The Challenges of Ground-based Astronomical Array Imaging at Far-Infrared Wavelengths

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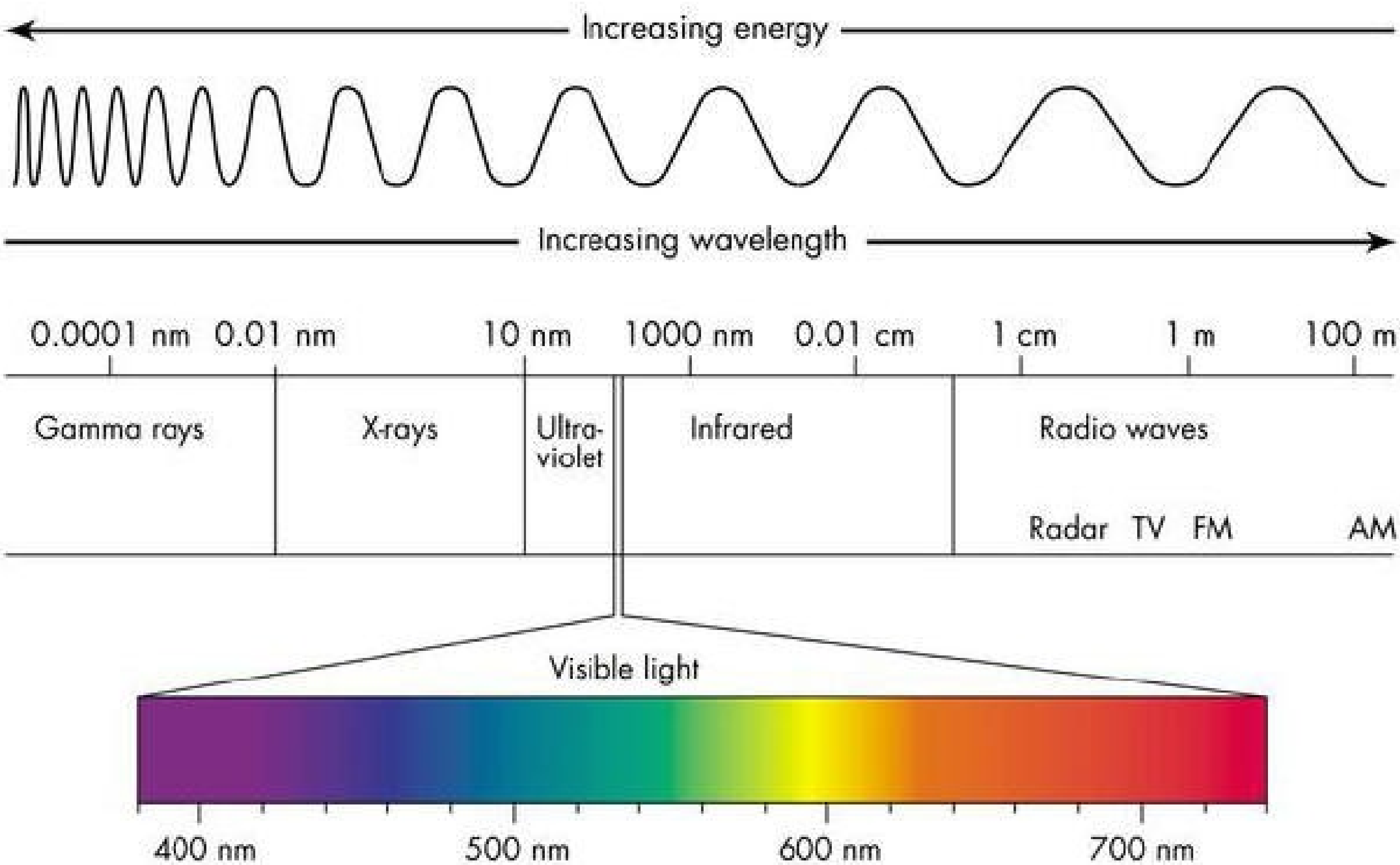
Part I

Data Reduction

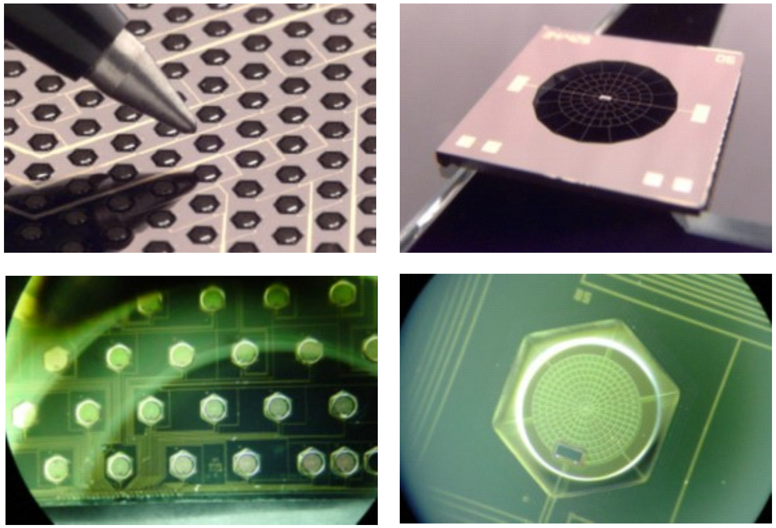
Part II

Scanning Strategies

The Electromagnetic Spectrum

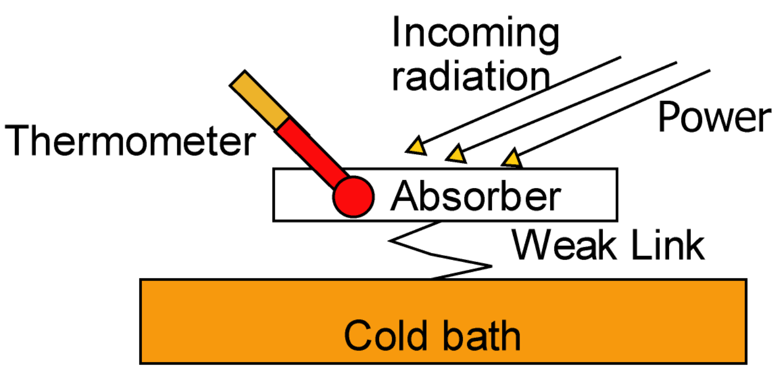


Bolometers



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

atmosphere
(300K)



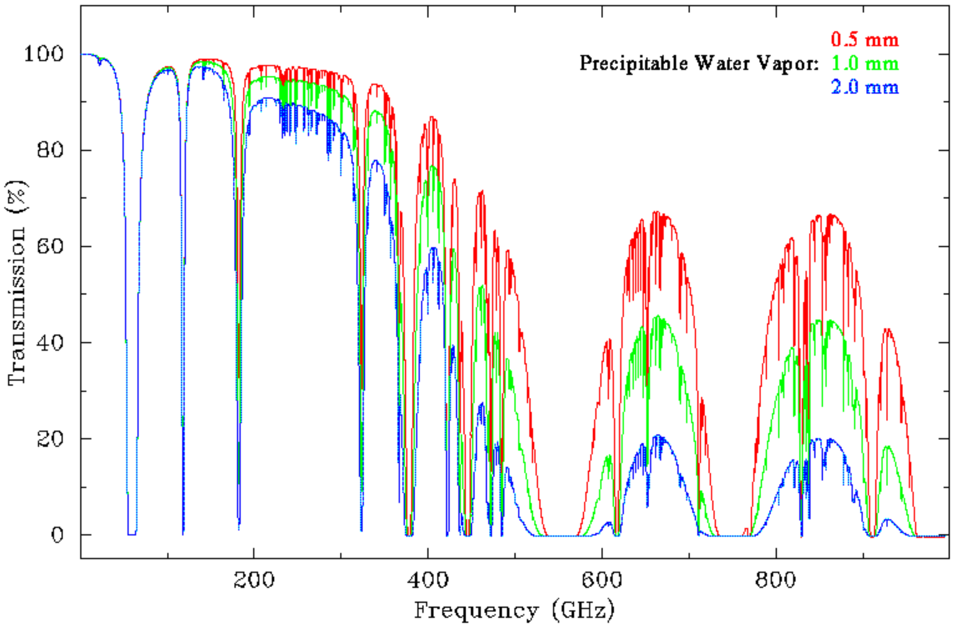
1/f noise

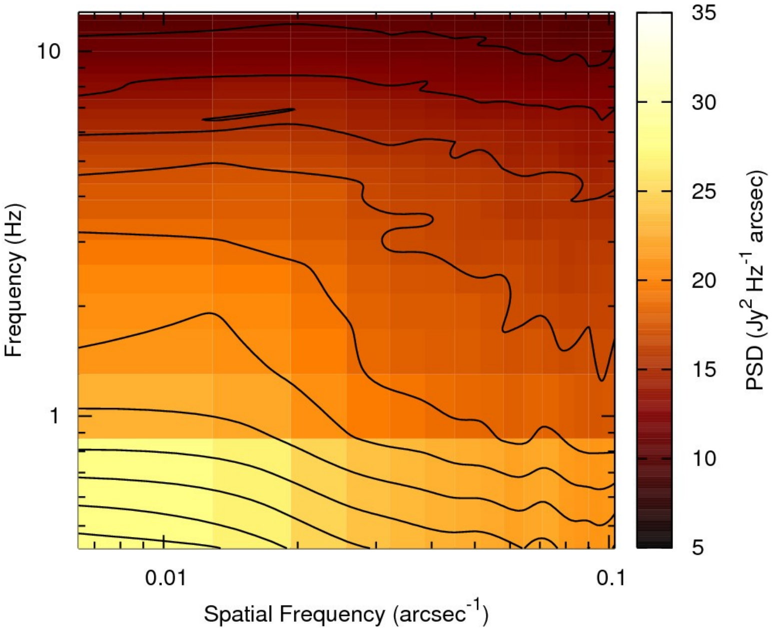
Unstable gain/noise

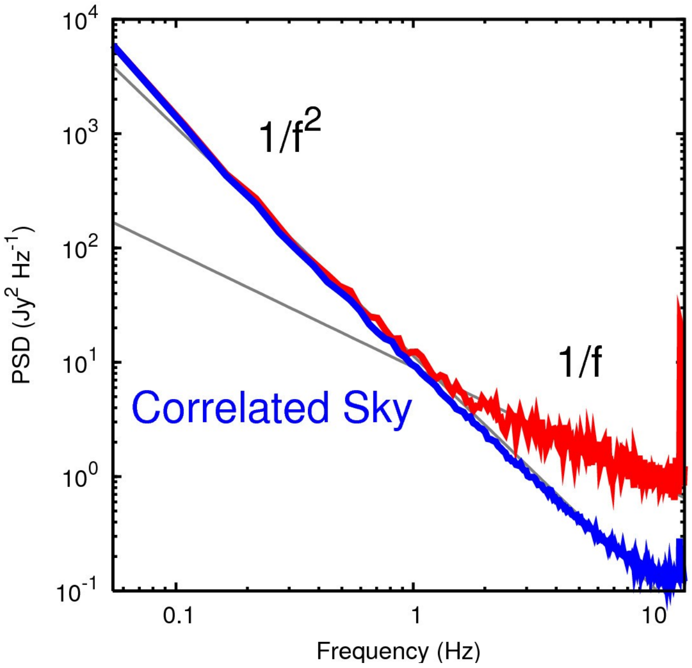
Microphonics

EM pickup

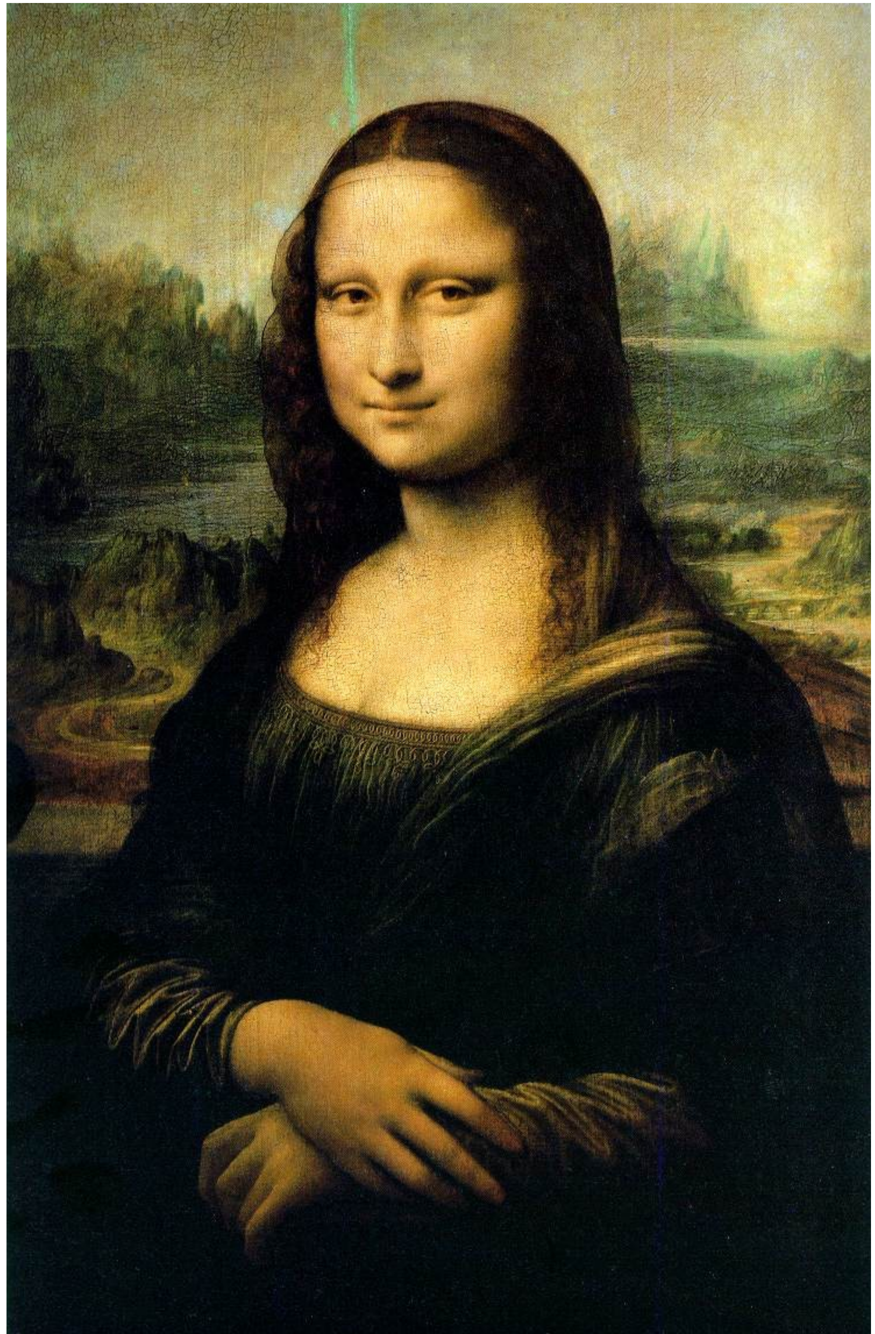
Observing from the Ground...

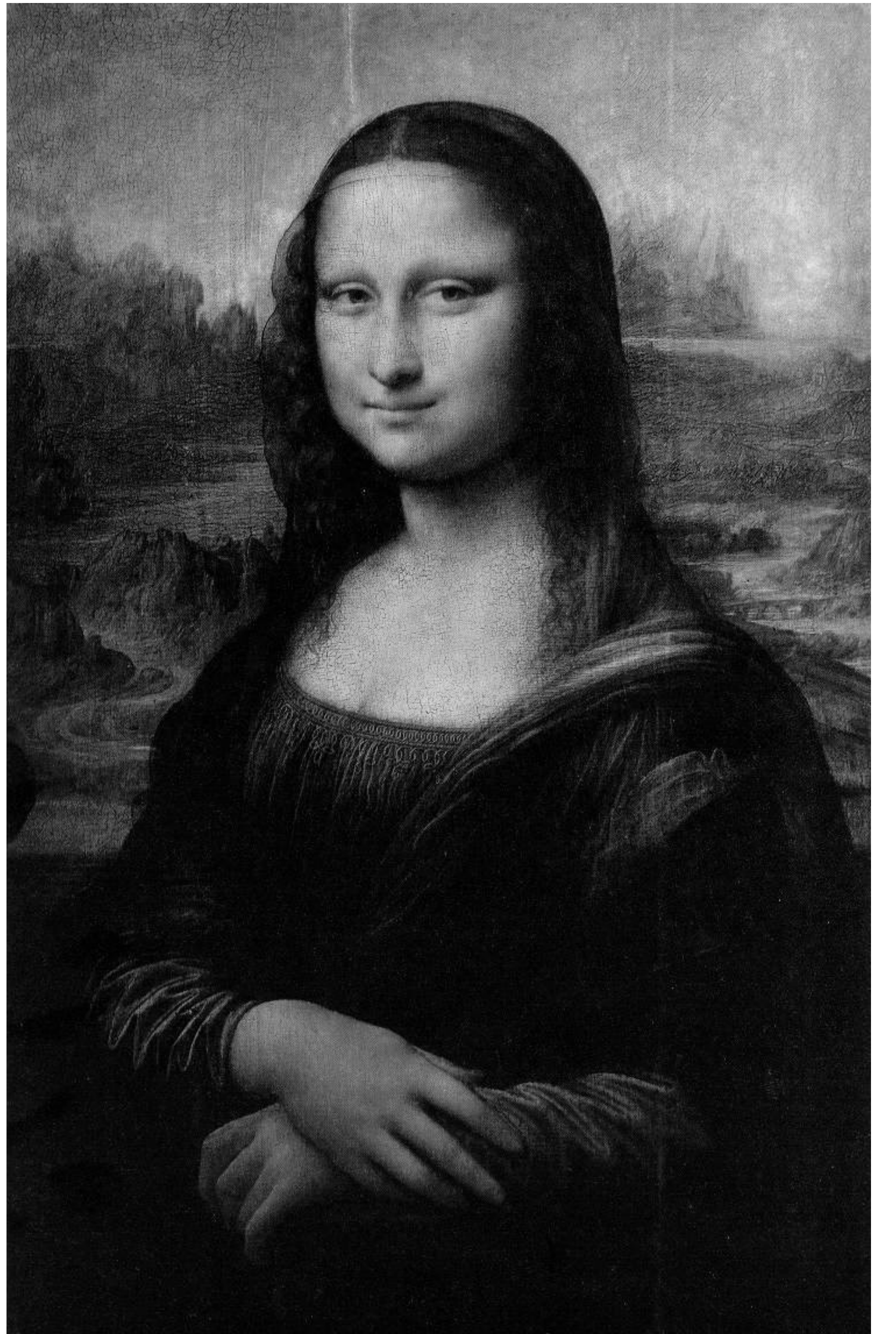






Ready for some pretty images?....

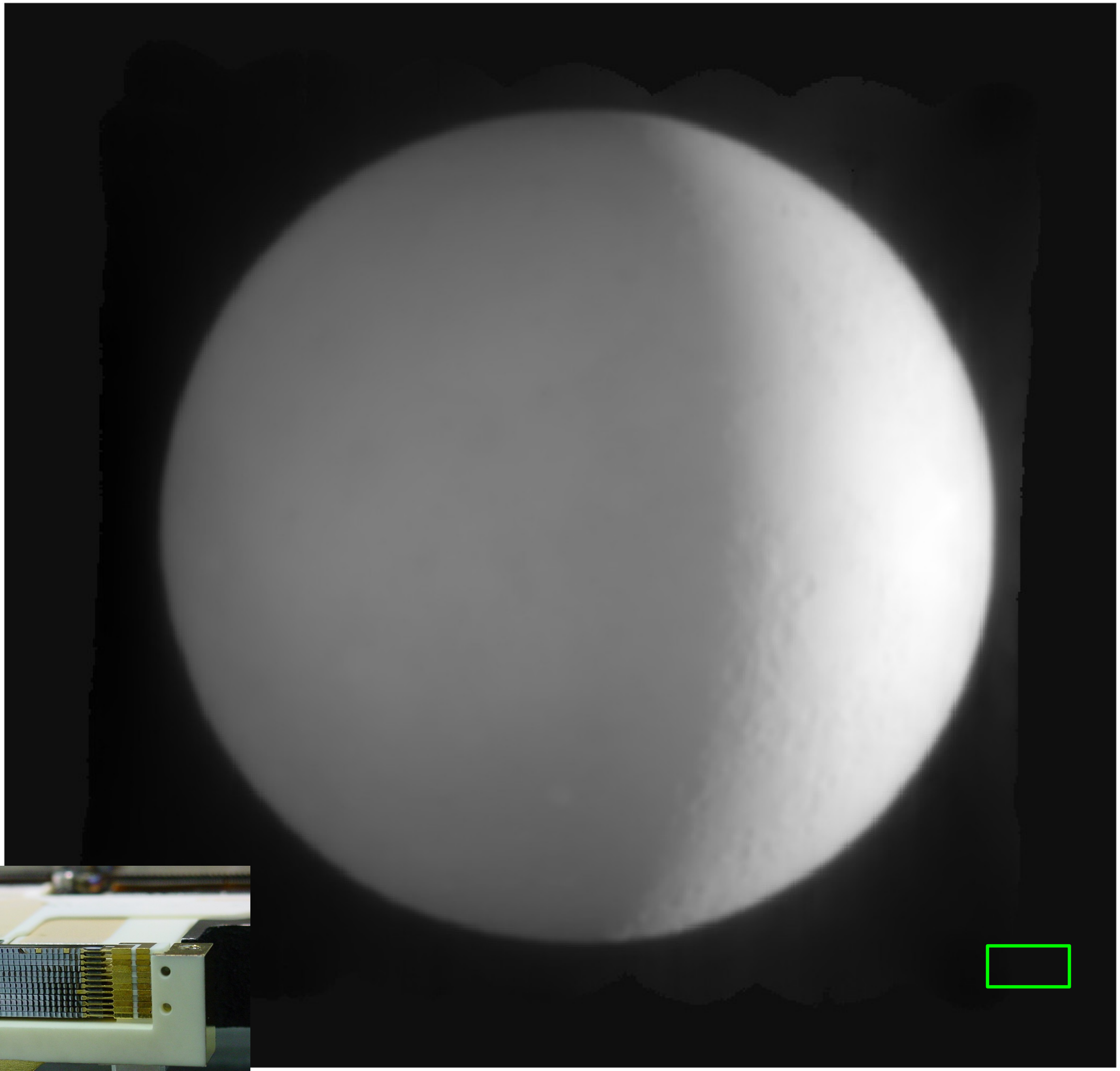


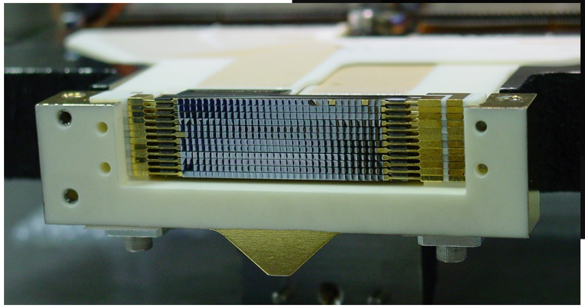


All real sub-mm images are produced by CRUSH...

(Kovacs 2006, 2008)

Moon at 350um

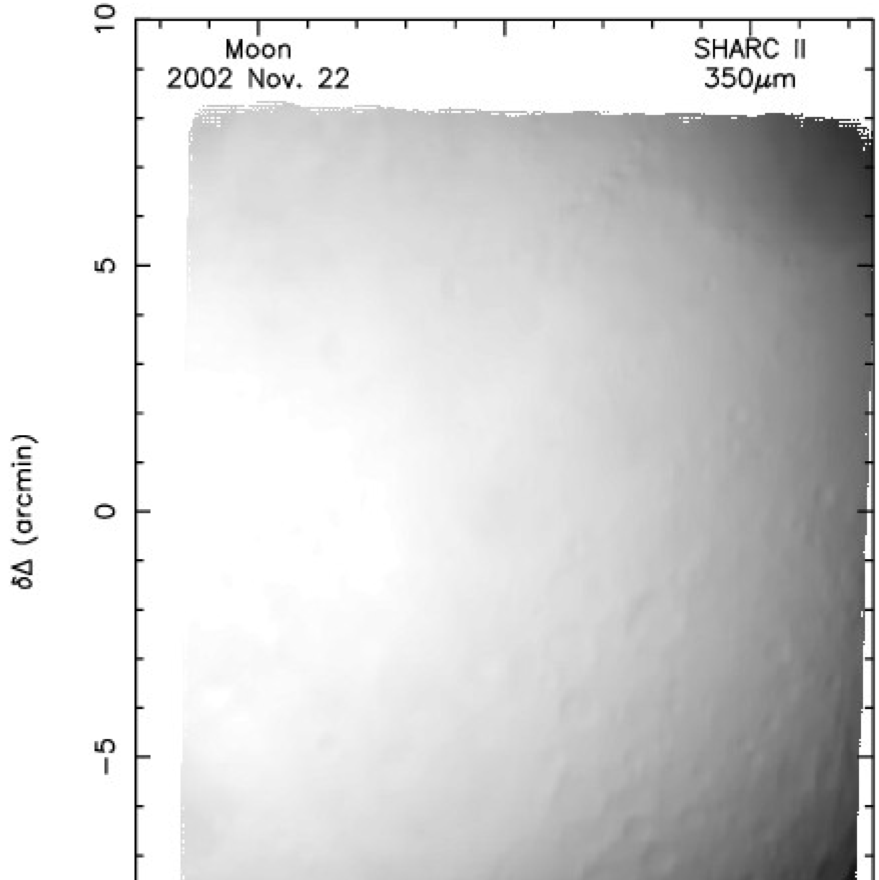


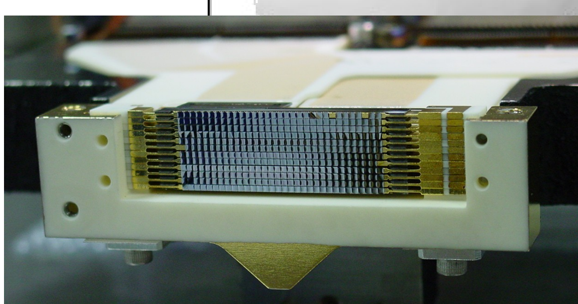


SHARC-2 (350 um)

Moon at 350um

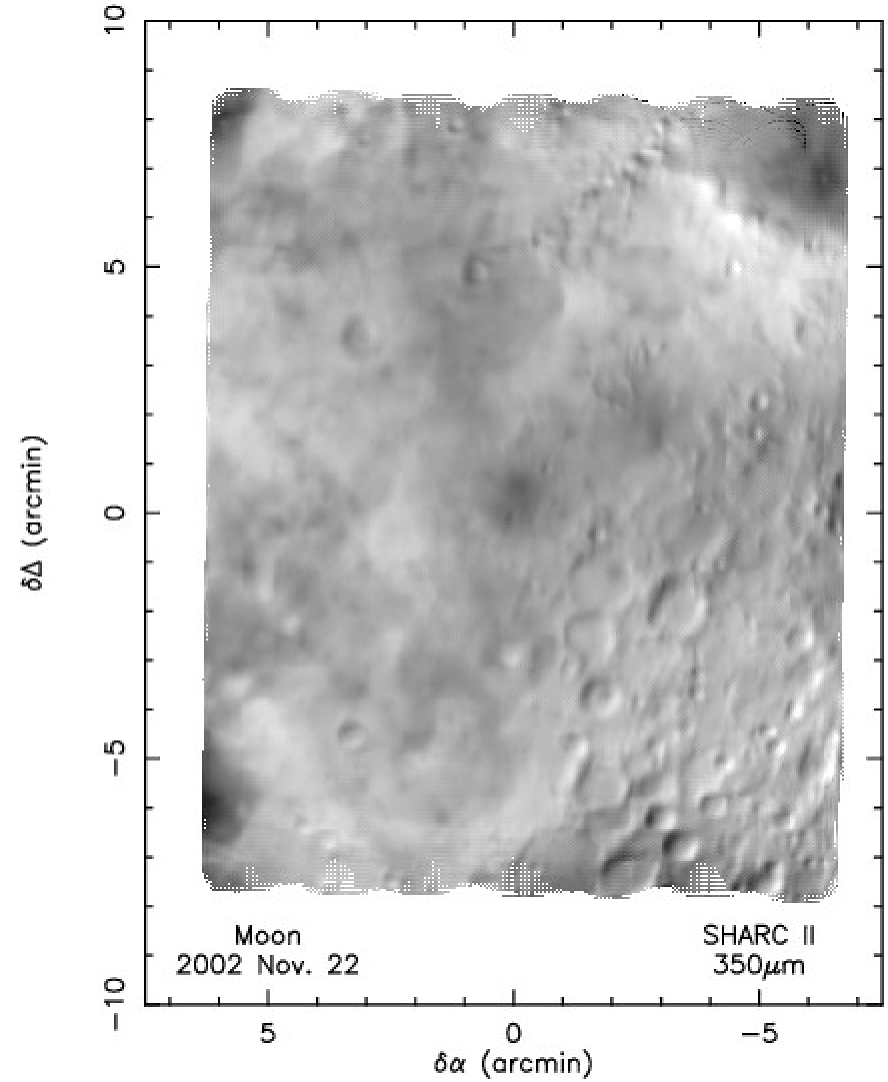
As seen (in total power)...





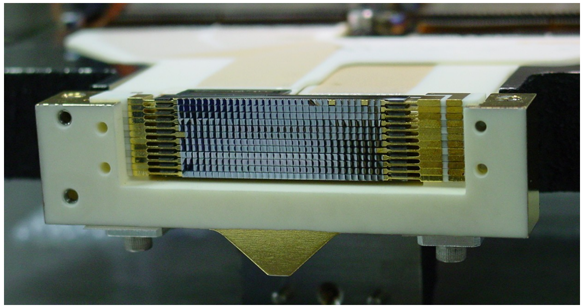
SHARC-2 (350 um)

After high-pass filtering...

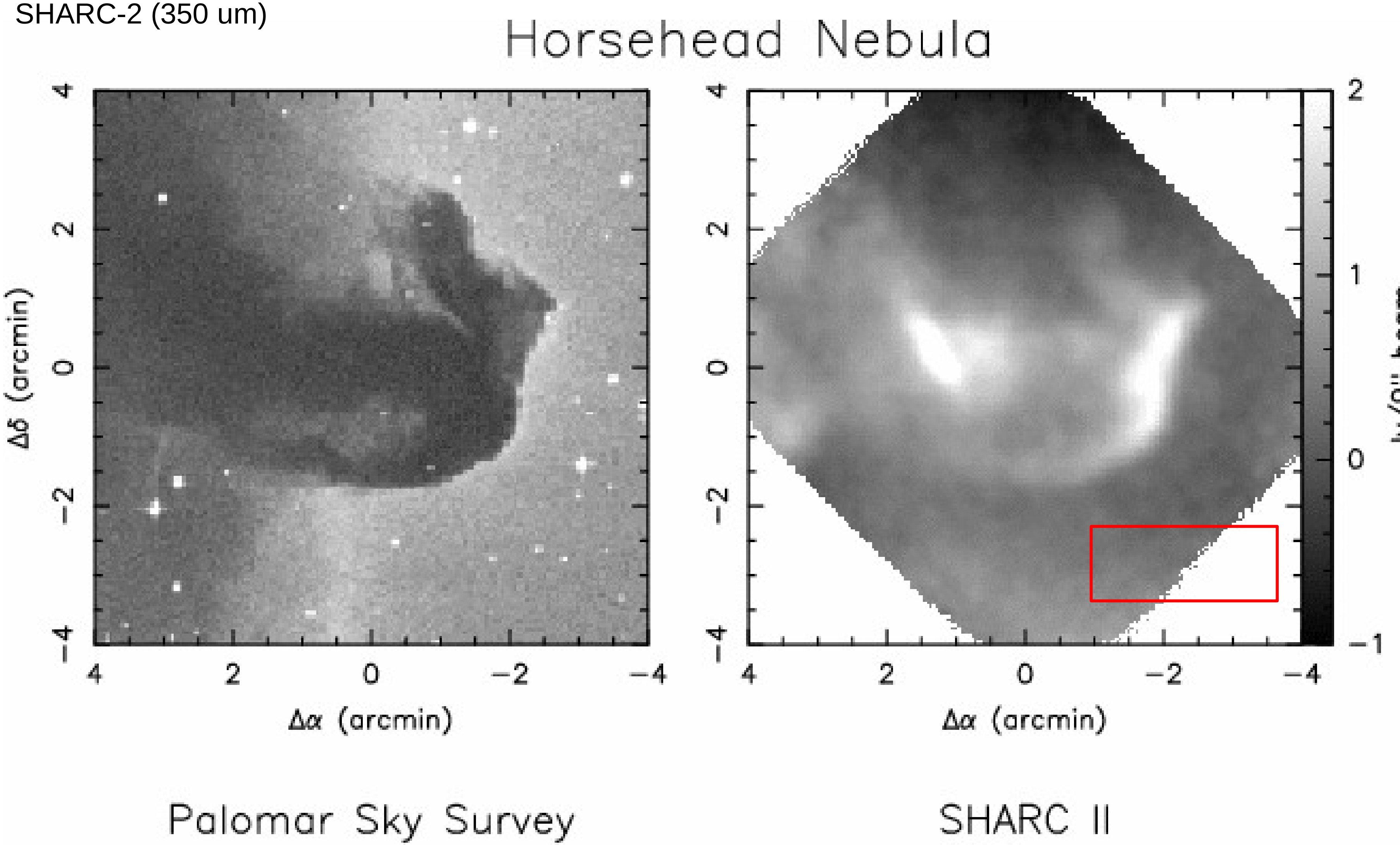


C.D. Dowell

Horse Head Nebula

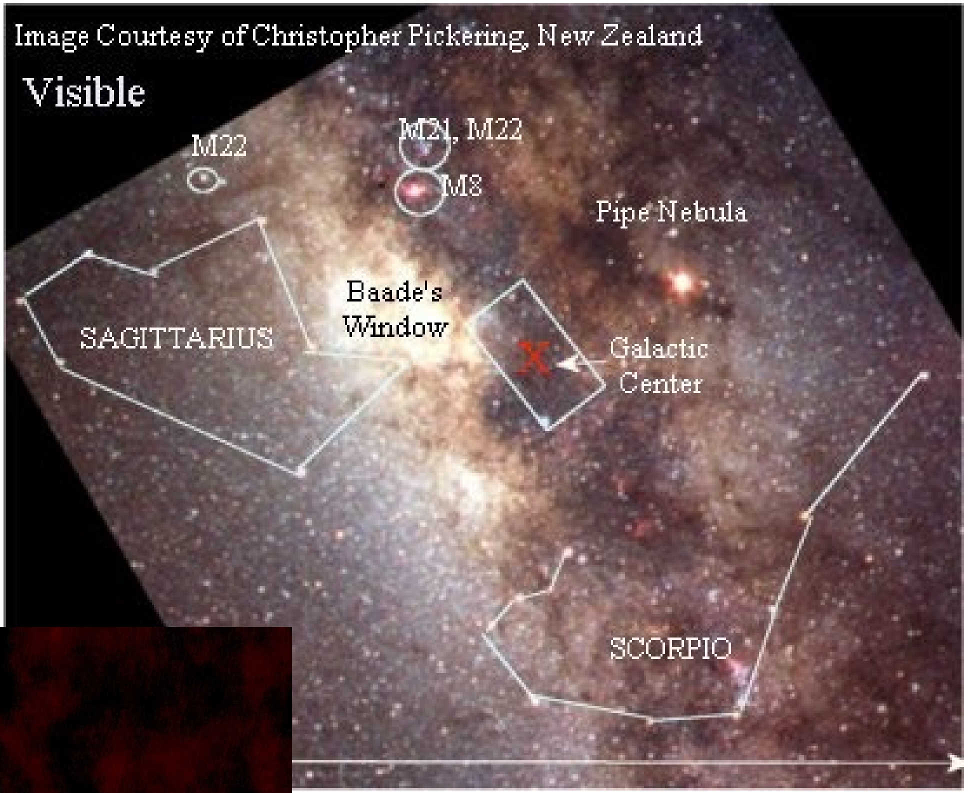


SHARC-2 (350 um)



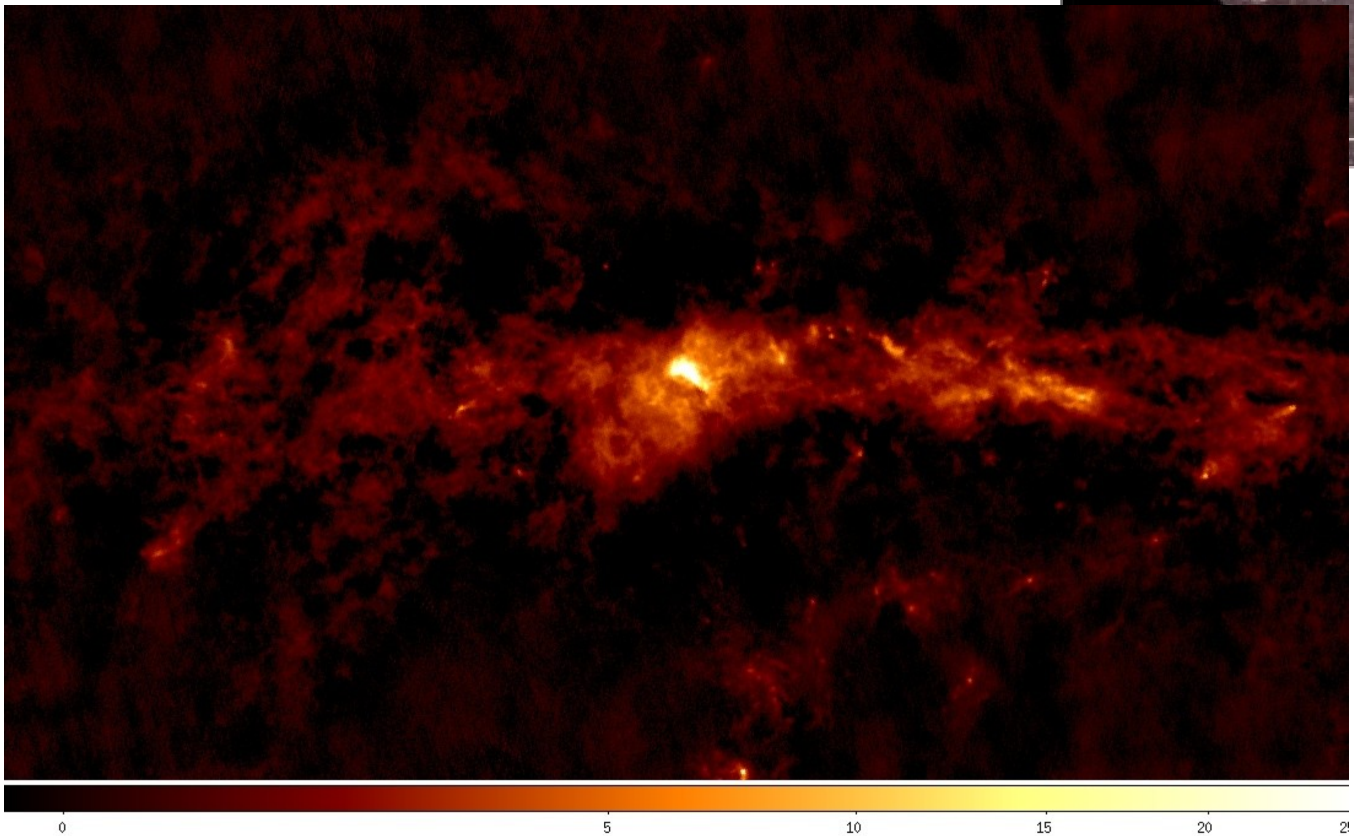
C.D. Dowell

The Galactic Center of the Milky Way

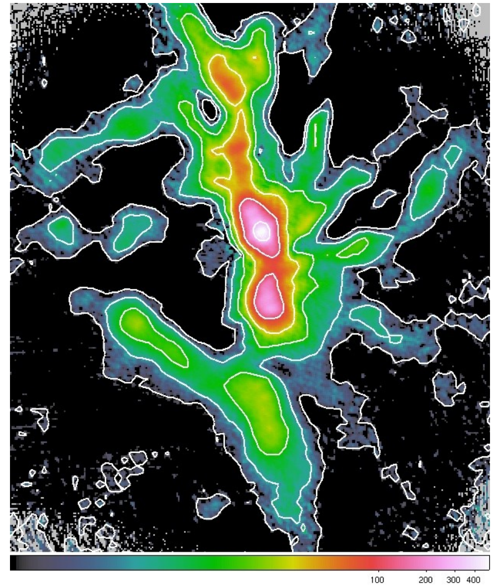


Visible light

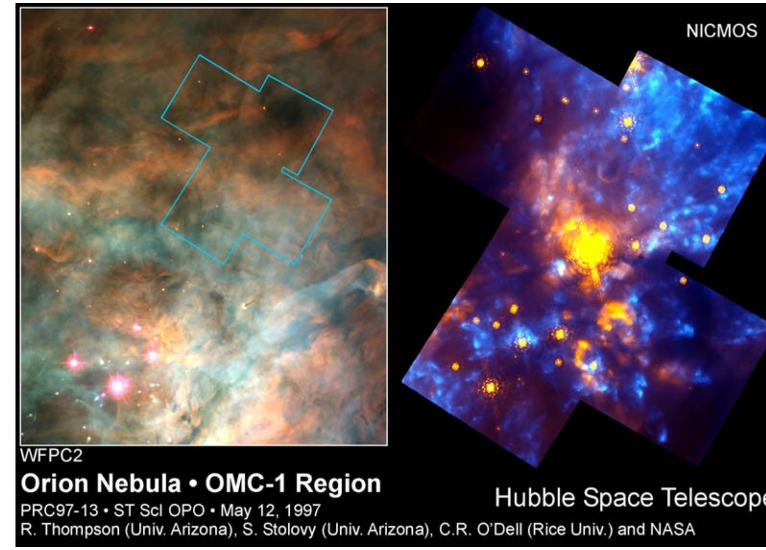
LABOCA (870um)



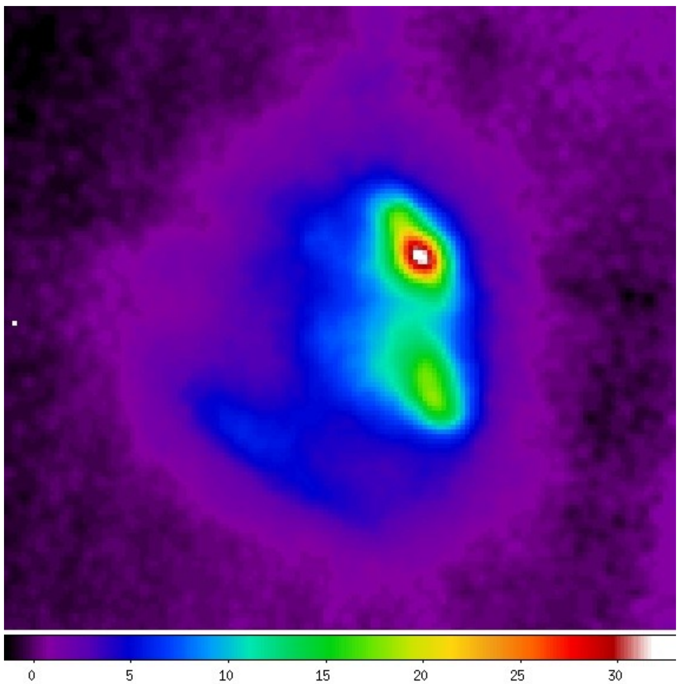
The Orion Molecular Cloud (OMC-1)



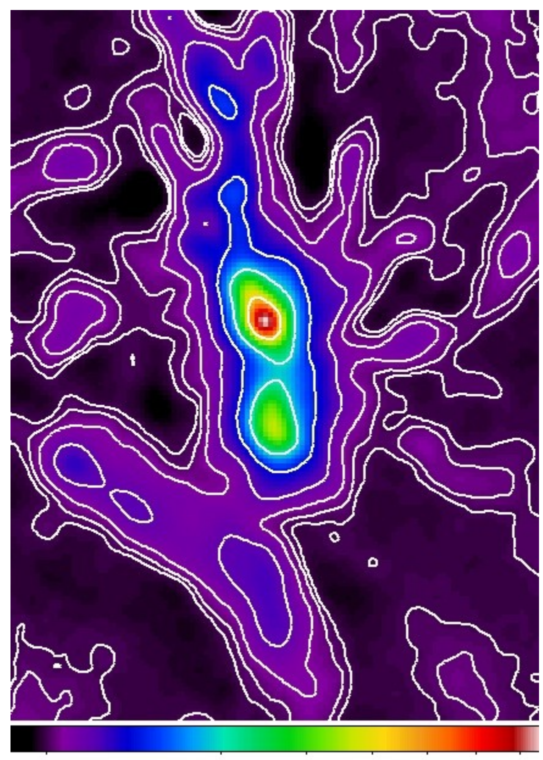
SABOCA (350um)



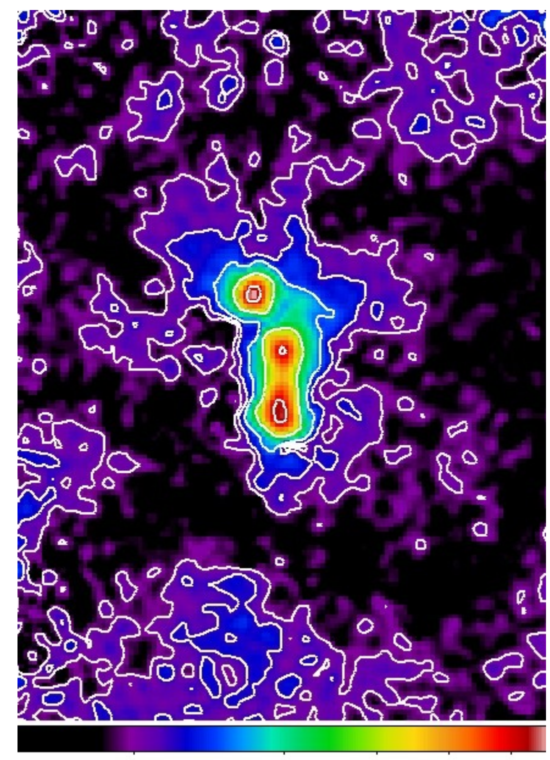
Optical and Near Infrared



GISMO (2 mm)

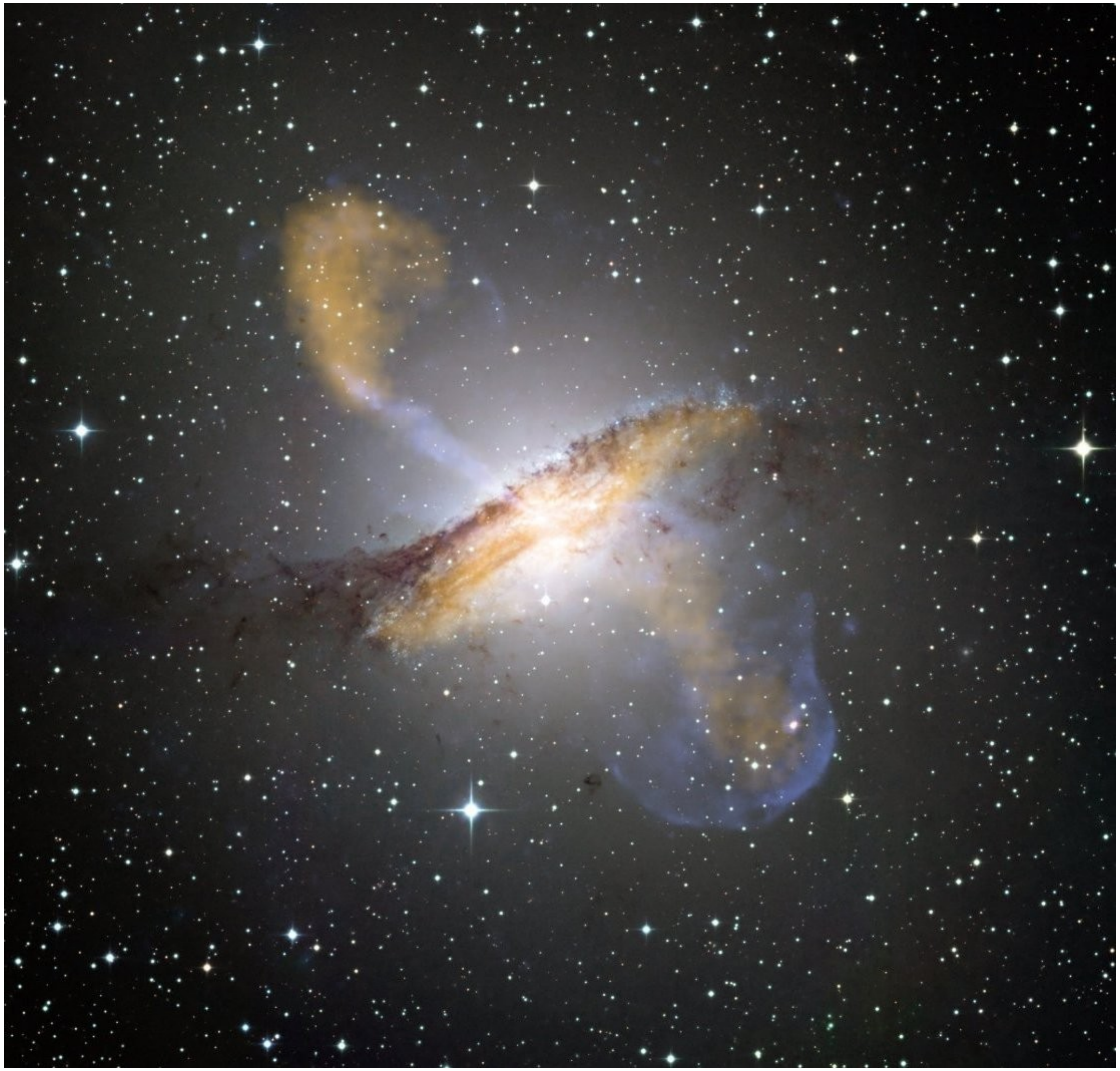


LABOCA (870um)

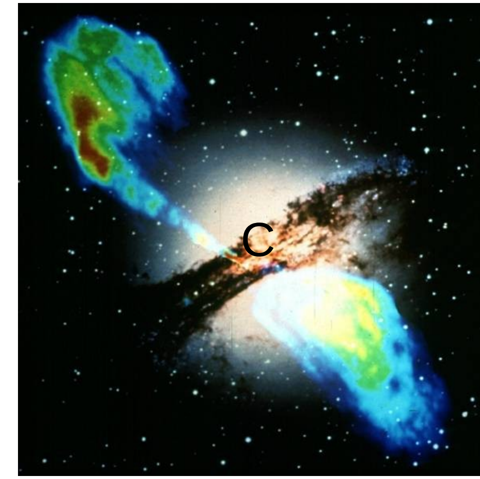


870um polarized flux

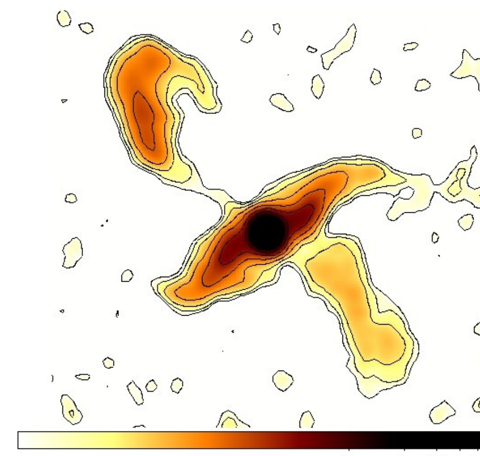
Centaurus A
(A. Weiss, A. Kovacs et al. 2008)



Multiband composite (ESO Press release picture)



Optical + radio

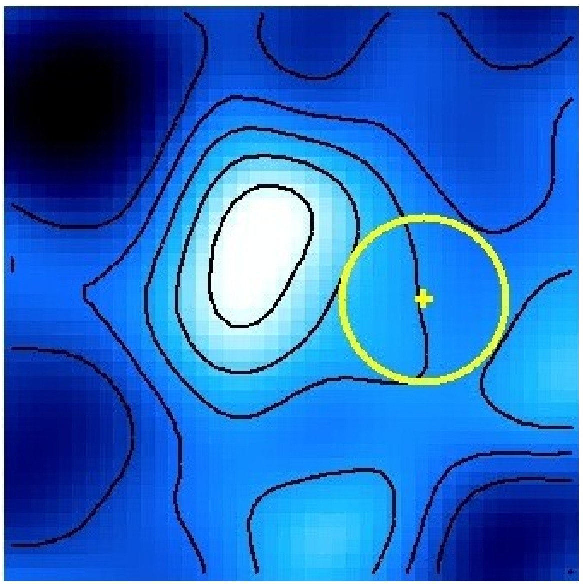


LABOCA (870um)

LABOCA (red)
Mid-infrared (green)
UV (blue)

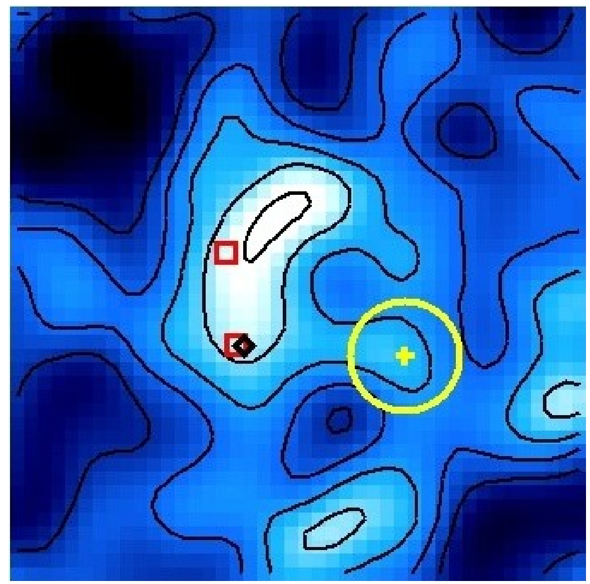
Distant Galaxies

Optimally (Wiener) filtered

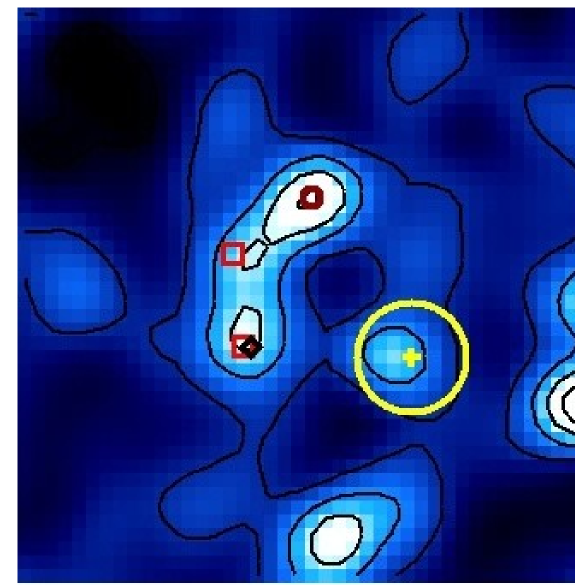


50 arcsec

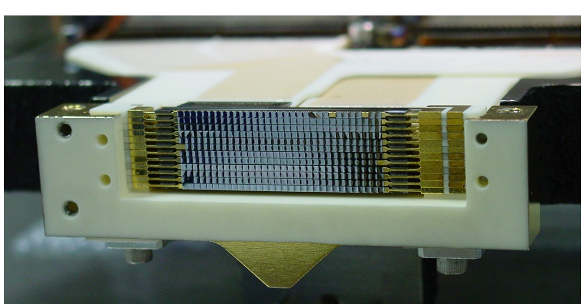
Around diffraction limit



Slightly deconvolved

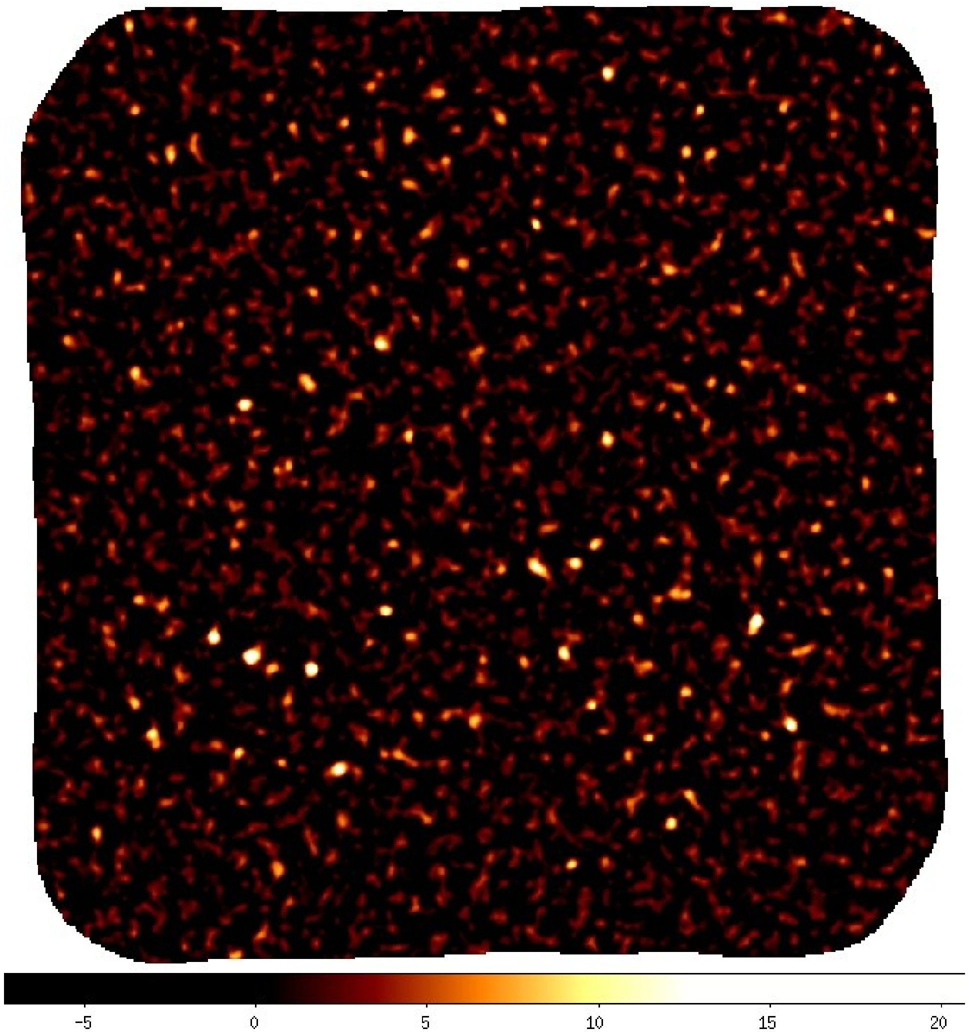


Kovacs et al., *in prep*



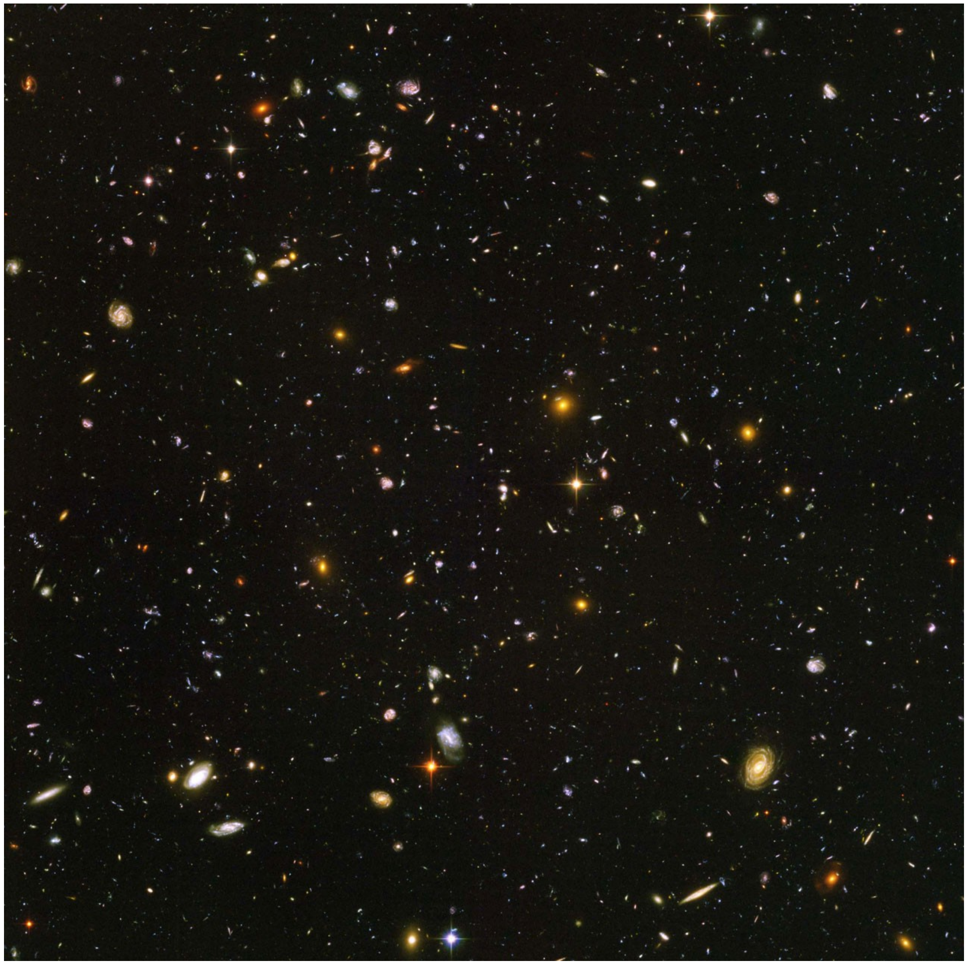
SHARC-2 350 um

LABOCA CDFS deep field survey
(A. Weiss & A. Kovacs)



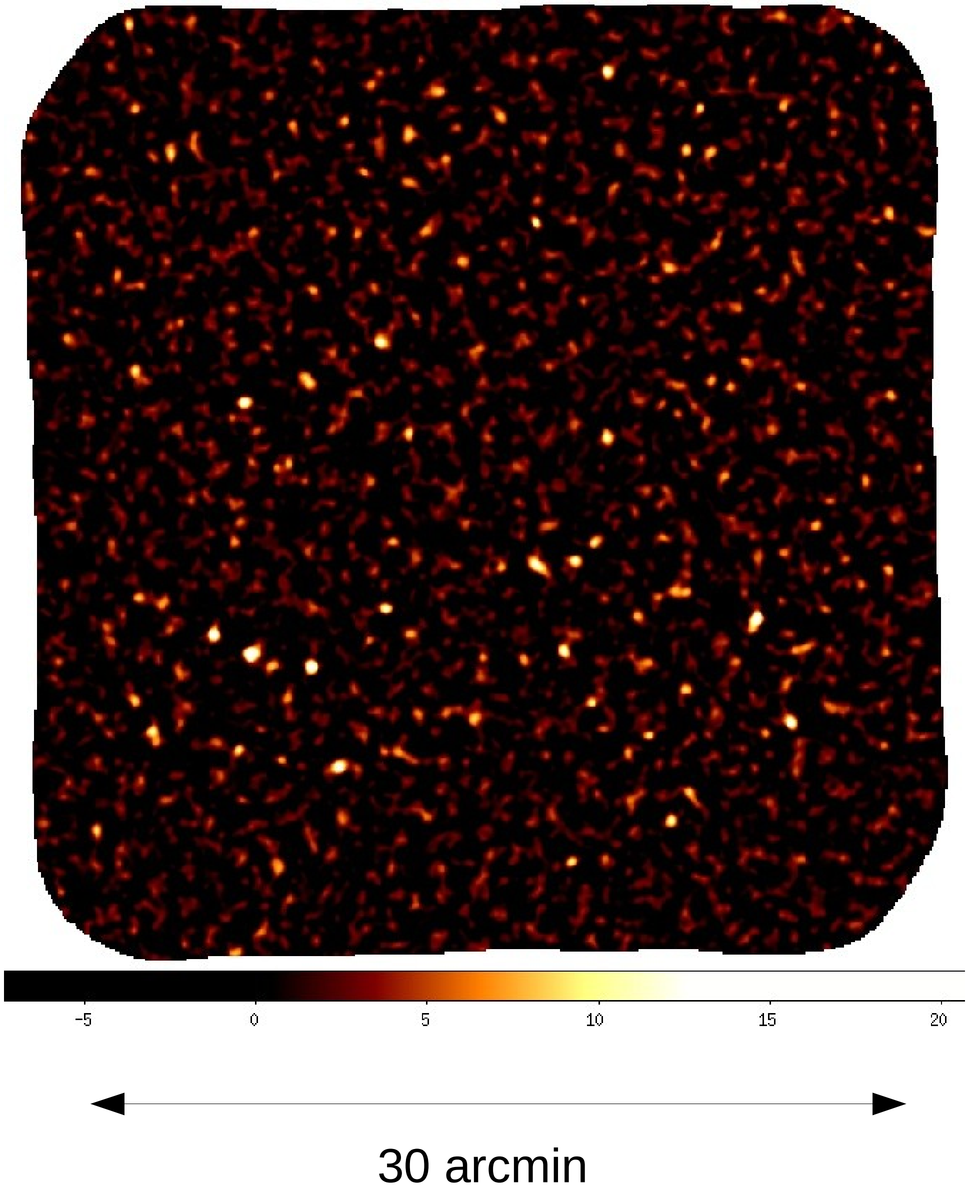
30 arcmin

Hubble Ultra Deep Field
(optical)



3 arcmin

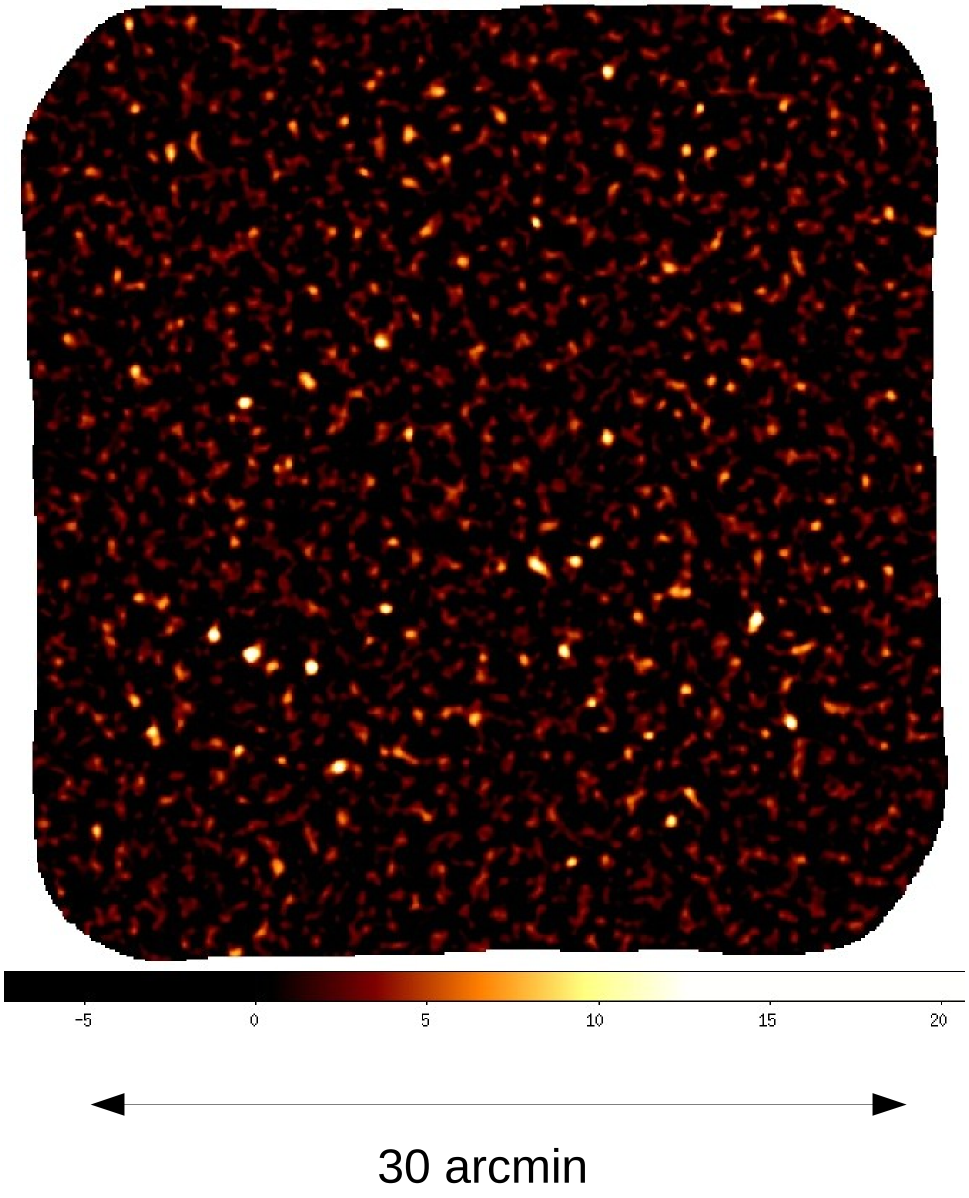
LABOCA CDFS deep field survey
(A. Weiss & A. Kovacs)

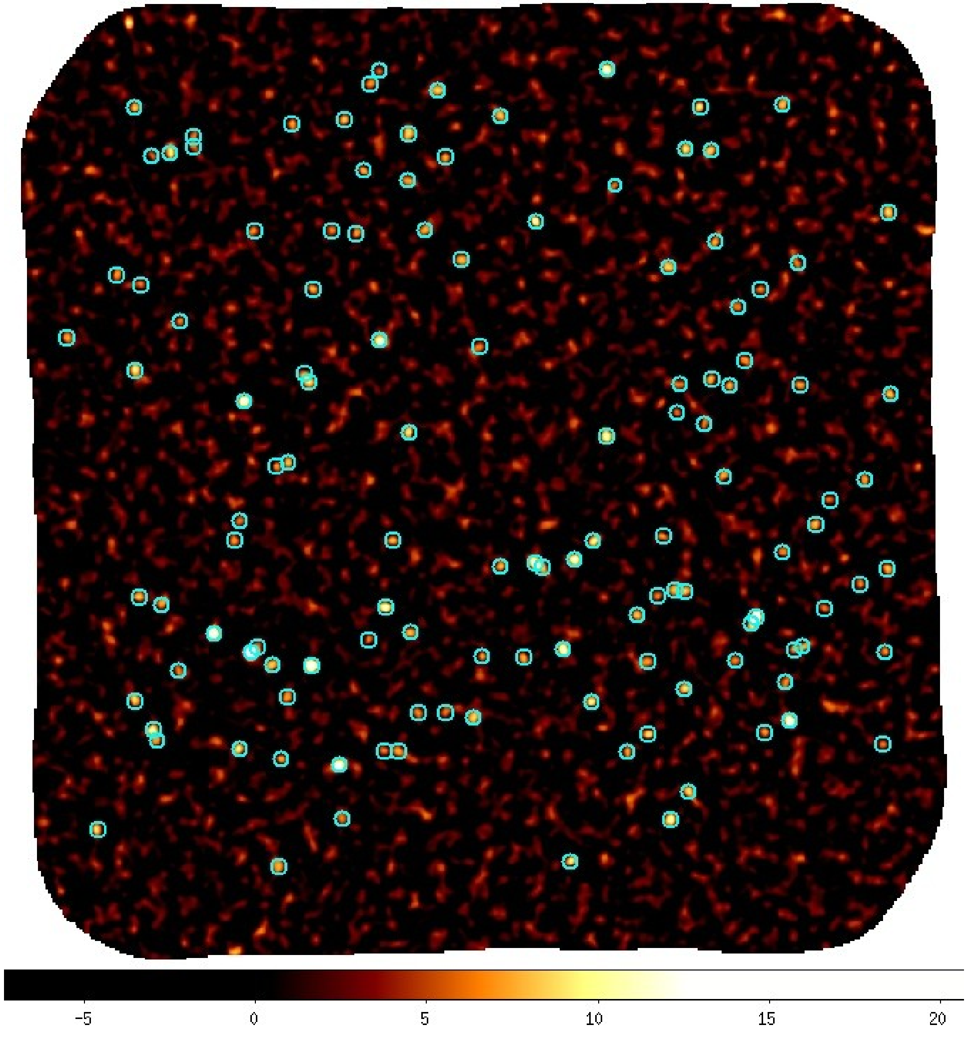


30 arcmin

Hubble Ultra Deep Field
(optical)

LABOCA CDFS deep field survey
(A. Weiss & A. Kovacs)

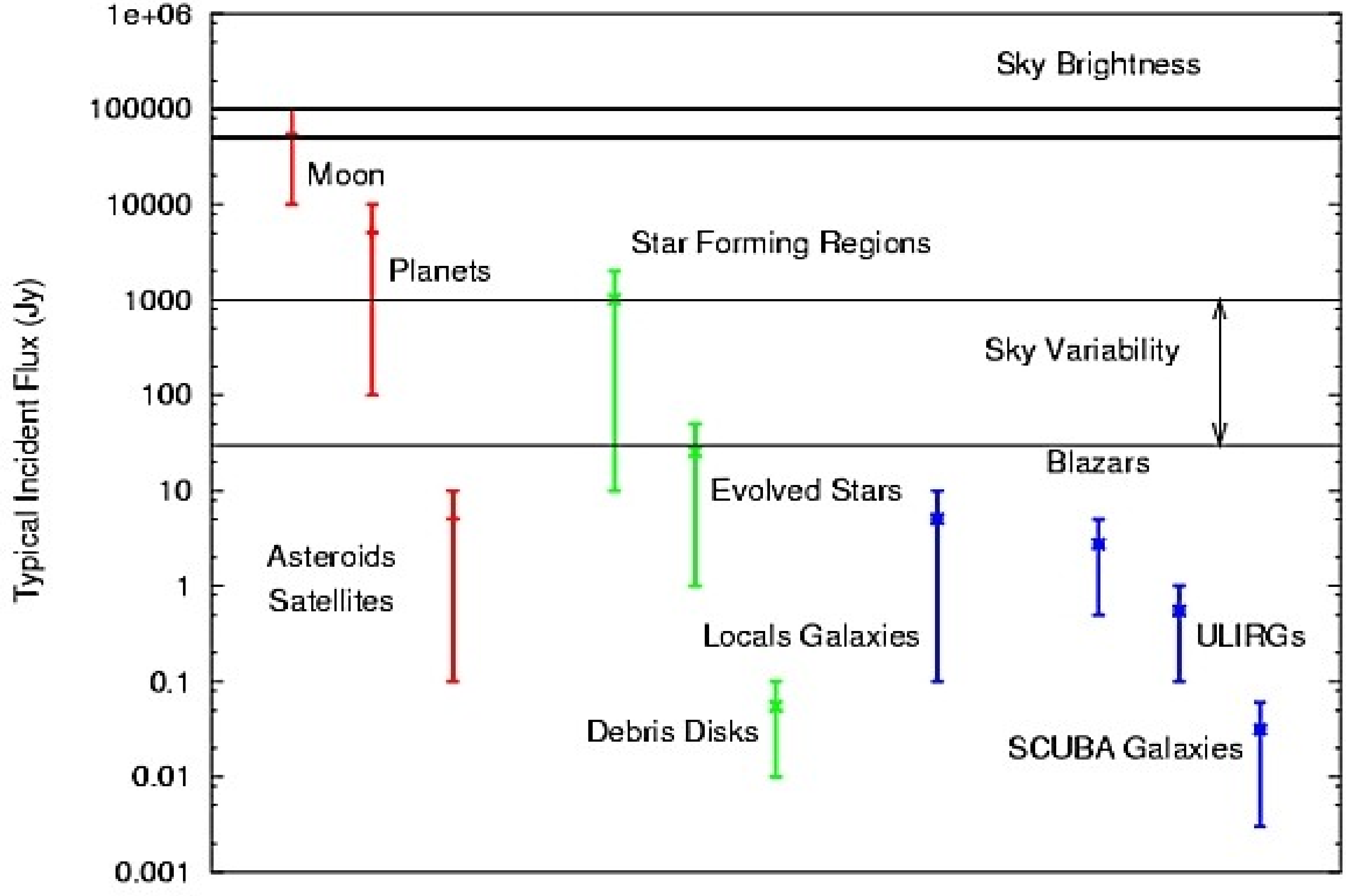




Part I

Data Reduction

Typical Object Brightness...

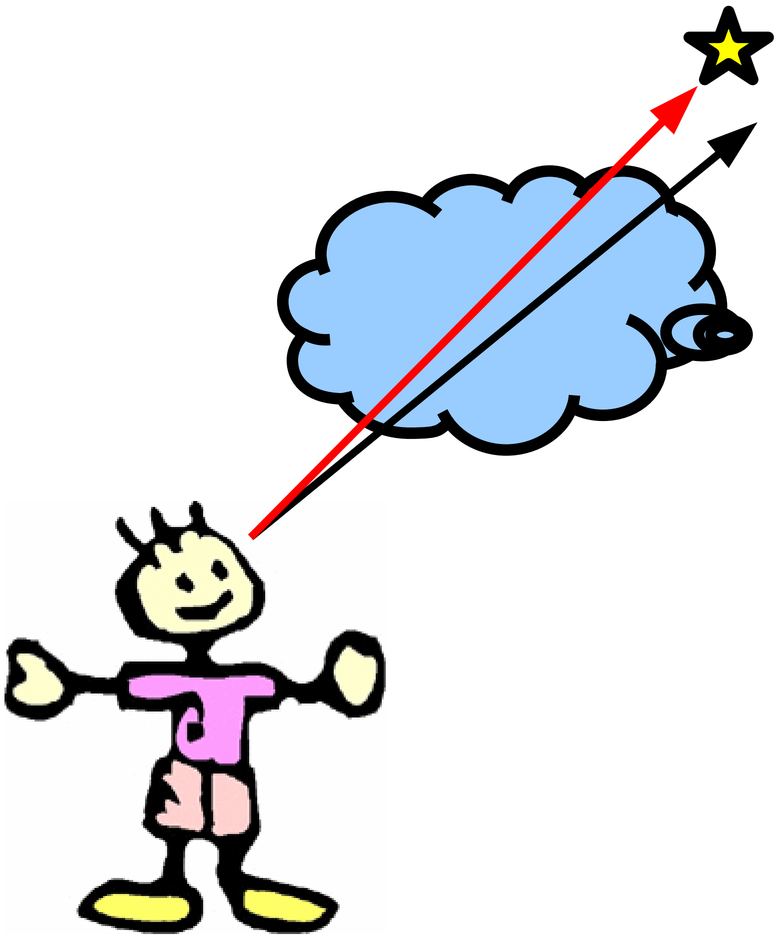


Chopping

Differential Signals

Fast switching of detectors between source and blank sky.
Analyze difference signals.

E.g. 45" switching at 4 Hz for SHARC



Problems

Differencing Noise
(2x observing time)

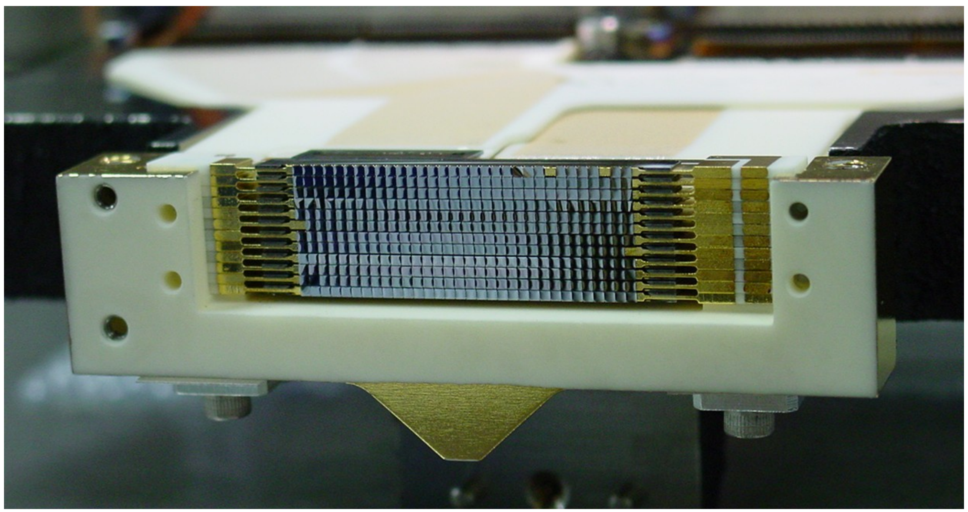
Insensitivity to Certain Spatial Components

Duty Cycle

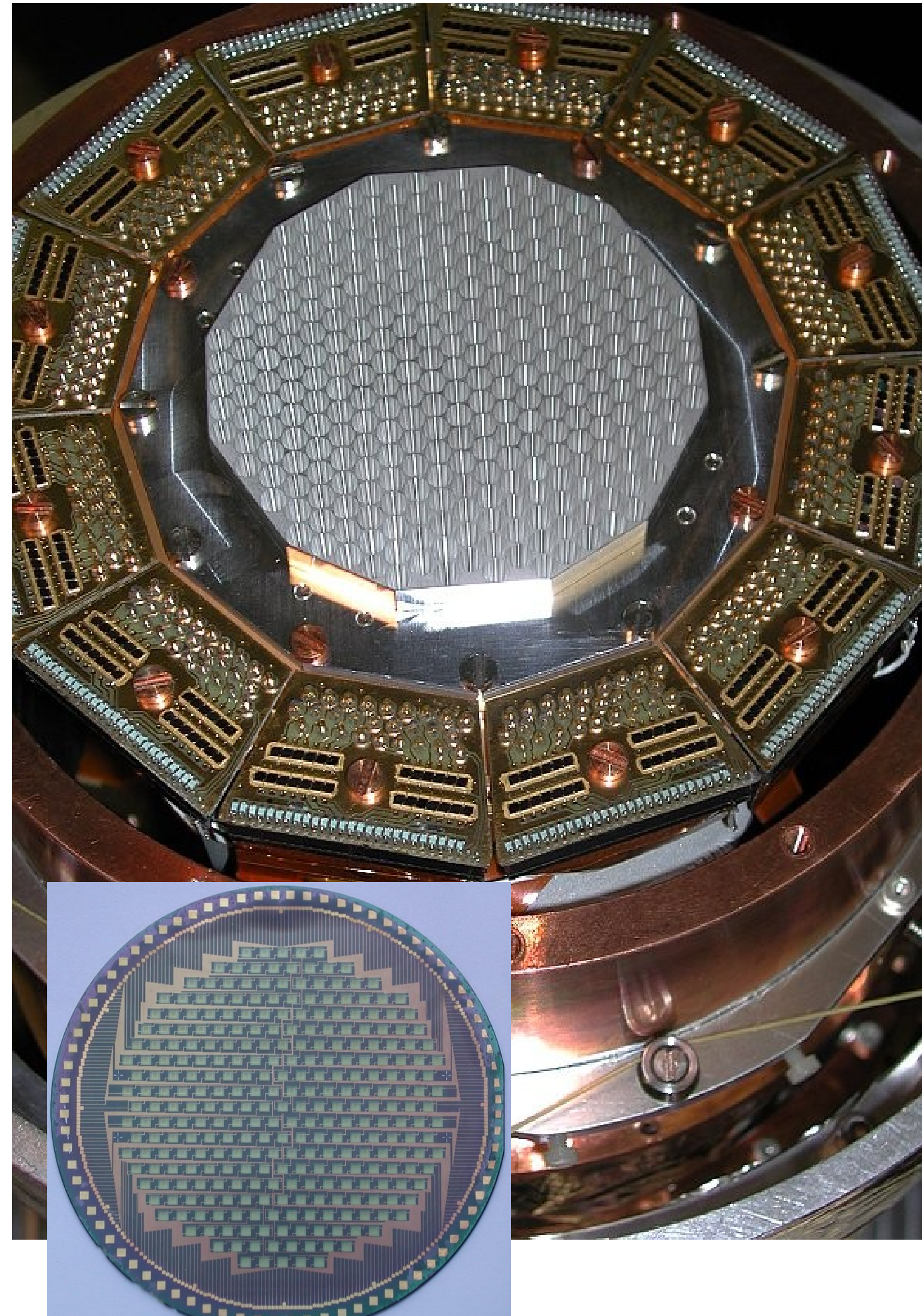
Striping
(Imperfect Sky Removal)

Large Arrays

SHARC-2



LABOCA



The Array Imaging Challenge

High background

Unstable detectors

Faint signals

Large data volumes
(100—10,000 pixels 10--100 Hz readout)

Do at least as well as chopping techniques...

Introducing CRUSH...

(2003 -- now)

Comprehensive **R**eduction **U**tility for **SH**ARC-2
(PhD thesis, Caltech 2006)

Also used for **LABOCA, SABOCA, ASZCA, ArTeMiS, PolKa, GISMO**...

Offsprings: **sharcsolve** (C. D. Dowell), **BoA** (F. Schuller, A. Beelen et al.)

40K lines of Java code (and growing...)

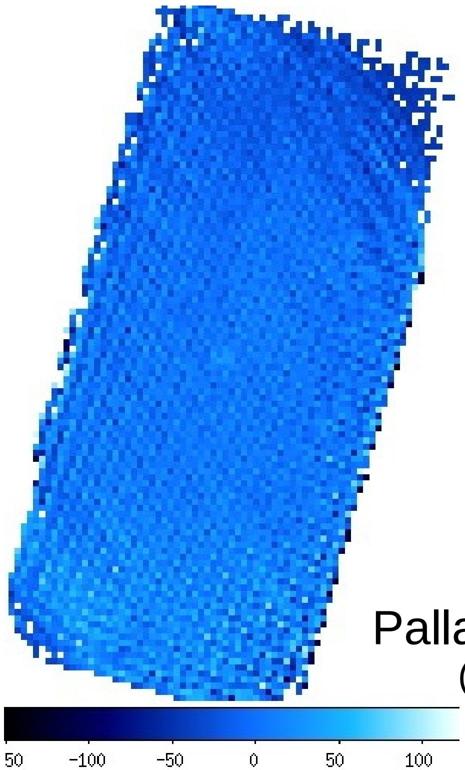
Fast (~1GB/min on 4-core HT CPUs)...

Low overheads.

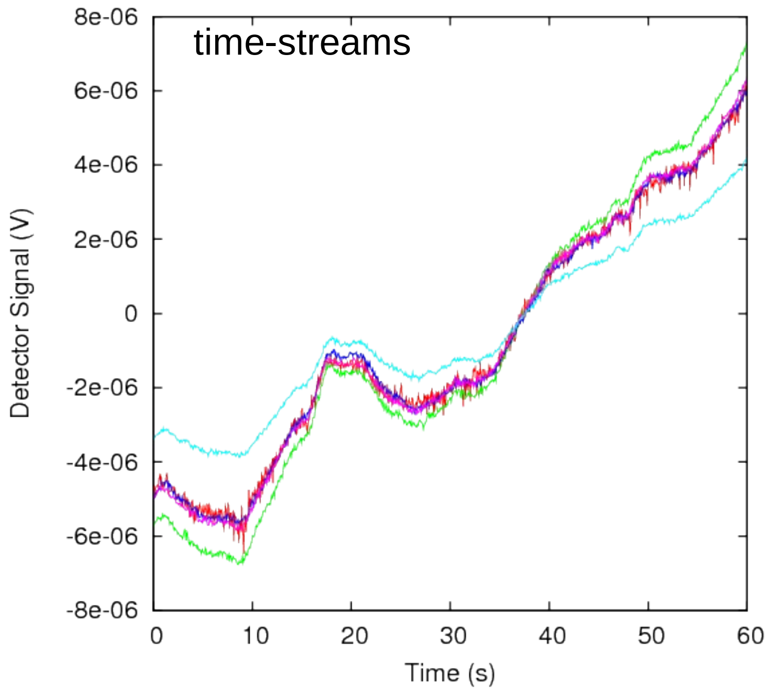
Future: more instrument, interferometry, other high background applications...

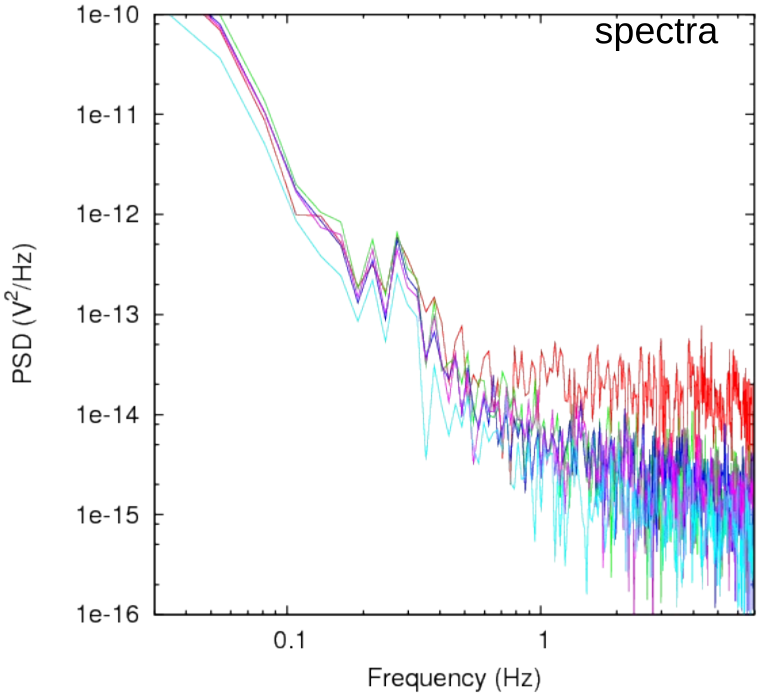
http://www.submm.caltech.edu/~sharc/crush

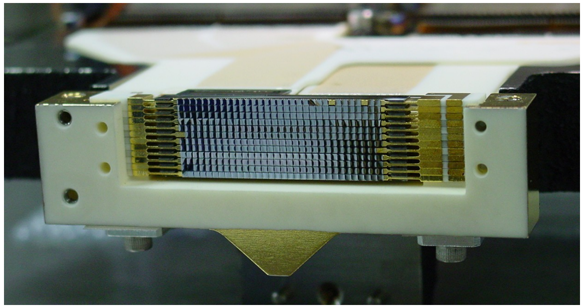
Direct Mapping
(lossless)



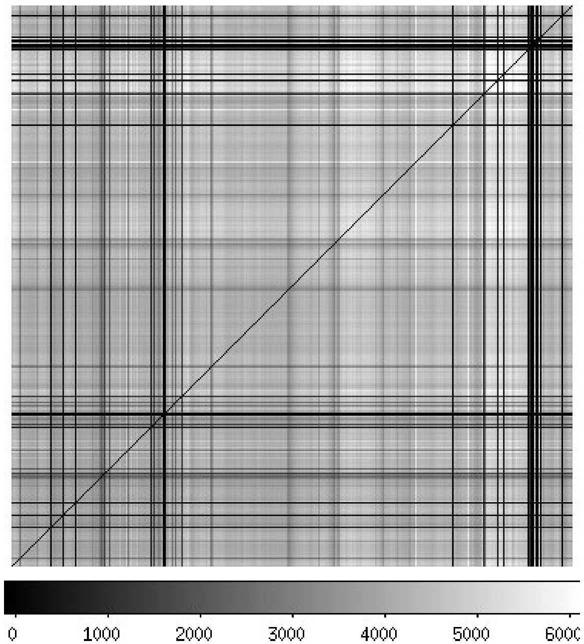
Pallas in 1 min
(350um)







SHARC-2



Pixel-to-pixel
covariance

The model parameters
That we want to solve for

The measurements

$$\mathbf{x = F\ b + n}$$

noise

A is the design matrix

Aij = dFi / σj

$$\mathbf{(A^T A)\ x = A^T b}$$

$$X_{ct} = G_{ct}\mathcal{M}_{ct}^{xy}S_{xy} + g_{1,c}C_{1,t} + \ldots + g_{\mathrm{k},c}C_{\mathrm{k},t} + n_{ct}$$

Need to know: **weights, gains, flags** before we can invert for **signals**

Incremental solutions

$$X_{ct} = G_{ct}\mathcal{M}_{ct}^{xy}S_{xy} + g_{1,c}C_{1,t} + ... + g_{\mathrm{k},c}C_{\mathrm{k},t} + n_{ct}$$

$$\mathbf{R} = \mathbf{X} - \hat{\mathbf{G}} \bullet (\mathcal{M} \cdot \hat{\mathbf{S}}) - \hat{\mathbf{g}}_1\hat{\mathbf{C}}_1^\top - ... - \hat{\mathbf{g}}_\mathrm{k}\hat{\mathbf{C}}_\mathrm{k}^\top$$

Let's worry about one thing at a time...

gain — *Correlated signal increment*

$$R_{ct} = ... + g_c\,\Delta C_t + ...$$

$$\Delta\mathbf{C} = \mathbf{C} - \hat{\mathbf{C}}$$

$$\chi^2 = \sum_{t,c} \frac{R_{ct} - \hat{g}_c\Delta\hat{C}_t}{\sigma_{ct}^2}$$

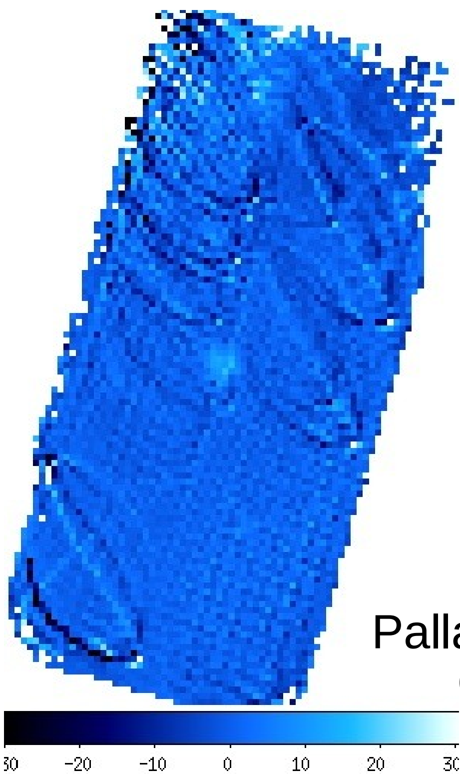
$$\Delta\hat{C}_t = \frac{\sum_c w_{ct}\hat{g}_c R_{ct}}{\sum_c w_{ct}\hat{g}_c^2}$$

$$\sigma^2(\hat{C}_t) = \frac{1}{\sum_c w_{ct}\hat{g}_c^2}$$

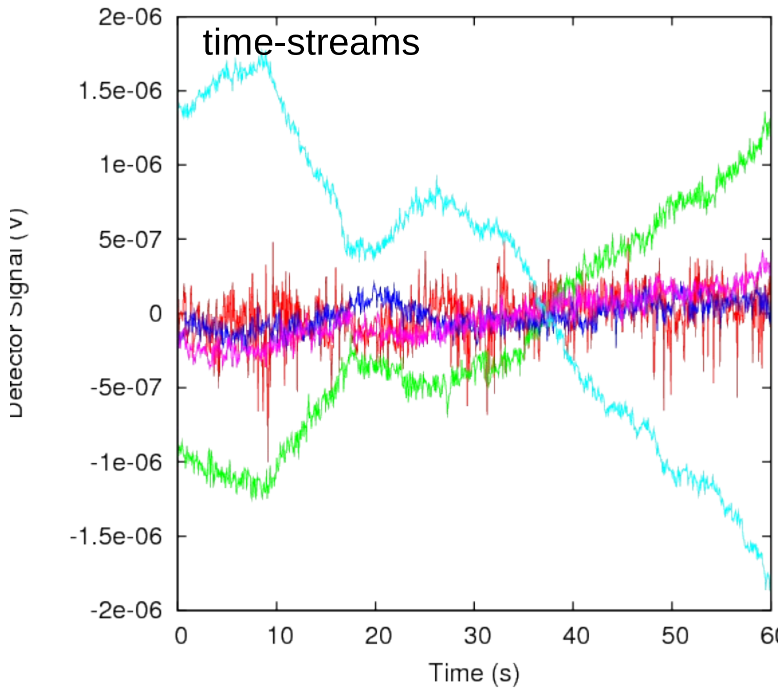
Maximum-likelihood estimator

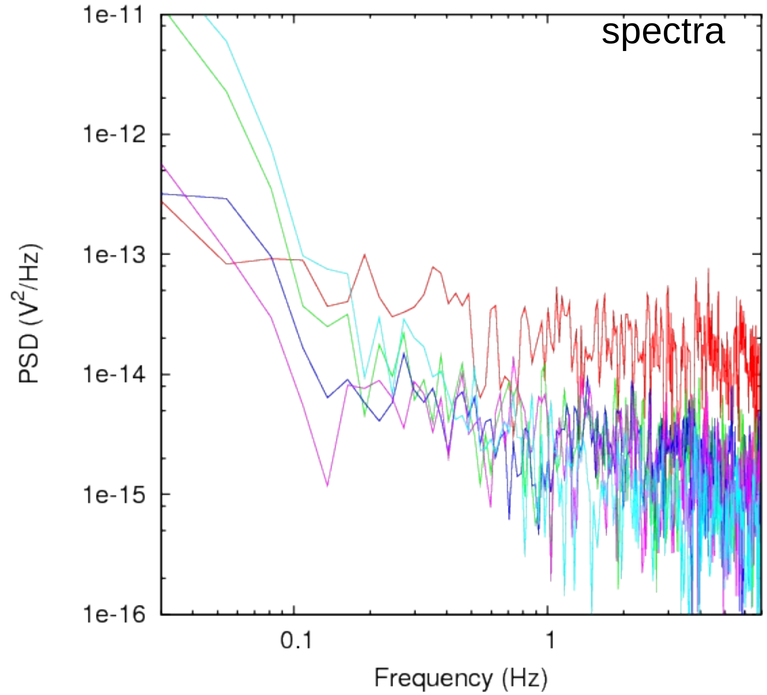
Can use other statistical estimators too...

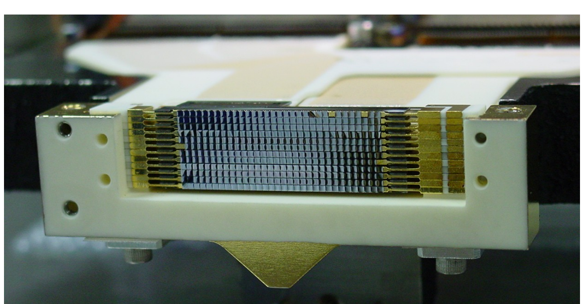
After Correlated Signal Removal



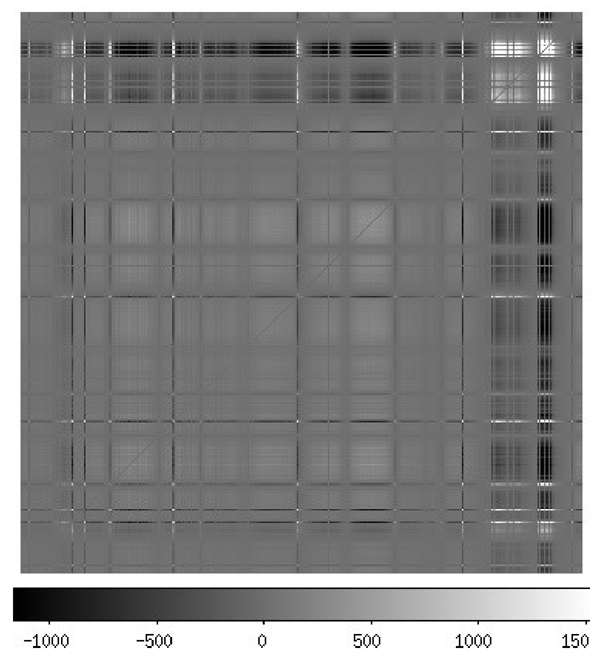
Pallas in 1 min
(350um)







SHARC-2



Pixel-to-pixel covariance

Can solve for gains too....

$$R_{ct} = ... + g_c \, \Delta C_t + ...$$

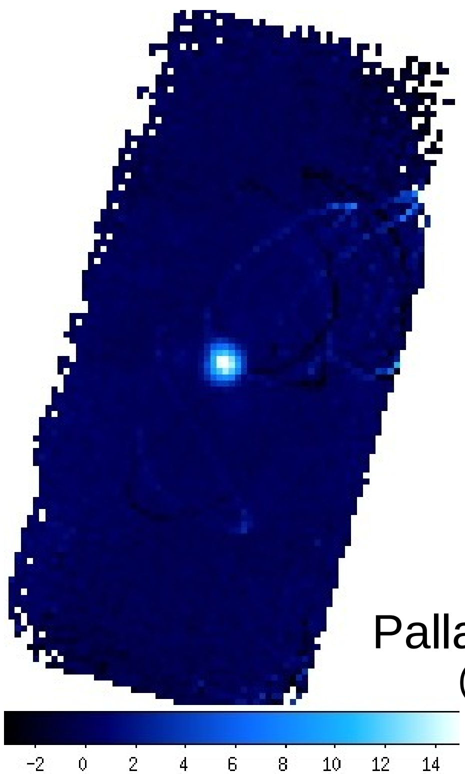
$$\chi^2 = \sum_{t,c} \frac{R_{ct} - \hat{g}_c \Delta \hat{C}_t}{\sigma^2_{ct}}$$

$$\Delta \hat{g}_c = \frac{\sum_t w_{ct} R_{ct} \hat{C}_t}{\sum_t w_{ct} \hat{C}_t^2}$$

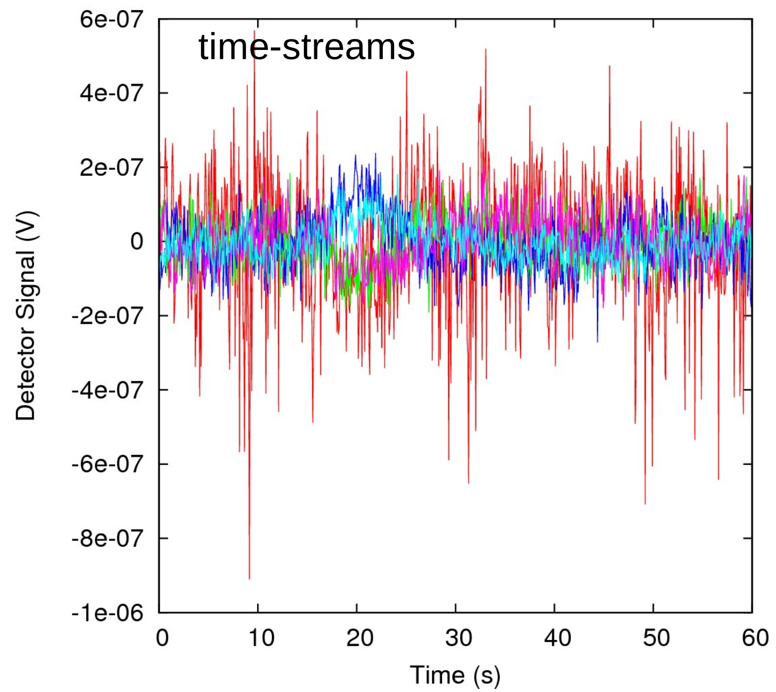
$$\sigma^2(\hat{g}_c) = \frac{1}{\sum_t w_{ct} \hat{C}_t^2}$$

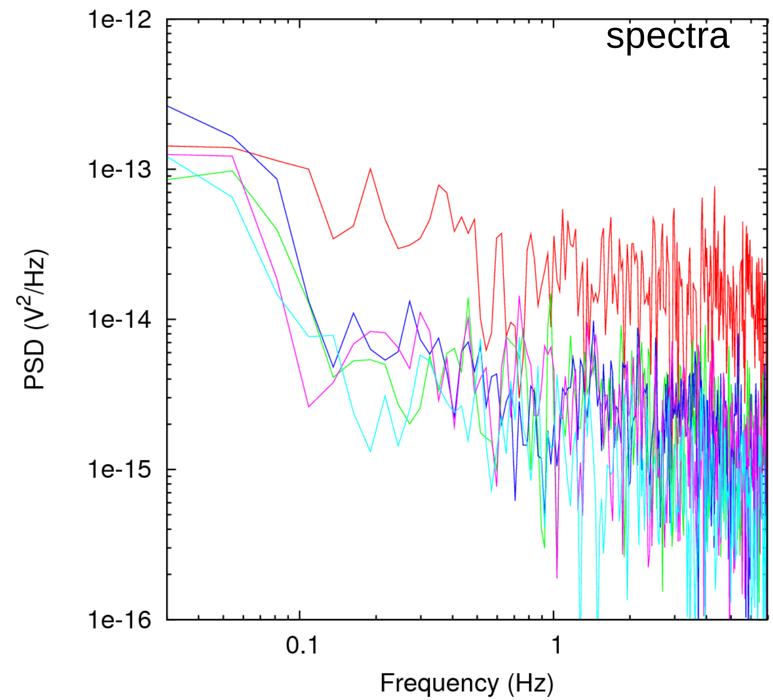
Maximum likelihood gain increment

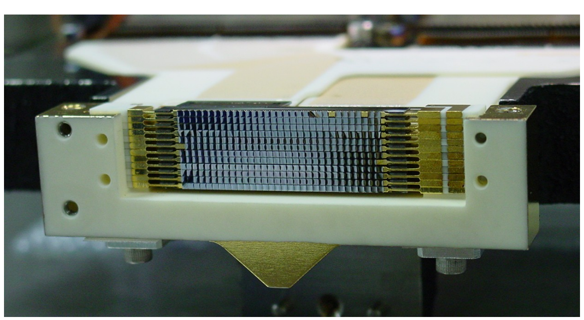
After sky gains...



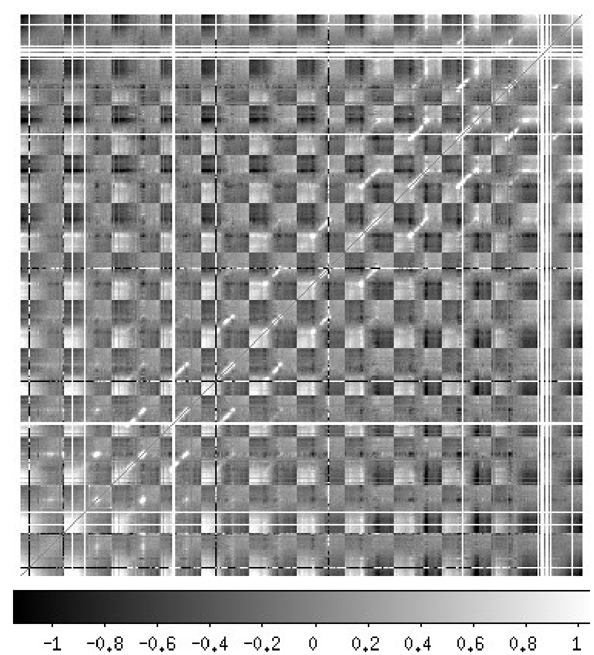
Pallas in 1 min
(350um)







SHARC-2



Pixel-to-pixel
covariance

Calculating noise weights...

assuming $w_{ct} = w_c \cdot w_t$

Channel weights:

$$\hat{w}_c = (N_t - P_c)\frac{\sum_t w_t}{\sum_t w_t R_{ct}^2}$$

Time weights:

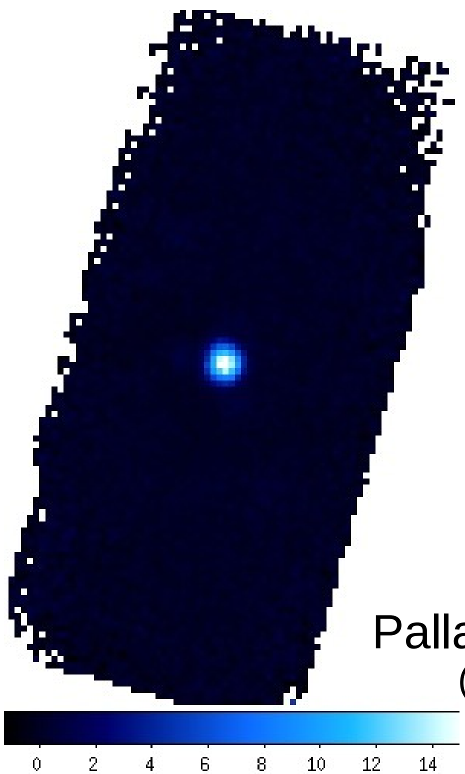
$$\hat{w}_t = (N_c - P_t)\frac{\sum_c w_c}{\sum_c w_c R_{ct}^2}$$

The devil is in the detail:

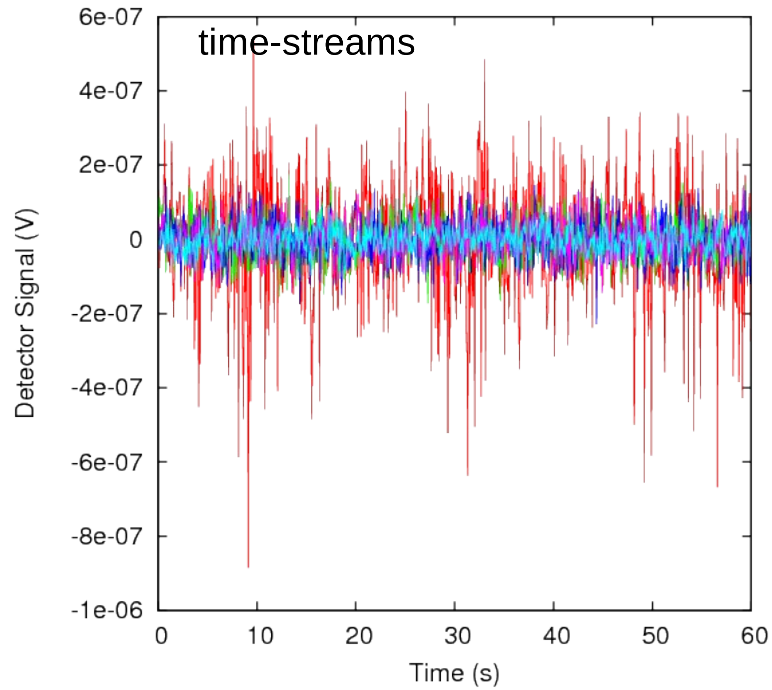
Specifically in calculating Pt and Pc right.

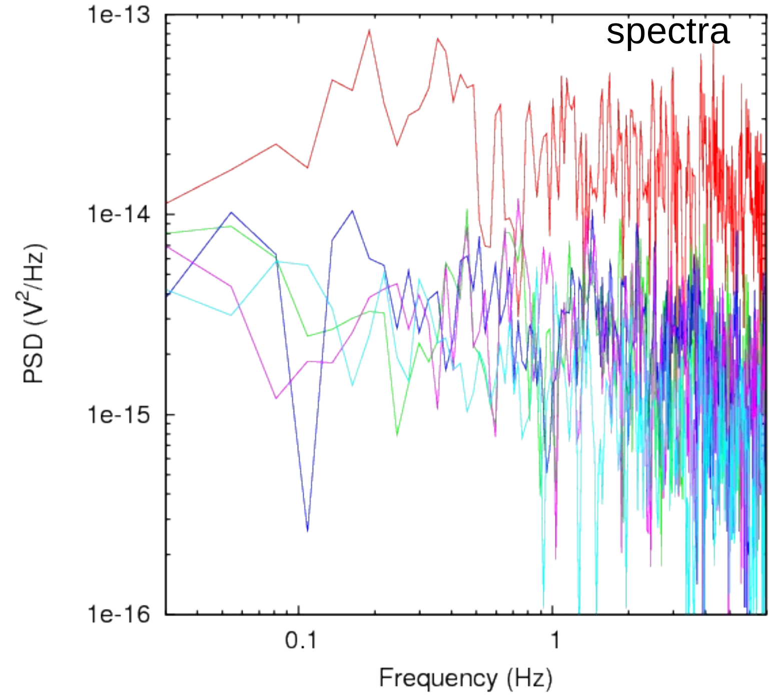
Else unstable solutions...

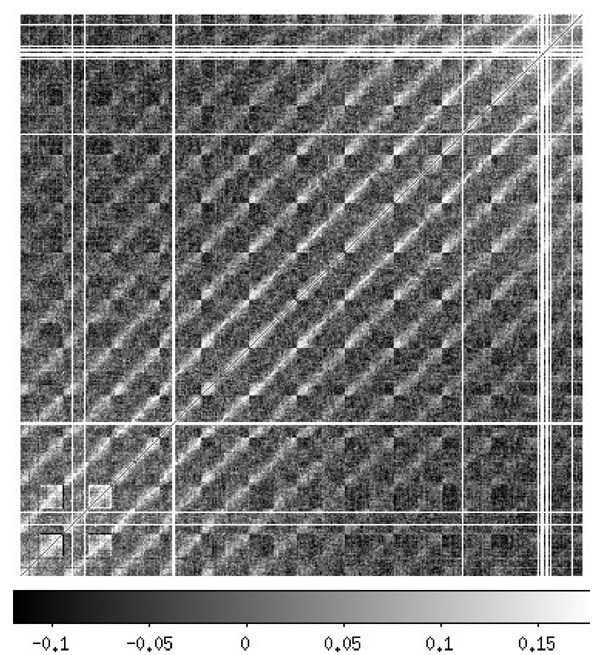
After 6 iterations...

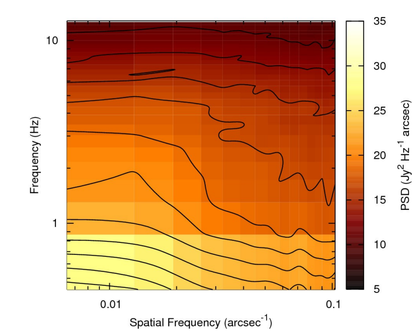


Pallas in 1 min
(350um)

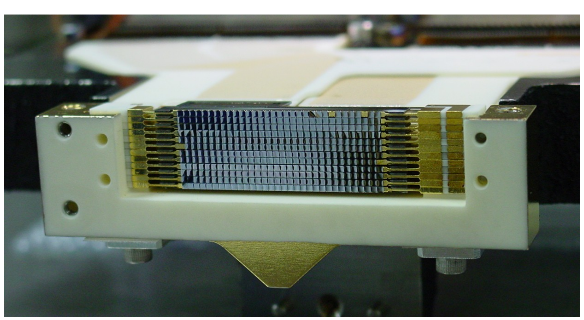








Pixel-to-pixel
covariance



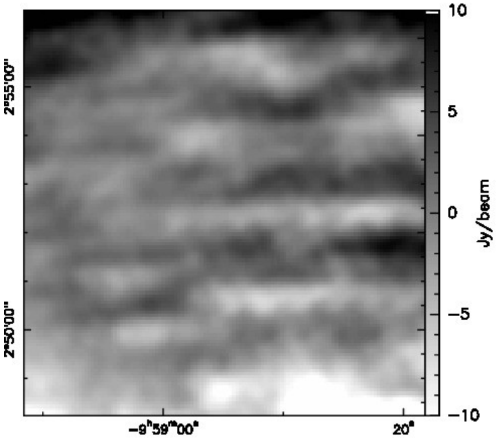
SHARC-2

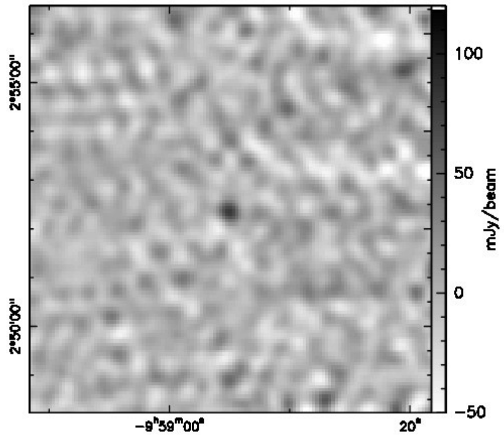
LABOCA (850um)

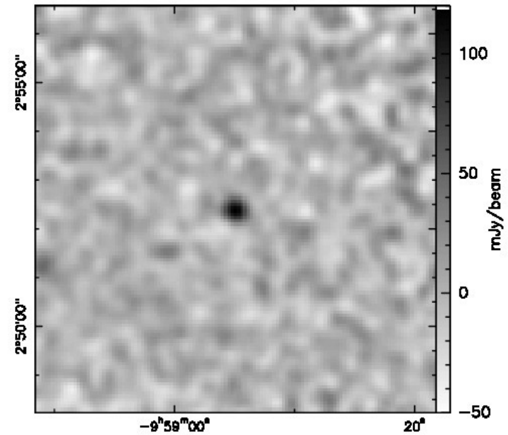
Direct mapping

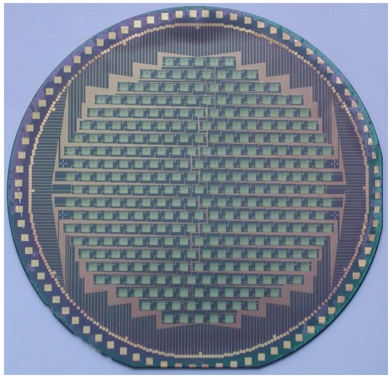
After sky removal

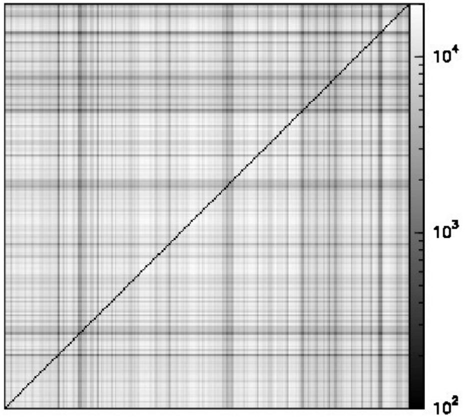
Decorrelating cables

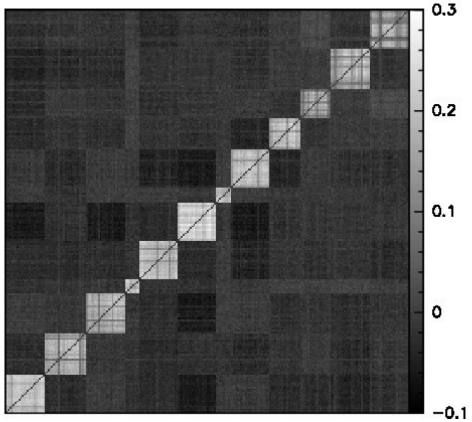


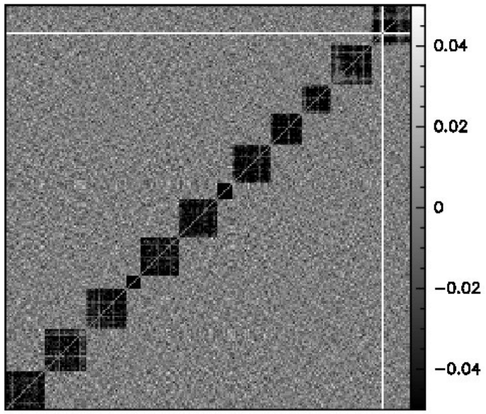


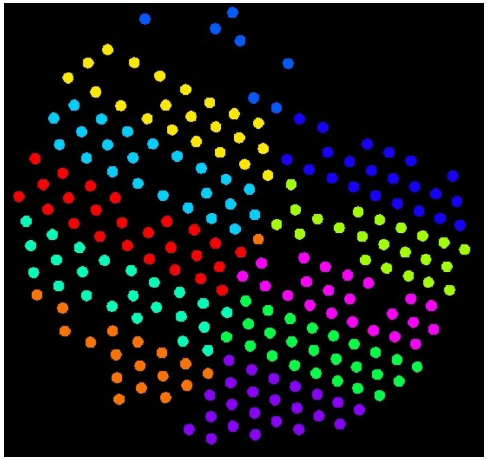




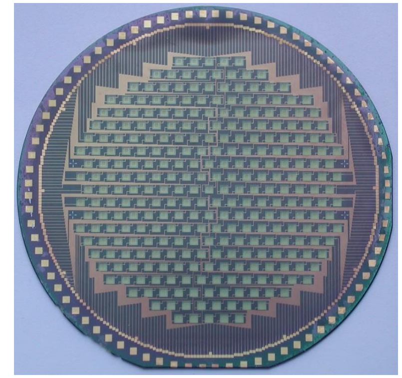


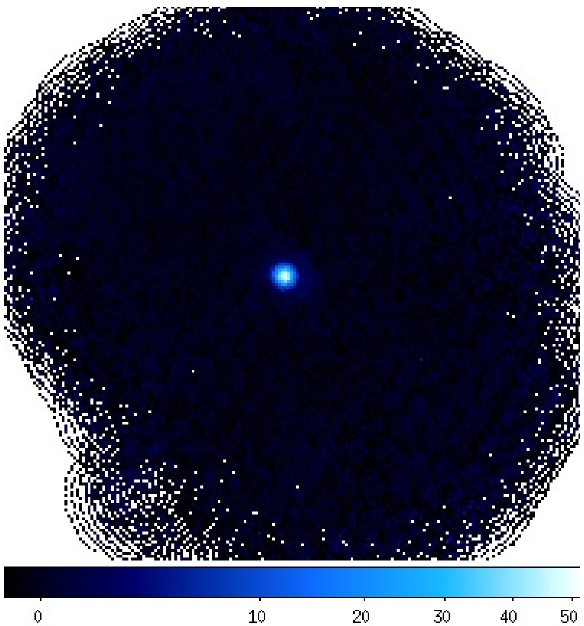




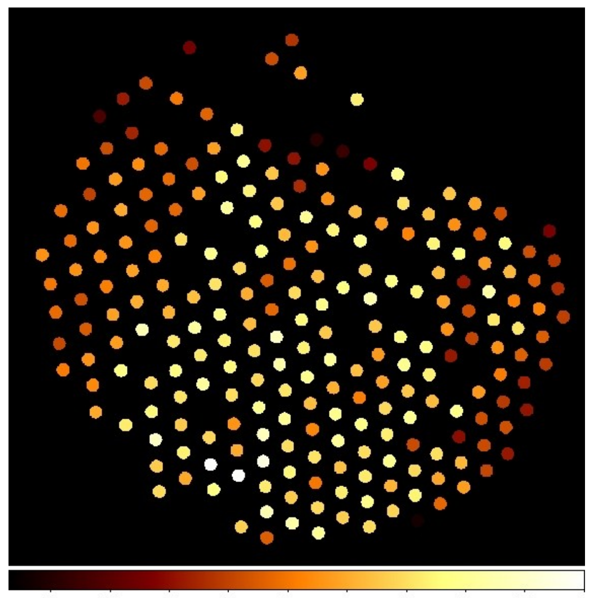


LABOCA (850um)

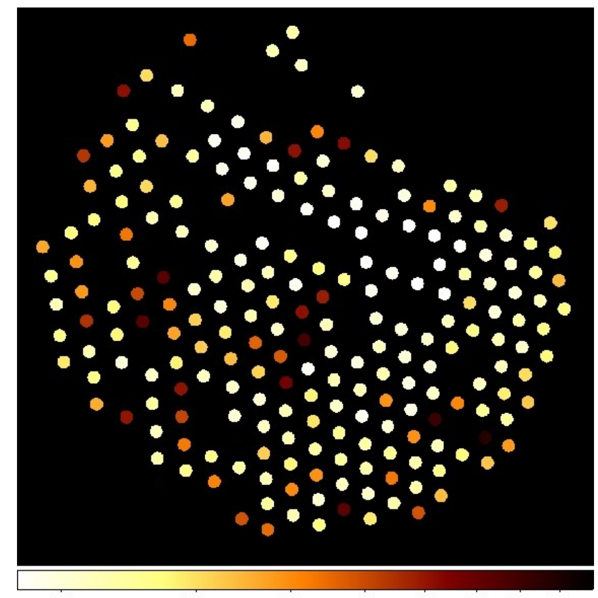




Astronomical signal
(Uranus @ 850um)

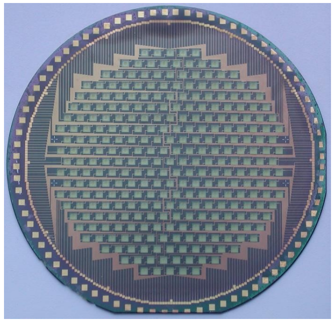


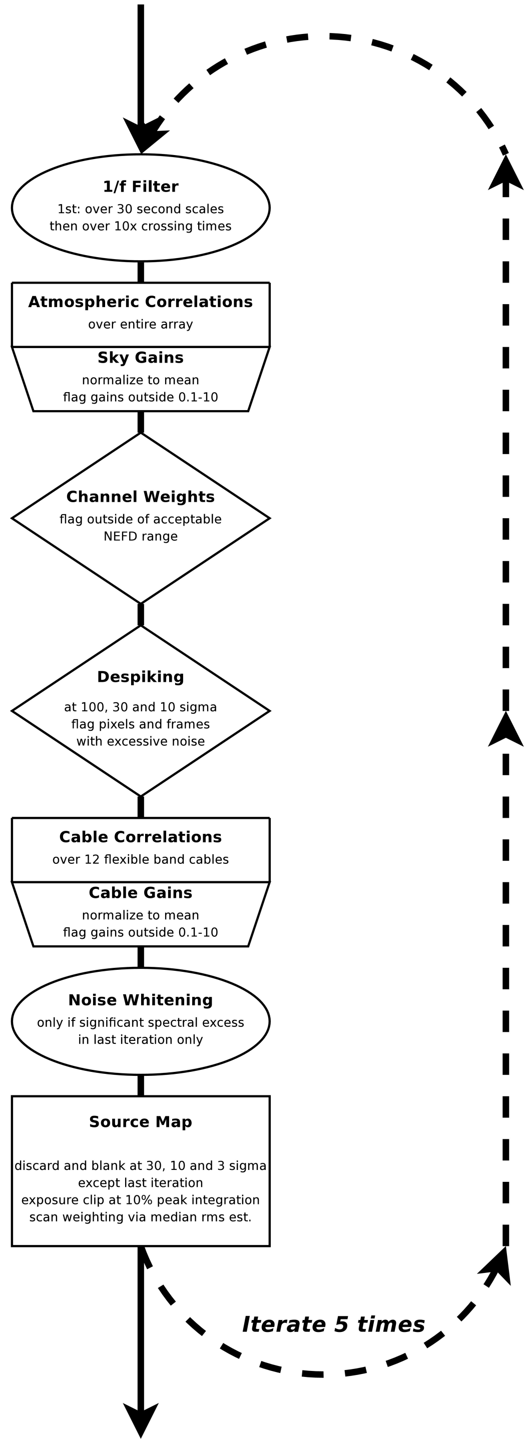
Relative pixel gains

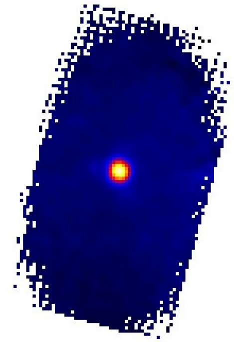


pixel noise

LABOCA (870um)

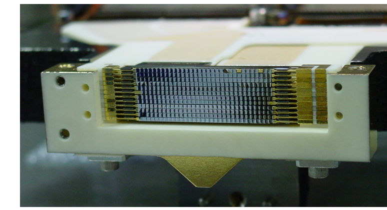


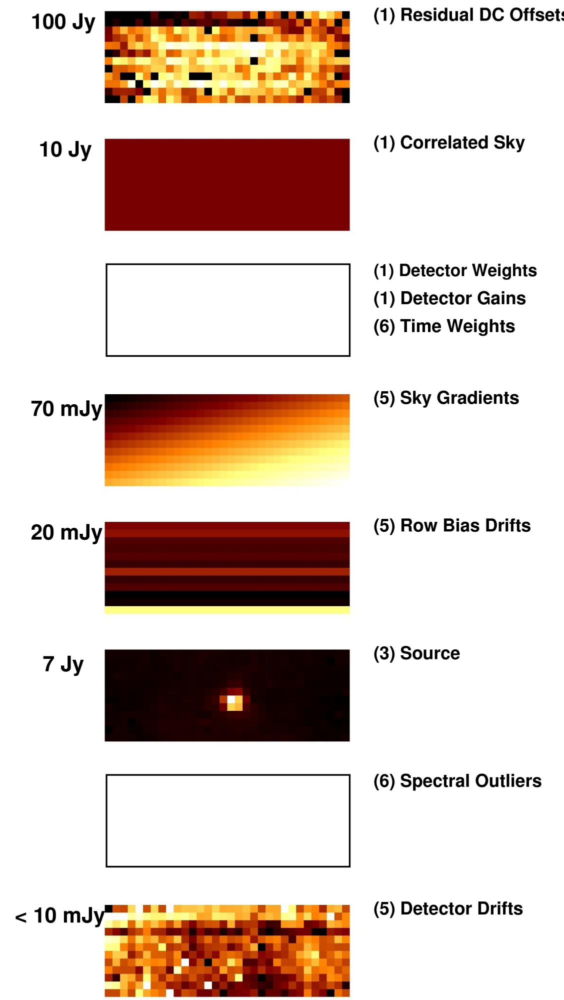




Pallas (23 Jy)

SHARC-2 (350um)

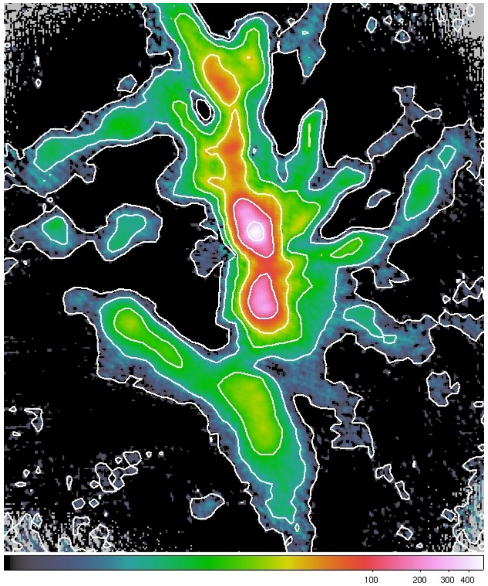




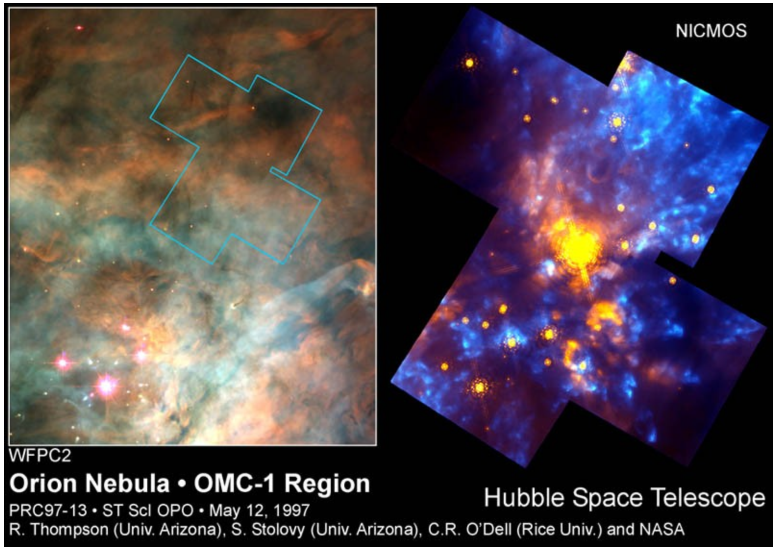
Typical further steps:

- Decorrelate instrumental signals.
- Remove sky gradients
- Channel flagging by gain
- Flag noisy pixels
- Despiking
- Noise whitening

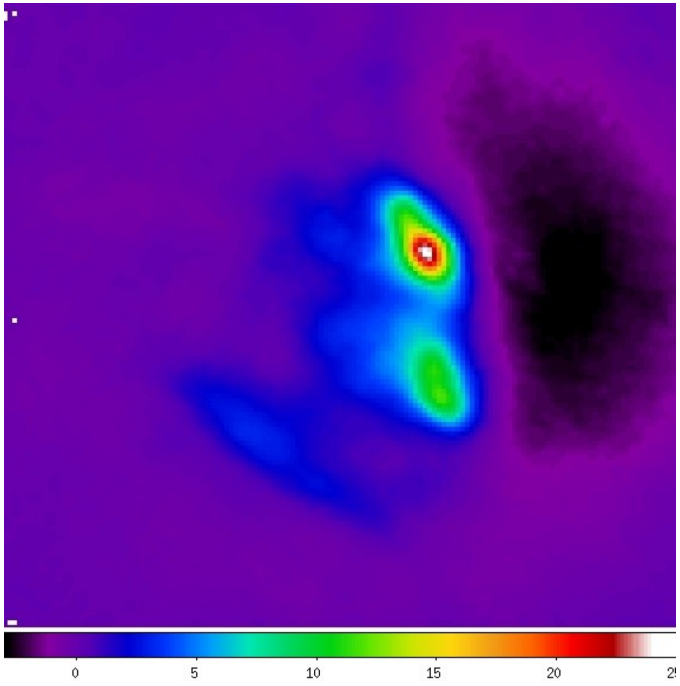
The Orion Molecular Cloud (OMC-1)



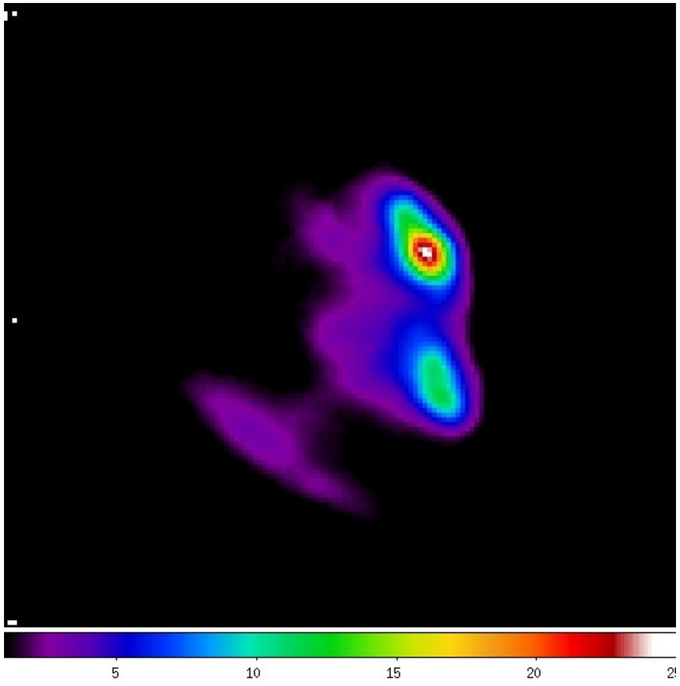
SABOCA (350um)



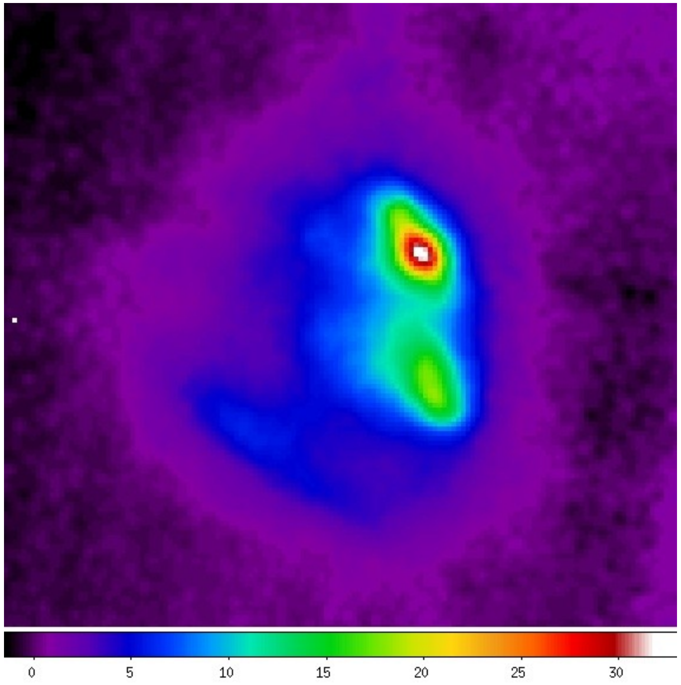
Optical and Near Infrared



Direct Maximum-Likelihood



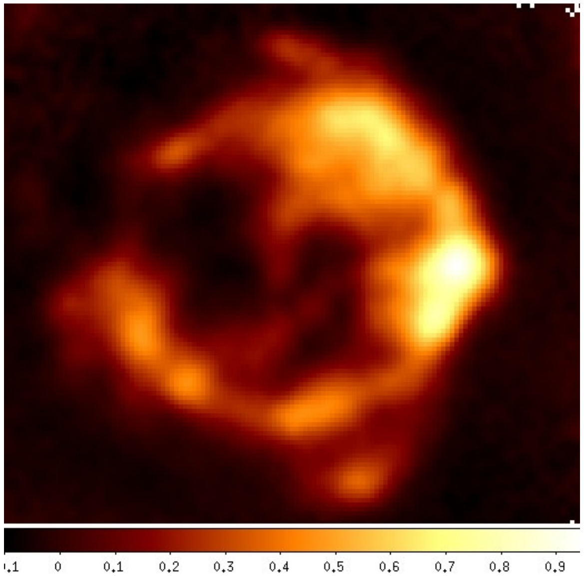
Clipped model (>1 Jy)



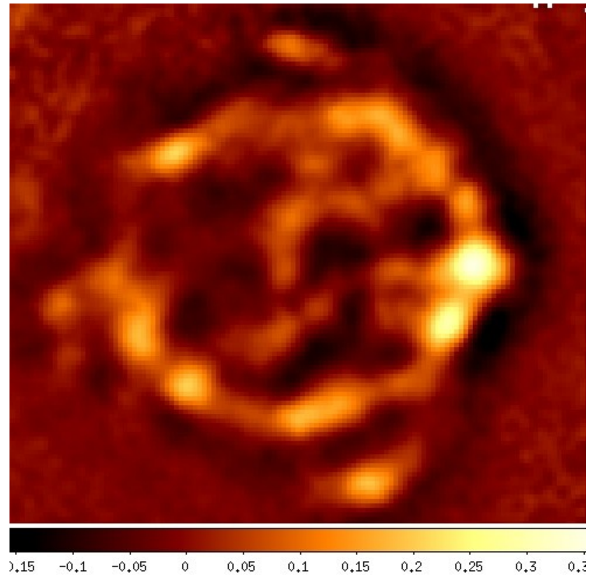
Iterated with clipped model

GISMO 2-mm Camera

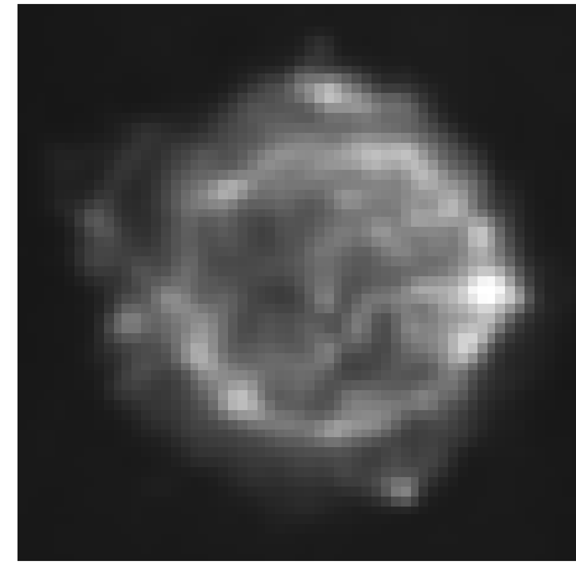
Cassiopeia A
(supernova remnant)



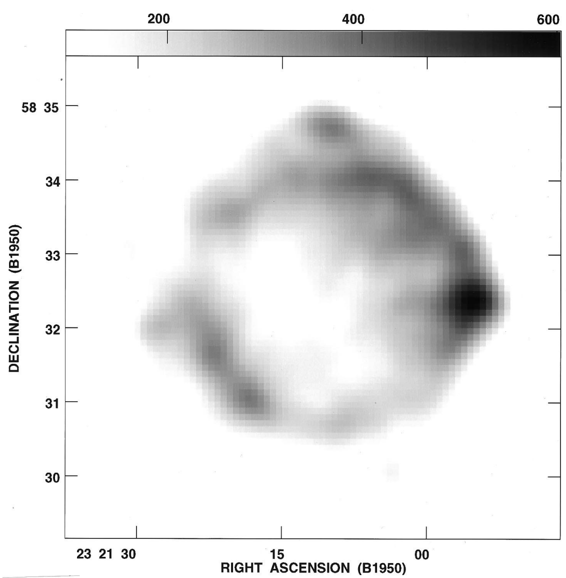
2 mm (GISMO with *crush*)



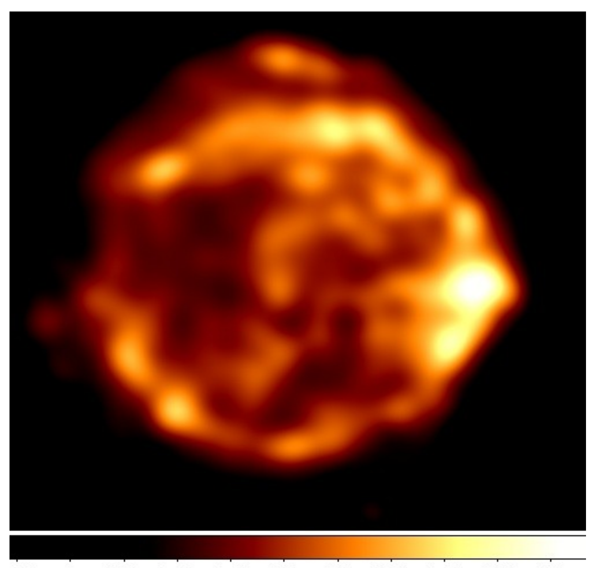
2 mm (filtered above 45”)



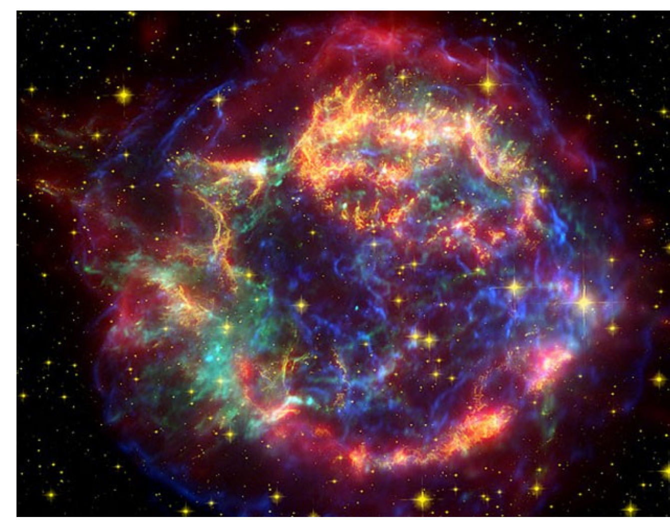
1.4 GHz (VLA)



74 GHz (Kassim et al. 1995)

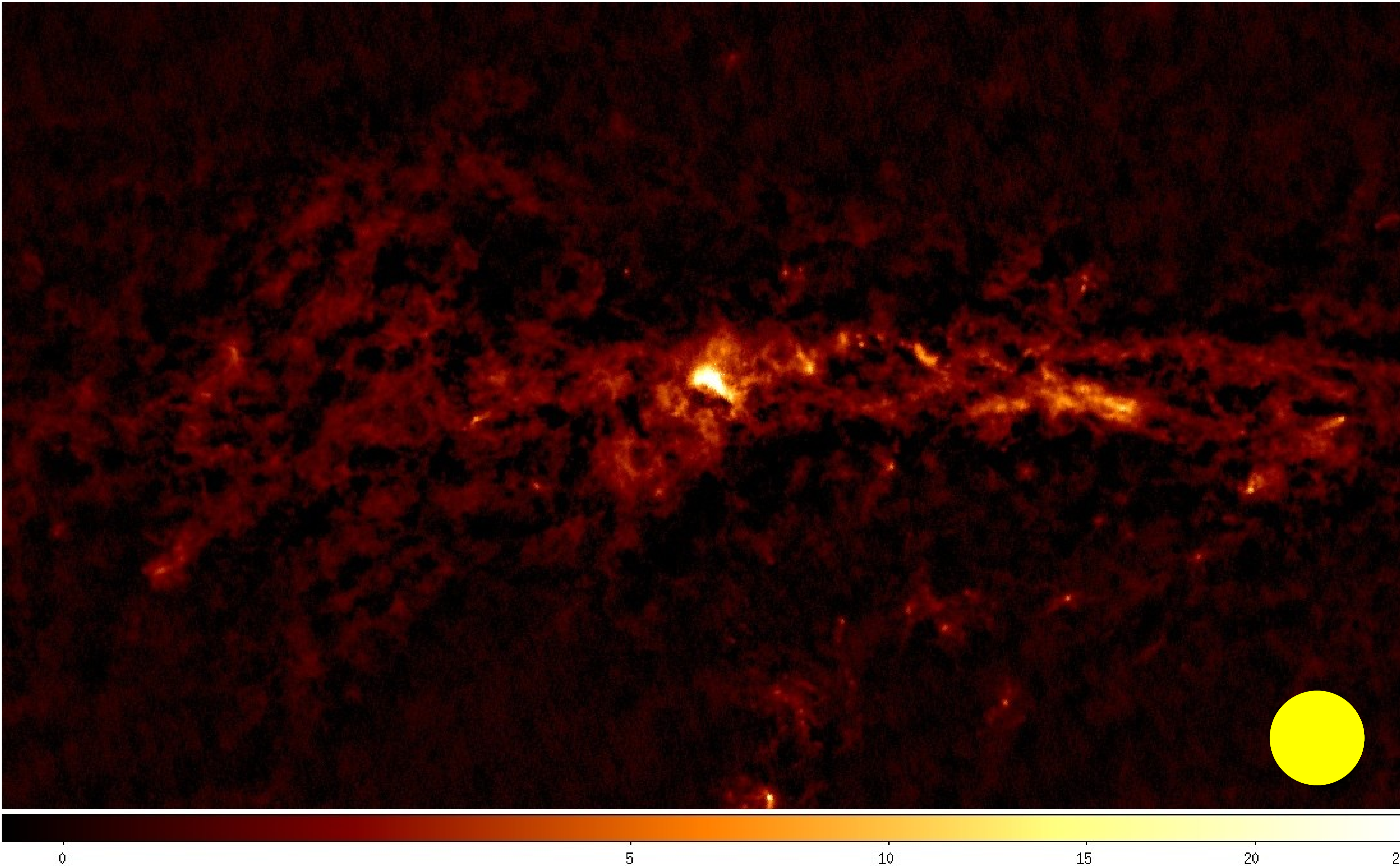


3.7 mm (BIMA + single dish)

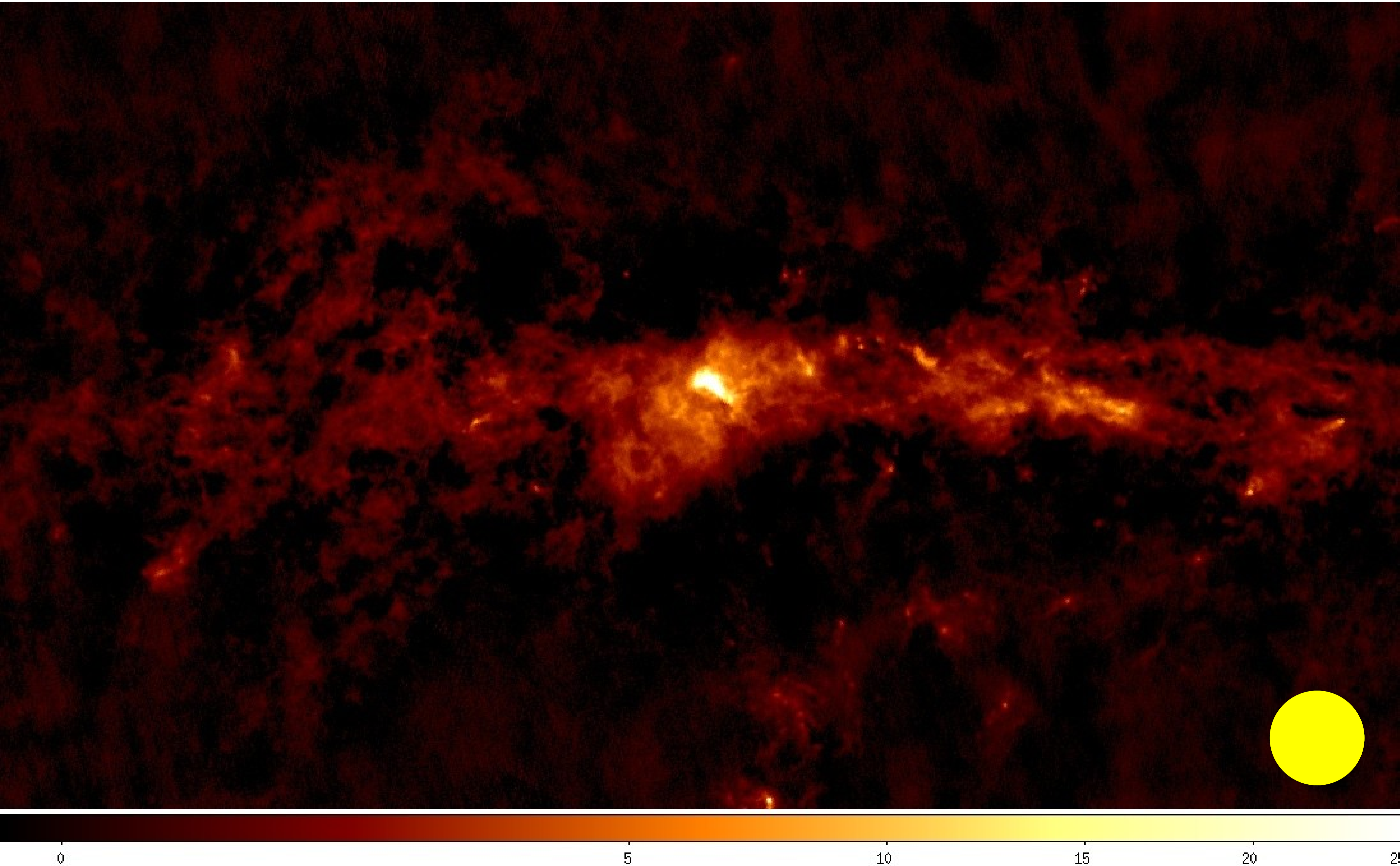


3.6-8 micron (*Spitzer*)

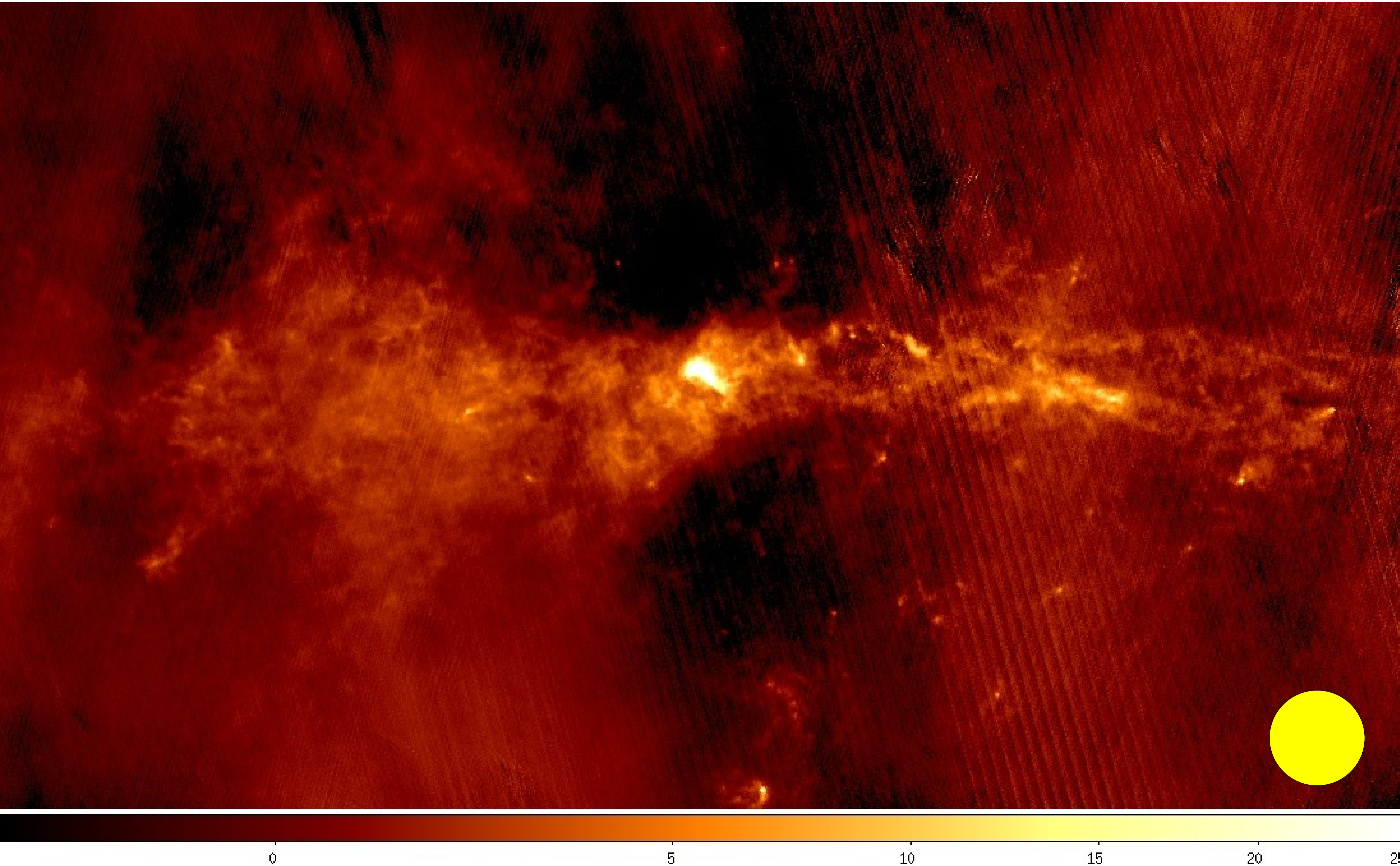
The Galactic Center at 850um with LABOCA



The Galactic Center at 850um with LABOCA



The Galactic Center at 850um with LABOCA



Data Reduction Summary

Works well (better than SVD of PCA)...

Fast (~1 GB/min on a modern PC)

Distributable (for cluster computing)

Linear computing requirement

Low overheads

Lets the astronomer decide what's best....

Part II

Scanning Strategies

Observing Mode Wish List

Noise Resistance (esp. 1/f)

Large-Scale Sensitivity

Coverage

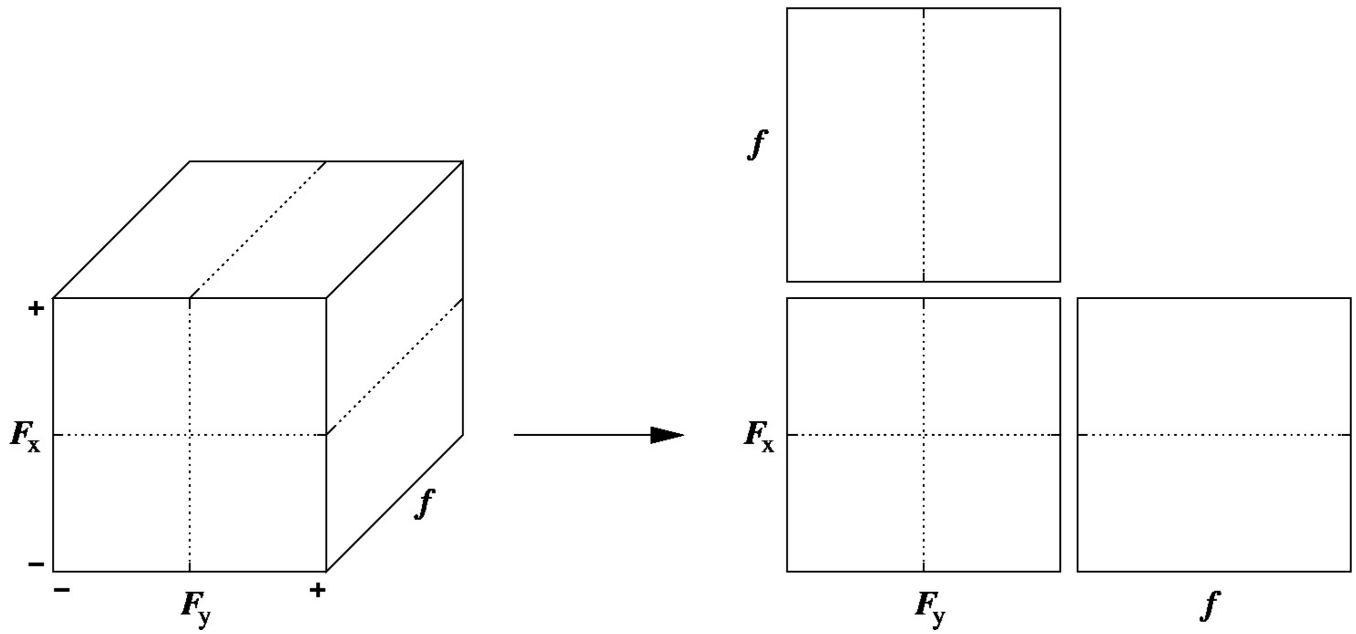
Dynamic Range

Feasibility of Implementation

Noise Resistance

Spectral Noise Locations

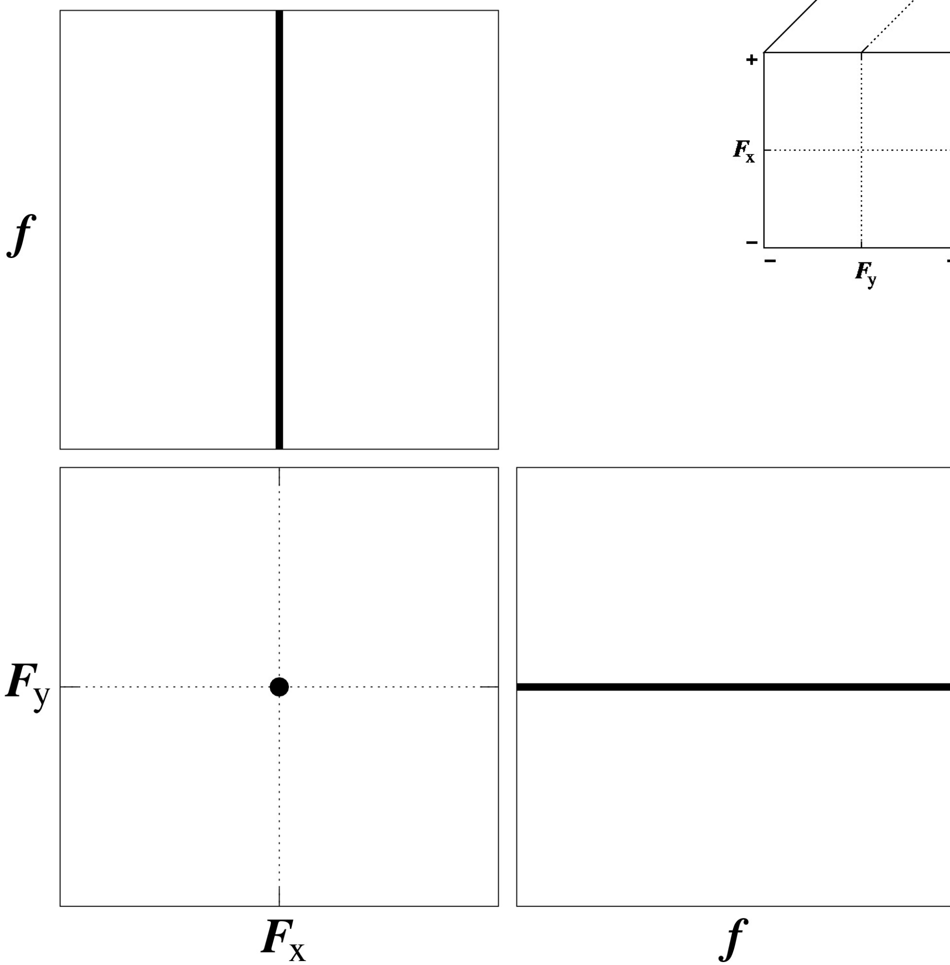
Stationary noise (in time and in space) is characterized by its power spectrum of independent components.

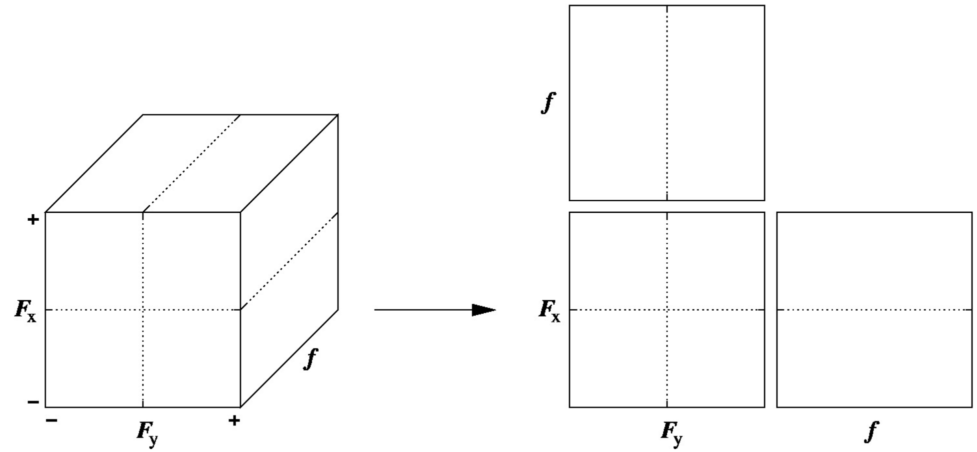


Projections of a spectral cube

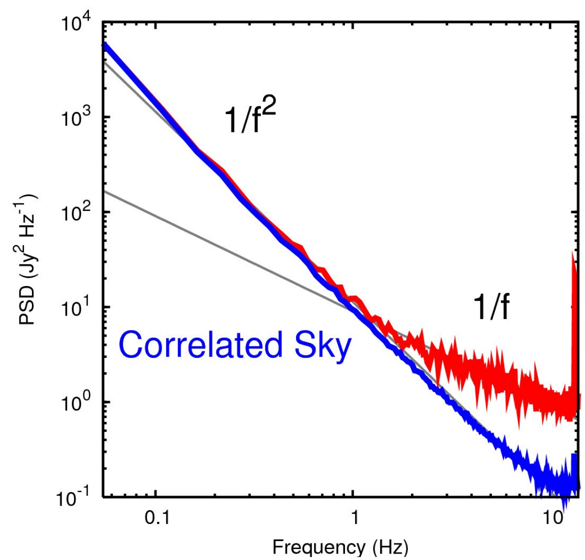
Noise Resistance

Spectral Noise Locations



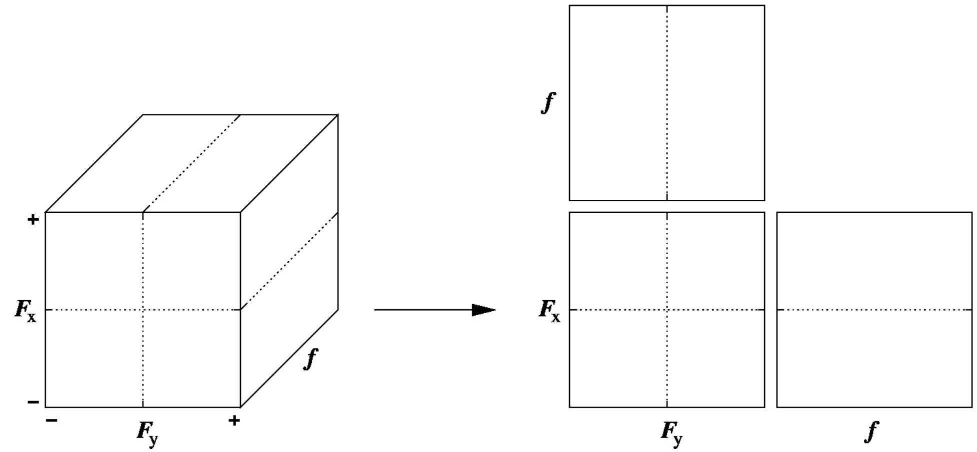


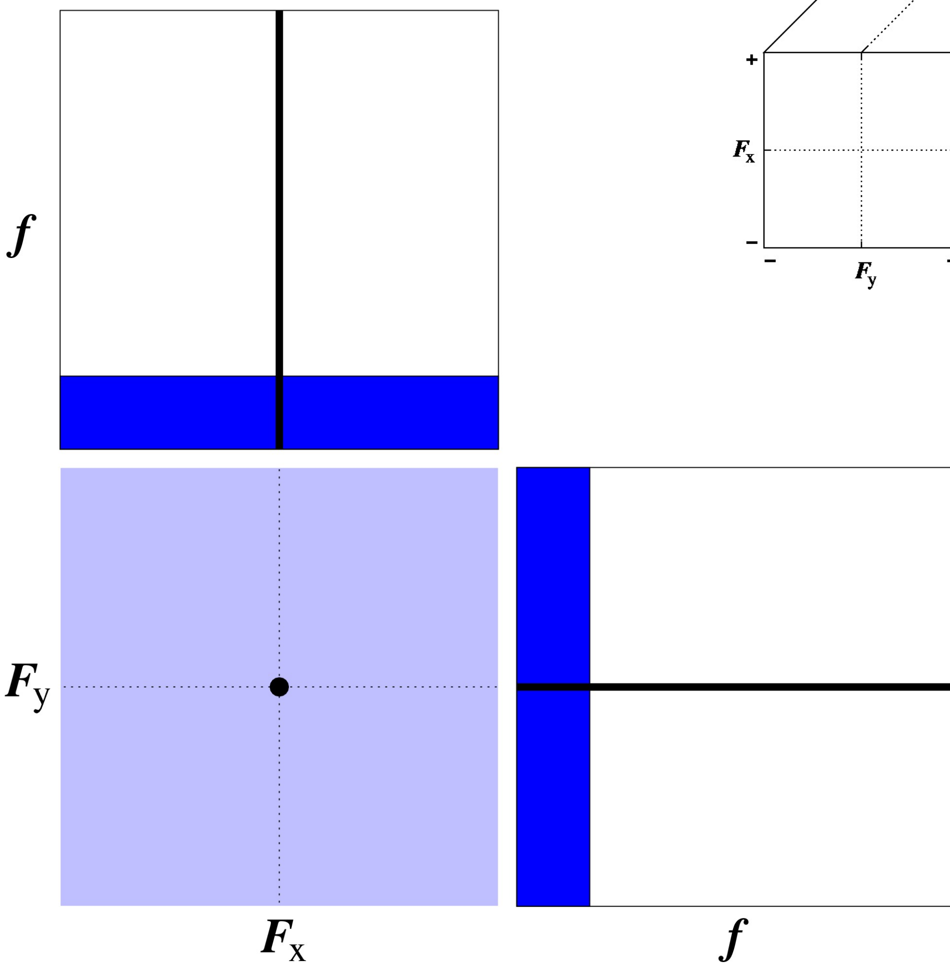
Correlated Noise
(atmosphere, T-fluctiation)



Noise Resistance

Spectral Noise Locations



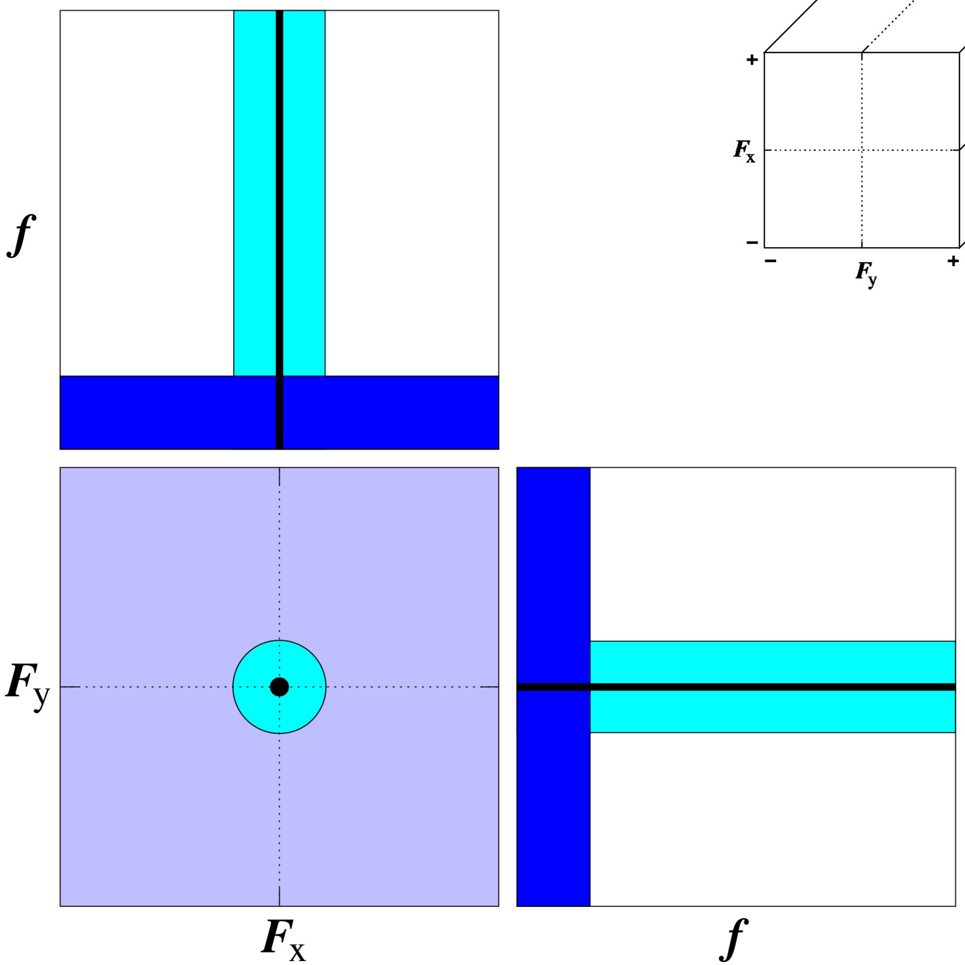


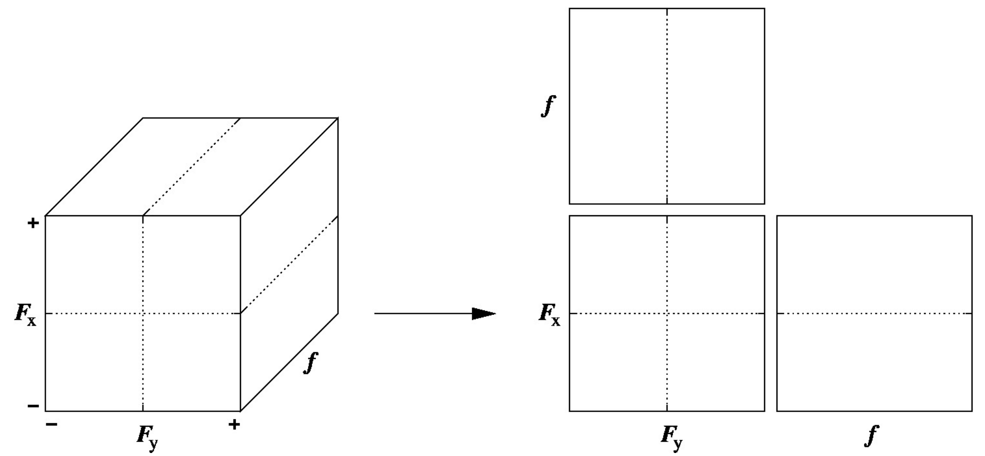
Correlated Noise
(atmosphere, T-fluctiation)

1/f Noise

Noise Resistance

Spectral Noise Locations





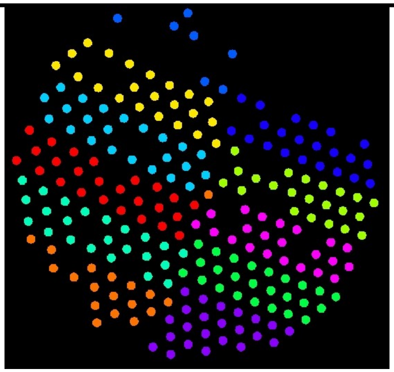
Correlated Noise (atmosphere, T-fluctiation)

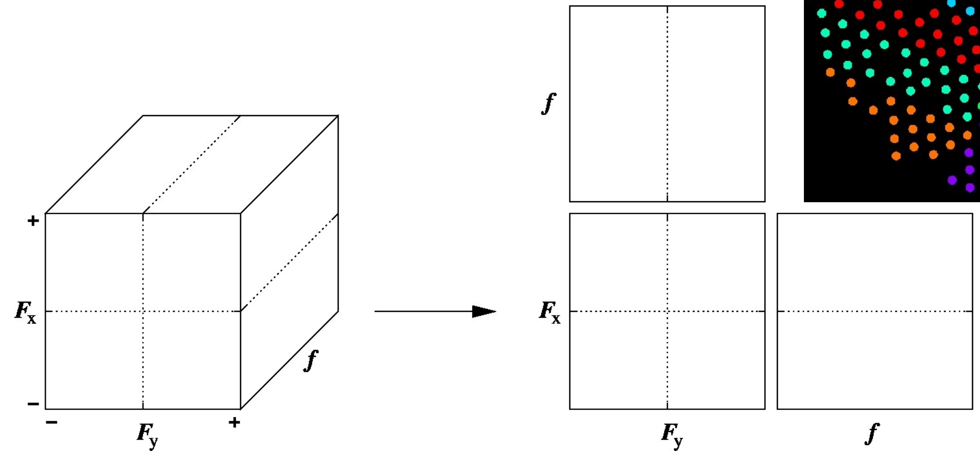
1/f Noise

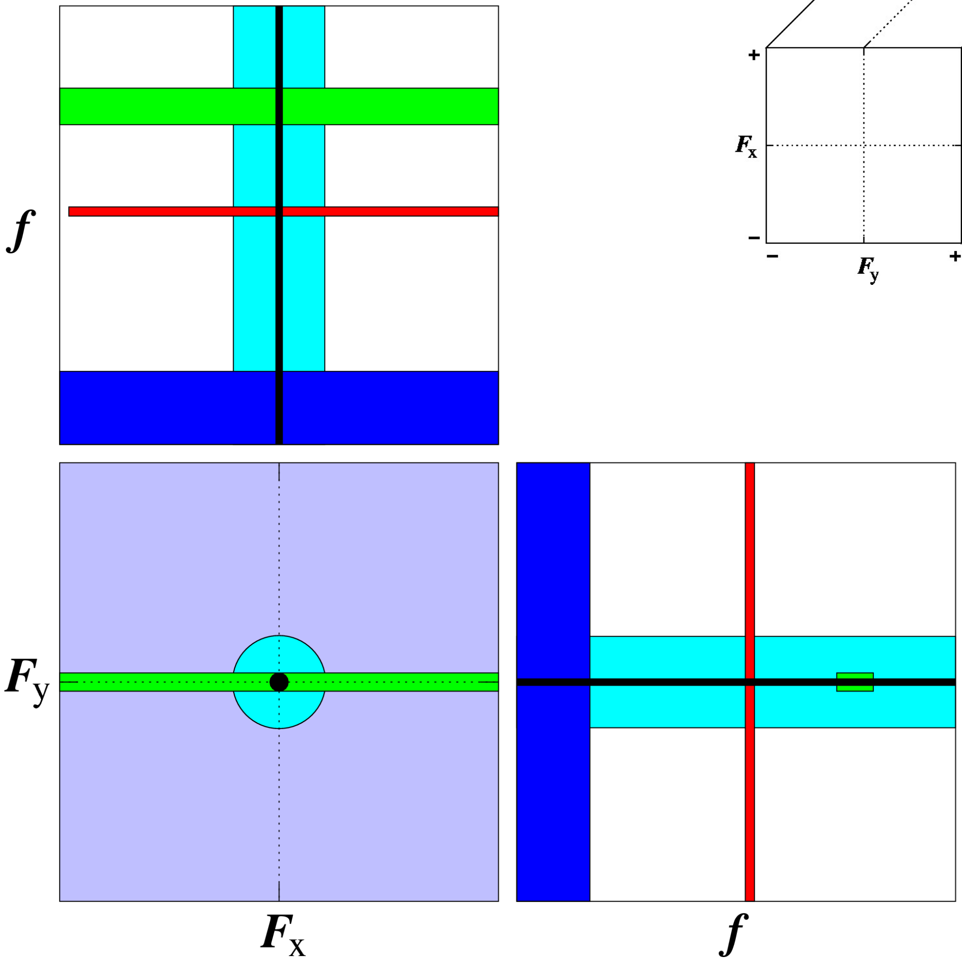
Sky Noise

Noise Resistance

Spectral Noise Locations







Correlated Noise (atmosphere, T-fluctiation)

1/f Noise

Sky Noise

Narrow-band Resonance (isotropic)

Wide-band Resonance (oriented)

Noise Resistance

Strategies

1/f Noise → Spread signals into the higher frequencies...

Faster Scanning

Generic Noise → Spread signals widely...

2-D Scanning
Random Source Crossings

Design Criteria

(1) Faster is Better!

(2) 2D Scanning.

(3) Random Source Crossings in Time-streams.
(non-repeating patterns...)

(4) Wide Strokes matching the Largest Faint Structures.

---

(5) Scanning with Primary (for ground-based submm).

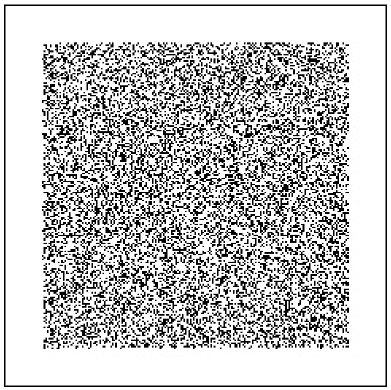
(6) Connected Patterns (settling time overheads).

(7) No Sharp Turns (acceleration overload).

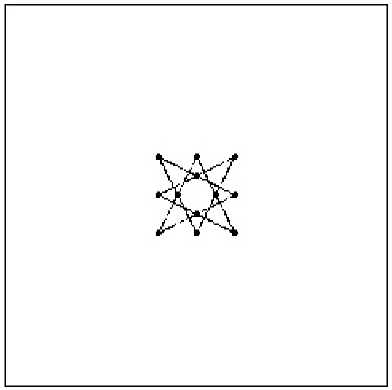
Simulations

Pattern Gallery

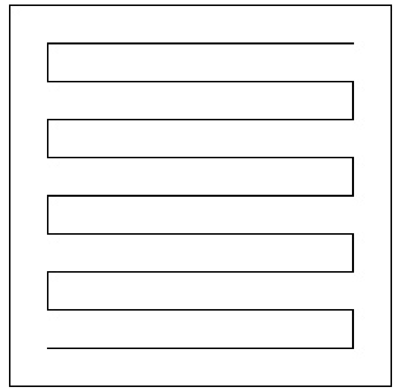
random



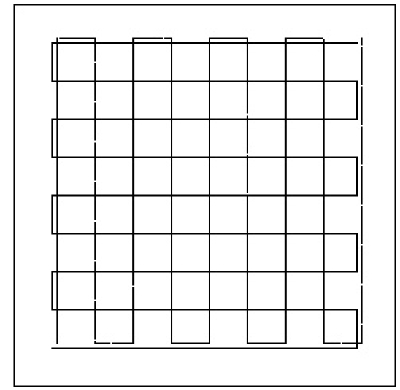
DREAM



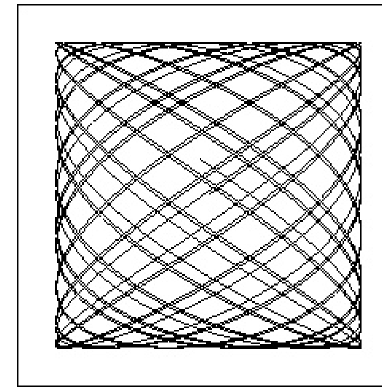
OTF



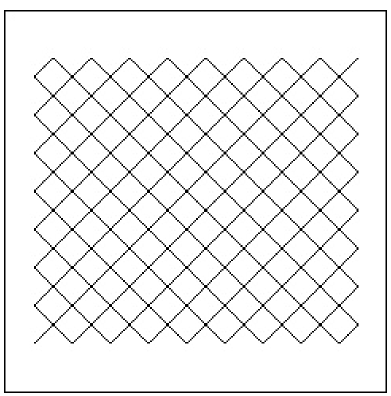
OTF (cross-linked)



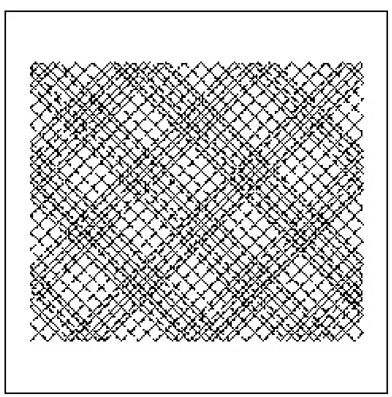
Lissajous



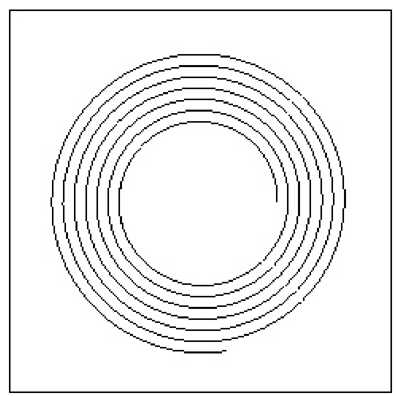
Billiard (closed)



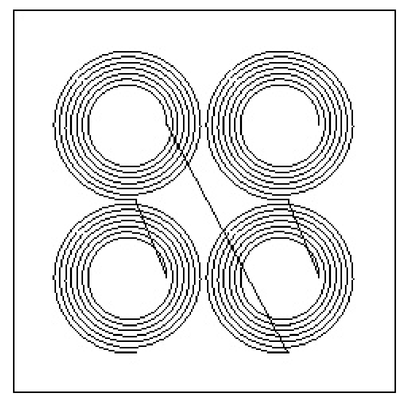
Billiard (open)



spiral



raster-spiral

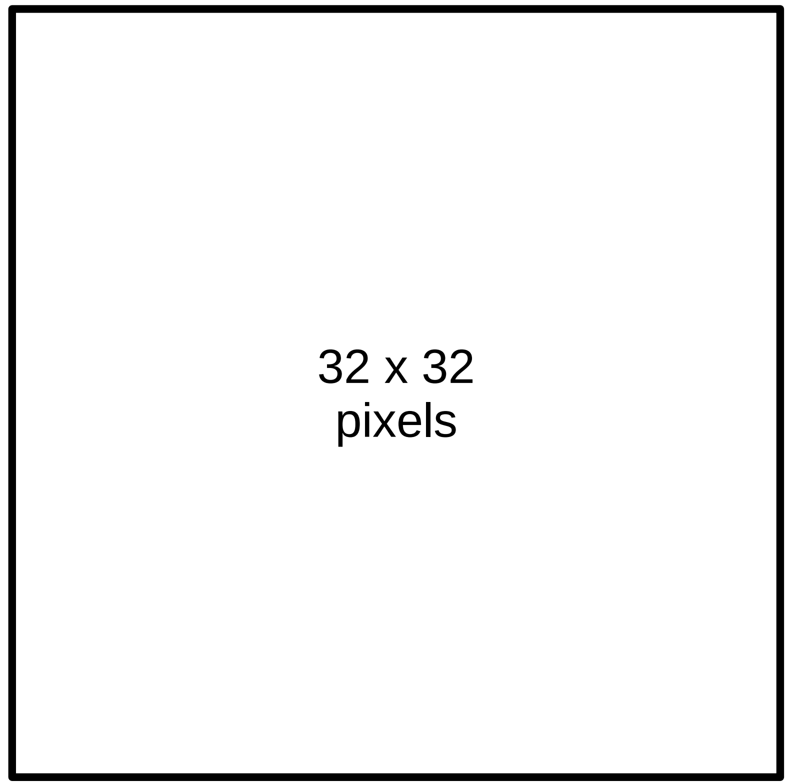


... and other patterns...

What is your favourite?

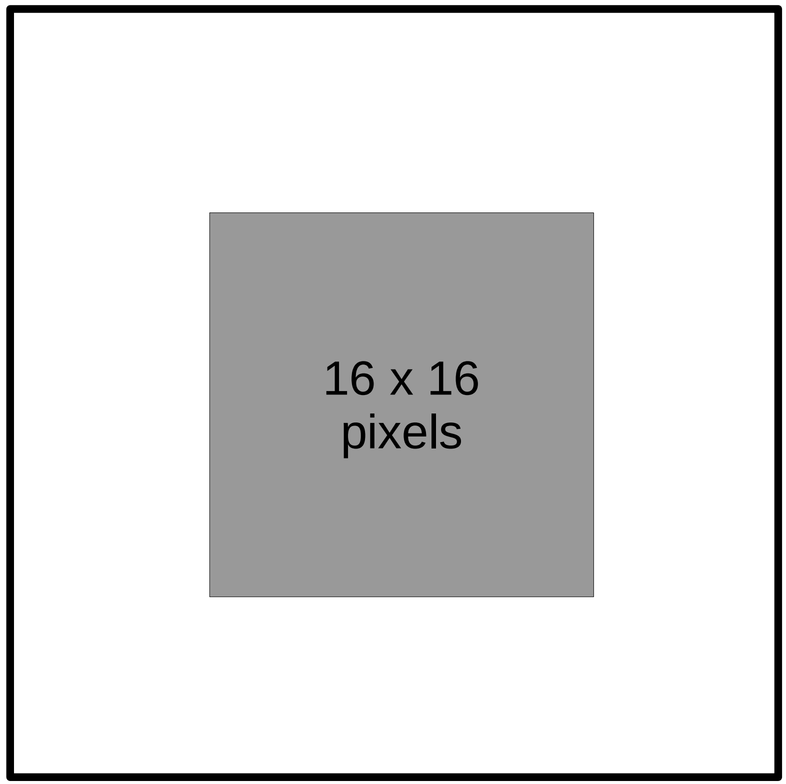
http://www.submm.caltech.edu/~sharc/scanning/

Simulations



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

Simulations



Size

Aim to cover same area

"Speed"

1 pixel/frame average scanning speed

(1 position/frame)

Spectral Moments

$$m_i = \left\langle f^i \hat{P}_{f,\mathbf{F}} \right\rangle = \frac{\sum_f \sum_{\mathbf{F}} f^i \hat{P}_{f,\mathbf{F}}}{\sum_f \sum_{\mathbf{F}} f^i}$$

$\mathbf{m_0}$: The fraction of phase space volume occupied by a point source observed with the pattern.

$\mathbf{m_1}$: Resistance against canonical 1/f noise (electronics)

$\mathbf{m_2}$: Resistance against $1/f^2$ noise (atmopshere + temperature fluctuations)

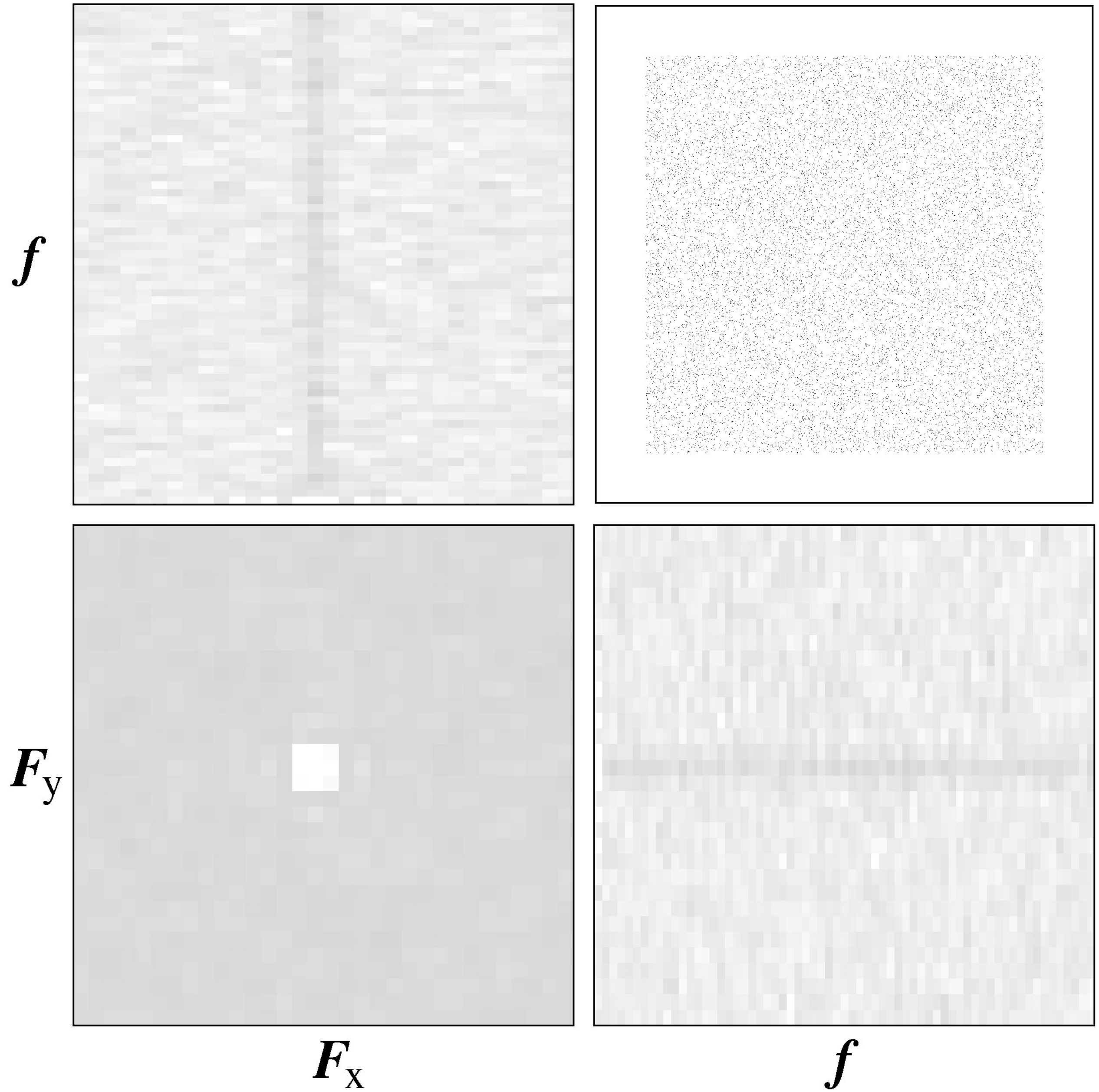
$\mathbf{m_1}$,$\mathbf{m_2}$: Also large-scale sensitivity indicators...

Random

$m_0 = 1.000$

$m_1 = 1.000$

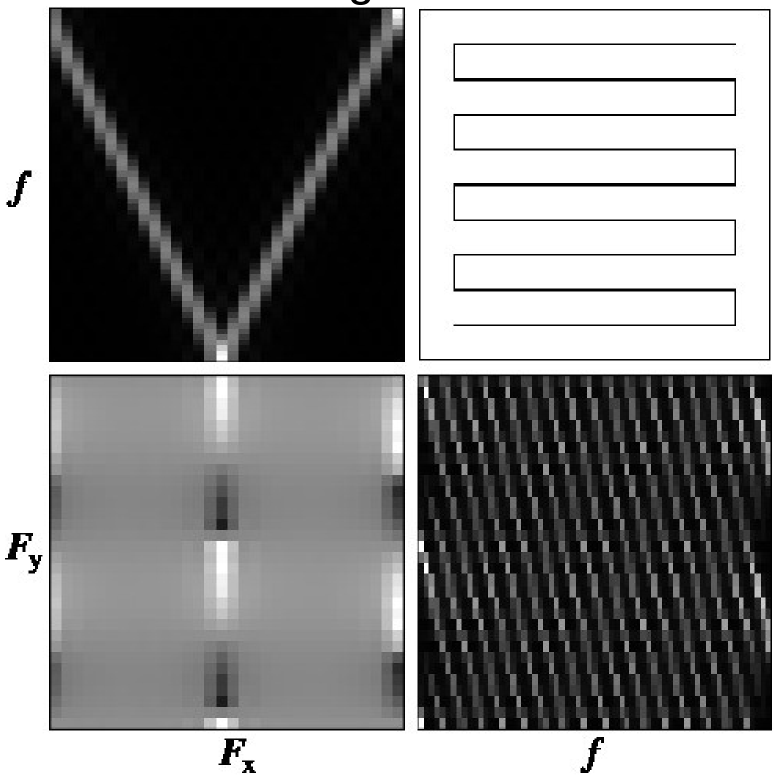
$m_2 = 1.000$

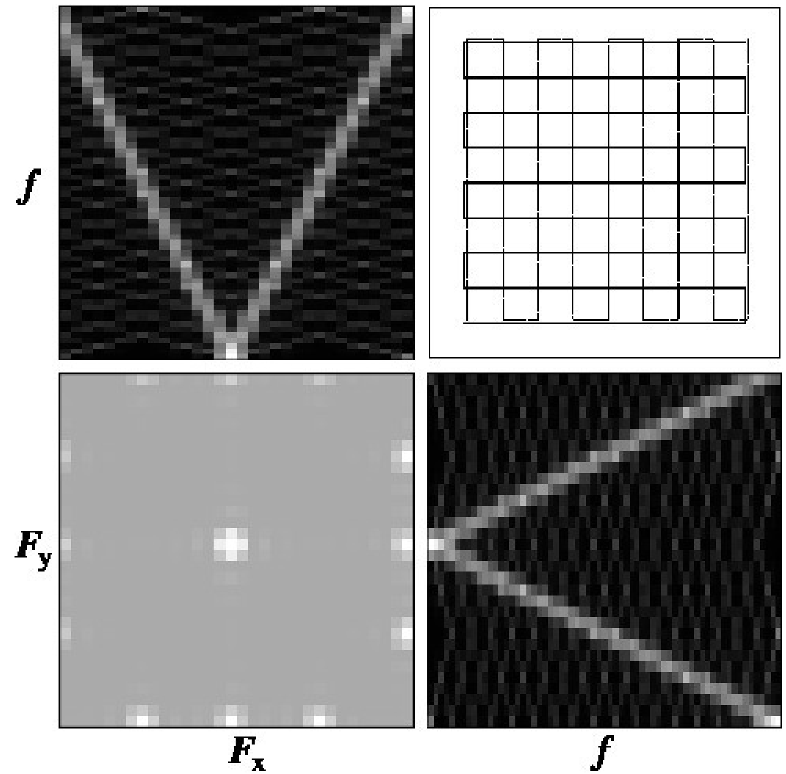


On-The-Fly (OTF) Scanning

a.k.a. 'Serpentine' or 'Raster Scan'

Directional Sensitivity
to Large Scales...





$m_0 = 0.018$

$m_1 = 0.018$

$m_2 = 0.018$

$m_0 = 0.035$

$m_1 = 0.035$

$m_2 = 0.035$

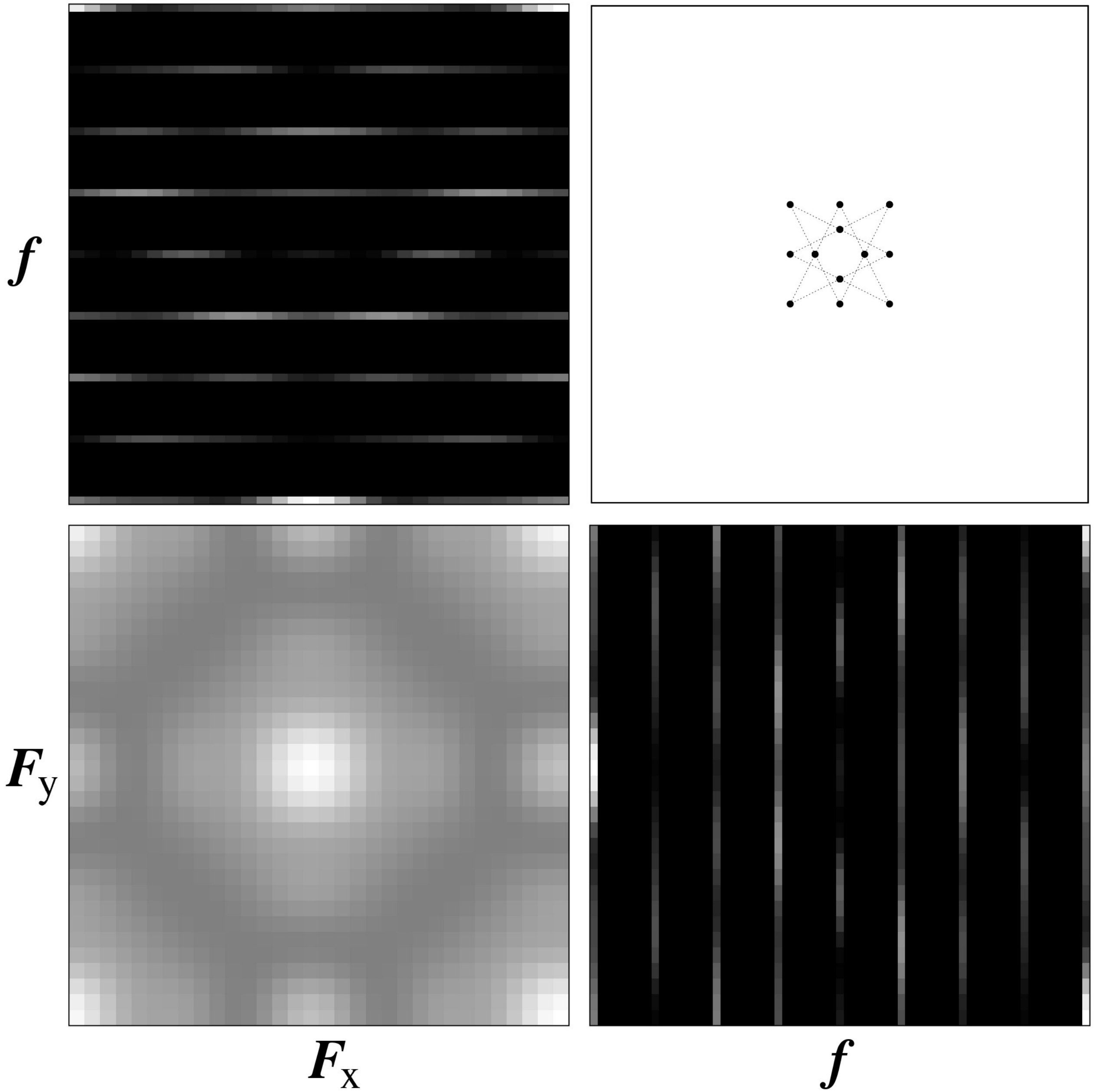
DREAM

Dutch Real-Time Acquisition Mode

m_0 = 0.0018

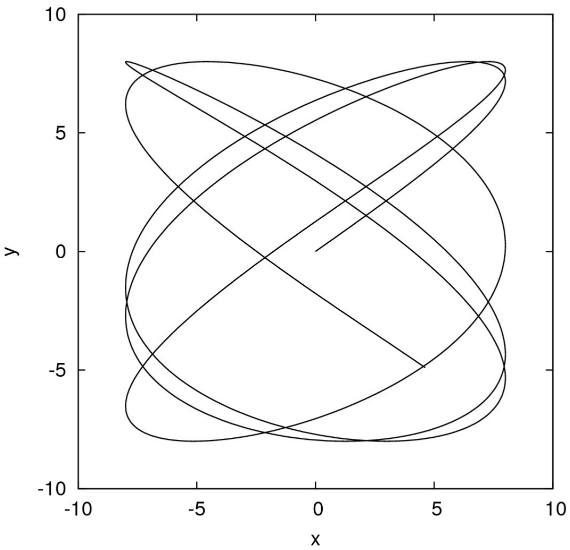
m_1 = 0.0018

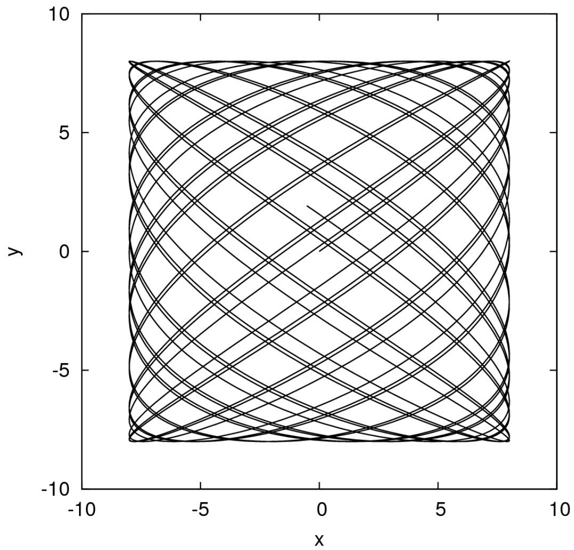
m_2 = 0.0019



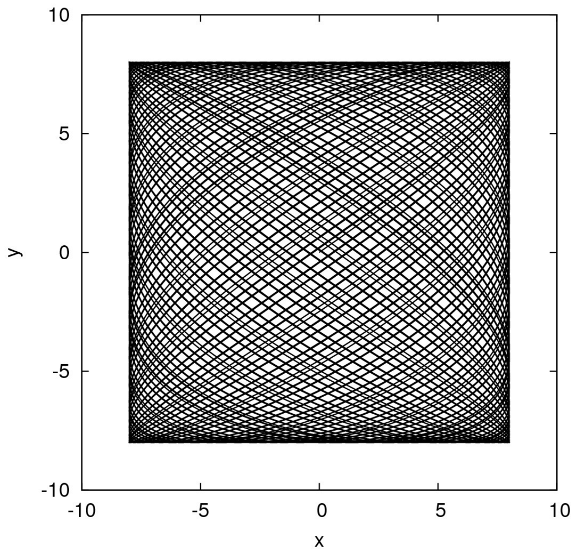
Lissajous

Used for SHARC-2 FoV mapping since 2003.





Irrational x and y frequencies lead to non-repeating, open patterns



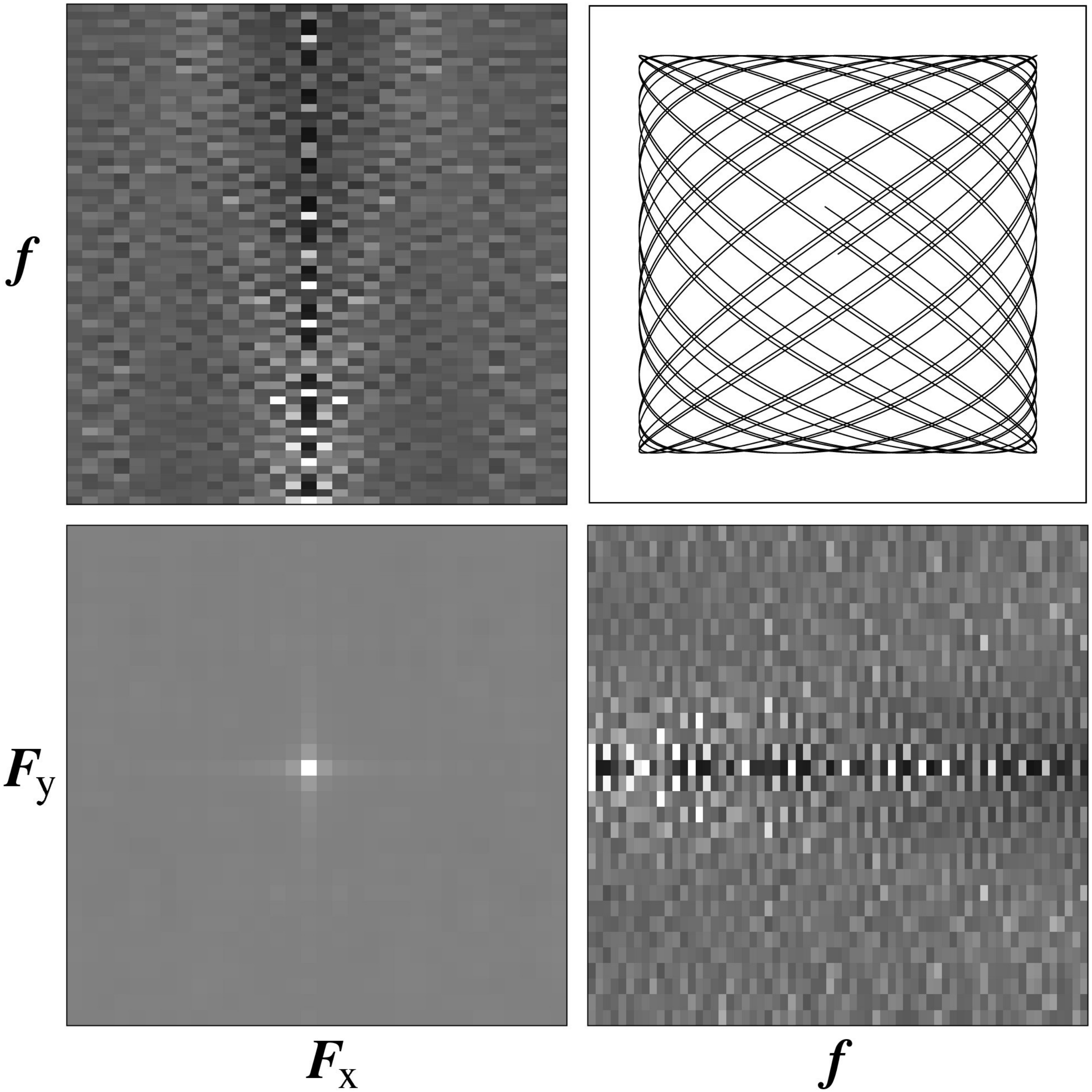
Edge-heavy coverage

Lissajous

m_0 = 0.129

m_1 = 0.126

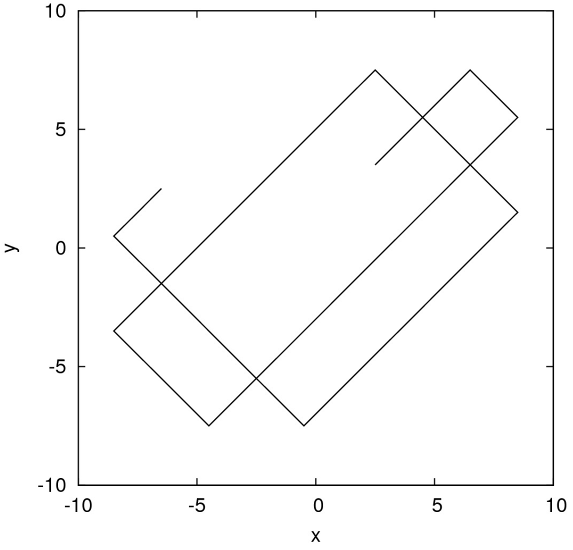
m_2 = 0.125

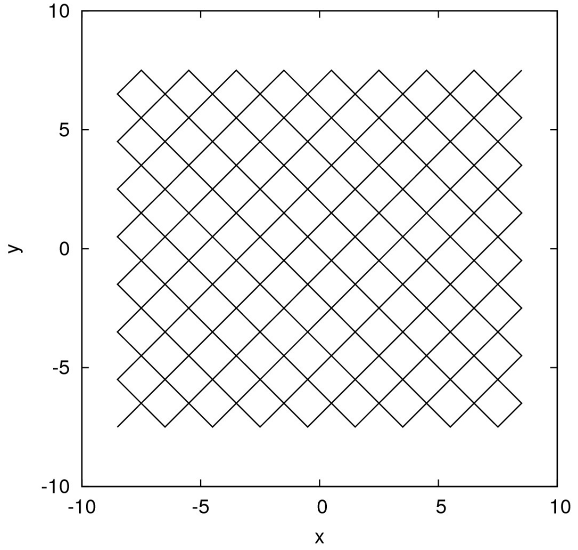


Billiard Scan

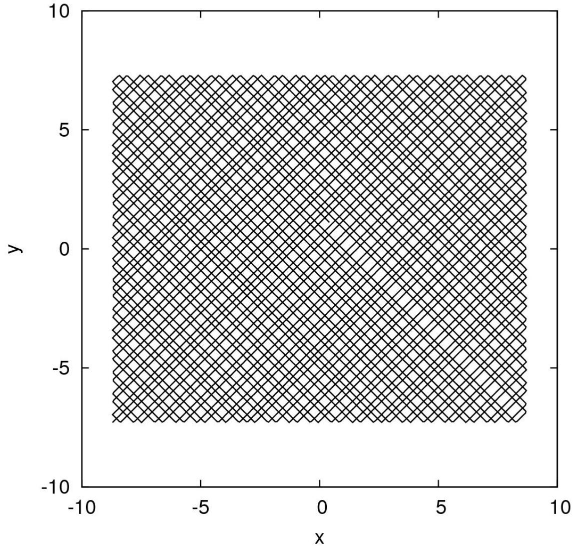
a.k.a. 'PONG' and 'box-scan'

Used for SHARC-2 large-field mapping since 2003 (Borys & Dowell).





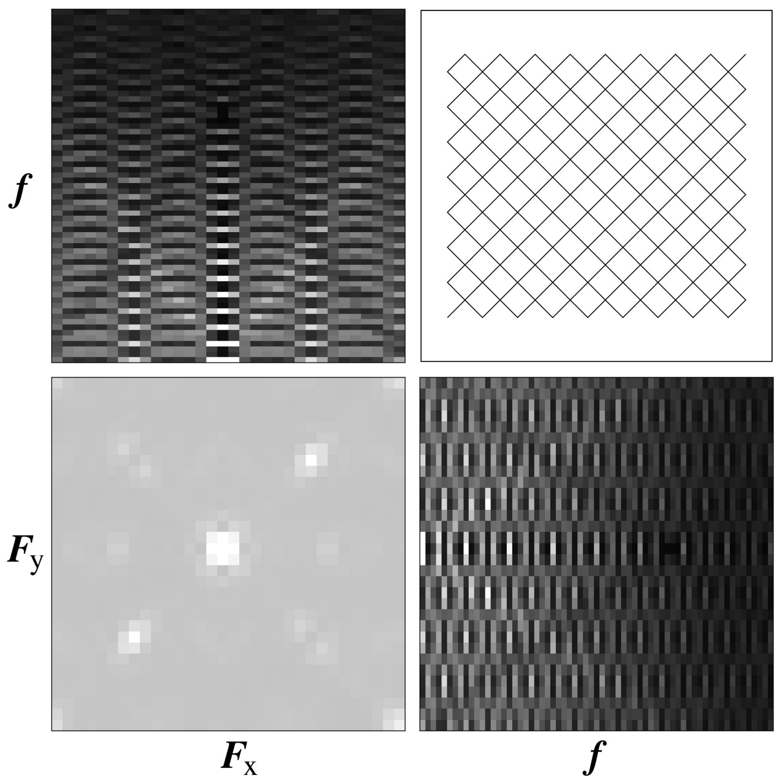
Rational x and y frequencies lead to closed patterns

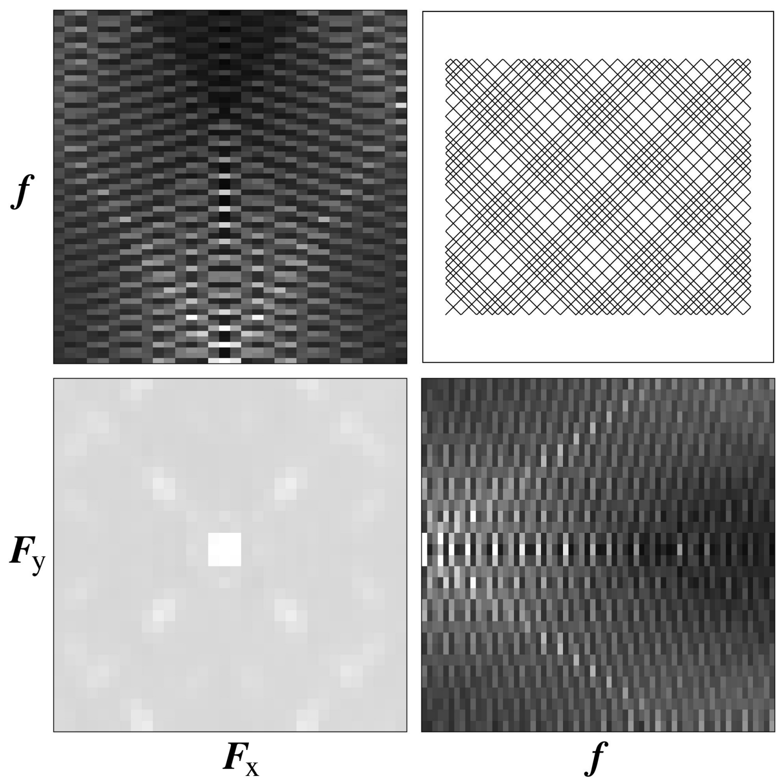


Irrational x and y frequencies lead to non-repeating, open patterns

Billiard Scan (closed)

a.k.a. 'PONG' and 'box-scan'





m_0 = 0.091

m_1 = 0.068

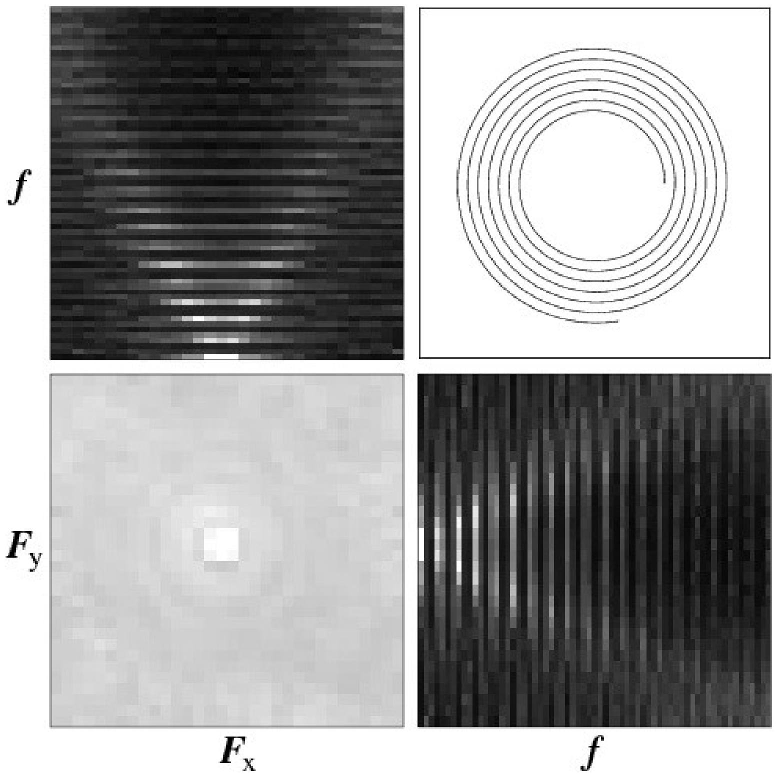
m_2 = 0.058

m_0 = 0.097

m_1 = 0.089

m_2 = 0.086

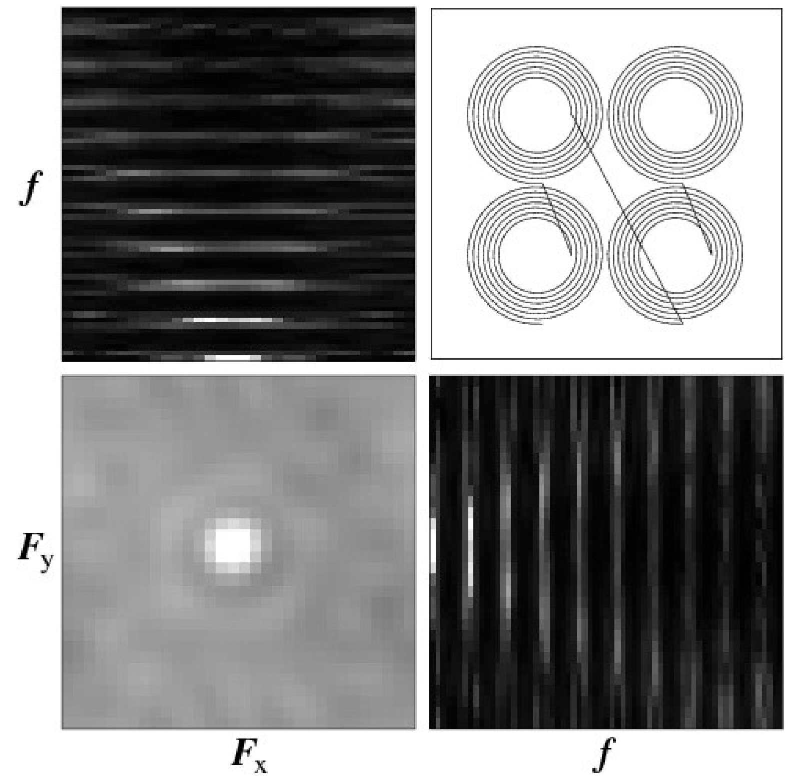
Archimedian Spirals



$m_0 = 0.061$

$m_1 = 0.056$

$m_2 = 0.054$



$m_0 = 0.080$

$m_1 = 0.073$

$m_2 = 0.070$

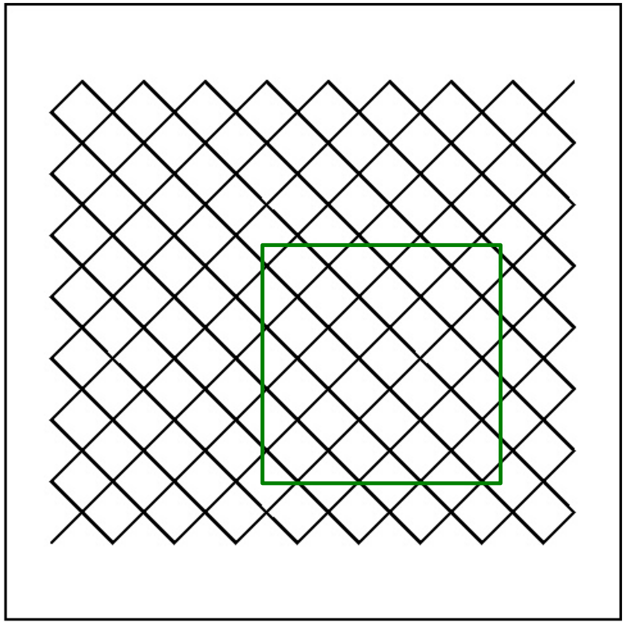
Score Card

Pattern	Geometric Paramters	Moments			l_c	Comments
		m_0	m_1	m_2		
random	a, b	1.000	1.000	1.000	a, b	discrete, unfeasible(?)
Lissajous	$A_x, A_y, \omega_y/\omega_x$	0.129	0.126	0.125	$2A_x, 2A_y$	smooth
billiard (open)	a, b, θ	0.097	0.089	0.086	a, b	
billiard (closed)	(see above)	0.091	0.068	0.058	a, b	
rotating OTF	$L, \Delta, \delta\Theta$	0.088	0.085	0.084	L	requires several angles 0–90°
raster of spirals	$\Delta_{\text{ras}}, r_0, r_{\max}$	0.080	0.073	0.070	$2r_{\max}$	
spiral	$r_0, r_{\max}$	0.061	0.056	0.054	$2r_{\max}$	smooth
crossed OTF (90°)	L, Δ	0.035	0.035	0.035	L	
chop	d	0.030	0.030	0.045	d	discrete, (oriented), secondary
OTF	L, Δ	0.018	0.018	0.018	Δ, L	strongly oriented
DREAM		0.018	0.018	0.019	4 pixels	discrete, secondary
stare		n/a	0.000	0.000	FOV	up to 4× integration time

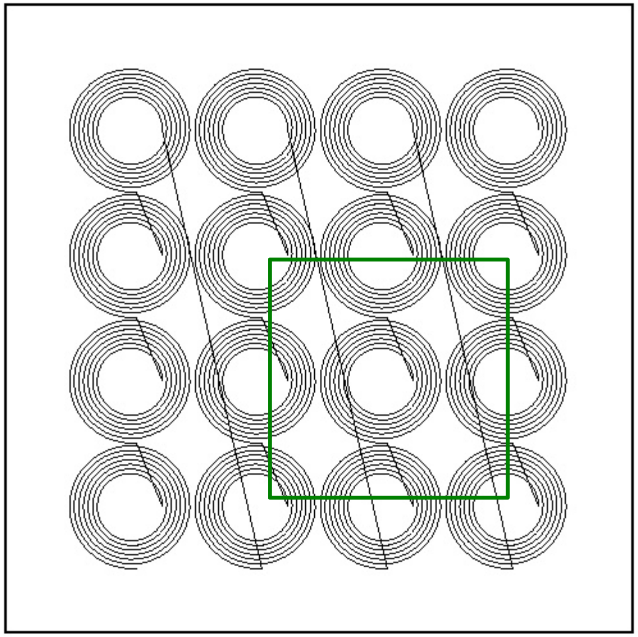
Large Fields

What's the best strategies for fields > FoV?

All at once...



Little by little...



The answer does not depend on field size.
It depends entirely on the pattern chosen!!!

Conclusions

I. Recipes for Designing Better Patterns

II. Rankings:

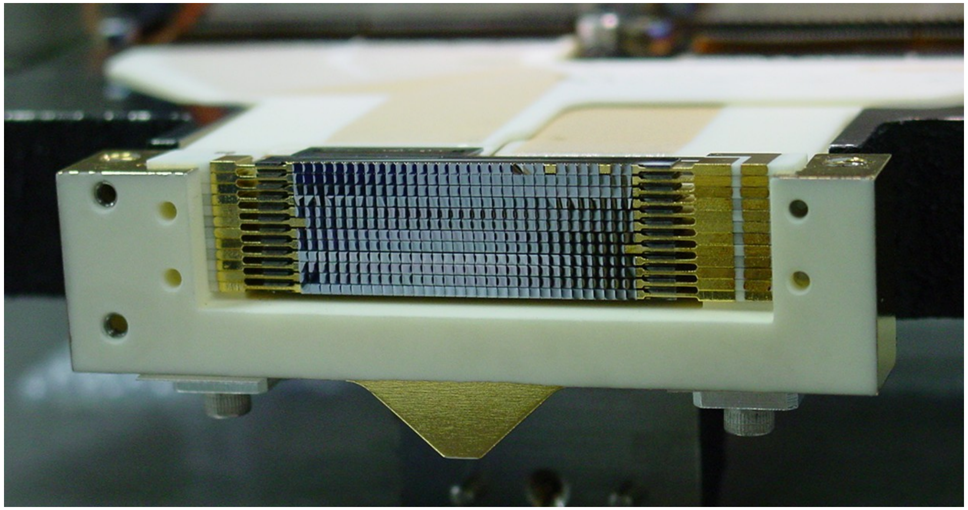
(1) Random
(2) Lissajous, Billiard, Spirals
(3) Cross-Linked OTF

III. Evaluate you own pattern at

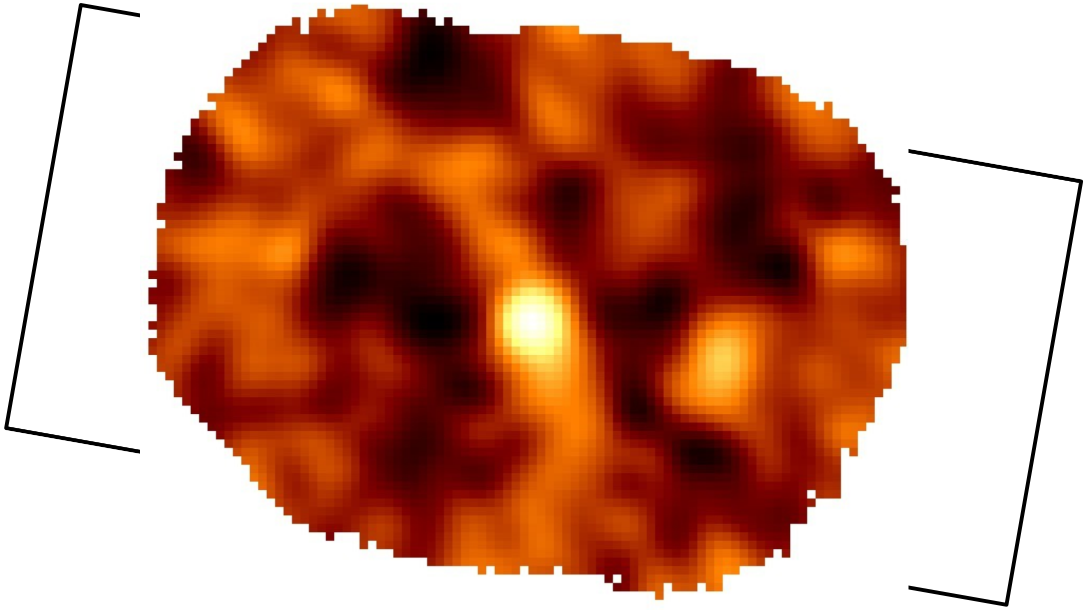
http://www.submm.caltech.edu/~sharc/scanning

Lissajous

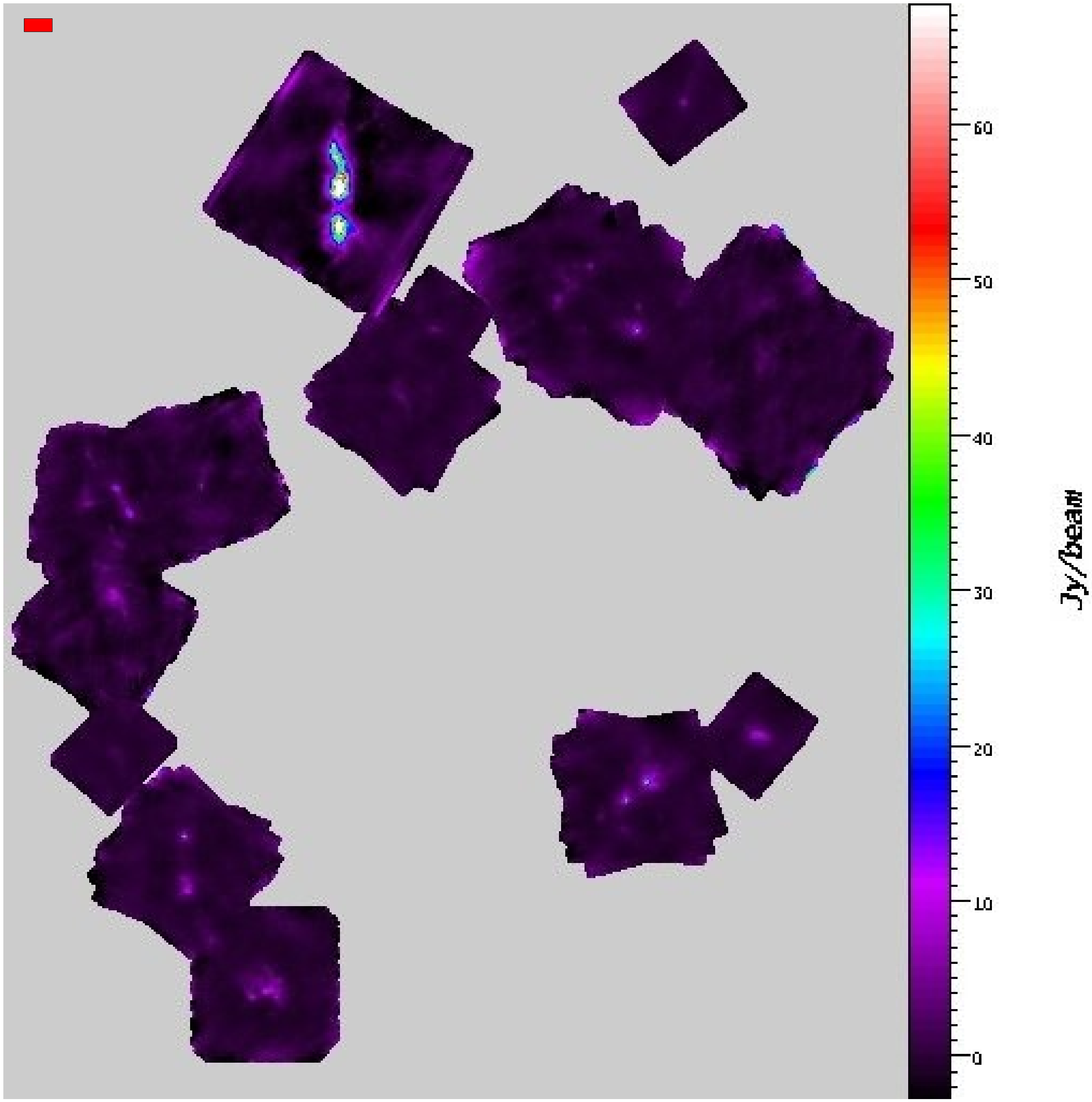
SHARC-2



SMM J163631.47 +405546.9



Billiard

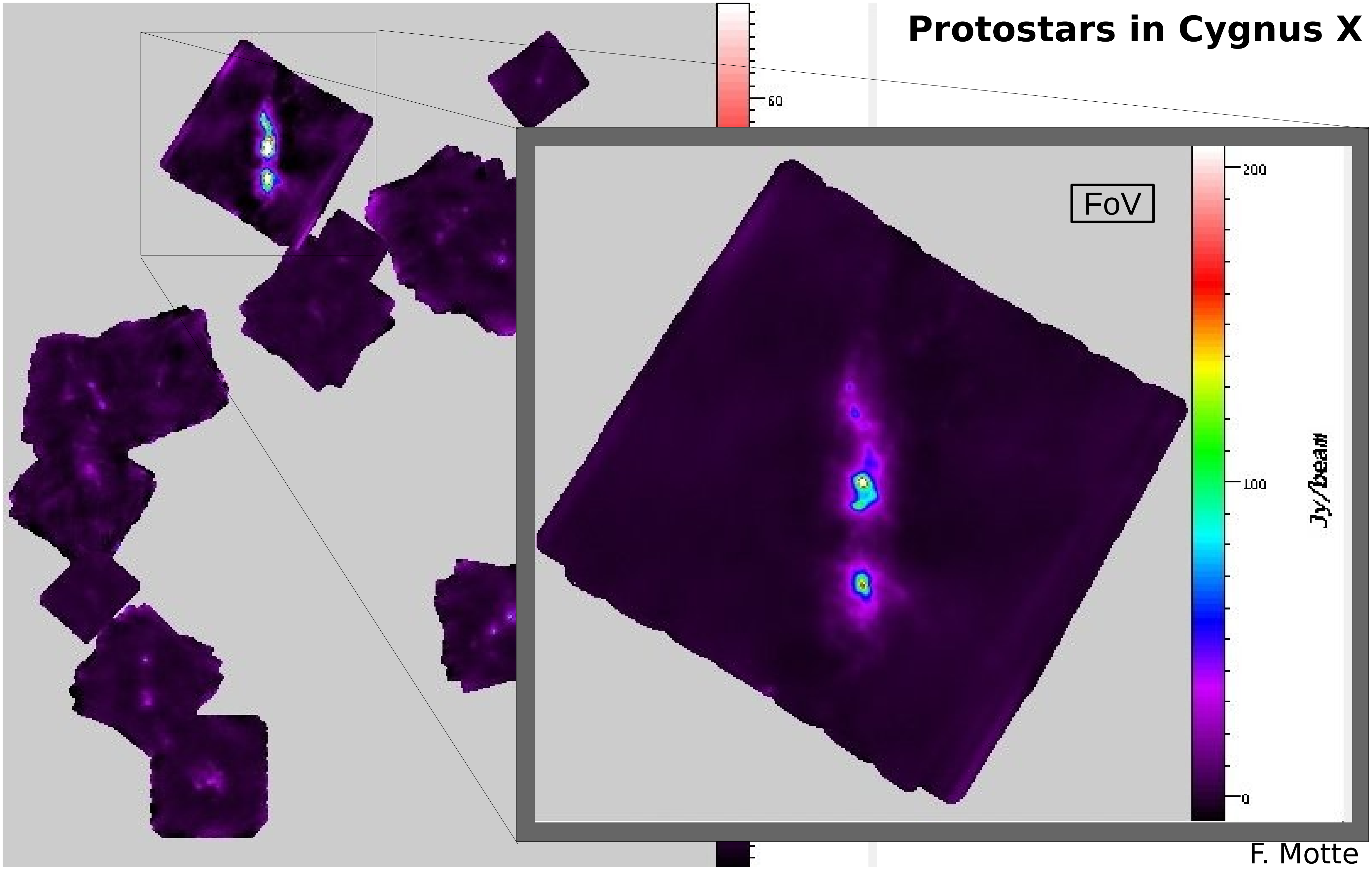


Protostars in Cygnus X

F. Motte

Billiard

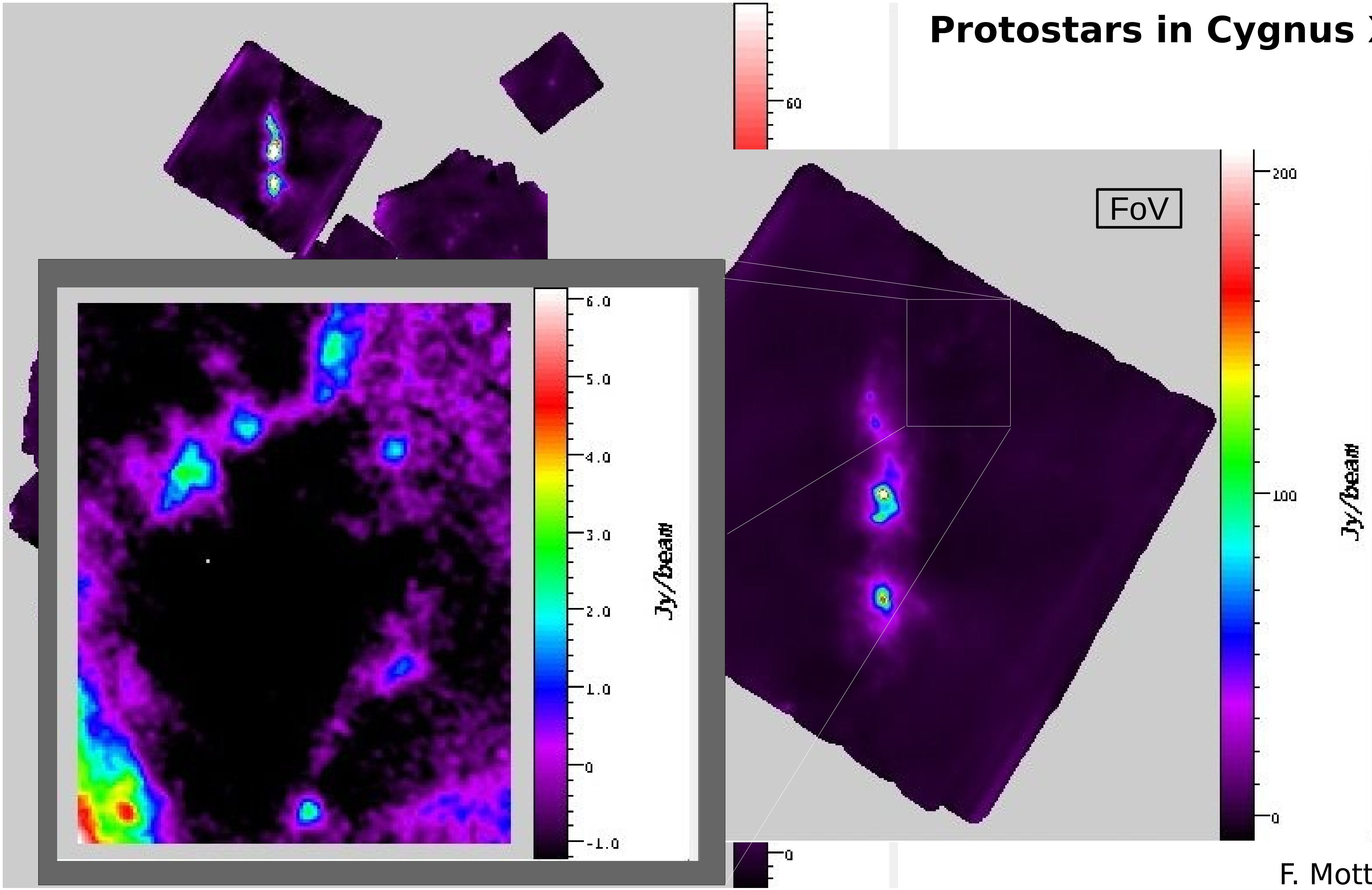
Protostars in Cygnus X



F. Motte

Billiard

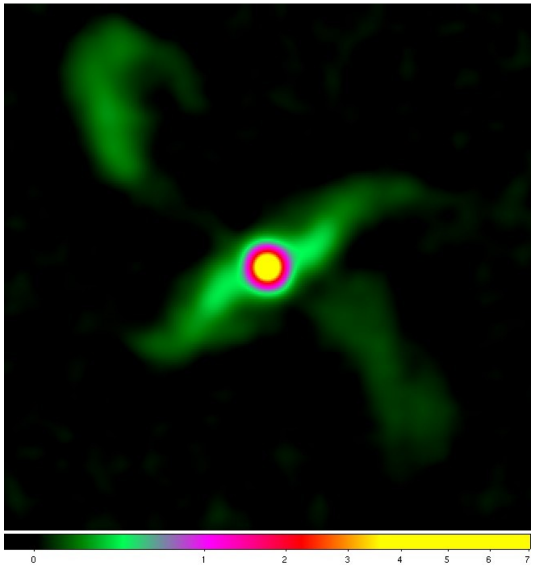
Protostars in Cygnus X

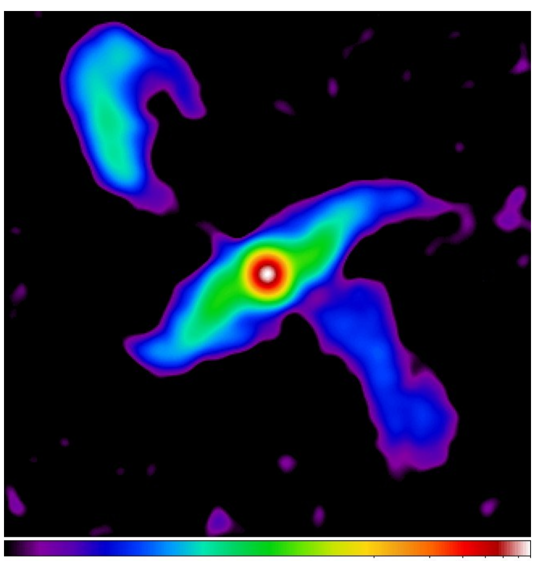


F. Motte

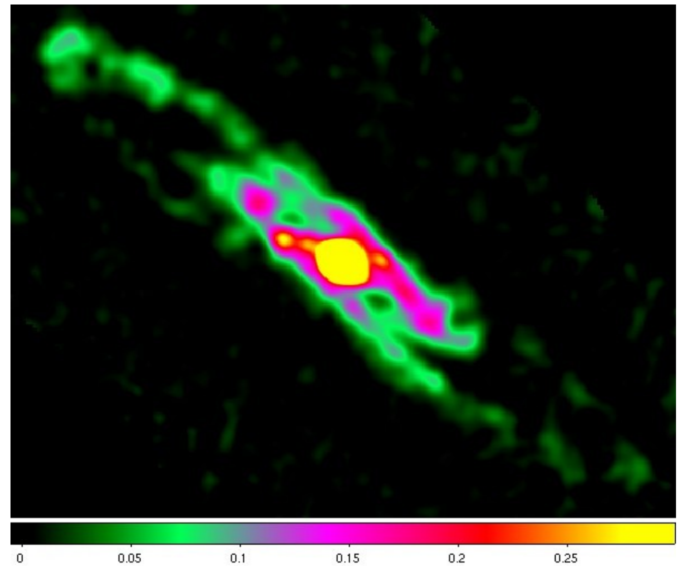
Raster of Spirals

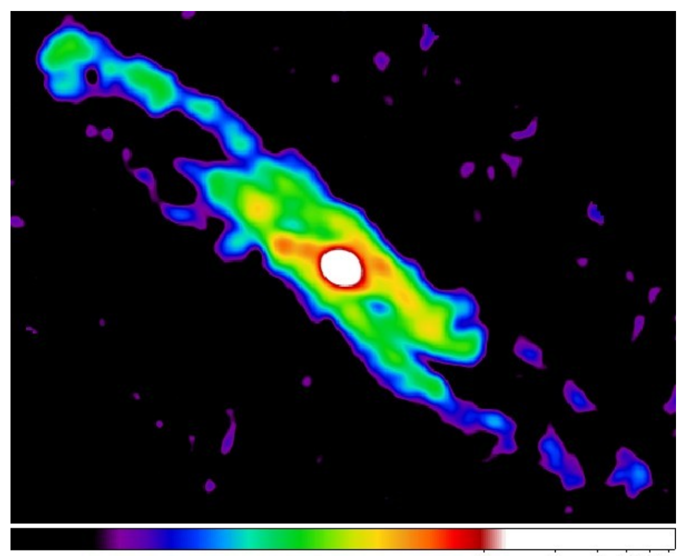
Centaurus A



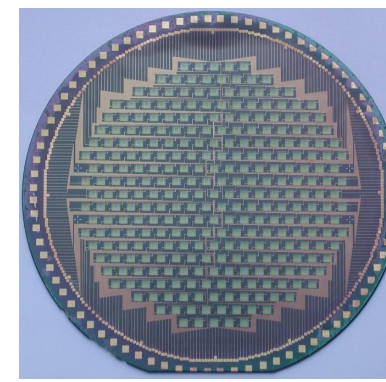


NGC 253

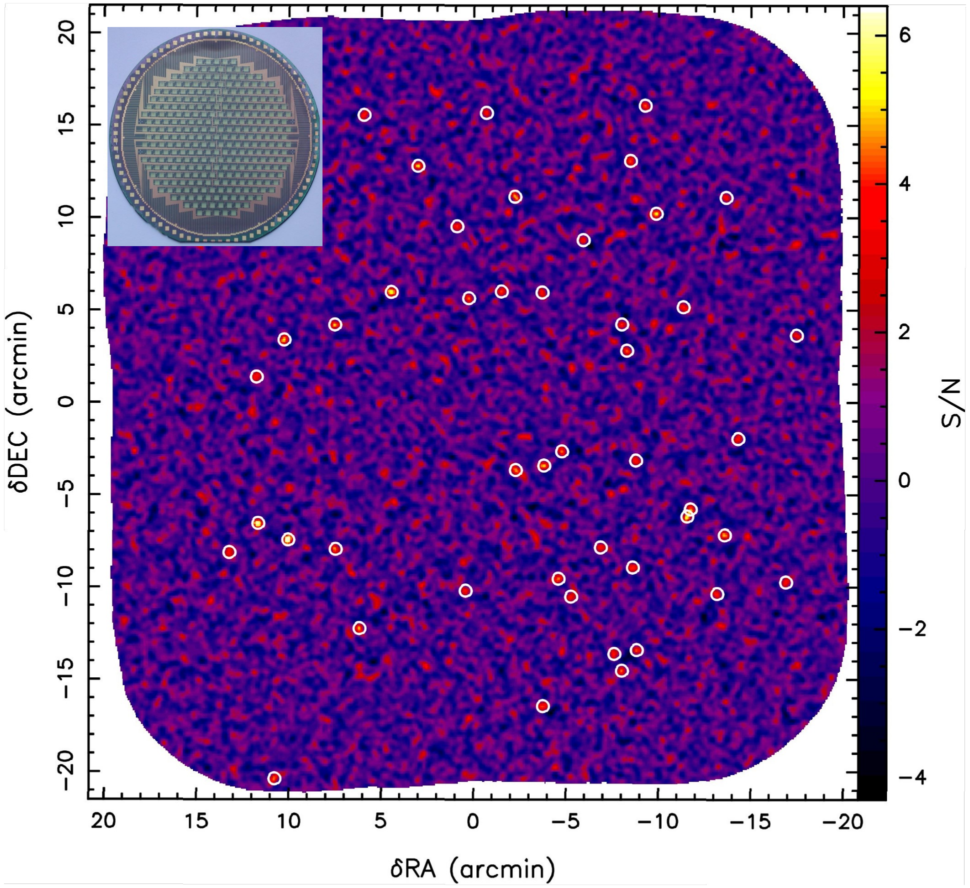


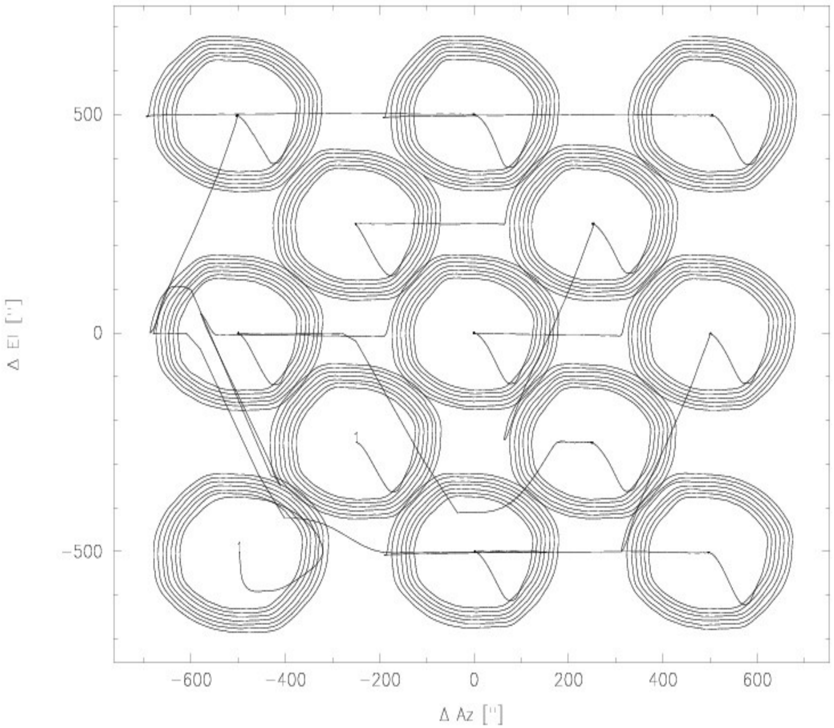


LABOCA



Raster of Spirals





Conclusions

High background imaging works, provided:

I. Scanning Strategies

II. Data Reduction Techniques

Any suggestions for improvement?

(kovacs@astro.umn.edu)

Mapping (nearest pixel algorithm)

Put signal from channel c at time t Into map pixel x,y

Map pixel increment:

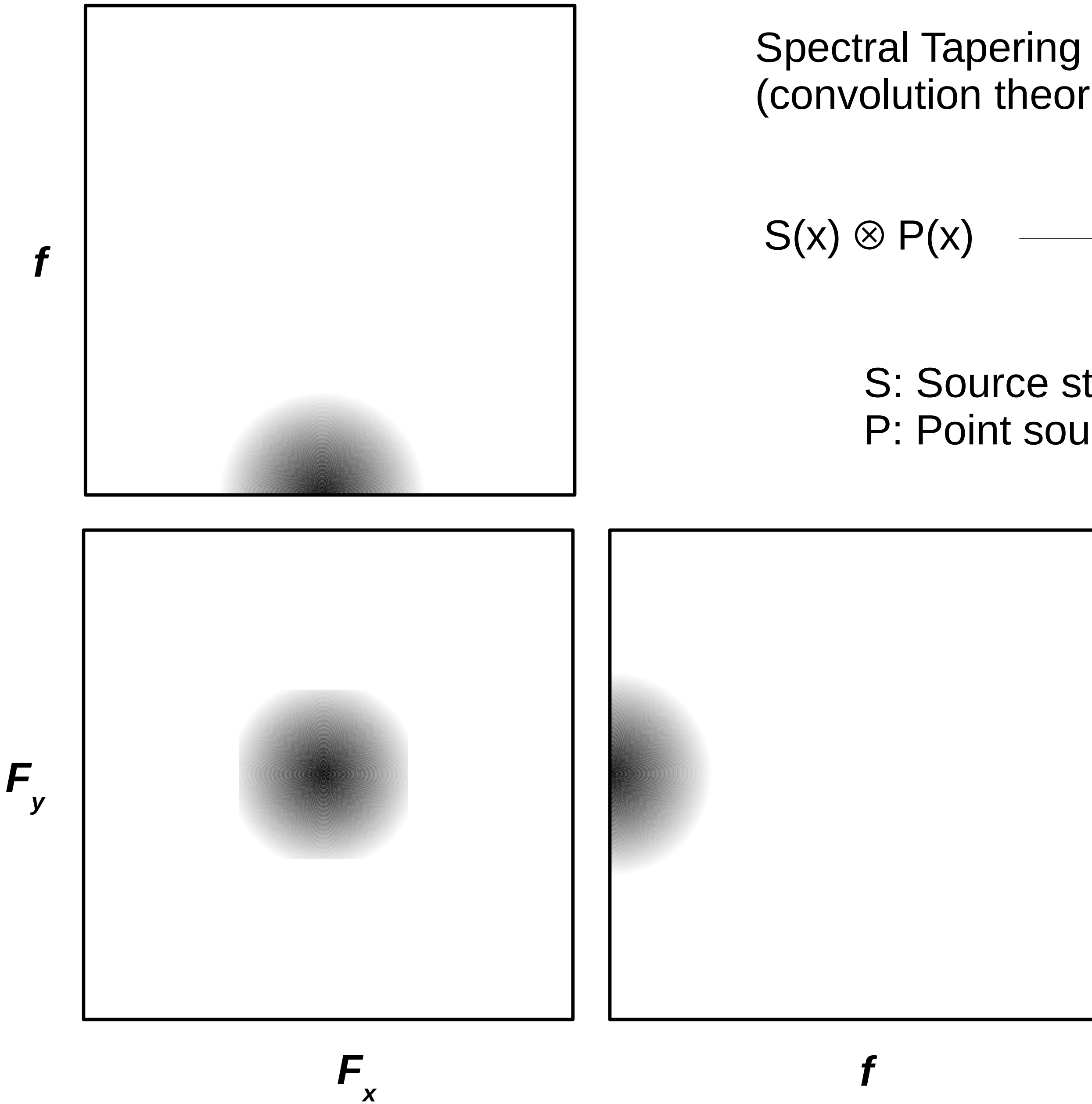
$$\Delta \hat{S}_{xy} = \frac{\sum_{ct} \delta_{ct}^{xy} w_{ct} \hat{G}_{ct} R_{ct}}{\sum_{ct} \delta_{ct}^{xy} w_{ct} \hat{G}_{ct}^2}$$

Map pixel variance:

$$\sigma^2(\hat{S}_{xy}) = \frac{1}{\sum_{ct} \delta_{ct}^{xy} w_{ct} \hat{G}_{ct}^2}$$

For Gaussian telescope beams, at 2.5 or more pixels per FWHM required...

Sensitivity to Large Scales



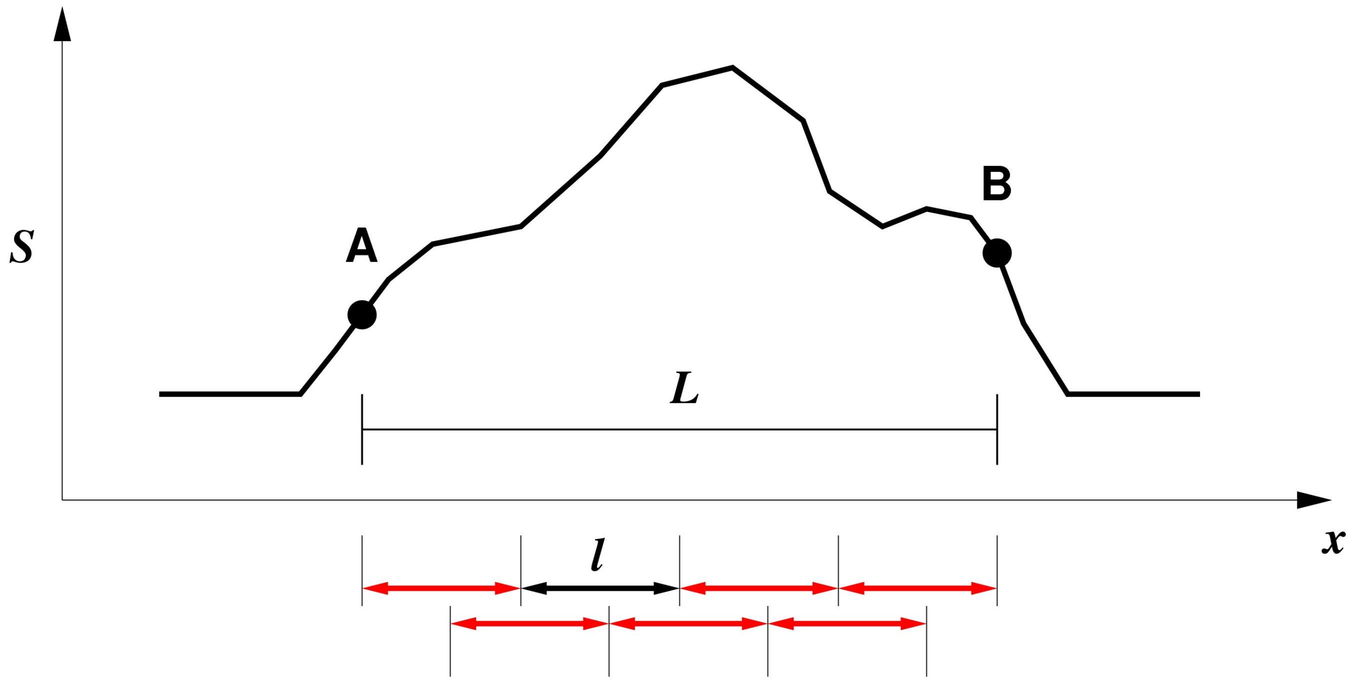
Spectral Tapering
(convolution theorem)

$S(x) \otimes P(x) \longrightarrow S(f) \times P(f)$

S: Source structure
P: Point source spectrum

Sensitivity to Large Scales

$$\sigma_L \approx \left(1 + \frac{L}{l}\right)^{1/2} \sigma_0$$



Scanning Wide

What's Wrong with Staring?

Detector Noise Limited

$\sigma_{det} > \sigma_{bg}$

Dark Frame Calibration Time

=

On-Source Time

4 x overhead!!!

Heavily Background Limited

$\sigma_{det} << \sigma_{bg}$

Dark Frame Calibration Time

<<

On-Source Time

small overhead

Space-based and airborne sub-mm
and far-infrared instrumentation

Ground-based sub-mm
cameras

optical/IR cameras