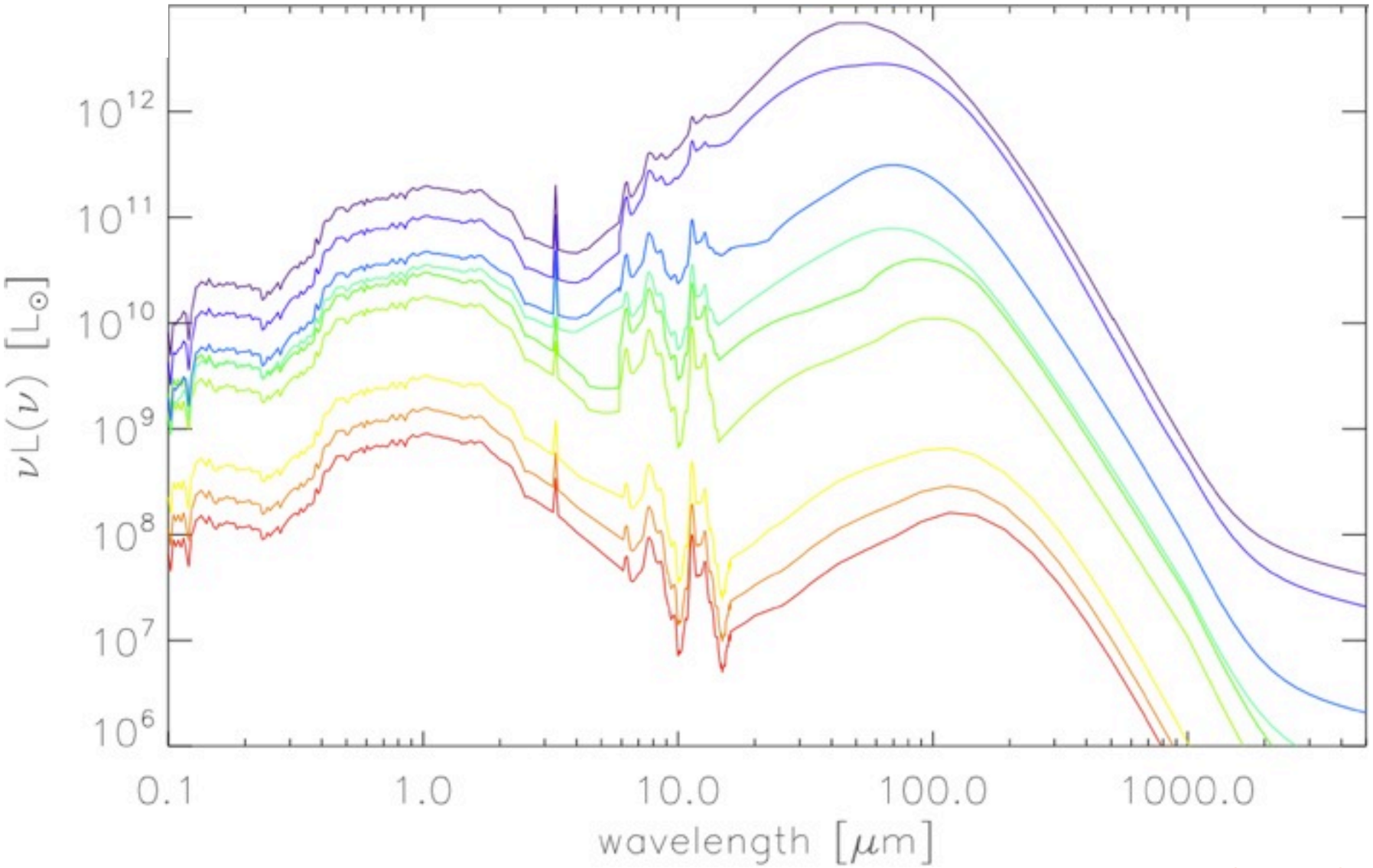
Clustering of Dusty Star-Forming Galaxies

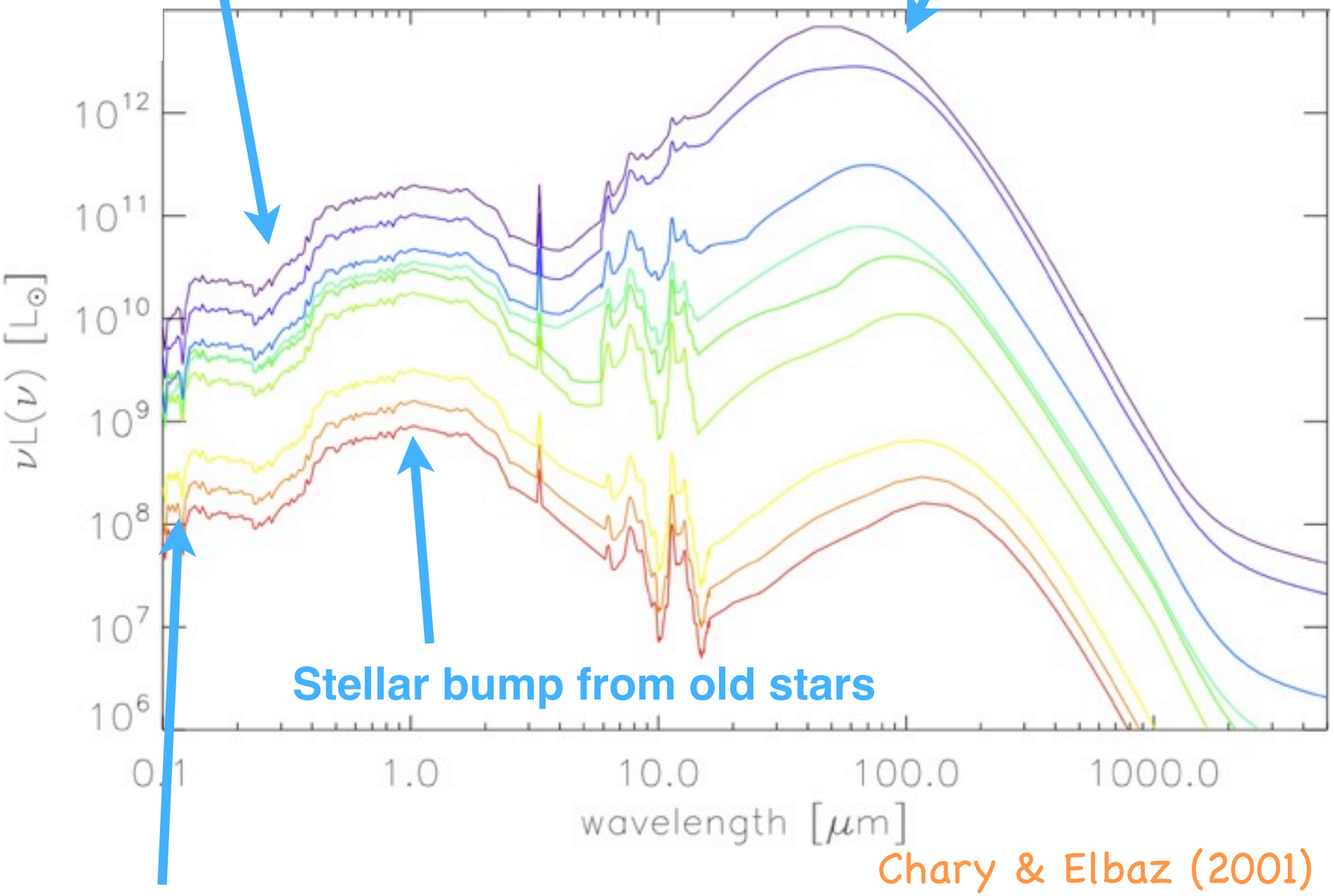
marco viero



Chary & Elbaz (2001)

Dust re-emits in the FIR

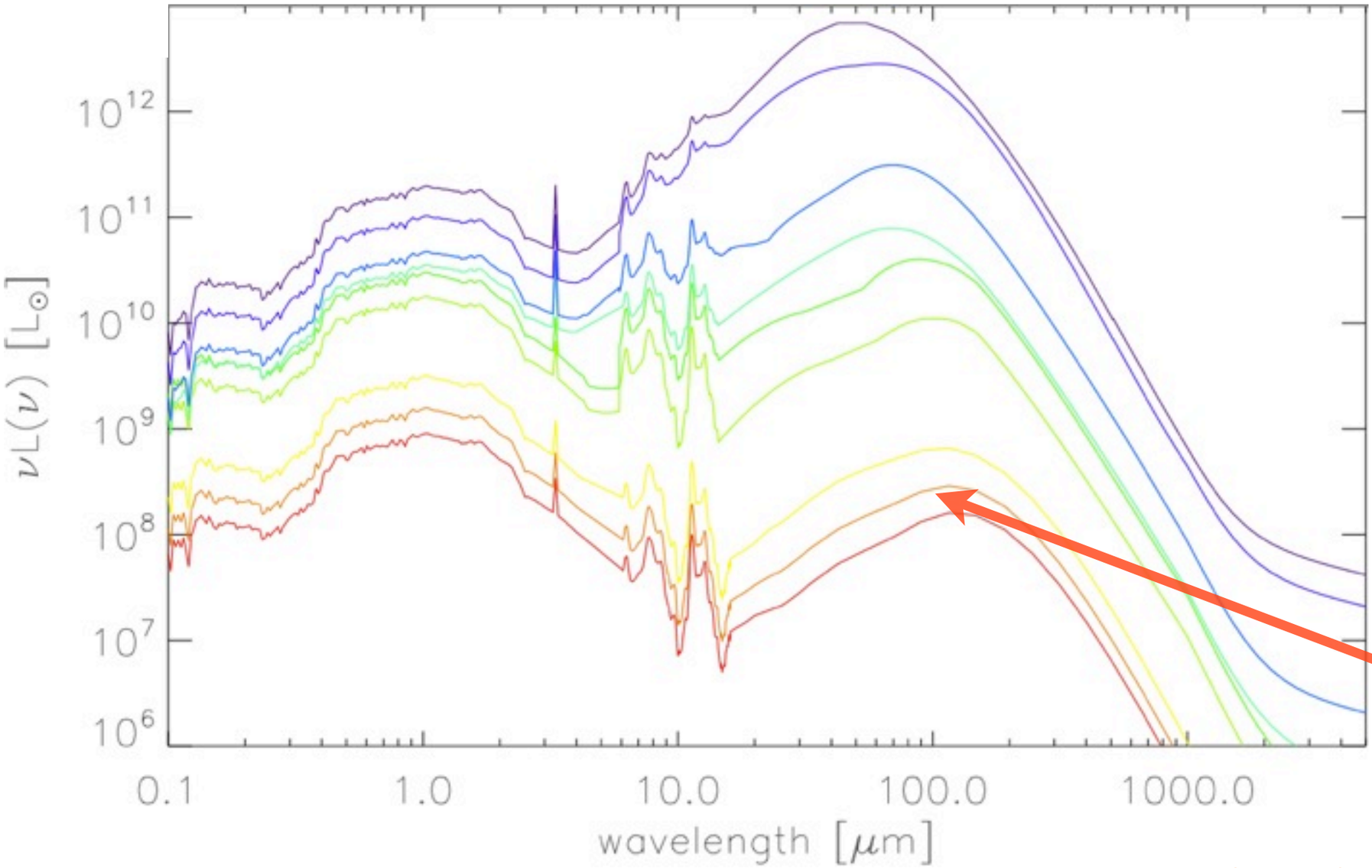
Optical/UV Starlight absorbed by dust



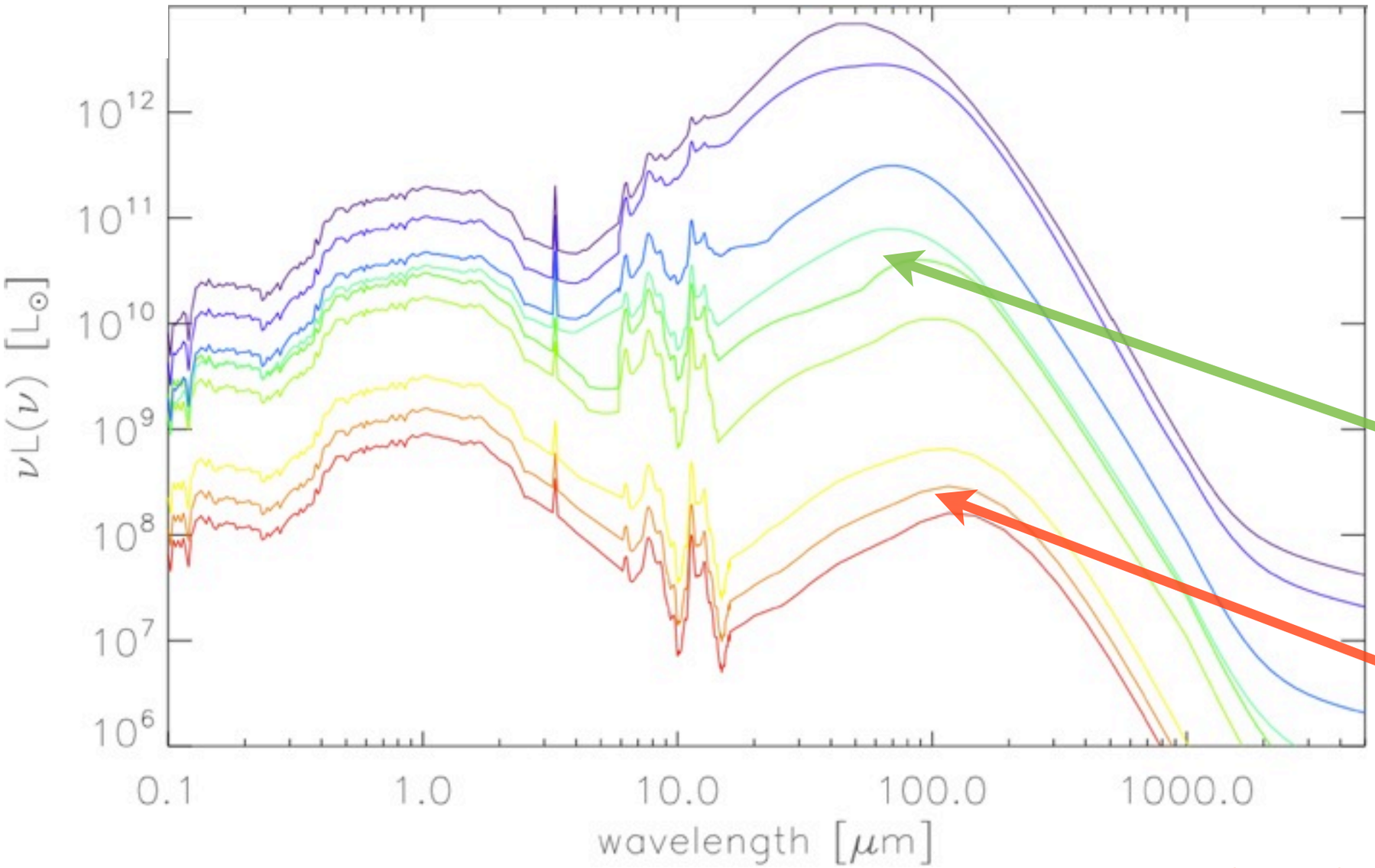
Stellar bump from old stars

Chary & Elbaz (2001)

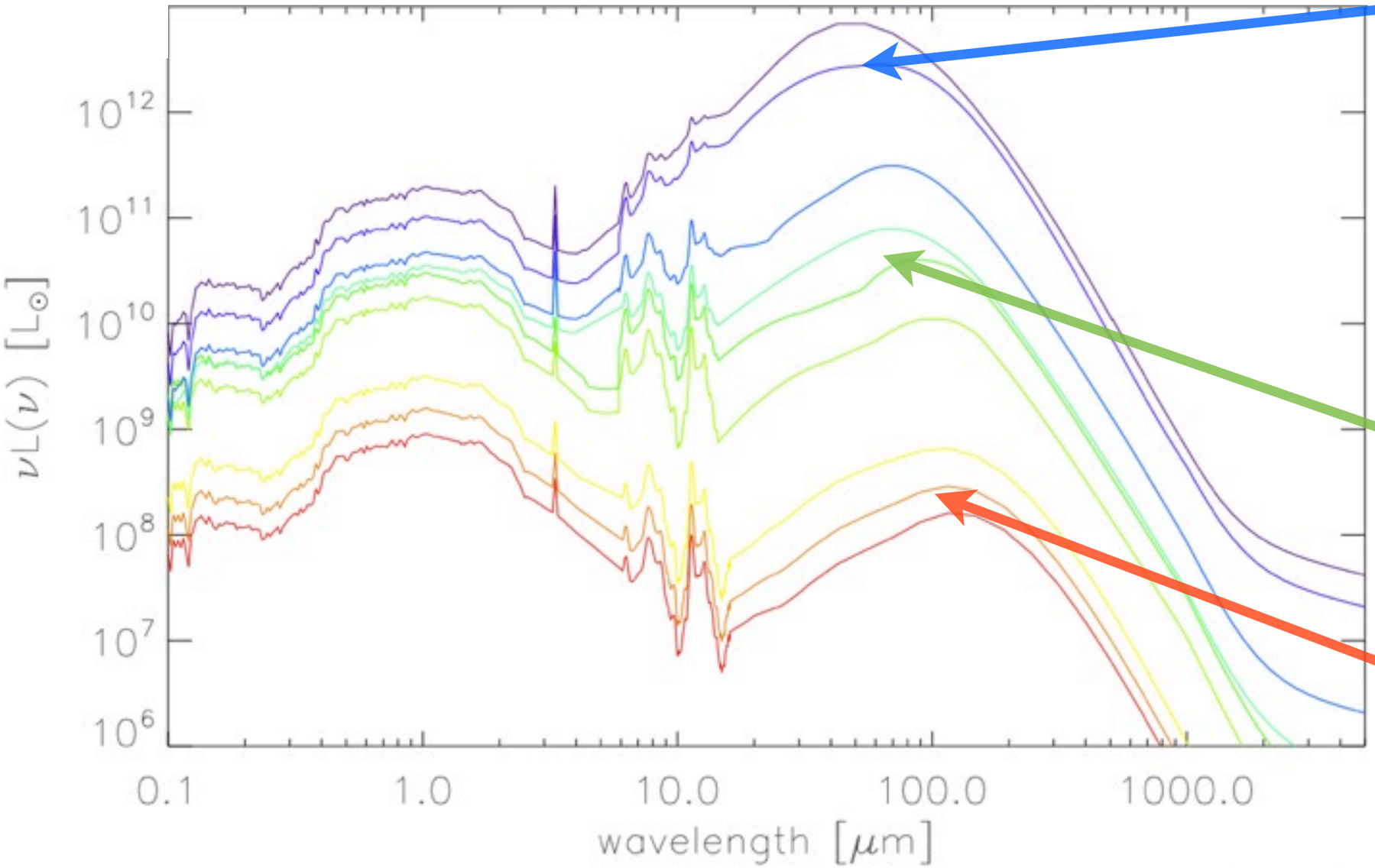
UV from young, hot stars



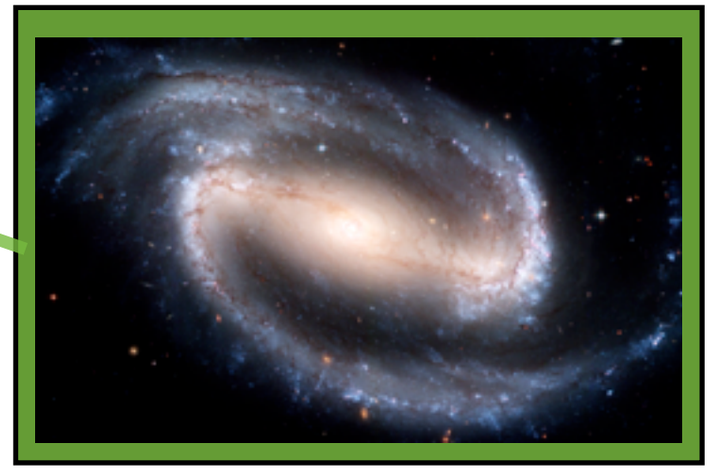
Chary & Elbaz (2001)

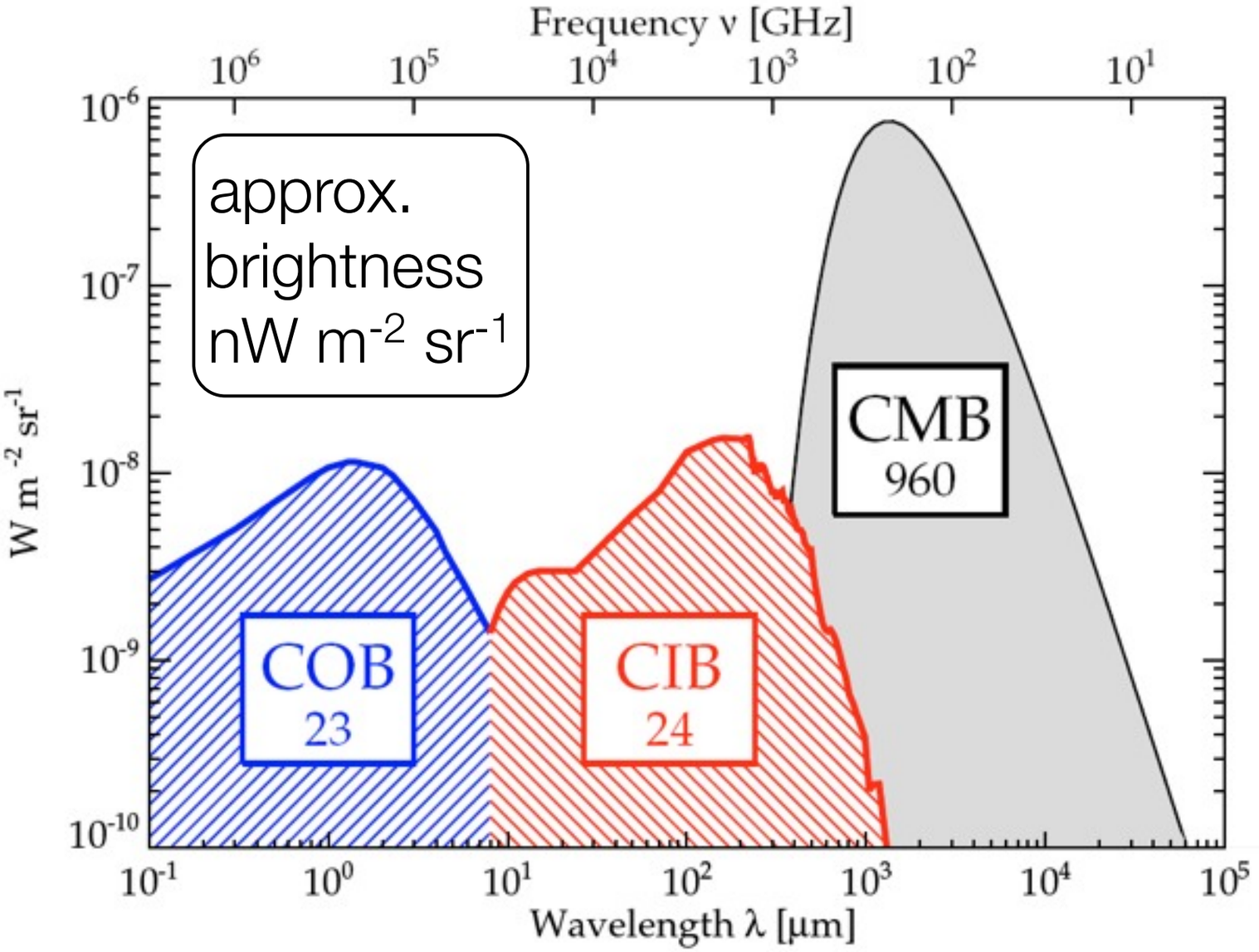


Chary & Elbaz (2001)



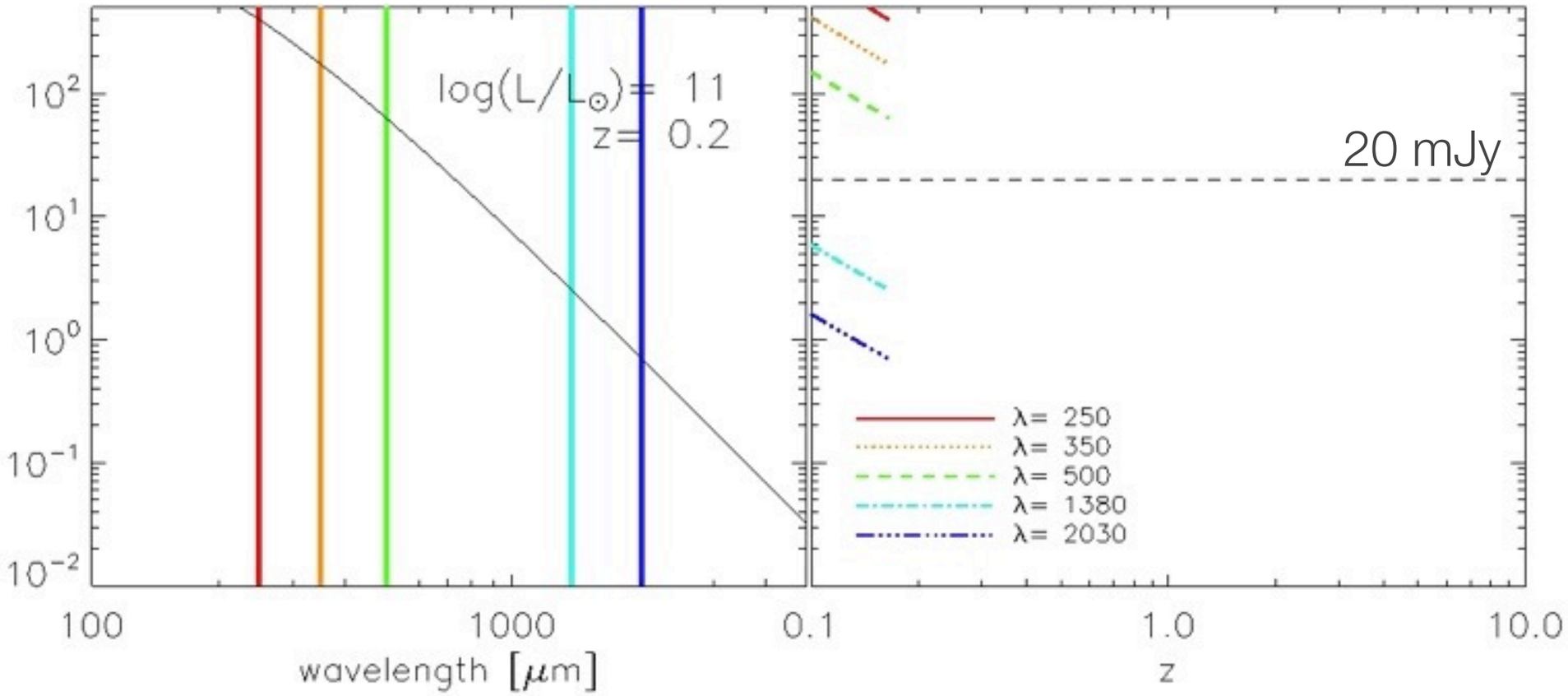
Chary & Elbaz (2001)



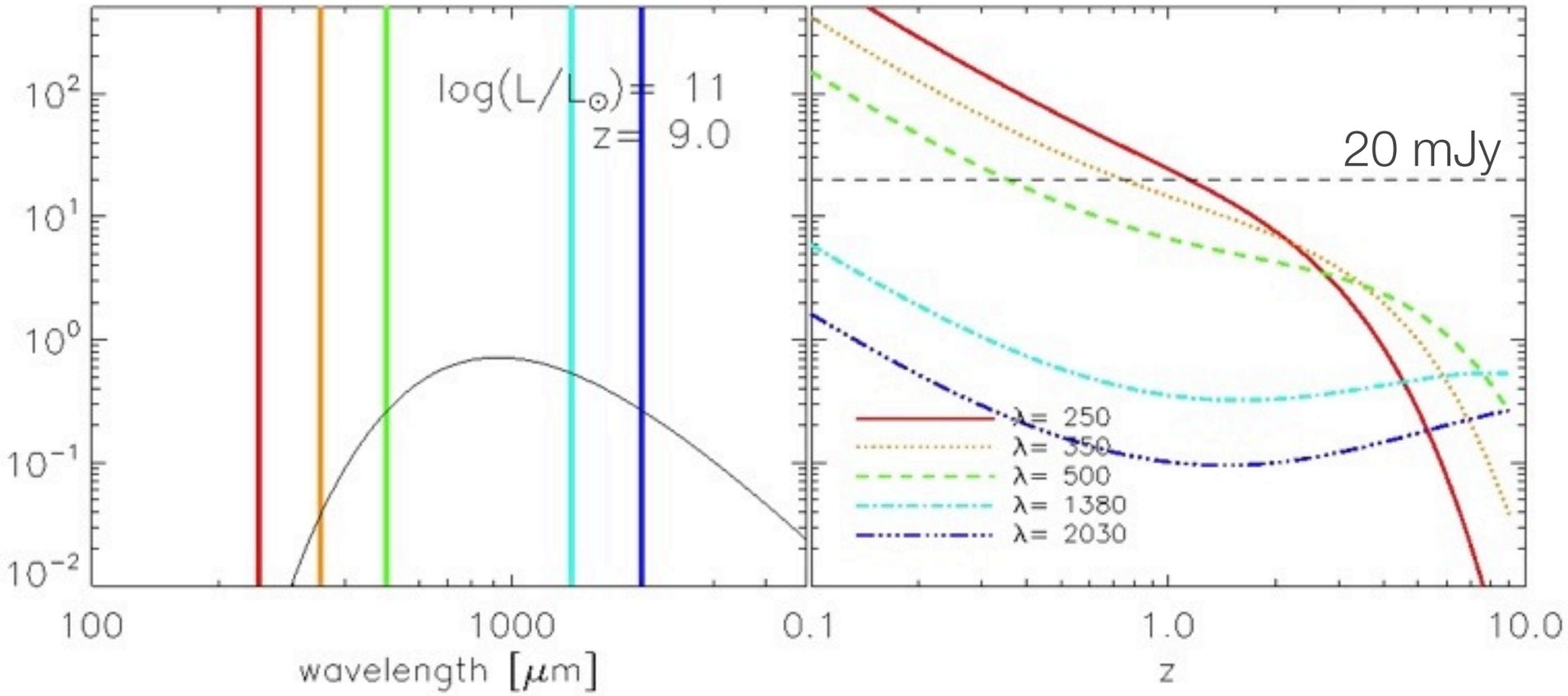


Dole et al. 2006

Extragalactic Background Light (EBL)

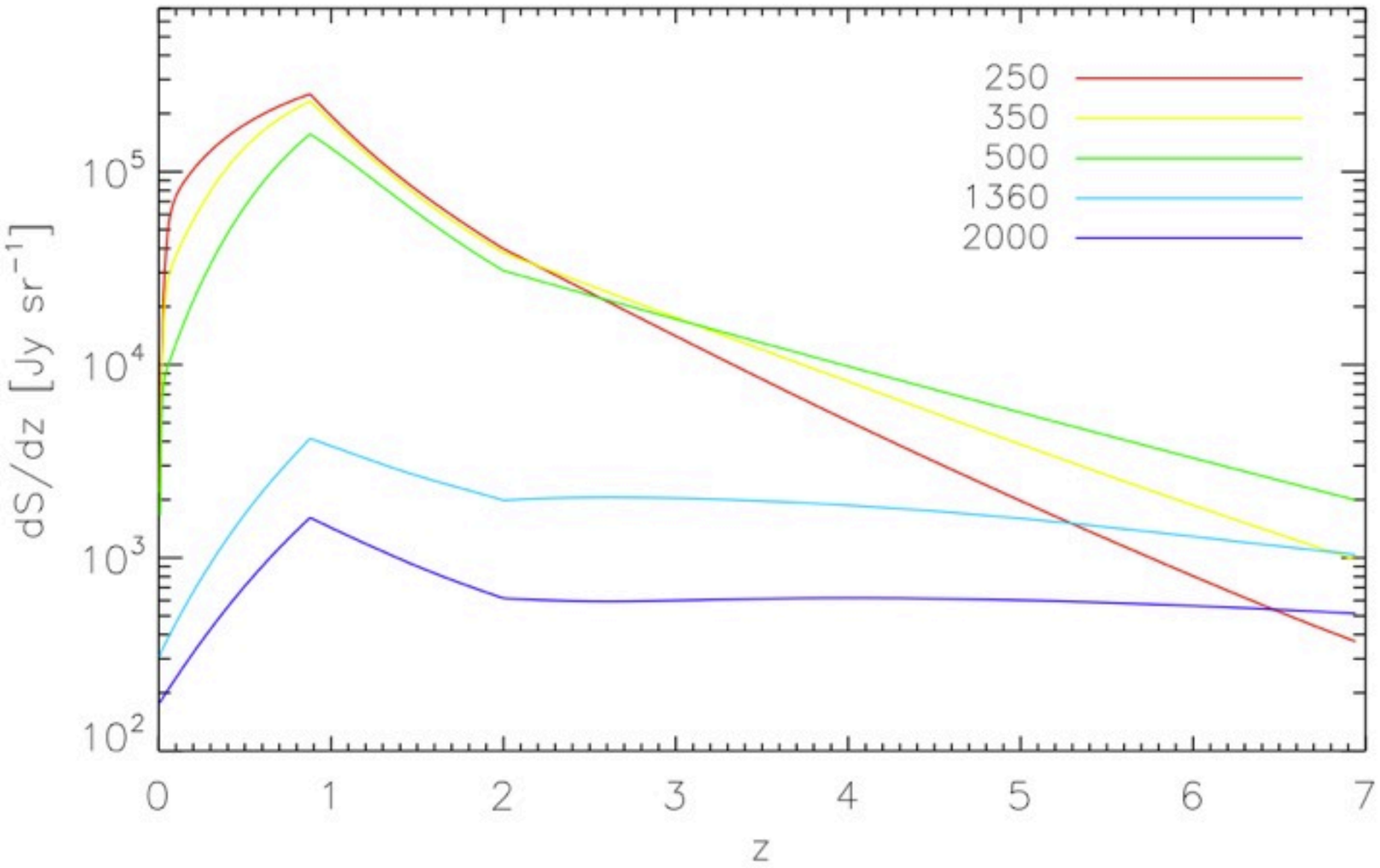


Negative K-correction



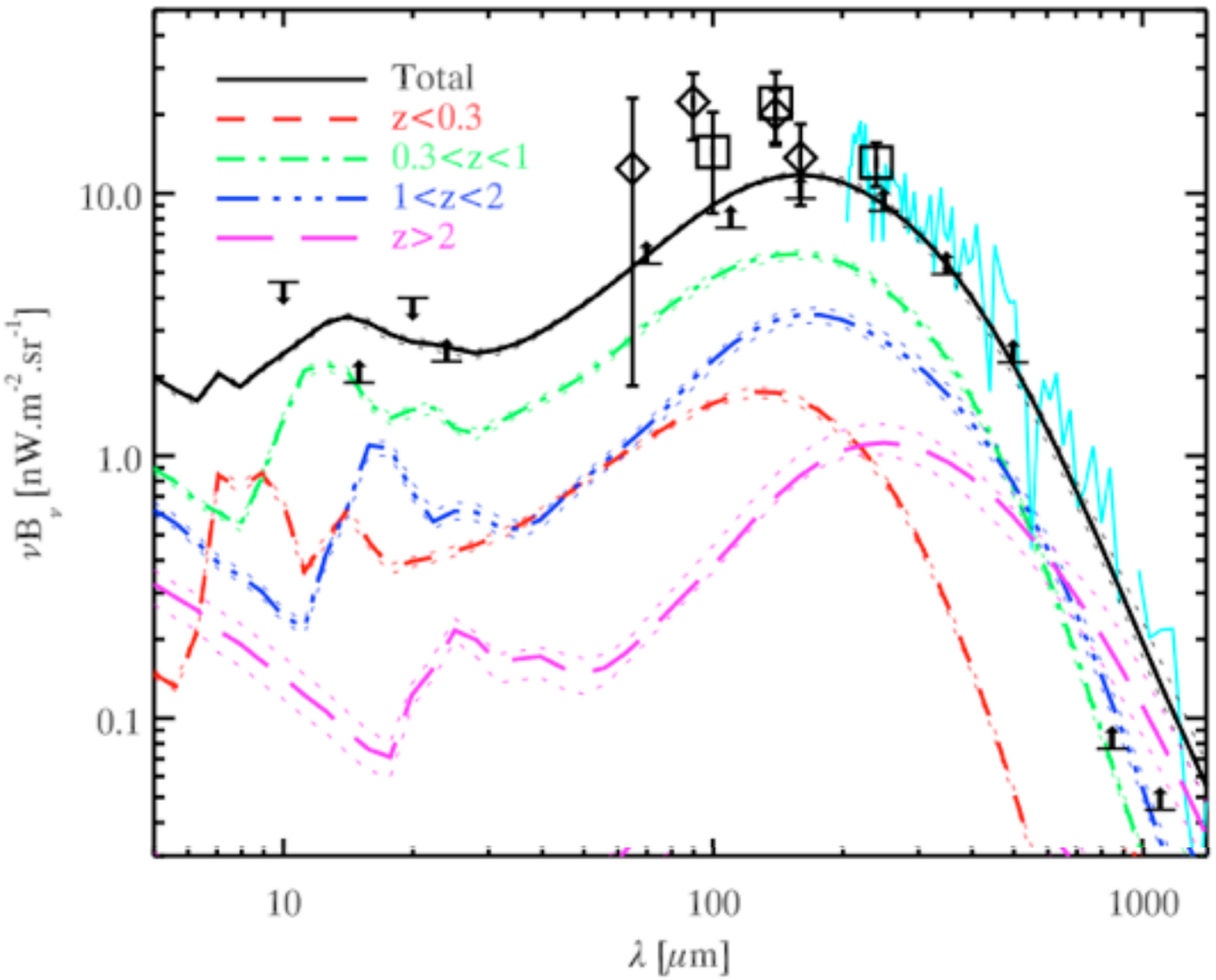
Negative K-correction

get this data @ http://www.ias.u-psud.fr/irgalaxies/model.php#Counts



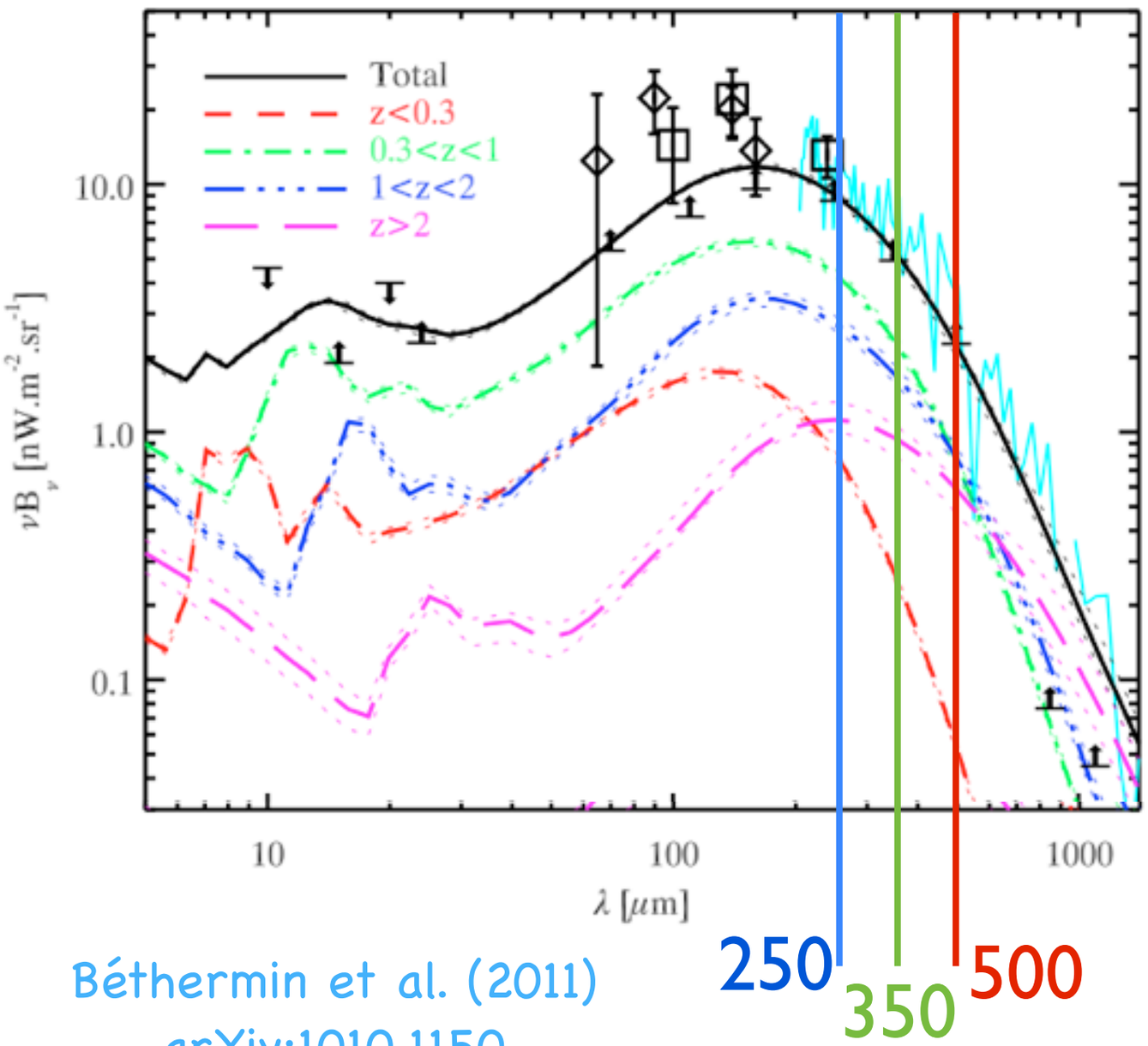
Béthermin et al. (2011)
arXiv:1010.1150

Redshift Distribution



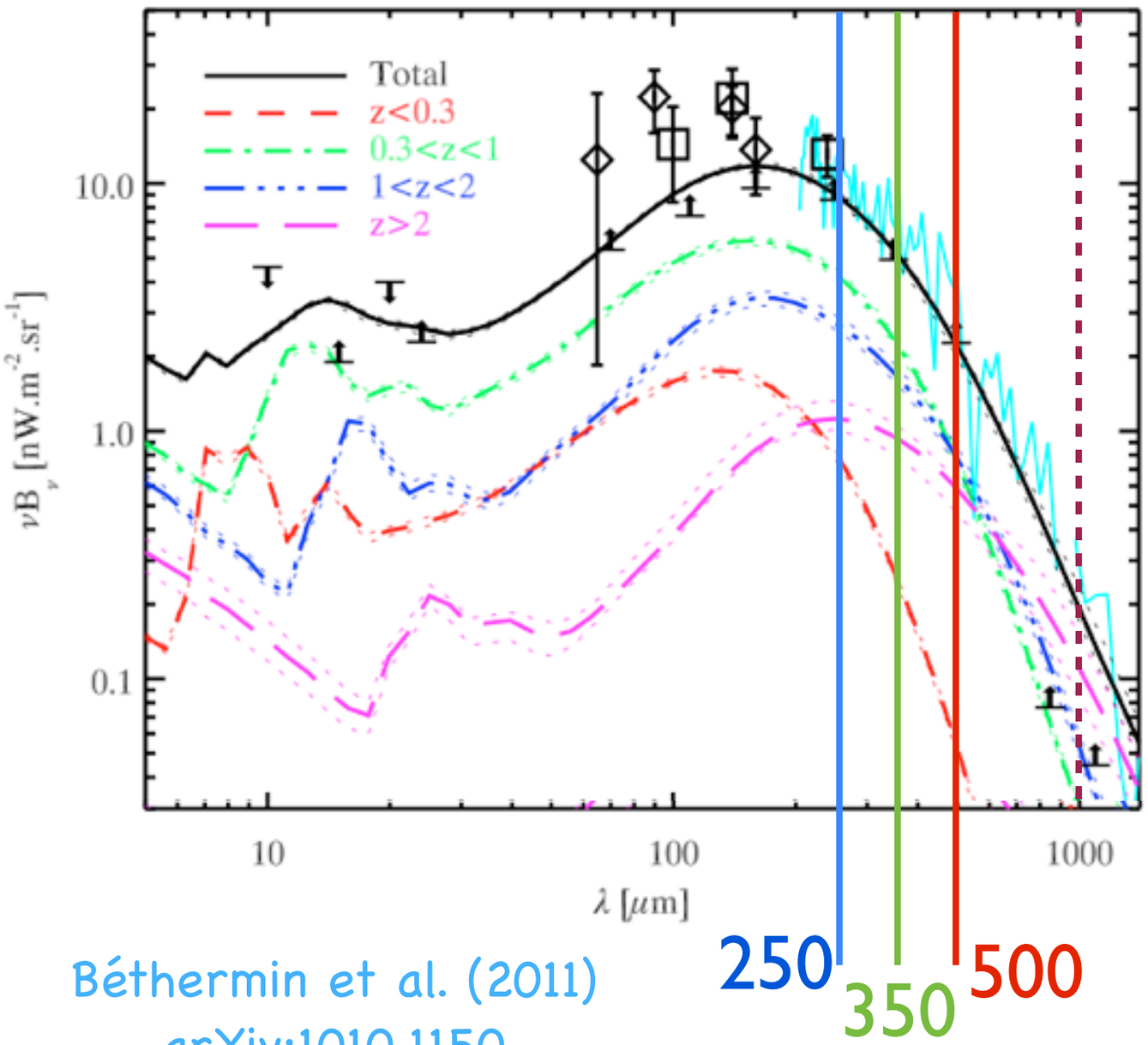
Béthermin et al. (2011)
arXiv:1010.1150

Total Infrared Background



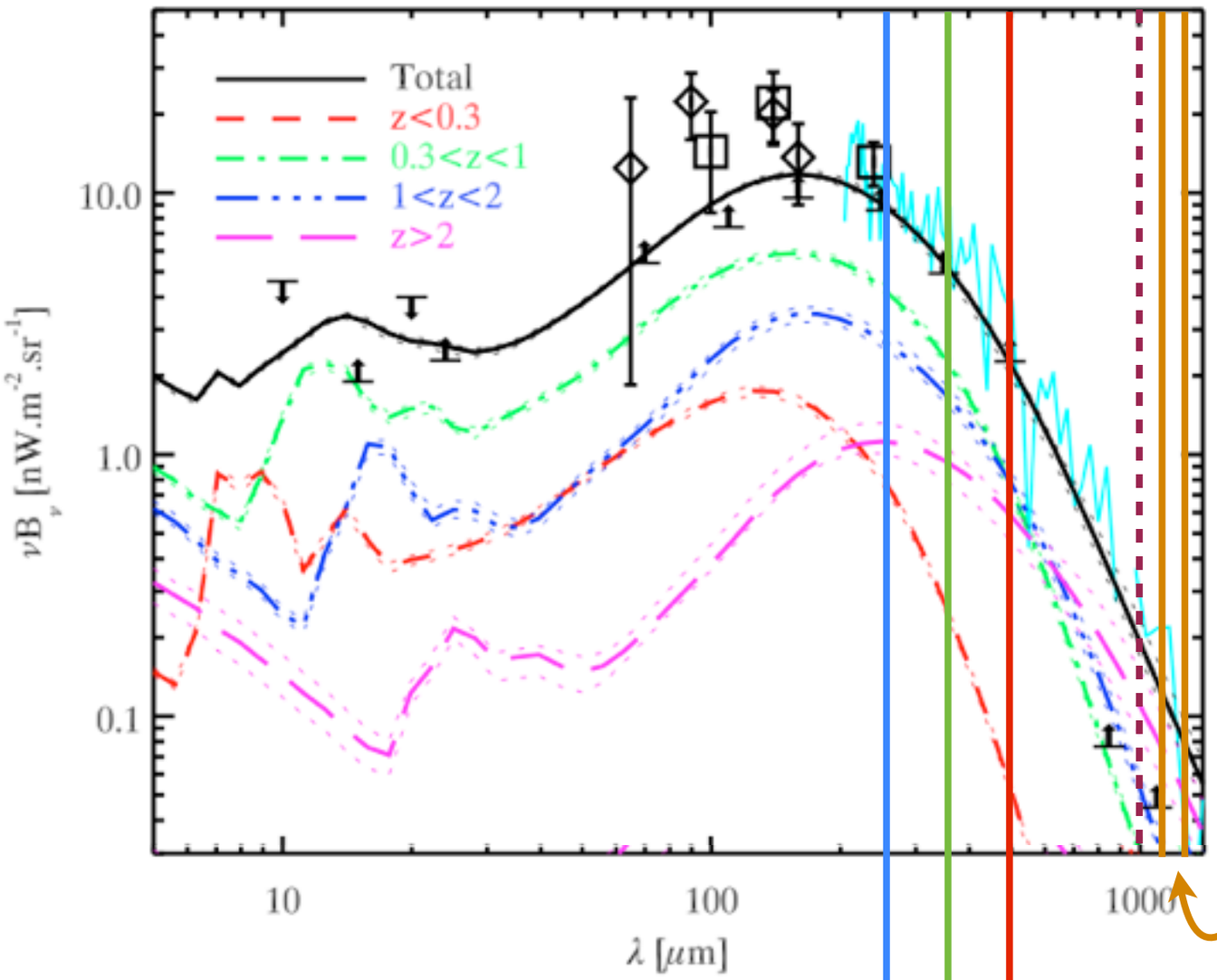
Béthermin et al. (2011)
arXiv:1010.1150

Total Infrared Background



Béthermin et al. (2011)
arXiv:1010.1150

Infrared Background
at $\lambda > 1$ mm (< 300 GHz)
dominated by
high-redshift sources



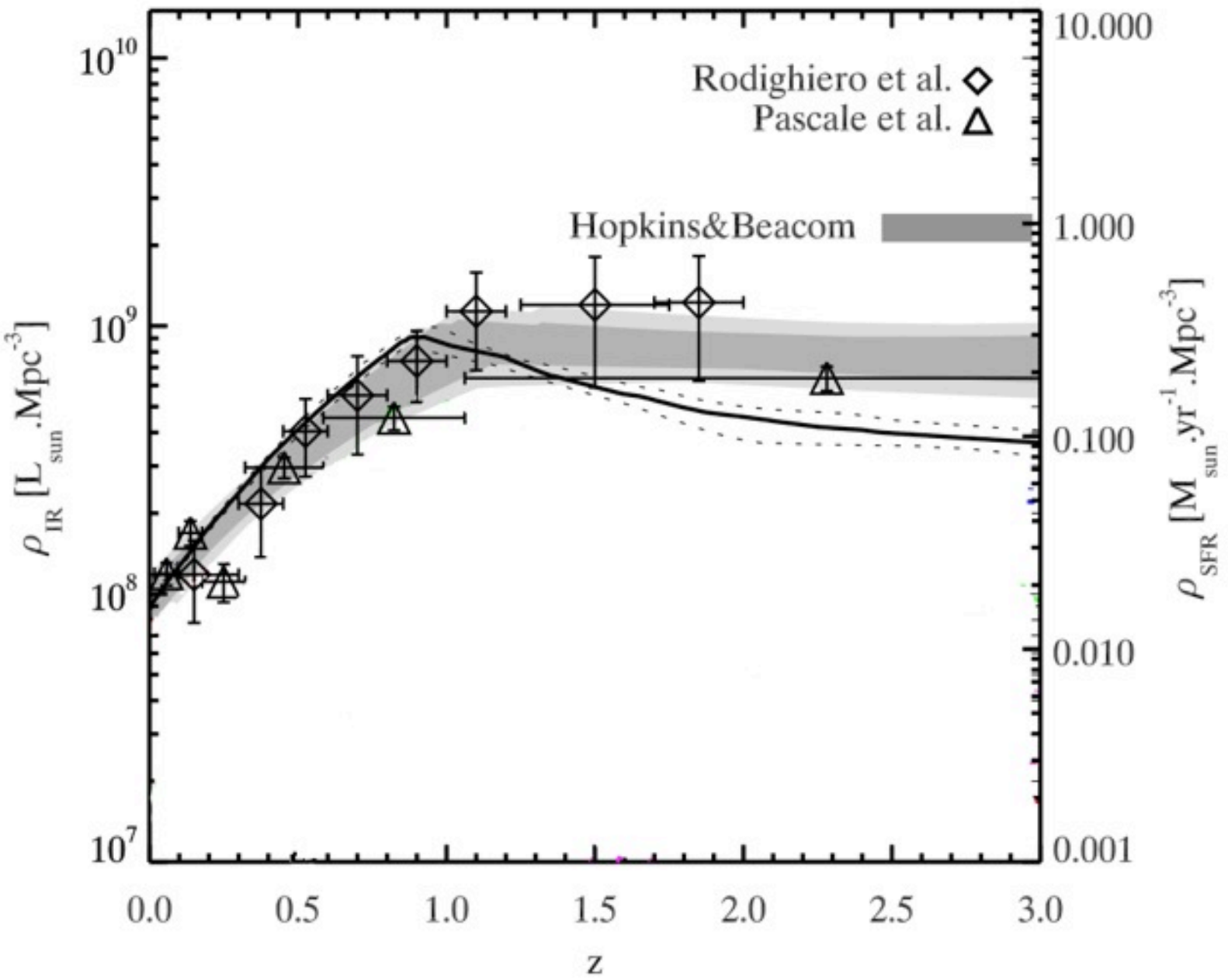
Béthermin et al. (2011)
arXiv:1010.1150

250
350
500

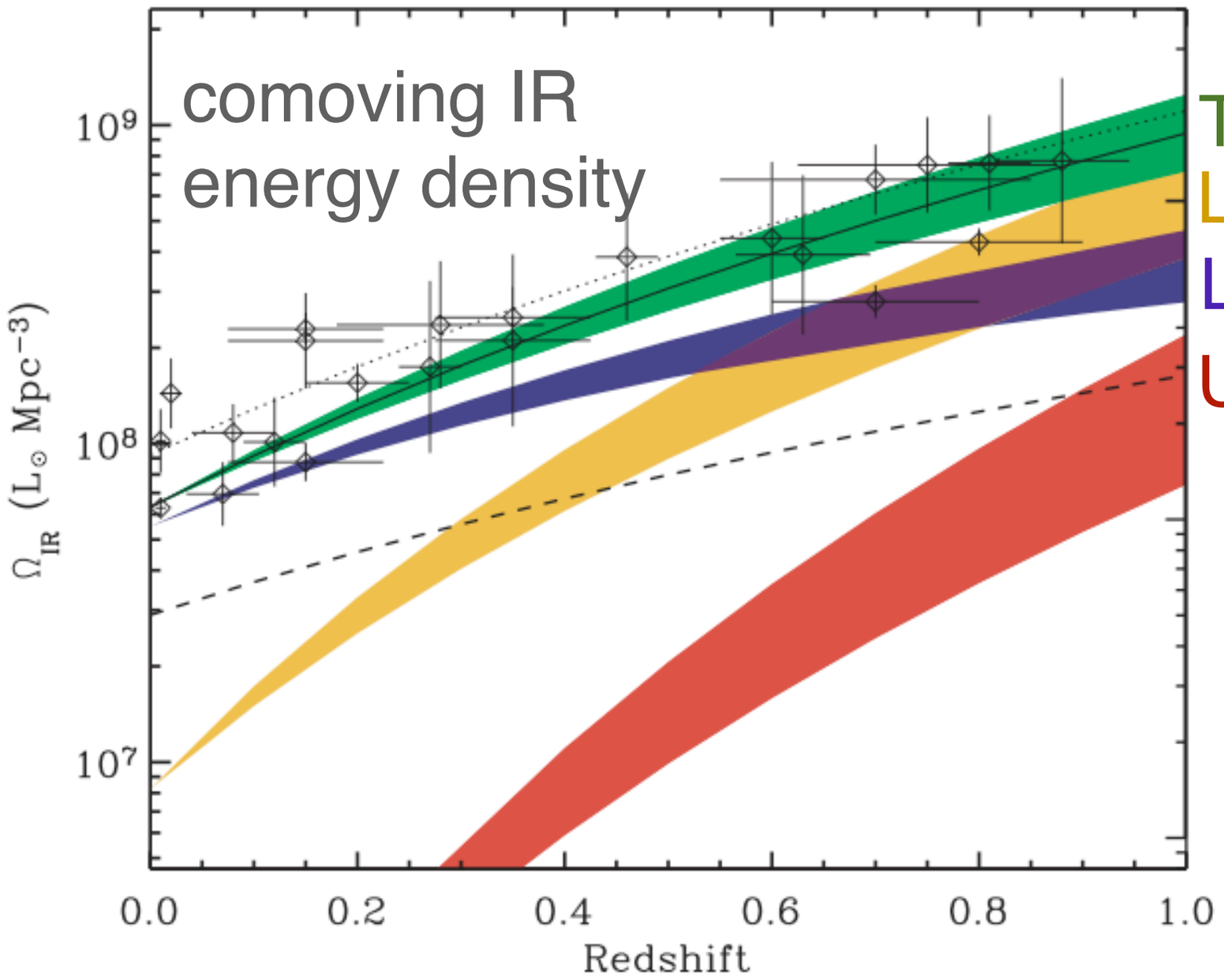
Infrared Background
at $\lambda > 1$ mm (< 300 GHz)
dominated by
high-redshift sources

CMB bands at
220 GHz (1.4 mm)
148 GHz (2 mm)

Total Infrared Background



Béthermin et al. (2011)
arXiv:1010.1150



Total

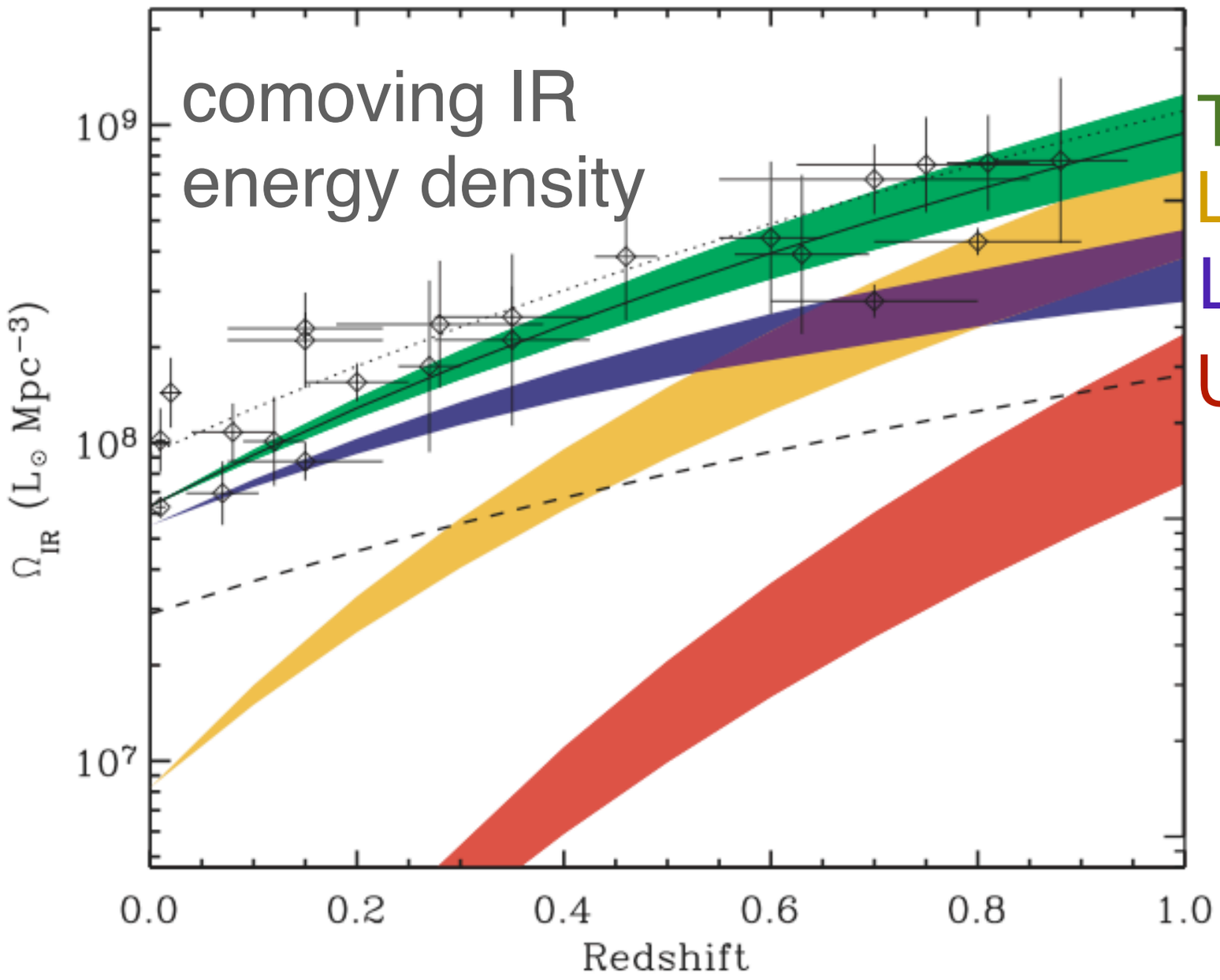
LIRGS+ULIRGS

$L < 10^{11}\ L_{sun}$

ULIRGS ($L_{FIR} > 10^{12} L_{sun}$)

Le Floc'h et al. (2005)

What are they?



Le Floc'h et al. (2005)

Total

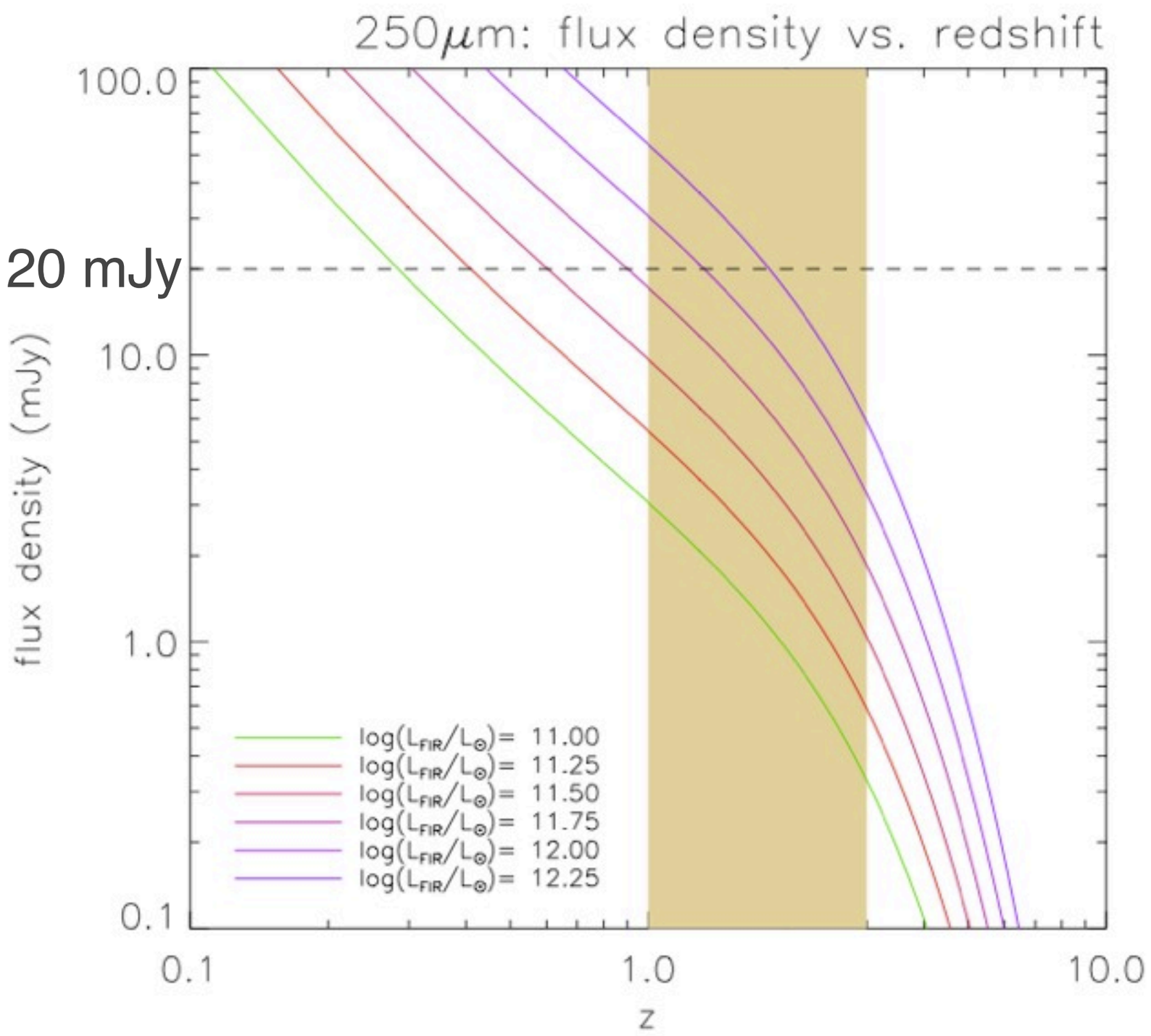
LIRGS+ULIRGS

$L < 10^{11}\ L_{sun}$

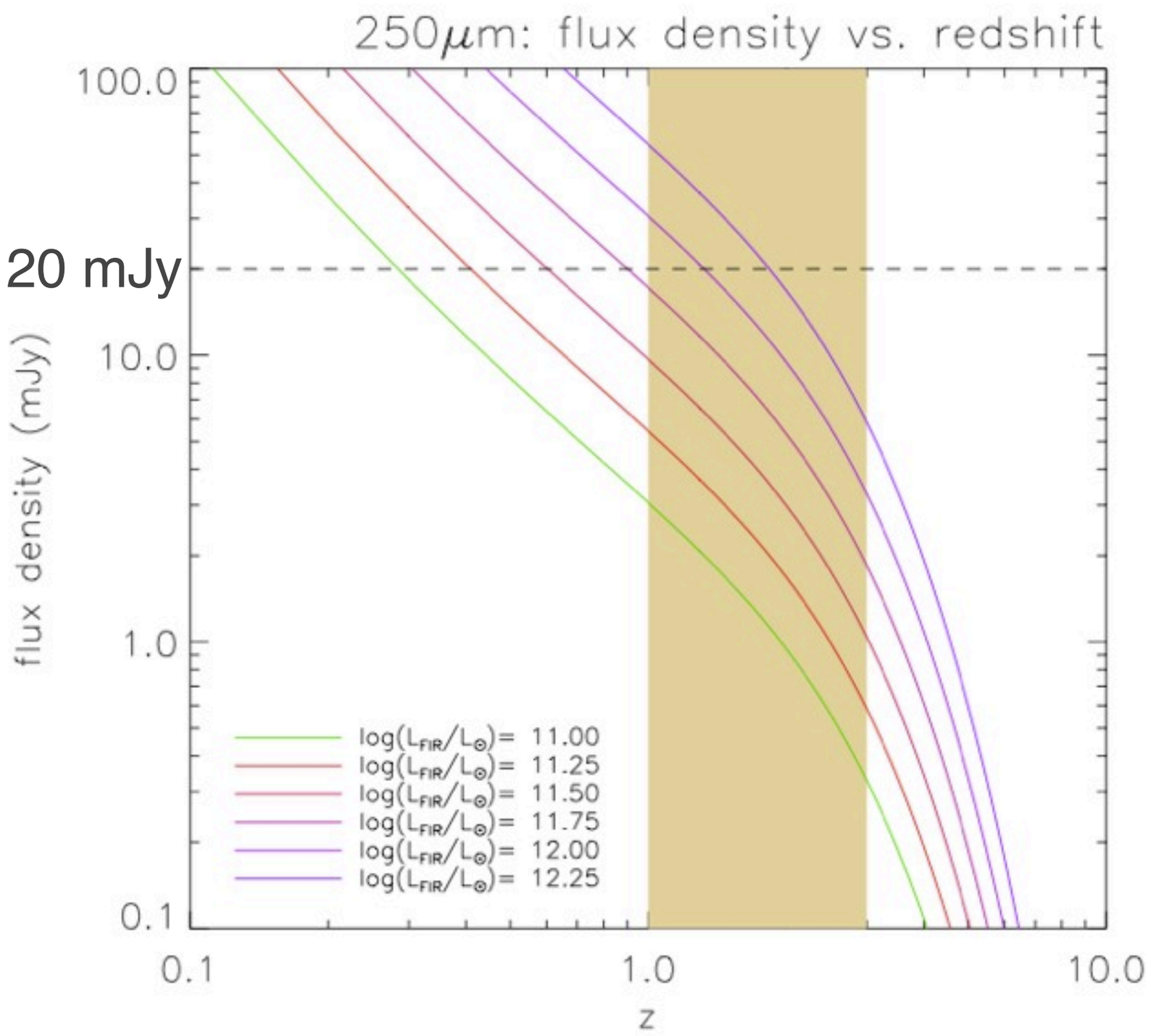
ULIRGS ($L_{FIR} > 10^{12} L_{sun}$)

Most of that Star Formation occurs in LIRGS, i.e.: $L_{FIR}=10^{11}$-$10^{12}\ M_{sun}$

What are they?



What are they?



Typical LIRGS at z~1-3 have flux densities S_{250} ~ 1-10 mJy

What are they?

Goal:

Measure the spatial distribution (clustering) of galaxies responsible for most of the SF in the Universes History

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Measure the spatial distribution (clustering) of galaxies responsible for most of the SF in the Universes History

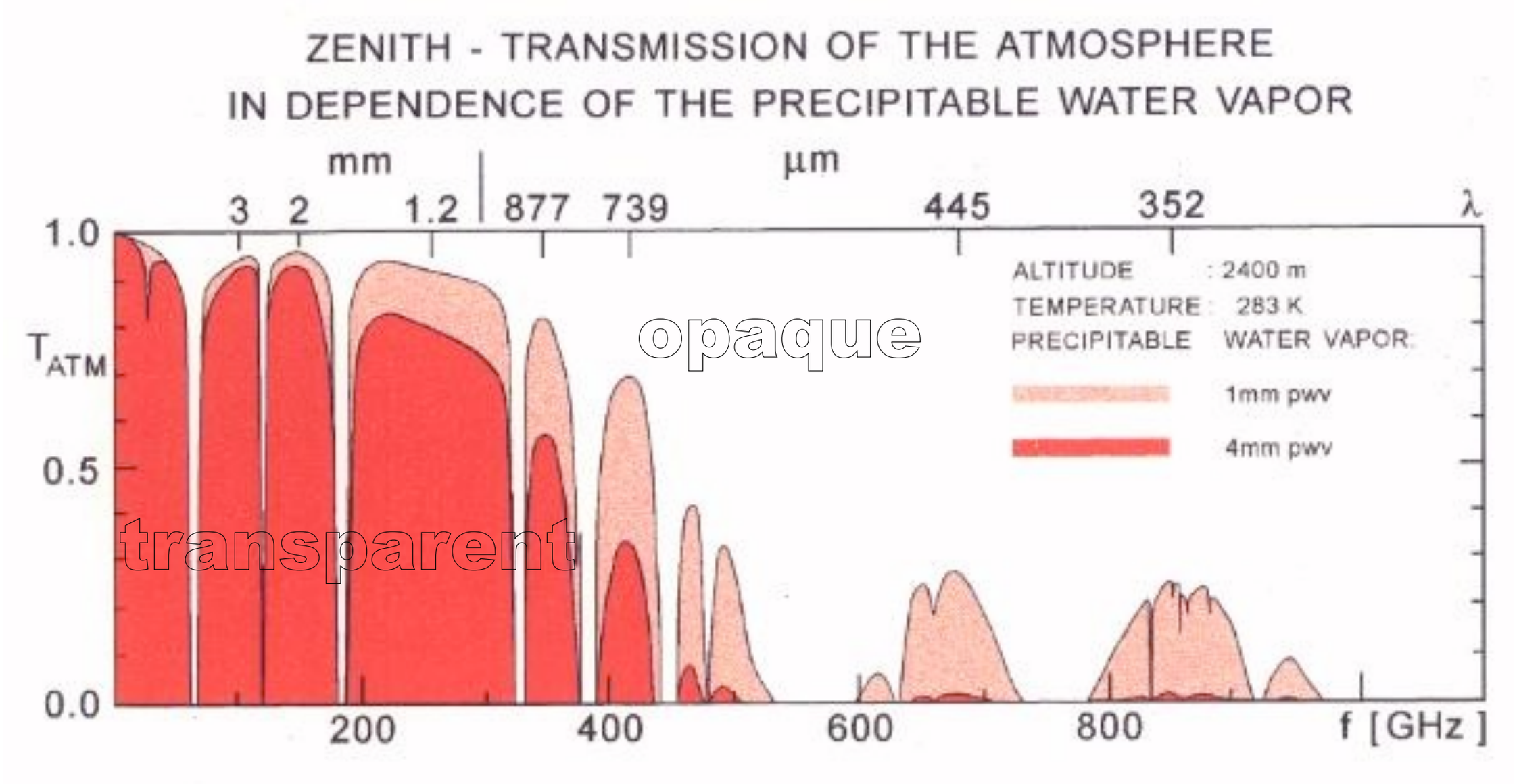
1. Provides link to descendants/progenitors

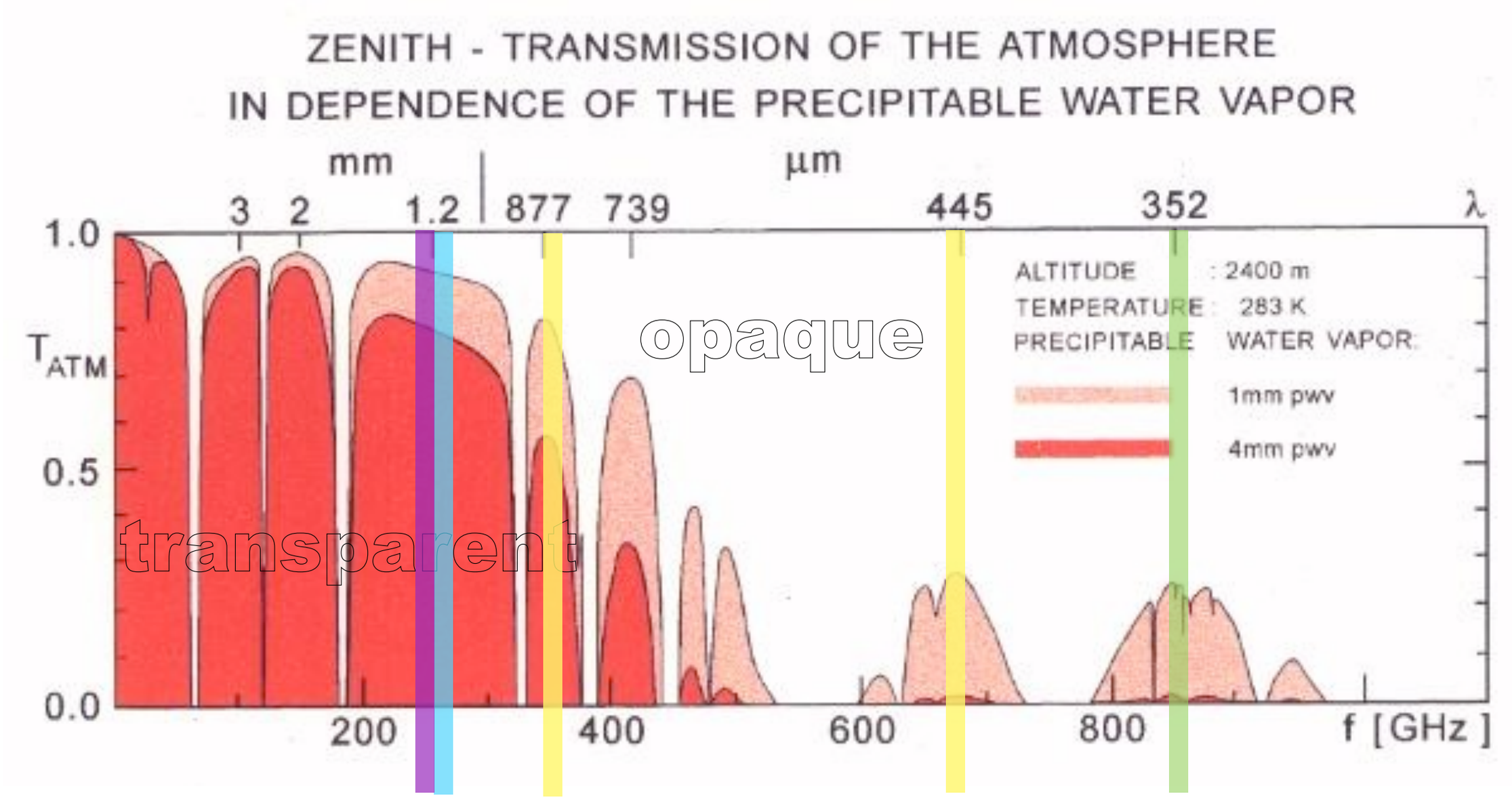
Goal:

Measure the spatial distribution (clustering) of galaxies responsible for most of the SF in the Universes History

1. Provides link to descendants/progenitors
2. Informs galaxy formation models

Observing in the submillimeter


ZENITH - TRANSMISSION OF THE ATMOSPHERE
IN DEPENDENCE OF THE PRECIPITABLE WATER VAPOR
mm
μm
3
2
1.2
877
739
445
352
λ
1.0
T_{ATM}
0.5
0.0
opaque
transparent
ALTITUDE : 2400 m
TEMPERATURE : 283 K
PRECIPITABLE WATER VAPOR:
1mm pwv
4mm pwv
200
400
600
800
f [GHz]



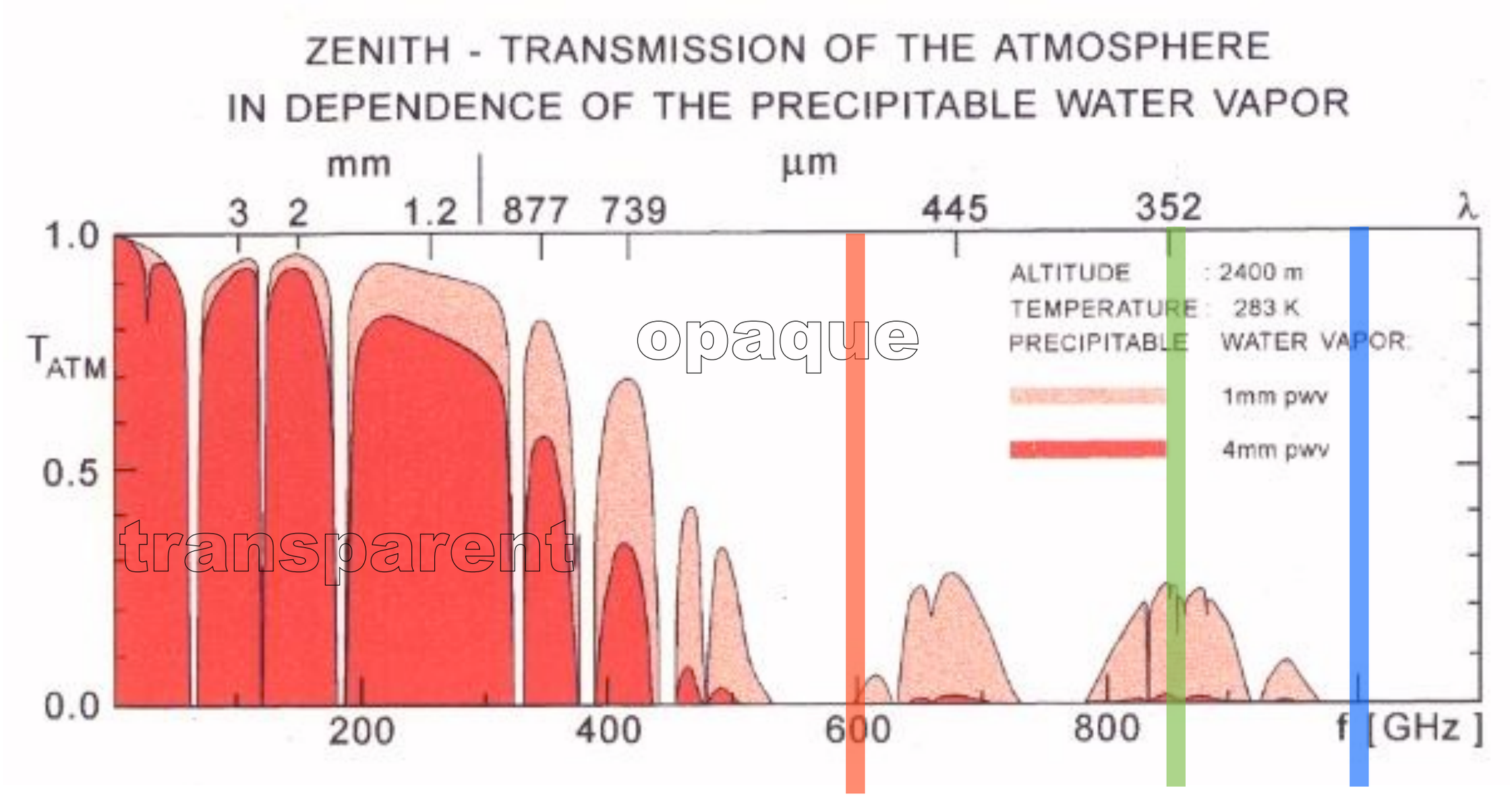
MAMBO

AzTEC

SCUBA

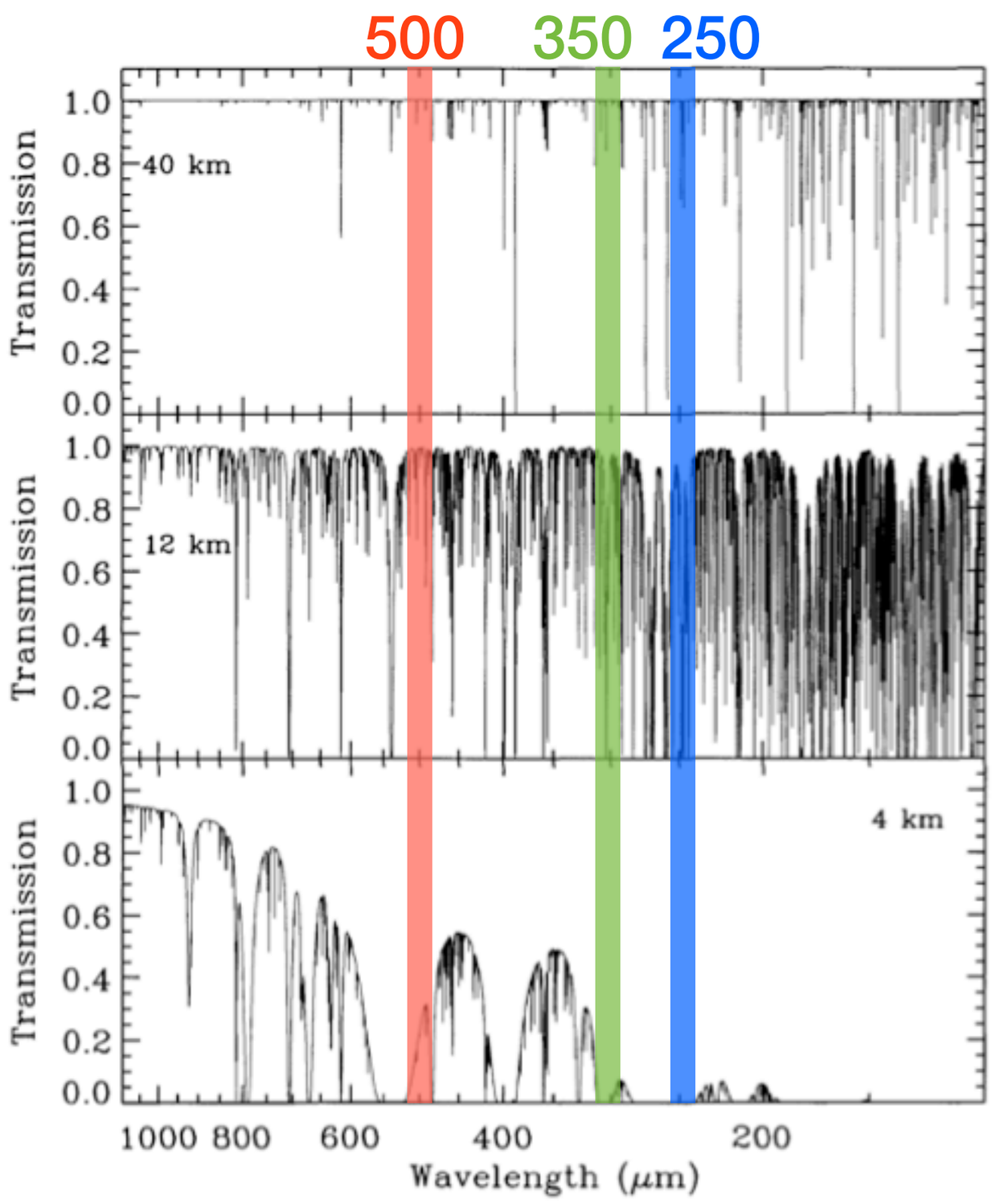
SHARC

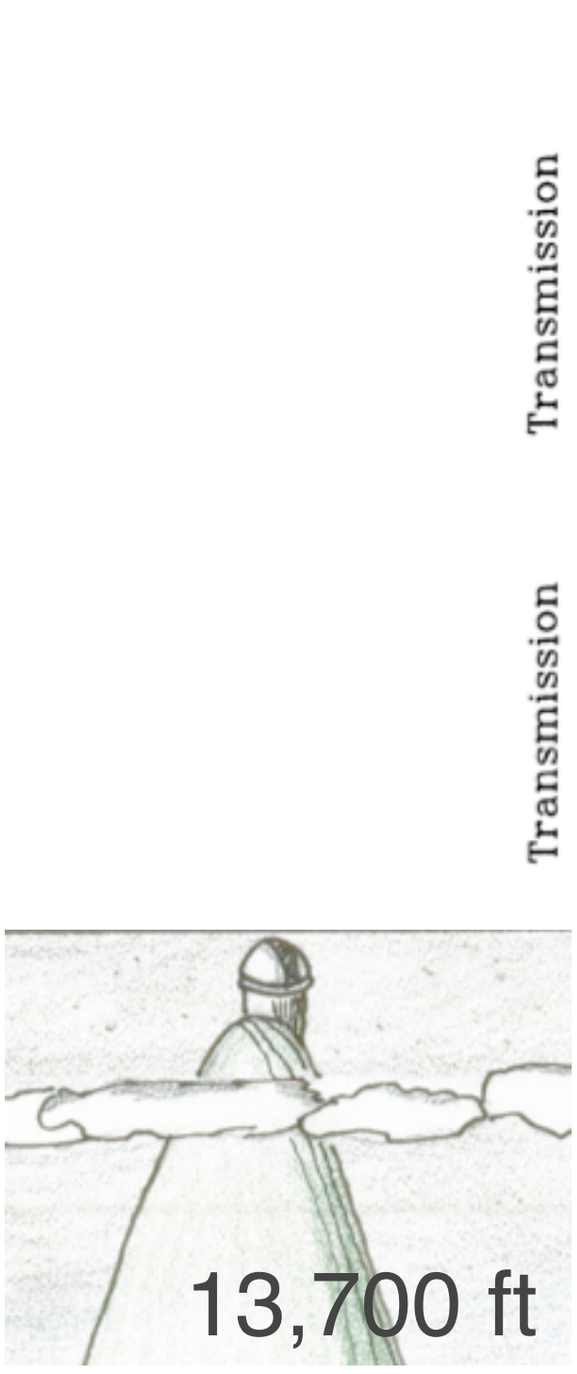
Submm Observations

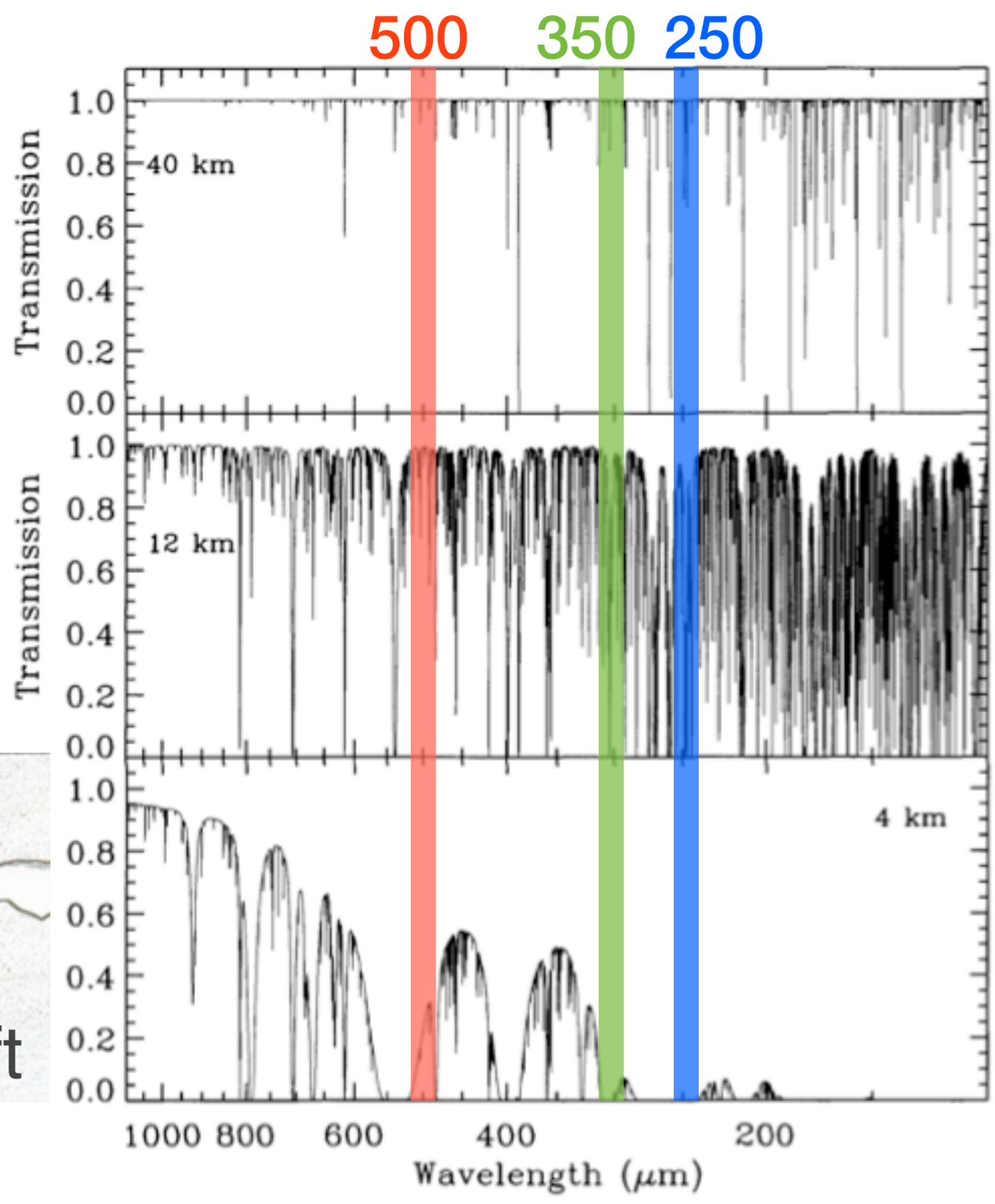


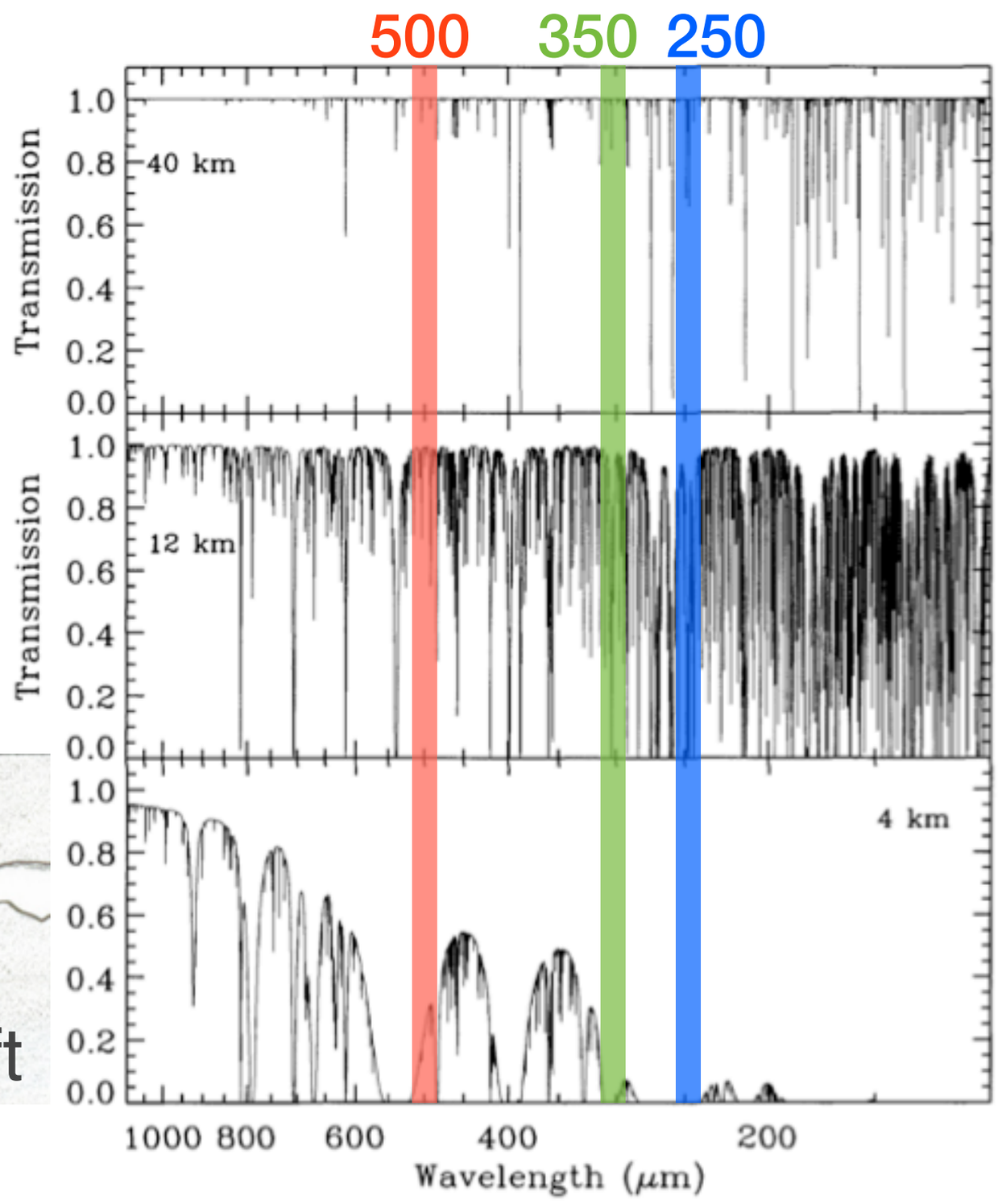
500 350 250

Submm Observations


500
350
250
40 km
12 km
4 km
Transmission
1.0
0.8
0.6
0.4
0.2
0.0
1000
800
600
400
200
Wavelength (μm)


13,700 ft


500
350
250
Transmission
40 km
12 km
4 km
1.0
0.8
0.6
0.4
0.2
0.0
1000
800
600
400
200
Wavelength (μm)

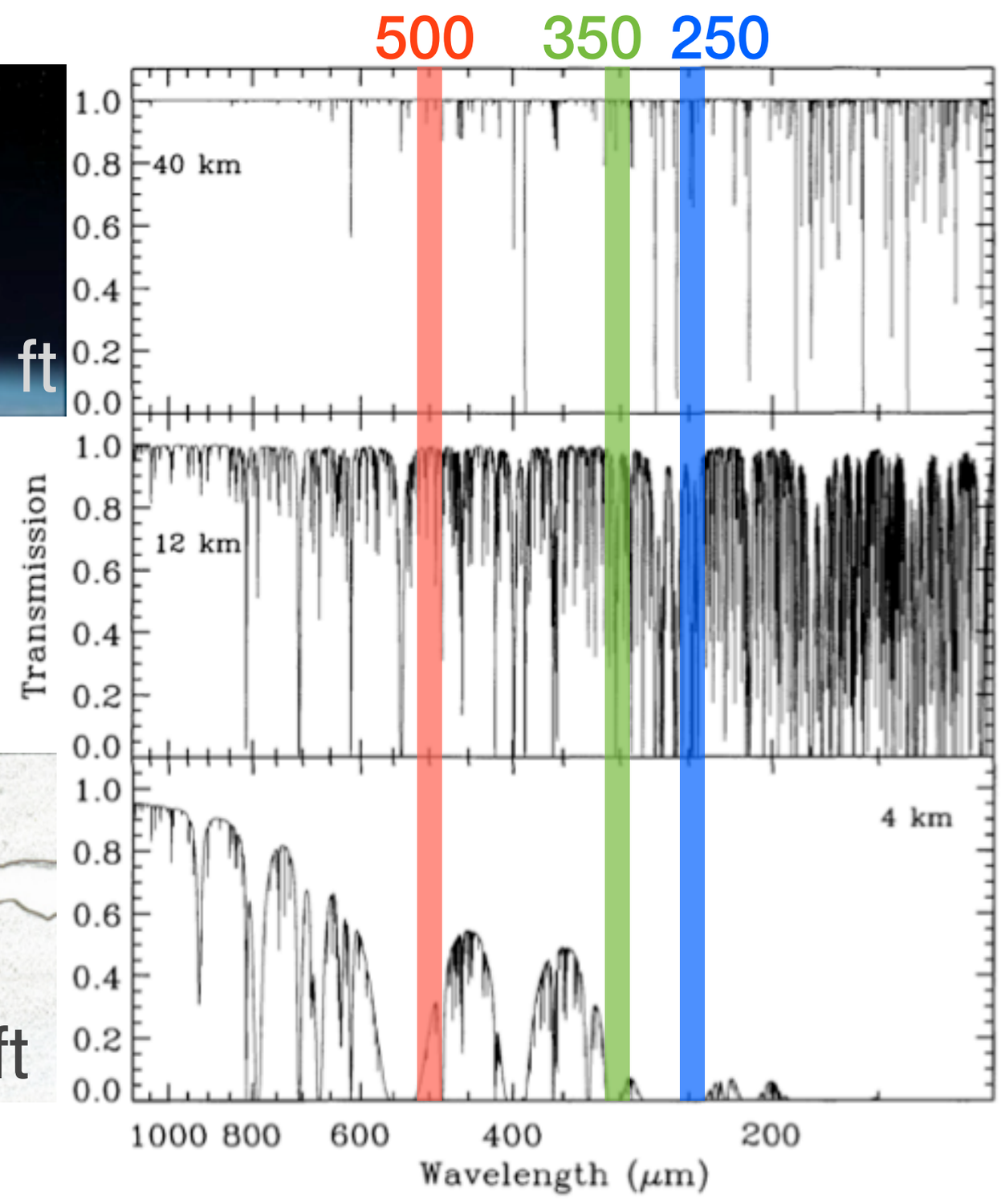

500
350
250
Transmission
1.0
0.8
0.6
0.4
0.2
0.0
40 km
12 km
4 km
1000
800
600
400
200
Wavelength (μm)


13,700 ft

NASA
DLR
SOFIA
41,000 ft


137,000 ft

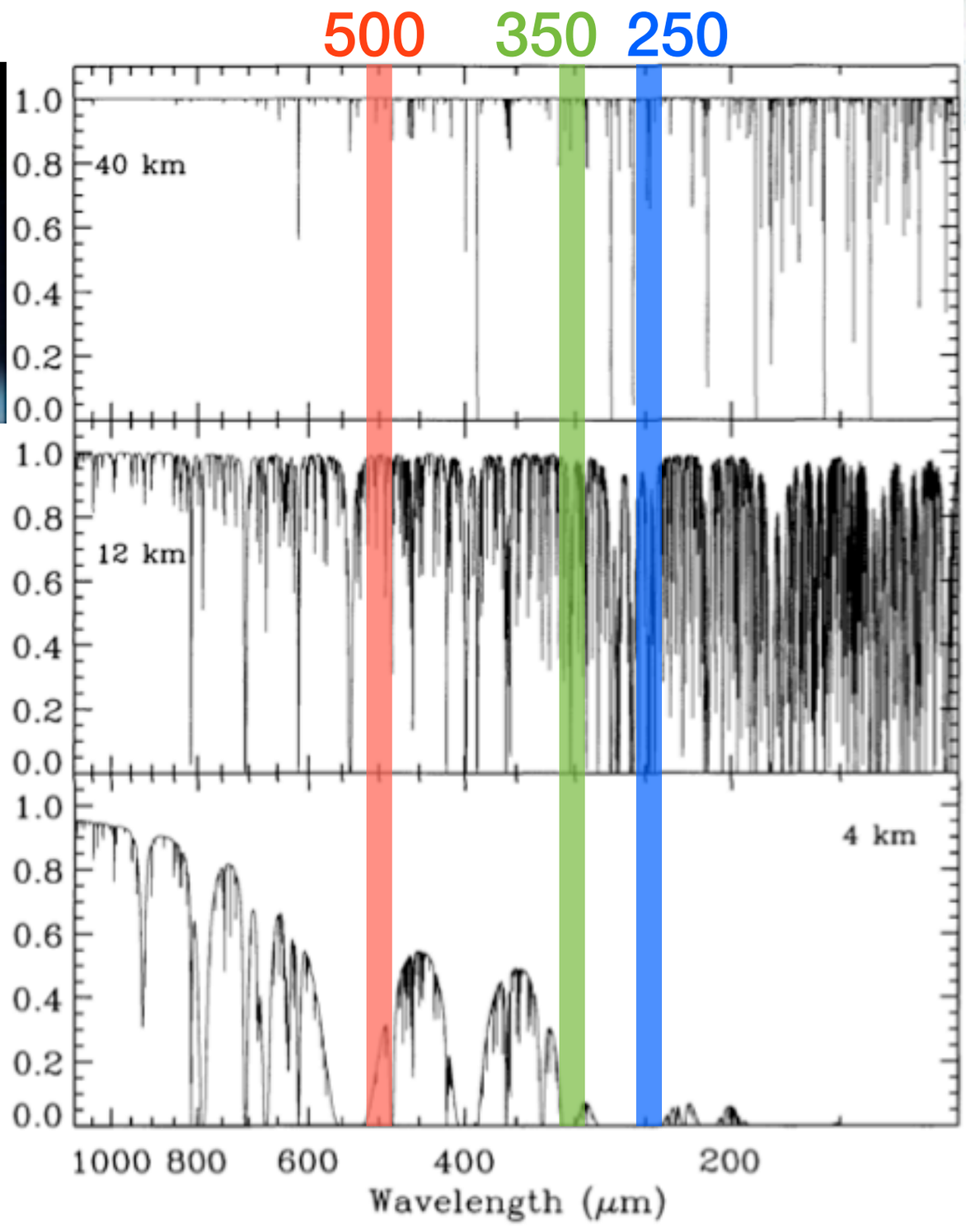
13,700 ft


500
350
250
40 km
12 km
4 km
Transmission
1.0
0.8
0.6
0.4
0.2
0.0
1000
800
600
400
200
Wavelength (μm)

NASA
DLR
SOFIA
41,000 ft


137,000 ft

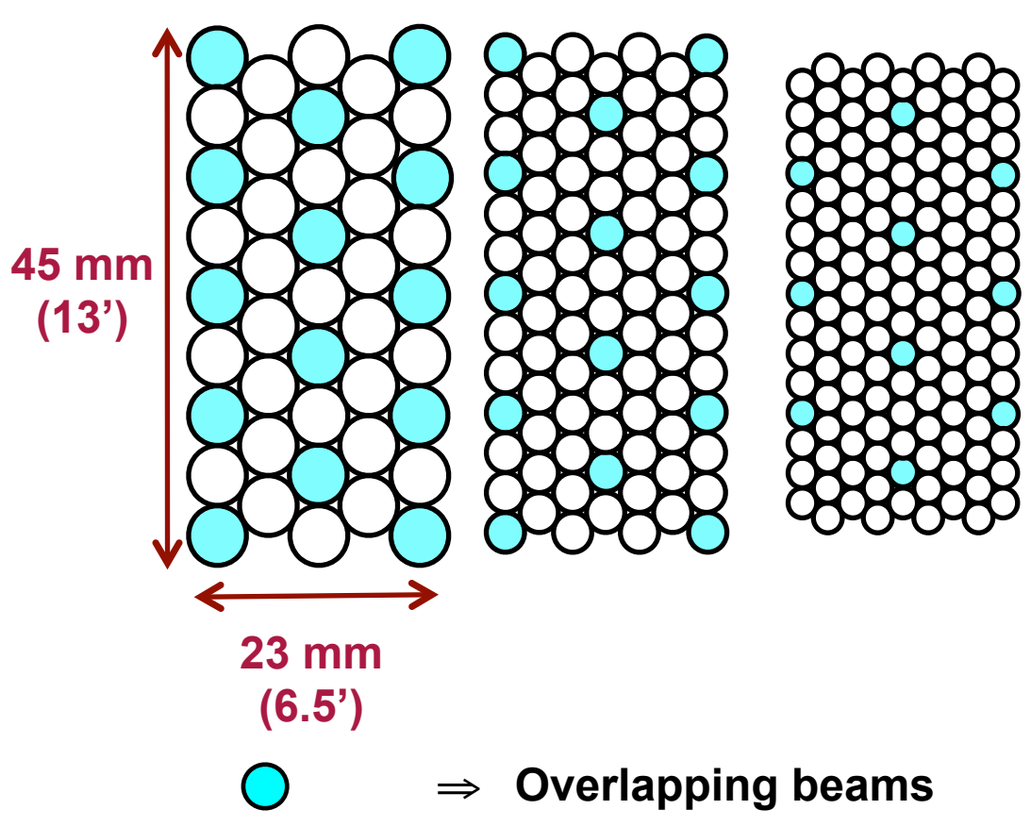

HERSCHEL


500
350
250
40 km
12 km
4 km
Transmission
1.0
0.8
0.6
0.4
0.2
0.0
1000
800
600
400
200
Wavelength (μm)

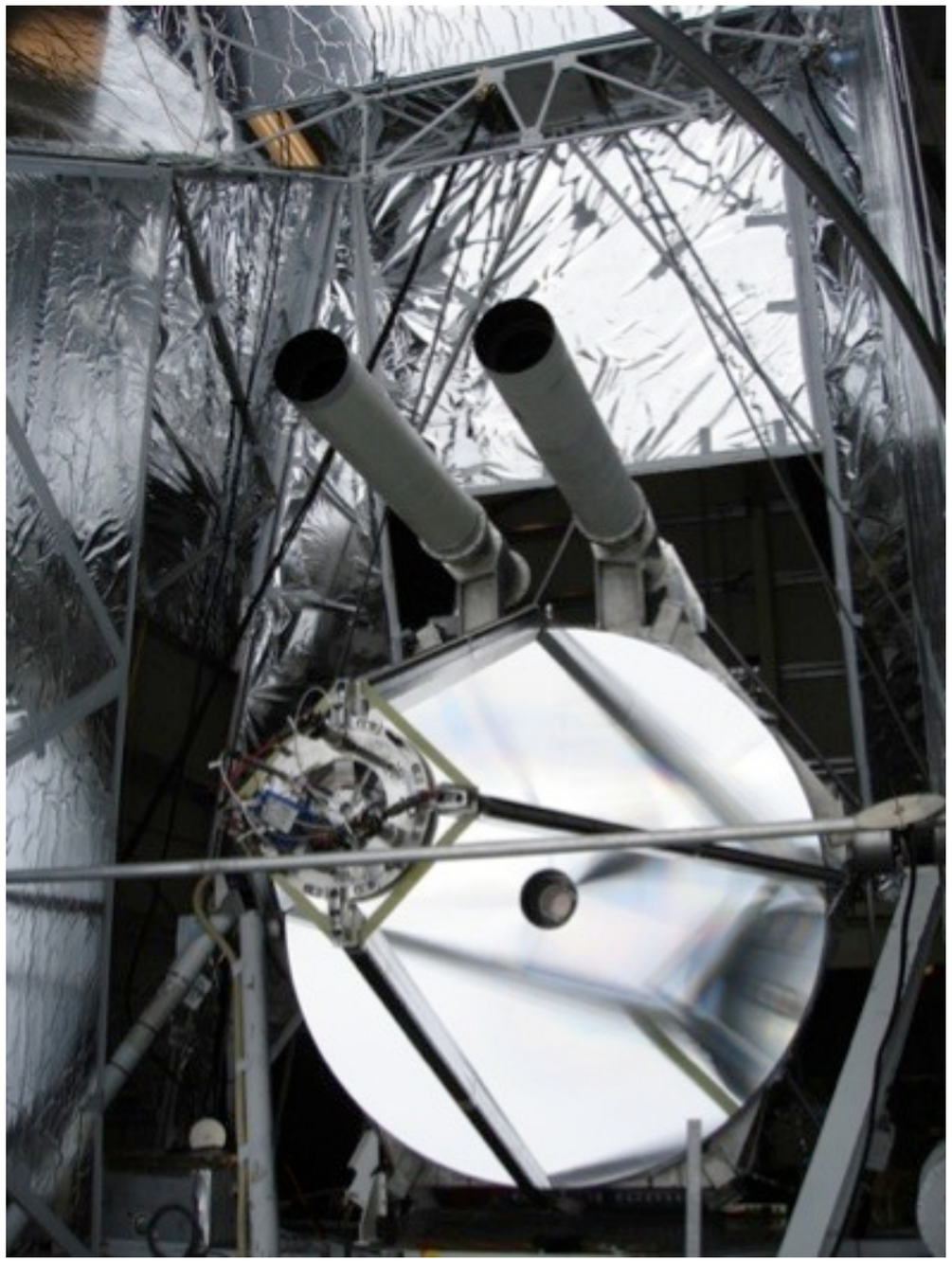

NASA
DLR
SOFIA
41,000 ft


13,700 ft

SPIRE-like
spider-web bolometer
detector arrays...



BLAST



SPIRE-like
spider-web bolometer
detector arrays...

... but a 1.8 m primary
resulting in beams:

36” - 250 μm

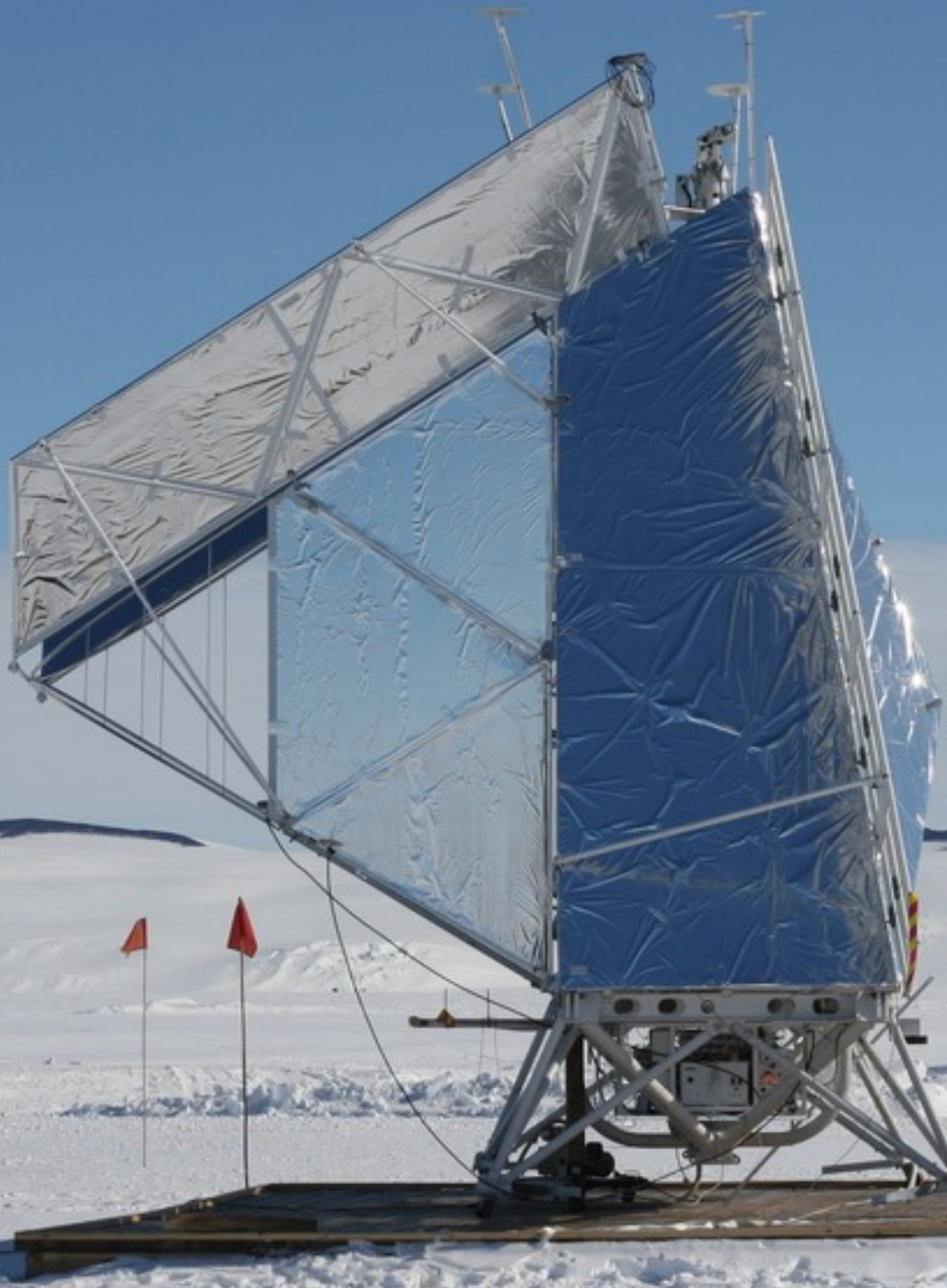
45” - 350 μm

60” - 500 μm

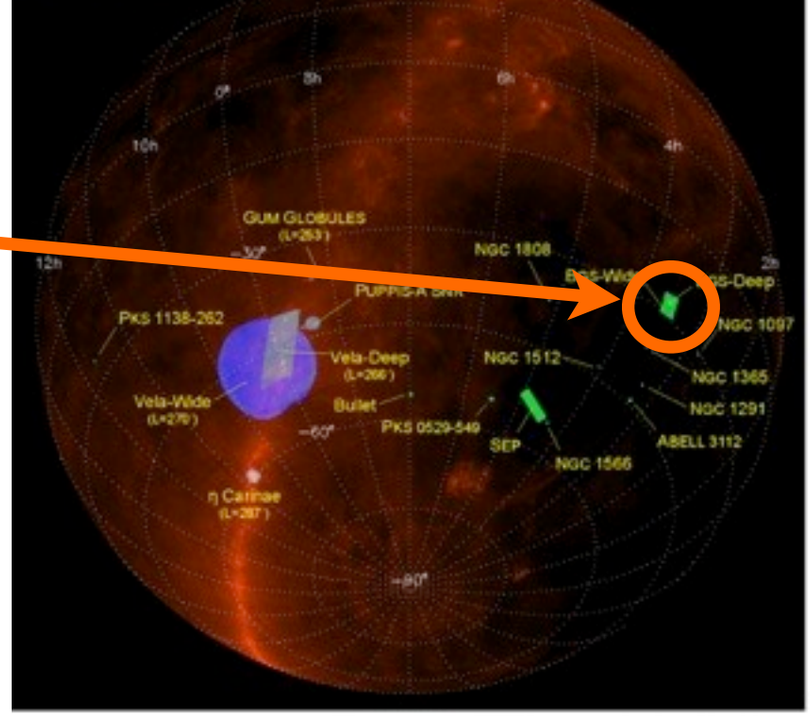
i.e., twice the size of SPIRE’s beams

BLAST


A-333-S
ICECUBE
SURF2DOM



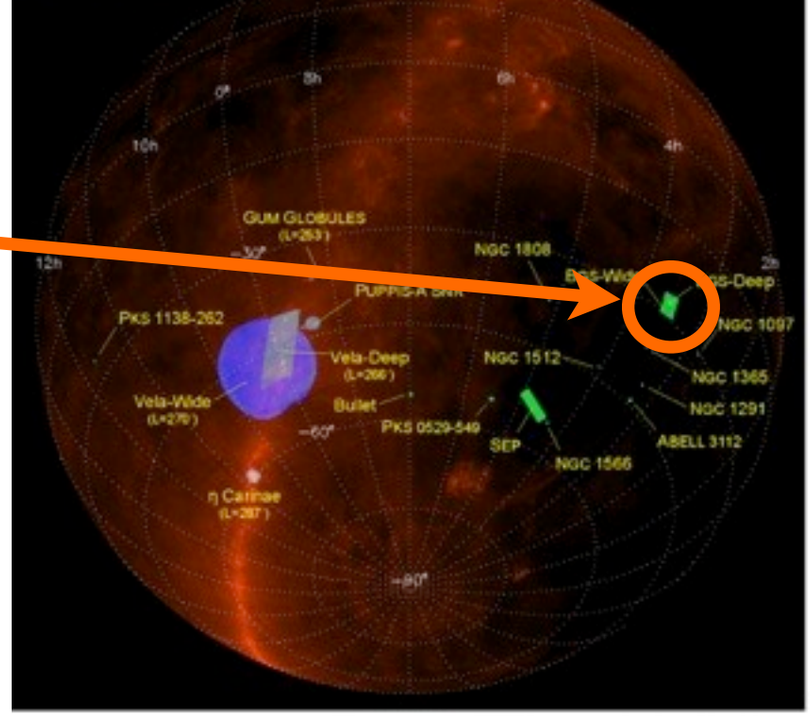
BLAST GOODS-south

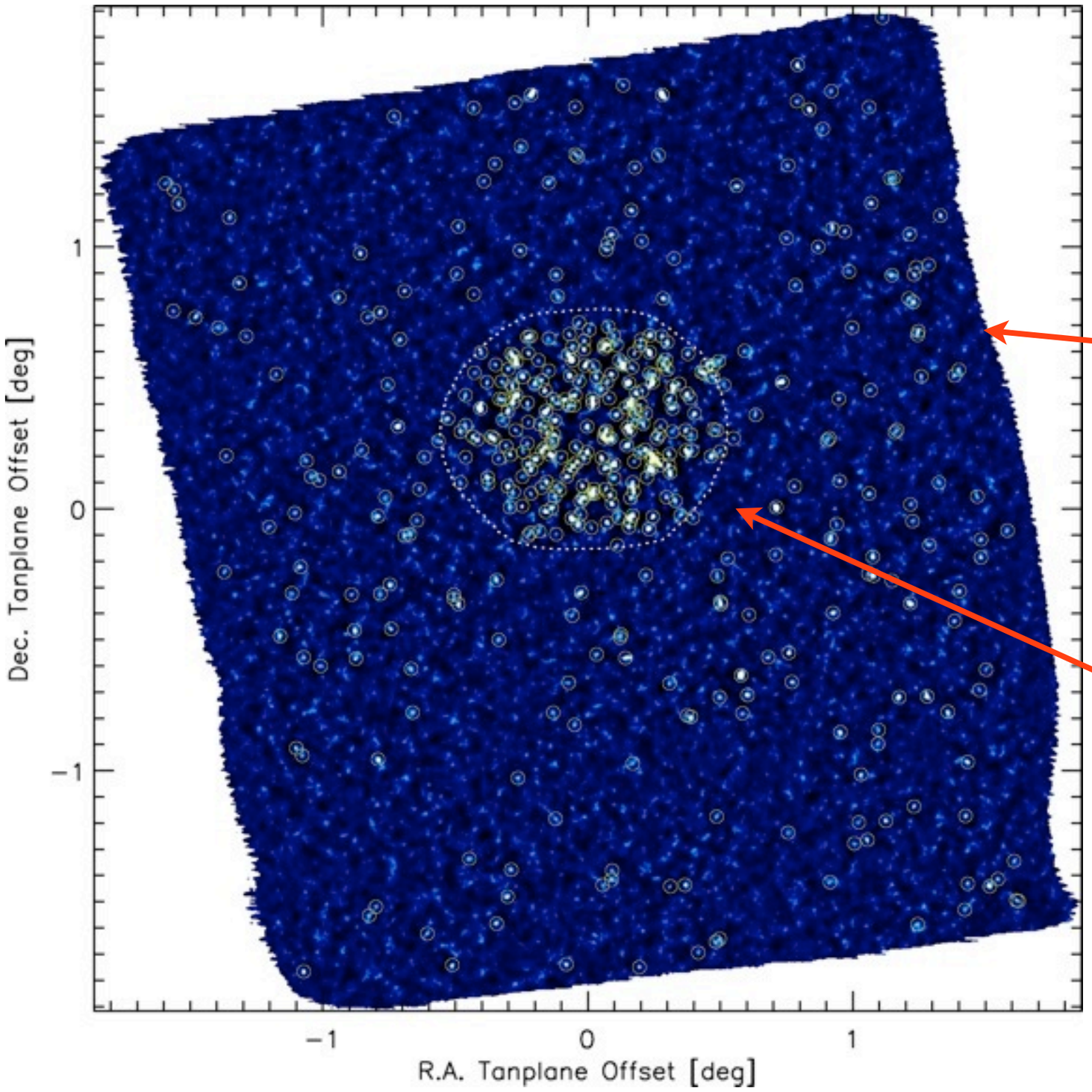


Noise BGS-wide:
36 mJy beam^{-1}
21 mJy beam^{-1}
20 mJy beam^{-1}

Noise BGS-deep:
11 mJy beam^{-1}
9 mJy beam^{-1}
6 mJy beam^{-1}

BLAST GOODS-south





Noise BGS-wide:
36 mJy beam^{-1}
21 mJy beam^{-1}
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Noise BGS-deep:
11 mJy beam^{-1}
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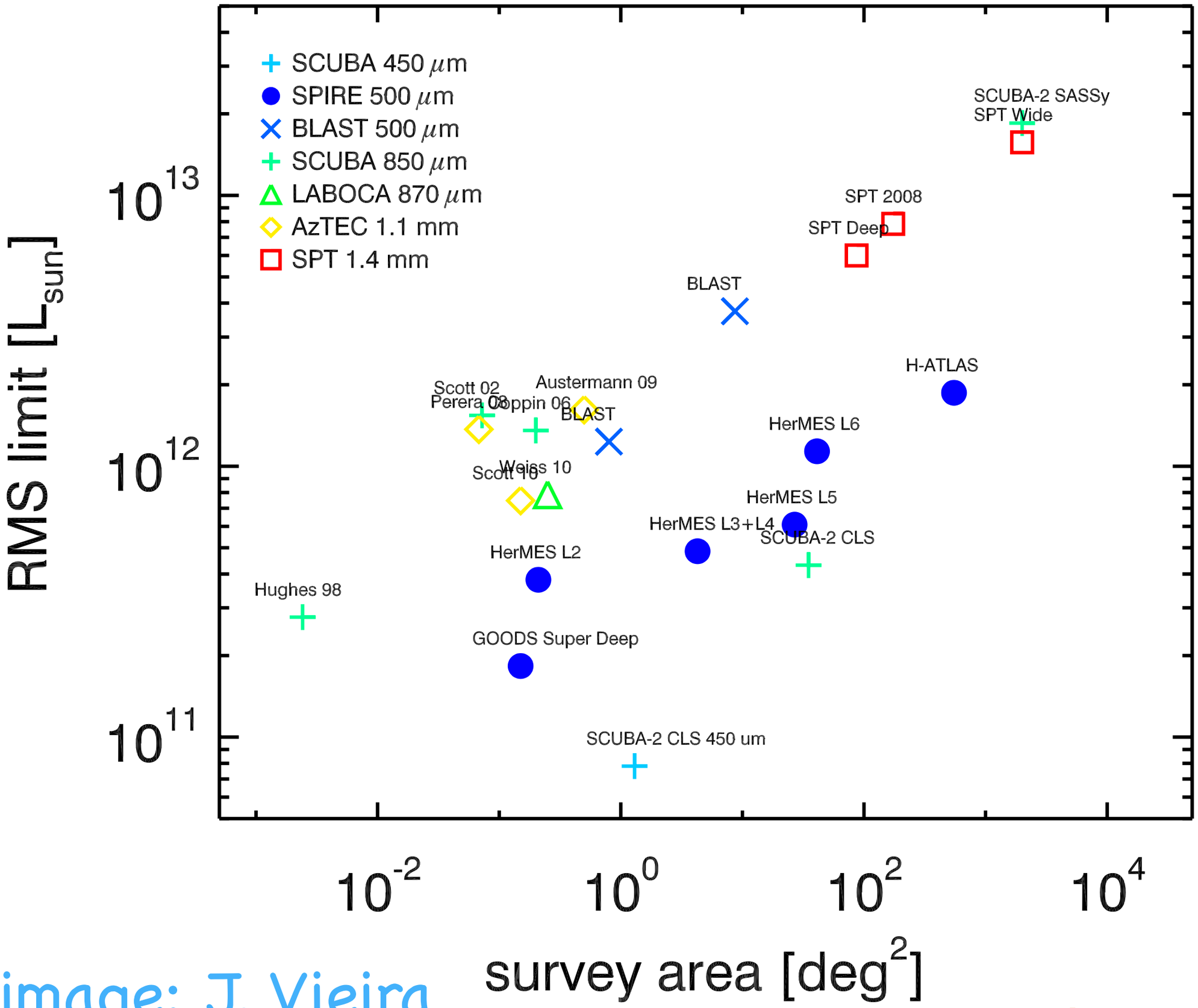


image: J. Vieira

submm surveys

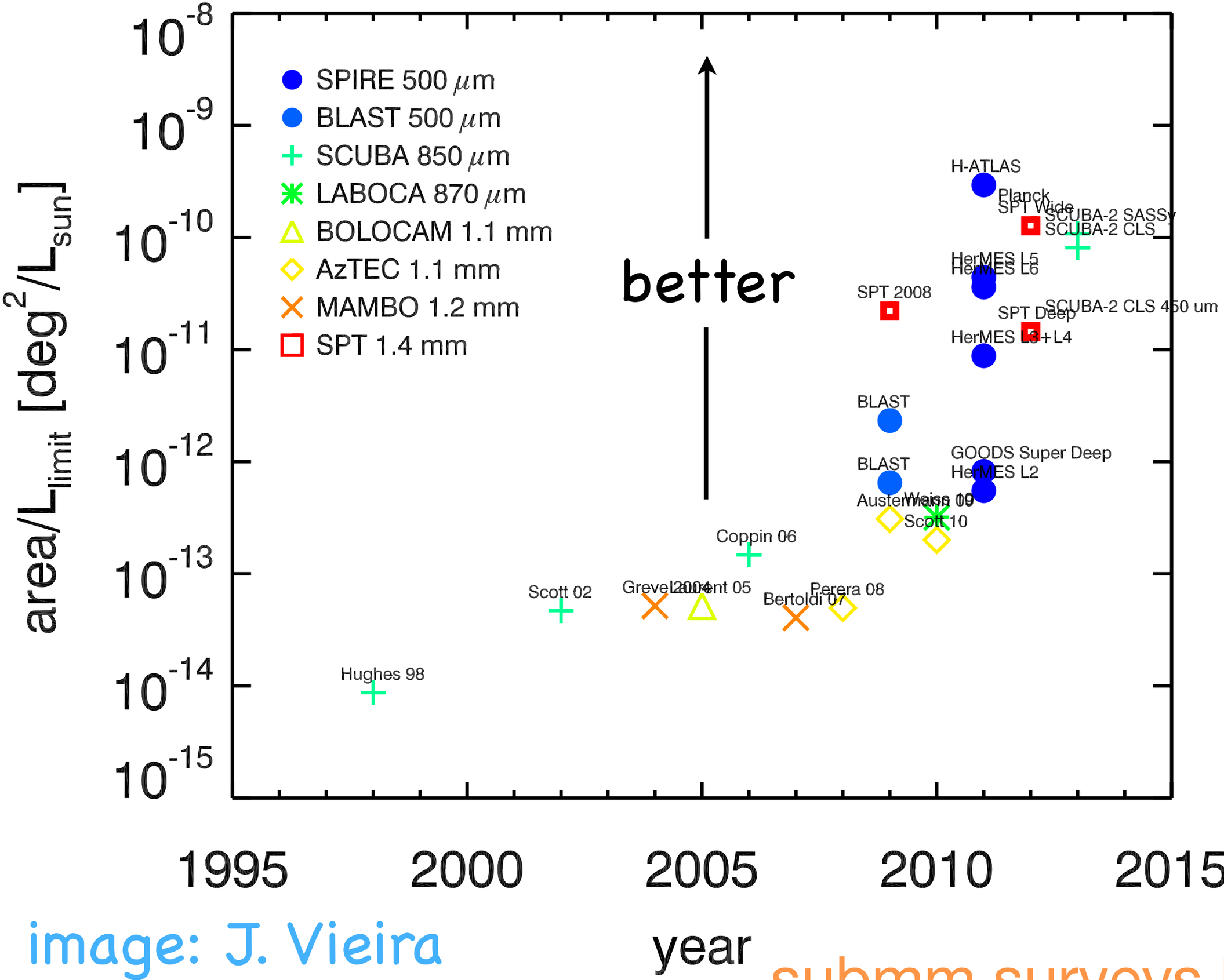
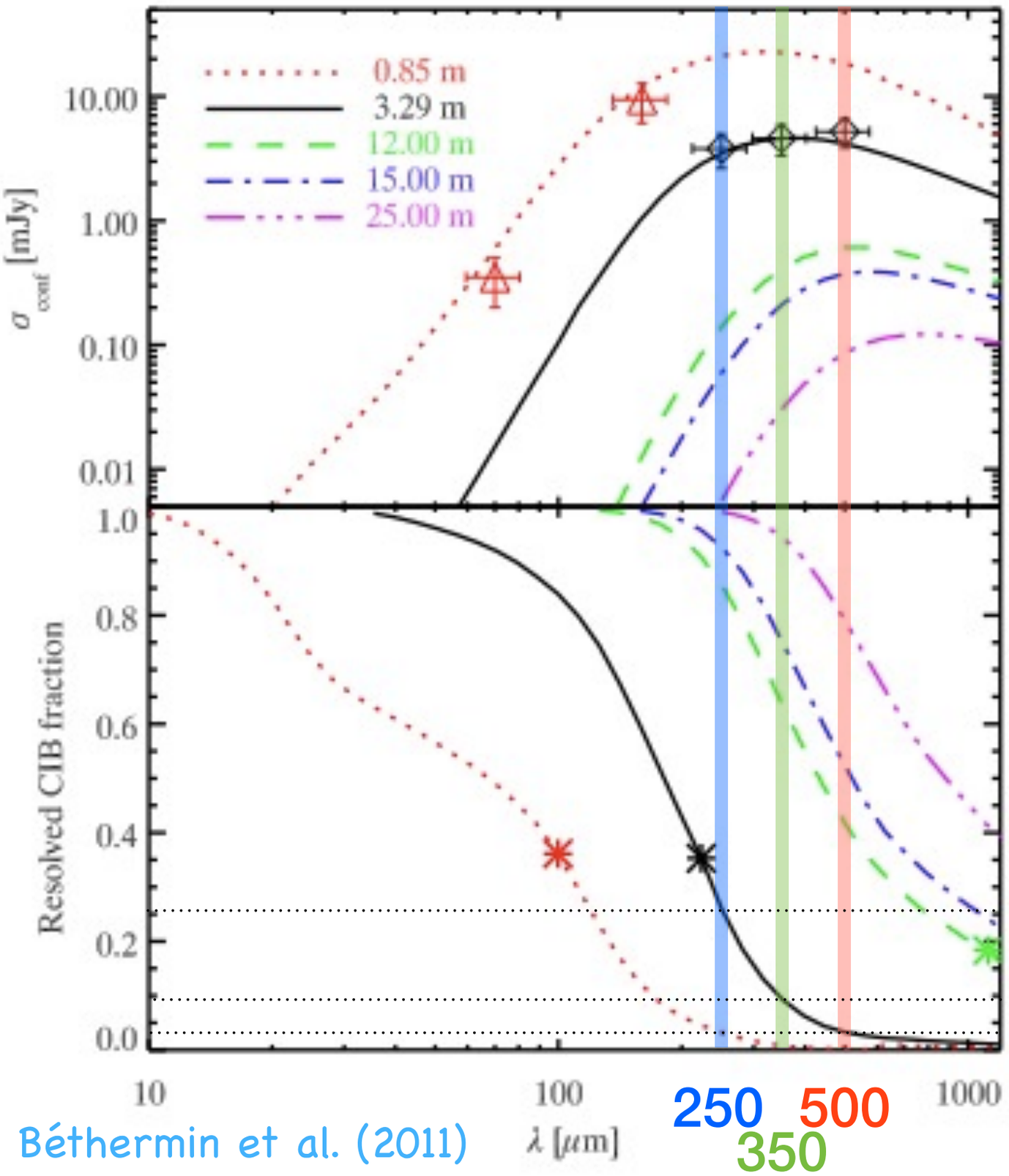


image: J. Vieira

submm surveys by year



Béthermin et al. (2011)
arXiv:1010.1150

Spitzer (Frayer 2009)

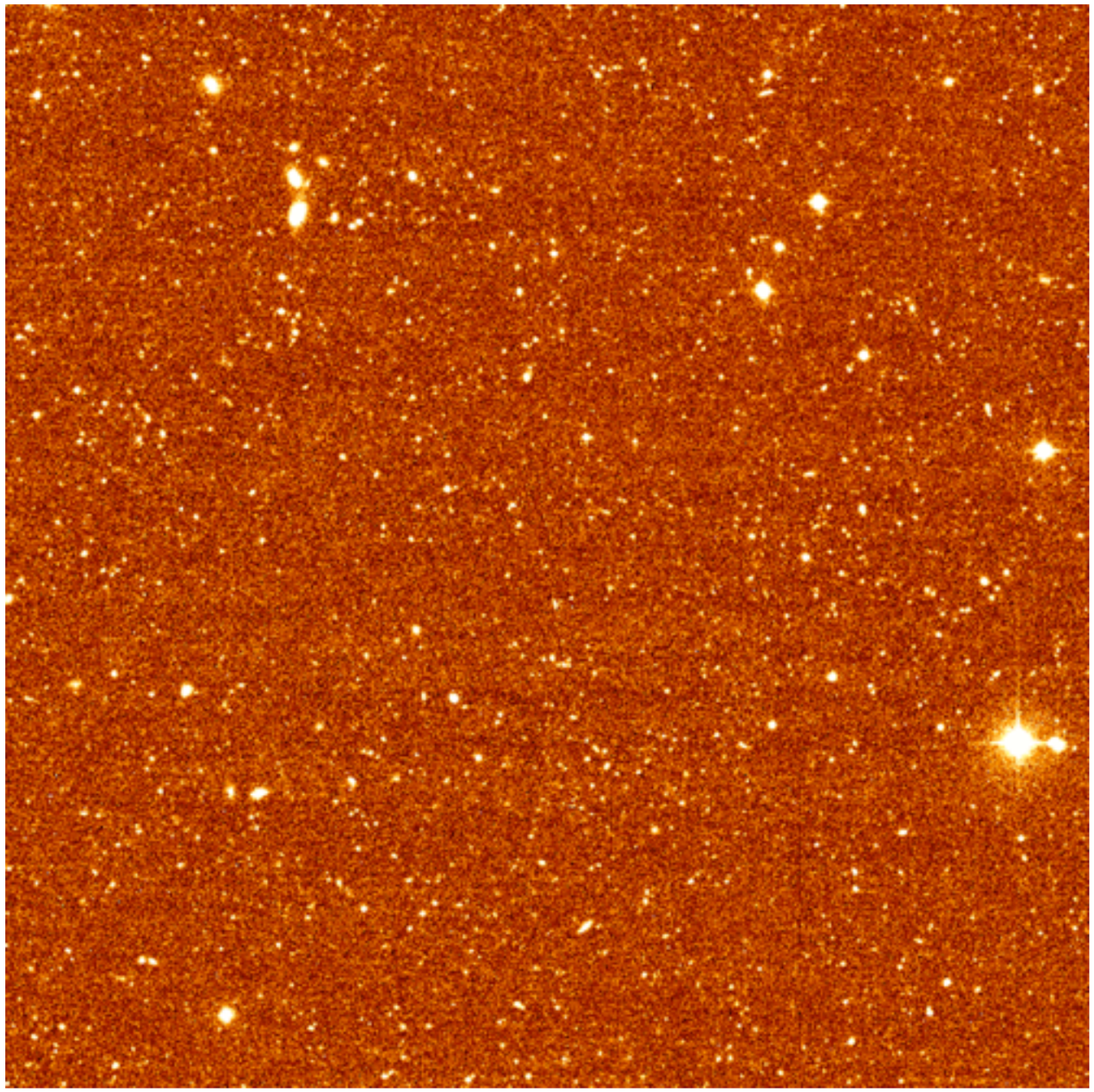
Herschel (Nguyen 2010)

APEX

CSO

CCAT

Confusion

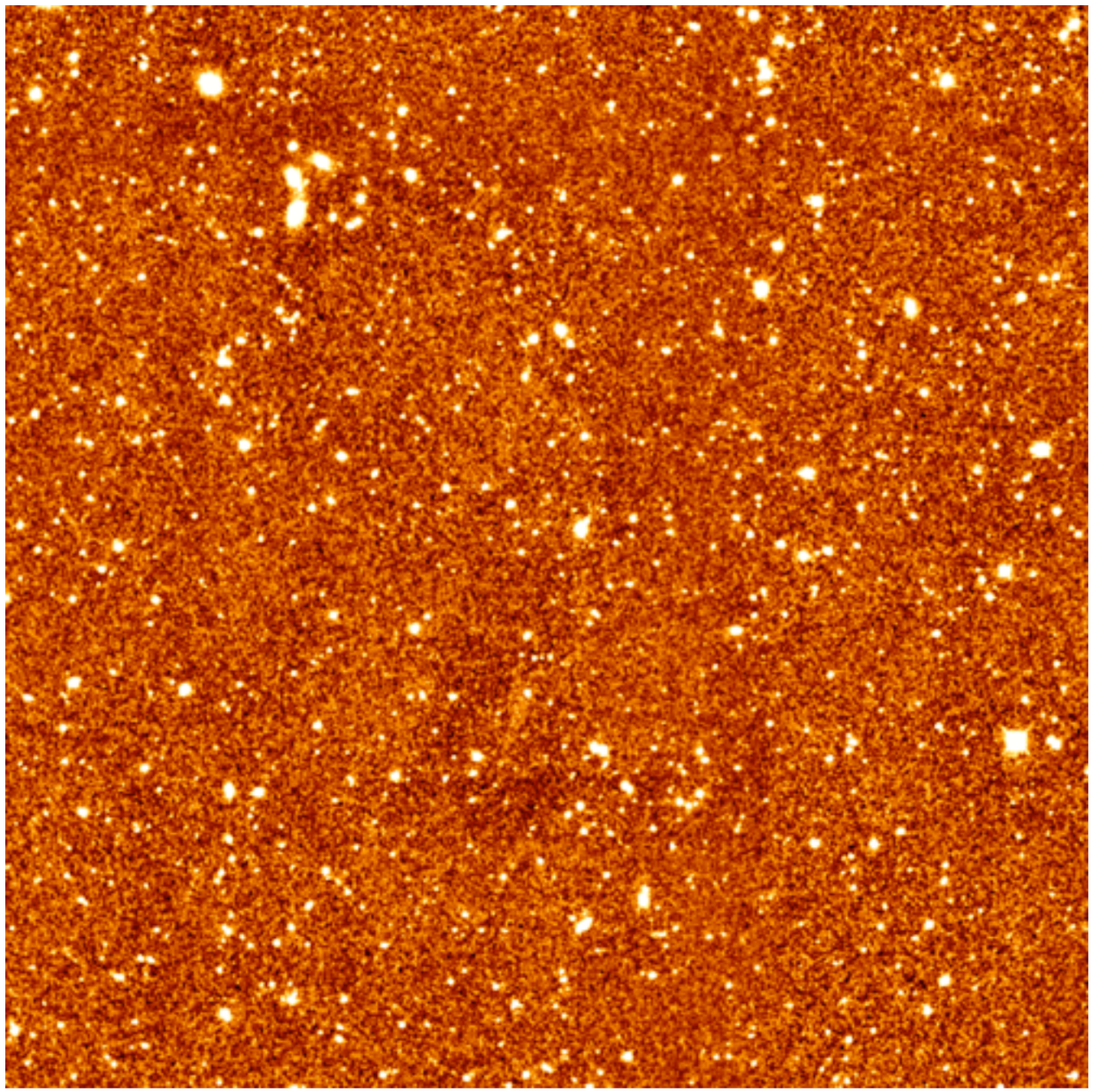


10 ‘

U-band : MUSYC

U-band
~ 60 sources/
arcmin^2

Confusion



K-band : MUSYC

10 ‘

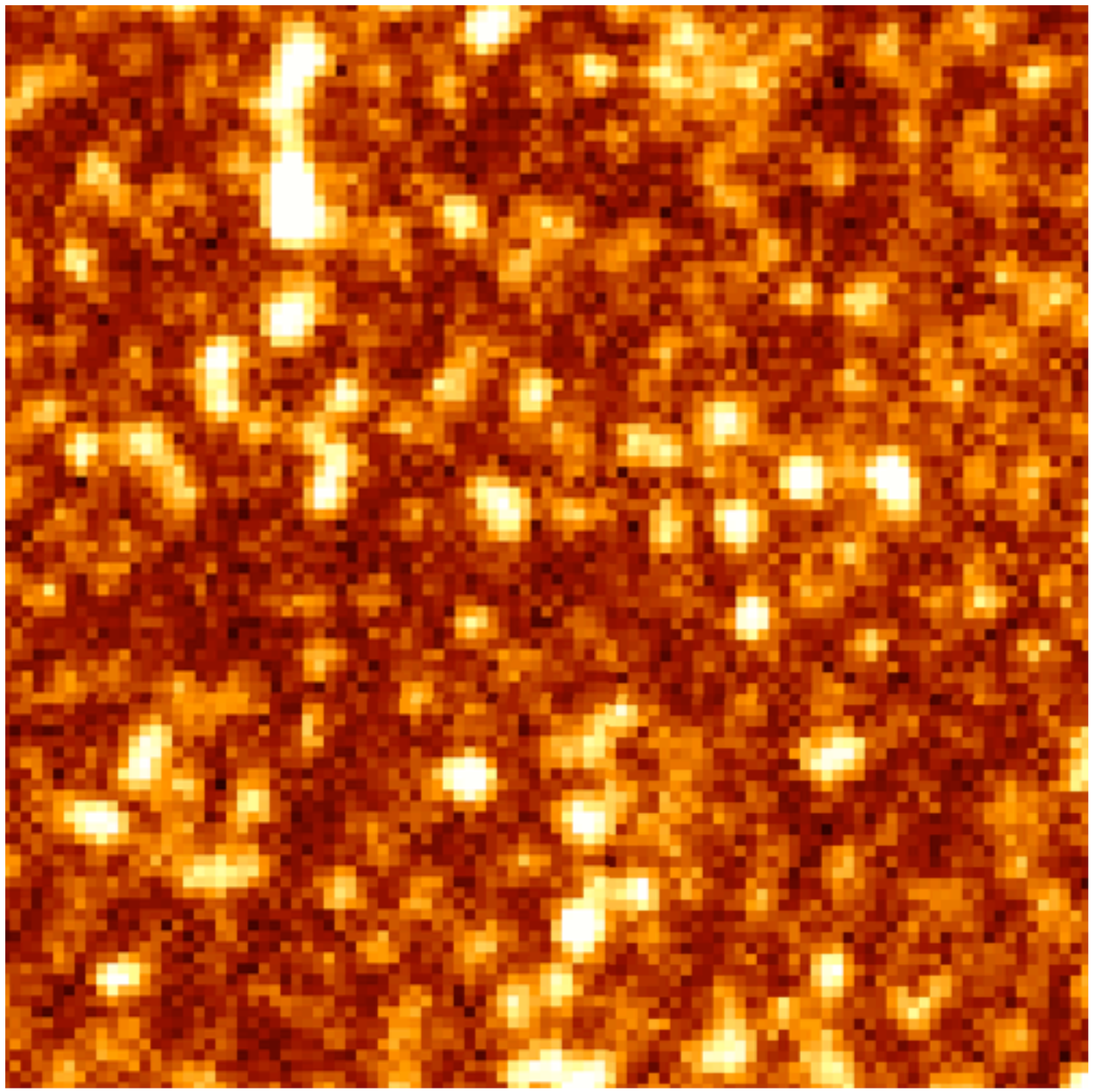
U-band

~ 60 sources/ arcmin²

K-band

~ 45 sources/ arcmin²

Confusion

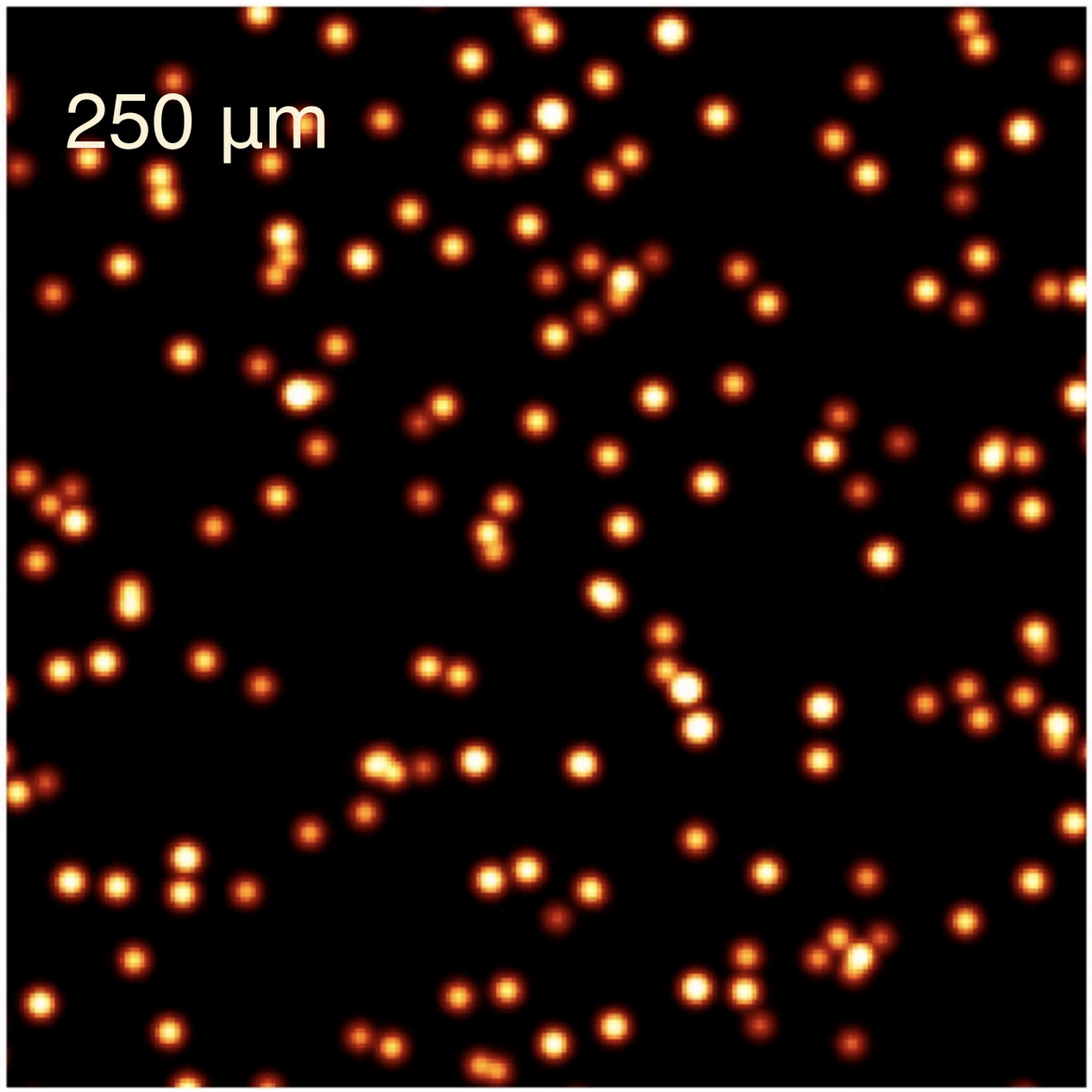


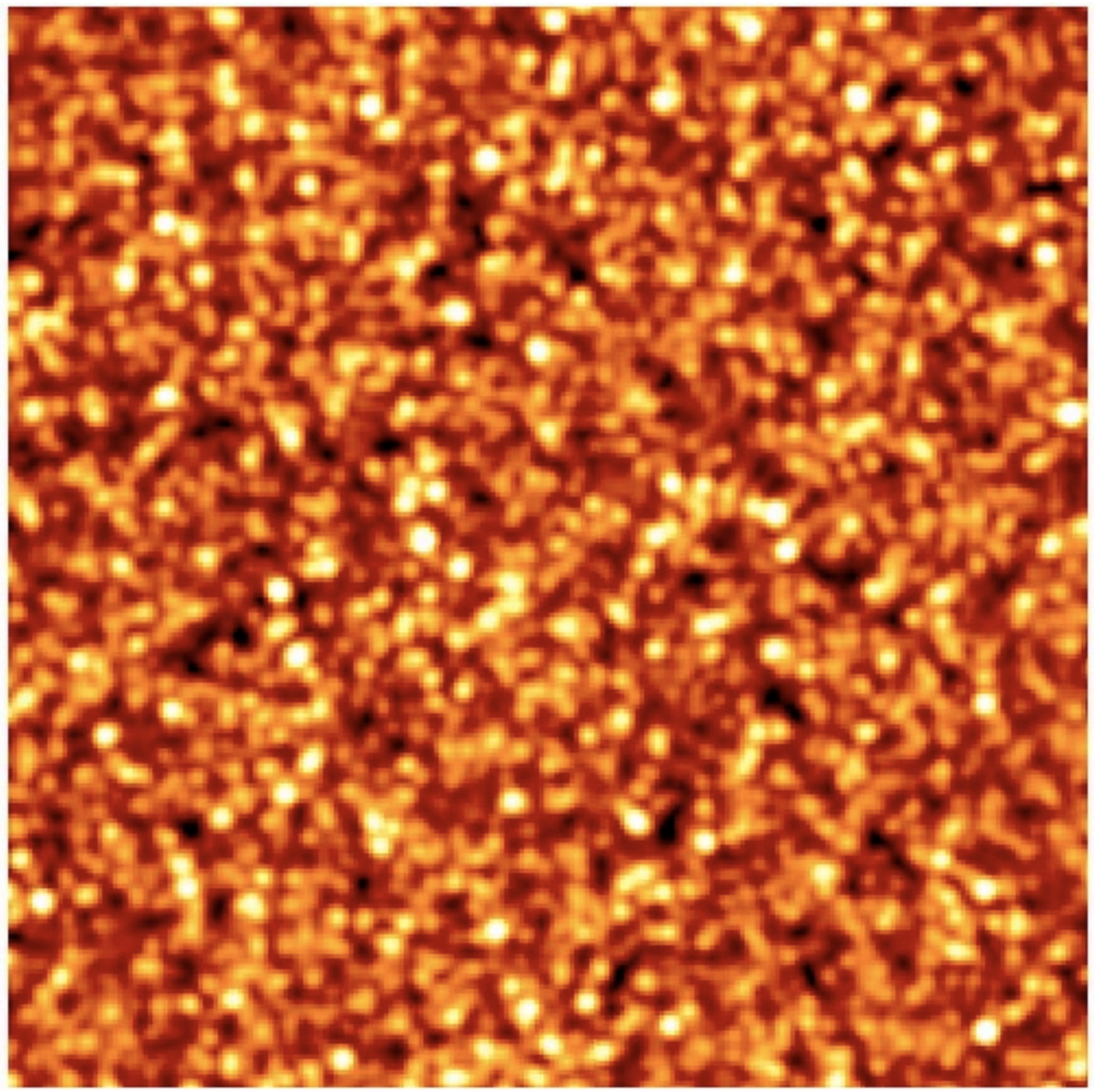
U-band
~ 60 sources/ arcmin^2

K-band
~ 45 sources/ arcmin^2

SPIRE
~ 0.5 sources/ arcmin^2

Confusion

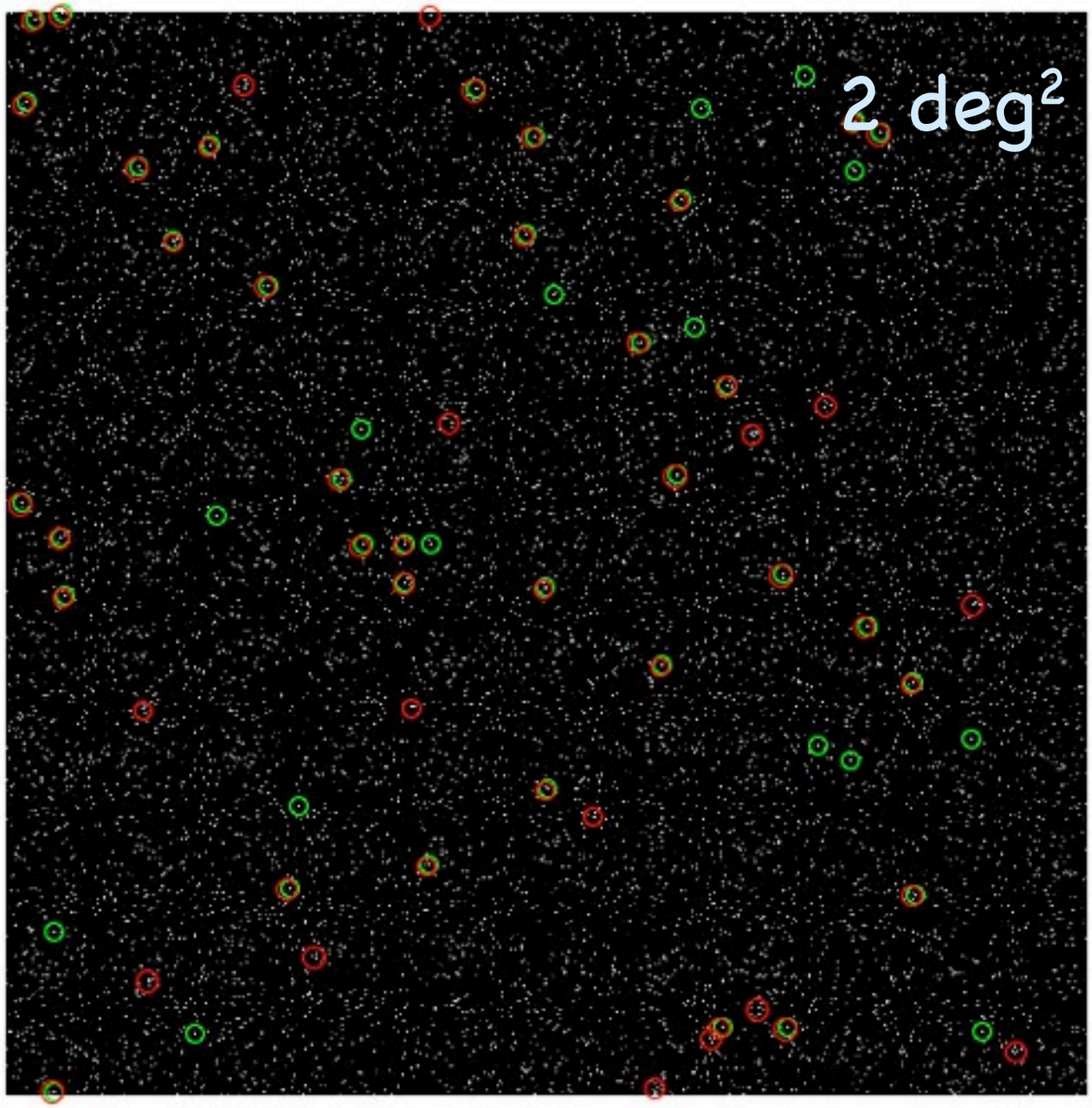


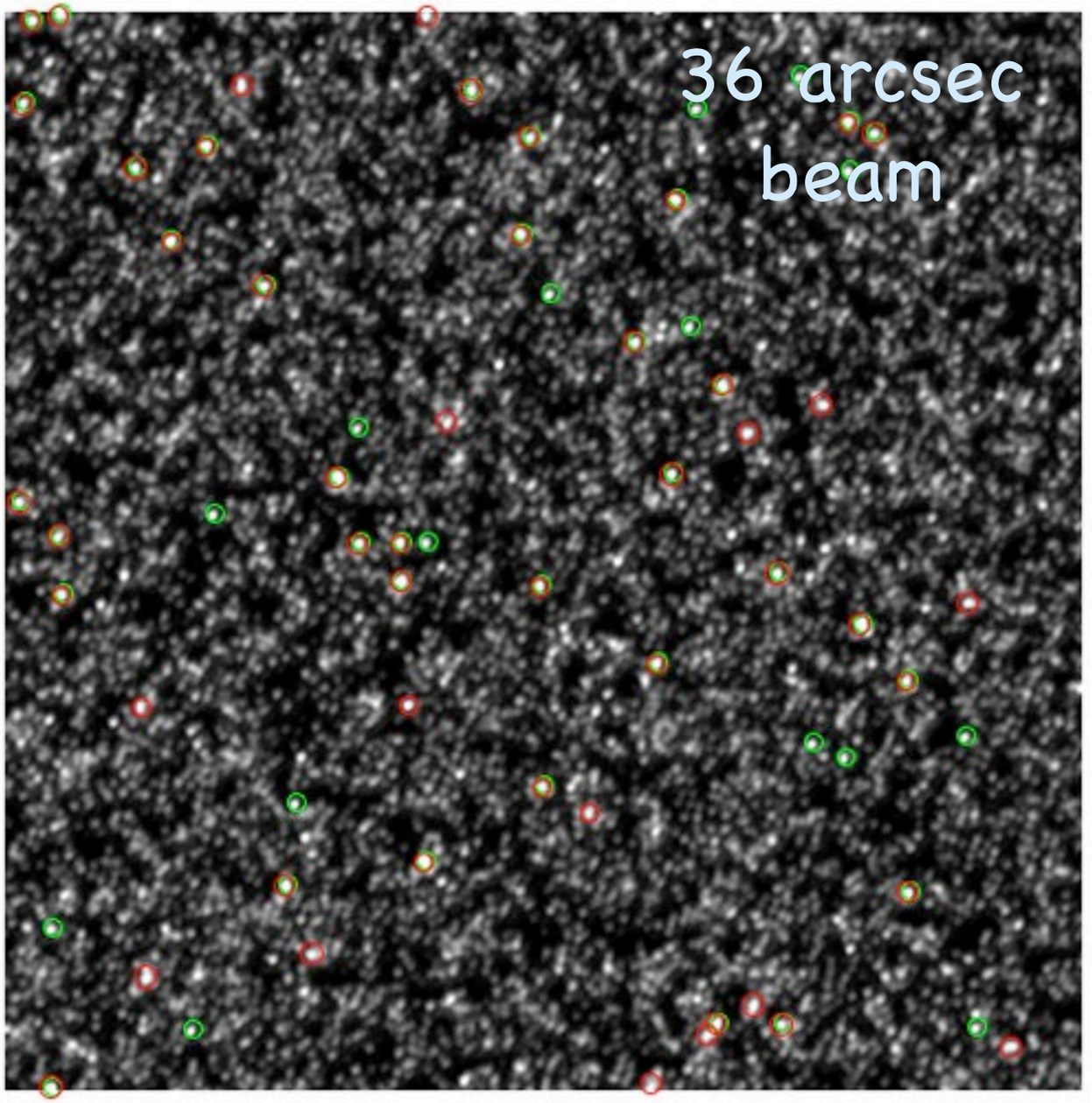


S > 20 mJy : 1,200/deg²

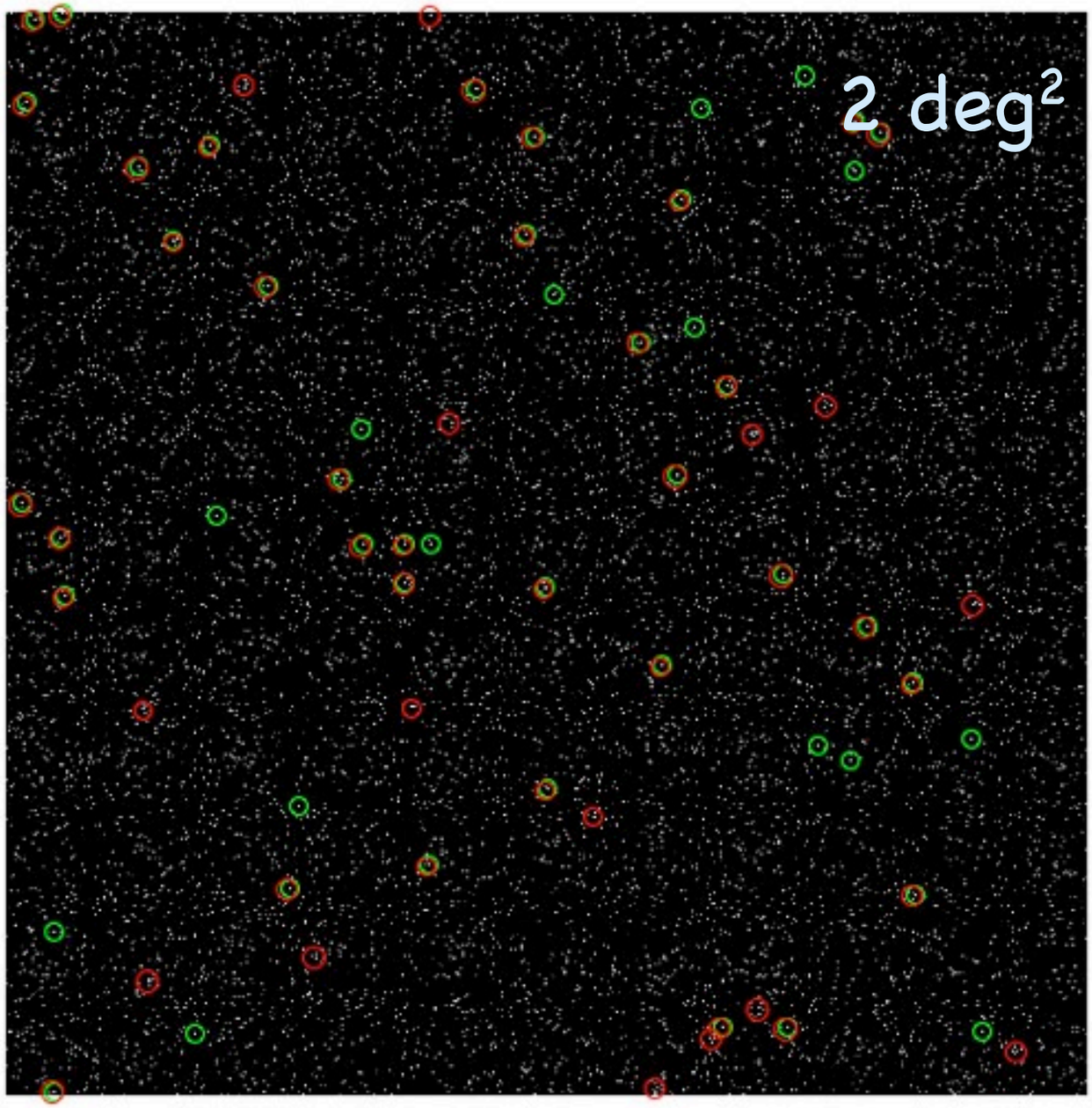
S < 20 mJy : 480,000/deg²

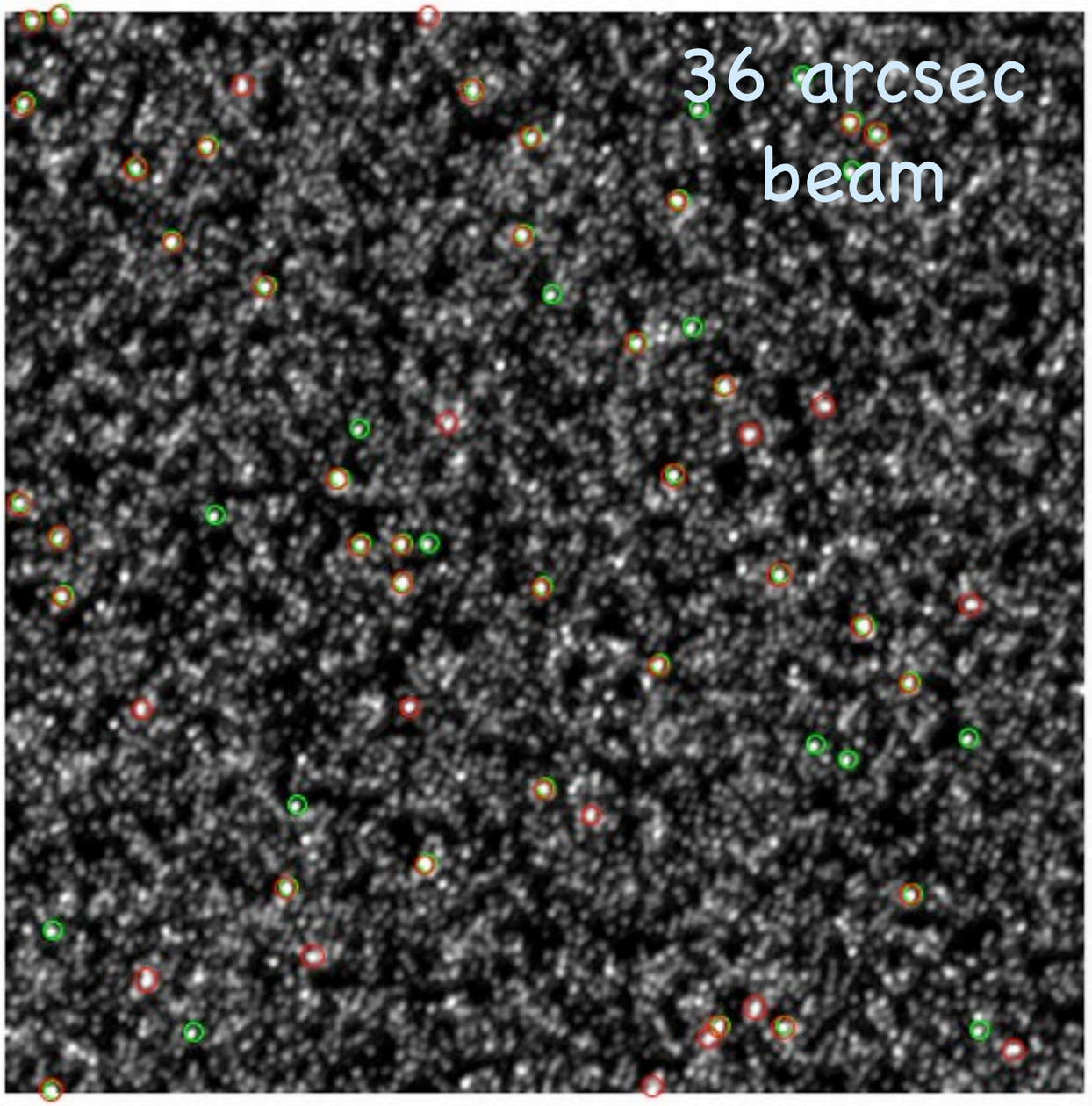
Confusion





Confusion

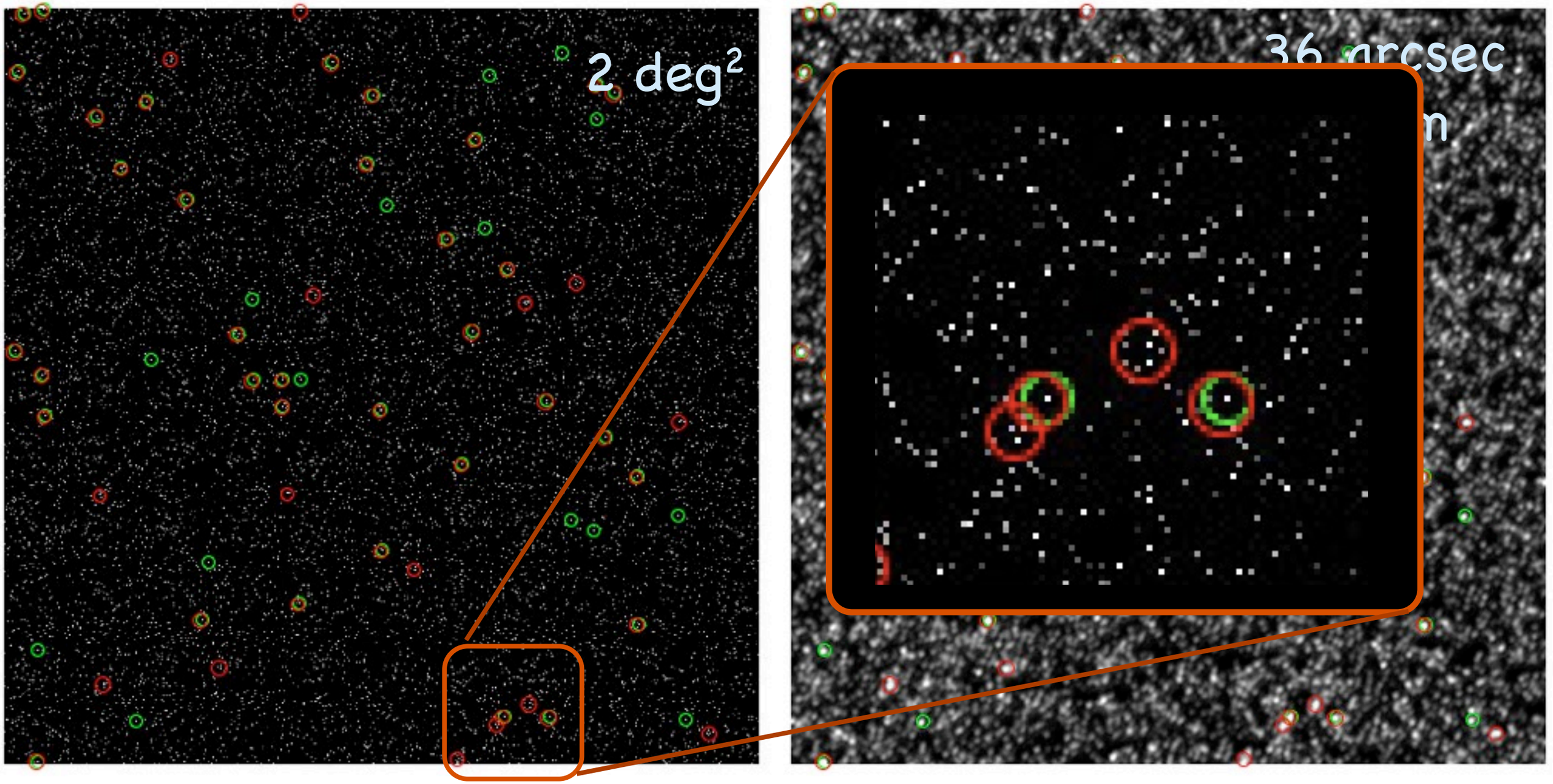




50 brightest
(top 0.5%)

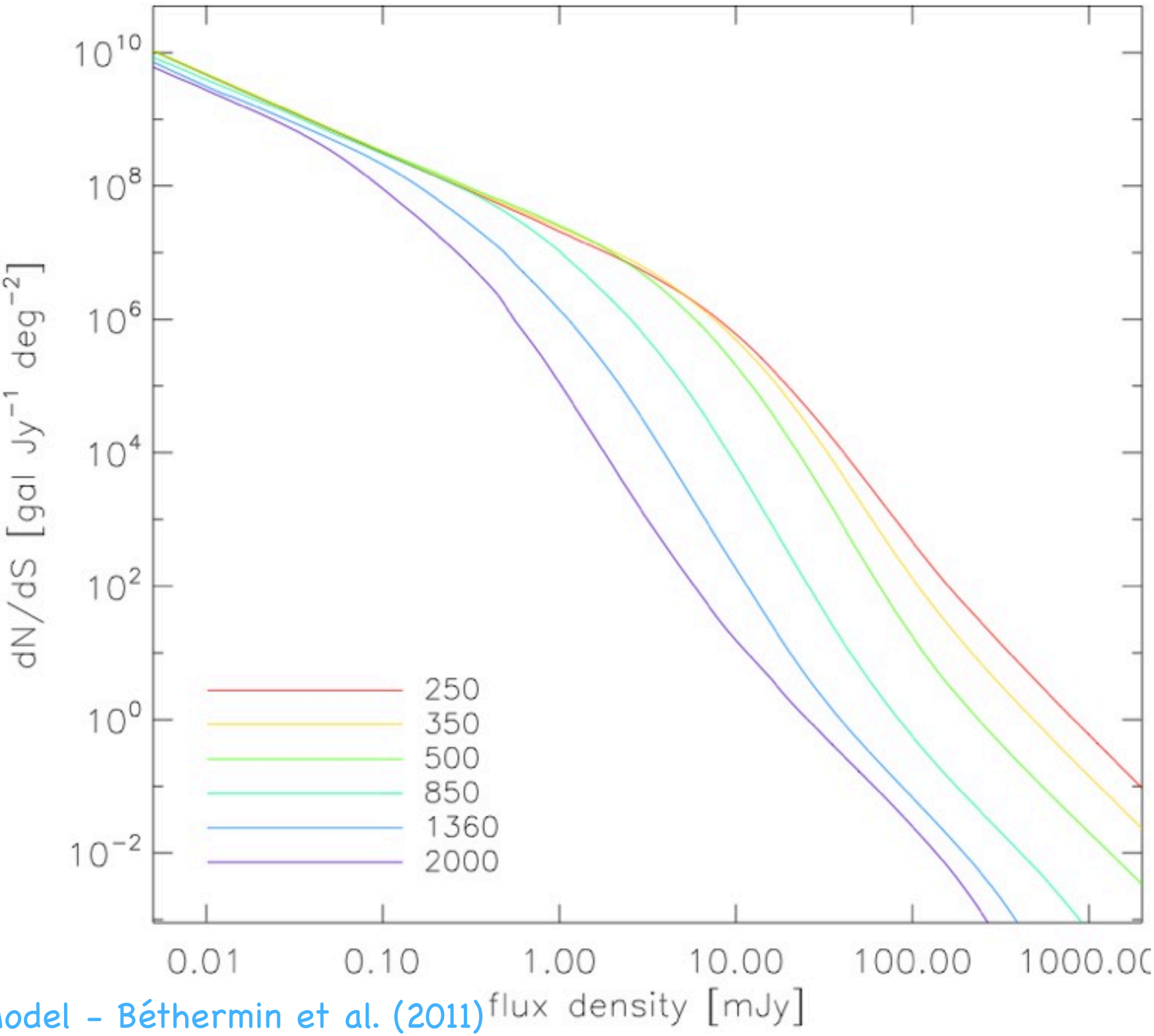
50 brightest
recovered

Confusion



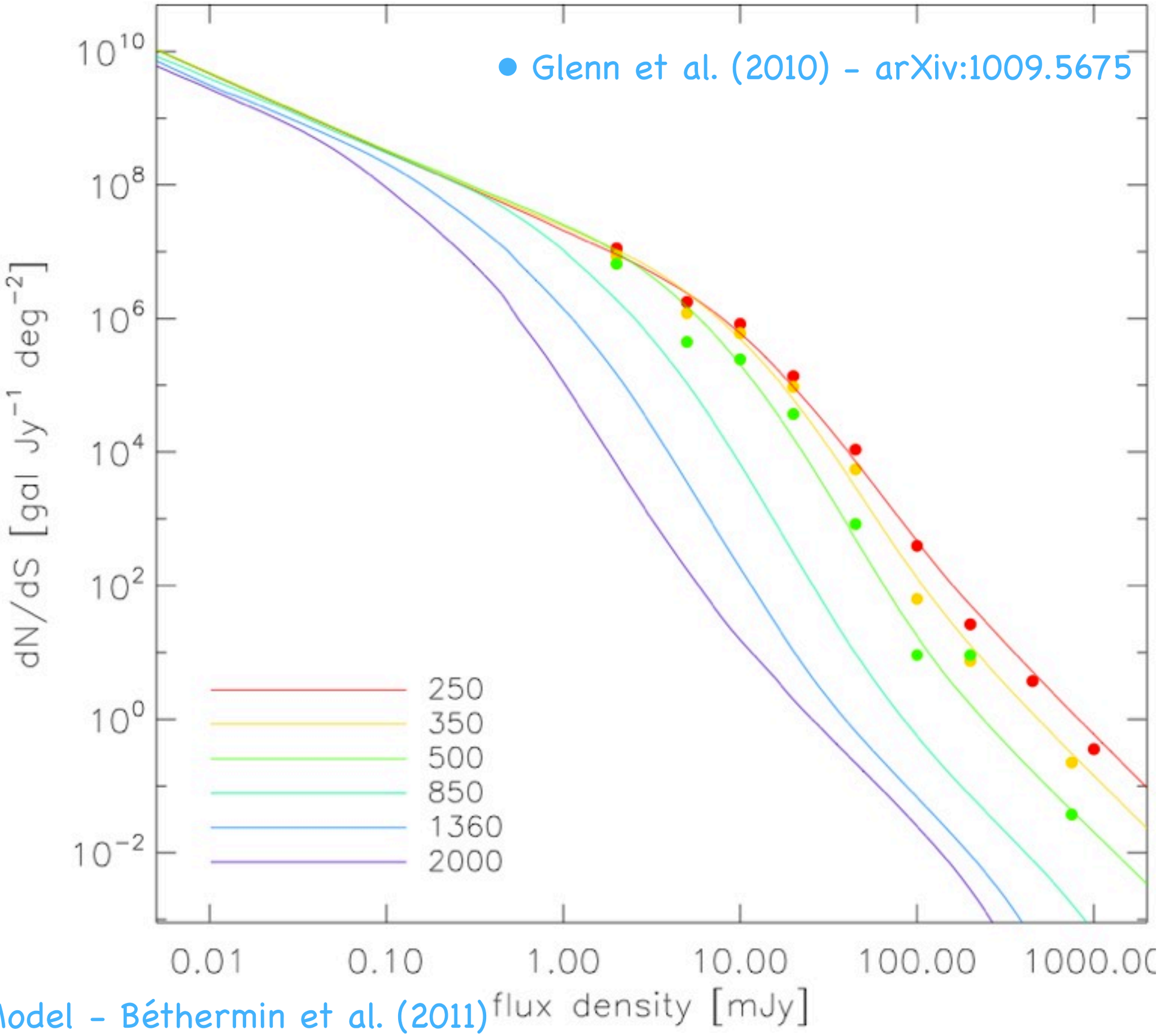
70% of top
0.5%
recovered

Confusion



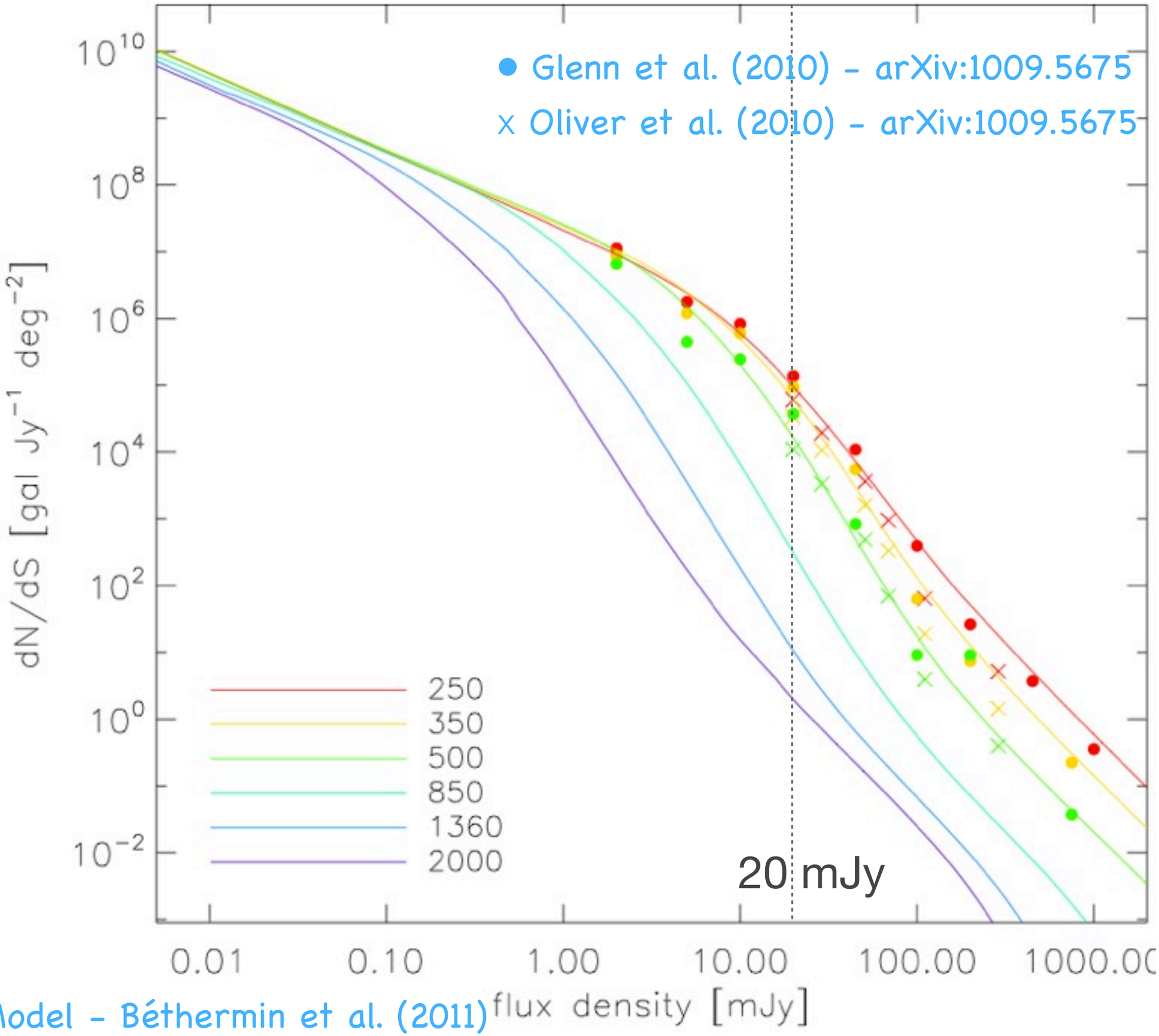
Model - Béthermin et al. (2011) arXiv:1010.1150

Measured Number Counts



Model - Béthermin et al. (2011) arXiv:1010.1150

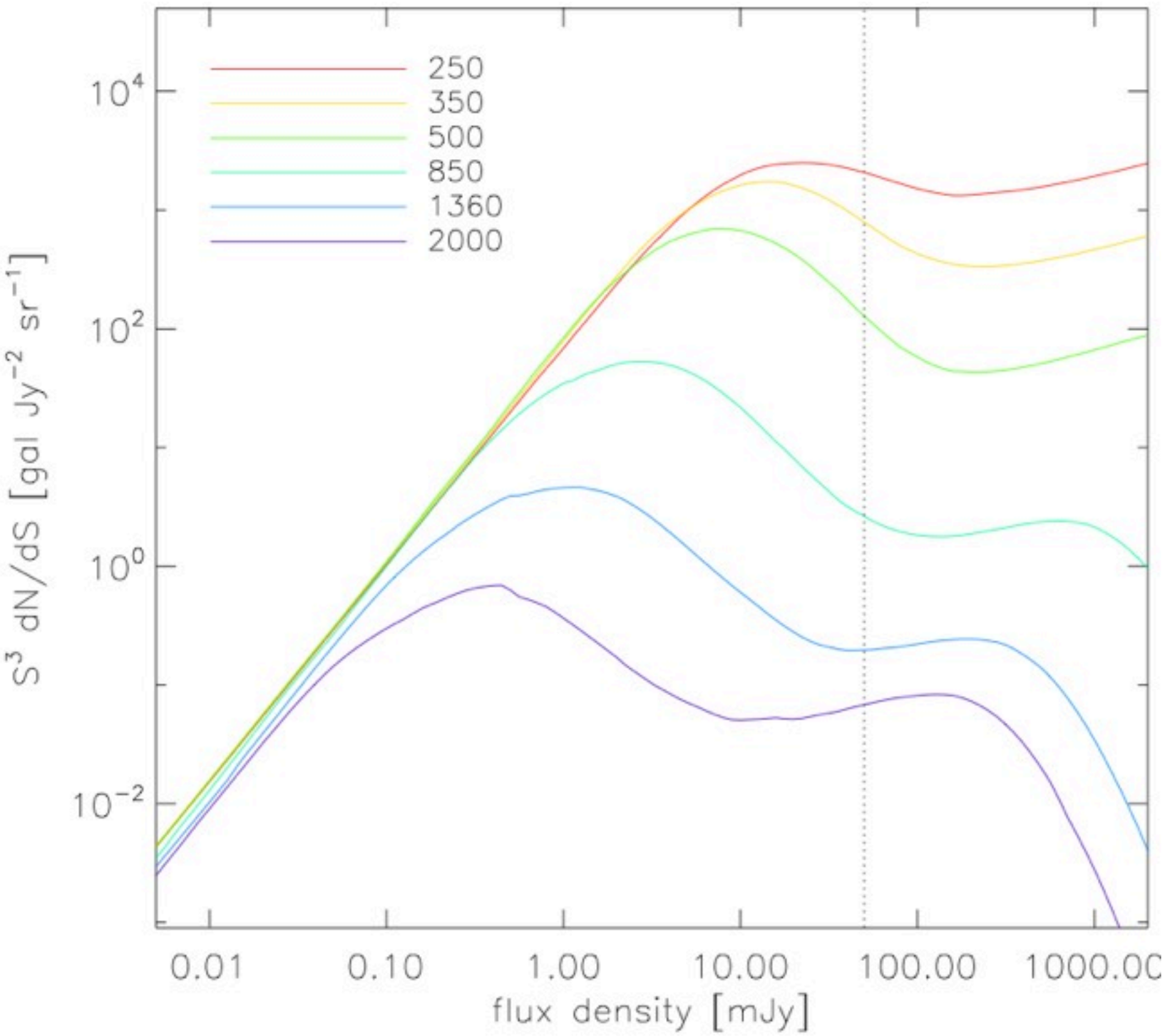
Measured Number Counts



Model - Béthermin et al. (2011) arXiv:1010.1150

Measured Number Counts

How do you measure clustering when most of what you see are fluctuations?



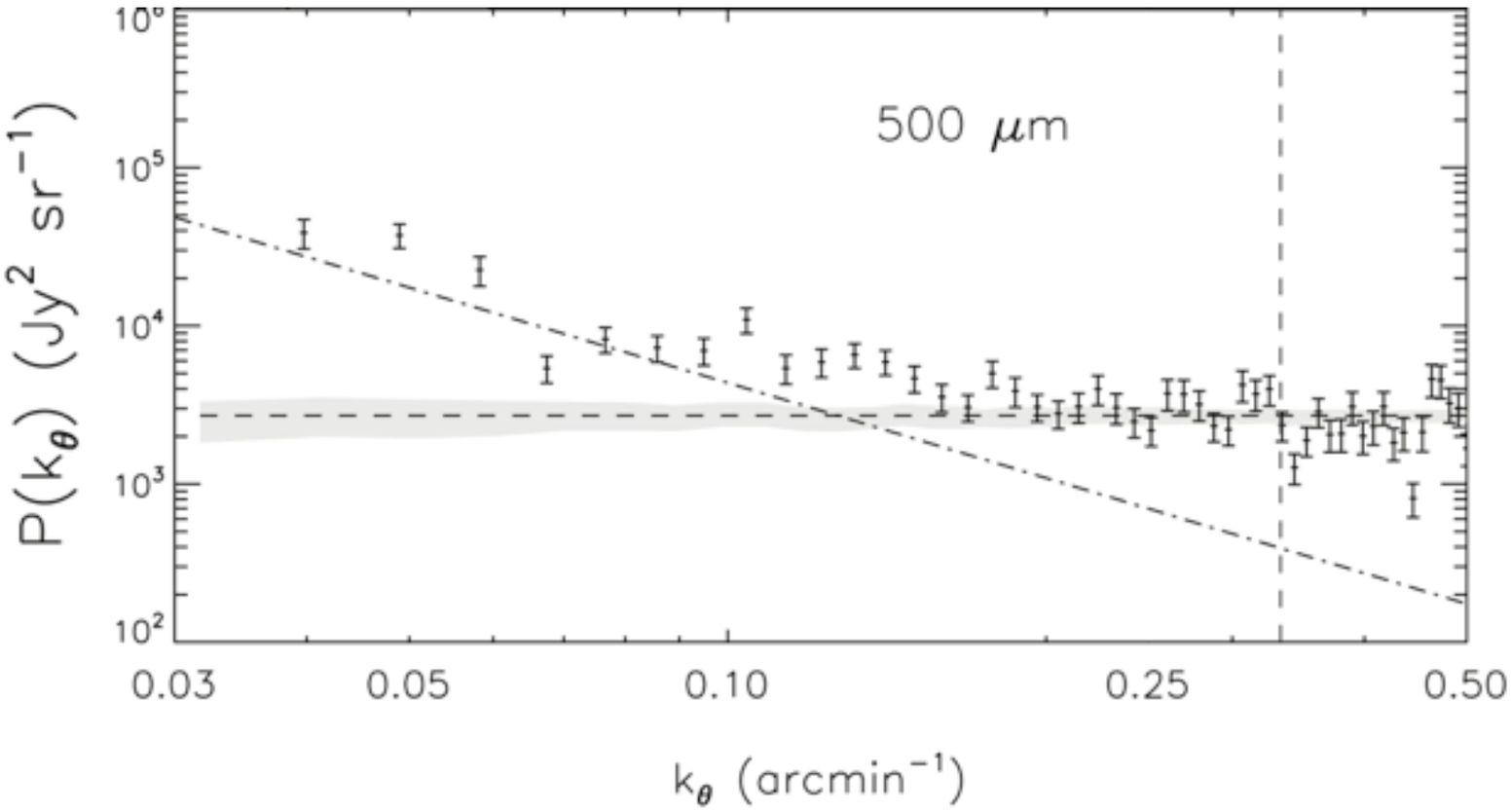
$P_{shot}=S^2dN/dS$

Poisson (shot) Noise

Star Forming Galaxies are biased tracers of Dark Matter

Star Forming Galaxies are
biased tracers of Dark Matter

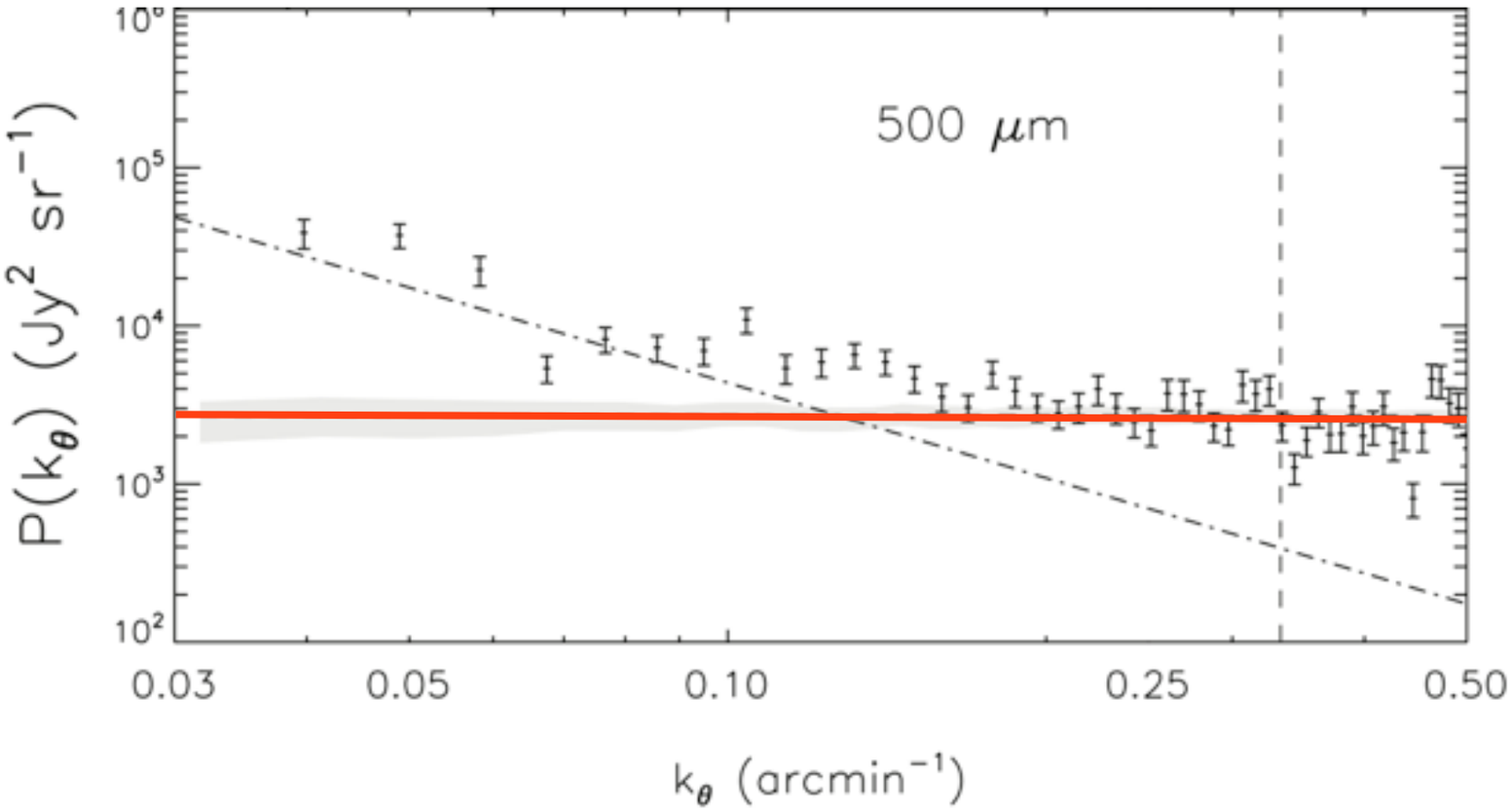
BLAST Power Spectrum



Viero et al. (2009)

arXiv: 0904.1200

BLAST Power Spectrum

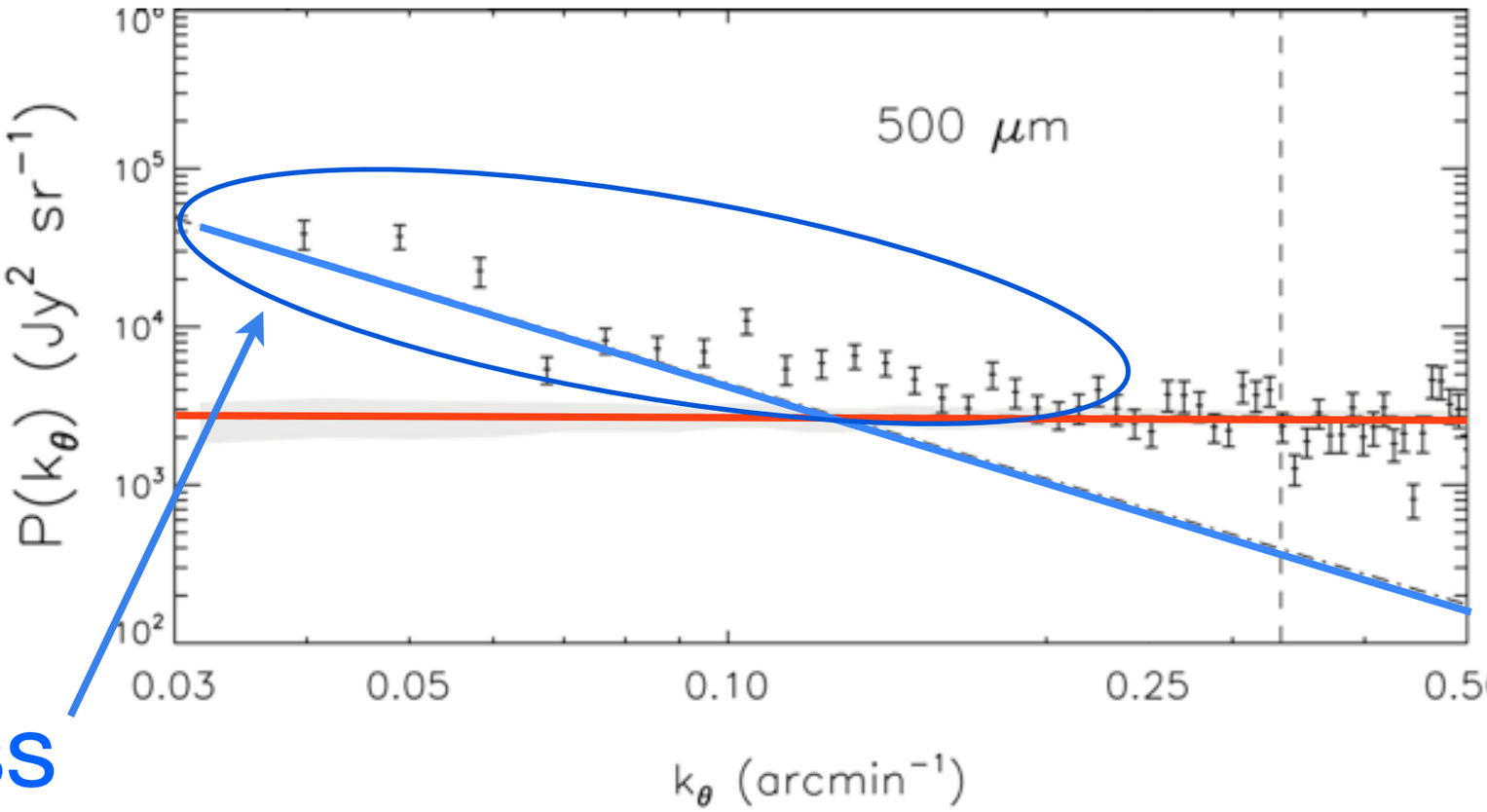


Shot Noise

Viero et al. (2009)

arXiv: 0904.1200

BLAST Power Spectrum



Shot Noise

Clustering

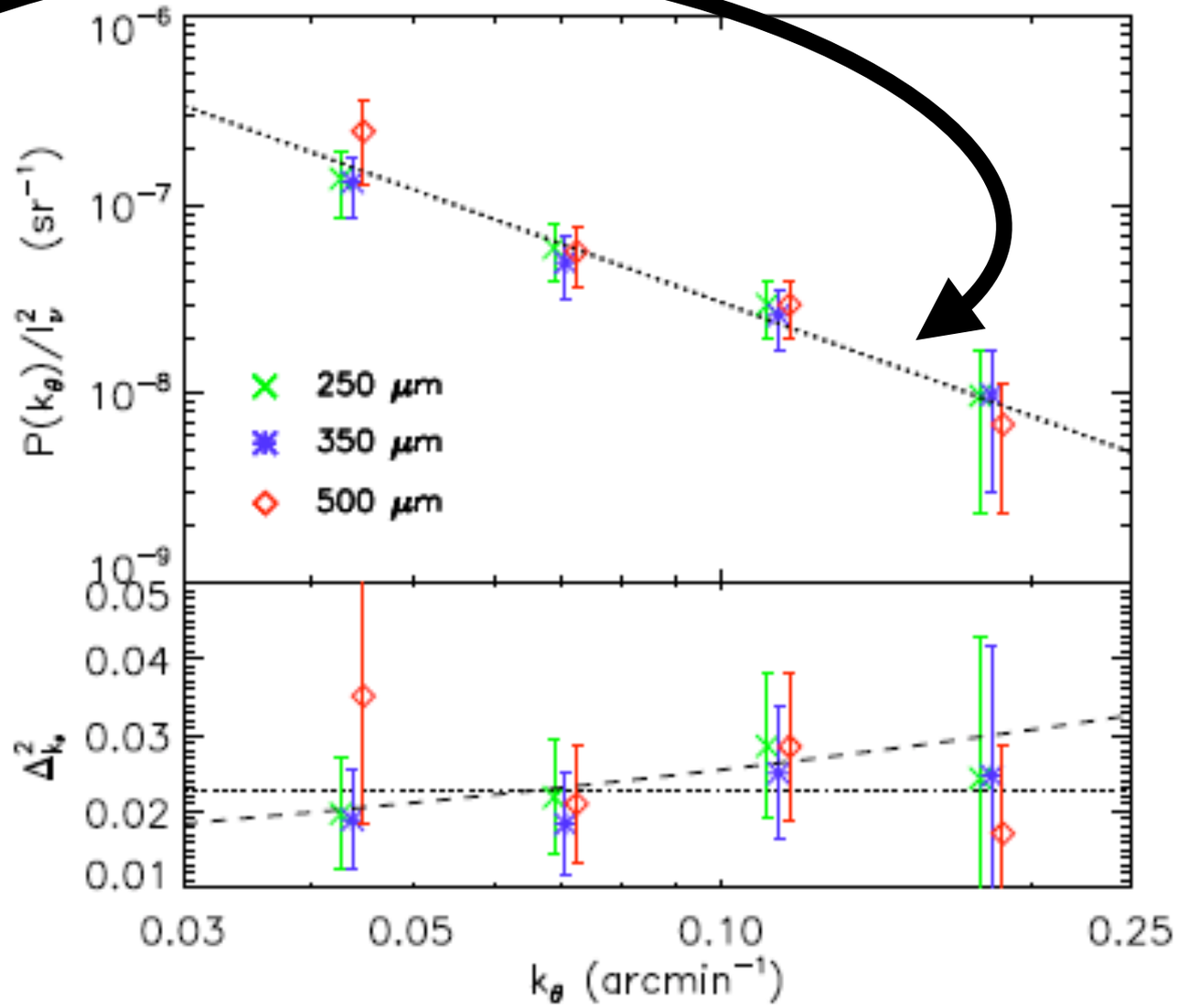
Excess Signal from Galaxy Clustering

Viero et al. (2009)

arXiv: 0904.1200

BLAST Power Spectrum

Clustering Signal After Removal of Shot Noise

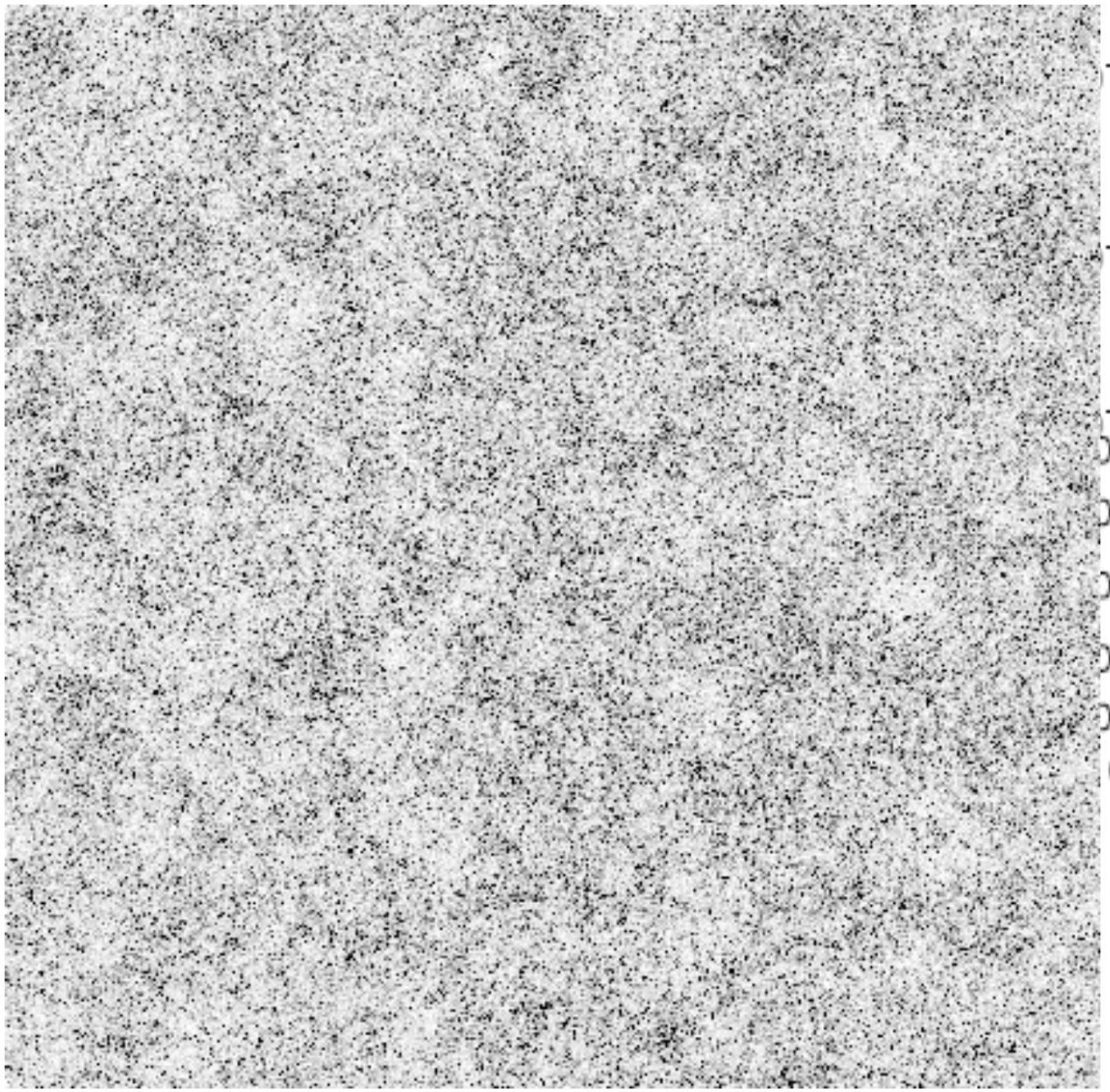


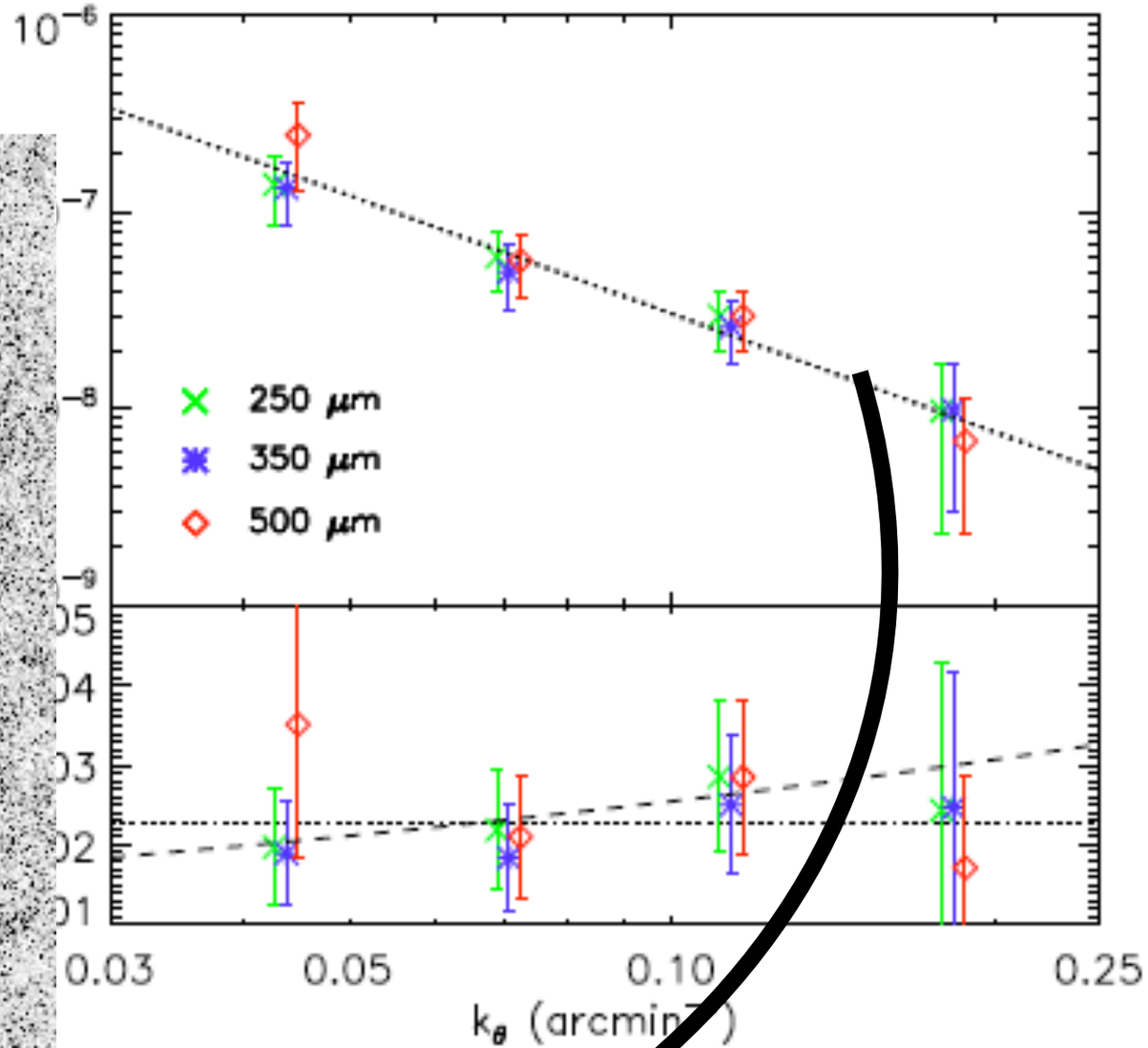
Viero et al. (2009)

arXiv: 0904.1200

BLAST Power Spectrum

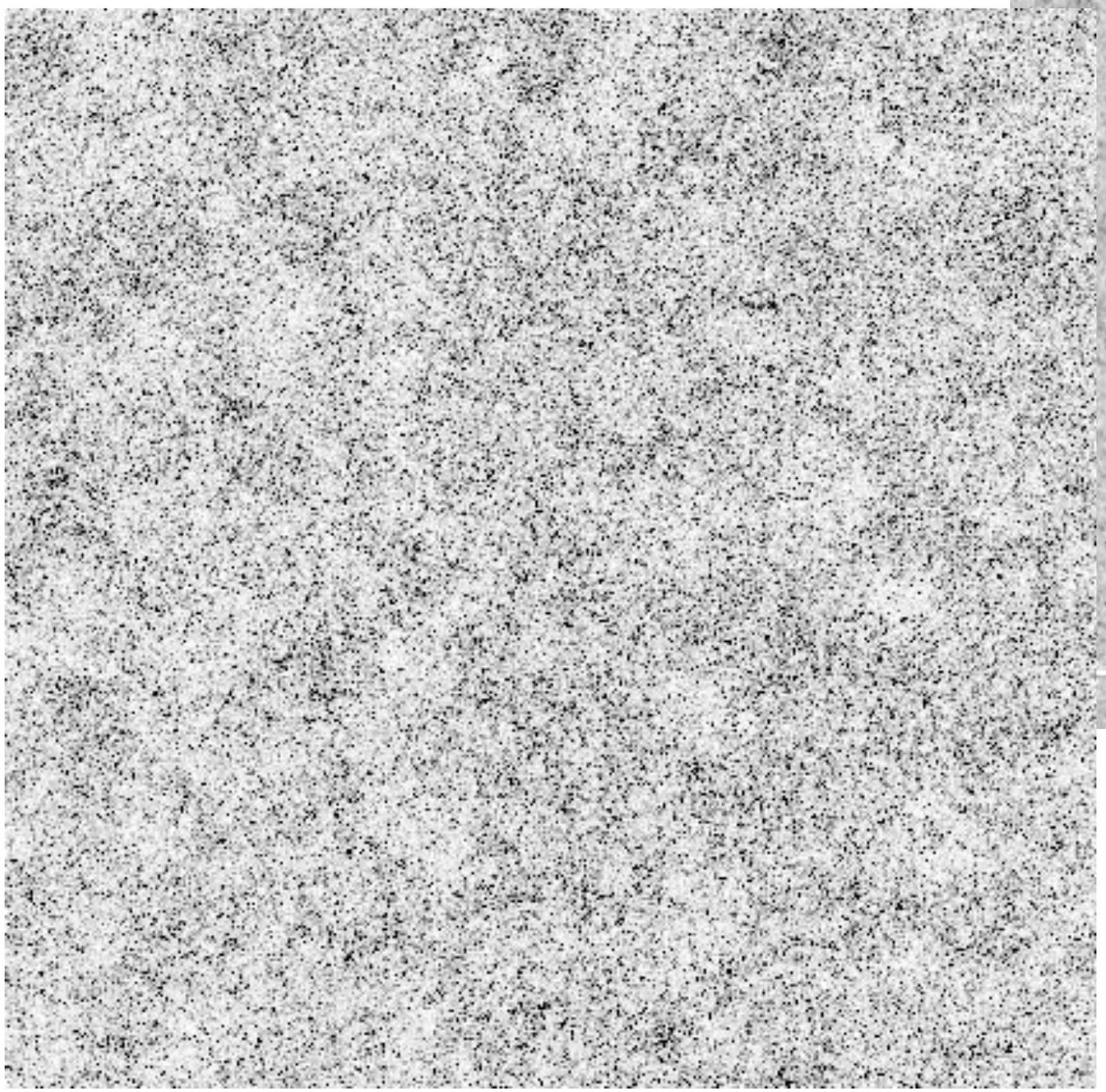
BLAST simulation...

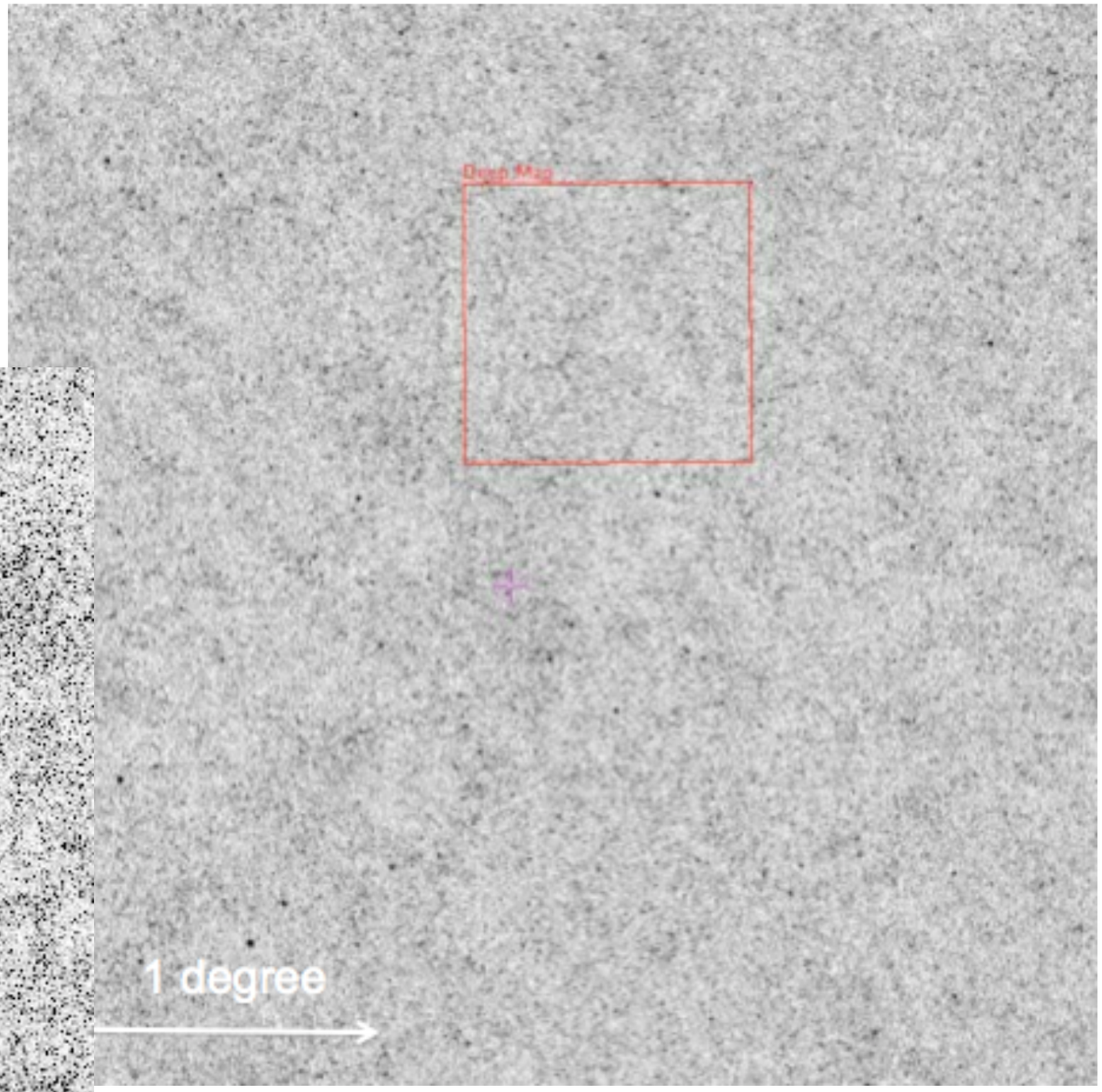




BLAST Power Spectrum

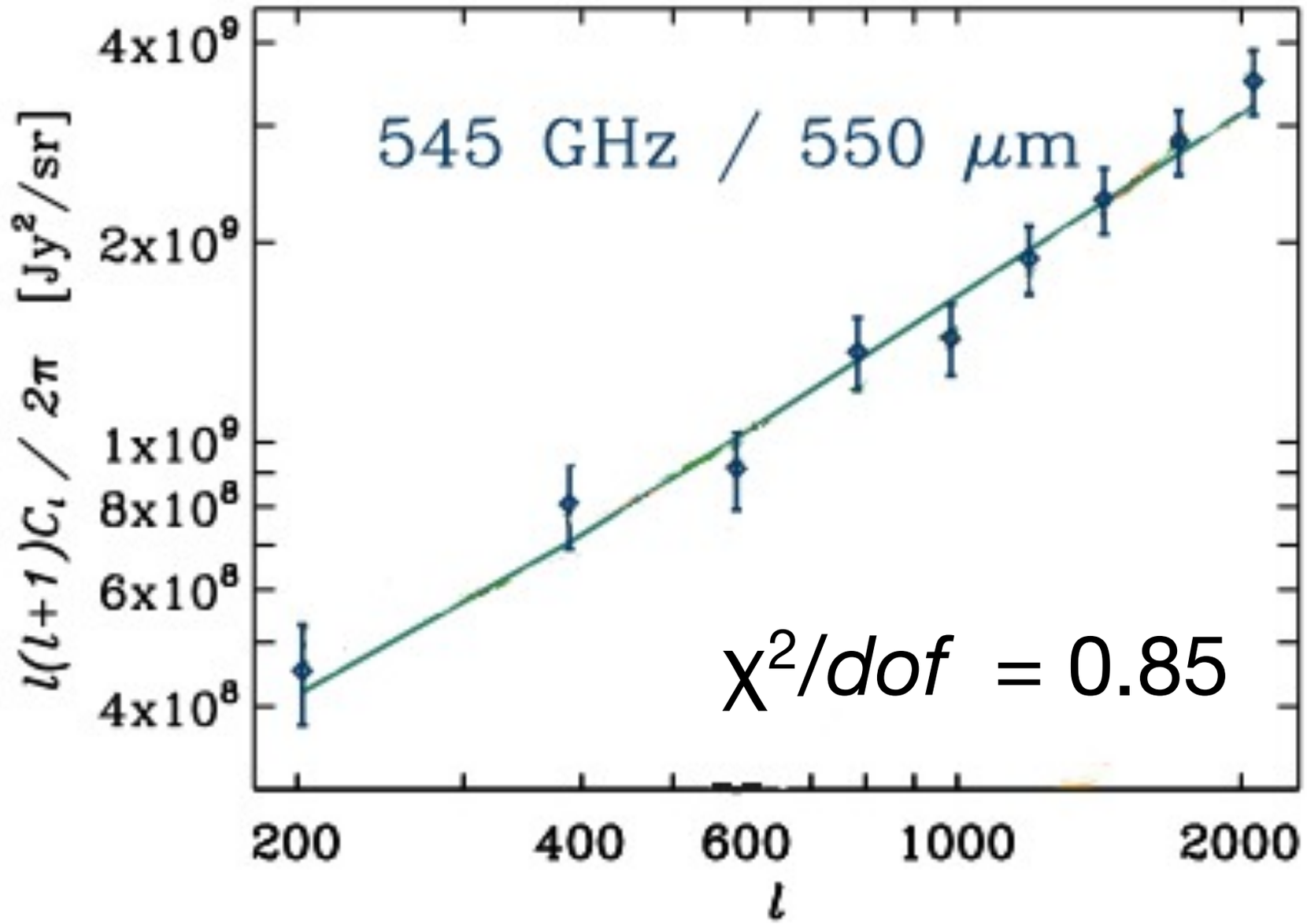
BLAST simulation...





... Herschel observation

BLAST Power Spectrum

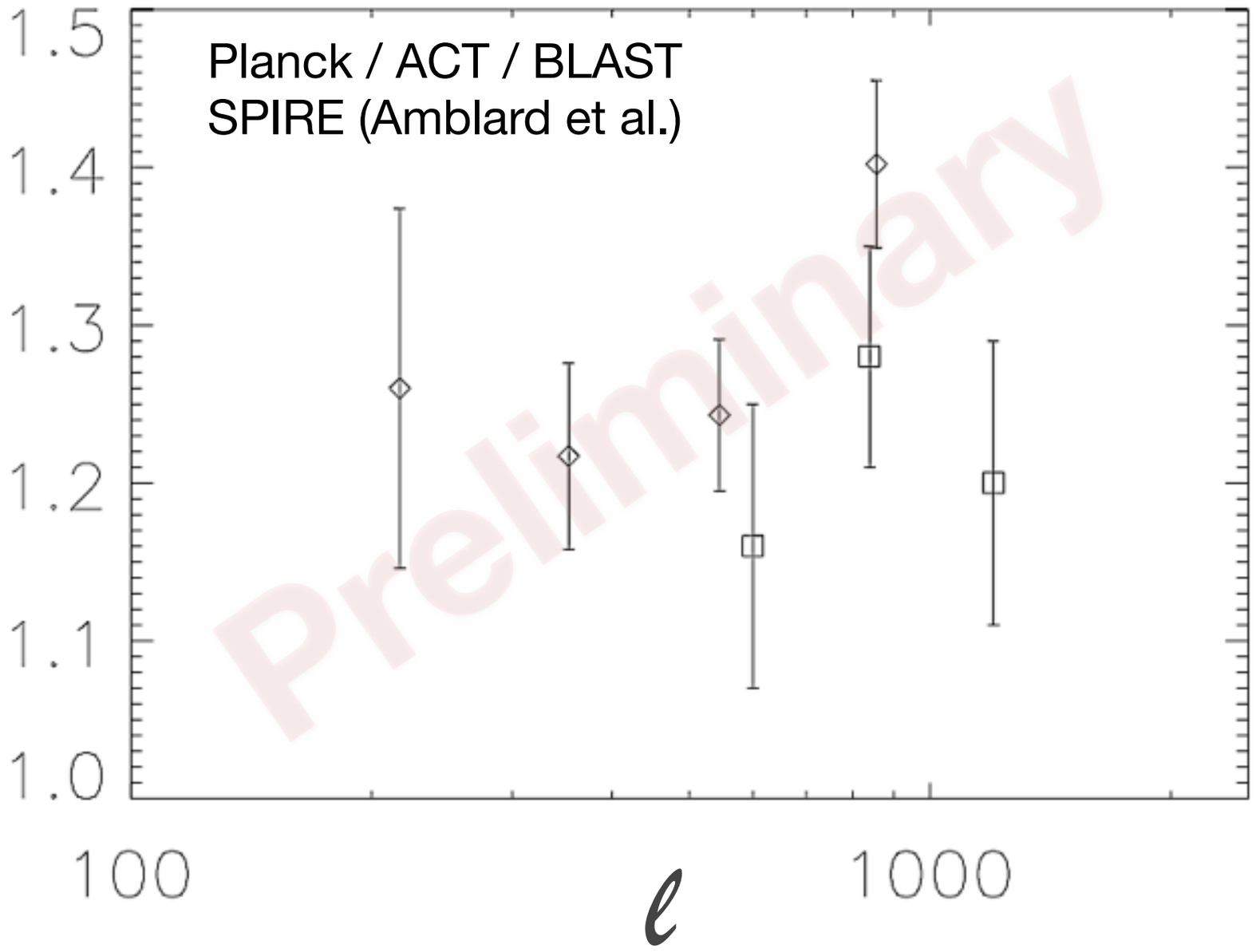


Planck Collaboration et al. (2011)

arXiv: 1101.2028

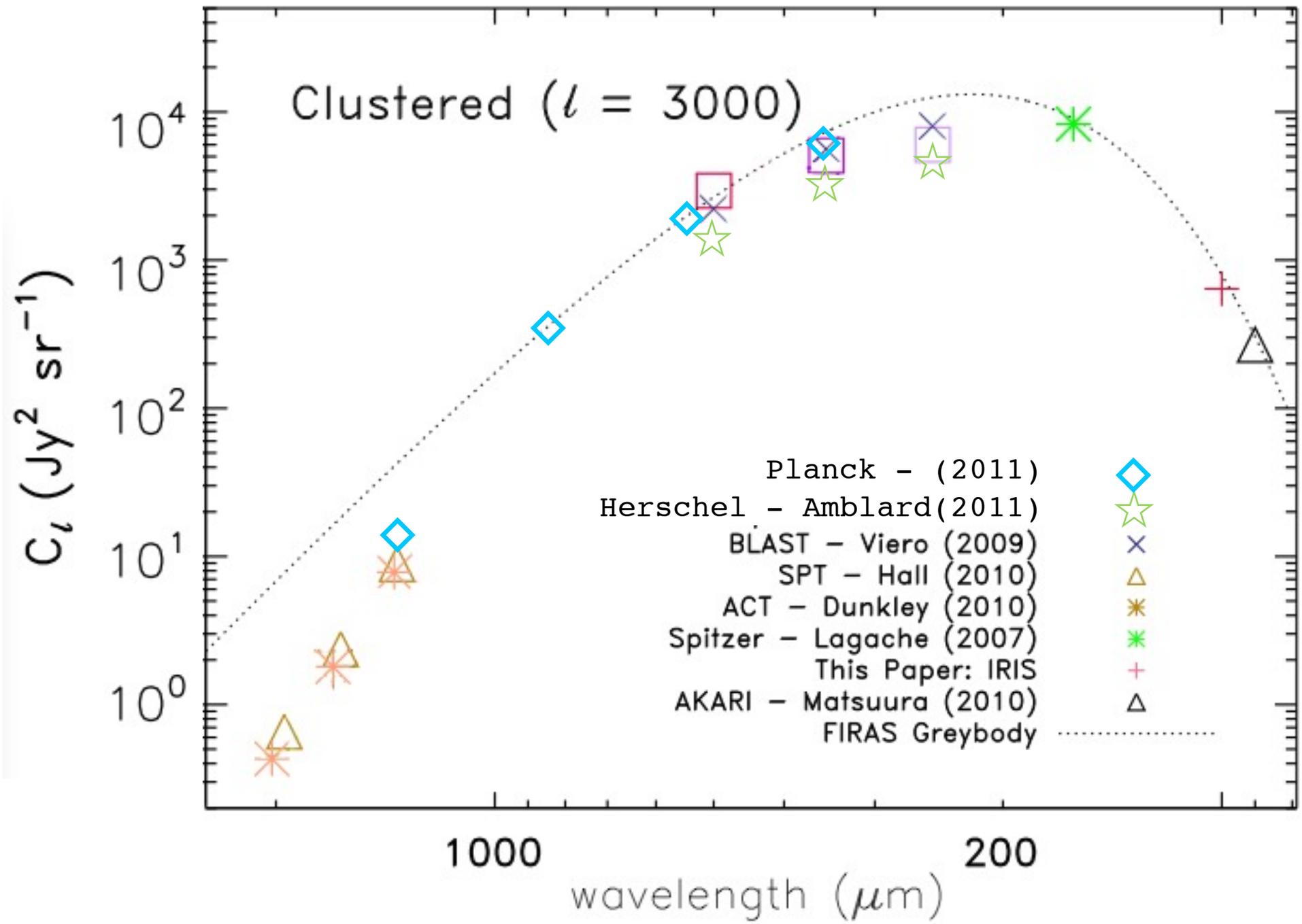
Planck Power Law

$$P(\ell) = P_{shot} + A\,(\ell/1000)^{-n}$$

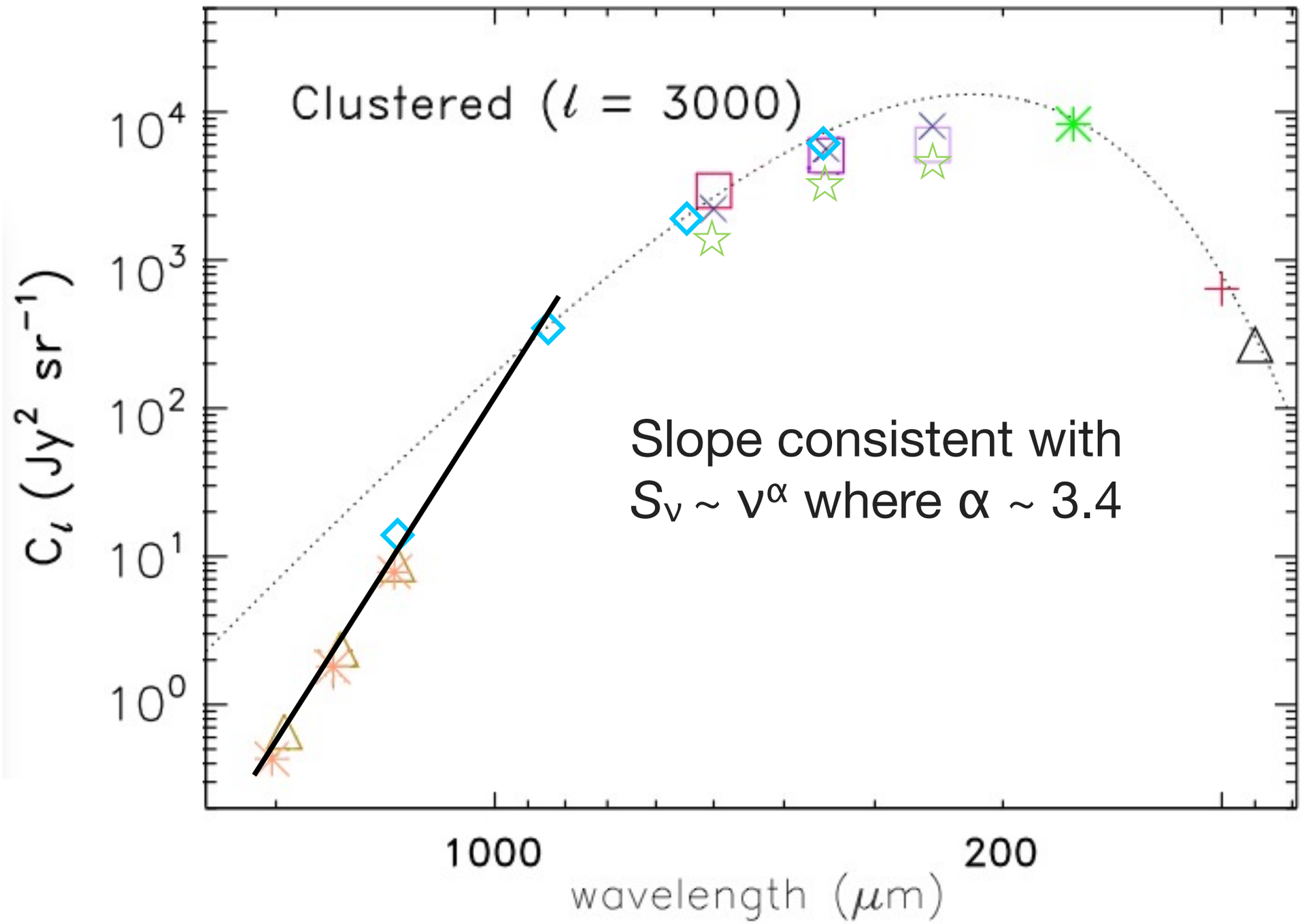


Addison et al. (in prep.)

Frequency-dependence of Power-law



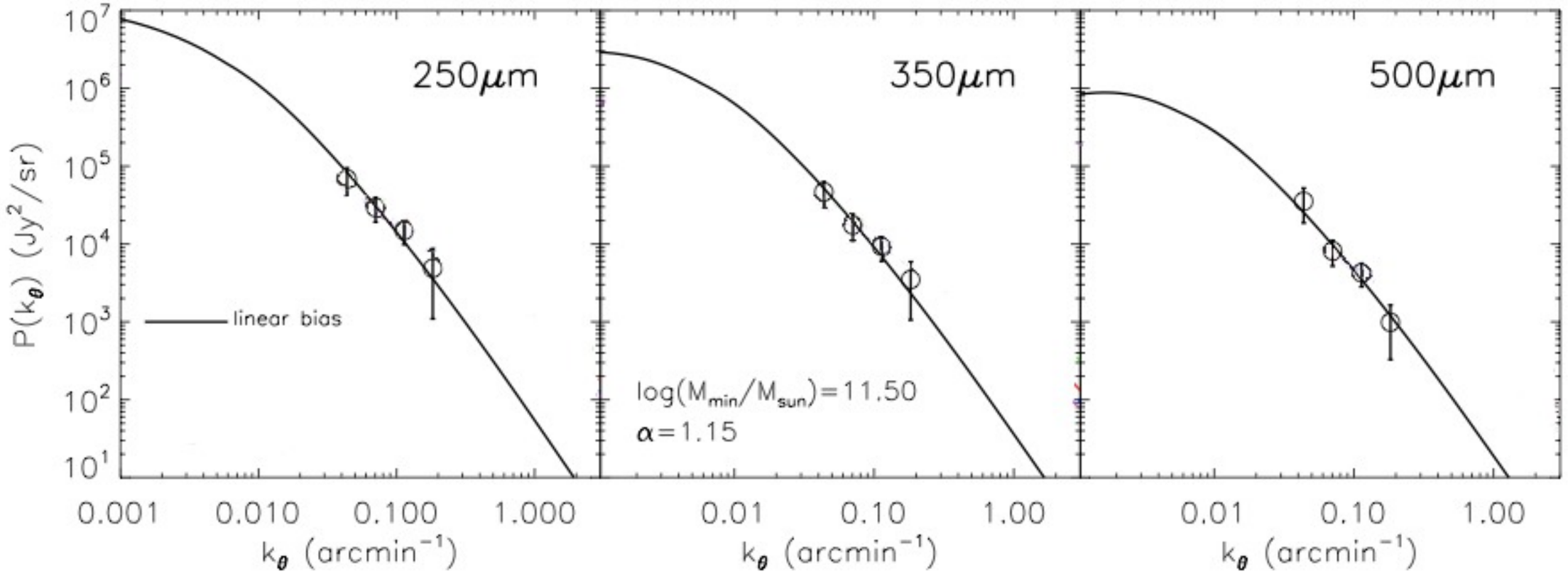
Latest Power Spectra



see also Shirokoff et al. (2010) - arXiv: 1012.4788

Millea et al. (2011) - arXiv: 1102.5195

Latest Power Spectra

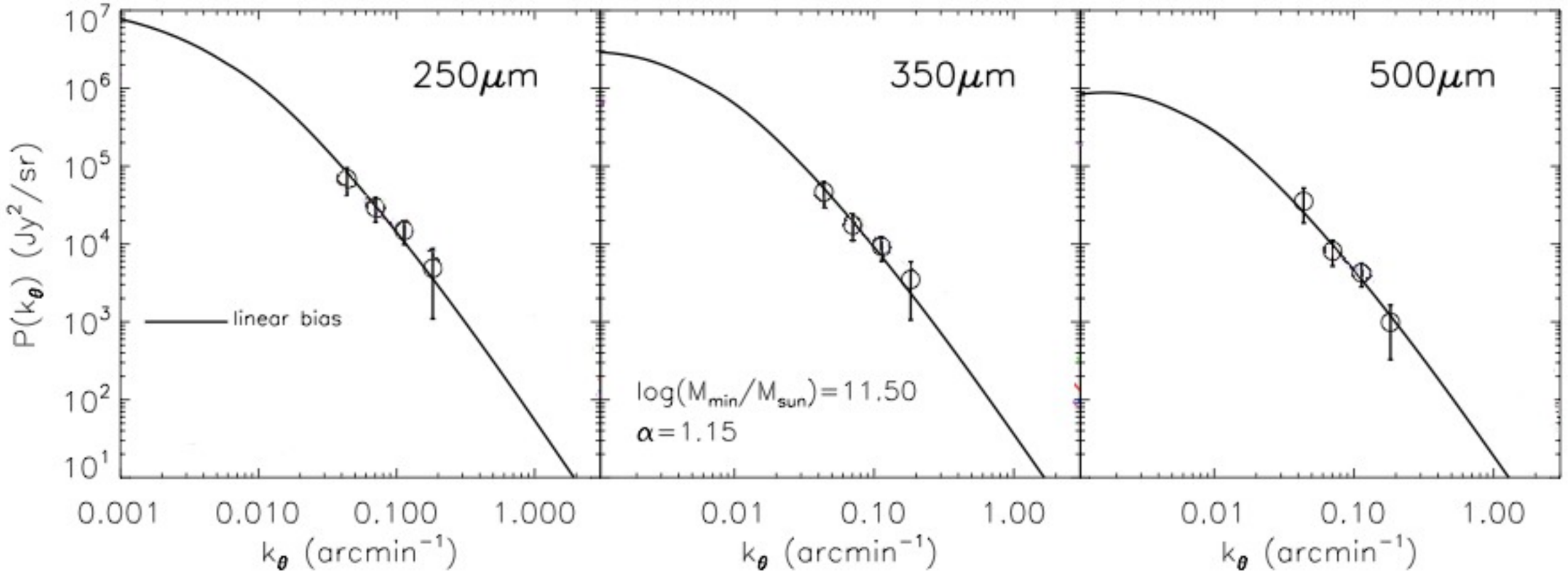


Viero et al. (2009)

arXiv: 0904.1200

$$P(k)=b^2 P_{DM}(k,z)$$

Linear Bias



$$P(k)=b^2 P_{DM}(k,z)$$

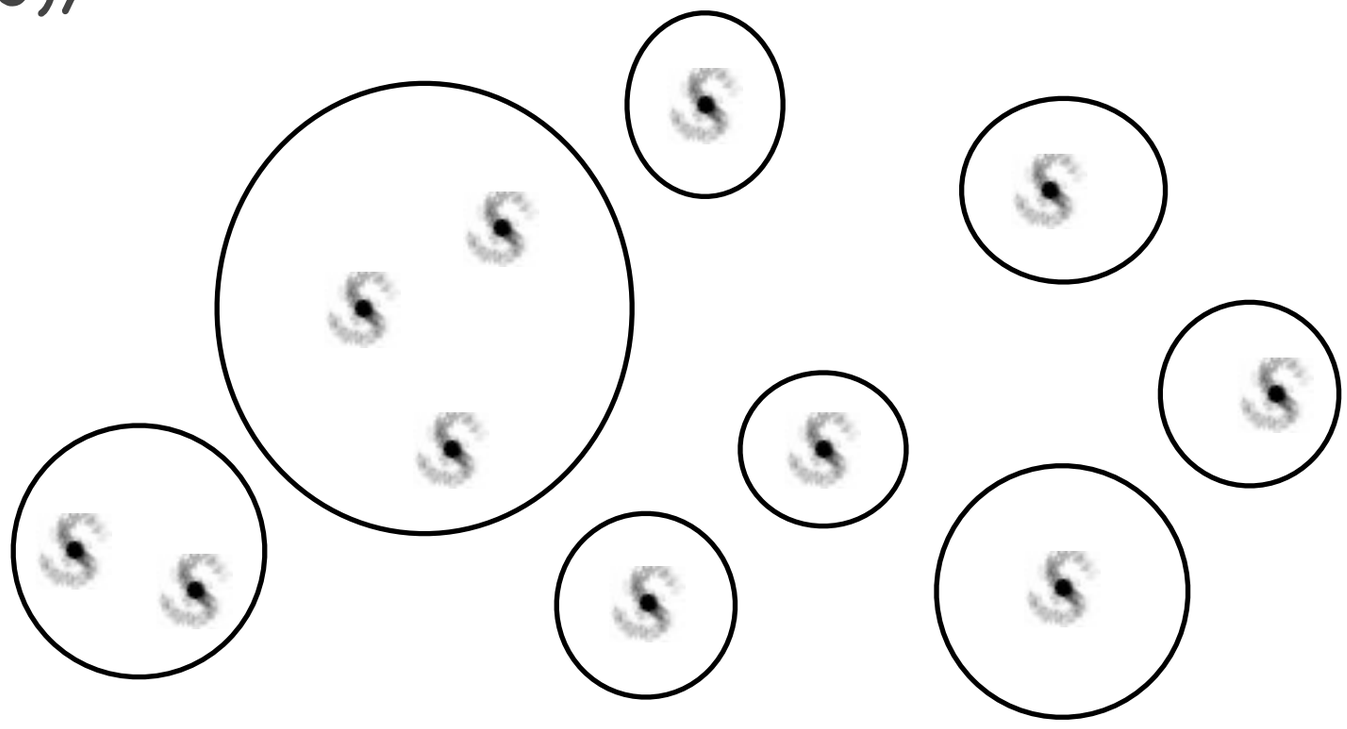
Linear Bias

see e.g., Cooray & Sheth (2000),
Zehavi et al. (2005, 2008)

BLAST Halo Model

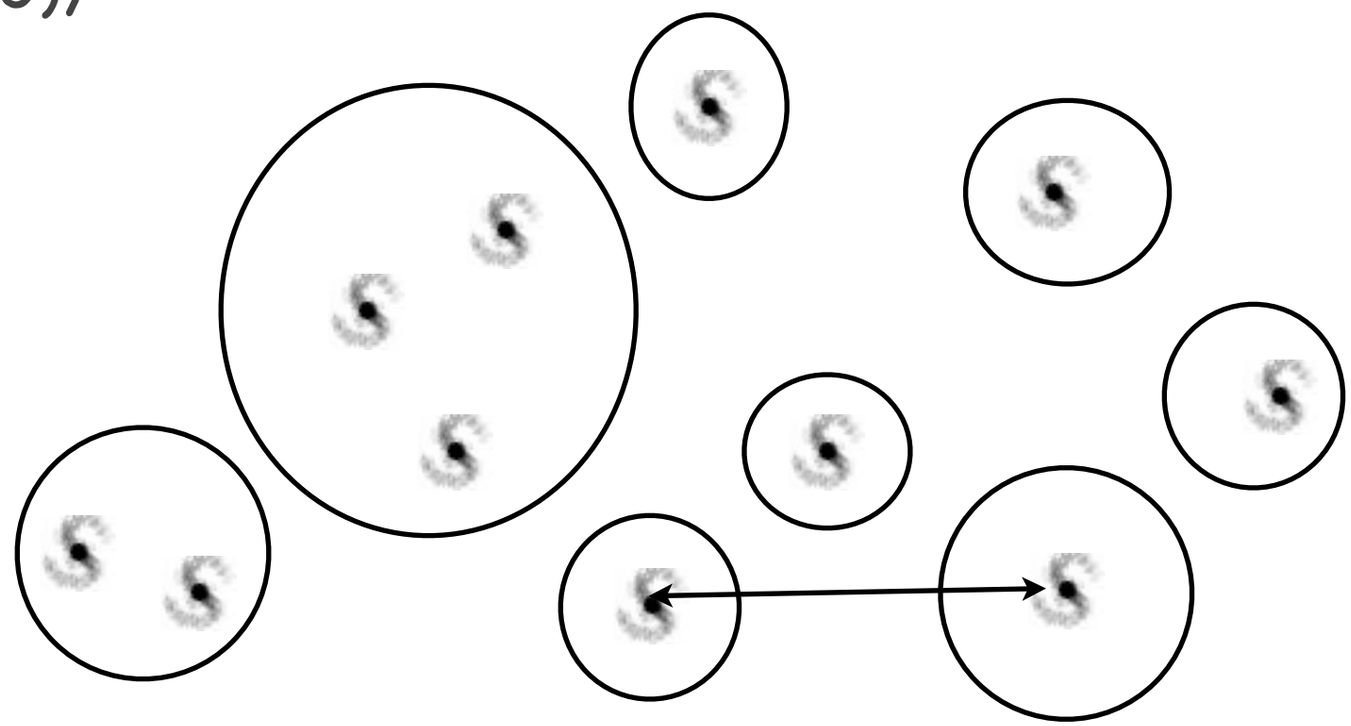
see e.g., Cooray & Sheth (2000),
Zehavi et al. (2005, 2008)

- Clustering Signal made up of two regimes

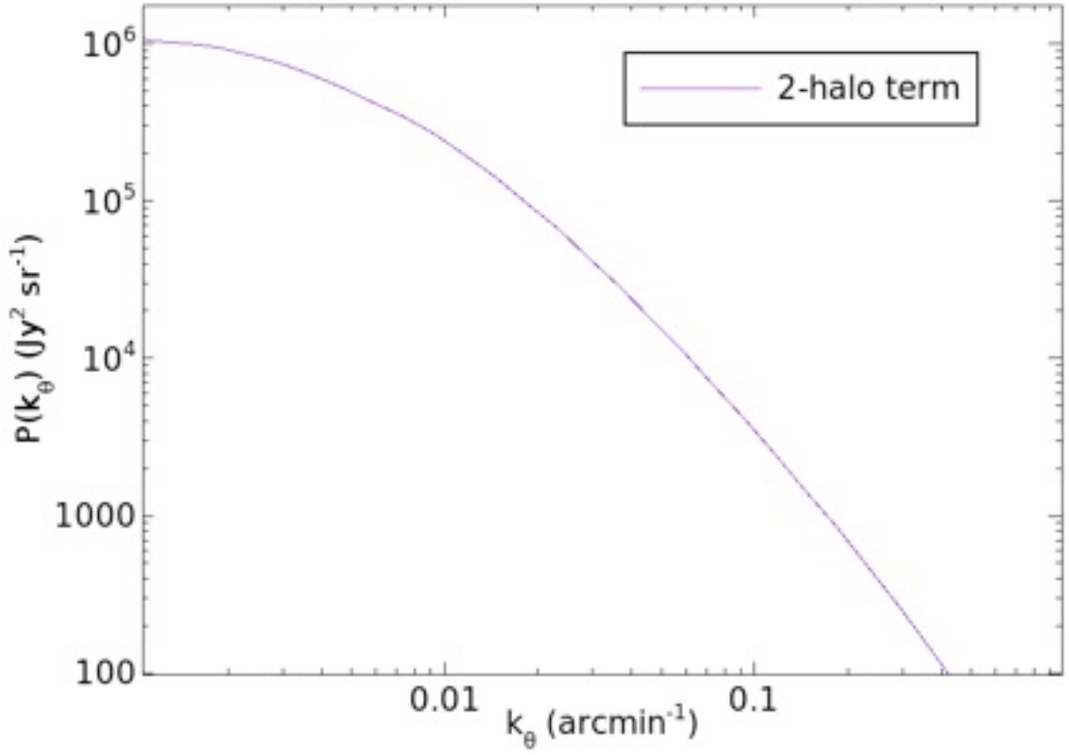


BLAST Halo Model

see e.g., Cooray & Sheth (2000),
Zehavi et al. (2005, 2008)



- Clustering Signal made up of two regimes
  - 2-halo: Linear Regime (large scales)



BLAST Halo Model

see e.g., Cooray & Sheth (2000),
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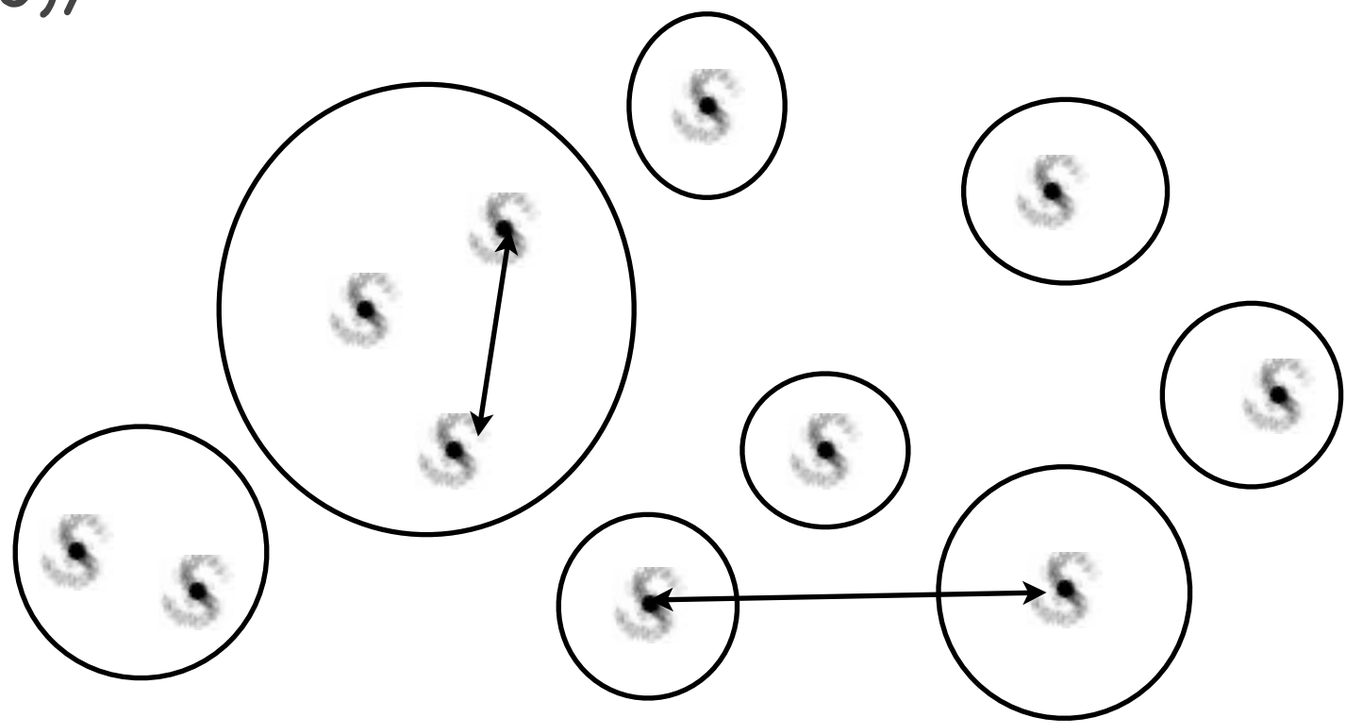
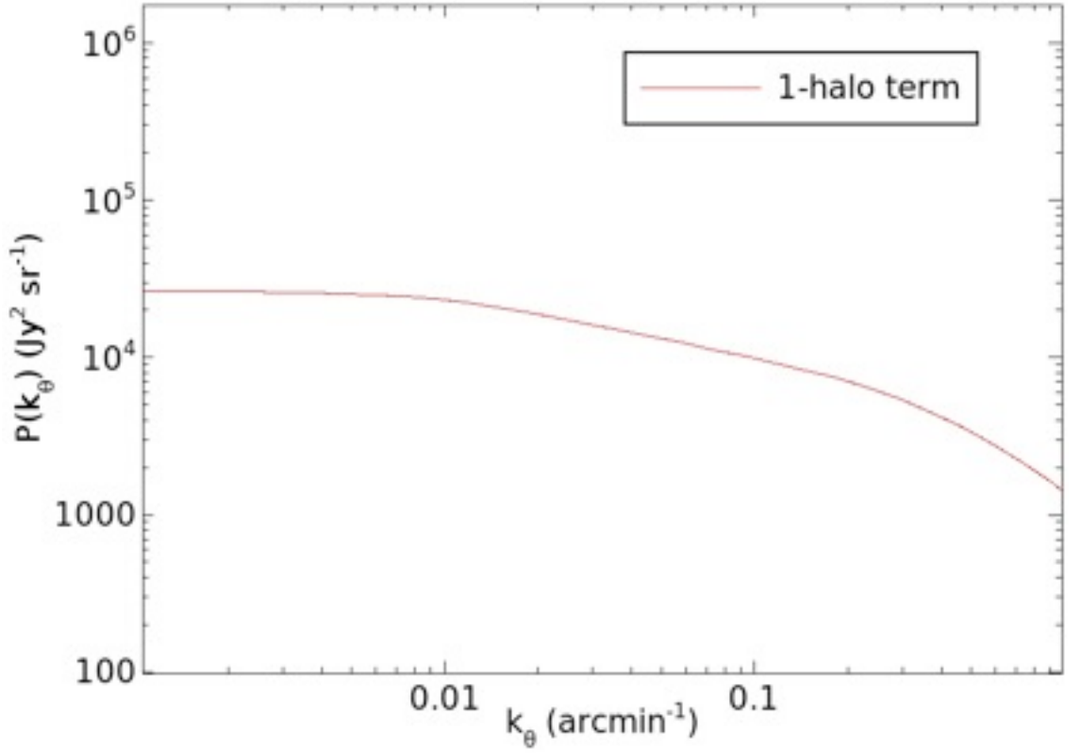


- Clustering Signal made up of two regimes
  - 2-halo: Linear Regime (large scales)
  - 1-halo: Non-Linear Regime

(small scales)



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see e.g., Cooray & Sheth (2000),
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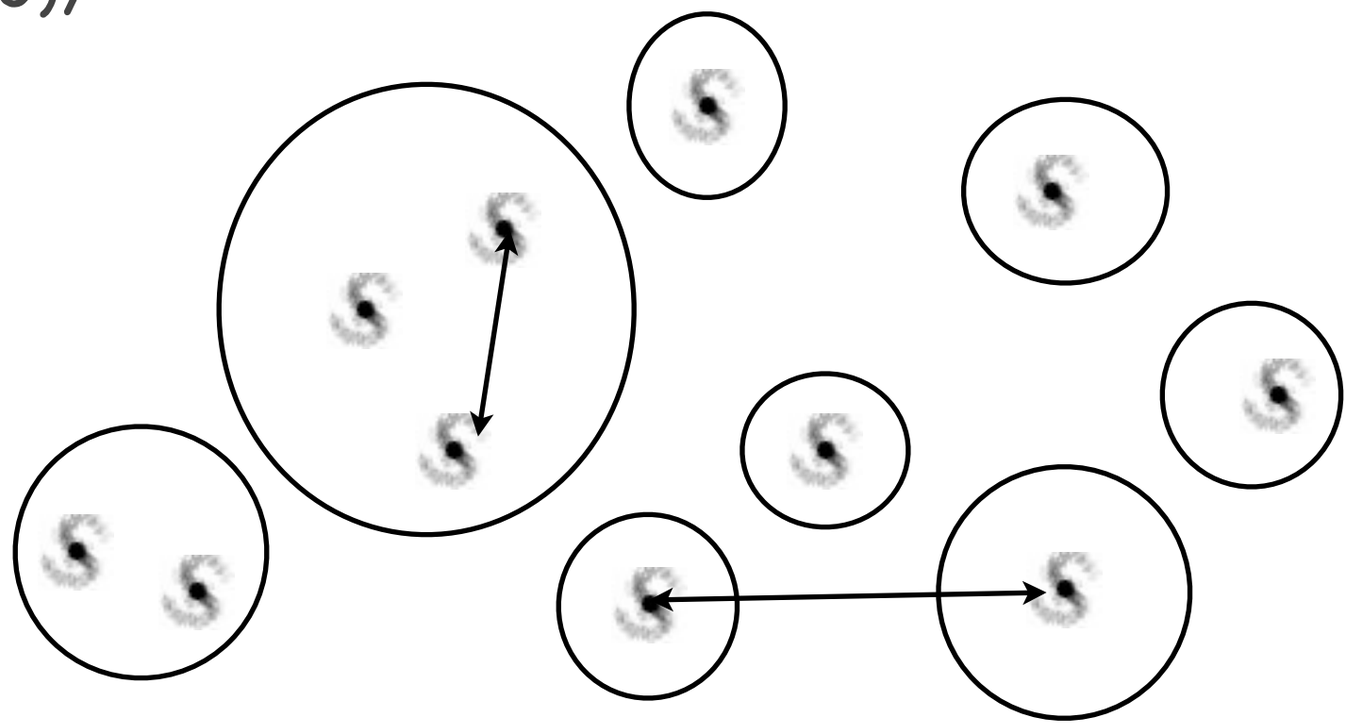

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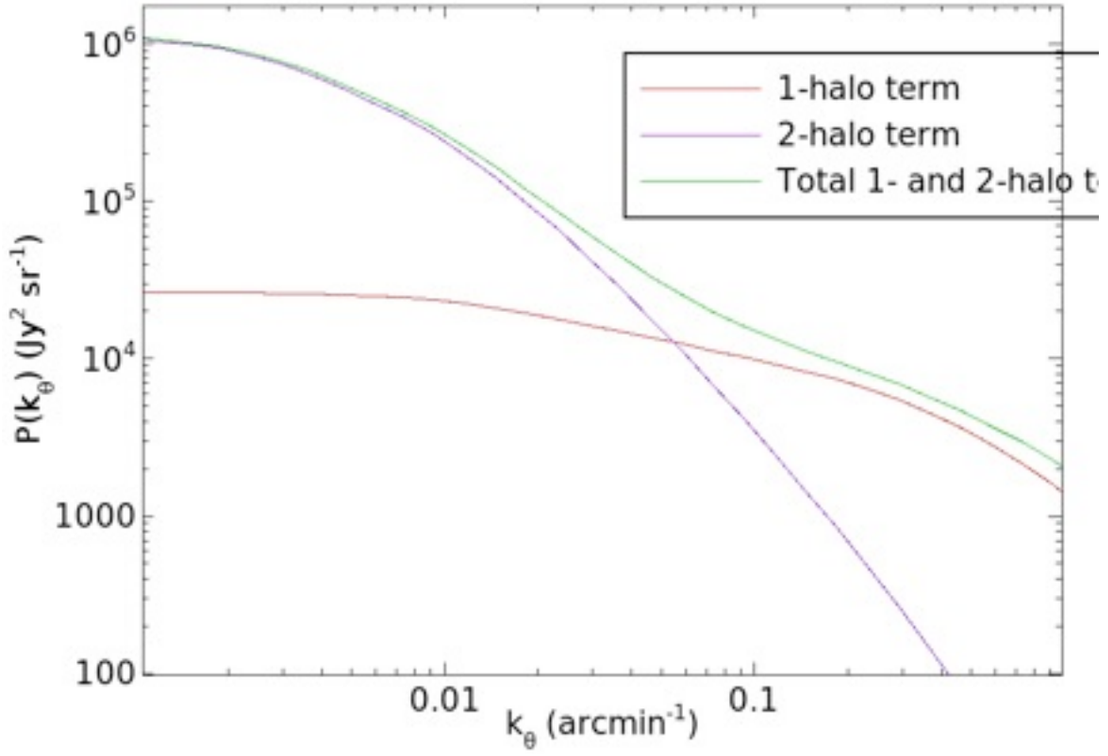

BLAST Halo Model

What are you *actually* fitting?

$$P_{1h}(k,z) = \int_{\mathcal{M}} n_{\rm halo}(M,z)\big[2N_{\rm cen}(M)N_{\rm sat}(M)u_{\rm DM}(k,z|M) + N^2_{\rm sat}(M)u^2_{\rm DM}(k,z|M)\big]dM\,/\,n^2_{\rm gal}(z),$$

$$P_{2h}(k,z) = P_{\rm DM}(k,z)\bigg[\int_{\mathcal{M}} n_{\rm halo}(M,z)N_{\rm gal}(M,z) \times b(M,z)u_{\rm DM}(k,z|M)dM\bigg]^2 \Big/ n^2_{\rm gal}(z).$$

$$n_{\rm gal}(z) = \int_{\mathcal{M}} n_{\rm halo}(M,z)\left[1+\left(\frac{M}{M_1}\right)^{\alpha}\right]dM$$

and for each M_{min}-α pair, M_1 fixed to agree to source model by requiring:

$$\int_0^{\infty} \frac{dN}{dS\,dz}(S,z)\,dS = n_{\rm gal}(z)\,dV_c(z)$$

BLAST Halo Model

What are you *actually* fitting?

$$P_{1h}(k,z) = \int_{\mathcal{M}} n_{halo}(M,z)\left[2N_{cen}(M)N_{sat}(M)u_{DM}(k,z|M) + N_{sat}^2(M)u_{DM}^2(k,z|M)\right]dM/n_{gal}^2(z),$$

$$P_{2h}(k,z) = P_{DM}(k,z)\left[\int_{\mathcal{M}} n_{halo}(M,z)N_{gal}(M,z) \times b(M,z)u_{DM}(k,z|M)dM\right]^2 \Big/ n_{gal}^2(z).$$

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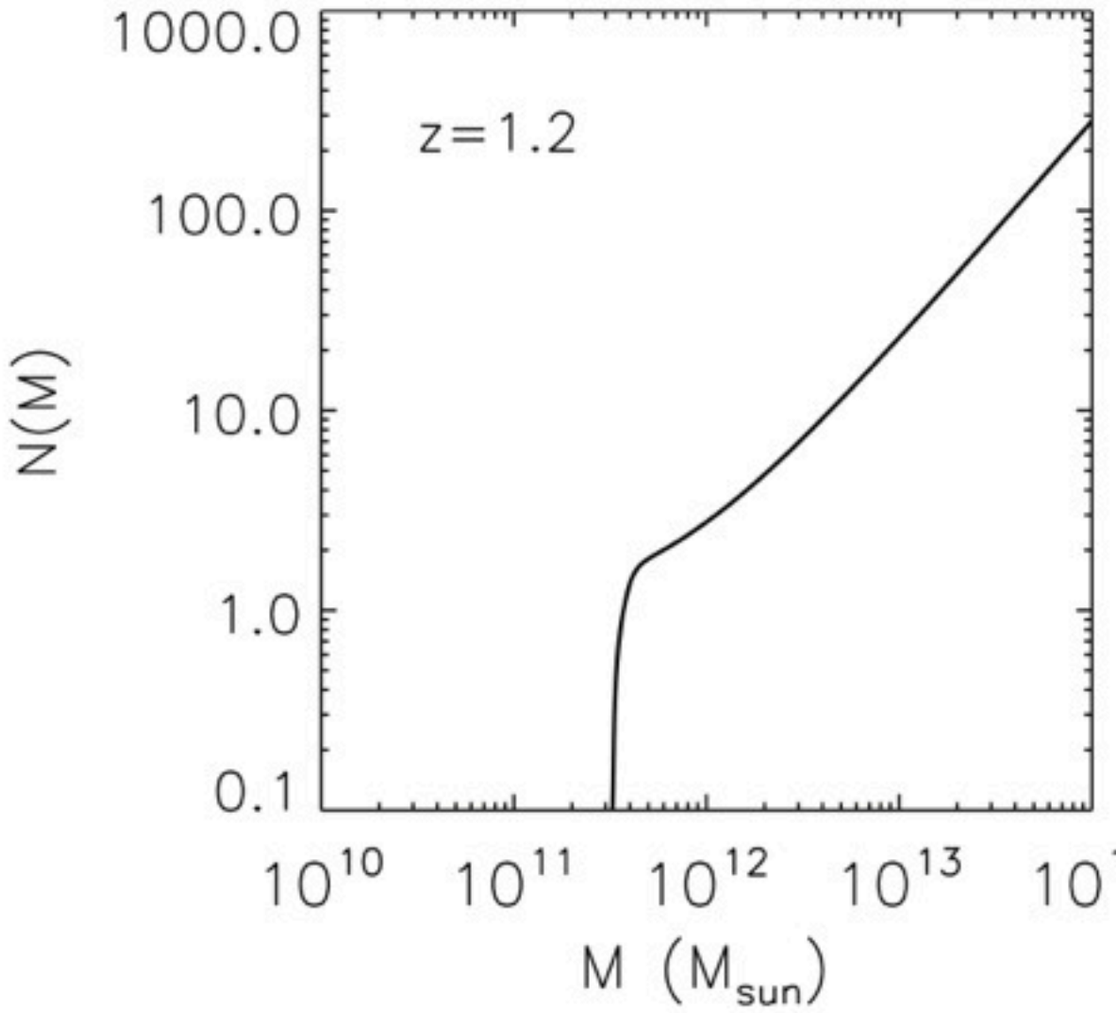
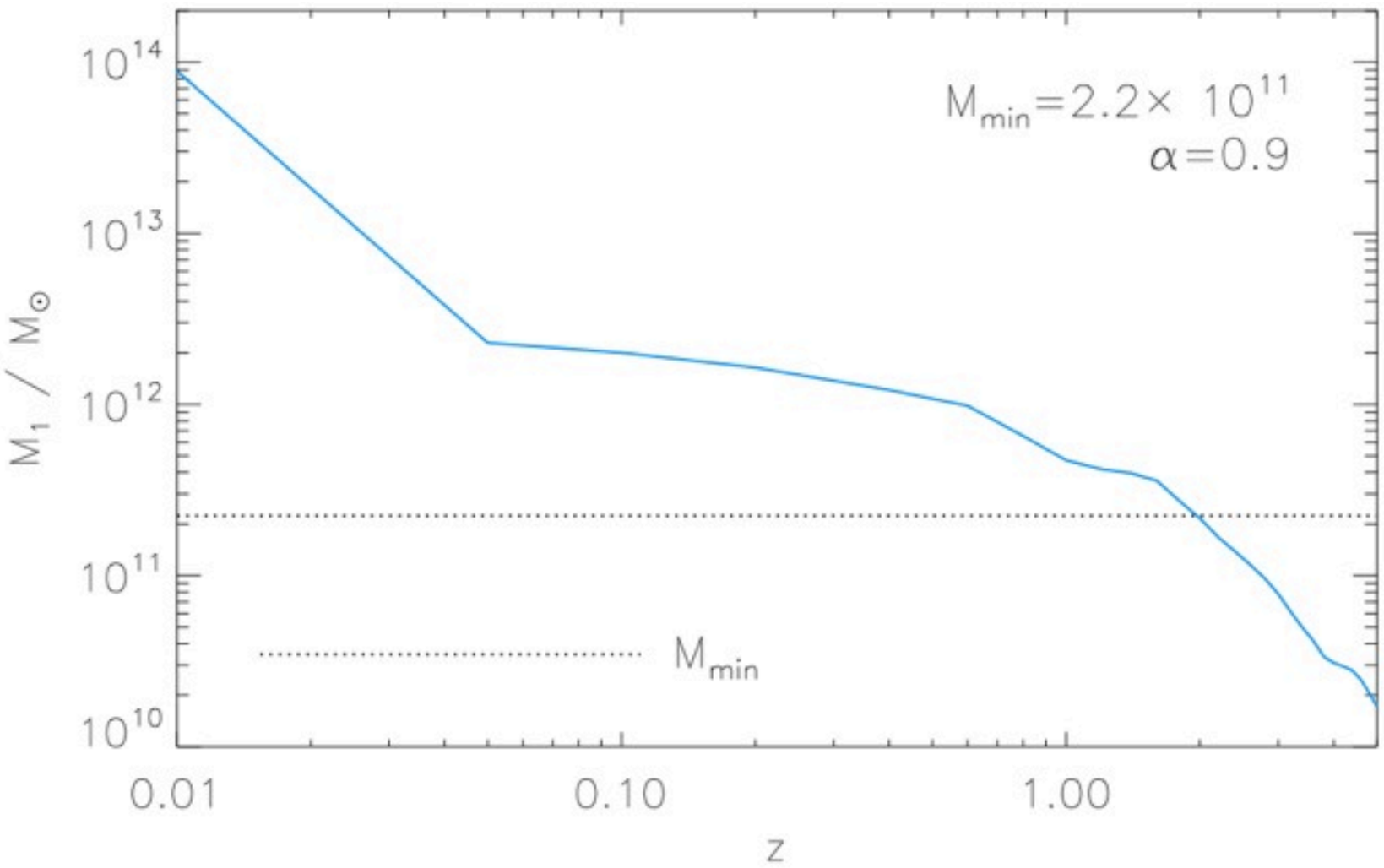
$M_{min} \approx 3\times10^{11}\ M_{sun}$

$\alpha \approx 1.1$



Viero et al. (2009)

BLAST Halo Model



$$n_{\rm gal}(z) = \int_{\mathcal{M}} n_{\rm halo}$$

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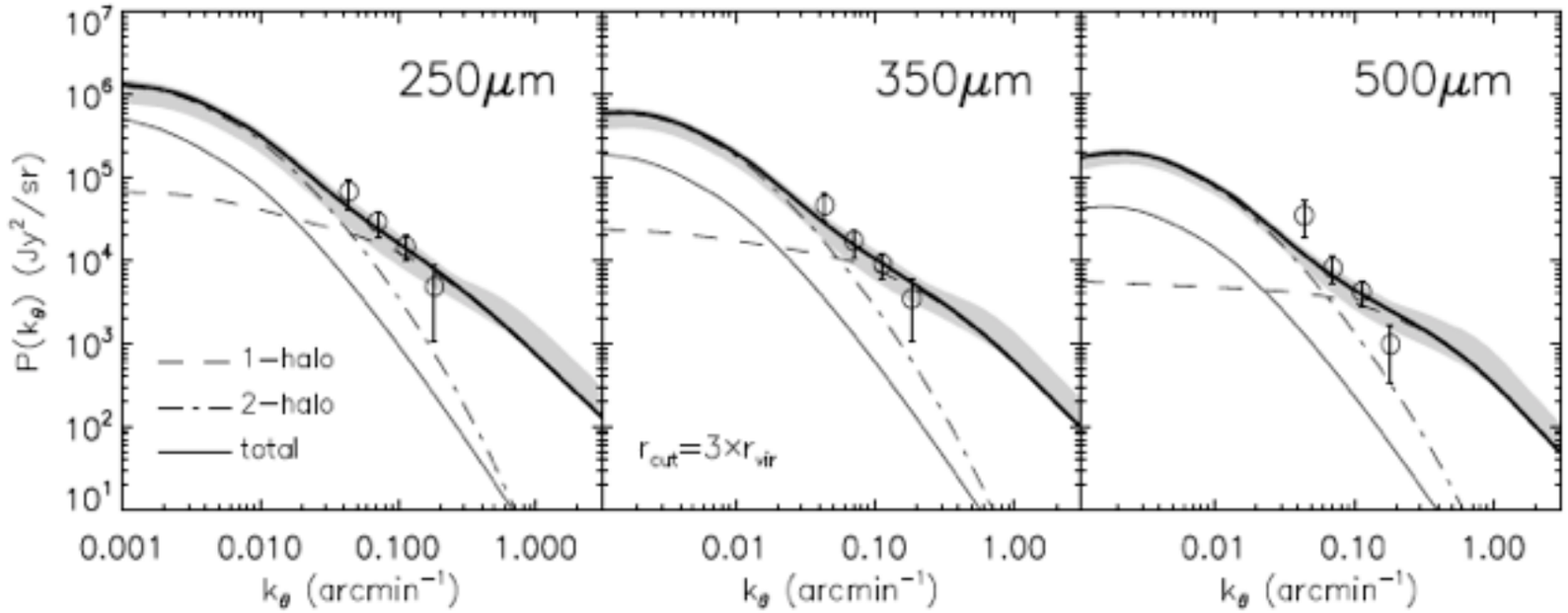
BLAST Halo Model

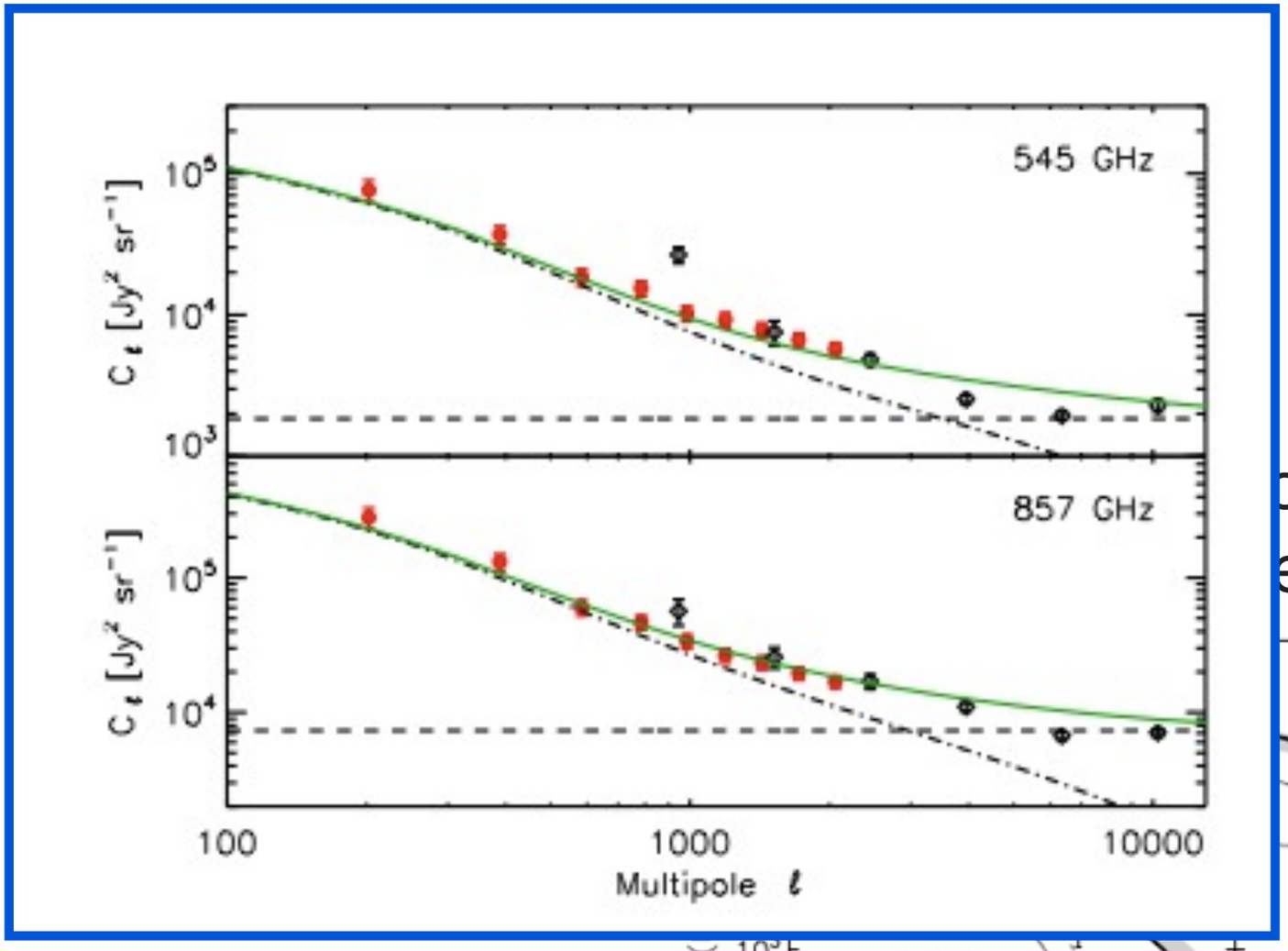
Halo Model of Mattia Negrello &
Source Model of Lagache 2004



Viero et al. (2009)

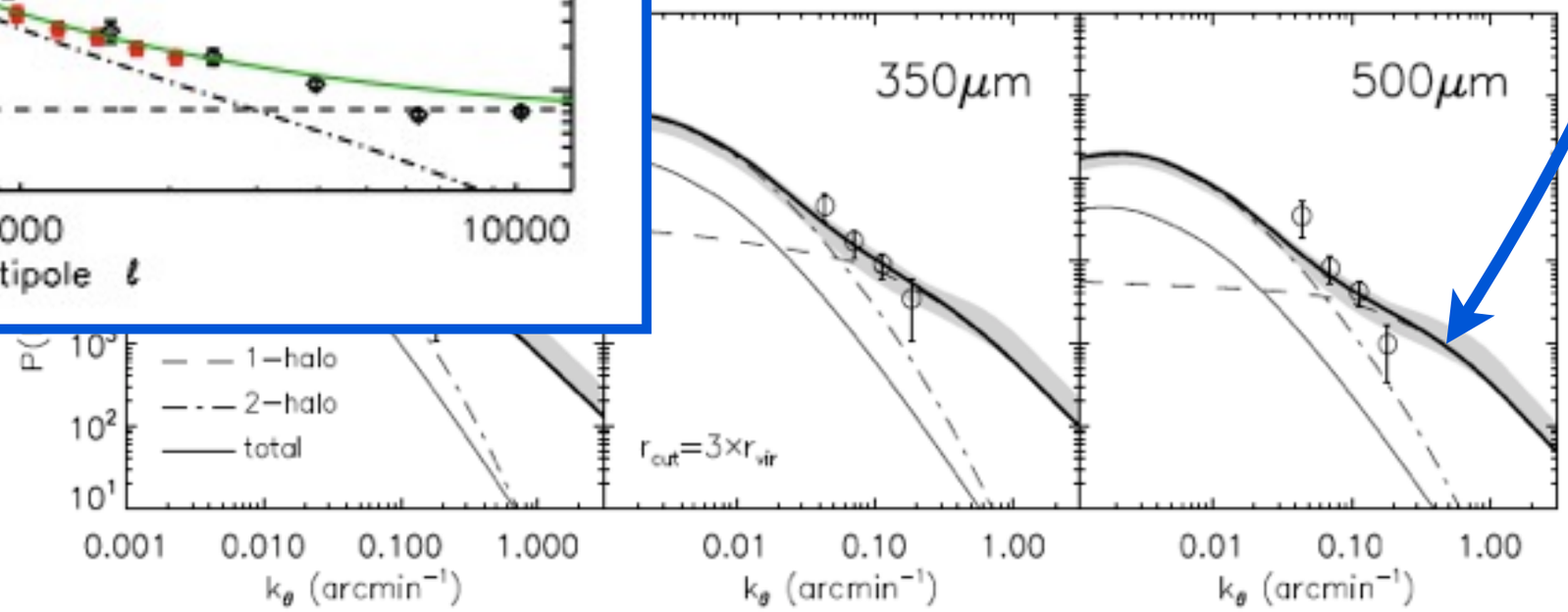
arXiv: 0904.1200

BLAST Halo Model



Agrees w/ Planck!

of Mattia Negrello &
el of Lagache 2004



Viero et al. (2009)

arXiv: 0904.1200

BLAST Halo Model

At z ~ 2

- $b_{linear} \approx 4.0$
- $M_{eff} \approx 6 \times 10^{12}\ M_{sun}$
- $M_{min} \approx 3 \times 10^{11}\ M_{sun}$
- $b_{eff} \approx 2.4$

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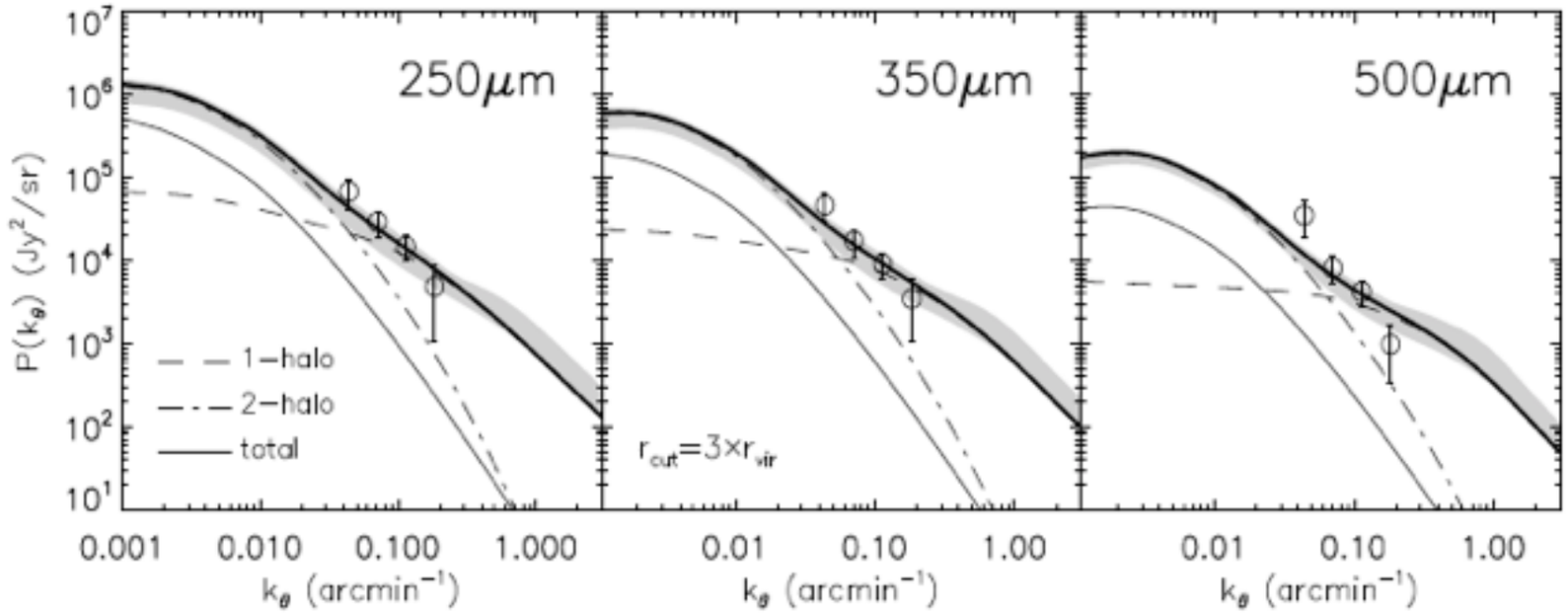
Source Model of Lagache 2004



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Confirmed by Herschel!

Sub-millimetre galaxies reside in dark matter halos with masses greater than 3×10^{11} $M_\odot$

A. Amblard[1], A. Cooray[1,2], P. Serra[1], B. Altieri[3], V. Arumugam[4], H. Aussel[5], A. Blain[2], J. Bock[2,6], A. Boselli[7], V. Buat[7], N. Castro-Rodríguez[8,9], A. Cava[8,9], P. Chanial[10], E. Chapin[11], D.L. Clements[10], A. Conley[12], L. Conversi[3], C.D. Dowell[2,6], E. Dwek[13], S. Eales[14], D. Elbaz[5], D. Farrah[15], A. Franceschini W. Gear[14], J. Glenn[12], M. Griffin[14], M. Halpern[11], E. Hatziminaoglou[17], E. Ibar[18], K. Isaak[14], R.J. Ivison[18,4], A.A. Khostovan[1], G. Lagache[19], L. Levenson[2,6], N. Lu[2,20], S. Madden[5], B. Maffei[21], G. Mainetti[16], L. Marchetti[16], G. Marsden[11], K. Mitchell-Wynne[1], H.T. Nguyen[6,2], B. O'Halloran[10], S.J. Oliver[15], A. Omont[22], M.J. Page[23], P. Panuzzo[5], A. Papageorgiou[14], C.P. Pearson[23,24], I. Pérez-Fournon[8,9], M. Pohlen[14], N. Rangwala[12], I.G. Roseboom[15], M. Rowan-Robinson[10], M. Sánchez Portal
M. Sy
L. Vig

Using the halo model fits, we estimate the mininum dark matter mass scale for dusty star-forming galaxies at the peak of the star formation history of the universe to be $\log_{10} M_{\rm min}/{\rm M}_\odot = 11.5^{+0.7}_{-0.2}$ at 350 μm with a bias factor for the galaxies of $2.4^{+1.0}_{-0.2}$. The minimum halo masses $\log_{10} M_{\rm min}/{\rm M}_\odot$ at 250 and 500 μm are $11.1^{+1.0}_{-0.6}$ and $11.8^{+0.4}_{-0.3}$, respectively. The corresponding bias factors for the galaxies are $2.0^{+0.9}_{-0.1}$ and $2.8^{+0.4}_{-0.5}$ at 250 and 500 μm, respectively. The differences in the minimum halo masses and the bias factors between the three wavelengths are likely due a combination of effects including overall calibration uncertainties, the fact that at longer wave-

arXiv: 0904.1200

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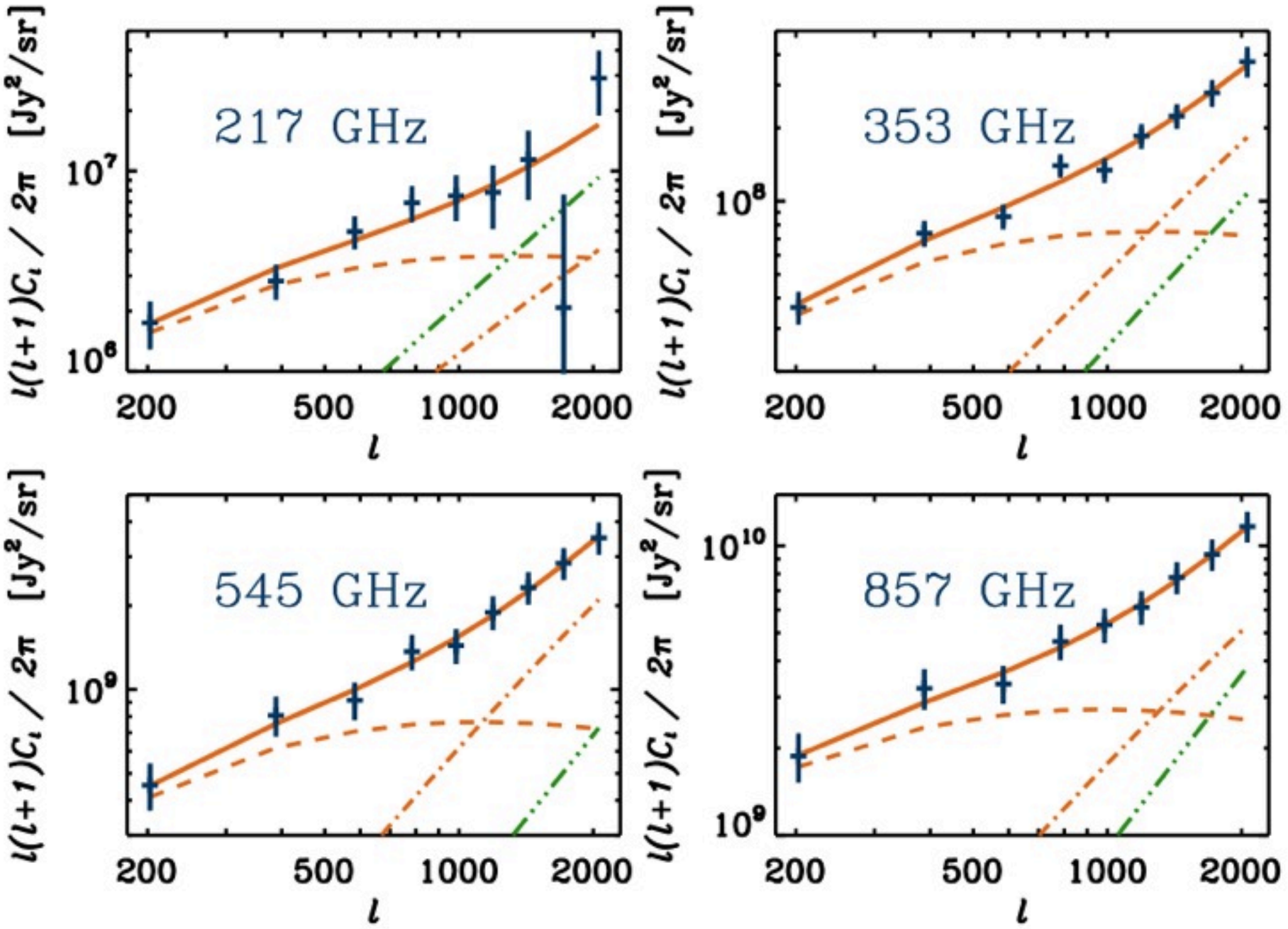
Confirmed by Herschel!

Sub-millimetre galaxies reside in dark matter halos with masses greater than 3×10^{11} $M_\odot$

A. Amblard[1], A. Cooray[1,2], P. Serra[1], B. Altieri[3], V. Arumugam[4], H. Aussel[5], A. Blain[2], J. Bock[2,6], A. Boselli[7], V. Buat[7], N. Castro-Rodríguez[8,9], A. Cava[8,9], P. Chanial[10], E. Chapin[11], D.L. Clements[10], A. Conley[12], L. Conversi[3], C.D. Dowell[2,6], E. Dwek[13], S. Eales[14], D. Elbaz[5], D. Farrah[15], A. Franceschini W. Gear[14], J. Glenn[12], M. Griffin[14], M. Halpern[11], E. Hatziminaoglou[17], E. Ibar[18], K. Isaak[14], R.J. Ivison[18,4], A.A. Khostovan[1], G. Lagache[19], L. Levenson[2,6], N. Lu[2,20], S. Madden[5], B. Maffei[21], G. Mainetti[16], L. Marchetti[16], G. Marsden[11], K. Mitchell-Wynne[1], H.T. Nguyen[6,2], B. O'Halloran[10], S.J. Oliver[15], A. Omont[22], M.J. Page[23], P. Panuzzo[5], A. Papageorgiou[14], C.P. Pearson[23,24], I. Pérez-Fournon[8,9], M. Pohlen[14], N. Rangwala[12], I.G. Roseboom[15], M. Rowan-Robinson[10], M. Sánchez Portal
M. Sy
L. Vig

Using the halo model fits, we estimate the mininum dark matter mass scale for dusty star-forming galaxies at the peak of the star formation history of the universe to be $\log_{10} M_{\rm min}/{\rm M}_\odot = 11.5^{+0.7}_{-0.2}$ at 350 μm with a bias factor for the galaxies of $2.4^{+1.0}_{-0.2}$. The minimum halo masses $\log_{10} M_{\rm min}/{\rm M}_\odot$ at 250 and 500 μm are $11.1^{+1.0}_{-0.6}$ and $11.8^{+0.4}_{-0.3}$, respectively. The corresponding bias factors for the galaxies are $2.0^{+0.9}_{-0.1}$ and $2.8^{+0.4}_{-0.5}$ at 250 and 500 μm, respectively. The differences in the minimum halo masses and the bias factors between the three wavelengths are likely due a combination of effects including overall calibration uncertainties, the fact that at longer wave-

BLAST Halo Model

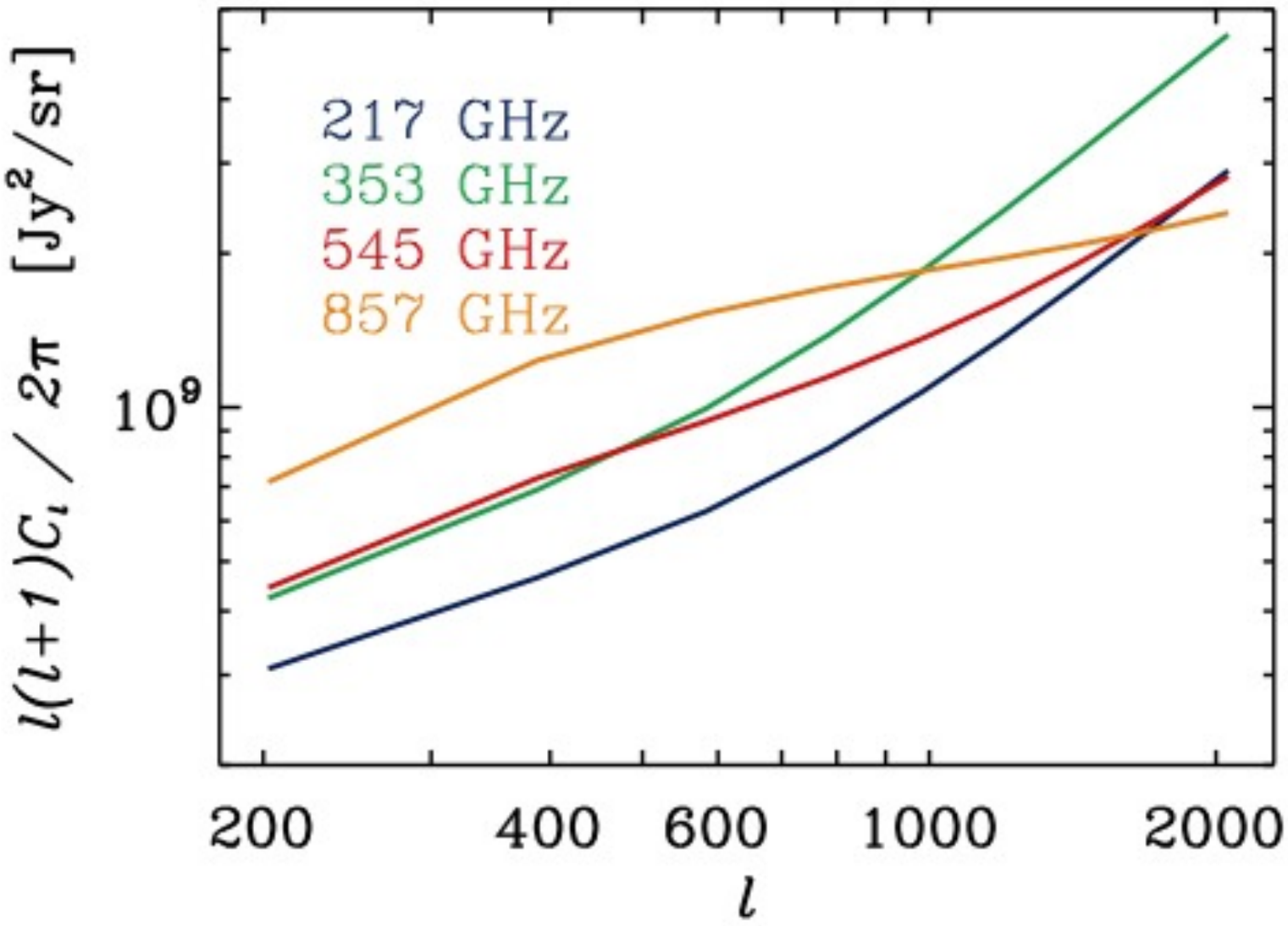


- Fix $M_1/M_{min}=10$
- Use B10 model for Poisson term

Planck Collaboration et al. (2011)

arXiv: 1101.2028

Planck Halo Model



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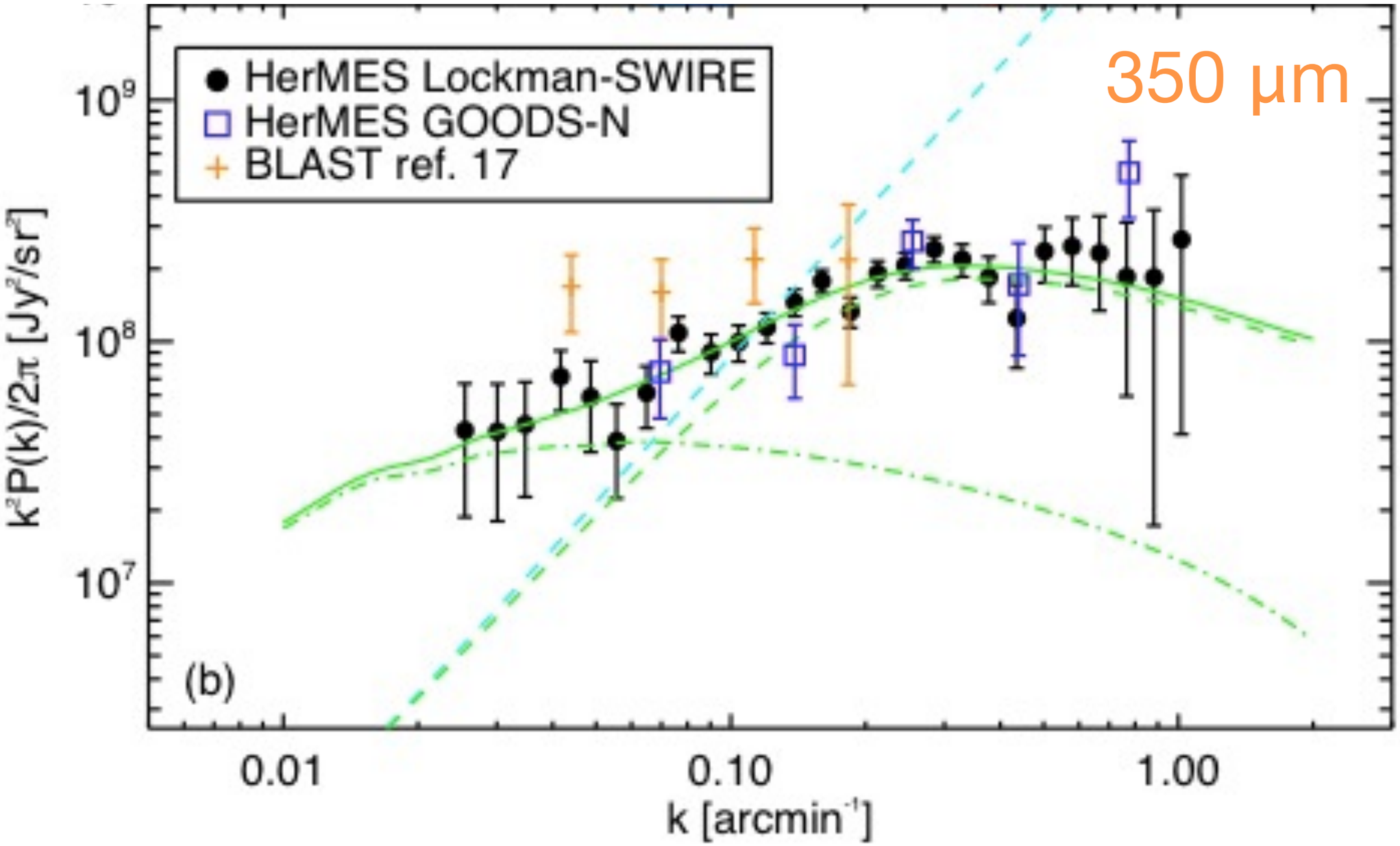
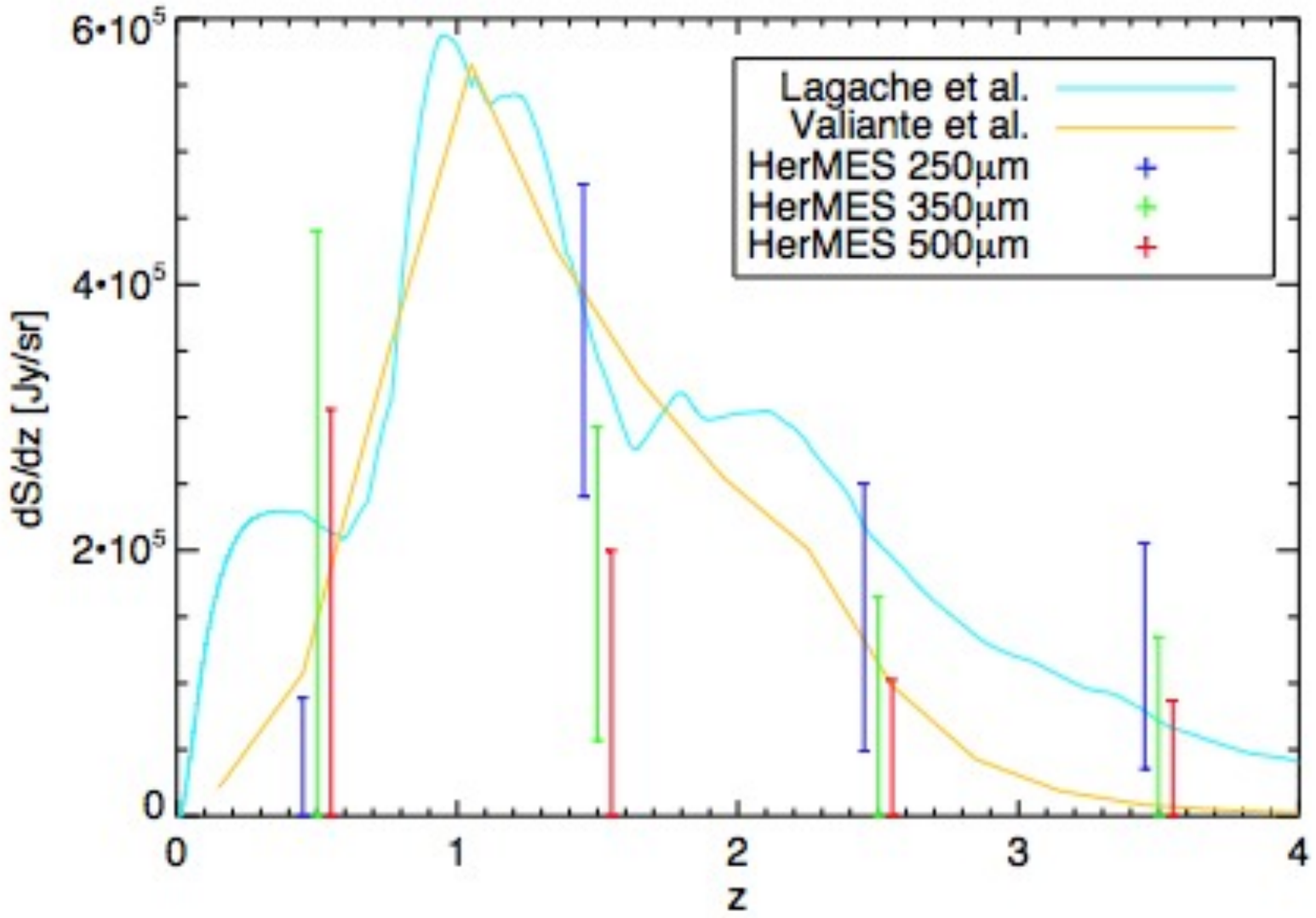


Amblard et al. (2011)

arXiv: 1101.1080

Herschel Halo Model

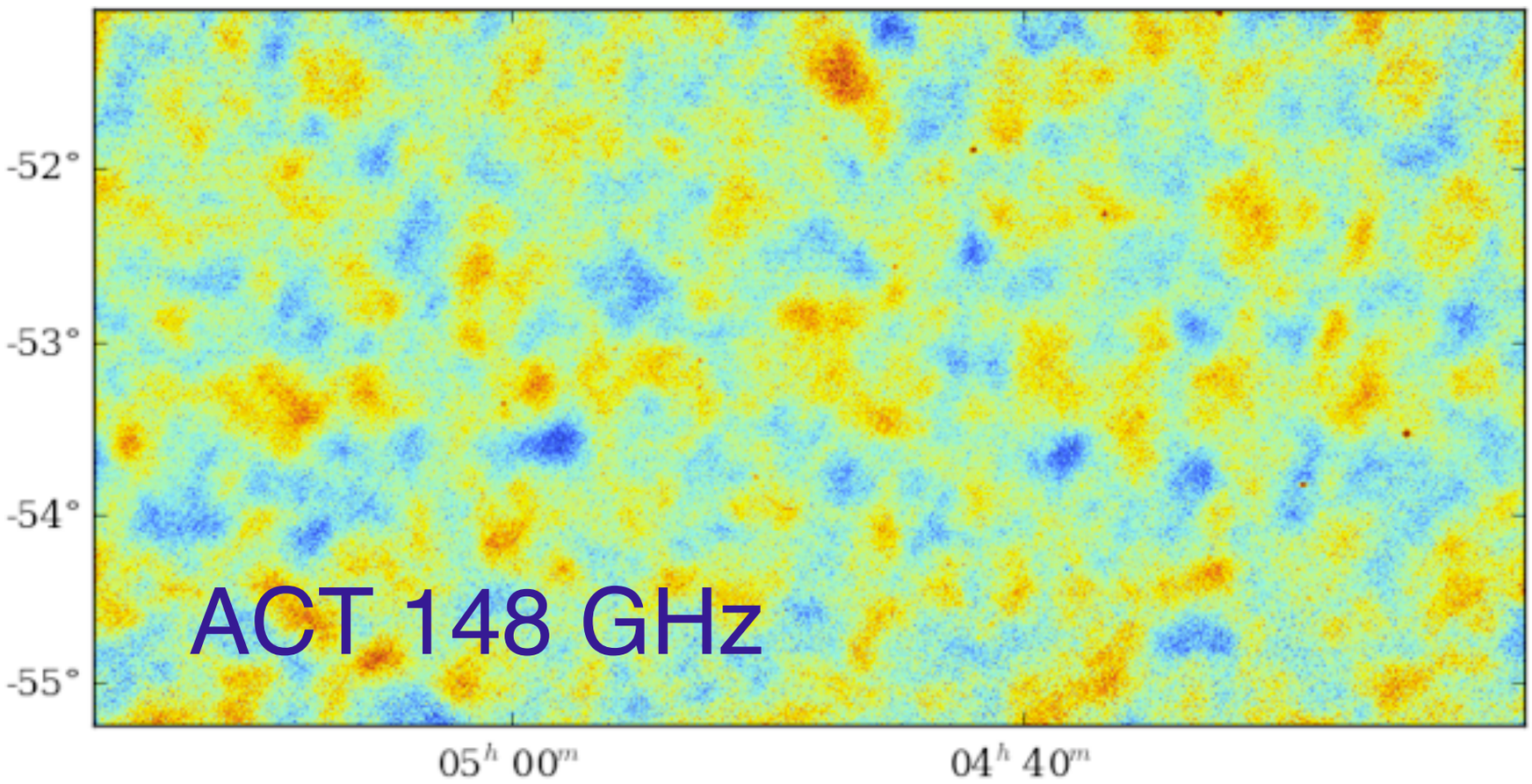


Amblard et al. (2011)

arXiv: 1101.1080

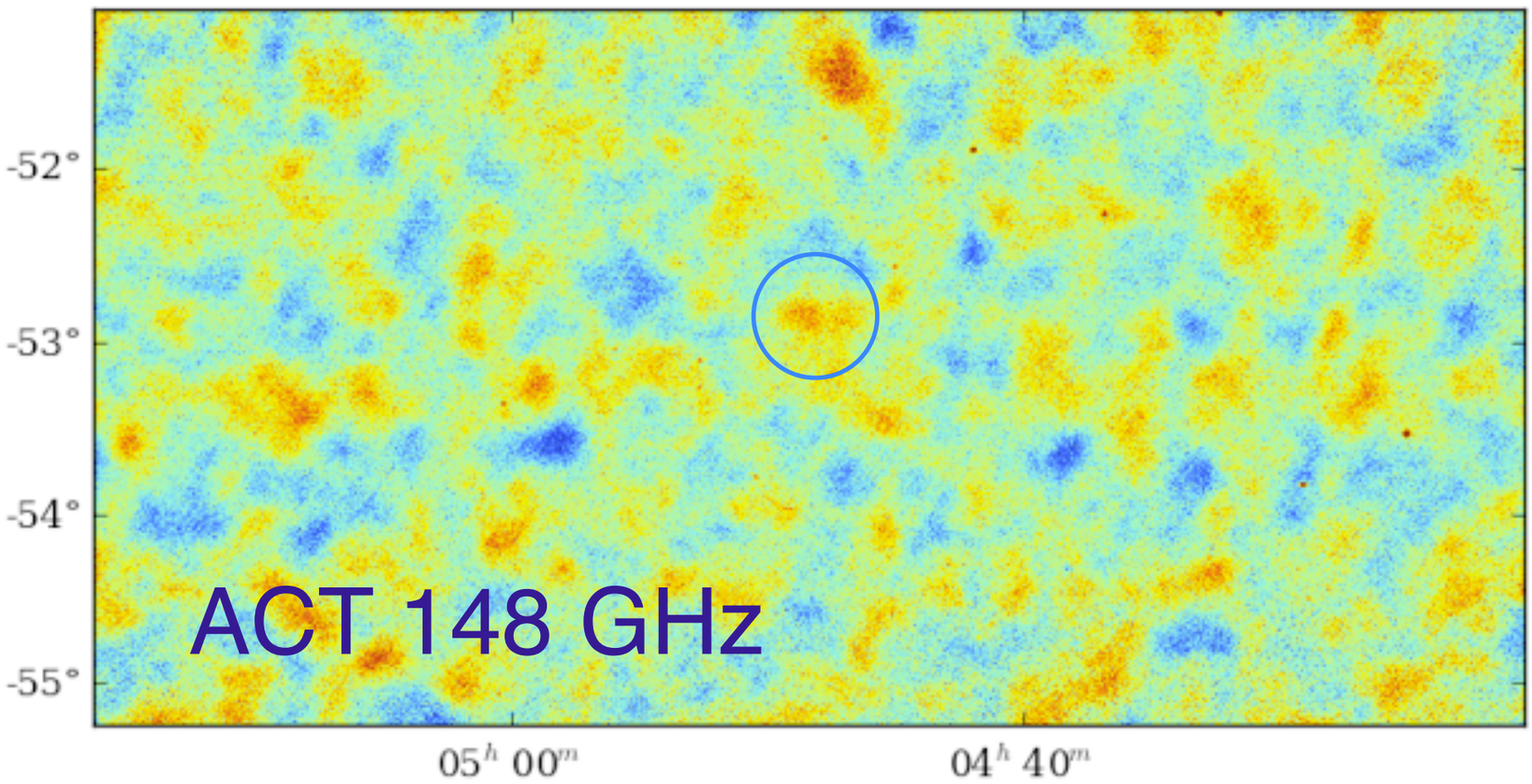
Herschel Halo Model

cmb?



The high-ℓ CMB sky

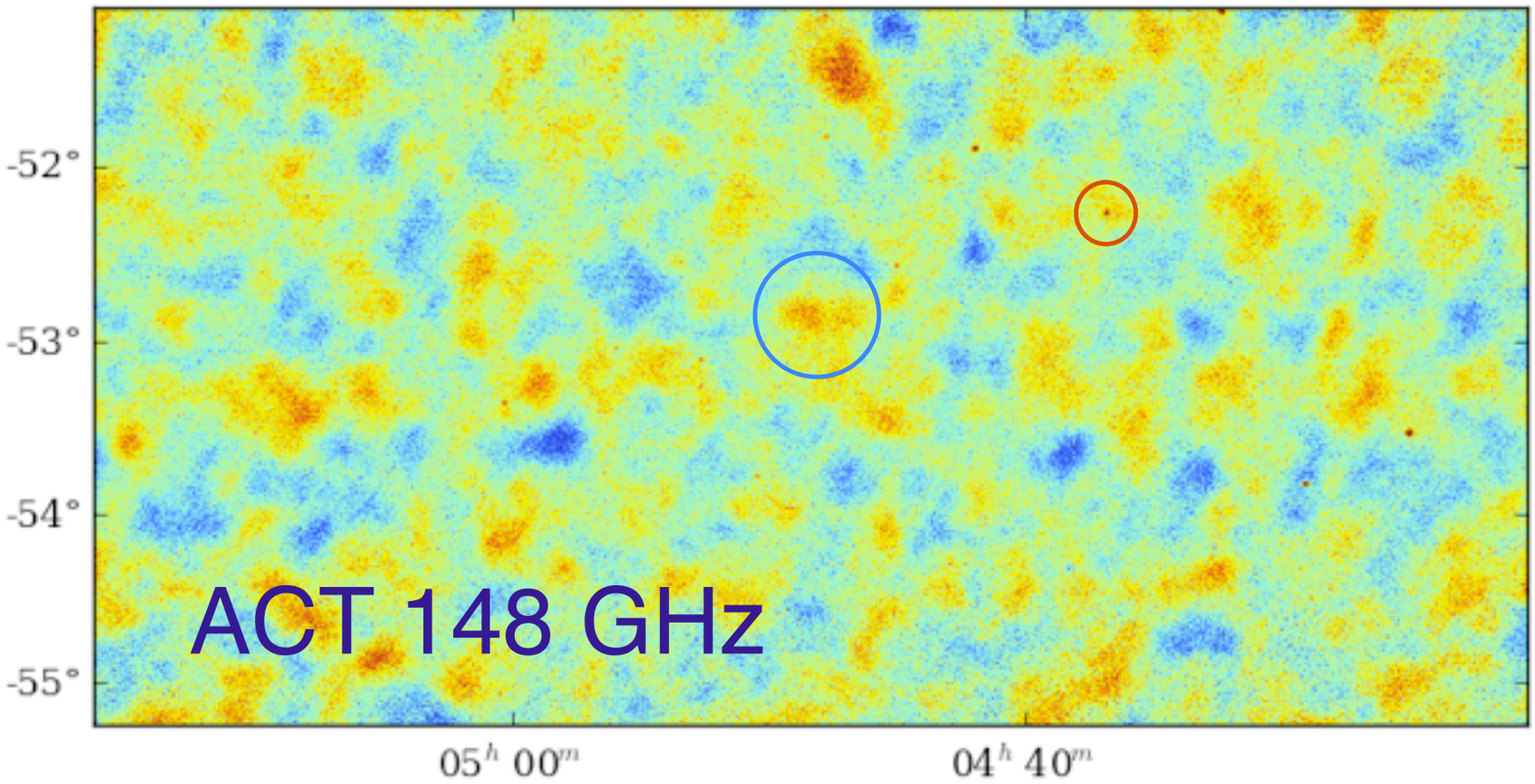
CMB



The high-ℓ CMB sky

CMB

Galaxies

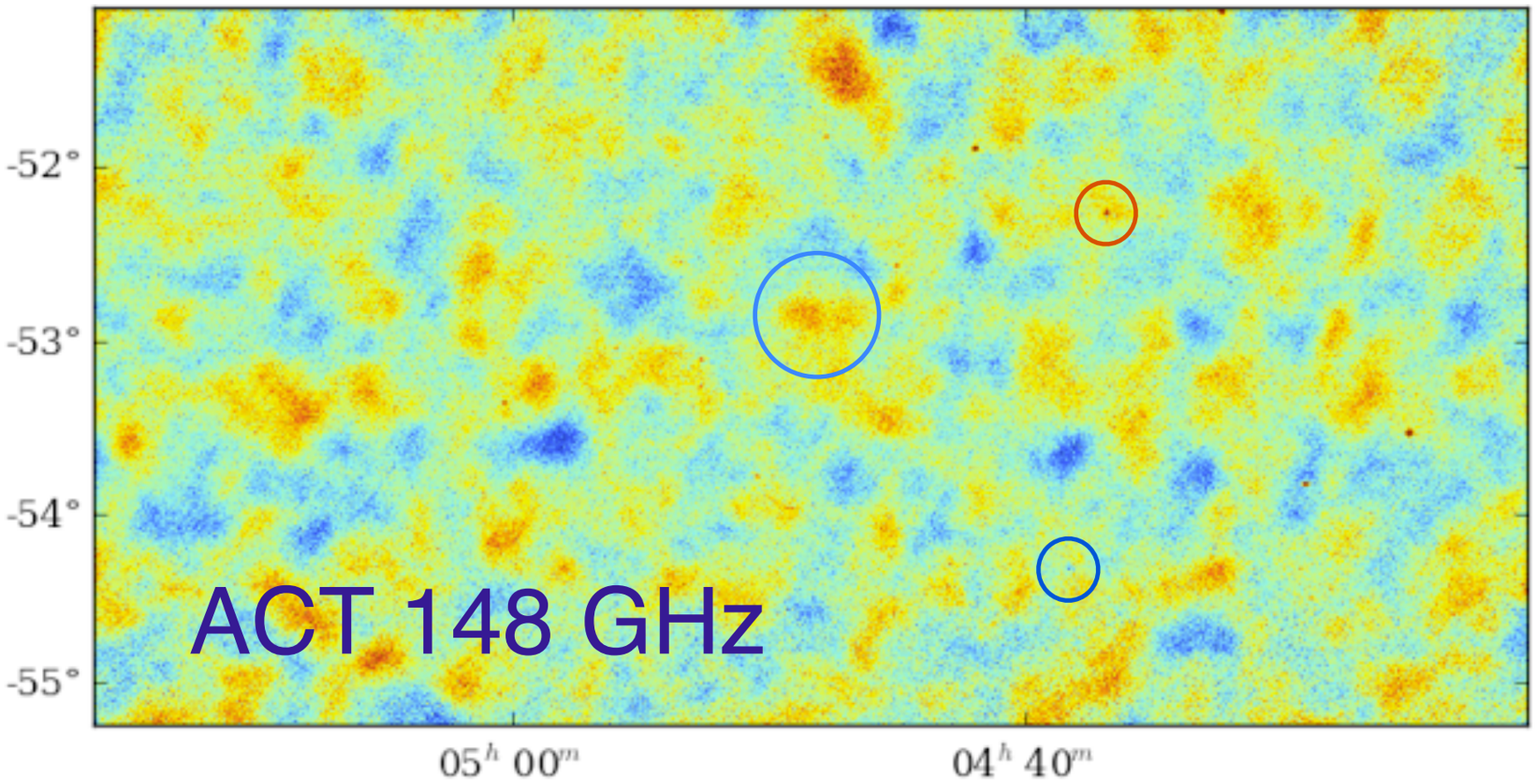


The high-ℓ CMB sky

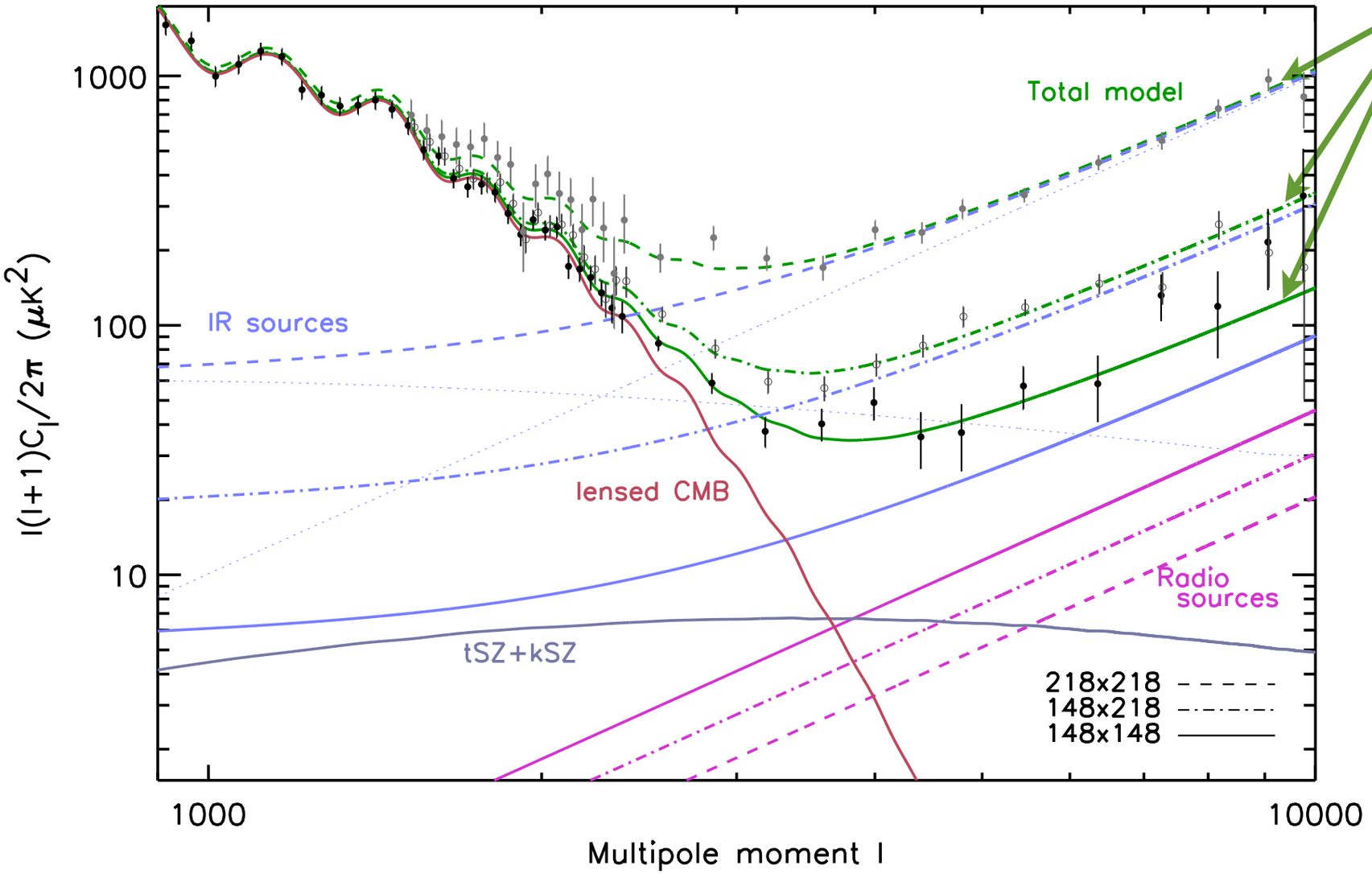
CMB

Galaxies

SZ Clusters



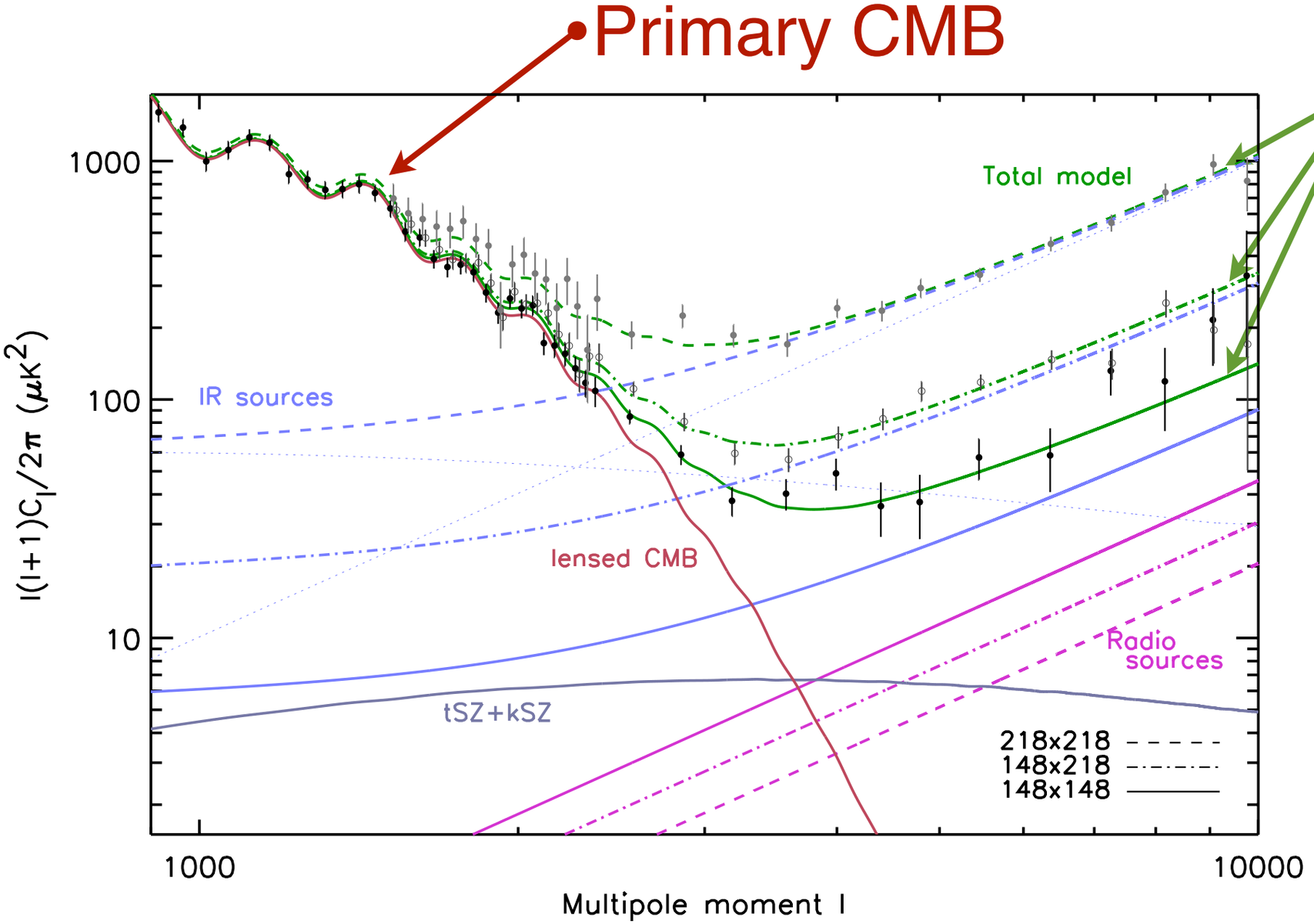
The high-ℓ CMB sky



Total Signal

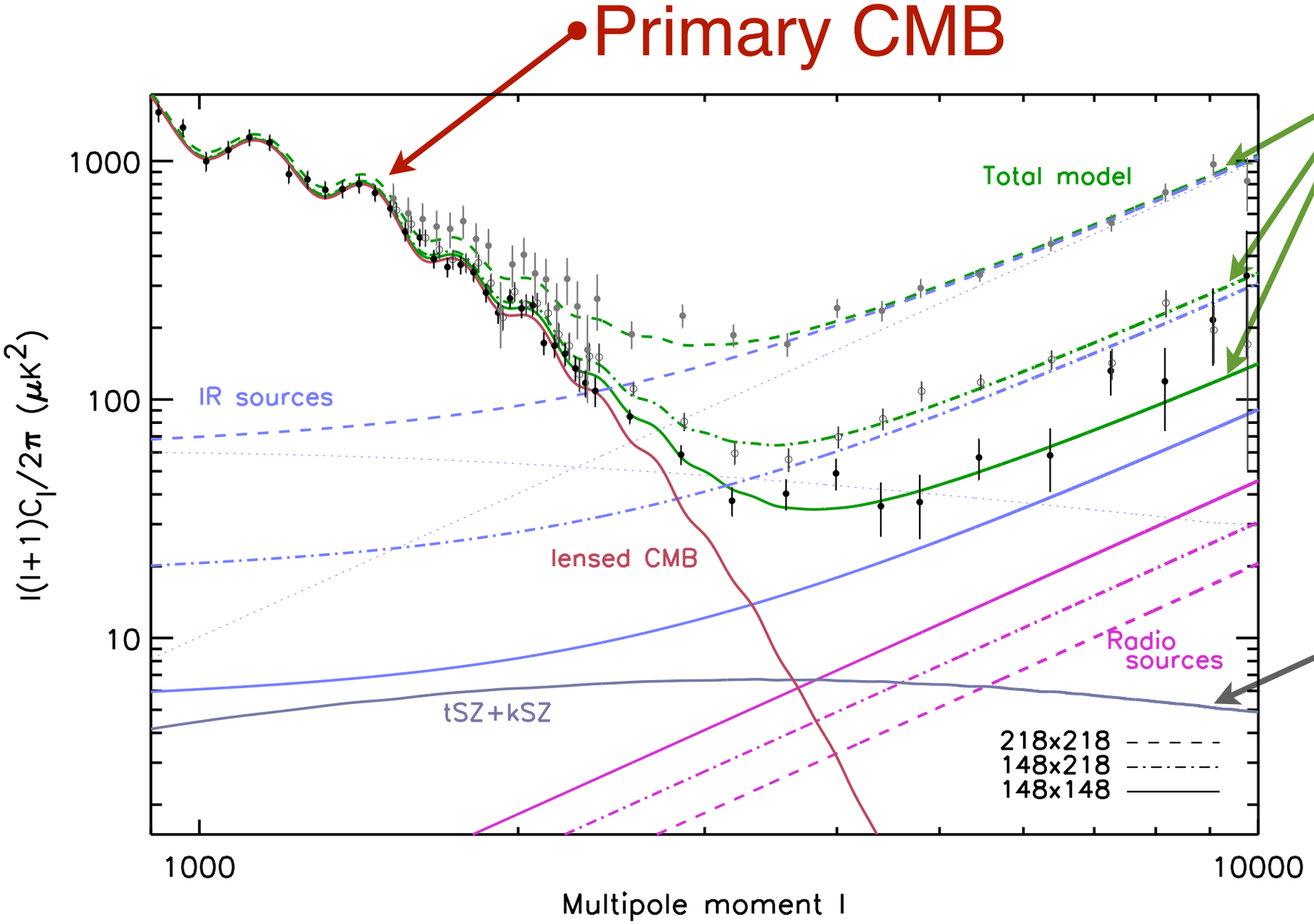
Dunkley et al. 1009.0866

CMB Foregrounds



Dunkley et al. 1009.0866

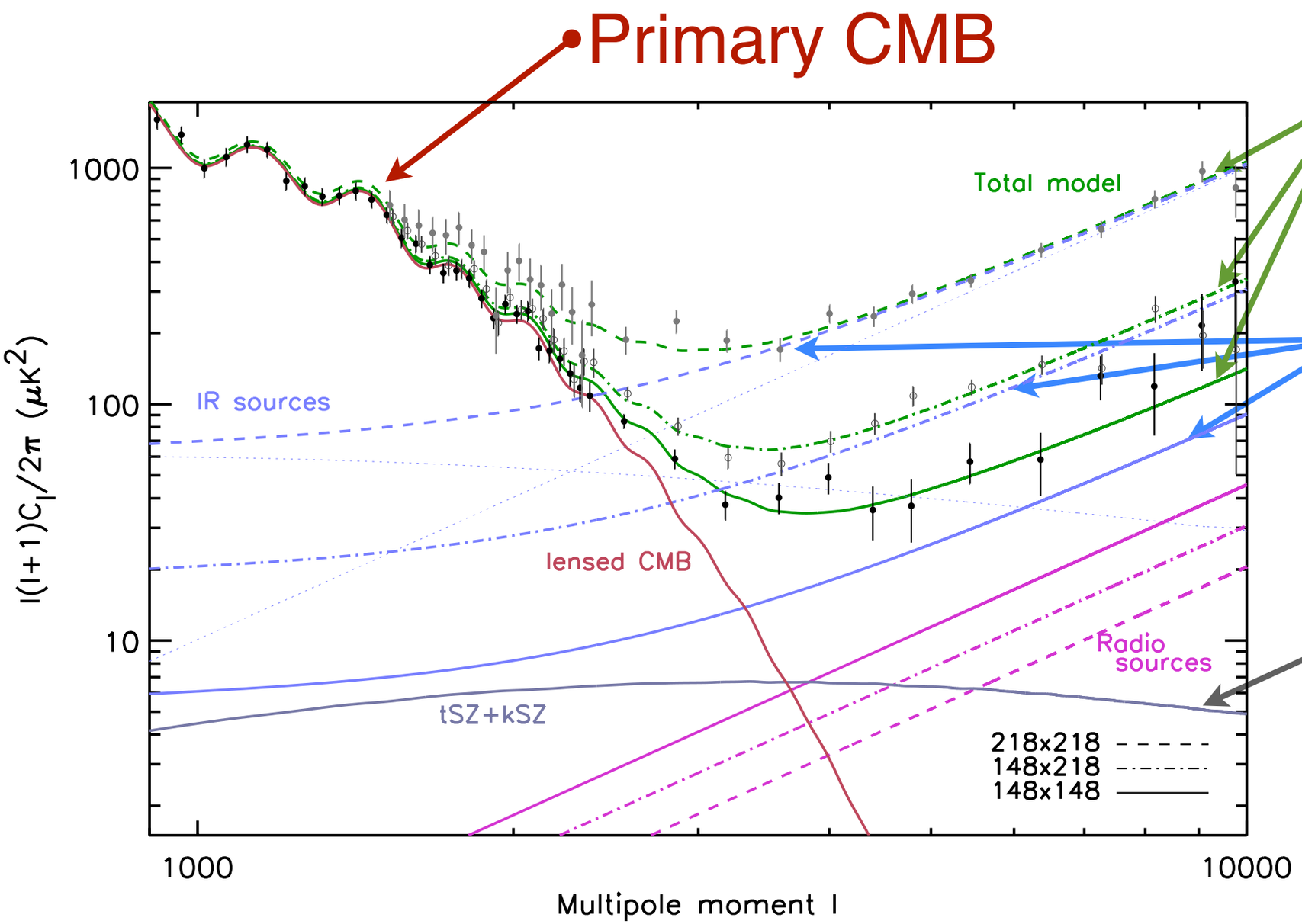
CMB Foregrounds



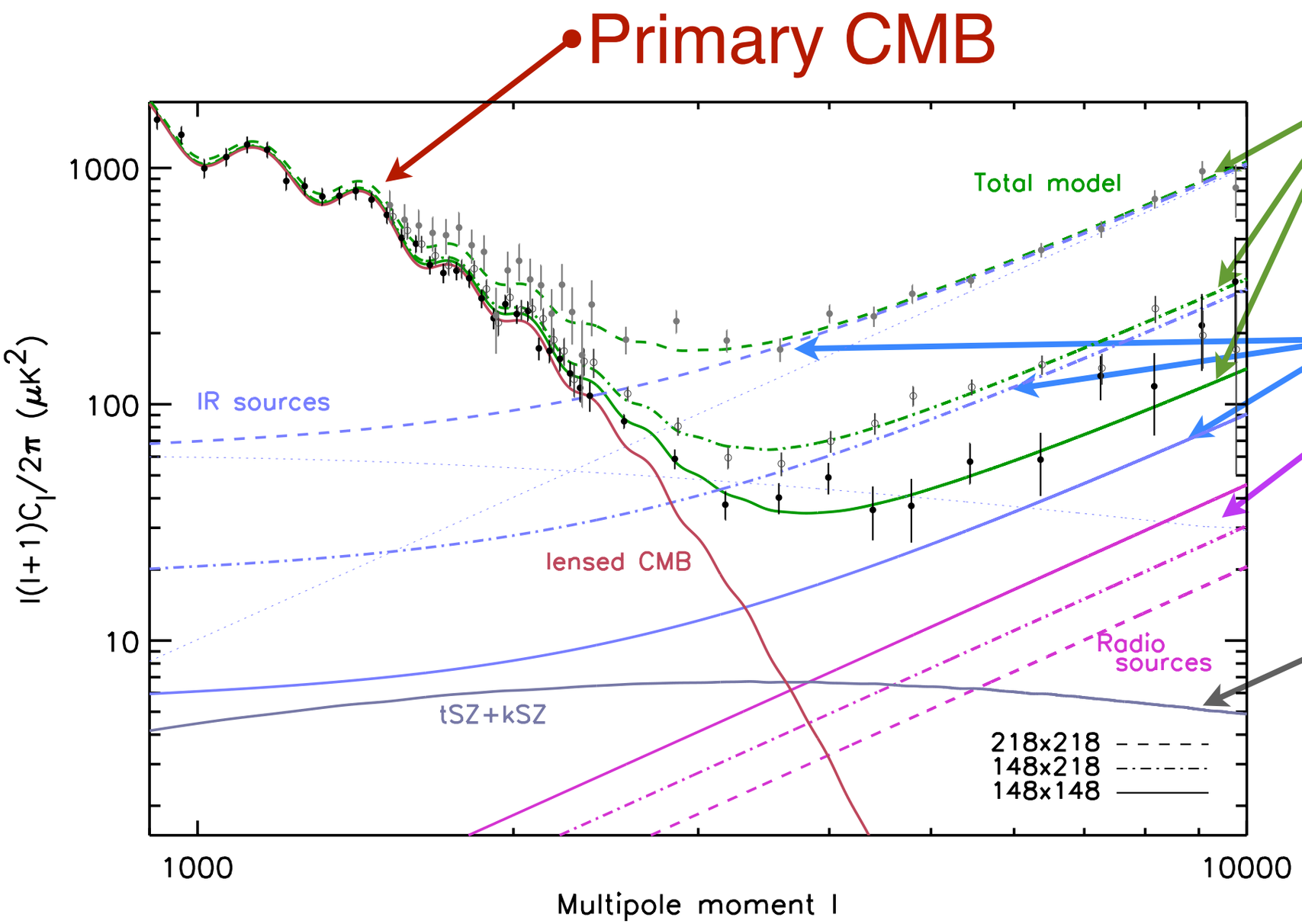
Secondary CMB:

- Sunyaev-Zel'dovich (SZ)

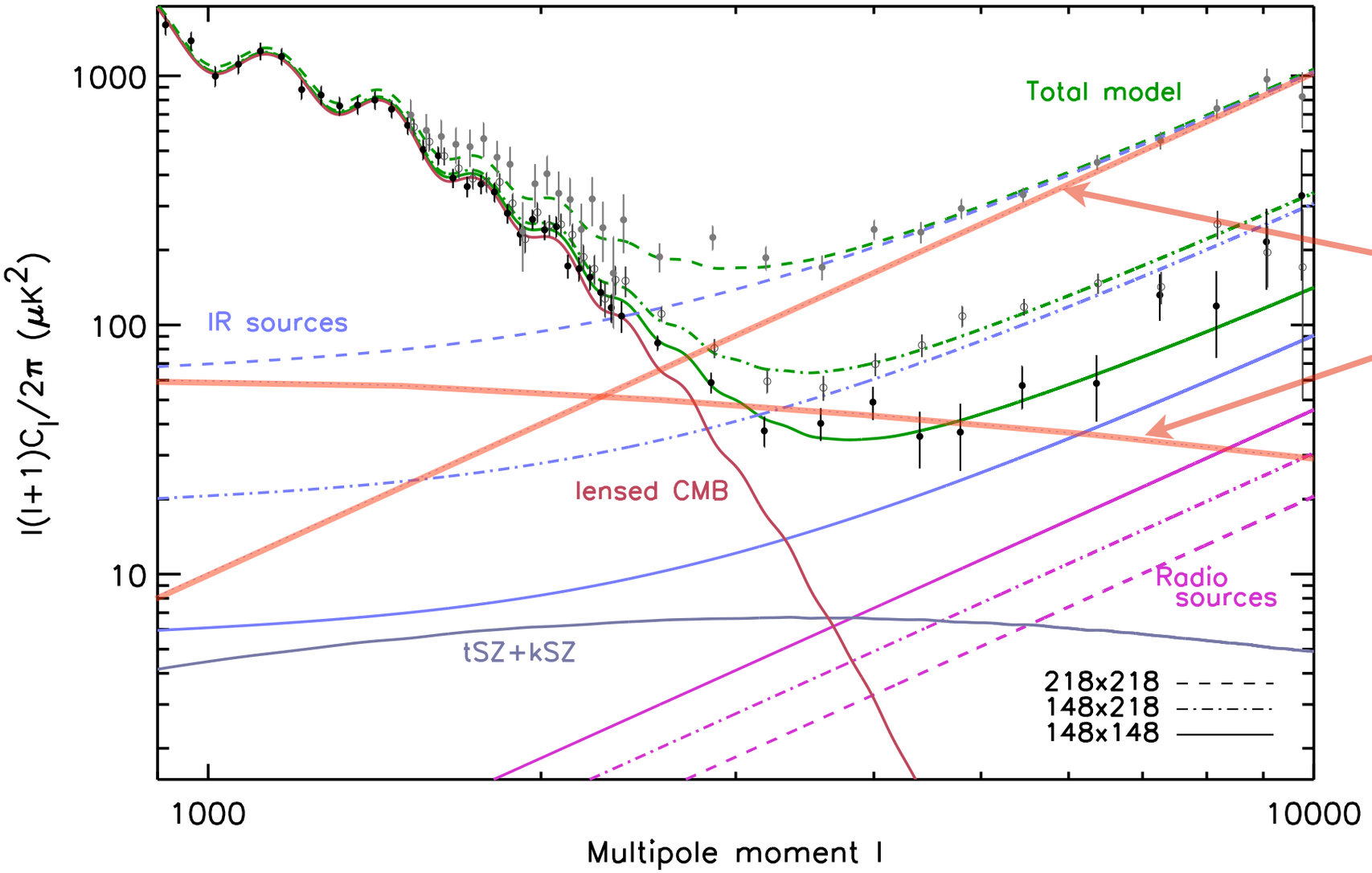
Dunkley et al. 1009.0866



Dunkley et al. 1009.0866



Dunkley et al. 1009.0866



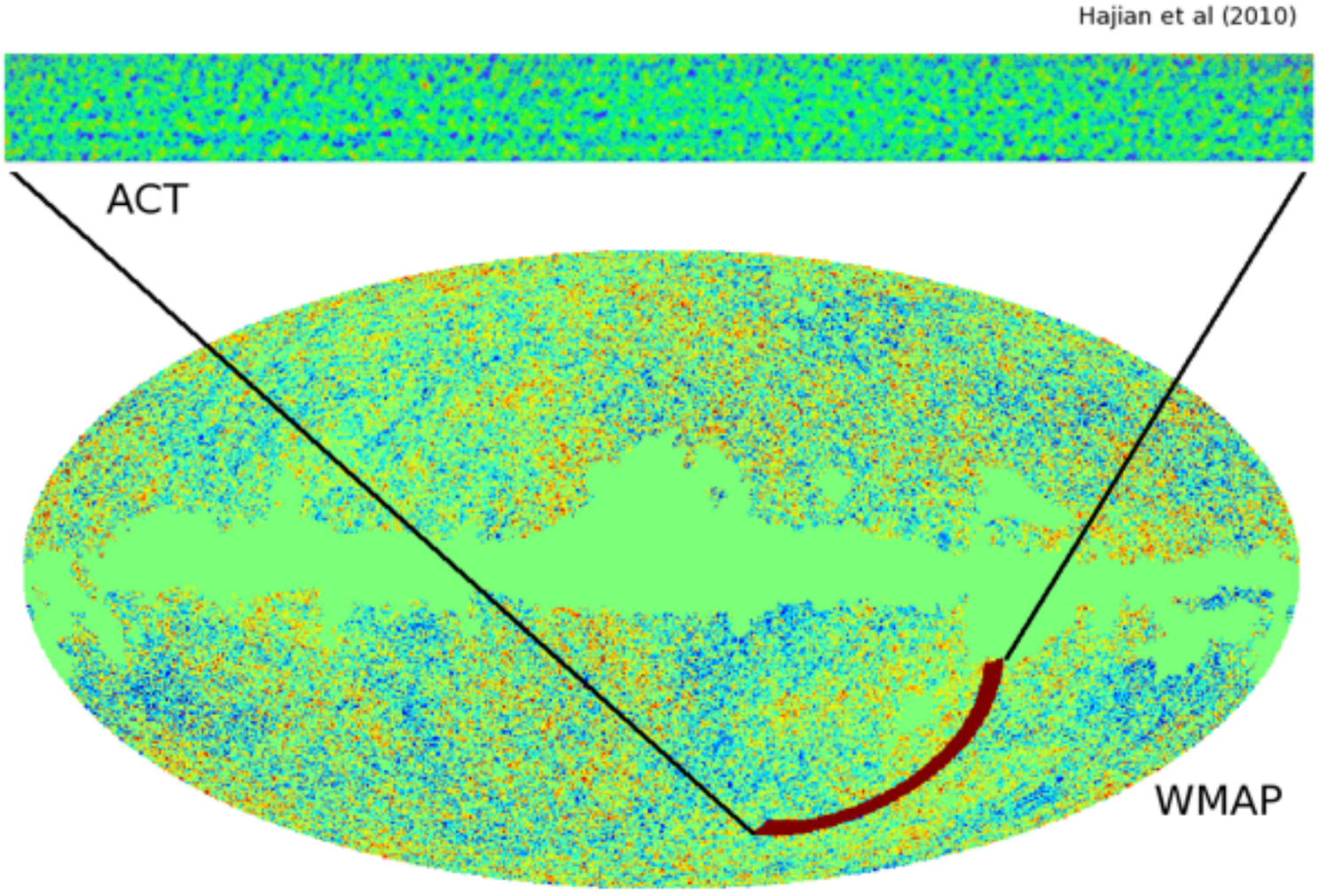
Galaxies:

- Shot
- Clustered

Dunkley et al. 1009.0866

Atacama Cosmology Telescope (ACT)

ACT Southern Field

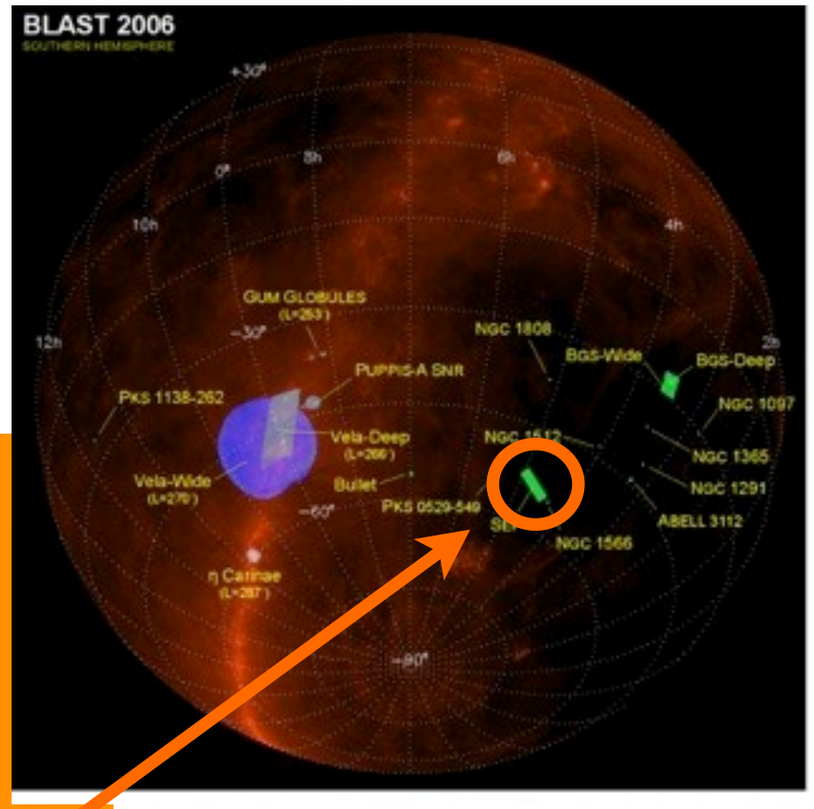


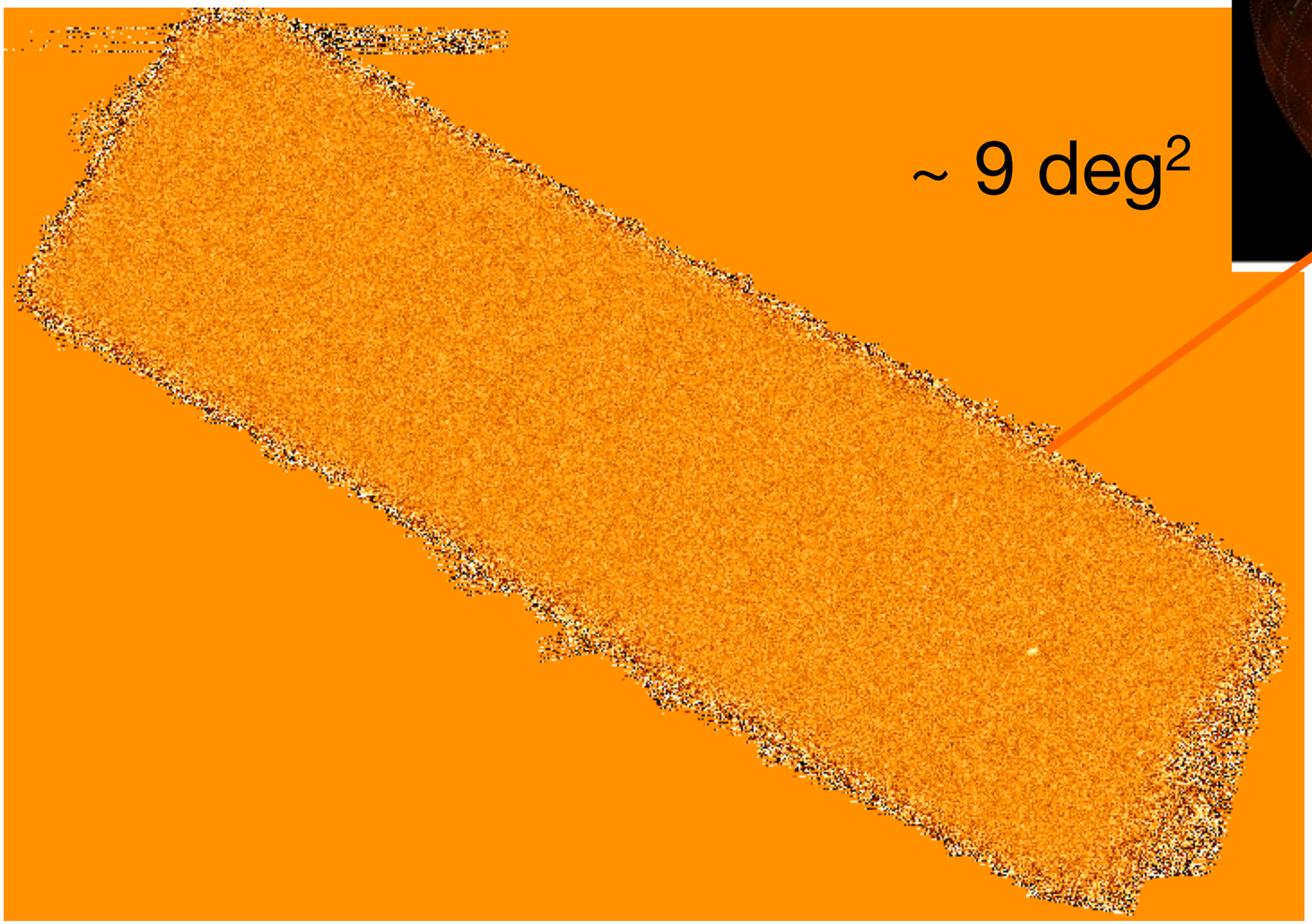
- 300 deg^2
- 1′ resolution
- 3 bands

148 GHz (~2.0 mm)

218 GHz (~1.4 mm)

277 GHz (~1.1 mm)



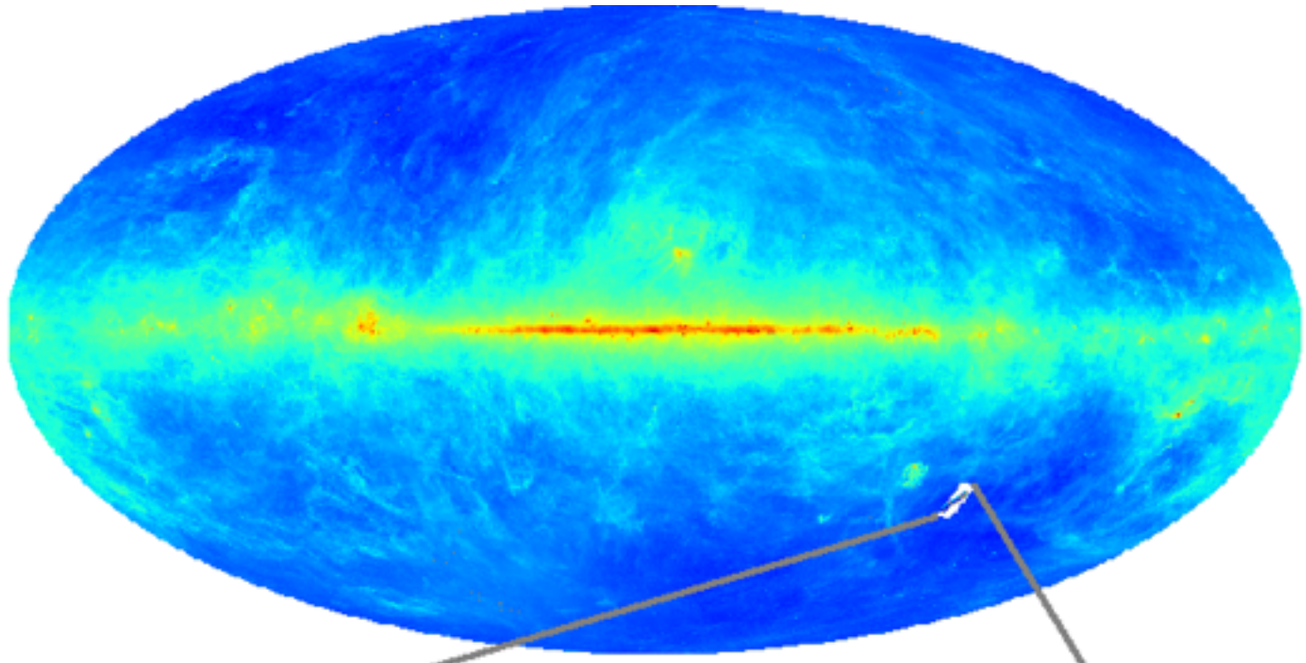


~ 9 deg^2

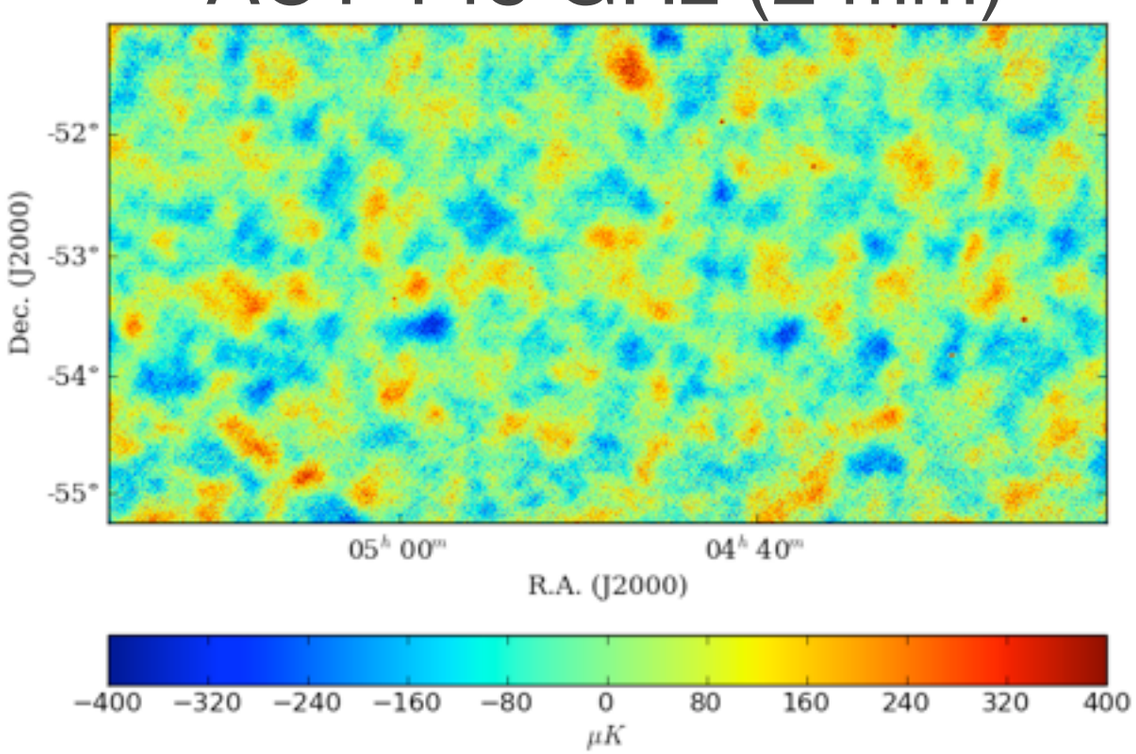
Noise r.m.s.:
36.7 mJy beam^{-1}
27.2 mJy beam^{-1}
19.1 mJy beam^{-1}

SEP

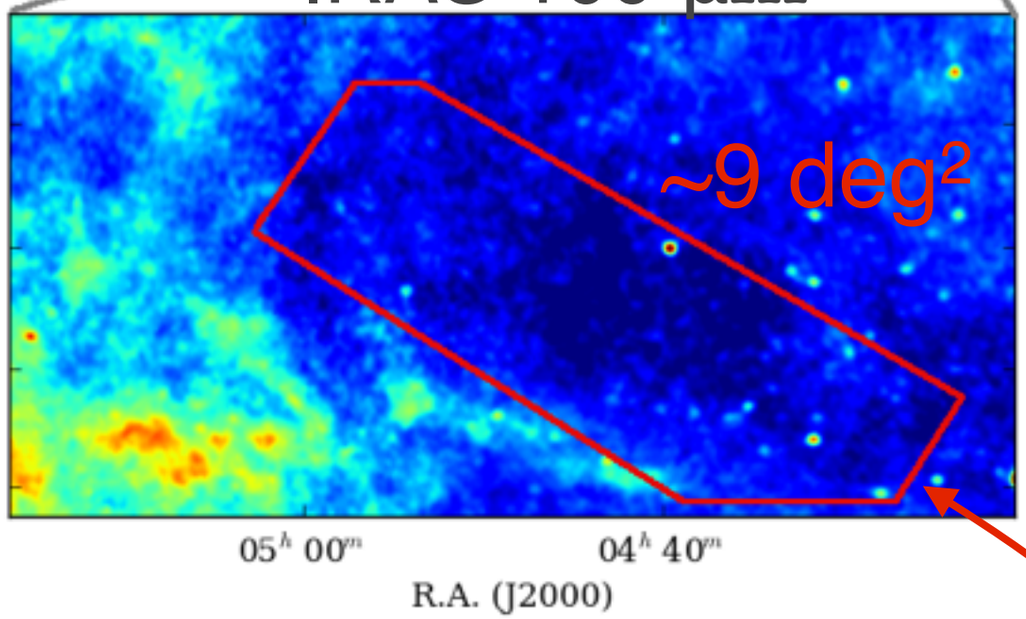
Overlap:
BLAST-SEP Field



ACT 148 GHz (2 mm)

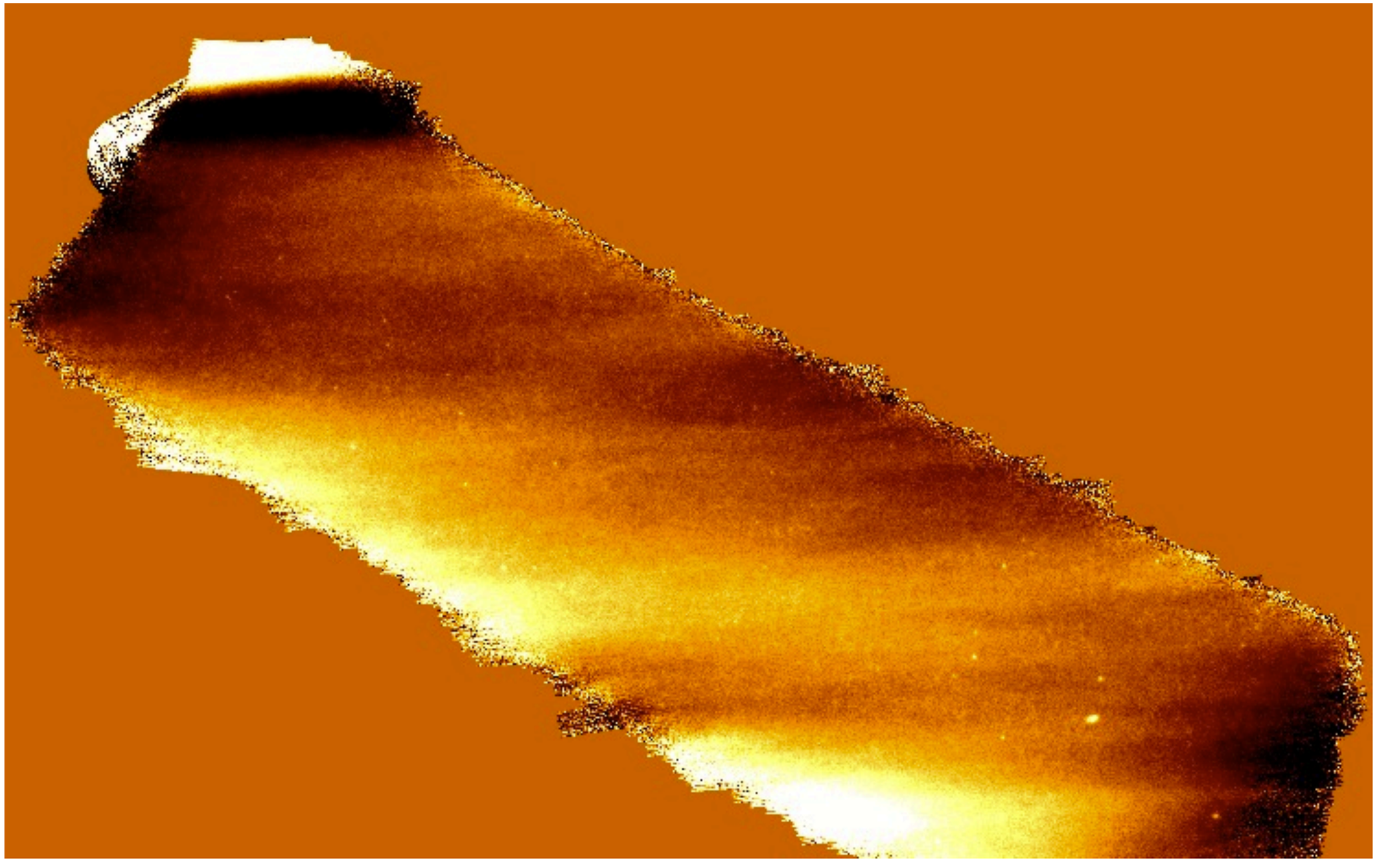


IRAS 100 μm

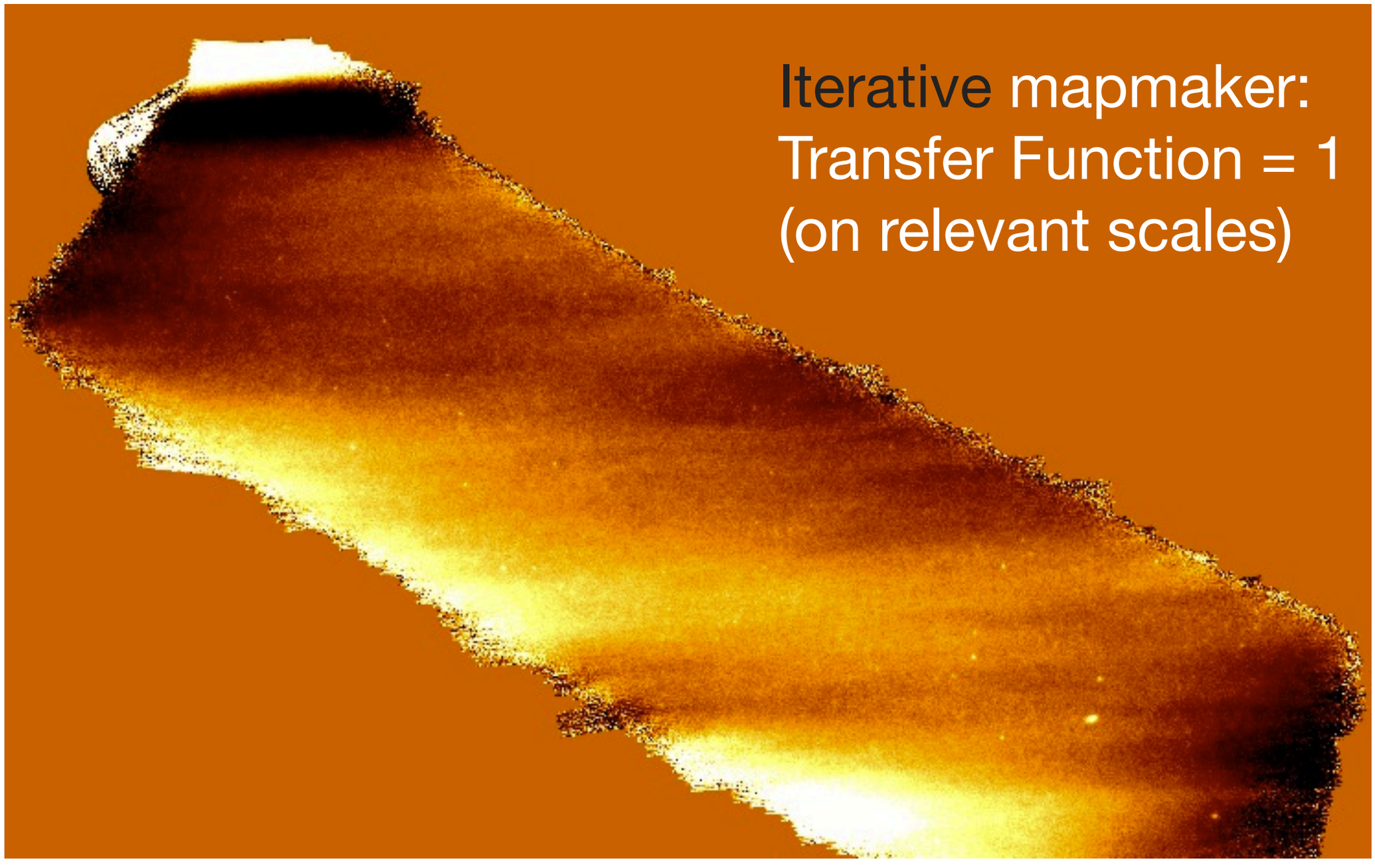


Mean Flux ~ 1.1 MJy/sr

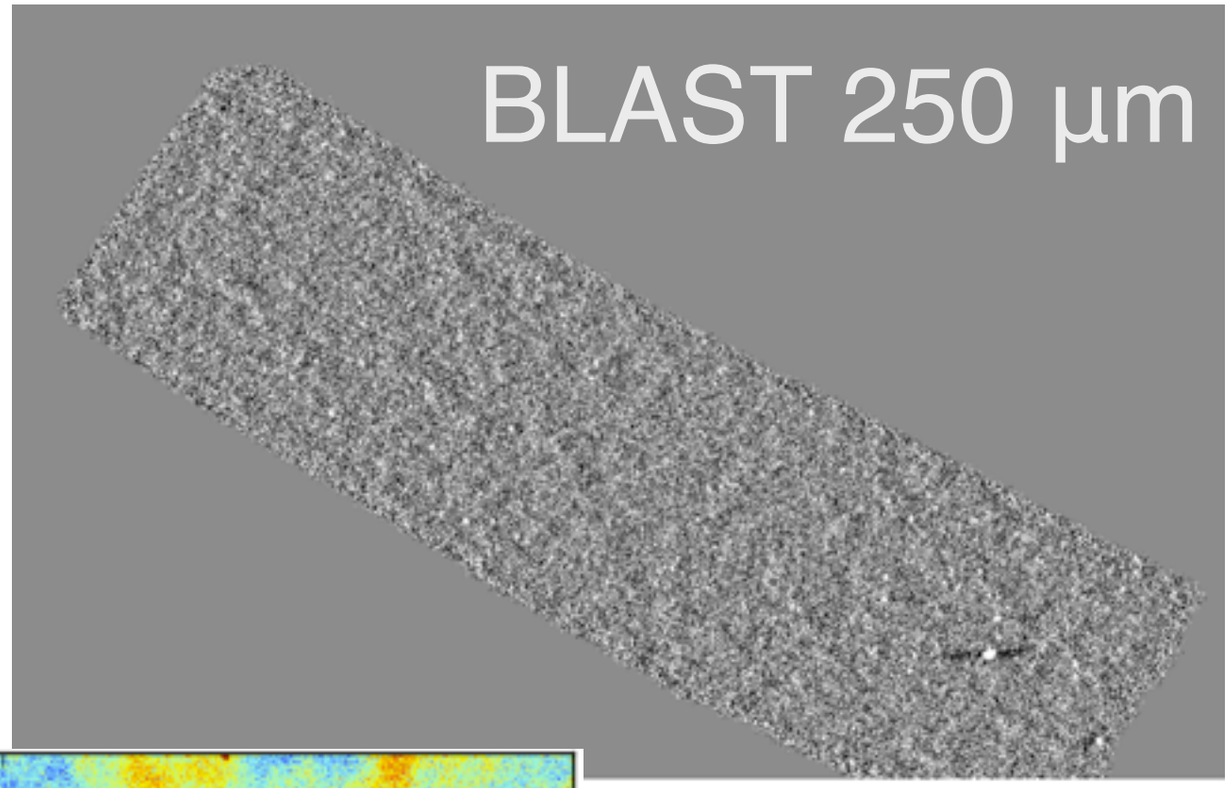
BLAST-Maps made with SANEPIC

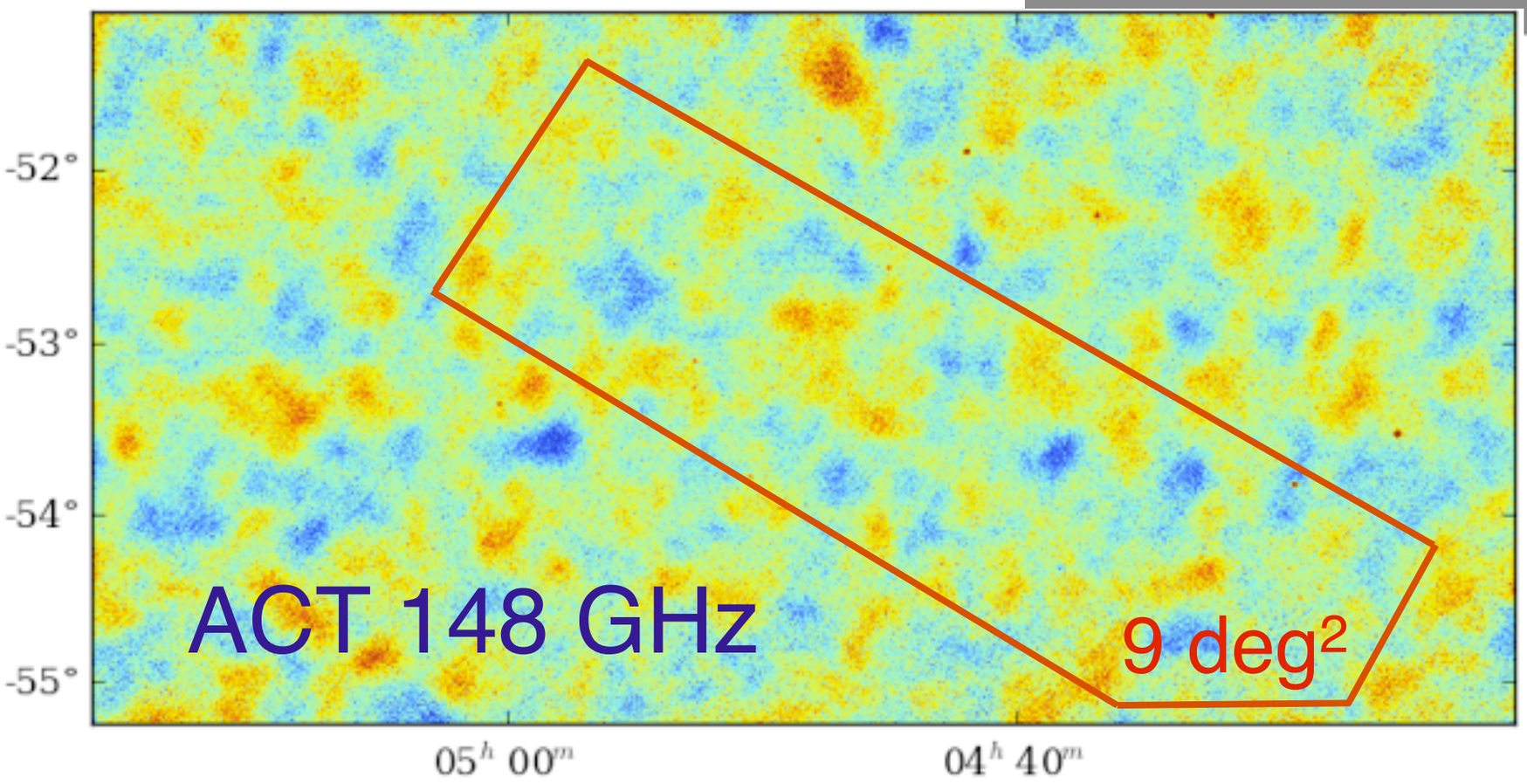


BLAST-Maps made with SANEPIC



Cross-Correlations Isolate Dusty Galaxies from the Rest





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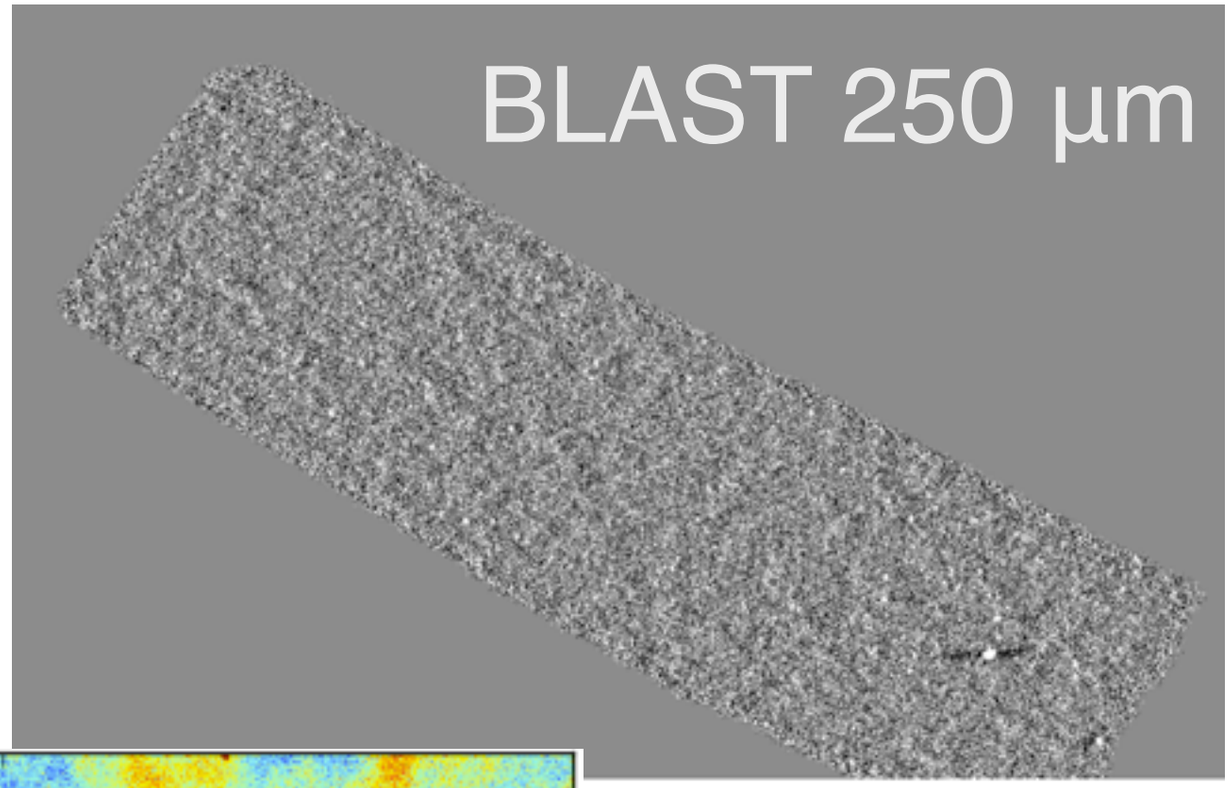
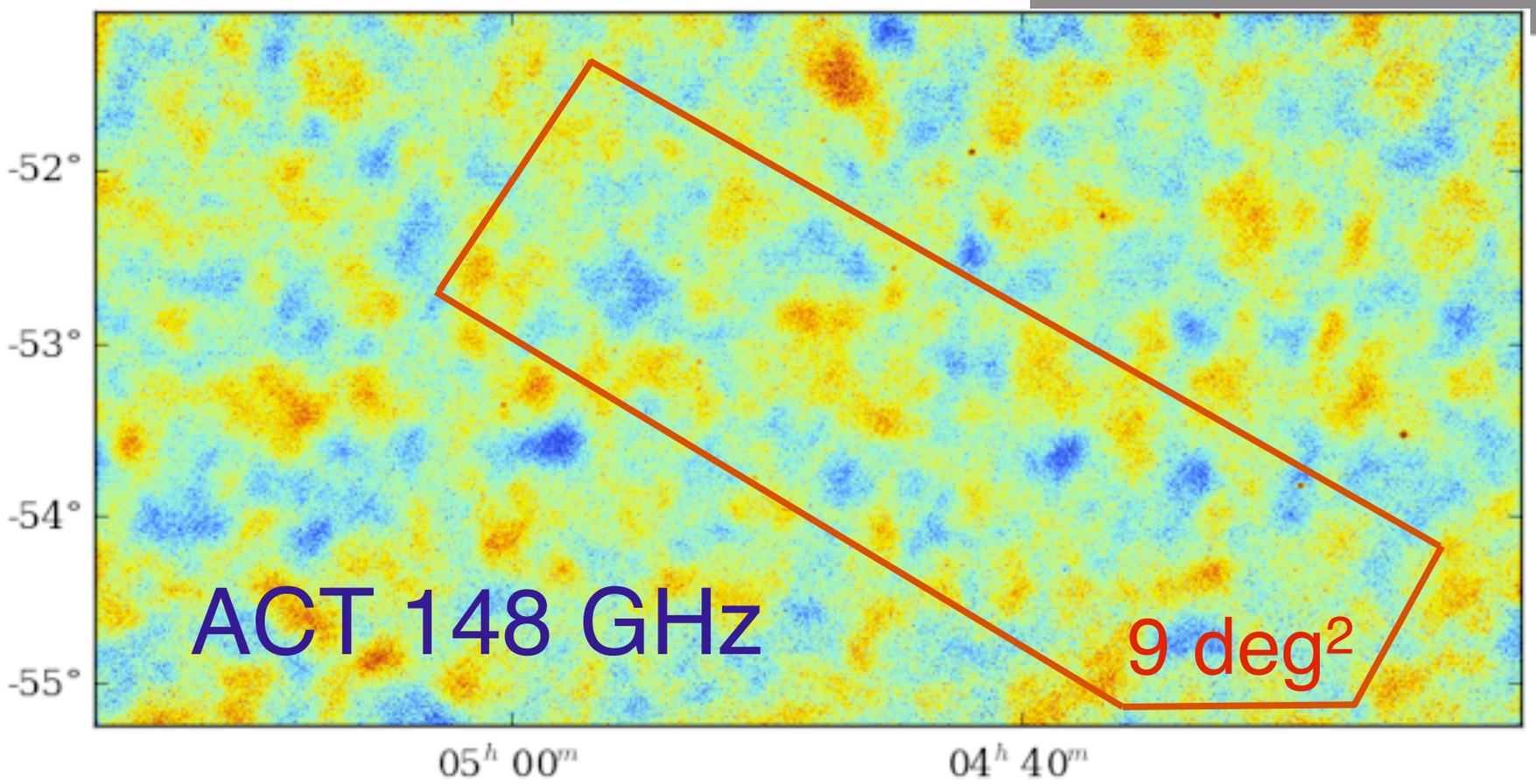
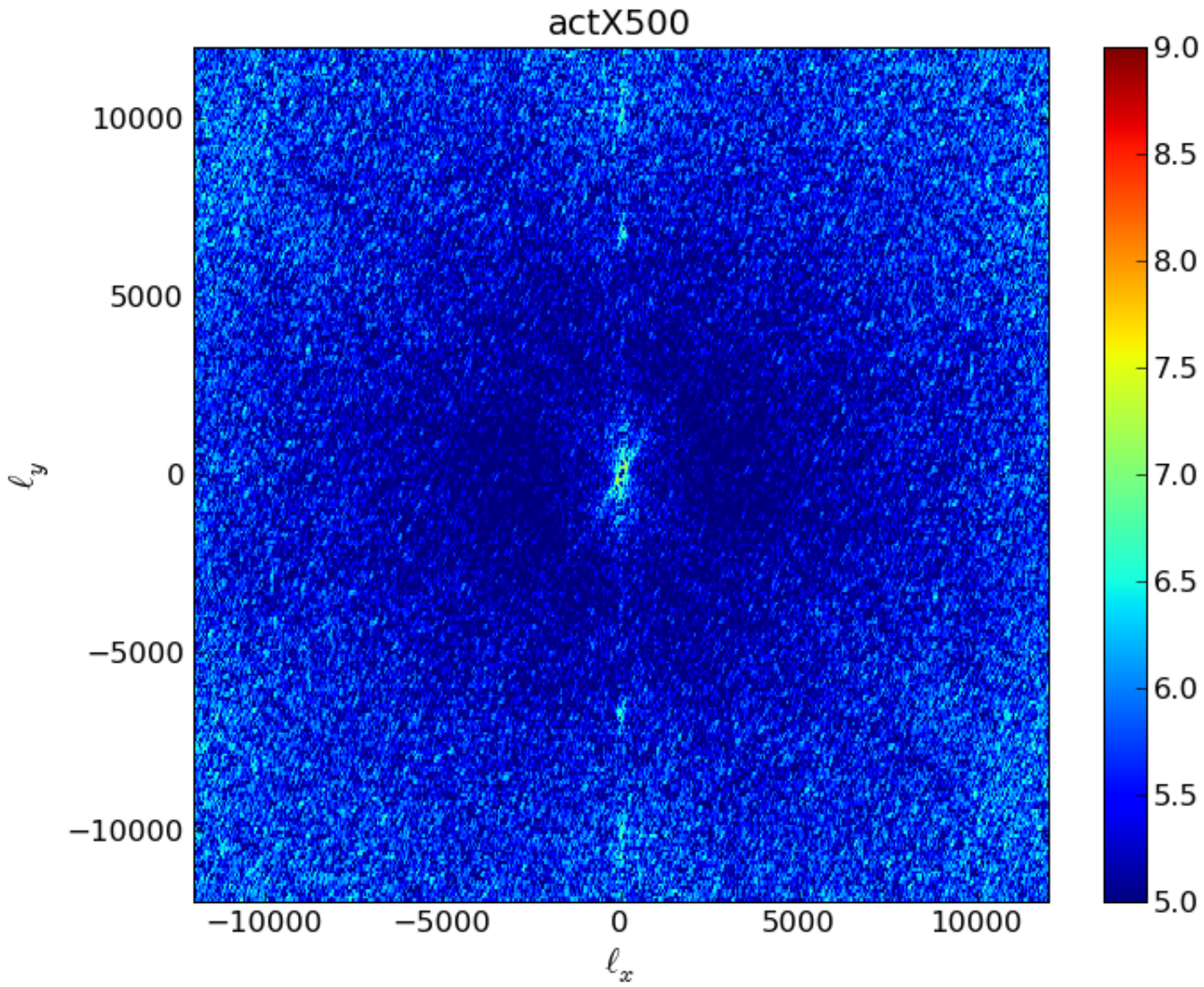


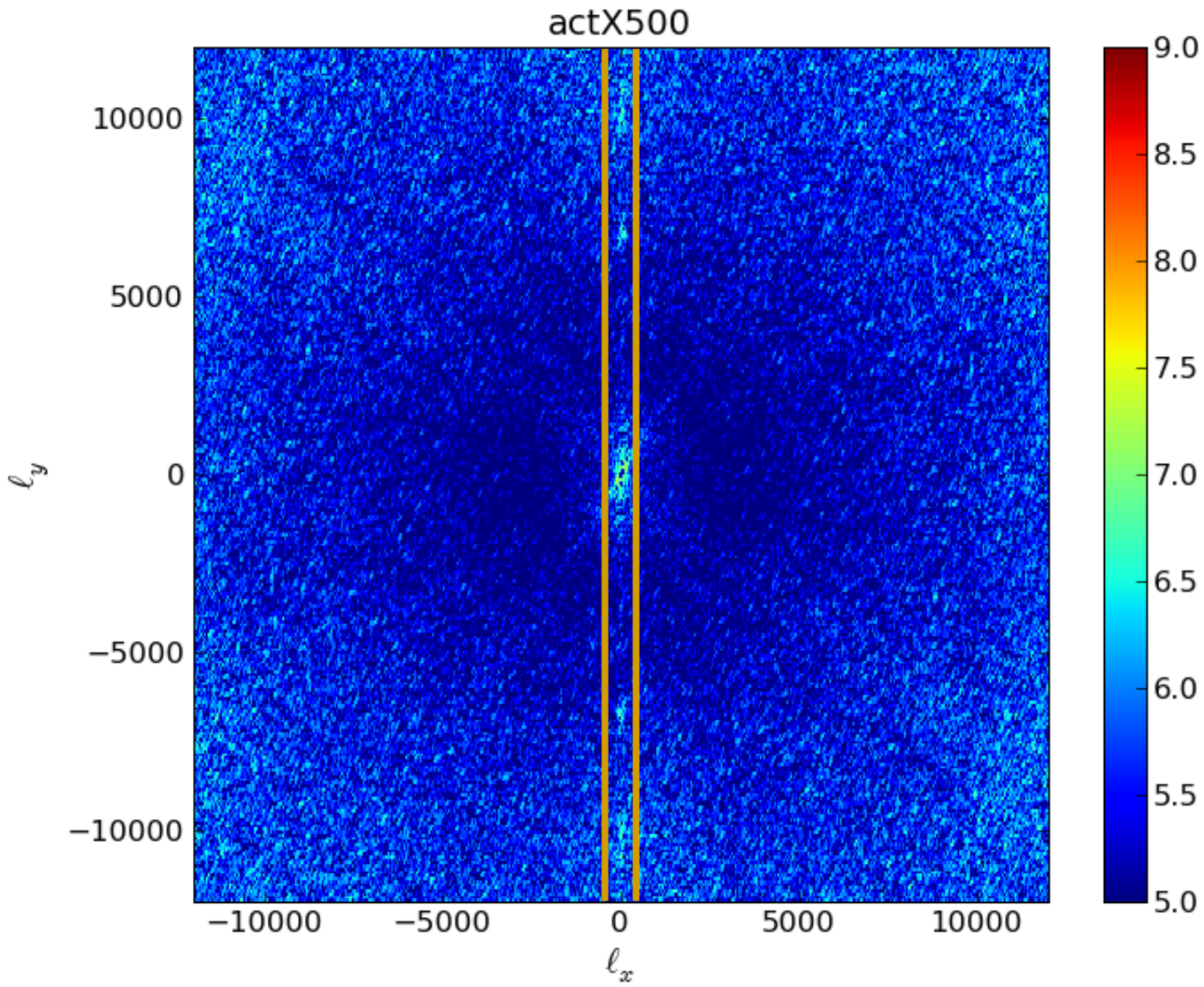


ACT X BLAST

Cross-correlation in Fourier Space

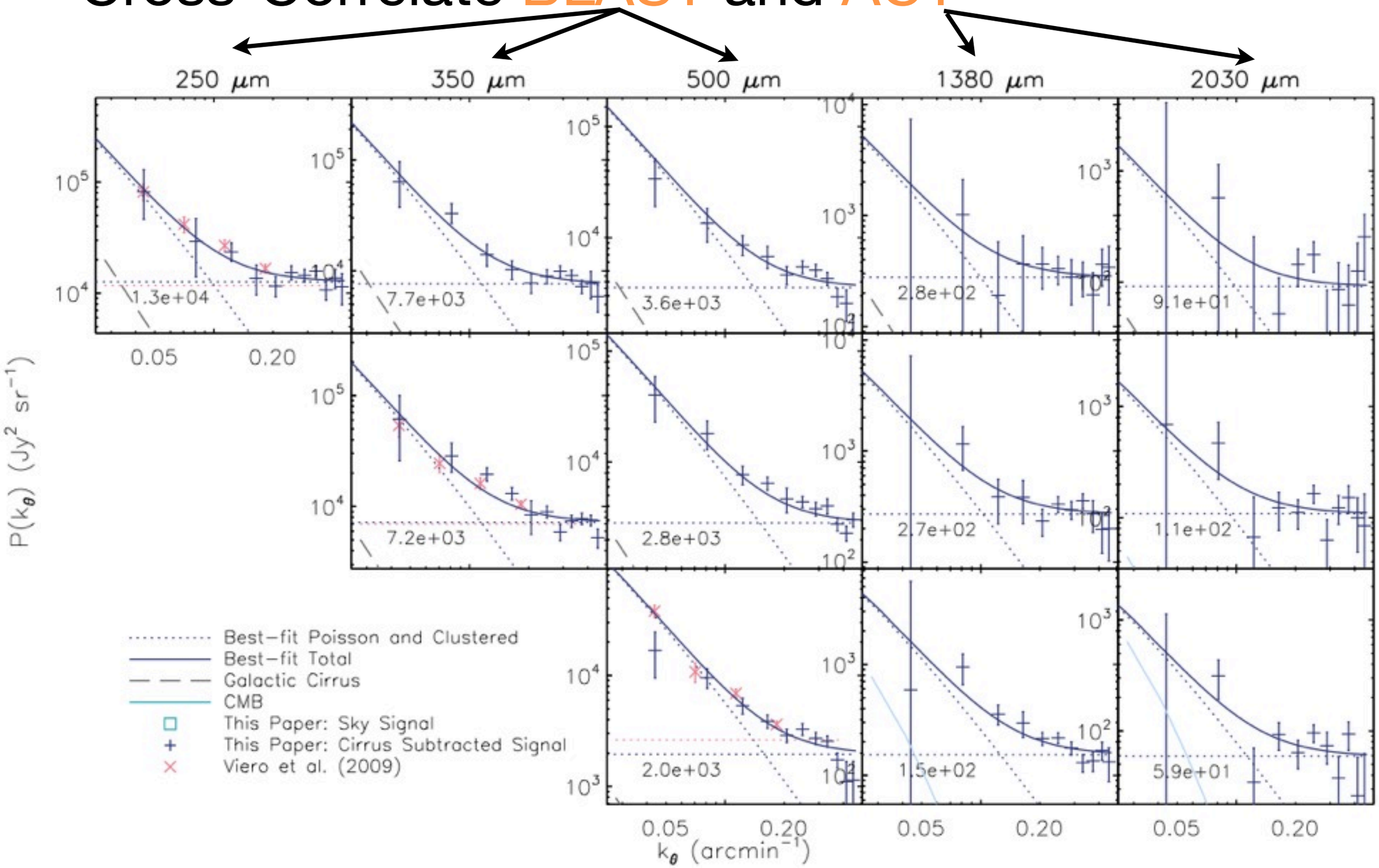


Cross-correlation in Fourier Space



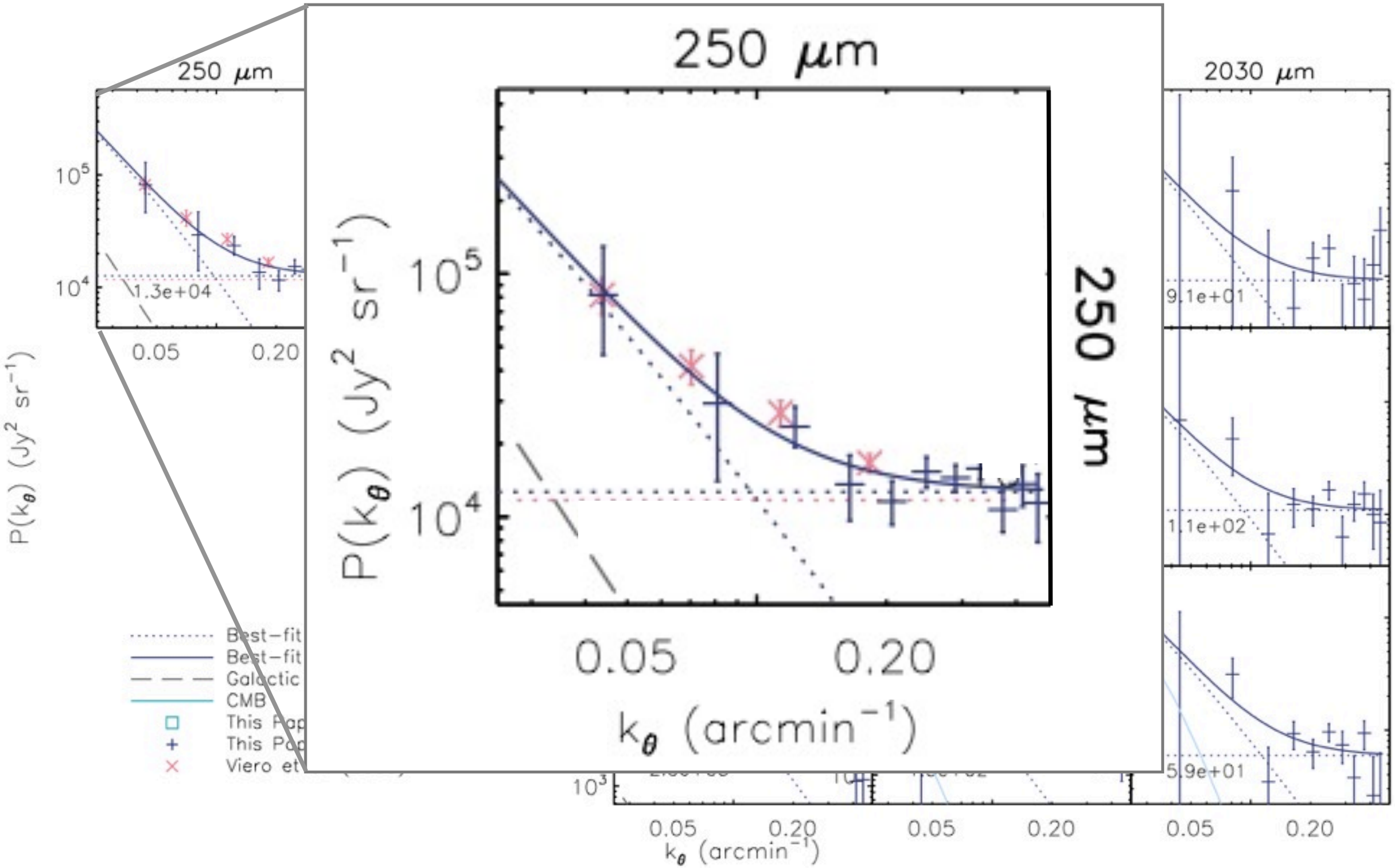
Fourier Domain Filter

Cross-Correlate BLAST and ACT



Hajian & Viero et al.

arXiv:1101.1517



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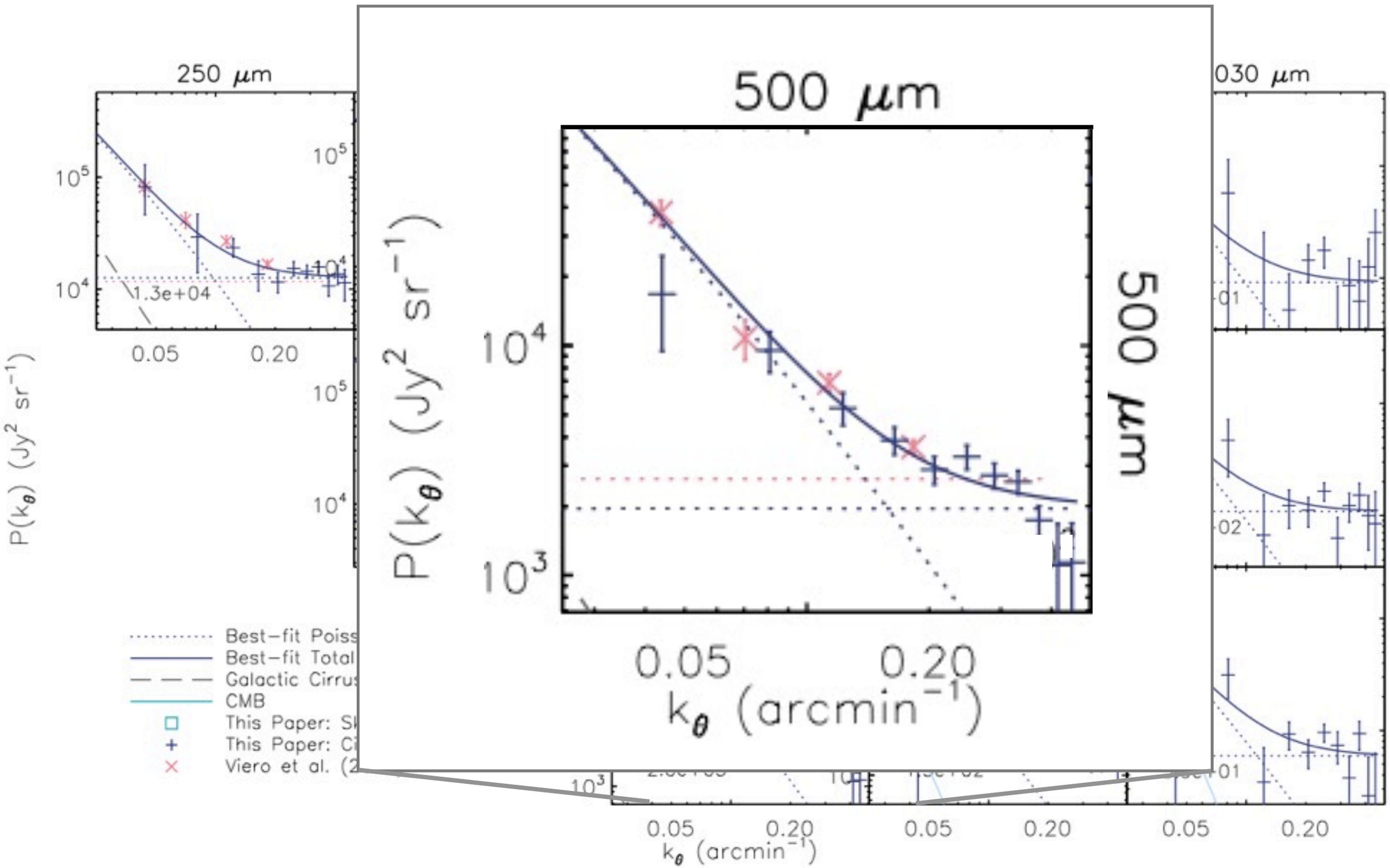

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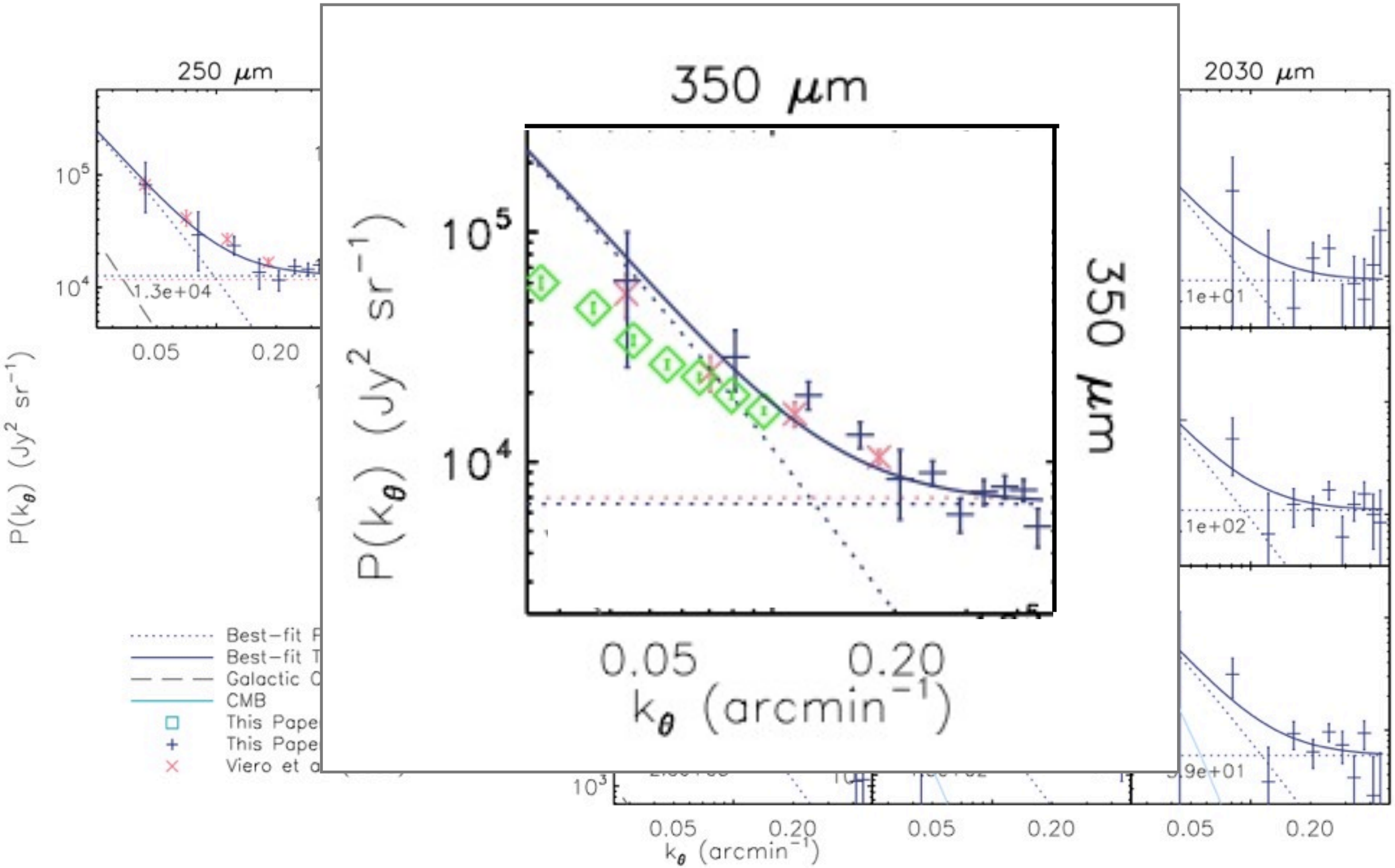

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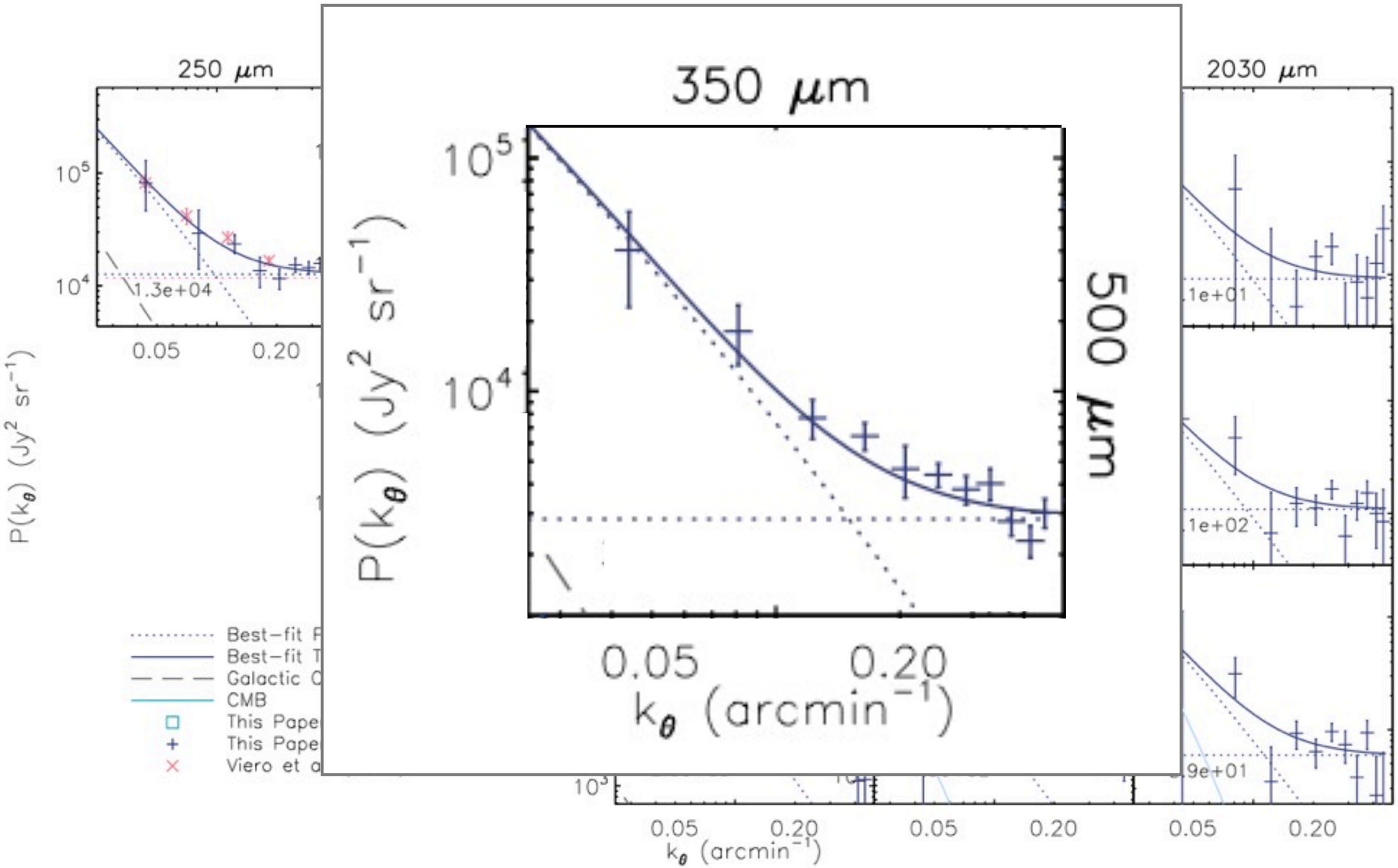

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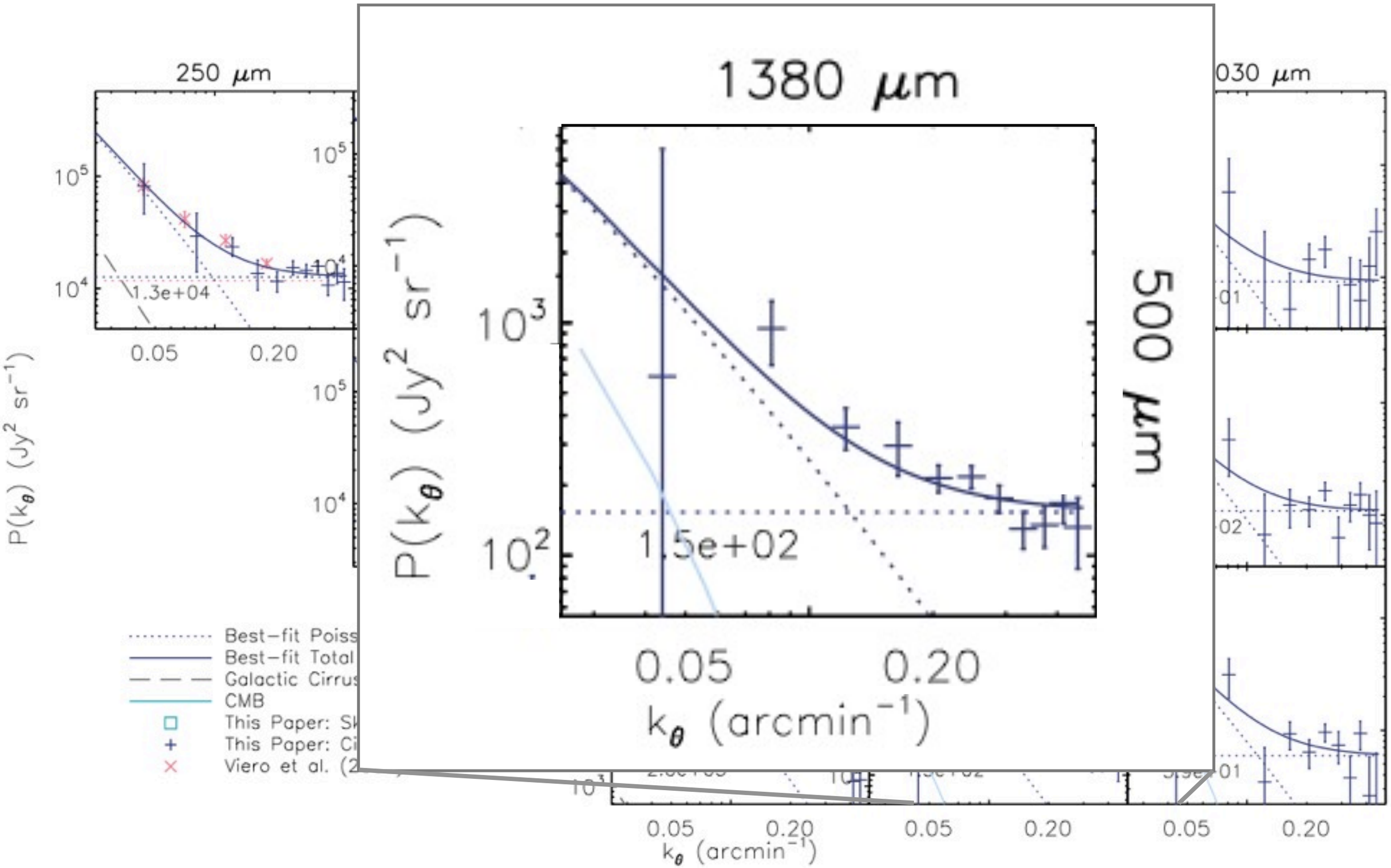

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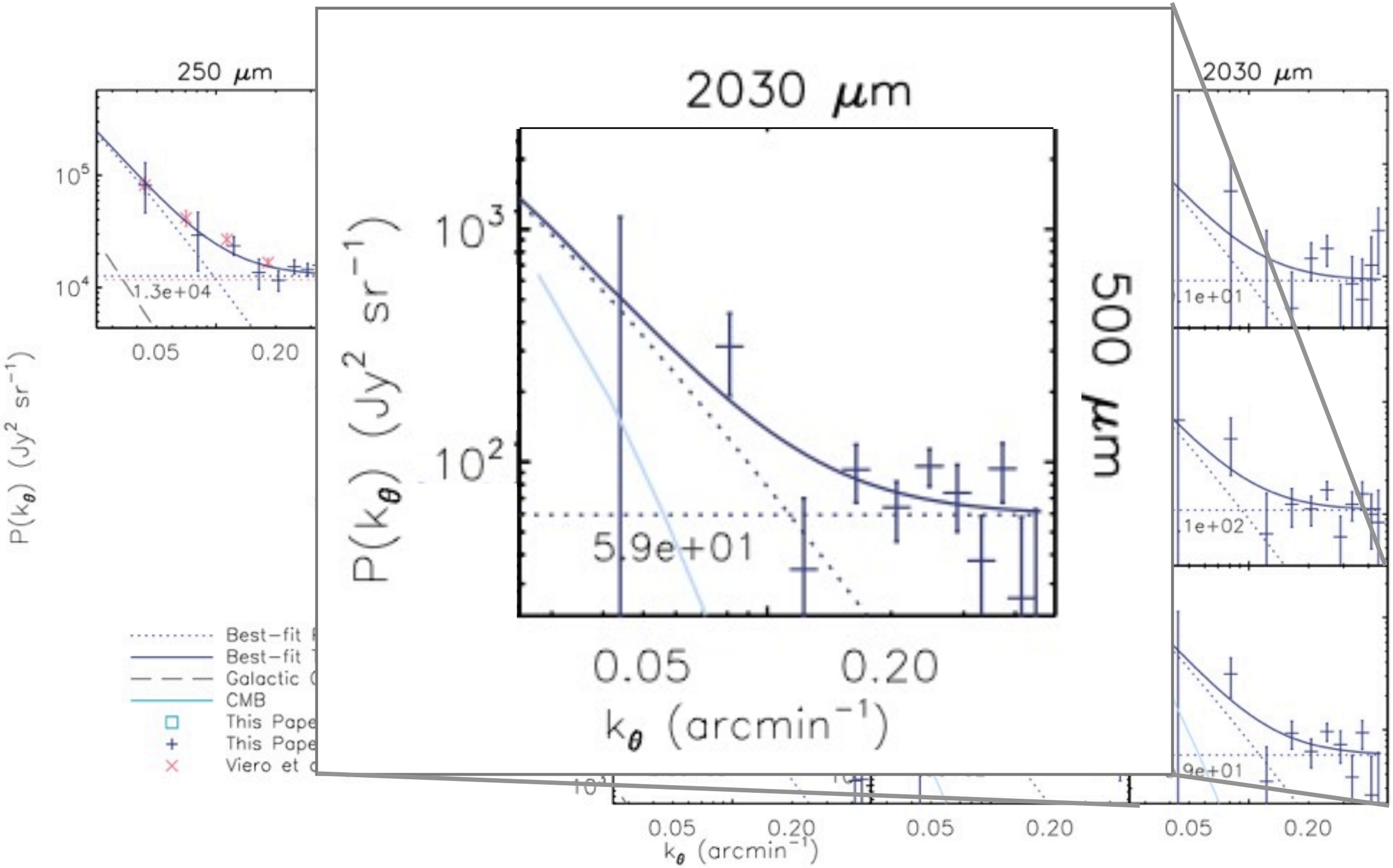
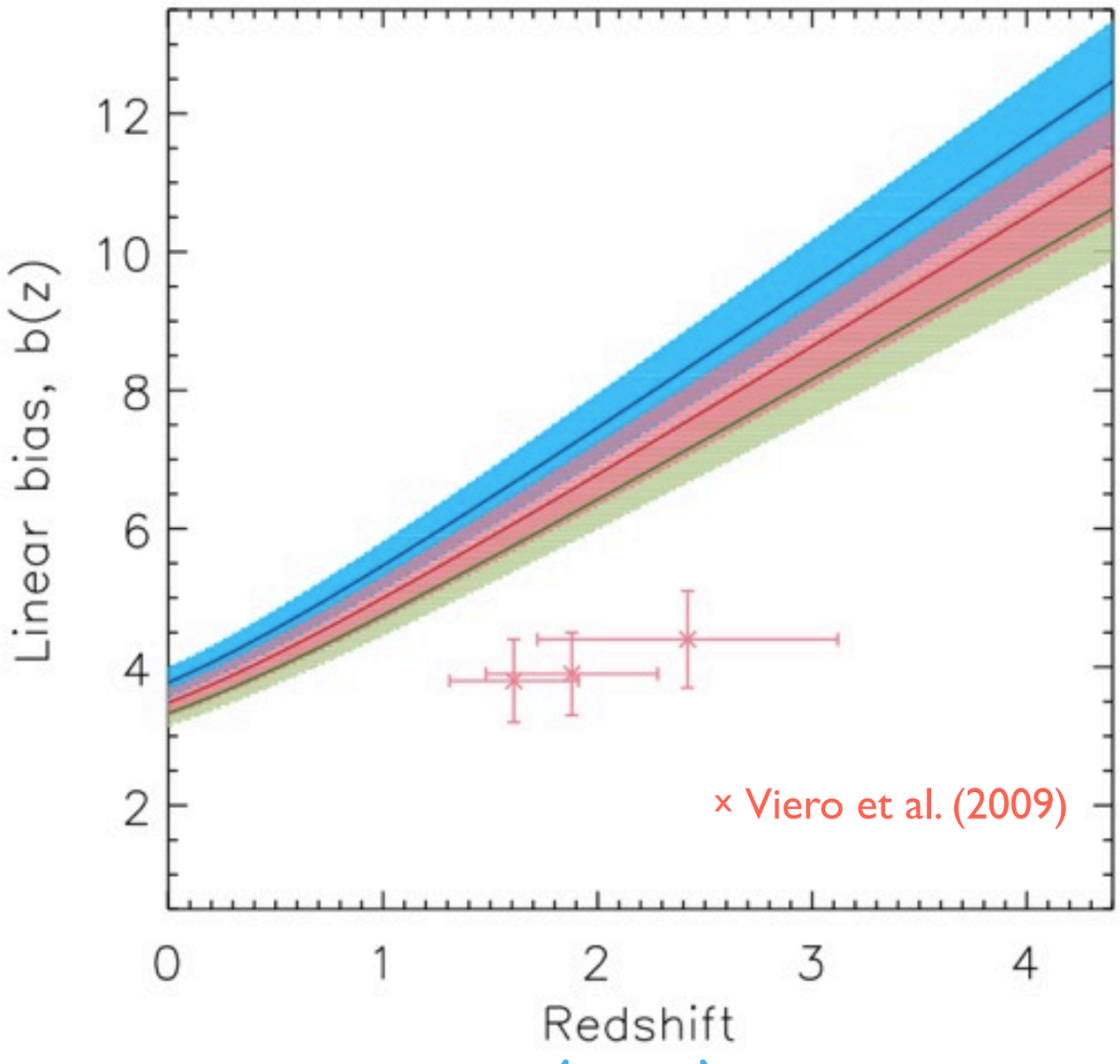


Hajian & Viero et al.

arXiv:1101.1517

Fit a Linear bias simultaneously to each band

Source model of Béthermin et al. (2010)
& Linear bias model of Graeme Addison



Constrains the evolution using redshift information

Finds bias strongly dependent on model

Hajian & Viero et al. (2011)

arXiv: 1101.1517

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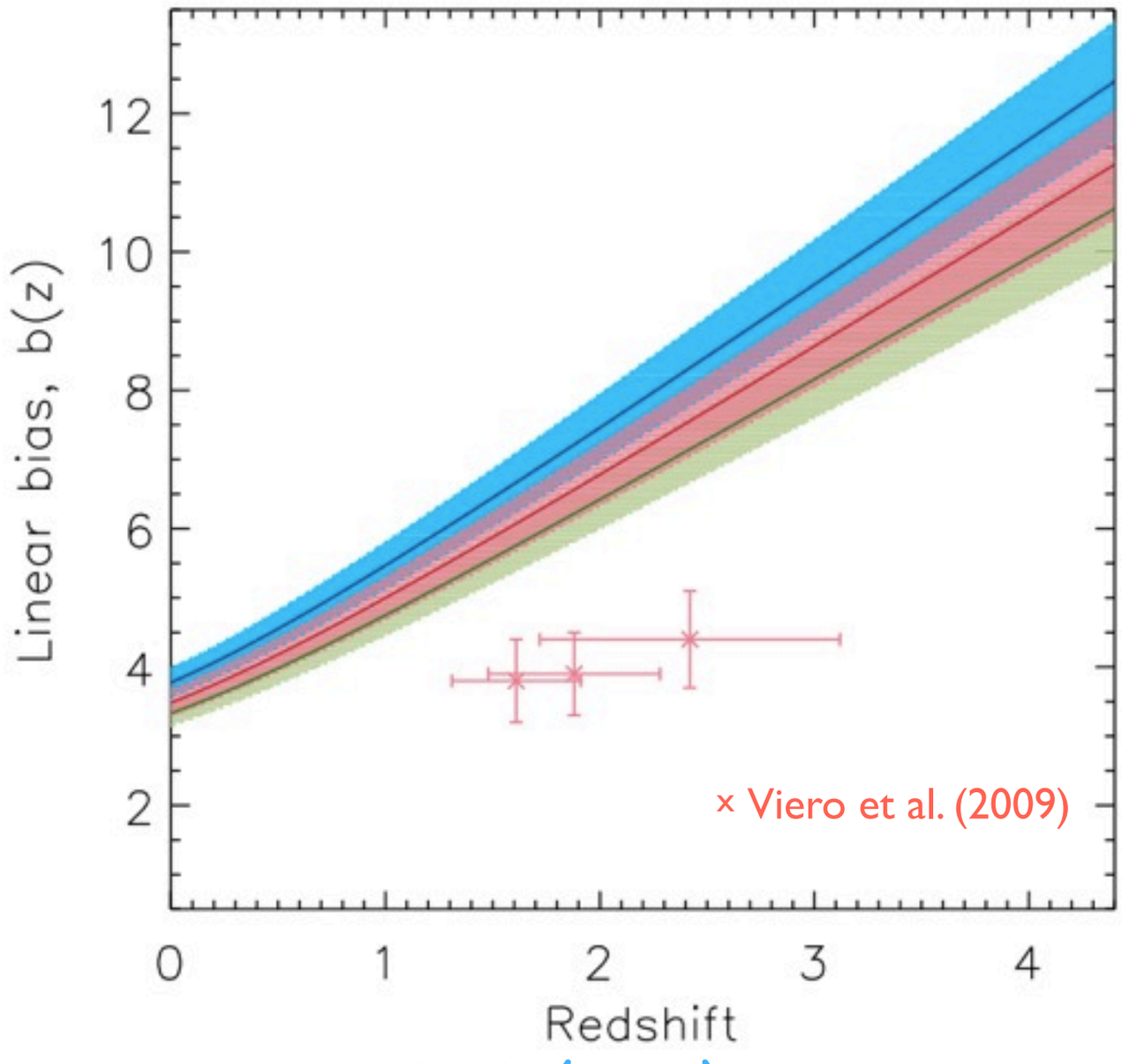

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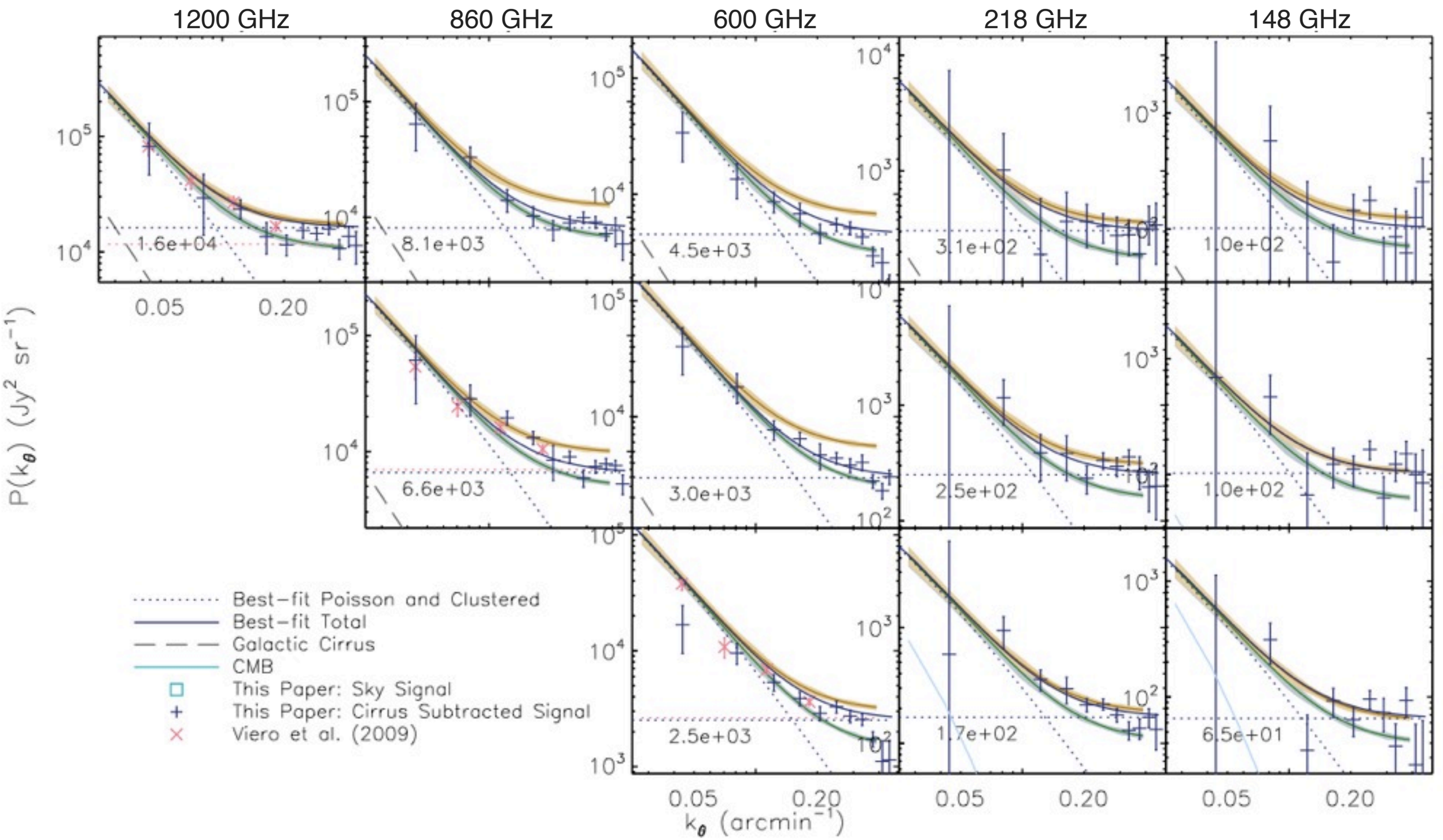
ACT X BLAST



Model: Marsden et al. 1010.1176

Model: Béthermin et al. 1010.1150

- Auto-Frequency Correlations:

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  ✓ Measure *Clustering* of DSFGs

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  ✓ Constrain physical properties of Host Halos, such as bias and M_{min}

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- Cross-Frequency Correlations:

- Auto-Frequency Correlations:

  ✓ Measure *Clustering* of DSFGs

  ✓ Constrain physical properties of Host Halos, such as bias and M_{min}

- Cross-Frequency Correlations:

  ✓ Isolate Dusty Galaxies in CMB maps

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  ✓ Constrain physical properties of Host Halos, such as bias and M_{min}

- Cross-Frequency Correlations:

  ✓ Isolate Dusty Galaxies in CMB maps

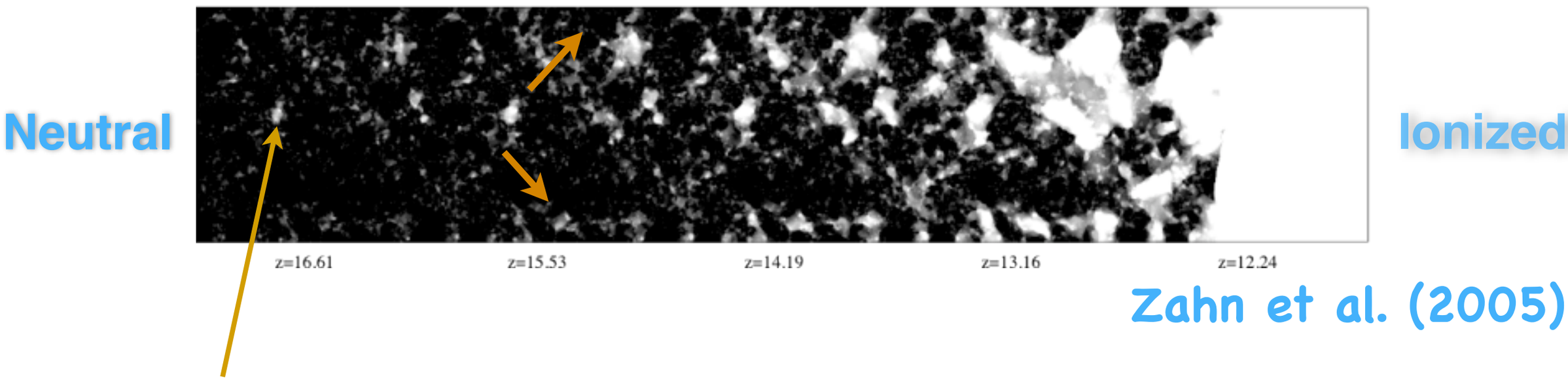
  ✓ Identify the High-z Clustering Signal

  ✓ Constrain Phenomenological Galaxy Models

Summary

future surveys

image: Joaquin Vieira



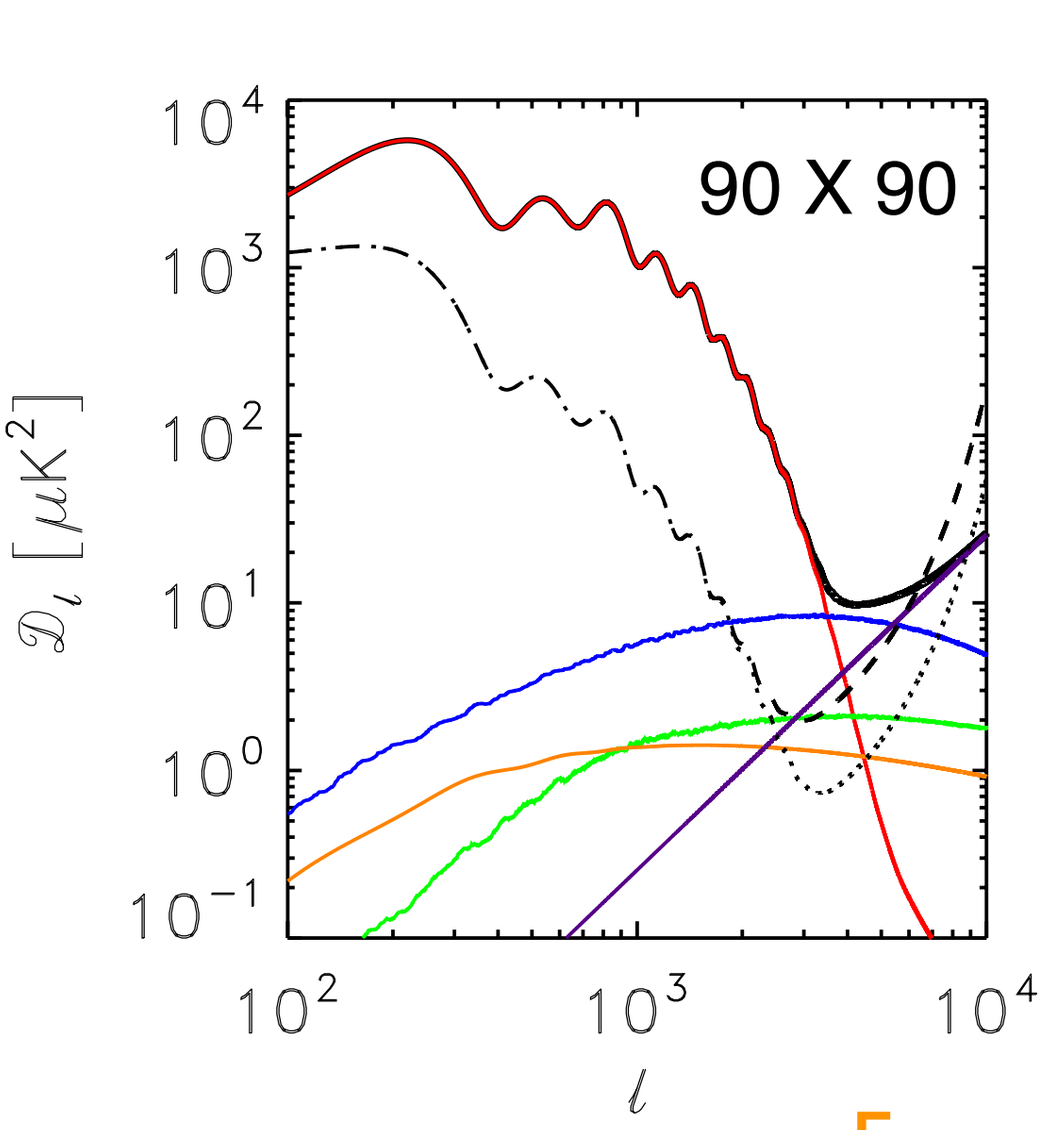
Zahn et al. (2005)

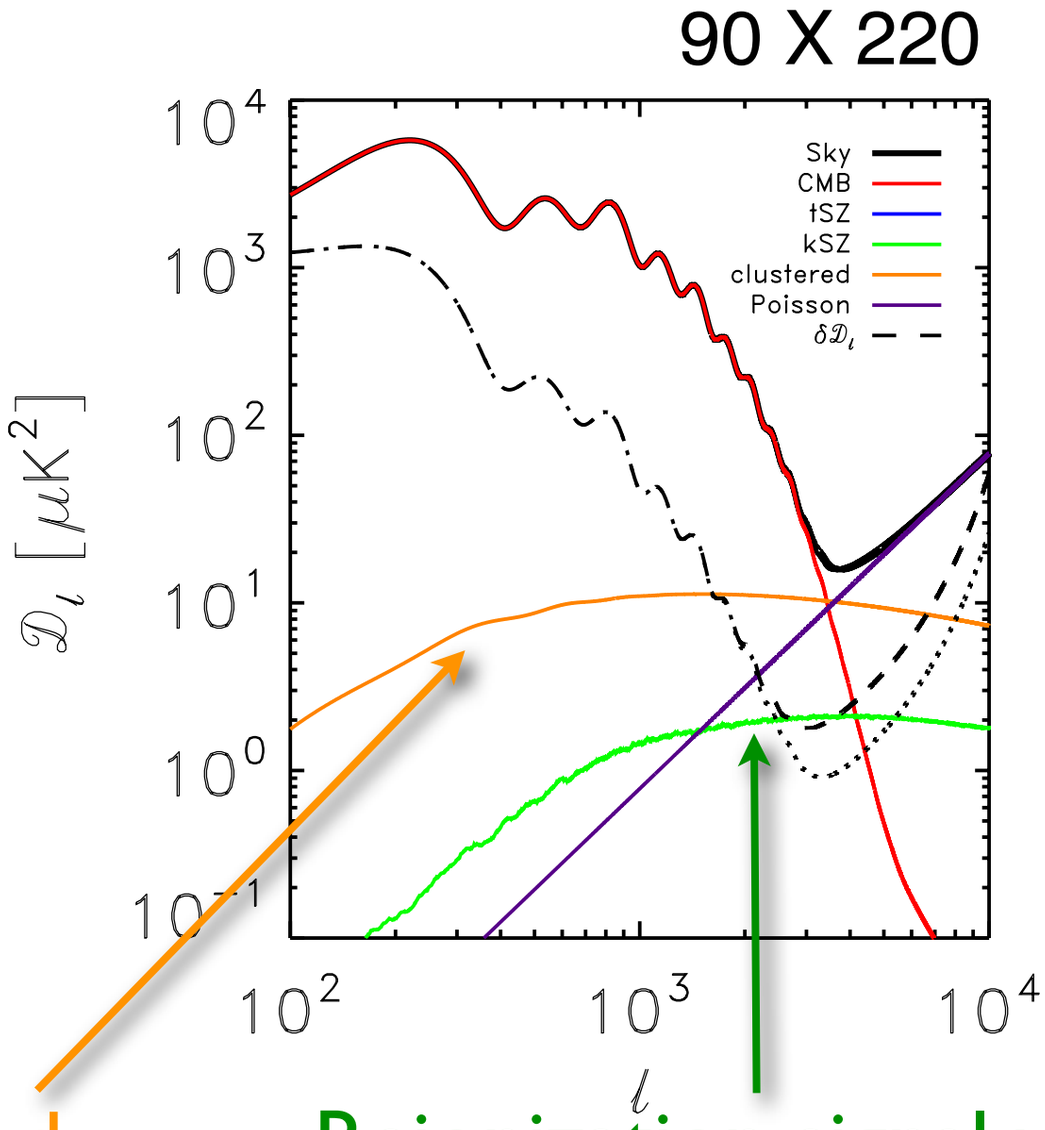
At z<30, Reionized bubbles form around UV sources

Bubbles Moving with respect to CMB, thus distort it

Strength and Shape of kSZ signal depends on details of Reionization

Again, Problem of Foregrounds



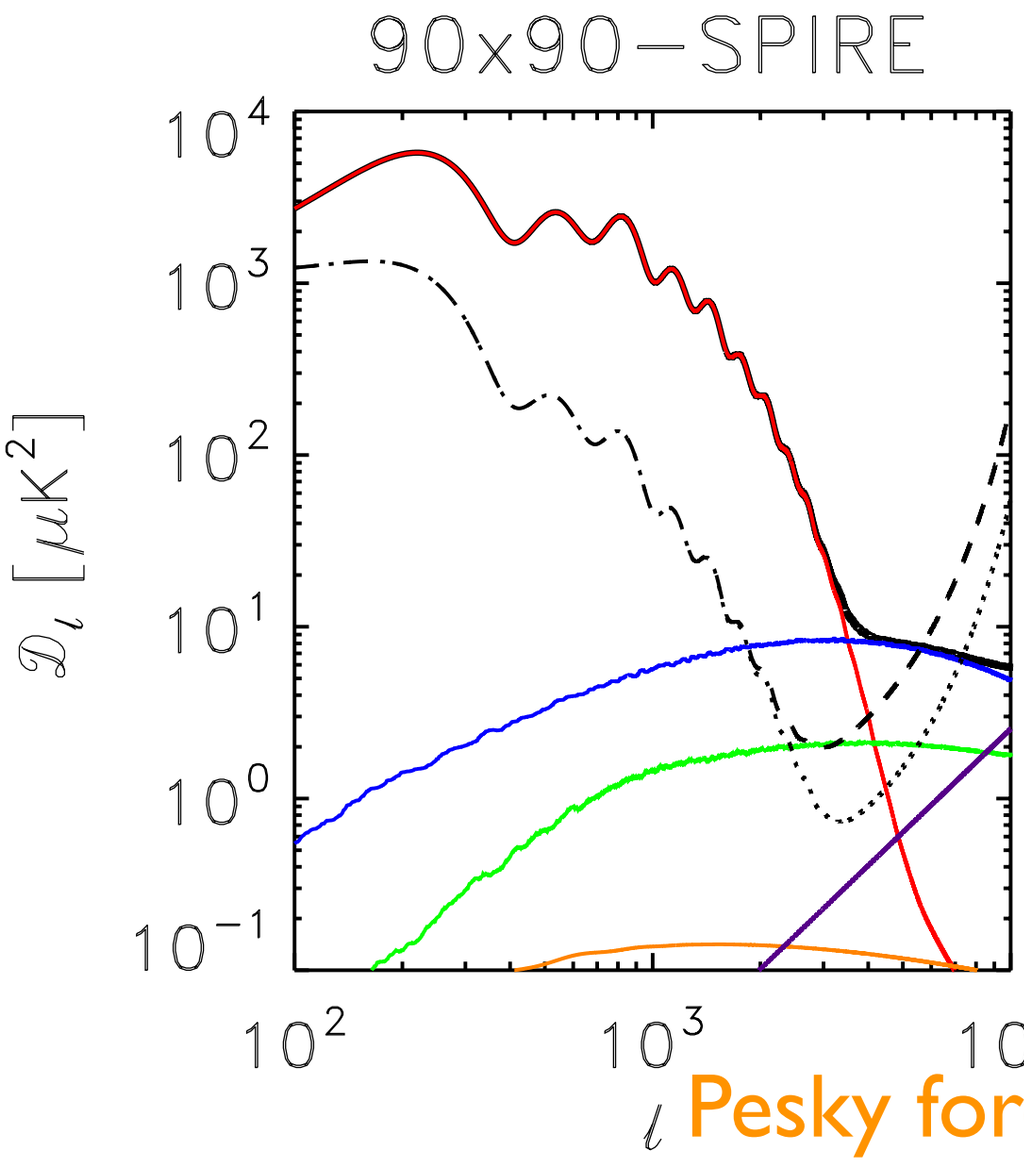


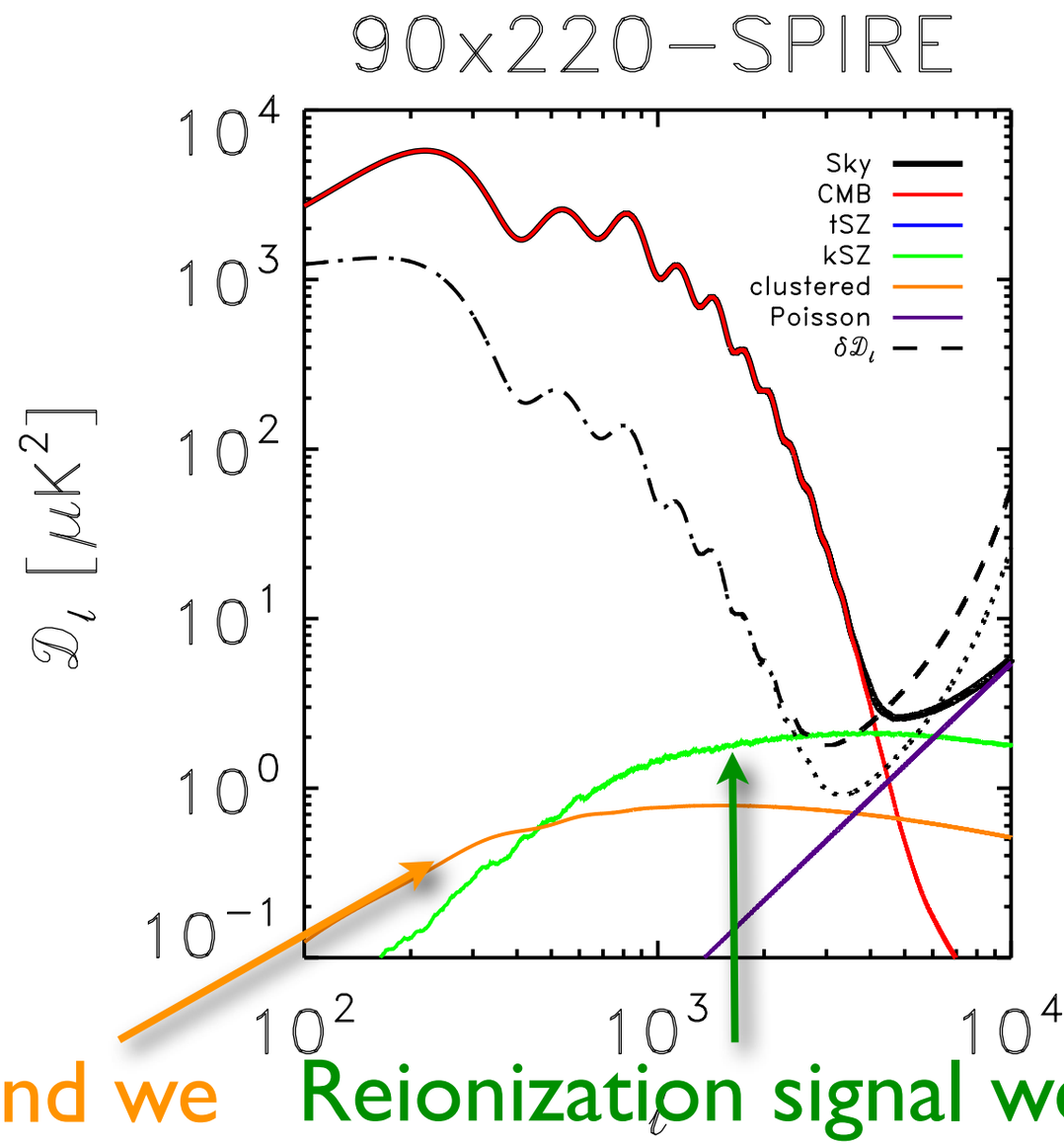
Foreground Galaxies

Reionization signal we want to measure

Courtesy Joaquin Vieira

To Get Weak kSZ Signal, you need SPIRE!





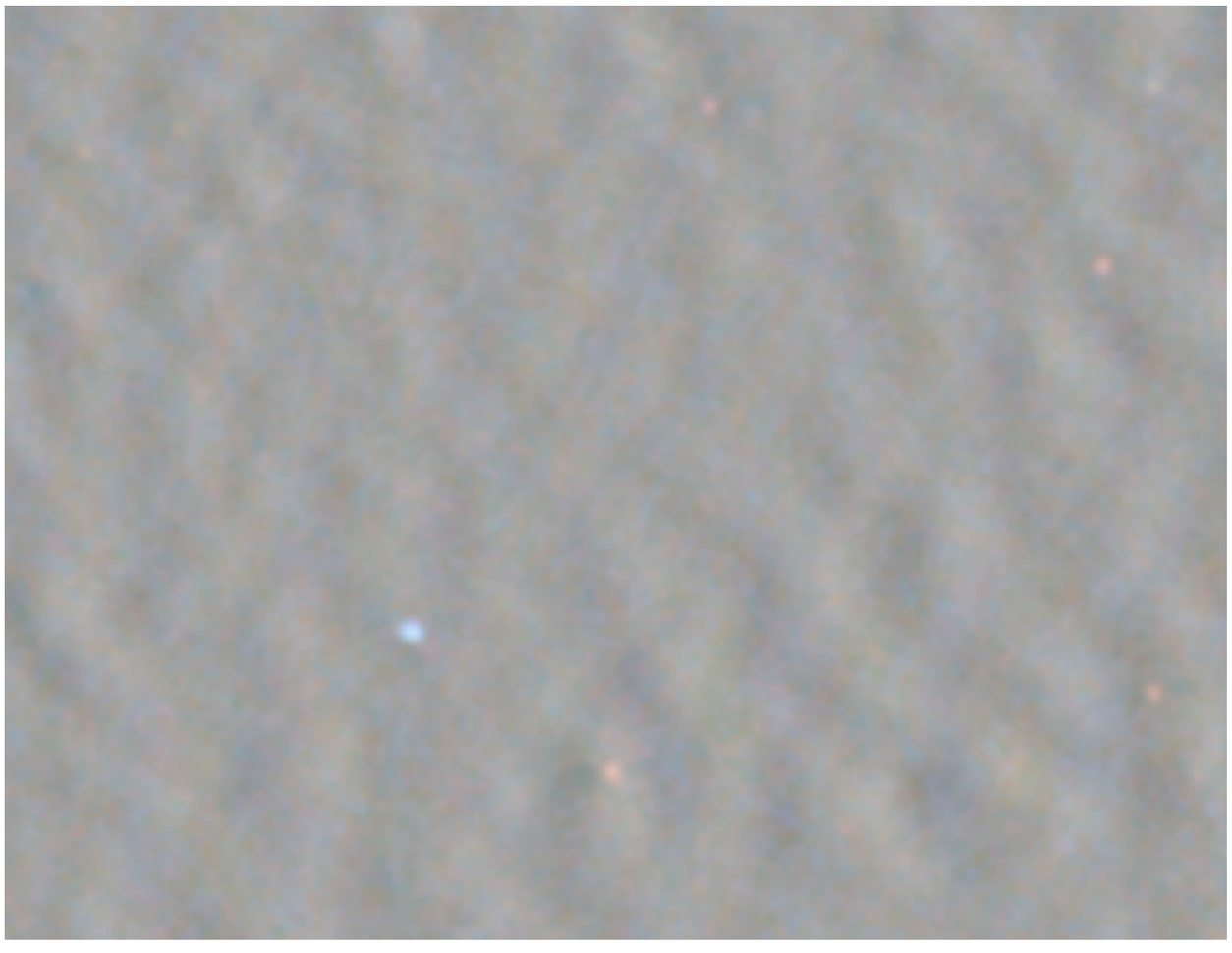
Pesky foreground we want to remove

Reionization signal we want to measure

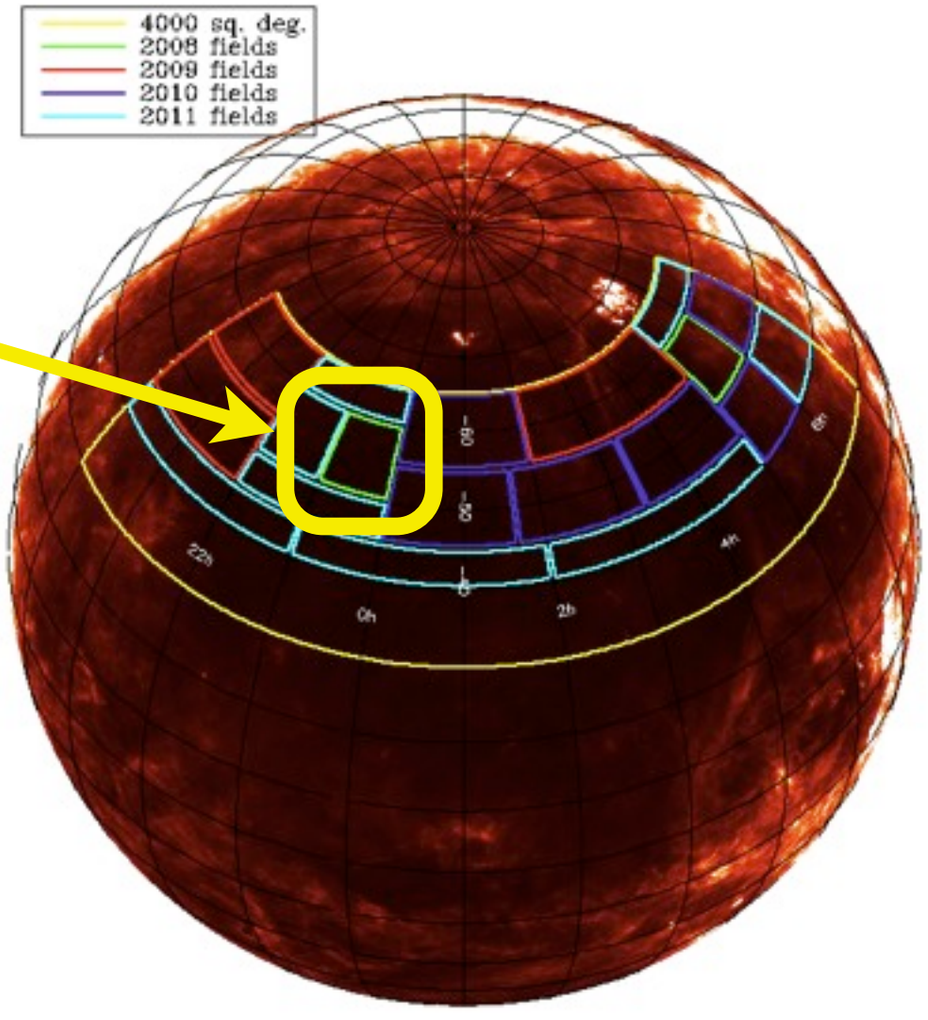
Courtesy Joaquin Vieira

Measuring Epoch of Reionization
Herschel/SPIRE X SPT-Deep Field

SPT 100 deg^2 deep field is the deepest mm map in existence and will remain so for the next decade.



Courtesy Joaquin Vieira



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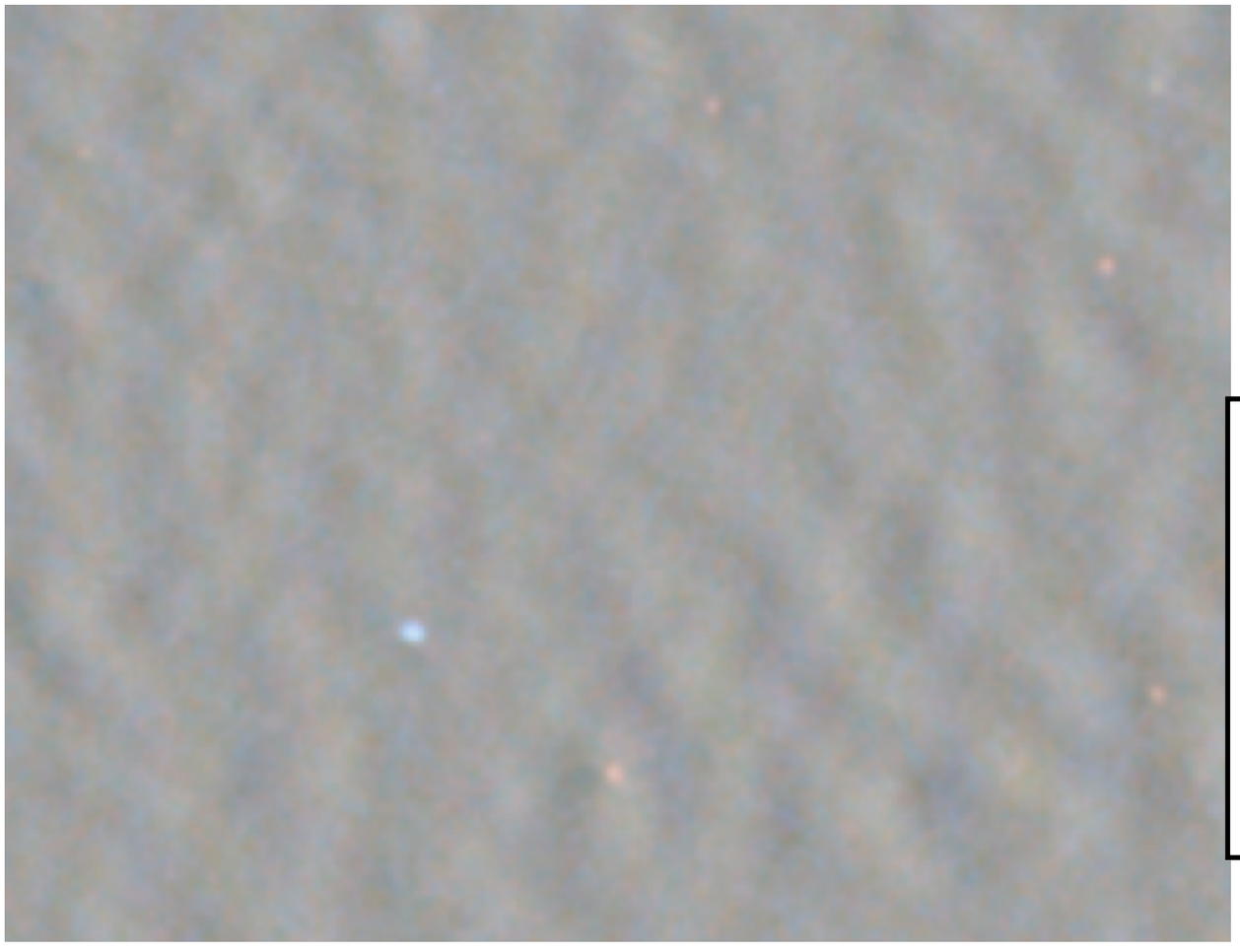
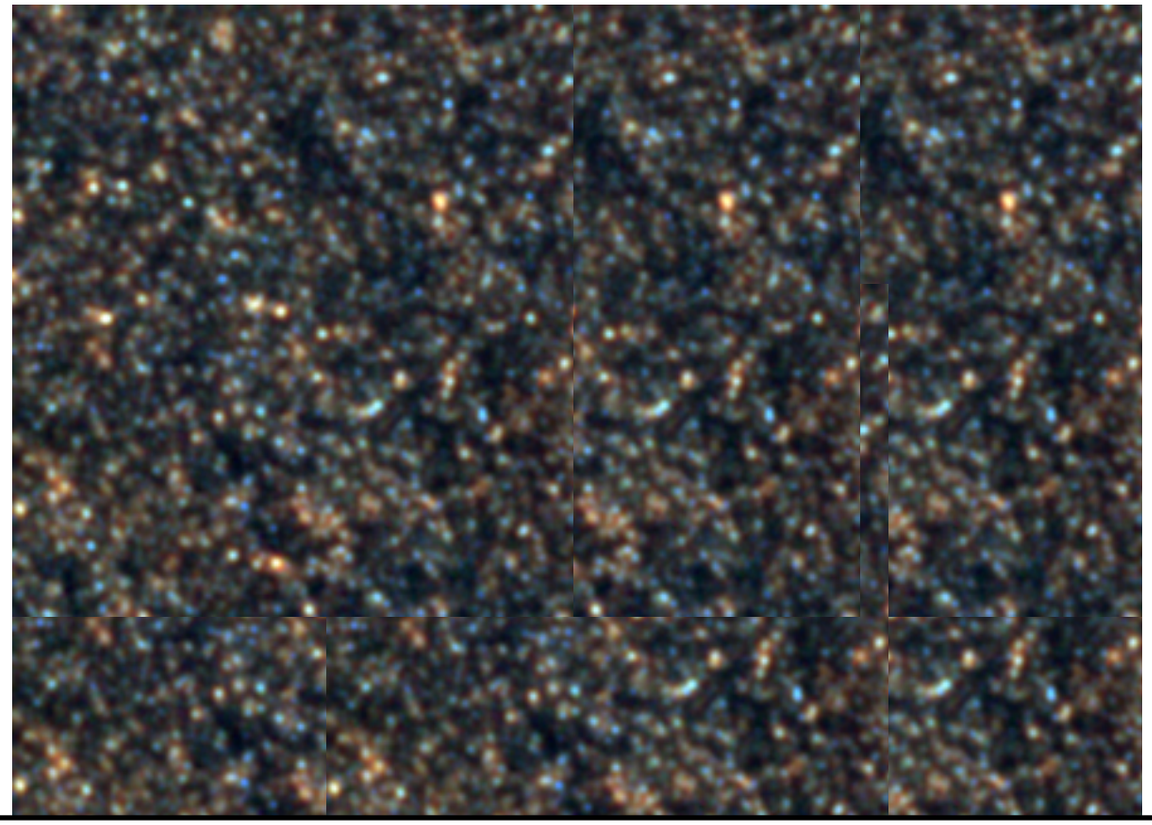


Courtesy Joaquin Vieira



Given 79 hours to map a 100 deg^2 with SPIRE

Measuring Epoch of Reionization
Herschel/SPIRE X SPT-Deep Field

SPT 100 deg² deep field is the deepest mm map in existence and will remain so for the next dec

The HOTAC called this proposal a "Must-Do"

Given 79 hours to map a 100 deg² with SPIRE

Courtesy Joaquin Vieira

end