Extragalactic astrophysics experiments & instruments with the 25 meter Atacama telescope

Matt Bradford (JPL)

Outline

Unique scientific capabilities inherent to the observatory and site determine the potential experiments, thus the instruments.

1) Far-IR / mm continuum observations

Probe of dust properties, luminosity history

→ *Large arrays provide large-scale mapping capability and survey speed*

→ *Large telescopes are necessary for study of dust properties at high redshift*

2) Broad band / imaging spectroscopy

Probe of ISM conditions, nature of luminosity source

→ *Access to the atomic and warm molecular ISM, line surveys and redshift measurement*

Astronomical capability provided by the AT25

Background-limited sensitivity:

$$\mathrm{NEFD} \sim \frac{h\nu\,(n(n+1))^{1/2}}{\eta_{inst}\eta_{tel}\eta_{atm}A_{tel}(\Delta\nu)^{1/2}}$$

$$n = \varepsilon_{load}\eta_{inst}(e^{h\nu / kT} - 1)^{-1}$$

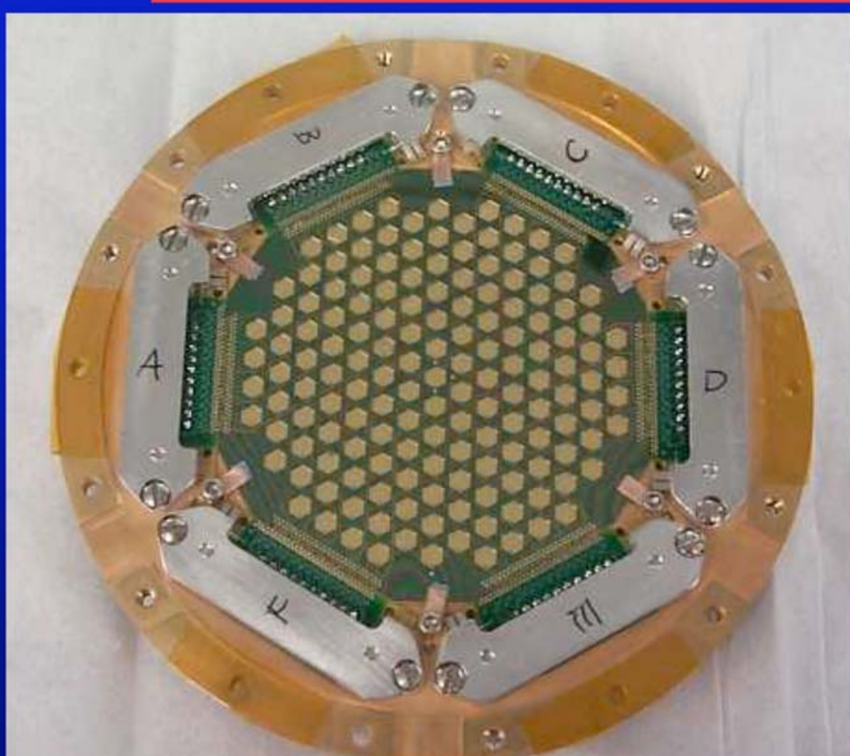
Telescope size, surface quality, site are important

→ ALMA will have large **A**

→ Single apertures can have large η's and larger $\Delta\nu$ for continuum observations.

→ **Bolometer arrays cover N times more sky**

Bolometer Arrays: Bolocam



144 Detectors

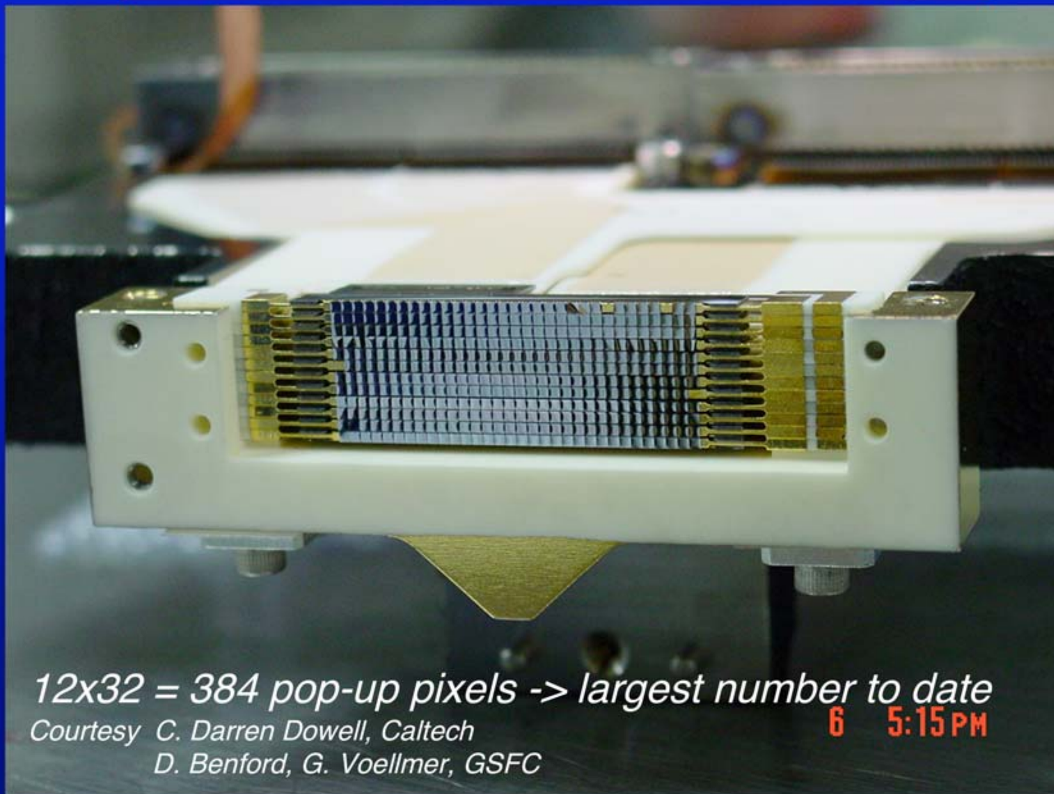
3 Bands

$\lambda \sim$ 1–3 mm

at CSO

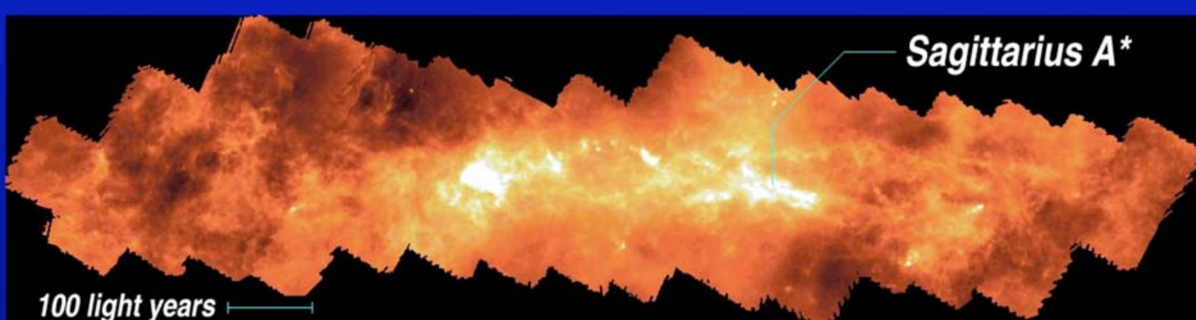
Courtesy
J. Glenn

Bolometer Arrays – SHARC II at 350 μm



Background-limited bolometer arrays allow sensitive large-scale surveys of the dust emission

In the galactic plane….

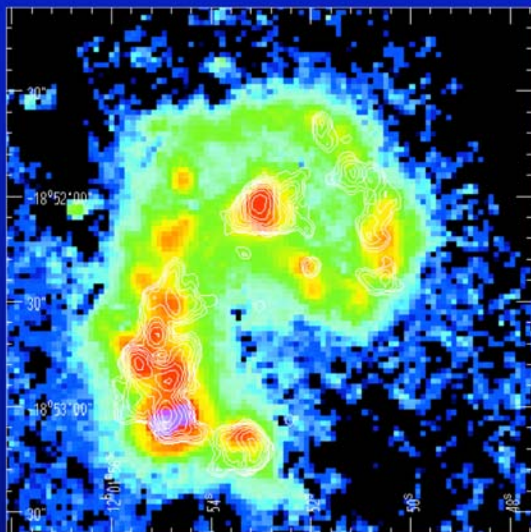


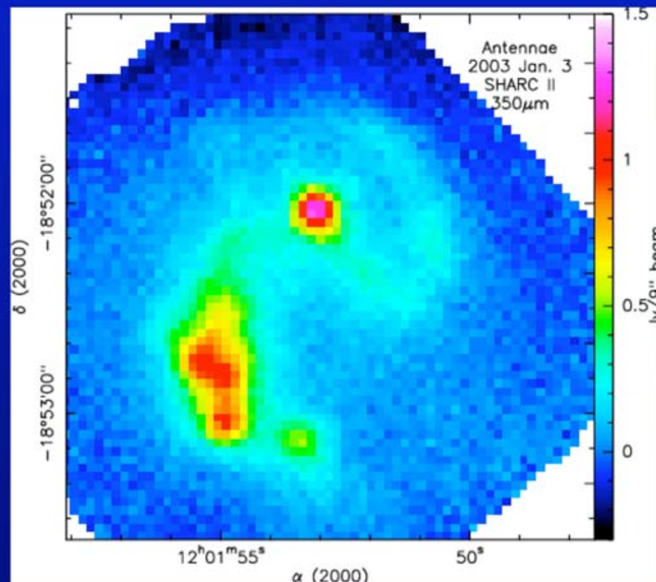
Galactic Center Molecular Zone
850 μm, 450 μm
Mass ~ 20×10^6 Mo, T~ 21 K

Pierce-Price et al., Holland et al. SCUBA / JCMT

Background-limited bolometer arrays allow sensitive large-scale surveys of the dust emission

In nearby galaxies….





color scale – ISO 15 μm – Mirabel et al. (1998)

white contours – CO 1-0 – Wilson et al. (2000)

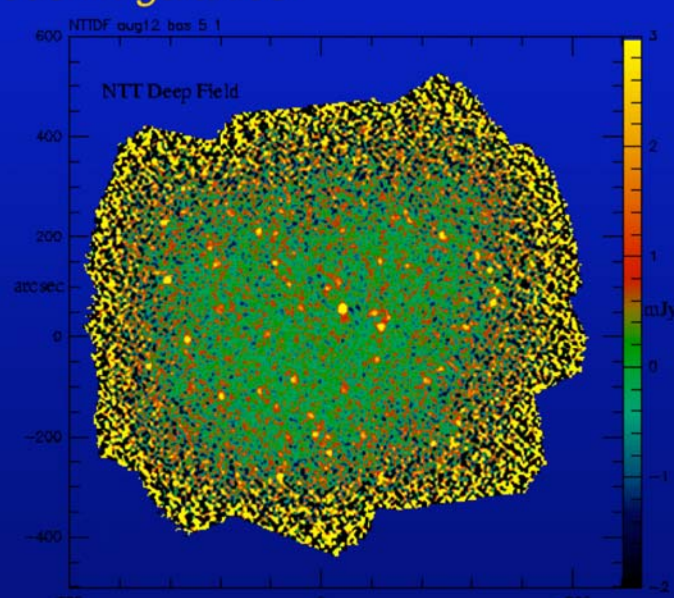
Background-limited bolometer arrays allow sensitive large-scale surveys of the dust emission

In high redshift-galaxies

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)

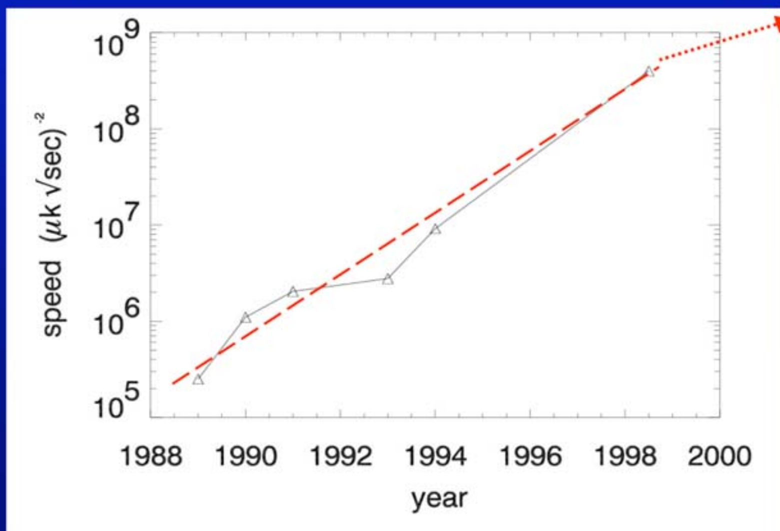
Large-format observations are resolving most of the background light at λ~1 mm



Example: bolometer arrays for CMB studies

From 1960 to 2000:
Sensitivity ×10^8
Number of pixels ×10^2
Speed of measurement ×10^{18}
Doubled every 12 months for 40 years!

(Technology is identical for submm – mm continuum astronomy)



Bolocam

But…

- Detectors now close to the ultimate sensitivity limit for ground-based observations
→Photon noise from the telescope and atmosphere
(Sky noise effectively removed!)
- Can only improve in array size (and only until full telescope throughput is coupled)

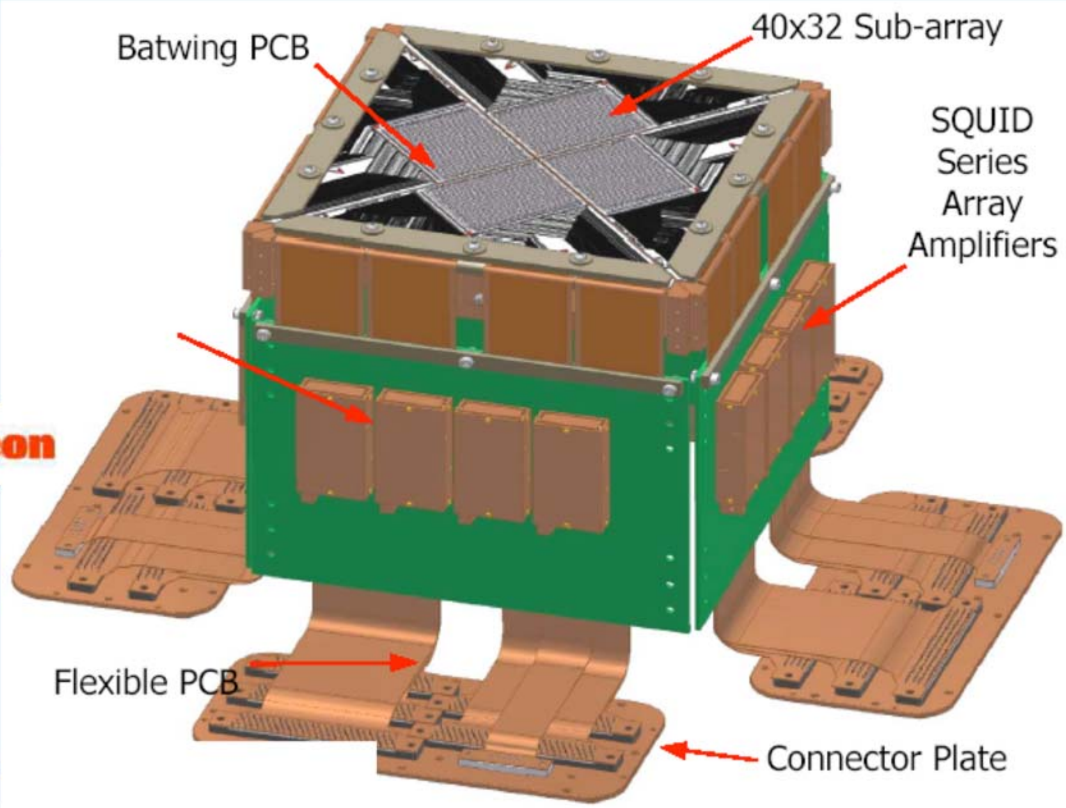
Flight Data MAX-MAXIMA
P.L. Richards, J.J. Bock

SCUBA-2 array module

SCUBA 2

Raytheon

NIST

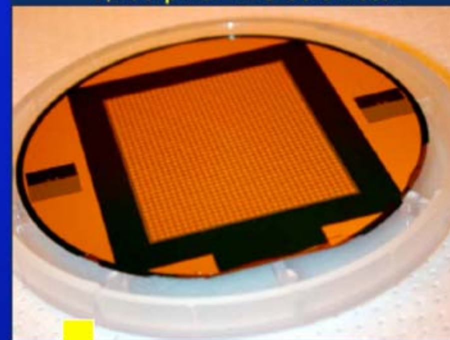


SCUBA-2 array technology progressing well

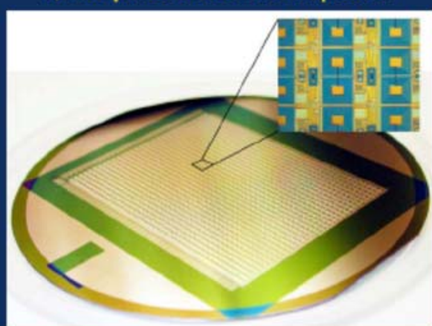
- **SCUBA-2**: two 5120-element arrays (850, 450 μm) of TES bolometers with SQUID MUXes.
- First 850 μm subarray complete
- Commissioning at the JCMT 2006
- Further development for flight projects (BLISS / SAFIR / CMBpol) -- ***technology will be available for LSAT***

Kent Irwin, William Duncan, SCUBA-2 team

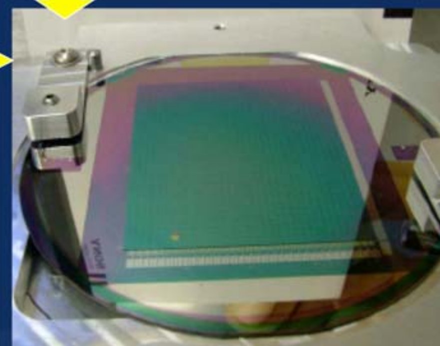
1,280-pixel TES bolometer



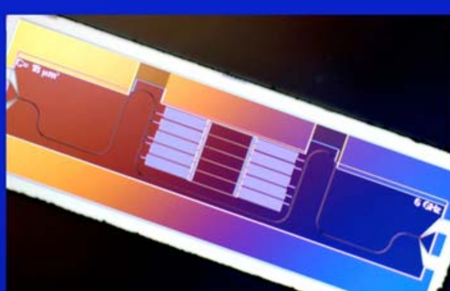
1,280-pixel SQUID Multiplexer



Bump bonding TES+MUX



New technologies for LSAT: kinetic inductance detectors (KIDs)



letters to nature

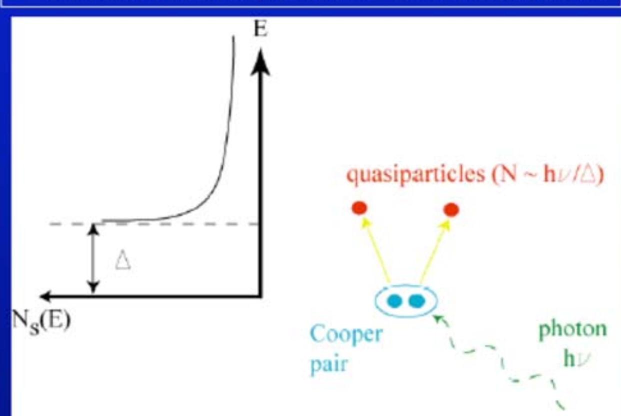
A broadband superconducting detector suitable for use in large arrays

Peter K. Day[1], Henry G. LeDuc[1], Benjamin A. Mazin[2], Anastasios Vayonakis[2] & Jonas Zmuidzinas[2]

[1]*Jet Propulsion Laboratory, Pasadena, California 91107, USA*
[2]*California Institute of Technology, 320-47, Pasadena, California 91125, USA*

Peter Day, Rick LeDuc / JPL
Jonas Zmuidzinas / Caltech

- Bandgap detector
- Elegantly multiplexed readout uses room-temperature GHz electronics!

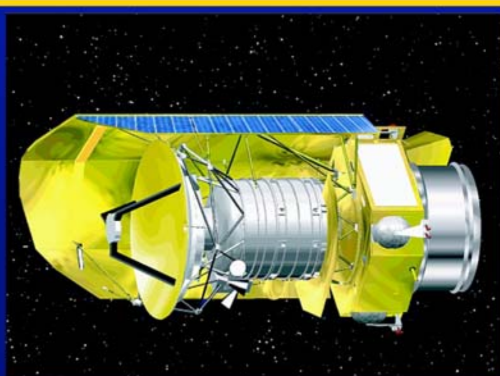


Advantage: quasiparticle G-R noise scales as

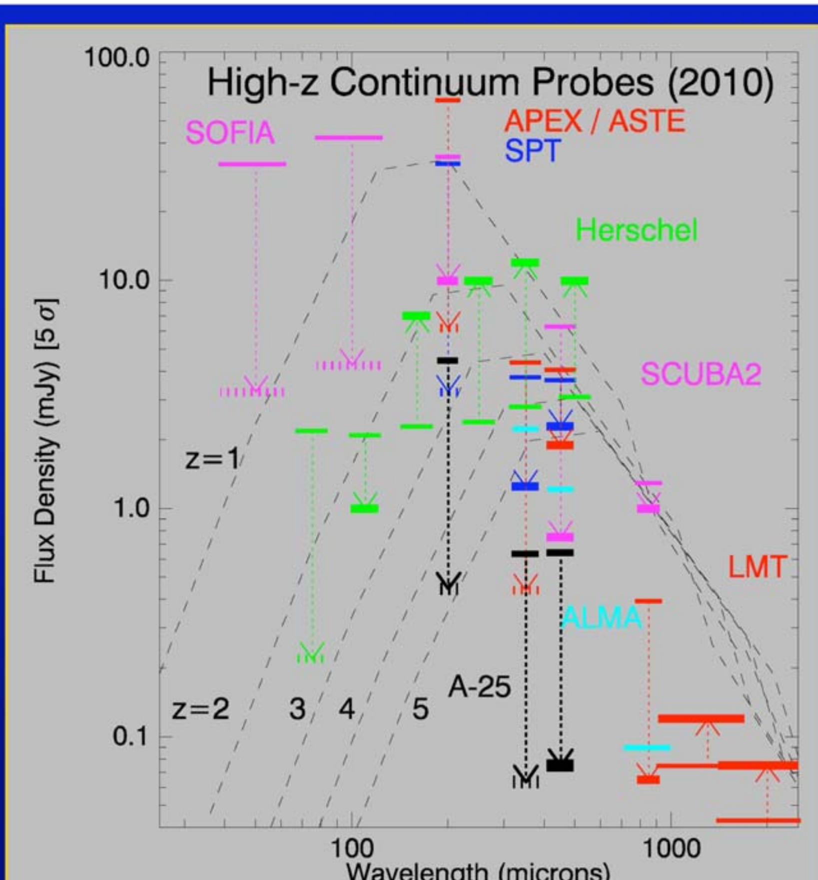
$$(n_{qp} / t_{qp})^{1/2} \sim \exp(-\Delta/kT)$$

Far-IR observatories: SOFIA and Herschel

- NASA/USRA/DLR
- 2.5m telescope
- 747 SP aircraft
- 6+2 first-light instruments
  - -first science in 2005 ?



- ESA/NASA
- 3.5m telescope
- 3 instruments
  - **PACS**
  - **SPIRE**
  - **HIFI**
- 2007 launch



Assumptions

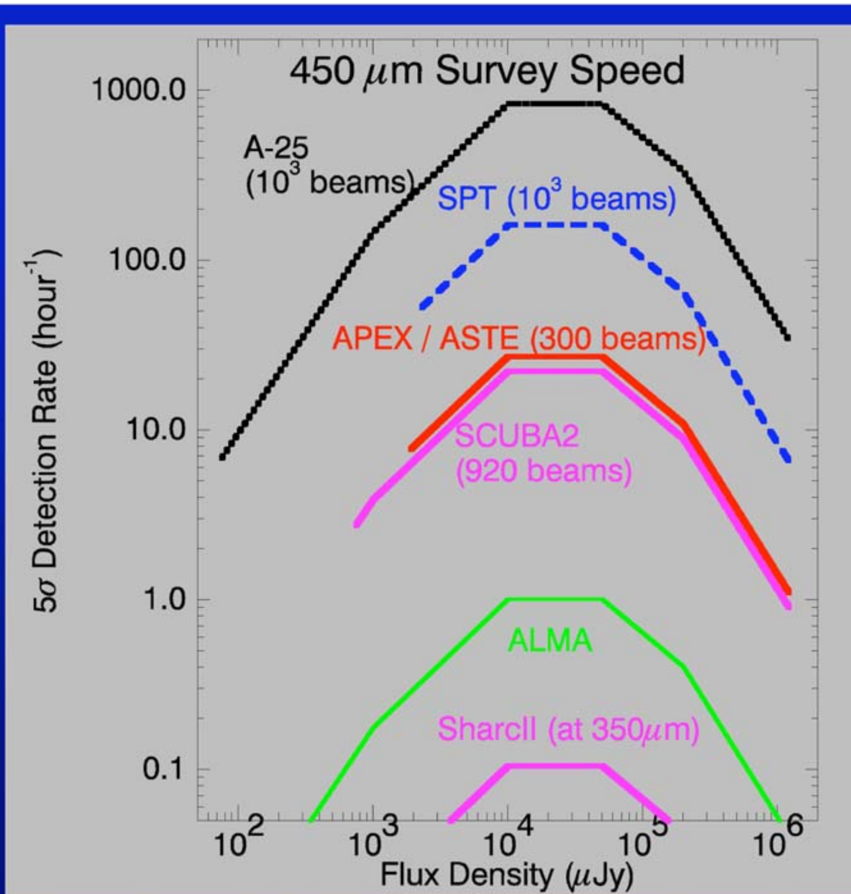
APEX / ASTE
12m, 0.5mm, 18μm

SPT
10m, 0.4mm, 15μm

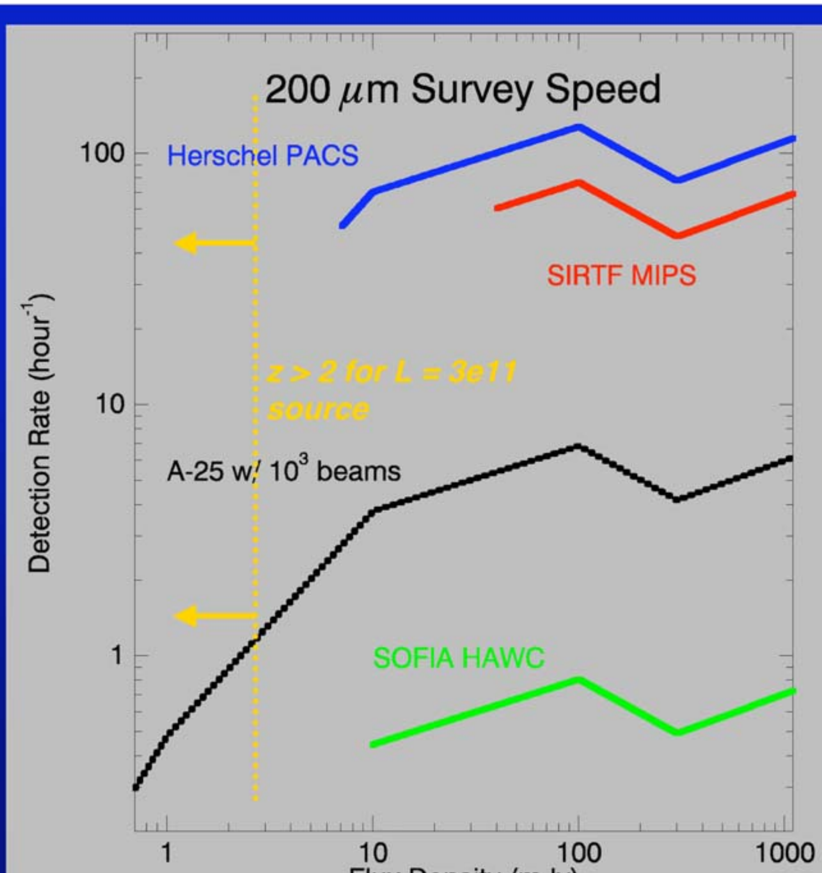
SCUBA2
15m, 0.7mm, 20μm

LMT
50m, 0.8mm, 70μm

A-25
25m, 0.4mm, 12μm



450 μm Survey Speed
5σ Detection Rate (hour^{-1})
1000.0
100.0
10.0
1.0
0.1
A-25
(10^3 beams)
SPT (10^3 beams)
APEX / ASTE (300 beams)
SCUBA2
(920 beams)
ALMA
SharcII (at 350μm)
10^2
10^3
10^4
10^5
10^6
Flux Density (μJy)



200 μm Survey Speed
Detection Rate (hour^{-1})
100
10
1
Herschel PACS
SIRTF MIPS
z > 2 for L = 3e11
source
A-25 w/ 10^3 beams
SOFIA HAWC
1
10
100
1000
Flux Density (mJy)

Spectroscopy with the LSAT

ALMA will offer a substantial advantage at its operational frequencies for pointed spectroscopy (known α, δ and ν)

There is no longer a bandwidth advantage

But a fully-functional ALMA is still a decade away, and ALMA's highest frequencies may be the longest in coming.

And with ALMA in place there will remain important niches at the short submillimeter and far-IR wavelengths:

→ Broad bandwidth spectral surveys can measure redshifts of known continuum sources (known α, δ, unknown ν)

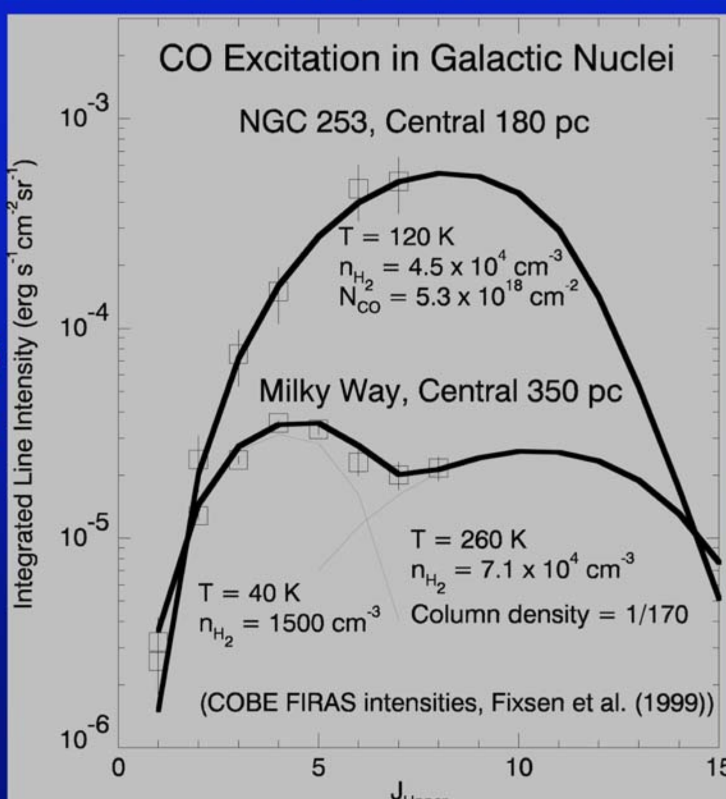
→ Wide-field imaging spectroscopy of nearby galaxies

→ CI, CO, NII ?

→ Array receivers for rapid large-scale spectral mapping

High-J CO lines: Astrophysics of the molecular gas

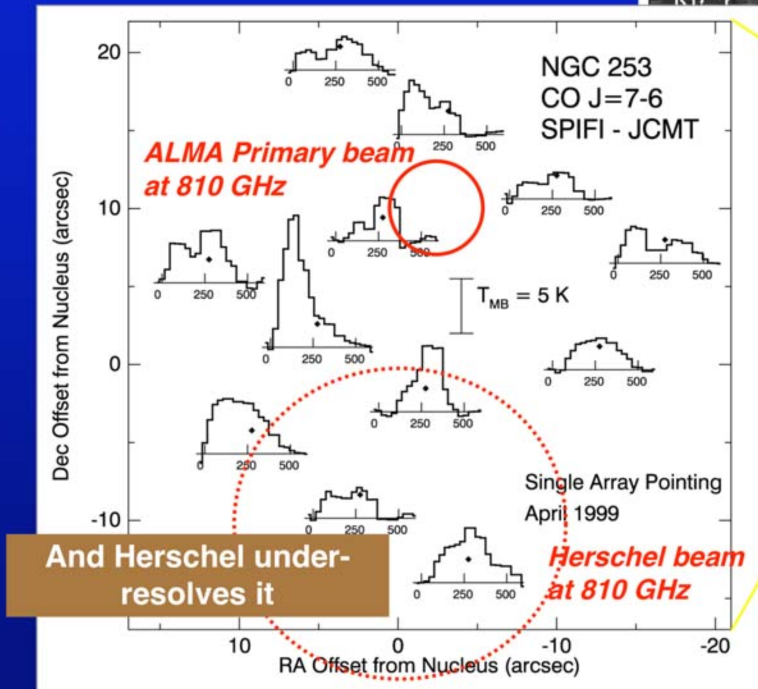
- LVG modeling: intensities → physical conditions
- Mid-J lines (J>4) distinguish low excitation from high excitation gas

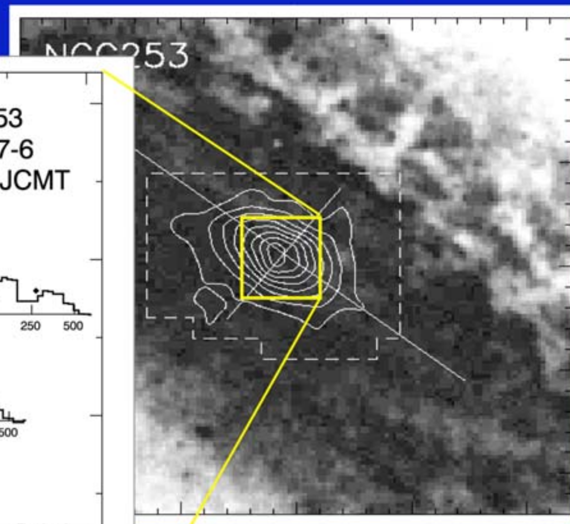


NGC 253: Bulk of molecular gas heated to T>100 K by cosmic rays, turbulence (SPIFI – JCMT) *Bradford et al '03*

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

ALMA will resolve out extended emission in nearby galaxies

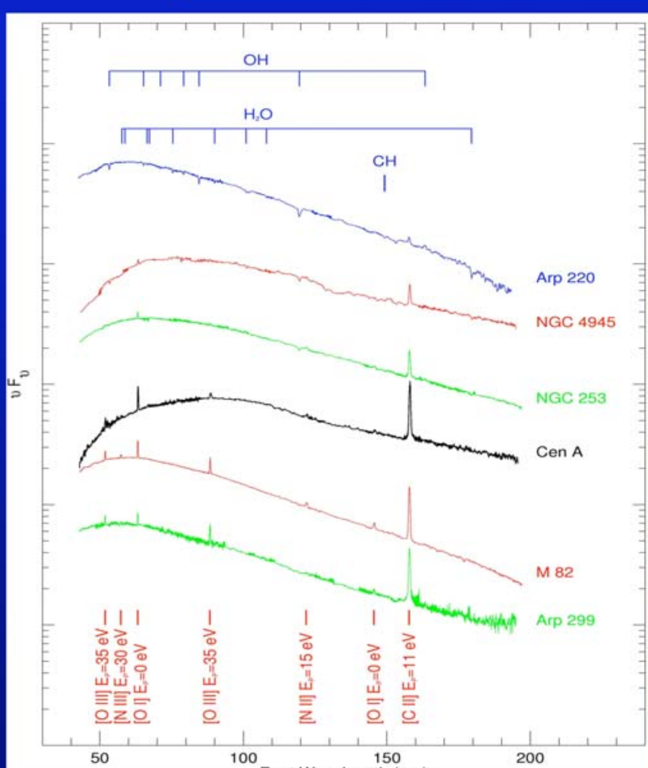




CO 3-2
M. Dumke et al. 2001,

CO 7-6
Bradford et al. 2003,

LSAT -- redshifted fine structure lines

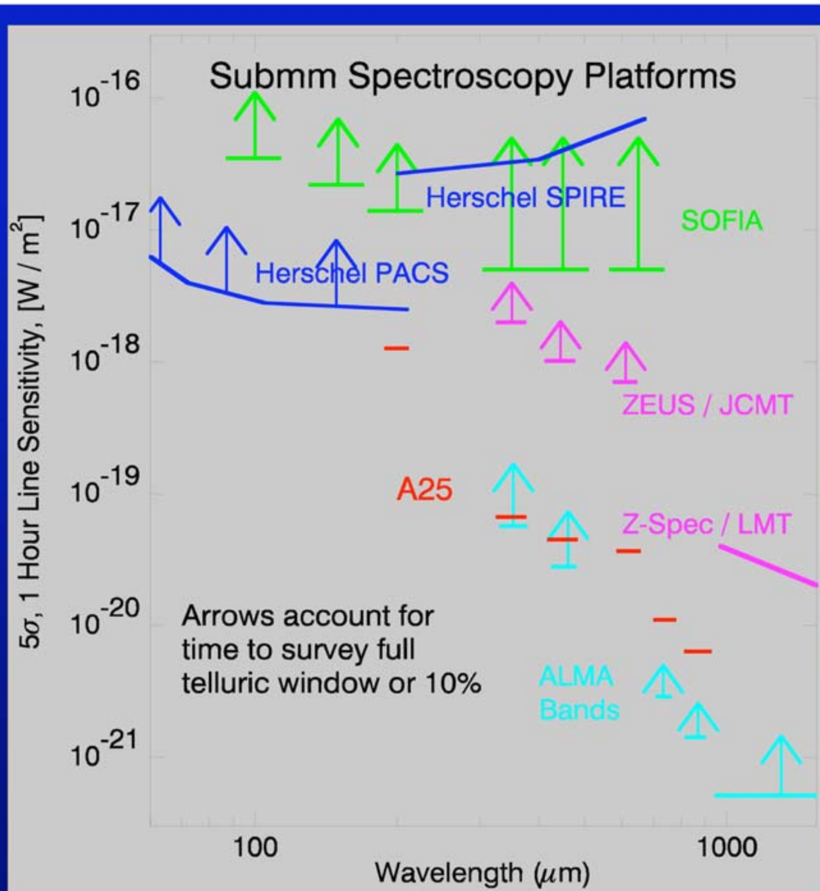


Fine structure lines probe ionized and neutral atomic gas.

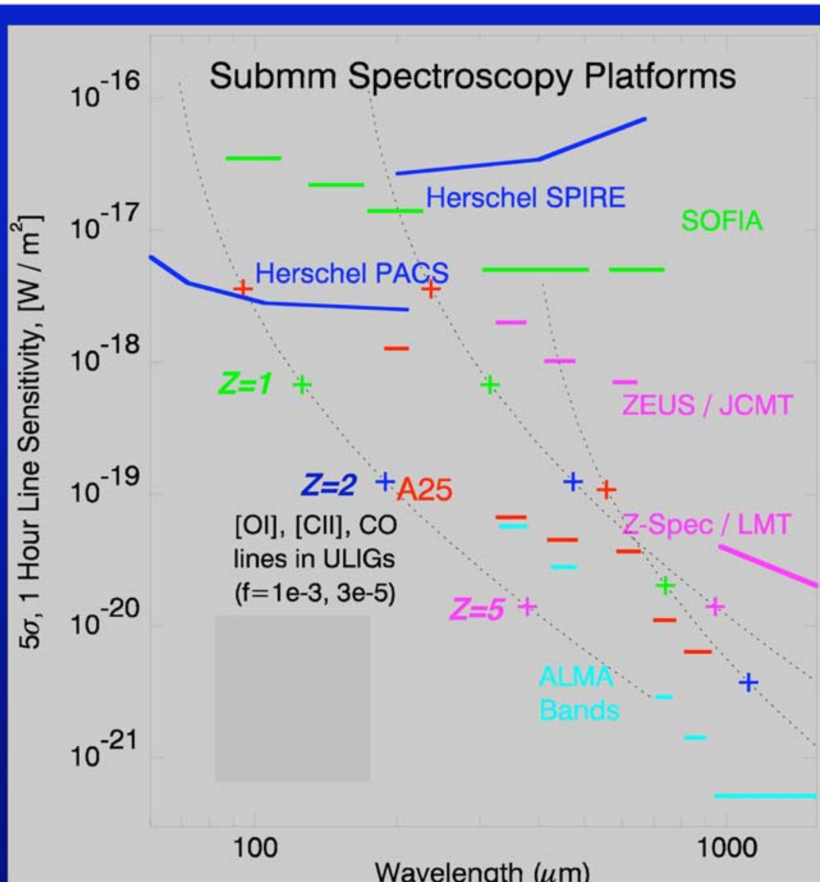
- → HII region densities
- → Atomic gas pressures
- → UV field strength and hardness
- → Starburst / AGN discriminator
- → Stellar mass function

• Suite of lines is redshifted into submillimeter atmospheric windows -- provides redshift template independent of optical follow-up.

J. Fischer et al.1999



Submm Spectroscopy Platforms
10^-16
10^-17
10^-18
10^-19
10^-20
10^-21
5σ, 1 Hour Line Sensitivity, [W / m²]
Herschel SPIRE
SOFIA
Herschel PACS
ZEUS / JCMT
A25
Z-Spec / LMT
Arrows account for
time to survey full
telluric window or 10%
ALMA
Bands
100
1000
Wavelength (μm)



Submm Spectroscopy Platforms
10^-16
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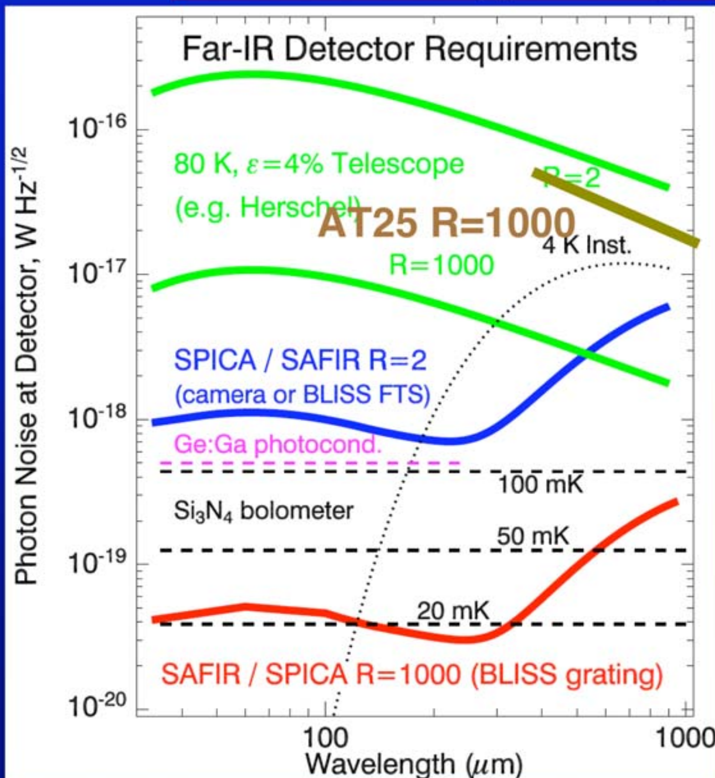
5σ, 1 Hour Line Sensitivity, [W / m²]
Herschel SPIRE
SOFIA
Herschel PACS
Z=1
ZEUS / JCMT
Z=2
A25
Z-Spec / LMT
[OI], [CII], CO
lines in ULIGs
(f=1e-3, 3e-5)
Z=5
ALMA
Bands
100
1000
Wavelength (μm)

Bolometer for ground-based spectroscopy -- technology developed for flight



Sensitive detectors are under development for low-background flight experiments.

Requirements for R=1000 at λ < 1 mm with the AT25 are of order a few x10^{-17} W $Hz^{-1/2}$.

Achievable with existing devices, probably at 300 mK (no ADR).

R~10,000 starts to become a relevant testbed for SAFIR / SPICA detectors.

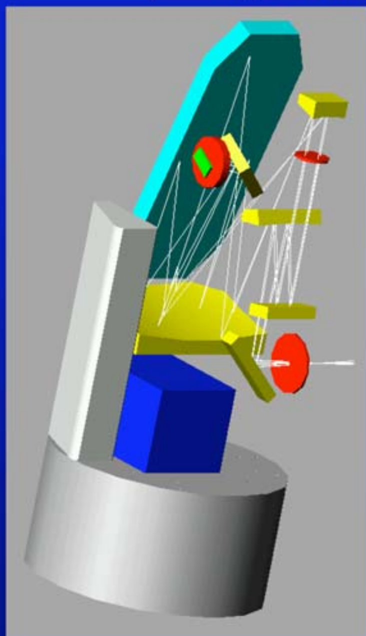
4 K instrument: $A\Omega = 3\ mm^2$, $\Delta\lambda/\lambda = 50\ \%$, $\varepsilon = 10\ \%$

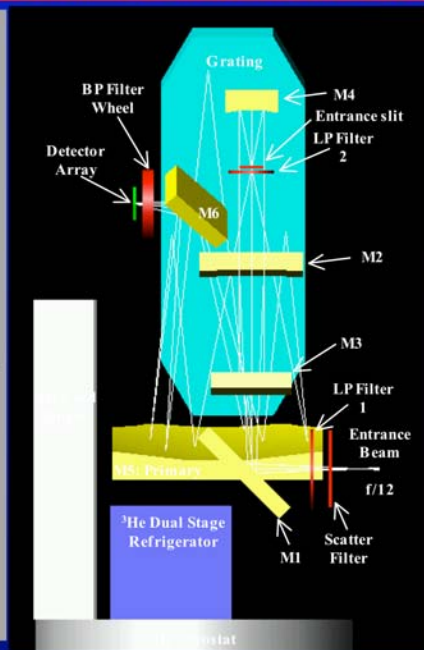
Options for far-IR through mm spectrometers

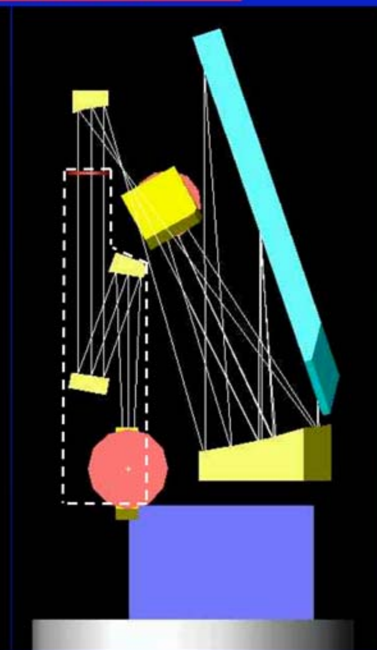
- **Grating spectrometer is the best choice for point sources**
  - **1st order → octave of instantaneous bandwidth**
  - **Good efficiency**
  - **But only moderate resolution**
- **Fabry-Perot naturally accommodates spectral mapping**
  - **But scanning time results in sensitivity penalty, esp for searching**
- Fourier transform spectrometer (FTS) couples the full band to a single detector
  - Sensitivity penalty
- Heterodyne receivers provide the highest spectral resolution
  - But suffer from 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 limited bandwidth:
    - 10 GHz IF bandwidth at 1 THz gives $\nu / \Delta\nu \sim 100$

Examples of submillimeter-wave broadband systems: ZEUS for the JCMT / APEX







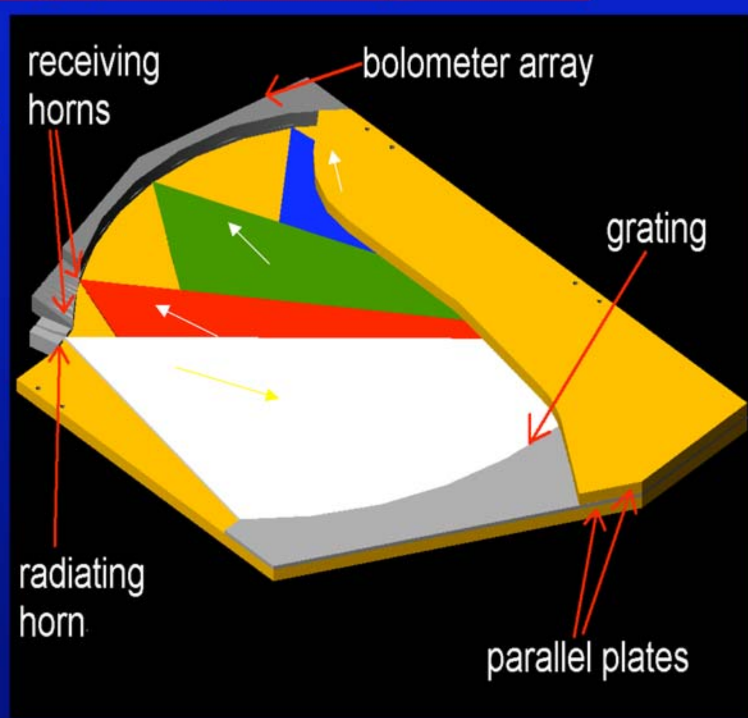
Cornell -- Stacey et al.

350, 450 μm windows w/ R~1000-1500

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

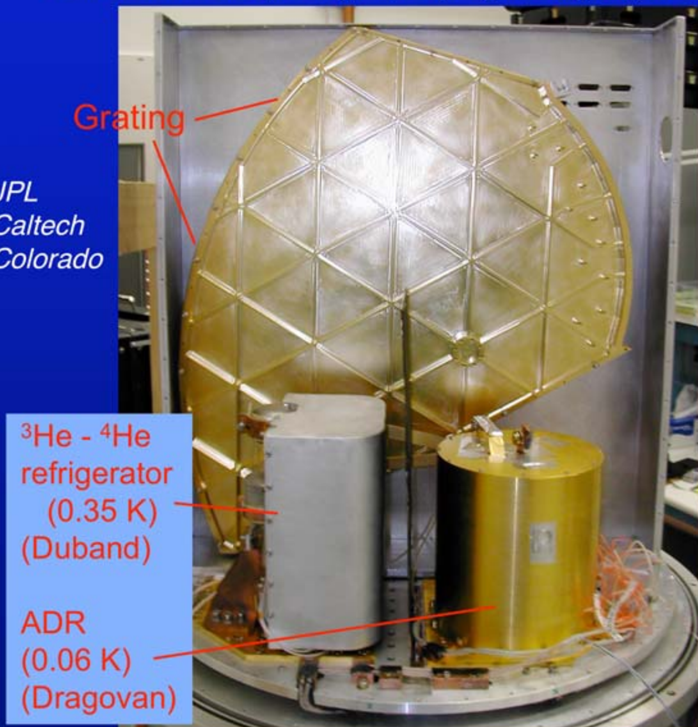


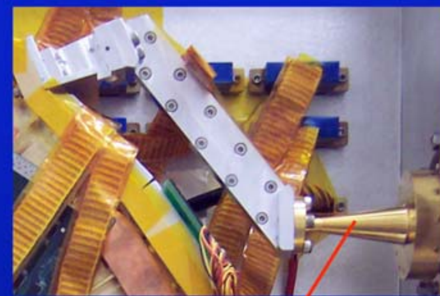
H.A. Rowland, 1883, Phil. Mag 16
K.A. McGreer, 1996, IEEE Phot. Tech. 8

WaFIRs waveguide offers broadband performance

λ=1 mm WaFIRs prototype (Z-Spec) undergoing integration, first light at telescope in 2005

JPL
Caltech
Colorado





Single-mode illuminating feed and transformer

Multi-mode detector feeds

Challenges for far-IR through mm spectrometers for ground-based telescopes

Best use of good weather depends on scientific goals

- Spectral mapping of galactic regions, nearby galaxies:
  → Optimize number of spatial elements with sufficient spectral coverage **Fabry-Perot or image slicer**
- Galactic nuclei, point sources w/ known redshifts:
  → Optimize sensitivity w/ a few spectral elements → maximize throughput **High-efficiency echelle slit spectrograph**
- Follow up of point sources w/ unknown redshifts:
  → Maximize number of simultaneous spectral resolution elements (Width of telluric bands presents the fundamental limit) $\delta\nu / \nu \sim 0.1$
  WaFIRS Grating
- The future → multi-object submm spectroscopy?
  → $\delta\nu / \nu \sim$ 0.1--0.4 *AND* R=1000 *AND* $N_{sources} \sim$ 10-100

Summary

• For continuum observations, the point source sensitivity obtainable with 25-meter-class high-accuracy telescopes at the best sites (such as LSAT) can be comparable to that of ALMA in the short submillimeter bands.

• When equipped with a large bolometer arrays, the corresponding mapping / survey speeds are 1–4 orders of magnitude faster than ALMA will offer.

• For $\lambda > 100\mu m$, Herschel and SOFIA will quickly be confusion-limited at ~10 mJy and the bulk of the resolved sources will be at $z<2$. However, LSAT will be capable of surveying much deeper and will be effectively not confusion-limited.

• For broadband line surveys, or wide-field imaging spectroscopy the LSAT will offer a capability which is better than SOFIA and Herschel, and comparable to ALMA.

• Future instruments at the LSAT will make ever increasing use of the photons collected by the telescope, sorting in both position and frequency. Broadband multi-object spectroscopy could increase capabilities several-fold.