Dark age 21cm signal
and low reheating temperature

Collaboration with Fumiya Okamatsu and Tomo Takahashi

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Contents

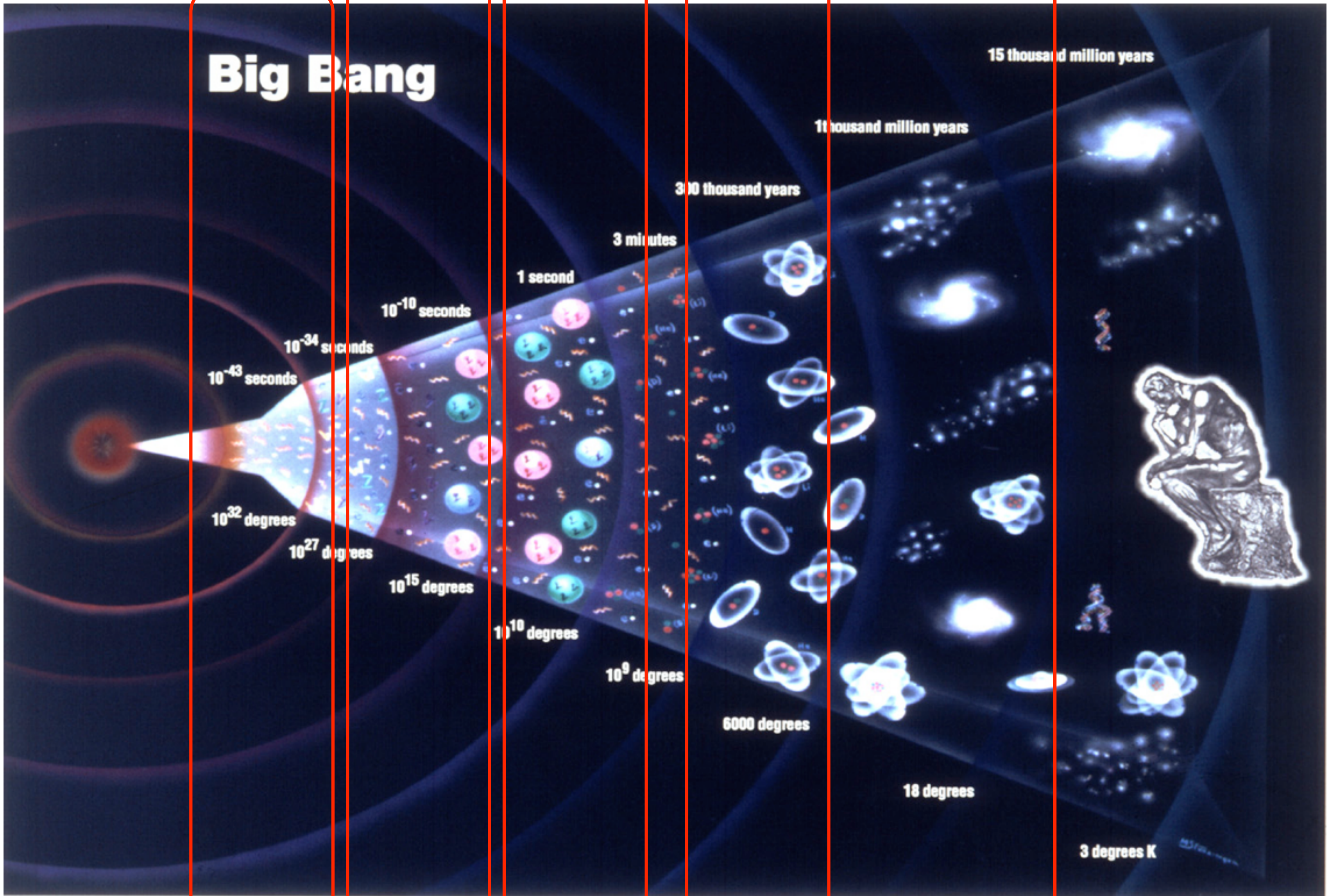
- Standard Big Bang Universe and early matter domination (eDM)

- WIMP annihilation and constraint on eDM and reheating temperature

- 21cm lines and brightness temperature

- History of Universe

Inflation | Phase transition | 1sec BBN | 380,000yrs Recombination | 13.8Gyrs Present



$T_{\rm reh} \sim ?$

$T \sim 10^{10}\,{\rm K}$ ~ 1 MeV

$T \sim 4000\,{\rm K}$ ~ 0.3 eV

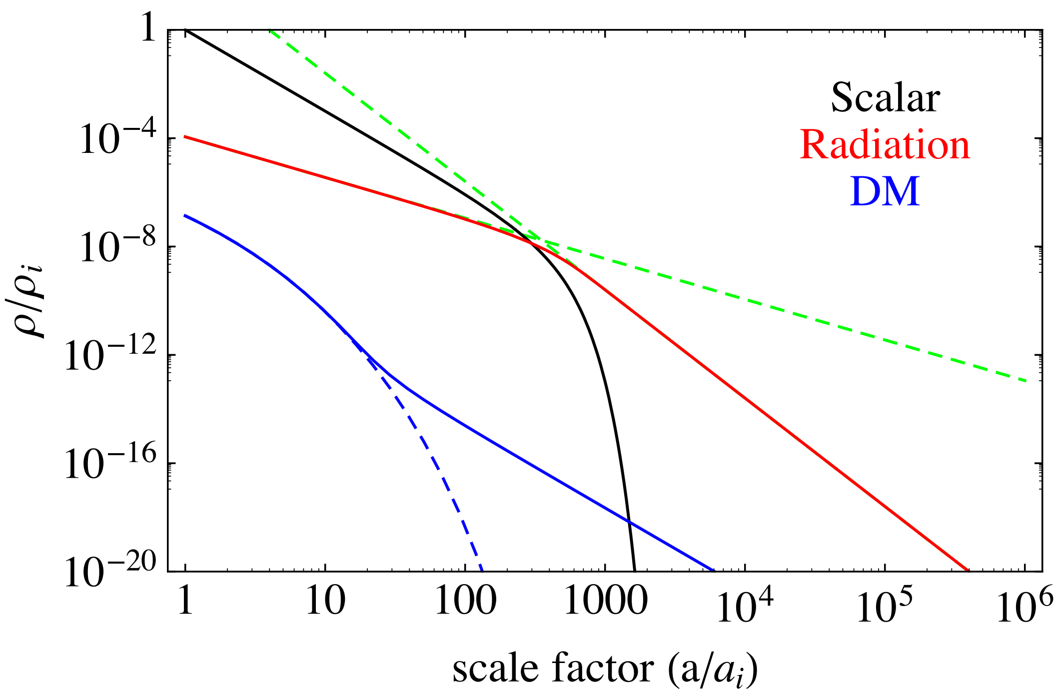
$T_{\gamma,0} \sim 2.725\,{\rm K}$ $\sim 10^{-4}$ eV

Early Matter Domination (eMD) and Low Reheating Temperature

The Universe is dominated by heavy particles (early matter domination) and reheated (radiation domination) by the decay of them. It happens for:

$$T_{\rm reh} \simeq \left(\frac{90}{\pi^2 g_*}\right)^{1/4} \sqrt{\Gamma M_P}$$

- Inflaton oscillation
- Thermal inflation
- Curvaton domination
- Heavy axino and saxion
- Moduli
- .....



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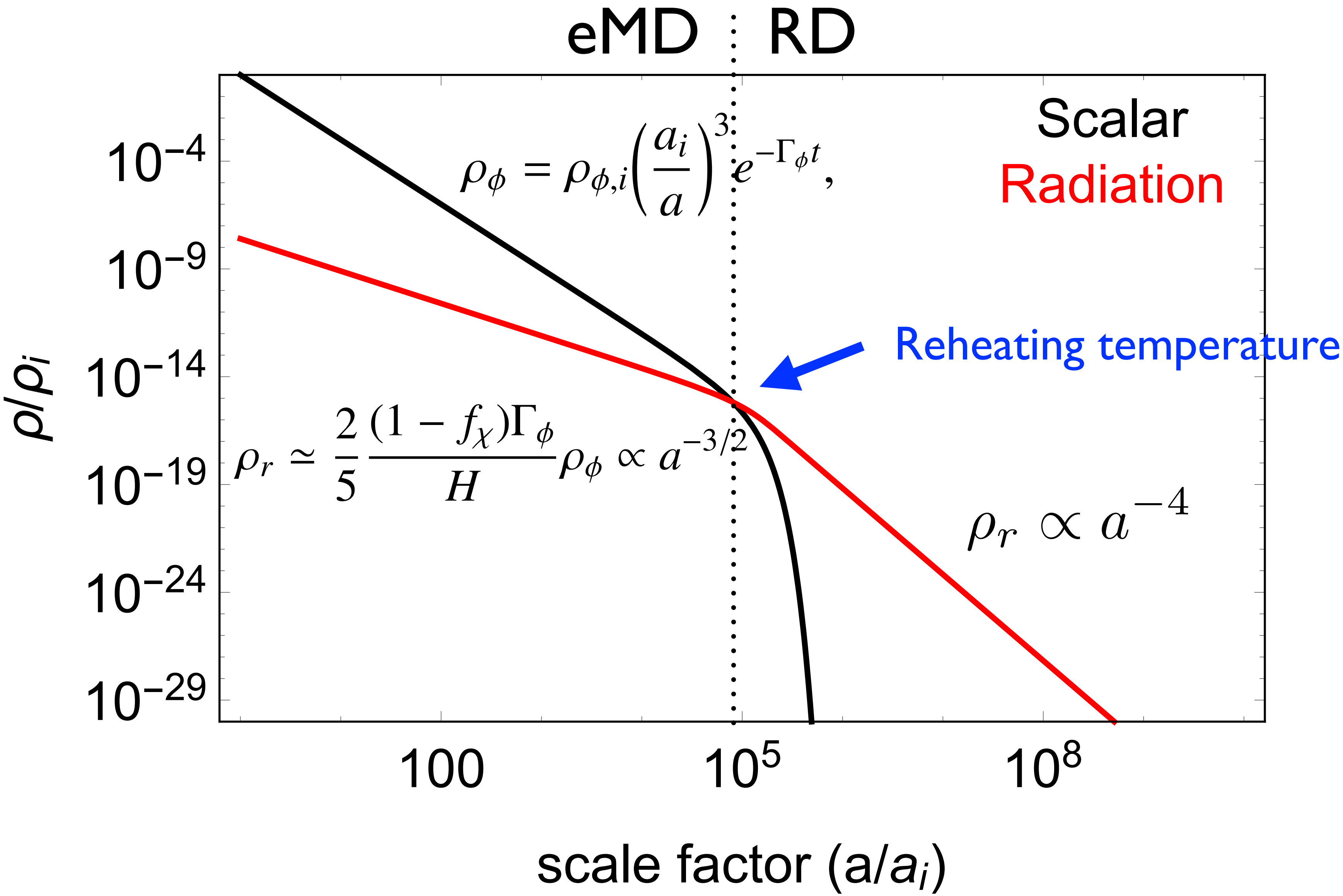
Background Energy Density: eMD to RD



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Low bound on Reheating Temperature

1. Big Bang Nucleosynthesis
: at low-reheating temperature, neutrinos are not fully thermalised and the light element abundances are changed,

$$T_{\rm reh} \gtrsim 0.5 - 0.7\,{\rm MeV}$$

$$T_{\rm reh} \gtrsim 2.5\,{\rm MeV} - 4\,{\rm MeV}$$ for hadronic decays

[Kwasaki, Kohri, Sugiyama, 1999, 2000]

2. BBN+CMB
: precise calculation of the cosmic neutrino background and CMB

$$T_{\rm reh} \gtrsim 4.7\,{\rm MeV}$$

[Salas, Lattanzi, Mangano, Miele, Pastor, Pisanti, 2015]

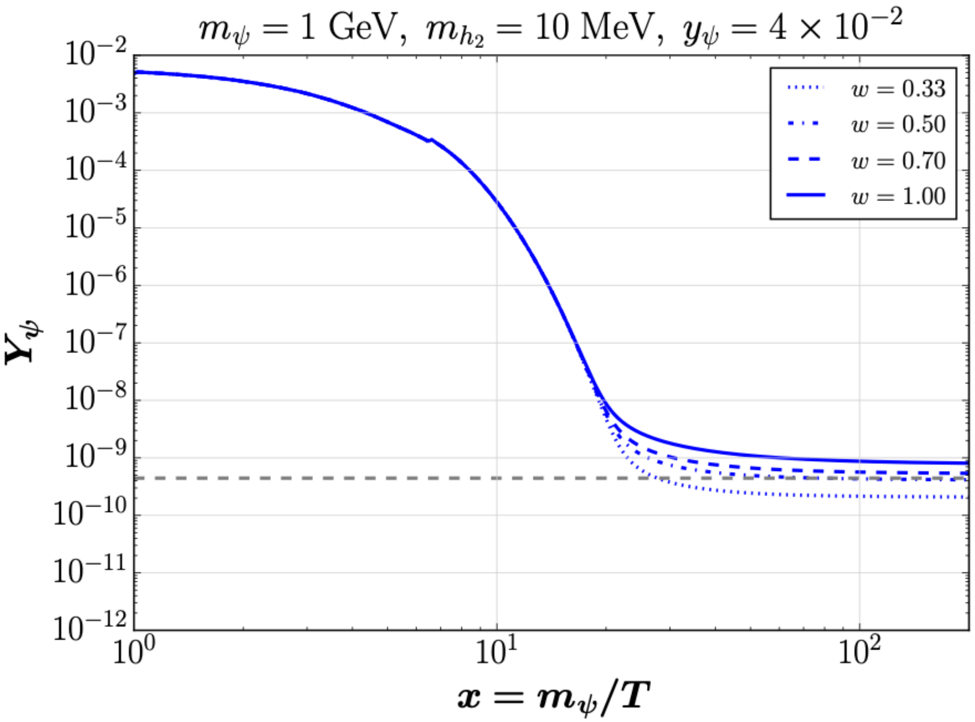
Implications of eMD to cosmology

The period of eMD affects several phenomenon in cosmology.

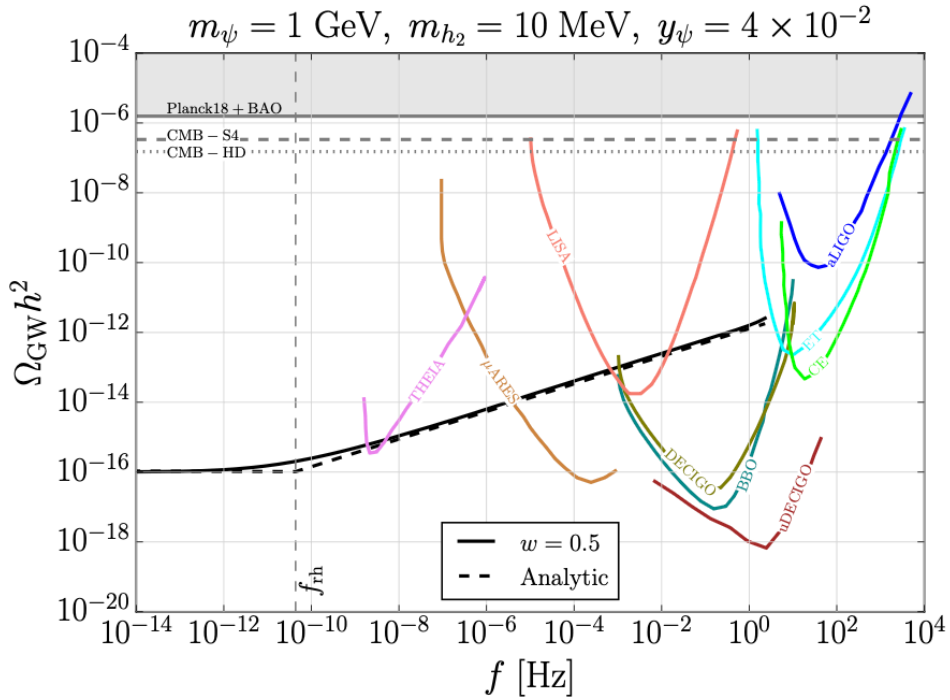
- altering the expansion rate
- dark matter production
- matter-antimatter asymmetry
- gravitational wave spectra
- primordial power spectra

Light Dark Matter and Correlated Gravitational Wave Signatures

[KYC, E.Lkhagvadorj, S.Mahapatra, 2026]



Corrected DM relic density with sub GeV mass



Enhanced GW spectrum during eMD

Power Spectrum of DM

1. Enhanced Power Spectrum of DM during eMD

2. Creation of Isocurvature Perturbation of WIMP DM during eMD with even kinetic equilibrium with background radiation

Cf) Baryons in the kinetic equilibrium with photons have suppressed perturbations.

Creation of Isocurvature Perturbation of WIMP DM

After chemical decoupling and before kinetic decoupling during scalar-domination (eDM):

Dark matter and radiation are still kinetically coupled:

Radiation is still produced from decay of the dominating scalar, however dark matter is not produced any more.

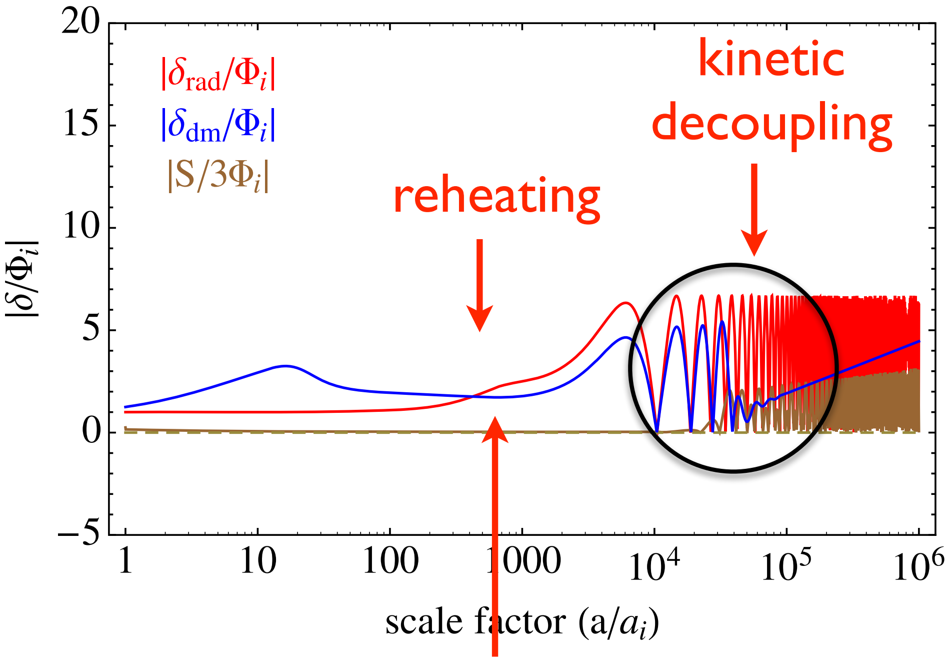
The difference in the number density creates the isocurvature perturbation between dark matter and radiation.

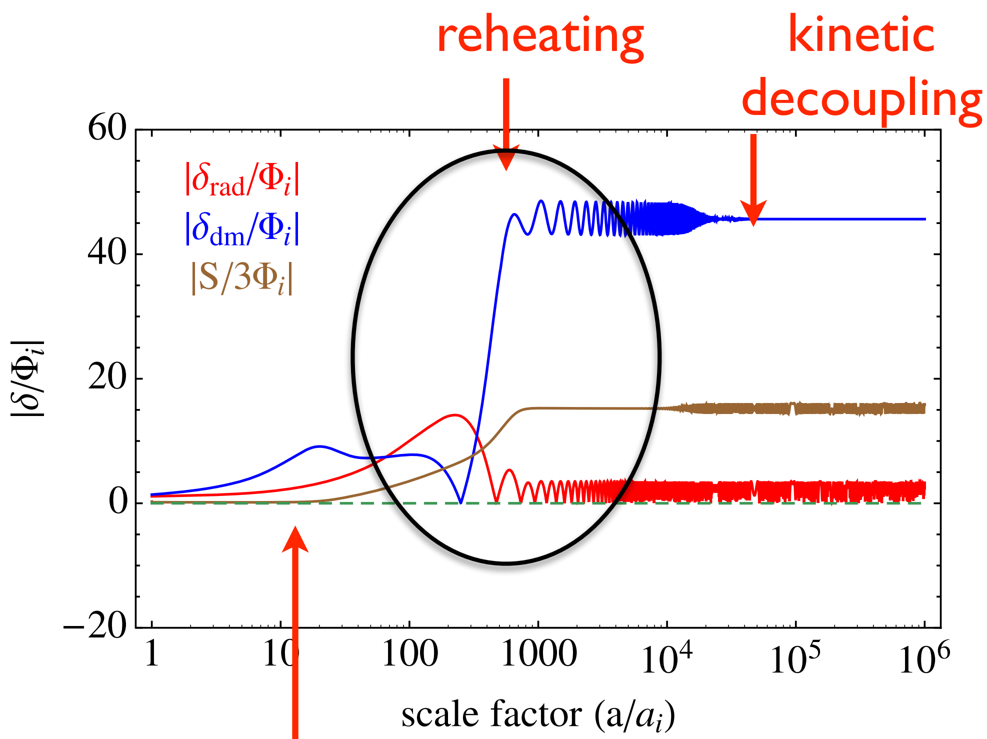
$$S(t_{\rm reh}) \approx -\frac{3}{4}\int_{t_i}^{t_{\rm reh}} dt \frac{\Gamma_\phi \rho_\phi \delta_\phi}{\rho_r} \approx \frac{5}{4}\Phi_i \left(\frac{k}{k_{\rm reh}}\right)^2.$$

[KYChoi, Gong, Shin 2015PRL]

Creation of Isocurvature Perturbation of WIMP DM

[KYChoi, Gong, Shin 2015]





Horizon entry after reheating

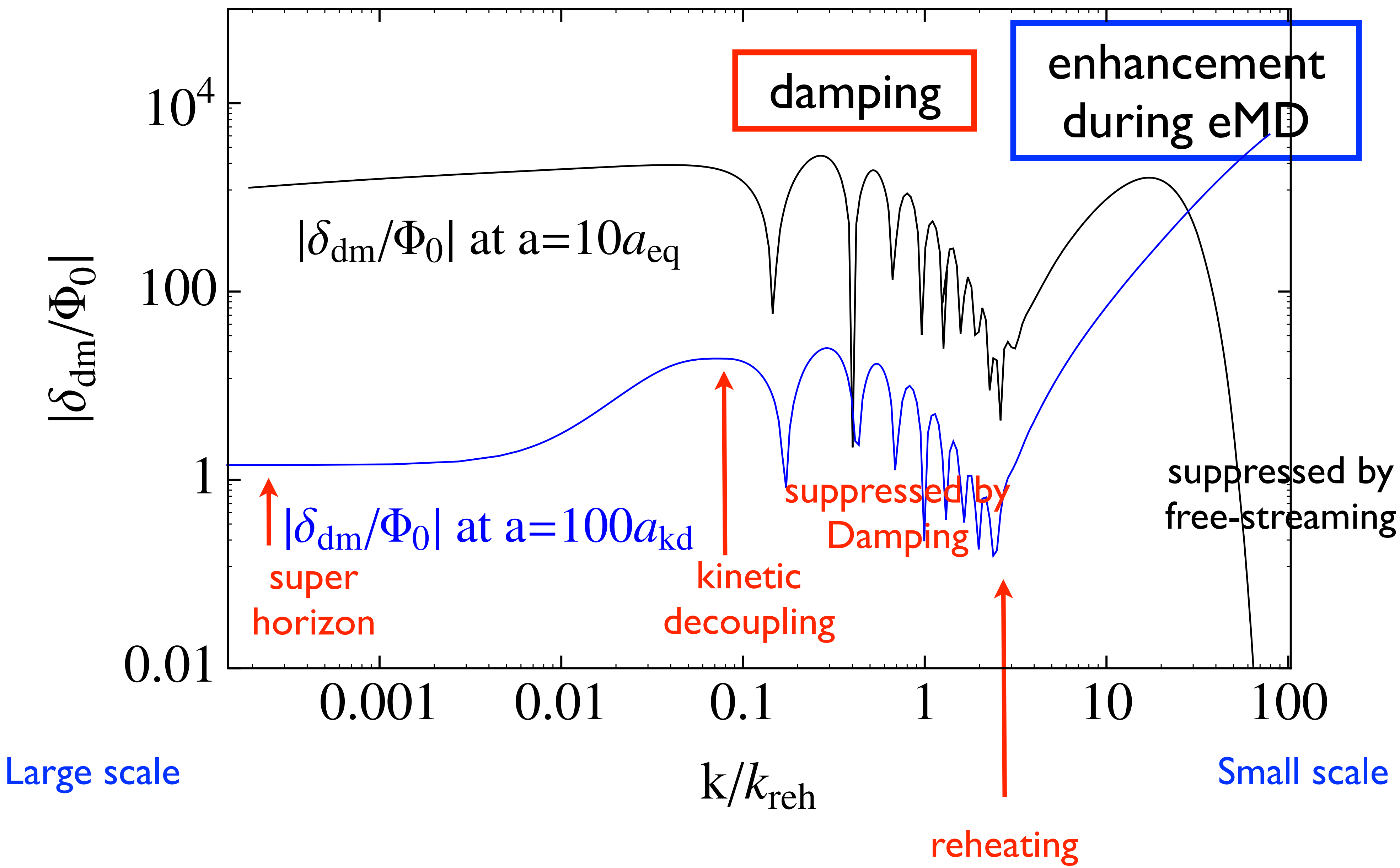
Damping erases the perturbations.

Horizon entry during early MD before reheating

Enhancement and No damping.

Damping and Enhancement of Density Perturbation

[KYChoi, Gong, Shin 2015]



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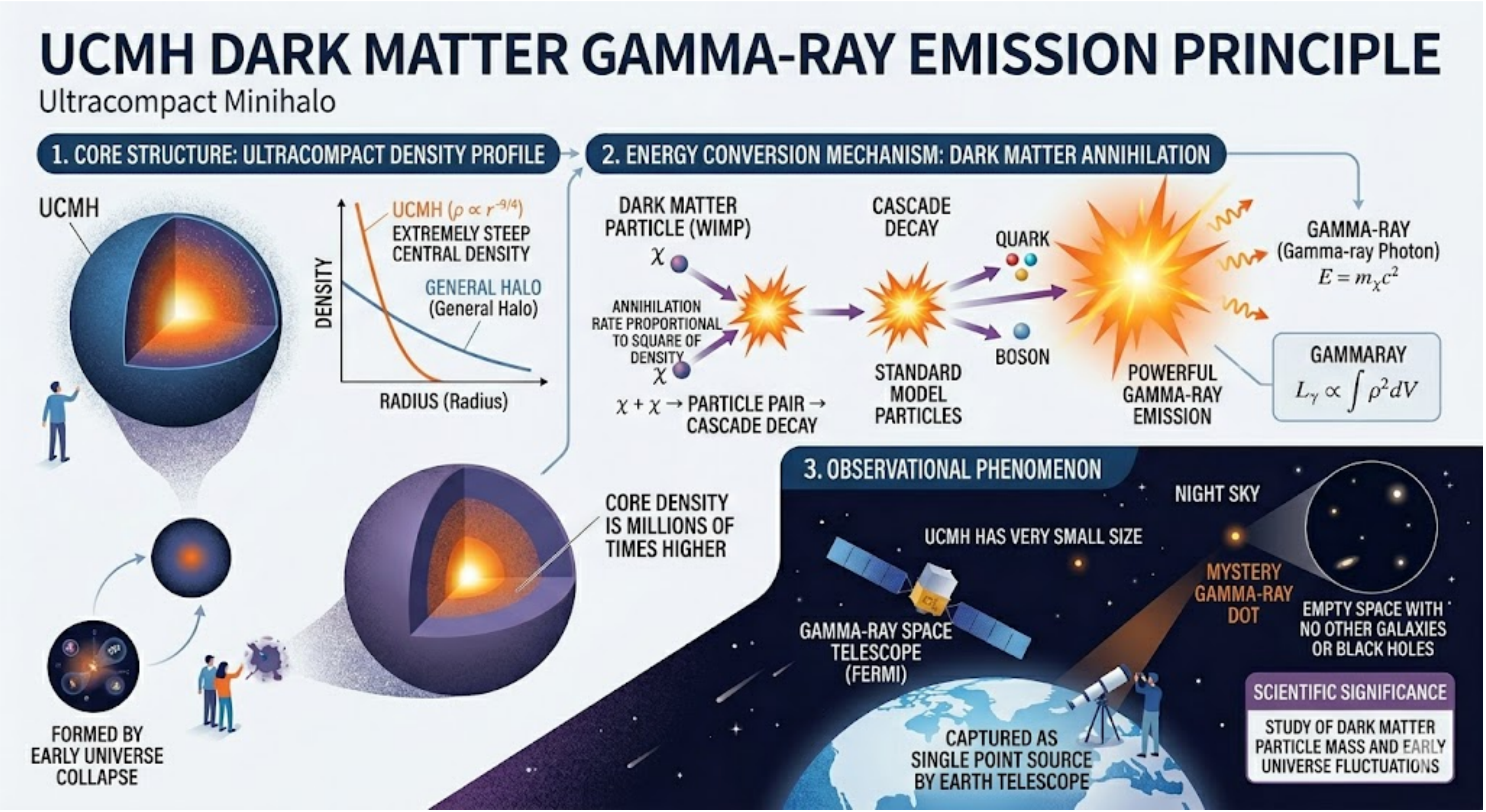
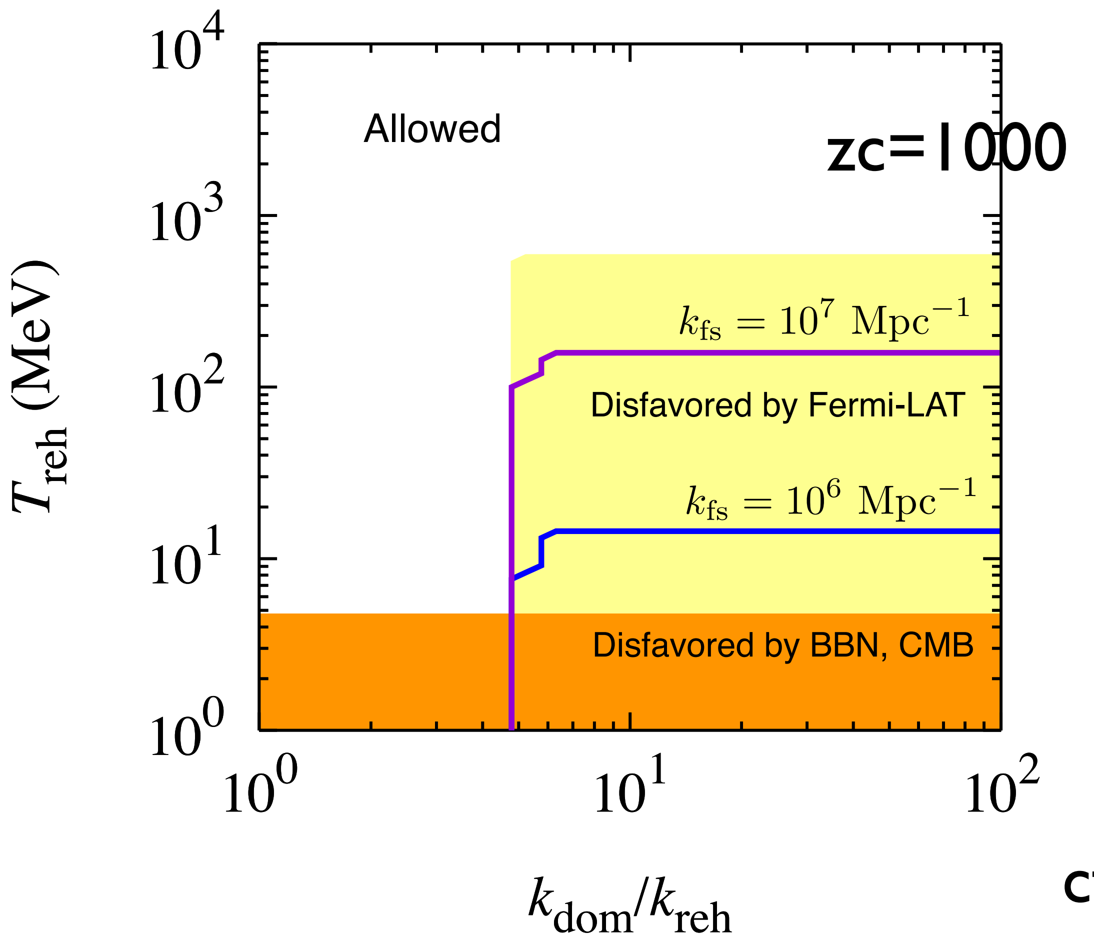


WIMP annihilations in the UCMHs can produce gamma-ryas, which might be detected on Earth.

Low bound on Treh with WIMP DM of UCMHs

UCMH production from the large perturbation



UCMH constraint by Fermi-LAT from annihilation of WIMP DM.

$$T_R \gtrsim 10 - 100\,\mathrm{MeV}$$

[KYChoi, Tomo Takahashi, 2017]

$k_{1\mathrm{MeV}} = 10^4\,\mathrm{Mpc}^{-1}$

cf) $T_{\rm reh} \gtrsim 4.7\,\mathrm{MeV}$ BBN+CMB

[Kwasaki, Kohri, Sugiyama, 1999, 2000]
[Salas et al 2015]

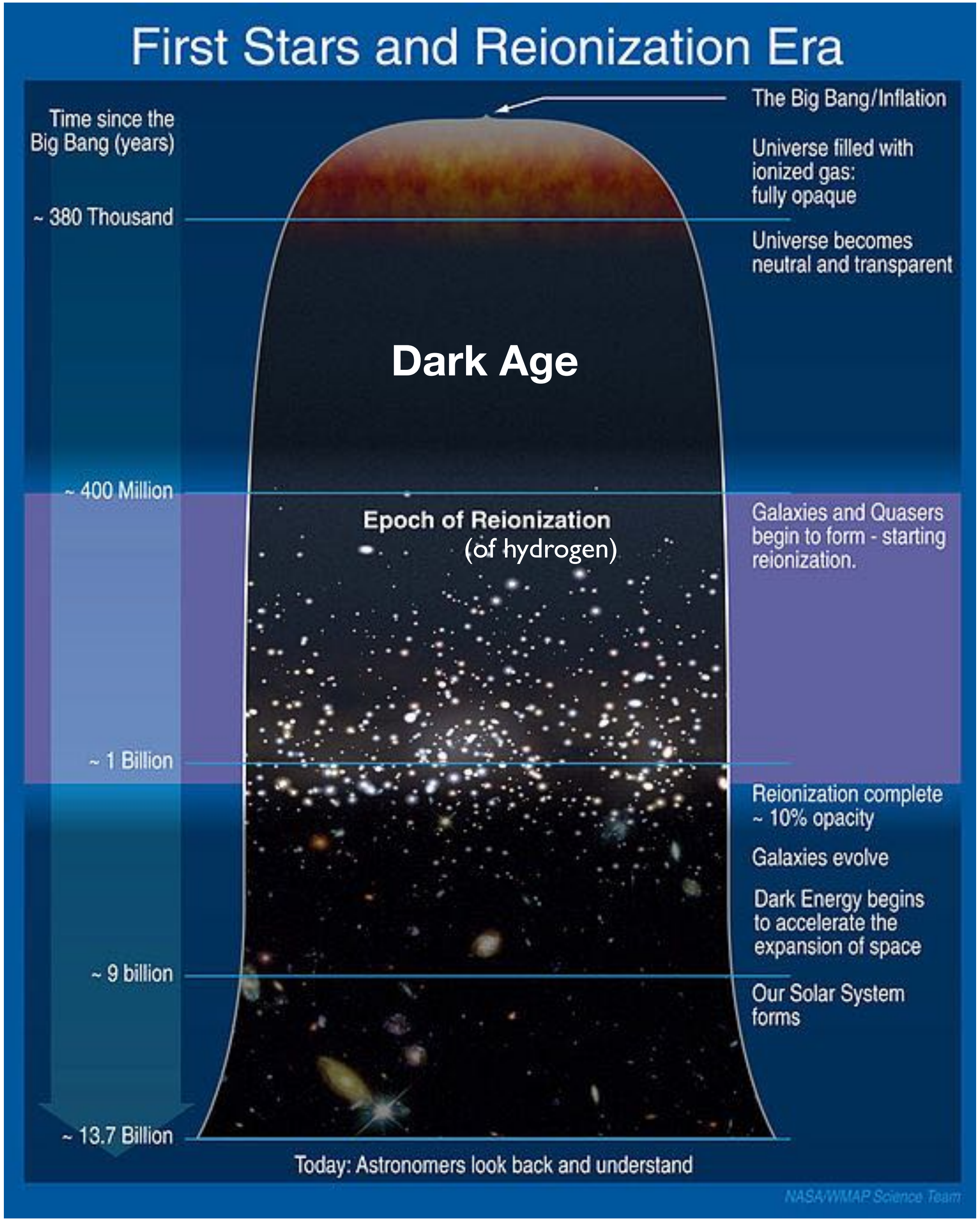
New bound on low-reheating temperature

[KYChoi, Tomo Takahashi, PRD 2017]

3. Dark matter halos (Ultra Compact Mini-Halos, UCMHs)
: density perturbation during early matter-domination and no observation of small scale DM halos with WIMP DM

$$T_{\rm reh} \gtrsim 10\,{\rm MeV} - 100\,{\rm MeV}$$

21 cm signal from Dark Age



Expanding Universe

Redshift of the wavelength of photon

$$1 + z = \frac{a_0}{a}$$

Dark Age: z = 30~300

Cosmic dawn:
The era when the first astrophysical sources of light were formed (13<z<27).

$$35.4\text{K}(3\text{meV}) < T < 73.6\text{K}(6.3\text{meV})$$

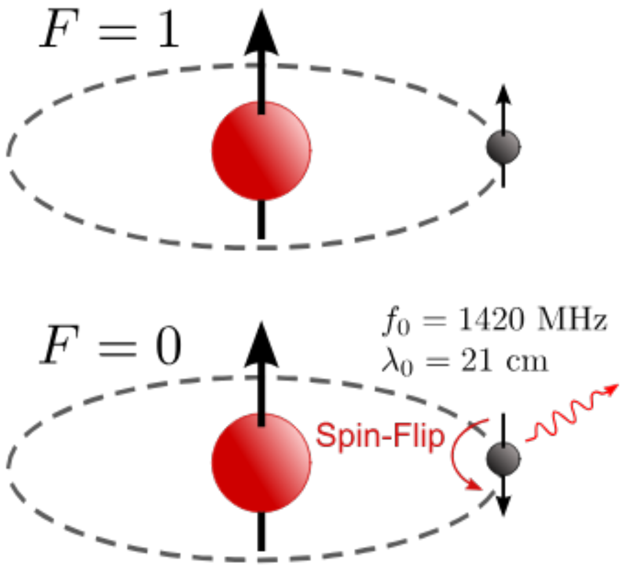
Reionization:
Re-ionization of neutral hydrogen atoms due to energetic radiation from first astrophysical objects formed (6<z<13).

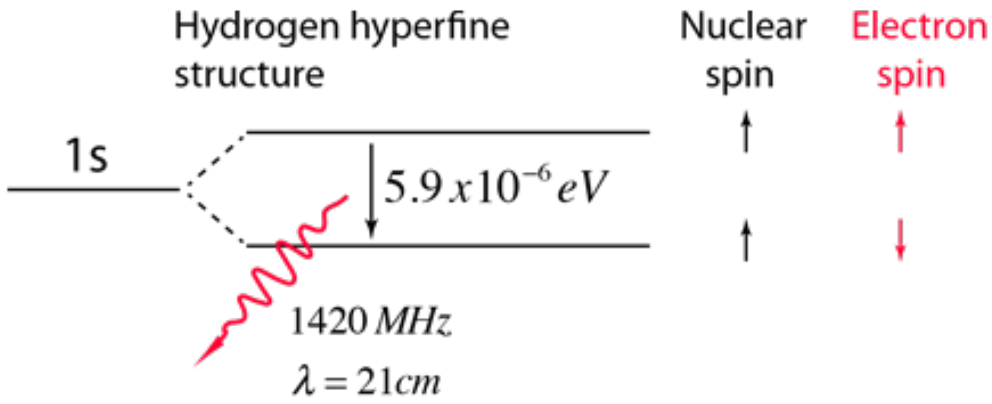
During matter-domination,

$$t \sim t_0/(1+z)^{3/2}$$

What happens during Dark Age?

21 cm line from neutral hydrogen





The 21cm photons can be emitted or absorbed by the hydrogen.

$$\frac{n_1}{n_0} = 3 \exp\left[-\frac{h\nu_{21cm}}{kT_s}\right]$$

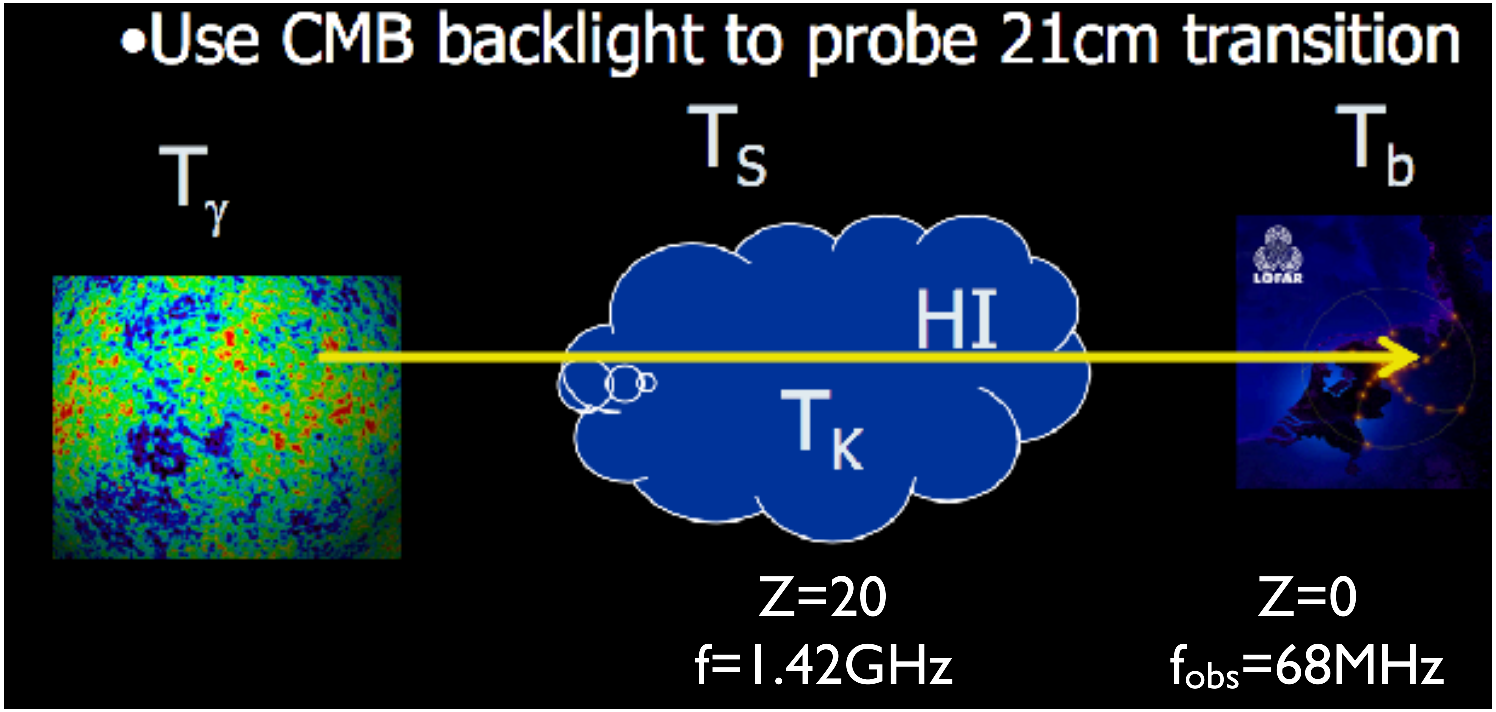
spin temperature

Spin Temperature

Spin temperature is affected by the absorption of microwave photons, as well as by resonant scattering of Lyman-alpha photons and atomic collisions.

$$T_S^{-1} = \frac{T_{\rm CMB}^{-1} + x_c T_{\rm gas}^{-1} + x_\alpha T_c^{-1}}{1 + x_c + x_\alpha}$$

Here $T_{\rm gas}$ is the (kinetic) gas temperature, T_c is the effective (color) Lyα temperature which is very close to $T_{\rm gas}$, and x_c and x_α are the coupling coefficients for collisions and Lyα scattering, respectively. In Eq. (1) we neglect the peculiar



21cm → 441cm

In the equilibrium with CMB, $T_s = T_\gamma$

If $T_s < T_\gamma$ more absorption $T_b < T_\gamma$

If $T_s > T_\gamma$ more emission $T_b > T_\gamma$

Differential Brightness Temperature

$$\Delta T_b = T_b - T_{CMB}$$

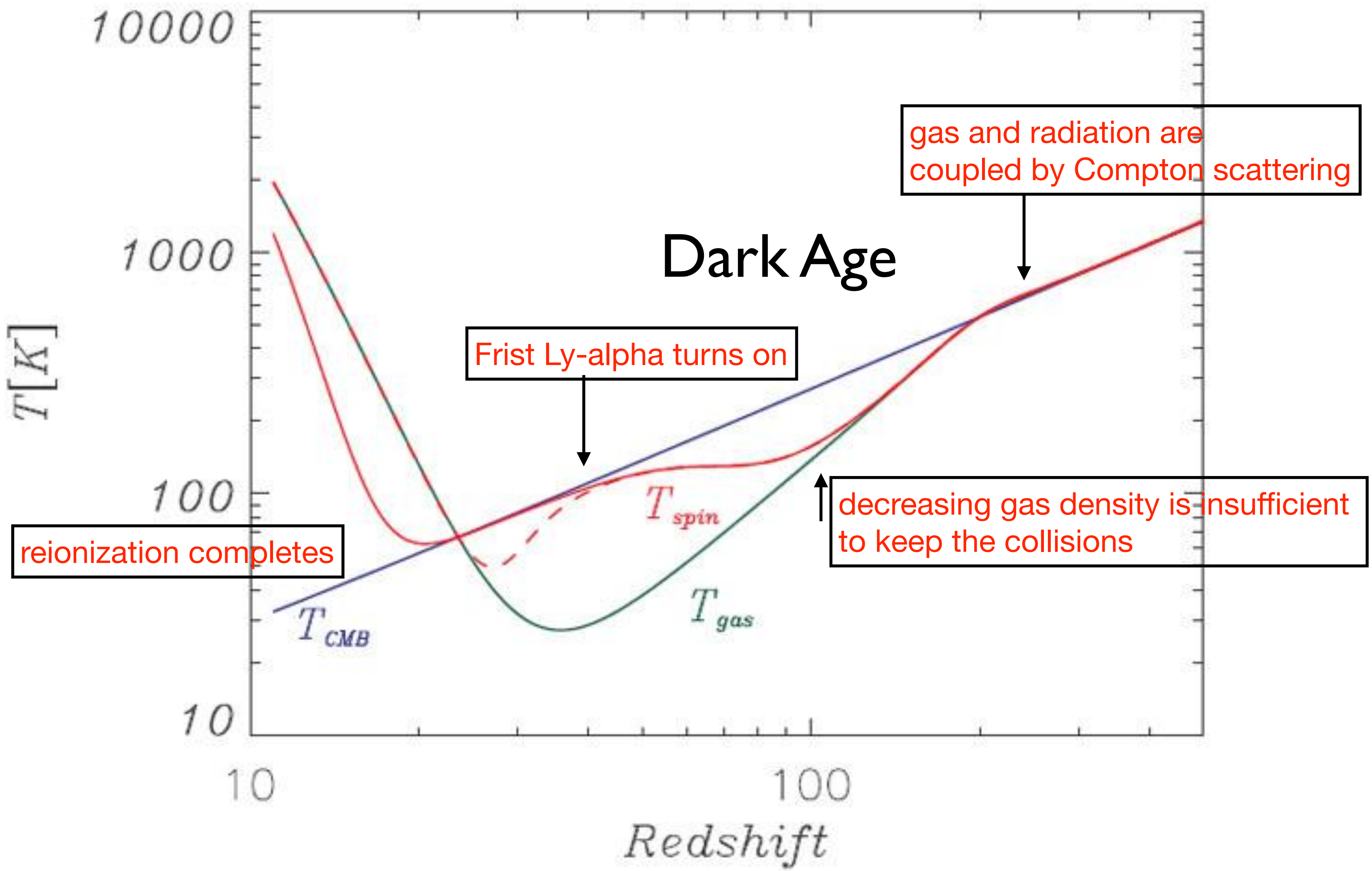
How much brighter or dimmer the neutral hydrogen 21-cm signal is compared to the background radiation (CMB)

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

x_{HI} is the fraction of neutral hydrogen

T_R is the temperature of the background radiation,

$\nu = 1{,}420/(1+z)$ MHz



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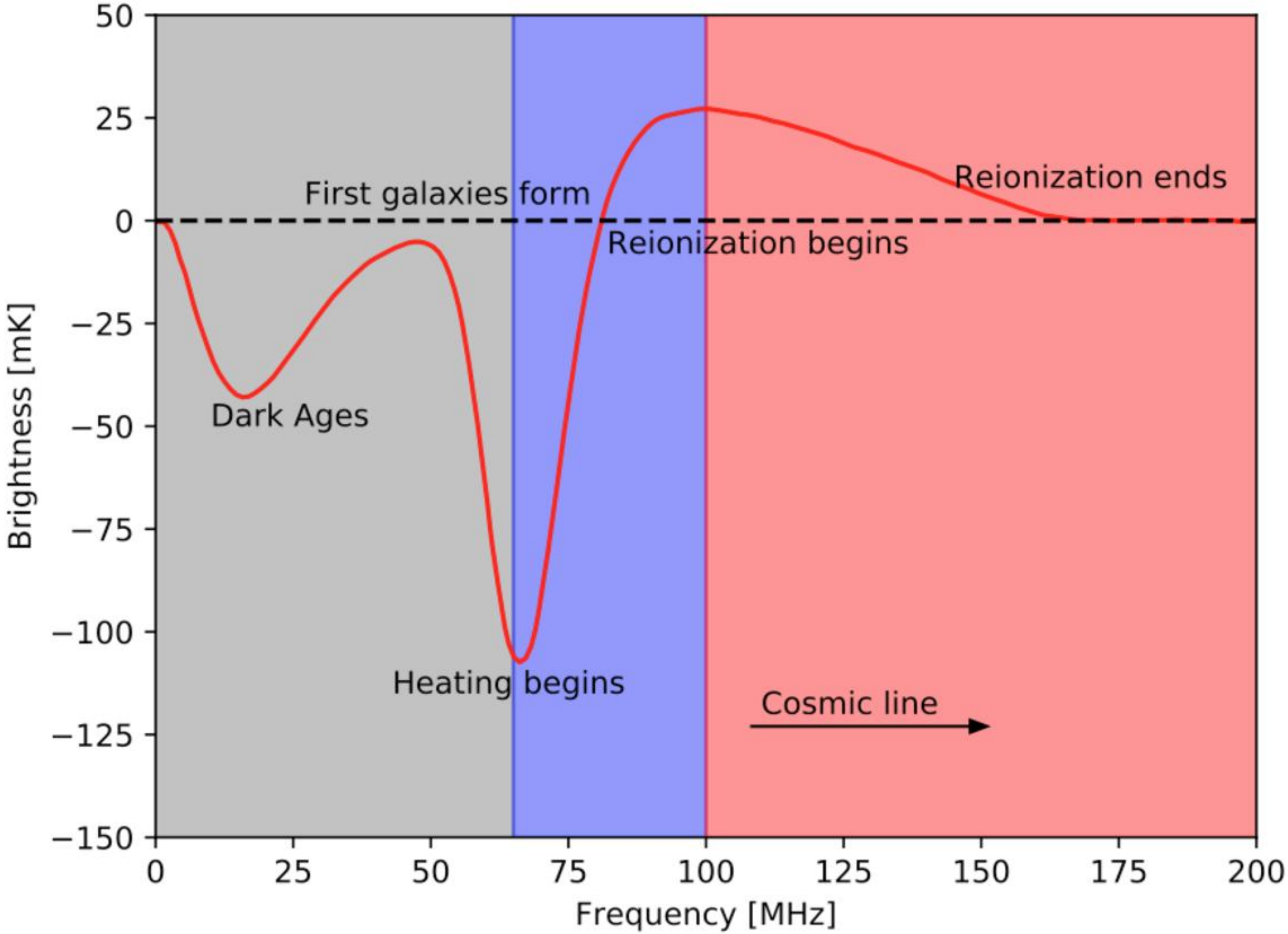

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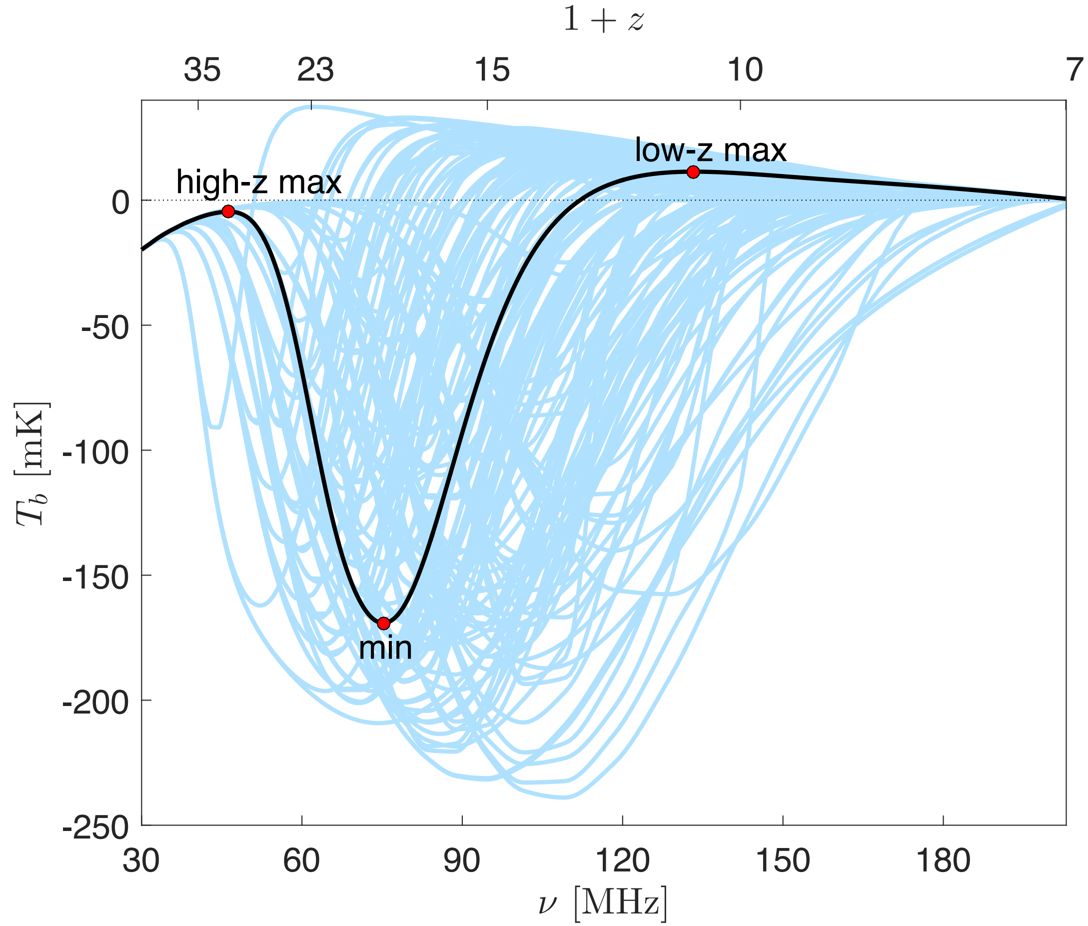
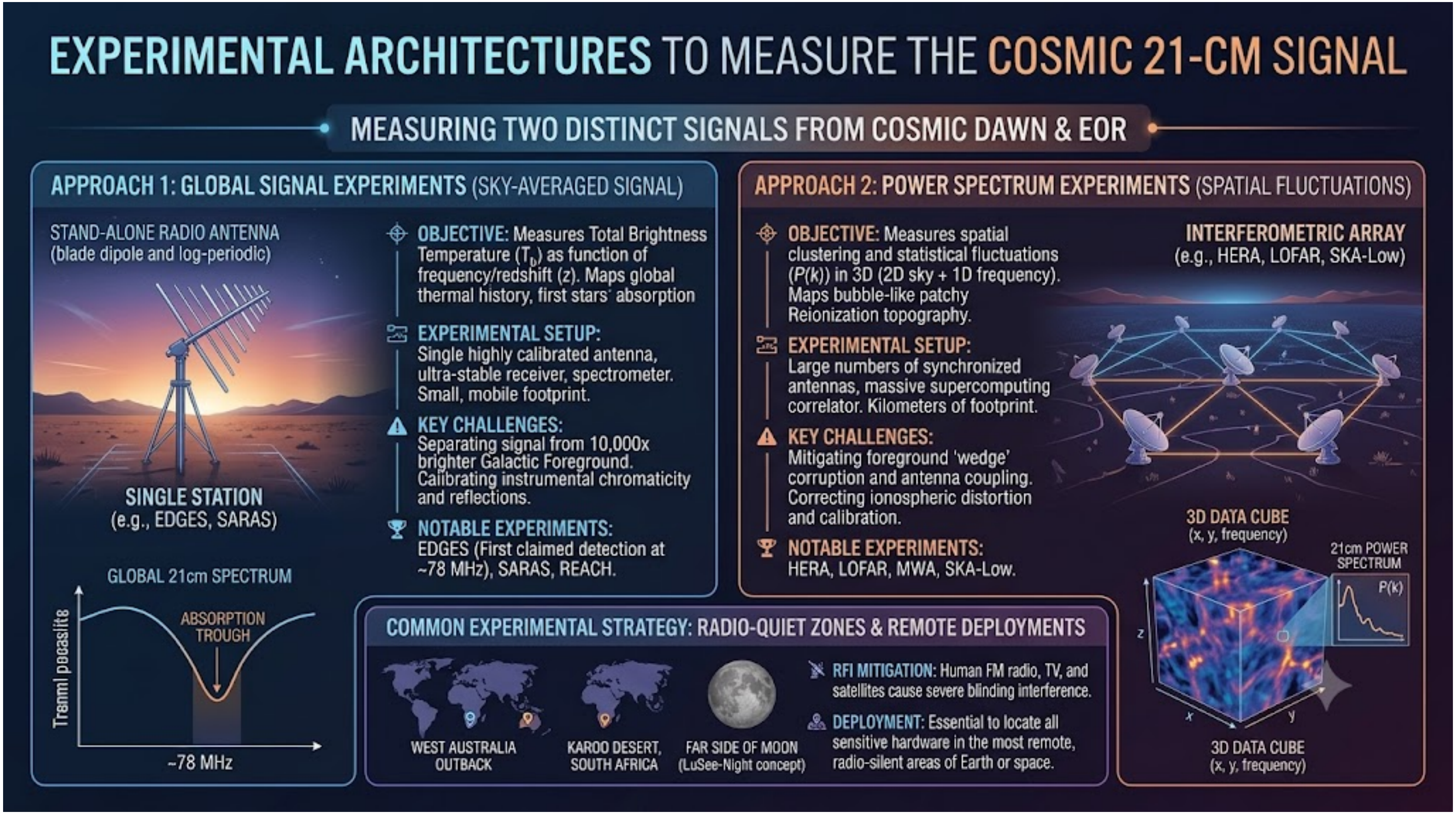
21cm signal from astrophysical models



[Cohen et.al,1609.02312]

Figure 1. The 21-cm global signal as a function of redshift for our standard case (black line), with red points marking the three turning points (from left to right: the high-z maximum, the minimum, and the low-z maximum). Light-blue lines show the entire set of realizations of the 21-cm signal for the 193 different astrophysical models discussed in this paper and summarized in Table 1. The full list of models appears in Appendix A.



EXPERIMENTAL ARCHITECTURES TO MEASURE THE COSMIC 21-CM SIGNAL
MEASURING TWO DISTINCT SIGNALS FROM COSMIC DAWN & EOR
APPROACH 1: GLOBAL SIGNAL EXPERIMENTS (SKY-AVERAGED SIGNAL)
STAND-ALONE RADIO ANTENNA (blade dipole and log-periodic)
OBJECTIVE: Measures Total Brightness Temperature (T_b) as function of frequency/redshift (z). Maps global thermal history, first stars' absorption
EXPERIMENTAL SETUP: Single highly calibrated antenna, ultra-stable receiver, spectrometer. Small, mobile footprint.
KEY CHALLENGES: Separating signal from 10,000x brighter Galactic Foreground. Calibrating instrumental chromaticity and reflections.
NOTABLE EXPERIMENTS: EDGES (First claimed detection at ~78 MHz), SARAS, REACH.
SINGLE STATION (e.g., EDGES, SARAS)
GLOBAL 21cm SPECTRUM
ABSORPTION TROUGH
~78 MHz
APPROACH 2: POWER SPECTRUM EXPERIMENTS (SPATIAL FLUCTUATIONS)
OBJECTIVE: Measures spatial clustering and statistical fluctuations ($P(k)$) in 3D (2D sky + 1D frequency). Maps bubble-like patchy Reionization topography.
EXPERIMENTAL SETUP: Large numbers of synchronized antennas, massive supercomputing correlator. Kilometers of footprint.
KEY CHALLENGES: Mitigating foreground 'wedge' corruption and antenna coupling. Correcting ionospheric distortion and calibration.
NOTABLE EXPERIMENTS: HERA, LOFAR, MWA, SKA-Low.
INTERFEROMETRIC ARRAY (e.g., HERA, LOFAR, SKA-Low)
3D DAYA CUBE (x, y, frequency)
21cm POWER SPECTRUM
P(k)
z
x
y
3D DATA CUBE (x, y, frequency)
COMMON EXPERIMENTAL STRATEGY: RADIO-QUIET ZONES & REMOTE DEPLOYMENTS
WEST AUSTRALIA OUTBACK
KAROO DESERT, SOUTH AFRICA
FAR SIDE OF MOON (LuSee-Night concept)
RFI MITIGATION: Human FM radio, TV, and satellites cause severe blinding interference.
DEPLOYMENT: Essential to locate all sensitive hardware in the most remote, radio-silent areas of Earth or space.

Early Universe Physics with 21cm

$$21\text{cm} \rightarrow P_m(k, z) \rightarrow \begin{cases} \sum m_\nu \\ \text{DM properties} \\ N_{\text{eff}} \\ \text{inflation} \\ f_{\text{NL}} \\ \text{primordial features} \\ \text{early dark energy} \\ \text{dark-sector interactions} \end{cases}$$

Early Matter Domination and 21cm

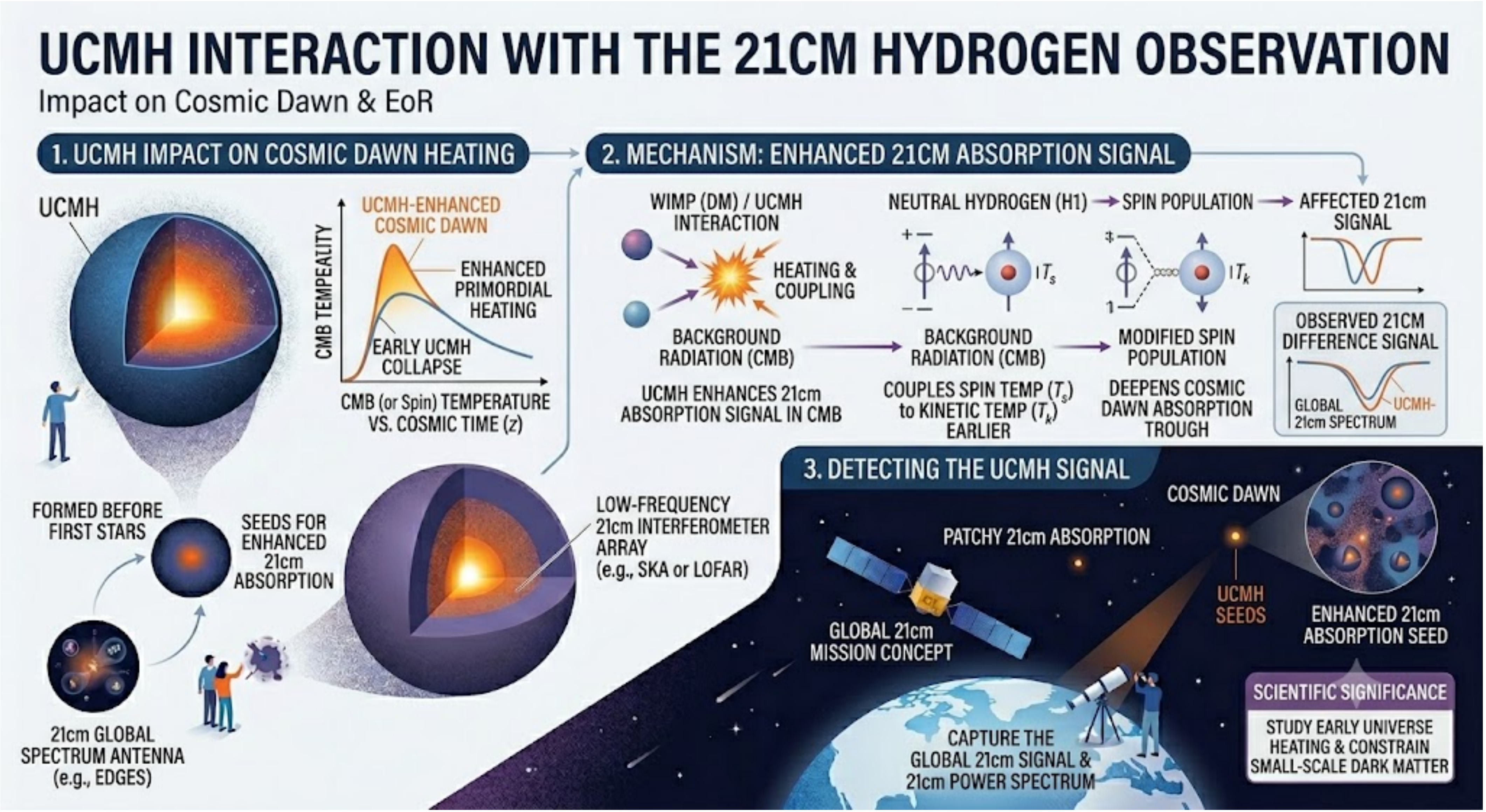
Early matter domination

→ Enhance matter power spectrum at small scales

→ Enhance the DM halo density (UCMHs)

→ DM annihilation changes thermal history of IGM

→ Impact on the global 21cm observation



WIMP annihilations in the UCMHs can release energy, which might affect the thermal history of Universe and 21cm lines.

Formation of UCMHs

In standard Universe, the condition of UCMH formation $\delta \gtrsim 10^{-3}$

UCMHs(Ultra Compact Mini Halos) can form from overdense regions.

$$M_{\rm UCMHs}(z) = M_i \left(\frac{1+z_{\rm eq}}{1+z}\right),$$

$$M_i \simeq \left[\frac{4\pi}{3}\rho_{\rm DM} H^{-3}\right]_{aH=1/R} = 4\pi M_P^2 H_0^2 \Omega_{\rm DM,0} R^3 = 1.3\times 10^{11} M_\odot \left(\frac{\Omega_{\rm DM,0}h^2}{0.112}\right)\left(\frac{R}{\rm Mpc}\right)^3,$$

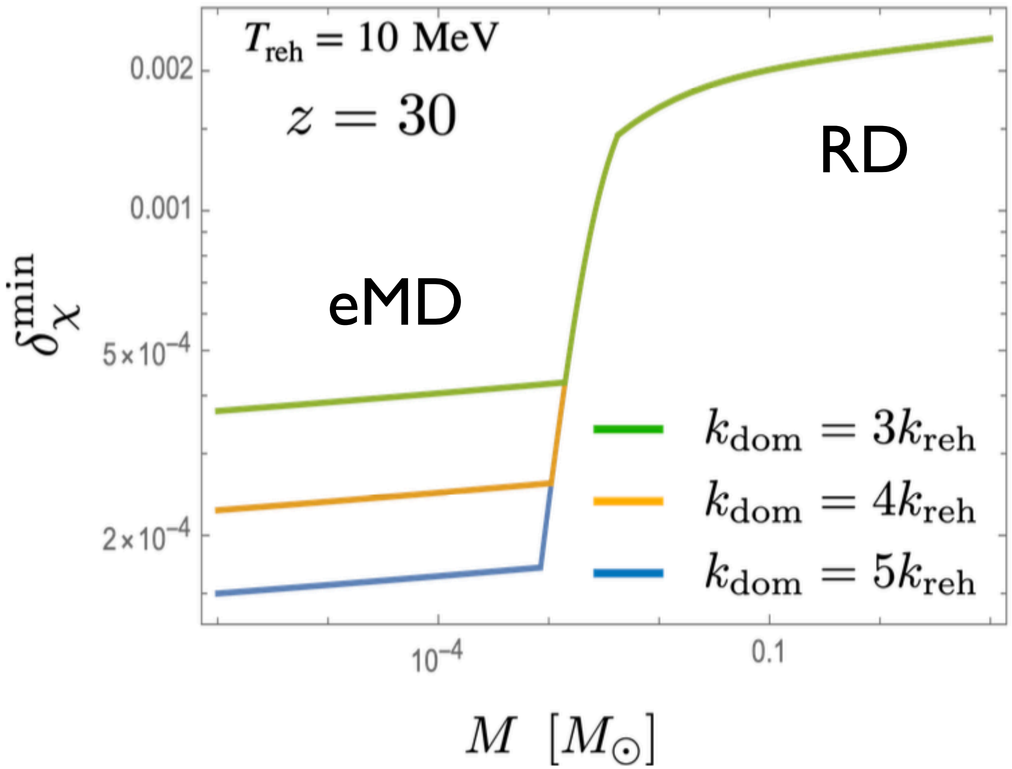
With the halo density profile

$$\rho_{\rm UCMHs}(r,z) = \frac{3 f_\chi M_{\rm UCMHs}(z)}{16\pi R_{\rm UCMHs}^{3/4}(z) r^{9/4}},$$

Formation of UCMHs with eMD

During eMD, the perturbation can grow more during eMD.

This changes the initial condition to make UCMHs,
with smaller density perturbations. More UCMHs can form.



$$\delta_\chi^{min} \ll 10^{-3}$$

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Mass function of UCMH

Press-Schechter theory: non-linear effects on small scales from linear power spectrum

$$\frac{dn}{dM} = \frac{\bar{\rho}}{M}\frac{dF}{dM} \simeq 2\frac{\bar{\rho}}{M}\frac{d\beta(R,z)}{dM}$$

where the probability to form UCMHs for coming size R

$$\beta(R,z) = \frac{1}{\sqrt{2\pi\sigma^2(R)}}\int_{\delta_{\rm min}}^{\delta_{\rm max}} \exp\left[-\frac{\delta^2}{2\sigma^2(R)}\right] d\delta,$$

DM mass variance

$$\sigma_M^2(t) \equiv \sigma^2(R,t) = \int_0^\infty W^2_{\rm top-hat}(kR)\mathcal{P}_\chi(k,t)\frac{dk}{k},$$

with $W(x) = \frac{3\,(\sin x - x\cos x)}{x^3}$

Mass function of UCMH with eMD

Modified mass function

$$\frac{dn}{dM} = \sqrt{\frac{2}{\pi}} \frac{\bar{\rho}_0}{M^2} \left(\frac{\delta_{\rm min}}{\sigma_M}\right) \left(\frac{1+10}{1+z}\right) \left[\frac{d\log\sigma_M}{d\log M} - \frac{d\log\delta_\chi^{\rm min}}{d\log M}\right] e^{-\frac{1}{2}\left(\frac{\delta_{\rm min}}{\sigma_M}\right)^2}$$

With modified minimum density

$$\delta_\chi^{\rm min}(k, z_c) = \frac{a^2}{t^2}\bigg|_{z_c} \frac{2}{3}\left(\frac{3\pi}{2}\right)^{2/3} \frac{\theta_k^2 T_\chi(\theta_k)}{k^2 T(\kappa)} = \frac{a^2}{t^2}\bigg|_{z_c} \frac{2}{9}\left(\frac{3\pi}{2}\right)^{2/3} \frac{T_\chi(\theta = 1/\sqrt{3})}{k^2 T(\kappa)},$$

With modified transfer functions

$$T(\kappa) = T(\kappa)|_{\rm std} \times \begin{cases} 1 + \frac{1}{3}\frac{(k/k_{\rm reh})^2}{(k^2 T(\kappa)/k_{\rm reh}^2 T(\kappa_{\rm reh}))} & \text{for } k < k_{\rm dom} \\ 1 + \frac{1}{3}\frac{(k_{\rm dom}/k_{\rm reh})^2}{(k_{\rm dom}^2 T(\kappa_{\rm dom})/k_{\rm reh}^2 T(\kappa_{\rm reh}))} & \text{for } k > k_{\rm dom}. \end{cases}$$

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Energy release from DM annihilation

DM annihilation in the halo releases energy per time per volume

$$\left.\frac{dE}{dV\,dt}\right|_{\rm DM} = (1+z)^3 \frac{\langle \sigma v \rangle}{m_\chi} \int dM \frac{dn}{dM} \int 4\pi r^2 \rho_\chi^2(r) dr,$$

Which is injected into IGM, and changes gas temperature T_k

$$(1+z)\frac{dx_e}{dz} = \frac{1}{H(z)}\left[R_s(z) - I_s(z) - I_{\rm DM}(z)\right],$$

$$(1+z)\frac{dT_k}{dz} = \frac{8\sigma_T a_R T_{\rm CMB}^4}{3 m_e c H(z)} \frac{x_e (T_k - T_{\rm CMB})}{1 + f_{\rm He} + x_e} - \frac{2}{3 k_B H(z)} \frac{K_{\rm DM}}{1 + f_{\rm He} + x_e} + 2T_k,$$

x_e: ionization fracrion

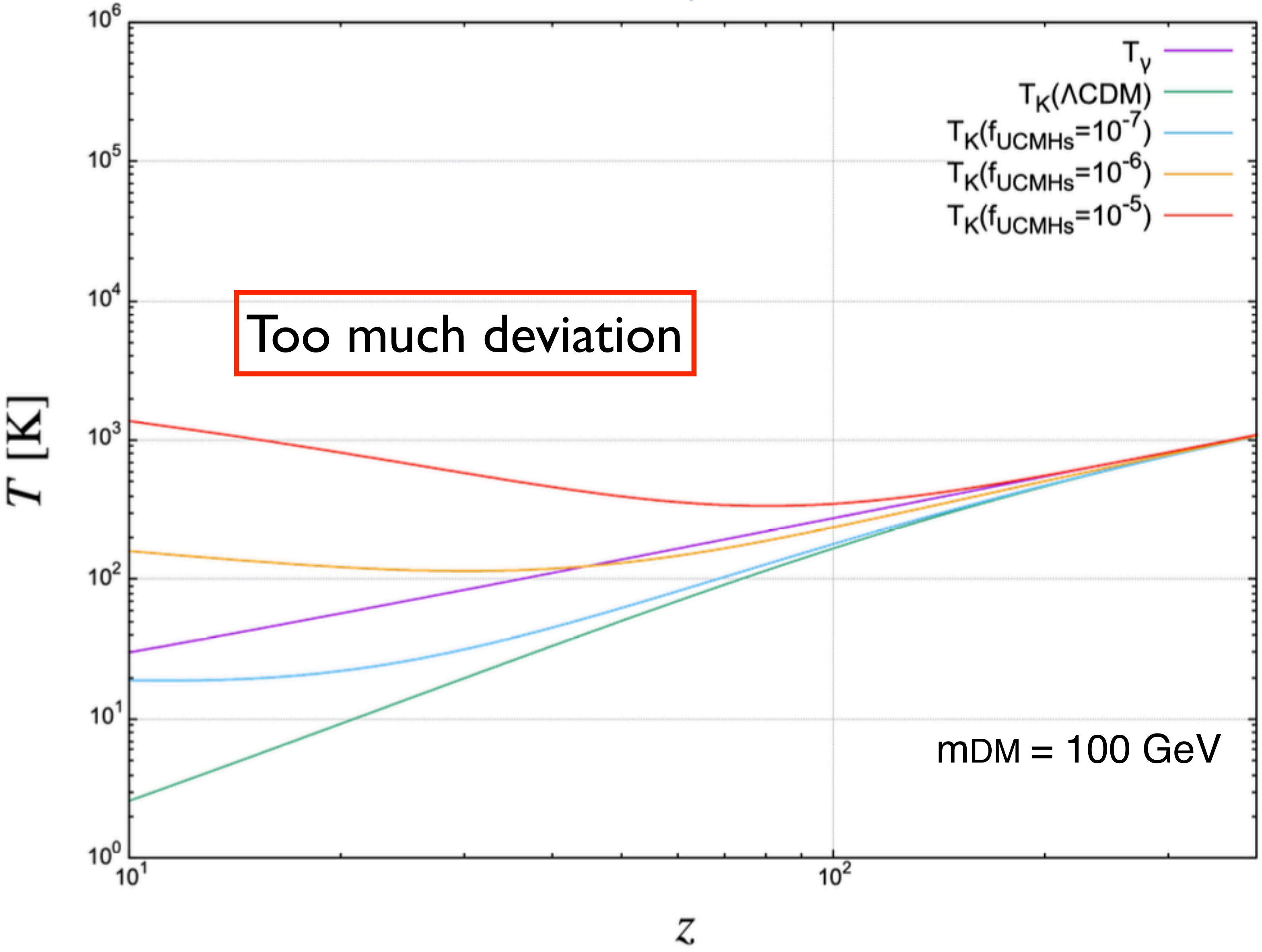
$$I_{\rm DM} = f_i(z) \frac{1}{n_b} \frac{1}{E_0} \left.\frac{{\rm d}E}{{\rm d}V{\rm d}t}\right|_{\rm DM}$$

$$K_{\rm DM} = f_h(z) \frac{1}{n_b} \left.\frac{{\rm d}E}{{\rm d}V{\rm d}t}\right|_{\rm DM}$$

f(z) Energy fraction into IGM

CMB and gas temperature with UCMHs

[KYC, Fumiya Okamatsu and Tomo Takahashi]



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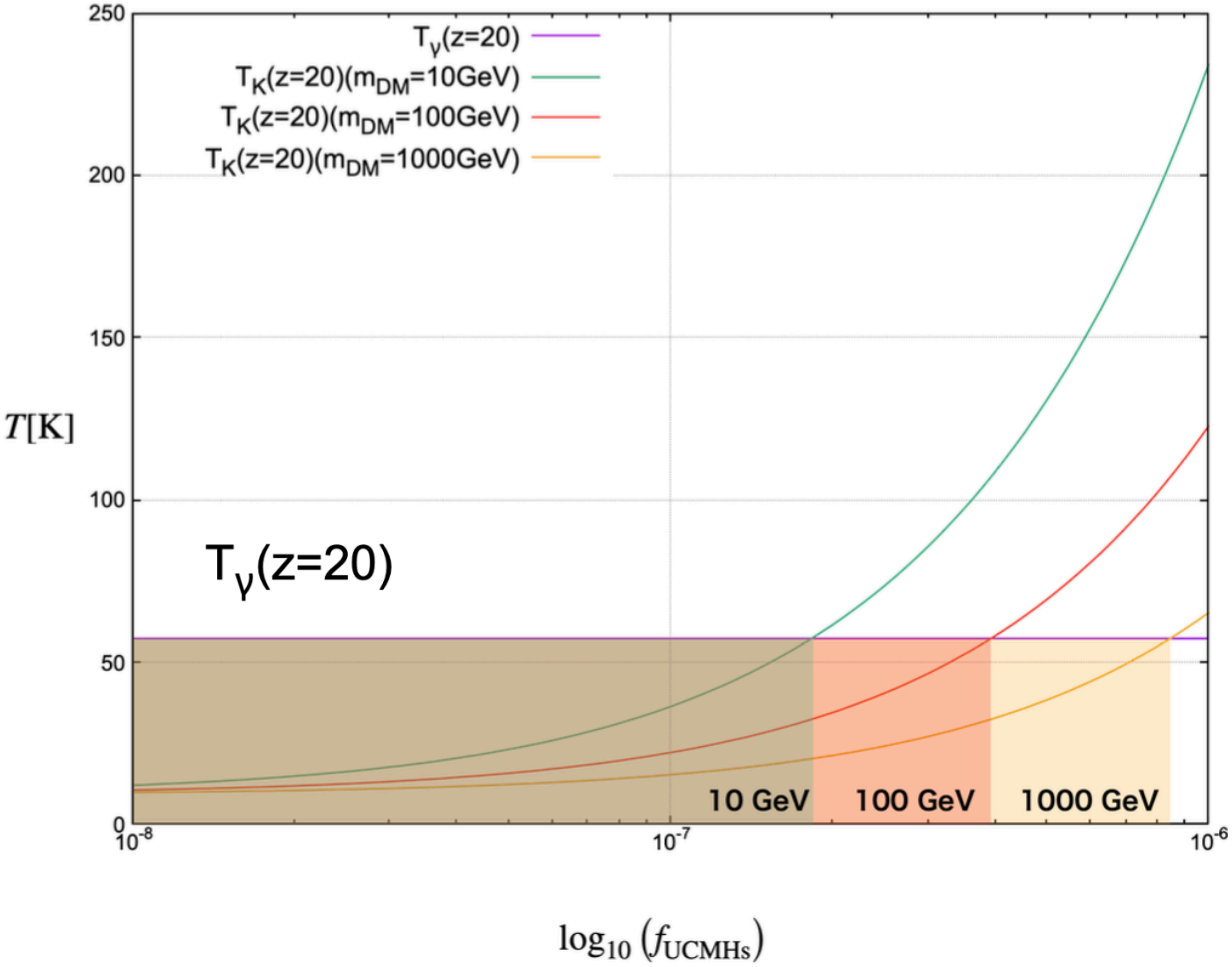
CMB and gas temperature with UCMHs

[KYC, Fumiya Okamatsu and Tomo Takahashi]



Summary

- Early Matter Domination (eMD) occurs often.

: Density perturbation can grow during eMD

- The smallest scale of objects

: More PBH/UCMHs can develop and exists, where DM annihilates and may change the thermal history of Universe, including 21cm lines.

- Bound on eDM: duration and the reheating temperature

:The deviation of brightness temperature can be used to constrain the amount of UCMHs and also the physics of eMD

Thank You!