SHARC-2 350μm Observations of Distant Submillimeter-Selected Galaxies and Techniques for the Optimal Analysis and Observing of Weak Signals

Thesis Presentation
by
Attila Kovács

19 May 2006
Pasadena, California

Part I

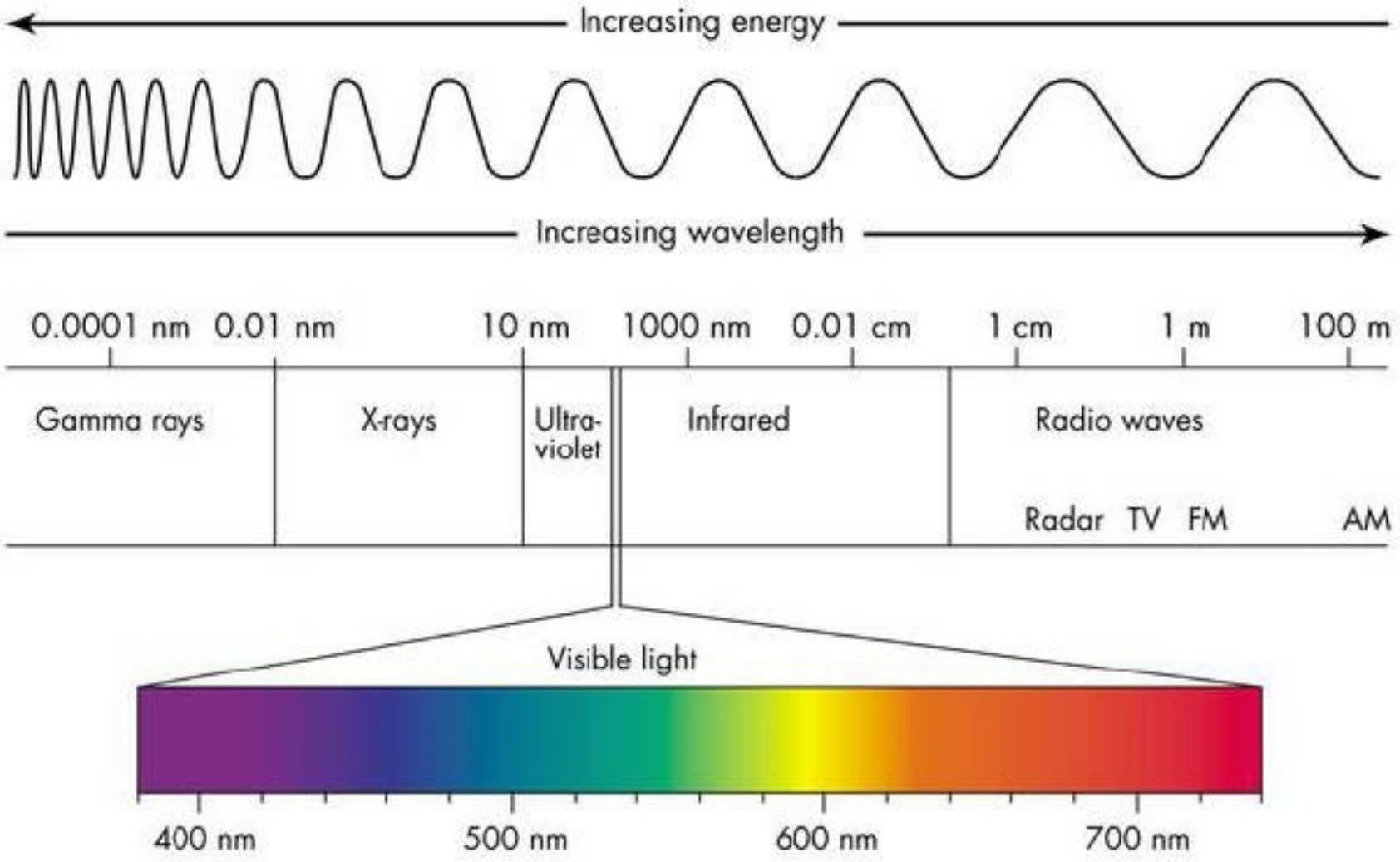
Distant Galaxies

Kovács, A., Chapman, S. C., Dowell, C. D., Blain, A. W., Ivison, R. J., Smail, I. 2006, ApJ, in press

Part II

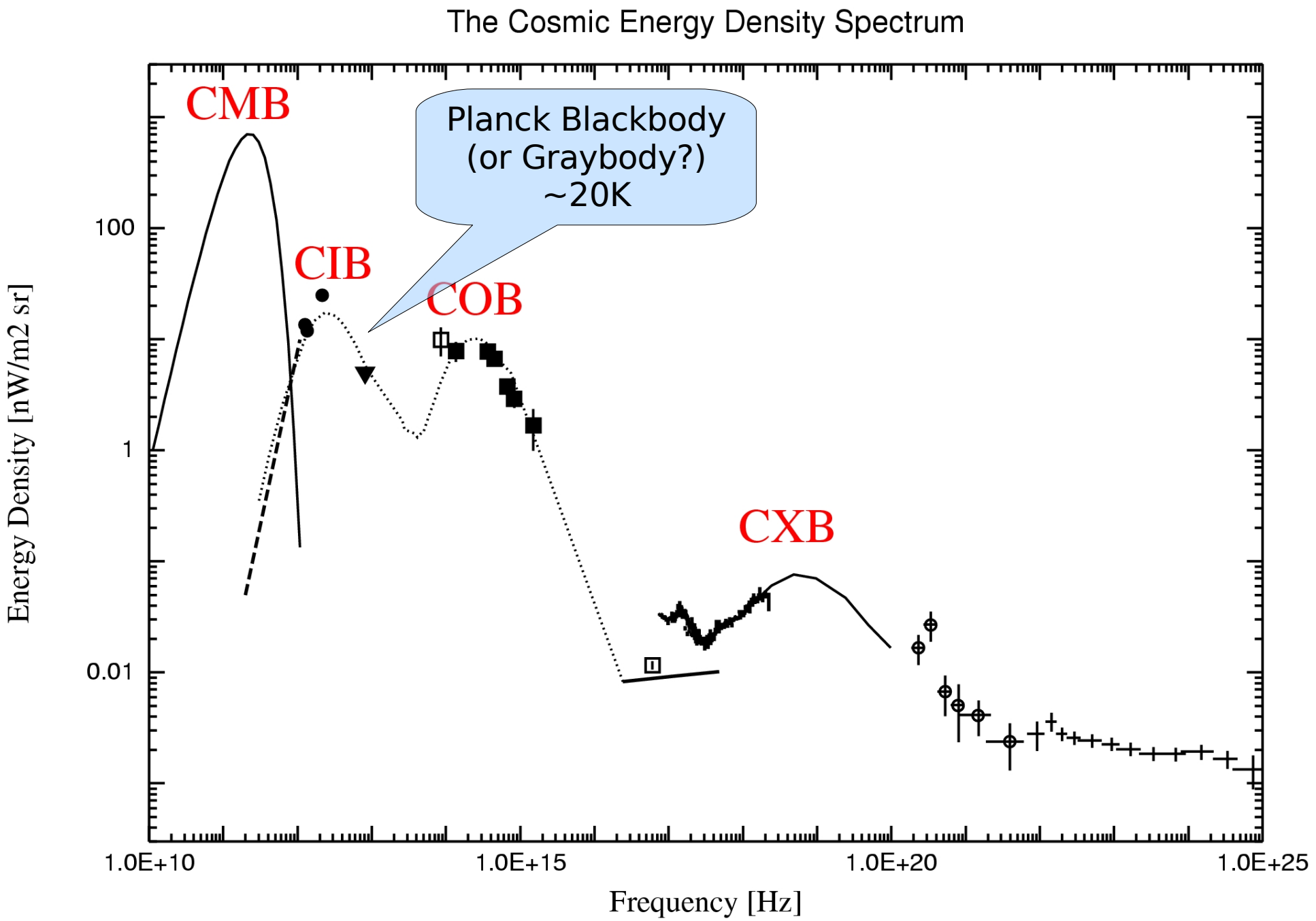
Data Reduction
(CRUSH)

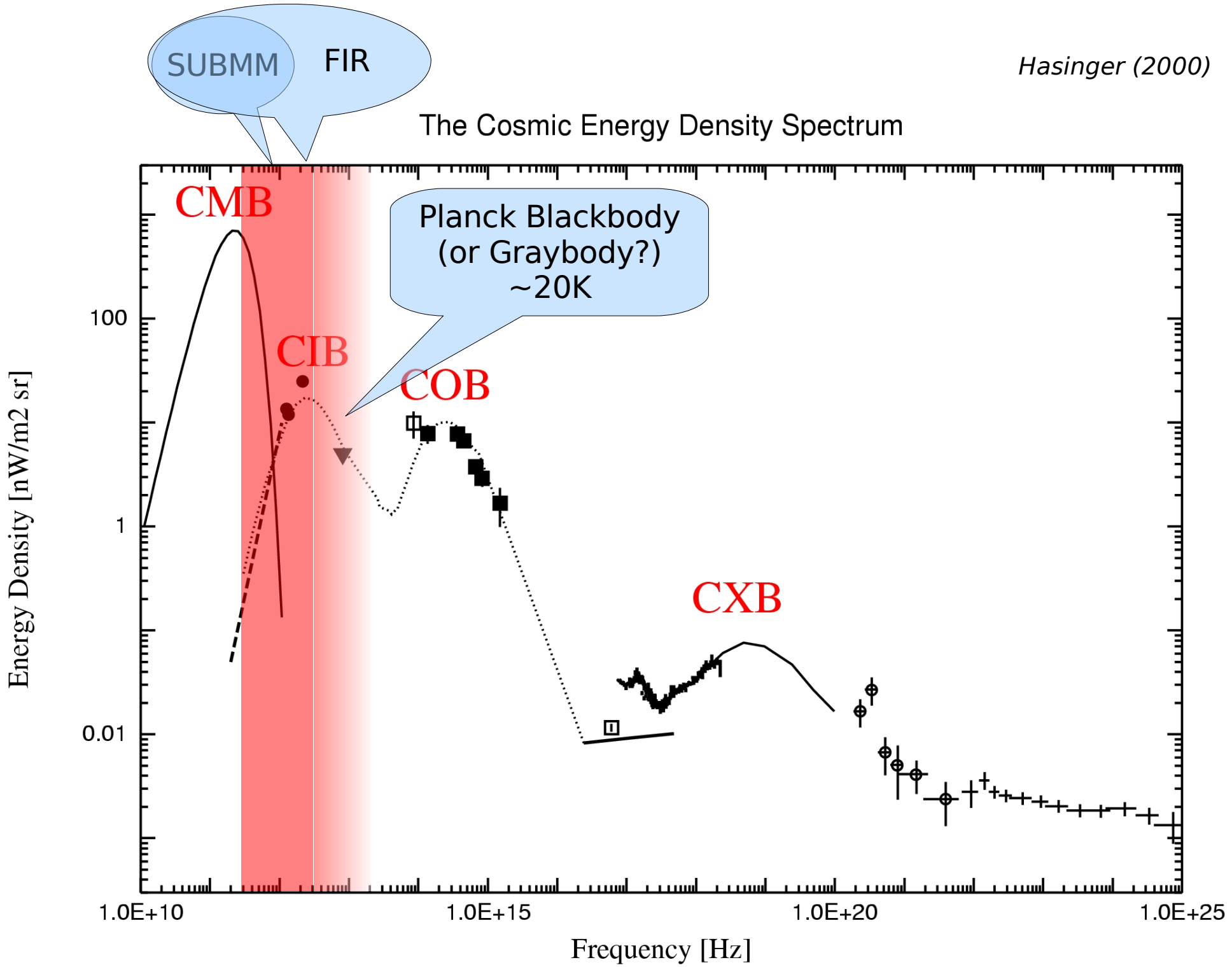
The Electromagnetic Spectrum

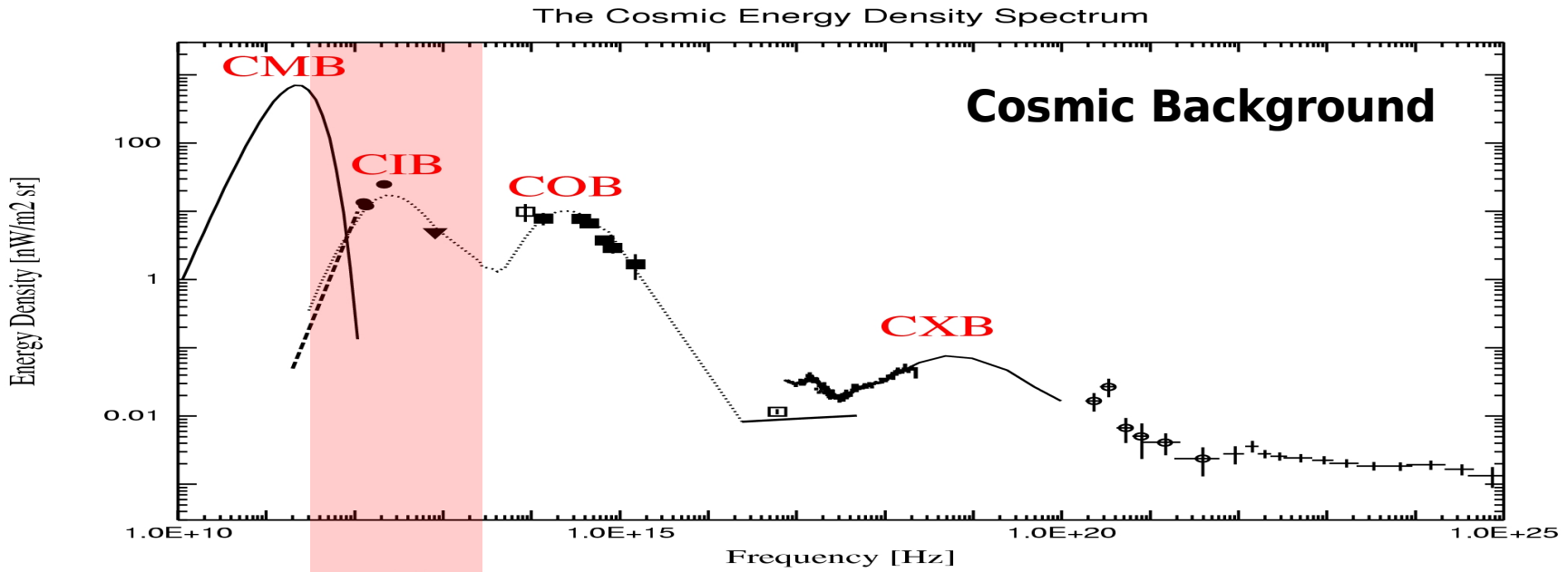


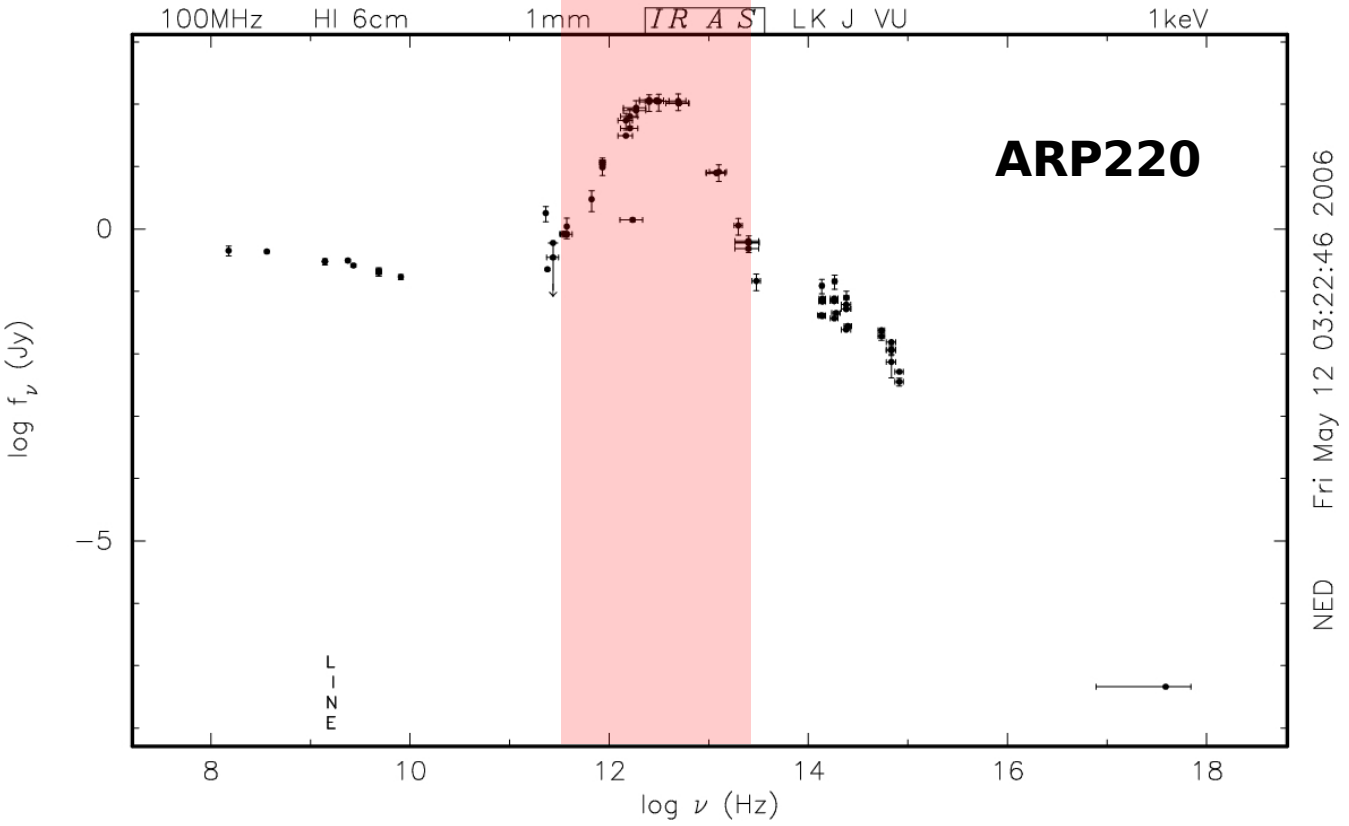
Cosmic Backgrounds

Hasinger (2000)




SUBMM
FIR
Hasinger (2000)
The Cosmic Energy Density Spectrum
CMB
Planck Blackbody
(or Graybody?)
~20K
CIB
COB
CXB
100
1
0.01
Energy Density [nW/m2 sr]
1.0E+10
1.0E+15
1.0E+20
1.0E+25
Frequency [Hz]

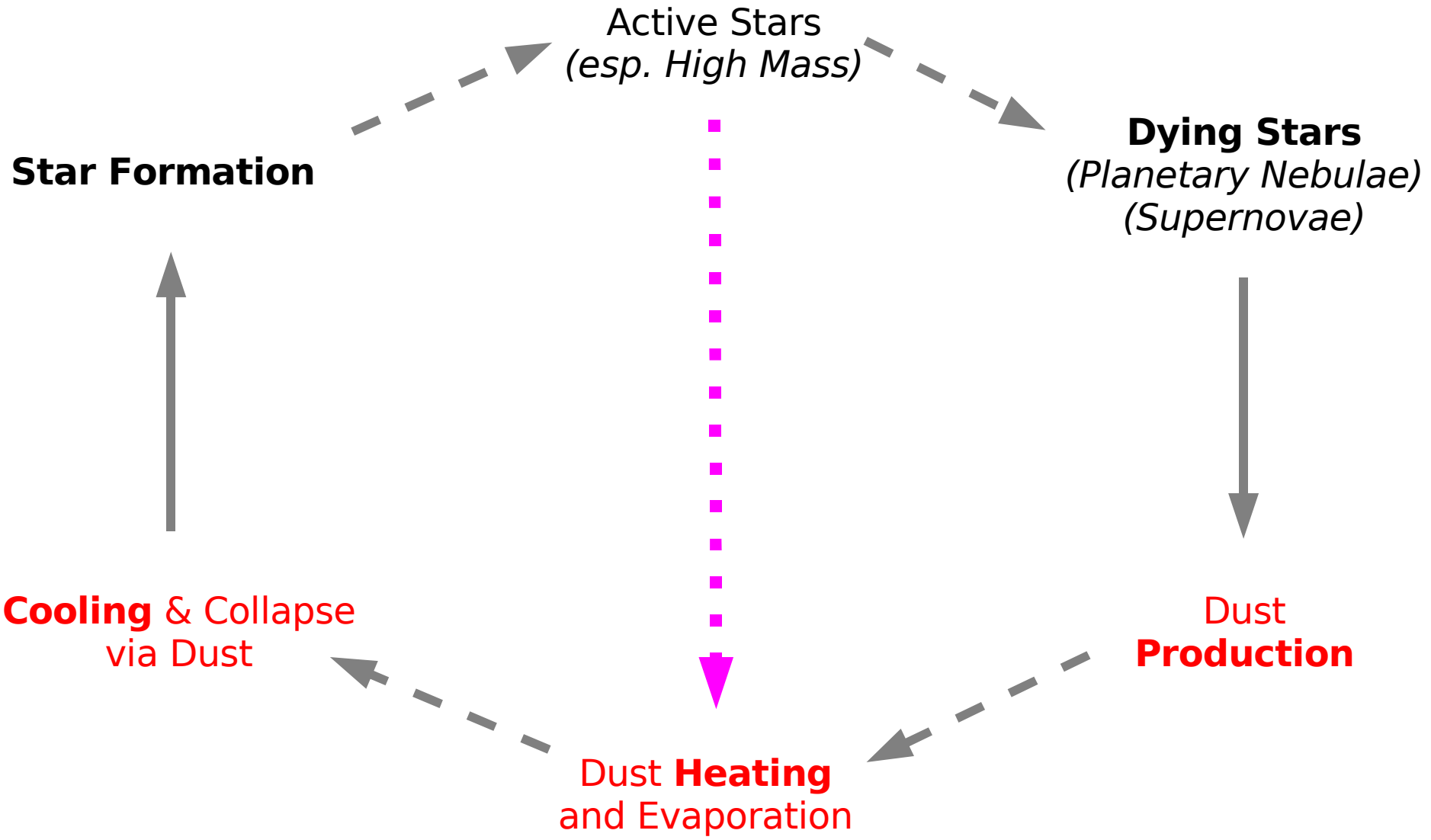




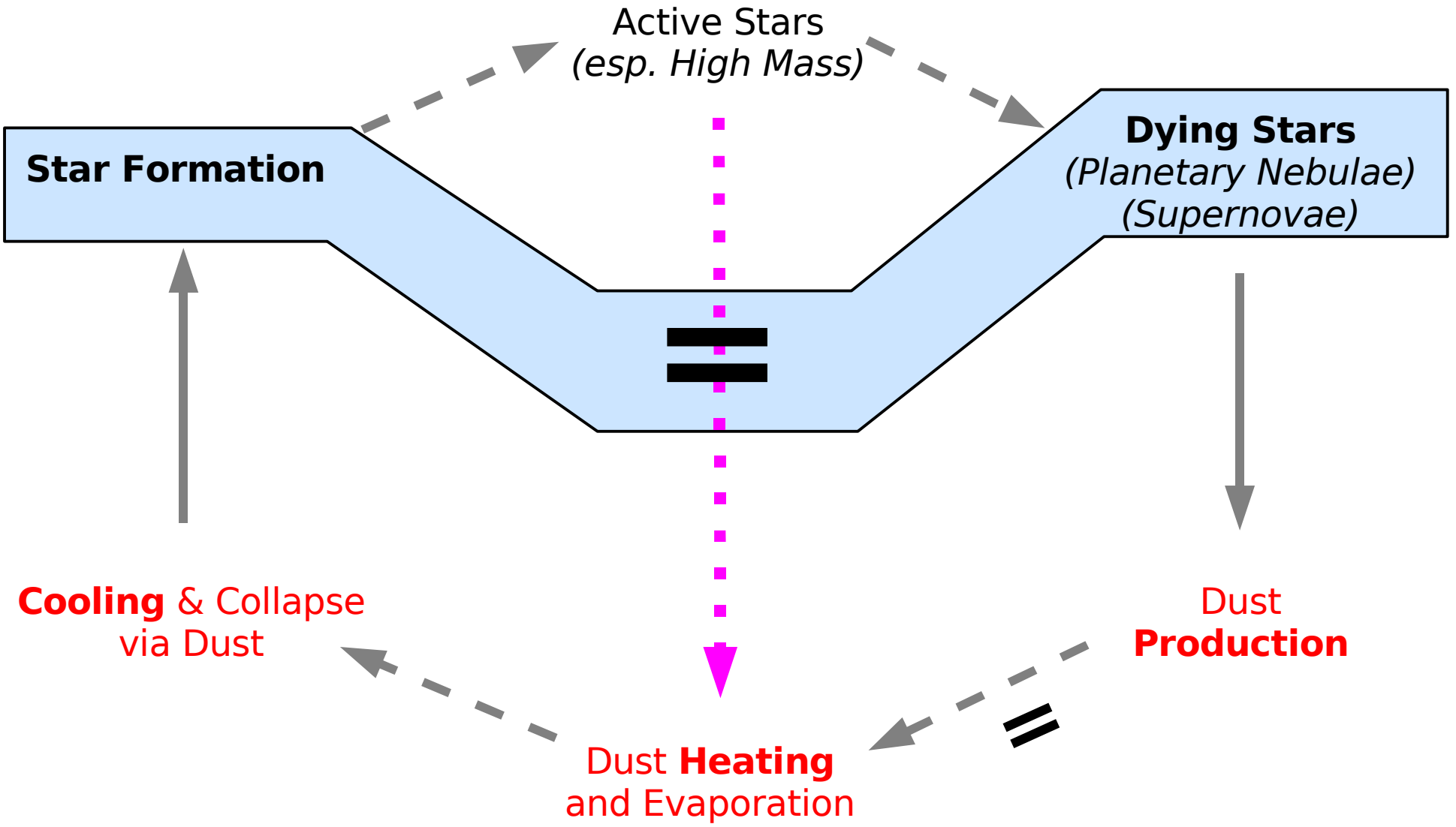
Black- or Graybody Energy Spectrum

- Plasma (Hot!)
- Solids
  - Small Particles (Dust)
    - **Dusty Galaxies**

Lifecycle of Dust and Stars



Lifecycle of Dust and Stars (Equilibrium)



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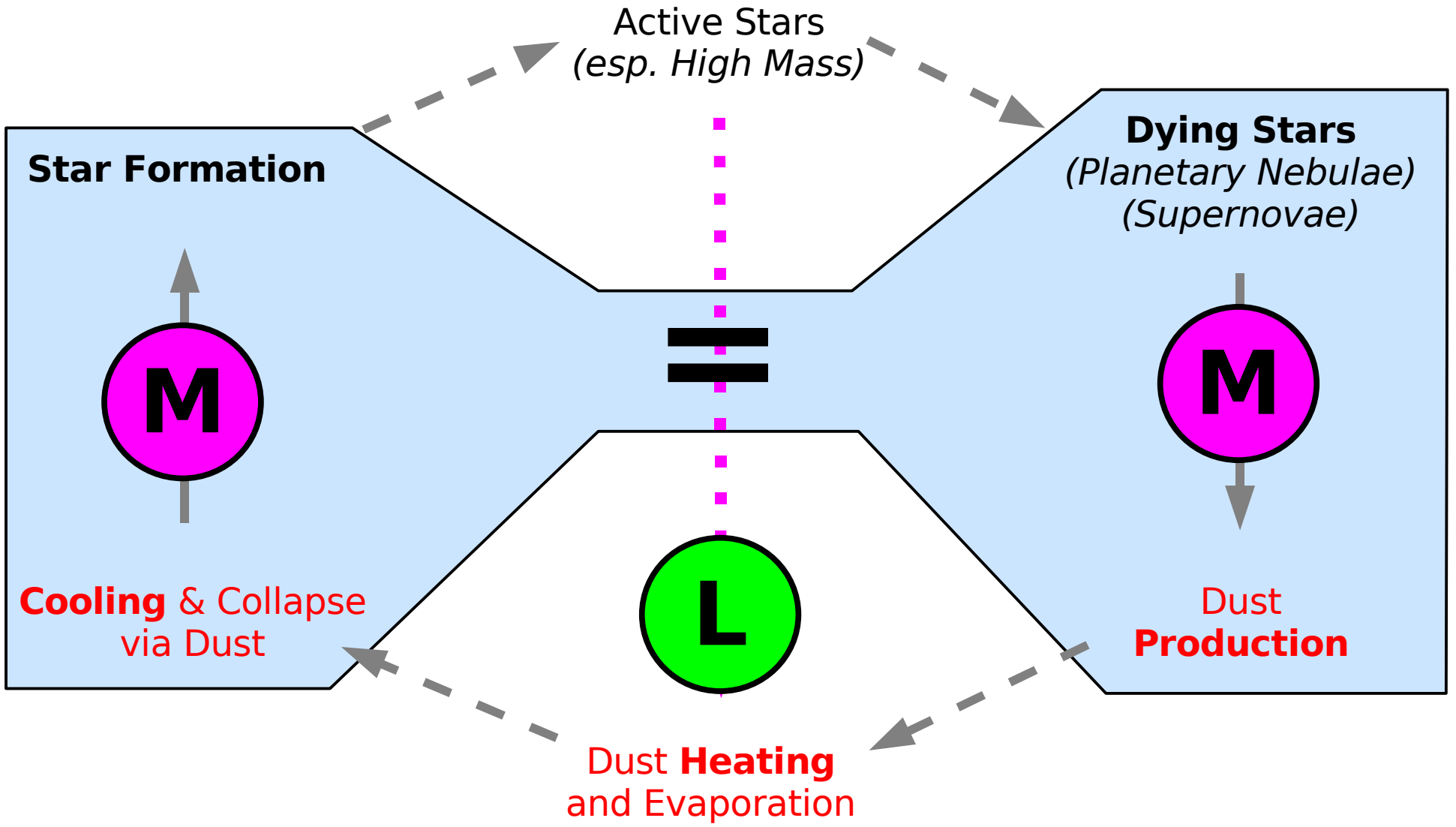
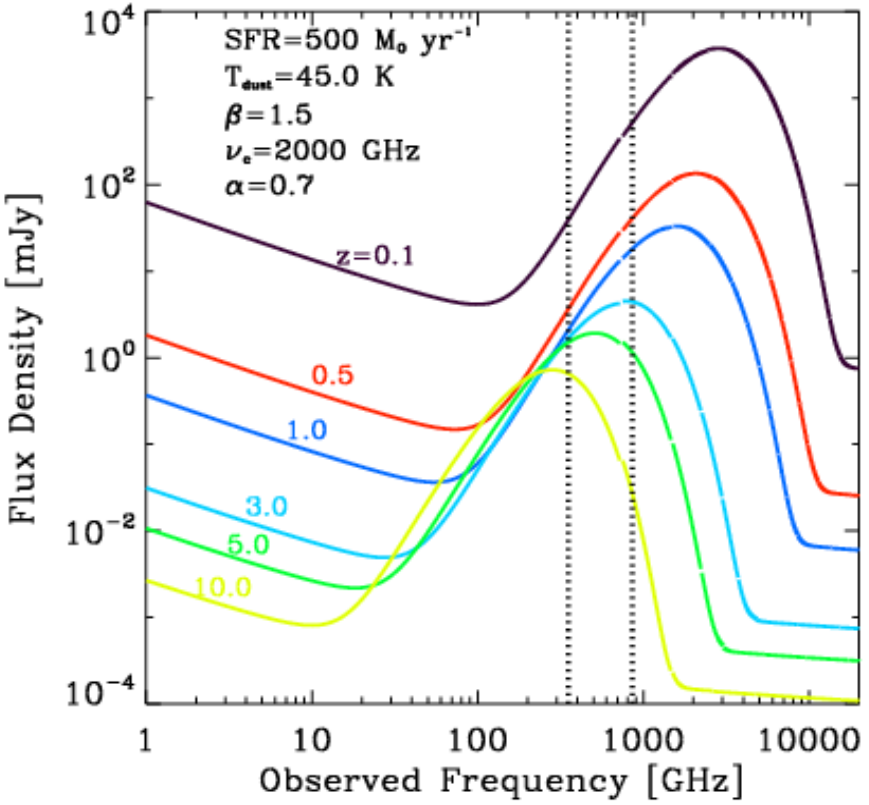
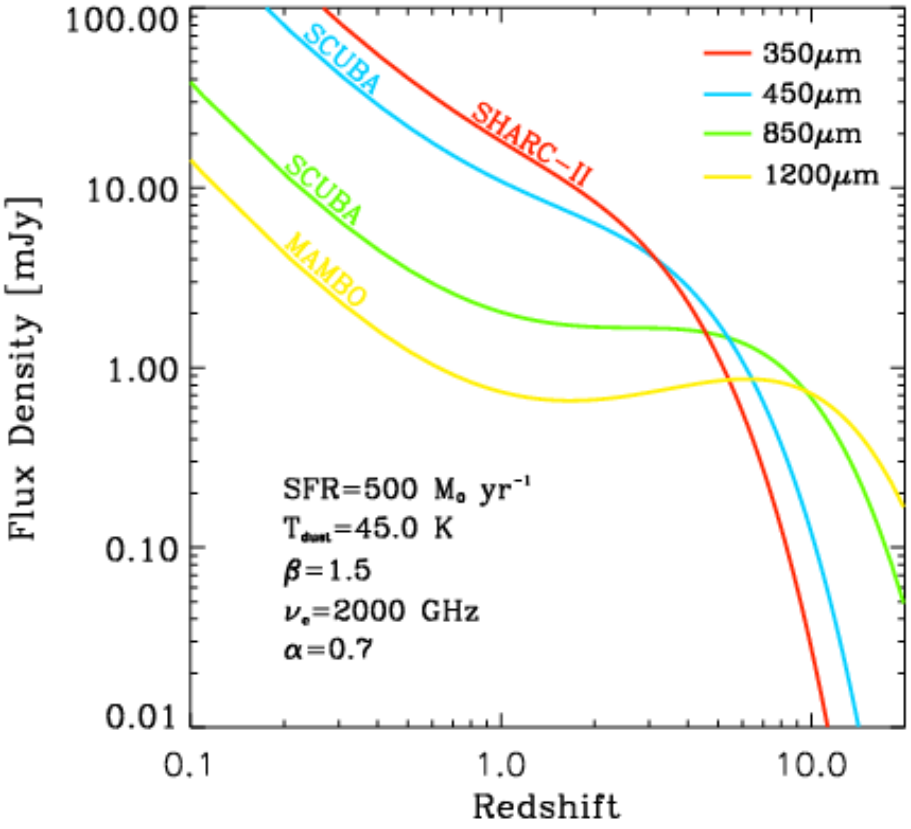


K-correction Benefits

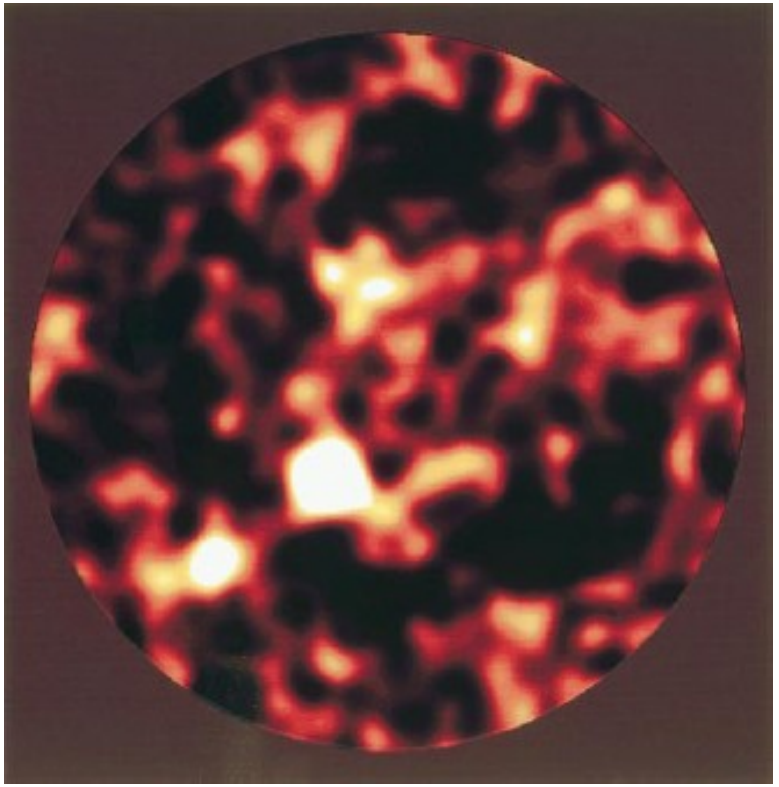




Submm survey can probe large volumes with limited selection bias. (SCUBA z ~ 1-8)

T. Greve

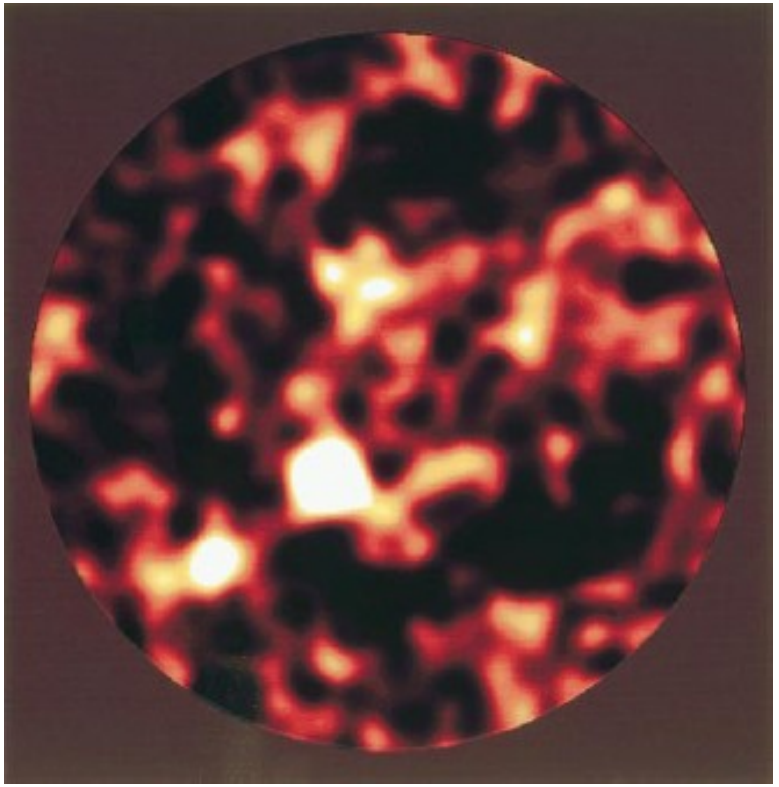
A Submillimeter Galaxy Population



Hughes et al. (1998)

?

A Submillimeter Galaxy Population



Hughes et al. (1998)

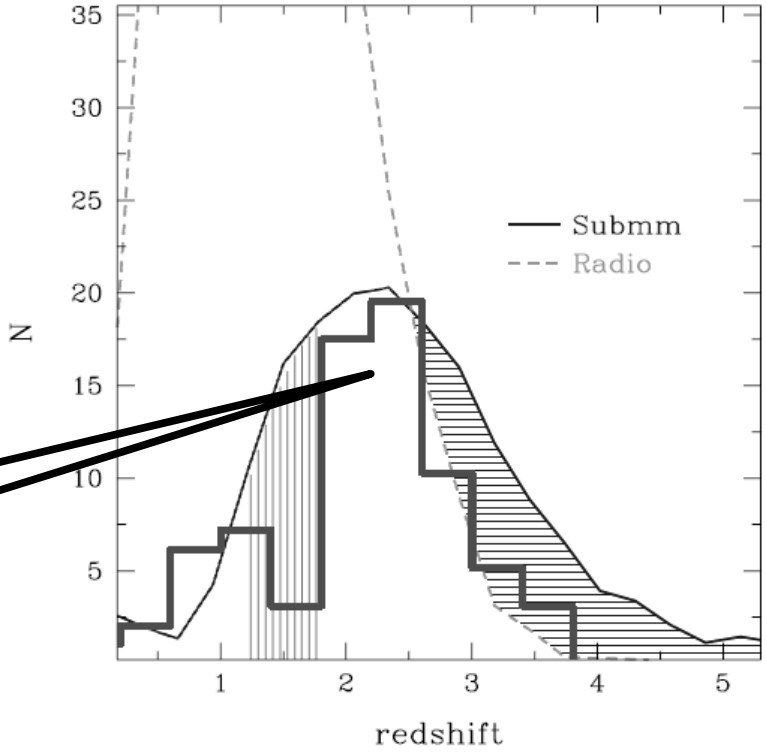
Radio and Optical (UV) Identifications

Borys et al. (2003), Chapman et al. (2003), Webb et al. (2003), Smail et al. (2000), Ivison et al. (2002)

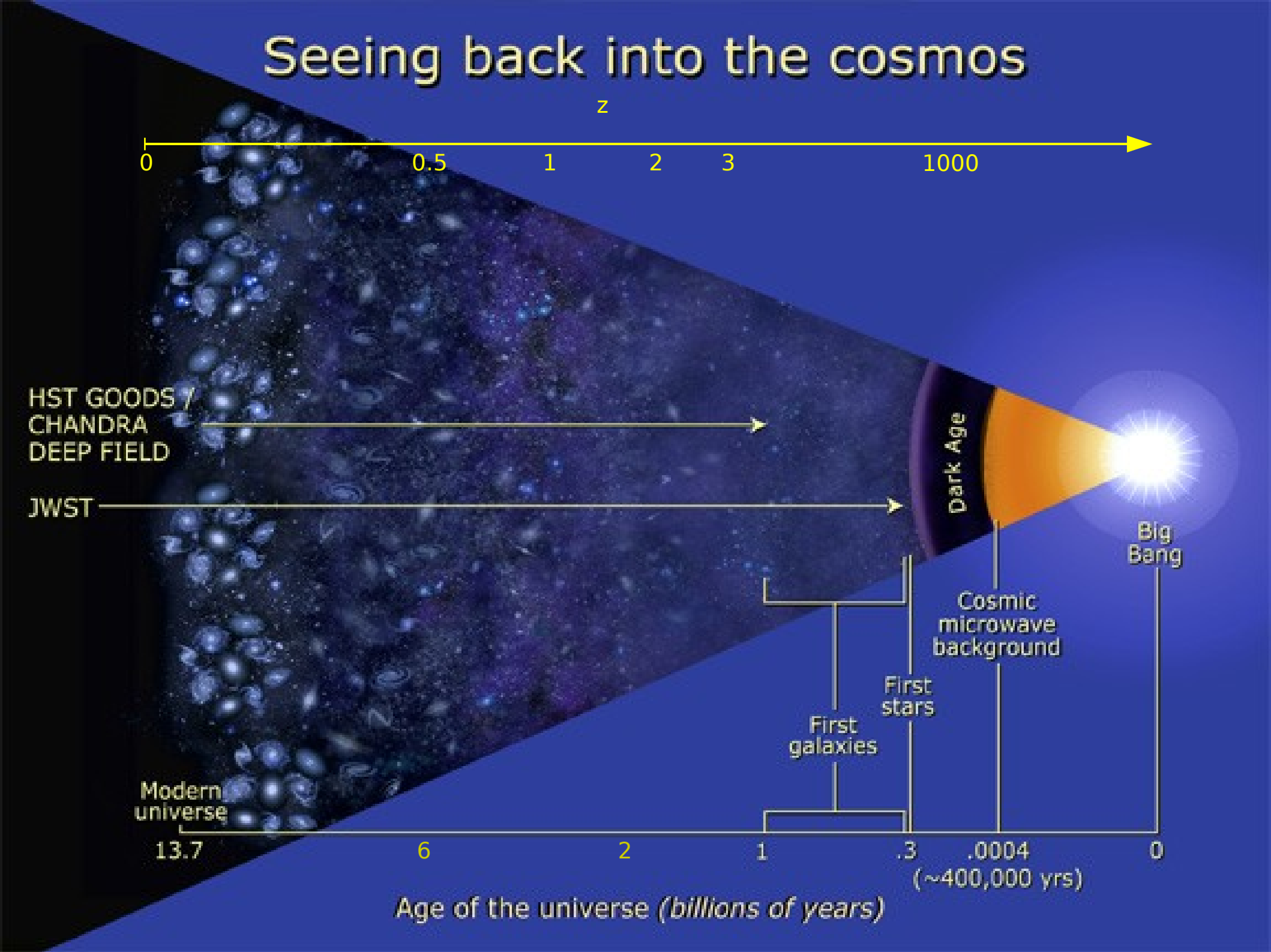
Optical Redshifts

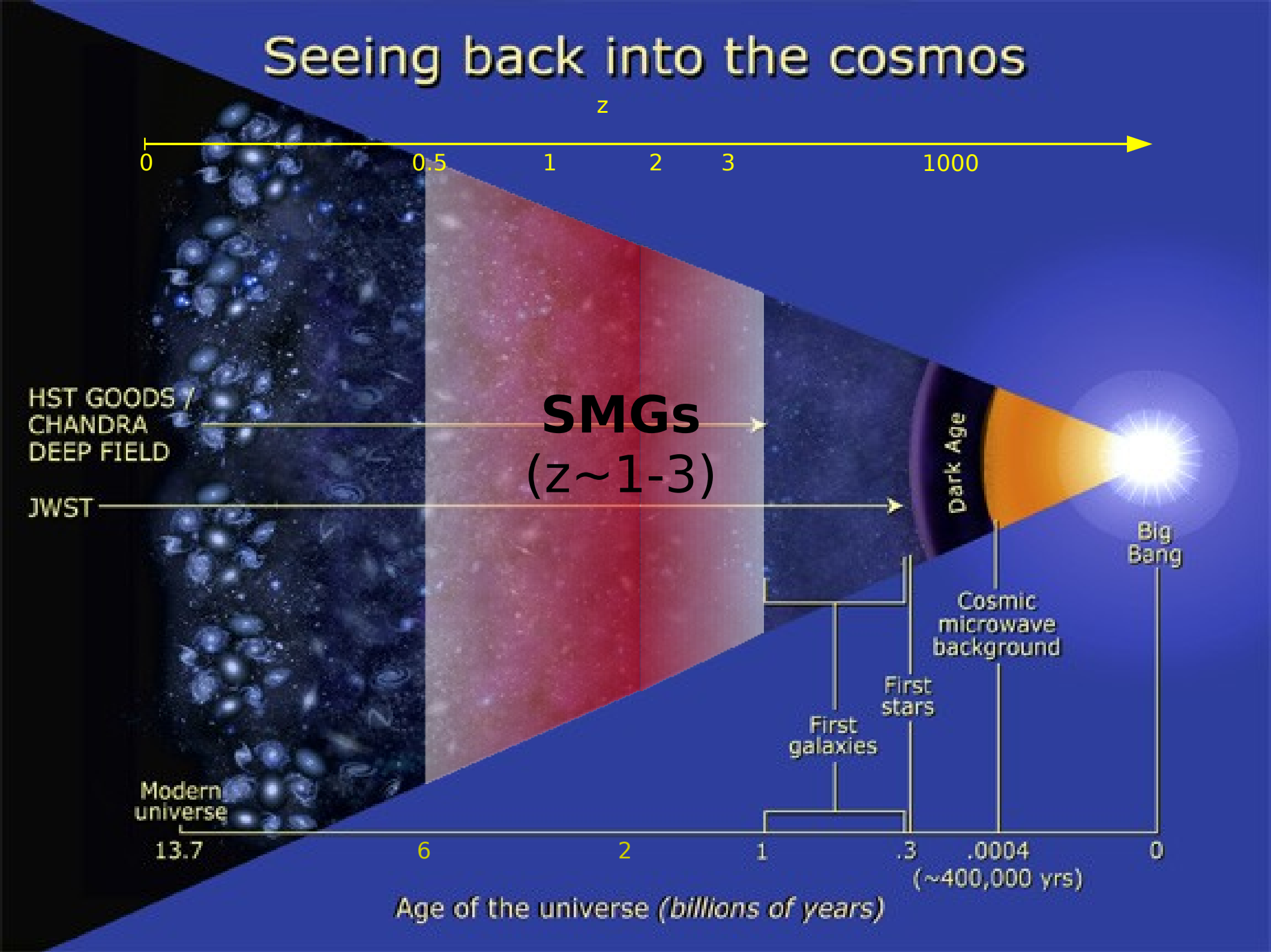
Chapman et al. (2003,2005)

Chapman et al. (2005)



Median Redshift ~ 2.4


Seeing back into the cosmos
z
0
0.5
1
2
3
1000
HST GOODS / CHANDRA DEEP FIELD
JWST
Dark Age
Big Bang
Cosmic microwave background
First stars
First galaxies
Modern universe
13.7
6
2
1
.3
.0004
(~400,000 yrs)
0
Age of the universe (billions of years)


Seeing back into the cosmos
z
0
0.5
1
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3
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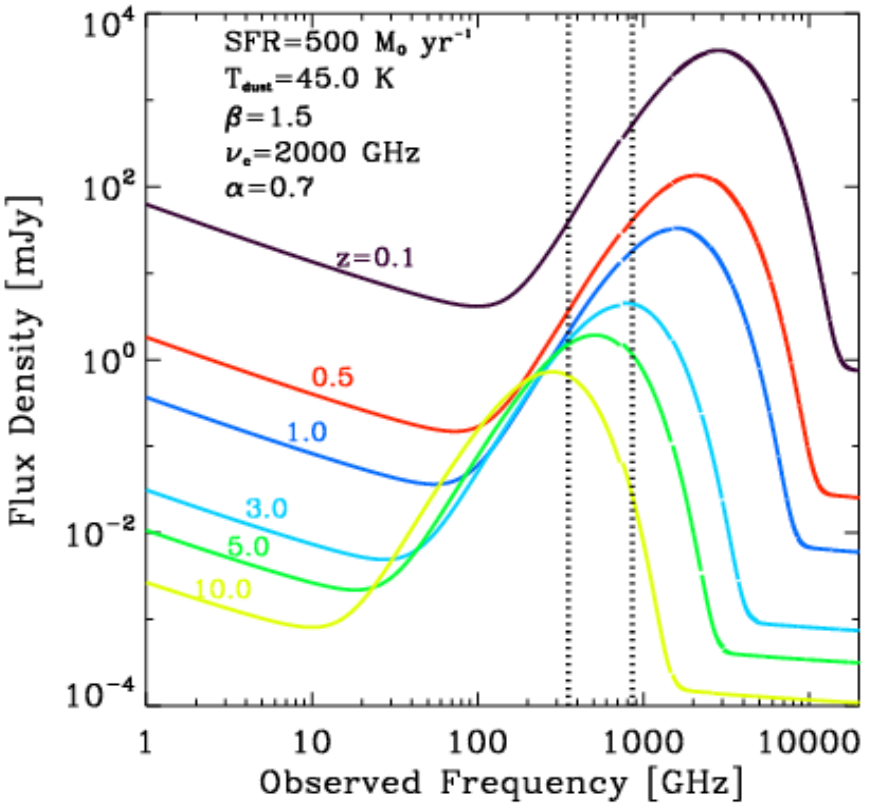
HST GOODS / CHANDRA DEEP FIELD
JWST
SMGs
(z~1-3)
Dark Age
Big Bang
Cosmic microwave background
First stars
First galaxies
Modern universe
13.7
6
2
1
.3
.0004
(~400,000 yrs)
0
Age of the universe (billions of years)

Need For More Data



The observed bands do not provide powerful constraints of the SEDs.

Chapman et al. (2003, 2005) got around this assuming the radio – FIR correlation (?)

Need data near peak or other side of SED.

Need sensitive shorter wavelength data to confirm suspected dust

Temperatures

&

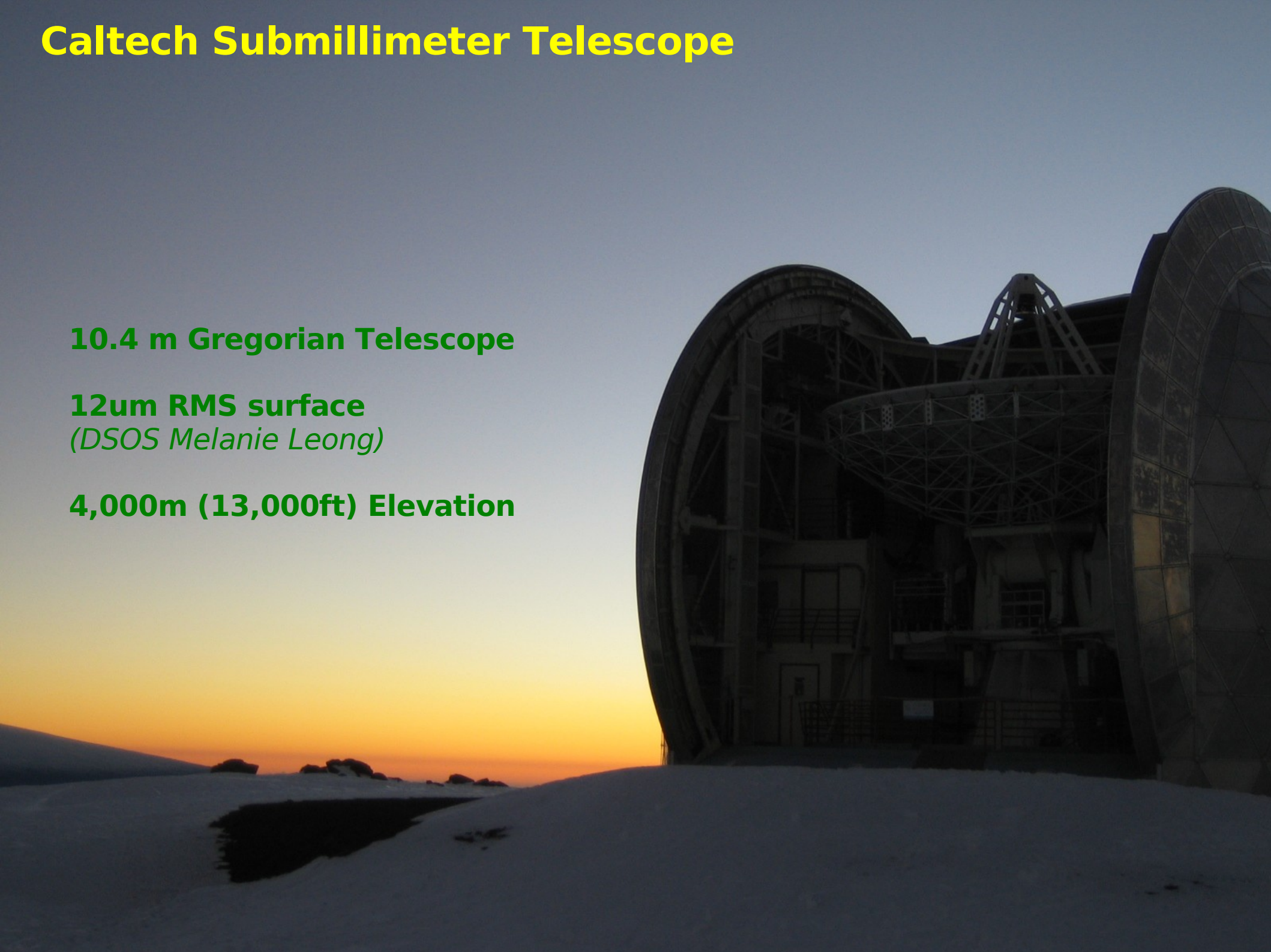
Luminosities

Part I

Distant Galaxies

Kovács, A., Chapman, S. C., Dowell, C. D., Blain, A. W., Ivison, R. J., Smail, I. 2006, ApJ, in press

Caltech Submillimeter Telescope

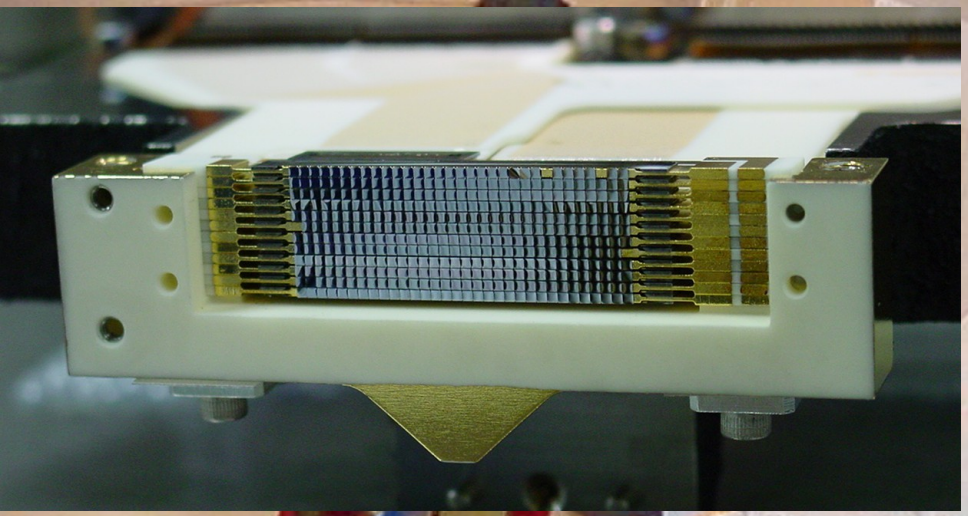


10.4 m Gregorian Telescope

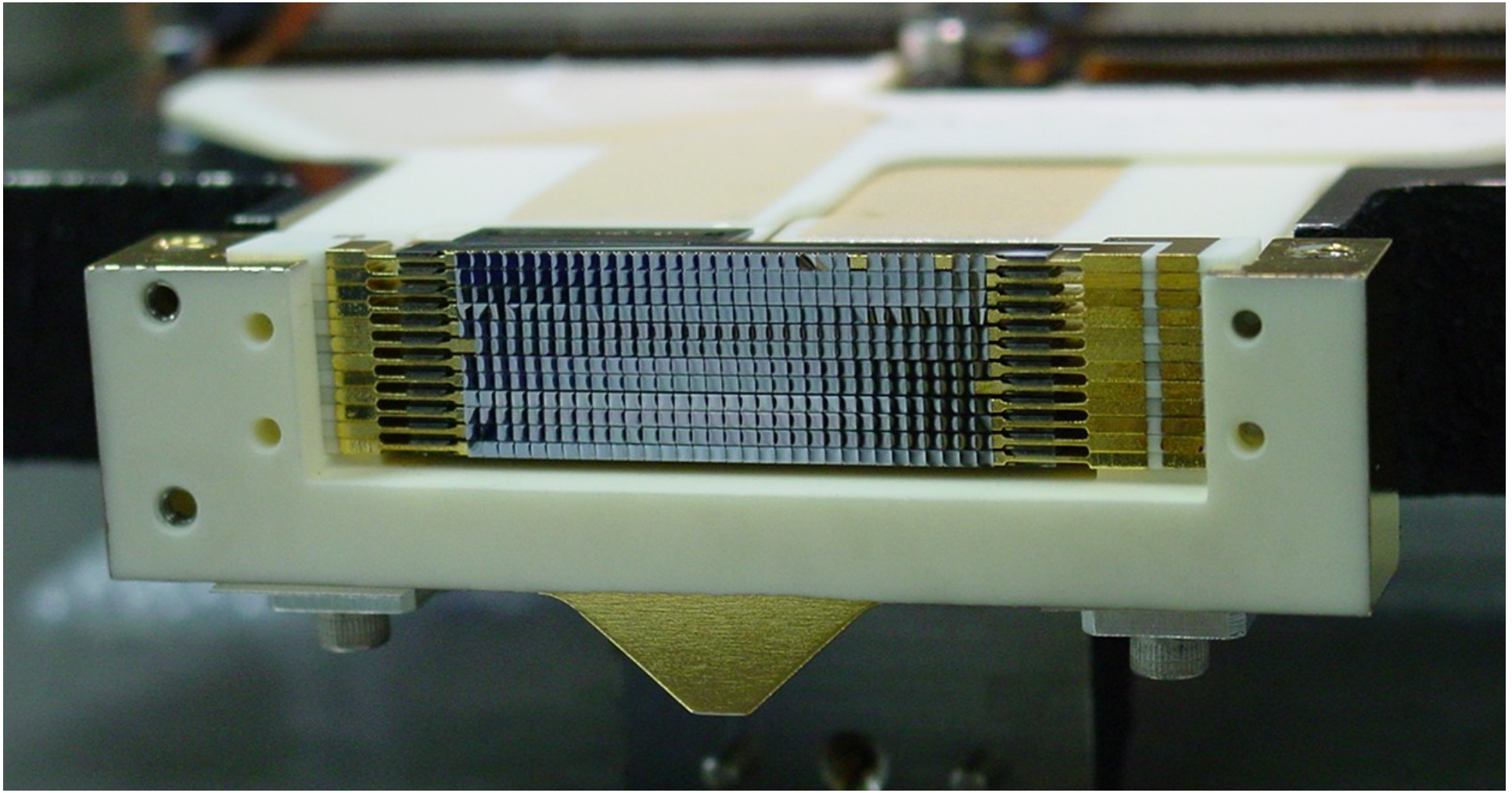
12um RMS surface
(DSOS Melanie Leong)

4,000m (13,000ft) Elevation

SHARC-2



SHARC-2 *(Dowell et al. 2003)*



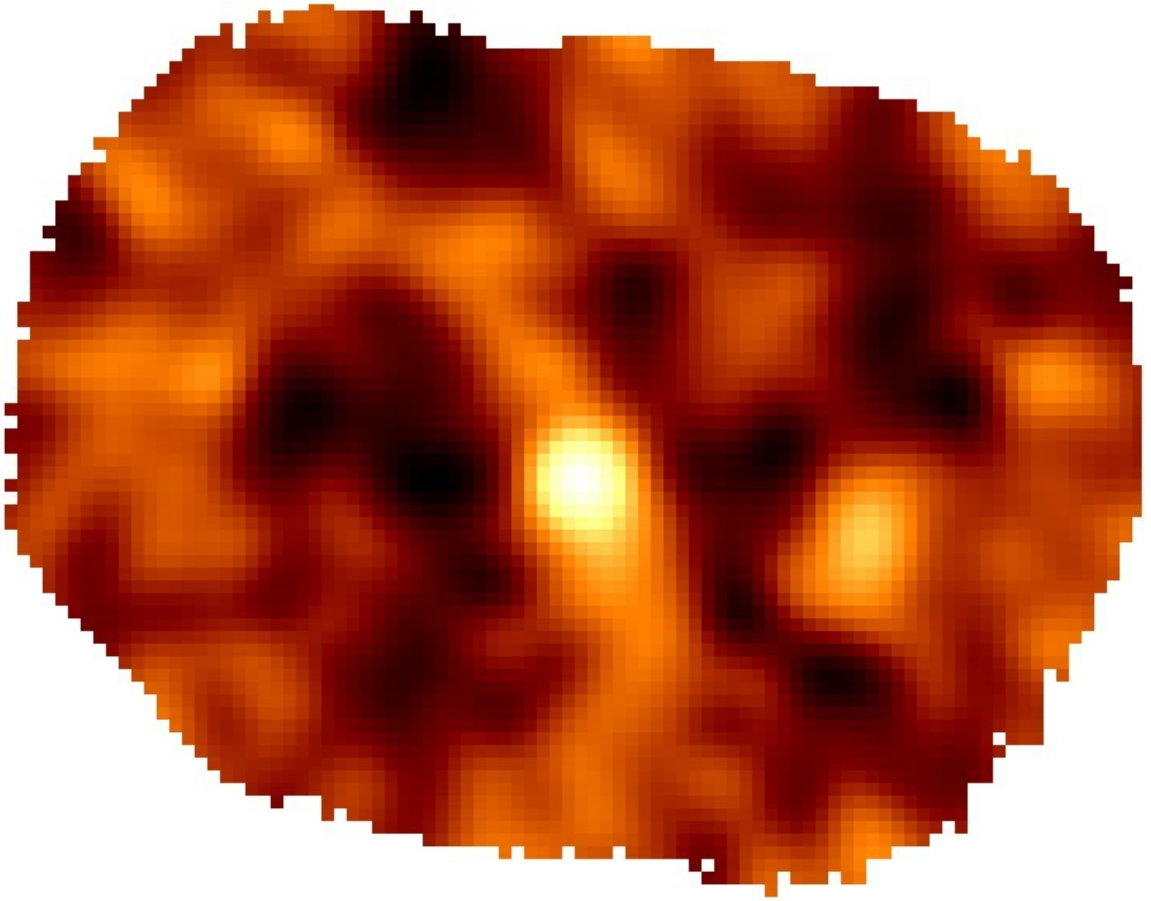
32 x 12 = 384 bolometers

1 Jy $s^{1/2}$ in good weather

SHARC-2 Observations...

- **8 Observing Runs (November 2002 – April 2005)**
- **Requires BEST submm weather (τ_{225GHz} < 0.05) (15-20% Chance)**
- **2-4 hours of integration (+ overhead) per SMG targetting sensitivities of ~10 mJy/beam**
- **Lissajous Patterns for Small Field Observing.**
- **Interlaced with frequent pointing and calibration scans.** *(Planets, asteroids, Arp220, CO stars, compact HII)*

SMM J163631.47 +405546.9



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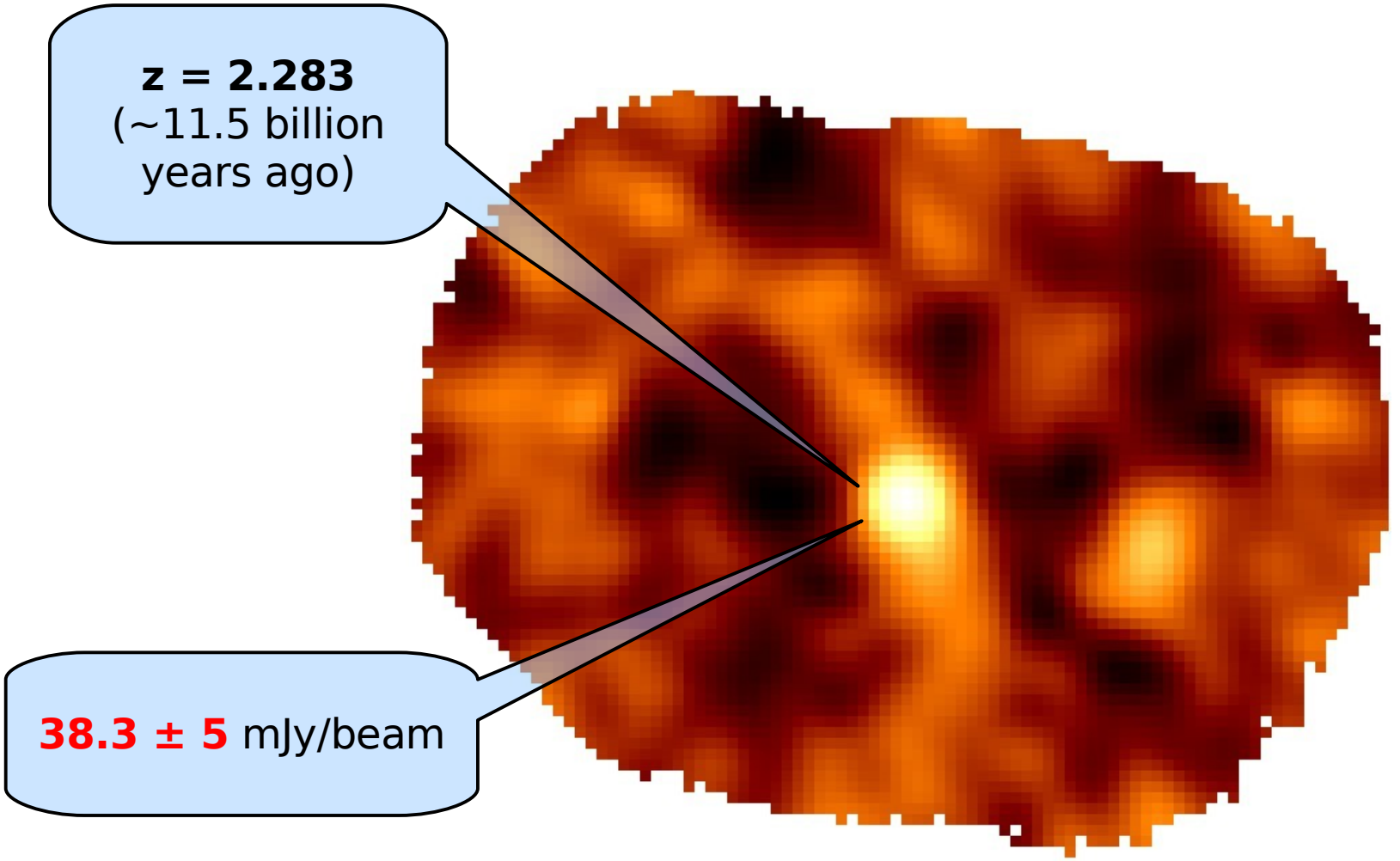

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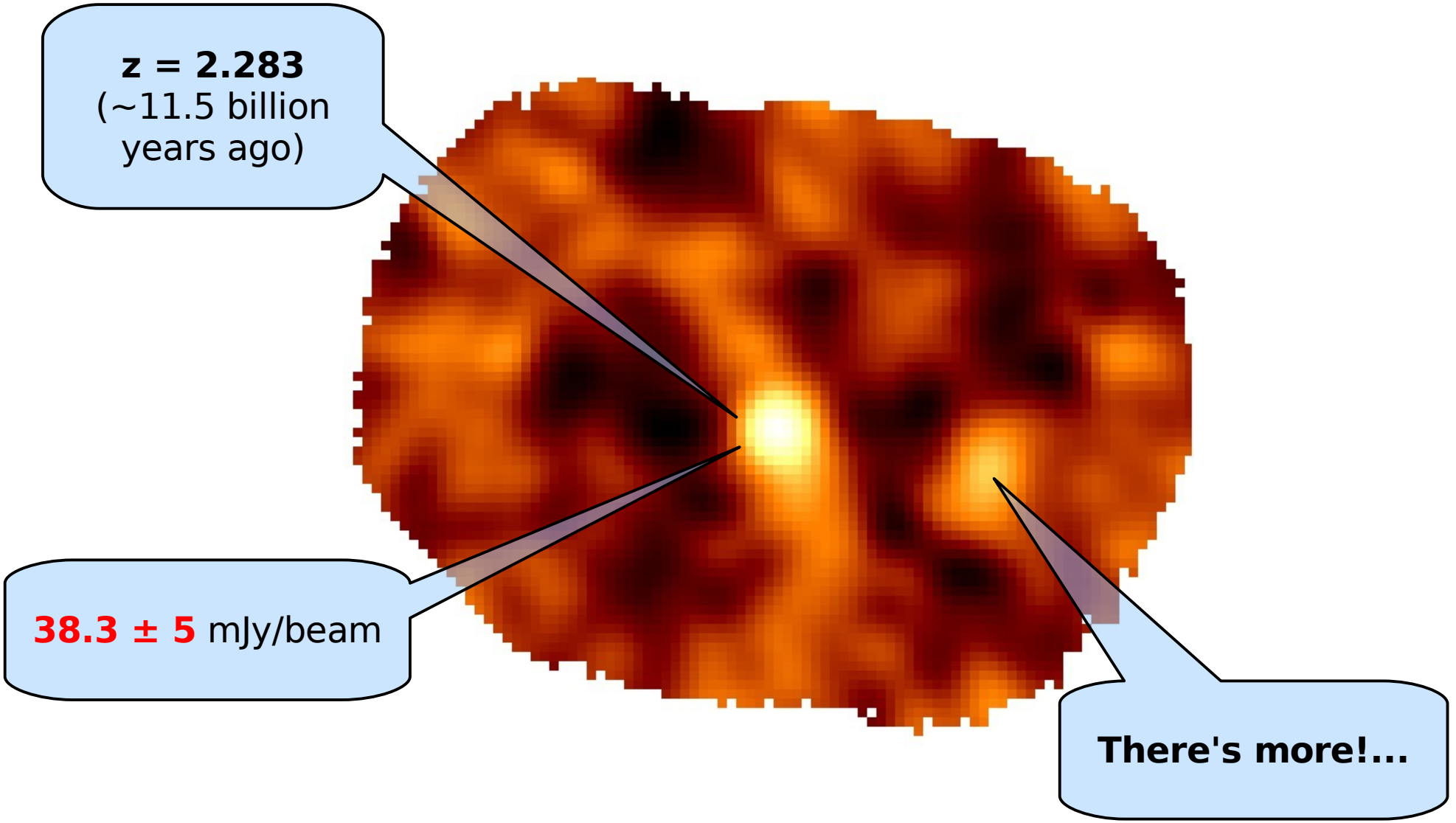
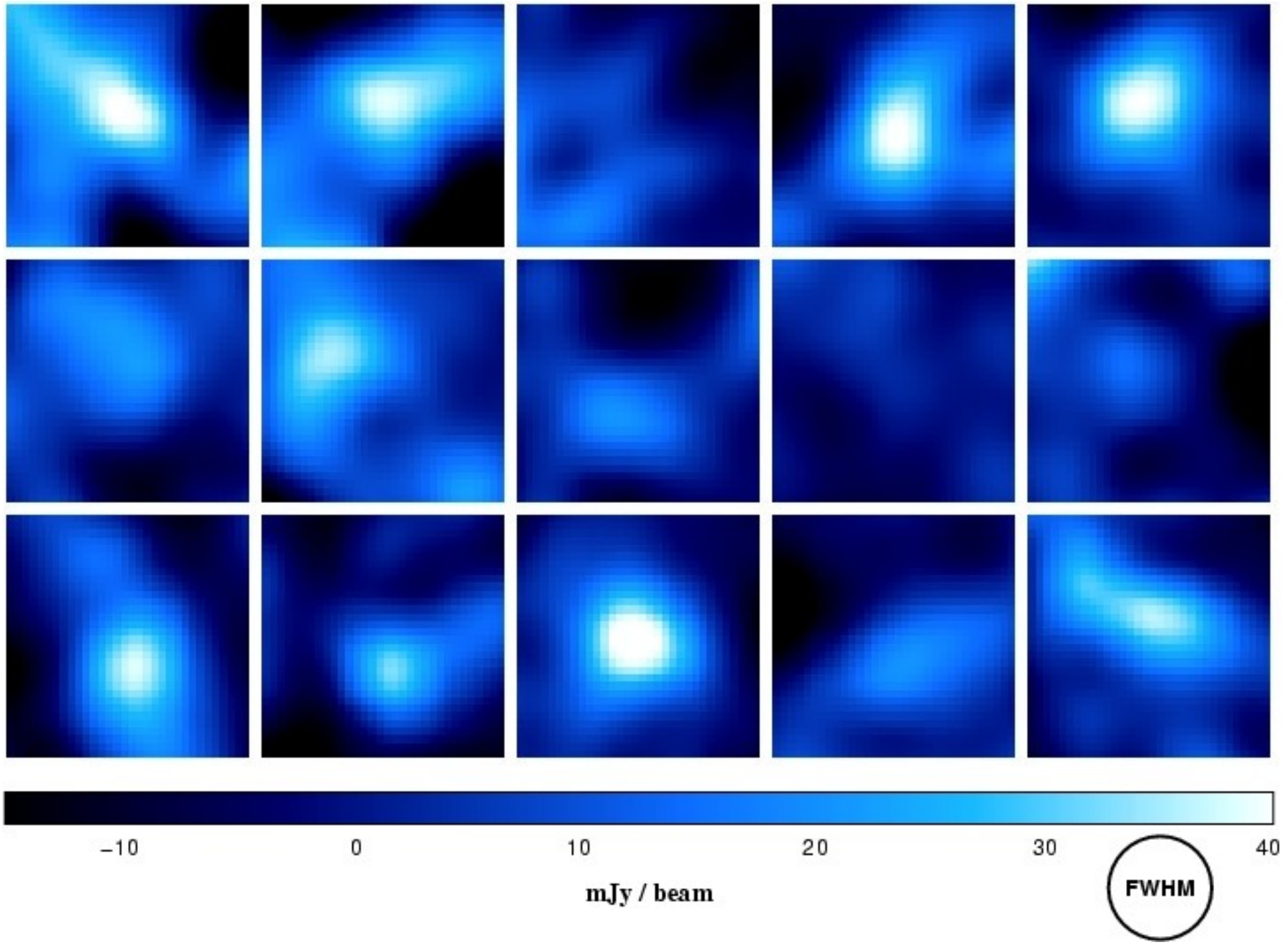


SMGs at 350um with SHARC-2 (30” x 30”)



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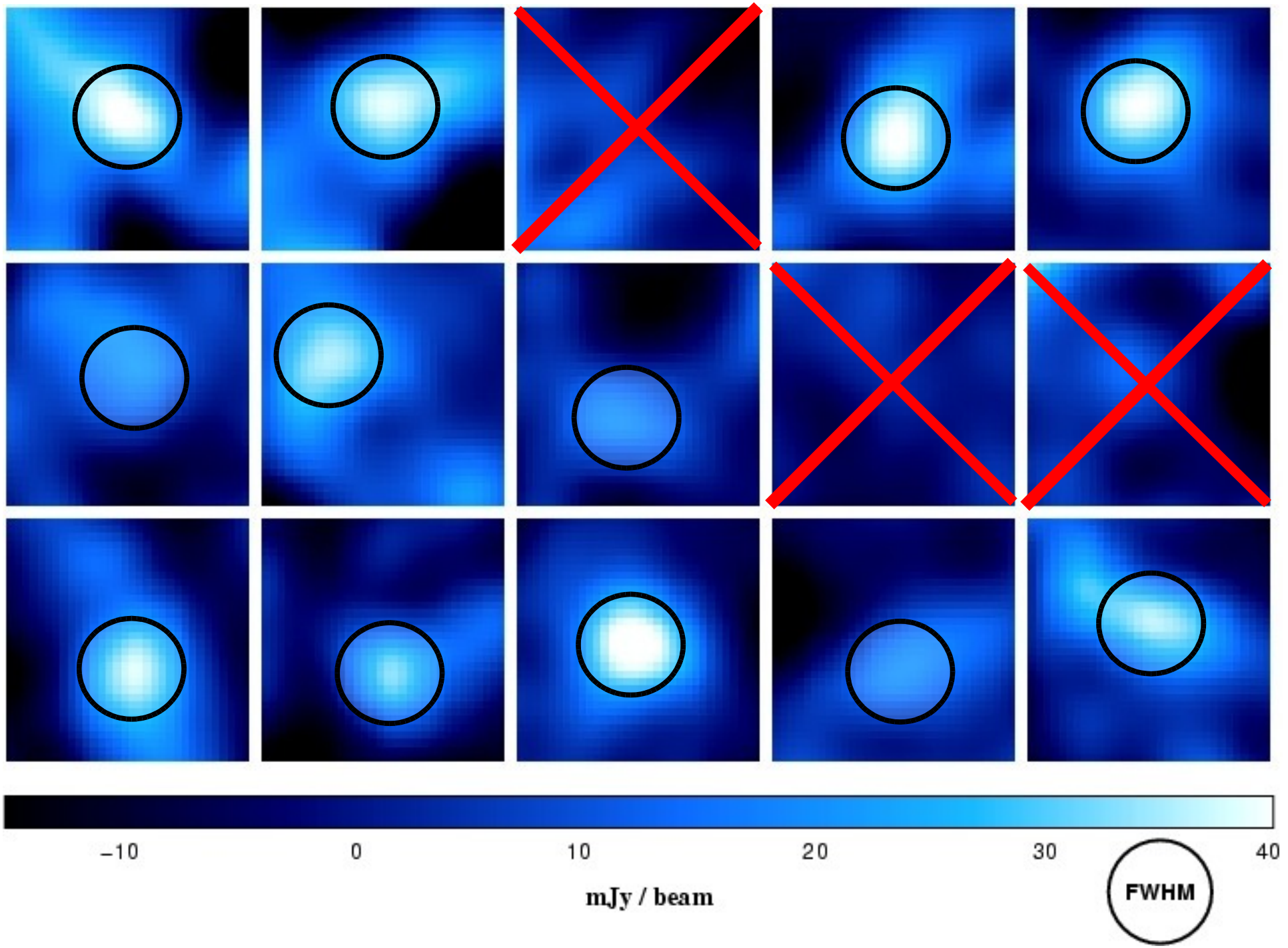
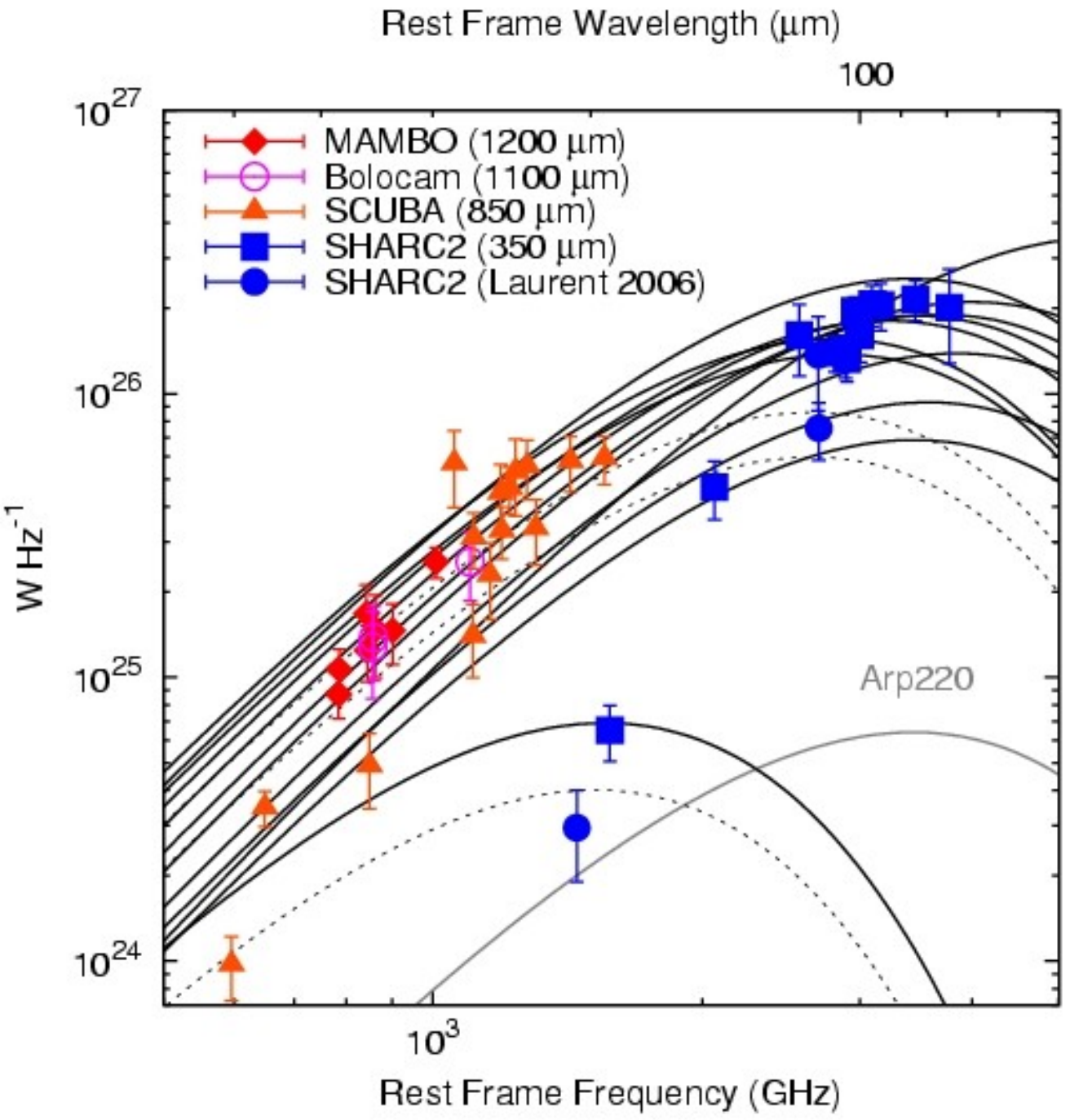
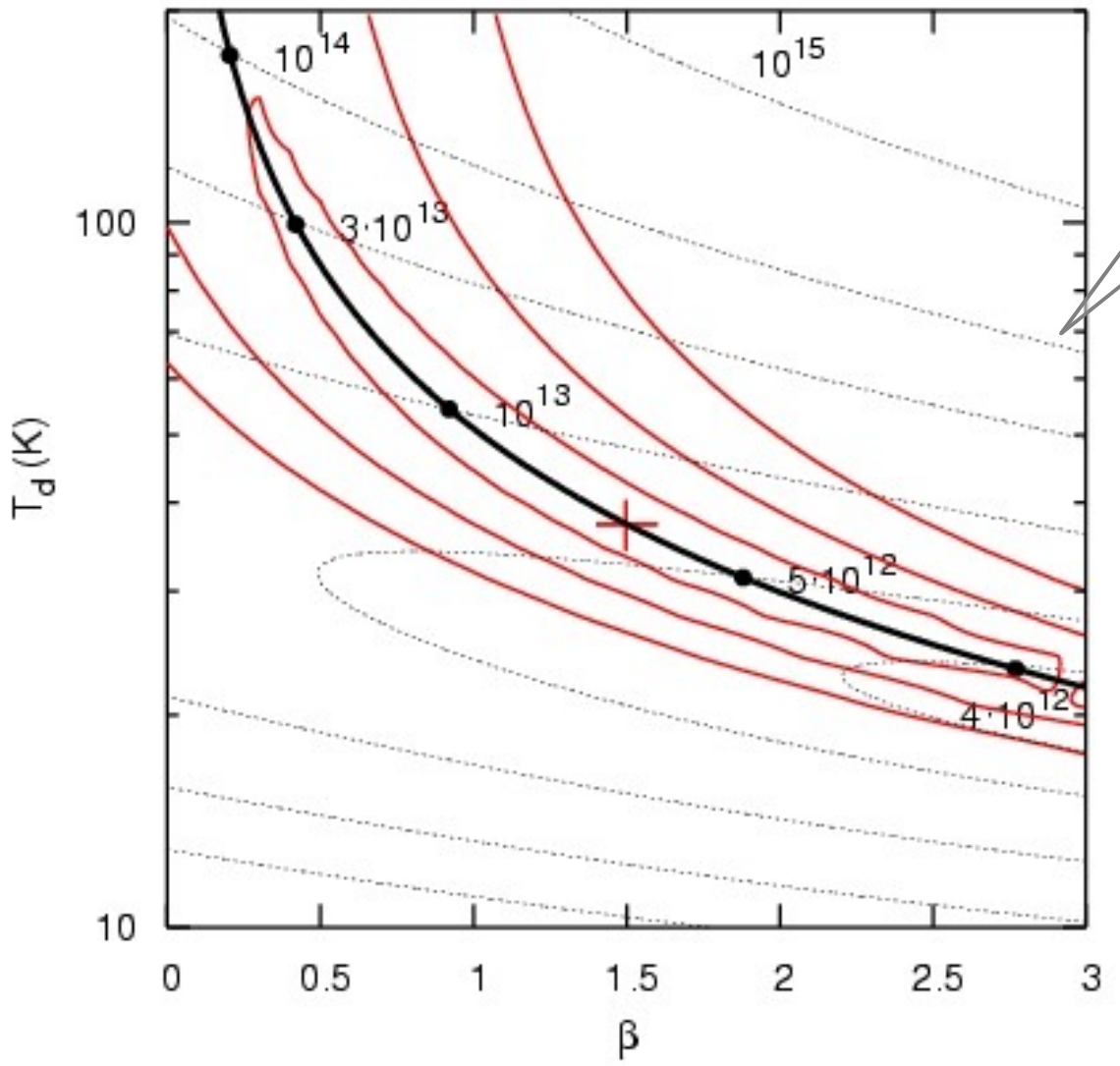


SMGs: Spectral Energy Distributions (SEDs)

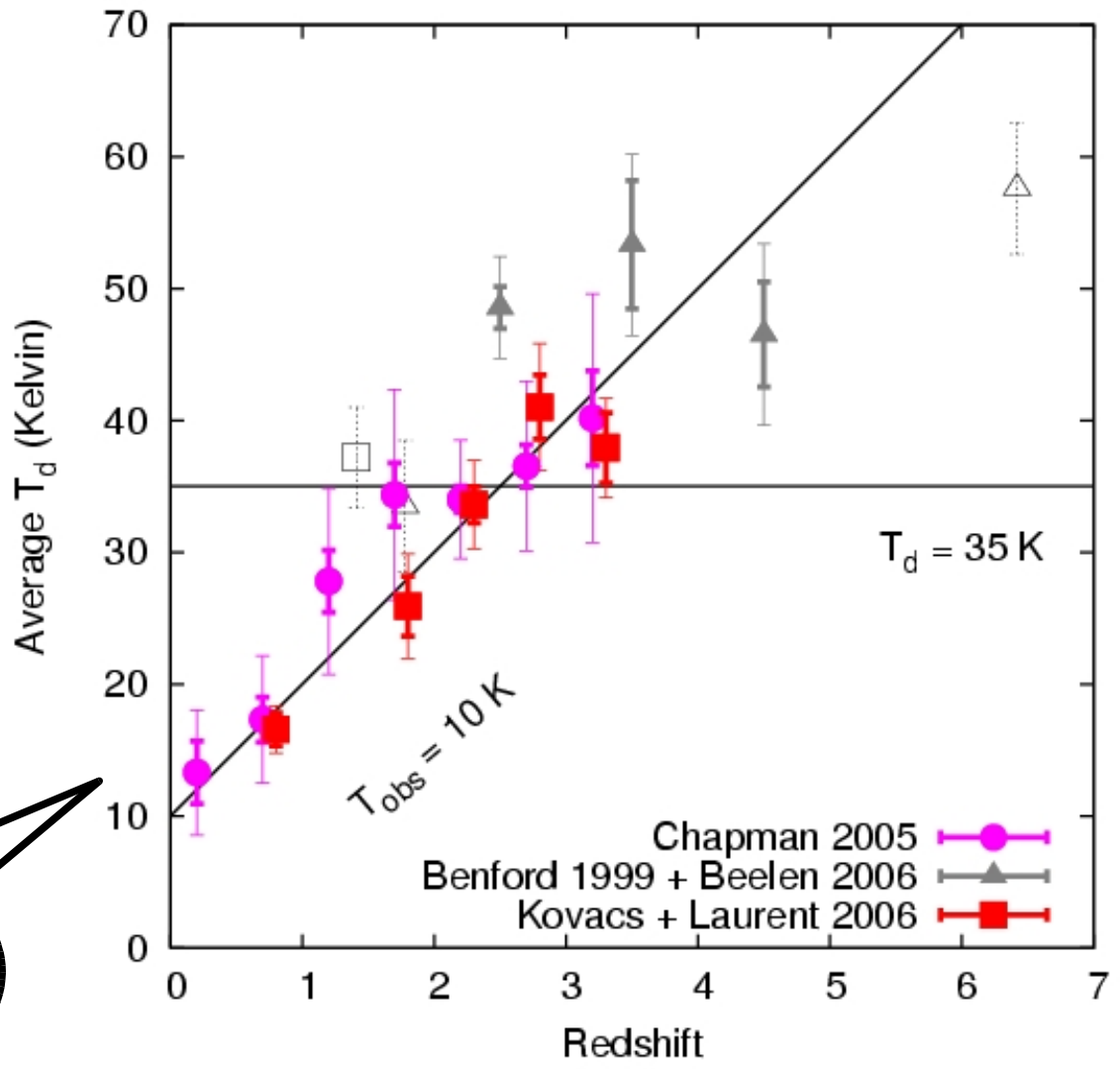


Dust Temperature and Emissivity

T and β are correlated parameters of the SED fits...



Temperature Evolution?

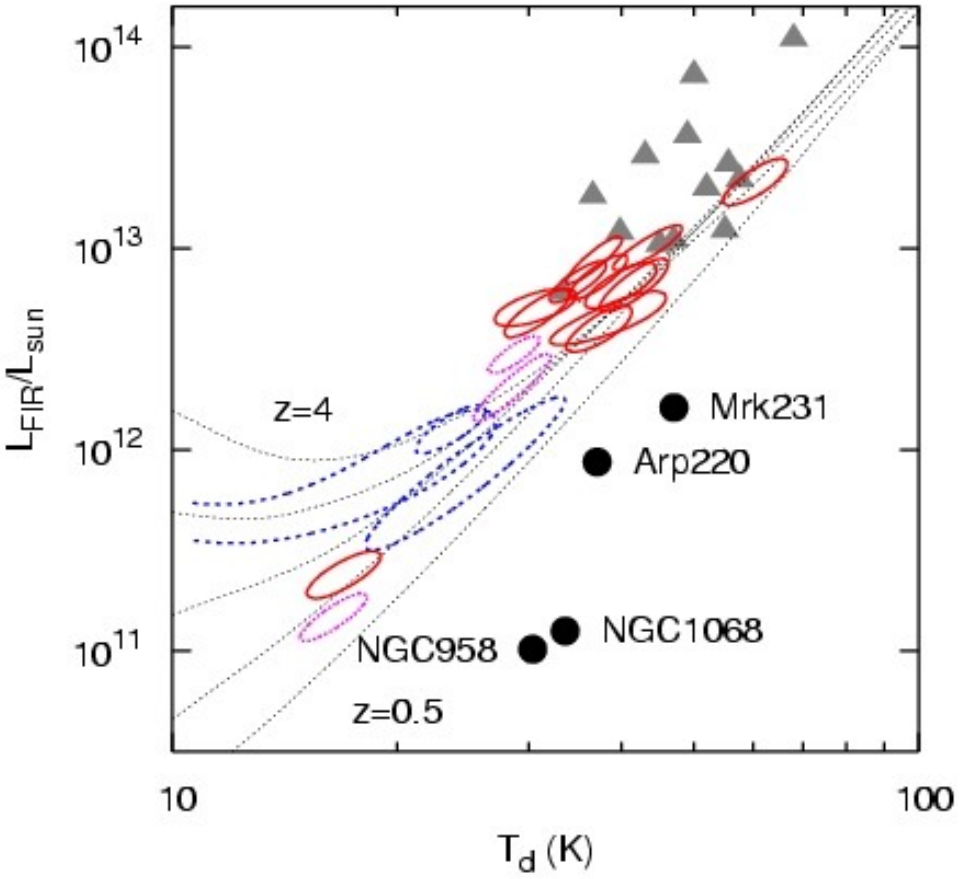


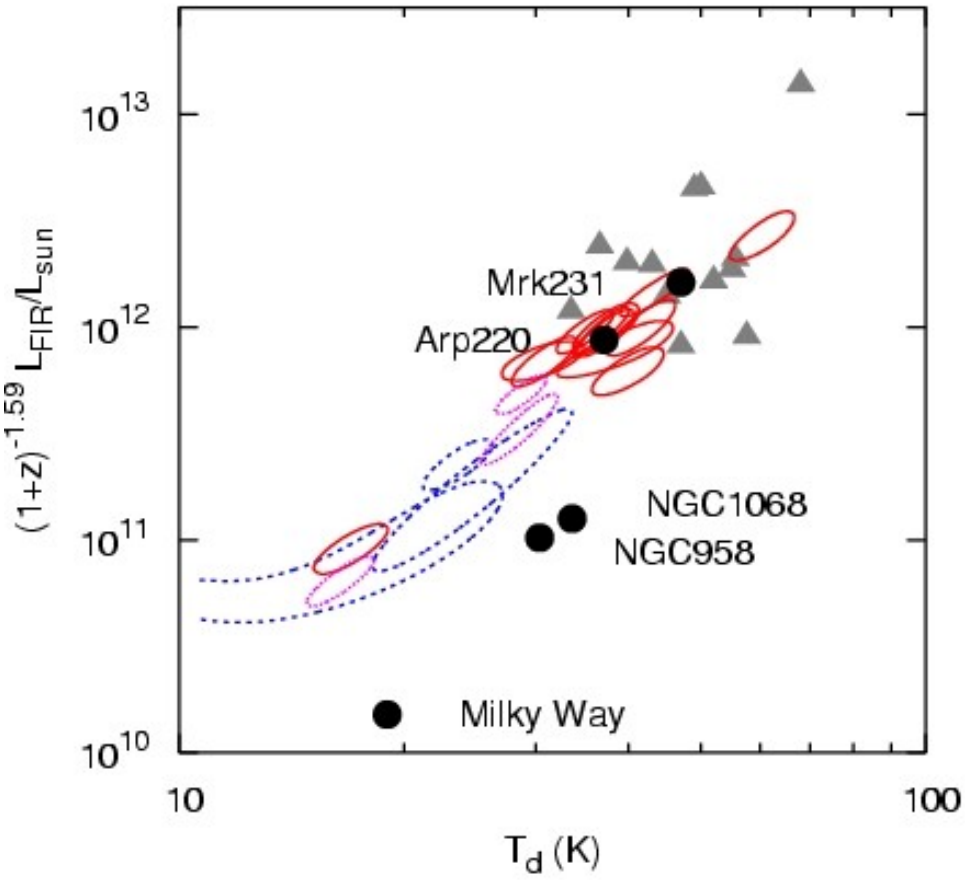
SMG = 35K
???

T_d ~ (1+z)
???

Luminosity – Temperature Relations

Strongly Affected by Selection!!!

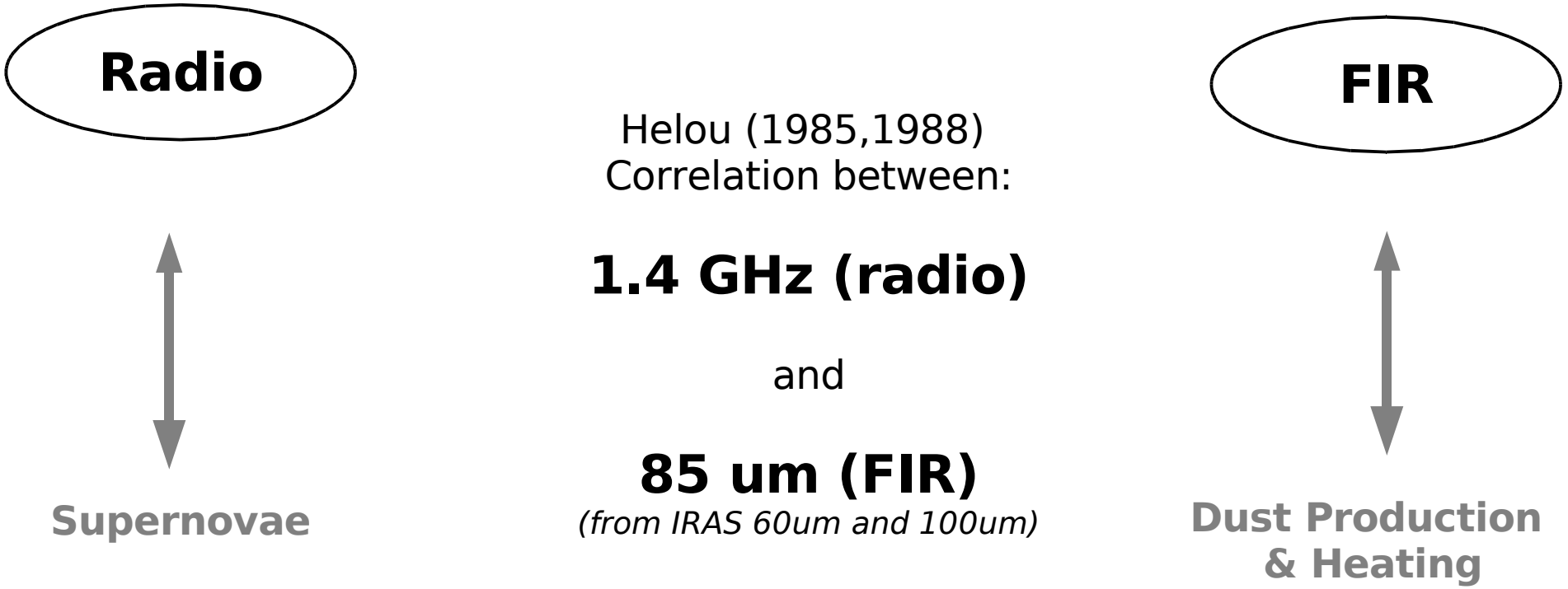




$$L_{FIR} = \mathcal{L}_0 T_d^{\gamma} \times (1+z)^{\mu}$$

After Dividing out the Redshift Dependence
(Selection Correction?)

Correlation Between Radio and FIR Luminosities



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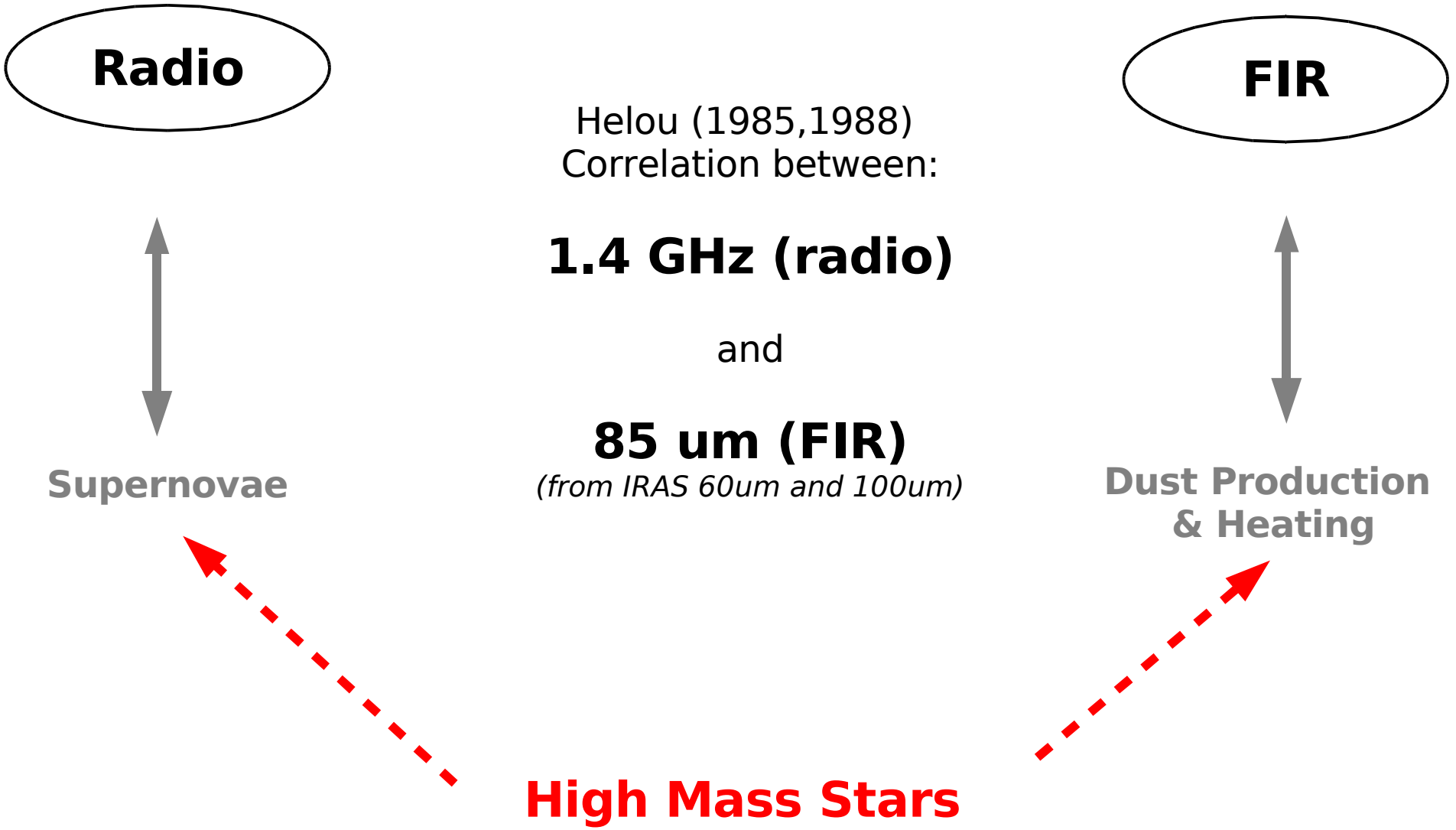
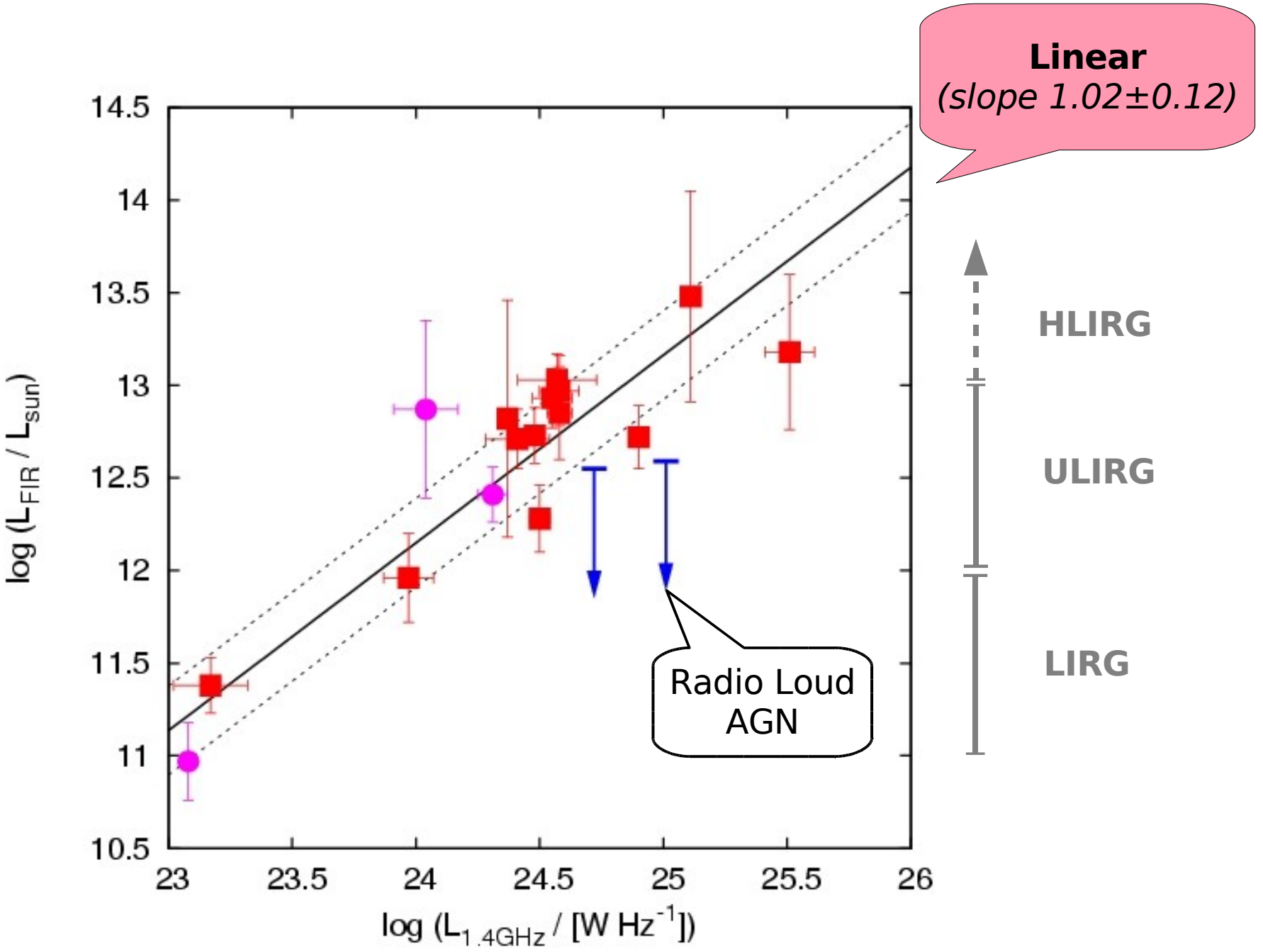


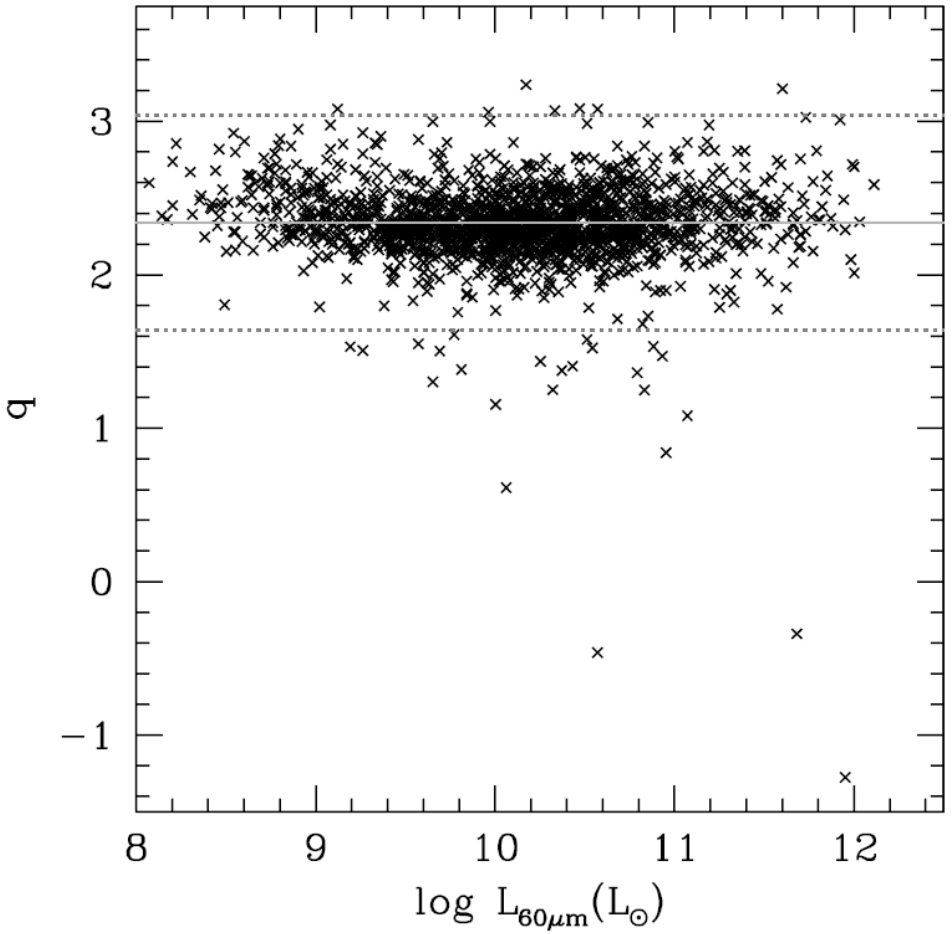
Correlation Between Radio and FIR Luminosities



Radio to Far-Infrared Correlation

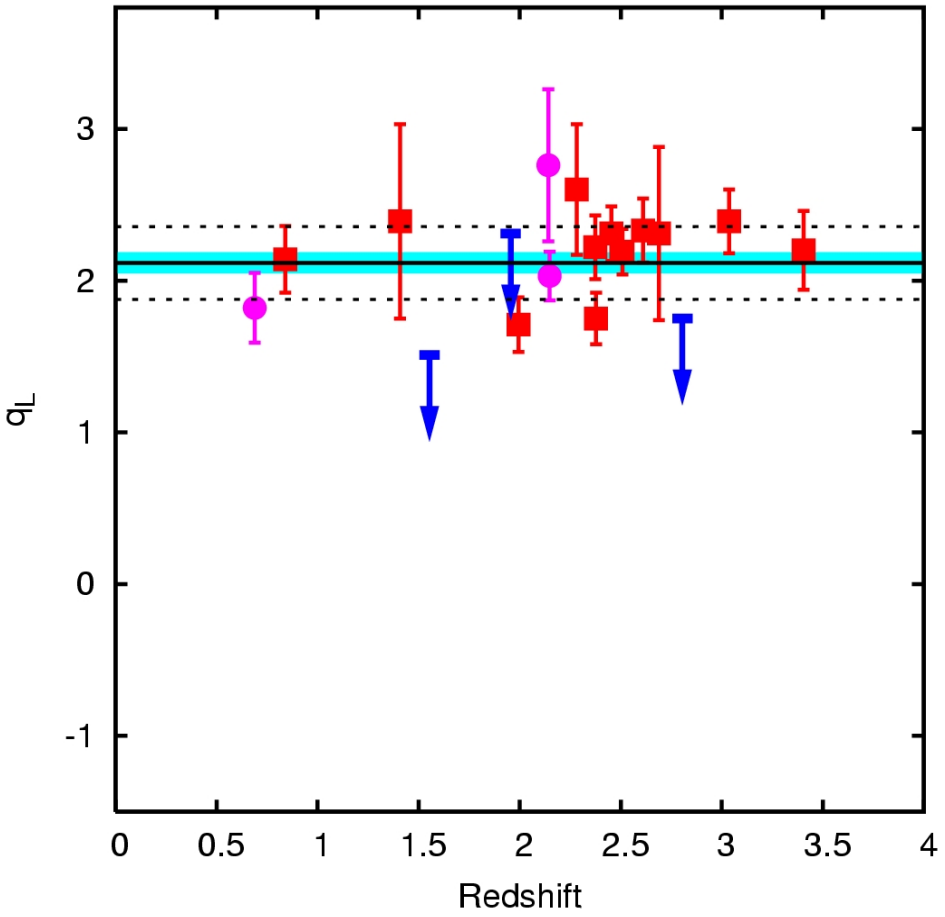
q ~ L(*FIR*) / L(*1.4 GHz*)

Local IRAS Galaxies



Yun et al. (2001)

SMGs



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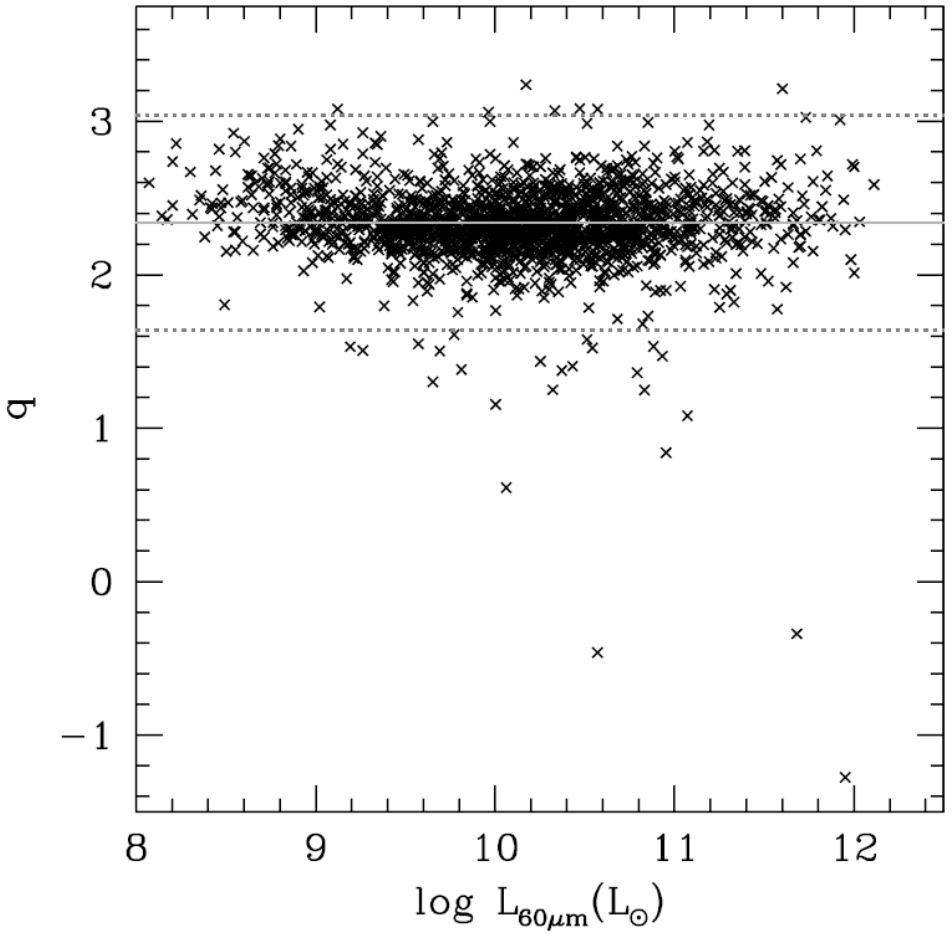

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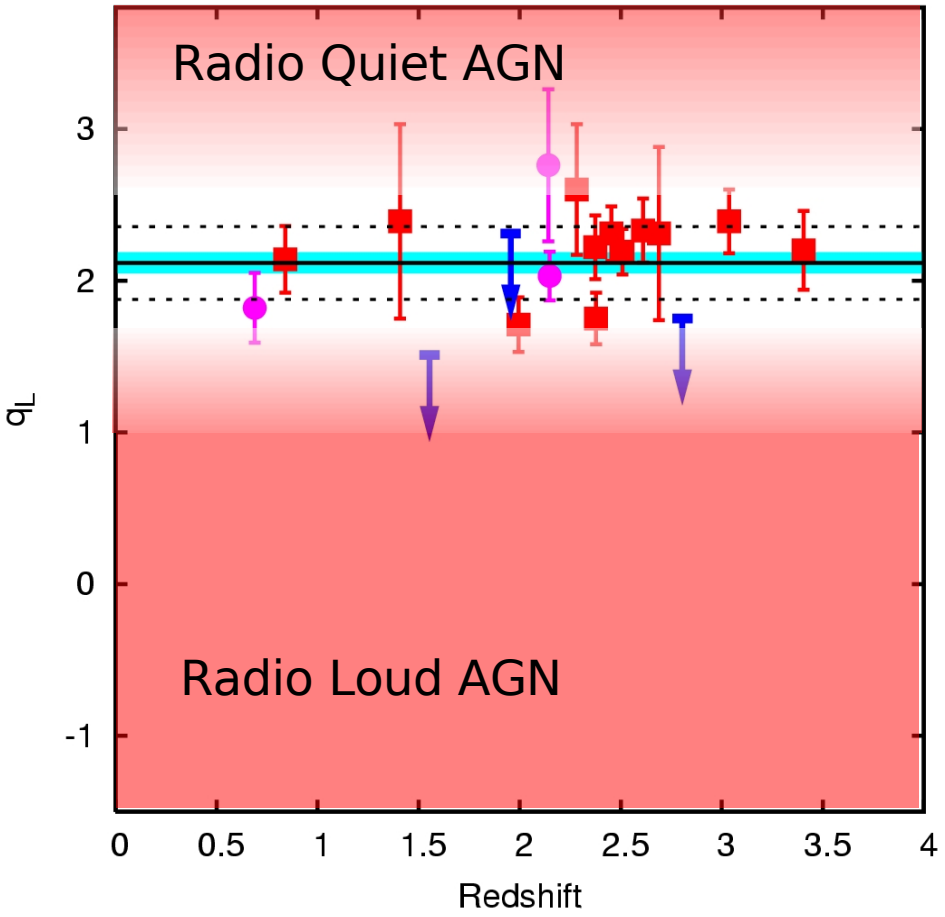
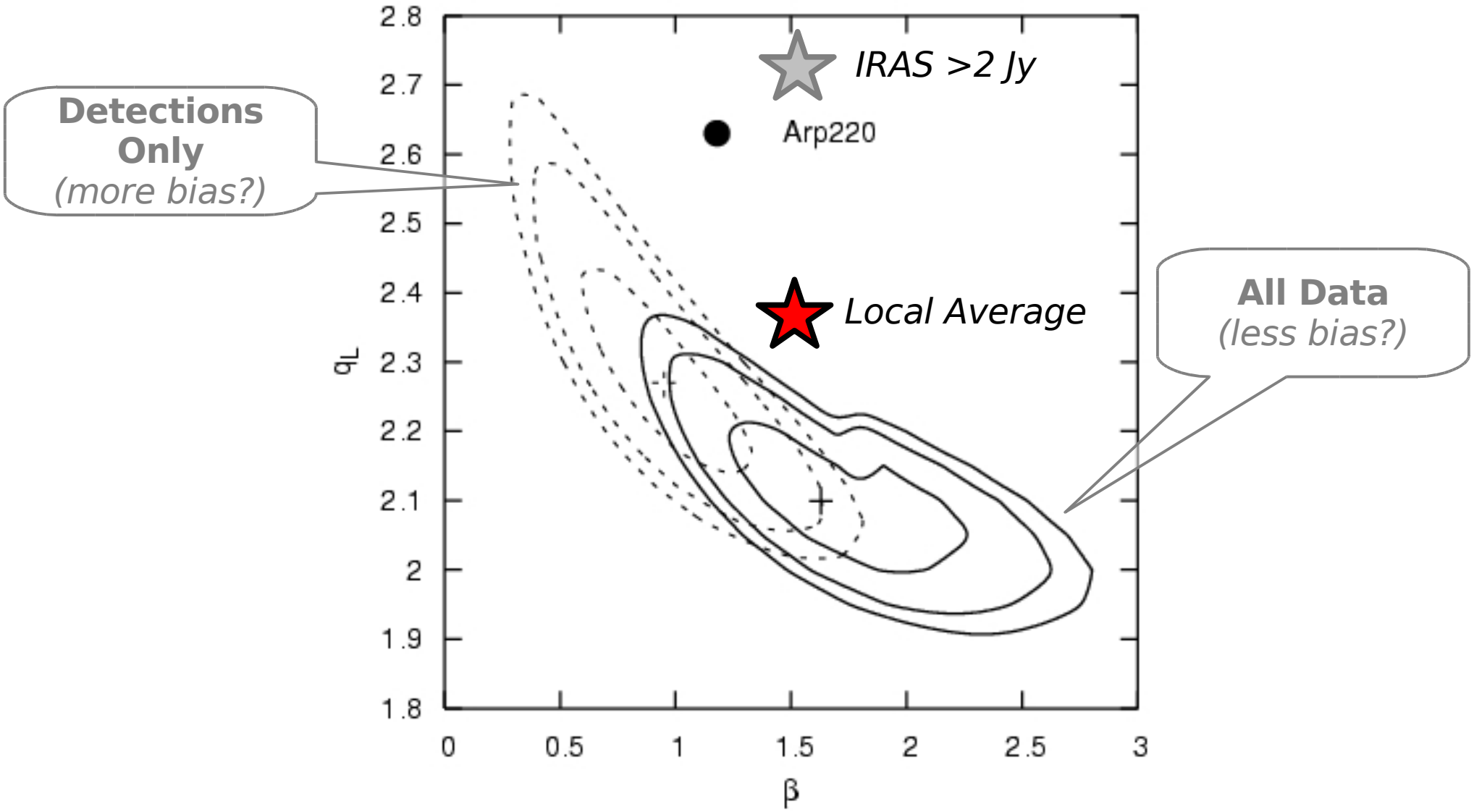


Radio-FIR Correlation & Dust Emissivity



Photometric Redshift

A Great Desire for it to work...

1) $T_d = T_{obs}\,(1+z)$

(Carilli & Yun 1999,2000; Wiklind 2003)

Photometric Redshift

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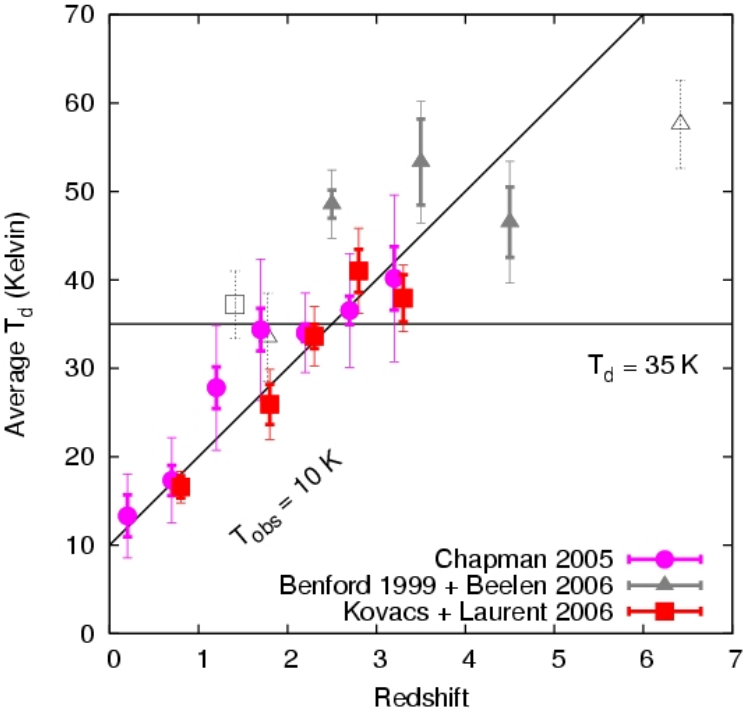

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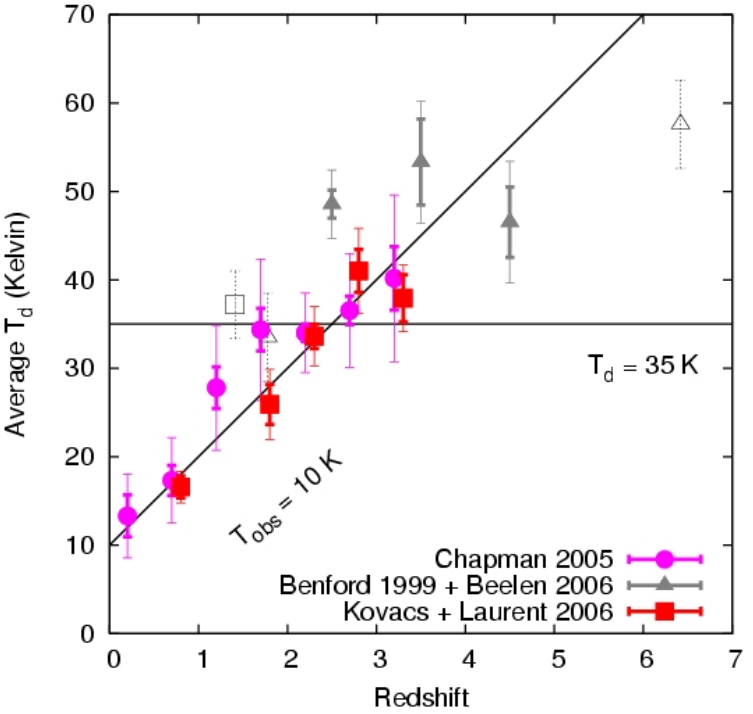

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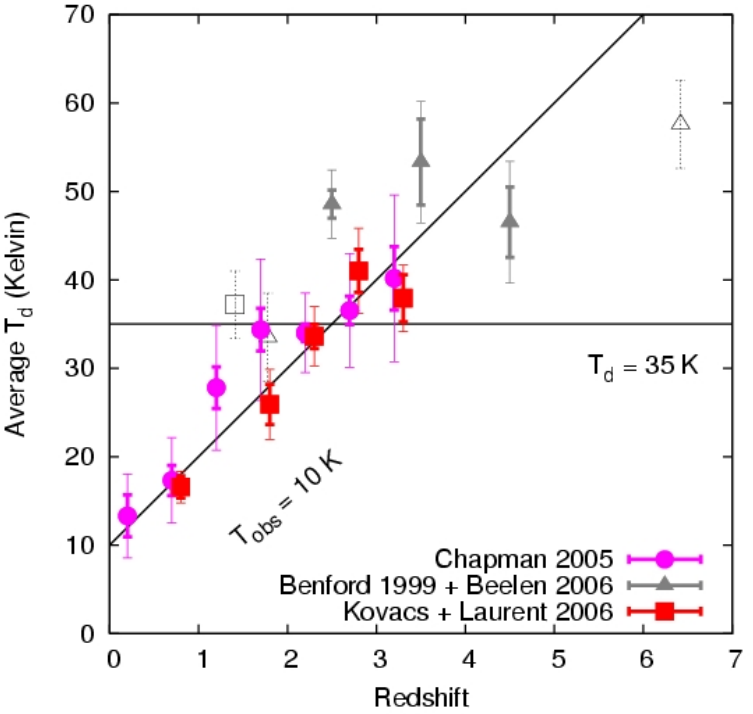

2) $T_{obs,}\ S_{obs,}\ L(T,z) \rightarrow z$

Photometric Redshift

A Great Desire for it to work...

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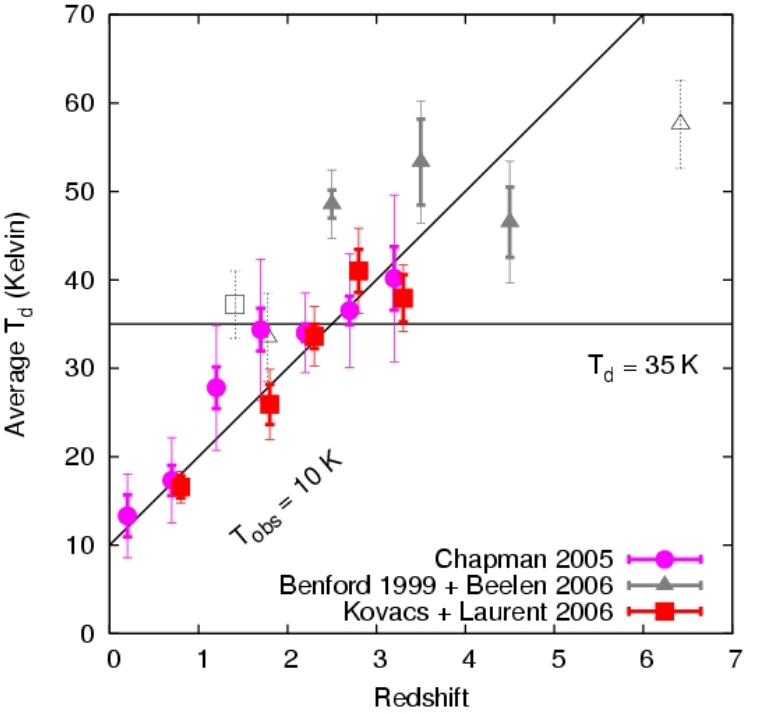

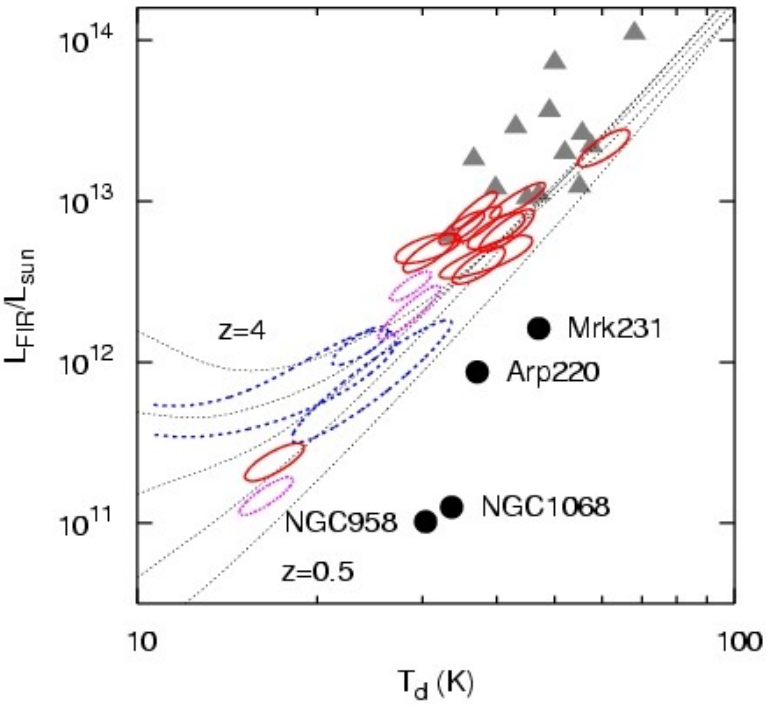

Photometric Redshift

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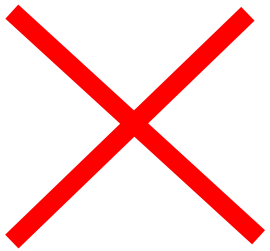
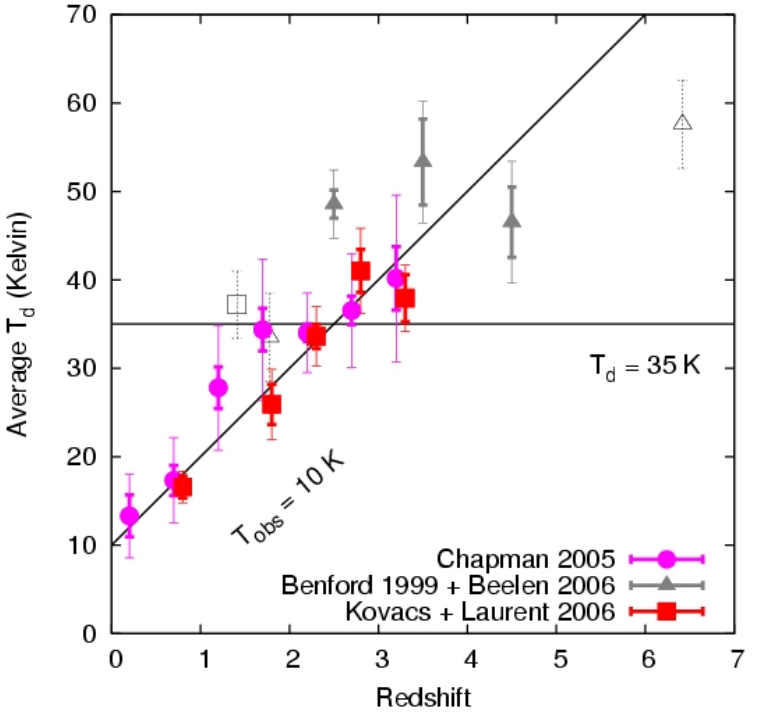
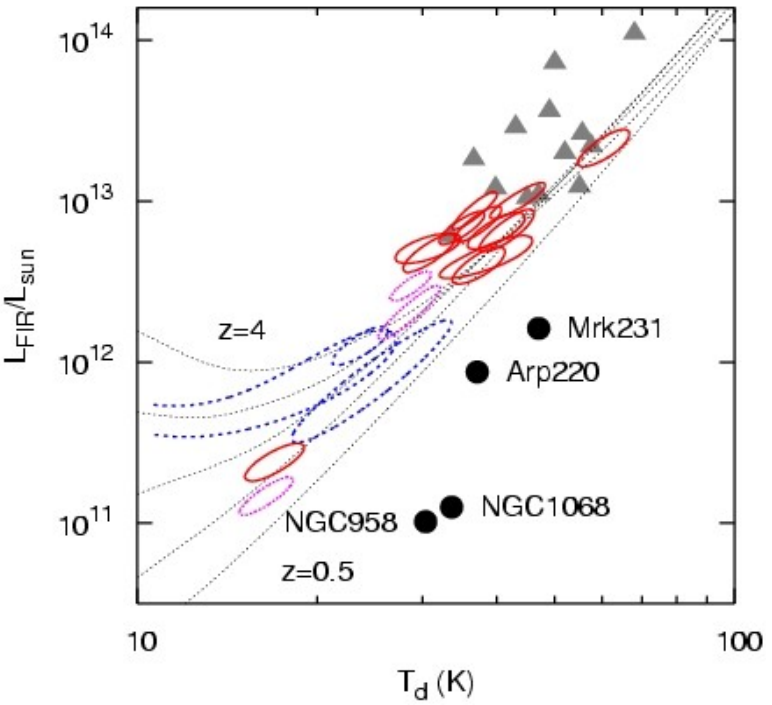
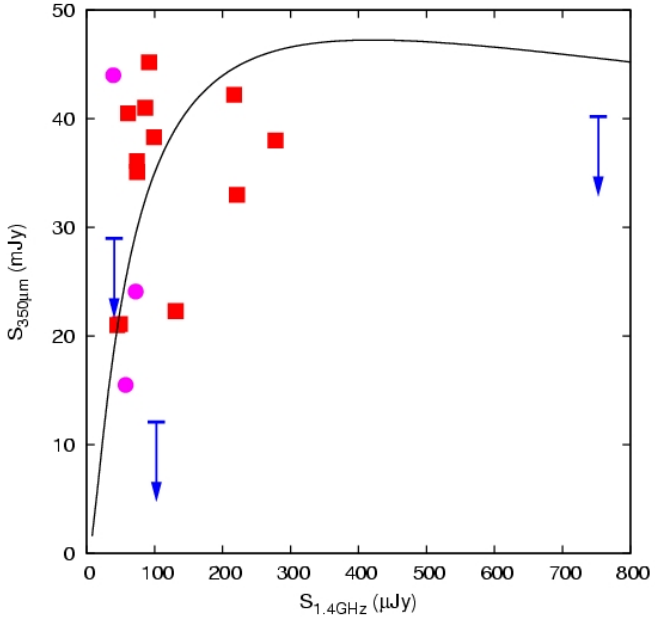


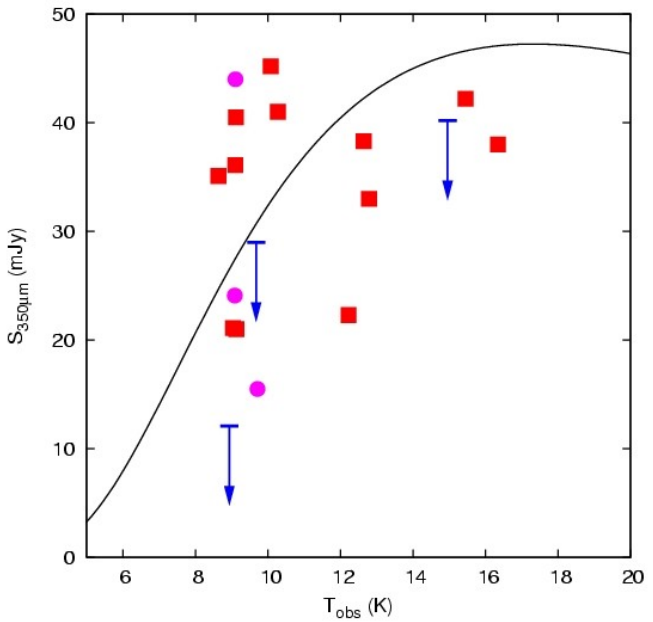




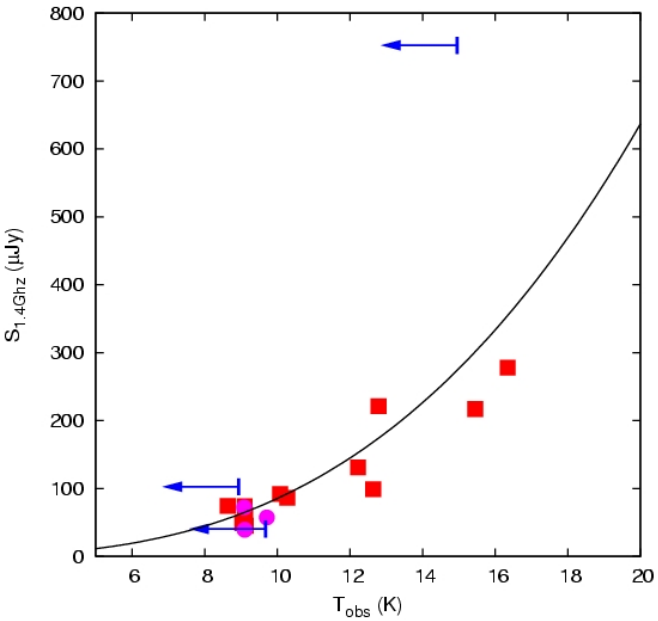
The Good News:
Scaling Relations for the Observed Quantities



Radio vs 350um Fluxes



350um Flux vs T_{obs}



Radio Flux vs T_{obs}

A single measurement might constrain observed SED
(future radio and submillimeter surveys)

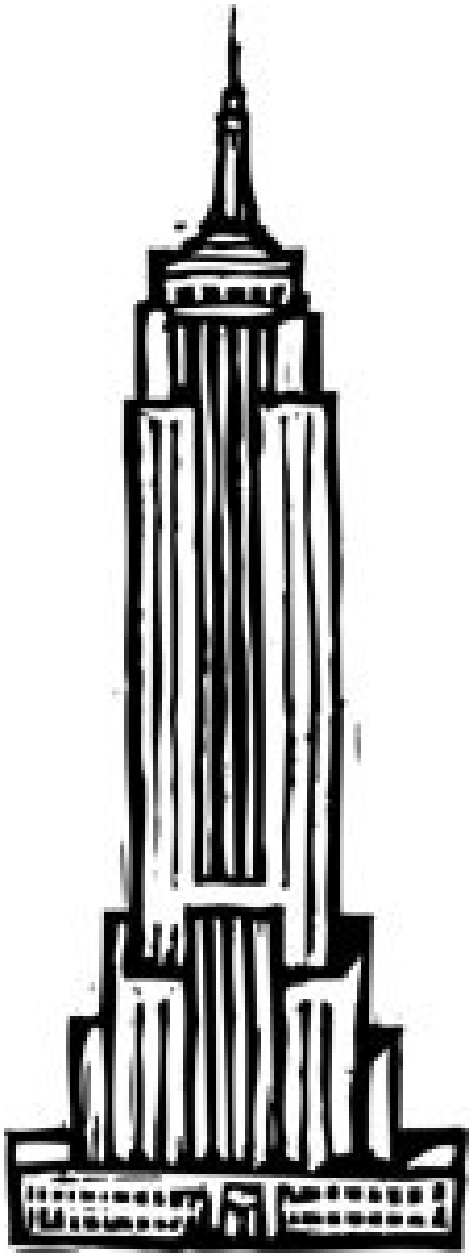
Conclusions

- **15 observed – 12 detected, 3 too faint.**
- **Accurate Dust Temperatures and Luminosities.**
- **Linear Radio – FIR correlation.**
  Star Formation not AGN dust heating.
  q or β different than locally.
- **L – T (with evolution)**
- **Probably no Photometric redshift from radio or FIR...**
- **...but SEDs might be constrained from detection photometry.**

Part II

Data Reduction
(CRUSH)

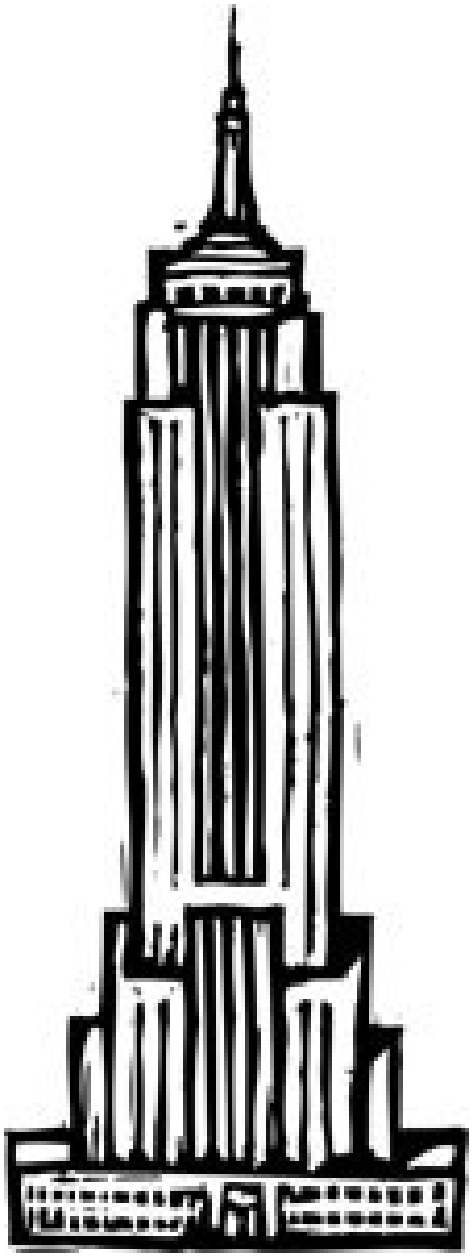
Sky Brightness
(~1000 Jy)



Sky Variability
(~10 Jy/min$^{1/2}$)

Submillimeter Galaxy
(~0.01 Jy)

Sky Brightness
(~1000 Jy)



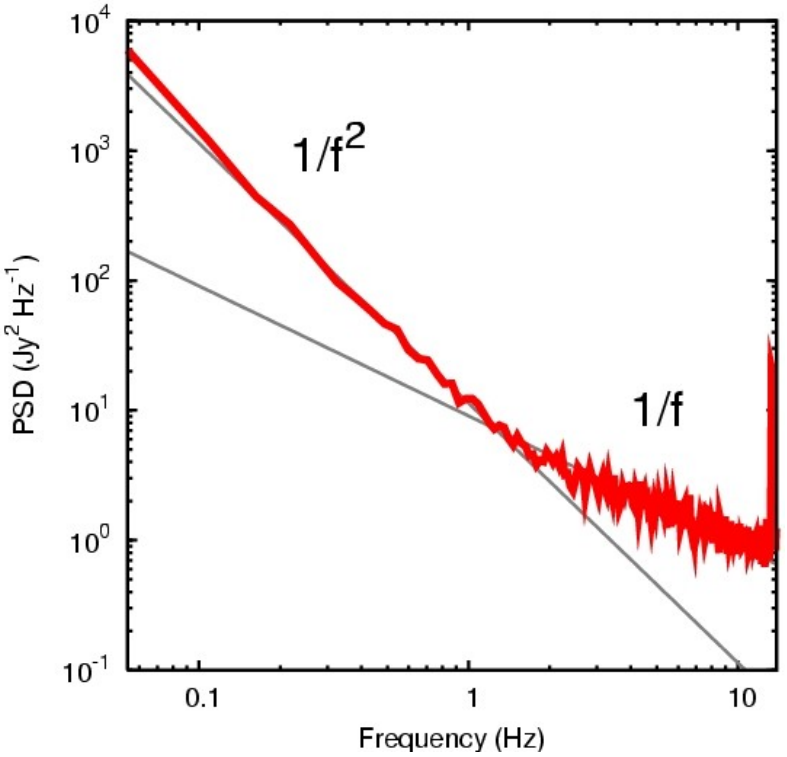
15 mag star in broad daylight...

(...1000 times fainter than
the faintest star visible
on a clear night...)

Sky Variability
(~10 Jy/min$^{1/2}$)

Submillimeter Galaxy
(~0.01 Jy)

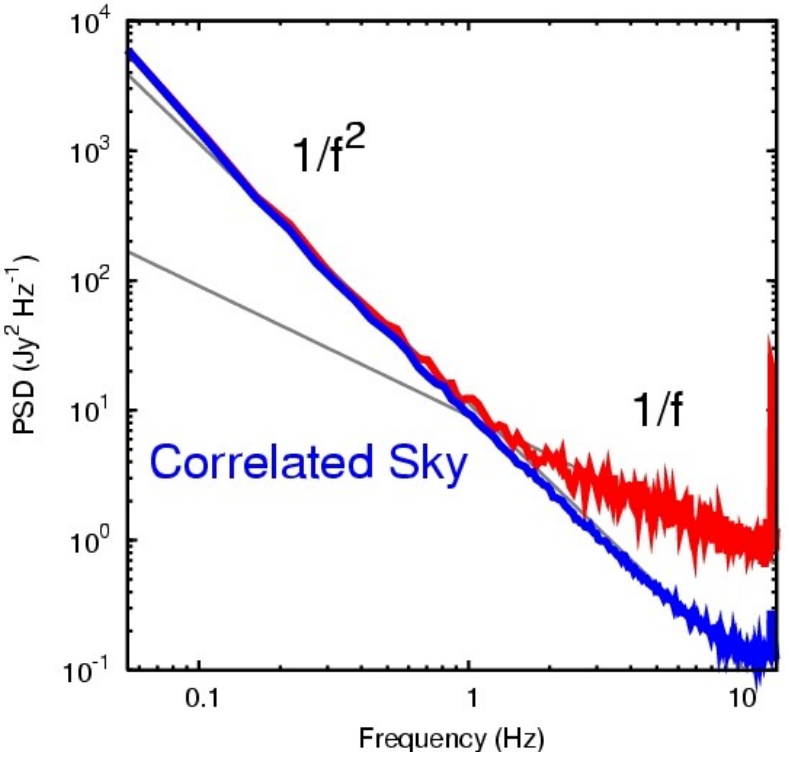
1/f Noise (the real problem!)



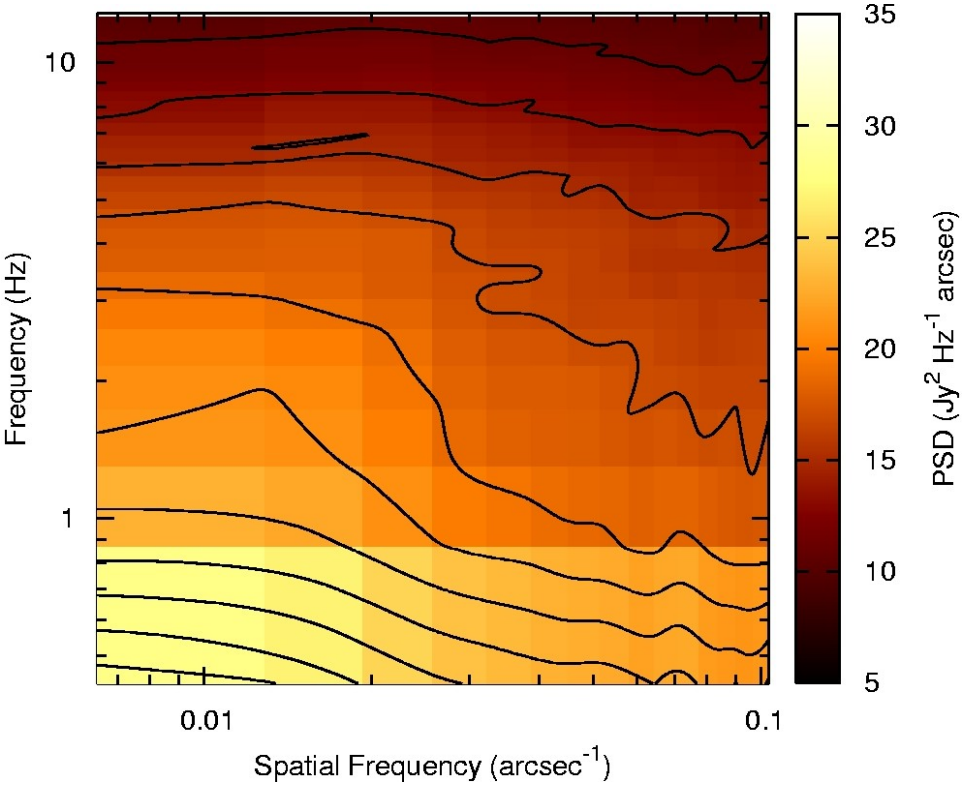
A SHARC-2 pixel

1/f Noise (the real problem)

Correlated in space!!!



A SHARC-2 pixel



Atmopsheric Spectrum
from SHARC-2

Chopping (the Simple Way…)

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

E.g. 45” switching at 4 Hz for SHARC

Problems

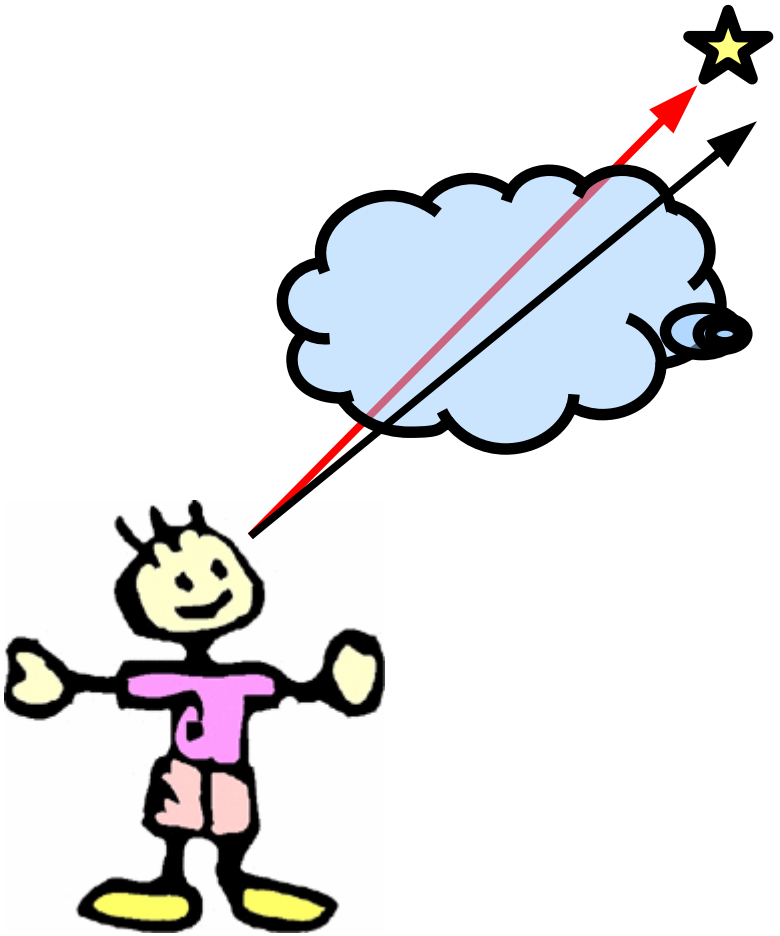
Lost Sensitivity to Some Spatial Components

Differencing Noise

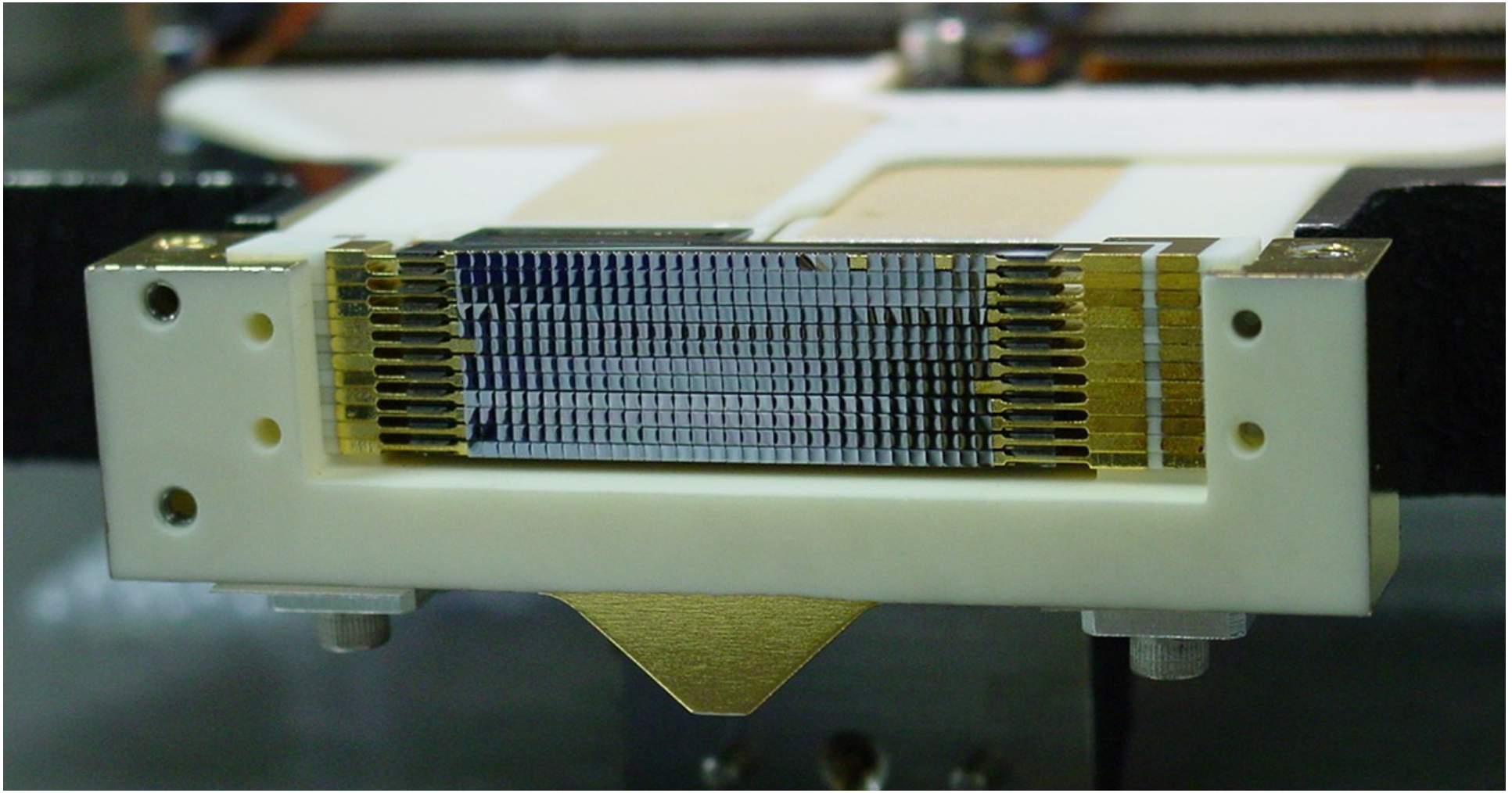
Duty Cycle

On-Source Efficiency
(small arrays)

Striping
(Imperfect Sky Removal)



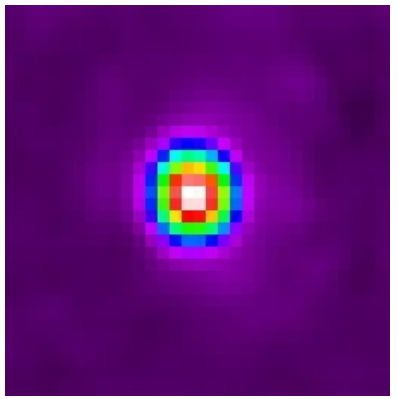
Large Format Arrays *(SHARC-2)*



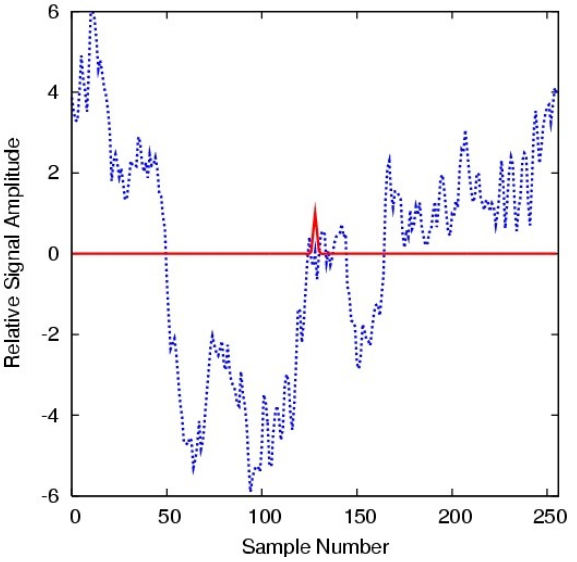
32 x 12 = 384 bolometers

Detectors Measure Sky Simultaneously!

From Source to Data...

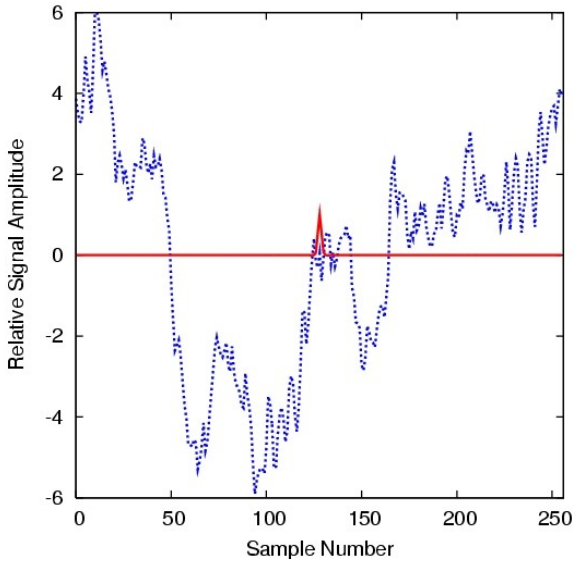


+ Noise =

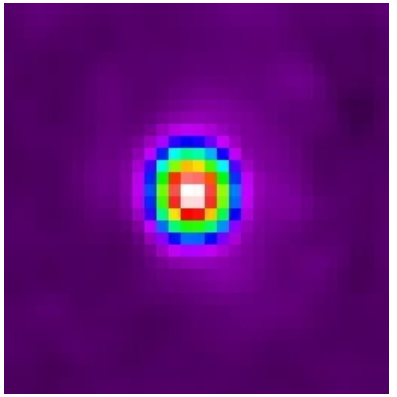


$$\mathcal{M}(S)+N = D$$

From Data to Source – The Inversion Problem



?



$$\mathbf{S} = \mathcal{A}(\mathbf{D})$$

Noiseless

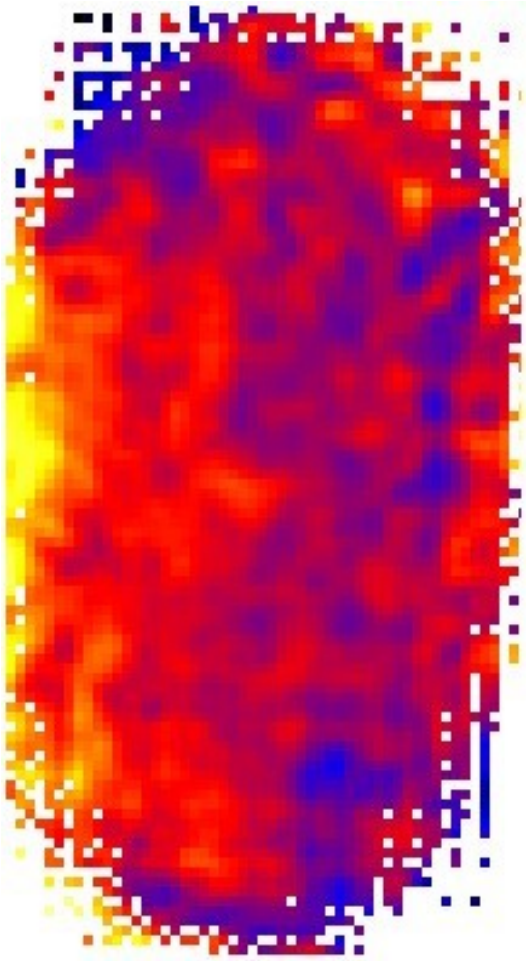
$$\mathbf{S} + \mathcal{A}(\mathbf{N}) = \mathcal{A}(\mathbf{D})$$

$$\mathcal{A} \circ \mathcal{M} = \mathbf{1}$$

From Data to Source – The Inversion Problem

Pallas (23 Jy) in 2 minutes

Simple Inversion (Maximum Likelihood)

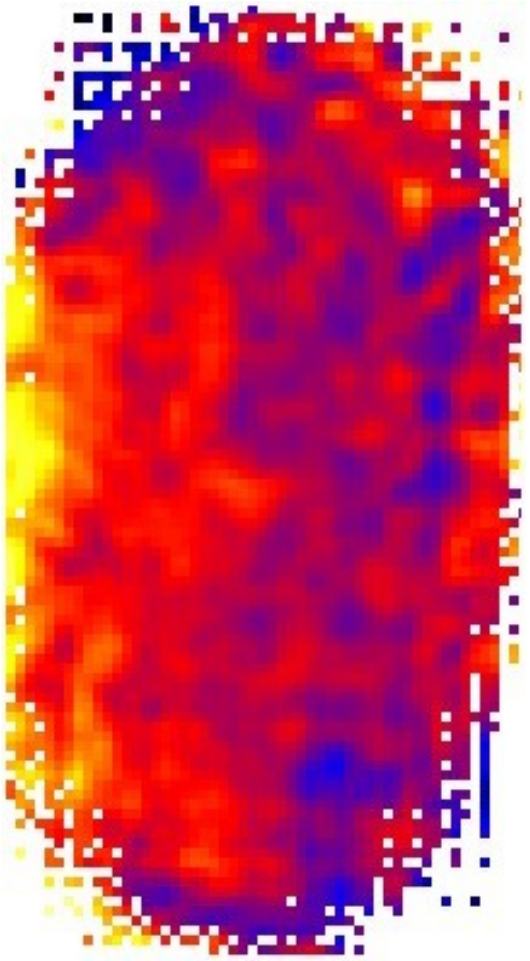


6 Jy/beam RMS

From Data to Source – The Inversion Problem

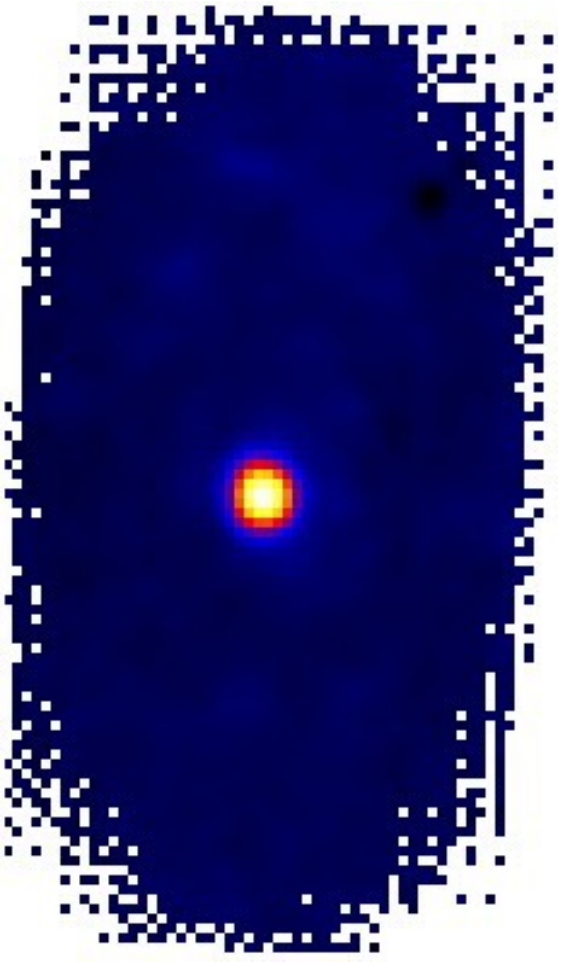
Pallas (23 Jy) in 2 minutes

Simple Inversion (Maximum Likelihood)



6 Jy/beam RMS

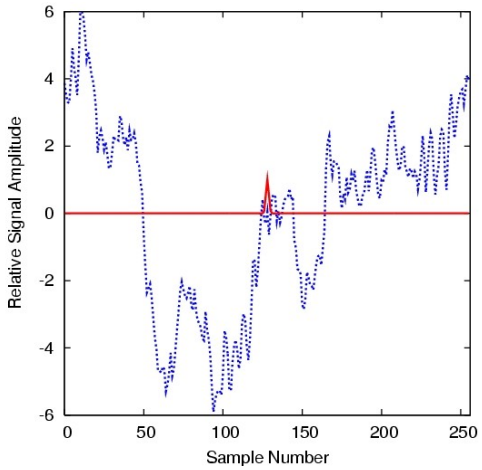
CRUSH (Filtering)



0.1 Jy/beam RMS

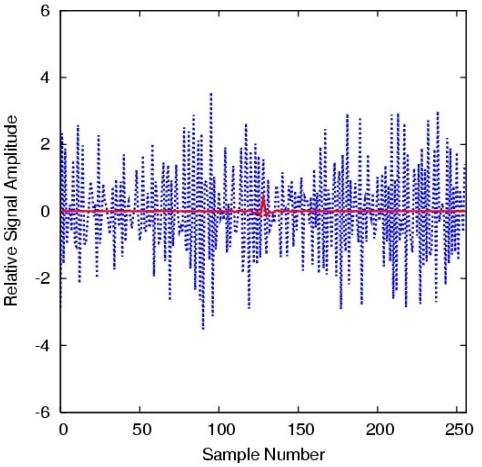
Approximate Inversion

$$\mathcal{F}' \circ \mathcal{A} \circ \mathcal{F}(\mathbf{D}) \longrightarrow \mathbf{S}$$

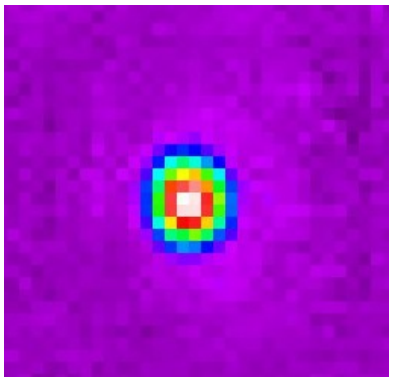


$\mathcal{F}$

Whiten

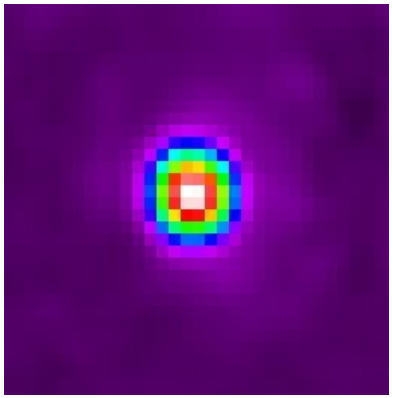


$\mathcal{A}$



Lossy!!!

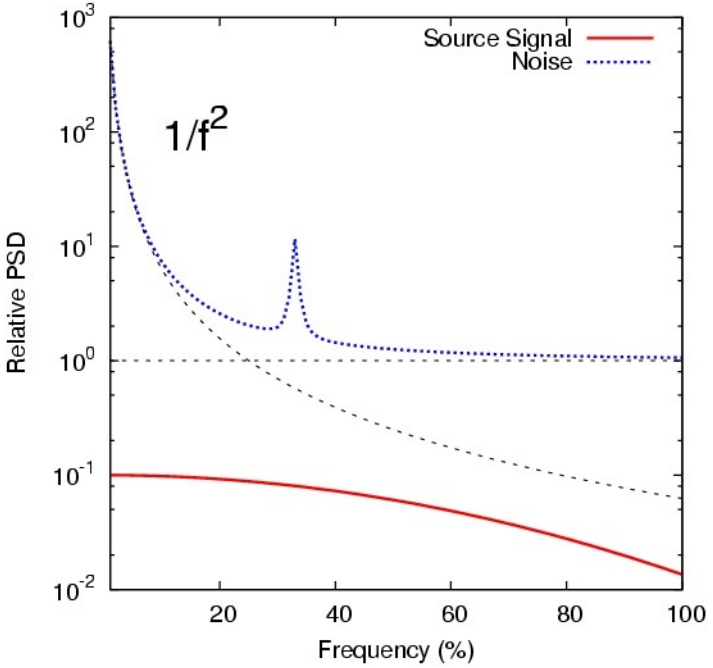
Maximize Fidelity
and
Minimize Noise

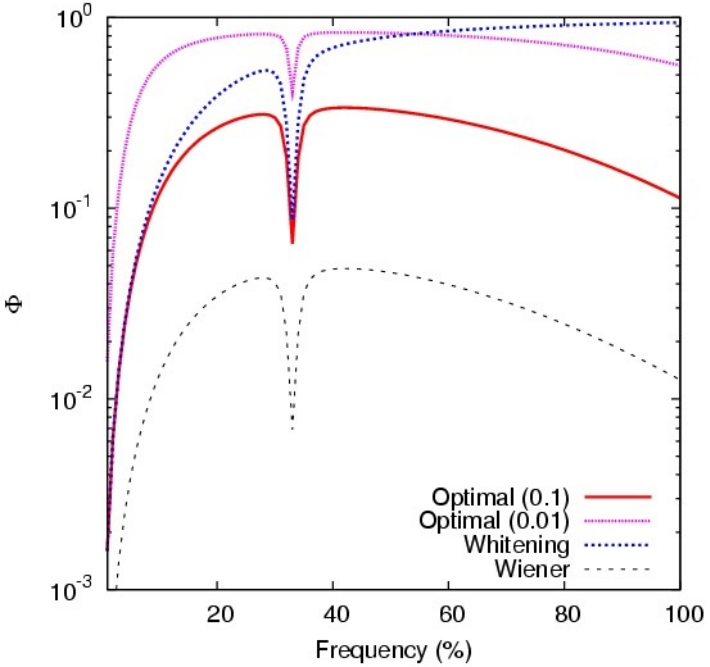


$\mathcal{F}$

I. Practical Filtering...

Noisy Signal Spectrum

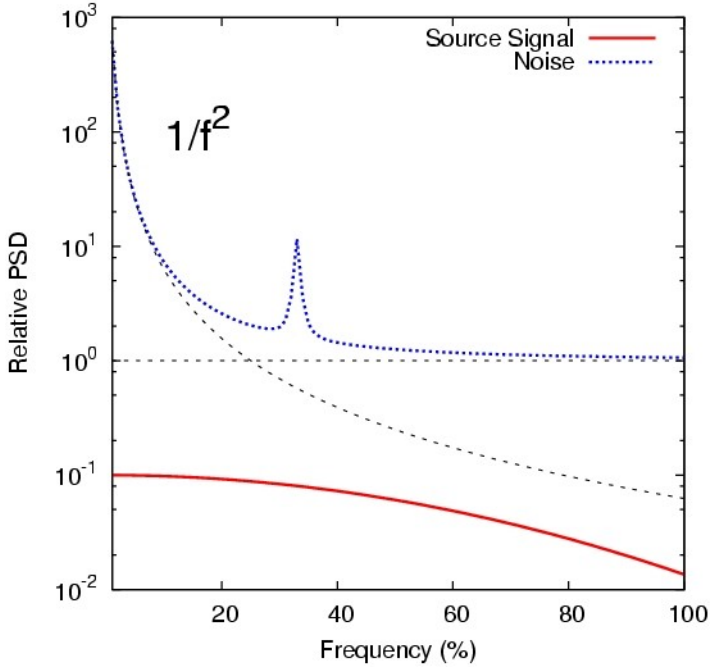


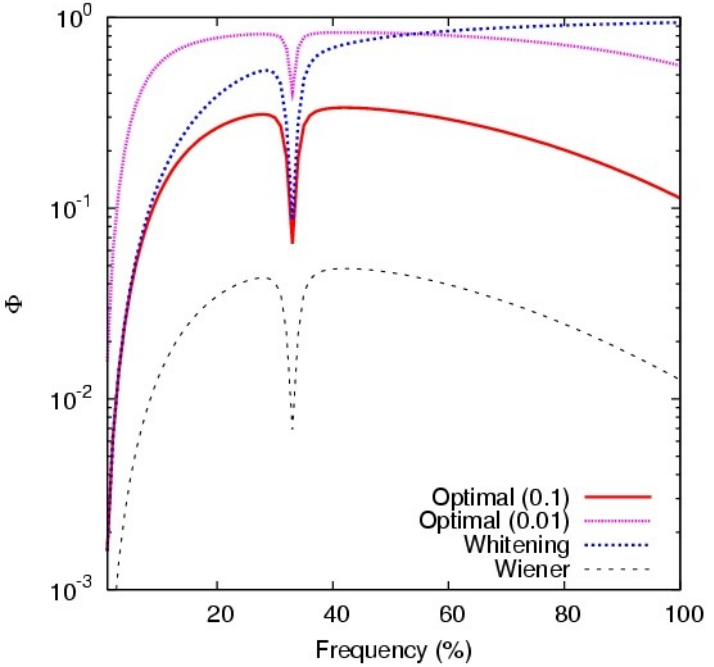


Filters

I. Practical Filtering...

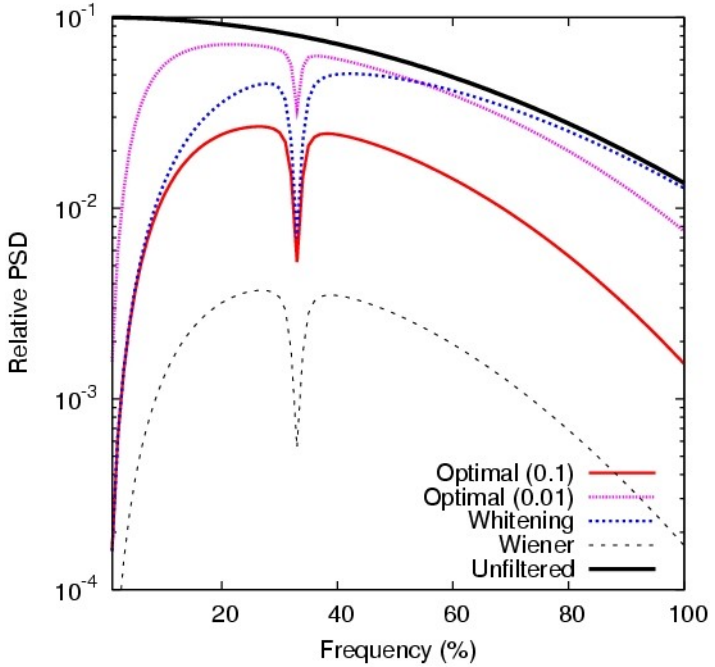
Noisy Signal Spectrum

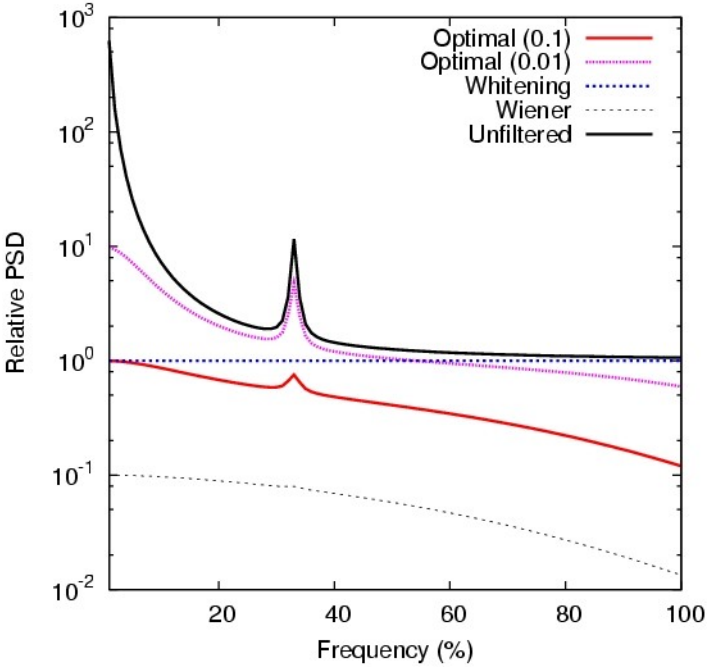




Filters

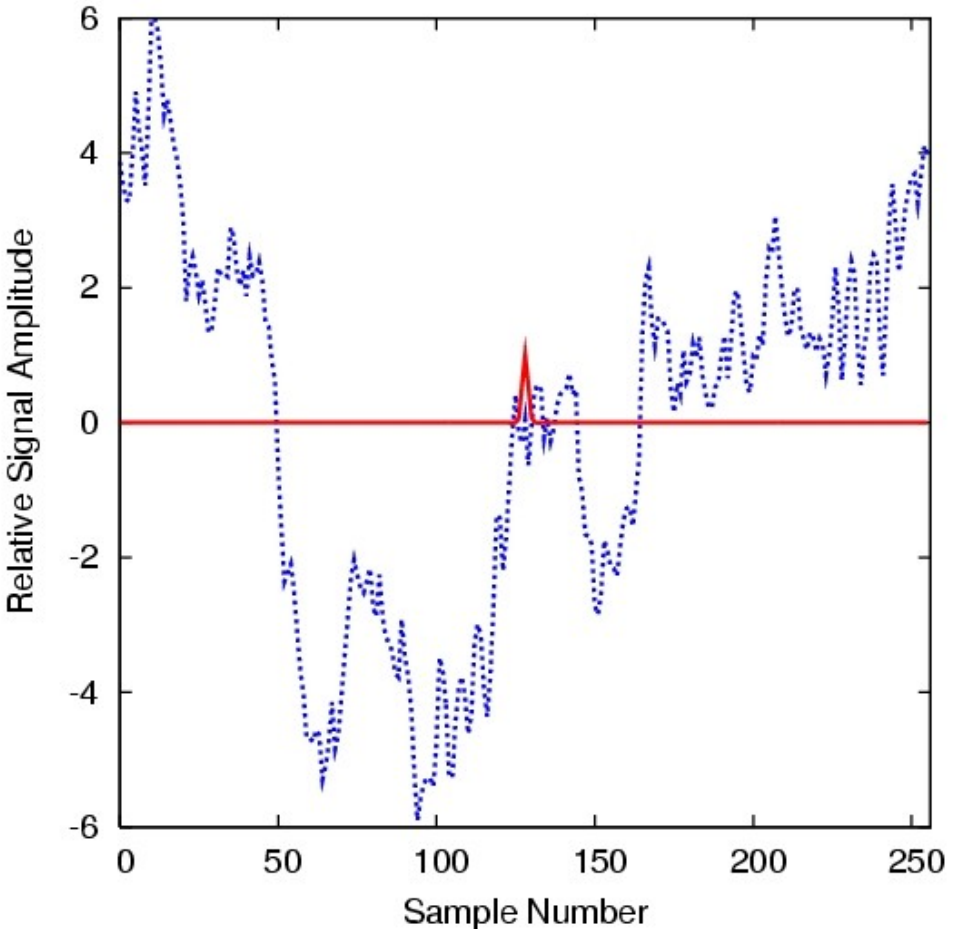
Filtered Source



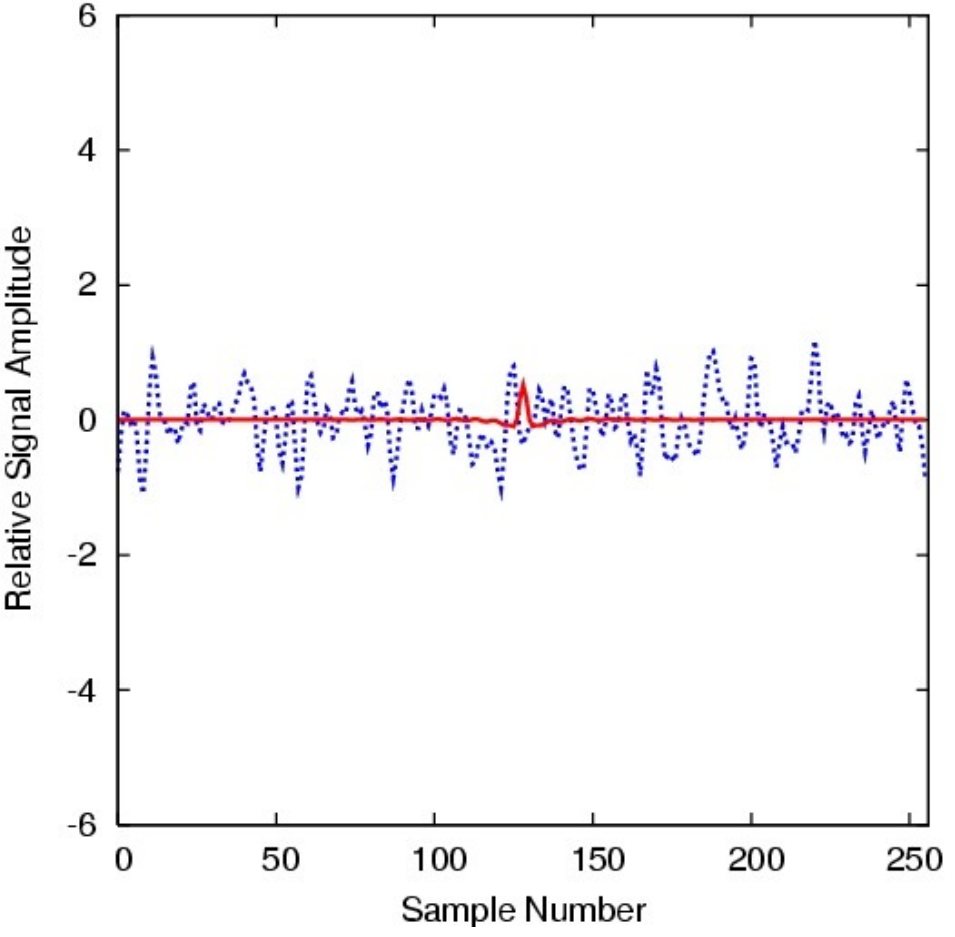


Filtered Noise

I. Practical Filtering (time stream)

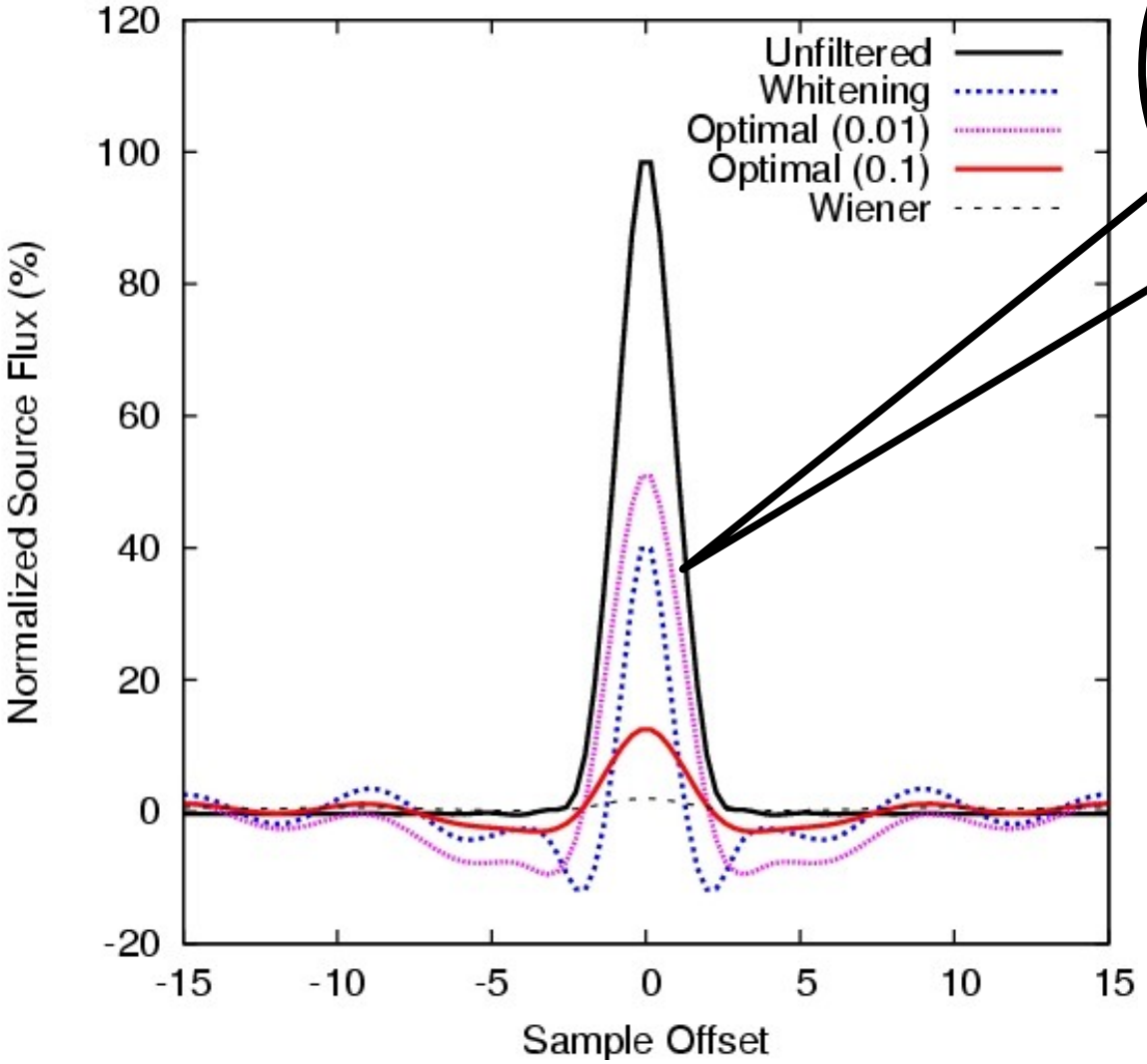


Original Signal



Filtered Signal

I. Filtering of Source Signals



Systematic Effect

If source shape is known then corrections...

II. Inversion Step Statistics

Combine several data points into single map pixel

weighted averages $$\langle X \rangle = \frac{\sum_i w_i X_i}{\sum_i w_i}$$

covariance matrix $$[C_D]_{k,l} = \mathbf{E}\left[(D_k - \langle D \rangle)(D_l - \langle D \rangle)\right]$$

optimal weights $$w_i \propto \sum_j [C_X^{-1}]_{i,j}$$

III. Gain Knowledge

Absolute Gains from External Calibration

$$\left|\frac{\delta g_i}{g_S}\right| \ll \frac{\langle|S|\rangle}{\langle|N_i|\rangle}$$

SHARC-2

Atmospheric Variations require gain knowledge to 4-5 significant figures.

IV. Observing Patterns

Sensitivity

Faithfulness

Robustness

Feasibility

Faster

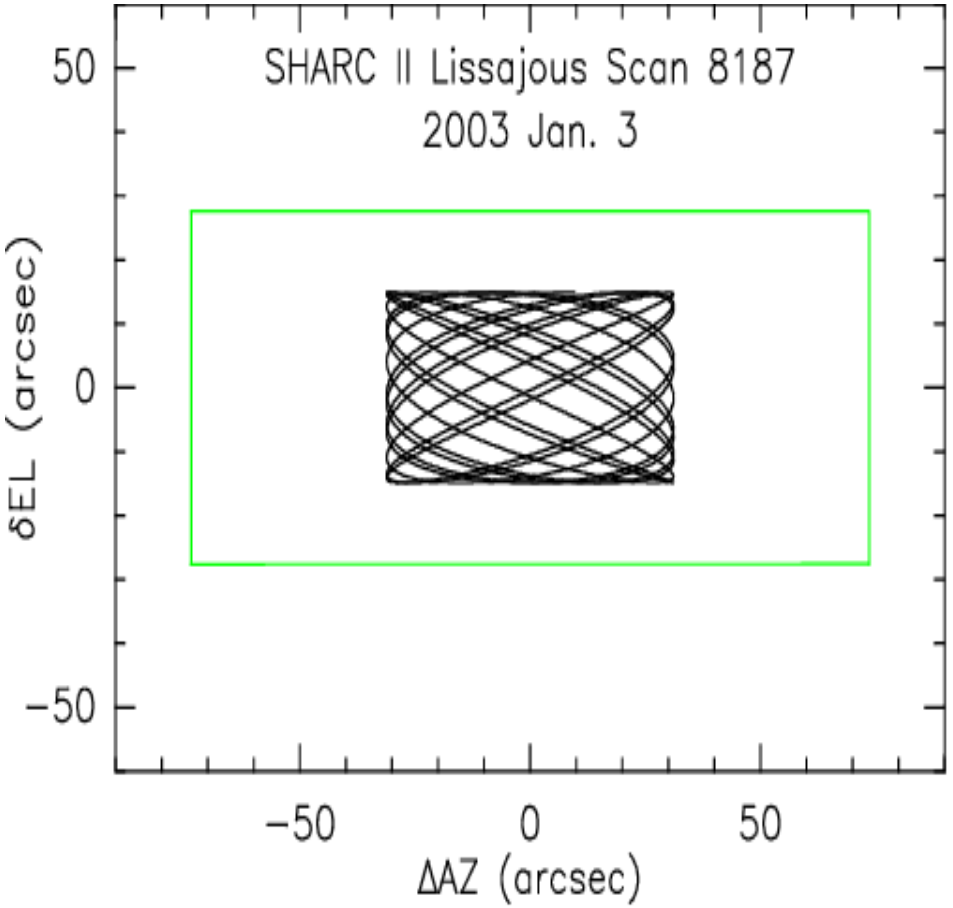
Crossing

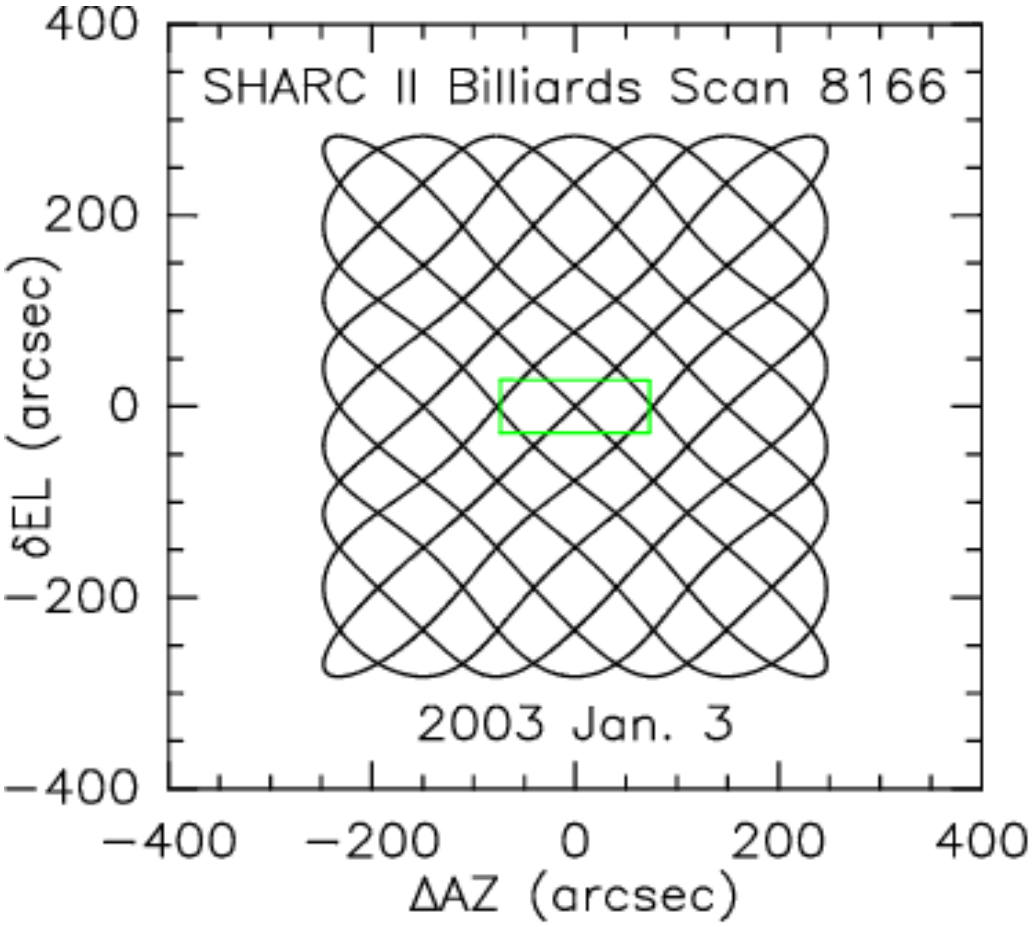
Random (appearance)

IV. Observing Patterns

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





General Conclusions

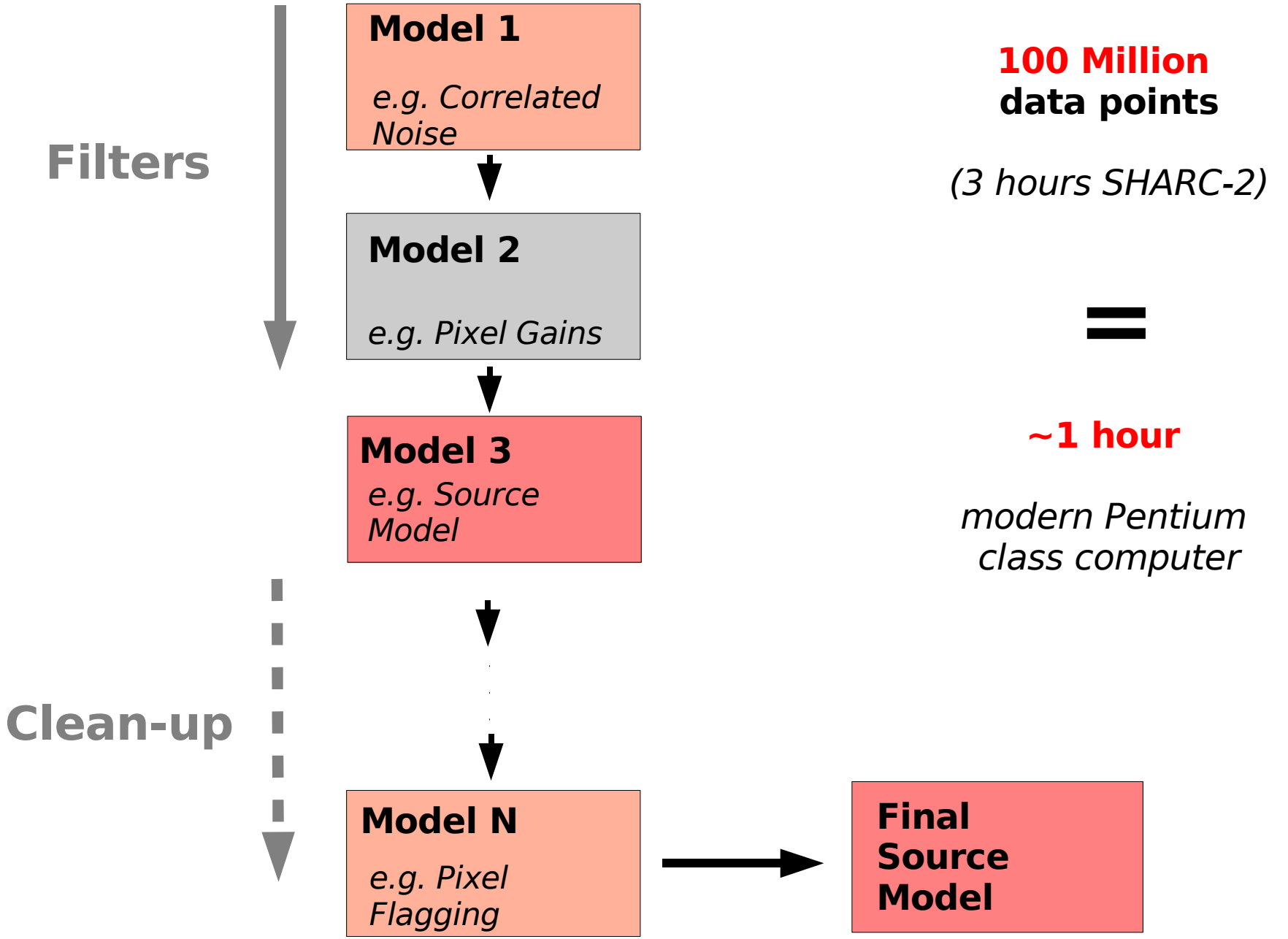
I. Optimal Filtering

II. Noise Weighting

III. Gain Knowledge

IV. Observing Patterns

CRUSH (an iterated pipeline)



Computing Requirements...

	Brute Force	Clever (CMB Mapping)	CRUSH
$\mathcal{A}$	N^3	N	N
$\mathcal{F}$	N^2	$N \log N$	N

CRUSH: Inside

Statistical Estimators
(Maximum Likelihood, Maximum Entropy, Robust)

Weights from Residual Noise Properties

Gains from correlated detector response

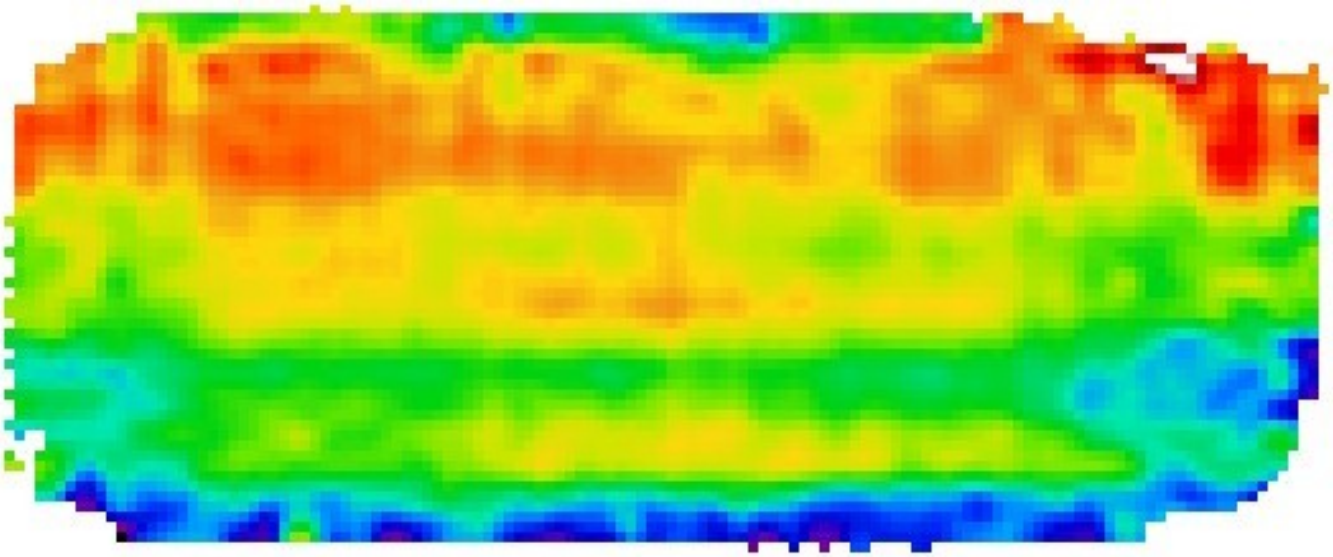
Statistical Tests for Identifying Bad Data

Filtering from Ordering

Convergence in a handful of iterations...

Source Generation 0 – Direct Mapping

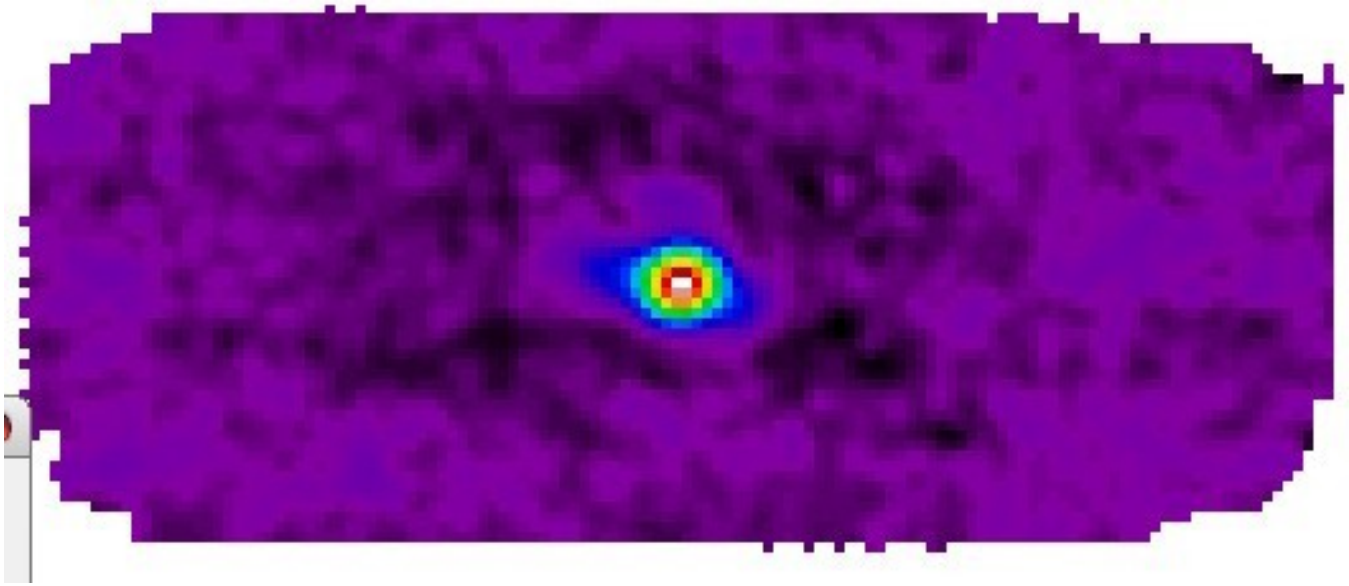
$\chi^2 = 442602$



VESTA (~5Jy)
4 January 2003

Source Generation 1

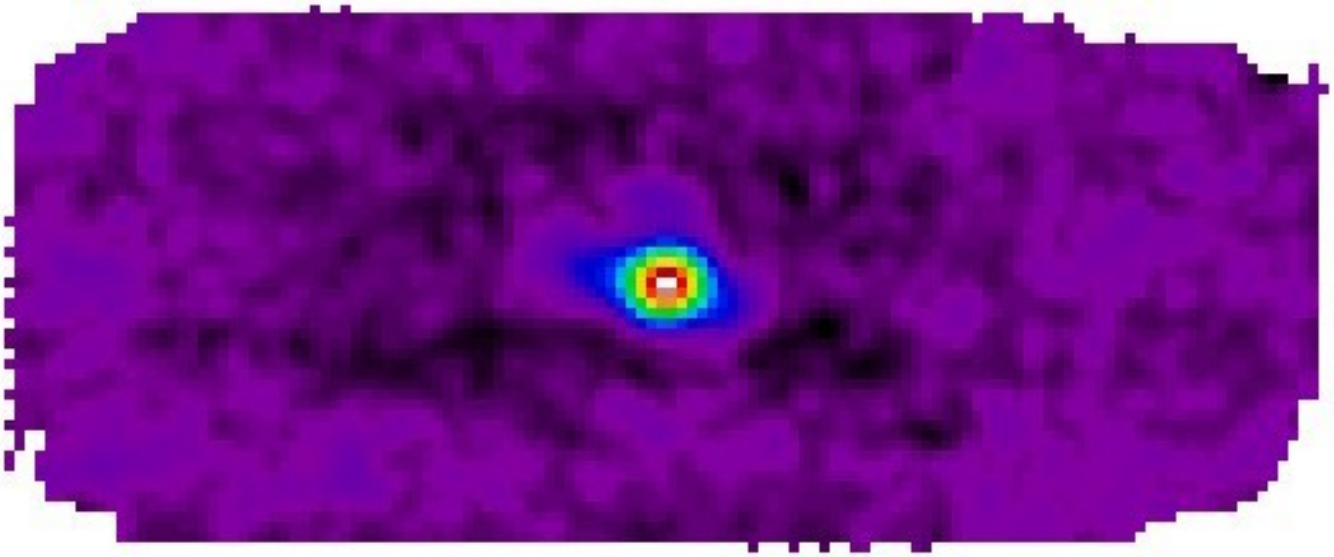
$$\chi^2 = 1.161$$



VESTA (~5Jy)
4 January 2003

Source Generation 2

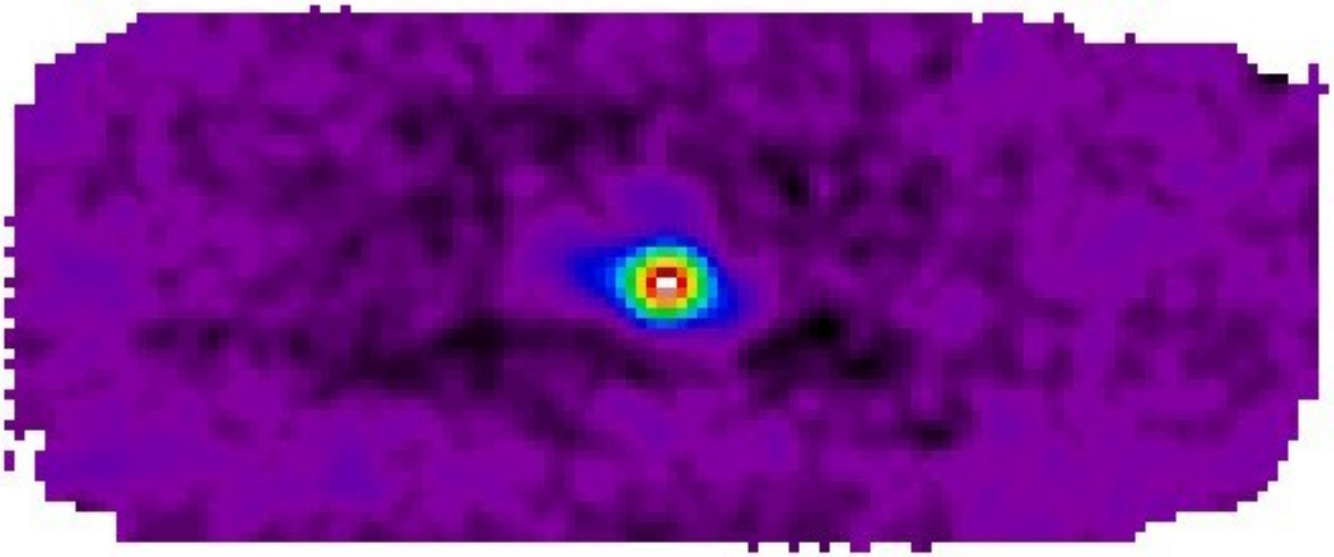
$\chi^2 = 1.045$



VESTA (~5Jy)
4 January 2003

Source Generation 3

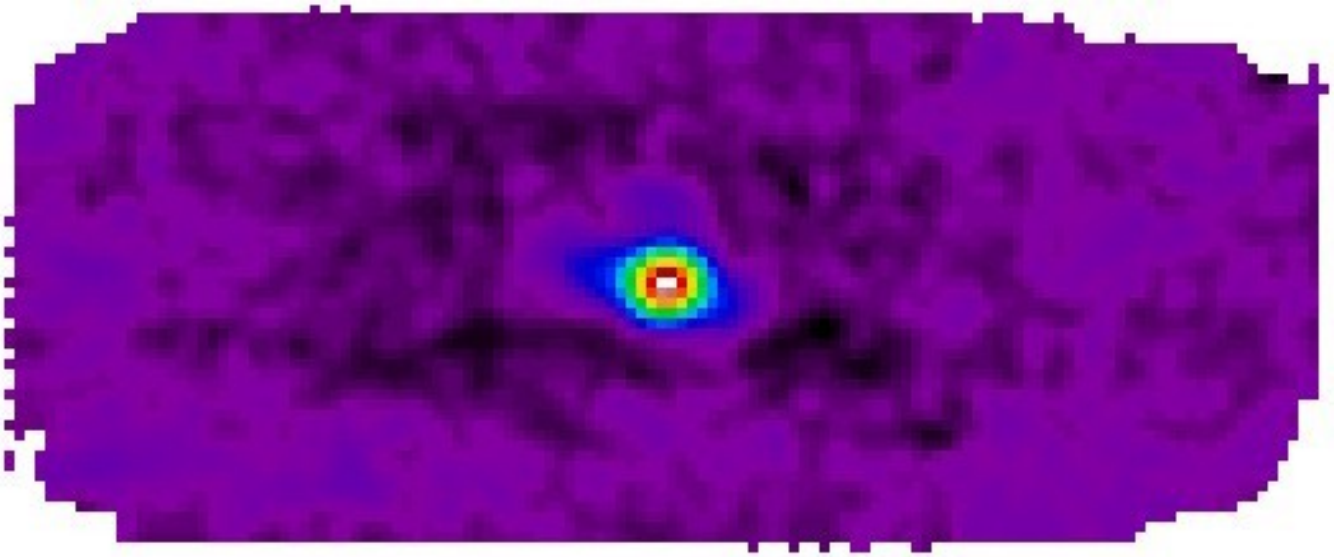
$\chi^2 = 1.050$



VESTA (~5Jy)
4 January 2003

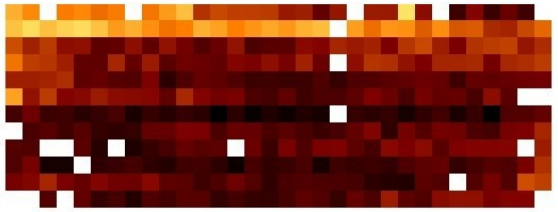
Source Generation 10

$\chi^2 = 1.058$



VESTA (~5Jy)
4 January 2003

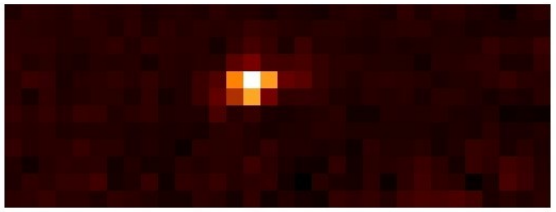
CRUSH: Model Breakdown



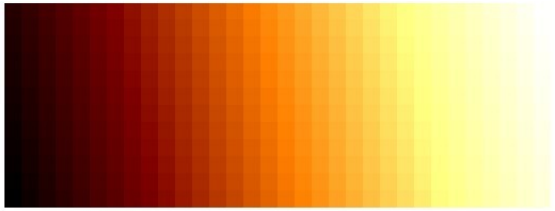
Static
Residual Pixel
Offsets
~ 100 Jy

Vesta 8293
5 January 2003
Excellent Conditions

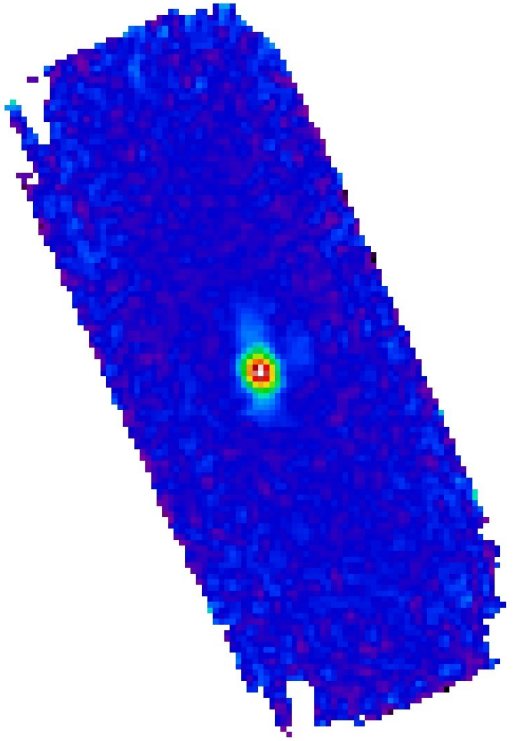
Source Model
~ 5 Jy



Gradients
~ 0.3 Jy

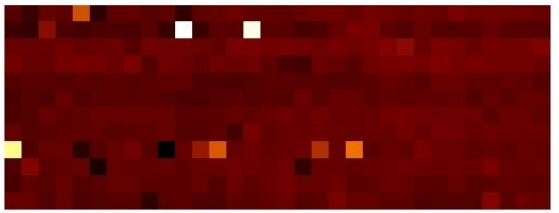


=



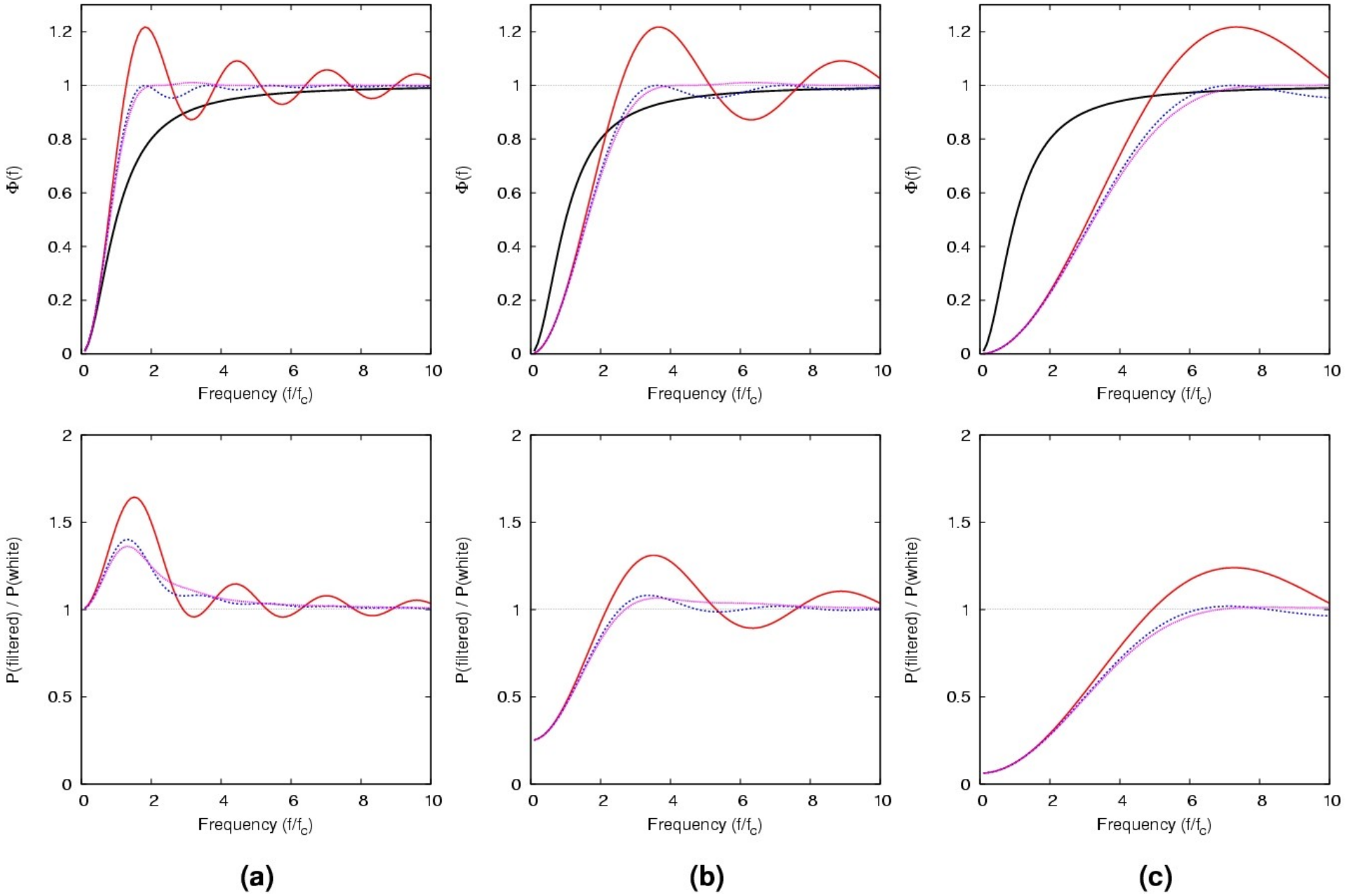
Electronic
Row Drifts
~ 0.3 Jy

Detector 1/f
Drift Model
~ 0.1 Jy

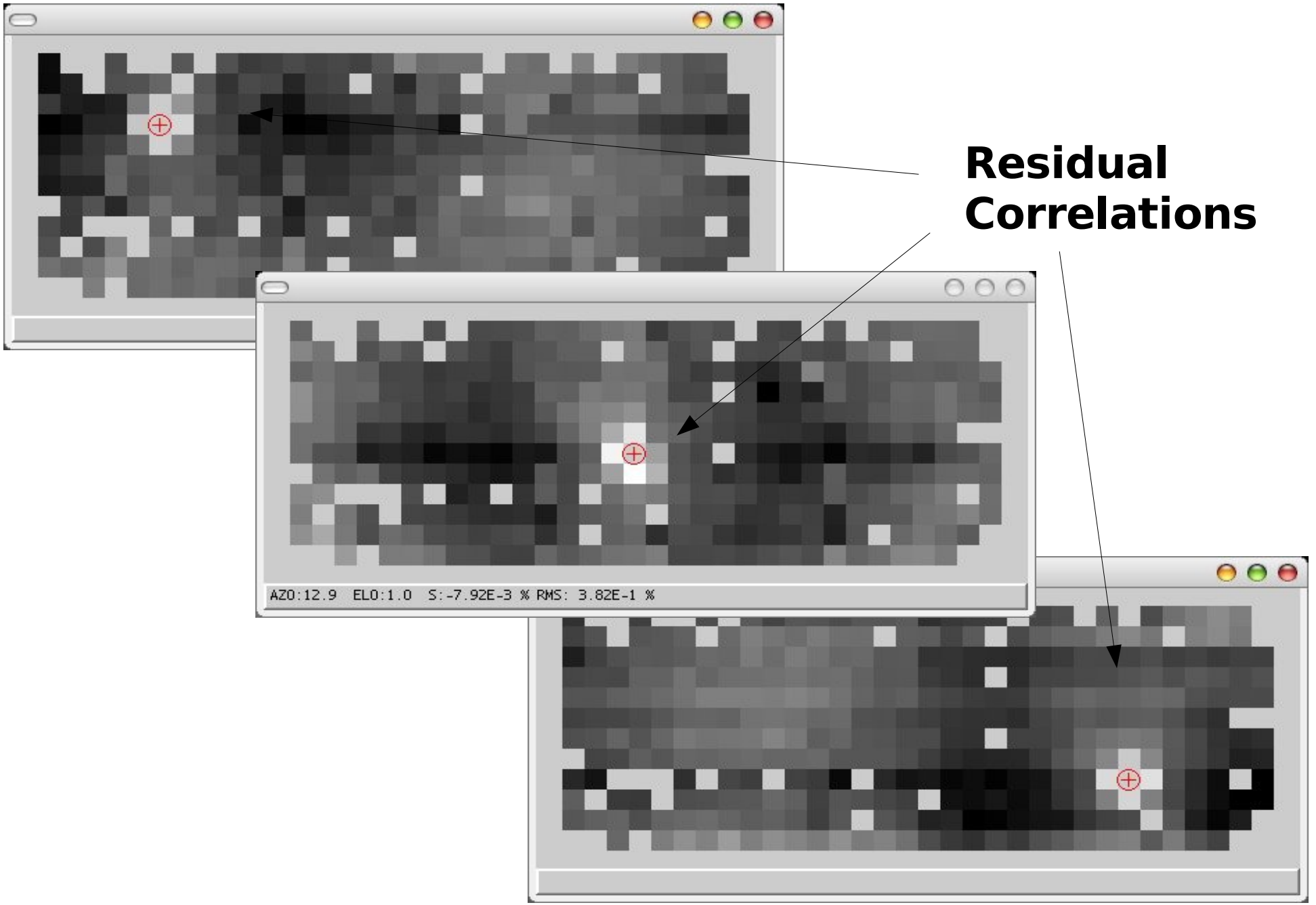


CRUSH: Filtering Properties ($1/f^2$)

Nearly Optimal



CRUSH: Residual Noise Structure



CRUSH: Conclusions

Fast

Close to Optimal

Configurable

Non-linear Capable

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

CRUSH: Conclusions

Fast

Close to Optimal

Configurable

Non-linear Capable

Optimal for:

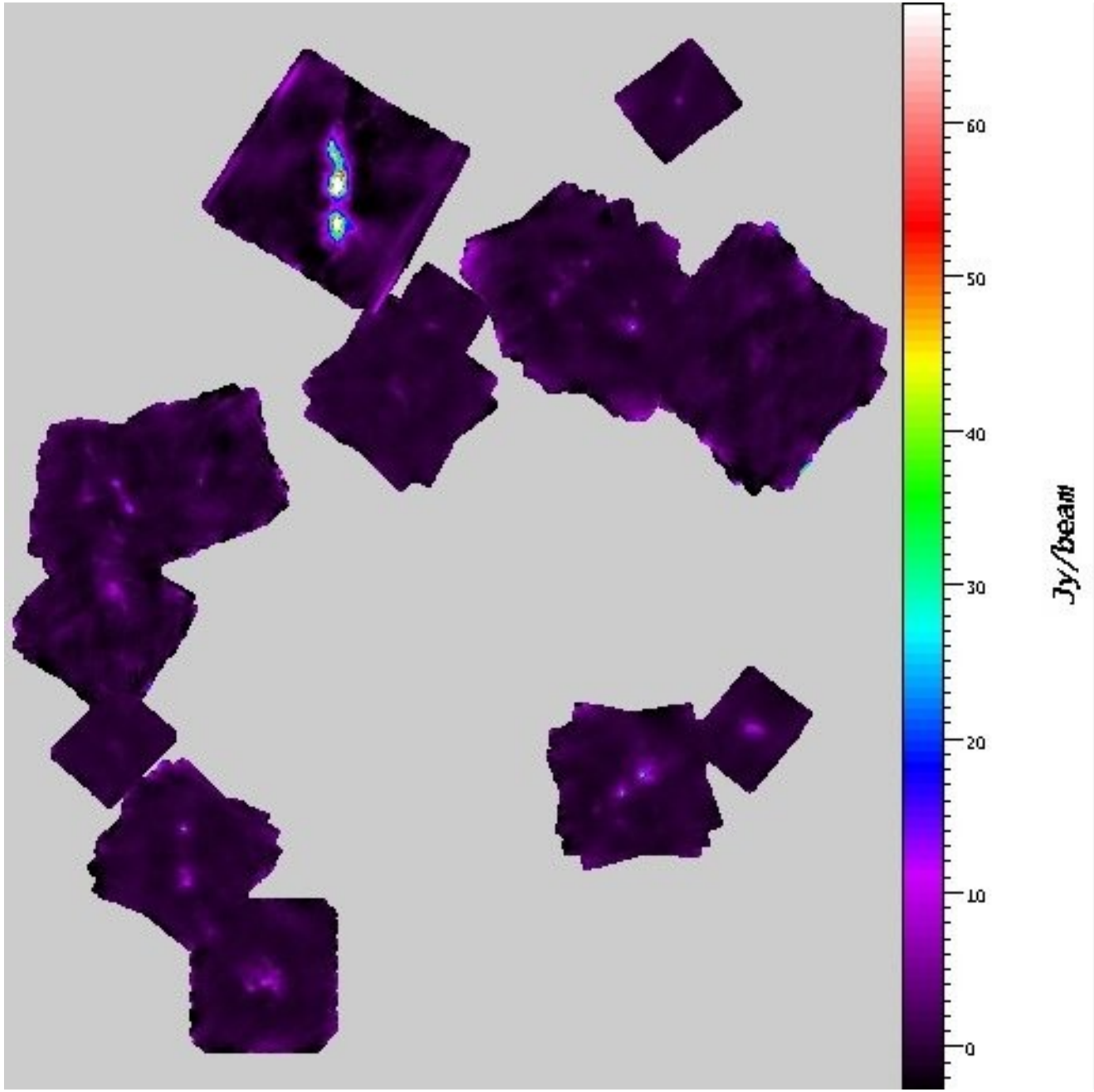
Future Large Bolometer Arrays (SCUBA-2)

Any other experiment with correlated 1/f type noise interference
(e.g. heterodyne spectrometers)

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

SHARC2 Gallery

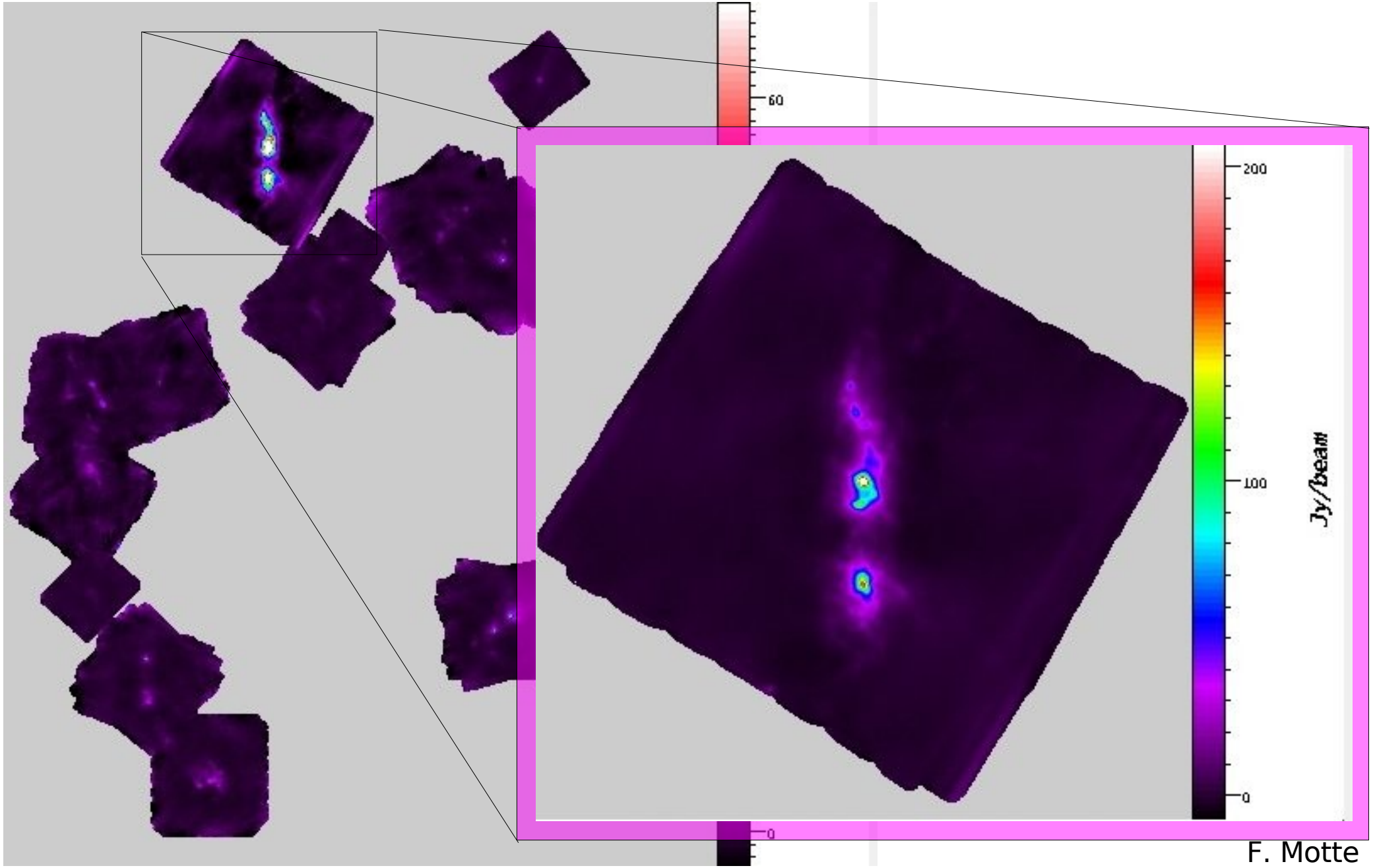
Protostars in Cygnus X



F. Motte

SHARC2 Gallery

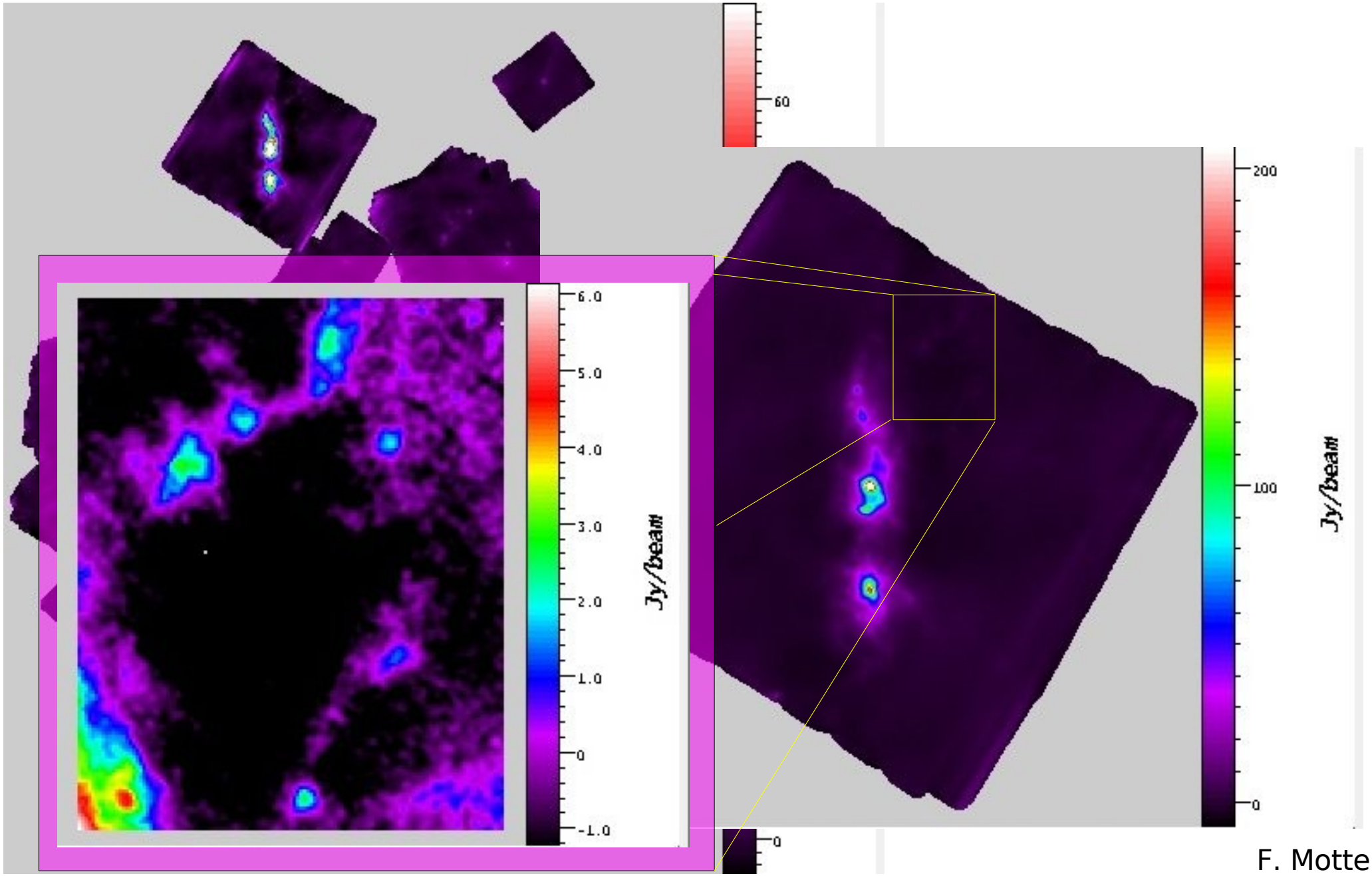
Protostars in Cygnus X



F. Motte

SHARC2 Gallery

Protostars in Cygnus X



F. Motte

Acknowledgements

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Andrew Blain

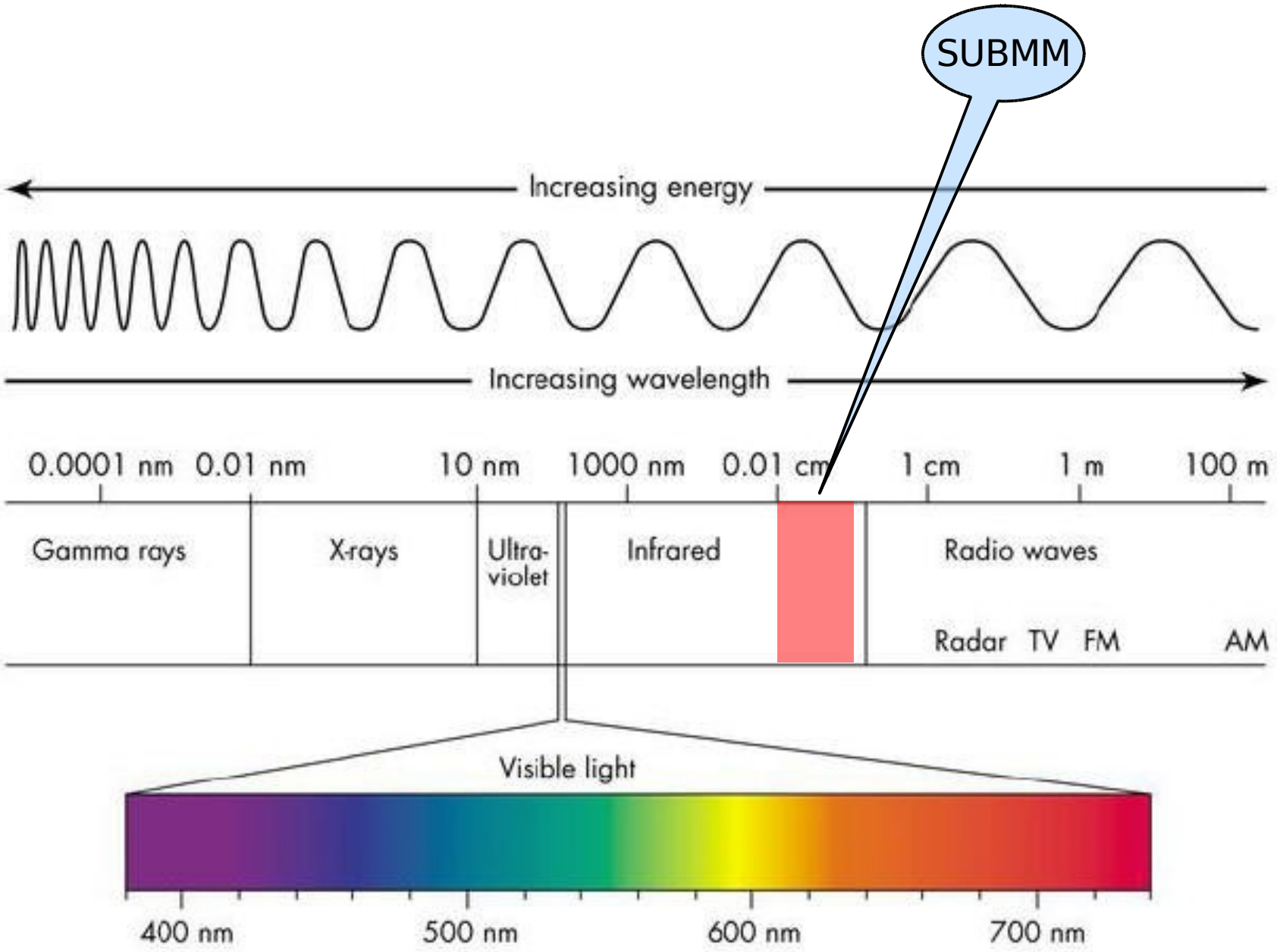
Marc Kamionkowski

Darren Dowell
&
the Submillimeter Group

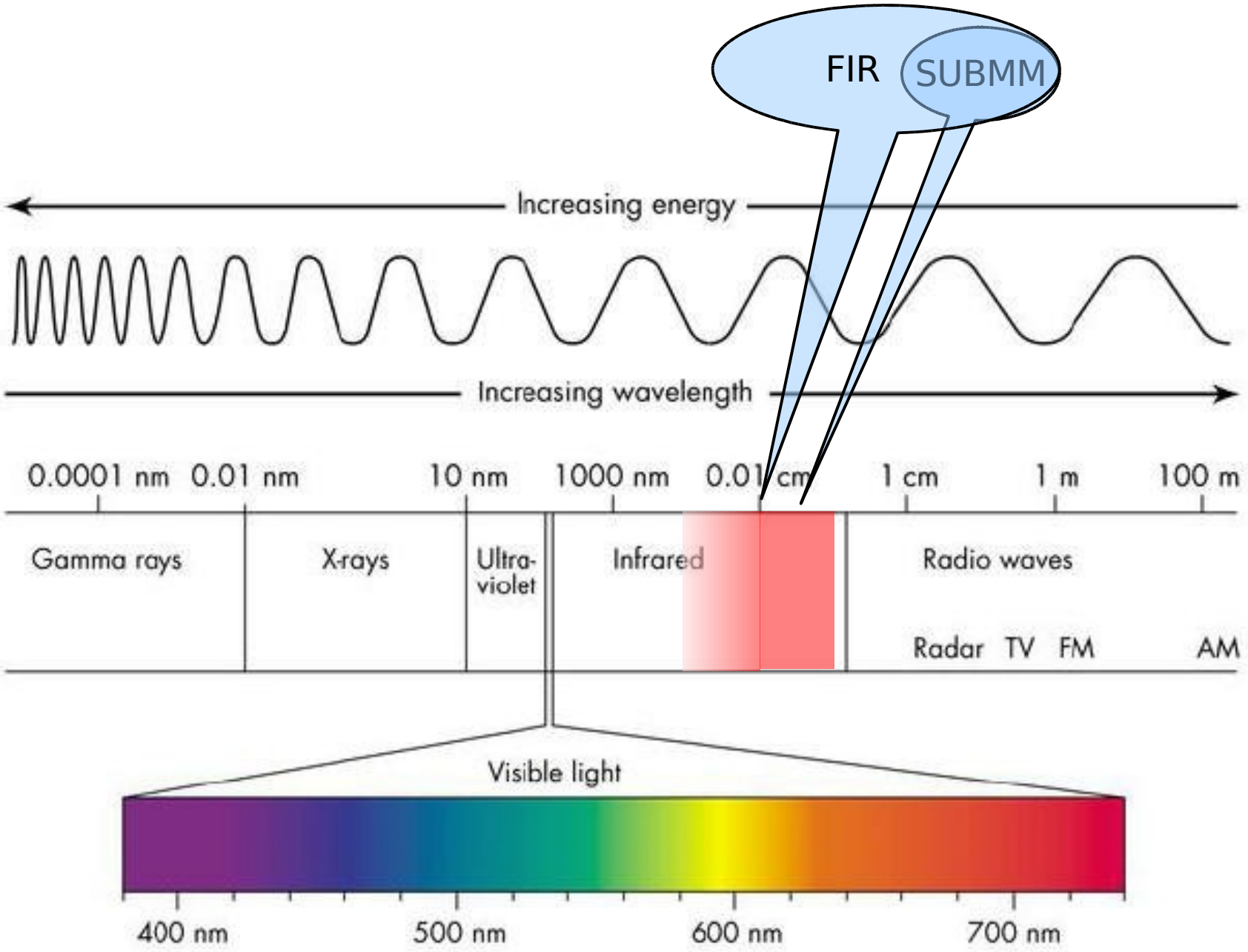
Connie

and friends!

Submillimeter & Far-Infrared



Submillimeter & Far-Infrared



Submillimeter & Far-Infrared