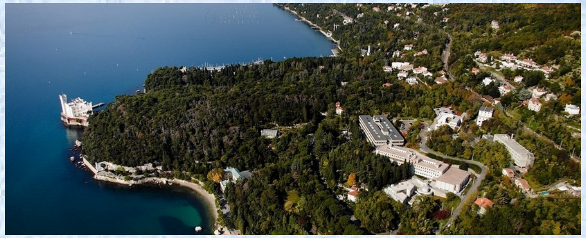

Cosmology 2023 in Miramare,

Aug 28 – Sep 2,

Trieste, Italy

Global signal in the redshifted 21-cm line from Dark Ages as a cosmology test

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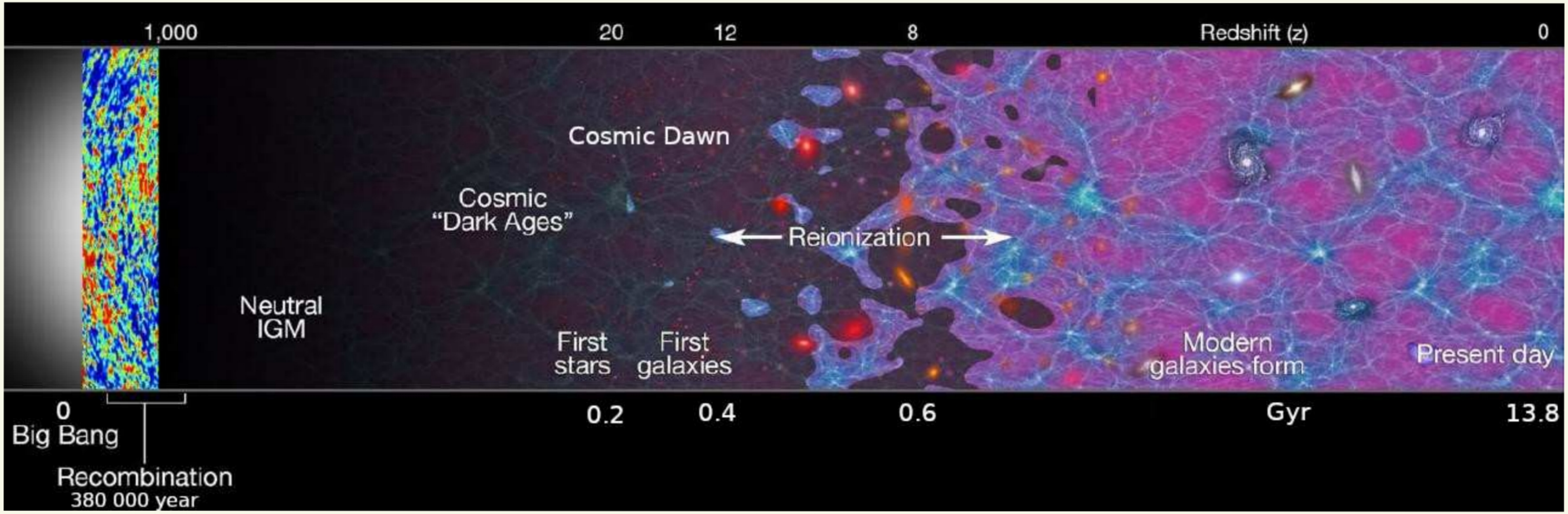
[1]Ivan Franko National University of Lviv, Lviv, Ukraine

[2]International Center of Future Science, Jilin University, Changchun, China

Dark Ages: physical conditions



Robertson et al., Nature, 468, 49 (2010)

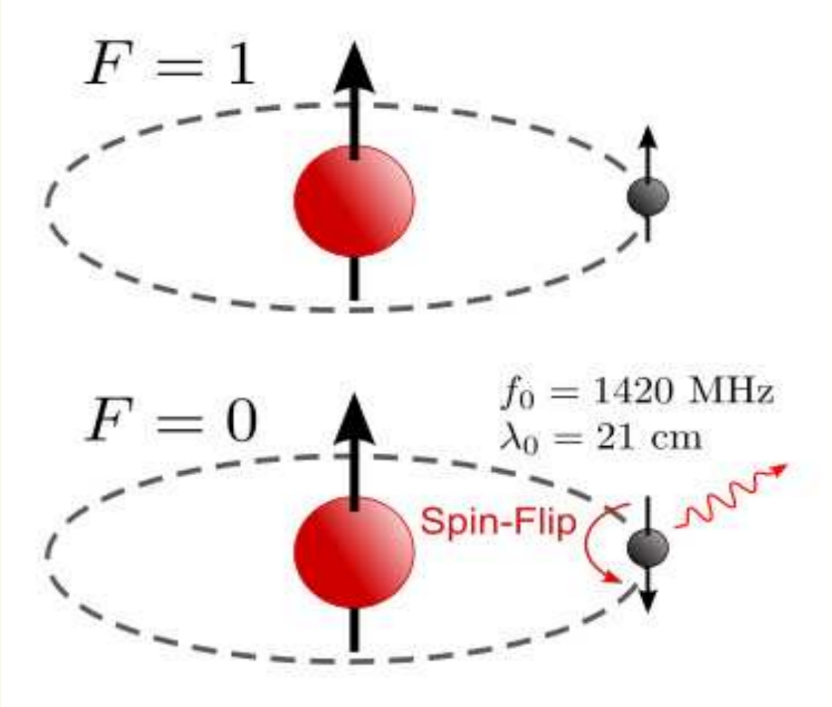
Physical conditions at $z = [1000 - 6]$:

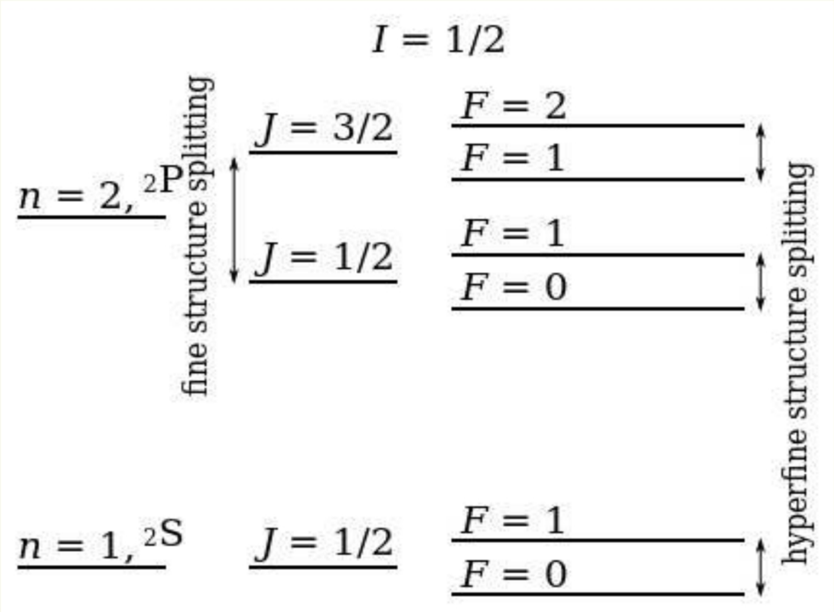
$T_{cmb} = [2730 - 20]$ K, $\quad T_m = [2730 - 2.0]$ K,

$n_H = [2 \cdot 10^2 - 9 \cdot 10^{-5}]$ cm^{-3}, $\quad n_\gamma = 2 \cdot 10^9 n_b$,

$J_{fl}(\nu, z) > 0$ at $z < 50$.

Hydrogen atom lines: hyperfine 21-cm



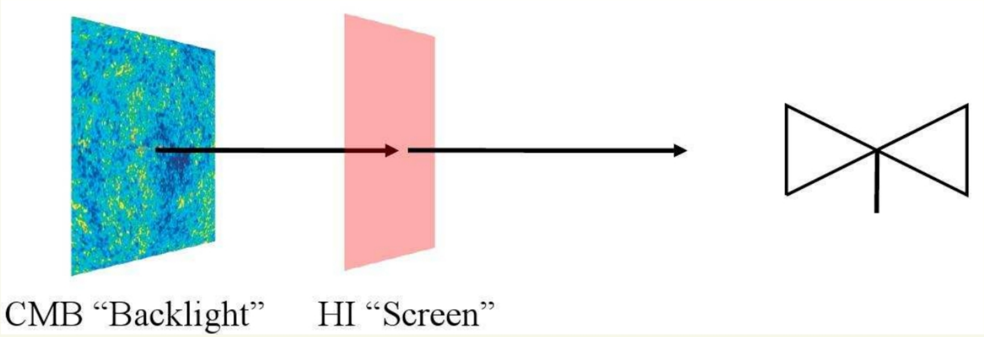


Theoretically predicted by H. van de Hulst in 1945.

It was first observed in 1951 by Evan & Purcel (Harvard University) and Muller & Oort (Leyden Radio Observatory).

The possibility of 21-cm line emission or absorption by neutral H at high redshift has been considered by Hogan & Rees (1979), Scott & Rees (1990), Subramanian & Padmanabhan (1993), Kumar, Padmanabhan & Subramanian (1995), Bagla, Nath & Padmanabhan (1997), Madau, Meiksen & Rees (1997), Shaver et al. (1999), Tozzi et al. (2000), Zaldariaga et al. (2004):

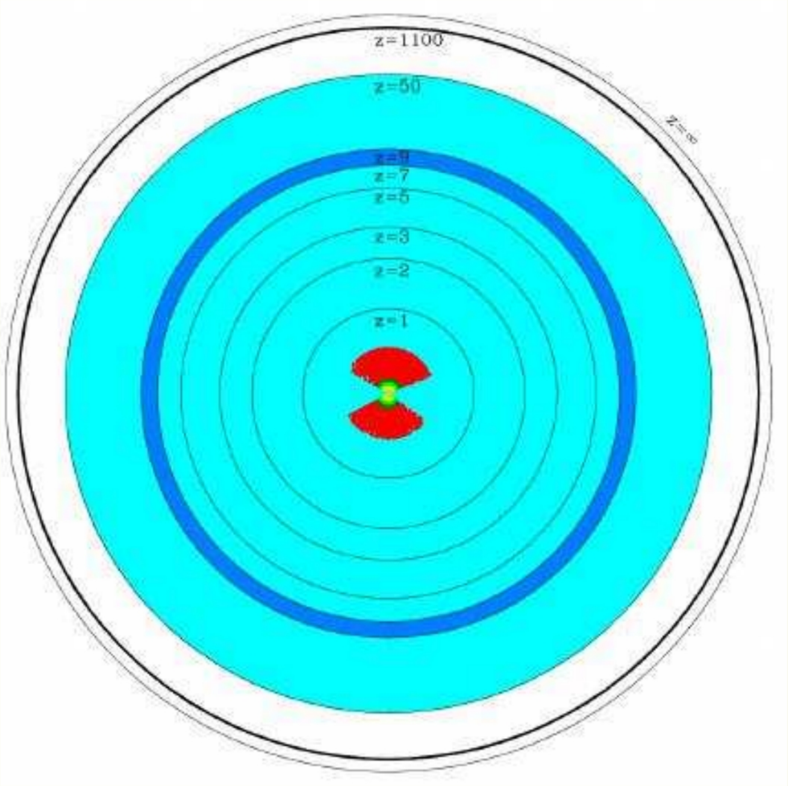
H 21 cm line from the Dark Ages

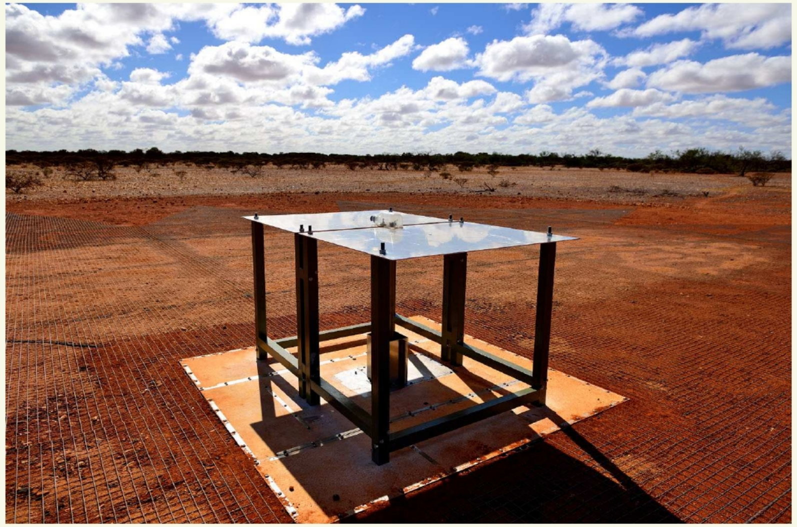


z=1100 z=100...10 z=0

The line is 21 cm in its own frame of reference: $\lambda_0 = 21\,\text{см}$,
$\nu_0 = 1420\,\text{MHz}$,
$T_* \equiv h_P \nu_0 / k_B = 0.068\,\text{K}$;

The 21 cm line in the Earth observer's frame of reference:
$\lambda_z = \lambda_0(1+z), \quad \nu_z = \nu_0/(1+z)$;



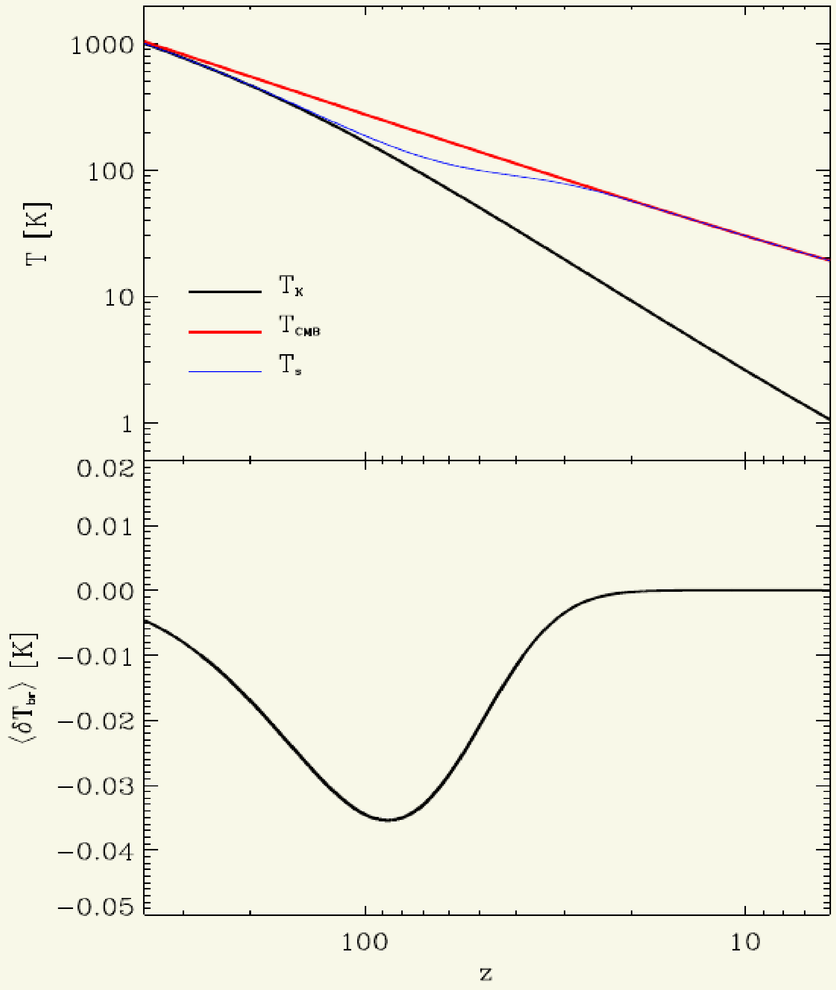


Absorption line 21 cm from the Dark Ages

$$-(1+z)H\frac{dx_{HII}}{dz} = R_{HI}x_{HI} + C_i n_i x_{HI} - \alpha_{HII}x_{HII} + \\ + \left[(1+z)H\frac{dx_{HII}}{dz}\right]_{nSM},$$

$$-\frac{3}{2}n_{tot}k_B(1+z)H(z)\frac{dT_b}{dz} = \Gamma_{C_{cmb}} - \Lambda_{ad} + \\ + \Gamma_{nSM} - \Lambda_{nSM},$$

$$H = H_0\sqrt{\Omega_r(1+z)^4 + \Omega_m(1+z)^3 + \Omega_\Lambda},$$



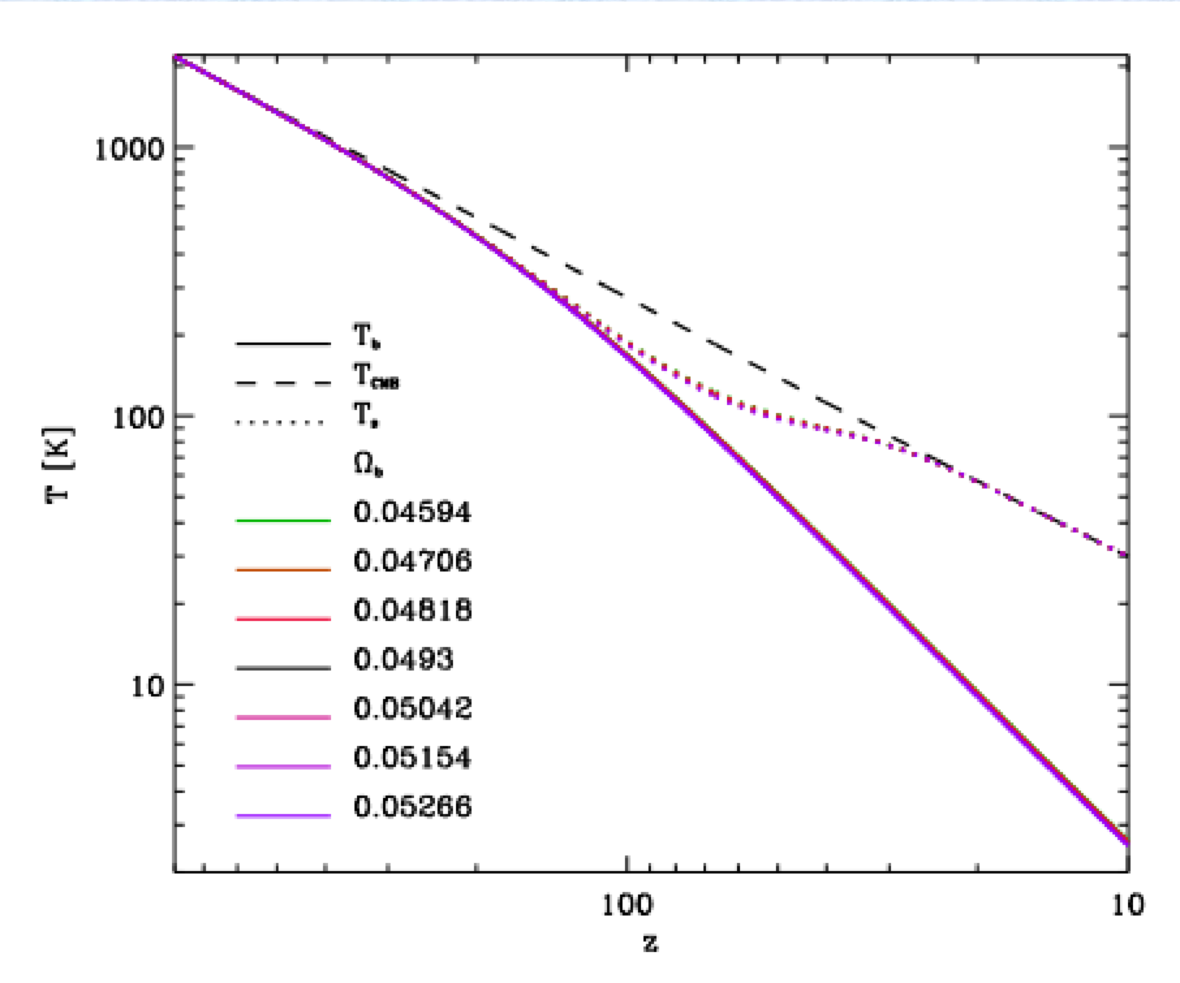
$$T_s \equiv \frac{k_B}{h_P\nu_{10}} \ln \frac{g_1}{g_0}\frac{n_0}{n_1},$$

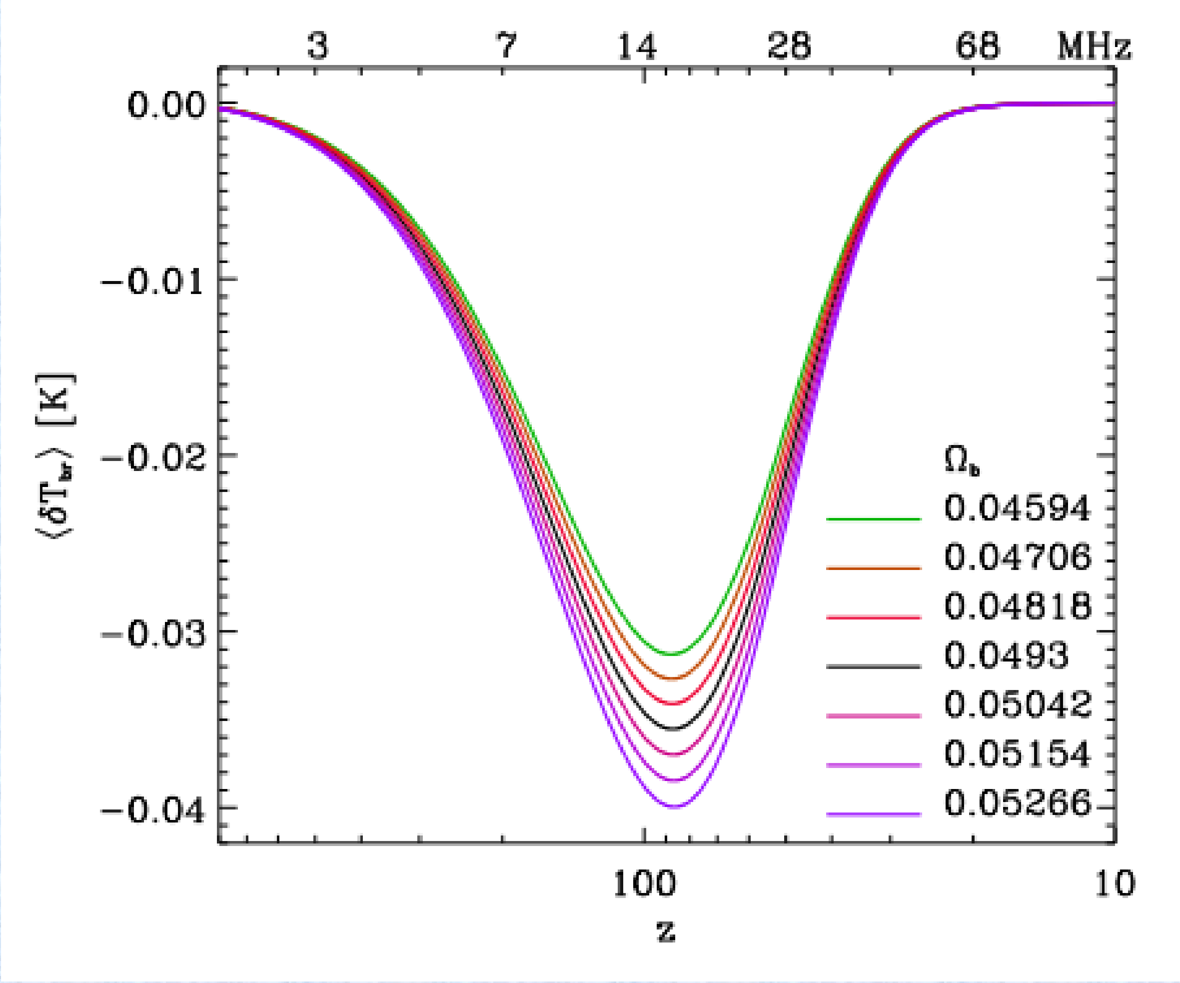
$$T_s = T_m(z)\frac{A_{10}T_{cmb}(z) + T_* C_{10}}{A_{10}T_m(z) + T_* C_{10}} \text{ K}$$

$$\delta T_{br}(z) = 0.023(1+\delta_b)x_{HI}\left[\left(\frac{0.15}{\Omega_m}\right)\left(\frac{1+z}{10}\right)\right]^{\frac{1}{2}}\left(\frac{\Omega_b h}{0.02}\right)\left[1 - \frac{T_{cmb}(z)}{T_s(z)}\right] \text{ K}$$

Madau et al. 1997, Zaldarriaga et al. 2004, Furlanetto et al. 2006, Pritchard & Loeb 2012

Standard cosmology: dependence on Ω_b

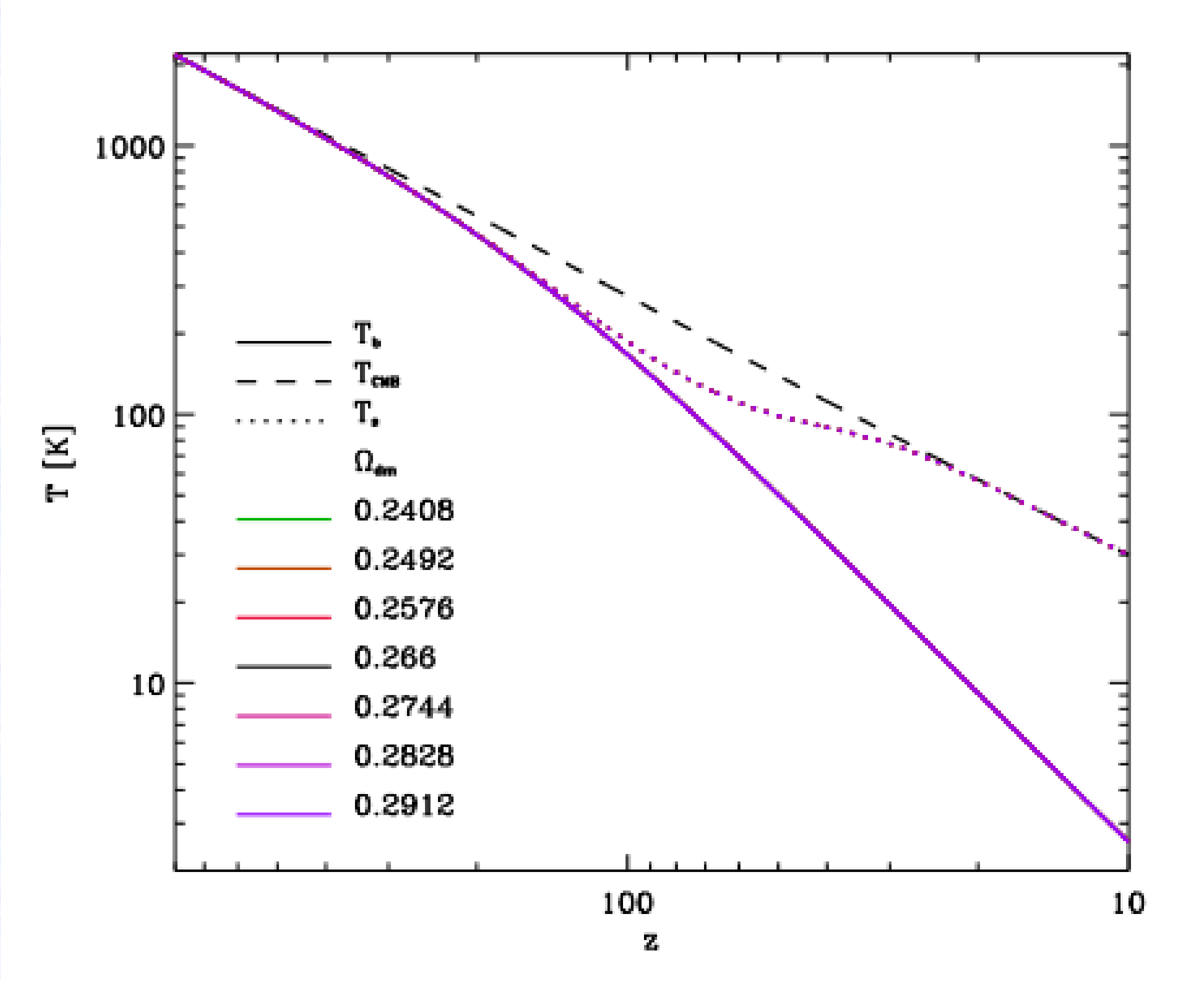


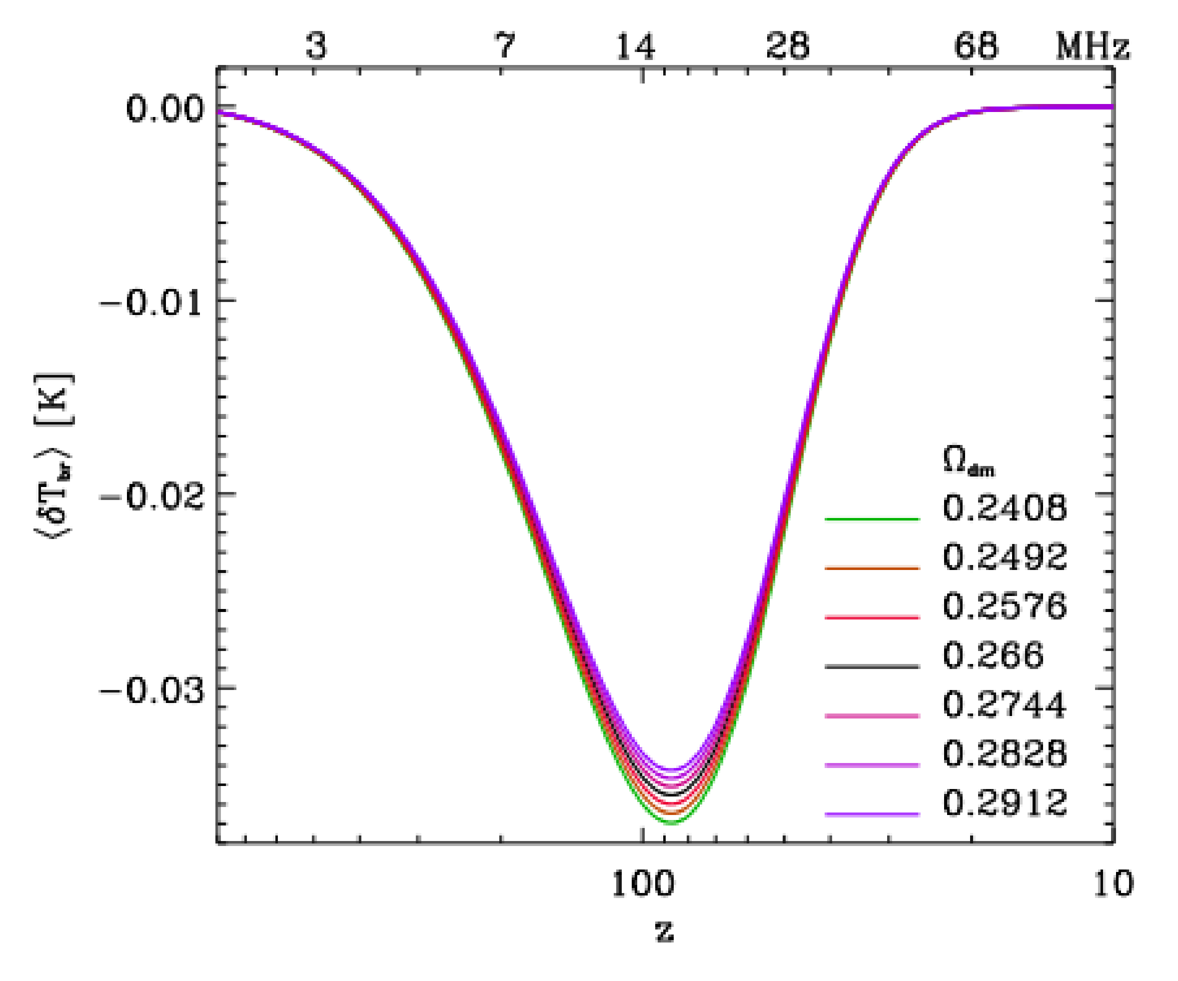


$$\Omega_b + \Omega_{dm} + \Omega_\Lambda + \Omega_K = 1, \qquad \Delta\Omega_b = -\Delta\Omega_\Lambda$$

Ω_b=0.0493, Ω_{dm}=0.266, Ω_Λ=0.6847, Ω_K=0, H_0=67.36 km/s·Mpc (*Planck collaboration, 2020*)

Standard cosmology: dependence on Ω_{dm}

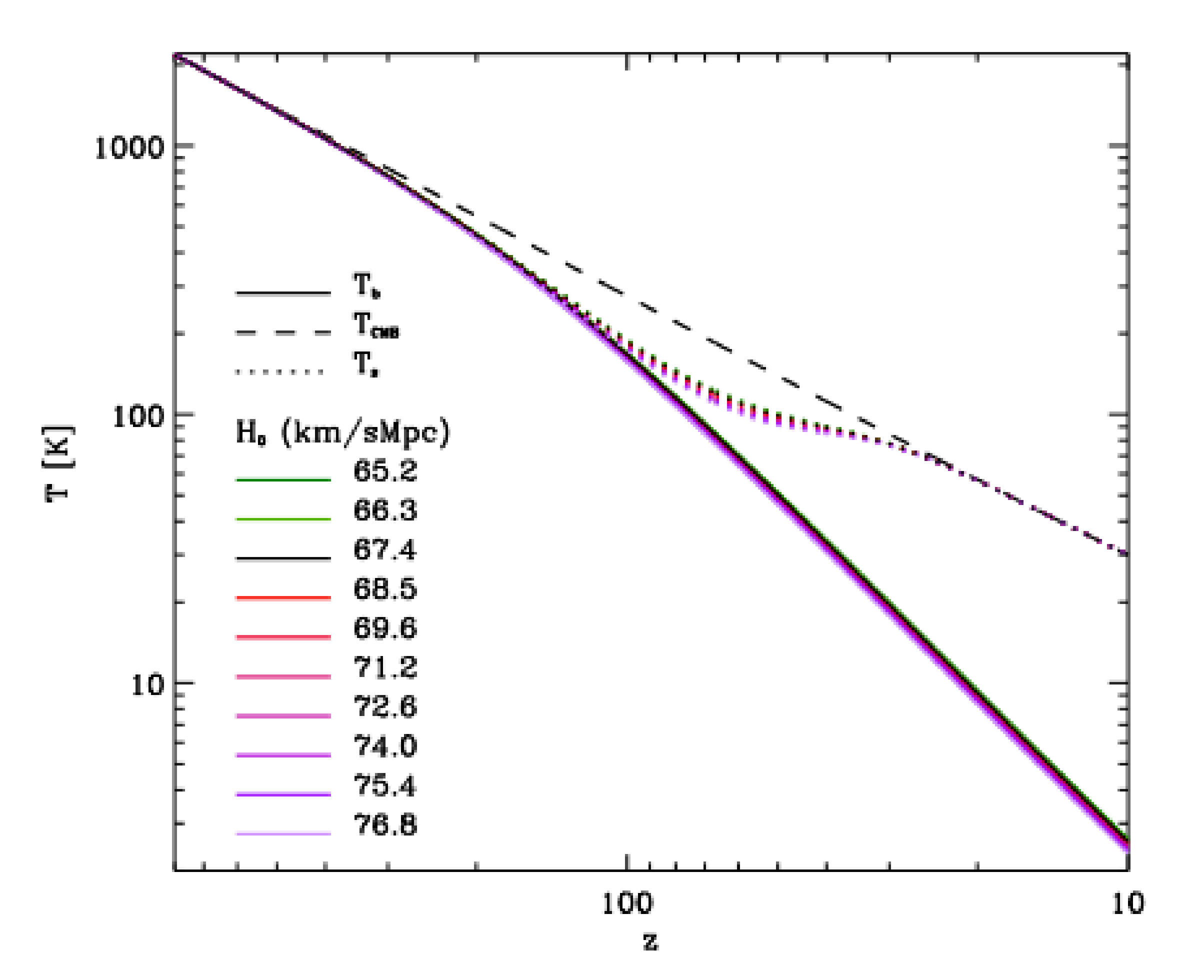


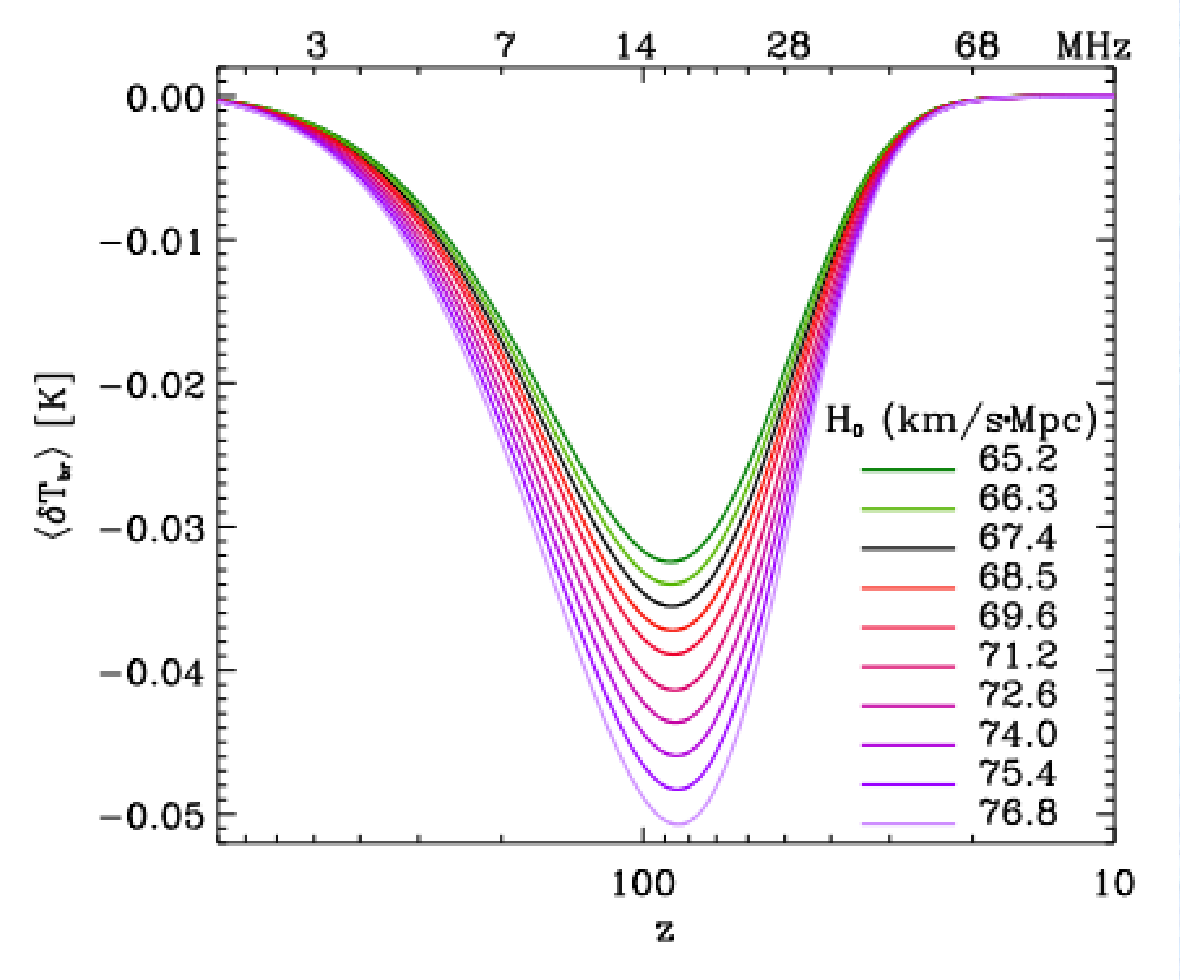


$$\Omega_b + \Omega_{dm} + \Omega_\Lambda + \Omega_K = 1, \qquad \Delta\Omega_{dm} = -\Delta\Omega_\Lambda$$

Ω_b=0.0493, Ω_{dm}=0.266, Ω_Λ=0.6847, Ω_K=0, H_0=67.36 km/s·Mpc (*Planck collaboration, 2020*)

Standard cosmology: dependence on H_0



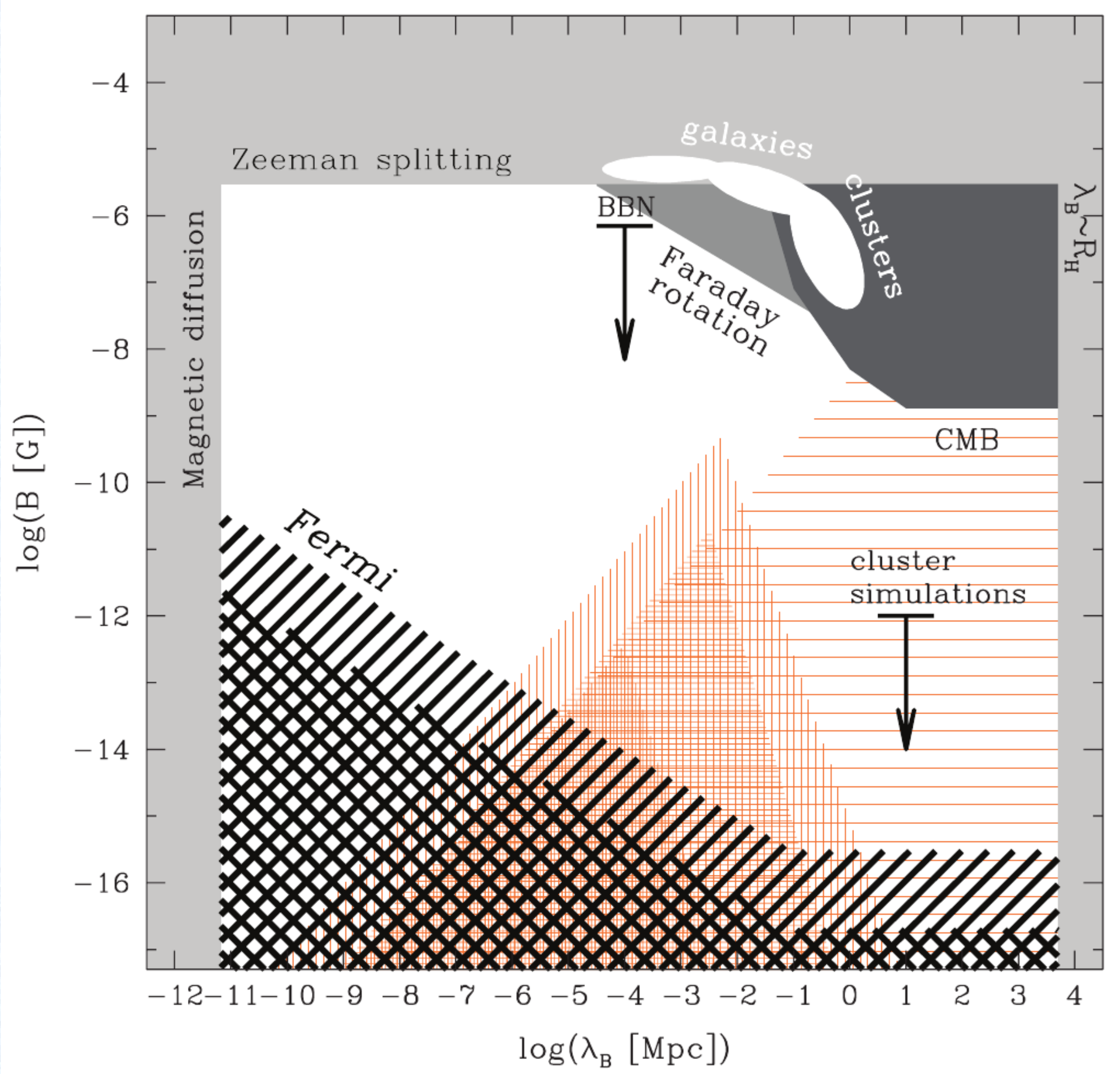


Ω_b=0.0493, Ω_{dm}=0.266, Ω_Λ=0.6847, Ω_K=0, H_0=67.36 km/s·Mpc (*Planck collaboration, 2020*)

Non-standard cosmology: primordial stochastic magnetic field

Heating of baryonic gas caused by

- **decaying magnetic turbulence,**
- **ambipolar diffusion**



Neronov A., Vovk I., Science, 328, p. 73-75.

Heating due to decaying turbulence of the primordial magnetic field (Sethi & Subramanian 2005; Chluba et al. 2015):

$$\Gamma_{mfdt} = 1.5\rho_{mf}H(z)[f_D(z)]^{n_B+3}\frac{ma^m}{(a+1.5\ln((1+z_{cr})/(1+z)))^{m+1}} \quad \text{for} \quad z<z_{cr},$$
$$\Gamma_{mfdt} = 1.5\rho_{mf}H(z)\frac{m}{a}[f_D(z)]^{n_B+3}\exp\left\{-\frac{(z-z_{cr})^2}{5000}\right\}\left(\frac{1+z_{cr}}{1+z}\right)^4 \quad \text{for} \quad z\geq z_{cr}, \tag{42}$$

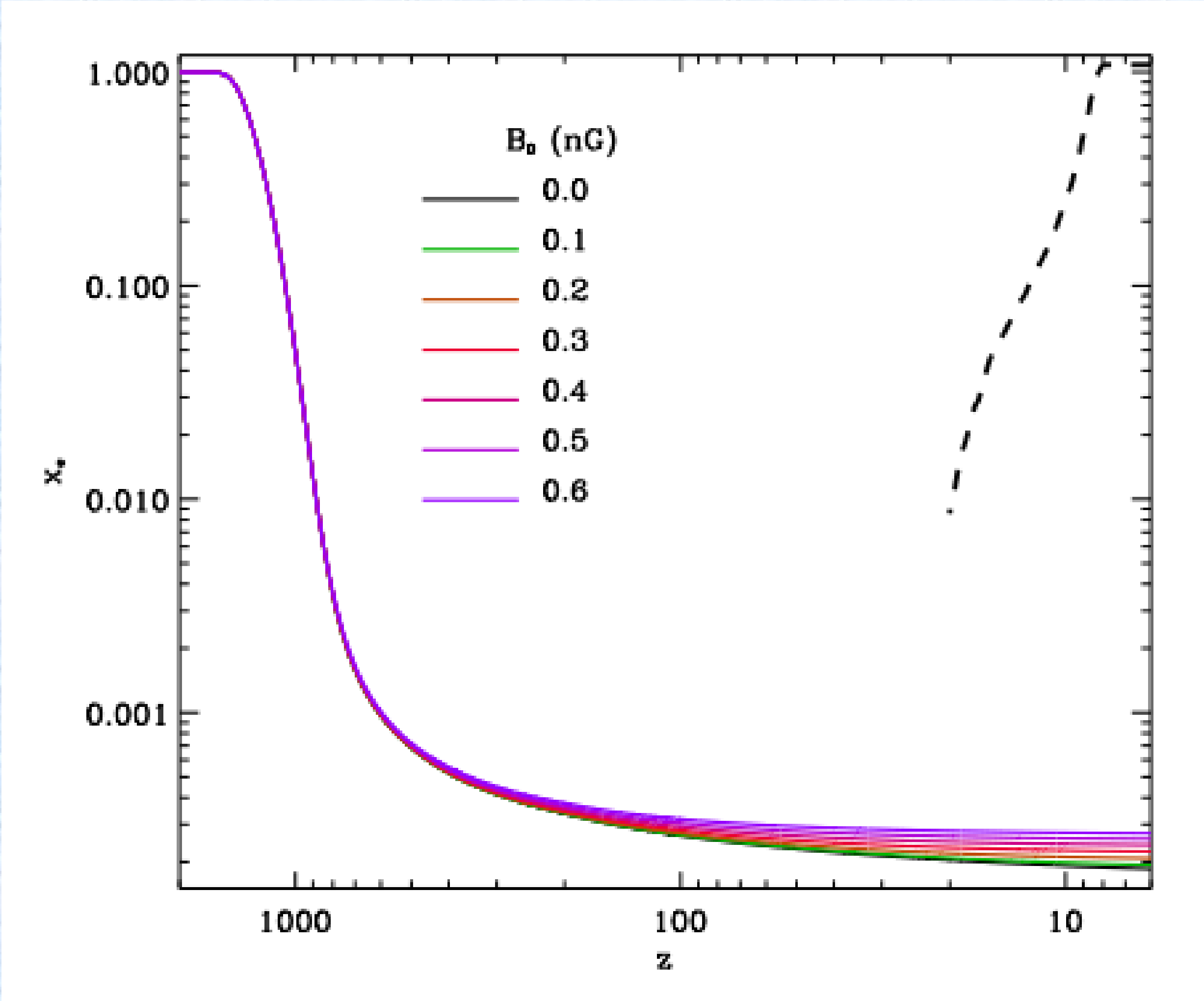
where $z_{cr}=1088$, $\rho_{mf}=3.98\cdot10^{-21}\,(B_0/\mathrm{nG})^2\,(1+z)^4$ J·m^{-3}, $n_B=-2.9$, $a=\ln(1+t_\mathrm{d}/t_\mathrm{rec})$, $m\equiv 2(n_B+3)/(n_B+5)$, $t_\mathrm{d}/t_\mathrm{rec}=14.8/(B_0k_D)$, $k_D=(2.89\cdot10^4h)^{1/(n_B+5)}B_\lambda^{-2/(n_B+5)}k_\lambda^{(n_B+3)/(n_B+5)}$ Mpc^{-1}, $\lambda=1$ Mpc, $B_\lambda=B_{1\,\mathrm{Mpc}}=B_0$, $k_\lambda=k_{1\,\mathrm{Mpc}}=2\pi$ Mpc^{-1}. The factor $f_D(z)^{n_B+3}$ describes the energy loss by the primordial magnetic field (see Minoda et al. (2019)), which we approximate as $[f_D(z)]^{n_B+3}\simeq 0.6897525+0.2944149\cdot10^{-3}z-0.3805730\cdot10^{-6}z^2+0.2259742\cdot10^{-9}z^3+0.6354026\cdot10^{-13}z^4$ for $z<1178$, fixed values of n_B and k_D (for $z\geq1178$ $f^{n_B+3}(z)\equiv1$).

Heating due to ambipolar diffusion caused by the primordial magnetic field (Chluba et al. 2015; Minoda et al. 2019):

$$\Gamma_{mfad}=\frac{1-x_{HII}}{g(T_b)x_{HII}}[f_D(z)]^{2n_B+8}\left[\frac{(1+z)k_D}{3.086\cdot10^{22}}\frac{\rho_{mf}}{\rho_b}\right]^2 f_L, \tag{43}$$

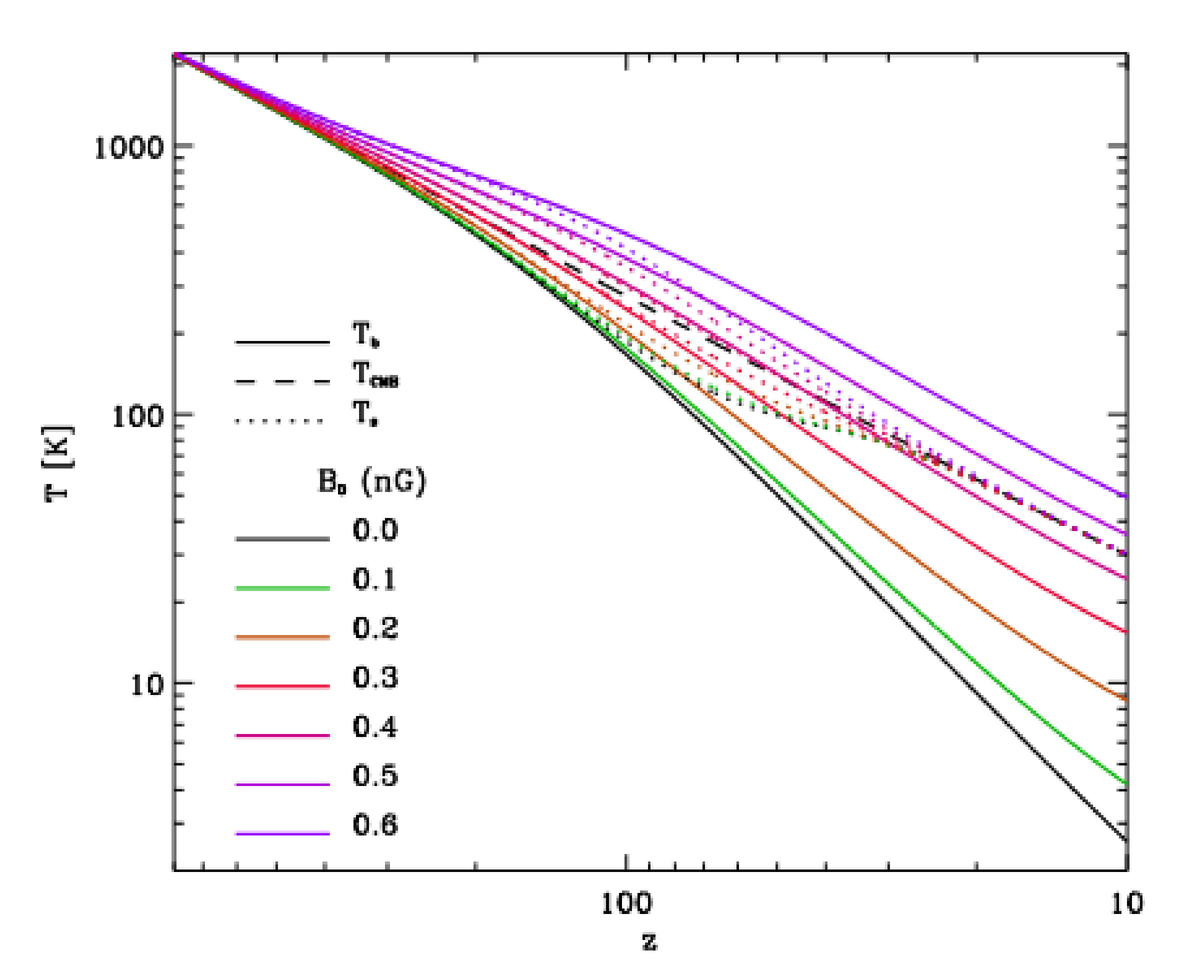
where $x_{HII}=n_{HII}/n_H$, $f_L=0.8313(n_B+3)^{1.105}(1.0-0.0102(n_B+3))$, $g(T_b)=1.95\cdot10^{11}T_b^{0.375}$ m^3/s/kg, $\rho_b=\rho_{cr}^{(0)}\Omega_b(1+z)^3$, $k_D=286.91(B_0/\mathrm{nG})^{-1}$ Mpc^{-1}.

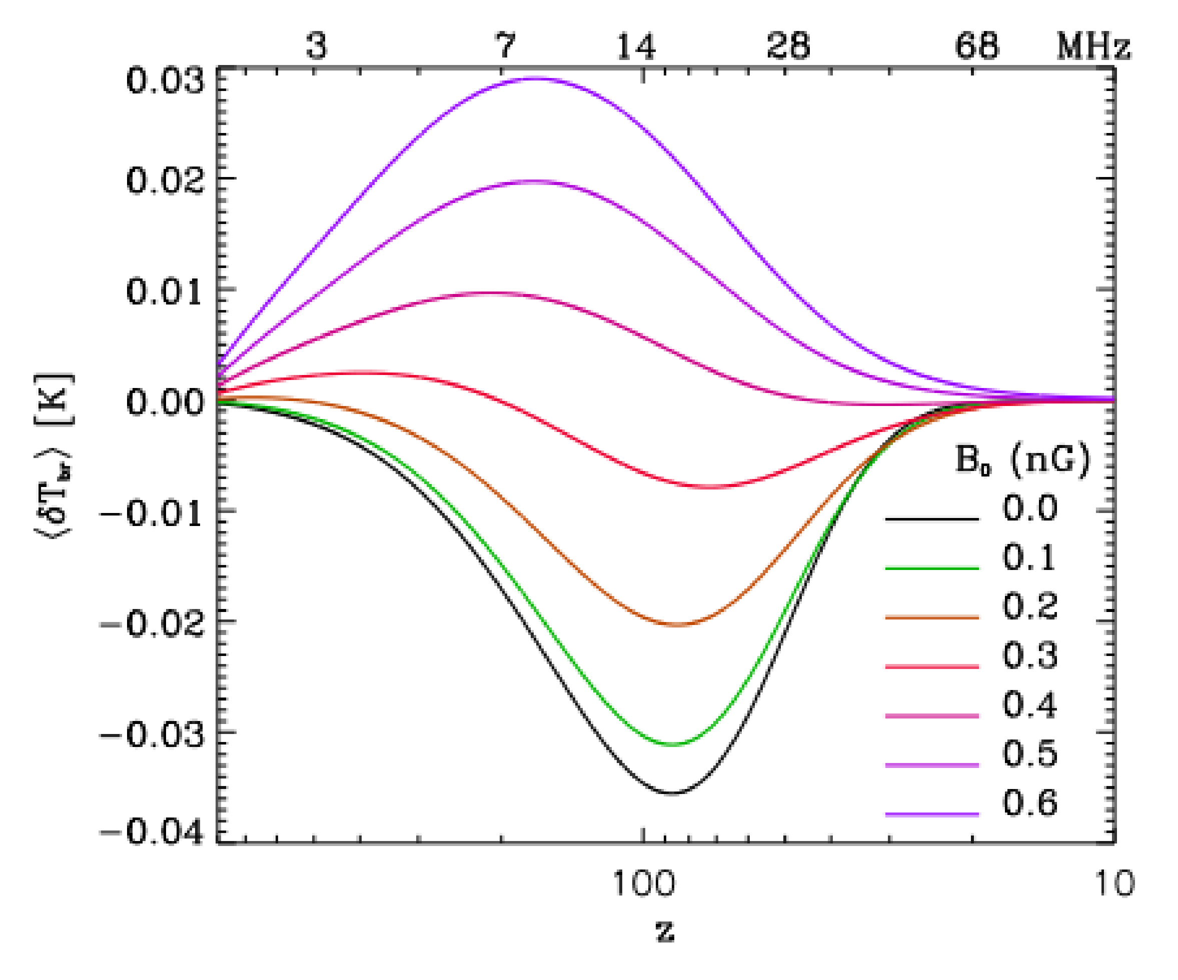
Non-standard cosmology: primordial magnetic field, ionization



SM: Ω_b=0.0493, Ω_{dm}=0.266, Ω_Λ=0.6847, Ω_K=0, H_0=67.36 km/s·Mpc (***Planck collaboration, 2020***)

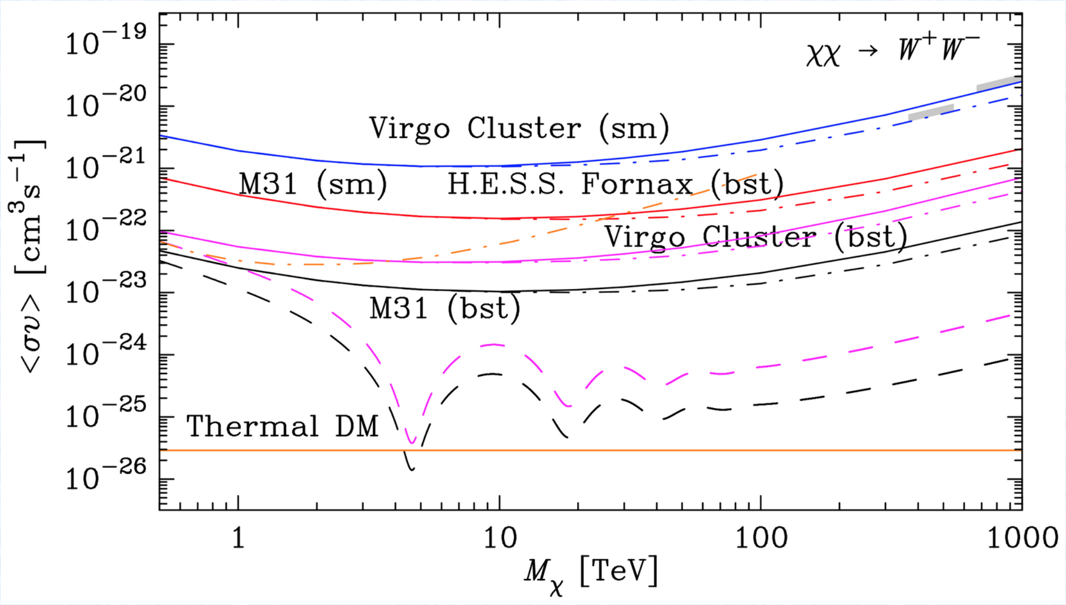
Non-standard cosmology: primordial magnetic field



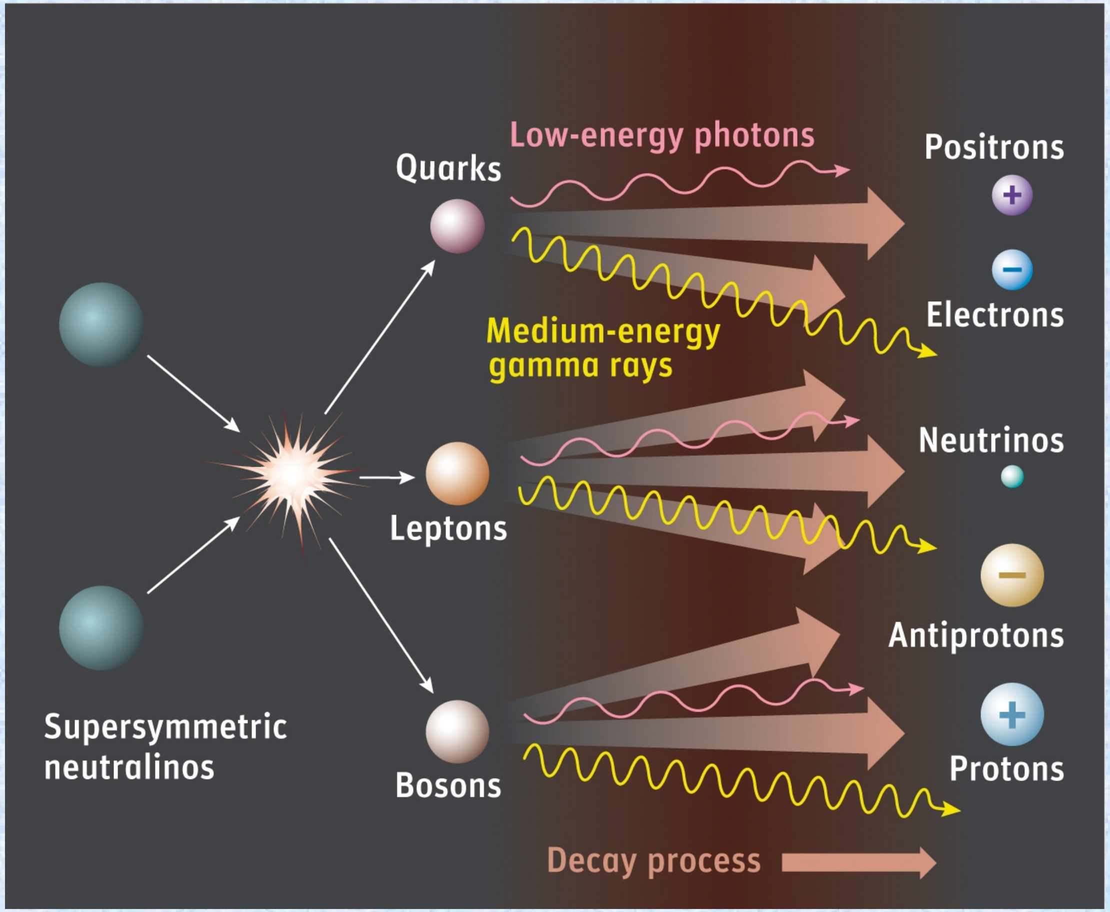


SM: Ω_b=0.0493, Ω_{dm}=0.266, Ω_Λ=0.6847, Ω_K=0, H_0=67.36 km/s·Mpc (***Planck collaboration, 2020***)

Non-standard cosmology: self-annihilating dark matter



Abeysekara et al. [HAWC Collaboration]. PRD, 90, 122002 (2014)



Marcus Woo, Fermi Gamma-ray Space Telescope

Energy deposit into

- heating of baryonic gas,
- ionization of hydrogen and helium,
- excitation of atoms and molecules

Non-standard cosmology: self-annihilation dark matter, ionization

The heating function of baryonic matter and the rate of ionization of hydrogen and helium atoms due to self-annihilation of dark matter particles (Chluba 2010):

$$\Gamma_{dman} = 1.6 \cdot 10^{-12} g_h f_{dman} \varepsilon_0 n_H (1+z)^3 \quad \mathrm{erg/cm^3 s},$$

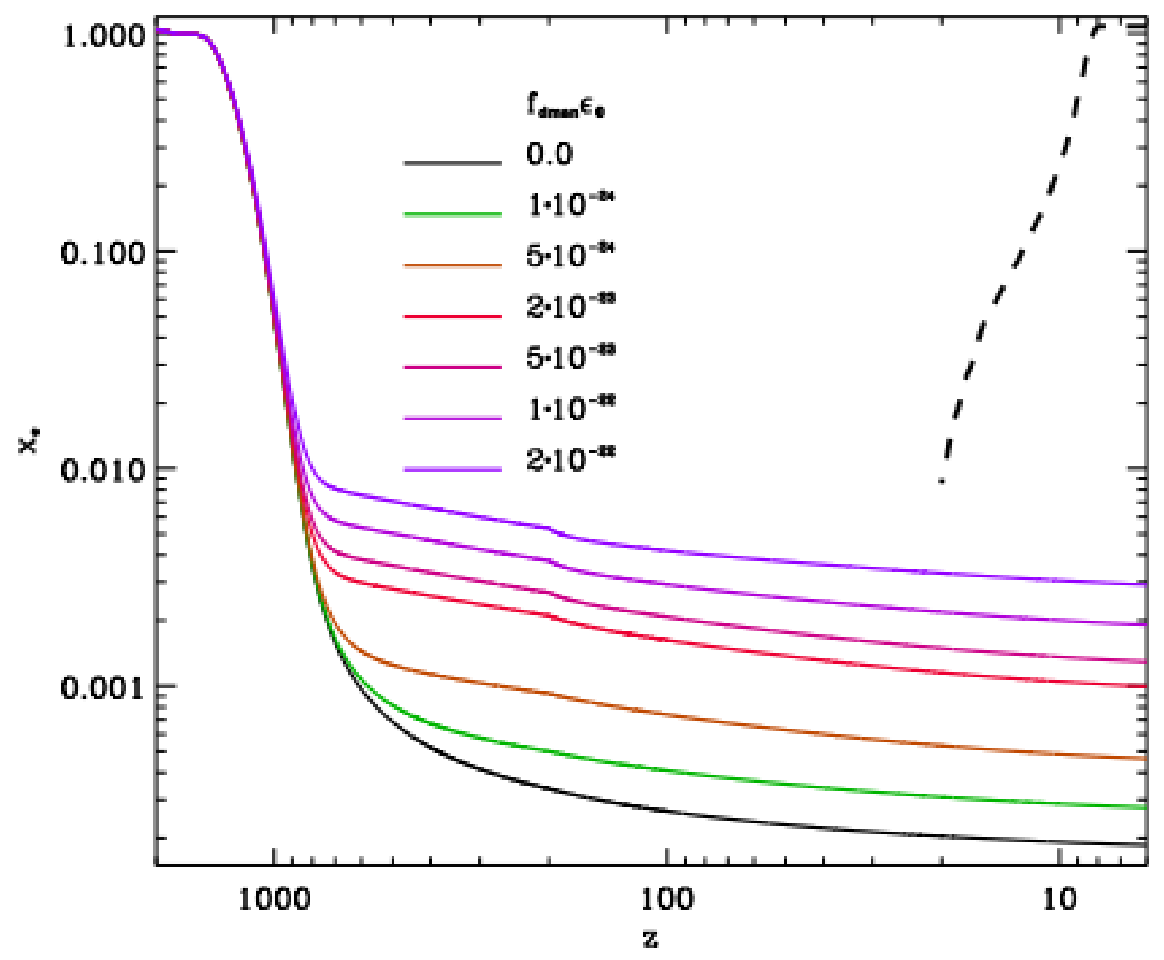
$$\frac{dx_{HI}}{dt} = -7.35 \cdot 10^{-2} g_{ion}^{(HI)} \frac{f_{dman} \varepsilon_0 n_H}{n_{HI}(1+f_{He})} (1+z)^3,$$

$$\frac{dx_{HeI}}{dt} = 4.065 \cdot 10^{-2} g_{ion}^{(HeI)} \frac{f_{dman} \varepsilon_0 n_H f_{He}}{n_{HeI}(1+f_{He})} (1+z)^3.$$

Here

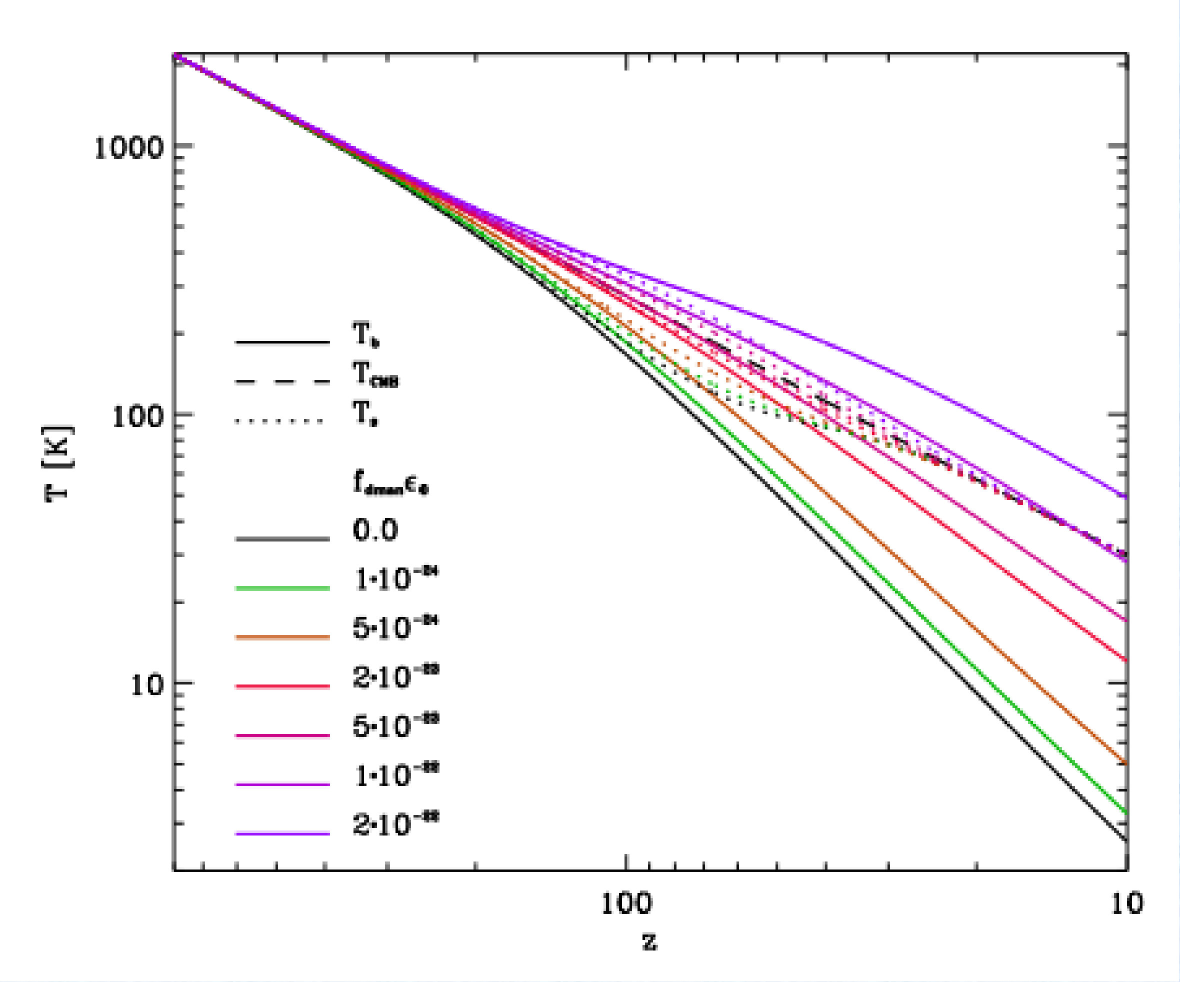
$$\varepsilon_0 = 5 \cdot 10^{-25} \left[\frac{100\mathrm{GeV}}{M_{dm}}\right] \left[\frac{\Omega_{dm} h^2}{0.13}\right]^2 \left[\frac{\langle \sigma v \rangle}{10^{-26} \mathrm{cm^2/s}}\right]$$

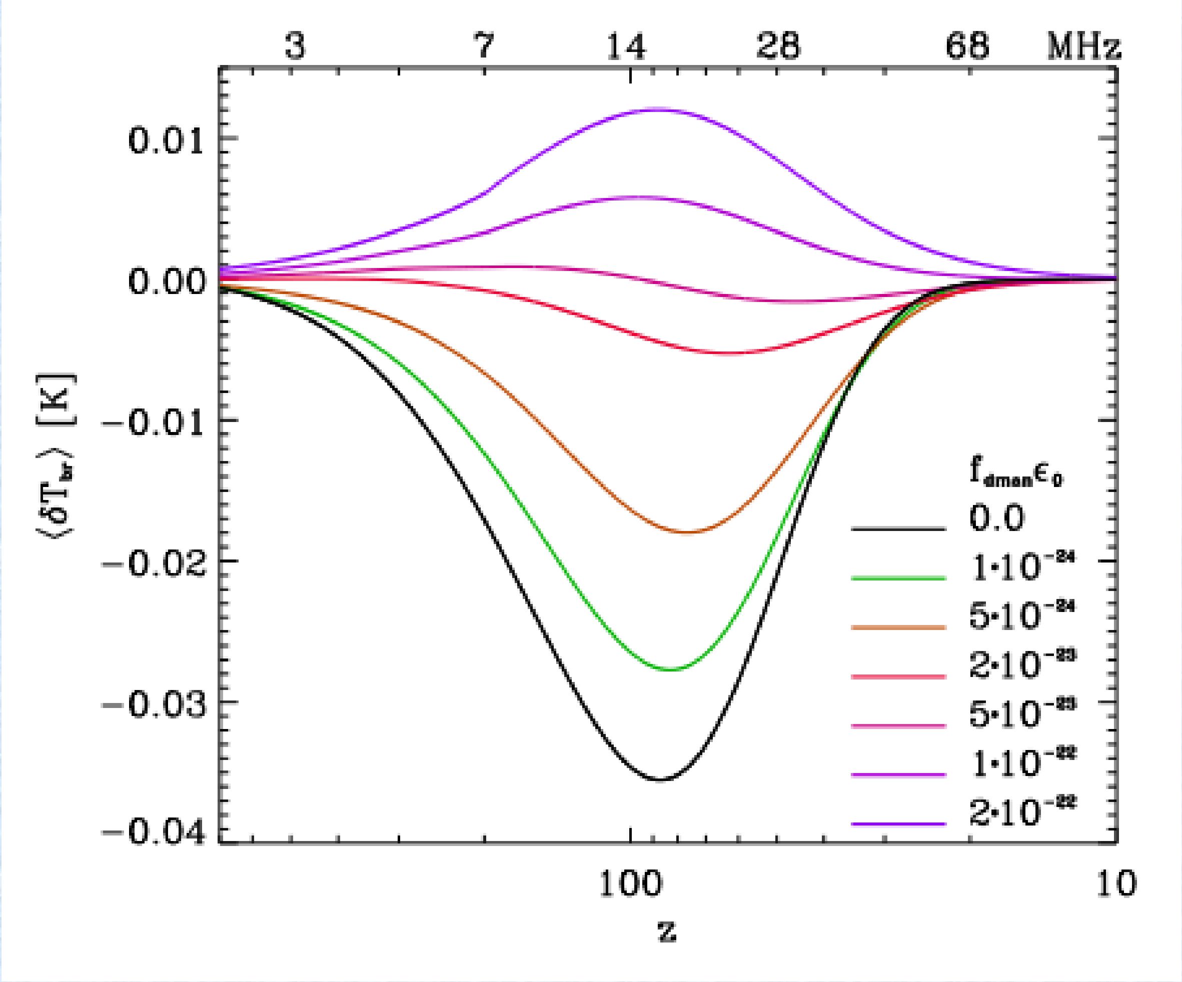
is the dimensionless parameter, f_{dman} is fraction of self-annihilating dark matter, and $[n_H]$=cm^{-3}.



SM: Ω_b=0.0493, Ω_{dm}=0.266, Ω_Λ=0.6847, Ω_K=0, H_0=67.36 km/s·Mpc (*Planck collaboration, 2020*)

Non-standard cosmology: self-annihilating dark matter



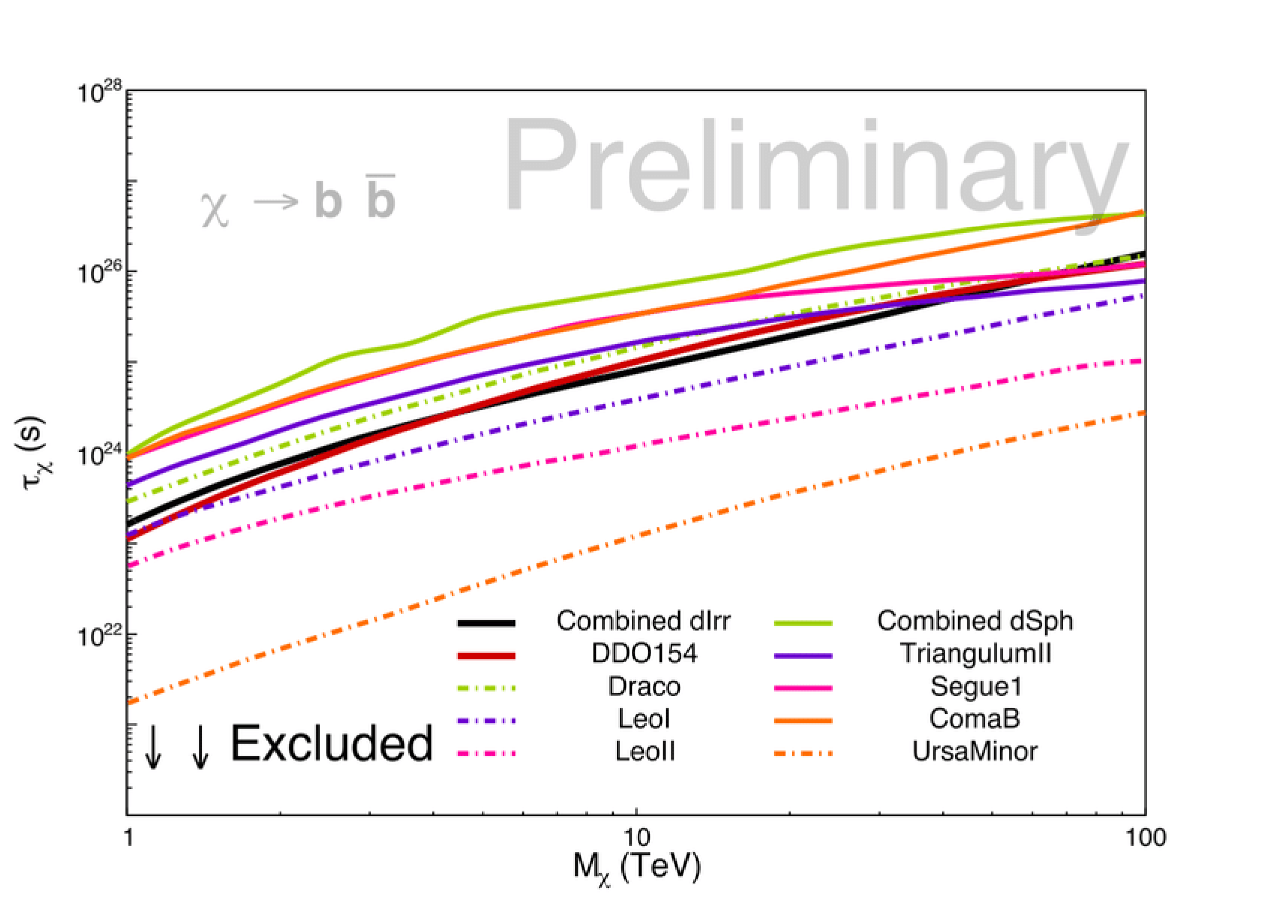


SM: Ω_b=0.0493, Ω_{dm}=0.266, Ω_Λ=0.6847, Ω_K=0, H_0=67.36 km/s·Mpc **(*Planck collaboration, 2020*)**

Non-standard cosmology: decaying dark matter

Energy deposit into

- **heating of baryonic gas,**
- **ionization of hydrogen and helium,**
- **excitation of atoms and molecules**



Cadena et al. (HAWC Collaboration), arXiv: 1908.08884

Non-standard cosmology: decaying dark matter, ionization

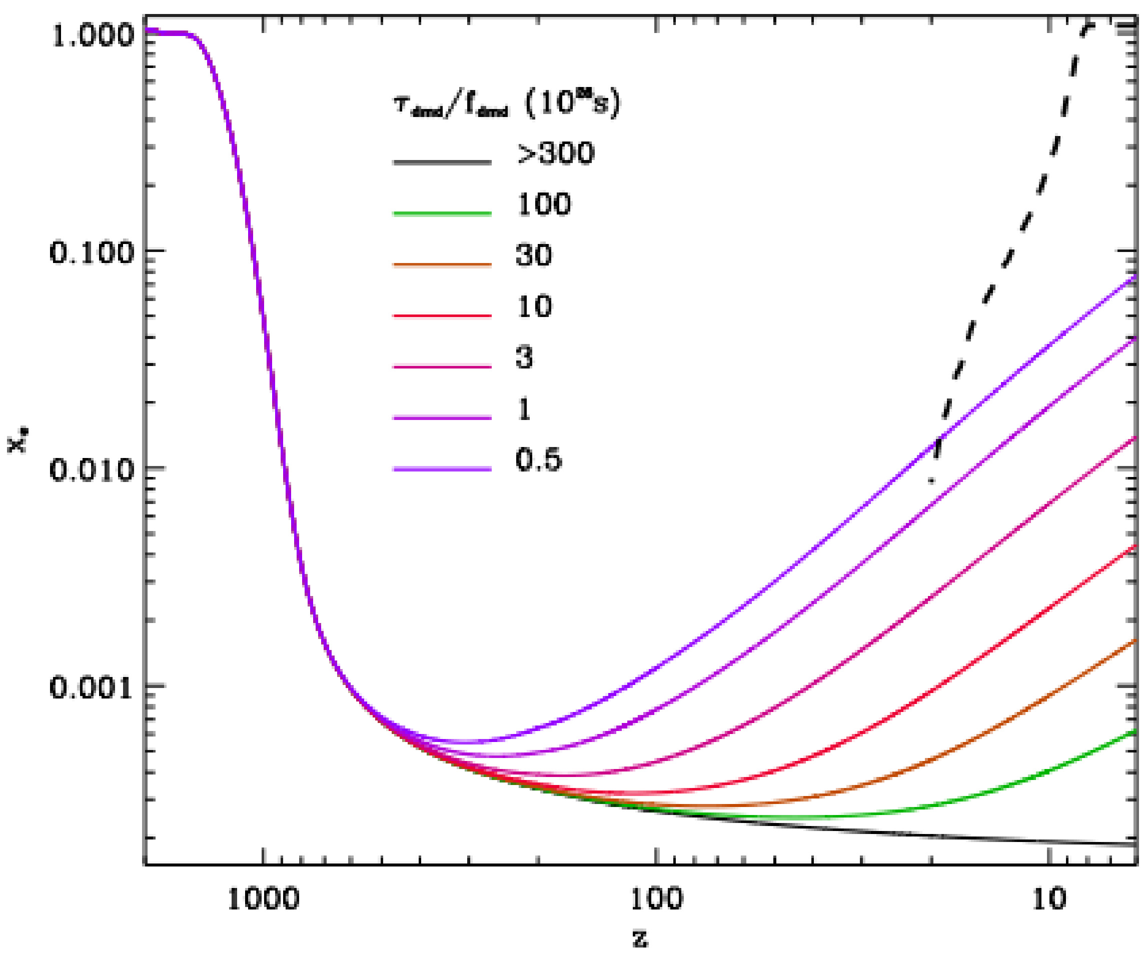
The heating function of baryonic matter and the rate of ionization of hydrogen and helium atoms due to decay of dark matter particles (Chluba 2010; Liu & Slatyer 2018):

$$\Gamma_{dmd} = 1.69 \cdot 10^{-8} g_h \frac{f_{dmd}\Omega_{dm}h^2}{\tau_d}(1+z)^3 \quad \frac{erg}{cm^3 s},$$

$$\frac{dx_{HI}}{dt} = -774.68 g_{ion}^{(HI)} \frac{f_{dmd}\Omega_{dm}h^2}{n_{HI}\tau_d(1+f_{He})}(1+z)^3,$$

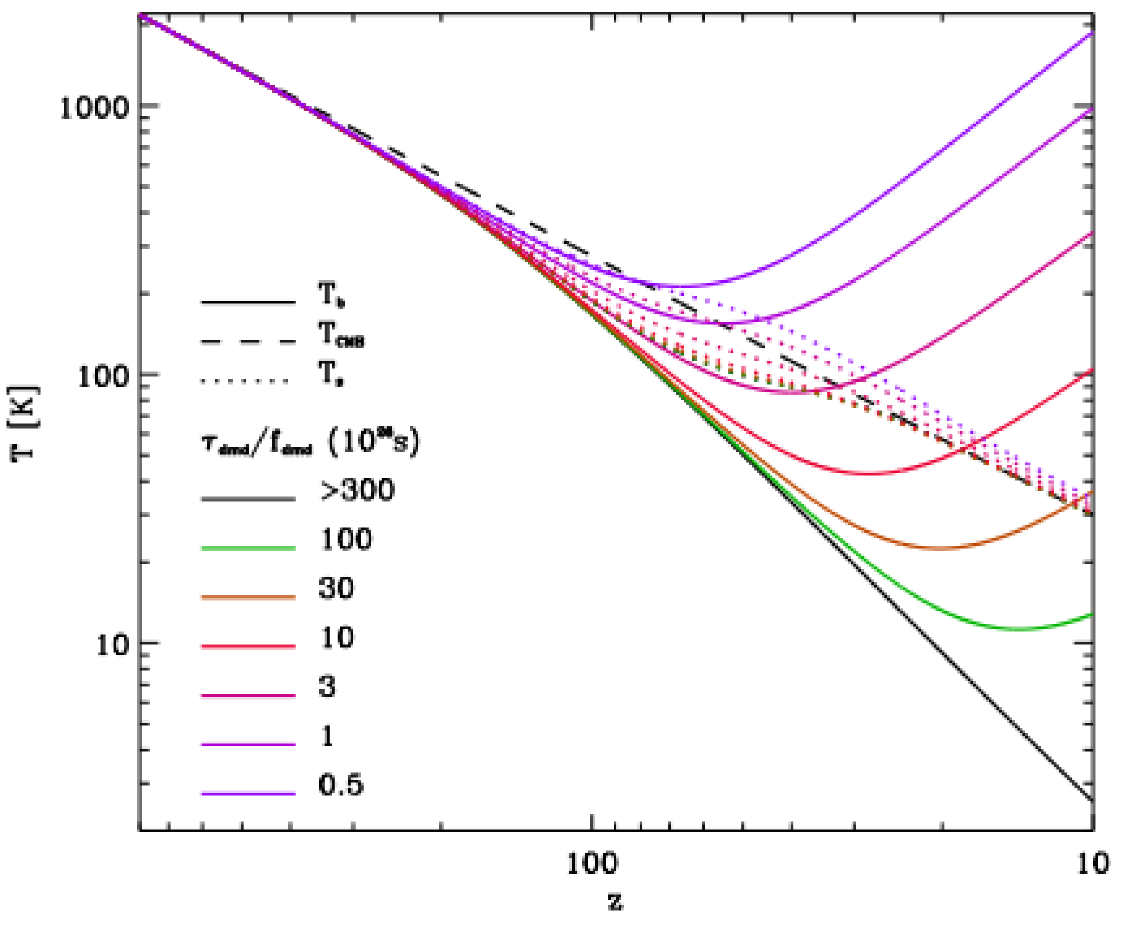
$$\frac{dx_{HeI}}{dt} = -428.28 g_{ion}^{(HeI)} \frac{f_{dmd}\Omega_{dm}h^2 f_{He}}{n_{HeI}\tau_d(1+f_{He})}(1+z)^3$$

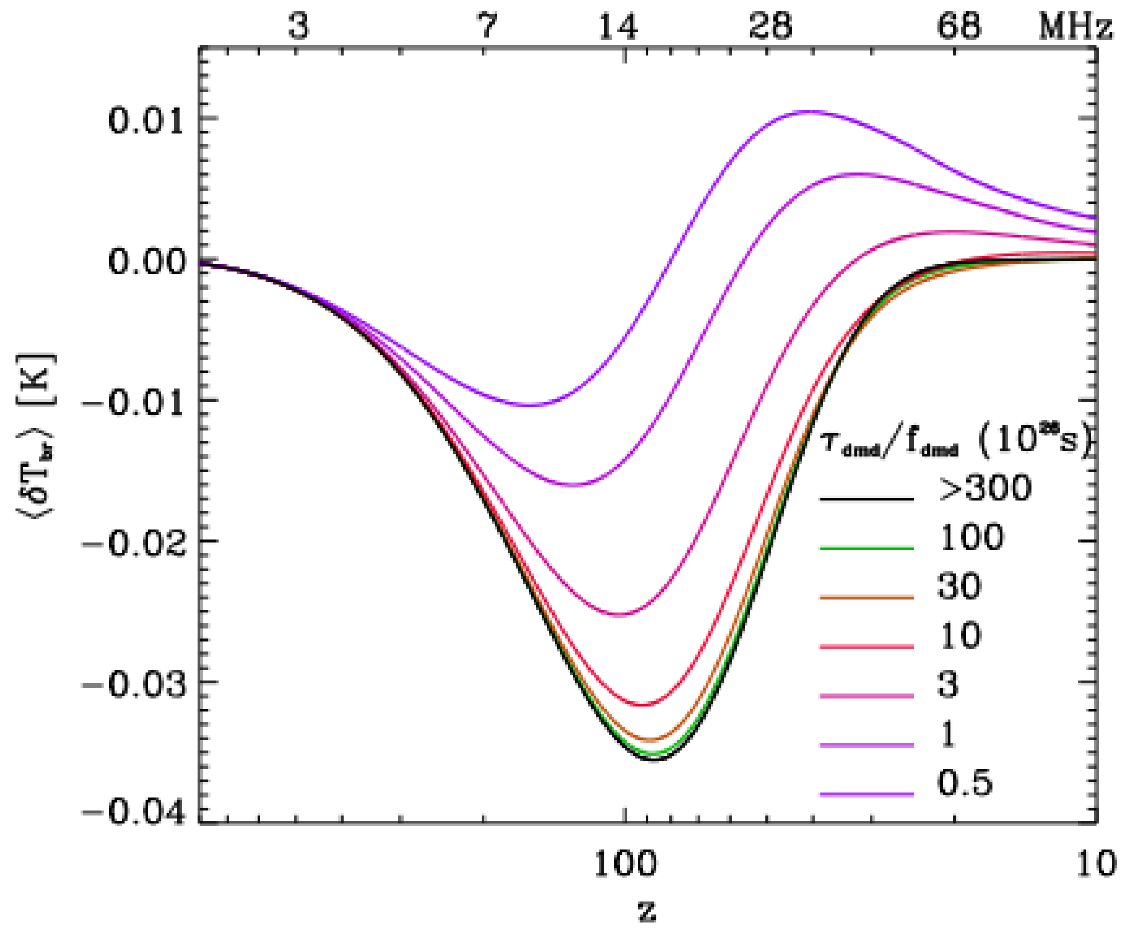
Here $[\tau_d]$=s, $[n_{HI}]=[n_{HeI}]$=cm^{-3}.



SM: Ω_b=0.0493, Ω_{dm}=0.266, Ω_Λ=0.6847, Ω_K=0, H_0=67.36 km/s·Mpc (*Planck collaboration, 2020*)

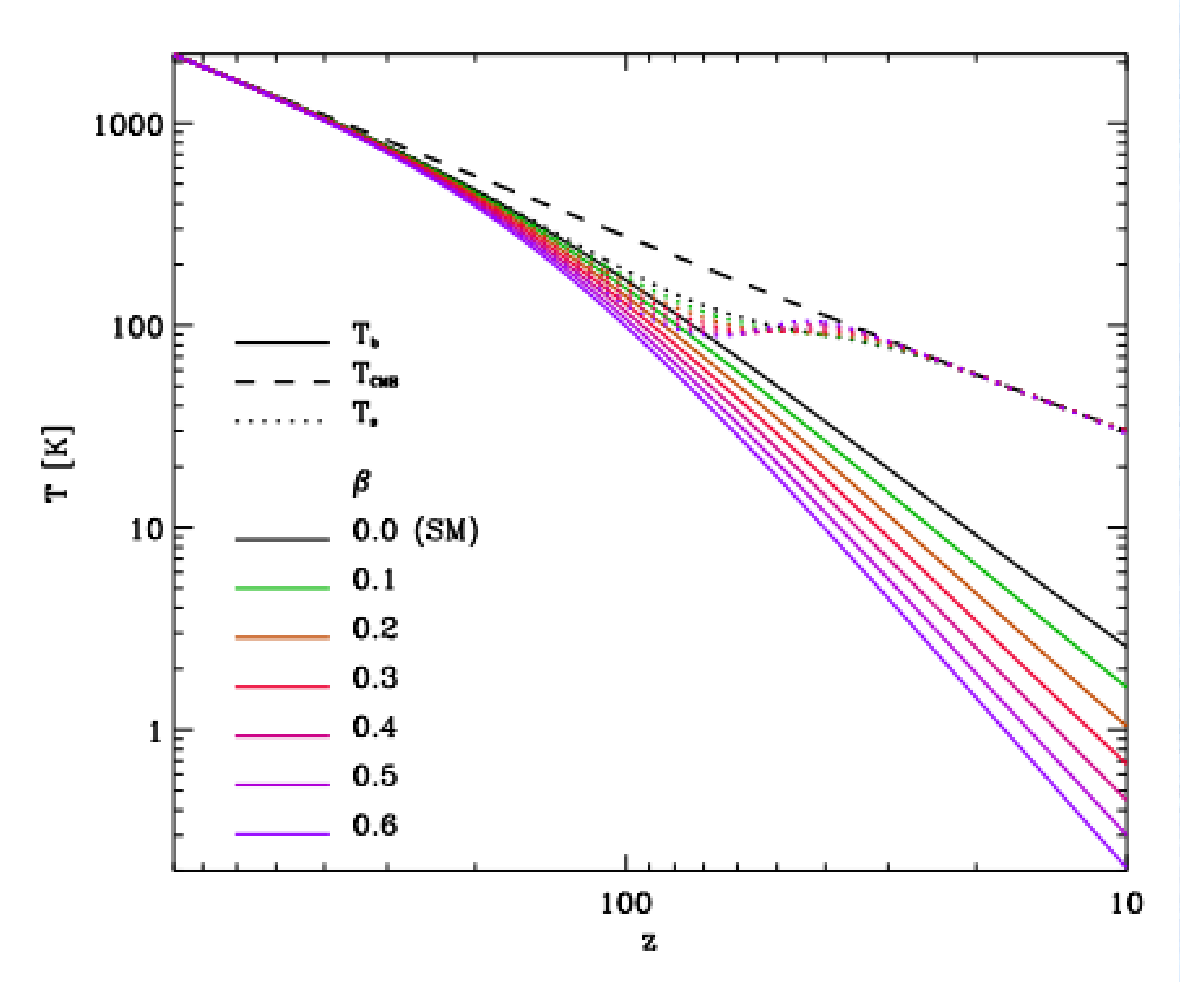
Non-standard cosmology: decaying dark matter

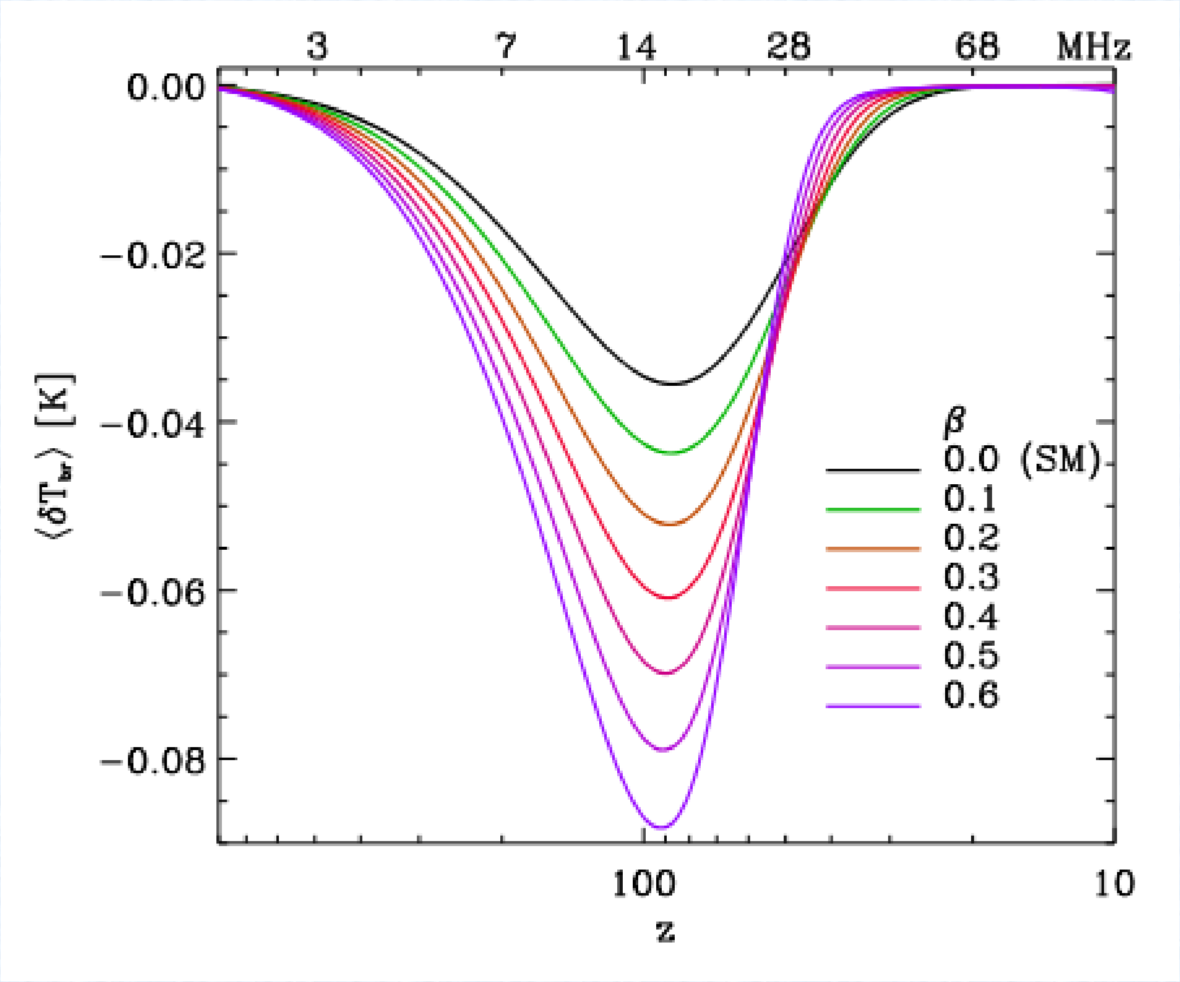




SM: Ω_b=0.0493, Ω_{dm}=0.266, Ω_Λ=0.6847, Ω_K=0, H_0=67.36 km/s·Mpc **(*Planck collaboration, 2020*)**

Non-standard cosmology: additional cooling ($\Lambda_{add.cool.}=\beta\cdot\Lambda_{ad}$)

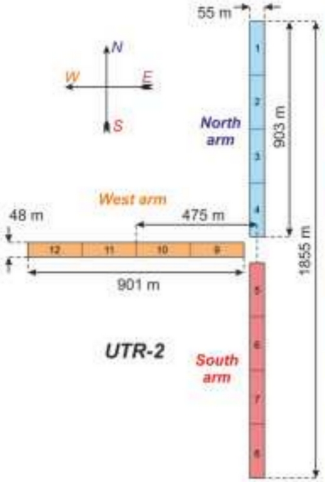




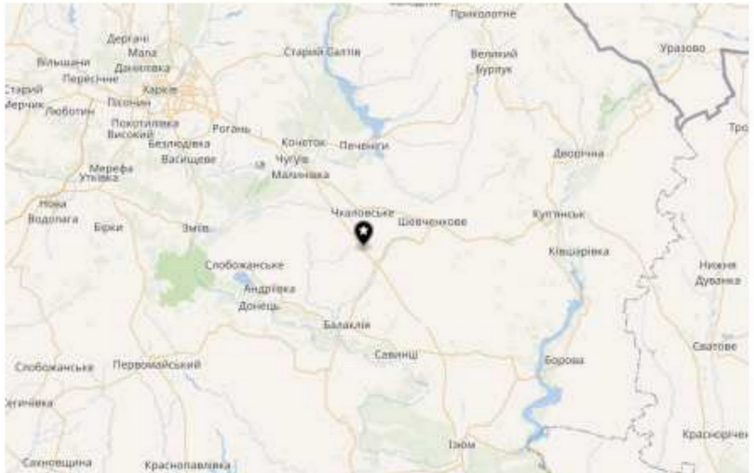
SM: Ω_b=0.0493, Ω_{dm}=0.266, Ω_Λ=0.6847, Ω_K=0, H_0=67.36 km/s·Mpc (*Planck collaboration, 2020*)

The Ukrainian Radio Telescope UTR-2 is the world's largest low-frequency radio telescope at 8-30 MGHz

The half-width of absorption line H 21 cm is at $z \sim 150 - 50$, that for Earth observers is at $\nu_{21} \sim 9 - 28$ MHz!

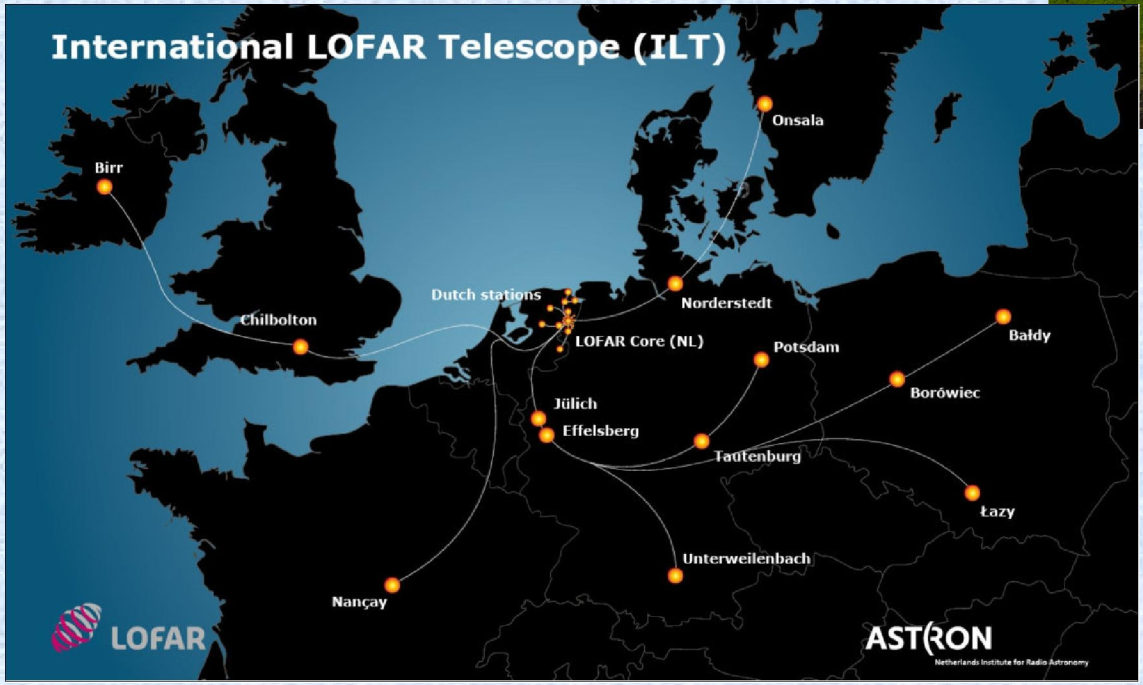


The UTR-2 consists of an array of 2040 dipole elements in two arms each containing 6 rows of elements, oriented in a T shape: a north–south arm consisting of 1440 elements covering an area of 1800×60 meters, and an east–west arm consisting of 600 elements covering an area of 900×60 meters. The basic element is a broadband cage dipole 1.8 m in diameter and 8 m long made of galvanized steel wire, mounted 3.5 m above the ground, with a balun to connect it to the transmission line. The dipoles are all oriented along the east–west axis, with the spacing between rows of 7.5 m in east–west direction and 9 m in north–south. It has a total area of 150,000 square metres (1,600,000 sq ft), and a resolution of about 40 arcminutes at the middle frequency 16.7 MHz. The operating frequency range is 8–33 MHz. The sensitivity is about 10 mJy.



LOFAR

The Low-Frequency Array (LOFAR) is a large radio telescope, with an antenna network located mainly in the Netherlands, and spreading across other European countries.

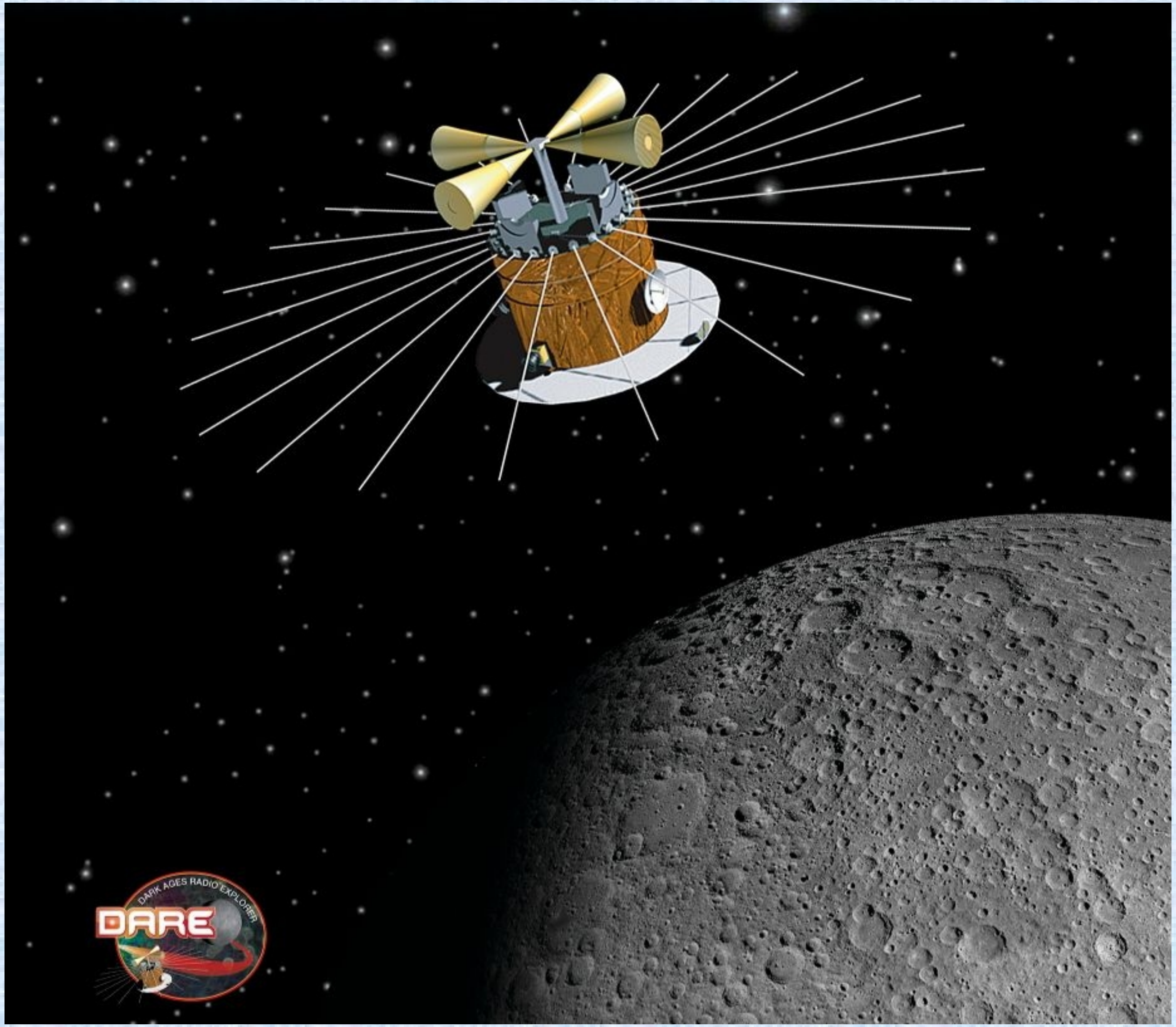


Low Band Antenna (LBA) and High Band Antenna (HBA), optimized for 10-80 MHz and 120-240 MHz respectively

The Lunar Surface Electromagnetic Explorer (LuSEE-Night)

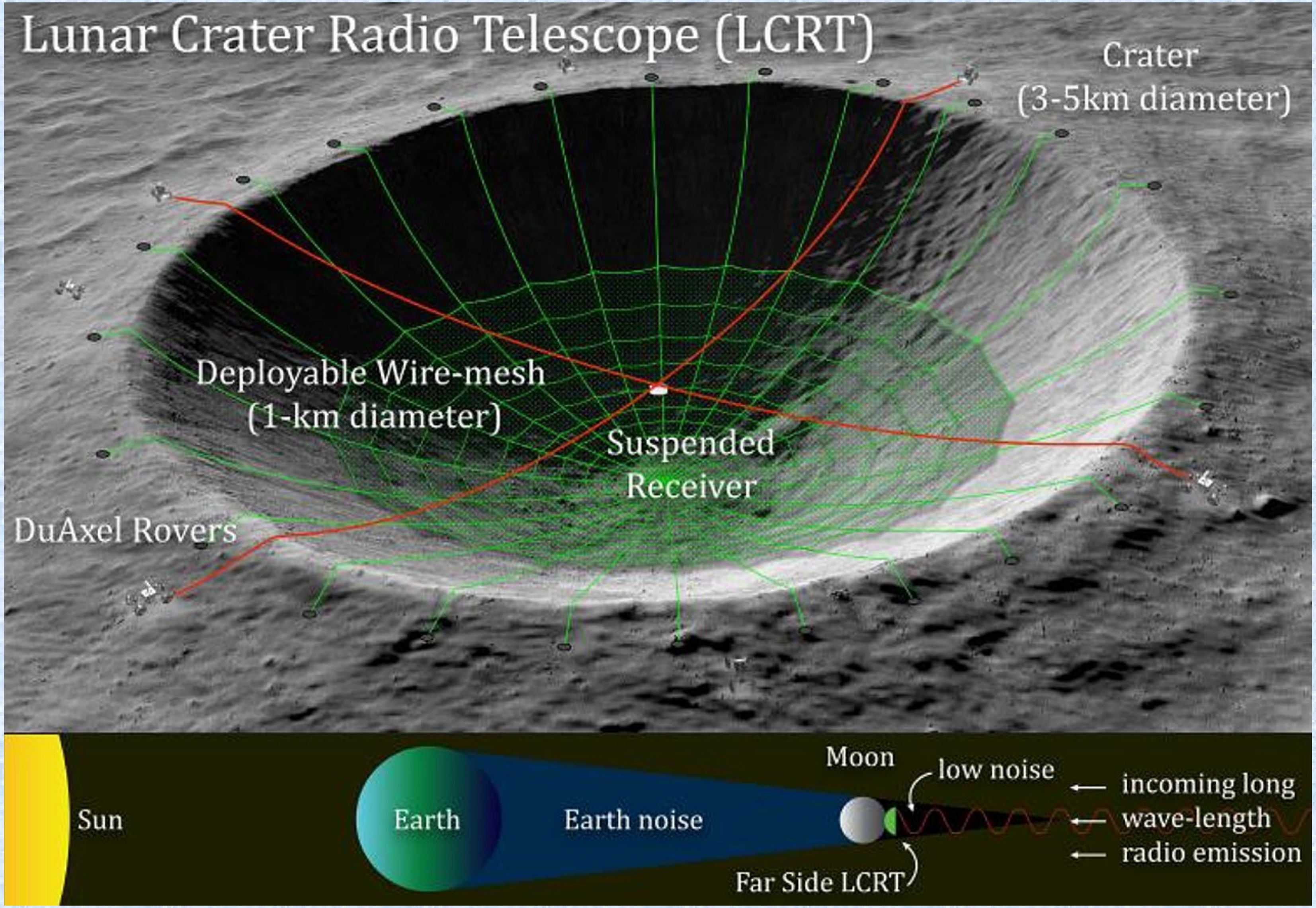
LuSEE-Night: 0.1-50 MHz, Lunar radio telescope (expected launch 2025/2026)

The Dark Ages Radio Explorer (DARE)



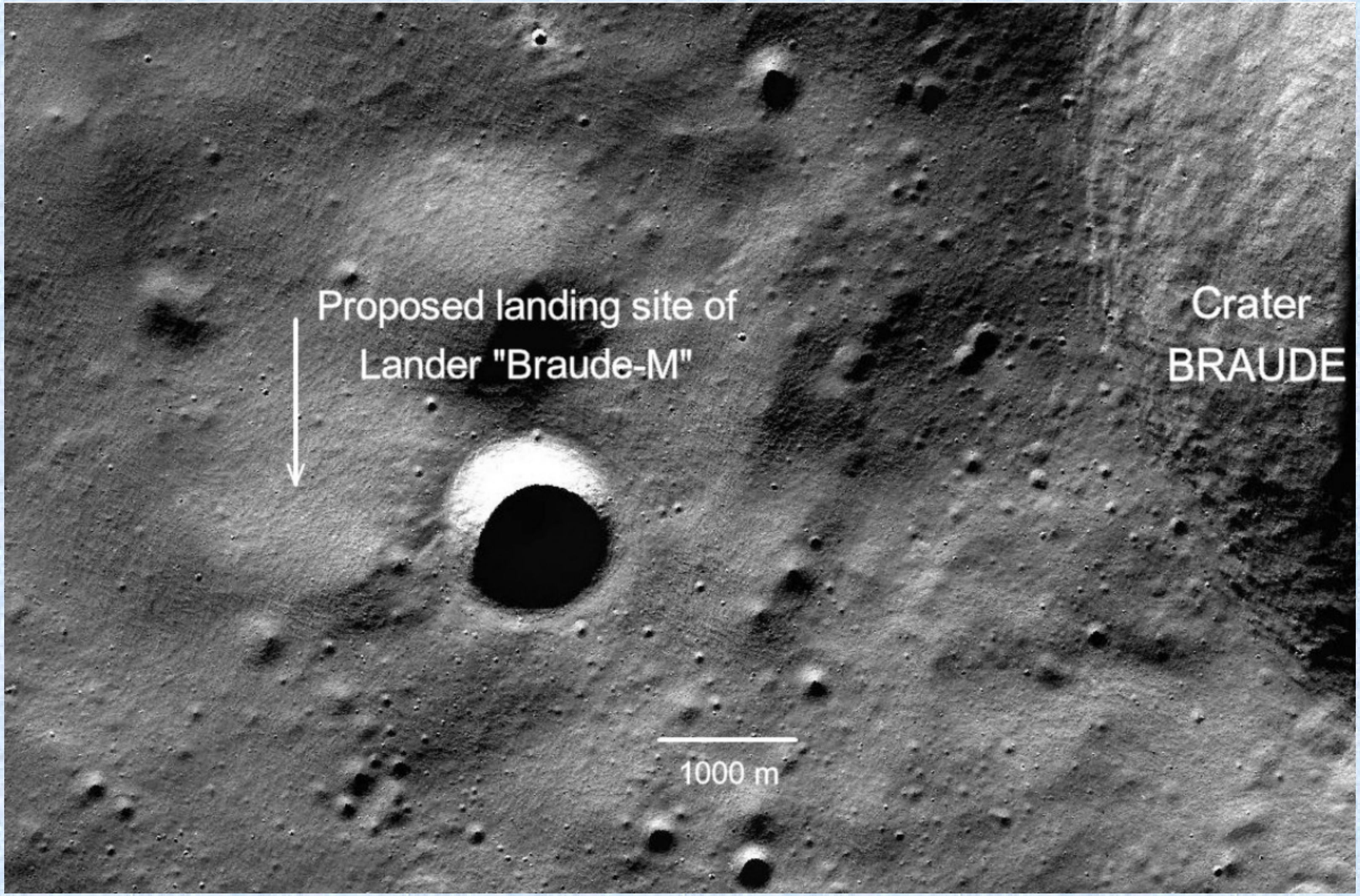
DARE: 40-120 MHz, Lunar orbiter (expected to launch in

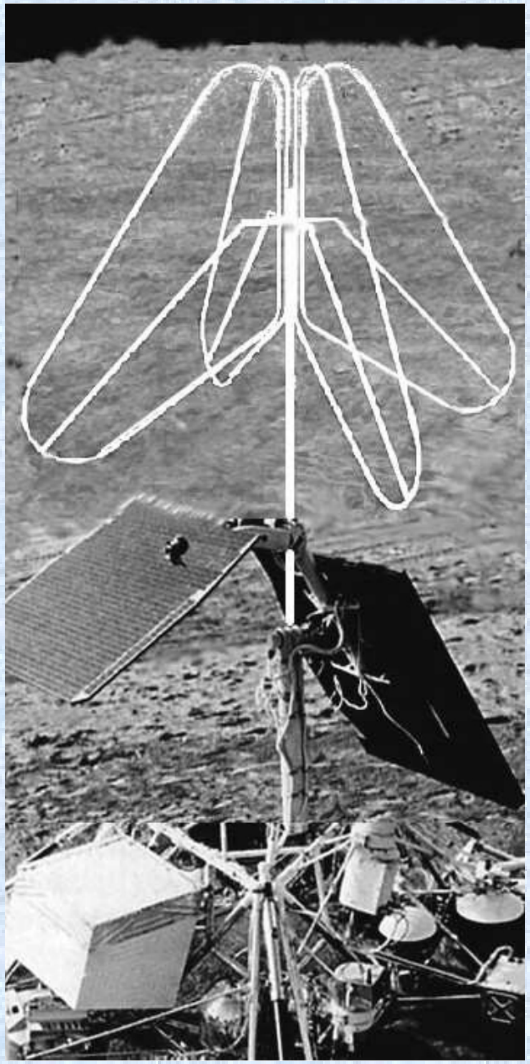
Lunar Crater Radio Telescope (LCRT)



LCRT: 10-30 MHz, D 350 m (NASA proposal)

Big Radio Astronomy Universe, Demonstrating Exploration on the Moon (“BRAUDE-M”)





Shkuratov Y., Konovalenko A., Zakharenko V. et al. Acta Astronautica, 2019, 154, p. 214-226.

Conclusions

- In the standard cosmological model, an absorption line of 21 cm of neutral hydrogen is formed during the Dark Ages at $30 \leq z \leq 300$ with a differential brightness temperature $\delta T_{br} \approx -35$ mK at $z \approx 87$. The frequency of the line in the absorption trough is 16 MHz, the effective half-width of the line is 12 MHz.
- The depth of line is moderately sensitive to Ω_b and H_0, weakly sensitive to Ω_{dm}, and insensitive to other parameters of the standard ΛCDM model.
- The line is very sensitive to additional mechanisms of heating or cooling of baryonic matter during the Dark Ages, so it can be a good test of non-standard cosmological models.
- In the models with decaying and self-annihilating dark matter, as well as with a primordial magnetic field, the temperature of baryonic matter in this period is higher the larger is the fraction of these energy components of dark matter, f_{dmd} and f_{dman}, and strength of magnetic field B_0. The depth of the absorption line decreases and transitions to emission at values of the component parameters lower than the upper limits on them, which result from the set of available observed data.