Cosmic IR Background
&
COBE, Spitzer and WISE

by

Ned Wright (UCLA)

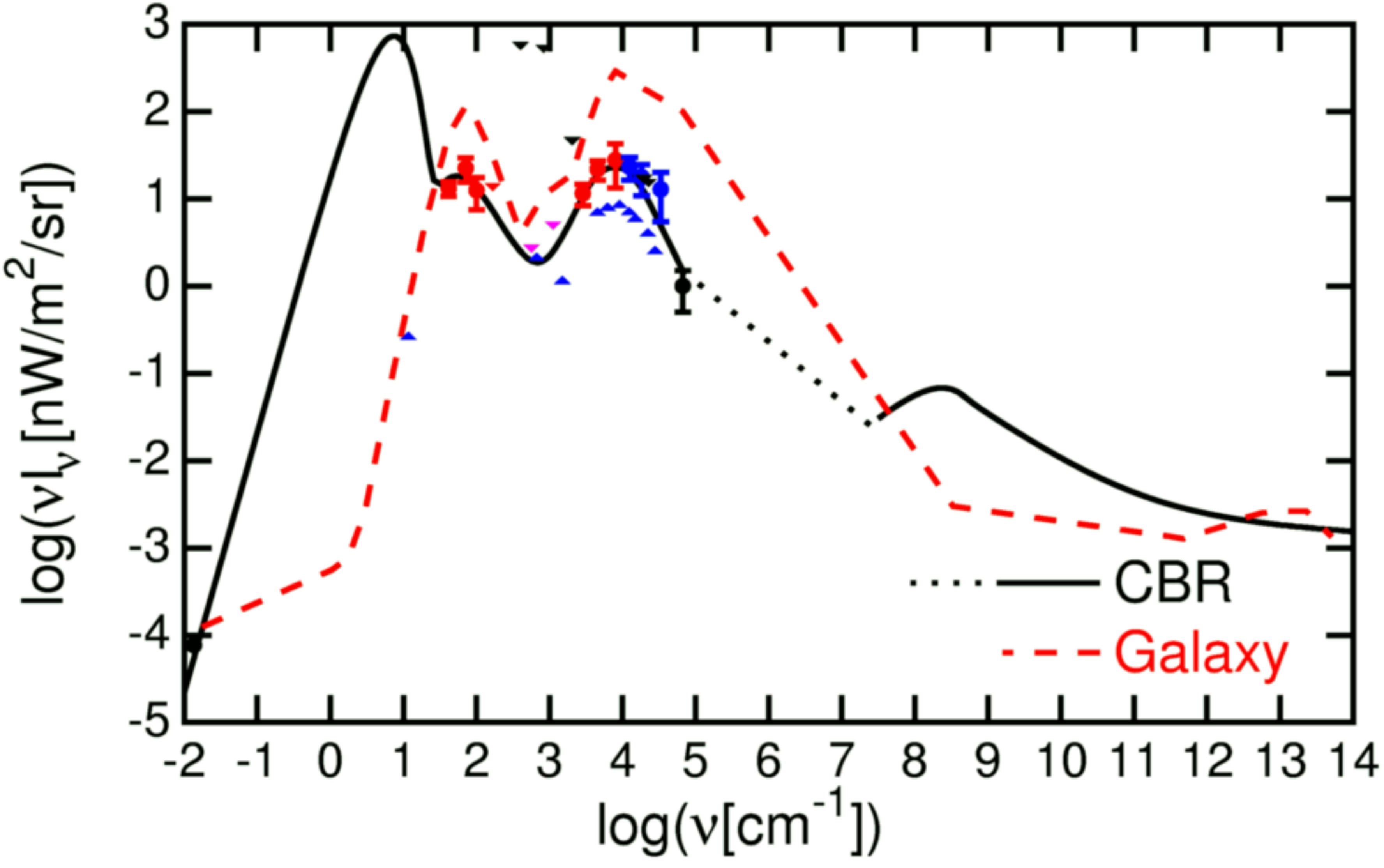
http://www.astro.ucla.edu/~wright/intro.html

See:

- http://www.astro.ucla.edu/~wright/cosmolog.htm
- http://www.astro.ucla.edu/~wright/DIRBE
- http://www.astro.ucla.edu/~wright/CIBR
- http://spitzer.caltech.edu
- http://wise.astro.ucla.edu

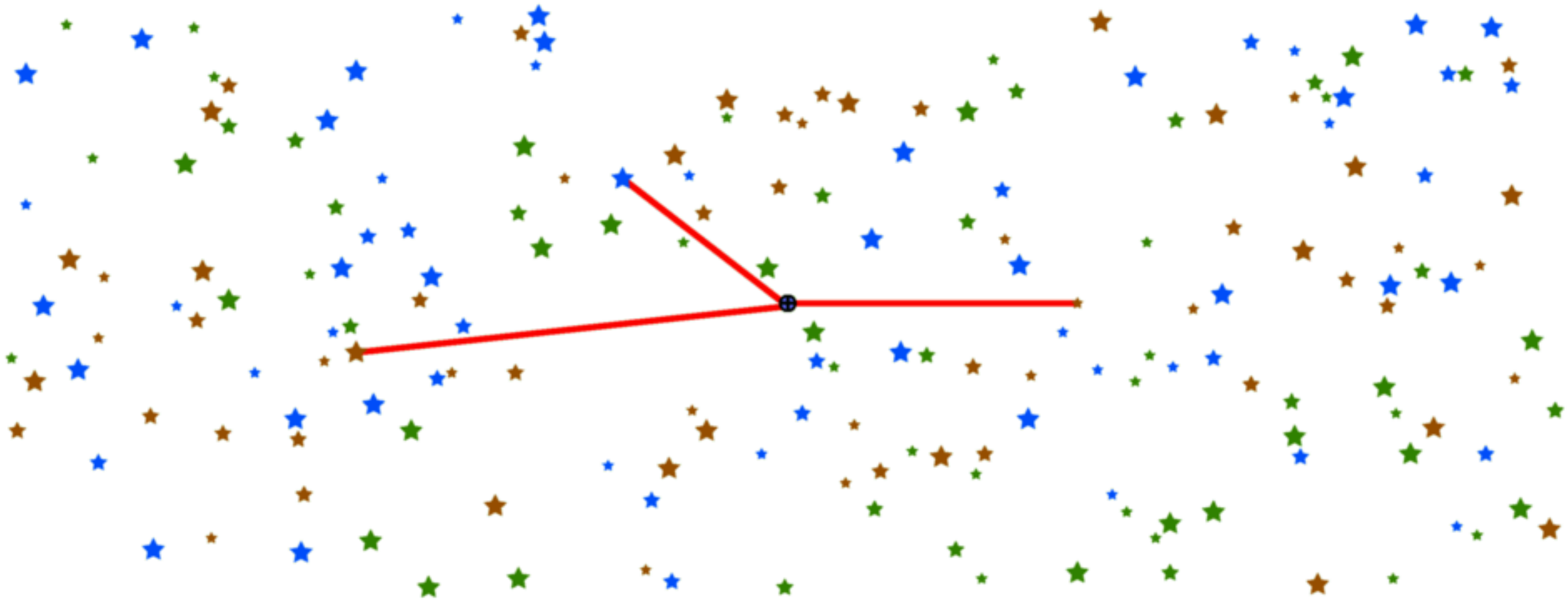
- I_ν - specific intensity, energy per (area×time×frequency×solid angle).
  10^{-20} W/m^2/Hz/sr = 1 MegaJansky/sr [MJy/sr].
- $I = \int I_\nu d\nu$ - bolometric intensity, energy per (area×time×solid angle).
  1 nW/m^2/sr.
- νI_ν - intensity per octave, energy per (area×time×logarithmic bandwidth ×solid angle).
  1 nW/m^2/sr.
- $J_\nu = (4\pi)^{-1} \int I_\nu d\Omega$: mean intensity – the angle averaged intensity.
- $F_\nu = \int I_\nu \cos\theta d\Omega$: monochromatic flux, energy per (area×time×frequency).
  10^{-20} W/m^2/Hz = 1 MegaJansky [MJy].

Wide window on the CBR



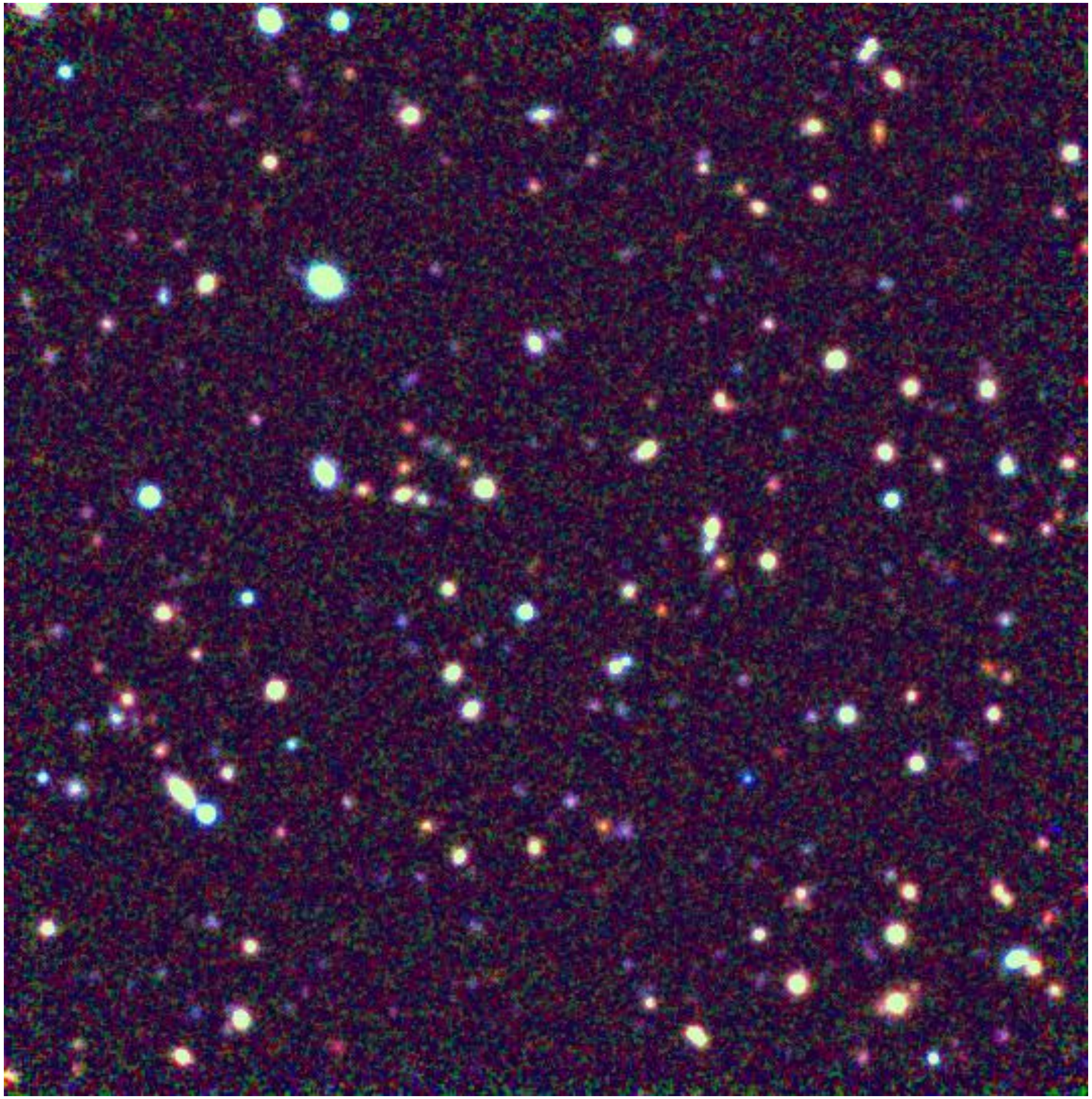
Backgrounds

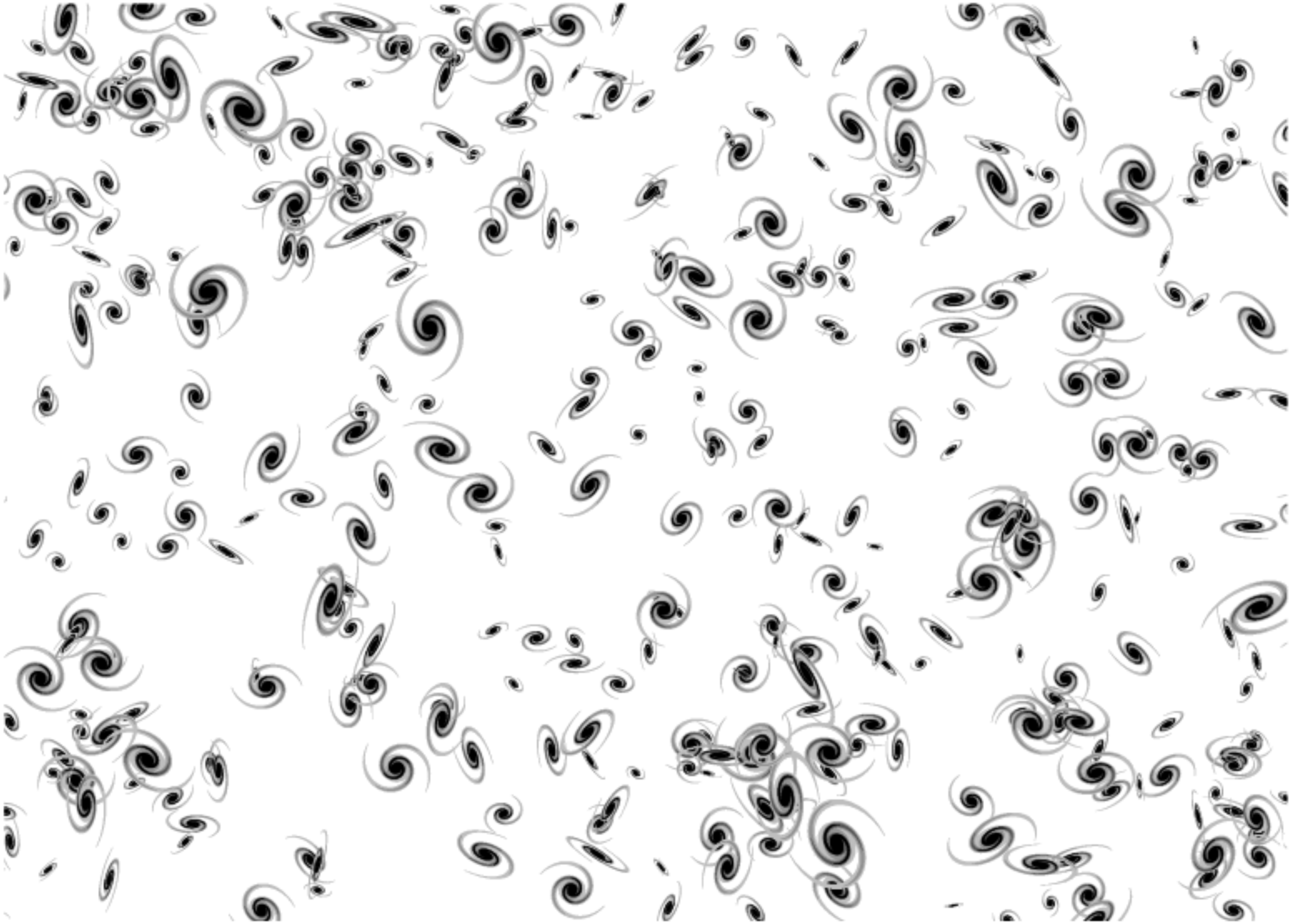
- Microwave – the CMB is 10,000 times brighter than the galactic foreground & the spectrum is very close to a blackbody
- Far Infrared – the FIRB is 10 times fainter than the galaxy with a spectrum similar to the galaxy
- Near IR and Optical – also 10 times fainter than galaxy
- X-ray – the XRB is 10 times brighter than the galaxy

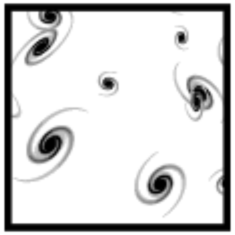


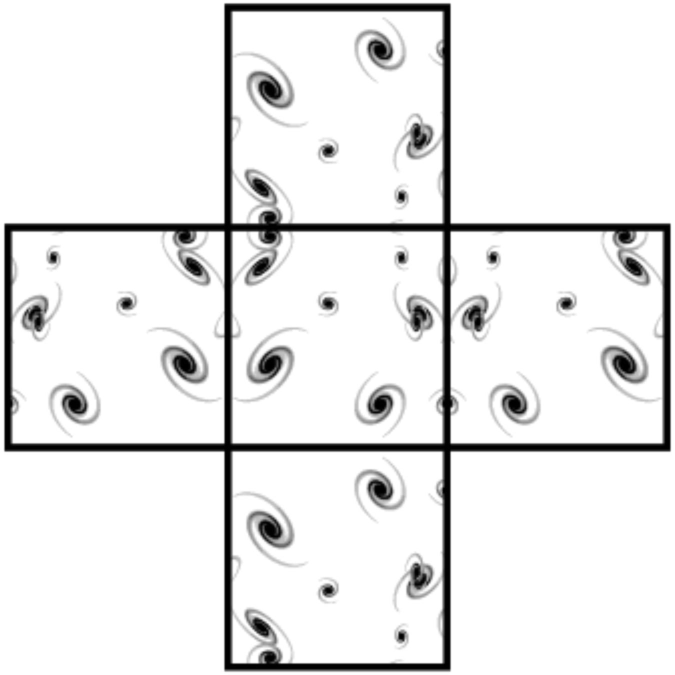
In a homogeneous unchanging Universe every line of sight will end on a star. So why is the night sky not as bright as the surface of a star? The Cosmic Infrared Background is what remains after this Olbers' paradox is resolved.

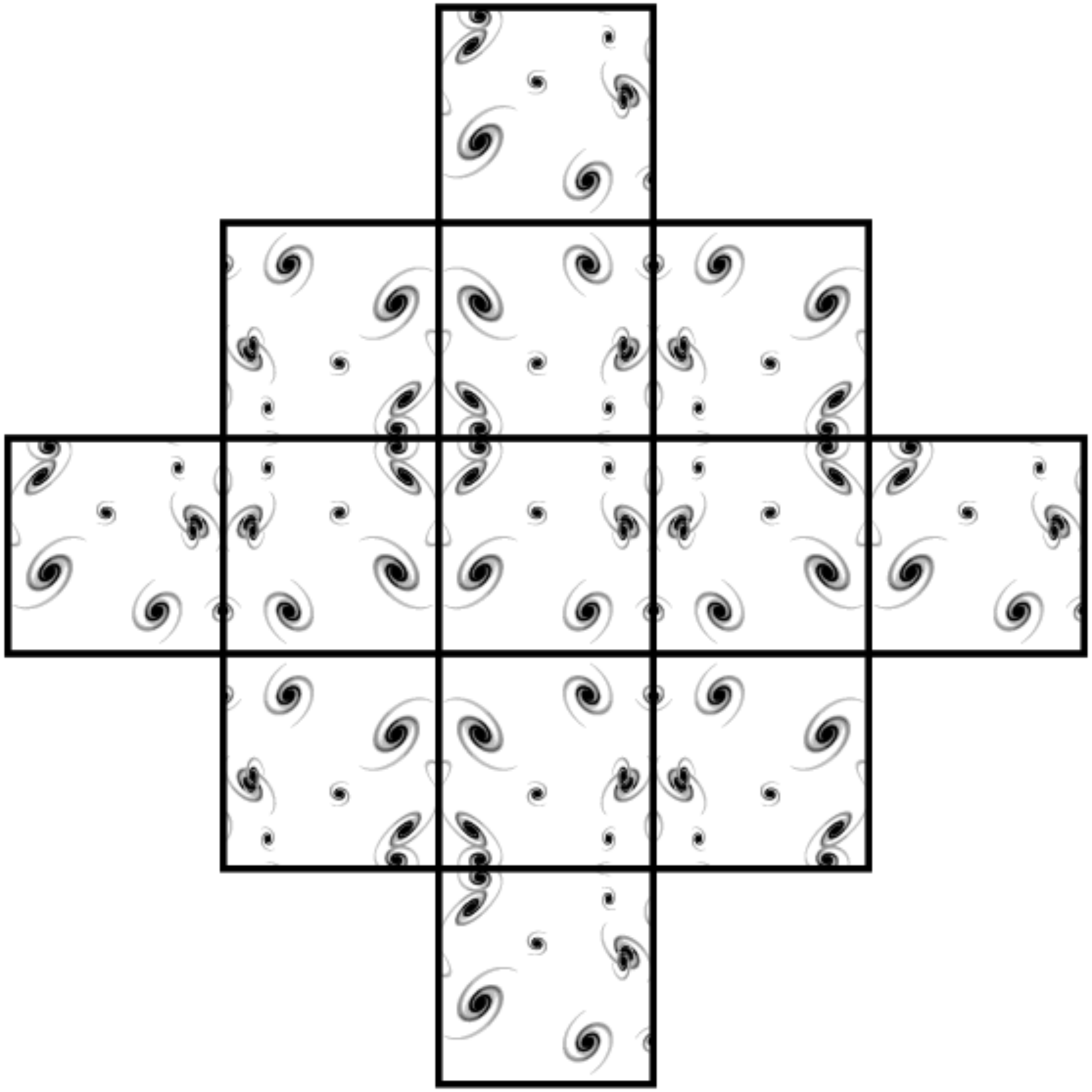
Sources of the CIRB

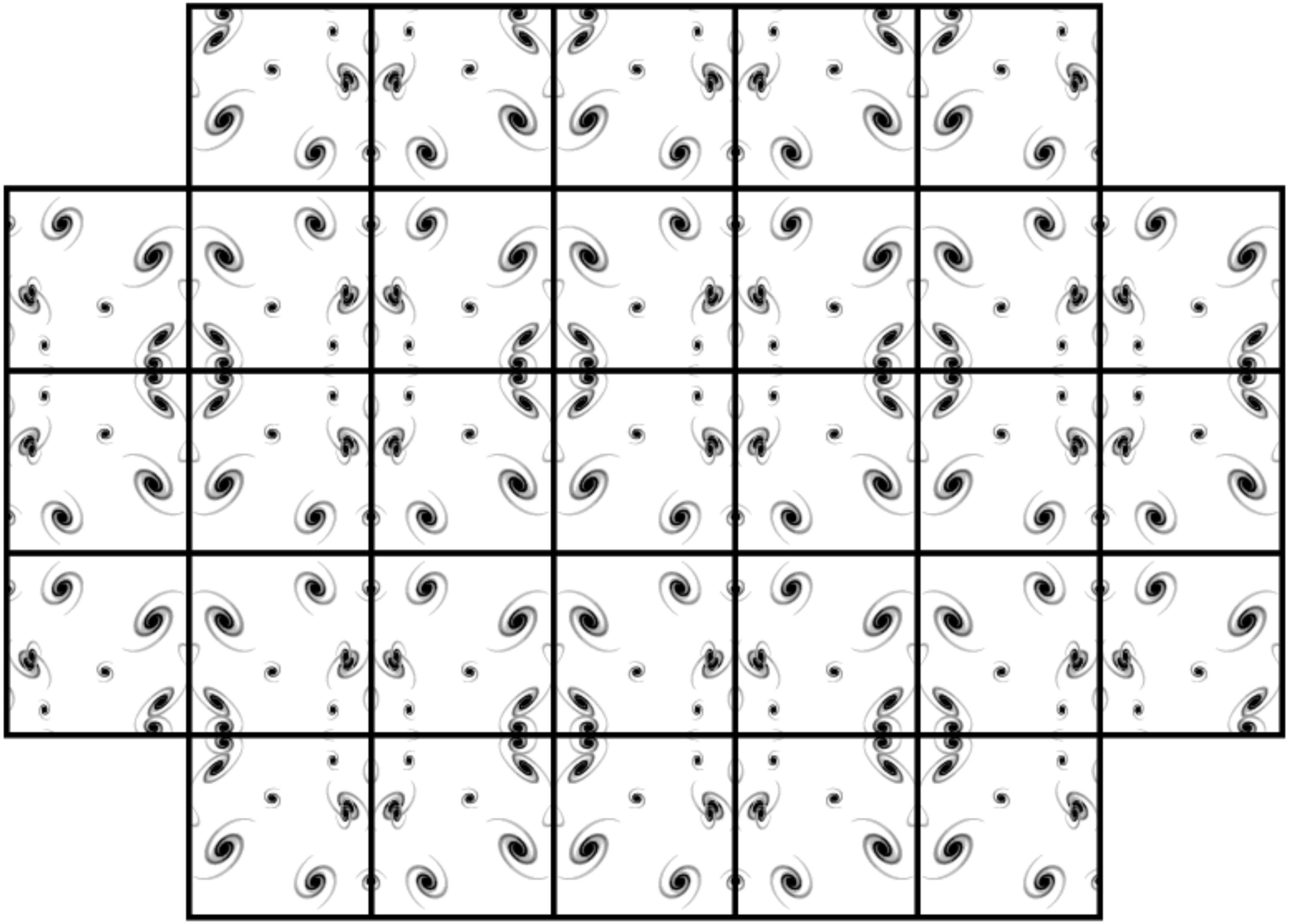


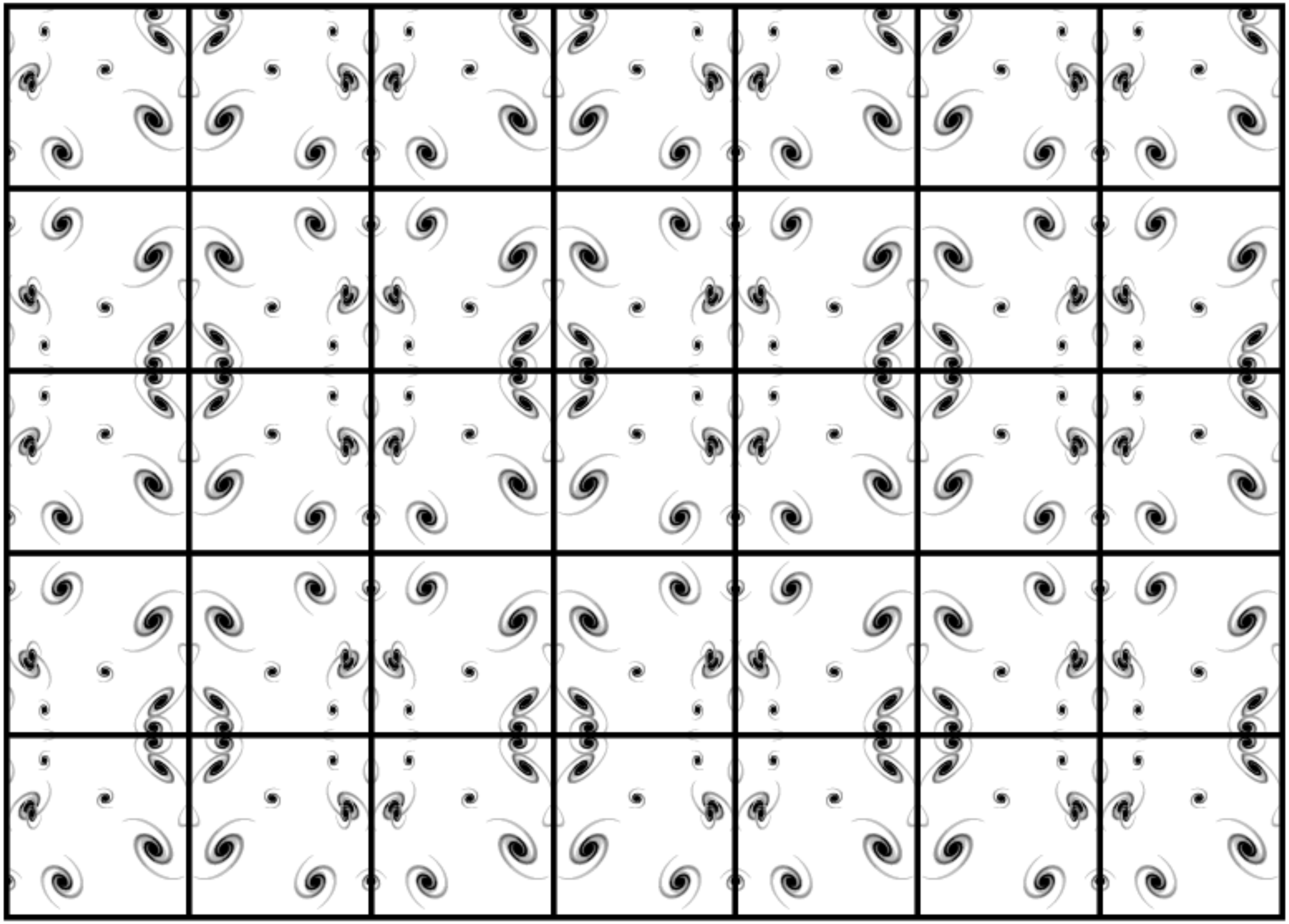




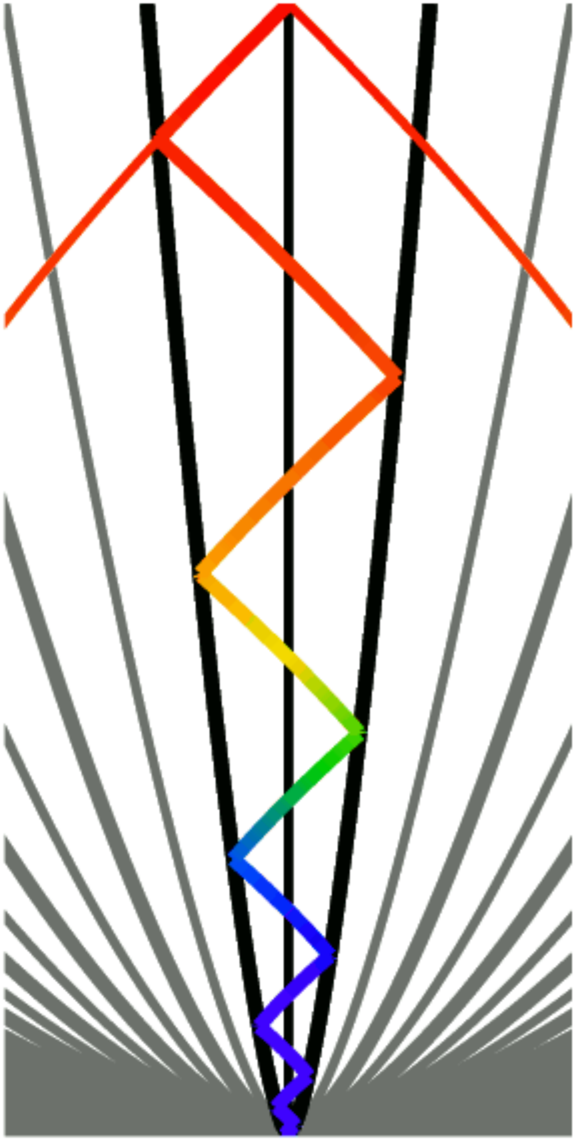








Expanding Mirrored Box



- The Universe is *homogeneous* & *isotropic*.
- Reflections in a mirrored box look like the Universe.
- Expanding mirrored box gives a redshift with $\lambda \propto a(t)$.

Consider a mirrored box, where the mirrors move with the galaxies in the Hubble flow, and define the *comoving luminosity density*:

$$\ell(t) = \frac{\sum_{\text{in box}} L_{gal}(t)}{V_{box}(t_\circ)}$$

For a static, unchanging Universe the energy density in the box now is

$$u(t_\circ) = \frac{4\pi J}{c} = \int_{-\infty}^{t_\circ} \ell(t_\circ)dt \rightarrow \infty \qquad \text{[Olber's Paradox]}$$

In an expanding Universe with scale factor $a(t)$, and $1 + z = a(t_\circ)/a(t)$, then:

$$u(t_\circ) = \frac{4\pi J}{c} = \int_0^{t_\circ} \frac{\ell(t)}{1+z} dt$$

The total energy produced, $\int \ell(t)dt$, is more than the CIRB energy density because it does not have the $(1+z)$ factor in the denominator. For the baryon density given by Big Bang Nucleosynthesis, $\Omega_B h^2 = 0.02$, if 1% of the baryons are converted from hydrogen to helium releasing 0.7% of their mass into energy, then

$$\int \ell(t)dt = 0.02 \times 0.01 \times 0.007 \times 10539.4 \frac{\mathrm{eV}}{\mathrm{cm}^3} = \frac{1}{68} \frac{\mathrm{eV}}{\mathrm{cm}^3}$$

$c/[4\pi]$ times this energy density is 56 nW/m^2/sr.

The relationship between time and redshift is

$$t = \frac{2}{3H_\circ(1+z)^{1.5}} \qquad \text{so} \qquad \frac{dt}{dz} = \frac{-1}{H_\circ(1+z)^{2.5}}$$

for the Einstein-de Sitter Universe with $\Omega = 1$, and the Hubble constant is $H_\circ = (2/3)/t_\circ$.

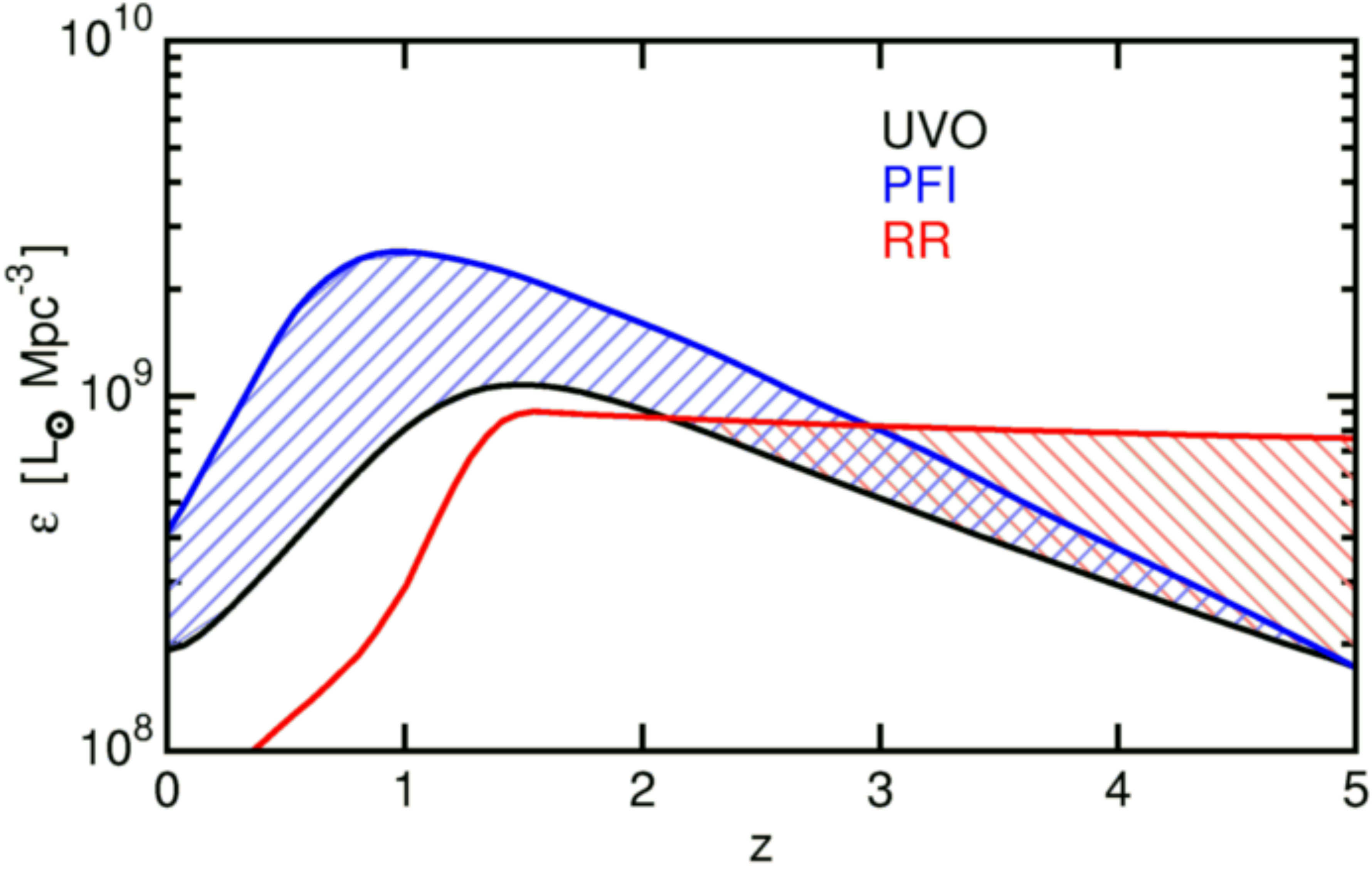
Thus if $\ell(t)$ is CONSTANT, the energy density of the CIRB would be

$$u = \frac{1}{H_\circ}\int \frac{\ell(t_\circ)}{(1+z)^{3.5}}dz = \frac{3}{5}\int \ell(t)dt = 0.6\ell(t_\circ)t_\circ$$

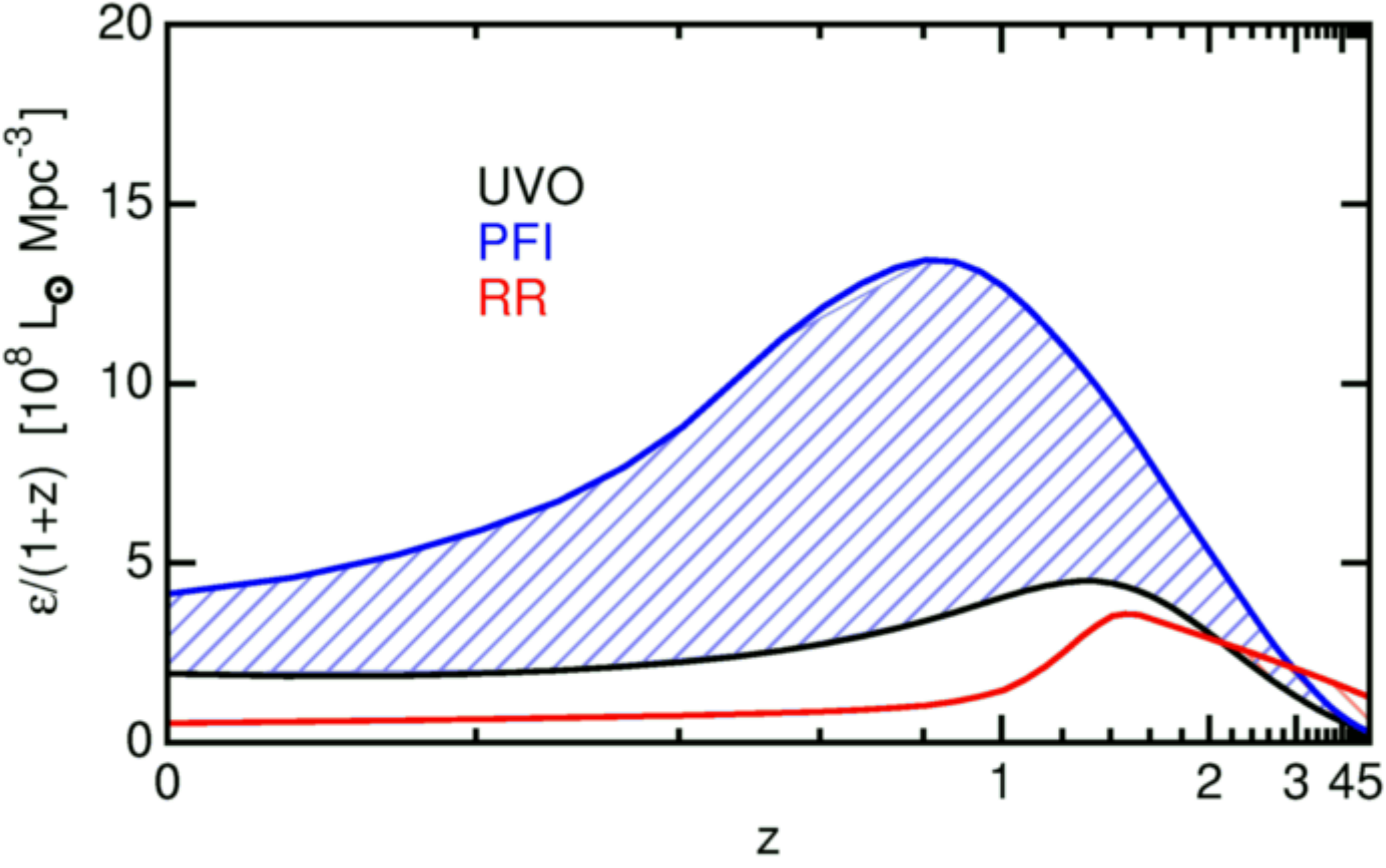
If $\ell(t)$ is proportional to $(1+z)$, then the energy density of the CIRB would be

$$u = \frac{1}{H_\circ}\int \frac{(1+z)\ell(t_\circ)}{(1+z)^{3.5}}dz = \frac{1}{3}\int \ell(t)dt = \ell(t_\circ)t_\circ$$

Luminosity density vs. redshift



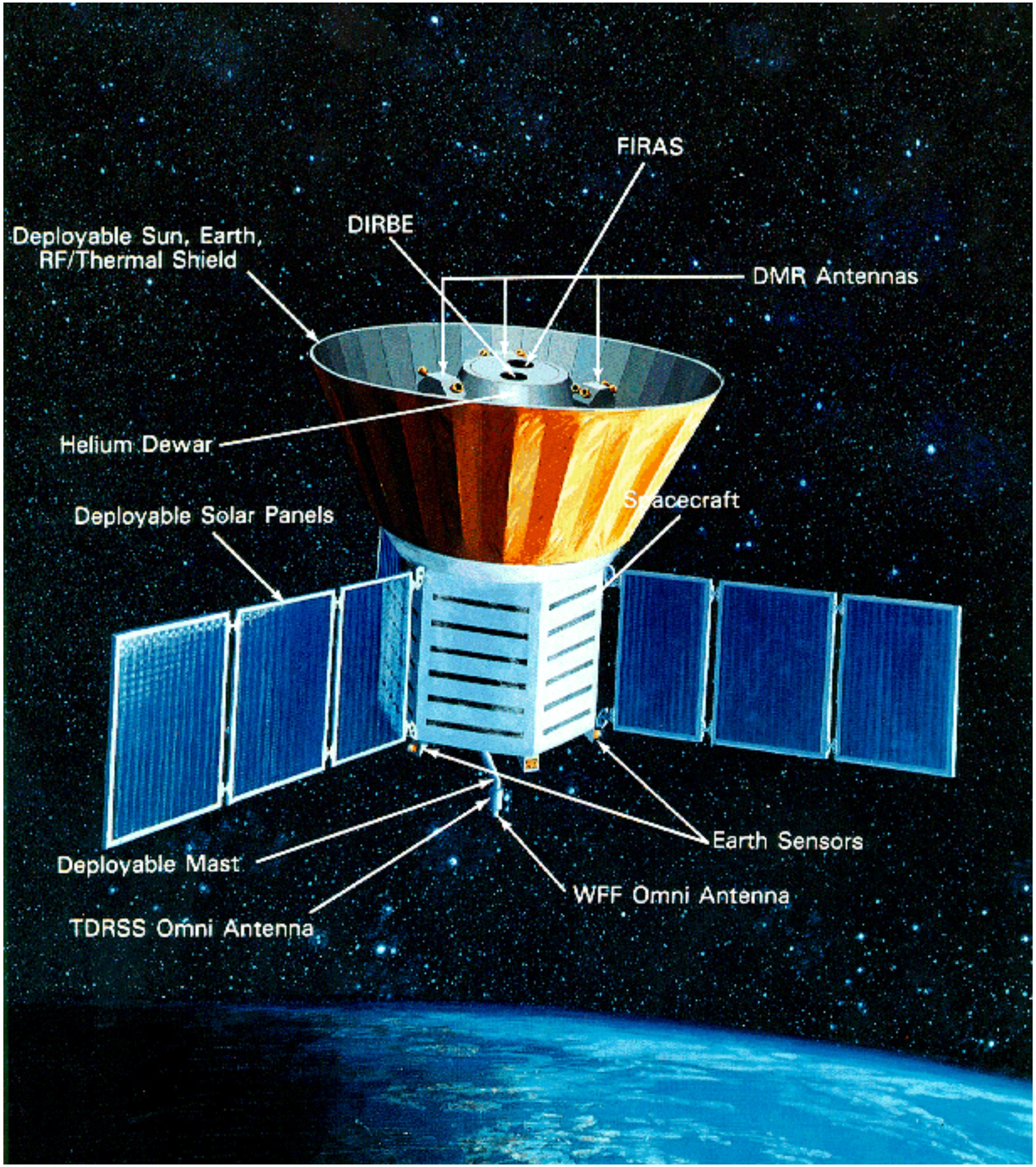
L/(1+z) vs. time

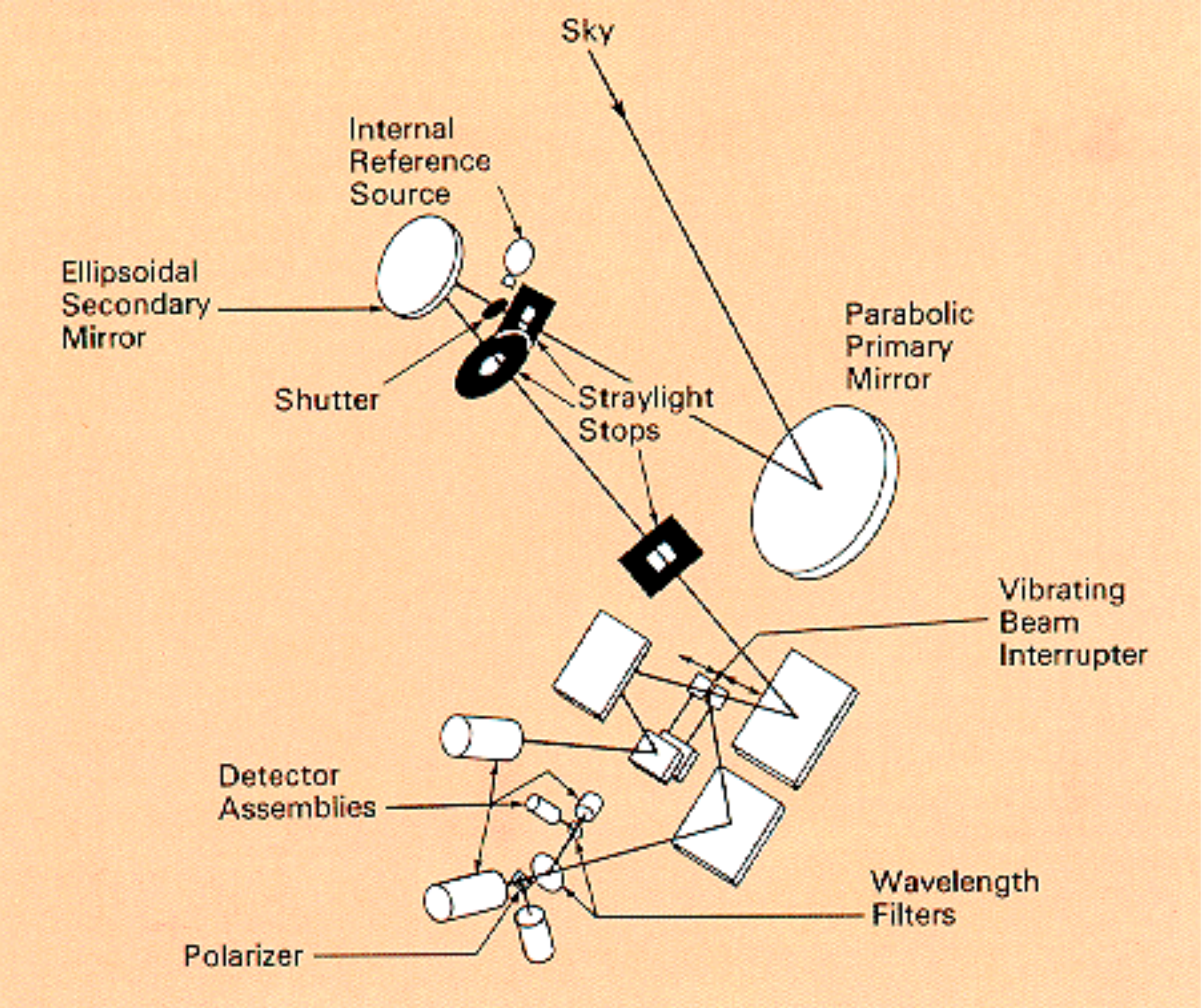


Fluctuation Analysis

$$\begin{aligned}\mathrm{var}(F) &= \int \left(\frac{L}{4\pi D_L(z)^2}\right)^2 (1+z)^3 n_{CM}(z) D_A(z)^2 c\,dt\,d\Omega \\ &= (4\pi)^{-2} \int \frac{n_{CM}(z) L^2}{(1+z) D_L(z)^2} c\,dt\,d\Omega\end{aligned}$$

- Diverges like $1/z_{min}$ or $(F_{cut})^{0.5}$
- Always dominated by the brightest unmasked sources: galaxy edges, dwarf galaxies, z=1 sources
- Contribution from high z highly suppressed
- Good for about 2X lower flux than catalog limit

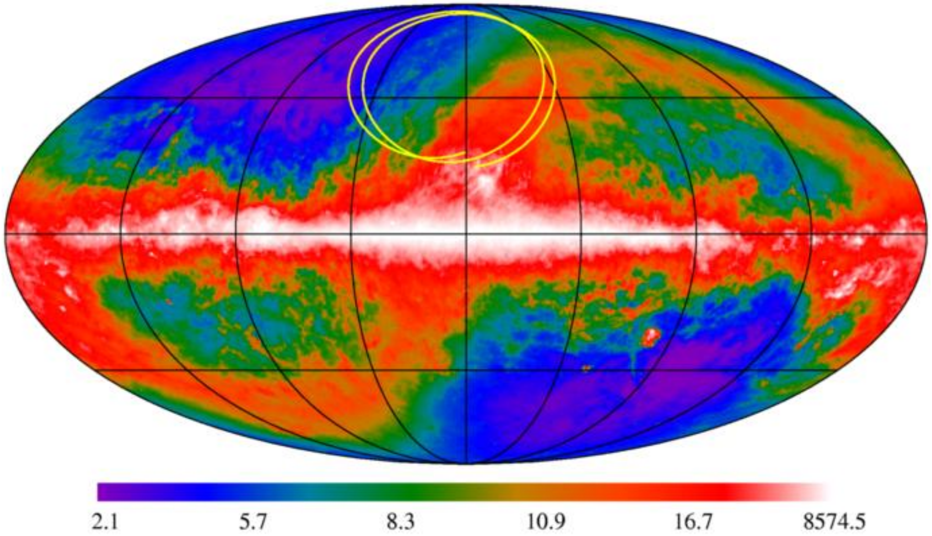

FIRAS
DIRBE
Deployable Sun, Earth, RF/Thermal Shield
DMR Antennas
Helium Dewar
Spacecraft
Deployable Solar Panels
Earth Sensors
Deployable Mast
WFF Omni Antenna
TDRSS Omni Antenna

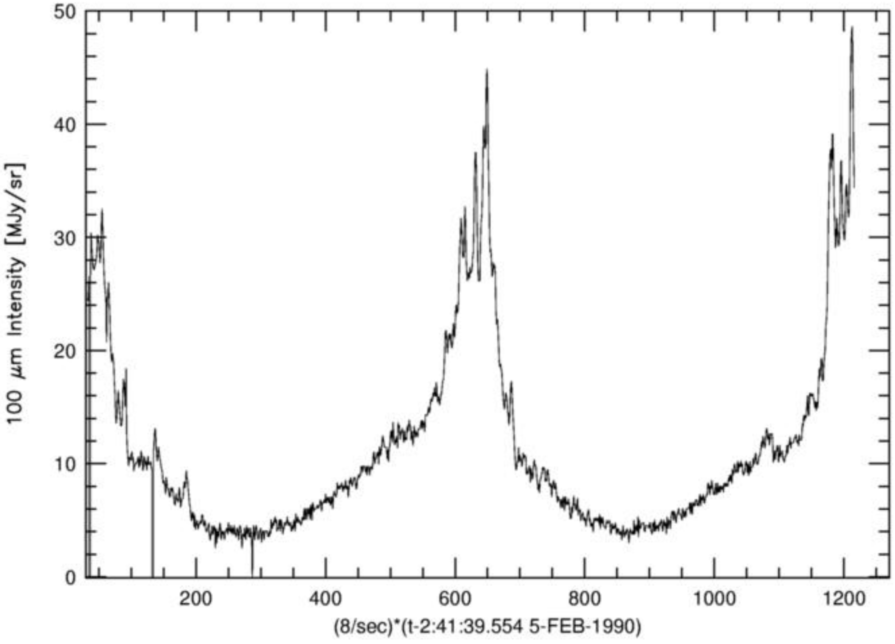

Sky
Internal Reference Source
Ellipsoidal Secondary Mirror
Parabolic Primary Mirror
Shutter
Straylight Stops
Vibrating Beam Interrupter
Detector Assemblies
Wavelength Filters
Polarizer

DIRBE Beam Size

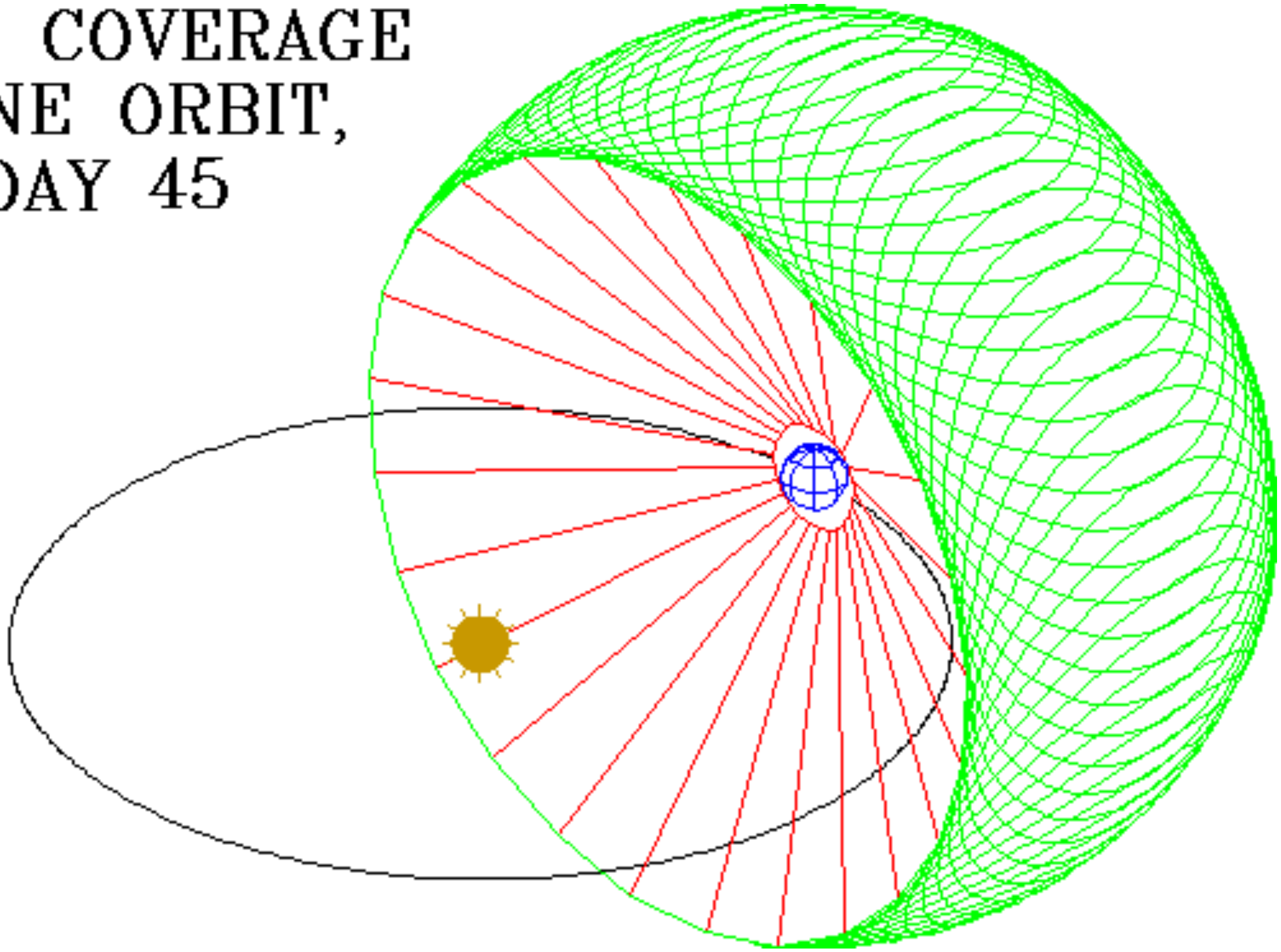
0.7°

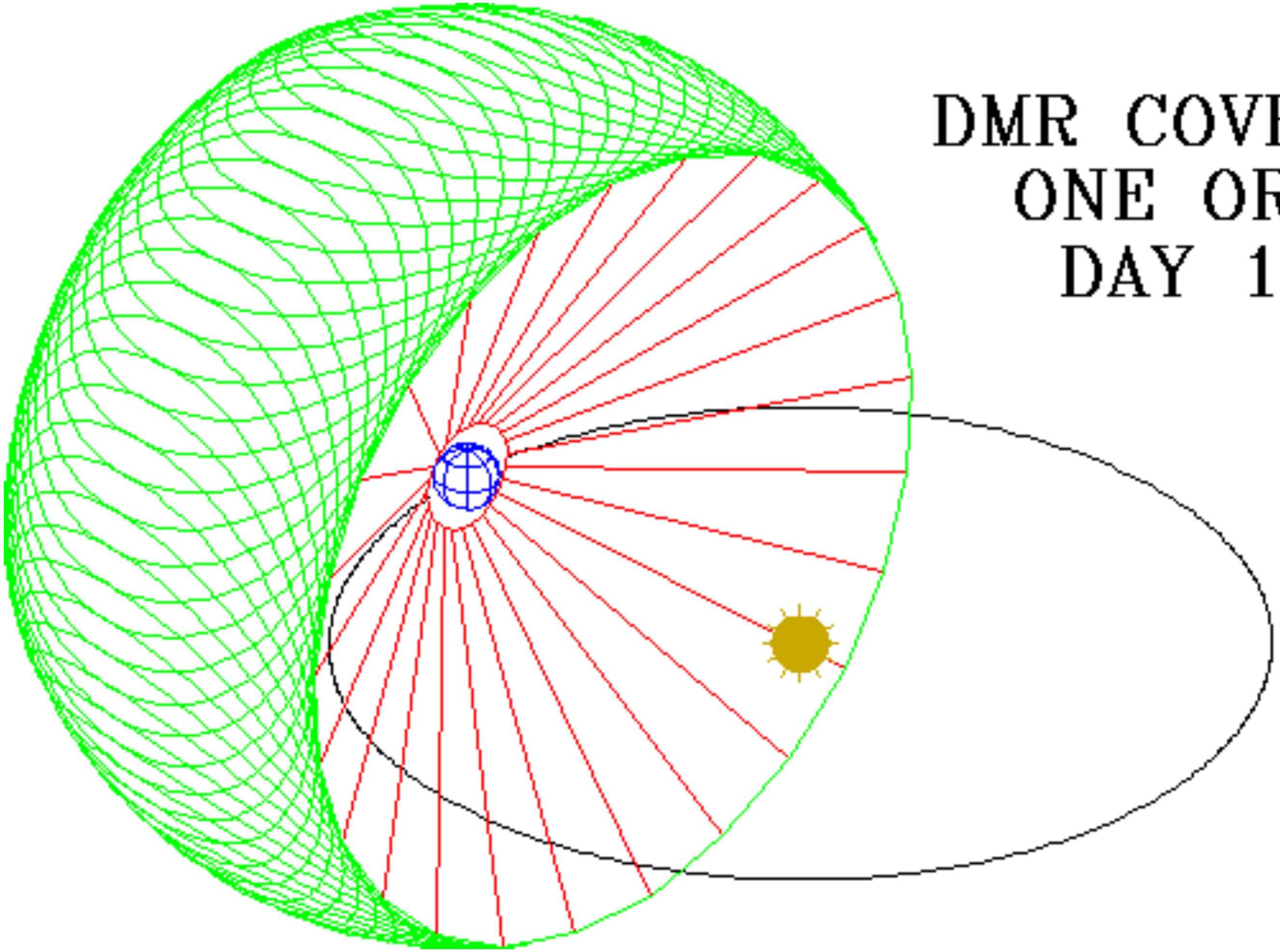
Band 8 with 5-Feb-90 Scan



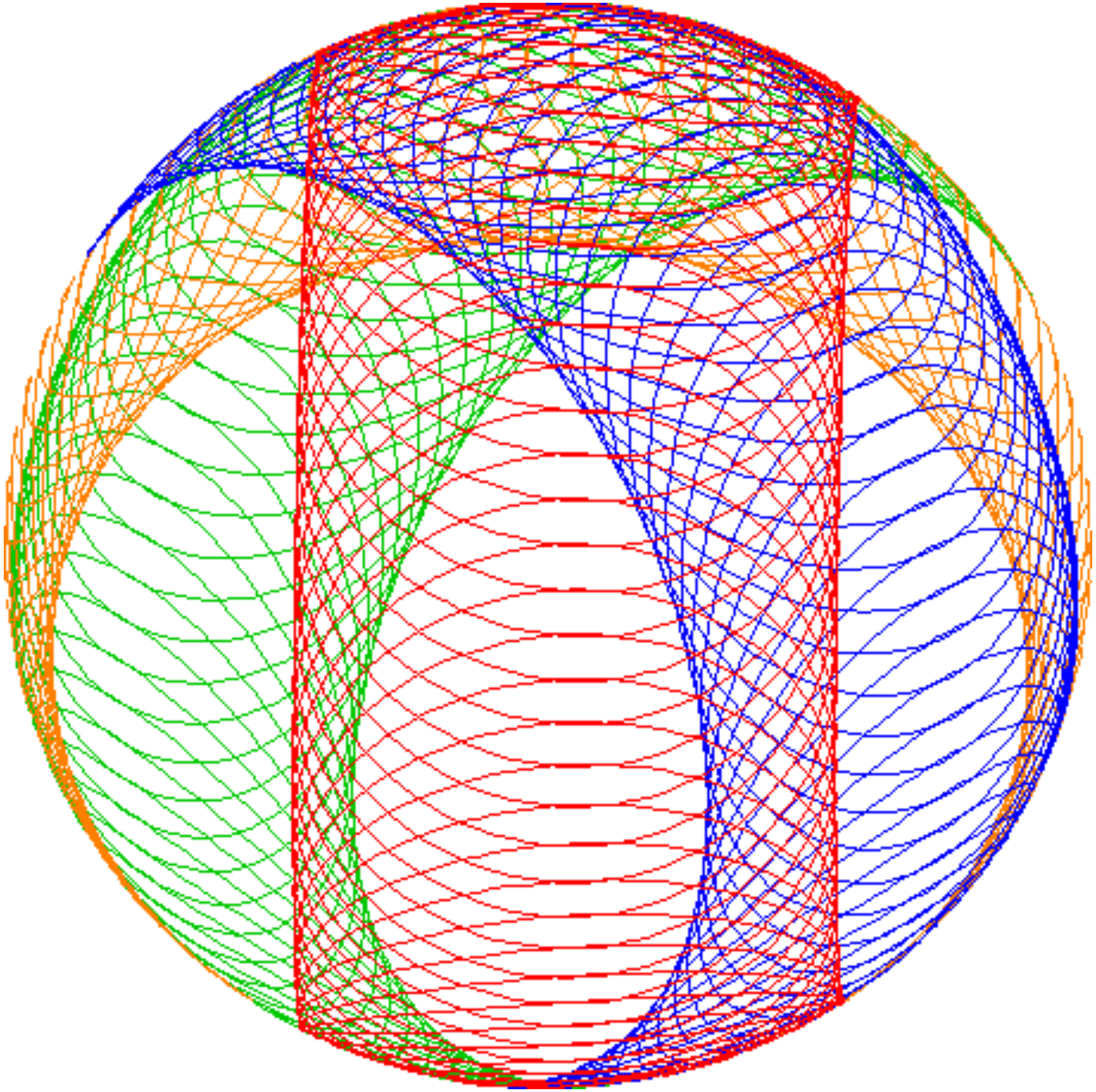


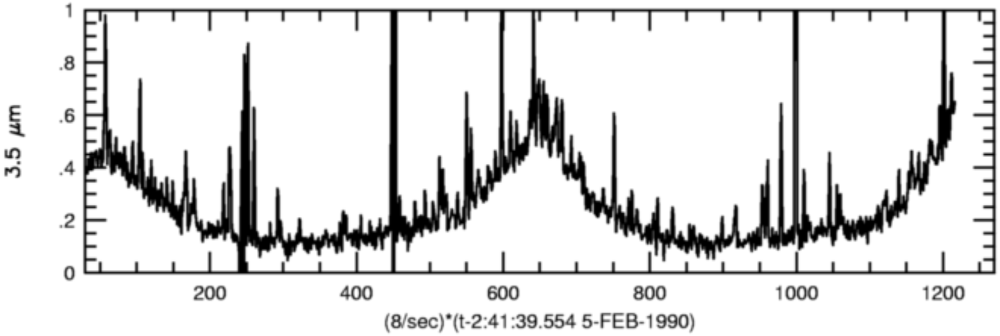
DMR COVERAGE
ONE ORBIT,
DAY 45

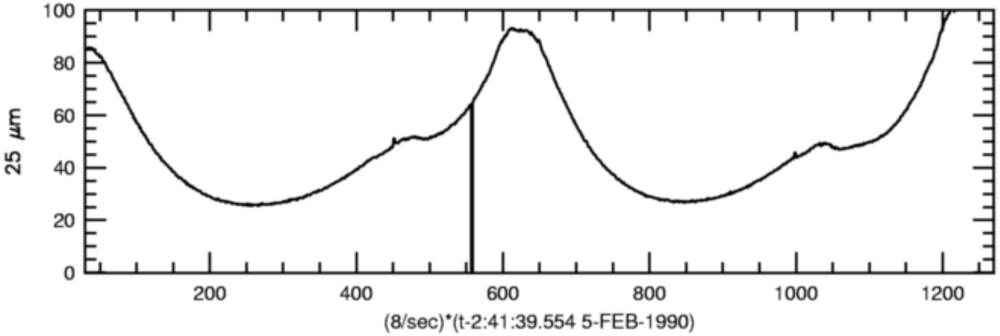


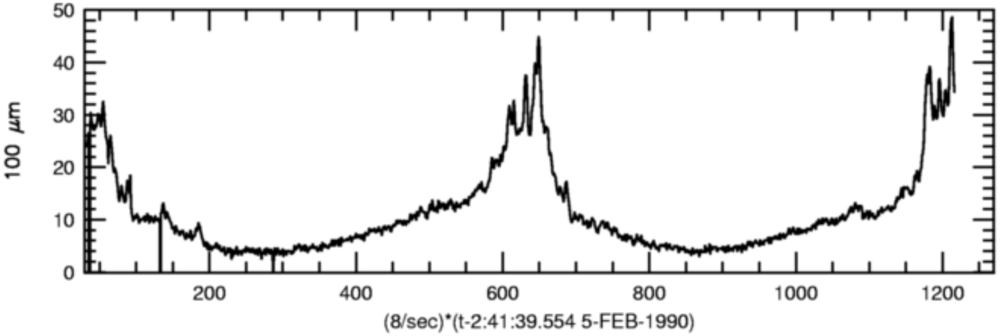


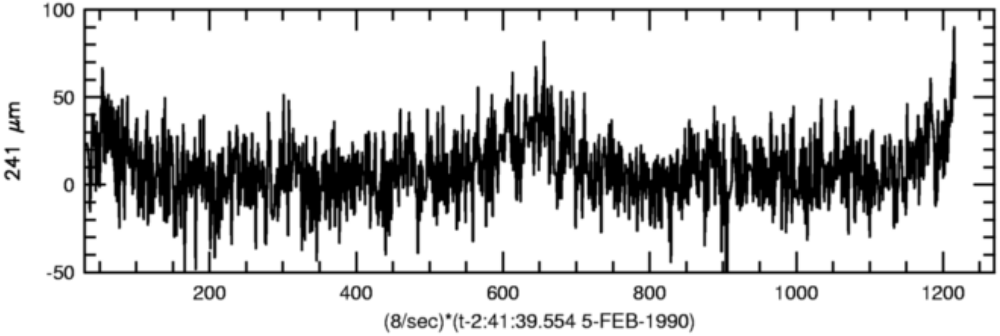
DMR COVERAGE ONE ORBIT, DAY 135



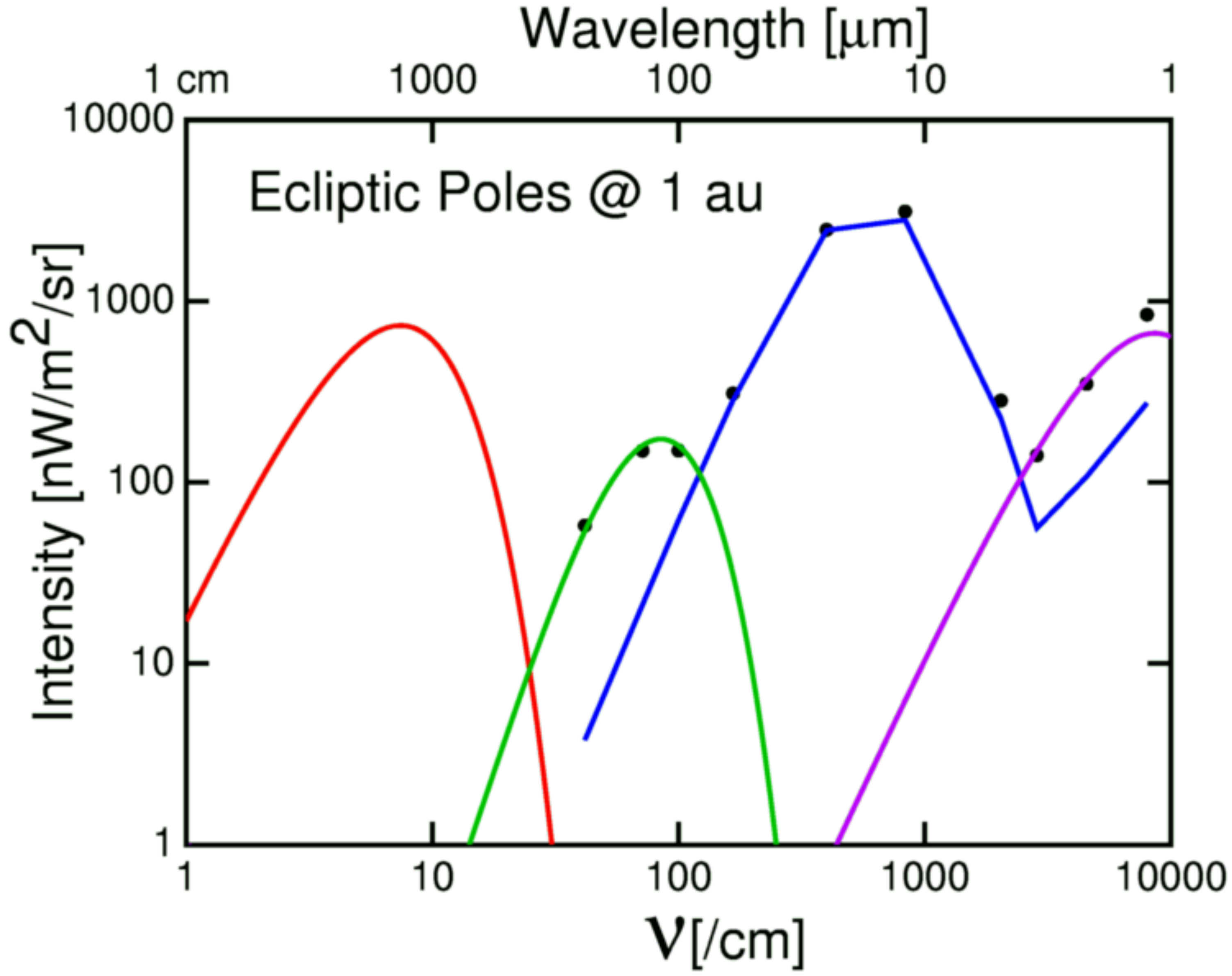

3.5 μm
1
.8
.6
.4
.2
0
200
400
600
800
1000
1200
(8/sec)*(t-2:41:39.554 5-FEB-1990)


25 μm
100
80
60
40
20
0
200
400
600
800
1000
1200
(8/sec)*(t-2:41:39.554 5-FEB-1990)

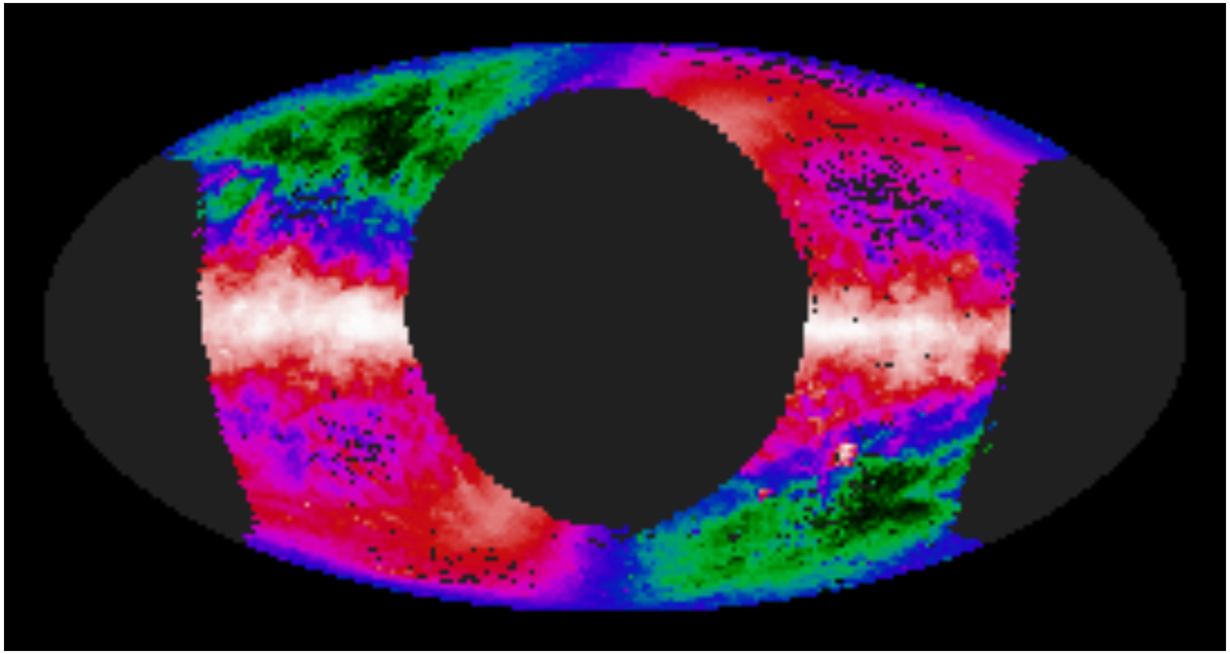

100 μm
50
40
30
20
10
0
200
400
600
800
1000
1200
(8/sec)*(t-2:41:39.554 5-FEB-1990)


241 μm
100
50
0
-50
200
400
600
800
1000
1200
(8/sec)*(t-2:41:39.554 5-FEB-1990)

Bump Chart: Where is the CIRB?

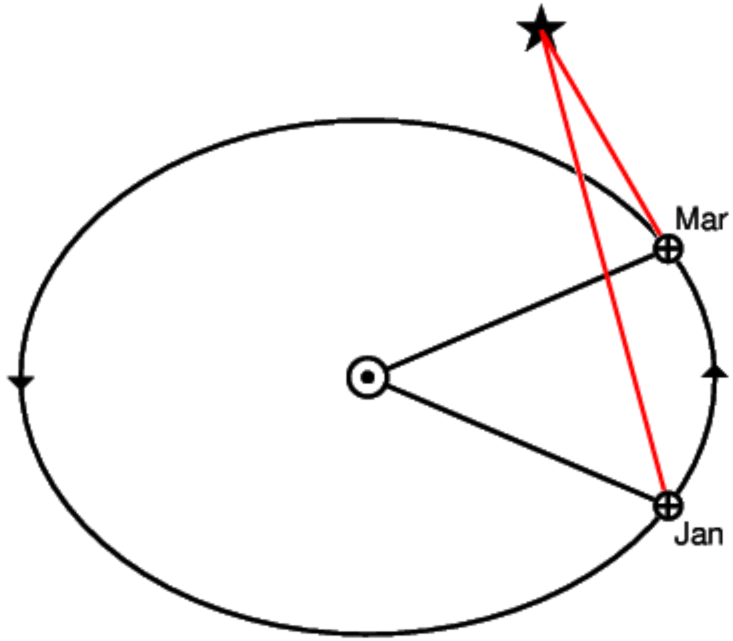


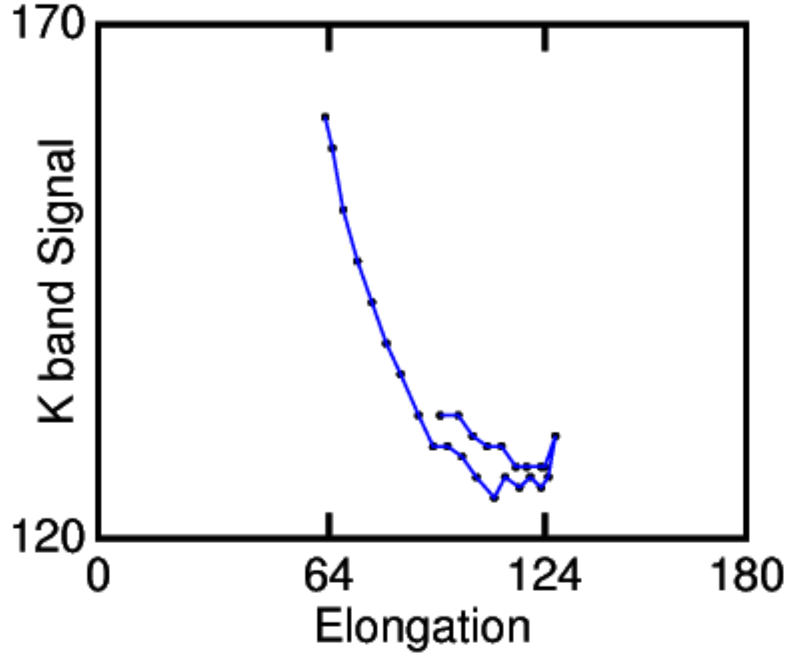
DIRBE 100 μm Weekly Maps



Note the triangles of zodiacal emission along the ecliptic on either side of the solar exclusion hole.

Extrapolation to Outside Solar system?





- Observe same spot on the sky through different amounts of interplanetary dust.

- Fit a model to the change in intensity *vs.* elongation (or time).

Interplanetary Dust Cloud Models

The observed intensity depends on a line-of-sight integral of an emissivity that depends on the dust density, $n(x, y, z, t, \mathrm{size,shape,composition})$, a function of at least 7 variables. The data are given by $I(\nu, l, b, t)$, a function of only 4 variables.

Simplification is needed. For a time independent solution, the density depends only on the integrals of the motion: E, L, and L_z which map into a, e and i. The eccentricity has little effect on the line-of-sight integral, so assume the density is function only of r and i.

Let $n(r, i) = R_1(r)I_1(i) + R_2(r)I_2(i) + \ldots$

Radial Density Profile

The Poynting-Robertson effect gives a torque of

$$T = -\sigma \frac{r v_{orb}}{c^2} \frac{L}{4\pi r^2}$$

and since the angular momentum is $L = m\sqrt{GMr}$ this gives an inward drift rate of

$$\frac{dr}{dt} = \frac{T}{dL/dr} = -(2\pi)^{-1} \frac{\sigma}{m} \frac{L}{c^2} r^{-1}$$

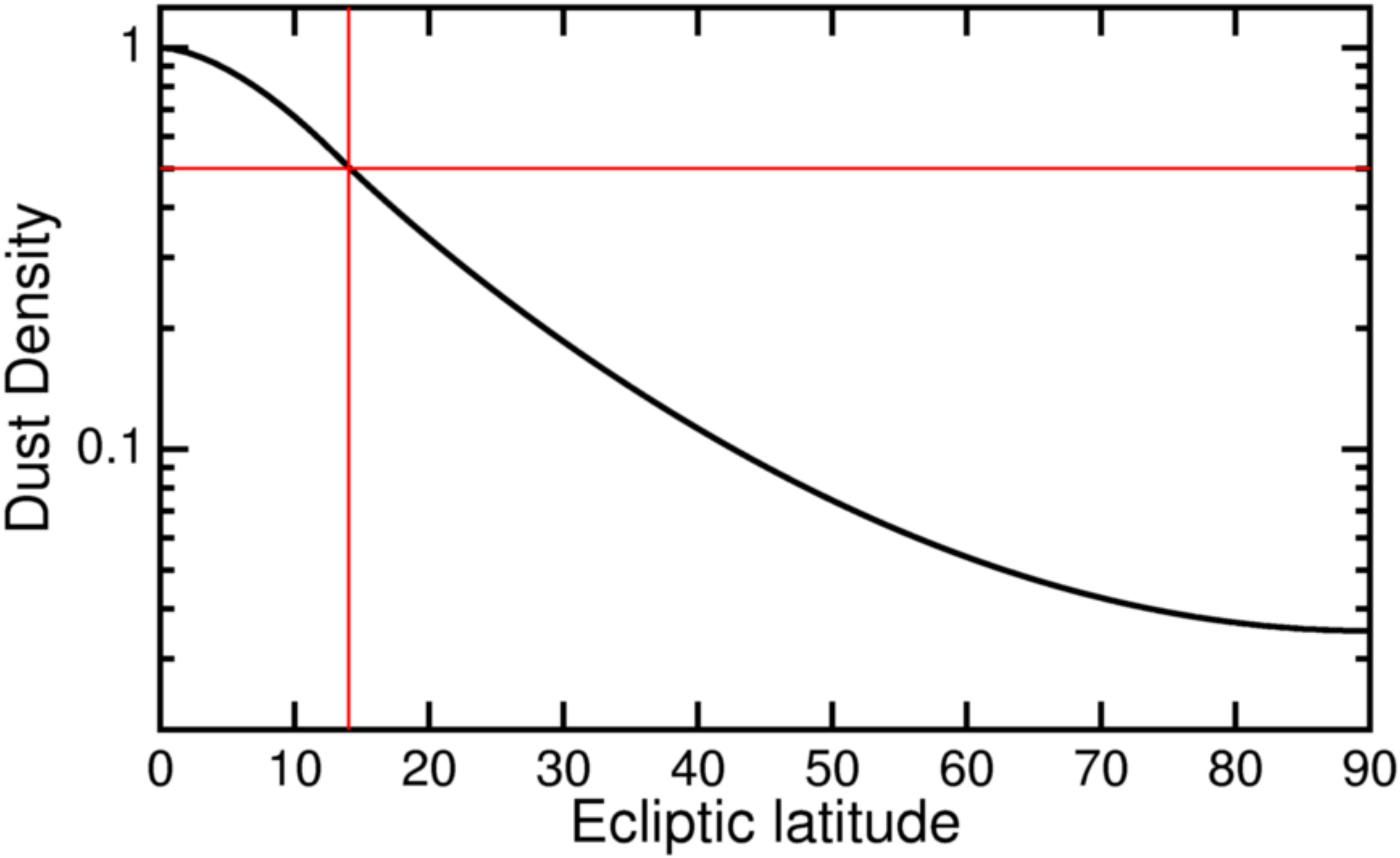
A steady state requires that

$$\frac{\partial}{\partial r} \left(n(r) r^2 \frac{dr}{dt} \right) = 0$$

and thus that $n(r) \propto r^{-1}$.

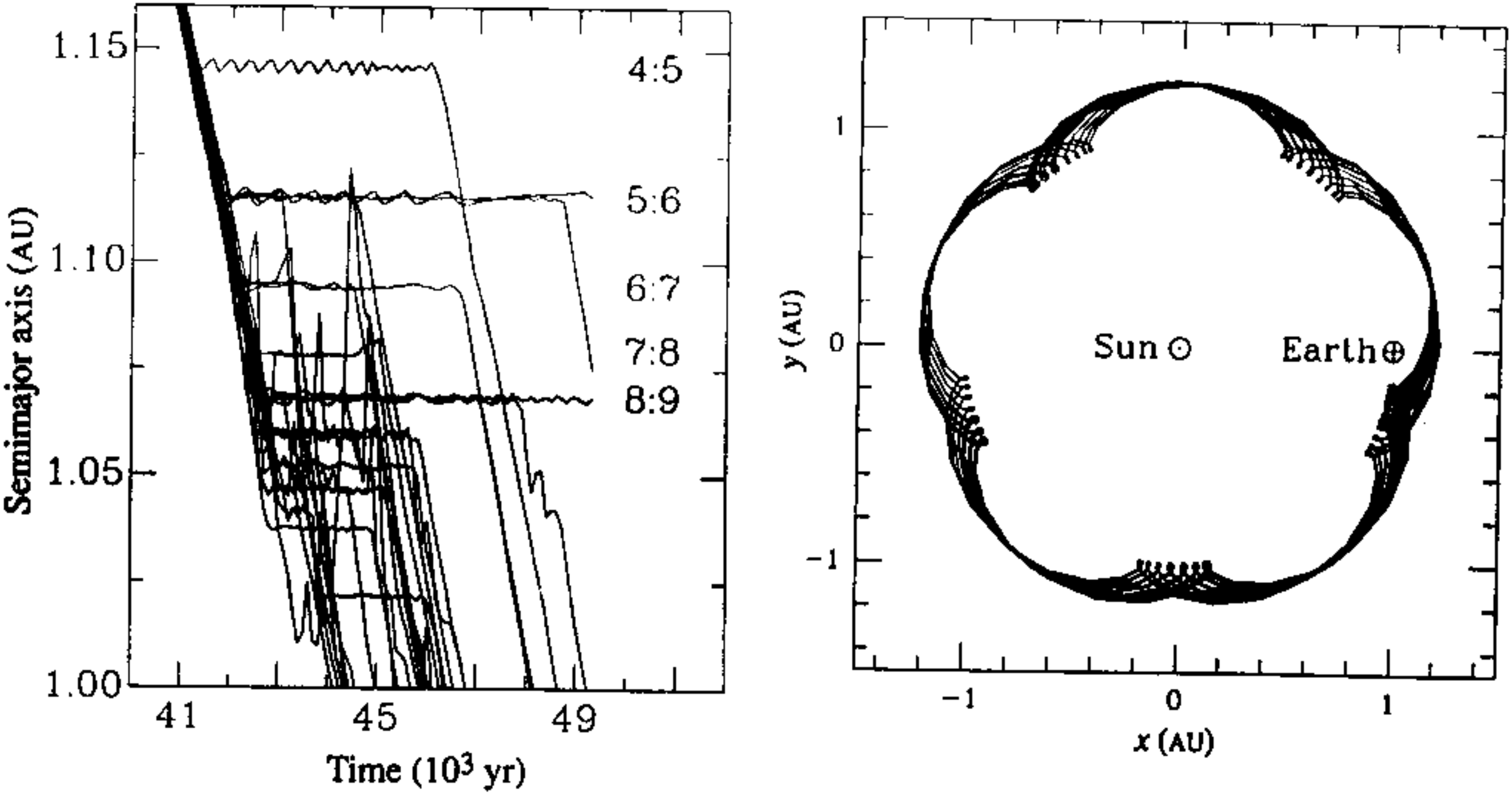
$\boxed{\text{FIT gives } r^{-1.23}}$

Dust Density vs inclination

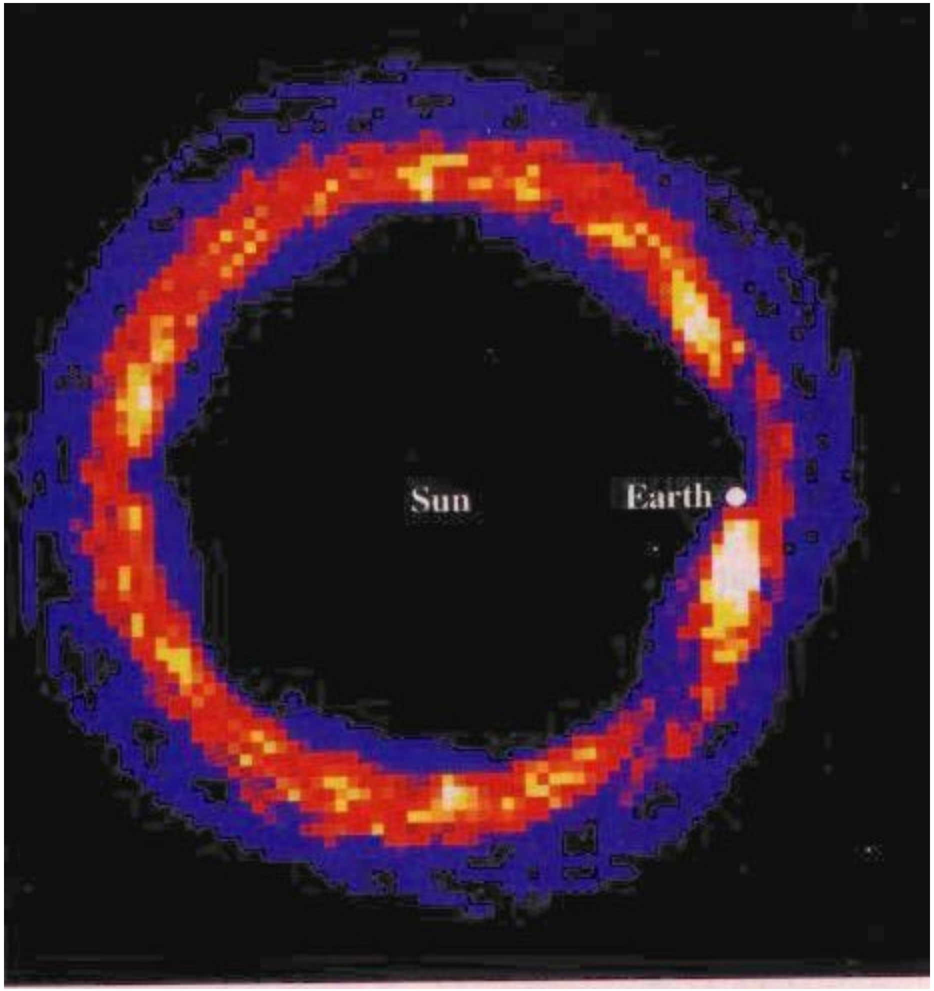


A Circumsolar Ring of Asteroidal Dust in Resonant Lock with the Earth

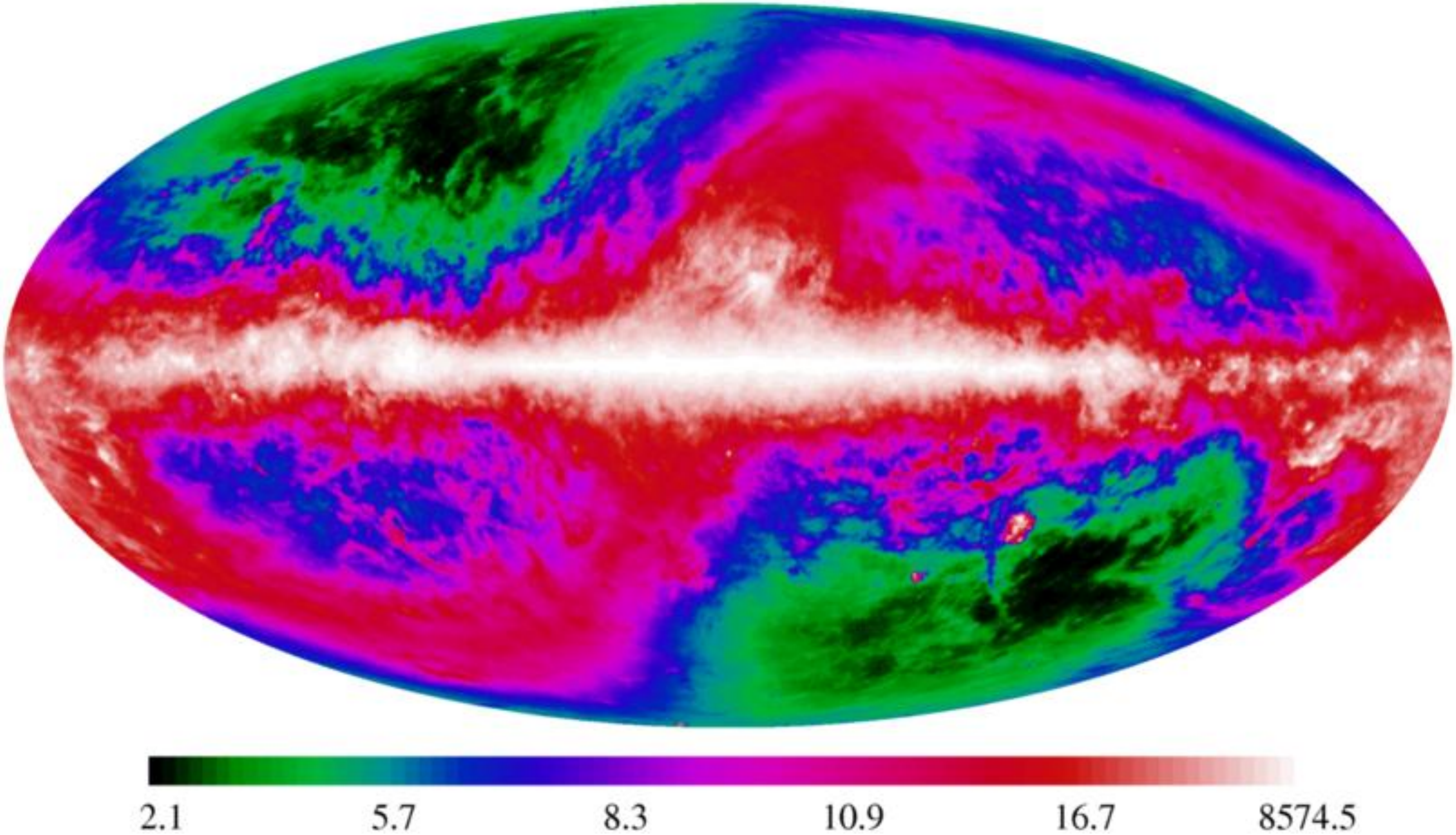
Dermott et al., 1994, Nature, 369, 719



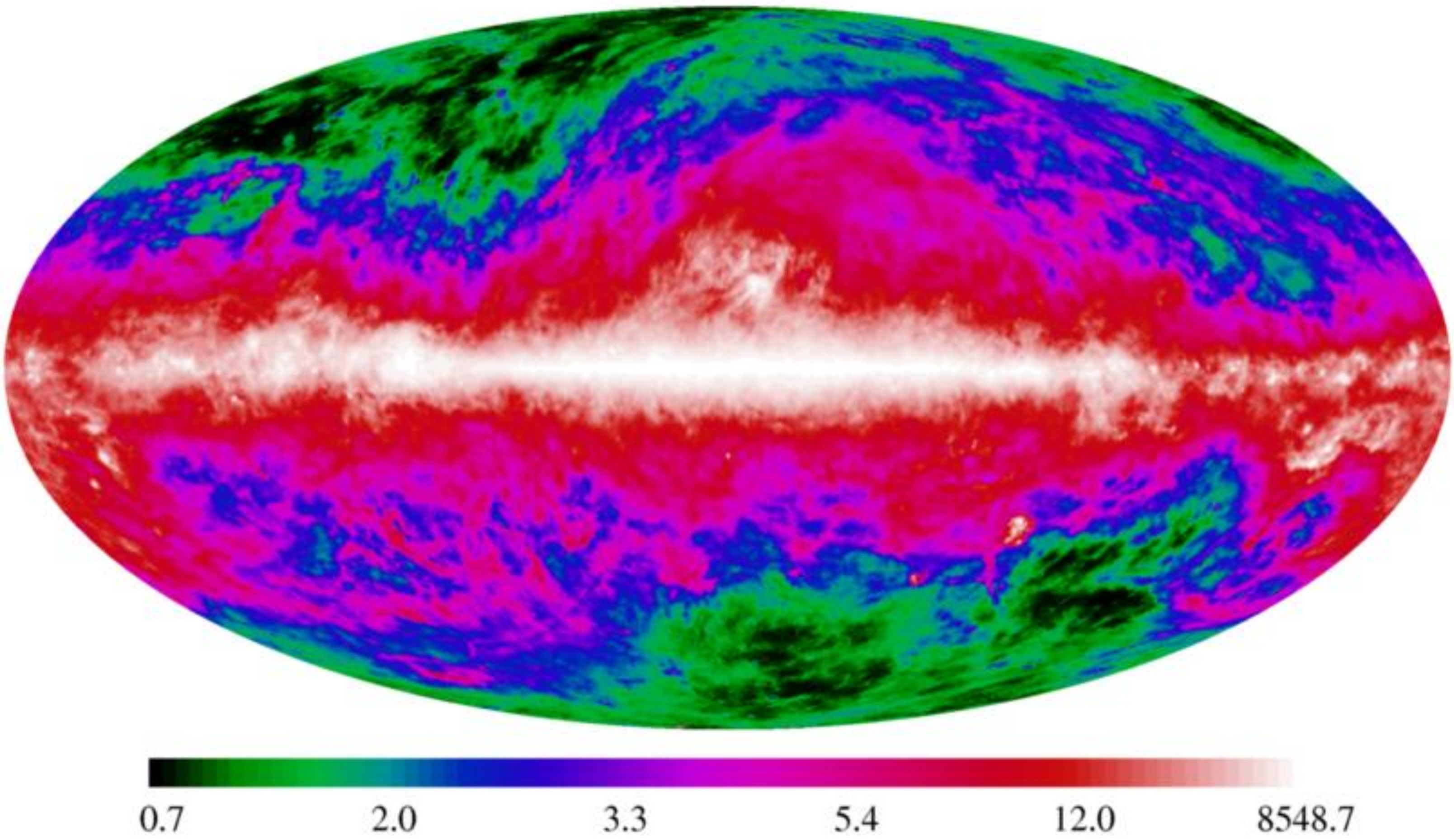
A Ring and a Trailing Clump



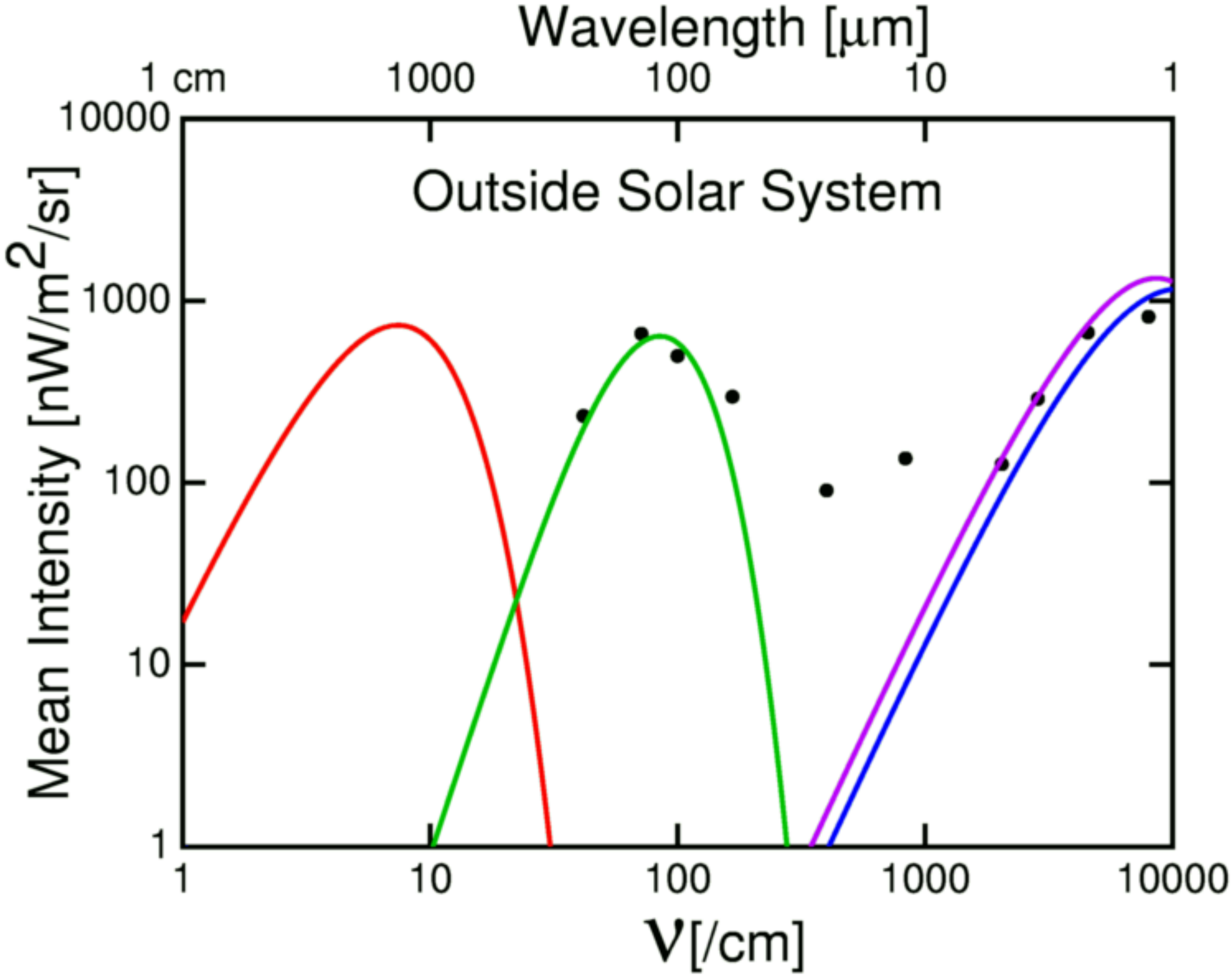
100 Micron Total



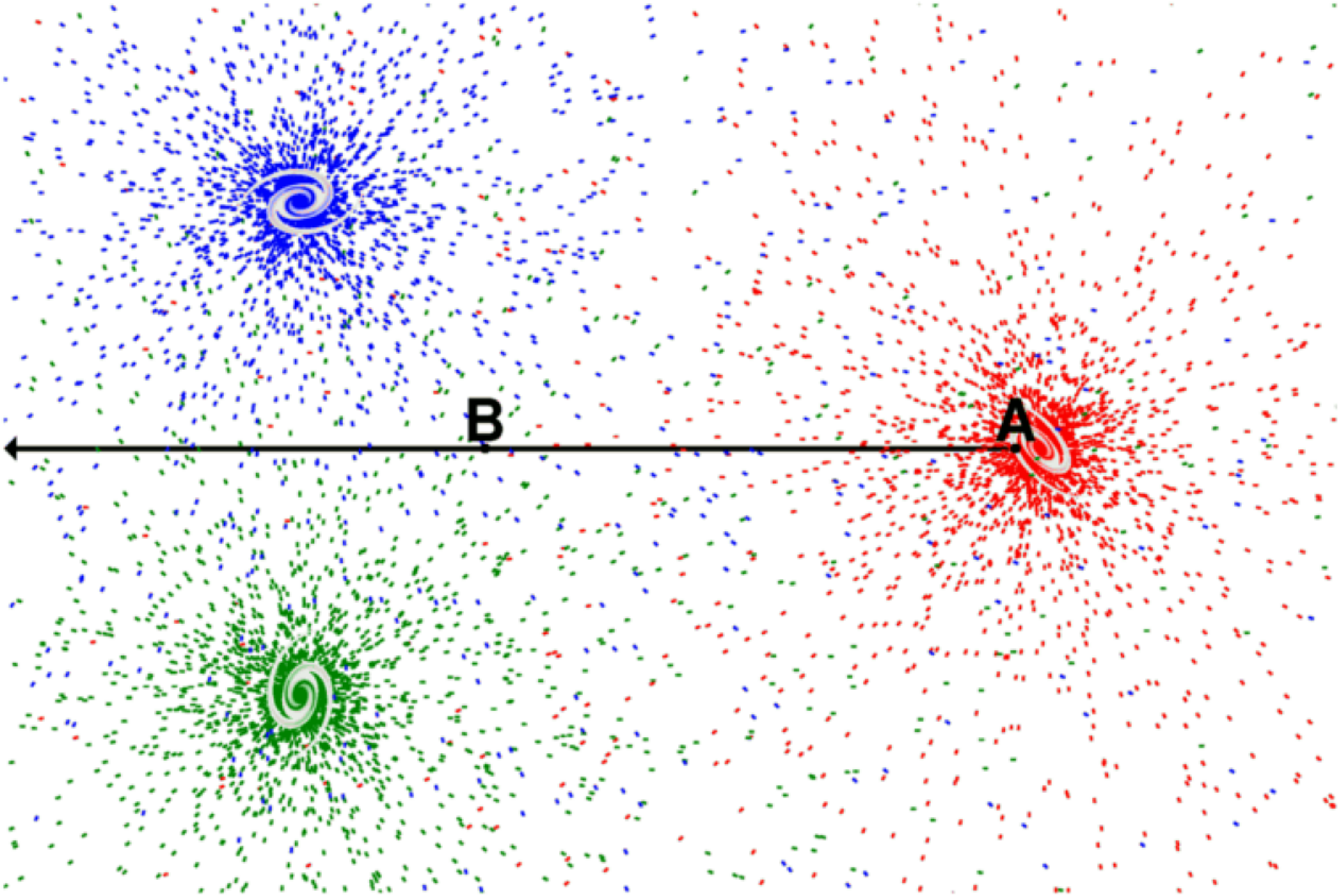
Zodi Subtracted 100 Micron



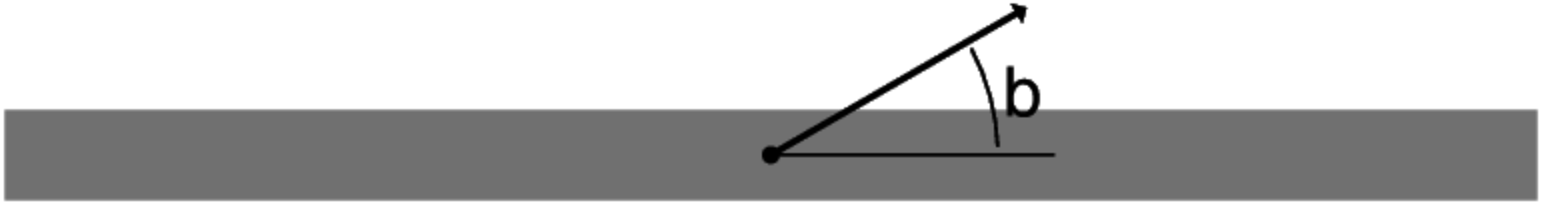
Still no CIRB Bump:



We want νJ_ν at B but sit at A

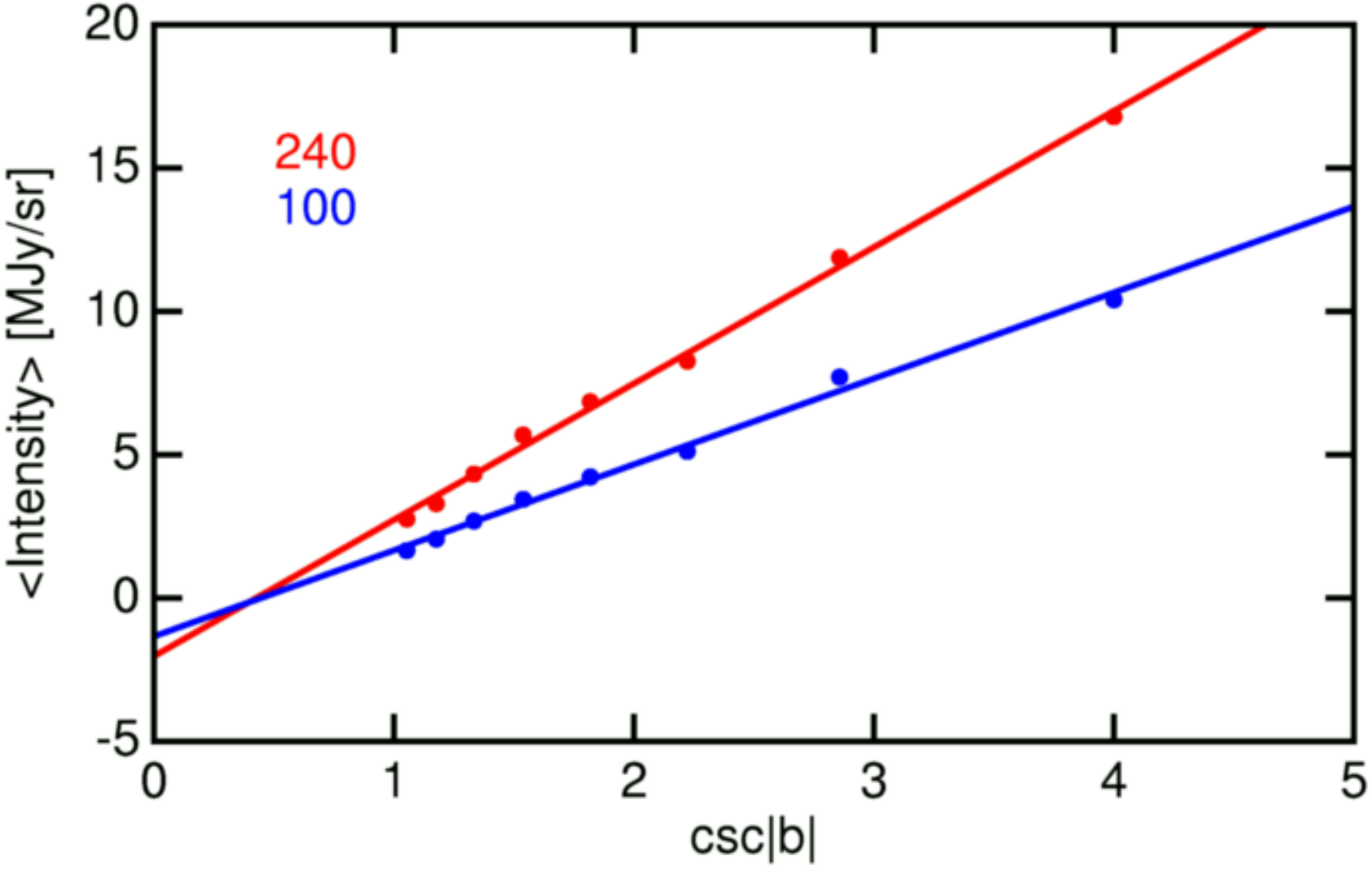


Extrapolation to NO Galaxy?

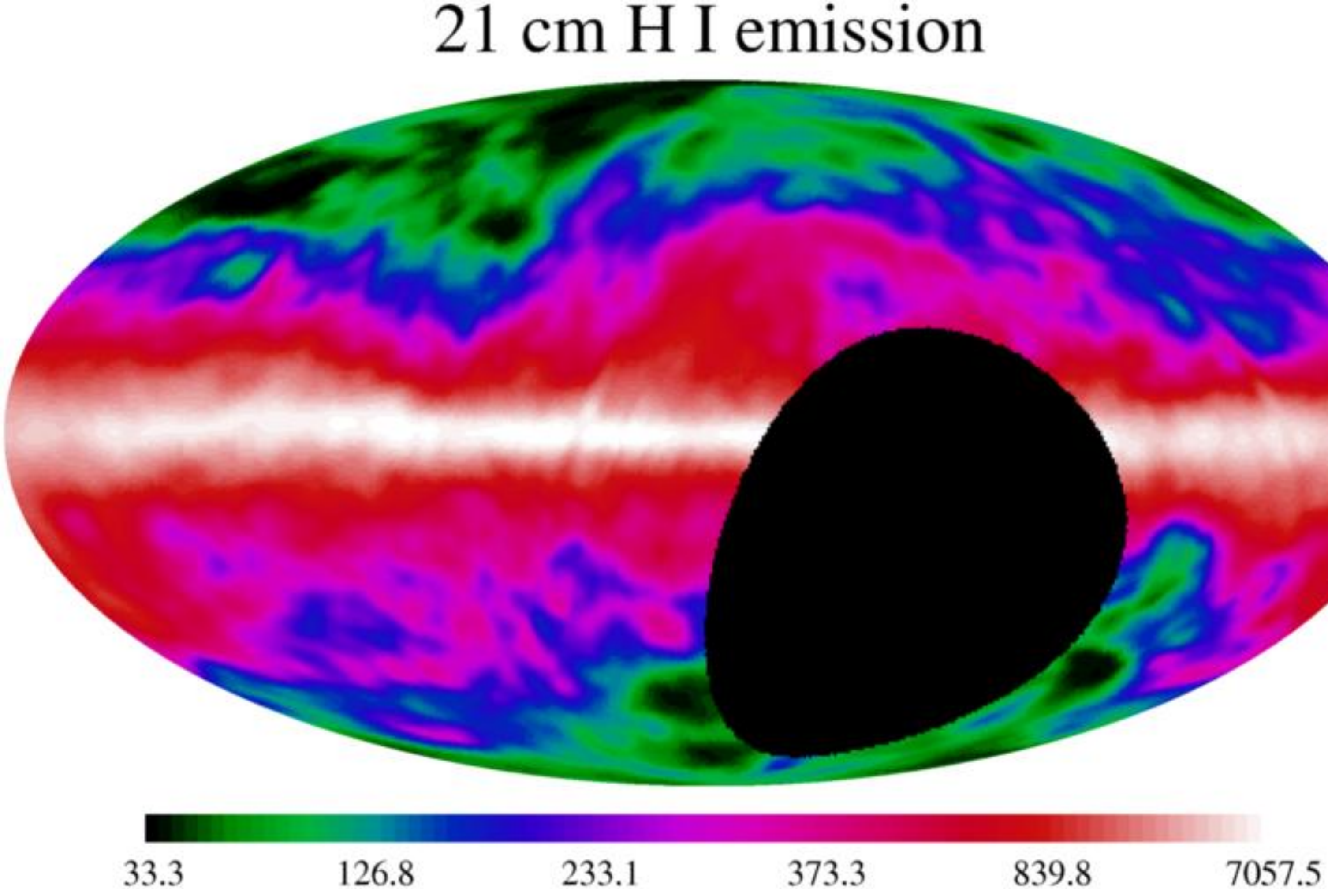


- Galaxy is a *very* thin disk
- Average column density $\propto \csc|b|$

Extrapolation to csc|b|=0 in Far IR



Atomic Hydrogen Map

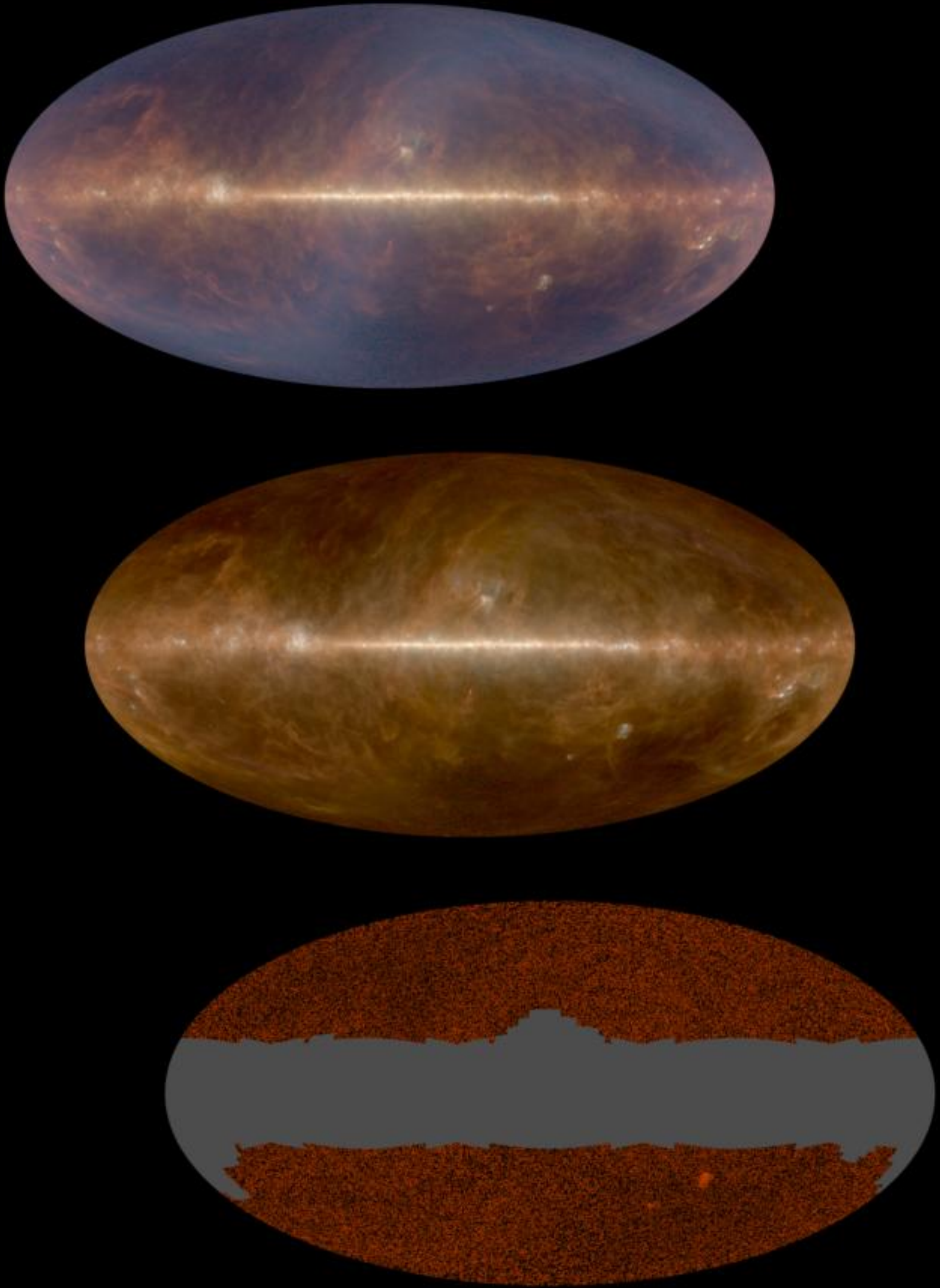


"The COBE Diffuse Infrared Background Experiment Search for the Cosmic Infrared Background. I. Limits and Detections", Hauser *et al.* (1998, ApJ, 508, 25)

"The COBE Diffuse Infrared Background Experiment Search for the Cosmic Infrared Background. II. Model of the Interplanetary Dust Cloud", Kelsall *et al.* (1998, ApJ, 508, 44)

"The COBE Diffuse Infrared Background Experiment Search for the Cosmic Infrared Background. III. Separation of Galactic Emission from the Infrared Sky Brightness", Arendt *et al.* (1998, ApJ, 508, 74)

"The COBE Diffuse Infrared Background Experiment Search for the Cosmic Infrared Background. IV. Cosmological Implications", Dwek *et al.* (1998, ApJ, 508, 106)



DIRBE Team IRB Results

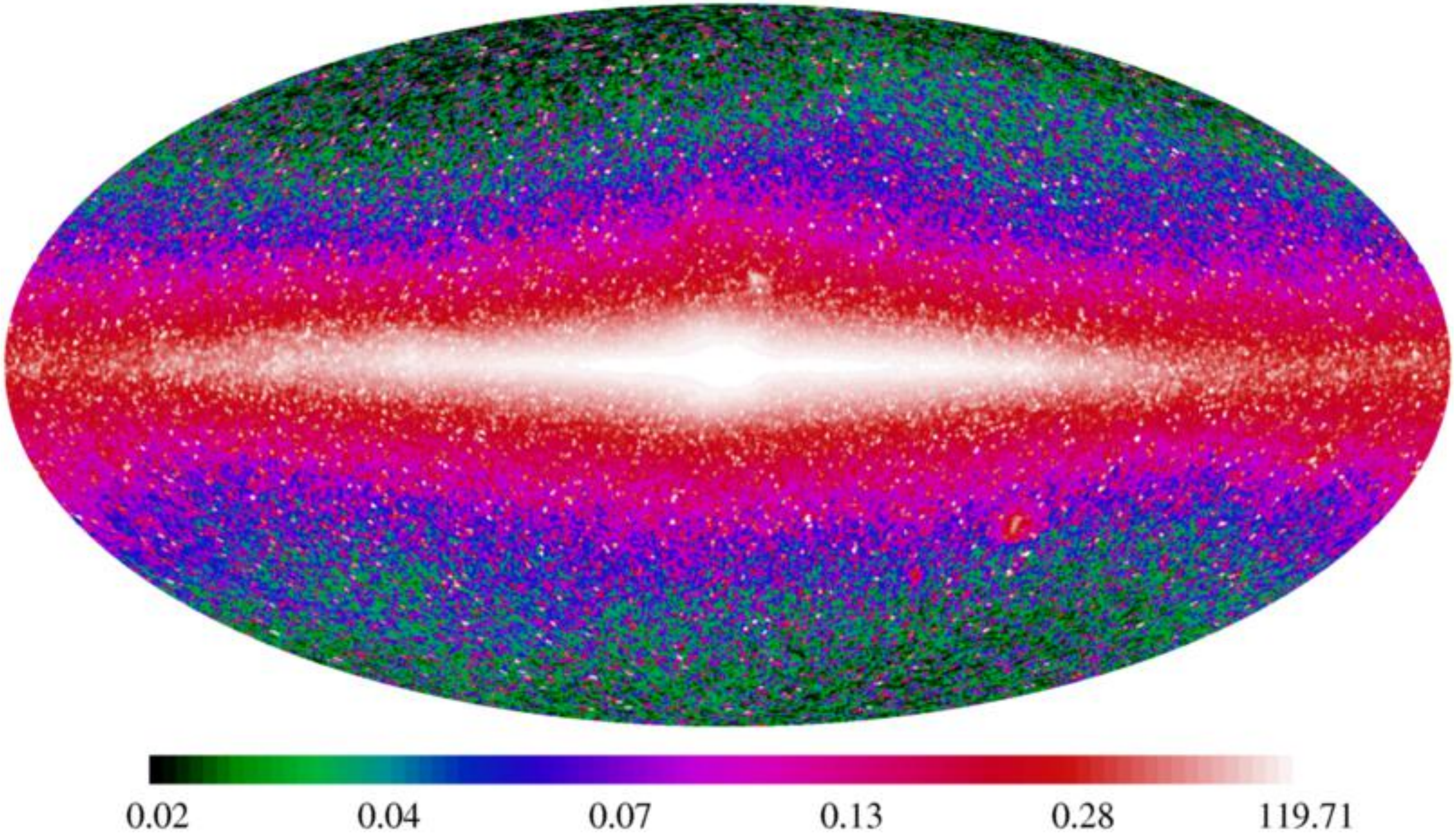
Hauser, …, Wright (1998, ApJ, 508, 25)

λ [μm]	νI_ν [nW m^{-2} sr^{-1}]	I_ν [MJy sr^{-1}]
1.25	$< 75.$	< 0.031
2.2	$< 39.$	< 0.029
3.5	$< 23.$	< 0.027
4.9	$< 41.$	< 0.067
12.	$< 468.$	< 1.87
25.	$< 504.$	< 4.2
60.	$< 75.$	< 1.5
100.	$< 38.$	< 1.27
140.	25.0 ± 6.9	1.17 ± 0.32
240.	13.6 ± 2.5	1.09 ± 0.2

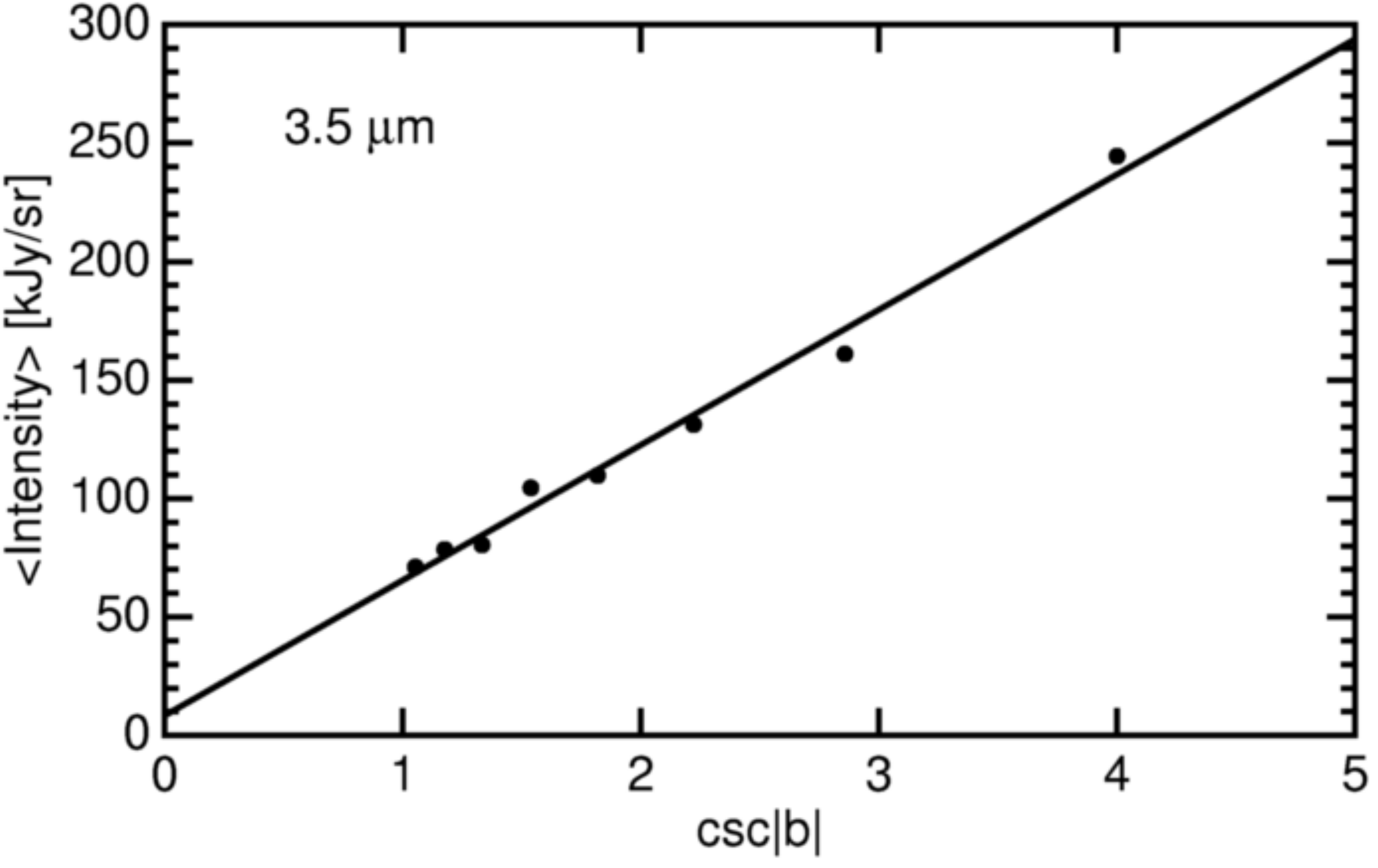
$$I_\nu \approx (1.3 \pm 0.4) \times 10^{-5} (\tilde{\nu}/100)^{0.64\pm0.12} B_\nu(18.5 \pm 1.2\ \mathrm{K})$$

Fixsen *et al.*, 1998, ApJ, 508, 123

Zodi Subtracted 3.5 Microns



Extrapolation to csc|b|=0 at 3.5 μm



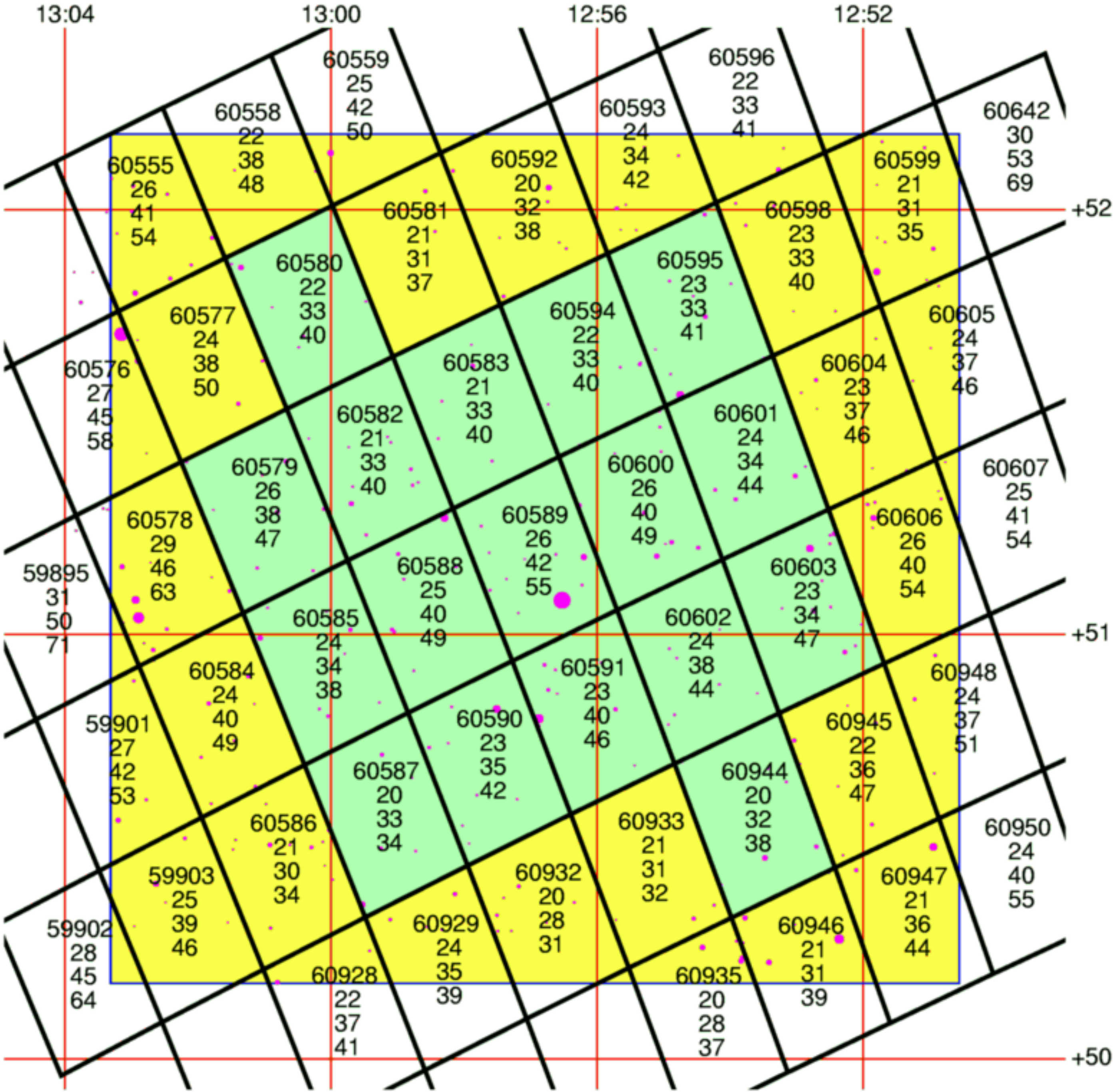
UNIVERSITY OF CALIFORNIA
LOS ANGELES

Detecting the Cosmic Infrared Background at 2.2μm with Ground Based and Space Based Observations

A dissertation submitted in partial satisfaction of the
requirements for the degree
Doctor of Philosphy in Physics and Astronomy

by

Varoujan Gorjian
1998


13:04
13:00
12:56
12:52
+52
+51
+50
60559 25 42 50
60558 22 38 48
60555 26 41 54
60596 22 33 41
60593 24 34 42
60592 20 32 38
60581 21 31 37
60642 30 53 69
60599 21 31 35
60598 23 33 40
60580 22 33 40
60595 23 33 41
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60583 21 33 40
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60582 21 33 40
60601 24 34 44
60579 26 38 47
60600 26 40 49
60607 25 41 54
60578 29 46 63
60589 26 42 55
60606 26 40 54
59895 31 50 71
60588 25 40 49
60603 23 34 47
60585 24 34 38
60602 24 38 44
60584 24 40 49
60591 23 40 46
60948 24 37 51
59901 27 42 53
60590 23 35 42
60945 22 36 47
60587 20 33 34
60944 20 32 38
60586 21 30 34
60933 21 31 32
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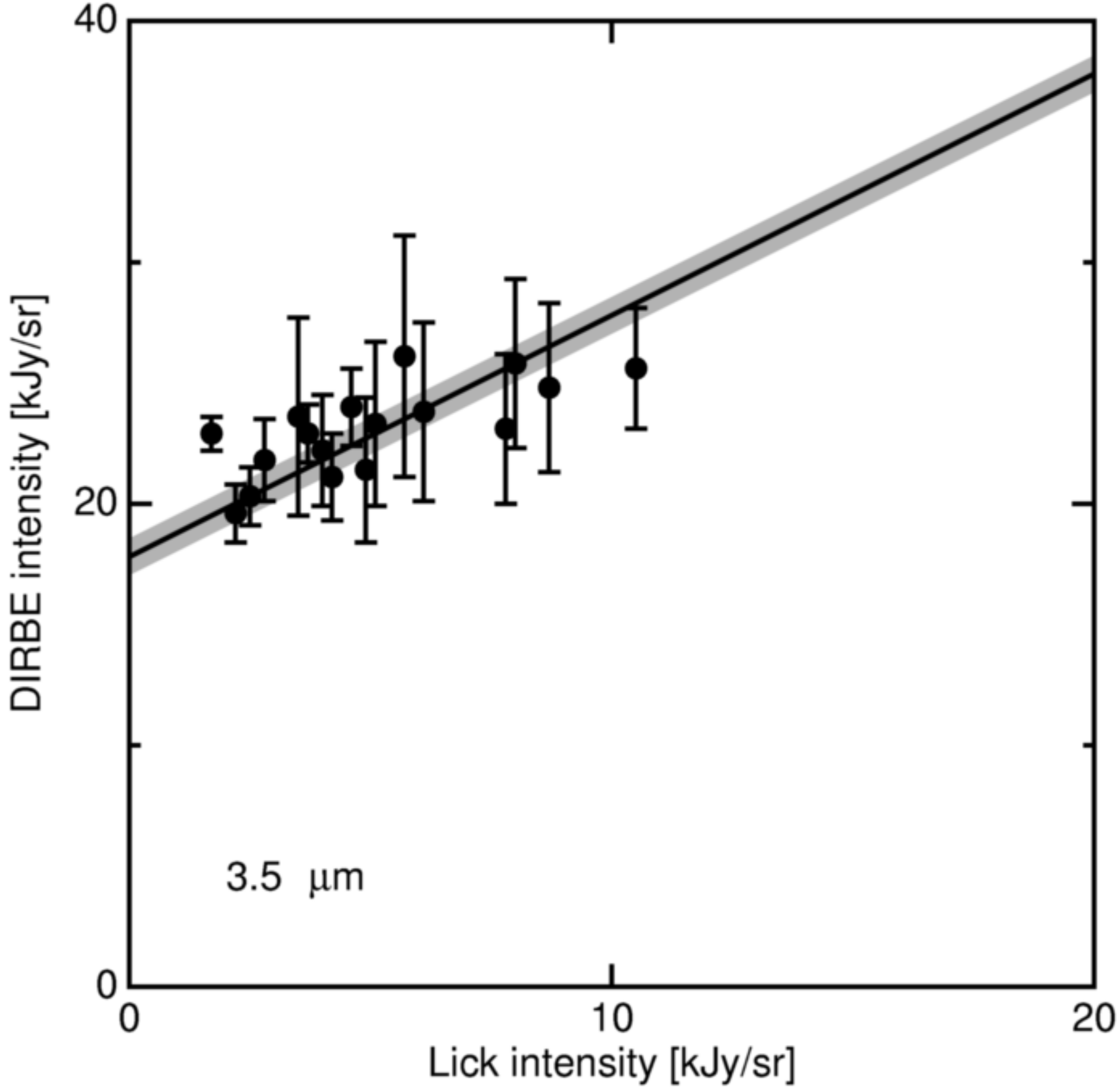
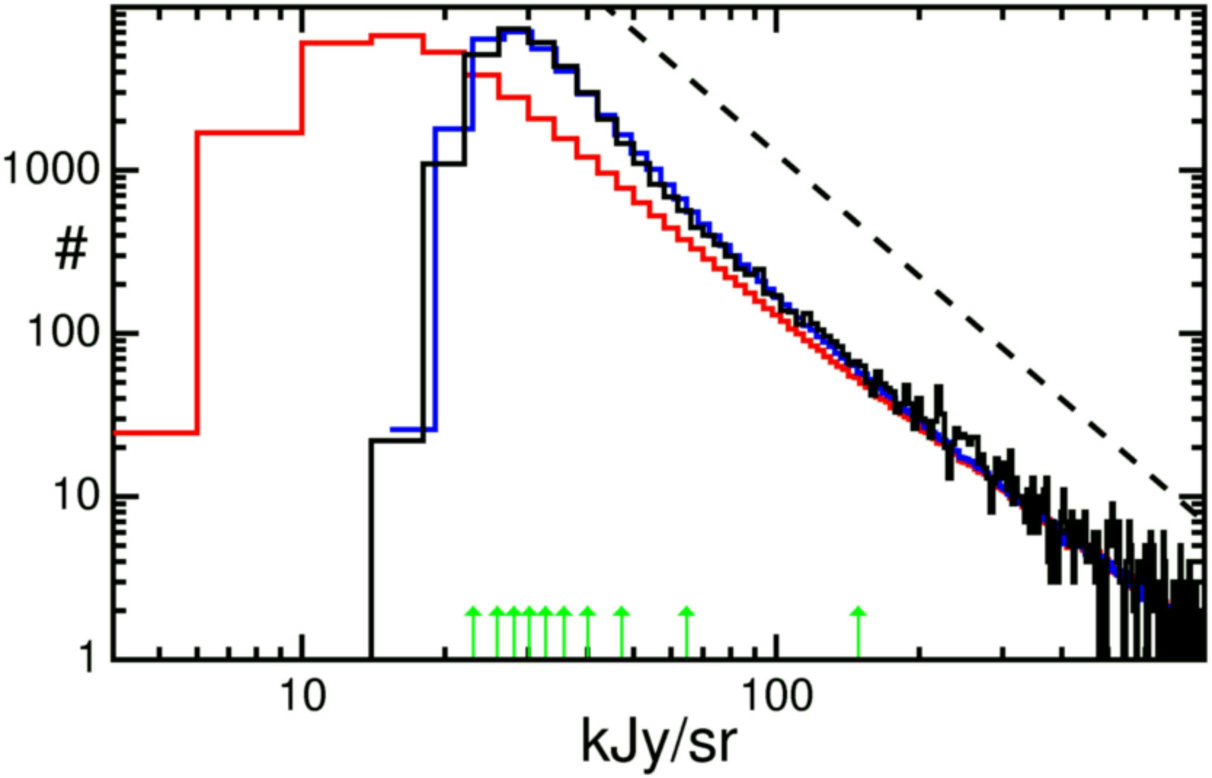
59902 28 45 64
60928 22 37 41
60935 20 28 37


40
20
0
0
10
20
DIRBE intensity [kJy/sr]
Lick intensity [kJy/sr]
3.5 μm

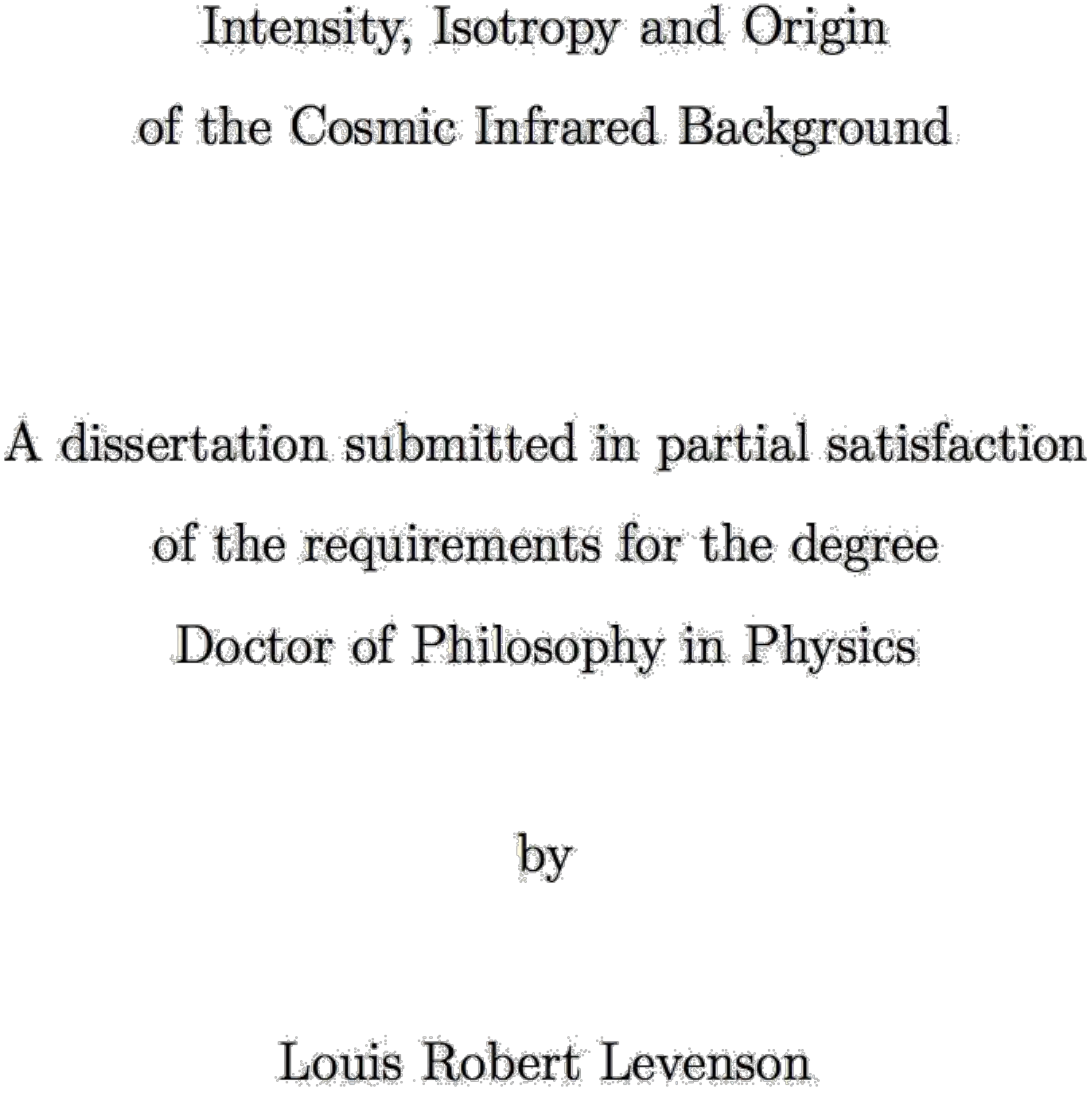
Wright & Reese, 2000

- Generated many fake star fields, |b| > 64°
- Properly allocated fluxes to DIRBE pixels
- Resulting model histogram
- Histogram shifted by 14.4 kJy/sr
- Actual zodi-subtracted DIRBE data
- Dashed: Euclidean



CIBR = 23.1±5.9 kJy/sr at 2.2 μm
14.4±3.7 kJy/sr at 3.5 μm

Levenson
2008 PhD

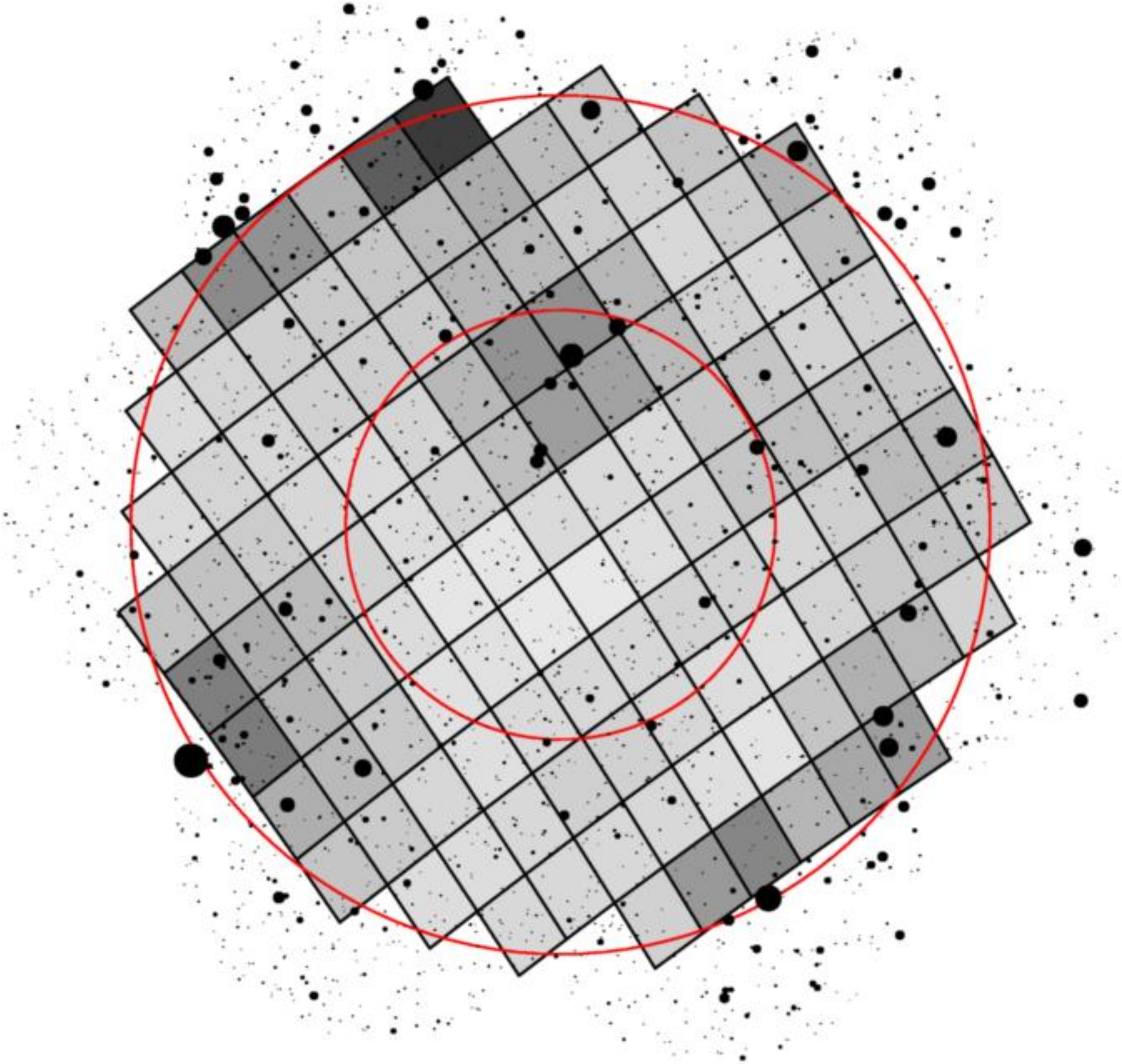


Intensity, Isotropy and Origin of the Cosmic Infrared Background

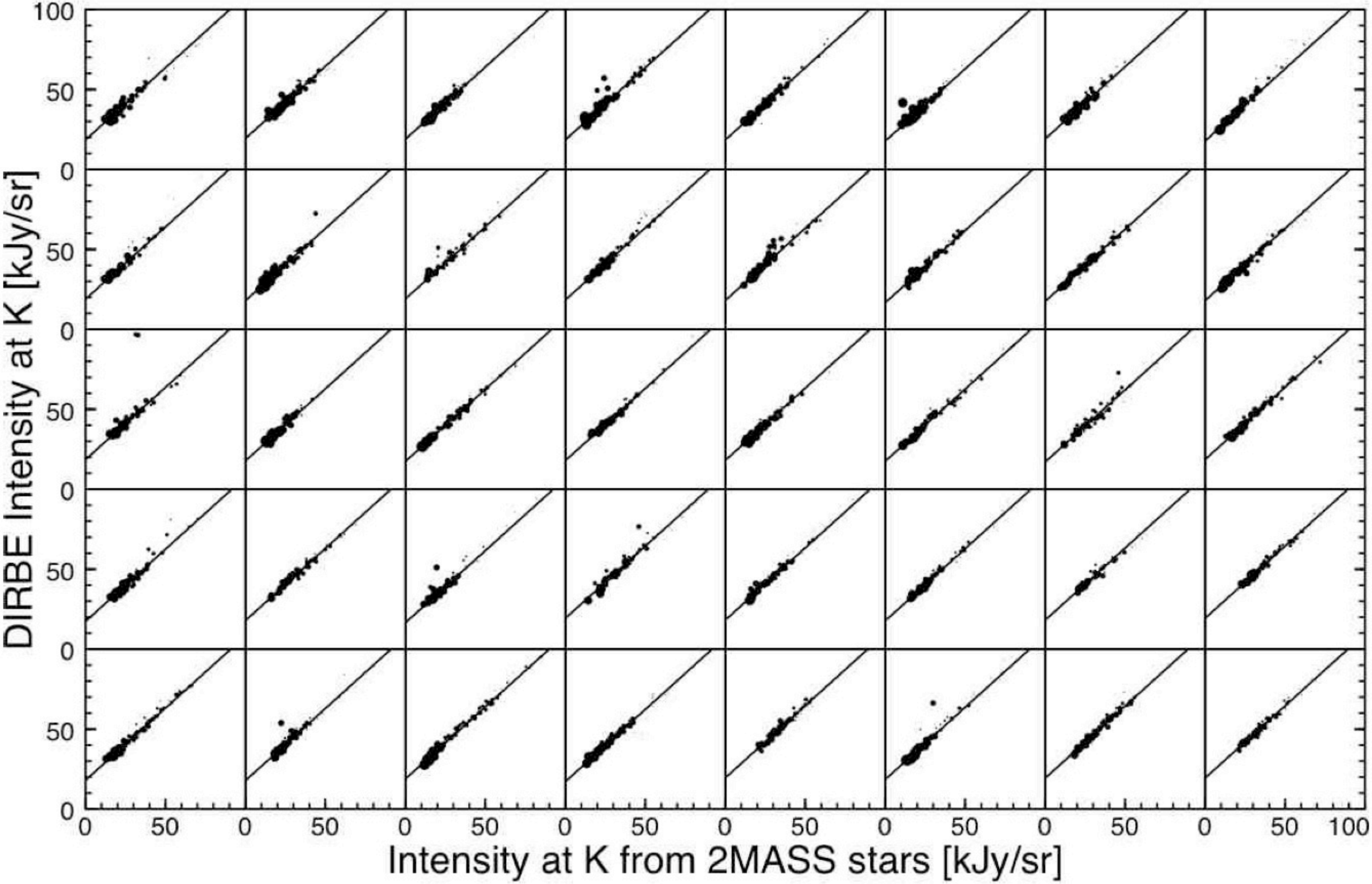
A dissertation submitted in partial satisfaction
of the requirements for the degree
Doctor of Philosophy in Physics

by

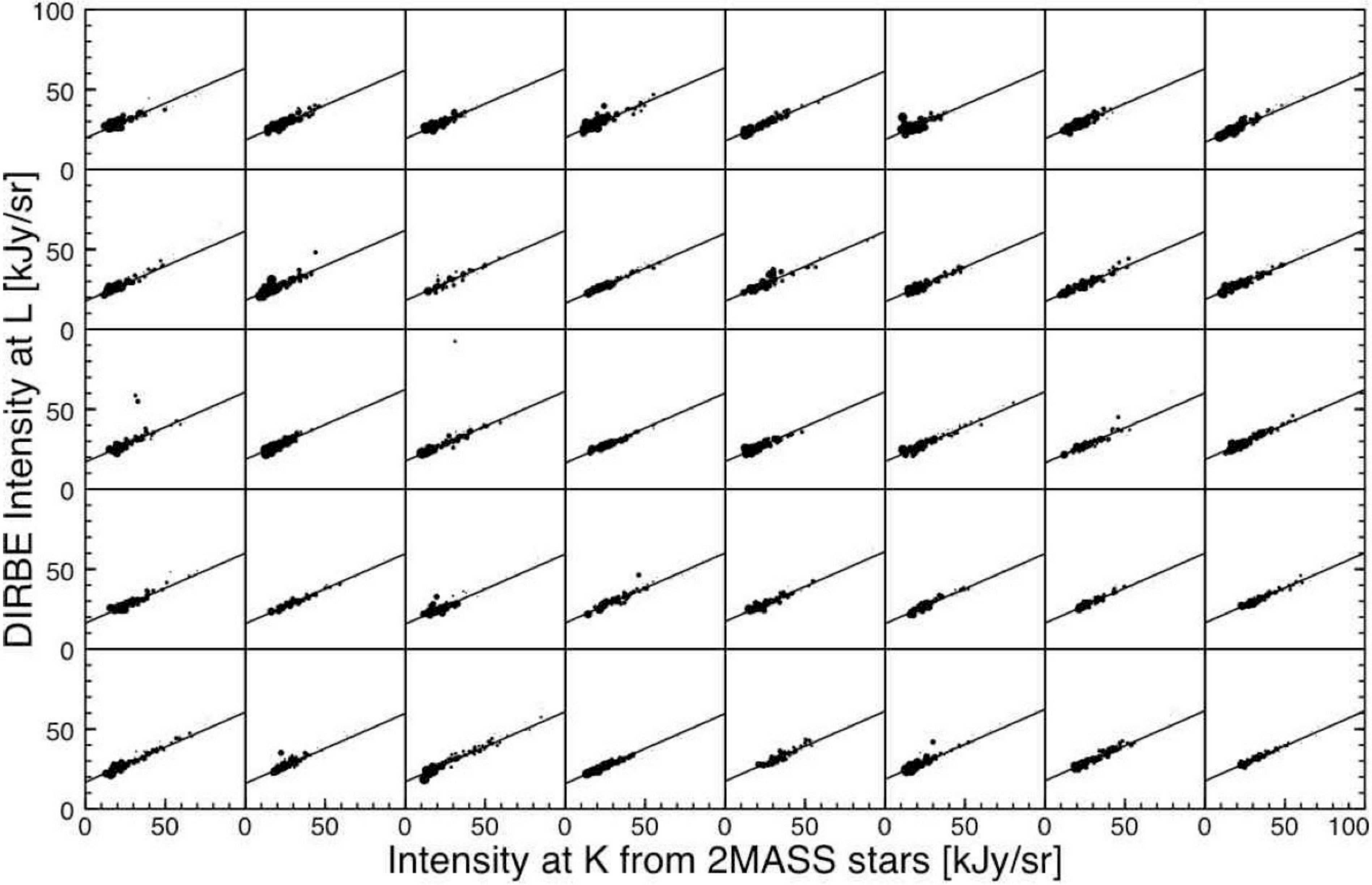
Louis Robert Levenson



DIRBE vs. 2MASS Fits at K

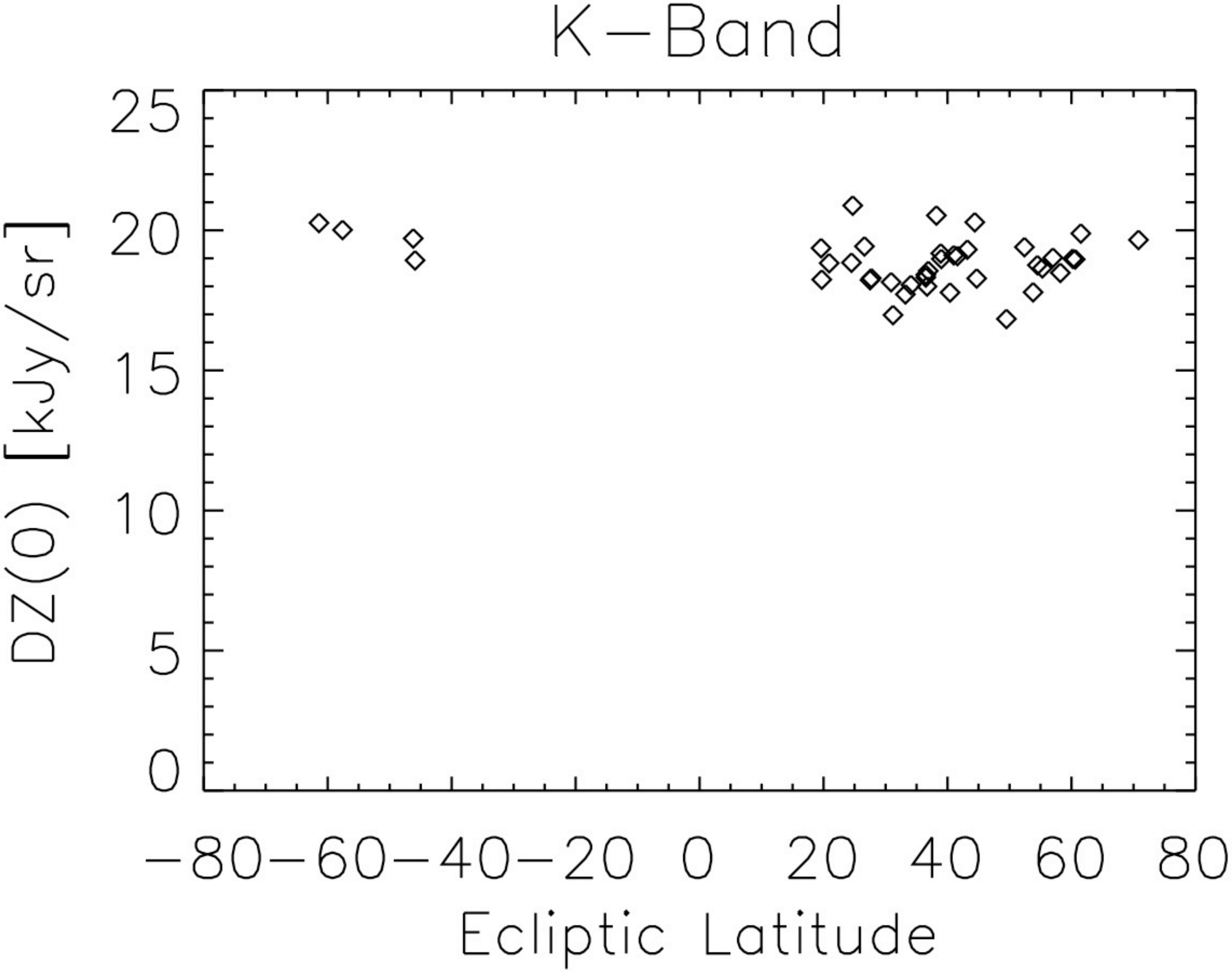


DIRBE at L vs 2MASS at K



We don’t need arc-sec resolution to subtract galactic stars. DIRBE was almost good enough.

DIRBE-2MASS vs ecliptic latitude



NO ZODI Principles

$$I_{obs}(\lambda, l, b, t) = Z(\lambda, l, b, t; p) + I_c(\lambda, l, b)$$

- Weak No Zodi: No restriction on I_c
- Strong No Zodi: $I_c(\lambda, l, b)$ independent of (l, b) for $|b| > 20^\circ$ and $\lambda = 25\ \mu$m.
- Very Strong No Zodi: $I_c(\lambda, l, b) = 0$ for $|b| > 20^\circ$ and $\lambda = 25\ \mu$m.

The Incredible Weakness of Nozoding

- For a spherical shell at distance $R > 1$ AU from the Sun,

$$I \propto \left(1 - R^{-2}\sin^2\theta\right)^{-0.5}$$
$$\Delta I_{rms}/\langle I\rangle \approx 0.04/R^2 < 1\% \text{ for } R > 2.$$

- For a uniform density dust cloud with a cavity of radius $R > 1$ AU,

$$I_{bol} \propto \sin^{-1}(R^{-1}\sin\theta)/\sin\theta$$
$$\Delta I_{rms}/\langle I\rangle \approx 0.0125/R^2$$

Thus spherical components in the outer Solar System cannot be determined by applying the Weak No-Zodi Principle to DIRBE data.

Comparison of Zodi Models

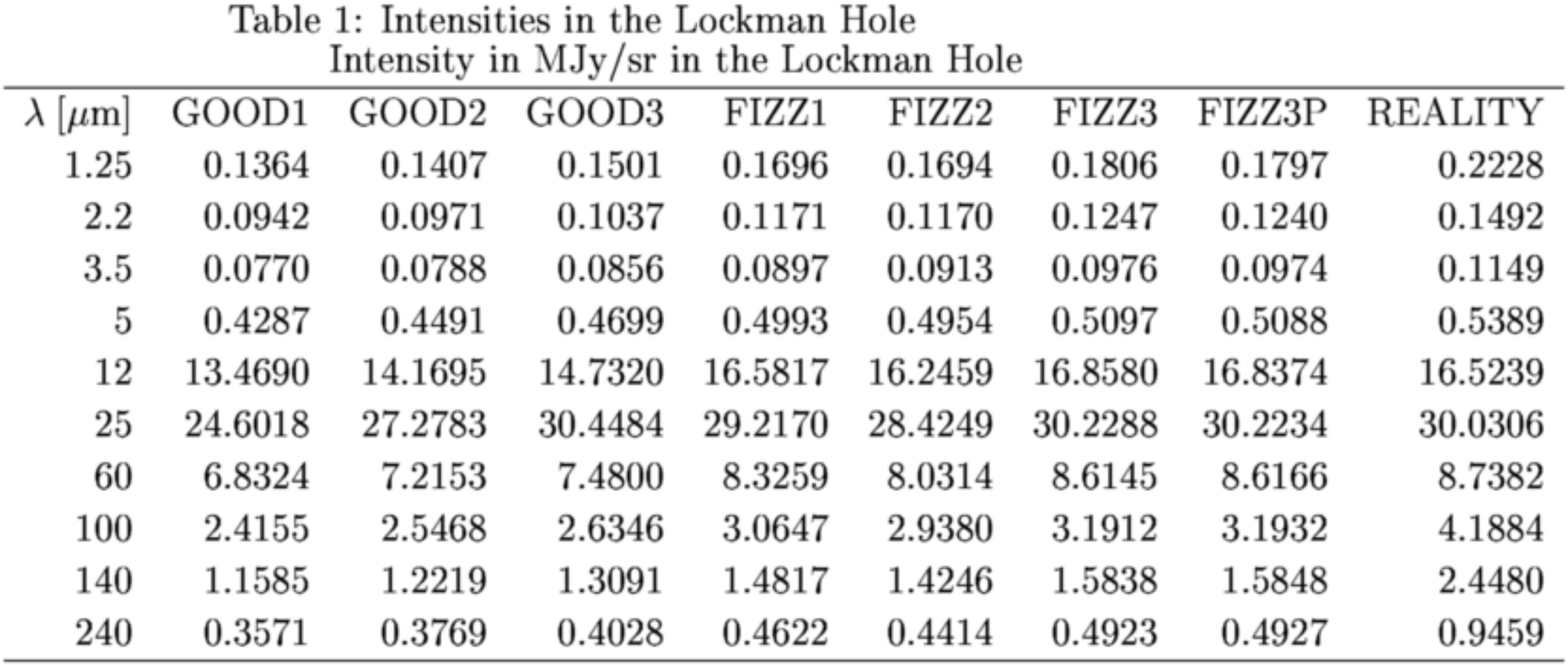


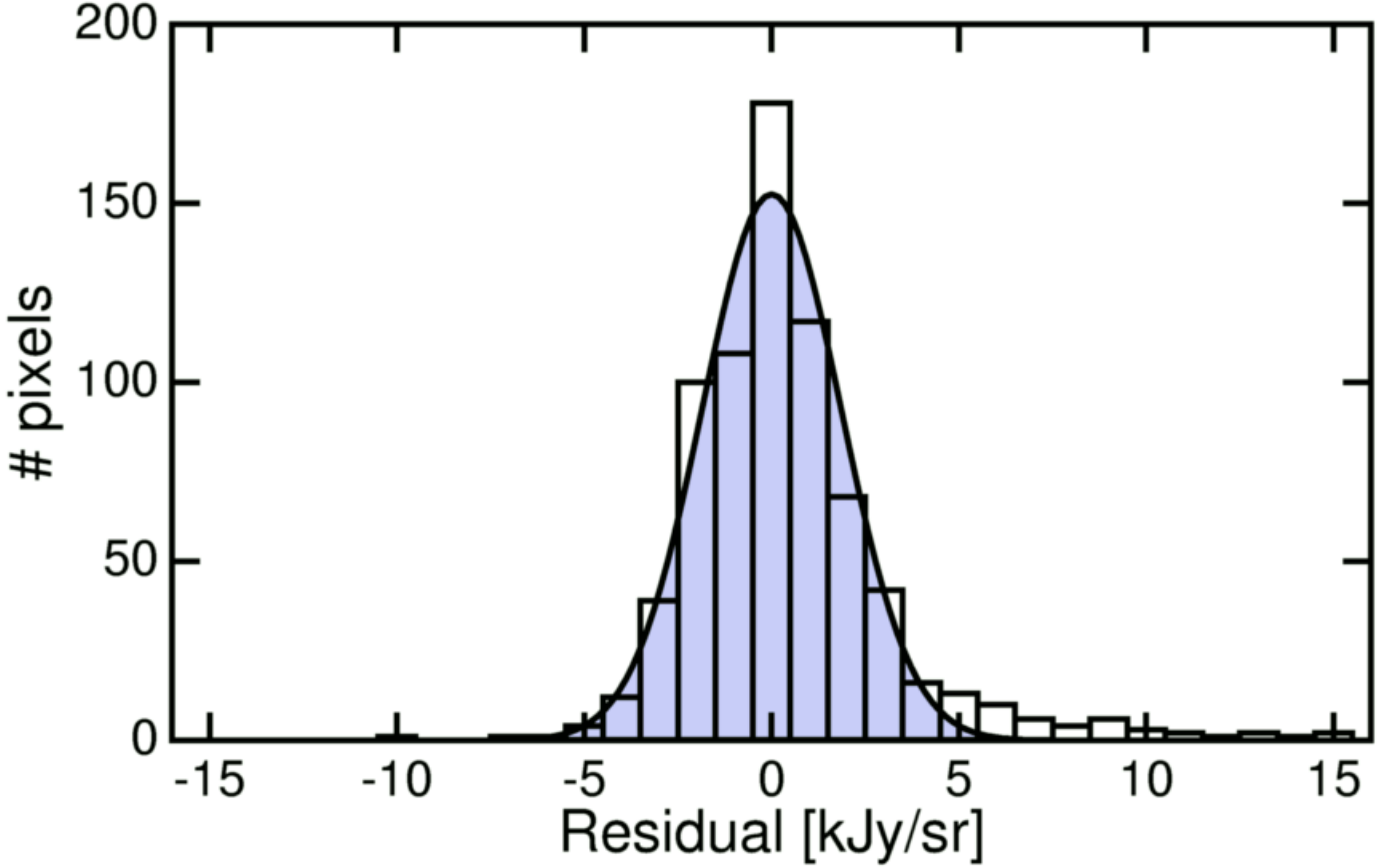
Table 1: Intensities in the Lockman Hole

Intensity in MJy/sr in the Lockman Hole

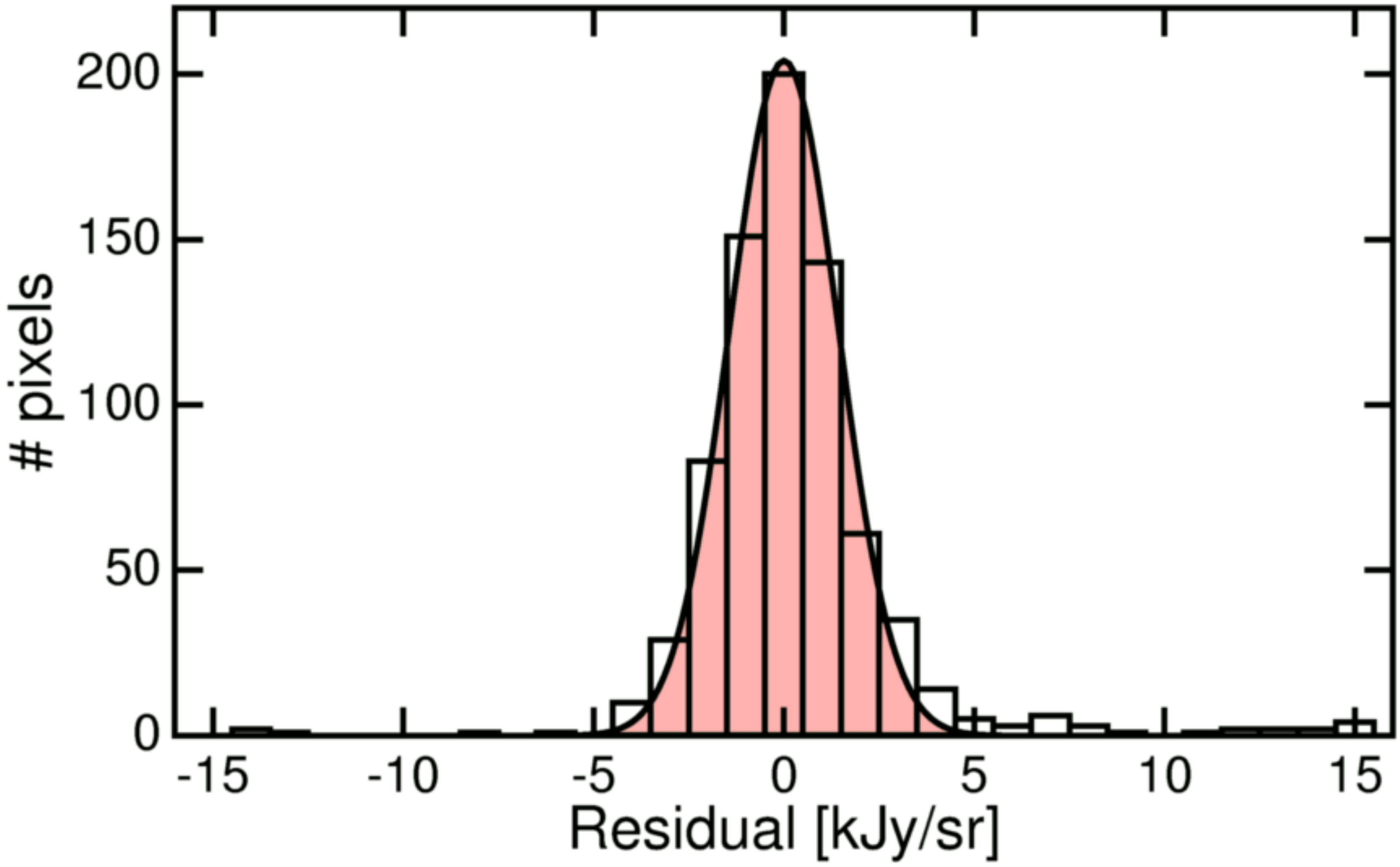
λ [μm]	GOOD1	GOOD2	GOOD3	FIZZ1	FIZZ2	FIZZ3	FIZZ3P	REALITY
1.25	0.1364	0.1407	0.1501	0.1696	0.1694	0.1806	0.1797	0.2228
2.2	0.0942	0.0971	0.1037	0.1171	0.1170	0.1247	0.1240	0.1492
3.5	0.0770	0.0788	0.0856	0.0897	0.0913	0.0976	0.0974	0.1149
5	0.4287	0.4491	0.4699	0.4993	0.4954	0.5097	0.5088	0.5389
12	13.4690	14.1695	14.7320	16.5817	16.2459	16.8580	16.8374	16.5239
25	24.6018	27.2783	30.4484	29.2170	28.4249	30.2288	30.2234	30.0306
60	6.8324	7.2153	7.4800	8.3259	8.0314	8.6145	8.6166	8.7382
100	2.4155	2.5468	2.6346	3.0647	2.9380	3.1912	3.1932	4.1884
140	1.1585	1.2219	1.3091	1.4817	1.4246	1.5838	1.5848	2.4480
240	0.3571	0.3769	0.4028	0.4622	0.4414	0.4923	0.4927	0.9459

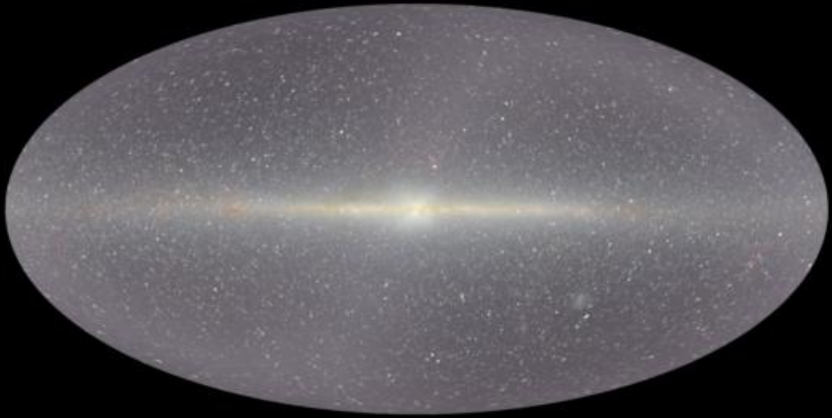
Biggest uncertainty is from the zodi models: change of 8 out of 90 kJy/sr at 3.5 µm for different no-zodi principles.

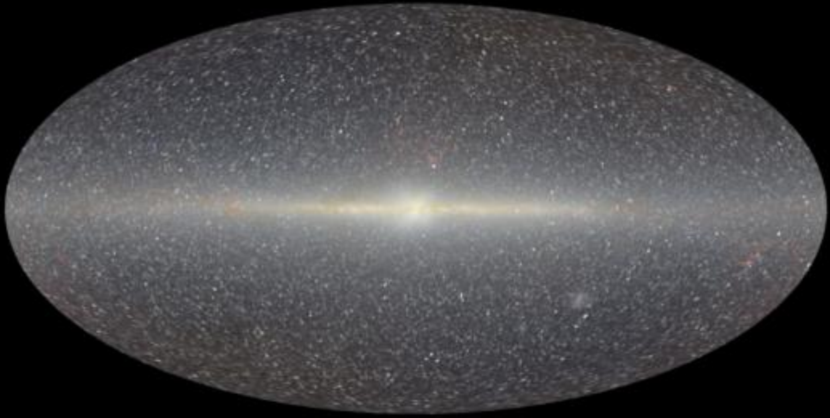
DIRBE-2MASS Residuals at K: σ = 1.83 kJy/sr



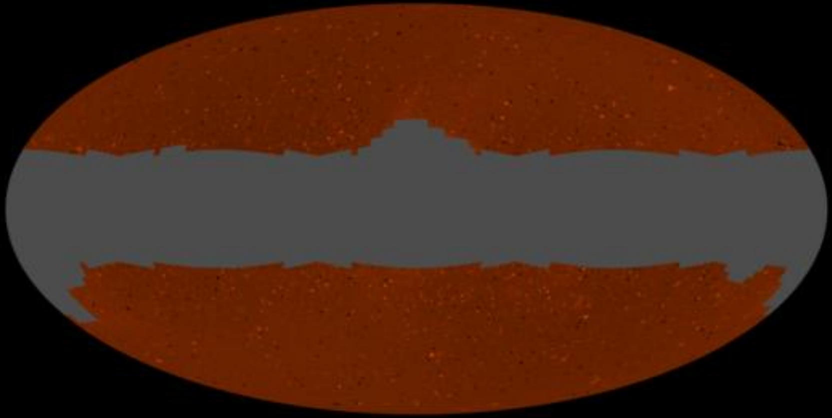
DIRBE-2MASS Residuals at L: σ = 1.43 kJy/sr



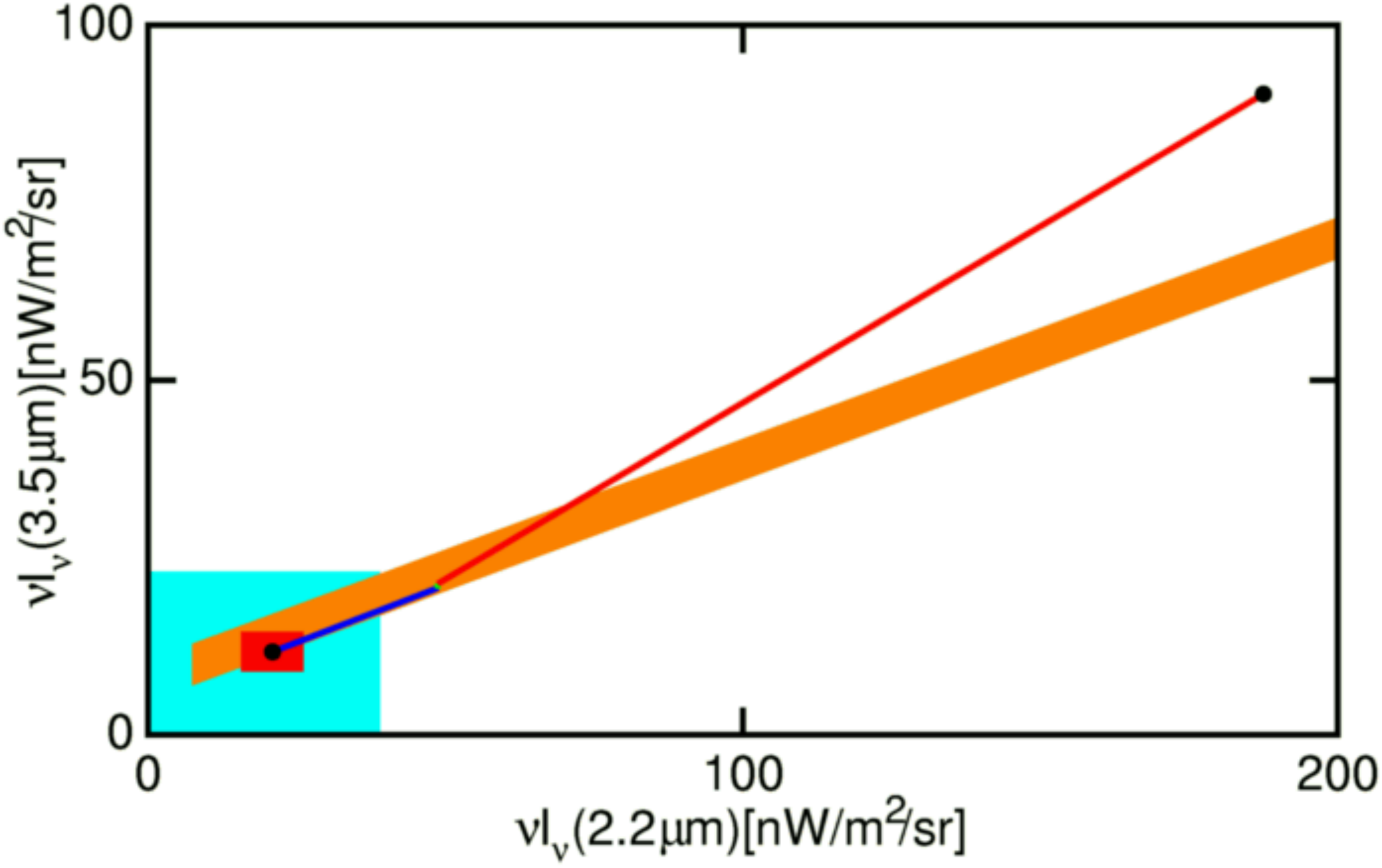


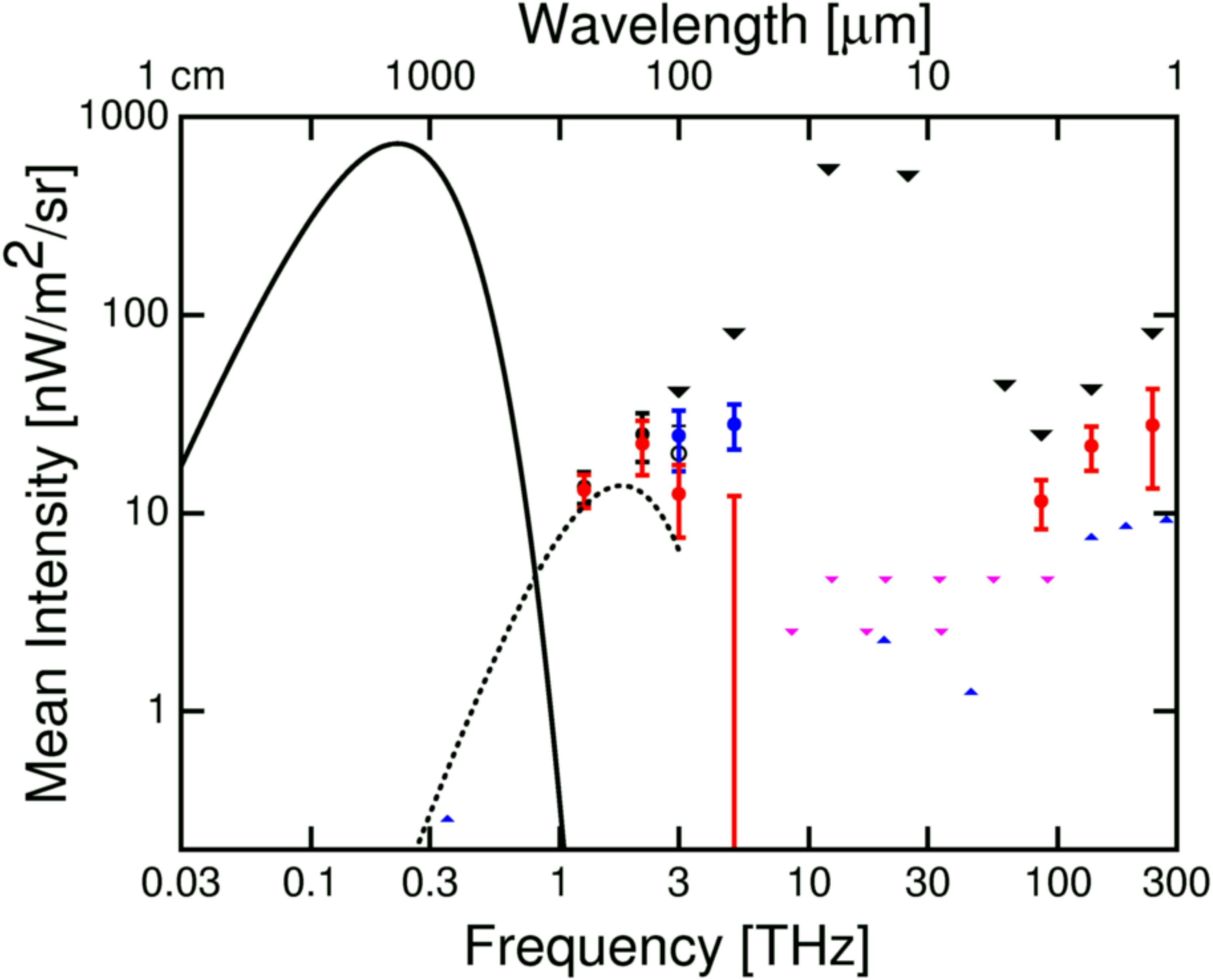


Dwek & Arendt (1998): L-0.5K (in Jy) is very smooth



Near IR Decomposition




Wavelength [μm]
1 cm
1000
100
10
1
Mean Intensity [nW/m^2/sr]
1000
100
10
1
0.03
0.1
0.3
1
3
10
30
100
300
Frequency [THz]

Discrepancy between Counts & Measurements

- Rebecca Bernstein gets about $2\times$ more optical extragalactic background light than one derives from the sum of the galaxy counts:

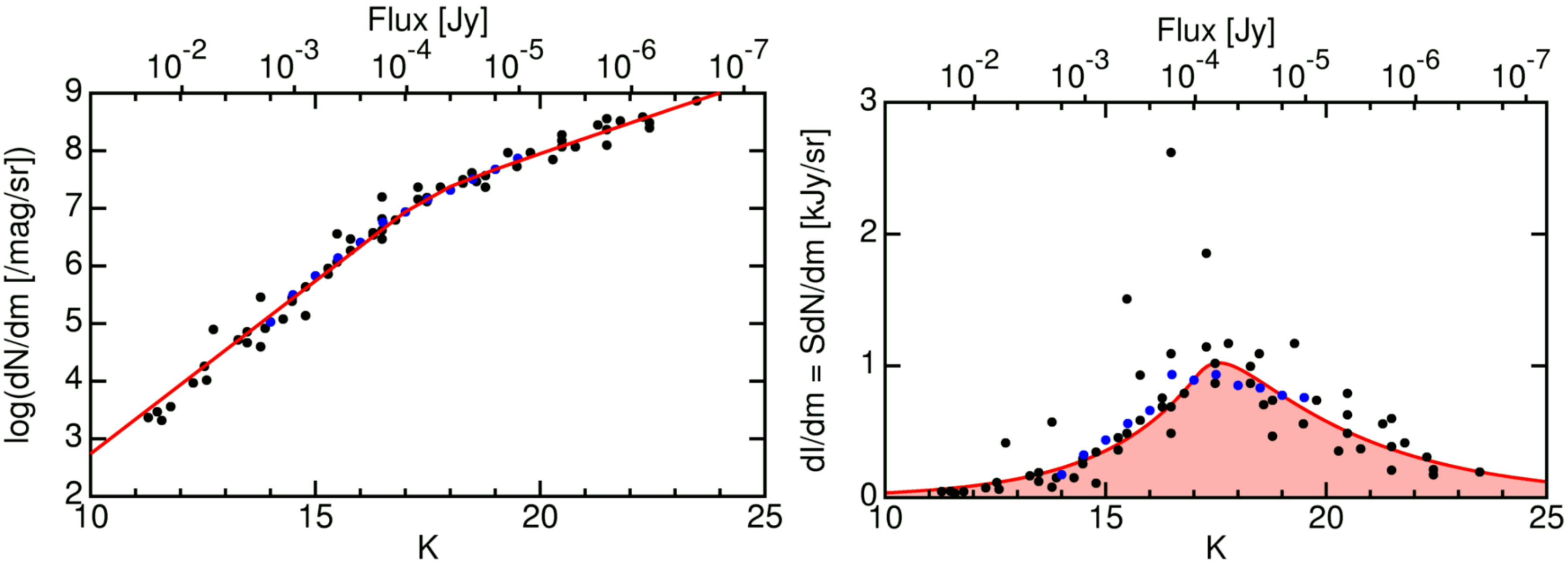
$$I_{counts} = \int S dN = \int S \left| \frac{\partial N}{\partial \ln S} \right| d \ln S$$

$$I_{obs} \approx 2 \times I_{counts}$$

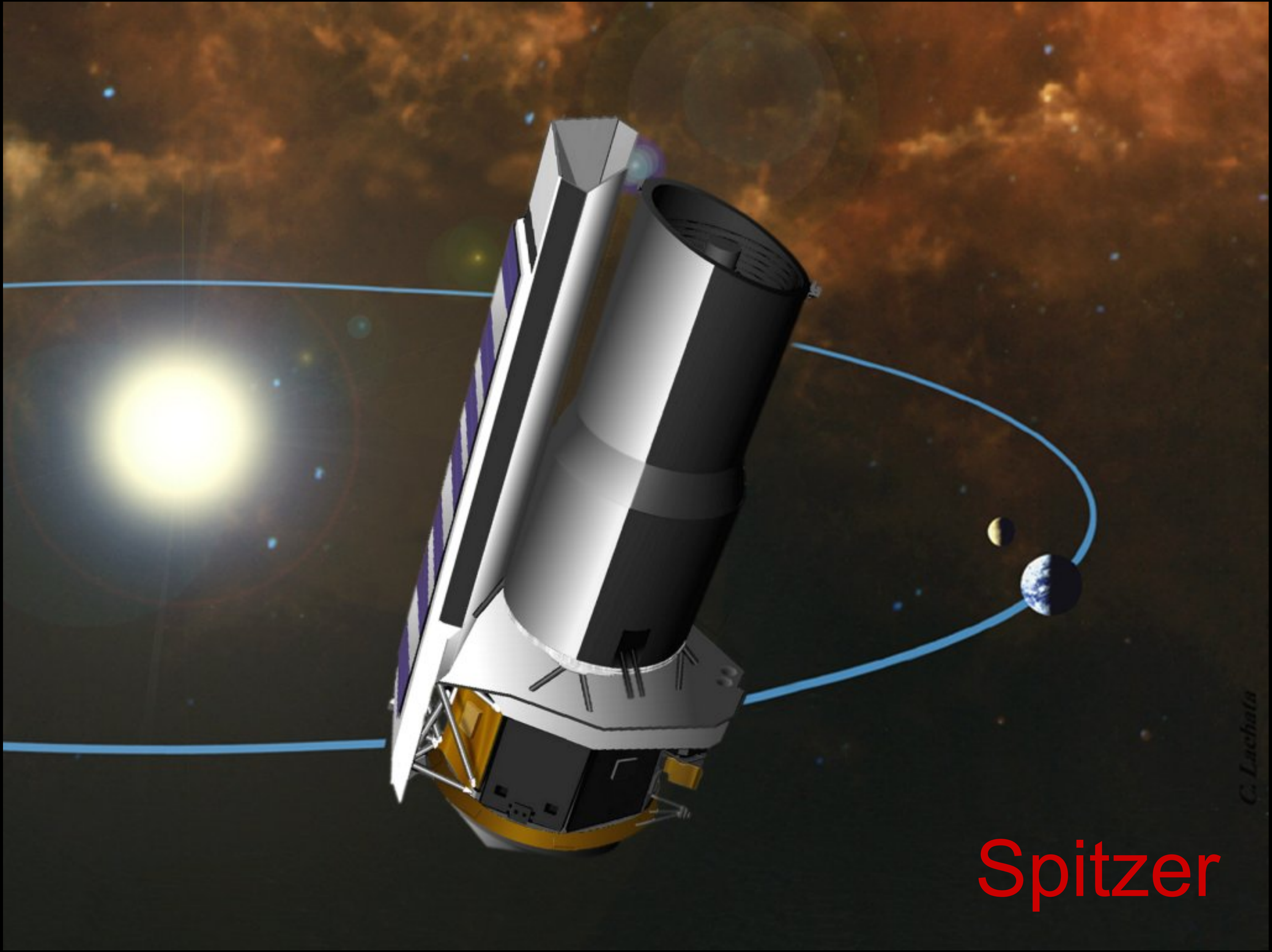
- Wright gets about $(2 \pm 0.5)\times$ more near infrared cosmic background light than is expected from deep K-band counts.

Both measurement involve difficult and uncertain zodiacal light corrections but they use entirely different techniques.

2.2 μm Galaxy Counts

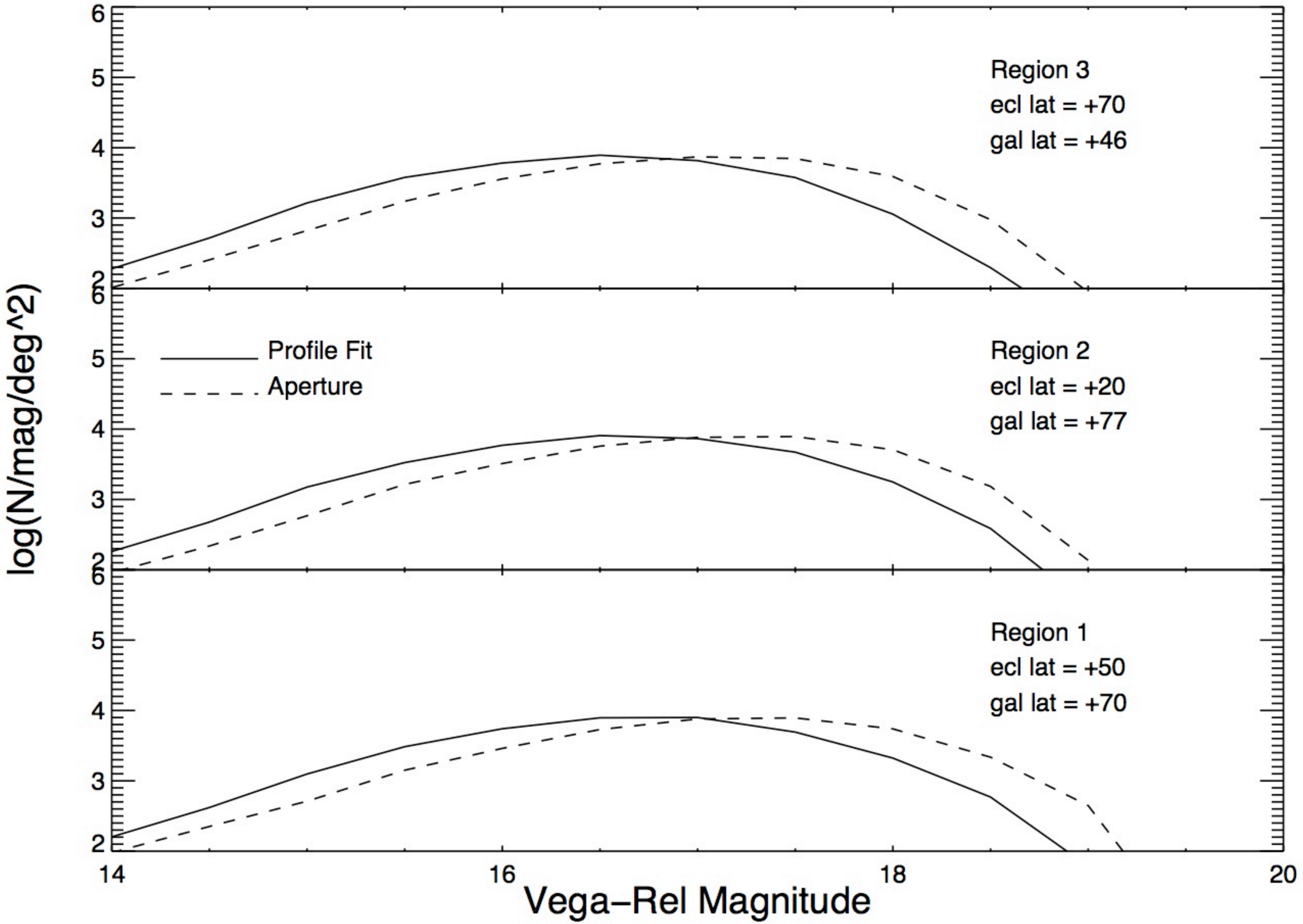


- K counts from Figure 1 of Madau & Pozzetti, MNRAS, 312, L9-L15 (2000)
- CADIS counts from Huang etal astro-ph/0101269
- Integral under fit gives 6.3 kJy/sr or 8.6 nW/m^2/sr

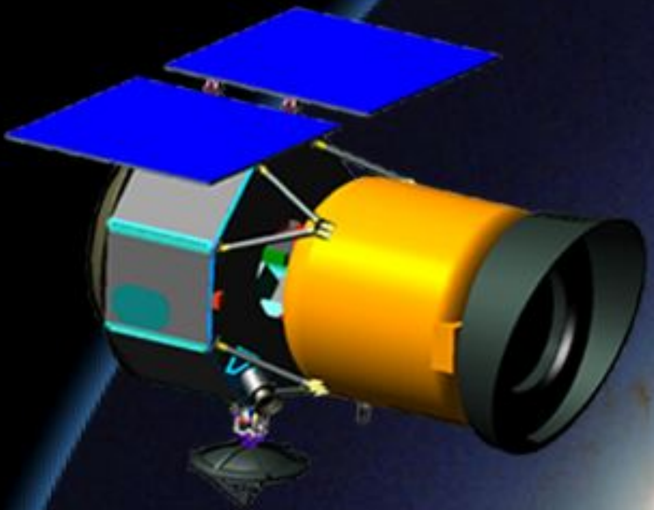


Spitzer

Aperture fluxes systematically low



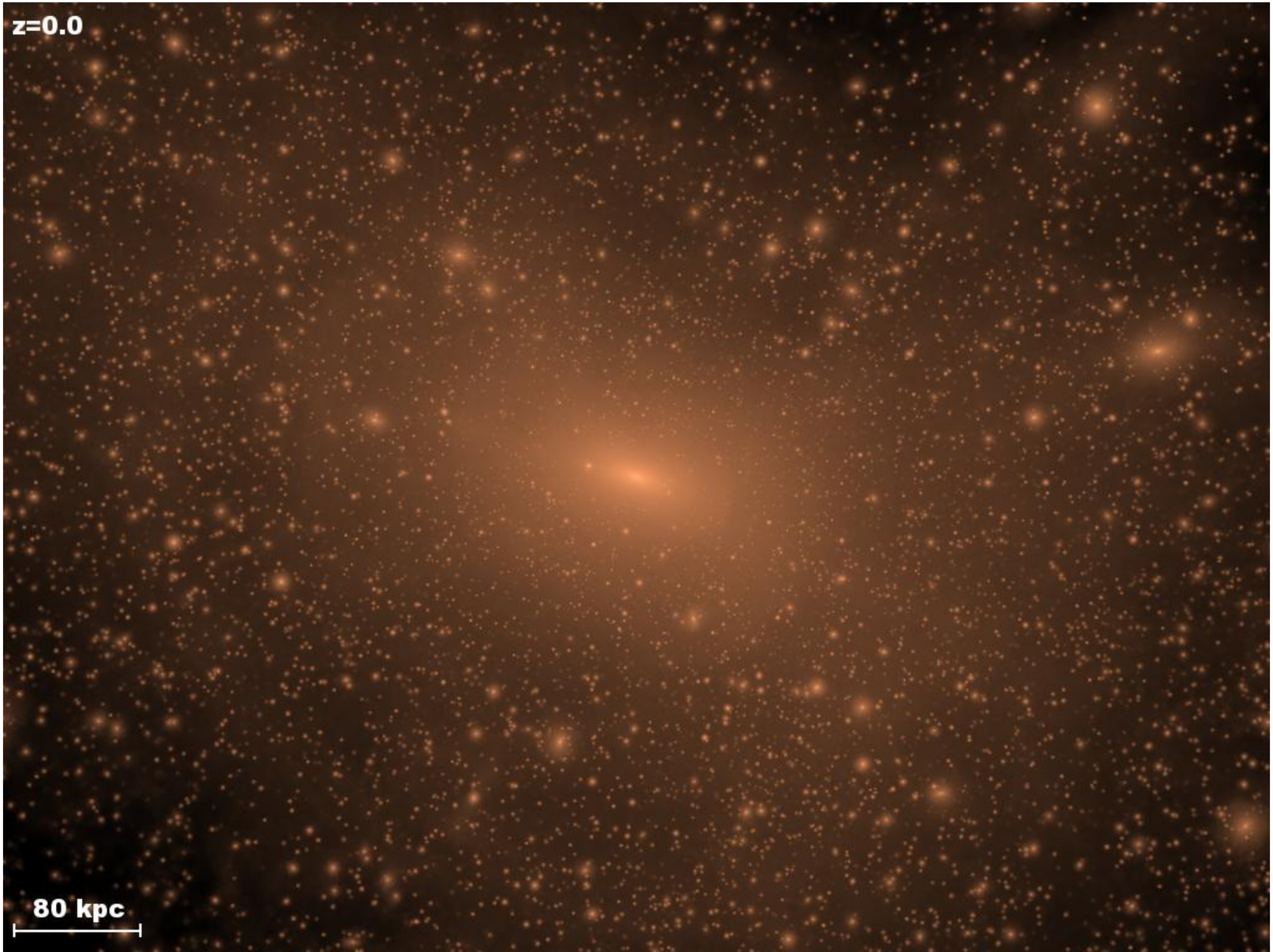
WIDE-FIELD INFRARED SURVEY EXPLORER



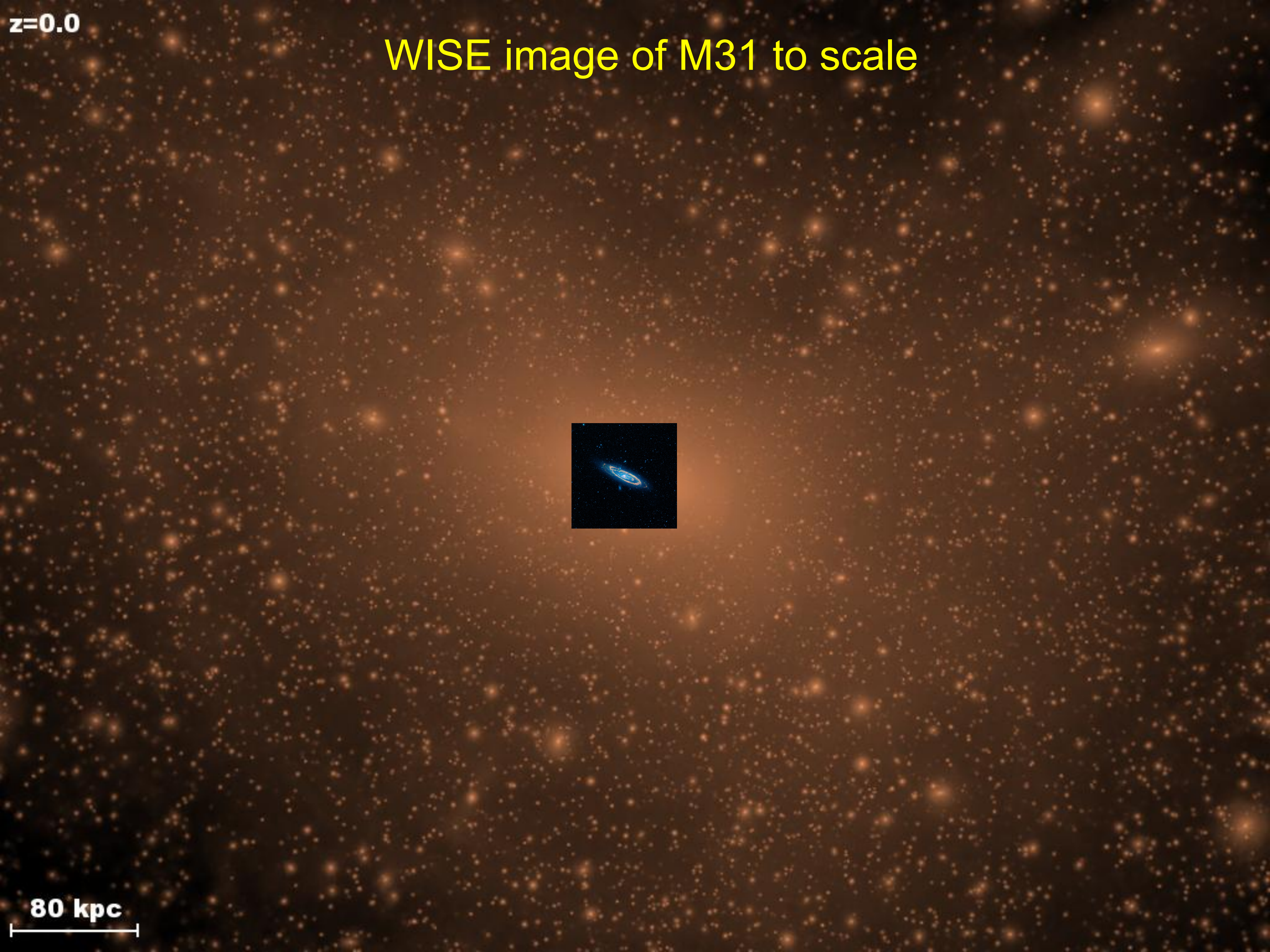
I am the PI on WISE, an all-sky survey in 4 bands from 3.4 to 22 μm. WISE found the closest stars to the Sun, the most luminous galaxies in the Universe, and also measured 100’s of millions of galaxies that contribute to the CIRB.

WISE launched 14 Dec 2009, and released an all-sky survey on 14 Mar 2012.

M31-sized halo from Via Lactea

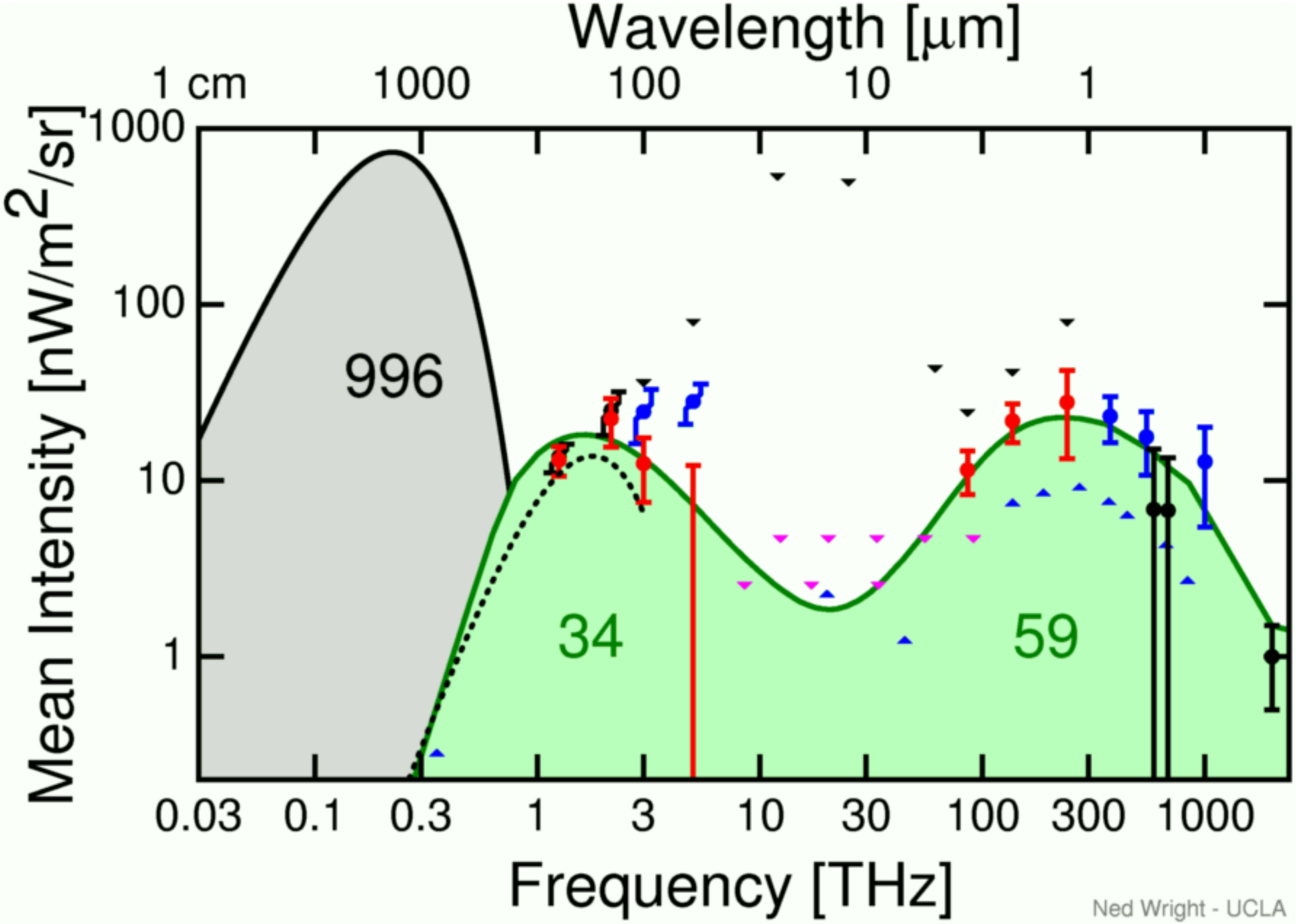


WISE image of M31 to scale



There is no blank sky between galaxies

Cosmic Optical & IR Background



Ned Wright - UCLA

γ-Ray Connection

- The reaction $\gamma_1 + \gamma_2 \rightarrow e^+ + e^-$ has a threshold of $E_1 E_2 > (m_e c^2)^2$.
- The peak cross-section of 1.7×10^{-25} cm^2 occurs at twice the threshold energy.
- 1 MJy/sr corresponds to a photon density of 0.63 cm^{-3}oct^{-1}.
- Expect absorption of γ-rays over distance of 3 Mpc for 1 MJy/sr, or $450/\lambda[\mu\mathrm{m}]$ Mpc for 20 nW/m^2/sr, at $E \approx 400\lambda[\mu\mathrm{m}]$ GeV.

VERITAS

- Operating at Mt Hopkins base camp
- Four 12 meter diameter segmented mirror telescopes
- Competitive with HESS in Namibia

Ablaze in the distance

- Blazar H1426+428 has a flux of 4×10^{-12} erg/cm^2/sec at $E > 1$ TeV.
- Redshift $z = 0.129$
- 96% γ-ray absorption at 1 TeV for my CIRB
- Many other blazars now known
- But see Kusenko Tuesday morning about the "proton tunnel"

Conclusions

- The CIRB has been detected in both the far IR and the near IR windows through the interplanetary dust, but measurements between 5-60 μm are impossible from 1 AU
- Bolometric OIR background is about 100 nW/m^2/sr
- Ratio of optical plus near IR to the far IR is about 2:1
- Biggest uncertainty is the zodiacal light, & DESIRE, LZM or ZEBRA would help.

Discussion: ΔX

- For UVO "Madau" curve, fuel burn over current energy density ratio is $f/U_o = 1.9$
- Current CIRB bolometric energy density is about 100 nW/m^2/sr
- Therefore $\Delta X = -0.033$
- Madau curve with Rowan-Robinson addon at high z burns more fuel at high redshift, so $f/U_o = 2.3$, $\Delta X = -0.04$
- At 1/3 solar from cluster gas, $\Delta X = -0.02$
- Do we need more baryons [CMB], more AGN, or less CIRB [zodi]?

White Dwarf Helium Reservoir?

- Oppenheimer *et al.* (2001) claim 3% of local halo in old WDs

$$\Delta X = -0.04h \, \frac{f_{WD}}{0.03} \, \frac{M_H}{5 \times 10^{11}} \, \frac{\ell_{\mathrm{ONIR}}}{5.6h \times 10^8} \, \frac{3 \times 10^{10}}{L_{\mathrm{MW}}}$$

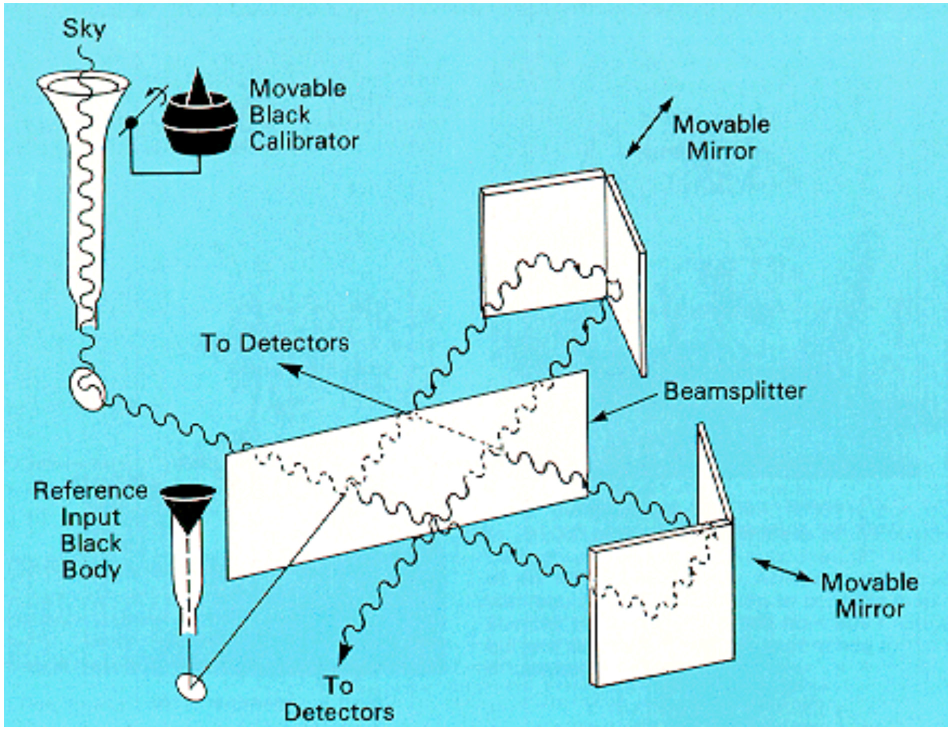
- BUT Richer on 2 Apr 2001 withdrew the claimed detection of faint, high proper motion stars in the HDF [astro-ph/9908270]
- The Oppenheimer *et al.* objects do not have a halo velocity distribution, and can not be part of a spherical halo.

REFERENCES

COSMOLOGY TUTORIAL:
http://www.astro.ucla.edu/~wright/cosmolog.htm
http://www.astro.ucla.edu/~wright/CIBR

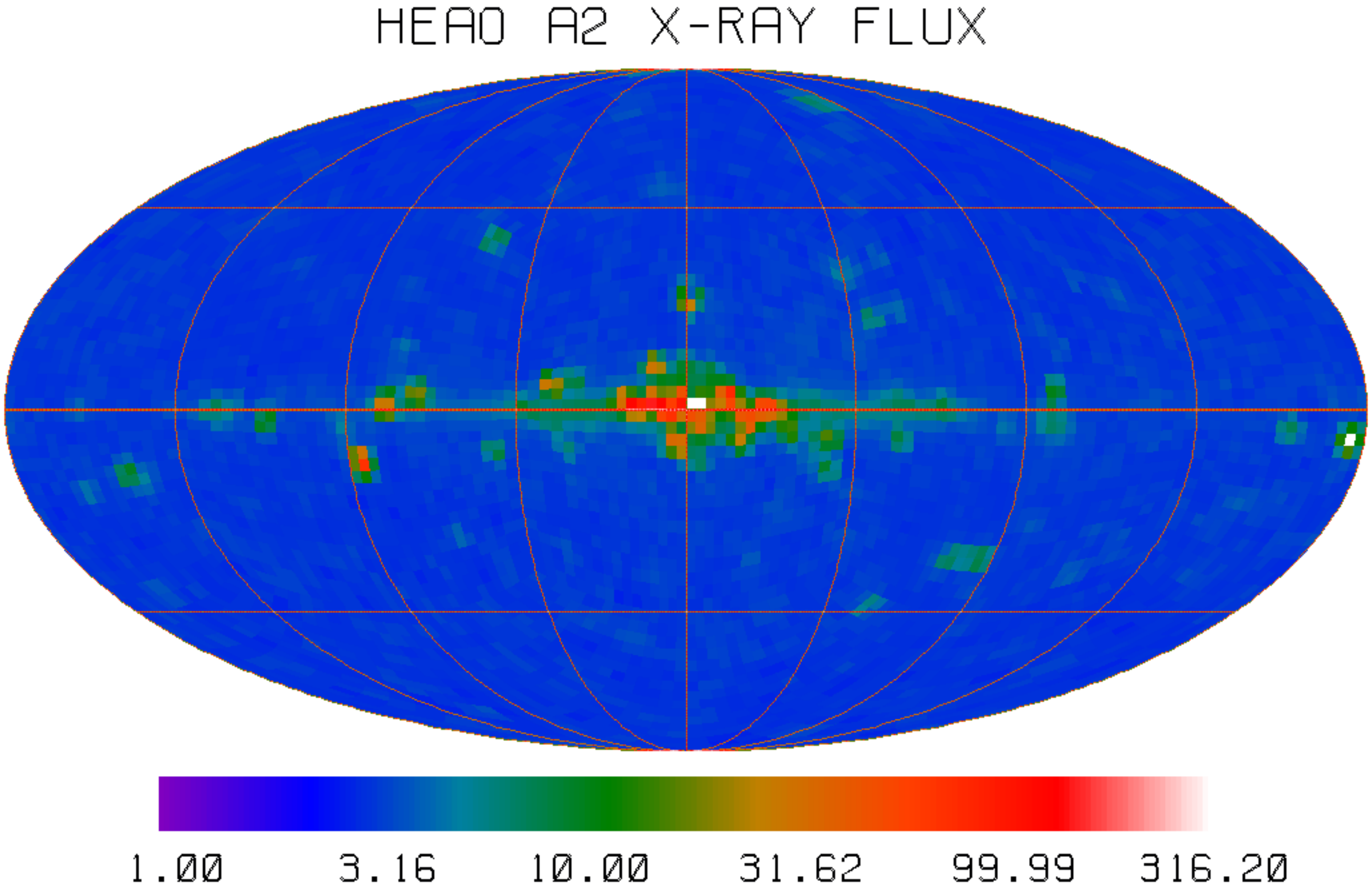
- DIRBE: http://www.astro.ucla.edu/∼wright/DIRBE/
- SIRTF: http://sirtf.caltech.edu/
- http://xxx.lanl.gov/abs/astro-ph/9909428 (Dark Spot)
- http://xxx.lanl.gov/abs/astro-ph/9912523 (Histogram)
- http://xxx.lanl.gov/abs/astro-ph/0004192 (2MASS)

FIRAS measured the CMB spectrum



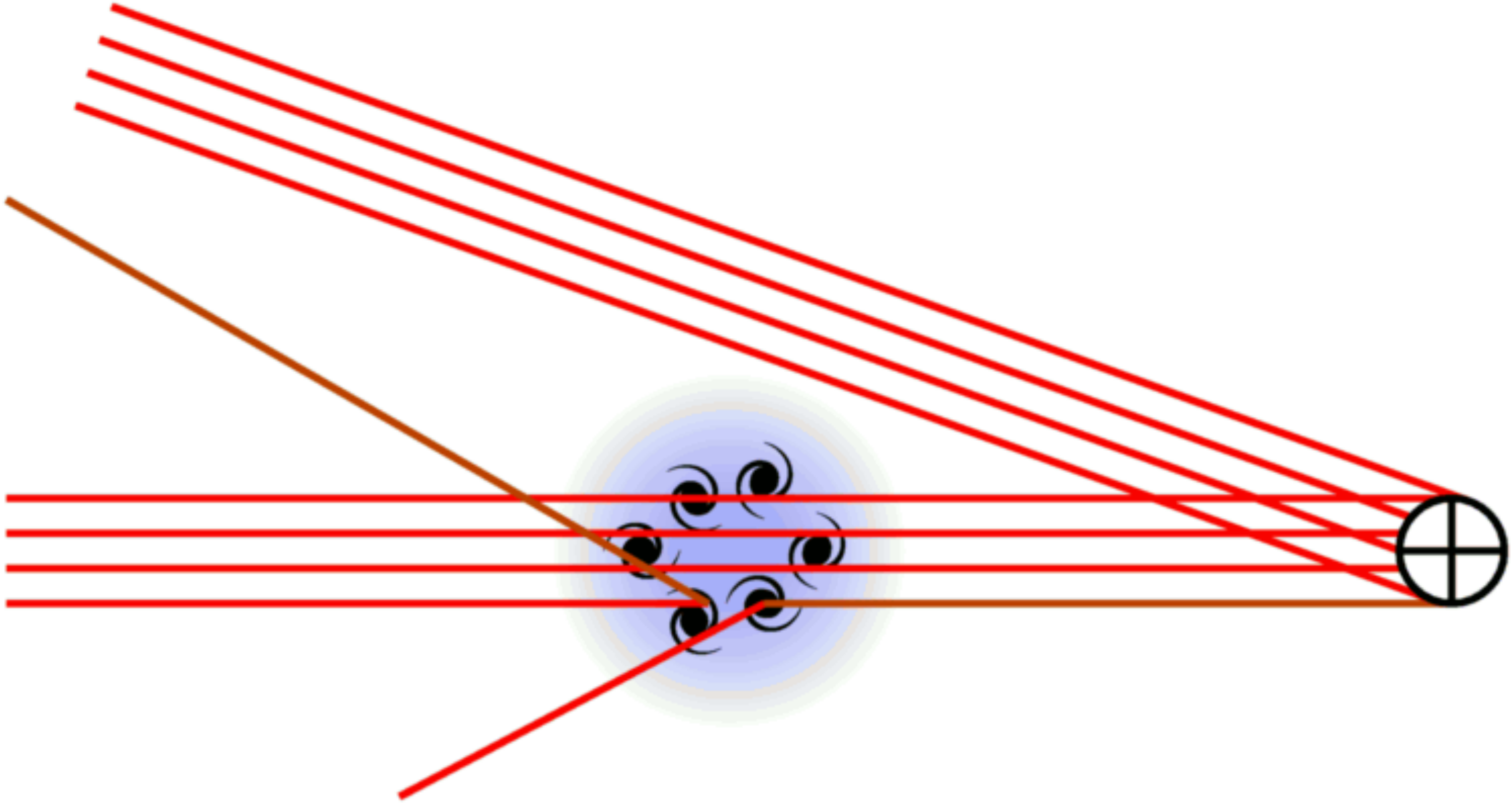
- Far InfraRed Absolute Spectrophotometer
- A differential polarizing Michelson interferometer
- Zero output when the two inputs are equal
- One input is either the sky or a very good blackbody, other is a pretty good blackbody

X-Ray Background



Hot diffuse plasma gives right spectrum but violates FIRAS limit on y. Source thought to be highly obscured AGNs.

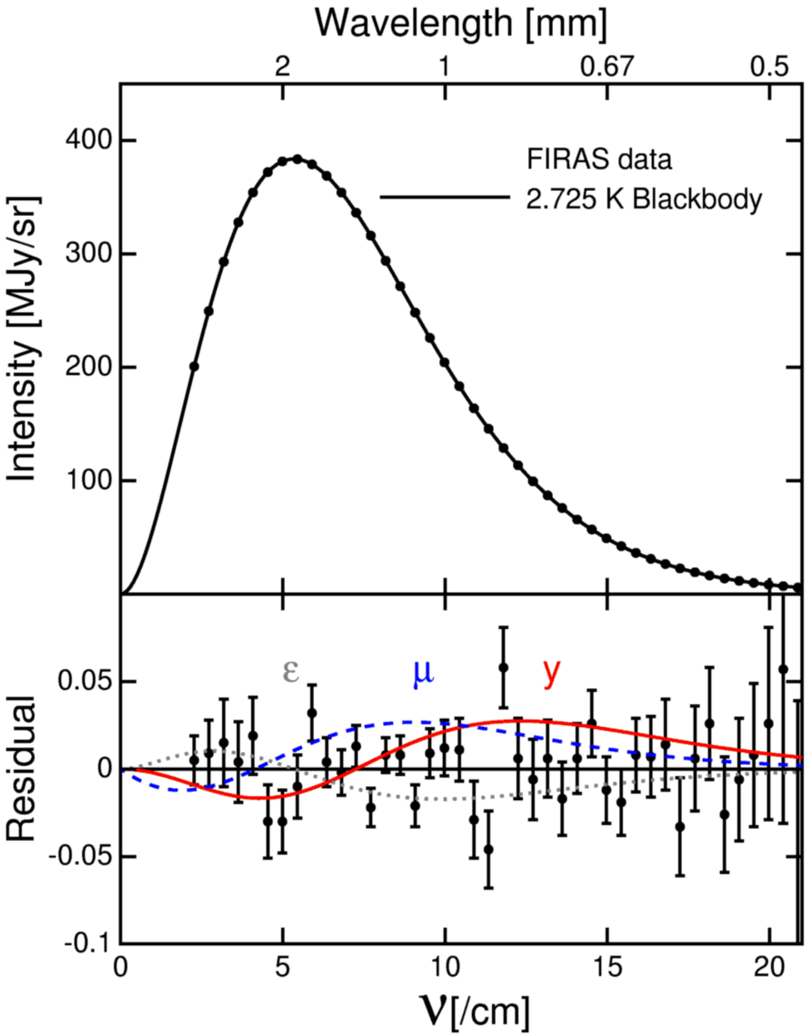
Sunyaev-Zeldovich Effect



Hot electrons increase high ν’s, decrease low ν’s

FIRAS Final Spectrum

- SZ Effect $\propto$ $y = N_e \sigma_T k T_e / m_e c^2 < 15 \times 10^{-6}$
- Bose-Einstein $\mu < 9 \times 10^{-5}$
- Energy from hot electrons into CMB < 60 parts per million



FIRAS Far IR Background

- Any proposed FIR background must be compatible with the limits on the CMB distortion.
- This means the FIRB is either small or similar to the galactic spectrum.
- The FIRAS fit to the $N_H = 0$ intercept of the high frequency channel, [astro-ph/9803021]

$$I_\nu = 1.3\times10^{-5}(\nu/100)^{0.64}B_\nu(18.5\ \mathrm{K}),$$

fails with $\Delta\chi^2 = 22.6$ (4.75 σ)

No simple limit at 850 μm

- FIRAS fit fails with $\Delta\chi^2 = 22.6$ but
  $I_{850} = 143$ kJy/sr
- Lagache *et al*. fit [astro-ph/9901059] is marginal with $\Delta\chi^2 = 5.8$ but
  $I_{850} = 115$ kJy/sr
- The modified scaled Primack model on the next slide is fine with $\Delta\chi^2 = 2.2$ but
  $I_{850} = 195$ kJy/sr

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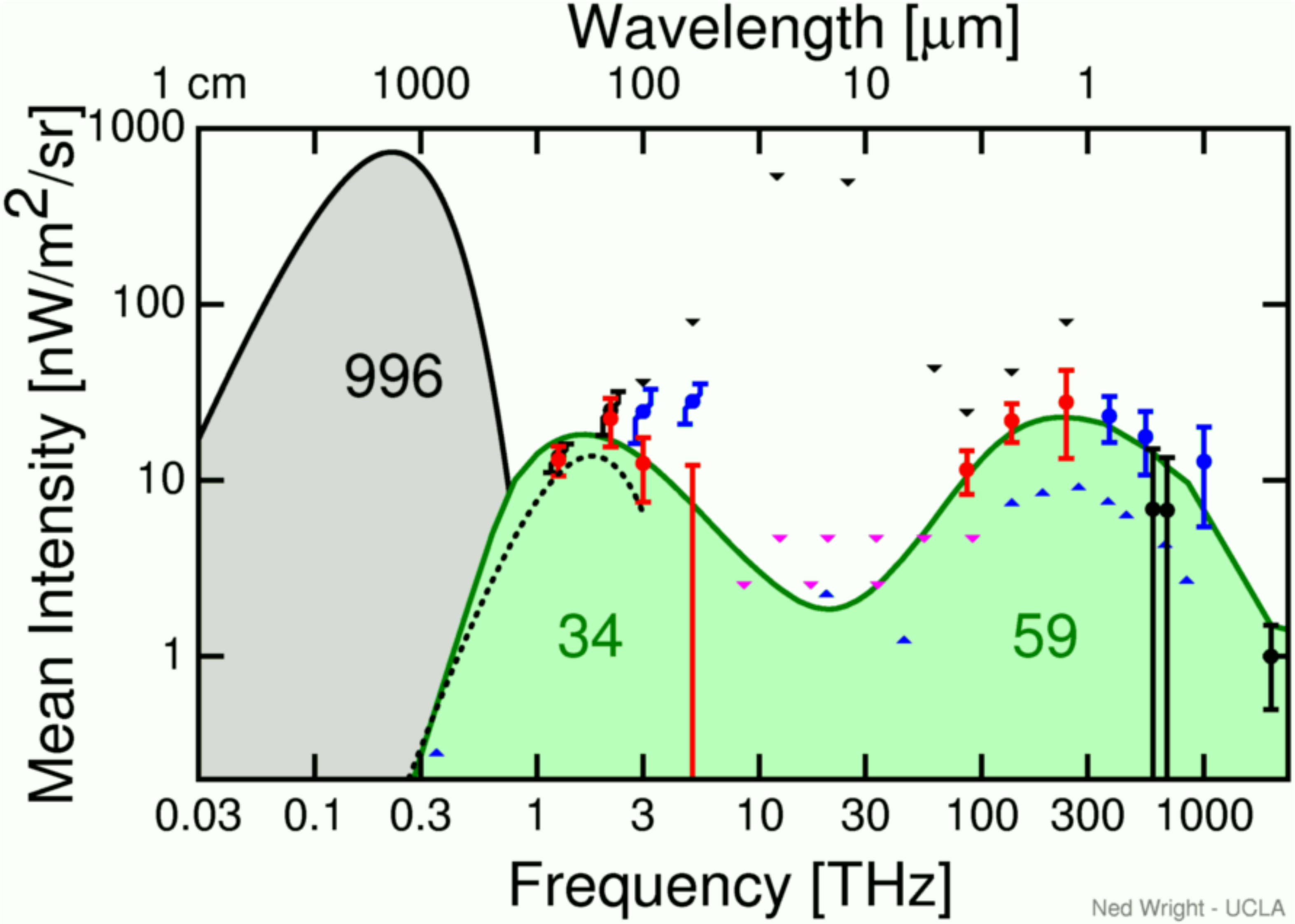

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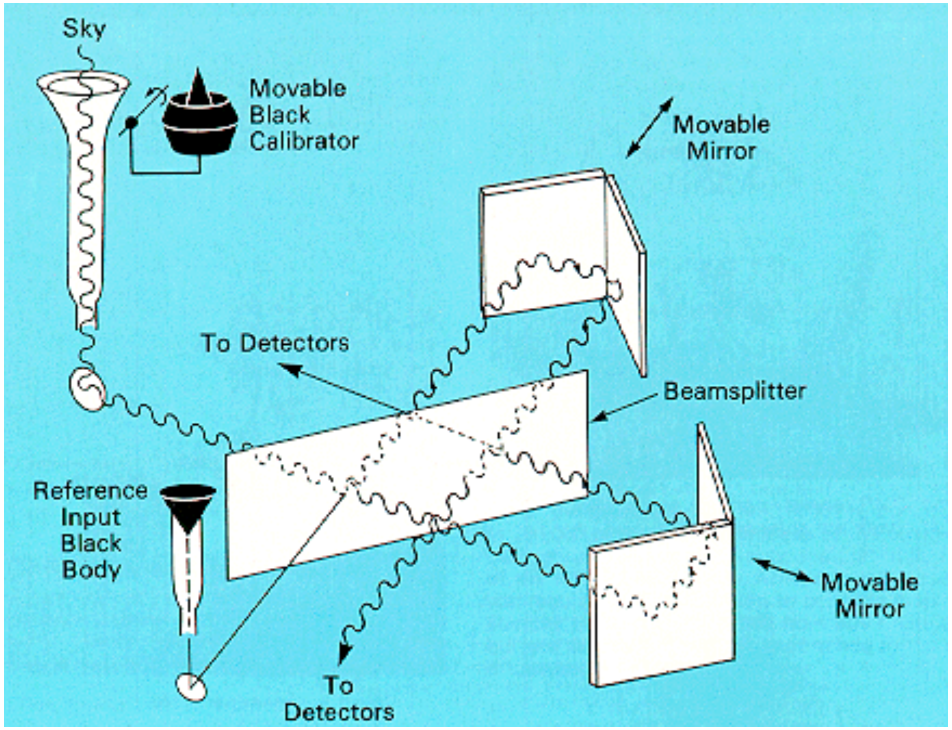

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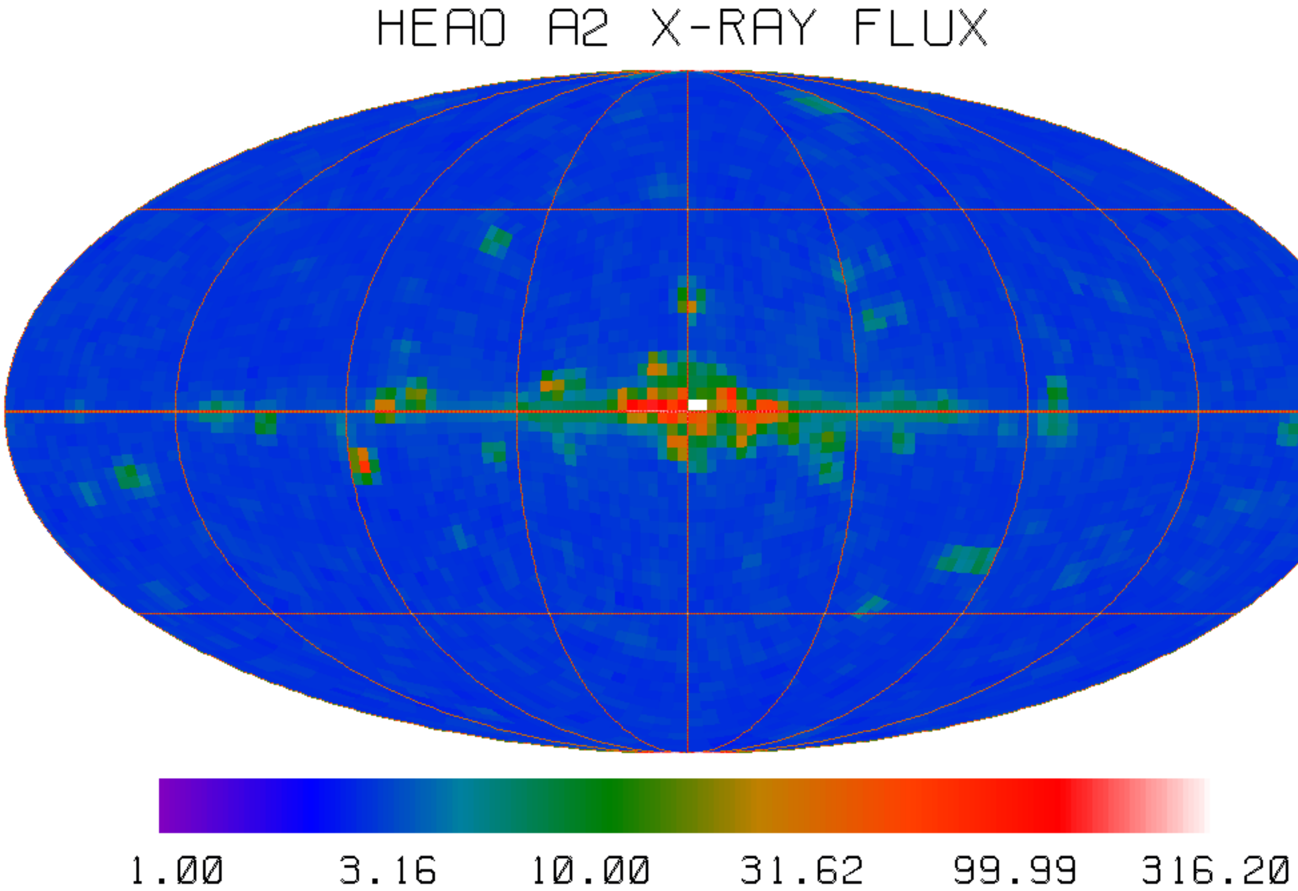

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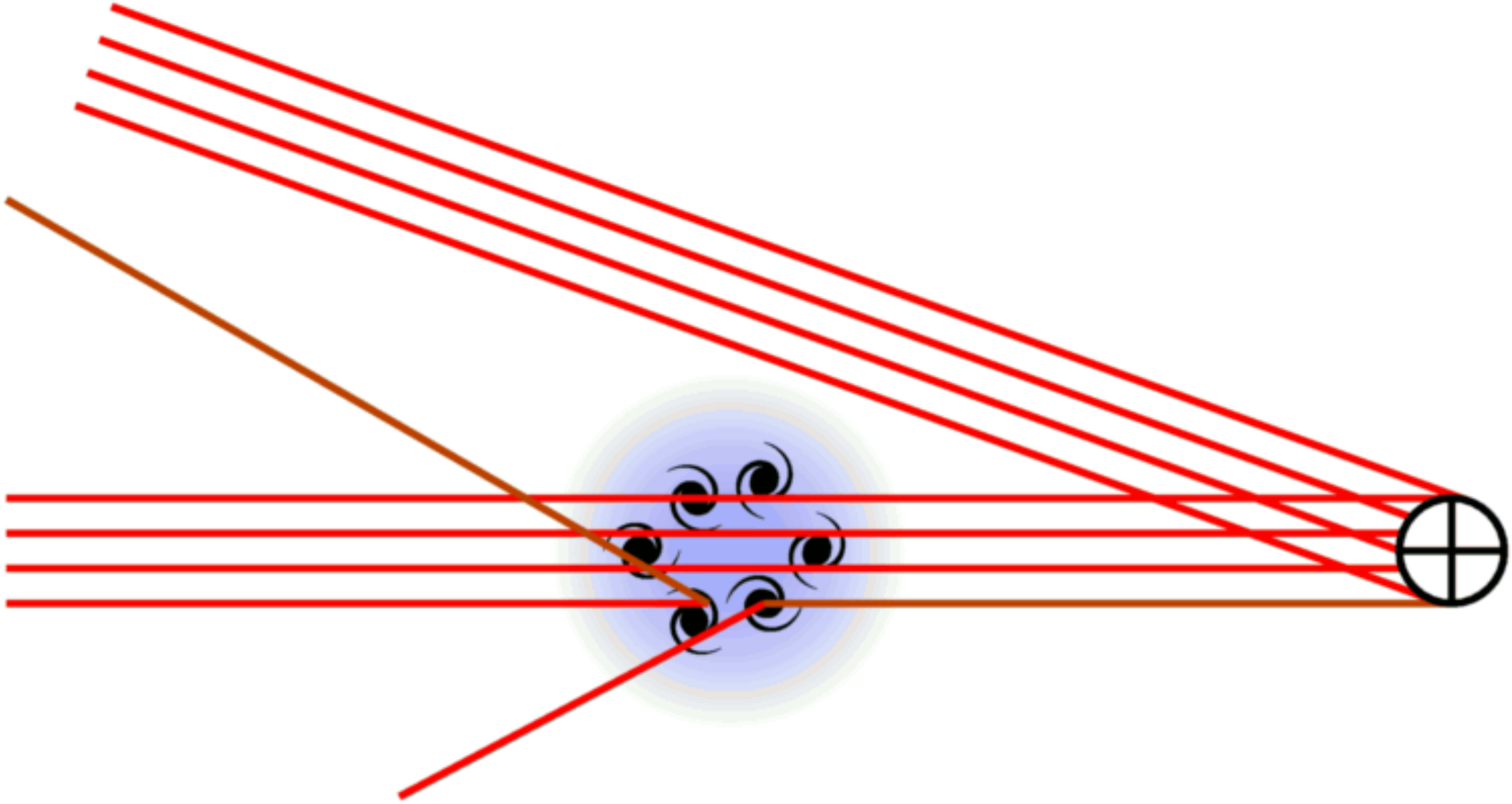

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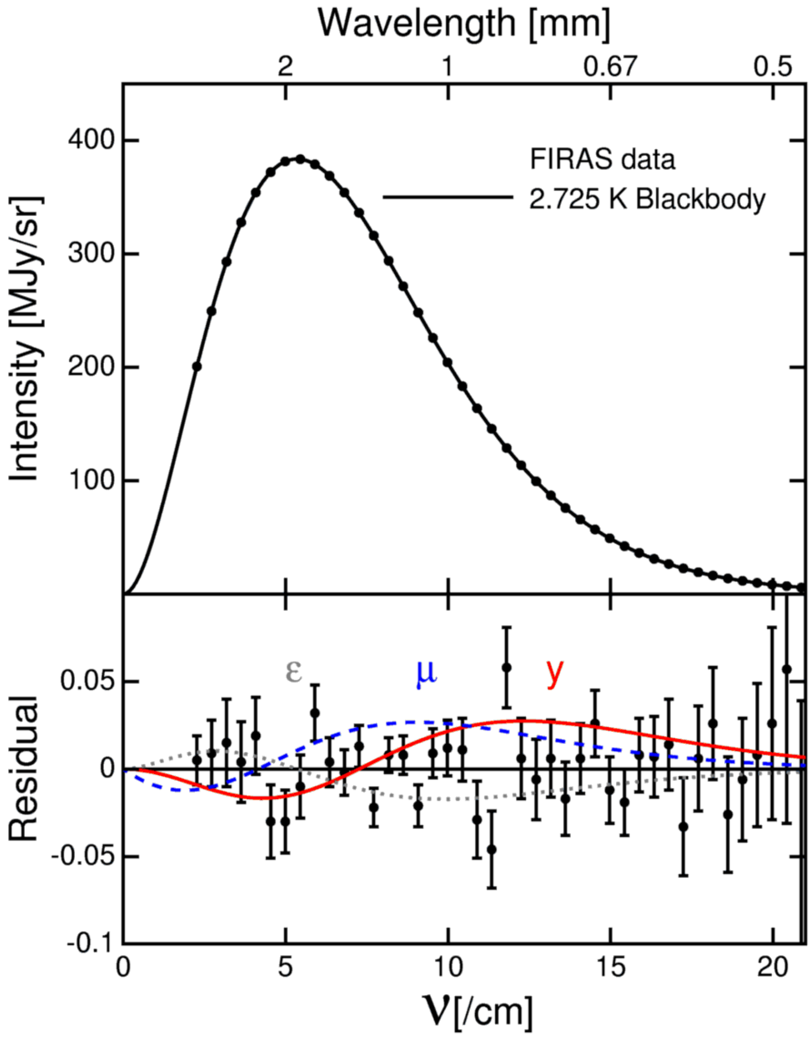

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