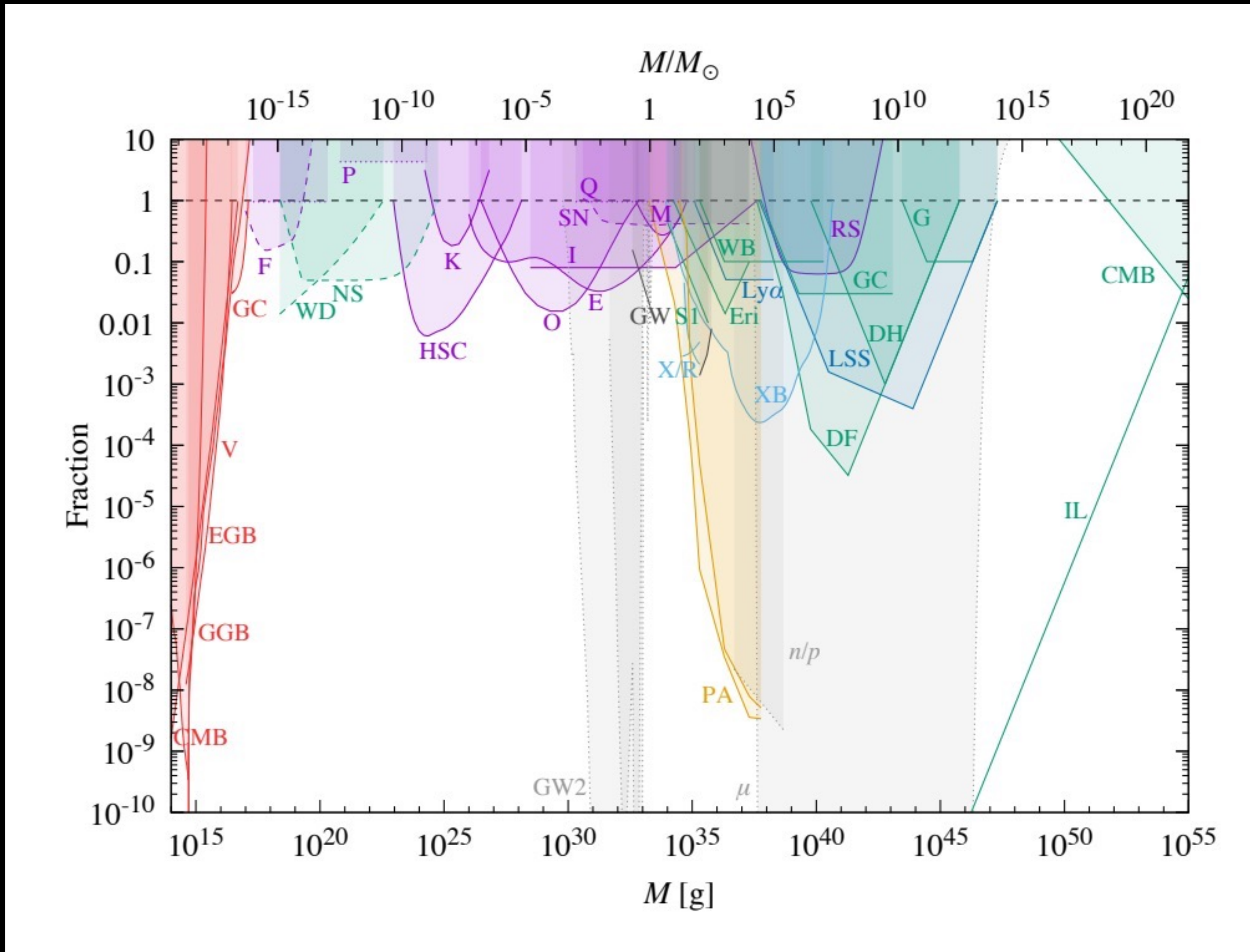
Impact of PBH-baryon streaming motion on IGM thermal history



Teppei Minoda, Hiroyuki Tashiro, and Joseph Silk

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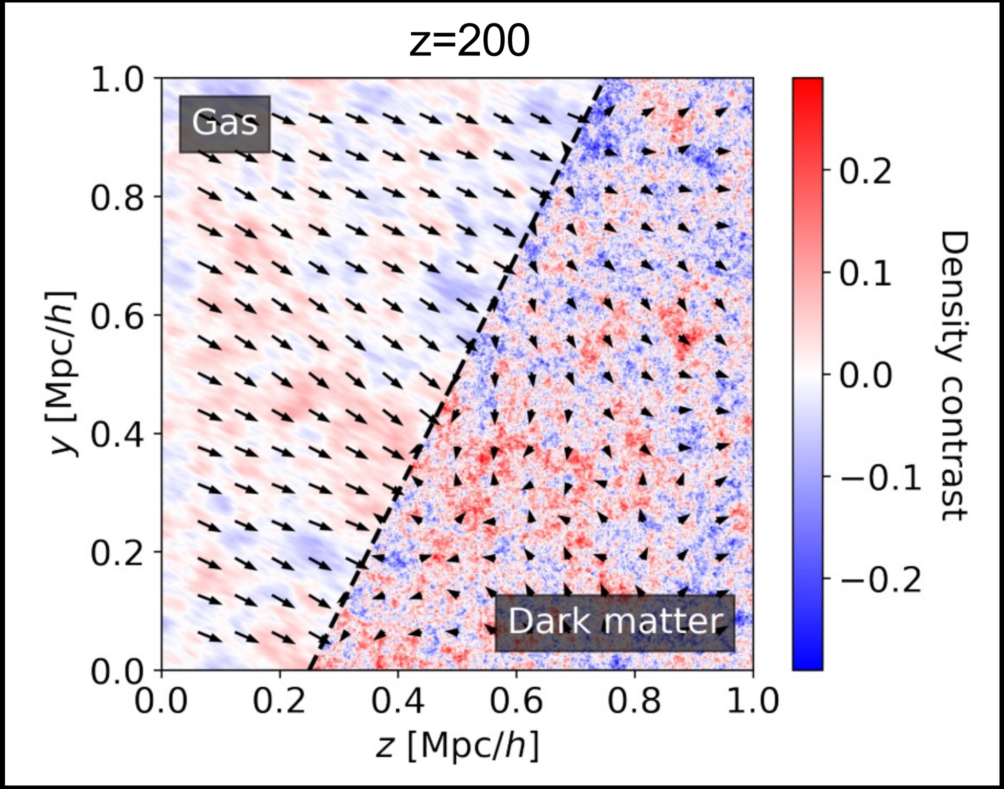
Dark matter-baryon streaming motion

Tseliakhovich and Hirata (2010) first pointed the relative velocity of dark matter and baryonic fluids.

Before recombination,

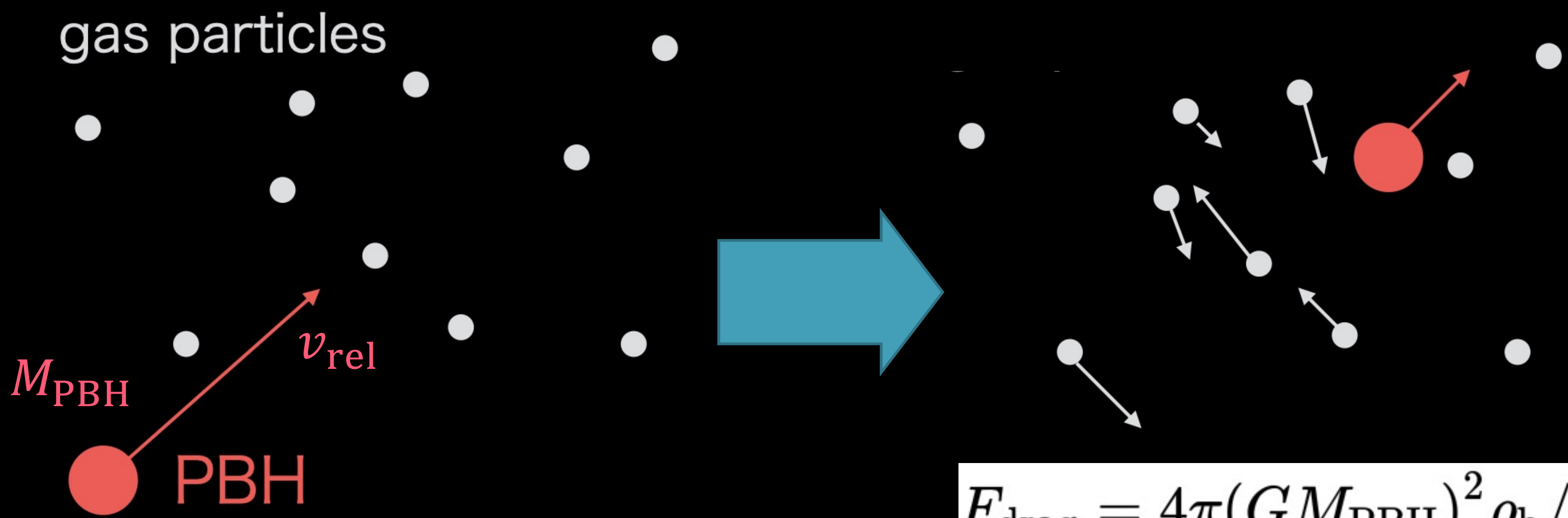
- Density perturbations of baryon gas are strongly suppressed by photon pressure
- Those of dark matter can grow via gravitation



(Park et al. 2020, ApJ)

Dynamical friction of PBHs in gas

In the baryon rest frame,
kinetic energy of CDM particles (PBHs)
are converted into thermal energy of baryon gas



$$F_{\mathrm{drag}} = 4\pi (G M_{\mathrm{PBH}})^2 \rho_{\mathrm{b}} / v_{\mathrm{rel}}^2$$

(Ostriker 1999, ApJ)

Energy injection due to dynamical friction

Drag force acting on a massive particle moving in gaseous fluid

$$F_{\rm drag} = 4\pi (G M_{\rm PBH})^2 \rho_{\rm b} / v_{\rm rel}^2$$

Energy density injecting into the baryon gas via dynamical friction

$$\frac{d}{dt}\left(\frac{3}{2} n_{\rm b} k_B T_{\rm gas}\right) = \boldsymbol{F}_{\rm drag} \cdot n_{\rm U} \boldsymbol{v}_{\rm rel} = 4\pi (GM)^2 \rho / v_{\rm rel} \; n_{\rm PBH}$$

(Ostriker 1999, ApJ)

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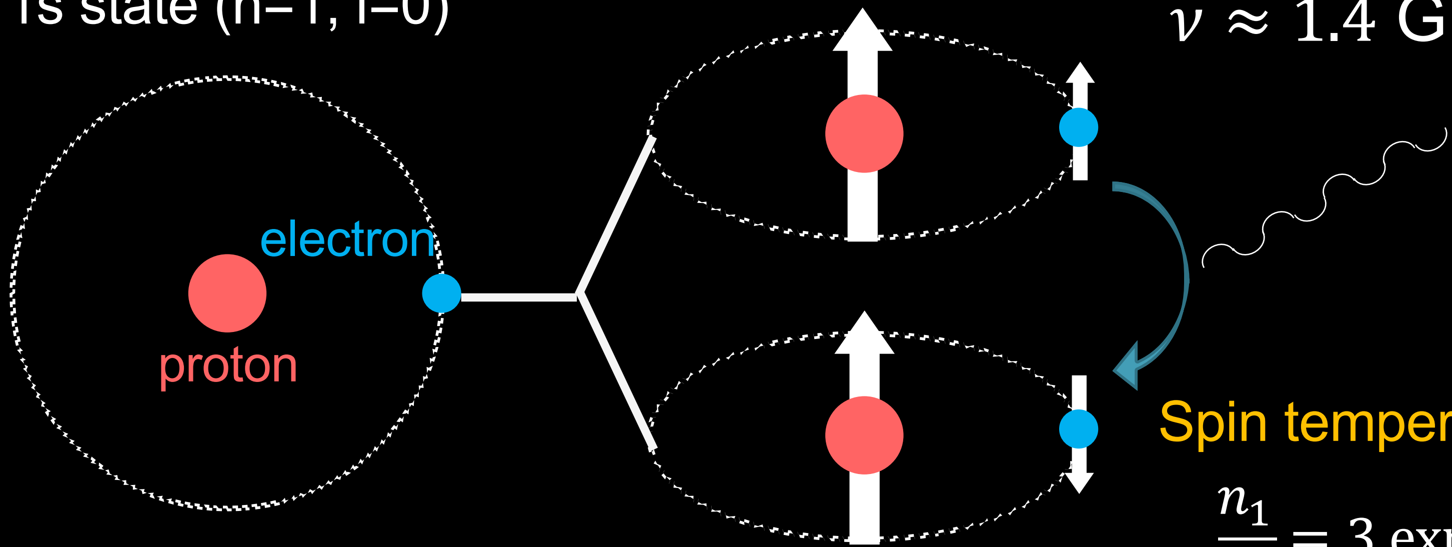
Physics of 21-cm line

Atomic hydrogen
1s state (n=1, l=0)

Hyperfine structure

$\Delta E = 5.9\times10^{-6}$ eV,
$\nu \approx 1.4$ GHz, $\lambda \approx 21$ cm



21-cm line

Spin temperature T_{spin} $(\neq T_{\text{K}})$

$$\frac{n_1}{n_0} = 3\exp\left(-\frac{\Delta E}{k_{\text{B}} T_{\text{spin}}}\right)$$

Observation of redshifted 21-cm line intensity
=> physical state of HI gas at the redshift
(density, temperature, EoR processes, …)

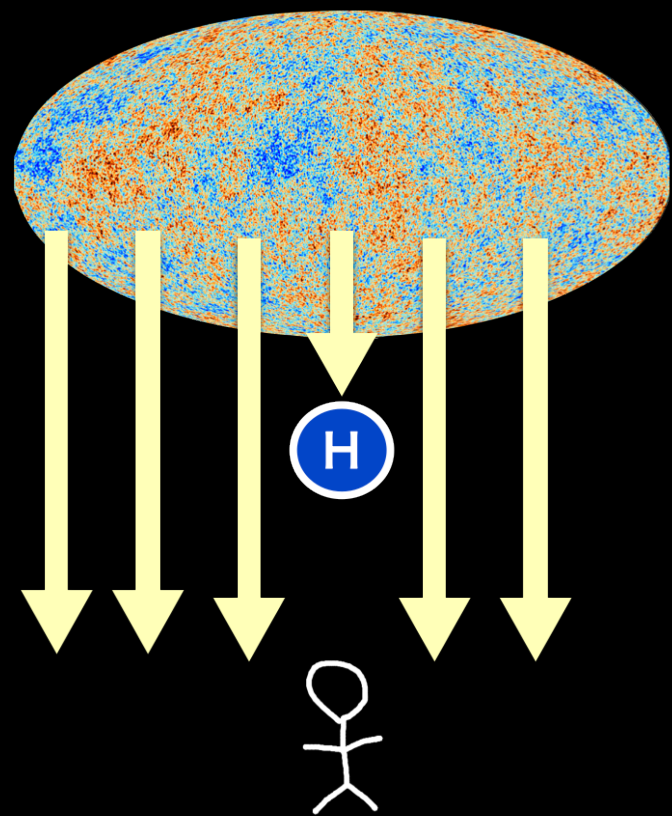
21-cm line global signal

Observable: differential brightness temperature

$$\delta T_b \simeq 27\, x_{\rm HI} \left(1 - \frac{T_{\rm CMB}}{T_{\rm spin}}\right) \left(\frac{1+z}{10}\right)^{1/2} \ [\rm mK]$$

Emission: $T_{\rm K} \geq T_{\rm spin} \geq T_{\rm CMB}$

Absorption: $T_{\rm K} \leq T_{\rm spin} \leq T_{\rm CMB}$



How can T_{spin} be determined?

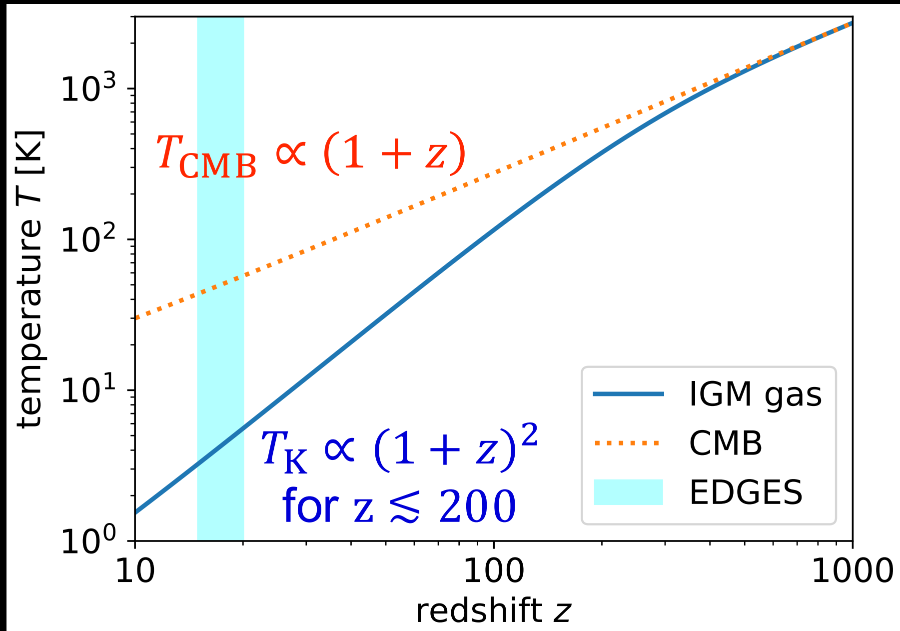
Physical quantities to determine $T_{\rm spin}$:

- (kinematic) temperature of gas $T_{\rm K}$
- Temperature of CMB $T_{\rm CMB}$

Primary processes :

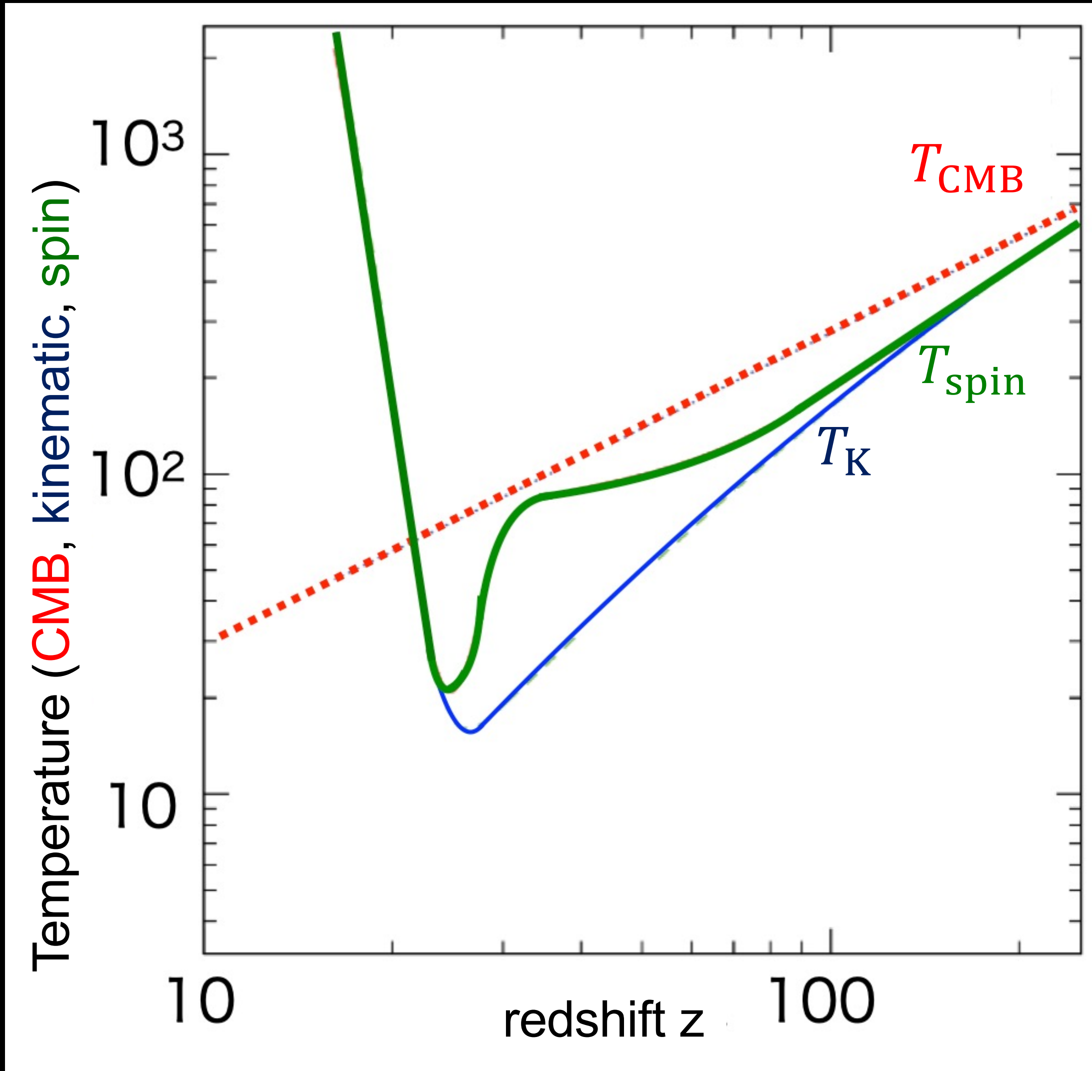
- Collision between gas
- Interaction of Ly-α and gas
- Interaction of CMB and gas

$$T_{\rm spin} = \frac{T_{\rm CMB} + (y_\alpha + y_{\rm c})T_{\rm K}}{1 + y_\alpha + y_{\rm c}}$$



Evolution of spin temperature

1. CMB decoupling
2. Gas collision
   $T_K \cong T_{spin} \leq T_{CMB}$
3. Excitation by CMB
   $T_K < T_{spin} < T_{CMB}$
4. Ly-α from first stars
   $T_K \leq T_{spin} < T_{CMB}$
5. UV and X-ray heating
6. Reionization
   $T_K \cong T_{spin} > T_{CMB}$



(Mesinger et al. 2011, MNRAS, 411, 955)

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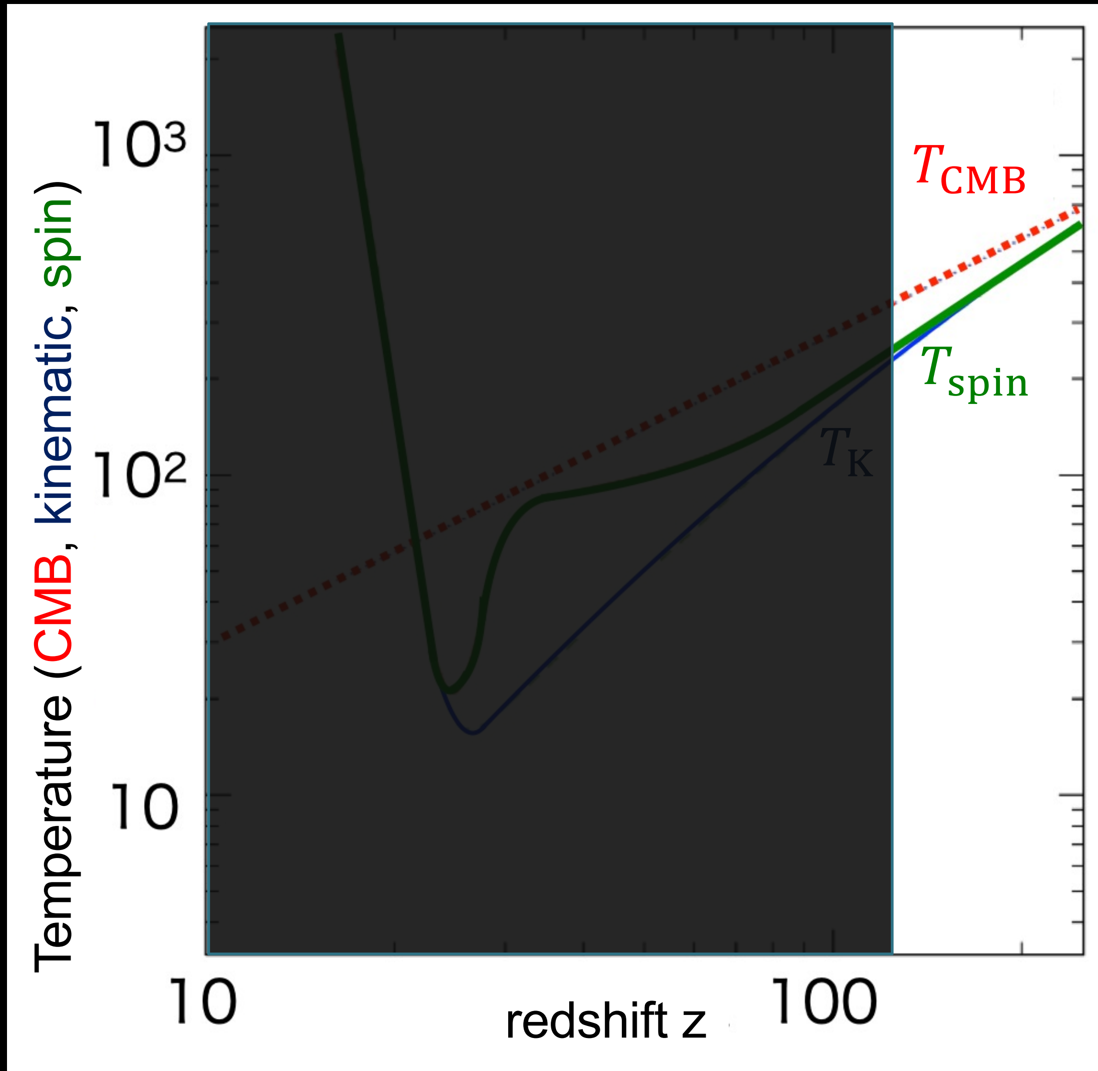

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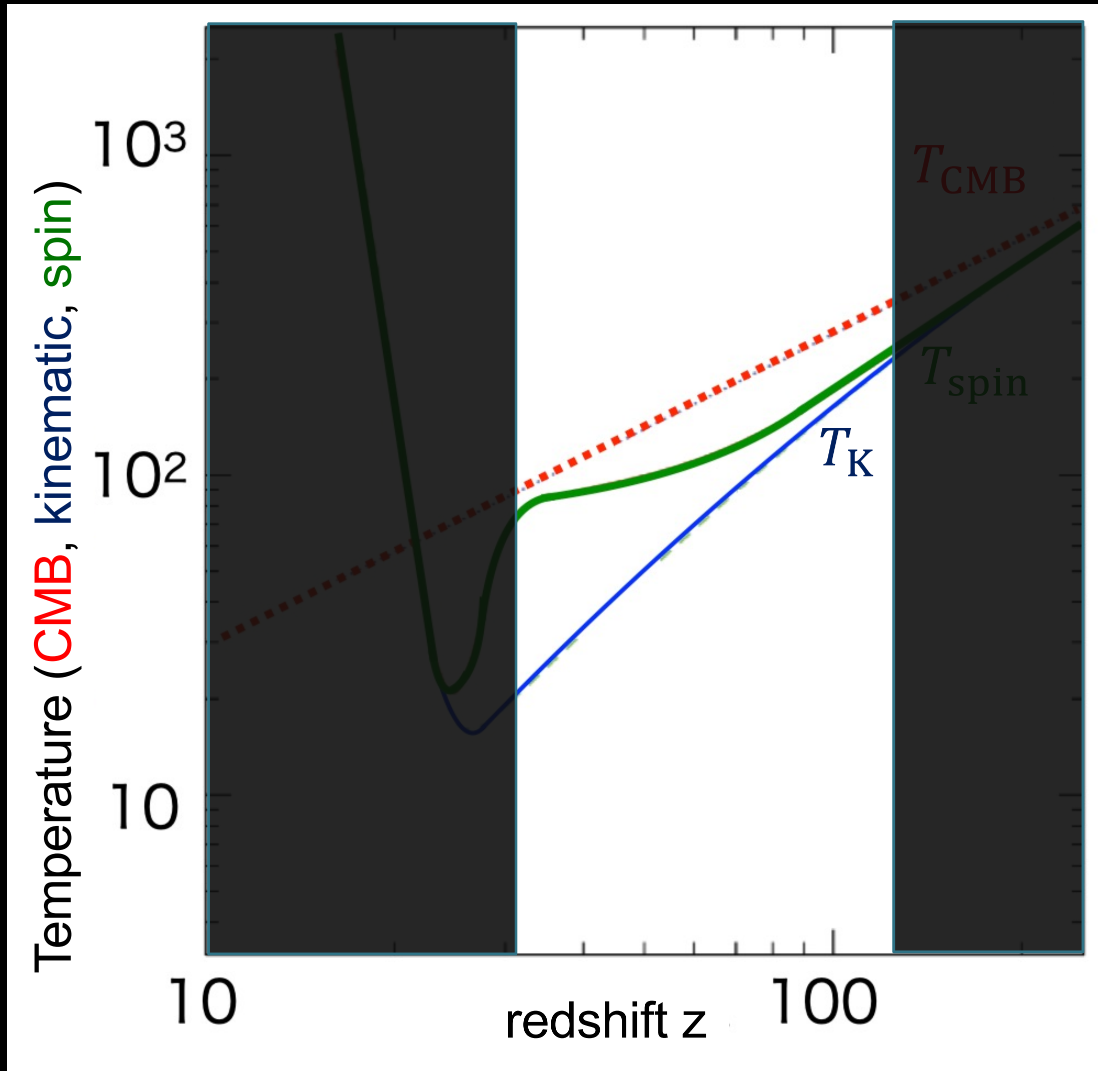

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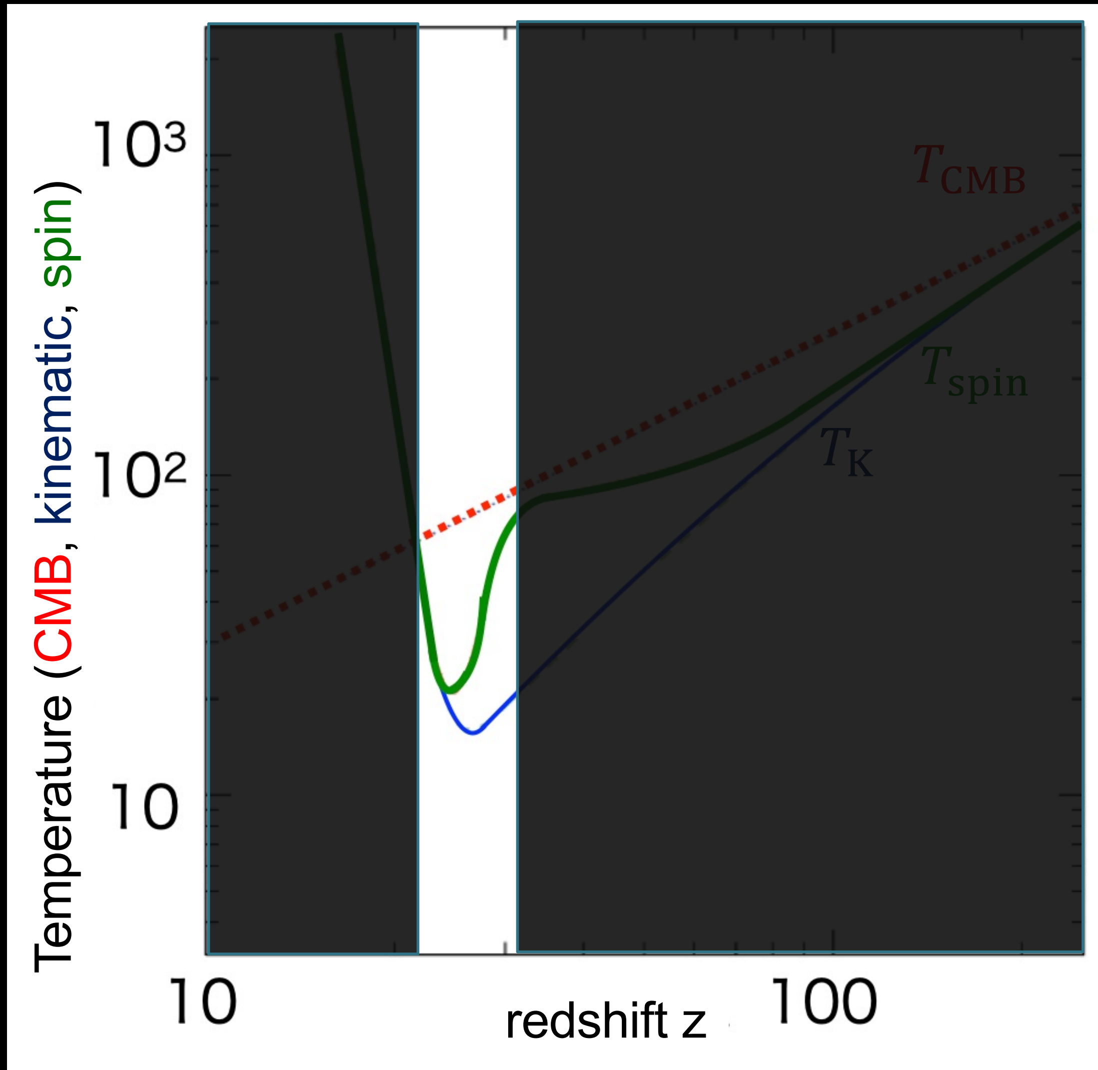

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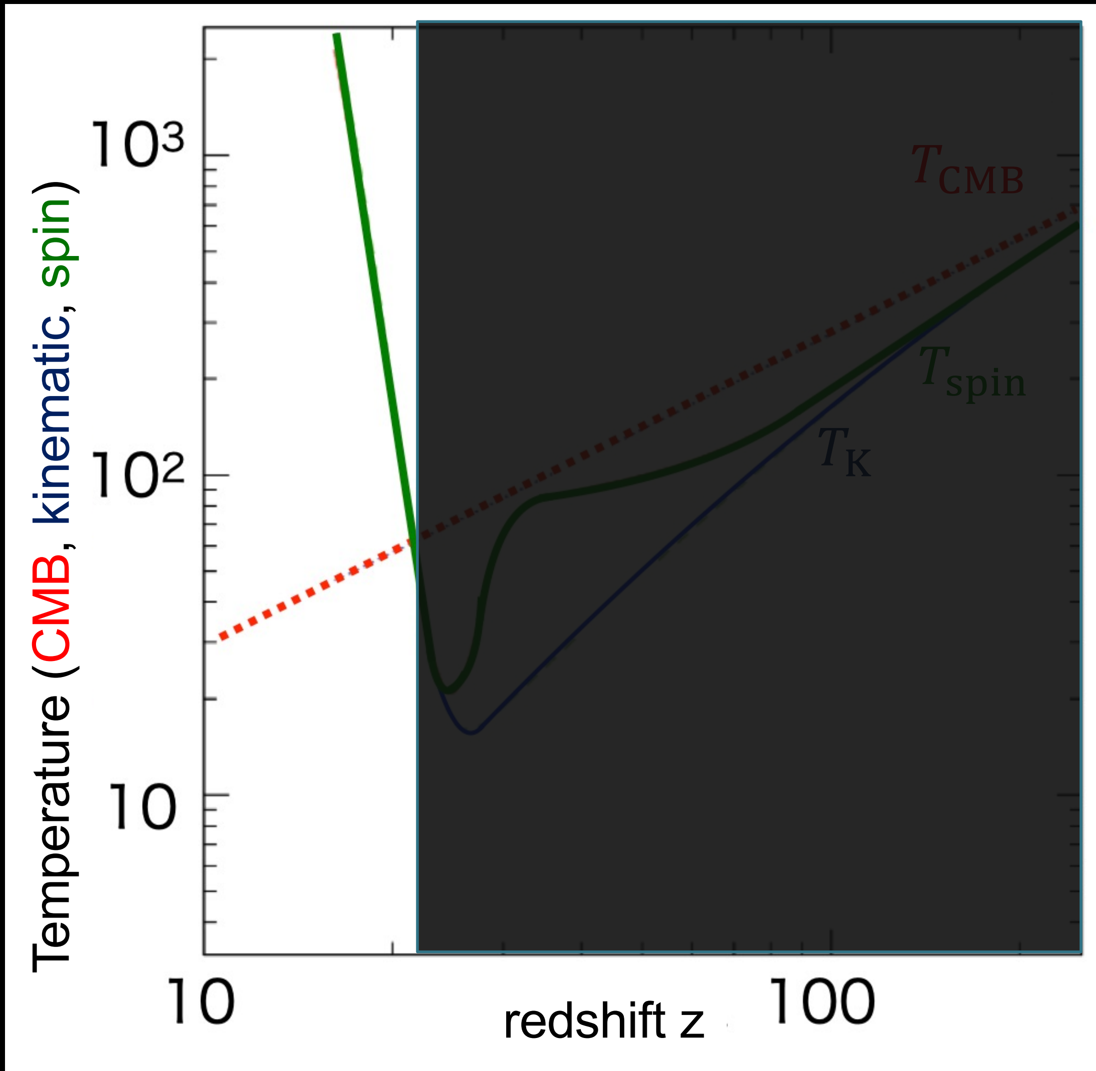

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21-cm line global signal

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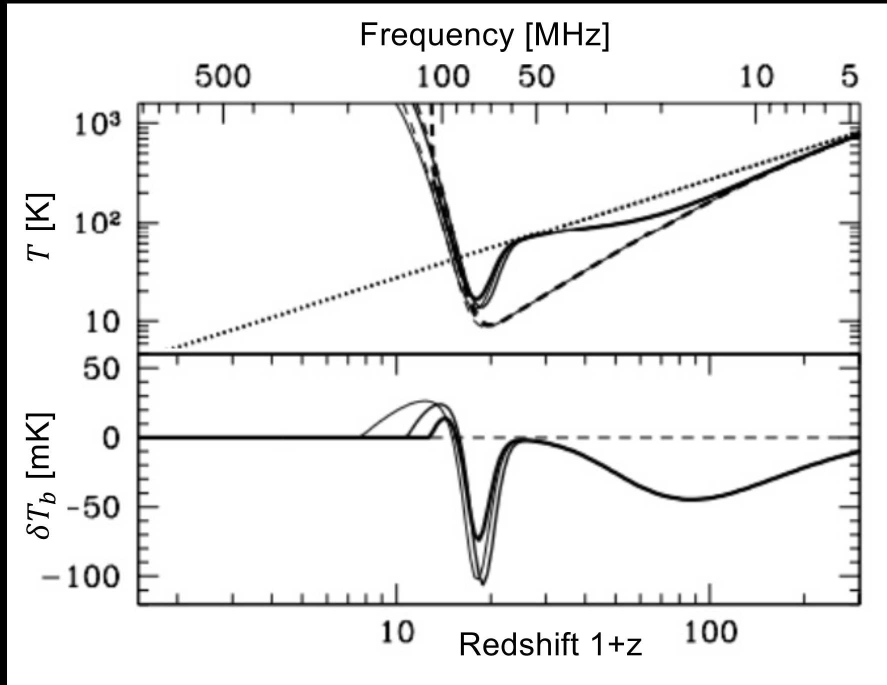

Theoretical prediction of the 21-cm global signal
(Pritchard and Loeb, 2008, PRD, 78, 103511.)

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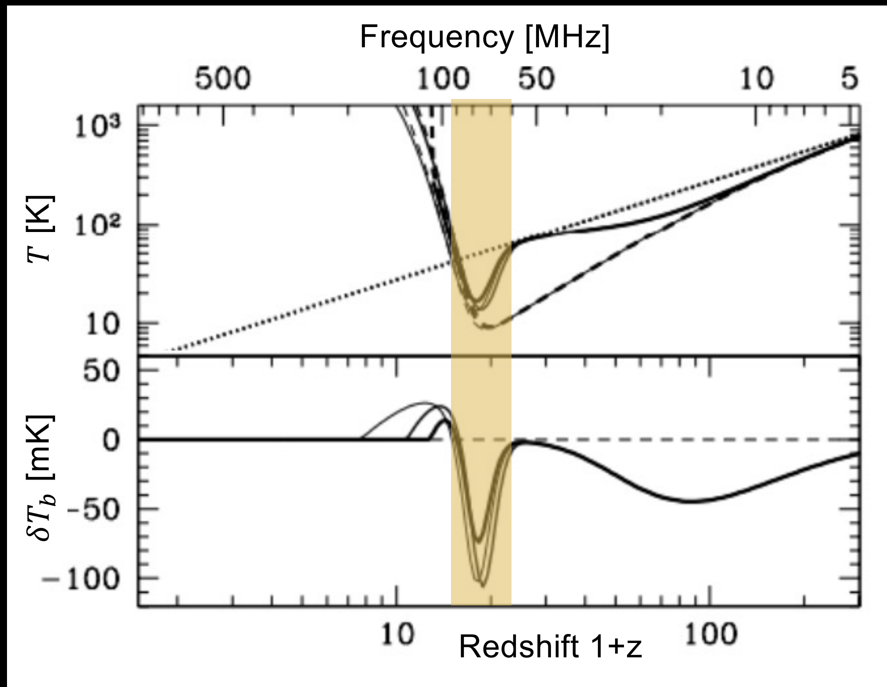
Absorption: $T_{\rm K} \leq T_{\rm spin} \leq T_{\rm CMB}$

Strong absorption signal is expected around z~20 (frequency ~80 MHz)
> **Detection was reported!!**



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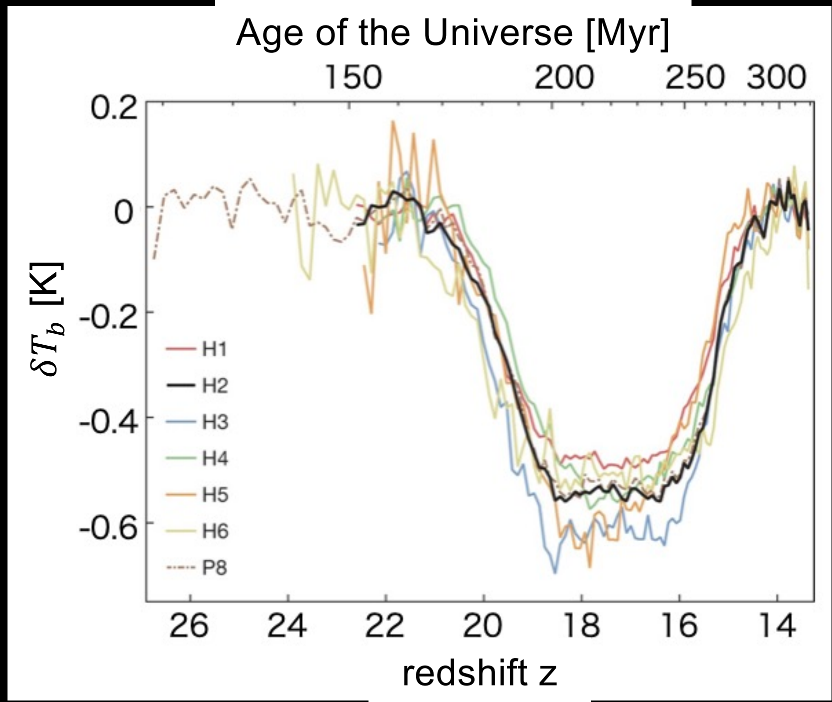
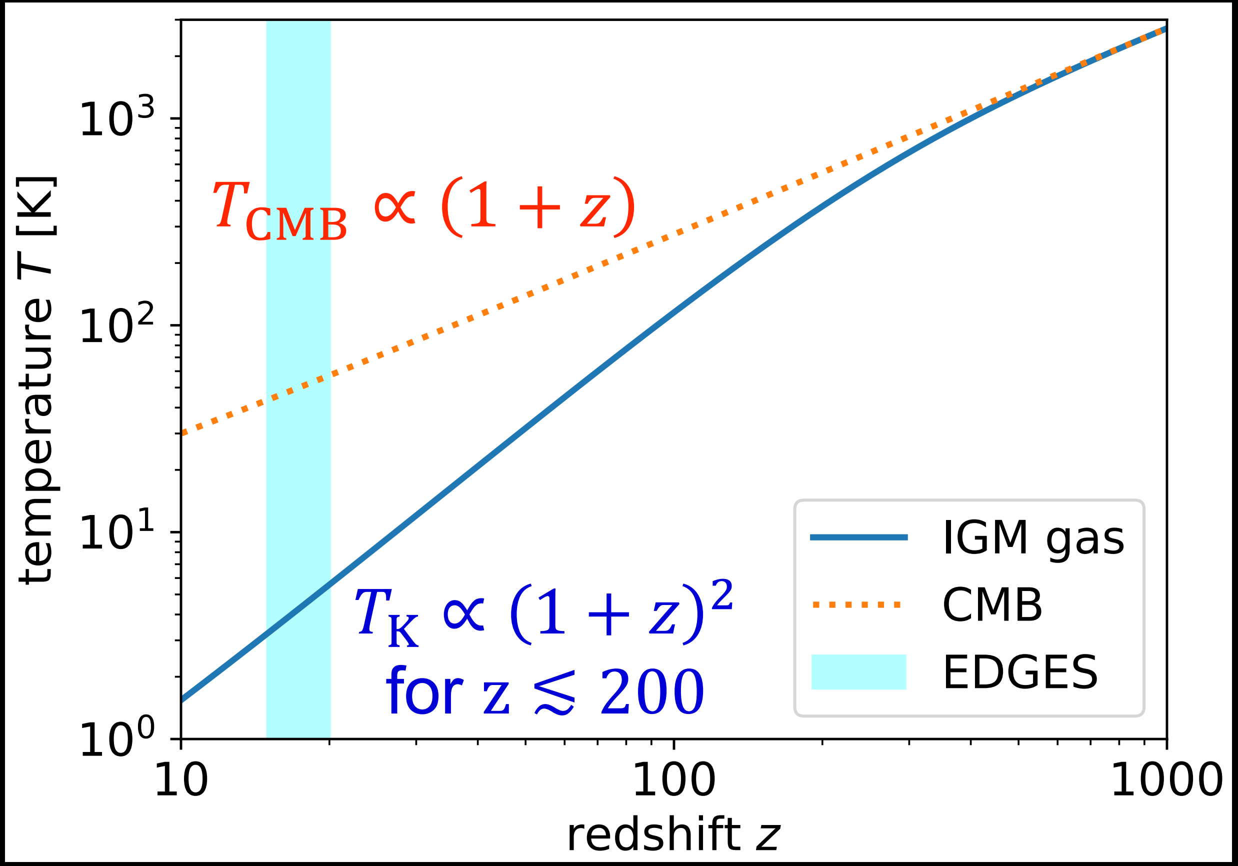
Experiment to Detect the Global EoR Signature (EDGES, https://www.colorado.edu/)



Reported 21-cm line global signal (Bowman et al., 2018 Nature, 555, 67)

IGM thermal history

For adiabatic evolution, $T_{\mathrm{CMB}} > T_{\mathrm{K}}$ (absorption) at $z{\sim}17$



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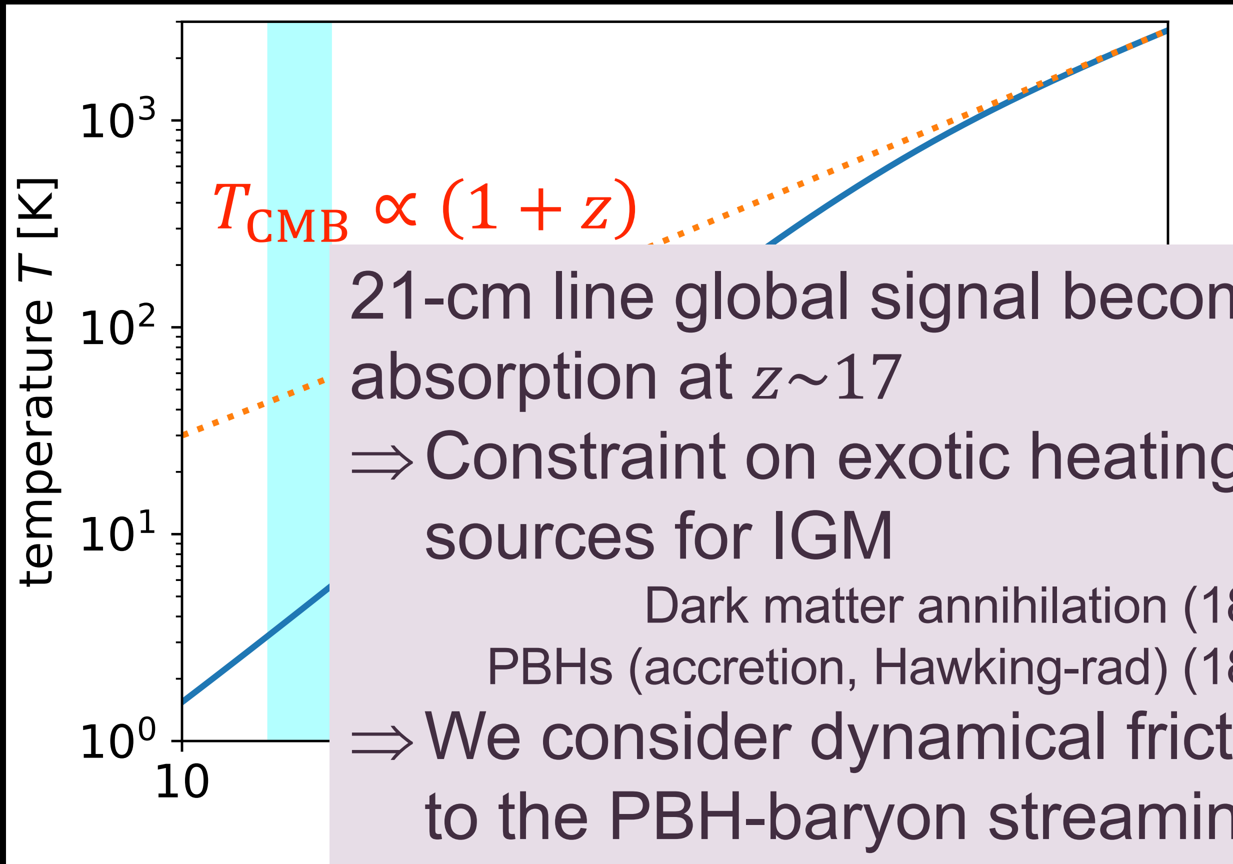

21-cm line global signal becomes absorption at $z \sim 17$

$\Rightarrow$ Constraint on exotic heating sources for IGM

Dark matter annihilation (1803.03629)

PBHs (accretion, Hawking-rad) (1803.09390)

$\Rightarrow$ We consider dynamical friction due to the PBH-baryon streaming velocity as a heating source

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Equation: IGM thermal history

$$\frac{dT_{\rm gas}}{dt} = \frac{x_e}{1+x_e}\frac{8\rho_{\rm CMB}\sigma_{\rm T}}{3m_e c}\left(T_{\rm CMB} - T_{\rm gas}\right) - 2HT_{\rm gas} + \dot{Q}_{\rm PBH}$$

Compton scattering

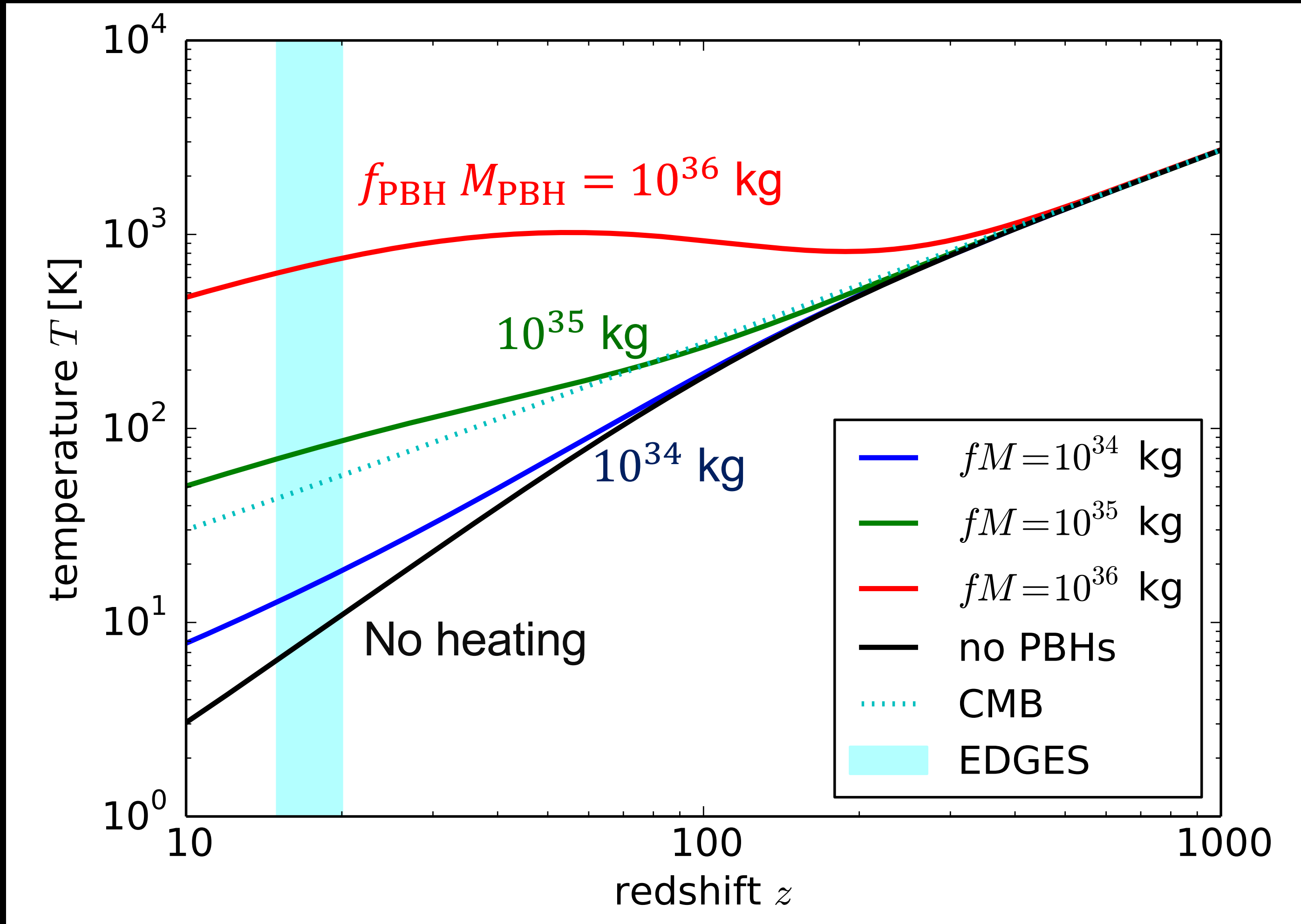
Cosmic expansion

Heating by PBHs

$$\dot{Q}_{\rm PBH} = \frac{8\pi}{3}\frac{\mu m_{\rm p}}{k_B}\left\langle \zeta_{\rm s}\, v_{\rm rel}^{-1}\right\rangle G^2\, \rho_{\rm CDM,0}\,(1+z)^3\, f_{\rm PBH}\, M_{\rm PBH}$$

$$\propto f_{\rm PBH}\, M_{\rm PBH}$$

Results: IGM thermal history



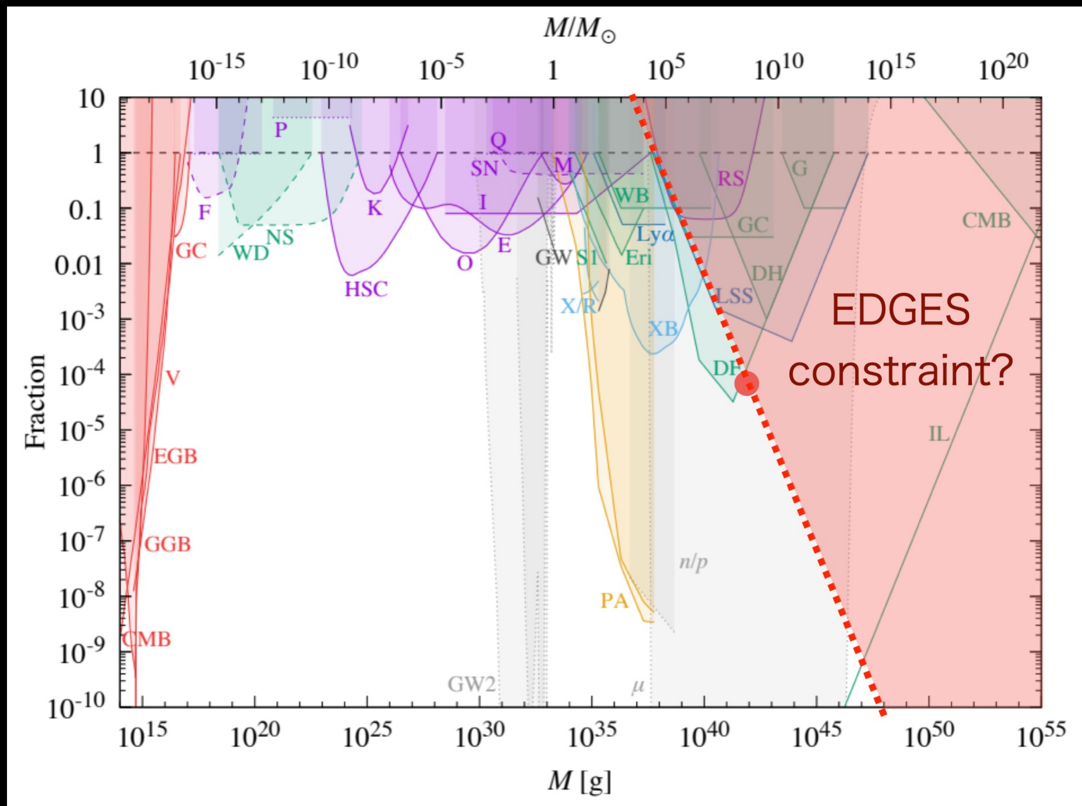
Constraint on PBH abundance

Calculating thermal history for various $f_{\rm PBH}$ $M_{\rm PBH}$

Imposing the absorption signal of 21-cm line as $T_{\rm K} < T_{\rm CMB}$ (for $z \sim 17$)

Then, we obtain

$$f_{\rm PBH} \lesssim 6 \times 10^{-5} \left(\frac{10^{39}\ {\rm kg}}{M_{\rm PBH}} \right)$$



Discussion:

considering back-reaction?

> ongoing…

Conclusion

✓ Estimate the impact of dynamical friction of PBHs on the IGM thermal history

✓ 21-cm global absorption signal at $z \sim 17$

=> constraint on the PBH abundance

$$f_{\mathrm{PBH}} \lesssim 6 \times 10^{-5} \left(\frac{10^{39}\ \mathrm{kg}}{M_{\mathrm{PBH}}} \right)$$

Future prospects:

✓ Need to discuss the overestimate for IGM heating

=> Including decay of the streaming velocity

Discussion: overestimate

We have not considered the back-reaction to the relative velocity;
Even for $f_{\rm PBH} = 1$, the thermal energy is comparable with kinetic energy

Detailed calculations?
> Ongoing…