

A Journey into the Full CMB Secondary Tomography

Milky Way Dust

- Chiang & Menard **2019**, ApJ, 870, 2, 120
- Chiang **2023**, ApJ, 958, 2, 118

Thermal SZ History

- Chiang+ **2020**, ApJ, 902, 1, 56
- Chiang+ **2021**, ApJ, 910, 1, 32

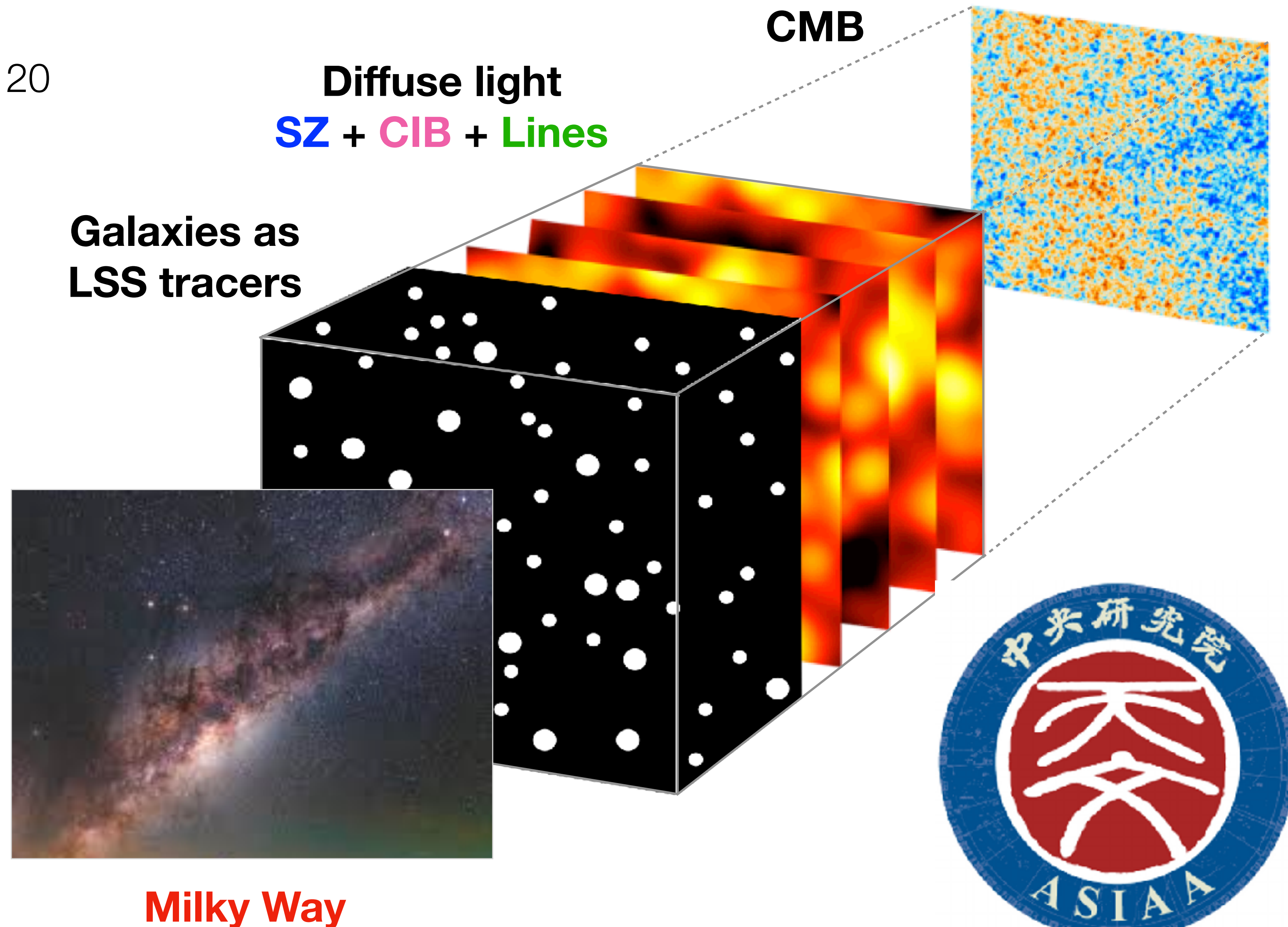
CIB, Cosmic Dust & Star-Formation

- Chiang+ **2025** ApJ, 992, 1, 651

CO & CII Lines for Cosmic Gas

- Chiang, under review.

Yi-Kuan Chiang
ASIAA



Long-term interest: cosmic energy inventory

Fukugita & Peebles 2004



ABSTRACT

We present an inventory of the cosmic mean densities of energy associated with all the known states of matter and radiation at the present epoch. The observational and theoretical bases for the inventory have become rich enough to allow estimates with observational support for the densities of energy in some 40 forms. The result is a global portrait of the effects of the physical processes of cosmic evolution.

$$\Omega_x \equiv \rho_x / \rho_{\text{crit},0}$$

x = dark energy, dark matter, light, stars, neutrinos...

F&P compiled 40 Ω_x at $z = 0$ — Summary of the present Universe

My goal: evolution of the cosmic inventory and energy transport

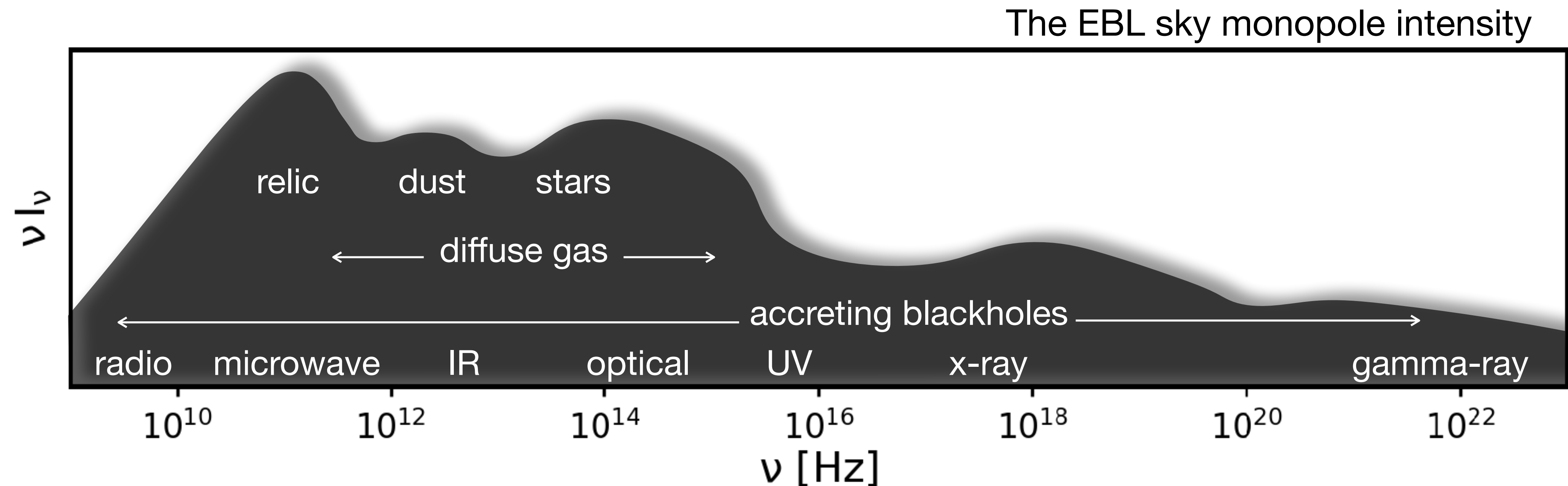
$$\Omega_x(z)$$

$$\dot{\Omega}_x(z)$$

$$\Omega_1(z) \longrightarrow \Omega_2(z)$$

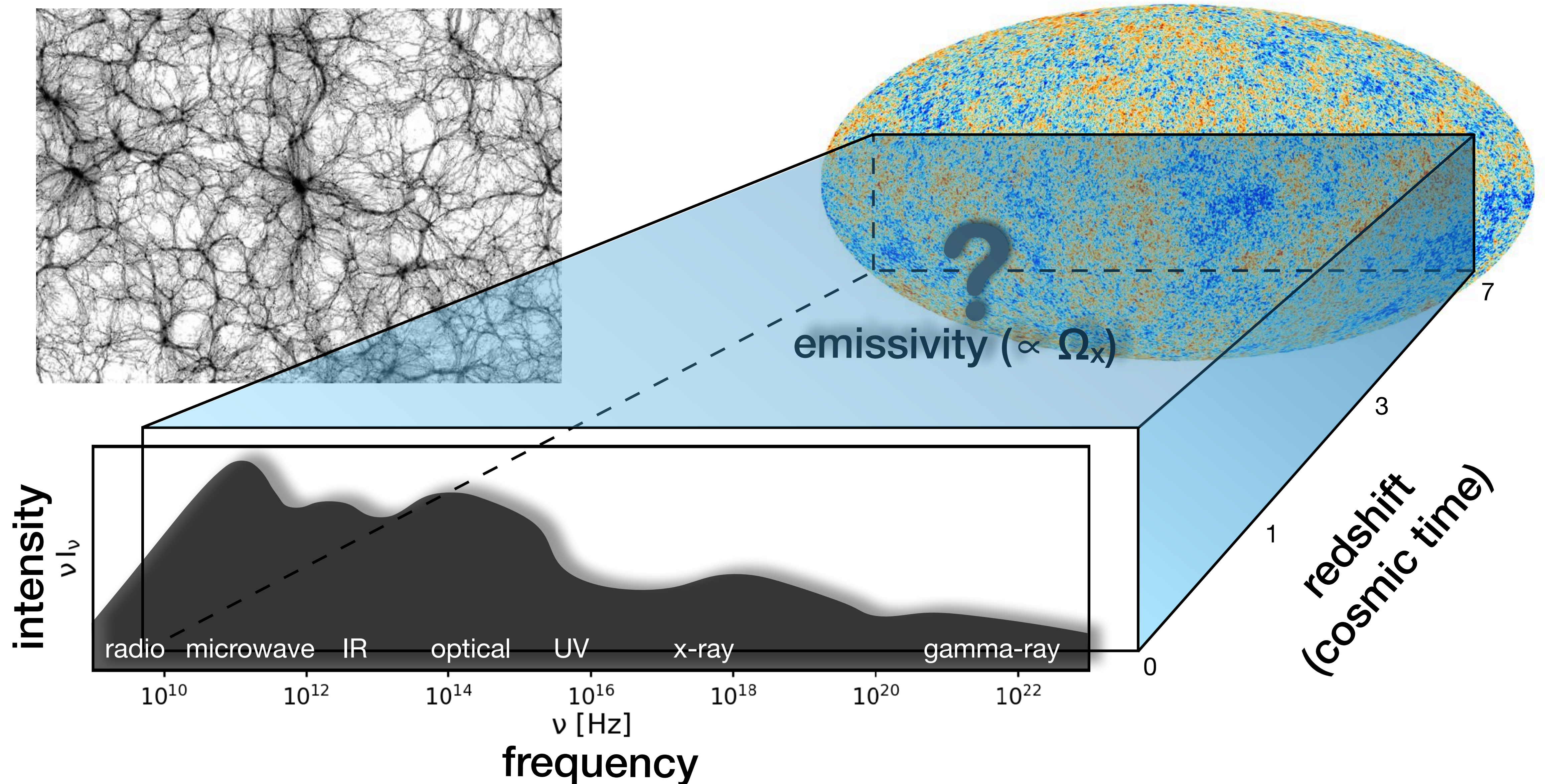
Messenger: extragalactic background light (EBL)

The integrated radiation from all sources in the Universe



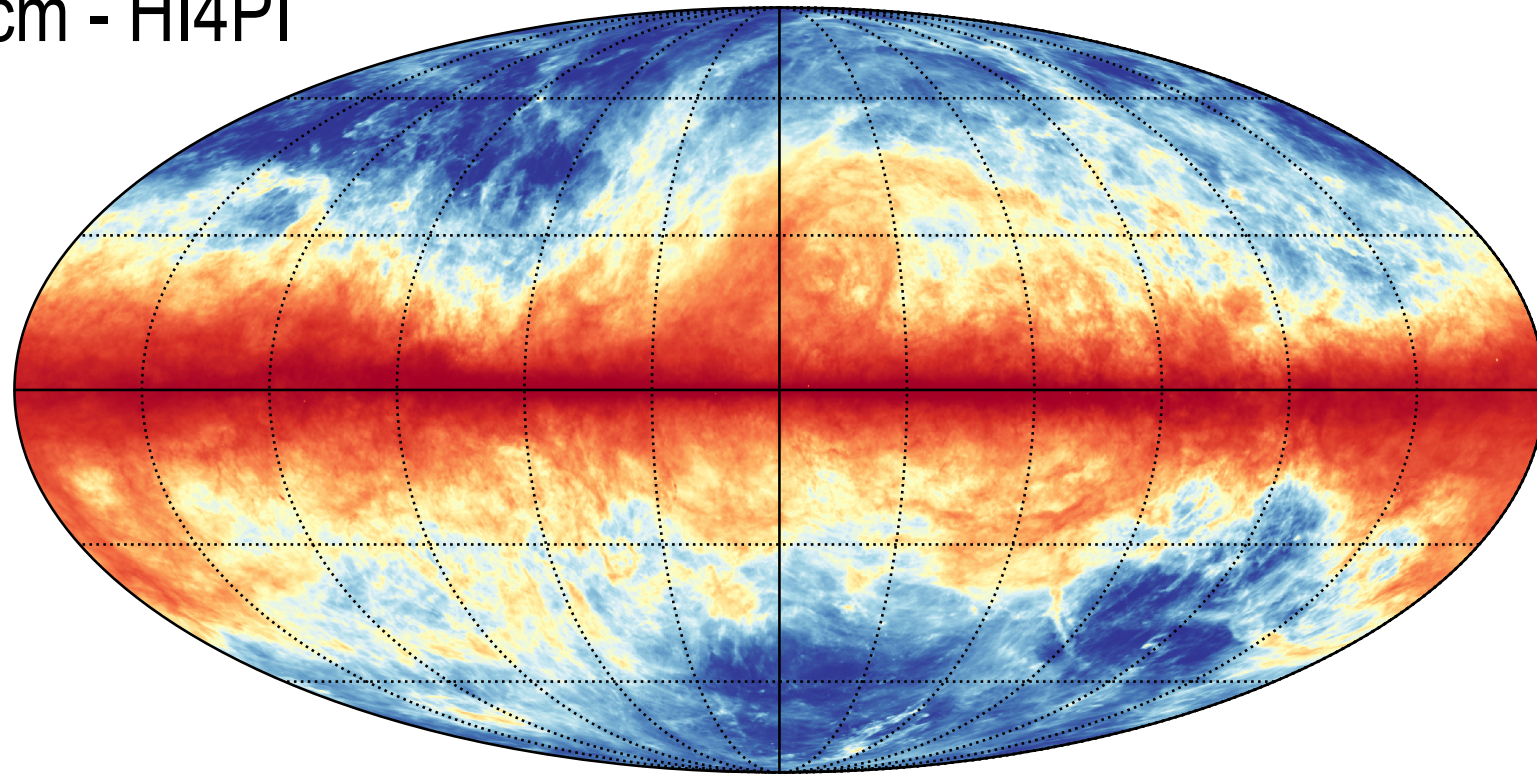
EBL is $\Omega_{\text{radiation}}$. It also informs about stars, dust, gas... if we know the radiative mechanisms

Big challenge in astronomy — projection effects

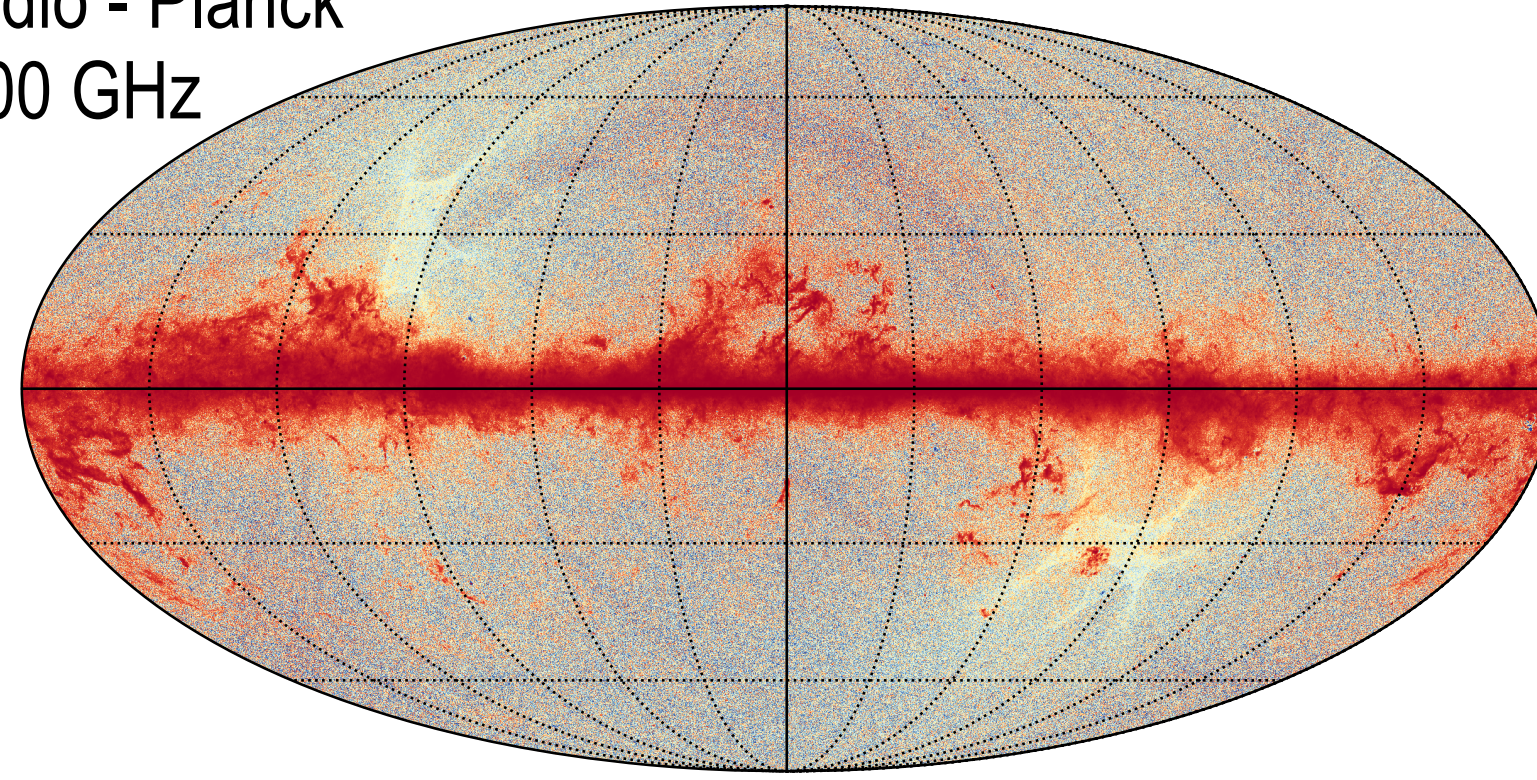


Data: Multiwavelength maps of the diffuse sky

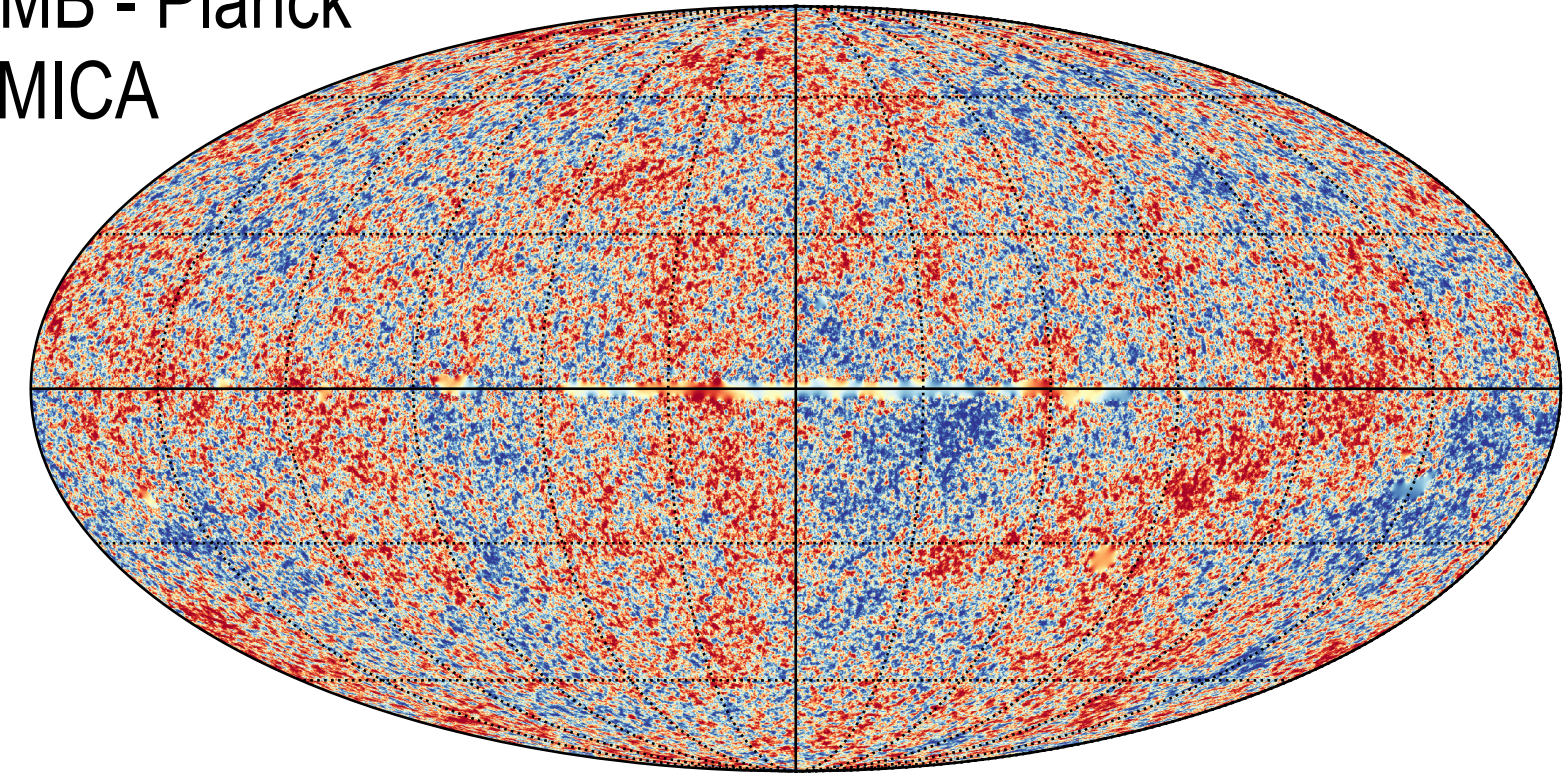
21 cm - HI4PI



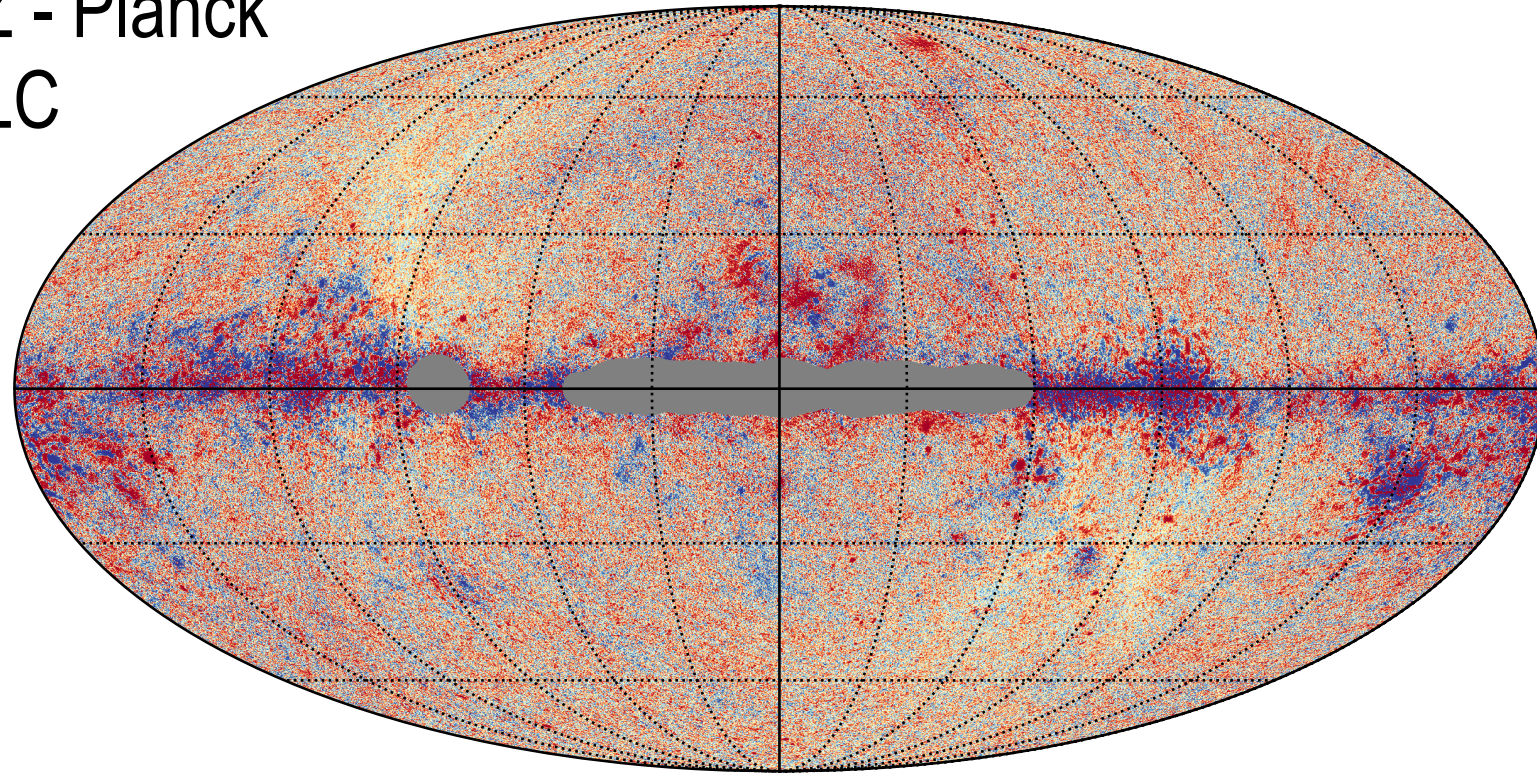
radio - Planck
100 GHz



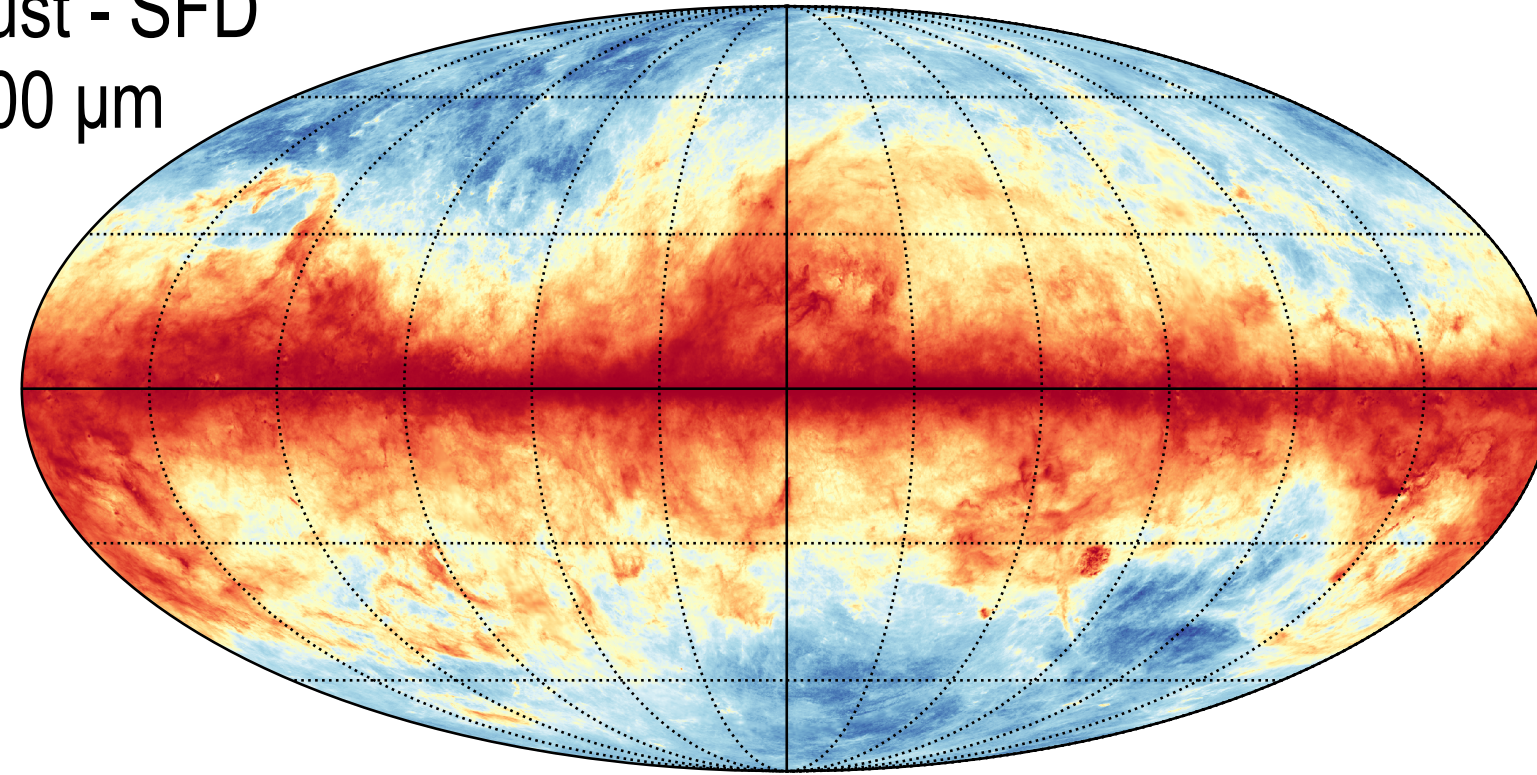
CMB - Planck
SMICA



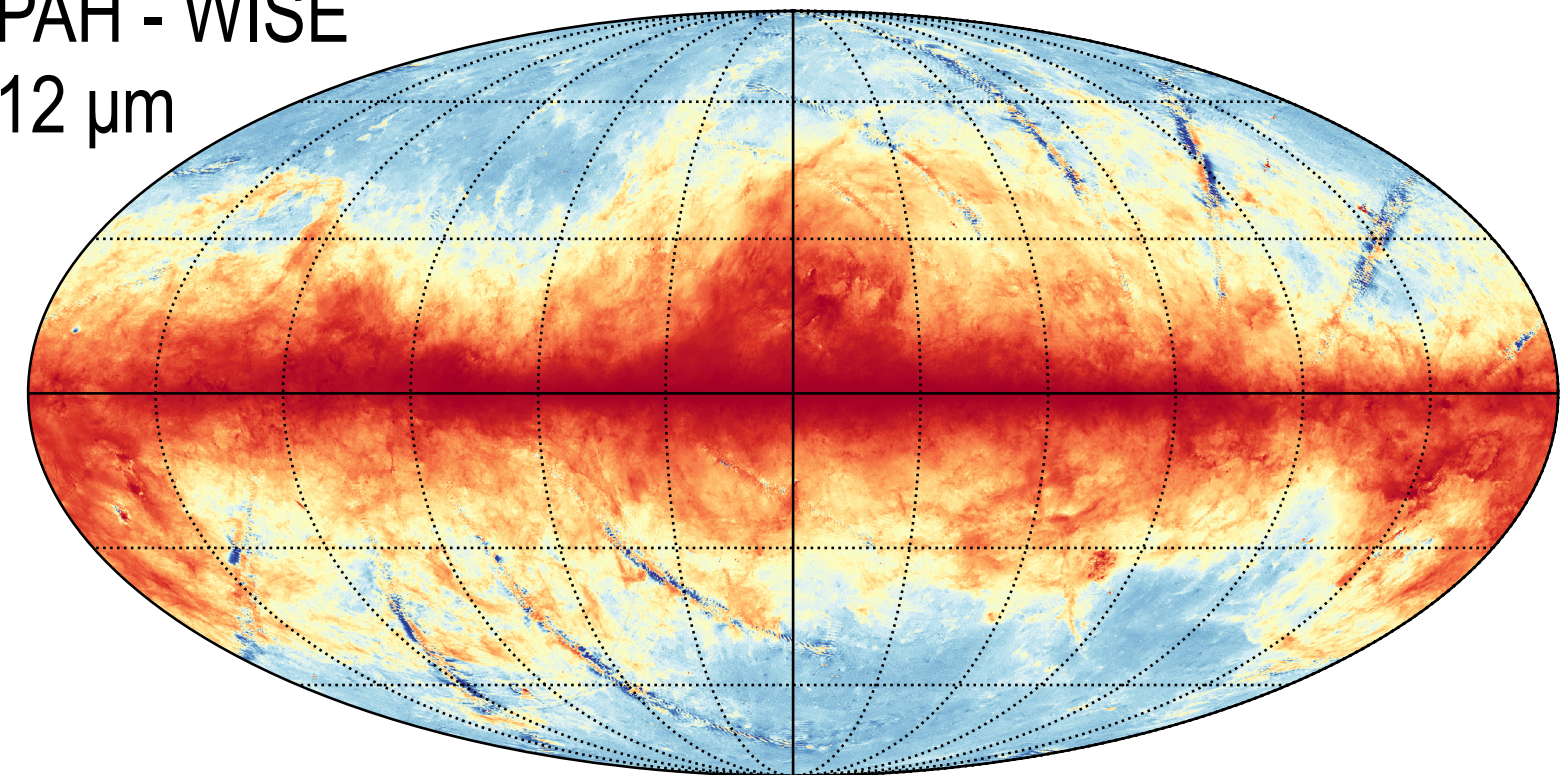
tSZ - Planck
NILC



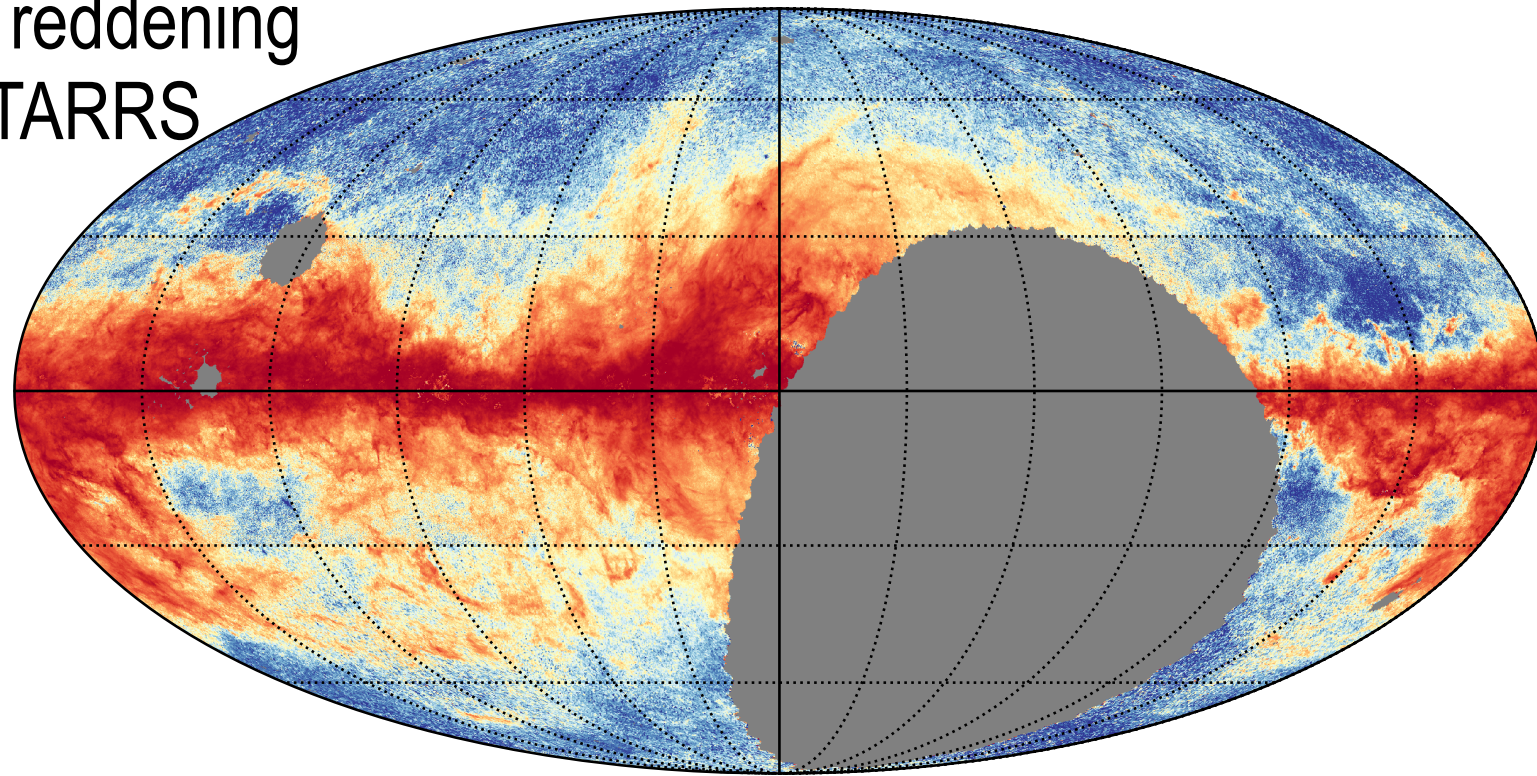
dust - SFD
100 μ m



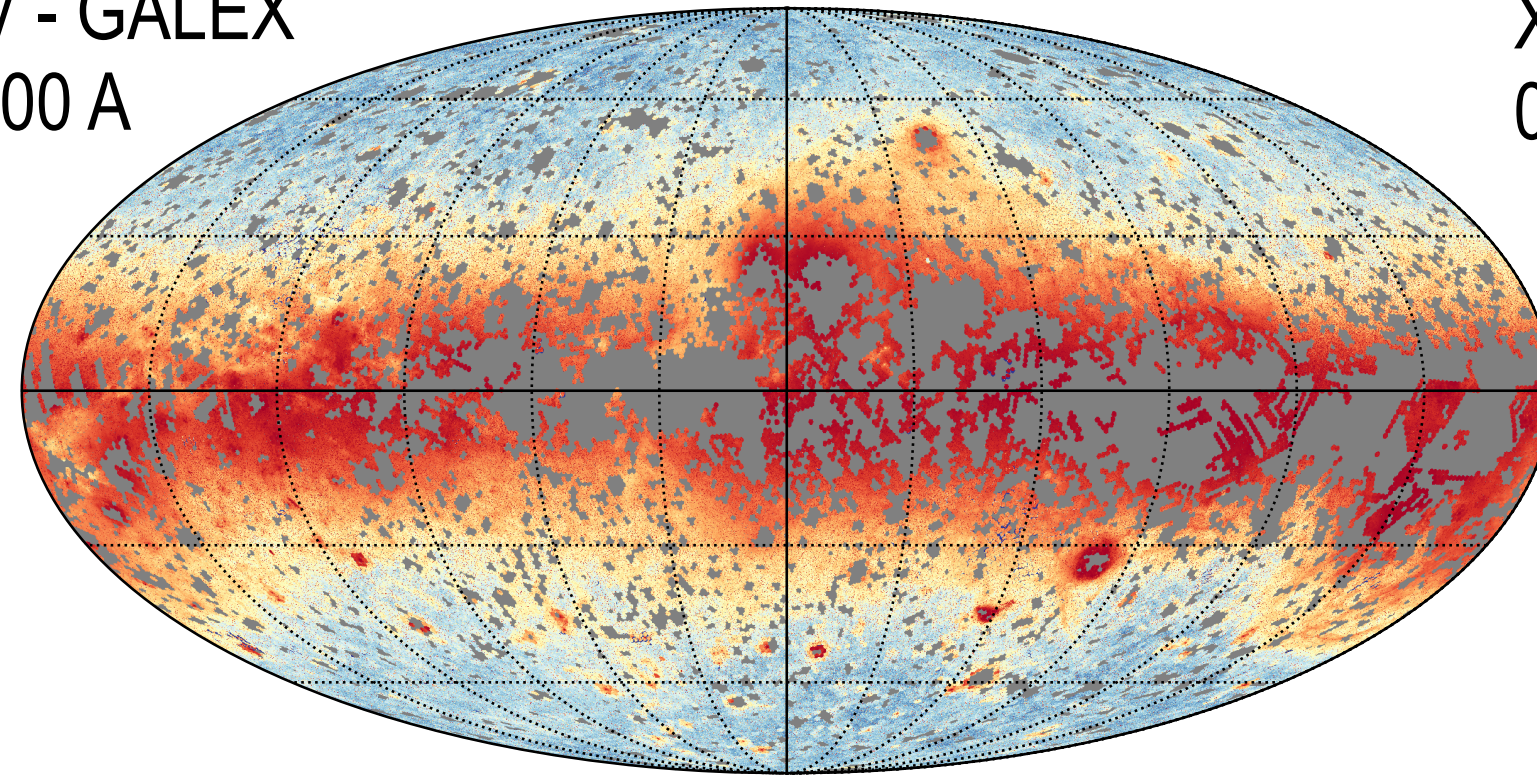
PAH - WISE
12 μ m



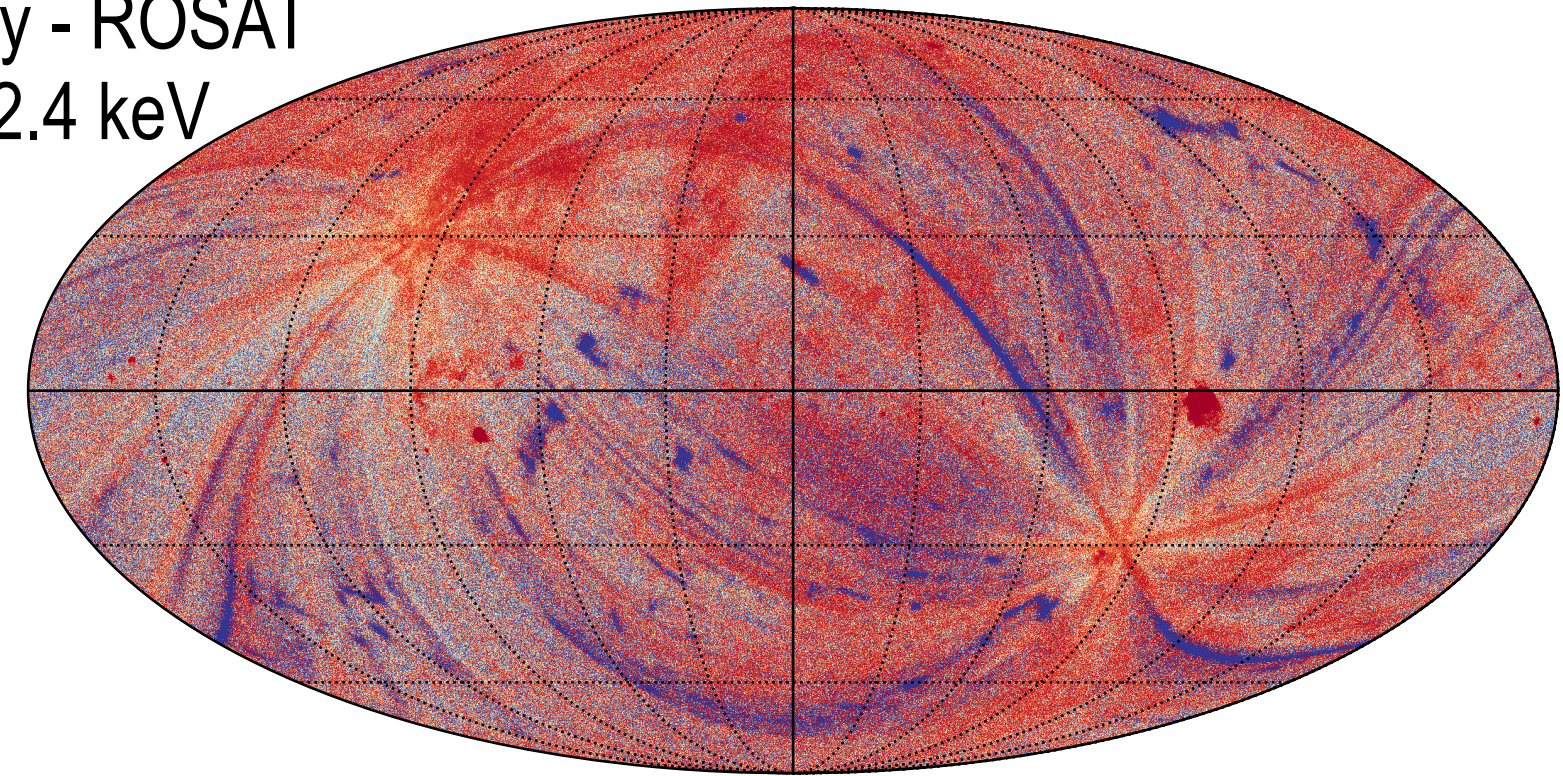
optical reddening
Pan-STARRS



UV - GALEX
2300 Å



X-ray - ROSAT
0.1-2.4 keV



CMB secondary tomography

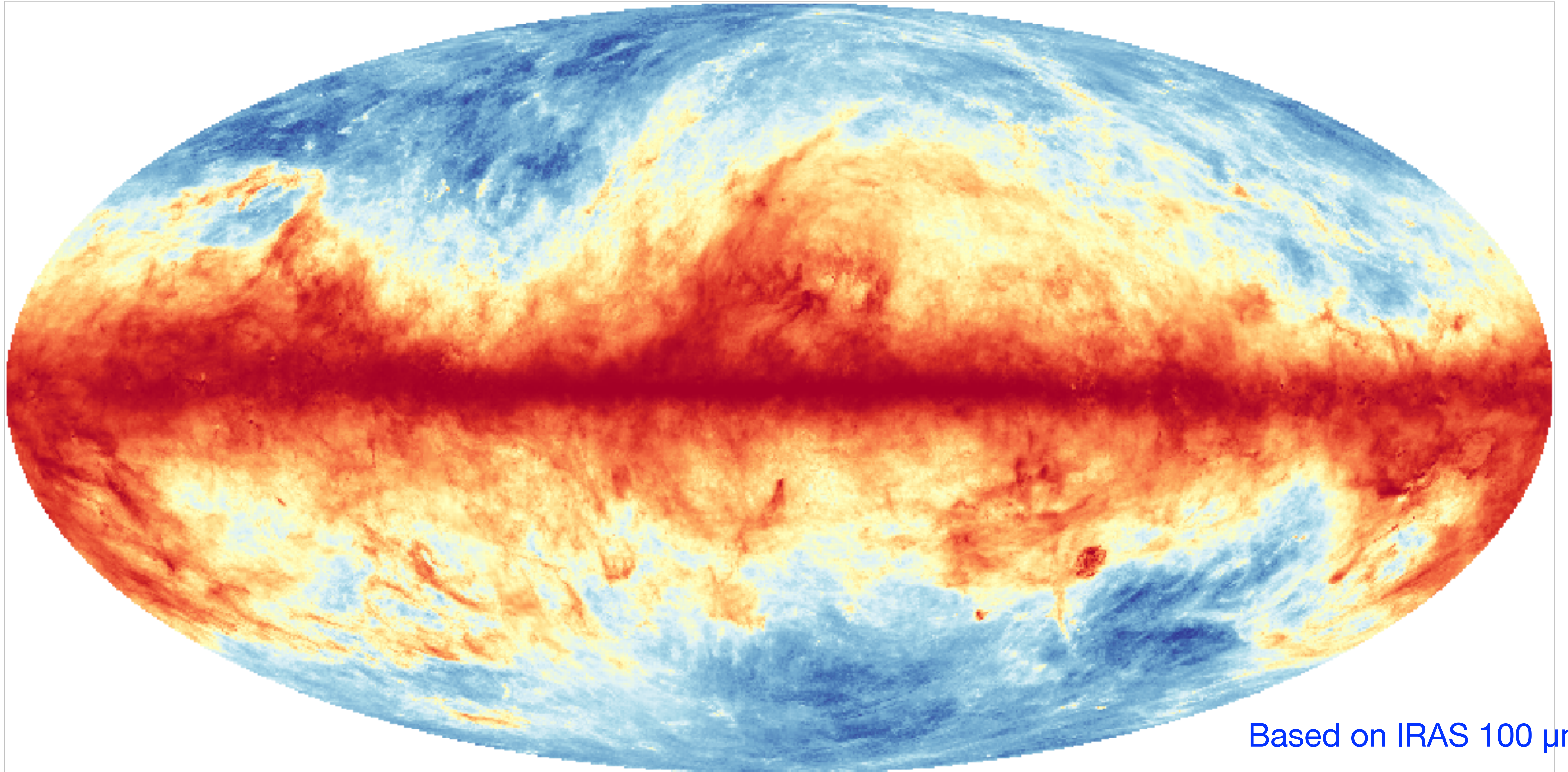
- **Milky Way Dust**
- Sunyaev–Zeldovich Effect
- Cosmic Infrared Background
- Lines

Milky Way dust



Schlegel, Finkbeiner, Davis (SFD) 1998 dust map

Key for extinction correction for UV-Opt-NIR astronomy (13810 citations and growing)



Schlegel, Finkbeiner, Davis (SFD) 1998 dust map

Key for extinction correction for UV-Opt-NIR astronomy (13810 citations and growing)

Stacking galaxies reveals the CIB

Kashiwagi+13

$N_g=1099475$

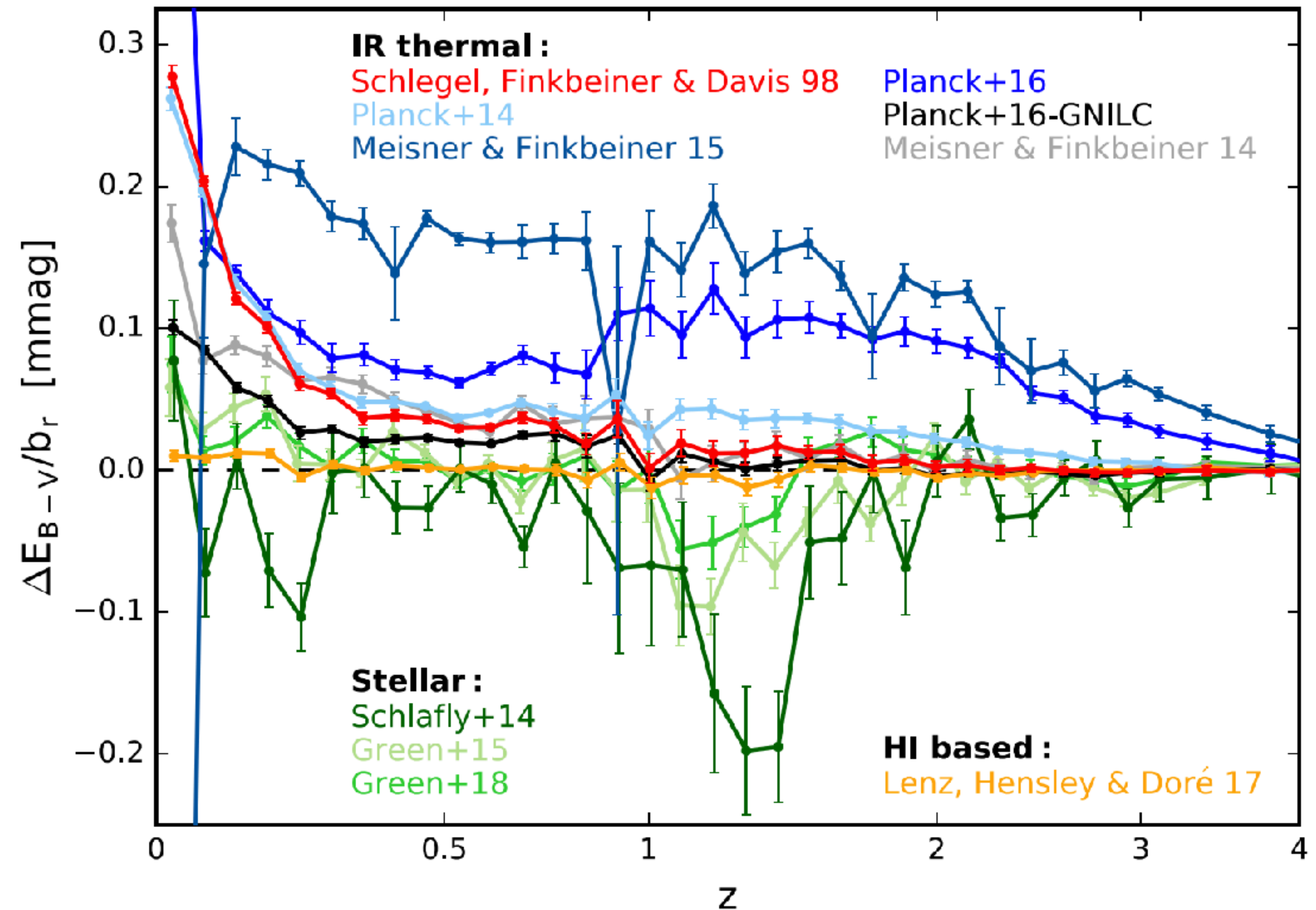
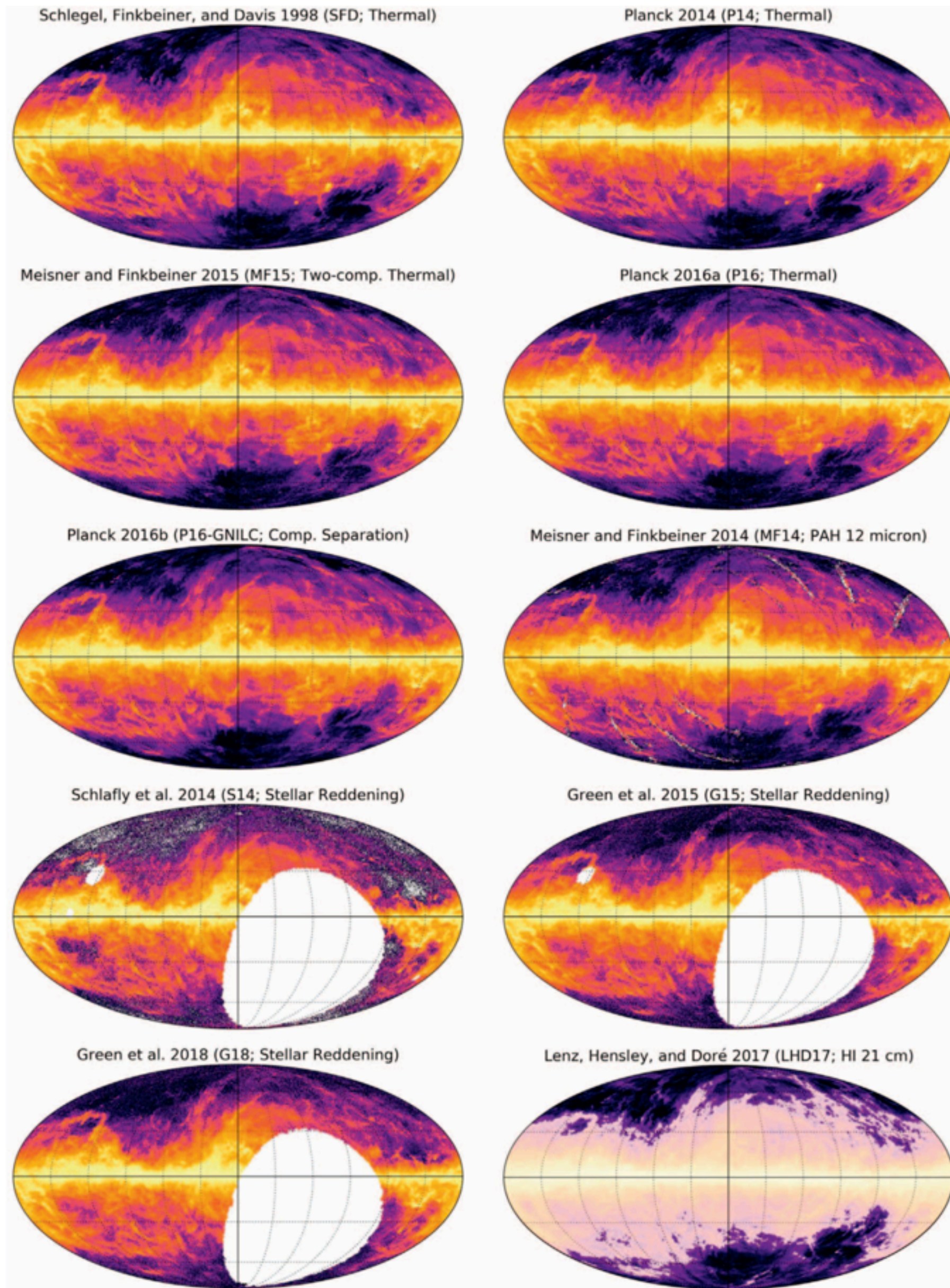
$m_r=18.5-19.0$

$\Delta E(B-V)$ due to CIB

Based on IRAS 100 μm

All dust maps contaminated by CIB & LSS, biasing cosmology

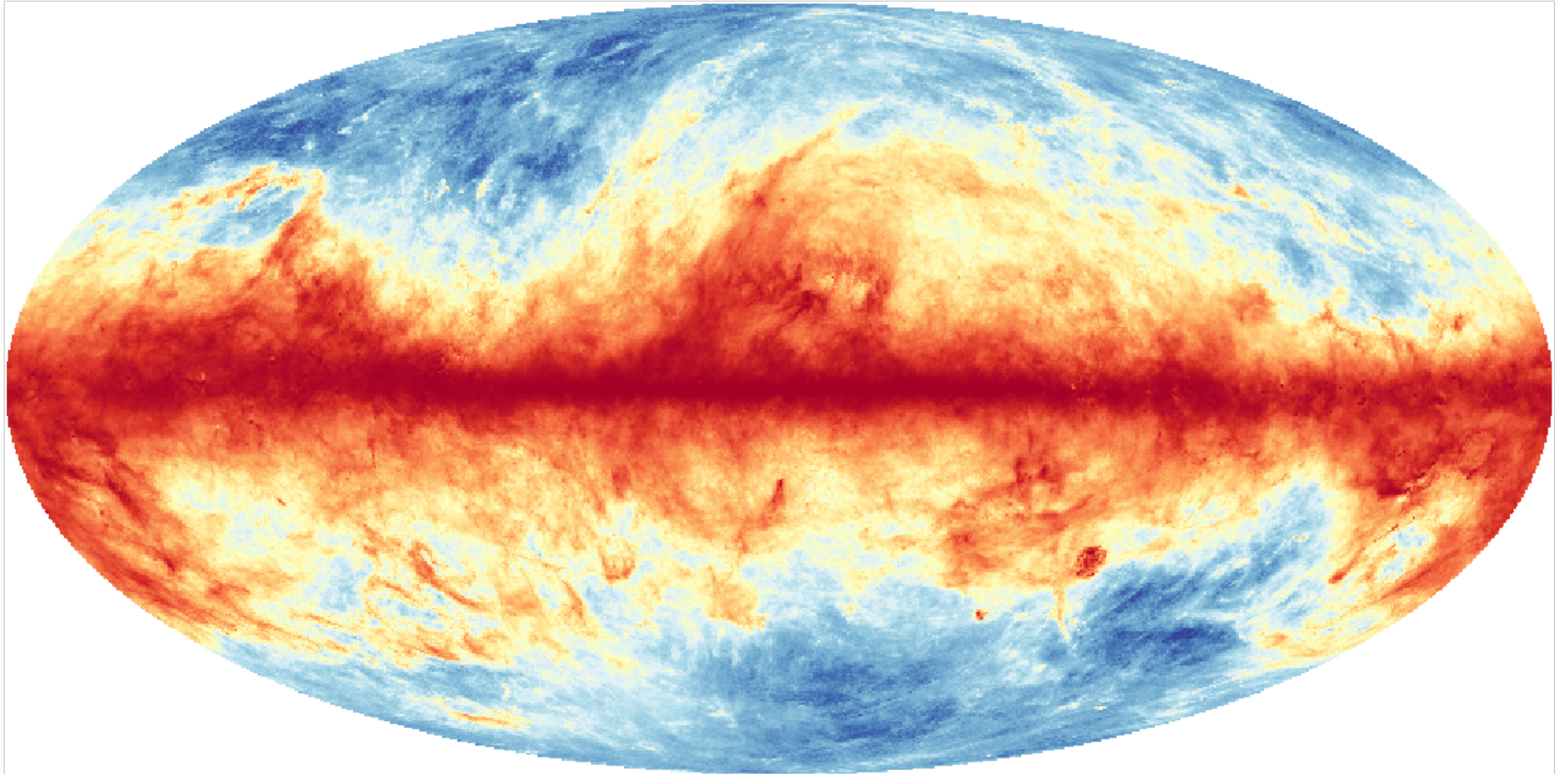
Chiang & Menard 19



Extinction over-correction (similar to lensing but unphysical)
Bias supernova cosmology, galaxy clustering, & lensing...

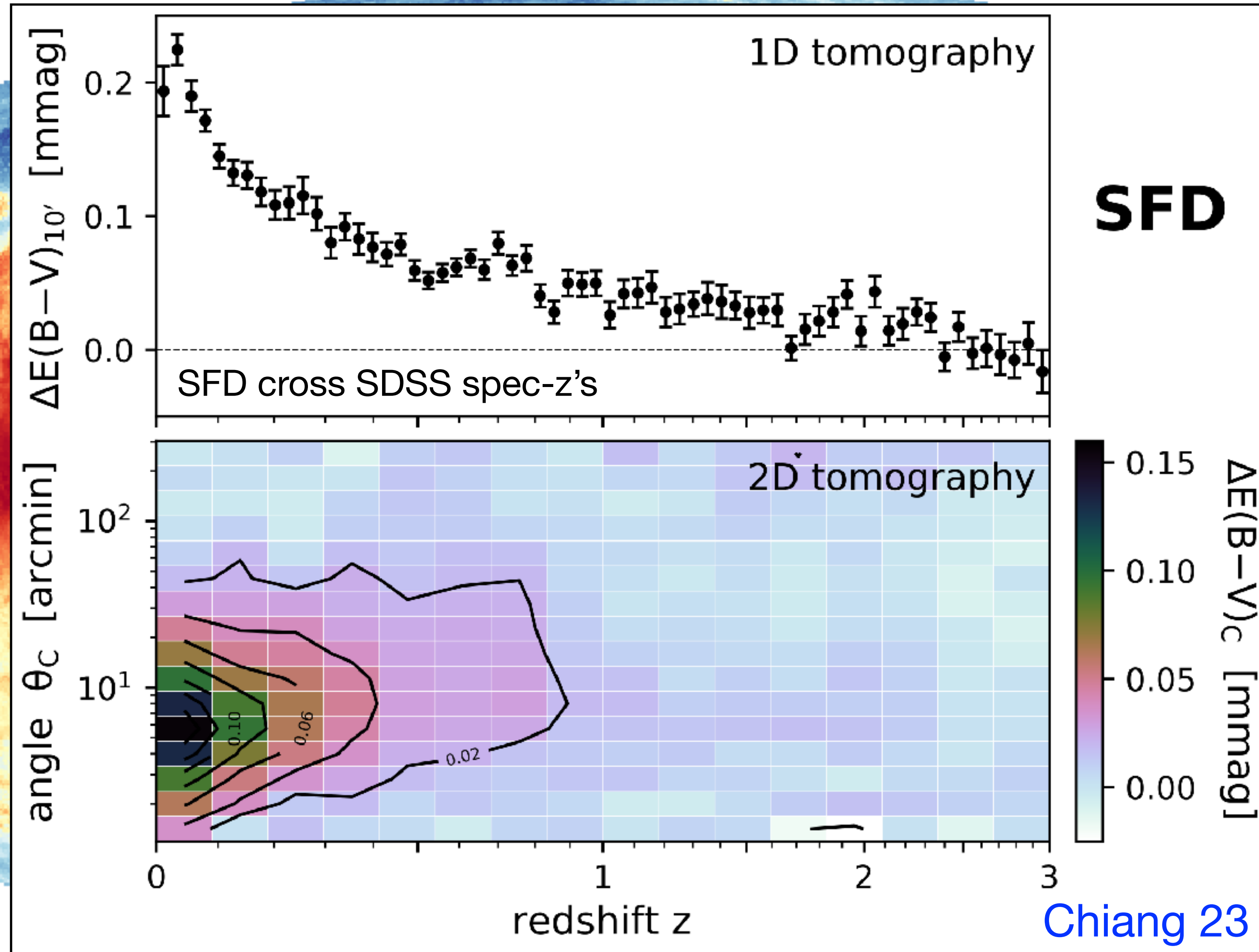
CIB $\ll$ Milky Way but noticeable. How to remove it?

1. Cross-correlation tomography to exhaust all 2-pt statistics



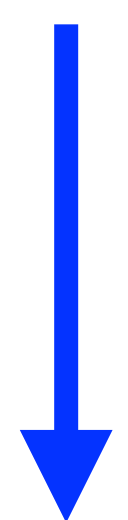
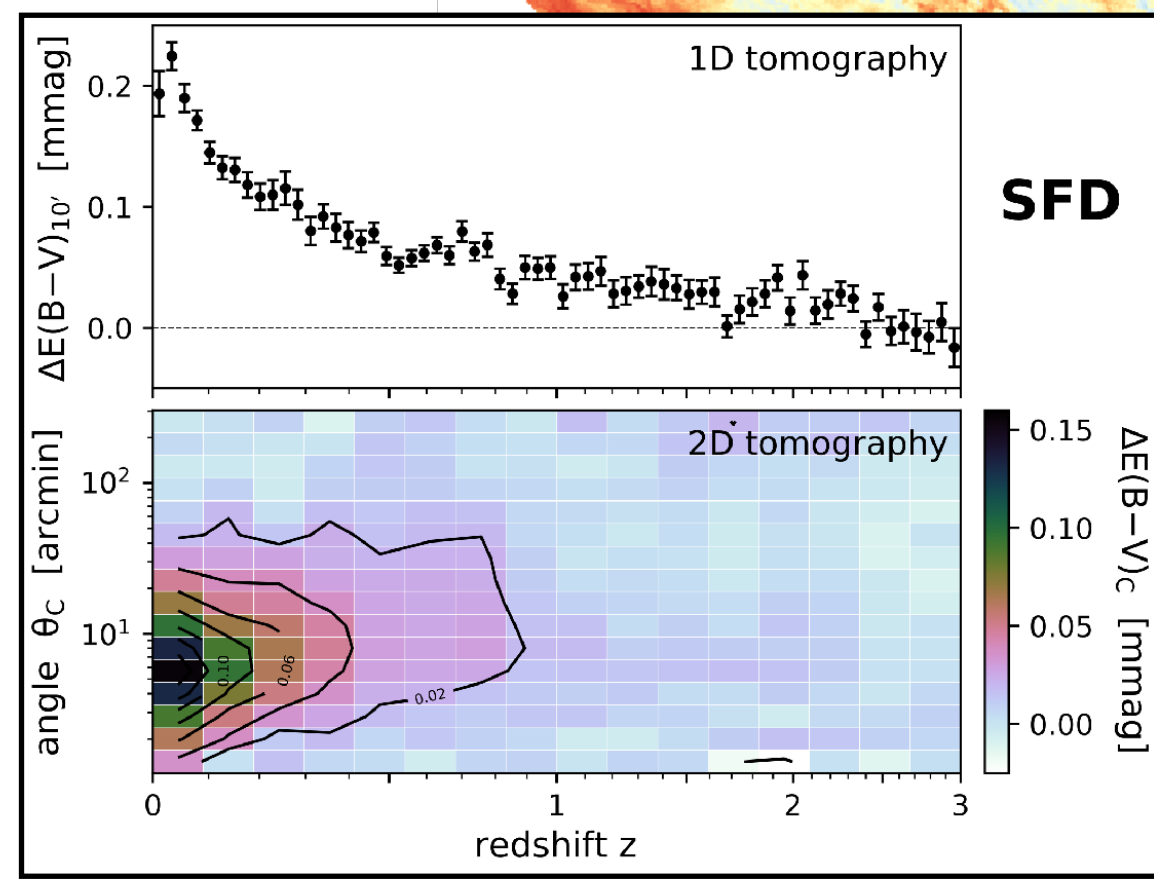
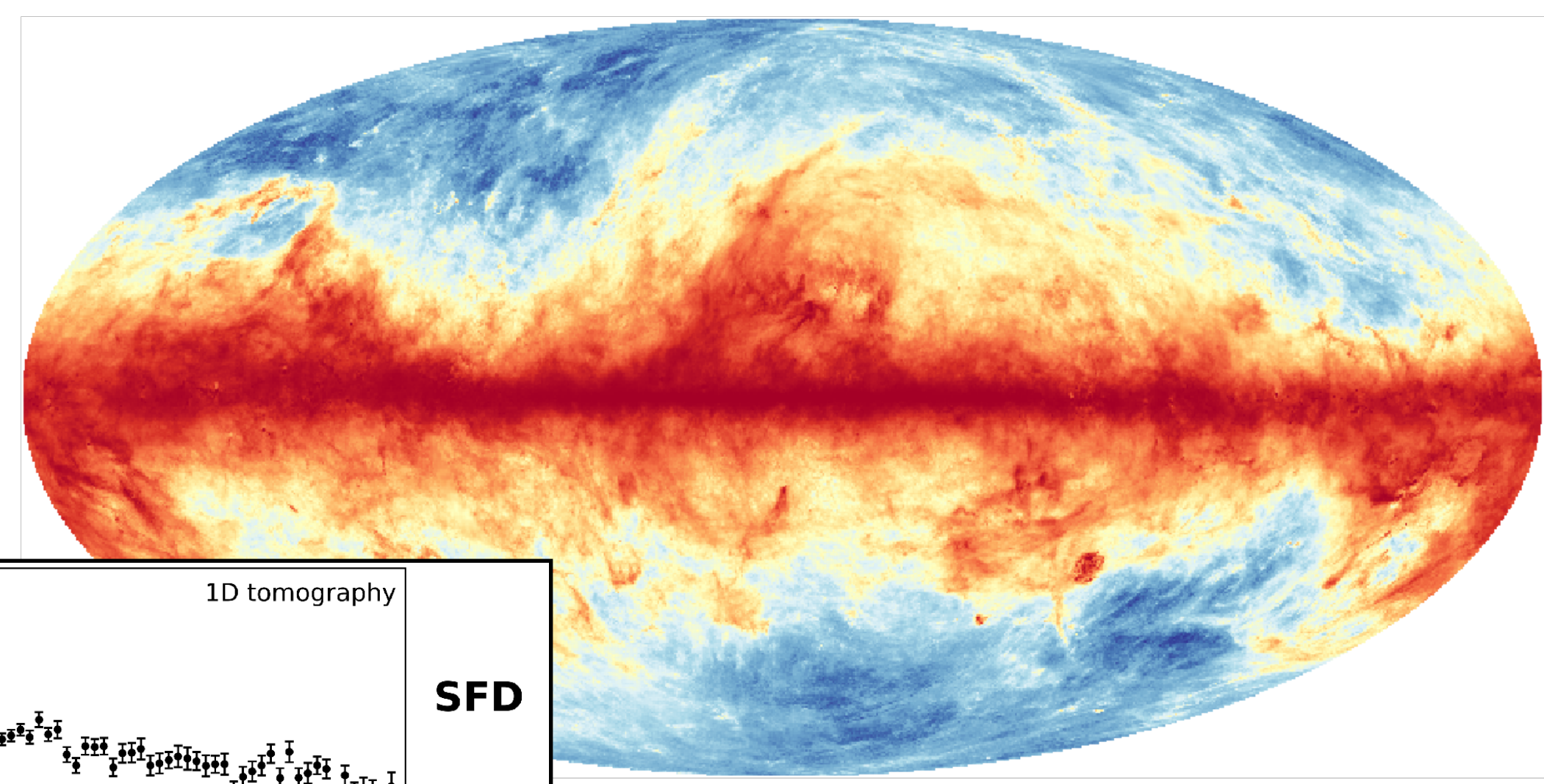
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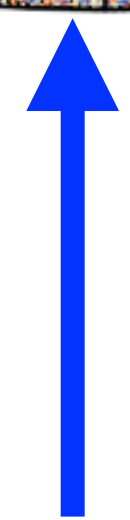
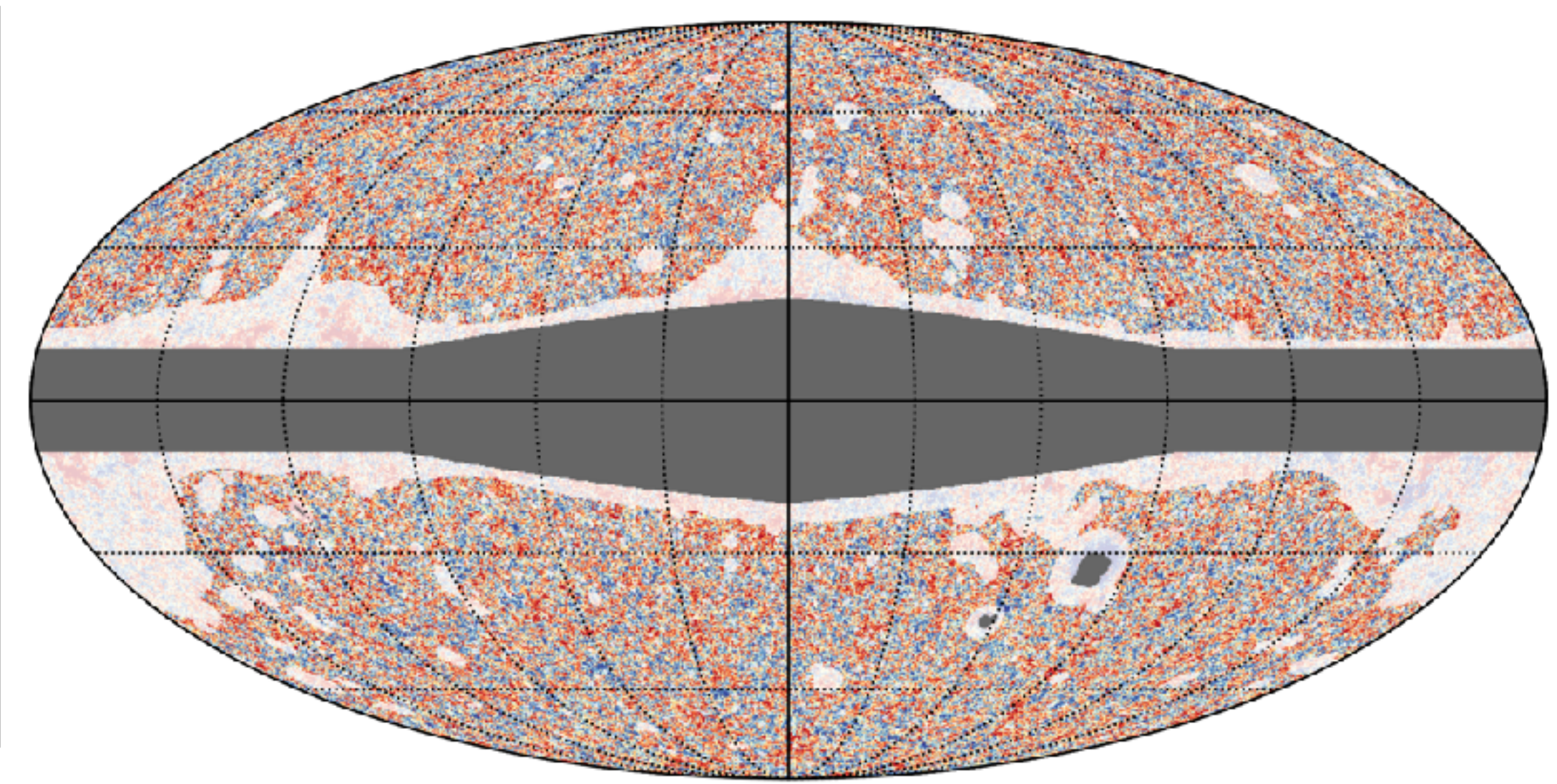


Any maps:

$$\mathbf{I} = \mathbf{I}_{\text{non LSS}}^{\text{Milky Way, CMB}} + \mathbf{I}_{\text{LSS}}^{\text{CIB, tSZ}}$$



Clean 3D LSS statistics
how many overdensities are there?



+ Fourier phases
where the overdensities are in 3D?

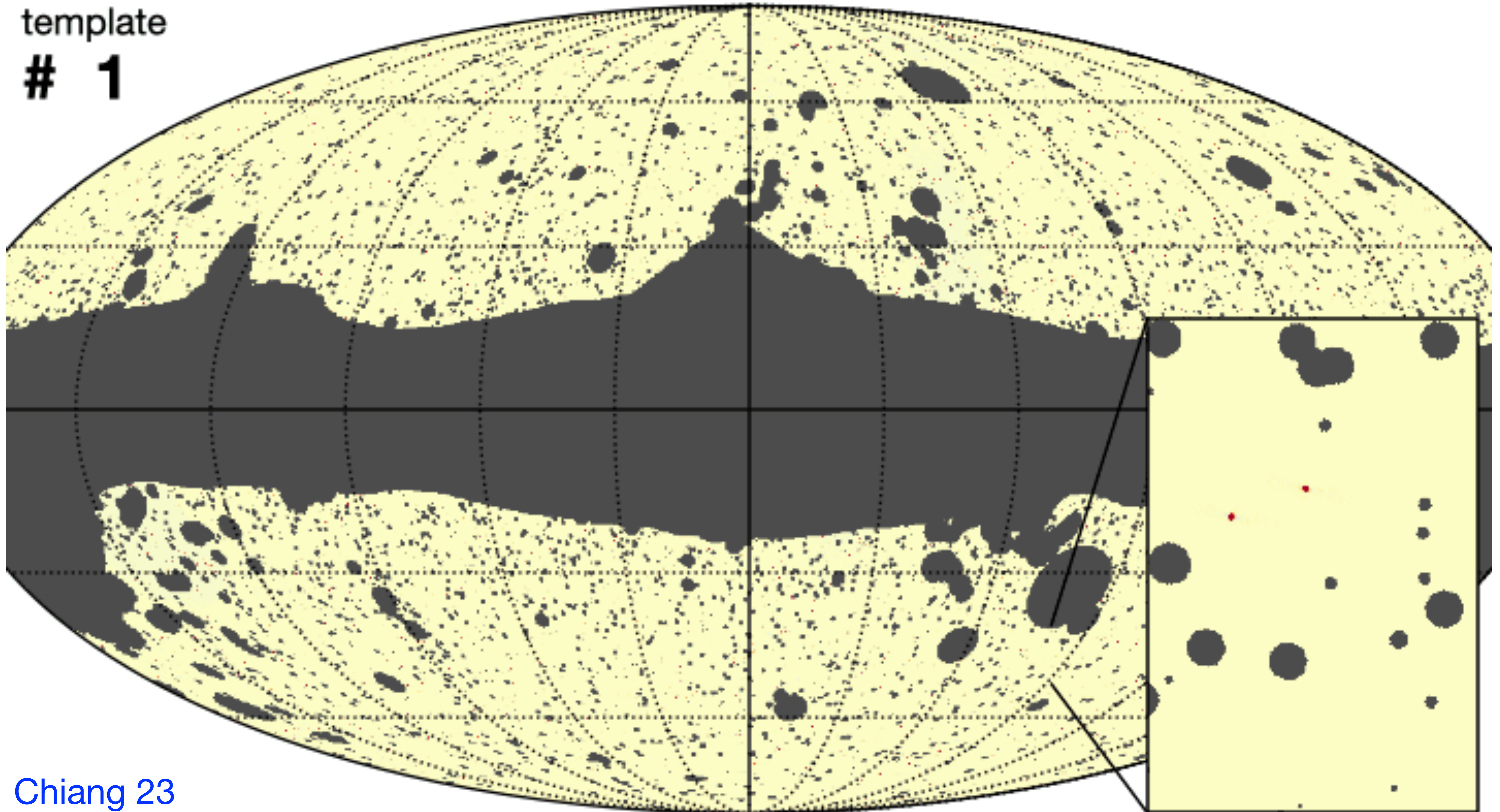
Solution must be deeply data-intensive

2. Build $30 \times 6 = 180$ LSS templates from 600M WISE galaxies

Forming an **over-complete** basis set for LSS

template

1

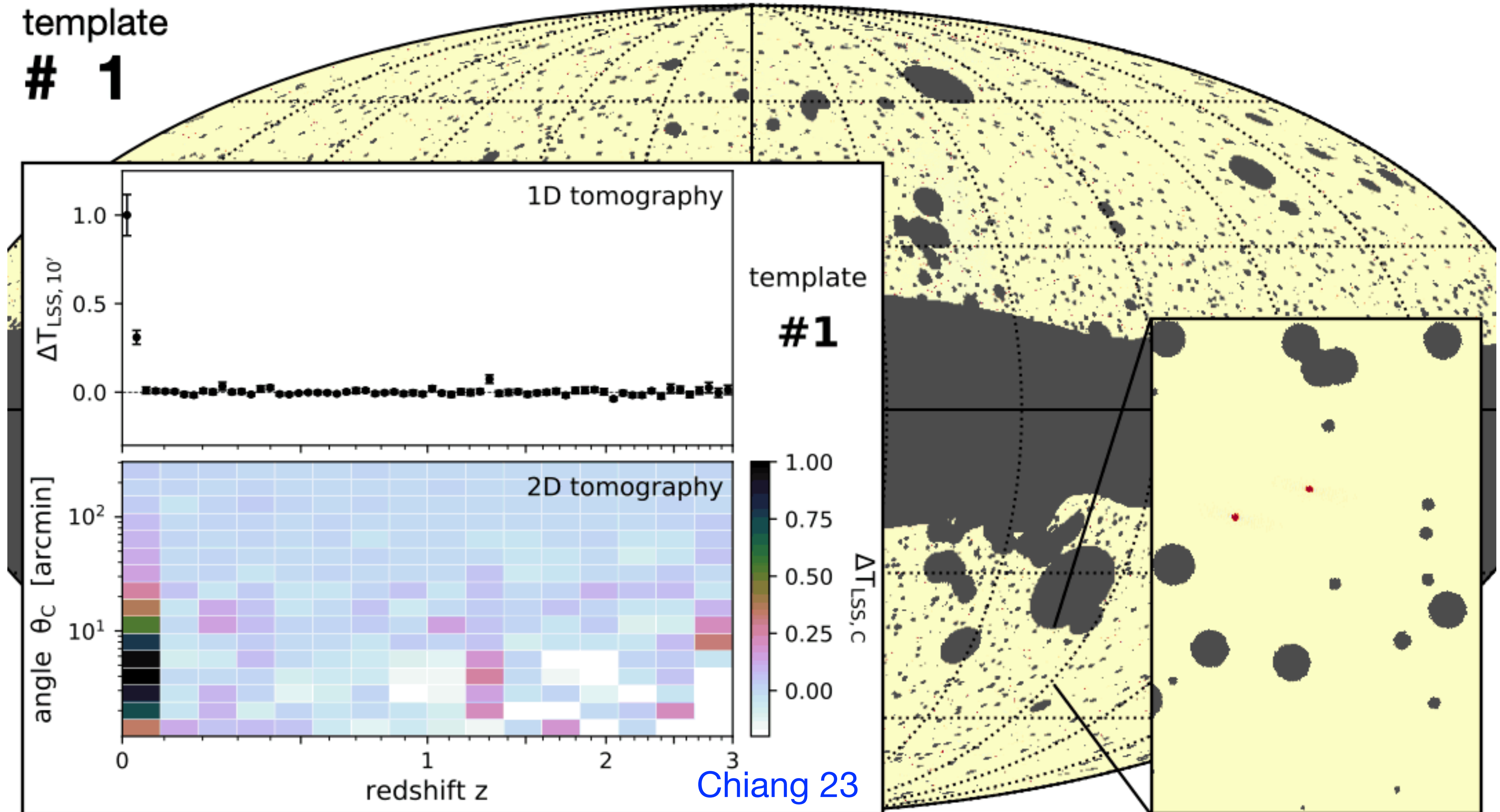


3. Measure same cross-correlation stats for all templates

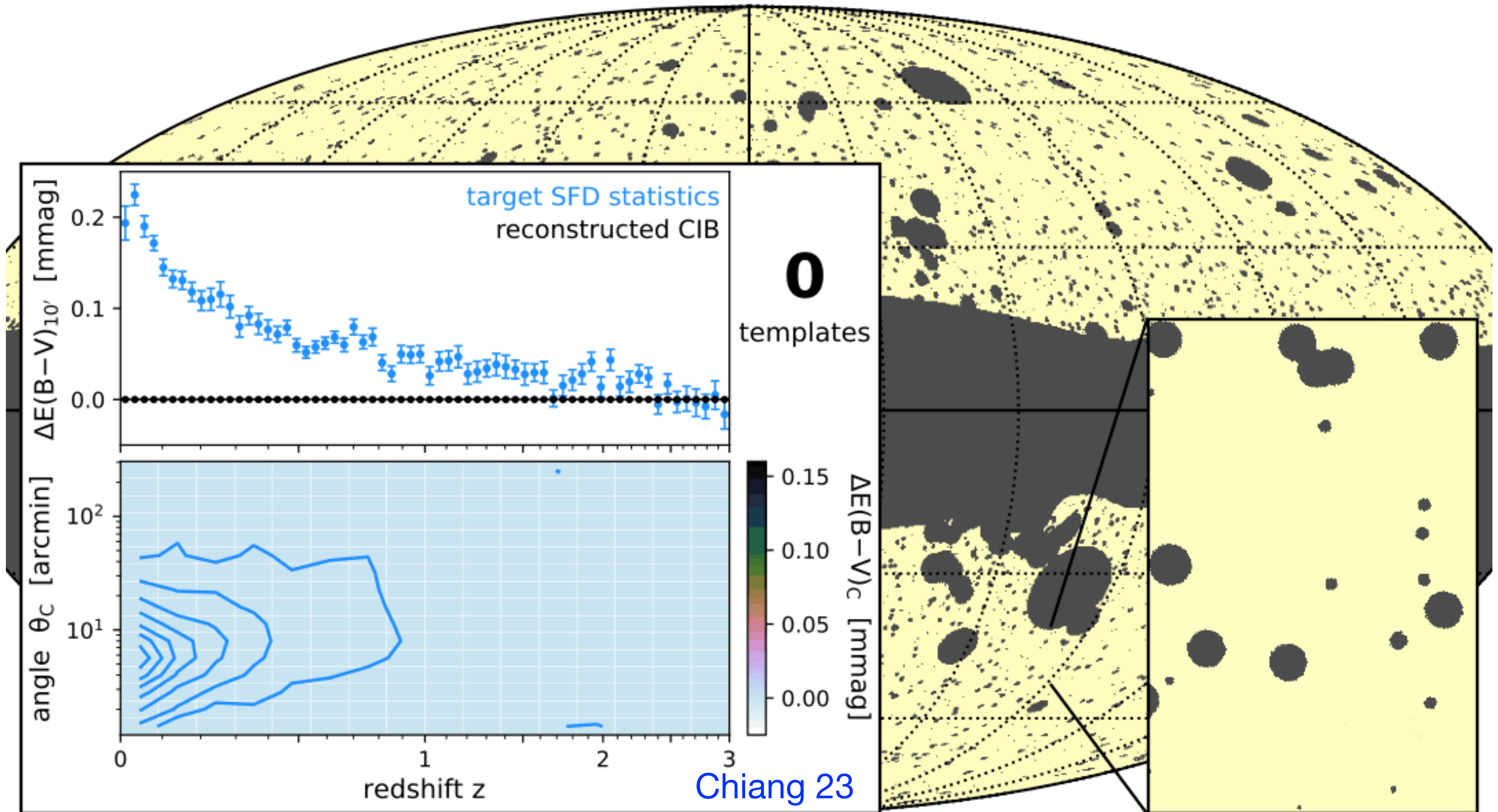
computing intensive: 10^7 2-pt function amplitudes

template

1

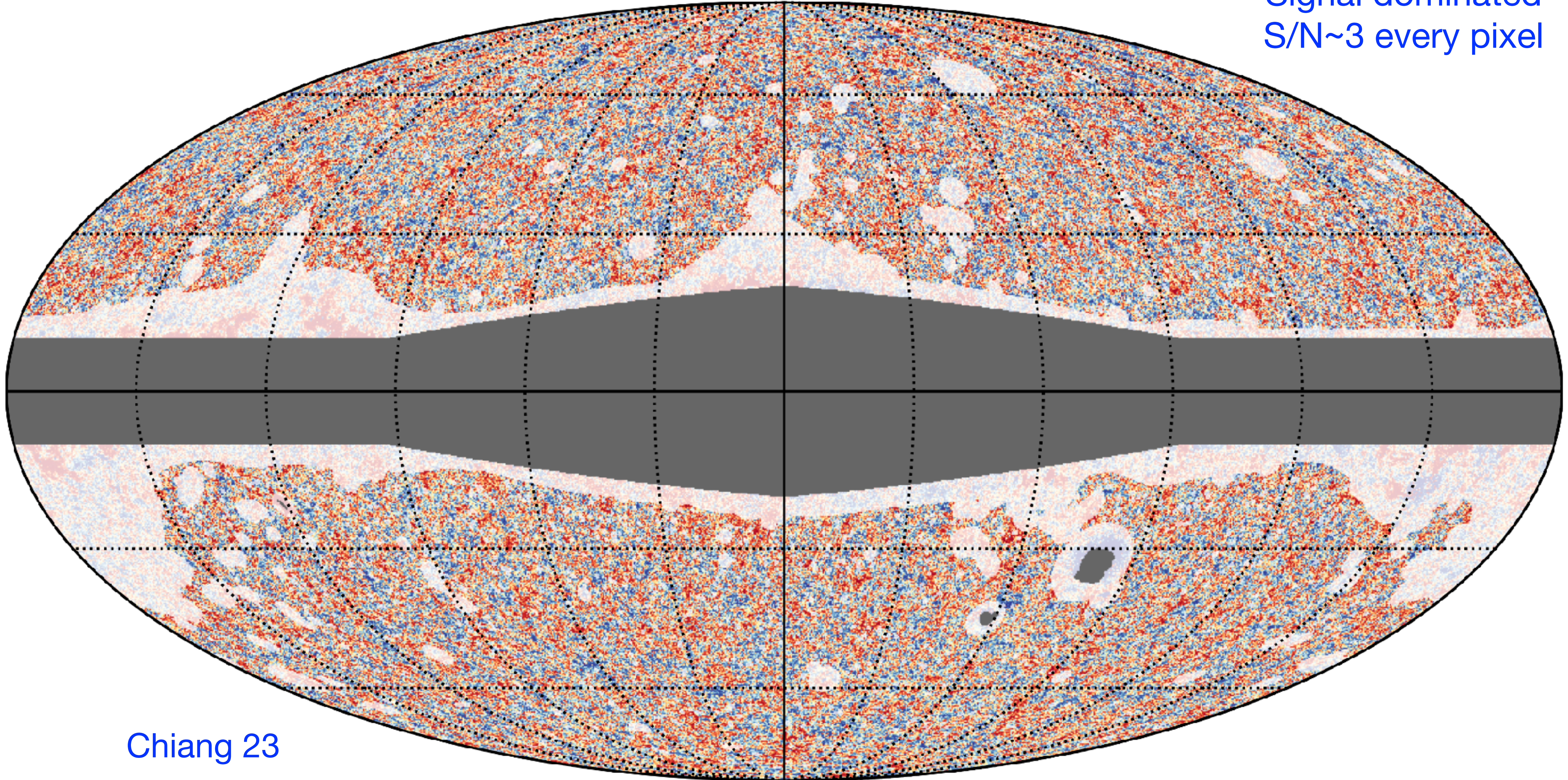


Reconstruction: $I_{\text{CIB}}(\phi) = \sum C_i \times T_{LSS,i}(\phi)$ **(Sum of basis)**



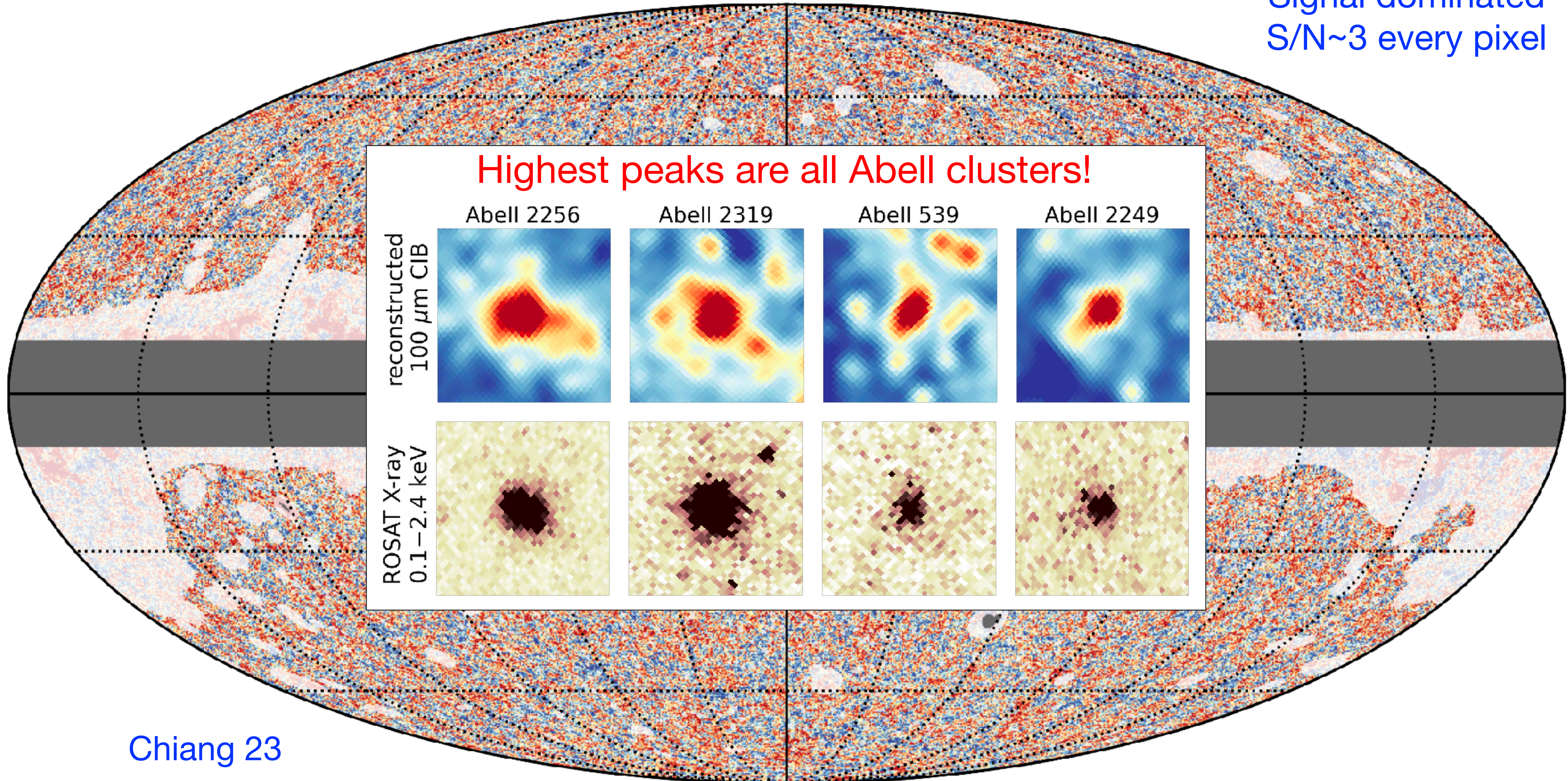
Reconstructed CLB map (100 micron)

Signal dominated
S/N~3 every pixel



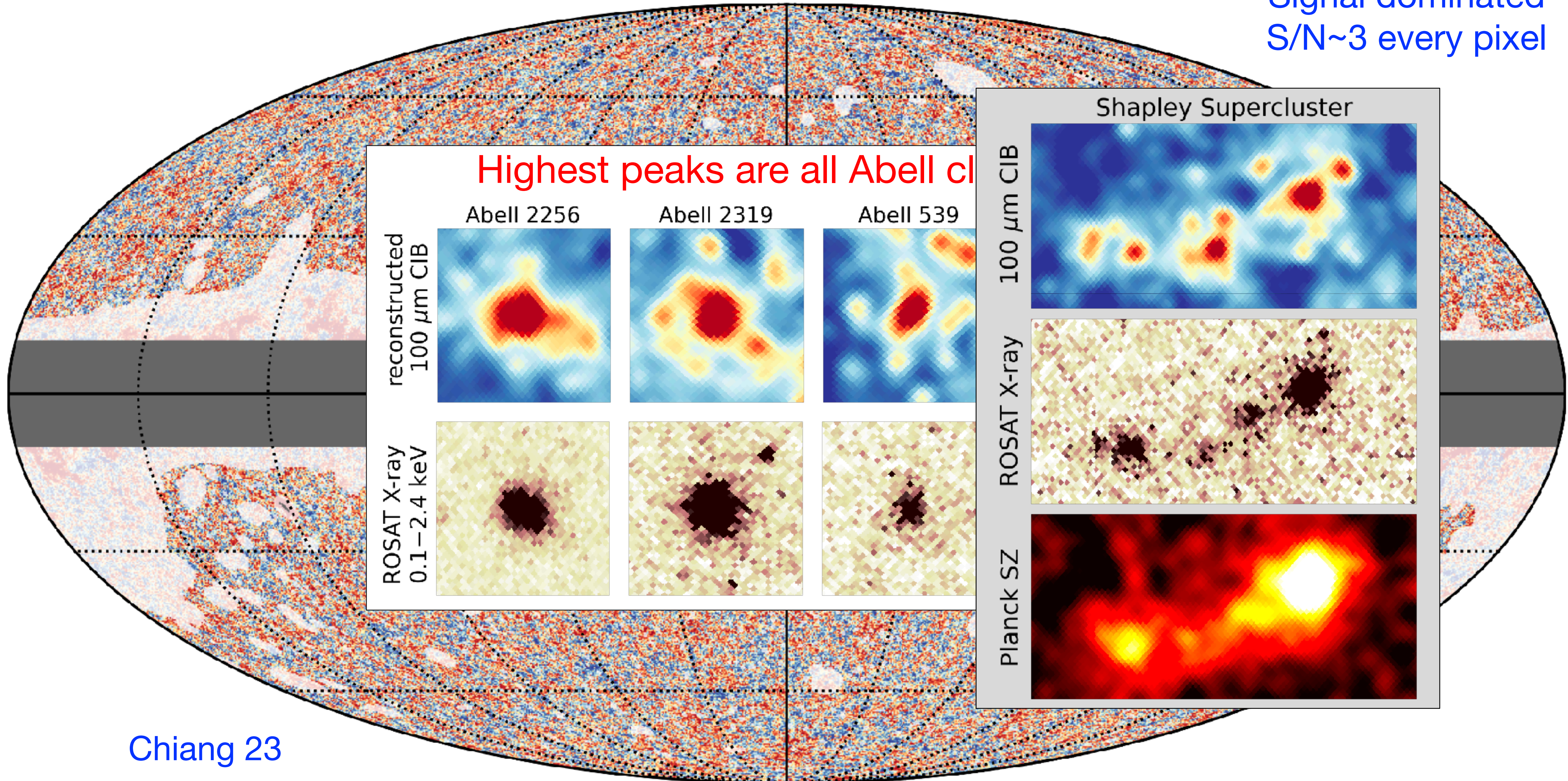
Reconstructed CIB map (100 micron)

Signal dominated
 $S/N \sim 3$ every pixel



Reconstructed CIB map (100 micron)

Signal dominated
 $S/N \sim 3$ every pixel



Corrected SFD (CSFD) = SFD – CIB

All-purpose dust map for extinction correction & foreground cleaning



1K

1K VIEWS

2K

2K DOWNLOADS

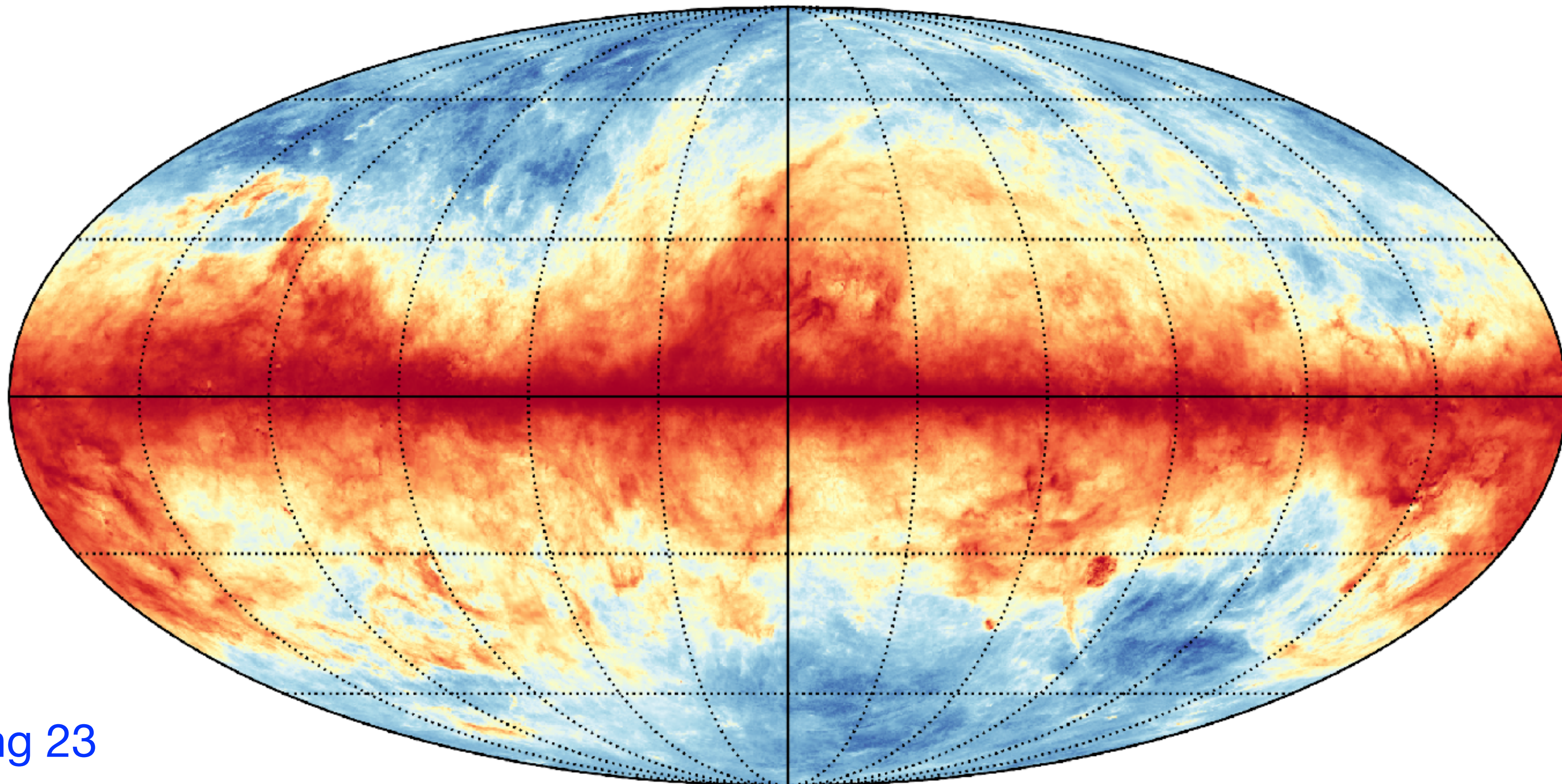
<https://zenodo.org/records/8207175>

Or



Or

One line Python query with `dustmaps` (Green 18) package



Corrected SFD (CSFD) = SFD – CIB

All-purpose dust map for extinction correction & foreground cleaning



1K
VIEWS

2K
DOWNLOADS

1

Or



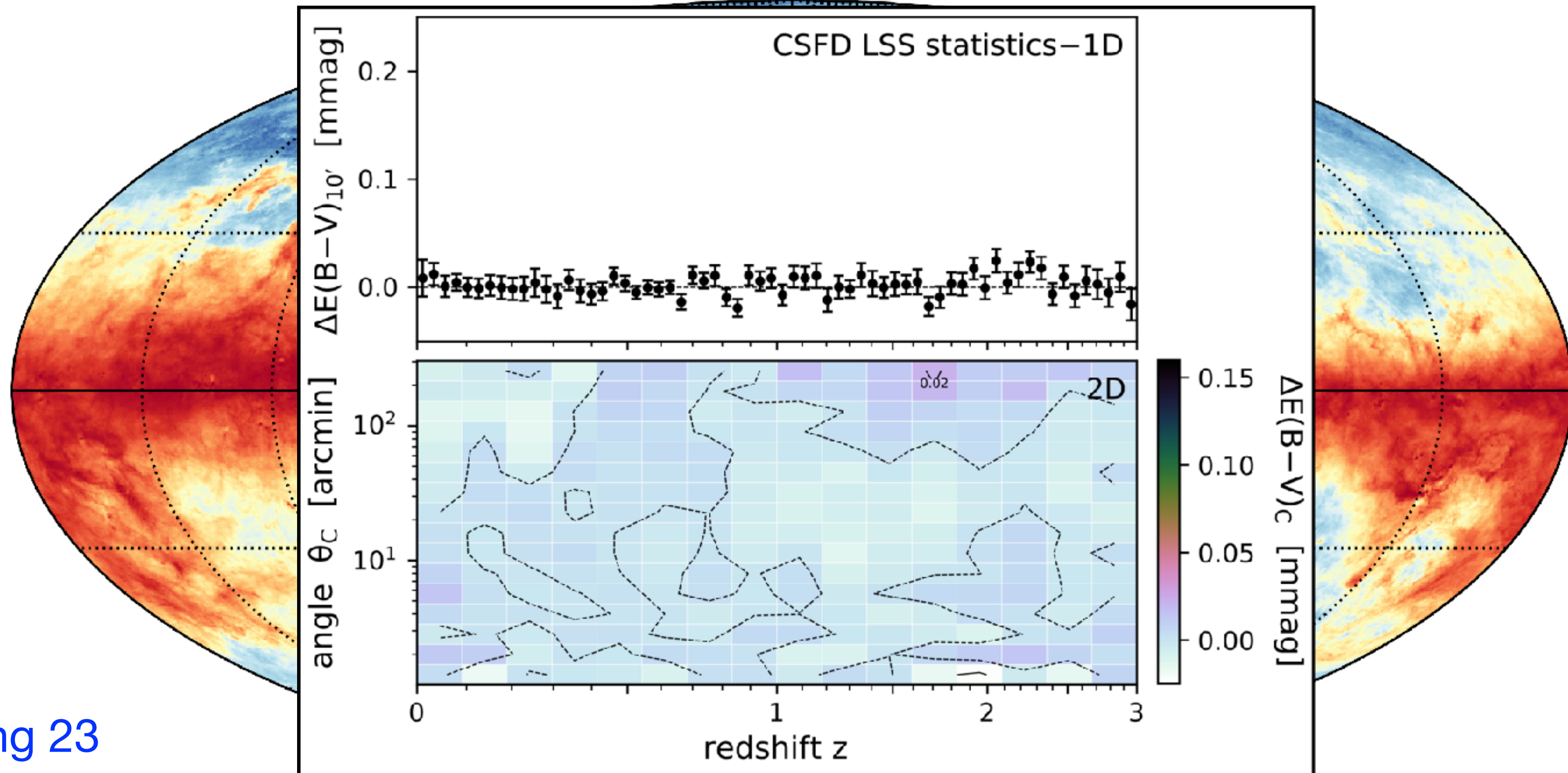
2

Or

3

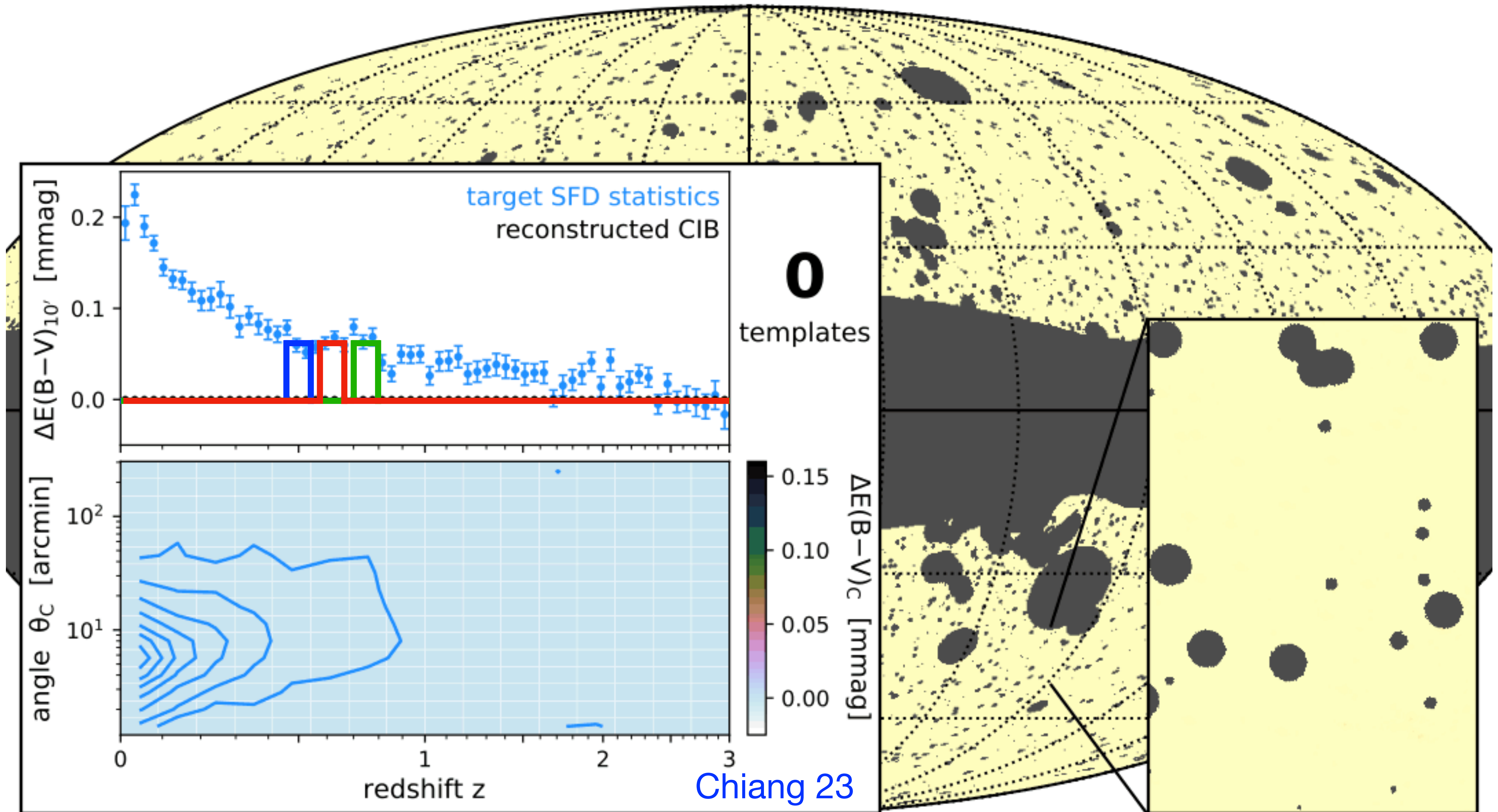
One line Python query with
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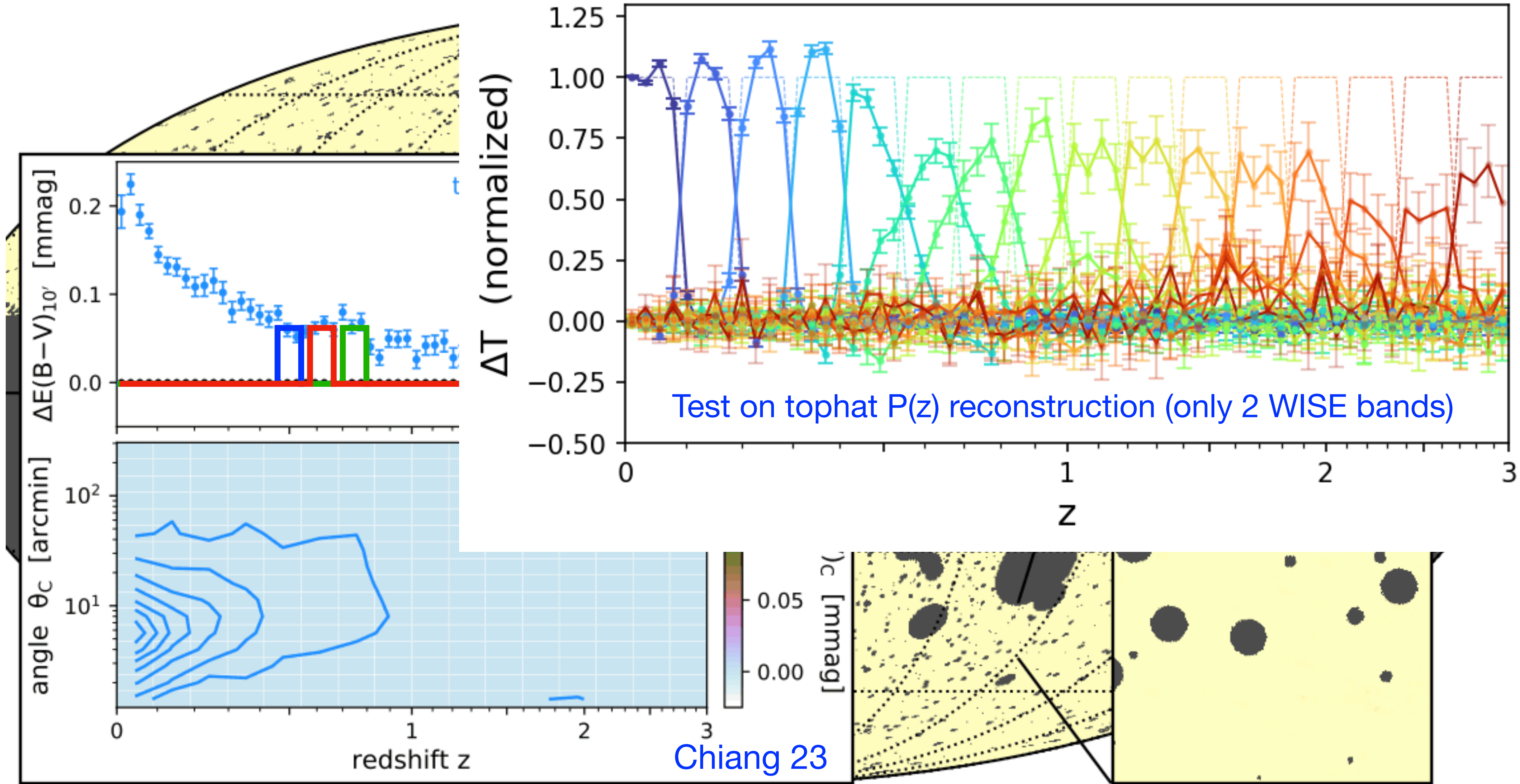
Outlook: full-sky 3D reconstruction (SPHEREx for 1% Δz)

[arXiv:2511.02985](https://arxiv.org/abs/2511.02985)



Outlook: full-sky 3D reconstruction (SPHEREx for 1% Δz)

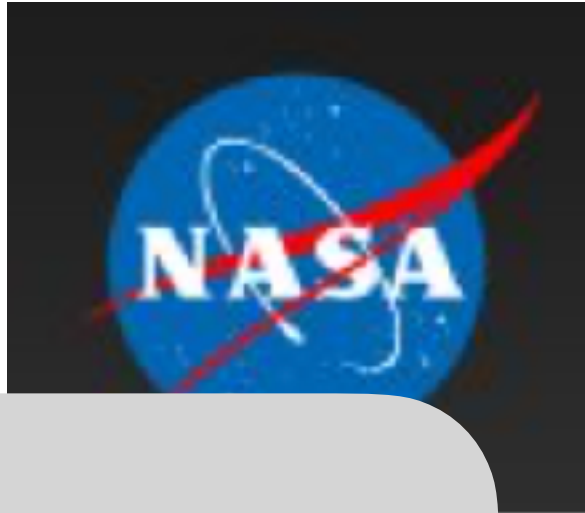
arXiv:2511.02985



List of **Component Separation** methods—\$\$\$ question in CMB

Internal Linear Combination (ILC)	
Name	Description
pyilc Code	pyilc is a pure-python implementation of the needlet internal linear combination (NILC) algorithm for CMB component separation. Harmonic-space ILC is also implemented in the code. For details see the inpainting code, diffusive_inpaint, that diffusively inpaints a masked region with the mean of the unmasked neighboring pixels.
WMAP ILC	The pixel-based ILC method (Bennett et al., 2003) applied to WMAP data that forms linear combinations of the WMAP bands, minimizing the variance with the constraint that the cosmological component is preserved.
Tagmark ILC	Harmonic-space ILC (Tagmark et al. 2003) is similar to the pixel-space version but performed on the spherical harmonic coefficients instead of pixel values, which allows for a higher resolution.
NILC	The Needlet ILC is an implementation (Delabrouille et al. 2009) of internal linear combination (ILC) that works in the needlet (wavelet) domain. The input maps are decomposed into needlets and the CMB is produced by minimizing the variance at each scale. This has the advantage that the weights used to combine the data can vary with position on the sky and also with angular scale. The
MILCA	The Modified ILC Algorithm (Hurier et al. 2010) is generalized for the case of multiple astrophysical components with known spectra. For the Planck project, it was used to isolate both the Sunyaev-Zeldovich effect and the thermal emission from the galaxy cluster foreground.
Spin-SILC	This is an internal linear combination method (Rogers et al. 2016) that uses spin wavelets to analyse the spin-2 polarisation signal $P = Q + iU$. T. Data Products available.

Template Removal	
Name	Description
Delta-Map	This is a method to remove CMB foregrounds with spatially varying spectra from polarization maps (Ichiki et al. 2018). It extends the internal template foreground removal method by accounting for spatially varying spectral parameters such as the spectral indices of synchrotron and dust emission and the dust temperature. As the previous algorithm had to assume that the spectral parameters are uniform over the full sky (or some significant fraction of the sky), it resulted in a bias in the tensor-to-scalar ratio parameter r estimated from foreground-cleaned polarization maps of the cosmic microwave background (CMB). The new algorithm, "Delta-map method", accounts for spatially varying spectra to first order in perturbation. The only free parameters are the cosmological parameters such as r and the sky-averaged foreground parameters. We show that a cleaned CMB map is the maximum likelihood solution to first order in perturbation, and derive the posterior distribution of r and the sky-averaged foreground parameters using Bayesian statistics.
WI-FIT	Wavelet based high resolution fitting of internal templates. The WI-FIT method (Hansen et al. 2006) computes CMB-free foreground plus noise templates from differences of the observations in different channels, and uses those to fit and subtract foregrounds from the CMB dominated channels in wavelet space.
SEVEM	SEVEM ("Spectral Estimation Via Expectation Maximisation") is an implementation (Martínez-González et al. 2003, Leach et al. 2008, Fernández-Cobos et al. 2012) of the template cleaning approach to component separation that works in the map domain. Foreground templates are typically constructed by differencing pairs of maps from the low- and high-frequency channels. The differencing is done in order to null the CMB contribution to the templates. These templates are then used to clean each CMB-dominated frequency channel by finding a set of coefficients to minimize the variance of the map outside of a mask. Thus SEVEM produces multiple foreground-cleaned frequency channel maps. The final CMB map is produced by combining a number of the

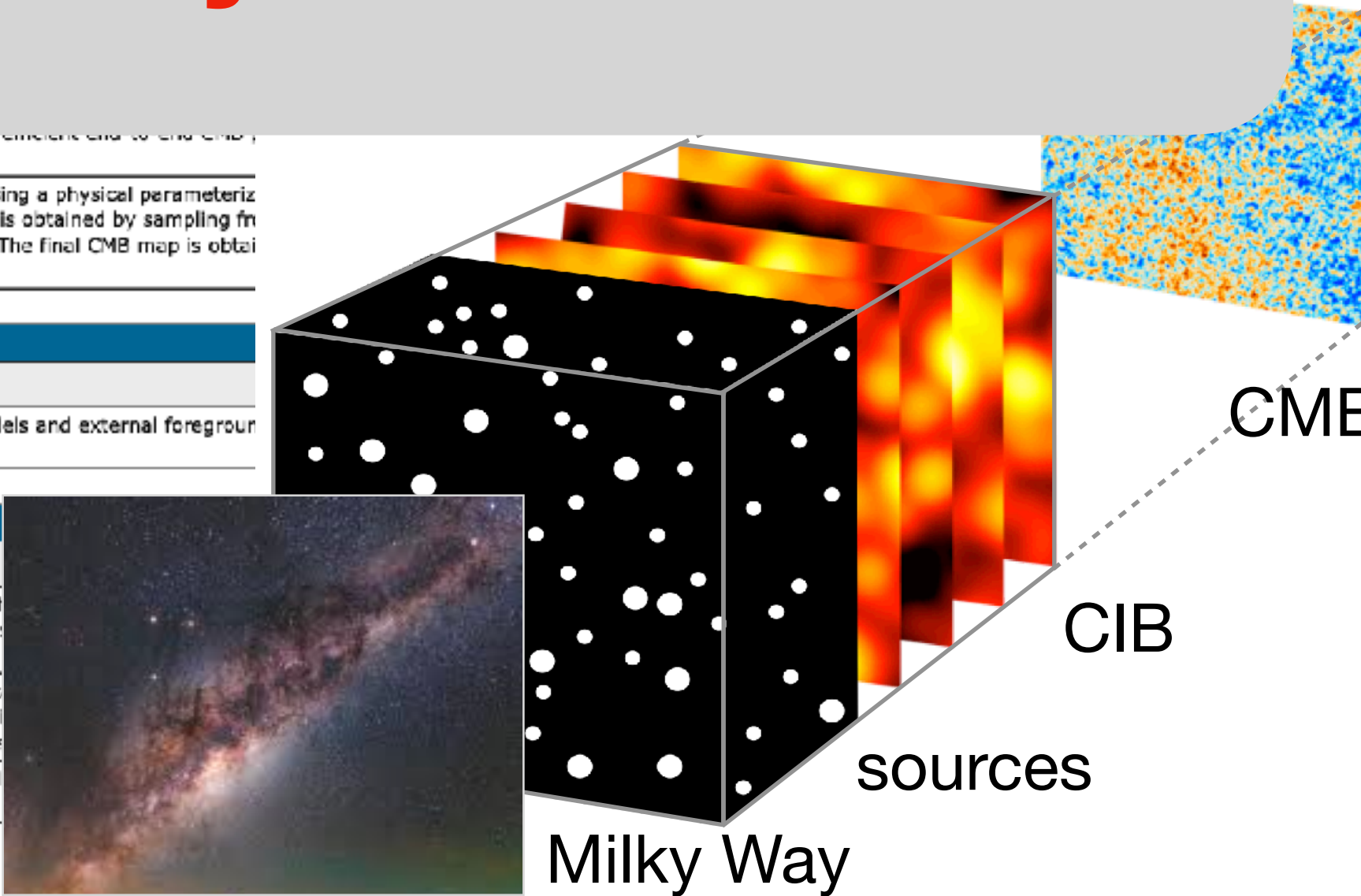


None uses **“field-level, 3D galaxy density information”**

Commander2 Code	Commander2 is the public release of the most recent version of Commander (Commander is an open-source code for the extraction of the CMB component maps from the CMB data). Commander is a Bayesian parametric method (Eriksen et al., 2006, Eriksen et al., 2008) that works in the map domain. Both the CMB and foregrounds are modelled using a physical parameterization. The joint solution for all components is obtained by sampling from the posterior likelihood and a set of priors. To produce a high-resolution CMB map, the separation is performed at multiple resolutions with different combinations of input channels. The final CMB map is obtained by combining the results from all resolutions.
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Maximum Entropy	
Name	Description
FastMEM	The FastMEM is a harmonic-space maximum entropy method that estimates (Hobson et al., 1998, Stolyarov et al., 2002) component maps given frequency scaling models and external foreground weights. It is a nonblind, non-linear approach, which assumes a maximum-entropy prior probability distribution for the underlying components.

Blind	
Name	Description
GMCA Code	Generalised Morphological Component Analysis (Bobin et al., 2007) is a semi-blind source separation method which disentangles the components by assuming that each component is smooth in some domain. GMCA can be used in two ways: GMCA-blind to optimize the separation of the CMB component, and GMCA-model to optimize the separation of the CMB component. The application to CMB was almost incidental; the method is far more generic.
FastICA	The Independent Component Analysis (ICA) algorithm implemented in FastICA (Maino et al., 2002) is aimed at recovering both the spatial pattern and the frequency spectrum of the components. It requires no a priori knowledge of the components except that they are statistically independent and all, except possibly the CMB, are non-Gaussian. The main advantage of this approach is that the algorithm is able to learn how to reconstruct independent components from the data.
CCA	Correlated Component Analysis (Bedini et al., 2005) starts with an estimation of the mixing matrix on patches of sky by exploiting spatial correlations in the data, supplied by the user. The estimated parameters are then used to reconstruct the components by Wiener filtering in the harmonic domain.



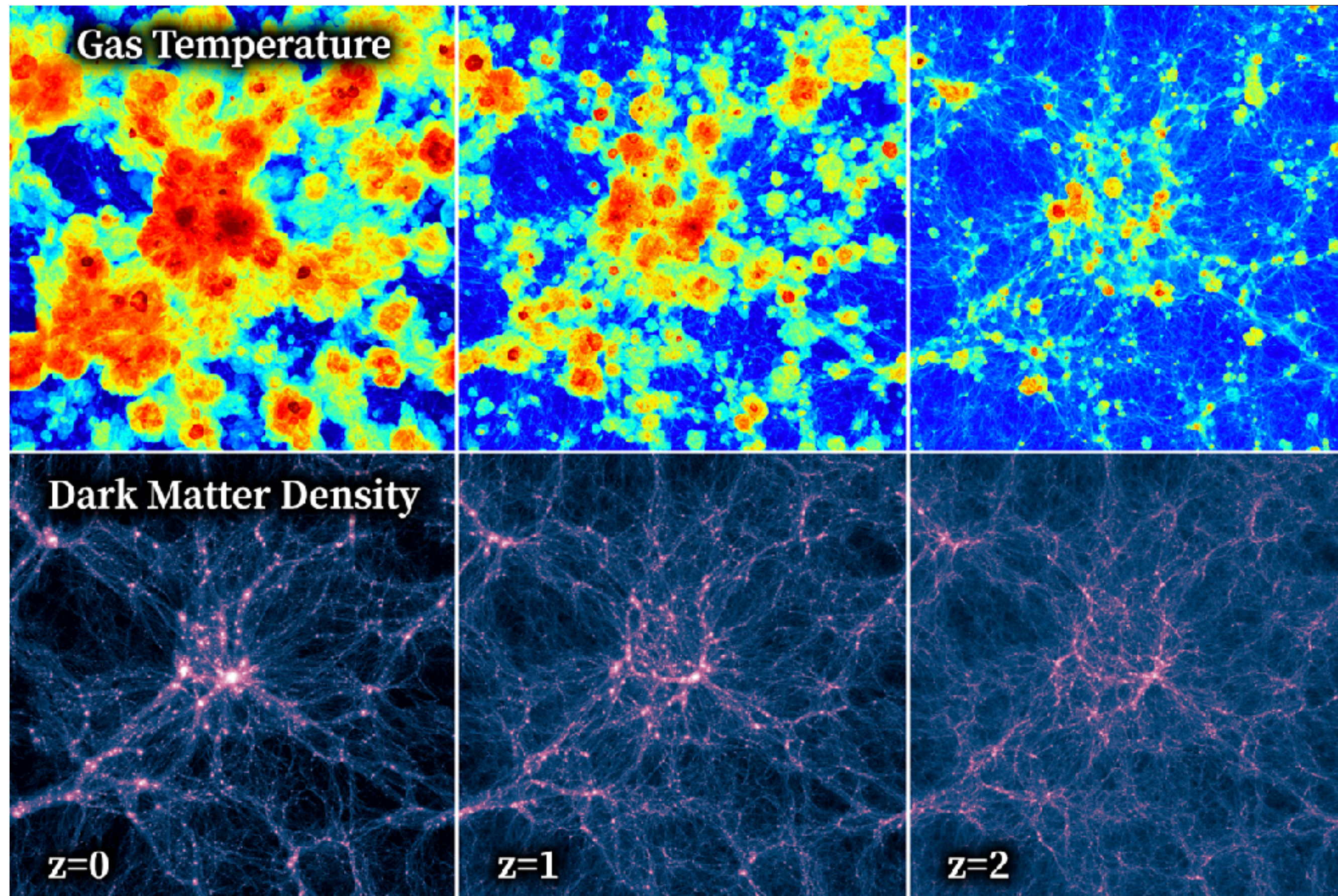
CMB secondary tomography

- Milky Way Dust
- **Sunyaev–Zeldovich Effect**
- **Cosmic Infrared Background**
- Lines

Thermal energy associated with the large-scale structure

Ω_{th} is missing in Fukugita & Peebles 2004, but it's important for structure formation

Sunyaev-Zel'dovich (SZ) effect



Inverse Compton scattering of
CMB photons by hot electrons

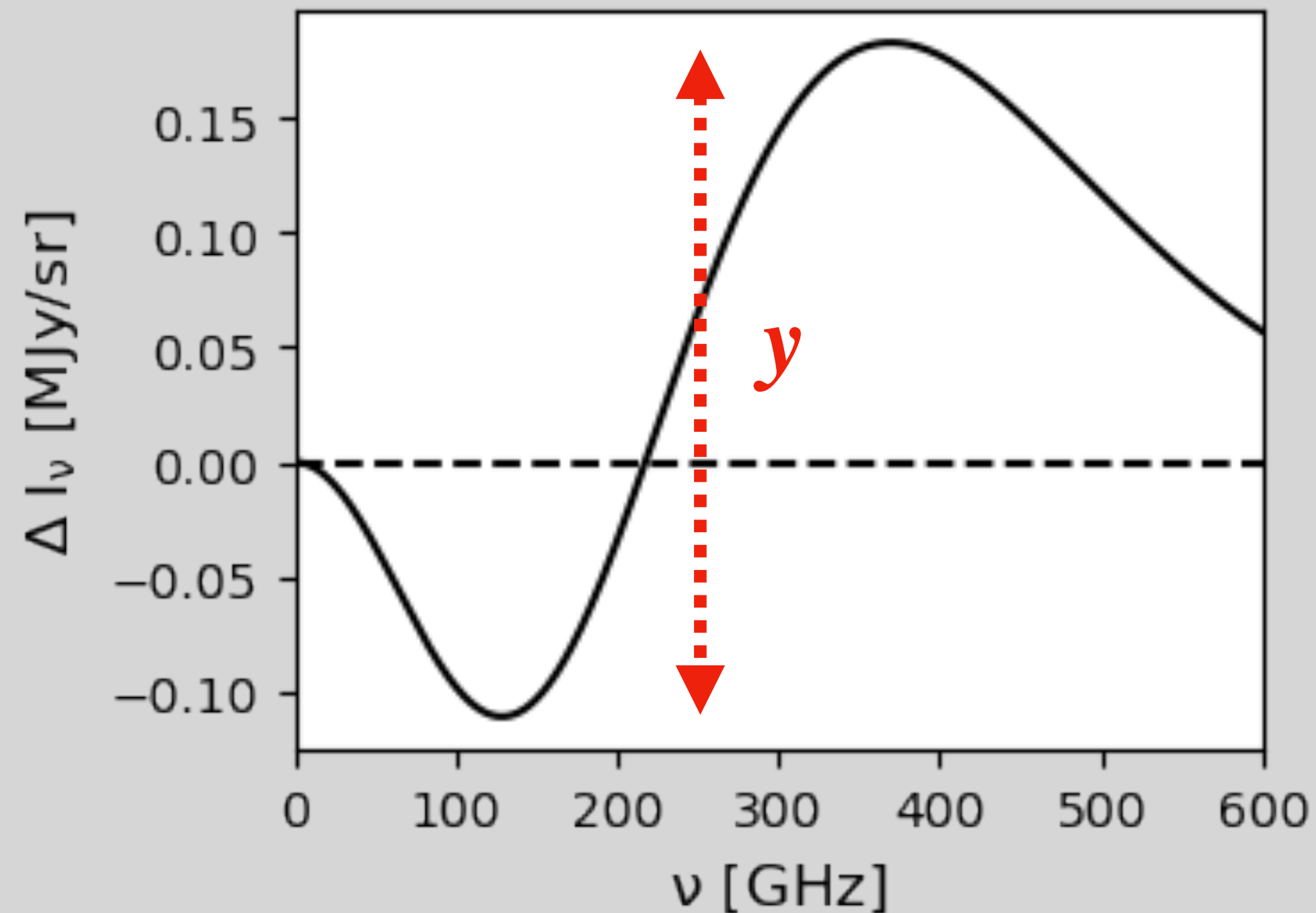
Image credit: Dylan Nelson, Illustris Collaboration

Sunyaev & Zeldovich 1972

Thermal energy associated with the large-scale structure

Ω_{th} is missing in Fukugita & Peebles 2004, but it's important for structure formation

Spectral distortion of the CMB



Direct SZ:

$$y \propto \int P_e dl$$

With tomography:

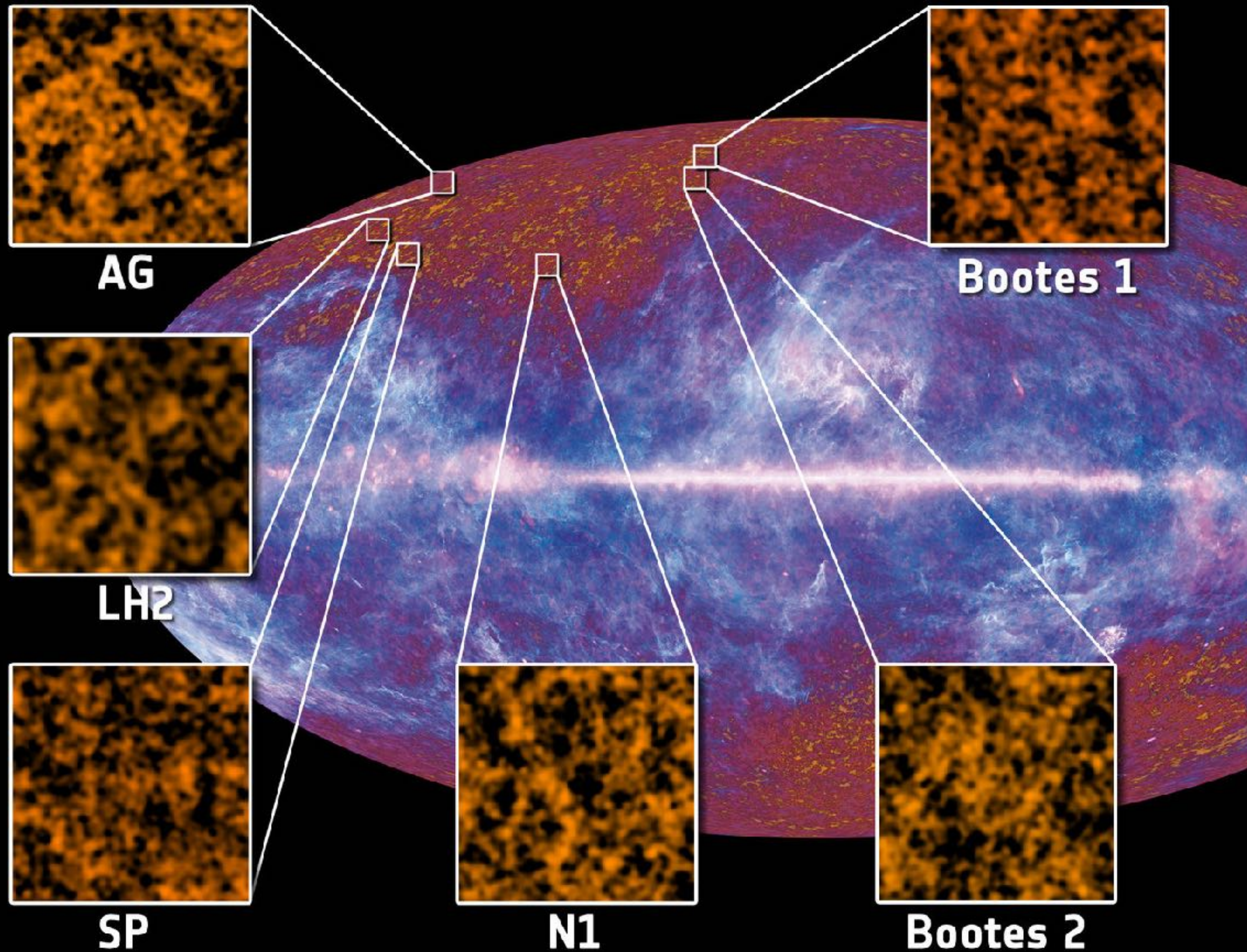
$$P_e \propto k_B T$$

Sunyaev-Zel'dovich (SZ) effect

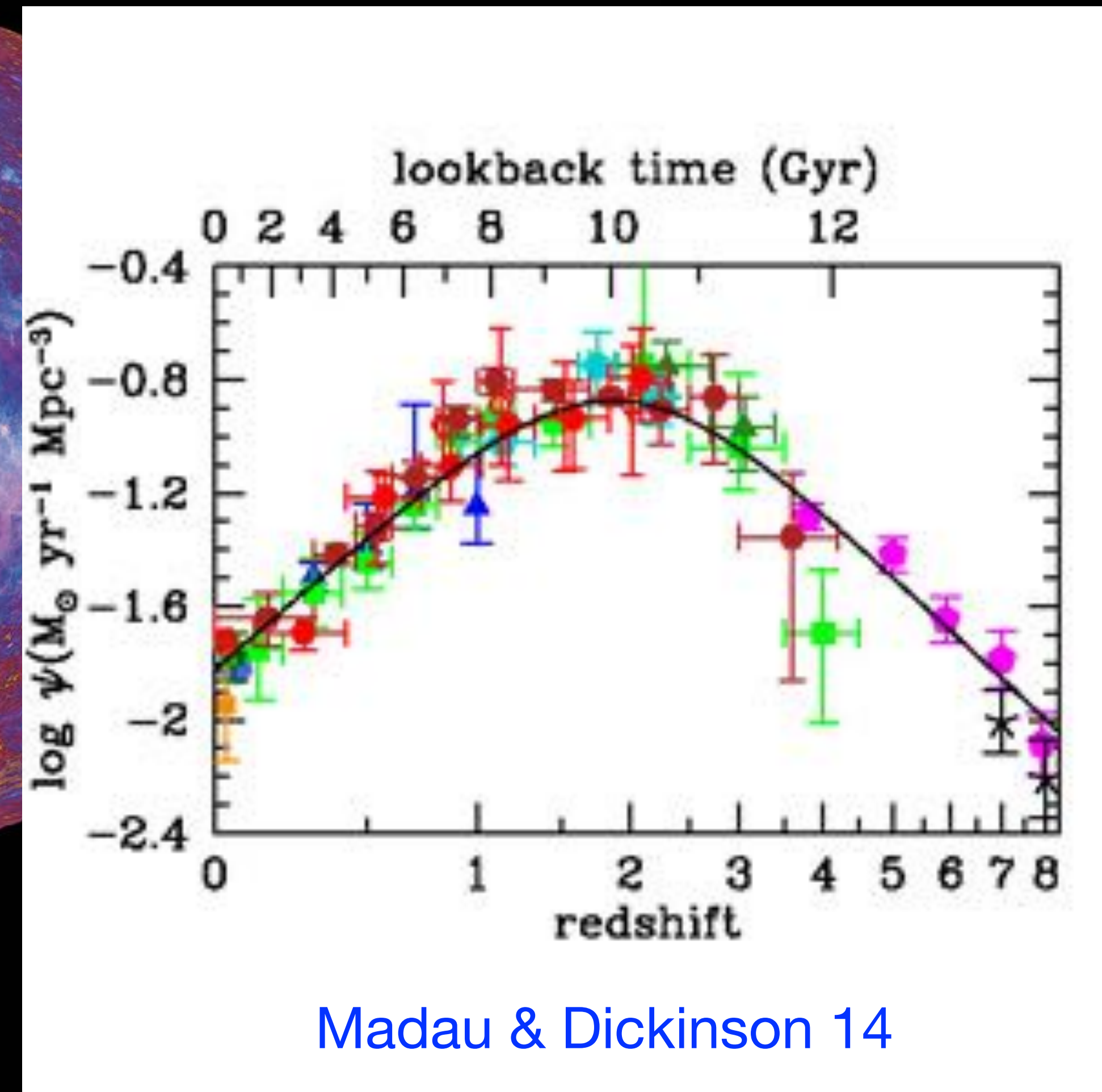
Inverse Compton scattering of
CMB photons by hot electrons

Sunyaev & Zeldovich 1972

tSZ is not alone, as ClB is just much brighter

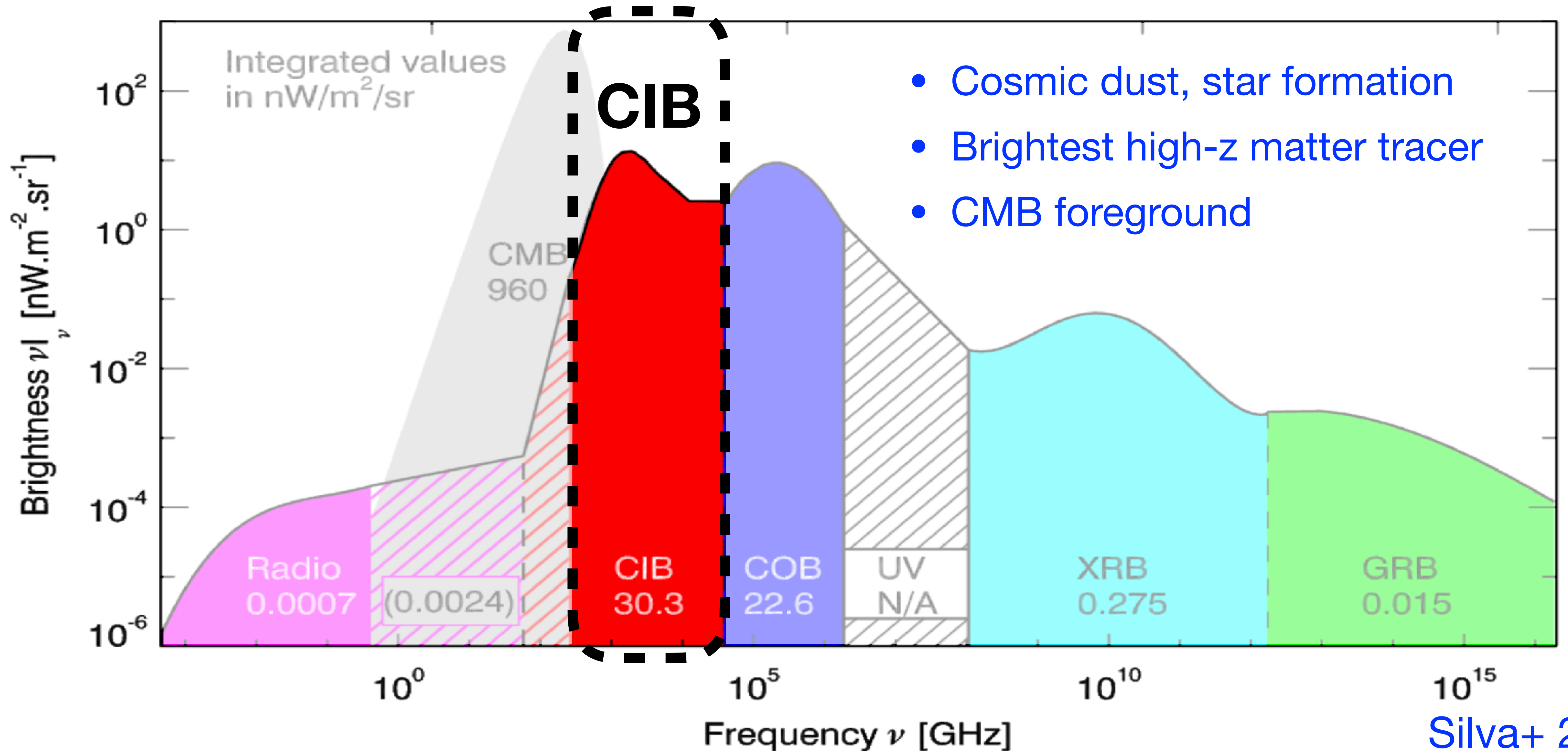


Planck 2011

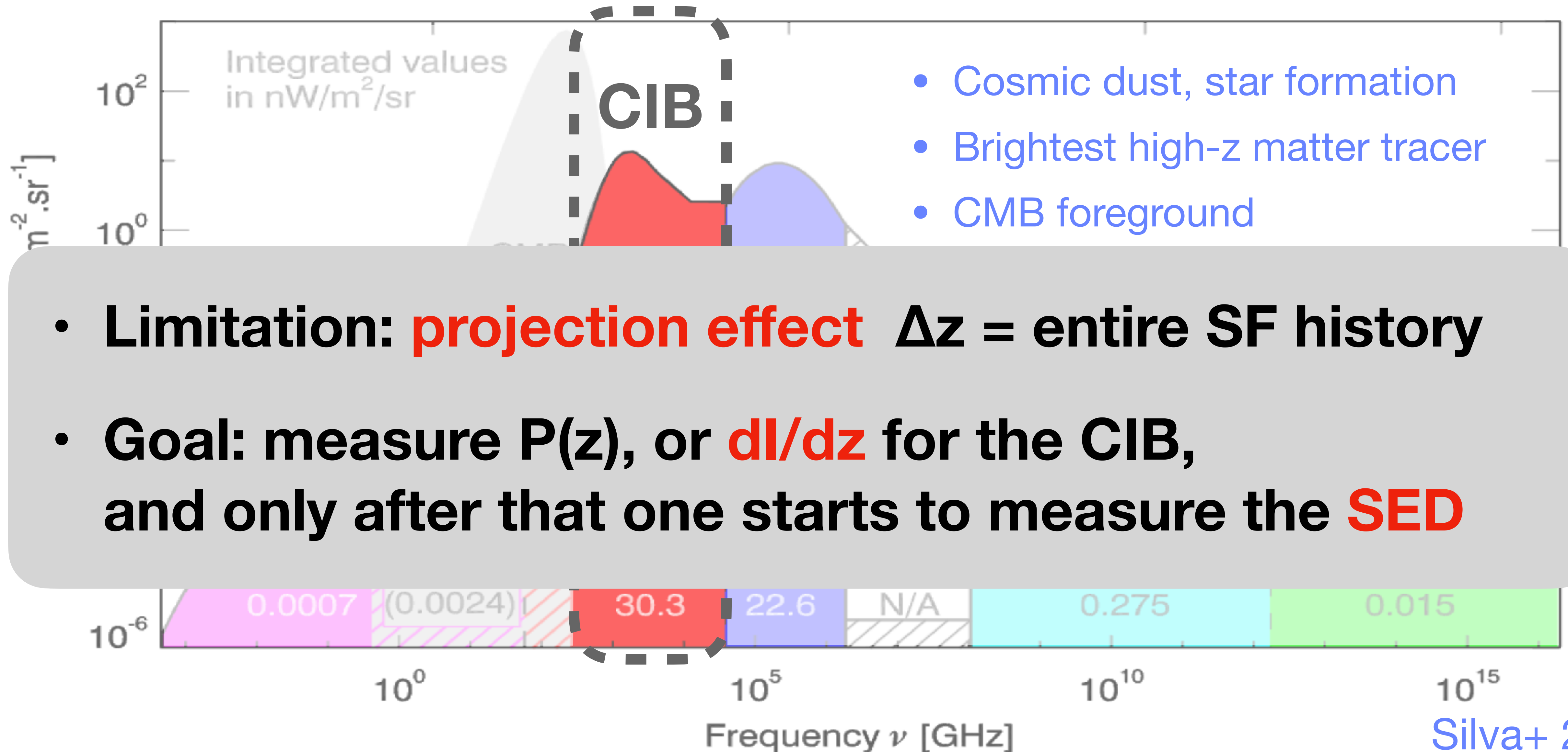


Madau & Dickinson 14

Cosmic infrared background (CIB)

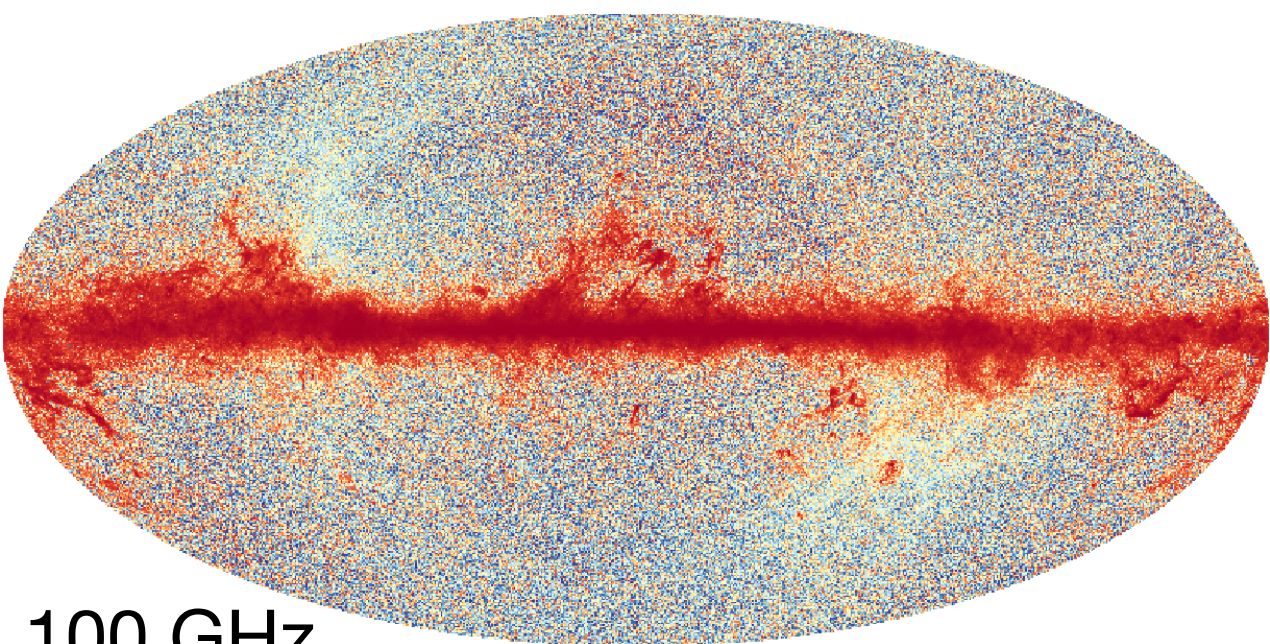


Cosmic infrared background (CIB)

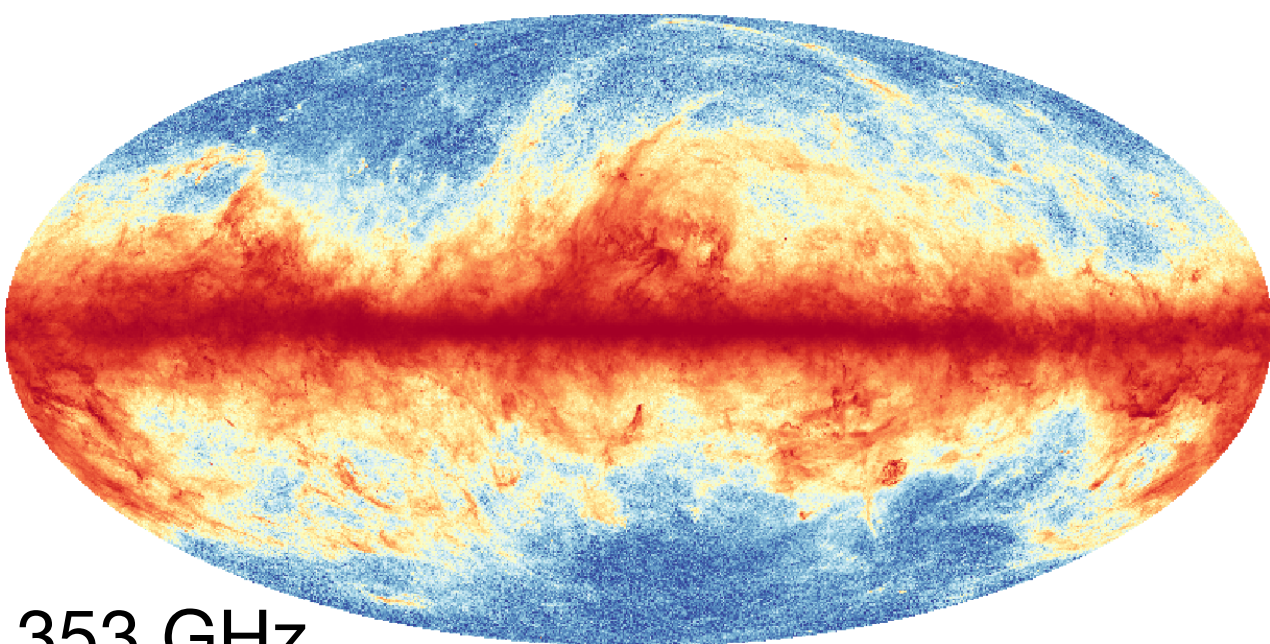


Probing CIB+SZ using 11 maps covering 50-fold frequencies

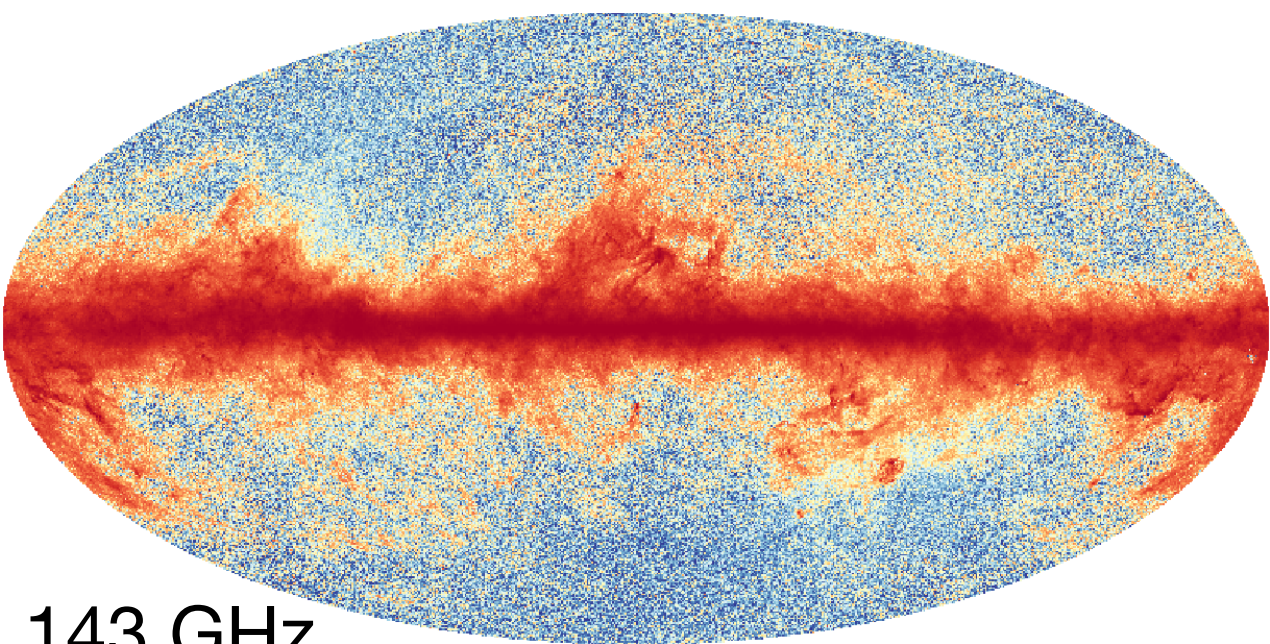
Planck



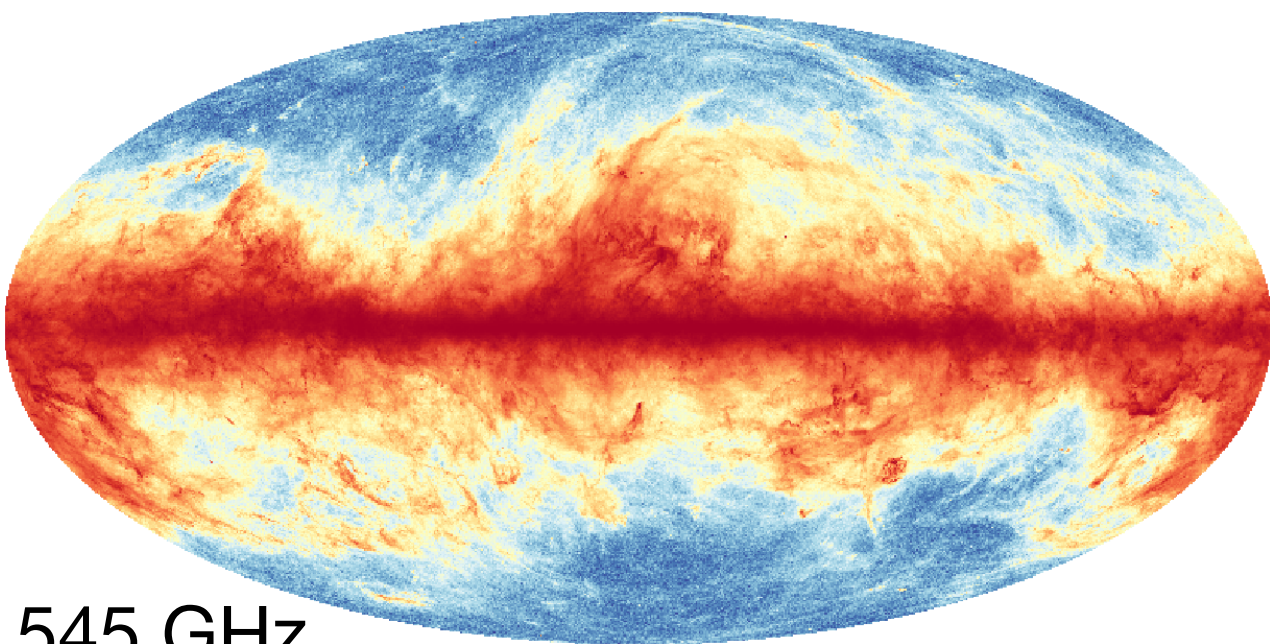
100 GHz



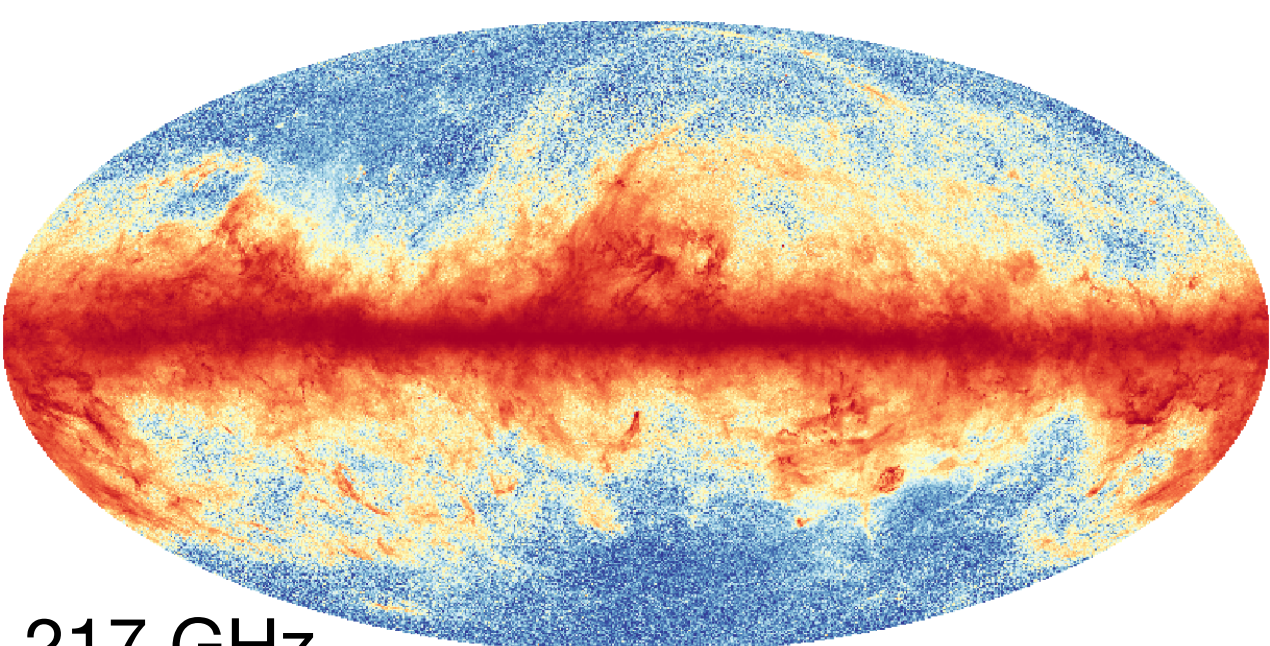
353 GHz



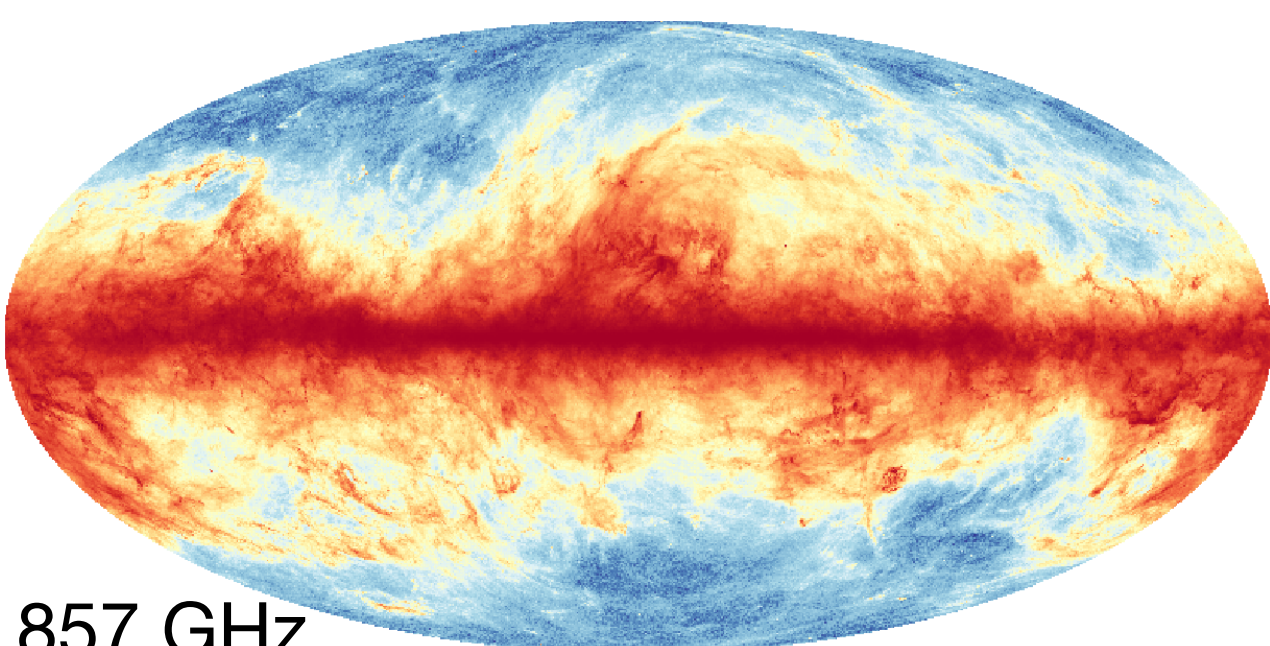
143 GHz



545 GHz

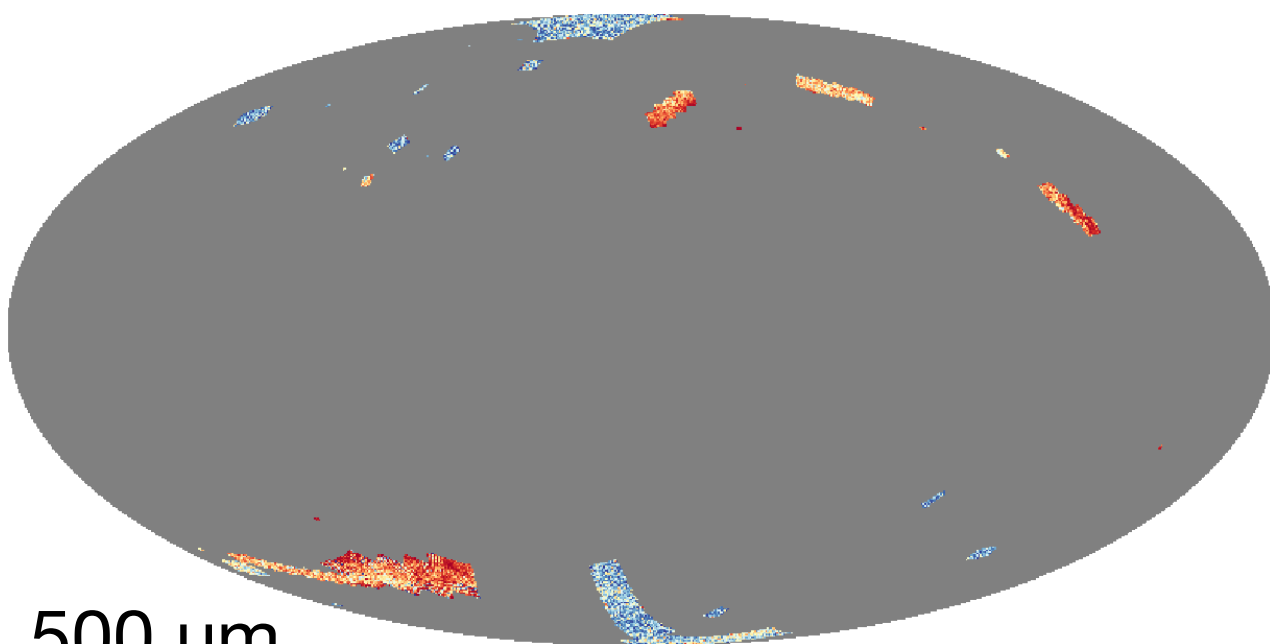


217 GHz

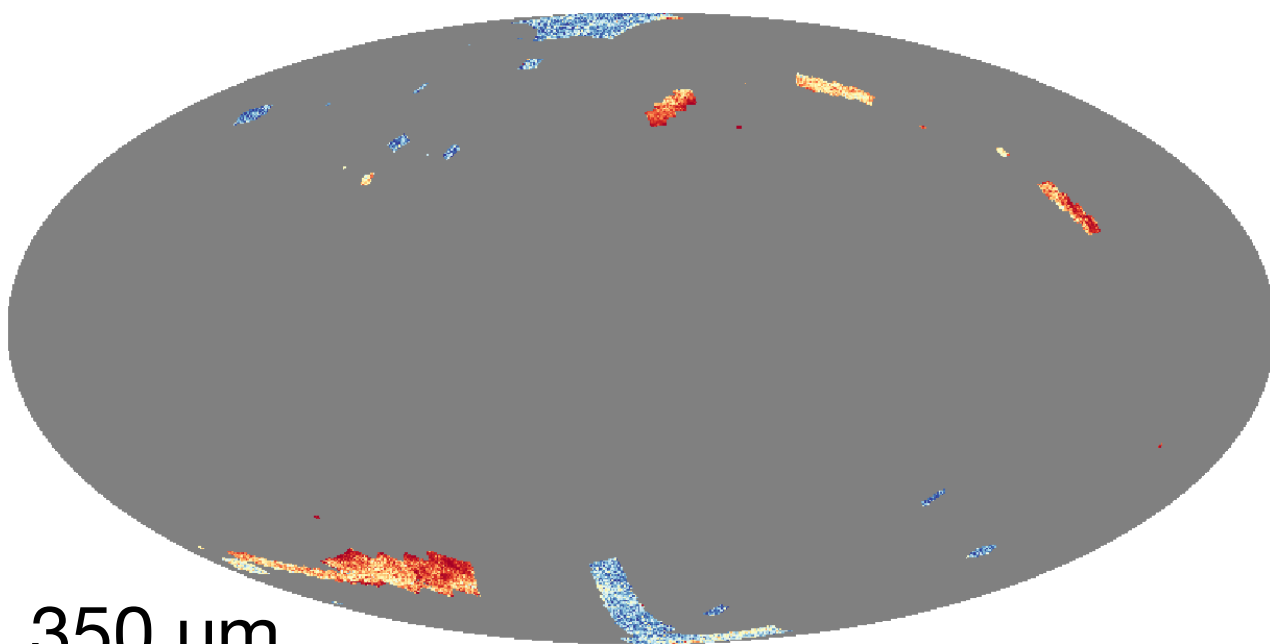


857 GHz

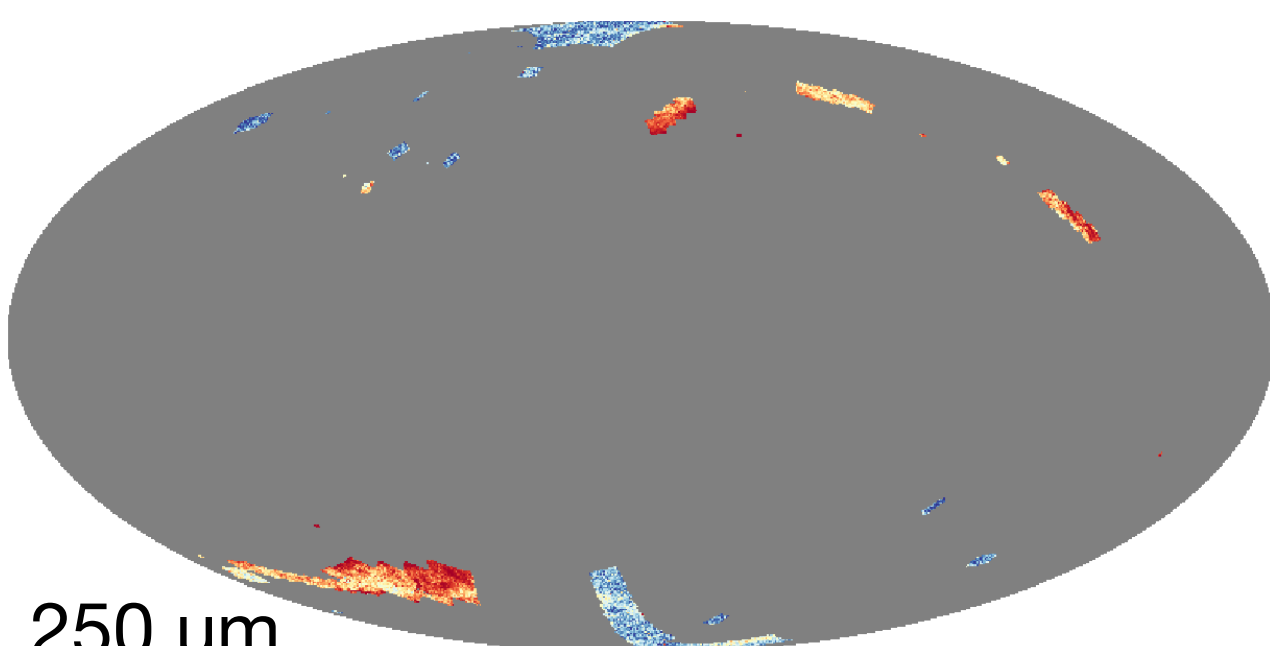
Herschel



500 μm

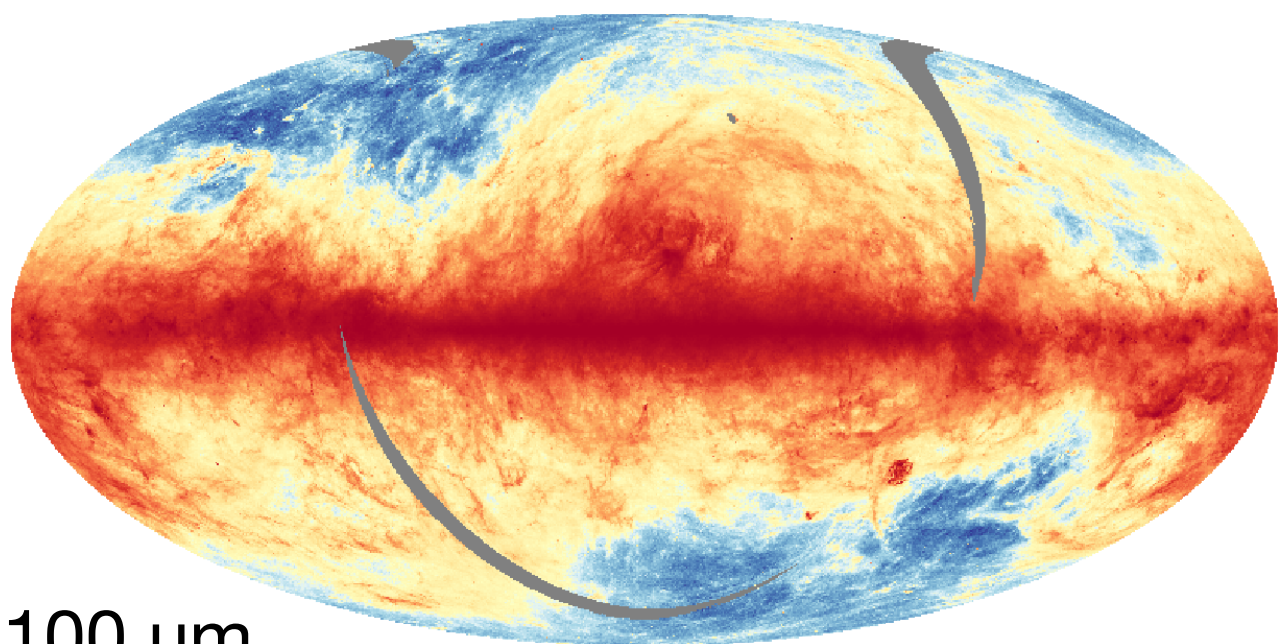


350 μm

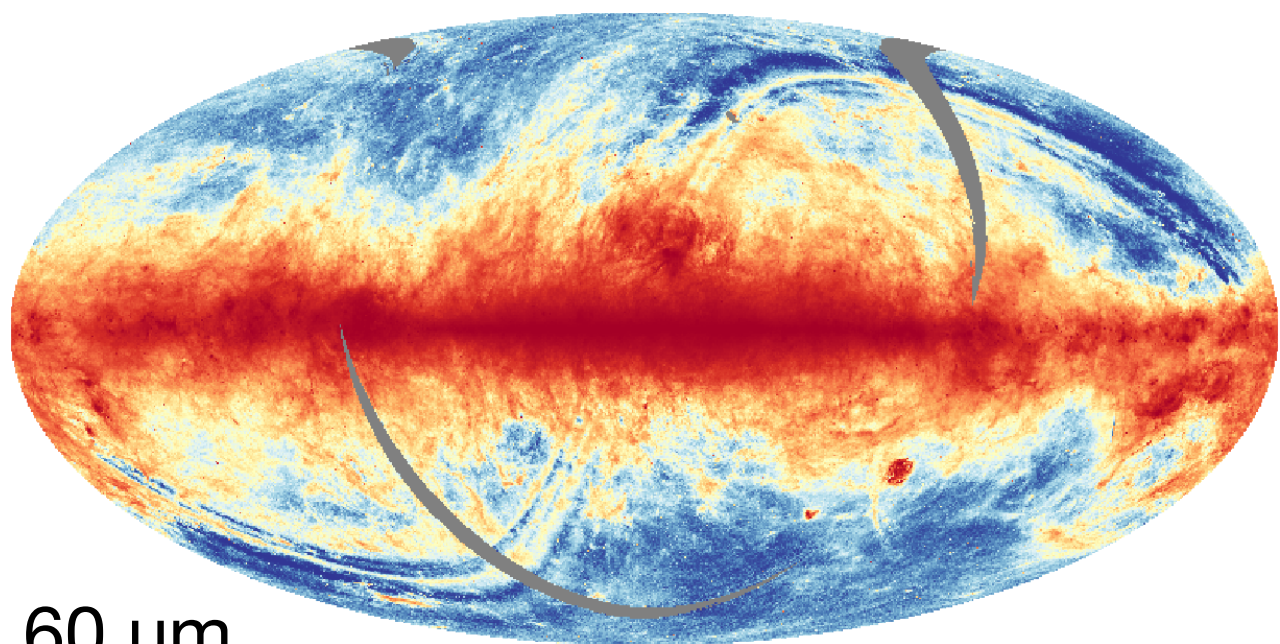


250 μm

IRAS



100 μm



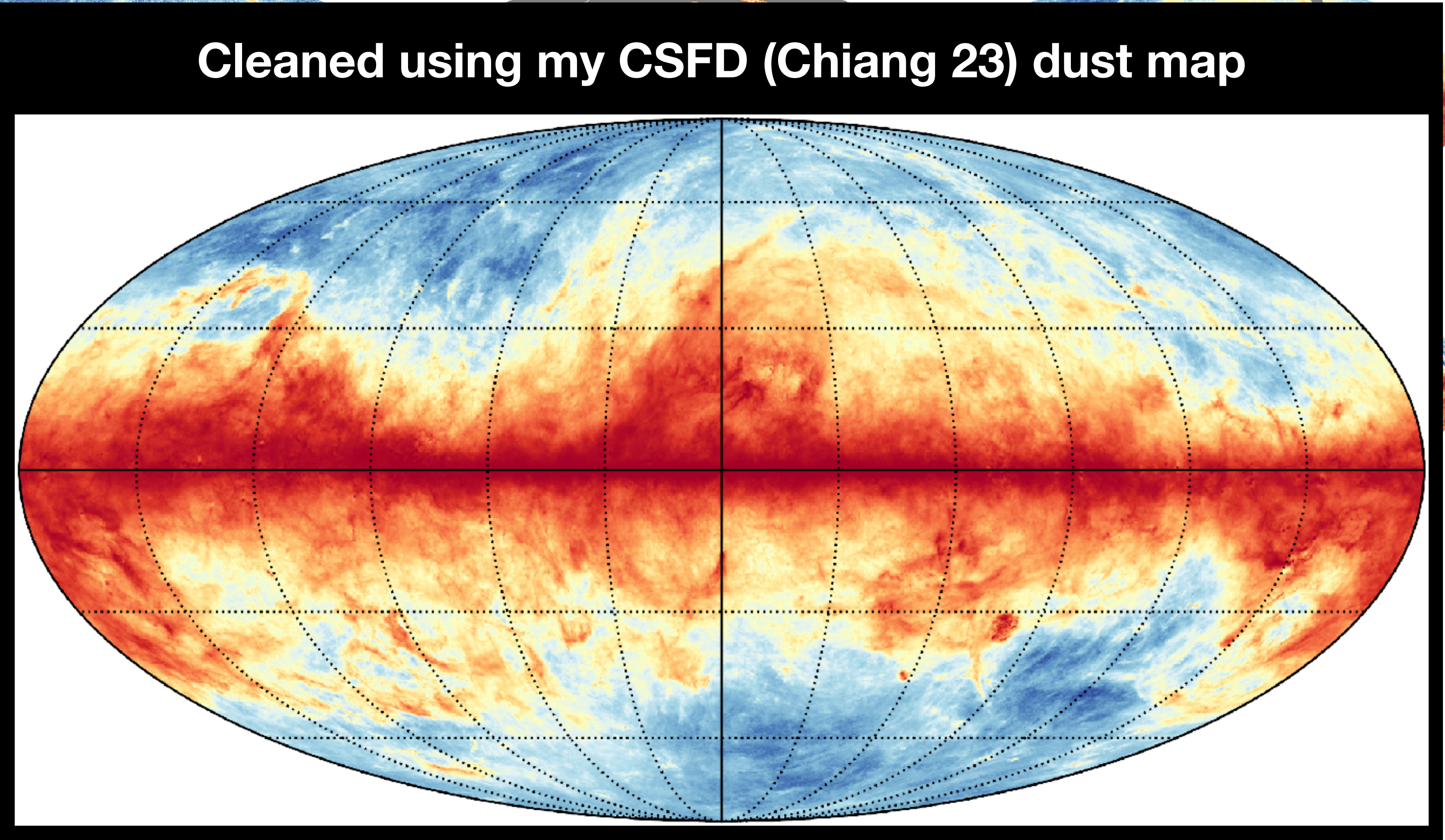
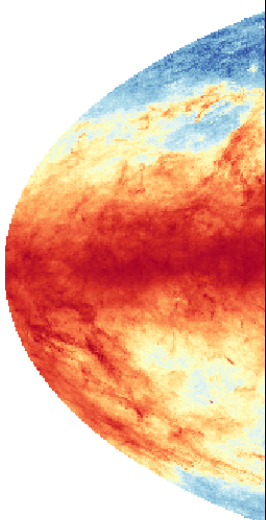
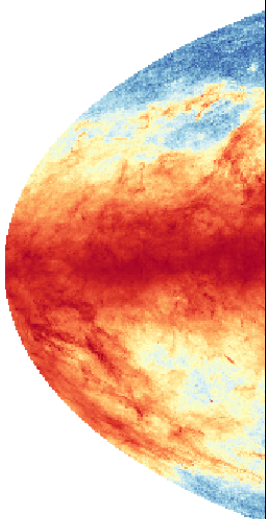
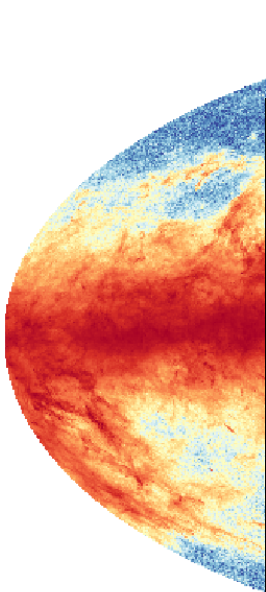
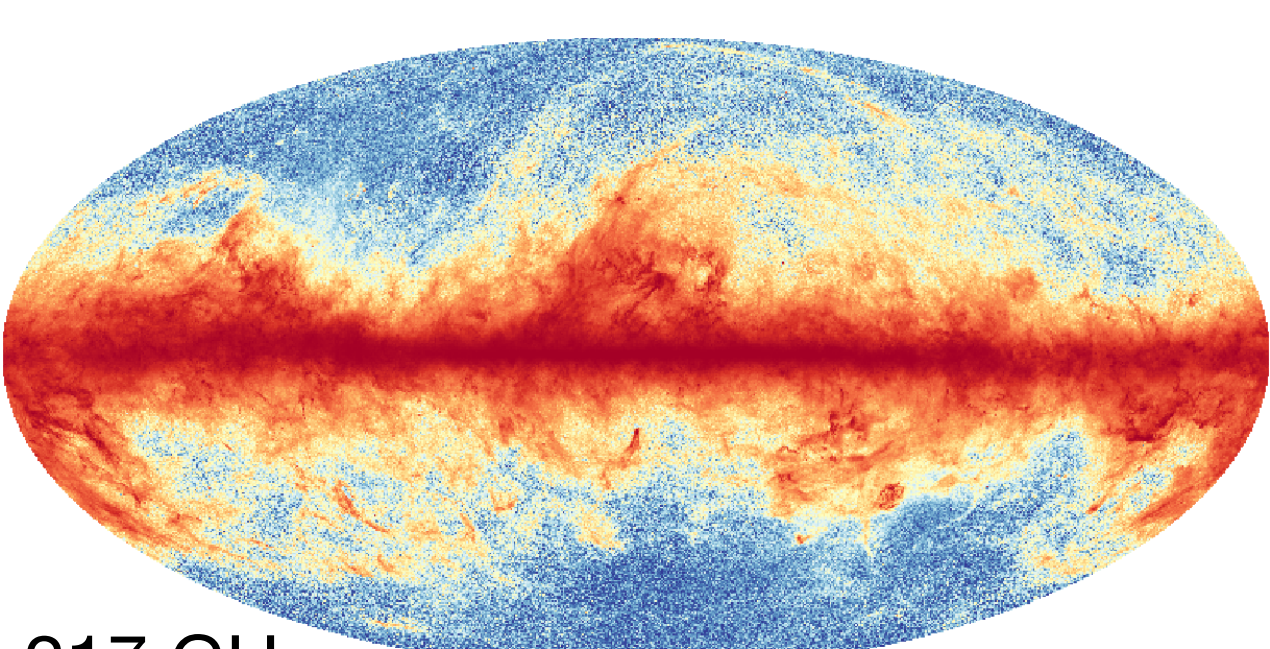
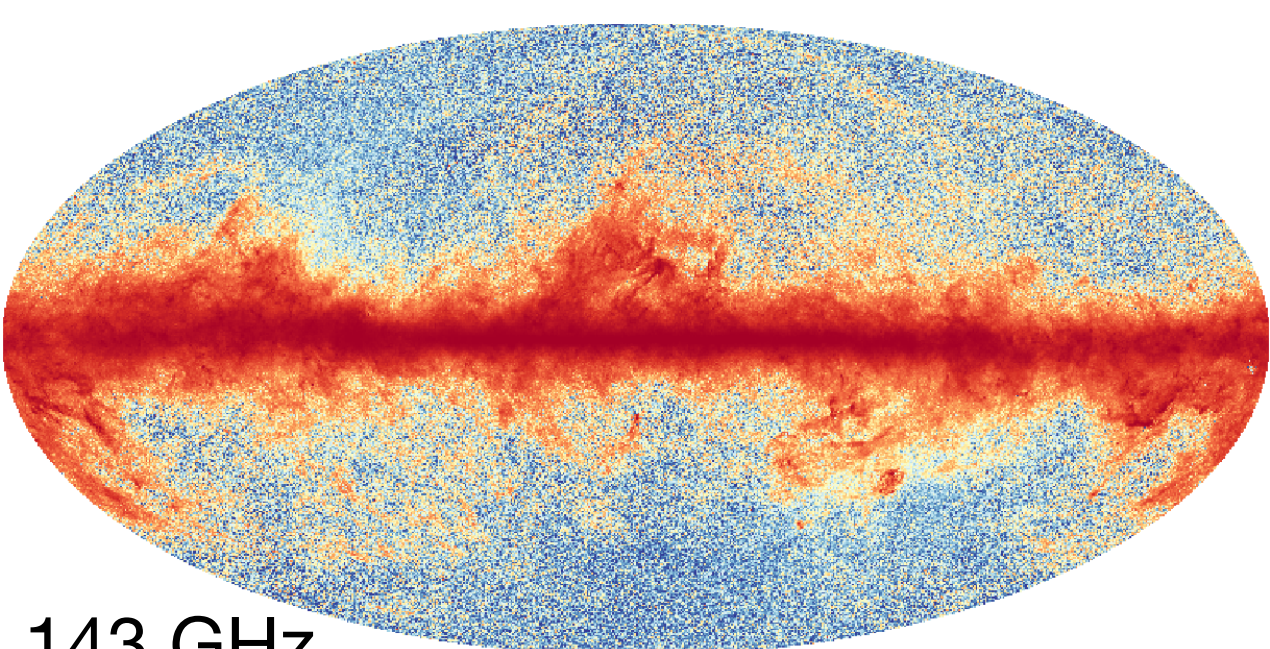
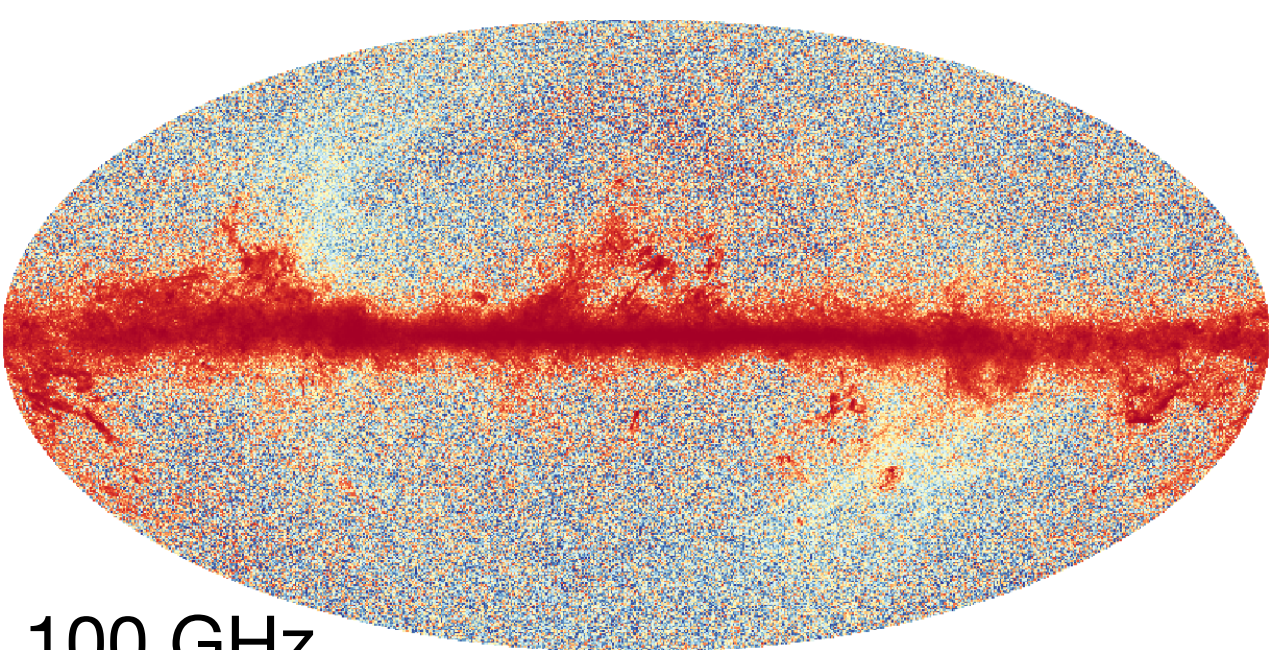
60 μm

Probing CIB+SZ using 11 maps covering 50-fold frequencies

Planck

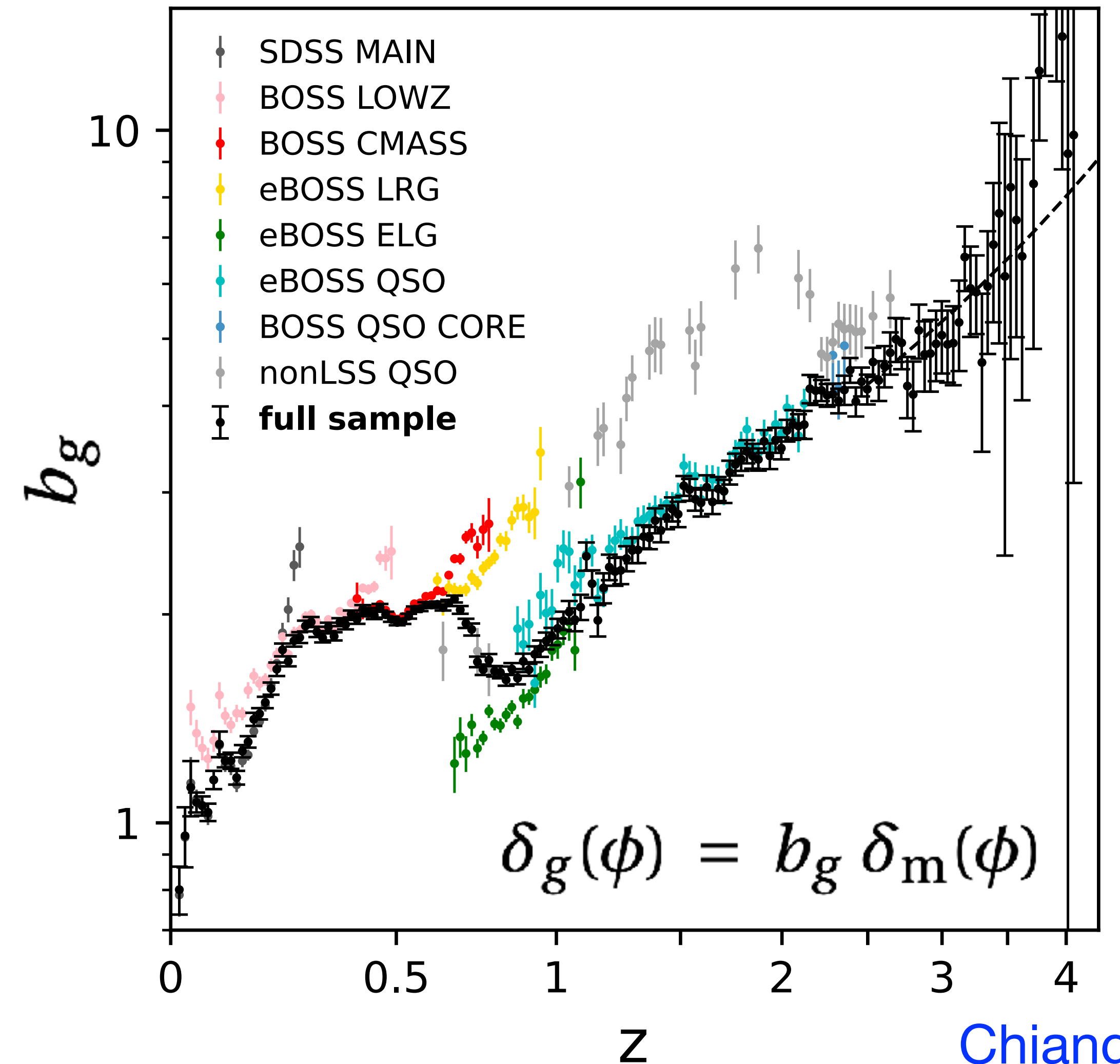
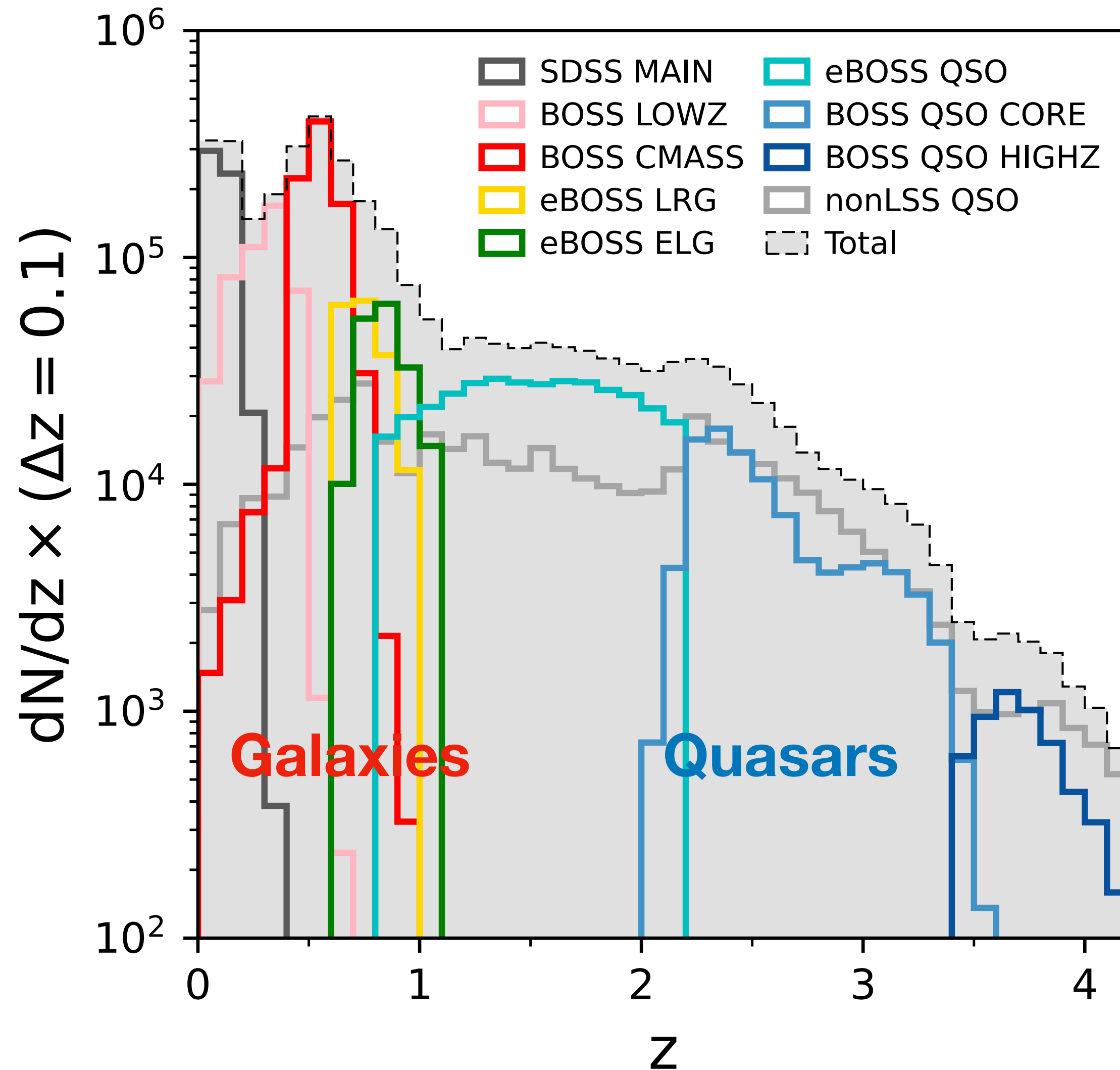
Herschel

IRAS



3D cross-correlation references

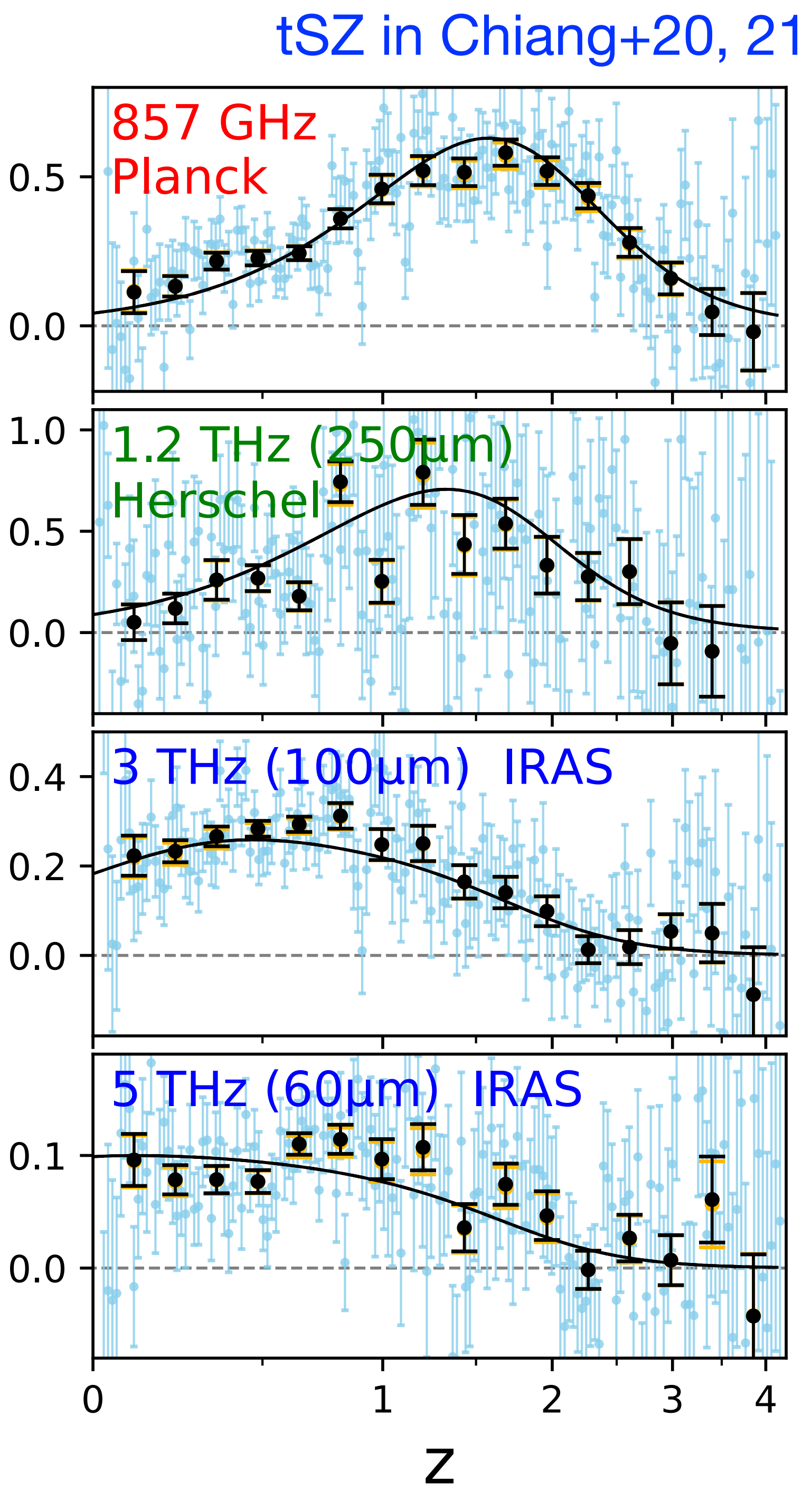
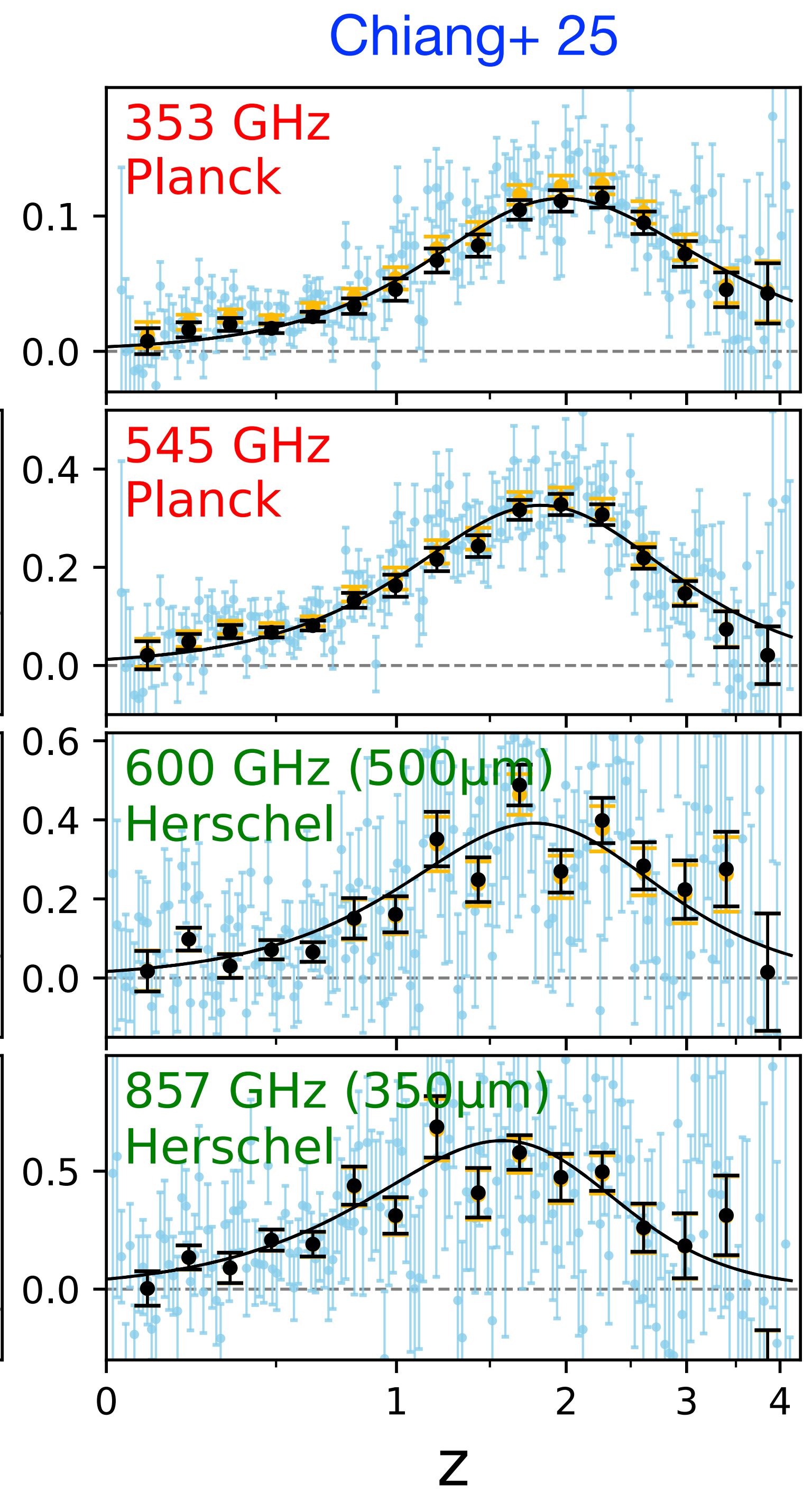
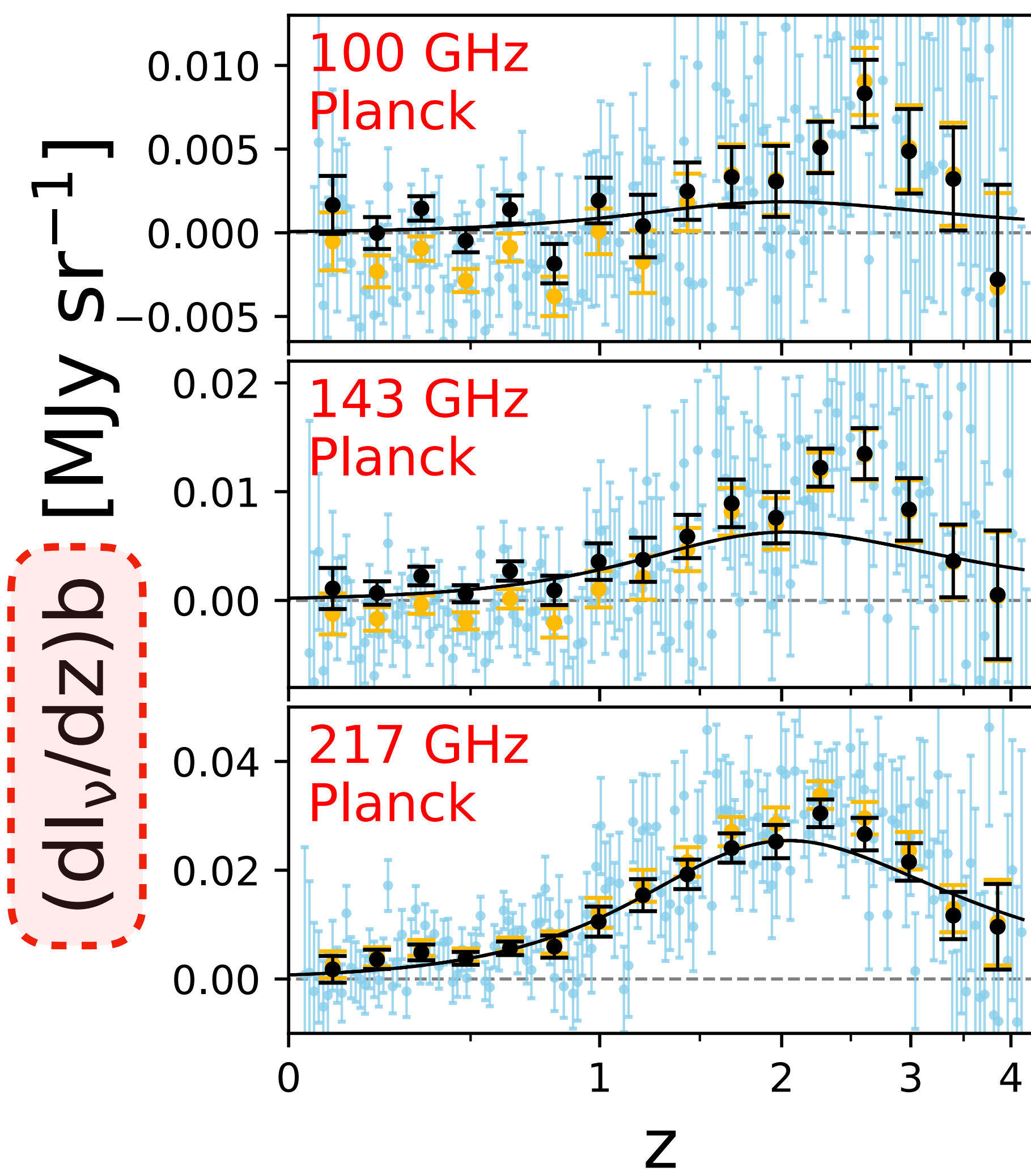
3 million spectroscopic redshifts in SDSS/BOSS/eBOSS



Clustering redshifts

$$w_{Ig}(z_i) \propto \frac{dI}{dz} b_I b_g w_m(z_i)$$

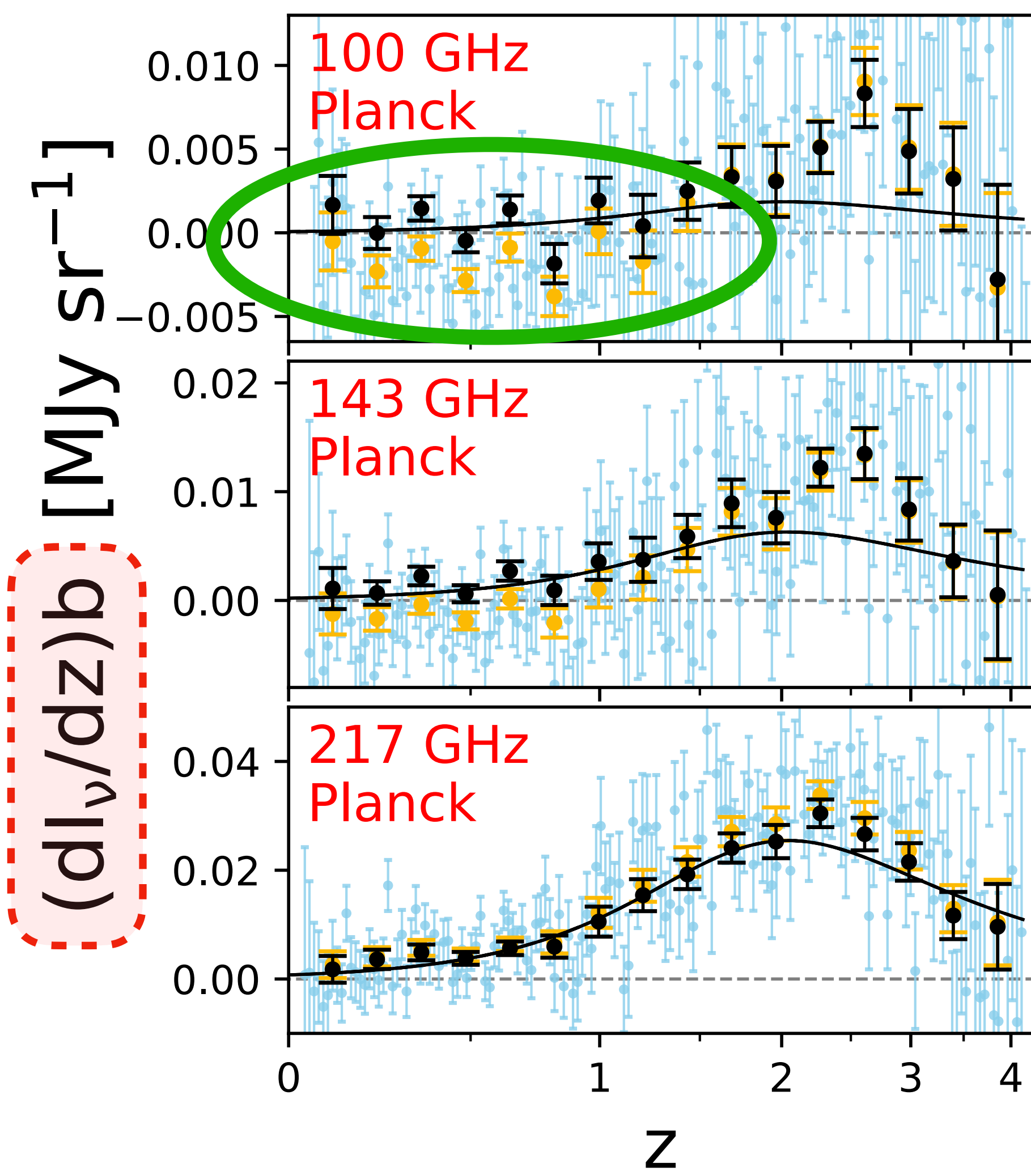
Ménard+13, Newman+08, Chiang+19



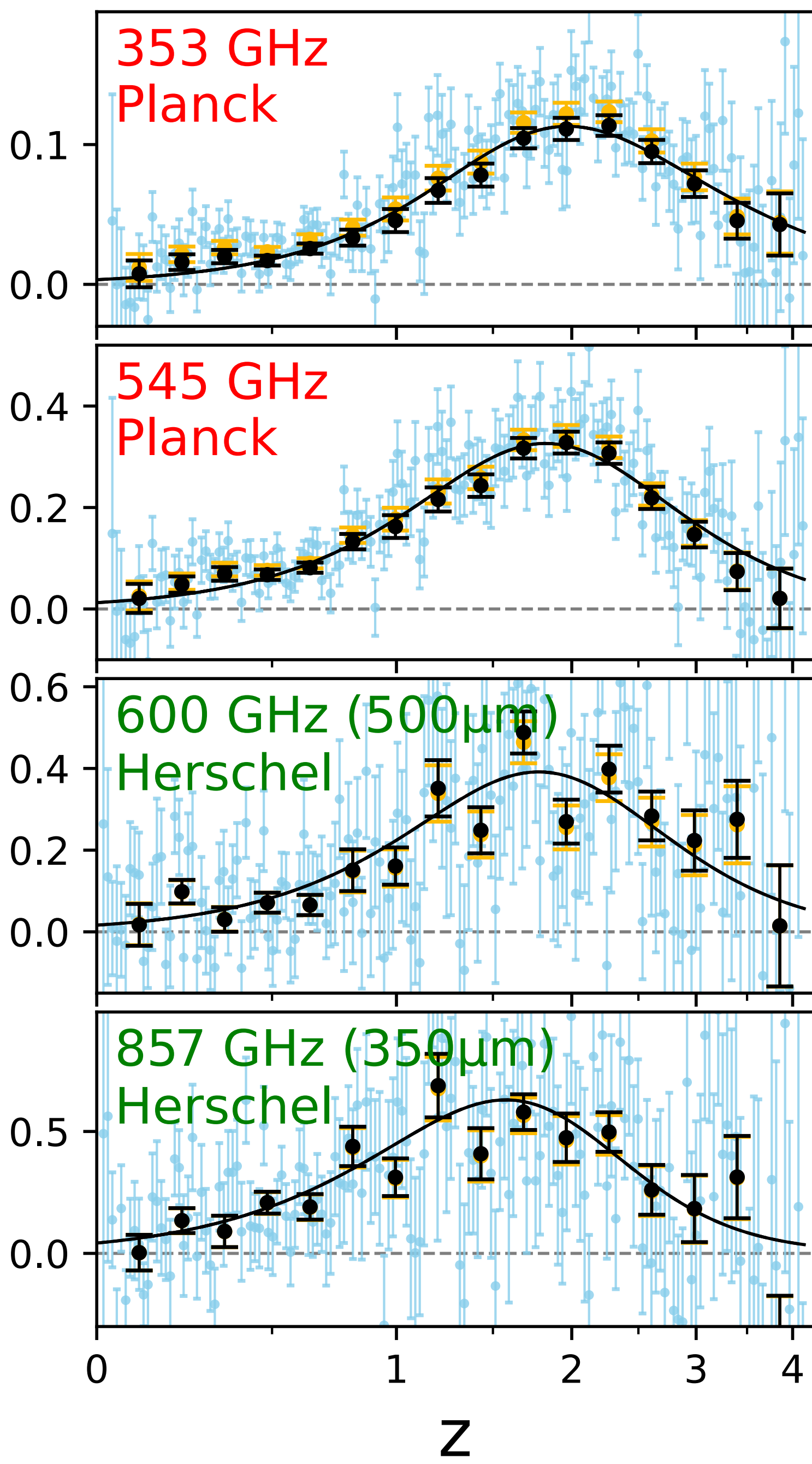
Clustering redshifts

$$w_{Ig}(z_i) \propto \frac{dI}{dz} b_I b_g w_m(z_i)$$

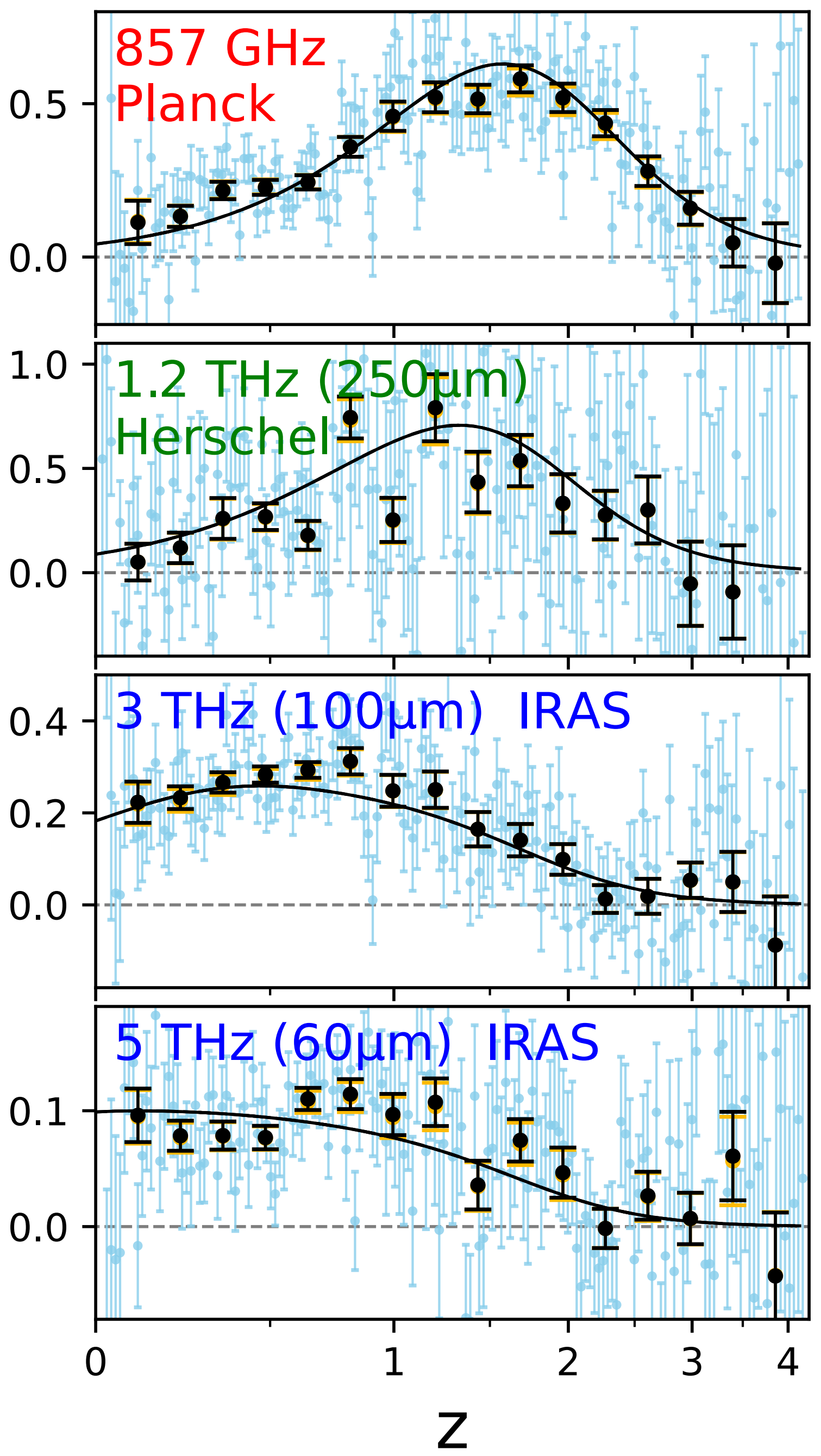
Ménard+13, Newman+08, Chiang+19



Chiang+ 25



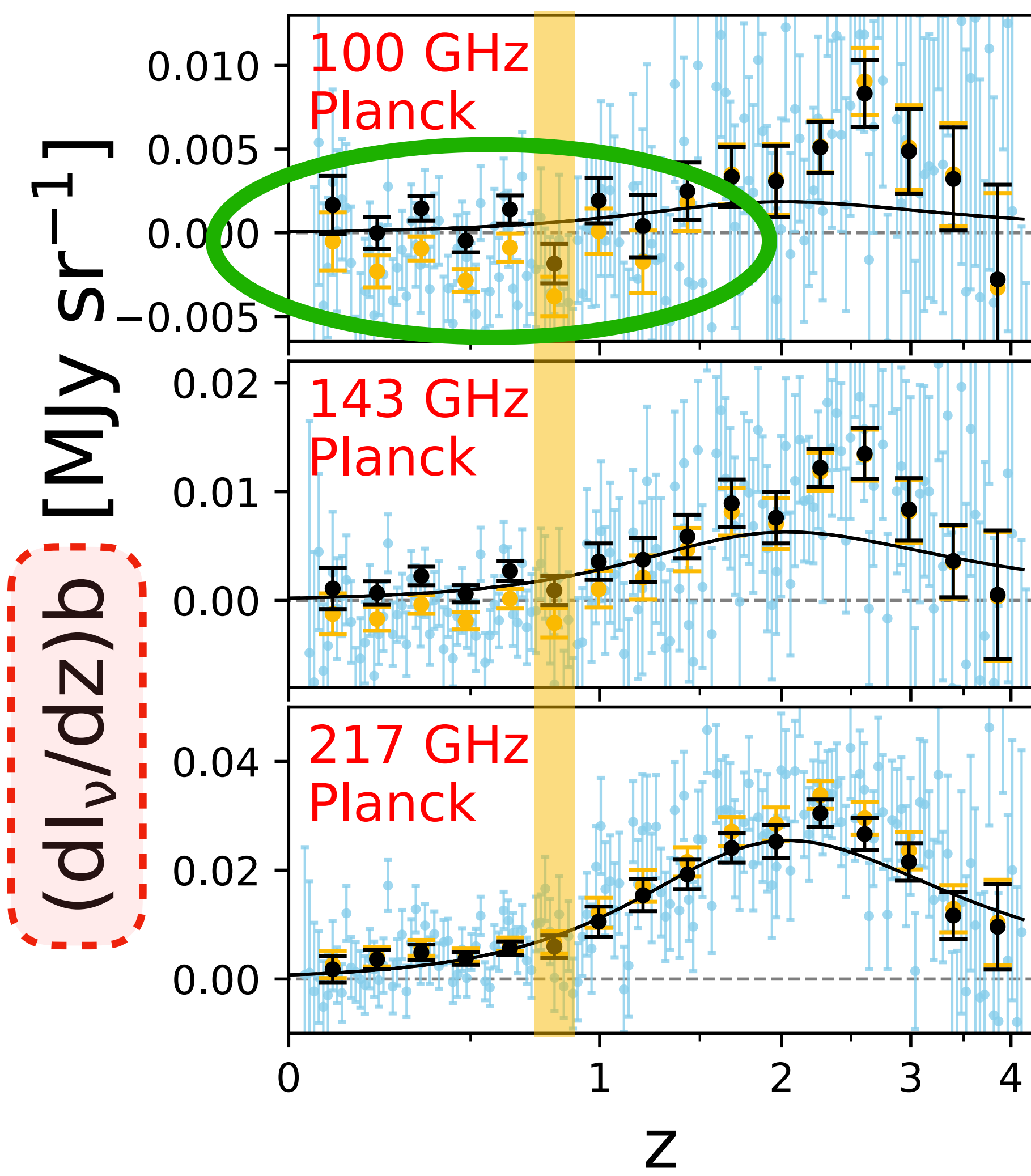
tSZ in Chiang+20, 21



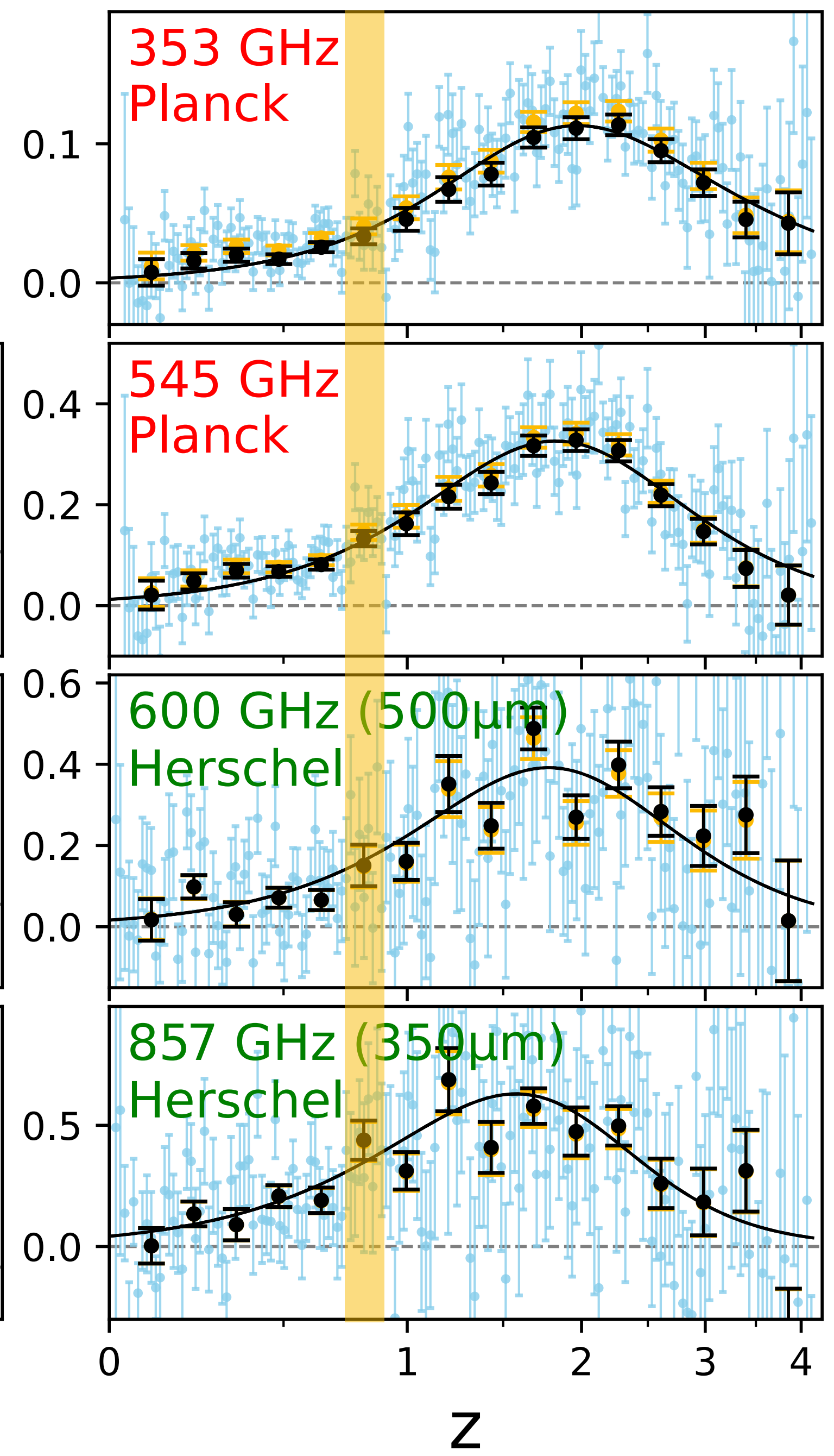
Clustering redshifts

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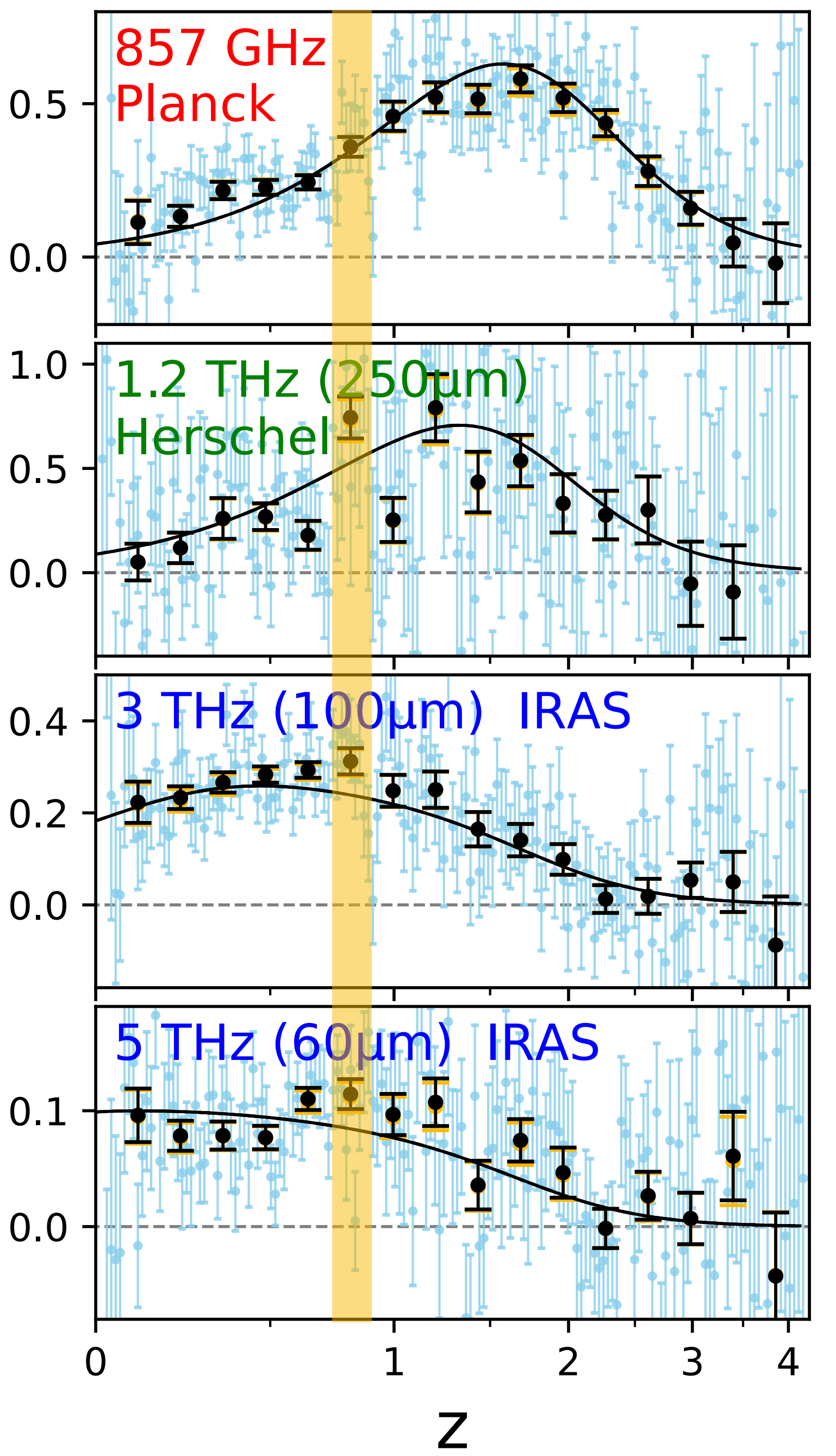
Ménard+13, Newman+08, Chiang+19



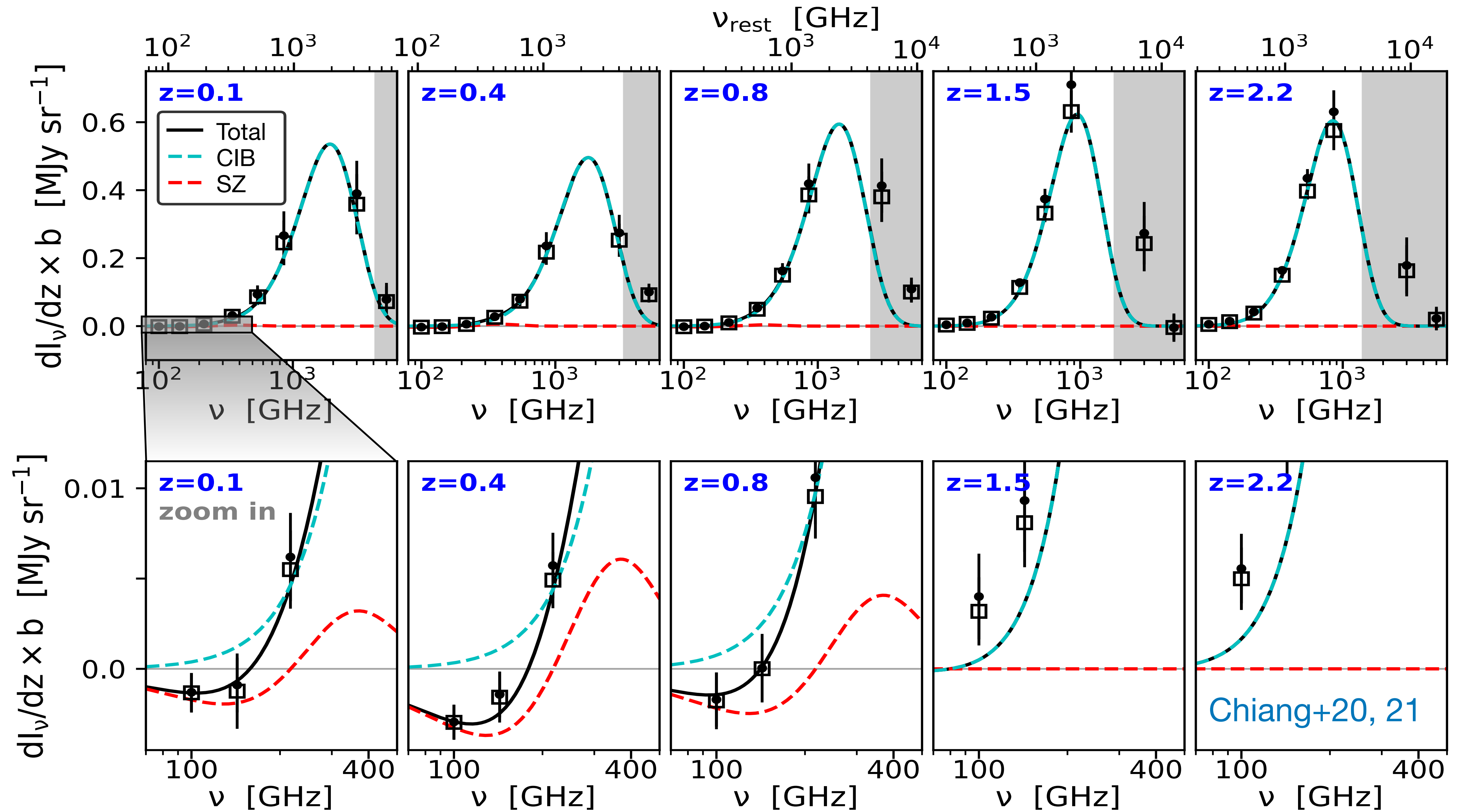
Chiang+ 25



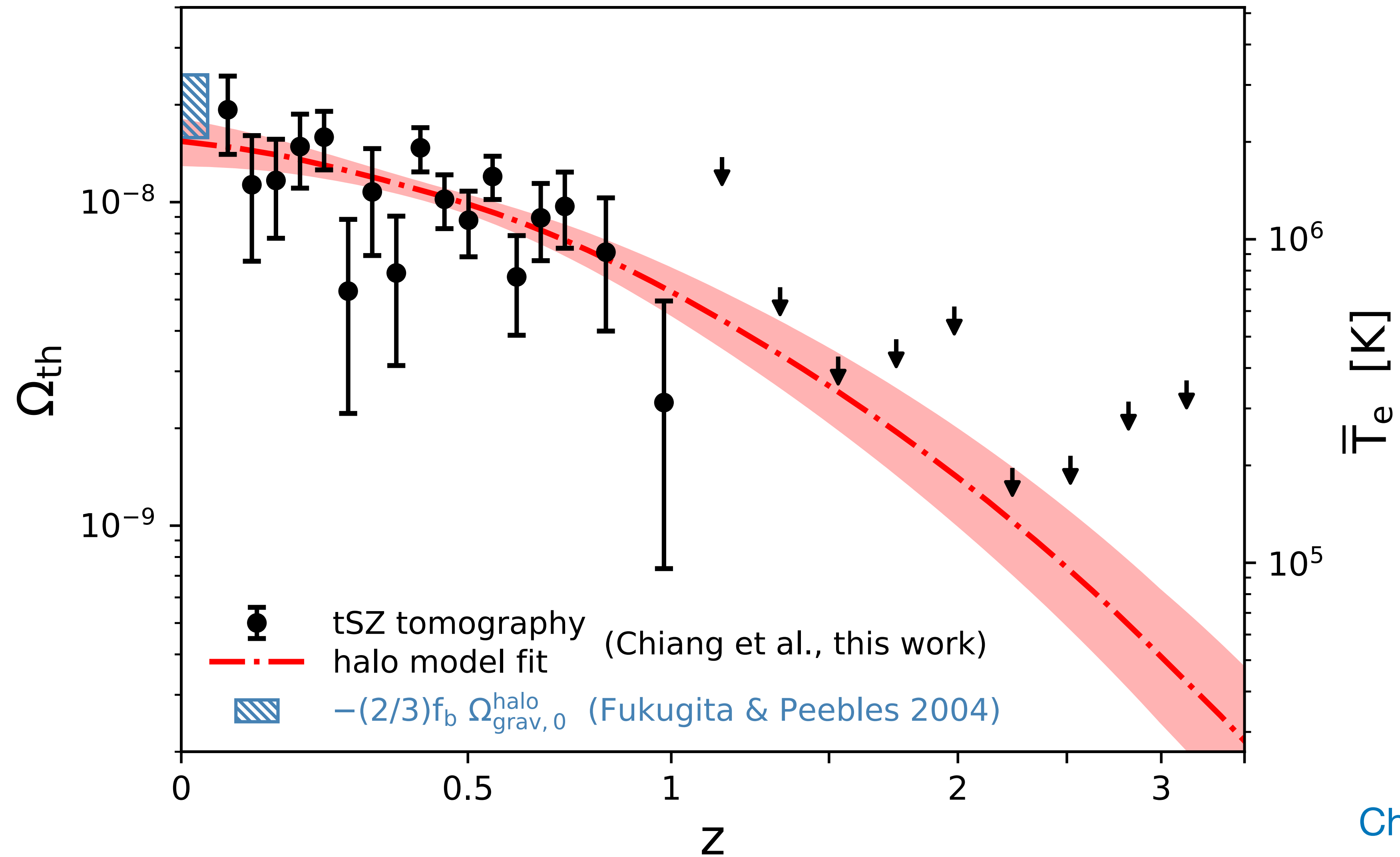
tSZ in Chiang+20, 21



Tomographic CIB + SZ spectrum

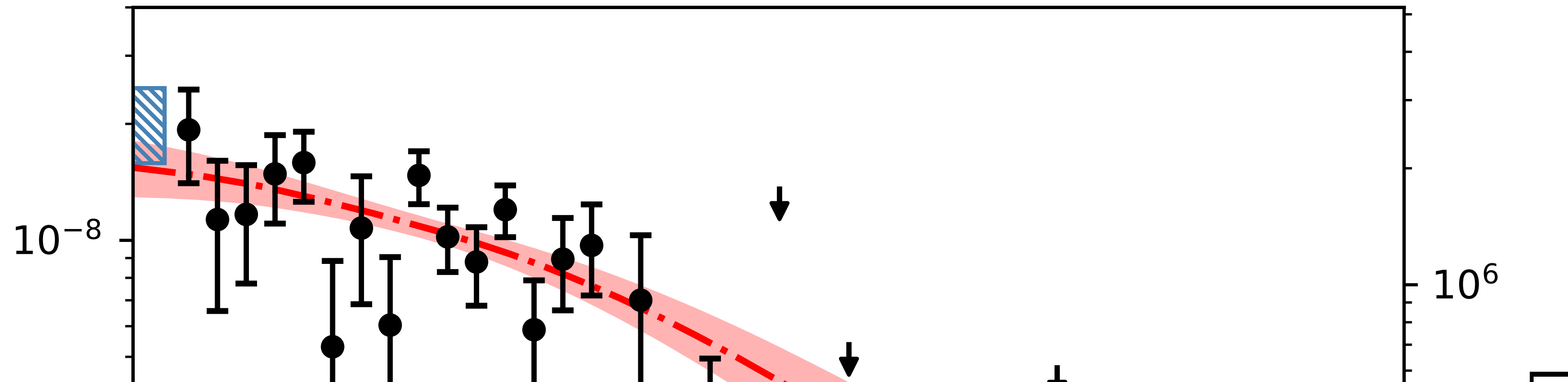


Cosmic thermal history Ω_{th} as a new target for cosmology

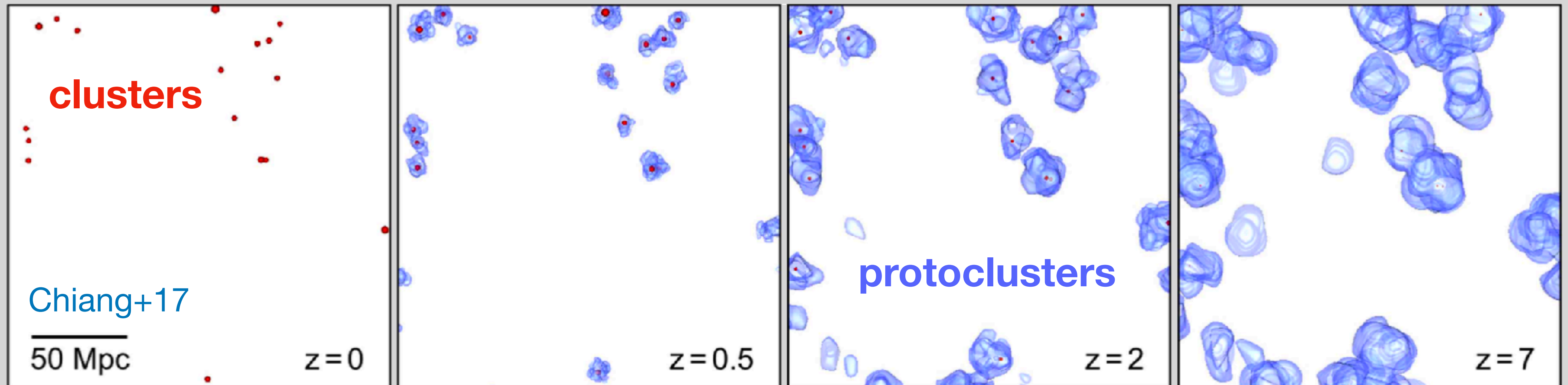


Where did the thermal energy come from?

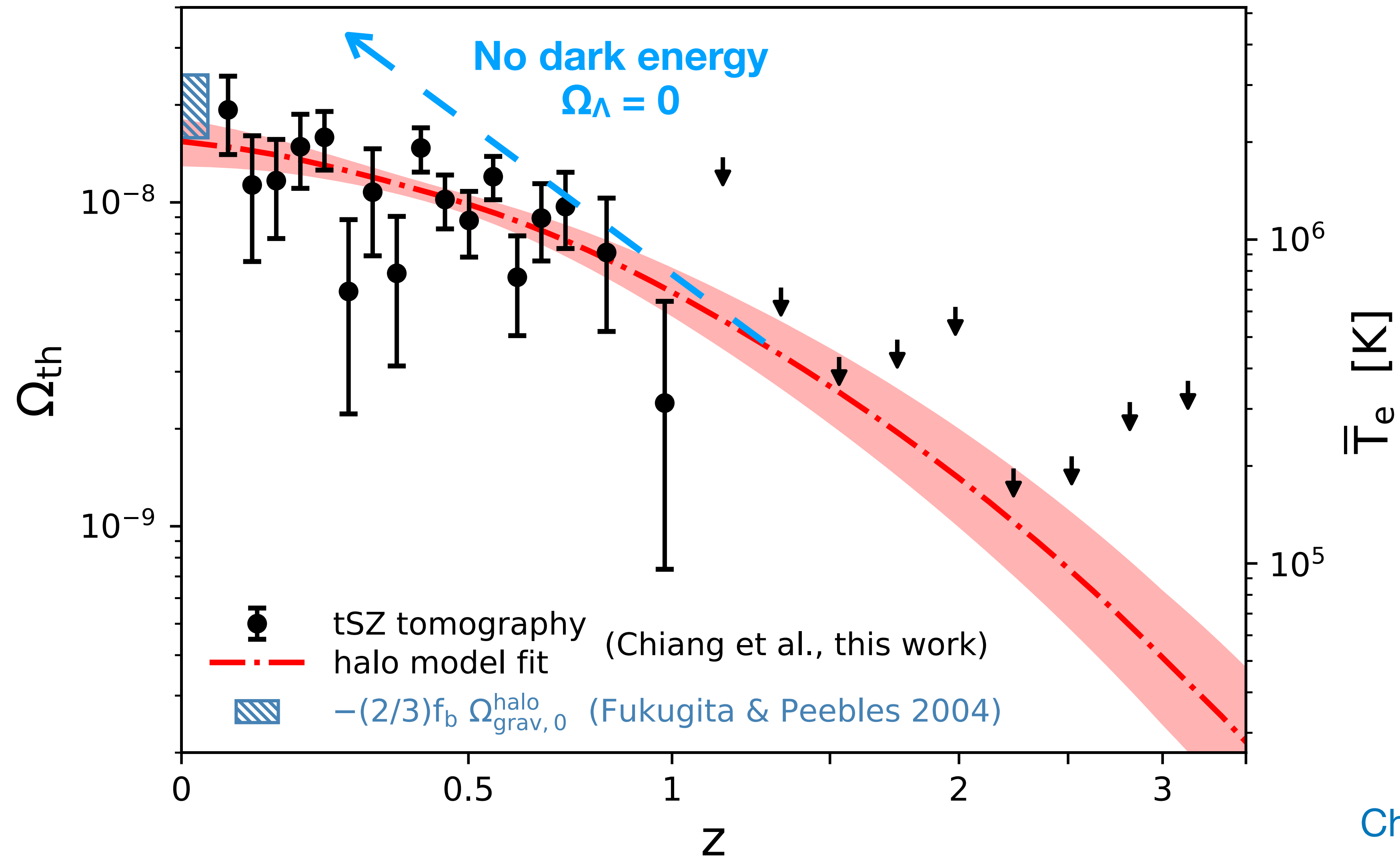
A large fraction of Ω_{th} at $z=0$ is locked in galaxy clusters ($\Omega_{\text{th}} \sim M_h^{5/3}$)



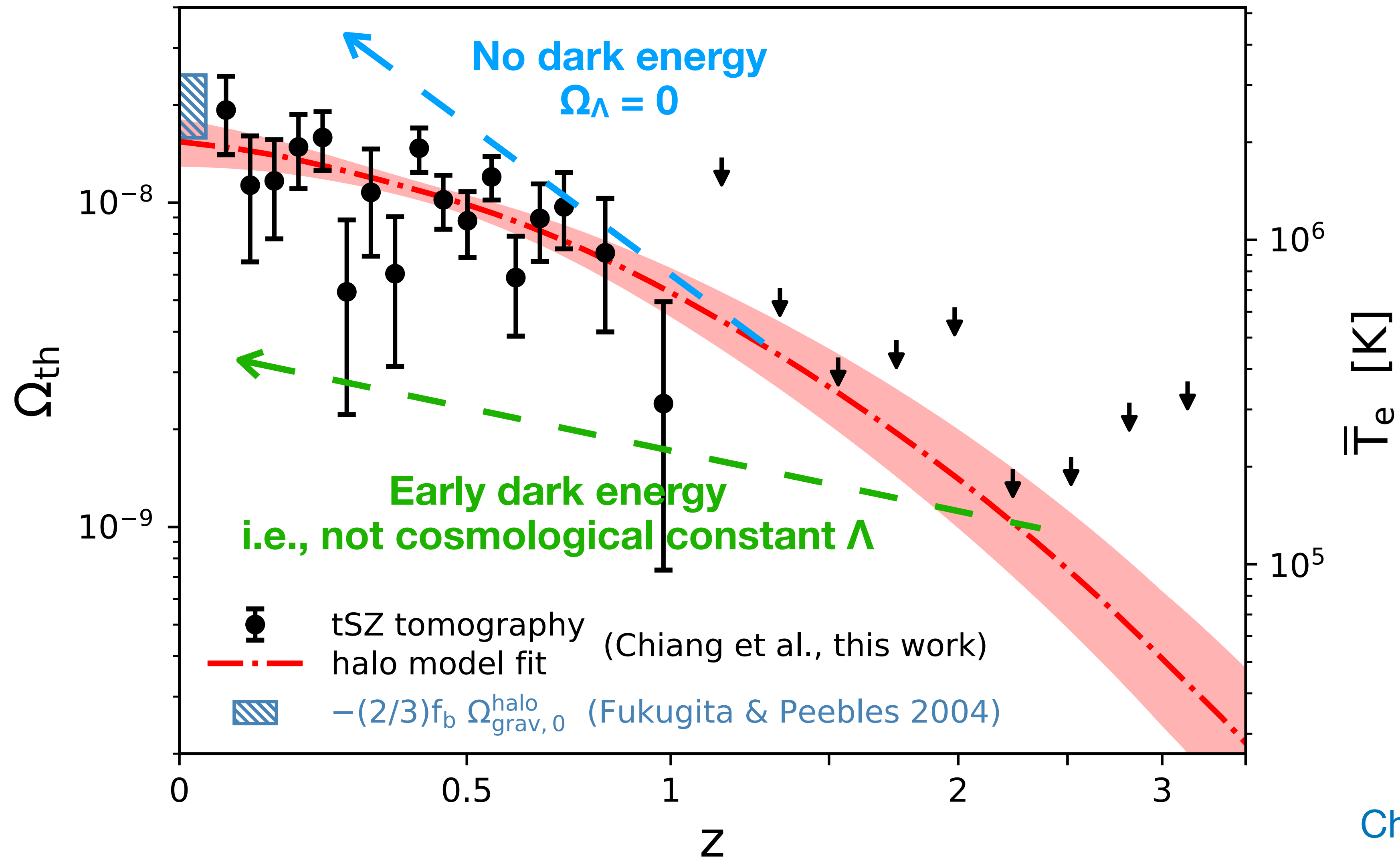
thermal $\leftarrow$ kinetic $\leftarrow$ gravitational potential



Cosmic thermal history Ω_{th} as a new target for cosmology



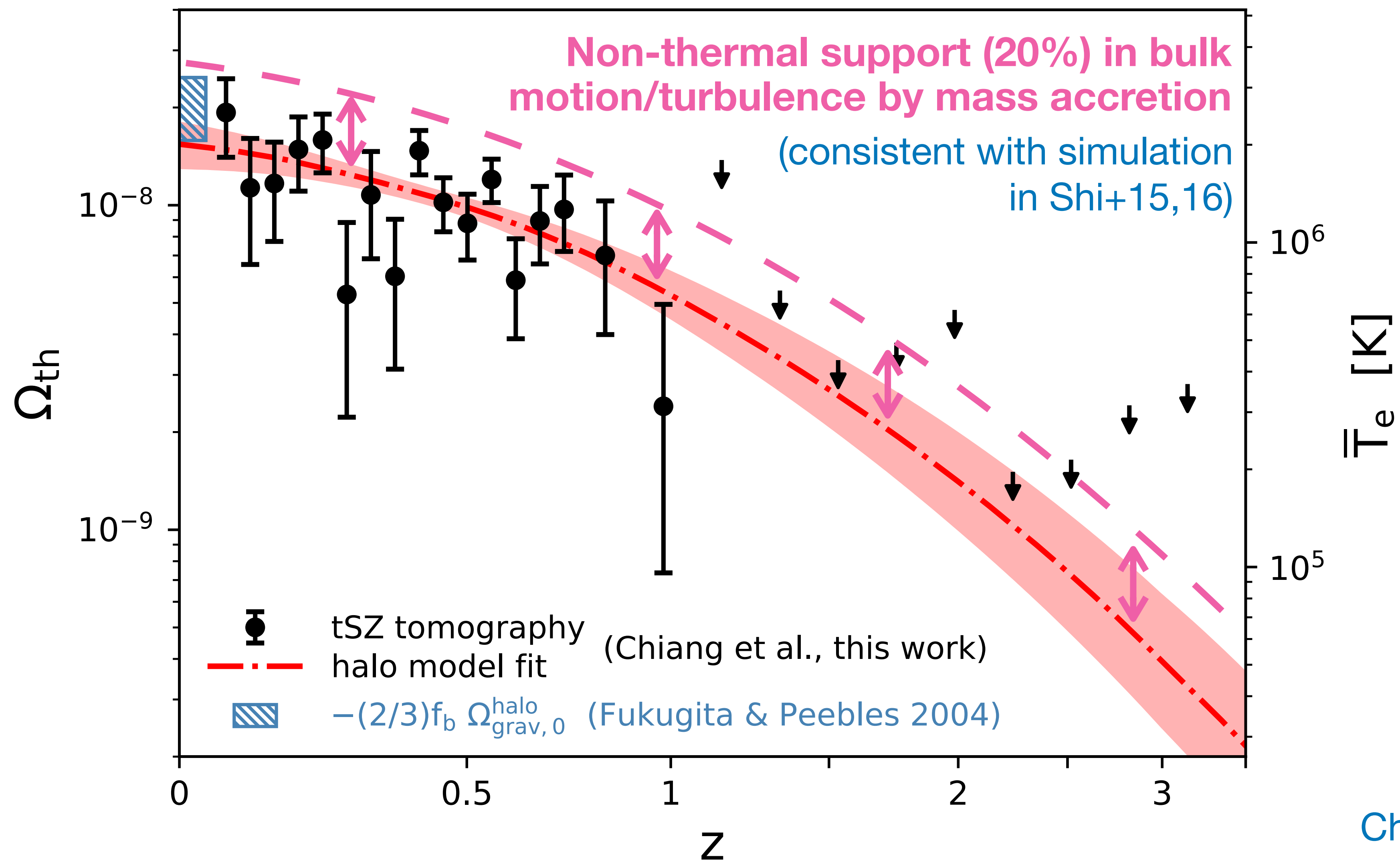
Cosmic thermal history Ω_{th} as a new target for cosmology



Chiang+20, 21

$$\Omega_{\text{th}} + \Omega_{\text{non-th}} = \Omega_{\text{grav}}$$

Our first case of energy balance between multiple Ω_x , see Chiang+21



PTT: Taiwanese

Reddit or 5ch

Where people talk about life of celebrities

批踢踢實業坊

看板

Gossiping

推 button986: 這跟全球暖化有關對吧? by文組

推 z0953781935: 這我早就知道了

推 ilovemiao: 跟我想的一樣

推 cattgirl: 地球溫室效應怎麼擴散到全宇宙 應該消滅人類

推 soaring: 那跟大爆炸比勒?

推 kamichu: 就說暖化是假議題 太陽只要燃燒多一點就熱多少了

推 RAR5278: 熵增加了

推 love12548: 九成是吸管害的

推 asiaking5566: 所以沒碳排放的事了 大家一起燒煤吧

→ csi9507121: 不對啊, 宇宙膨脹, 溫度不是該越低, 一直到熱寂嗎? 怎

→ csi9507121: 麼溫度反而變高? **Science discussion**

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推 fnm525: 宇宙膨脹是Space在膨脹, 可是星雲內部會因為重力塌縮而變

→ kamichu: 碳排放是西方國家掠奪開發國家的藉口而已

→ fnm525: 熱啊

推 pipiayin: 怎麼證明完全無關啊

→ turbomom **“Aliens must have high carbon footprints”**

推 losage: 一定是外星人碳排放太高了

推 gentleman317: 全宇宙都在霸凌北極熊

推 dbalruke: 非同 **“The whole Universe is bullying polar bears”**

→ awaken: 一定是支那造成的, 讓我們滅掉中國垃圾國

推 yesjimmy62: 欸內文居然沒講, 研究作者是台灣人啊

→ atbb: 200萬 K?! 有沒有打錯啊?

推 ice76824: 一定是外星人再偷偷排碳

噓 skygray2: 都是全球暖化的鍋

Galaxies Have Gotten Hotter As They've Gotten Older

10, 2020

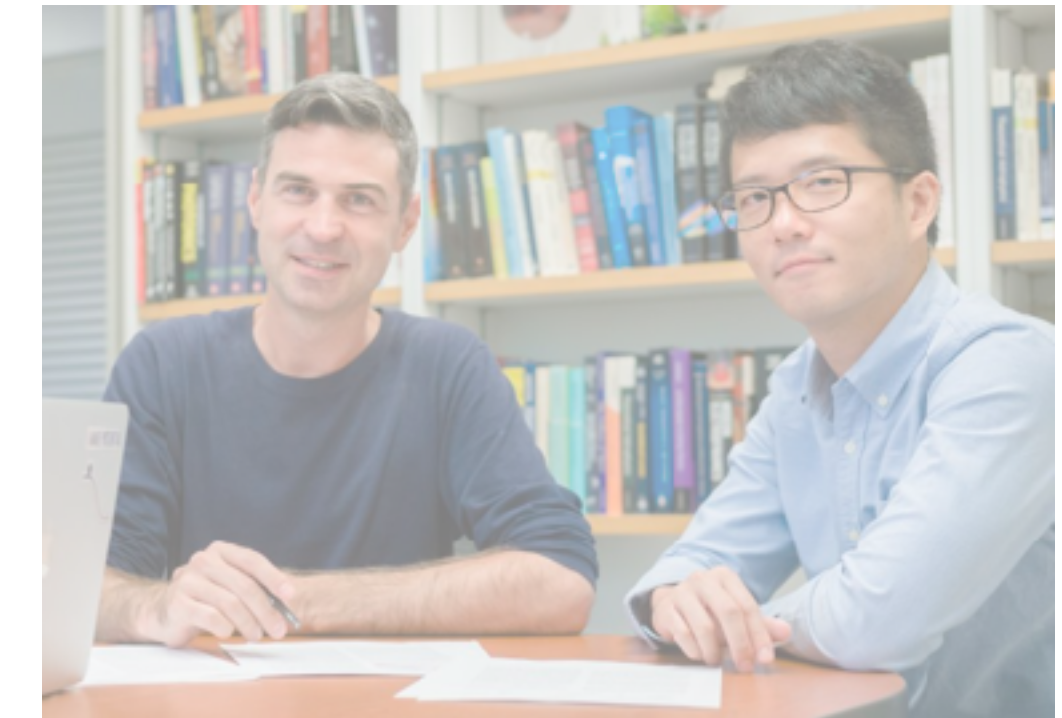
CONTACT: Doug Donovan

443-462-2947

donovan@jhu.edu

ugdonovan

says you can't get hotter with age?



Die Temperatur des Universums: es wird heißer

Making the temperature of the Universe

Wie heiß ist das Universum heute? Wie heiß war es in der Vergangenheit? Eine neue Studie, die in der Fachzeitschrift "Astrophysical Journal" veröffentlicht wurde, deutet darauf hin, dass sich die mittlere Temperatur großer Strukturen im Universum in den letzten zehn Milliarden Jahren um das Zehnfache erhöht hat und heute etwa zwei Millionen Grad beträgt.



MAX-PLANCK-INSTITUT
FÜR ASTROPHYSIK



TechNews

科技新報

宇宙在不斷升溫, 科學家測出氣體平均溫度較早期高了 10 倍

作者 Emma stein | 發布日期 2020 年 11 月 12 日 15:27 | 分類 天文, 自然科學

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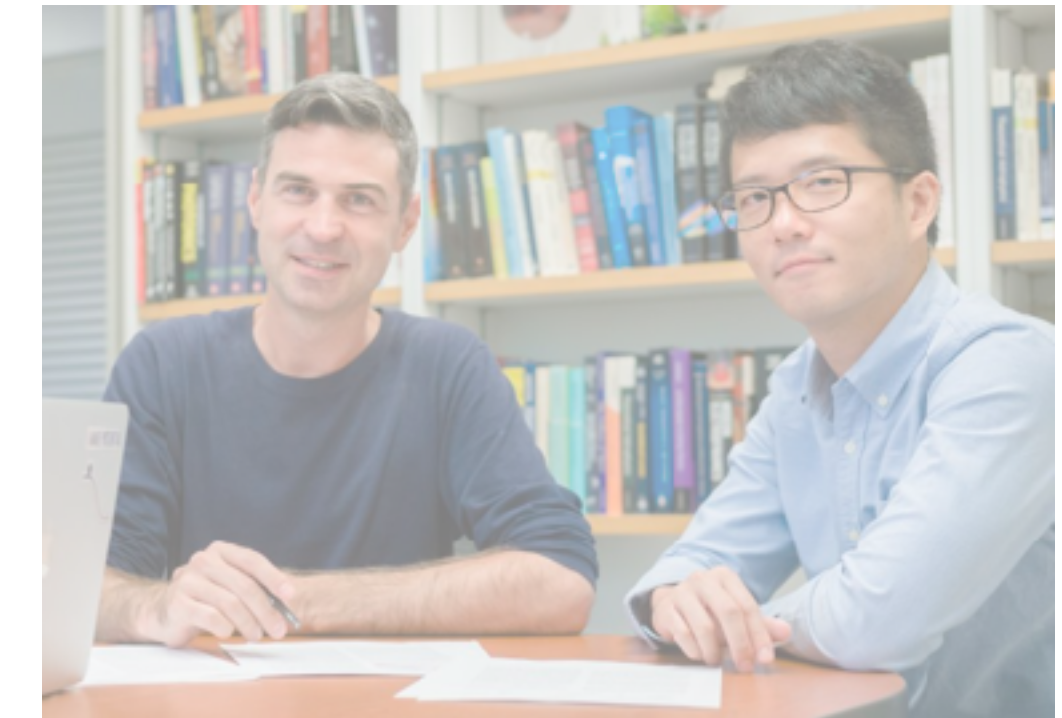
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ugdonovan

says you can't get hotter with age?



Cosmic heat



○ Annemarie Pearce <[redacted]@gmail.com>

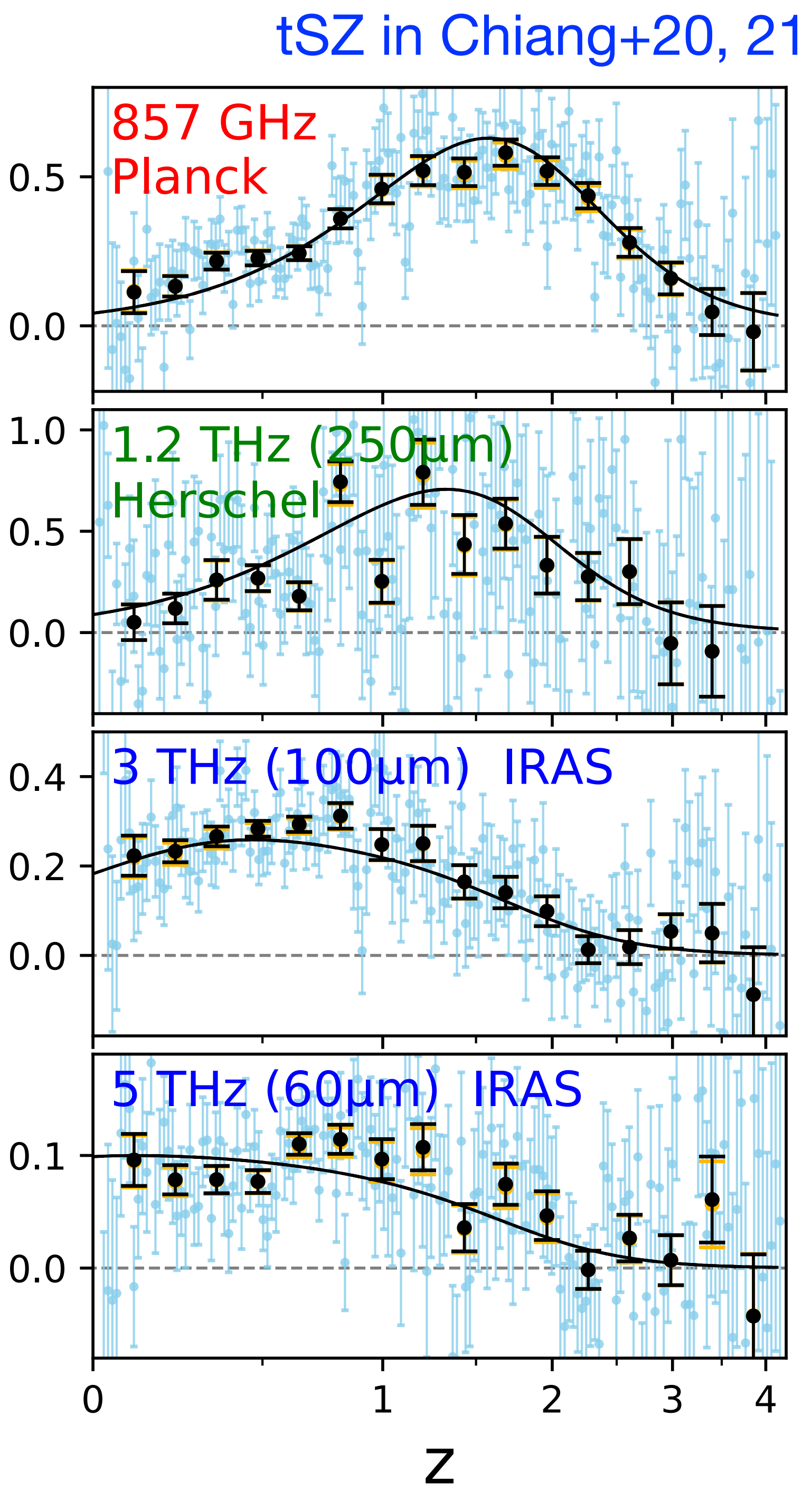
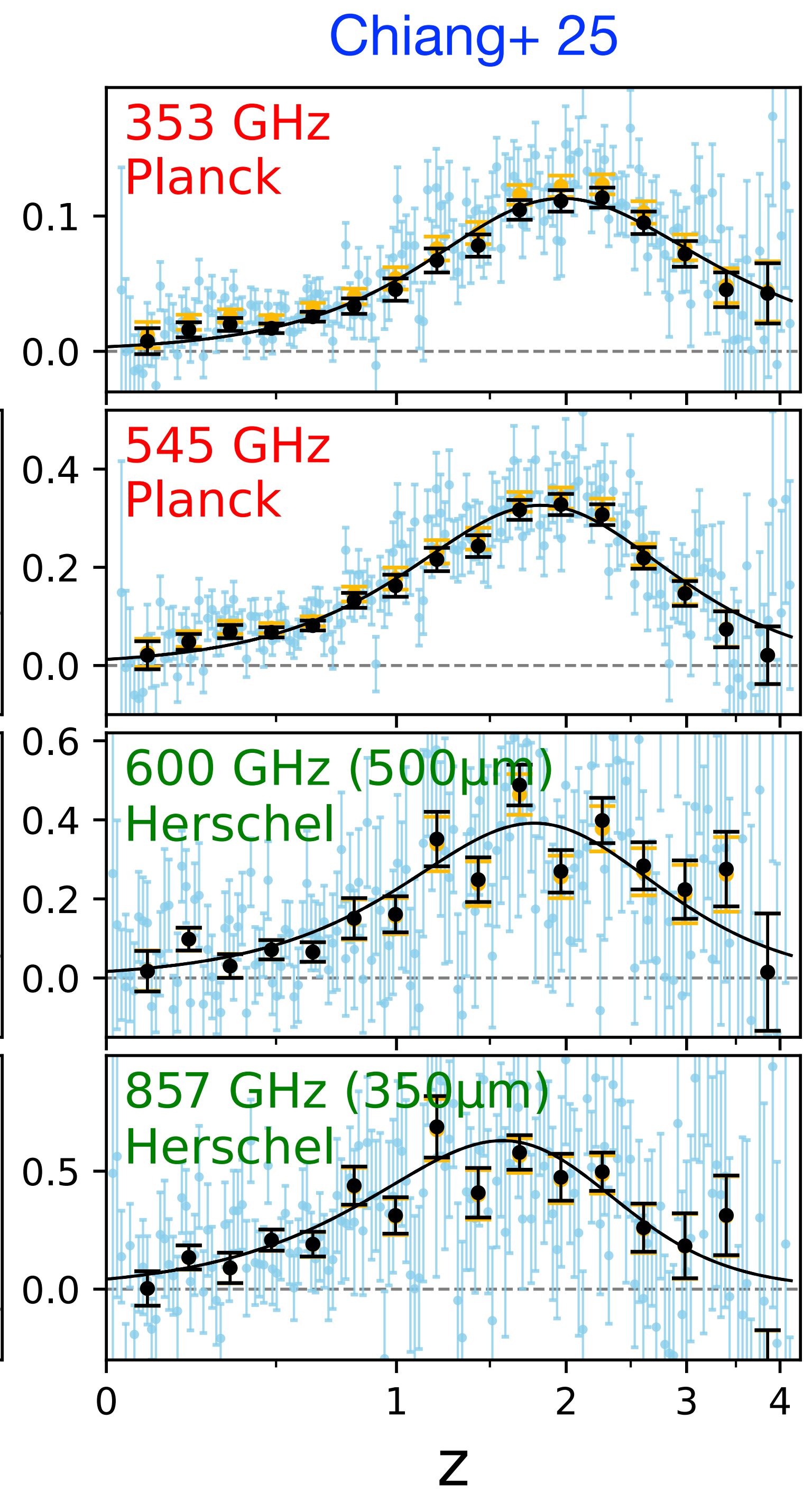
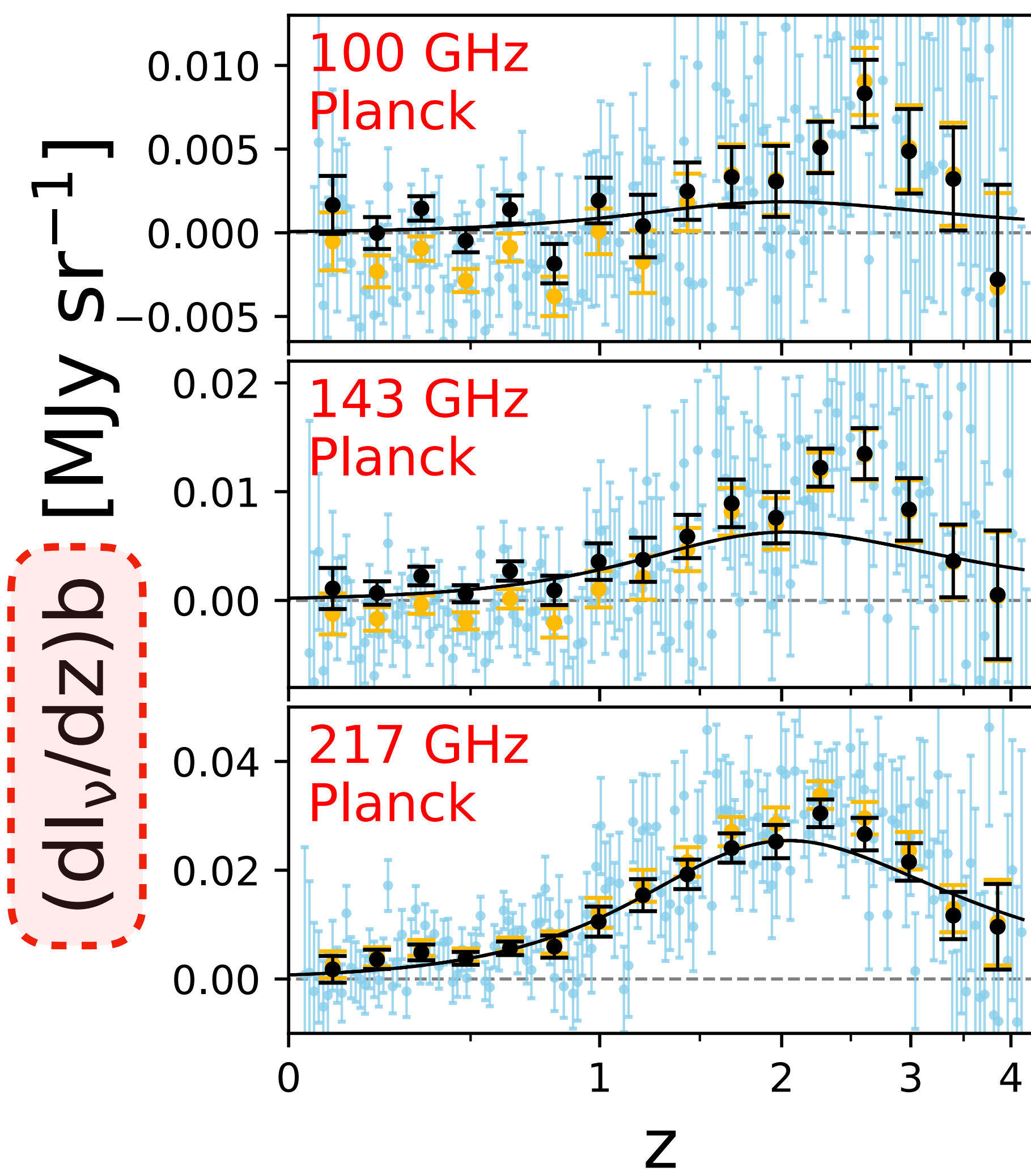
To: ○ Chiang, Yi-Kuan

So tell us how do you know what cosmic heat was billions of years ago. There is no way to measure that, **unless, of course, you are a time traveler...**

Clustering redshifts

$$w_{Ig}(z_i) \propto \frac{dI}{dz} b_I b_g w_m(z_i)$$

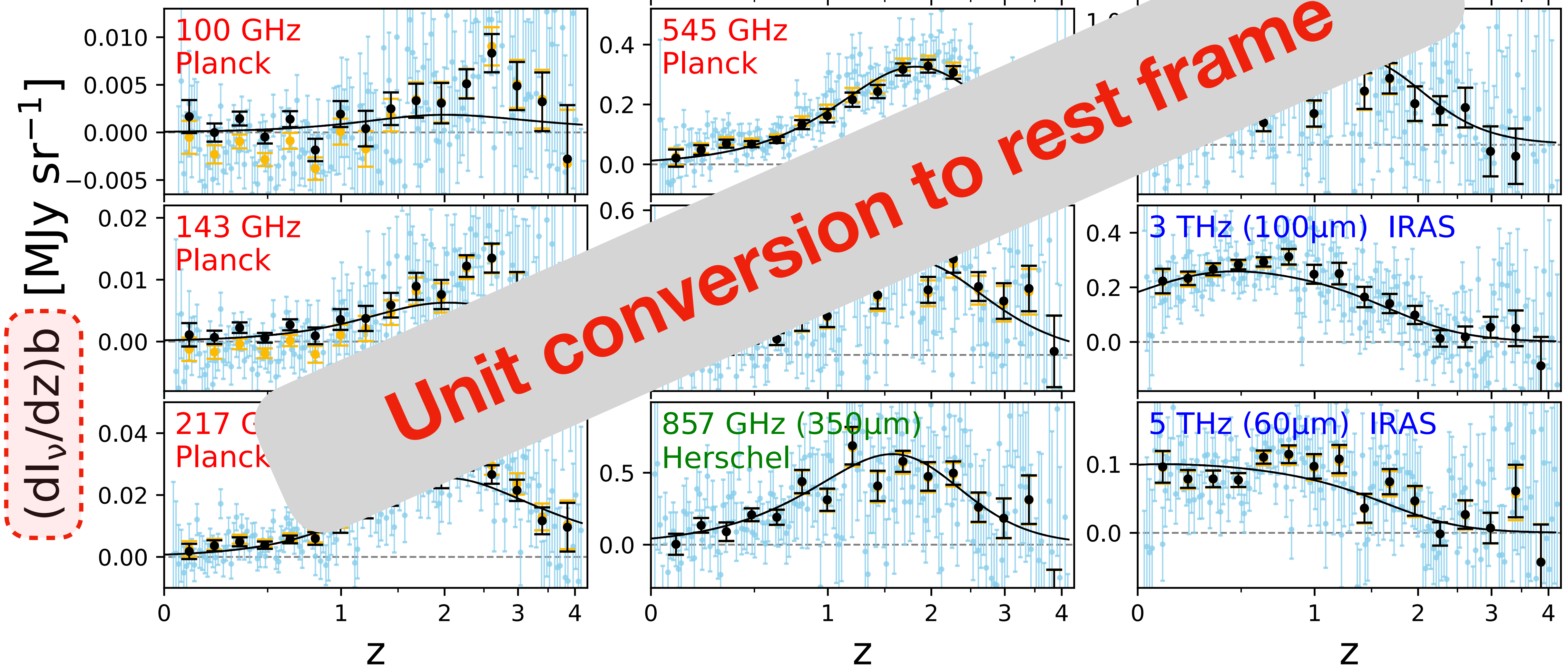
Ménard+13, Newman+08, Chiang+19



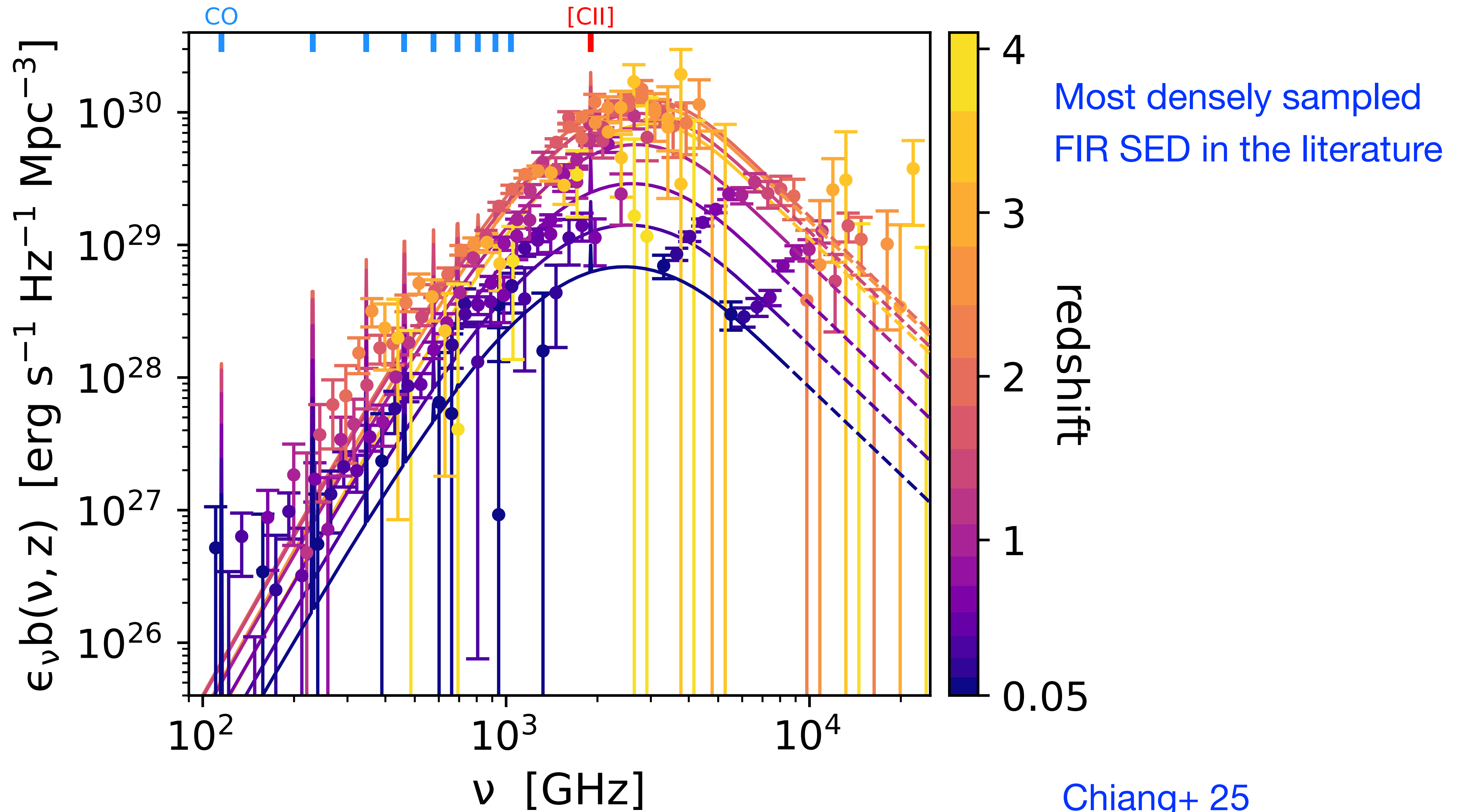
Clustering redshifts

$$w_{Ig}(z_i) \propto \frac{dI}{dz} b_I b_g w_m(z_i)$$

Ménard+13, Newman+08, Chiang+19



Tomographic CIB spectrum

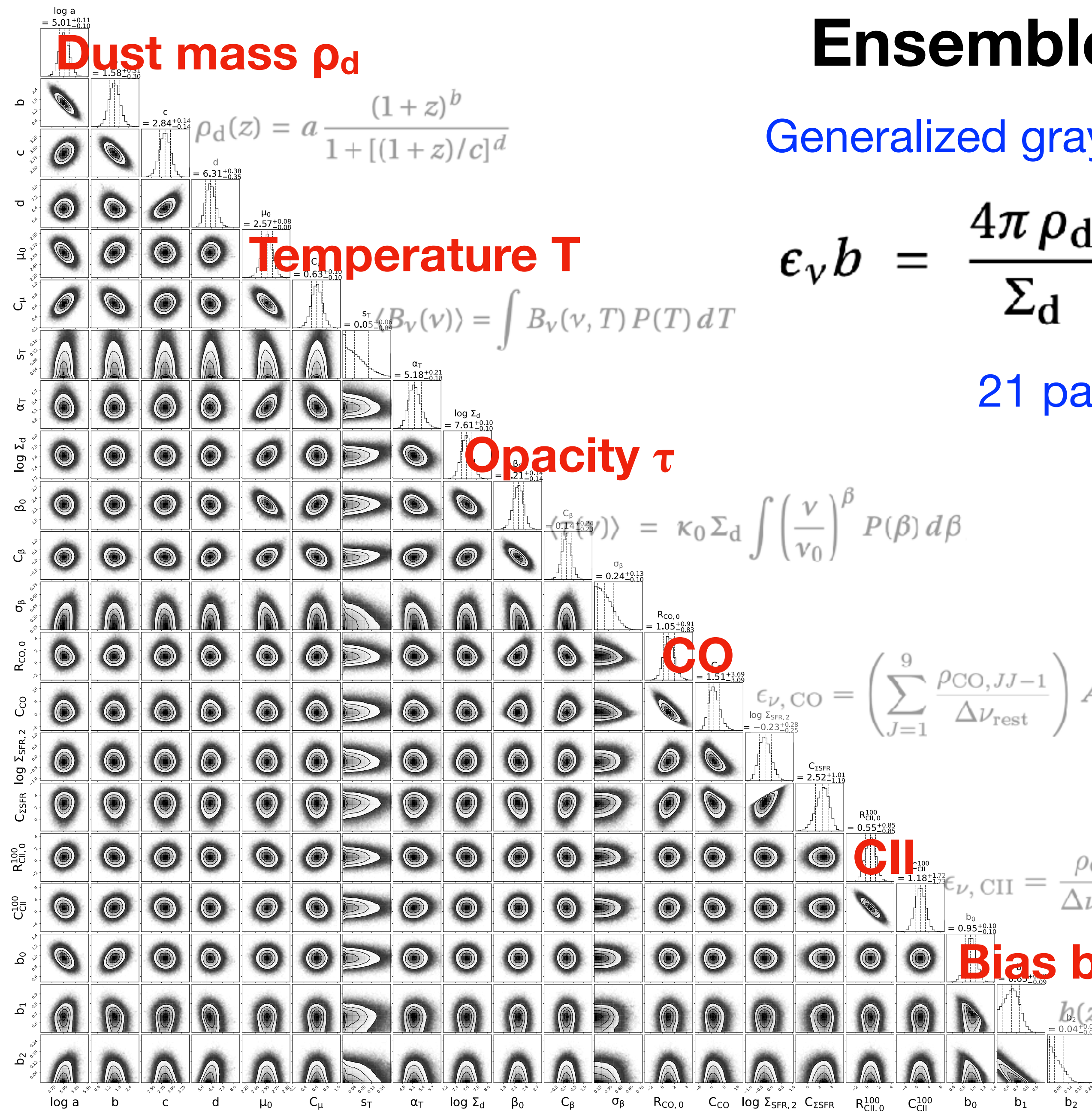


Ensemble cosmic dust SED

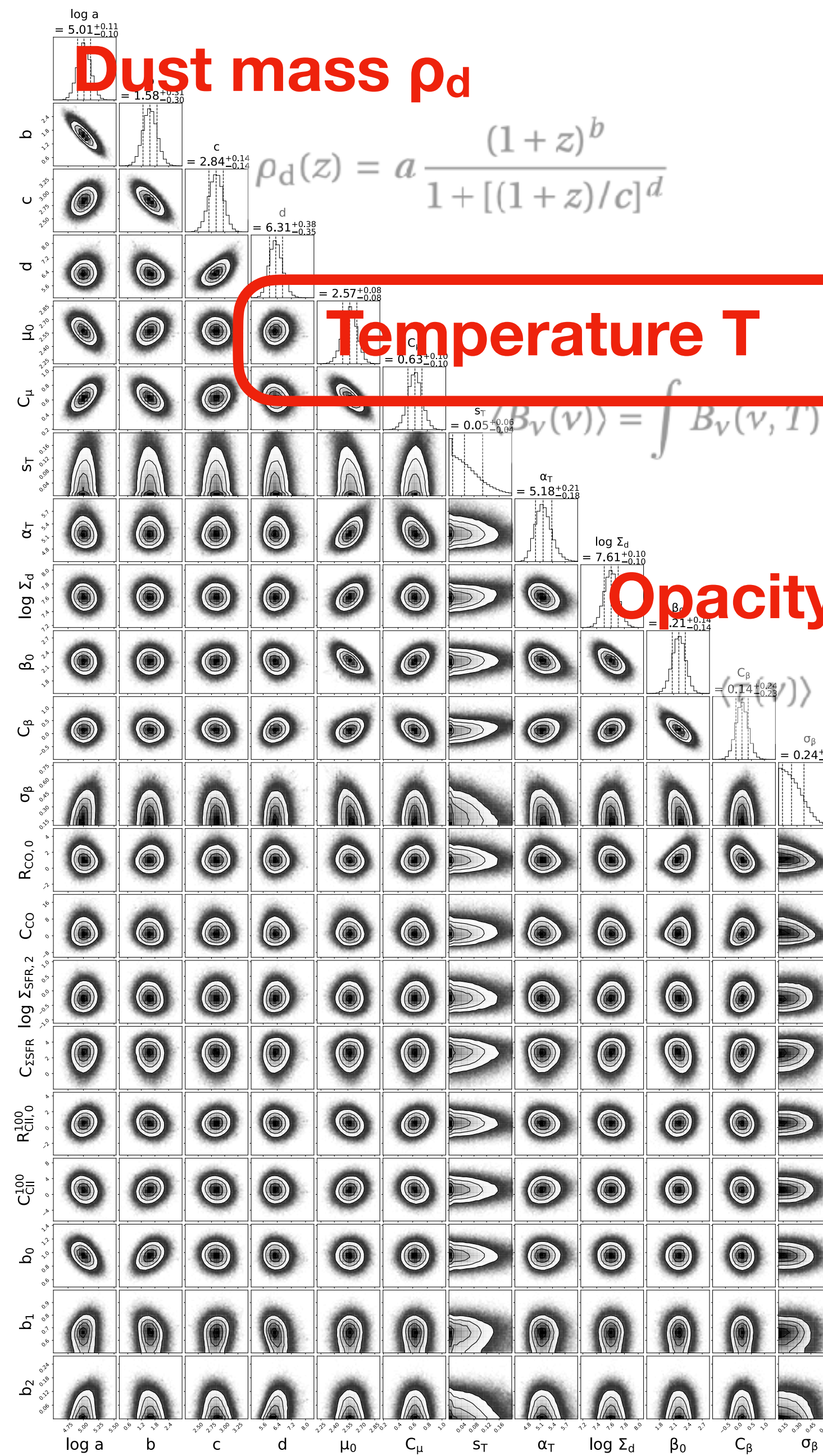
Generalized graybody with population effect

$$\epsilon_{\nu} b = \frac{4\pi \rho_d}{\Sigma_d} (1 - e^{-\langle \tau(\nu) \rangle}) \langle B_{\nu}(\nu) \rangle b(z)$$

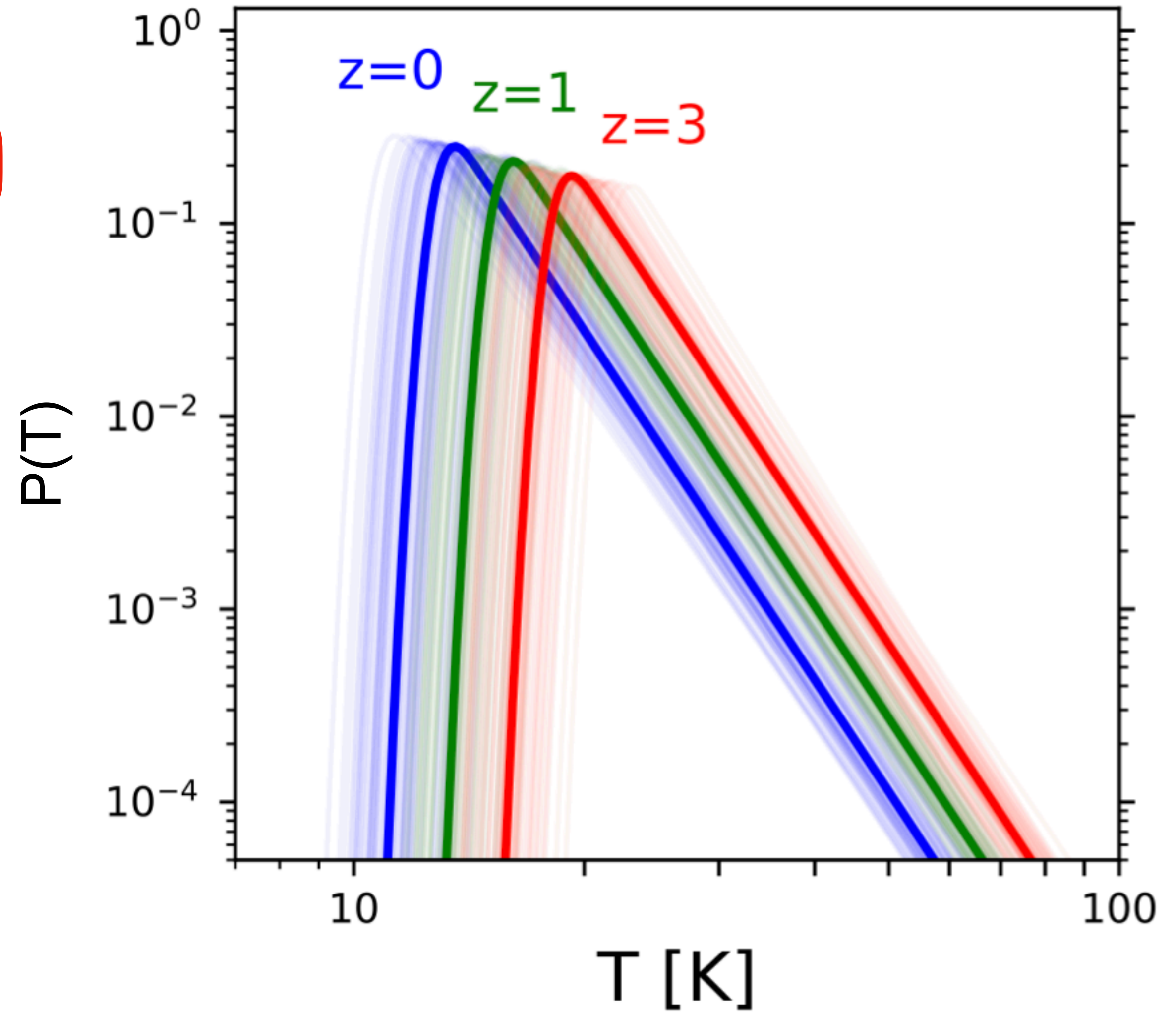
21 parameters, only 3 prior-driven



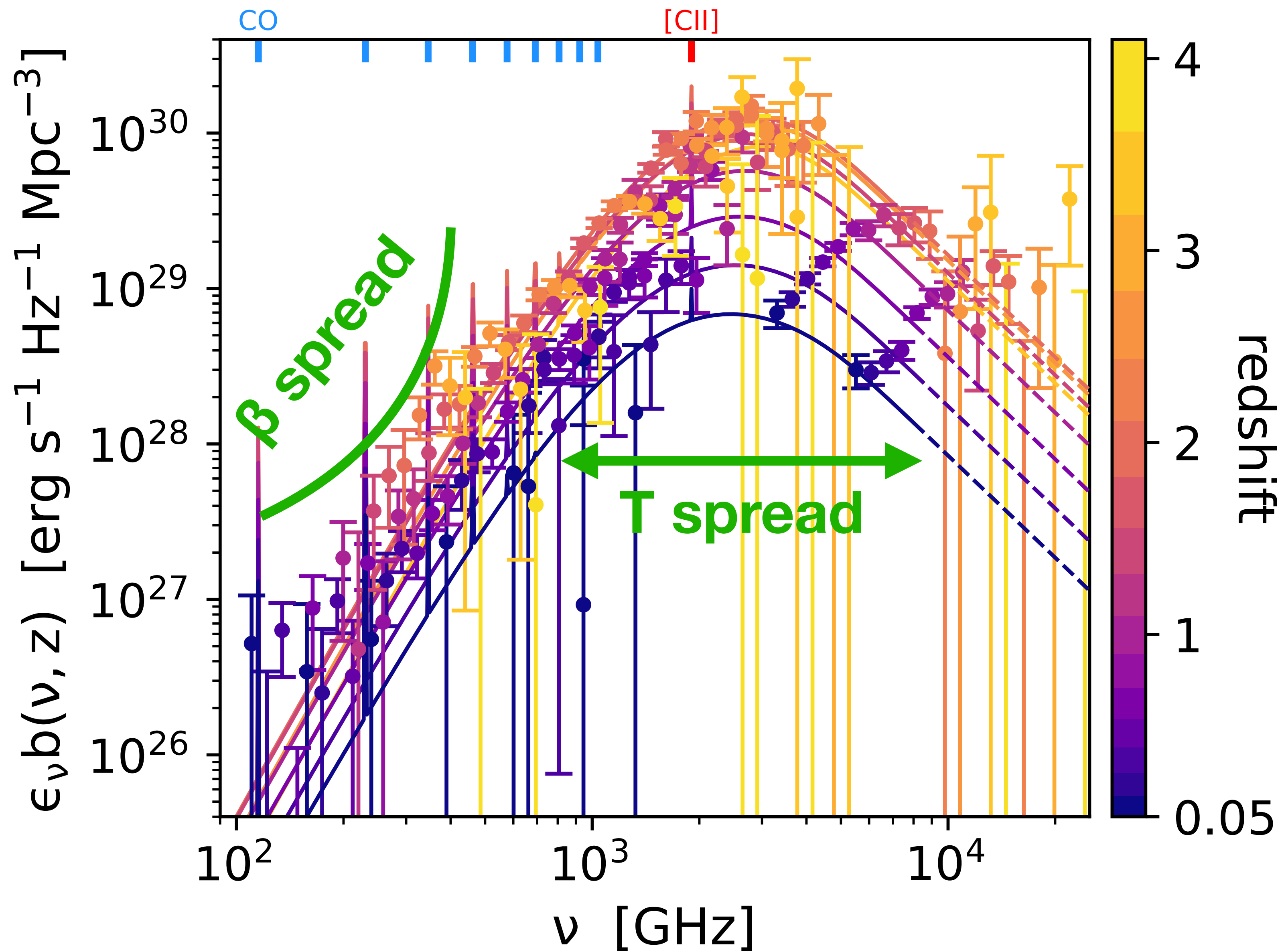
Chiang+ 25



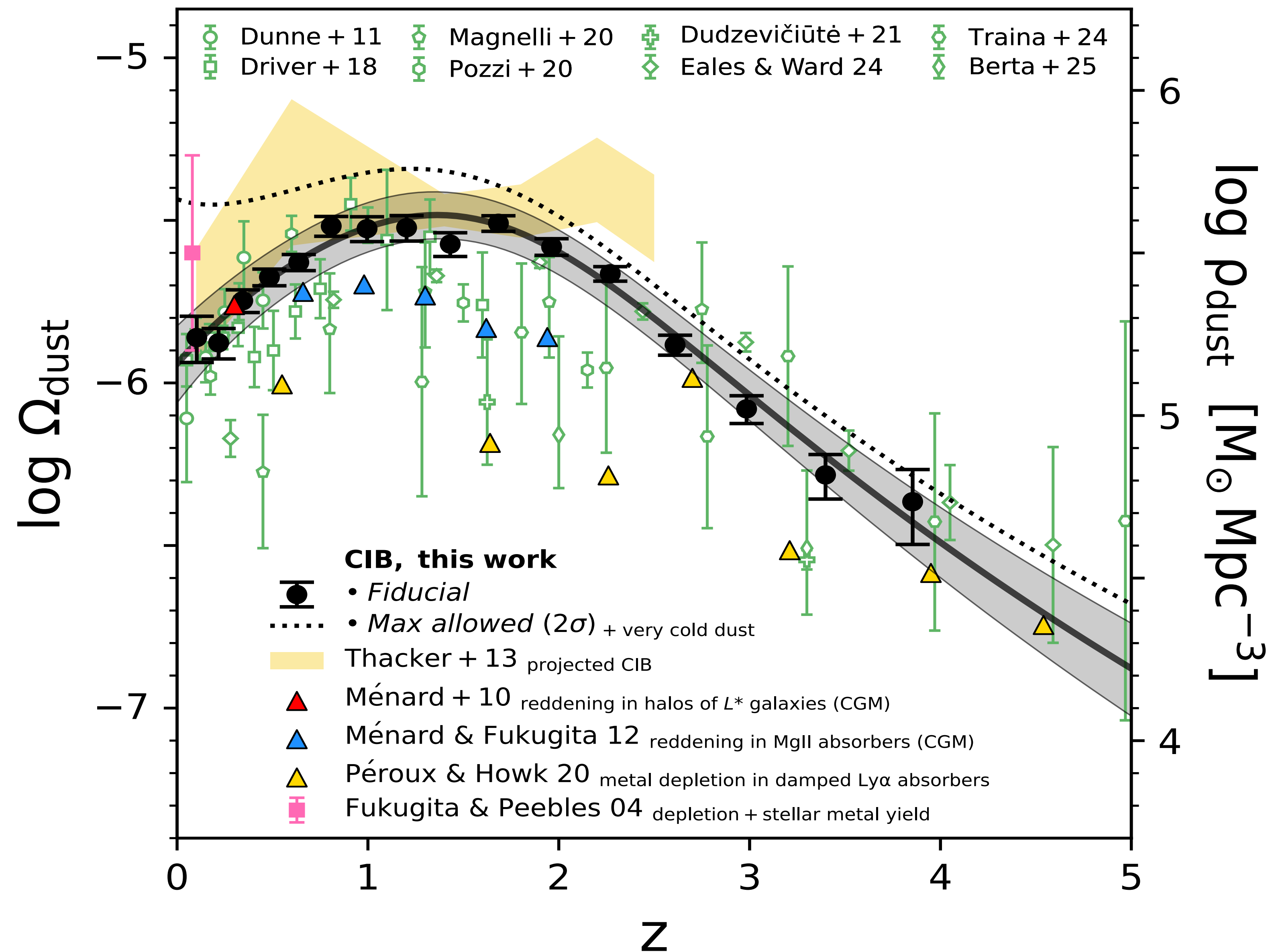
Full T distribution posterior



Single T, β MBB is not enough



Census of cosmic dust in all environments (from low freq.)

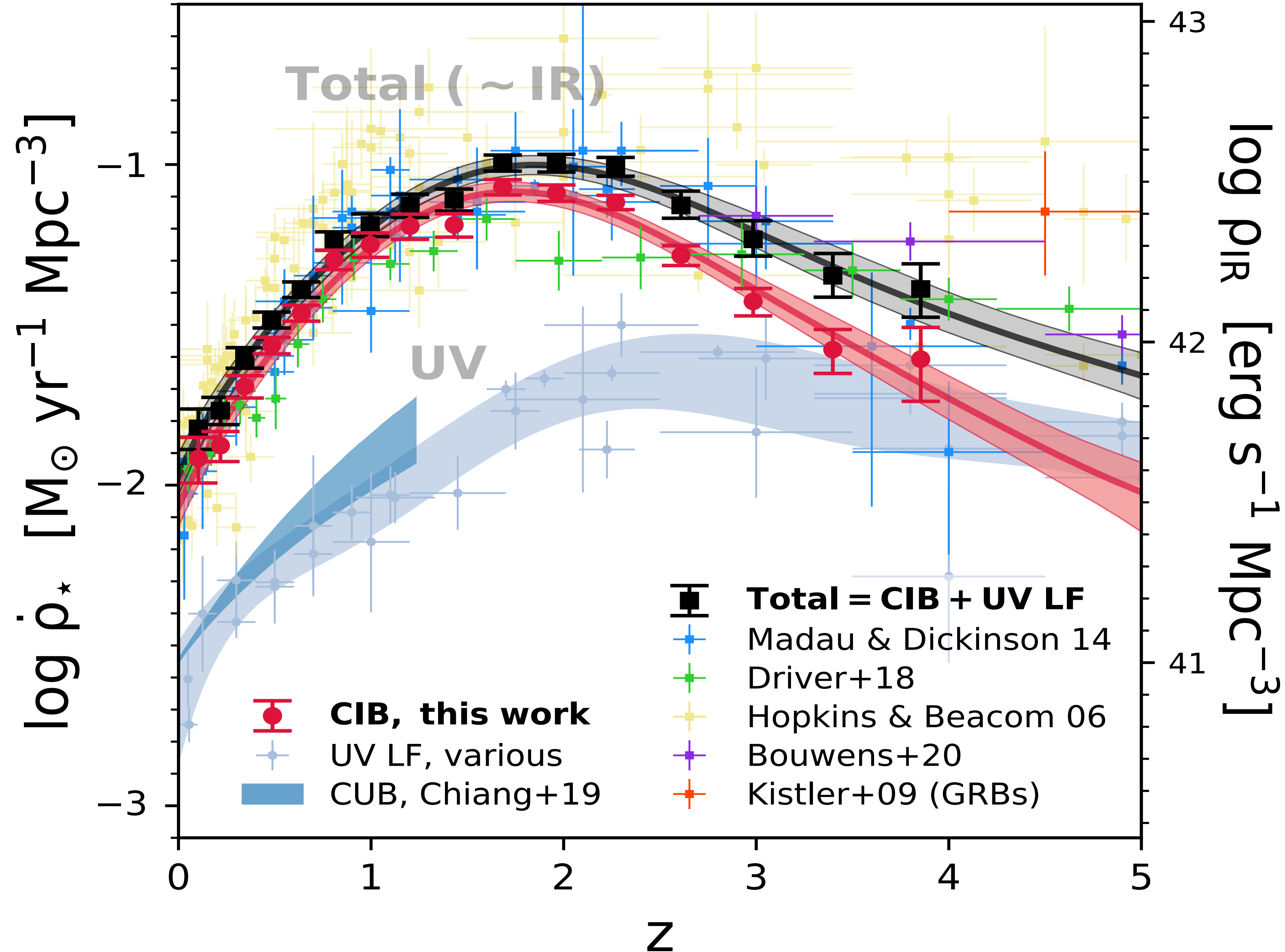


Upper envelope of
galaxy surveys

Dust gets destructed
at low z

Chiang+ 25

Cosmic star formation is 80% dust-obscured (from total IR)

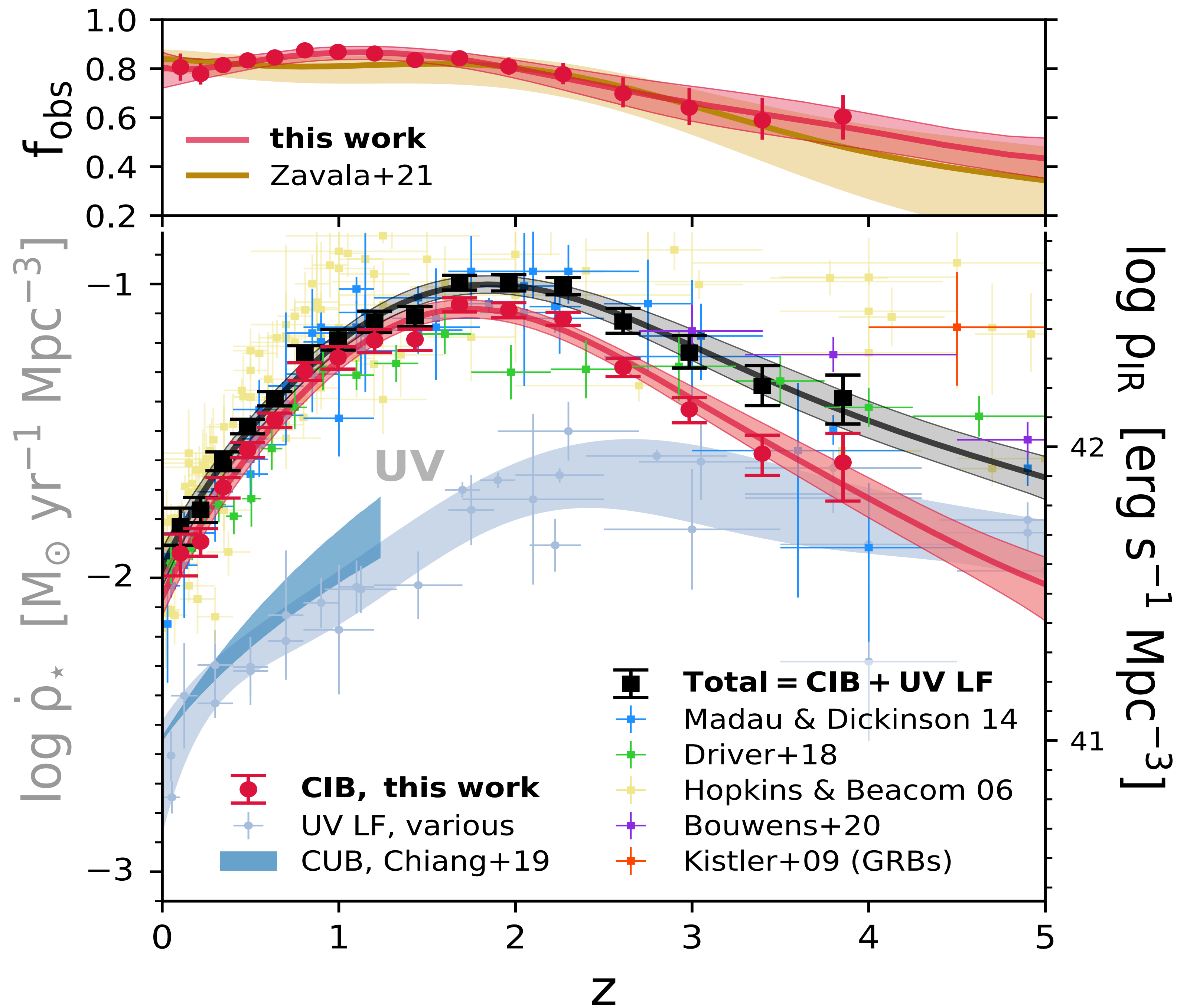


Tightest CSFR
constraint

No cosmic variance
No SED systematic

Complete to the
faintest galaxies

Chiang+ 25



Tightest CSFR
constraint

No cosmic variance
No SED systematic

Complete to the
faintest galaxies

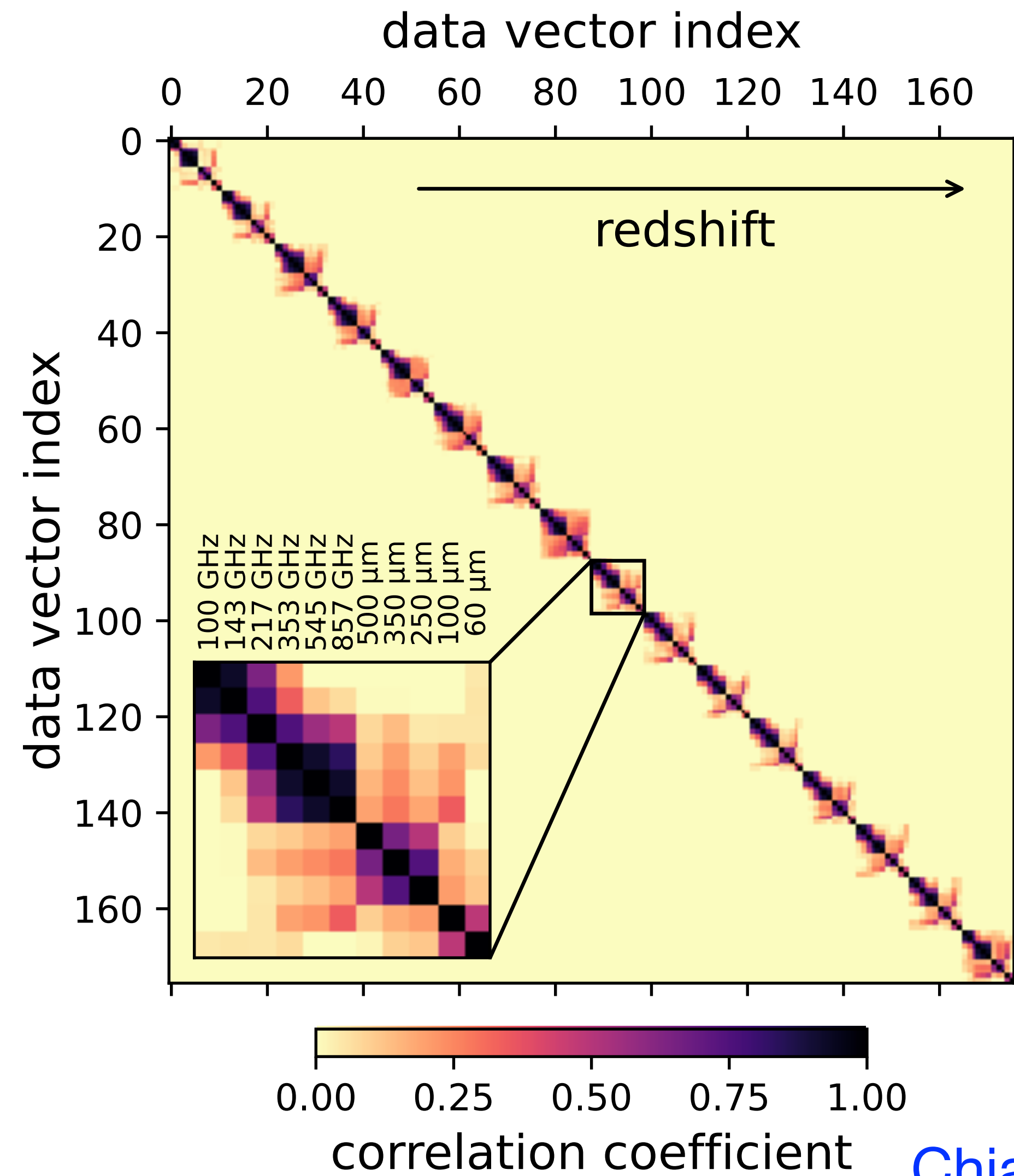
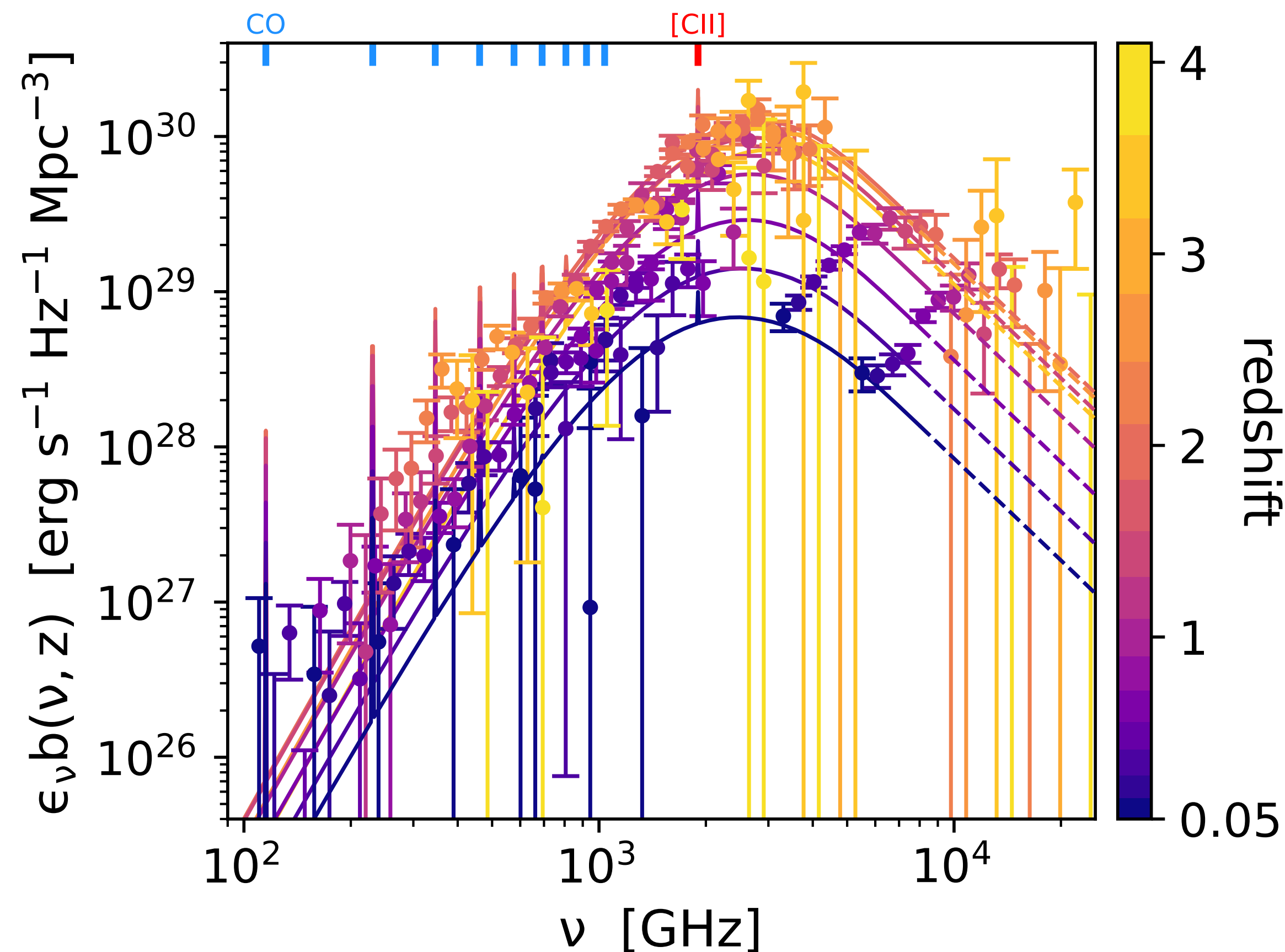
Chiang+ 25

Everything is publicly available

Data, covariance, SED at $z=0-10$, dL/dz redshift distributions, $b(z)$, Ω_d , CSFR, monopole, tSZ ...



<https://zenodo.org/records/15149425>

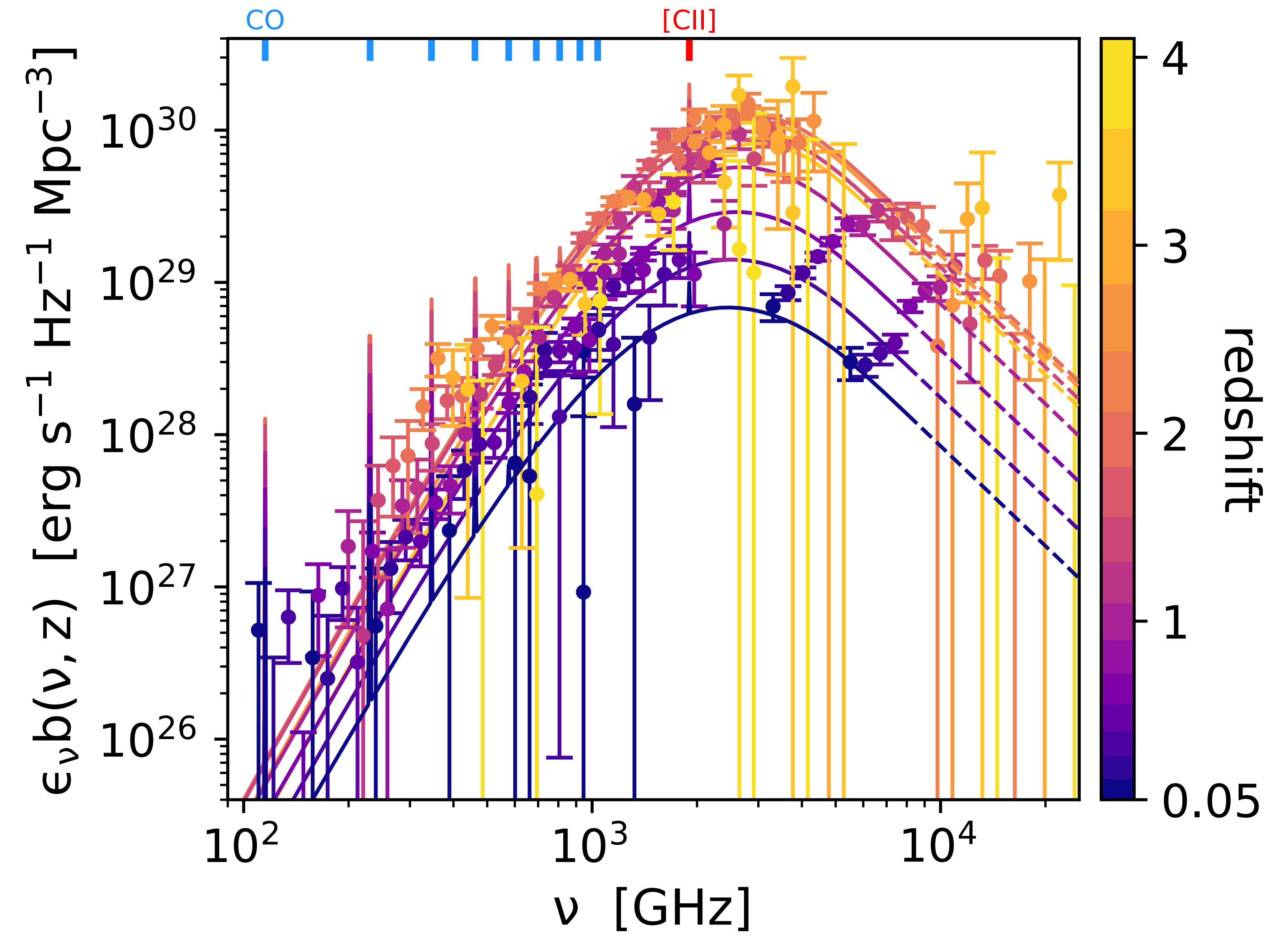


Chiang+ 25

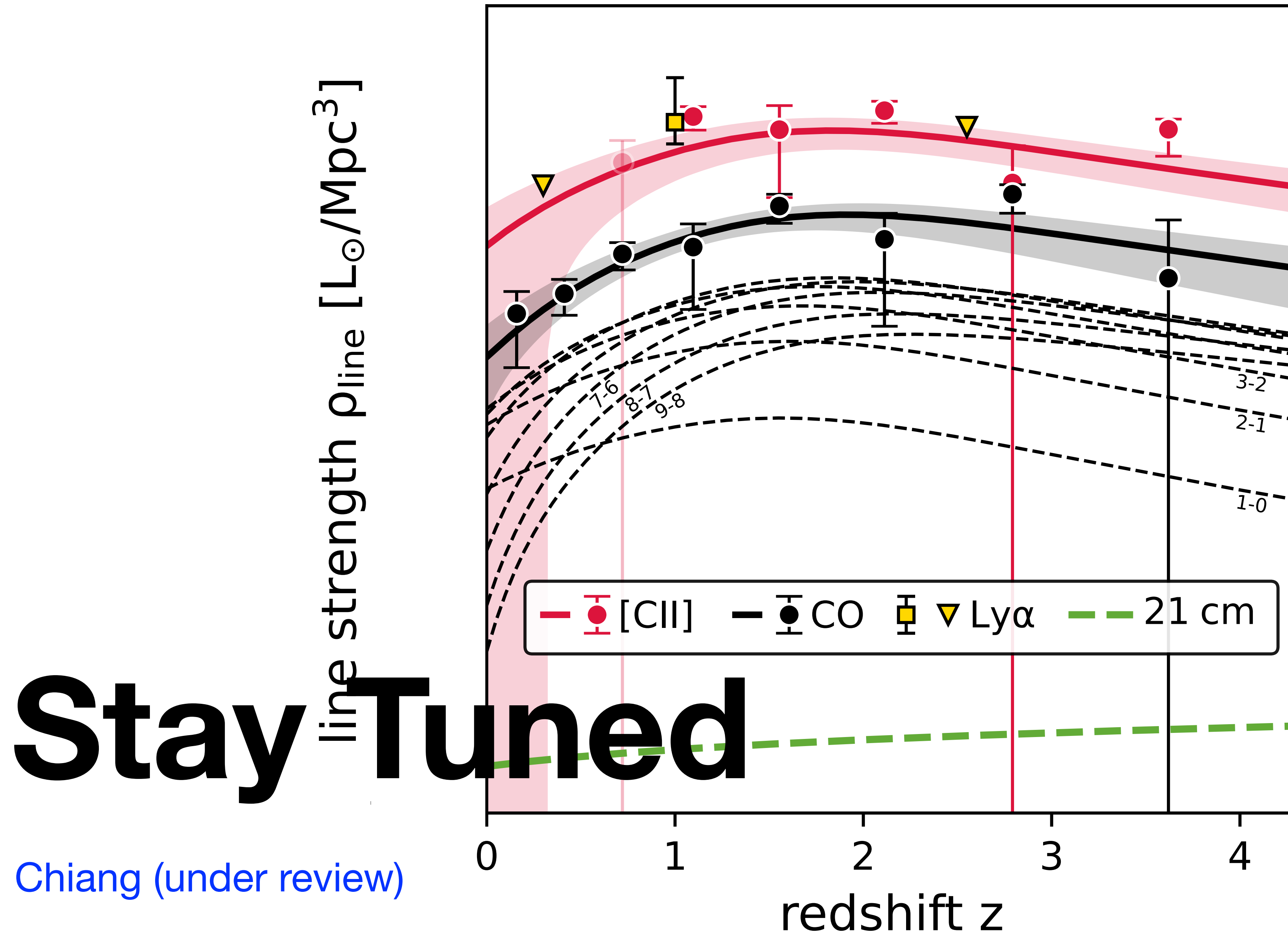
CMB secondary tomography

- Milky Way Dust
- Sunyaev–Zeldovich Effect
- Cosmic Infrared Background
- **Lines**

CO & [CII] line revealed only after continuum SED measured to % level



First intensity mapping CO & [CII] detections



[CII] competing with Ly α
as the brightest line
—> trace SF

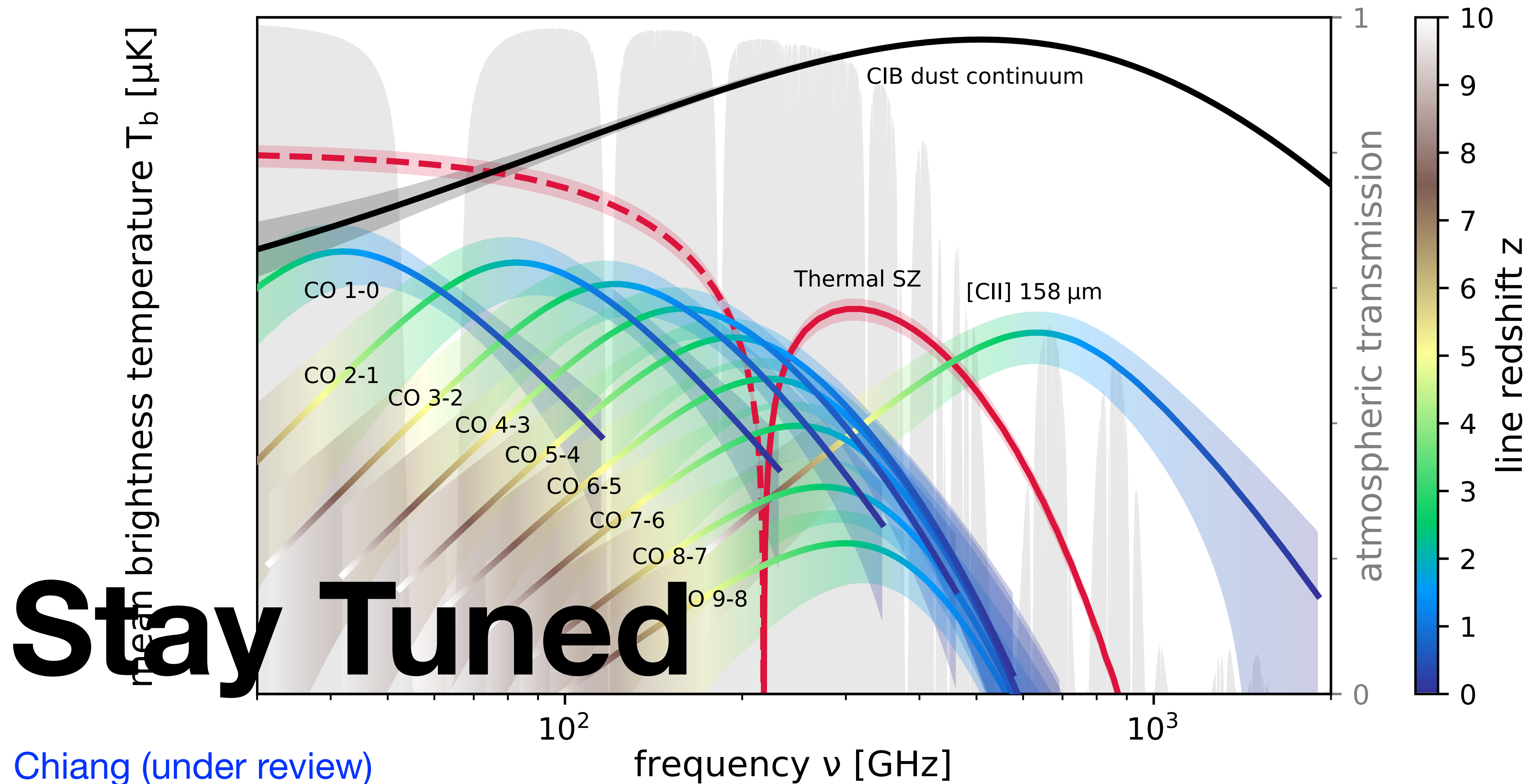
CO is brightest relative to
continuum
—> trace molecular gas

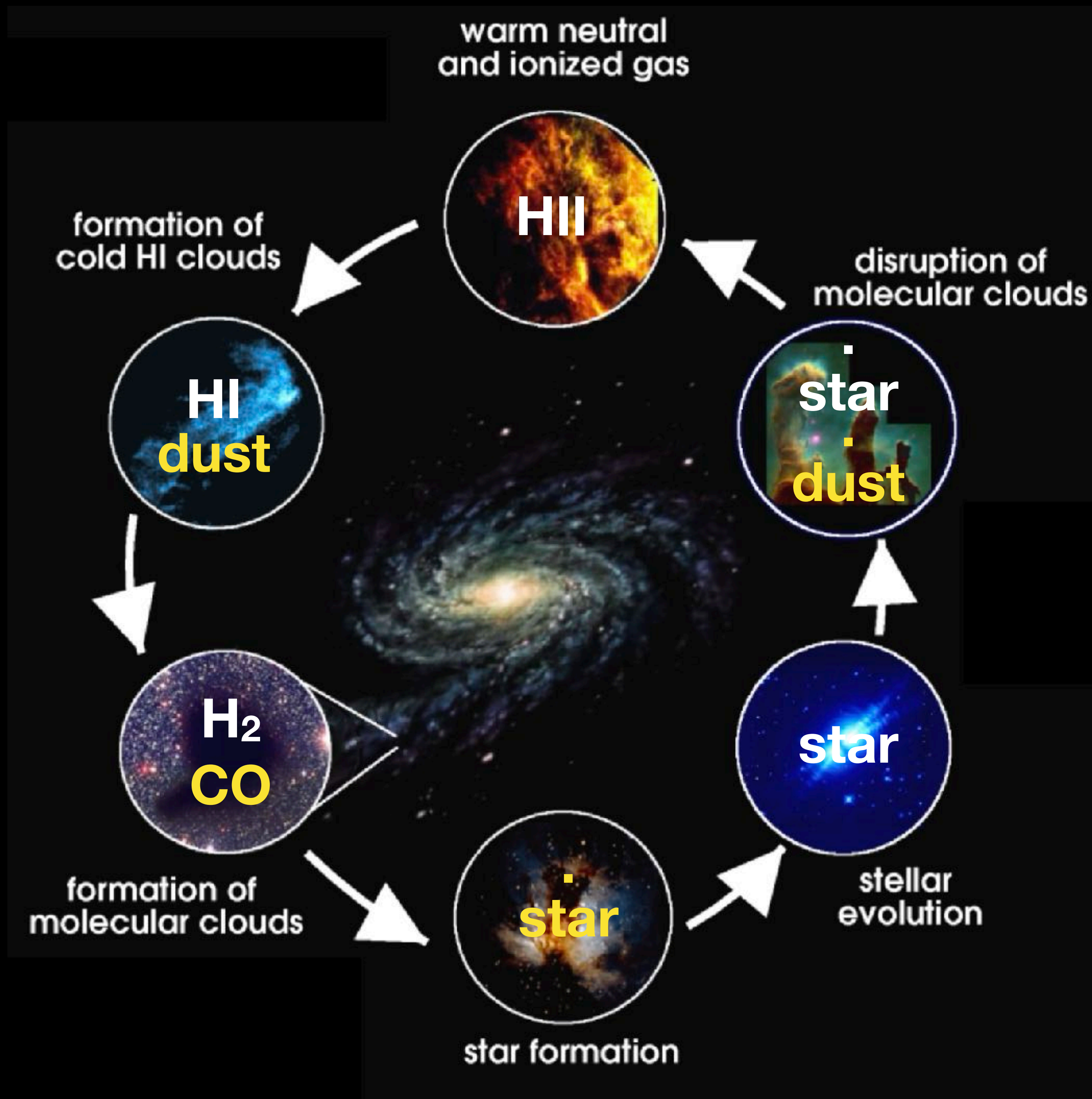
Both prime targets for
3D line intensity mapping

Stay Tuned

Chiang (under review)

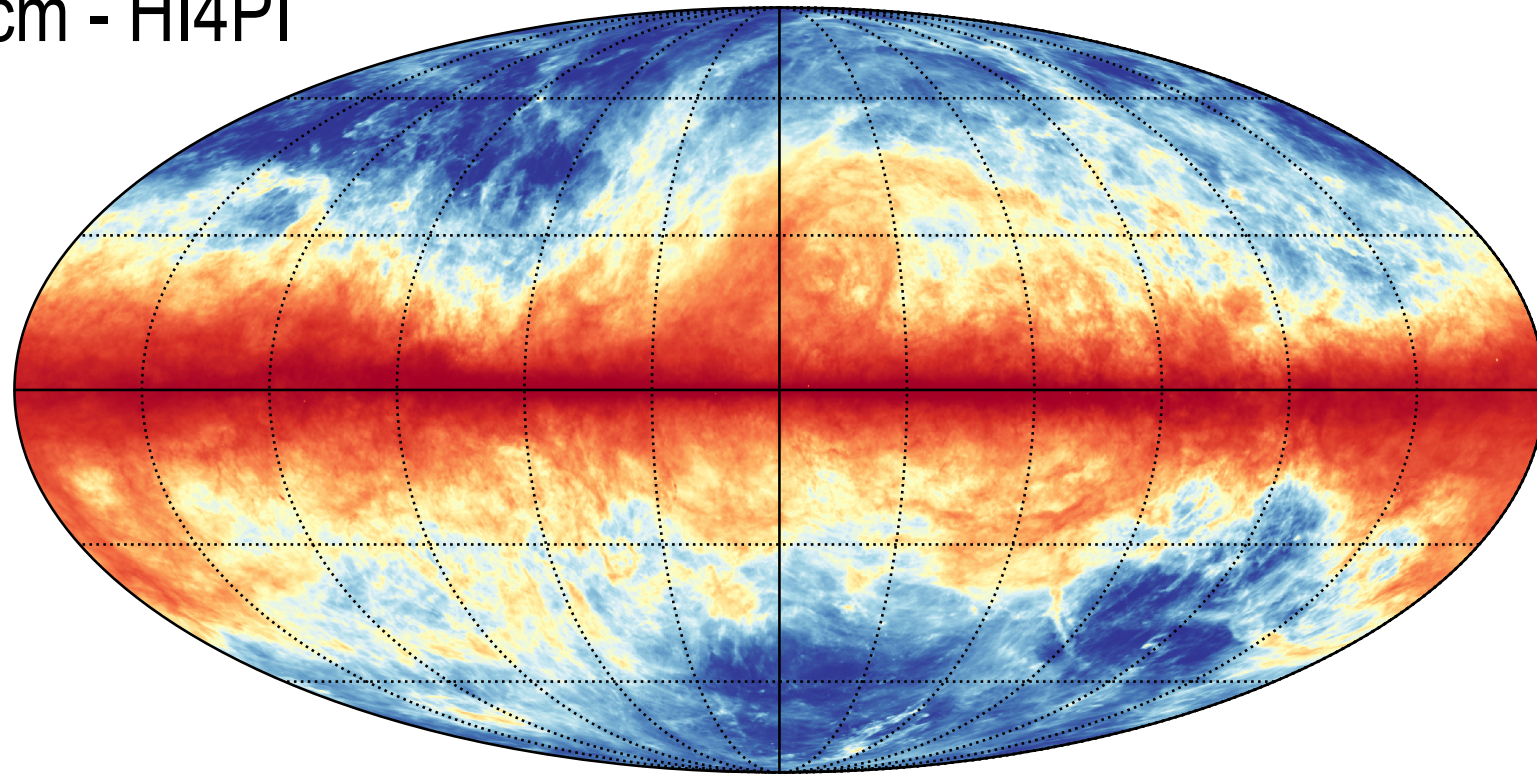
First intensity mapping CO & [CII] detections



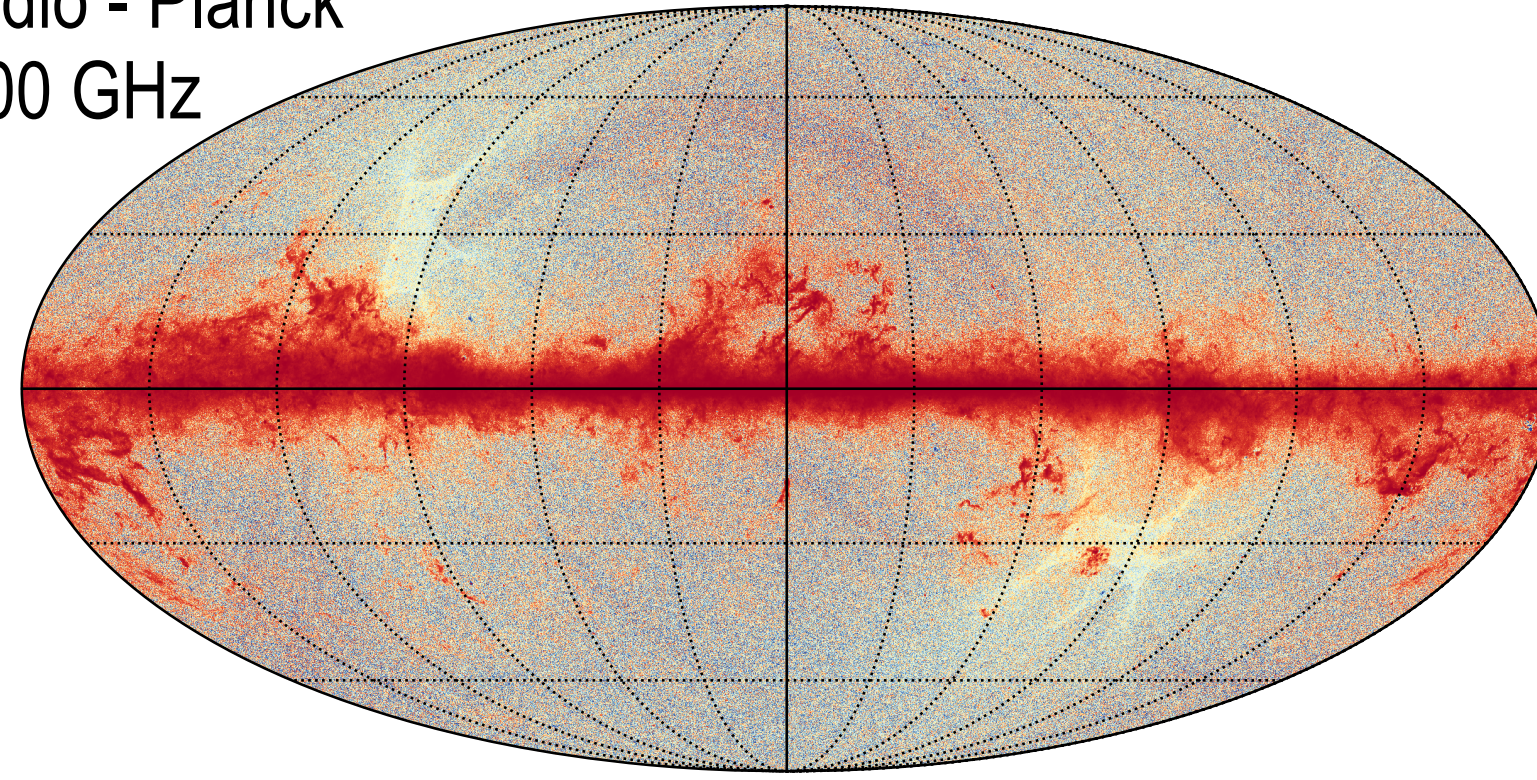


Multiwavelength view of the diffuse sky

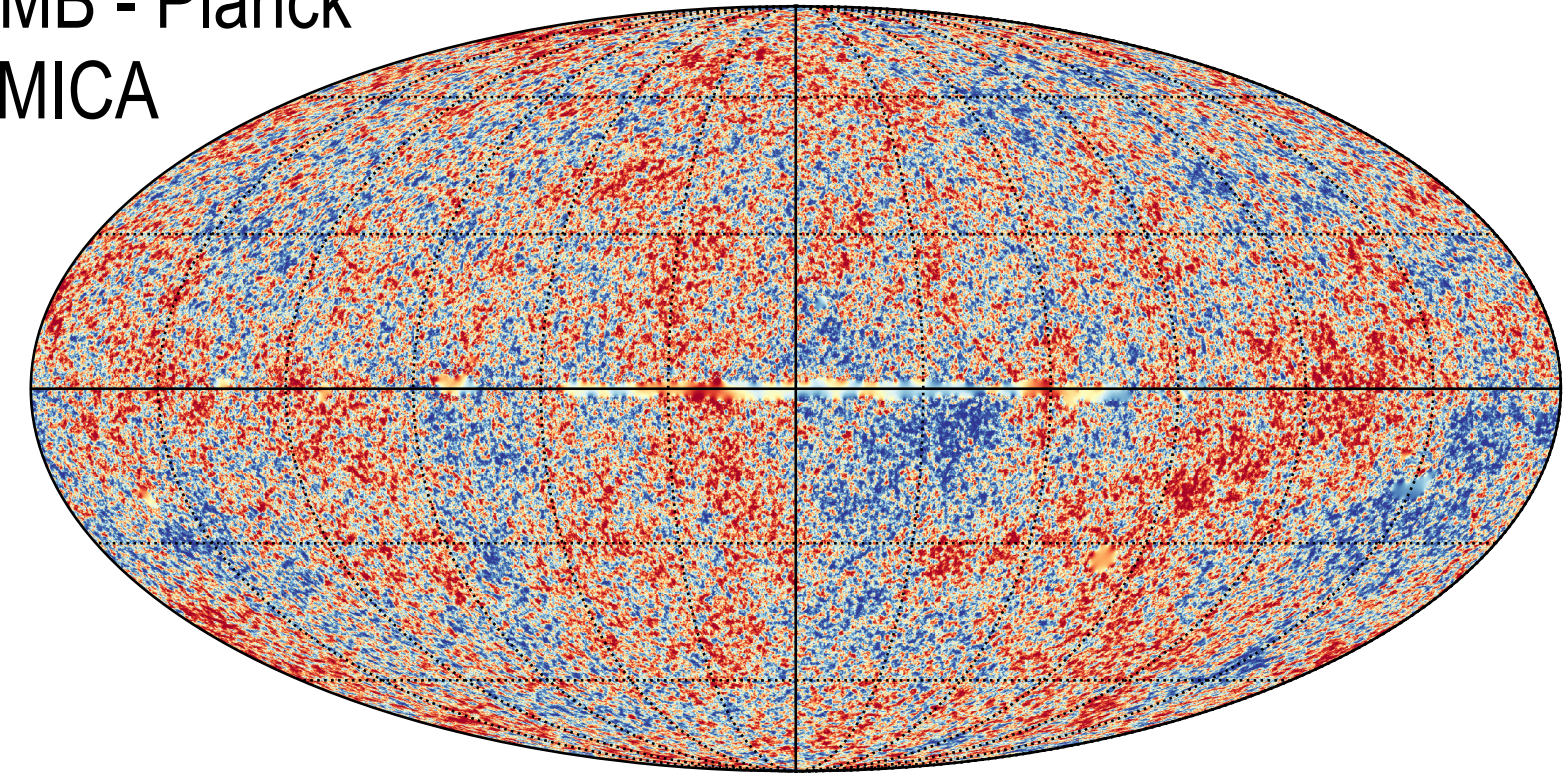
21 cm - HI4PI



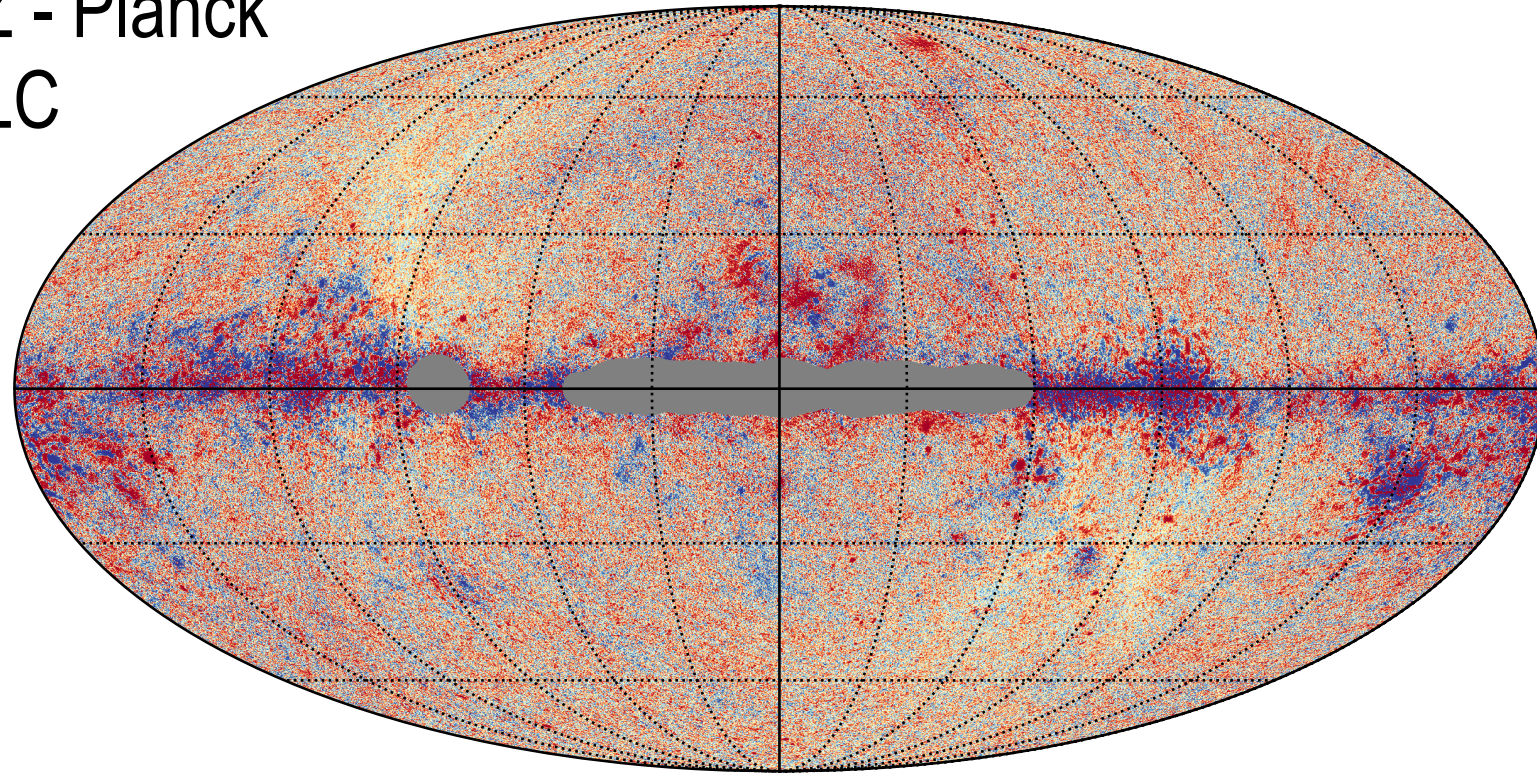
radio - Planck
100 GHz



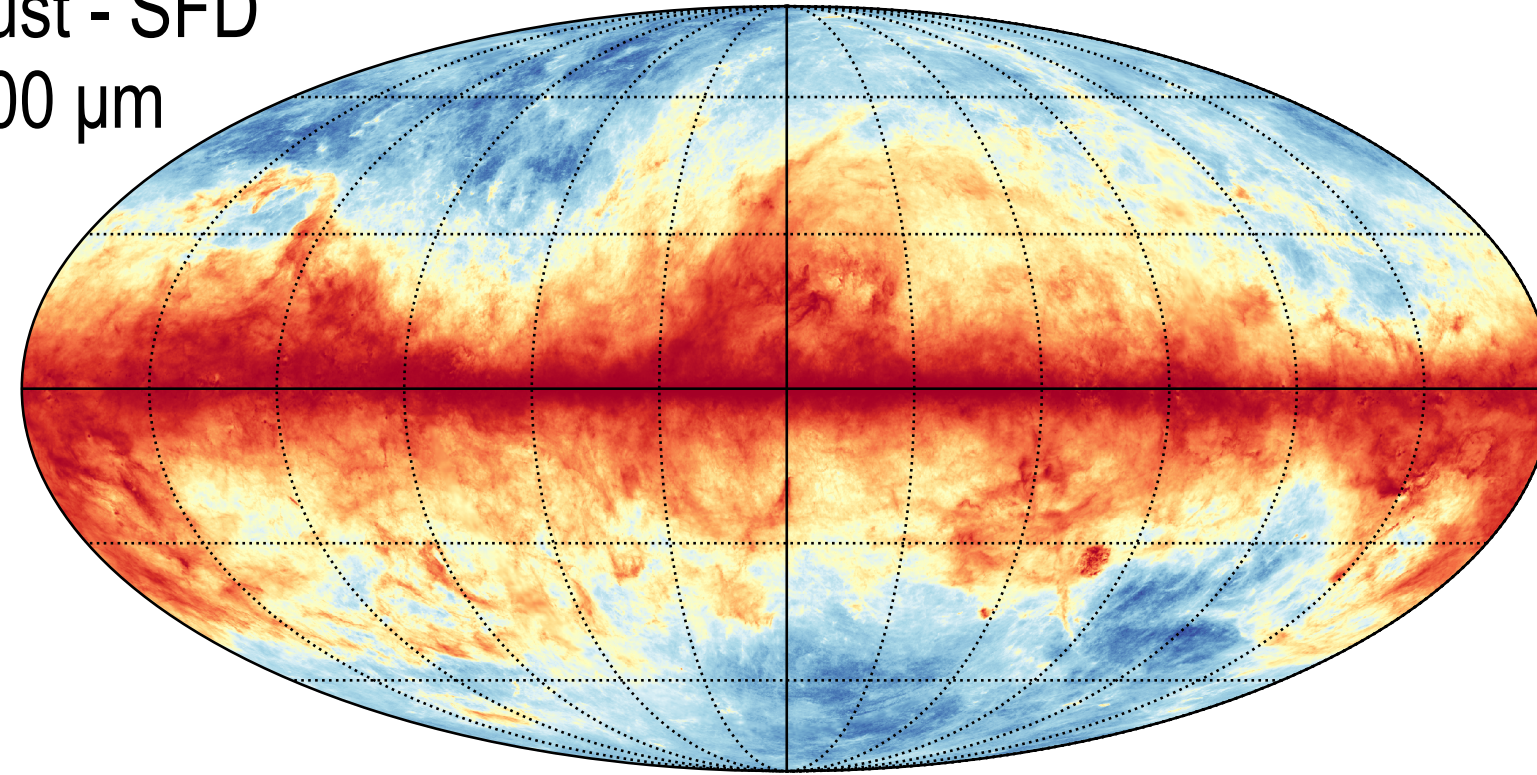
CMB - Planck
SMICA



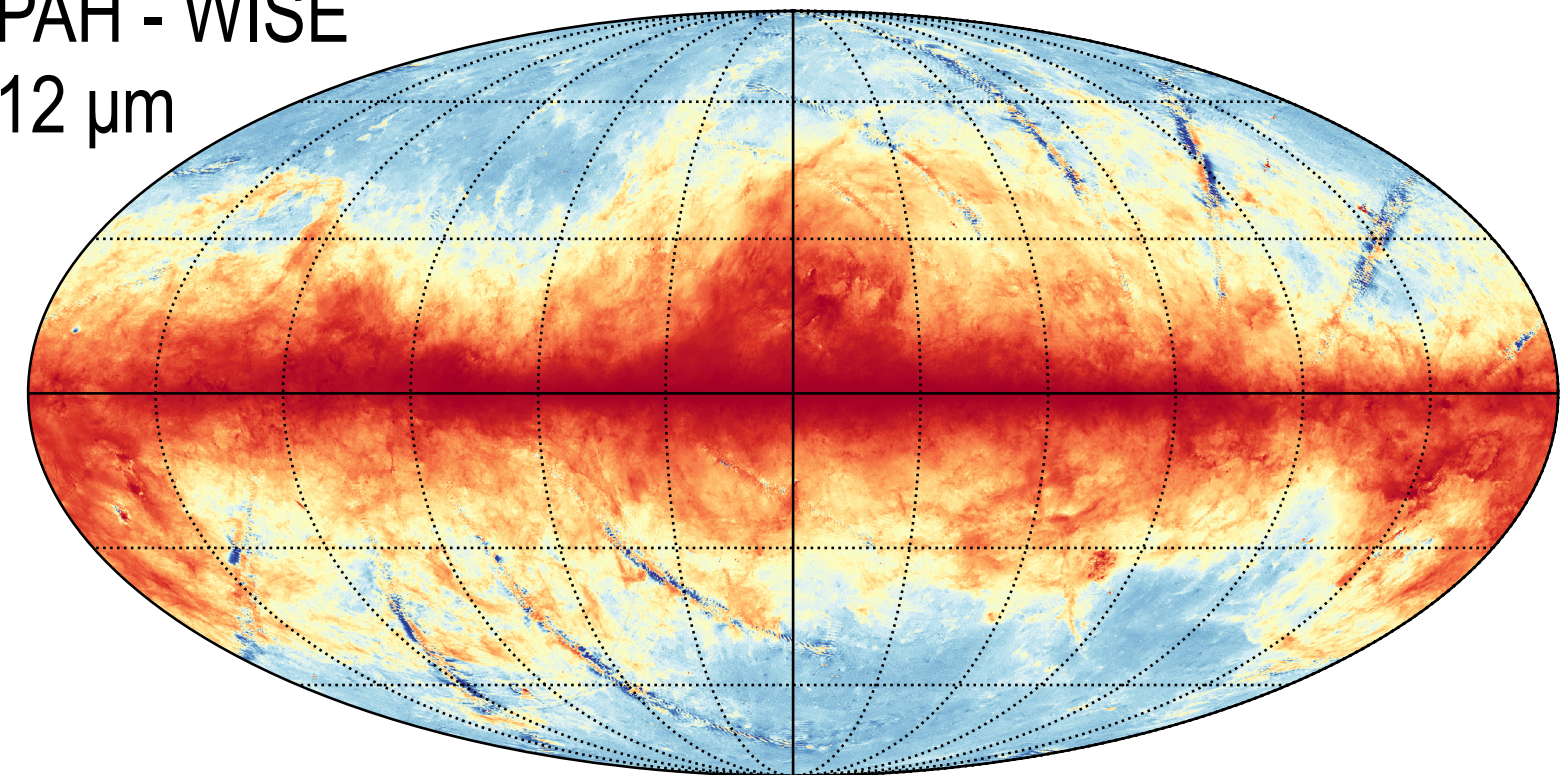
tSZ - Planck
NILC



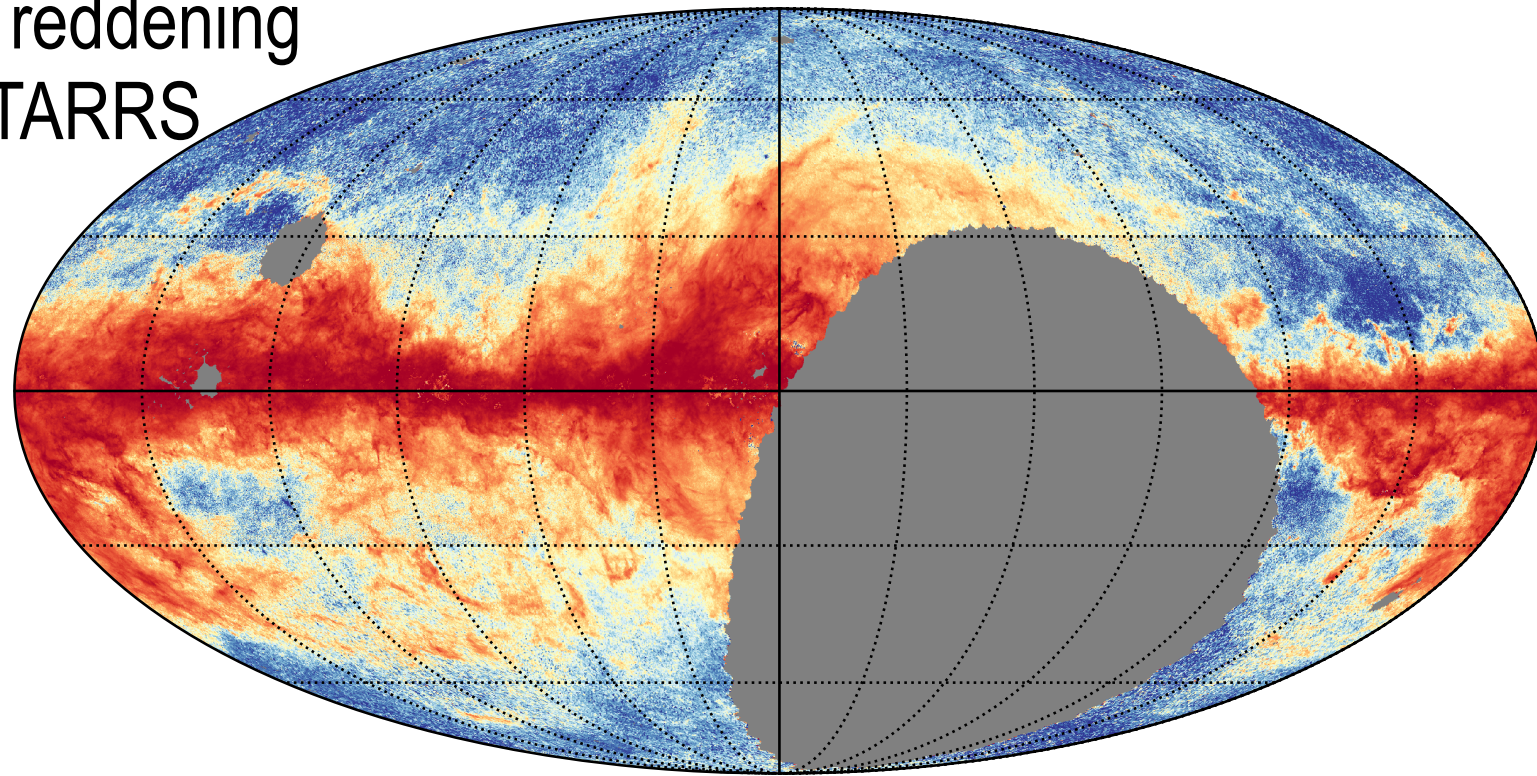
dust - SFD
100 μ m



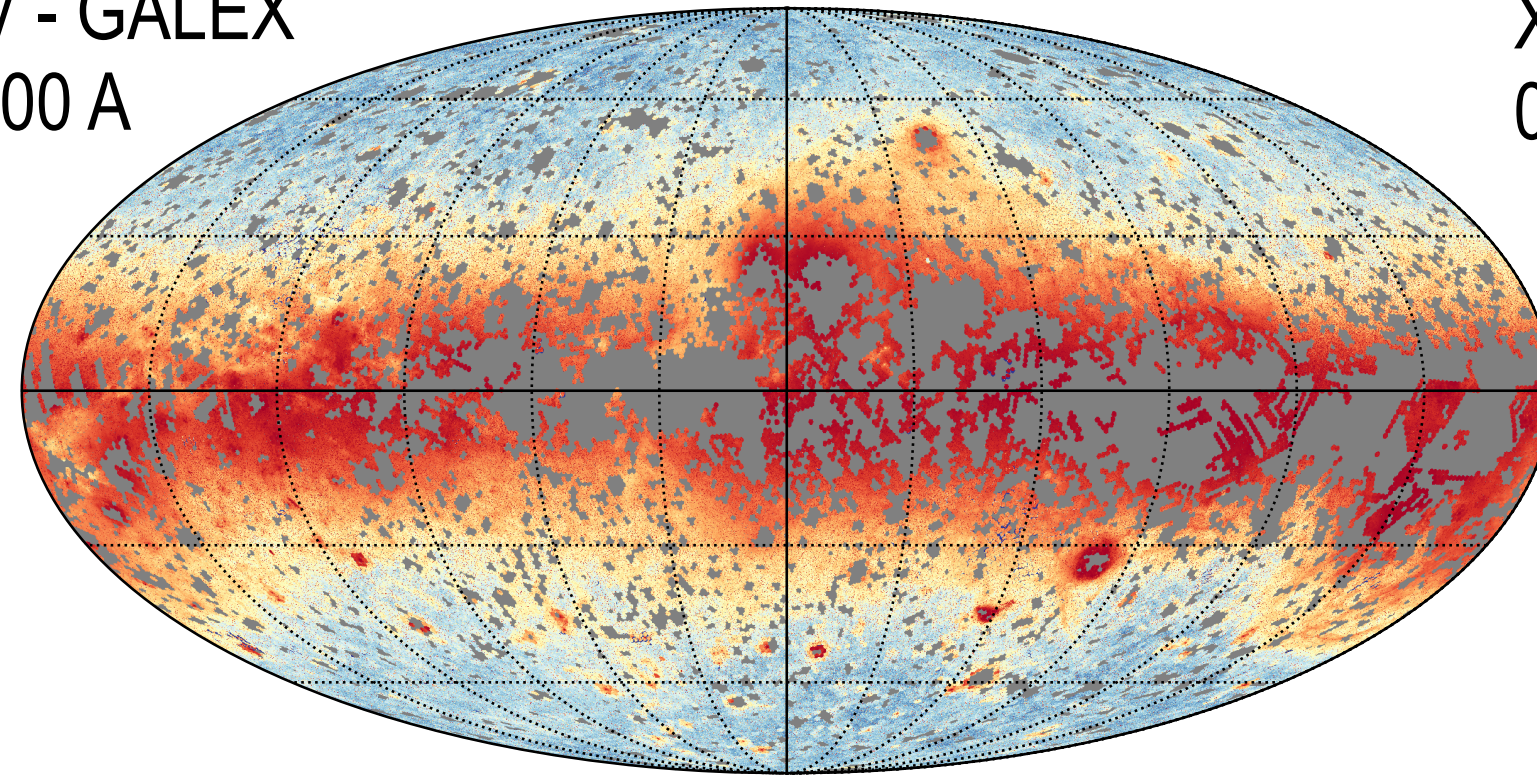
PAH - WISE
12 μ m



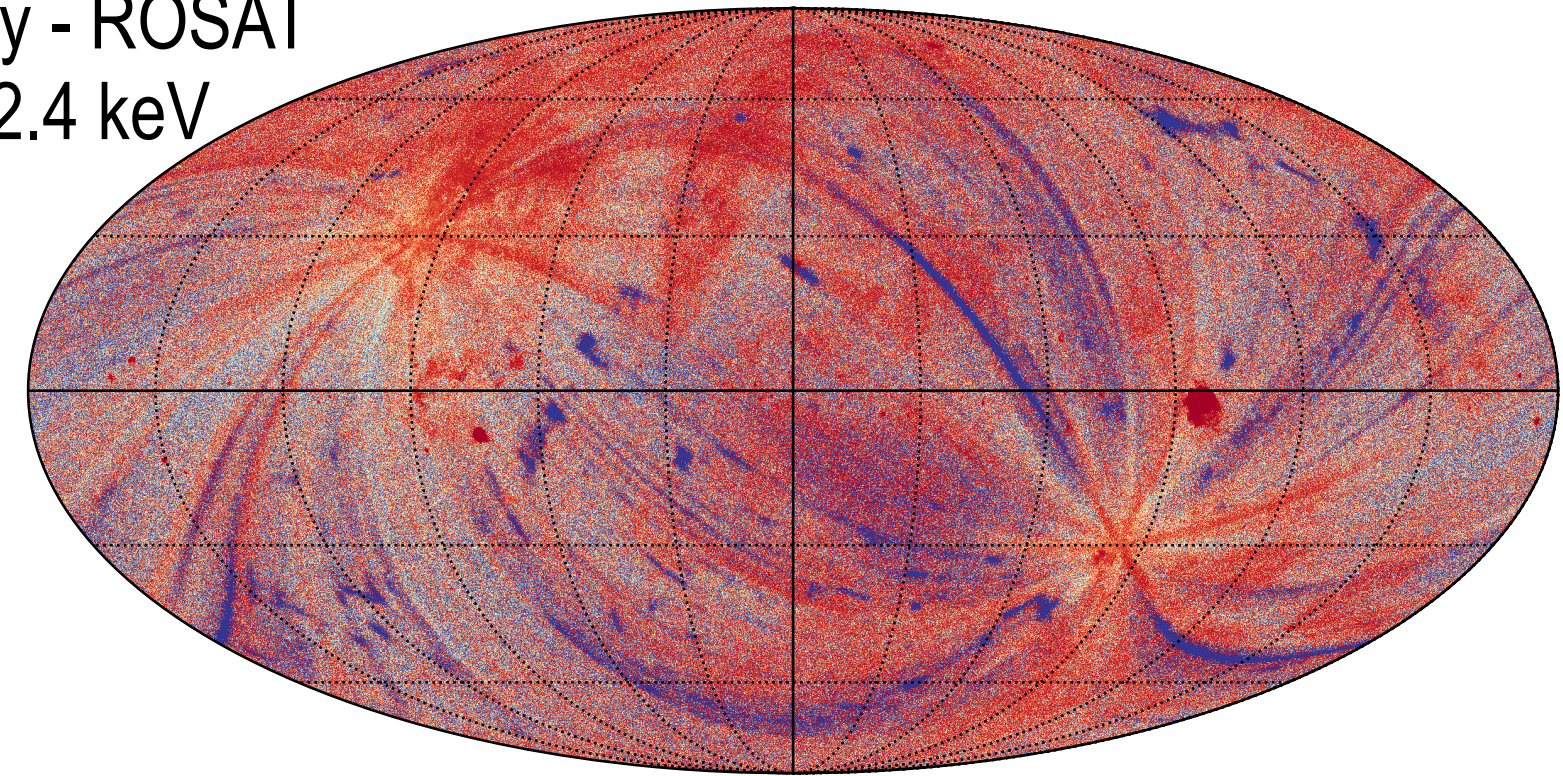
optical reddening
Pan-STARRS



UV - GALEX
2300 A

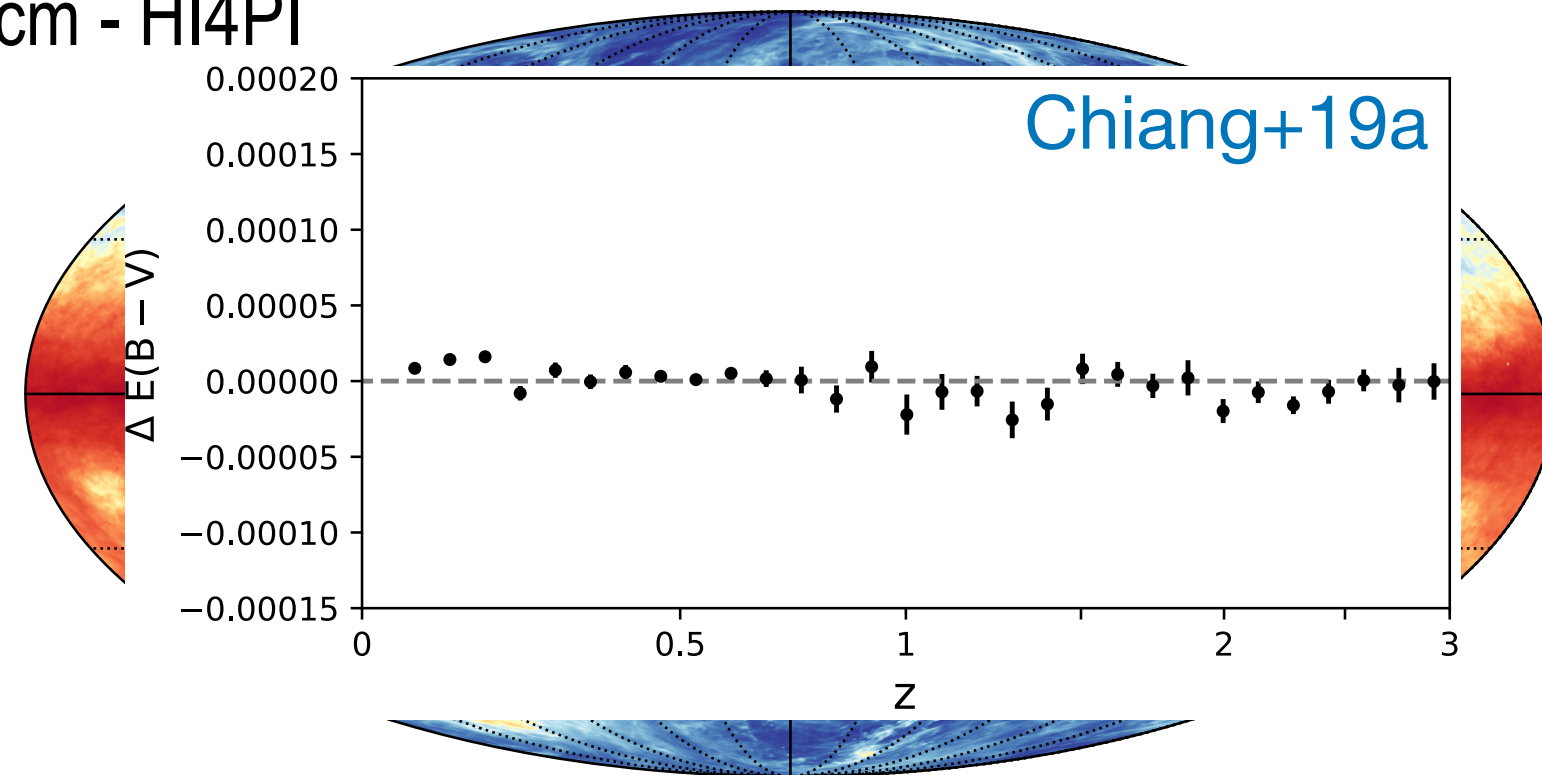


X-ray - ROSAT
0.1-2.4 keV

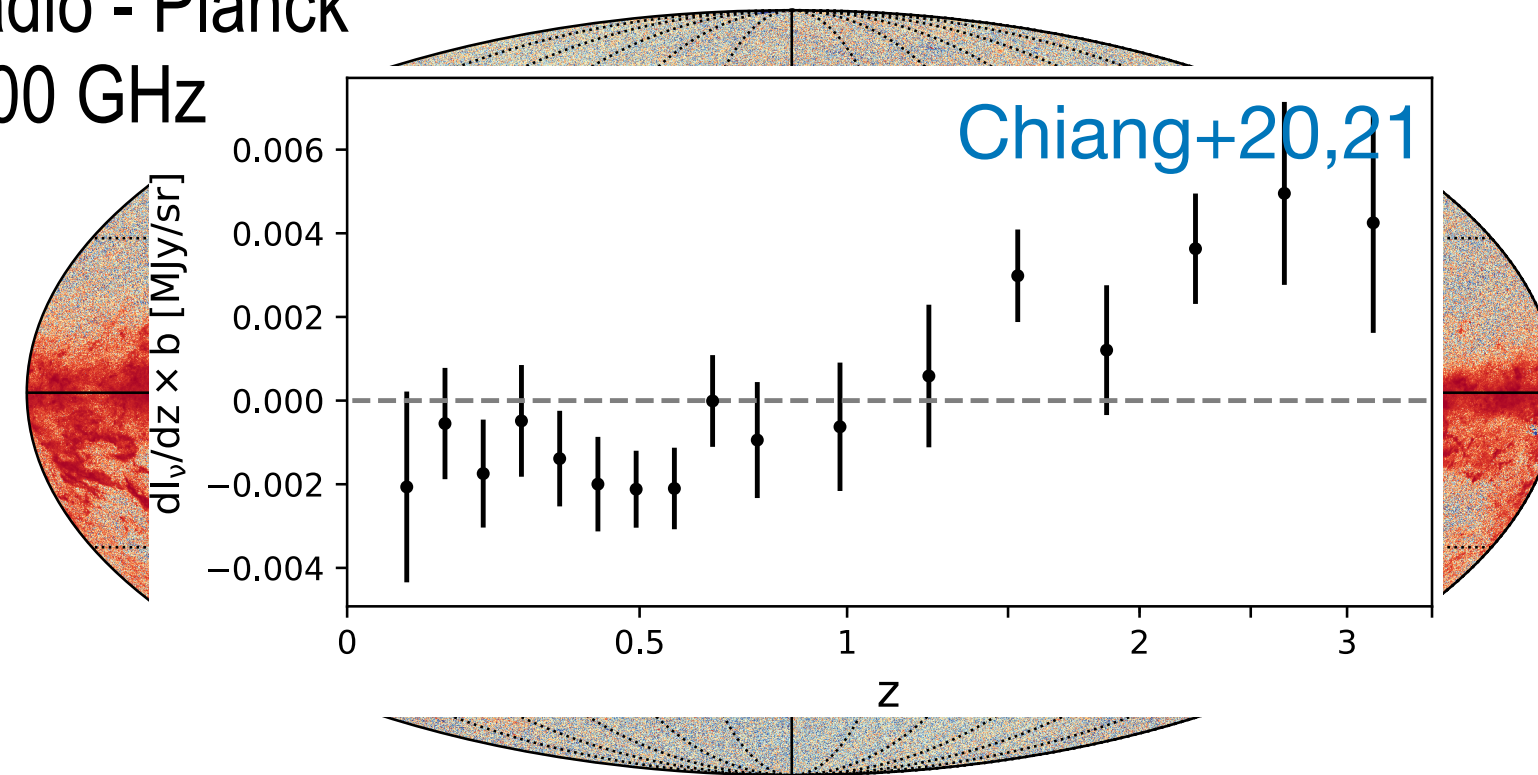


Multiwavelength view of the diffuse sky

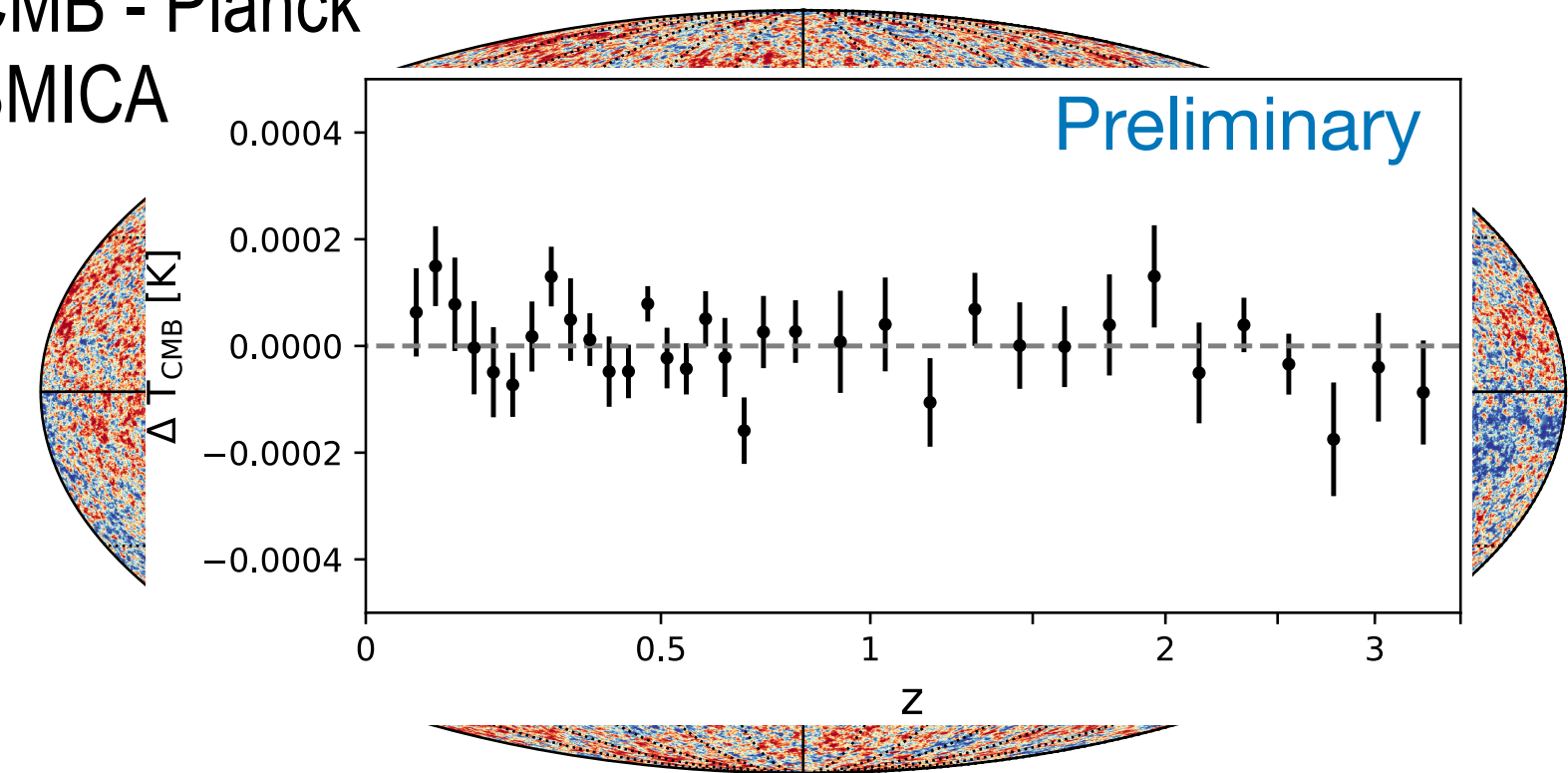
21 cm - HI4PI



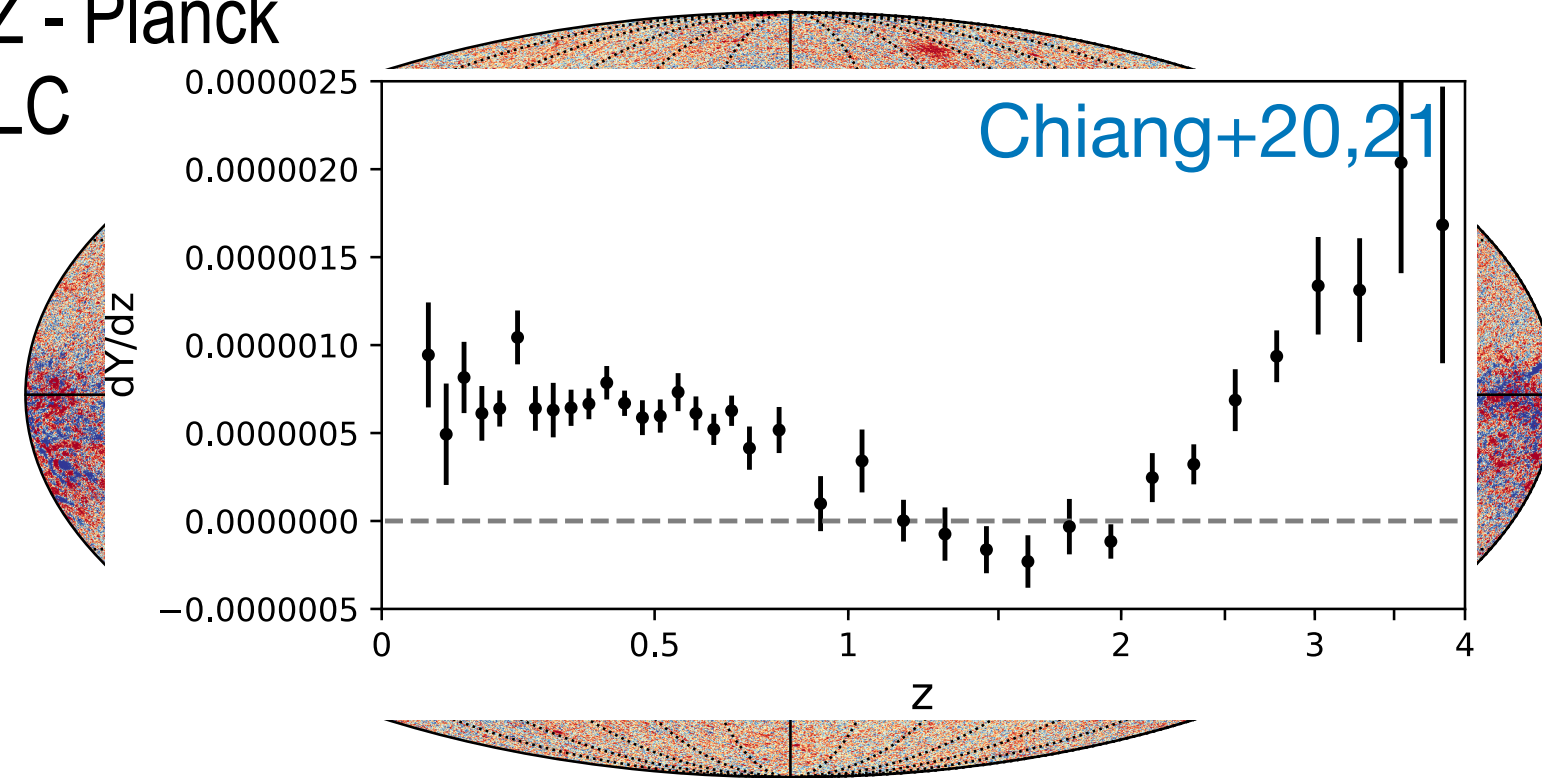
radio - Planck
100 GHz



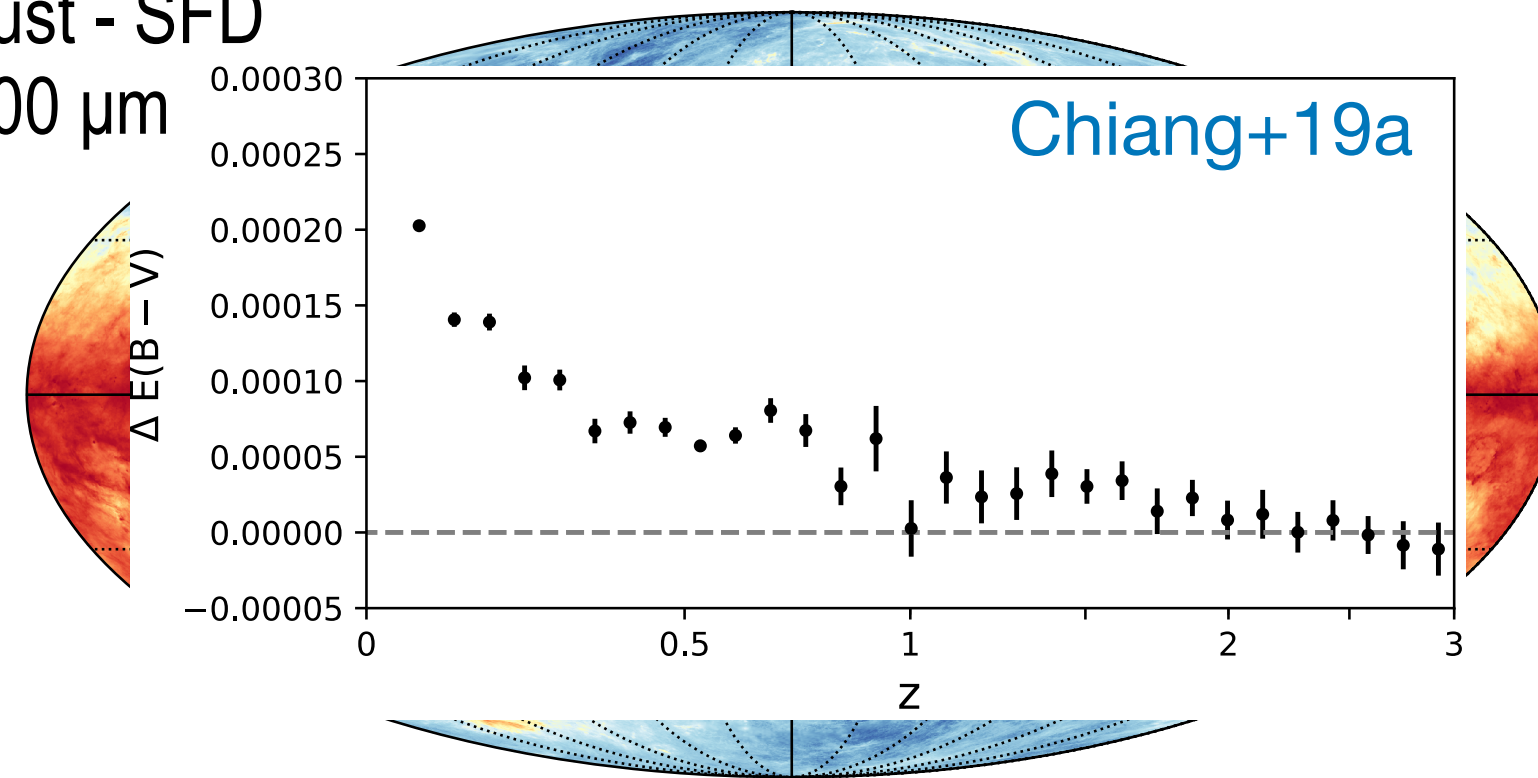
CMB - Planck
SMICA



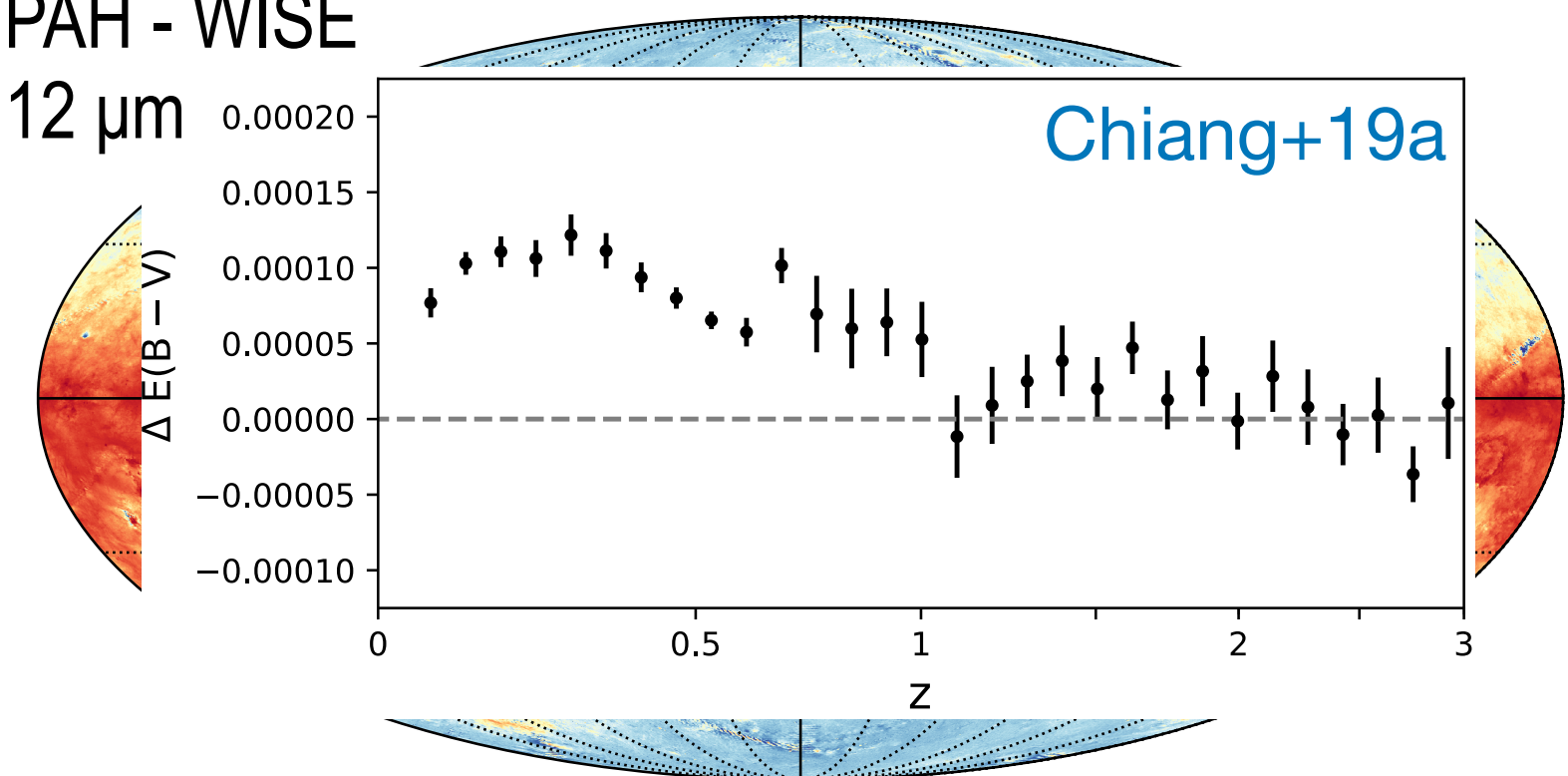
tSZ - Planck
NILC



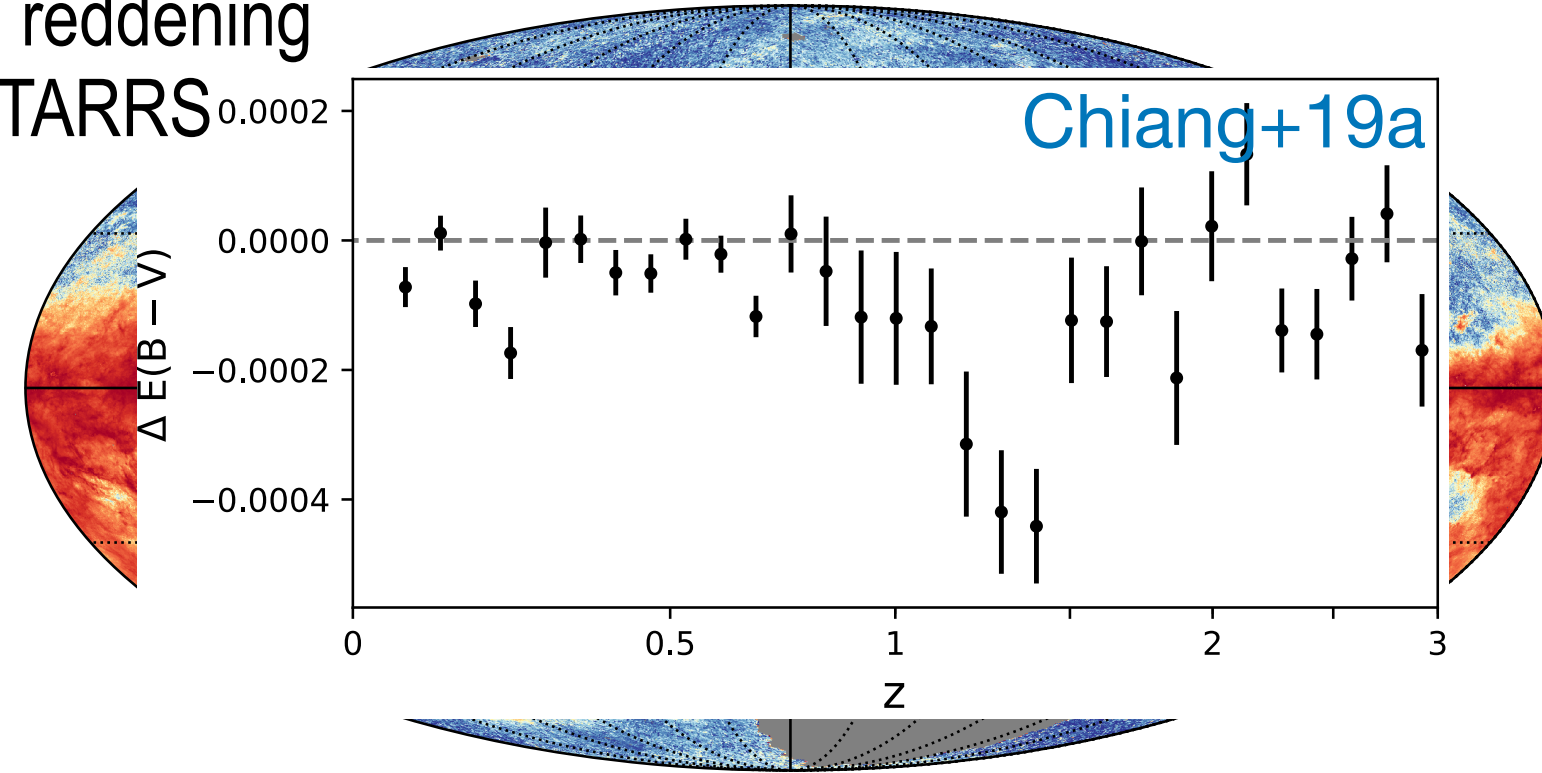
dust - SFD
100 μm



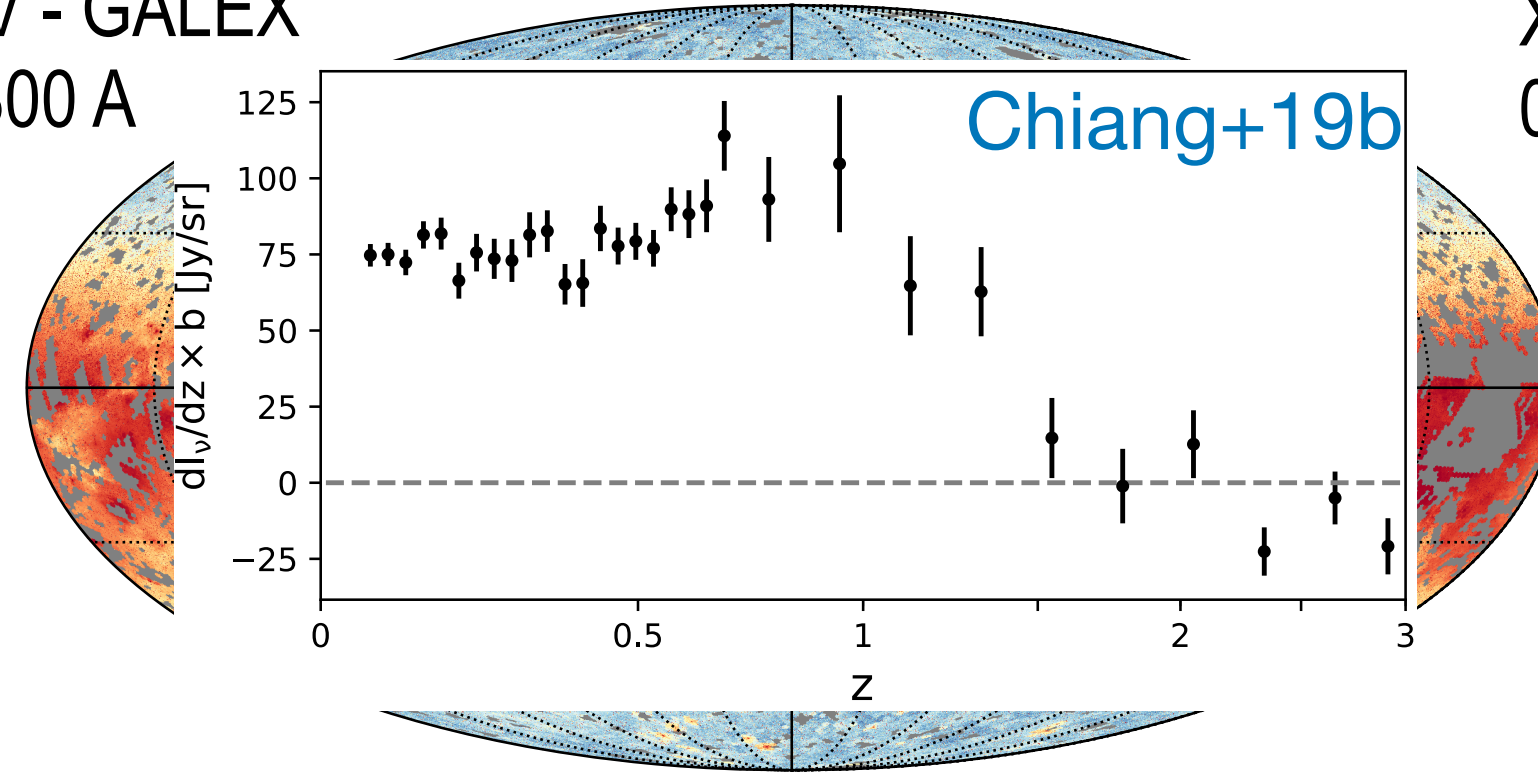
PAH - WISE
12 μm



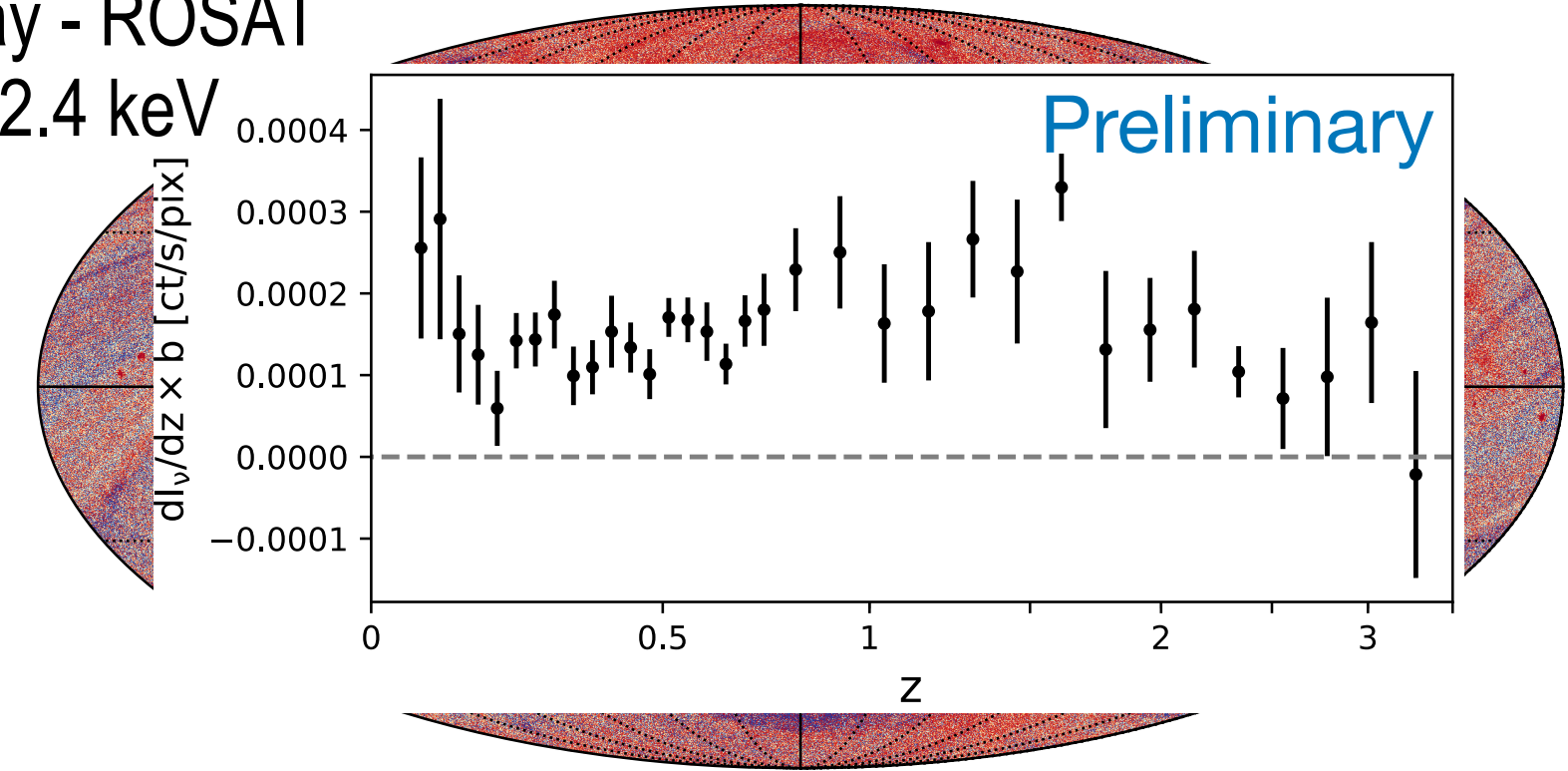
optical reddening
Pan-STARRS



UV - GALEX
2300 Å



X-ray - ROSAT
0.1-2.4 keV



Takeaways

- Revealed & removed CIB in **MW dust** mapping, key for galaxy surveys & intensity mapping
- Introduced Ω_{th} , thermal energy density, as a new probe for structure formation
- Direct measurement of **CIB redshift** distributions and **SEDs** (and T_{dust})
- Census of Ω_{dust} and **SF history** to 0.04 dex using one of the most intensive data fusion
- **CO** and **[CII]** coming, milestone for line intensity mapping

Legacy products, methods, benchmark results for CMB, LIM & galaxy formation science

