The Redshift (z) and Early Universe Spectrometer (ZEUS)

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Project is the PhD thesis topic of Steve Hailey-Dunsheath

ZEUS

- Long slit grating spectrometer optimized for studies of starformation in the Universe from about 1 to 2 billion years after the Big Bang to the current epoch
- Our primary spectral probes are the submillimeter and far-infrared fine structure lines of abundant elements and the mid-J CO rotational transitions
- ZEUS had an engineering run on JCMT in March 2005, and is set for science runs on CSO in March and May of 2006
- Goals of this talk:
  - Science objectives
  - Design specifications
  - Performance
  - ZEUS-Like spectrometers on CCAT

Primary Scientific Objectives

- Investigate starburst and Ultraluminous Infrared Galaxies (ULIGs) via their [CI] and mid-J 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 number counts as a function of z.
  - What is the evolutionary history of starformation in the Universe?

Starburst and ULIG Galaxies

- Gas excitation through observations of mid-J CO and [CI] lines
  - Physical conditions (temperature, density)
  - Molecular and neutral gas mass
  - UV fields in a photodissociation region paradigm
- What is heating the gas?
  - UV flux from stars
  - Cosmic rays
  - AGN – gravity
- Is the starburst self-propagating, or self limiting?

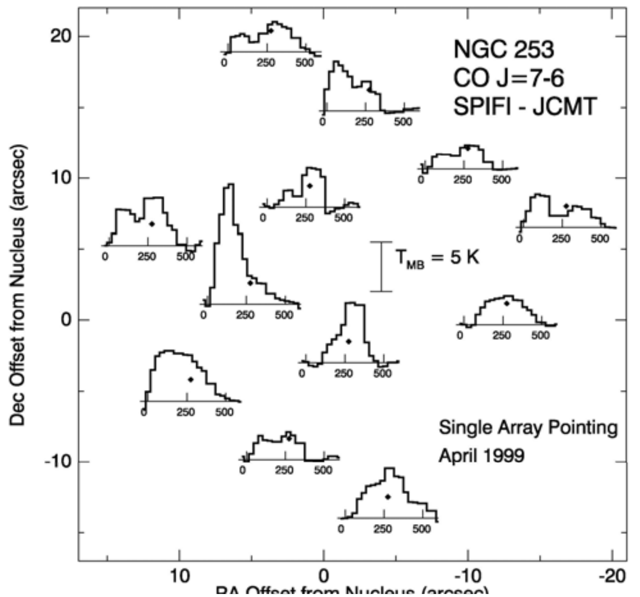
- Use examples from our imaging Fabry-Perot, SPIFI that has been used on the JCMT (now back from AST/RO)
- For point sources, ZEUS is 3 to 5 times more sensitive than SPIFI

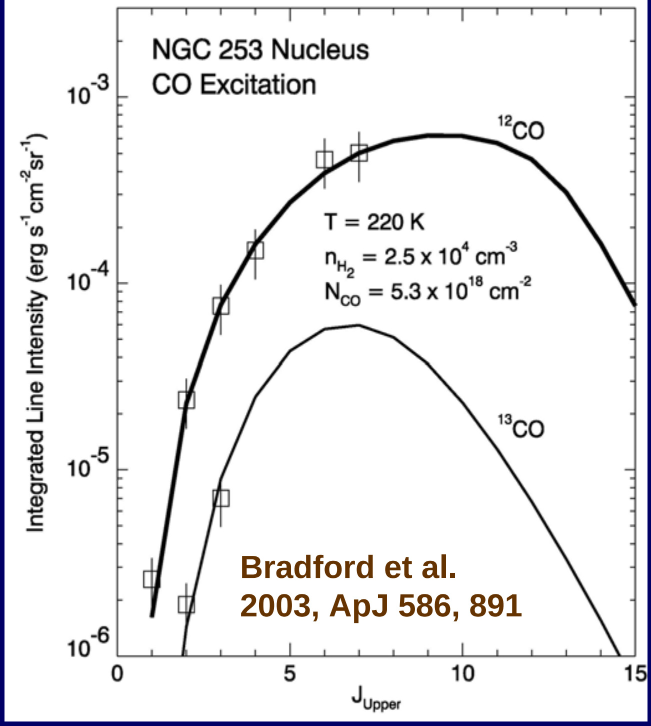
Starburst Galaxies: Mid-J CO

- SPIFI CO(7→6) 372 μm maps of NGC 253 shows emission extended over 500 pc
- Most of 2-5 × 10^7 $M_\odot$ nuclear molecular gas is in a single highly excited component:
  - $n(H_2) \sim 4.5 \times 10^4$ cm^{-3}, T = 120 K

    Consistent with CO and ^{13}CO and H_2 rotational line emission
- This warm molecular gas is 10 to 30 times PDR gas mass (traced by [CII] & [OI] lines)
  - UV heating from starlight (PDR scenario) can not heat this much molecular gas
  - ⇒ ***CO is heated by cosmic rays*** (~800 × MW value) from the nuclear starburst
  - Provides a natural mechanism for heating the entire volume of gas

    Added heat at cloud cores will inhibit further star formation





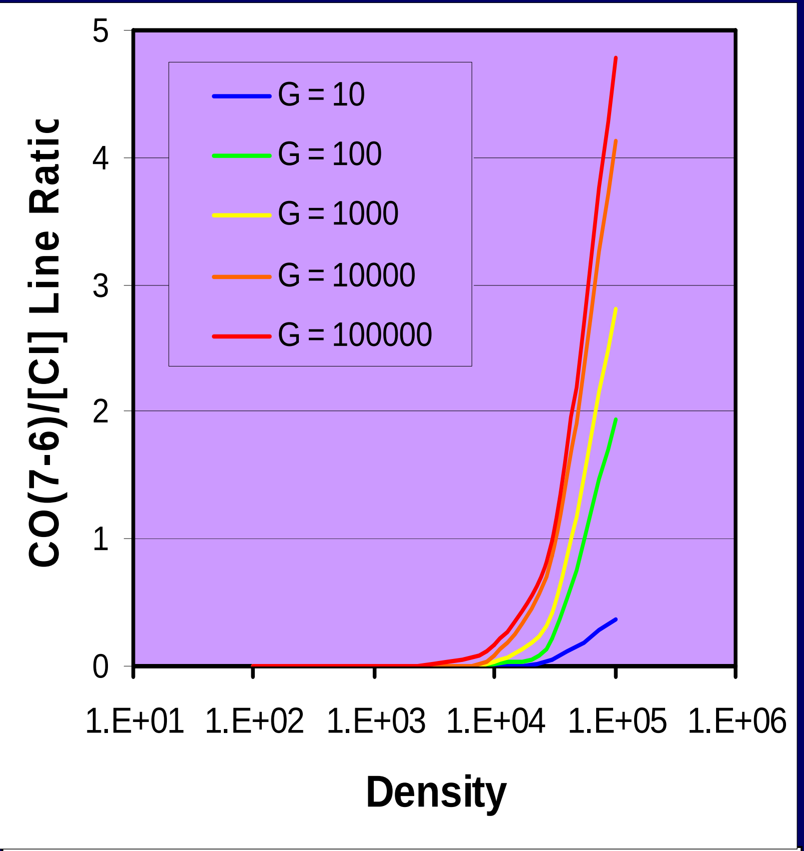
Bradford et al. 2003, ApJ 586, 891

The [CI] and CO(7→6) Lines

- **[CI]:** Lines cool the neutral ISM – more cooling power than CO
- Both [CI] lines (370 μm and 610 μm) are detectable with ZEUS
- They are easily thermalized and optically thin ⇒ ***Line ratio gives T_{gas}***
- **CO:** Run of CO line intensity with J constrains

  Molecular gas pressure
- **CO and [CI]:** ZEUS detects both the CO(7→6) and [CI] $^3P_1 \rightarrow {}^3P_1$ (370 μm) lines simultaneously ⇒
  - Excellent relative calibration
  - "Perfect" spatial registration
  - Ratio divides out filling factor
- The CO(7→6)/[CI] (370 um) line ratio of particular interest, as it is very density sensitive

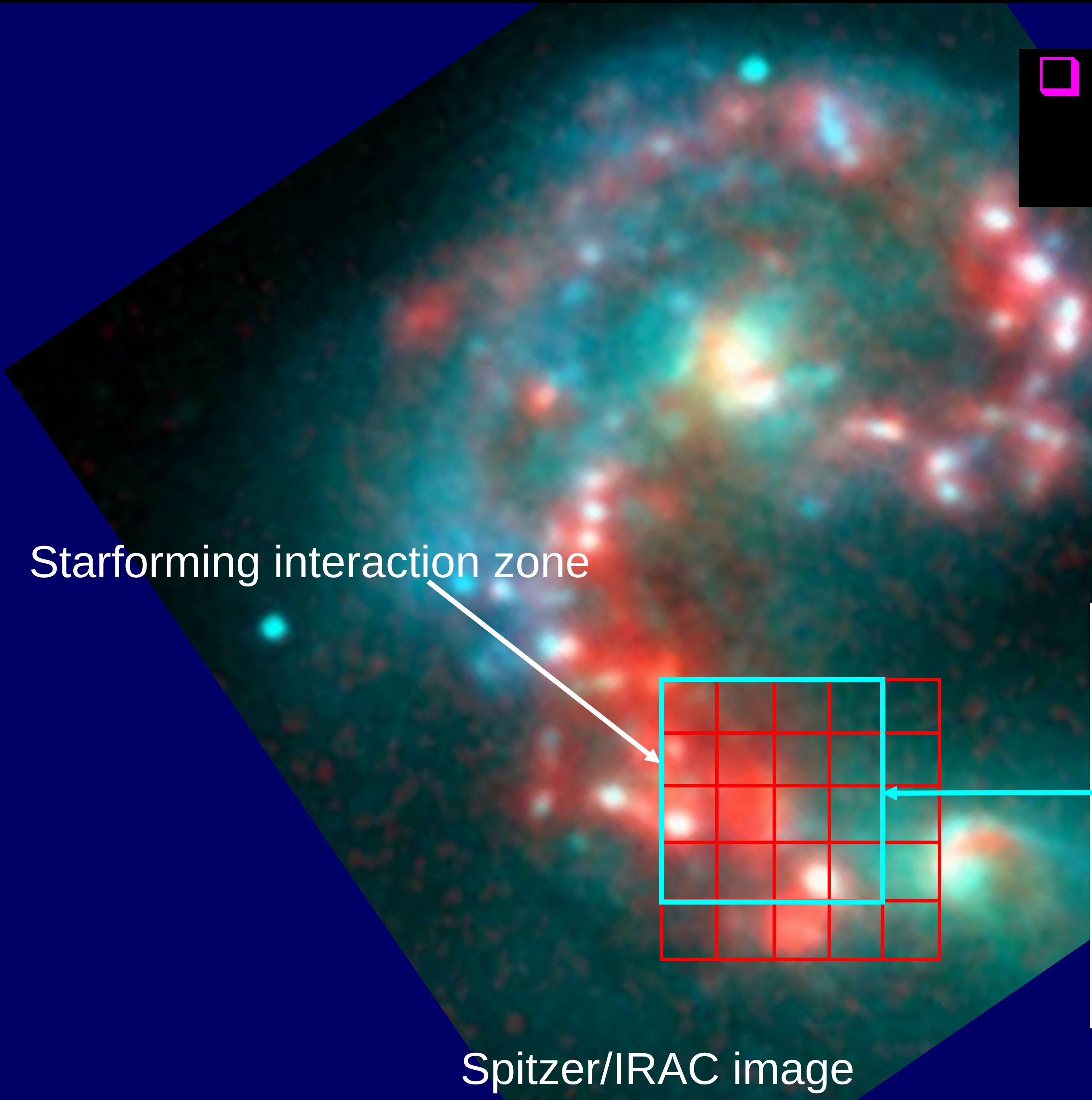
High ratio is a signpost for warm dense starforming clouds



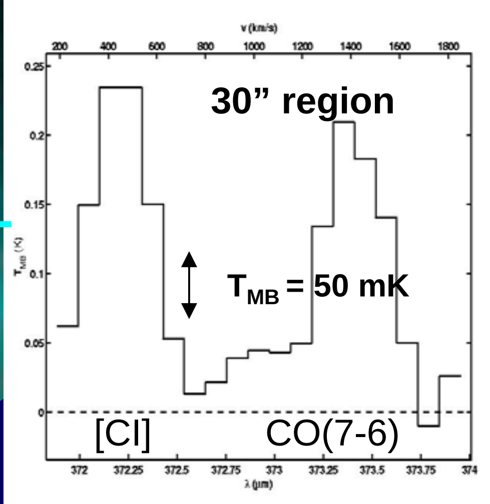
CO(7-6)/[CI] 370 μm line intensity ratio vs. density for various values for the strength of the ISRF, G (Kaufman et al. 1999)

CO(7-6) and [CI] from the Antennae Galaxies

- [CI] line stronger than CO and ubiquitous: it cools the galactic ISM

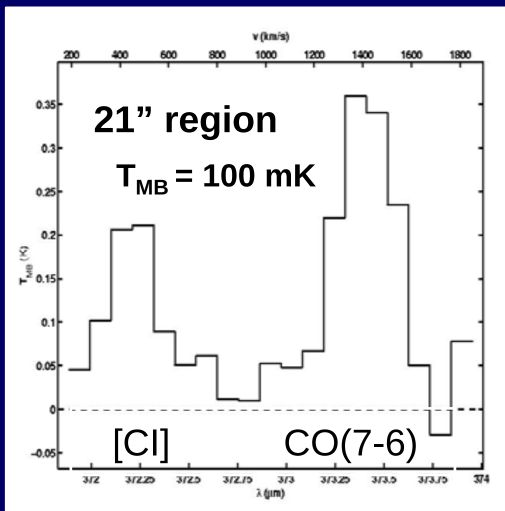


Spitzer/IRAC image

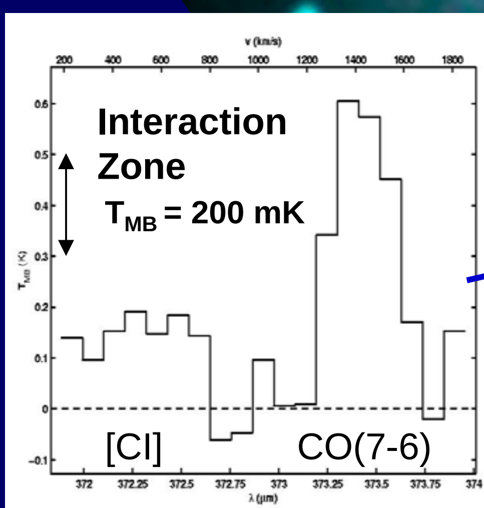


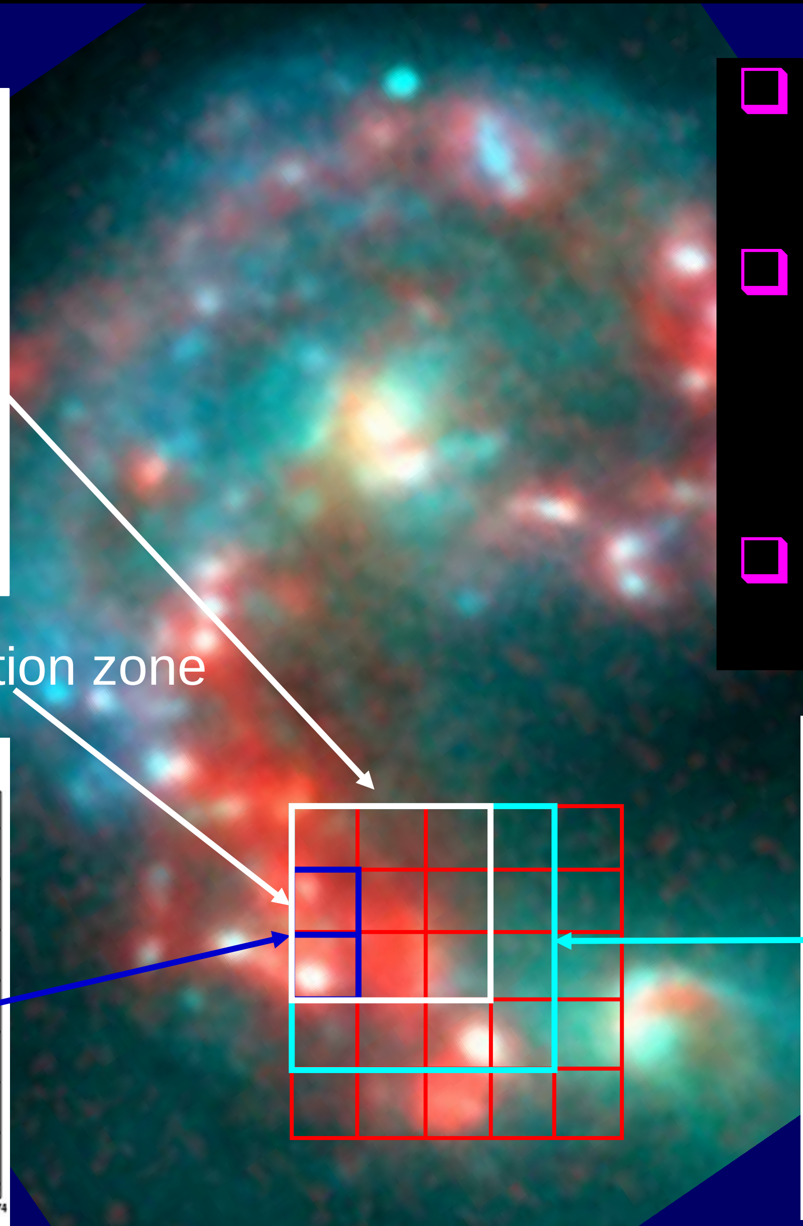
Isaak et al. 2006

CO(7-6) and [CI] from the Antennae Galaxies



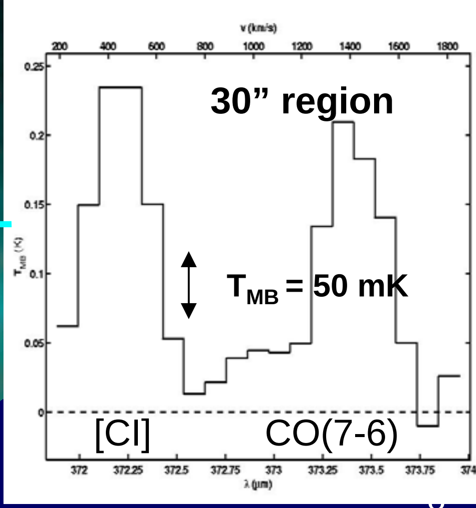
Starforming interaction zone





Spitzer/IRAC image

- [CI] line stronger than CO and ubiquitous: it cools the galactic ISM
- [CO(7-6) is greatly enhanced at the starburst interaction zone reflecting the high gas excitation there
- Strong mid-J CO emission reflects influence of OB stars

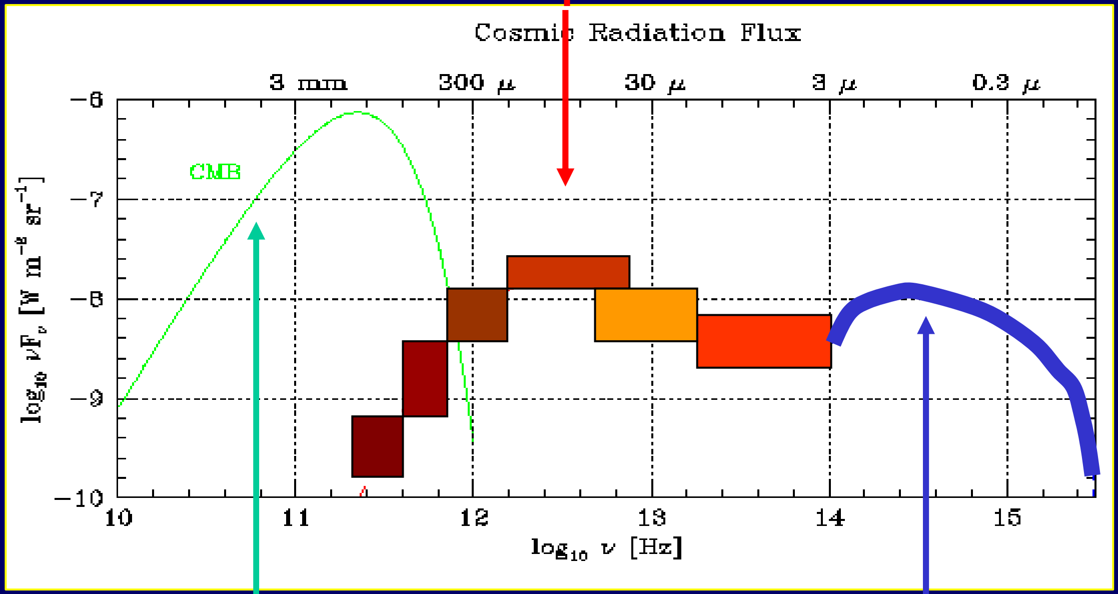


Isaak et al. 2006

Galaxies at High Redshift : The Submillimeter Background

- COBE discovered a submillimeter excess in cosmic microwave background with as much light as visible from galaxies

Photospheric light Reprocessed by dust

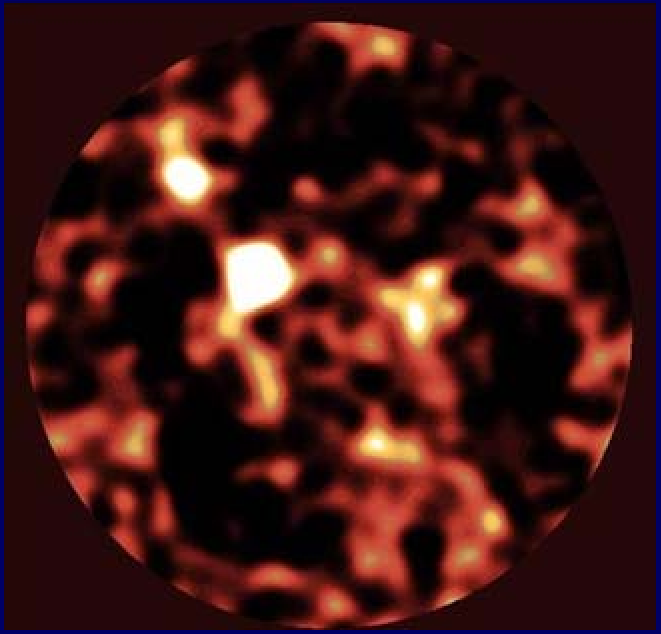


Microwave Background

Photospheric light from stars

SCUBA Observations

- Excess emission first resolved with the SCUBA, ISOCAM, and MAMBO surveys
  - Deep integrations at 15, 850 and 1200 um on “blank sky”
  - Detected here-to-fore undetected galaxies – submillimeter galaxies
- These sources account for much of the excess submillimeter background

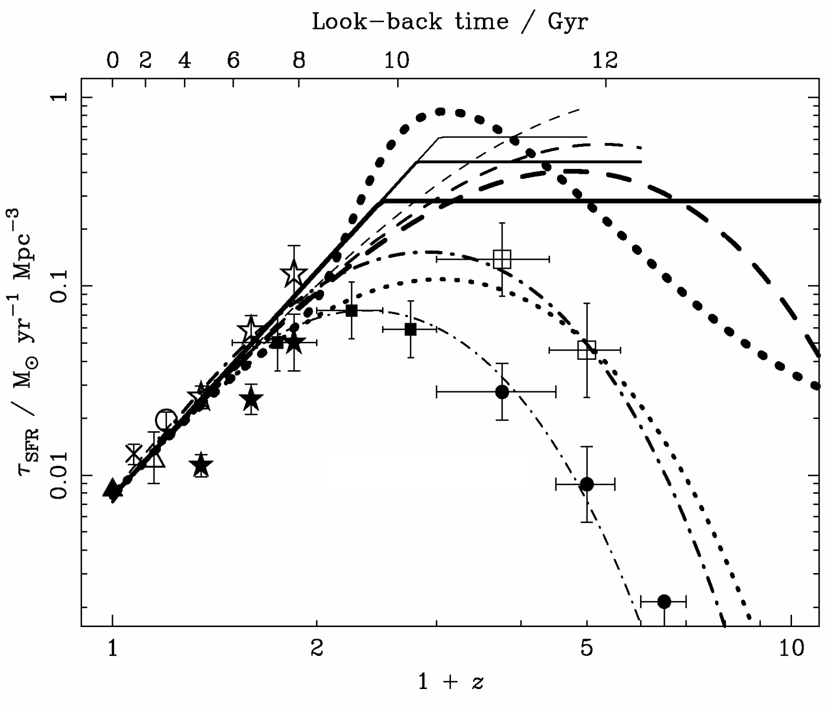


What are these sources? Their submm colors indicate:

Starforming progenitors of giant elliptical galaxies!

Starformation History of the Universe

- In contrast to prior optical results, the IR/submm counts show that star formation per unit co-moving volume peaked at early epochs z ~ 3 or even 4, or *only 1 to 2 billion years after the Big Bang*
- It is a challenge to get galaxies and stars to form (and create metals – dust) that quickly!



Estimates of the comoving star formation history (Blain et al. 1998). Filled squares and circles toward the bottom represent the original Madau plot based on optical/UV HDF observations (Madau et al. 1996). Open squares correct this data for dust extinction (Pettini et al. 1998). The upper seven curves are models that are consistent with the SCUBA data. The solid lines beneath the curves mark the redshft ranges accessible to ZEUS.

Redshifts for Submm Galaxies

- To better quantify the star formation history of the Universe, it is important to both obtain redshifts for the submm galaxies, and to characterize their starburst properties.
- SMGs are optically very faint $\Rightarrow$ it is challenging to get optical redshifts
  - however by taking advantage of the radio-IR correlation, Chapman et al. have recently had fairly good success using VLA positions for Keck follow-up spectroscopy
- We plan to use the several far-IR fine-structure lines that are quite bright and can also cover the optical redshift "desert"

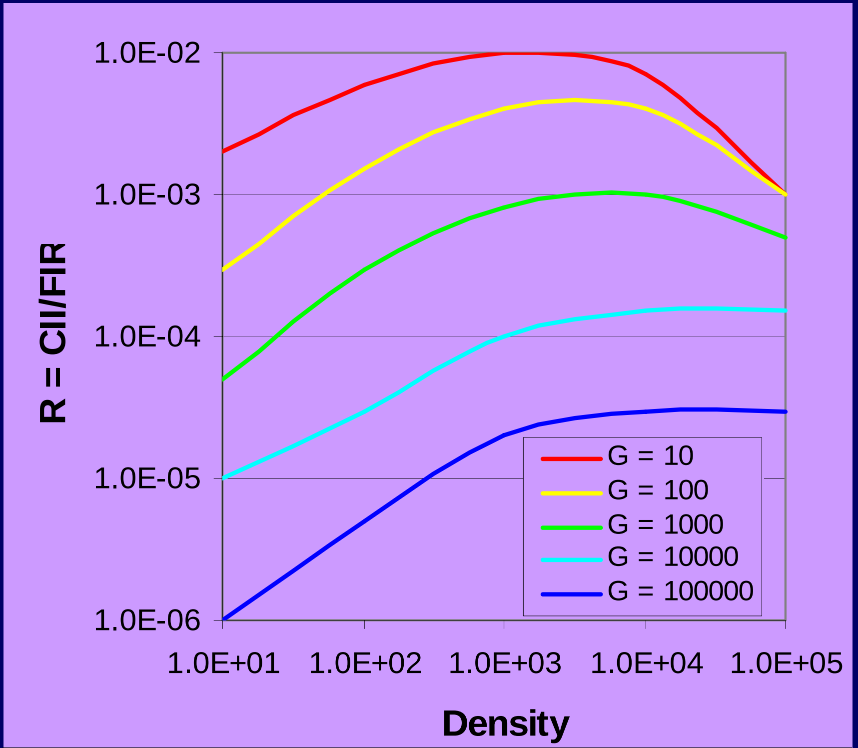
Redshifts for Submm Galaxies

- The best far-IR spectral probe is the 158 μm [CII] line
  - *The line is very bright:* For starforming galaxies, the [CII]/far-IR continuum ratio is ~ 0.1 to 0.3%
  - *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.
  - It is also easily detectable in starforming galaxies such as these

We have constructed a new spectrometer, ZEUS to detect the [CII] line from distant submm galaxies

Redshifted [CII]

- The [CII]/far-IR continuum is a sensitive indicator of the strength of the ambient ISRF, G so that *the [CII] line detection yields the concentration of the starburst*
  - In regions with the highest UV fields (young starbursts, ULIRGS, AGNs), the [CII]/far-IR continuum ratio is depressed
    - Reduced efficiency of photoelectric effect
    - Increased cooling in [OI] 63 μm line
  - More diffuse fields (like M82 and Milky Way) results in larger [CII]/far-IR ratio
  - Combined [CII], [OI], far-IR continuum ratios yield gas density and temperature, and the strength of the ISRF, G



The [CII]/far-IR continuum ratio as a function of G (from Kaufmann et al 1999)

Detecting [CII] from highly redshifted galaxies probes star formation in the epoch of galaxy formation

Is [CII] a viable redshift probe?

- 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 in CO lines
  - Net result is factor of 5 to 20 easier to detect a redshifted [CII] line – *providing the starburst ratio applies*

Off course, the real exciting physics is to get both a set of CO lines (ala Z-Spec) and [CII]!

- [CII] is a unique probe in redshift range from about 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

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 (we would also like to look earlier, to when small galaxies assembled into larger galaxies, but this awaits a larger telescope – see end of talk…)
- At z ~ 1 to 3, the [CII] line is transmitted through the short submillimeter telluric windows with about 40% coverage
- At z ~ 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

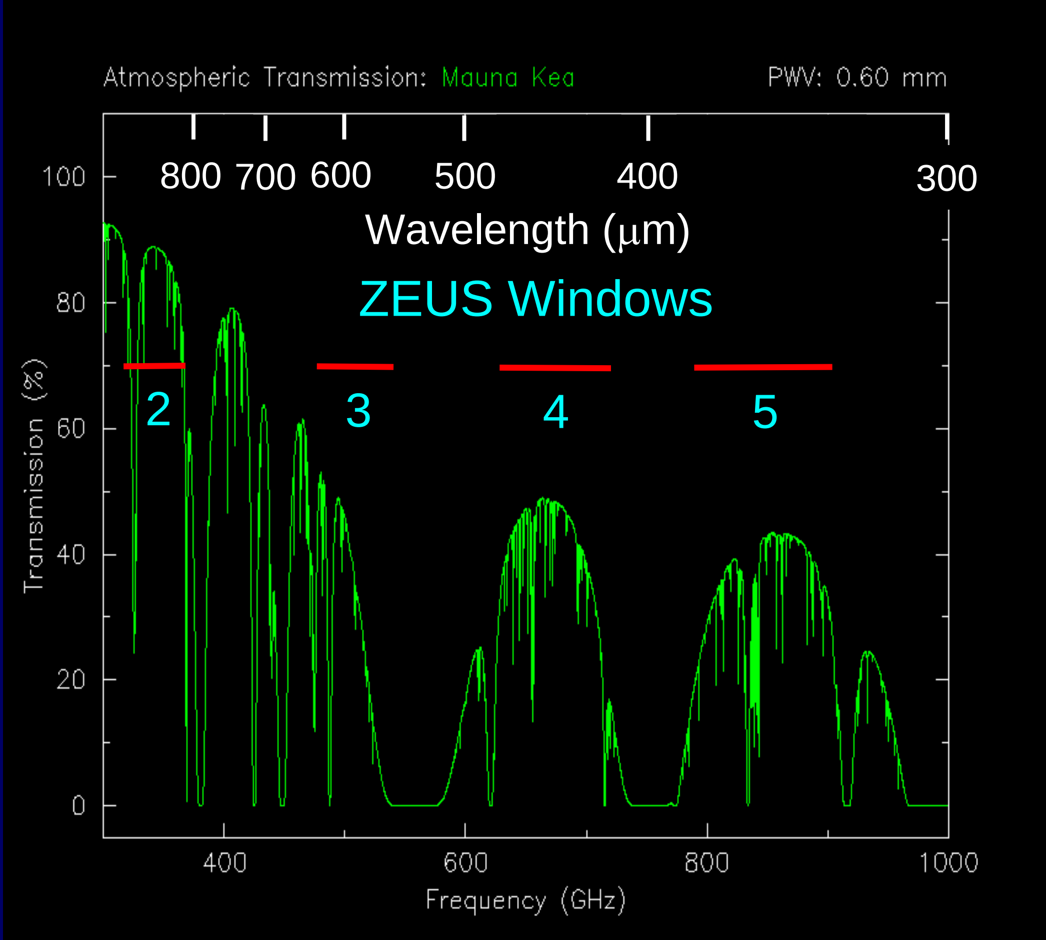
Design Criteria - 2

- In addition, very broad spectral coverage is required for sources for which the redshift is unknown, or poorly known
- It can be shown that the best system for detecting broad lines from point sources is a spectrally multiplexing direct detection spectrometer
  - In principle direct detection is more sensitive than coherent detection due to quantum noise
  - It is easy to achieve very broad bandwidths – one can cover the entire telluric windows with BW ~ 100 GHz
- Modern detectors are easily background limited in the high backgrounds available to Earth-bound observers.

Therefore, the instruments of choice for maximum sensitivity to point sources over broad bands are spectrally multiplexed monochrometers such as a grating spectrometers

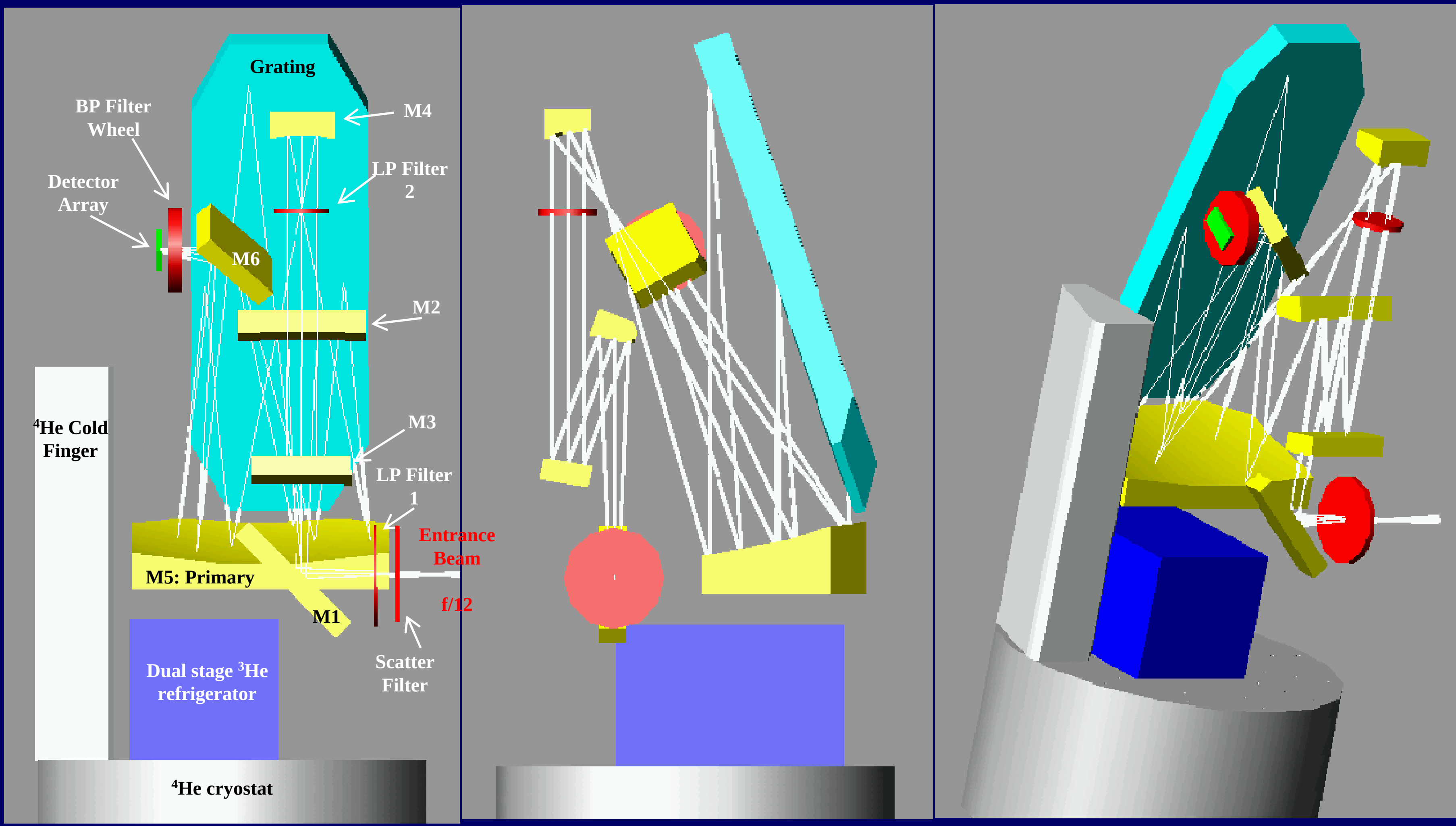
Design Criteria - 3

- Desire $R \equiv \lambda/\Delta\lambda \sim 1000$ to optimally detect extragalactic lines (about 300 km s^{-1} wide)
- Operate near diffraction limit:
  - One beam encloses the entire galaxy at high z
  - This maximizes sensitivity to point sources
  - This minimizes the size of the grating for a given R
- Long slit desirable
  - Spatial multiplexing
  - Correlated noise removal for point sources
- Choose to operate in n = 2, 3, 4, & 5 orders which covers the 890, 610, 450 and 350 μm windows respectively



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

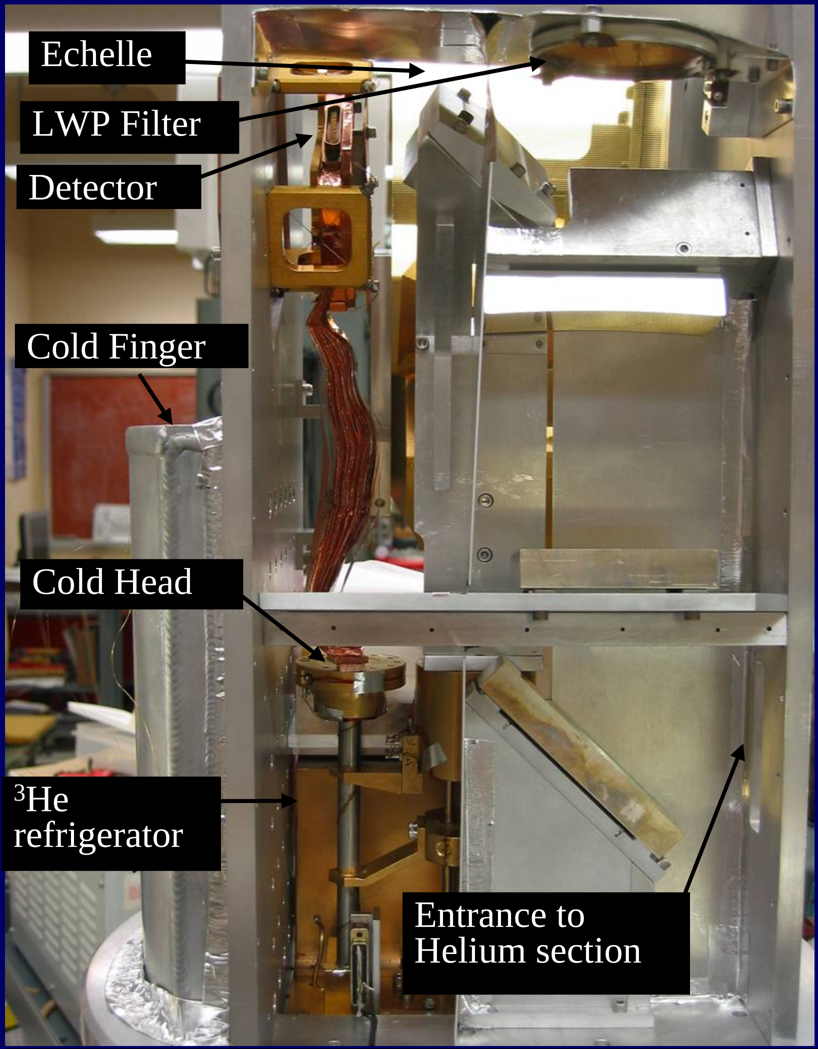
ZEUS: Optical Path



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

ZEUS Optics

- Detector sensitivity requirements are modest, so that a dual stage ^{3}He refrigerator (T ~ 250 mK) suffices – much less trouble than an ADR
- 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

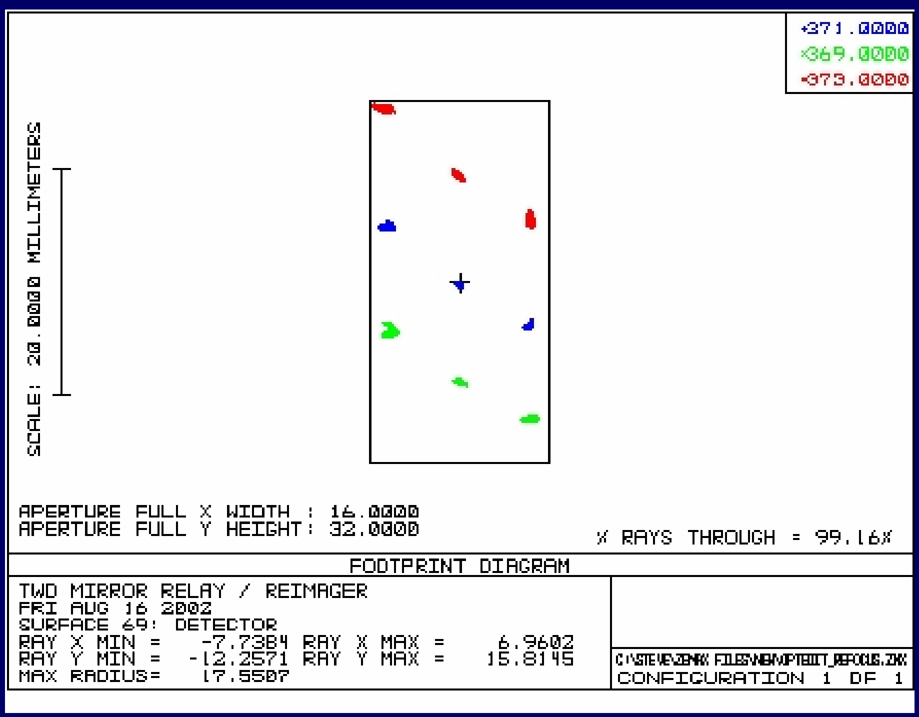


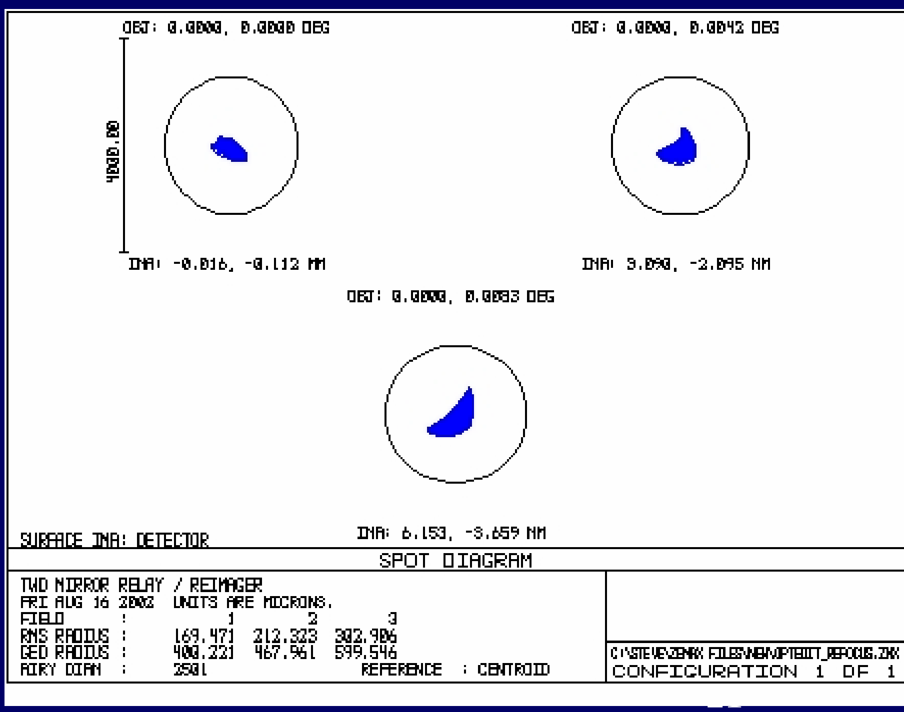
Interior of ZEUS with some baffles removed. The collimating mirror is hidden behind the middle wall baffles.

Ray trace

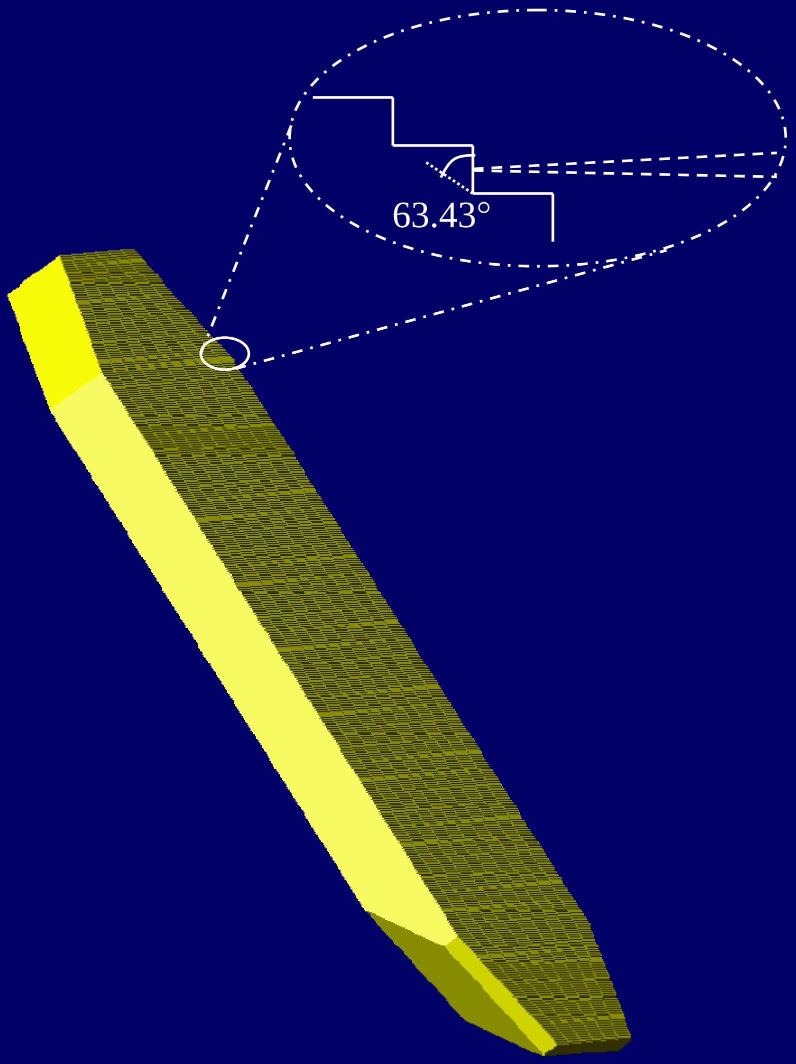
- Slit Size on CSO (Adjustable): - 7.2” @ 350 & 450 μm
  - 14.4” @ 610 & 890 μm
- Plate Scale: 7.2” per 1 mm pixel ⇒ 7.2” x 86” (12 x 32 (or 64) array)

The Footprint and Spot Size



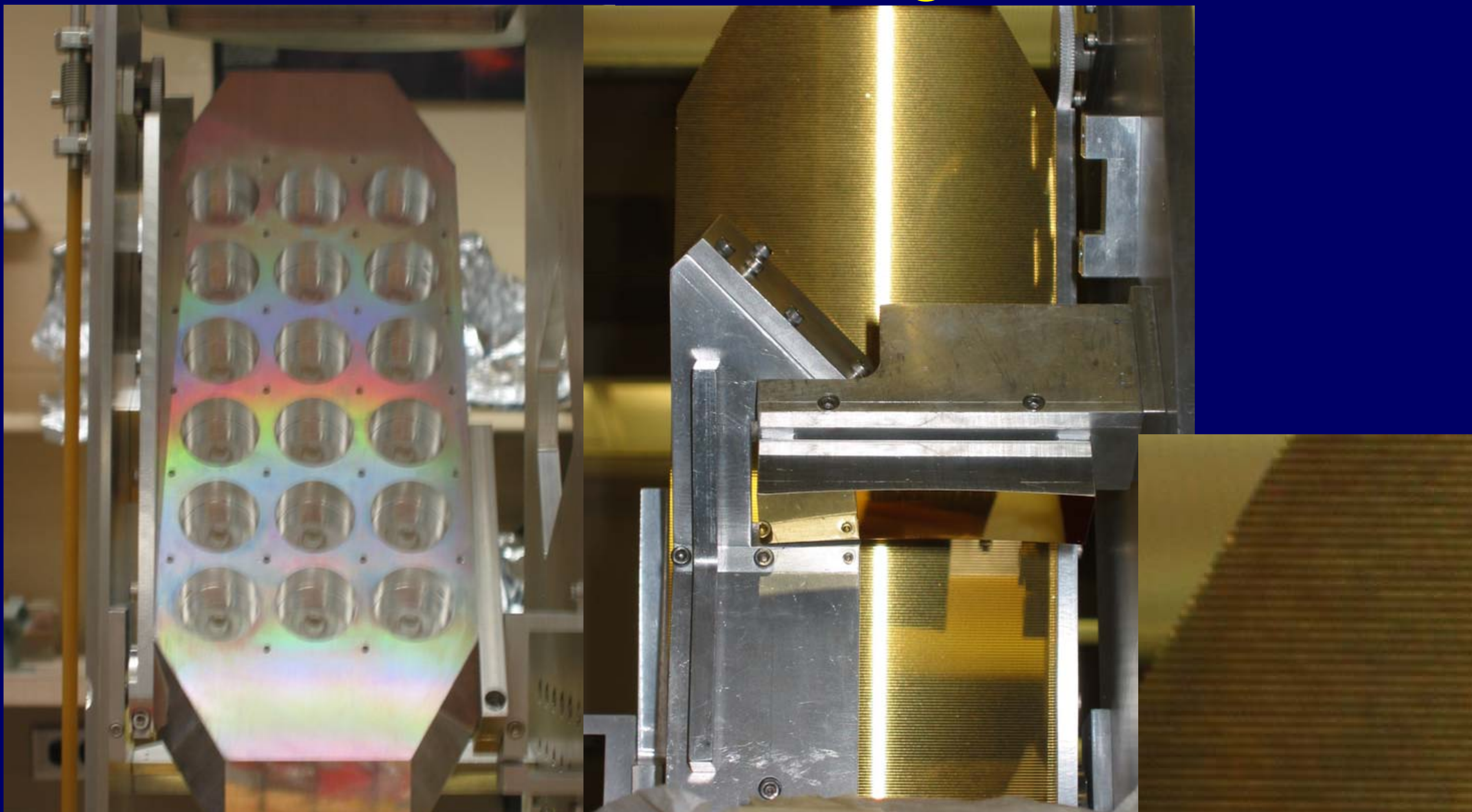


ZEUS: The Grating



- Littrow Mode
- Length of the Grating: 35 cm
- R2 Echelle (Blaze Angle: 63.43°)
- Grid Constant: 992 mm
- Orders:
  - 5th @ 359 μm
  - 4th @ 449 μm
  - 3rd @ 598 μm
  - 2^{nd} @ 898 μm
- Tilt Range: 57° to 73°
- Resolution: ~ 300 to 1500
- With a 32 pixel array, each submm window is covered with 3 to 4 “tunings” of the grating for line searches
- 64 pixel array reduces this to 1.5 to 2 tunings
- About 40% coverage for z ~ 1 to 3

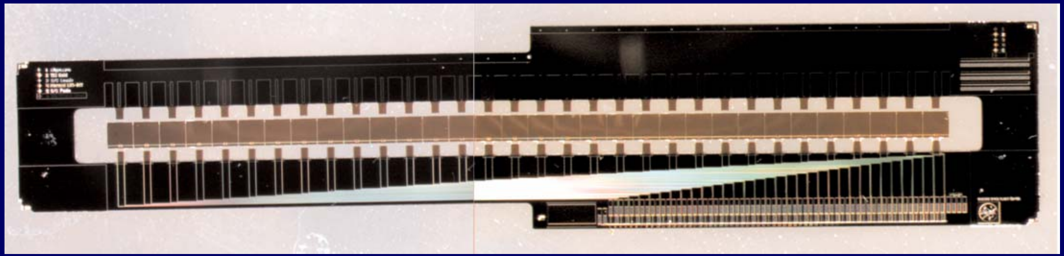
ZEUS Grating

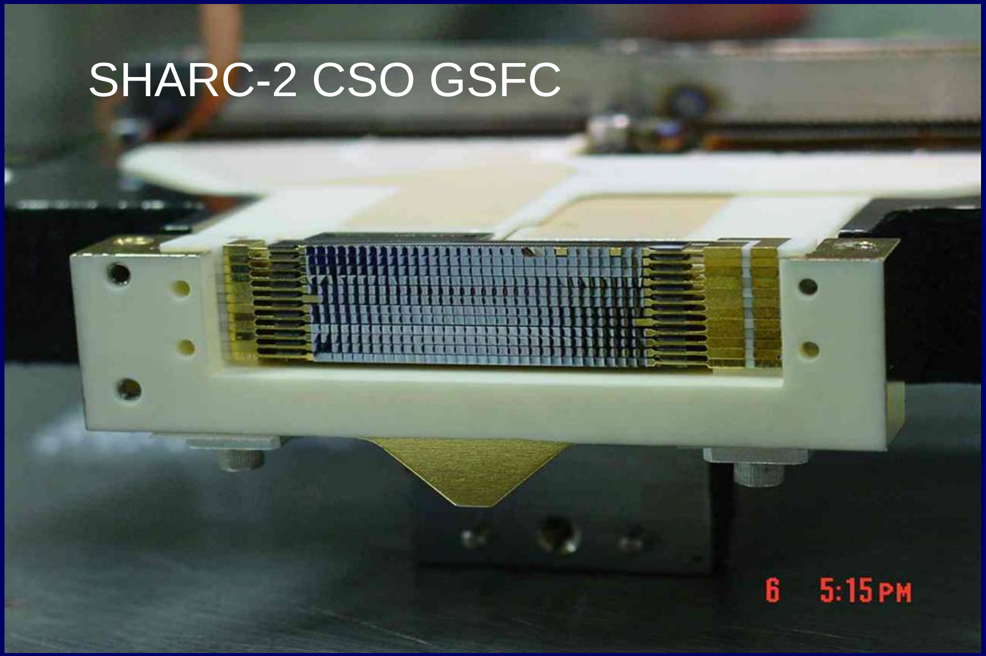


- *Manufactured by Zumtobel Staff GmbH (Austria).*

ZEUS Detector Array

- First run with a 1 × 32 pixel thermister sensed array from GSFC (SHARC-2 prototype)
- 1 × 32 GSFC TES in preliminary testing
- Larger format (4 to 12 × 32) expected later – yields 2 to 12 spatial positions each of which has a 32 element spectrum
- Ultimate is 12 × 64 pixel array





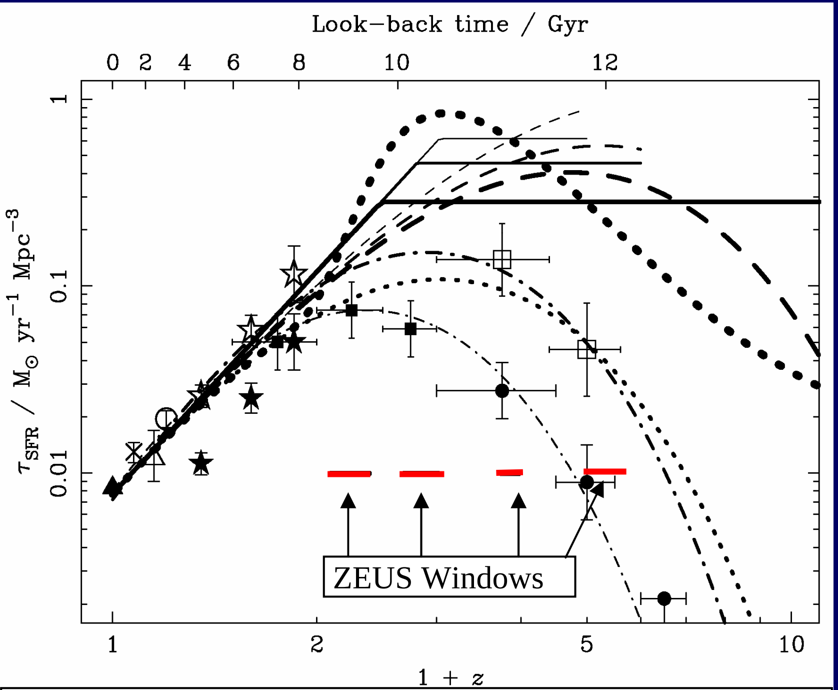
ZEUS/CSO System Parameters and Sensitivity Estimates – 0.8 mm H_2O

λ	Slit (")	R ($\lambda/\Delta\lambda$)	η(sky)	η_{point}	η_{pixel}	NEF (W $m^{-2}Hz^{-1}$)	MDLF (W m^{-2})	T_{rec} (SSB)
333	7.2	710	25%	47%	67%	9.8E-17	2.9E-18	42
355	7.2	920	33%	51%	62%	5.6E-17	1.6E-18	45
370	7.2	1200	25%	54%	60%	6.0E-17	1.8E-18	41
379	7.2	1500	13%	56%	58%	1.0E-16	3.1E-18	37
422	7.2	620	20%	63%	52%	8.5E-17	2.5E-18	35
444	7.2	740	39%	66%	48%	3.3E-17	9.8E-19	42
474	7.2	1200	30%	69%	43%	3.4E-17	9.9E-19	47
590	14.4	550	25%	79%	72%	4.4E-17	1.3E-18	24
604	14.4	620	38%	80%	71%	2.3E-17	6.9E-19	25
626	14.4	810	44%	81%	69%	1.6E-17	4.7E-19	24
833	14.4	280	60%	89%	53%	1.1E-17	3.3E-19	25
885	14.4	370	86%	90%	48%	4.0E-18	1.2E-19	25
948	14.4	600	85%	91%	43%	3.1E-18	9.2E-20	25

- NEF on APEX likely 1.5 times better at the shorter wavelengths due to the better site, and larger area (12 m vs. 10.4 m)

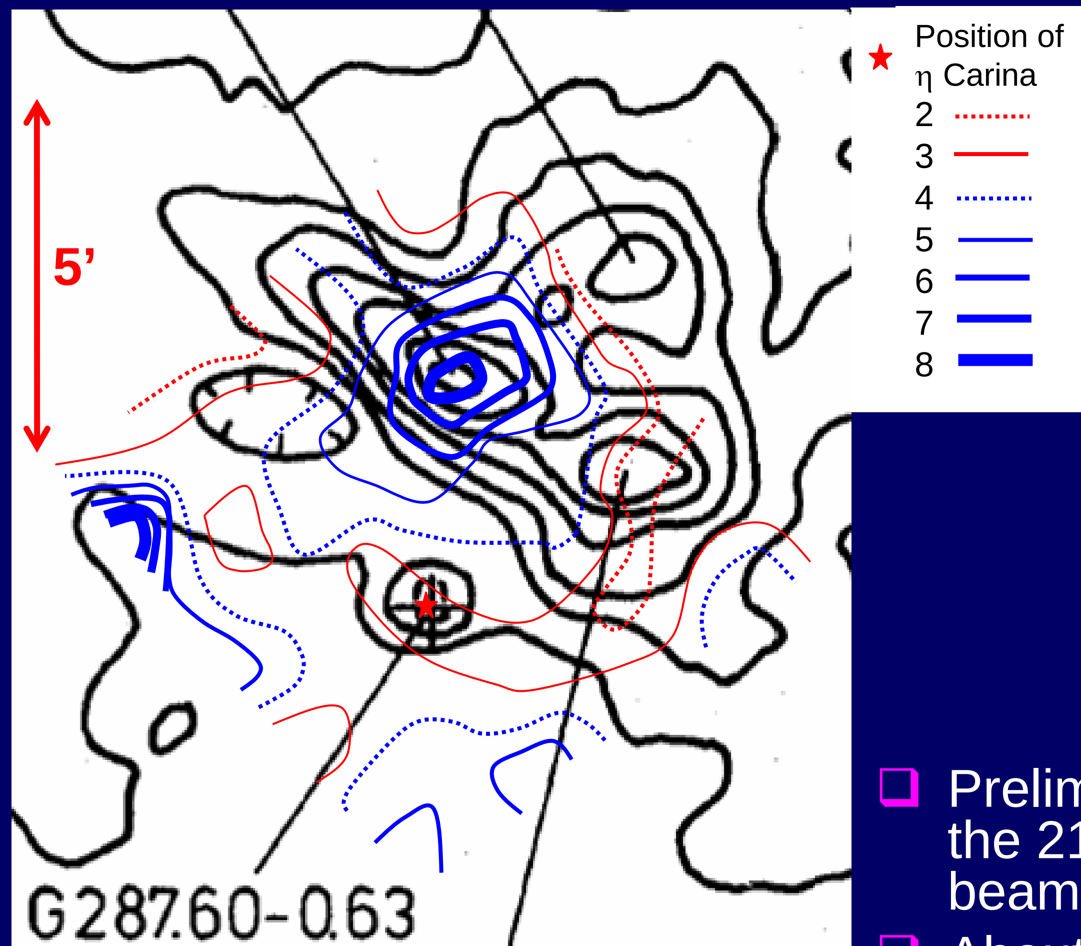
ZEUS and the Early Universe

- One can detect the [CII] line and several other far-IR lines in the redshift intervals from 1 to > 5
  - [CII] PDRs, low density HII regions, atomic clouds
  - [OI] PDRs
  - [NII] low density HII regions
  - [OIII] HII regions, O stars
- Covers just the region of redshift space where the most evolution per co-moving volume occurs, and also where the UV/optical techniques are most affected by extinction

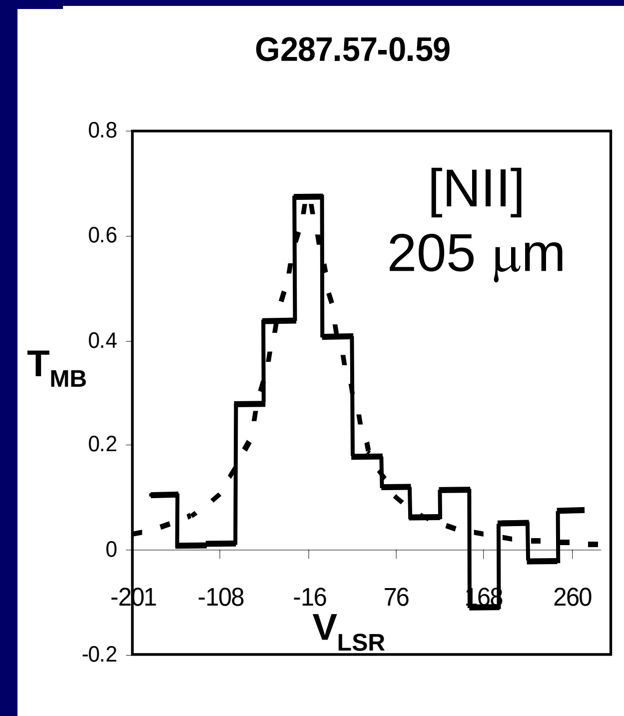


Estimates of the comoving star formation history (Blain et al). Filled squares and circles toward the bottom represent the original Madau plot based on optical/UV HDF observations (Madau et al). Open squares correct this data for dust extinction (Pettini et al). The 7 upper curves are models that are consistent with the SCUBA data. The solid lines beneath the curves mark the redshft ranges accessible to ZEUS.

Detection of [NII] 205 μm in the Very Local Universe with AST/RO: Carina II



Oberst et al. 2006



- Preliminary [NII] map superposed on the 21 cm radio continuum map (50” beam, Retallack, D.S 1983)
- About 20% of our data
- Zenith transmission 2.9%
- [NII] line detected over the entire HII region, largely following the free-free contours

Far-IR Lines from High-Z Galaxies Detectable with ZEUS

Line	Redshift Interval	Window	$L_{far\text{-}IR}$ [$L_\odot$]	F_{line}[W m^{-2}]
[CII]: 157.741 μm	1.10 → 1.39 1.69 → 2.02 2.74 → 2.97 4.25→ 5 .00	350 μm 450 μm 620 μm 850 um	> 3.0×10^{12} > 6.0×10^{12} > 1.3×10^{13} > 1.1×10^{13}	1.0×10^{-18} 6.2×10^{-19} 4.8×10^{-19} 1.3×10^{-19}
[NII]: 121.898 μm	0.70 → 0.84 1.07 → 1.33 1.88 → 2.06	350 μm 450 μm 620 μm	> 3.0×10^{12} > 5.5×10^{12} > 1.4×10^{13}	1.0×10^{-18} 6.2×10^{-19} 4.8×10^{-19}
[OIII]: 88.356 μm	2.75 → 3.27 3.80 → 4.40	350 μm 450 μm	> 1.1×10^{13} > 2.1×10^{13}	1.0×10^{-18} 6.2×10^{-19}
[OI]: 63.184 μm	4.24 → 4.97 5.71 → 6.55	350 μm 450 μm	> 3.4×10^{13} > 4.6×10^{13}	1.0×10^{-18} 6.2×10^{-19}

- SNR are ***5 σ in 4 hours on CSO*** using fundamental limits
- There are ***more than a dozen SMGs known*** that ZEUS can detect with SNR > 20 in 4 hours with ***current sensitivities***

ZEUS and Submm Galaxies

- At present ZEUS on CSO can detect redshifted [CII] from any (5σ) SCUBA source that falls into the telluric windows
  - SNR > 5 (4 hours) at z = 1 to 4 ***with current sensitivity*** on CSO
  - Fundamental limits are twice as good
- The large scale Spitzer surveys, such as the SWIRE survey are uncovering ***many hundreds of distant galaxies observable in their [CII] line radiation with ZEUS***
- ***The detection of [CII] from a quasar at z = 6.42 gives a real boost to these studies (***Maiolino ***et al. 2005)***

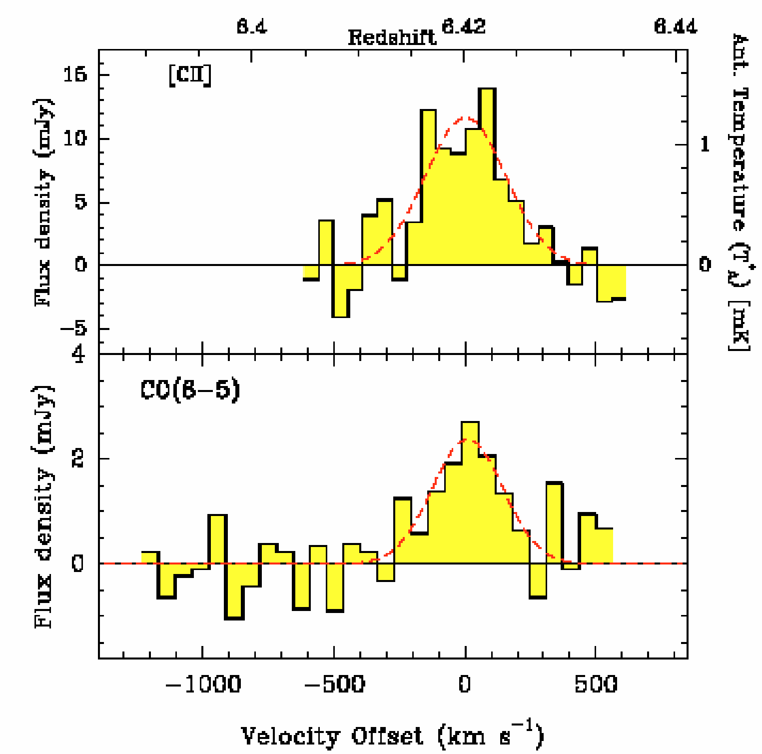


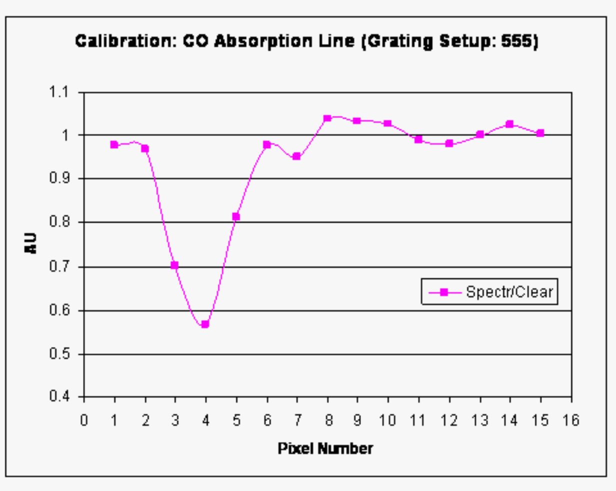
Fig. 1. Spectrum of the [CII] 157.74 μm emission line in the quasar J1148+5251 at $z = 6.42$ shown with a velocity resolution of 56 km s^{-1} (*top panel*) compared to the CO(6–5) emission line (*bottom panel* – from Bertoldi et al. 2003b). The dashed curves show the gaussian fits to the line profiles (see Table 1).

ZEUS in the Lab

We specialize in ***putting the “re” into research***

Current Status

- We had an engineering run on JCMT in March of 2005.
  - Instrument fully interfaced to telescope
  - Lab sensitivity was within a factor of 2 of the fundamental limits ⇔ T_{rec} ~ 60 K (DSB)
  - Mounted in the receiver cabin, sensitivity was within 10% of laboratory values
  - Unfortunately, no real data on the sky was obtained



CO calibration spectrum obtained on the telescope

ZEUS mounted on JCMT

Future Plans

- We have science runs on CSO in March and May
  - Will use our thermister sensed array in March
  - We hope to have improved sensitivity – still in the works
  - Working towards TES array installation for our May run
  - CSO Science Collaborators: C. Matt Bradford, C. Borys (Caltech), M. Gerin (Paris Observatory)
- Primary science
  - CO/[CI] studies of ULIRGs
  - CO/[CI] mapping of nearby starforming galaxies
  - Detecting redshifted fine-structure lines from galaxies at z ~ 1.1 to 4.4
    - Source list includes 15 sources with SNR > 10 in 4 hours of integration time using laboratory sensitivities
- We hope to continue with runs on CSO, JCMT, SMT, and/or APEX in the near future, and…

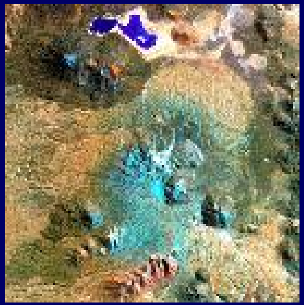
The Cornell Caltech Atacama Telescope (CCAT) Project

In February 2004, Cornell and Caltech/JPL signed an MOU to study to development of a 25 m class submillimeter telescope at a high site near ALMA. We are now nearing the end of our study phase.

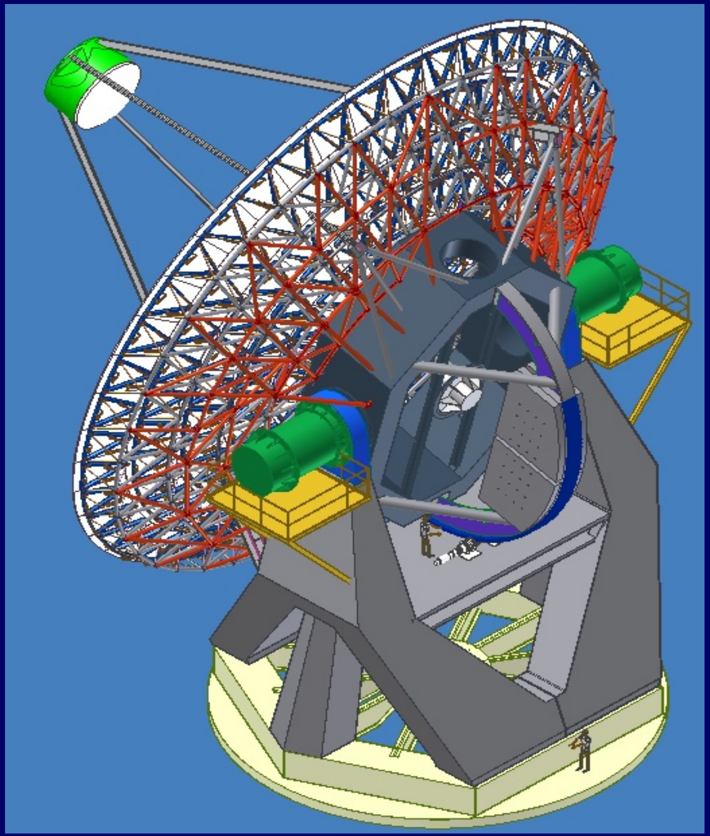
Requirements:

- Water Vapor Burden: Need burden < 1 mm to enable the short submm windows (200, 350, 450 μm) ⇒ high site
- Surface Accuracy: High surface accuracy (~ 10 μm rms) assures good efficiency in these windows
- Field of View: Faint source surveys a forte ⇒ large FOV > 5’ in short submm, and 20’ in near mm (>32,000 pixel arrays)
- Timeliness: Facility is to be completed at the same time as ALMA ~ 2012.

Primary Science Areas



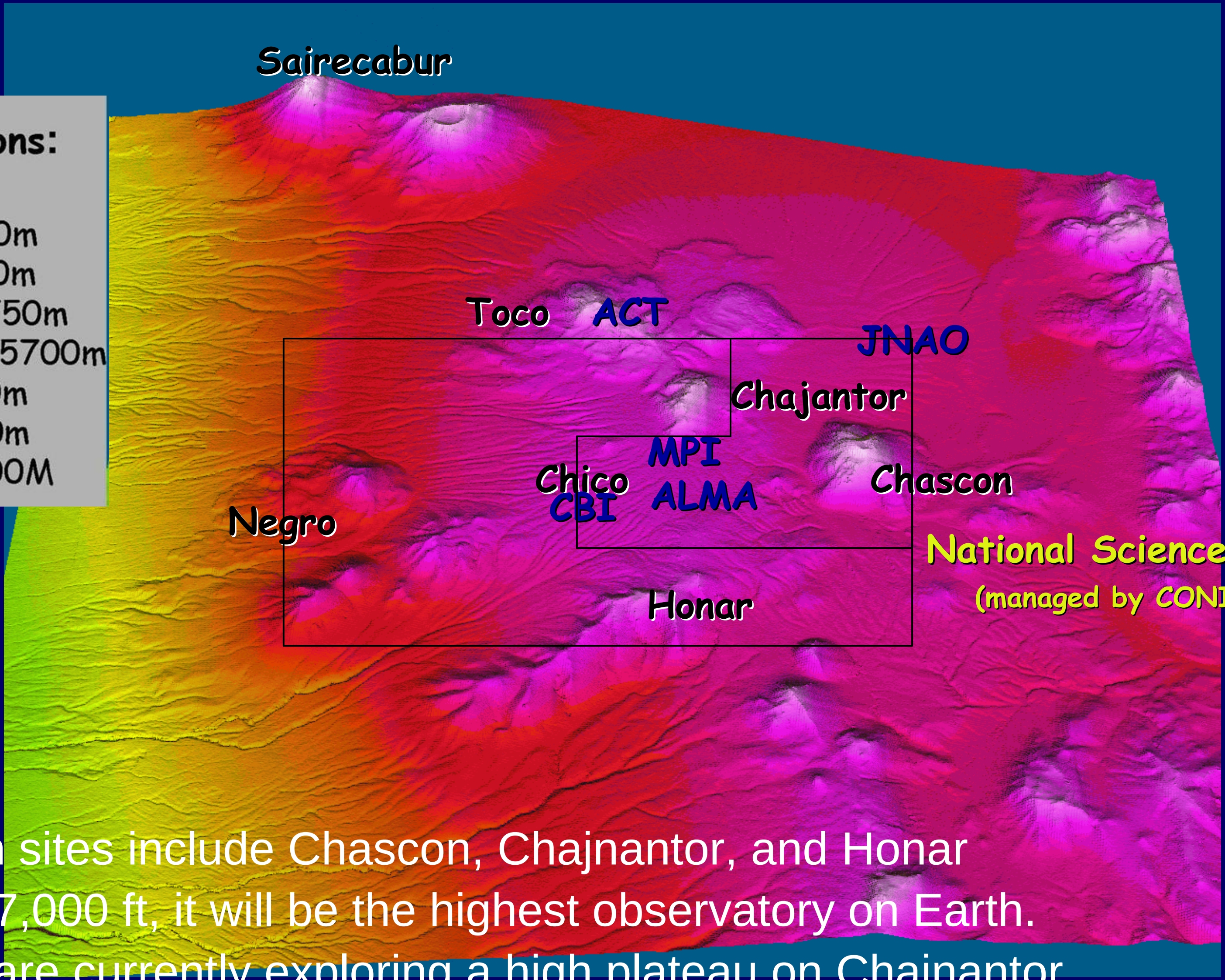
- Early Universe and Cosmology
- Galaxy Formation & Evolution
- Disks, Star & Planet Forming Regions
- Cosmic Microwave Background, SZE and
- Solar System Astrophysics



The Site

Elevations:

Honar 5400m
Negro 5150m
Chascon 5750m
Chajnantor 5700m
Toco 5650m
Chico 5150m
Plateau 5000M

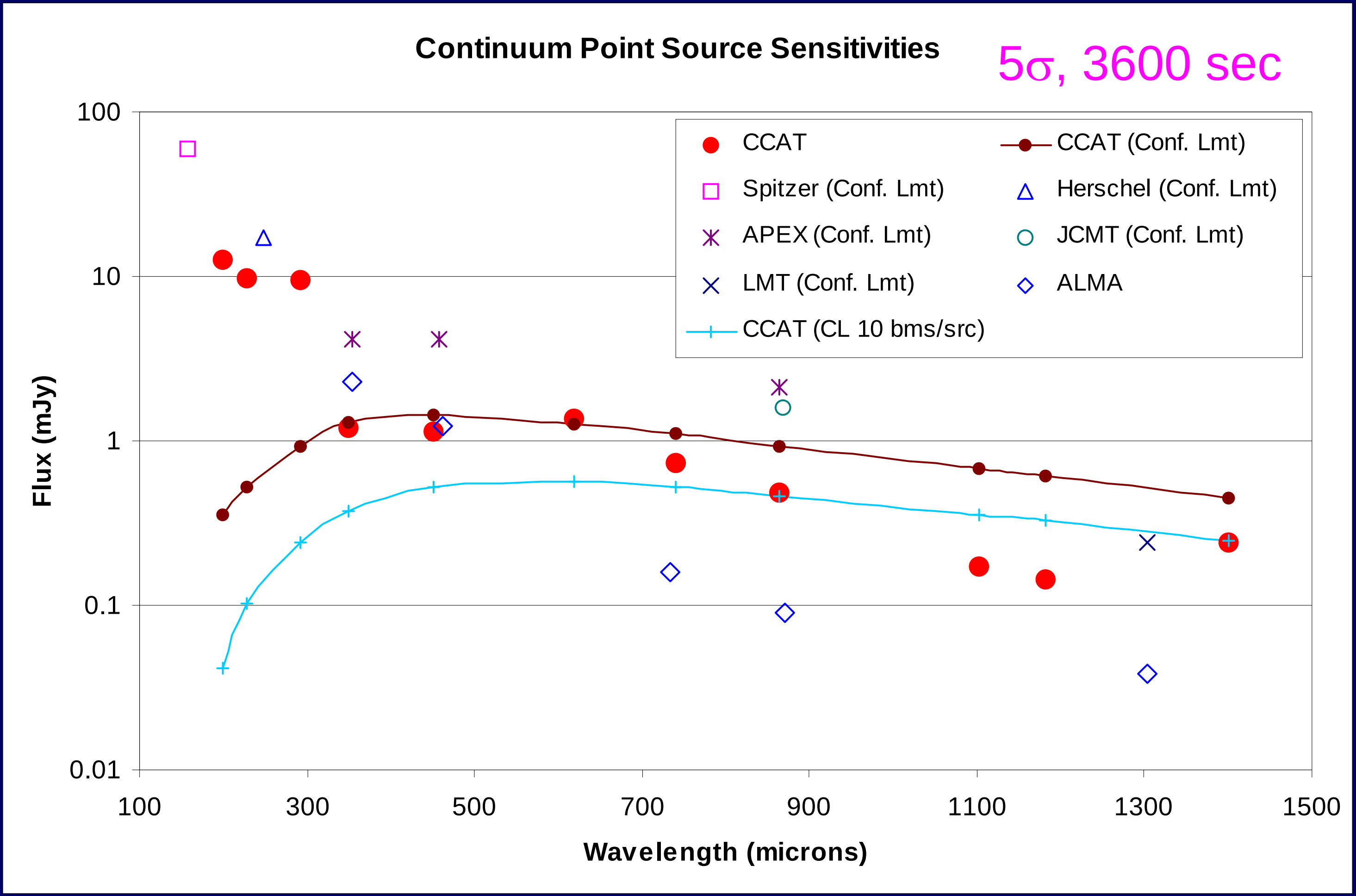


- High sites include Chascon, Chajnantor, and Honar
- At 17,000 ft, it will be the highest observatory on Earth.
- We are currently exploring a high plateau on Chajnantor

Instrumentation

- Short Submm wave camera
  - > 32,000 pixels (baselined SCUBA 2-like)
  - FOV 5' × 5', Nyquist sampled at 350 μm
  - Growth potential to 20' × 20' FoV (400,000 pixels)
  - Filter wheel covering 200, 350, 450, 620 μm
- mm Wave camera
  - 740, 870 μm, 1.1, 1.4, and 2.0 mm
  - Slot dipole antenna coupled KID arrays
  - 1024 to 16,384 pixels depending on wavelength
  - 10' × 10', or 20' × 20' FoV
- Transferred spectrometers
  - ***ZEUS-like multi-object grating spectrometer***
  - Z-Spec-like broad-band spectrometer
  - Heterodyne receivers

CCAT Camera Sensitivity



- Computed for precipitable water vapor appropriate to that band.
- Confusion limits shown are 30 beams/source except for 10 beams/source case shown for CCAT.

CCAT Science

- Galaxy formation:
  - Find millions of distant star forming galaxies ($z \sim 1$-5) at rate $>10^3$ hr^{-1}
  - Submm SEDs provide photometric redshifts
  - Redshifted fine-structure lines for subsample
    - [CII] from $2 \times$ MW to $z \sim 2$, $10 \times$ MW to $z > 5$
    - Accurate redshifts
    - UV fields, properties of ISM within galaxies

Starformation history of the Universe

Evolution of large scale structure

Detecting Redshifted [CII] with CCAT

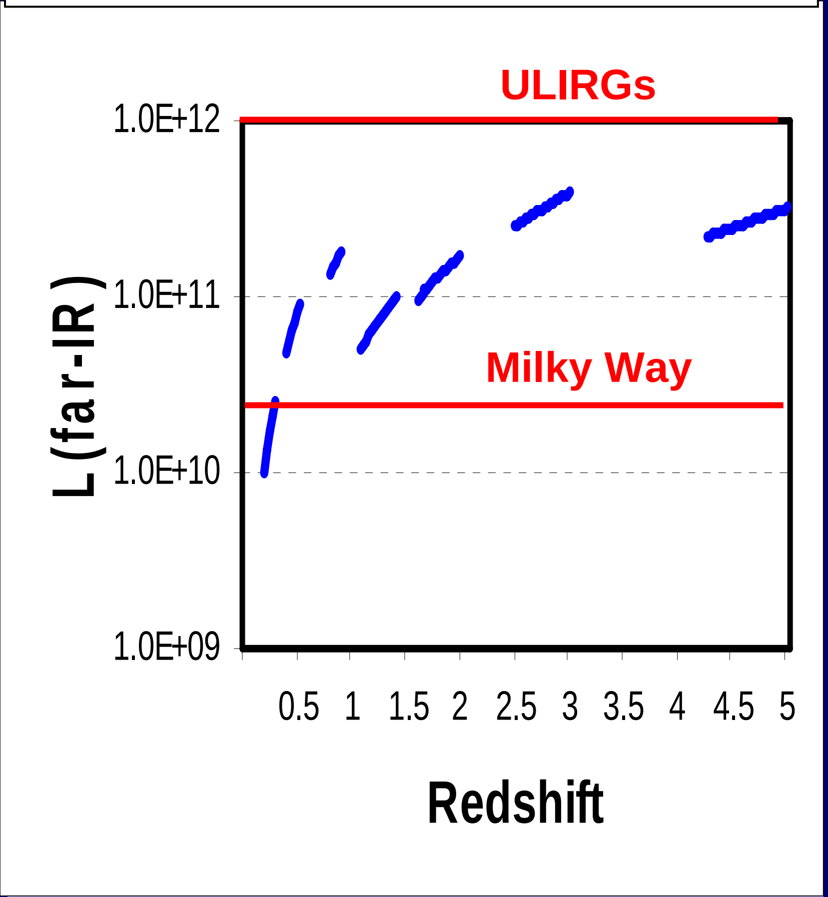
- ZEUS on CCAT should be 10 to 20 times more sensitive than it is on CSO
  - Better site
  - Better surface
  - Larger antenna
- Would open up more windows (e.g. 200 and 230 μm)
- Would implement multi-object feeds (10 to 20 objects)
- Typically takes 4 times as long to detect the line, as the continuum
  - For normal or starburst galaxies, the line to continuum ratio (when the line is resolved) is ~ 5:1
  - The detection BW for the continuum is typically ~ 10%, while for lines is is only 0.1%
  - Flux sensitivity is proportional to $\sqrt{BW}$
  - The line SNR is half as great

Redshifted [CII] Emission Yields Far-UV Field Strength and Redshifts

- The [CII] line is detectable (MW ratio) at redshifts in excess of 5 for $L_{far\text{-}IR} > 3 \times 10^{11} L_{\odot}$
- ULIGS have $L > 10^{12} L_{\odot}$, and [CII]/far-IR > 0.03% --

  [CII] still readily detectable!
- It is the lower luminosity systems that are most interesting with respect to galaxy assembly – these will likely have relatively bright [CII] line emission
- We can reach down to nearly MW luminosities for z < 1.5
- [CII] line is uniquely bright, but redshifts can be verified (again with a gain to the physical understanding) by observing the other bright far-IR lines.

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



5 σ in 4 hours

Far-IR Lines from High-Z Galaxies Detectable with CCAT

Line	Redshift Interval	Window	L_{far-IR} [$L_\odot$]	F_{line}[W m^{-2}]
[CII]: 157.741 μm	1.10 → 1.39 1.69 → 2.02 2.74 → 2.97 3.7 4.5 6.0	350 μm 450 μm 620 μm 740 μm 865 μm 1103 μm	$> 8 \times 10^{10}$ $> 1.3 \times 10^{11}$ $> 3.1 \times 10^{11}$ $> 2.1 \times 10^{11}$ $> 3.0 \times 10^{11}$ $> 2.7 \times 10^{11}$	1.1×10^{-19} 7.7×10^{-20} 6.6×10^{-20} 2.3×10^{-20} 1.6×10^{-20} 8.4×10^{-21}
[NII]: 121.898 μm	1.72 → 2.12 2.48 → 2.91 3.84 → 4.14	350 μm 450 μm 620 μm	$> 1.1 \times 10^{12}$ $> 2.1 \times 10^{12}$ $> 3.6 \times 10^{12}$	1.1×10^{-19} 7.7×10^{-20} 6.6×10^{-20}
[NII]: 205.178 μm	0.70 → 0.84 1.07 → 1.33 1.88 → 2.06	350 μm 450 μm 620 μm	$> 1.7 \times 10^{11}$ $> 5.6 \times 10^{11}$ $> 1.1 \times 10^{12}$	1.1×10^{-19} 7.7×10^{-20} 6.6×10^{-20}
[OIII]: 88.356 μm	2.75 → 3.27 3.80 → 4.40	350 μm 450 μm	$> 1.0 \times 10^{12}$ $> 1.9 \times 10^{12}$	1.1×10^{-19} 7.7×10^{-20}
[OI]: 63.184 μm	4.24 → 4.97 5.71 → 6.55	350 μm 450 μm	$> 4 \times 10^{12}$ $> 5 \times 10^{12}$	1.0×10^{-19} 7.7×10^{-20}

- ***CCAT continuum surveys will uncover many tens of thousands of distant galaxies observable in their [CII] line radiation with direct detection spectrometers***

Summary

- ZEUS is a submm grating spectrometer optimized for detecting extragalactic point sources
- ZEUS has modest resolving power: R ~ 1000
  - Well matched to extragalactic lines
  - BW currently 3.2%, expandable to 6.4%
- We have jumped the first hurdles for real science
  - Lab sensitivity currently within a factor of two of fundamental limits with thermister sensed array
  - Expect background limited performance with TES sensed array – in testing
  - Larger format arrays will become available soon
- ZEUS is a powerful tool for detecting redshifted fine structure lines from SMGs on current large submm telescopes
- ZEUS can detect these same lines from more modest systems on CCAT