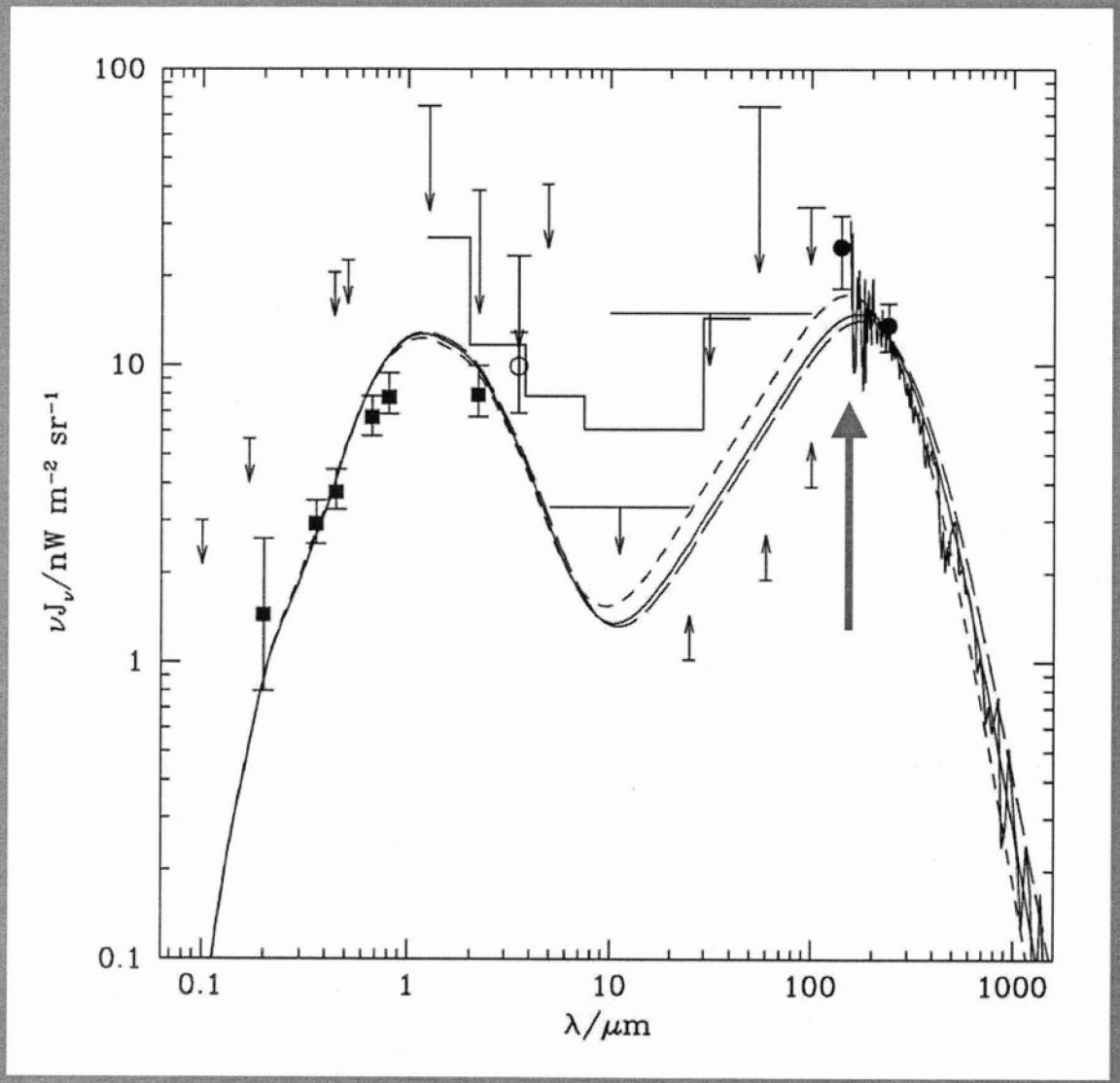
Background-Limited Infrared--Submillimeter Spectroscopy (BLISS)

Matt Bradford

June 10, 2004

Thanks to the ISM in galaxies, half the power in the universe emerges in the far-IR

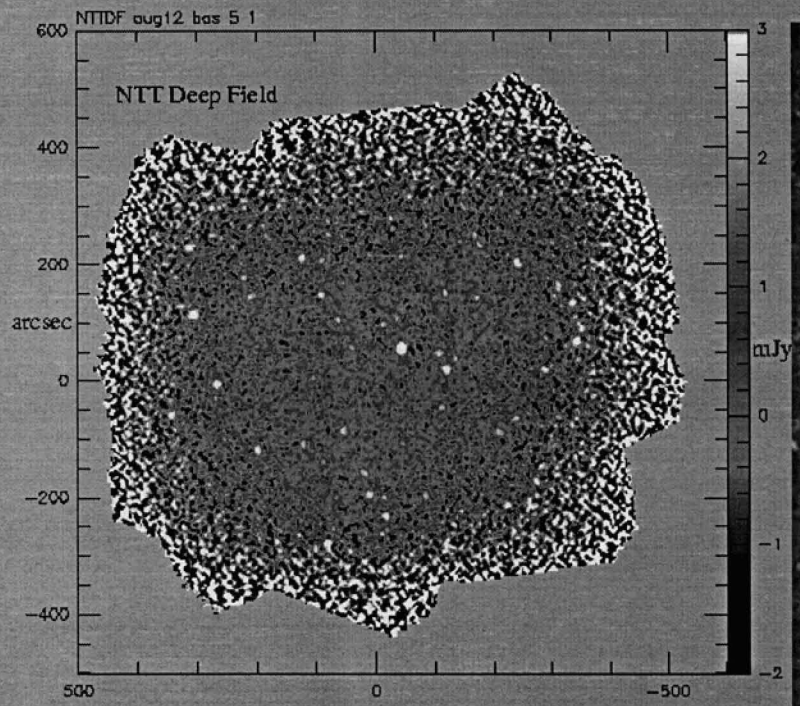


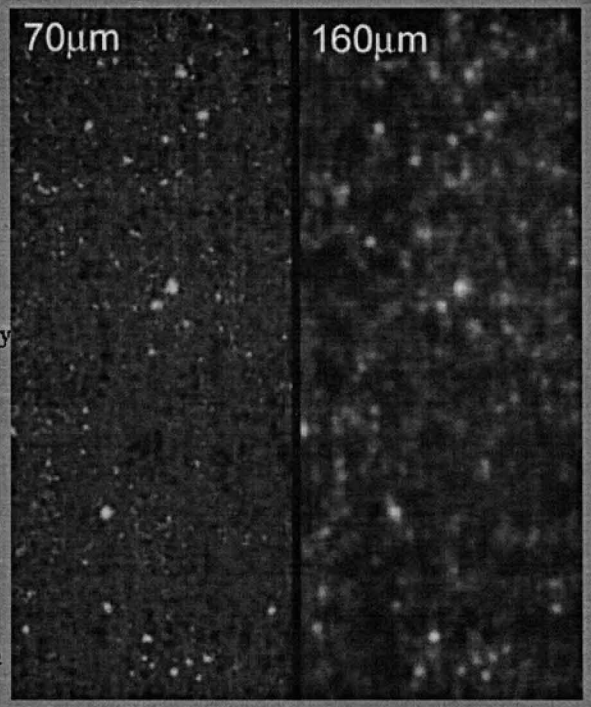
- Dust reprocesses star formation and accretion luminosity into the far-IR
- Dust hides luminosity sources at their short wavelengths
- Dust extinction is typically associated with the dense ISM.

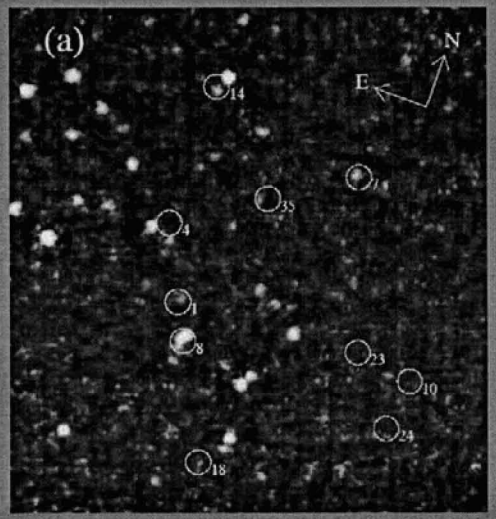
➔Mid-IR through mm wavelengths is the way to study the dense ISM

S. Michael Fall, IAU V. 204, 2001

Far-IR background being resolved into galaxies







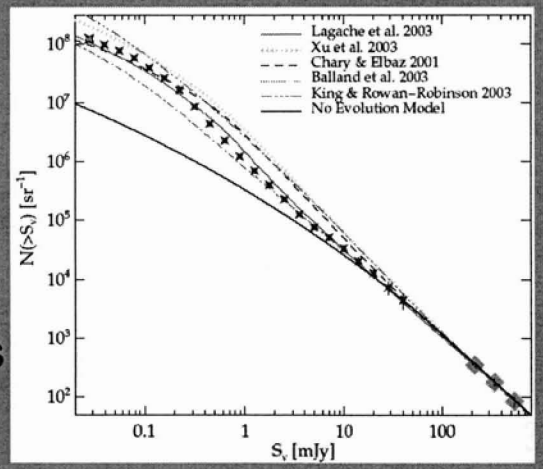
Spitzer MIPS 24 μm
Lockman Hole
Egami et al. (2004)

MAMBO / IRAM 30 m
1.3 mm 60 hours, 40 sources

Bertoldi et al. (2000);
Carilli et al. (2001c, 2002b);
Dannerbauer et al. (2002);
Voss (2002);
Eales et al. (2002)

Spitzer MIPS
Chandra Deep Field South
70 (23%) 160 (7%)

Dole et al. (2004)



MIPS 24 μm counts
Bulk of background
Papovich et al. 2004

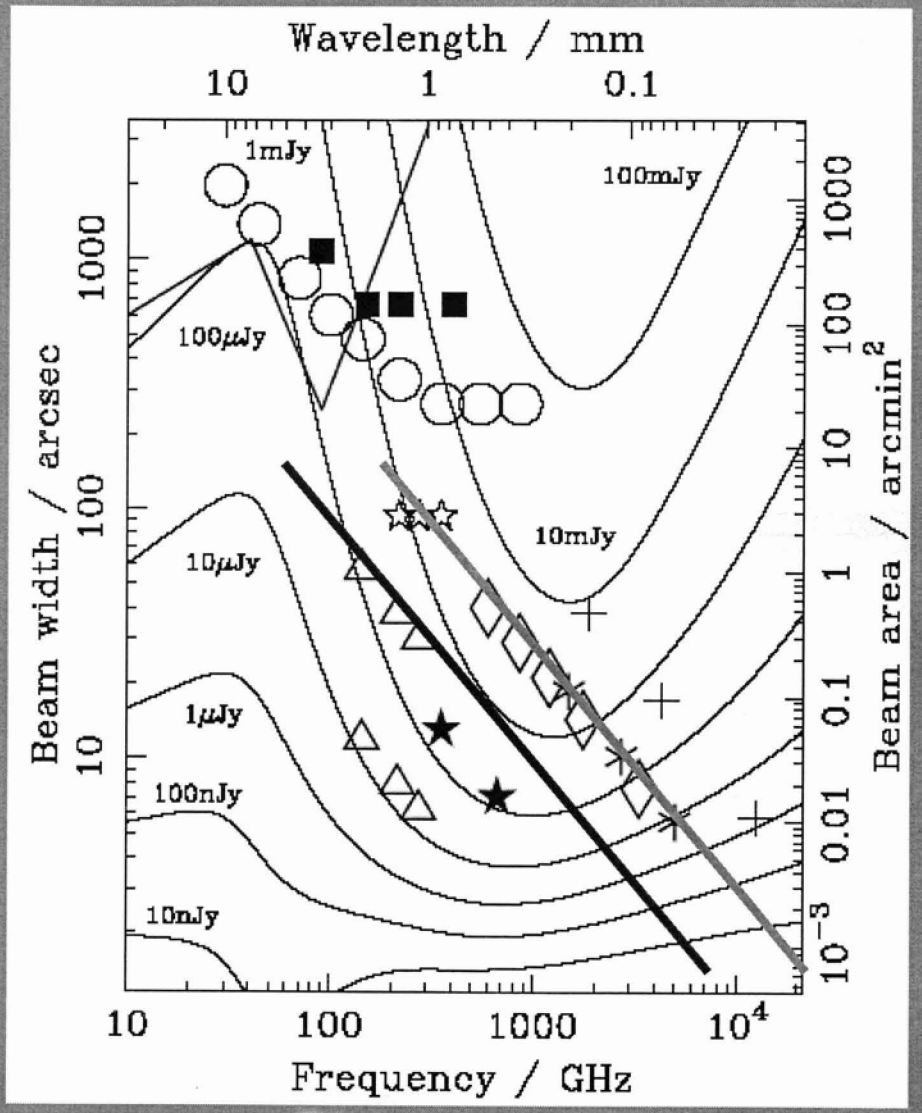
Larger telescopes will resolve the bulk of the background

TABLE 3
POTENTIAL RESOLUTION OF THE COSMIC INFRARED BACKGROUND

	24 μm[a]	70 μm[a]	160 μm[a]
Spitzer	74%	59%	18%
Herschel[b]/SPICA	98%	93%	58%
JWST[b]	99%	–	–
SAFIR	100%	99%	94%

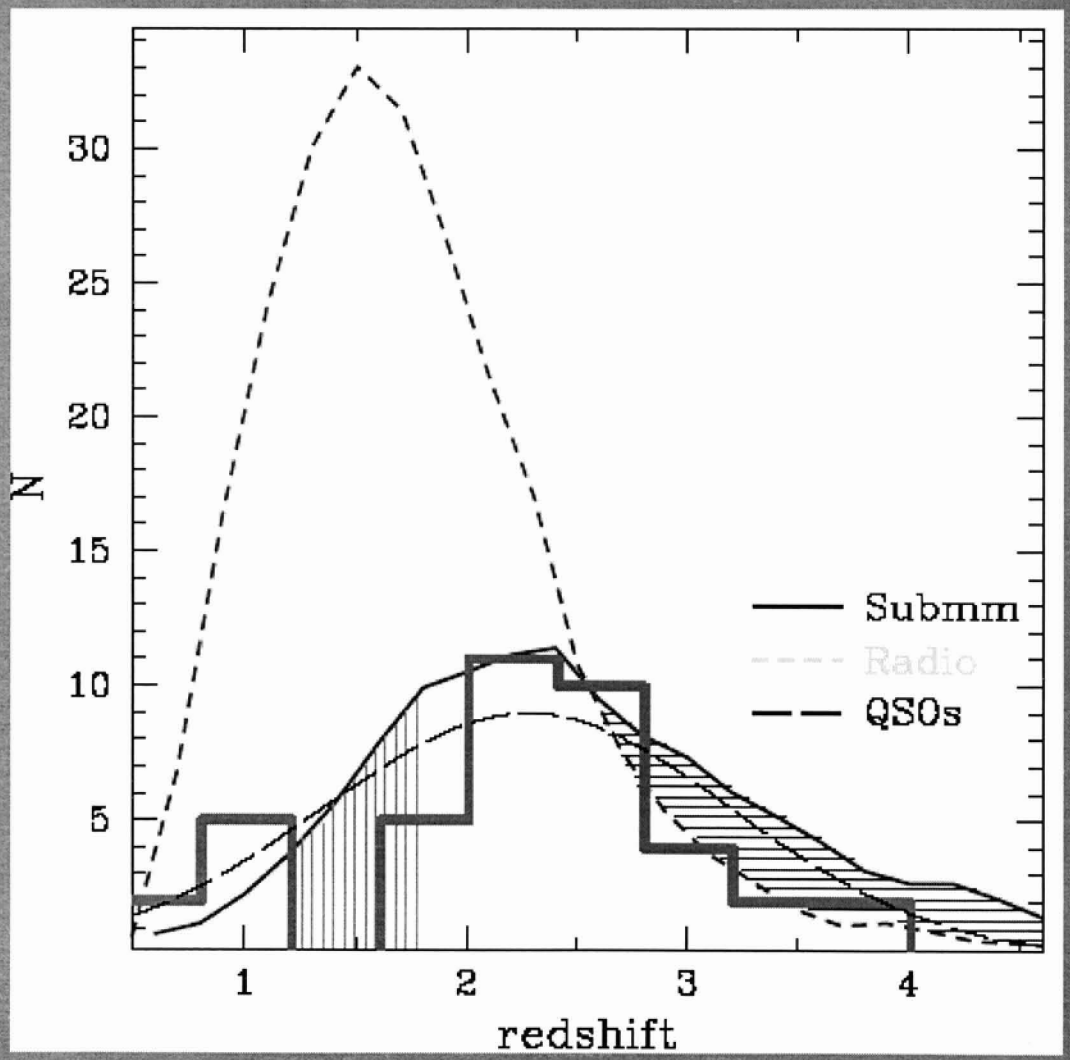
NOTE. — (a) Using the CIB value from Lagache et al. (2004) and using the limiting flux using the SDC limit and assuming confusion-limited surveys. (b) This hypothesis might not be valid for Herschel and JWST.

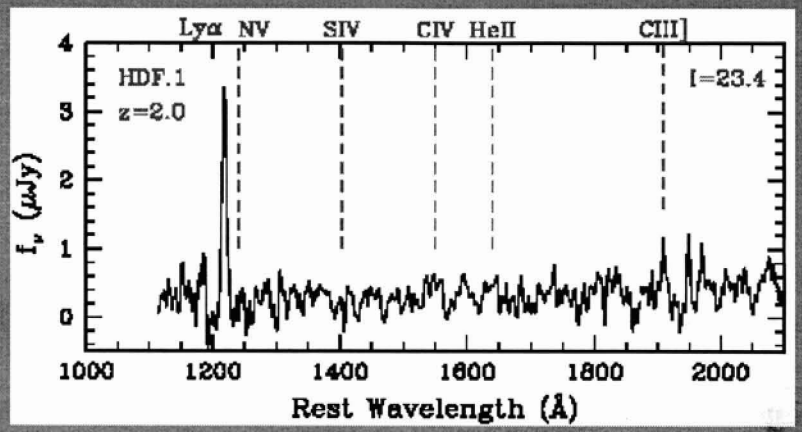
Dole et al. (2004)

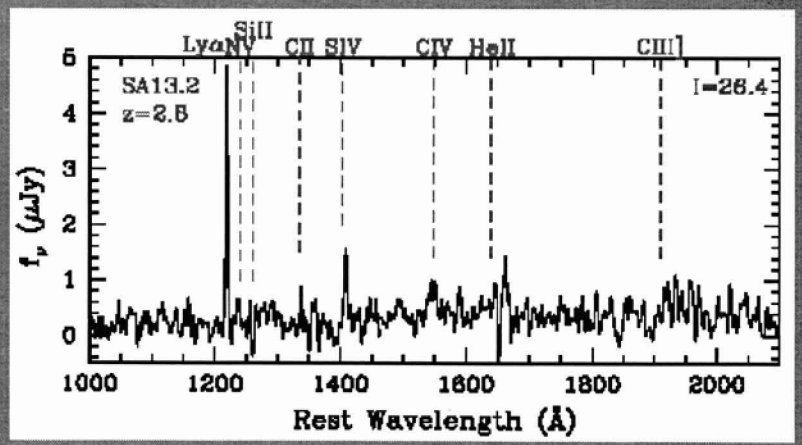


Blain et al. (2002)

Submillimeter-radio selected sources are luminous galaxies at 1<z<4

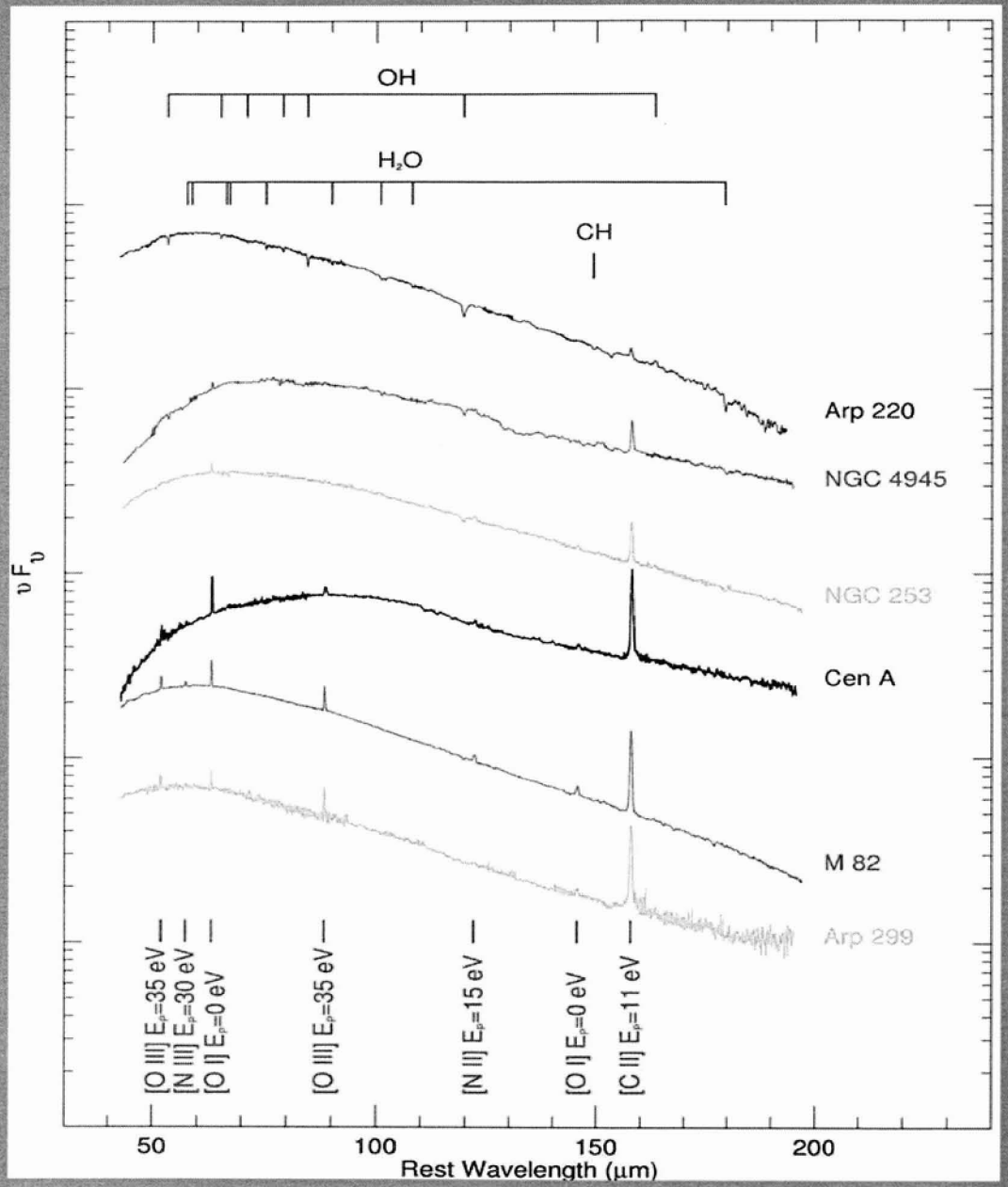






Chapman et al. (2003)

Spectral Features for λ_{rest} = 10 – 500 μm



- Suite of lines provides redshift template independent of optical follow-up.
- Fine structure lines probe ionized and neutral atomic gas.
  - → HII region densities
  - → Atomic gas pressures
  - → UV field strength and hardness
  - → Starburst / AGN discriminator
  - → Stellar mass function
- Rotational transitions cool molecular gas.
  - → Measures temperature, density and total mass.
- Lowest H_2 rotational lines cool primordial gas forming first stars.
  - → 12-28 mm at z ~ 10-50

J. Fischer et al.1999

Reminder: Dense ISM mass budget

More than 99% is gas

ionized	~10%
neutral atomic	~50%
UV-illuminated molecular	~10%
UV-shielded molecular	~50%

Top 3 are the interesting phases, not traced with mm-wave probes.

and mid to far-IR is the only way to overcome extinction.

High frequency spectral lines probe the interaction between stars / AGN and ISM

Table 2. Far-Infrared Spectral Features

Species	Wavelength [μm]	f (M82)	f (Arp220)	Diagnostic Utility
		Ionized Gas Fine Structure Lines		
O IV	25.9, 54.9			Primarily AGN
S IV	10.5	2.1 (-5)		
Ne II	12.3	1.2 (-3)	7.5 (-5)	Probes gas density and
Ne III	15.6, 36.0	2.05 (-4)		UV field hardness in
S III	18.7, 33.5	1.0 (-3)	7.3 (-5)	star formation HII
Ar III	21.83	9.1 (-6)		regions.
O III	51.8, 88.4	1.3 (-3)		
N III	57.3	4.2 (-4)		
N II	122, 205	2.1 (-4)		Diffuse HII regions
		Neutral Gas Fine Structure Lines		
Si II	34.8	1.1 (-3)	7.7 (-5)	Density and temperature probes
O I	63.1, 145	2.2 (-3)	6.8 (-5) (abs)	of photodissociated-neutral
C II	158	1.6 (-3)	1.3 (-4)	gas interface between HII
C I	370	6.2 (-6)	1.2 (-5)	regions and molecular clouds.
		Molecular Lines		
H_2	9.66, 12.3, 17.0, 28.2	2 (-5)	3 (-5)	Coolants of first collapse
CH	149		4 (-5)	Ground state absorbtion:
OH	34.6, 53.3, 79.1, 119	2 (-6)	2 (-4) (abs)	gives column and abundance.
OH	98.7, 163		5 (-5)	Emission: gas coolants, constrain
H_2O	73.5, 90, 101, 107, 180		5 (-5)	temperature, density of warm
CO	325, 372, 434, 520	3 (-6)	1 (-5)	(50K < T < 500 K) mol. gas

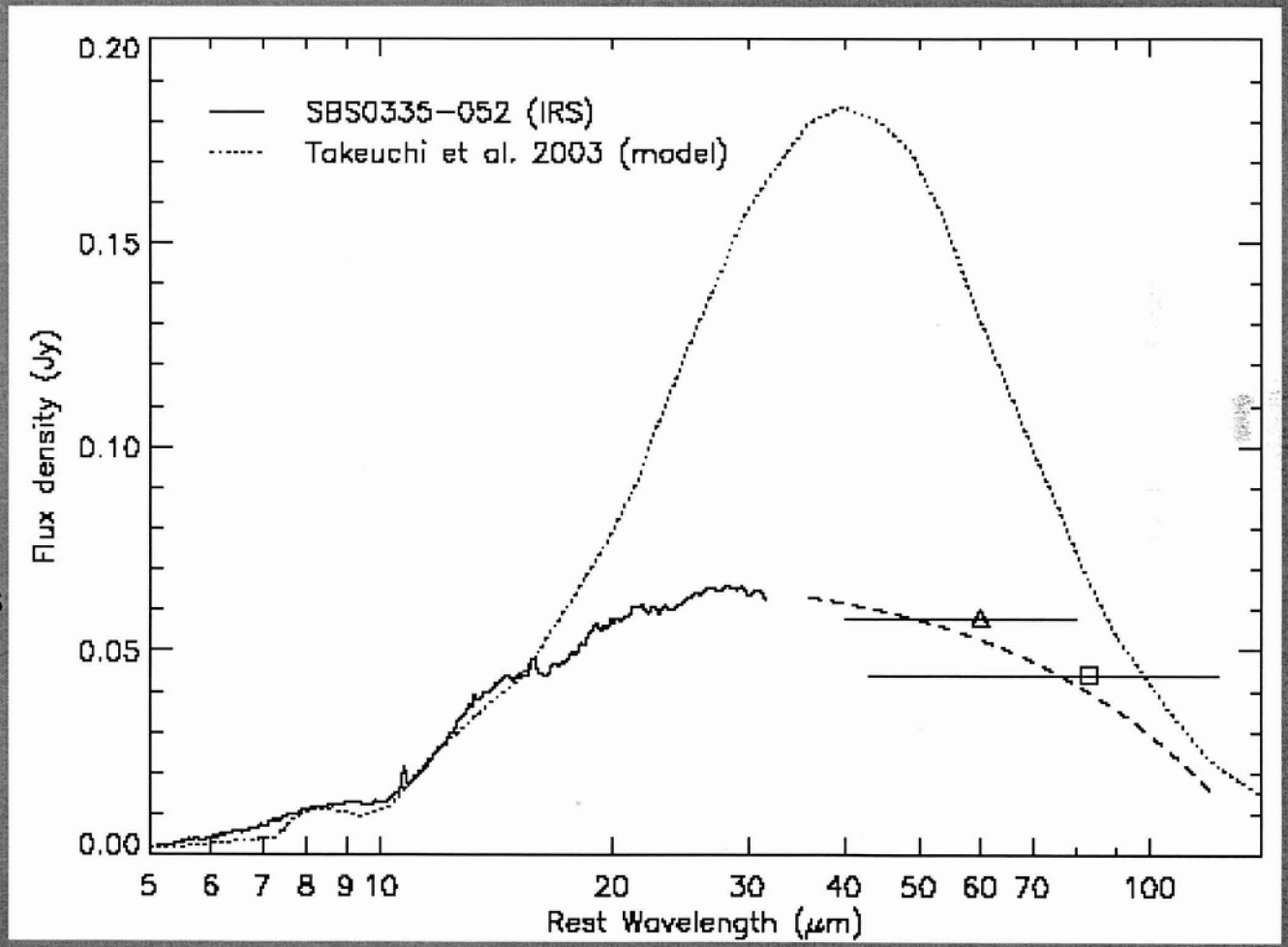
Note: f(M82) and f(Arp220) are the fraction of the total IR luminosity that emerges in each line. Observations are from ISO (C99, G98, FS01, F99)

Even low-metallicity starbursts emit most of their flux in the IR

In this case, the mid-IR--> 20 microns.

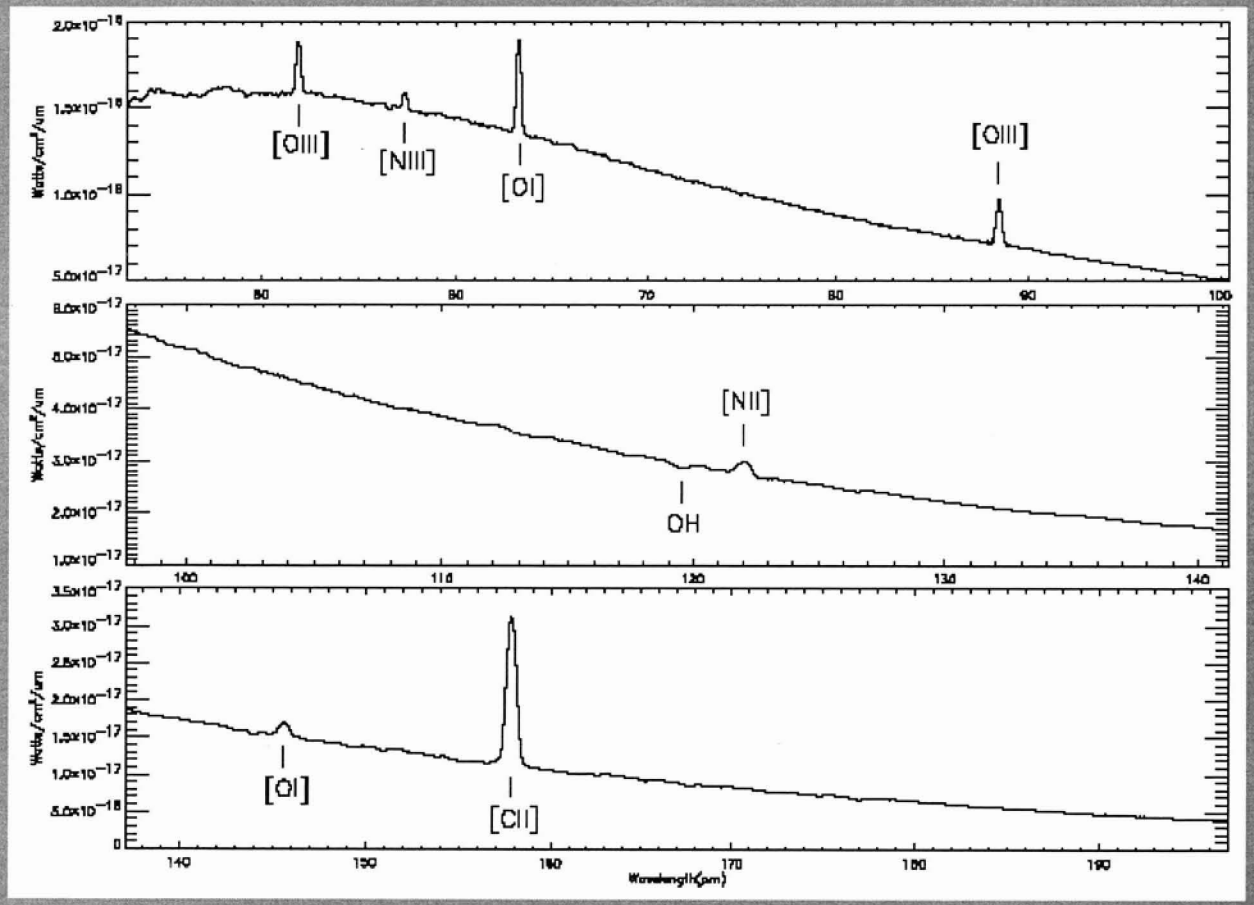
SBS0335-052
Optical $Z/Z_o \sim 1/41$

SiIV, NeIII fine structure lines imply:
-> $T_{eff} > 40{,}000$ K
-> Ne, S abundance higher than $Z_o/41$
IR-emitting region polluted by WR winds, SN remnants



Houck et al. 2004

M82: An extragalactic case study for far-IR spectroscopy



Colbert, Malkan et al. 1998

ISO LWS Grating Spectum:

7 fine structure lines

HII regions:
$n_e \sim 250\ cm^{-3}$

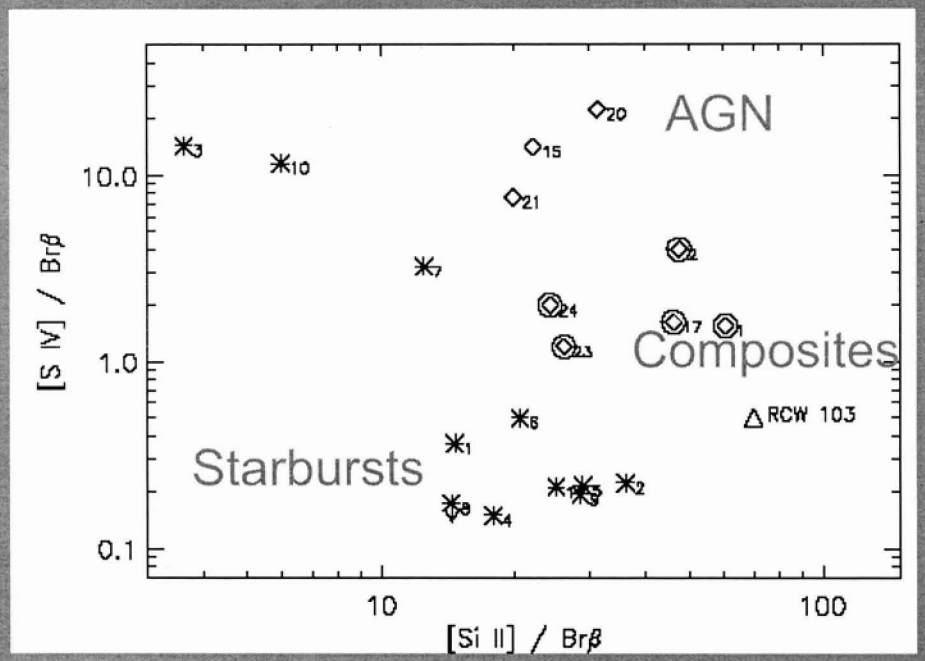
PDRs:
$n \sim 10^{3.3}$,
$G0 \sim 10^{2.8}$

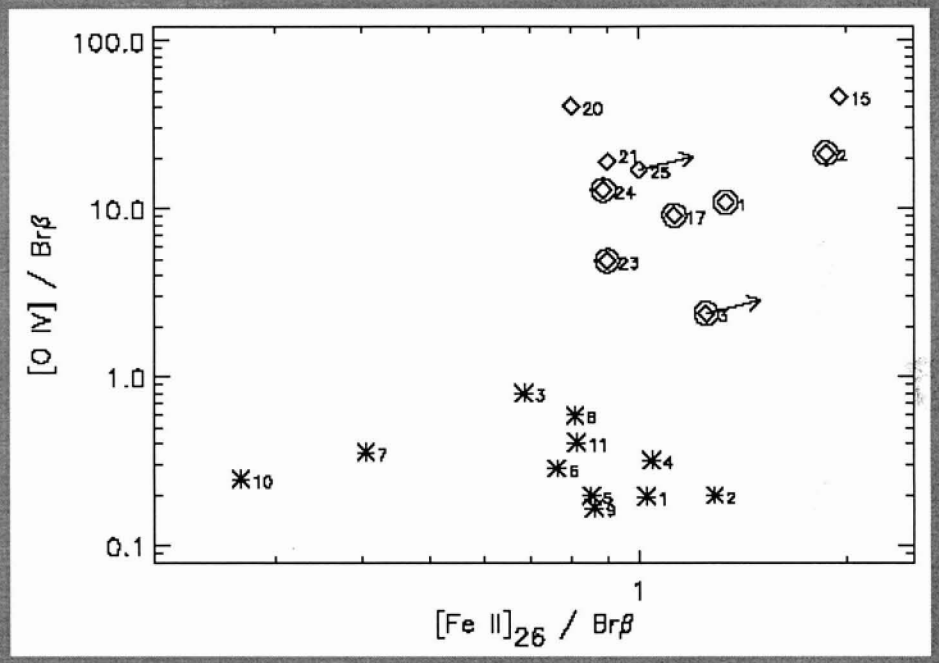
CII from PDRs (75%)
and HII regions (25%)

Model: 3-5 Myr starburst with 100 $M_\odot$ cutoff

Starburst mass ~0.5-1.3x10^8 $M_\odot$
≈ 1/2 the total gas mass

Line ratios rapidly distinguish starburst from AGN luminosity source





Sturm et al. 2002 -- ISO SWS data

see also Malkan et al poster-- far-IR (LWS) diagnostic diagrams

Far-IR / submm Molecular Gas Probes

•Mid- and high-J lines of CO are required to accurately constrain molecular gas mass, temperature, and luminosity.

•A host of small molecules have their fundamental rotational transitions in the far-IR.

$\nu_0 \sim 1$ / (Moment of Inertia)

OH

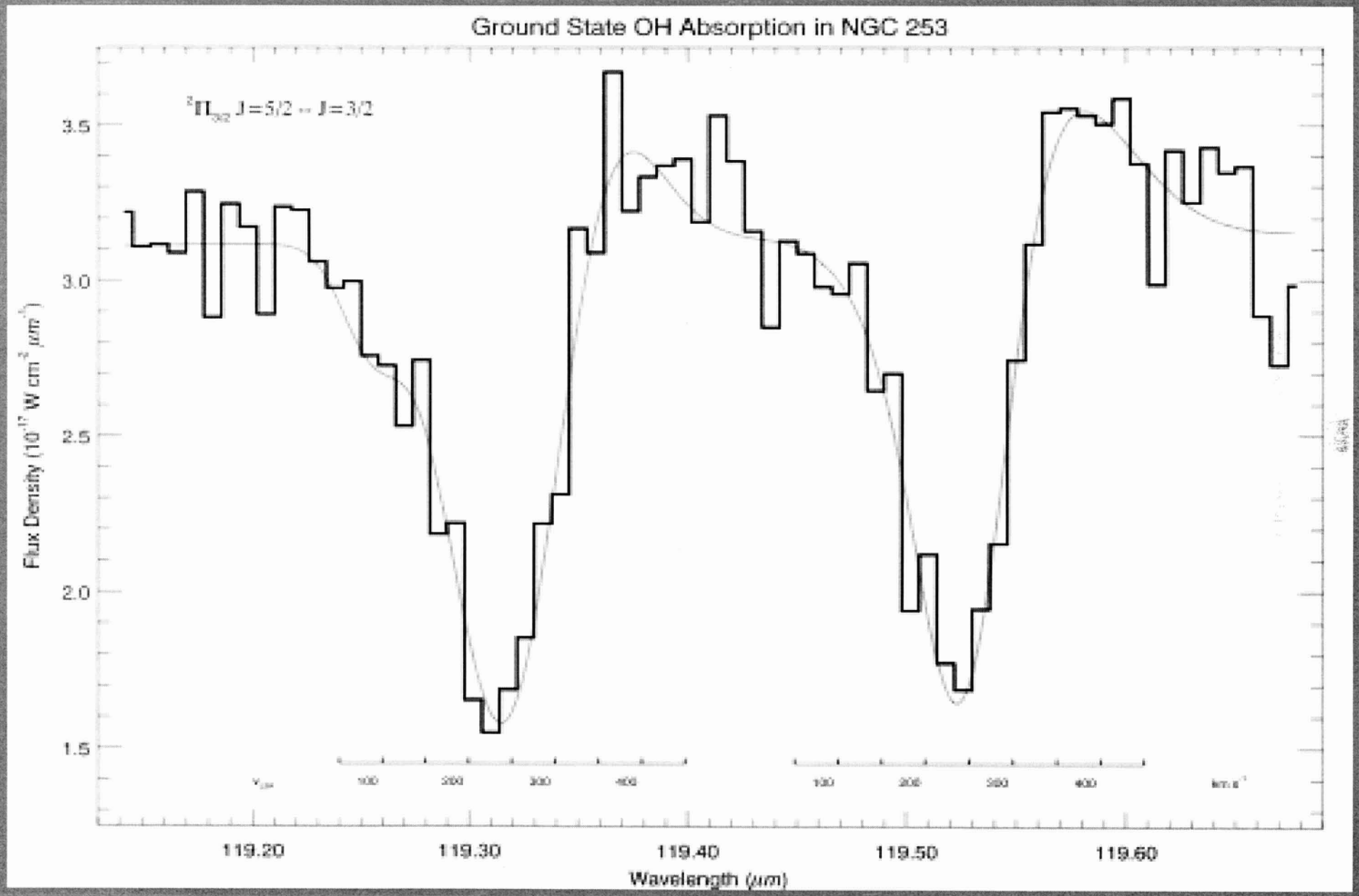
CH

HD

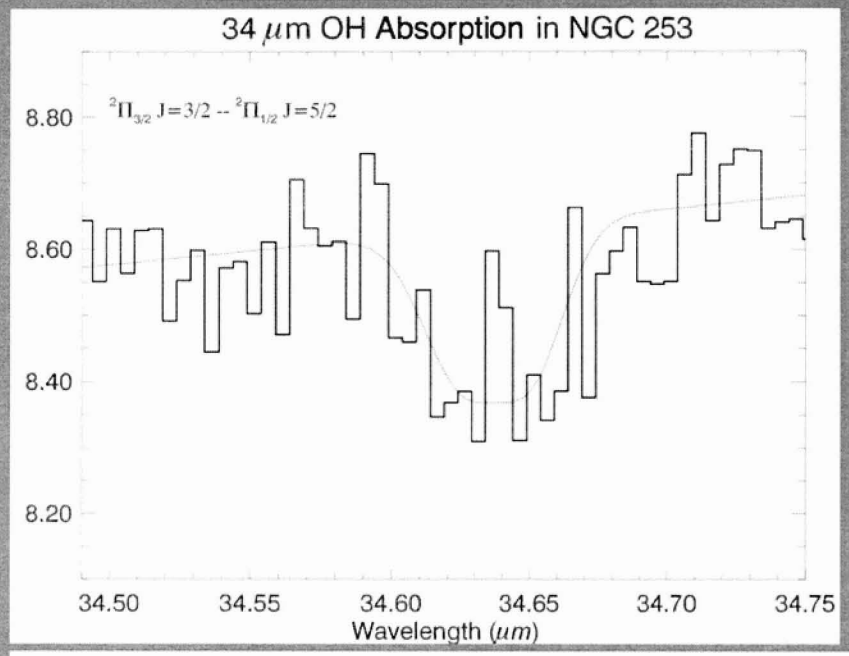
•Bright far-IR continuum can give absorption --> direct column density measure.

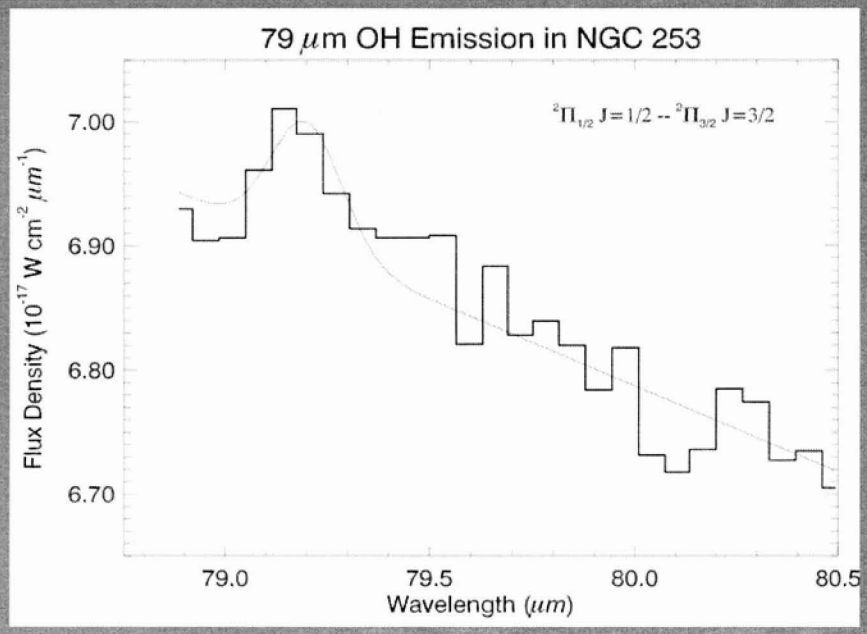
•Pumps Masers

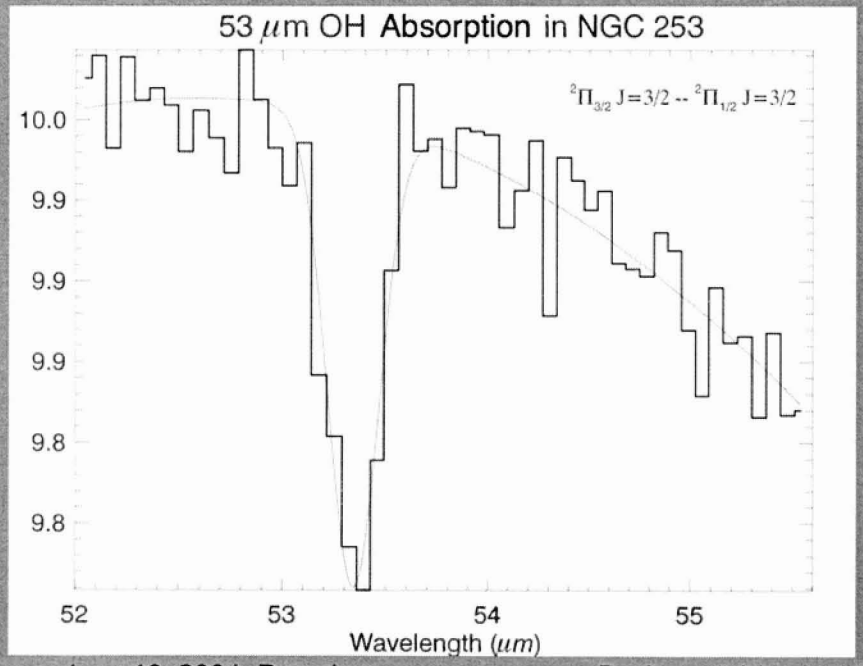
Example of far-IR galaxy-scale molecular probes: OH in NGC 253

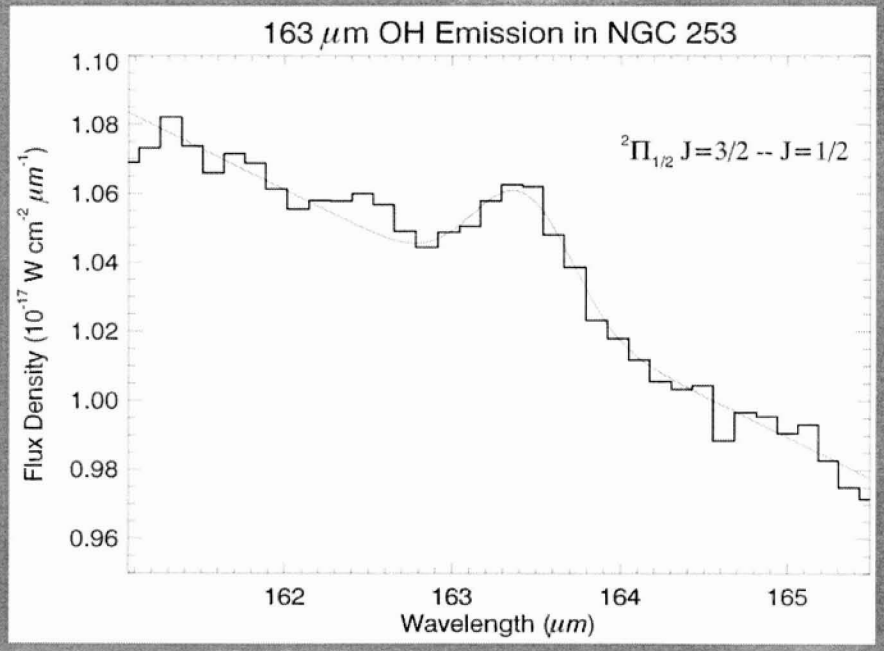


Example of far-IR galaxy-scale molecular probes: OH in NGC 253

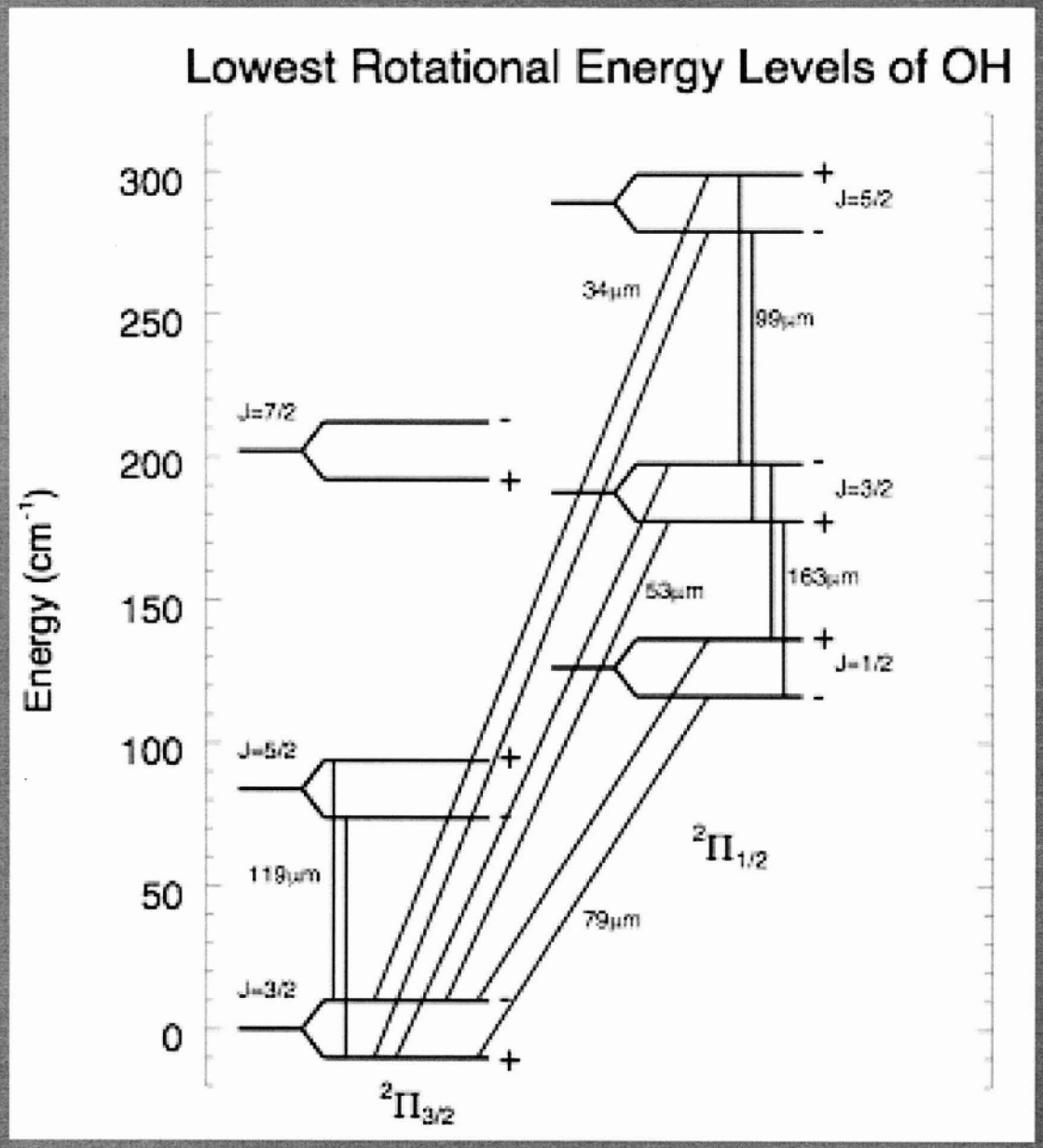








Example of far-IR galaxy-scale molecular probes: OH in NGC 253



OH -- radiative rates are very fast, transitions not thermalized -- must account for radiative cascade.

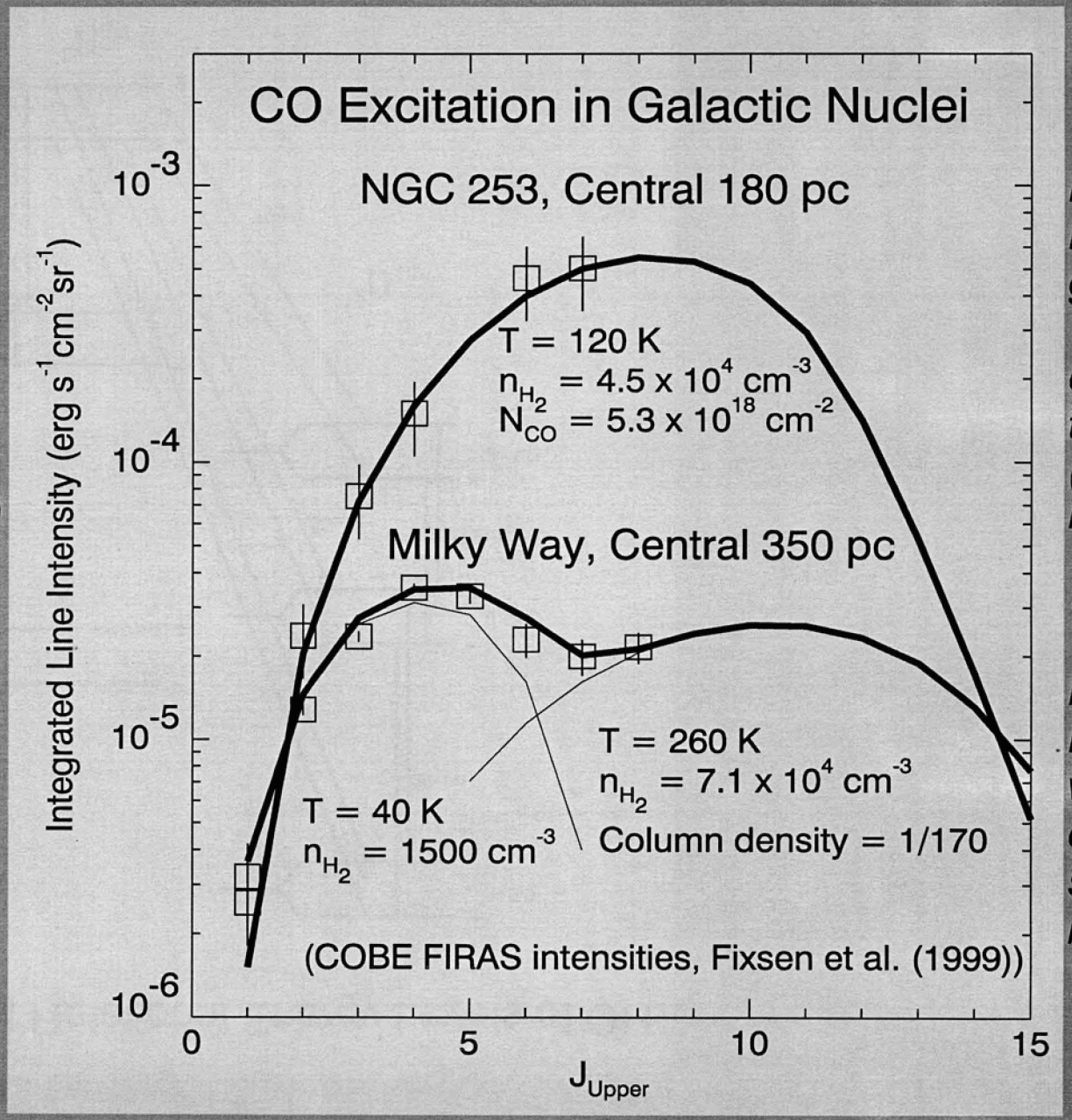
34 μm --> $\tau \sim 0.5$
53 μm --> $\tau \sim 0.12$
119 μm --> $\tau \sim 16$

Modeling with multiple transitions -> $N_{OH} = 1.0e17\ cm^{-2}$
$X_{OH} = 1.4e-7$

Bradford et al. 1999

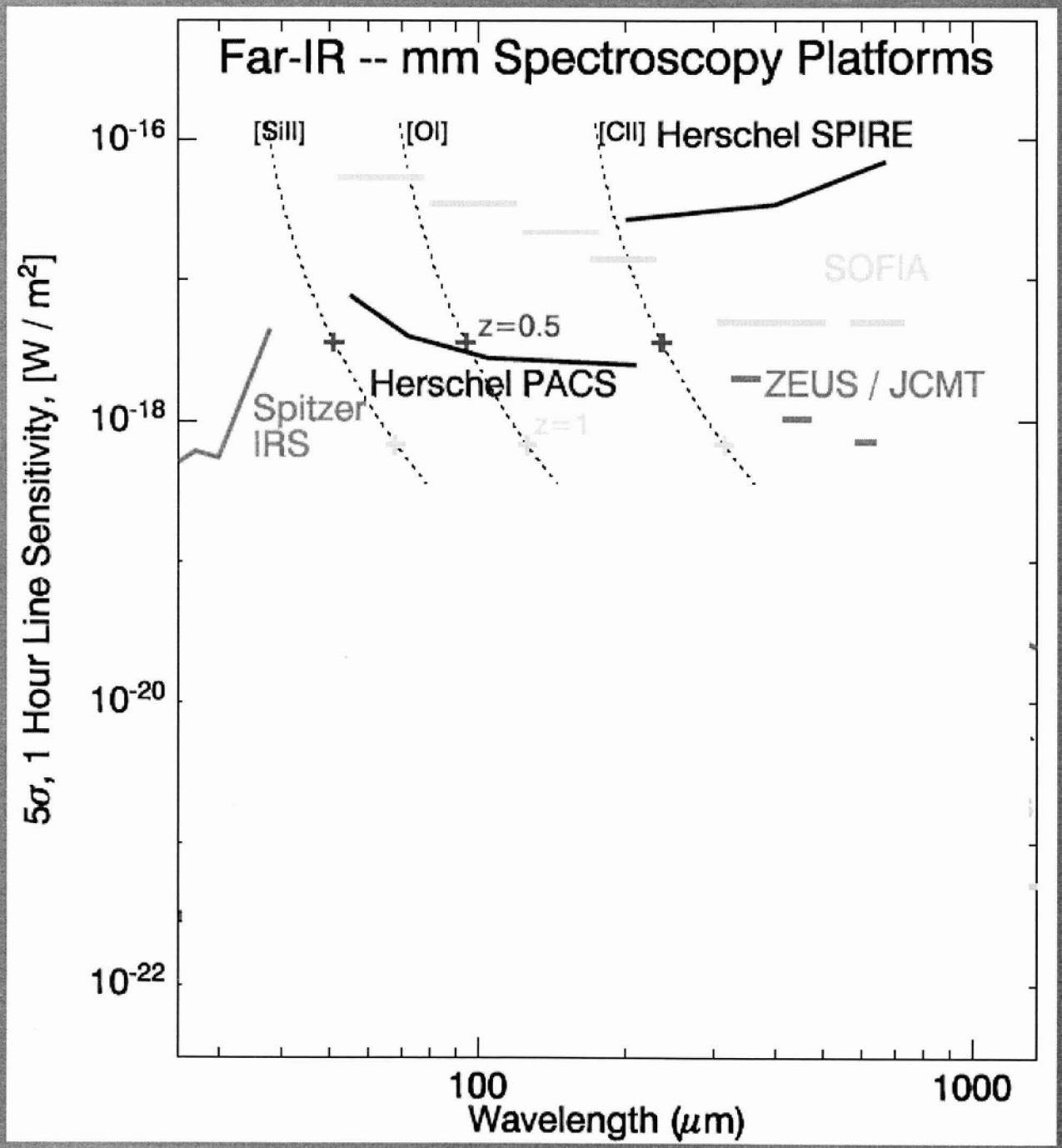
High-J CO lines: Astrophysics of the molecular gas

- LVG modeling: intensities → physical conditions
- Mid-J lines (J>4) distinguish low excitation from high excitation gas



NGC 253: Bulk of molecular gas heated to T>100 K by cosmic rays, turbulence (SPIFI – JCMT)
Bradford et al '03

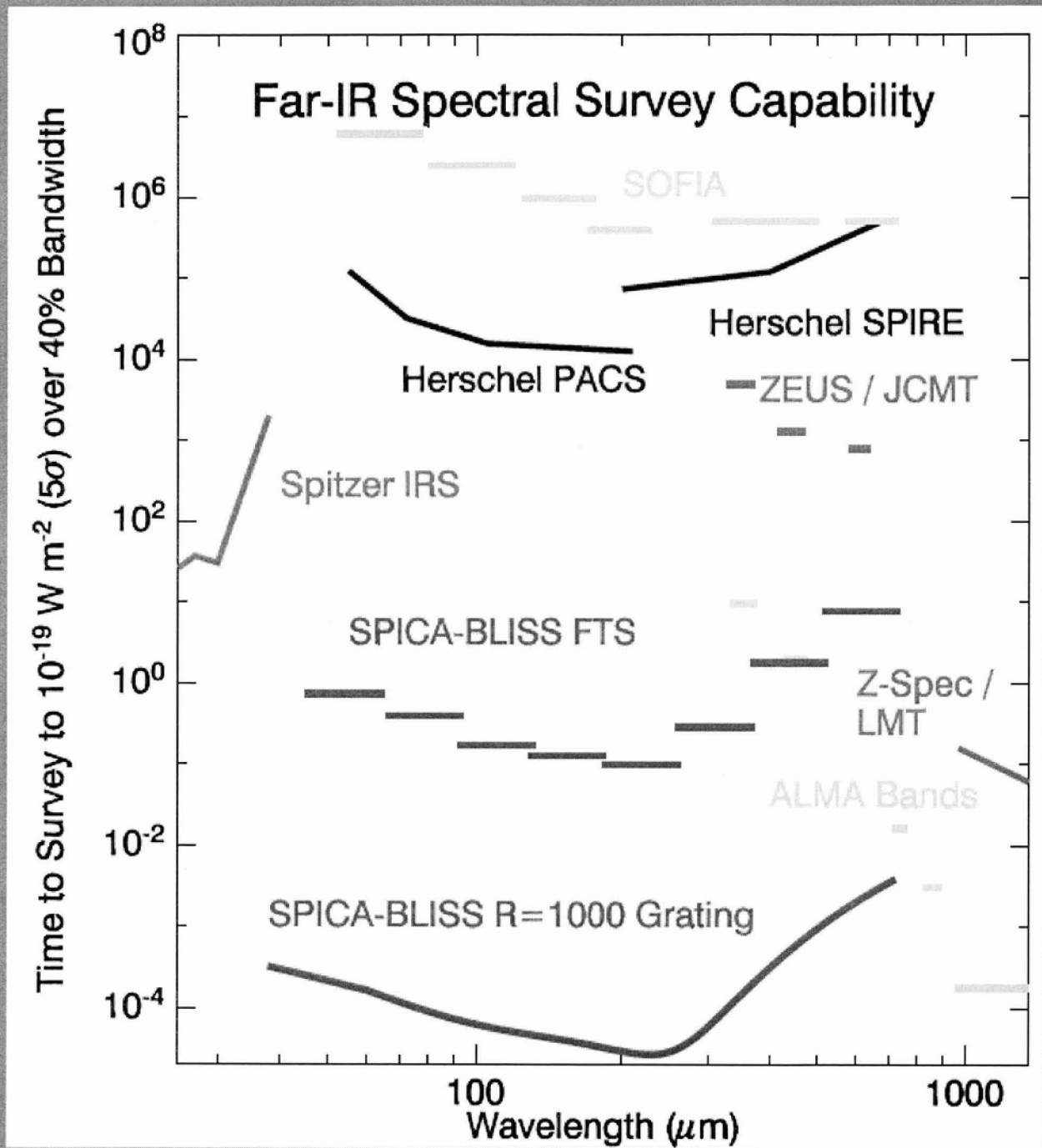
Milky Way: Mostly cool gas with small warm component from star formation regions, CND



Huge advances are still possible in the far-IR with a cold space telescope.

Herschel, SOFIA and ground based platforms are are limited by emission from warm telescopes.

Ultimate limitation is photon noise from the astrophysical backgrounds.



Capability increase for broadband line surveys is even greater...

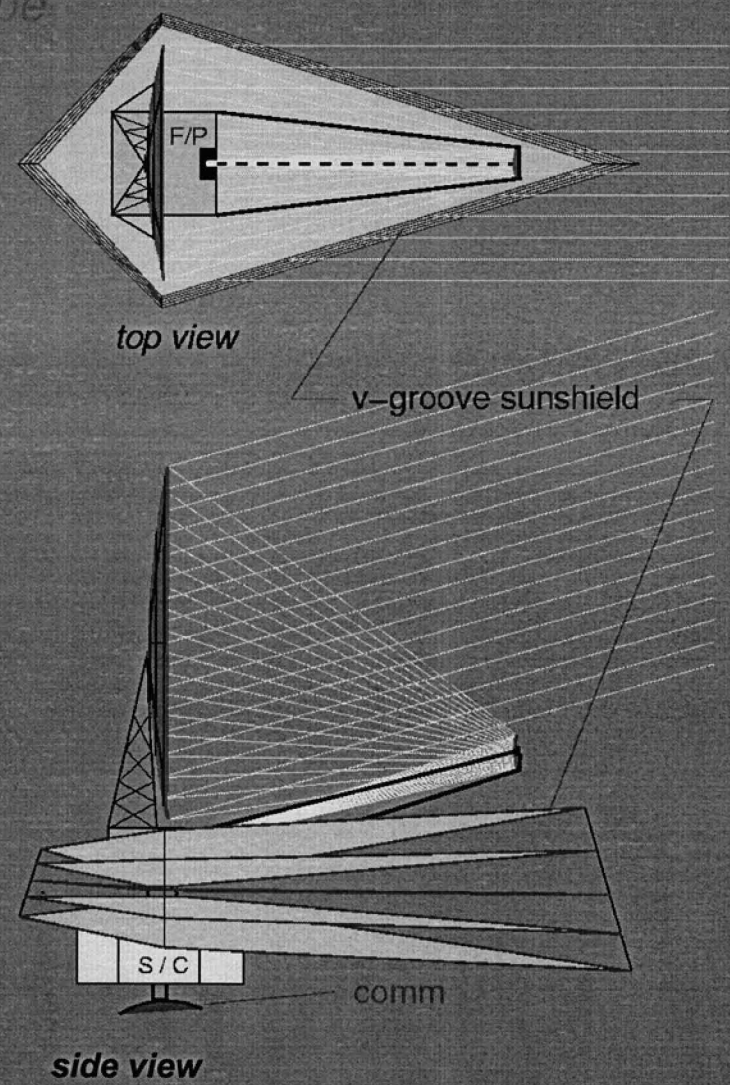
Most existing spectrometers are not well-suited to a large instantaneous bandwidth -- incur a time (sensitivity) penalty in obtaining a complete spectrum.

Note: Spitzer IRS is notable exception.

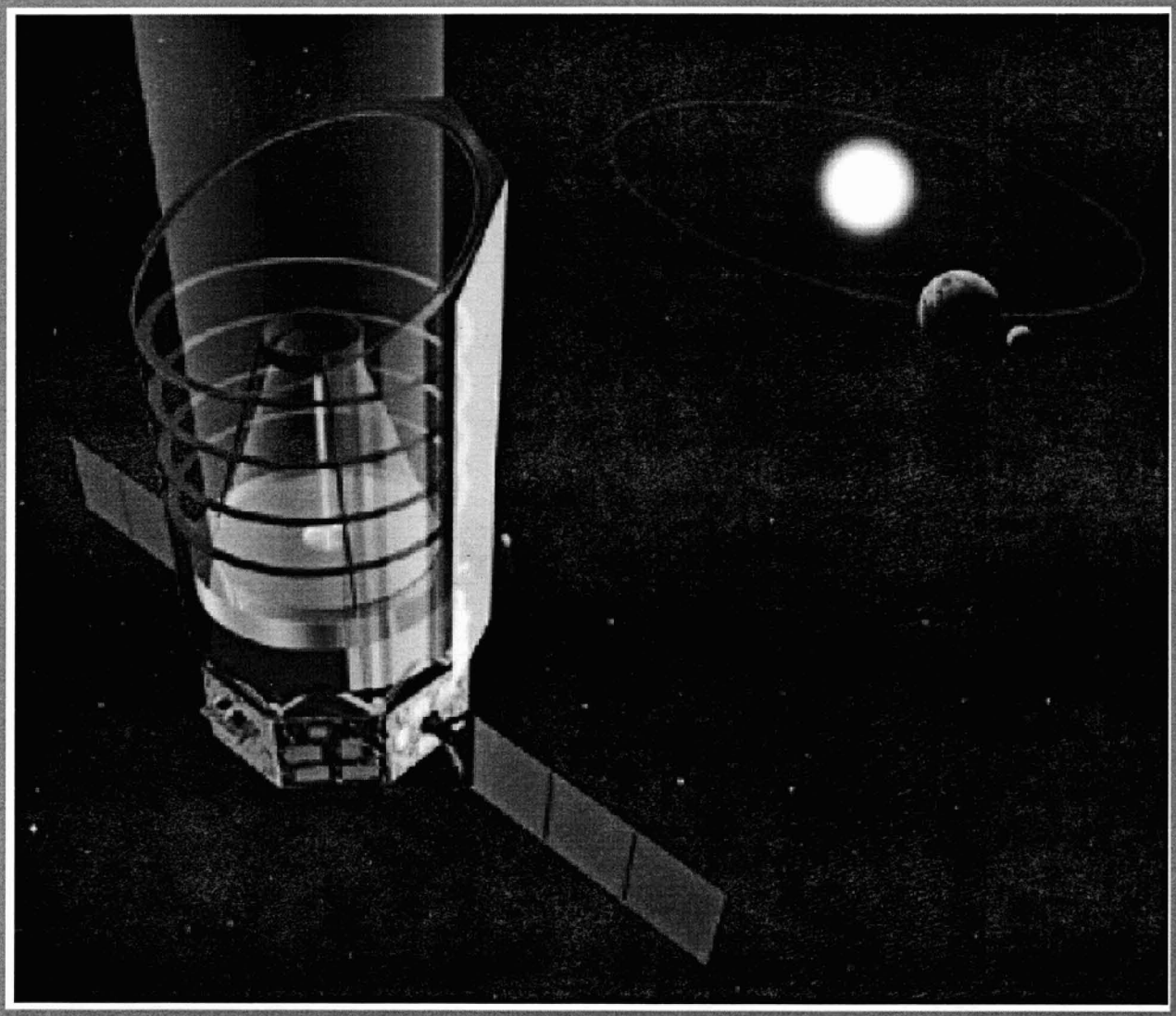
Platforms for BLISS: CALISTO

Cryogenic Aperture Large IR Space Telescope
an Origins Probe concept -- PI Hal Yorke (JPL)

- **Telescope** – 4 x 6 m primary, deployable secondary
  - Diffraction limited @ 40 μm
  - Off-axis design
- **Instrument** – Bridge wavelength gap between JWST and ALMA
  - Imaging photometry
  - Spectrograph
    - 20 – 300 μm @ R~3000
- Delta II **launch**
- Earth-Sun L2 halo **orbit**
  - Similar to Herschel, Planck, JWST
  - Stable thermal orbit; Sun/Earth side fixed
- Mission **lifetime**
  - Limited by component lifetime (cryocoolers, gyros)
  - 3 year baseline, possible extended mission



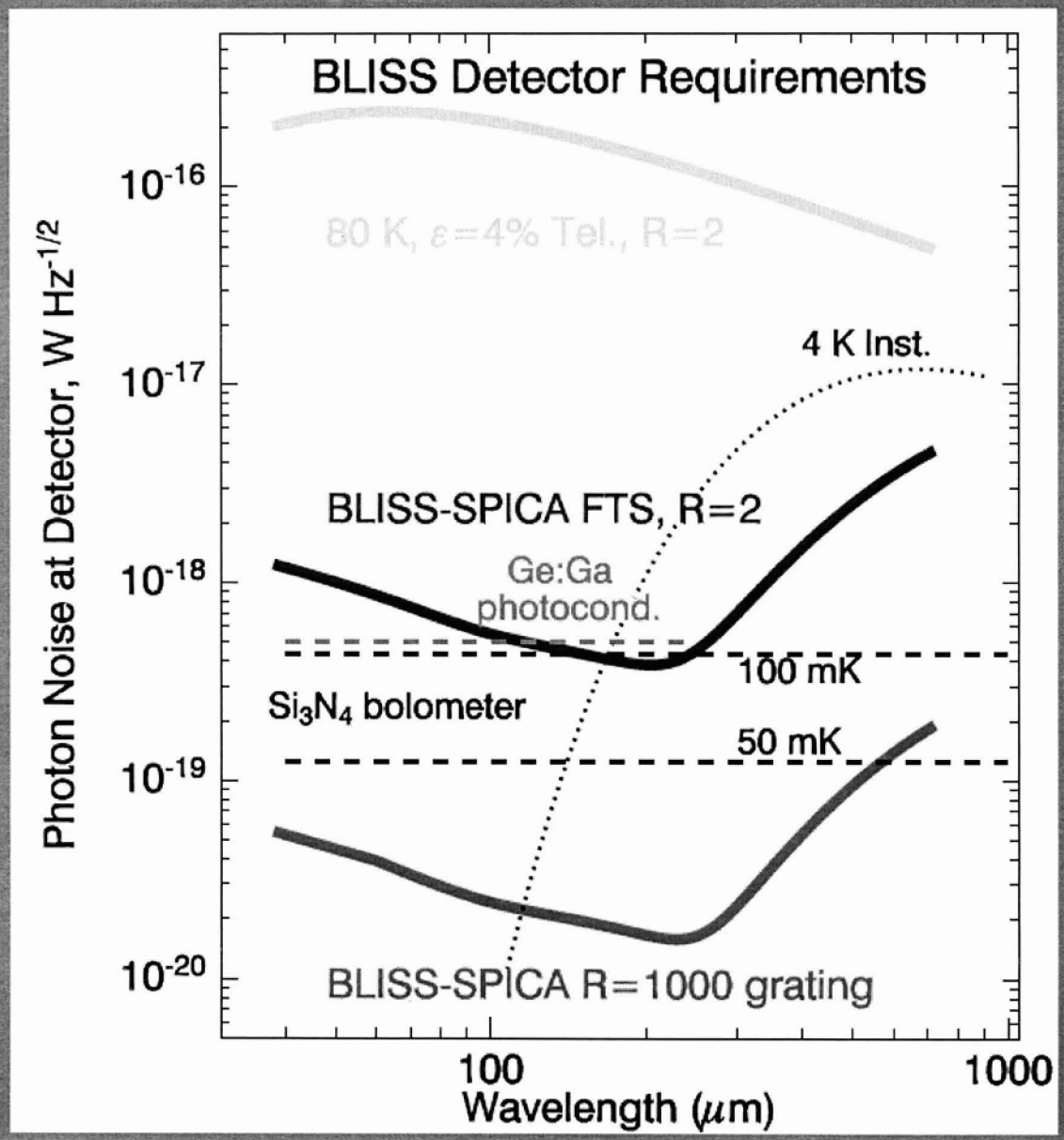
Platforms for BLISS: SPICA



Space Infrared Telescope for Cosmology and Astrophysics; T. Nakagawa PI

- **Size:** 3.5 m
- **Temperature:** 4.5 K
- **Cryogenics:** Stirling + J-T closed cycle
- **Facility heat lift at 1.7 K:** 10 mW
- **Orbit:** L2
- **Lifetime:** 5 years +
- **Launch:** ~2012

BLISS Detector Requirements

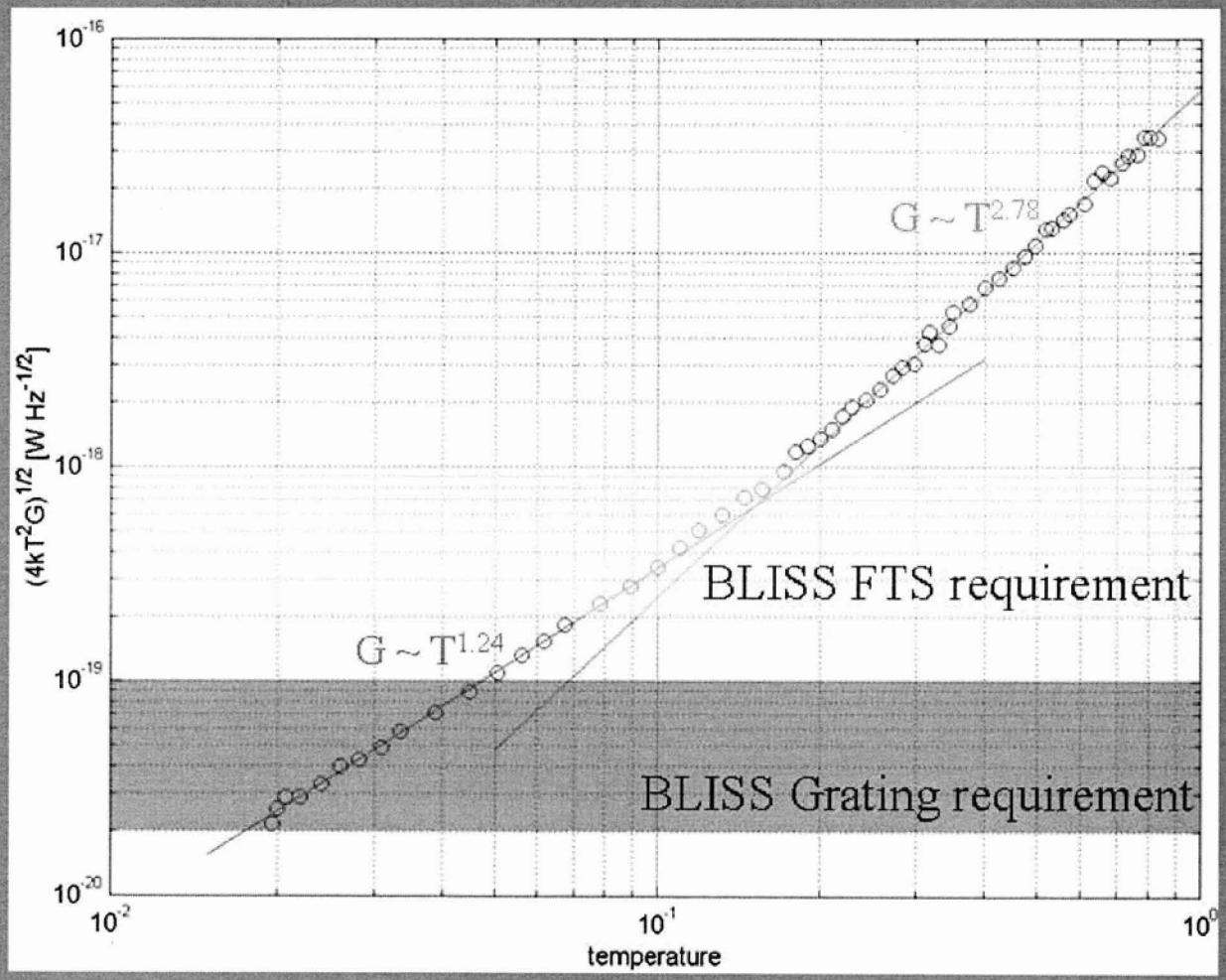


R=1000 is more challenging than any far-IR experiment thus far, no currently available devices for R=1000 spectroscopy.

BUT FTS background a good match to existing devices.

NB: Background from inside even 4 K instrument can become important.

Progress with SiN-suspended devices



Peter Day, JPL

Bolometers limited by shot noise in phonon transport:

NEP ~ $(4kT^2G)^{1/2}$

Measure G (T), can infer NEP.

3×10^{-20} at 30 mK

BLISS Architecture

Optimum sensitivity, large instantaneous band, reliability more important than spatial mapping, high spectral resolution

- **Grating spectrometer is the best choice**
  - 1st order → octave of instantaneous bandwidth
  - Good efficiency
- Fabry-Perot requires scanning for full spectral coverage
  - Scanning time prohibits spectral searching
- Fourier transform spectrometer (FTS) couples the full band to a single detector
  - Sensitivity penaltyrelative to monochromater for perfect detectors
  - Naturally accommodates 2-D spatial mapping
  - Flexible observing modes
  - **Best option for detector-noise limited operation**
- Heterodyne receivers subject to quantum noise
  - $NEP_{QN} \sim h\nu\,[\delta\nu]^{1/2}$ vs. $NEP_{BG} \sim h\nu\,[n\,(n+1)\,\delta\nu]^{1/2}$
  - Also offer small bandwidth:
    - 10 GHz backend at 1 THz gives $\nu / \Delta\nu \sim 100$

Imaging Fourier-Transform BLISS

Have flight heritage with Herschel SPIRE (Swinyard, Griffin)

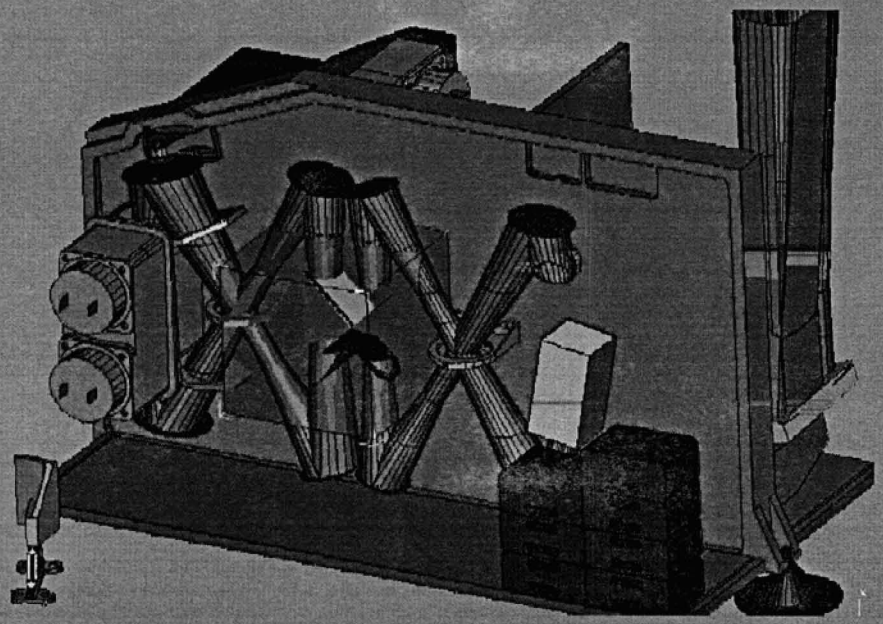
many problems solved

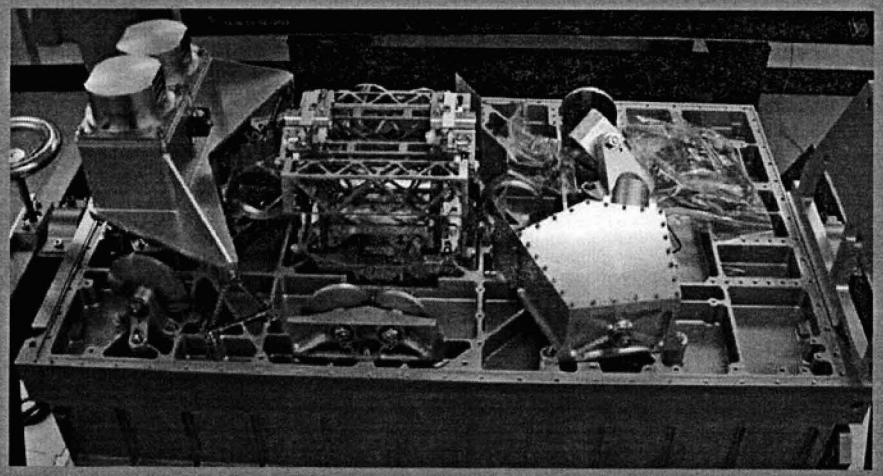
--> broadband beam splitter

Instrument backgrounds must be lower --> optics colder

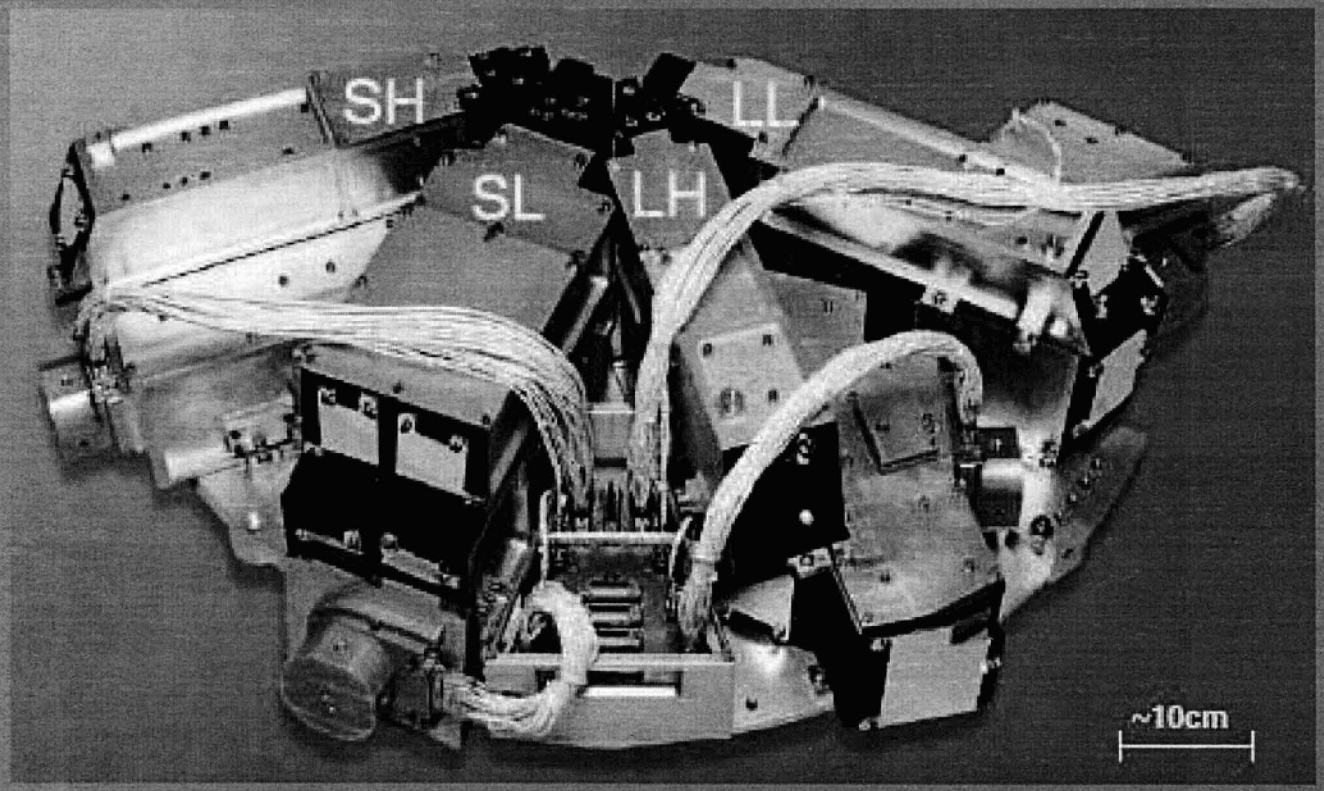
Detector NEP are achievable with today's devices

Could start construction on a sensitive far-IR FTS today!





Broadband Grating Spectrometers



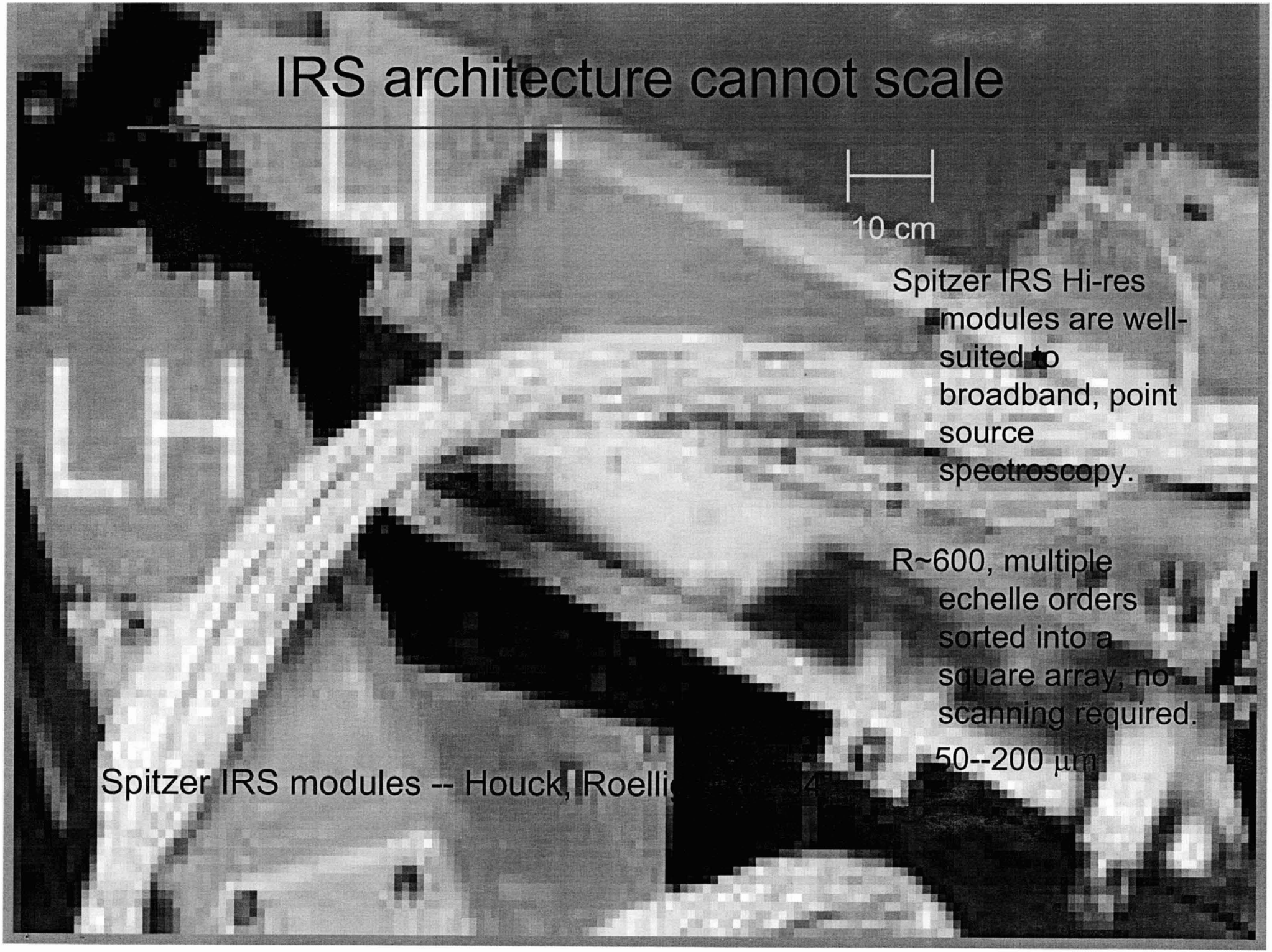
Spitzer IRS modules -- Houck, Roellig et al. 04

Spitzer IRS Hi-res modules are well-suited to broadband, point source spectroscopy.

R~600, multiple echelle orders sorted into a square array, no scanning required.

10--40 μm

IRS architecture cannot scale



Spitzer IRS Hi-res modules are well-suited to broadband, point source spectroscopy.

R~600, multiple echelle orders sorted into a square array, no scanning required.

50--200 μm

Spitzer IRS modules -- Houck, Roelli

Instrument size an issue for long λ grating systems

Conventional broadband grating systems are huge when scaled to λ~100 μm

SIRTF IRS Long-Hi module:
40 x 15 x 20 cm for R=600 at 37 μm.
→For 200 μm, this module would be over 2 meters in size

→Much larger than required by fundamental limit: L ~ R x λ.

SIRTF IRS long-high module--Roellig et al. 1999

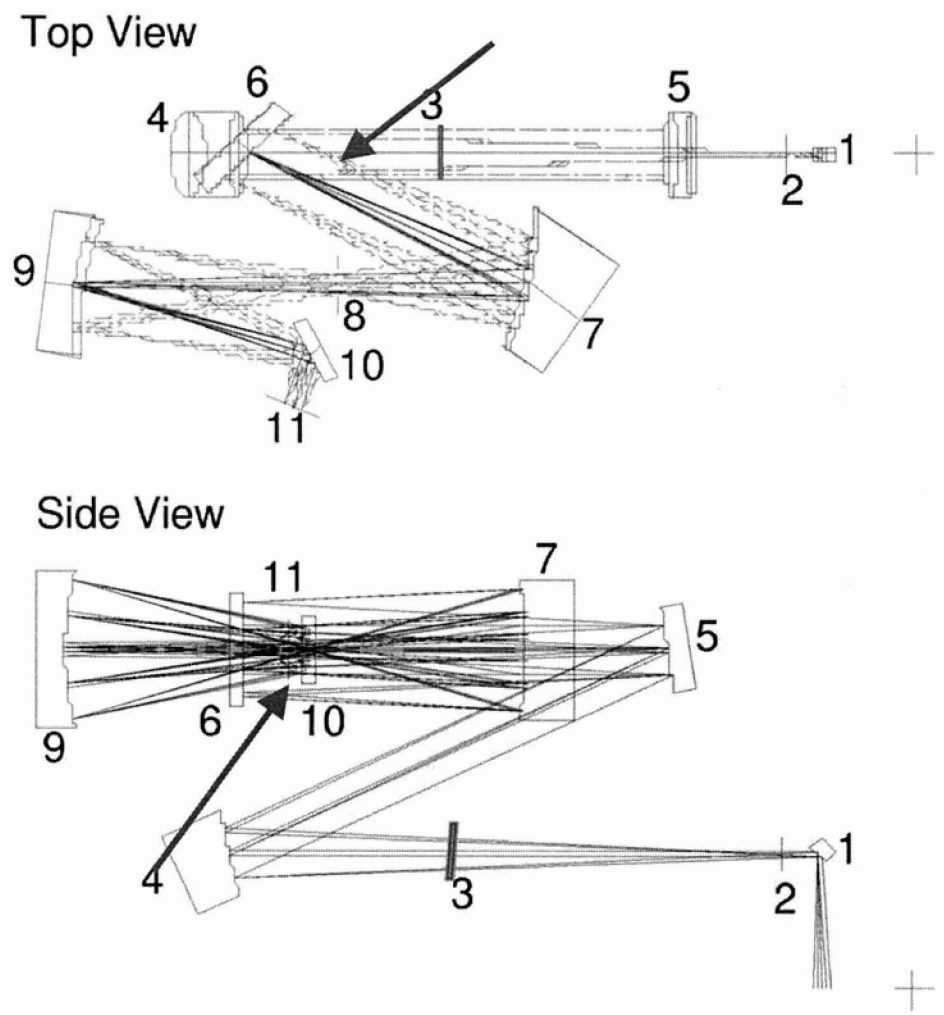
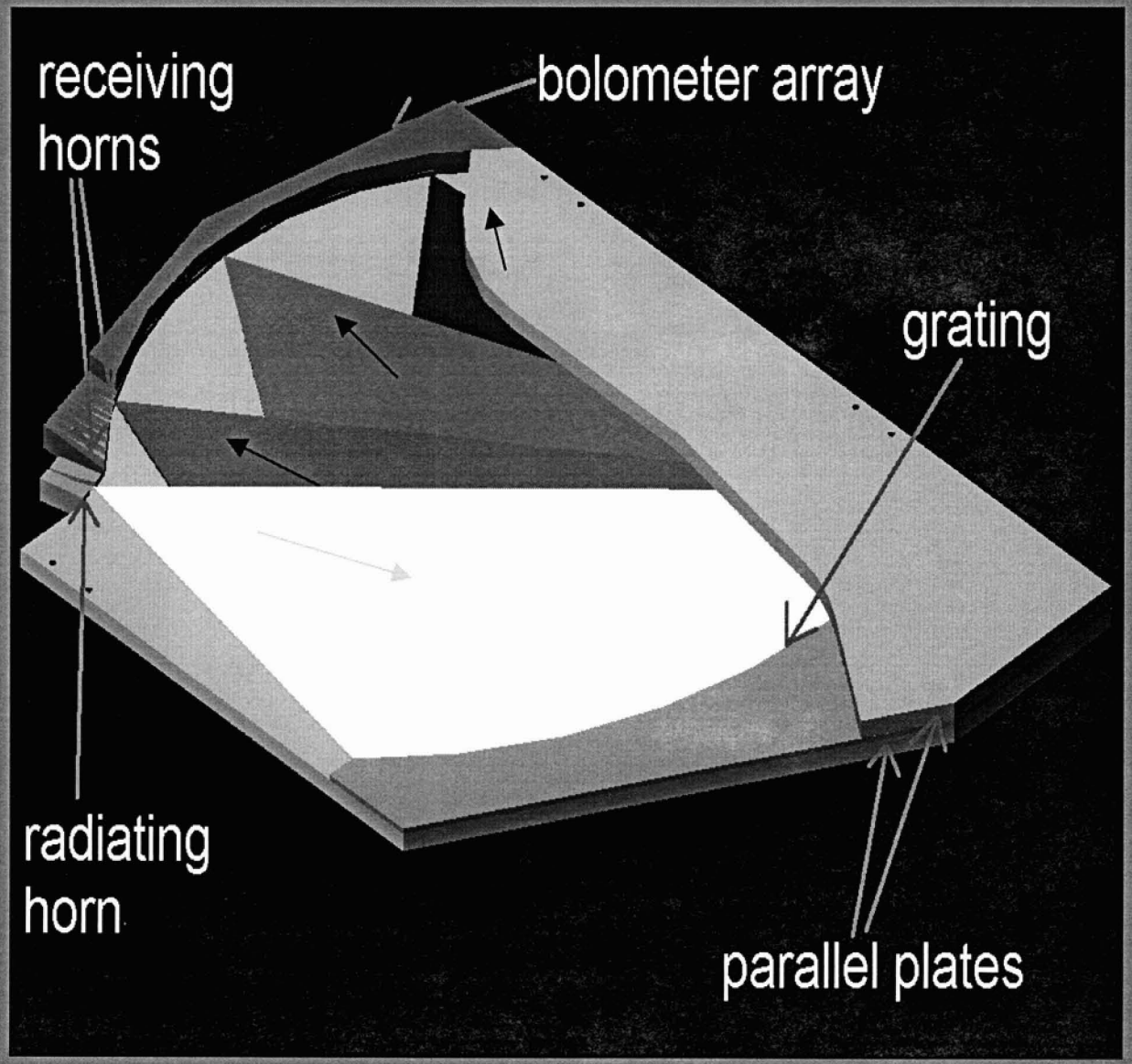


Figure 5. The IRS long-high module optical layout.

Solution: WaFIRS Spectrometer Module

curved grating in parallel plate waveguide

- Propagation confined in parallel-plate waveguide
  - 2-D Geometry
  - Stray light eliminated
- Curved grating diffracts and focuses
  - Efficient use of space
  - No additional optical elements

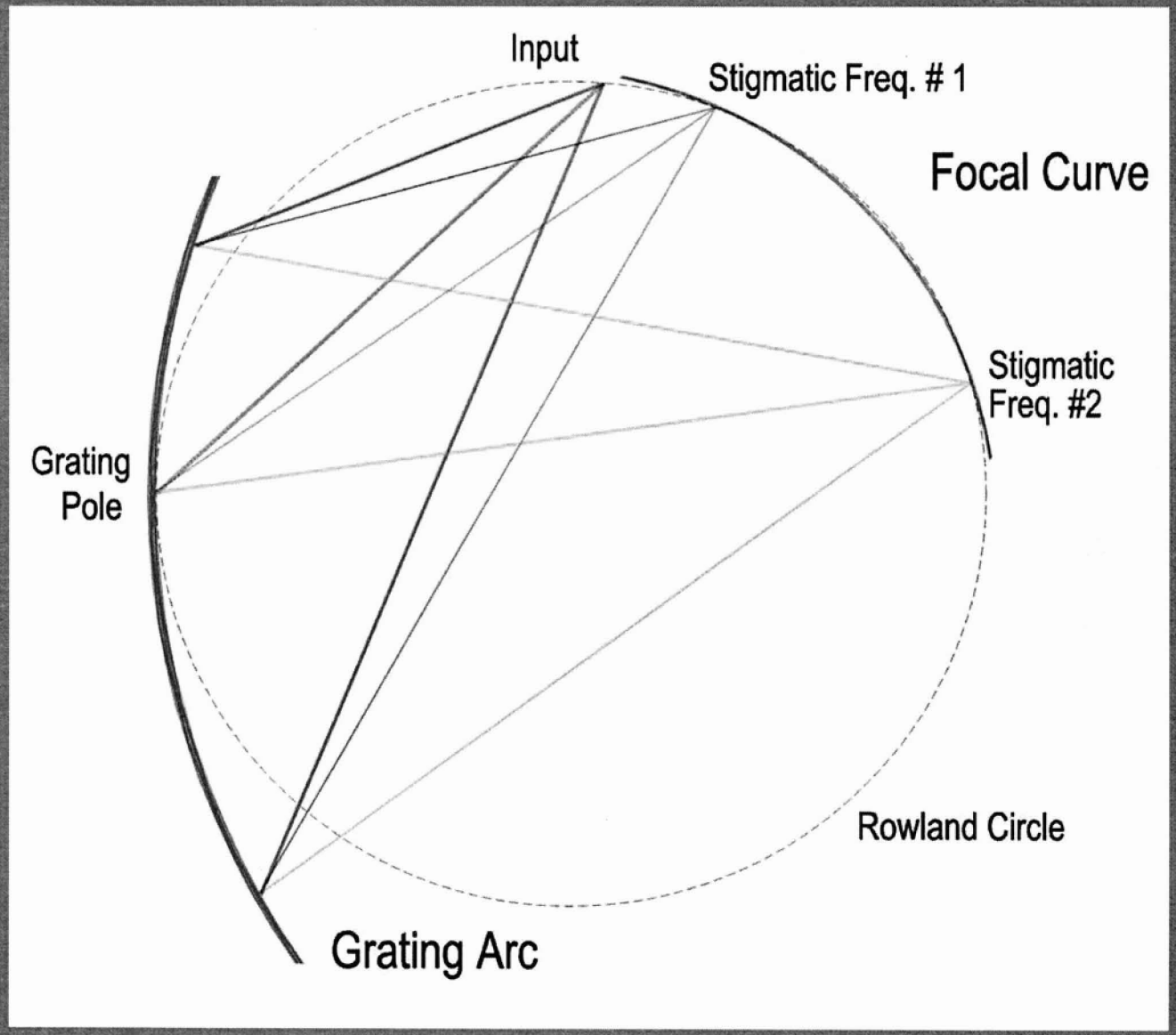


H.A. Rowland, 1883, Phil. Mag 16
K.A. McGreer, 1996, IEEE Phot. Tech. 8

Curved grating has stigmatic design

Each facet positioned to provide perfect performance at two frequencies

➔System is diffraction-limited over the full band.



Z-Spec is WaFIRS prototype for ground-based mm-wave spectroscopy

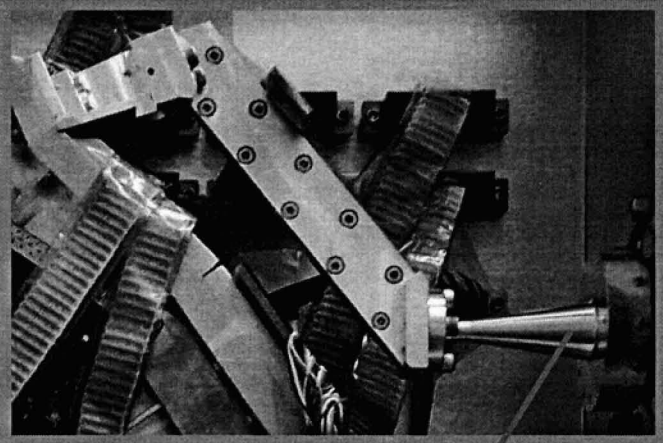
Z-Spec is multi-institutional collaboration:

Colorado: Glenn
JPL: Bradford, Bock, Nguyen, Dragovan
Caltech: Zmuidzinas
ISAS, Japan: Matsuhara
CEA, Saclay: Duband

Cover 195-310 GHz window instantaneously with R=250-450
-> Measure redshifts with CO lines in high-z galaxies
-> CSO, IRAM, LMT

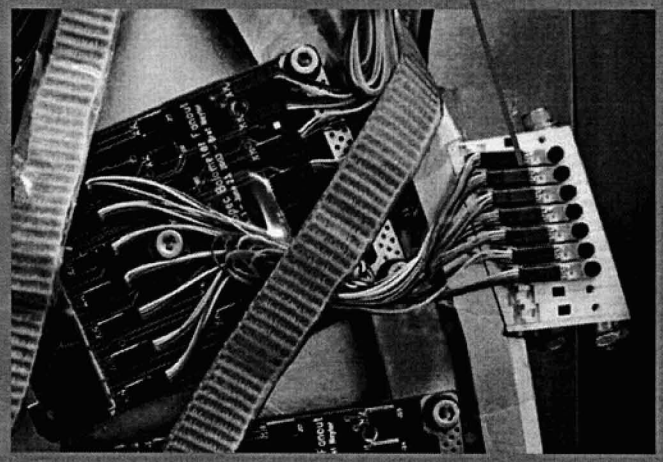
160 Si_3N_4 micromesh bolometers, BG limited on ground
-> Entire device cooled to < 0.1 K

Z-Spec is WaFIRS prototype for ground-based mm-wave spectroscopy



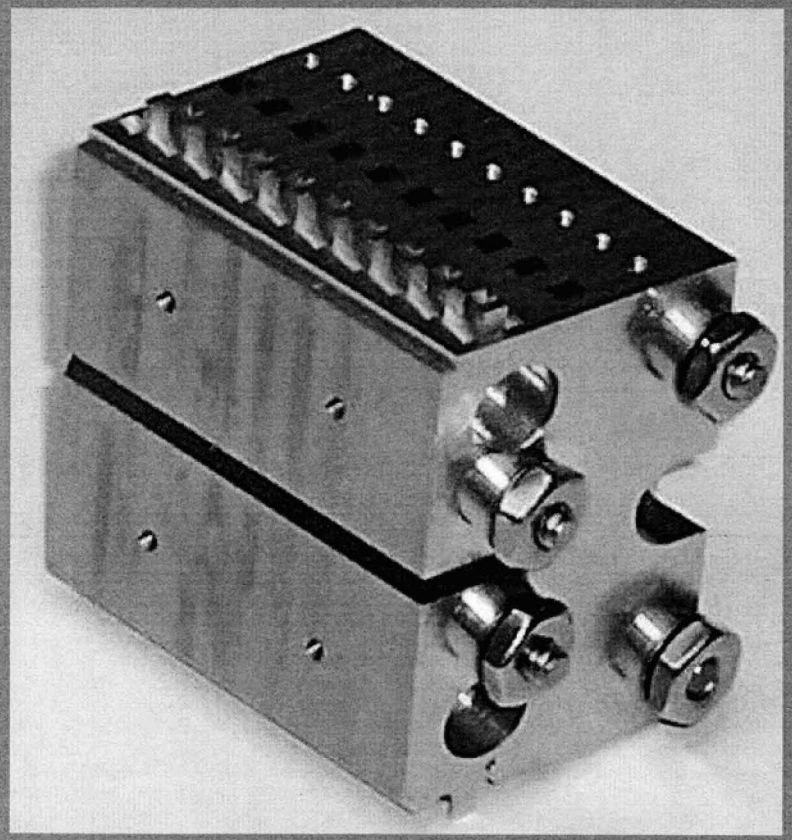
Single-mode illuminating feed and transformer

Multi-mode detector feeds

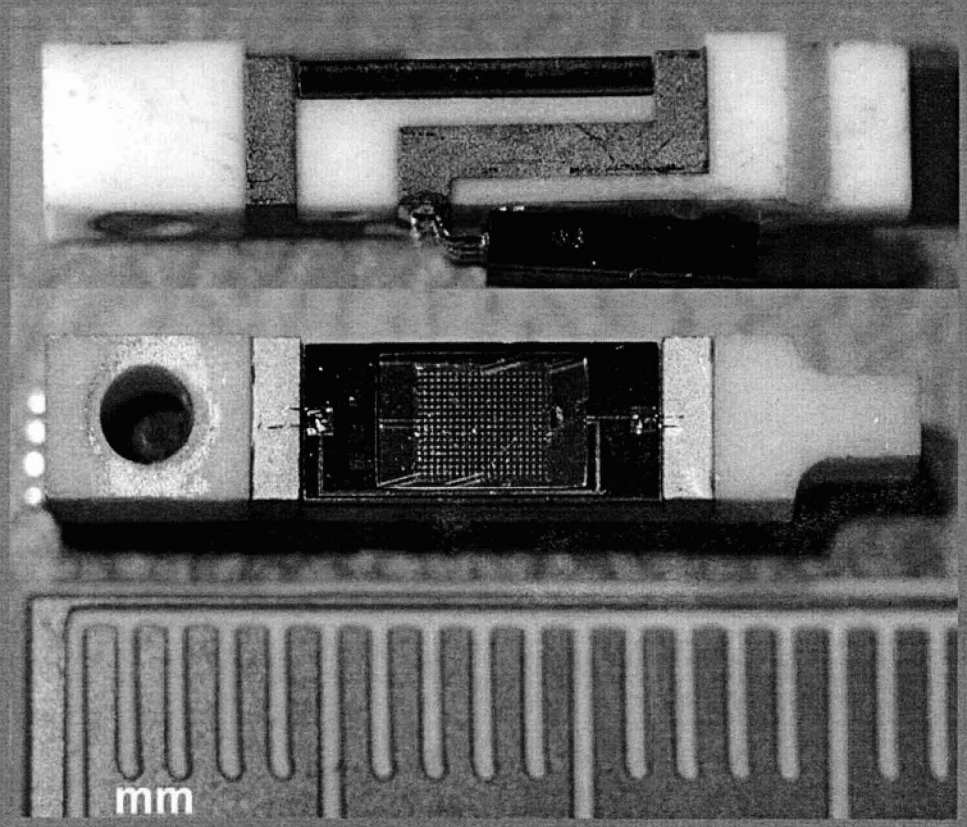


Z-Spec is WaFIRS prototype for ground-based mm-wave spectroscopy

See also Naylor poster, Jason Glenn



8 waveguide feed blocks -- each illuminates 20 bolometers



micromesh NTD-thermistor bolometers, each individually mounted.

Mm-wave WaFIRS prototype ought to scale to shorter wavelengths, higher R

Table 3. Scalability of WaFIRS Modules

Design Parameter		Z-Spec (built)	SPICA far-IR	SPICA far-IR
Wavelength	μm	970-1540	160-300	160-300
Medium		Vacuum	Vacuum	Silicon
Detectors	#	160	500	500
Facets	#	480	4000	4000
Resolving Power	$\lambda/\Delta\lambda$	250-400	1000-1600	1000-1600
Spacing	mm	2.5	0.6	0.18
Tolerance	μm	40	5	1.5
Length	mm	610	550	160
Efficiency		0.78-0.85	0.90-0.93	0.90-0.93

- 2-D geometry offers potential for stacking multiple modules in the focal plane.
- Dielectric immersion can further reduce size, mass.

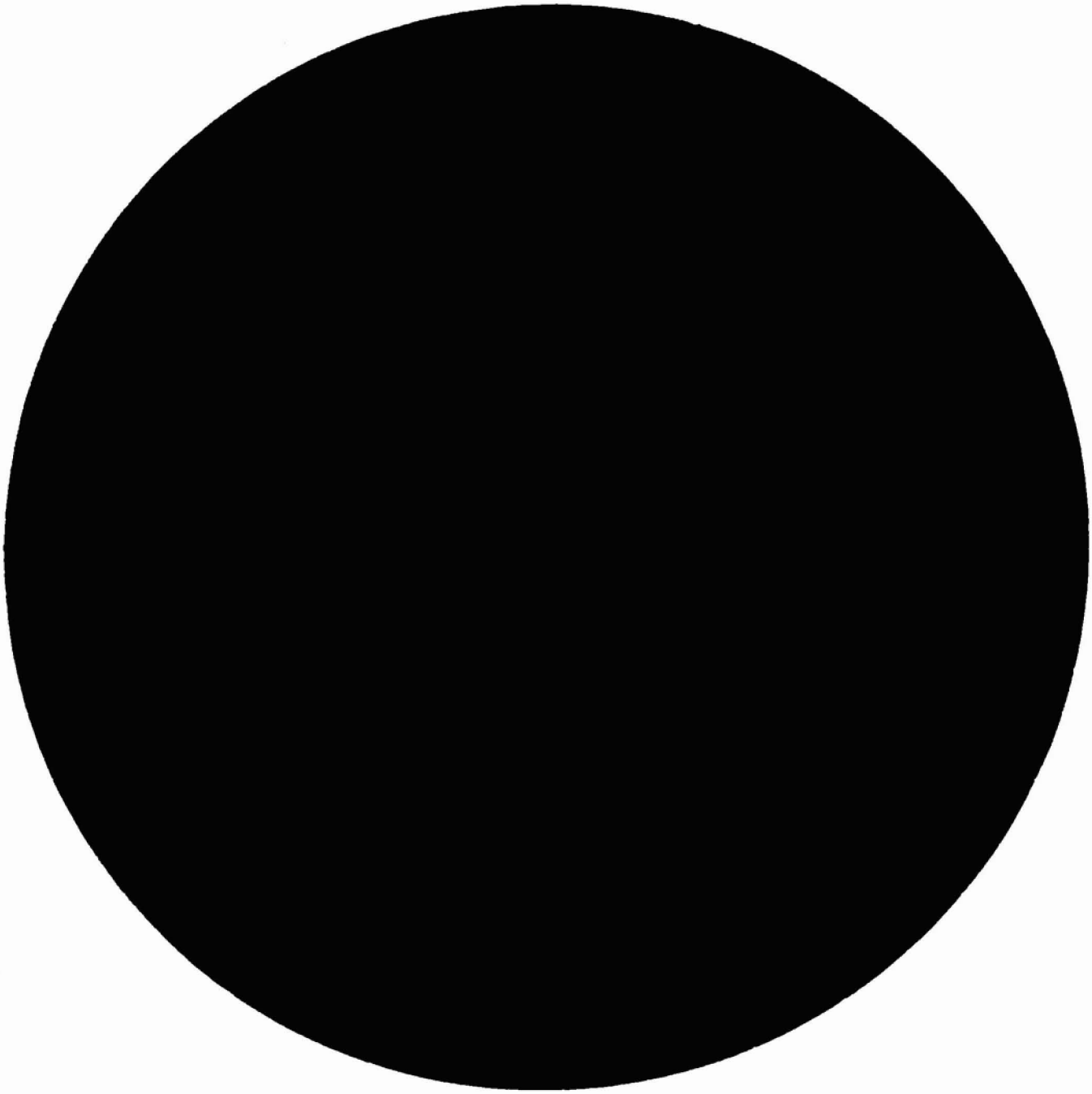
Summary

- The bulk of the cosmic far-IR background light will soon be resolved into its individual sources with Spitzer, Astro-F, Herschel, and submm / mm ground-based cameras. The sources will be dusty galaxies at z ~ 1-4. Their physical conditions and processes in these galaxies are directly probed with moderate-resolution spectroscopy from 30 μm to 1 mm.

- The combination of large cold telescopes with sensitive direct detectors is now at hand, offering the potential for mid-far-IR spectroscopy at the background limit (BLISS). The capability will allow routine observations of even modest high-redshift galaxies in a variety of lines. SPICA and US probe-class missions are excellent candidates for operation within the decade, leading the way for SAFIR.

- An imaging Fourier-Transform system is a good match to present-day detector technology.

- The most efficient broadband instrument uses a grating spectrometer with NEP~10^{-20} detectors.

- Classical grating spectrometer architectures are prohibitively large for far-IR wavelengths, and new architectures such as WaFIRS are required.

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