Precise Measurements of the Cosmic Microwave Background Temperature at $z = 0.68$ and $z = 0.89$

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image : ESA and the Planck Collaboration

1. Background

Cosmic Microwave Background (CMB)

- Blackbody radiation at $T^0_{\rm CMB} = 2.725 \pm 0.001$ K Fixsen 2009
- Observational evidence for the Big Bang model

Super hot and dense state → Today (Adiabatic expansion)

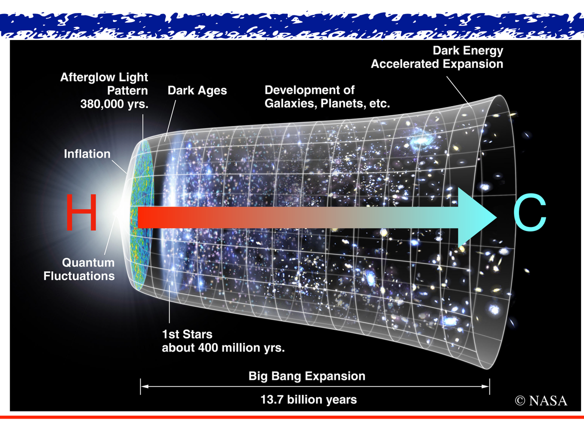
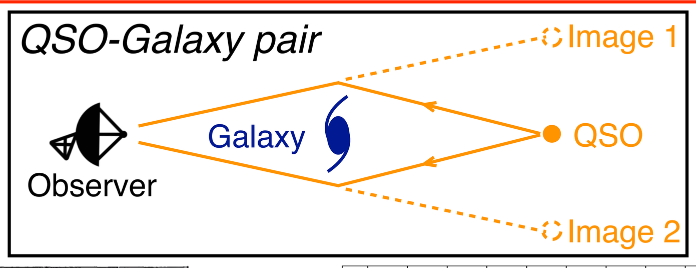


Fig.1 The Big Bang model.

Redshift Dependence of CMB Temperature

- The standard Big Bang model : $T_{\rm CMB}(z) = T^0_{\rm CMB}(1+z)$
- Previous measurements at $z \gtrsim 1$: Quasar absorption lines
  - Elec. trans. of C I or CO @UV
  - Rot. trans. of molecules @mm → $T_{\rm CMB}(0.89) = 5.08 \pm 0.10$ K Muller et al. 2013

Cosmological model can be tested by measuring $T_{\rm CMB}(z)$ at various redshifts



Target Quasar Absorption Line Systems

Quasar	$z_{\rm emi}$	$z_{\rm abs}$	Line of sight	Molecular Species
PKS1830−211	2.51	0.89	SW	> 60
B0218+357	0.94	0.68	A	~ 20

e.g., Lidman et al. 1999 ; Cohen et al. 2003; Wiklind & Combes 1995, 1996

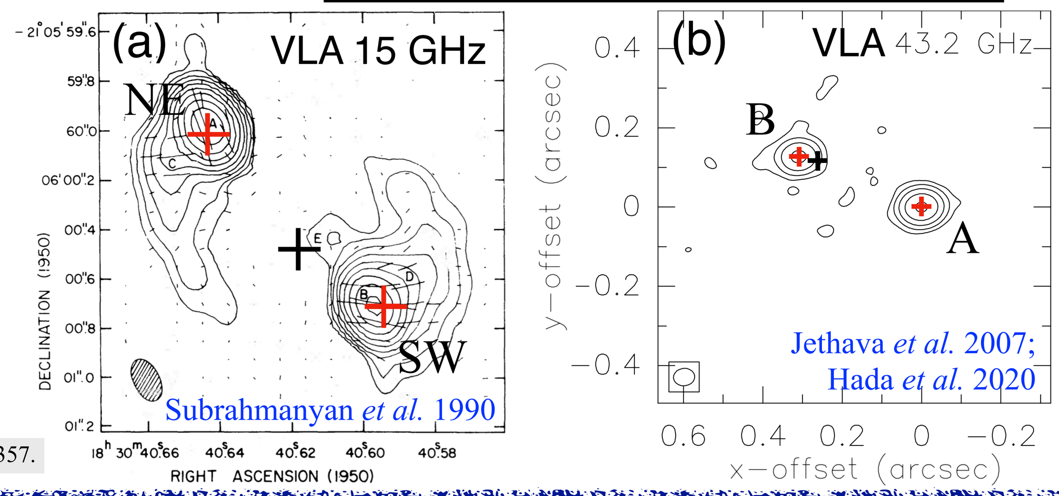


Fig.2 The images of (a) PKS1830−211 and (b) B0218+357.

2. Data Processing

ALMA Archival Data

Fig.3 ALMA.

- PKS1830−211

Project code	Band	Obs. date [yy/mm/dd]	Beam size [arcsec×arcsec]	Molecule	Transition
2013.1.01099.S	3	14/08/27	0.748×0.552	HCN	J=2←1
2017.1.01119.S	4	18/03/17	0.893×0.797	HCN	J=3←2
2018.1.00051.S	5	19/07/28	0.059×0.053	HCN	J=4←3
2018.1.00692.S	6	19/04/11	0.680×0.470	HCN	J=5←4

- B0218+357

Project code	Band	Obs. date [yy/mm/dd]	Beam size [arcsec×arcsec]	Molecule	Transition
2016.1.00031.S	3	17/07/08	0.555×0.437	HCN, HCO$^+$, HNC	J=2←1
2016.1.00031.S	4	16/10/07	0.442×0.188	HCN, HCO$^+$, HNC	J=3←2

Reduction & Spectra Extraction

- Spectra were extracted by UVMULTIFIT Martí-Vidal et al. 2014

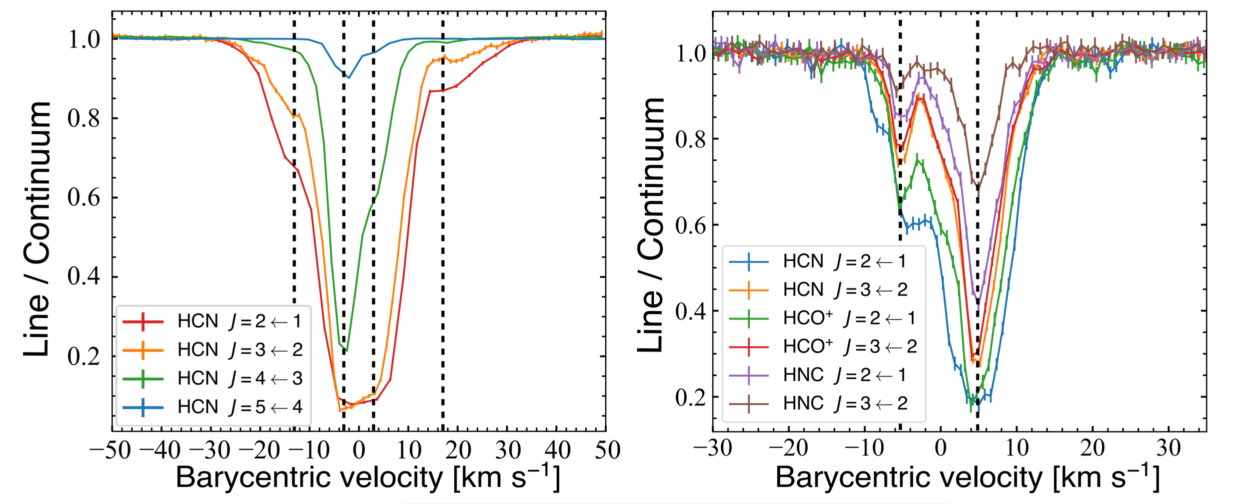


Fig.4 The absorption spectra toward each source.

3. Analyses

Optical Depth

- Derivation

$$\tau_{\rm obs} = -\ln\left(1 - \frac{1}{f_c}\frac{\Delta I}{I_c}\right)$$

f_c : continuum covering factor

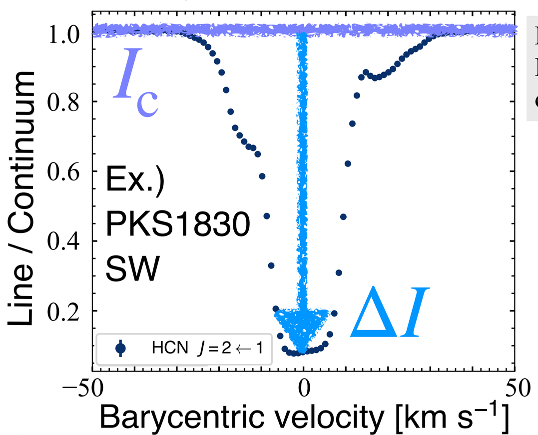


Fig.5 Derivation of optical depth.

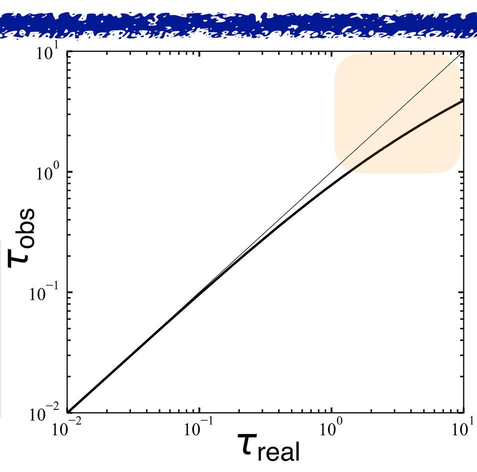


Fig.6 Calculated relationship between $\tau_{\rm obs}$ and $\tau_{\rm real}$.

$\tau_{\rm obs}$ are underestimated → Convert $\tau_{\rm obs}$ to $\tau_{\rm real}$ & Correct for underestimation

- Non-uniformity correction
  ✳ Actual optical depth $\tau_{\rm real} \propto$ (N) → Assume a log-normal distribution of Orion A GMC

Comparable to each absorber ($\sim 1.5 \times 10^{22}$ cm^{-2}) Ma et al. 2020

Excitation Temperature and Column Density

- Assumption: Weak-LTE Wiklind & Combes 1995
- Equations to be solved (Observational input)

$$\frac{8\pi\nu_0^3 \int \tau dV}{c^3 A_{J+1,J}\, g_{J+1}} = \frac{N}{Z(T_{\rm ex})} \frac{e^{-\frac{E_{J+1}}{kT_{\rm ex}}}}{e^{\frac{h\nu_0}{kT_{\rm ex}}} - 1}$$

$T_{\rm ex}$ and N are determined by the weighted least-squares fitting

4. Results

✦ PKS1830−211

Optical Depth / Excitation Temperature Profiles

- Resampled onto the velocity grid of the J=5–4 data
  ✳ $V_{\rm bar} = -3 \sim +3$ km s^{-1} comp.
  J=2–1 & J=3–2 lines are saturated → f_c can be constrained to 0.91–0.92 from the bottoms

CMB Temperature

- Physical conditions:
  $n_{\rm H_2} \sim 2600$ cm^{-3} $\ll n^{\rm HCN}_{\rm crit}$ Henkel et al. 2009
  → Collisional excitation is negligible
  $T_{\rm CMB} = T_{\rm ex}$ Wiklind & Combes 1996; Menten et al. 1999
- $T_{\rm ex}$ for this comp. are the most reliable estimate of $T_{\rm CMB}$

Weighted mean

$$\langle T_{\rm ex}\rangle \equiv \sum \frac{T_{\rm ex}}{\sigma^2_{T_{\rm ex}}} \Big/ \sum \frac{1}{\sigma^2_{T_{\rm ex}}}$$

$T_{\rm CMB}(0.89) = 5.13 \pm 0.06$ K

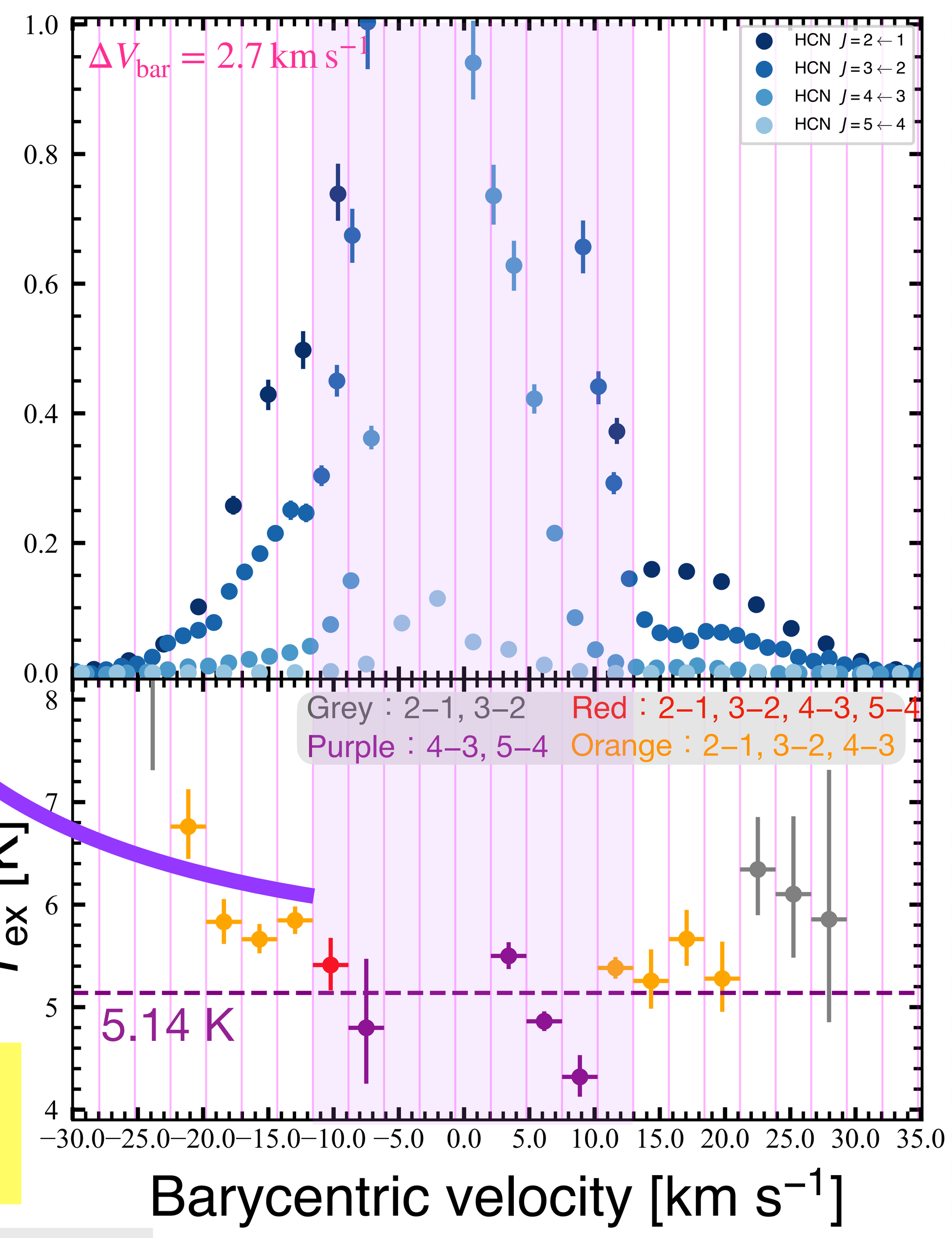


Fig.7 Optical depth profiles (Top) and excitation temperature profiles (Bottom). Colors represent the J transition sets used to derive $T_{\rm ex}$ and N.

✦ B0218+357

Optical Depth / Excitation Temperature Profiles

- Resampled onto the velocity grid of the J=3–2 data

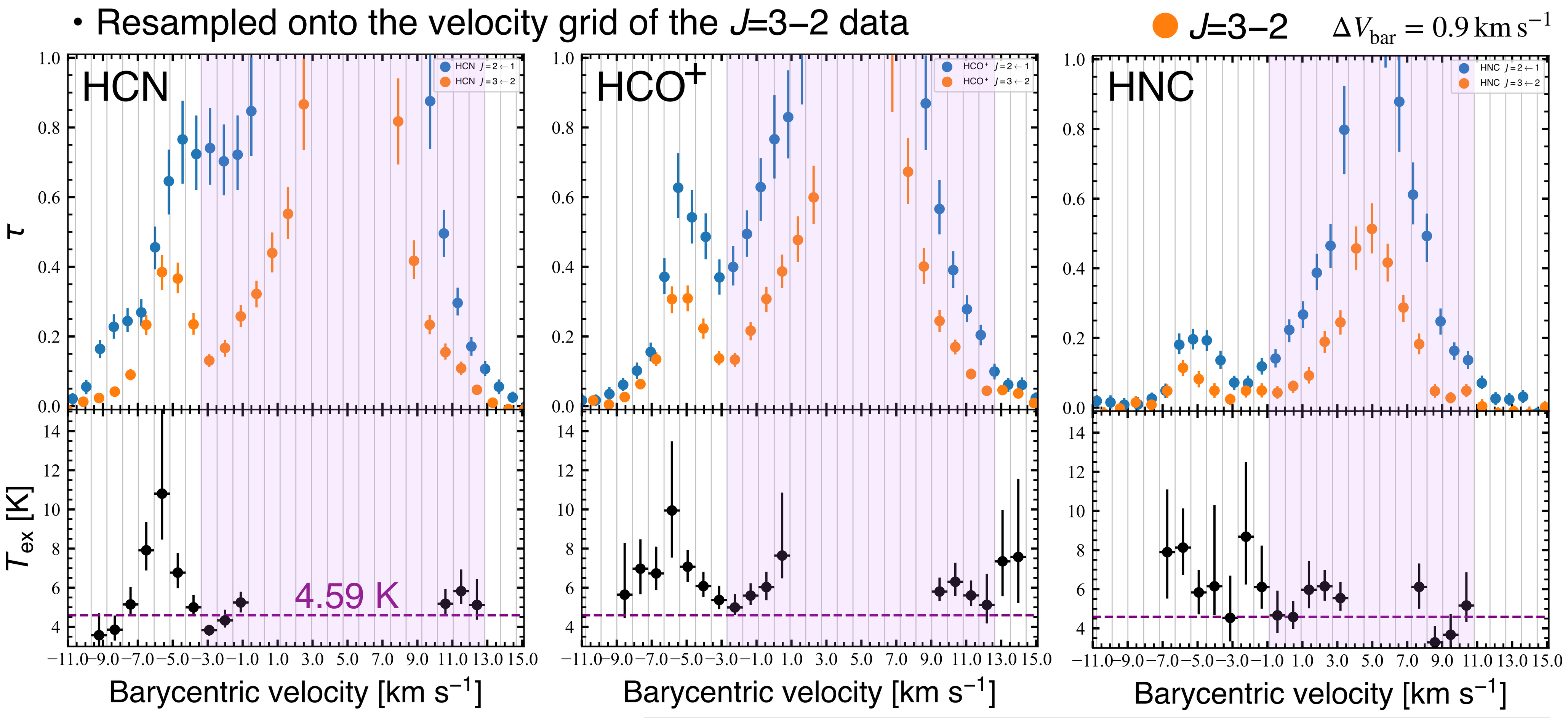


Fig.8 Optical depth profiles (Top) and excitation temperature profiles (Bottom) of HCN, HCO$^+$, and HNC.

✳ $V_{\rm bar} = +5$ km s^{-1} comp.
HCN J=2–1 line is saturated → f_c can be constrained to ~0.8

CMB Temperature

	HCN	HCO$^+$	HNC
Weighted mean of +5 km s^{-1} comp.	4.42 ± 0.20 K	$5.62^{+0.26}_{-0.25}$ K	$4.71^{+0.35}_{-0.32}$ K
	Λ	V	Λ
RADEX calculations ($T_{\rm kin}$=55 K, $n_{\rm H_2}$=10^4 cm^{-3}) van der Tak et al. 2007; Henkel et al. 2005; Zeiger & Darling 2010	~ 4.8 K	~ 5.3 K	~ 4.8 K

✳ HCO$^+$ { 1. Lowest $n_{\rm crit}$ → Sensitive to collisional excitation; 2. 3rd component contamination (~ 0 km s^{-1}) } → $T_{\rm CMB} \neq T_{\rm ex}$

✳ HCN and HNC Collisional excitation is negligible → $T_{\rm CMB} = T_{\rm ex}$

Weighted mean ▶ $T_{\rm CMB}(0.68) = 4.50 \pm 0.17$ K

Consistent with $T_{\rm CMB}(z) = T^0_{\rm CMB}(1+z)$

5. Discussion

$T_{\rm CMB}$ from This Study

- One of the most precise $T_{\rm CMB}$ measurements at $z \sim 0.7$
- Independent of SZ method
- Demonstrates power of molecular absorption

Constraints on Cosmological Models

- Previous measurements are fitted together by $T_{\rm CMB}(z) = T^0_{\rm CMB}(1+z)^{1-\beta}$ Lima et al. 2000

Compatible with the Standard Big Bang Model

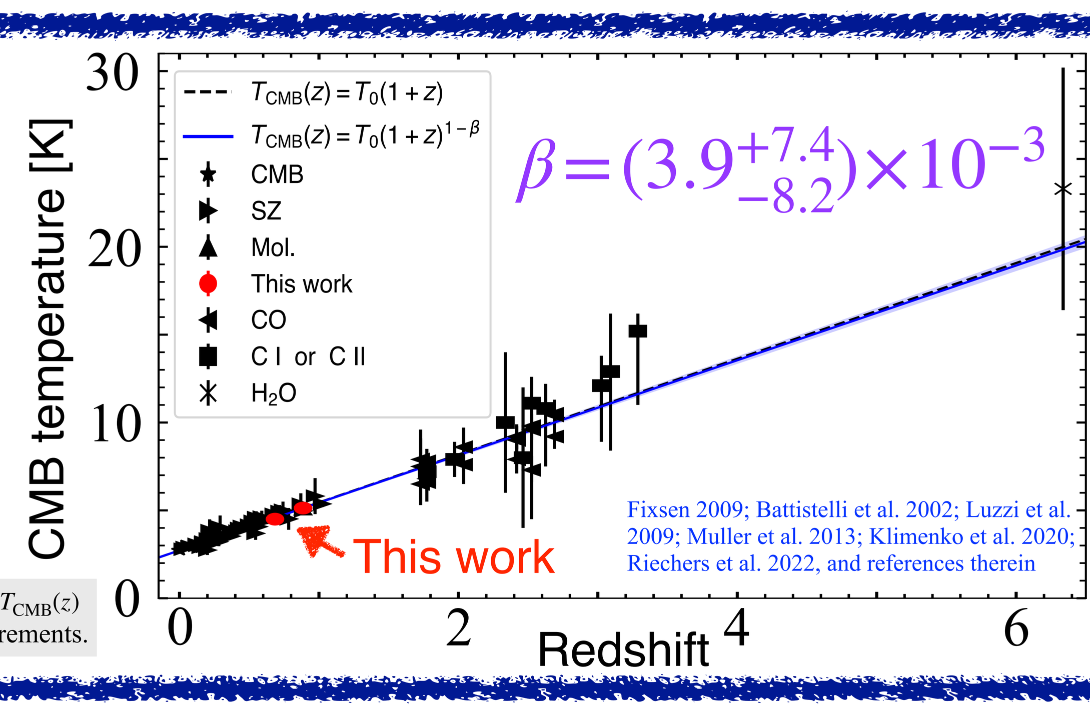


Fig.9 $T_{\rm CMB}(z)$ measurements.

6. Future Prospects 🚀

Increase the number of $T_{\rm CMB}(z)$ measurements

- New measurements → $1 < z < 2$ (NOEMA, ALMA)
- Higher precision → $z \sim 3$ (VLA)

Looking for Promising Targets