

SOME OF THE PHYSICS IN 21CM COSMOLOGY



Institut Spatial de McGill



McGill Space Institute

CIFAR

Adrian Liu
McGill University



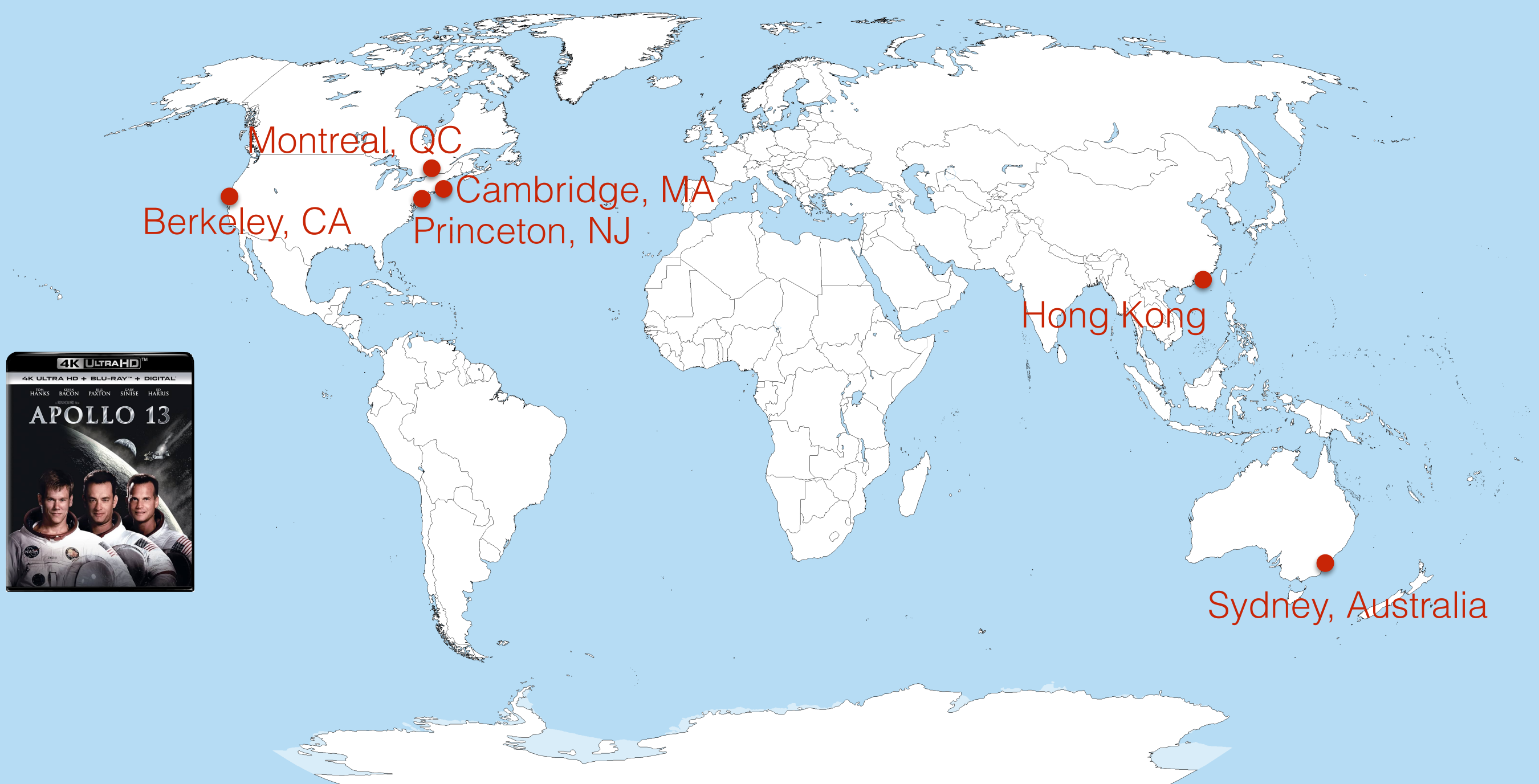
McGill



Prof. Adrian Liu (he/him)

I'm a cosmologist who uses radio telescopes to explore our early Universe

Former outreach chair, EDI chair; current Postdoc Mentoring Committee Chair



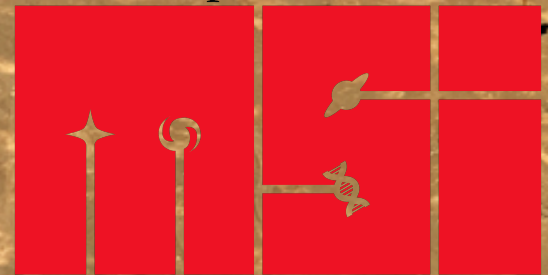
Princeton University (Bachelor's)
MIT (PhD)
UC Berkeley (BCCP/Hubble Fellow)
McGill University (Faculty)



SOME OF THE PHYSICS IN 21CM COSMOLOGY



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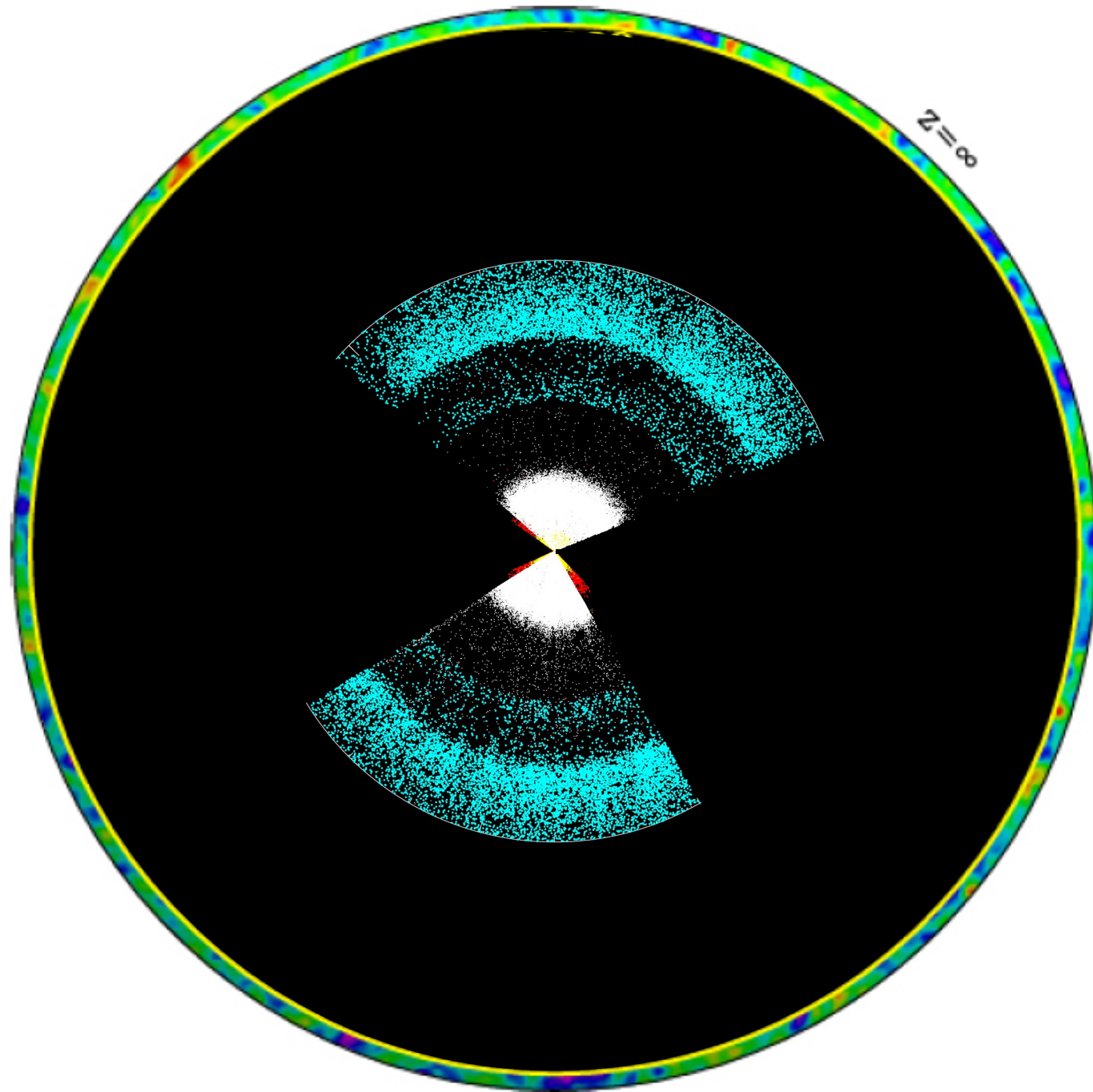
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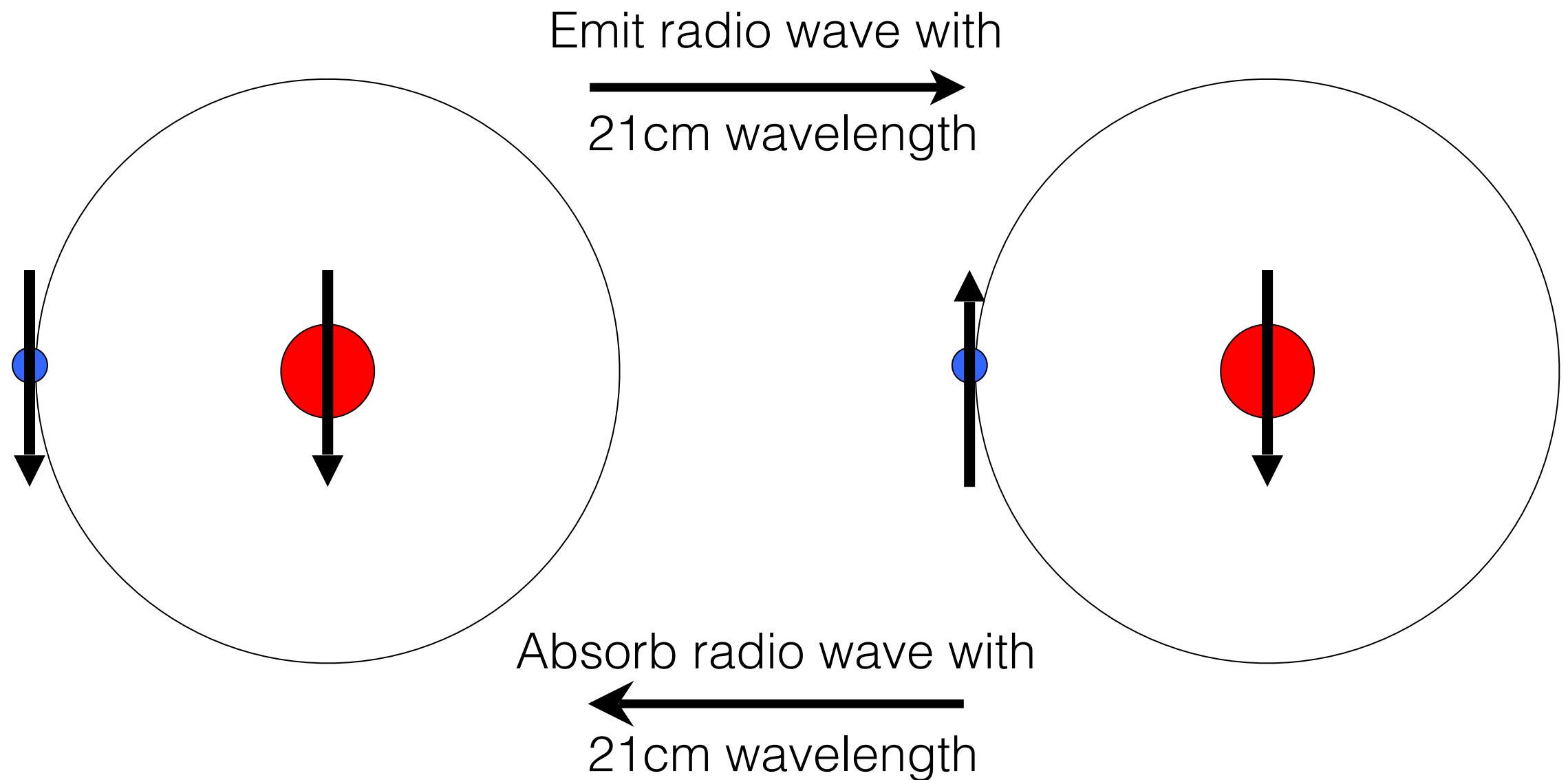
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Why are we doing this? What are the broad motivations?

We have yet to observe most
of the observable Universe



Hydrogen is everywhere, and the 21cm line allows us to trace hydrogen



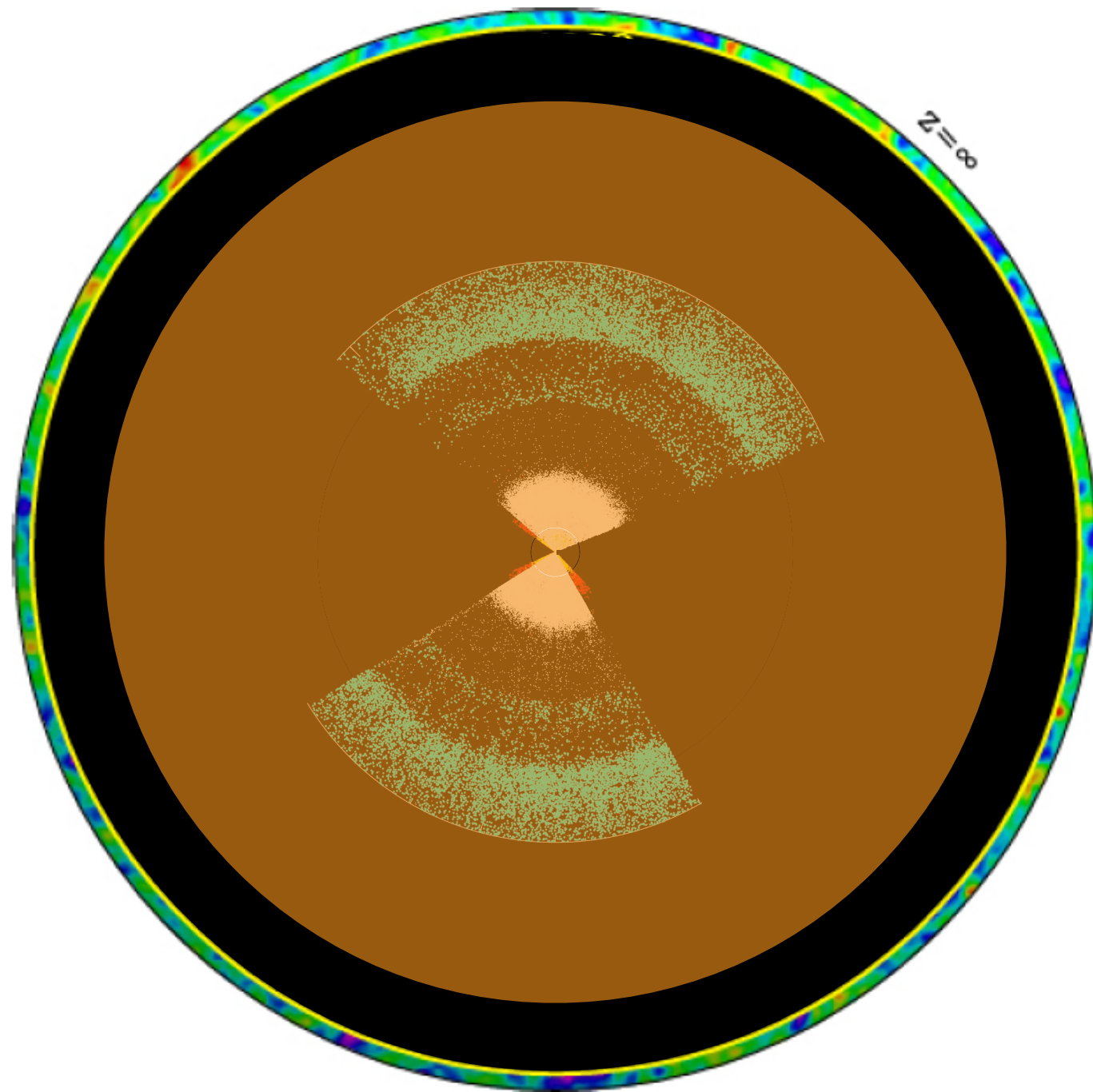
Hydrogen is everywhere, and the 21cm line allows us to trace hydrogen

$$\lambda_0 = 21 \text{ cm}$$

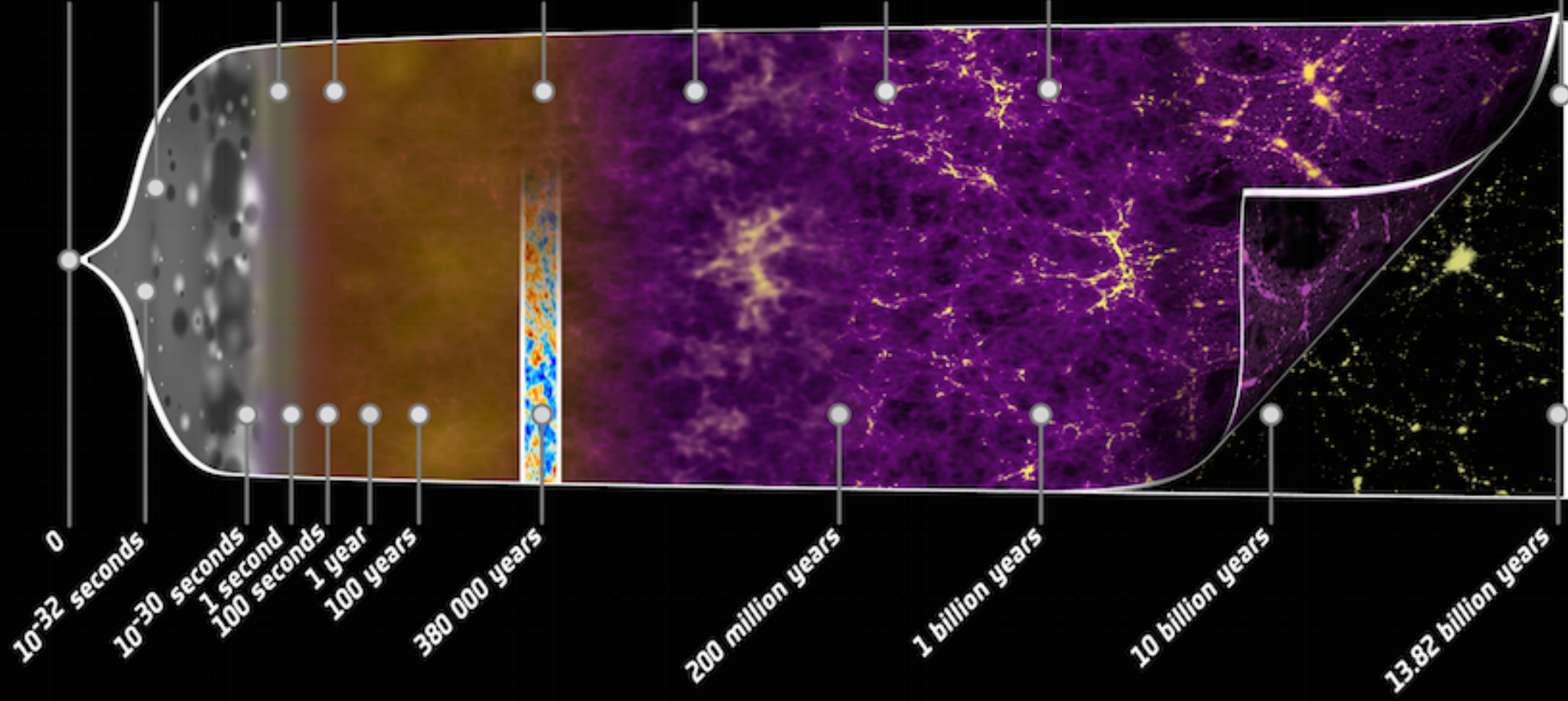
$$\nu_0 = 1420 \text{ MHz}$$

$$1 + z = \frac{\nu_0}{\nu_{obs}} = \frac{\lambda_{obs}}{\lambda_0}$$

The spectral nature of the 21cm line allows us to fill in this volume



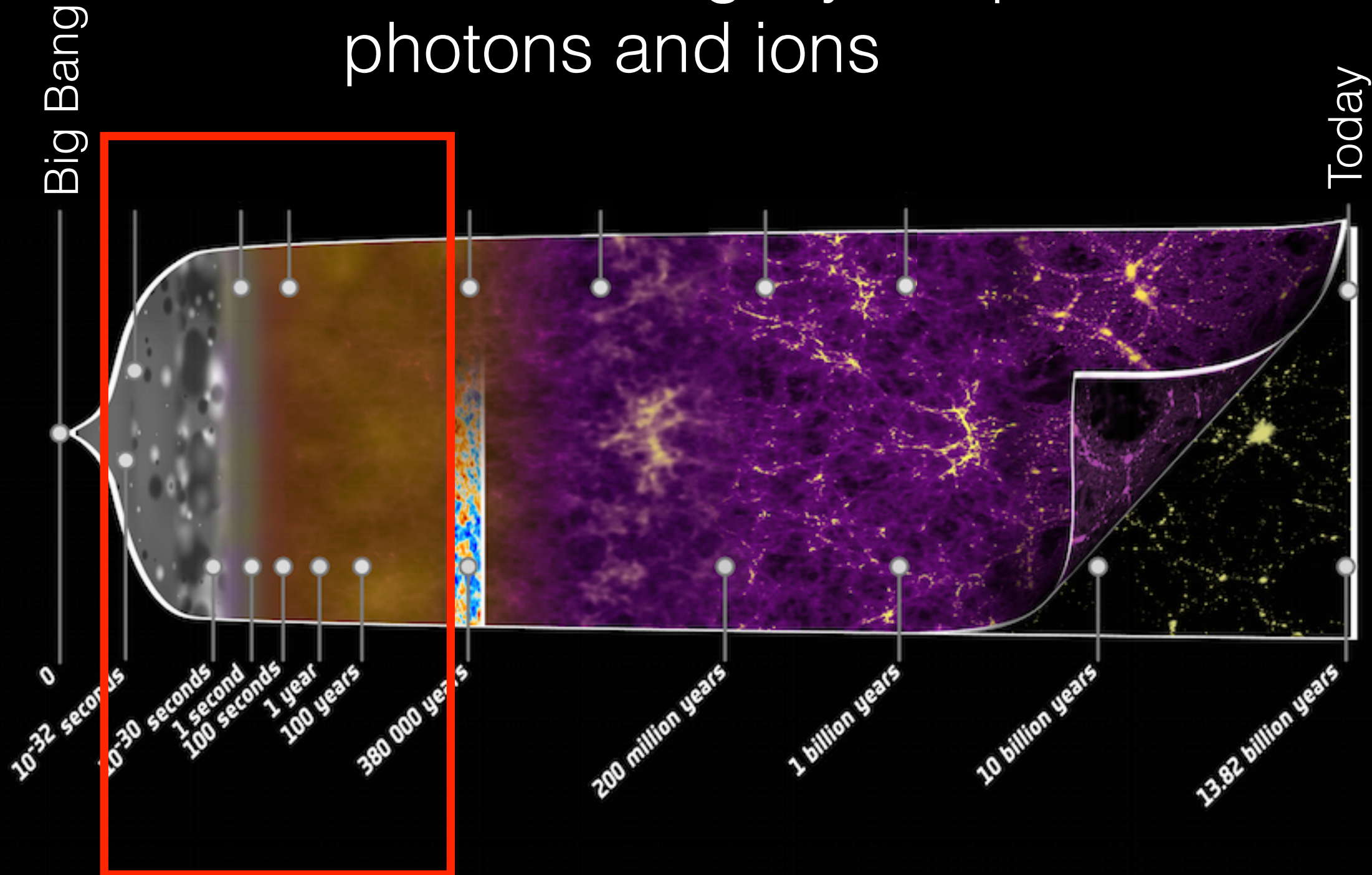
Big Bang

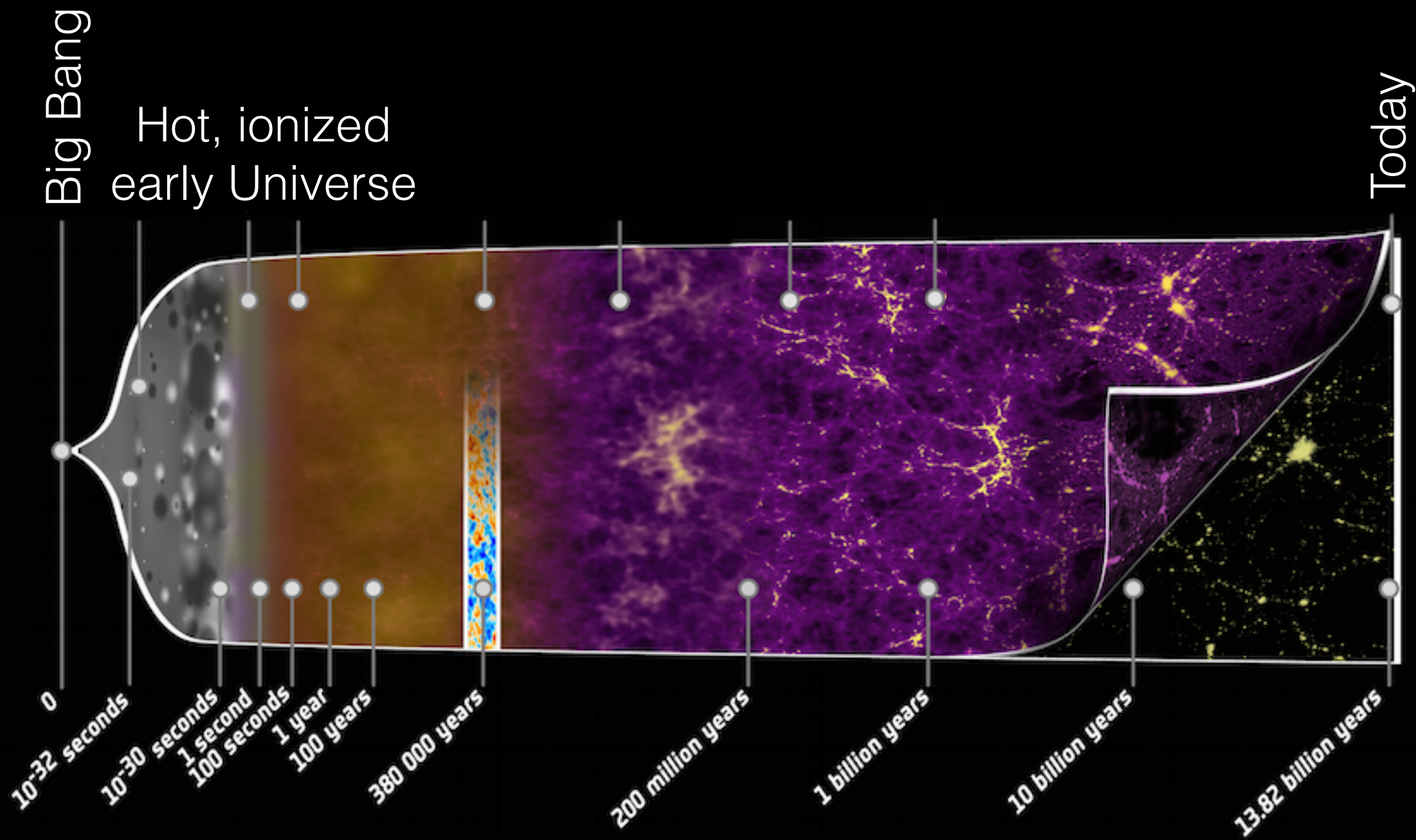


Today

Early Universe:

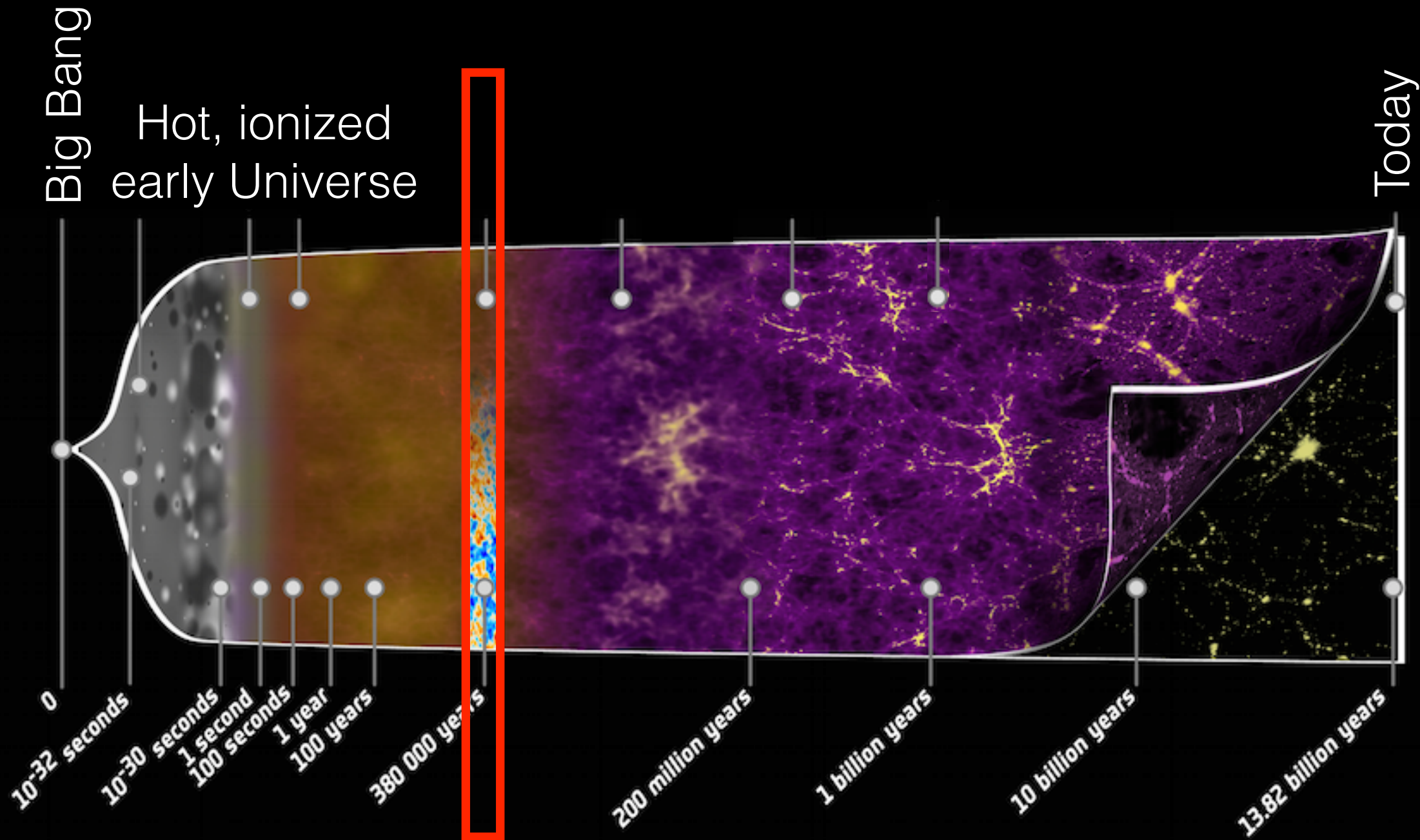
- Hot, dense
- Plasma of tightly coupled photons and ions

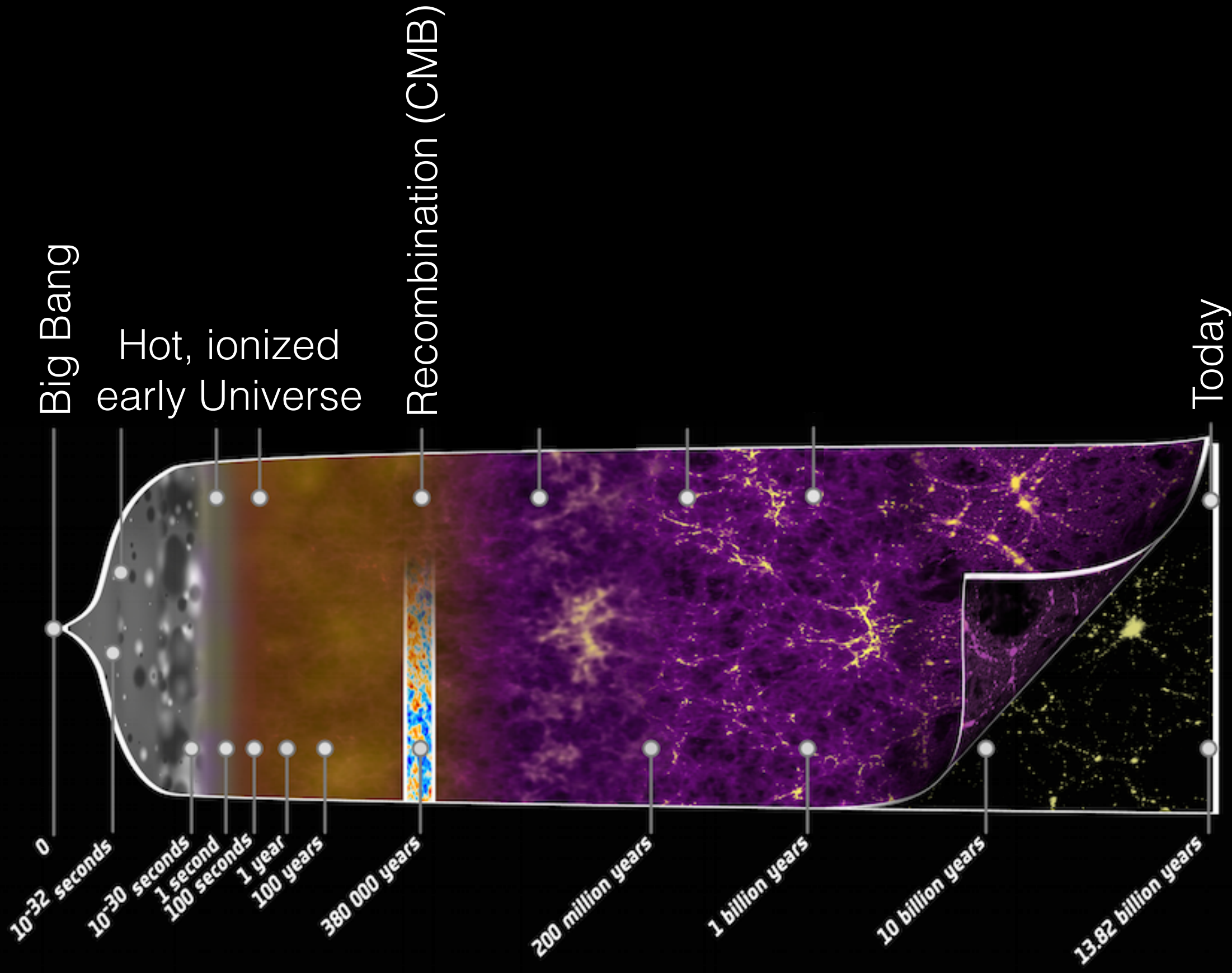




Recombination:

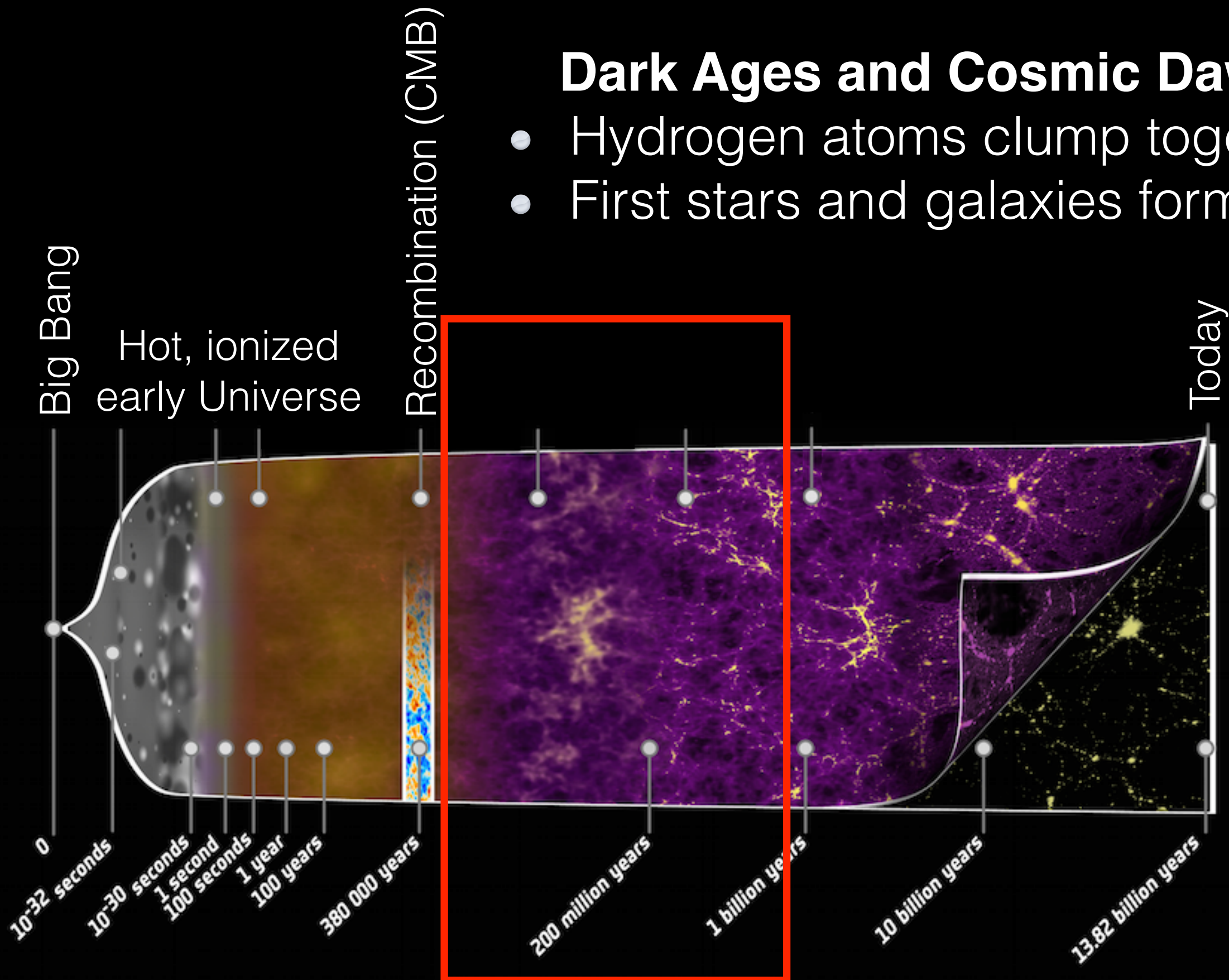
- CMB released
- Universe becomes neutral

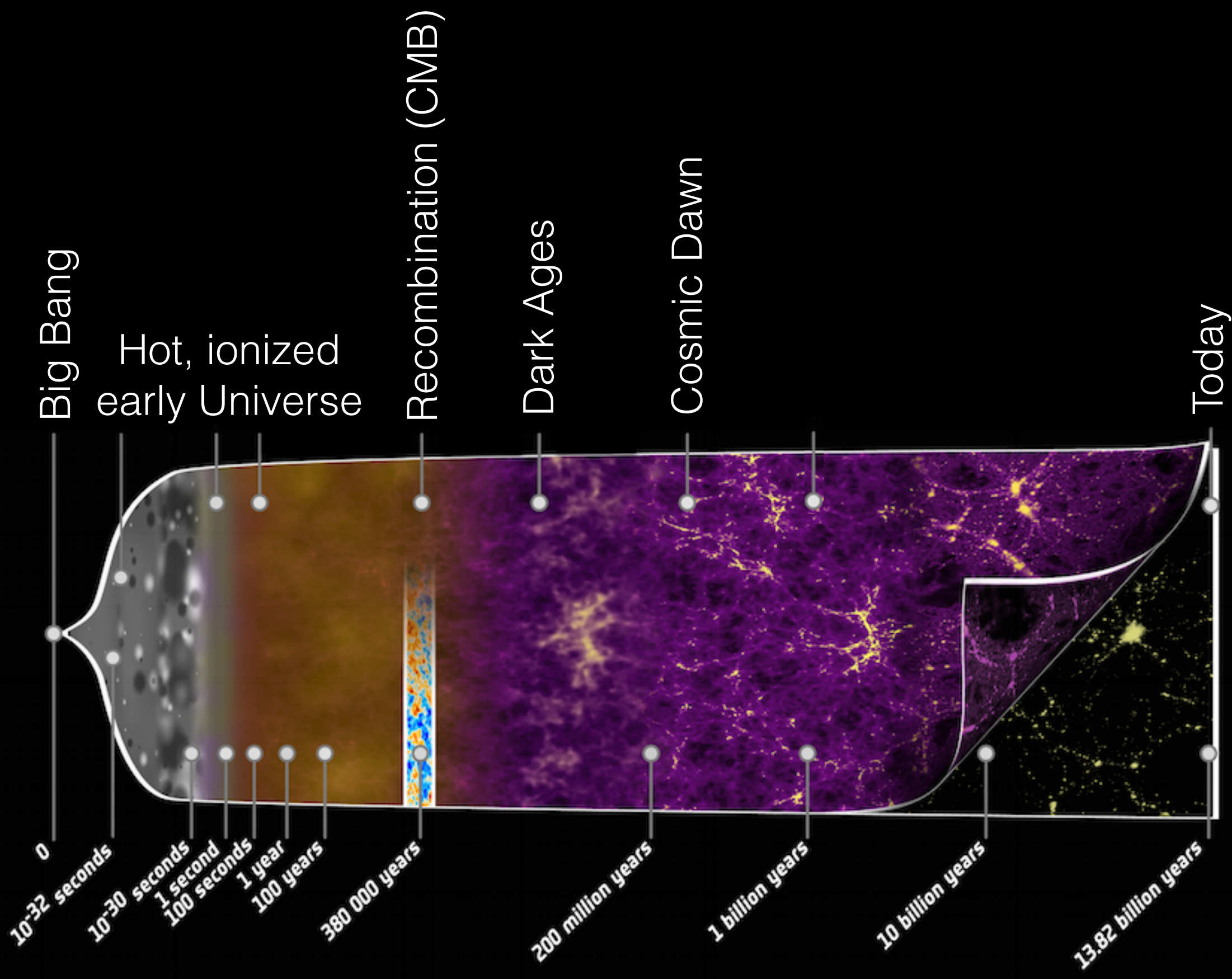




Dark Ages and Cosmic Dawn:

- Hydrogen atoms clump together
- First stars and galaxies form

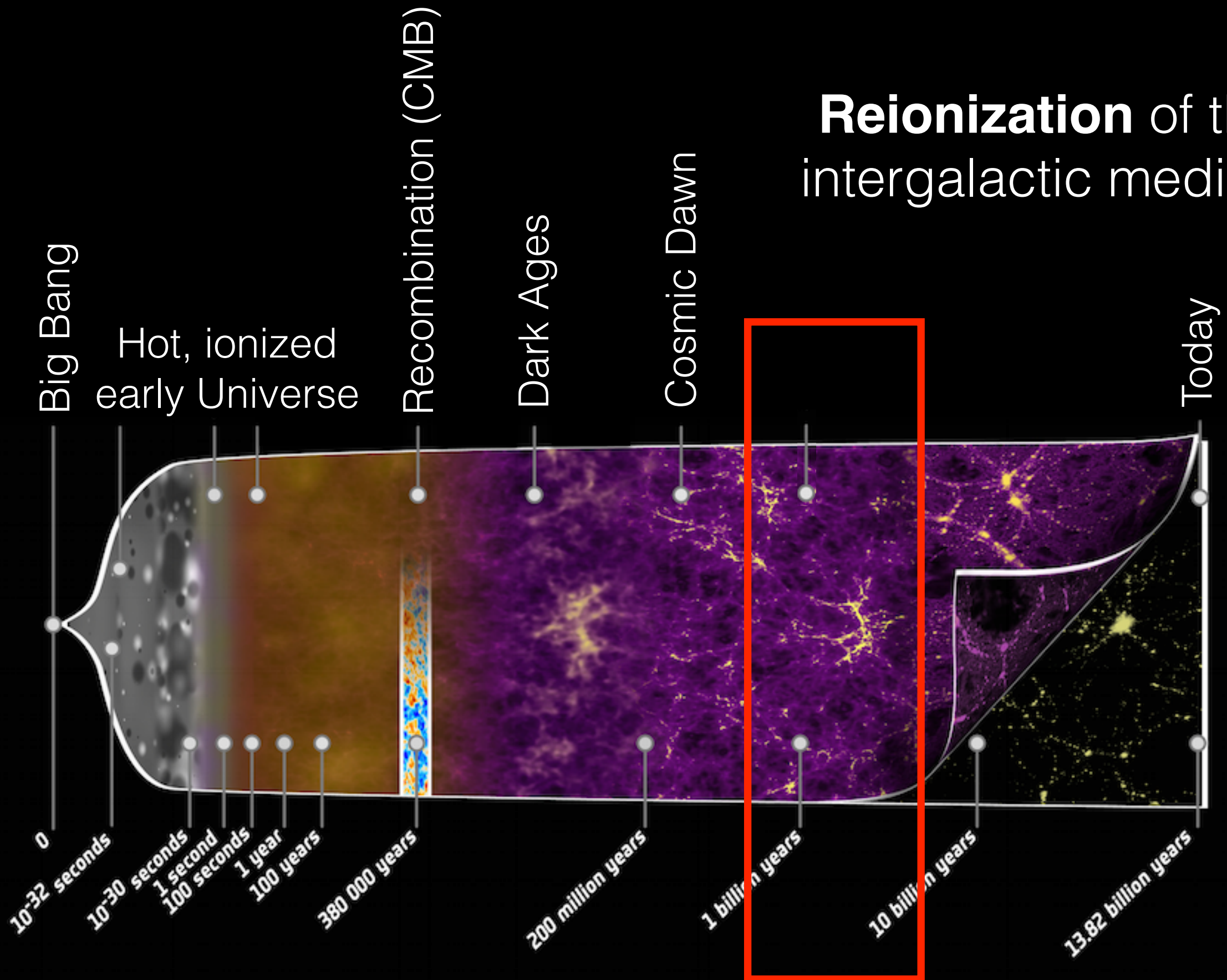


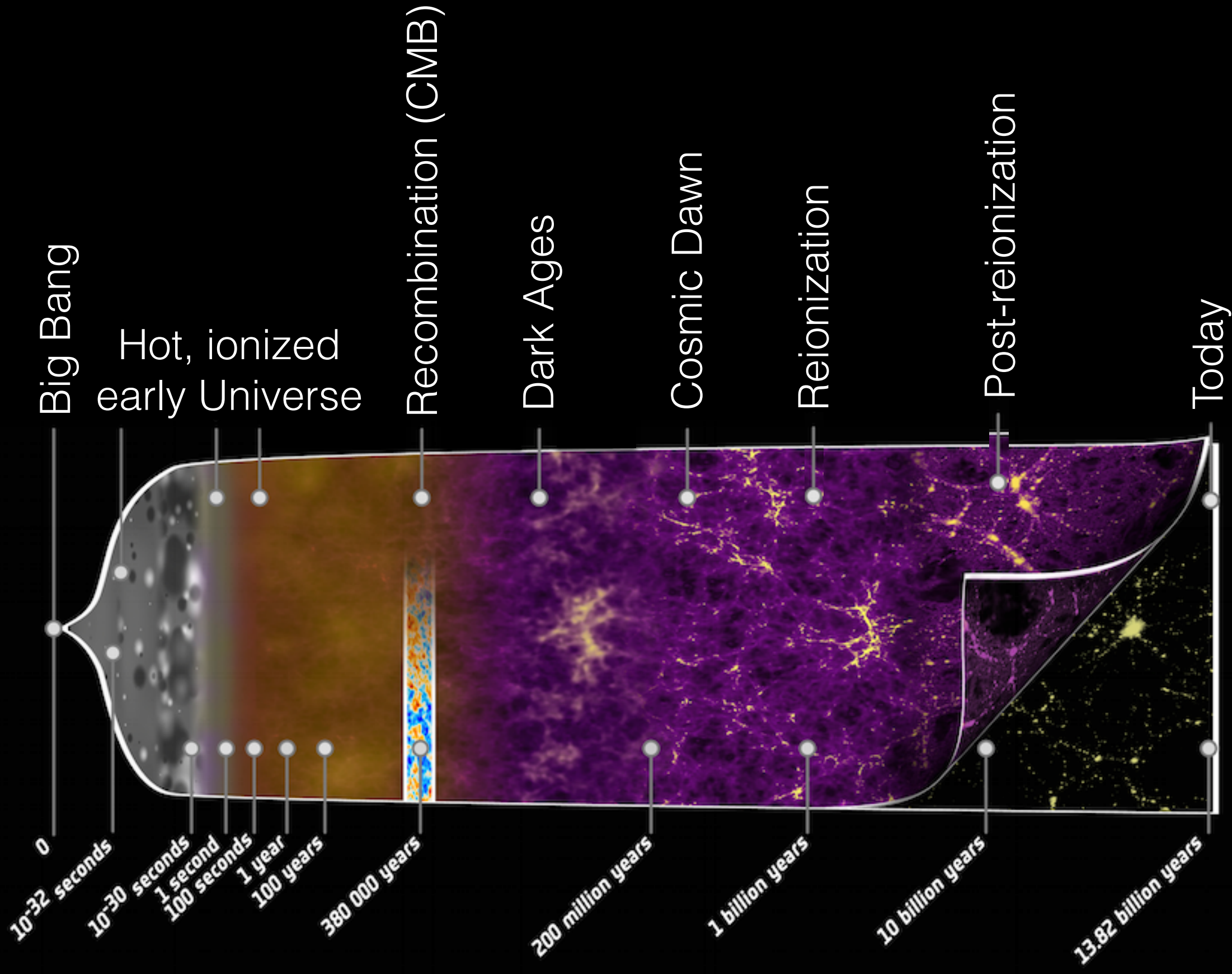




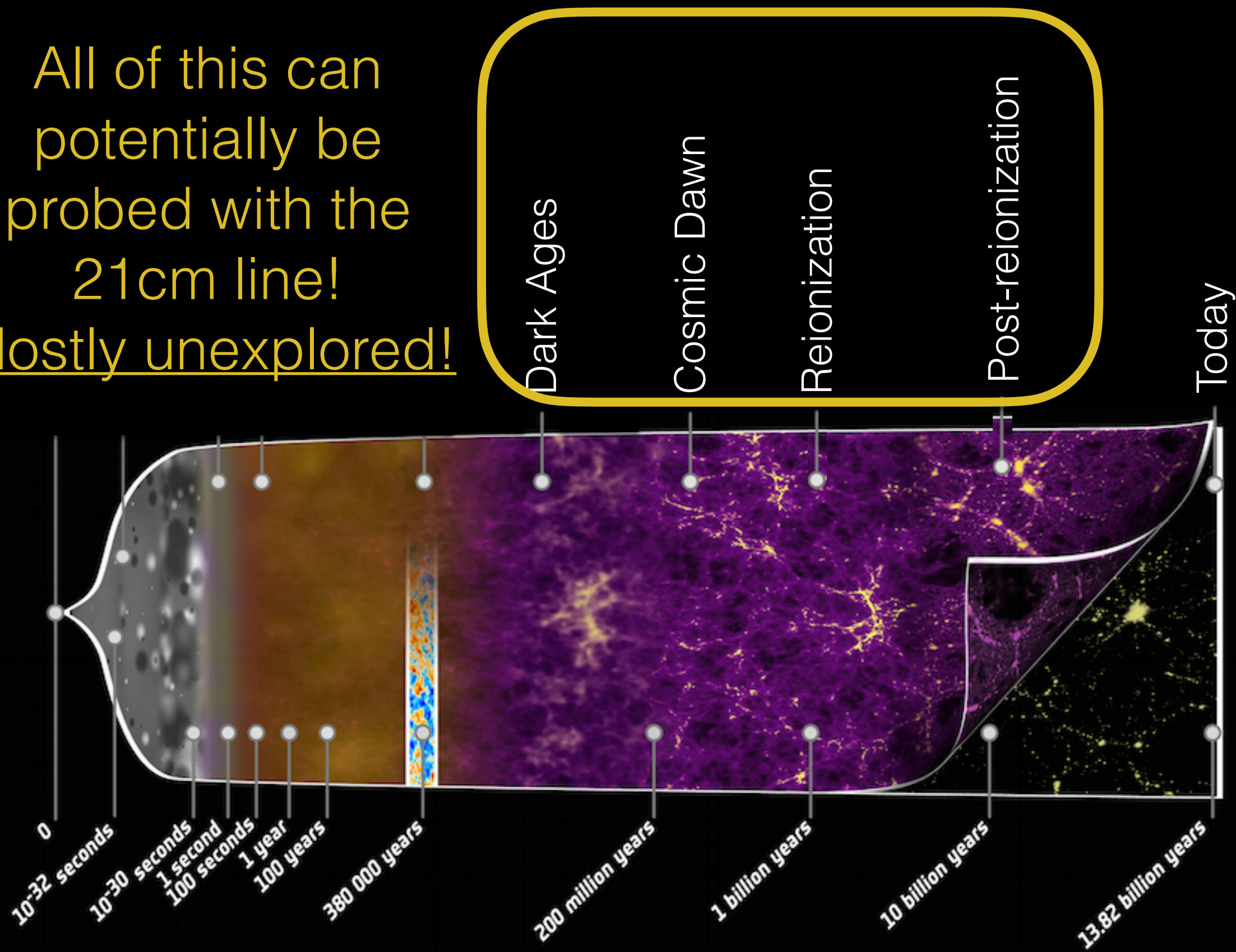
Alvarez et al. (2009)

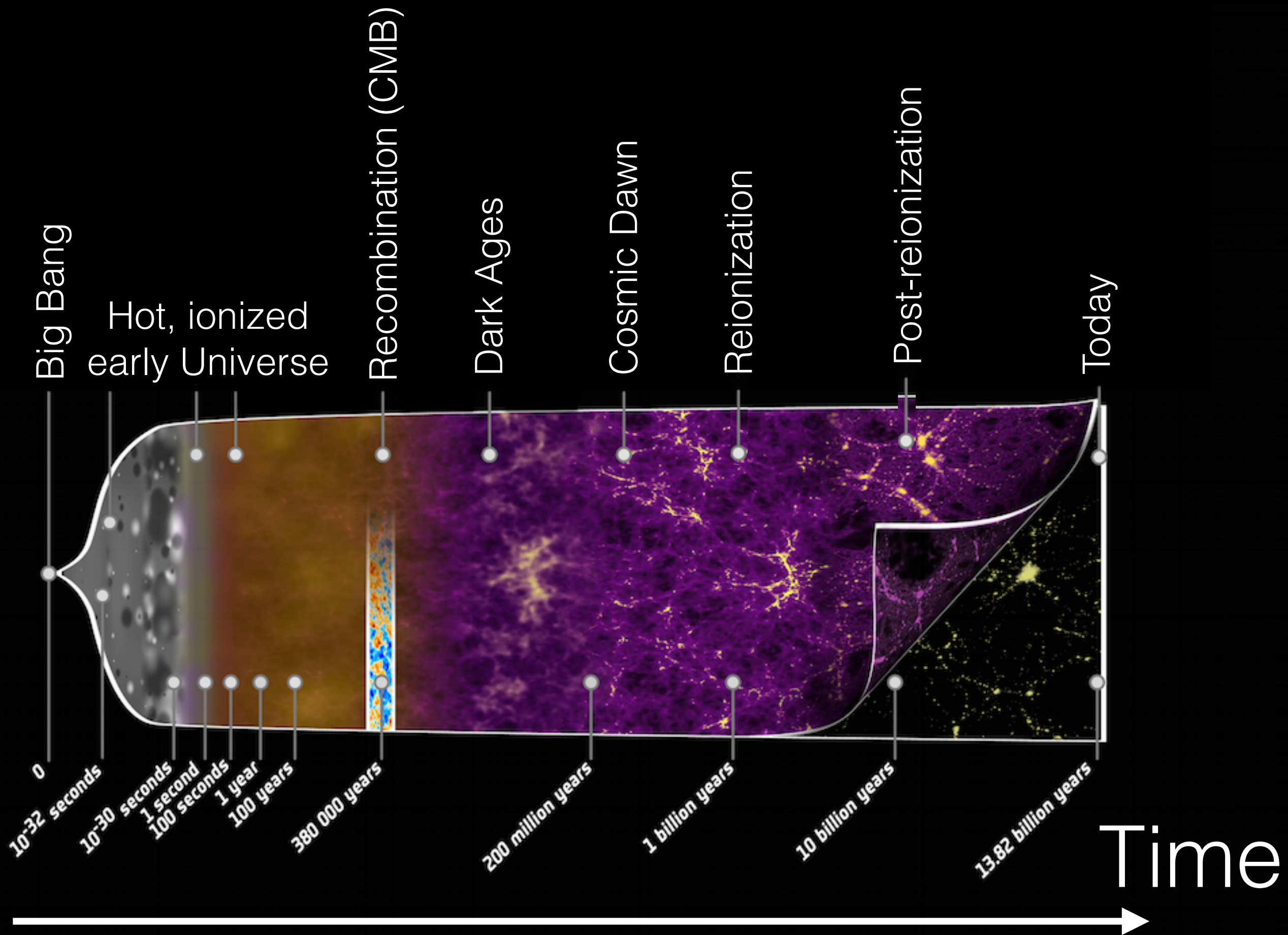
Reionization of the intergalactic medium

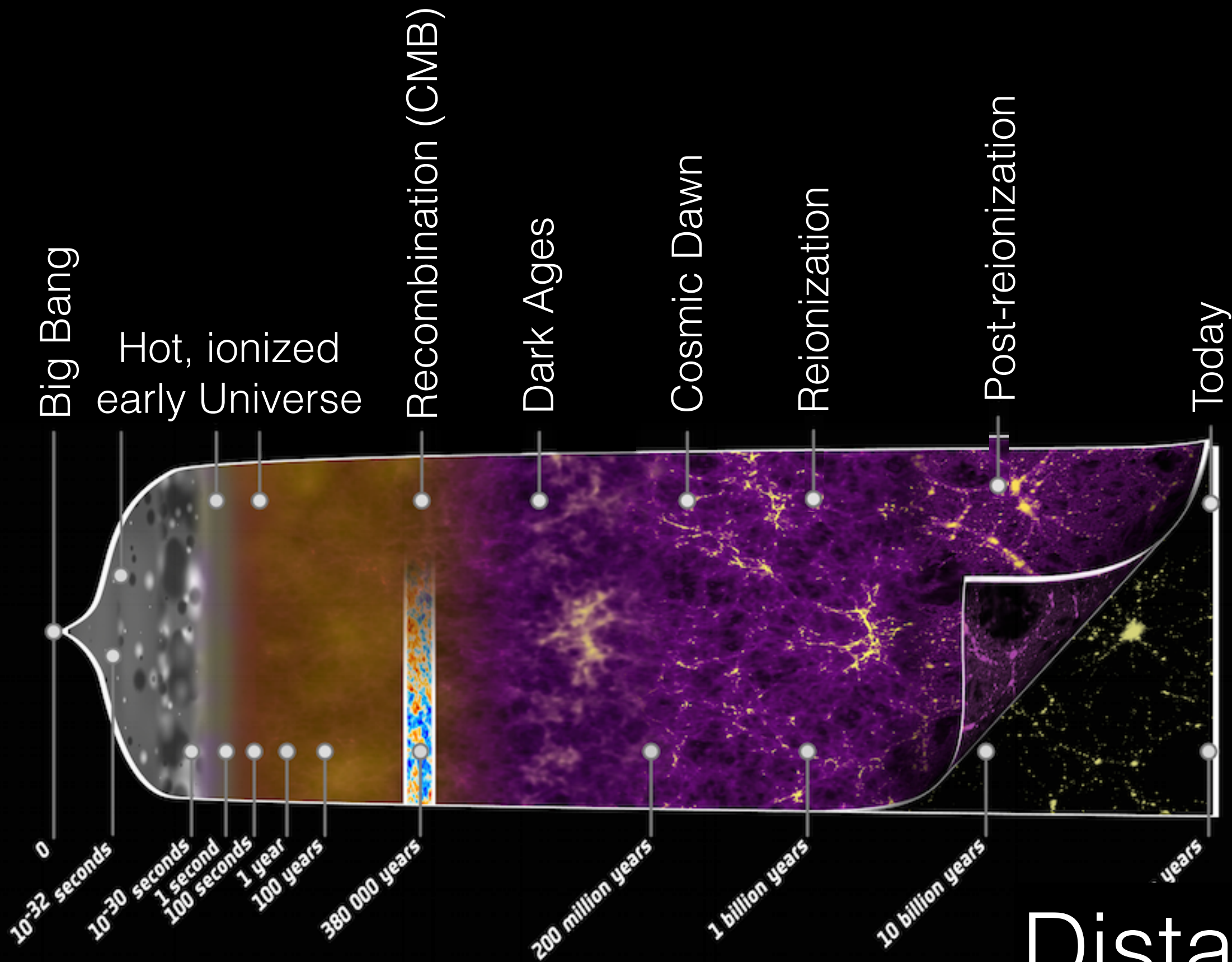


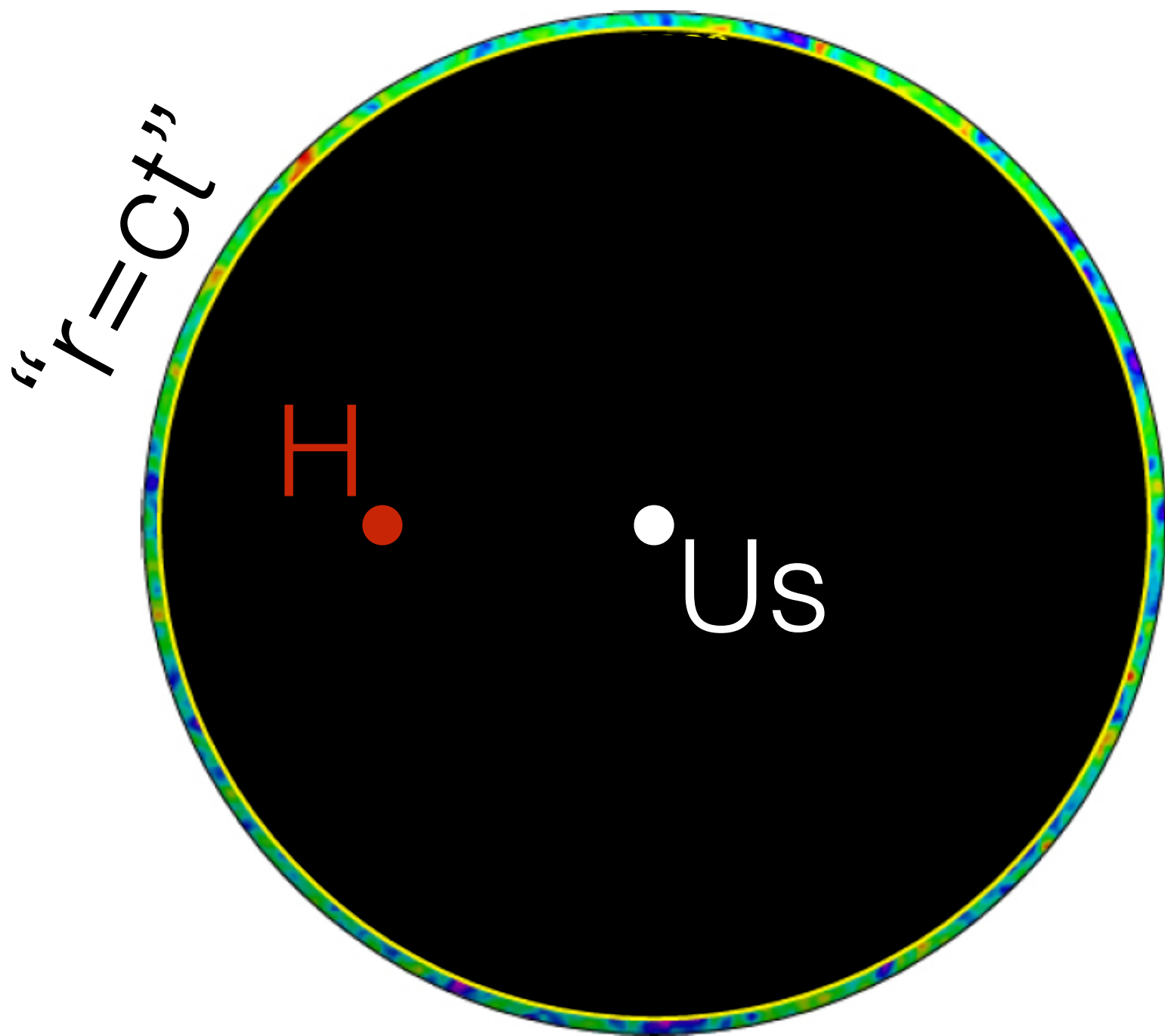


All of this can
potentially be
probed with the
21cm line!
Mostly unexplored!



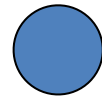
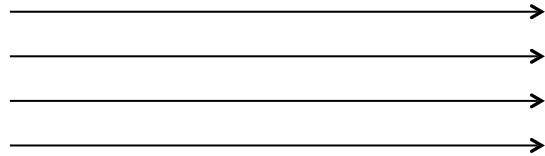




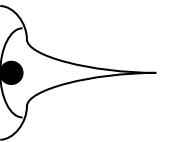
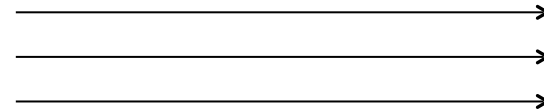


CMB

CMB



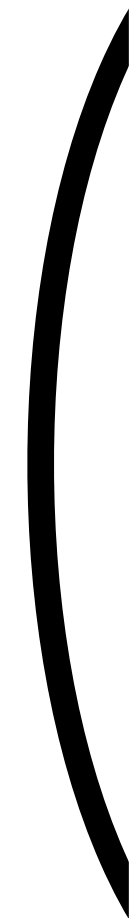
Hydrogen
atom



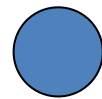
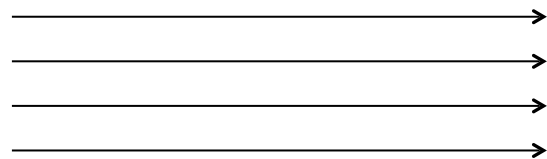
$\Delta T_b \equiv 21\text{cm}$ brightness temperature contrast

$\delta_b \equiv$ baryon overdensity

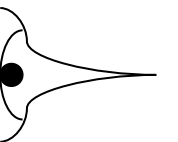
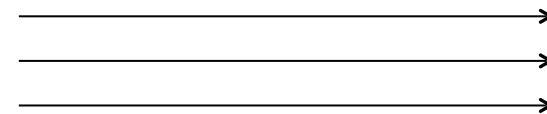
CMB



CMB



Hydrogen
atom

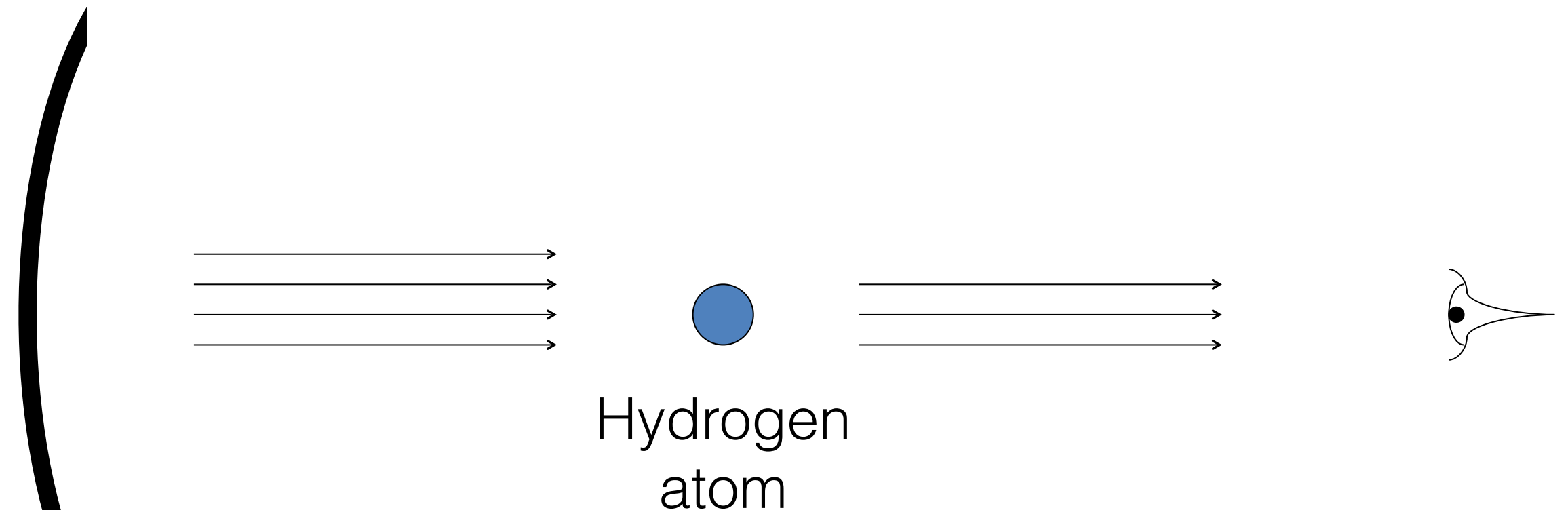


$$\Delta T_b \propto (1 + \delta_b)$$

$\Delta T_b \equiv$ 21cm brightness temperature contrast

$\delta_b \equiv$ baryon overdensity

CMB $x_{HI} \equiv$ neutral fraction (between 0 and 1)



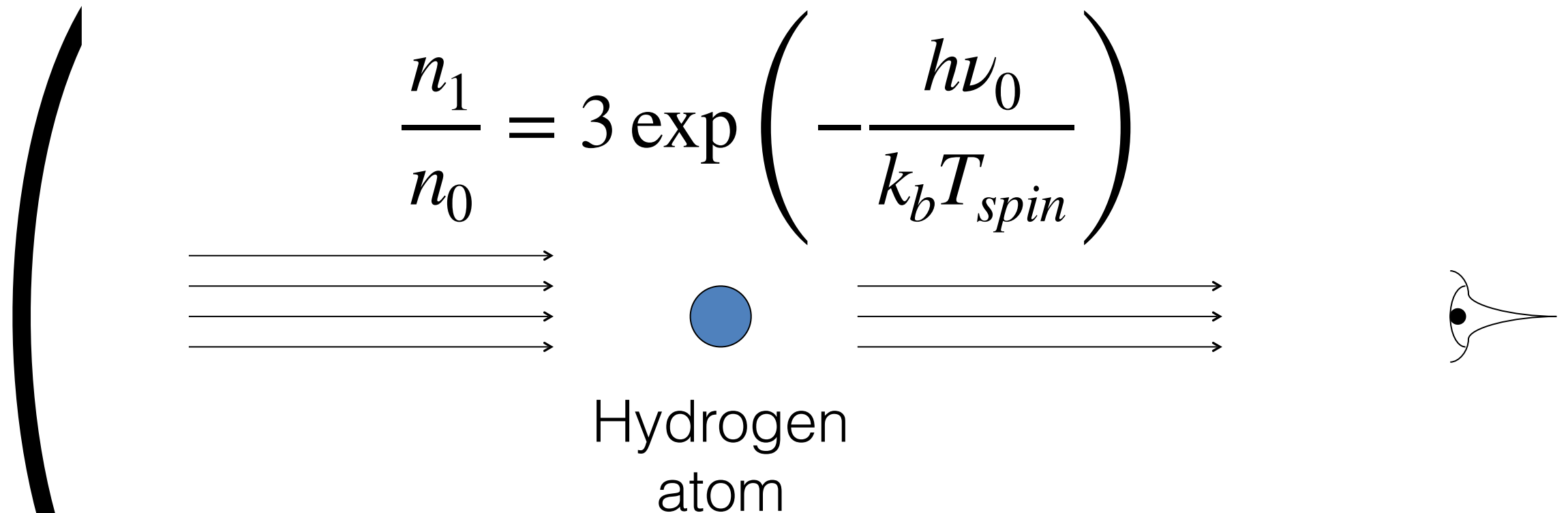
CMB

$$\Delta T_b \propto (1 + \delta_b) x_{HI}$$

$\Delta T_b \equiv$ 21cm brightness temperature contrast

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CMB $x_{HI} \equiv$ neutral fraction (between 0 and 1)

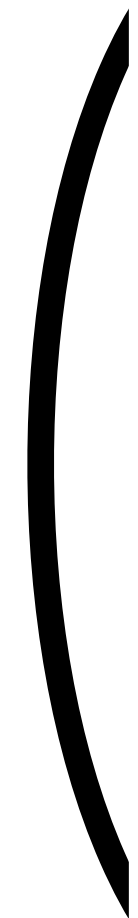


CMB

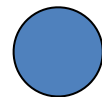
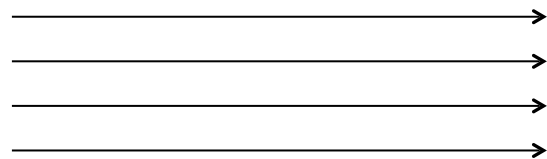
$$\Delta T_b \propto (1 + \delta_b) x_{HI} \left(1 - \frac{T_{\text{CMB}}}{T_{\text{spin}}} \right)$$

The redshifted 21cm line is very sensitive to **physics** and **astrophysics**

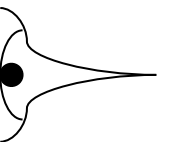
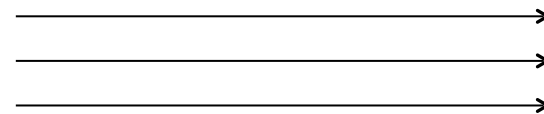
CMB



CMB

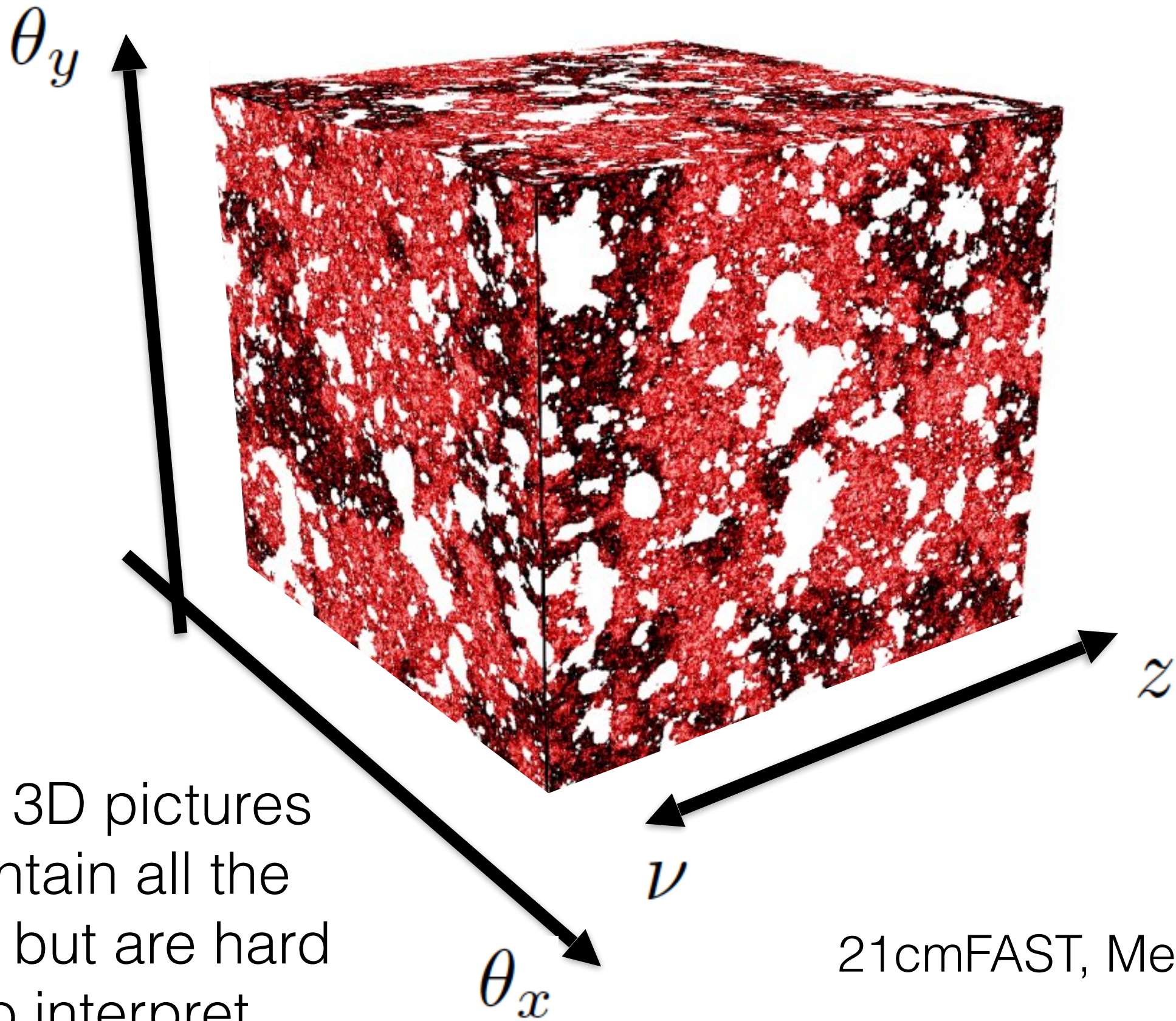


Hydrogen
atom



$$\Delta T_b \propto (1 + \delta_b) x_{HI} \left(1 - \frac{T_{\text{CMB}}}{T_{\text{spin}}} \right)$$

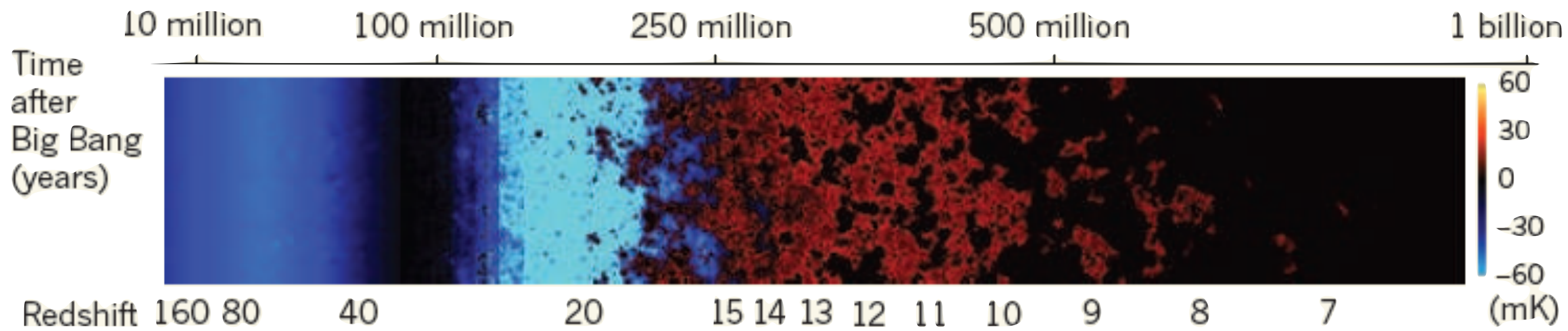
How do we extract this
information?



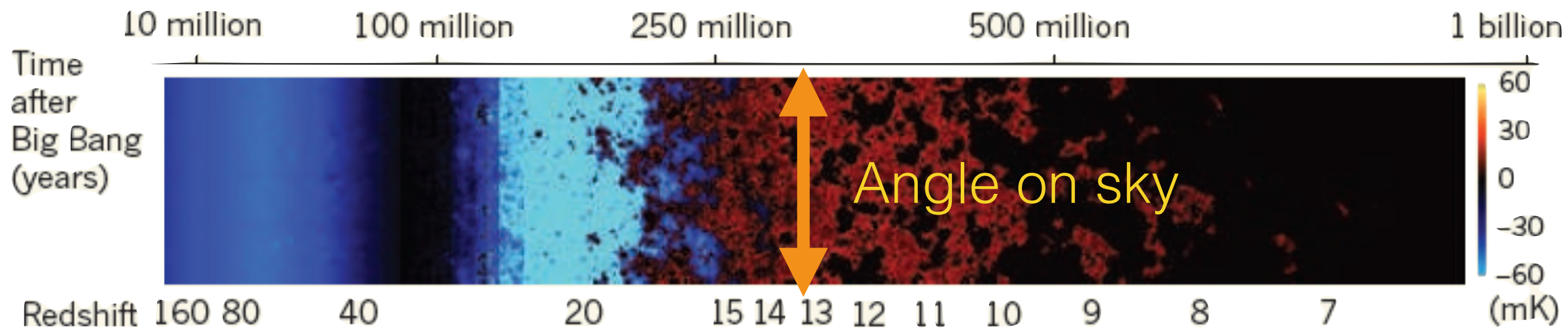
Full 3D pictures
contain all the
info, but are hard
to interpret

21cmFAST, Mesinger et al.

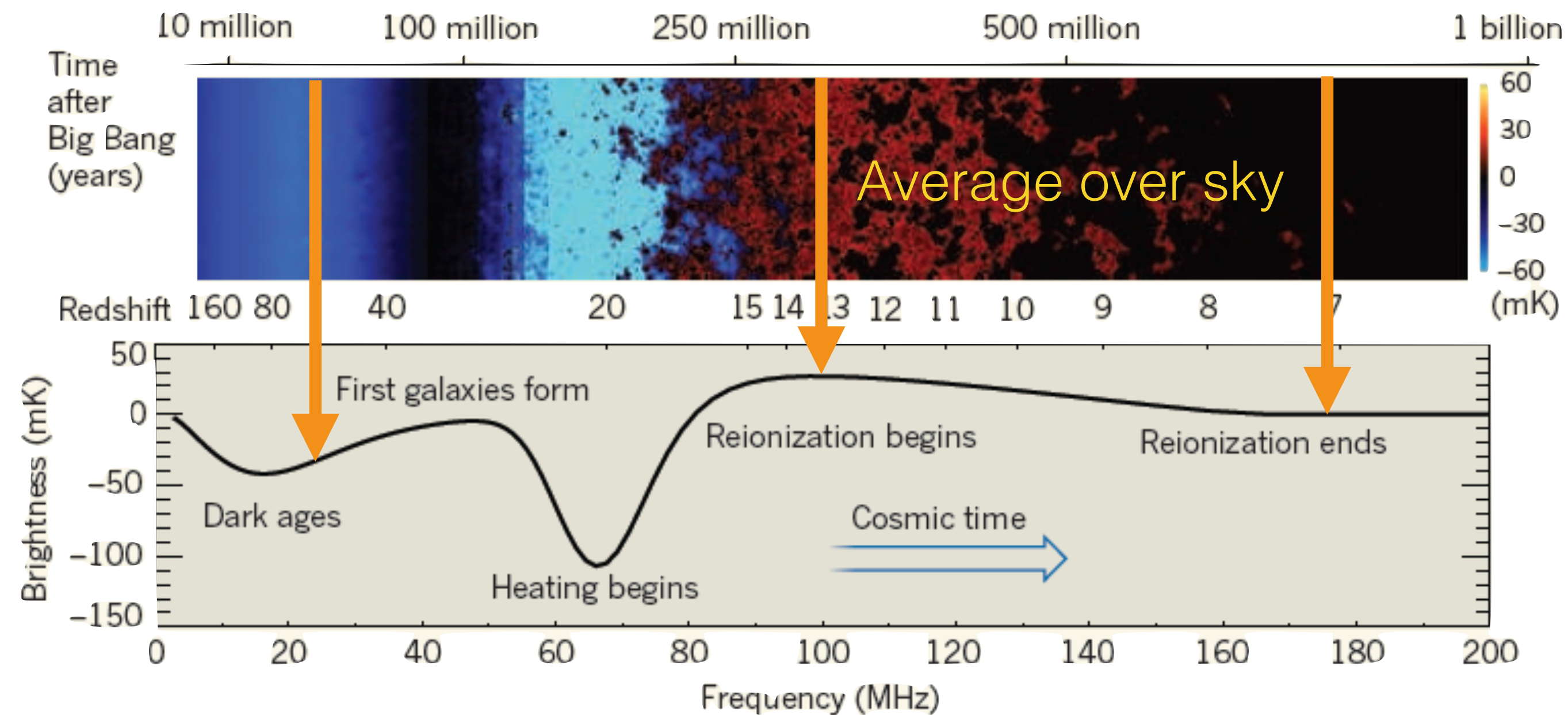
A simpler summary statistic:
the “global signal”



Pritchard & Loeb (2010)

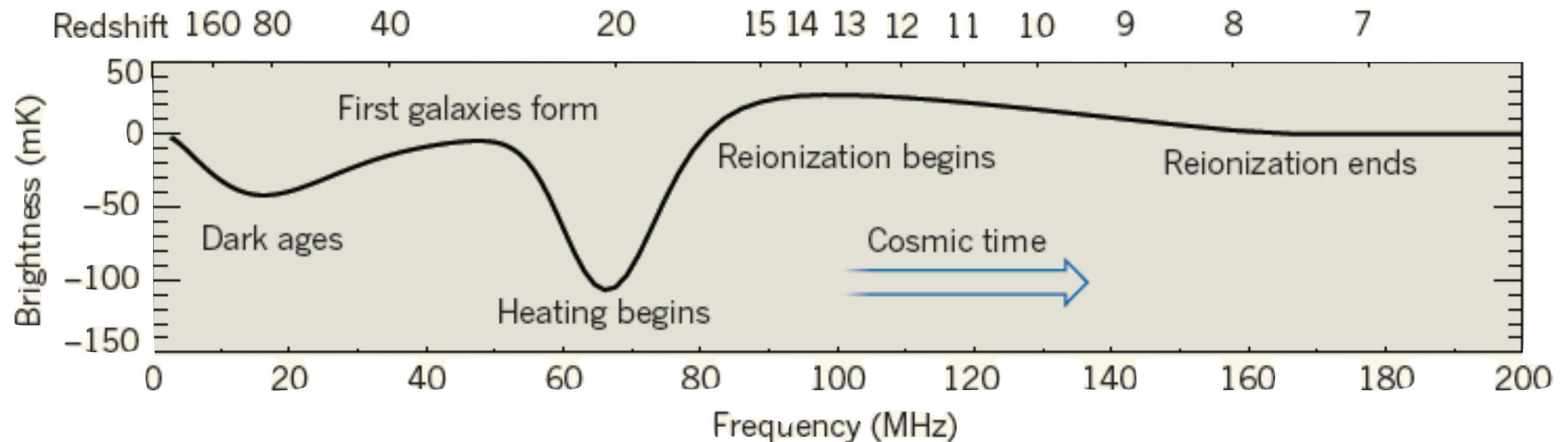


Pritchard & Loeb (2010)



Pritchard & Loeb (2010)

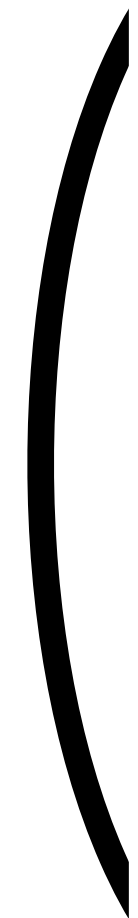
What gives rise to this shape?



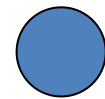
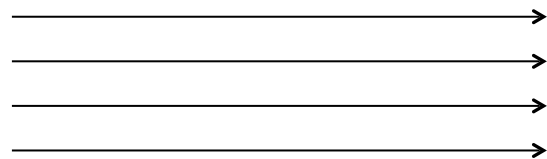
Pritchard & Loeb (2010)

The redshifted 21cm line is also sensitive to **astrophysics**

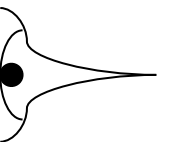
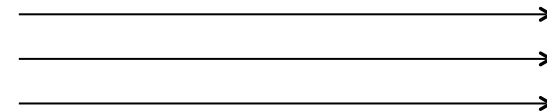
CMB



CMB

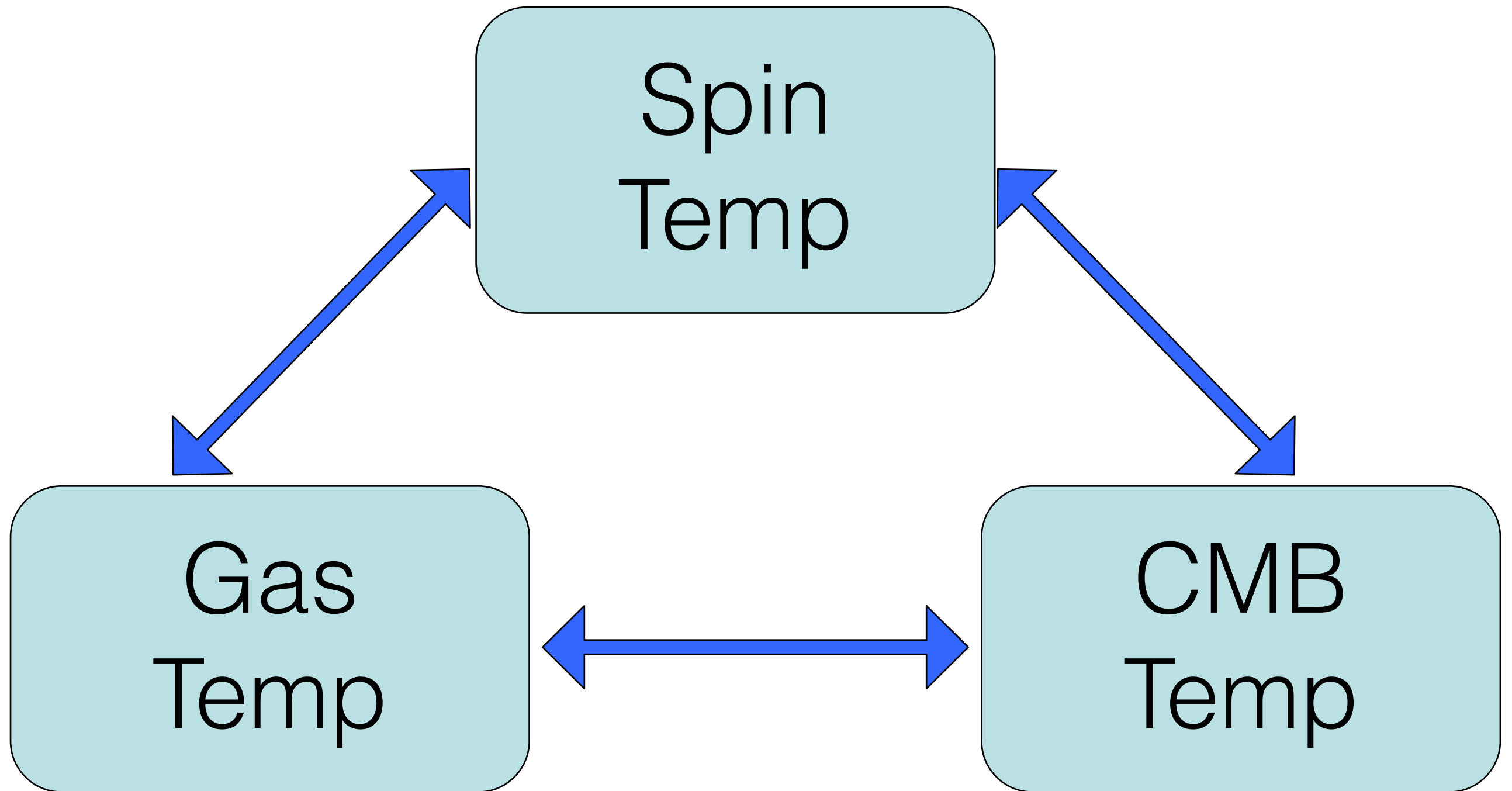


Hydrogen
atom

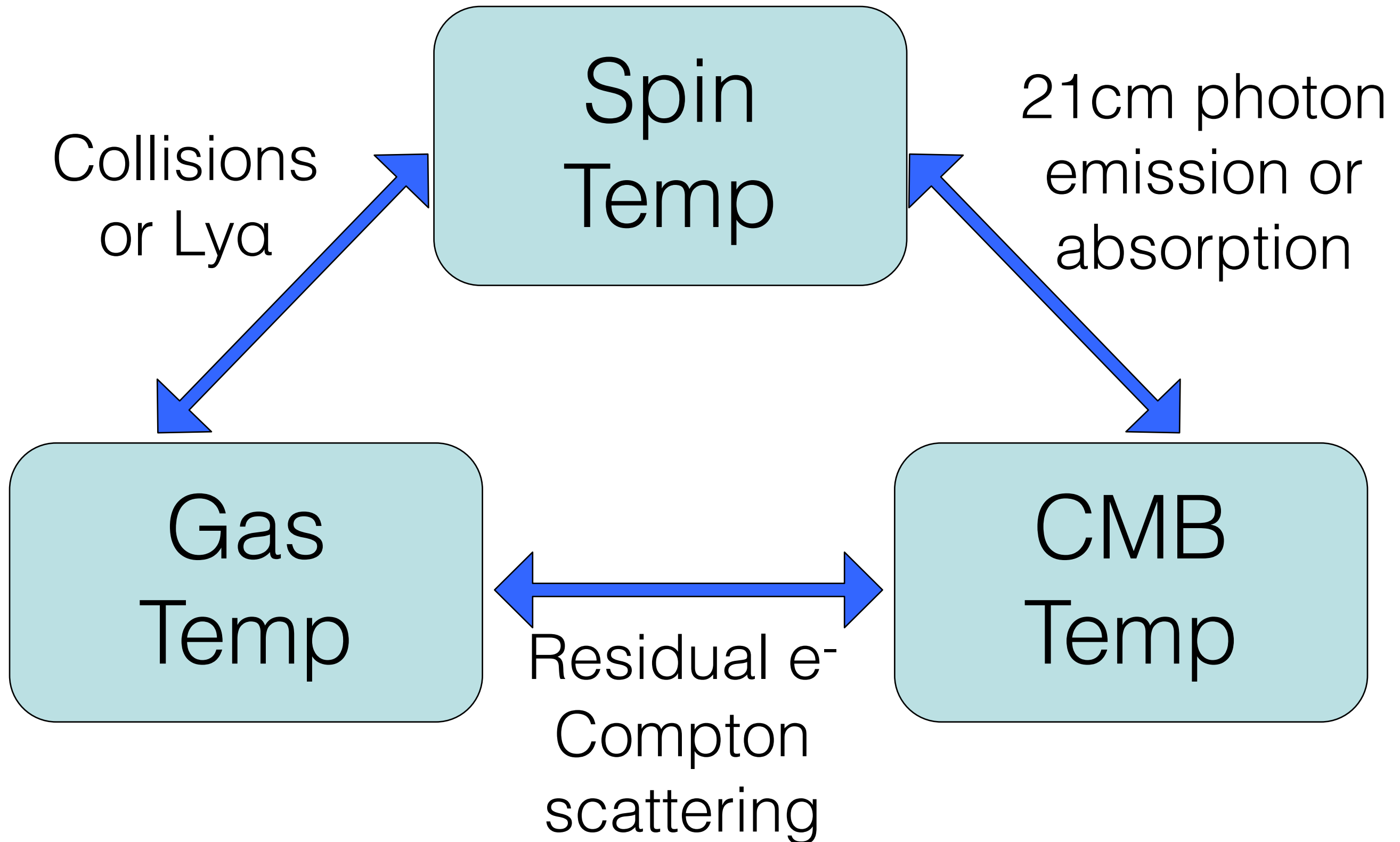


$$\Delta T_b \propto (1 + \delta_b) x_{HI} \left(1 - \frac{T_{\text{CMB}}}{T_{\text{spin}}} \right)$$

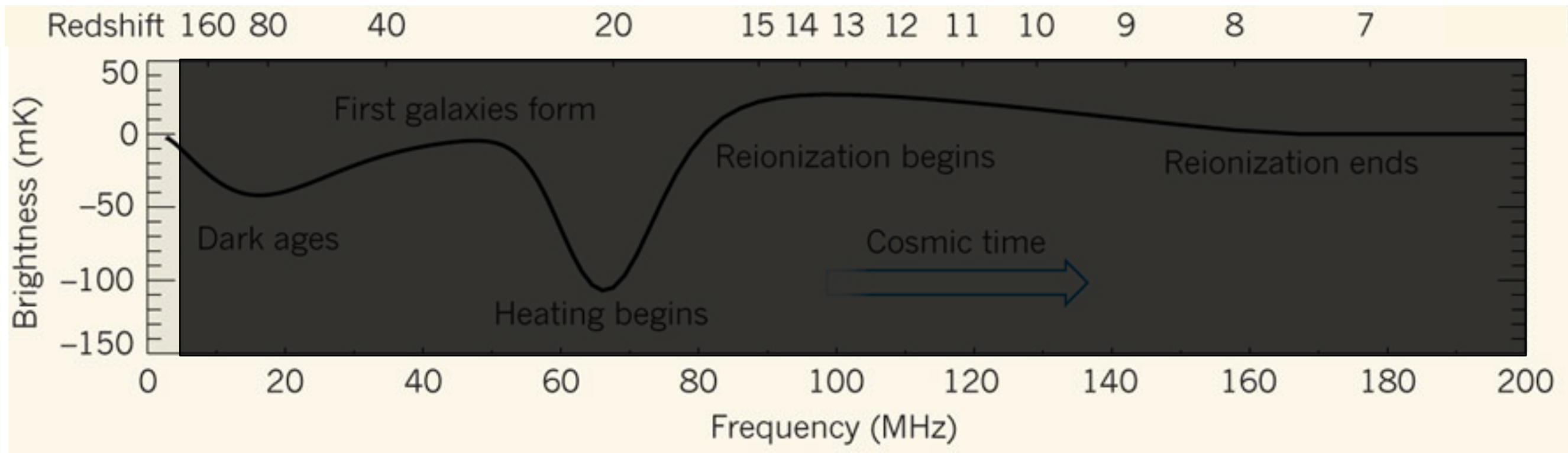
So many temperatures!



So many temperatures!



Phase I



- Residual electrons drive T_{gas} to T_{CMB} via Compton scattering
- Collisions drive T_{gas} to T_{spin}

In this phase, we see the
hydrogen...

- A. As an **absorption** signal
- B. There is **no** signal
- C. As an **emission** signal

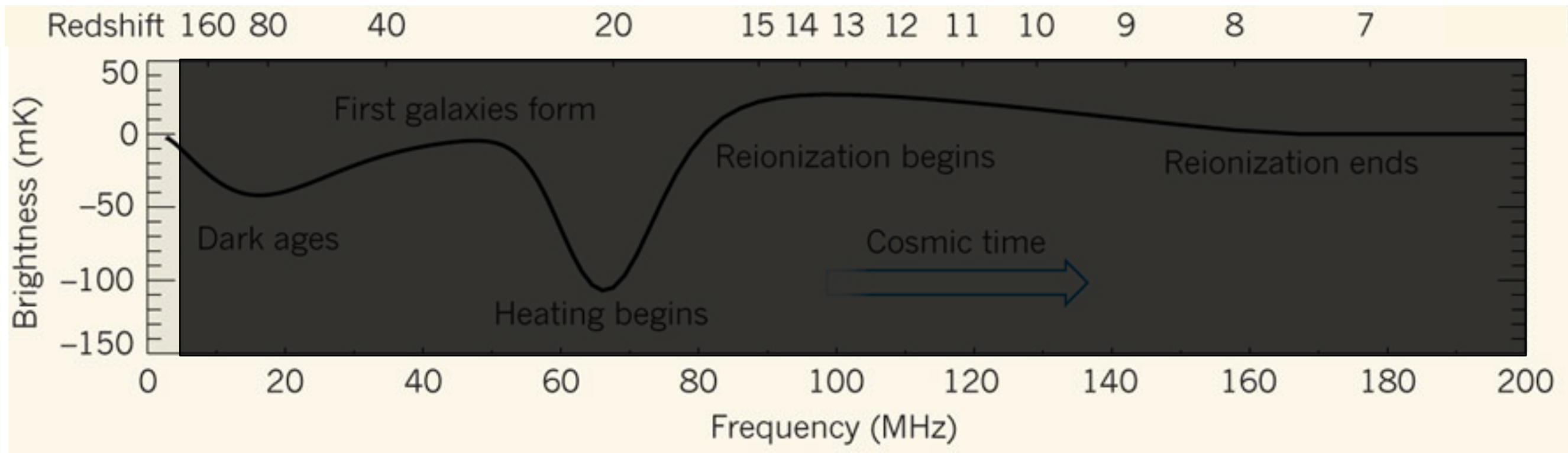
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A. As an **absorption** signal

B. There is **no** signal

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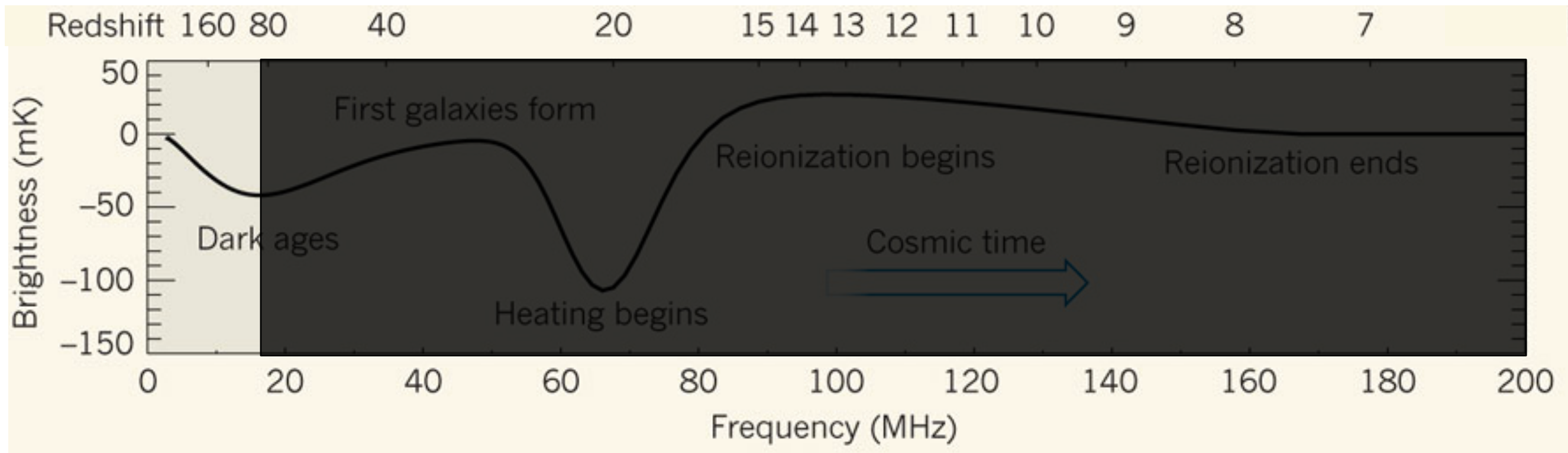
Phase I: No Signal



- Residual electrons drive T_{gas} to T_{CMB} via Compton scattering
- Collisions drive T_{gas} to T_{spin}

NO SIGNAL

Phase II



- Collisions maintain T_{gas} and T_{spin} equilibrium
- CMB has become too dilute for T_{CMB} and T_{gas} coupling
- $T_{\text{spin}} = T_{\text{gas}} \sim a^{-2}$ while $T_{\text{CMB}} \sim a^{-1}$

In this phase, we see the
hydrogen...

- A. As an **absorption** signal
- B. There is **no** signal
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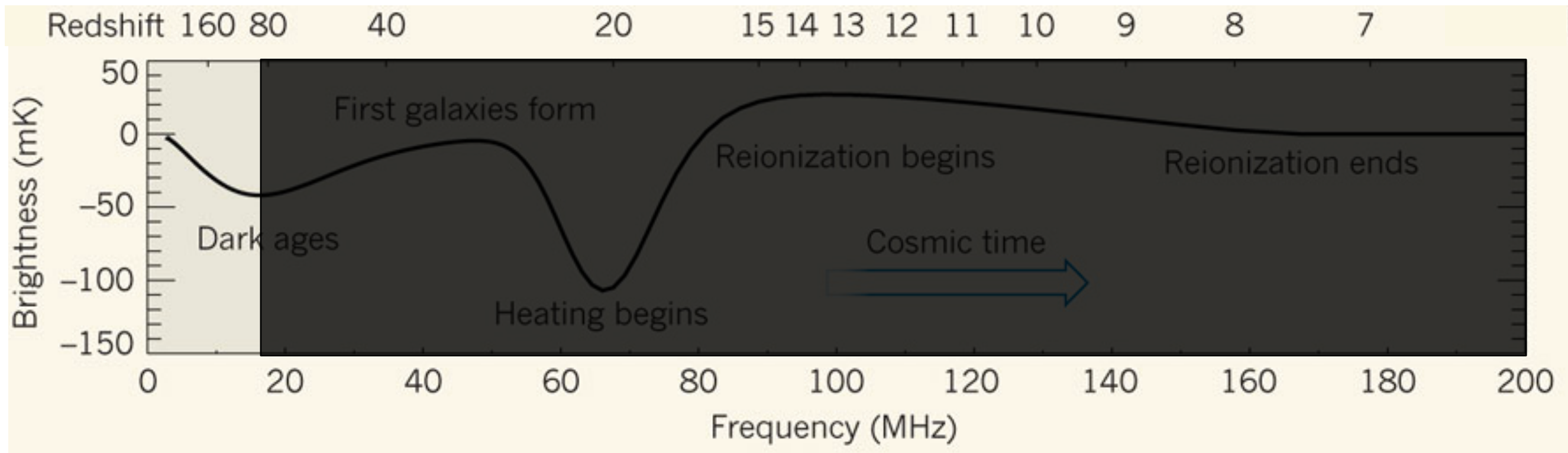
In this phase, we see the
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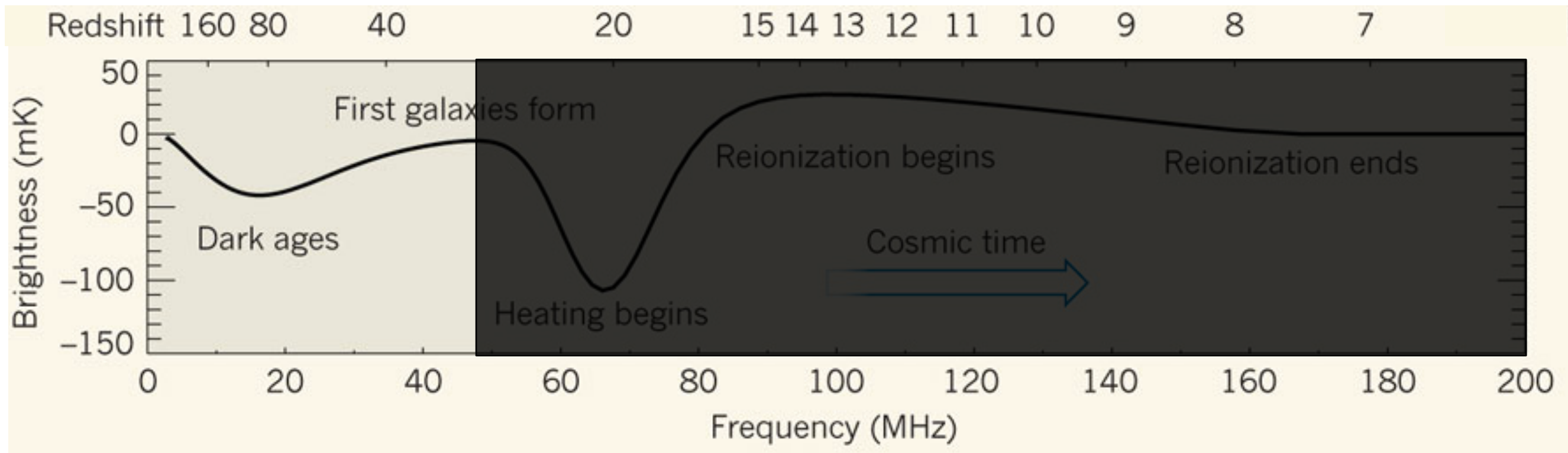
Phase II: Absorption Signal



- Collisions maintain T_{gas} and T_{spin} equilibrium
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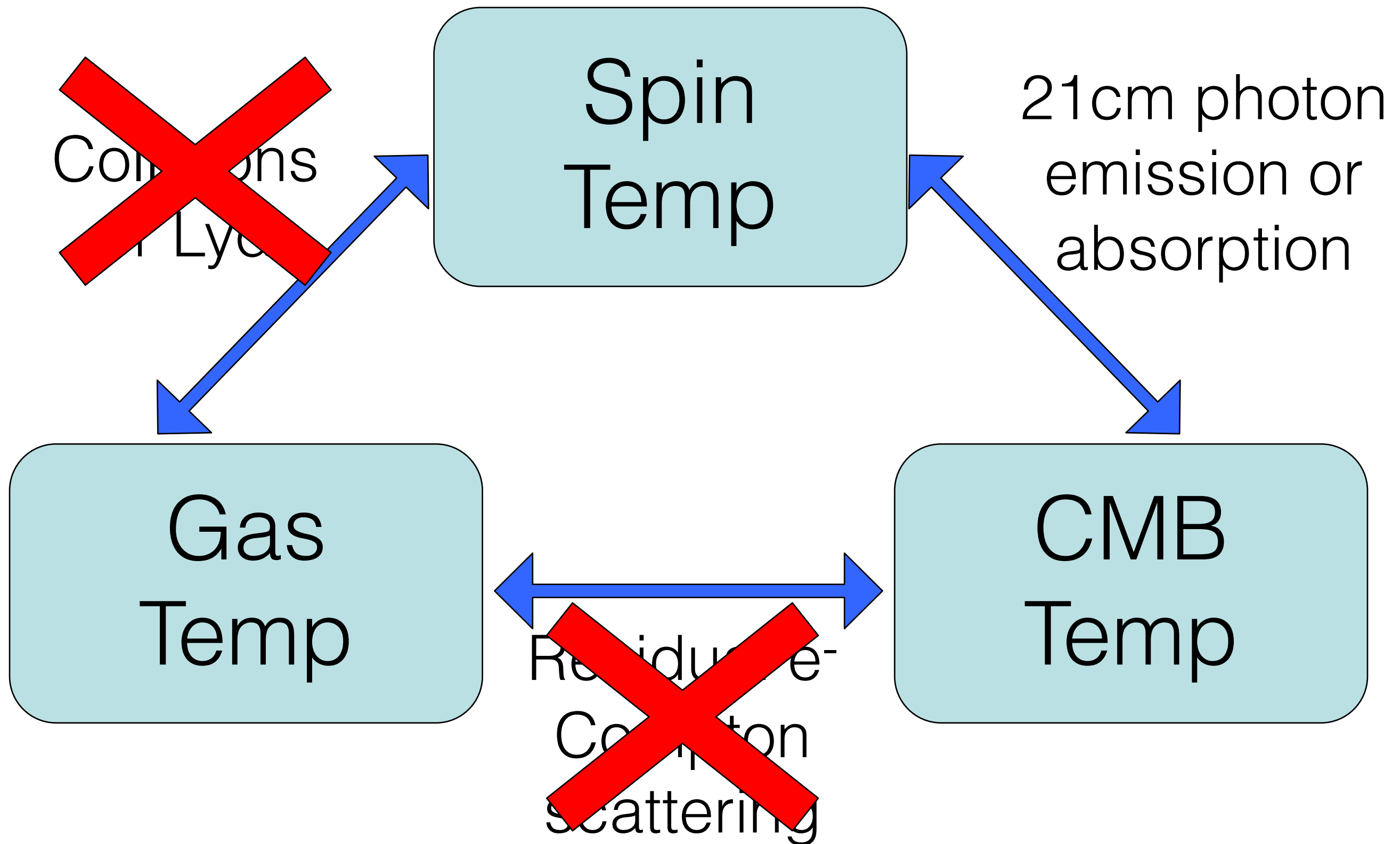
ABSORPTION

Phase III: Back to nothing

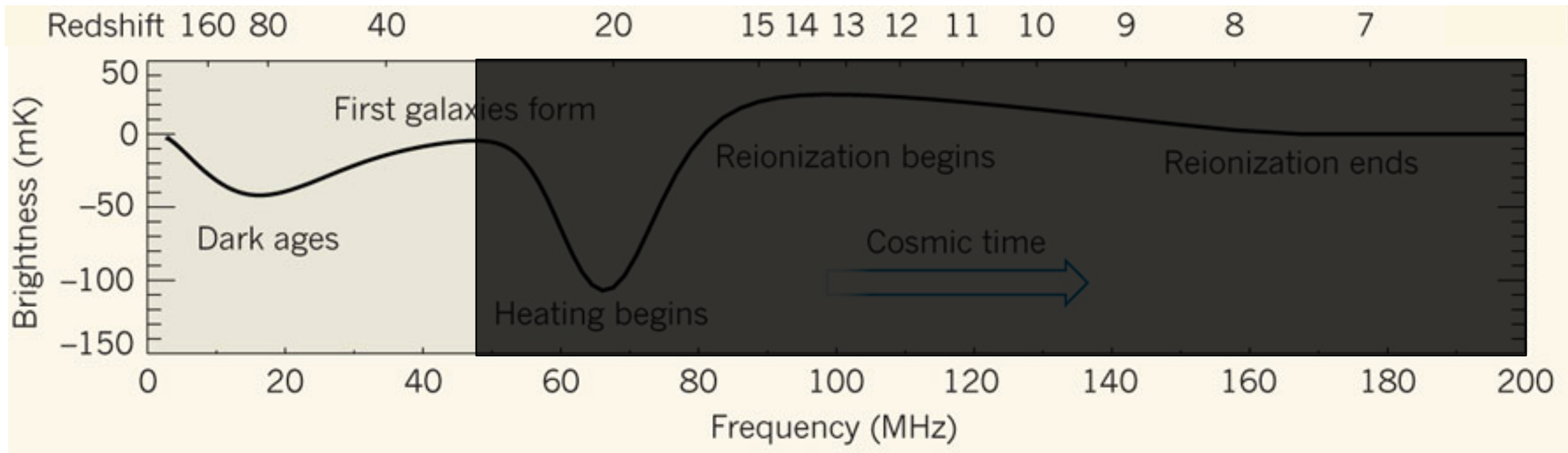


- Gas becomes too dilute for collisions to keep T_{gas} and T_{spin} in equilibrium

So many temperatures!



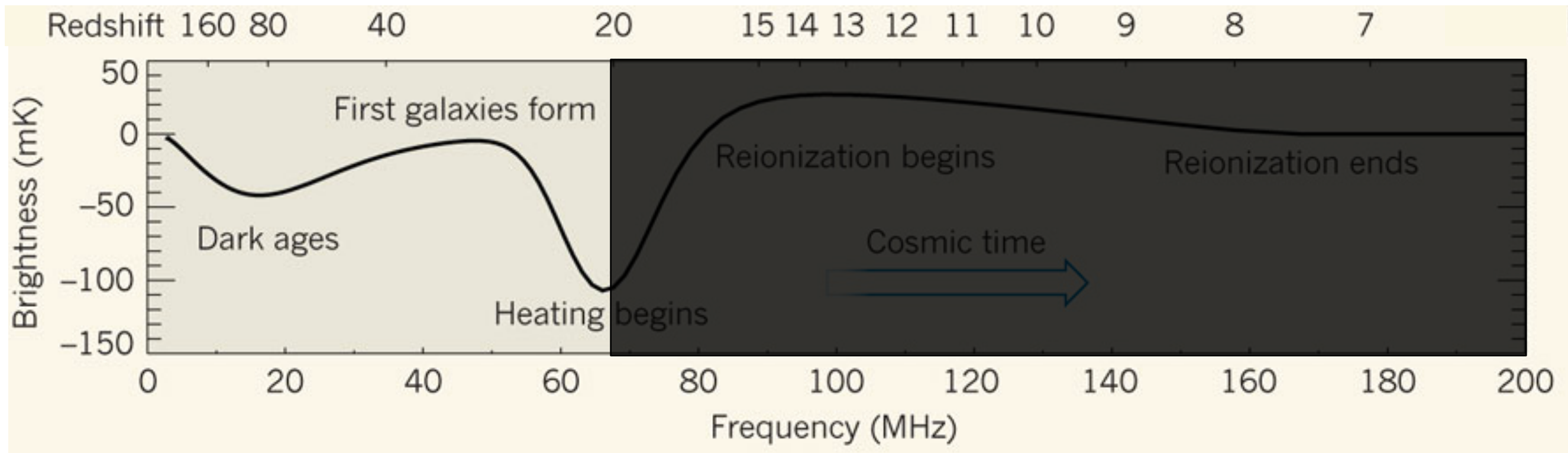
Phase III: Back to nothing



- Gas becomes too dilute for collisions to keep T_{gas} and T_{spin} in equilibrium
- Absorp./emission of 21cm photons makes $T_{\text{spin}} = T_{\text{CMB}}$

NO SIGNAL

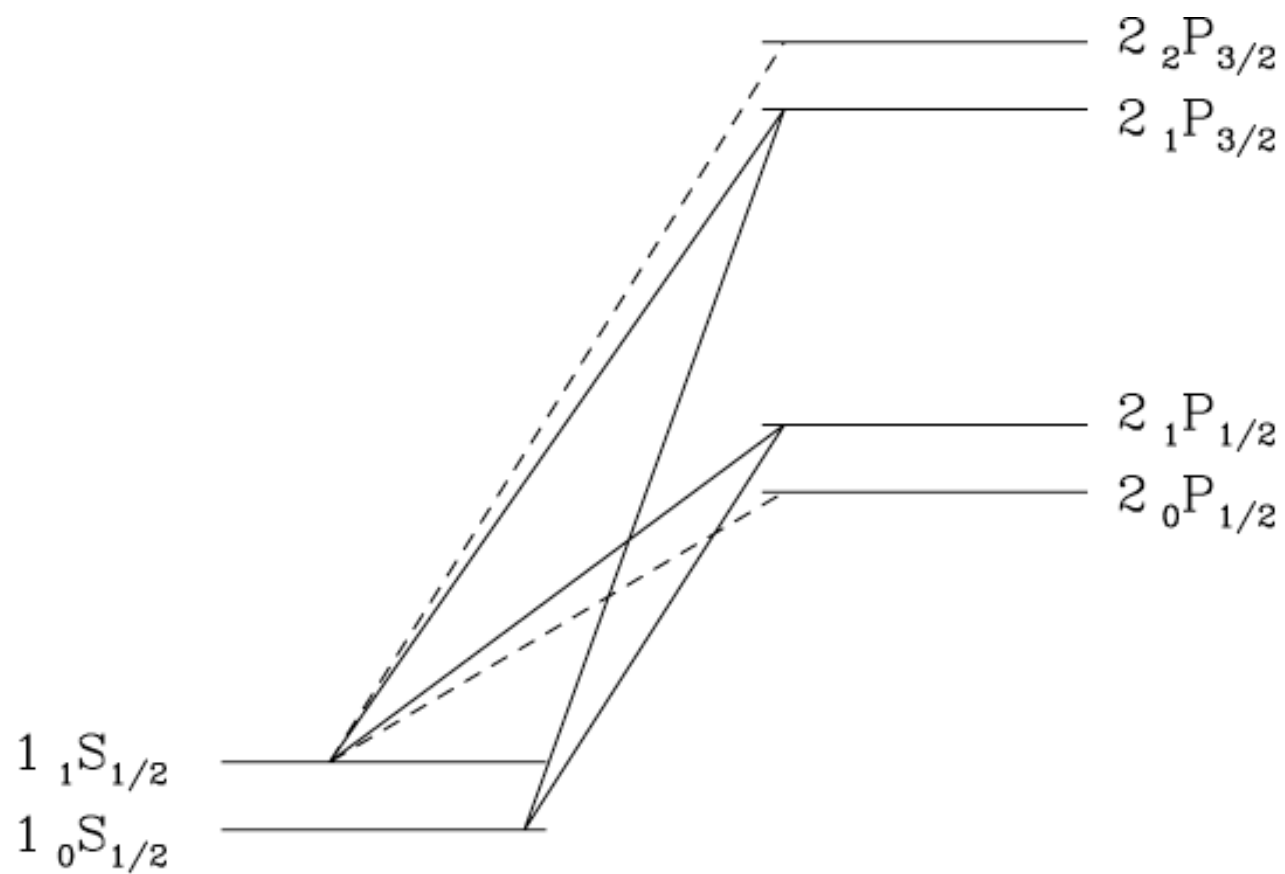
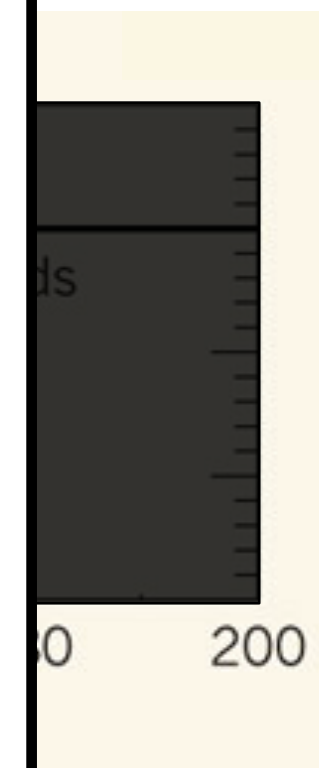
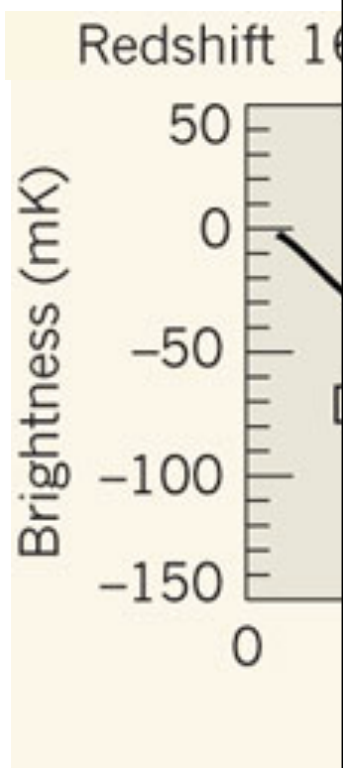
Phase IV: First stars/galaxies form



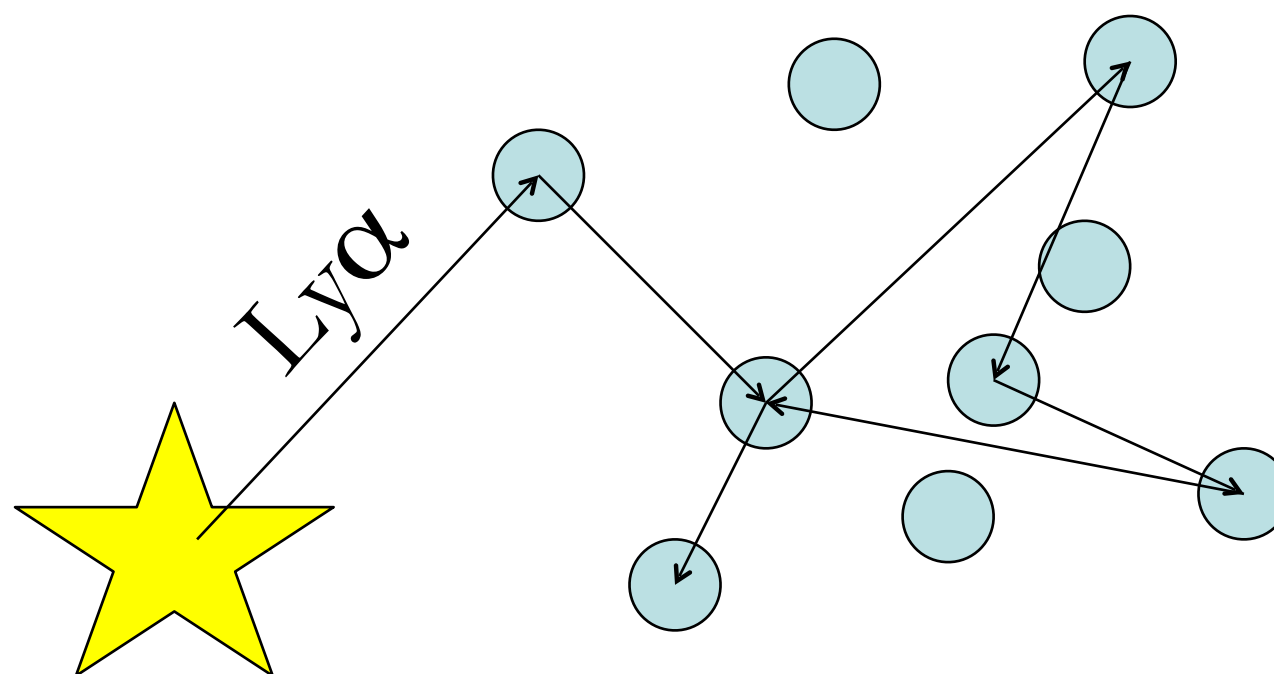
- First stars create Ly α photons, causes coupling between T_{gas} and T_{spin} via Wouthuysen-Field effect

Phase

form

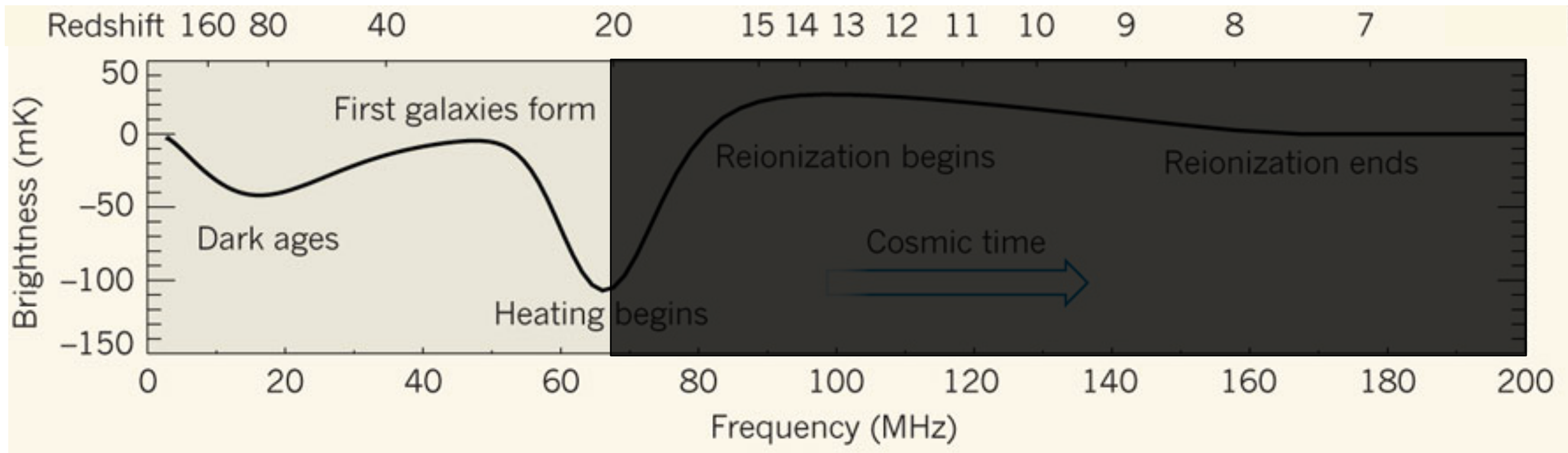


- First
between



ect

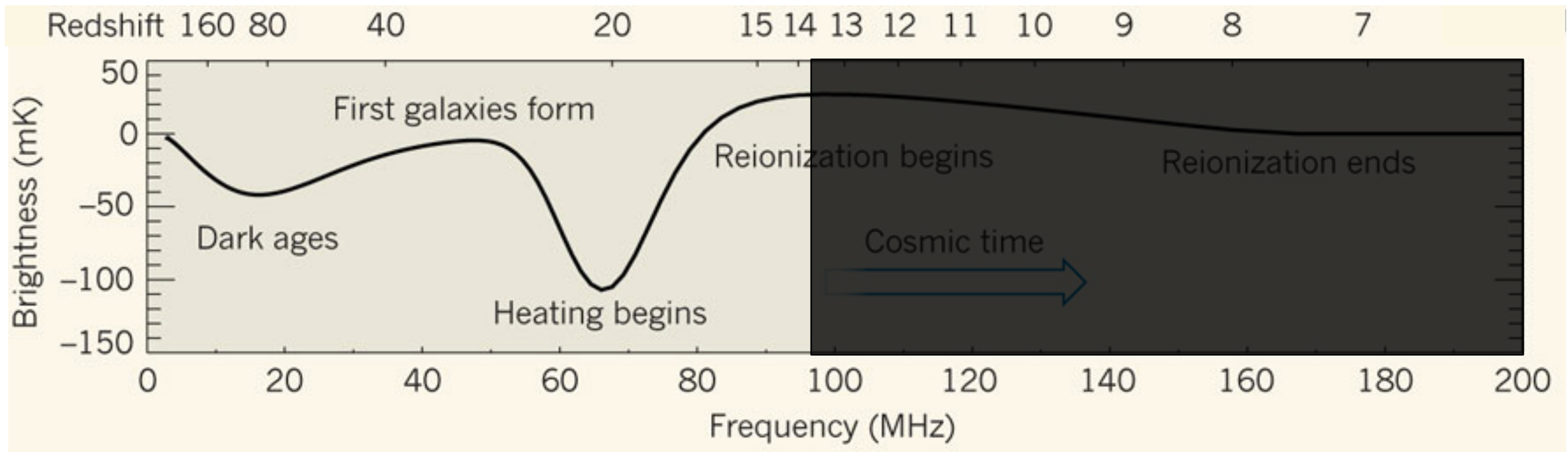
Phase IV: First stars/galaxies form



- First stars create Ly α photons, causes coupling between T_{gas} and T_{spin} via Wouthuysen-Field effect
- $T_{\text{spin}} = T_{\text{gas}} < T_{\text{CMB}}$, so...

ABSORPTION

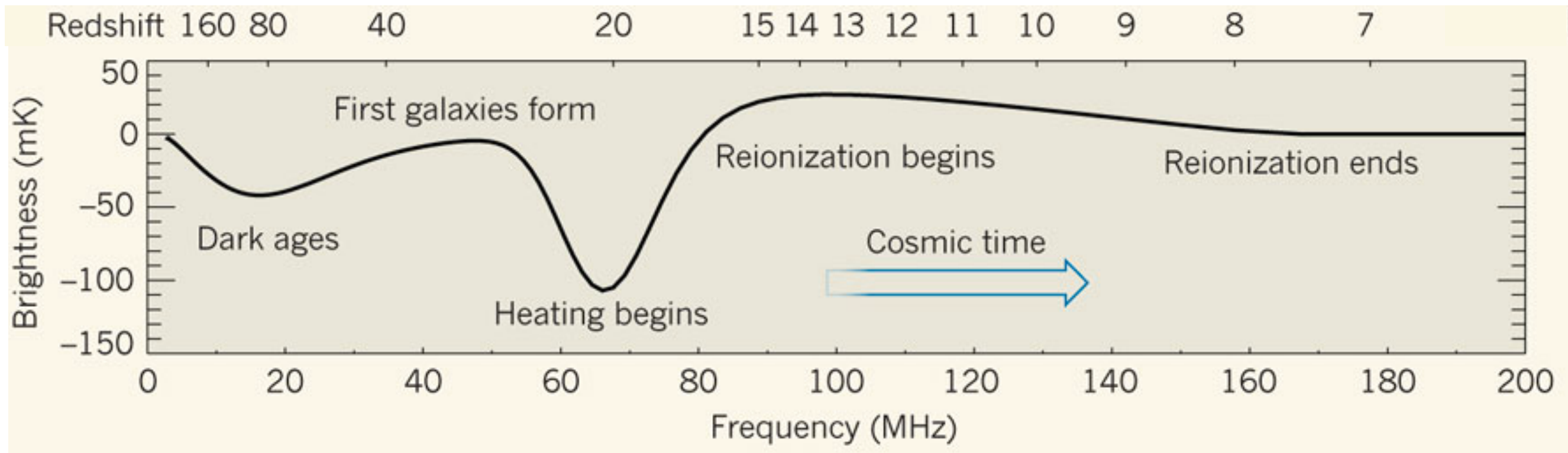
Phase V: X-ray reheating



- X-rays from early AGNs heat the IGM, raising T_{gas}
- Electrons undergo all sorts of atomic transitions, giving off all sorts of photons causing $T_{\text{spin}} = T_{\text{gas}} > T_{\text{CMB}}$

EMISSION

Phase VI: Reionization



- Eventually, reionization rids us of all neutral hydrogen atoms.

NO MORE SIGNAL

On March 1st, 2018...

On March 1st, 2018...

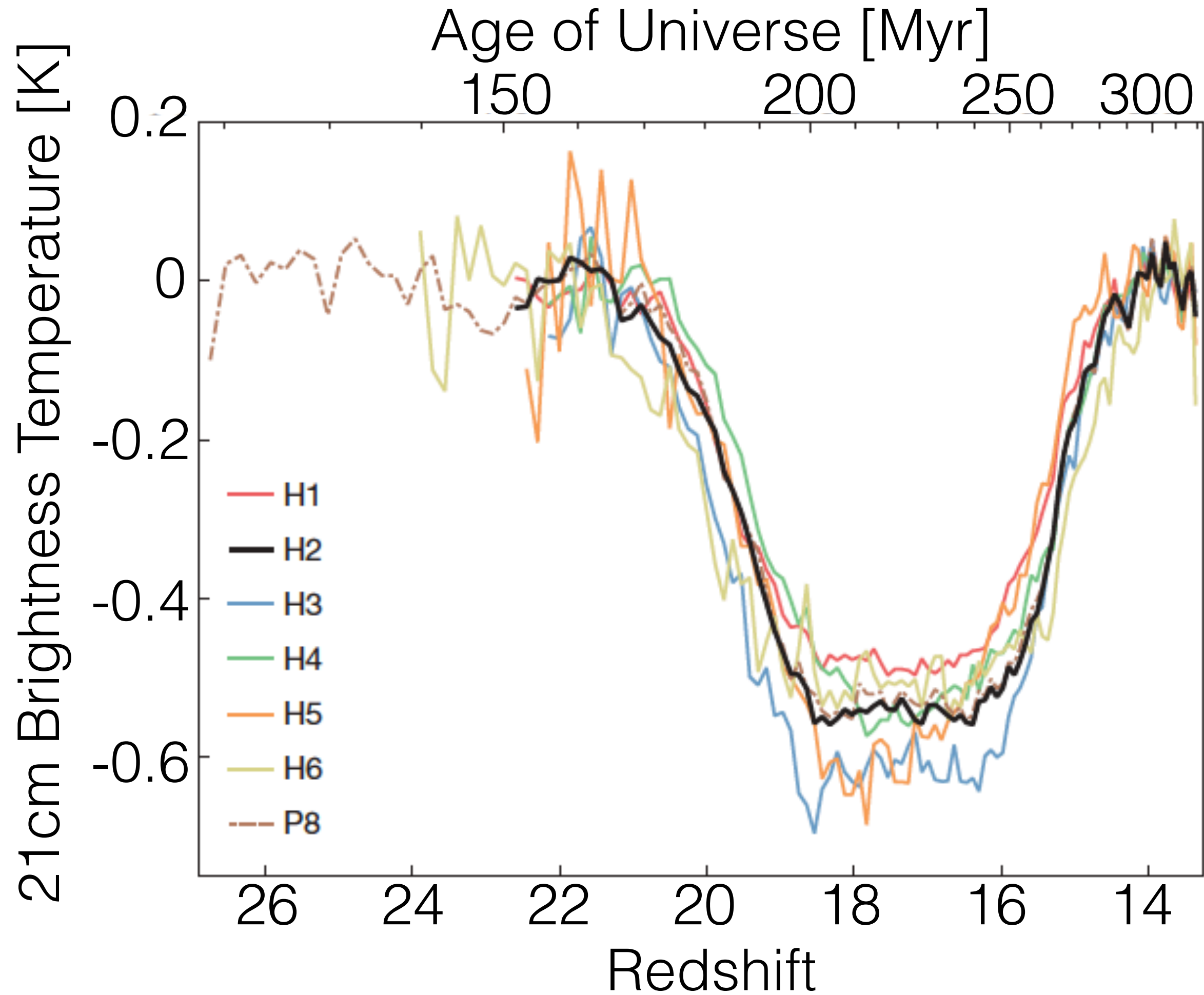
LETTER

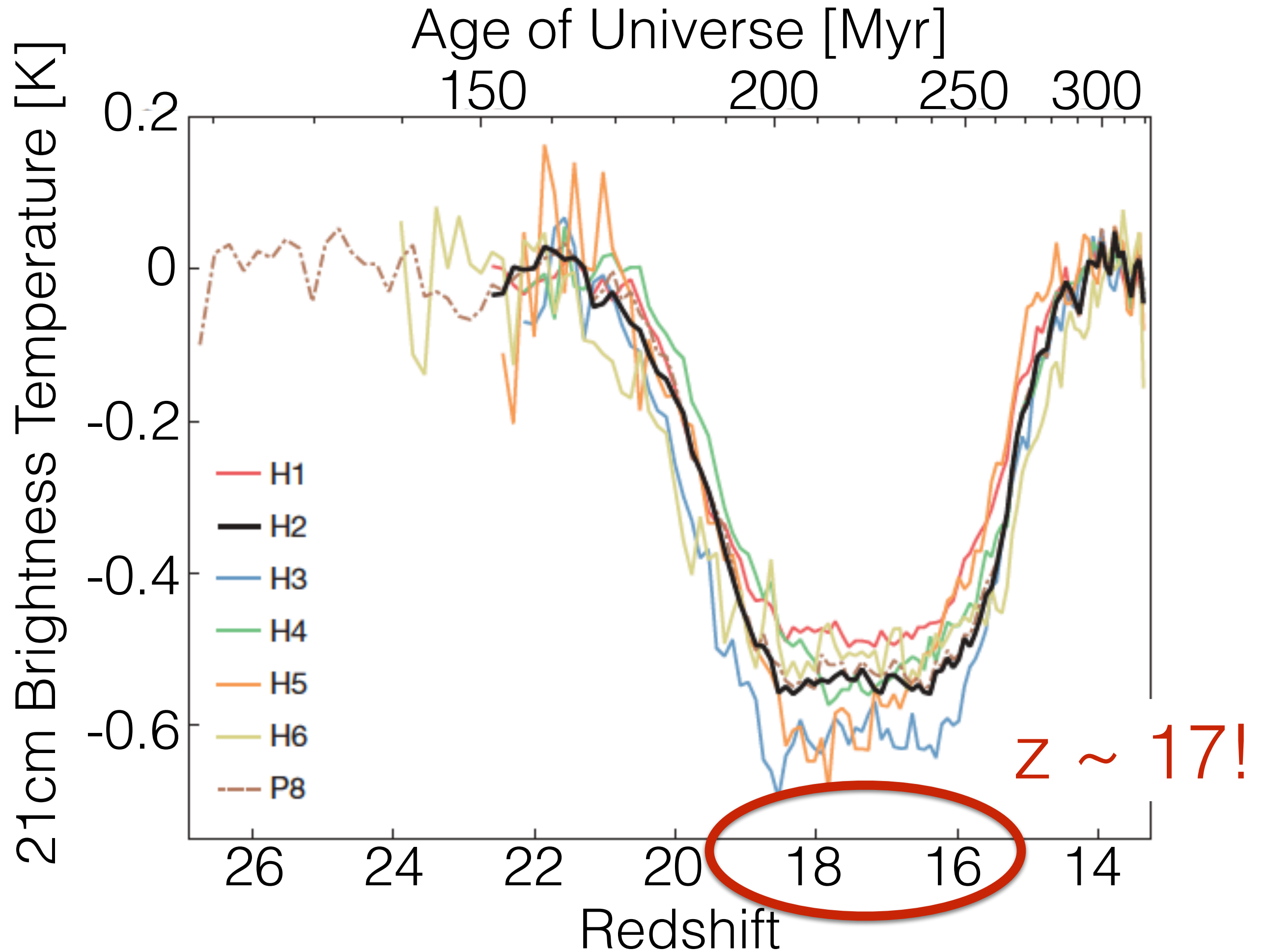
doi:10.1038/nature25792

An absorption profile centred at 78 megahertz in the sky-averaged spectrum

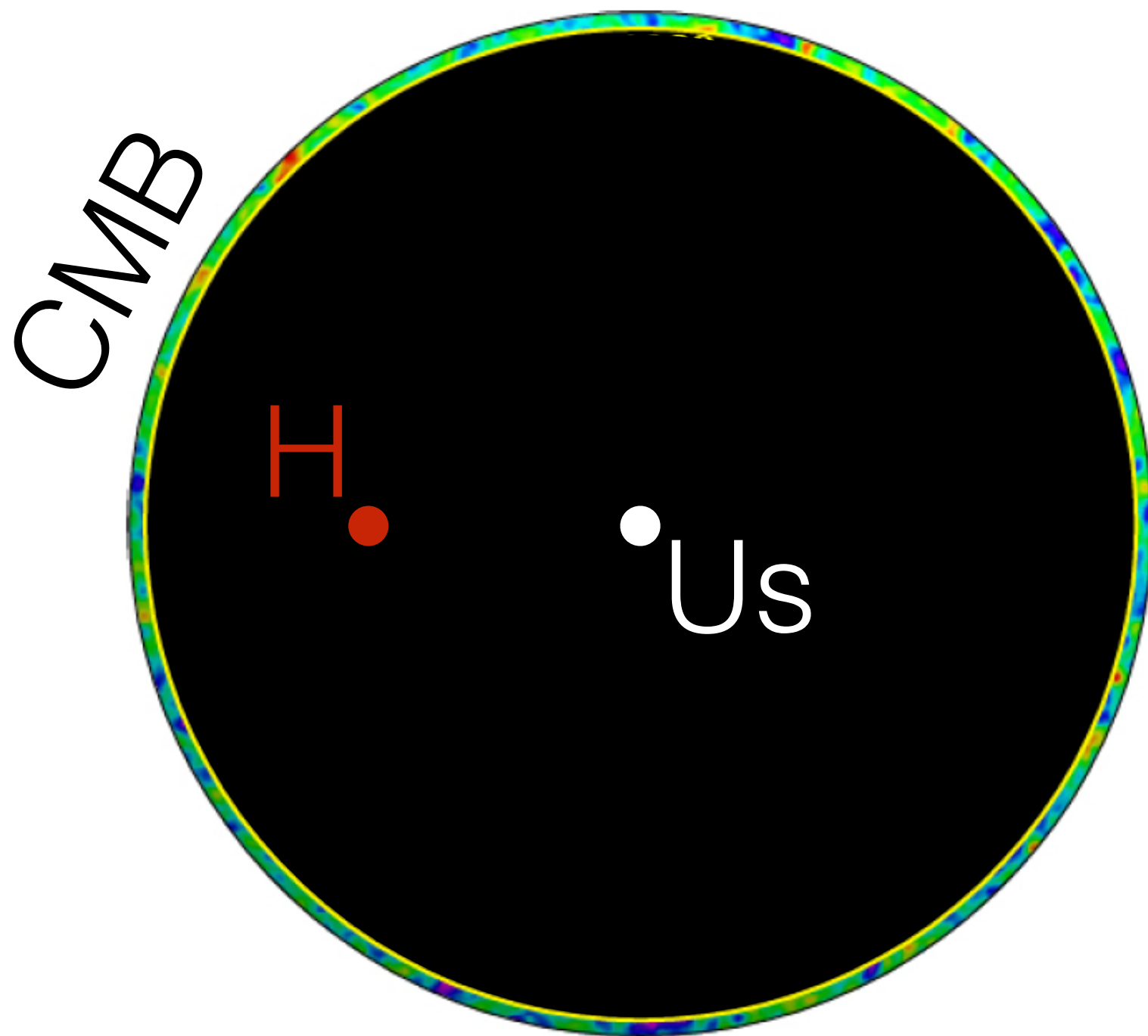
Judd D. Bowman¹, Alan E. E. Rogers², Raul A. Monsalve^{1,3,4}, Thomas J. Mozdzen¹ & Nivedita Mahesh¹





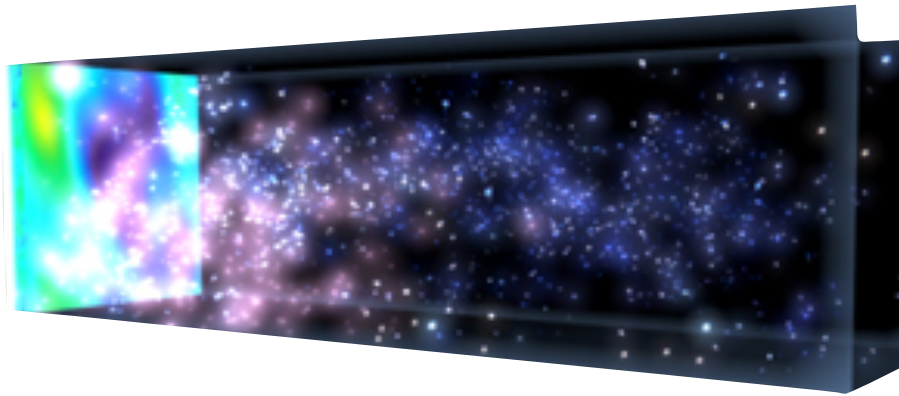


This was weird. Why?





Cold hydrogen
gas

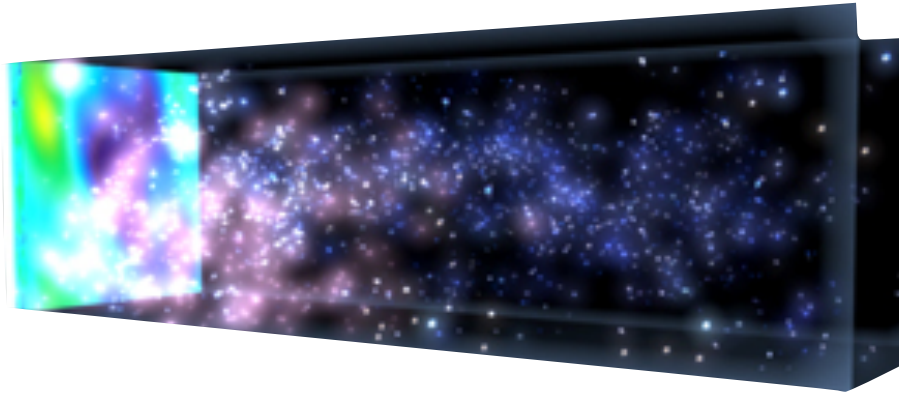


(Relatively)
hot CMB



Cold hydrogen
gas





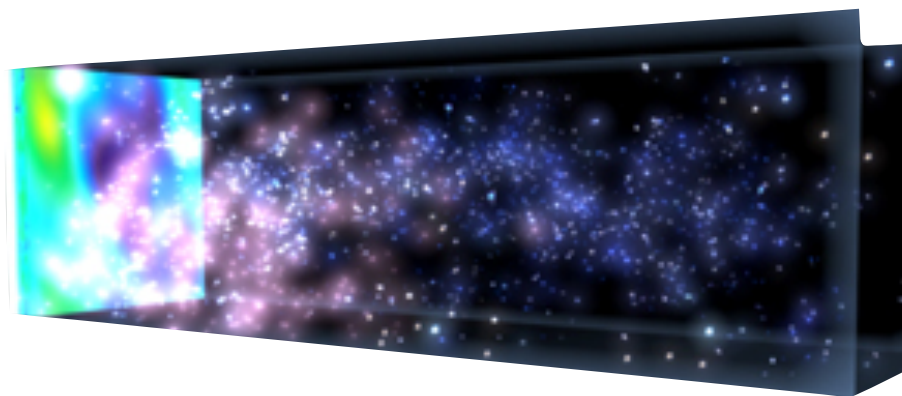
(Relatively)
hot CMB



Cold hydrogen
gas



BIG
contrast,
large signal

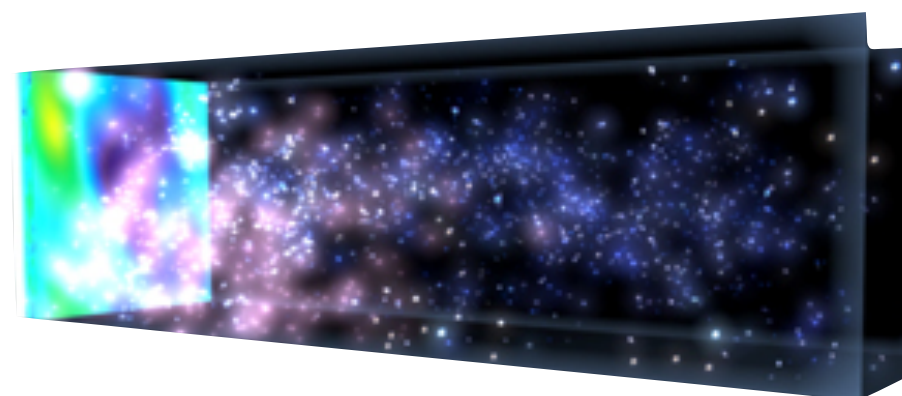


(Relatively)
hot CMB

Cold hydrogen
gas



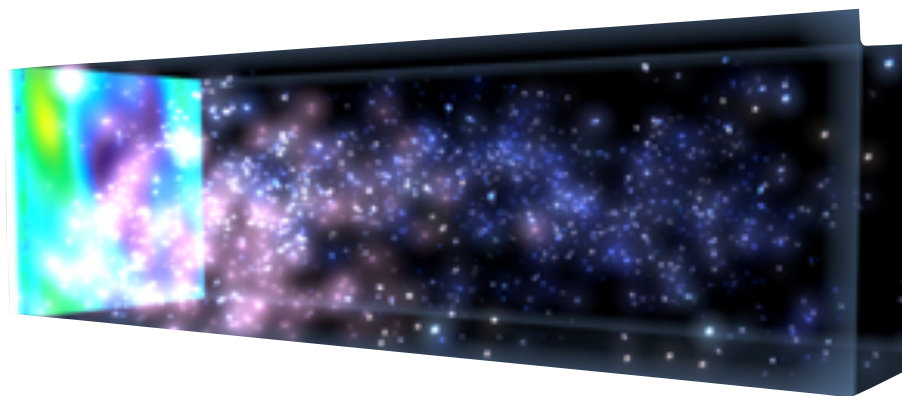
BIG
contrast,
large signal



(Relatively)
hot CMB

Warm
hydrogen gas



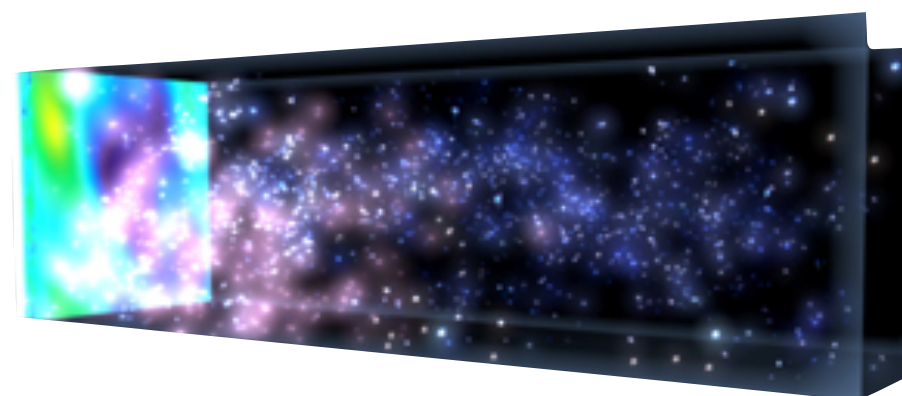


(Relatively)
hot CMB

●
Cold hydrogen
gas



BIG
contrast,
large signal



(Relatively)
hot CMB

●
Warm
hydrogen gas



Small contrast, small signal

The EDGES signal was so deep
that it needed the intergalactic gas
to be colder than if it had just
adiabatically cooled!

Even something as simple as a single antenna in the desert can inform us about our Universe



Hands-on Exercise

For this exercise, we will use a Google Colab notebook written by Thomas Gessey-Jones at Cambridge University. I've put a slightly modified version here: <https://colab.research.google.com/drive/1vL2VHqm9m4Bn3GiQ6J46HcFyu9fkOM8G?usp=sharing>.

Make a copy of the notebook (File -> Save a copy in Drive). This notebook contains a simplified (believe it or not!) model for 21cm cosmology during Cosmic Dawn. I suggest ignoring most of the text for now (this is for further study in your own time). Instead, run all of the cells in the notebook and then do the exercise at the bottom. The idea is to look at how different astrophysical parameters affect the global 21cm signal. Can you explain the trends that you find? Are you able to create an absorption trough as deep as what EDGES saw?