Welcome

SUMMER SCHOOL ON ASTROPHYSICS 2025

A two-week hybrid program for undergraduate students and early-career researchers, organized by Copernicus Astronomical Memorial of SUST (CAM-SUST) for the first time in Bangladesh

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Area of Interest: 21cm Cosmology (EoR), Exoplanet Detection and Characterization

Social Rules

No well-actually's

> Alice: I just installed Linux on my computer!
> Bob: Well, actually it's called GNU/Linux.

No feigning surprise

> Dan: What's the command line?
> Carol: Wait, you've never used the command line?

No backseat driving

> Bob: Hey do you know how to open a .txt file using Python?
> Alice: Use NumPy
> Eve: (from across the room) You should use pandas. It's more elegant.

No subtle -isms

> Carol: Linux is so hard to use.
> Bob: No way. Linux is so easy to use that even my mom can use it.

cc: https://www.recurse.com/social-rules

Check Points

Share on Slack

> Share your thoughts, travelling or working on the project pictures, memes, on our slack channels

Tag on Socials

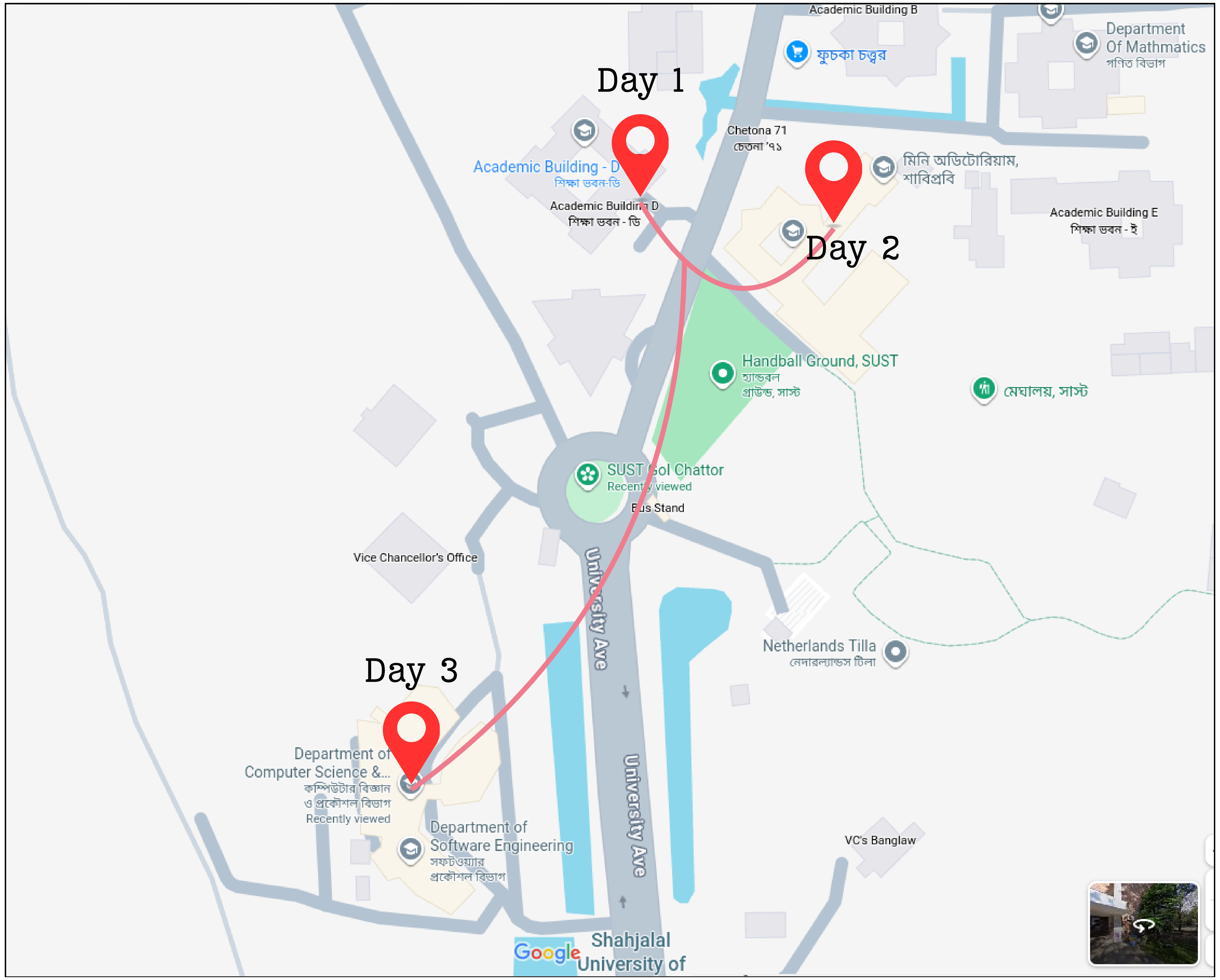
> Tag us on your social media posts sharing your experience here with us in this summer school

Feedback Form

> Fill up the feedback form after the hands-on session. It'll help us grow in future.

Group Presentation

> Keep in mind that, you'll have to create a team and present a topic related to these hands-on sessions.



Simulating the Early Universe Using 21cmFAST

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Hubble's Universe

$$\vec{v} = H_0\vec{r}$$

There was a big bang! The universe is expanding. The farther away the galaxy, the faster it is receding away from us.

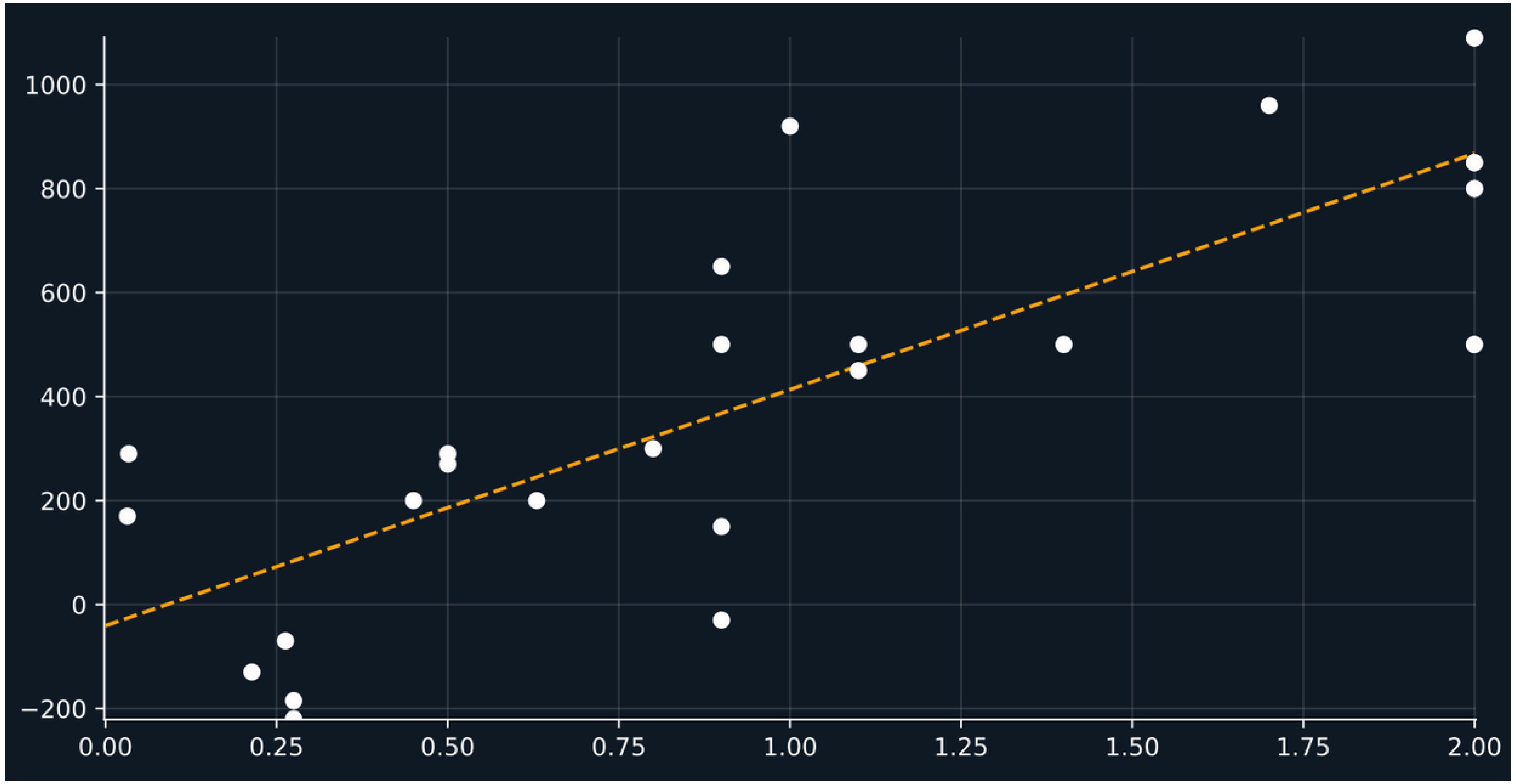


Figure 1.1: *x axis - Distance from the Observer in MPc, y axis - Recesional Velocity of galaxies in km/s. Original Data from Hubble 1929*

- The absorption lines in the spectra gets red shifted if the source is moving away from us.

- For Hydrogen, using Rydberg equation, we can calculate the wavelength of these absorption lines.

  Hα : n1 = 2, n2 = 3 ~ 656.3 nm
  Hβ : n1 = 2, n2 = 4 ~ 486.1 nm

- Redshift is defined as

$$z = \frac{\lambda_{obs} - \lambda_{src}}{\lambda_{src}}$$

- $z > 2$ is called high redshift
- $z > 6$ is called the early universe

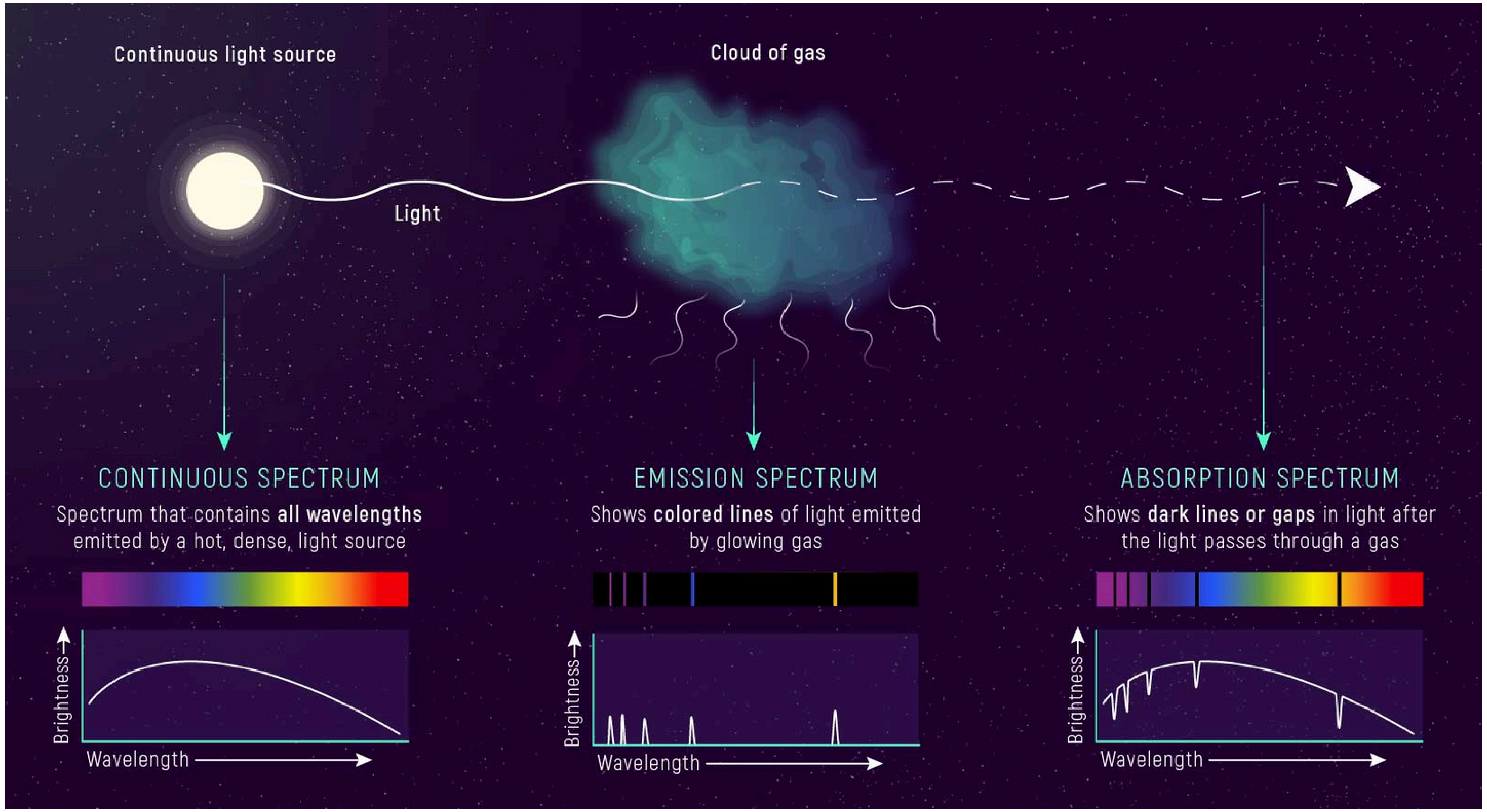
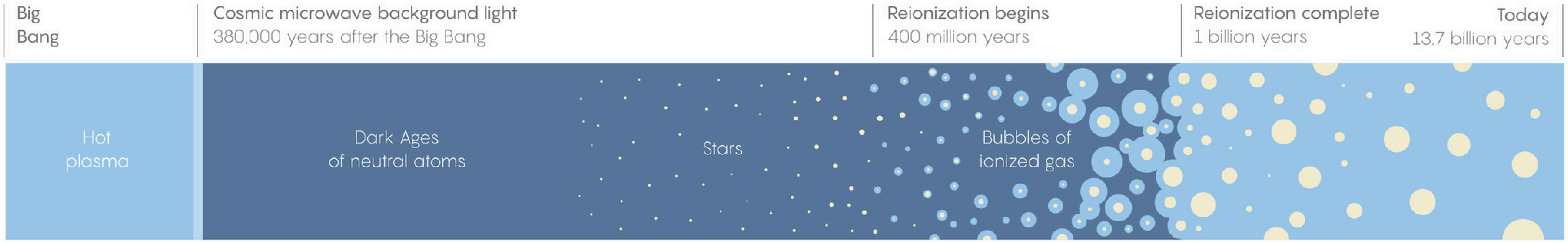


Figure 1.2: *Starlight can also heat up a cloud of gas, exciting the atoms and molecules within the gas, and causing it to emit light. from NASA, ESA, and L. Hustak (STScI).*

The First Light

The universe went through an unimaginably violent infancy before settling down into an exceedingly quiet adolescence. For most of its first billion years, the universe was filled with an atomic gas that absorbed starlight. Now researchers are tracking the first cosmic objects that broke that gas apart, rendering the universe transparent.



Post-Big Bang

The early universe was filled with a hot, energetic plasma that scattered light.

Dark Ages Begin

As the universe expanded and cooled, protons and electrons came together to make atoms. These atoms absorbed energetic light from the early universe.

The First Stars

Eventually, the first stars formed. But much of their high-energy light was absorbed by the neutral atom gas.

Reionization

Stars, galaxies and quasars emitted intense ultraviolet light that stripped electrons from protons, slowly returning the universe to an ionized state. With time, the light broke apart the atomic gas in galaxies and traveled out to reionize the universe at large. By the end of reionization, the universe was largely transparent.

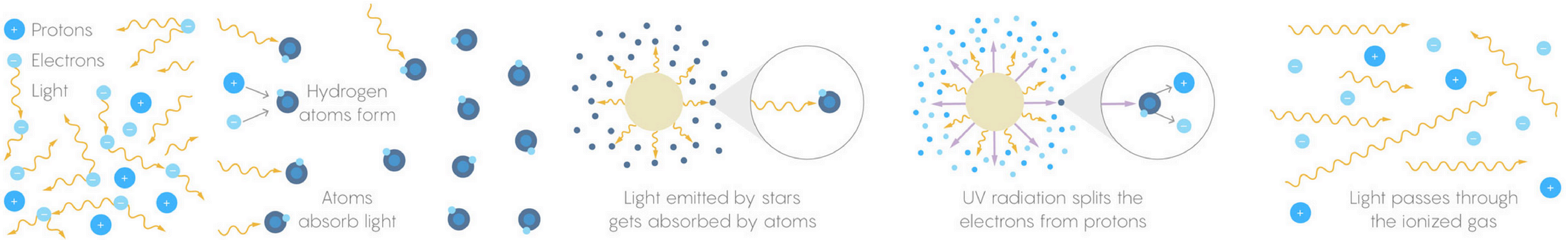


Figure 1.3: A brief timeline of the big bang cosmology events from Lucy Reading-Ikkanda/Quanta Magazine

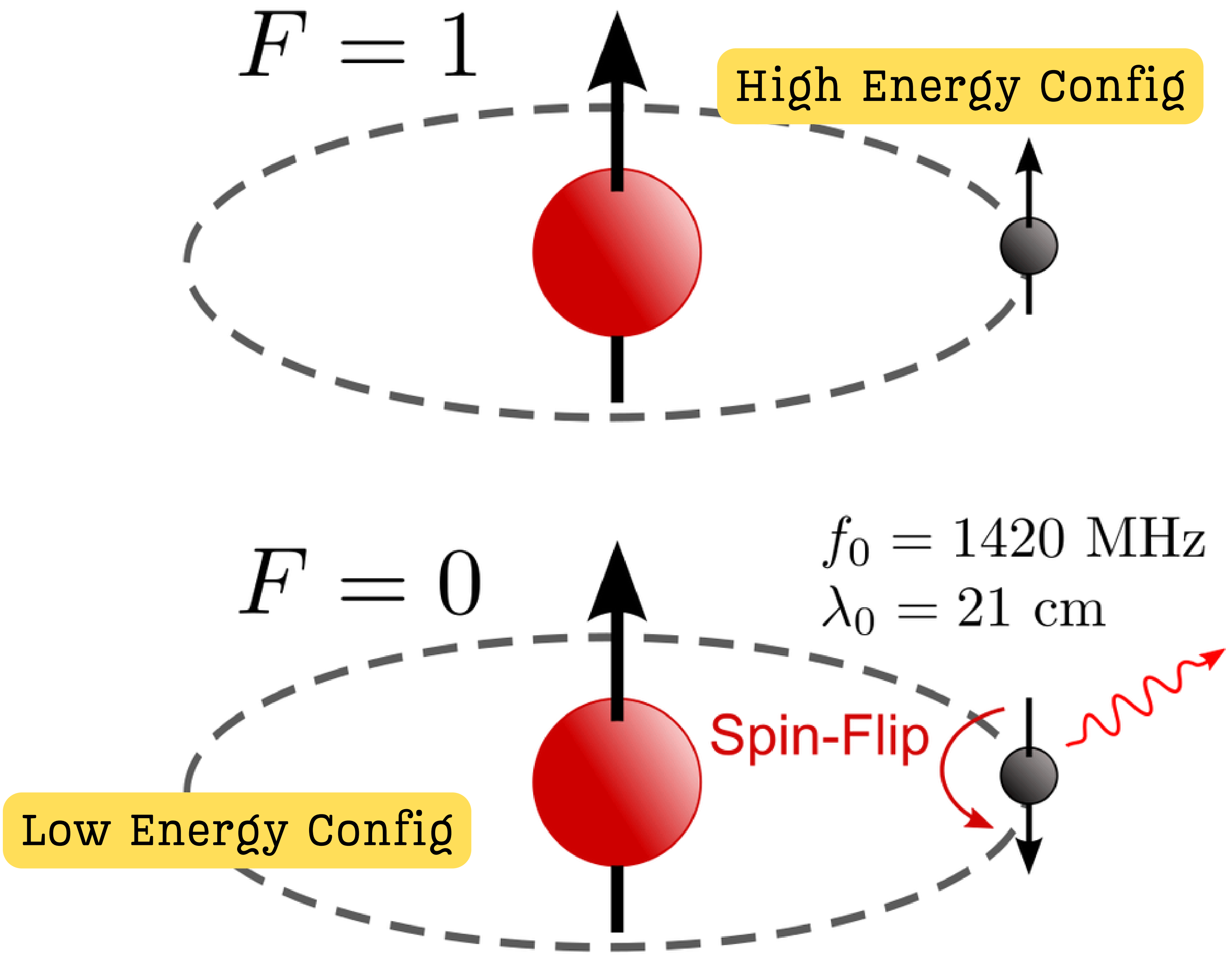


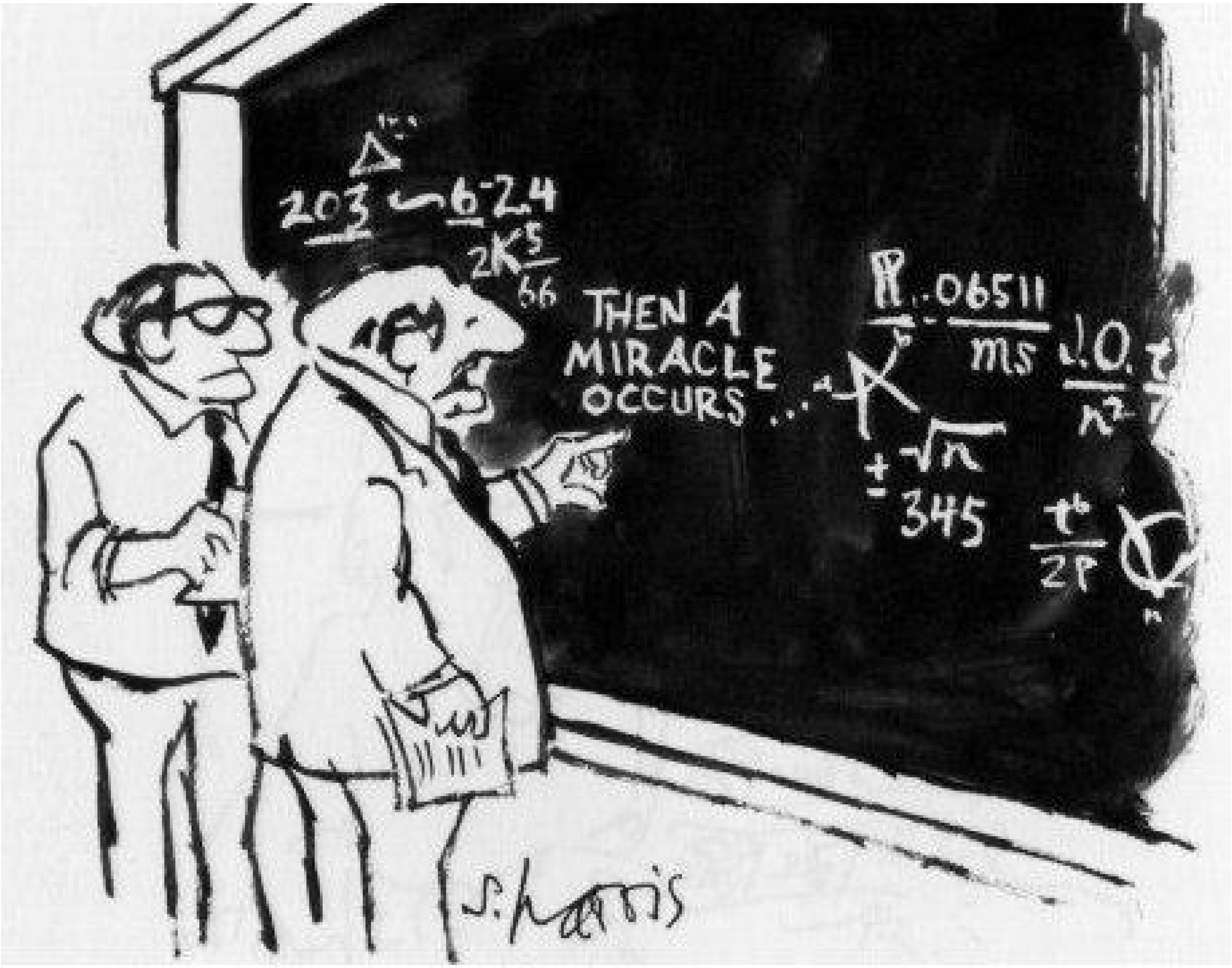
Figure 1.3: *A hydrogen atom with proton and electron spins aligned (top) undergoes a flip of the electron spin, resulting in emission of a photon with a 21 cm wavelength (bottom). from Tiltek via Wikimedia*

Why?

Answer to this question is left as an exercise for the reader.

kidding: Check On The Power Of Cosmic Hydrogen by Akbar Ahmed Chowdhury

WARNING! EQUATIONS COMING!



"I think you should be more explicit here in step two."

Brightness Temperature

$$I_\nu = \frac{dE}{dt\,dA\,d\Omega\,d\nu}$$

Specific Intensity is the energy content per unit time, per unit area, per unit solid angle, per second

Using Rayleigh-Jeans Approximation

$$T_b(\nu) \approx \frac{I_\nu c^2}{2k_B\nu^2}$$

Brightness temperature and specific intensity can be used as equivalent

Neutral hydrogen fraction at redshift z
1: fully neutral universe
0: fully ionized

Ts: Spin temperature of neutral hydrogen
Tγ: CMB temperature at redshift z
Ts>Tγ: Emission   Ts<Tγ: Absorption   Ts=Tγ: No Signal

Baryon Density Parameter

$$\delta T_b(\nu) \approx 27\, x_{HI}(1+\delta)\left[1-\frac{T_\gamma(z)}{T_S}\right]\left[\frac{H(z)/(1+z)}{dv_{\parallel}/dr_{\parallel}}\right]\sqrt{\frac{1+z}{10}\,\frac{0.3096}{\Omega_m h^2}}\left[\frac{\Omega_b h^2}{0.049}\right]\ \mathrm{mK}$$

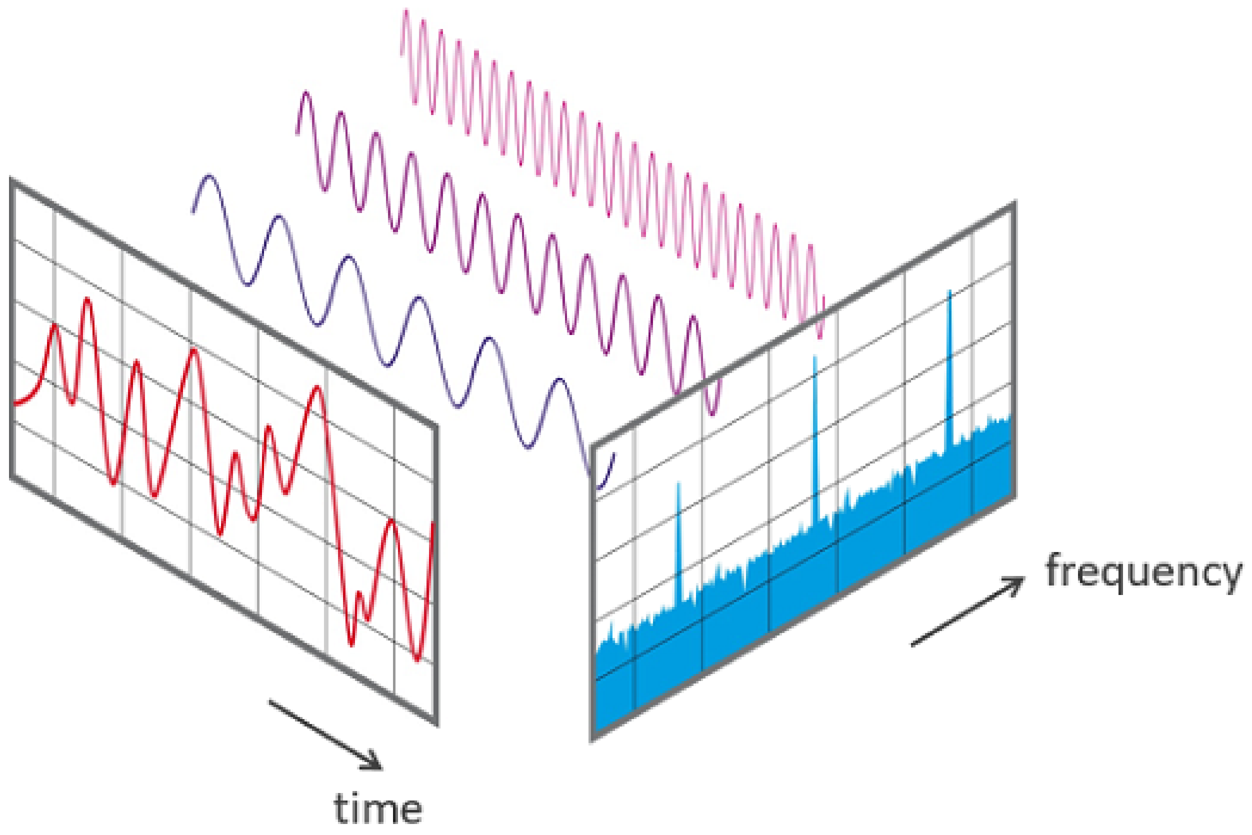
differential brightness temperature at observed frequency

Local matter over density

Gradient of Proper Velocity (Hubble Flow + Peculiar Velocity)

Matter Density Parameter

Power Spectrum



Any periodic signal can be written as the sum of sinusoids. The frequency component of such a composite signal can be determined using the Fourier Transform defined as

$$\tilde{f}(k) = \int f(x) e^{ikx} dx$$

$$\delta T_b(\nu) \approx 27\, x_{HI}(1+\delta) \left[1 - \frac{T_\gamma(z)}{T_S}\right] \left[\frac{H(z)/(1+z)}{dv_\parallel/dr_\parallel}\right] \sqrt{\frac{1+z}{10}\frac{0.3096}{\Omega_m h^2}} \left[\frac{\Omega_b h^2}{0.049}\right] \mathrm{mK}$$

Fourier Transform: $$\delta\tilde{T}_b(k) = \int_{-\infty}^{\infty} \delta T_b(r) e^{ikr} dr^3$$

Power Spectrum: $$P(k) = |\delta\tilde{T}_b(k)|^2$$

Dimensionless Power Spectrum: $$\Delta^2(k) = \frac{k^3}{2\pi^2} P(k)$$

Parameter of 21cmFAST i

Cosmological Parameters

Parameter	Description	**Default Value**
Ω_m	Matter density parameter	0.3089
Ω_b	Baryon density parameter	0.04897
h	Hubble parameter	0.6766 km/s/Mpc
n_s	Scalar spectral index	0.9667
σ_8	RMS mass variance	0.8159

Astrophysical Parameters 1

Parameter	Description	**Default Value**
ε	Ionizing efficiency of high-z galaxies	30.0
$f_{*,10M_\odot}$	Fraction of galactic gas in stars for 10^{10} solar mass haloes	-1.3
$f_{*,7M_\odot}^{mini}$	Fraction of galactic gas in stars for 10^7 solar mass minihaloes	-2
α_*	Power-law index of fraction of galactic gas in stars as a function of halo mass	0.5
f_*	Star formation efficiency factor	0.05

Parameter	Description	**Default Value**
$f_{\mathrm{esc},10M_\odot}$	Escape fraction for 10^{10} solar mass haloes	-1.0
$f_{\mathrm{esc}}^{\mathrm{mini}}$	Escape fraction for minihalos	-2.0
α_{esc}	Power-law index of escape fraction as a function of halo mass	-0.5
M_{turn}	Turnover mass for quenching of star formation in halos	8.7
R_b^{max}	Mean free path of ionizing photons within ionizing regions	None

Parameter of 21cmFAST iii

Astrophysical Parameters 2

Parameter	Description	Default Value
T_{vir}	Minimum virial temperature of star-forming haloes. Given in log10 unit.	4.69897
$L_X^{\star}$	Specific X-ray luminosity per unit star formation	40.0
$L_X^{\mathrm{mini},\star}$	Specific X-ray luminosity per unit star formation for minihalos	40.0
$h\nu_X^{\mathrm{th}}$	X-ray energy threshold for self-absorption by host galaxies	500.0
ζ_X	X-ray efficiency factor	30
Γ_X	X-ray spectral energy index	-

Parameter	Description	Default Value
$T_{vir}^{\mathrm{min},X}$	Minimum halo virial temperature for X-ray production	None
f_{H_2}	Self-shielding factor of molecular hydrogen	0.0
t_{star}	Fractional characteristic time-scale defining the star-formation rate of galaxies	0.5
A_{LW}, β_{LW}	Impact of the LW feedback on Mturn for mini-haloes	2.0, 0.6
A_{VCB}, β_{VCB}	Impact of the DM-baryon relative velocities on Mturn for minihaloes	1.0, 1.8

Expected Results i

$$5 < z < 14$$

Cosmological Parameters

Model	Default Value	Varied Value
Y_h	$h = 0.80$	$h = 0.6766$
Y_m	$\Omega_m = 0.40$	$\Omega_m = 0.3096$
Y_C	$h = 0.80$ and $\Omega_m = 0.40$	$h = 0.6766$ and $\Omega_m = 0.3096$

Expected Results ii

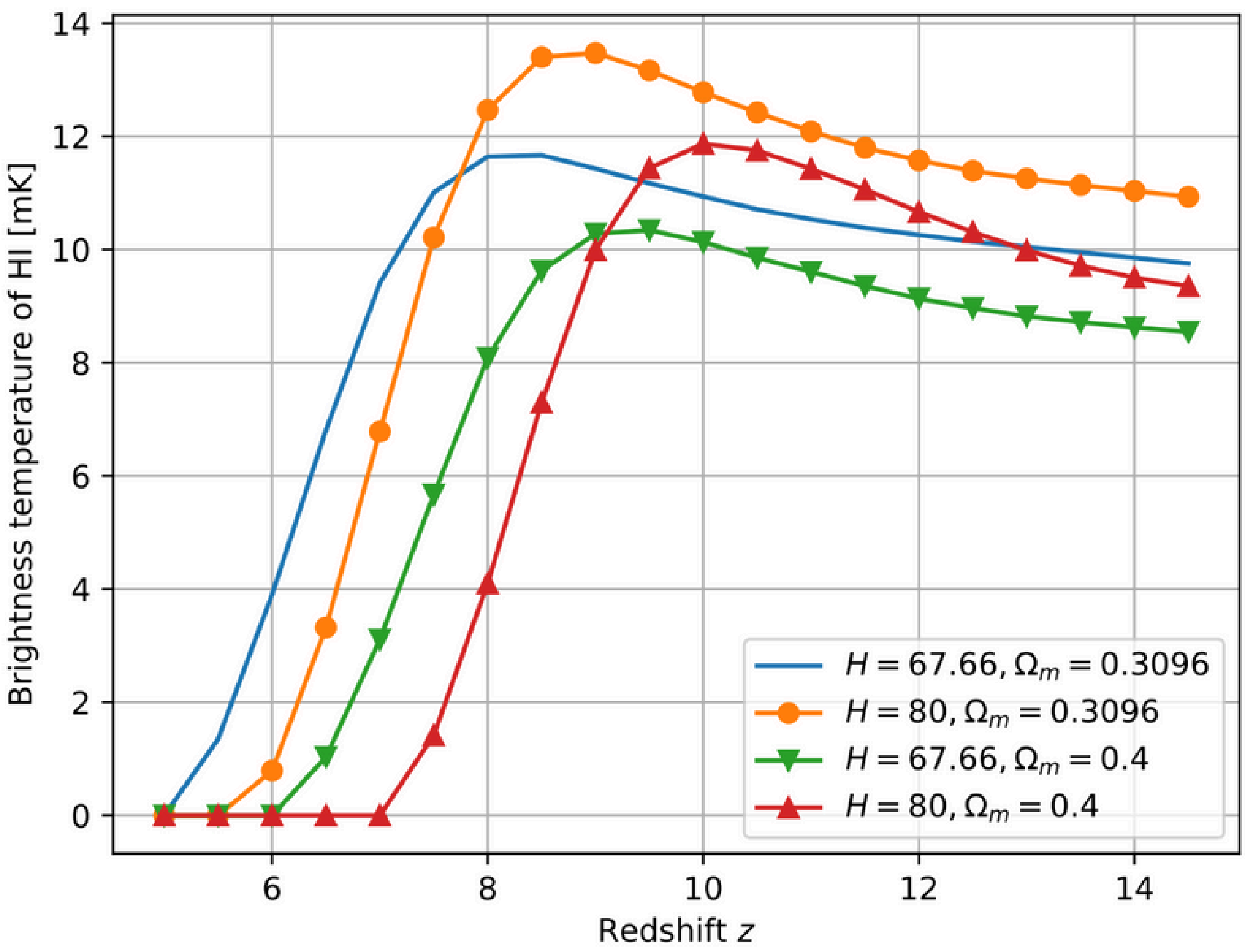


Figure: *The plots show the Spectrum of the Brightness Temperature of neutral hydrogen for different cosmological models.*

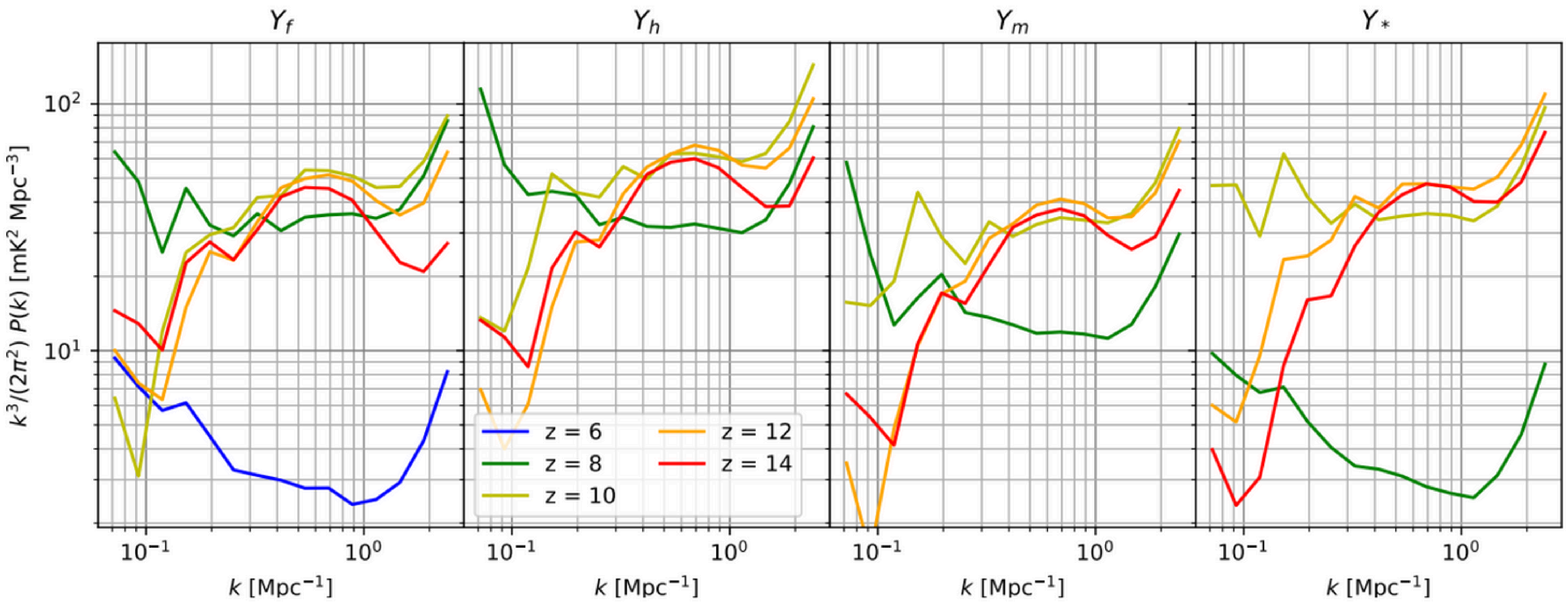


Figure: *Power spectrum of the chosen cosmological models with respect to Fourier scale, k. Each color represents a different redshift as shown in the legend.*

Expected Results iii

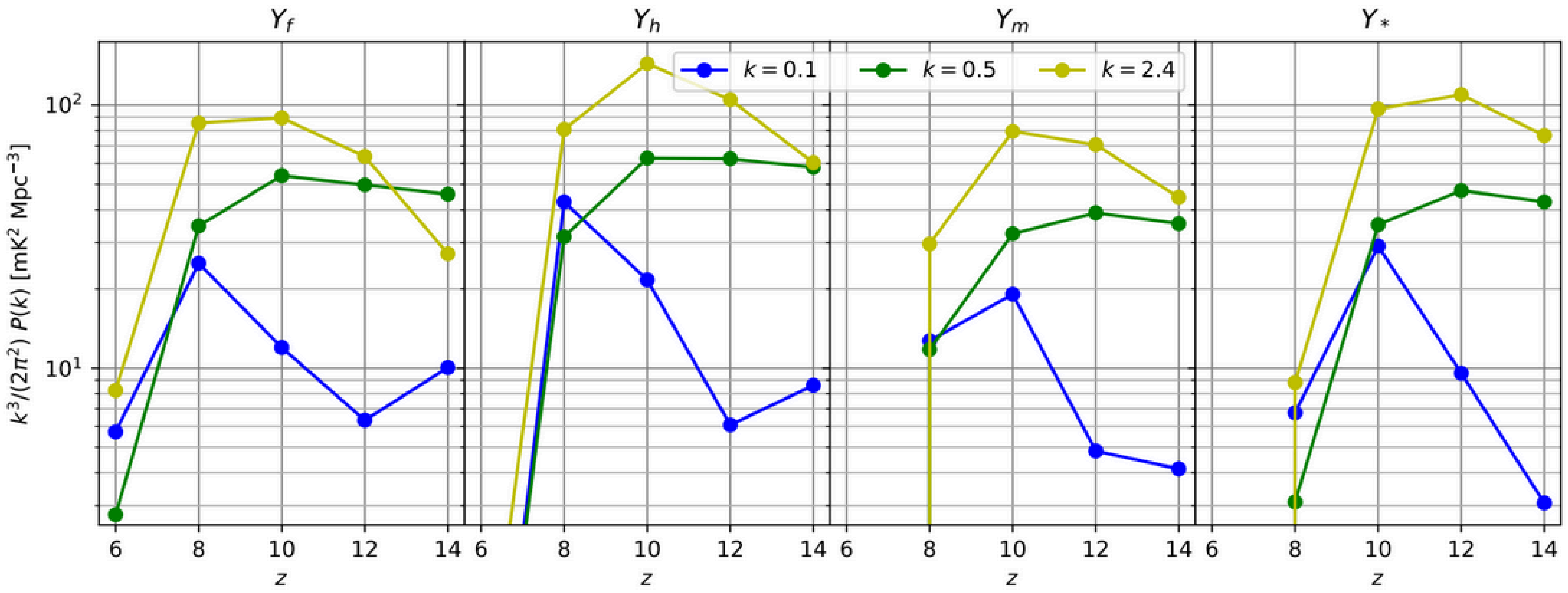


Figure: *These plots are based on the power spectrum plot above but with respect to redshift for different fourier scales chosen conveniently.*

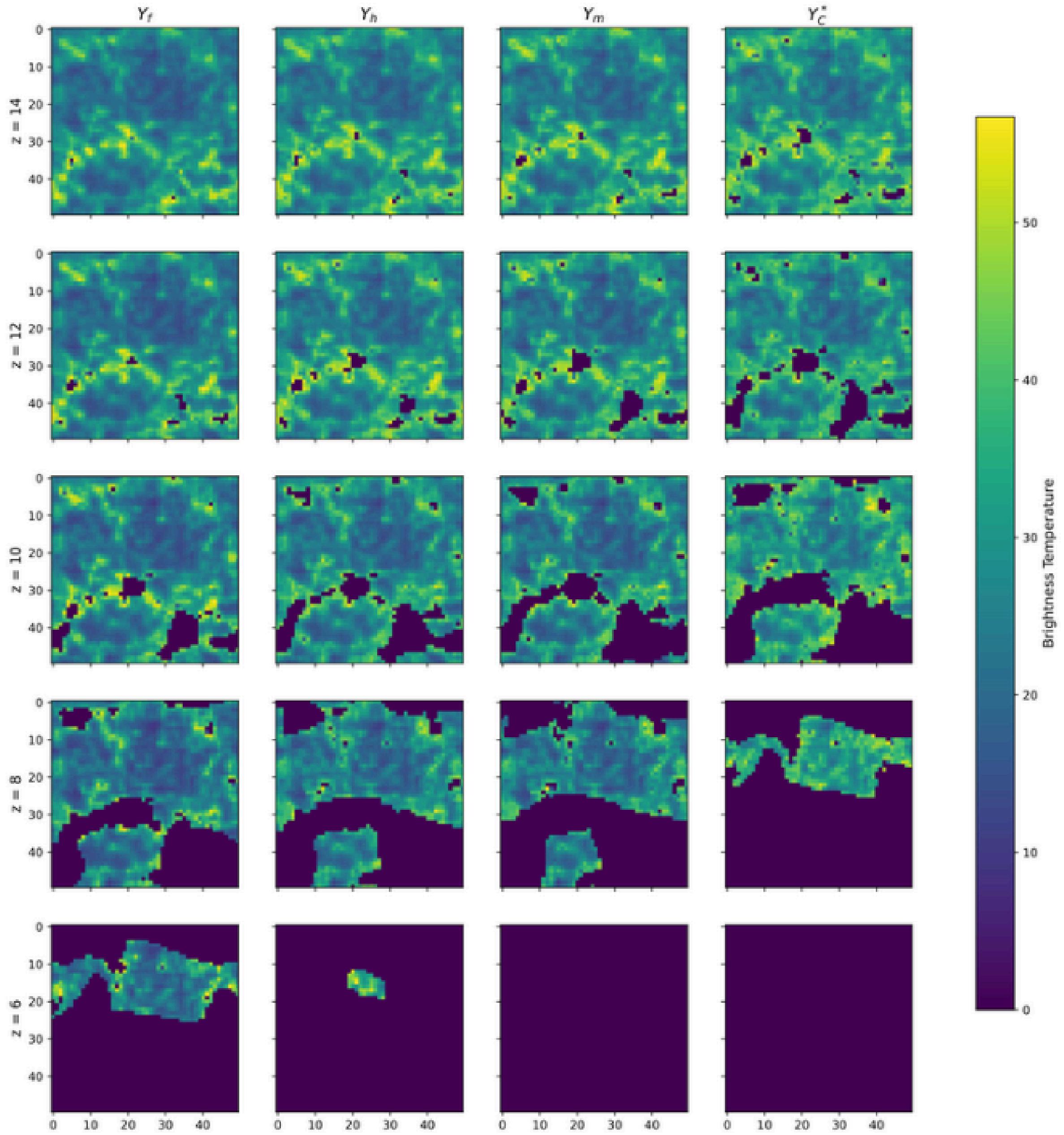


Figure: *The distribution of brightness temperature emitted from HI gas of the chosen cosmological models (Yh, Ym, and Yc) in comparison with Yf*

Time for $ome #Coding