CS-10C

The 11th East-Asian Meeting on Astronomy

A Precise Measurement of the Cosmic Microwave Background Radiation Temperature at $z = 0.89$ Toward PKS1830–211

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Cosmic Microwave Background Temperature

Cosmic Microwave Background Radiation (CMB)

- Blackbody radiation at $2.725 \pm 0.001\,\mathrm{K}$ Fixsen 2009
- Observational evidence for the Big Bang model

Super hot and dense state → Today

Adiabatic expansion

Redshift Dependence of CMB Temperature

- The standard Big Bang model

$$T_{\mathrm{CMB}}(z) = T^0_{\mathrm{CMB}}\,(1+z)$$

Current value

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

Previous Measurements of $T_{\mathrm{CMB}}(z)$

- $z \gtrsim 1$: Quasar absorption lines
  - Elec. trans. of C I or CO @UV
  - Rot. trans. of molecules @mm

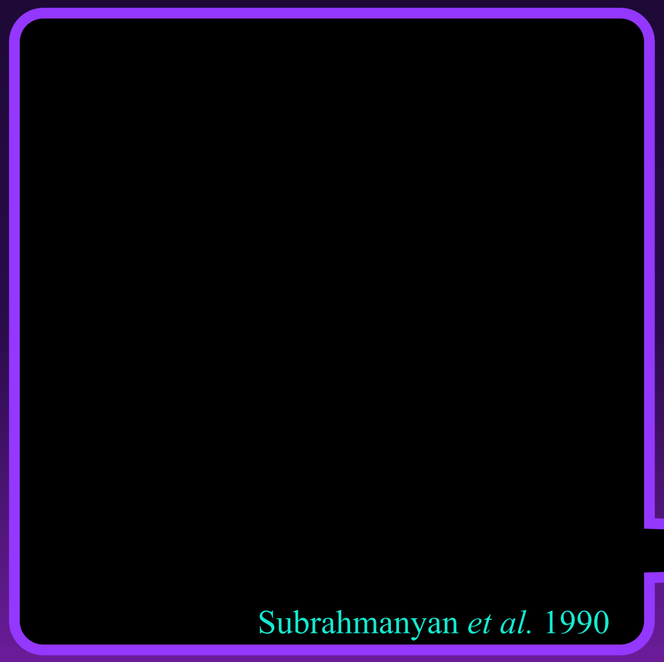
$T_{\mathrm{CMB}}(0.89) = 5.08 \pm 0.10\,\mathrm{K}$ Muller *et al.* 2013

Target Quasar Absorption Line System

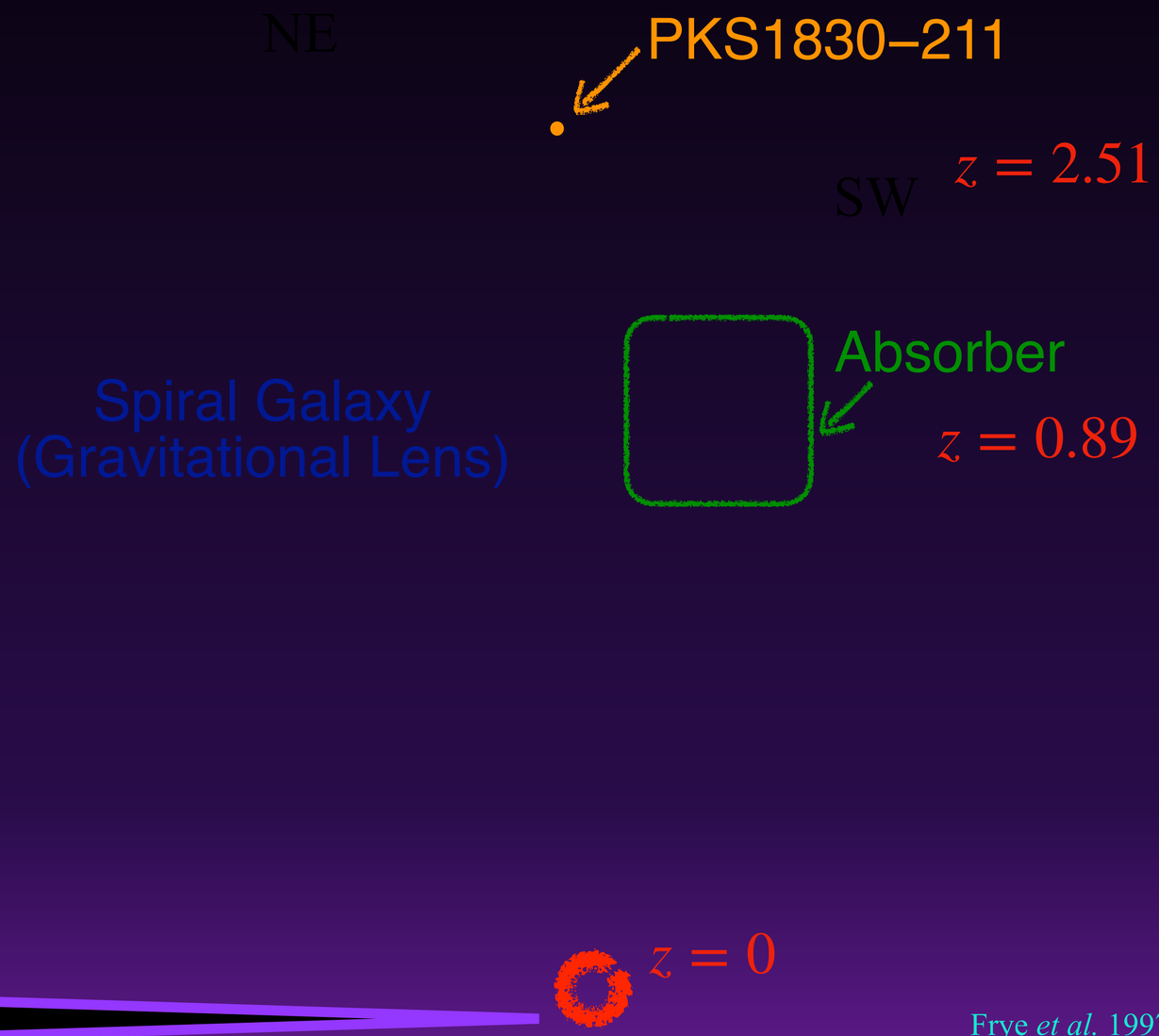
PKS1830–211

- Quasar at $z_{\rm emi} = 2.51$ Lidman *et al.* 1999
- Absorption occurs in a spiral galaxy at $z_{\rm abs} = 0.89$ Wiklind & Combes 1996; Winn *et al.* 2002
- SW line of sight shows a rich molecular absorption line system

  More than 60 species (CO, HCO^+, HCN, HNC etc.)



Subrahmanyan *et al.* 1990



Frye *et al.* 1997

Data Processing

ALMA Archival Data

Project code	Band	Obs. date [yy/mm/dd]	Beam size [arcsec×arcsec]	Absorption line	Redshifted freq. [GHz]
2013.1.01099.S	3	14/08/27	0.748×0.552	HCN J=2←1	93.997
2017.1.01119.S	4	18/03/17	0.893×0.797	HCN J=3←2	140.992
2018.1.00051.S	5	19/07/28	0.059×0.053	HCN J=4←3	187.985
2018.1.00692.S	6	19/04/11	0.680×0.470	HCN J=5←4	234.973

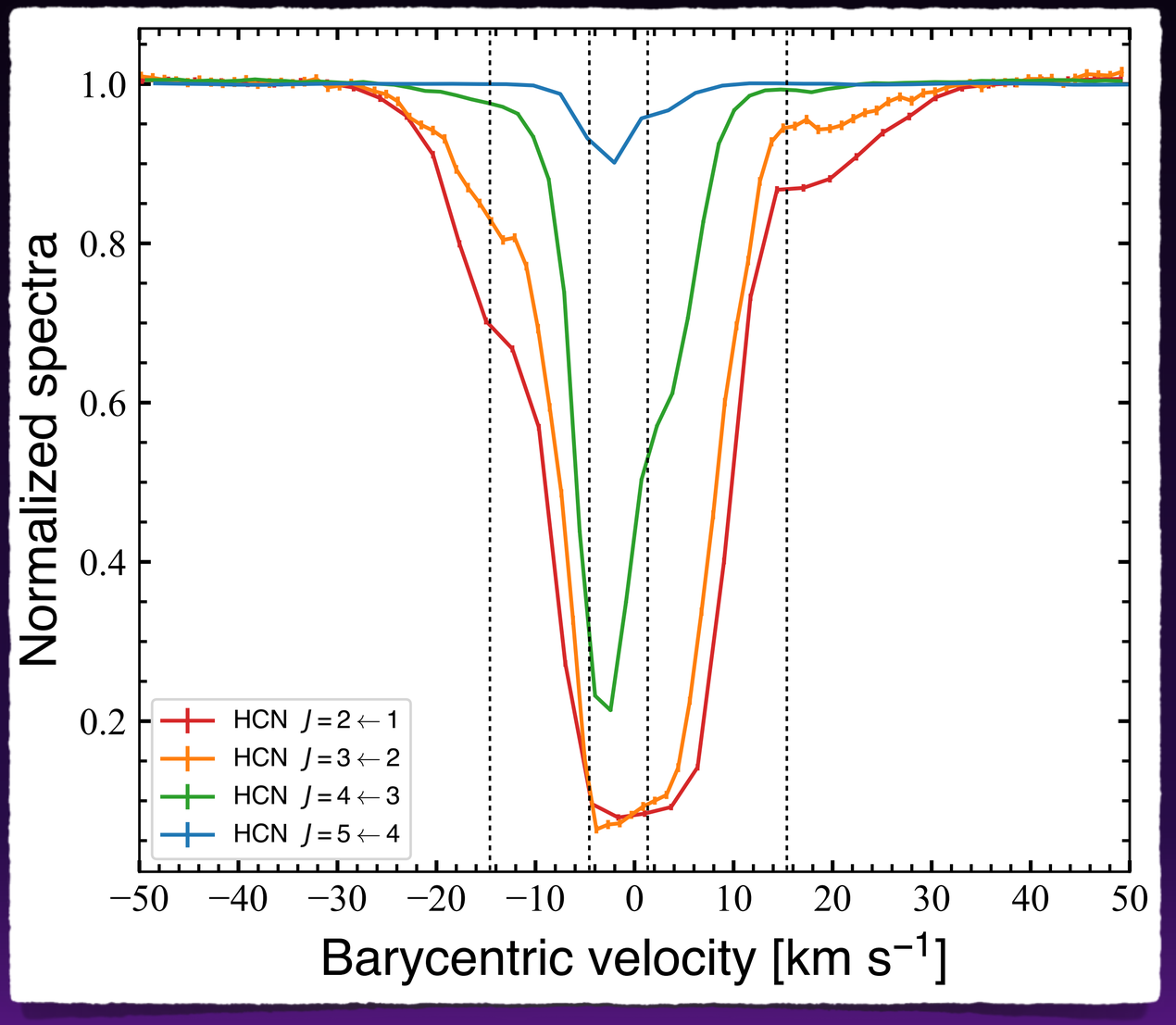
Reduction & Spectra Extraction

- Data calibration and reduction were performed by the standard procedure within the CASA package CASA Team *et al.* 2022
- SW spectra were extracted by `UVMultiFit` Martí-Vidal *et al.* 2014

Optical Depth

Absorption Spectra

- J=2←1 & J=3←2 profiles are saturated
- At least four components centered at $V_{\rm bar} = -13, -3, +3, +17\,{\rm km\,s^{-1}}$



Optical Depth

$$\tau_V = -\ln\left(1 - \frac{1}{f_{\rm c}}\frac{\Delta I}{I_{\rm c}}\right)$$

$f_{\rm c}$: continuum covering factor

⚠ Actual clouds have non-uniform column densities !

Optical Depth

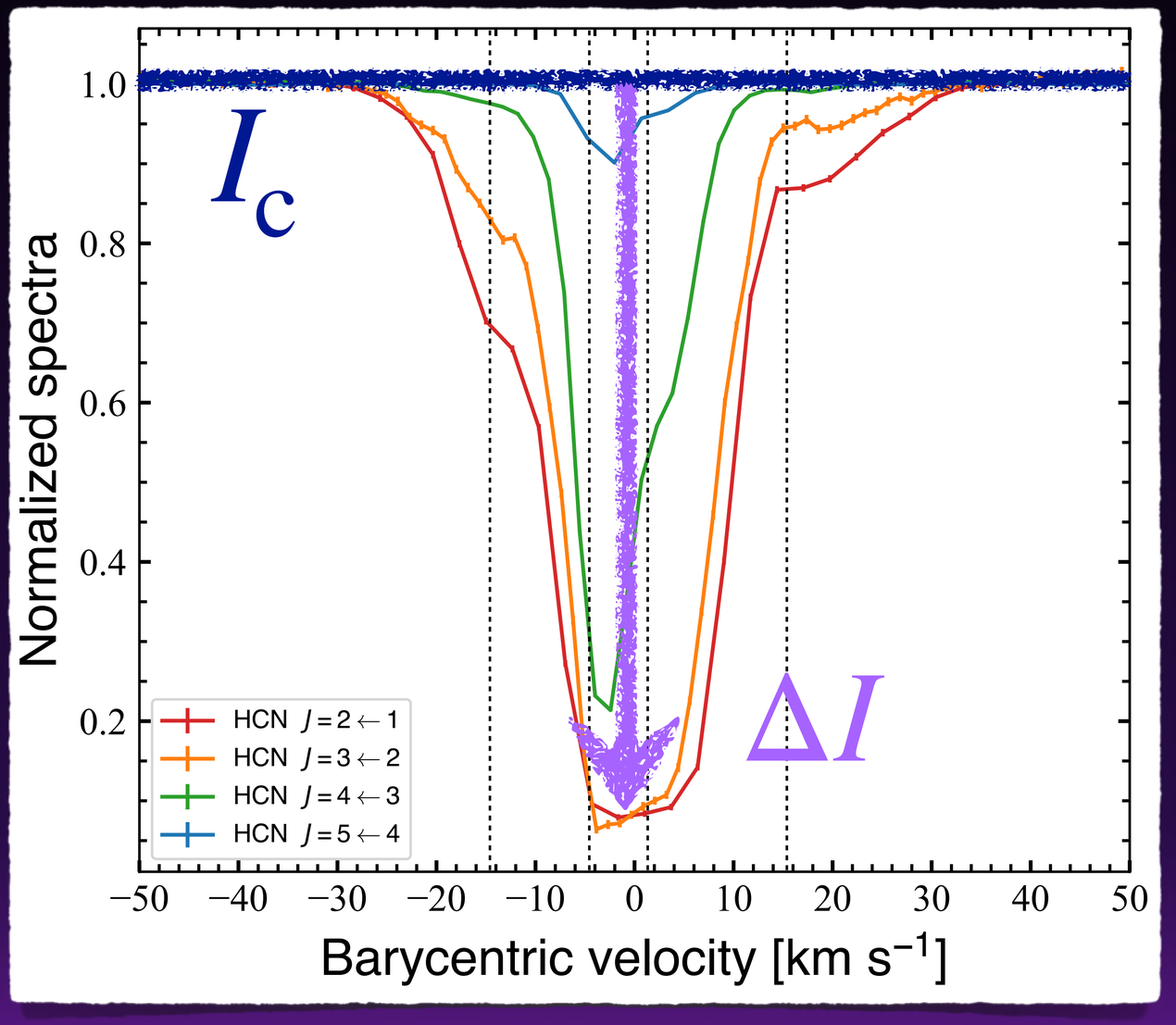
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Correction for Non-uniformity

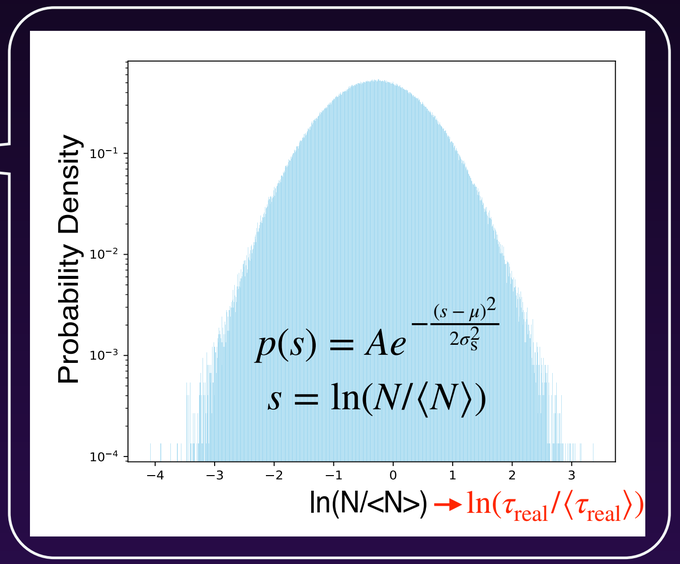
Actual Optical Depth $\tau_{\rm real}$ ($\propto N$)

- Depend on column density distribution

→ Assume a log-normal distribution of Orion A GMC

$$\begin{cases} \sigma_{\rm s} = 0.76 \\ \mu = -\sigma_{\rm s}^2/2 \end{cases}$$

Ma *et al.* 2020



Observed Optical Depth $\tau_{\rm obs}$

- Generate $\tau_{\rm real}$ samples correspond to each $\langle\tau_{\rm real}\rangle$

$$\tau_{\rm obs} = -\ln\left(\frac{1}{N}\sum_{N} e^{-\tau_{\rm real}}\right)$$

Convert $\tau_{\rm obs}$ to $\tau_{\rm real}$ and Correct for underestimation

Excitation Temperature Profile

Calculate $T_{\rm ex}$ for Each Velocity Bin

- Resampled onto the velocity grid of the J=5←4 data
- Limit to optically thin ($\tau < 1$) regions
- Equations to be solved (LTE) :

$$\frac{8\pi\nu_{J+1,J}^3}{c^3 A_{J+1,J} g_{J+1}} \int \tau_{J+1,J} \sqrt{\frac{1+V/c}{1-V/c}} \frac{1}{(1+V/c)^2} dV = \frac{N}{Z(T_{\rm ex})} \exp\left(-\frac{E_{J+1}}{k_{\rm B} T_{\rm ex}}\right) \left[\exp\left(\frac{h\nu_{J+1,J}}{k_{\rm B} T_{\rm ex}}\right) - 1\right]$$

✦ $V_{\rm bar} = -13, +17\ {\rm km\ s^{-1}}$ components

Show no saturation, leaving their $f_{\rm c}$ unconstrained

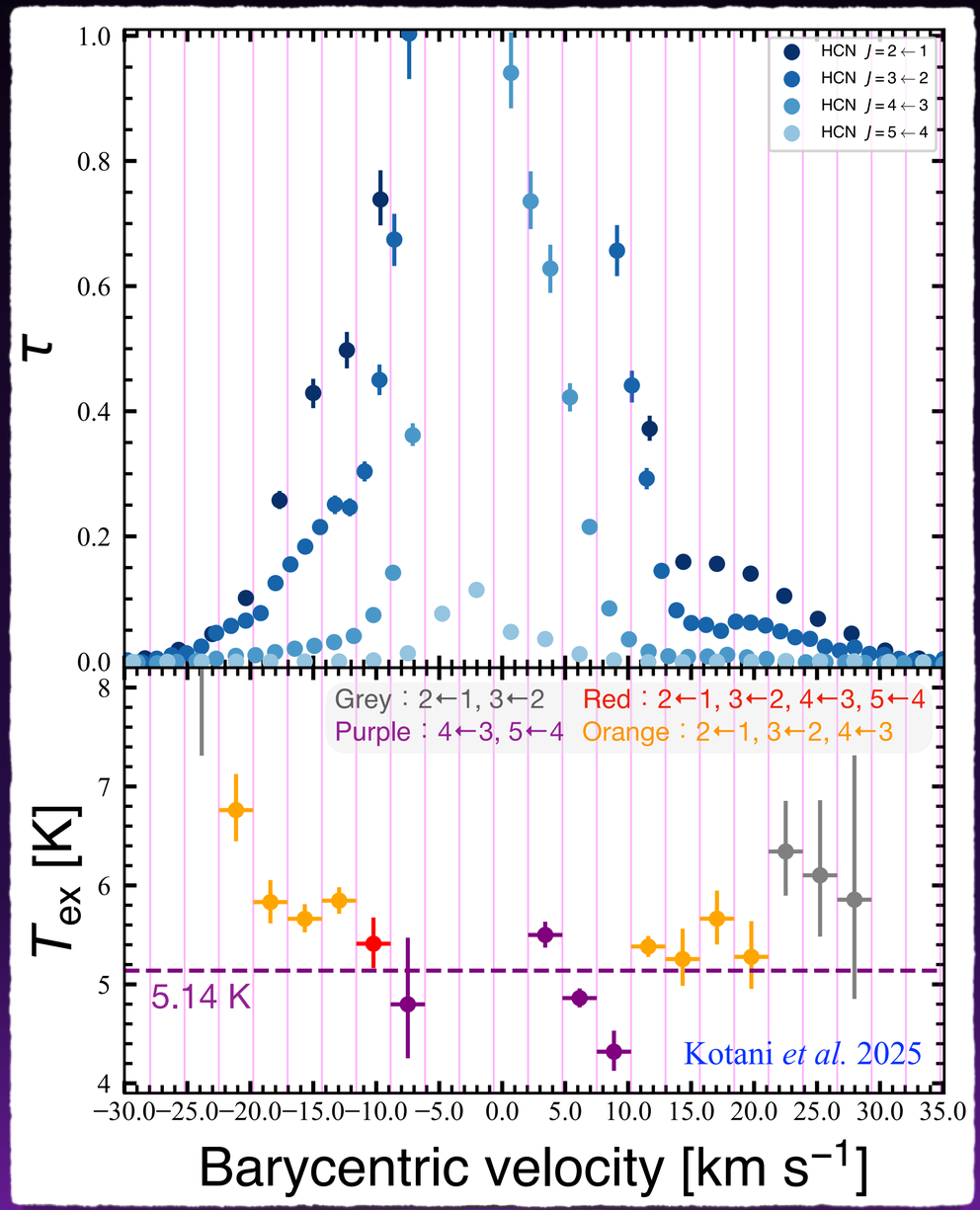
➔ Derived $T_{\rm ex}$ are uncertain

✦ $V_{\rm bar} = -3 \sim +3\ {\rm km\ s^{-1}}$ component

J=2←1 and J=3←2 lines are saturated

➔ $f_{\rm c}$ can be constrained to 0.91–0.92 from the bottoms

$\Delta V_{\rm bar} = 2.7\ {\rm km\ s^{-1}}$



CMB Temperature

Physical Condition of $z = 0.89$ Absorber

$$n_{\mathrm{H_2}} \sim 2600\,\mathrm{cm^{-3}} \ll n_{\mathrm{crit}}^{\mathrm{HCN}}$$ Henkel *et al.* 2009

- Collisional excitation is negligible
- Rotational level populations of HCN are in equilibrium with the CMB

$$\Rightarrow\ T_{\mathrm{CMB}} = T_{\mathrm{ex}}$$ Wiklind & Combes 1996; Menten *et al.* 1999

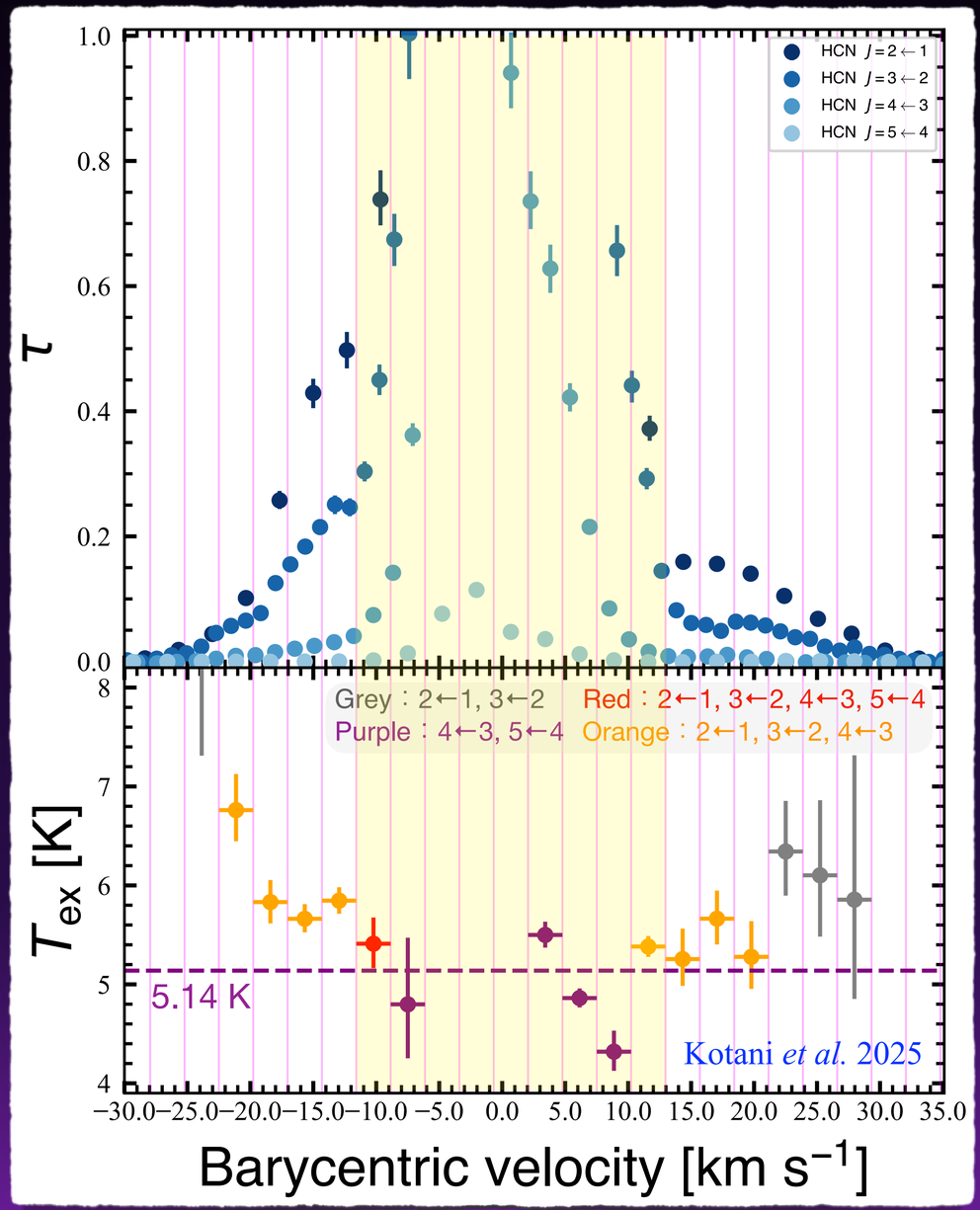
T_{ex} for the $V_{\mathrm{bar}} = -3 \sim +3\,\mathrm{km\,s^{-1}}$ component as the most reliable estimate of the T_{CMB}

Weighted mean

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

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

Consistent with the standard Big Bang model prediction (= 5.14 K) within the uncertainty !



Constraints on Cosmological Models

Determined Value

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

Deviation from the Standard Model

- Values from previous studies are fitted together by $T_{\mathrm{CMB}}(z) = T^0_{\mathrm{CMB}}\,(1+z)^{1-\beta}$

Lima *et al.* 2000

→ $\beta = (3.2^{+7.5}_{-8.4}) \times 10^{-3}$

Consistent with the recent value of $(3.4^{+8.1}_{-7.3}) \times 10^{-3}$

Riechers *et al.* 2022

$T_{\mathrm{CMB}}(z)$ measurements are compatible with the standard Big Bang model

Fixsen 2009; Battistelli et al. 2002; Luzzi et al. 2009; Muller et al. 2013; Klimenko et al. 2020; Riechers et al. 2022, and references therein

Conclusions & Future Prospects

- ✓ Analyzed HCN absorption lines toward the quasar PKS1830–211 SW
- ✓ Obtained the CMB temperature at $z = 0.89$ to be $5.13 \pm 0.06\,\mathrm{K}$
- ✓ The measurement resulted in $\beta = (3.2^{+7.5}_{-8.4}) \times 10^{-3}$, supporting the standard Big Bang model



Future Prospects:

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

$$\begin{cases} \text{New measurements} \rightarrow z = 0.68,\ 1 < z < 2 \\ \text{Higher precision} \rightarrow z \sim 3 \end{cases}$$