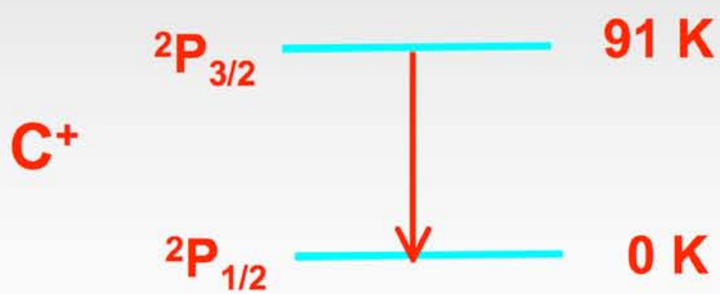
The 158 μm [CII] Line and CCAT

- The [CII] line is a ubiquitous coolant for the interstellar medium
  - Photo-dissociated surfaces of molecular clouds (PDRs)
  - Atomic clouds
  - Low density ionized gas regions
- PDR emission usually dominates the line
  - Traces the physical conditions of the gas and stellar radiation field
  - The line to far-IR continuum ratio traces G, Φ_{beam}, i.e. the strength and spatial extent of the starburst.
  - With other fine structure and CO lines: n, N, mass, radiation field hardness (age of starburst, or AGN?)
- Since it is uniquely bright, the [CII] line is an excellent redshift probe.

The [CII] Line

- Carbon is the 4th most abundant
- Low IP – found in both neutral and ionized gas
- Easily excited – 91 K
- ⇒ Expect the [CII] line to be an important coolant for both ionized and neutral gas



Element	Ionization Potential	Abundance
H	13.60 eV	9.35E-1
He	24.59 eV	6.5E-2
O	13.62 eV	6.32×10^{-4}
C	11.26 eV	3.47×10^{-4}
N	14.53 eV	1.10×10^{-4}
Ne	21.56 eV	1.01×10^{-4}

Is the [CII] Line Important?

Major components of the interstellar medium

Component	T (K)	n (cm^{-3})	Mass Fraction	Volume Fraction
Molecular clouds	15	300	50%	0.2%
Cold HI (atomic clouds)	93	30	33%	1.3%
Diffuse HI	(5-8000)	~0.5	15%	36%
Dense HII	7500	30	1%	0.05%
Diffuse HII	9000	0.3	2%	8%
Hot HII			-	>50

Sources

Cox, D.P. ARAA 43, 2005, 337

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Diffuse HII	9000	0.3	2%	8%
Hot HII	$>10^6$	<<1	-	>50

Major Coolant

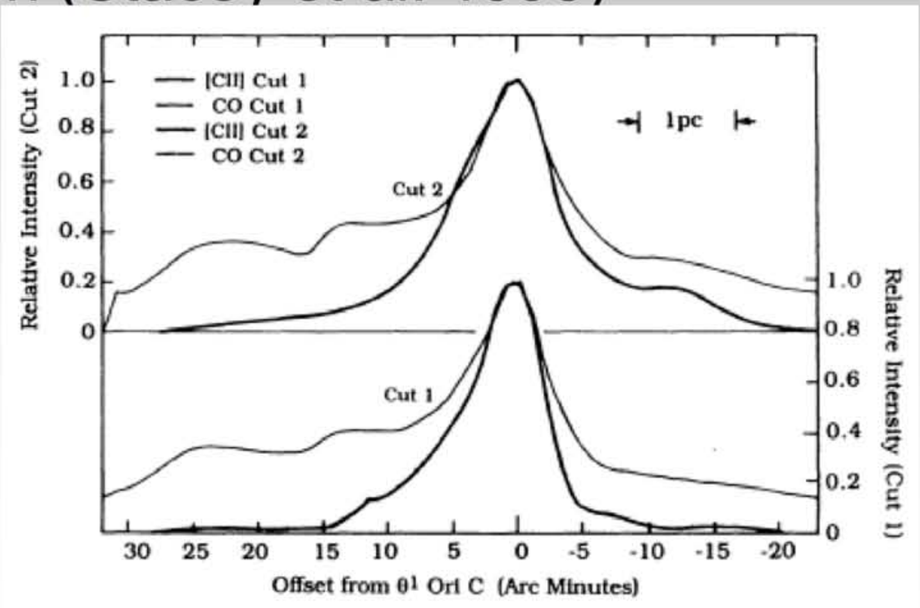
Cox, D.P. ARAA 43, 2005, 337

Where does the [CII] line come from?

- At first thought to be important primarily for atomic clouds (Dalgarno and McCray 1972)
- However, first observations of Galactic star formation regions (Russell et al. 1979):
  - Line very bright: 2000 to 5000 $L_\odot$ ⇔ ~1% L_{FIR}
  - Indicated a much denser medium (2000 cm^{-3}) associated with molecular clouds
- Cuts across the Galactic plane indicated the molecular ISM (Stacey et al. 1983, 1985, Shibai et al. 1991)
  - Scale height – similar to HII and molecular clouds
  - Intensity – HII and atomic clouds won't work: needed the dense molecular medium

Where does the [CII] line come from?

- First extragalactic observations showed a [CII] – CO(1-0) line intensity correlation (Crawford et al. 1985)
- Tielens and Hollenbach (1985) produced their classic paper on photodissociation regions (PDRs)
- Association with molecular clouds dramatically verified by cuts across GMC surfaces: M17 (Stutzki et al. 1989), Orion (Stacey et al. 1993)

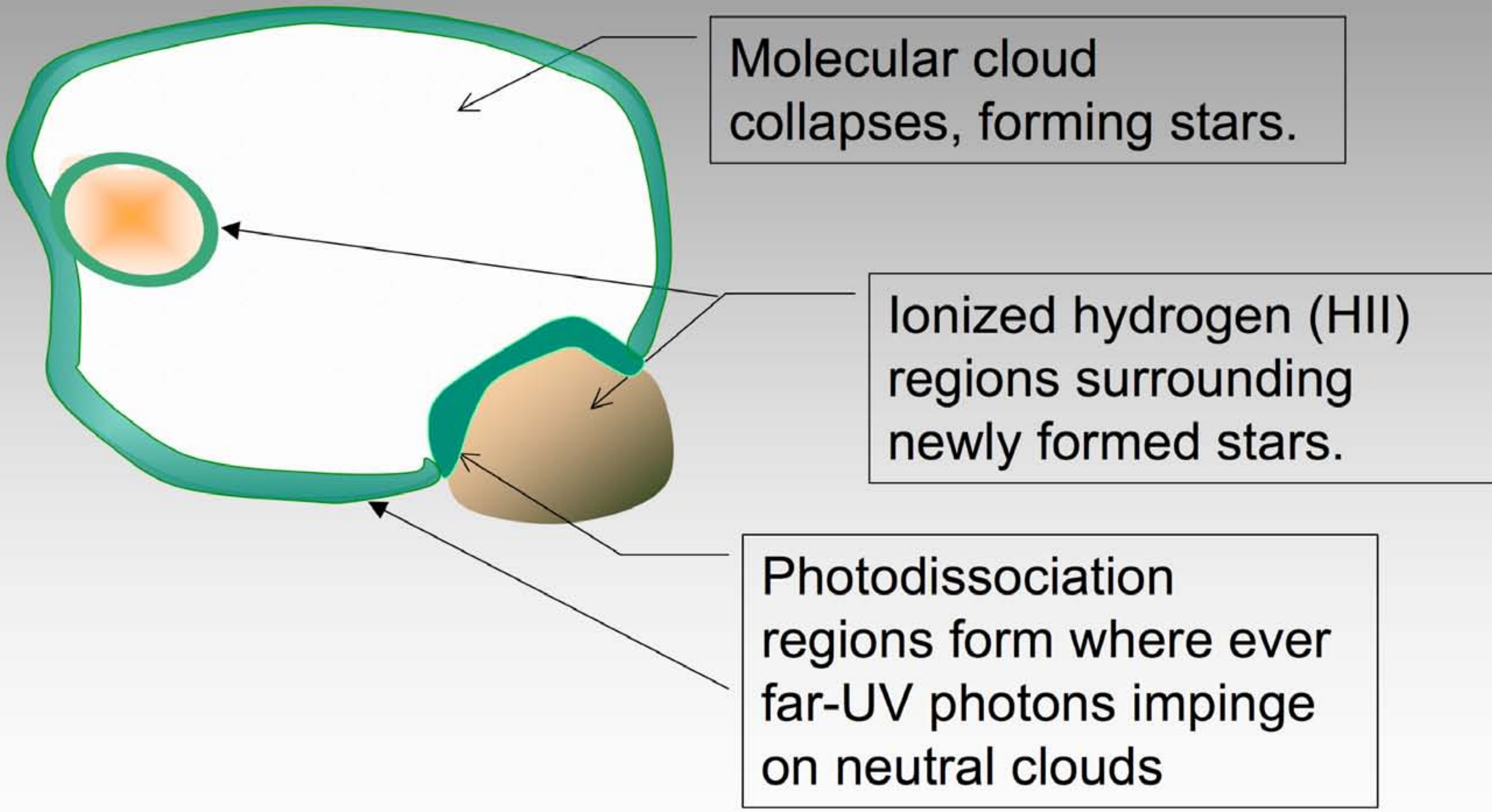


⇒ ***[CII] line emission dominated by PDRs***

Photodissociation Regions

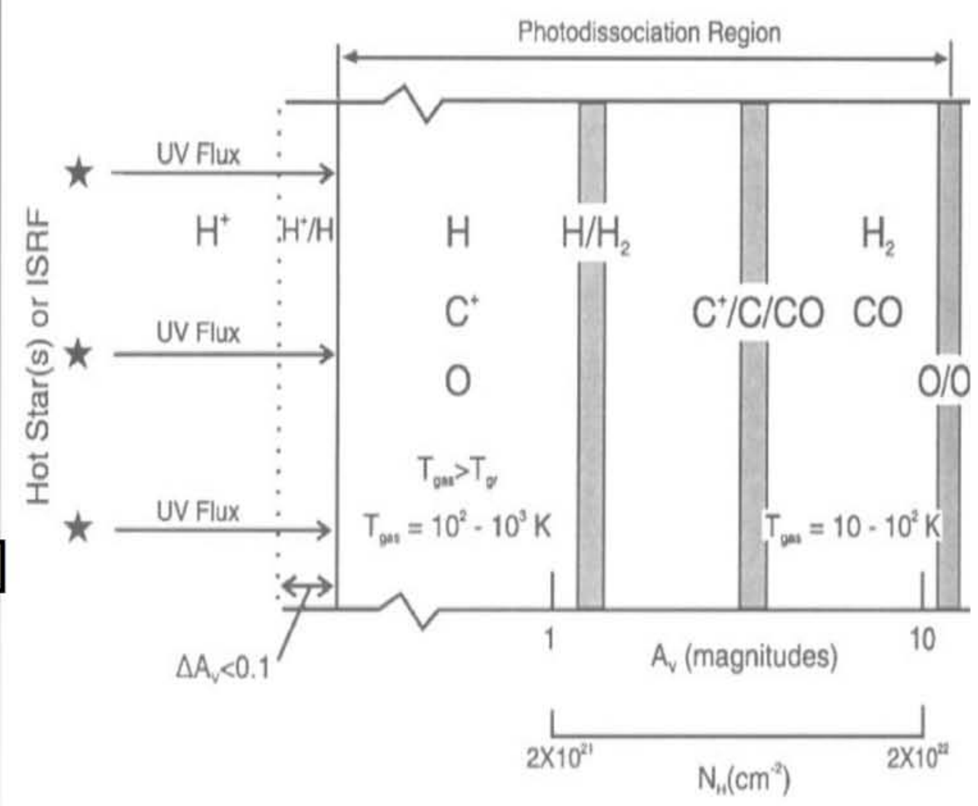
- Whenever far-UV photons impinge on a neutral clouds, molecules -- dissociated & elements ionized if their I.P. <13.6 eV, forming a “photodissociation region”, or PDR
- Far-UV photons heat the gas and dust ⇒ intense emission in the dust continuum, polycyclic aromatic hydrocarbon (PAH)’s, far-IR F.S. lines (e.g. [CII] 158 μm [OI] 63 and 146 μm), the H_2 rotational and ro-vibrational transitions, and (deeper into the cloud) CO rotational lines and the F.S. lines of [CI] at 370 and 609 μm
- PDRs emission can dominate line and continuum emission and even ISM mass in Galaxies.
- All HI gas, and much of the molecular ISM is in PDRs (also known as photon dominated regions)

Photodissociation Regions



Structure of the PDR

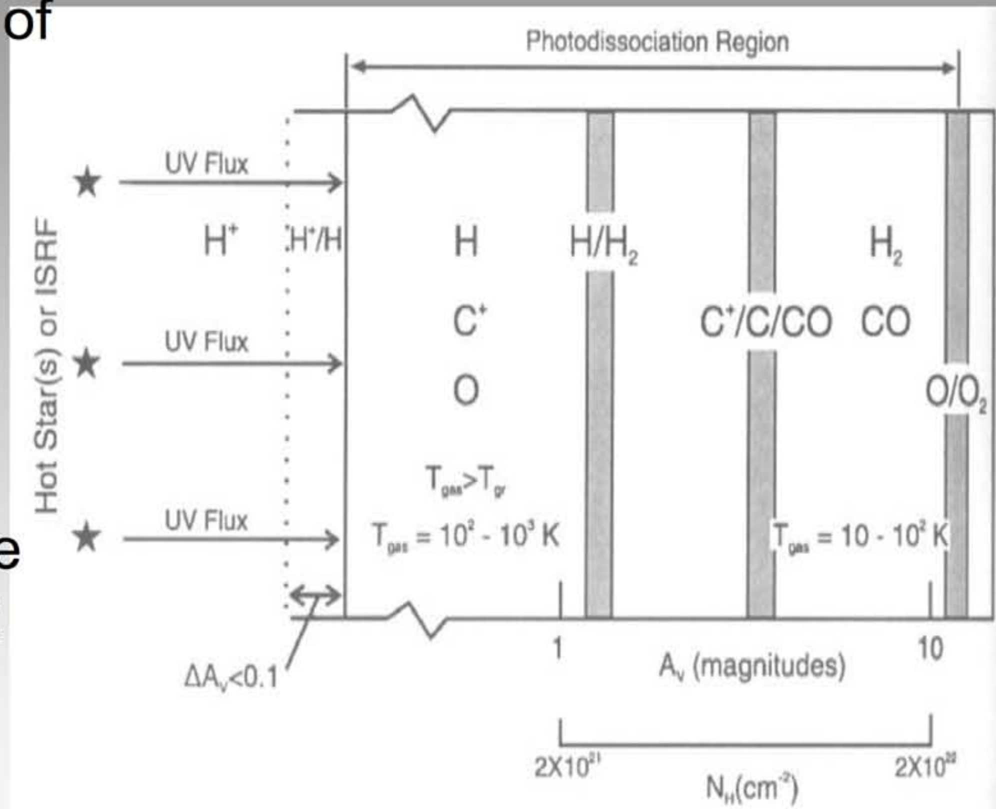
- Neutral gas is illuminated by hot stars or the ISRF
- There is a thin HII/HI interface that absorbs the Lyman continuum photons
- Detailed structure depends on G/n:
  - G far-UV (6-13.6 eV) ISRF [1.6×10^{-3} erg $cm^{-2}s^{-1}$]
  - N: gas density
- Typically, HI layer extends to A_V~1-2, or N_{HI} ~ 2-4 × 10^{21} cm^{-2} from the ionization front
- Far-UV pumped H_2 emission peaks at the HI/H_2 interface



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

Structure of the PDR

- C^+ layer extends to $A_V \sim 2\text{-}4$ – determined by extinction of far-UV photons by dust
- O is atomic to $A_V \sim 5\text{-}10$ – this defines the extent of the PDR
- Neutral C exists at the C^+/CO interface
- Atomic clouds (CNM) or the WNM typically have $A_V < 2$ so that they are nearly entirely atomic.

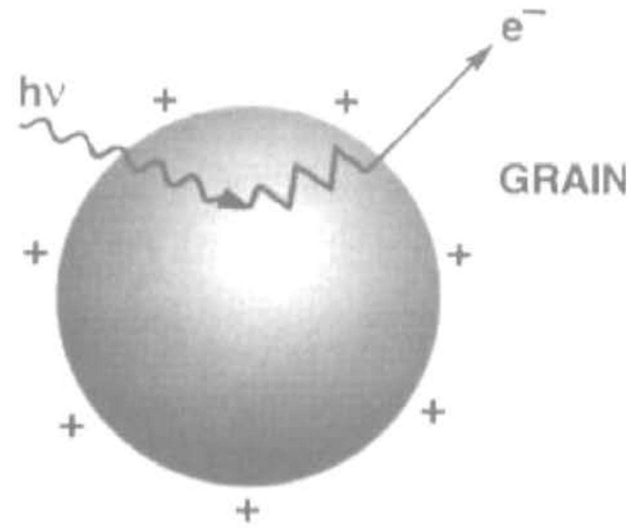


Heating of PDRs

- There are two primary heating mechanisms for photodissociation regions
  - Photoelectric heating
  - Heating through collisional de-excitation of vibrationally excited H_2

Photoelectric Heating

- The physics of P.E. heating is:
  - Far-UV photons absorbed by the grain create energetic (~ several eV) electrons
  - e^- diffuse through grain and on reaching the grain surface they can escape if K.E. > the work function of the grain, W, and any Coulomb potential, ϕ_C
  - Any excess K.E. is then injected into the gas phase



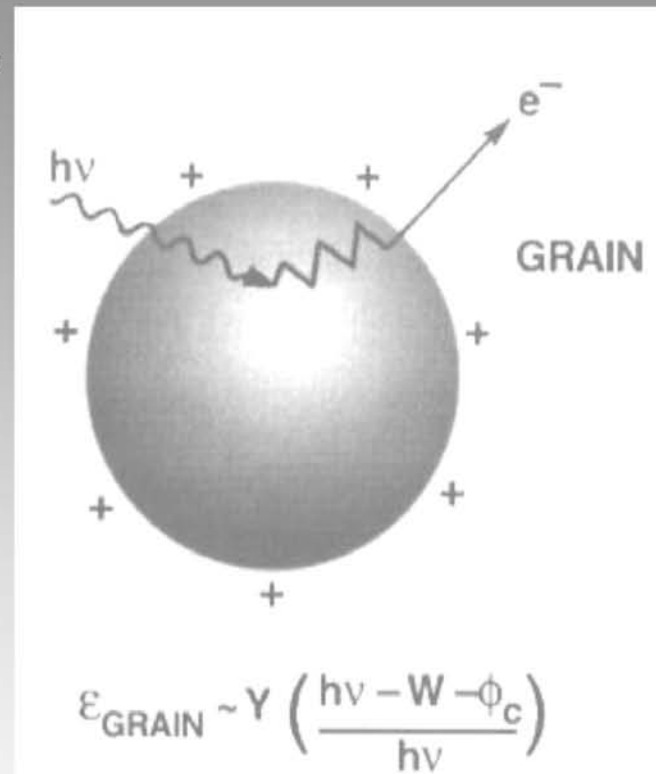
$$\varepsilon_{GRAIN} \sim Y \left(\frac{h\nu - W - \phi_c}{h\nu} \right)$$

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

Photoelectric Heating

- The efficiency of the P.E. effect, ε_{grain}, is the ratio of the gas heating rate to the grain far-UV absorption rate.
- It is given by the yield, Y (the probability that an e^- escapes) times the fraction of the photon energy that is carried away by the electron:

$$\varepsilon_{grain} \cong Y\left(\frac{h\nu - W - \phi_C}{h\nu}\right)$$



Photoelectric Heating

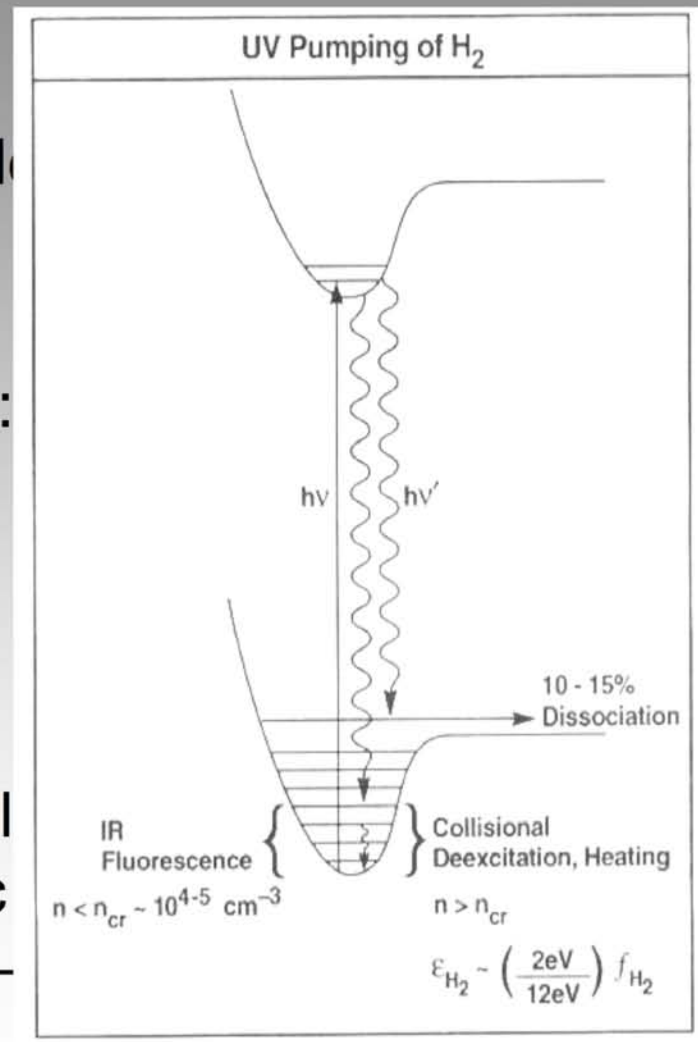
- The yield, Y is a complex function of the grain size, a, the collision length scale for electrons in solids (l_e ~ 10 Å), and the photon energy $h\nu$
- For large grains, photons with energy well above threshold are absorbed ~ 100 Å inside the grain, so that they therefore rarely escape:

$$Y \sim l_e / l_a \cong 0.1$$

  - With typical far-UV energies of 10 eV, and a work function of 5 eV, the efficiency is therefore ~ 5%
- For smaller grains, the yield can be much larger and efficiencies can be up to 15% - so smaller grains dominate the heating
- ***In general, efficiencies are far less due to grain charging***

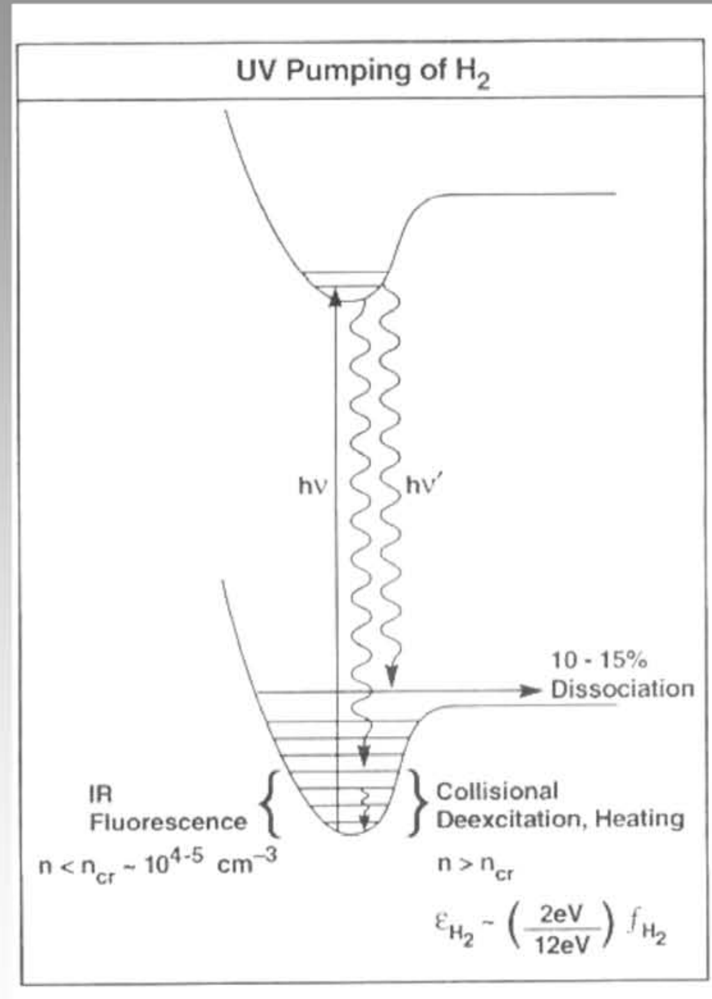
H_2 Heating

- The absorption of a far-UV photon can pump an H_2 molecule to a bound excited electronic state
- The excited molecule will decay:
  - Back to the vibrational continuum of the ground electronic state (10 – 15% of the time) – dissociation
  - Back to an excited vibrational state of the ground electronic state (85 – 90% of the time) – radiative excitation



H_2 Heating

- Most absorptions leads to an excited molecule with $E_{vib} \sim 2$ eV
- At low densities, the molecule will cascade down, leading to a characteristic near-IR ro-vibrational spectrum
- At high densities ($n > 10^{4-5}$ cm^{-3}) collisional de-excitation by hydrogen is important which heates the gas with efficiency as large as 4%

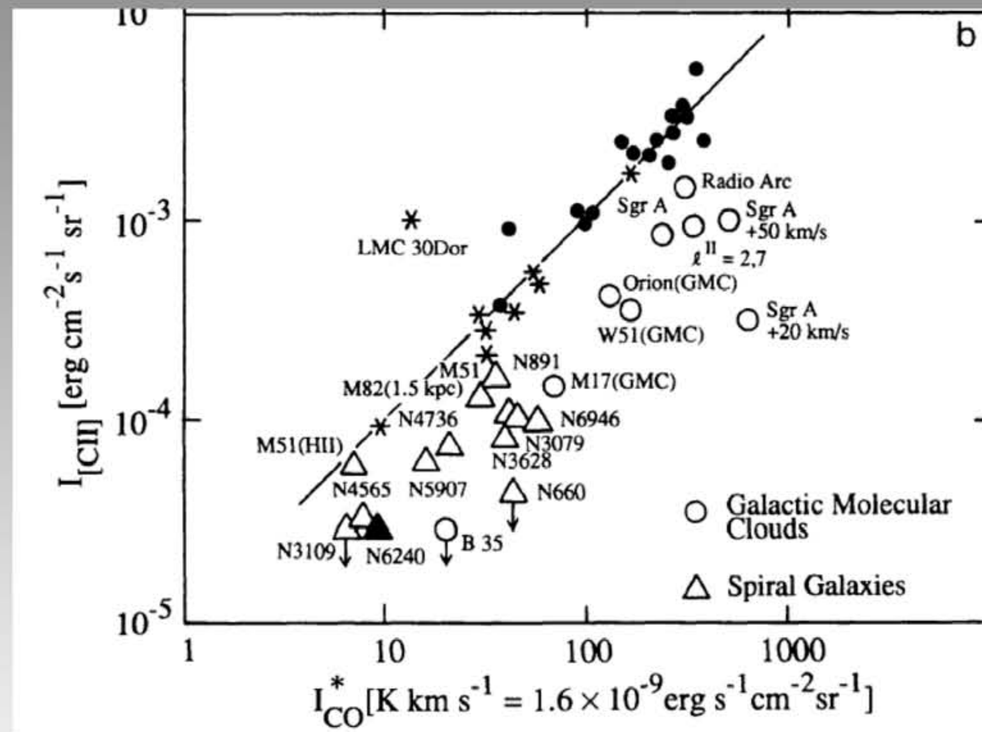


Cooling of PDRs

- The gas in PDRs is cooled by the far-IR fine structure lines of abundant species such as:
  - [CII] 158 μm
  - [OI] 63 and 146 μm
  - [SiII] 35 μm
  - [CI] 609 and 370 μm
- And, by the molecular rotational lines of CO and H_2
- At the PDR surface the dominant coolants are [CII] and [OI]
- The [OI] line becomes progressively more important at high gas densities due to its higher critical density
- ***By measuring the cooling lines, we measure the heating, hence G and n***

First Extragalactic Surveys

- [CII] is bright in star forming galaxies ~ 0.1 to 1% of the far-IR continuum (Crawford et al. 1985)
- [CII] arises from PDRs on the surfaces of UV exposed GMCs
- [CII], CO and [OI] lines and far-IR continuum well explained by PDRs (e.g. Malhotra et al. 1997, Nigishi et al. 2001)

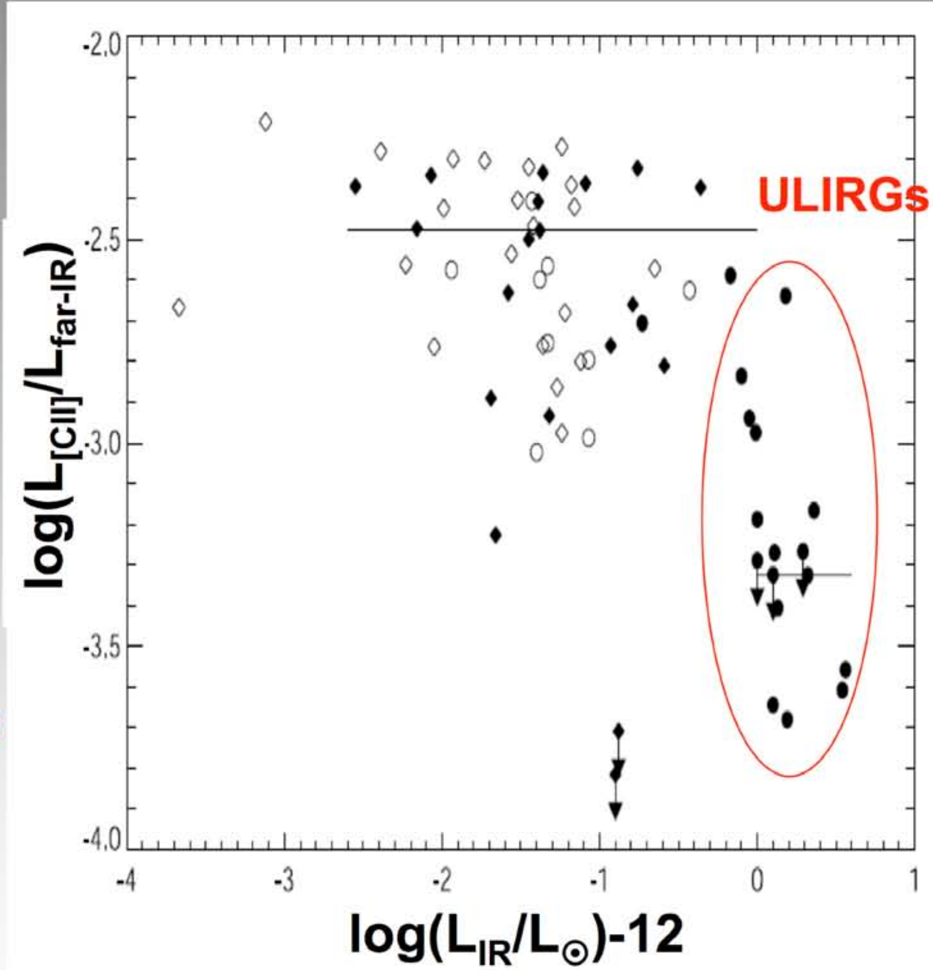


Stacey et al. 1991

- Correlation between [CII] and CO(1-0) for Galactic star formation regions and starburst nuclei: ratio ~ 4400 well explained by PDR models
- Ratio is 3 times smaller for non-starburst galaxies and quiescent molecular clouds ⇒ ratio is tracer of starformation activity

ISO Surveys: the [CII] "Deficit"

- Luhmand et al. (1997, 2003) studied 15 ULIRG galaxies
- Find [CII] underluminous w.r.t. far-IR continuum by a factor of ~ 6 when compared with "normal" galaxies
- Examine pathways
  - High G and/or n
  - Dust extinction
  - Self absorption in [CII]
  - ***Non-PDR sources of far-IR continuum***
- Dust bounded HII regions – *which means star formation sites are entirely different in ULIRG galaxies,* or…
- AGN illuminated tori

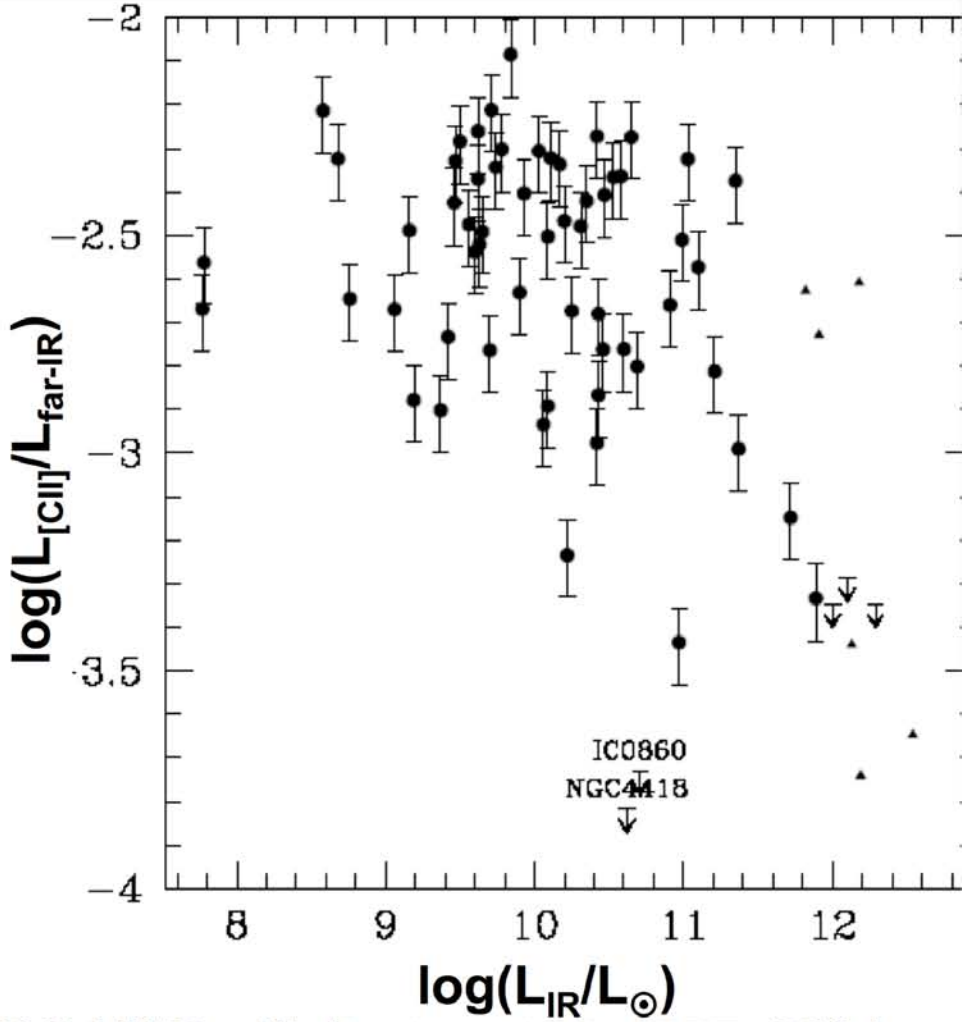


ISO LWS: Luhman et al. 1998, 2003

ISO "Normal Galaxies"

- For 2/3 of the galaxies, the [CII]/far-IR ratio is constant, for the other 1/3 it declines steeply (Malhotra et al.)
- Due to increased grain charge in the warmer, more active galaxies which *lowers the p.e. heating efficiency*
- Tight correlation between [OI]/[CII] and warm dust colors: both gas and dust temperature increase together

G is correlated with n which means higher UV field PDRs are denser⇒ more cooling in the [OI] line



ISO LWS: Malhotra et al. 1997, 2001

ISO "Normal Galaxies"

- For 2/3 of the galaxies, the [CII]/far-IR ratio is constant, for the other 1/3 it declines steeply (Malhotra et al.)
- Due to increased grain charge in the warmer, more active galaxies which *lowers*

Fall-off in ratio is due to higher UV fields (more intense starburst) ∴ decreased p.e. heating efficiency – a more satisfying solution

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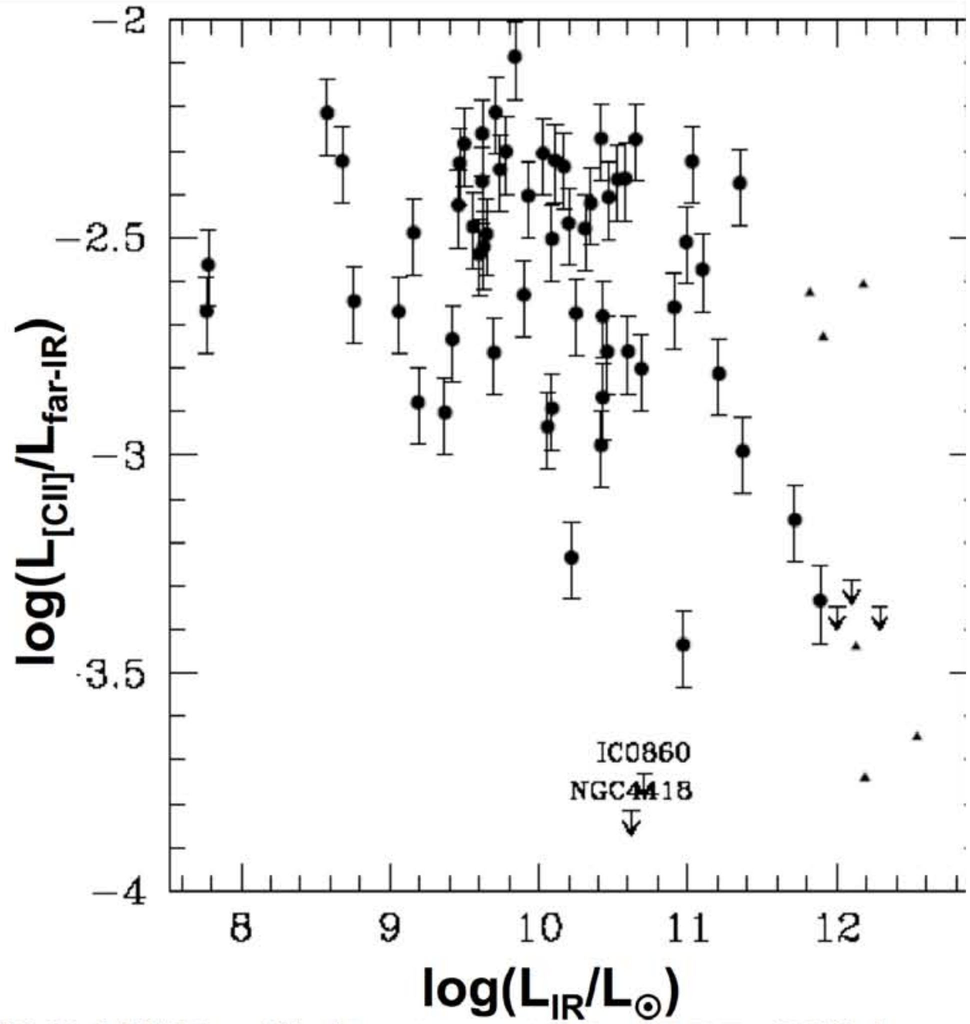


ISO LWS: Malhotra et al. 1997, 2001

Important Goals for CCAT Spectroscopy

CCAT will detect millions of moderately high submm bright galaxies in its surveys

- Redshift – we need bright lines to characterize the population as a function of z, providing source distance, luminosity, and calibrating photo-z
  - What is the evolutionary history of star formation in the Universe?
  - What can we learn about large scale structure?
- Physical properties of the ISM – how do the tremendous luminosities affect the natal ISM?
- Properties of the starburst itself – the apparent huge far-IR luminosities of these sources imply a different mode of star formation
  - Was the IMF different?
  - Were starbursts more intense, or did they occur over larger scales?

What CCAT Offers with [CII]: Redshifts

- The 158 μm [CII] line is arguably the best redshift probe for submillimeter galaxies
  - ***The line is very bright:*** For starforming galaxies, the [CII]/far-IR continuum ratio is ~ 0.1 to 1% -- for ULIRGs, it is ~ 6 times weaker but still strong
  - ***The line is unique:*** One can show that for redshifts beyond 1, [CII] is unique enough to yield the redshift
  - ***The line is the dominant coolant*** for much of the interstellar medium, and is therefore a sensitive probe of the physical parameters of the source.
  - ***The line is readily detectable with CCAT*** over > 50% of the redshift bands from 0.25 to 5.

Is [CII] as "good" as CO for redshifts?

- Uniquely bright in nearly all systems – typically 200 × brighter than mid-J CO lines
  - However, background is lower in mm regime ⇒ receivers can be 10 to 40 × more sensitive for CO lines
  - Net result is factor of 5 to 20 easier to detect a redshifted [CII] line (with the same telescope) – *providing the starburst ratio applies*
  - *And about equal if the ULIRG ratio applies*

Off course, the real exciting physics is to get both a set of CO lines and [CII]!

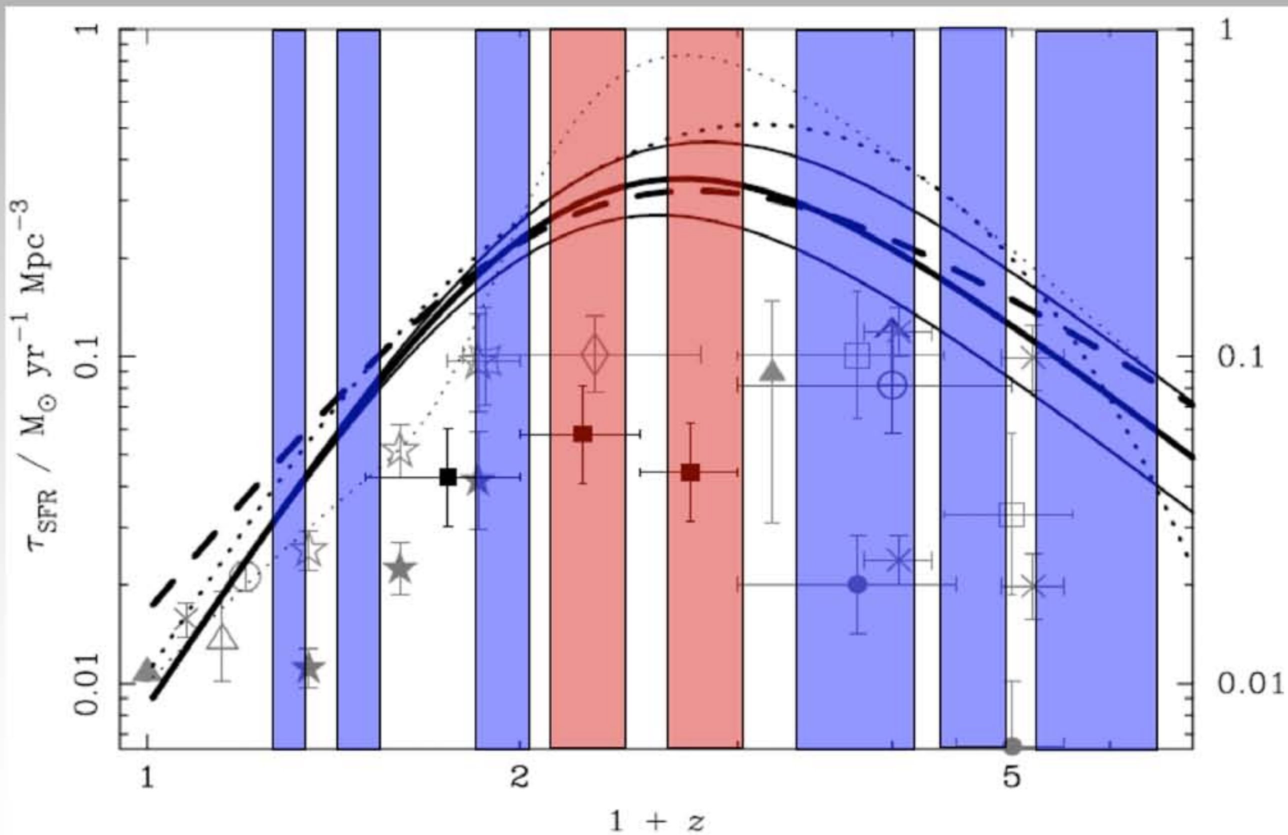
Is [CII] a unique redshift indicator?

- [CII] is a unique probe in redshift range from ~ 1 to 4
  - Next brightest lines at longer λ's
    - [NII] 205 μm – will be relatively weak ⇒ high L ⇒ check for [CII]
    - mid-J CO (e.g. 7-6) ⇒ nearby object, optically visible
  - Next bright lines at short λ's are 88 μm [OIII] and 63 μm [OI]
    - ⇒ very luminous systems ($L_{far\text{-}IR} > 1\text{-}2 \times 10^{13}\ L_{\odot}$)
    - ⇒ detect [CII] in longer λ windows

Again, the most interesting physics arises from the set of lines plus continua studies

CCAT [CII] Redshift Coverage

- Redshifts from 0.25 to 5 are accessible with > 50% coverage – including the important z ~ 1 to 3 range
- Covers the ***peak in the starformation rate*** per co-moving volume

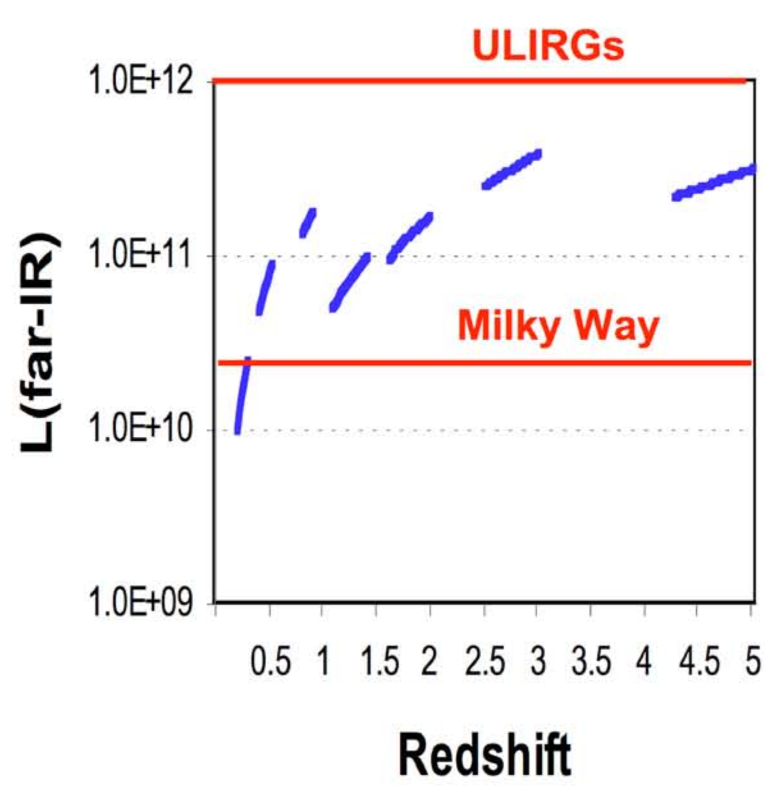


Blain et al. 2002, Phys. Rep., 369, 111

Detectability

- With a Milky Way ratio ($L_{[CII]}/L_{far\text{-}IR}$ ~ 0.3%, the [CII] line is detectable at redshifts in excess of 5 for $L_{far\text{-}IR}$ > 3 × 10^{11} $L_{\odot}$
- ULIGS typically have 5 times weaker line ratio, so that a 1.5 × 10^{12} $L_{\odot}$ ULIRG is also readily detectable!
- Note that for the Milky Way ratio, the line to continuum ratio (optimally resolved line) is ~ 5:1
  - Now an optimized (R ~ 1000 spectrometer is 10 times less sensitive than an optimized (R ~ 10) photometer
  - Therefore, ***the line is detected at only 2 times worse SNR than the continuum in the same integration time.***

[CII] Limits in terms of $L_{far\text{-}IR}$



5 σ in 4 hours

The Redshift (z) and Early Universe Spectrometer: ZEUS

- Submm (650 and 850 GHz) grating spectrometer optimized for extragalactic spectroscopy from z ~ 5 to the current epoch:
  ◊ $R \equiv \lambda/\Delta\lambda \sim 1200$ ◊ Bandwidth ~ 20 GHz ◊ T_{rec}(SSB) ~ 55 K
- Single beam at present, upgrade underway to 5 color (200, 350, 450, 610, 900 μm bands), 40 GHz, 10, 9, 5 beam system
- Primary spectral probes: submm & far-IR fine structure lines of abundant elements and the mid-J CO rotational transitions

Primary Scientific Objectives

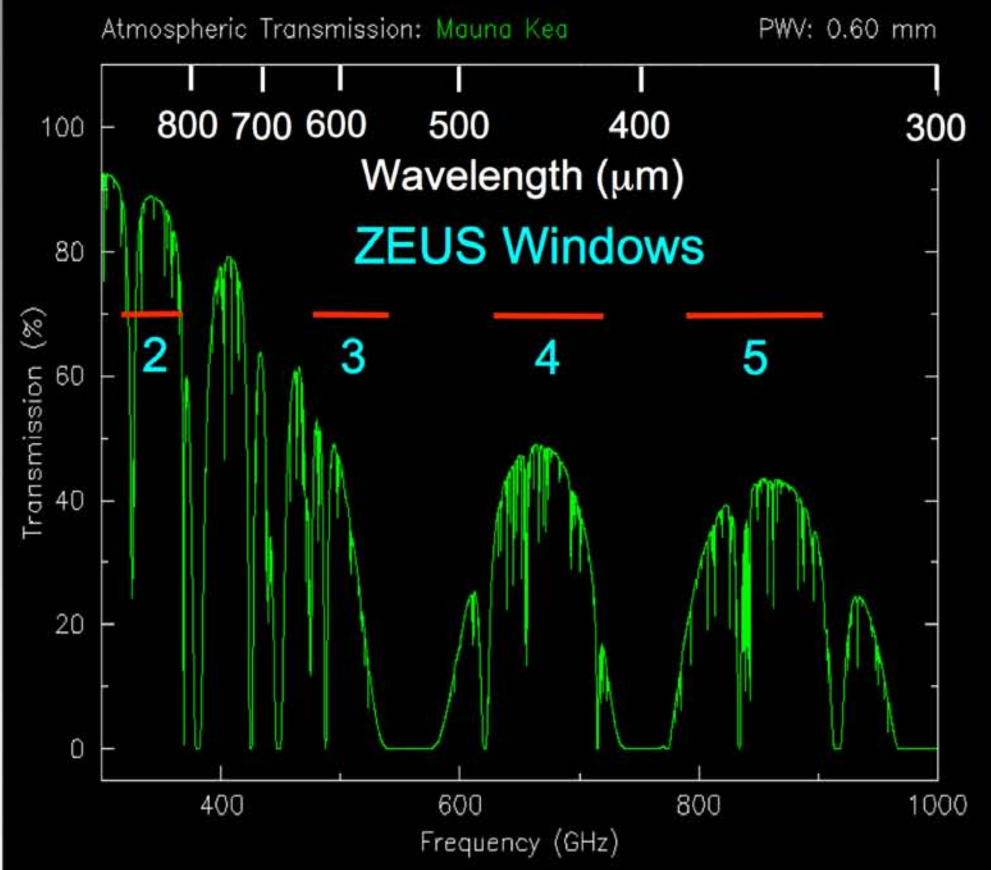
- Investigate starburst and Ultraluminous Infrared Galaxies (ULIGs) via their [CI] and mid-J ^{12}CO and ^{13}CO line emission:
  - What are the origins of their tremendous IR luminosities?
  - What regulates star formation in galaxies?
- Probe star formation in the early Universe using highly redshifted far-IR fine-structure line emission -- especially that of the 158 μm [CII] line.
  - How strong are starbursts in the early Universe?
- Provide redshifts for SMGs, providing source distance, luminosity, and calibrating photo-z
  - What is the evolutionary history of starformation in the Universe?

Design Criteria - 1

- Arguably the most interesting epoch for which to trace the [CII] line emission from galaxies is that between redshifts of 1 and 3, during which the starformation activity of the Universe apparently peaked
- At $z \sim 1$ to 3, the [CII] line is transmitted through the short submillimeter telluric windows with about 40% coverage
- At $z \sim 1$ to 3, galaxies are essentially point sources to current submillimeter telescopes a 5 to 9" beam @ 350 μm) corresponds to about 60 kpc at $z = 1$
- Therefore, we desire the best possible point source sensitivity ⇒ we select a (spectrally multiplexing) grating spectrometer

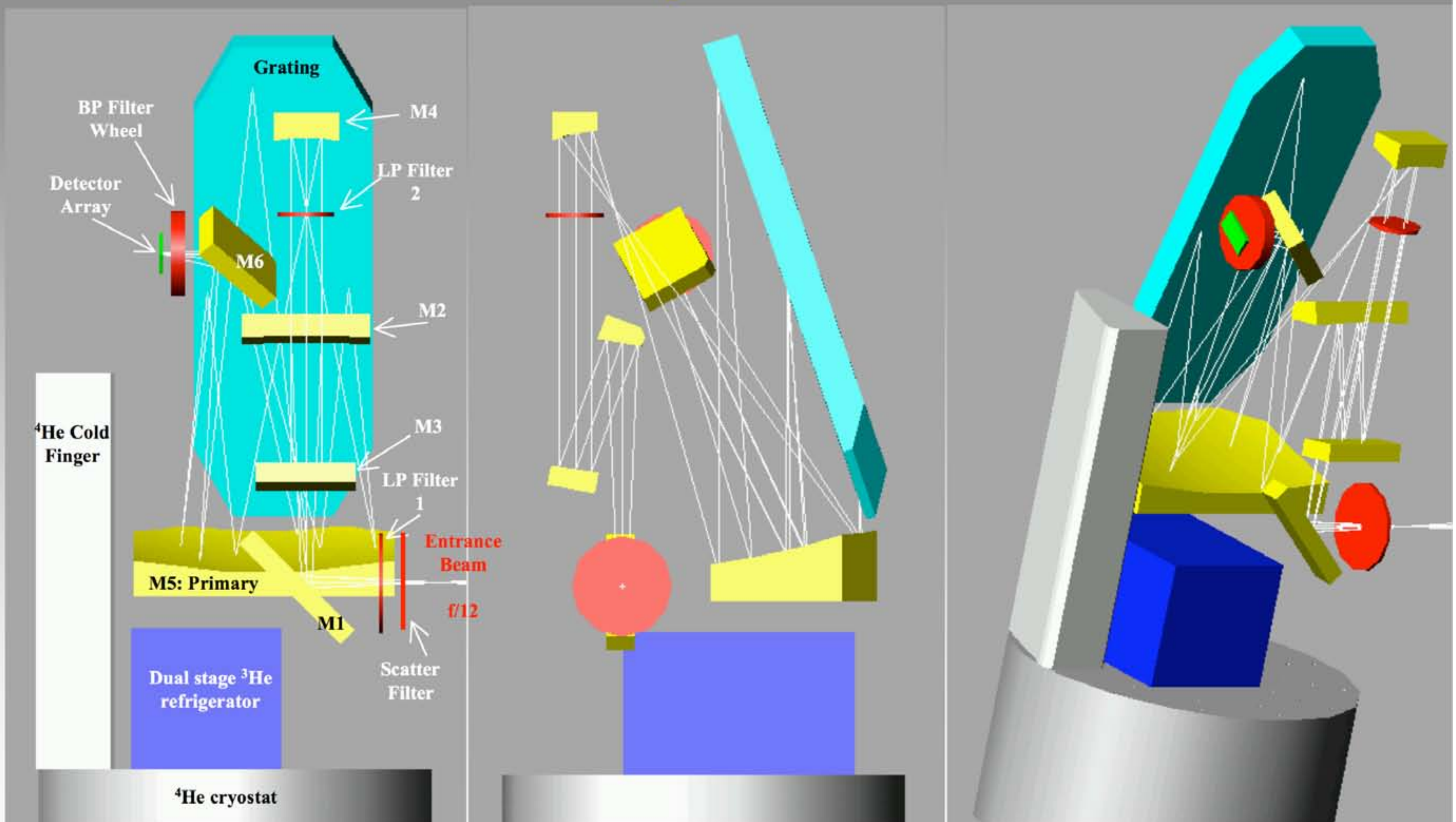
Design Criteria - 2

- Desire $R \equiv \lambda/\Delta\lambda \sim 1000$ optimized for detection of extragalactic lines
- Operate near diffraction limit:
  - Maximizes sensitivity to point sources
  - Minimizes grating size for a given R
- Long slit desirable
  - Spatial multiplexing
  - Correlated noise removal for point sources
- Choose to operate in n = 2, 3, 4, 5, 9 orders which covers the 890, 610, 450, 350 and 200 μm windows respectively



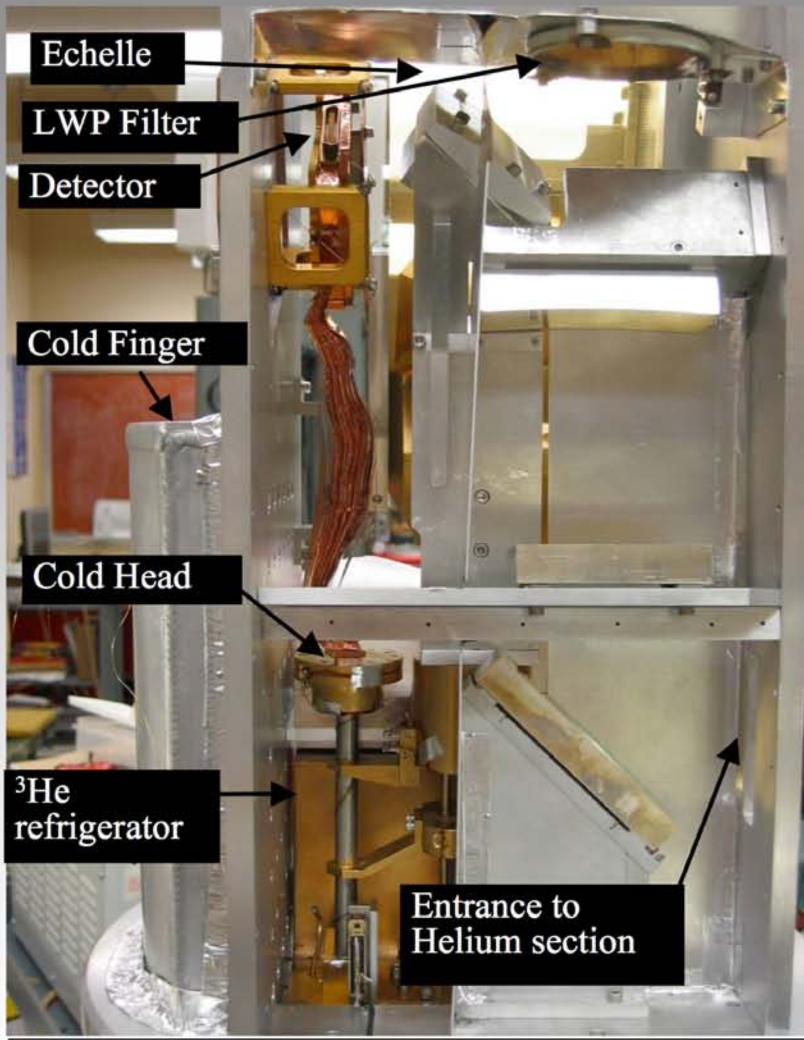
ZEUS spectral coverage superposed on Mauna Kea windows on an excellent night

ZEUS: Optical Path



- There is a series of a scatter, quartz, 2 long λ pass, and a bandpass filter in series to achieve dark performance (P. Ade)
- Total optical efficiency: ~ 30%, or 15% including bolometer DQE

ZEUS Optics

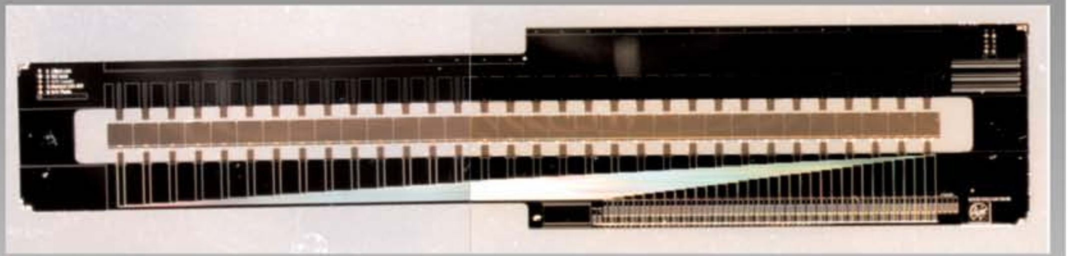


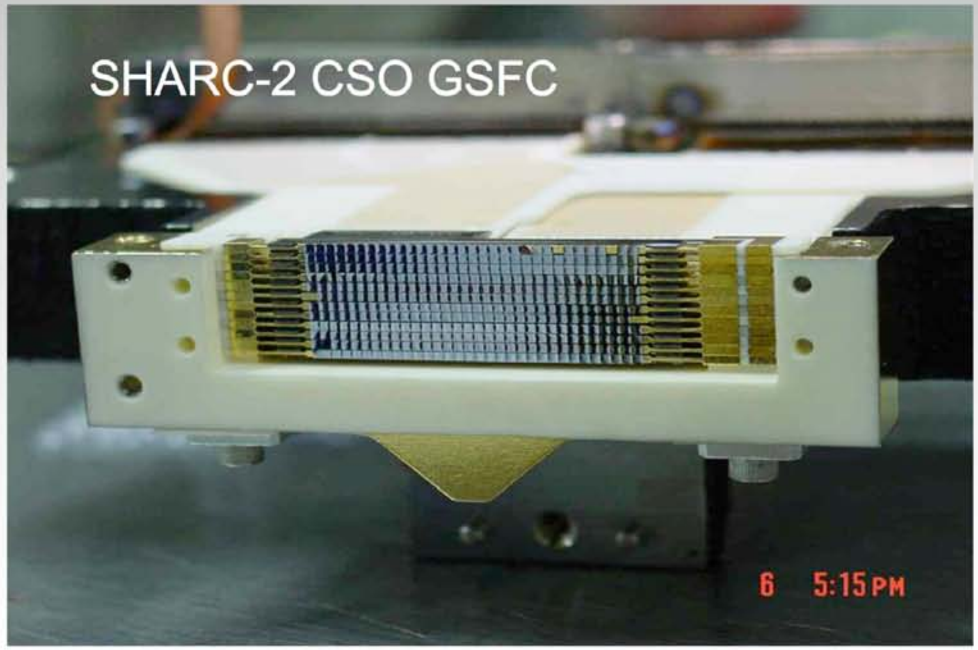
Interior of ZEUS with some baffles removed. The collimating mirror is hidden behind the middle wall baffles.

- Detector sensitivity requires a dual stage ^{3}He refrigerator (T ~ 250 mK)
- Spectral tuning is easy – turn the grating drive chain
- Switching telluric windows is easy – turn a (milli K) filter wheel
- Optics are sized to accommodate up to a 12 × 64 pixel array
  - 12 spatial samples
  - 64 spectral elements (> 6% BW)
  - Sampled at 1 res. el./pixel to maximize spectral coverage

ZEUS Detector Array

- ZEUS-1 has a 1 × 32 pixel thermister sensed array from GSFC (SHARC-2 prototype)
- Building ZEUS-2 with TES sensed NIST Arrays
  - 10 × 24 – 215 μm
  - 9 × 40 – 350, 450 μm
  - 5 × 12 – 645, 800 μm
- Resonantly tuned arrays – better sensitivity
- Closed cycle refrigerators





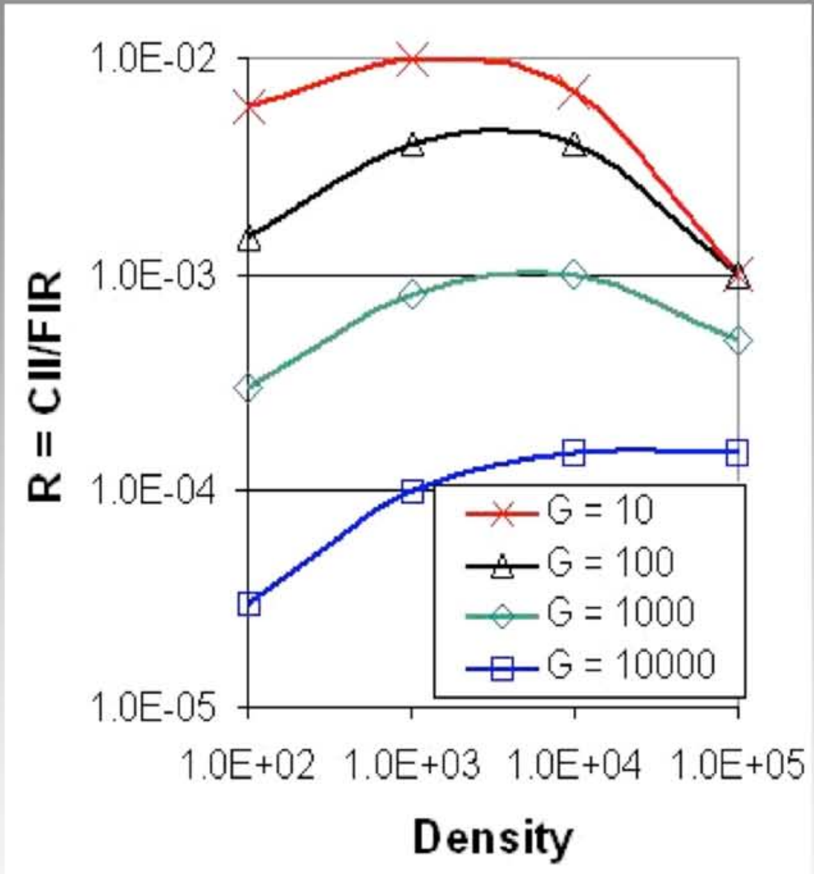
The [CII] in Star Forming Galaxies: what can you do with a single line?

- The 158 μm [CII] line is the brightest line in most star forming galaxies
  - Accounts for 0.1% to 1% of the FIR continuum
- Most of the [CII] emission arises from PDRs on the surfaces of molecular clouds exposed to far-UV radiation
- The gas in PDRs is heated through photoelectric heating
- About 1% of the incident UV starlight heats the gas, which cools through FIR line emission
  - Consistent with the observed [CII]/FIR ratio of 0.1% to 1%
- Most of the rest comes out as far-IR continuum down-converted by the dust in PDRs

[CII]/far-IR Constrains G

The [CII] to far-IR continuum luminosity ratio, R is a sensitive indicator of G

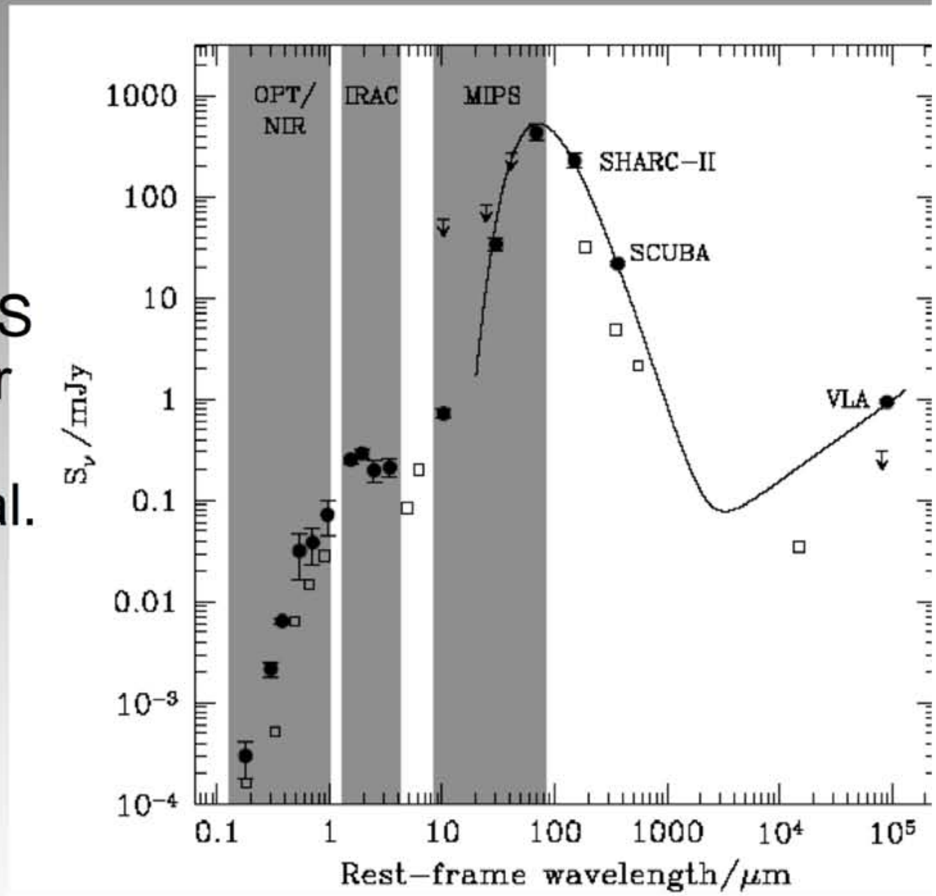
- In high UV fields (young starbursts, ULIRGS, AGNs), R is depressed
  - Reduced efficiency of photoelectric effect
  - Increased cooling in [OI] 63 μm line
- More diffuse fields (like M82 and the Milky Way) result in ***larger*** [CII]/far-IR ratio, R
- Stronger fields e.g. the Orion PDR have ***smaller*** R ~ 4 x 10^{-4}, G_0 ~ 2 x 10^4
- Therefore, we can use R to calculate G ~ 1/R



[CII]/far-IR continuum luminosity ratio vs. density for various G (from Kaufman 1999).

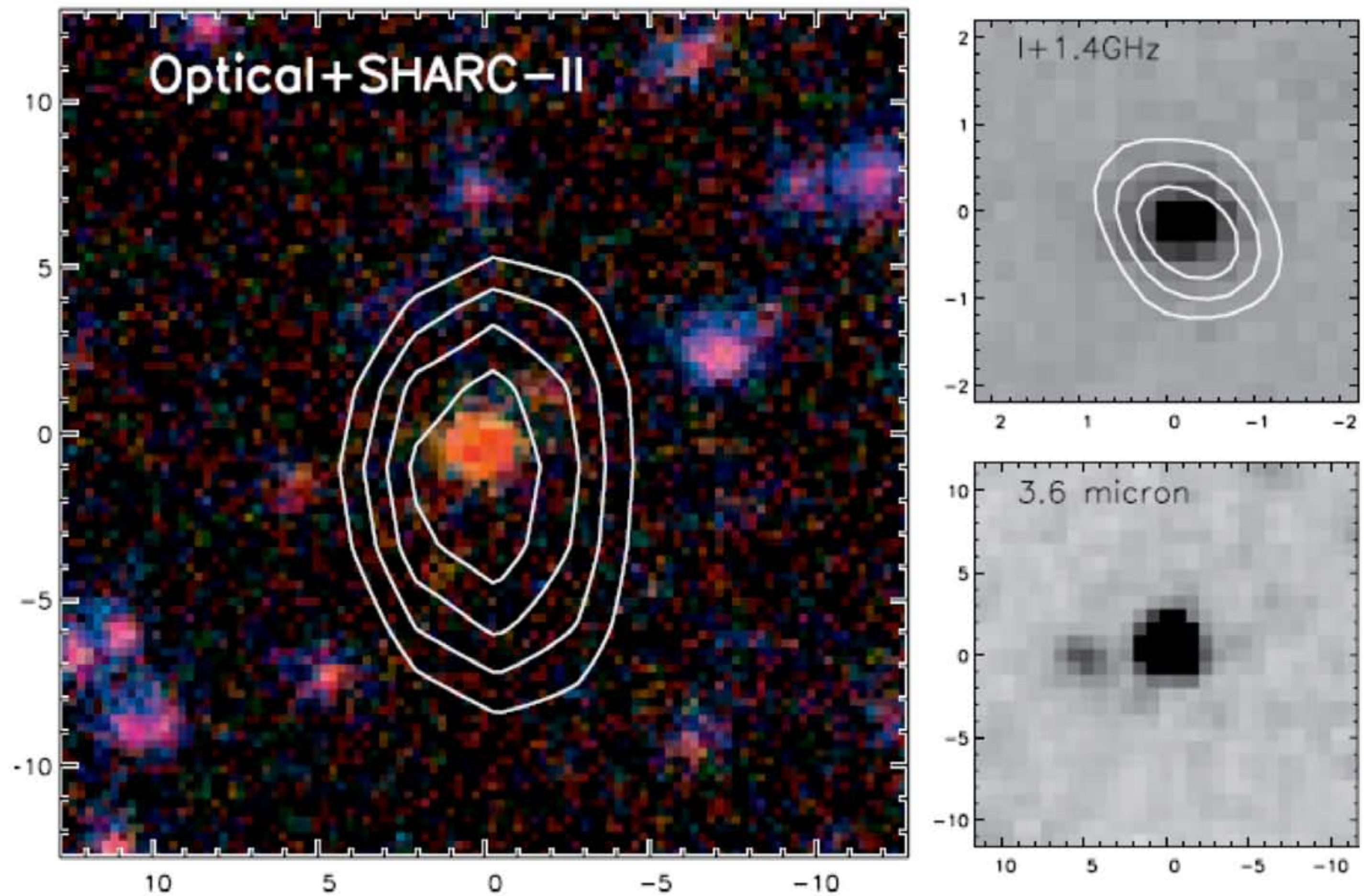
Detection of [CII] from MIPS J142824.0 +352619

- In April we detected the [CII] line emission from MIPS J142824.0 +352619 @ z = 1.325 with ZEUS on CSO
- System was discovered in MIPS Bootes field survey selected for compact, red objects with optical counterparts (Borys et al. 2006)
  - Optical/IR SEDs used to select high z sources
  - Optical/NIR spectroscopy confirmed z = 1.325
  - Detection at 350 μm with SHARC-II on CSO and 850 μm with SCUBA on JCMT



MIPS J142824.0 SED (Borys et al. 2006)

MIPS J142824.0 +352619

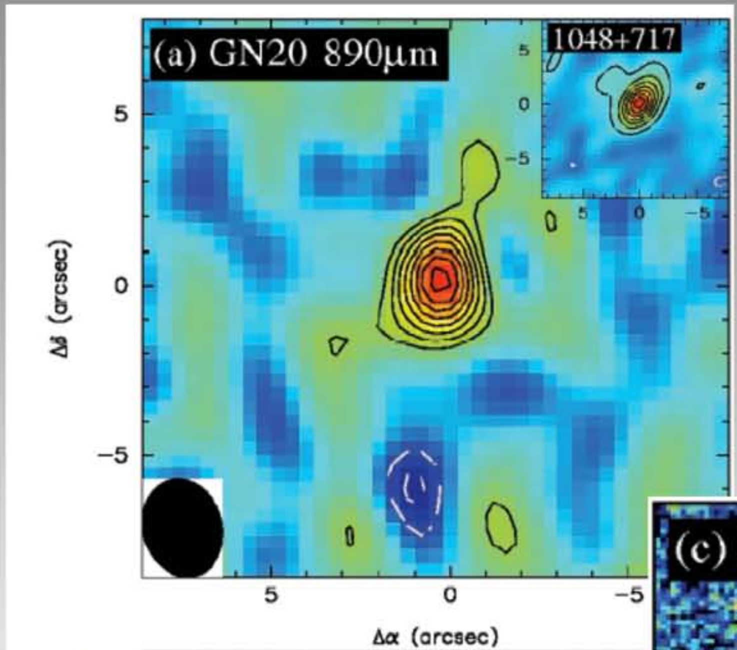


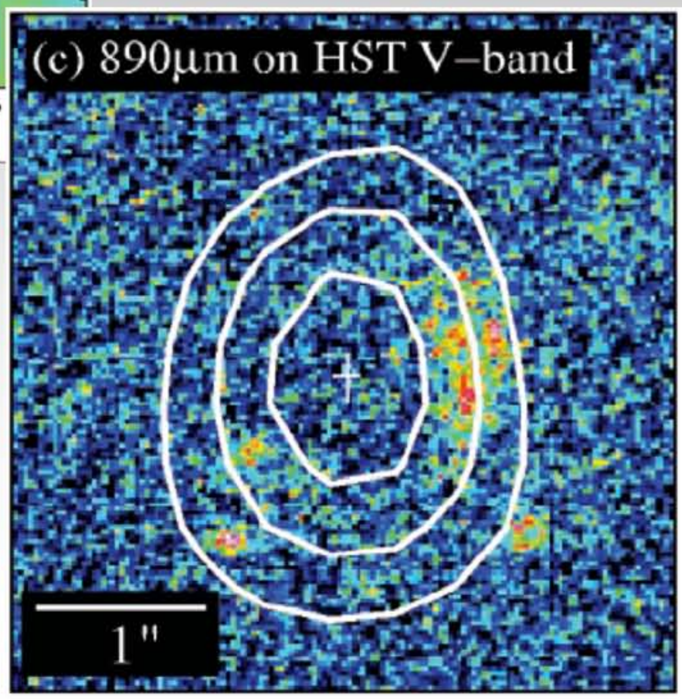
Borys et al. 2006

Properties

- Integrated far-IR SED corresponds to $L_{far\text{-}IR} \sim 3.2 \times 10^{13}\ L_{\odot}$
- Lacks any trace of AGN activity – likely a distant, luminous analogue of local IRAS selected galaxies, or distant submm selected galaxies
- Spectrum and far-IR – radio flux ratio consistent with a super starburst galaxy
- Source is likely lensed by a foreground (z = 1.034 elliptical, but magnification < 10

Submm Continuum Imaging of MIPS J142824.0 +352619

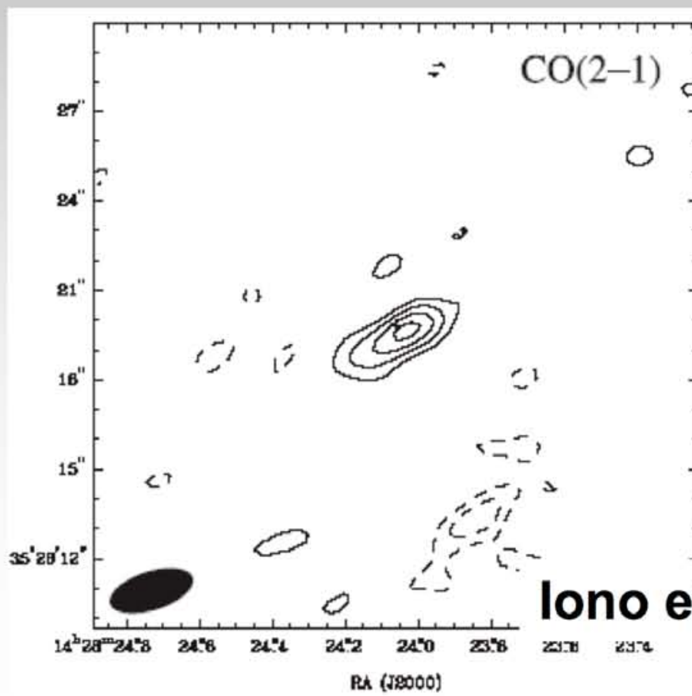




- Imaged in the submm using the SMA (Iono et al. 2006)
  - Submm source is unresolved and offset 0.8" from the optical source suggesting an interacting system
  - Source size < 1.2"

CO Lines from MIPS J142824.0 +352619

- Detected and imaged in CO(3-2) and (2-1) with Nobeyama
  - L_{CO}(3-2) ~ L_{CO}(2-1) ~ 1.3× 10^{11} K km/sec/pc^2 ⇔ M ~ 10^{11} $M_\odot$
  - Line ratio indicates n > 10^3 cm^{-3} – dense gas
  - Redshift = 1.3249 ±0.0002
  - Source size < 1.3" and Mag < 8



Iono et al. 2006

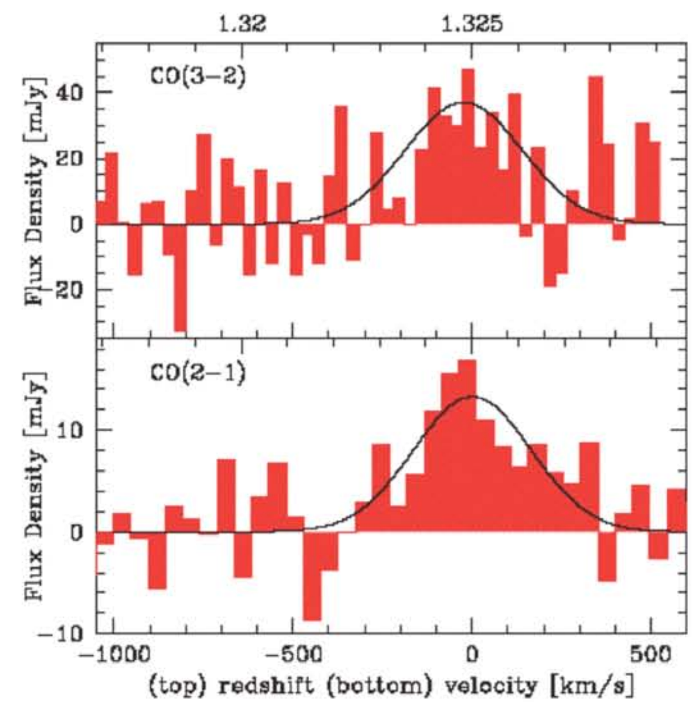


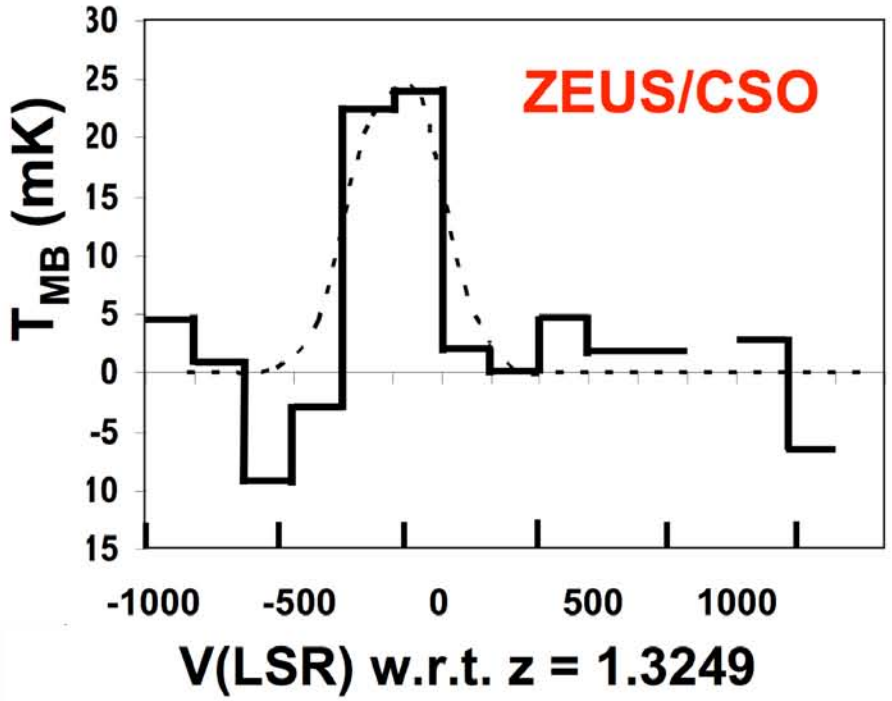
Fig. 2. CO (3–2) (top) and CO (2–1) (bottom) spectra of MIPS J1428 obtained at the NRO. The solid lines represent Gaussian fits to the CO spectra. These spectra are intentionally shifted from the center of the band in order to avoid the spurious feature that often appears in the center of the UWBC.

ZEUS/CSO Detection

- April 3, 2008
- 2 hours with τ_{2225} GHz ~ 0.05 to 0.06 ⇔ $t_{l.o.s.}$ ~ 10 to 20%
- Beam ~ 11"
- $I_{[CII]}$ ~ 9 K-km/sec
- F_{line} ~ 1.0 × 10^{-17} W m^{-2}
- $L_{[CII]}$ ~ 2.8 × 10^{10} $L_\odot$

MIPS J142824.0+352619

[CII] at z = 1.3249



Hailey-Dunsheath et al. 2008

[CII]/far-IR Constrains G

- $L_{[CIII]} \sim 2.8 \times 10^{10}\ L_{\odot}$
- $L_{far\text{-}IR} \sim 3.2 \times 10^{13}\ L_{\odot}$
- 30% from ionized medium

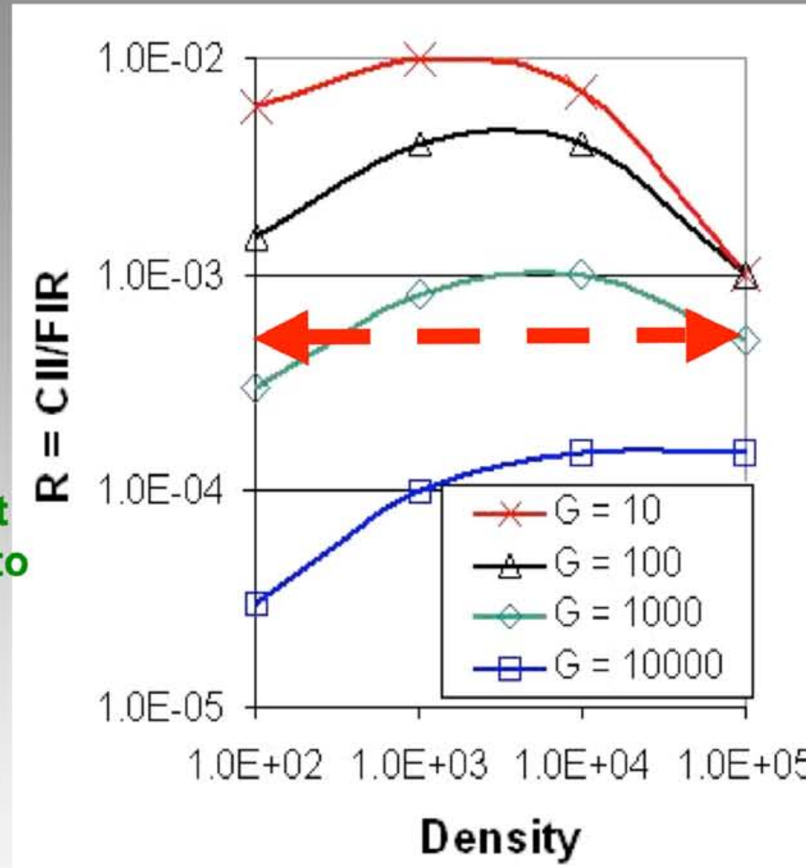
  $\Rightarrow R = 6 \times 10^{-4} \Rightarrow G \sim 2000$
- $\chi_{far\text{-}IR} = L/(4\pi D^2\Omega) = 14$
  - $D_L \sim 9.2$ Gpc
- $\Phi = \chi_{IR}/(G \cdot 2) = 3 \times 10^{-3}$

  $\Rightarrow \Omega = \Phi \cdot \Omega_{beam} = 0.3('')^2$

  $\Rightarrow l \sim 0.5'' \Leftrightarrow 6$ kpc

Starlight that contributes to χ but not G

Plane parallel single sheet geometry indicates galaxy-wide starburst



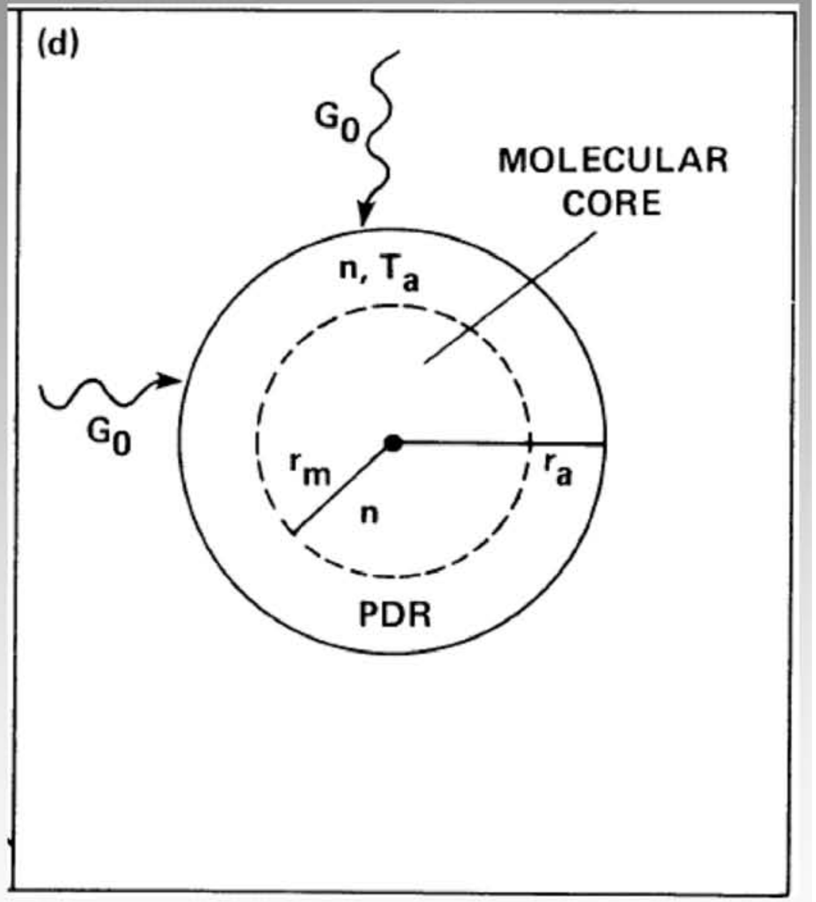
[CII]/far-IR continuum luminosity ratio vs. density for various G (from Kaufman 1999).

PDR Analysis

- A more sophisticated model would include gas clumping, which increases the area filling factor per cloud by a factor ~ 4 (e.g. Wolfire et al. 1990)

  $\Rightarrow$ Size ~ 3 kpc

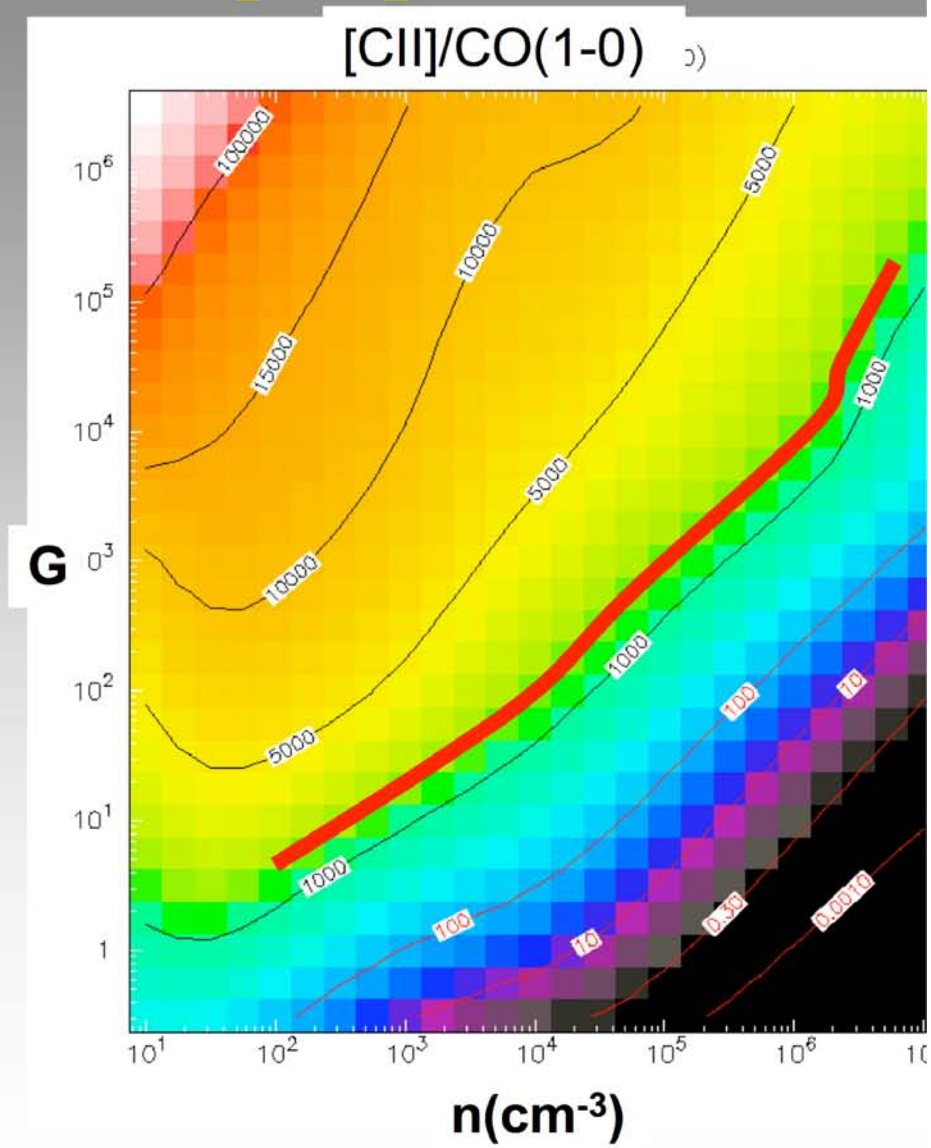
- Multiple clouds could exist along the line of sight decreasing the effective size of the starburst region further



CO Lines and [CII]

- We can go further still since CO line fluxes are available
  - $CO(2-1) \sim 1.8 \times 10^{-20}$ W m^{-2}
  - $CO(3-2) \sim 6.9 \times 10^{-20}$ W m^{-2}
  - $\Rightarrow F_{[CII]}/F_{CO(1-0)} \sim 1200$
- Constrains $G/n \sim 10^{-2}$

If $G \sim 2000$, $n \sim 2 \times 10^5$



"IR Toolshed" – Kaufman et al.

PDRs and the CO Line Ratios

- The CO line flux ratio is:

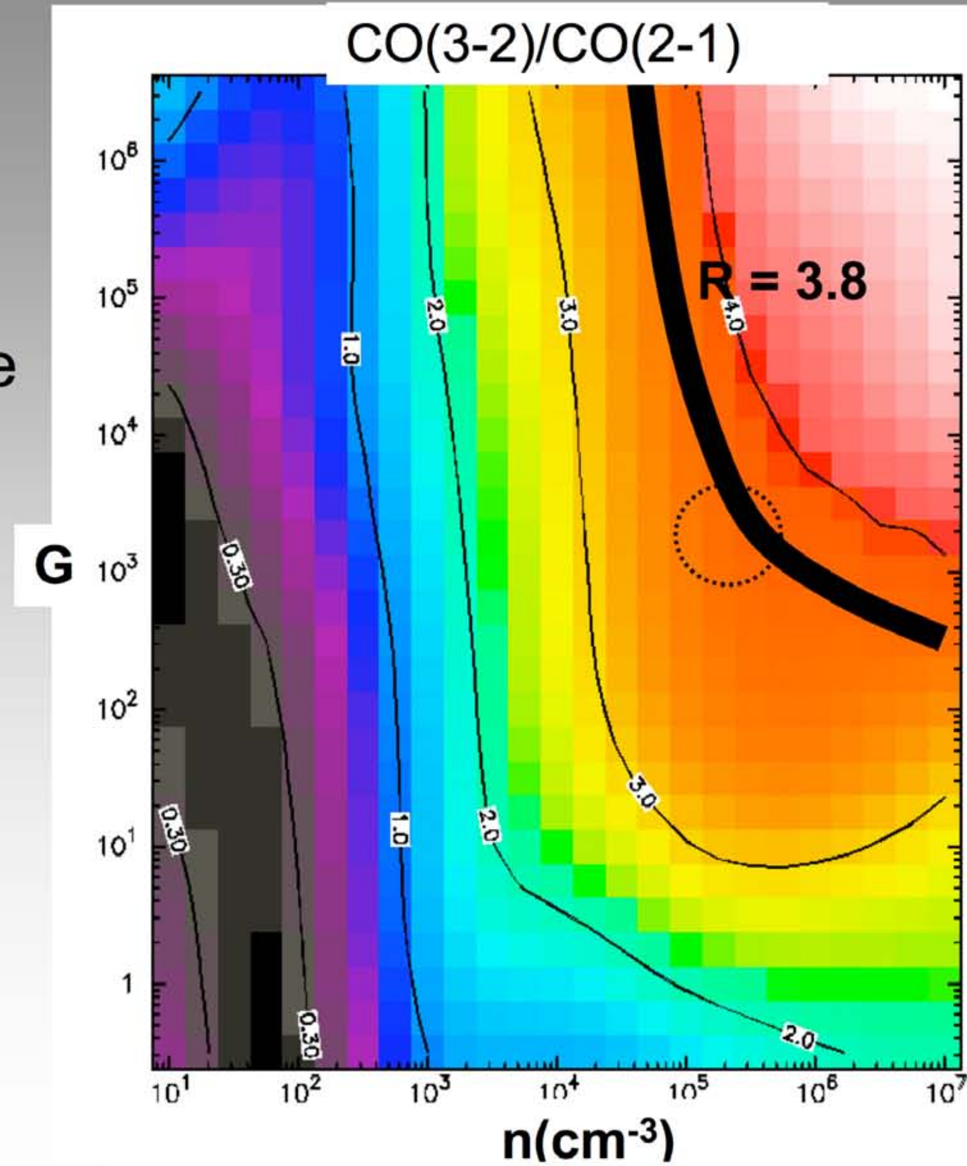
  $F_{CO(3-2)}/F_{CO(2-1)} = 3.8$

- This is consistent with our parameters derived from the [CII]/CO line ratio

  $G \sim 2000,\ n \sim 2 \times 10^5$

- So, a PDR model is consistent with the CO and [CII] lines ⇒

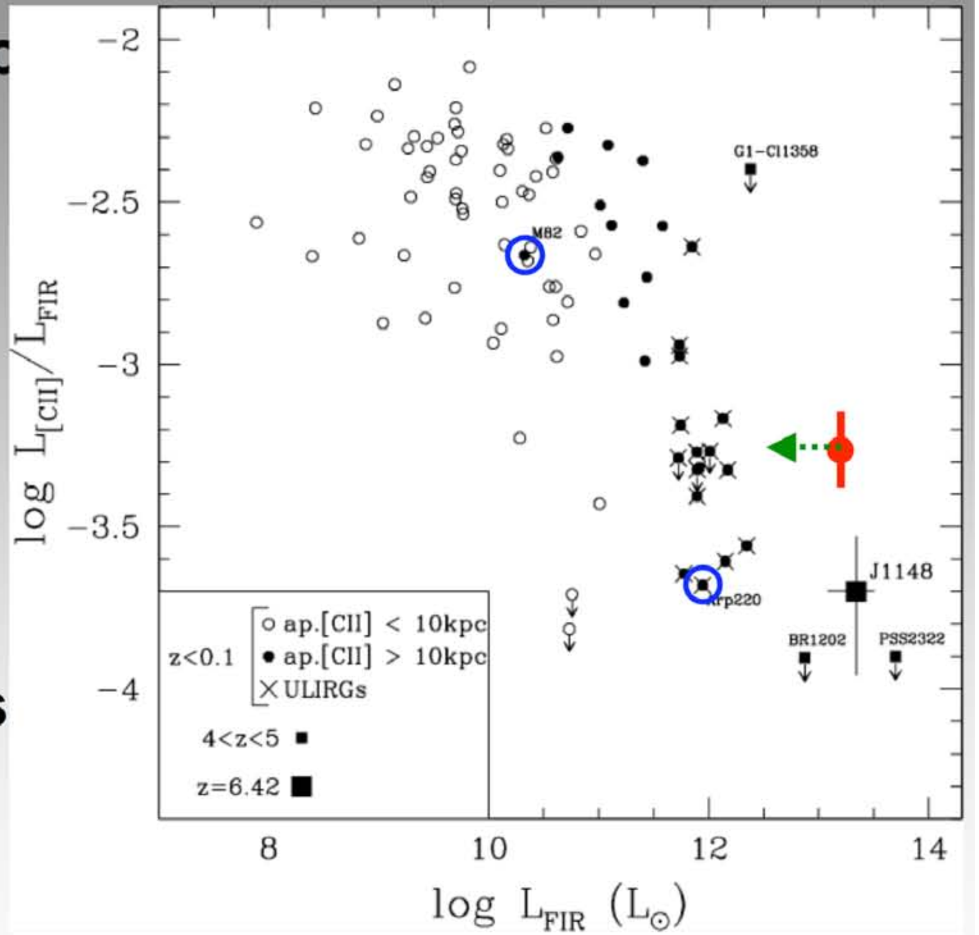
Massive, galaxy wide starburst as source of power



"IR Toolshed" – Kaufman et al.

ZEUS [CII] Detection

- Fall off in [CII]/far-IR ratio not universal
- Ratio for MIPS is consistent with ULIRG ratio
- Move it by M ~ 8 it becomes a luminous ULIRG
- We have 2 other sources that fill in the higher L regions



Maiolino, R., et al. 2005

Galaxy Wide Starburst?

- The high $L_{[CII]}$ suggests a *~ 3-6 kpc size starburst – is this possible?*
- A starburst triggered by a collision at ~ 400 km/s will propagate across 10 kpc in ~ 3 x 10^7 yrs
  - Comparable to the lifetime of a early B star
  - Consistent with inferred G_0 ~ 1000-3000
- VLA interferometry of a sample of SMGs find a median diameter of ~ 7 kpc (Chapman et al. 2004)
- Millimeter interferometry of a sample of SMGs find ~ half are resolved at ~ 4 kpc (Tacconi et al. 2006)

How Much [CII] from Ionized Media?

- Our PDR modeling is critically dependent on the assumed fraction of [CII] from PDRs – not easy to assess – estimates range from 10 to 50%!
- However, there is a happy co-incidence with [NII] 205 μm
  - N^+ only exists in HII regions (IP ~ 14.5 eV)
  - N^{++} and C^{++} take roughly the same energy photons to form (~ 24, 28 eV)
  - The 205 μm line has the same critical density as [CII] for ionized gas

  ⇒ Predict the [CII] line modulo N/C abundance ratio

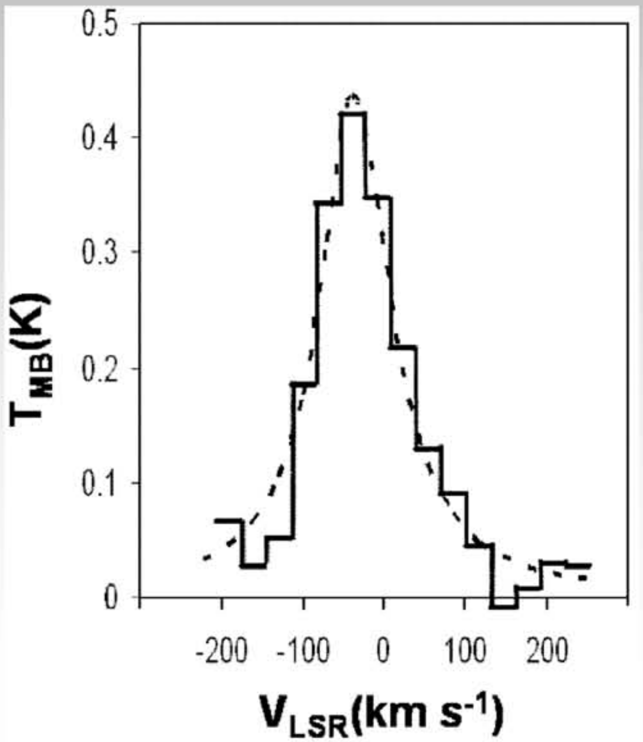
⇒ Line ratio is indicator of fraction of [CII] from ionized gas

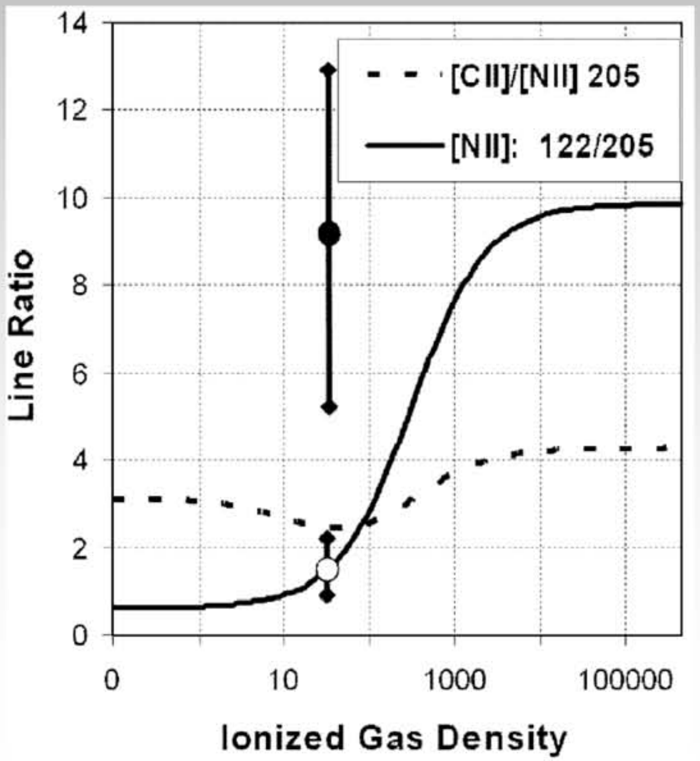
- Such ideas were used with the COBE data set, and with less reliability with the ISO data set that only had access to the [NII] 122 μm line with a different critical density

Example: [NII] in Carina Nebula

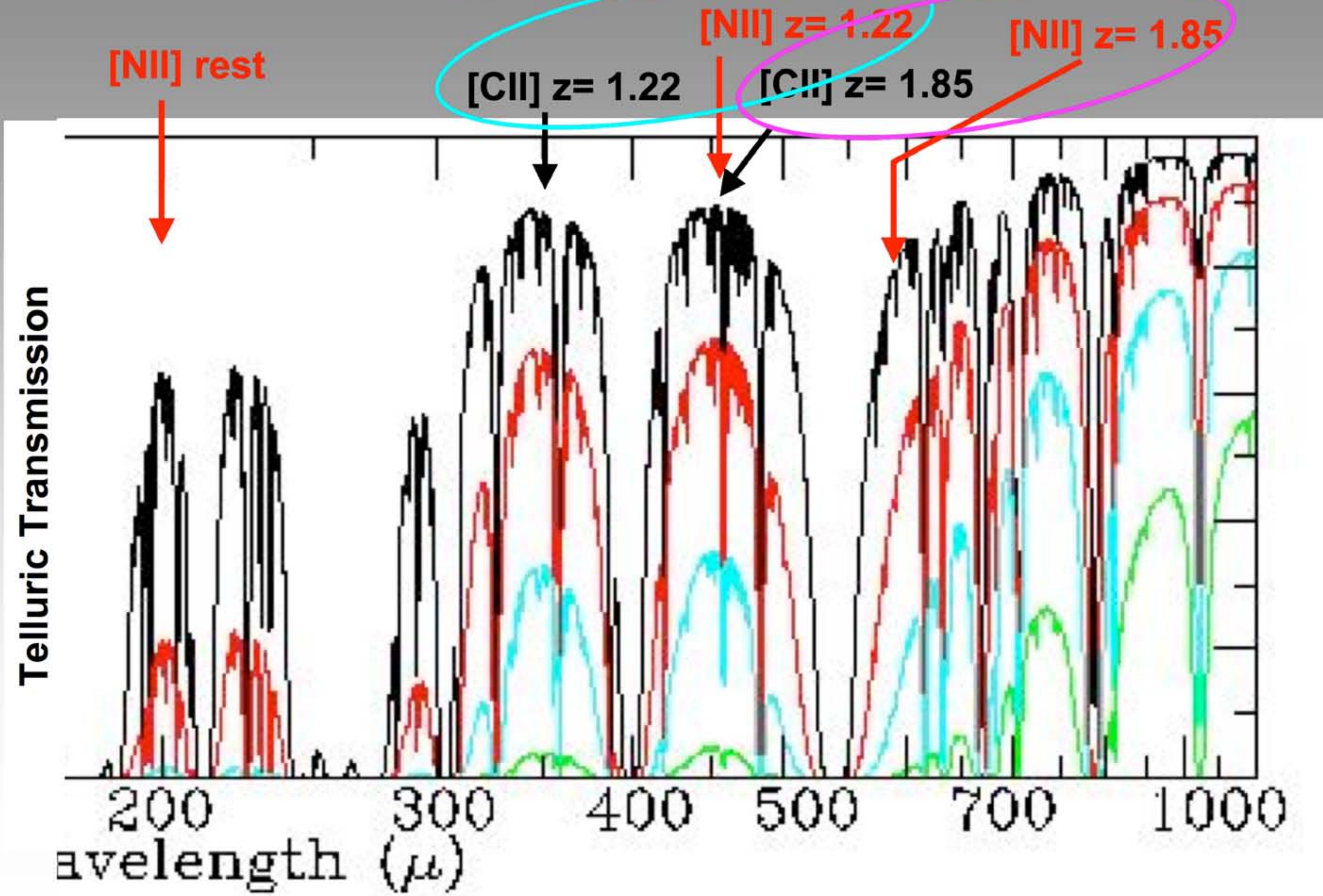
- [NII] 205 μm line from in the Carina Nebula with SPIFI on AST/RO at South Pole (Oberst et al. 2006)
- [NII] 122/205 μm line ratio ~ 1.8: 1 ⇒ n_e ~ 30 cm^{-3}
- [CII]/[NII] ratio ~ 9:1, predicted ratio ~ 2.4:1

⇒ 27% of [CII] originates from ionized gas





[NII] and [CII]



[NII] rest
[CII] z= 1.22
[NII] z= 1.22
[CII] z= 1.85
[NII] z= 1.85
Telluric Transmission
200
300
400
500
700
1000
avelength (μ)

Multiple Lines

- [NII] 205 μm and [CII] Can be done simultaneously with an echelle like ZEUS
  - Only 3% apart if n([CII]) = 4, n([NII]) = 3
  - Can just do it with ZEUS-2: n([CII]) = 5, n([NII]) = 4
- Easily done with Z-Spec like device covering 1.6 in bandwidth
- Other lines are bright and of great interest:

Line	Relative strength	Diagnostic
[CII] 158	1	
[NII] 205	1/10	UV field hardness and HII region density
[NII] 122	1/6	
[NIII] 57	1/10	
[OIII] 88	1	UV field hardness and HII region density
[OIII] 52	1/2	
[OI] 63	1/2	PDR parameters, density
[OI] 146	1/10	

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[CII] 158	1
[NII] 205	1/10
[NII] 122	1/6
[NIII] 57	1/10
[OIII] 88	1
[OIII] 52	1/2
[OI] 63	1/2
[OI] 146	1/10

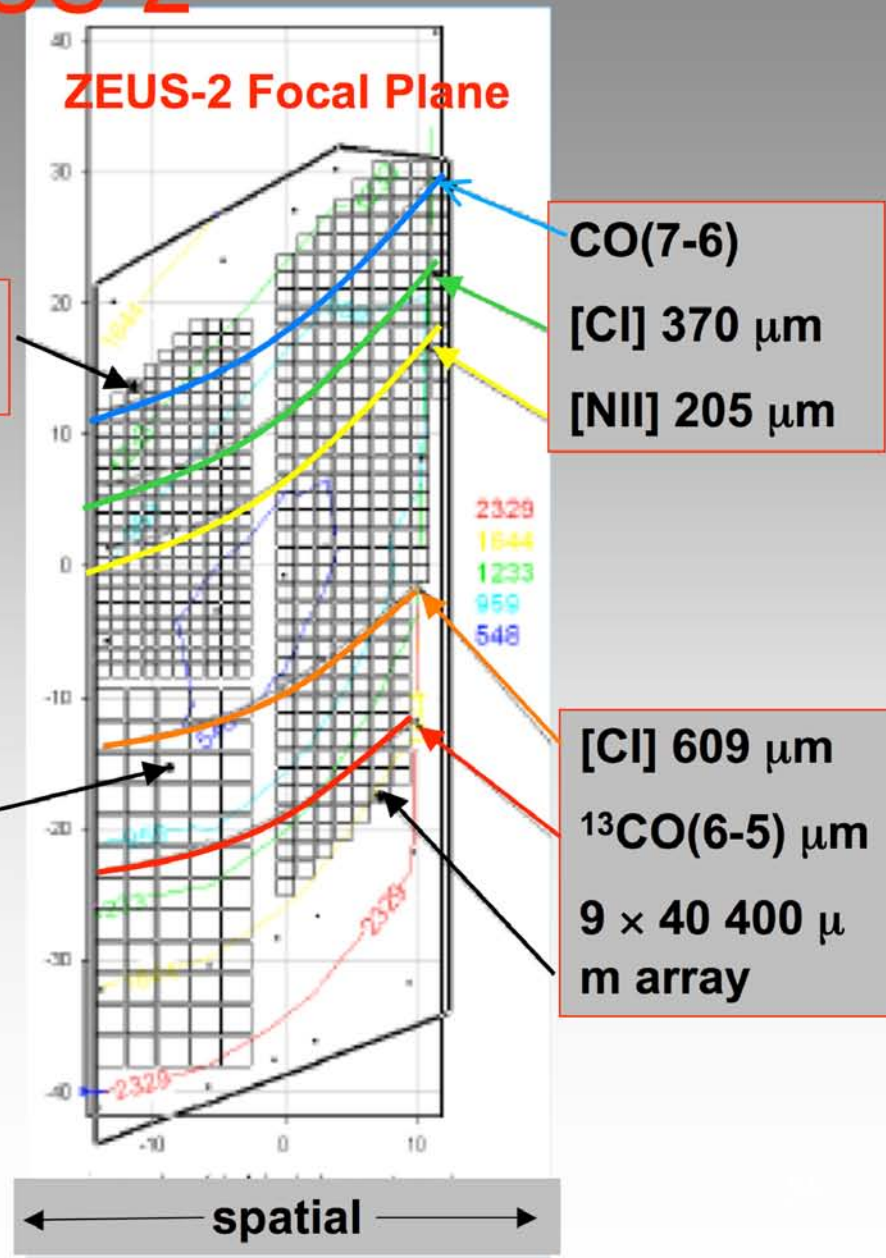
UV field hardness and HII region density ([NII] 205, [NII] 122)

N/O abundance ratio: "Age of the ISM" ([NIII] 57, [OIII] 88, [OIII] 52)

PDR parameters, density ([OI] 63, [OI] 146)

ZEUS-2

- Upgrading to (3) NIST 2-d TES bolometer arrays
- 4 bands (1.5 THz, 850, 650, 490 GHz) simultaneously
- 5 lines simultaneously
- Imaging capability (9-10 beams)
- CSO and APEX

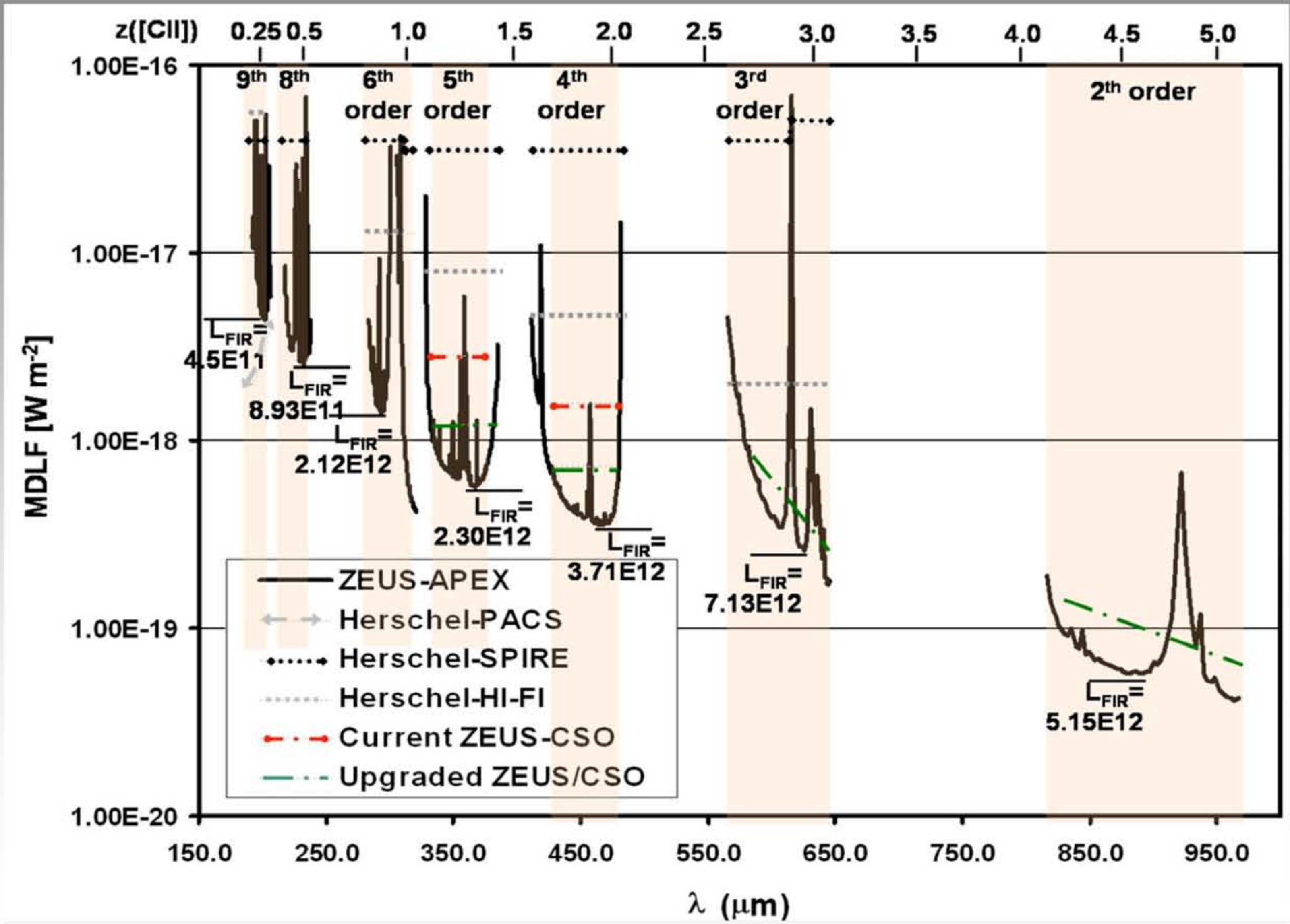


Multiple Beam Systems

Ideal spectrometers are similar to ZEUS and Z-Spec – made into multi-object systems

- ZEUS-like spectrometer with a long slit can easily accommodate 20 beams or more along the slit
- Z-Spec can also accommodate multiple beams by incorporating multiple models
- Cameras will detect ~ 200 sources per field – could follow up with say 10% of these in spectroscopy
- How to “pipe” the light
  - Movable mirrors
  - Dielectric fibers

ZEUS II + APEX



z([CII])
0.25 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0
9th 8th
6th order
5th order
4th order
3rd order
2th order
L_FIR= 4.5E11
L_FIR= 8.93E11
L_FIR= 2.12E12
L_FIR= 2.30E12
L_FIR= 3.71E12
L_FIR= 7.13E12
L_FIR= 5.15E12
ZEUS-APEX
Herschel-PACS
Herschel-SPIRE
Herschel-HI-FI
Current ZEUS-CSO
Upgraded ZEUS/CSO
MDLF [W m-2]
1.00E-16
1.00E-17
1.00E-18
1.00E-19
1.00E-20
150.0 250.0 350.0 450.0 550.0 650.0 750.0 850.0 950.0
λ (μm)