# 21cm anomaly and dark matter

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Phys.Rev.Lett. 108 (2012) 061304

O. Erken, P. Sikivie, H. Tam, Q. Yang.

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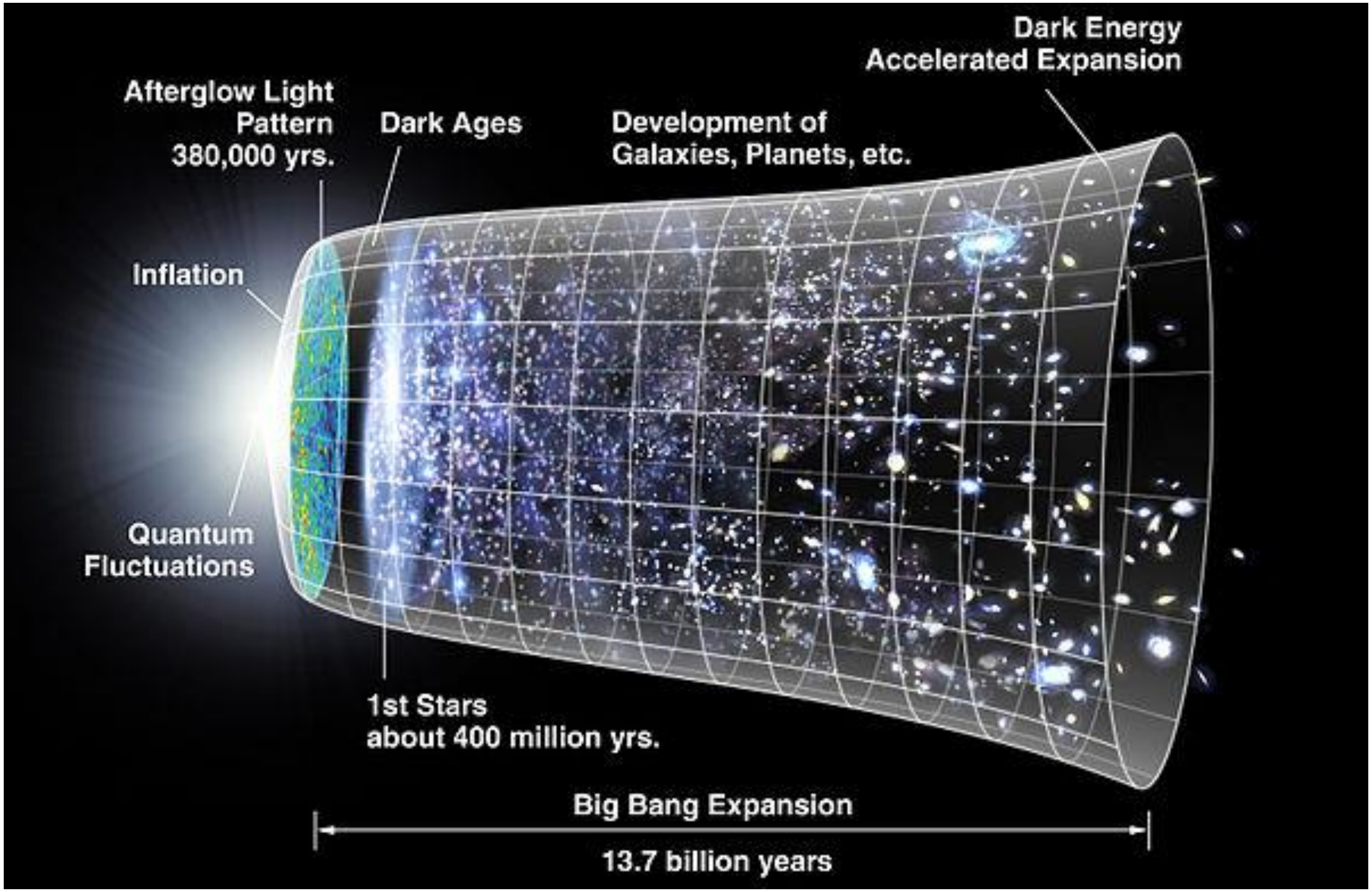
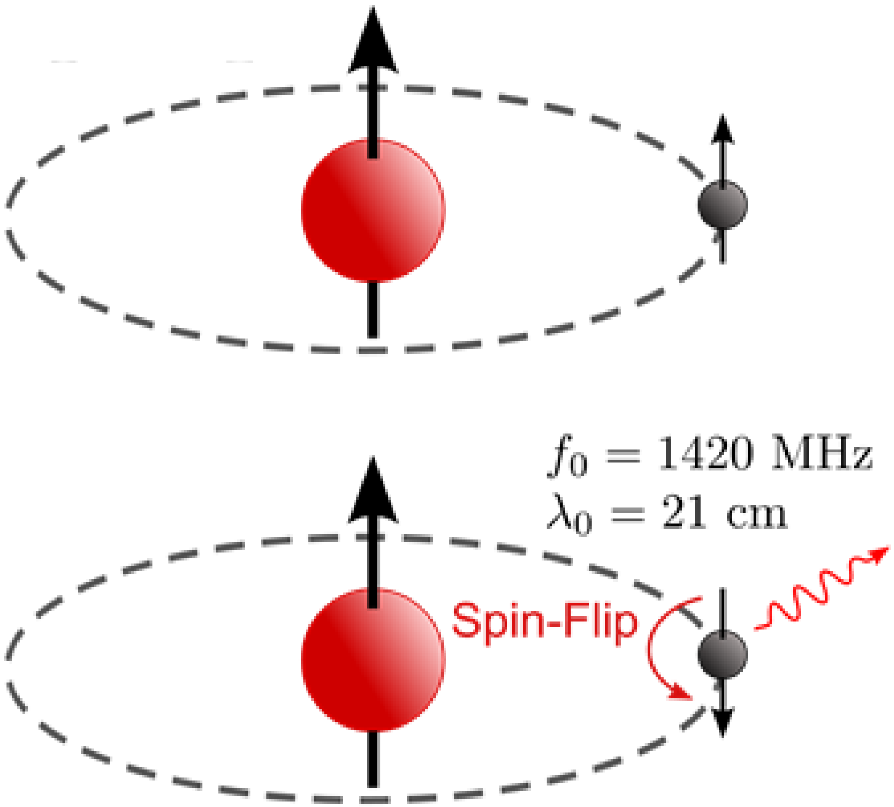
# Dark Ages




picture by NASA

# 21 cm transition



# Spin temperature

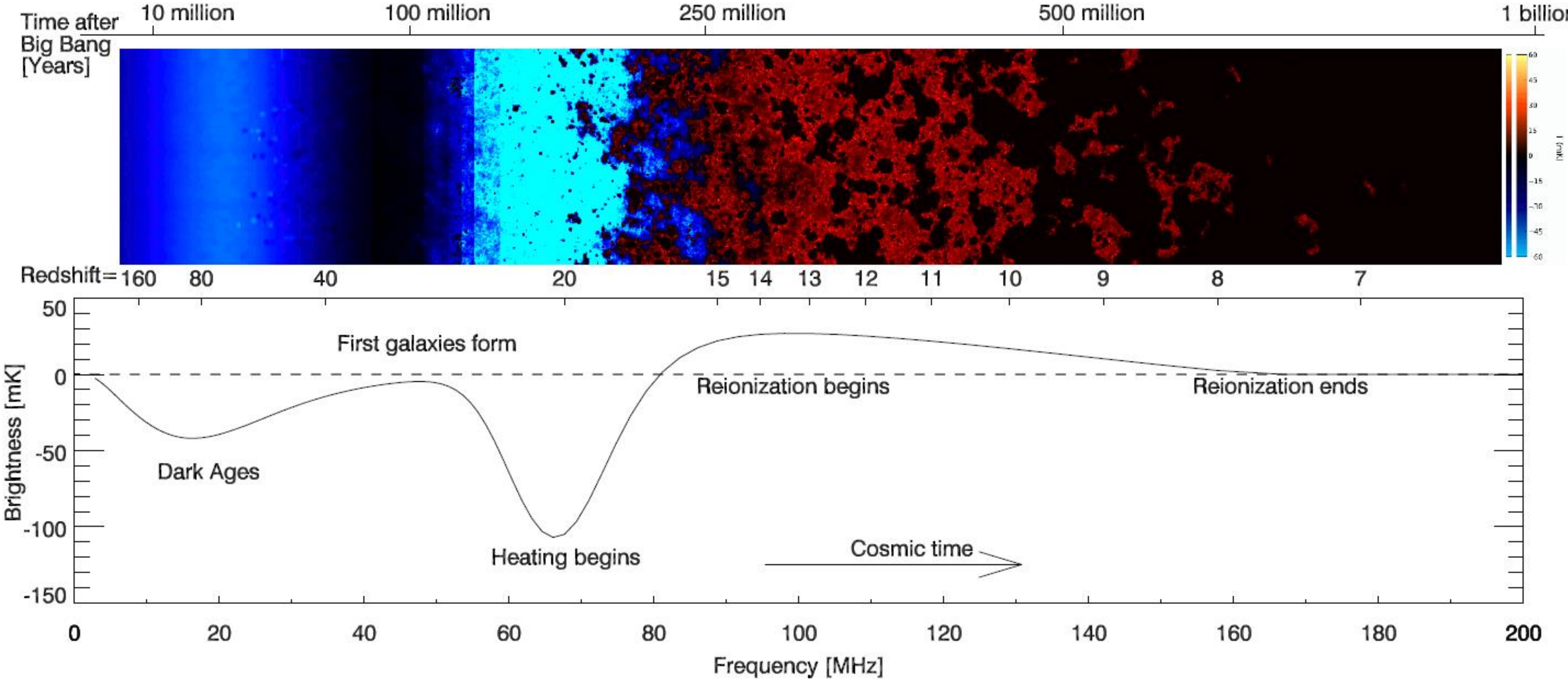
Determined by:

1. Absorption, emission of CMB photons

2. Kinetic collisions

3. Resonantly emission due to Ly$\alpha$ photons

# Dark Ages




Rep. Prog. Phys. 75, 086901 (2012), J. Pritchard, A. Loeb.

# The EDGES anomaly

$$T_{21} \simeq 35\mathrm{mK}\left(1 - \frac{T_\gamma}{T_s}\right)\sqrt{\frac{1+z}{18}} \simeq -0.5^{+0.2}_{-0.5}\,\mathrm{K}\,,$$

$$z \in (20, 15),$$

Standard LCDM $T_{21} > -0.2\mathrm{K}$, deviation is about $3.8\sigma$

# Cold Dark Matter (CDM)

- CDM is widely believed to be an important part of the universe based on a large number of observations:

a. Dynamics of galaxy clusters.
b. Rotation curves of galaxies.
c. Abundance of light elements.
d. Gravitational lensing.
e. Anisotropies of the CMBR.

# CDM

- Accounts 23% of total energy density of universe while baryonic matter accounts 4%.
- Properties:

**a. Pressureless**

Primordial velocity is very small , at most $\sim 10^{-8}c$ today .

**b.Collisionless**

Cold dark matter is weakly interacting (so dark), except for gravity.

# Axion Properties

- Introduced to solve the strong CP problem of the standard model.

In QCD, a formally total divergence term cannot be neglected due to the instanton solutions.

$$L_{\mathrm{QCD}} = \ \dots + \ \theta \frac{g^2}{32\pi^2} G^a{}_{\mu\nu} \tilde{G}^{a\mu\nu}$$

- This term violates CP invariance if $\theta \neq 0$
- The measurement of electric dipole moment of neutron gives a upper limit: $|\theta| \leq 10^{-9}$

To solve the strong CP problem, one introduces a new U(1) symmetry that is spontaneously broken

$$L_a = \ \ldots + \frac{\varphi}{f_a}\frac{g^2}{32\pi^2} G^a{}_{\mu\nu}\tilde{G}^{a\mu\nu} + \frac{1}{2}\partial_\mu\varphi\,\partial^\mu\varphi + \ldots$$

where $\theta = \varphi / f_a$ relaxes to zero.

A pseudo-Nambu-Goldstone boson is produced

- After QCD phase transition, the “PQ” Nambu-Goldstone boson acquires mass due to instanton effects, hence becoming a quasi-Nambu-Goldstone boson, the “axion”.

- Axion models: PQWW, KSVZ, DFSZ.

- Axion like particles (ALPs) can also arise from string compactifications.

# Cold axion properties

1. Small velocity dispersion:

$$\Delta v \sim [a(t_1)/a(t)] \cdot 1/mt_1 \quad .$$

2. High physical space density:

$$n(t) \sim \frac{4 \cdot 10^{47}}{\text{cm}^3} \left(\frac{f}{10^{12}\,\text{GeV}}\right)^{5/3} \left(\frac{a(t_1)}{a(t)}\right)^3$$

# Cold axion properties

3. High phase space density due to 1&2:

$$\mathcal{N} \sim \; n \, \frac{(2\pi)^3}{\frac{4\pi}{3}(m\delta v)^3} \sim 10^{61} \; \left( \frac{f}{10^{12}\ \mathrm{GeV}} \right)^{\frac{8}{3}}$$

4. Particles number is effectively conserved:

$$g_{a\gamma\gamma} \sim 10^{-22}\ \mathrm{eV}^{-1}$$

# Cold axions form BEC if they thermalize

- BEC results from the impossibility to allocate additional charges to the excited states for given temperature.
- Axion particle number is effectively conserved and is the relevant charge.
- Cold axions’ effective temperature is below the critical temperature which is very high due to axions high number density.

# axion BEC in three arenas:

1. in the linear regime within the horizon.

2. in the non-linear regime within the horizon.

3. upon entering the horizon.

Axion BEC in the linear regime within horizon.

- From first order of density perturbation theory within the horizon, we get:

$$\partial_t \delta + \frac{1}{a}\vec{\nabla} \cdot \vec{v} = -3\partial_t \phi + \frac{3H}{4m^2 a^2}\nabla^2 \delta$$

$$\partial_t \vec{v} + H\vec{v} = -\frac{1}{a}\vec{\nabla}\psi + \frac{1}{4m^2 a^3}\vec{\nabla}\ \nabla^2 \delta$$

where $\delta(\vec{x}, t) \equiv \frac{\delta\rho(\vec{x},t)}{\rho_0(t)}$

This implies a nonzero Jeans length compared with the collisionless DM.

$$\partial_t^2 \delta + 2H\partial_t \delta - \left(4\pi G\rho_0 - \frac{k^4}{4m^2a^4}\right)\delta = 0$$

From equation above, one gets:

$$k_j^{-1} = 1.02 \cdot 10^{14}\,\mathrm{cm}(10^{-5}\,\mathrm{eV}/m)^{1/2}[(10^{-29}\,\mathrm{g}/\mathrm{cm}^3)/\rho]^{1/4}$$

- The equation of motion in non-linear regime within horizon:

$$\partial_t \rho + \vec{\nabla} \cdot (\rho \vec{v}) = 0$$

$$\vec{\nabla} \times \vec{v} = 0$$

$$\partial_t \vec{v} + (\vec{v} \cdot \vec{\nabla}) \vec{v} = -\vec{F}_g - \vec{\nabla} q$$

$$q = -\nabla^2 (\psi \psi^*)^{1/2} / [2m^2 (\psi \psi^*)^{1/2}]$$

- In the galactic halos BEC has the property $\vec{\nabla} \times \vec{v} \neq 0$ by appearance of vortices.

- BEC is consistent with small scale structures.

- Most many particle systems are in the particle kinetic regime where:

$$\Gamma >> \delta E$$

- The cold axions are in the opposite regime:

$$\Gamma << \delta E$$

Let us call it “condensed regime”.

- The question is: starting with an arbitrary initial state, how quickly will the average axion state occupation numbers approach a thermal distribution?

- We derive evolution equations for the out of equilibrium system, as an expansion in powers of the coupling strength.

- The first order terms average to zero in the kinetic regime. The second order terms yield the ordinary Boltzmann equation.

- The axions can be written:

$$\varphi(\vec{x},t) = \sum_{\vec{n}} \left[ a(t)_{\vec{n}}\ \Phi_{\vec{n}}(x) \ + \ a^{\dagger}_{\vec{n}}(t)\Phi^{\star}_{\vec{n}} \right]$$

- The Hamiltonian is

$$H = \sum_{\vec{n}} \omega_{\vec{n}} a^{\dagger}_{\vec{n}} a_{\vec{n}} + \sum_{\vec{n}_1,\vec{n}_2,\vec{n}_3,\vec{n}_4} \Lambda^{\vec{n}_3,\vec{n}_4}_{\vec{n}_1,\vec{n}_2} a^{\dagger}_{\vec{n}_1} a^{\dagger}_{\vec{n}_2} a_{\vec{n}_3} a_{\vec{n}_4}$$

Solve the Heisenberg equation $\dot{a}_{\vec{n}} = i[H, a_{\vec{n}}]$
perturbatively,

$$a_{\vec{n}}(t) = e^{-i\omega_{\vec{n}}t}(A_{\vec{n}} + B_{\vec{n}}(t)) + \mathcal{O}(\Lambda^2)$$

where: $B_{\vec{n}}(0) = 0,\ A_{\vec{n}} = a_{\vec{n}}(0)$ .

One gets:

$$
\begin{aligned}
\dot{N}_{\vec{n}}(t) \;&=\; [-i \sum_{\vec{i},\vec{j},\vec{k}} \Lambda^{\vec{j},\vec{k}}_{\vec{n},\vec{i}} \, A^{\dagger}_{\vec{n}} \, A^{\dagger}_{\vec{i}} \, A_{\vec{j}} \, A_{\vec{k}} \, e^{-i\Omega t} + h.c.] \\
&+\; [\sum_{\vec{i},\vec{j},\vec{k}} |\Lambda^{\vec{j},\vec{k}}_{\vec{n},\vec{i}}|^2 \{ N_{\vec{i}} N_{\vec{j}} (N_{\vec{k}} + 1)(N_{\vec{n}} + 1) - N_{\vec{k}} N_{\vec{n}} (N_{\vec{i}} + 1)(N_{\vec{j}} + 1) \} \frac{sin(\Omega t)}{\Omega} \\
&+\; off - diagonal \;\; 2rd \;\; order \;\; terms] + \mathcal{O}(\lambda^3) \quad .
\end{aligned}
$$

- The second order terms yield the Boltzmann equation. The first order terms, along with the off diagonal second terms average to zero in the "kinetic regime".

- In the condensed regime, the first order terms no longer average to zero and dominate. Considering the high occupation numbers of axion states, we can replace the operator A, $A^+$ with complex numbers whose magnitude is of order $\sqrt{N_{\vec{n}}}$ .

We get a c-number equation:

$$< \dot{N}_{\vec{n}} > \simeq \sum_{\vec{i},\vec{j},\vec{k}} \Lambda_{\vec{n},\vec{i}}^{\vec{j},\vec{k}} \sqrt{< N_{\vec{n}} >< N_{\vec{i}} >< N_{\vec{j}} >< N_{\vec{k}} >}$$

which lead to the thermalization rate :

$$\Gamma_g \sim 4\pi G n m^2 l^2,$$

for the gravitational interaction.

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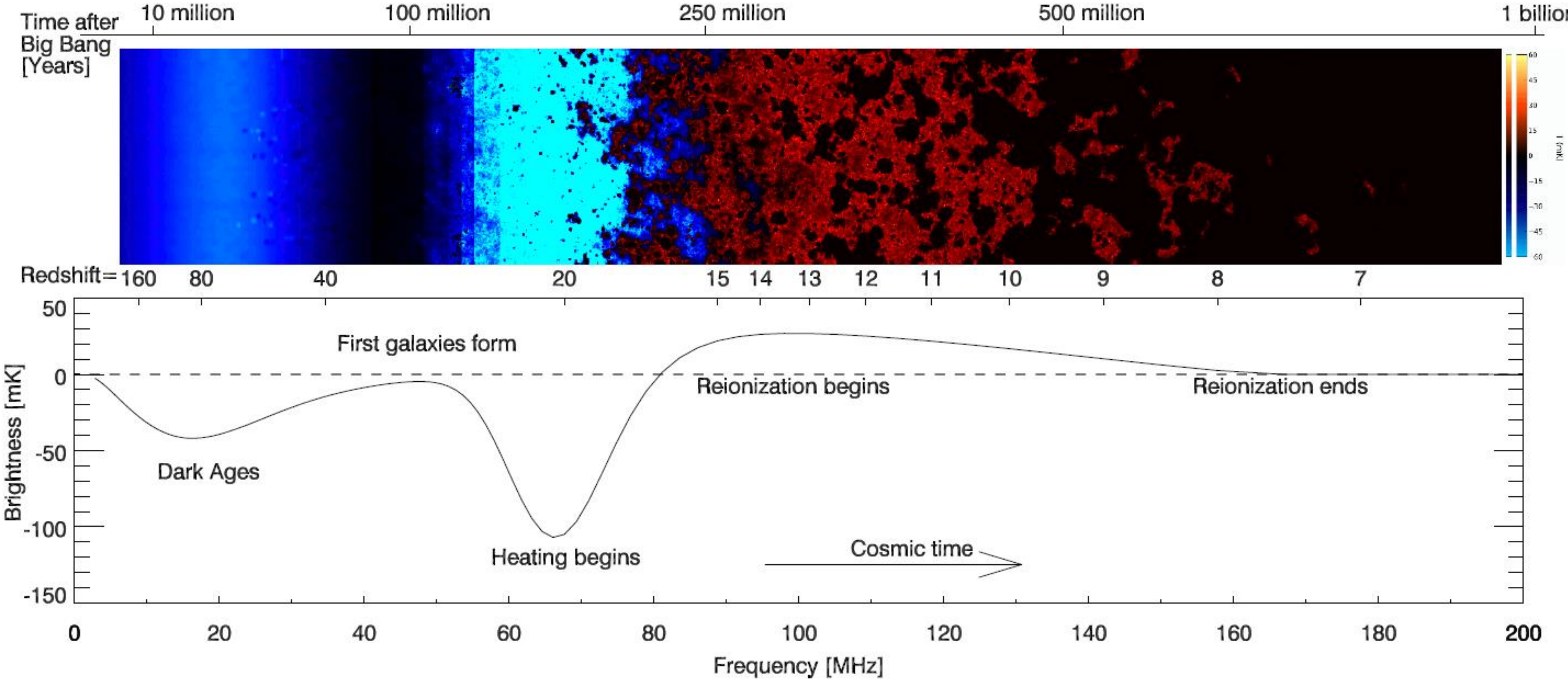


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$$\Gamma/H \sim 4\pi G m_a n_a l_a \omega/\Delta p H \gtrsim 1\,,$$

$$\rho_H\left(T_i\right) \simeq \rho_H\left(T_f\right) + \rho_a\left(T_f\right)\ .$$