Probing early matter domination and low reheating temperature with dark age 21cm global signal

Collaboration with Fumiya Okamatsu and Tomo Takahashi

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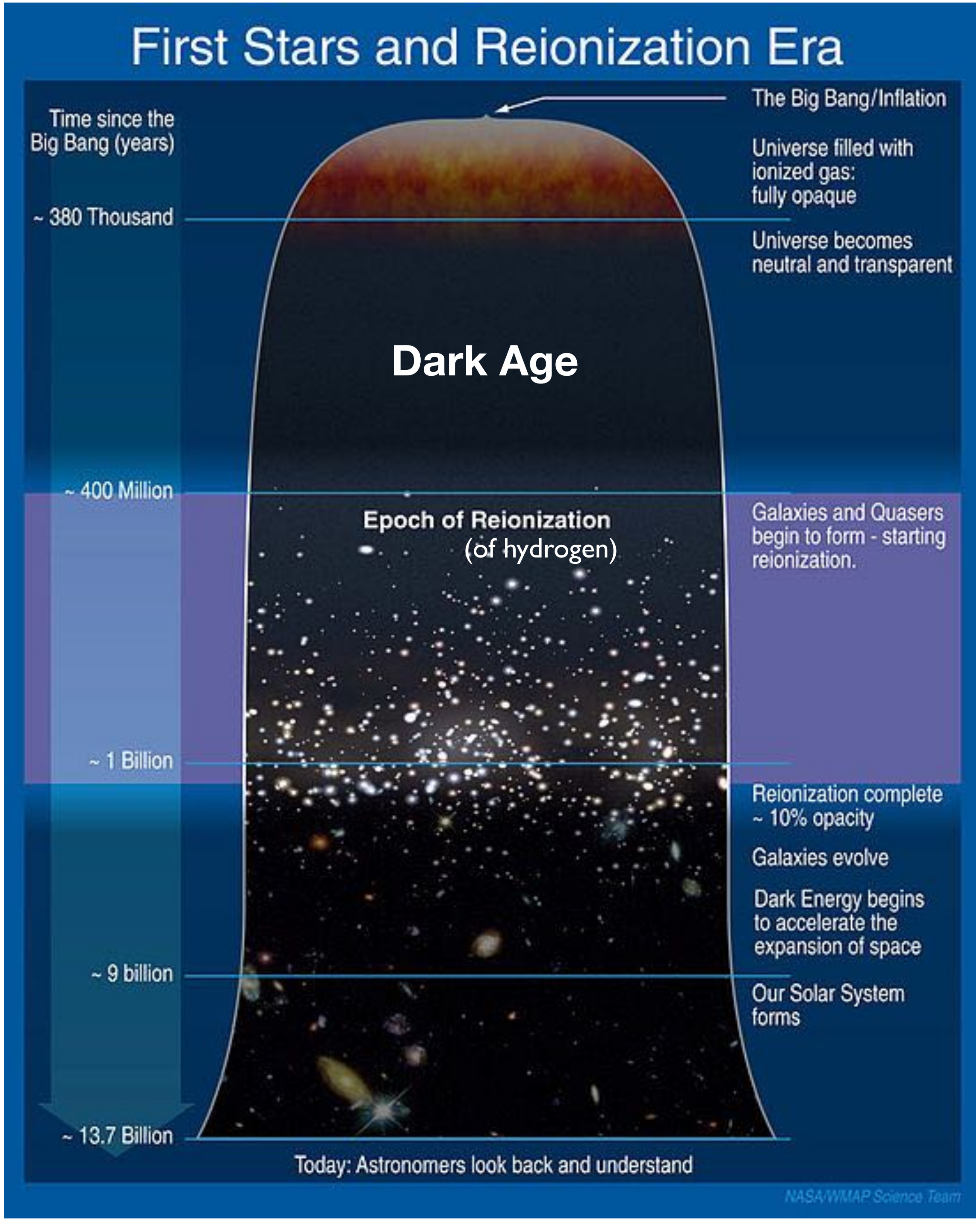
- 21cm lines and brightness temperature

- Early matter domination (eDM) and the formation of ultra compact mini halos (UCMHs)

- WIMP annihilation and constraint on eDM and reheating temperature

Dark Age and 21 cm signal



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).

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

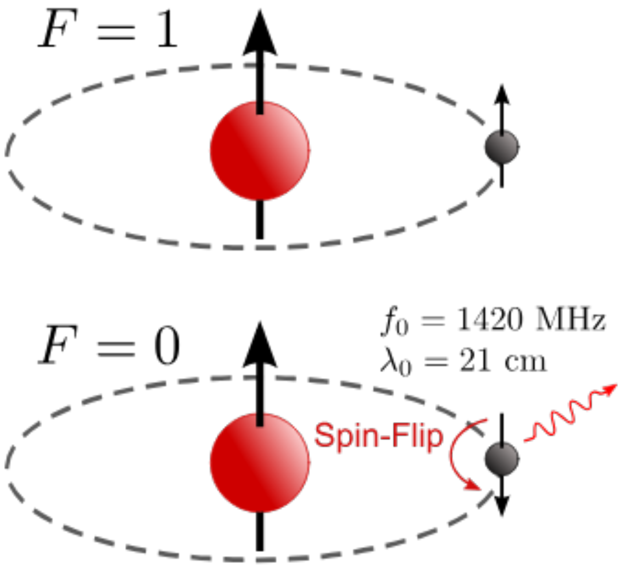
Reionization:
Re-ionization of neutral hydrogen atoms due to energetic radiation from first astrophysical objects formed (6<z<13).

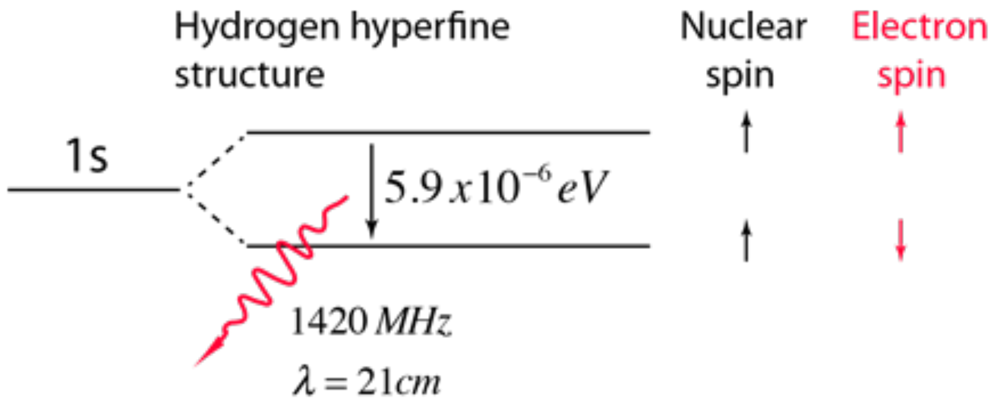
During matter-domination,

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

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

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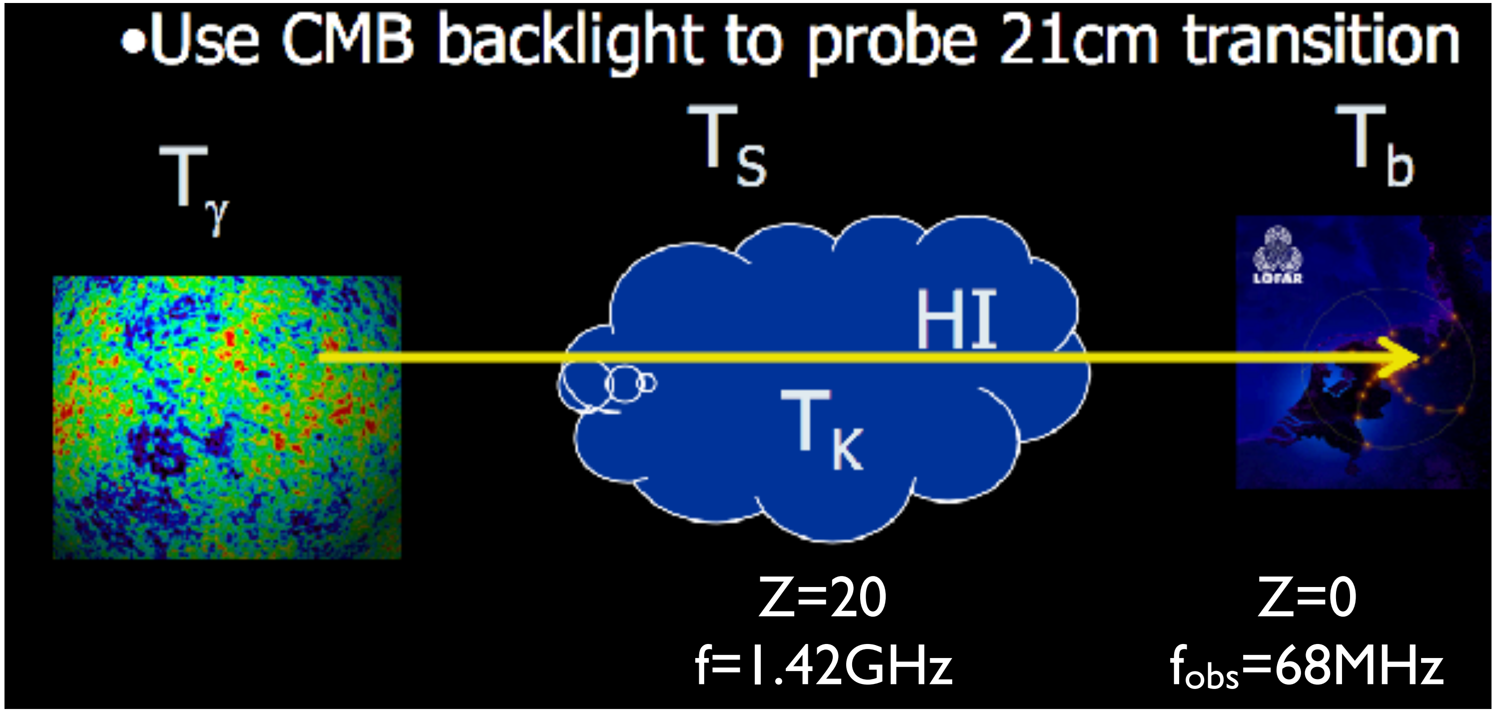
Spin Temperature

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

If $T_s > T_\gamma$ more emission

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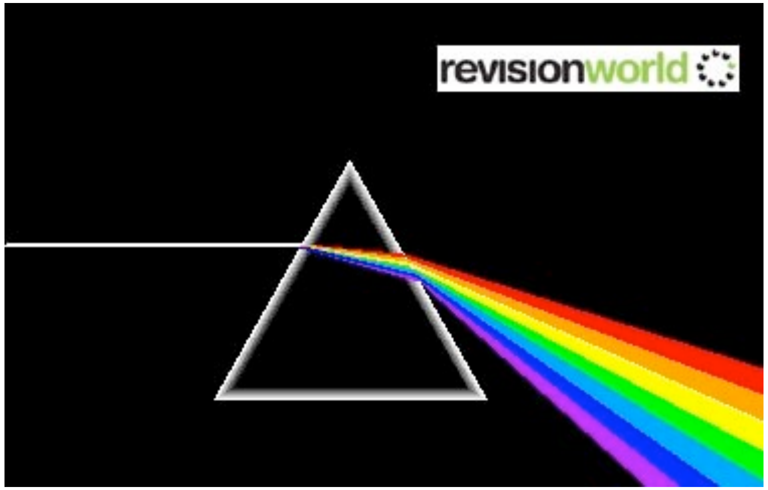
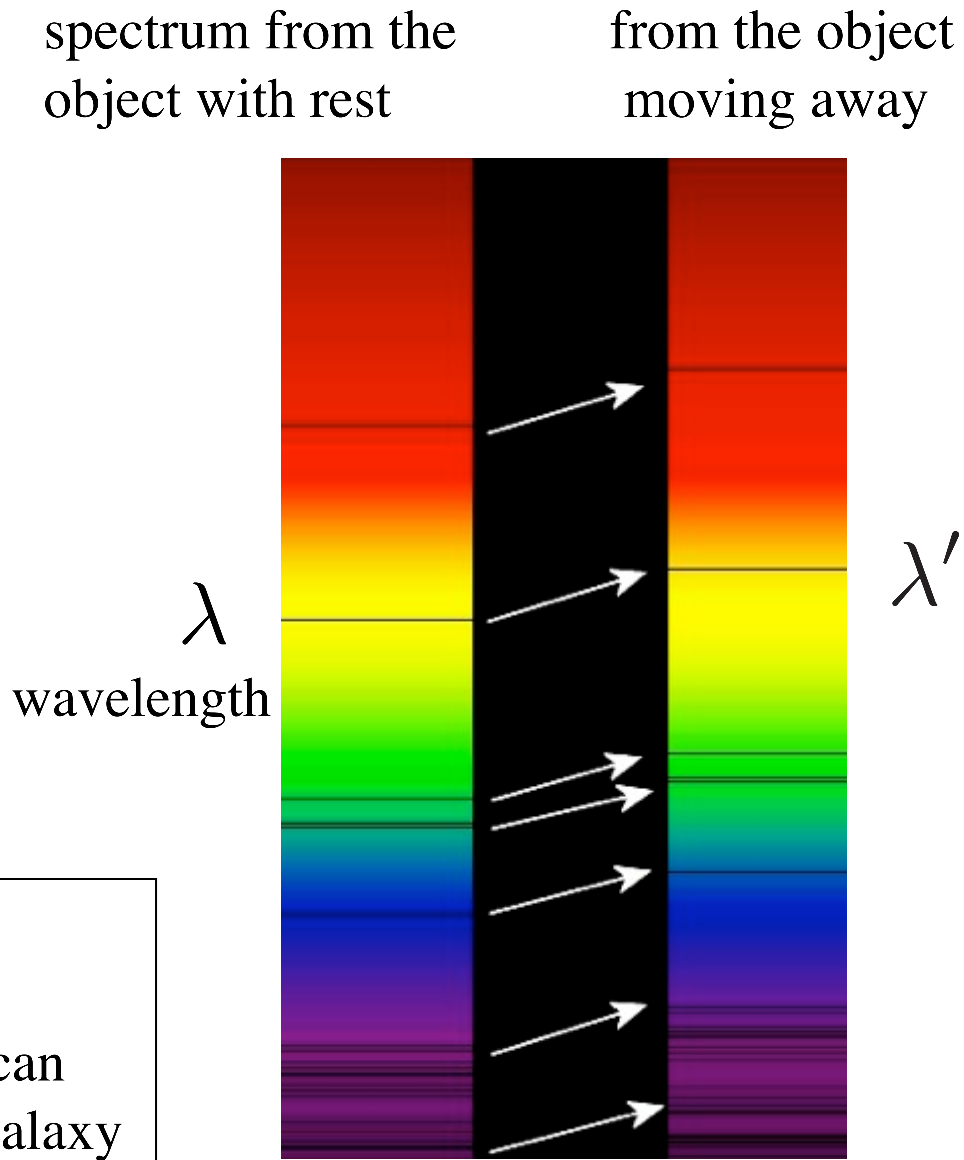
• Spectroscopy and Redshift

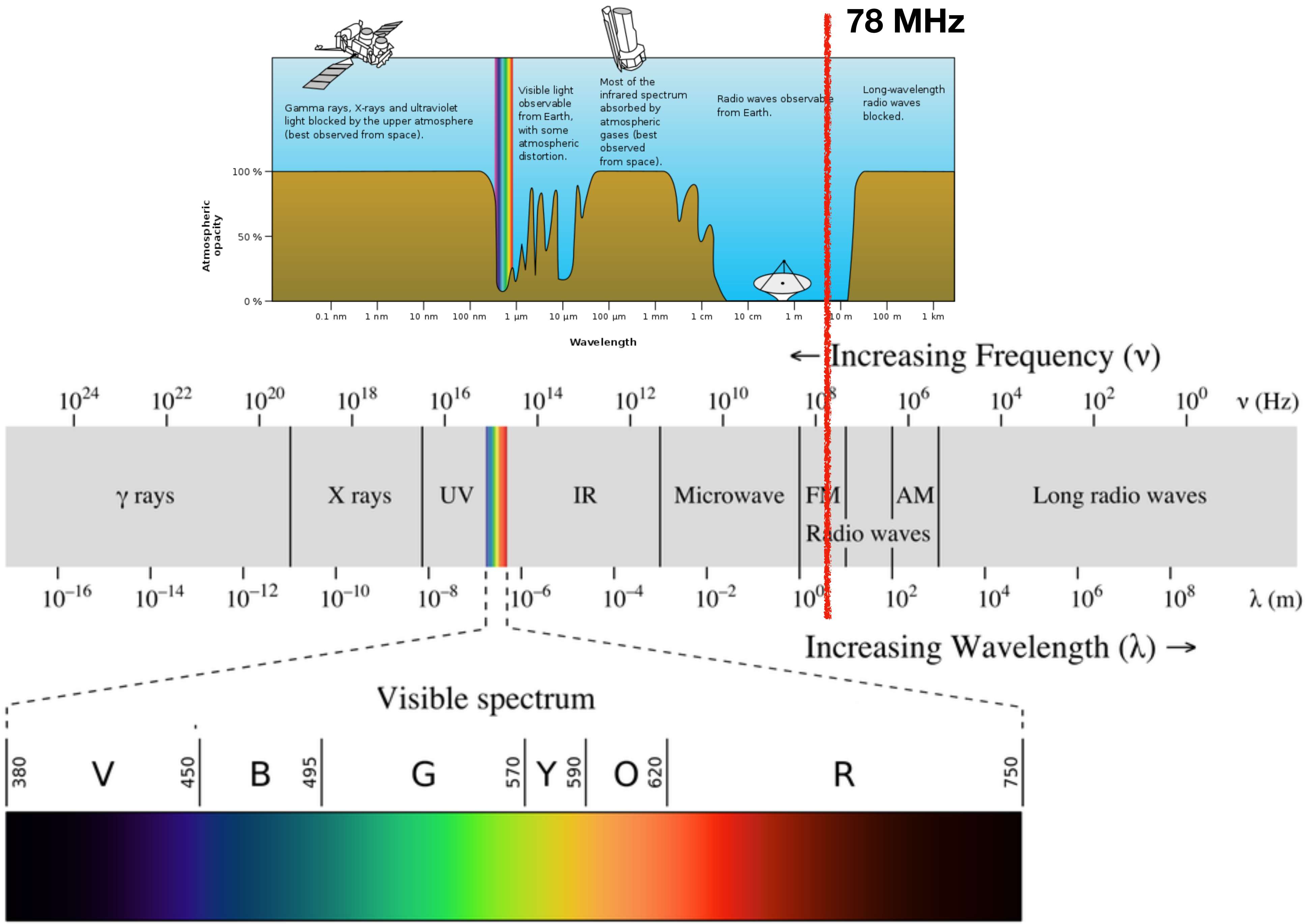


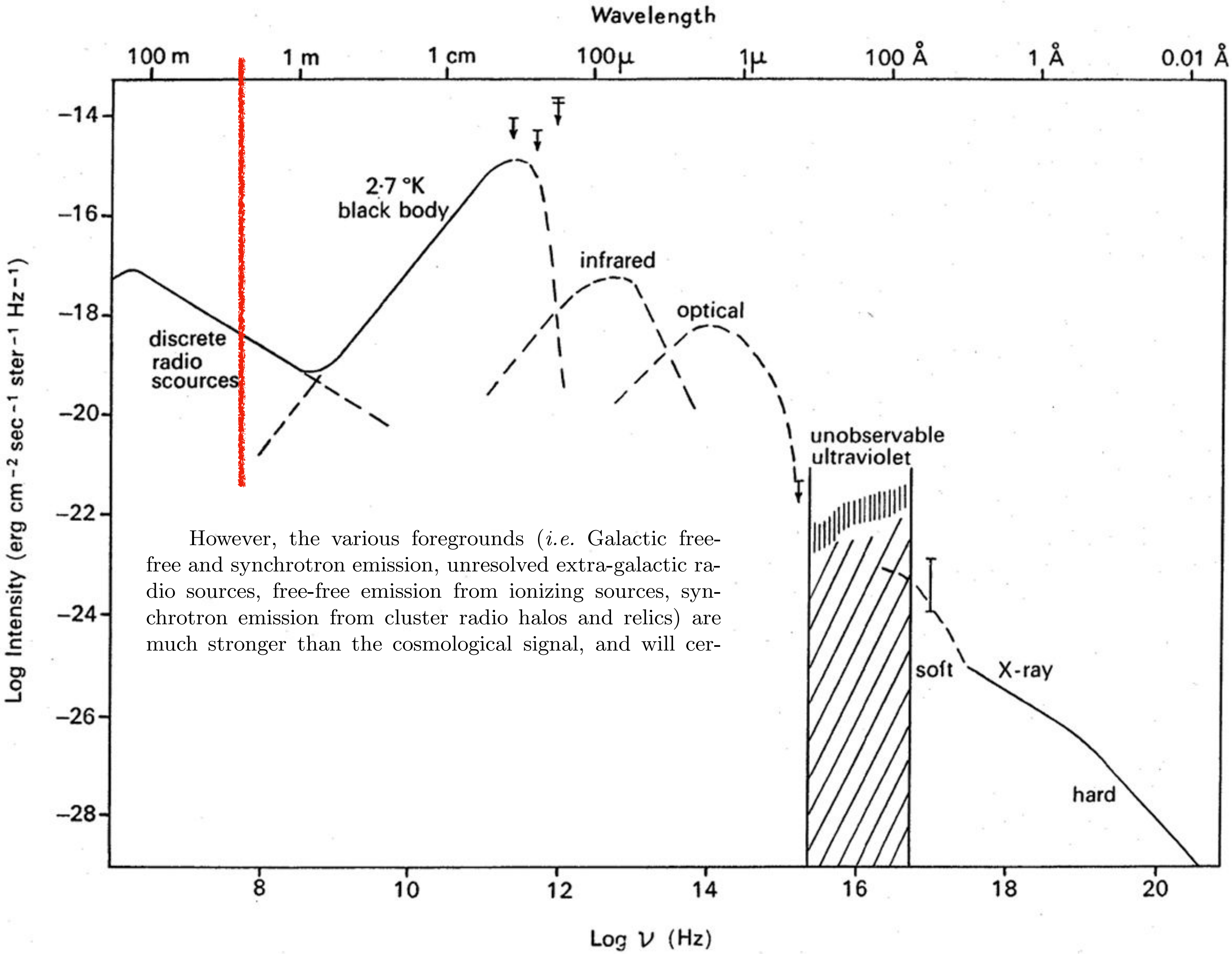
Analysis of white light by dispersing it with a prism is example of spectroscop

$$\frac{\lambda'}{\lambda} \equiv 1 + z$$

The wavelength from moving away becomes longer (Doppler effect). Comparing the absorption lines, we can calculate the recession velocity of a galaxy and cluster.




78 MHz
Gamma rays, X-rays and ultraviolet light blocked by the upper atmosphere (best observed from space).
Visible light observable from Earth, with some atmospheric distortion.
Most of the infrared spectrum absorbed by atmospheric gases (best observed from space).
Radio waves observable from Earth.
Long-wavelength radio waves blocked.
Atmospheric opacity
100 %
50 %
0 %
0.1 nm
1 nm
10 nm
100 nm
1 μm
10 μm
100 μm
1 mm
1 cm
10 cm
1 m
10 m
100 m
1 km
Wavelength
← Increasing Frequency (ν)
10^{24} 10^{22} 10^{20} 10^{18} 10^{16} 10^{14} 10^{12} 10^{10} 10^{8} 10^{6} 10^{4} 10^{2} 10^{0} ν (Hz)
γ rays
X rays
UV
IR
Microwave
FM
AM
Radio waves
Long radio waves
10^{-16} 10^{-14} 10^{-12} 10^{-10} 10^{-8} 10^{-6} 10^{-4} 10^{-2} 10^{0} 10^{2} 10^{4} 10^{6} 10^{8} λ (m)
Increasing Wavelength (λ) →
Visible spectrum
380
V
450
B
495
G
570
Y
590
O
620
R
750



However, the various foregrounds (*i.e.* Galactic free-free and synchrotron emission, unresolved extra-galactic radio sources, free-free emission from ionizing sources, synchrotron emission from cluster radio halos and relics) are much stronger than the cosmological signal, and will cer-

Differential Brightness Temperature

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

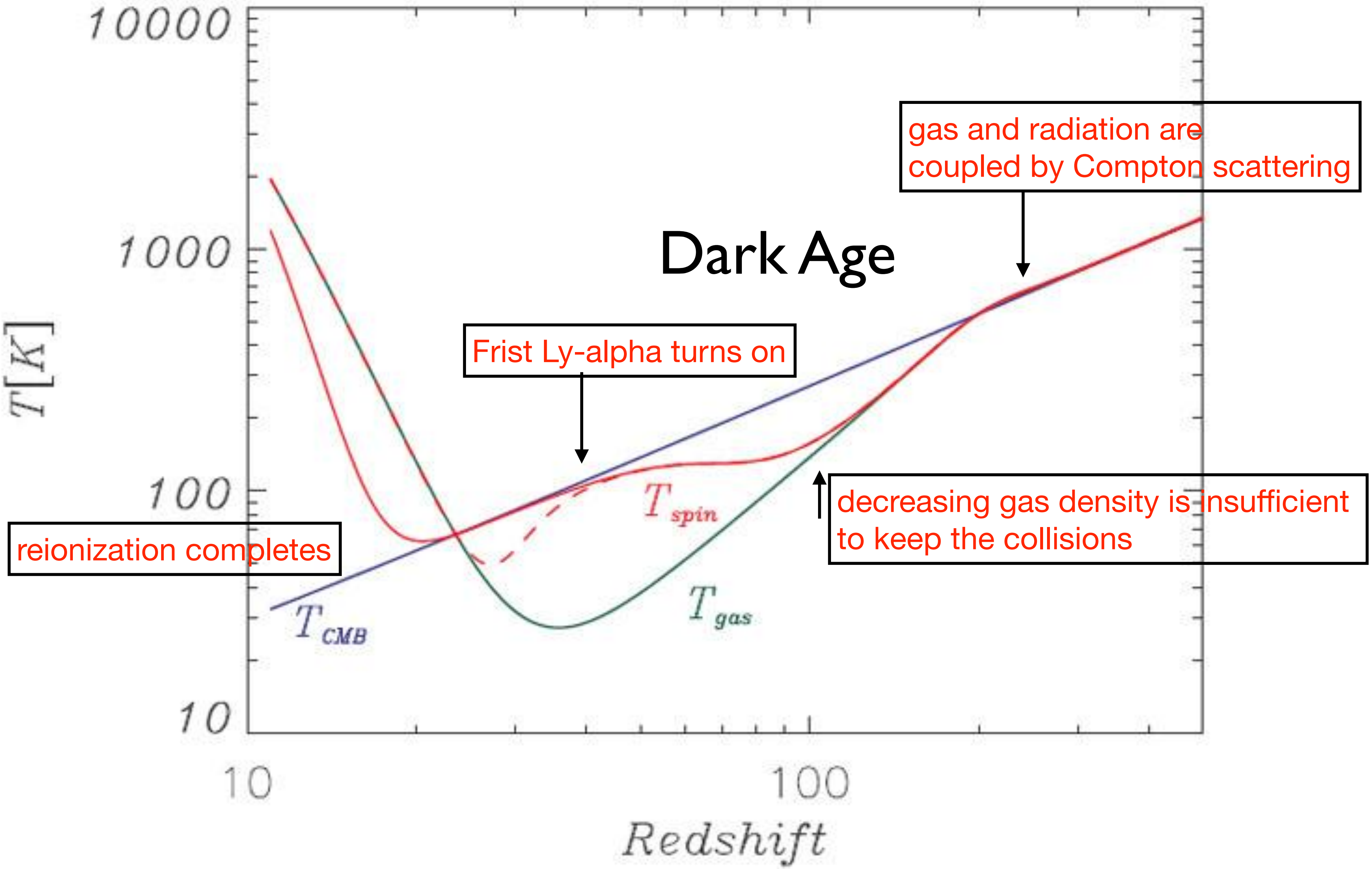
How much brighter or dimmer the neutral hydrogen 21-cm signal is compared to the background radiation (CMB)

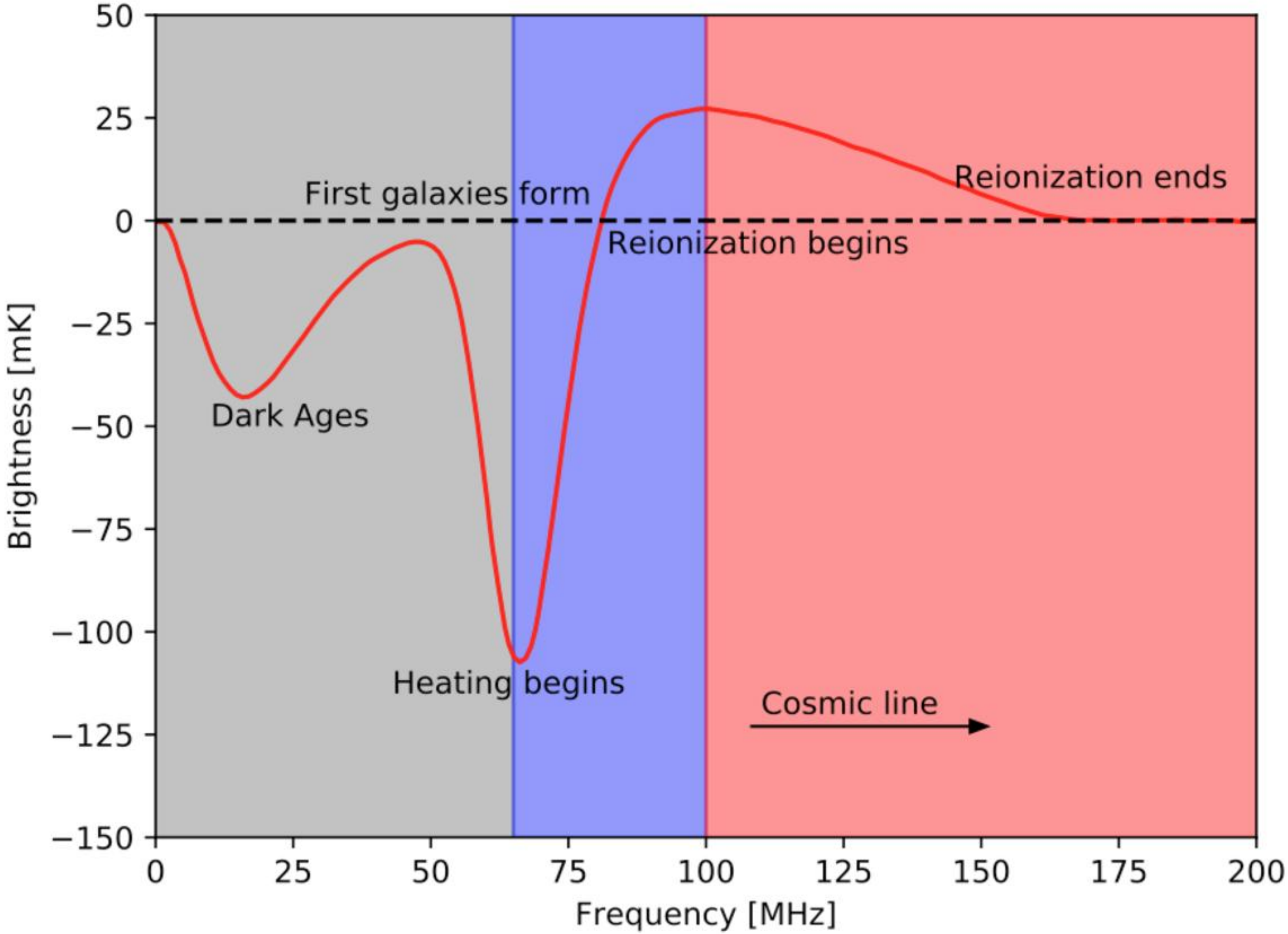
$$\Delta T_b \simeq 27 \text{ mK} \left(\frac{T_s - T_R}{T_s}\right)\left(\frac{1+z}{10}\right)^{1/2}\left(\frac{\Omega_b h^2}{0.023}\right)\left(\frac{0.15}{\Omega_m h^2}\right)^{1/2} x_{HI}$$

x_{HI} is the fraction of neutral hydrogen

T_{R} is the temperature of the background radiation,

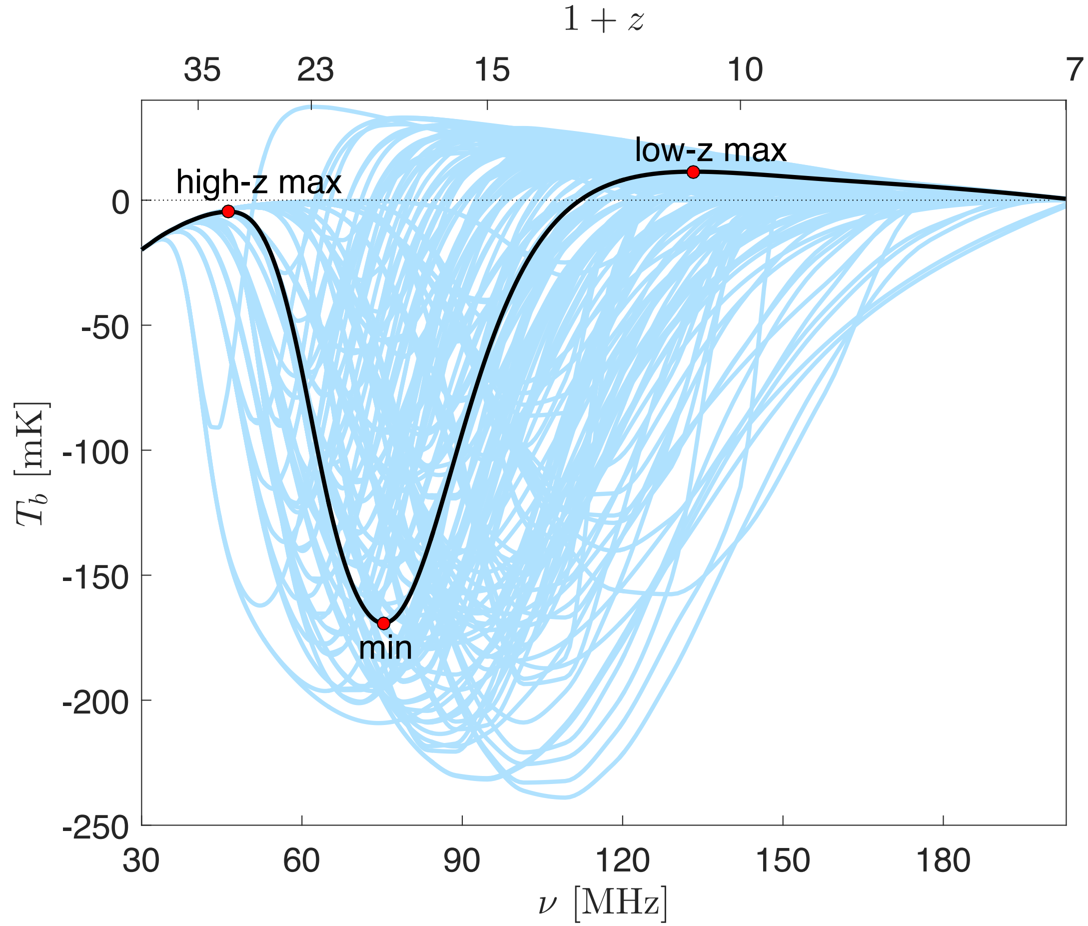
$\nu = 1{,}420/(1+z)$ MHz





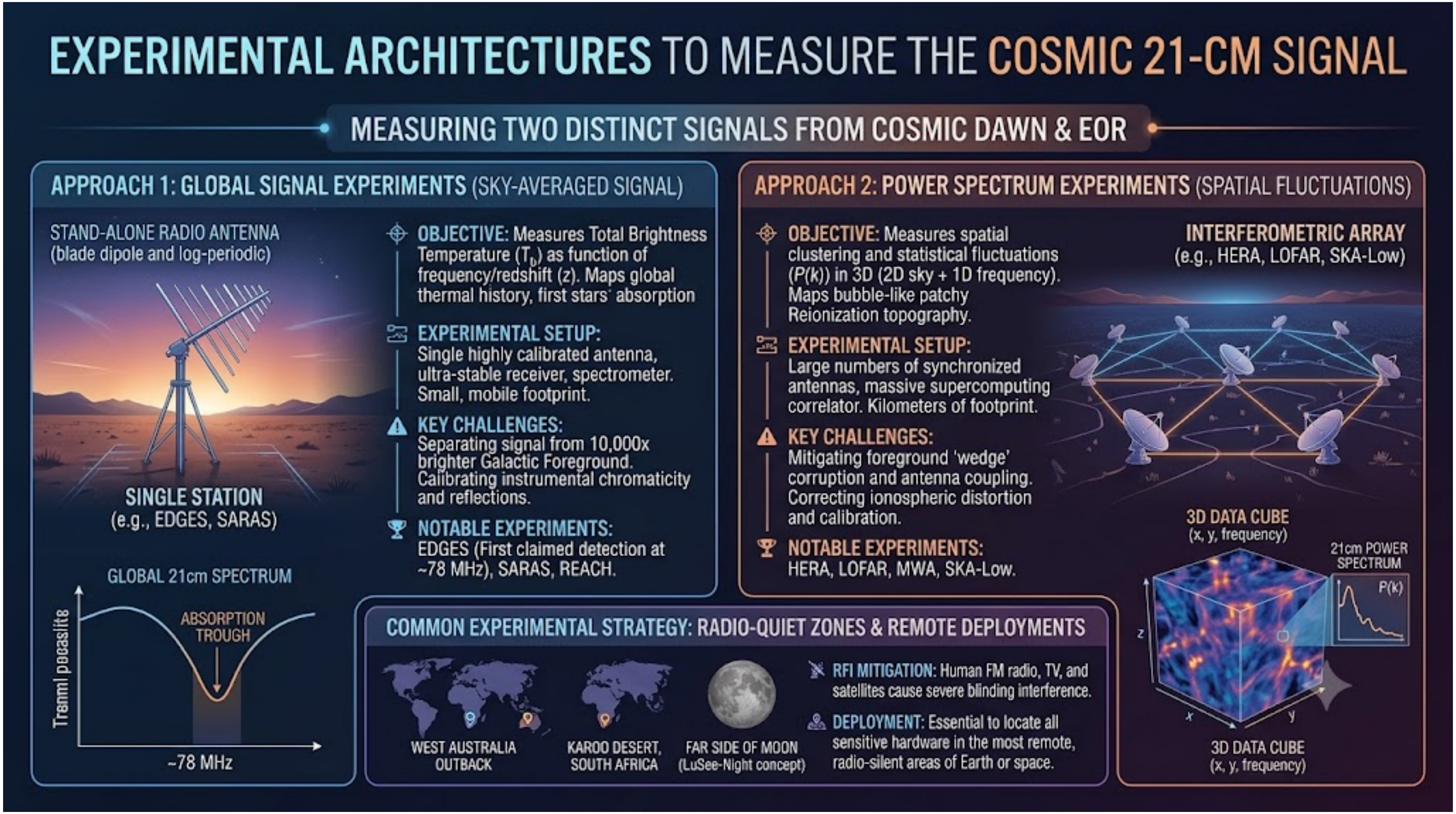
50
25
0
−25
−50
−75
−100
−125
−150
Brightness [mK]
0
25
50
75
100
125
150
175
200
Frequency [MHz]
First galaxies form
Reionization ends
Reionization begins
Dark Ages
Heating begins
Cosmic line

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.
SINGLE STATION (e.g., EDGES, SARAS)
NOTABLE EXPERIMENTS: EDGES (First claimed detection at ~78 MHz), SARAS, REACH.
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.
INTERFEROMETRIC ARRAY (e.g., HERA, LOFAR, SKA-Low)
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.
3D DATA 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.

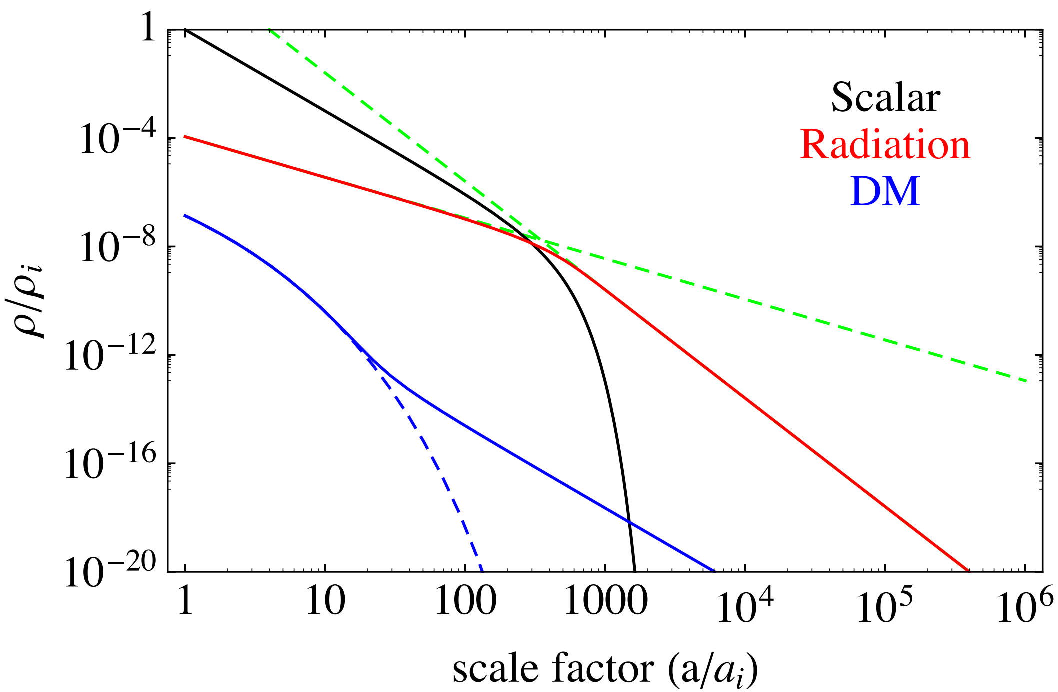
Early Matter Domination (eMD)
and
Low Reheating Temperature

Early Matter Domination (eMD) and Low Reheating Temperature

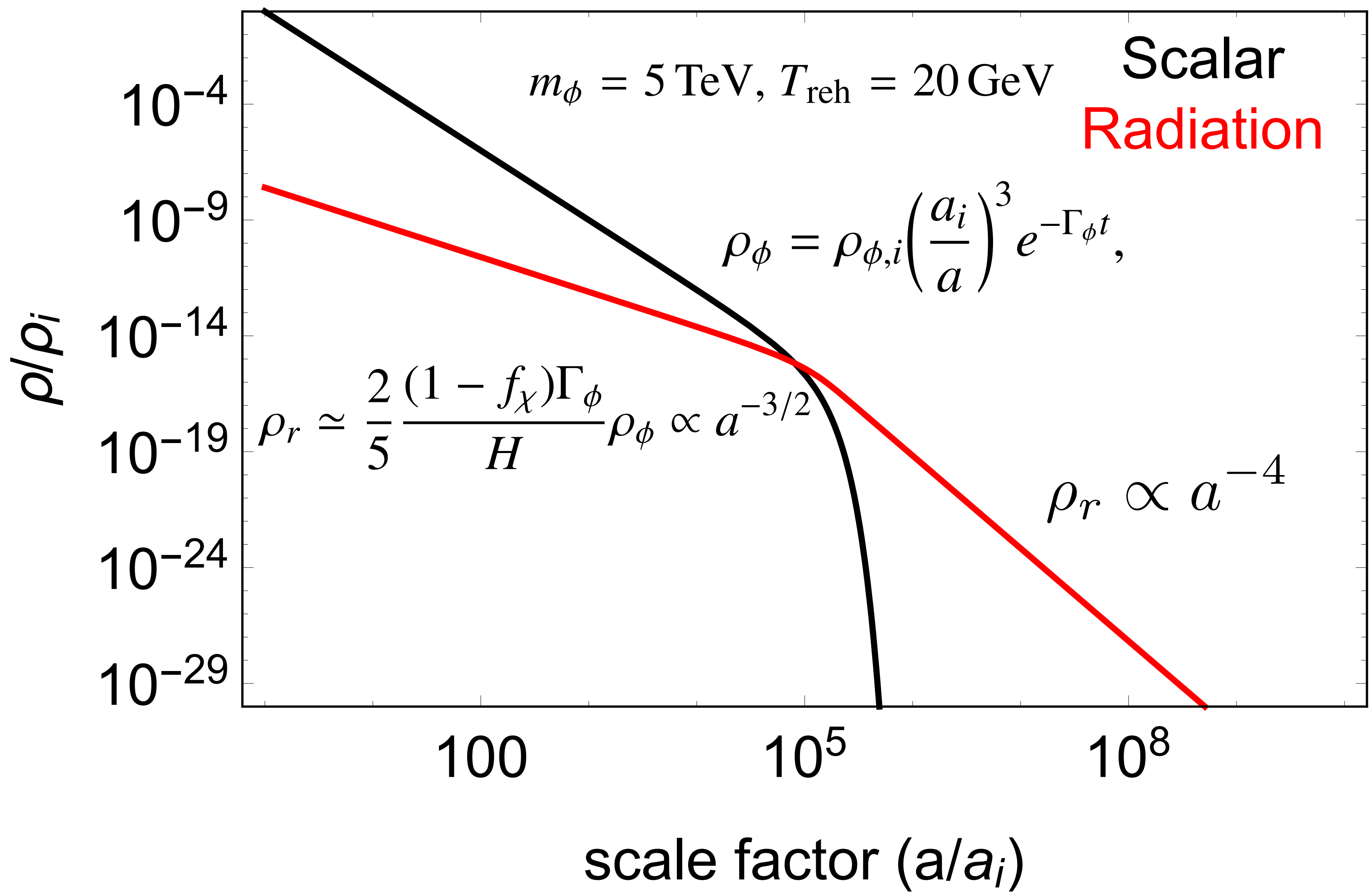
The Universe is dominated by heavy particles (early matter domination) and reheated (radiation domination) by the decay of them. It happens for:

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

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



Background Energy Density



Creation of Isocurvature Perturbation of WIMP DM

Creation of Isocurvature Perturbation of WIMP DM

After chemical decoupling and before reheating during scalar-domination:

Dark matter and radiation are still kinetically coupled: $\theta_m \approx \theta_r$.

$$\dot{\delta}_m \approx -\frac{\theta_r}{a},$$

$$\dot{\delta}_r \approx -\frac{4}{3}\frac{\theta_r}{a} + \frac{\Gamma_\phi \rho_\phi}{\rho_r}(\delta_\phi - \delta_r),$$

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

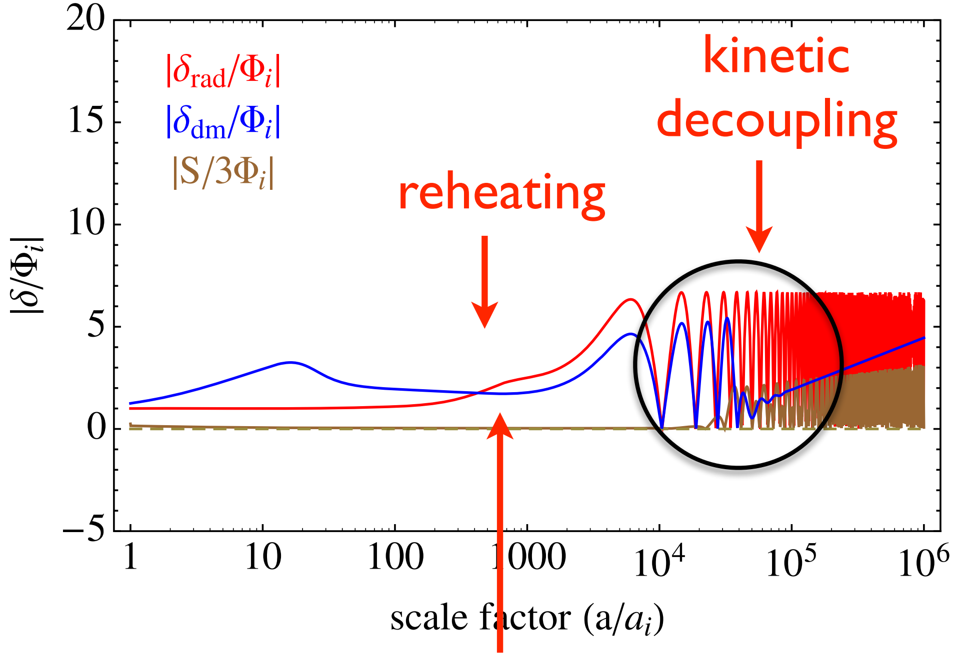
The difference in the number density creates the isocurvature perturbation between dark matter and radiation.

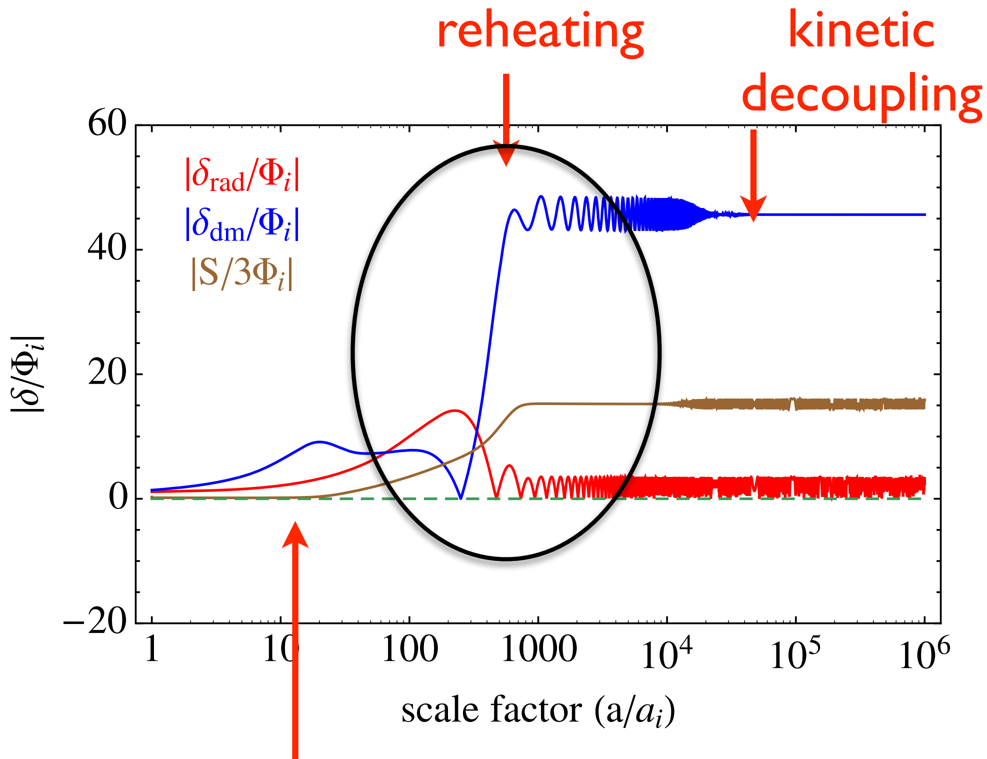
$$S(t_{\rm reh}) \approx -\frac{3}{4}\int_{t_i}^{t_{\rm reh}} dt \frac{\Gamma_\phi \rho_\phi \delta_\phi}{\rho_r} \approx \frac{5}{4}\Phi_i \left(\frac{k}{k_{\rm reh}}\right)^2.$$

[KYChoi, Gong, Shin 2015PRL]

Creation of Isocurvature Perturbation of WIMP DM

[KYChoi, Gong, Shin 2015]





Horizon entry after reheating

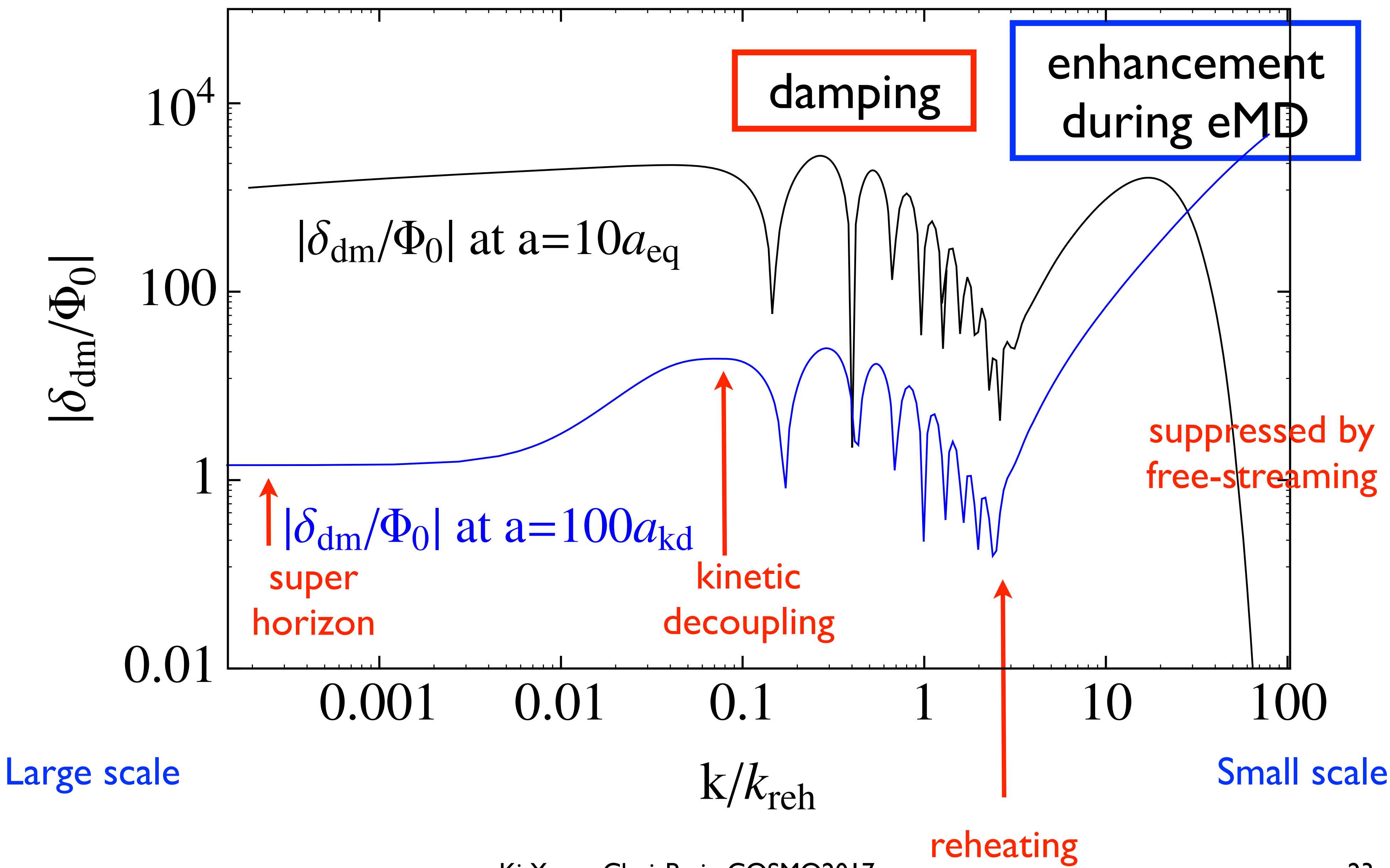
Damping erases the perturbations.

Horizon entry during early MD before reheating

Enhancement and No damping.

Damping and Enhancement of Density Perturbation

[KYChoi, Gong, Shin 2015]



The scale which enters during eMD, is not suppressed during the kinetic decoupling, and thus there exists smaller scale objects than the scale of kinetic decoupling.

Low-bound on reheating temperature with dark matter

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

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

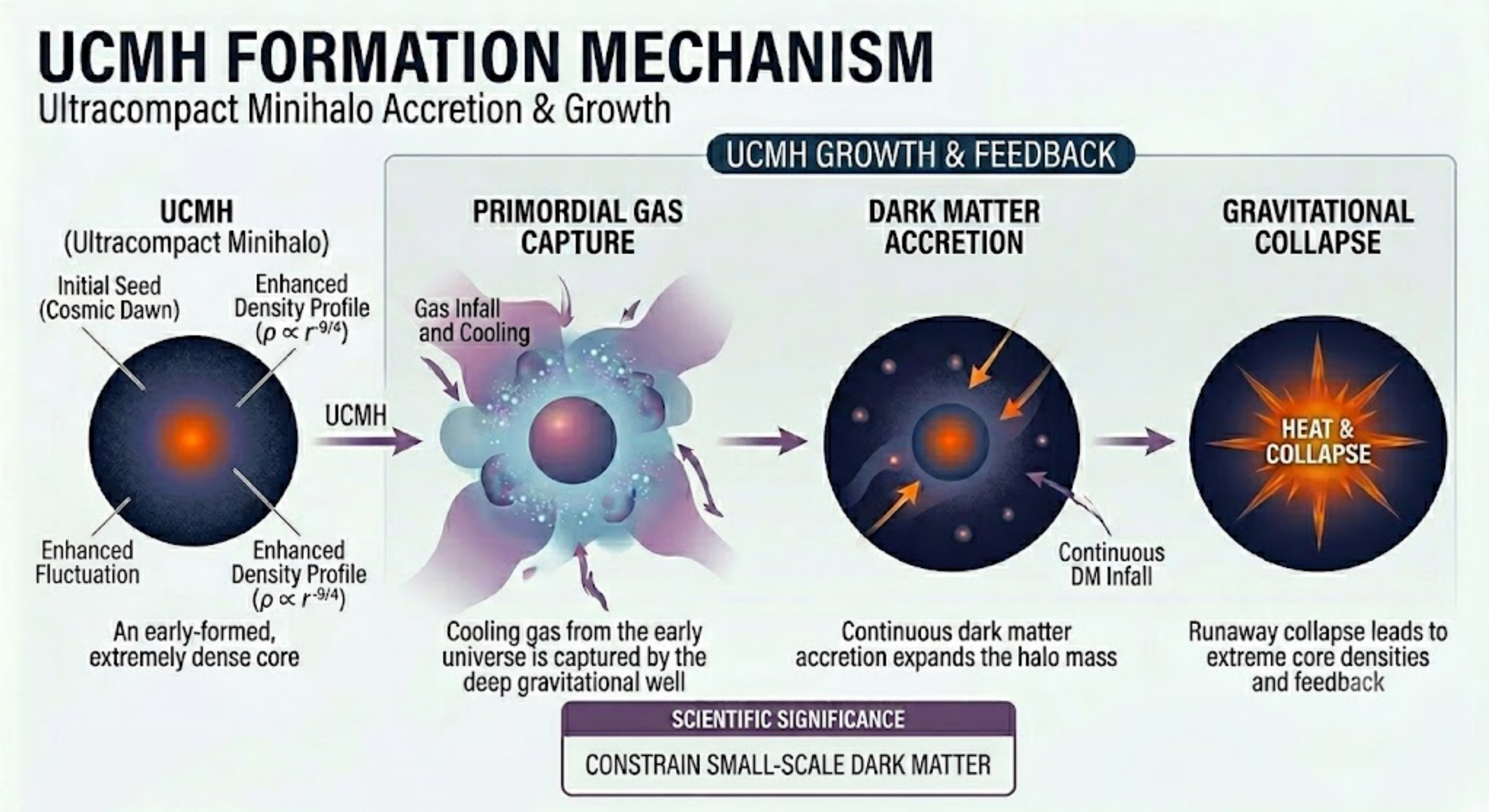
[Salas, Lattanzi, Mangano, Miele, Pastor, Pisanti, 2015]

New bound on low-reheating temperature

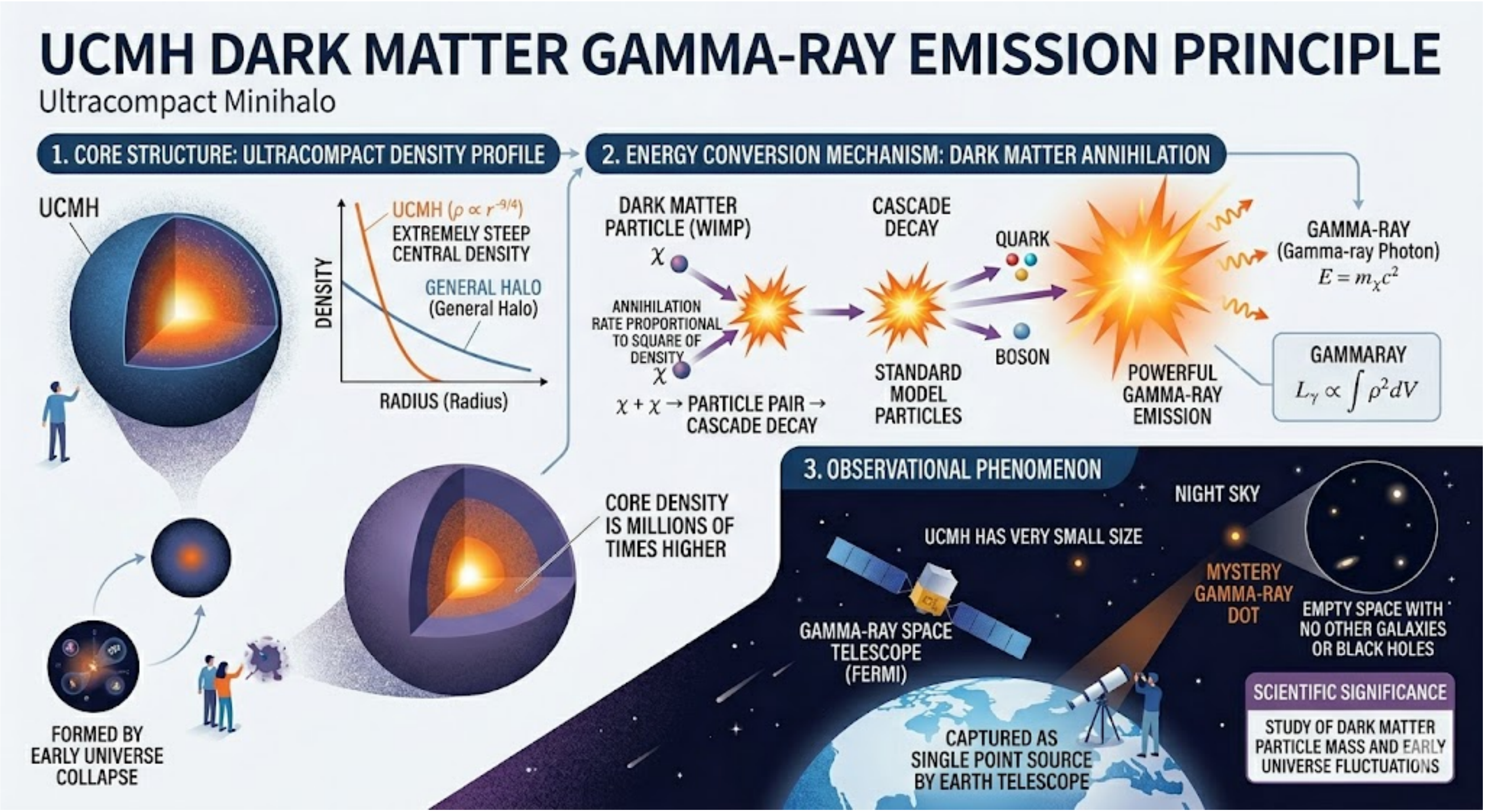
[KYChoi, Tomo Takahashi, PRD 2017]

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

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



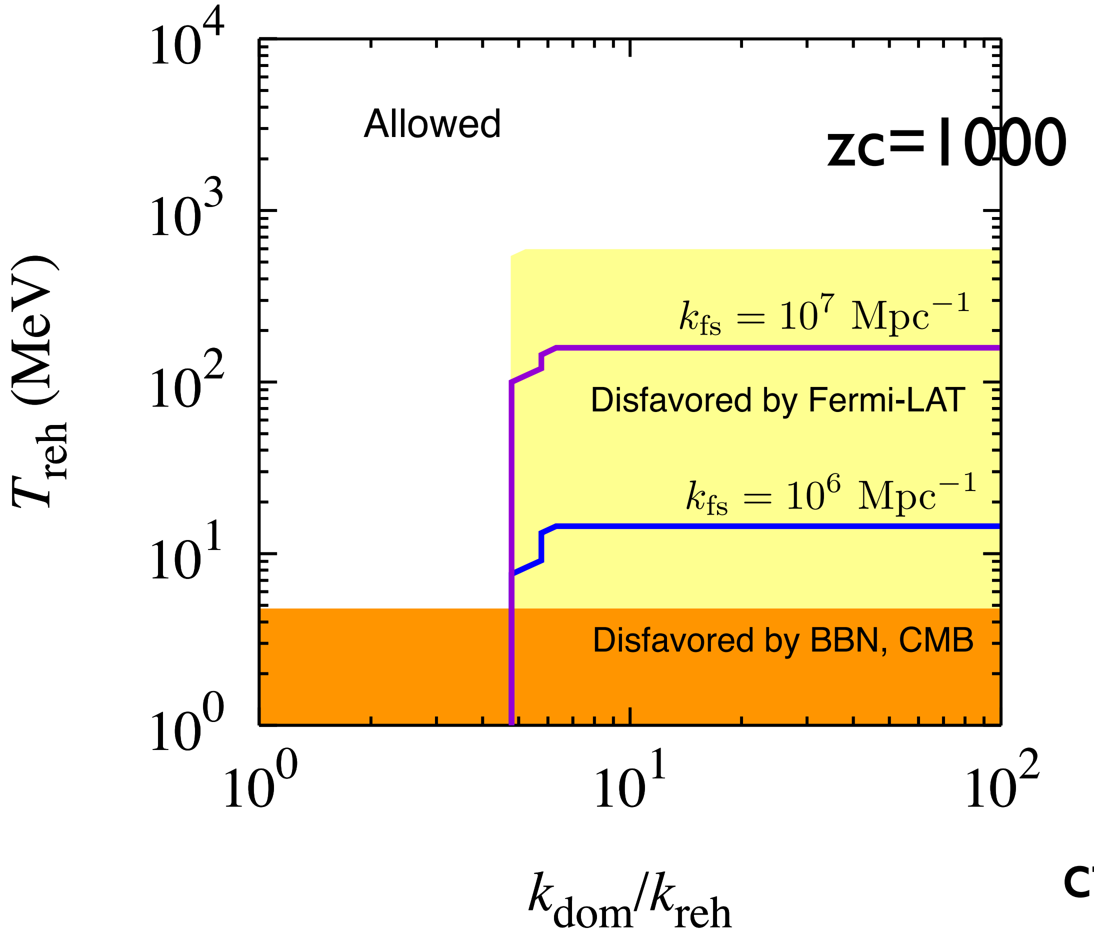
Density grows during eMD and becomes large enough to make UCMHs at later epoch, even with almost scale-invariant power spectrum.



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.

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

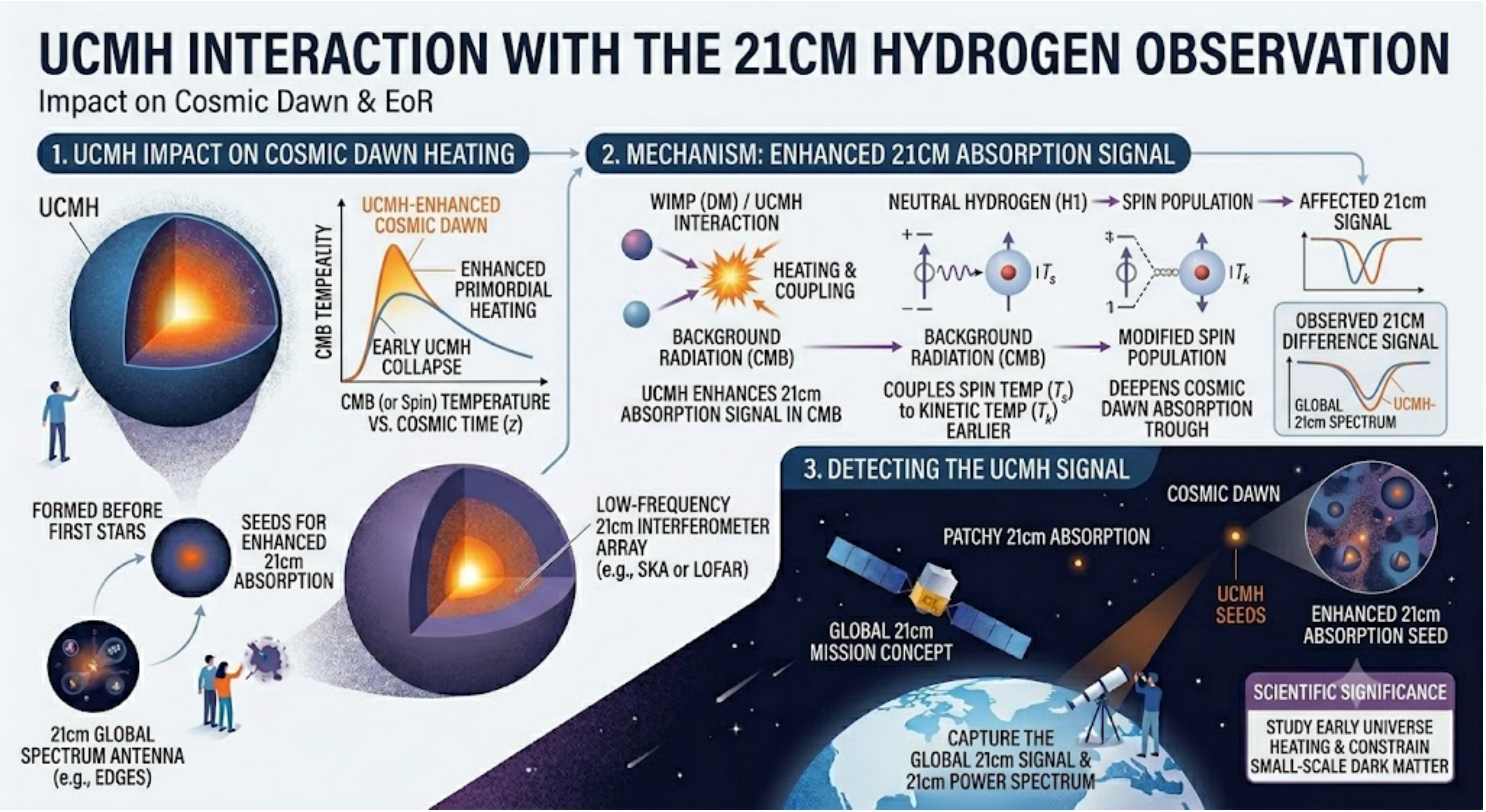
[KYChoi, Tomo Takahashi, 2017]

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

[Kwasaki, Kohri, Sugiyama, 1999, 2000]

[Salas et al 2015]

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



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

Early Matter Domination and 21cm

Early matter domination

→ Enhance matter power spectrum at small scales

→ Change of comoving DM halo density (UCMHs)

→ DM annihilation changes thermal history of IGM

→ Impact on the global 21cm observation

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

Energy release fromDM annihilation

DM annihilation in the halo releases energy per time per volume

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

changes thermal history of the Universe

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

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

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

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

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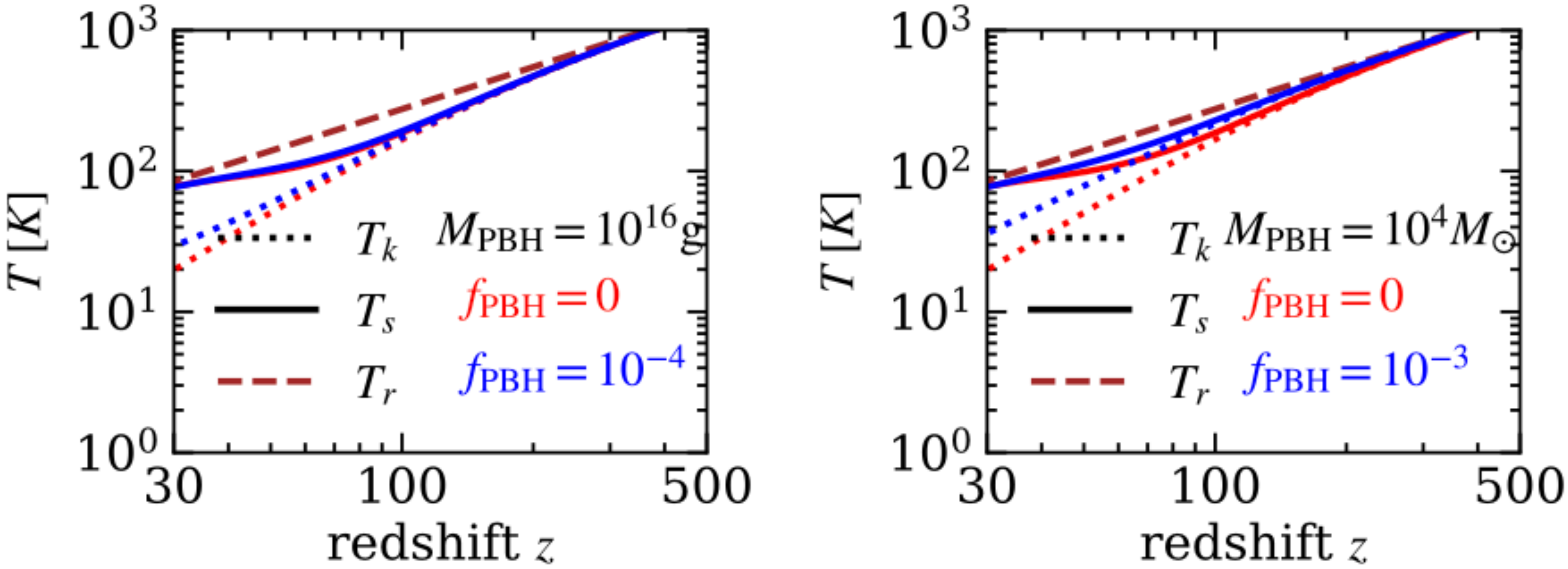
x_{HI} is the fraction of neutral hydrogen

T_R is the temperature of the background radiation,

Ki-Young Choi, Sungkyunkwan University, Korea

Impact of radiation from primordial black holes on the 21-cm angular-power spectrum in the dark ages

[Yupeng Yang, 2022]



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 physics of eDM

Thank You!