Star-formation in the (Early) Universe

a.k.a.

My Decade-long Quest to Learn about SMGs

Attila Kovács
University of Minnesota

Appetizer

Submillimeter Galaxies

Mezze

Innovations

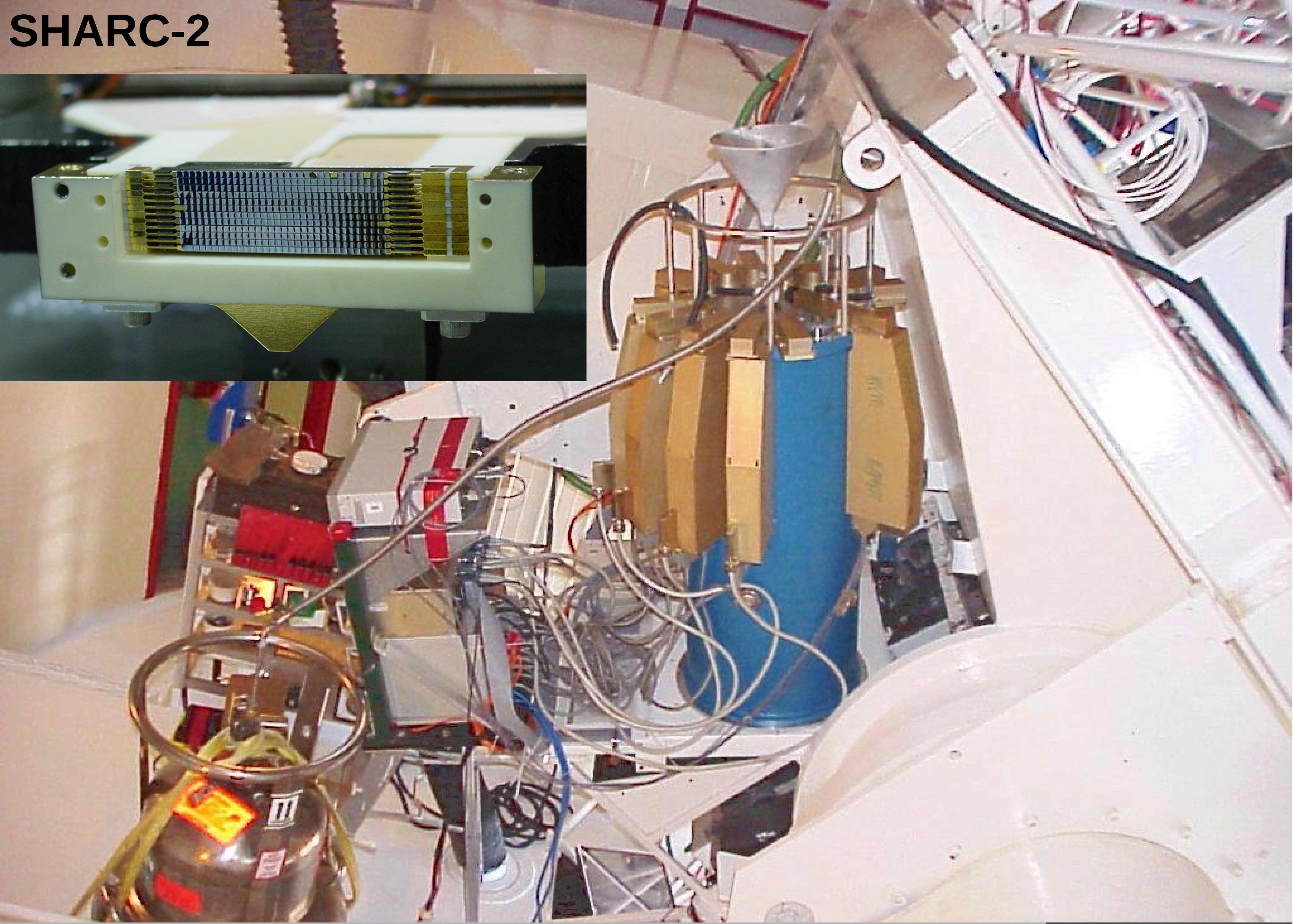
Entree

Interperting SMG Surveys
Disentangling Multiplets
FIR Characterizations
Dust SED Models

Dessert

Looking to the Future...

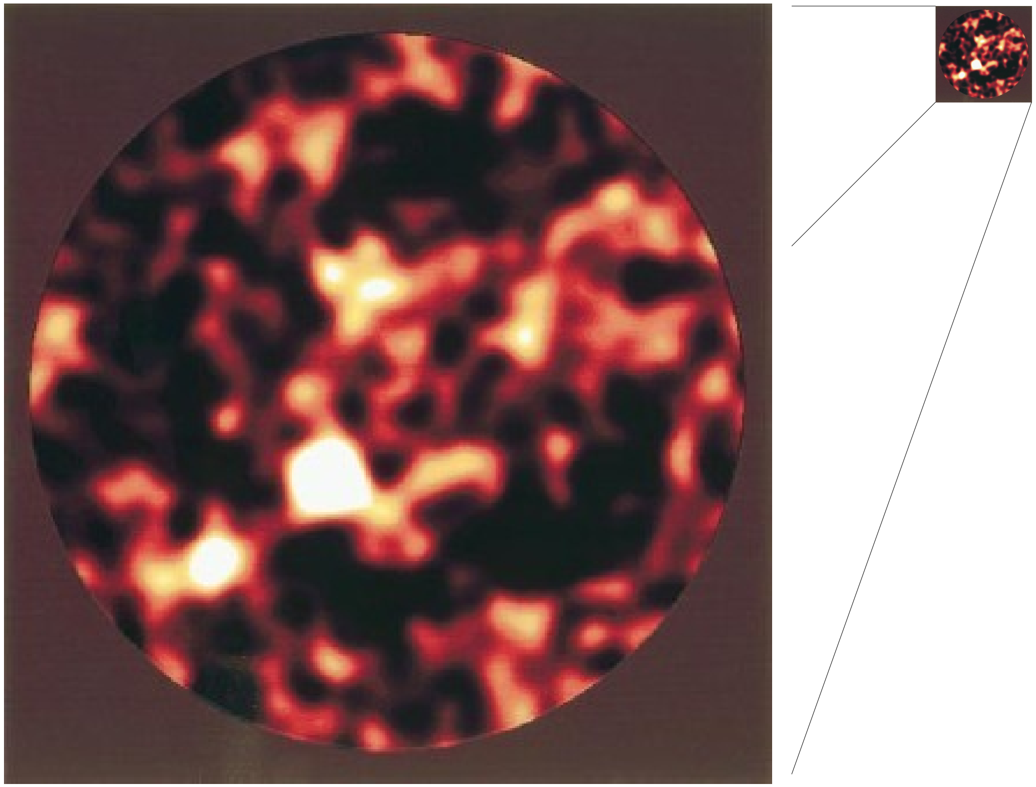
SHARC-2



Submillimeter Galaxies (SMGs)

1998

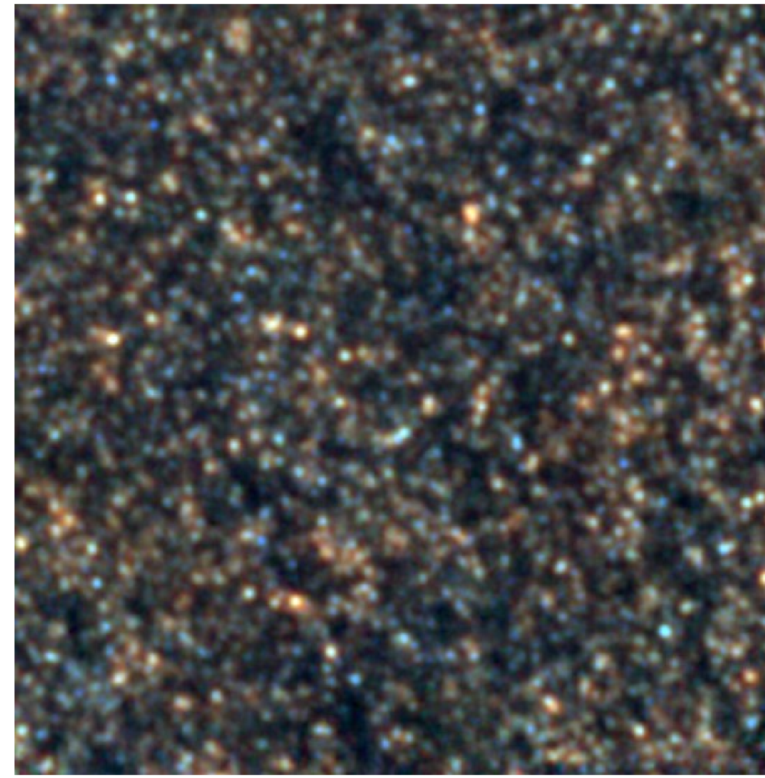
The First Detections



Hughes et al. 1998

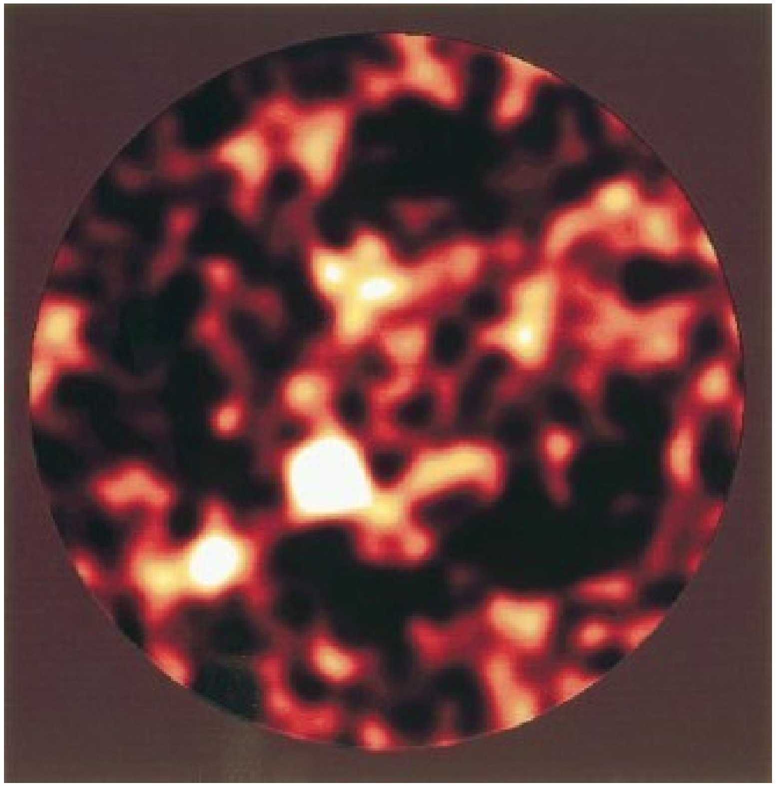
2011

~300,000 SMGs



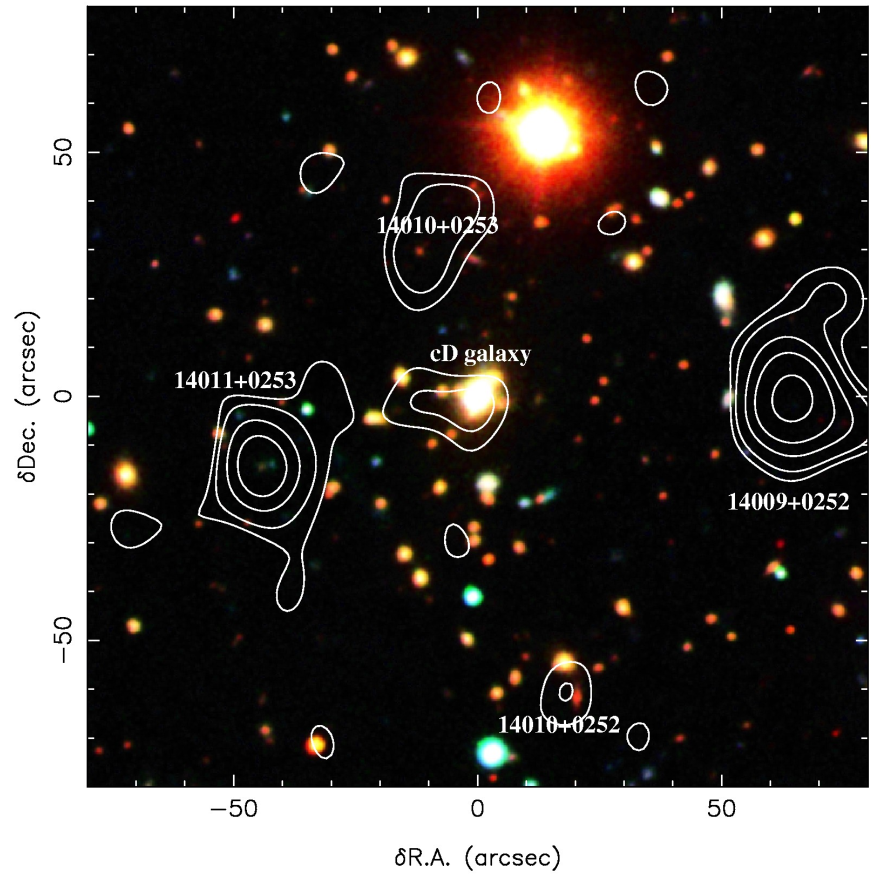
Submillimeter Galaxies (SMGs)

The First Detections



Hughes et al. 1998

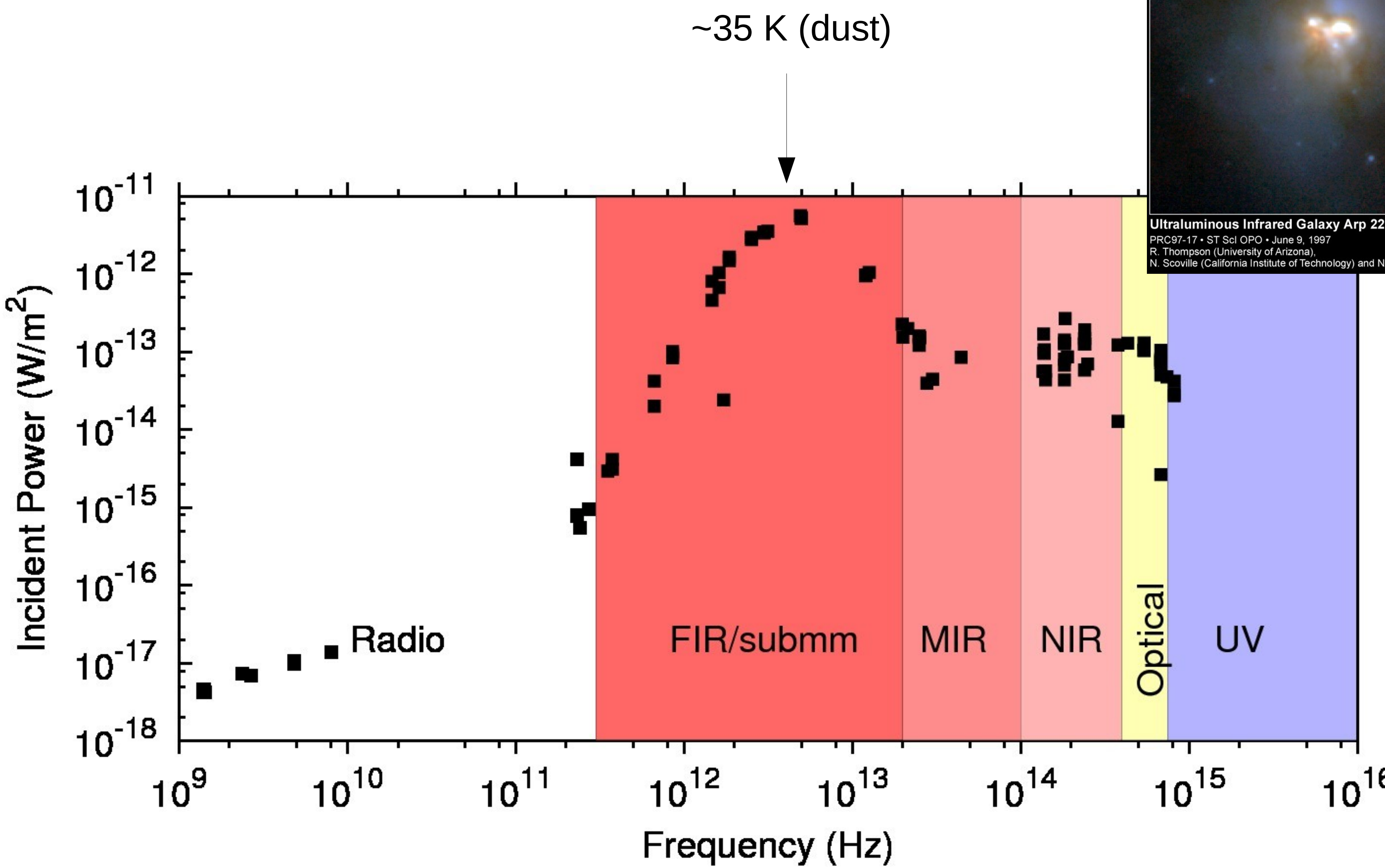
in Nature!!!

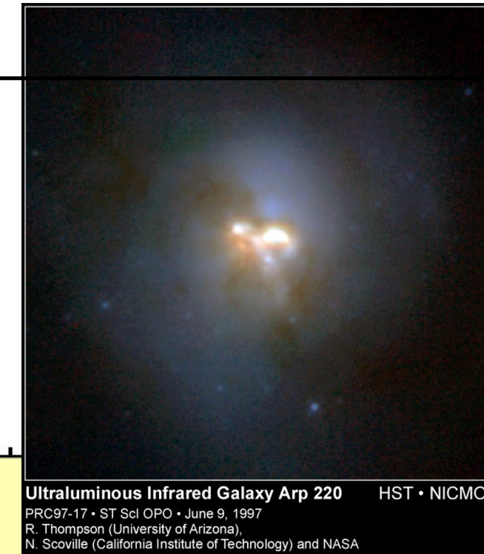


Too many optical counterparts
Or none at al...

Arp 220

The Energy Spectrum of a Luminous Galaxy

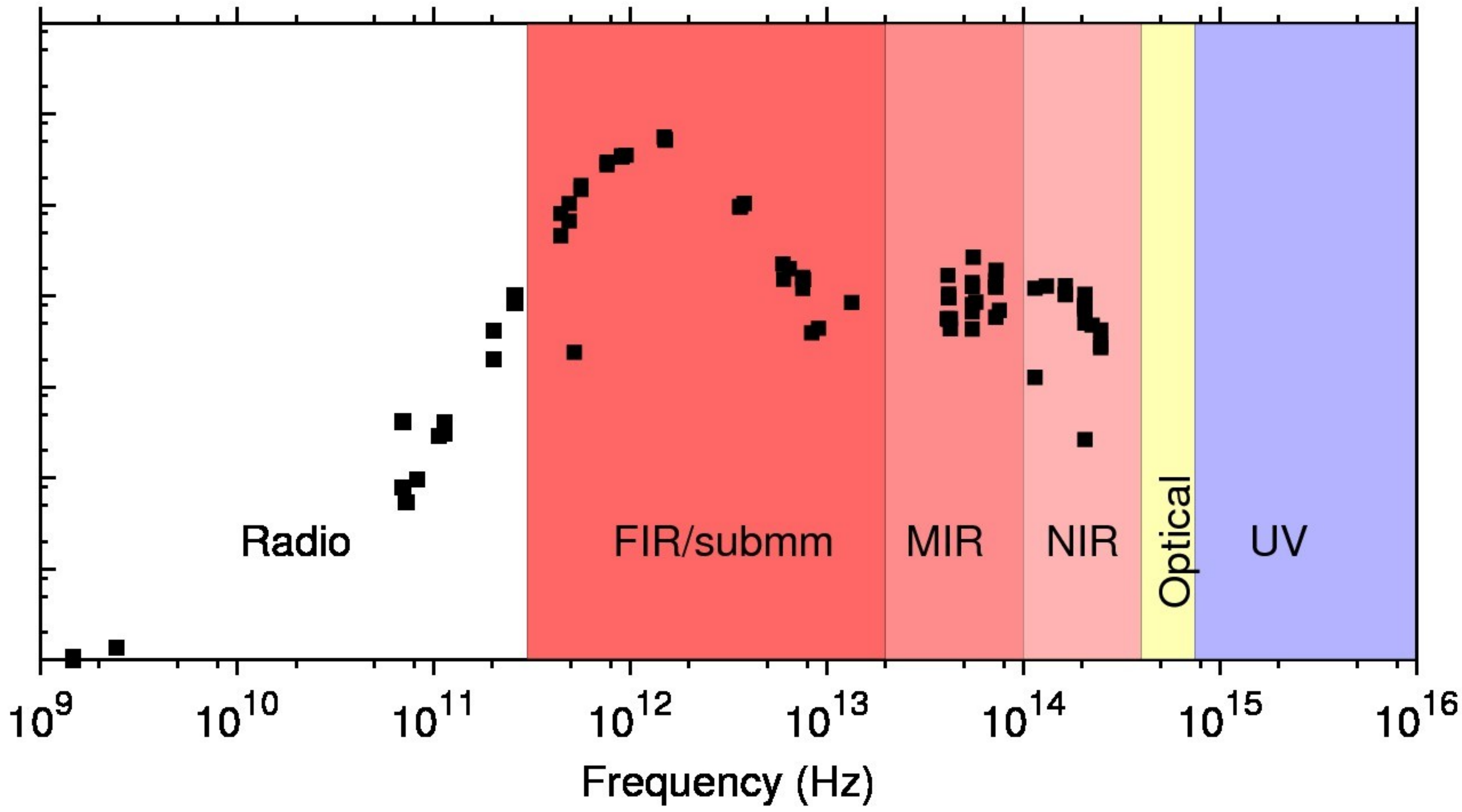




Milky Way FIR fraction is about 50%, T~16K

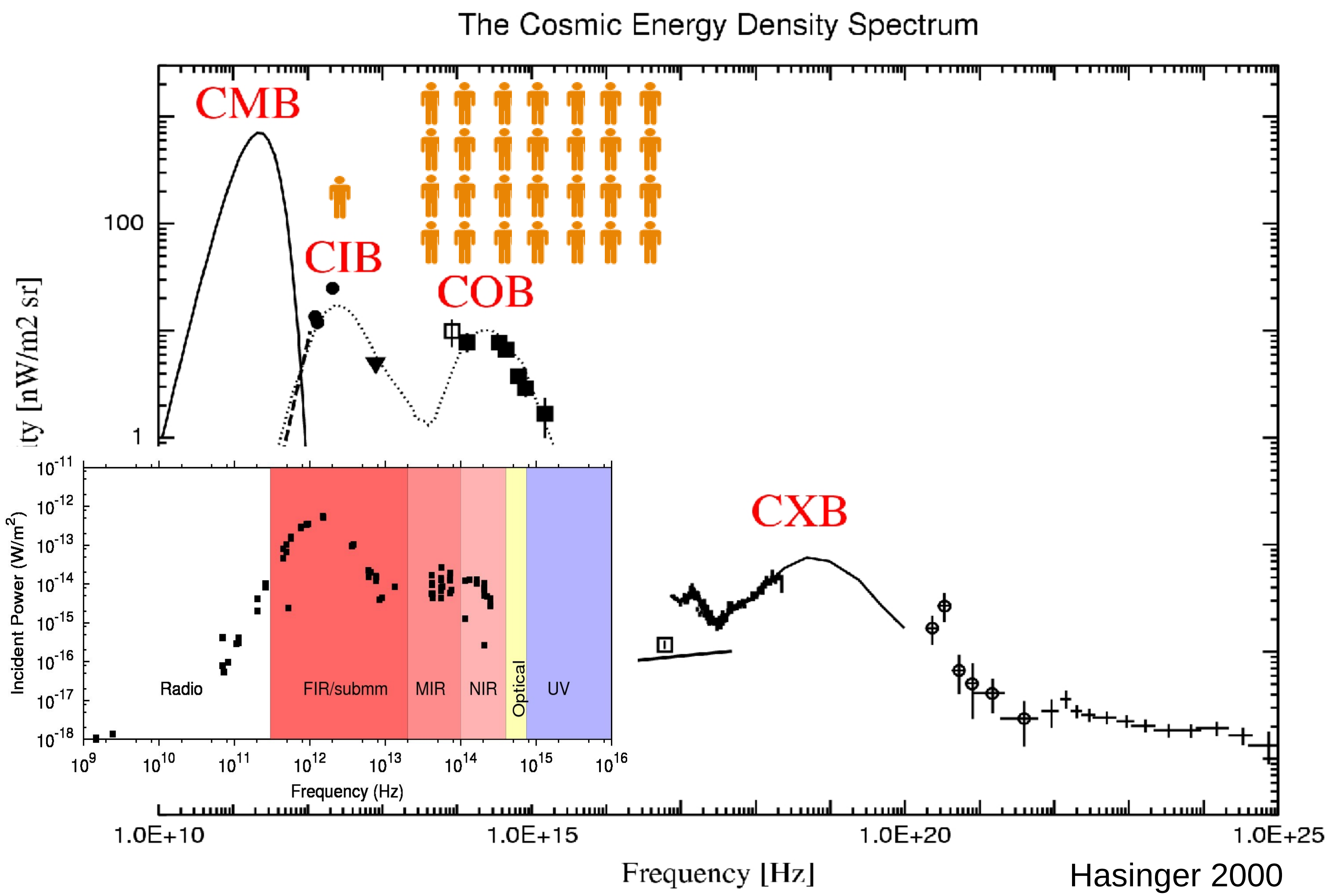
Arp 220 at z=2.3

The Energy Spectrum of a Distant Luminous Galaxy?



FIR/submm is great for studying distant populations!

The Cosmic Background



Hasinger 2000

Infrared background is due to such star-forming galaxies....

SMGs account for the bulk of the star-formation in the Universe

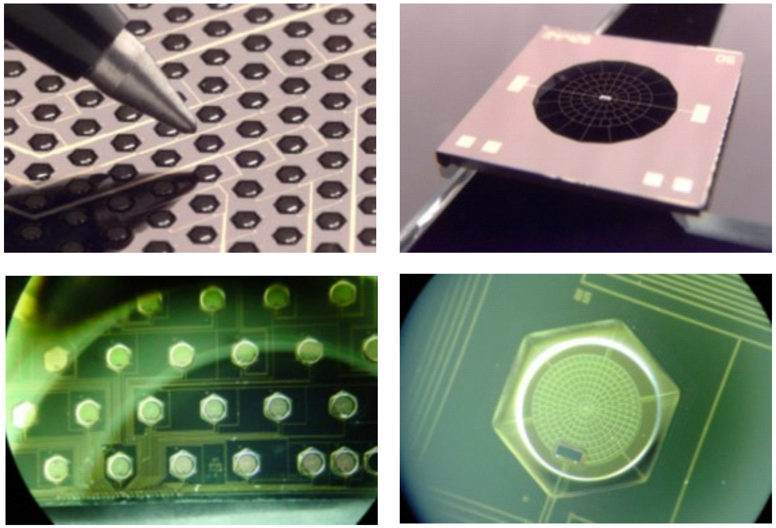
Essential Technologies

Total-power bolometers

Scanning strategies

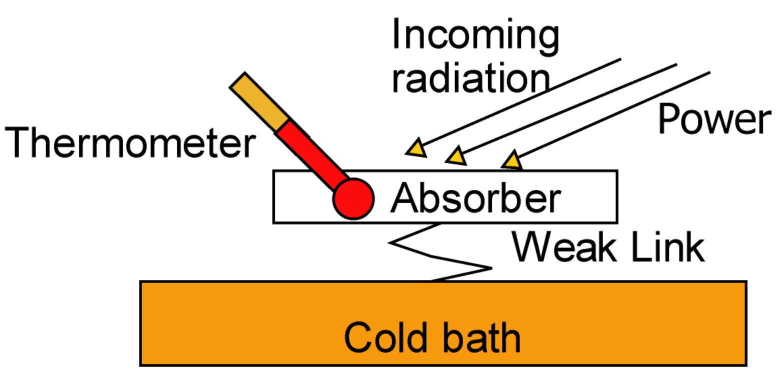
Data reduction

The challenges of ground-based observing



A Galaxy far far away...
(10 Gly, 35K)

atmosphere
(300K)



1/f noise

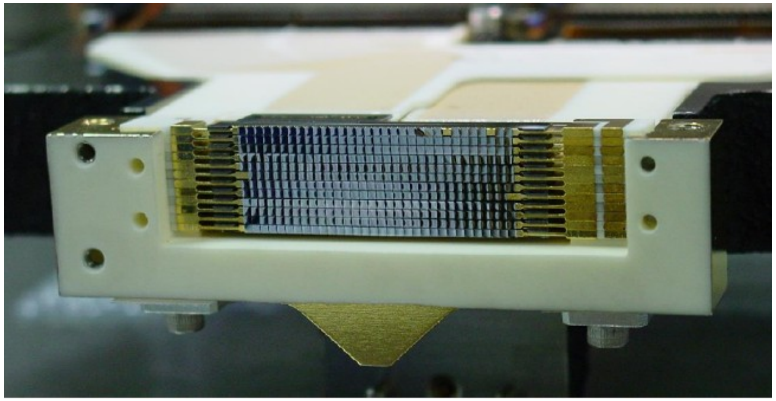
Unstable gain/noise

Microphonics

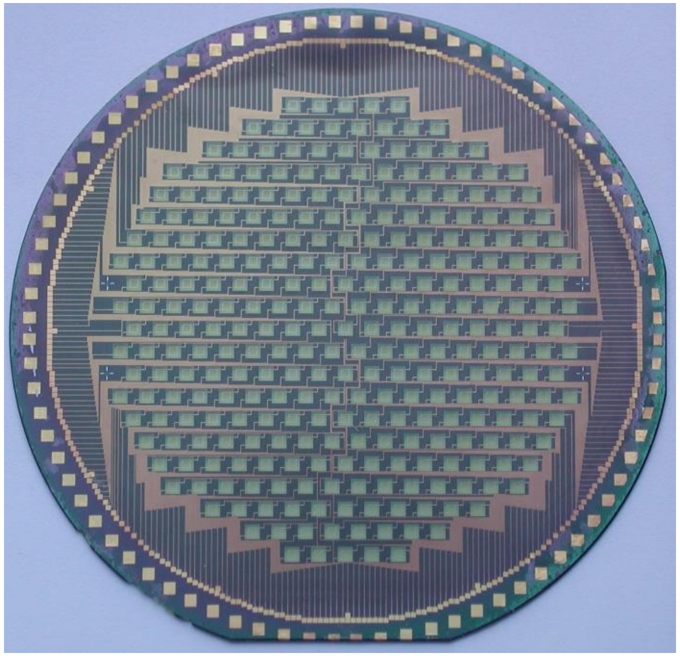
EM pickup

Total-power Bolometer Arrays

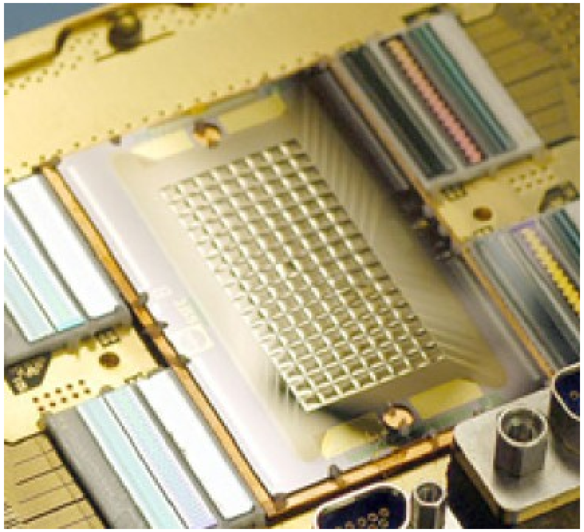
Kovács et al. 2010, ApJ, 717, 29



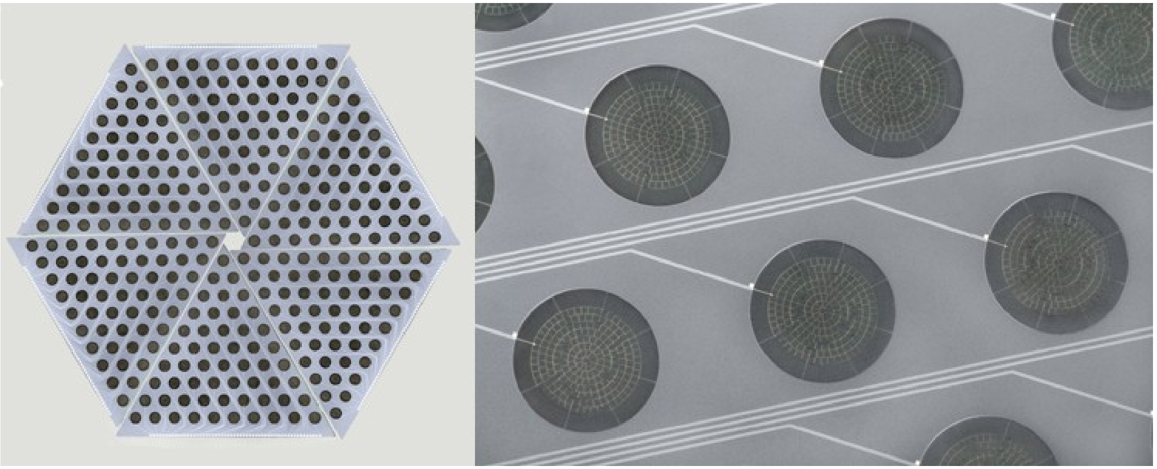
SHARC-2 (350um)



LABOCA (870um)



GISMO (2mm)



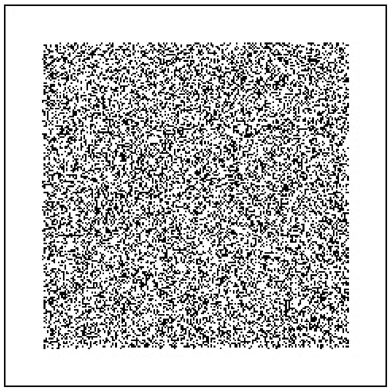
ASZCA (2mm)

Scanning Patterns for Imaging

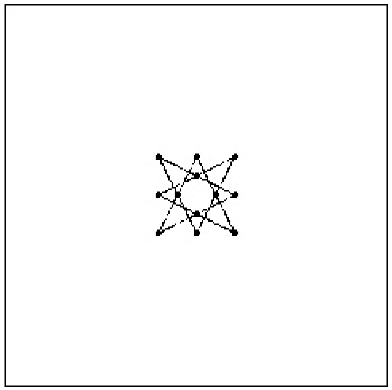
Kovács, 2008, *Proc.* SPIE 7020, 5

Pattern Gallery

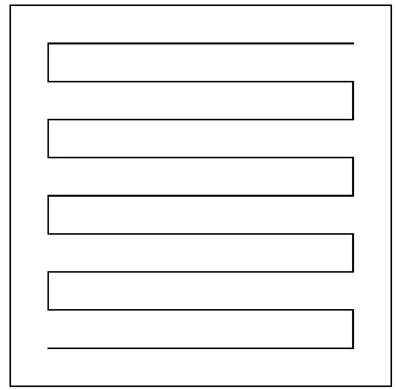
random



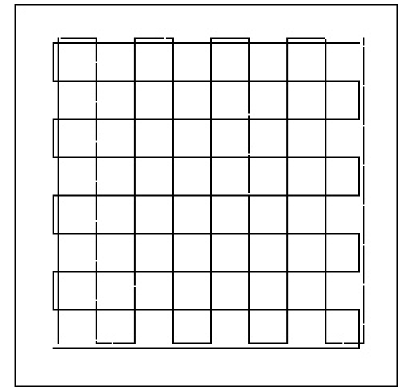
DREAM



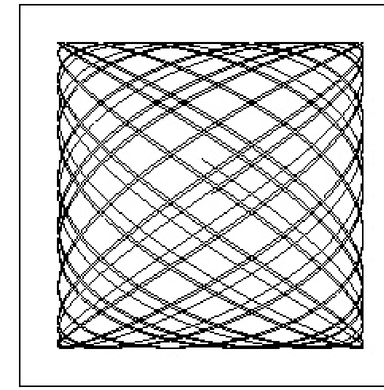
OTF



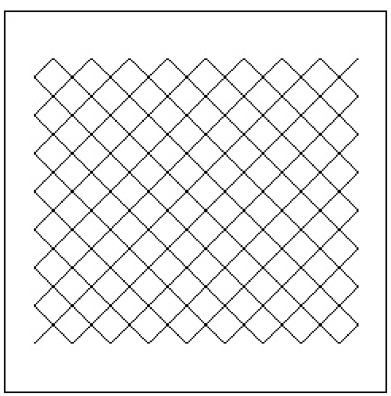
OTF (cross-linked)



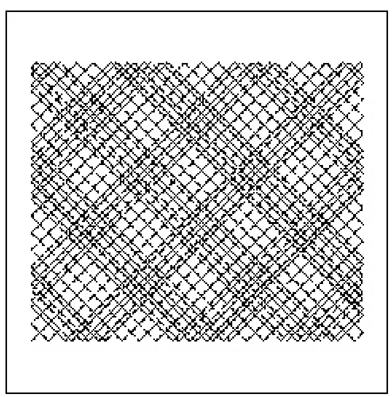
Lissajous



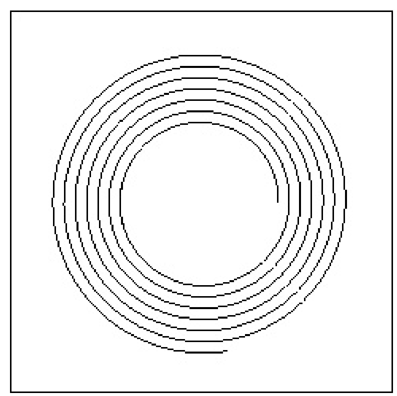
Billiard (closed)



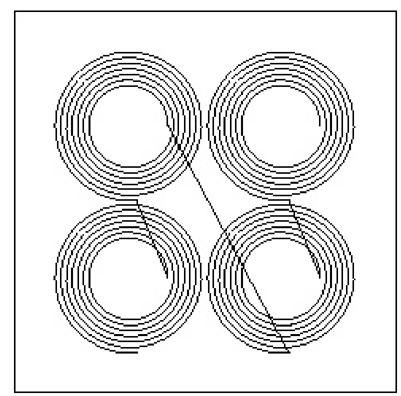
Billiard (open)



spiral



raster-spiral



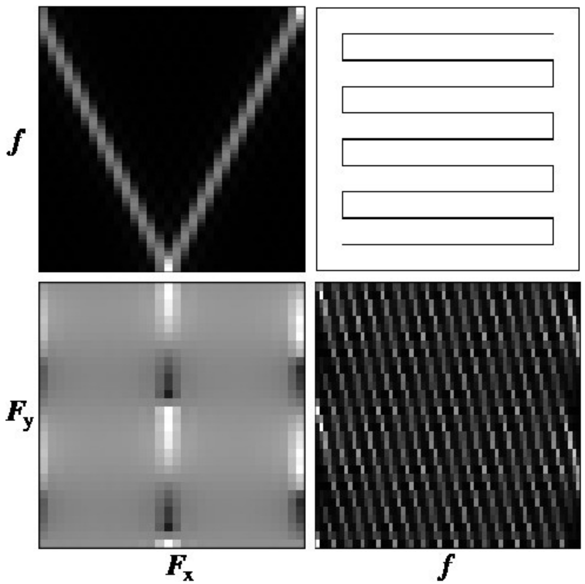
... and other patterns...

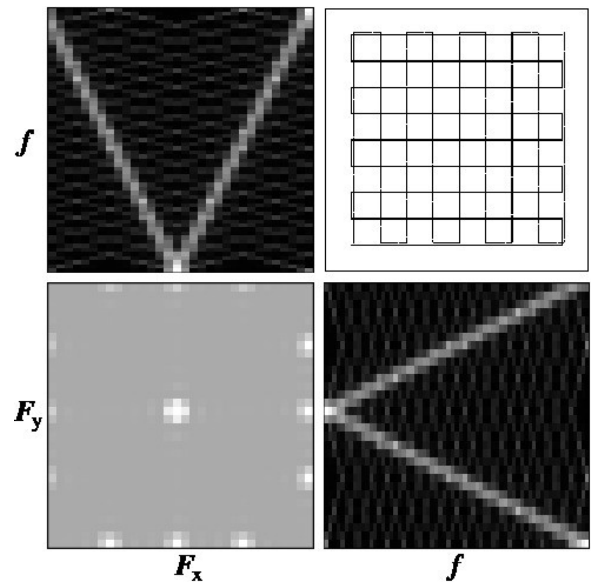
What is your favourite?

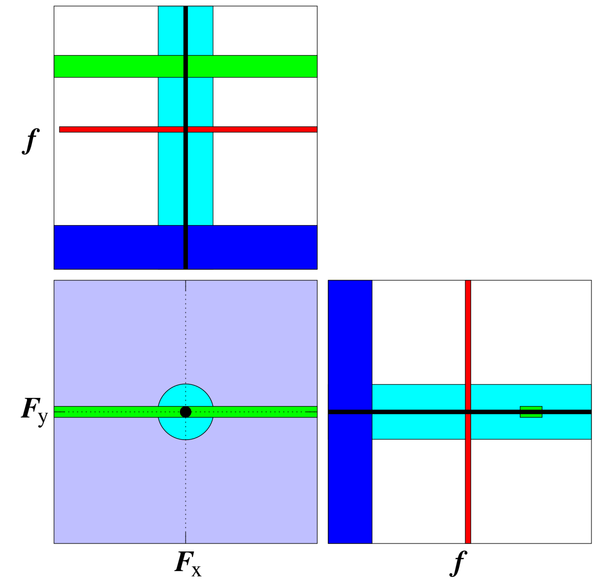
http://www.submm.caltech.edu/~sharc/scanning/

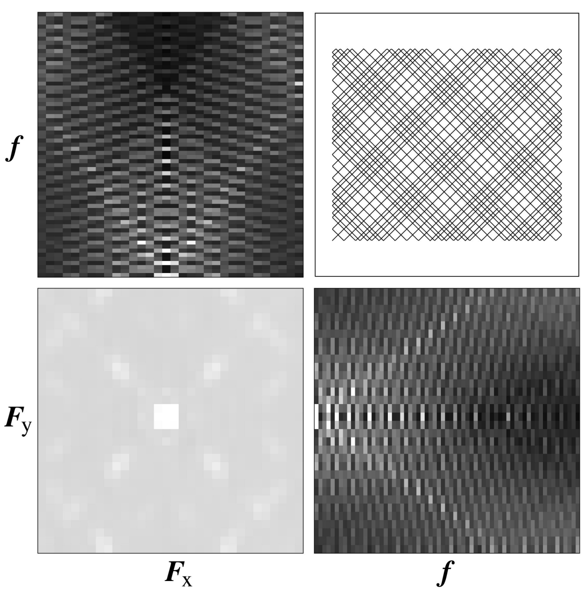
Scanning Patterns

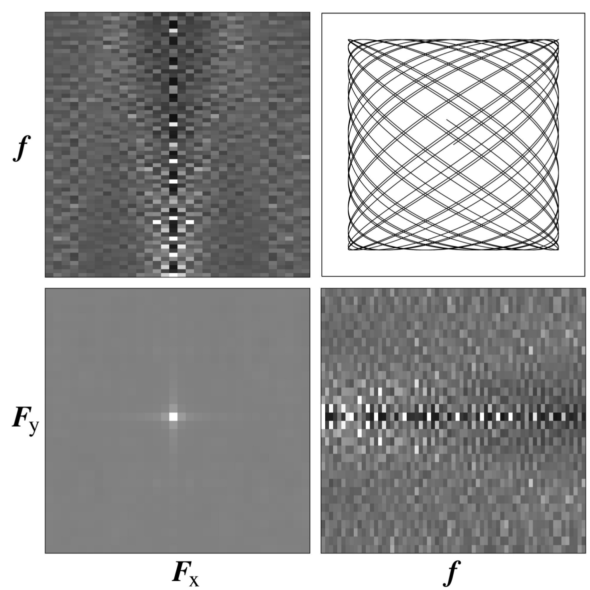
Spectral Dispersion (noise resistance)

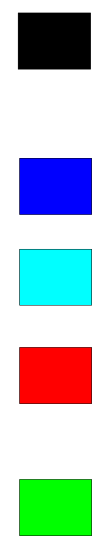












Correlated Noise (atmosphere, T-fluctiation)

1/f Noise

Sky Noise

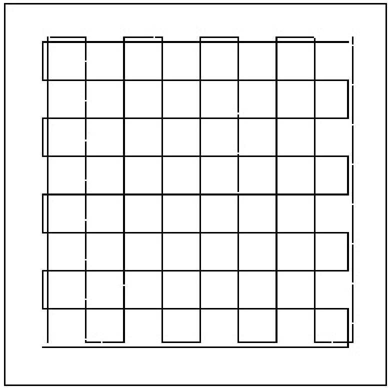
Narrow-band Resonance (isotropic)

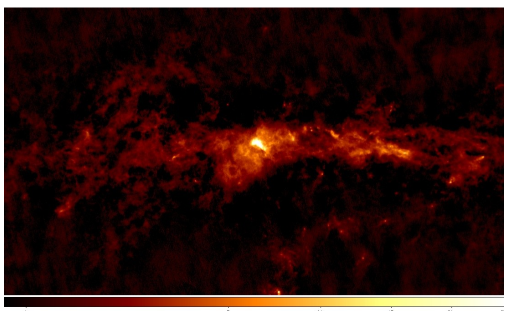
Wide-band Resonance (oriented)

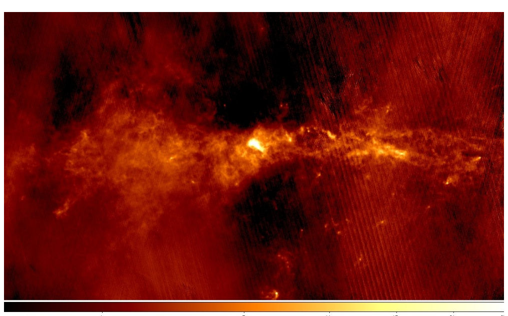
Scanning Patterns

Kovács, 2008, *Proc.* SPIE 7020, 5

OTF (cross-linked)

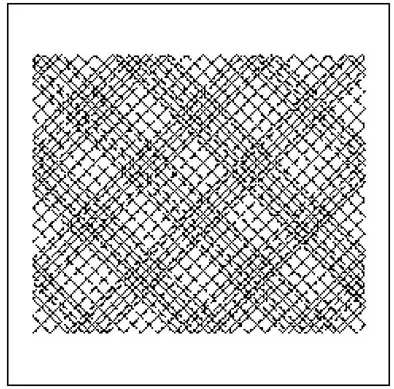


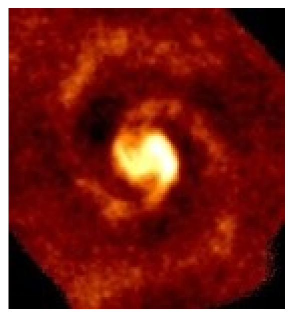




LABOCA
GISMO

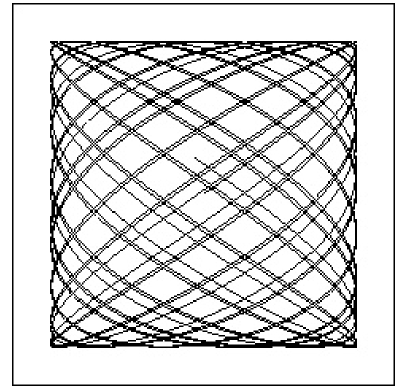
Billiard (open)

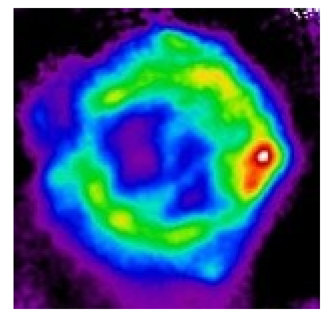


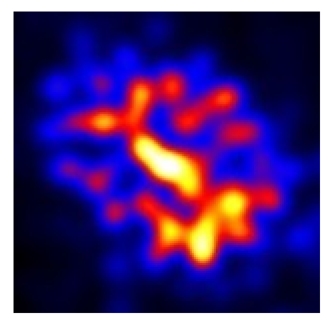


SHARC-2
SCUBA-2

Lissajous

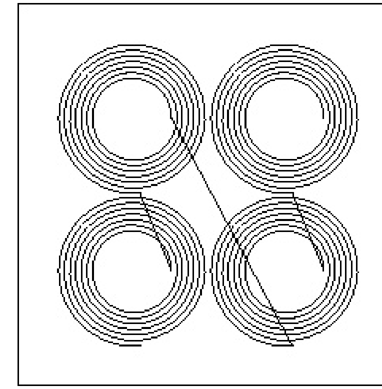


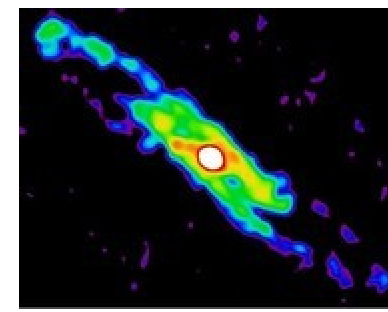


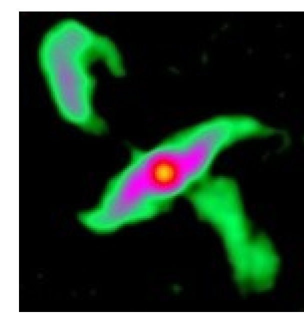


SHARC-2
GISMO
LABOCA, SABOCA

raster-spiral







LABOCA, SABOCA

CRUSH

Comprehensive Reduction Utility for SHARC-2 (and more...)

Kovács, 2008, *Proc.* SPIE 7020, 45

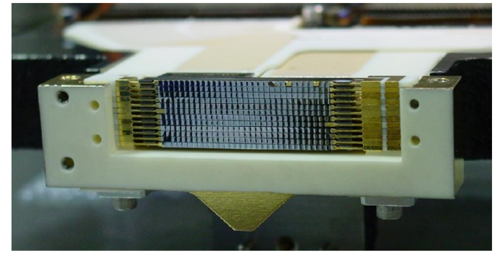
1/f noise

Unstable gain/noise

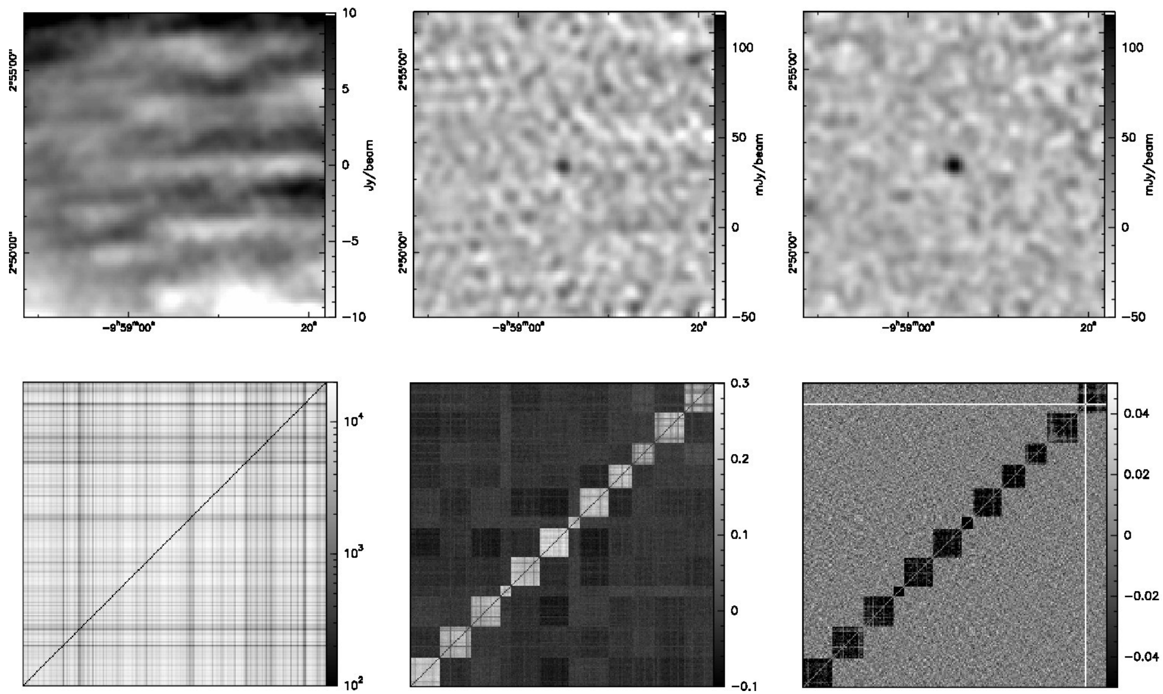
Microphonics

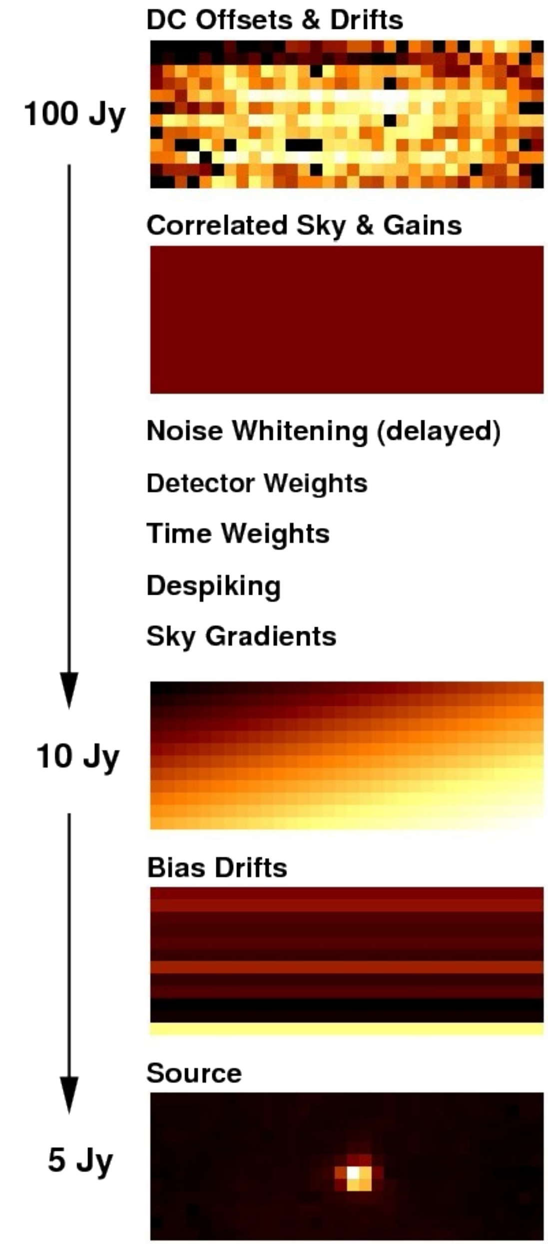
EM pickup

Glitches



SHARC-2 (350um)

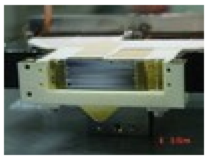
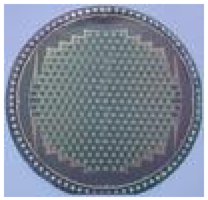
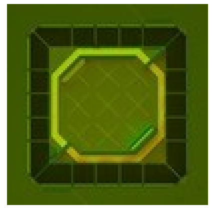
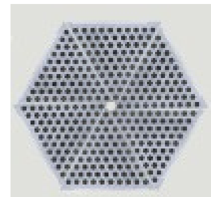


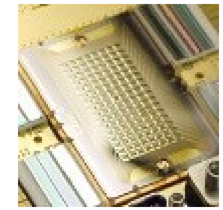


www.submm.caltech.edu/~sharc/crush

CRUSH

Comprehensive Reduction Utility for SHARC-2 (and more...)


SHARC-2	**LABOCA**	**SABOCA**	**ASZCA**	**p-ArTeMiS**	**PolKa**	**GISMO**	**SCUBA-2**
350um	870um	350um	2mm	200um 350um 450um	870um polarimetry	2mm	450um 850um
CSO (2003)	APEX (2007)	APEX (2008)	APEX (2006)	APEX (2011)	APEX (2010)	IRAM (2008+)	JCMT (2010+)
sharcsolve	**BoA**						**SMURF**

Easily expandable to more instruments...

... and different data types
(e.g. spectral scanning, heterodyne arrays, interferometry?)

Entree

Interpreting SMG Surveys

Disentangling Multiplets

A Larger, Deeper Survey of Submillimeter Galaxies

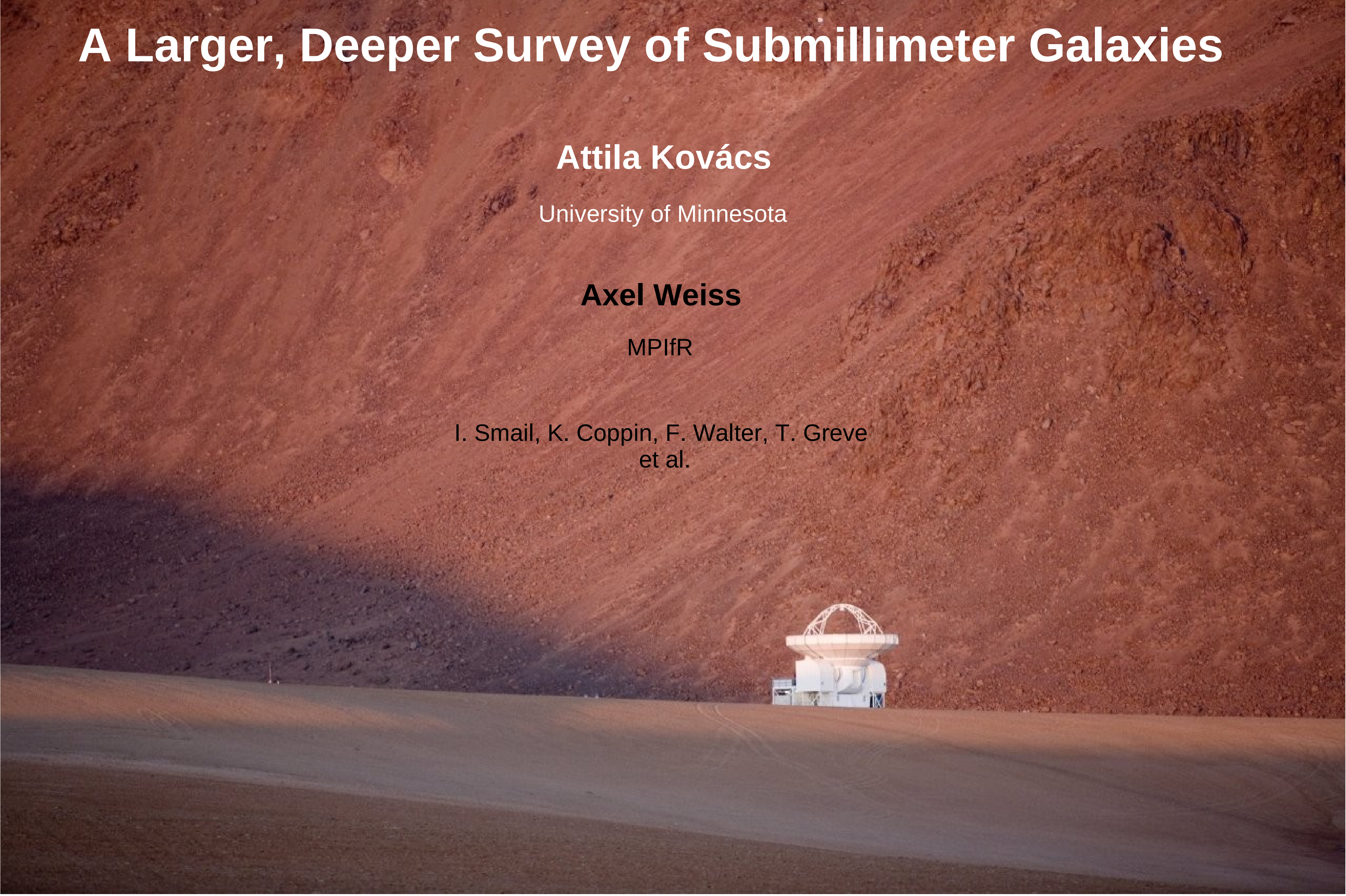
Attila Kovács

University of Minnesota

Axel Weiss

MPIfR

I. Smail, K. Coppin, F. Walter, T. Greve
et al.

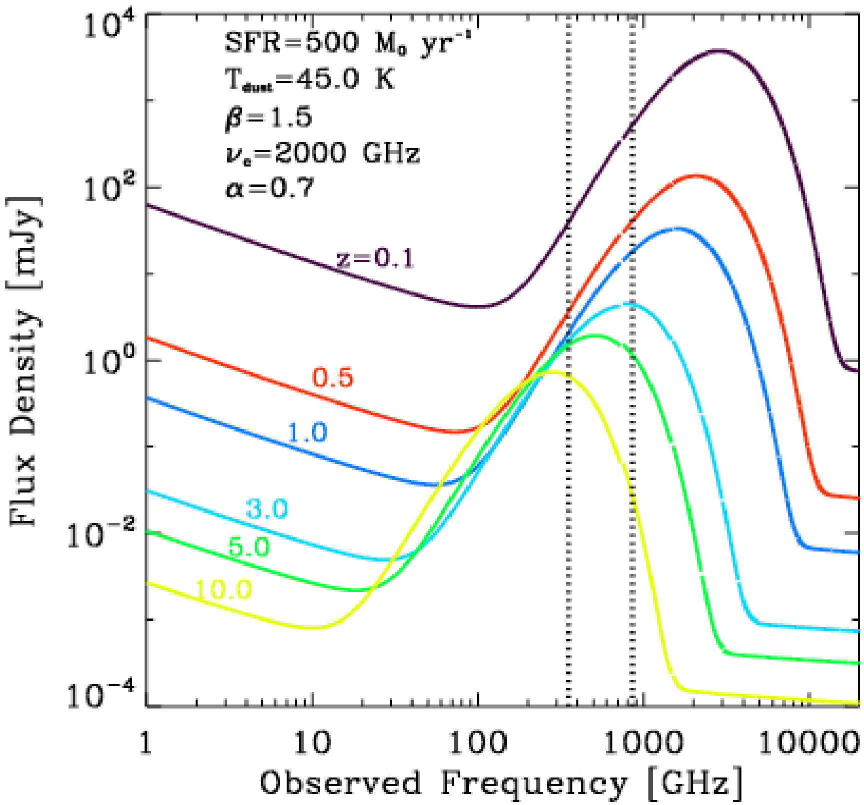


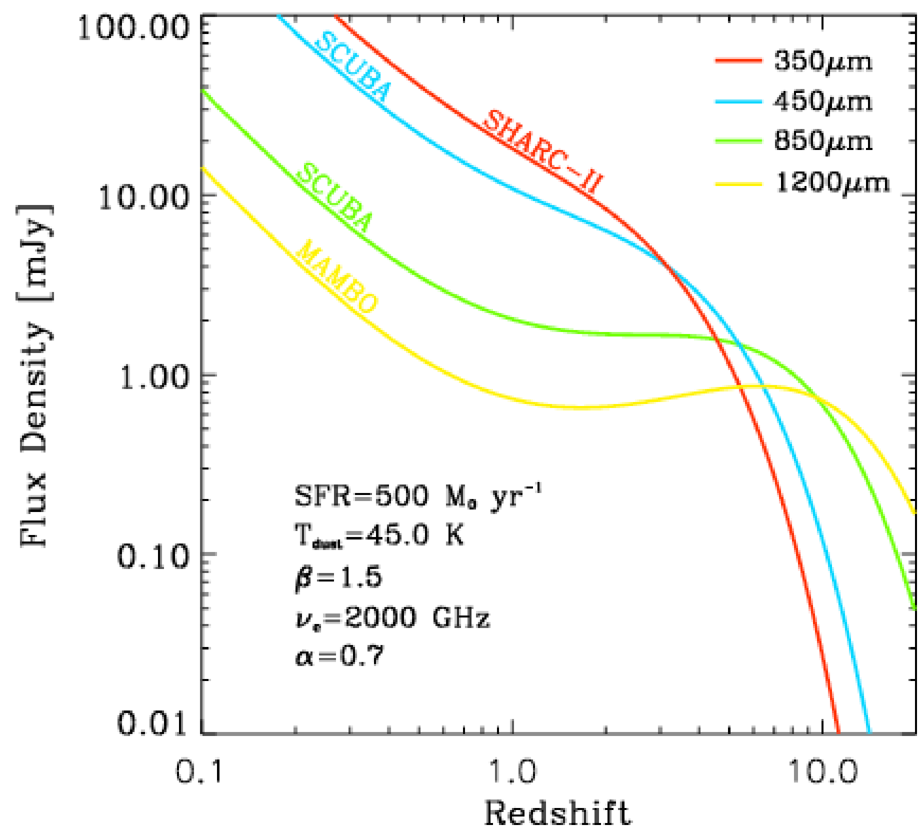
Max-Planck-Institut für Radioastronomie

MPE

Weiss et al., ApJ, 707, 42 (2009)

K-Correction Benefits...



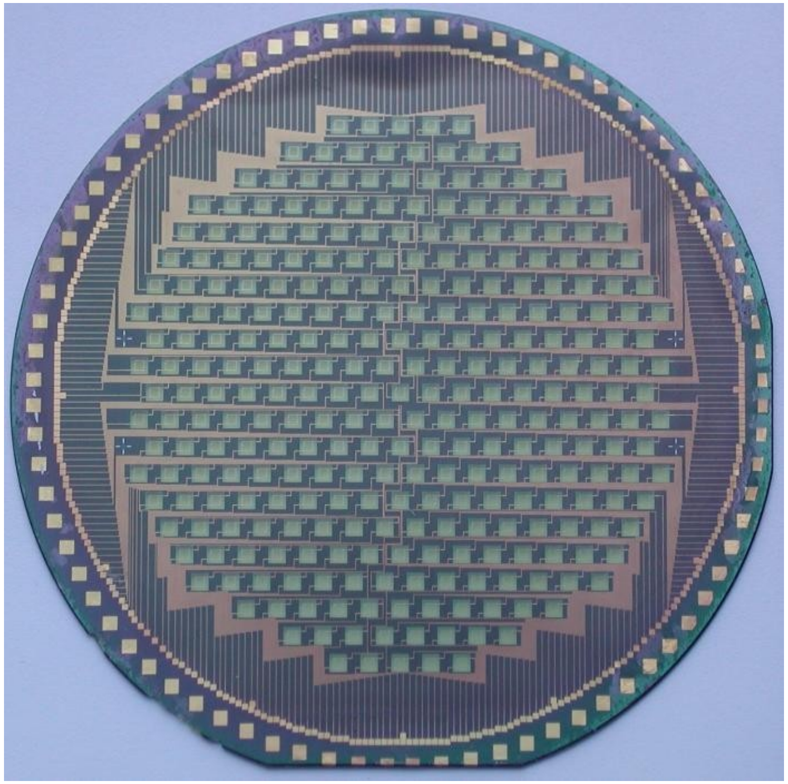


T. Greve

850 micron is equally sensitive to the *same* galaxy at z ~ 1–10...
(the shorter wavelengths less so...)

LABOCA

(Large Bolometer Camera)



Siringo et al. 2009

295 pixels

(870um)

The CDFS at 870 microns

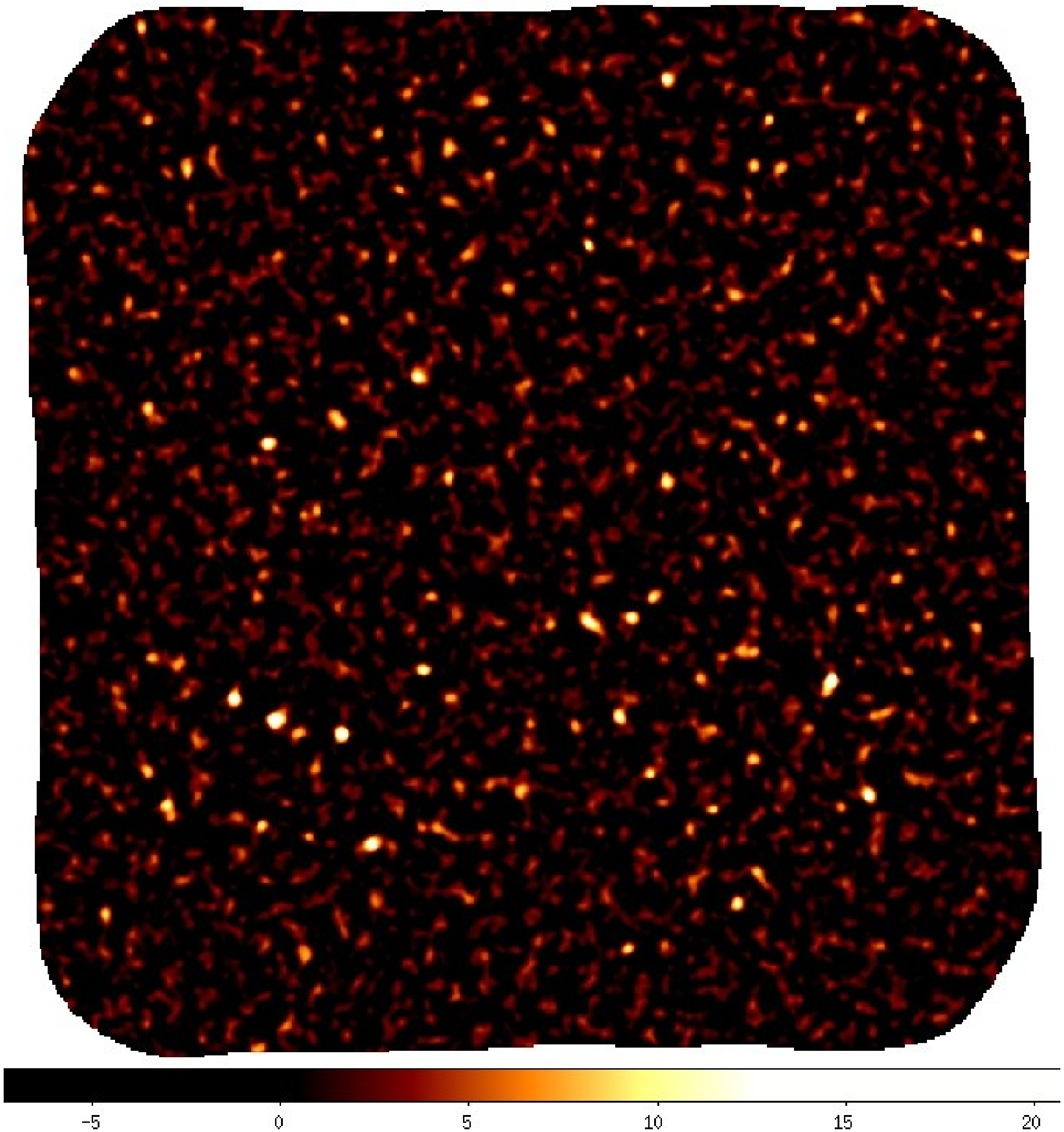
Weiss et al. 2009, ApJ, 707, 42

300 hours

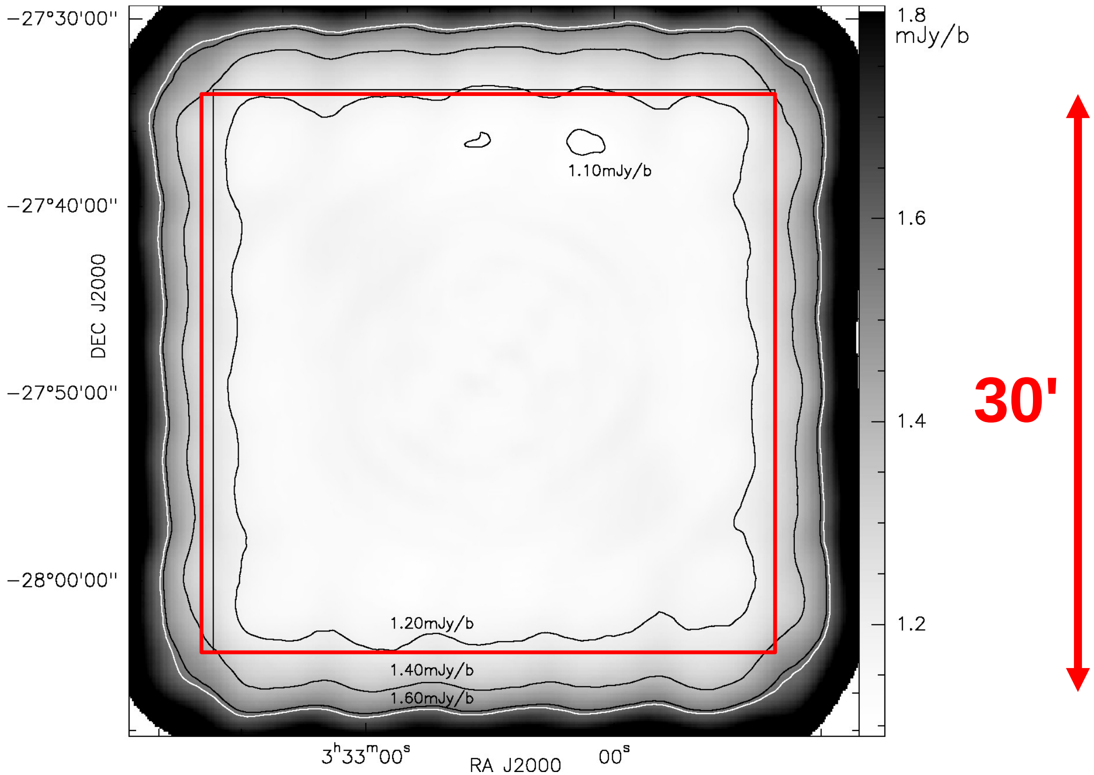
19” beam
(27” smoothed)

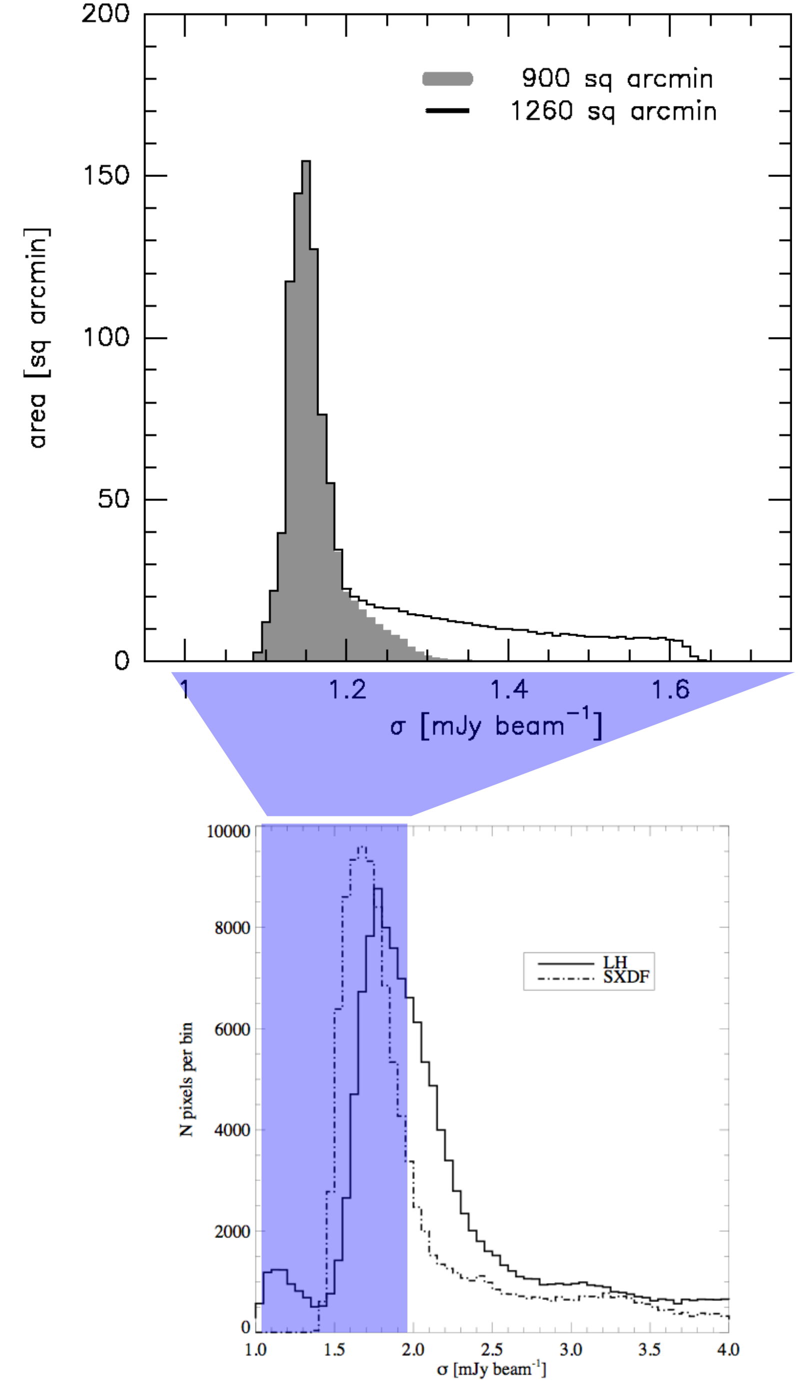
1.2 mJy/beam

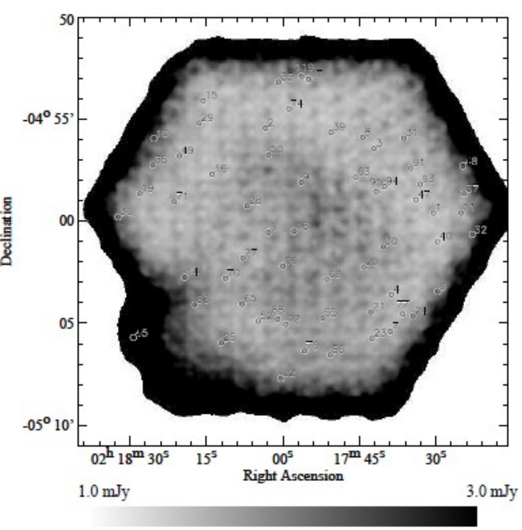
125 sources
(5 false)

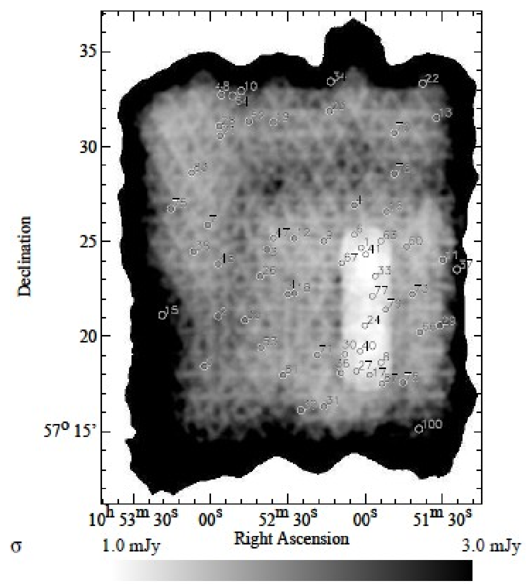


mJy/beam


−27°30'00''
−27°40'00''
−27°50'00''
−28°00'00''
DEC J2000
1.8 mJy/b
1.6
1.4
1.2
1.10mJy/b
1.20mJy/b
1.40mJy/b
1.60mJy/b
3h33m00s
RA J2000
00s
30'


900 sq arcmin
1260 sq arcmin
area [sq arcmin]
σ [mJy beam−1]
LH
SXDF
N pixels per bin
σ [mJy beam−1]


Declination
Right Ascension
1.0 mJy
3.0 mJy


σ
Declination
Right Ascension
1.0 mJy
3.0 mJy

How (Not) to Get Source Counts...

The "Direct" Method...

Luminosity Function

Evolution (color)

(z-Distribution)

Stellar Analogy:

IMF

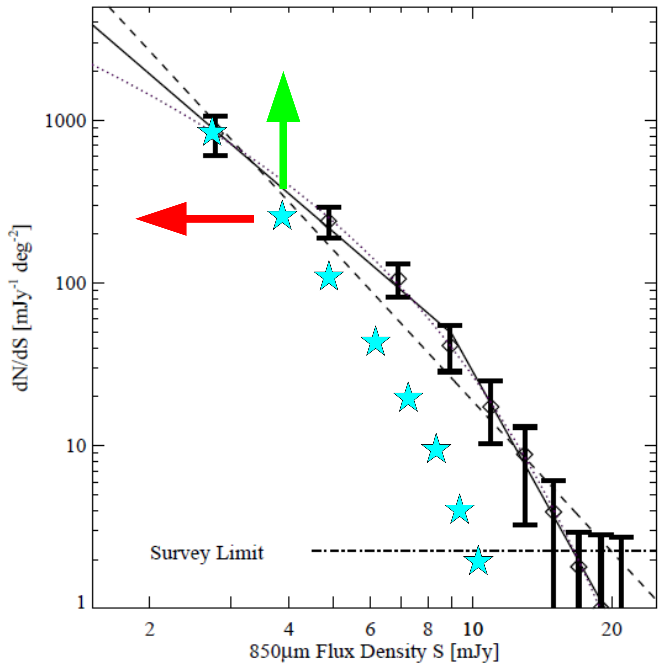
1. Bin your source brightnesses

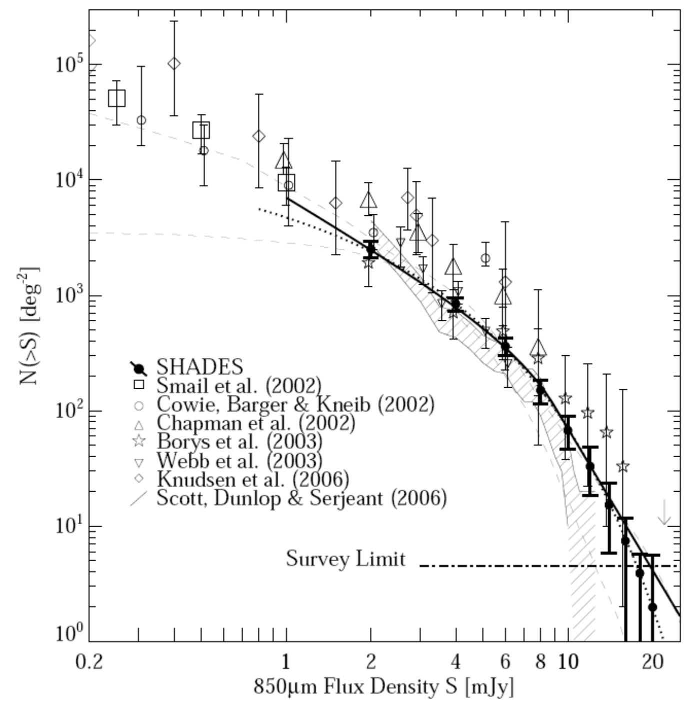
2. **Deboost** with

$$p(S) = \frac{\partial N}{\partial S}$$

3. **Completeness** correction

4. Get dN/dS





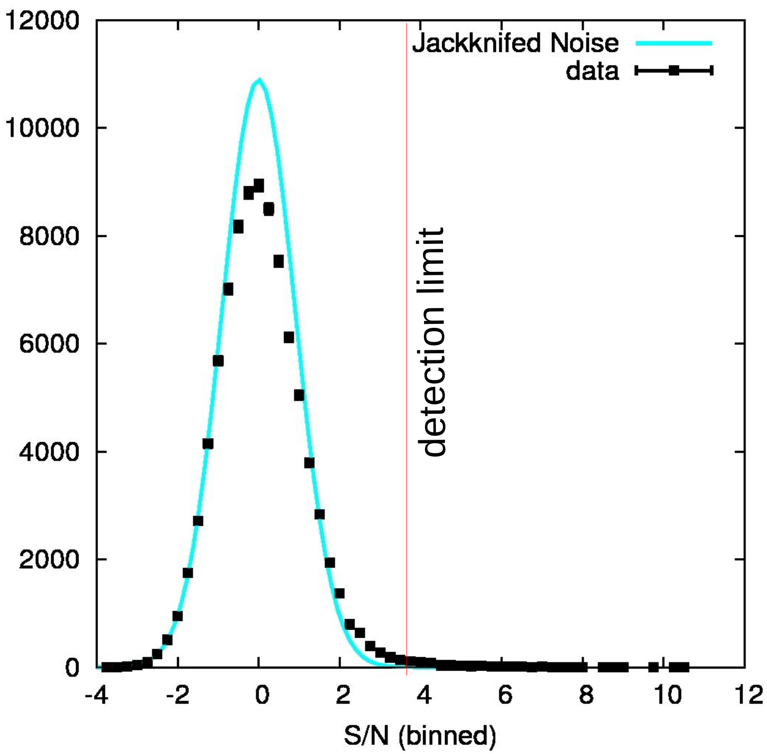
Coppin et al. 2006

Hidden caveat: one source per detection is typically assumed (i.e. no blending)

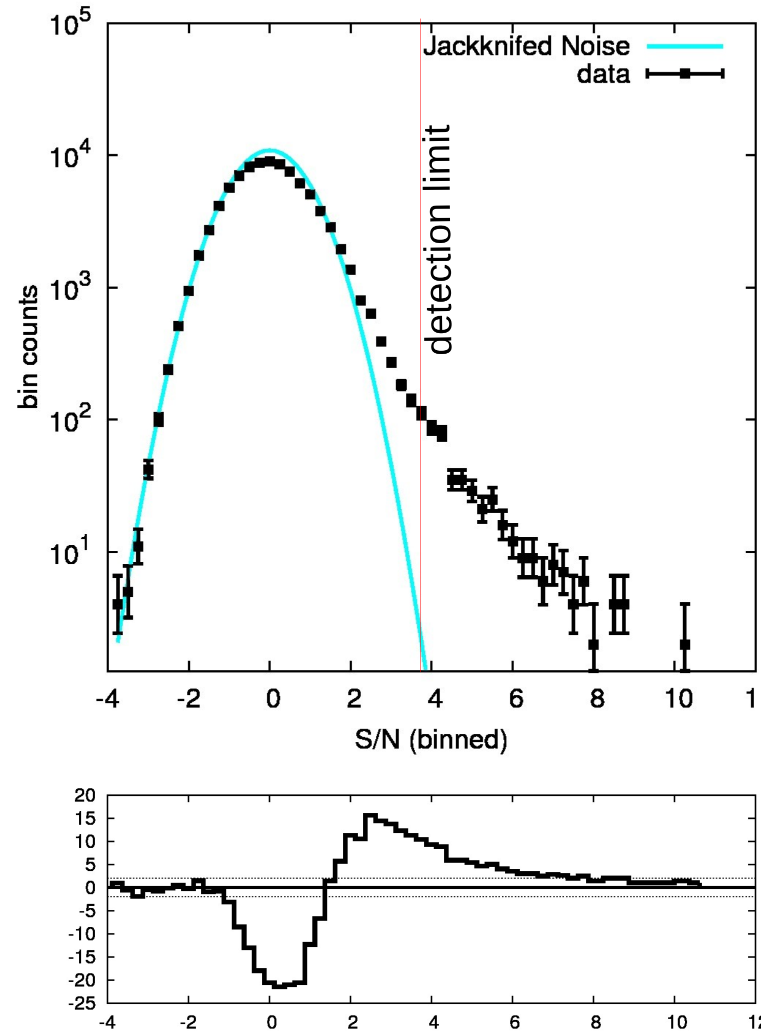
P(*D*) Analysis

Weiss et al. 2009, ApJ, 707, 42

Many faint sources
widen distribution
(confusion noise)



Bright sources
Produce tail

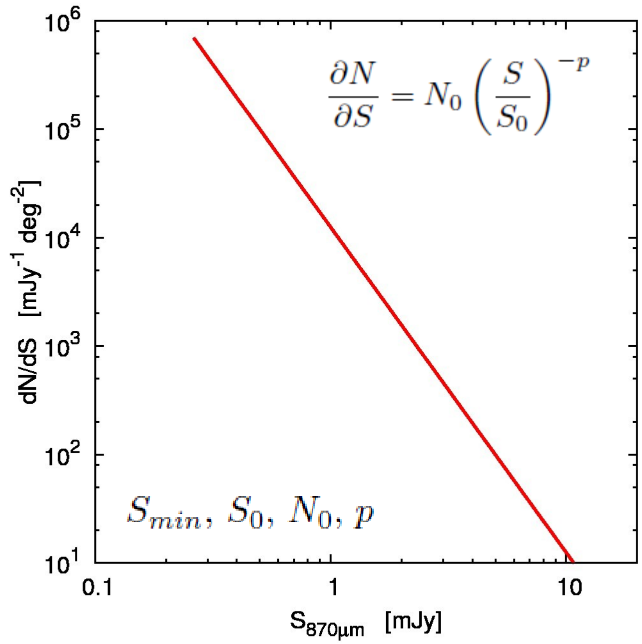


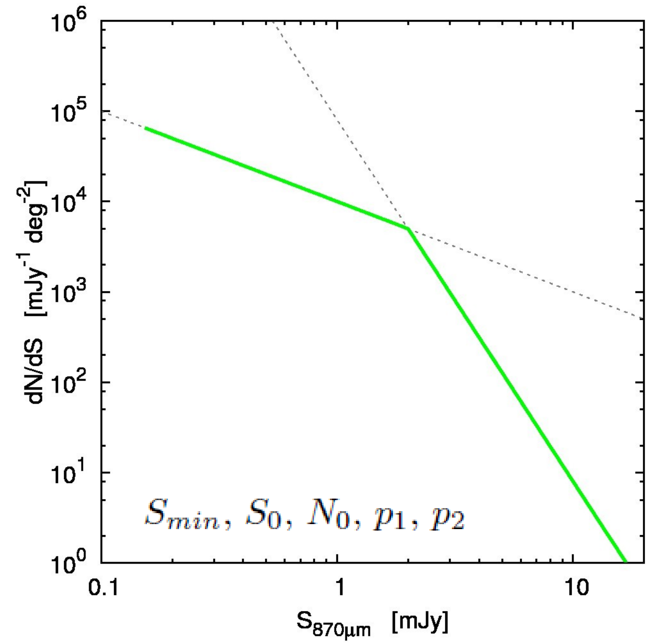
P(*D*) analysis

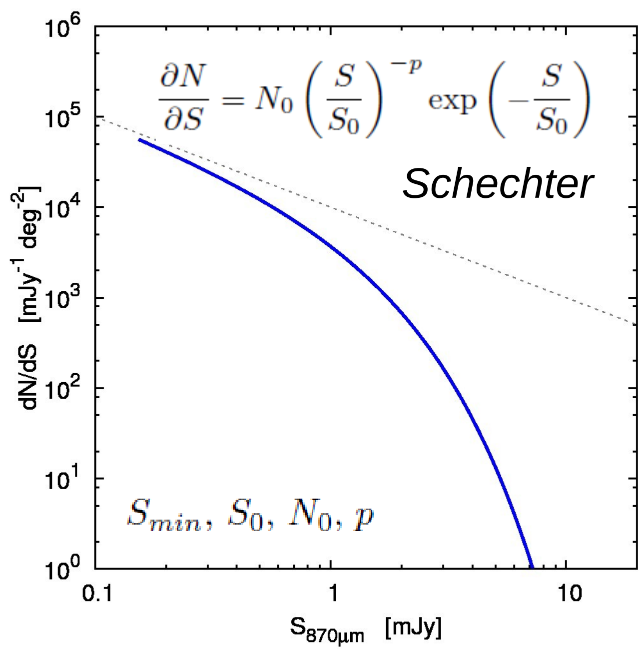
Observed distribution is a product of the source distribution and the underlying noise...

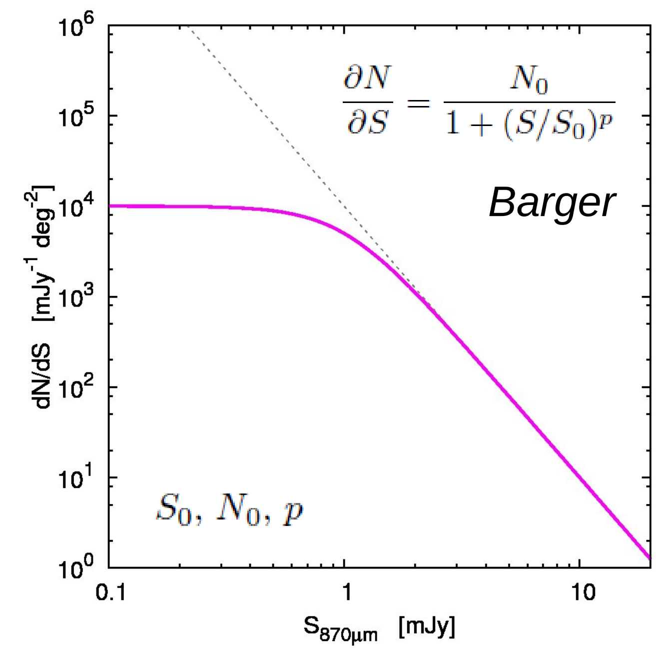
P(*D*) Analysis: Parameters

Weiss et al. 2009, ApJ, 707, 42









$P(D)$ Results

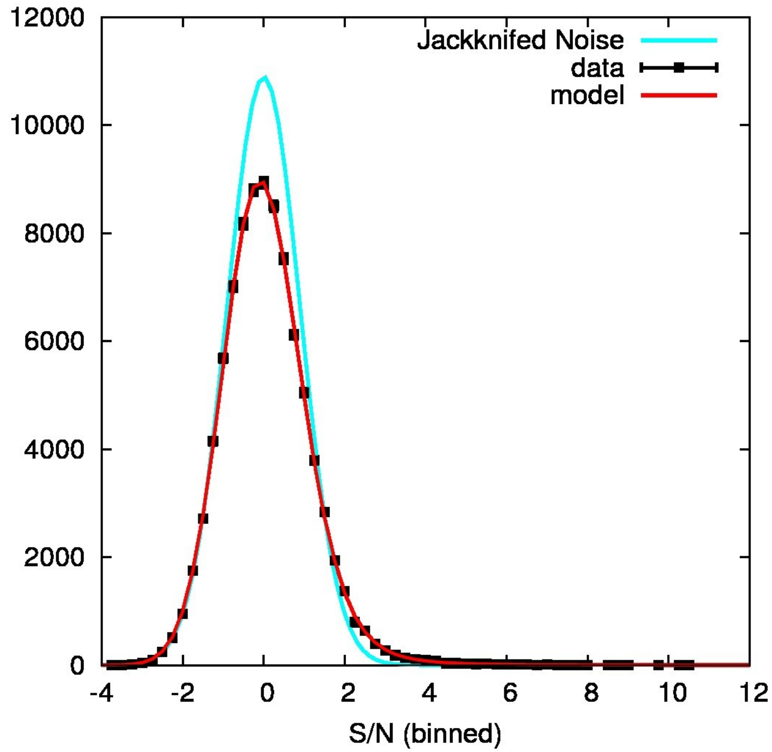
Weiss et al. 2009, ApJ, 707, 42

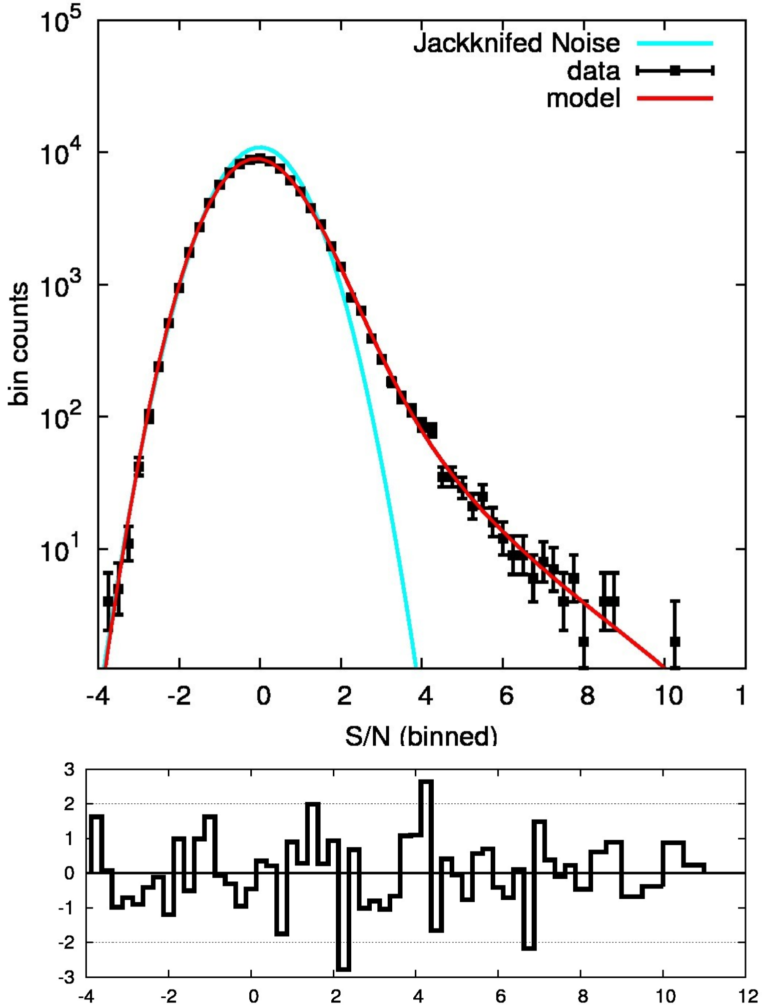
Power Law:

S_{min} = 0.5 mJy

N_0 = 92.7 $mJy^{-1}\ deg^{-2}$

p = 3.178



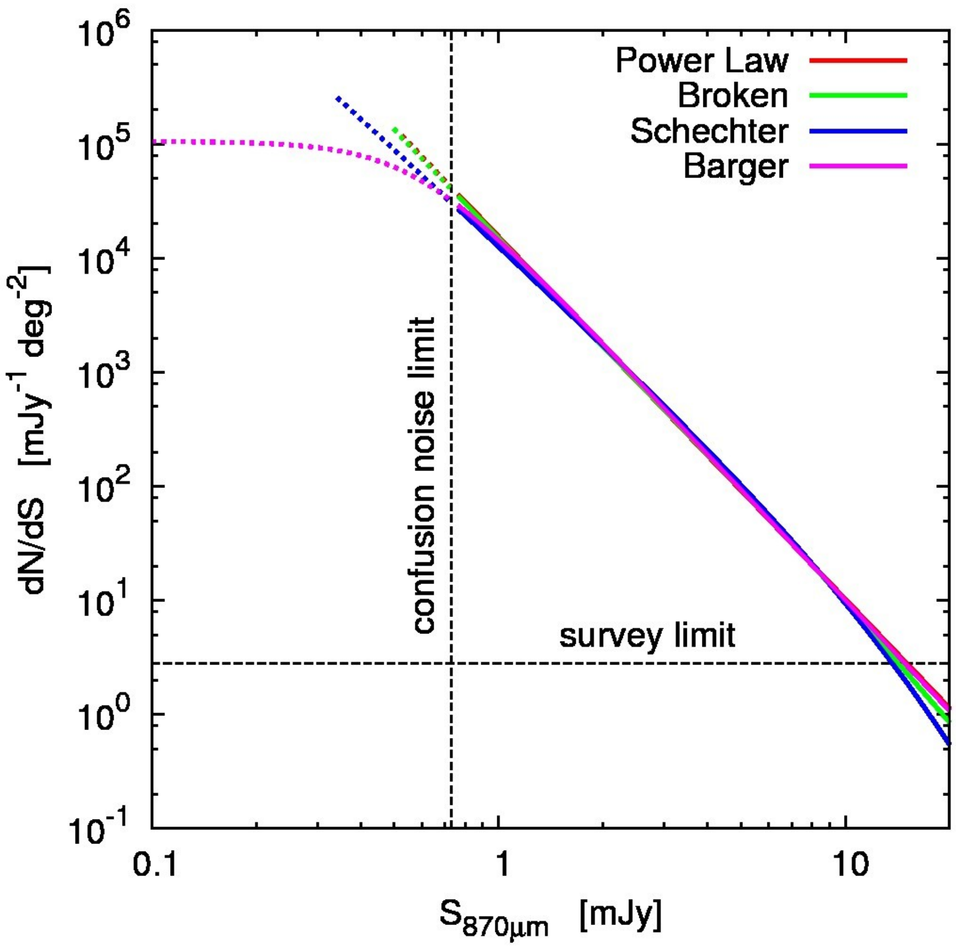


Source Counts from the CDFS

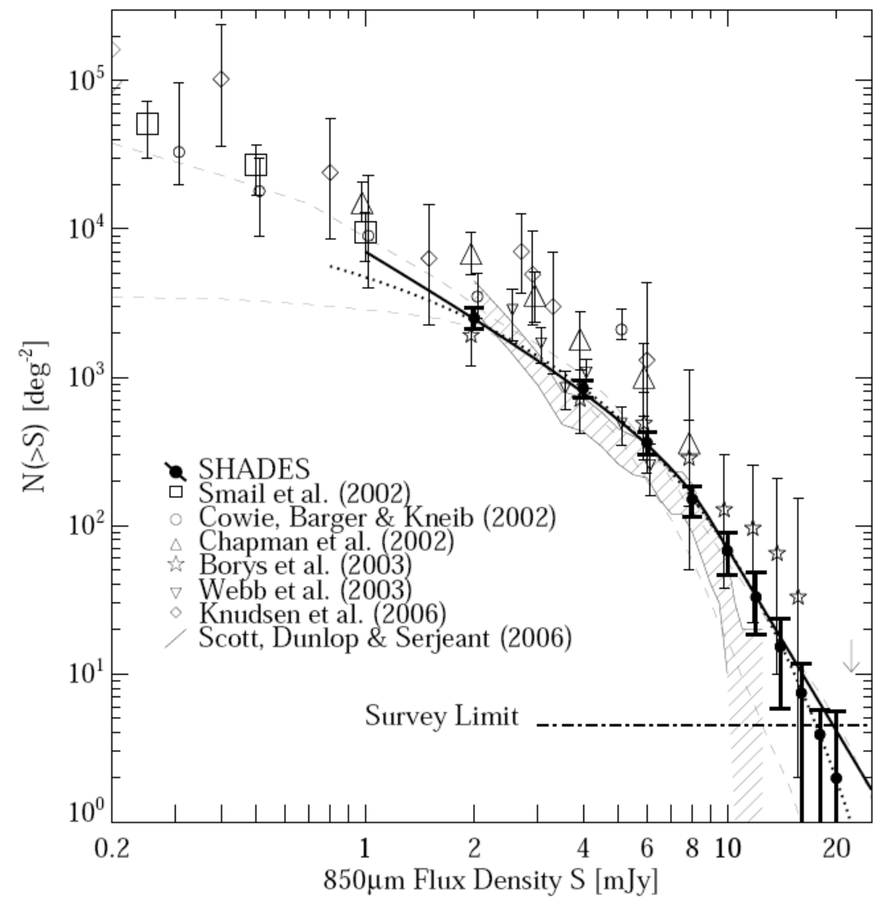
Weiss et al. 2009, ApJ, 707, 42

unbroken power law

CDFS



SHADES



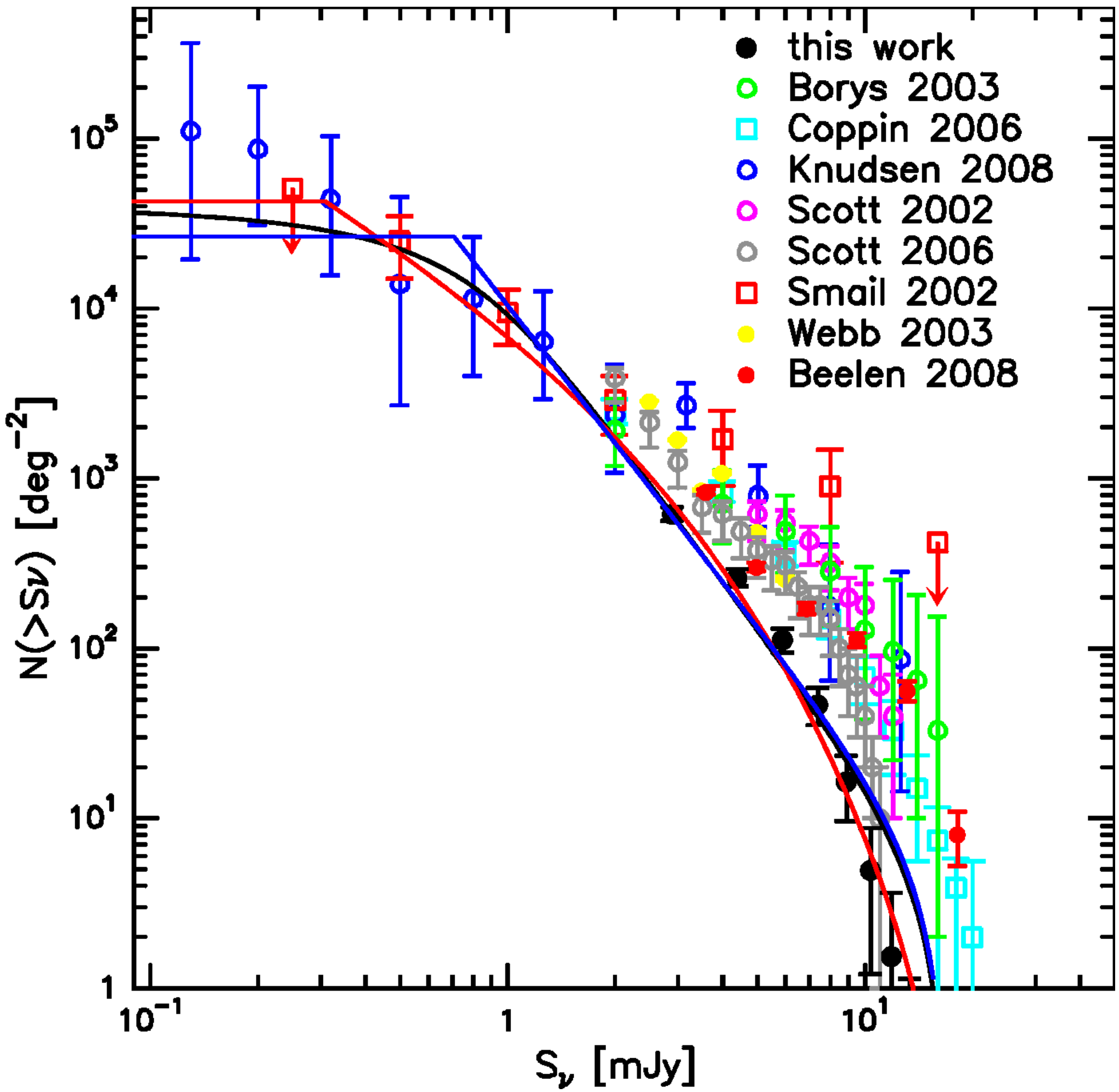
Coppin et al. 2006

Integrated 870um Background: 29-33 Jy/deg^2

COBE: 45 +- 5

Cosmic Variance?

Weiss et al. 2009, ApJ, 707, 42



Underdensities
In the CDFS:

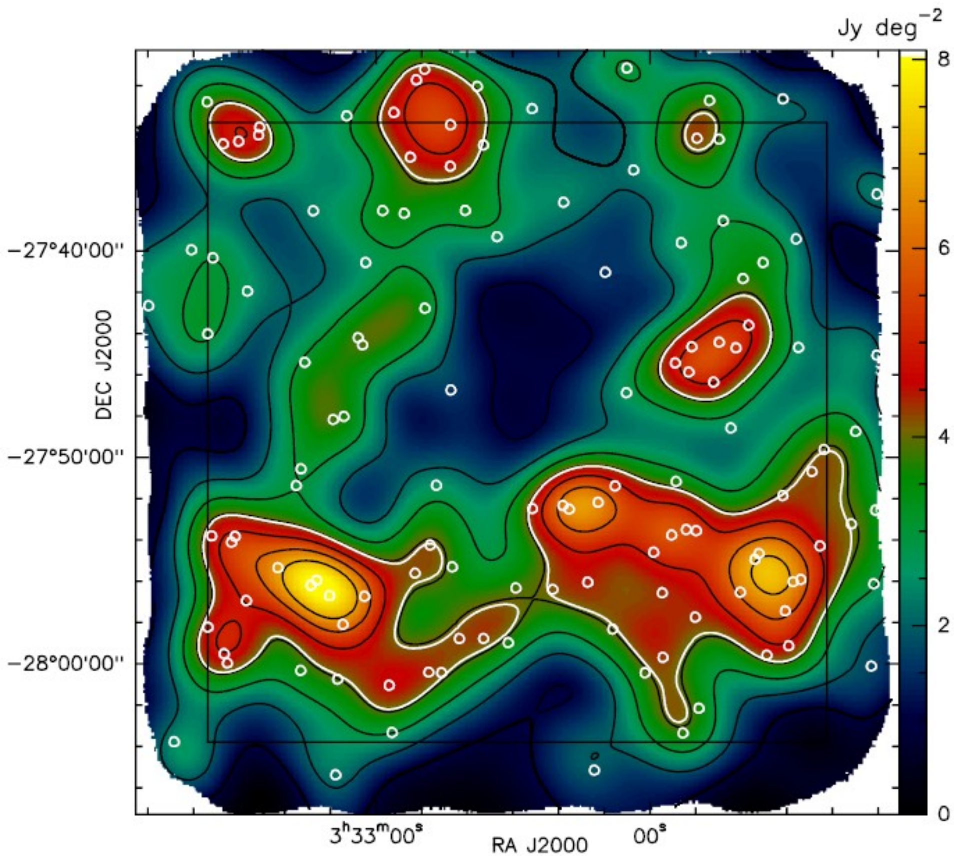
Z > 2 K-band selected galaxies are under-abundant by ~60%.
(Dokkum et al. 2006)

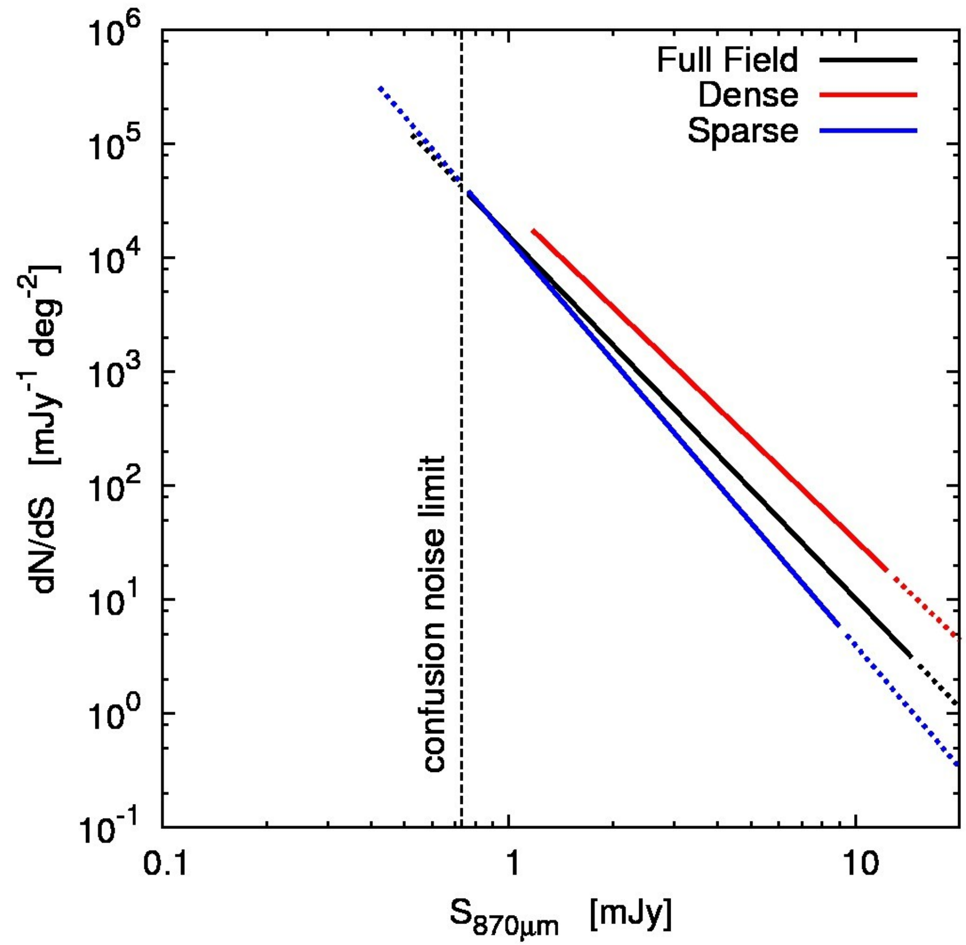
Z > 2.5 DRGs
(Marchesini et al. 2006)

High-z optically bright AGNs
(Dwelly & Page 2006)

Cosmic Variance?

Weiss et al. 2009, ApJ, 707, 42



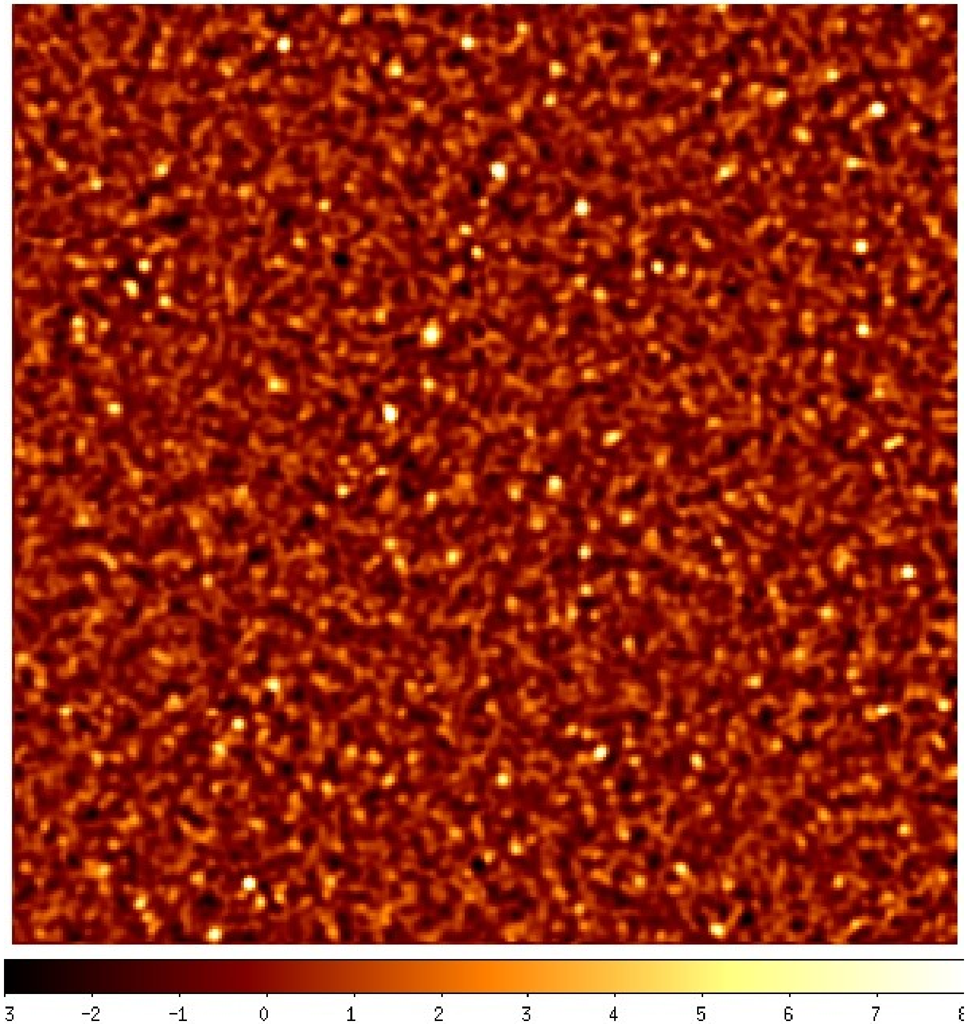


Seems more a variation in steepness rather than density

LABOCA vs *Herschel* Confusion

Weiss et al. 2009, ApJ, 707, 42

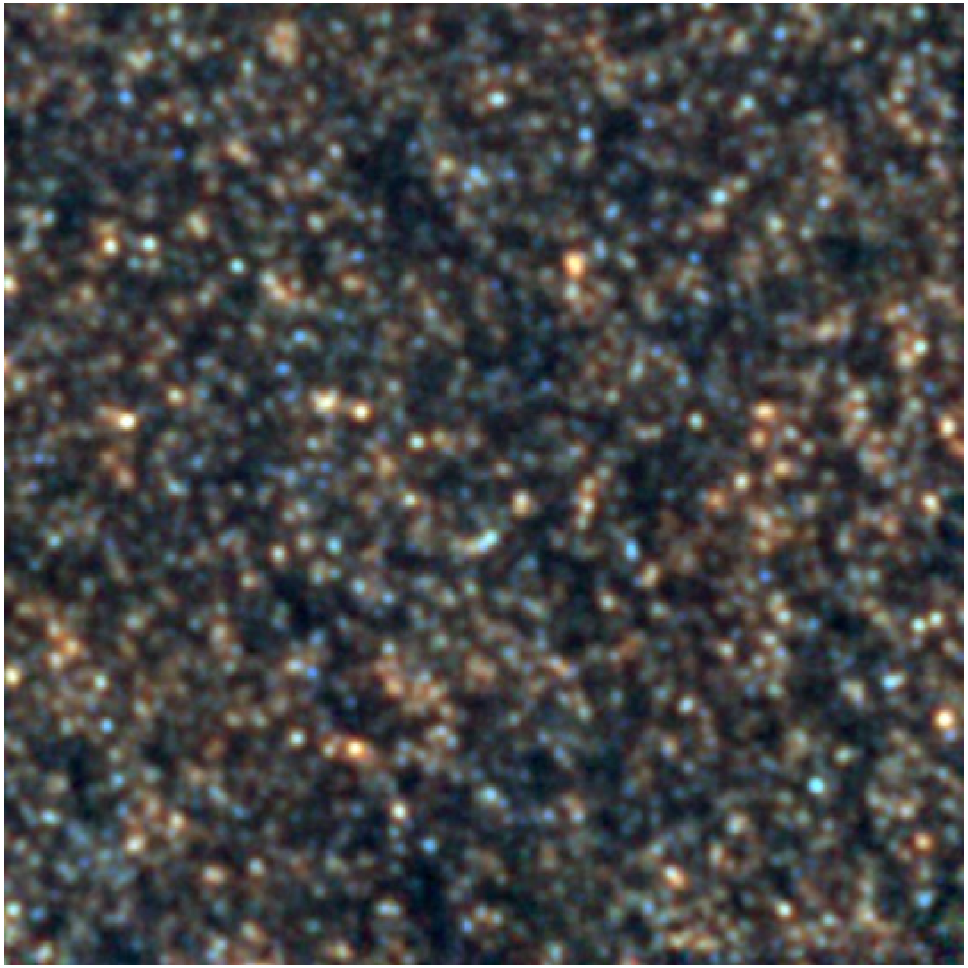
The 870um sky from a 12-m telescope



mJy/beam

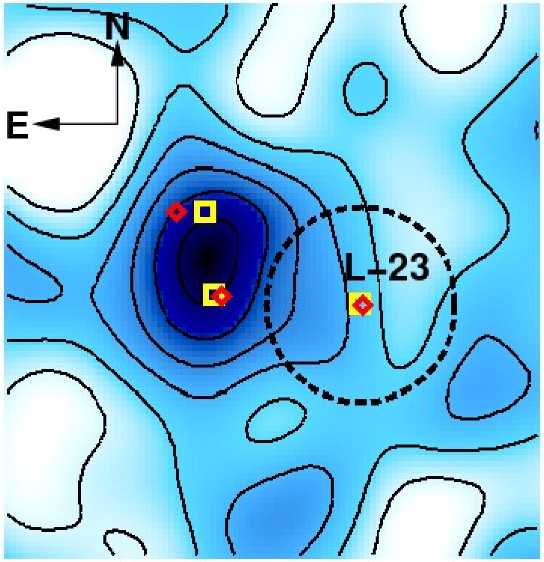
12K source inserted
(no clustering assumed)

Herschel Deep Field



Dominated by z<2 sources

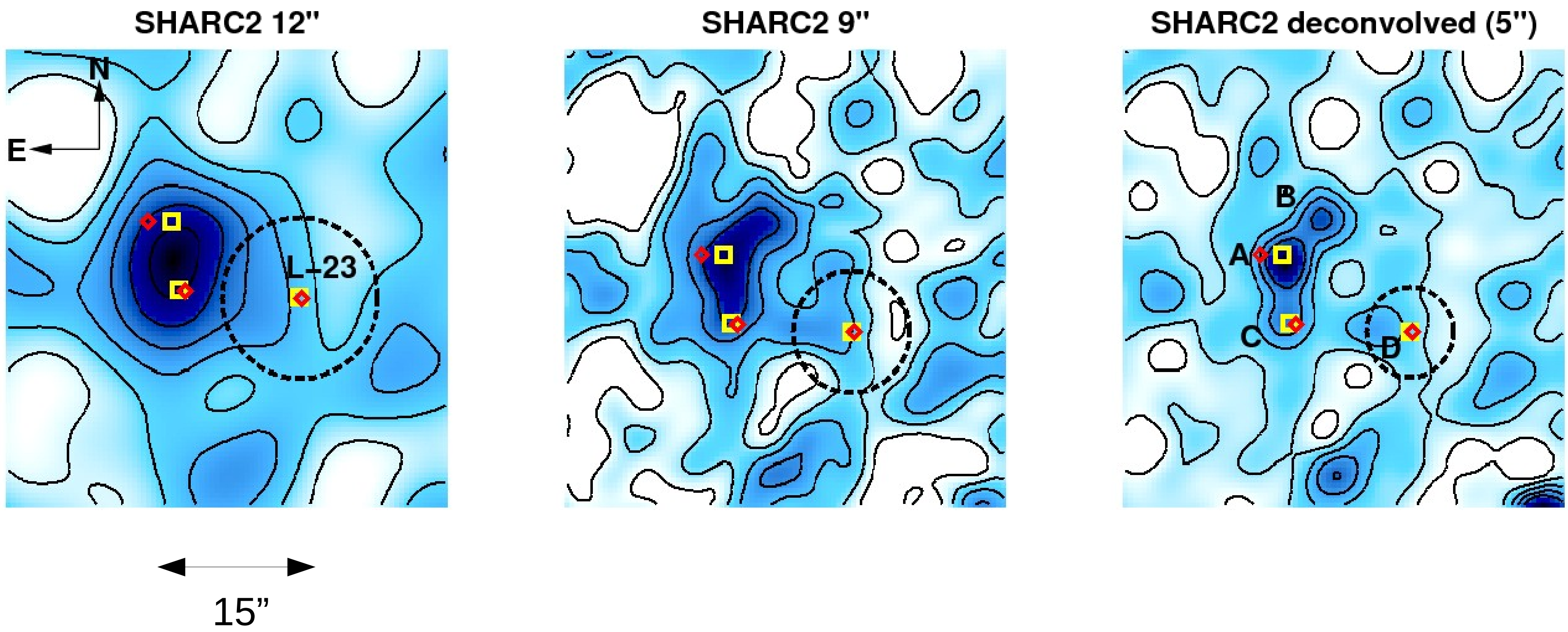
SHARC2 12"



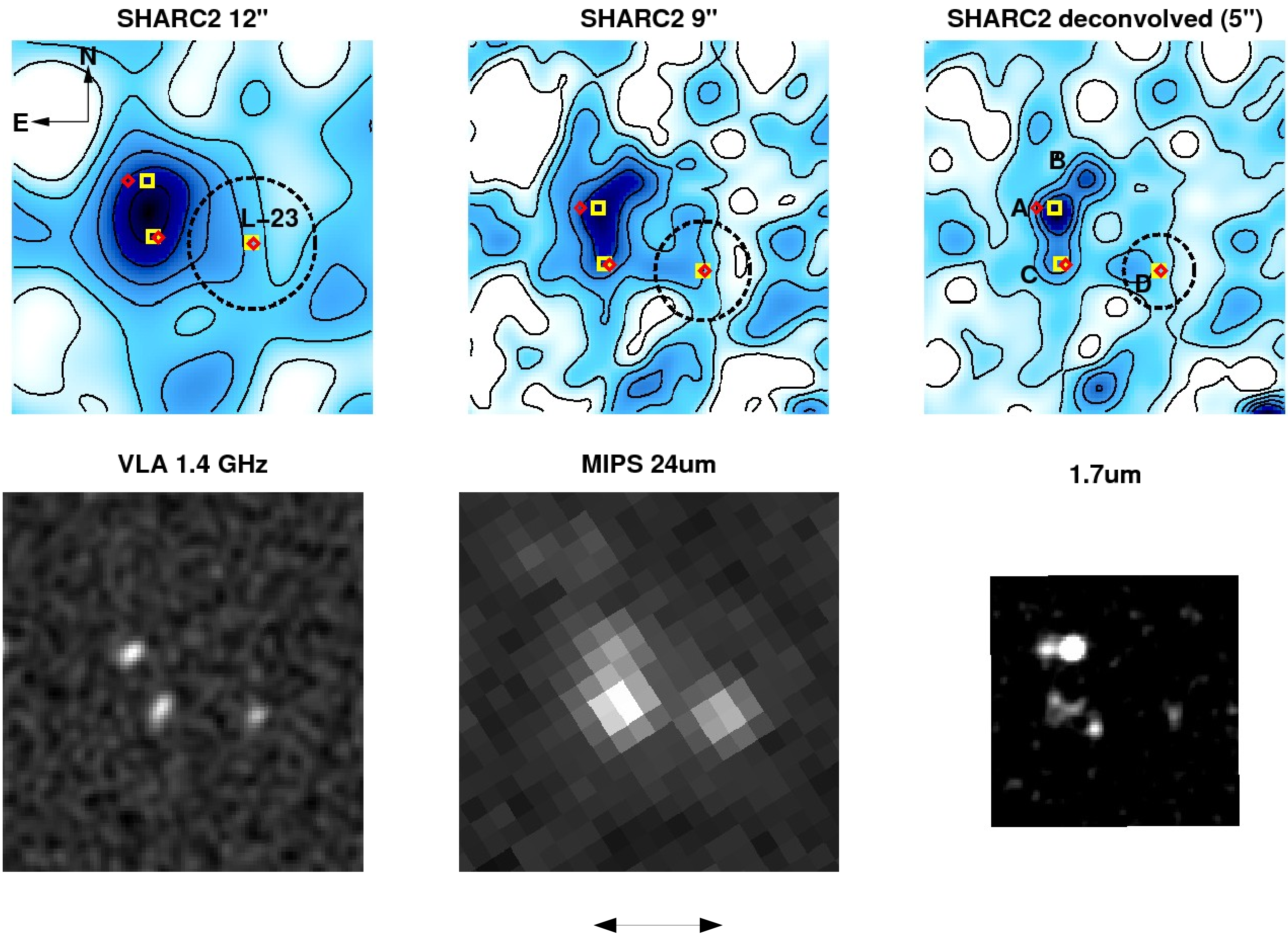
15”

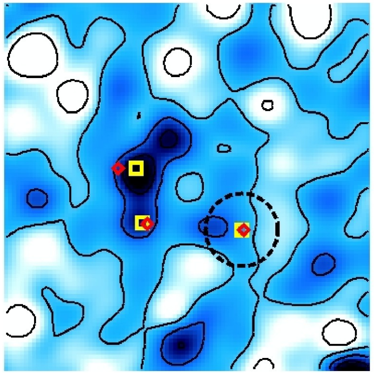
Do we know how to count?...

Kovács et al. 2010, ApJ, 717, 29

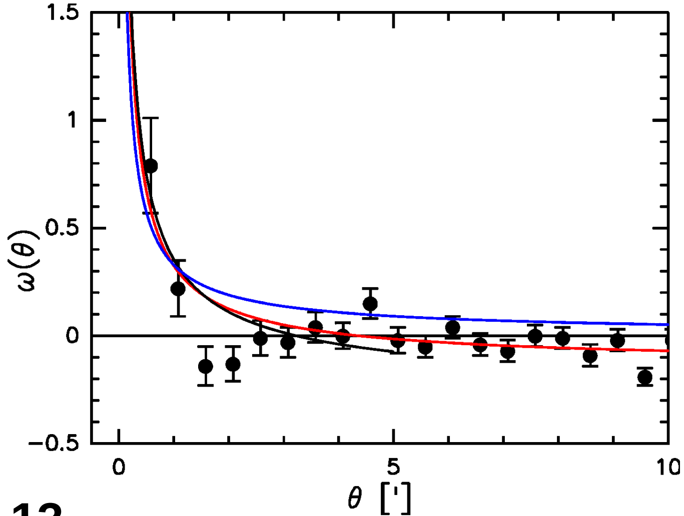


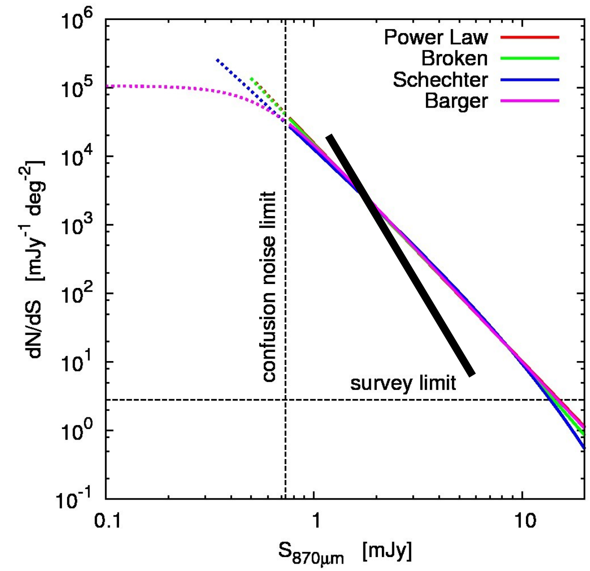
Kovács et al. 2010, ApJ, 717, 29





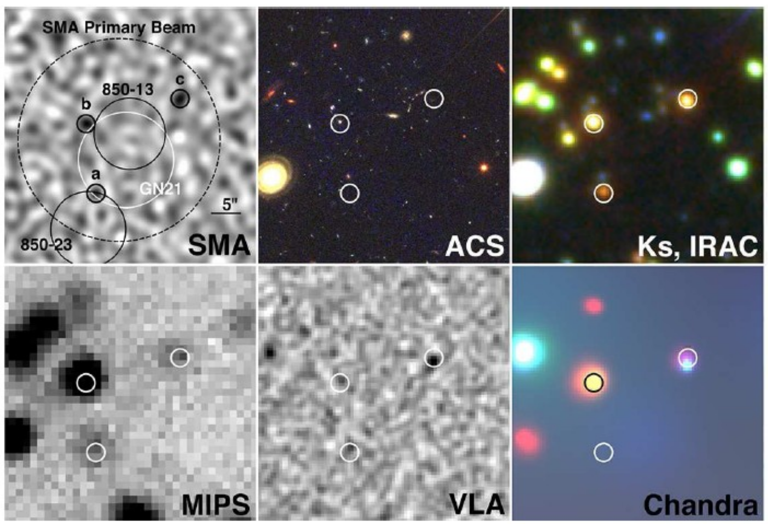
Kovács et al. 2010, ApJ, 717, 29



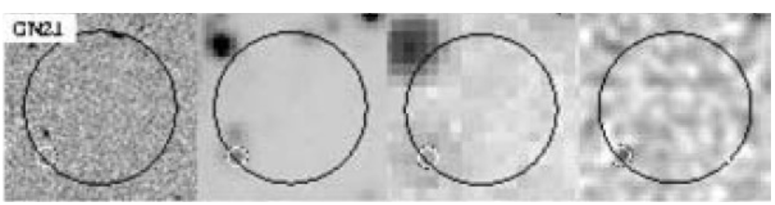


Weiss et al. (2009)

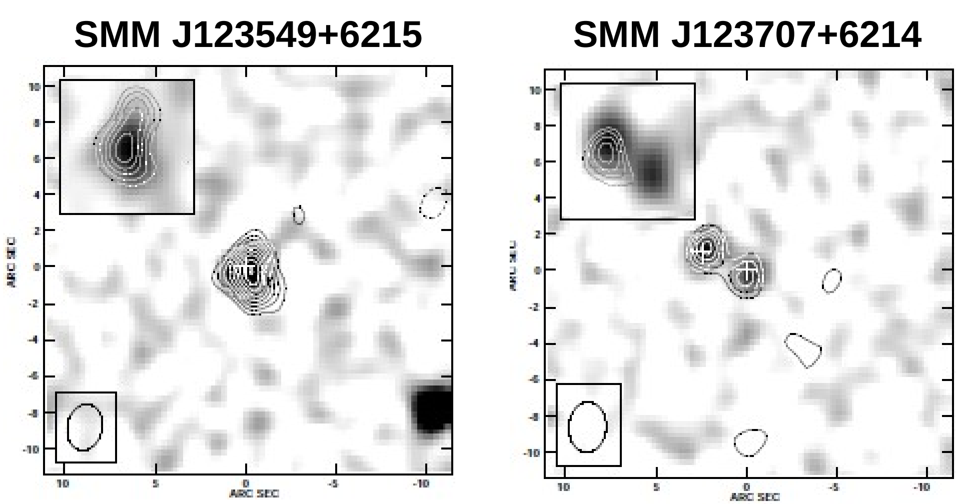
850-13



Wang et al. (2010)



Pope et al. (2006)



Ivison et al. (2010)

Source Counts: Conclusions

P(D) is a reliable way to get counts (and background!)

BUT

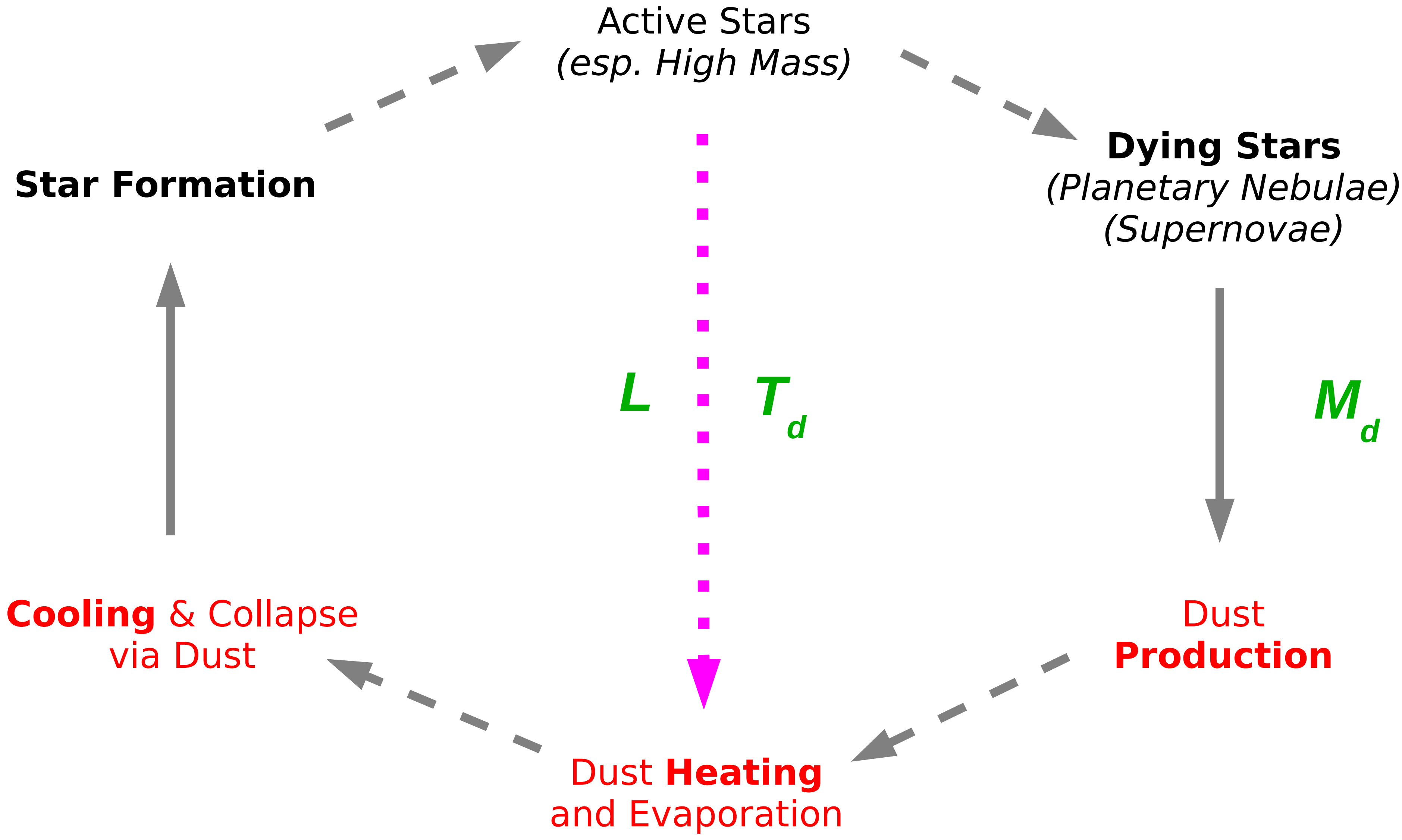
Need to know clustering to get it right....

Entree

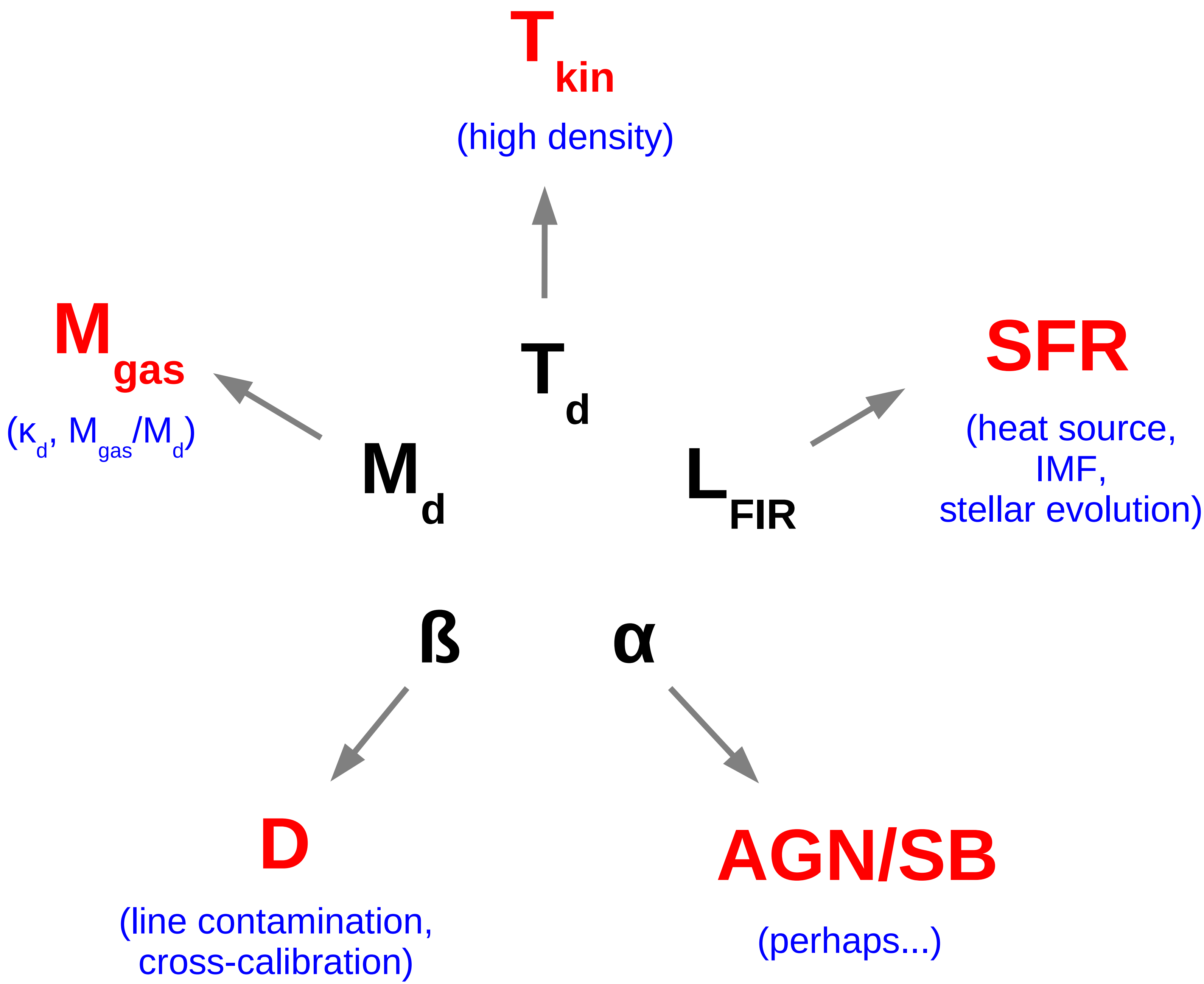
FIR Characterization

Dust SED Models

Lifecycle of Dust and Stars



Treasures in the Dust



Caltech Submillimeter Observatory

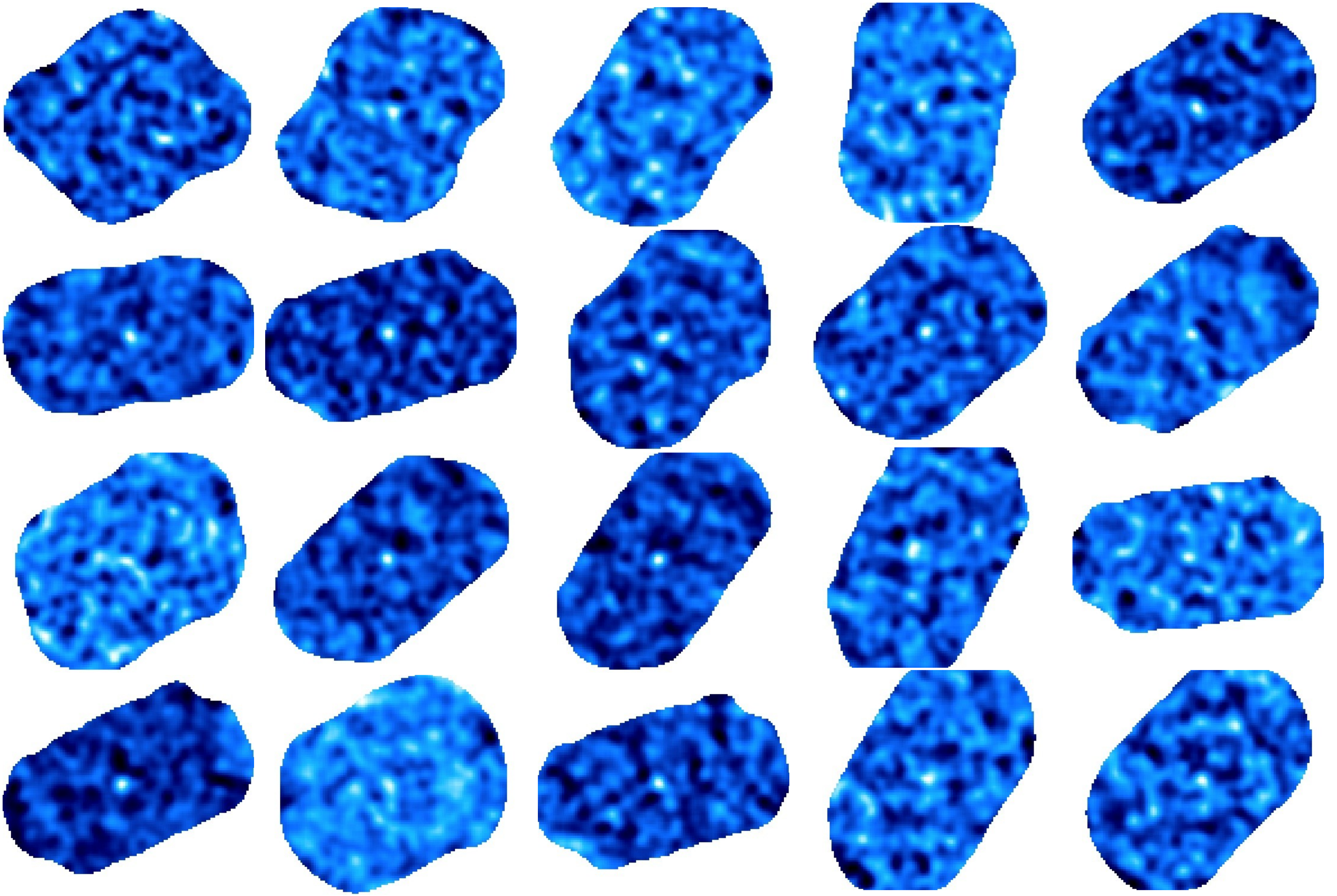
10.4 m Gregorian Telescope

12um RMS surface
(DSOS Melanie Leong)

4,000m (13,000ft) Elevation

SHARC-2 350um Image Gallery (2007-2009)

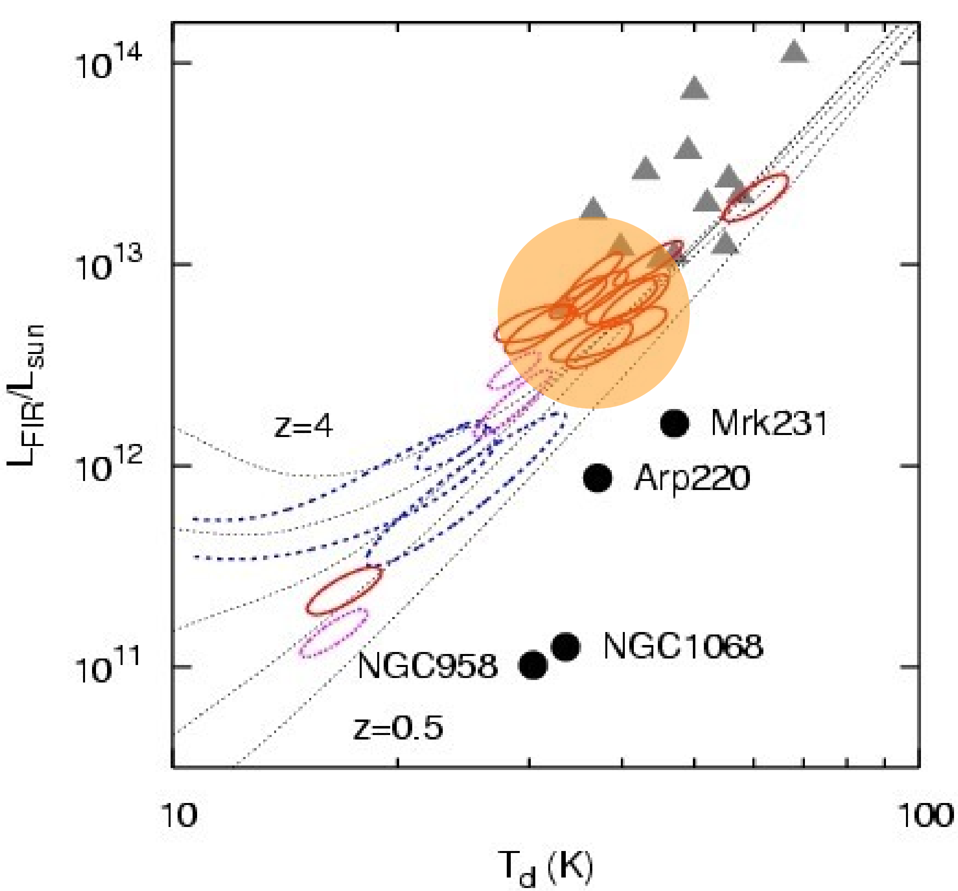
Kovács et al. 2010, ApJ, 717, 29



Characterization of SMGs

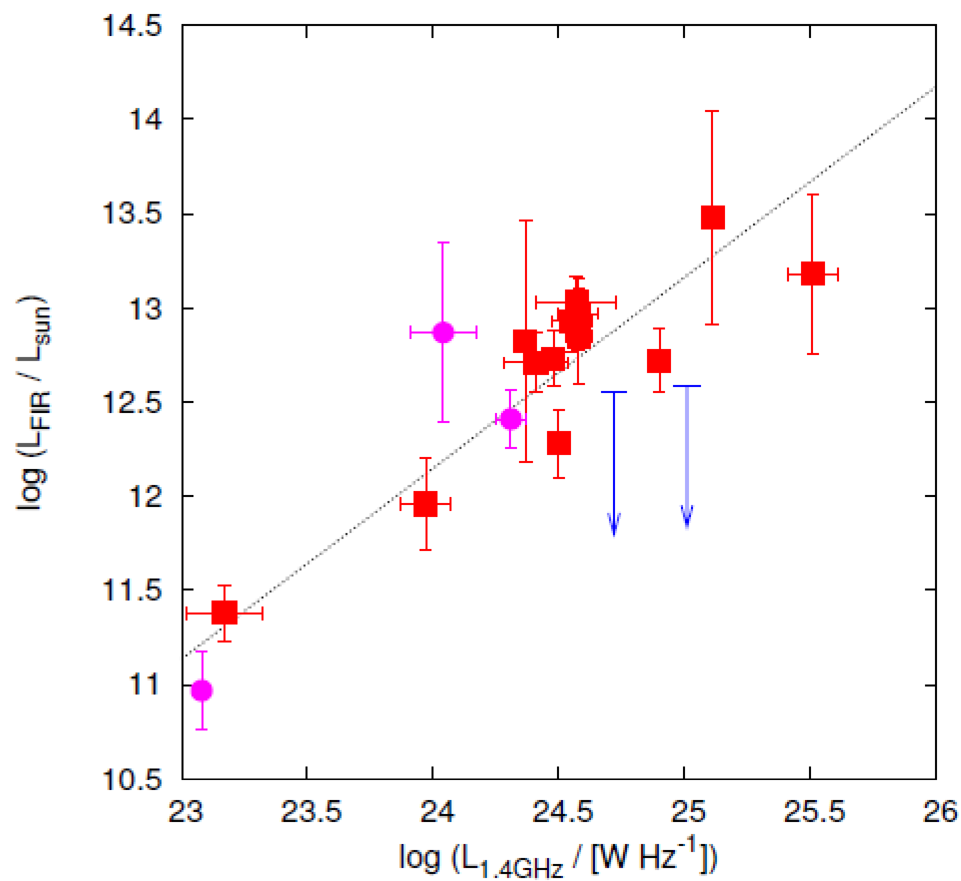
Kovács et al. 2006, ApJ, 650, 592

3 years of data...



Temperatures & Luminosities

T ~ 35K, L ~ 10^{13} L_{sun}

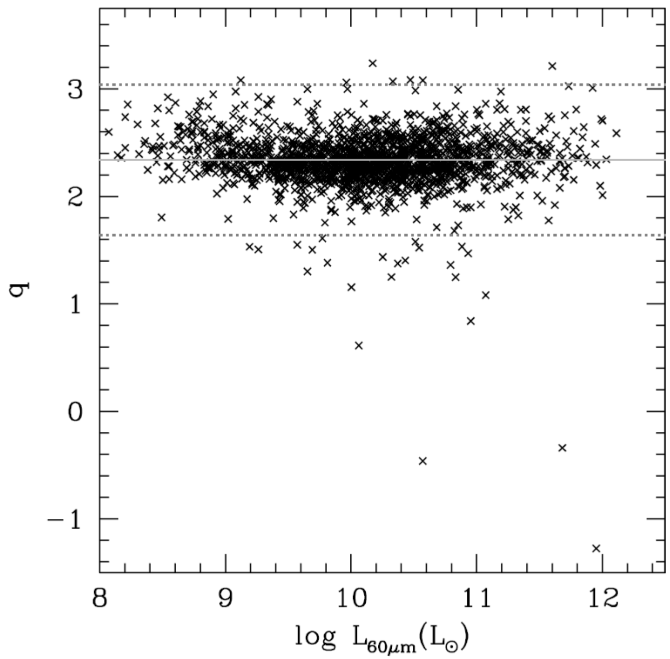


Radio-FIR Correlation

Radio—FIR Correlation

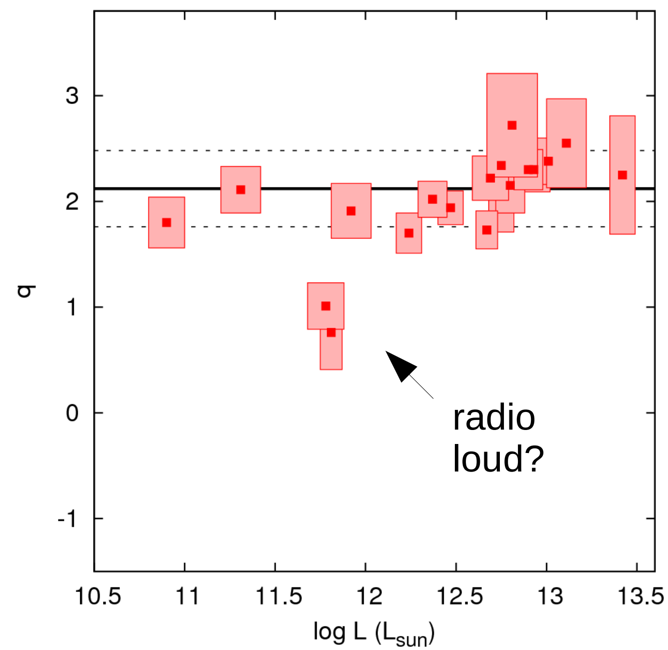
Kovács et al. 2006, ApJ, 650, 592

Local IRAS galaxies



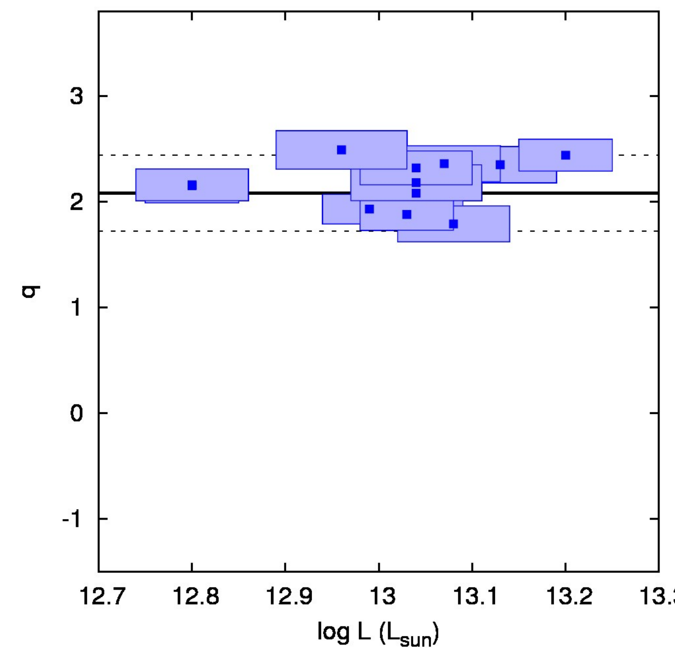
Yun et al. (2001)

Classical SMGs



Kovács et al. (2006)

***Spitzer* SMGs**

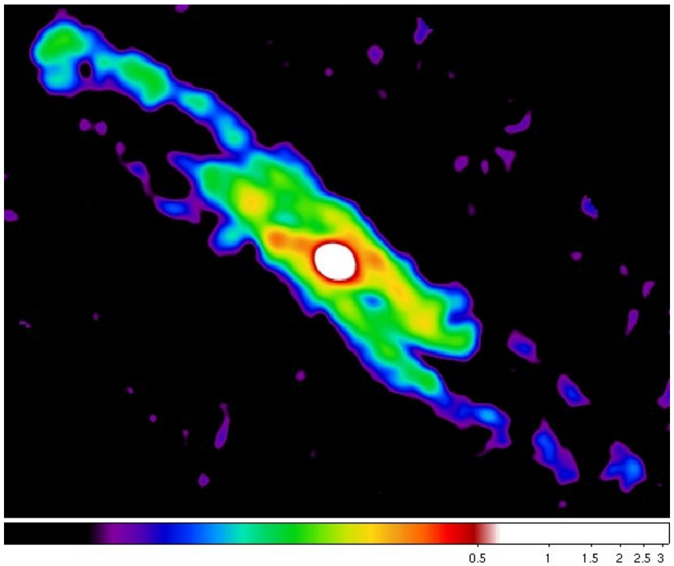


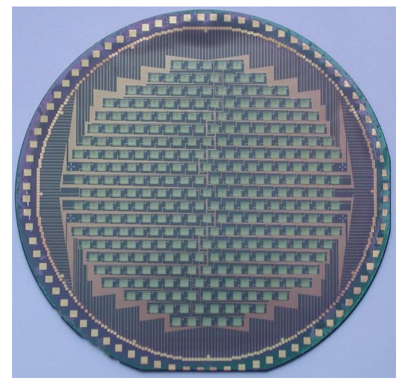
Kovács et al. (2010)

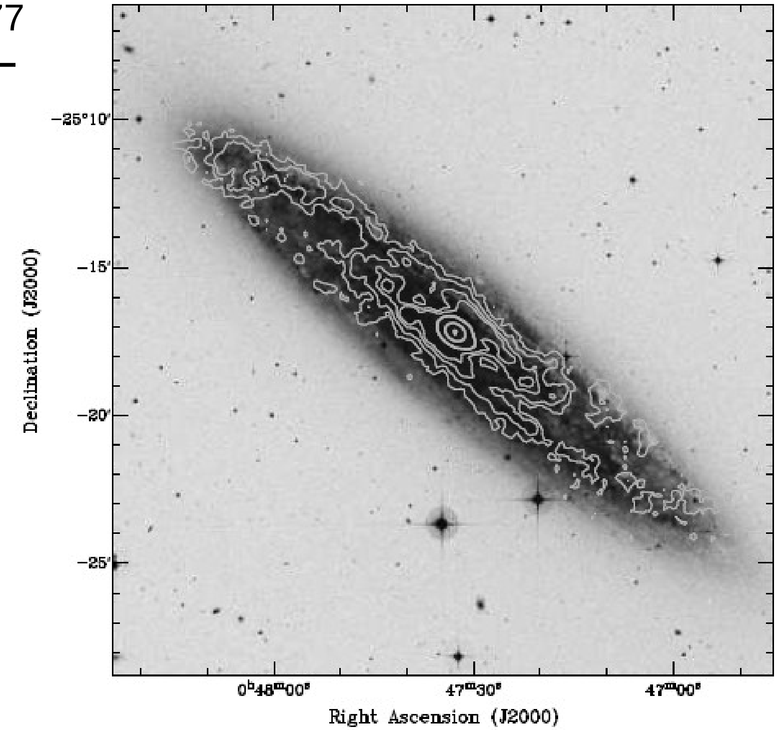
SMG Luminosities fueled by star-formation.

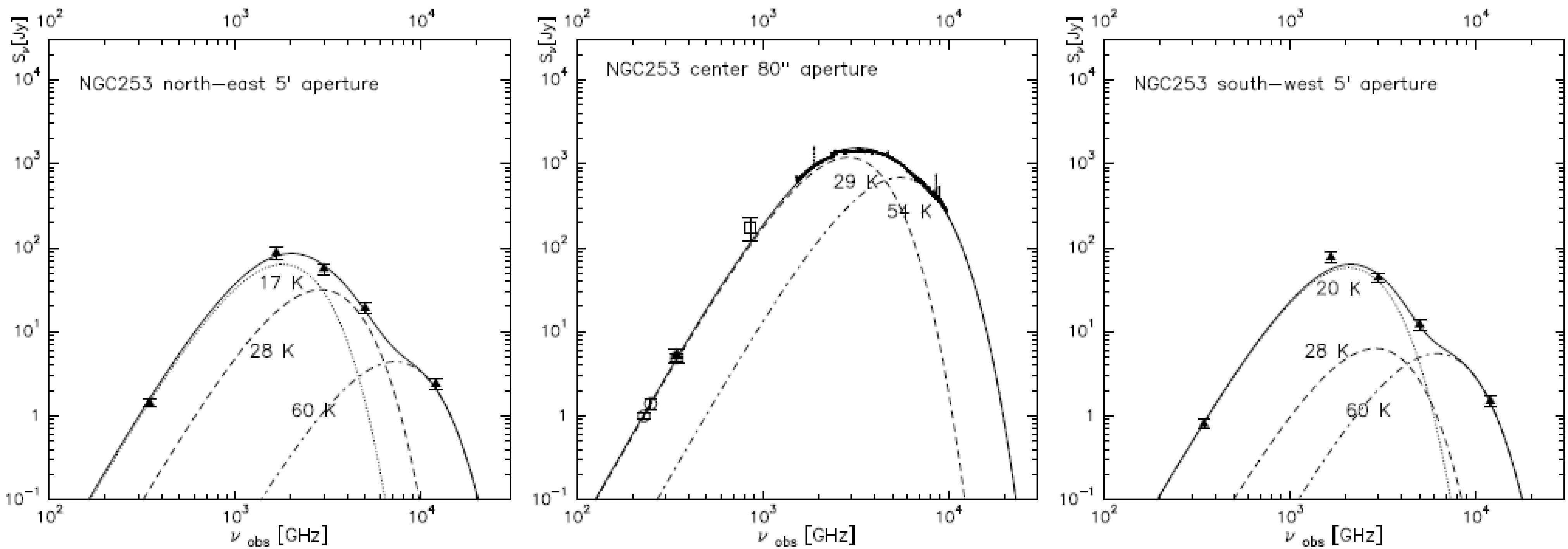
NGC 253

Weiss et al. 2008, A&A, 490, 77





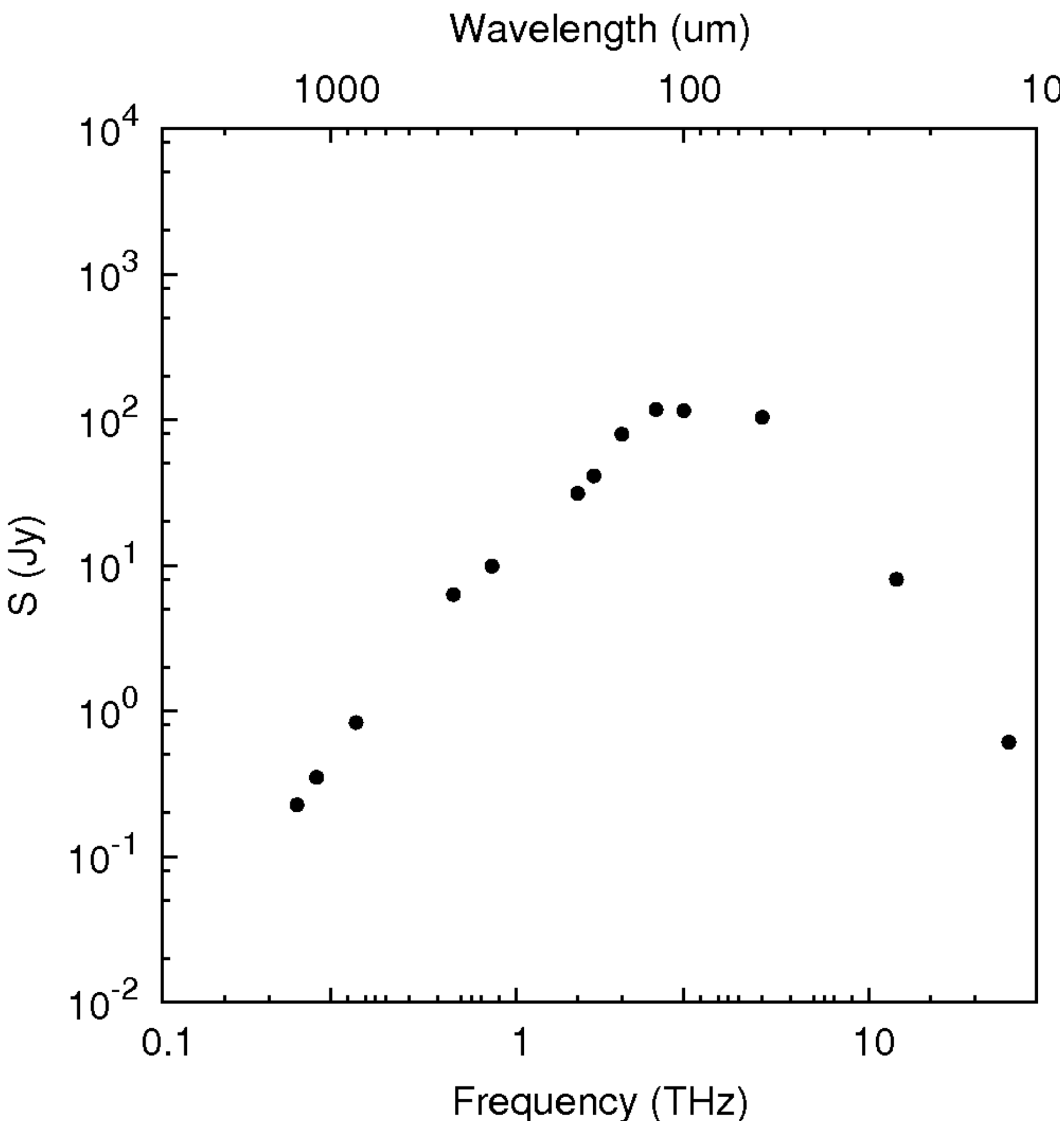




SED Case Study: Arp 220

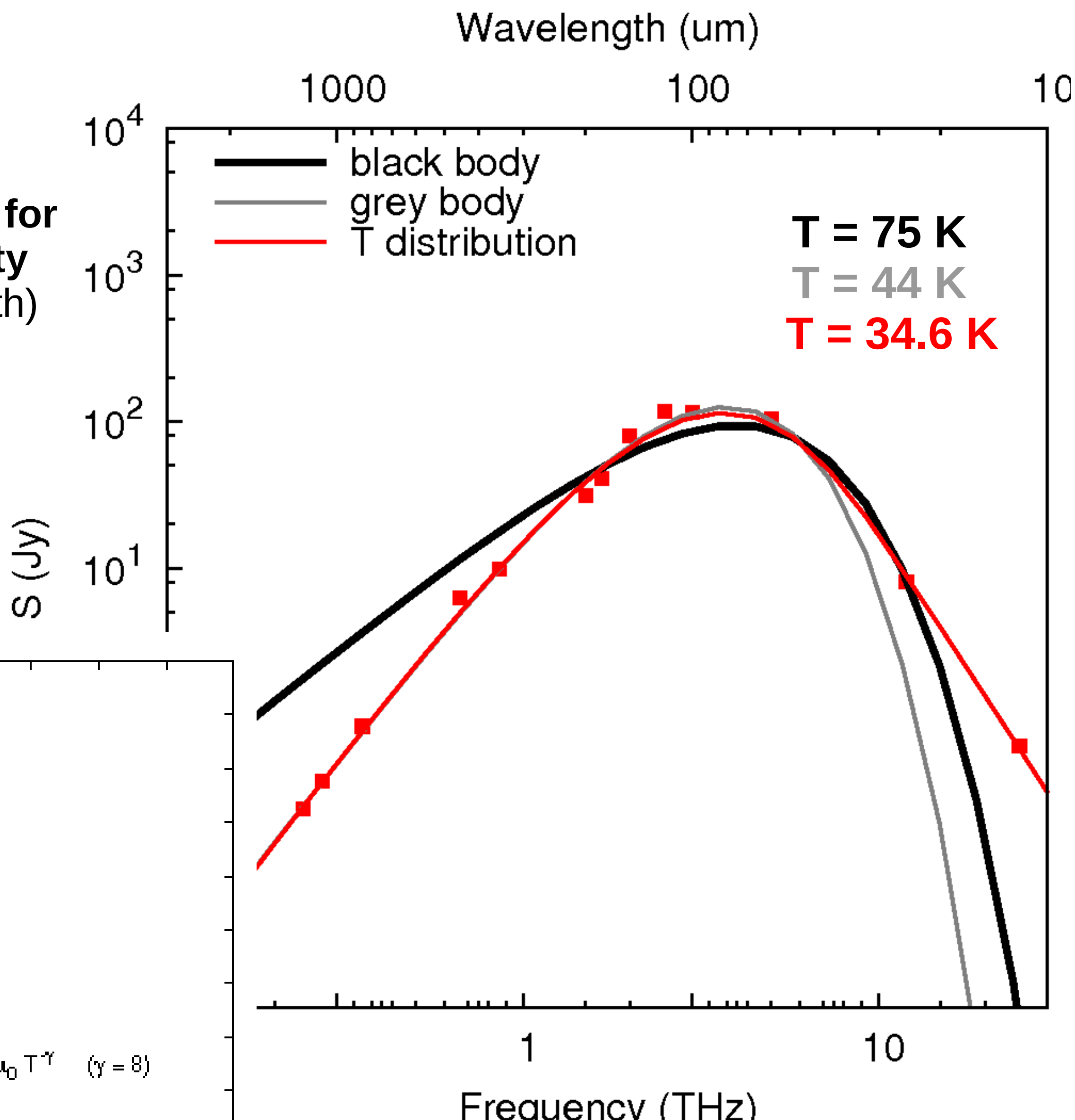
Flux data between 12 um and 2 mm

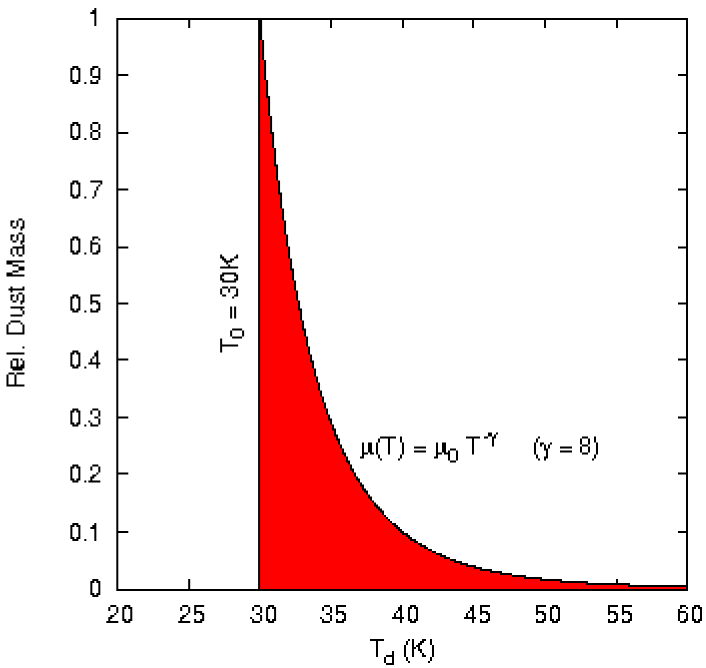
(source: NED)



SED Case Study: Arp 220

Analytic expressions for Integrated luminosity
(including optical depth)





parameters:

M_d T_c β γ (d)

Emissivity index is related to the fractal dimension of dust:

$$\beta = D - 1$$

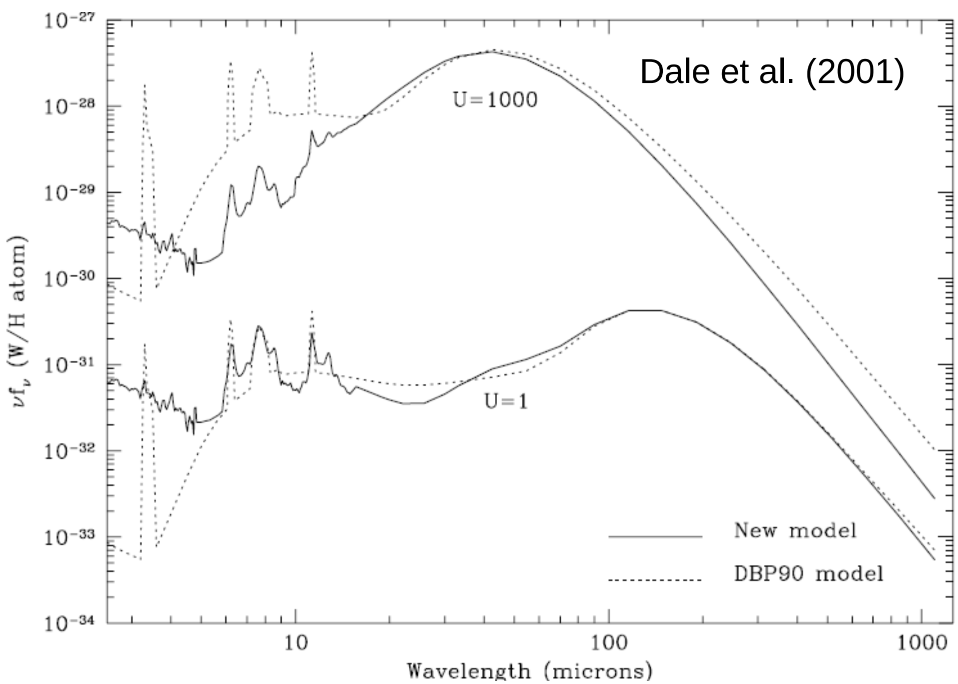
Thus it is expected in the range 1 – 2. Typical values are ~1.5.

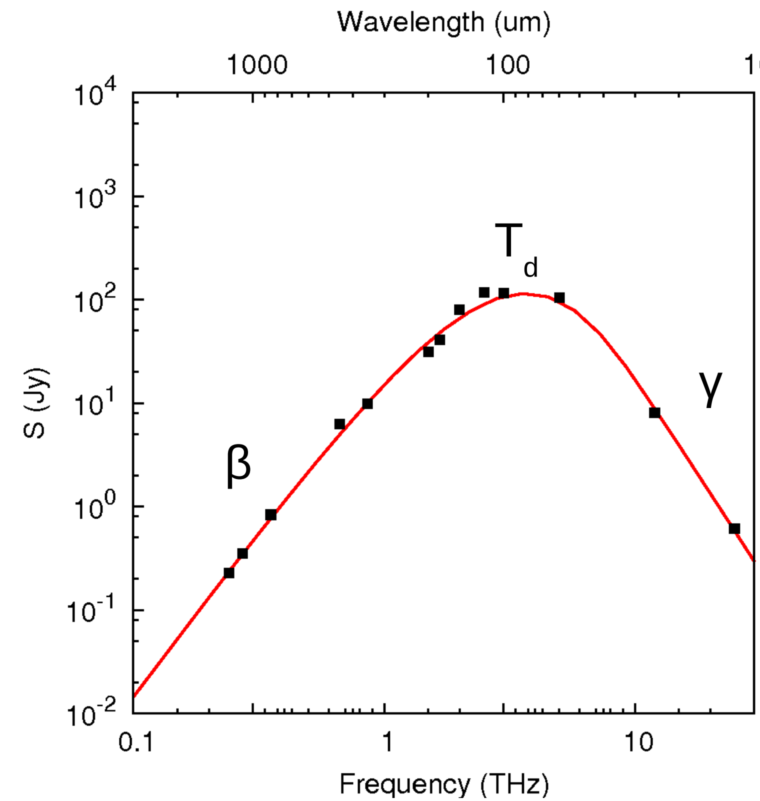
$$\kappa_d \sim \nu^{\beta}$$

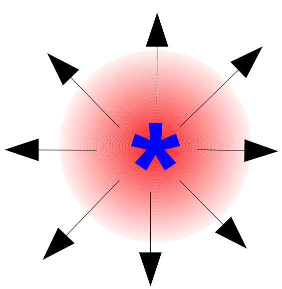
$$dM(T) \sim \mu_0 T^{-\gamma}$$

Mass-tempetature index γ is related to mass-FUV index α (Dale 2001)

The SED Flavour of the Day...

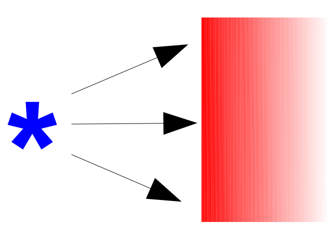






3 type of grains
2um – 2mm

dM(U)
α ~ 1 – 2.5



libraries

(radiative heating only)

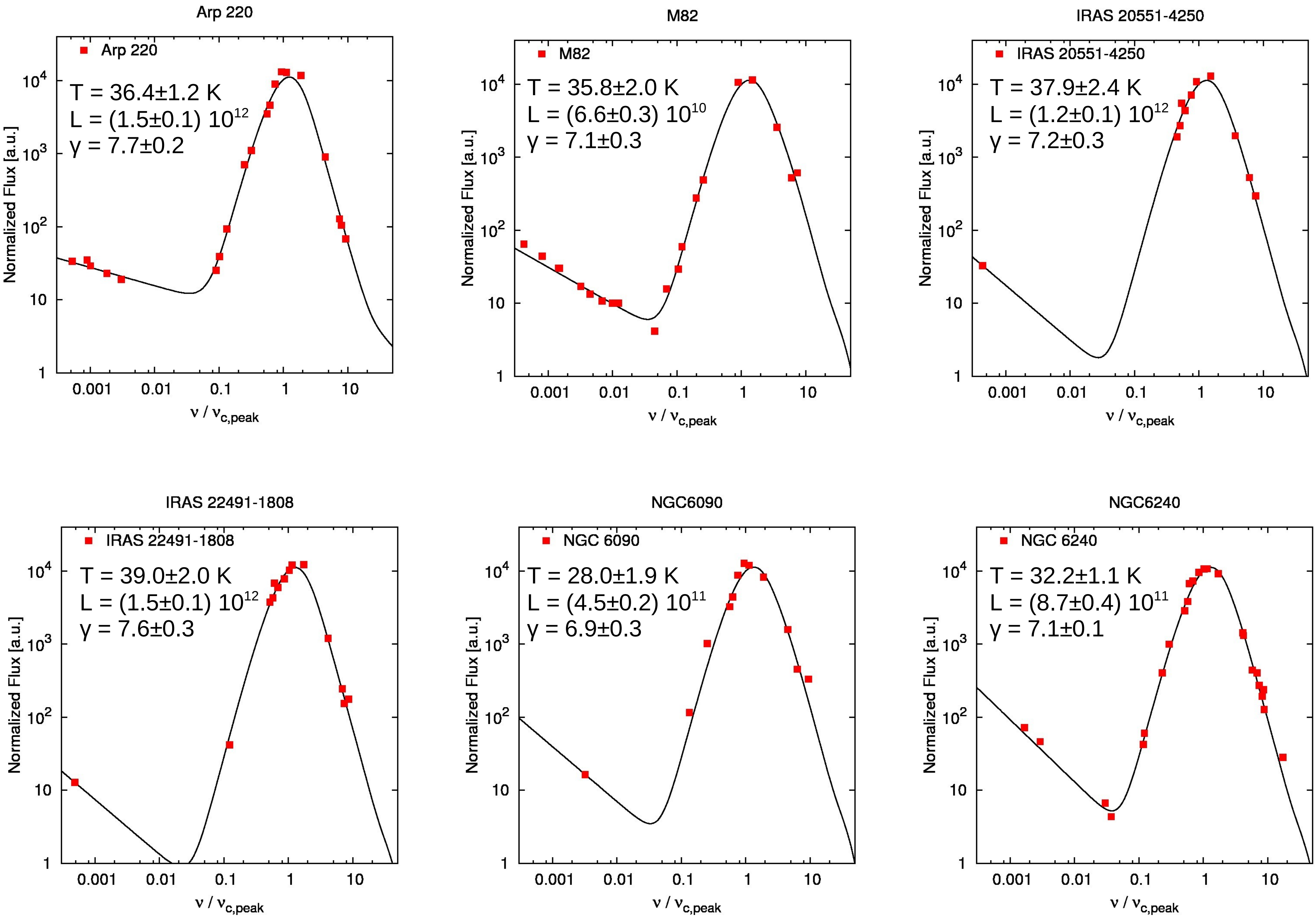
1 grain type
12um – 2mm

dM(T)
γ ~ 5 – 9.25?

parametric

(heating also by shocks or infall)

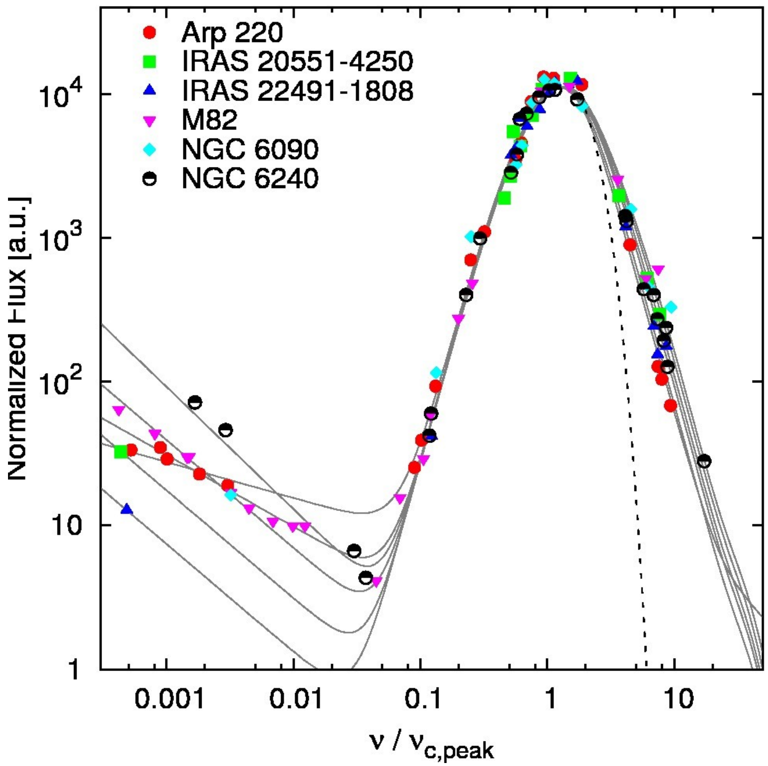
Kovács et al. 2010, ApJ, 717, 29



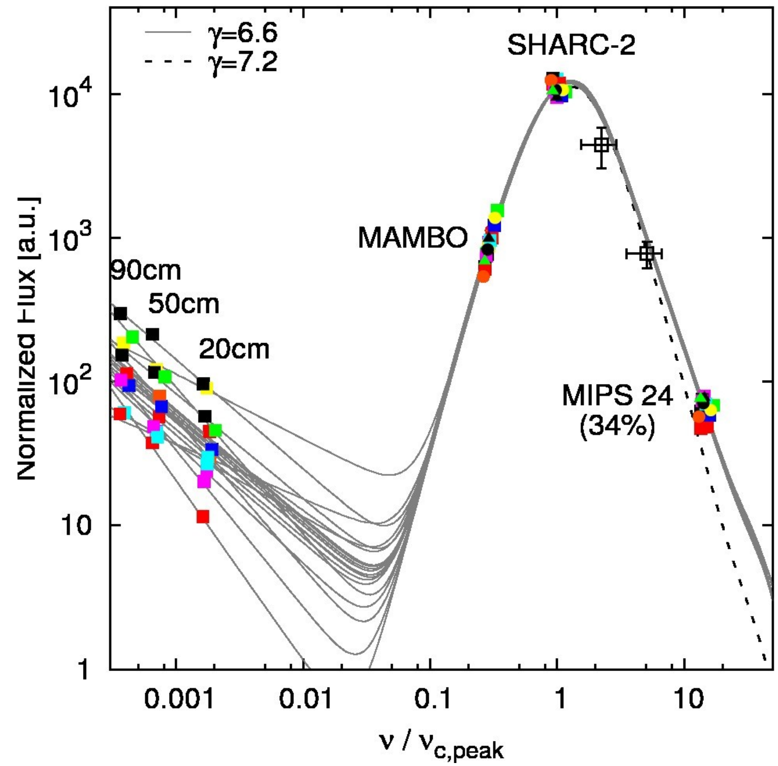
Dusty Starbursts Near and Far...

Kovács et al. 2010, ApJ, 717, 29

Local Starburts



Spitzer SMGs



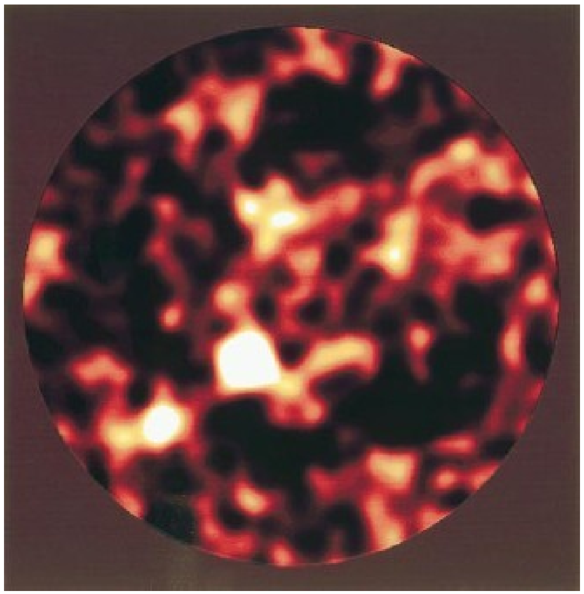
$\beta = 1.54 \pm 0.04$ (D~2.5)

$\gamma = 7.21 \pm 0.09$

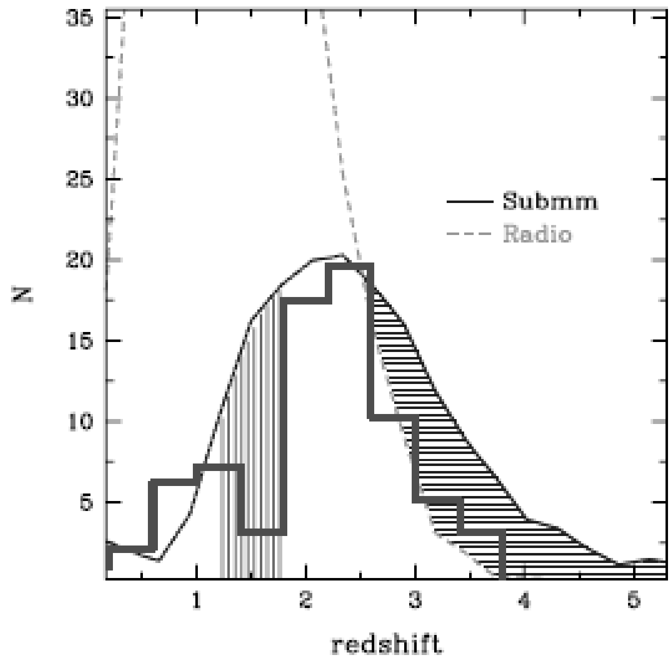
$\gamma = 6.6 \pm 0.1$

The Issues: 10+ years of SMGs on 1 Slide...

Hughes et al. 1998

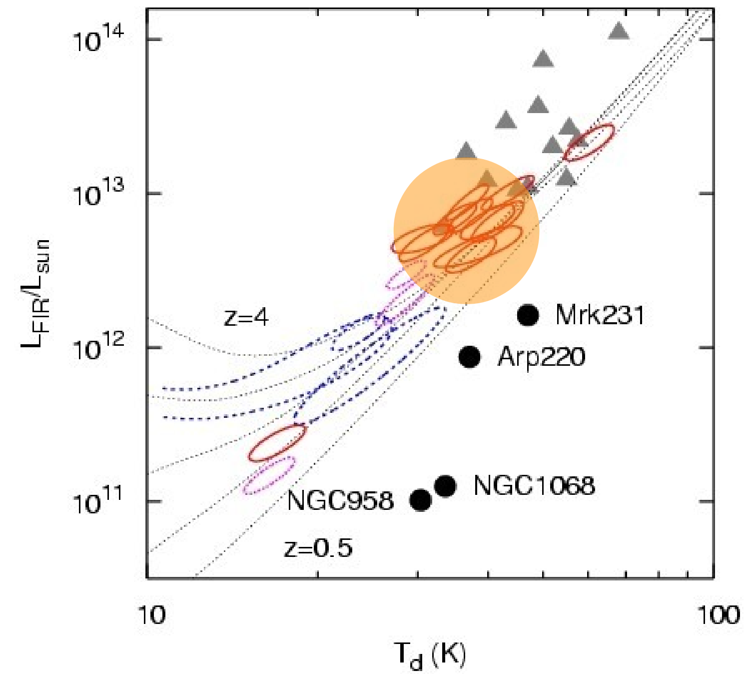


Chapman et al. 2003 & 2005



$z \sim 1$—3
(radio cutoff)

Kovács et al. 2006



$T \sim 35$ K
$L \sim 10^{13} L_{sun}$

~300,000
Detections

~150
Redshifts via radio ID

~40
Characterizations

The Spitzer (mid-IR) Hope...

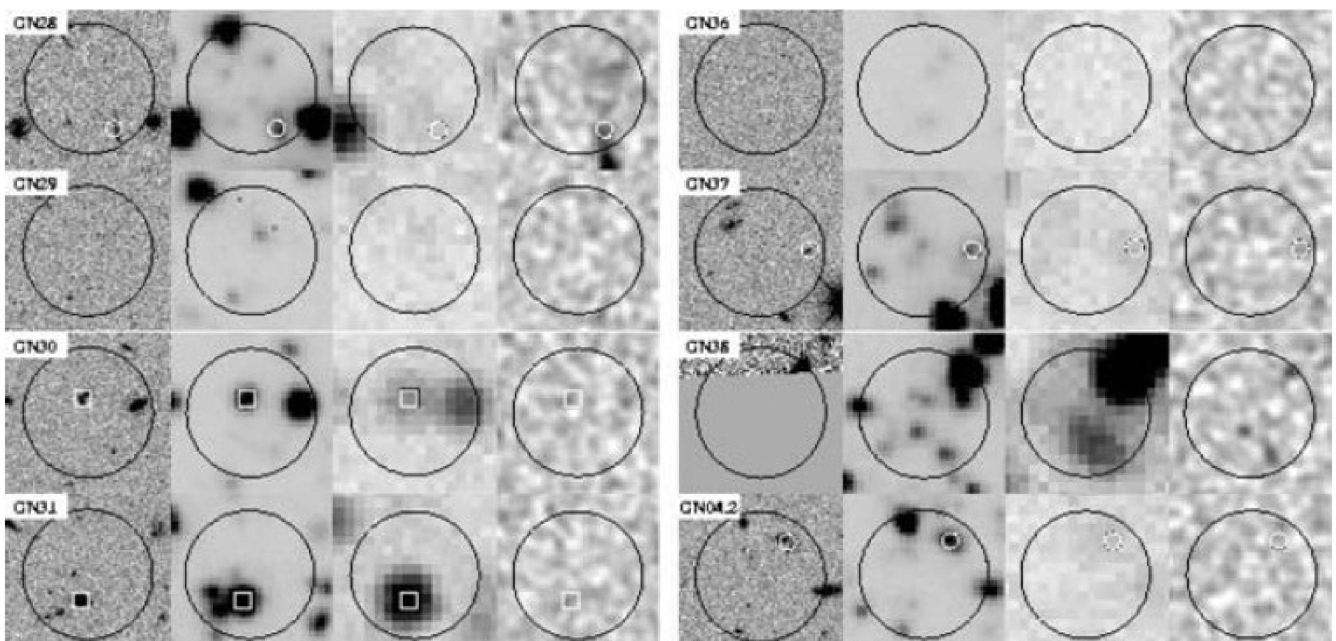
Photometric Redshifts

Characterization (starburst vs AGN)

Stellar Masses

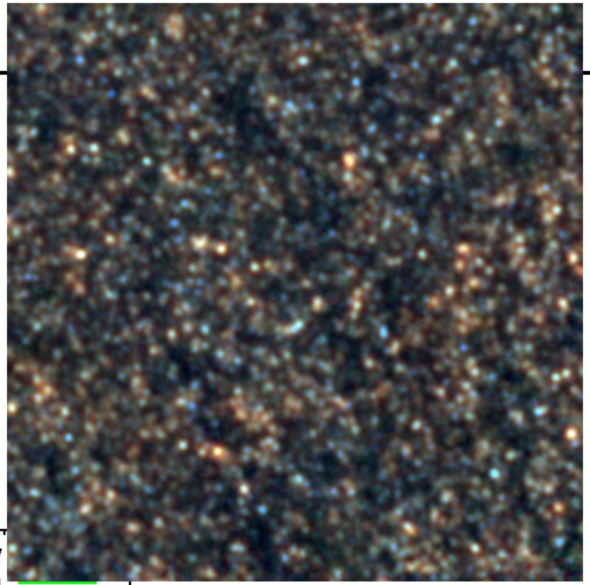
Only IRAC bands (and sometimes MIPS 24um) can see SMGs

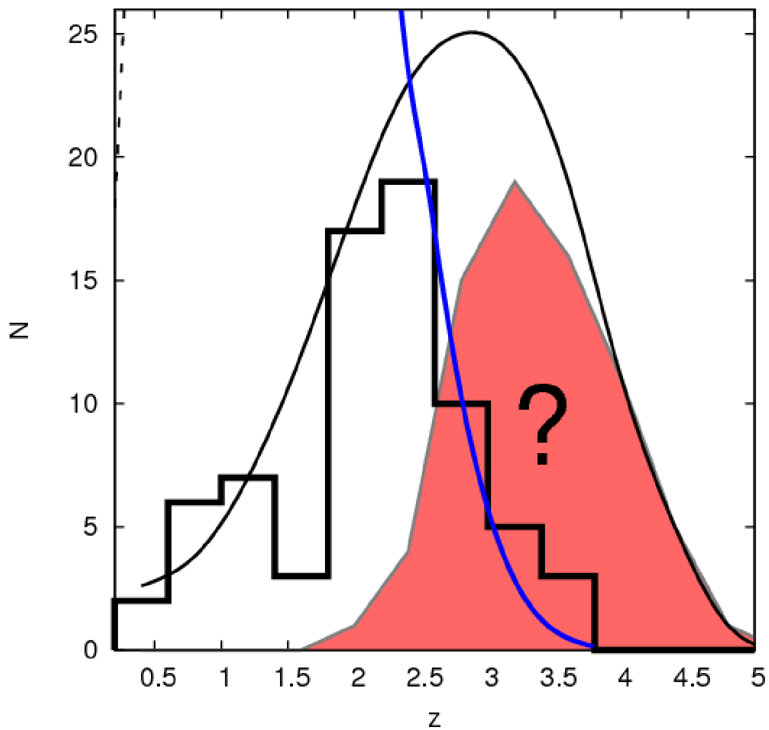
ACS 8um 24um VLA ACS 8um 24um VLA



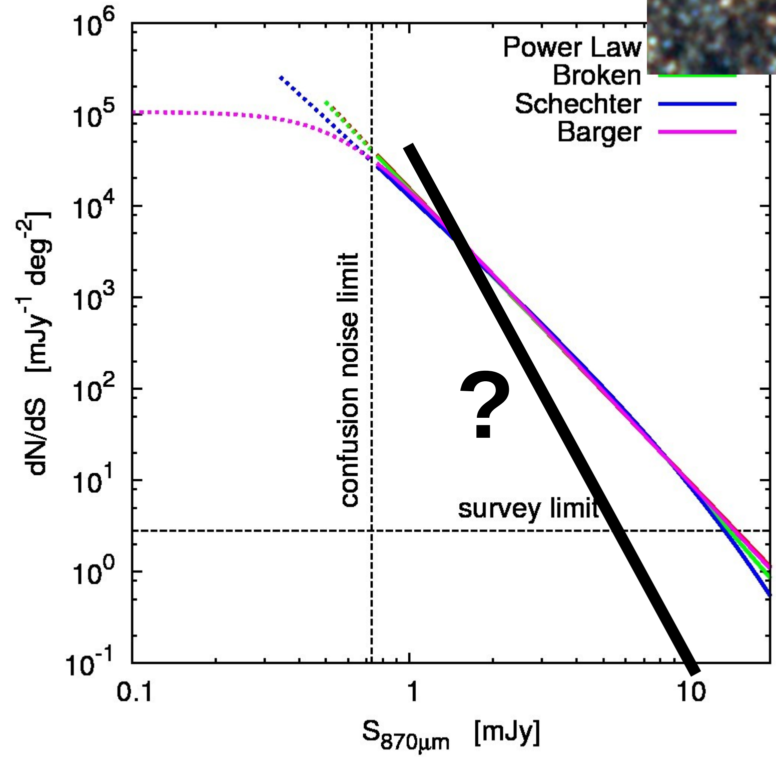
Pope et al. 2006

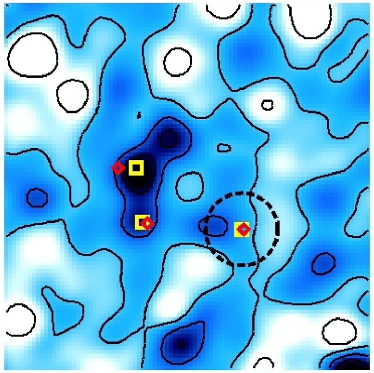
The Million-Dollar Questions





Formation epochs
Star-formation history
Mass-assembly

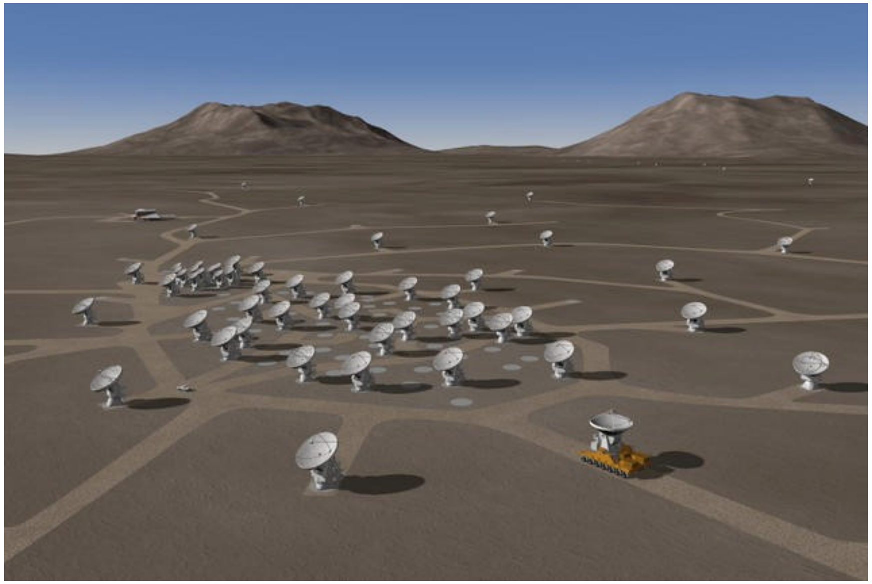




luminosity function
clustering

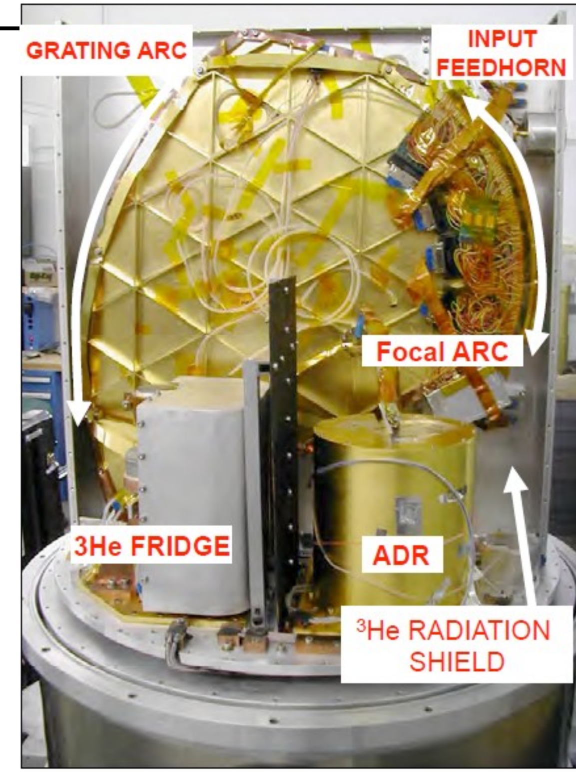
Solutions

ALMA
+
EVLA

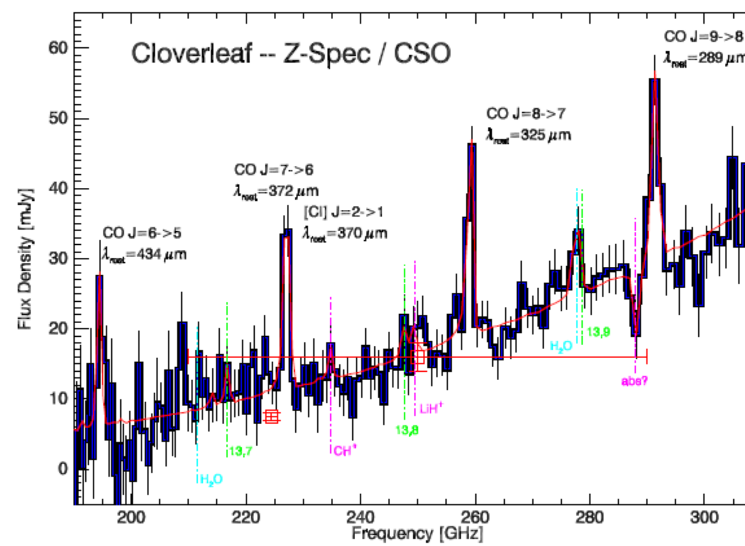


multibeam
R~700
spectro-
scopy

CCAT



Bradford et al. 2010



Transmission Line Spectrometers

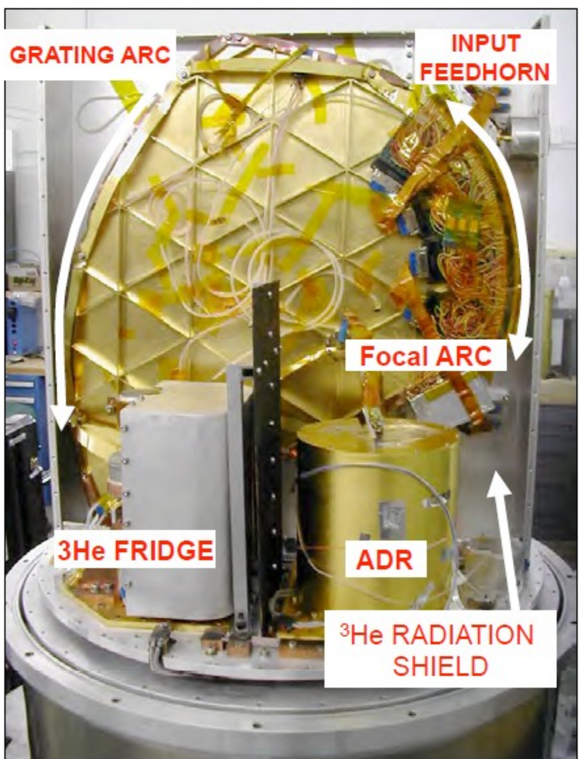
Kovács & Zmuidzinas 2011

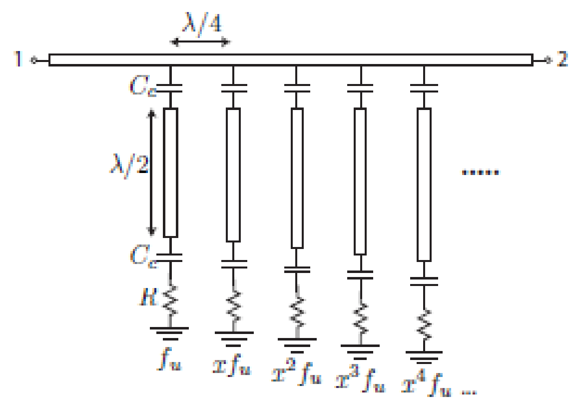
Fits “Z-spec” on an Fλ pixel

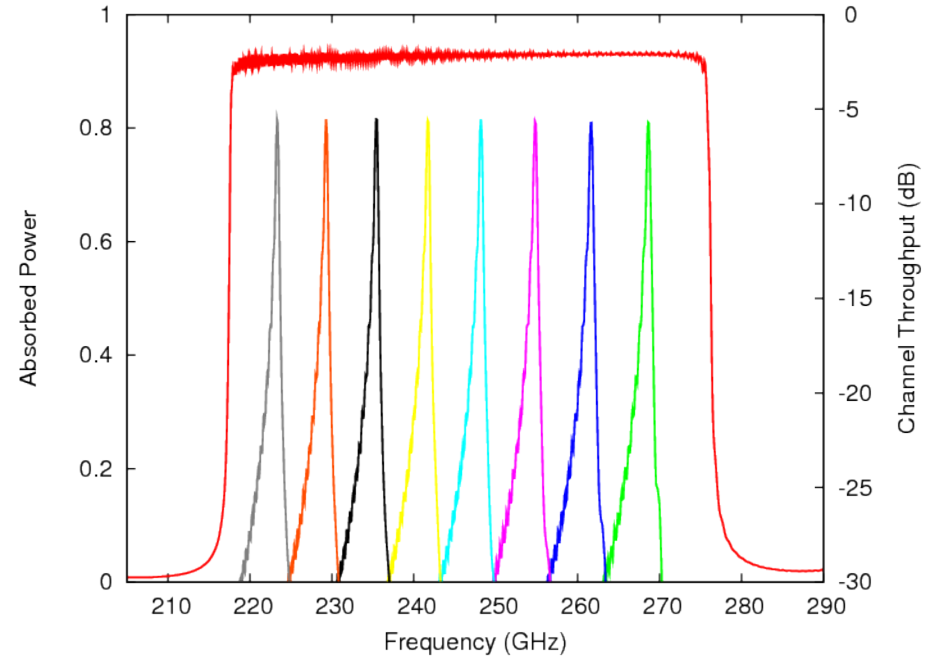
100 pixel arrays
for CCAT?

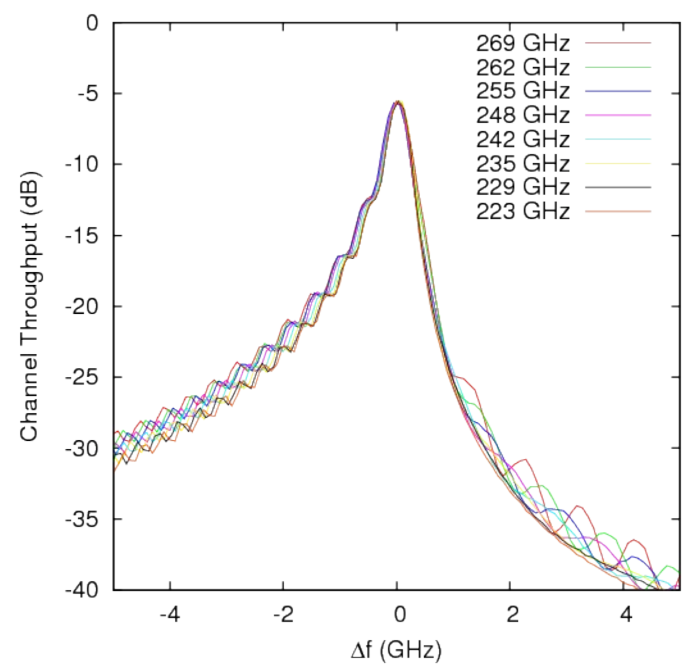
Over 100 redshifts per night

Over 100,000 redshifts in 3 years....









THE END