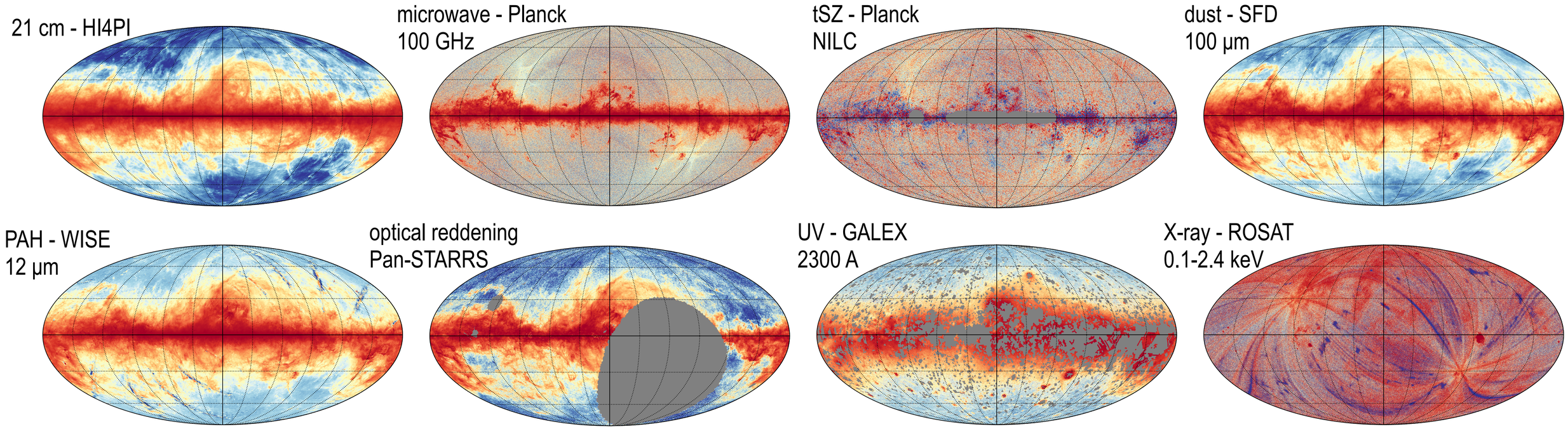
Probing The Cosmic Energy Density Inventory With Tomographic Intensity Mapping



Yi-Kuan Chiang

CCAPP Fellow, Ohio State University

Fukugita & Peebles 2004
See also Fukugita, Hogan, Peebles 98

The Cosmic Energy Inventory

Masataka Fukugita
Institute for Advanced Study, Princeton, NJ 08540 USA
and
Institute for Cosmic Ray Research, University of Tokyo, Kashiwa 277-8582, Japan

P. J. E. Peebles
Joseph Henry Laboratories, Princeton University, Princeton, NJ 08544 USA

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.

$$\Omega_x = \rho_x / \rho_{crit}$$

with x being Λ, DM, photons, stars, gas, dust, neutrinos, and other ~40 cosmic constituents

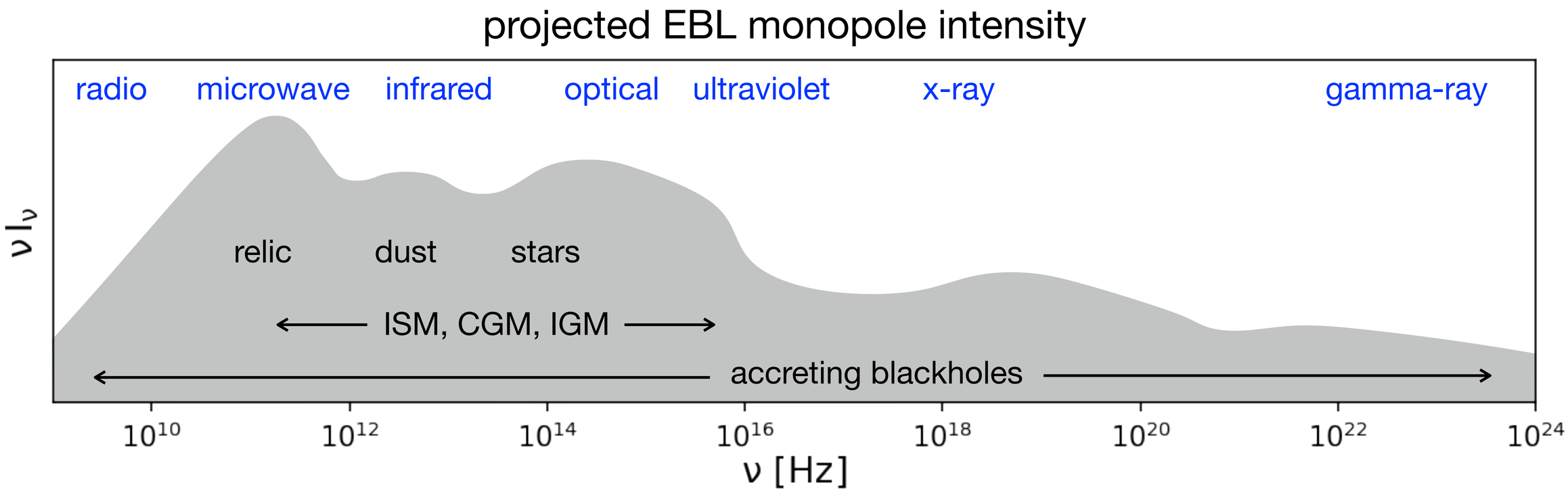
Fukugita & Peebles: $\Omega_{x,0}$ for all x

→ summary statistics of the present-day universe (to the 1st moment)

To complete the picture, need $\Omega_x(z)$, or the growth rates $\dot{\Omega}_x(z)$

→ summary statistics for the energy transfer in the universe

Extragalactic background light (EBL) as a messenger for Ω_x

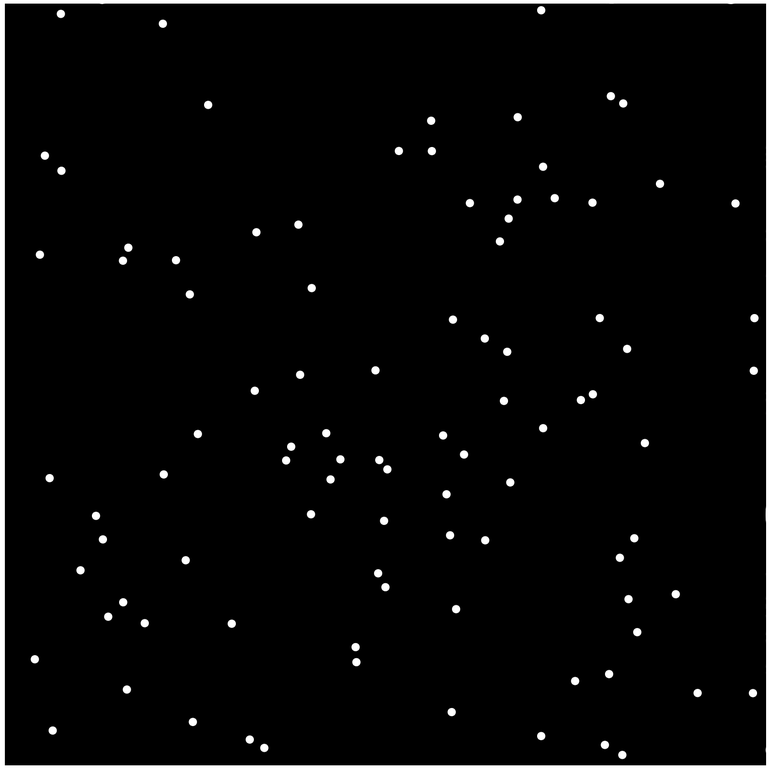


By definition, EBL is $\Omega_{radiation}$. It also provides constraints on Ω_{star}, Ω_{dust}, Ω_{gas}, Ω_{BH}… if we know the radiative mechanisms

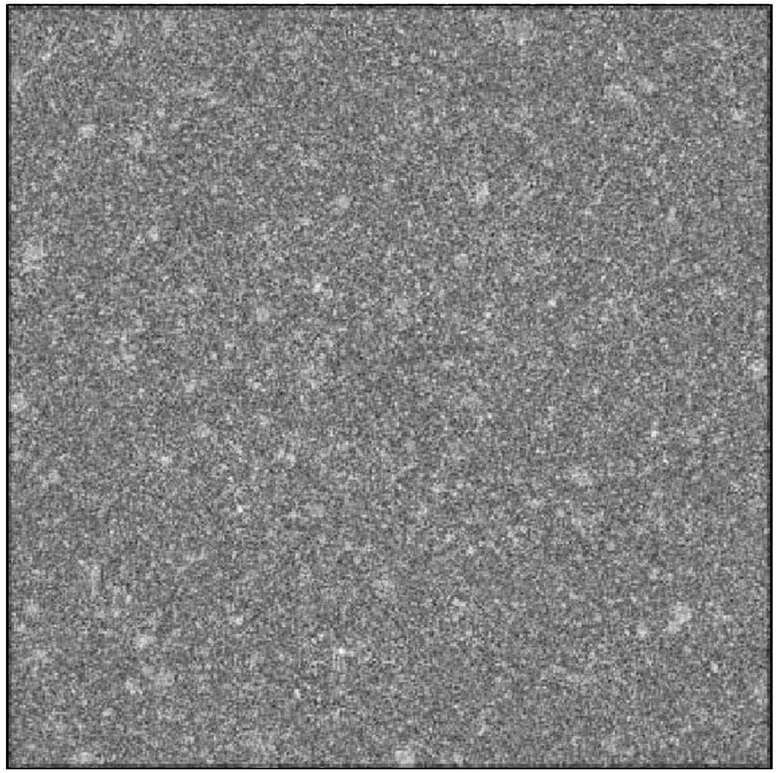
“Galaxy surveys” are incomplete for the EBL or Ω_x

“Intensity mapping” is complete, but contaminated & projected

galaxy catalog



intensity map



“Galaxy surveys” are incomplete for the EBL or Ω_x

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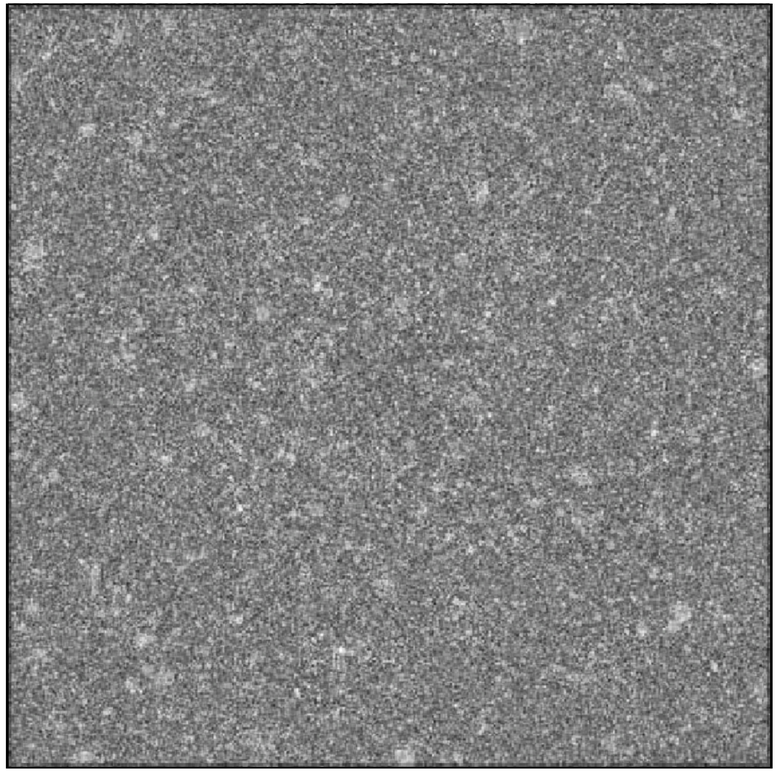
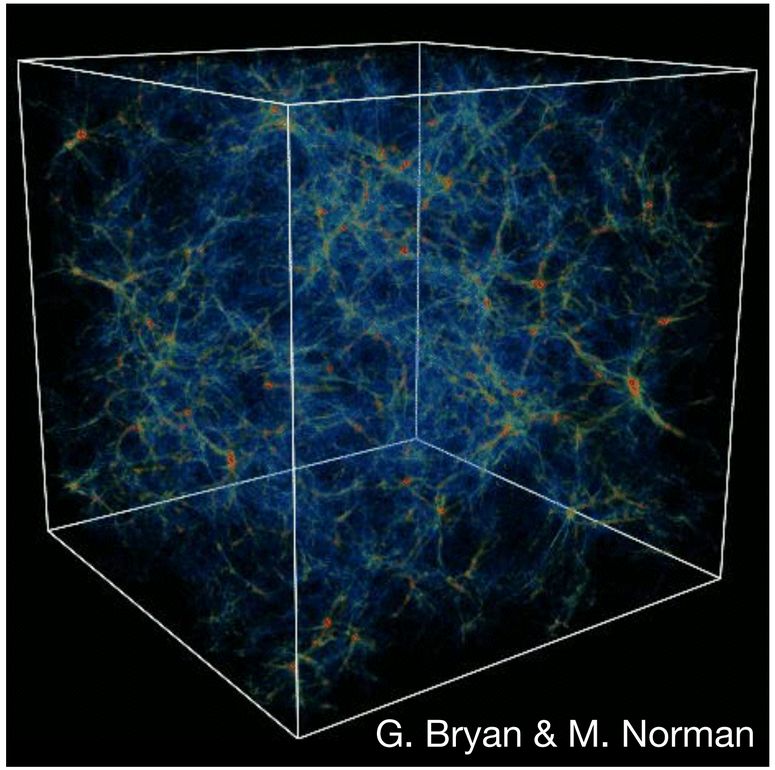
intensity map = projected cosmic web + foreground





- How do we filter out the foreground and get redshifts for photons to probe $\Omega_x(z)$?

Tomographic intensity mapping using z-dependent clustering

Intensity map = projected cosmic web + foreground

z_1 z_2 z_3 z_4 foreground 1 foreground 2

“clustering-based redshift estimation”: Newman+08, Menard+13, McQuinn+13

Tomographic intensity mapping using z-dependent clustering

2D intensity map from
any photometric survey

I(Φ) [Jy/sr]

“clustering-based redshift estimation”: Newman+08, Menard+13, McQuinn+13

Tomographic intensity mapping using z-dependent clustering

2D intensity map from
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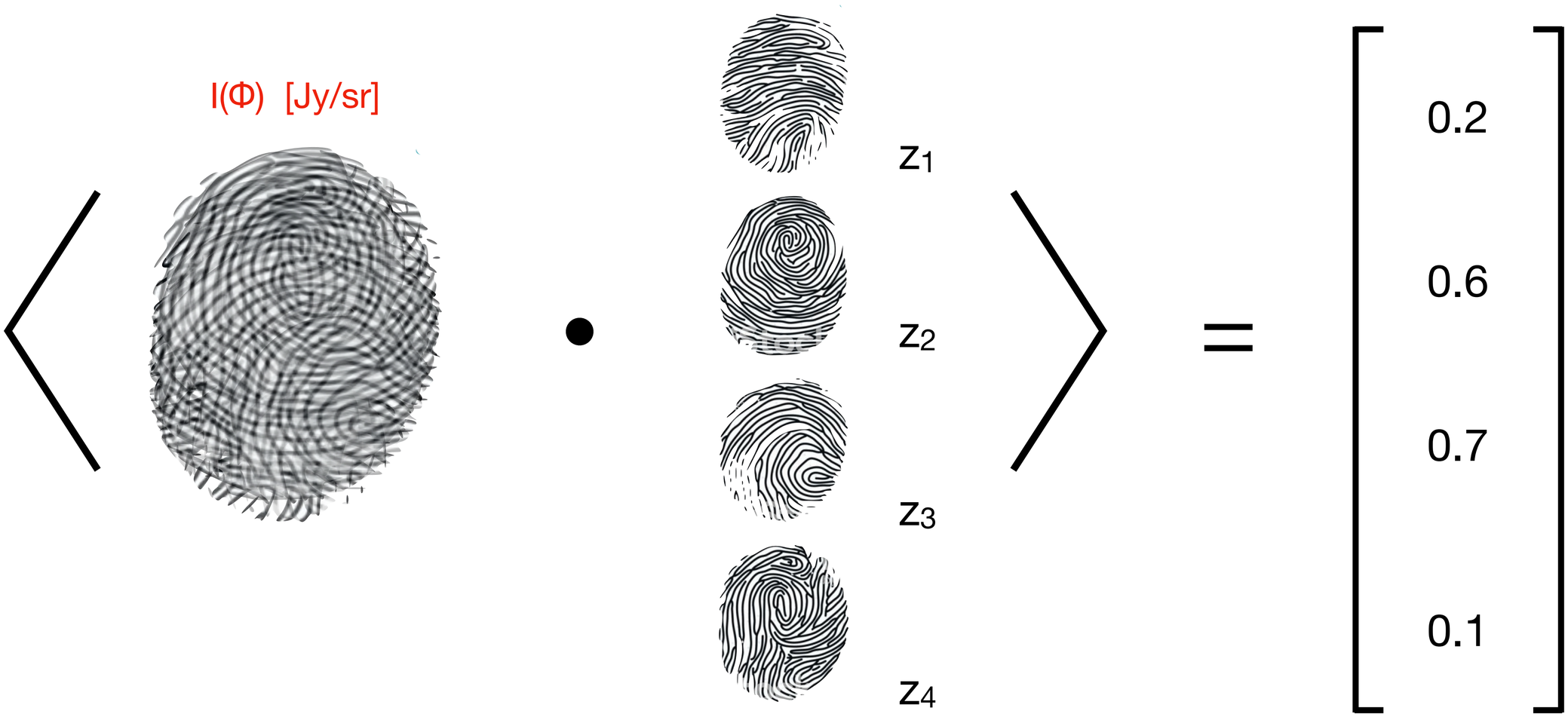
3D cosmic web tracers
from redshift surveys
(SDSS, DESI, PFS)



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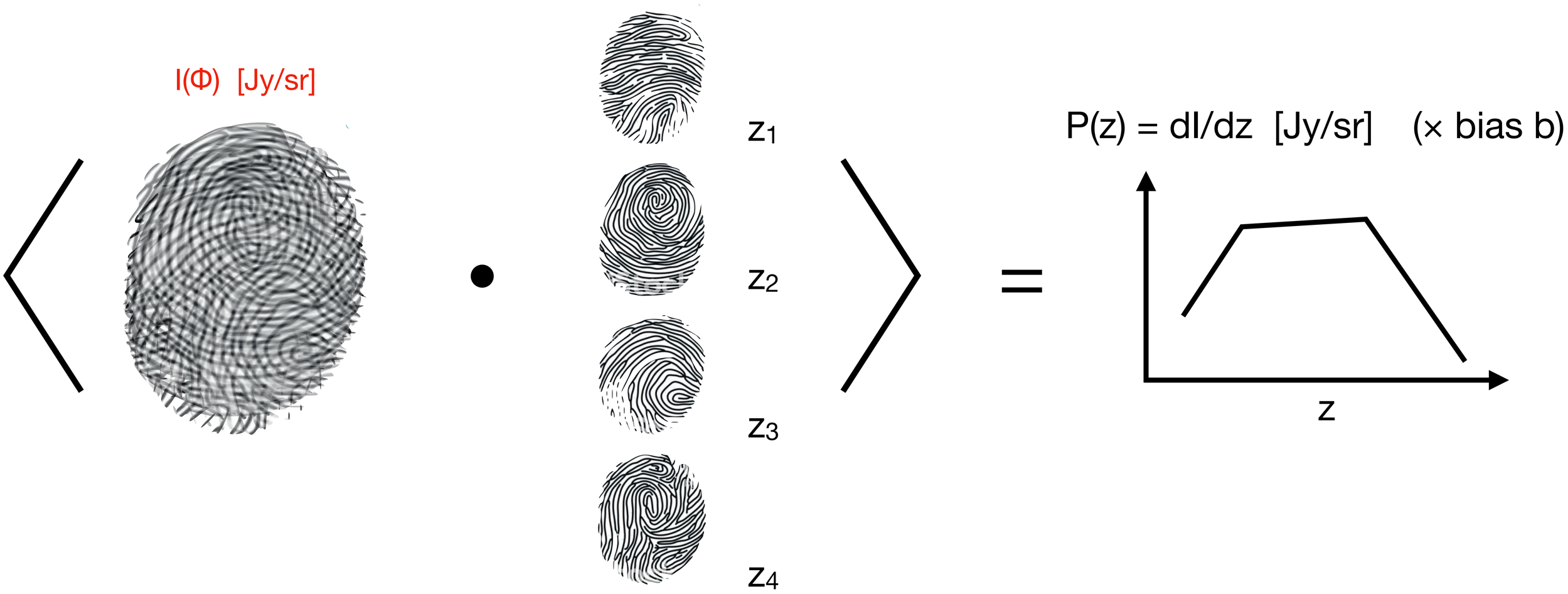

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Tomographic intensity mapping using z-dependent clustering

2D intensity map from
any photometric survey

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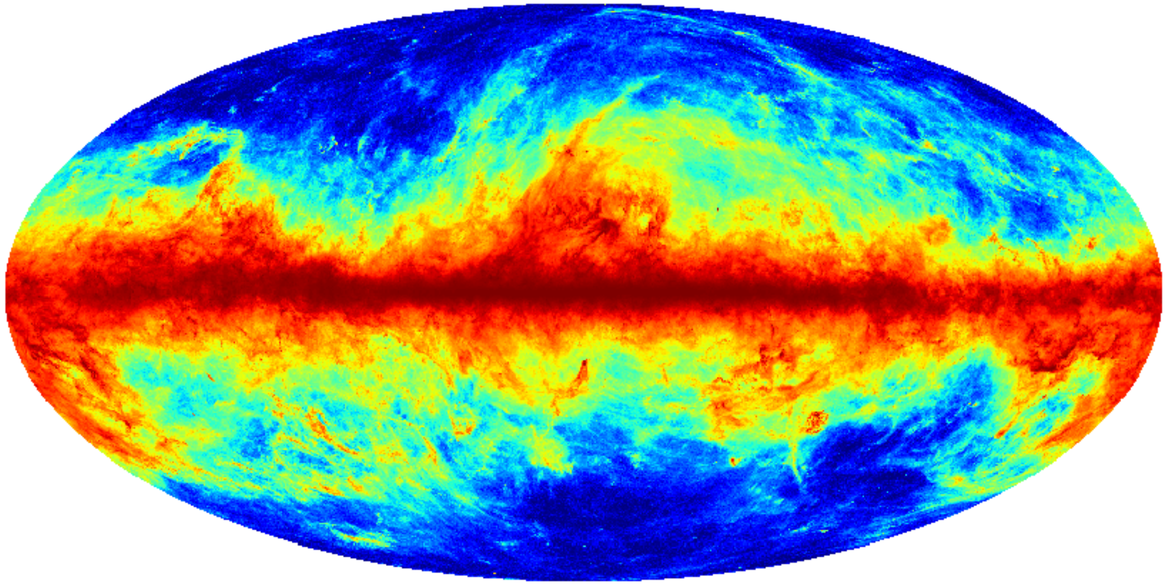
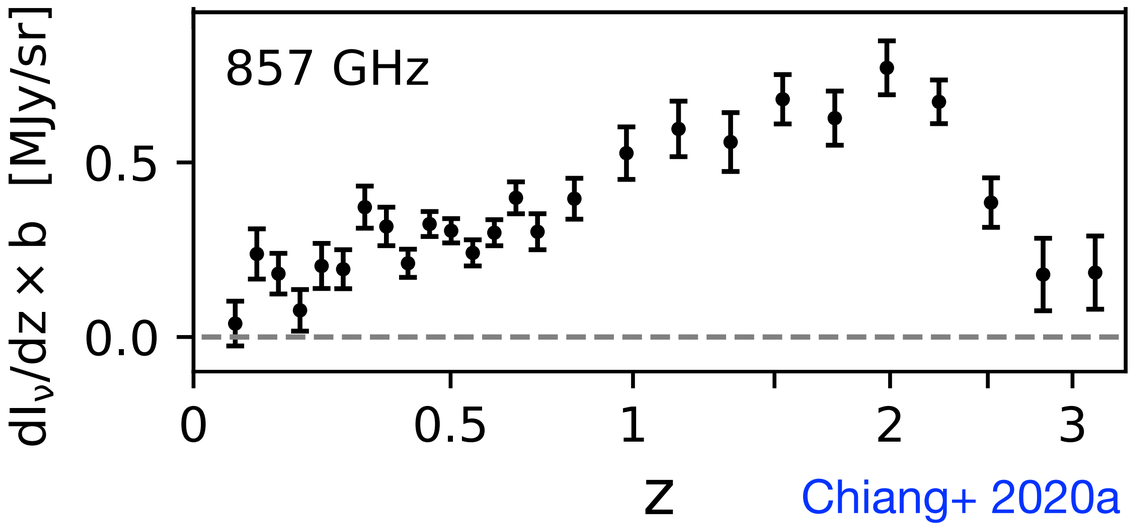
Example: Planck maps cross SDSS redshifts

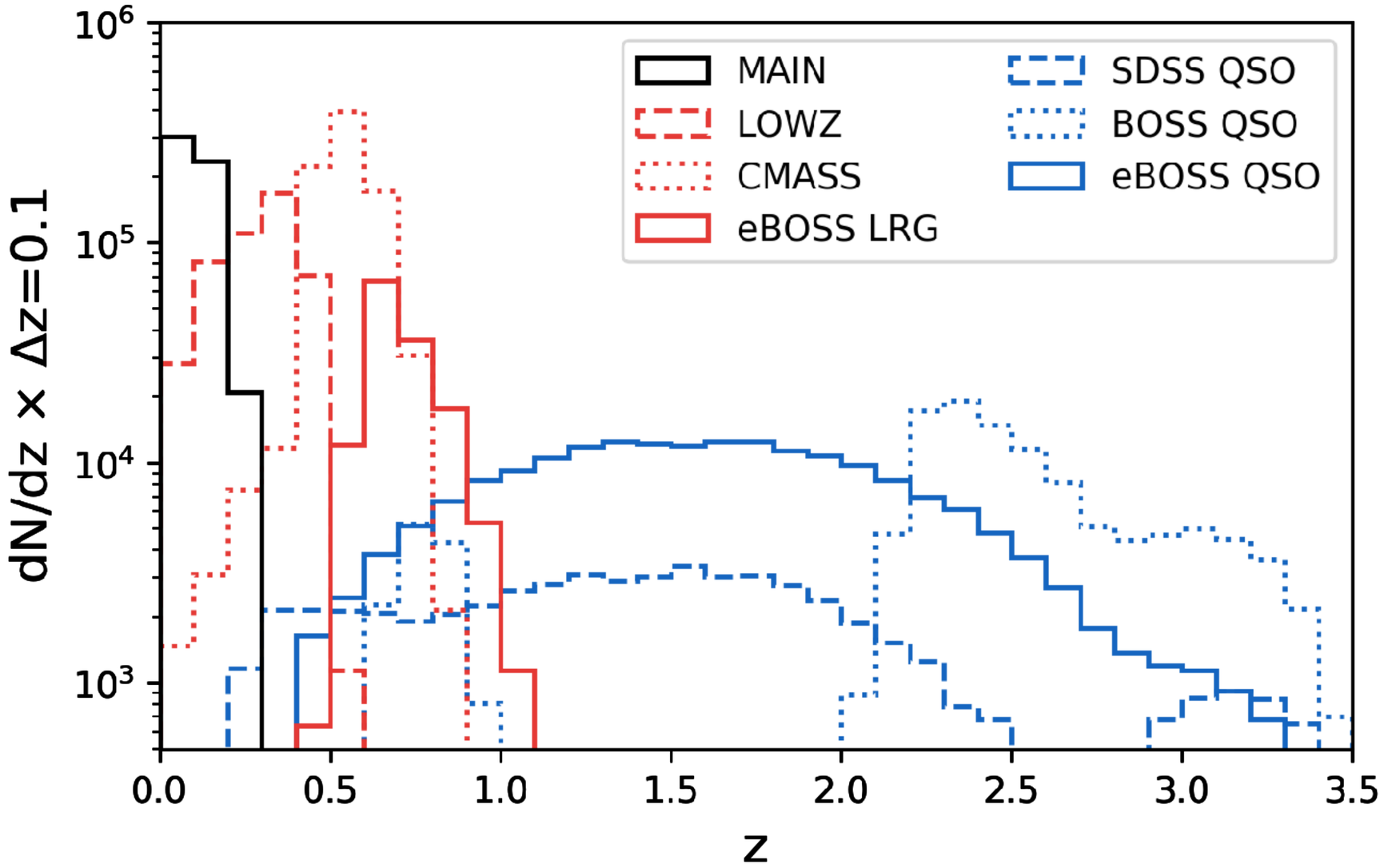




Chiang+ 2020a

"clustering-based redshift estimation": Newman+08, Menard+13, McQuinn+13

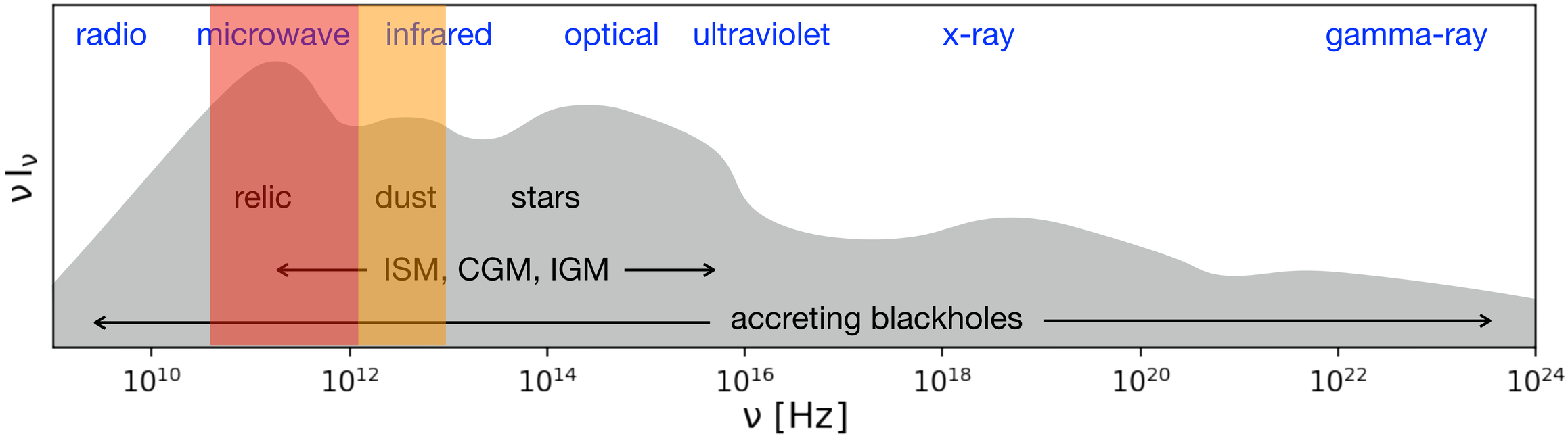
2 million spec-z reference sources in SDSS+BOSS+eBOSS



Blanton+05
Reid+16
Bautista+18
Schneider+10
Pâris+17
Ata+18

Will be expanded with DESI, PFS…, high quality photo-z's can also be used

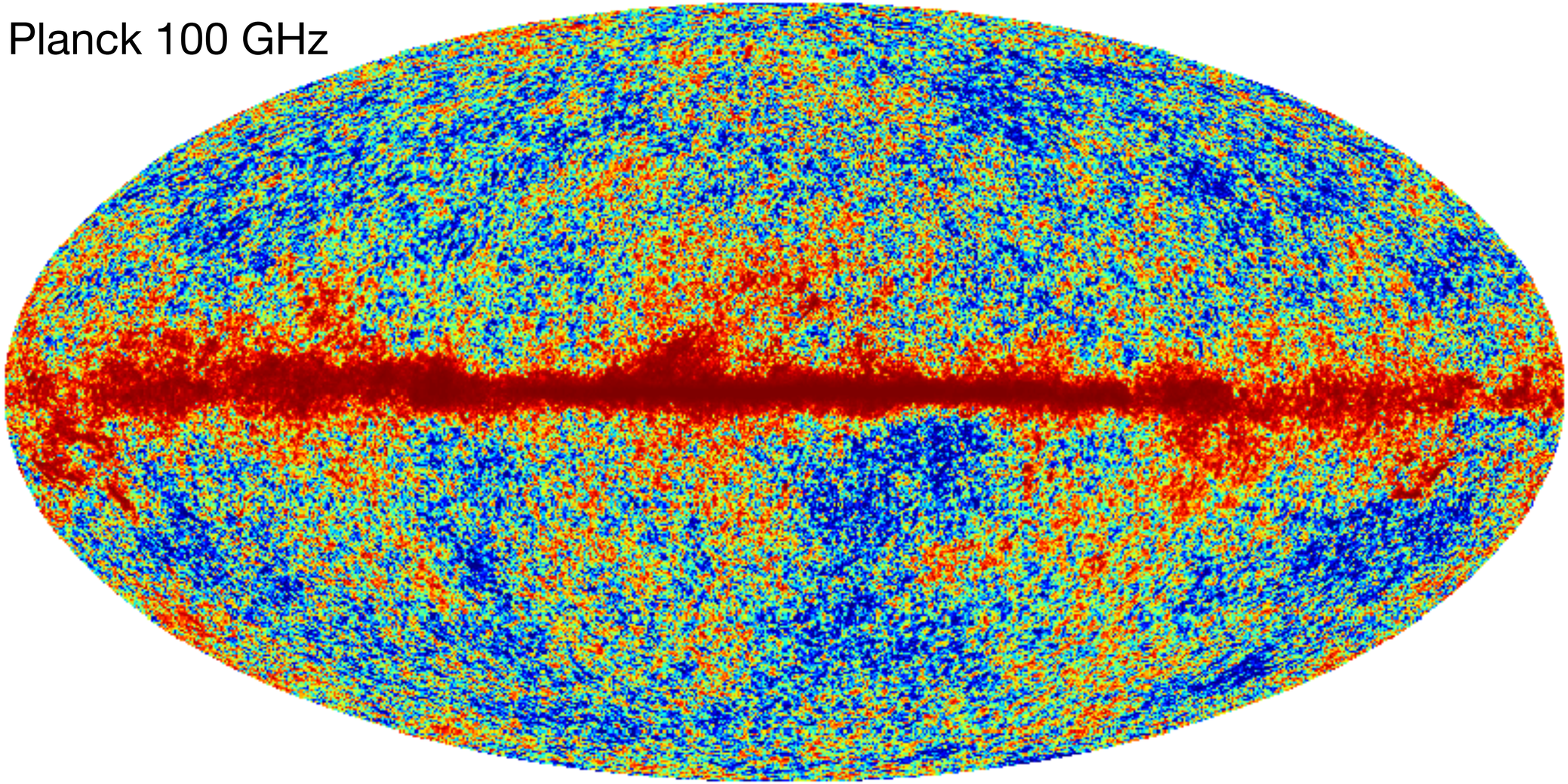
Clustering-based redshift tomography can be applied at any waveband

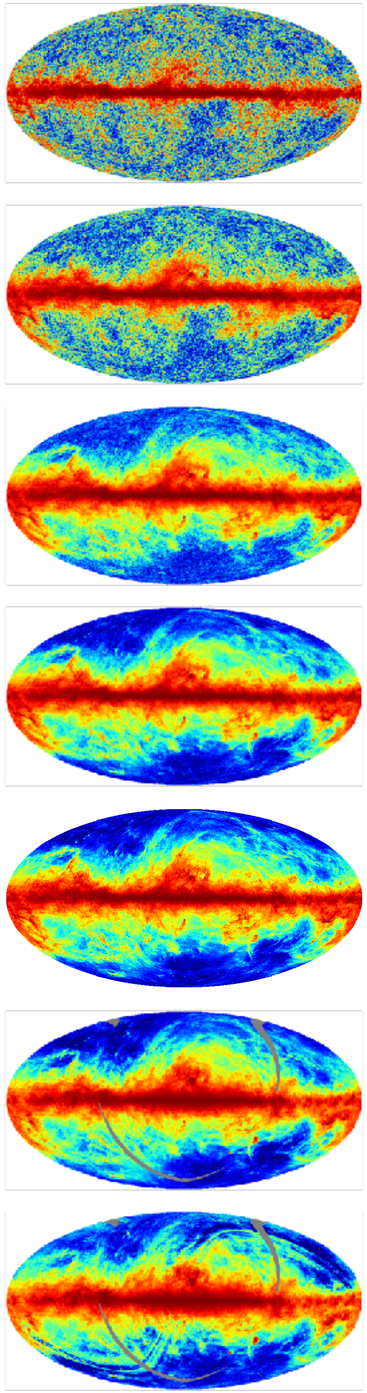


Sunyaev-Zel'dovich (SZ) & infrared background (CIB)

Data: Planck 100 to 857 GHz + IRAS 100 and 60 μm

Planck 100 GHz





Paper I
arXiv:2006.14650

The Cosmic Thermal History Probed by Sunyaev-Zeldovich Effect Tomography

Yi-Kuan Chiang,[1] Ryu Makiya,[2] Brice Ménard,[3,2] and Eiichiro Komatsu[4,2]

[1] *Center for Cosmology and AstroParticle Physics (CCAPP), The Ohio State University, Columbus, OH 43210, USA*
[2] *Kavli Institute for the Physics and Mathematics of the Universe (Kavli IPMU, WPI), University of Tokyo, Chiba 277-8582, Japan*
[3] *Department of Physics & Astronomy, Johns Hopkins University, 3400 N. Charles Street, Baltimore, MD 21218, USA*
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Paper II
arXiv:2007.01679

The thermal and gravitational energy densities in the large-scale structure of the Universe

Yi-Kuan Chiang,[1] Ryu Makiya,[2] Eiichiro Komatsu,[3,2] and Brice Ménard[4,2]

[1] *Center for Cosmology and AstroParticle Physics (CCAPP), The Ohio State University, Columbus, OH 43210, USA*
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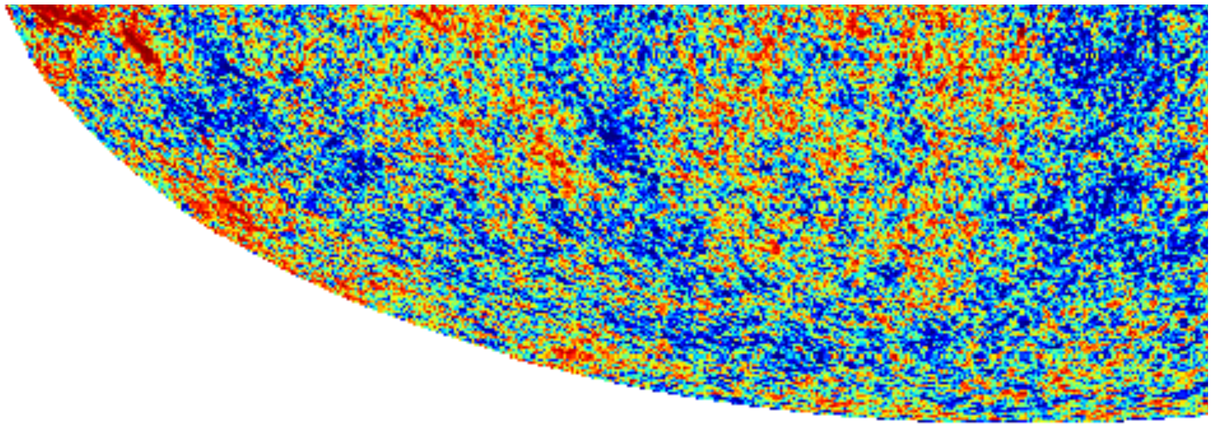
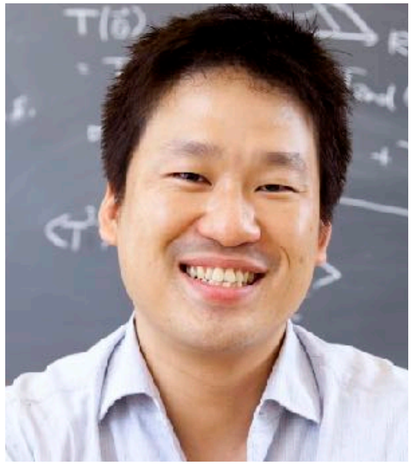
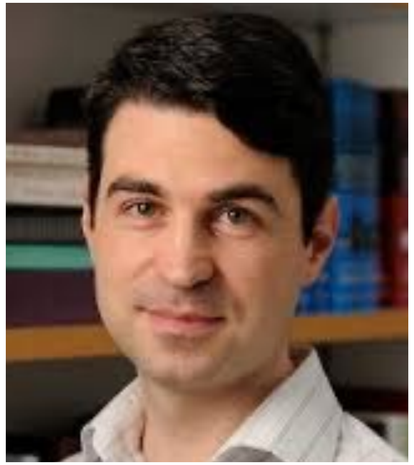
[3] *Max-Planck-Institut für Astrophysik, Karl-Sch*
[4] *Department of Physics & Astronomy, Johns Hopkins Unive*



Ryu Makiya



Eiichiro Komatsu



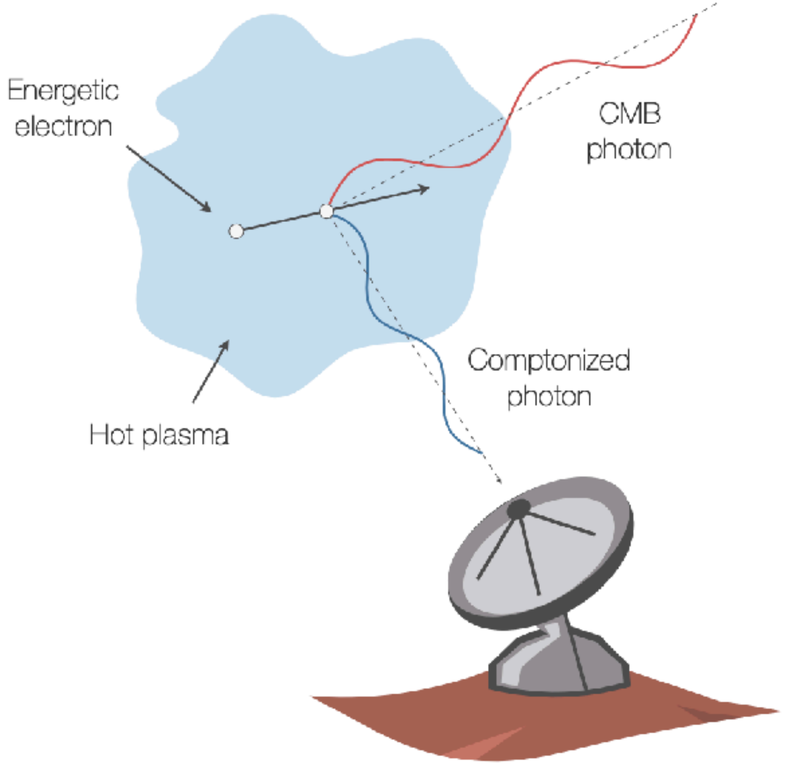
Brice Ménard

Ω_{th} — thermal energy, a clean probe of structure growth

Cen & Ostriker 99; Refregier+00

B. W. O'Shea with the Enzo code

Thermal Sunyaev-Zel'dovich effect



Sunyaev & Zel'dovich 1972

Mroczkowski +19

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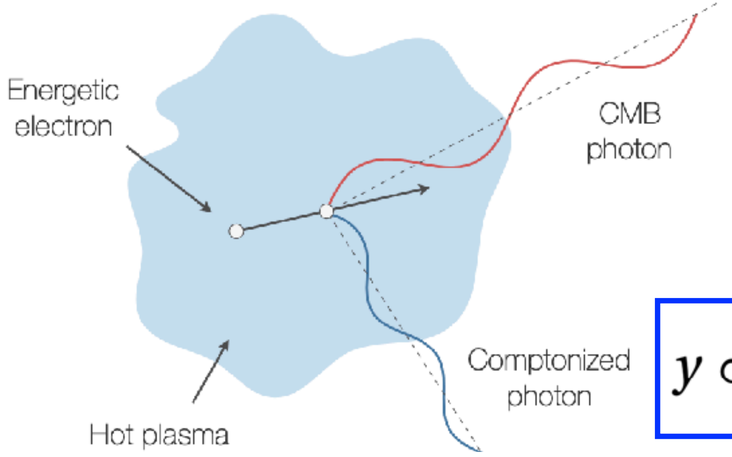
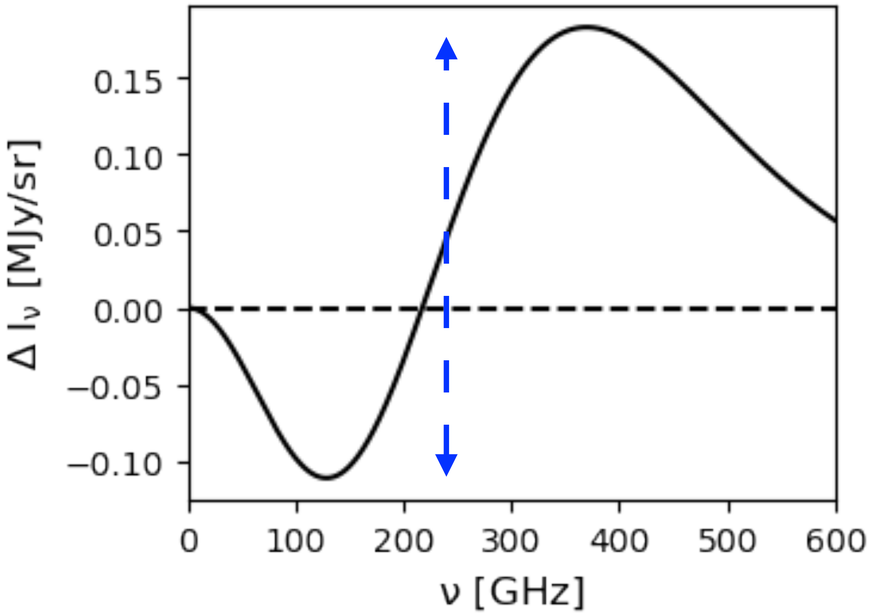
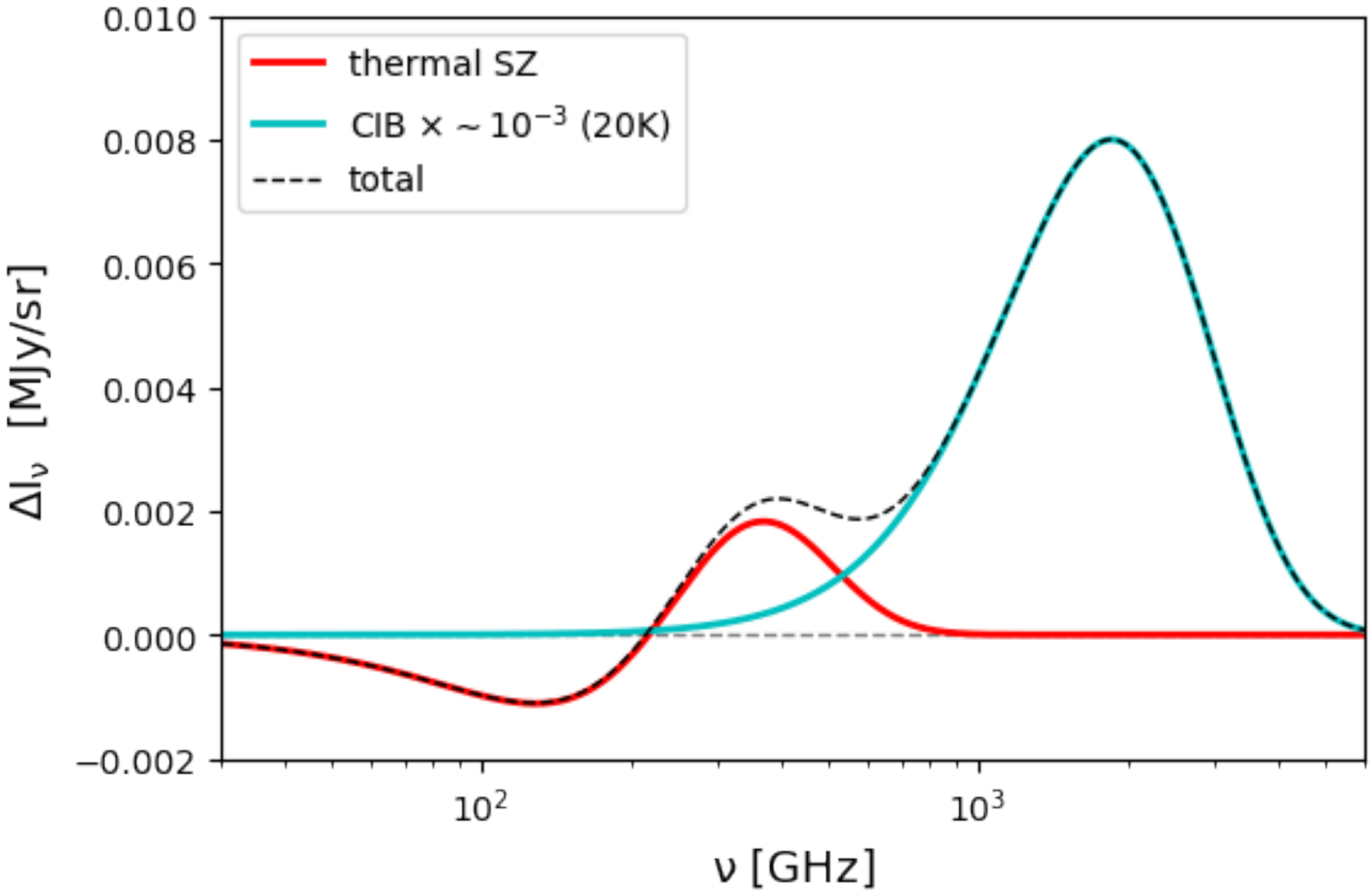


$$y \propto \int P_e \, dl$$



Spectral energy distribution (SED) of thermal SZ + CIB



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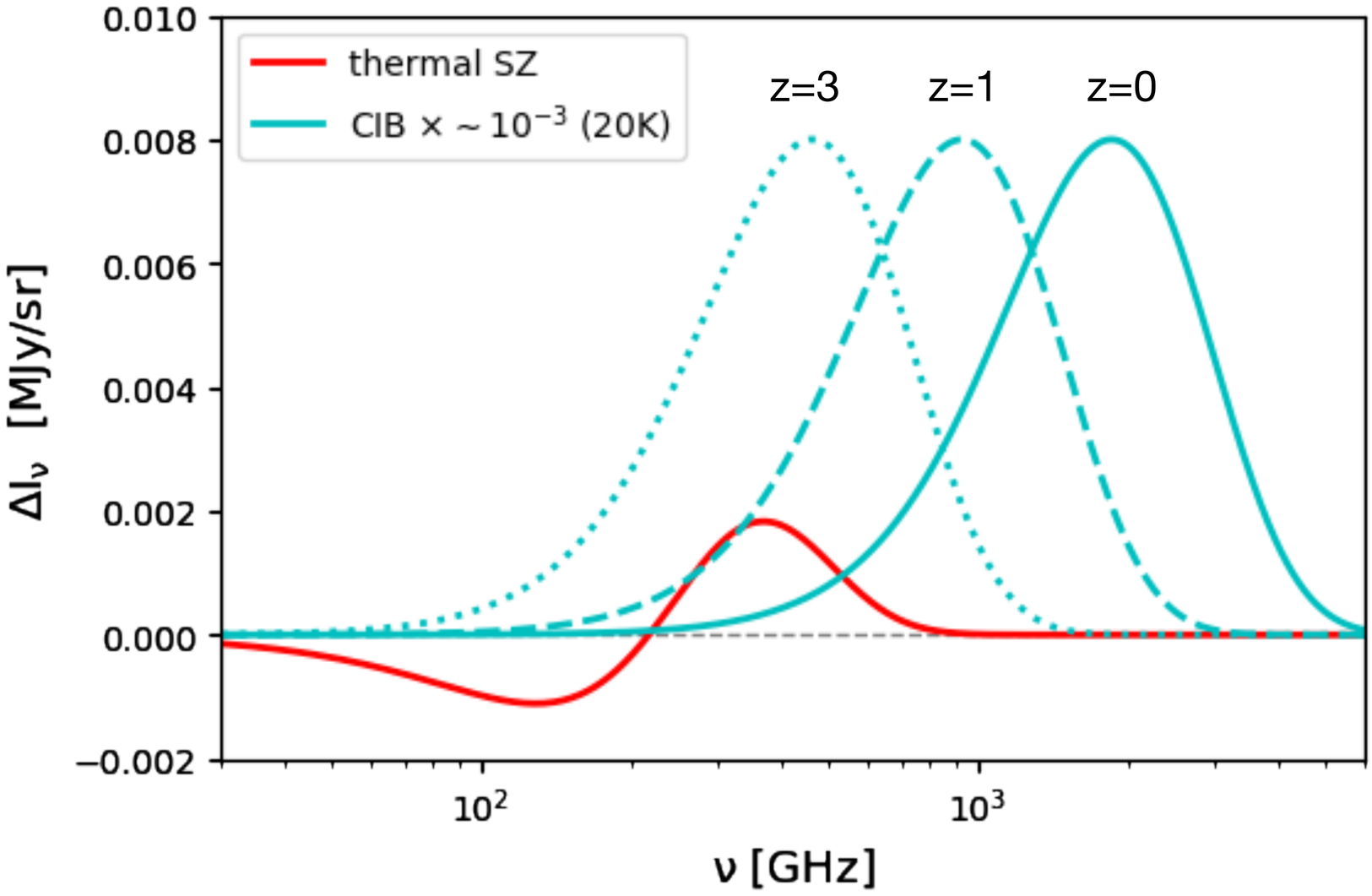
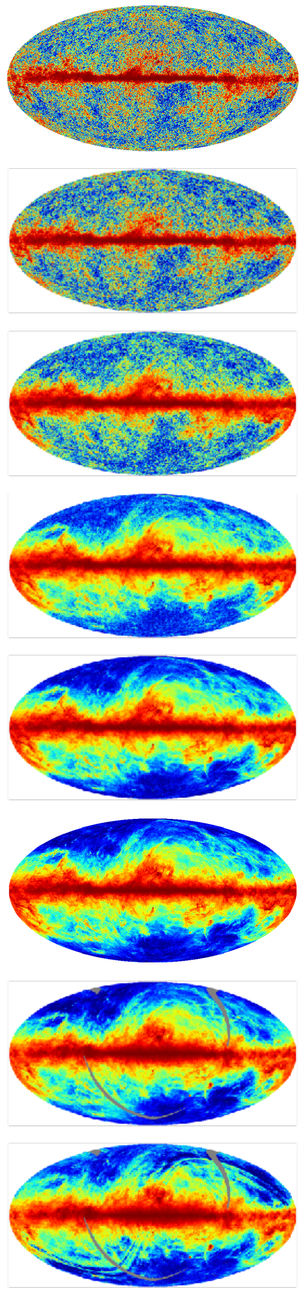
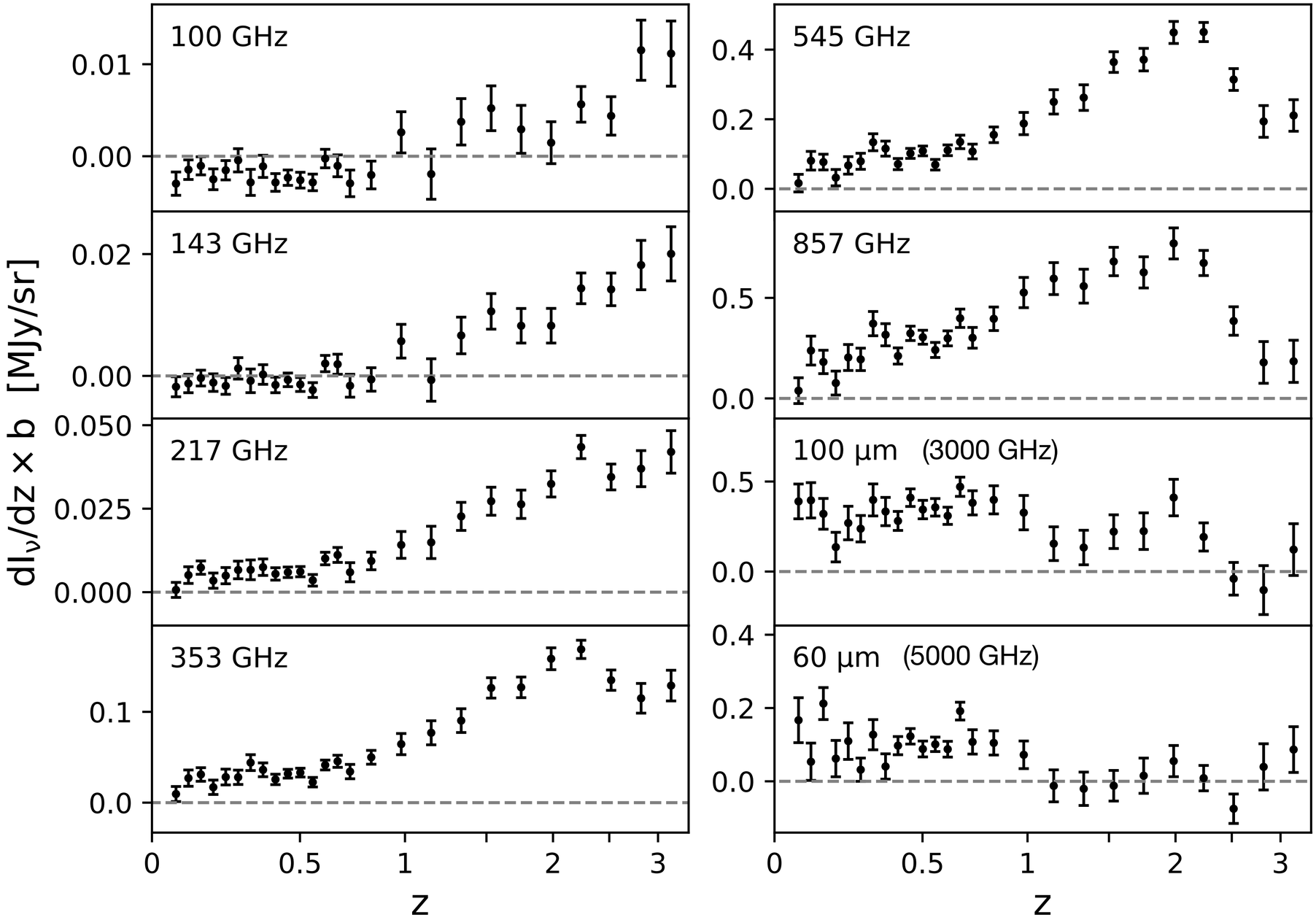


Planck + IRAS redshift deprojection

Chiang+ 2020a



× 2M SDSS redshifts



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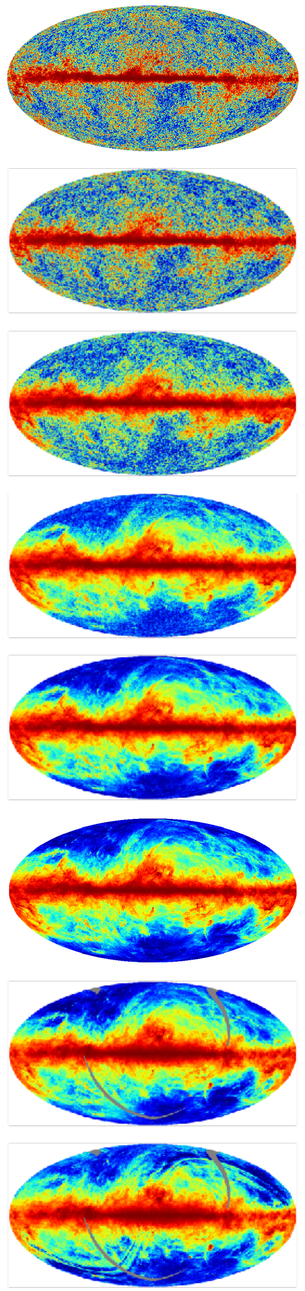

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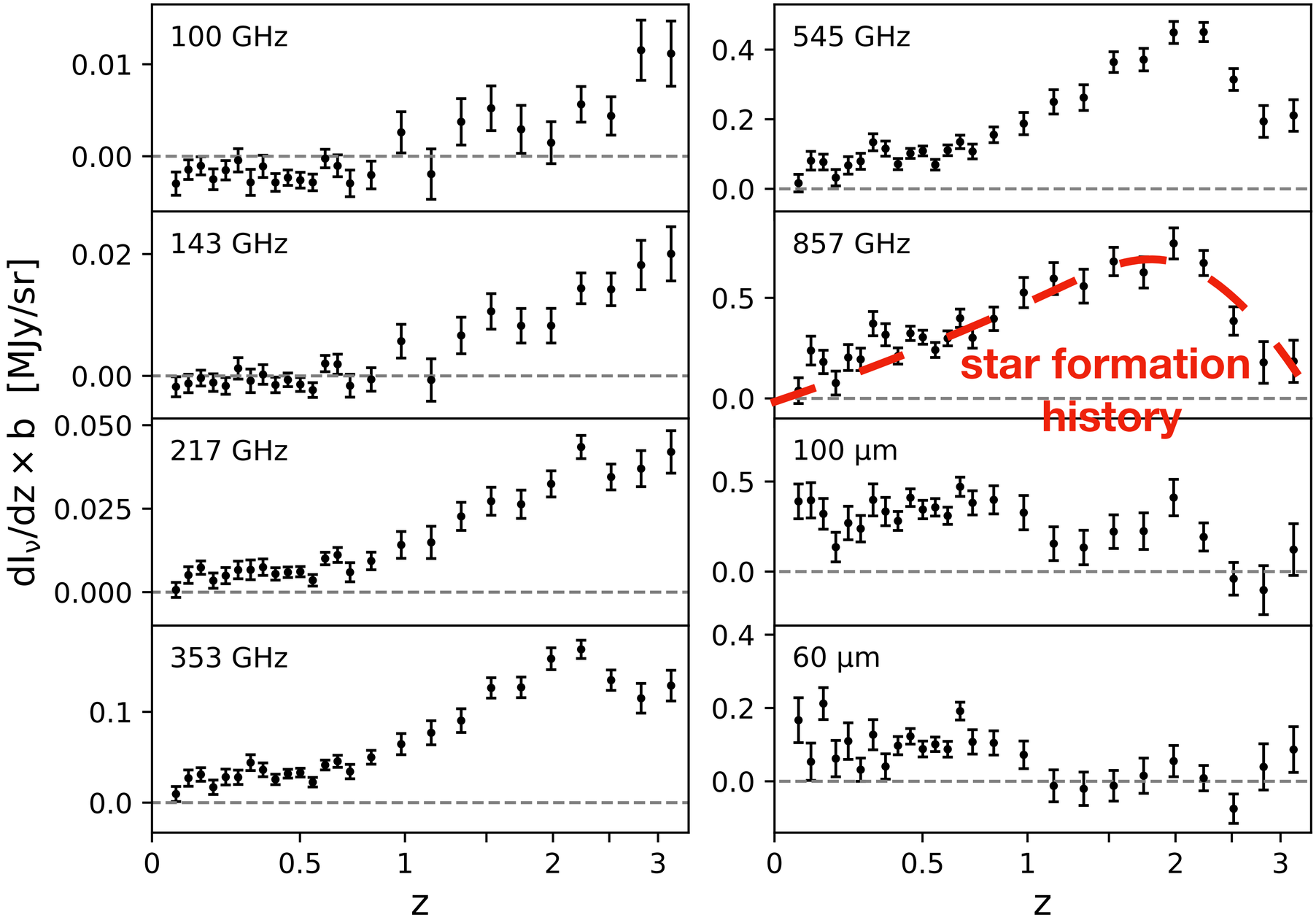

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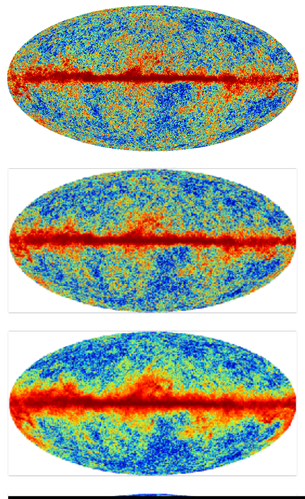

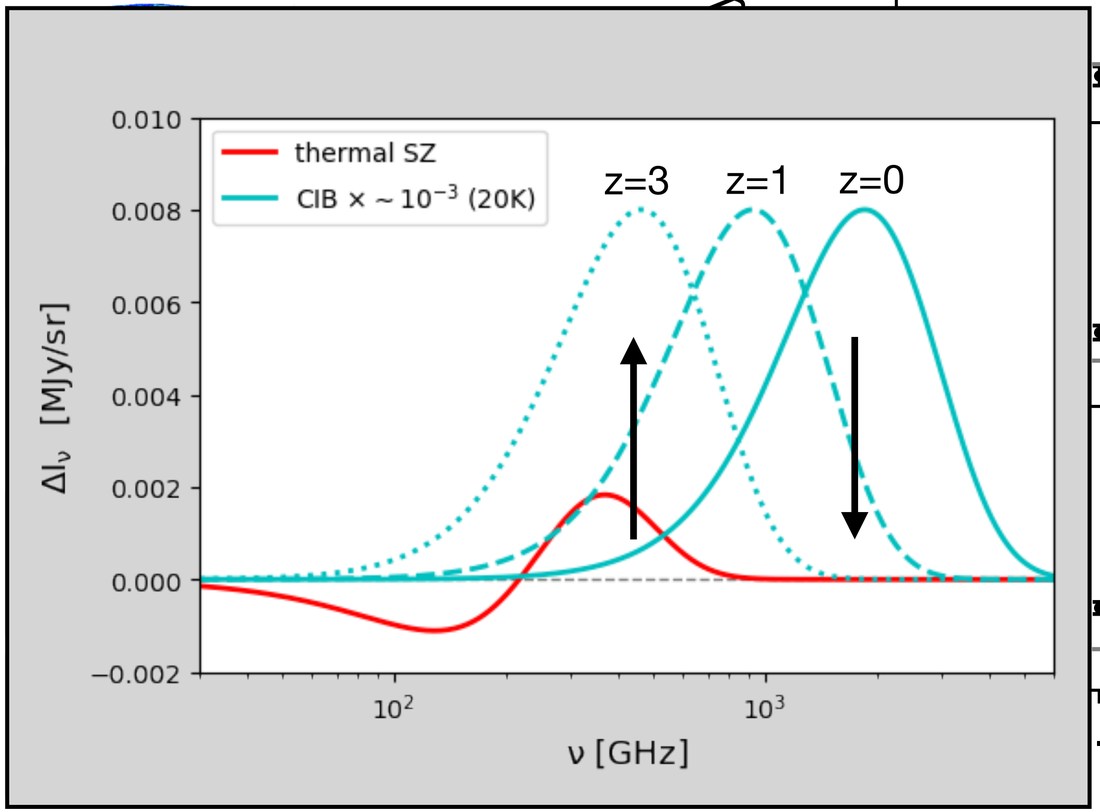

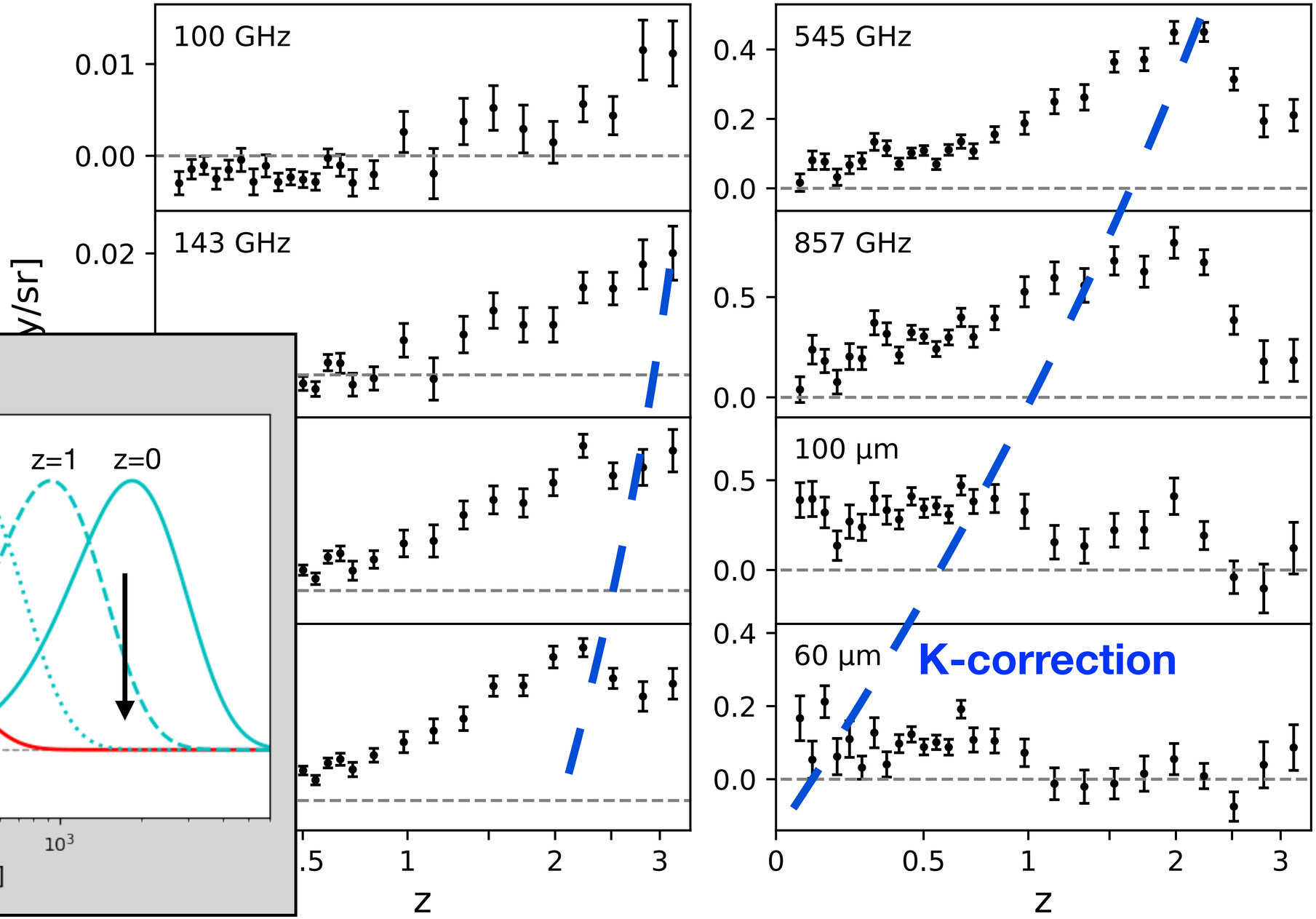

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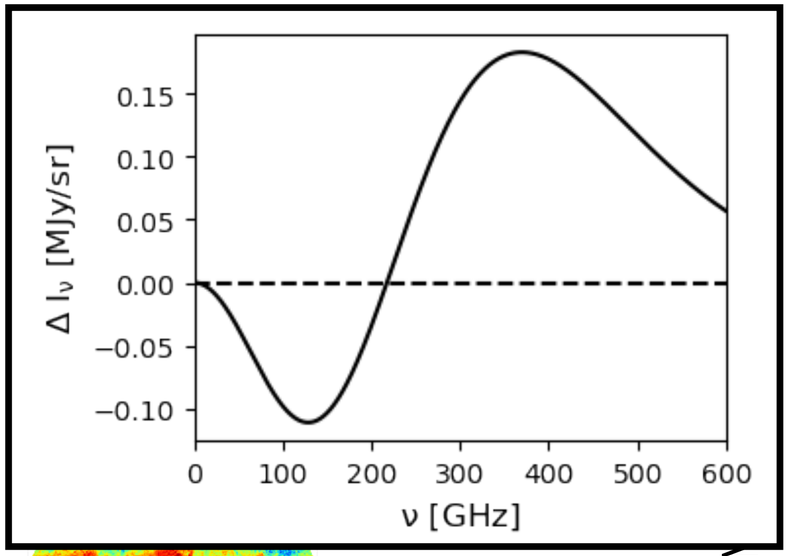
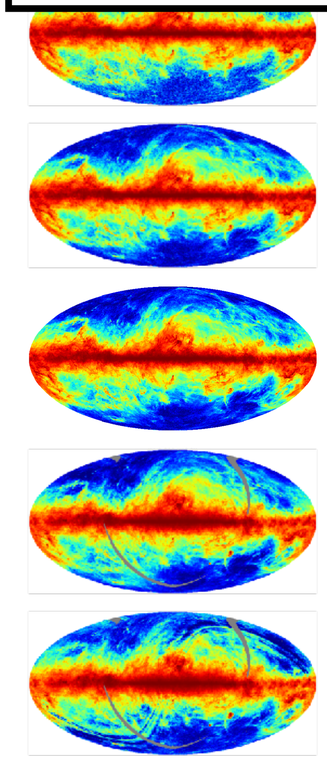
Chiang+ 2020a





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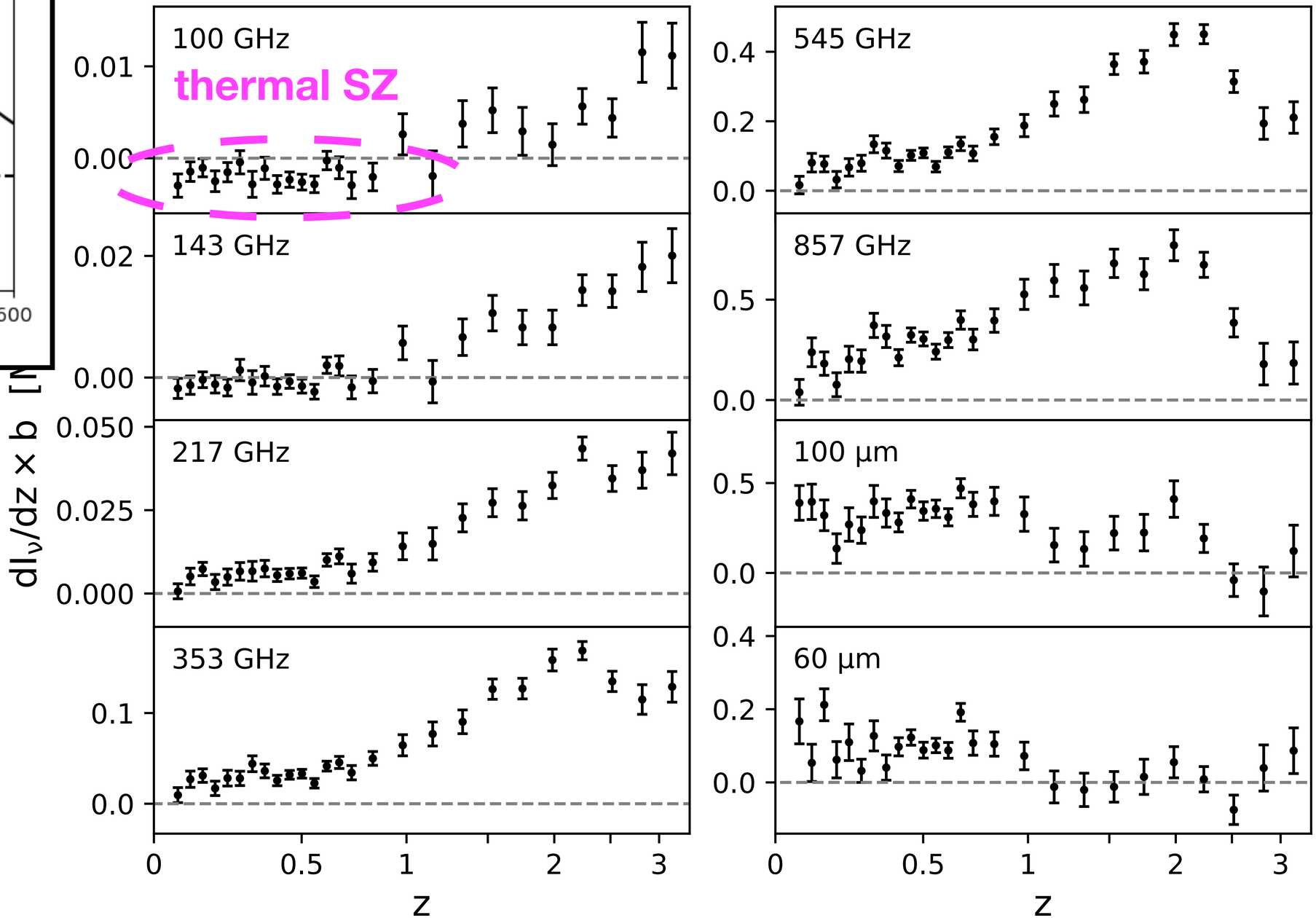

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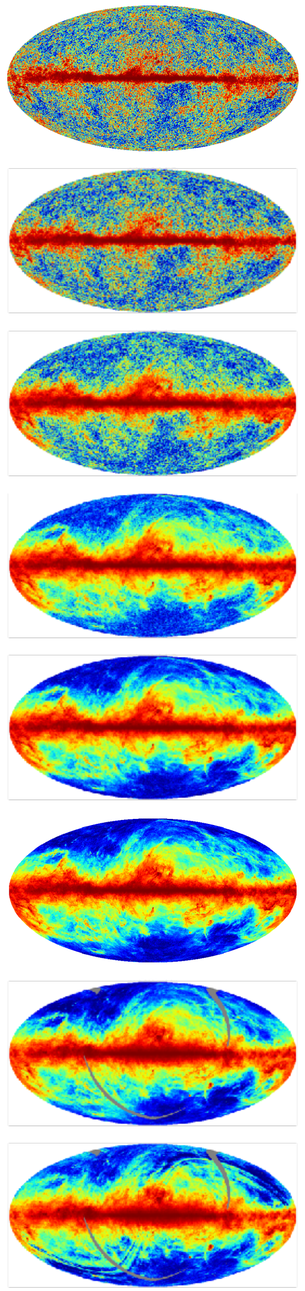
Chiang+ 2020a



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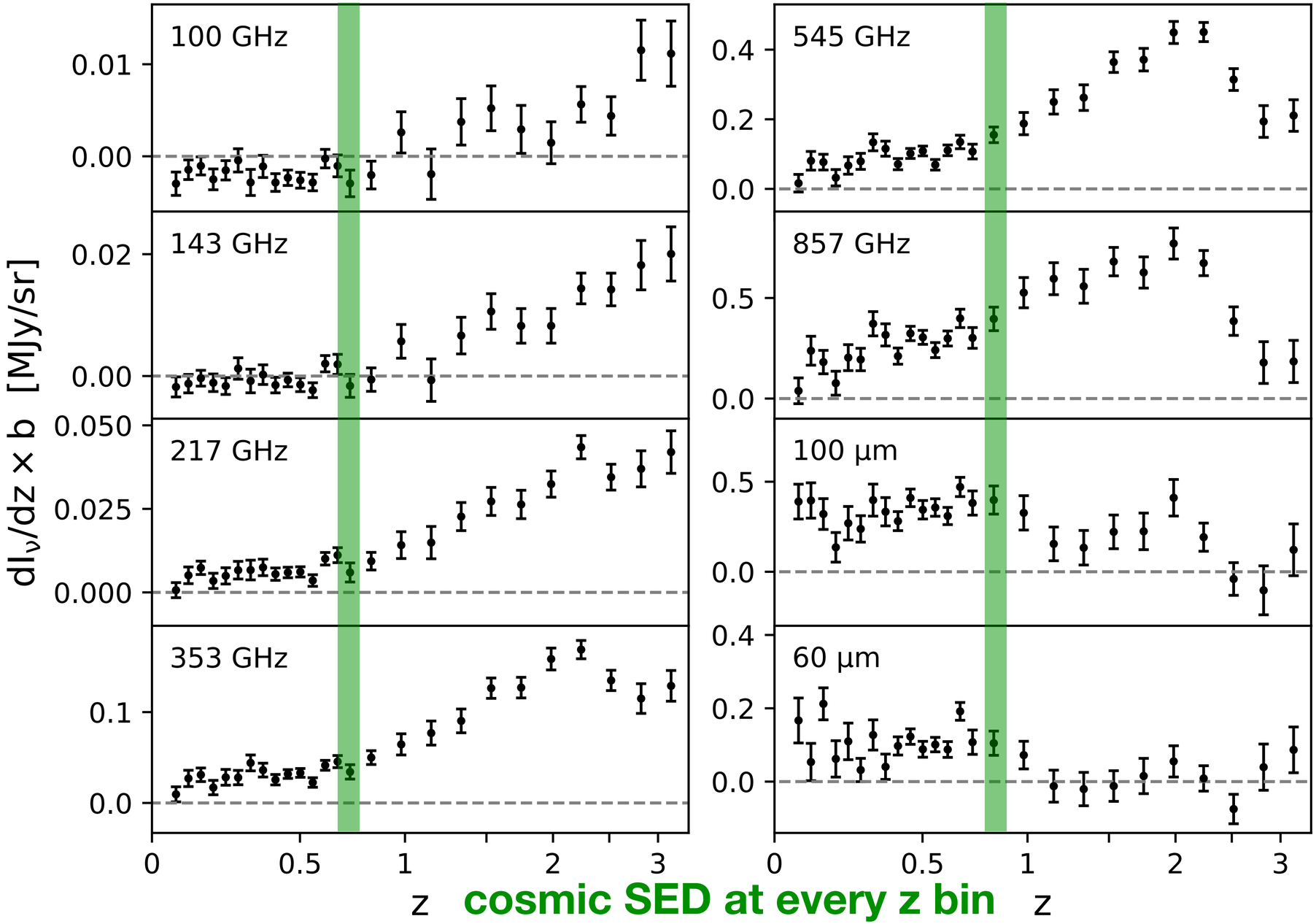
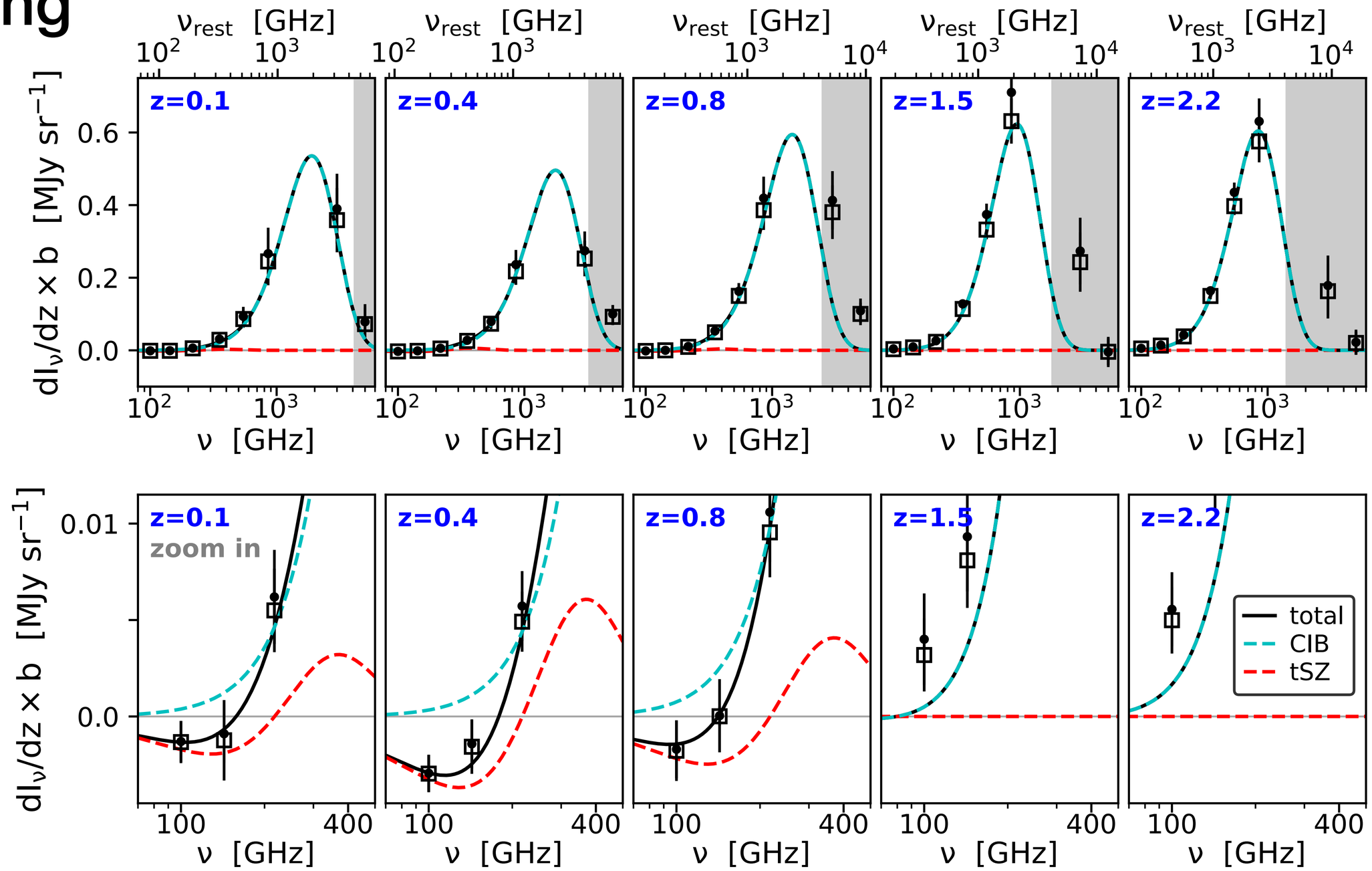


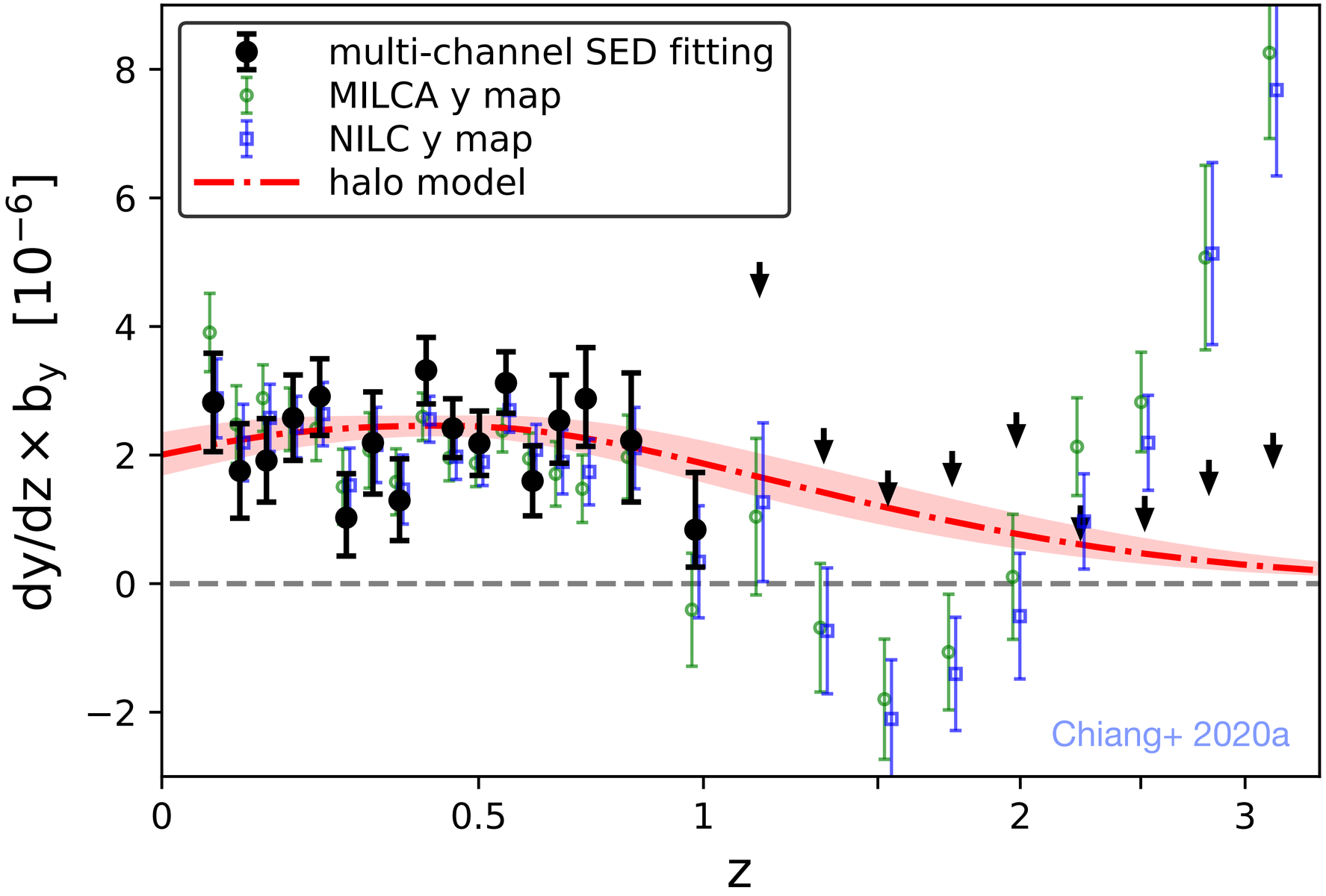
cosmic SED at every z bin

SED fitting

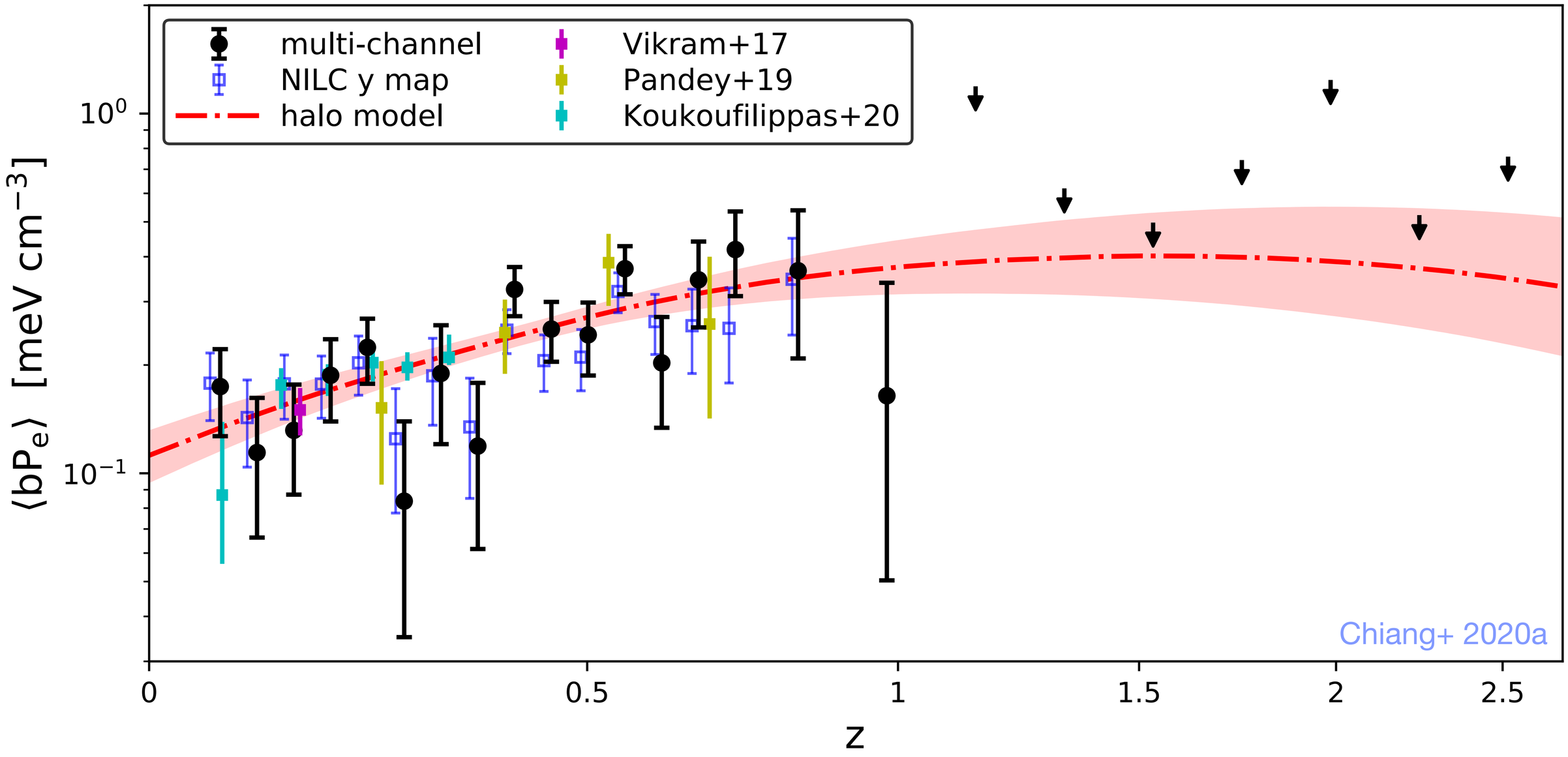


Chiang+ 2020a

tSZ compton y history



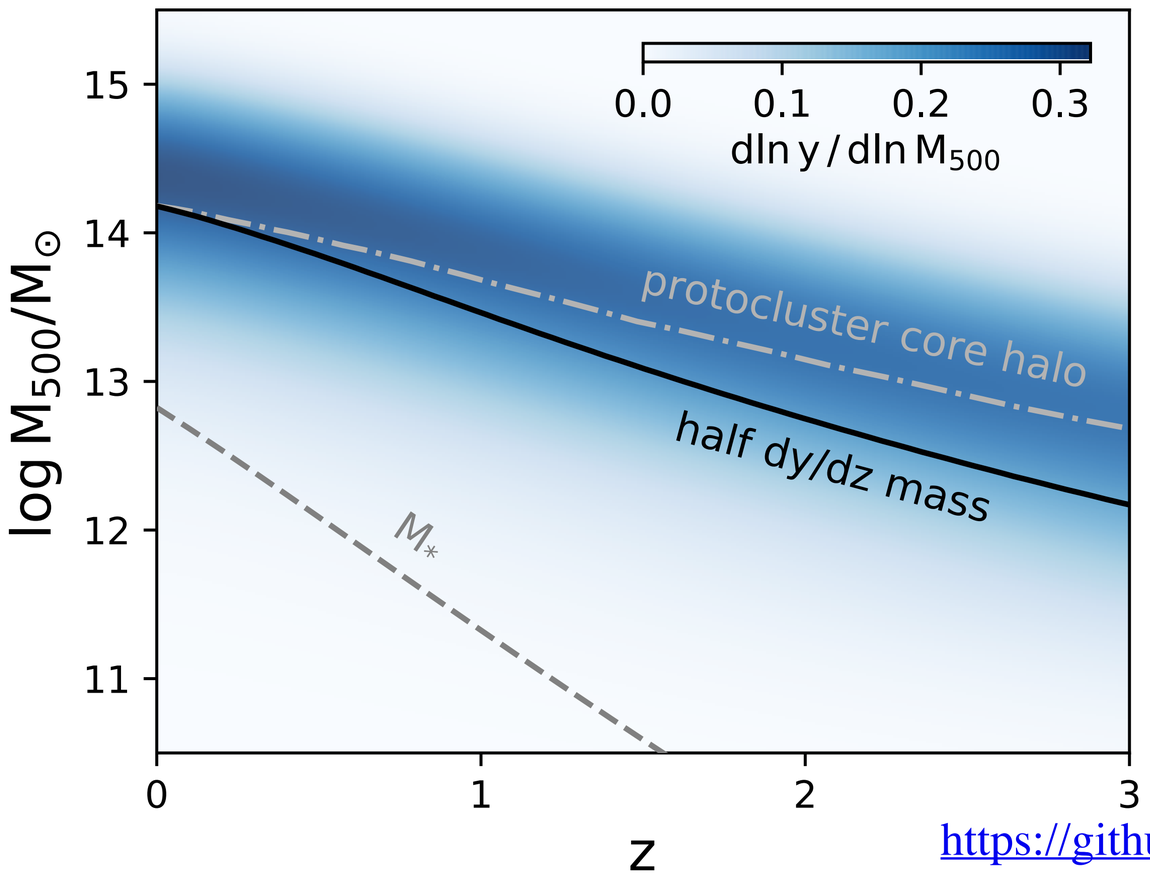
Bias-weighted gas pressure + Literature comparison

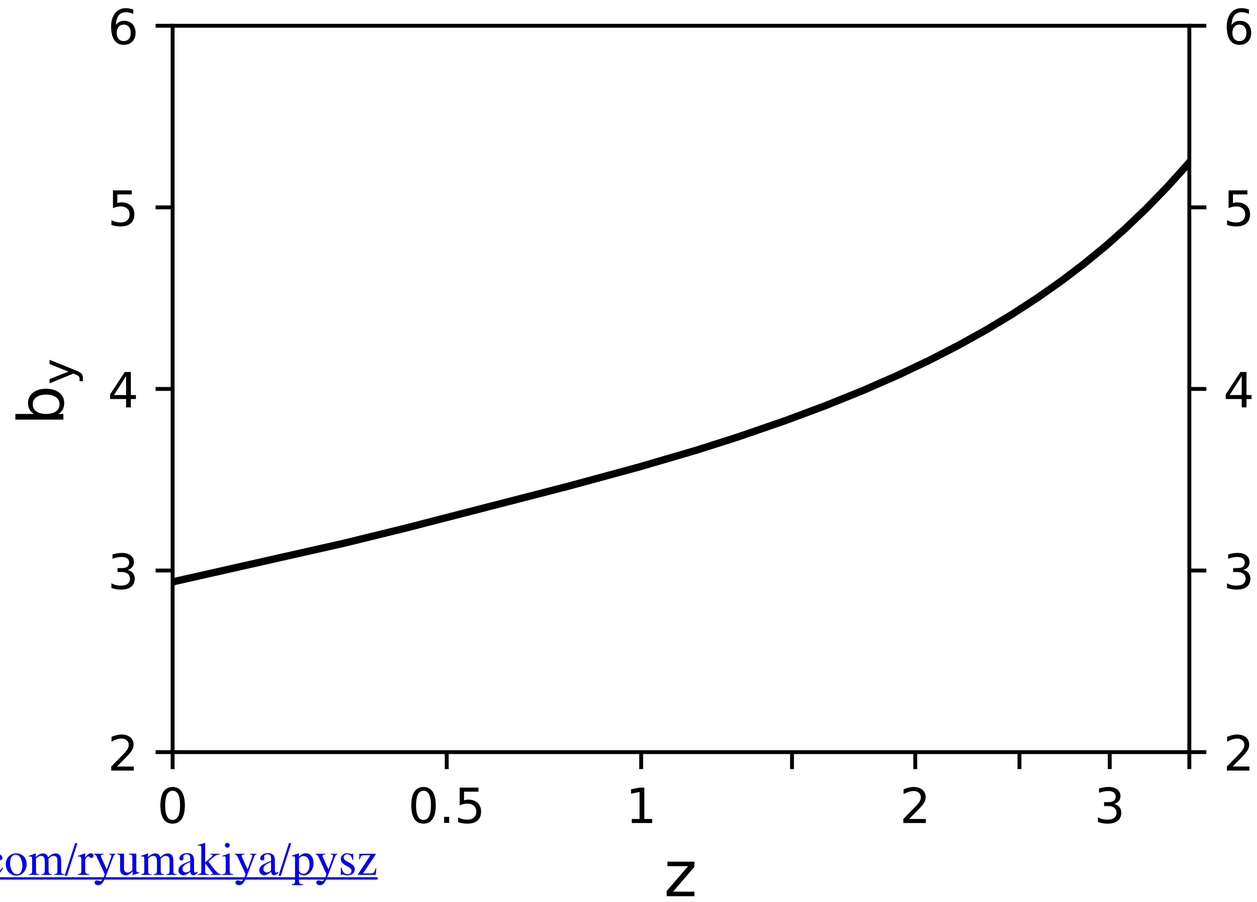


Insights from the halo model

Chiang+ 2020a, b

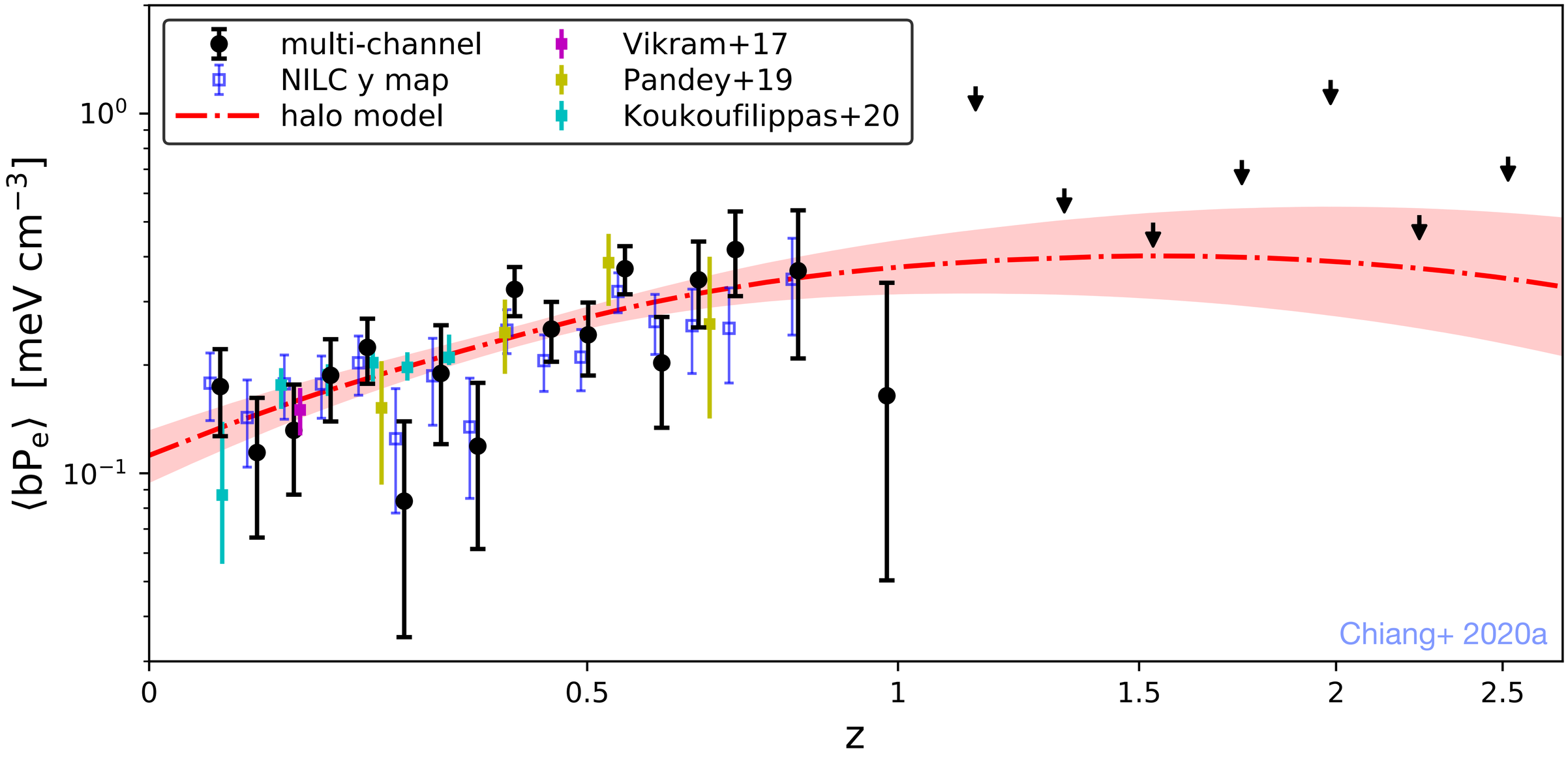
- Clusters, groups, and proto-clusters dominate cosmic y
- y weighted halo bias can be robustly predicted
- Cluster pressure profile is known empirically (Arnaud+10, Planck+13), but absolute mass calibration is not. Our tSZ measurements give mass bias **B = $M_{500,\,true}$ / $M_{500,\,empirical}$ ~1.27**



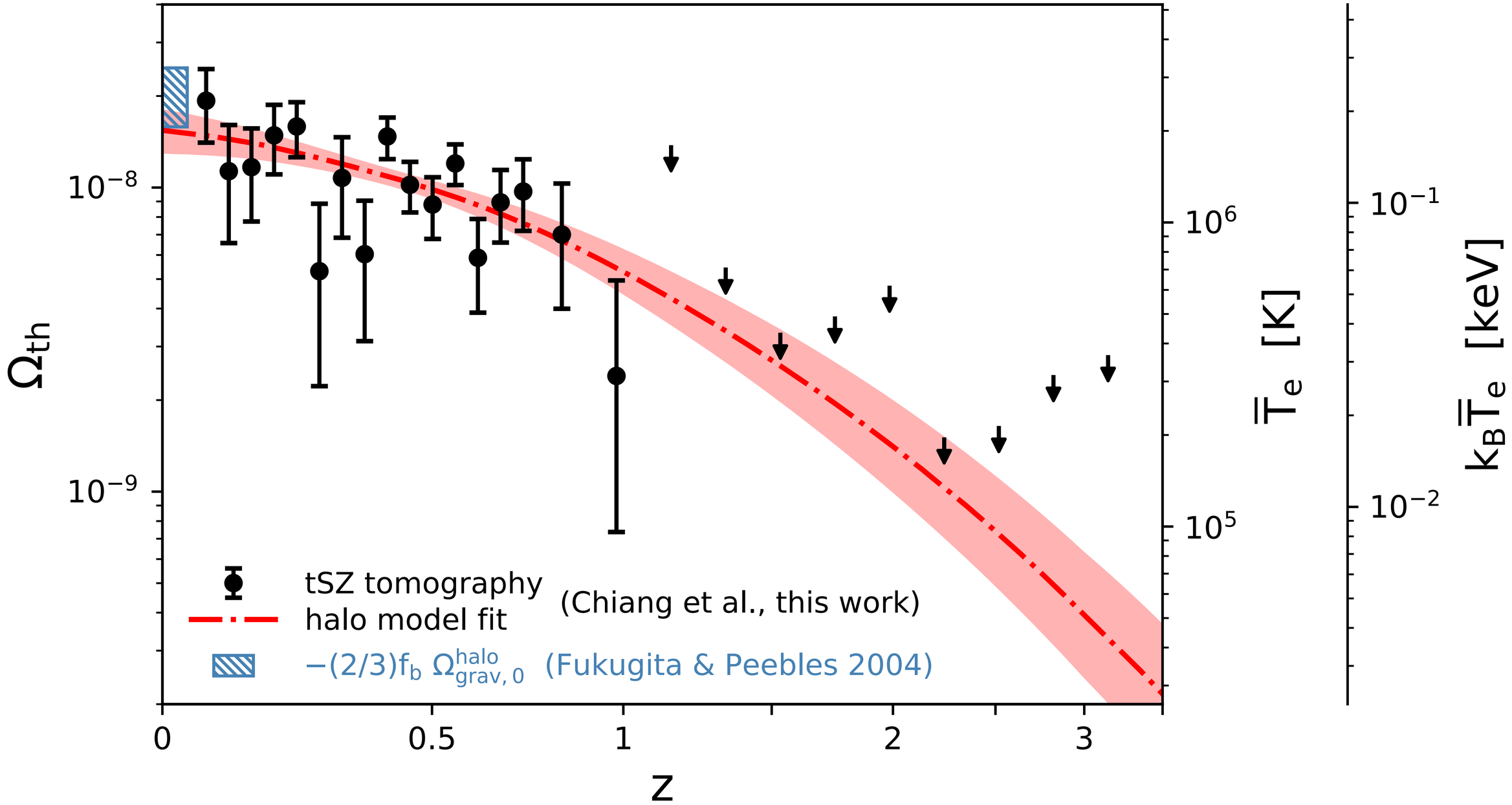


https://github.com/ryumakiya/pysz

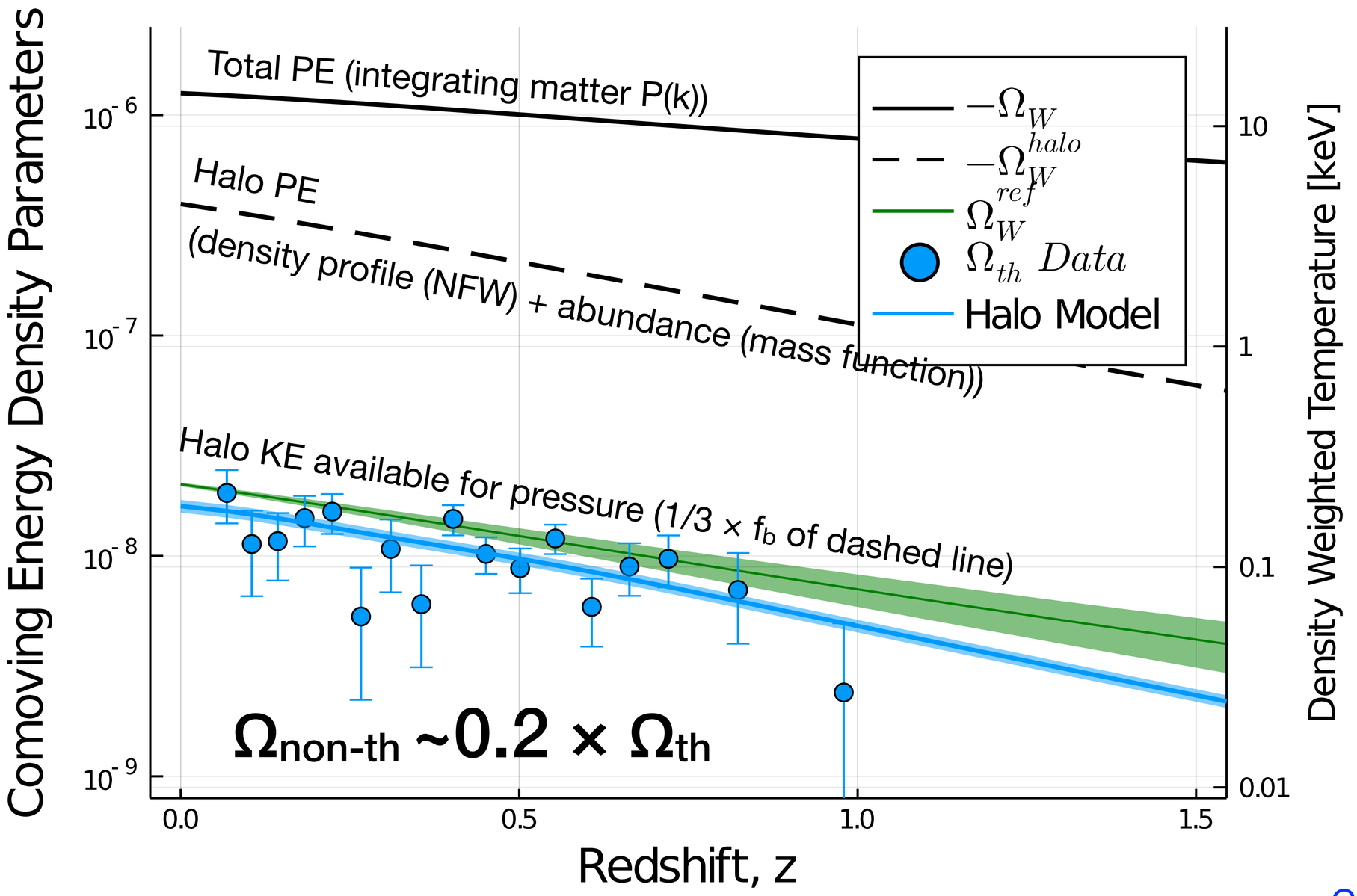
Bias-weighted gas pressure



Cosmic thermal energy parameter

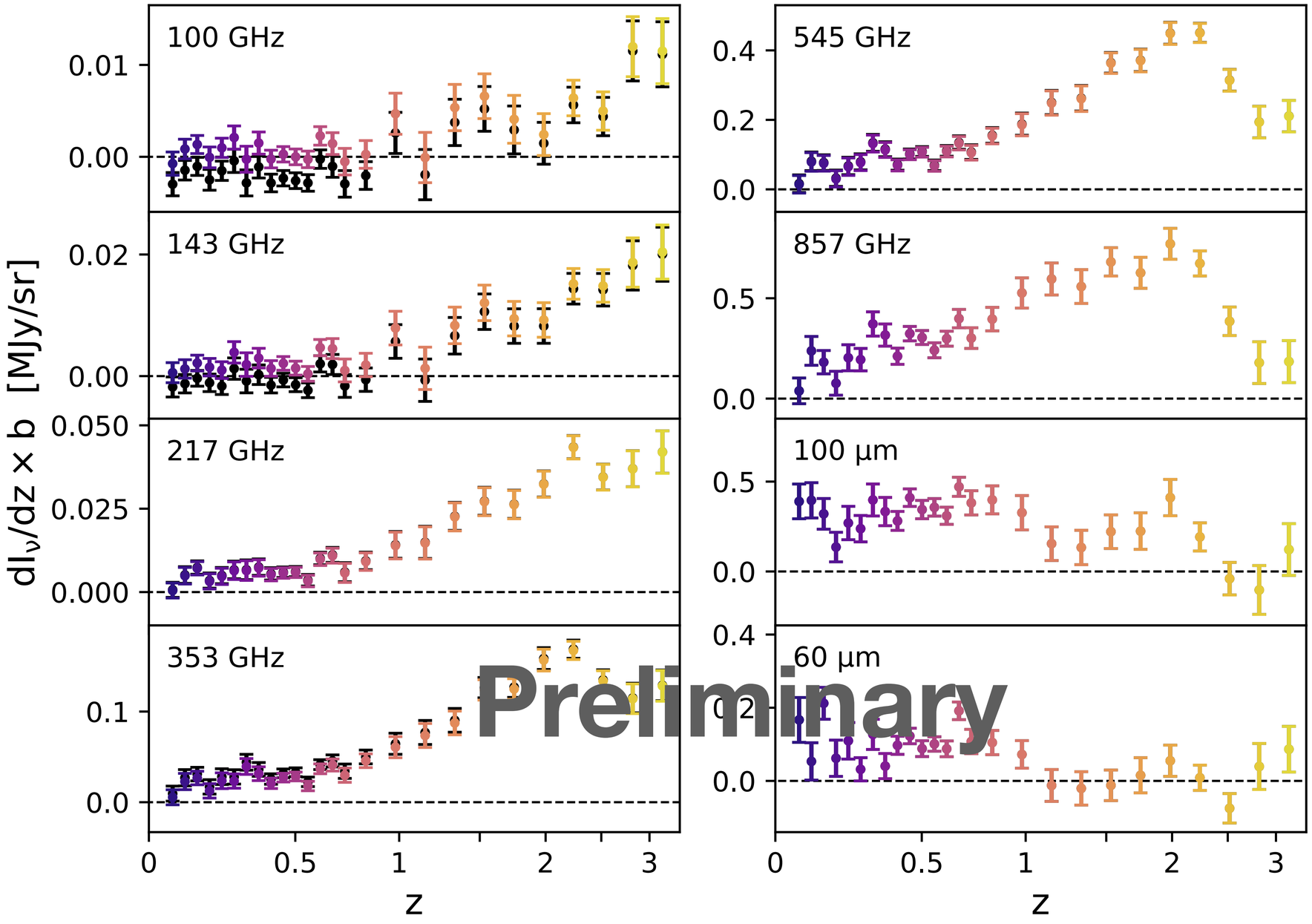


Thermal + non-thermal pressure balances gravity in halos

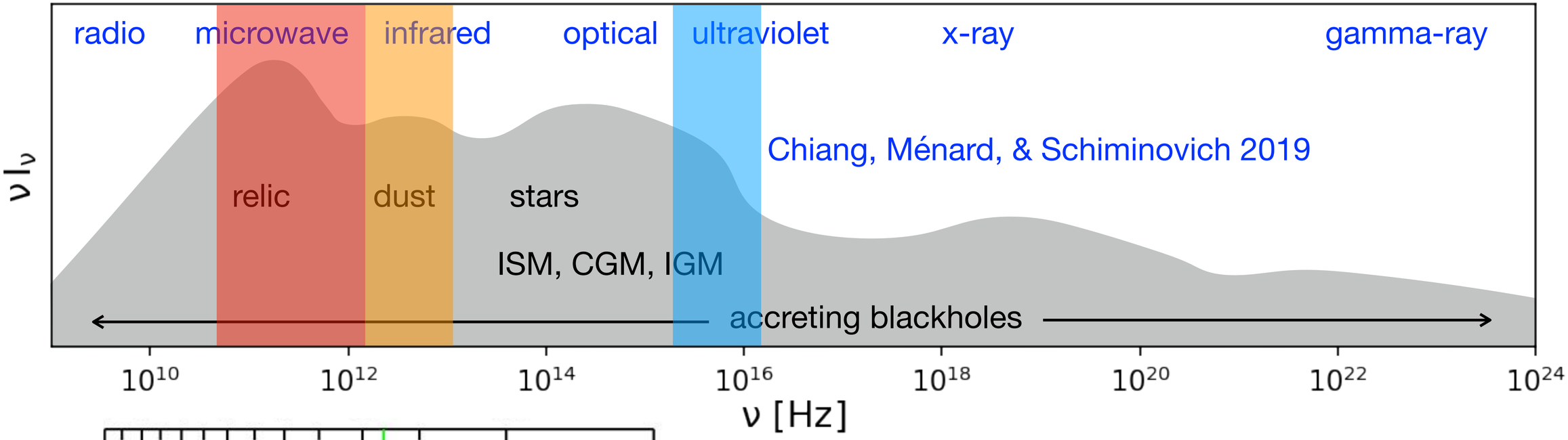


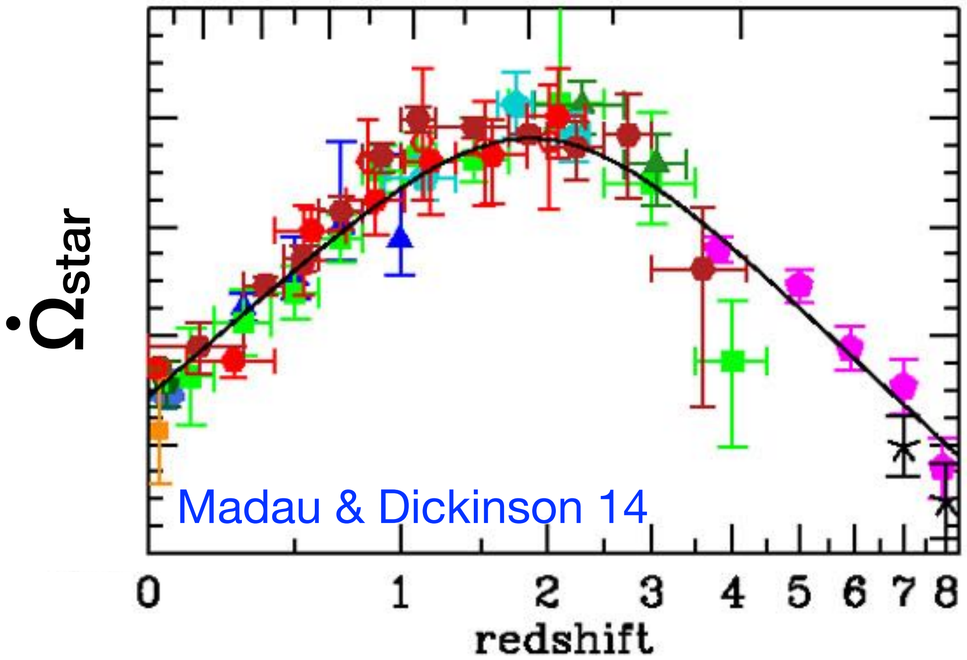
Chiang+ 2020b

Work in progress— CIB / Ω_{dust} analysis

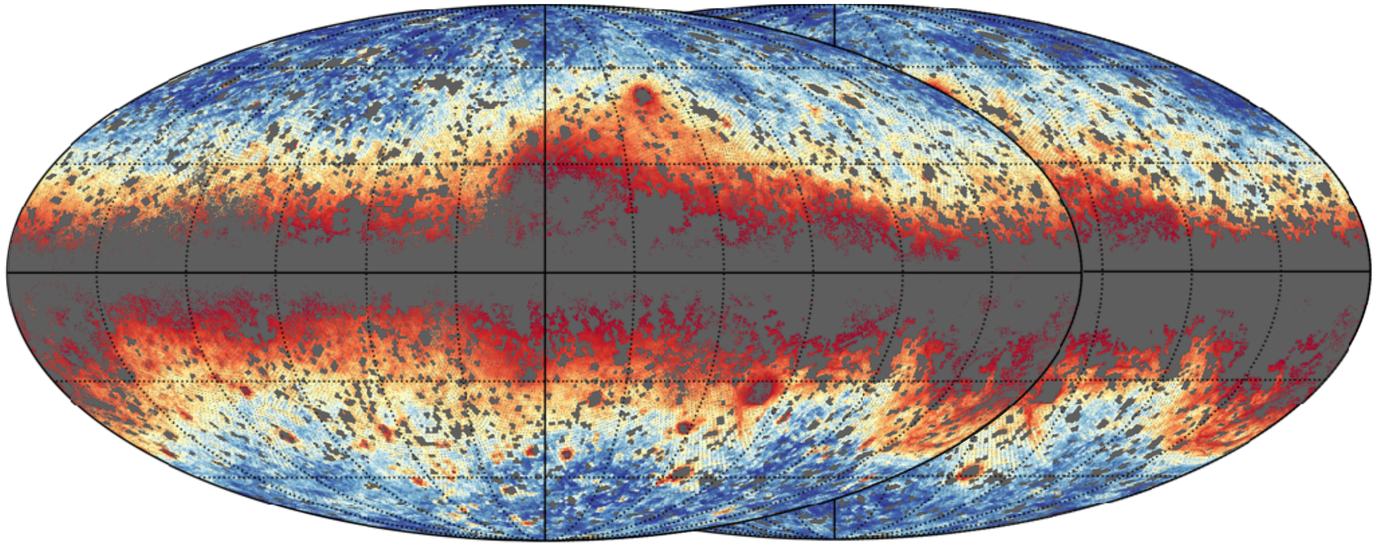


UV background, another piece of EBL with rich physics





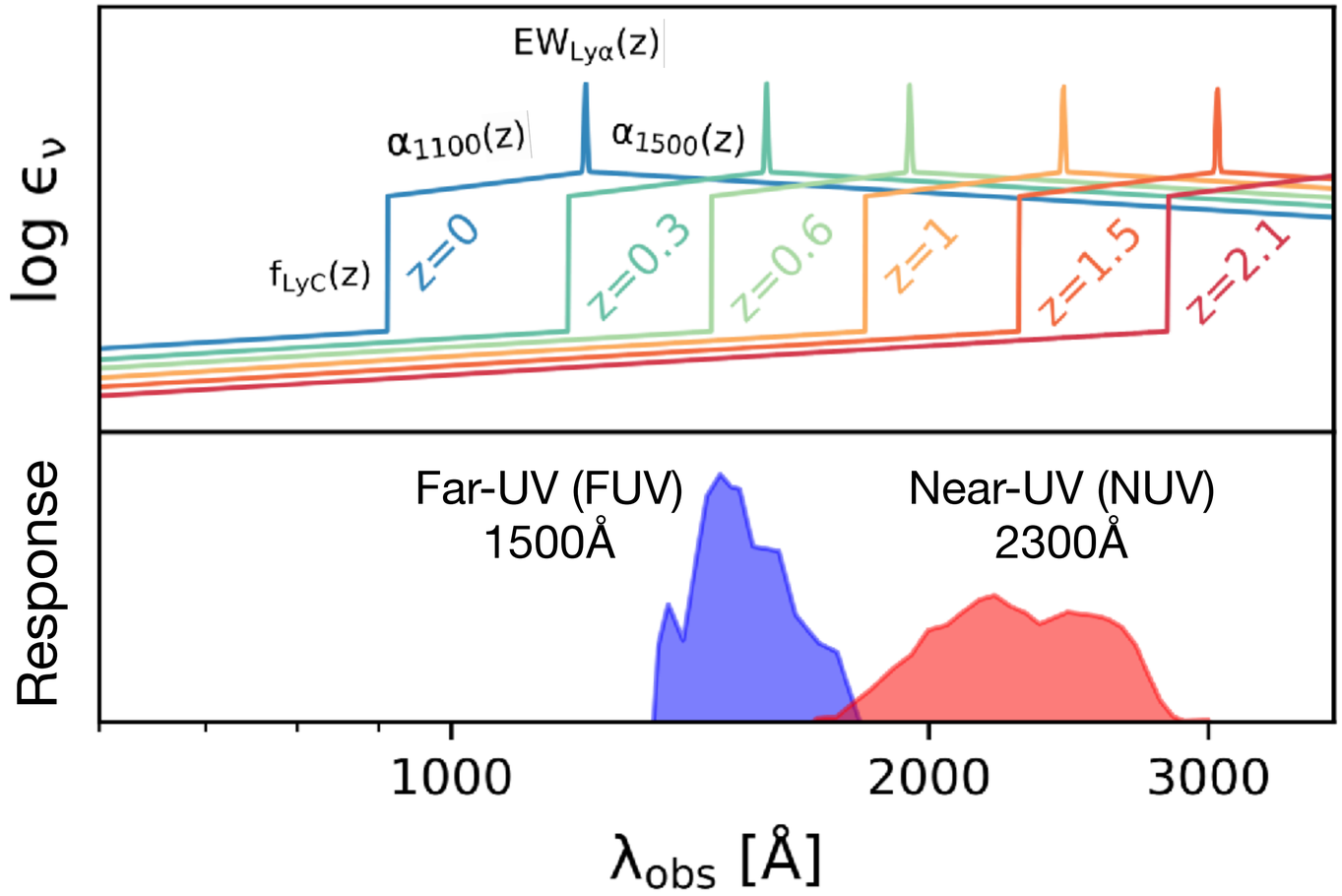
GALEX near-UV (NUV) 2300Å & far-UV (FUV) 1500Å



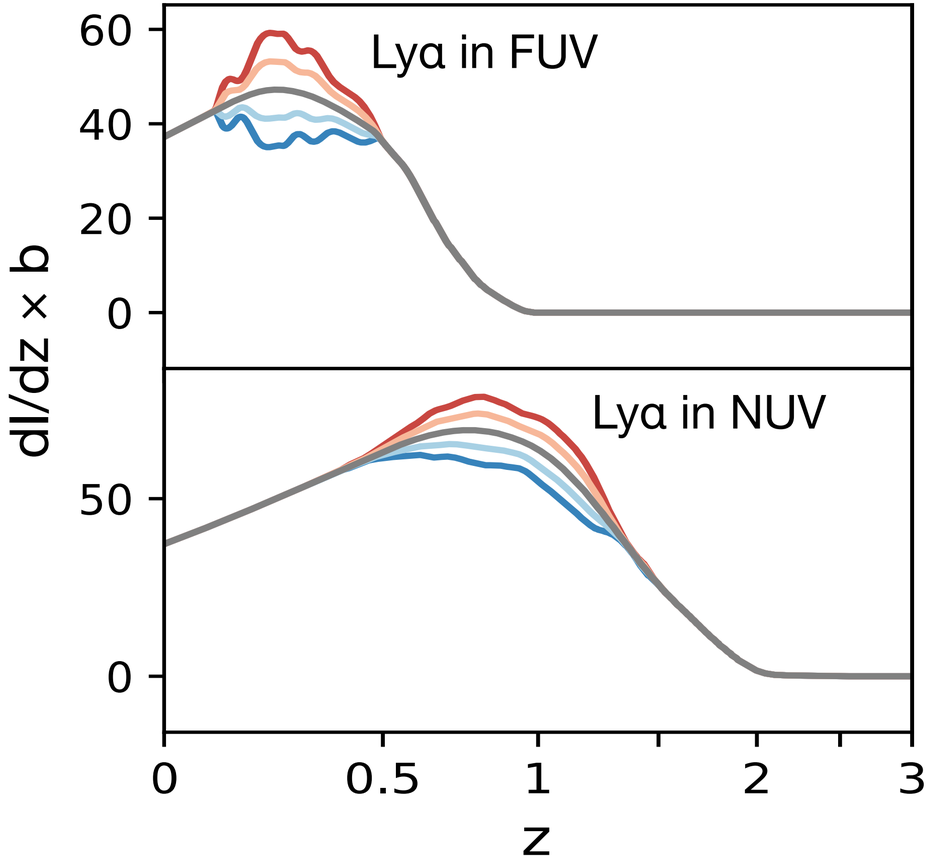
Redshift tomography is simultaneously a frequency tomography

Chiang+ 2019

UV background spectrum



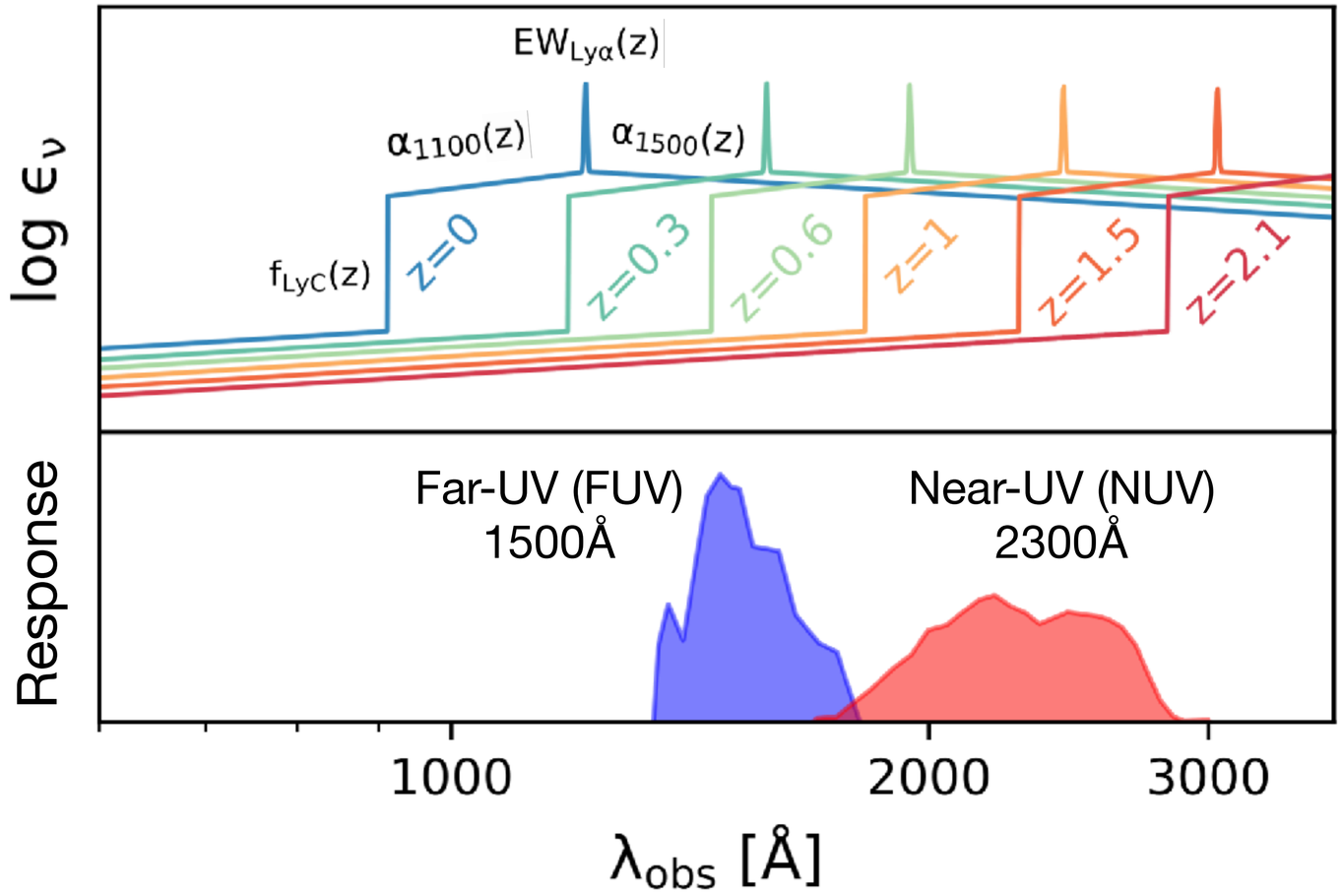
tomographic observable



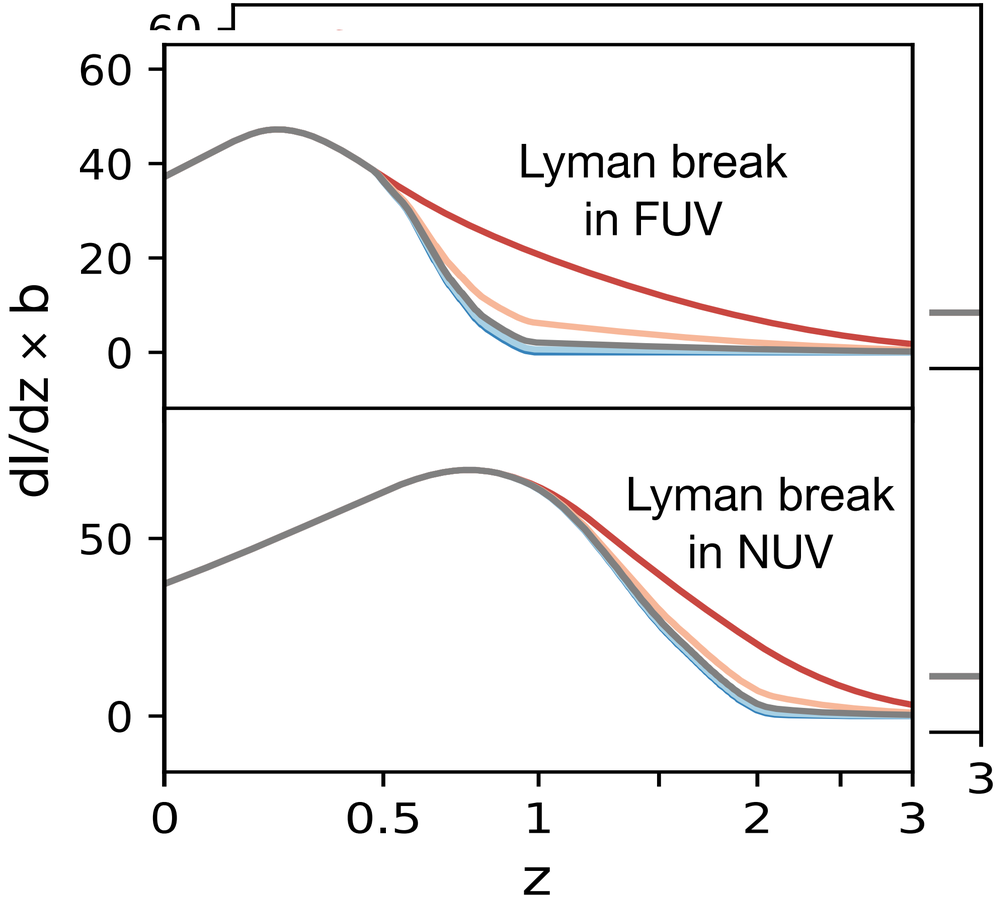
Redshift tomography is simultaneously a frequency tomography

Chiang+ 2019

UV background spectrum



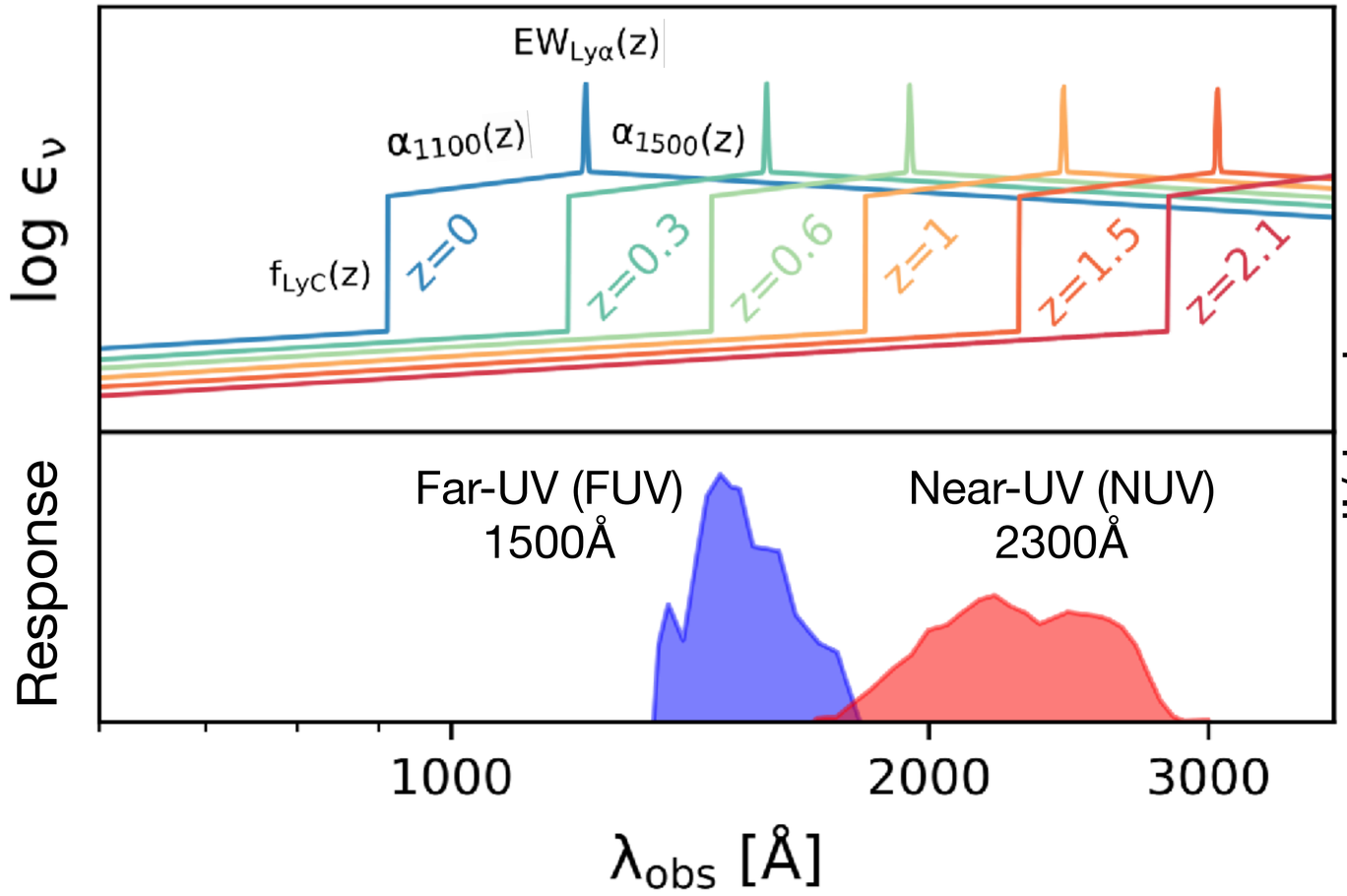
tomographic observable



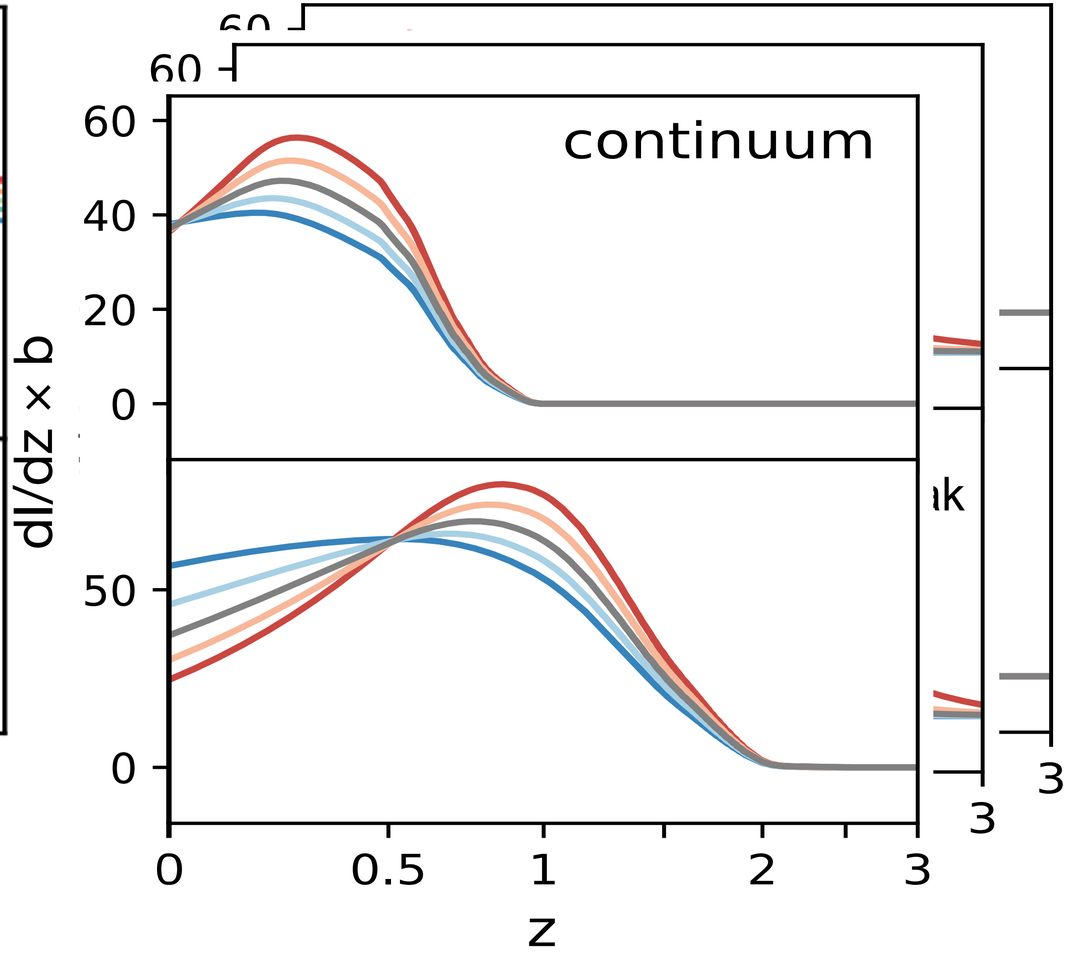
Redshift tomography is simultaneously a frequency tomography

Chiang+ 2019

UV background spectrum

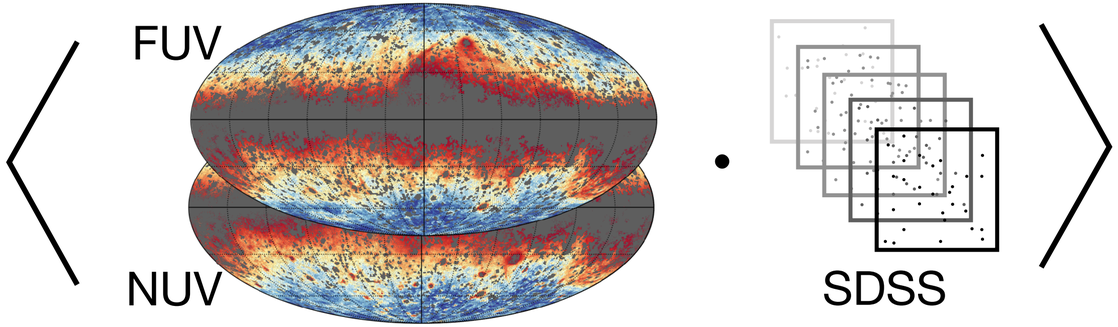


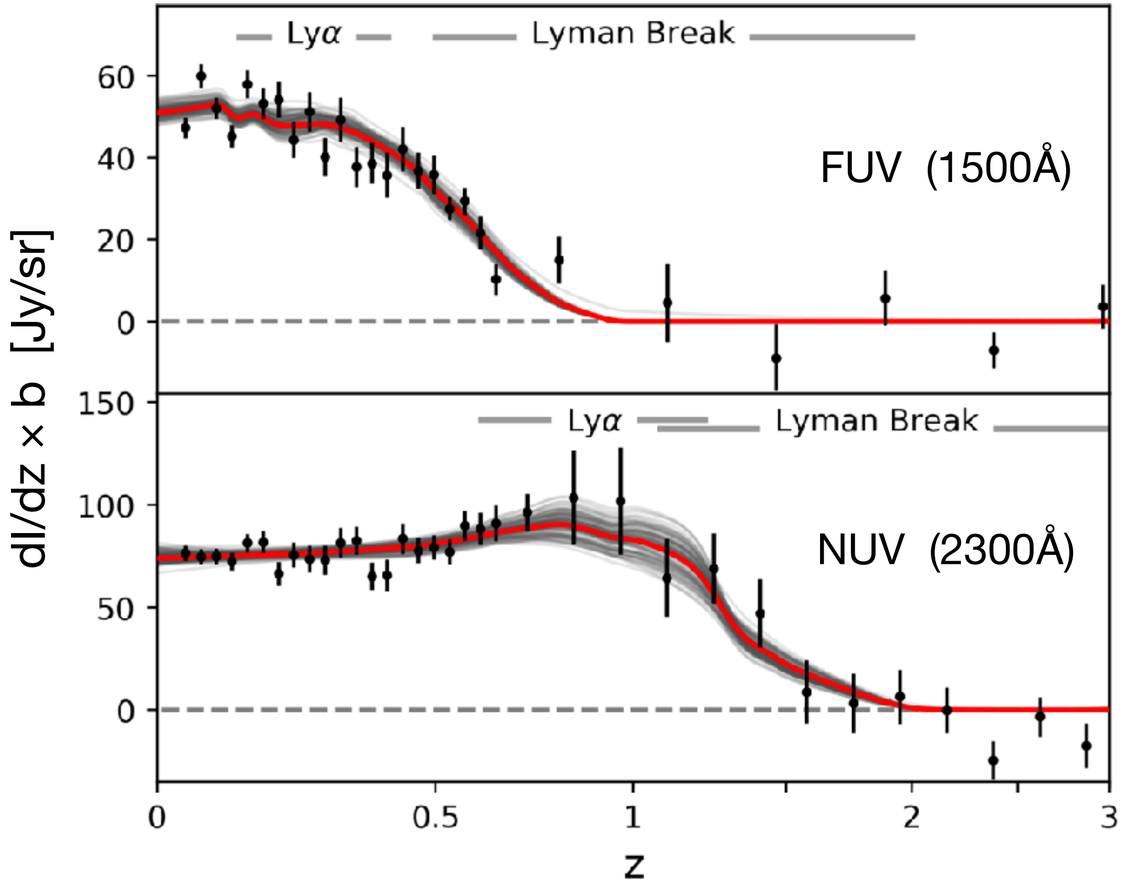
tomographic observable

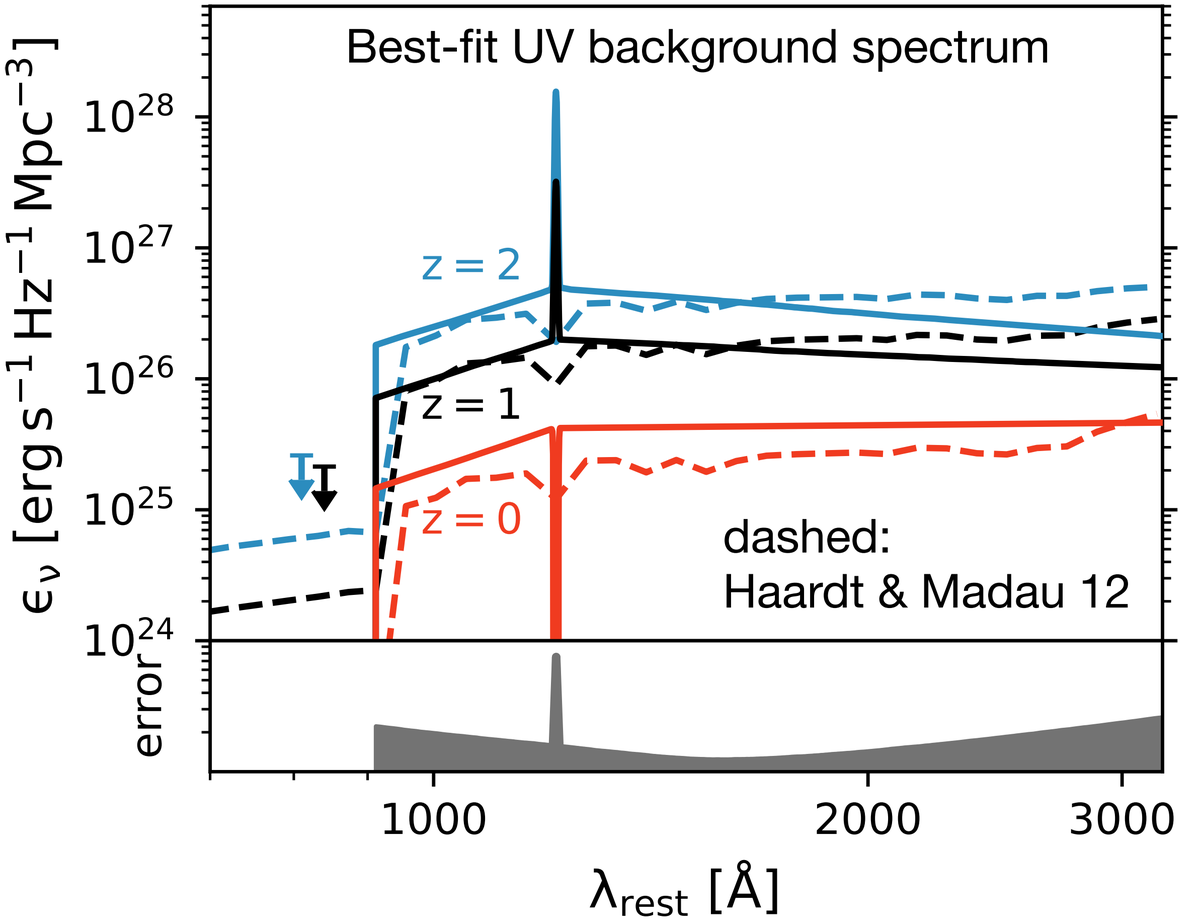


Spectral Tagging the Cosmic UV Background in GALEX

Chiang+ 2019

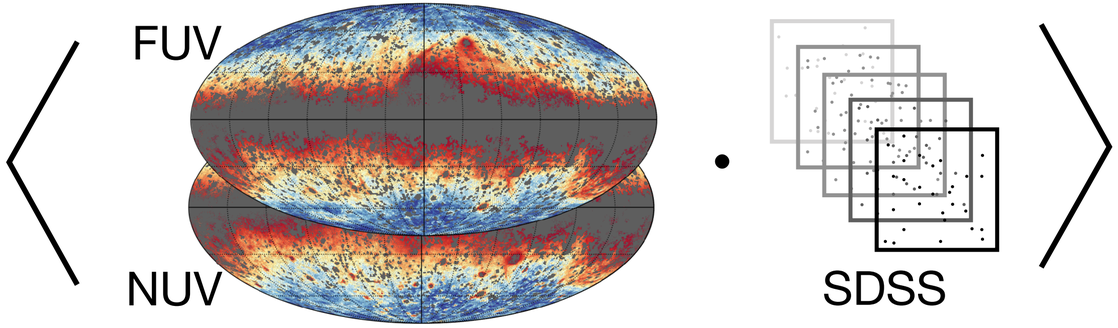


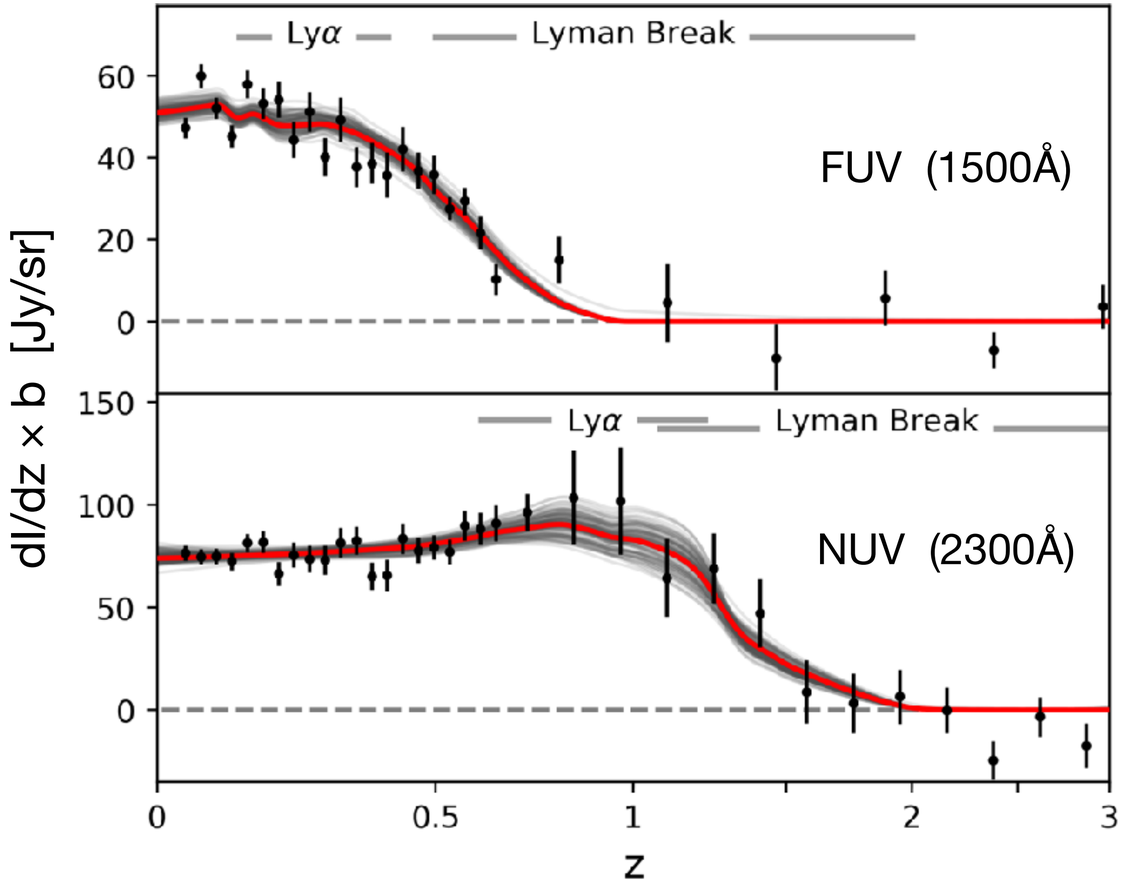


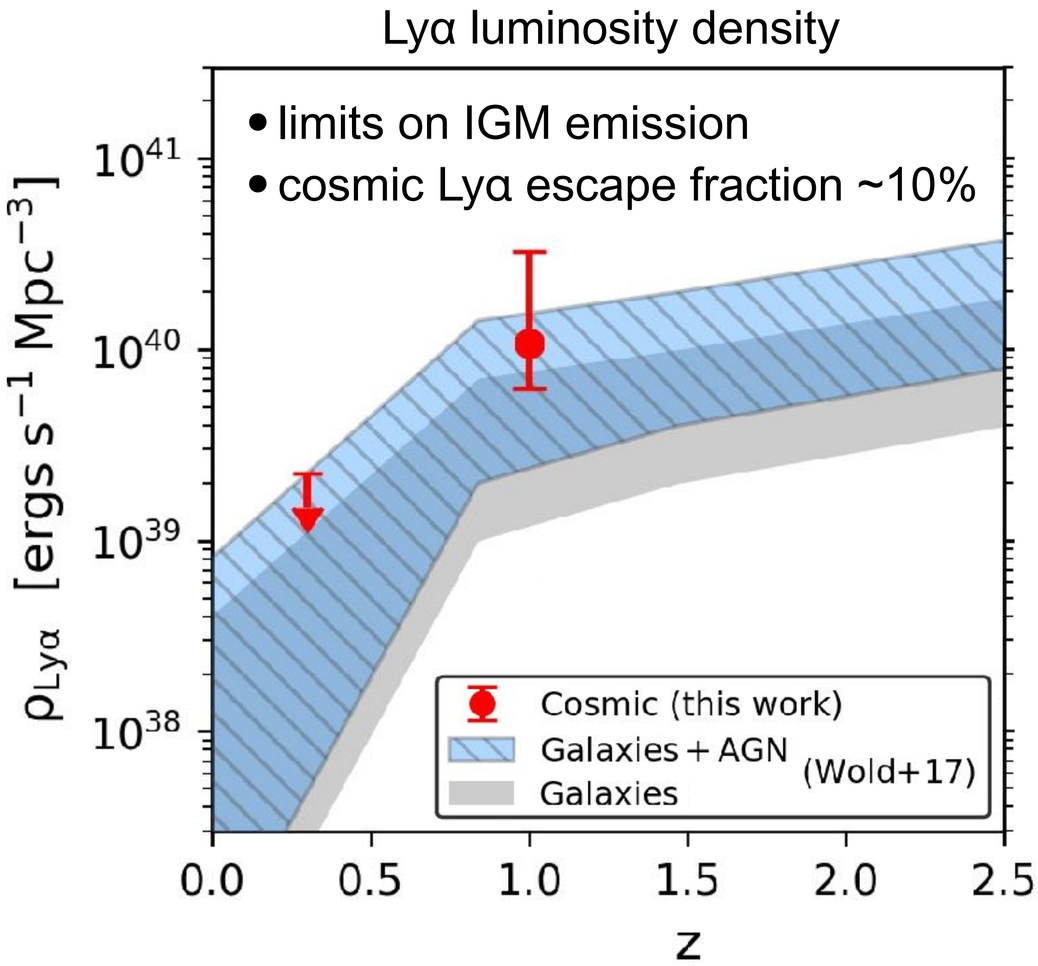


Spectral Tagging the Cosmic UV Background in GALEX

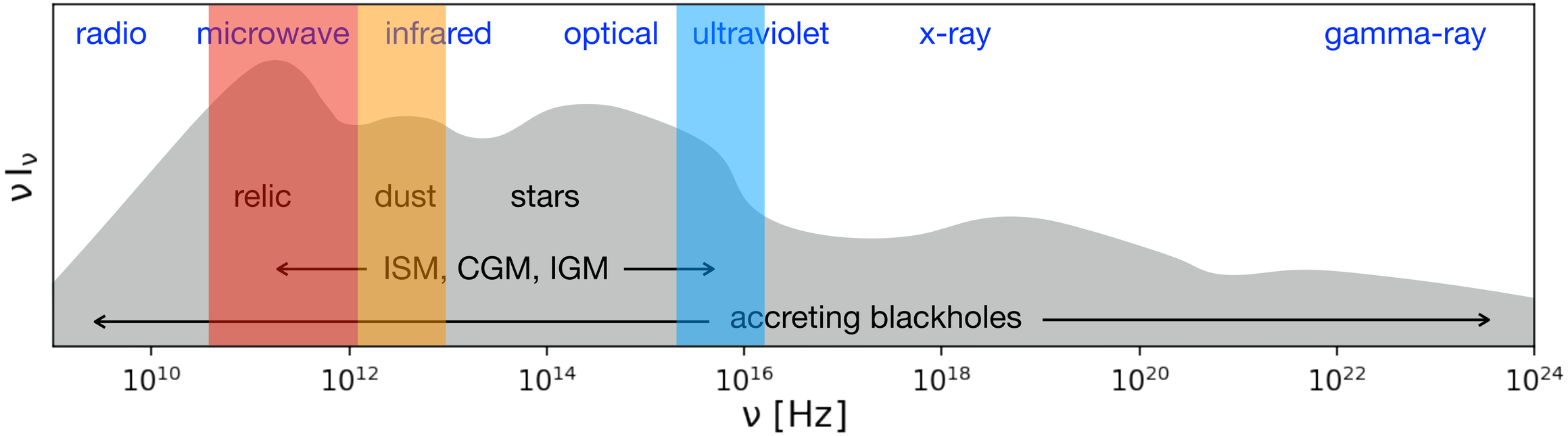
Chiang+ 2019



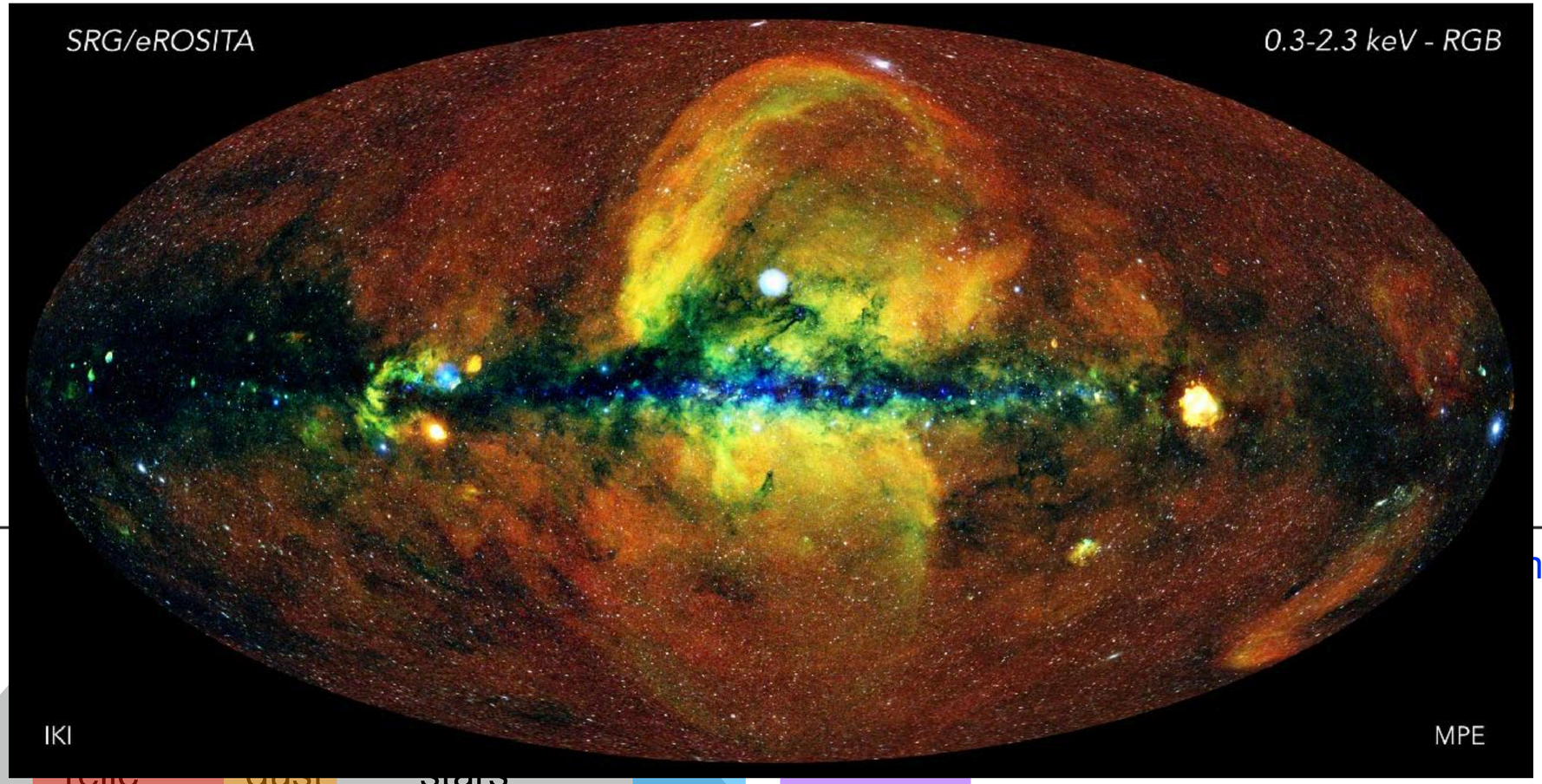


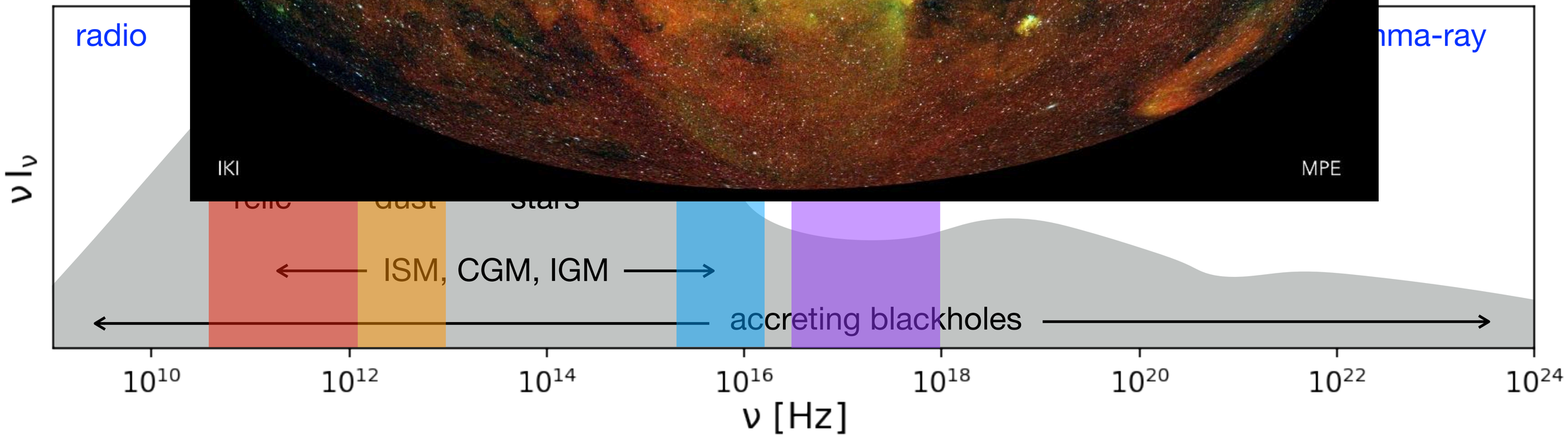


What's next?


radio
microwave
infrared
optical
ultraviolet
x-ray
gamma-ray
relic
dust
stars
ISM, CGM, IGM
accreting blackholes
νI_ν
10^{10}
10^{12}
10^{14}
10^{16}
10^{18}
10^{20}
10^{22}
10^{24}
ν [Hz]

What's next? X-ray background = $\dot{\Omega}_{SMBH}$ + clusters + WHIM





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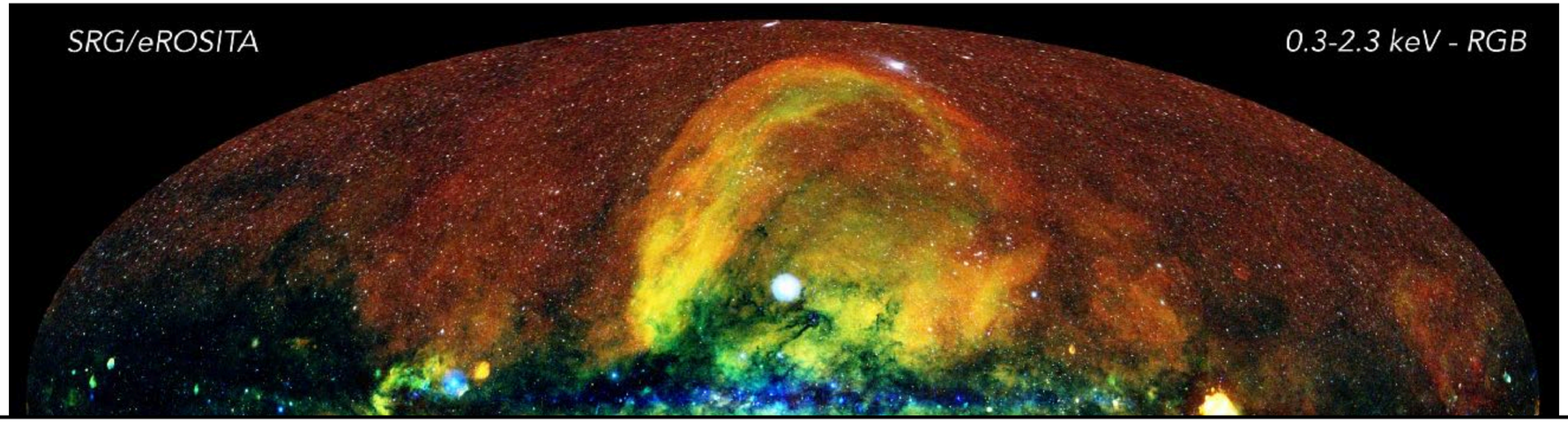
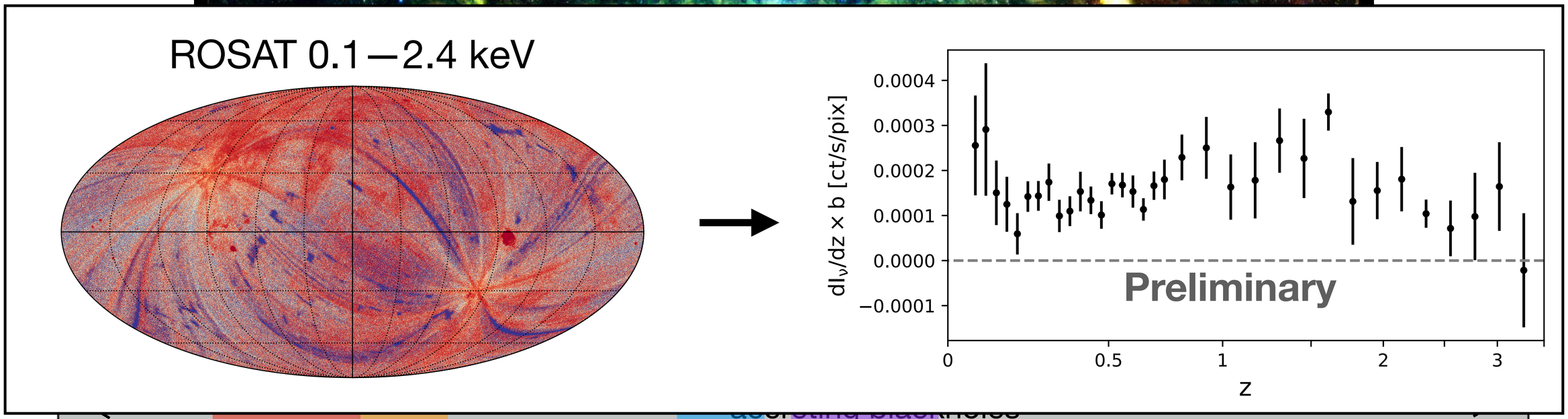
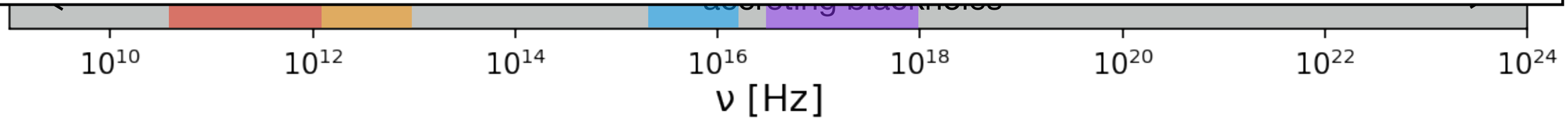




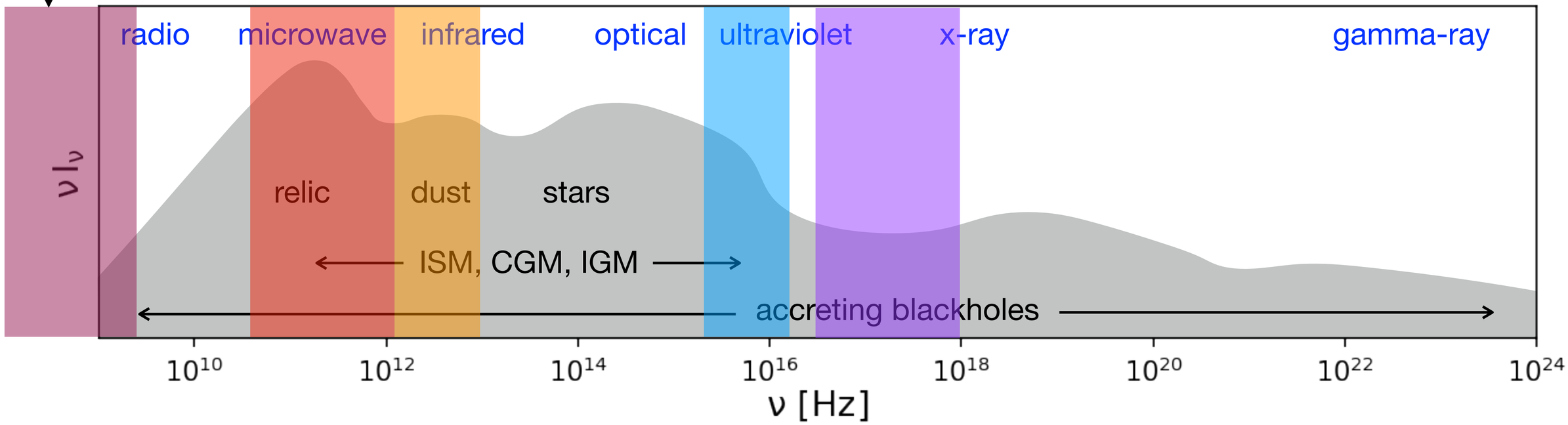


What's next?

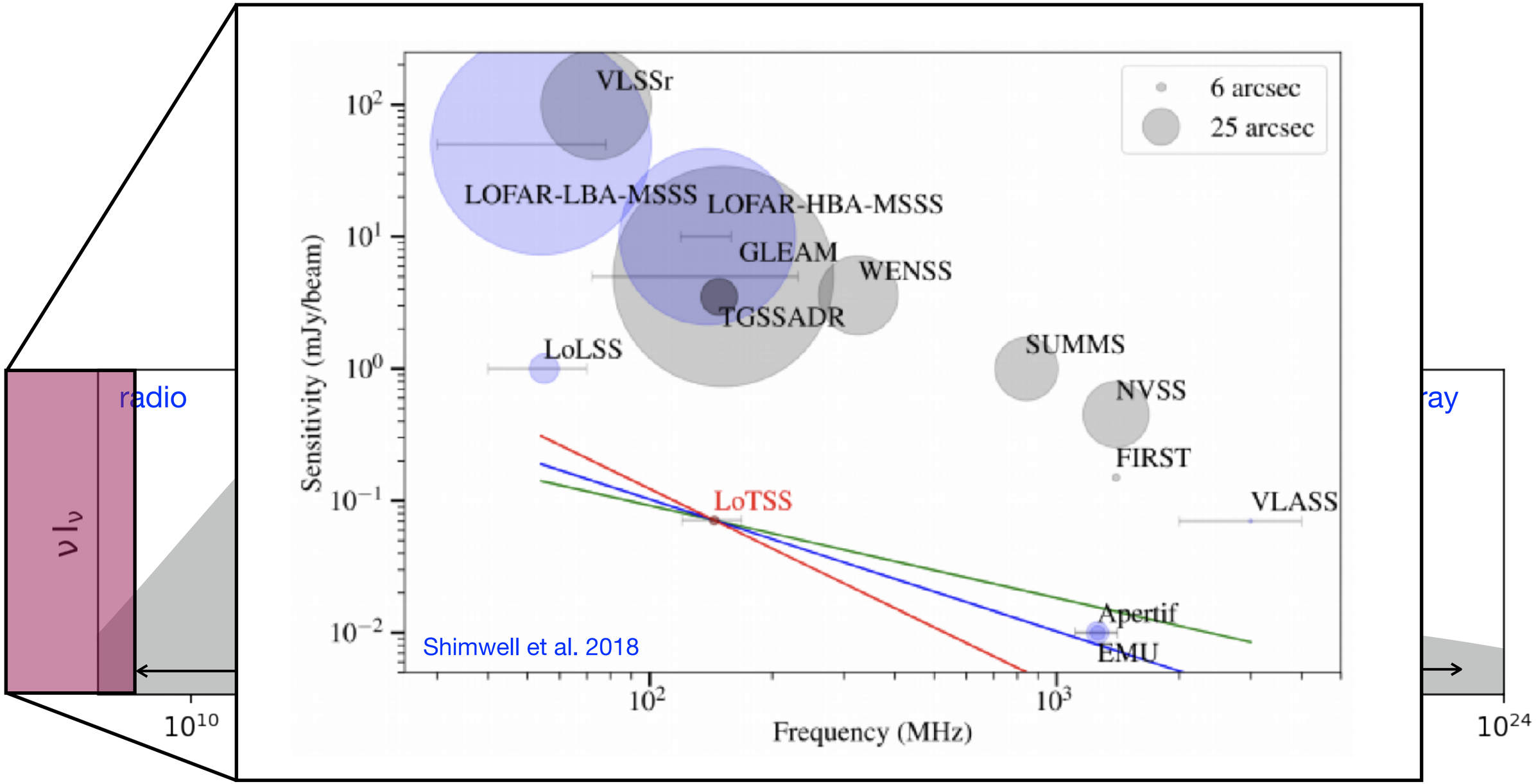
Cosmic synchrotron background

Why synchrotron?

- Potentially constrains cosmic magnetism Ω_B and cosmic rays Ω_{CR}
- Known sources + extrapolation < reported monopole (Singal+18)
- Data revolution is happening now to 2030s, thanks to the interest in EOR 21cm

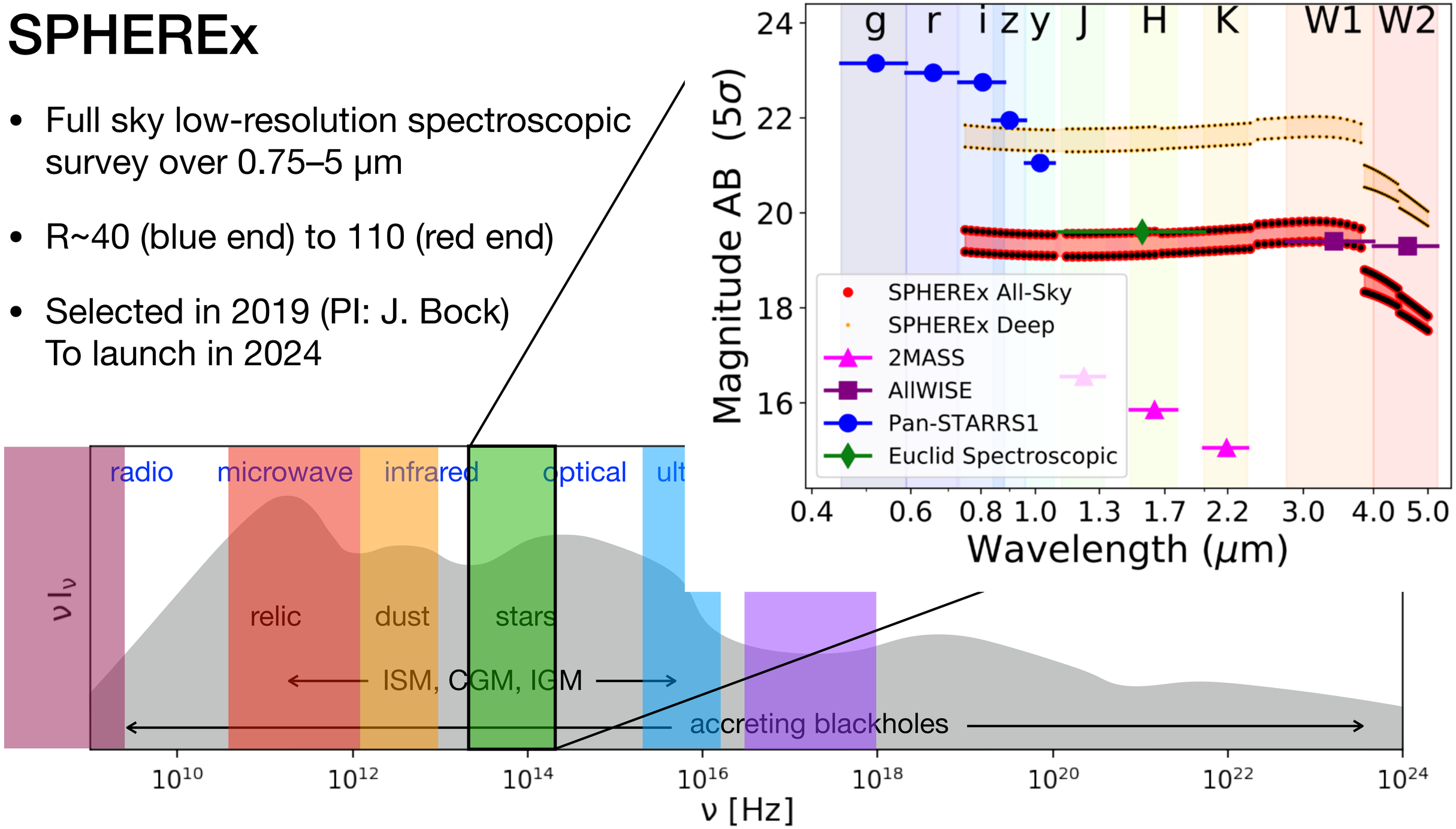


Long-wavelength radio survey landscape



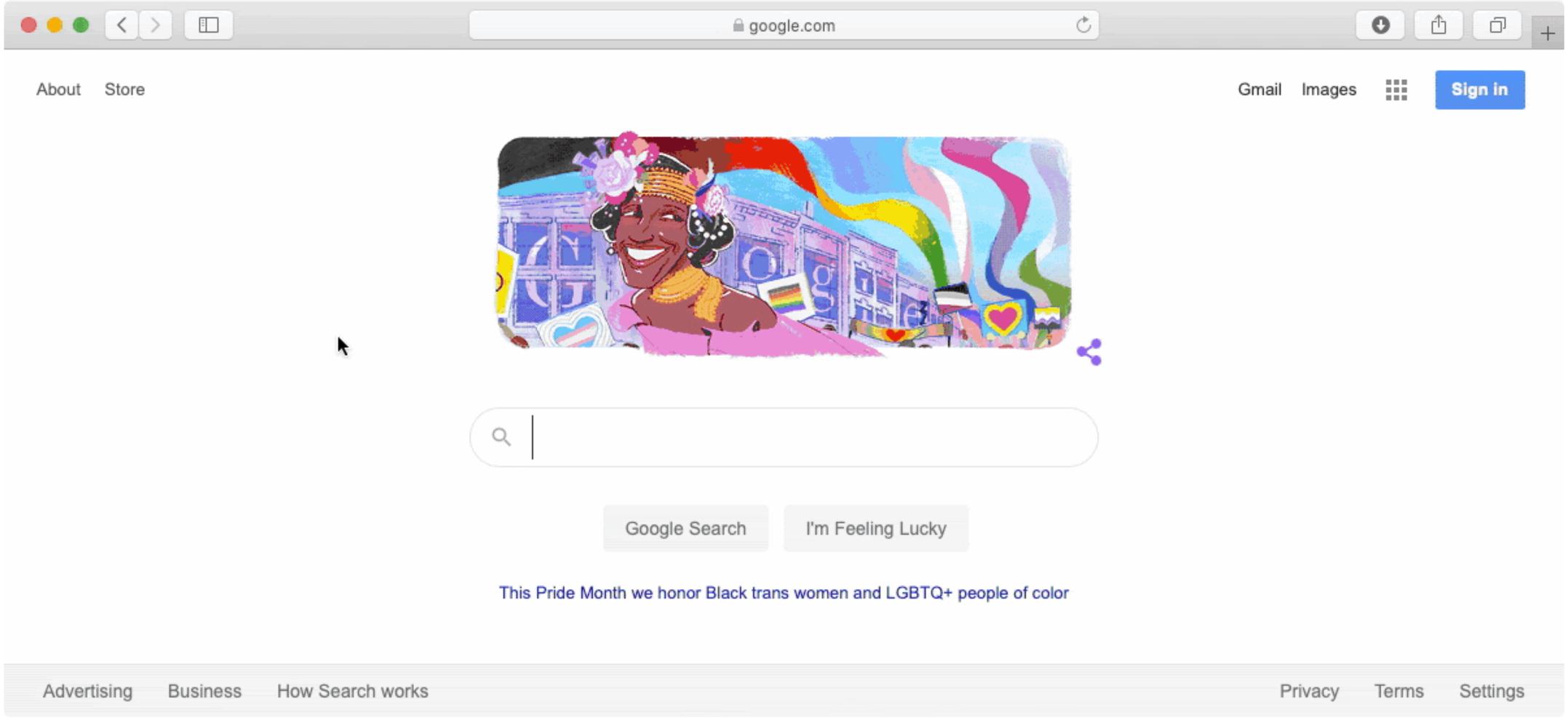
SPHEREx

- Full sky low-resolution spectroscopic survey over 0.75–5 μm
- R~40 (blue end) to 110 (red end)
- Selected in 2019 (PI: J. Bock)
  To launch in 2024



Topographer — clustering redshift on the cloud, for everyone

http://tomographer.org



Concept & algorithm: Yi-Kuan Chiang & Brice Ménard

Web platform: Manuchehr Taghizadeh-Popp

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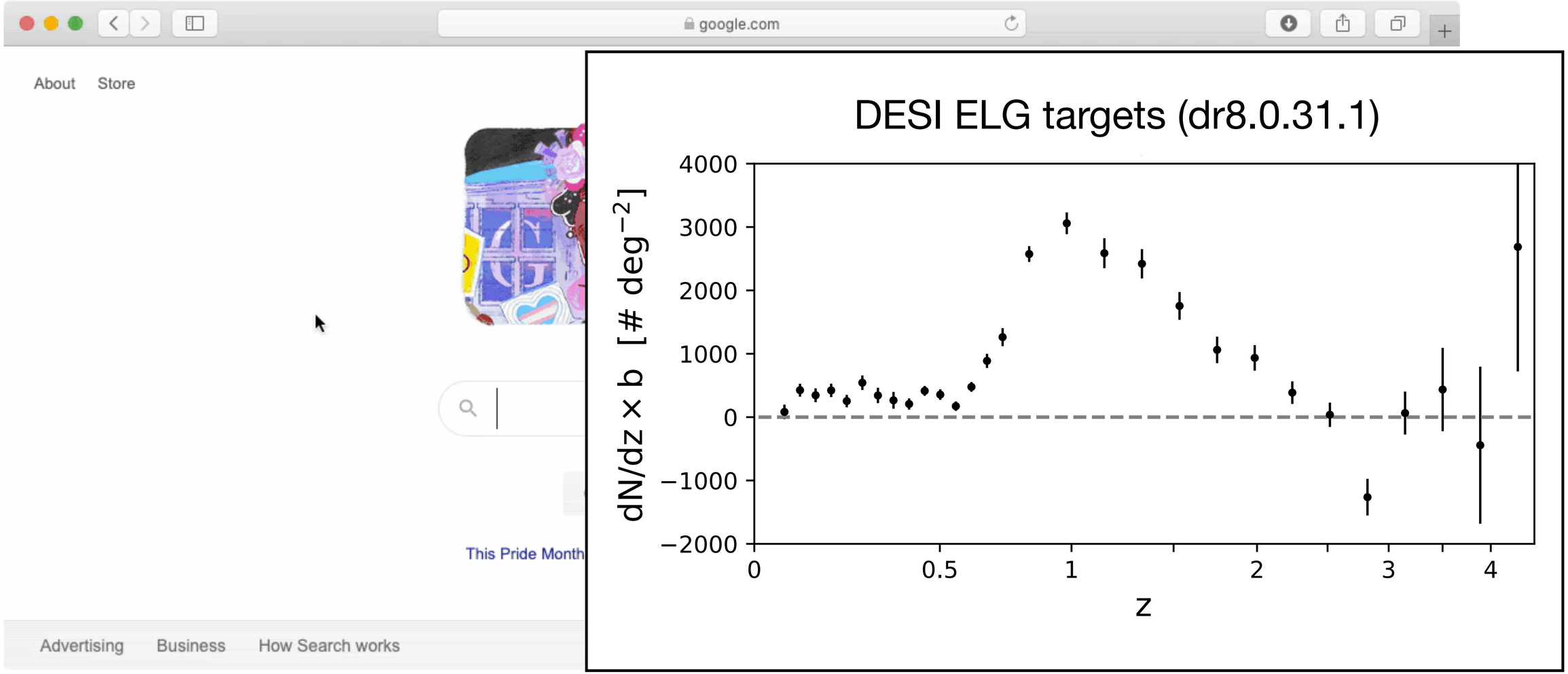

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Summary

- Cosmic SZ tomography constrains the universe's thermal history, Ω_{th} and $\Omega_{non\text{-}th}$
- Multiwavelength background light tomography can inform $\Omega_{radiation}$, Ω_{star}, Ω_{dust}, Ω_{SMBH}, Ω_B…, and their growth rates
- The technique can be used for exotic sources (e.g., FRB) and go beyond EM waves