21cm line as a probe of BSM
(beyond the Standard Model)

Tomo Takahashi
(Saga University)

Seminar
the 5th Toyama International Symposium on "Physics at the Cosmic Frontier”
@ University of Toyama
31 October, 2023

Plan of this talk

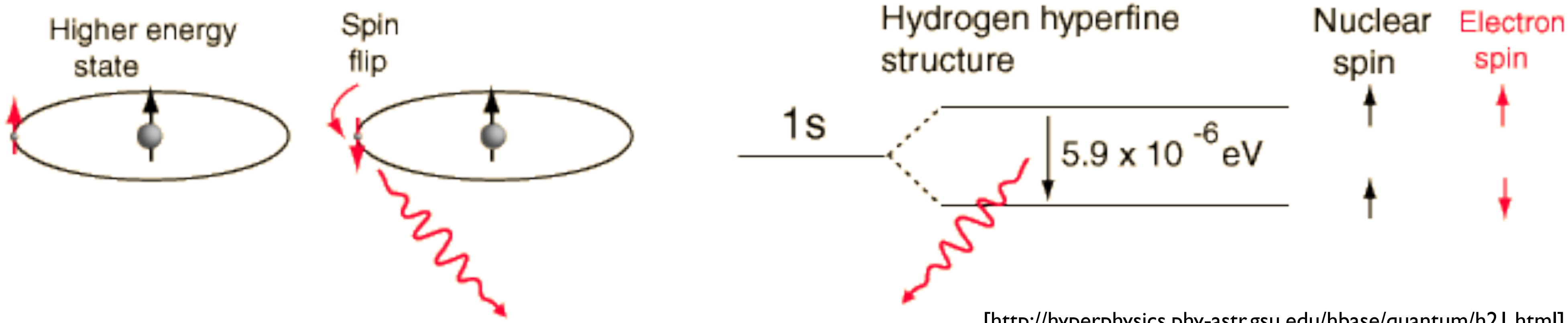
- Basics of 21cm line of neutral hydrogen and its signal

sky-averaged signal

- Observations of neutral hydrogen 21cm line (global signal)
- Examples of BSM and 21cm signal
- Dark age consistency ratio as a probe of BSM
- Summary

Basics of 21cm line of neutral hydrogen and its signal

What is 21cm?

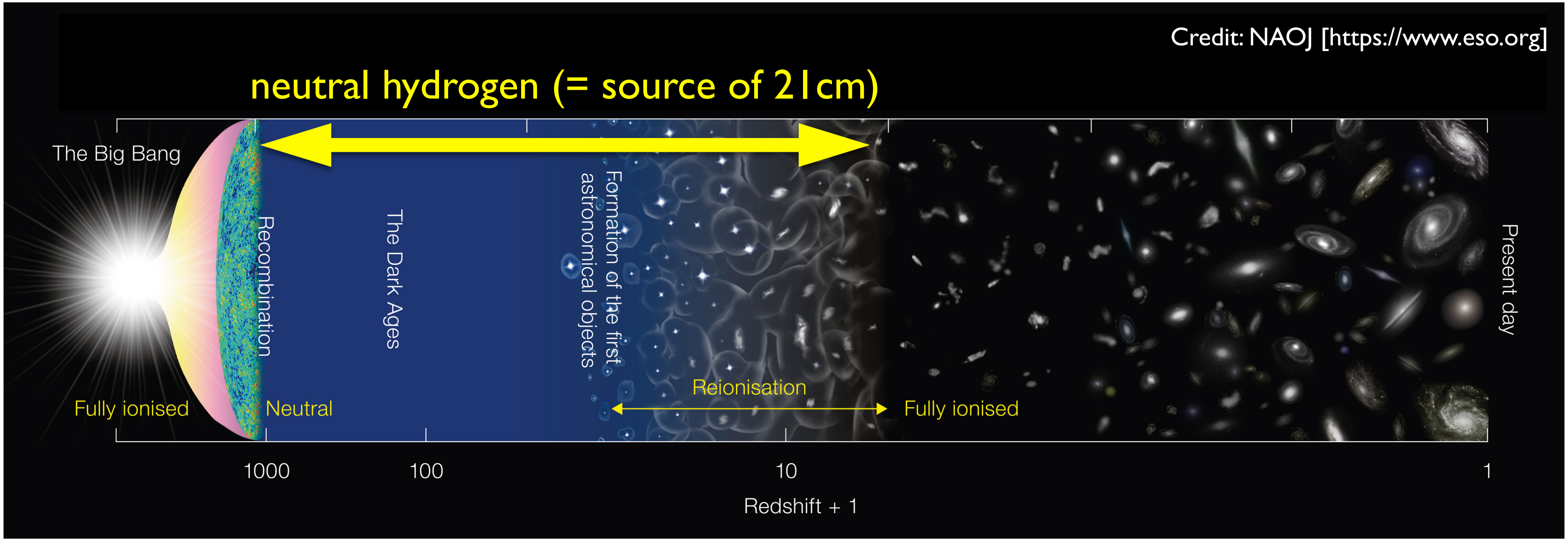


[http://hyperphysics.phy-astr.gsu.edu/hbase/quantum/h21.html]

$$\nu_0 = 1420.4057517 \text{ MHz}$$
$$\lambda_0 = 21.106114 \text{ cm}$$

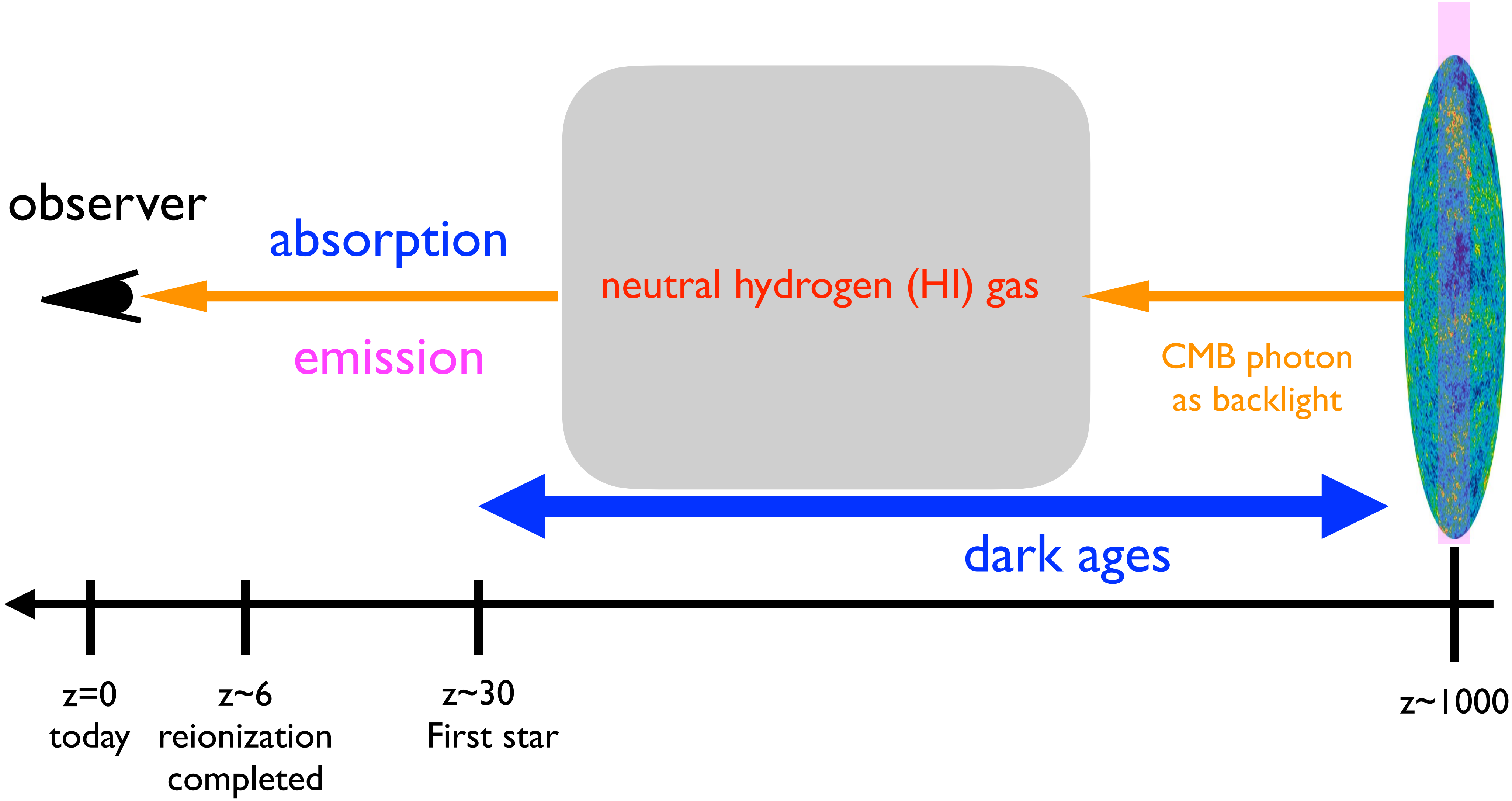
Frequency observed: $\nu = \dfrac{\nu_0}{1+z}$

21cm from neutral hydrogen

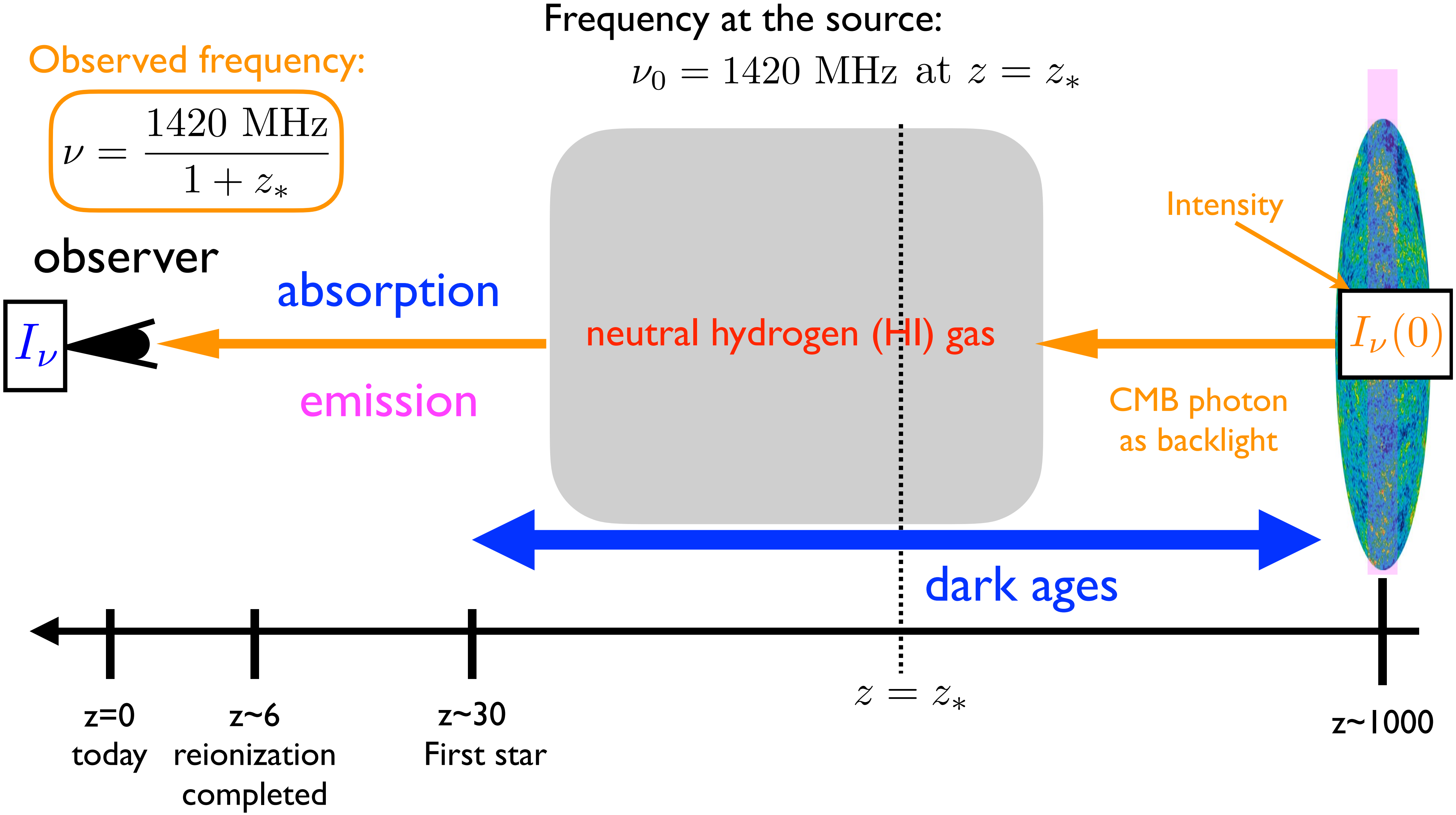


- After recombination, the Universe becomes neutral (neutral hydrogens are ubiquitous.)
- 21cm line from neutral hydrogen can also probe the so-called dark ages (which cannot be probed with other observations.)

21cm from neutral hydrogen



21cm from neutral hydrogen



Frequency at the source:

$$\nu_0 = 1420 \text{ MHz at } z = z_*$$

Observed frequency:

$$\boxed{\nu = \frac{1420 \text{ MHz}}{1 + z_*}}$$

observer

I_ν

absorption

emission

neutral hydrogen (HI) gas

Intensity

$I_\nu(0)$

CMB photon
as backlight

dark ages

$z = z_*$

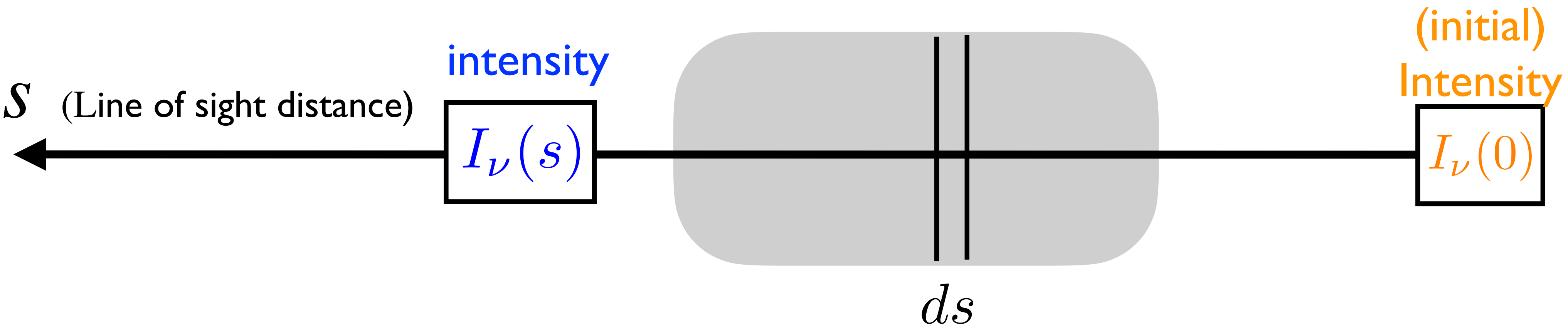
z=0
today

z~6
reionization
completed

z~30
First star

z~1000

Signal of 21cm line



- Intensity is often represented by an "effective" temperature called "brightness temperature" T_b

Definition: $I_\nu \equiv B_{\rm bb}(\nu, T_b)$

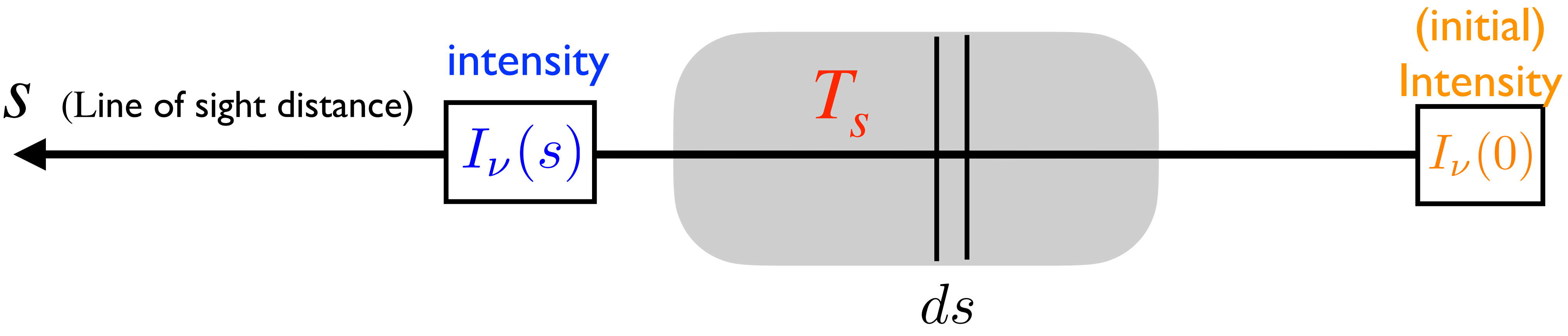
Black body distribution

- In Rayleigh-Jeans (low frequency) region,

$$B_{\rm BB}(\nu, T) \simeq 2\nu^2 T \quad \rightarrow \quad I_\nu \simeq 2\nu^2 T_b \quad \rightarrow \quad \boxed{T_b = \frac{I_\nu}{2\nu^2}}$$

(brightness temperature = intensity)

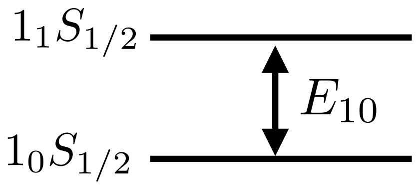
Signal of 21cm line



- The state of HI (neutral hydrogen) gas is characterized by the so-called "The spin temperature" T_s.

- "The spin temperature" T_s is defined by the ratio of two levels.

$$\frac{n_1}{n_0} \equiv \frac{g_1}{g_0} e^{-E_{10}/k_B T_s} = 3e^{-T_*/T_s}$$

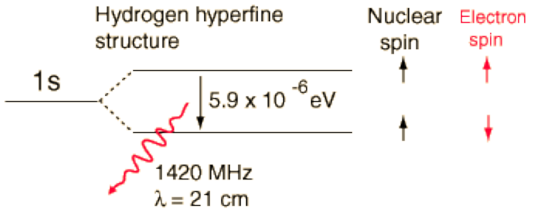


What determines the spin temperature?

- Absorption (and spontaneous emission) of CMB photon A_{10} B_{10} B_{01}

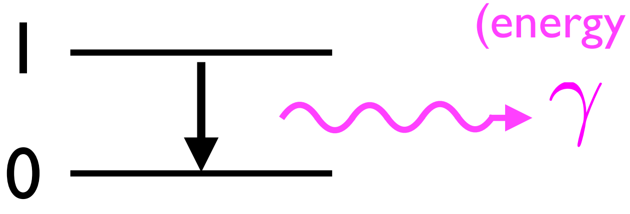
Einstein coefficients

- Description of the 2 level system



  - Spontaneous emission

(energy E_{01})

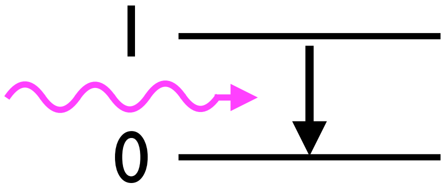


(Einstein A coefficient)

Probability: A_{10}

(# of events per unit time)

  - Absorption

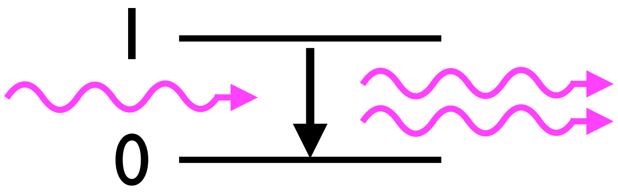


(Einstein B coefficient)

Probability: $B_{01} J_\nu$

(Radiation intensity)

  - Induced emission



Probability: $B_{10} J_\nu$

What determines the spin temperature?

- Absorption (and spontaneous emission) of CMB photon A_{10} B_{10} B_{01}

- Collisions (HH, He and Hp) C_{01} (excitation rate by collision)

  C_{10} (de-excitation rate by collision)

If this is effective: $T_s \to T_K$

T_K : Gas temperature $\frac{C_{01}}{C_{10}} = \frac{g_1}{g_0} e^{-T_\star/T_K} \approx 3 \left(1 - \frac{T_\star}{T_K}\right)$

Gas temperature T_k

- When the equilibrium between n_0 and n_1 is realized by the collisions, its temperature is called gas temperature.

  (The number density of n_0 and n_1 are given by Boltzmann distribution with T_k)

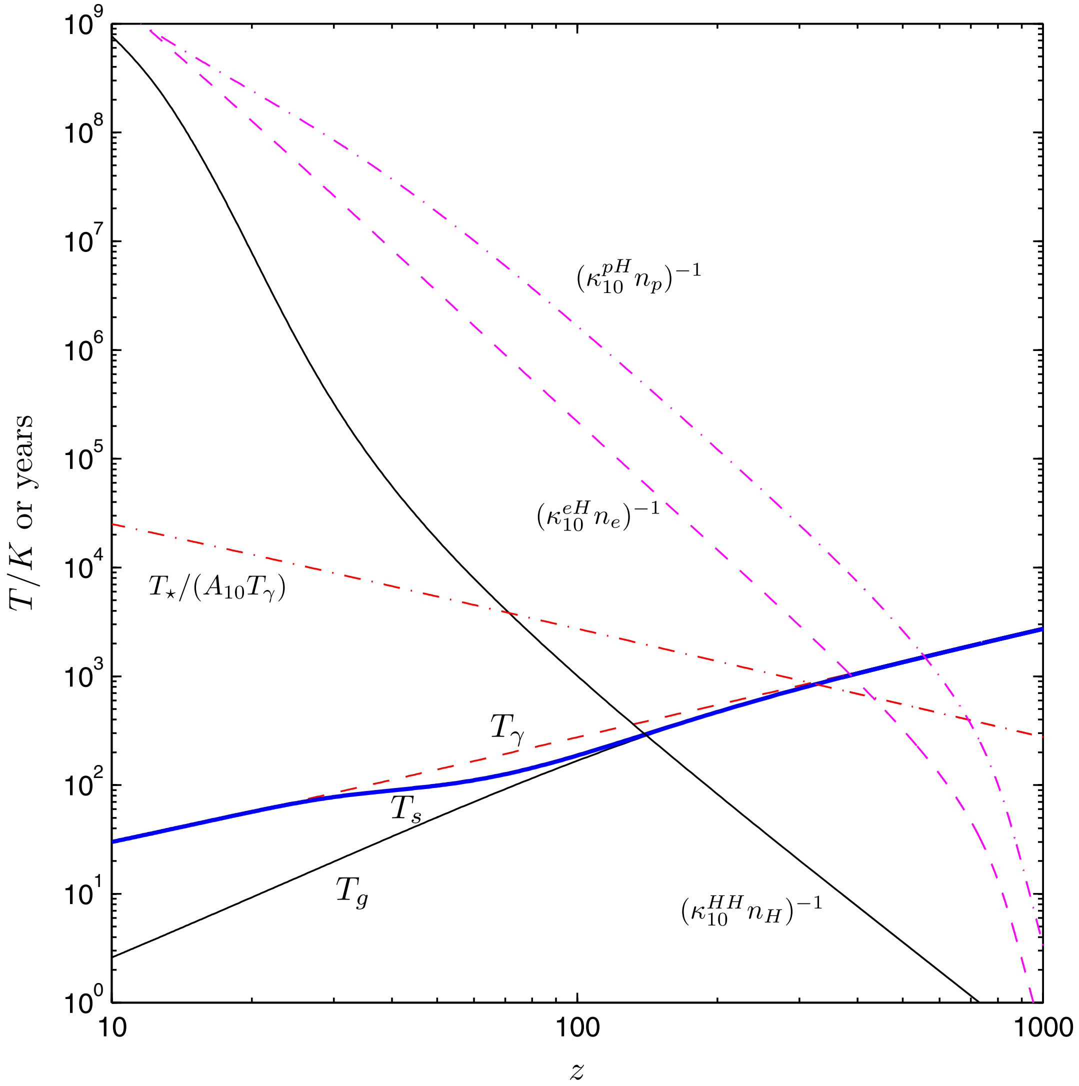
- Evolution equation for T_k:

$$\frac{dT_K}{dt} + 2HT_K = \frac{2}{3}\sum_j \frac{\epsilon_j}{n}$$

Injected energy

- When the gas cools adiabatically in an expanding Universe, T_k is given by $\boxed{T_k \propto a^{-2}}$

Time scale of collisions (HH, He and Hp)



[From Lewis, Challinor, PRD, 2007]

What determines the spin temperature?

- Absorption (and spontaneous emission) of CMB photon A_{10} B_{10} B_{01}

- Collisions (HH, He and Hp) C_{01} (excitation rate by collision)

  C_{10} (de-excitation rate by collision)

  If this is effective: $T_s \to T_K$

  T_K : Gas temperature $\frac{C_{01}}{C_{10}} = \frac{g_1}{g_0} e^{-T_\star/T_K} \approx 3\left(1 - \frac{T_\star}{T_K}\right)$

- Scattering of Lyα photons (After first astrophysical sources are switched on.)

  P_{01} (excitation rate by Lyα photon)

  P_{10} (de-excitation rate by Lyα photon)

  If this is effective: $T_s \to T_c \; (T_k)$

  T_c : Color temperature $\frac{P_{01}}{P_{10}} \equiv 3\left(1 - \frac{T_\star}{T_c}\right)$

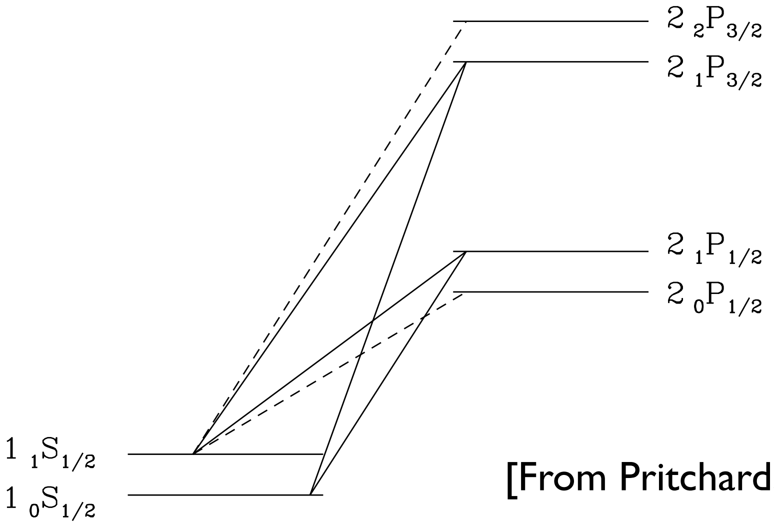
Wouthuysen-Field effect

- Resonant scattering of Lyα photon gives a transition between the singlet and triplet state via 2P state.

1S (singlet) → 2P → 1S (triplet)

1S (triplet) → 2P → 1S (singlet)

(Electric dipole selection rules allow $\Delta F = 0, \pm 1$)



[From Pritchard, Loeb 1109.6012]

Three processes determine the spin temperature

$$n_1(\underset{\uparrow}{C_{10}} + \underset{\uparrow}{P_{10}} + \underset{\uparrow}{A_{10}} + \underset{\uparrow}{B_{10}} I_{\rm CMB}) = n_0(\underset{\uparrow}{C_{01}} + \underset{\uparrow}{P_{01}} + \underset{\uparrow}{B_{01}} I_{\rm CMB})$$

collision Lyα Einstein coefficients

$$\Rightarrow \quad T_S^{-1} = \frac{T_\gamma^{-1} + x_c T_K^{-1} + x_\alpha T_c^{-1}}{1 + x_c + x_\alpha}$$

Collision Scattering of Lyα photons

- Coupling coefficients: $x_c \equiv \frac{C_{10}}{A_{10}} \frac{T_*}{T_\gamma}$ $\quad x_\alpha \equiv \frac{P_{10}}{A_{10}} \frac{T_*}{T_\gamma}$

(In most cases of interest, Tk = Tc)

Differential brightness temperature ΔT_b (21cm signal)

$$T_b(\tau_\nu) \simeq e^{-\tau_\nu} T_b + \left(\frac{\nu_{21}}{\nu}\right)^2 T_s \left(1 - e^{-\tau_\nu}\right)$$

Assuming $\tau_\nu \ll 1$

$$\Delta T_b \equiv \frac{T_b(z) - T_\gamma(z)}{1+z}$$

$$= \frac{T_s - T_\gamma(z)}{1+z}\left(1 - e^{-\tau_\nu}\right) \simeq \frac{T_s - T_\gamma(z)}{1+z}\tau_\nu$$

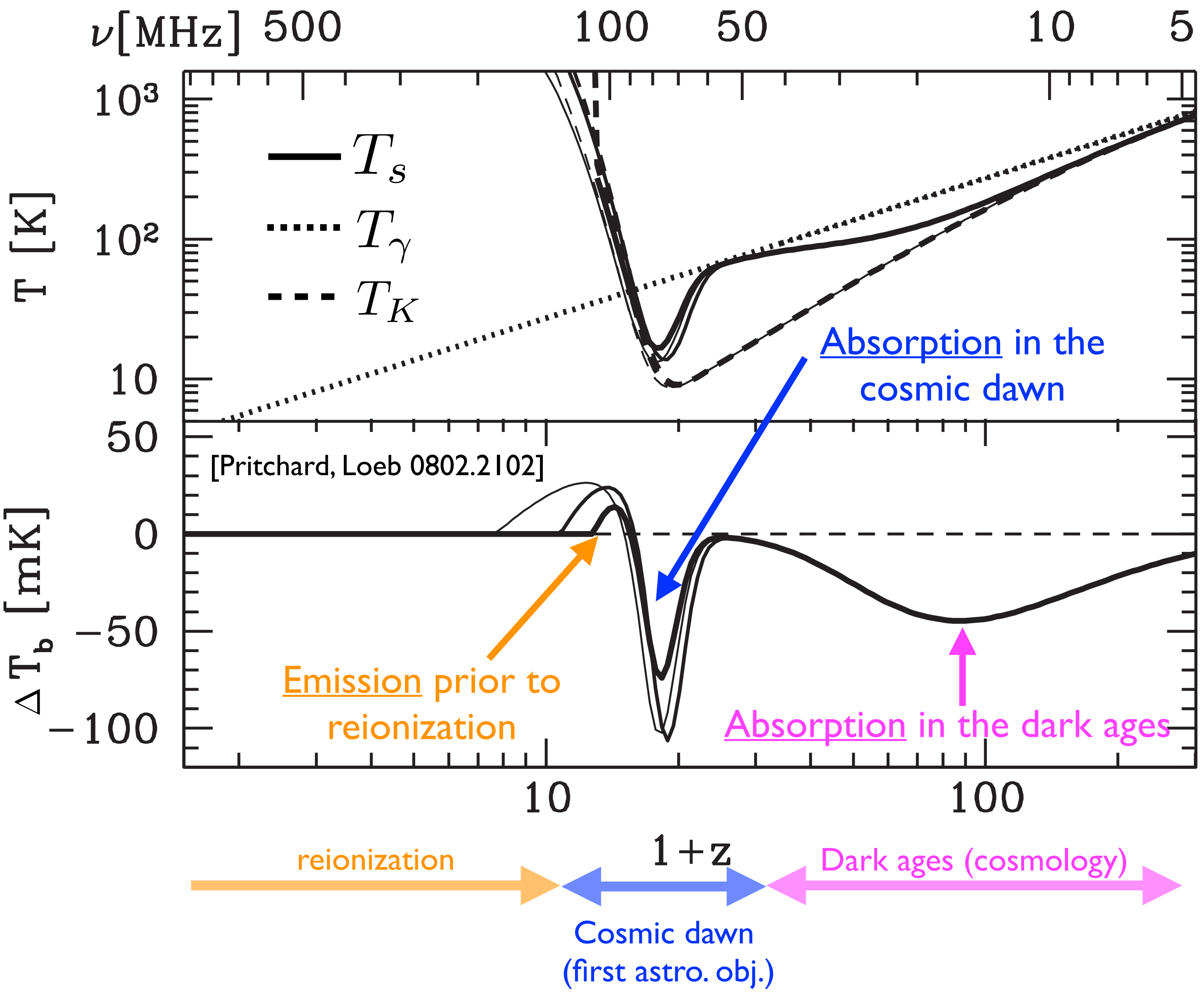
$$\boxed{\Delta T_b \simeq 27\ \mathrm{mK}\ \left(\frac{T_s - T_\gamma}{T_s}\right)\left(\frac{1+z}{10}\right)^{1/2}\left(\frac{\Omega_b h^2}{0.023}\right)\left(\frac{0.15}{\Omega_m h^2}\right)^{1/2} x_{HI}}$$

$T_s < T_\gamma$: absorption

$T_s > T_\gamma$: emission

- ΔT_b depends on baryon density, neutral fraction and the spin temperature

Evolution of ΔT_b



[Pritchard, Loeb 0802.2102]

Absorption in the cosmic dawn

Emission prior to reionization

Absorption in the dark ages

reionization

Cosmic dawn (first astro. obj.)

Dark ages (cosmology)

Current and future observations

Detection of 21cm absorption line by EDGES

- In 2018, EDGES (Experiment to Detect the Global Epoch of Reionization Signature) has reported the detection of 21cm absorption trough at $z \sim 17$.

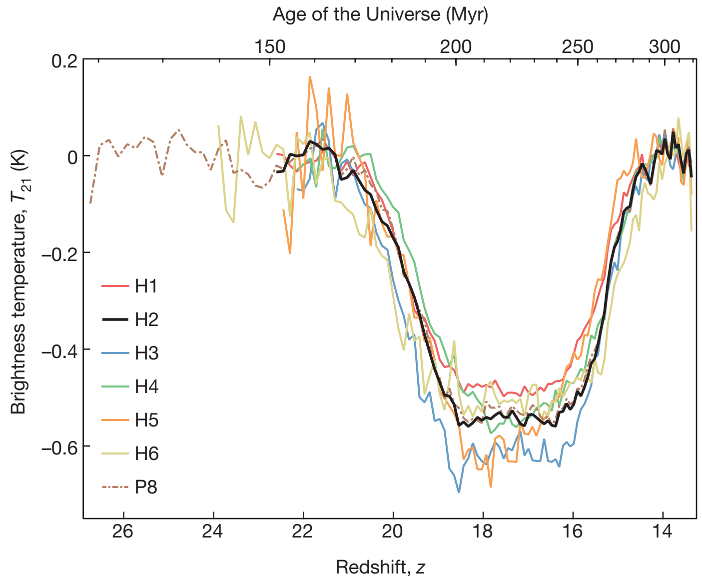
[Bowman et al. Nature 555, 67 (2018)]

- Brightness temperature:

$$T_b = -500^{+200}_{-500}\ \mathrm{mK} \quad (99\ \%\ \mathrm{C.L.})$$

- Actually, this signal is too low to be explained by standard scenarios.

→ Motivated a lot of works



- However, there have been several arguments regarding the detection.
  - SARAS3 excluded the EDGES signal at ~2σ level. [Singh et al. 2112.06778]
  - Some systematics? (foreground modeling? some artifact?)

[Draine et al. 1804.02250; Hill et al. 1805.01421; Bradley et al. 1810.0901; Singh, Subrahmanyan 1903.04540; Spinelli et al. 1908.05303]

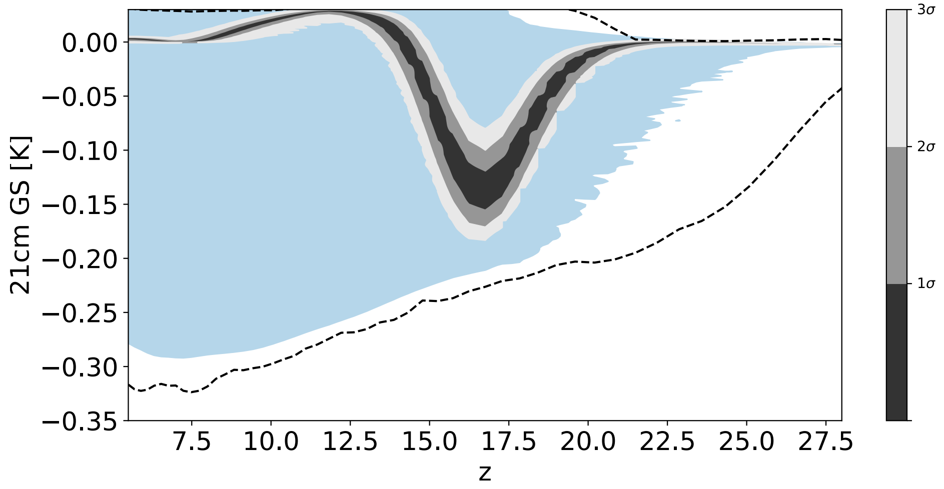
Detection of 21cm absorption line by EDGES

- Detection signal depends on the assumption of foreground, noise and systematics

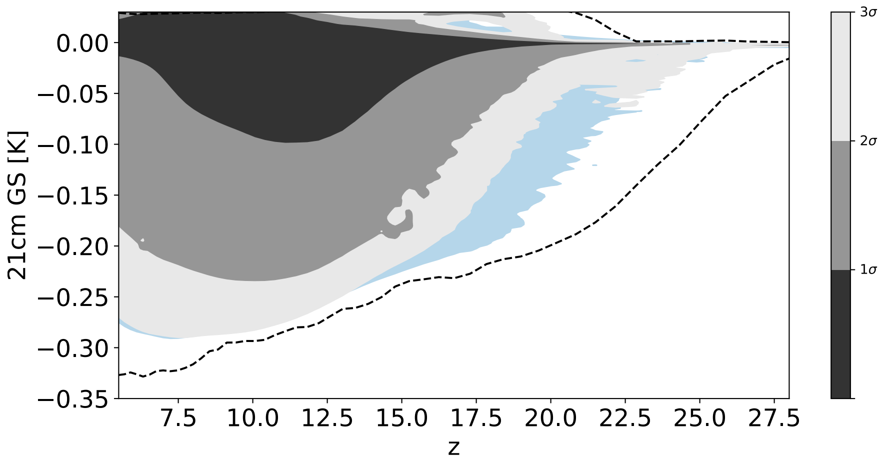
Foreground: $T_{\rm FG} = 10^{\sum_{i=0}^{N} d_i \log(\nu/\nu_0)^i}$ [K]

Systematics: $T_{\rm cal}(\nu) = \left(\frac{\nu}{\nu_0}\right)^b \{10^{a_0}\sin(2\pi\nu/P) + 10^{a_1}\cos(2\pi\nu/P)\}$ [K]

(FG: including up to 5th order)



(FG: including up to 7th order)



[Yoshiura, Minoda, TT 2305.11441]

Observations for the global 21cm signal (cosmic dawn/EoR)

- EDGES
  (Experiment to Detect the Global Epoch of Reionization Signature)

  [100 - 200 MHz (high band), 50 - 100 MHz (low band)]

  [Bowman et al. Nature 555, 67 (2018)]

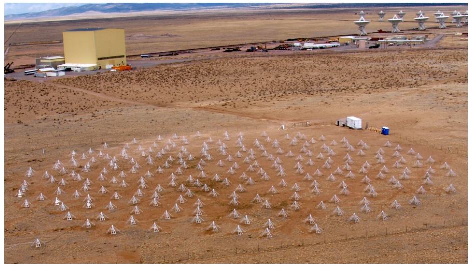
EDGES antenna in western Australia (photo credit: Judd Bowman/ASU)

https://www.haystack.mit.edu/ast/arrays/Edges/

- LEDA
  (Large-aperture Experiment to Detect the Dark Ages)

  [40 - 85 MHz]

  [Bernardi et al. MNRAS 461, 2847 (2016)]



http://www.tauceti.caltech.edu/leda/

$\nu = 200$ MHz	$\nu = 100$ MHz	$\nu = 50$ MHz	$\nu = 40$ MHz
$z = 6.1$	$z = 13.2$	$z = 27.4$	$z = 34.5$

Observations for the global 21cm signal (cosmic dawn/EoR)

- SARAS
  (Shaped Antenna measurement of the background RAdio Spectrum)

  [40 - 200 MHz] [Singh et al ApJ 858, 54 (2018)]

- SCI-HI
  (Sonda Cosmológica de las Islas para la Detección de Hidrógeno Neutro)

  [40 - 130 MHz] [Voytek et al ApJL 782, L9 (2014)]

- PRIZM
  (Probing Radio Intensity at high z from Marion)

  [40 - 130 MHz] [Philip et al 1806.09531]

- BIGHORNS
  (Broadband Instrument for Global HydrOgen ReioNisation Signal)

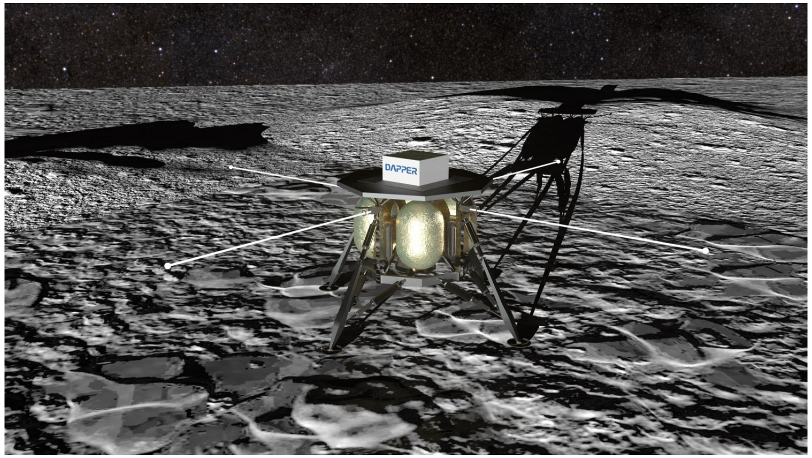
  [70 - 200 MHz] [Sokoloowski et al 1501.02922]

Observations for the global 21cm signal (during the dark ages)

(proposed observations on/around the moon)

- Dapper (Dark Ages Polarimeter Pathfinder)

[Burns et al. 2103.05085]

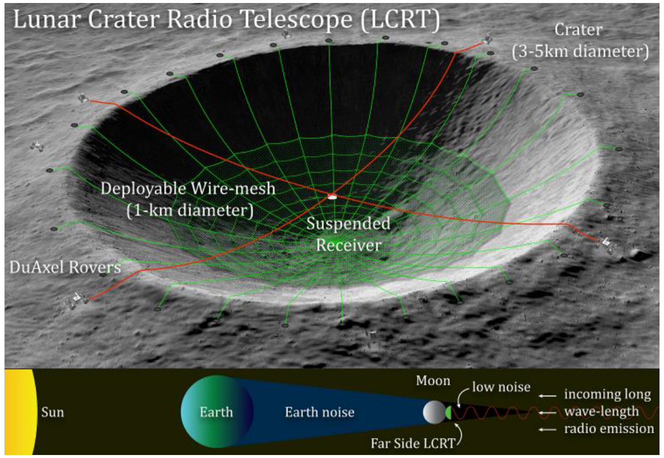


[https://www.colorado.edu/ness/dark-ages-polarimeter-pathfinder-dapper]

- FARSIDE (Farside Array for Radio Science Investigations of the Dark ages and Exoplanets) [Burns et al. Astro2020: Decadal Survey on Astronomy and Astrophysics, APC white papers]

- LCRT (Lunar Crater Radio Telescope)

[Goel et al. 2205.05745]

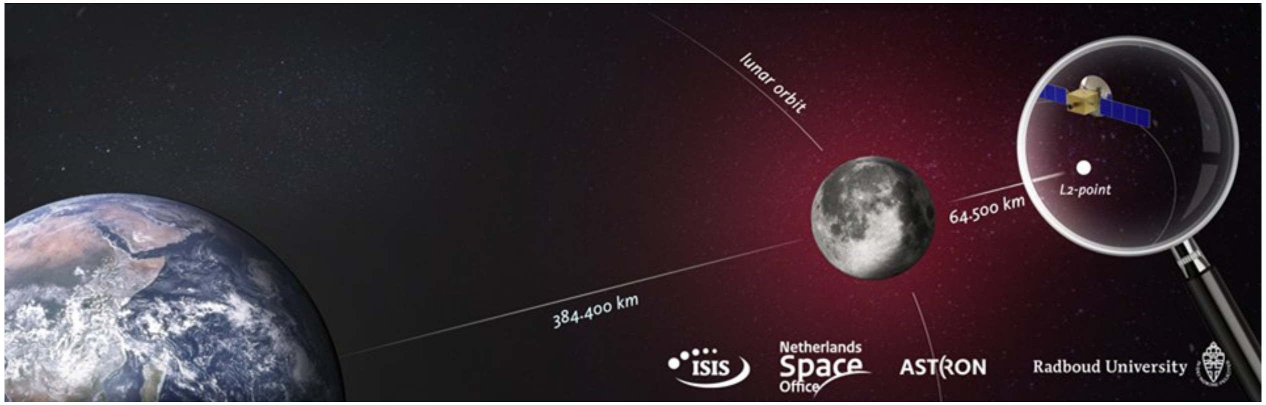


[https://www.nasa.gov/directorates/spacetech/niac/2020_Phase_I_Phase_II/lunar_crater_radio_telescope/]

Observations for the <u>global</u> 21cm signal (during the dark ages)

(proposed observations on/around the moon)

- NCLE (Netherlands-China Low frequency Explorer)



[https://www.ru.nl/astrophysics/radboud-radio-lab/projects/netherlands-china-low-frequency-explorer-ncle/]

- DSL (Discovering the Sky at the Longest Wavelengths)

[Chen et al. 1907.10853]

⋮

Observations for the <u>global</u> 21cm signal (during the dark ages)

(Japanese Project)

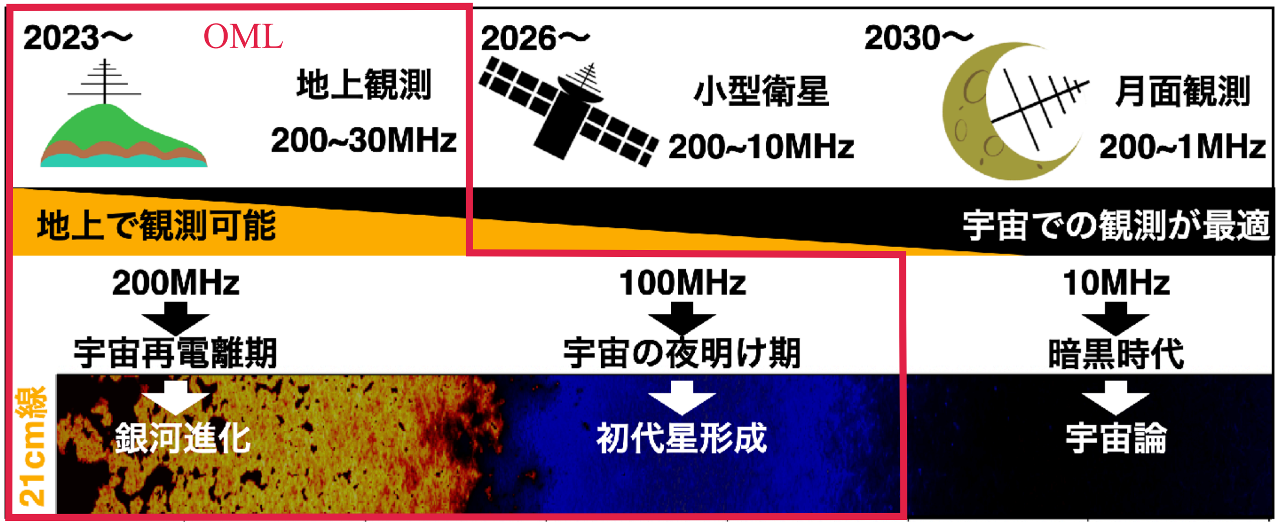
- TREED (The REceiver Exploring Dark-ages)

PI: Shintaro Yoshiura (NAOJ)

[TT is one of the members]

[http://ska-jp.org/treed/]

Plan of TREED



Examples of BSM and 21cm signal

Cosmology with 21cm global signal

sky-averaged signal

- Inflation (primordial fluctuations)
  - Power spectrum (Runnings, small scale amplitude, …)
    [Yoshiura, K.Takahashi, TT 1805.11806; Yoshiura, K.Takahashi, TT 1911.07442]
  - Isocurvature fluctuations
    [Minoda, Yoshiura, TT 2112.15135]

⋮

- Dark matter
  - Warm dark matter
    [Sitwell et al 1310.0029; Schneider 1805.00021, …]
  - Dark matter annihilation, decay
    [Valdes et al. 1209.2120; Clark et al. 1803.09390, ….]

⋮

- Dark components
  - Early dark energy [Hill, Baxter 1803.07555]

⋮

Cosmology with 21cm global signal

sky-averaged signal

- Inflation (primordial fluctuations)
  - Power spectrum (Runnings, small scale amplitude, …)

    [Yoshiura, K.Takahashi, TT 1805.11806; Yoshiura, K.Takahashi, TT 1911.07442]
  - Isocurvature fluctuations

    [Minoda, Yoshiura, TT 2112.15135]

  ⋮

- Dark matter
  - Warm dark matter

    [Sitwell et al 1310.0029; Schneider 1805.00021, …]
  - Dark matter annihilation, decay

    [Valdes et al. 1209.2120; Clark et al. 1803.09390, ….]

  ⋮

- Dark components
  - Early dark energy [Hill, Baxter 1803.07555]

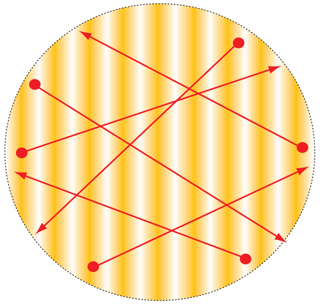
  ⋮

Warm Dark Matter and 21cm

Warm dark matter (WDM)

- Erases small scale structure by free-streaming effect

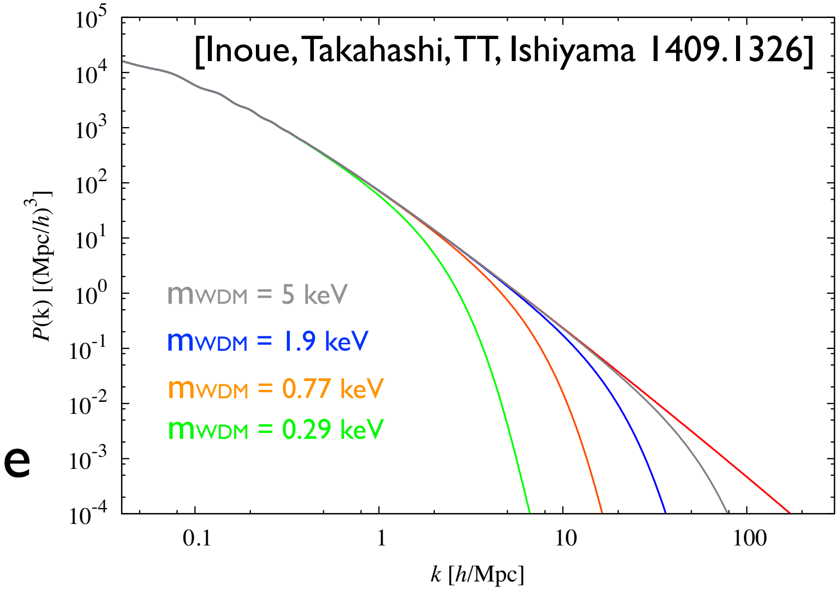
  - Relativistic dark matter particles erase fluctuations inside the scale $\lambda \sim ct$.



- Free-streaming length:

$$k_{\rm fs} \sim 15 \frac{h}{\rm Mpc} \left(\frac{m_{\rm WDM}}{1~\rm keV}\right)^{4/3} \left(\frac{0.12}{\Omega_{\rm WDM} h^2}\right)^{1/3}$$

  - Below the free-streaming scale, power spectrum is suppressed.



- Can be a possible solution to the small-scale problems

- There exist well-motivated candidates in particle physics.

  (sterile neutrino, gravitino, …)

Some of recent constraints on WDM mass (thermal WDM)

- Lyman α

$m_{\rm WDM} > 5.3\ {\rm keV}\ \ (95\,\%\,{\rm CL})$ [Iršič et al 1702.01764]

- Gravitational lensing

$m_{\rm WDM} > 5.2\ {\rm keV}\ \ (95\,\%\,{\rm CL})$ [Gilman et al., 1908.06983]

$m_{\rm WDM} > 5.58\ {\rm keV}\ \ (95\,\%\,{\rm CL})$ [Hsueh et al. 1905.04182]

- Milky Way satellite

$m_{\rm WDM} > 4.4\ {\rm keV}\ \ (95\,\%\,{\rm CL})$ [Dekker et al. 2111.13137]

$m_{\rm WDM} > 2.02\ {\rm keV}\ \ (95\,\%\,{\rm CL})$ [Newton et al. 2011.08865]

- UV luminosity function

$m_{\rm WDM} > 3.3\ {\rm keV}\ \ (95\,\%\,{\rm CL})$ [Shinohara, Yoshiura, TT in prep.]

$\vdots$

Some of recent constraints on WDM mass (thermal WDM)

Combinations of some data give a severer constraint:

- Strong lens+Lyman α+Milky-Way satellites

$$m_{\rm WDM} > 6.048 \ {\rm keV} \ \ (95\,\%\,{\rm CL})$$ [Enzi et al 2010.13802]

- Strong lens+Milky-Way satellites

$$m_{\rm WDM} > 9.7 \ {\rm keV} \ \ (95\,\%\,{\rm CL})$$ [Nadler et al 2101.07810]

(NB: Be cautious about the procedure of the analysis as constraints generally depend on the modelling/assumption, particularly some astrophysical uncertainties.)

Effects of warm DM on the 21cm global signal

- In WDM models, small scales structure are suppressed.

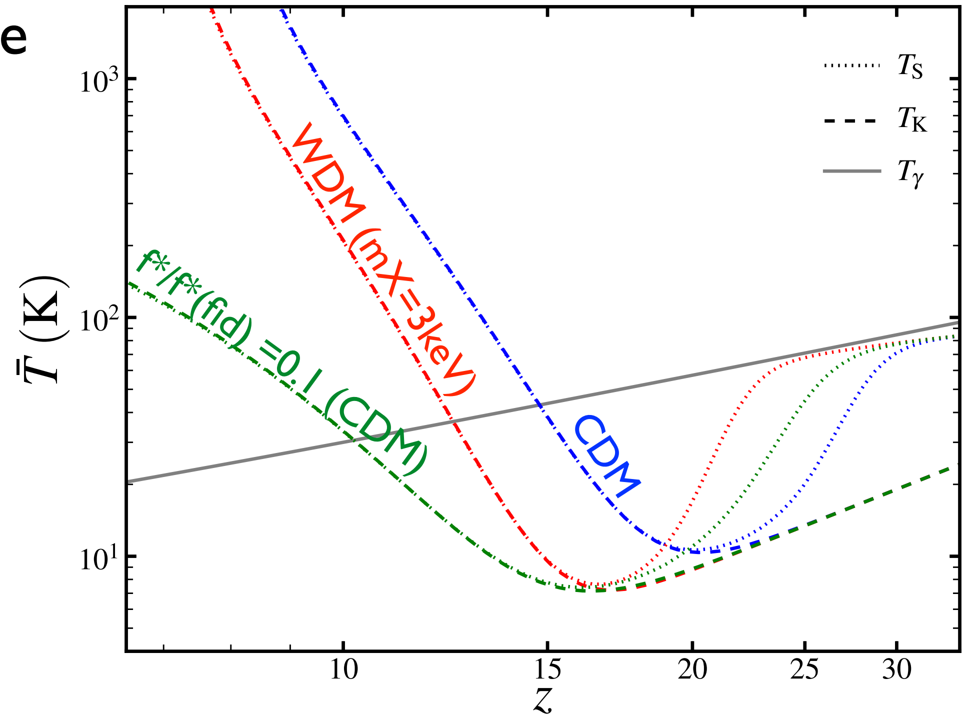
➡ Structure formation is delayed.

➡ Early star formation is delayed.

➡ Production of UV and X-ray background is delayed.

➡ Affects the evolution of the spin temperature.

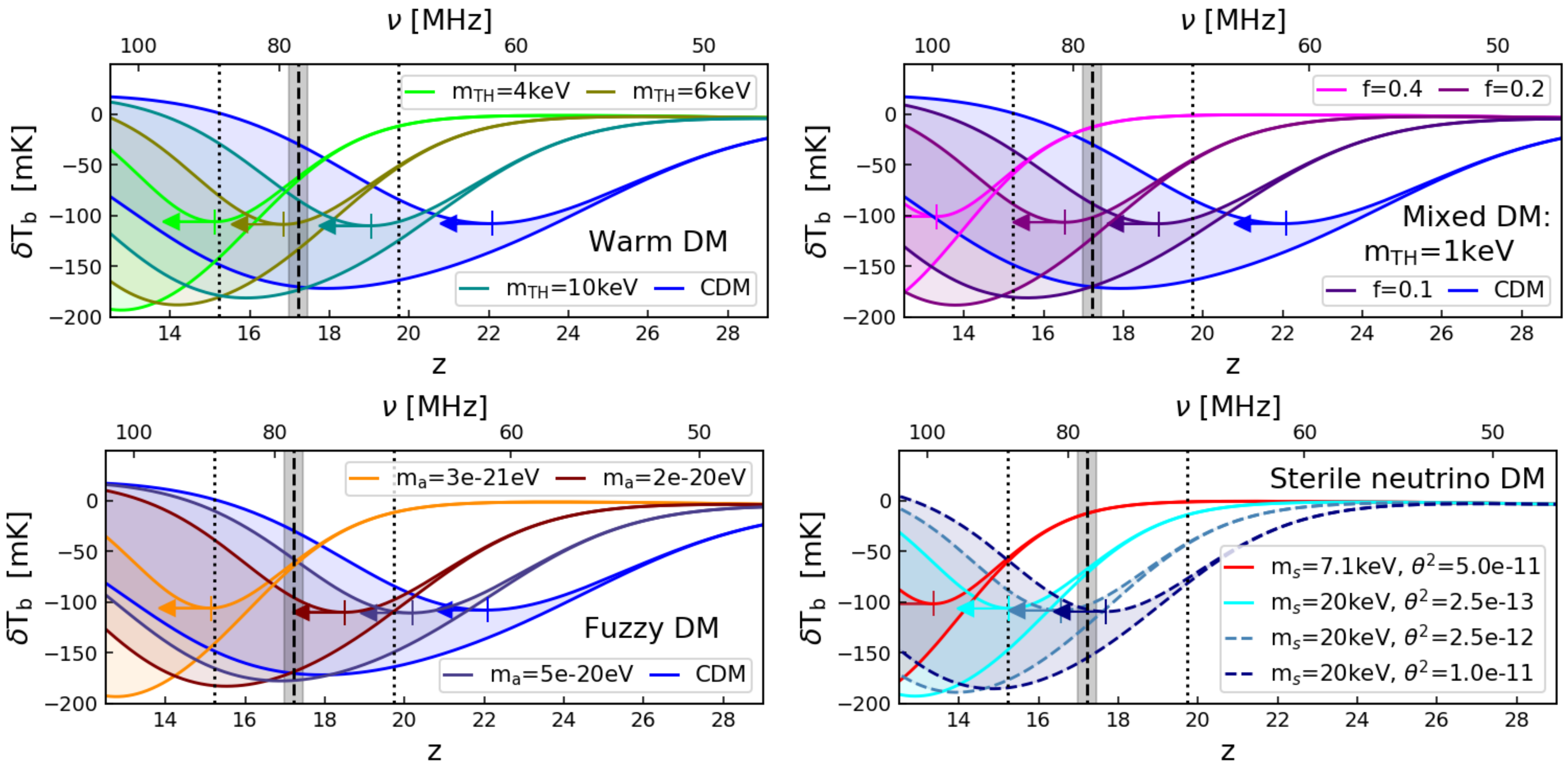
[Sitwell et al 1310.0029]



(f*: fraction of baryon incorporated into star)

Constraining warm dark matter

- Demanding that the timing of the absorption should be consistent with EDGES, one can obtain a bound on DM parameters (mass, …)



(Shaded area between lines quantifies the uncertainty of the gas heating process.)

[Schneider 1805.00021]

→ $m_{\mathrm{WDM}} > 6.1\ \mathrm{keV}$ (for thermal WDM)

Dark Matter annihilation and decay

Dark Matter annihilation effect on 21cm signal

- Dark matter annihilation deposits energy into IGM.

→ Affects the ionization fraction, kinetic temperature of the gas and the spin temperature.

$$\Delta T_b \simeq 27\ \mathrm{mK} \left(\frac{T_s - T_R}{T_s}\right) \left(\frac{1+z}{10}\right)^{1/2} \left(\frac{\Omega_b h^2}{0.023}\right) \left(\frac{0.15}{\Omega_m h^2}\right)^{1/2} x_{HI}$$

- ■ Ionization fraction (or neutral fraction)
- ■ Kinetic gas temperature:
- ■ Color (Lyα) temperature

} → Spin temperature

$$T_S^{-1} = \frac{T_\gamma^{-1} + x_c T_K^{-1} + x_\alpha T_c^{-1}}{1 + x_c + x_\alpha}$$

Dark Matter annihilation effect on 21cm signal

- Evolution of ionization fraction

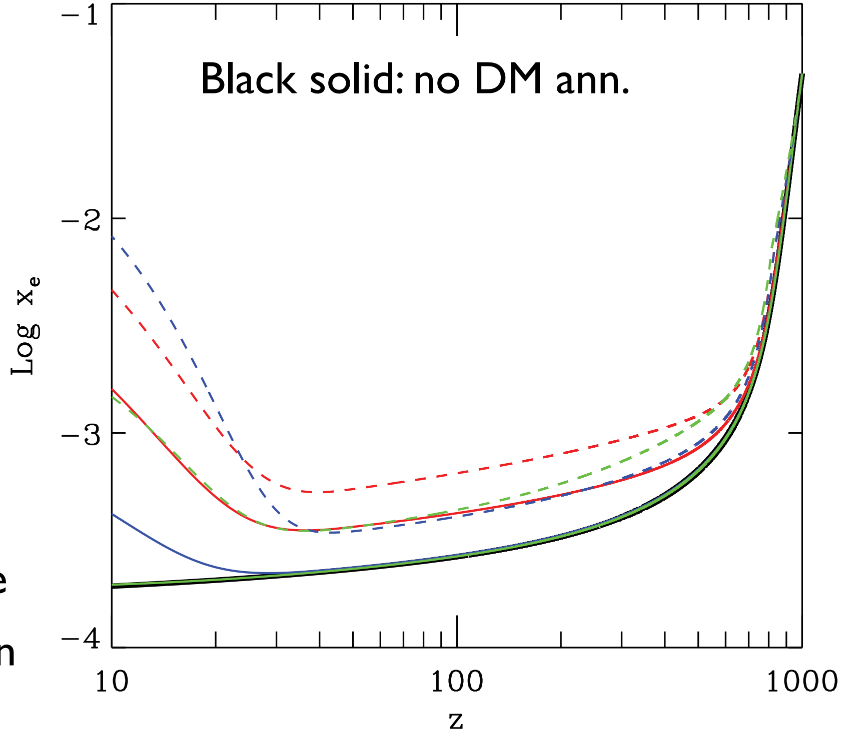
$$\frac{\mathrm{d}x_e}{\mathrm{d}z} = \frac{\mathrm{d}t}{\mathrm{d}z}\left[\Gamma_{\mathrm{ion}} - \alpha_{\mathrm{B}} x_e^2 n_{\mathrm{b}} f_{\mathrm{H}}\right]$$

Ionization rate: standard + DM annihilation
(astro) /decay

standard recombination rate

fH: Hydrogen number fraction

[Valdes et al 1209.2120]


Black solid: no DM ann.

DM model	Mass (GeV)	$\langle\sigma v\rangle$ (cm^3 s^{-1})	ϵ_0 (eV s^{-1})	$\delta\tau_e$	Line style
W^+W^-	200	$\langle\sigma v\rangle_{\mathrm{th}} = 3.0 \times 10^{-26}$	5.35×10^{-25}	1.53×10^{-3}	Blue solid
W^+W^-	200	$\langle\sigma v\rangle_{\mathrm{max}} = 1.2 \times 10^{-24}$	2.14×10^{-23}	6.09×10^{-2}	Blue dashed
$b\bar{b}$	10	$\langle\sigma v\rangle_{\mathrm{th}} = 3.0 \times 10^{-26}$	1.07×10^{-23}	1.80×10^{-2}	Red solid
$b\bar{b}$	10	$\langle\sigma v\rangle_{\mathrm{max}} = 1.0 \times 10^{-25}$	3.57×10^{-23}	5.76×10^{-2}	Red dashed
$\mu^+\mu^-$	1000	$\langle\sigma v\rangle_{\mathrm{th}} = 3.0 \times 10^{-26}$	1.07×10^{-25}	1.42×10^{-4}	Green solid
$\mu^+\mu^-$	1000	$\langle\sigma v\rangle_{\mathrm{max}} = 1.4 \times 10^{-23}$	4.99×10^{-23}	6.18×10^{-2}	Green dashed

Dark Matter annihilation effect on 21cm signal

- Contribution to Lyα intensity

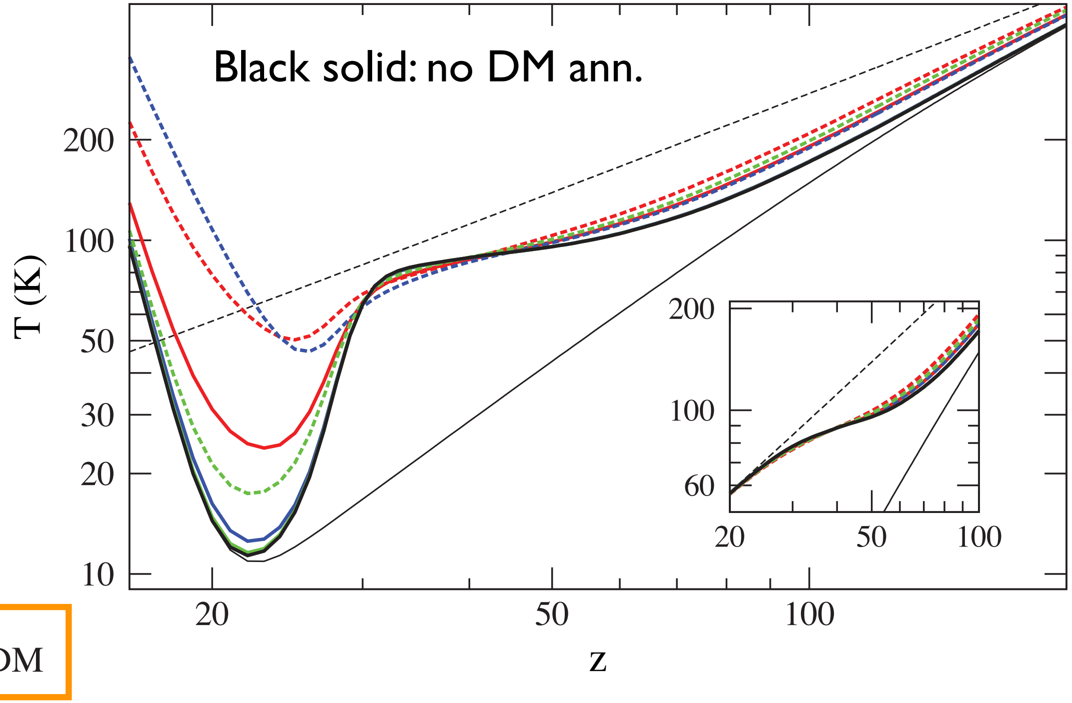
$$T_S^{-1} = \frac{T_\gamma^{-1} + x_c T_K^{-1} + x_\alpha T_c^{-1}}{1 + x_c + x_\alpha}$$

$$\boxed{x_\alpha \propto J_\alpha}$$

where J_α is the Lya flux

$$J_\alpha = J_{\alpha,R} + J_{\alpha,C} + J_{\alpha,*} + J_{\alpha,X} + \boxed{J_{\alpha,\mathrm{DM}}}$$

[Valdes et al 1209.2120]

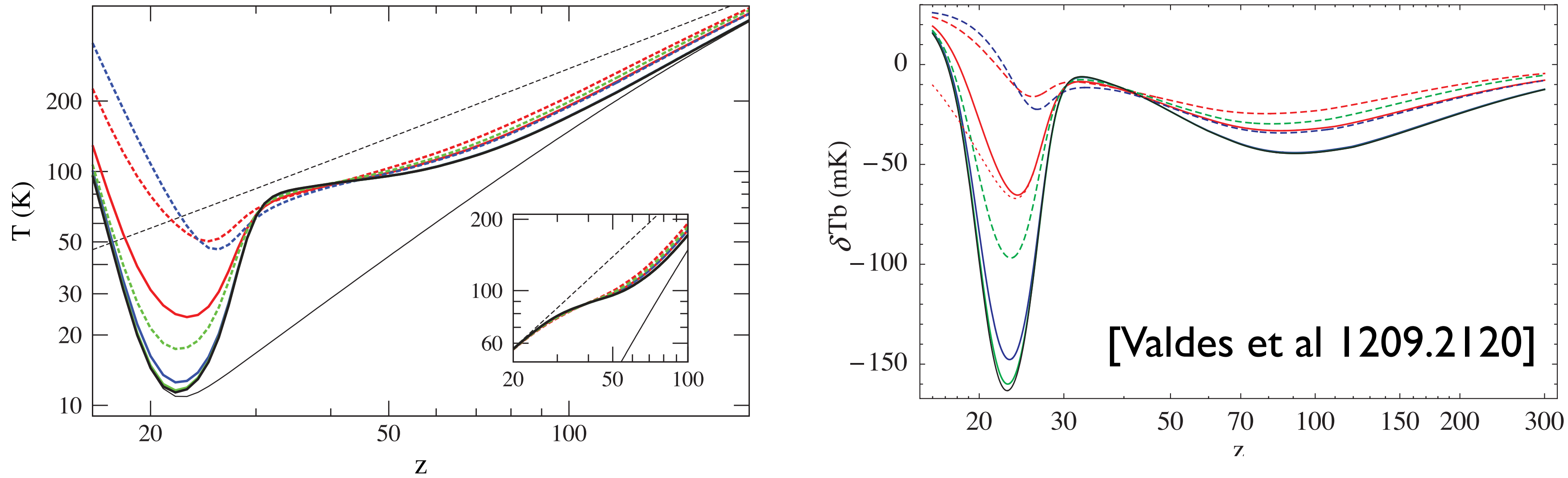


Black solid: no DM ann.

DM model	Mass (GeV)	$\langle\sigma v\rangle$ (cm^3 s^{-1})	ϵ_0 (eV s^{-1})	$\delta\tau_e$	Line style
W^+W^-	200	$\langle\sigma v\rangle_{\rm th} = 3.0 \times 10^{-26}$	5.35×10^{-25}	1.53×10^{-3}	Blue solid
W^+W^-	200	$\langle\sigma v\rangle_{\rm max} = 1.2 \times 10^{-24}$	2.14×10^{-23}	6.09×10^{-2}	Blue dashed
$b\bar{b}$	10	$\langle\sigma v\rangle_{\rm th} = 3.0 \times 10^{-26}$	1.07×10^{-23}	1.80×10^{-2}	Red solid
$b\bar{b}$	10	$\langle\sigma v\rangle_{\rm max} = 1.0 \times 10^{-25}$	3.57×10^{-23}	5.76×10^{-2}	Red dashed
$\mu^+\mu^-$	1000	$\langle\sigma v\rangle_{\rm th} = 3.0 \times 10^{-26}$	1.07×10^{-25}	1.42×10^{-4}	Green solid
$\mu^+\mu^-$	1000	$\langle\sigma v\rangle_{\rm max} = 1.4 \times 10^{-23}$	4.99×10^{-23}	6.18×10^{-2}	Green dashed

Dark Matter annihilation effect on 21cm signal

- Effects on differential brightness temperature



[Valdes et al 1209.2120]

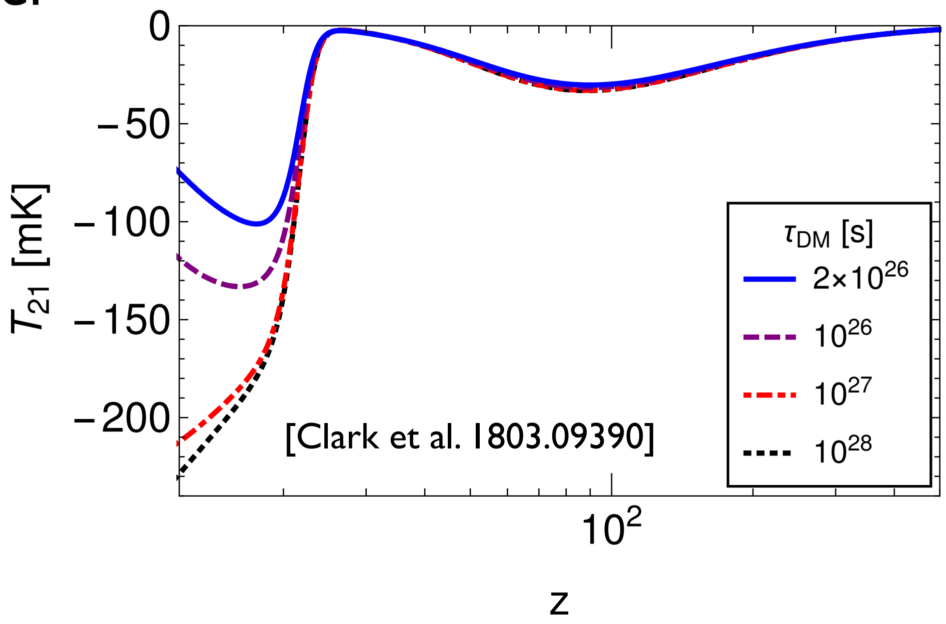
Due to additional heating from DM annihilation, T_s is driven to closer to T_{cmb}, which reduces the absorption features.

Decaying DM

- Using the EDGES result to constrain DM properties (not explaining the absorption signal)

\- (example) Decaying dark matter

$$\frac{\mathrm{d}E}{\mathrm{d}V\mathrm{d}t} = \Gamma_{\mathrm{DM}} \cdot \rho_{\mathrm{c},0}\Omega_{\mathrm{DM}}(1+z)^3$$



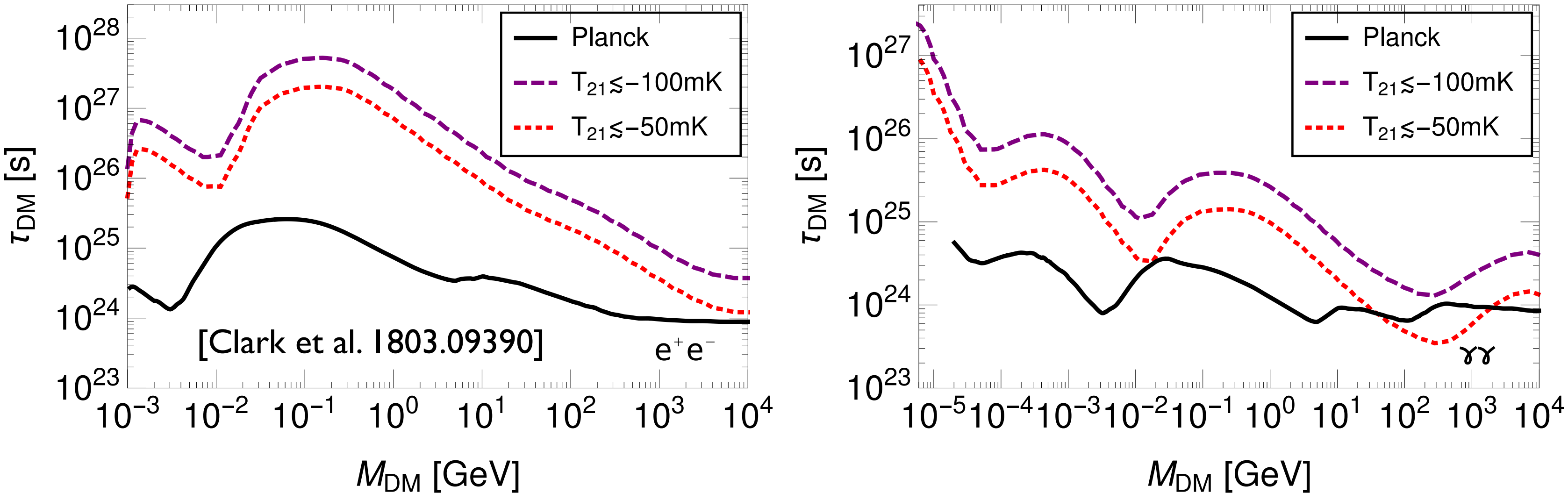
[Clark et al. 1803.09390]

Due to the energy injection from decay (annihilation) of DM, the gas is heated.

→ Constraints on life-time (decay rate) of DM.

Decaying DM

- By requiring the correction to T_b (=T_{21}) less than -50 mK or -100 mK, one can obtain the constraint on the lifetime of decaying DM.



[Clark et al. 1803.09390]

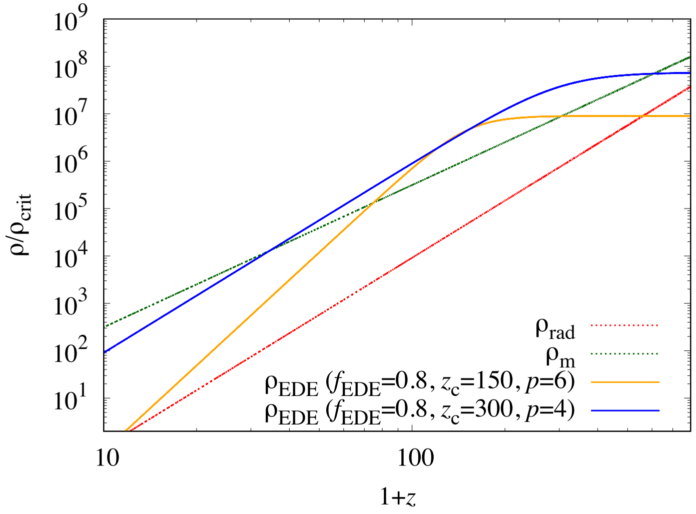
Similar analysis also applies for primordial black holes.

Dark components

Effects of early dark energy on 21cm signal

[Hill, Baxter 1803.07555]
[see also, Minoda, TT, Yamauchi, Yoshiura 2309.06762]

- The change of the expansion rate affects the timing of the decoupling



- Evolution equation of the gas temperature:

$$\frac{dT_{gas}}{dz} = \frac{T_{gas}(z) - T_\gamma(z)}{(1+z)H(z)t_C(z)} + \frac{2T_{gas}(z)}{(1+z)}$$

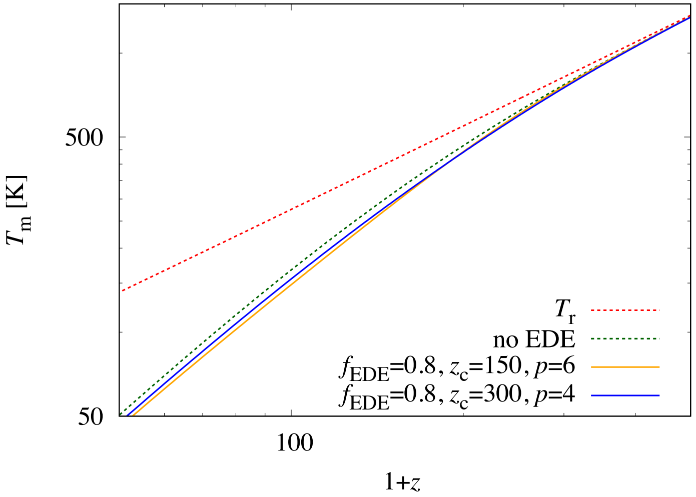
- Compton heating time scale:

$$t_C(z) = \frac{3m_e c}{8\sigma_T a_R T_\gamma^4(z)}\left(\frac{1+f_{\rm He}(z)+x_e(z)}{x_e(z)}\right)$$

When $H(t) \sim 1/t_c(t)$, the gas temperature decouples.

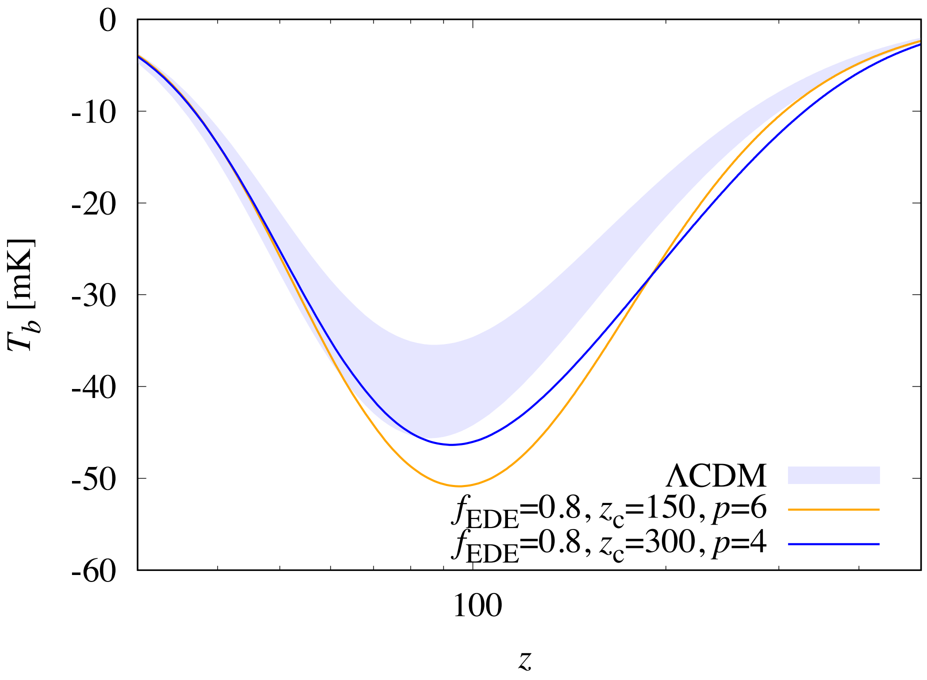
➡ A faster expansion rate leads to an earlier decoupling.

➡ The gas temperature gets cooler.



Effects of early dark energy on 21cm signal

- The 21cm global signal deviates from the ΛCDM one.



(Due to the cooler matter temperature, the absorption signal gets deeper.)

Dark age consistency ratio as a probe of BSM

[Okamatsu, Minoda, TT, Yamauchi, Yoshiura 2309.06762]

21cm global signal during the dark ages

- The dark age 21cm signal can be determined only from cosmology.

  (After astrophysical objects have been formed, uncertainties from astrophysics obscure cosmological information.)

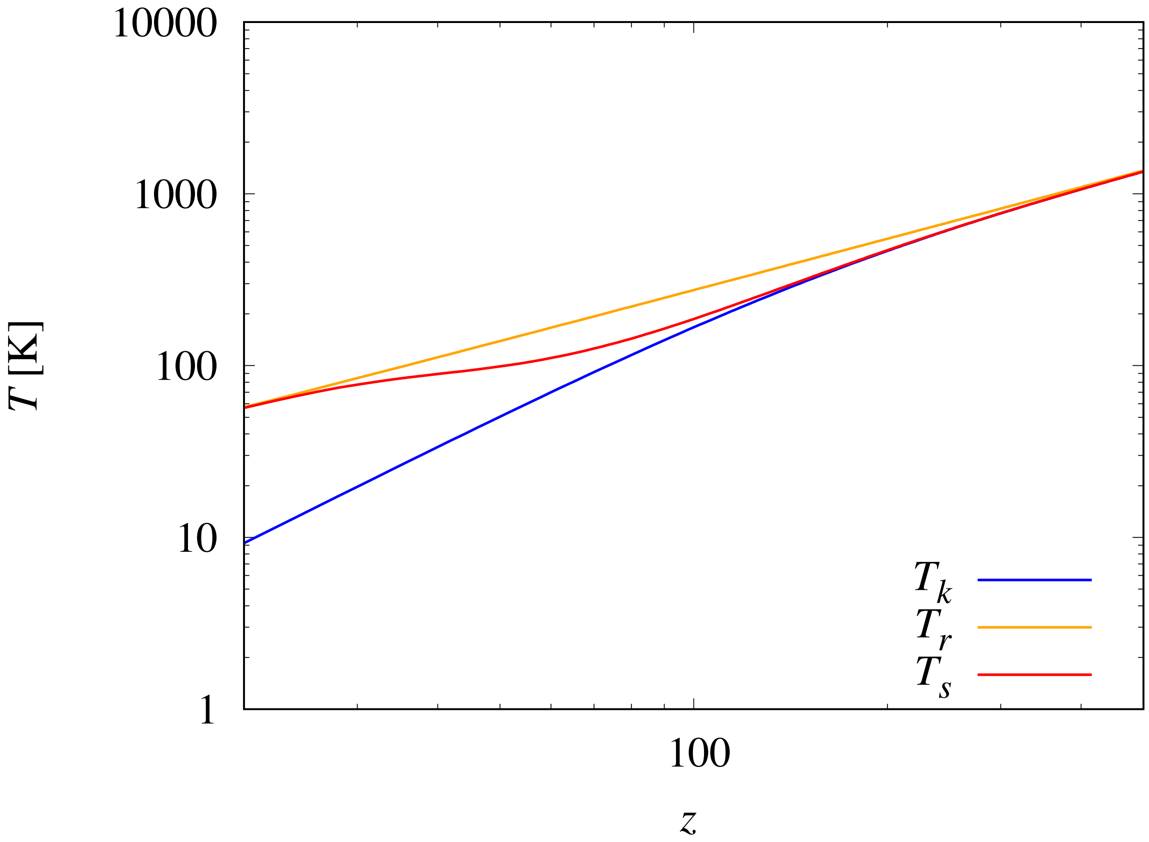
- So far, no observation has been done for the 21cm during the dark ages due to the Earth's ionosphere, radio frequency interference (RFI) and so on.

- However, to avoid those obstacles, telescopes on the moon/satellites around the moon are now being under serious consideration.

- Therefore it is quite timely to consider the 21cm signal from the dark ages and investigate what aspects of BSM can be explored.

21cm global signal during the dark ages

- Evolutions of the temperatures during the dark ages

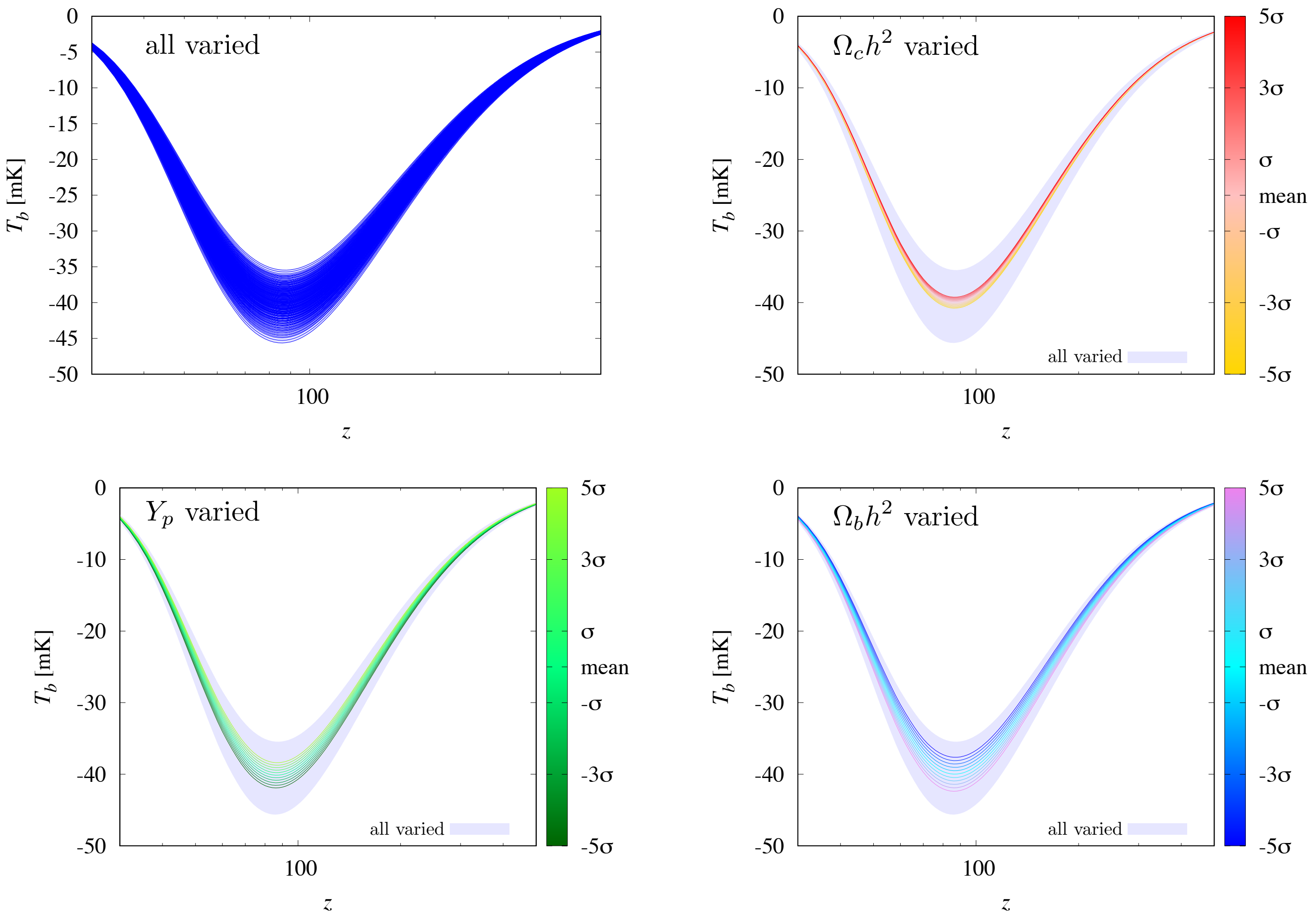


The brightness temperature is given by

$$\Delta T_b \simeq 27\ \mathrm{mK} \left(\frac{T_s - T_R}{T_s}\right)\left(\frac{1+z}{10}\right)^{1/2}\left(\frac{\Omega_b h^2}{0.023}\right)\left(\frac{0.15}{\Omega_m h^2}\right)^{1/2} x_{HI}$$

21cm global signal during the dark ages

- 21cm global signal for the standard case (ΛCDM model)



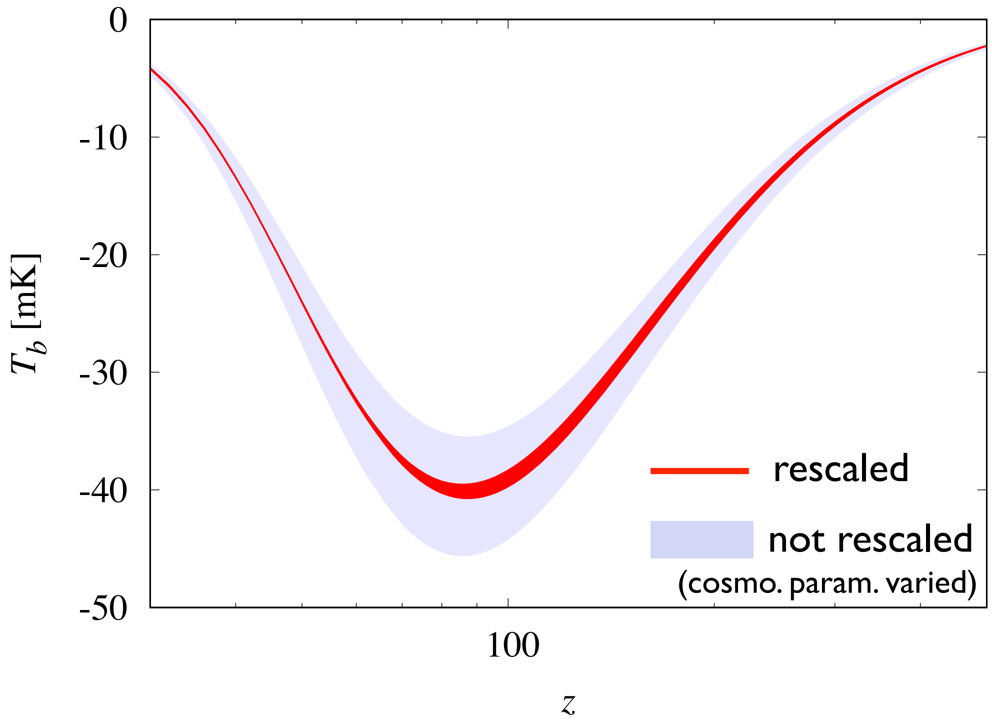
(Parameters are varied within 5σ limits from Planck)

The shape of the signal depends on the cosmological parameters.

“Shape” of the 21cm signal

- The shape of the 21cm signal is almost unchanged even if the cosmological parameters are varied by rescaling with the factor of

$$C(\omega_b, \omega_m, Y_p) \equiv \frac{\omega_b^2 (1 - Y_p)^2}{\omega_m^{1/2}}$$ (in the ΛCDM model during the dark ages)



Brightness temperature:

$$T_b \simeq 85\,\mathrm{mK} \left(\frac{T_s - T_\gamma}{T_s}\right)\left(\frac{\omega_b}{0.02237}\right) \times \left(\frac{0.144}{\omega_m}\right)^{1/2}\left(\frac{1 - Y_p}{1 - 0.24}\right)\left(\frac{1+z}{100}\right)^{1/2} x_{\mathrm{HI}}$$

One can rewrite the temperature dependent parts as

$$\frac{T_s - T_\gamma}{T_s} = \frac{x_c}{1 + x_c}\left(1 - \frac{T_\gamma}{T_k}\right)$$ where $x_c \propto \omega_b (1 - Y_p)$

$$\Rightarrow \quad T_b \propto \frac{\omega_b^2 (1 - Y_p)^2}{\omega_m^{1/2}}$$

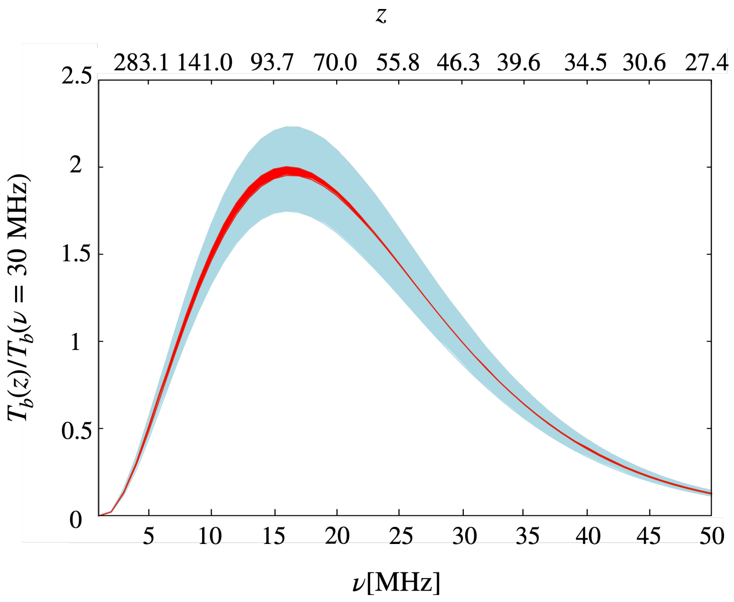
The shape of the signal depends on the cosmological parameters.

Dark age consistency ratio of 21cm signal

- Since the 21cm signal in the ΛCDM model during the dark ages keeps its shape, the ratio of the amplitude between some frequency (redshift) is (almost) fixed.

➔ Dark age consistency ratio: $R_{\nu_i/\nu_j} \equiv \dfrac{T_b(\nu = \nu_i\,[\mathrm{MHz}])}{T_b(\nu = \nu_j\,[\mathrm{MHz}])}$

ν_i	$R_{\nu_i/30}$	$T_b(\nu_i)$ [mK]
40	$0.3873 \pm 0.0029\ (0.76\%)$	$-7.923 \pm 1.0107\ (12.76\%)$
35	$0.6401 \pm 0.0016\ (0.24\%)$	$-13.10 \pm 1.7301\ (13.20\%)$
25	$1.4454 \pm 0.0023\ (0.16\%)$	$-29.59 \pm 3.9133\ (13.23\%)$
20	$1.8487 \pm 0.0126\ (0.68\%)$	$-37.82 \pm 4.8074\ (12.71\%)$



However, this ratio takes a different value in BSM models.

Dark age consistency ratio of 21cm signal

- Dark age consistency ratio deviates from the ΛCDM value when one (or more) of the following conditions are broken:

(i) The Universe is matter dominated. → ex) Change of the expansion rate (e.g., Early Dark Energy)

(ii) Lyman α sources are negligible. → ex) DM annihilation/decay

(iii) Matter and photons are coupled via the Compton scattering.

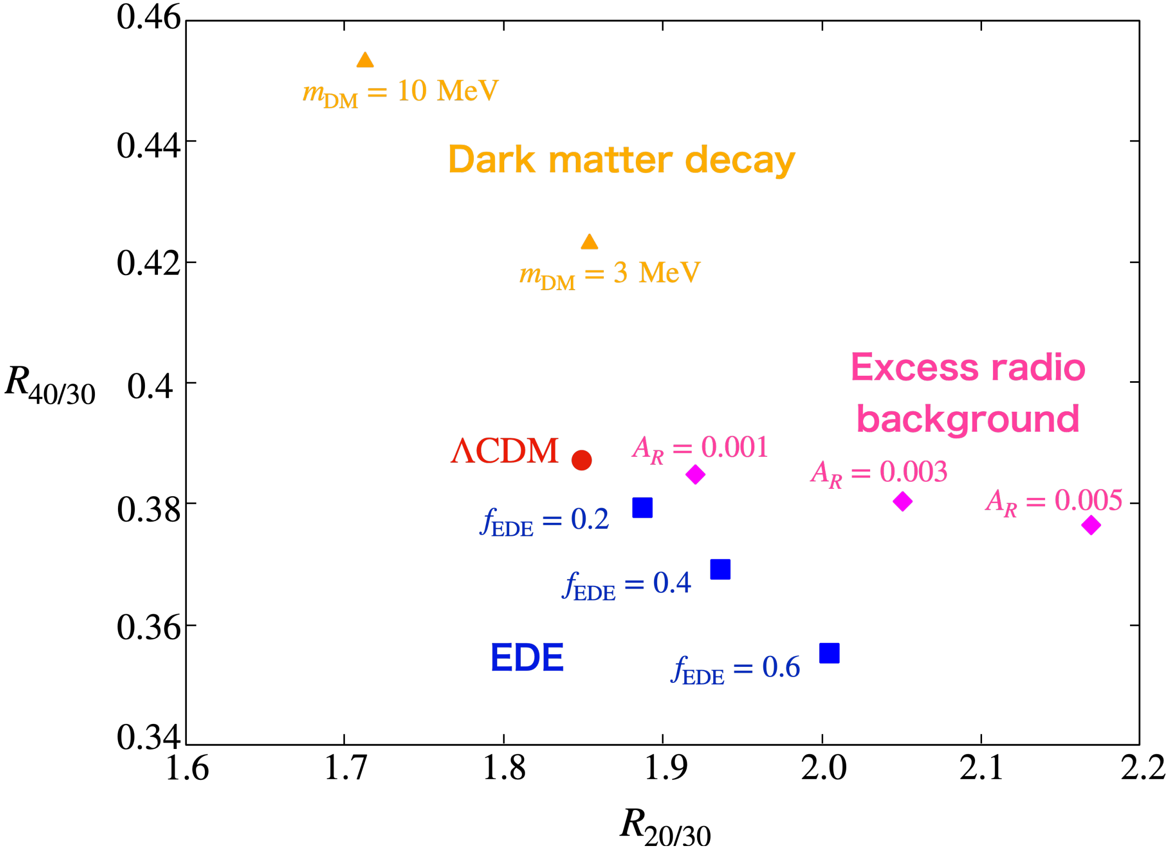
→ ex) DM annihilation/decay, baryon-DM interaction

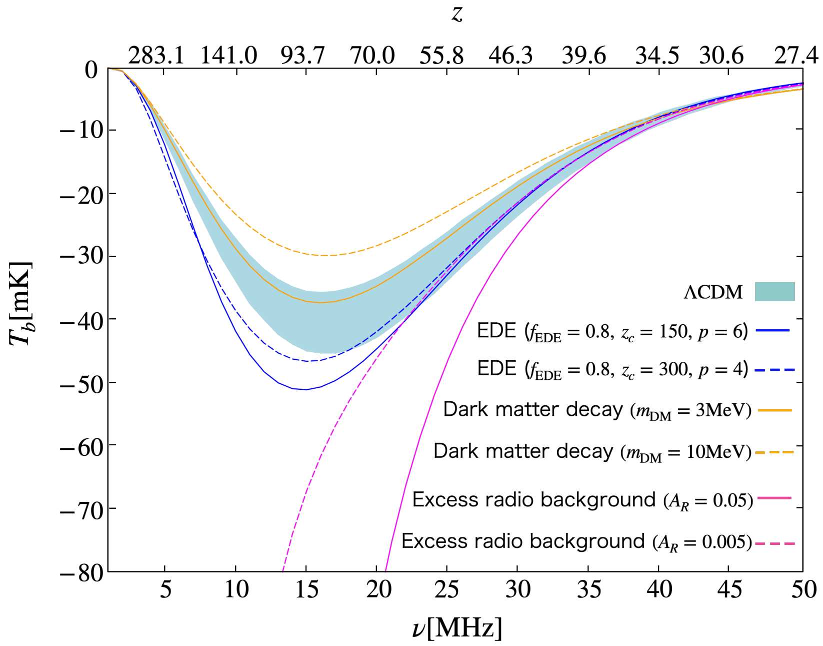
(iv) Radiation field is determined by CMB.

→ ex) Extra radio emission (from the decay of some exotic particles)

Dark age consistency ratio as a probe of BSM

- Dark age consistency ratio can be used as a diagnostics of models beyond the standard ΛCDM.





Summary

- Various aspects of cosmology and astrophysics can be probed by the signal of 21cm line.

  (we mainly discussed the 21cm signal as a probe of BSM.)

- A lot of observations are going on/planned/proposed.

  (including those for the dark ages)

- Dark age consistency ratio is a new observable to probe, especially, models beyond the standard ΛCDM.

- 21cm cosmology will bring a lot of insight into cosmology and astrophysics.