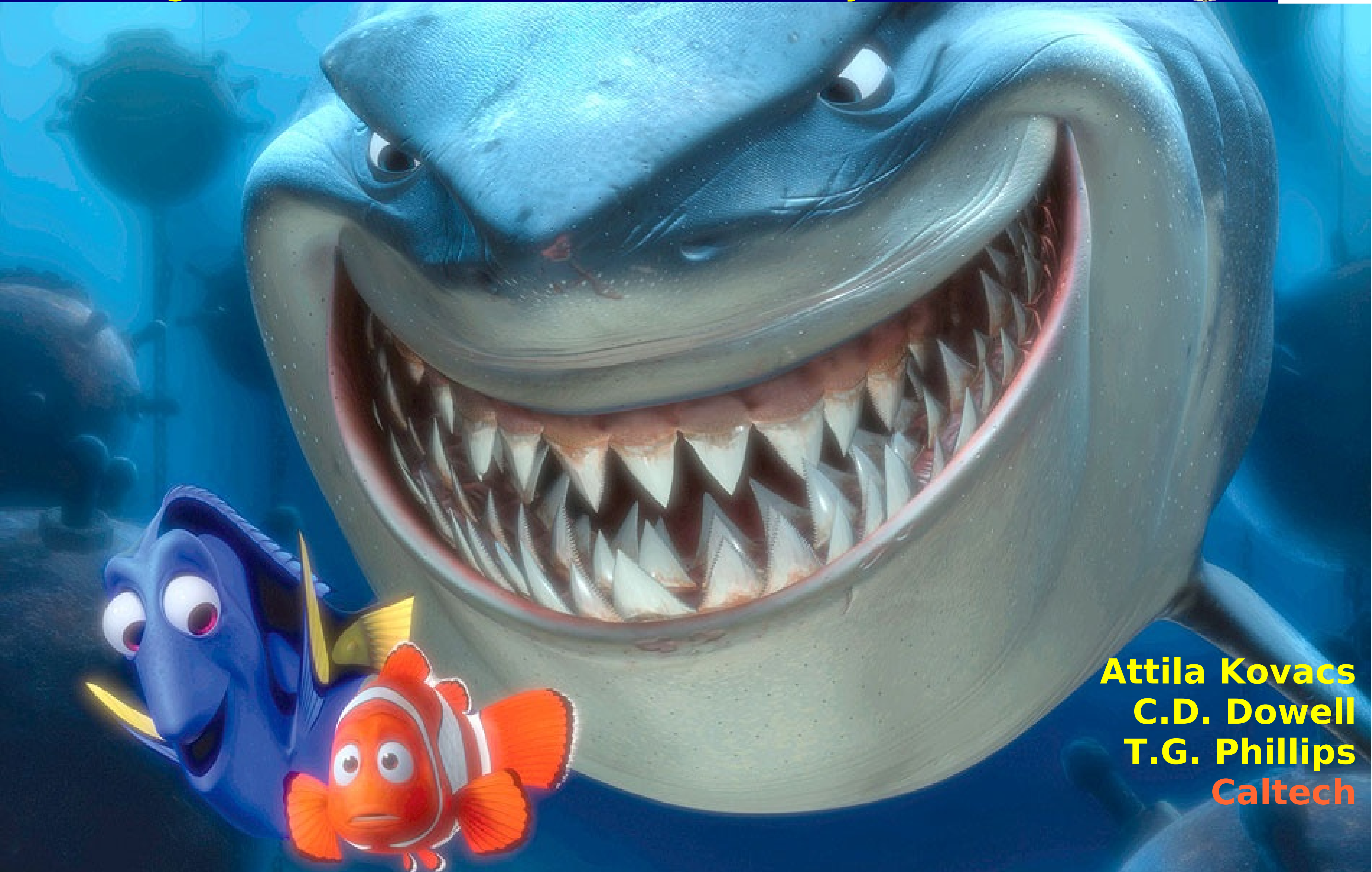
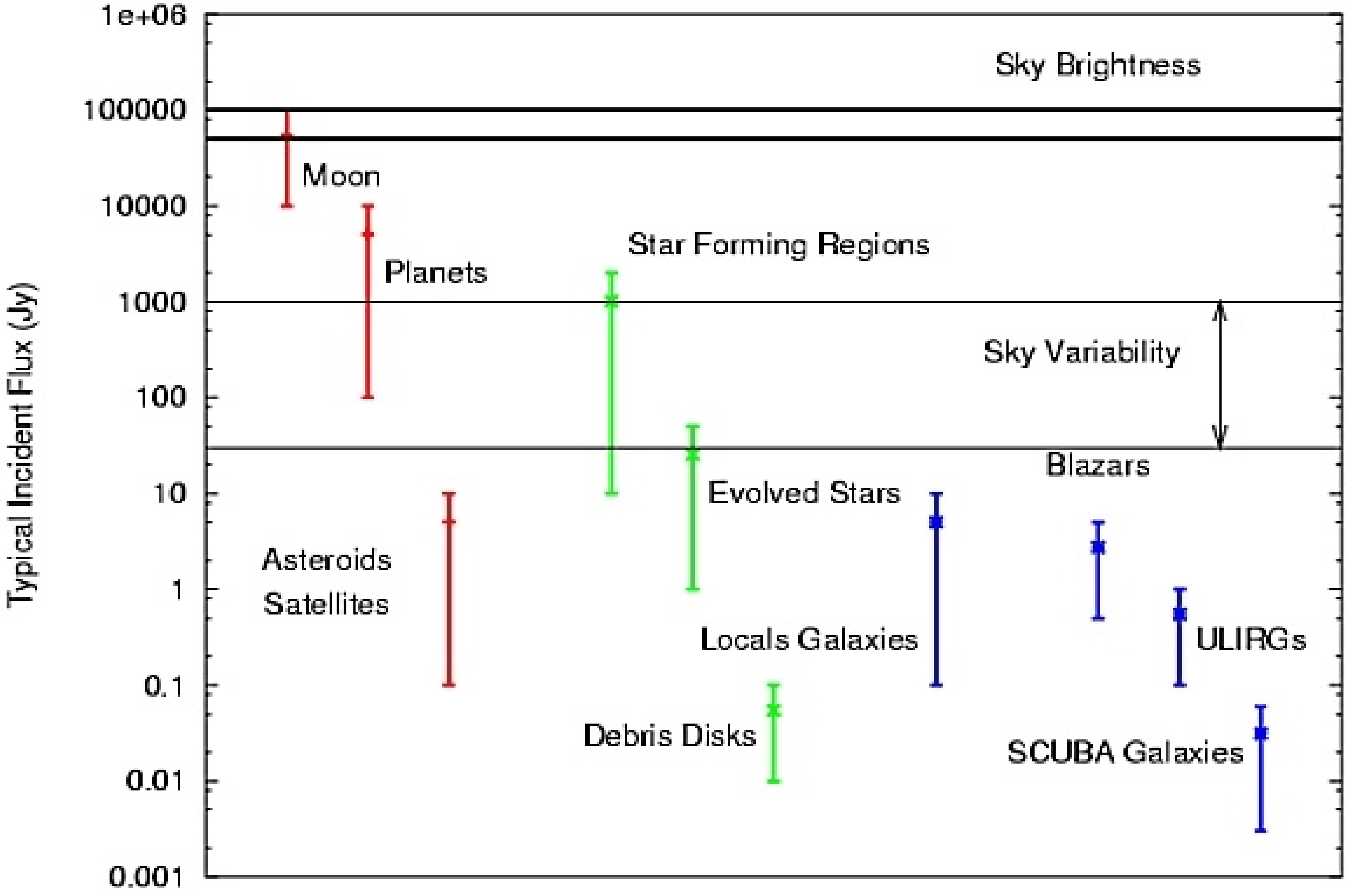
Estimator Based Data Reduction for Large Format sub-mm Bolometer Arrays



Attila Kovacs
C.D. Dowell
T.G. Phillips
Caltech

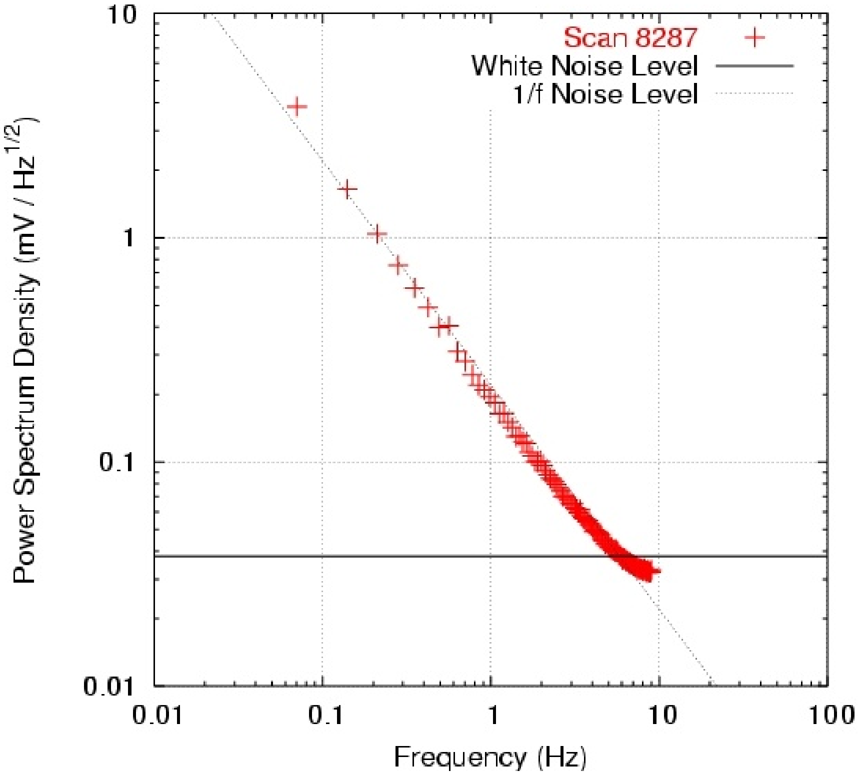
The Submillimeter Challenge

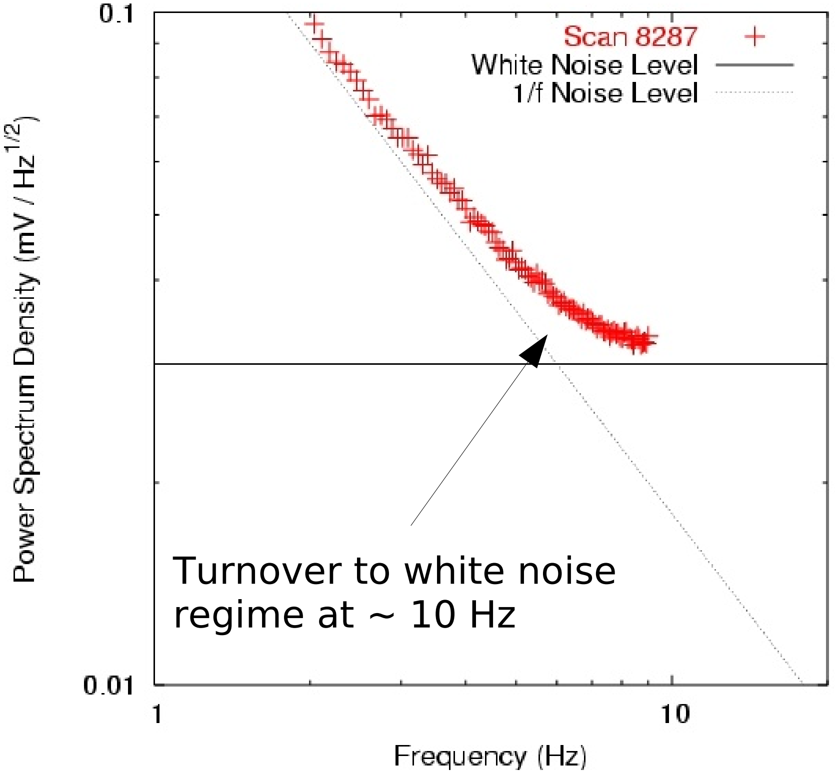


@350 um Atmospheric Background is 10^7 times brighter than faint galaxies. Analogous to Observing a ~16 Magnitude star at daytime!

The Atmospheric Power Spectrum (5 January 2003)

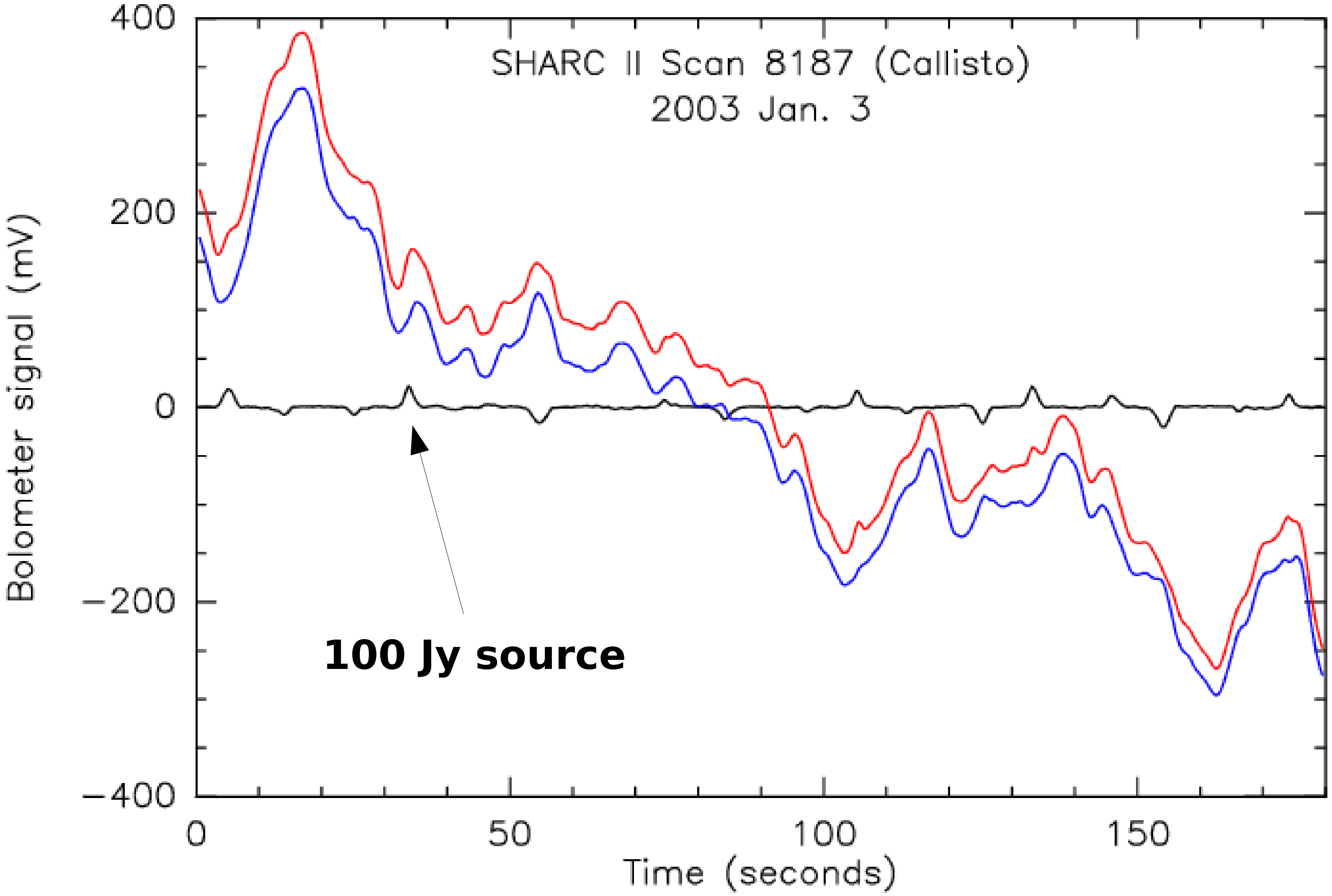
Strong 1/f characteristic





Need Fast Sampling of Background (SHARC-2 has samples every 36ms)

Differencing of Signals



Chopping - The Traditional Way of Differencing

Obtaining difference signal by fast switching between two nearby positions on the sky.

Invented for Single Bolometer instruments.

The Problems...

Residual Sky Noise

Differencing Noise

Deconvolution Noise / Artefacts

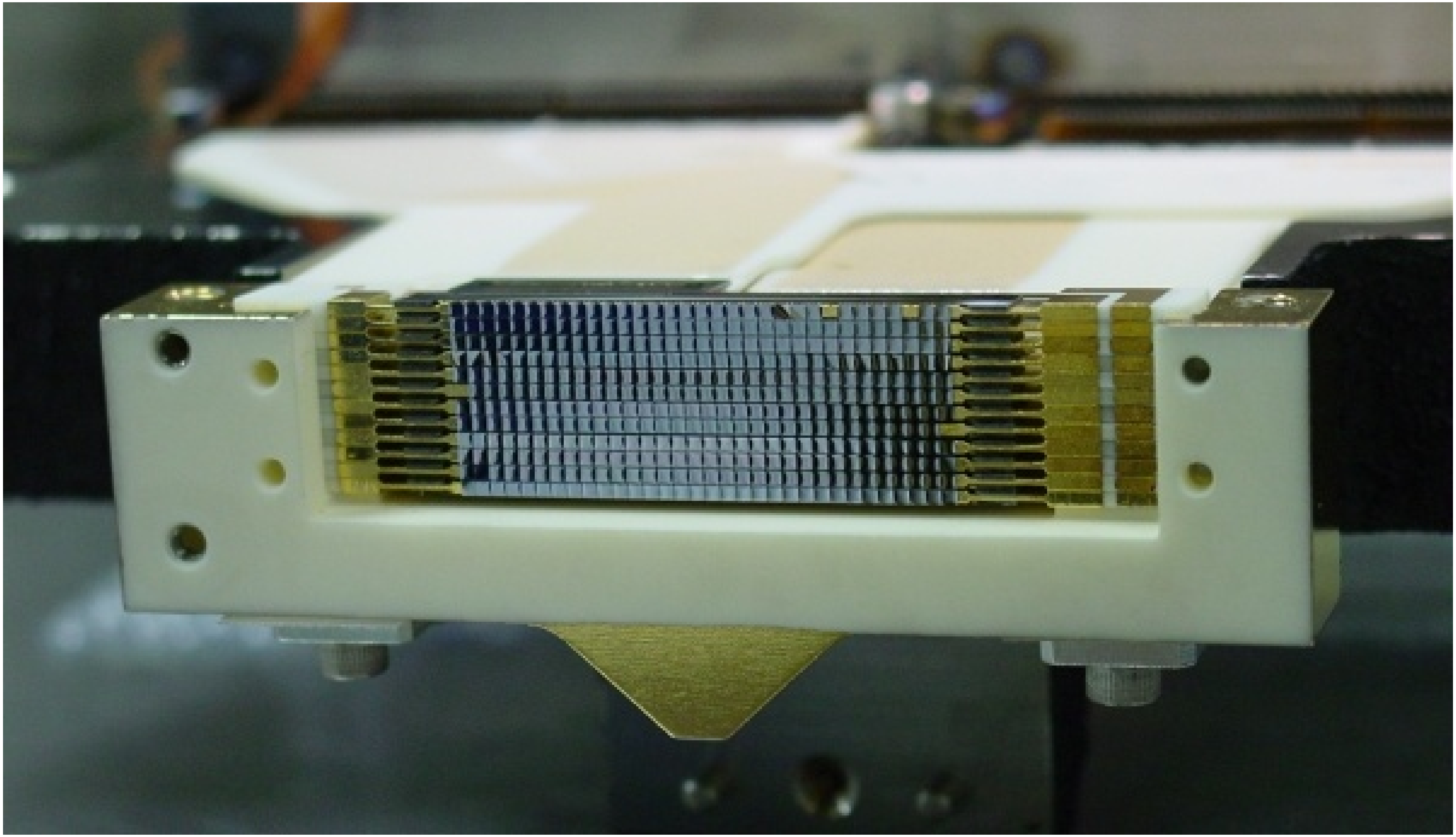
Filtering of Spacial Frequencies at Chopper Throw Harmonics

Filtering Structures Larger than Chopper Throw

Changing Illumination with Secondary Movement

To the Rescue – Large Format 2-D Arrays with Long Timescale (~30s) Detector Stability

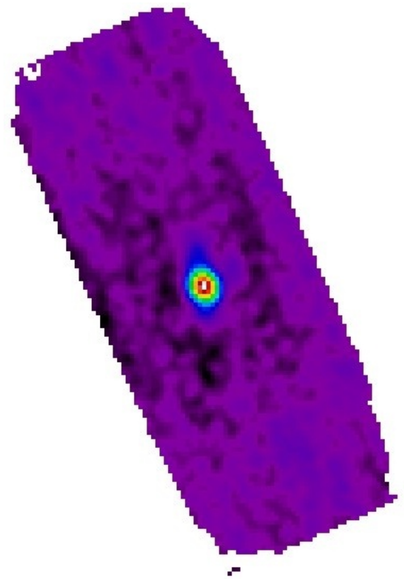
32 x 12 pixels. Nearly Nyquist Sampled at 350um.



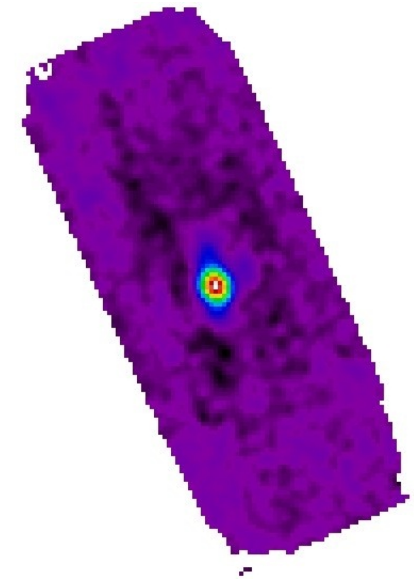
Chopping Noise / Artefacts

Simulated Chopped | **Lissajous Sweep**

Simulated 4 Hz chopper with 40” throw under better than average conditions

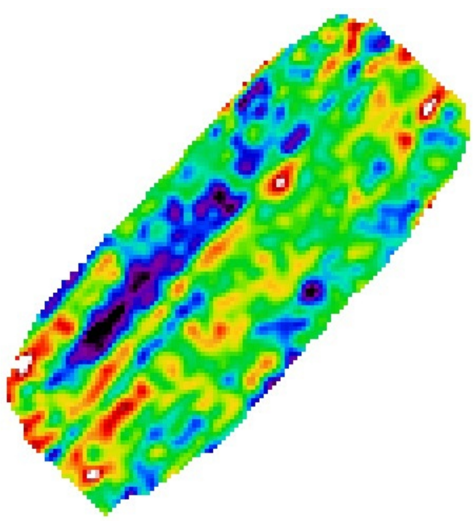


Vesta ~5 Jy (2 min)

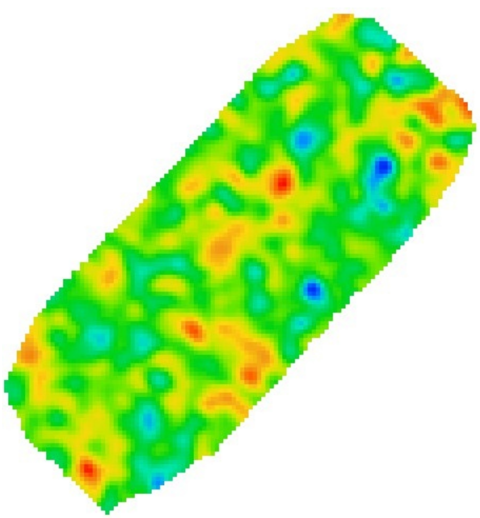


Chopped Image has Limiting noise up to **100%** higher than 'state of the art' reduction.

Not including deconvolution noise!!!



Blank Sky (10 min)



The Challenges of Total Power

'Complexity Noise' vs Chopping Noise

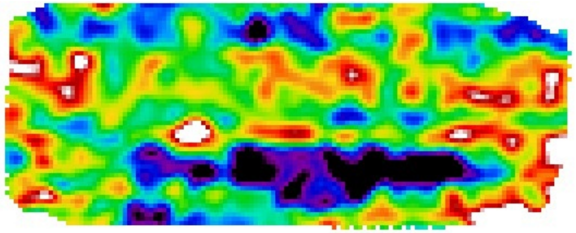
Incomplete Model Set

Inaccurate Knowledge of Gains

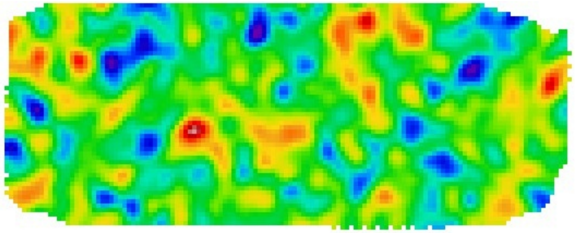
Presence of Anomalous Pixels

Source Coupling / Degeneracies

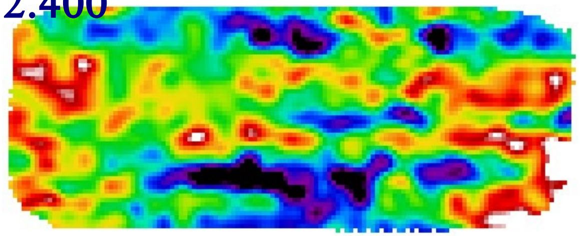
Chopped $\chi^2 = 1.878$



Optimal Total Power $\chi^2 = 0.997$



Unmodelled Signals $\chi^2 = 2.400$



Data Volume

From Chopped Data to Discreet Modeling

Singular Value Decomposition

Mathematically Rigorous Maximum Entropy Solution.

$$\mathbf{A} \cdot \mathbf{x} = \mathbf{b}$$

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

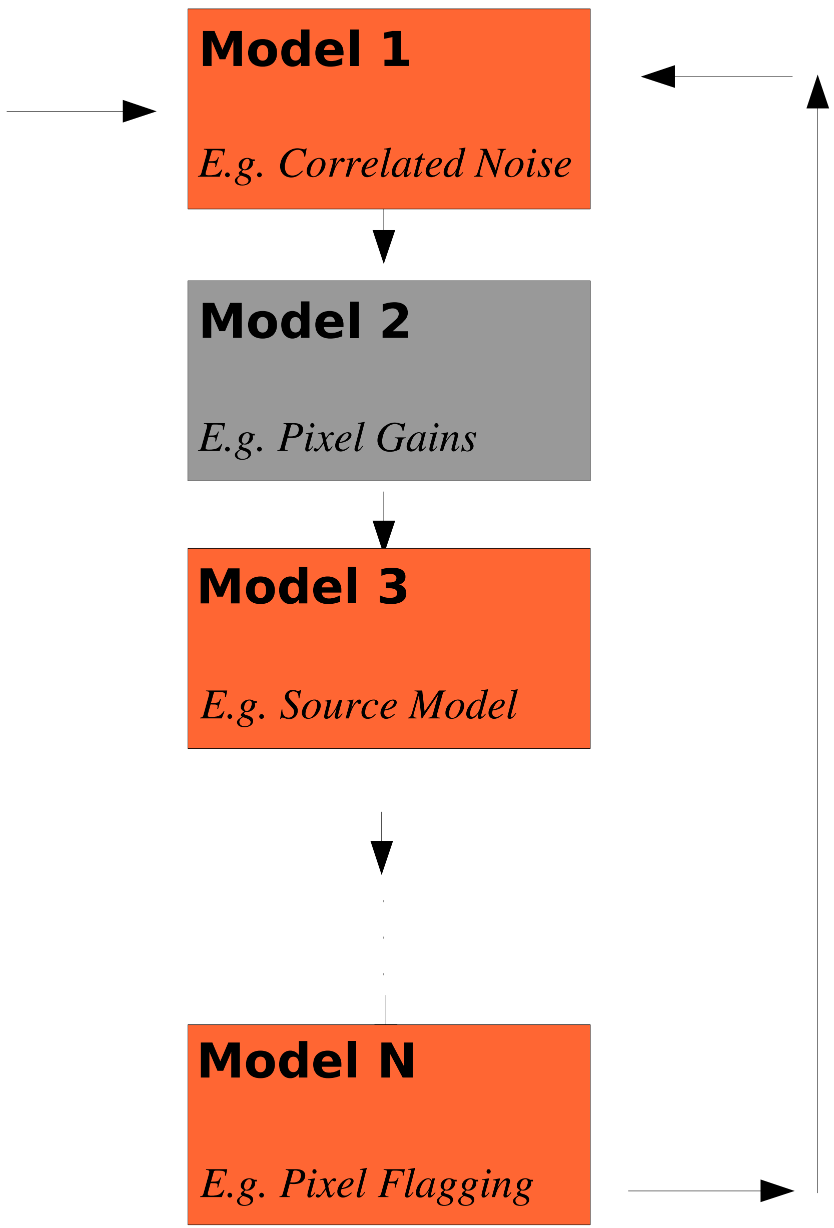
Difficulties with SVD

Computationally costly. (Large Matrices to invert)

Non-linearities. (Gain fitting).

Degeneracies, Singularities and Constraints

Parallel SVD Effort at Goddard Space Flight Centre

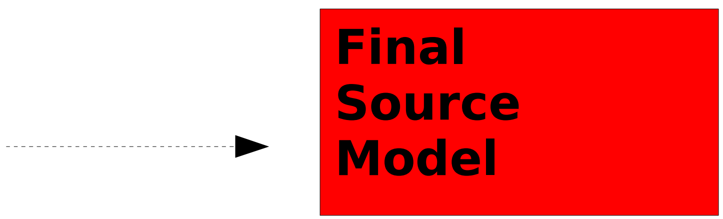


Iterated Pipeline

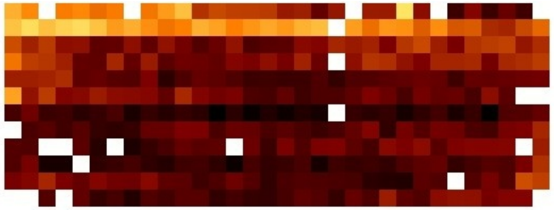
- Series of Maximum Likelihood Estimators.
- Brightest First
- Convergence via Iterating

Advantages

- Intuitive
- Fast. (Linear with Data Size)
- Able to Deal with Non-Linearities
- Easily Configurable / Changeable



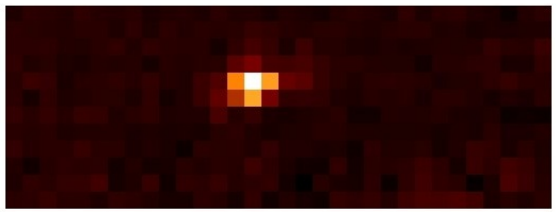
Instrument Specific Models



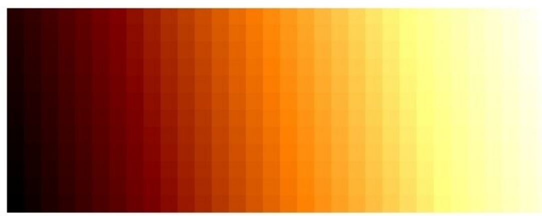
Static Residual
Pixel Offsets
~ 2000 Jy

Vesta 8293
5 January 2003
Excellent Conditions

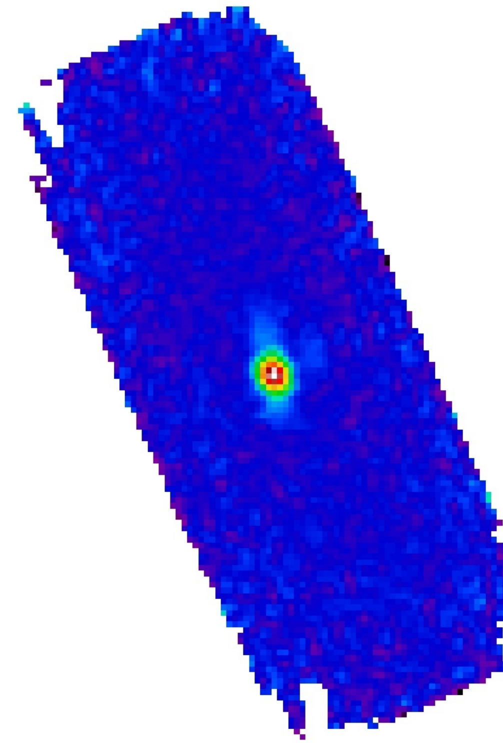
Source Model
~ 5 Jy



Gradients
~ 2 Jy

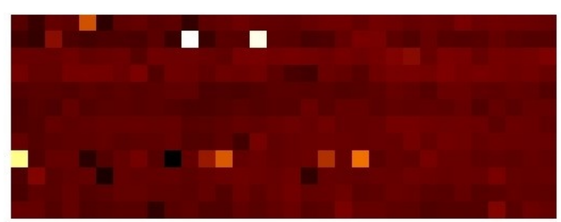


=



Electronic Row
Drifts
~ 1 Jy

Detector 1/f
Drift Model
~ 1 Jy

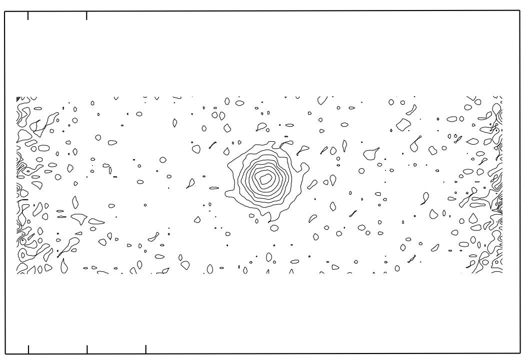


Preliminary Simulations for the Iterative Reduction Method

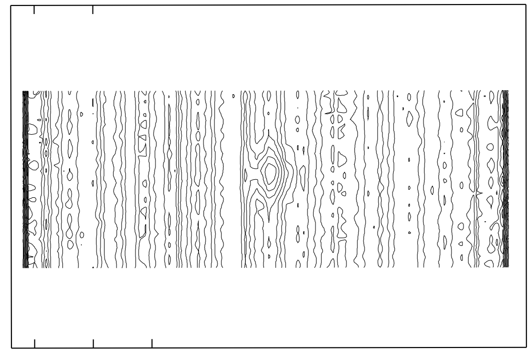
(Feb 2001)

Reduction Goal

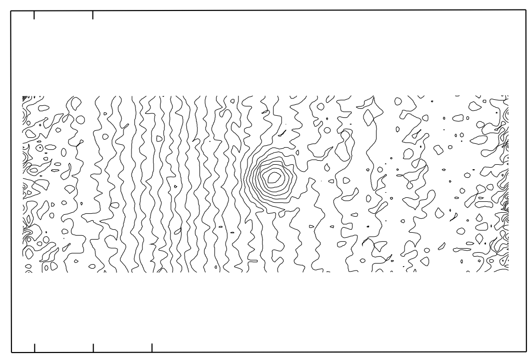
Simulated source with only white noise – this is the best any analysis could achieve



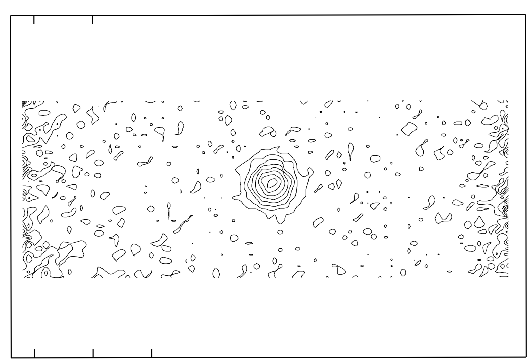
Simulated Raw Data (1/f correlated)



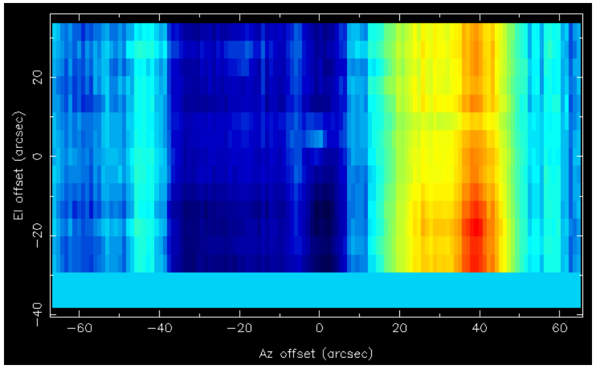
Partial Cleaning (50 iterations)



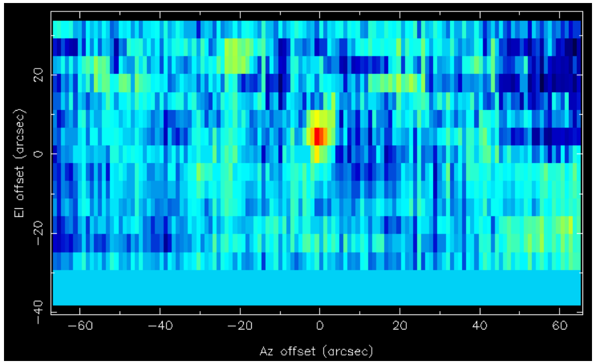
Deep Cleaning (200 iterations)



SHARC 1.5 Uranus Raw (Dowell)

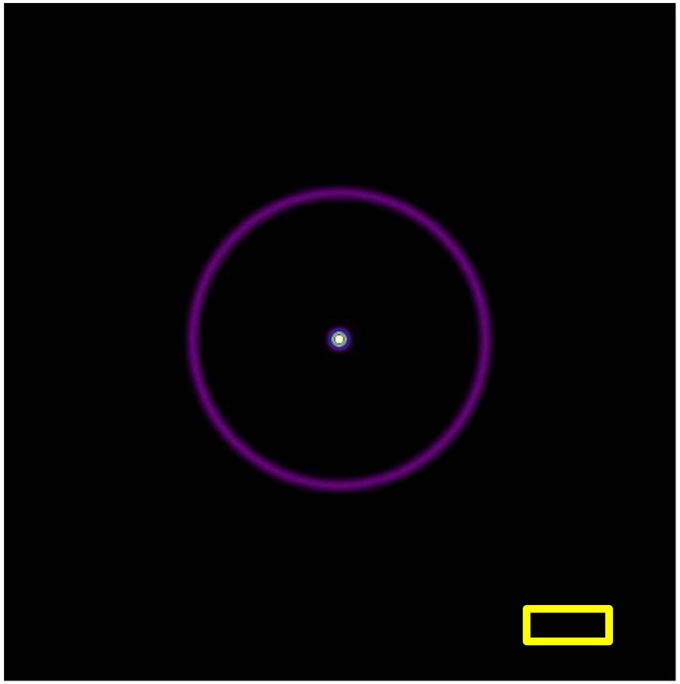


SHARC 1.5 Uranus Reduced (Dowell)



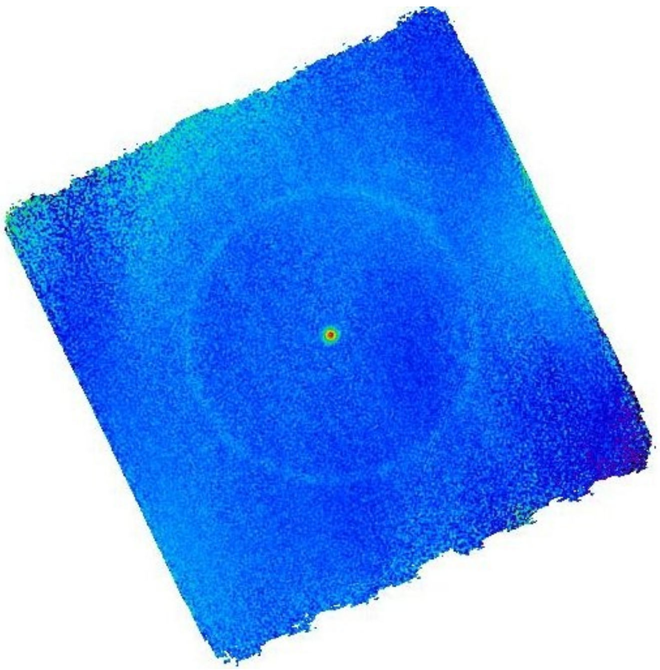
SHARC 1.5 – single row of bolometers. Edge pixels used for estimating correlated noise.

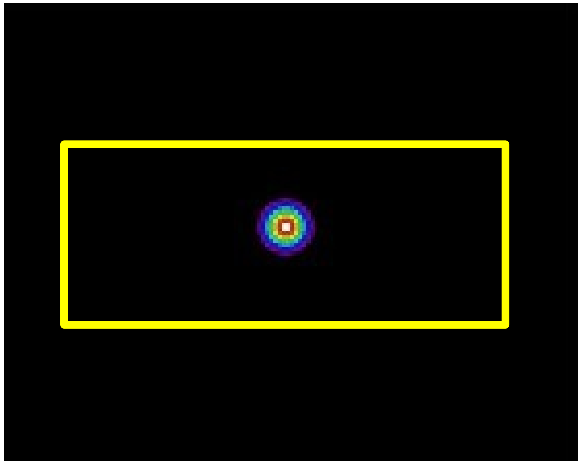
Simulations with CRUSH



Billiard Ball Scan
100 mJy Ring surrounding compact star in 1 hour
10' x 10'

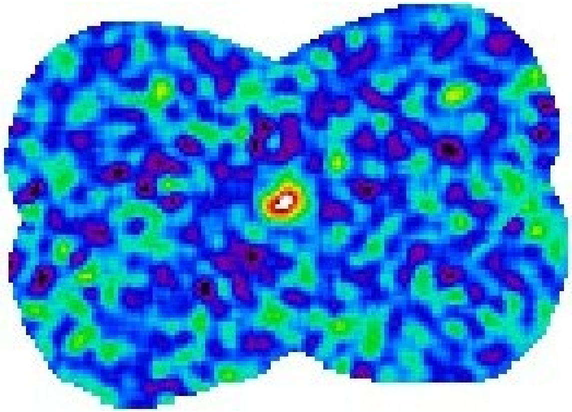
Imperfect cleaning of faint large scale structures





Lissajous Sweep
100 mJy Compact in 1 hour

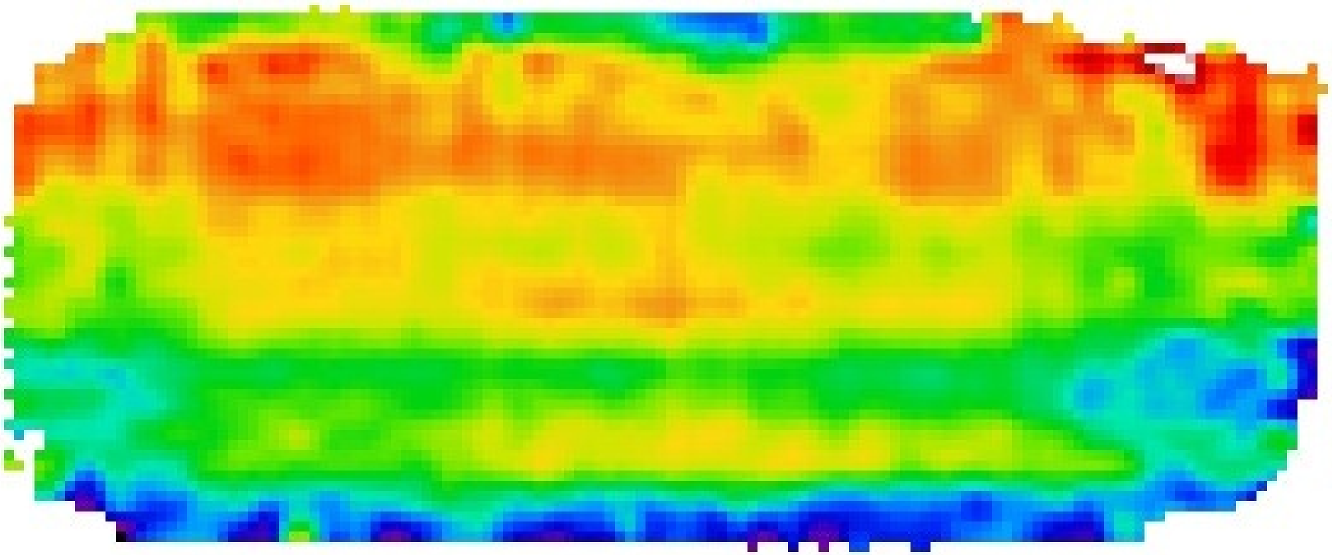
Imperfect cleaning of faint large scale structures



Source Fluxes Recovered within 1%

Source Generation 0 – Direct Mapping

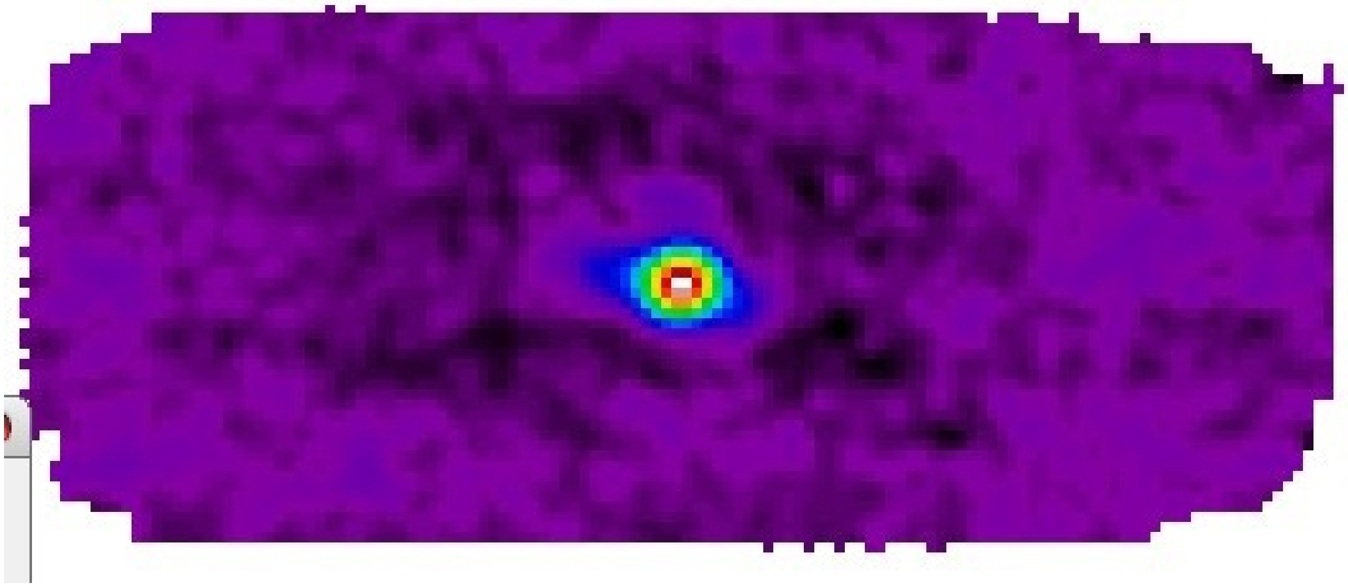
$$\chi^2 = 442602$$



VESTA (~5Jy)
4 January 2003

Source Generation 1

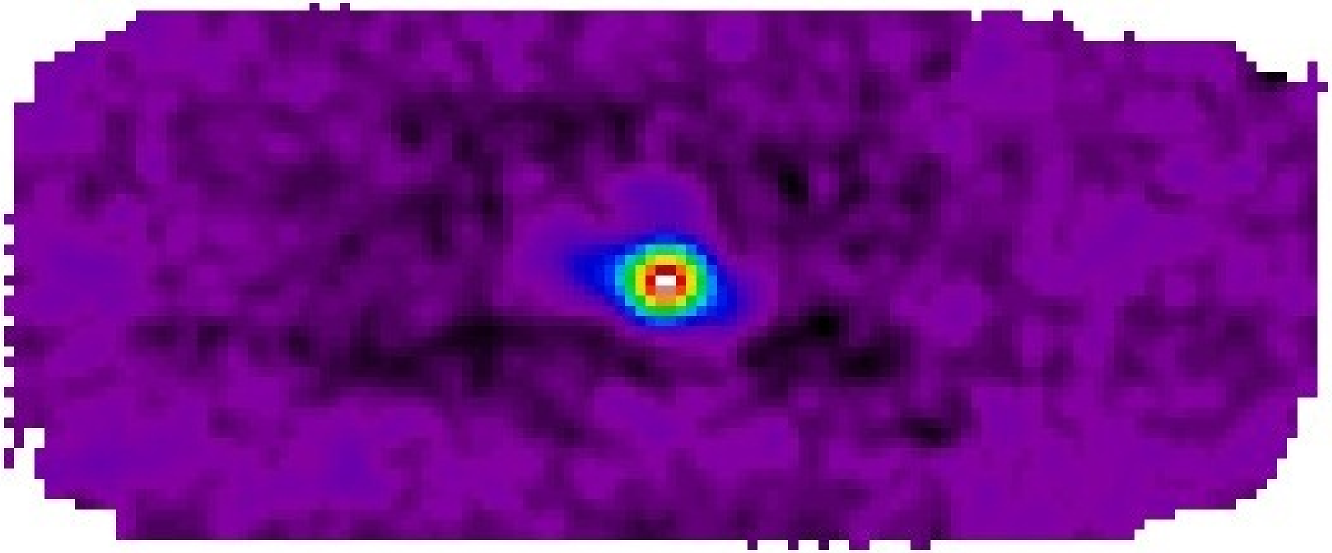
χ^2 = 1.161



VESTA (~5Jy)
4 January 2003

Source Generation 2

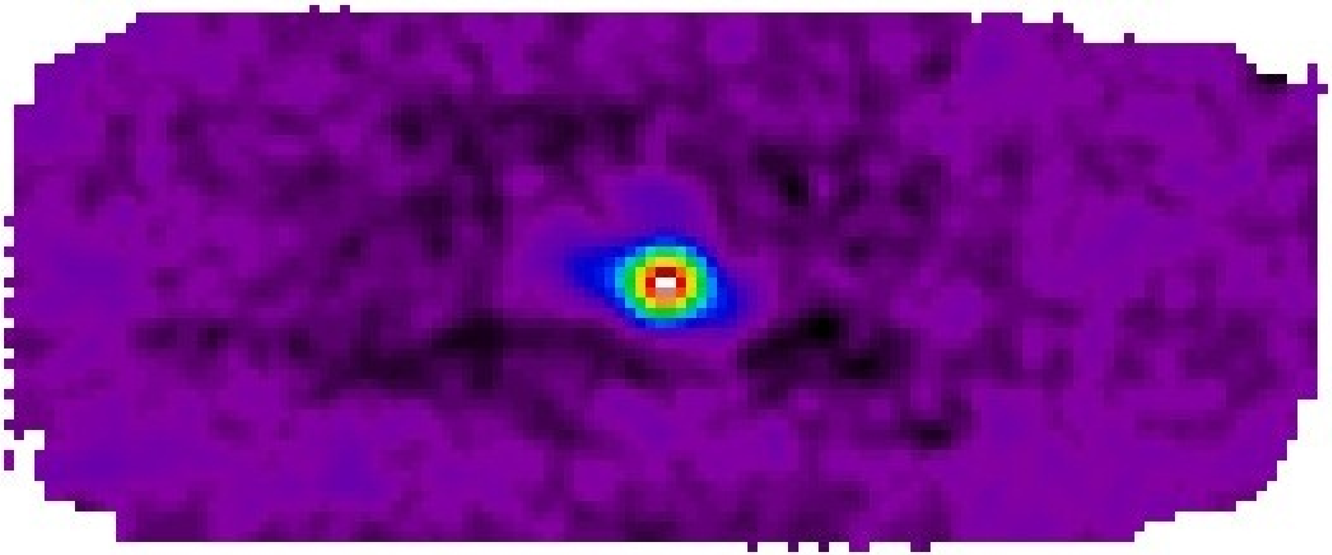
$$\chi^2 = 1.045$$



VESTA (~5Jy)
4 January 2003

Source Generation 3

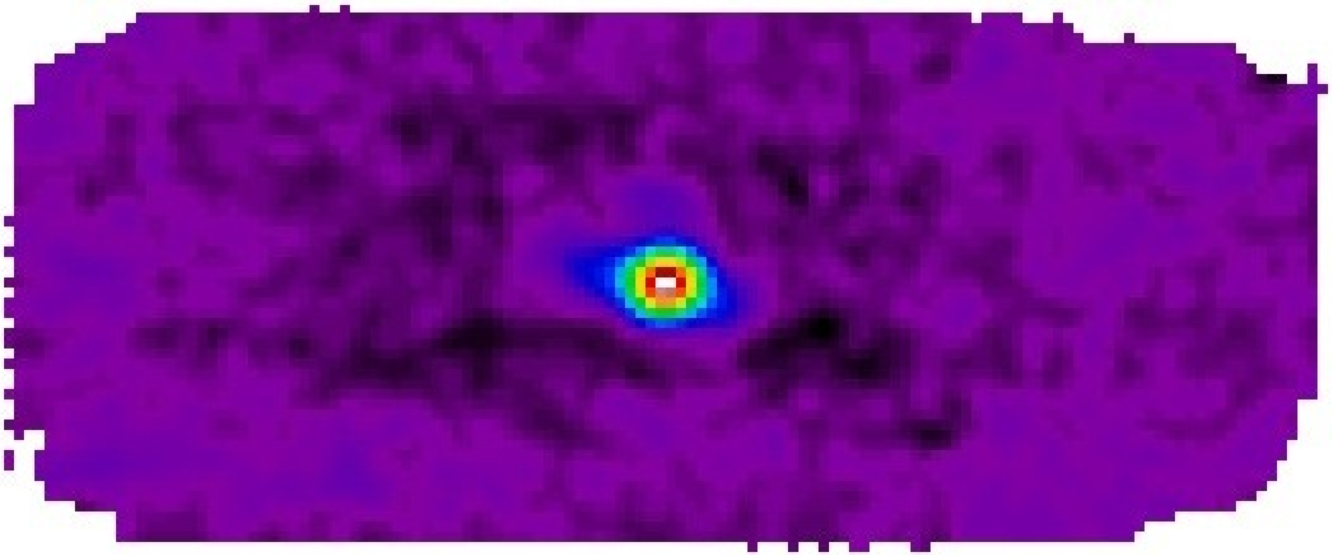
$\chi^2 = 1.050$



VESTA (~5Jy)
4 January 2003

Source Generation 10

χ^2 = 1.058



VESTA (~5Jy)
4 January 2003

Maximum Likelihood Estimators

$$I_{t,b} = \ldots + G_b \times A_{t\in\mathcal{T},b\in\mathcal{B}} + \ldots$$

Alternatively, in terms of the Residuals:

$$R_{t,b} = G_b \times A_{t\in\mathcal{T},b\in\mathcal{B}}$$

$$\chi^2 = \sum_t \sum_b w_{t,b} \times \left(R_{t,b} - G_b \times A_{b\in\mathcal{T},b\in\mathcal{B}}\right)^2$$

$$\frac{\partial \chi^2}{\partial A_{\mathcal{T},\mathcal{B}}} = 0 \quad \longrightarrow \quad A_{\mathcal{T},\mathcal{B}} = \frac{\sum_{b\in\mathcal{B}} \sum_{t\in\mathcal{T}} w_{t,b} G_b \times R_{t,b}}{\sum_{b\in\mathcal{B}} \sum_{t\in\mathcal{T}} w_{t,b} G_b^2} \equiv \langle A \rangle_{\mathcal{T},\mathcal{B}}$$

As if residuals only contained given model...

Correlated Noise And Gain Fitting

$$I_{t,b} = \ldots + G \times g_b C_t + \ldots$$

$$R_{t,b} = G \times g_b C_t$$

$$\sum_b w_b g_b \equiv 1$$

$$\chi^2 = \sum_t \sum_b w_{t,b} \times \left(R_{t,b} - G \times g_b \times C_t\right)^2$$

$$\frac{\partial \chi^2}{\partial C_t} = 0$$

$$\frac{\partial \chi^2}{\partial g_b} = 0$$

$$C_t = \frac{\sum_b w_b g_b R_{t,b}}{G \times \sum_b w_b g_b^2}$$

$$g_b = \frac{\sum_t w_t R_{t,b} \times C_t}{G \times \sum_t w_b C_t^2}$$

Non-Linear Response

$$G(I) \rightarrow G0(1-\alpha I)$$

$$G_{t,b} \equiv G \times g_b(1-\alpha_b C_t)$$

$$R_{t,b} = G \times g_b(1-\alpha_b C_t)C_t$$

$$C_t = \frac{\sum_b w_b g_b (1-2\alpha_b C_t) R_{t,b}}{G \times \sum_b w_b g_b^2 (1-\alpha_b C_t)(1-2\alpha_b C_t)} \longrightarrow C_t = \frac{\sum_b w_b g_{t,b} R_{t,b}}{\sum_b w_b G_{t,b} g_{t,b}}$$

where,

Small signal gain $\quad g_{t,b} = G \times g_b(1-2\alpha_b C_t)$

Large signal gain $\quad G_{t,b} = G \times g_b(1-\alpha_b C_t)$

Weighting

Weights Separated into a product of pixel-only weights and time-only weights.

$$\sigma_{t,b}^2 = {\chi_t}^2 {\sigma_{\mathcal{T},b}}^2 \quad \forall t \in \mathcal{T}$$

$$w_{t,b} = w_t \times w_b^{\mathcal{T}} \quad \forall t \in \mathcal{T}$$

$$\hat{\sigma}_{\mathcal{T},b}^2 = \frac{T_b^{\mathcal{T}}}{T_b^{\mathcal{T}} - P_b} \times \frac{\sum_{t \in \mathcal{T}} w_t (R_{t,b})^2}{\sum_{t \in \mathcal{T}} w_t}$$

$$\hat{\sigma}_{\mathcal{T},b}^2 = \frac{T_b^{\mathcal{T}}}{T_b^{\mathcal{T}} - P_b} \times \left\langle R^2 \right\rangle_{\mathcal{T}}$$

Where P is the number of fitted parameters in the time interval T

$$P_b = \sum_i \sum_\alpha P_{\alpha,b}^i$$

$$\frac{1}{w_{\mathcal{T}'}} = \frac{1}{B_{\mathcal{T}'} - P_{\mathcal{T}'}} \times \sum_{t \in \mathcal{T}'} \sum_b \frac{R_{t,b}^2}{\hat{\sigma}_{\mathcal{T},b}^2}$$

Where B is the number of Active Bolometers, and P is the number of Parameters fitted in the time interval T'

$$B_{\mathcal{T}'} = \sum_{t \in \mathcal{T}'} B_t \text{ and } P_{\mathcal{T}'} = \sum_{t \in \mathcal{T}'} P_t$$

Identifying Anomalous Pixel Behaviour

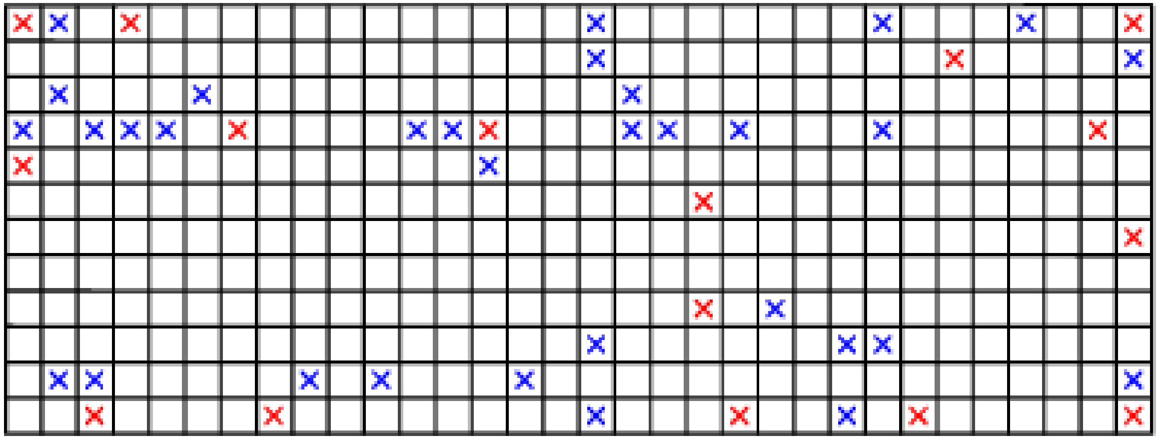
One of the Most challenging aspects of deep reductions

Removal of Residual Spikes

Flagging of Pixels with Unreasonable Gain Fits

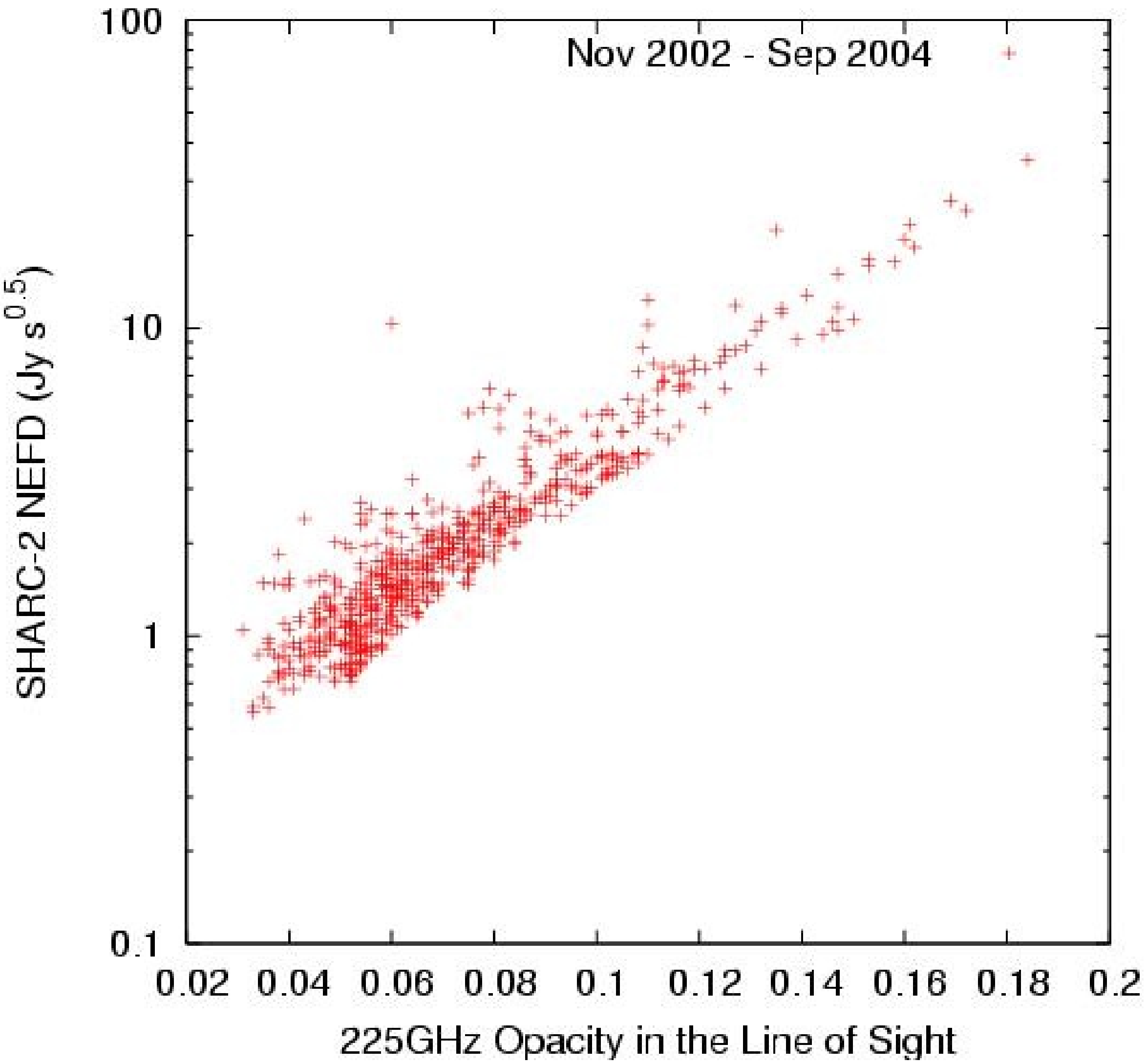
Looking for Statistically Significant Temporal Features...

... and Spectral Features

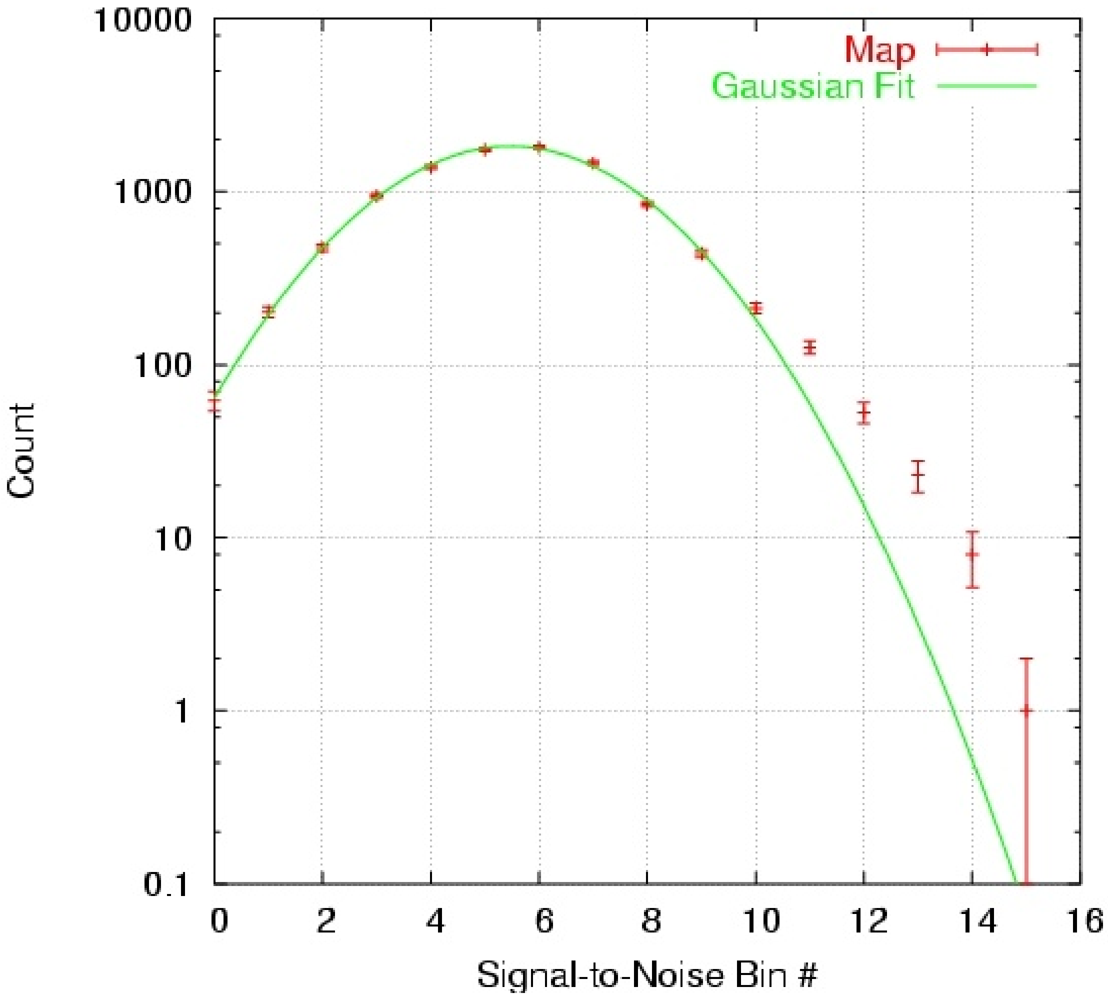


About 335 of 384 pixels are good enough

SHARC2 Point Source Sensitivity Statistics



Map Noise Characteristics & Detection Confidence

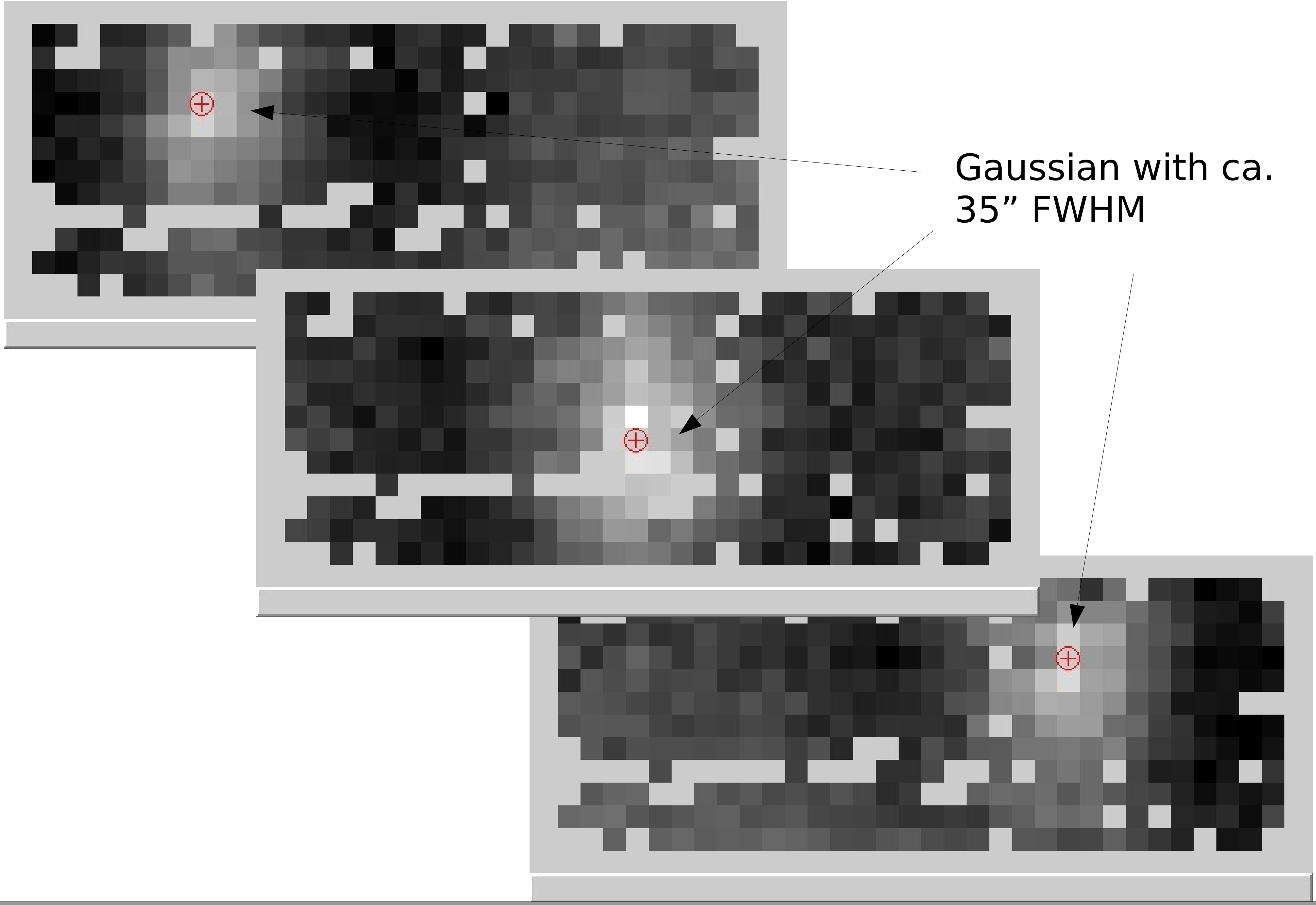


Perfectly Gaussian Noise

~2 Times wider than expected statistically from independent pixel noise! Detectors are NOT independent!

Positive tail Clearly indicating the presence of source flux.

Residual Pixel-to-Pixel Covariances (Learning from the Data Themself...)



Fundamental Limits to Reduction

Unremovable Degeneracies with Source Model

(e.g. Faint, Extended Structures)

Non-linear Modeling and Local Minima

Solutions & Considerations

Improve Scanning Strategy.

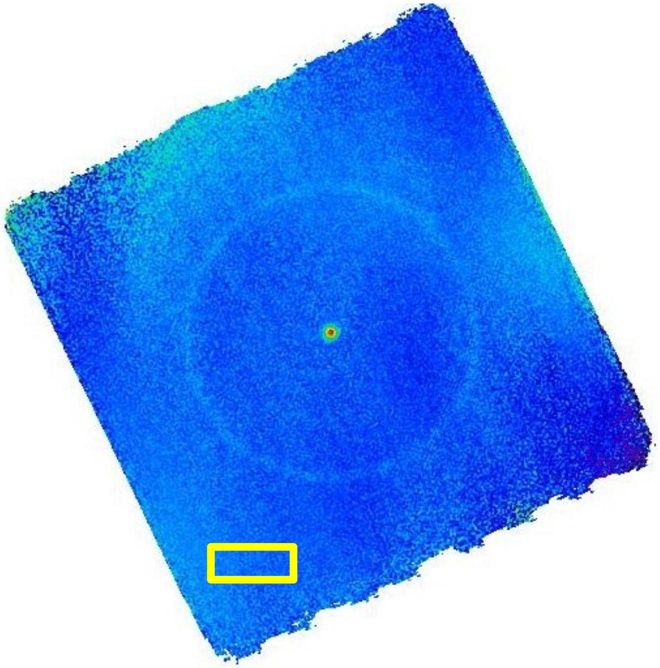
(Decouple source from other signals).

Constraints.

(Better knowledge of instrument, esp. gains).

Larger Arrays.

(SCUBA-2 and the next generation sub-mm arrays)



The Importance of Scanning Strategies

Moving Several pixels onto the same sky position within the limiting instrumental *time scale* '**calibrates**' pixels against one another.

The more pixels that can be thus related, the more **robust** the 'calibration' measurement.

'Calibrated' pixels can observe several positions on the sky within the limiting time scale, leading to **high fidelity maps**.

How to Choose a Scanning Strategy?

Decouple Source Signals from Instrumental & Background Signals
(Spread Source Evenly in Fourier Domain

Faster
(within Telescope Limits)

Better pixel-to-pixel calibration

Better Decoupling of Source Signals
(Larger and higher fidelity maps)

Smarter and Better

Crossing Sweep Patterns

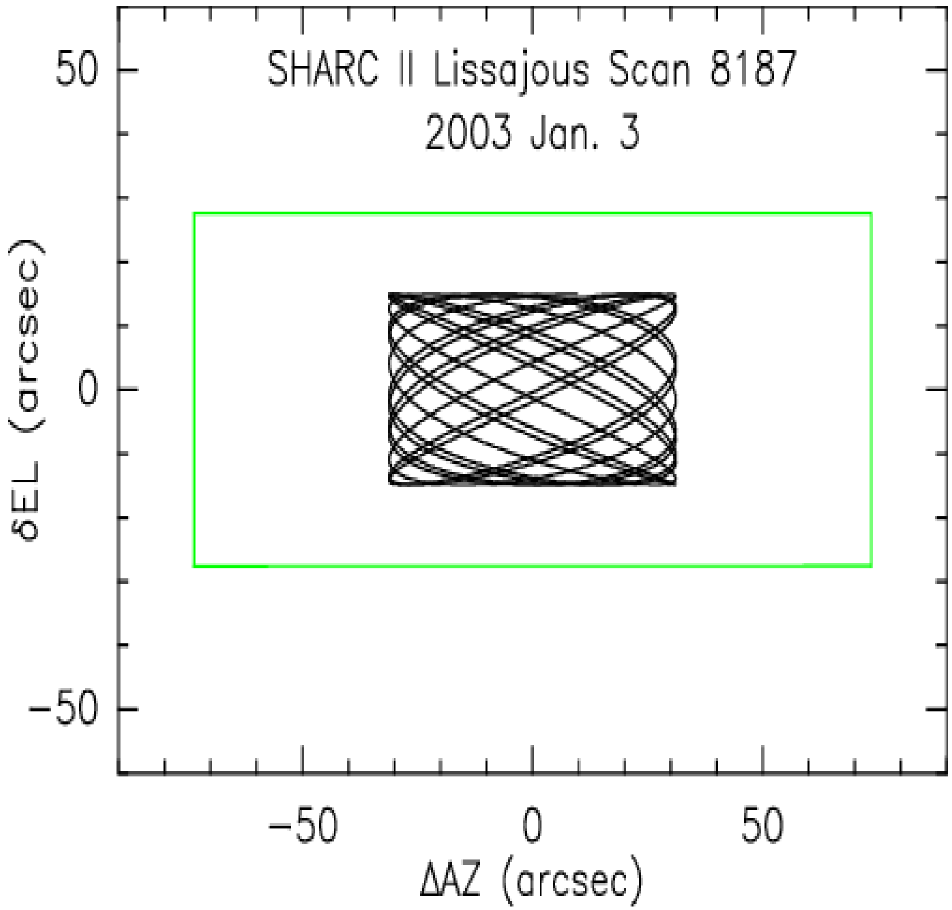
Non-periodic source crossing

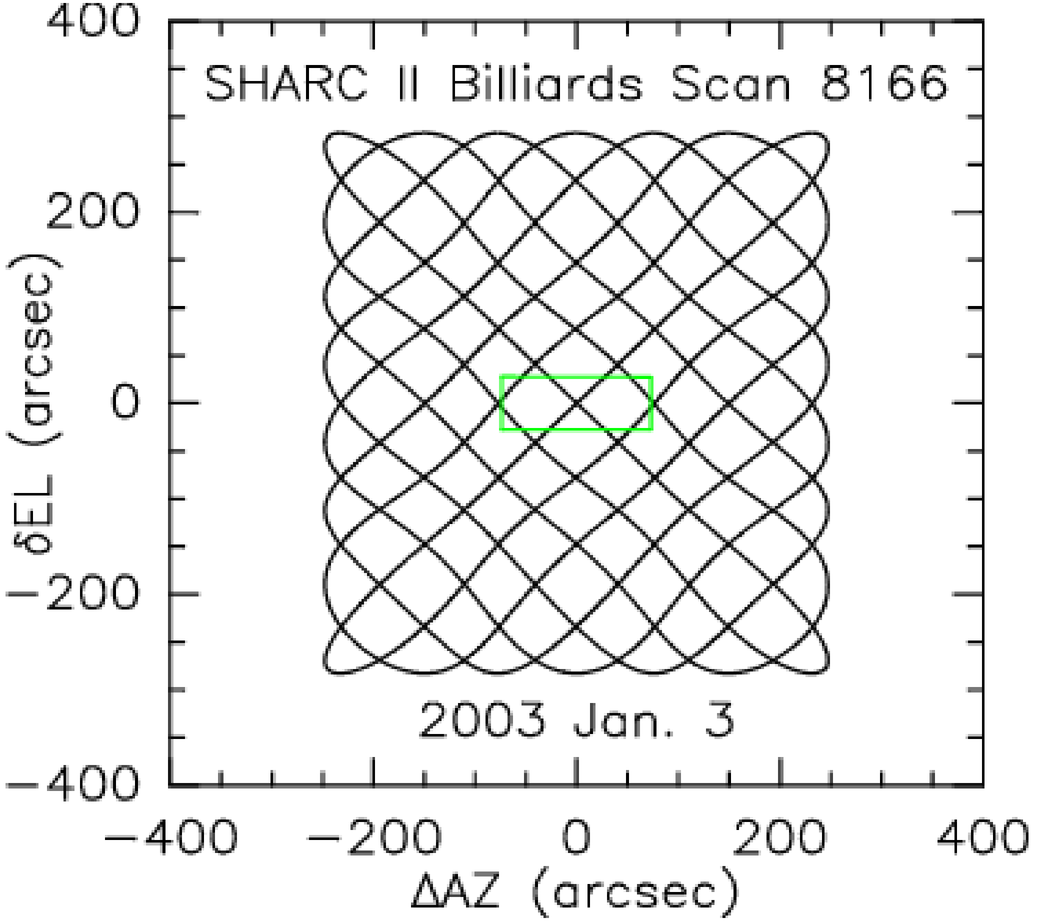
Move Primary to avoid changing illumination pattern

Scanning Strategies without a Chopping Secondary

For compact and point sources
Maximizes time coverage over a small area.

For large map making. Obtains uniform coverage over an area much larger than the array





Conclusions

Total Power Can Produce Clean High Fidelity Maps!!!

Provided:

- **Complete Modeling**
- **Detecting Anomalies**
- **Gain Fitting (if necessary)**
- **Carefully Designed Scanning Pattern**

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

Acknowledgements

D.C. Lis

C. Borys

T. Tyranowski

J. Zmuidzinas

R. Arendt

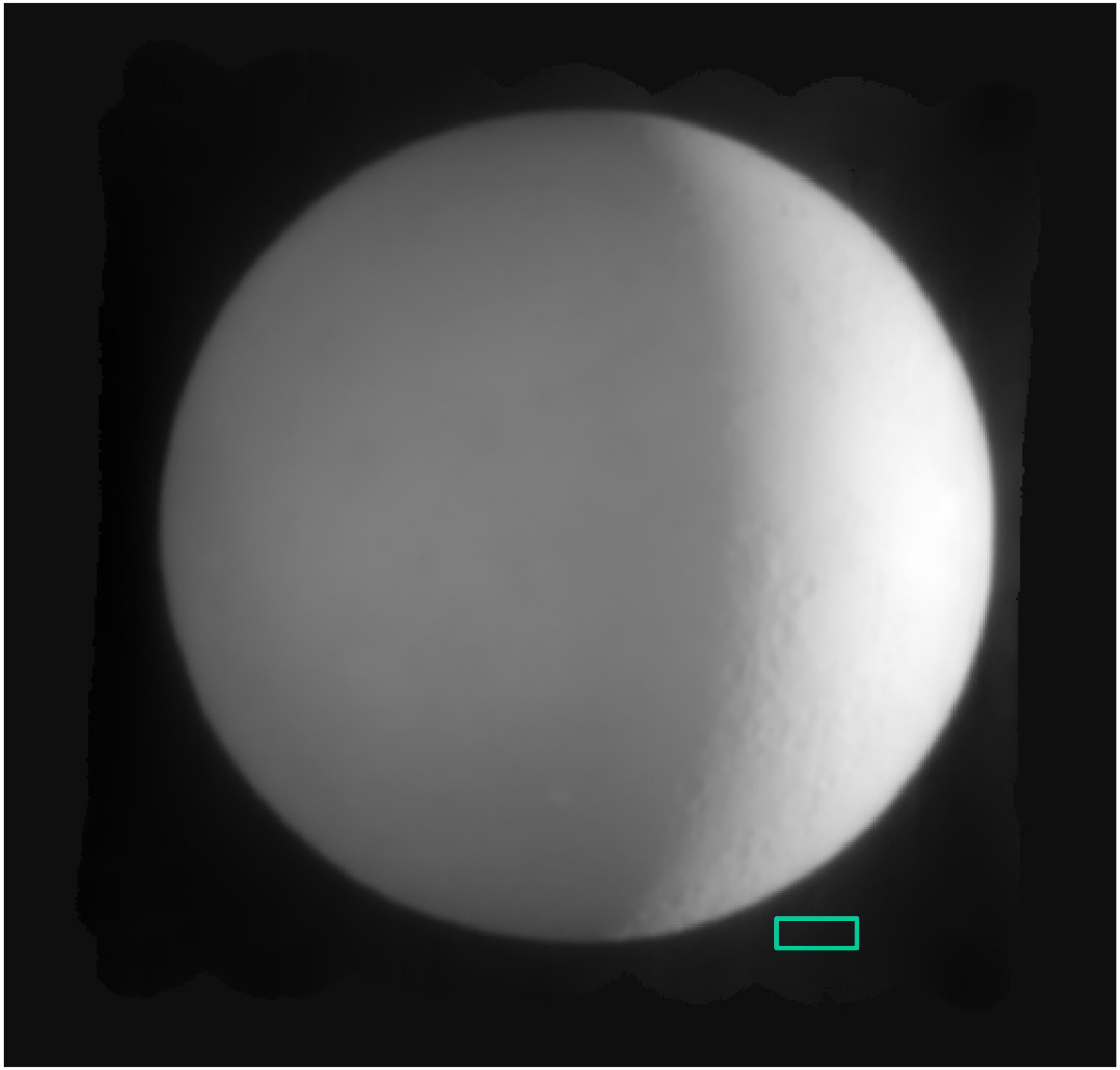
R. Shafer

D. Benford

J. Staguhn

H. Moseley

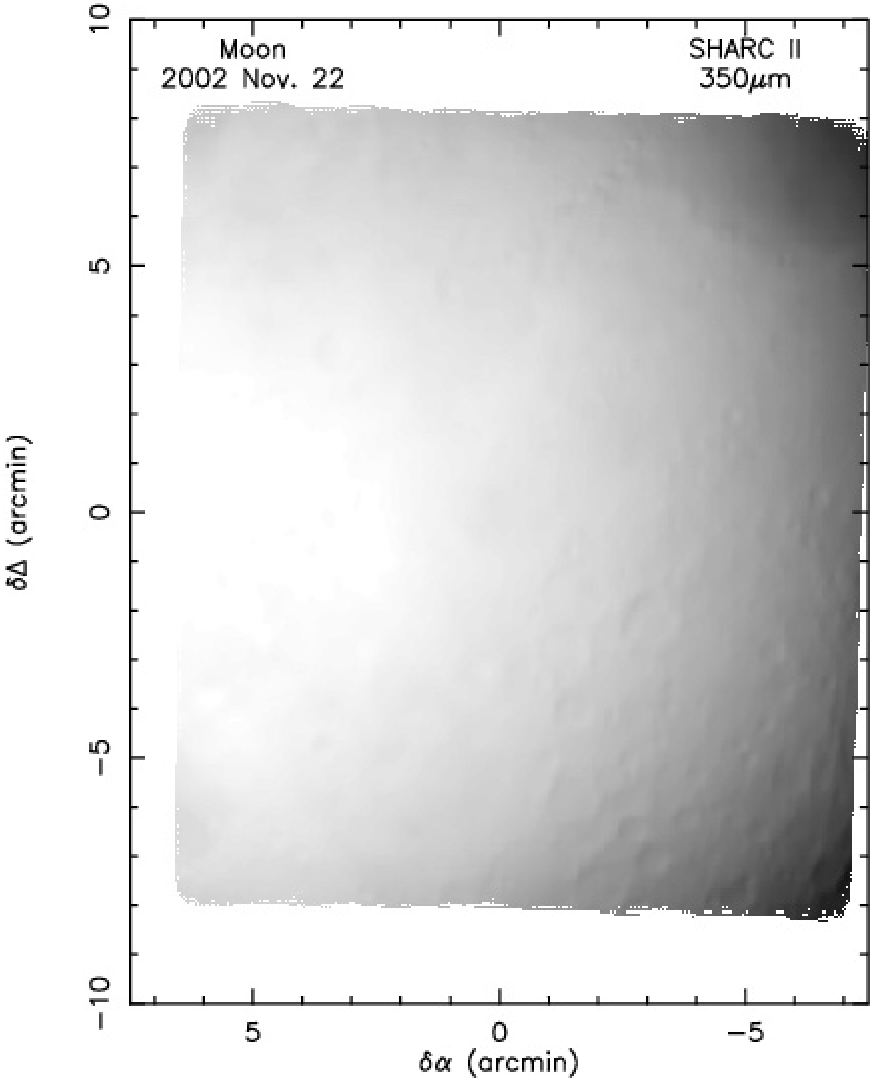
Moon at 850um



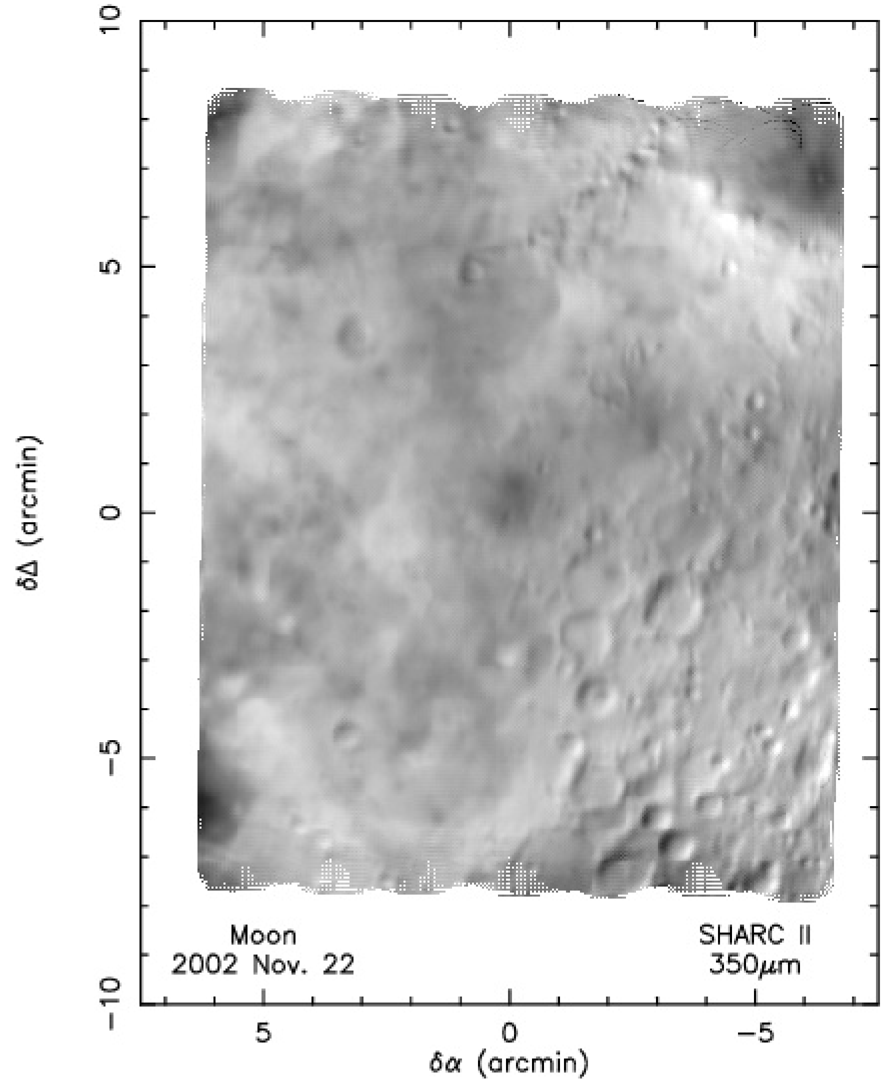
C.D. Dowell
A. Boogert

Moon at 350um

As seen (in total power)...



After high-pass filtering...

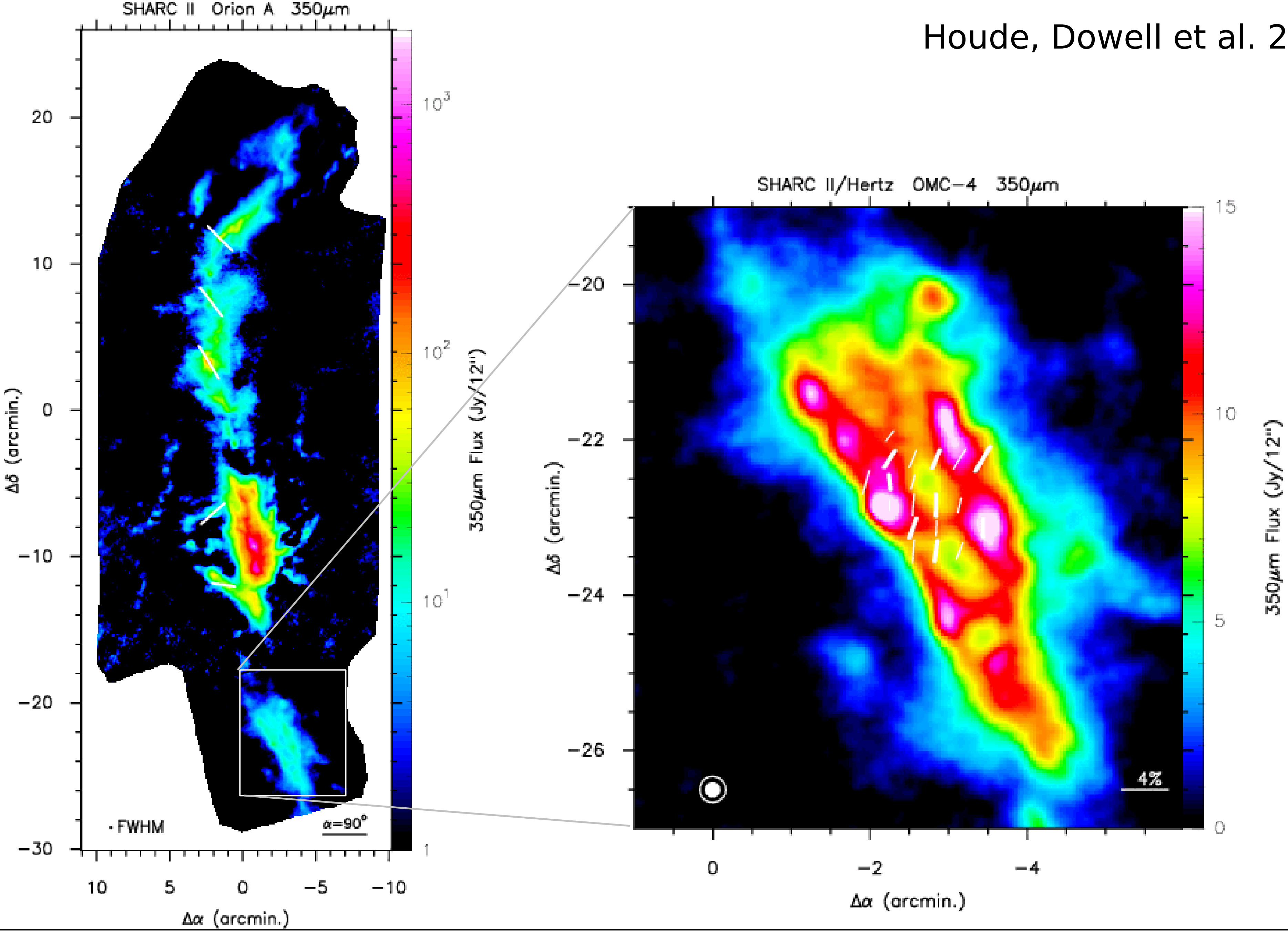


C.D. Dowell

SHARC2 Gallery

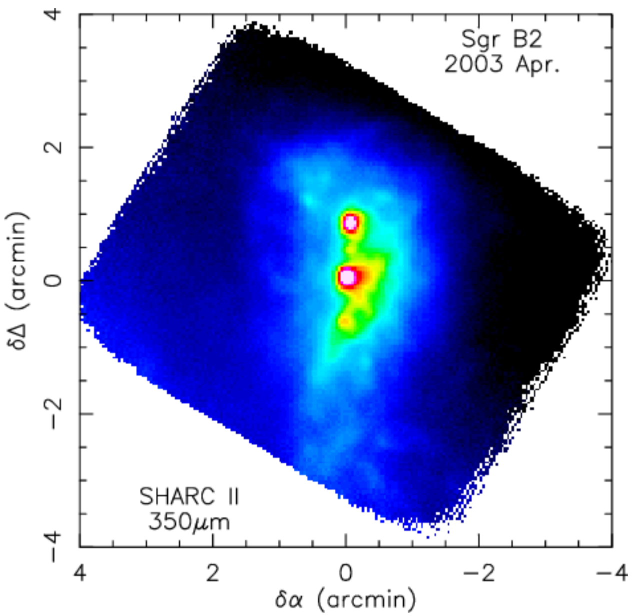
Orion A

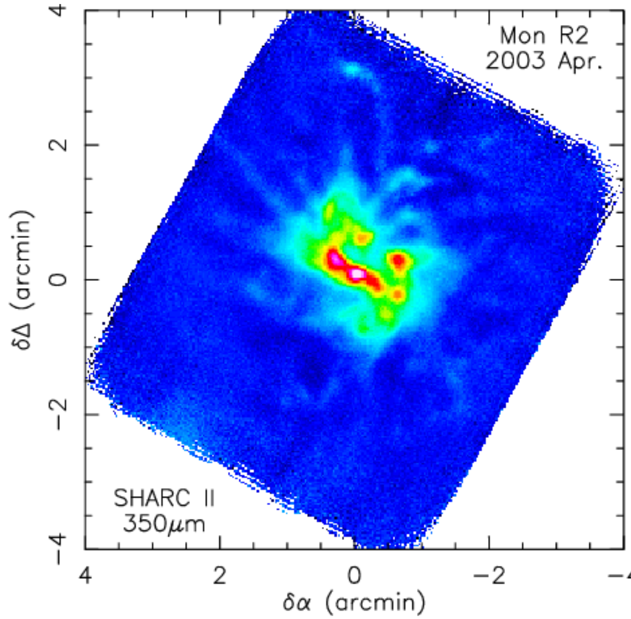
Houde, Dowell et al. 2003

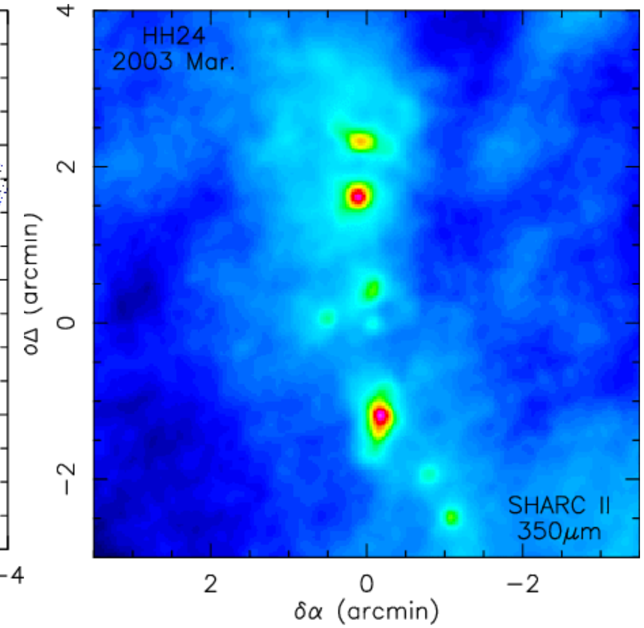


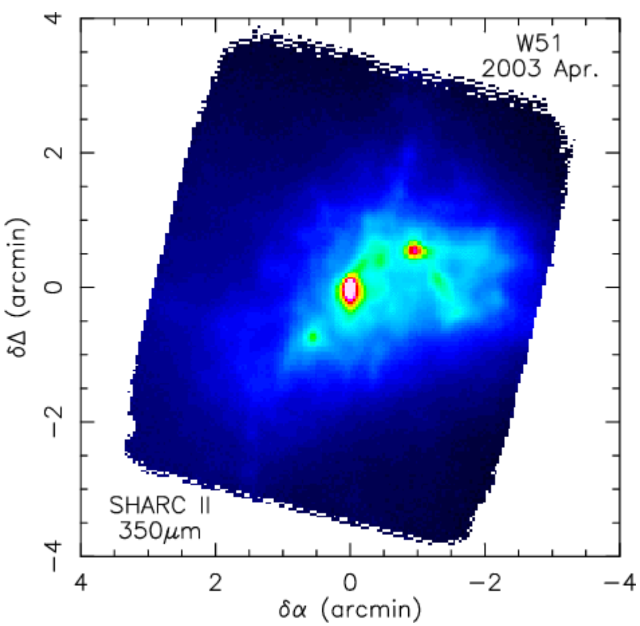
SHARC2 Gallery

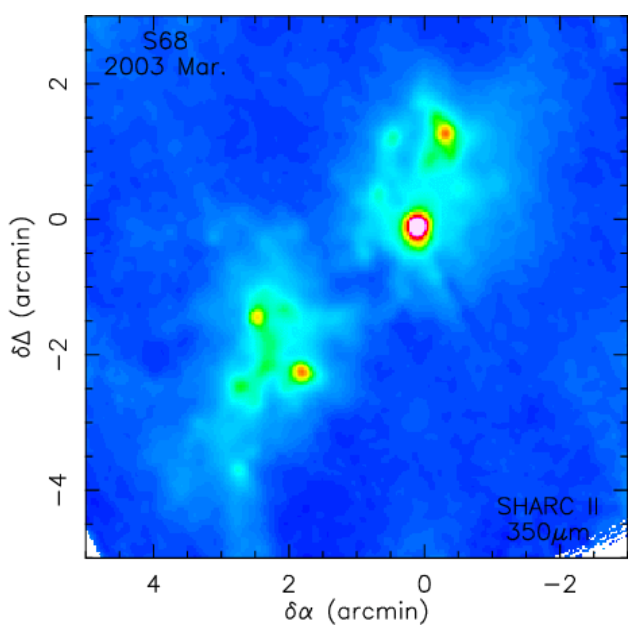
Galactic Star Forming Regions

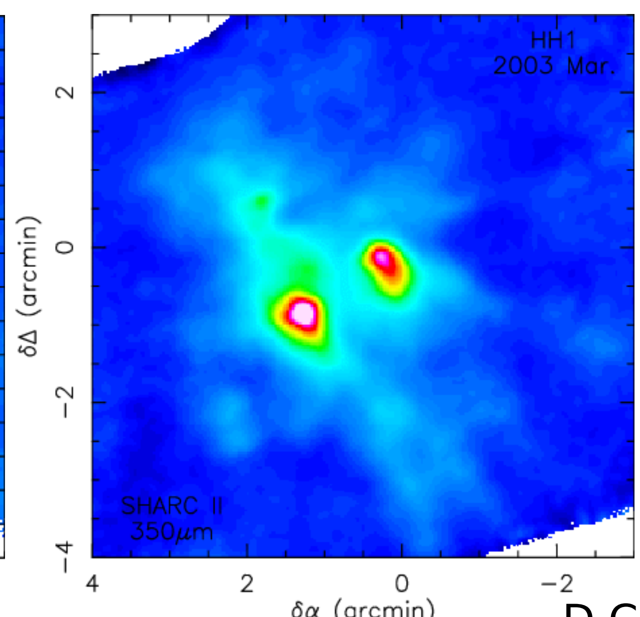






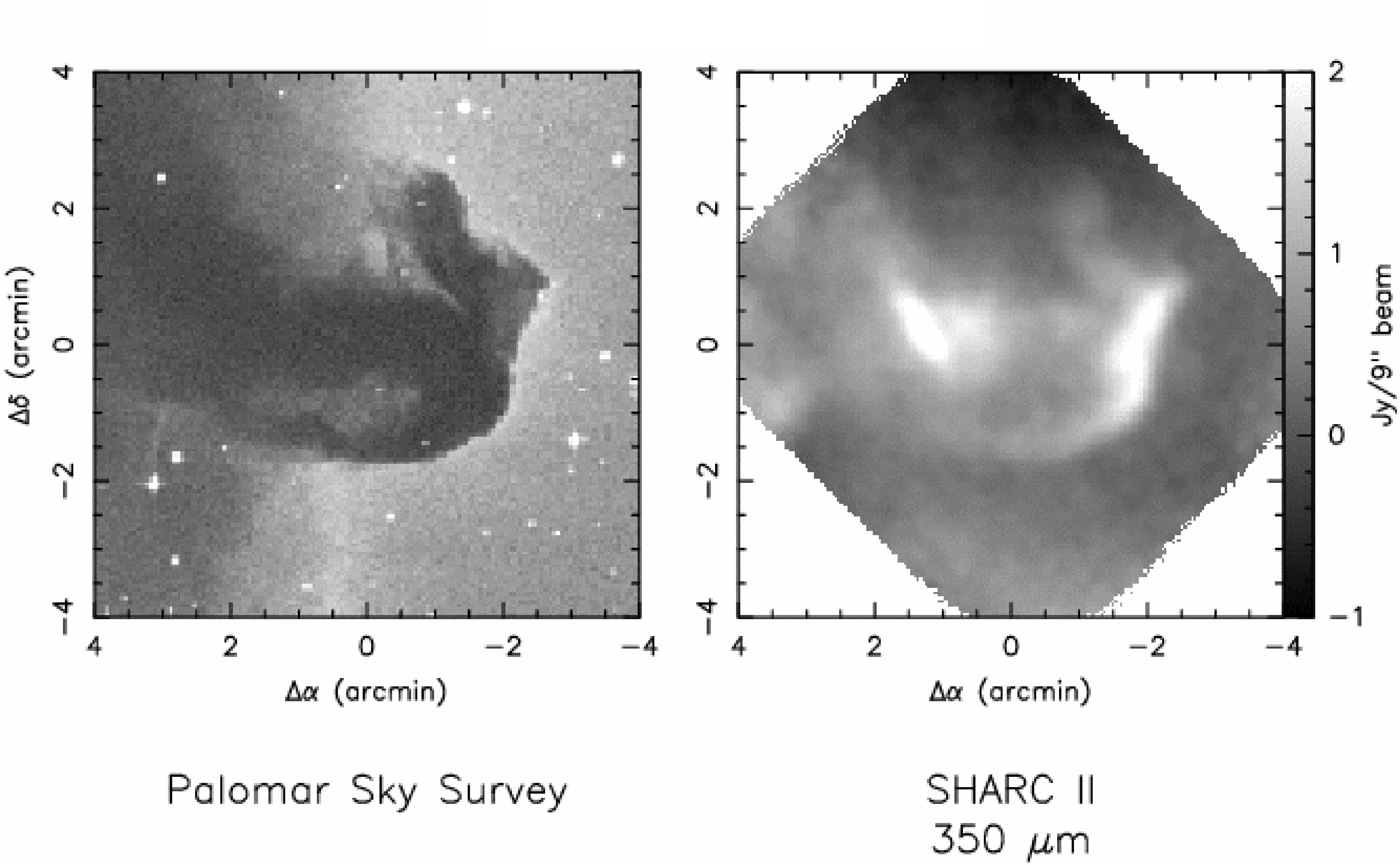




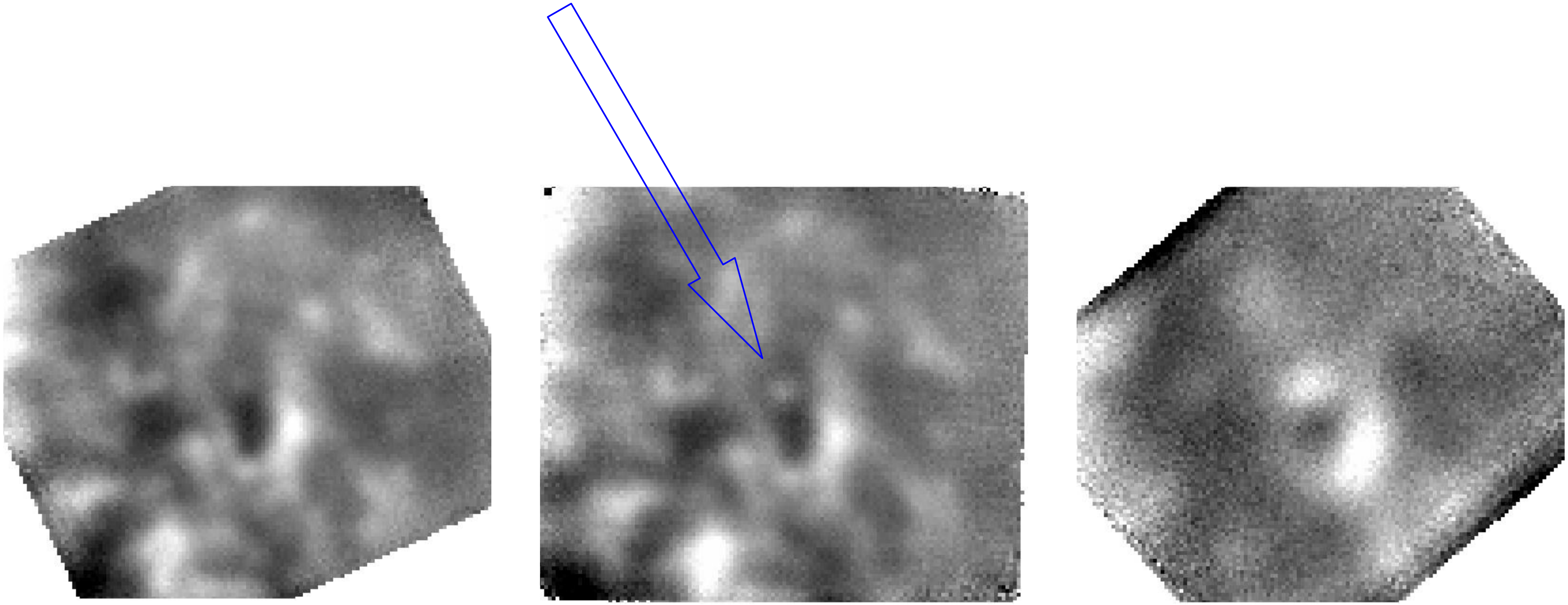


D.C. Lis

Horse Head Nebula



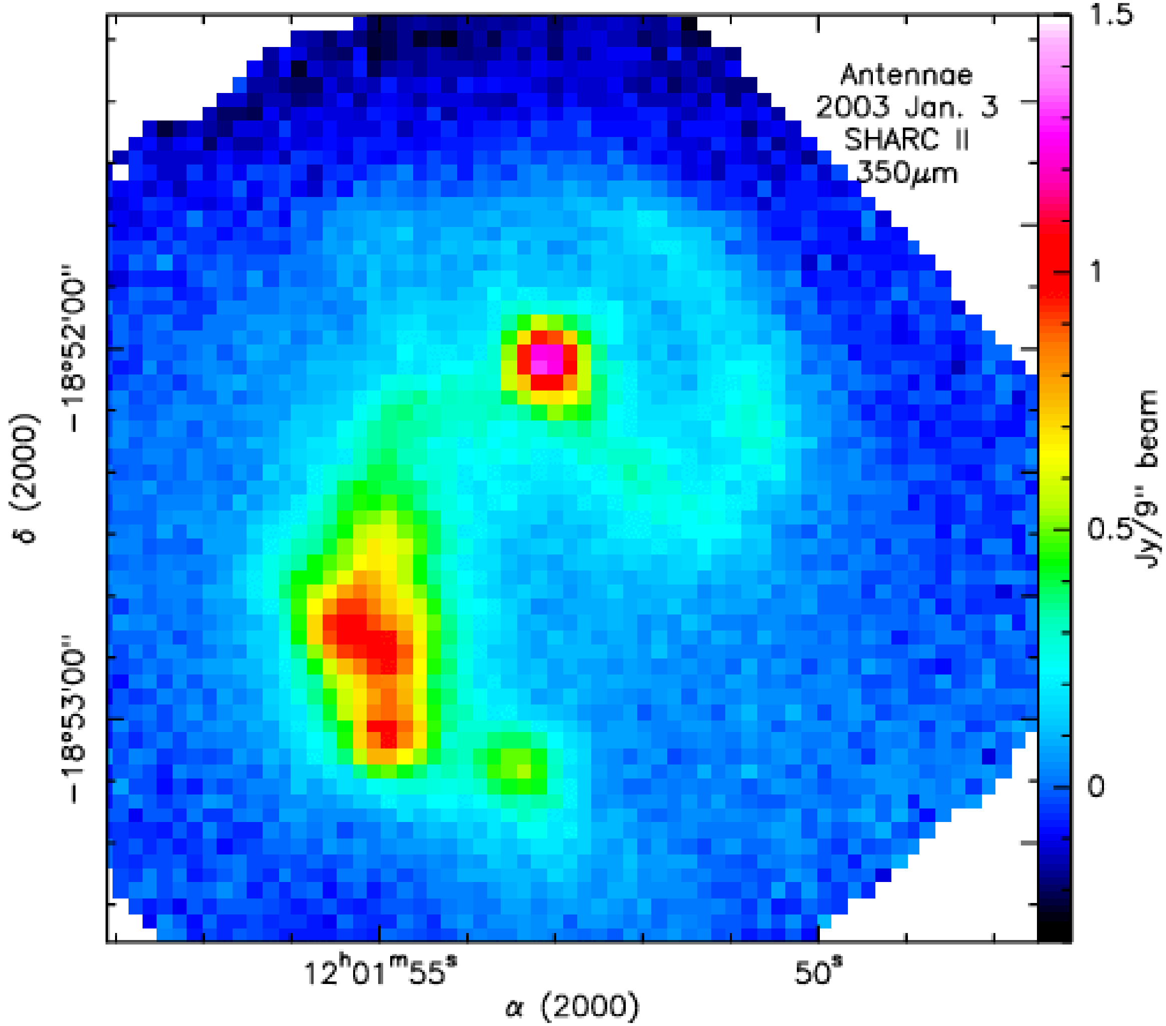
C.D. Dowell



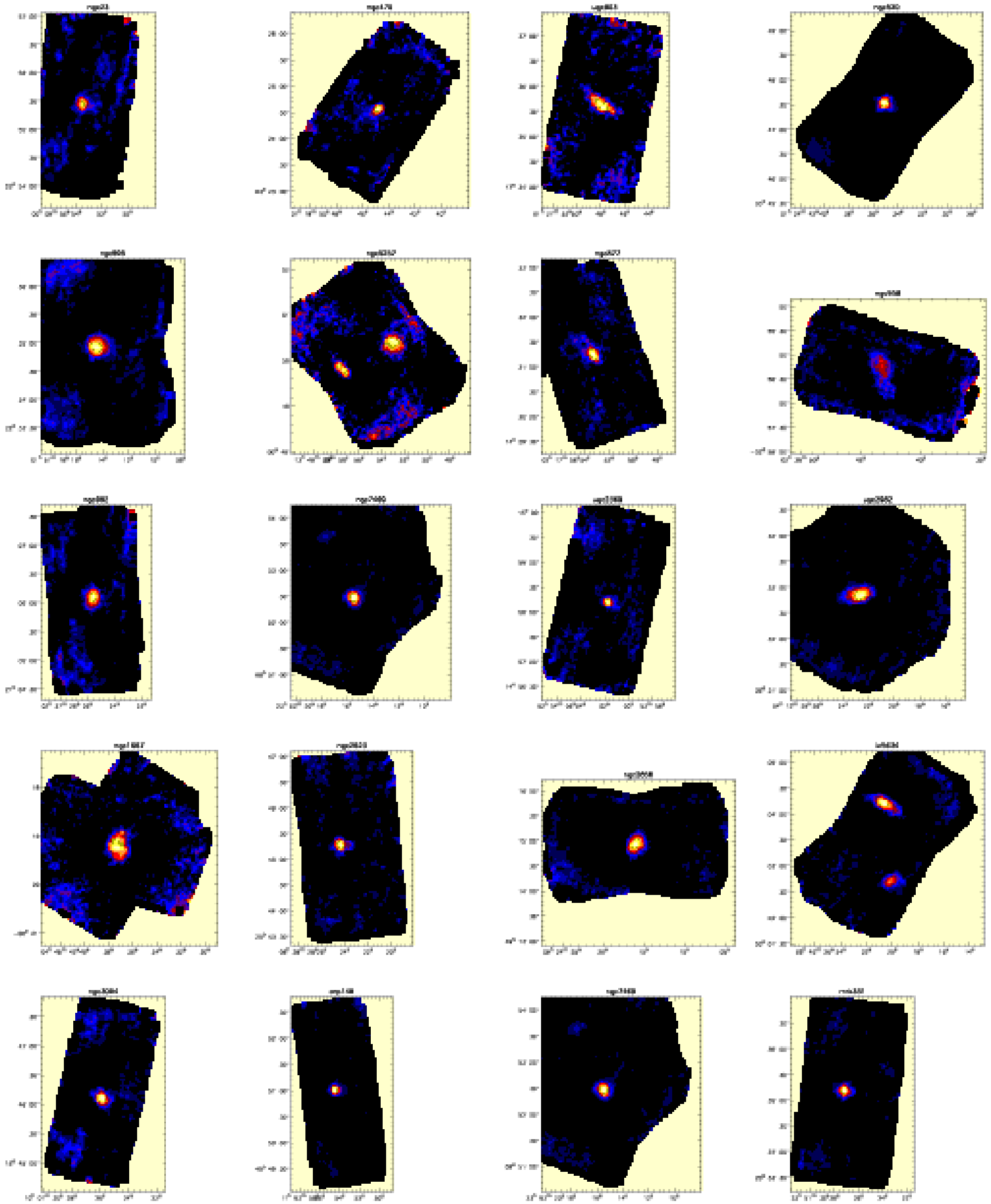
350μm 450 μm 850 μm

SHARC II / April 2004

C.D. Dowell


Antennae
2003 Jan. 3
SHARC II
350μm
1.5
1
0.5
0
Jy/9" beam
−18°52'00"
−18°53'00"
δ (2000)
12h01m55s
50s
α (2000)

C.D. Dowell



C. Borys

Lockman Hole