Title: Cosmic Infrared Background Tomography and a Census of Cosmic Dust and Star Formation

Speakers: Yi-Kuan Chiang

Collection/Series: Cosmic Ecosystems

Subject: Cosmology

Date: July 31, 2025 - 4:00 PM

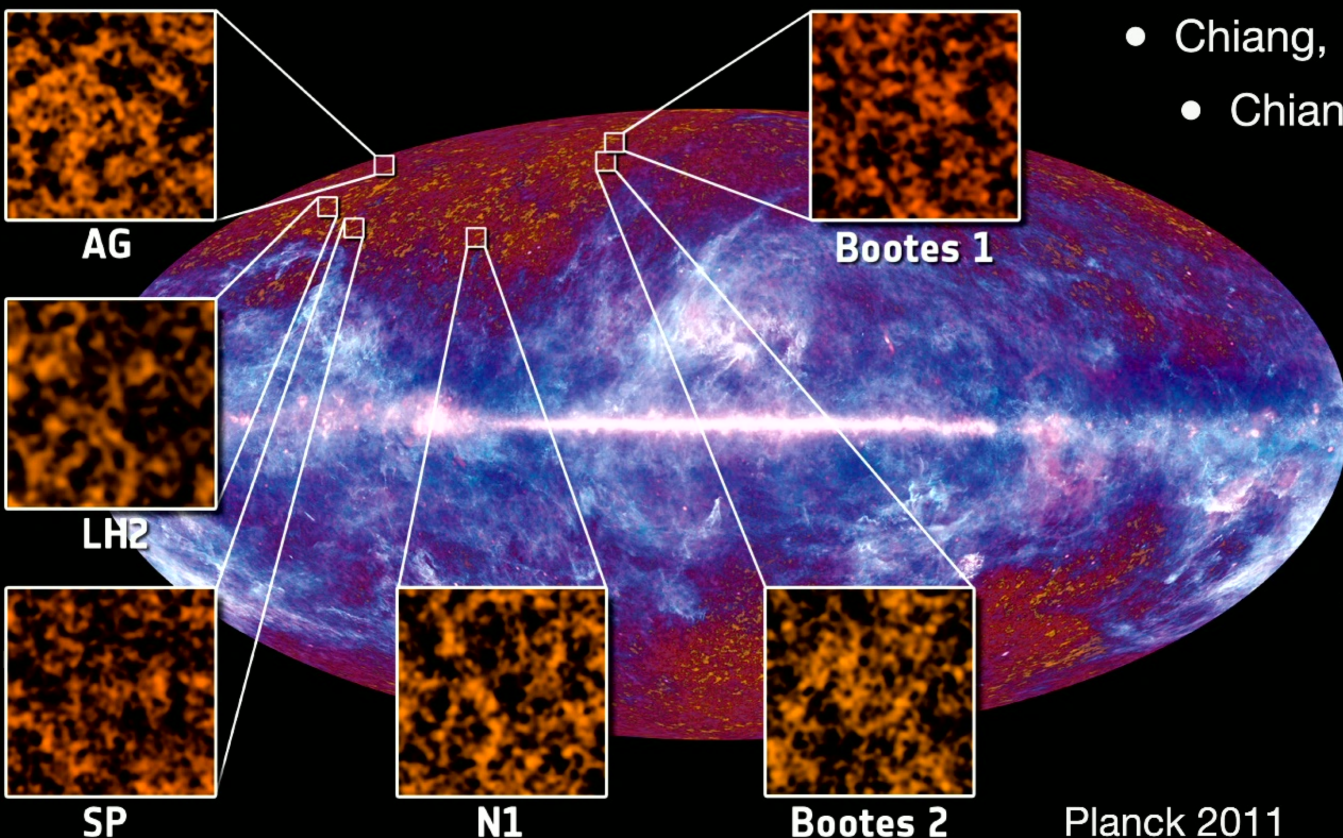
URL: https://pirsa.org/25070057

Abstract:

The cosmic far-infrared background (CIB) encodes dust emission from all galaxies and carries valuable information on structure formation, star formation, and chemical enrichment across cosmic time. However, its redshift-dependent spectrum remains poorly constrained due to line-of-sight projection effects. We address this in [arXiv:2504.05384][1] by cross-correlating 11 far-infrared intensity maps spanning a 50-fold frequency range from Planck, Herschel, and IRAS, with spectroscopic galaxies and quasars from SDSS I-IV tomographically. We mitigate foregrounds using [CSFD][2], a CIB-free Milky Way dust map, and also remove the tomographic SZ background from hot gas in the cosmic web detected in [arXiv:2006.14650][3]. These cross-correlation amplitudes on two-halo scales trace bias-weighted CIB redshift distributions and collectively yield a 60σ detection of the evolving CIB spectrum, sampled across hundreds of rest-frame frequencies over $0 < z < 4$. We break the bias-intensity degeneracy by adding monopole information from FIRAS. The recovered CIB spectrum reveals a dust temperature distribution that is broad, spanning the full range of host environments, and moderately evolving. Using low-frequency CIB amplitudes, we constrain cosmic dust density, Ω_dust, which peaks at z = 1-1.5 and declines threefold to the present. Our wide spectral and sky coverages enable a determination of the total infrared luminosity density with negligible cosmic variance across 90% of cosmic time. This yields a more precise yet consistent constraint on the cosmic star formation history compared to the Madau & Dickinson (2014) compilation. Additionally, we find that star formation occurs in a mode that is, on average, 80% dust-obscured at $z = 0$ and 60% at $z = 4$. Our results, based on intensity mapping, are complete, requiring no extrapolation to faint galaxies or low-surface-brightness components. We release our tomographic CIB spectrum and redshift distributions in [this link][4] as a public resource for future studies of the CIB, both as a cosmological matter tracer and CMB foreground.

[1]: https://arxiv.org/abs/2504.05384
[2]: https://arxiv.org/abs/2306.03926
[3]: https://arxiv.org/abs/2006.14650
[4]: https://zenodo.org/records/15149425

Cosmic Infrared Background Tomography and a Census of Cosmic Dust and Star Formation



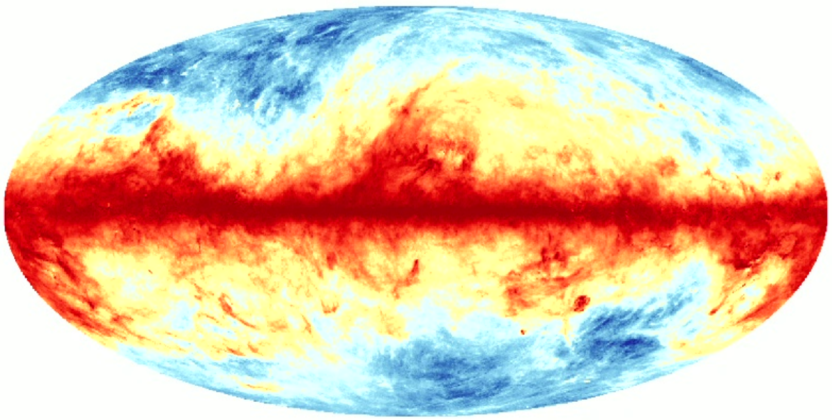
Planck 2011

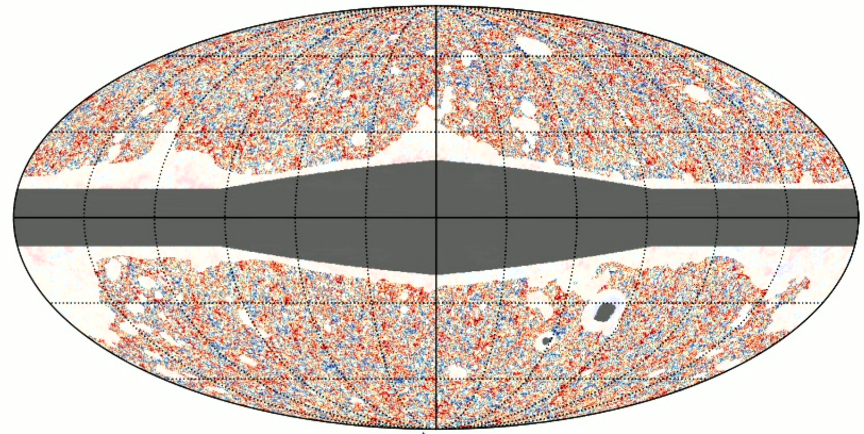
- Chiang, Makiya, & Menard 2025 (CIB)
    - Chiang 2023 (Milky Way dust map)

Yi-Kuan Chiang
ASIAA

Any maps:

$$I = I_{\text{non LSS}}^{\text{CMB, Milky Way …}} + \boxed{I_{\text{LSS}}^{\text{CIB, tSZ}}}$$





Part I of the talk ↓

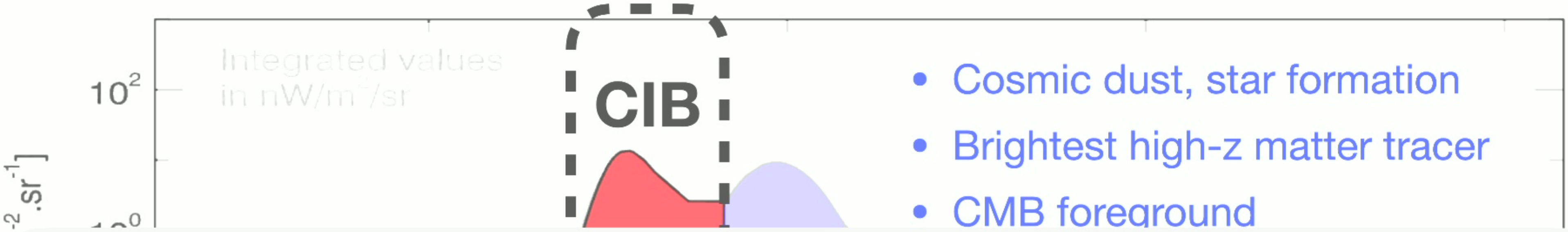
Part II of the talk ↑

Clean 3D LSS statistics + **Fourier phases**

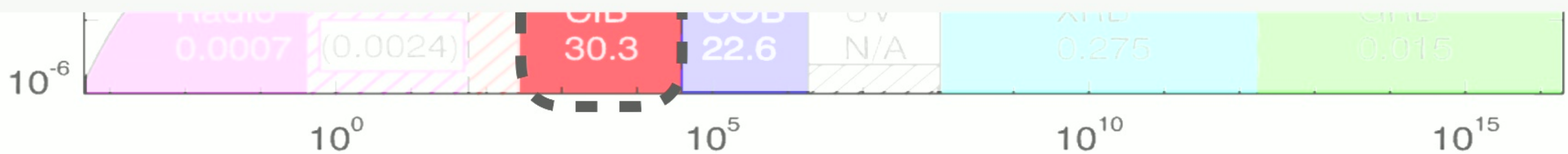
how many overdensities are there?

where the overdensities are in 3D?

Cosmic infrared background (CIB)

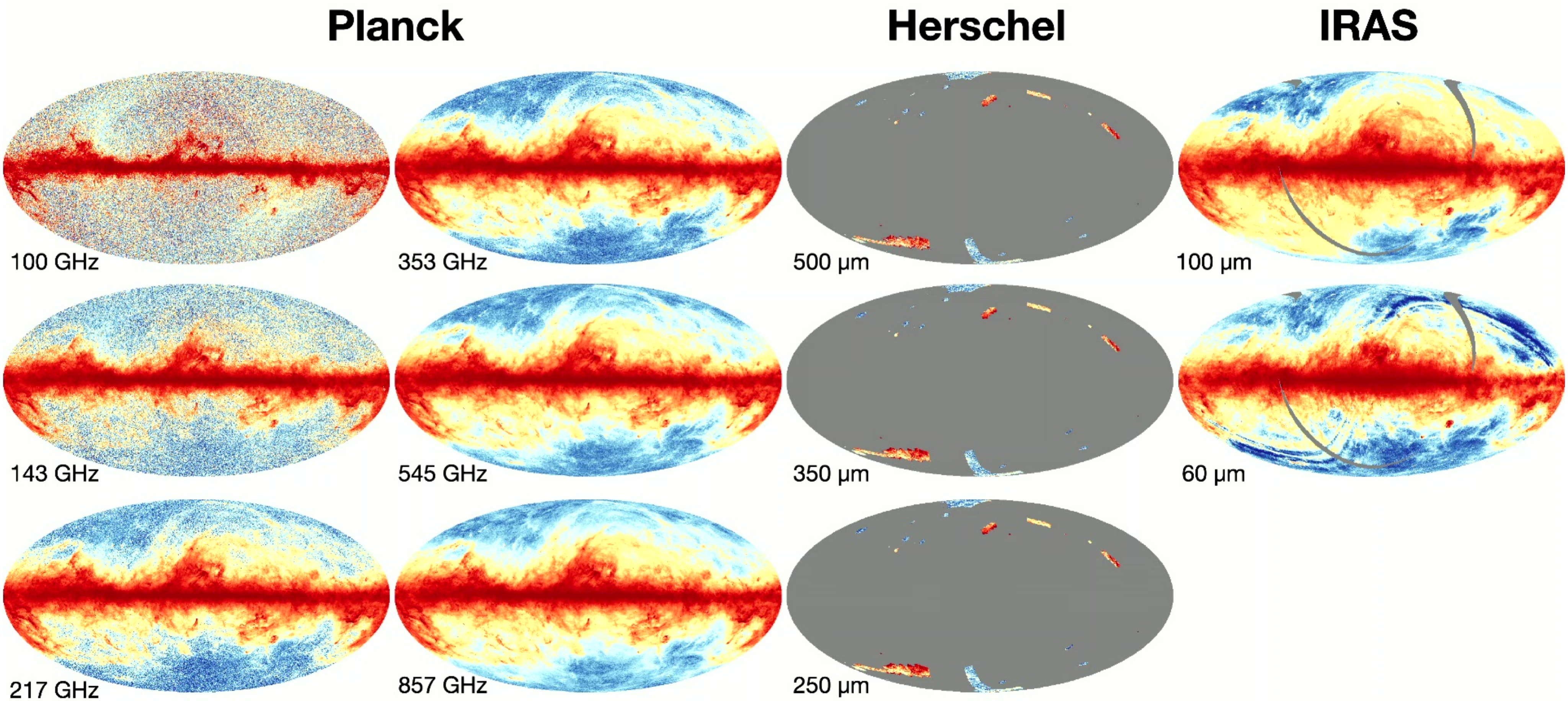


- **Limitation: projection effect** ***Δz*** **= entire SF history**
- **Goal: measure** ***P(z)*****, or** ***dI/dz*** **for the CIB**



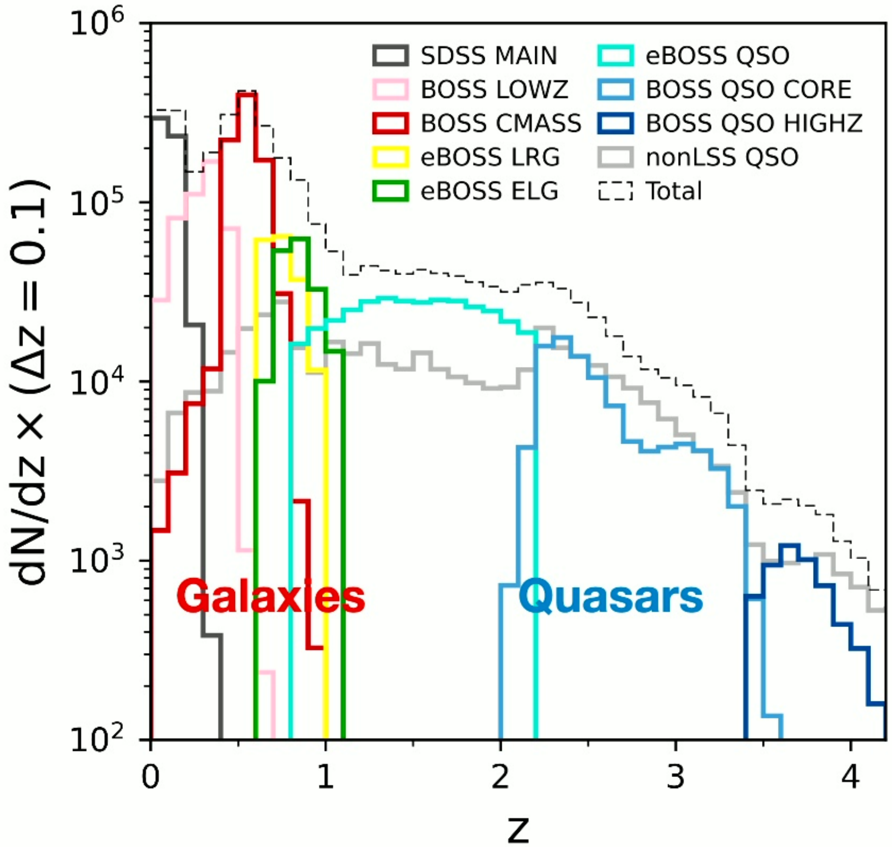
Silva+ 21

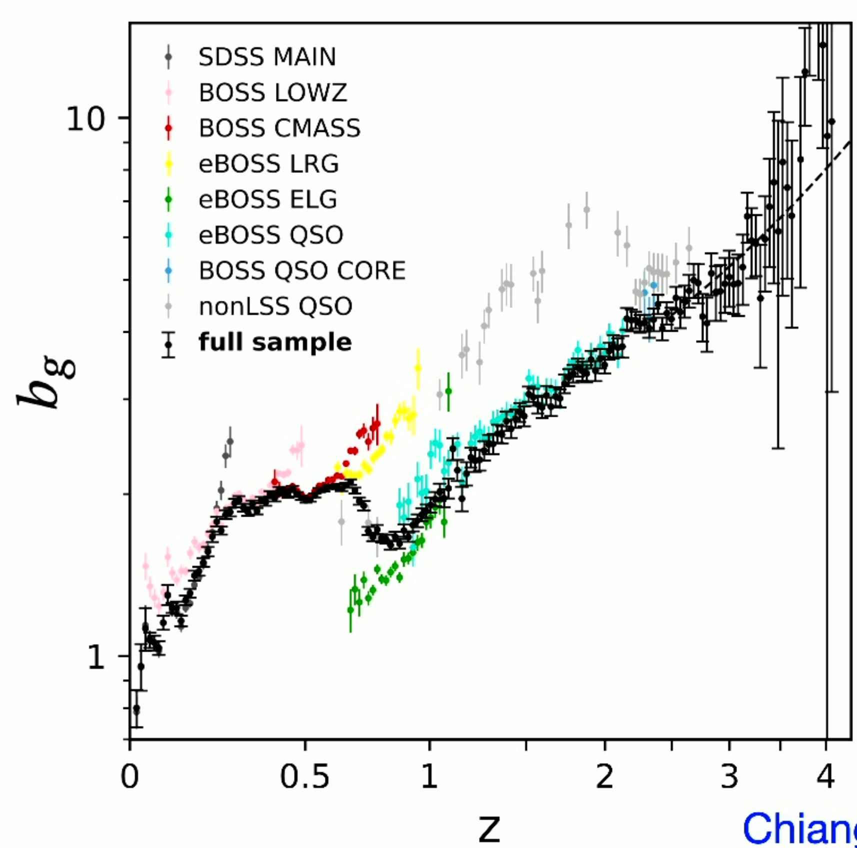
Probing the CIB using 11 maps covering 50-fold frequencies



3D cross-correlation references

3 million spectroscopic redshifts in SDSS/BOSS/eBOSS





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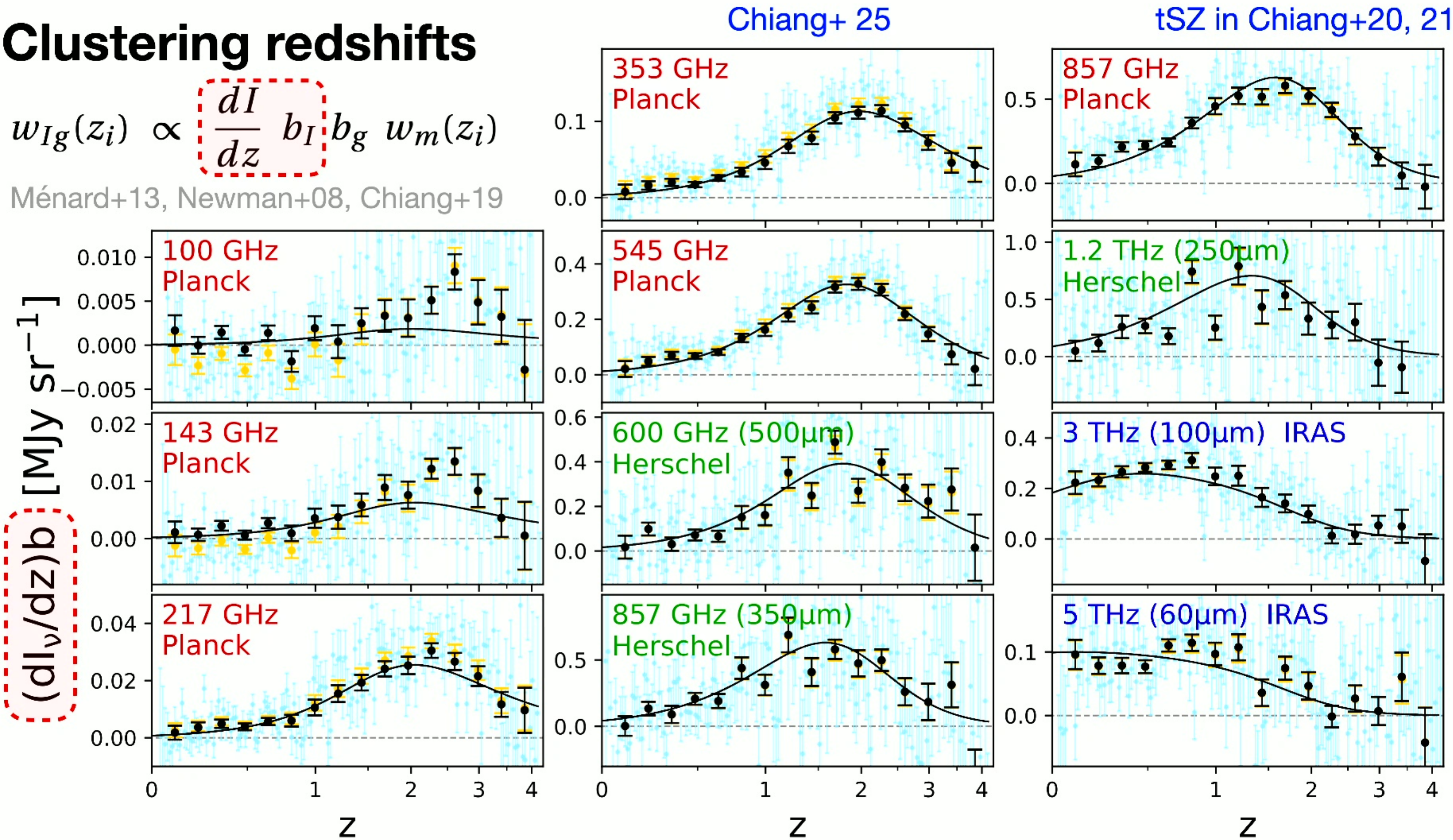
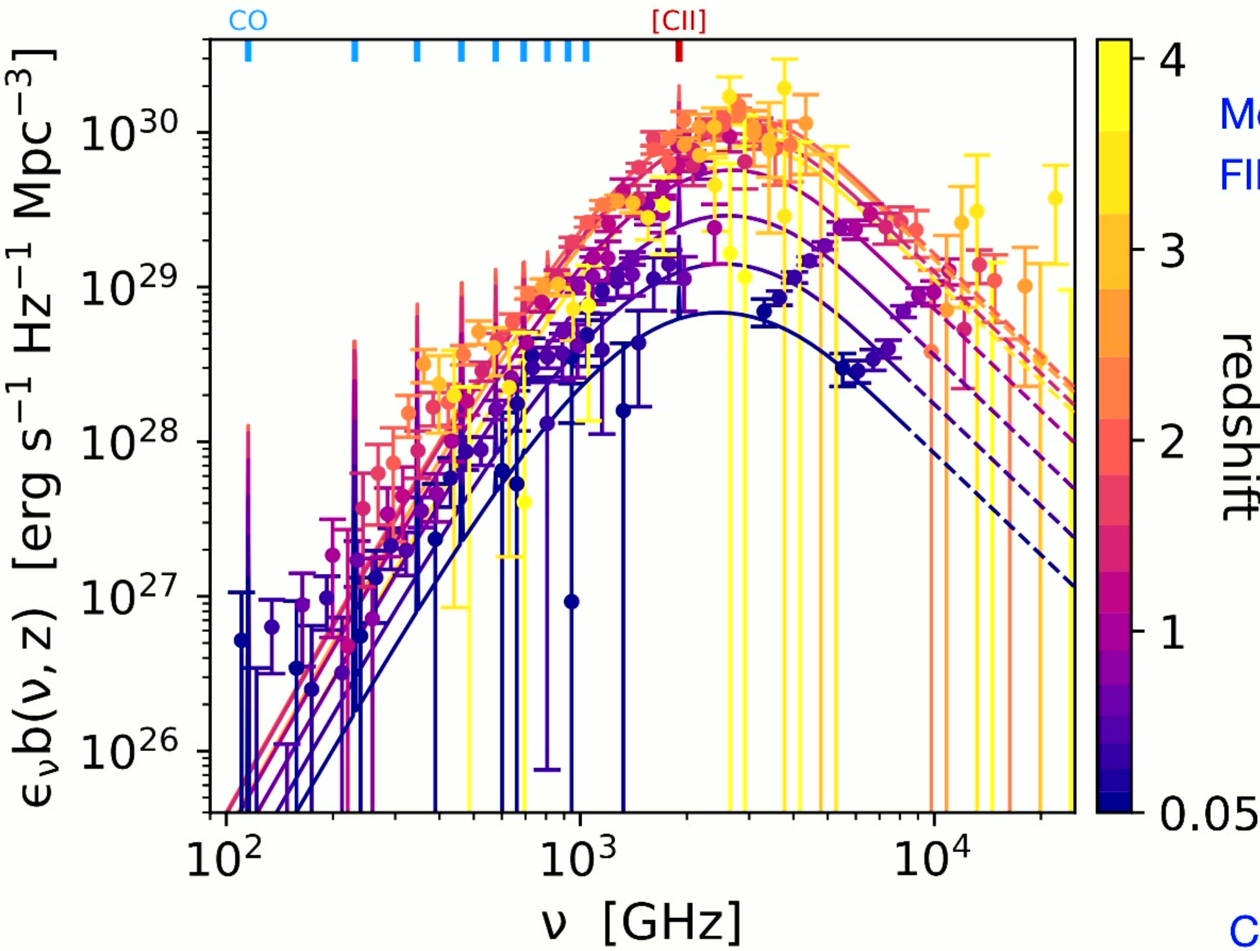
Clustering redshifts

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

Ménard+13, Newman+08, Chiang+19



Tomographic CIB spectrum



Most densely sampled FIR SED in the literature

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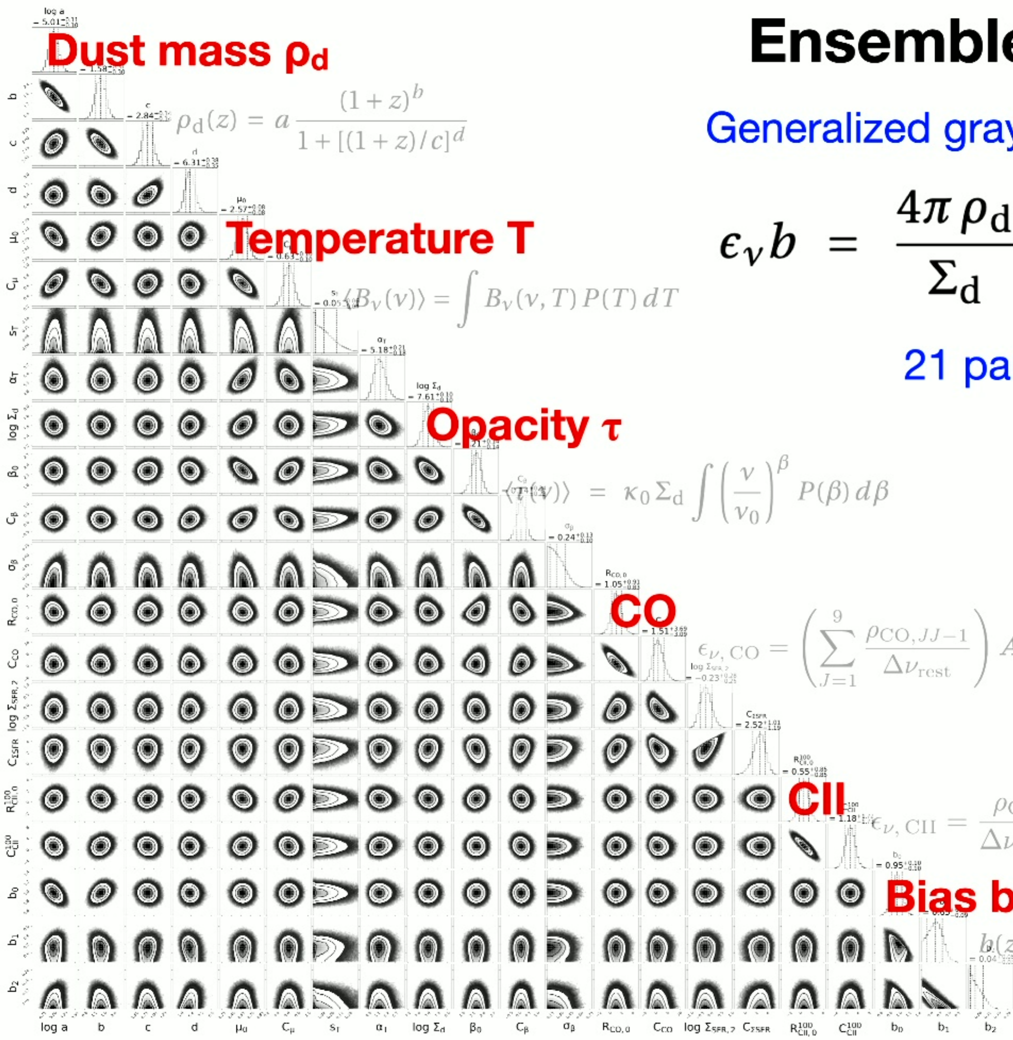
Ensemble cosmic dust SED

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



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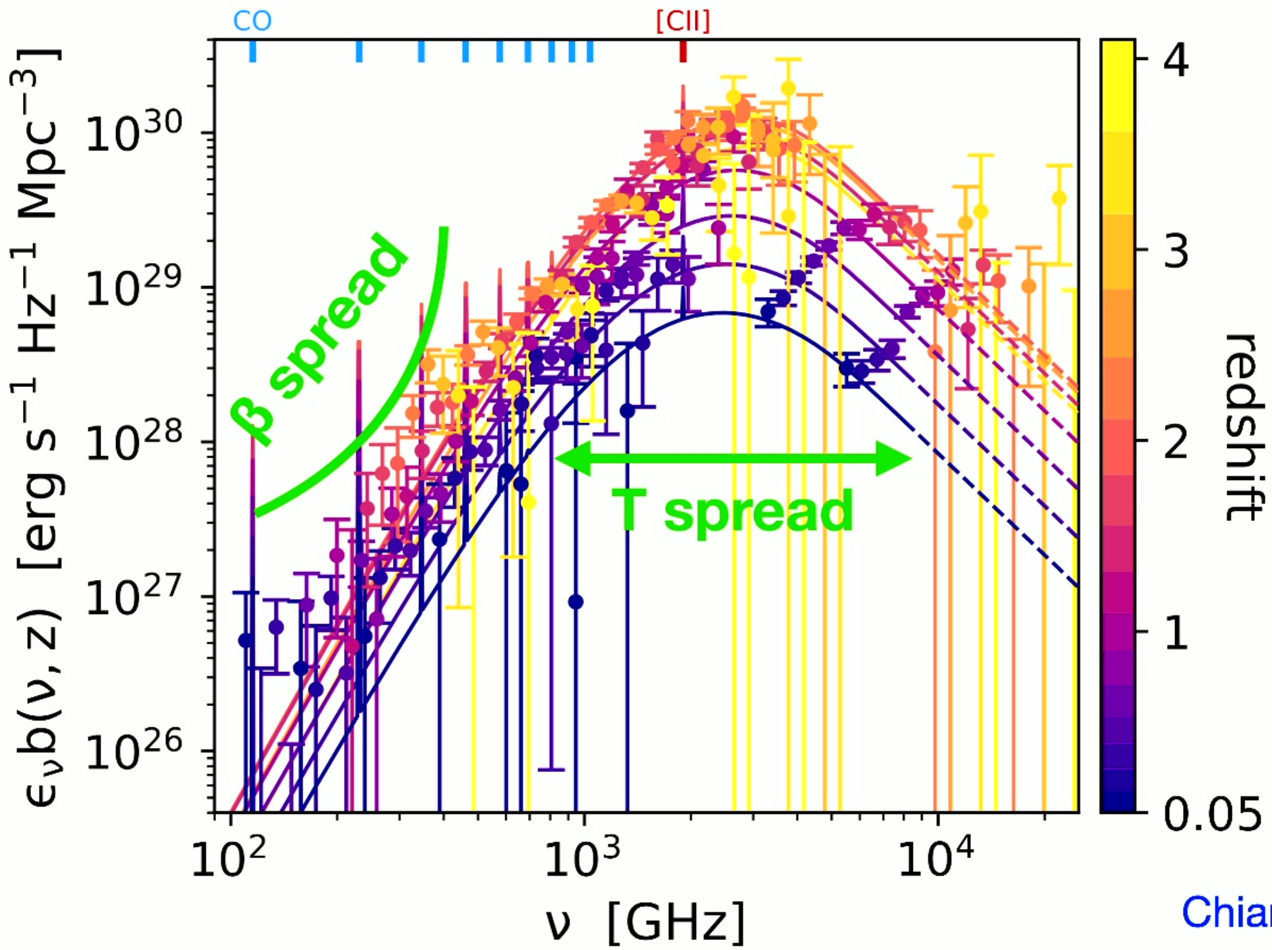
Single T, β MBB is not enough



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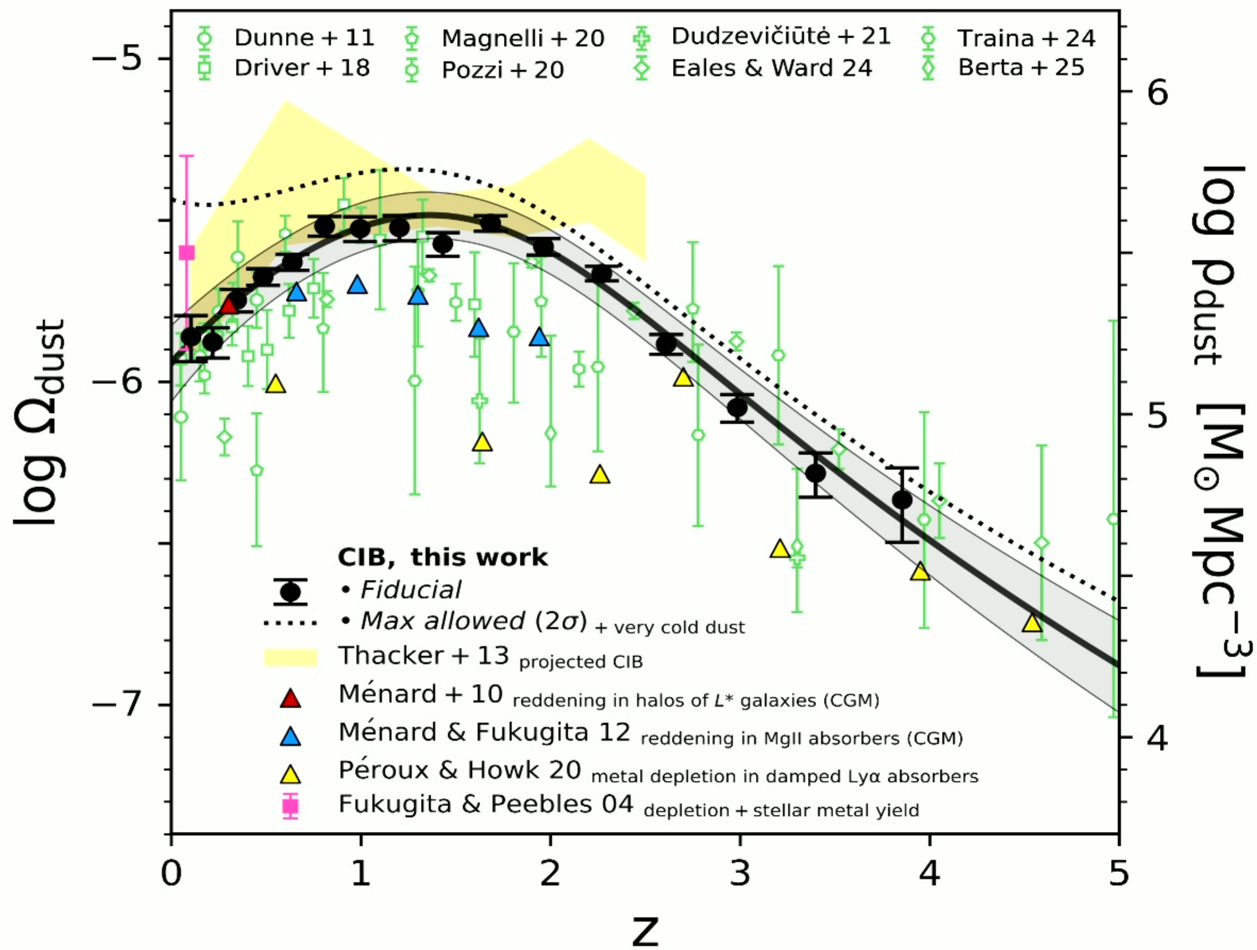
Census of cosmic dust in all environments



Upper envelope of galaxy surveys

Dust gets destructed at low z

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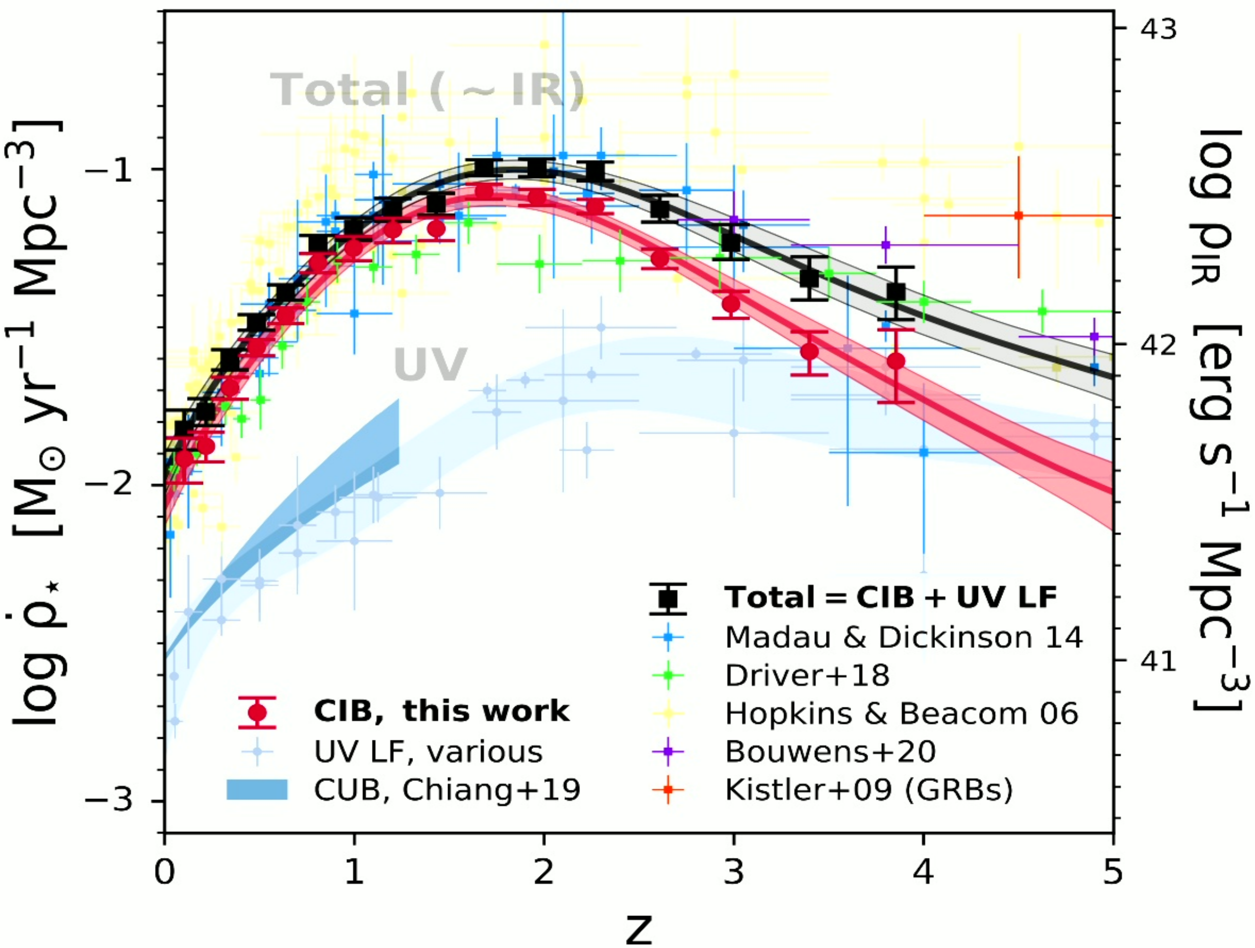
Cosmic star formation is 80% dust-obscured



Tightest CSFR constraint

No cosmic variance
No SED systematic

Complete to the faintest galaxies

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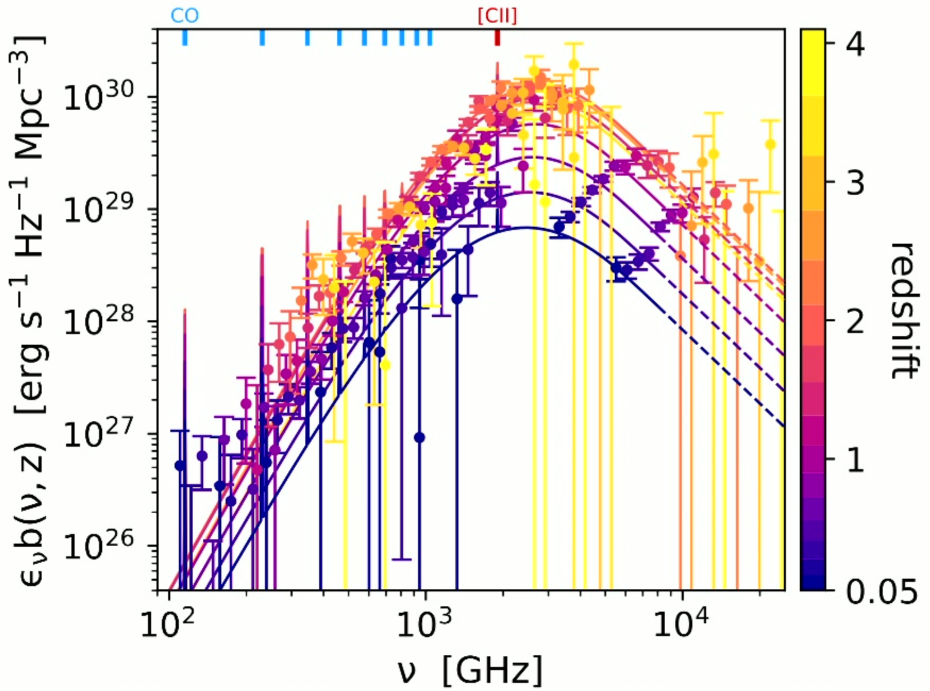
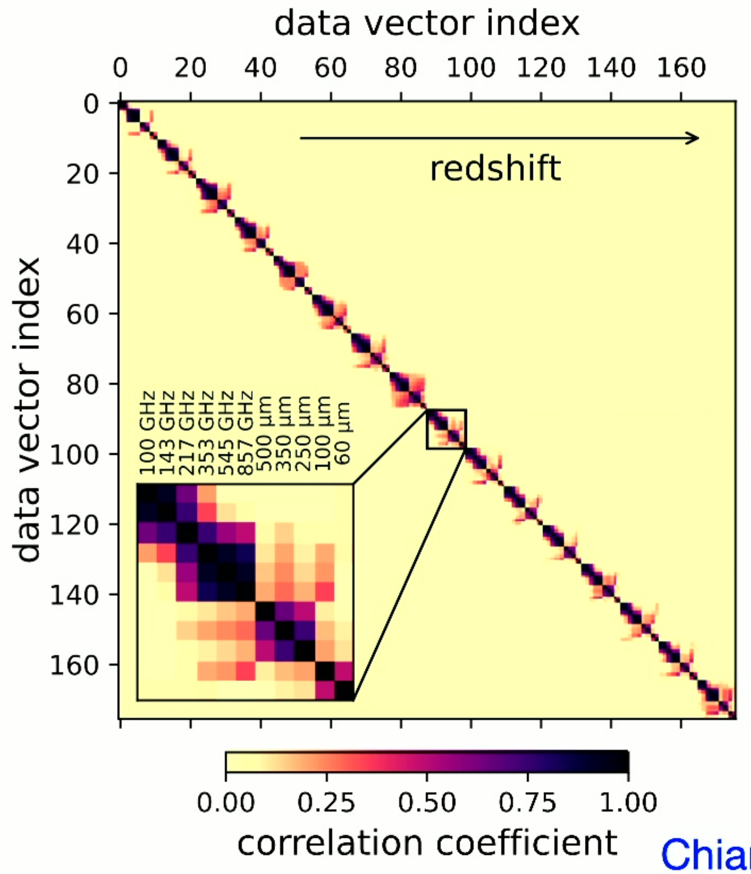
Everything is publicly available

Data, covariance, SED at z=0—10, dI/dz redshift distributions, b(z), Ω_d, CSFR, monopole, tSZ …

zenodo 136 VIEWS 12 DOWNLOADS

https://zenodo.org/records/15149425





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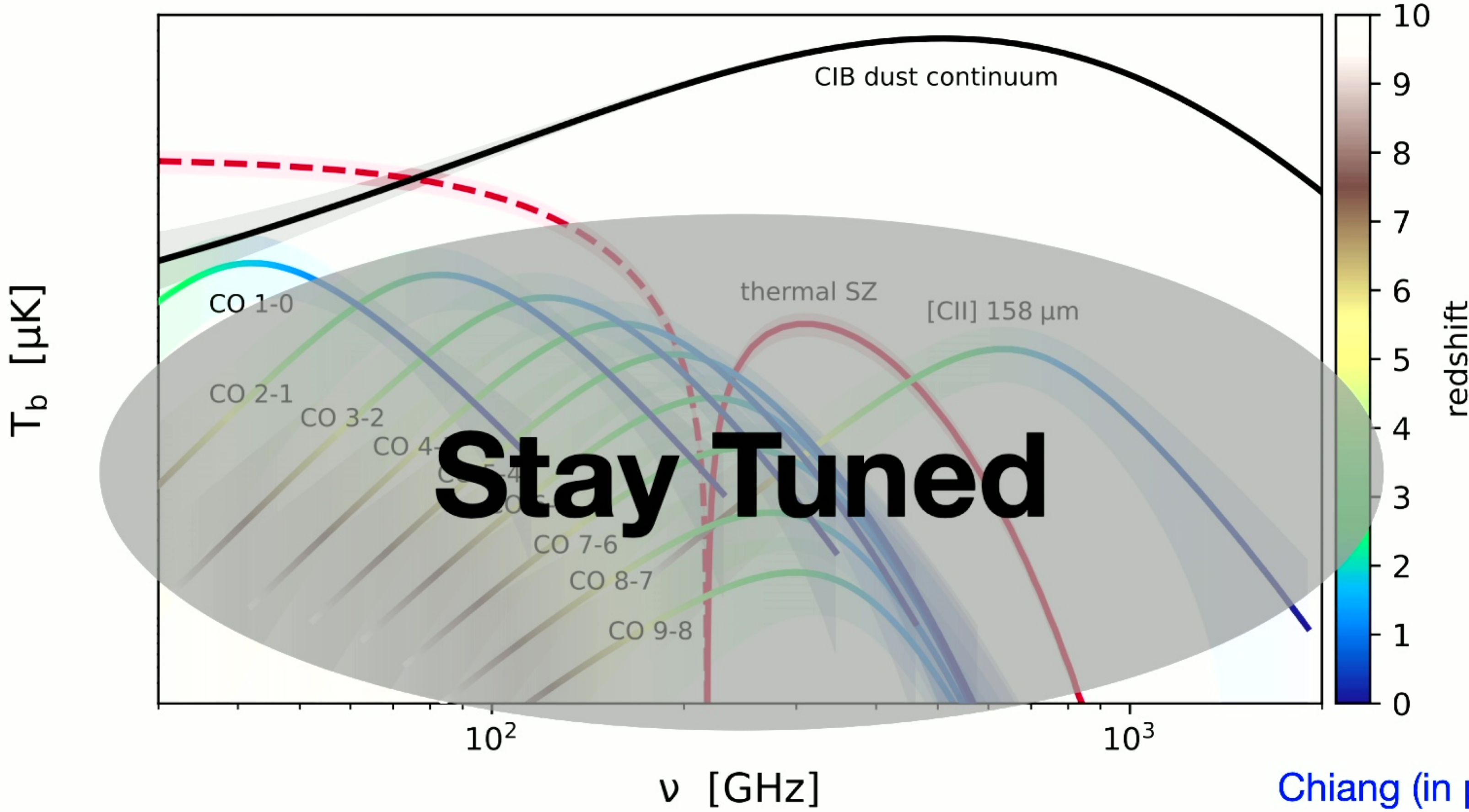
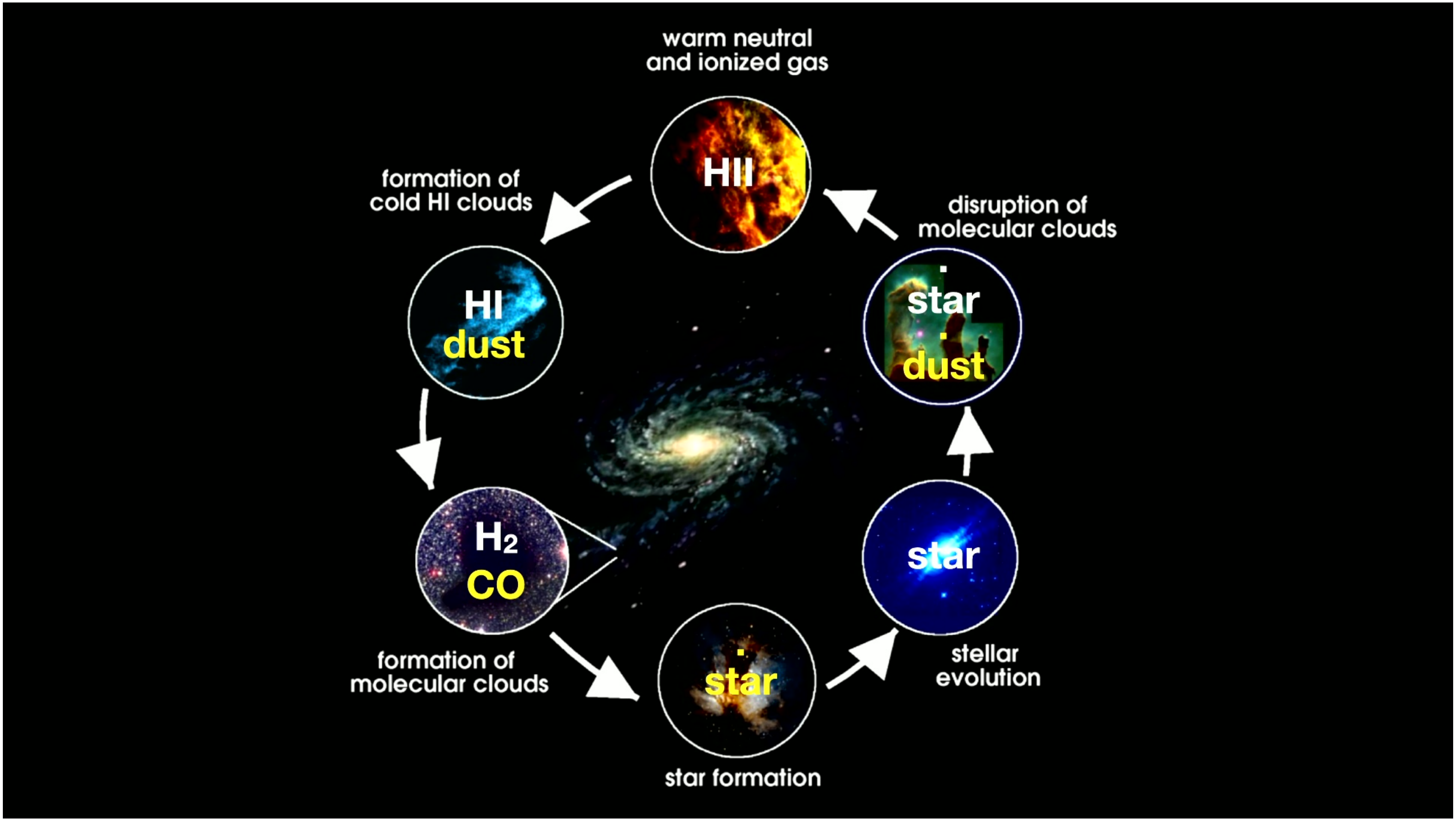
Cosmic mean CO & [CII] detected

First empirical baseline for line intensity mapping (LIM) experiments



Chiang (in prep)


warm neutral and ionized gas
HII
formation of cold HI clouds
HI
dust
disruption of molecular clouds
star
dust
H_2
CO
star
formation of molecular clouds
star
stellar evolution
star formation

Map-level CIB reconstruction

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

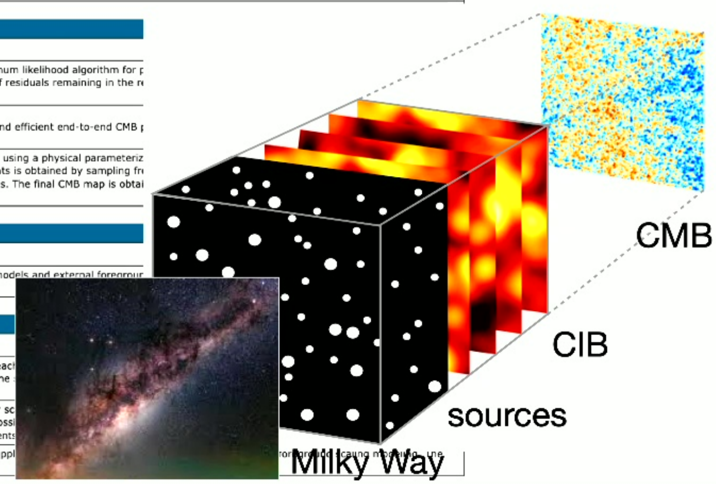
Internal Linear Combination (ILC)	
Name	**Description**
pyilc Code	pyilc is a pure-python implementation of the needlet internal linear combination (NILC) algorithm for CMB component separation. Harmonic-space ILC is also implemented in the code. For detai an inpainting code, diffusive_inpaint, that 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 c method to use Lagrange multipliers to compute the weights.
Tegmark ILC	Harmonic-space ILC (Tegmark 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 a 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 Suny
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 (Martinez-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 cleaned maps in harmonic space.
SMICA	SMICA (Spectal Matching Independent Component Analysis) is a non-parametric method (Delabrouille et al. 2003, Cardoso et al., 2008) that works in the spherical harmonic domain. Foregrounds are modelled as a small number of templates with arbitrary frequency spectra, arbitrary power spectra and arbitrary correlation between the components. The solution is obtained by minimizing the mismatch of the model to the auto- and cross-power spectra of the frequency channel maps. From the solution, a set of weights is derived to combine the frequency maps in the spherical harmonic domain to produce the final CMB map. Maps of the total foreground emission in each frequency channel can also be produced. In the analysis performed for the 2013 release (Planck Collaboration XII 2014), SMICA was the method that performed best on the simulated temperature data.

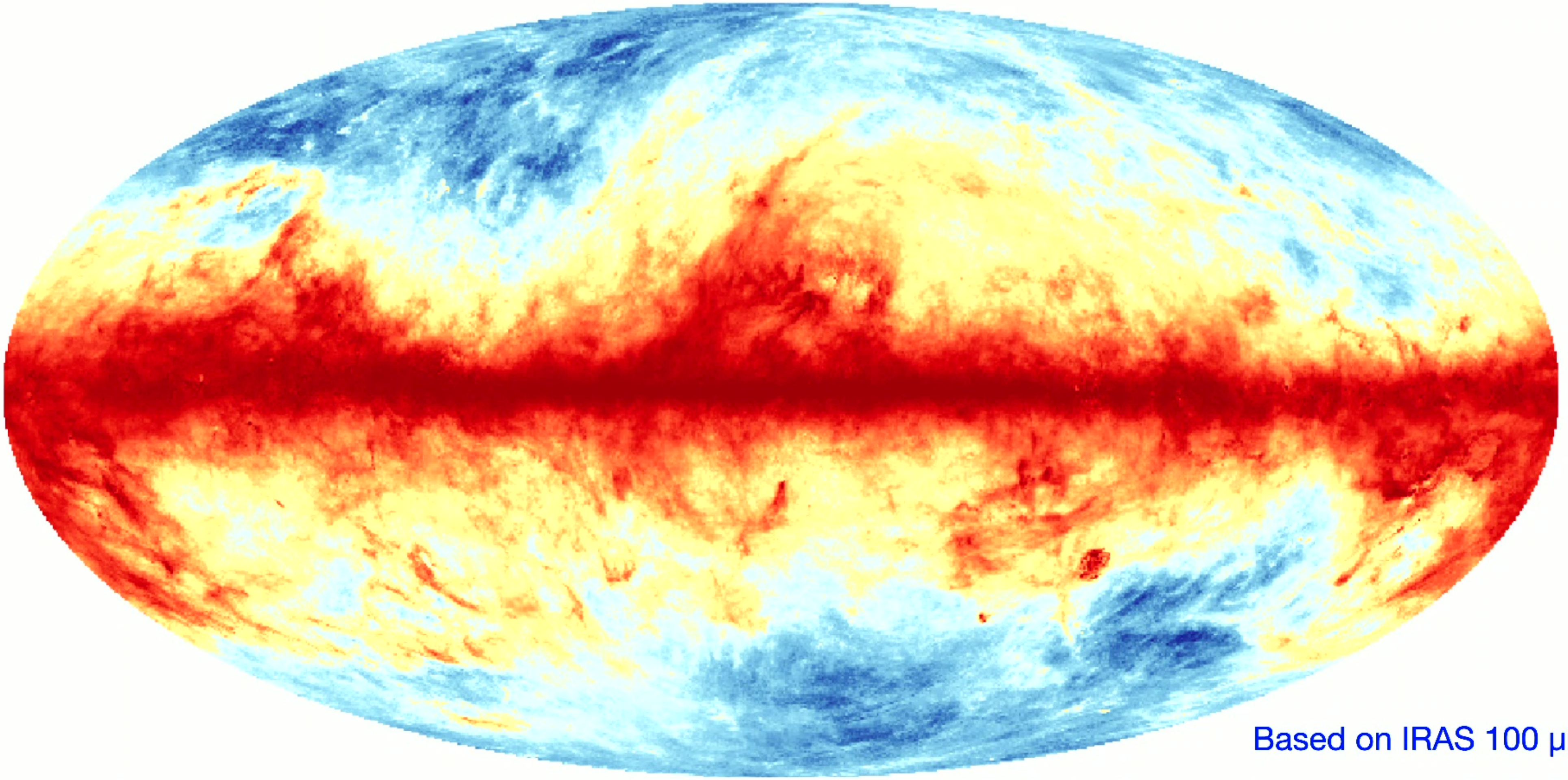
Monte-Carlo	
Name	**Description**
ForeGroundBuster Code	ForeGroundBuster ('fgbuster') is a library of functions designed to perform separation of a suite of frequency maps into astrophysical components. It utilizes a maximum likelihood algorithm for p Stompor et al (2009) , is a modified version of the two-step MCMC approach discussed by Eriksen et al. (2006). A framework is also provided to estimate the level of residuals remaining in the r parameter recovery.
Commander3 (BeyondPlanck release) Code	Commander3 is the public release of the most recent version of Commander (Commander is an Optimal Monte-carlo Markov chAiN Driven EstimatoR) code for fast and efficient end-to-end CMB p
Commander2 Code	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 parameteriz method is well suited to perform astrophysical component separation in addition to CMB extraction (Planck Collaboration X 2016). The joint solution for all components is obtained by sampling fr 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 obtai domain.

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 foregroun weight. 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 eac demonstrated in (Leach et al., 2008), GMCA can be used in two ways: GMCA-blind to optimize the separation of the CMB component, and GMCA-model to optimize 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 sc line-of-sight using multi-frequency observations. It requires no a priori knowledge of the components except that they are statistically independent and all, except possi CMB fluctuations and non-Gaussian foregrounds. The main advantage of this approach is that the algorithm is able to learn how to reconstruct independent components
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, suppl estimated parameters are then used to reconstruct the components by Wiener filtering in the harmonic domain.



A challenging case, where foreground is overwhelmingly strong: SFD (Schlegel, Finkbeiner, Davis 98) dust map = Milky Way + CIB



Based on IRAS 100 μm

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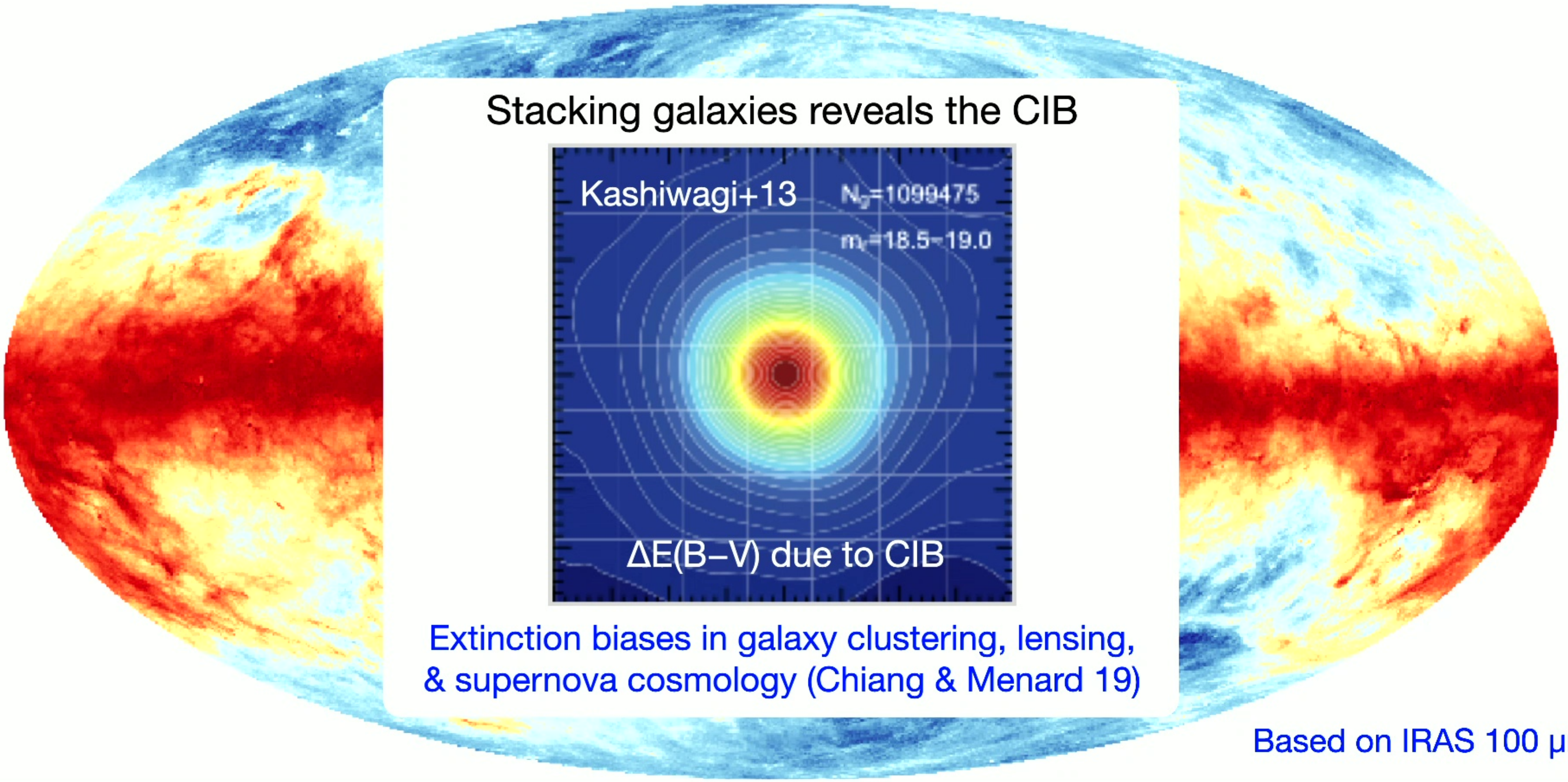


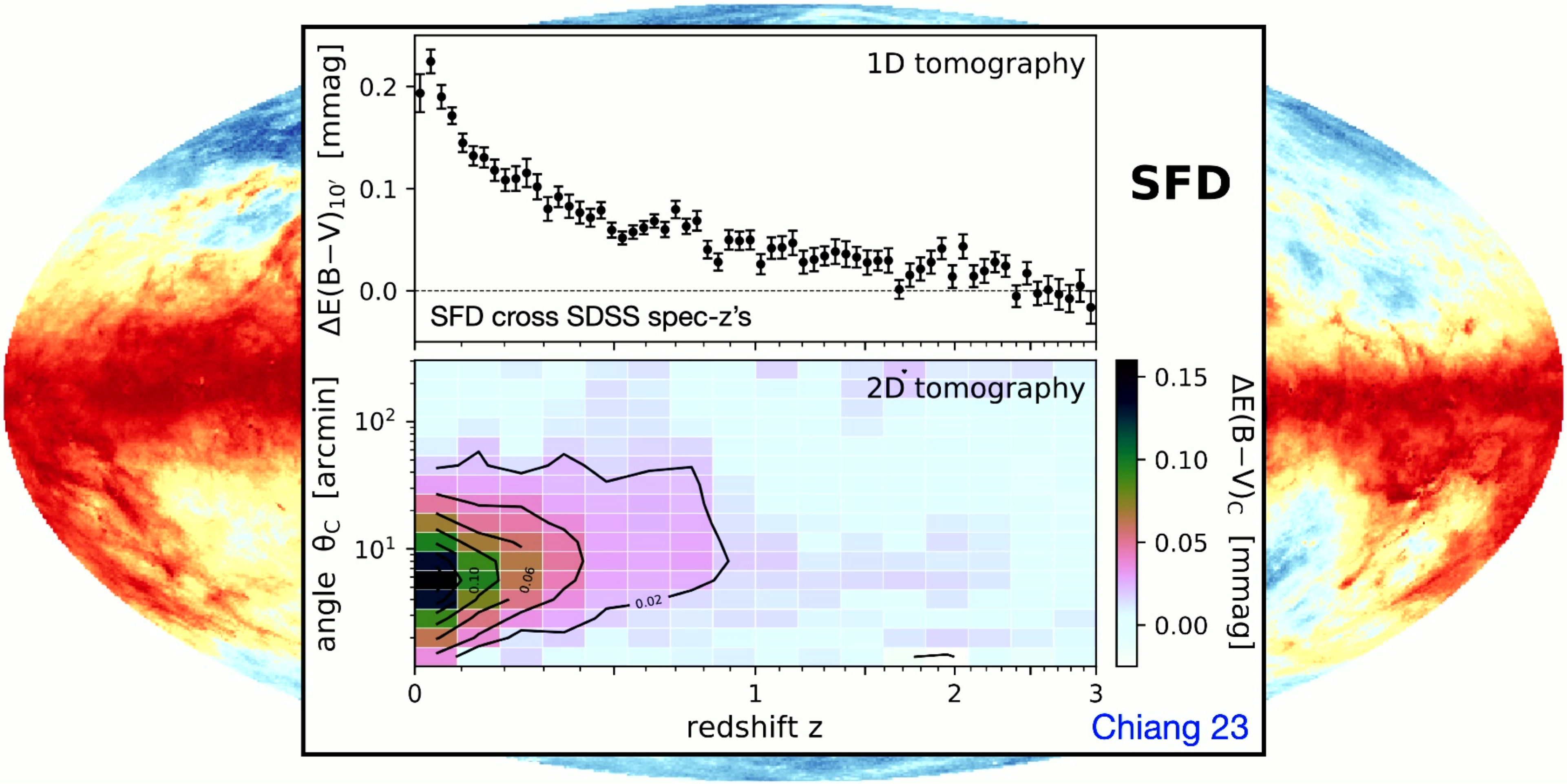
Stacking galaxies reveals the CIB

Extinction biases in galaxy clustering, lensing, & supernova cosmology (Chiang & Menard 19)

Based on IRAS 100 μm

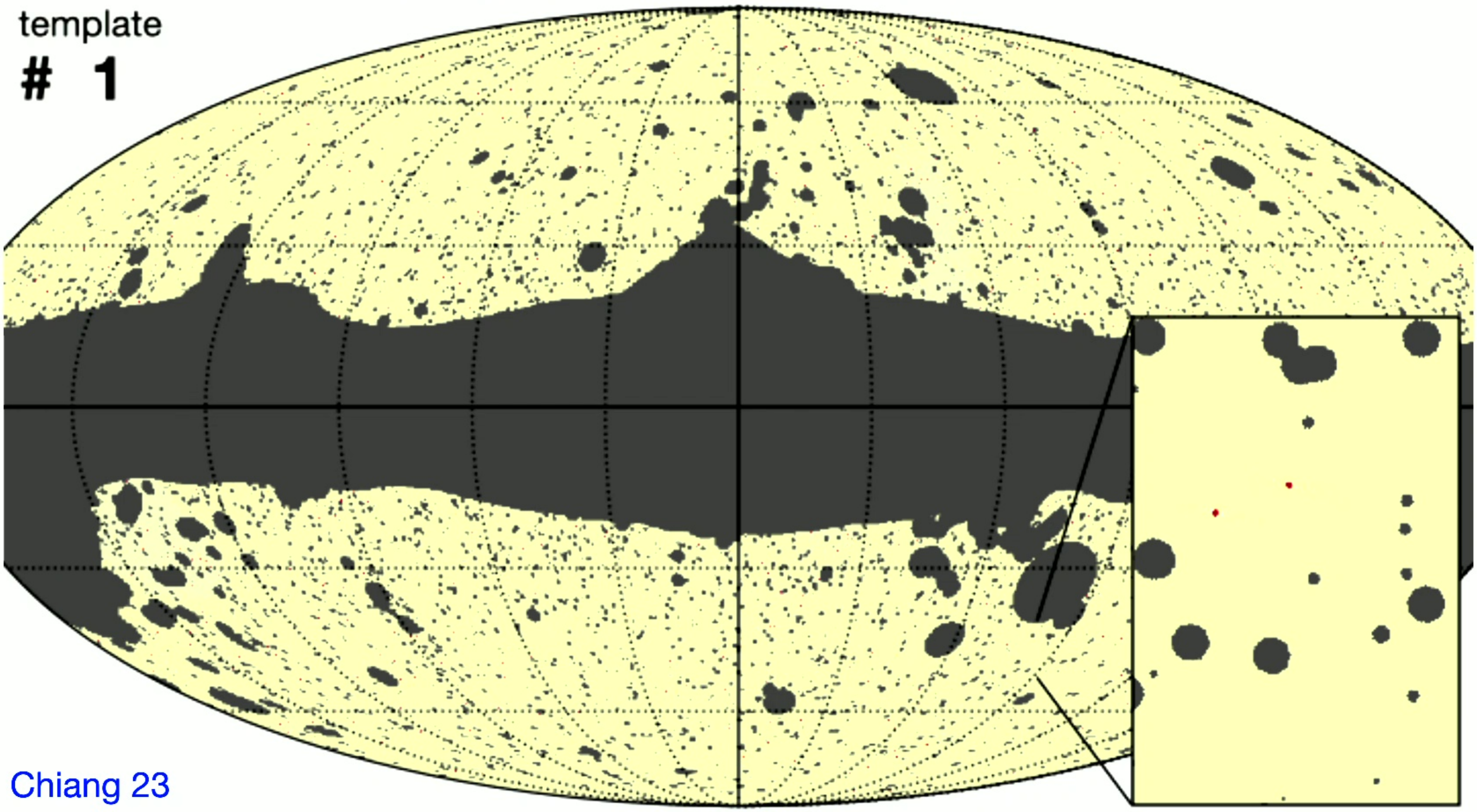
1. Cross-correlation tomography to exhaust all 2-pt statistics

Similar to the 11-band CIB analysis but now keep full angular dependence



2. Build 30×6=180 LSS templates from 600M WISE galaxies

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



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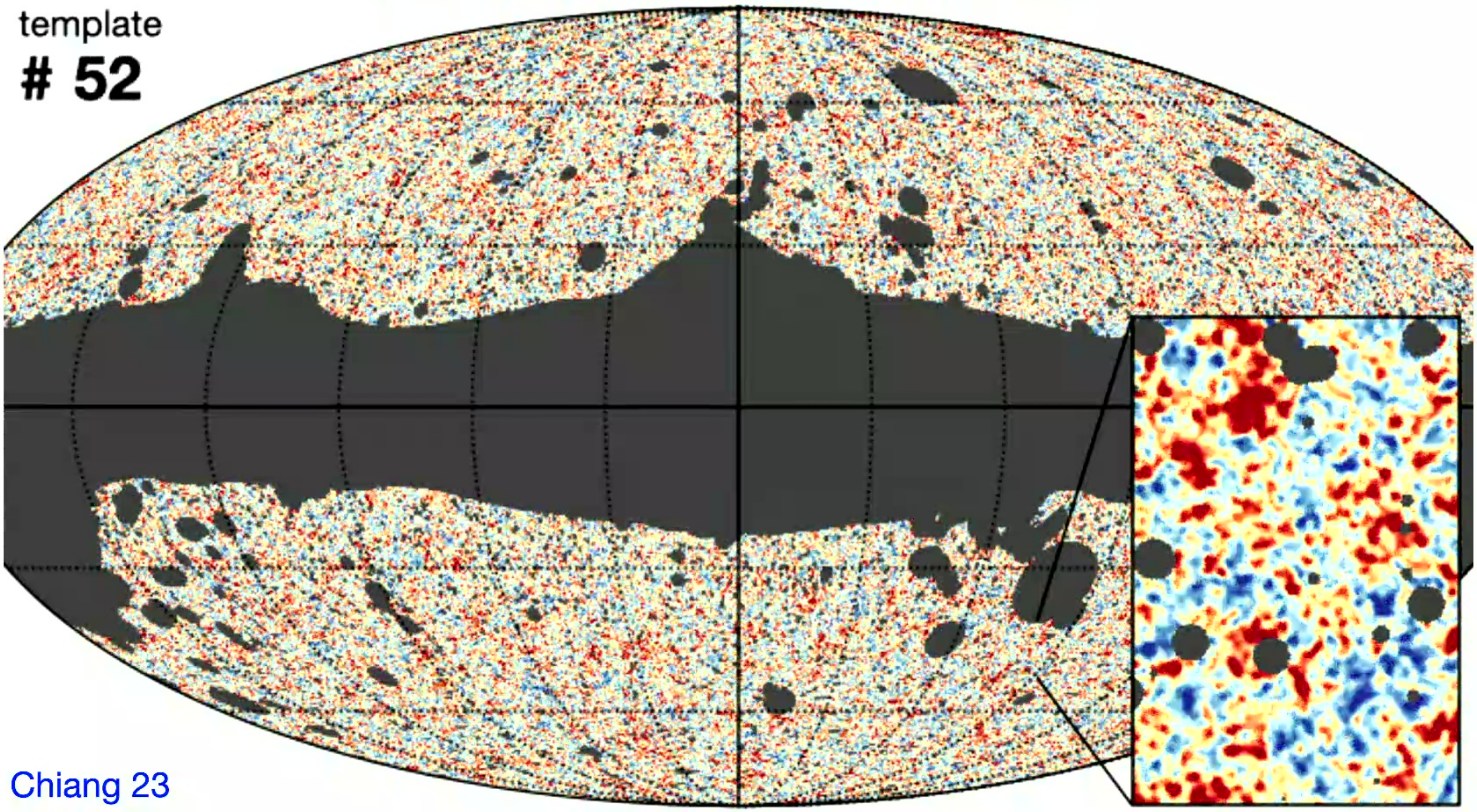
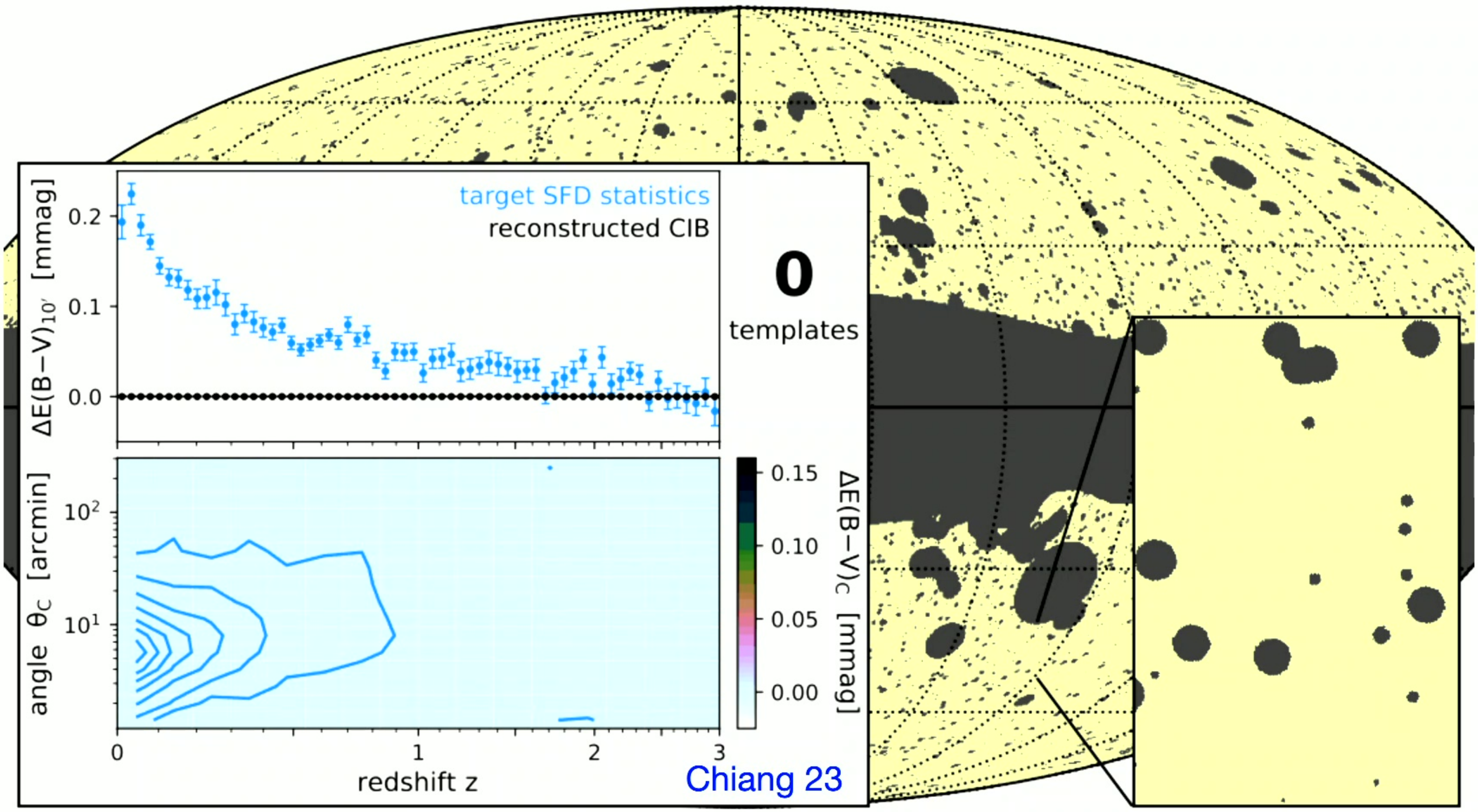


Reconstruction: $I_{\text{CIB}}(\phi) \;=\; \sum C_i \times T_{LSS,i}(\phi)$ (Sum of basis)



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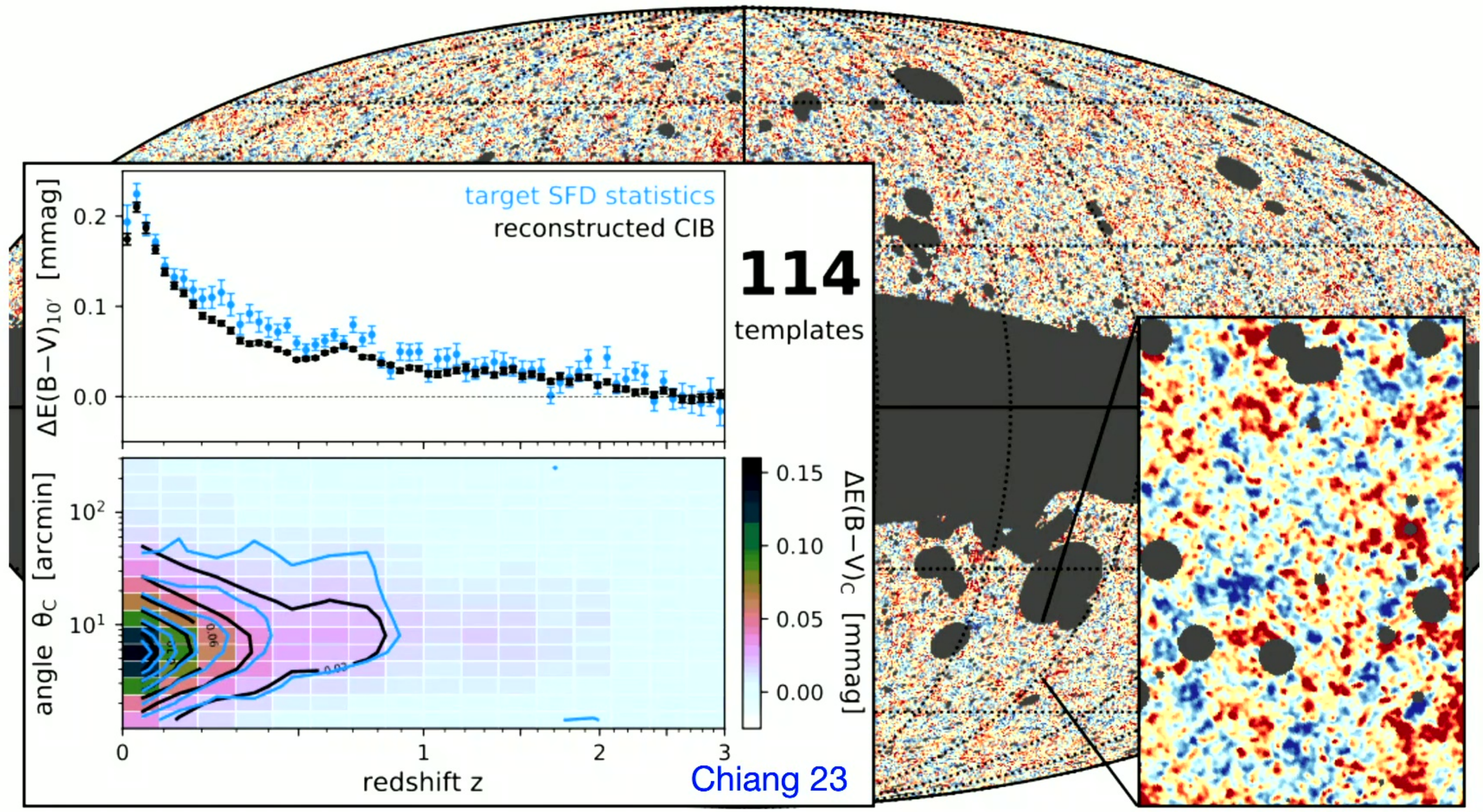
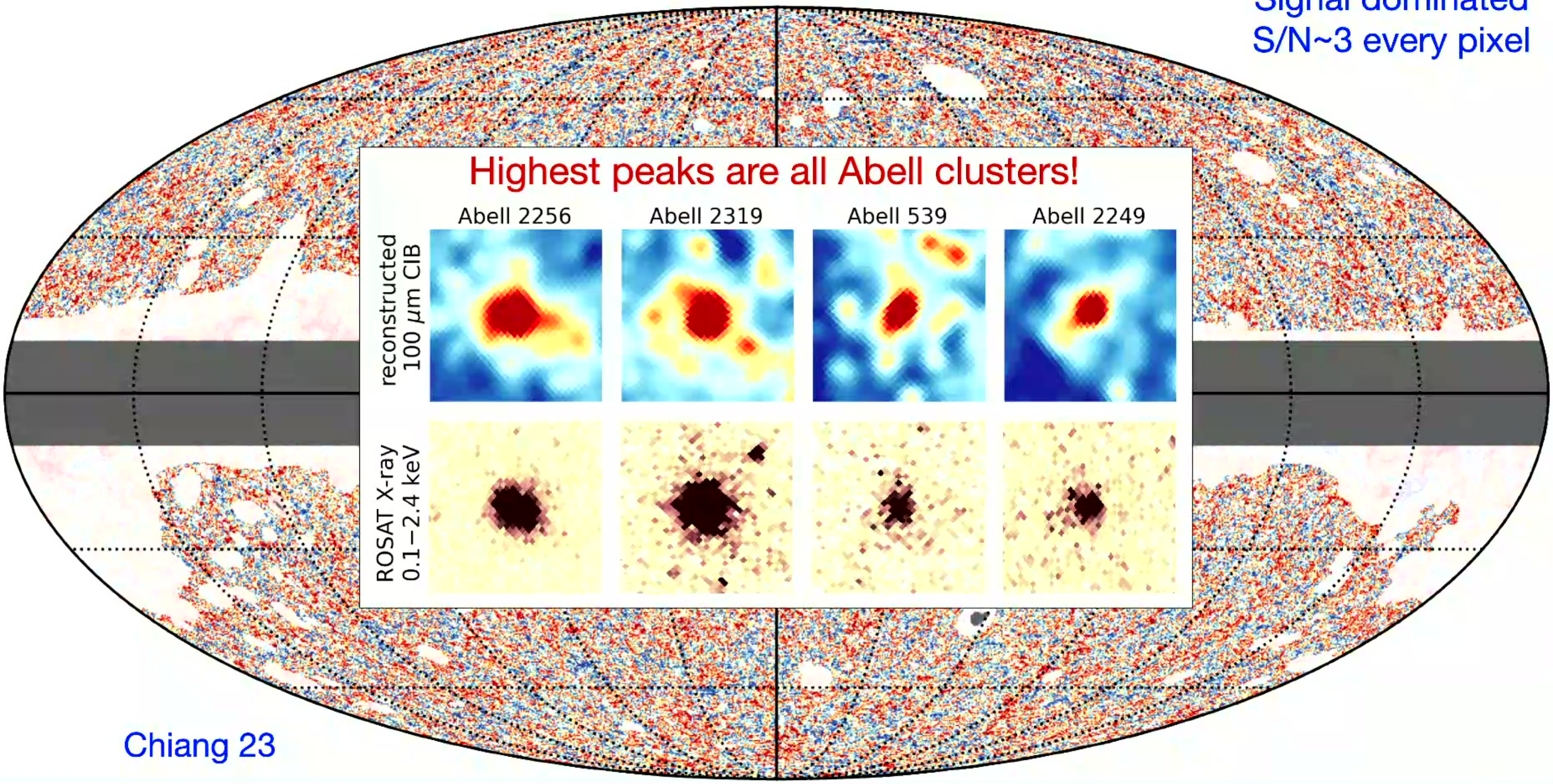


Reconstructed CIB map (100 micron)

Signal dominated
S/N~3 every pixel



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Corrected SFD (CSFD) = SFD – CIB

All-purpose dust map for extinction correction & foreground cleaning

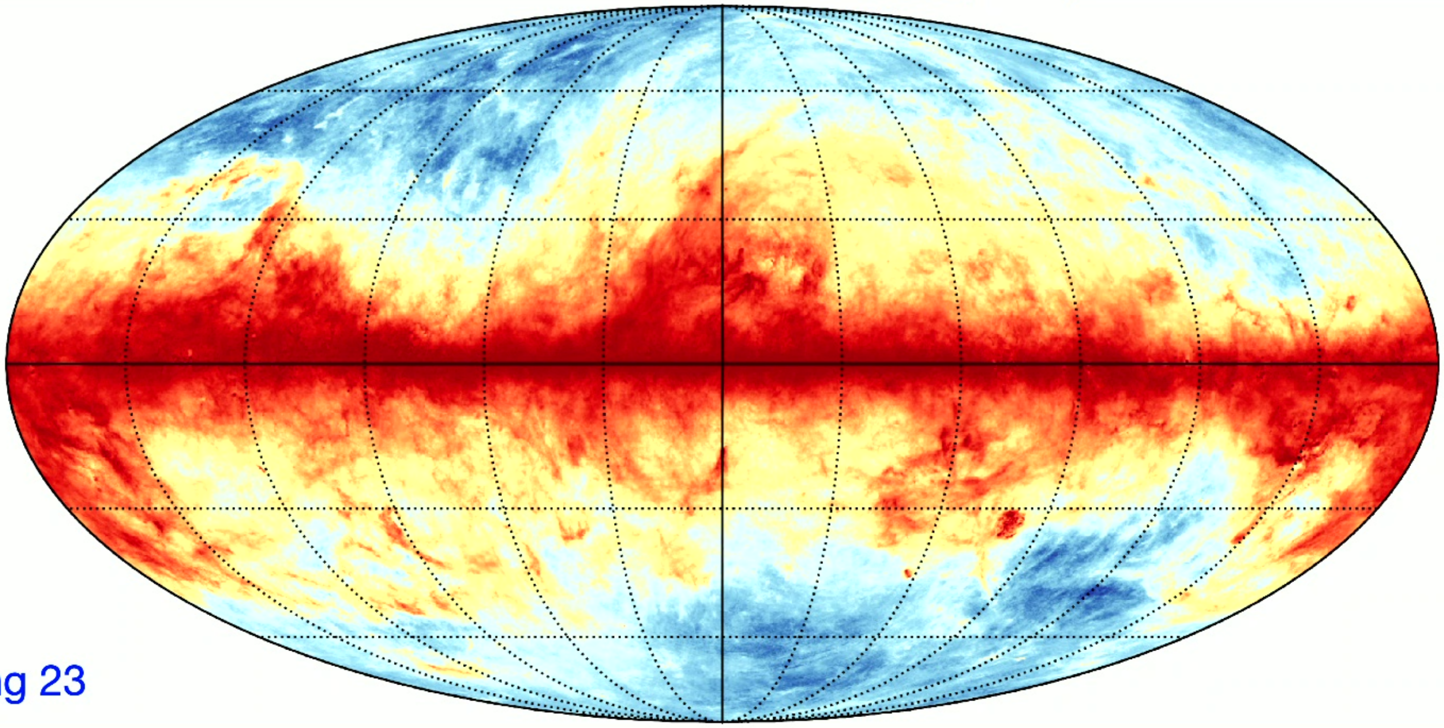
1. zenodo — 1K VIEWS, 2K DOWNLOADS — https://zenodo.org/records/8207175

Or

2. NASA LAMBDA

Or

3. One line Python query with dustmaps (Green 18) package



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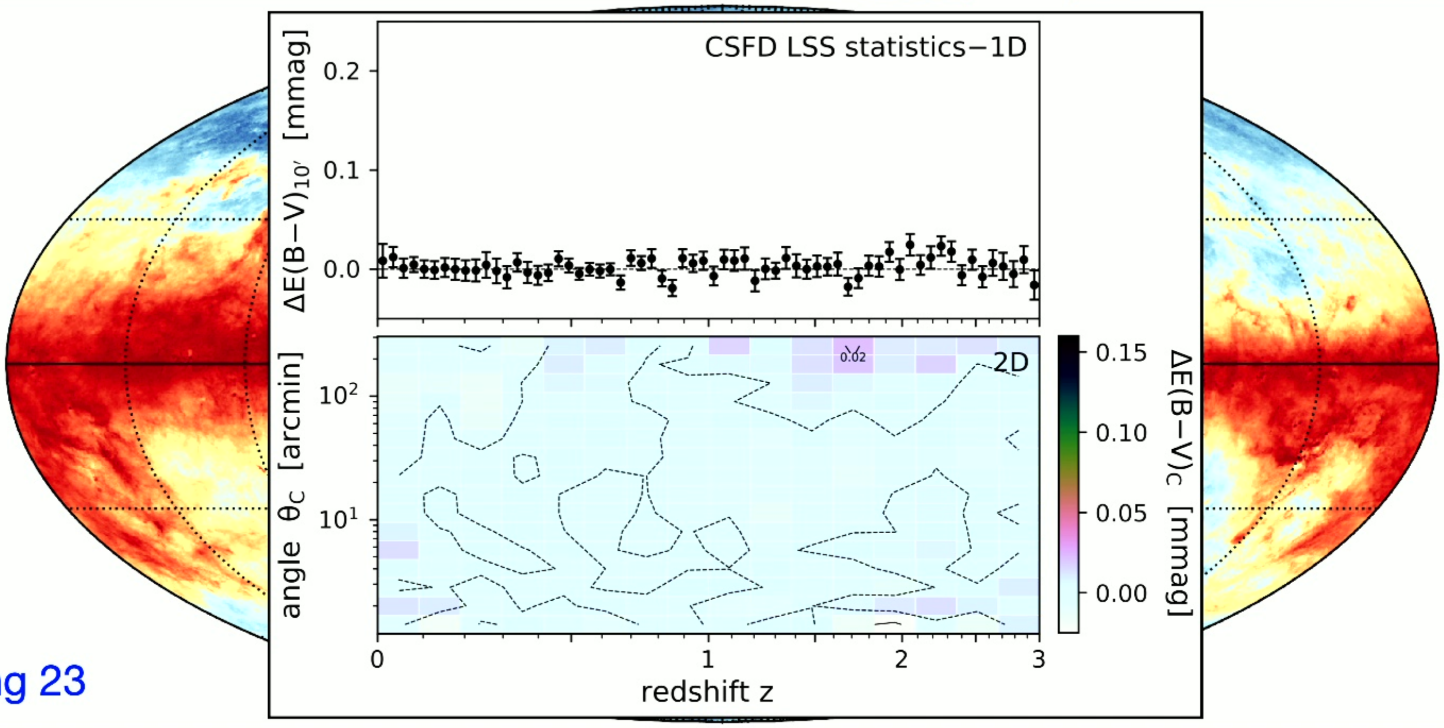
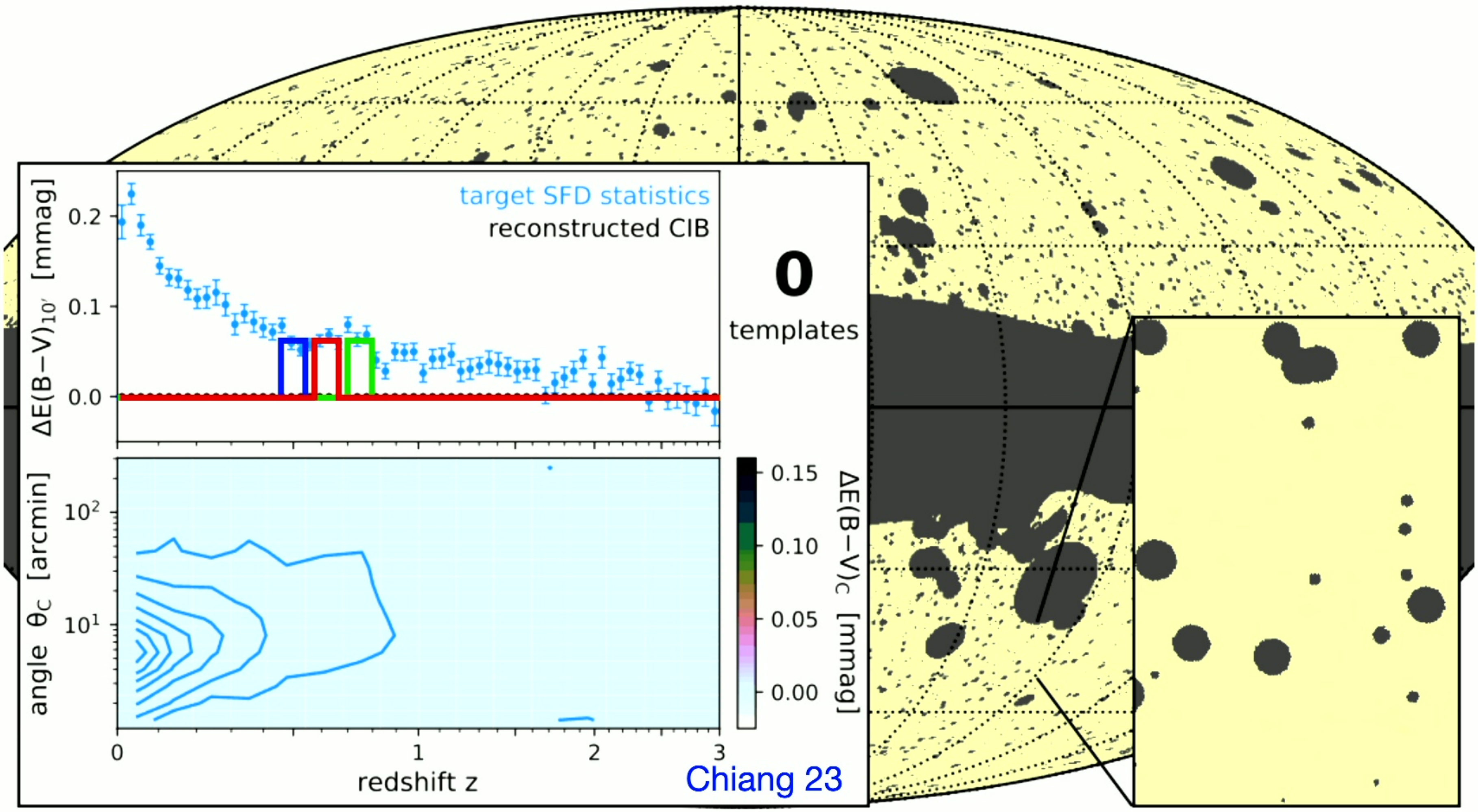


Chiang 23

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

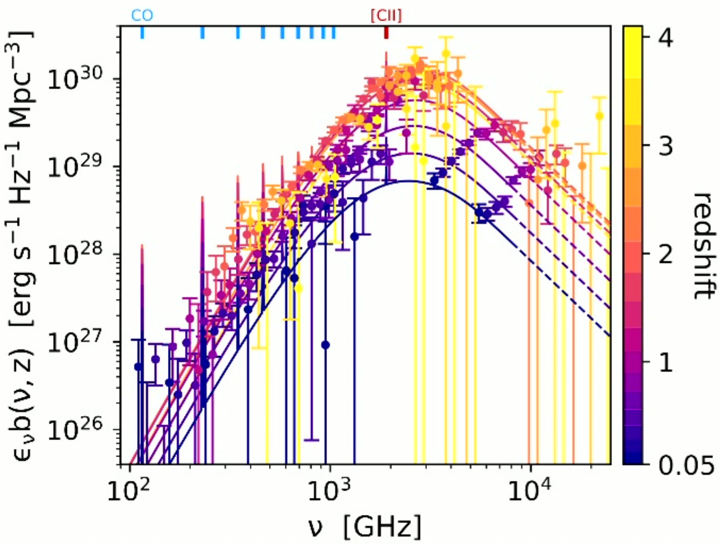


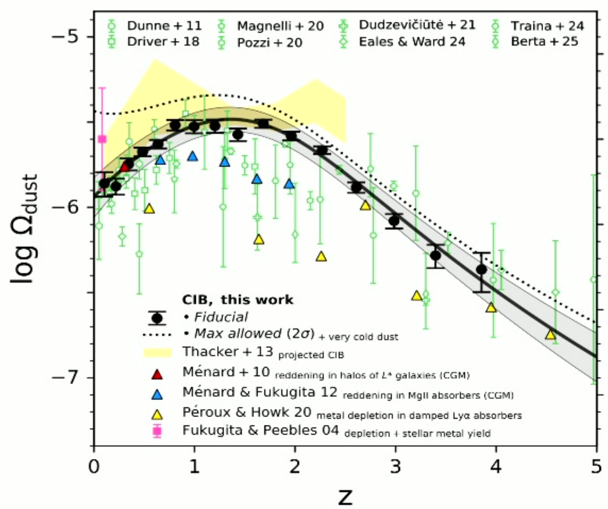
Takeaways

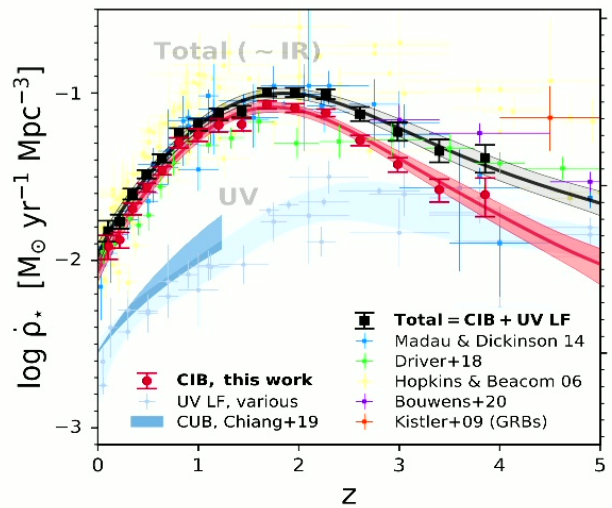
- 11 band CIB tomography, 50x frequency, $0 < z < 4$
- SED requires scatter in T and β (MBB not enough)
- Census of Ω_{dust}, star-formation history to 0.04 dex

} Legacy products for CMB & galaxy formation science

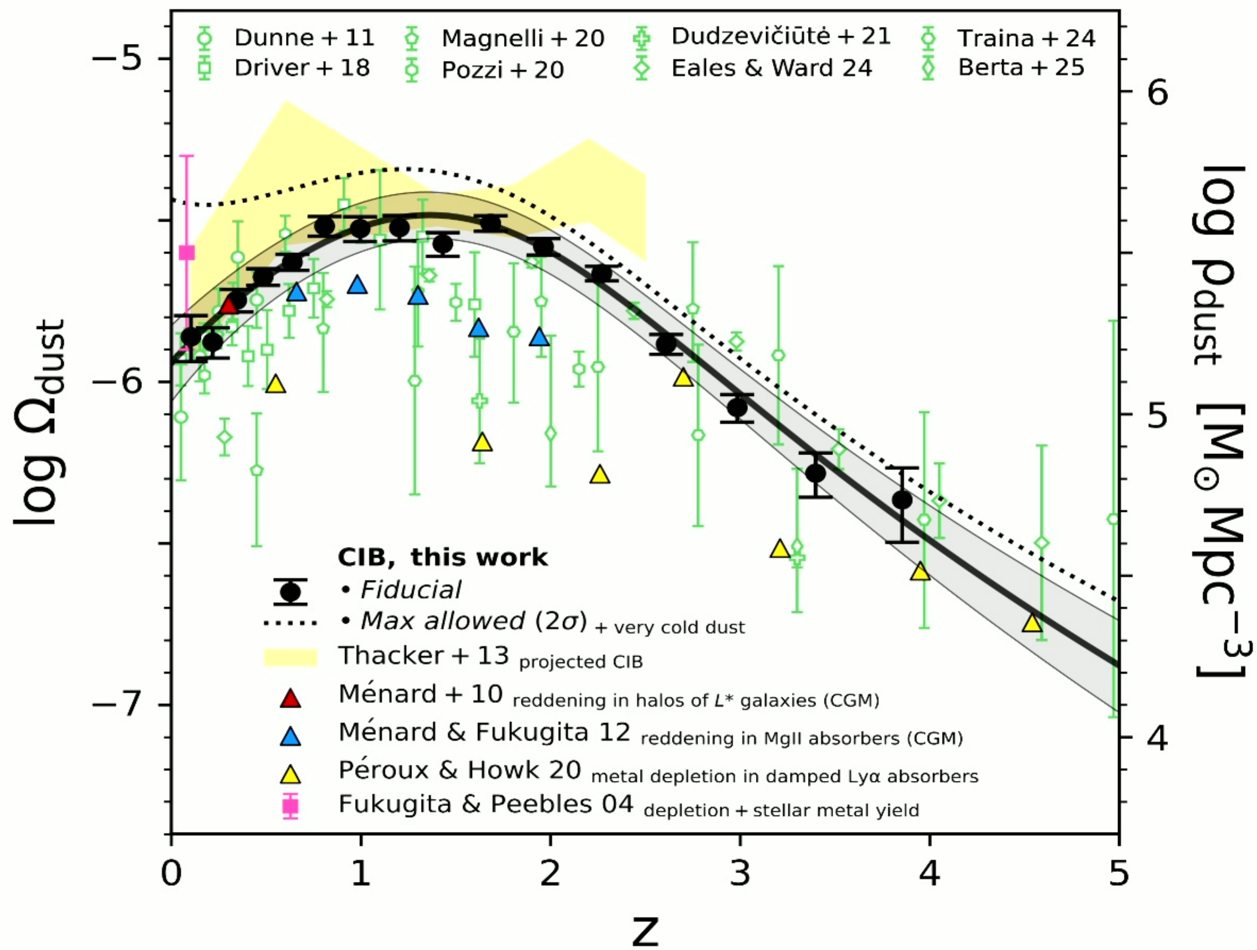
- CSFD: new CIB-free dust map for extinction correction & intensity foreground







Census of cosmic dust in all environments



Upper envelope of galaxy surveys

Dust gets destructed at low z

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