Seeing the trees through the forest: star formation history with CIB cross-correlations

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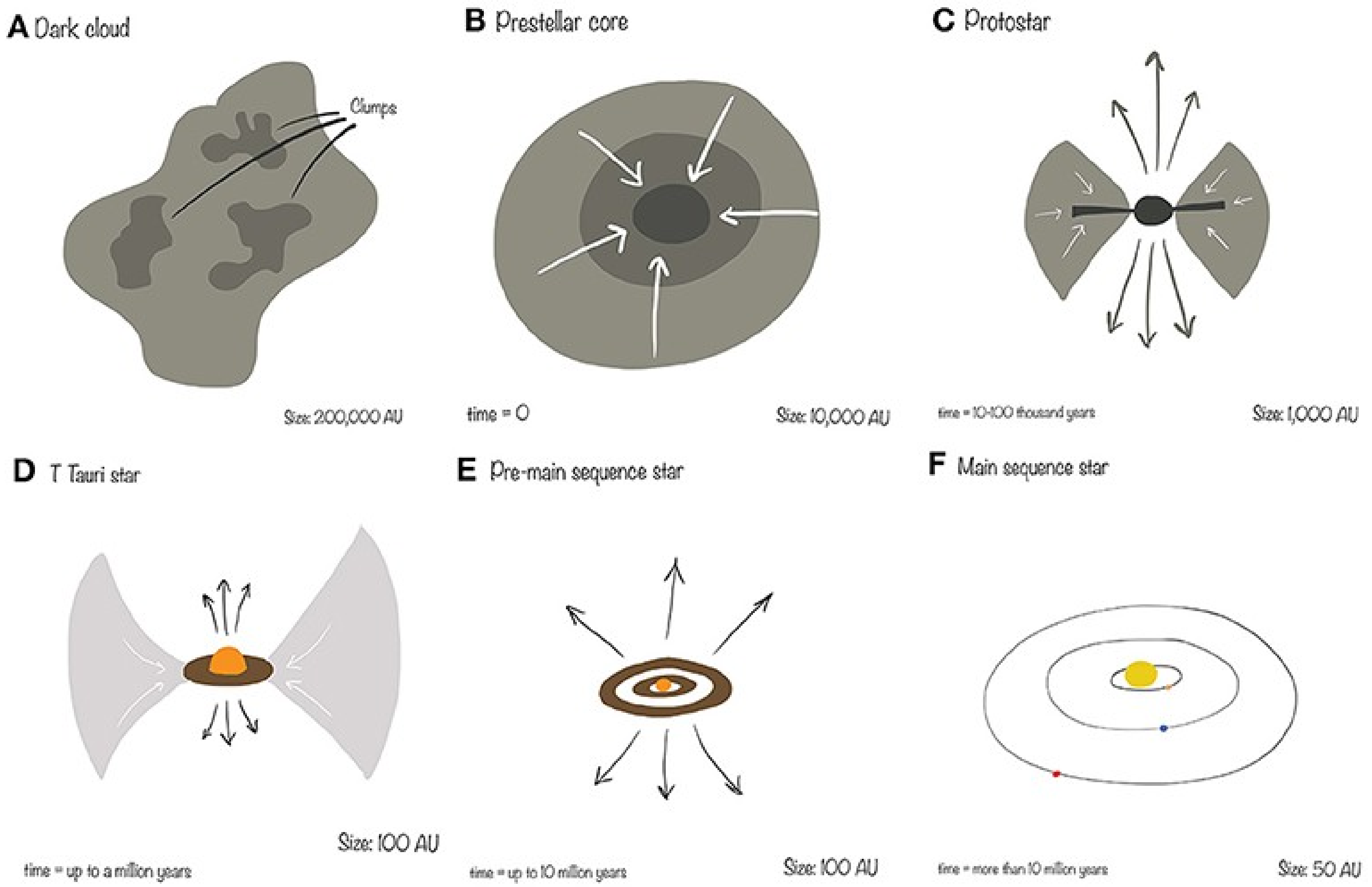
Background: star formation

How do stars form?



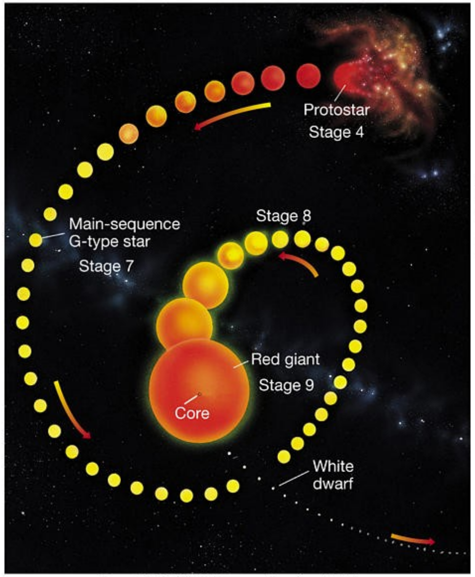
https://kids.frontiersin.org/articles/10.3389/frym.2019.00092

What can we learn from star formation?

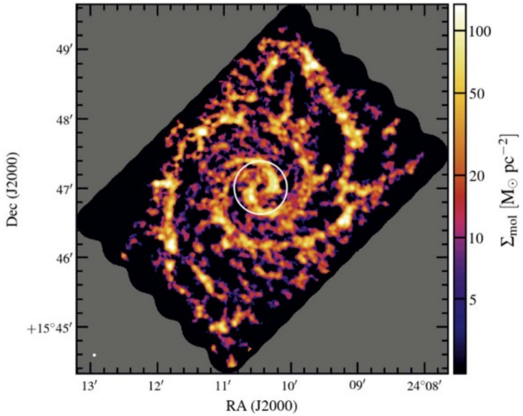
Star and galaxy scales:

Galaxy evolution

stellar evolution



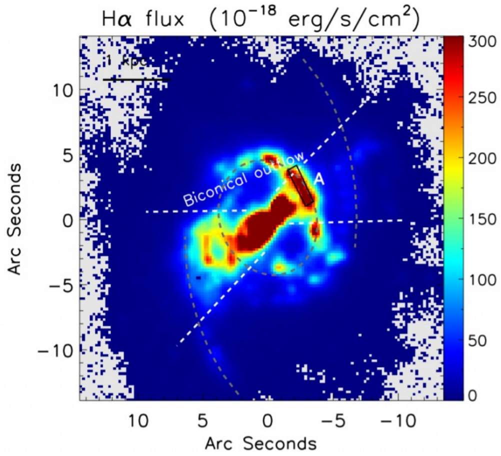
Molecular clouds



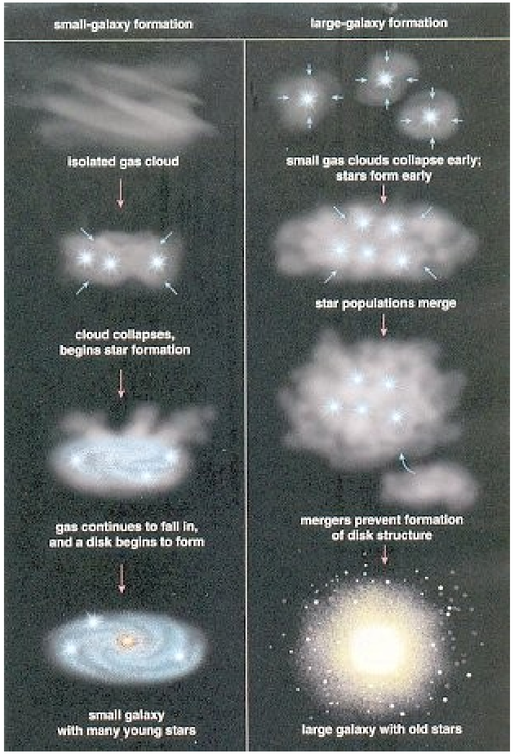
(1a) NGC 628 at 120 pc resolution

(Sun et al. 2020)

AGN, SN feedback



(Shin et al. 2019)

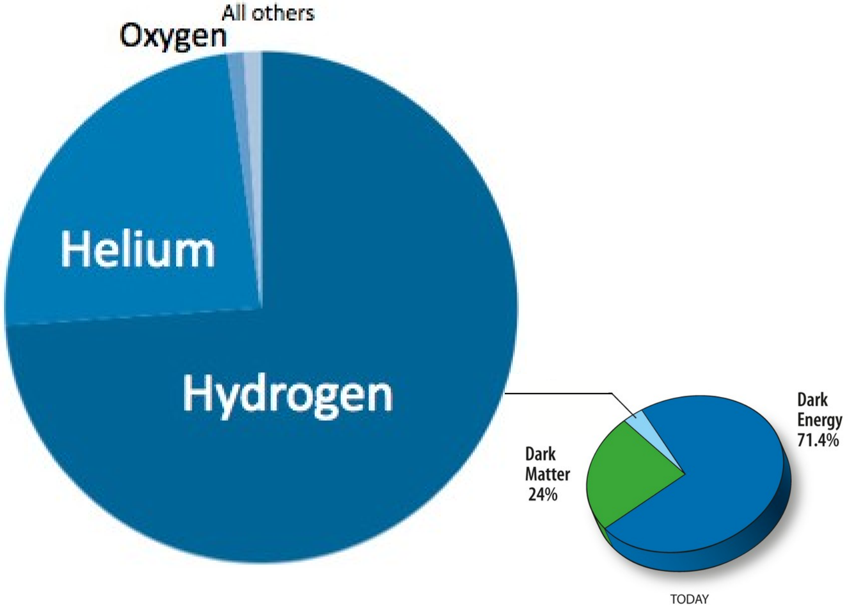


(https://universe-review.ca/F05-galaxy.htm)

What can we learn from star formation?

Cosmic scales:

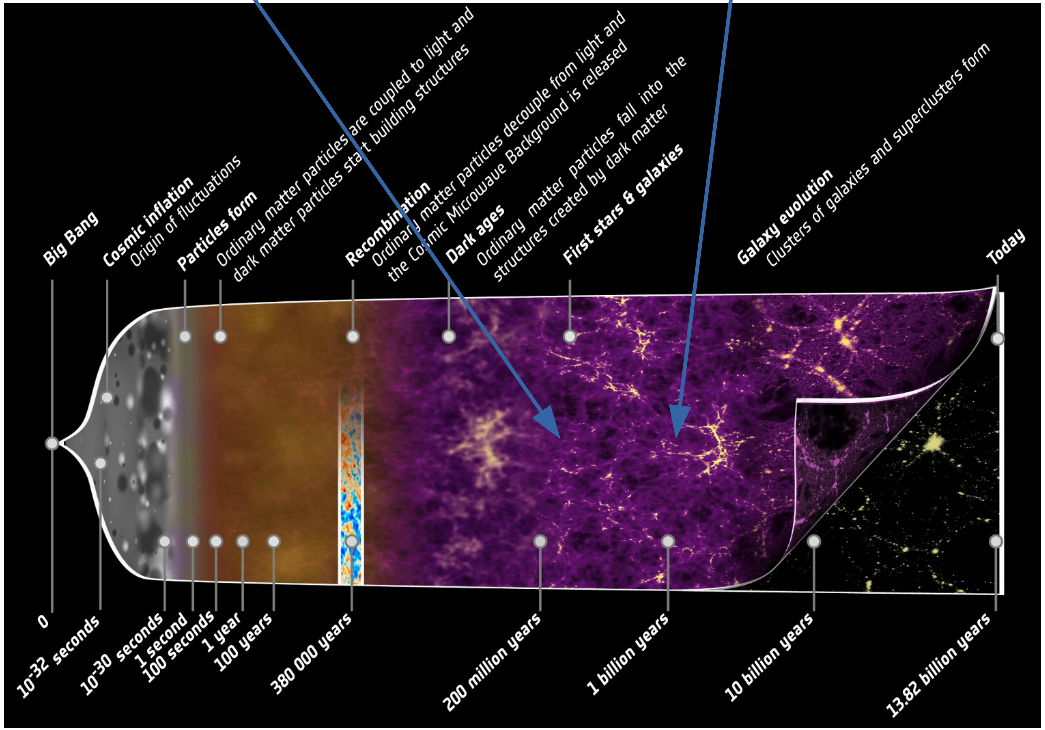
Abundance of elements



https://thespaceplaceforspace.weebly.com/relative-abundance-of-elements.html

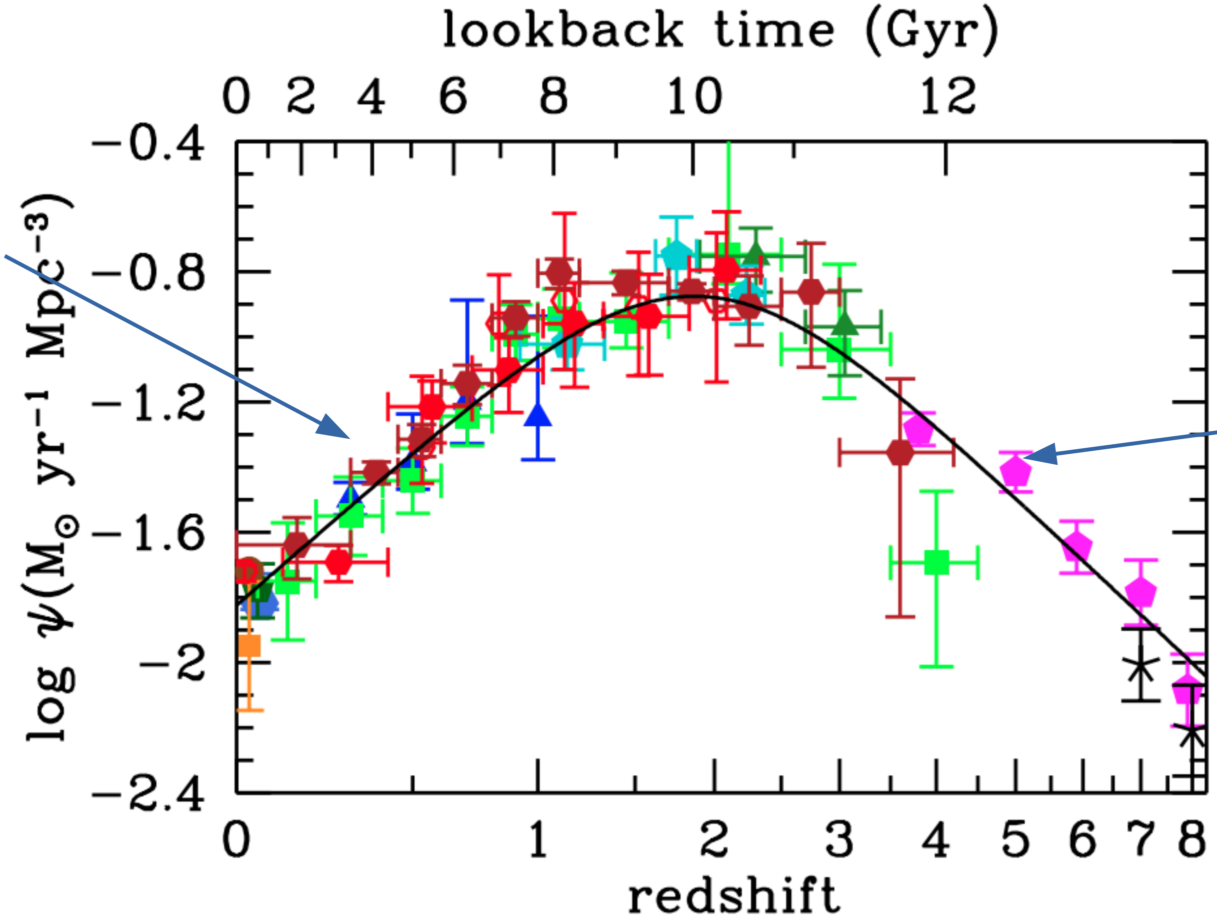
Reionization

structure formation



Cosmic star formation history: an overview

Gas running out
(quenching)



Reionization,
gas contraction,
Galaxy formation

(Madau & Dickinson 2014)

From light to SFR: multi-wavelength studies

Galaxy flux:
UV: from short-lived massive stars in star-forming active galaxies

IR: thermal radiation from interstellar dust heated up by absorbing UV emission

→ Galaxy luminosity → Star formation rate (SFR)

distance

Initial mass function (IMF); Kennicutt relation (Kennicutt, 1998):

$$\mathrm{SFR} = K_{\mathrm{B}} L_{\mathrm{B}}$$

Other tracers: emission lines, radio emission, X-rays.

From light to SFR: multi-wavelength studies

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UV: from short-lived massive stars in star-forming active galaxies

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→ distance →

Galaxy luminosity

→ Initial mass function (IMF); Kennicutt relation (Kennicutt, 1998):

$$\mathrm{SFR} = K_{\mathrm{B}} L_{\mathrm{B}}$$

→ Star formation rate (SFR)

Other tracers: emission lines, radio emission, X-rays.

Potential limitation: selection bias? Incompleteness?

Background: the cosmic infrared background

Infrared emission from star-forming regions

- Dust is heated up by new stars to a temperature of ~30 K, and emits infrared emission

Intense star formation in the Westerhout 43 region.
Credit: ESA/Herschel/PACS, SPIRE/Hi-GAL Project.

The Cosmic Infrared Background

- What is the CIB?

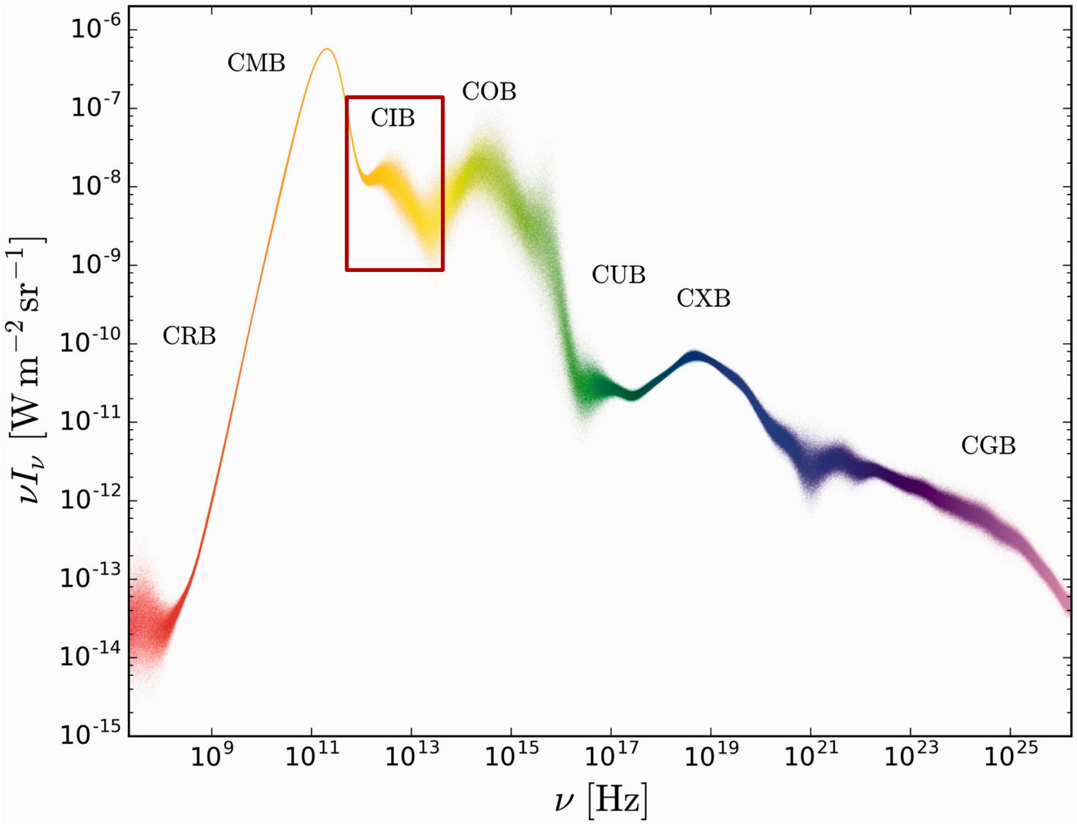
  the cumulative infrared emission from all galaxies throughout cosmic history, first detected by COBE (Dwek et al. 1998)

- What generates the CIB?

  The CIB is mainly generated by dust thermal emission from star-forming galaxies (e.g., Le Floc'h et al. 2005; Lagache et al. 2005; Viero et al.2009)

- What can we learn from the CIB?

  Dust thermodynamics, star forming history, galaxy distribution…



Spectrum of cosmic backgrounds (Hill et al. 2018)

The infrared sky is dominated by the Milky Way

2000 May 17

The Far Infrared Sky

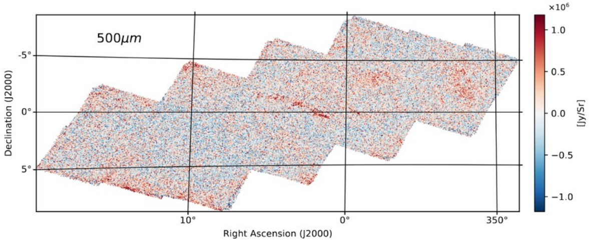
The infrared sky seen by COBE
(https://apod.nasa.gov/apod/ap000517.html)

How do we measure the CIB?

- **projecting IR flux** of all the galaxies detected by IR surveys (e.g *Spitzer* (Dole et al. 2006) and *Herschel* (Berta et al. 2010))

  - Clean from Galactic signal,
  - high angular resolution,
  - limited sky coverage,

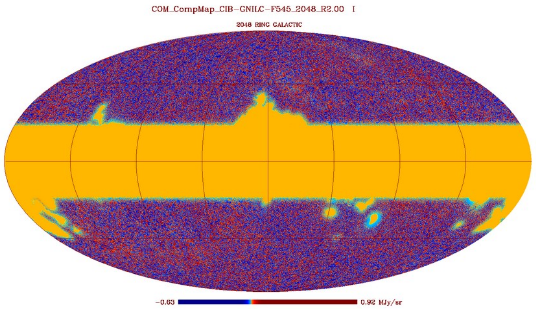
Herschel-SPIRE HeLMS maps at 500 um (Cao et al. 2020)



- **deprojecting Galactic IR signal** via internal linear composition (Planck Collaboration 2016)

  - Large sky coverage
  - Biased (Maniyar et al. 2018, Lenz et al. 2019)

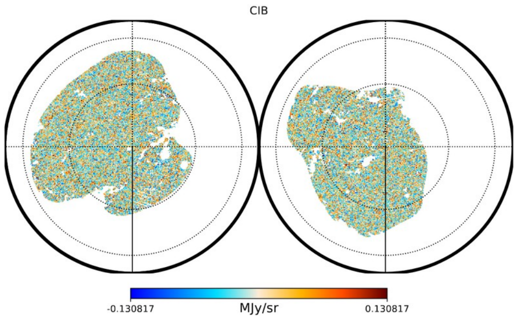
Planck GNILC CIB map at 545 GHz (IRSA/IPAC)



- **subtracting Galactic IR signal** with a template (Planck Collaboration 2014, Lenz et al. 2019)

  - Unbiased and complete
  - may contain Galactic residue
  - Limited sky coverage

CIB map at 545 GHz (Lenz et al. 2019)



CIB intensity

The projected CIB intensity map is an integral of IR emissions along the line of sight:

$$I_\nu(\boldsymbol{\theta}) = \int \mathrm{d}\chi a j_{(1+z)\nu}(\chi, \boldsymbol{\theta})$$

The CIB emission coefficient is connected to SFR density and spectral energy distribution (SED) of the dust (Maniyar et al. 2018):

$$j_{(1+z)\nu}(z) = \frac{\rho_{\mathrm{SFR}}(z)(1+z)S_{\mathrm{eff}}\left[(1+z)\nu, z\right]\chi^2}{K},$$

In the context of halo model, the SFR density is the average SFR over dark matter halos:

$$\rho_{\mathrm{SFR}}(z) = \int \mathrm{d}M \frac{\mathrm{d}n}{\mathrm{d}M} \mathrm{SFR}(M, z)$$

SFR-halo mass relation

SFR modeled as baryon accretion rate (BAR) times star-forming efficiency

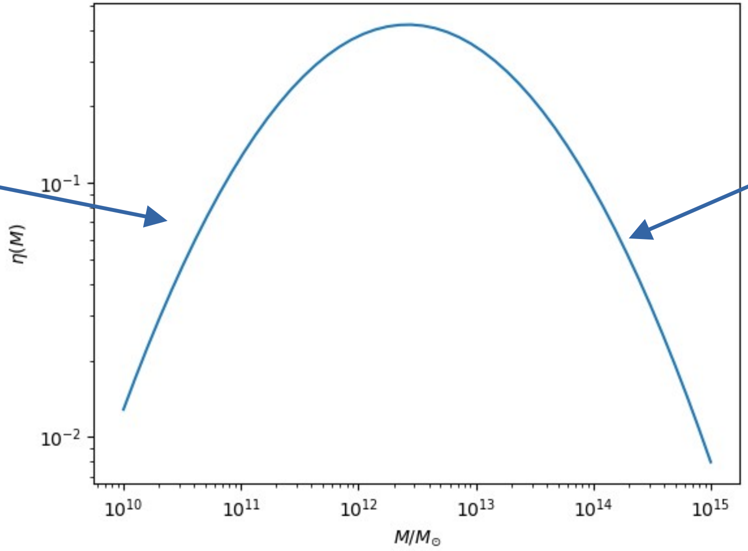
$$\mathrm{SFR}(M,z) = \mathrm{BAR}(M,z)\eta(M,z)$$

Generally speaking, η peaks at the halo mas ~ $10^{12} M_{\odot}$ (Bethemin et al. 2013)

Empirical model: lognormal (parametrized by peak SFR halo mass and width) (Maniyar, et al, 2021)

At lower mass end:

- insufficient gas to support star formation;
- supernovae feedback removes gas from the galaxy;

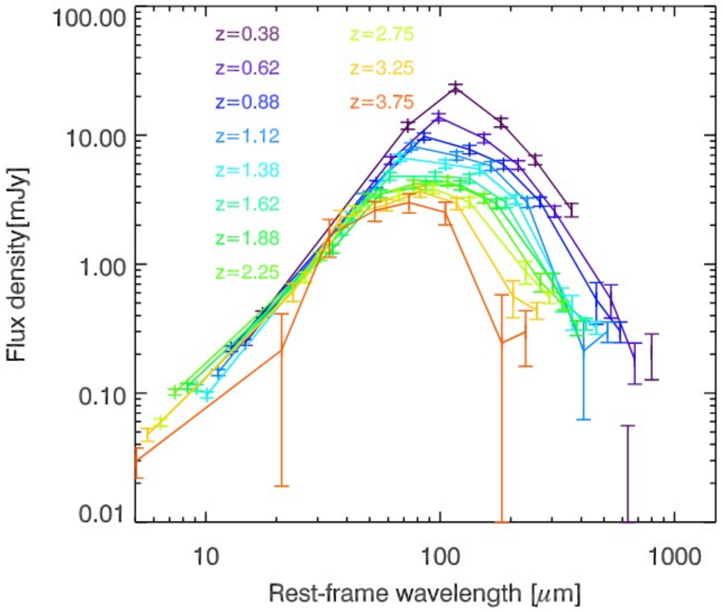


At higher mass:

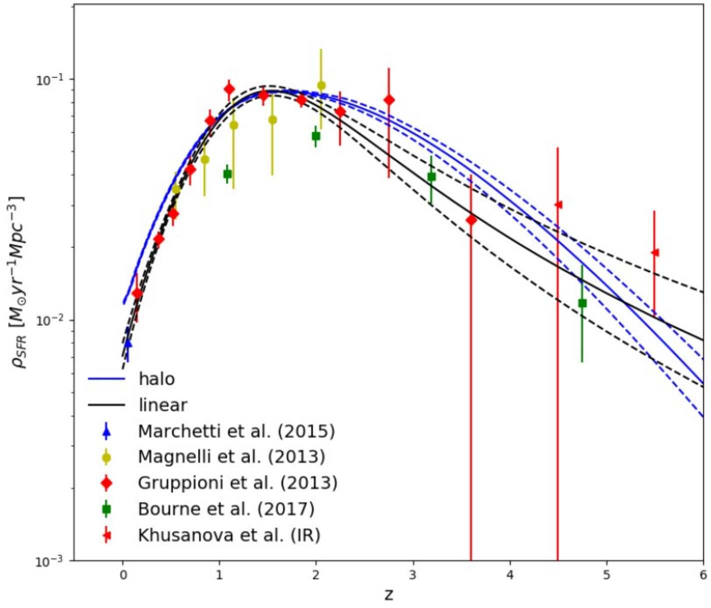
- AGN feedback;
- gas cooling time too long

Ingredients of CIB model

- Spectral energy distribution (SED)
- Star formation rate (SFR)
- IR galaxy abundance: halo occupation distribution (HOD)



The SED of CIB from flux stacking (Bethermin et al. 2015)

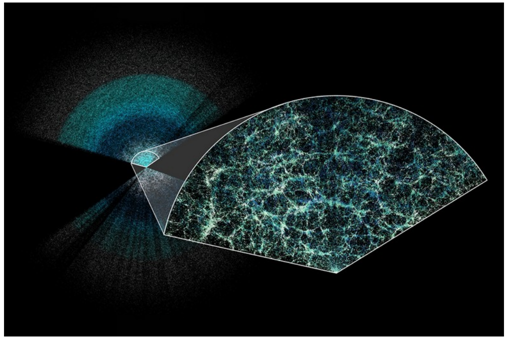


Star formation rate history from CIB power spectra (Maniyar et al. 2021)

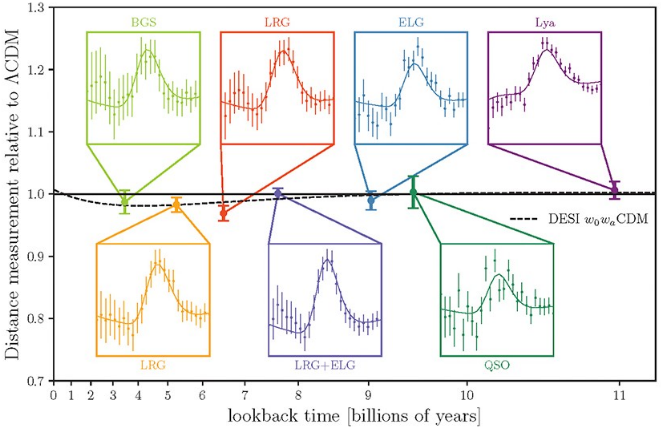
Cosmic star formation history from KiDS x CIB cross-correlations

Arxiv: 2204.01649

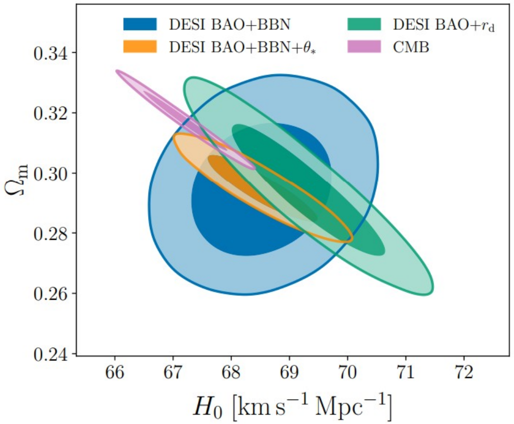
Seeing the trees through the forest: star formation with CIB cross-correlations



The LSS of our Universe measured by DESI(Claire Lamman/DESI collaboration)



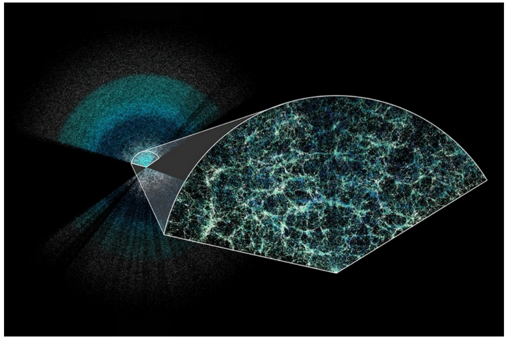
The **LSS statistics (correlation function)** of DESI galaxies (Credit: Arnaud de Mattia/DESI collaboration)



Cosmological constraints from the LSS statistics (DESI collaboration)

Cosmologists use **large-scale structure statistics** to study the Universe as a whole.

Seeing the trees through the forest: star formation with CIB cross-correlations



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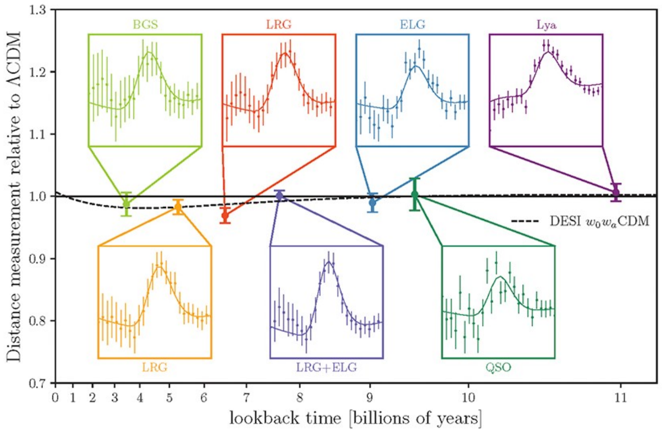

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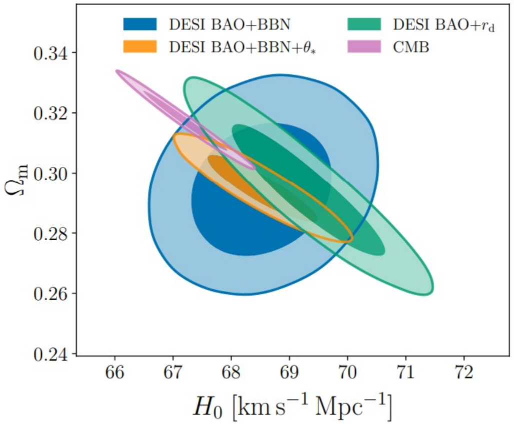


Cosmological constraints from the LSS statistics (DESI collaboration)

Cosmologists use **large-scale structure statistics** to study the Universe as a whole.

Can we use LSS statistics to study small scale physics, like star formation?

Tomographic CIB-galaxy cross-correlations

- Angular power spectra describes the **correlation amplitudes** on different angular scales.

$$C_\ell^{ab} = \frac{1}{2\ell+1}\sum_m a_{\ell m} b^*_{\ell m}$$

- Existing works:

  - CIB power spectra (Planck2013 XXX);

  - CIB x CMB lensing (Cao et al. 2020);

  - CIB x tSZ (Planck2015 XXIII)

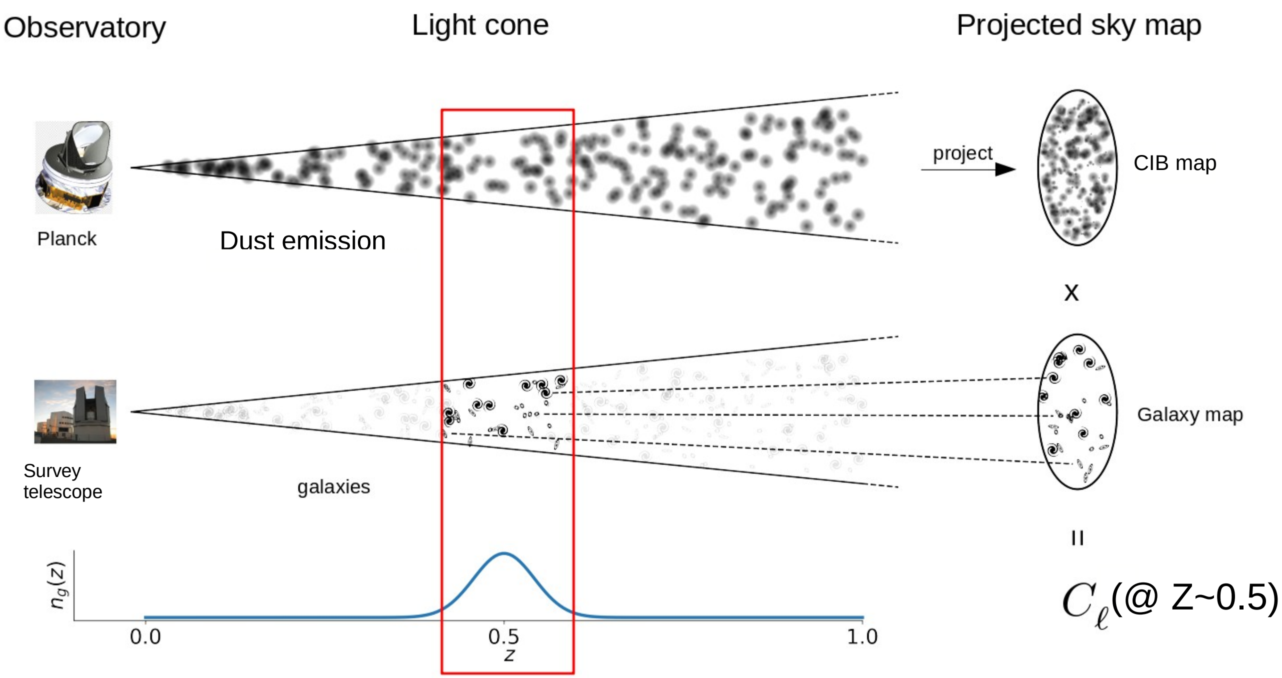
- Advantages of CIB x galaxy:

  - galaxy position is relatively easier to measure

  - higher S/N

  - tracing SFR history better (through **tomographic CC**)

  - obtaining CC for different types of galaxies



CIB data

- CIB map (Lenz et al. 2019):

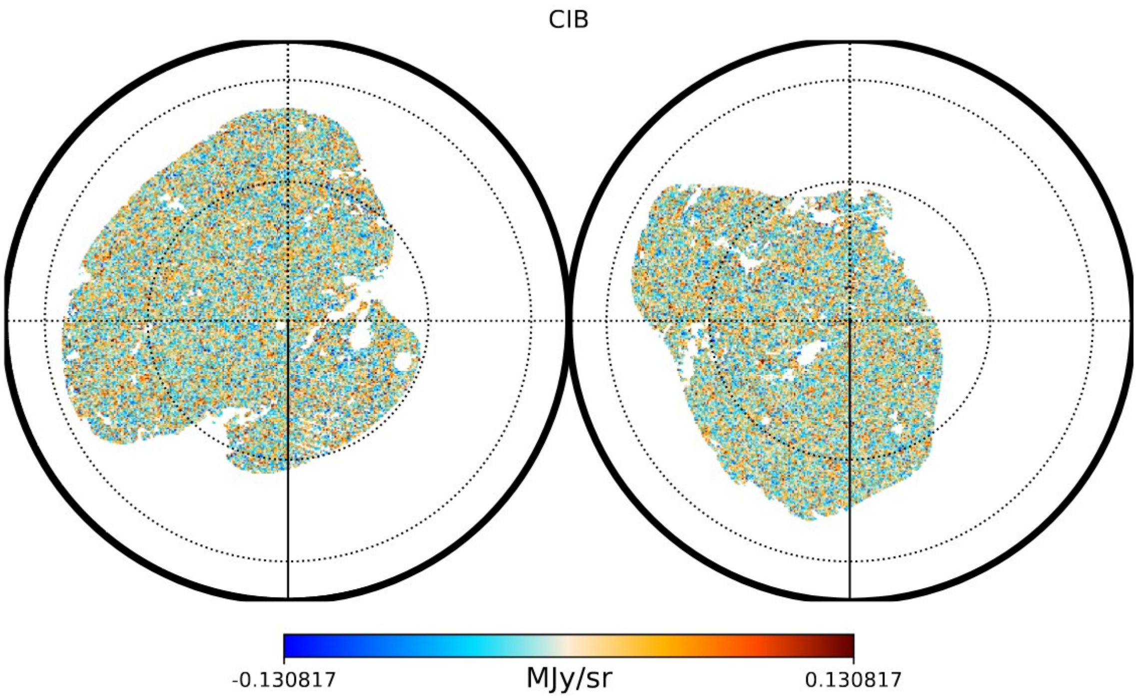
  - constructed from **Planck HFI sky maps**;

  - Galactic signal are removed with an HI template (threshold HI column density = 2.0e20 cm^-2)

  - CIB intensity maps in **353, 545, 857 GHz**

  - angular resolution: 5 arcmin

  - sky coverage **~25%**

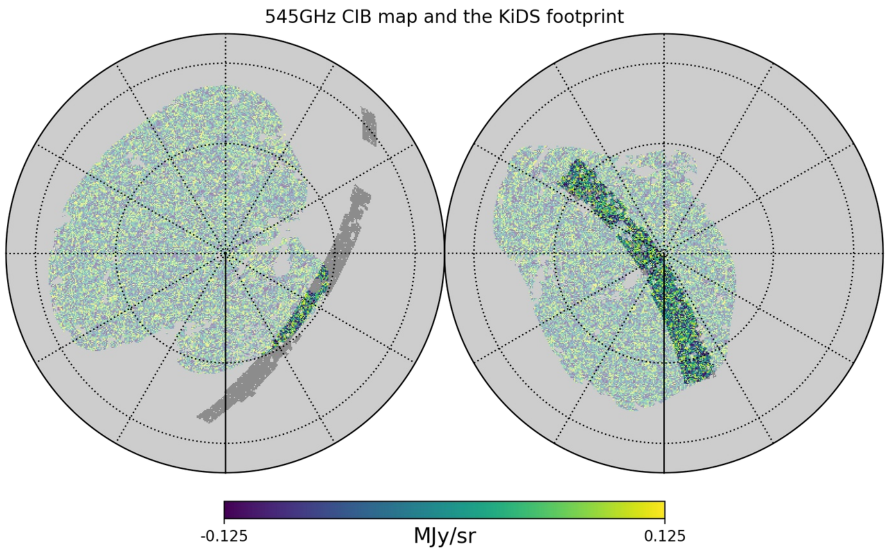


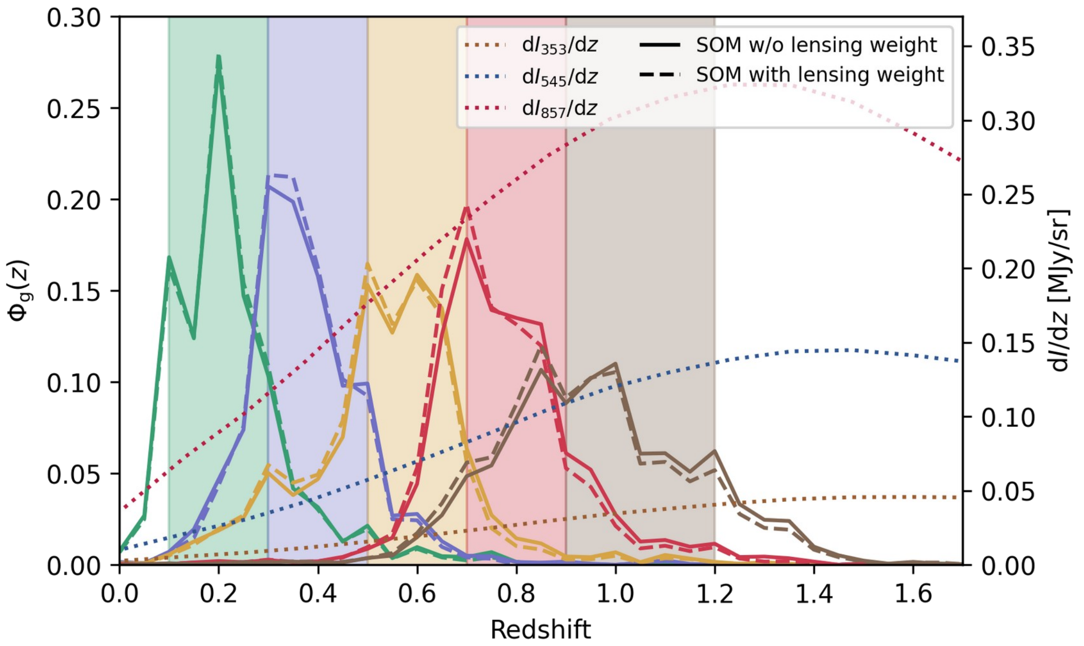
Galaxy data: KiDS gold sample

- Sky coverage: 1006 deg^2 (~2.2%, overlapped **~1.4%**) (Kuijken et al. 2019)

- 5 tomographic bins, redshift extending to **1.5** (Wright et al. 2020)

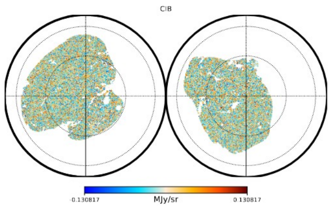
- ~~shape measured and calibrated for weak lensing cosmology~~ (Heymans et al. 2021)





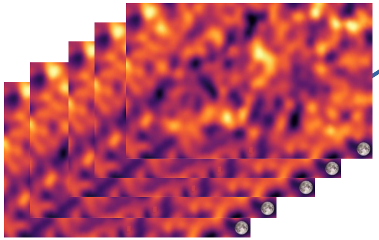
Analysis pipeline

CIB maps (x3)



$\times$

galaxy maps (x5)



Masks, beams, pixel window function are corrected

$C_\ell^{g\nu}$

Systematics correction

(+ external SFRD measurements from multiwavelength surveys)

Covariance matrices

$p(\boldsymbol{D}|\boldsymbol{M})$

Model (SED fixed)

MCMC

SFR parameters,
HOD parameters,
Shot noise amplitudes

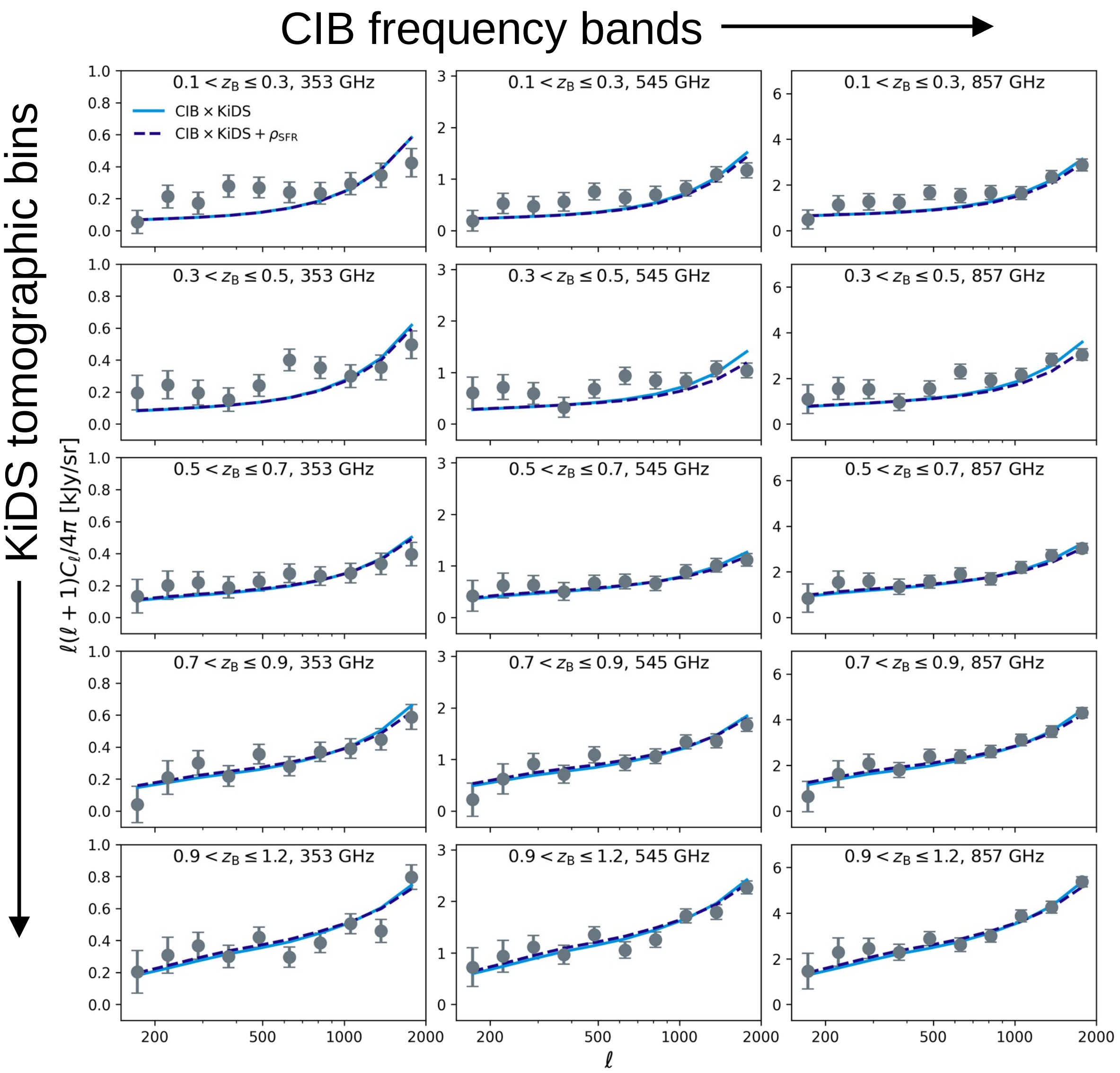
KiDS-CIB cross-correlation measurements

- Tools:
  Measurement: NaMaster (Alonso et al., 2019)
  Analysis: PYCCL (Chisari et al., 2018);

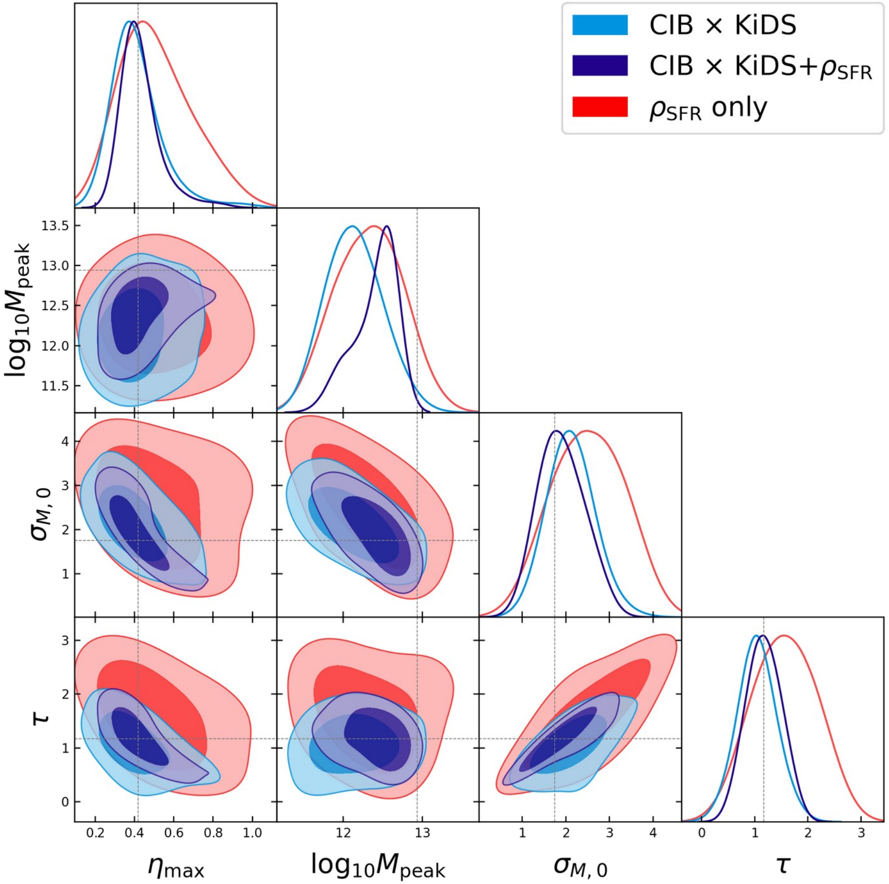
- beam and mode coupling corrected;

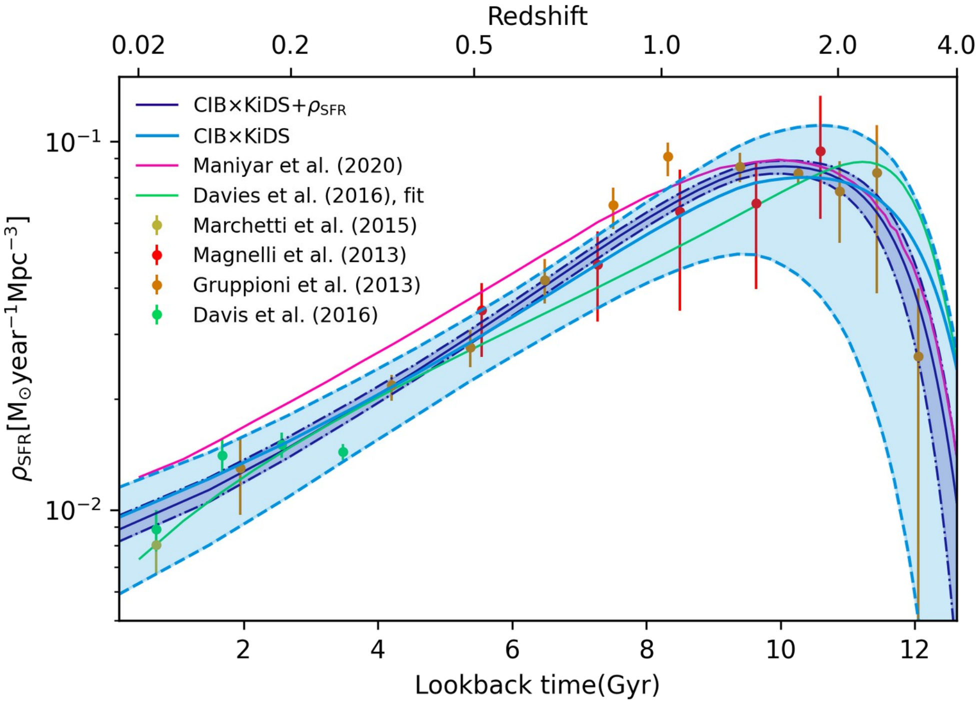
- logarithmic ℓ bin from 100 to 2000

- signal-to-noise: **43**



Constrain the SFR with KiDS x CIB



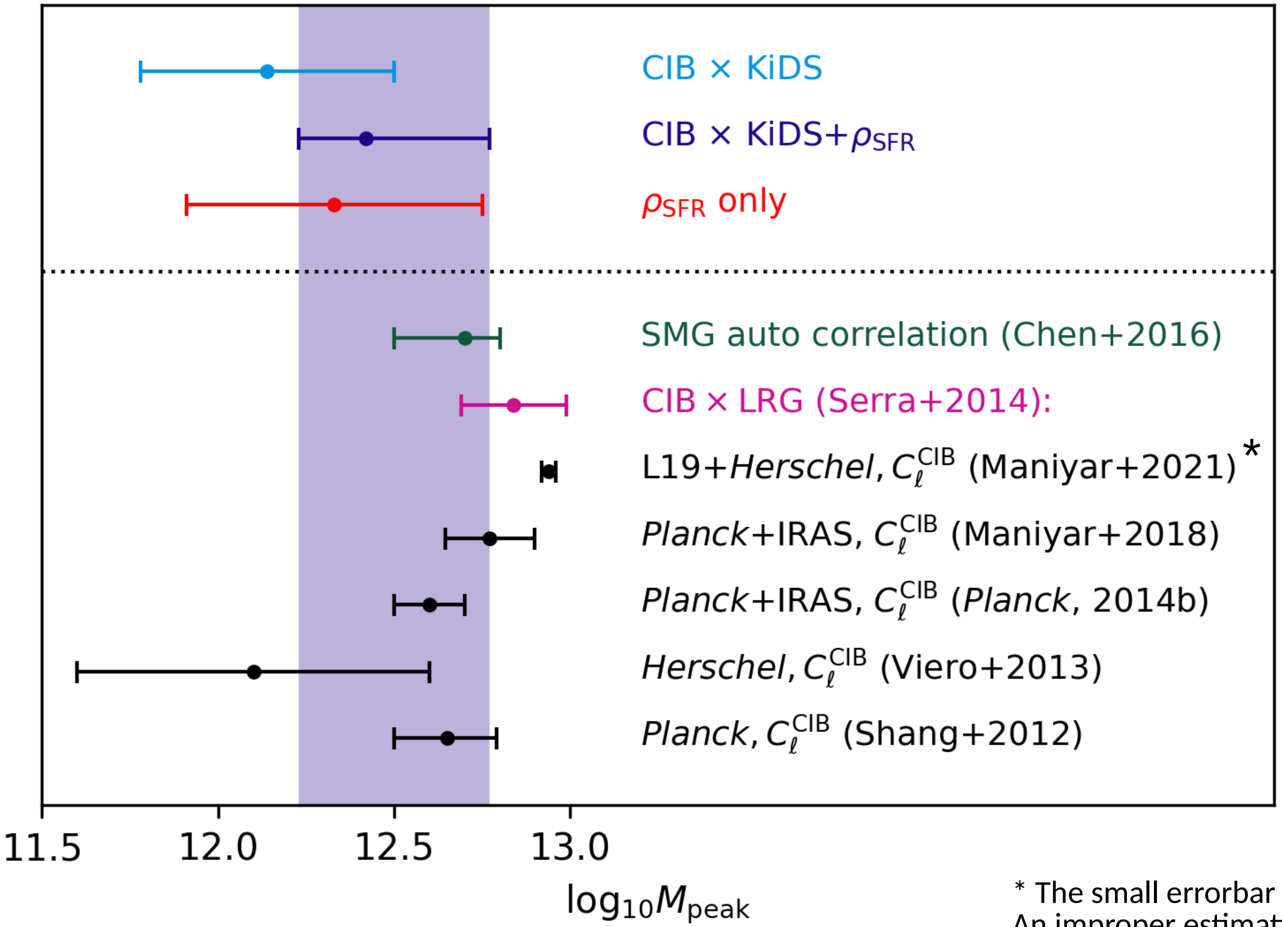


- Most of the parameters are **constrained**

- Three datasets give **consistent** constraints

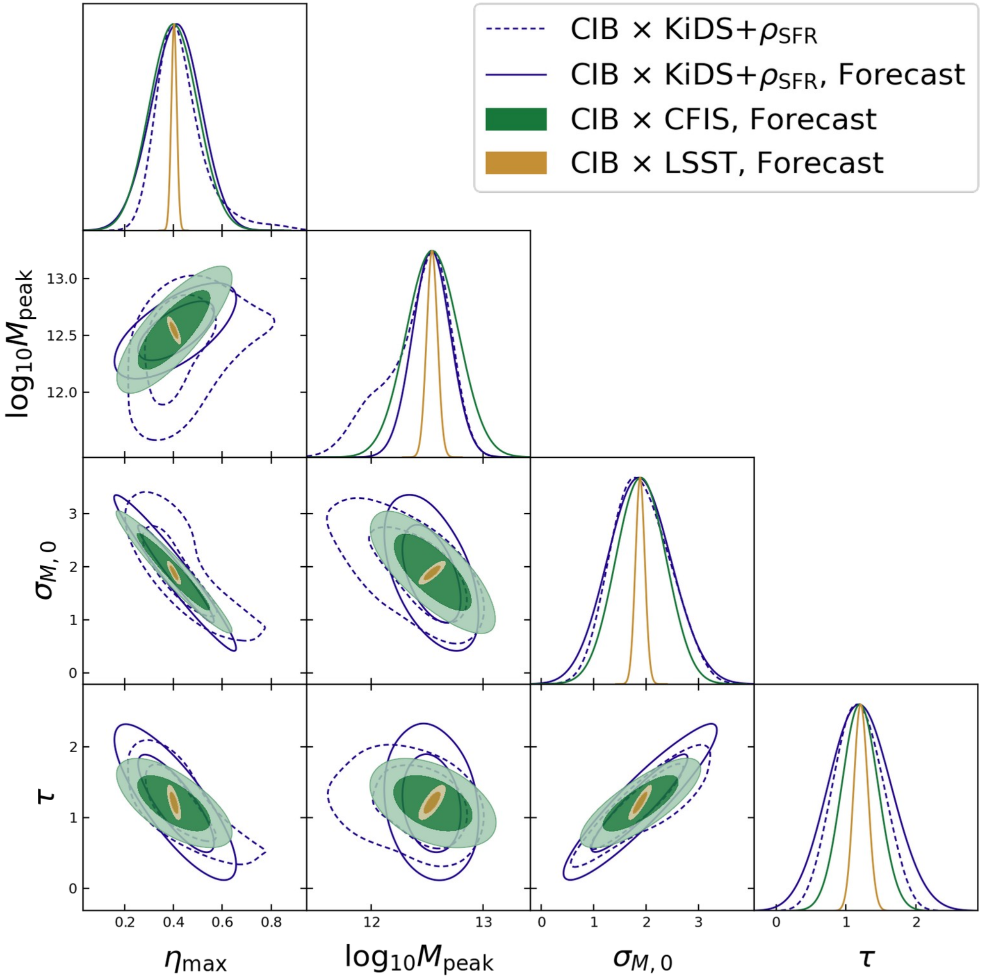
- The constraints **agree** with multi-wavelength measurements

Constraints of most-efficient halo mass



* The small errorbar of this constraint is due to
An improper estimation of the covariance matrix

Forecast for future surveys



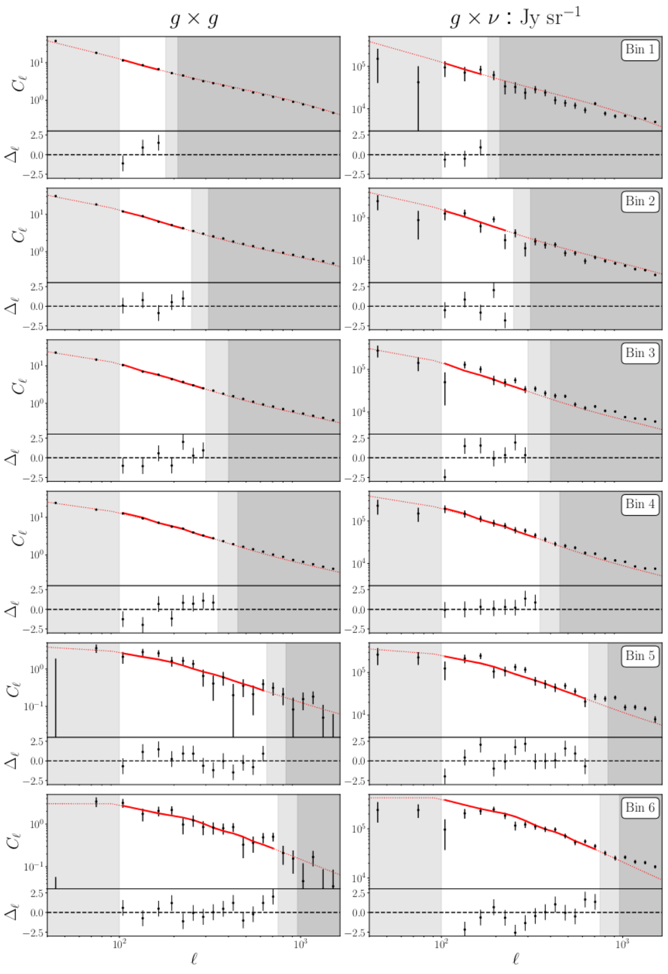
CFIS: Canada-France Imaging Survey
- sky coverage: 3500 deg^2;
- redshift range: similar as KiDS

LSST:
- sky coverage: 20000 deg^2
- redshift range: ~3

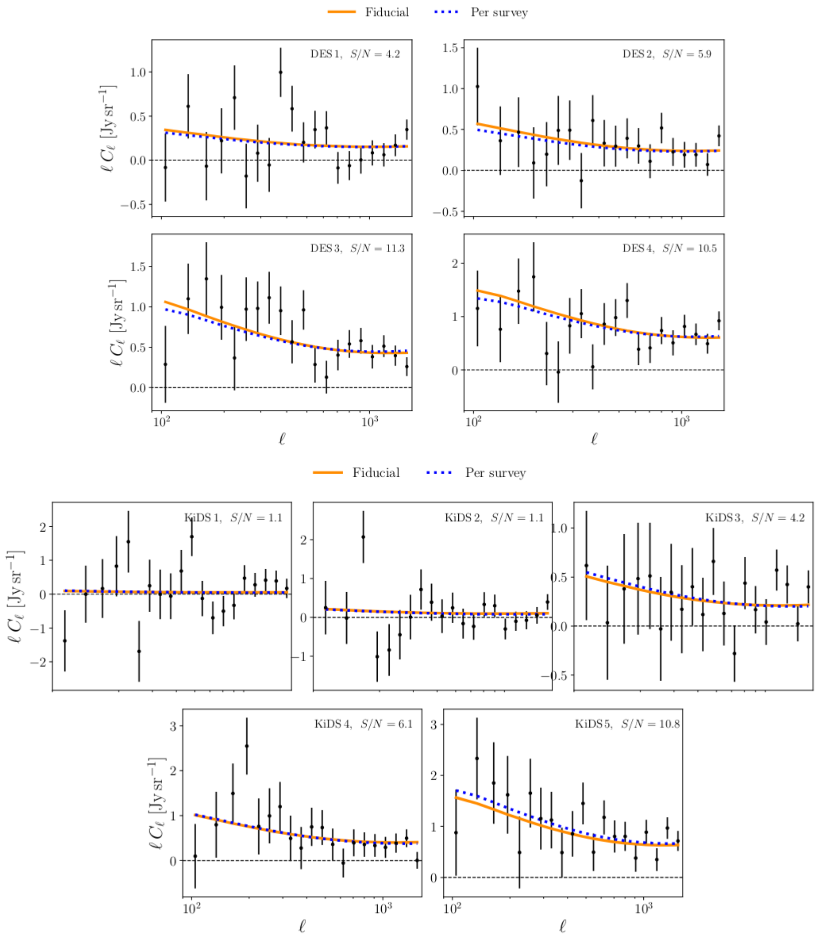
Forecast:
- CFIS can reach similar constaining power as CIB x KiDS + SFRD;
- Next generation surveys (including LSST, *Euclid*, and CSST) will improve the constraining a lot!

Other studies on CIB cross-correlations

SFR from other CIB cross-correlations

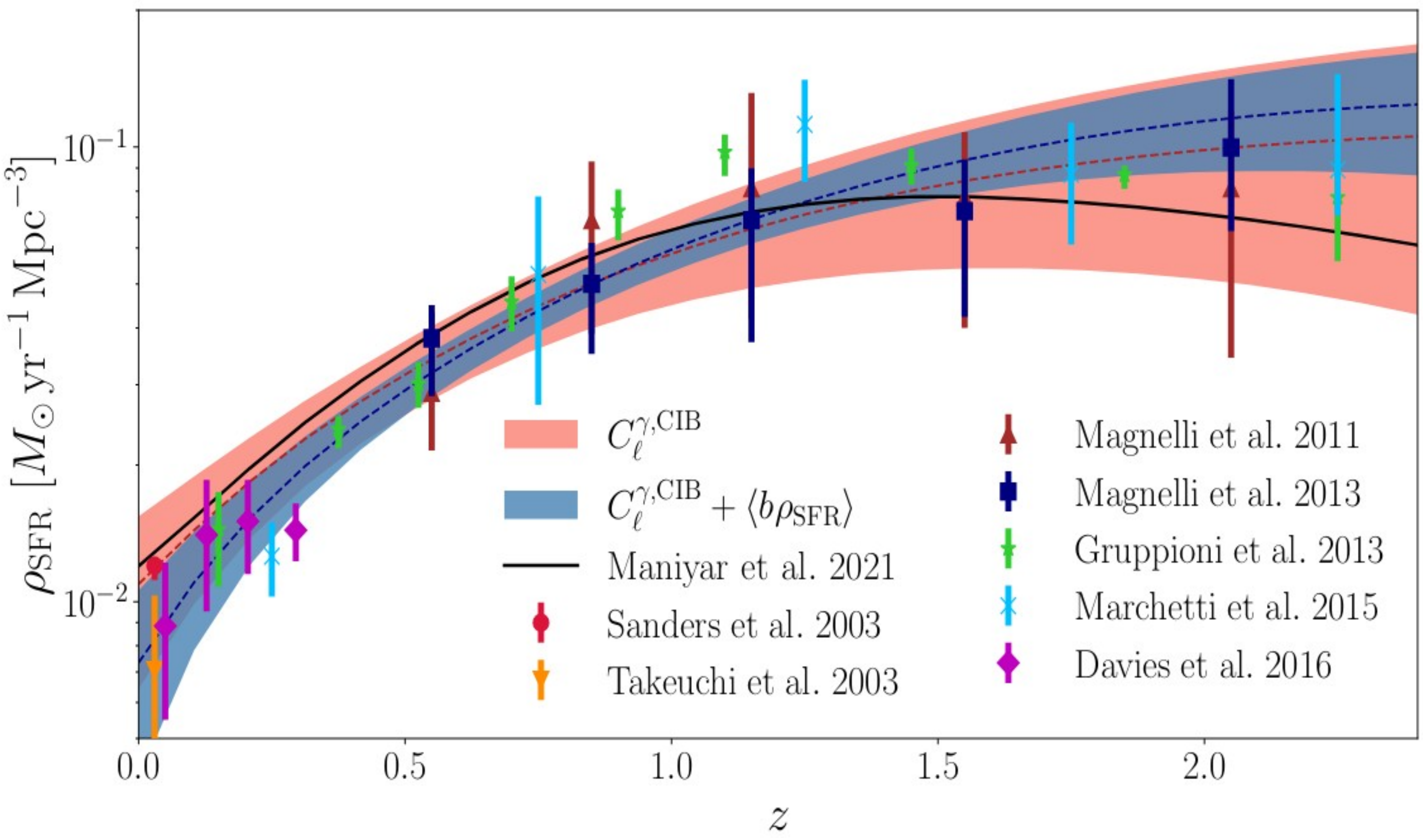


CIB x DELS, eBOSS galaxies (Jego+2022a)



CIB x shear (Jego+2022b)

SFR from other CIB cross-correlations

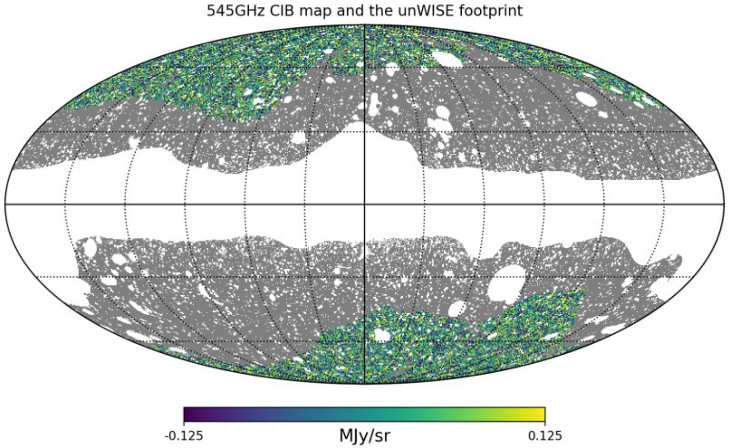


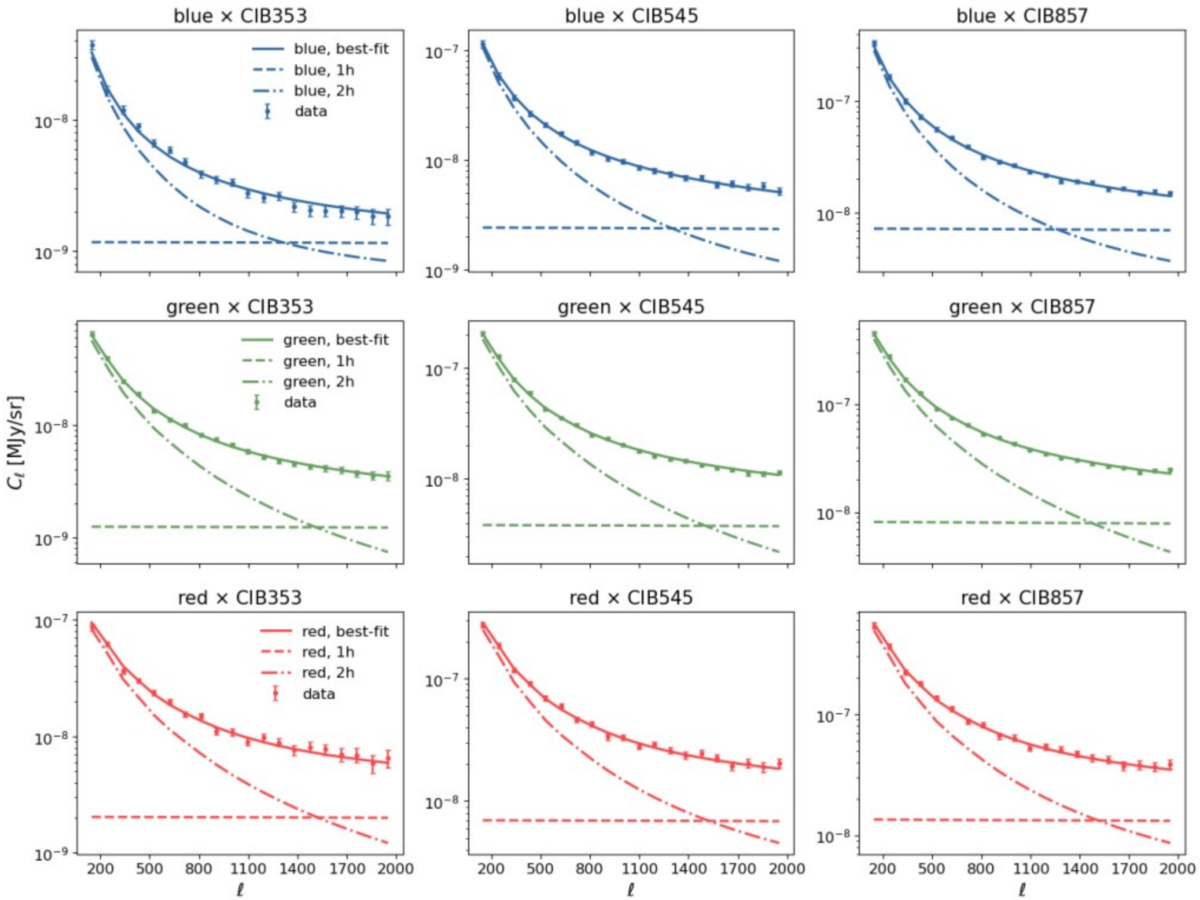
(Jego+2022b)

CIB-unWISE galaxy cross-correlation

- Galaxy sample: unWISE sample (covering **54%** of the sky), 3 tomographic bins

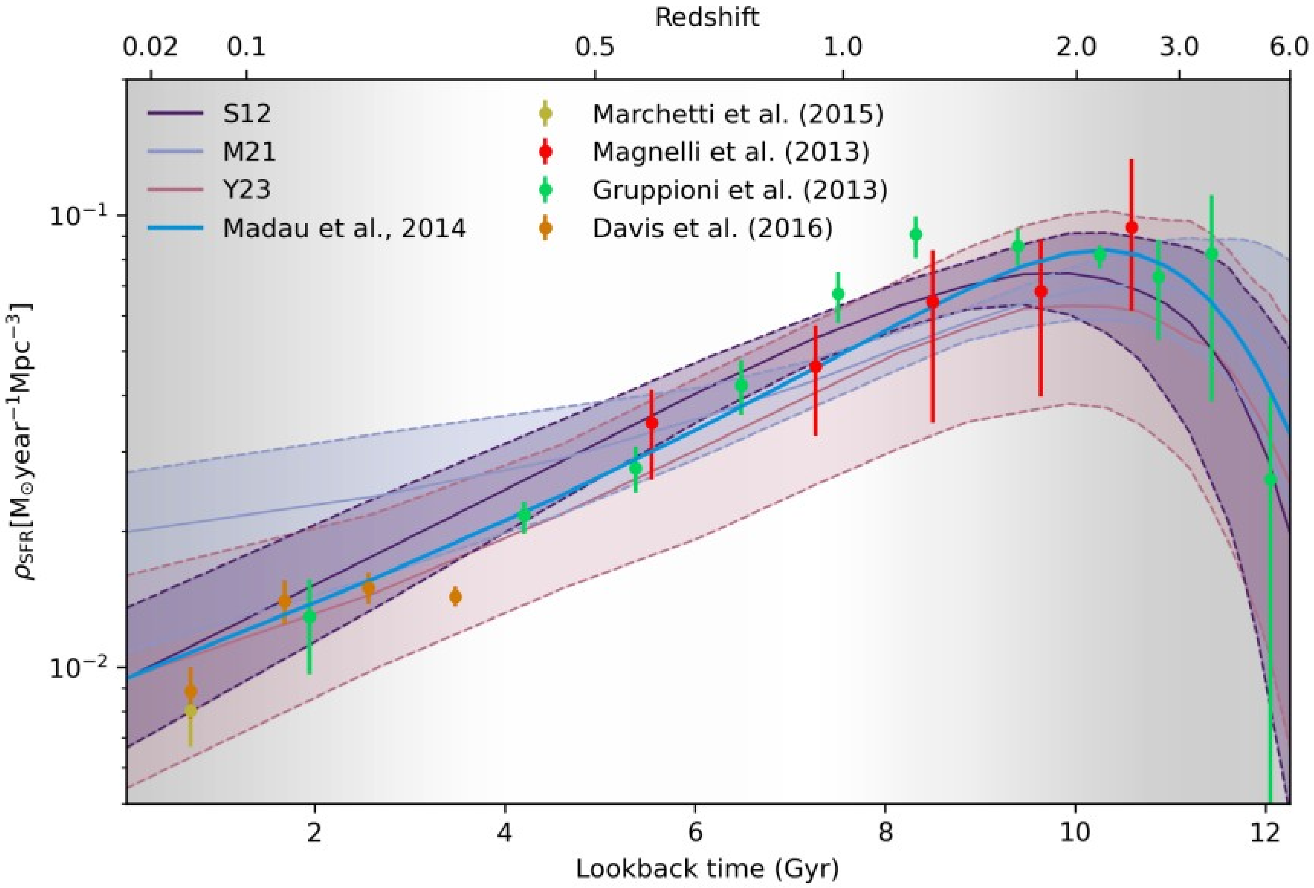
- signal-to-noise: **194**





(Yan et al., 2023, arxiv: 2310.10848)

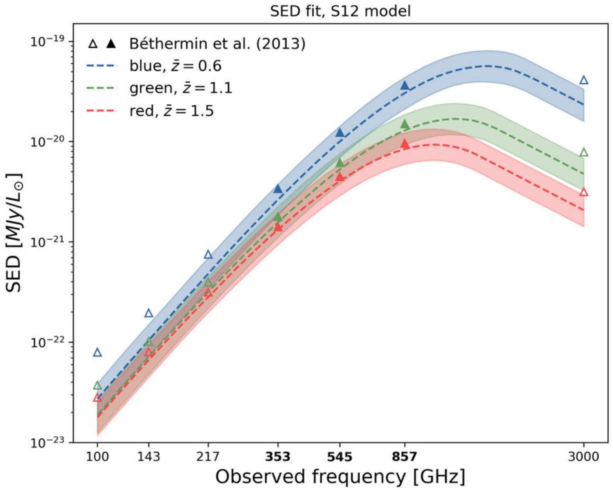
Star formation Constraints from unWISE x CIB

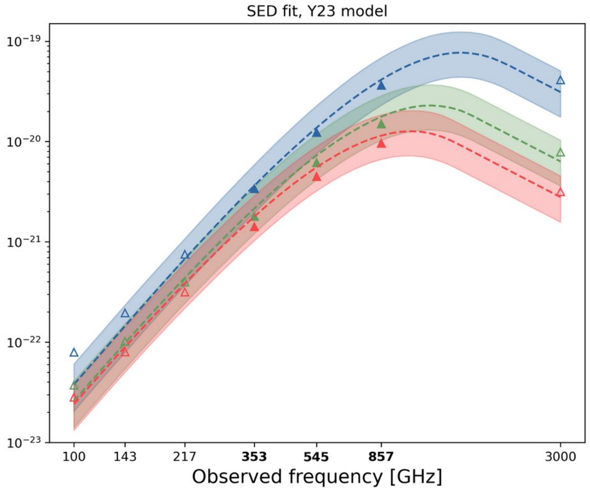


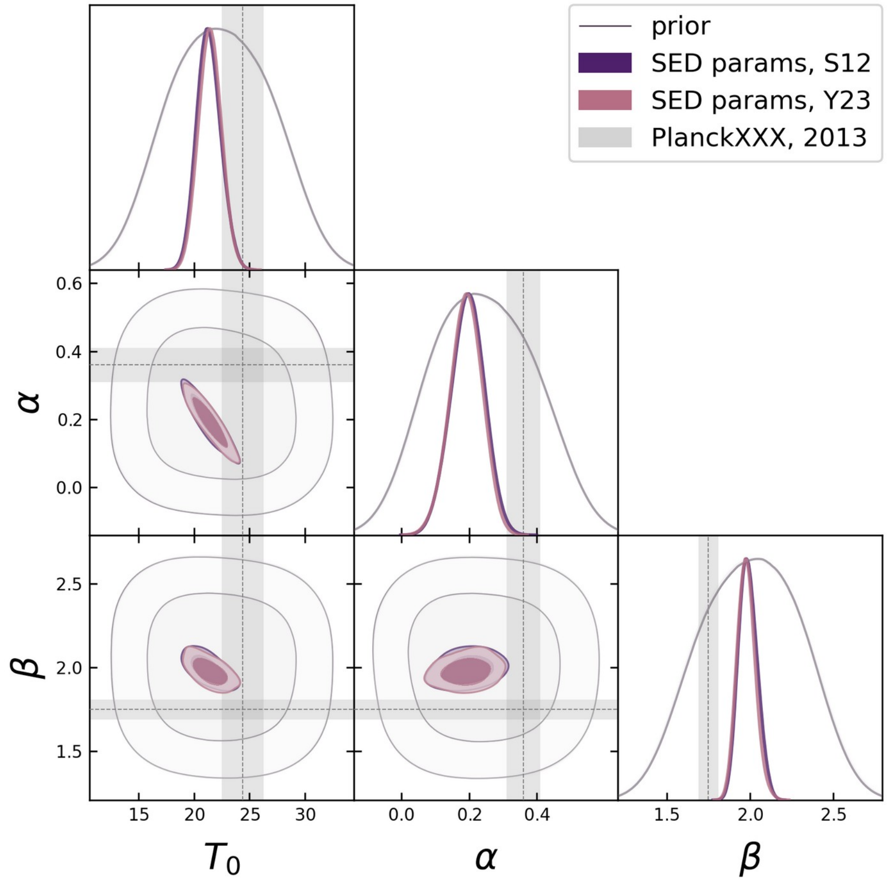
Dust SED Constraints from unWISE x CIB

SED model: **gray-body spectrum**

Dust temperature **~21K**







Conclusions and future prospects

- **We can study galaxy-scale physics by LSS statistics;**
- The CIB is **strongly correlated** with galaxy distribution;
- CIB-galaxy cross-correlation can be used to constrain cosmic star formation history and more;
- Consistencies between observations and models suggest that we are reaching a **converged picture** of IR-SFR related studies;
- Future galaxy surveys will provide more precise measurement of CIB cross-correlation, which might call for more sophisticated models (including feedback, quenching, galaxy type-dependent modeling, etc).

Thank you for listening!

Back-up slides

CIB intensity

The measured CIB intensity map (in MJy/sr) is an integral of IR emissions along the line of sight:

$$I_\nu(\boldsymbol{\theta}) = \int \mathrm{d}\chi a j_{(1+z)\nu}(\chi, \boldsymbol{\theta})$$

The IR emission coefficient at observed frequency is related to the IR luminosity via:

$$j_{(1+z)\nu}(z) = \int \mathrm{d}L \frac{\mathrm{d}n}{\mathrm{d}L} \frac{L_{(1+z)\nu}(z)}{4\pi} = \int \mathrm{d}M \frac{\mathrm{d}n}{\mathrm{d}M} \frac{L_{(1+z)\nu}(M, z)}{4\pi},$$

And the specific IR flux from a halo with mass M at redshift z is:

$$F_\nu(M, z) = \frac{L_{(1+z)\nu}(M, z)}{4\pi\chi^2(1+z)}$$

Angular cross-correlation model

A sky map of fluctuation of the ‘u’ field is its projected spatial fluctuation:

$$u(\boldsymbol{\theta}) = \int \mathrm{d}\chi W^u(\chi)\delta_u(\boldsymbol{\theta}, z(\chi))$$

	Radial kernels:	Spatial fluctuations:
CIB intensity:	$W^{\mathrm{CIB}}(\chi) = \frac{1}{1+z(\chi)}$	$j_\nu(\boldsymbol{\theta}, z)$
Galaxy count:	$W^g(\chi) = \frac{H(\chi)}{c} n_g(z(\chi))$	$\delta_g(\boldsymbol{\theta}, z)$

Limber approximation (valid for ℓ>10):

$$C_\ell^{\mathrm{g}\nu} = \int \frac{\mathrm{d}\chi}{\chi^2} W^{\mathrm{g}}(\chi) W^{\mathrm{CIB}}(\chi) P_{\mathrm{g}\nu}\left(k = \frac{\ell + 1/2}{\chi}, z(\chi)\right)$$

$$\left\langle \tilde{\delta}_{\mathrm{g}}(\boldsymbol{k}, z) \tilde{j}_\nu(\boldsymbol{k}', z) \right\rangle = (2\pi)^3 P_{\mathrm{g}\nu}(k, z) \delta^3(|\boldsymbol{k} - \boldsymbol{k}'|)$$

CIB-SFR connections

The specific IR flux is the total IR luminosity times the spectral energy distribution (SED):

$$F_\nu(M,z) = L_{\rm IR}(M,z) S_{\rm eff}[(1+z)\nu, z],$$

The total IR luminosity is linked with the SFR via Kennicutt relation:

$$L_{\rm IR}(M,z) = {\rm SFR}(M,z)/K$$

Therefore, the IR emission coefficients can be modelled as:

$$j_{(1+z)\nu}(z) = \frac{\rho_{\rm SFR}(z)(1+z)S_{\rm eff}\left[(1+z)\nu, z\right]\chi^2}{K},$$

CIB models used in unWISE x CIB

- The S12 model (Shang et al. 2012)

  - SFR history: given by a power law of (1+z);

  - SED: graybody (normalization factor fixed by introducing SFRD(z=0))

- The M21 model (Maniyar et al. 2021)

  - SFR history: BAR (fixed) x star forming efficiency (lognormal)

  - SED: fixed from IR flux stacking (Bethermin et al. 2013, Bethermin et al. 2015)

- The Y23 model

  - SFR history: BAR (fixed) x star forming efficiency (lognormal)

  - SED: graybody (normalization factor fixed by introducing SFRD(z=0))

Halo model for CIB x galaxy

The 1- and 2-halo terms of galaxy-CIB power spectrum:

$$P_{g\nu,1h}(k) = \int_0^\infty \mathrm{d}M \frac{\mathrm{d}n}{\mathrm{d}M} \langle \tilde{p}_g(k|M)\tilde{p}_\nu(k|M)\rangle$$
$$P_{g\nu,2h}(k) = \langle b_g\rangle(k)\langle b_\nu\rangle(k)P^{\mathrm{lin}}(k)$$
$$\langle b_{g/\nu}\rangle(k) \equiv \int_0^\infty \mathrm{d}M \frac{\mathrm{d}n}{\mathrm{d}M} b_h(M)\langle \tilde{p}_{g/\nu}(k|M)\rangle,$$

Cross-correlation of profiles in the 1-halo term

$$\begin{aligned}\langle p_g(k|M)p_\nu(k|M)\rangle = \frac{1}{4\pi}&\langle N_s(M)\rangle\langle L_{\nu,s}(M)\rangle p^2_{\mathrm{NFW}}(k|M) \\ &+ \langle N_c(M)\rangle\langle L_{\nu,s}(M)\rangle p_{\mathrm{NFW}}(k|M) \\ &+ \langle N_s(M)\rangle\langle L_{\nu,c}(M)\rangle p_{\mathrm{NFW}}(k|M).\end{aligned}$$

The halo occupation distribution (HOD)

Central and satellite galaxy counts:

$$\langle N_{\rm c}(M)\rangle = \frac{1}{2}\left[1+{\rm erf}\left(\frac{\ln\left(M/M_{\rm min}\right)}{\sigma_{\ln M}}\right)\right]$$

$$\langle N_{\rm s}(M)\rangle = N_{\rm c}(M)\Theta\left(M-M_0\right)\left(\frac{M-M_0}{M_1}\right)^{\alpha_{\rm s}},$$

SFR from central and satellite galaxies

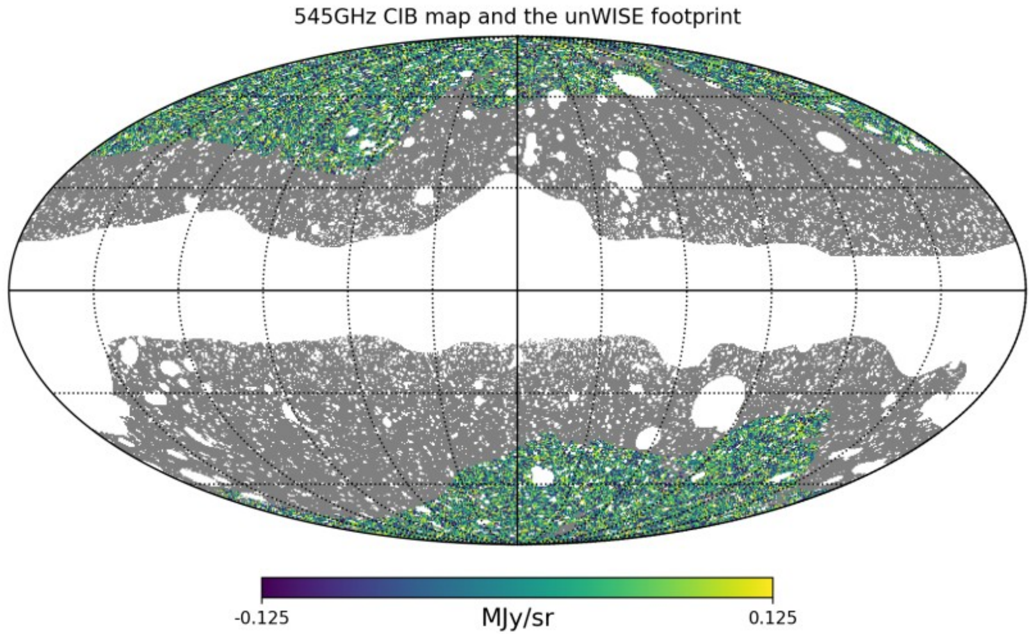
$$\mathrm{SFR_c}(M) = \langle N_{\rm c}(M)\rangle \times \mathrm{SFR}(M)$$

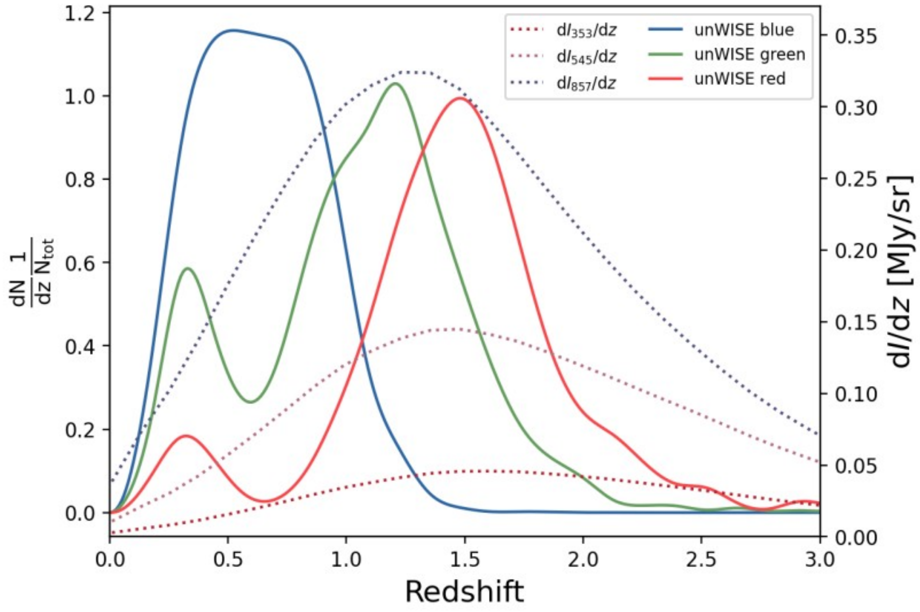
$$\mathrm{SFR_s}(M) = \int {\rm d}\ln m \left(\frac{{\rm d}N_{\rm sub}}{{\rm d}\ln m}\right)\mathrm{SFR_s}(m|M),$$

where $\mathrm{SFR_s}(m|M) = \min\left\{\mathrm{SFR}(m), m/M \times \mathrm{SFR}(M)\right\}.$

Galaxy data: unWISE catalog

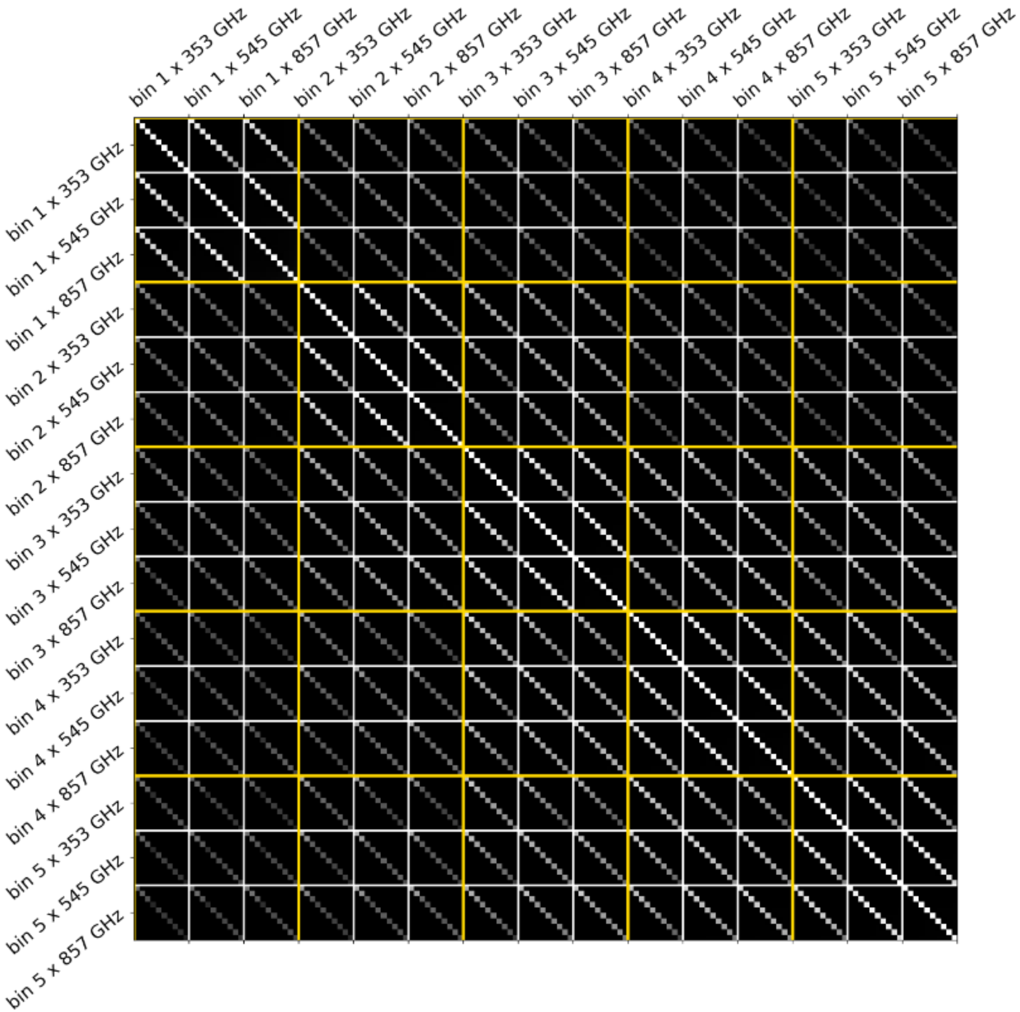
- Selected from the Wide Field Infrared Survey Explorer (WISE) satellite mission (Wright et al. 2010),
- Sky coverage: ~54% (overlapped region ~10%)
- 3 tomographic bins



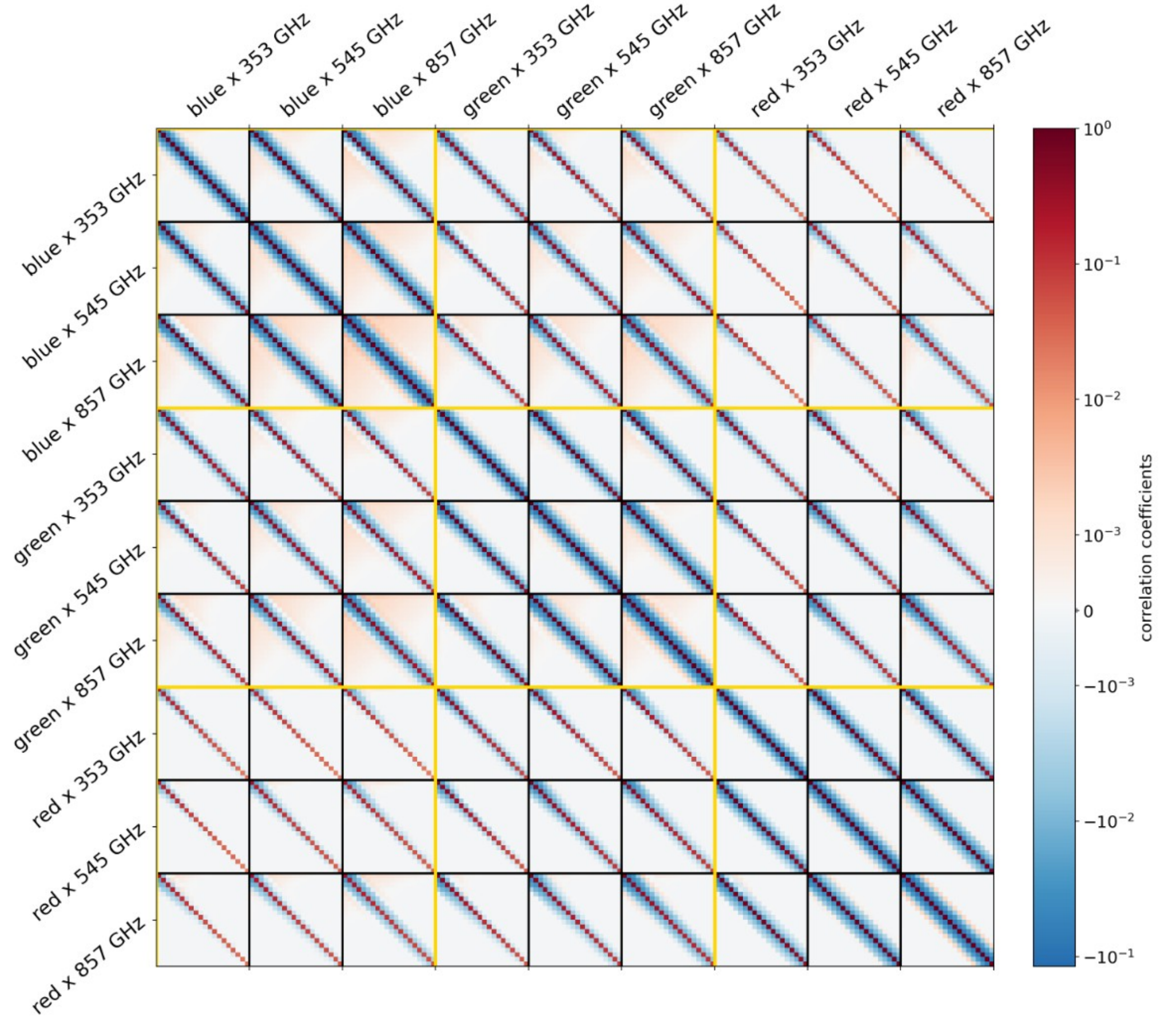


Covariance Matrix (KiDS x CIB)

Covariance matrix includes Gaussian, non-Gaussian connected, and super sample covariance



Covariance Matrix (unWISE x CIB)



Systematics considered

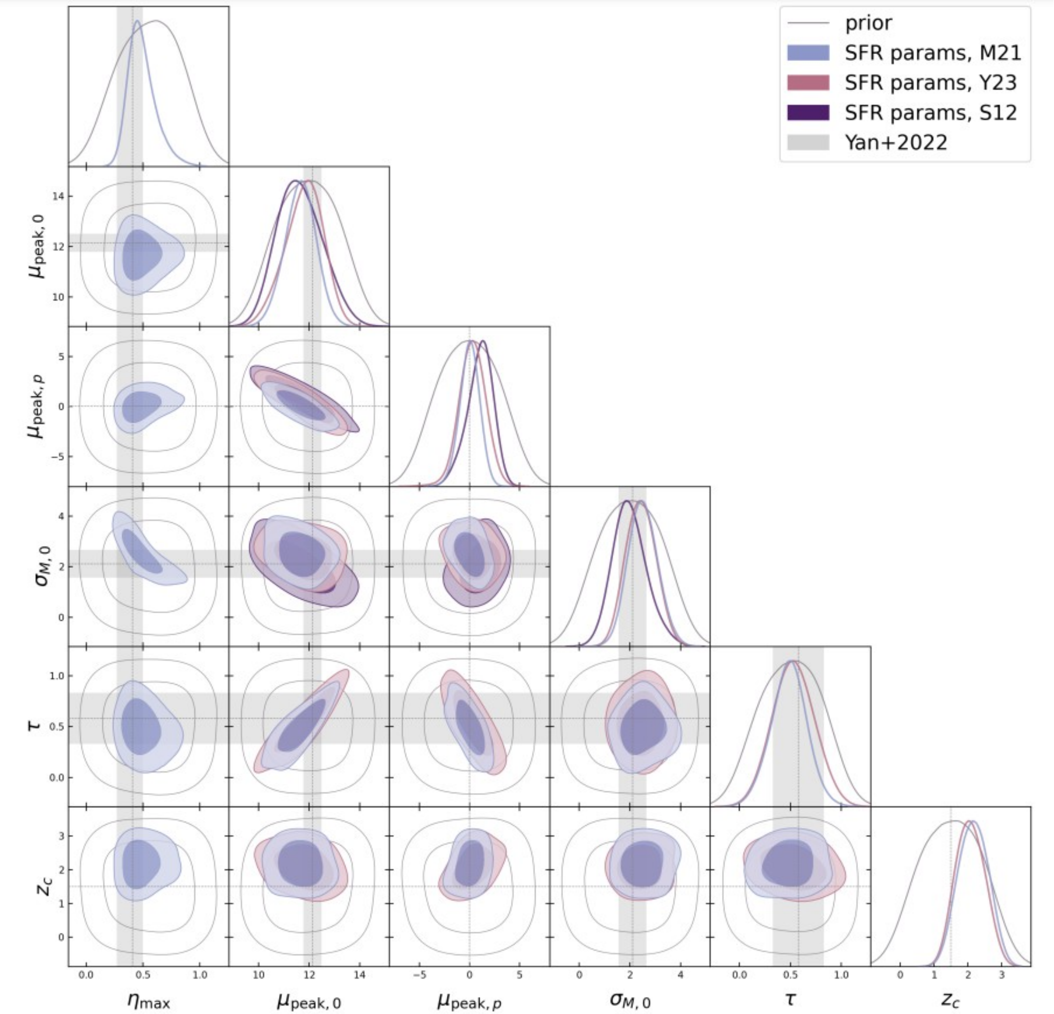
- Cosmic magnification;

- Redshift distribution uncertainty;

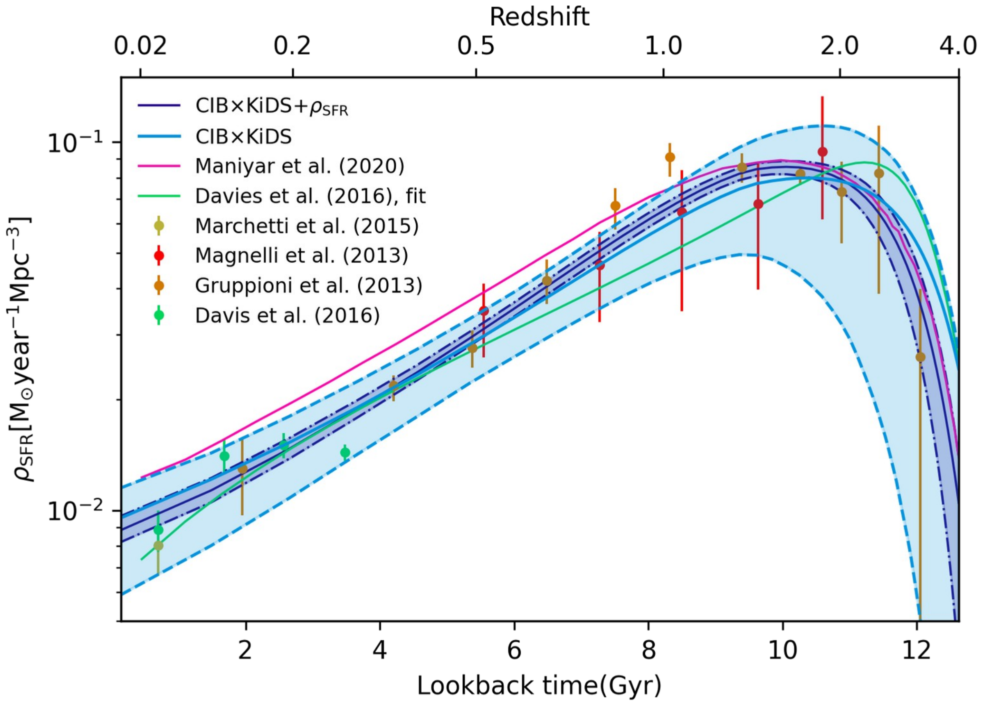
- CIB color-correction factor;

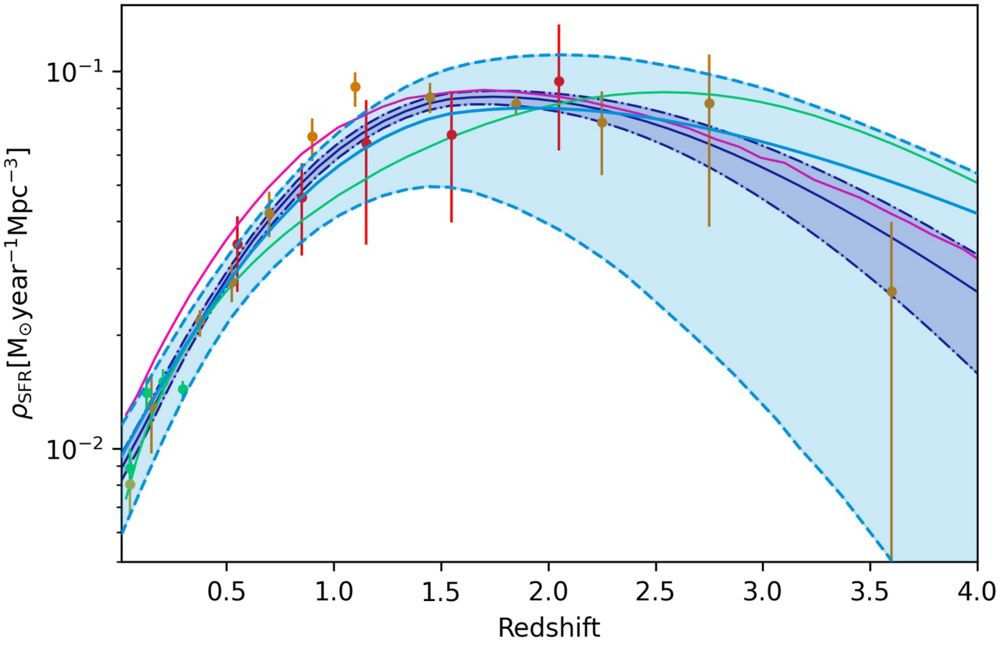
- one to two halo transition region smoothing (with HMCODE 2020);

Constrain the SFR with unWISE x CIB



SFR history Constraints

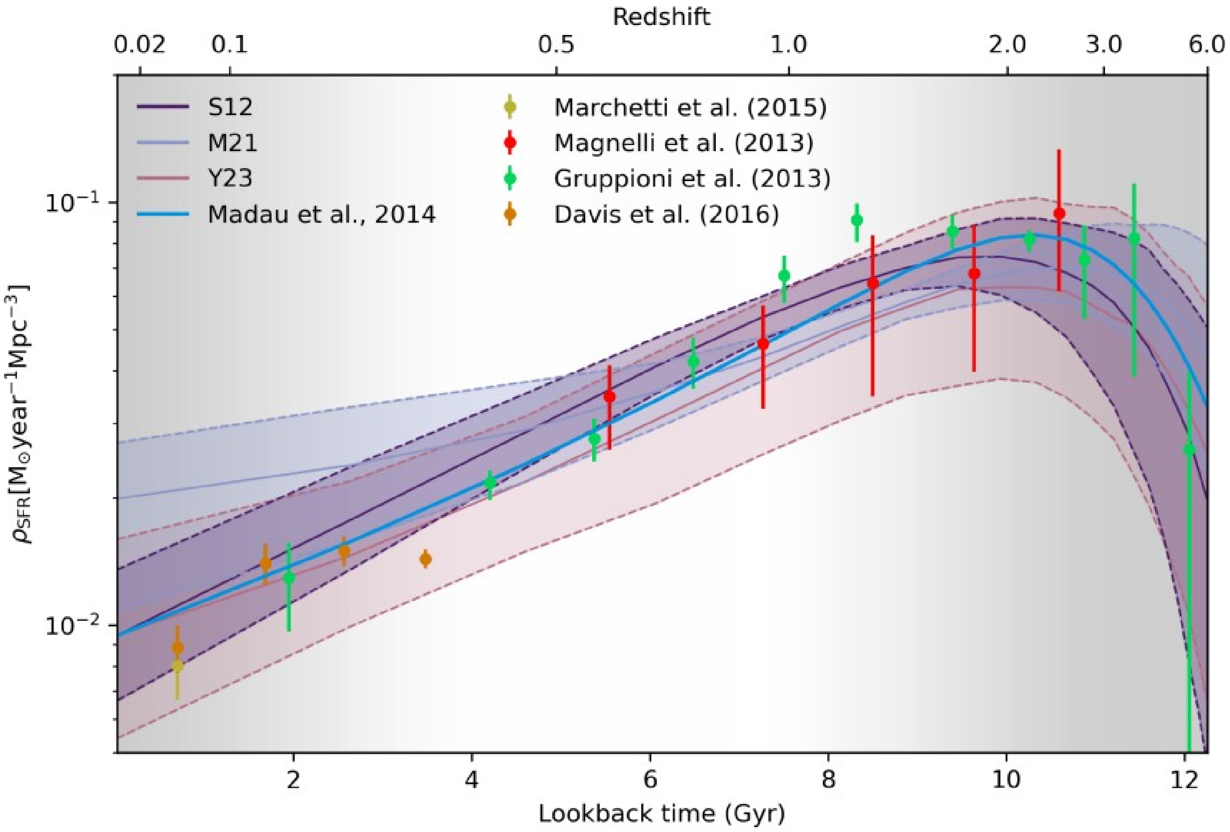




SFR history Constraints from unWISE x CIB

S12, M21, and Y23 are three CIB models different in their SED and SFR parametrization inspired by previous studies

In this work, we assume a evolving $M_{\rm peak}$ in our model and find no significant redshift dependence.



SED constraints from unWISE x CIB

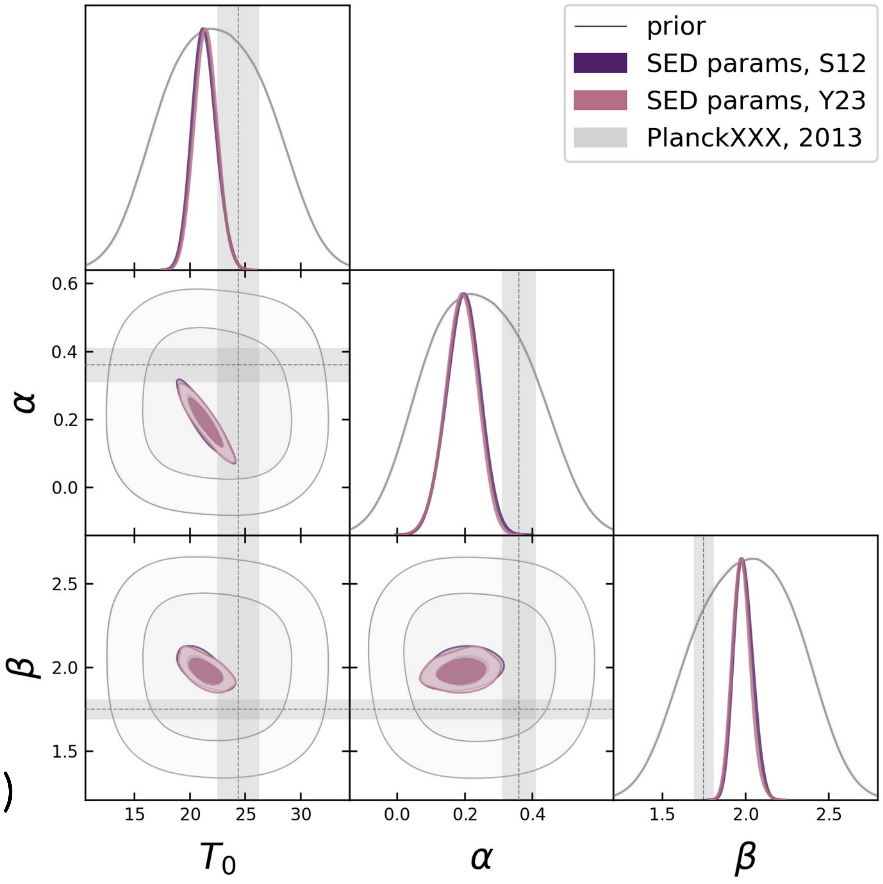
In the KiDS x CIB work, we fixed the dust SED as that measured from IR flux stacking (Bethermin et al. 2013)

In this project, we try to constrain the SED with unWISE x CIB by assuming a gray-body spectrum (Shang et al. 2012, Planck XXX, 2013)

$$\Theta_{\mathrm{eff}}(\nu', z) \propto \begin{cases} \nu'^{\beta} B_{\nu'}(T_{\mathrm{d}}) & \nu' < \nu'_0 \\ \nu'^{-\gamma} & \nu' \geqslant \nu'_0, \end{cases}$$

Where $\nu' = \nu(1+z)$ is the rest-frame frequency; dust temperature is modeled as $T_d(z) = T_0(1+z)^{\alpha}$

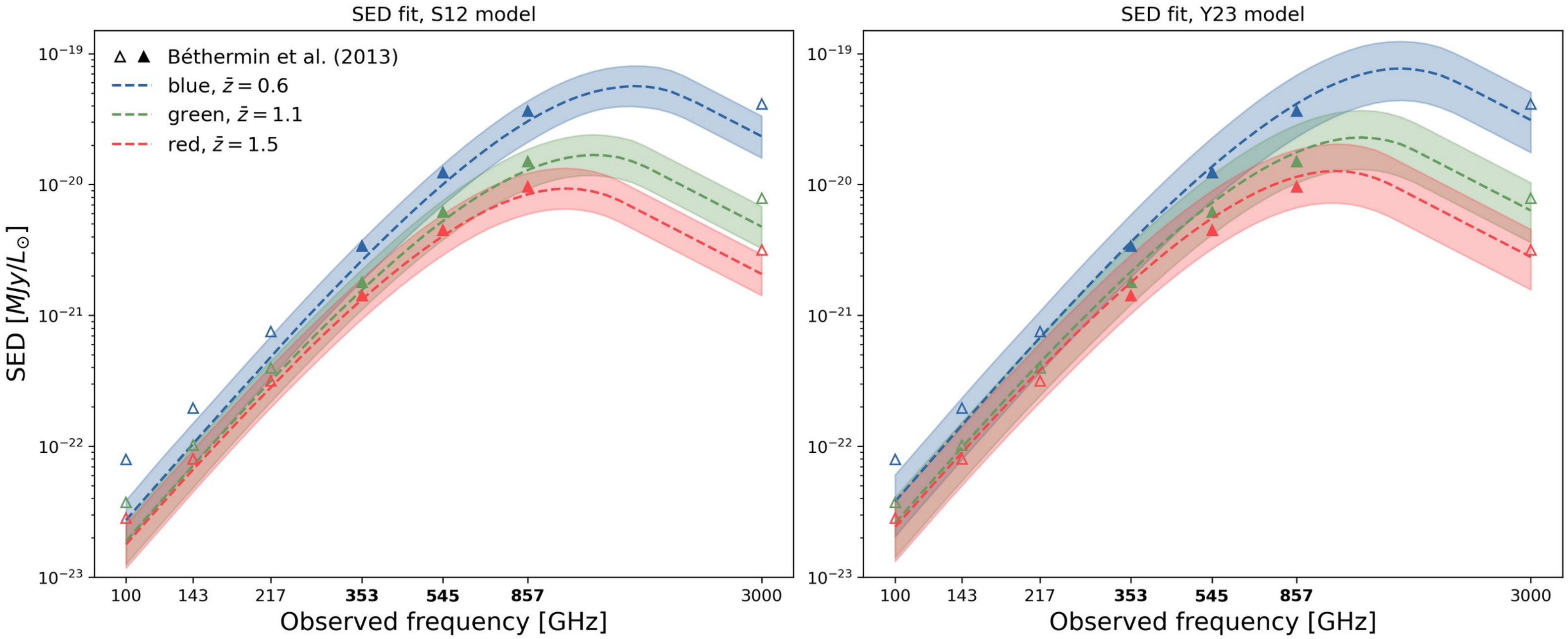
The connection frequency ν'_0 ensures the smoothness of two spectra (much higher than the Planck HFI frequencies)



SED constraints from unWISE x CIB

The SED normalization parameter is completely degenerate with the SFR. We fix it by fixing the SFRD at z=0 given by a synthesis of multiwavelength studies (Madau & Dickinson 2014)

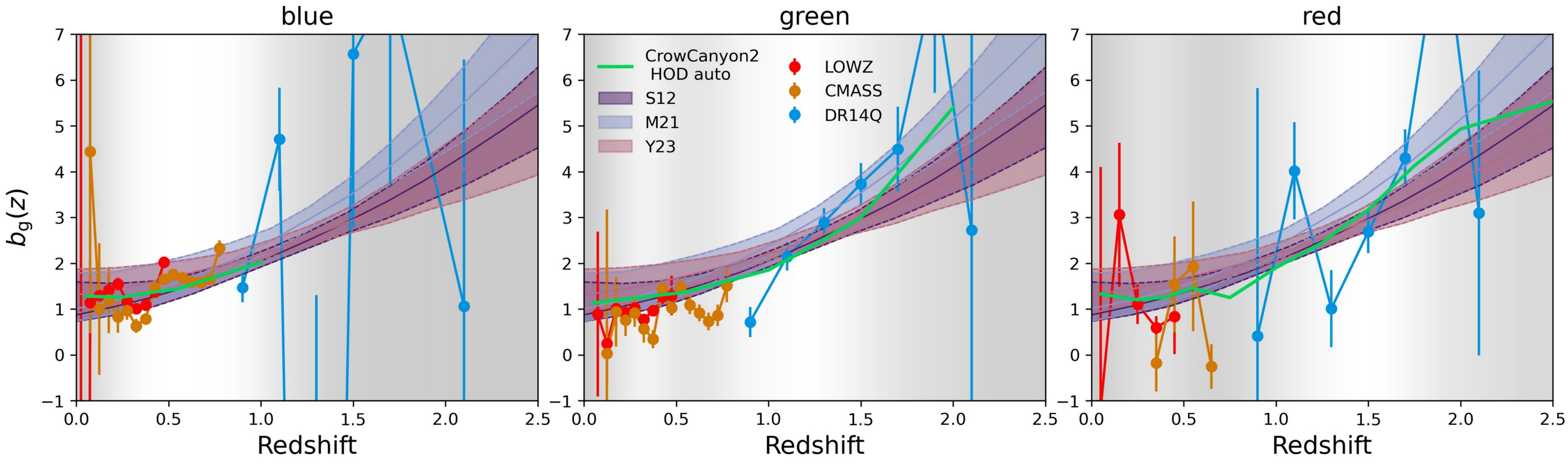
SED is constrained in agreement with IR flux stacking (Bethermin et al. 2013) at our frequency bands



Galaxy bias constraints from unWISE x CIB

Galaxy bias is derived from HOD parameters.

$$b_{\rm g}(z) = \frac{1}{\bar{n}_{\rm g}(z)} \int {\rm d}M \, \frac{{\rm d}n}{{\rm d}M} b_{\rm h}(M,z) \left[N_{\rm c}(M,z) + N_{\rm s}(M,z) \right],$$



Constrain the HOD with unWISE x CIB