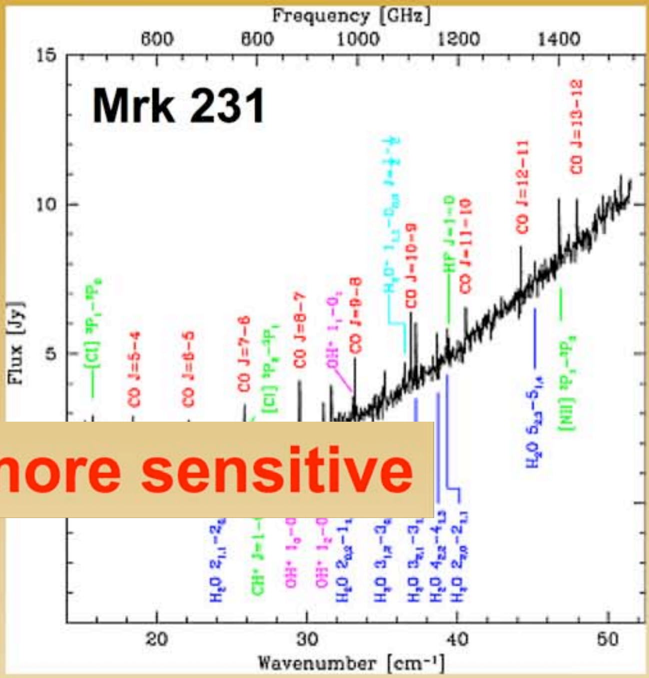
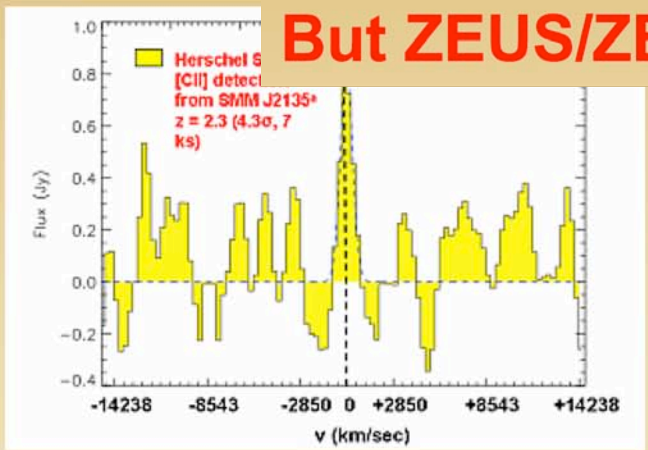


van der Werf et al. 2010, A&A, 515, L43

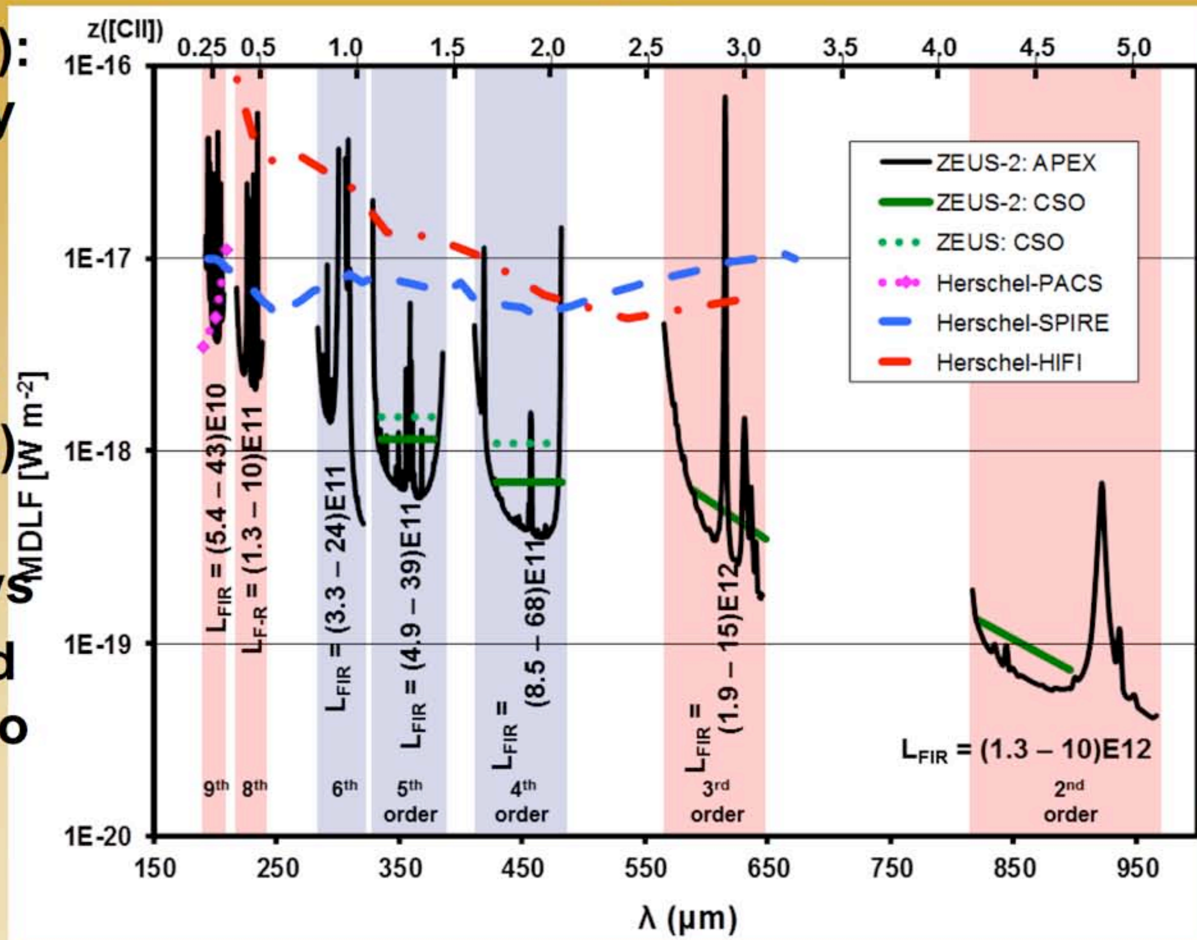


But ZEUS/ZEUS-2 is more sensitive

Ivison et al. 2010, A&A, 518, L35

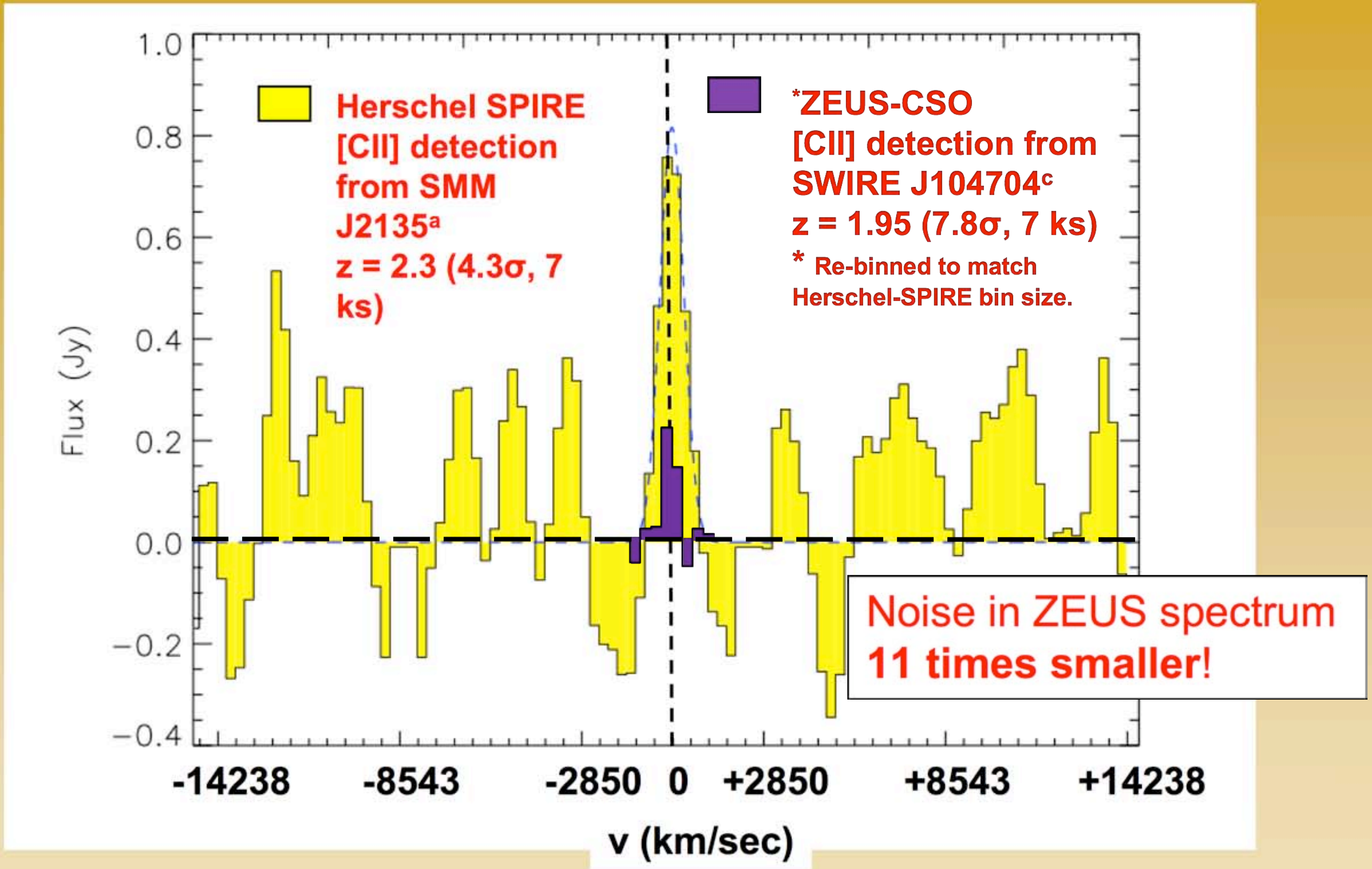
ZEUS/ZEUS-2 Optimized For High-z Spectroscopy

- **ZEUS-2 (APEX/CSO): detect lensed "Milky Ways" at high-z!**
- **Sampling large fraction of galaxy population (not just the bright monsters)**
- **In short λ-band: unlensed Milky Ways**
- **Next 3 years: extend our galaxy sample to >100 galaxies detected in red-shifted far-IR lines**



MDLF (5σ, 4 hr) for ZEUS-2 on APEX and on CSO

ZEUS Sensitivity Demonstration



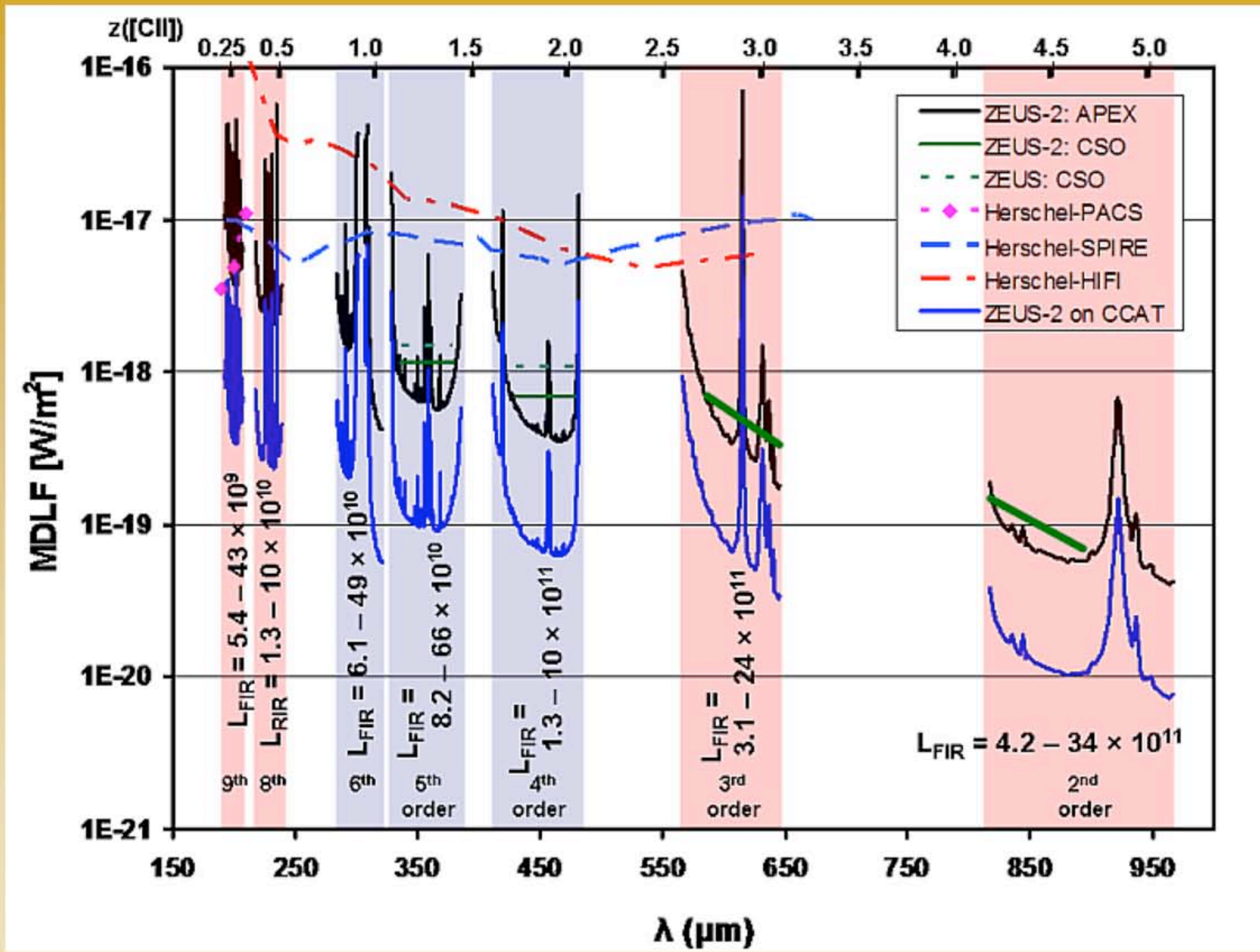
[a]Ivison et al. 2010, A&A, 518, L35 [c] Stacey et al. 2010, ApJ, 724, 957

Synergy: Herschel – ZEUS-2 – ALMA

- **[CII]/continuum (SF-D) = 10:1 ⇒ 350/450 μm source at Herschel/SPIRE 5σ (32 mJy) confusion limit is readily observable with ZEUS-2 on either CSO/APEX:**
  - **Get sources from Herschel**
  - **Get redshifts from ZSpec or Zpectrometer (GBT)**
  - **Get redshifted far-IR line with ZEUS-2 on CSO/APEX/CCAT**
  - **Get spatial information with ALMA**
- ***SKIP A STEP? – ZEUS-2 modification to z-machine***
  - **4^{th} and 3^{rd} order at 350 and 450 μm ⇒ *10% BW* in both bands**
  - **> 30% of SMGs within these windows**
  - **Can operate *simultaneously* w/ small loss (√2) in sensitivity**

Would detect [CII] (redshift) and [NII] (science) simultaneously

Outlook: ZEUS-2 on CCAT



ZEUS-2 & Offsprings eagerly await the birth of CCAT