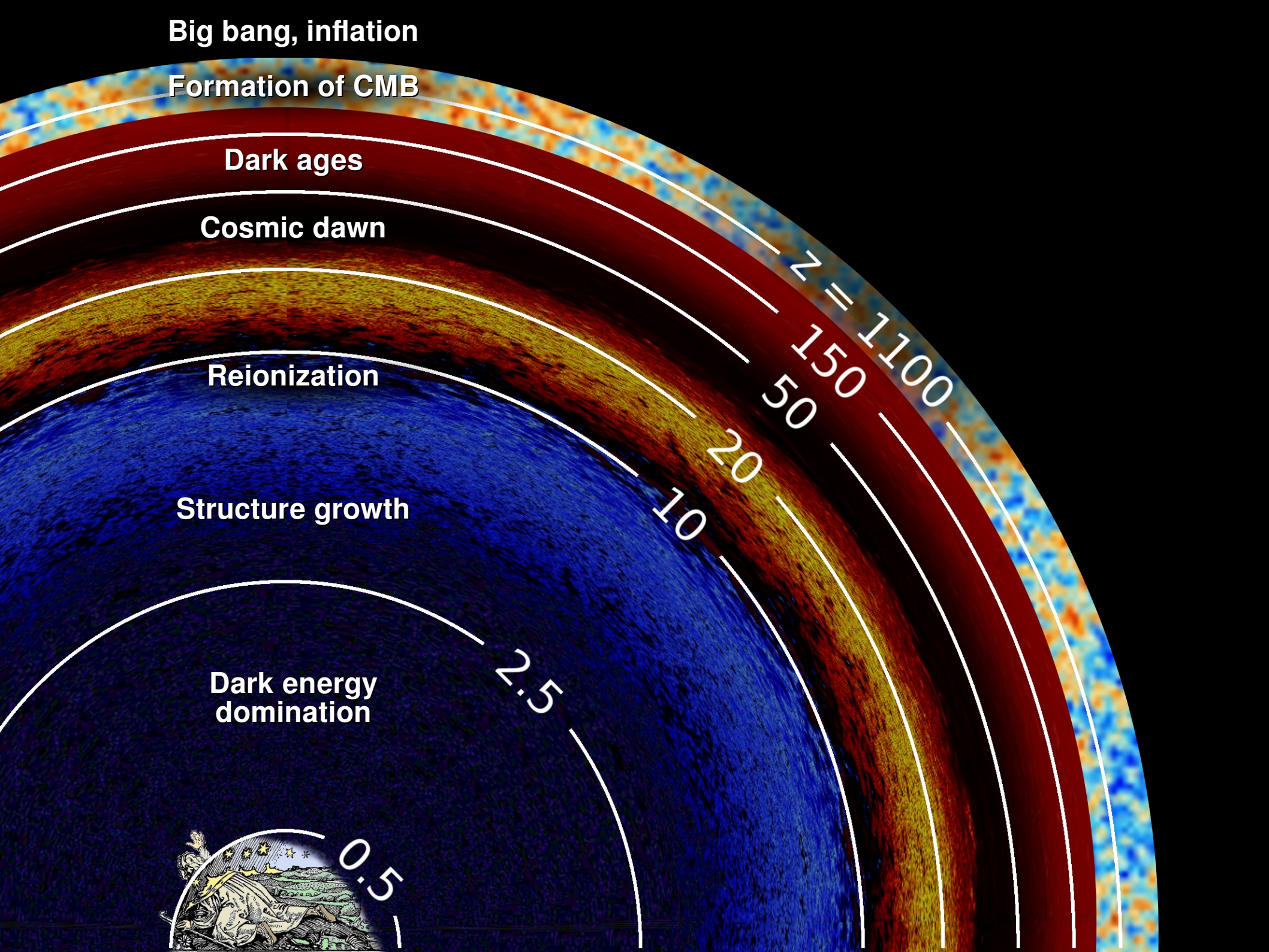
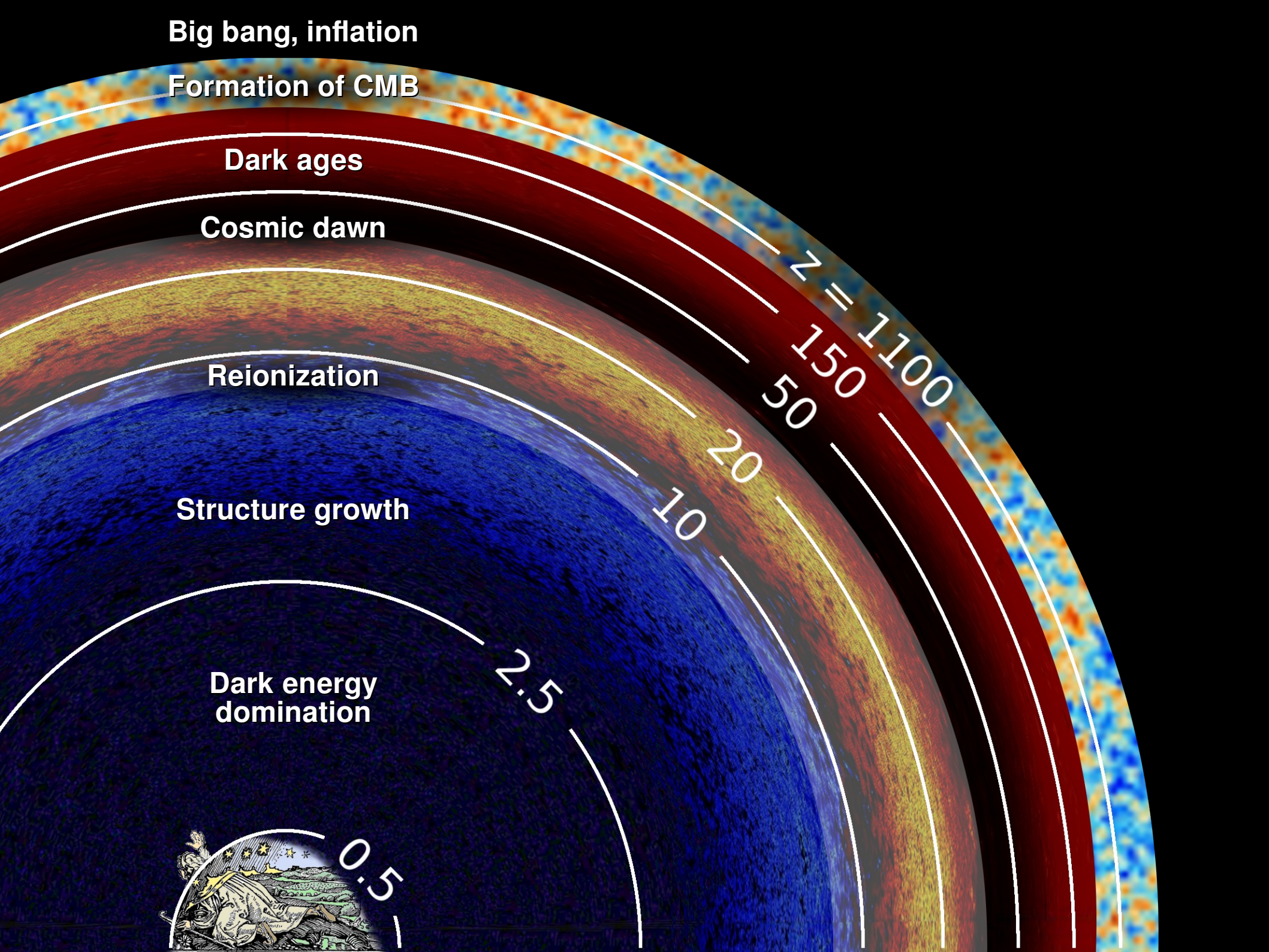
The Search for Cosmic Dawn

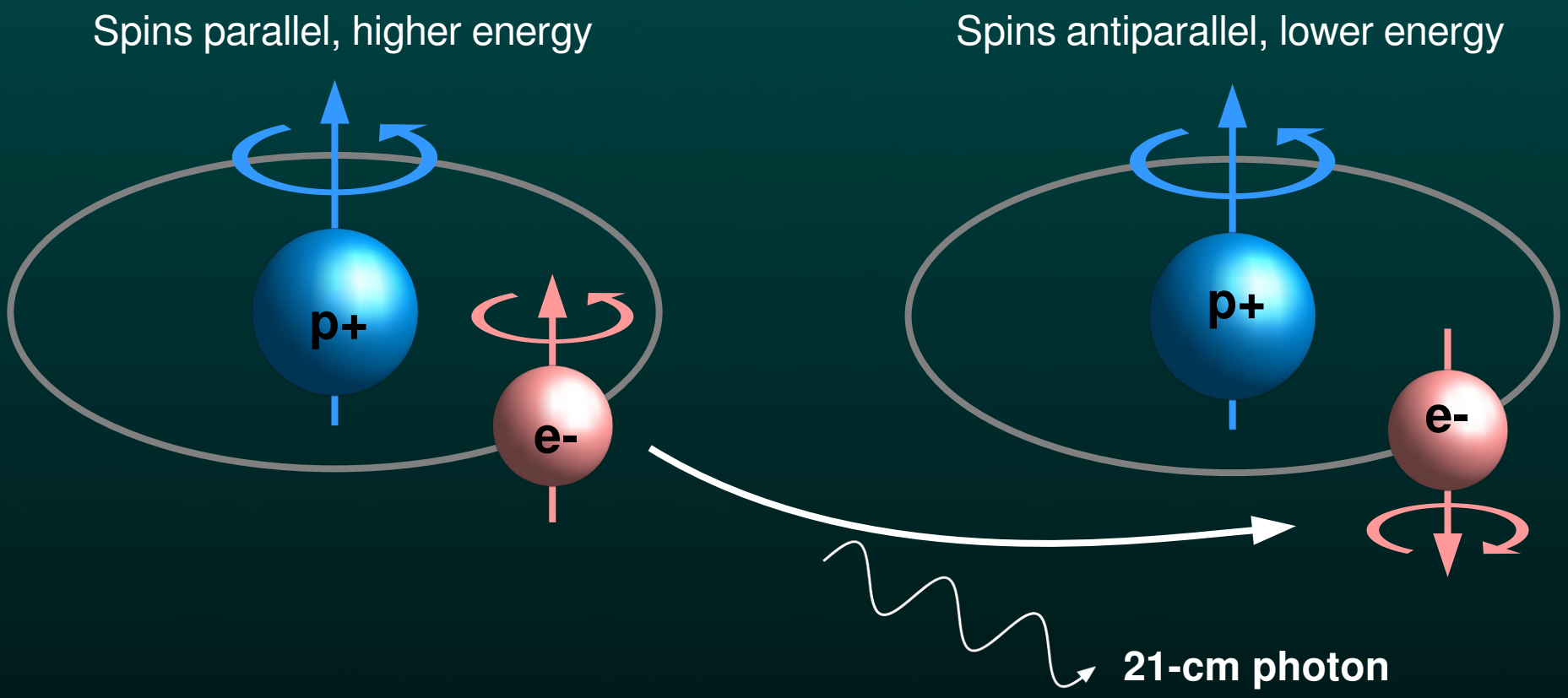
H. Cynthia Chiang
McGill University

New Directions in Theoretical Physics
10 January 2023


Big bang, inflation
Formation of CMB
Dark ages
Cosmic dawn
Reionization
Structure growth
Dark energy domination
z = 1100
150
50
20
10
2.5
0.5


Big bang, inflation
Formation of CMB
Dark ages
Cosmic dawn
Reionization
Structure growth
Dark energy domination
z = 1100
150
50
20
10
2.5
0.5

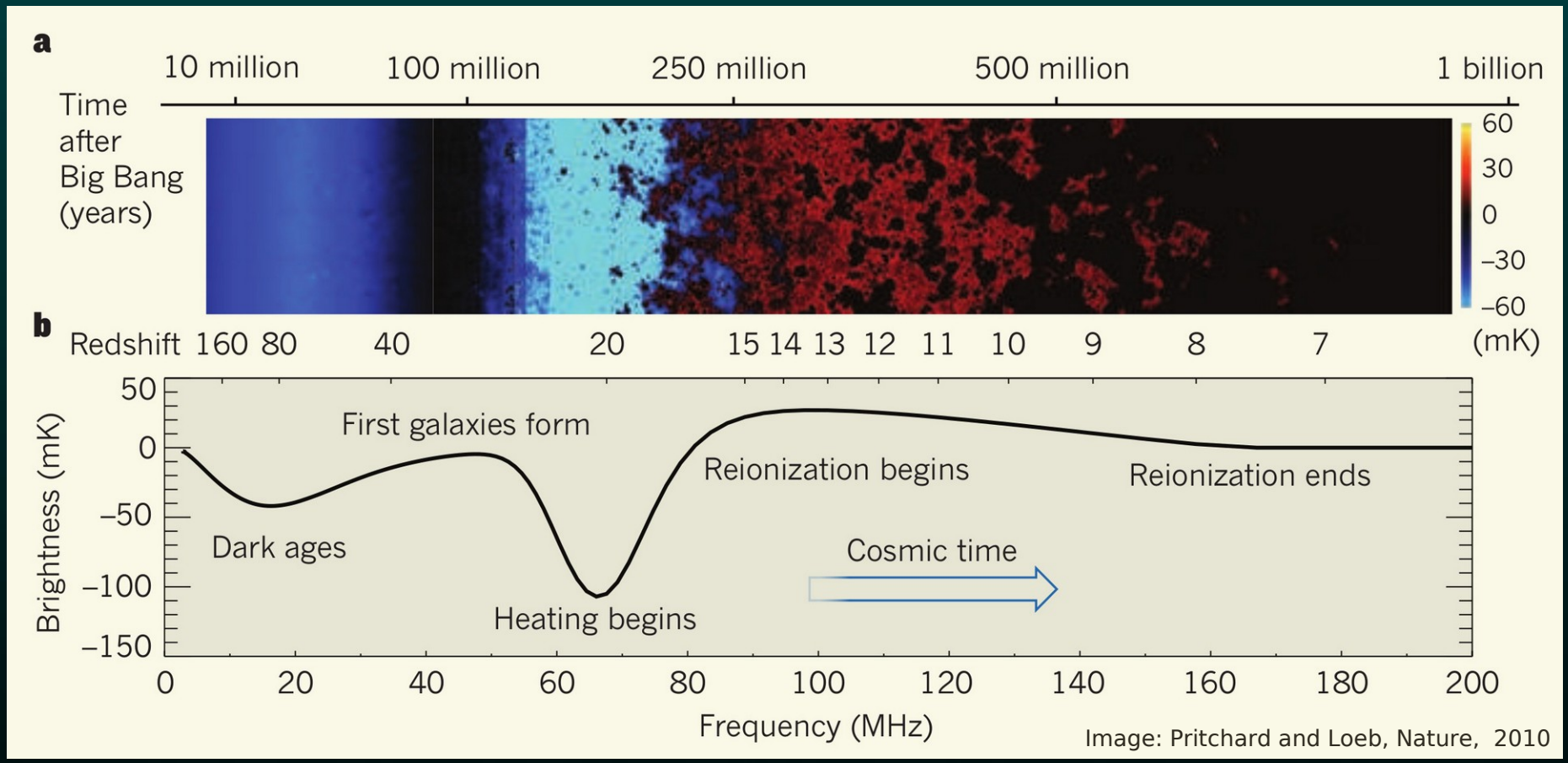
Redshifted 21cm emission



- Hyperfine transition in neutral hydrogen produces 21-cm (1.4 GHz) radiation (no emission from molecular or ionized hydrogen)
- Forbidden transition, lifetime of excited state ~10 million years
- 21-cm emission serves as a natural redshift marker for mapping hydrogen in the universe, tracer of large scale structure

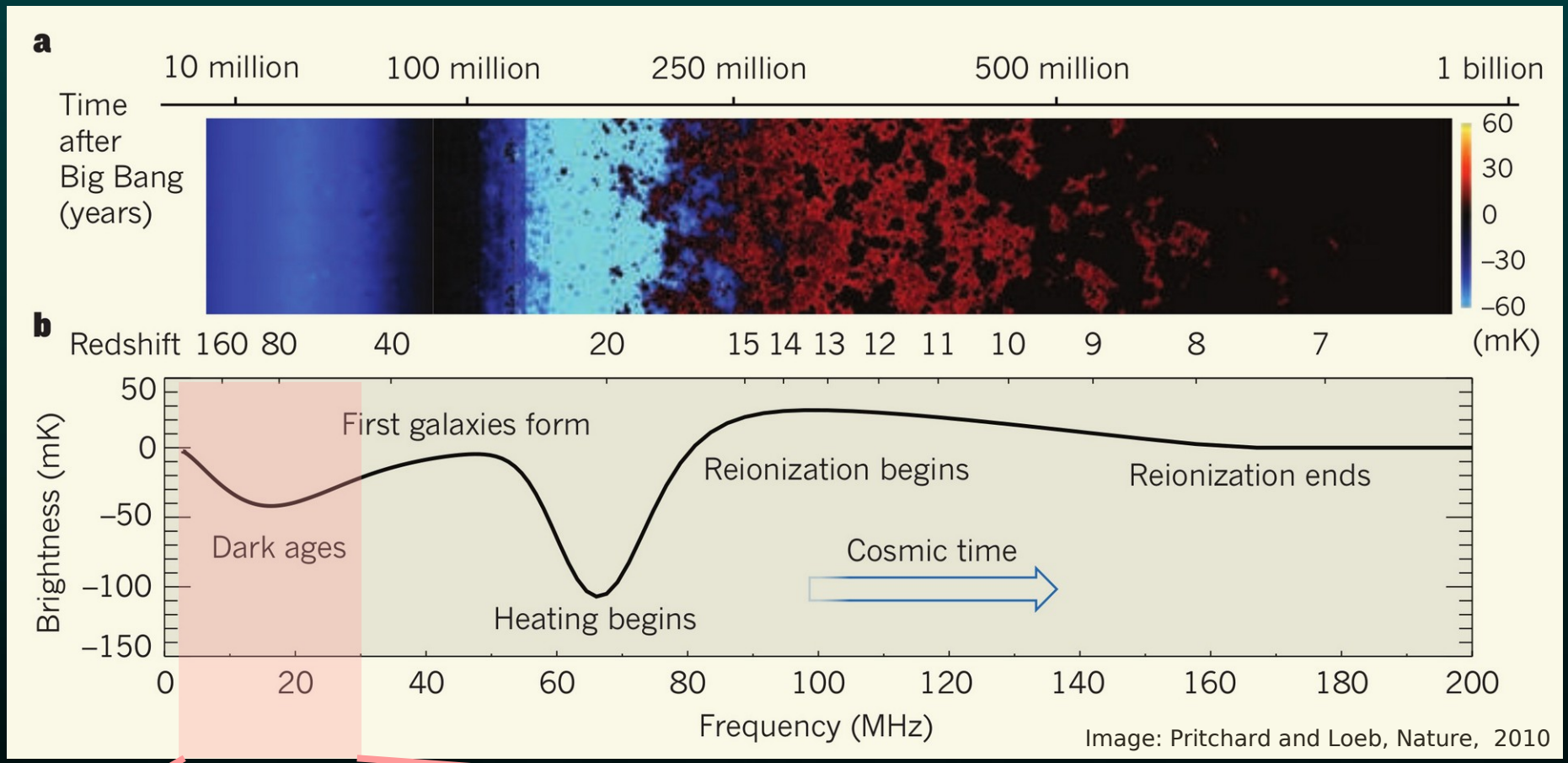
Global 21cm signal

$$\delta T_b \propto x_{HI} (1+z)^{1/2} (T_s - T_{CMB}) / T_s$$



Global 21cm signal

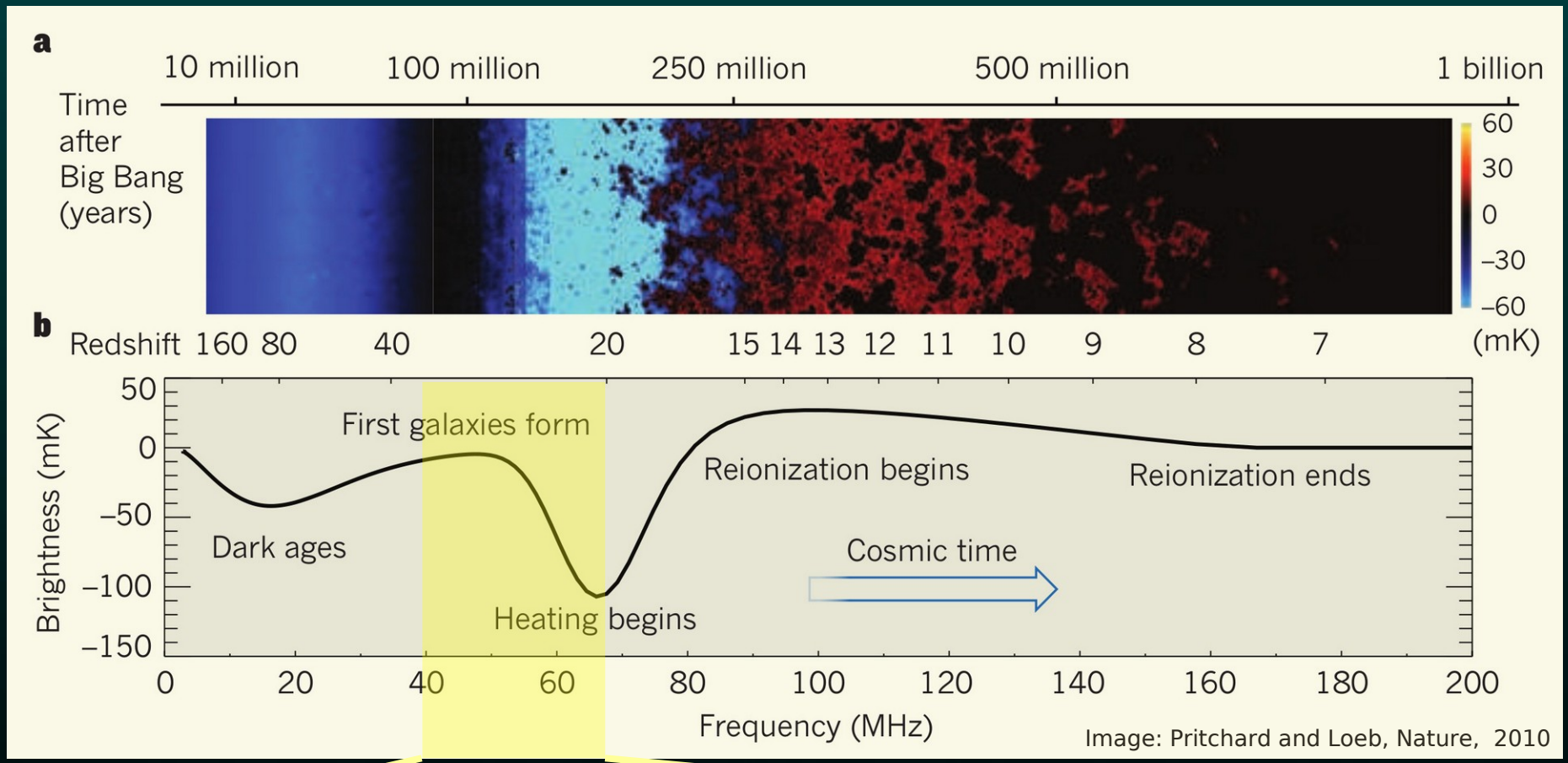
$$\delta T_b \propto x_{HI} (1+z)^{1/2} (T_s - T_{CMB}) / T_s$$



Hydrogen gas kinetic temp (T_K) falls below T_{CMB}. Collisions couple T_K and T_S at first. Later, CMB photons drive $T_S \rightarrow T_{CMB}$.

Global 21cm signal

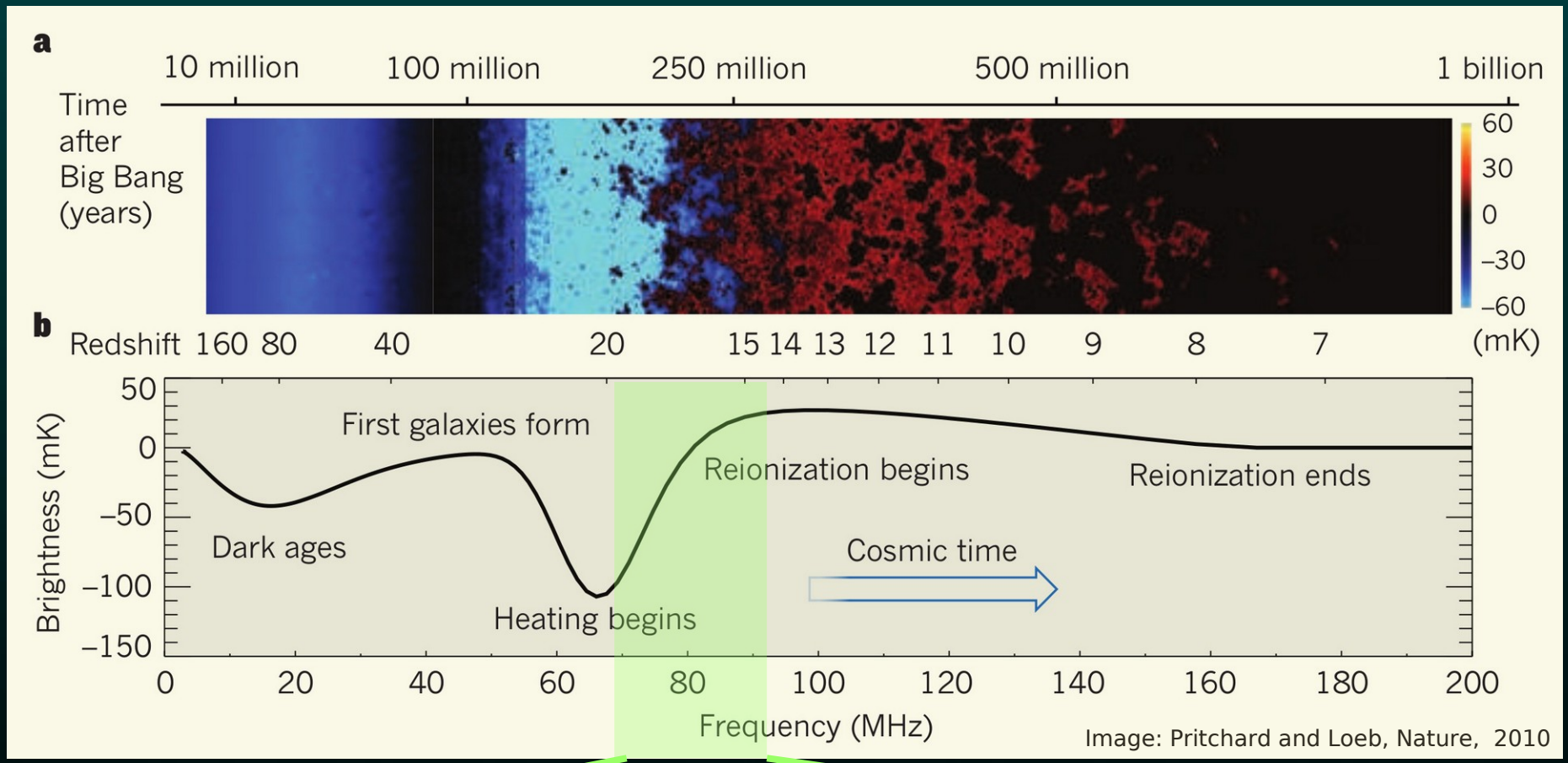
$$\delta T_b \propto x_{HI} (1+z)^{1/2} (T_s - T_{CMB}) / T_s$$



First stars form, Lyα photons couple T_K and T_S via Wouthuysen-Field mechanism

Global 21cm signal

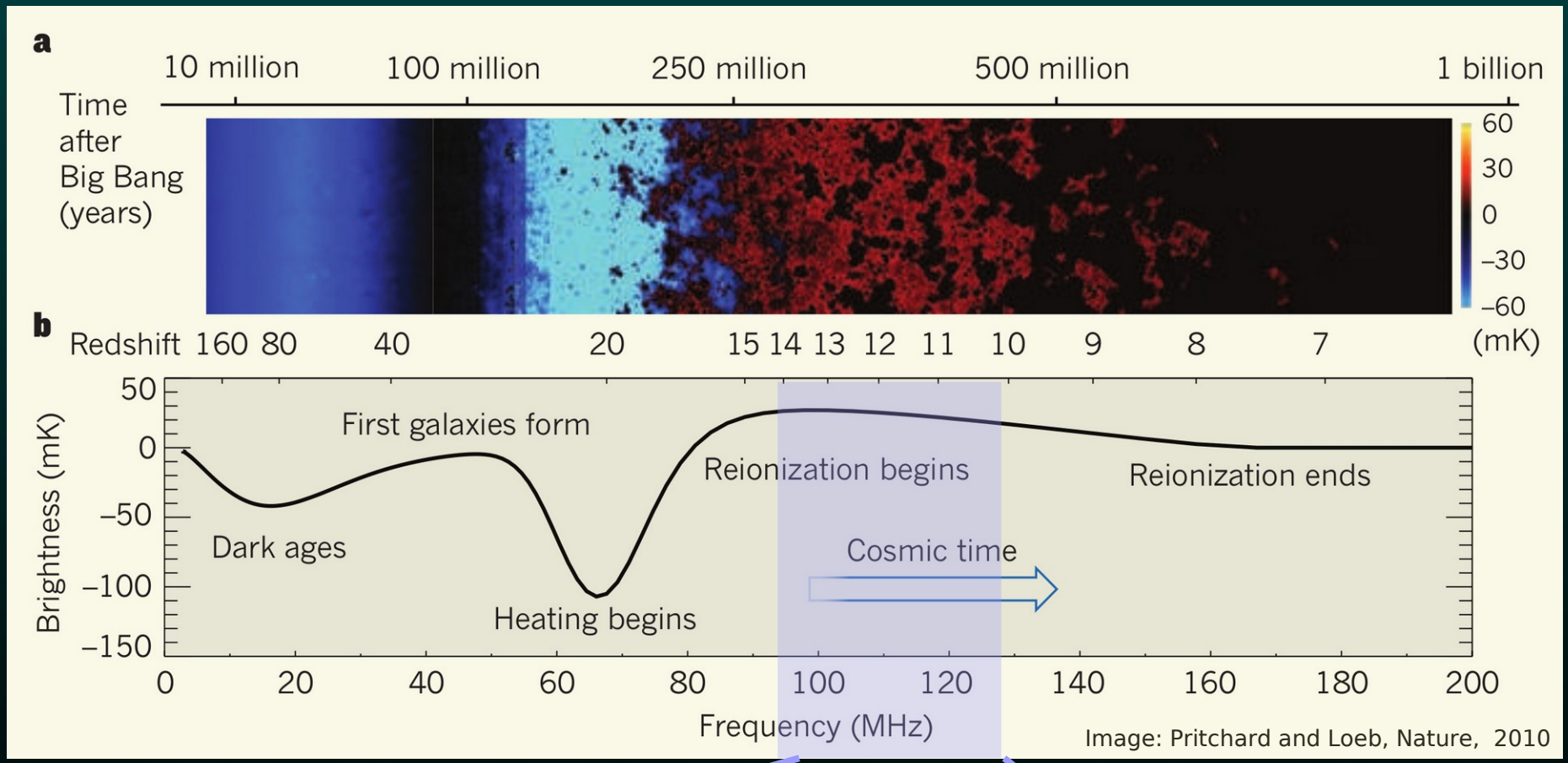
$$\delta T_b \propto x_{HI} (1+z)^{1/2} (T_s - T_{CMB}) / T_s$$



Heating by X-rays, gamma rays from first sources drives T_K above T_{CMB}

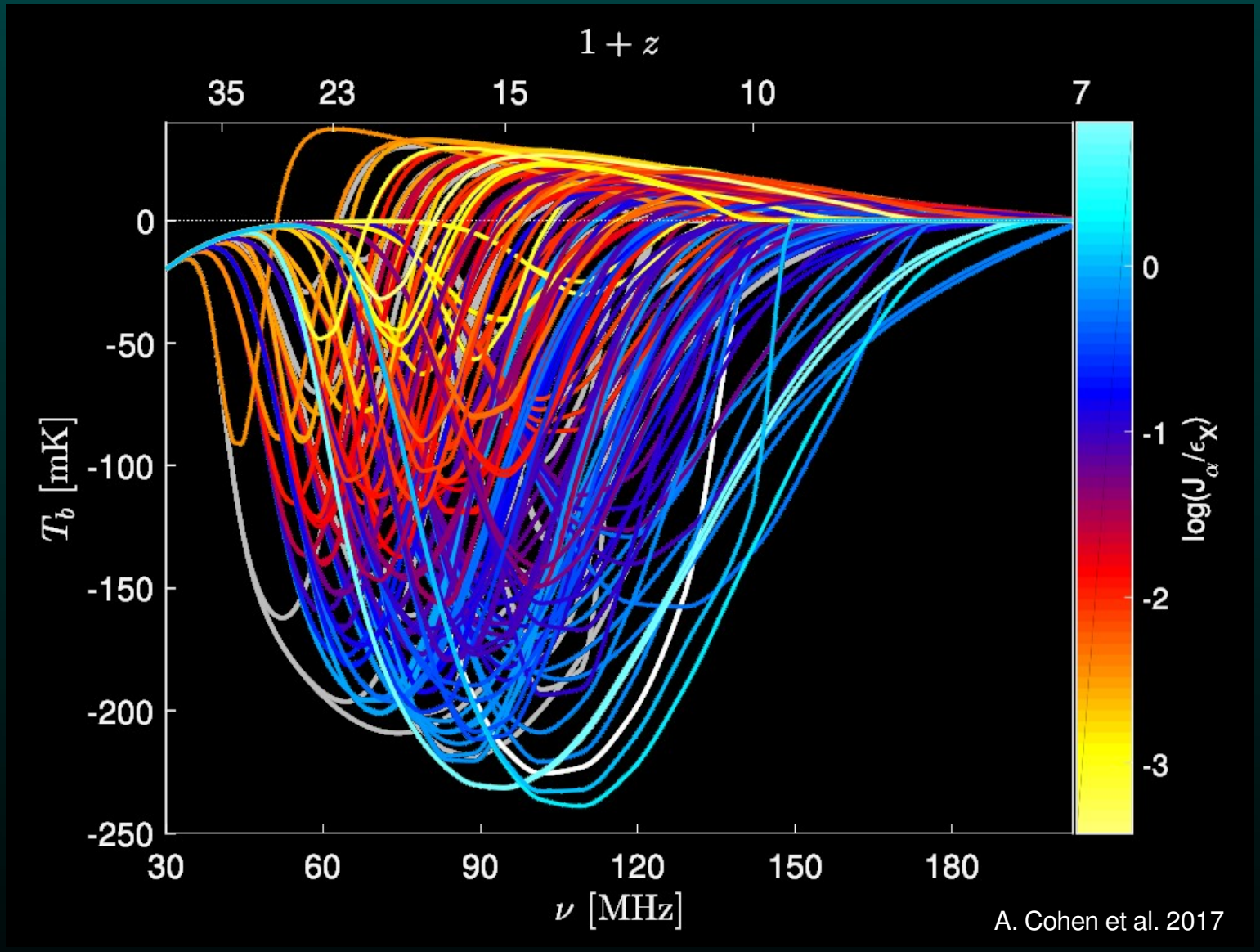
Global 21cm signal

$$\delta T_b \propto x_{HI} (1+z)^{1/2} (T_s - T_{CMB}) / T_s$$



Reionization erases HI signal

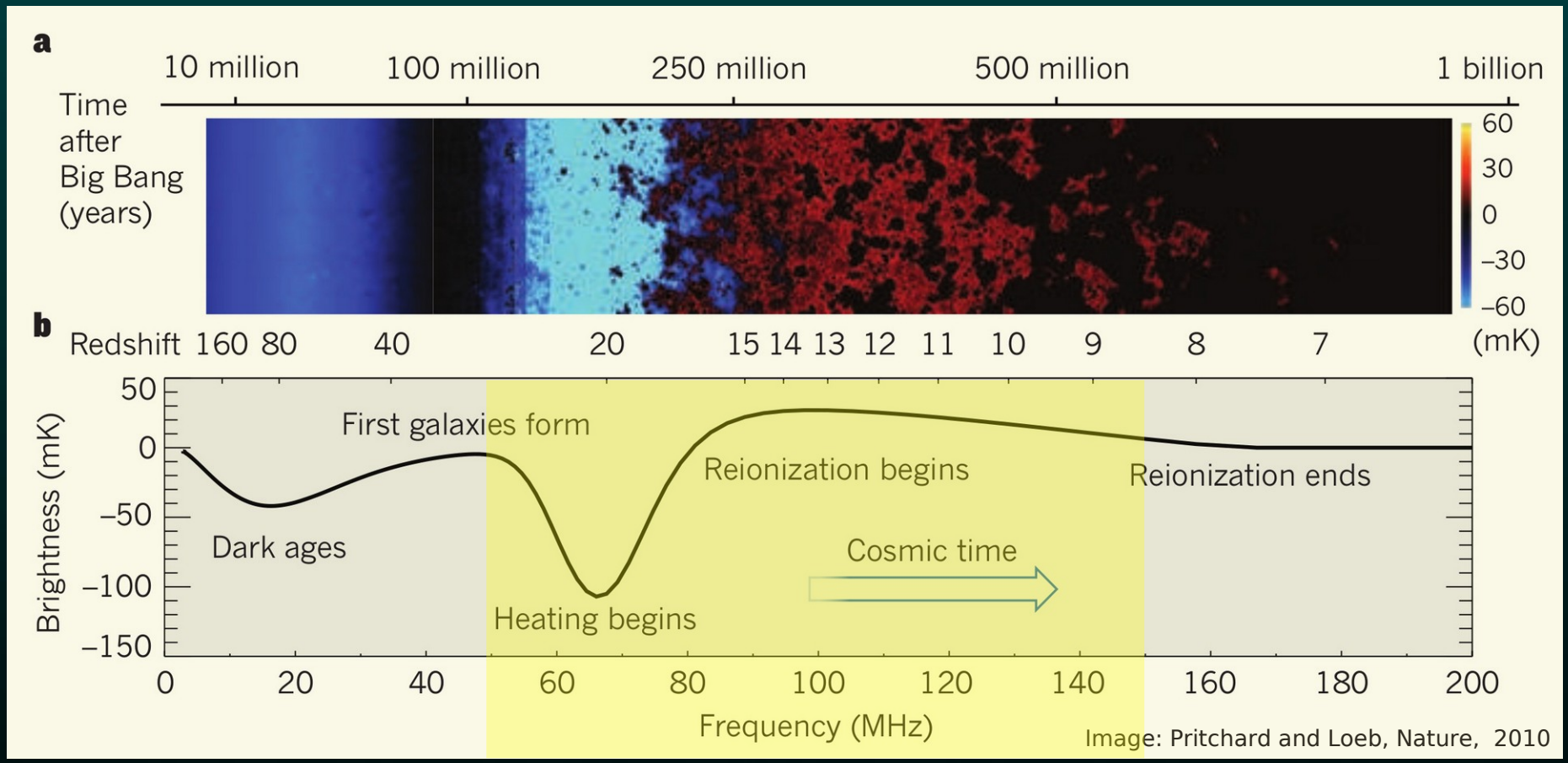
Wide range of model predictions



Color: ratio of Lyman alpha intensity to x-ray heating rate

Experimentalist's perspective...

$$\delta T_b \propto x_{HI} (1+z)^{1/2} (T_s - T_{CMB}) / T_s$$



Distinctive feature to search for in observations

$6 < z < 27$ corresponds to 200 – 50 MHz

Short integration time

Detecting cosmic dawn in 3 easy steps

1) For the global signal, you just need one antenna (e.g. a dipole).

2) Make the antenna broadband to bracket the spectral feature.
The frequency range is easy for electronics.

3) Integration time: considering statistical noise alone, you need only a few hours of observations.

Detecting cosmic dawn in ~~3 easy steps~~

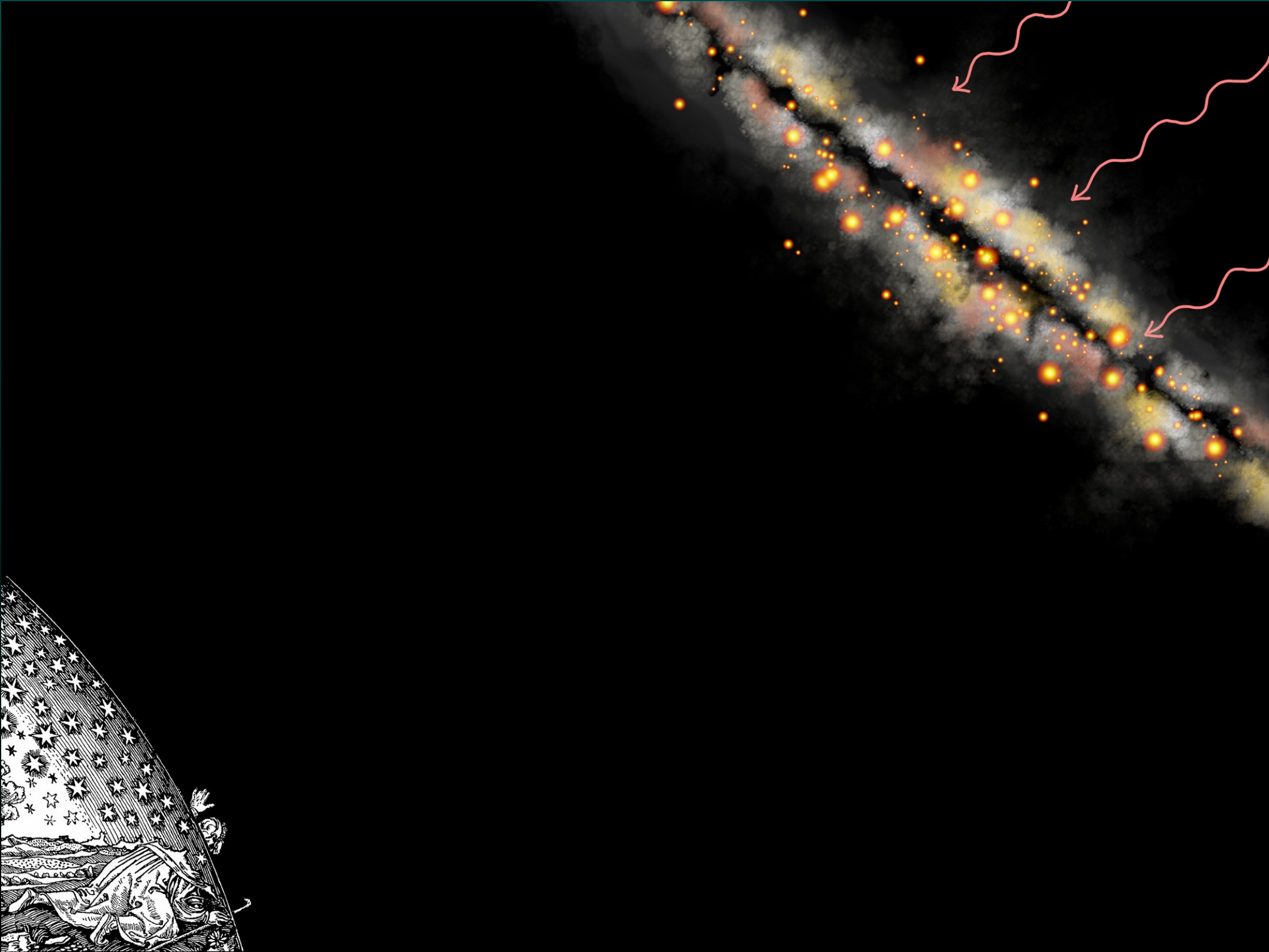
no upper limit on # steps, time, or pain

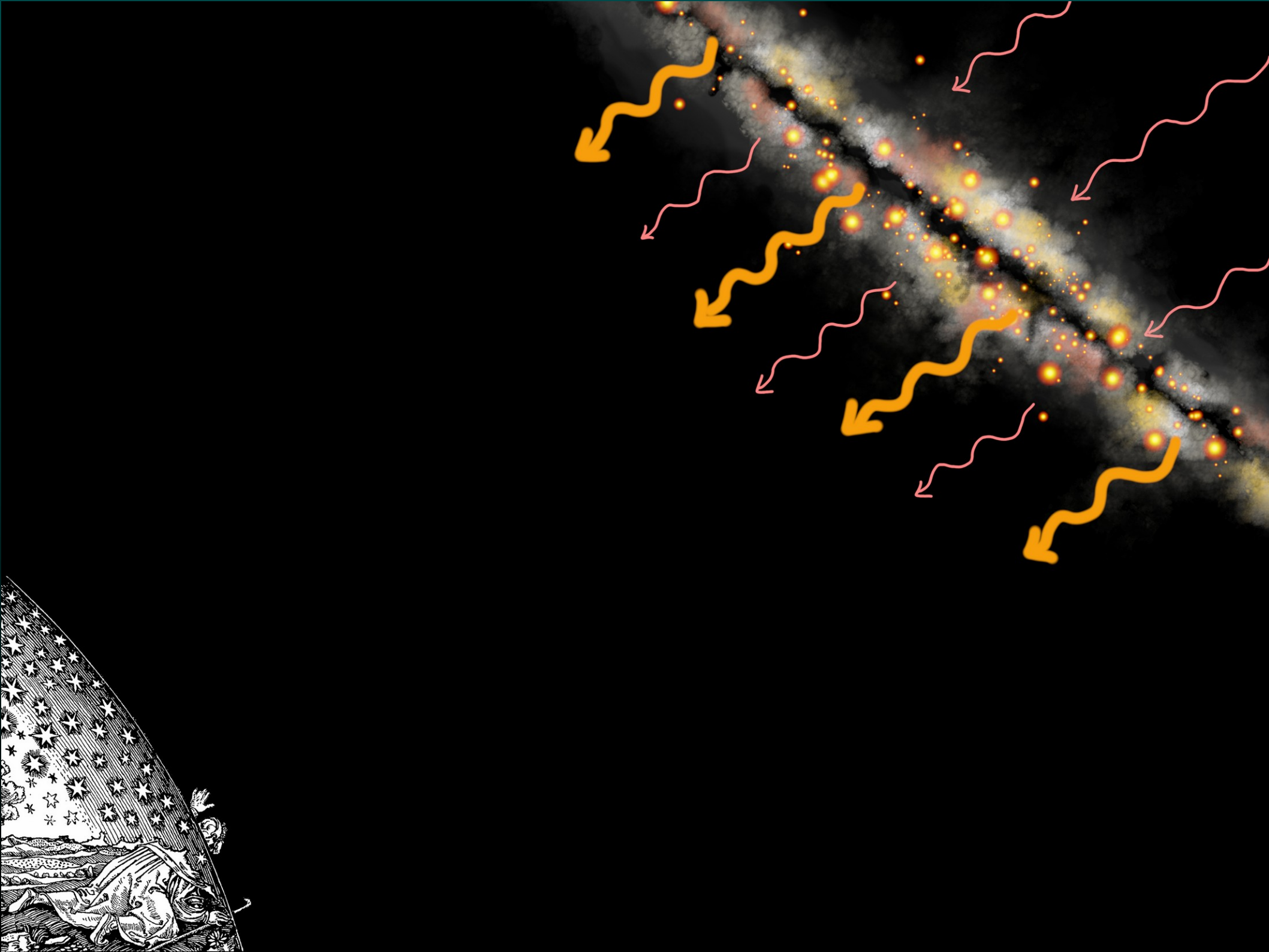
1) For the global signal, you just need one antenna (e.g. a dipole).

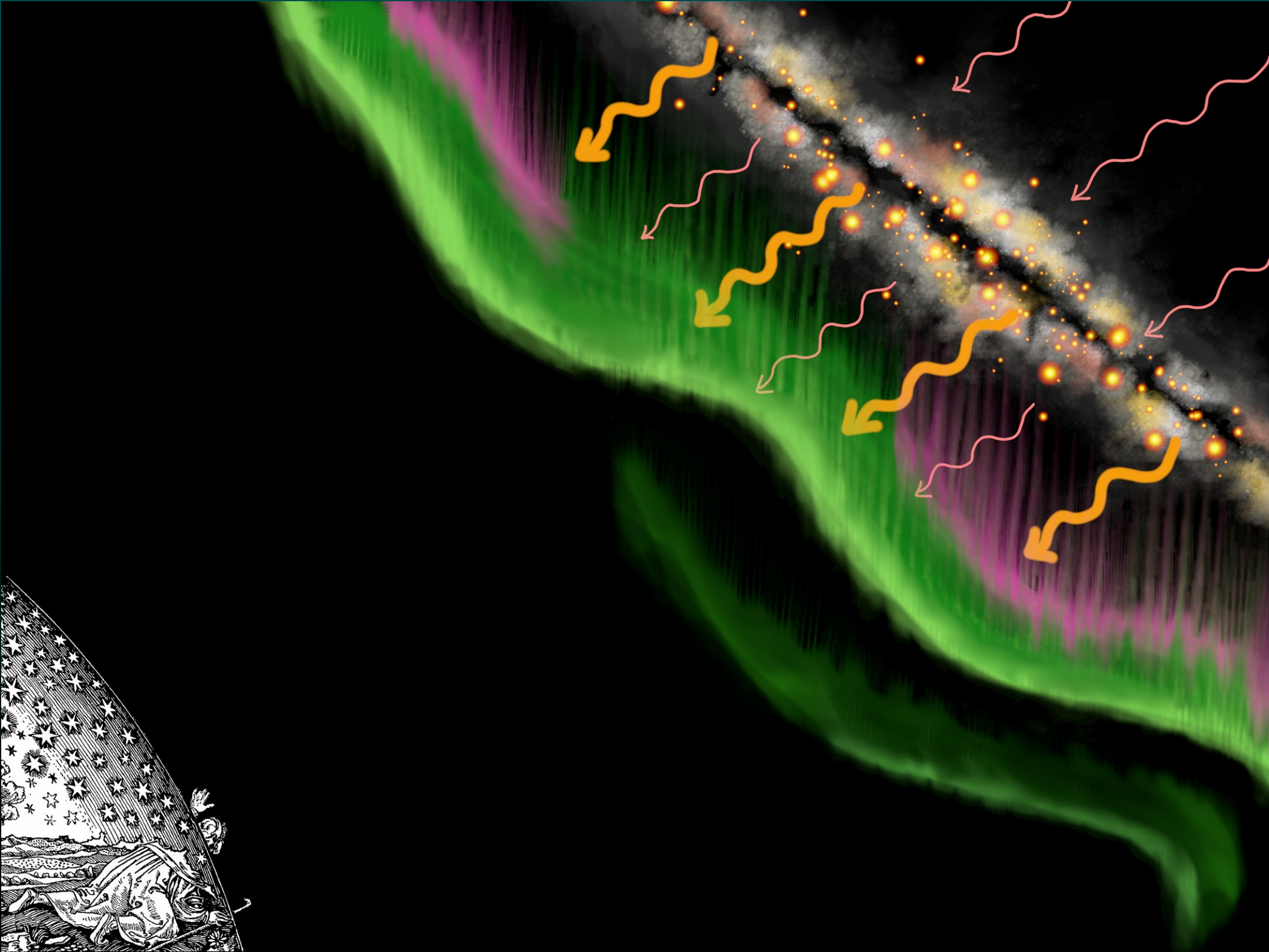
2) Make the antenna broadband to bracket the spectral feature.
The frequency range is easy for electronics.

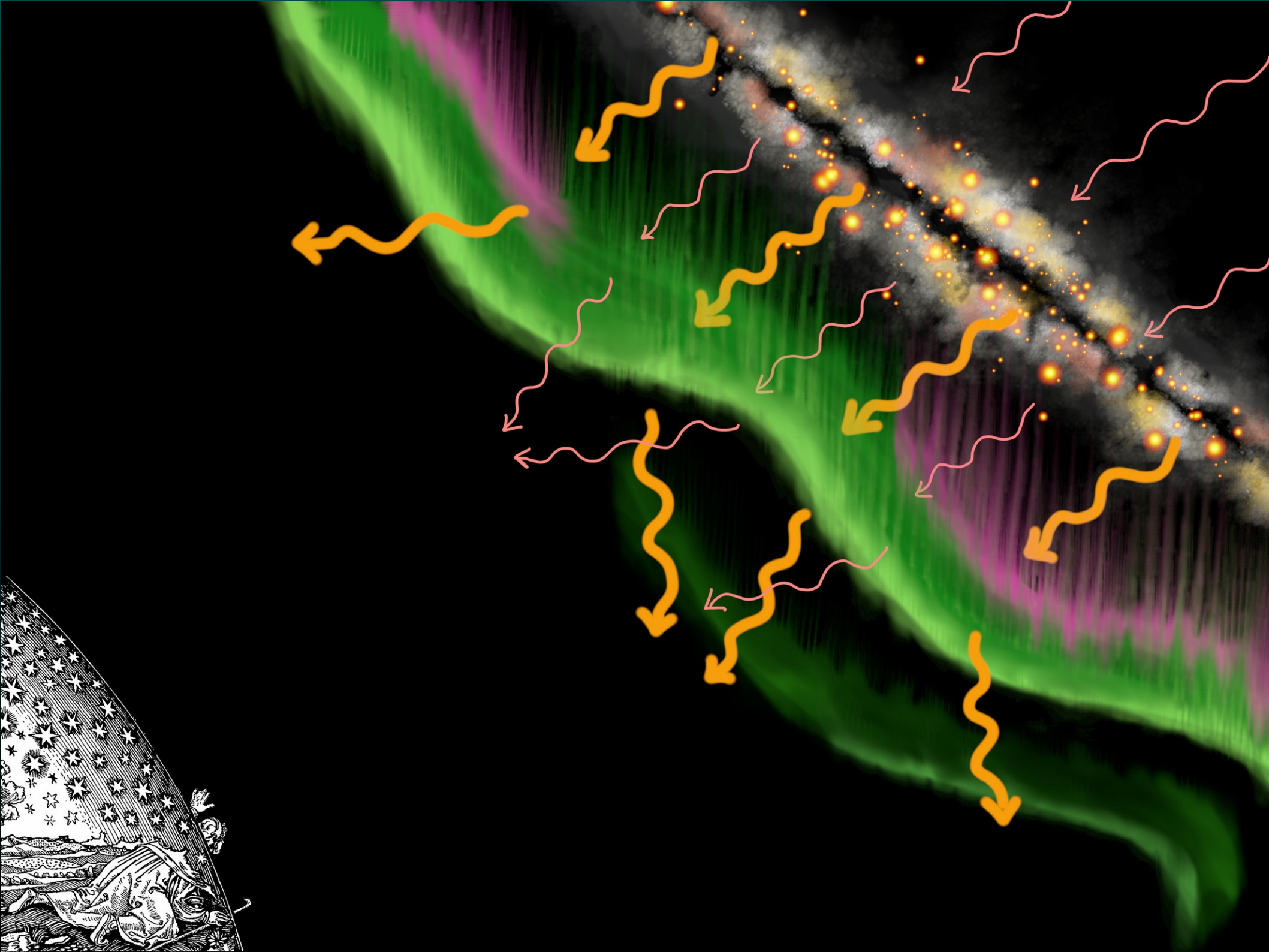
3) Integration time: considering statistical noise alone, you need only a few hours of observations.

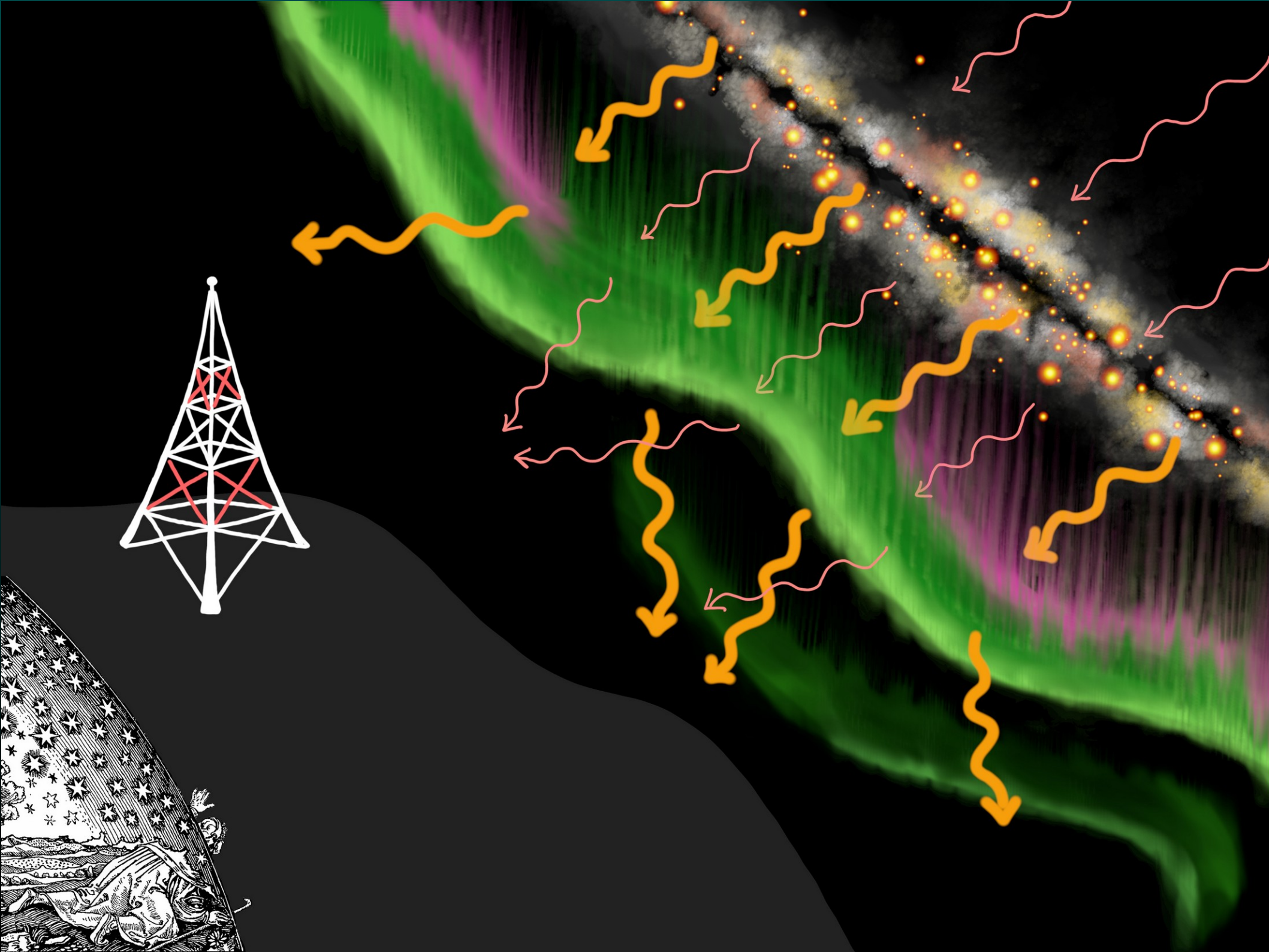
Fine print: for total power measurements, what you see is what you get, and systematic errors dominate. Not easy to separate sky signal from contaminants...

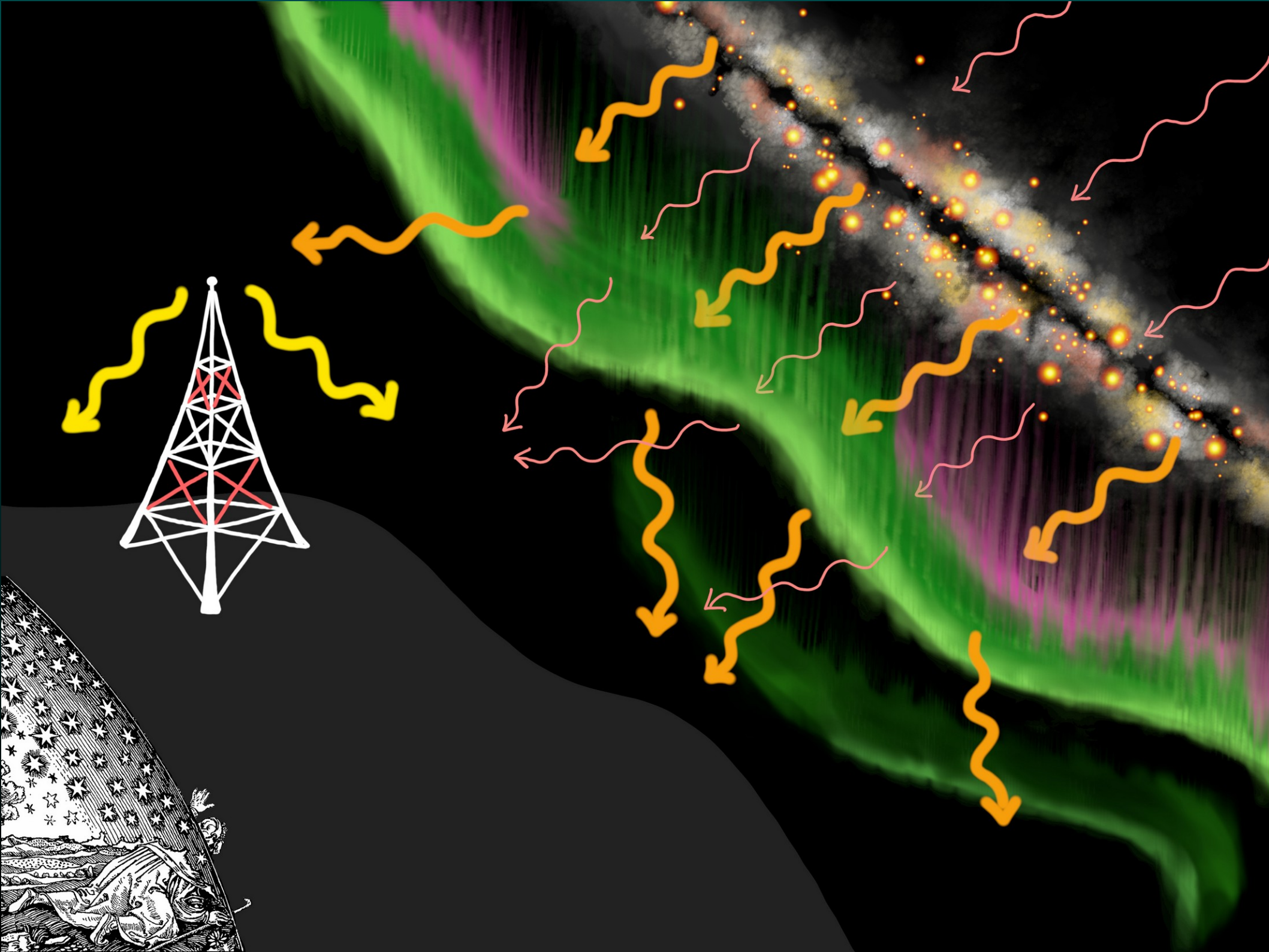


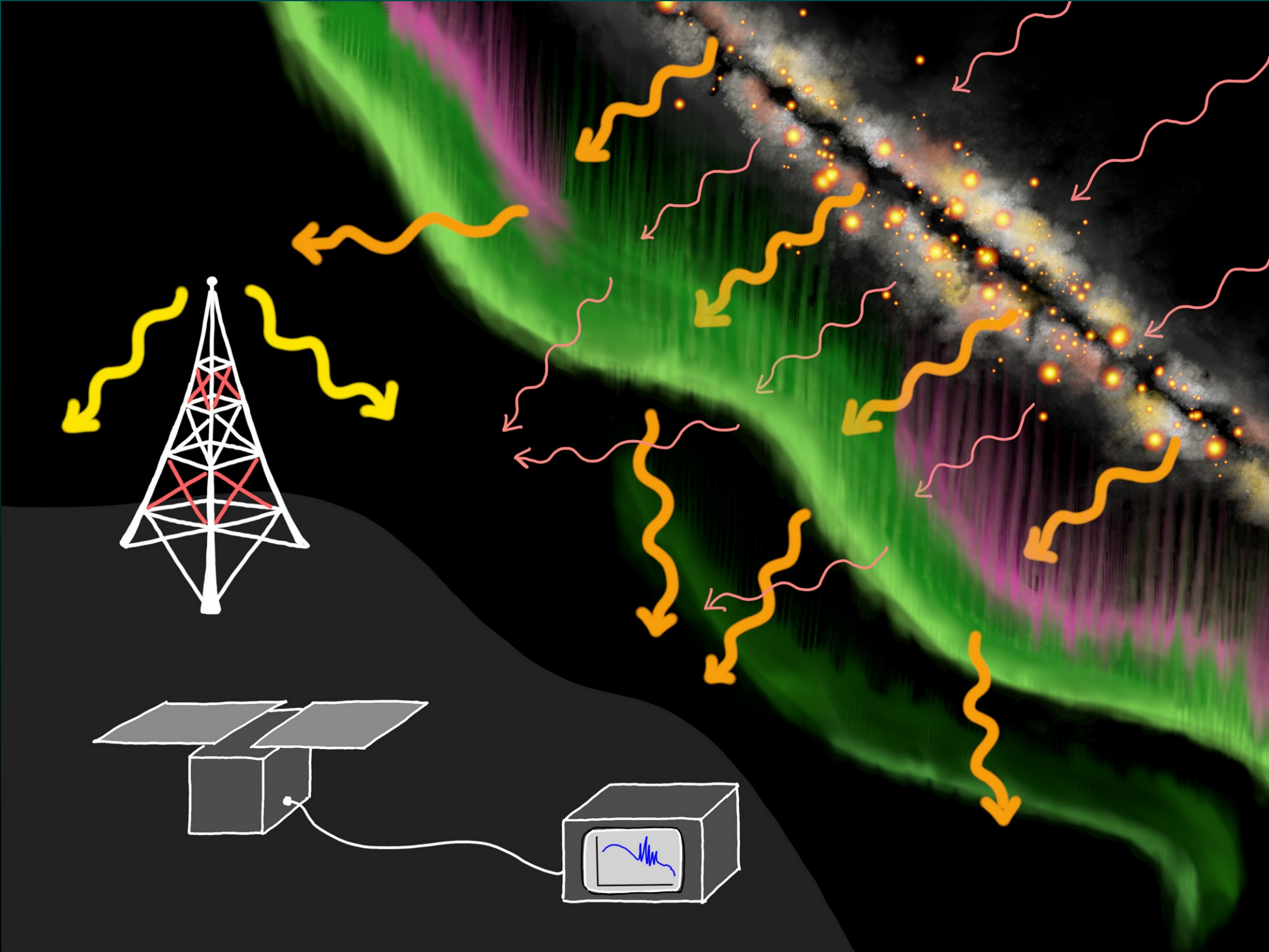


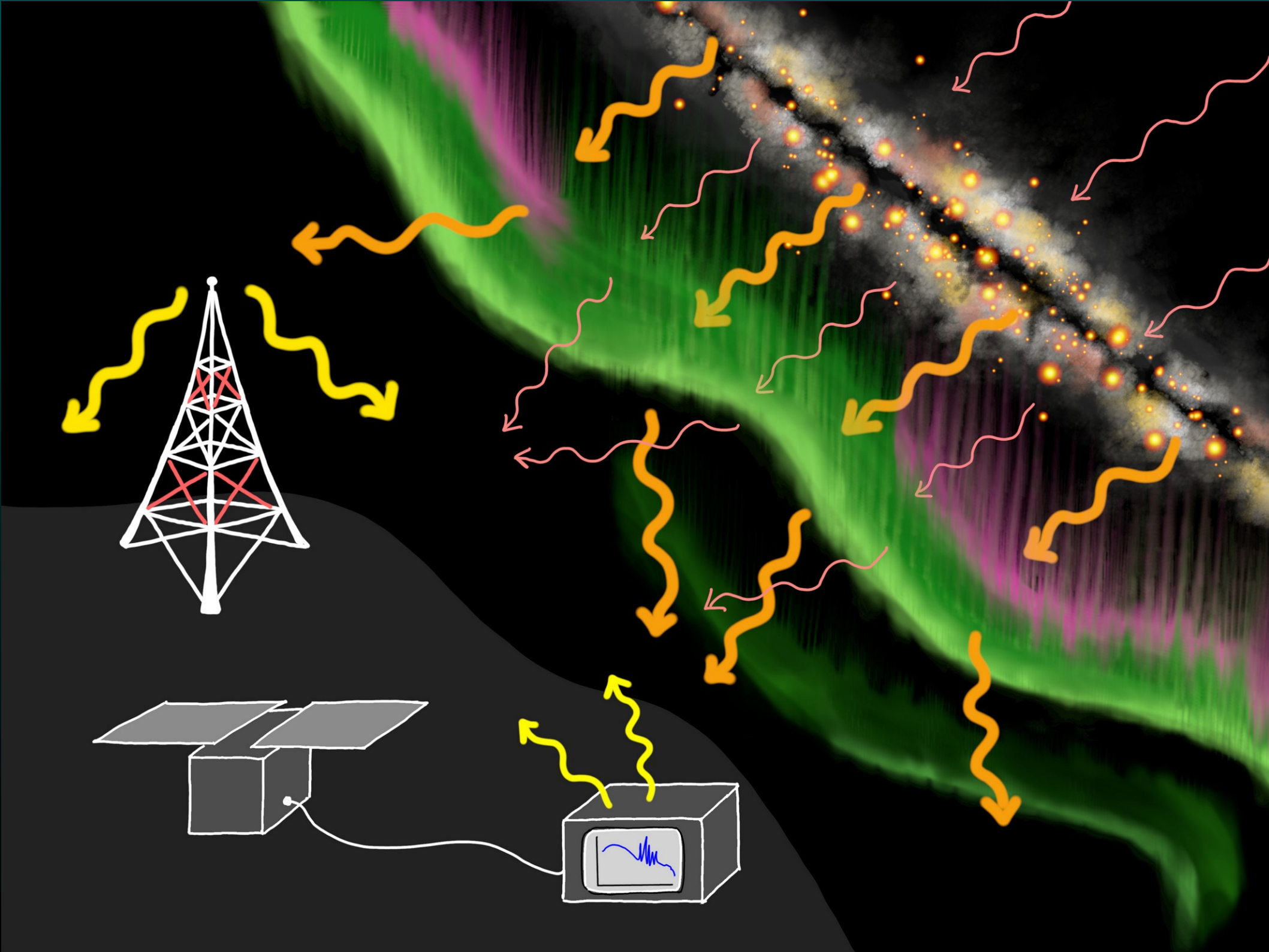


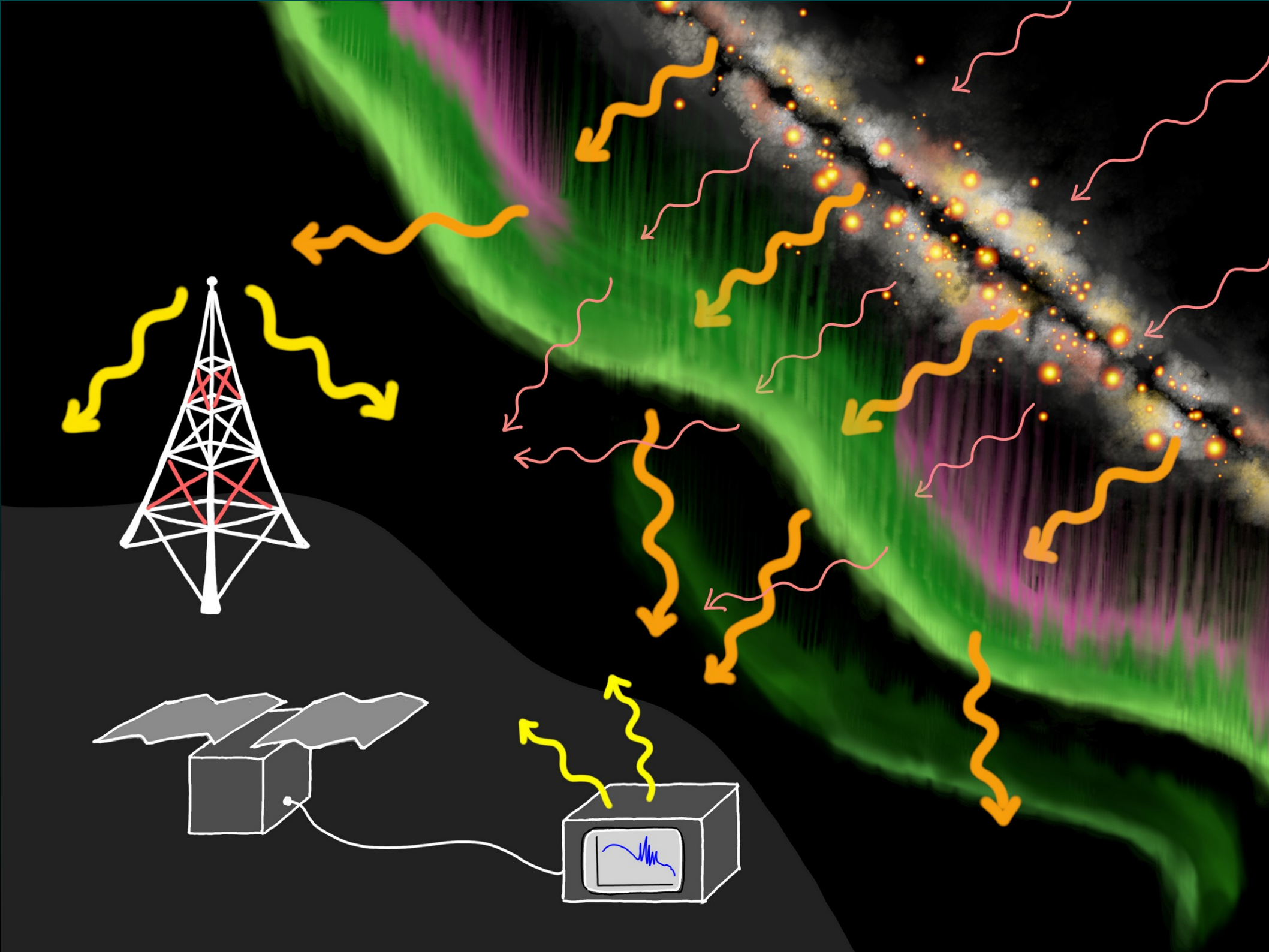


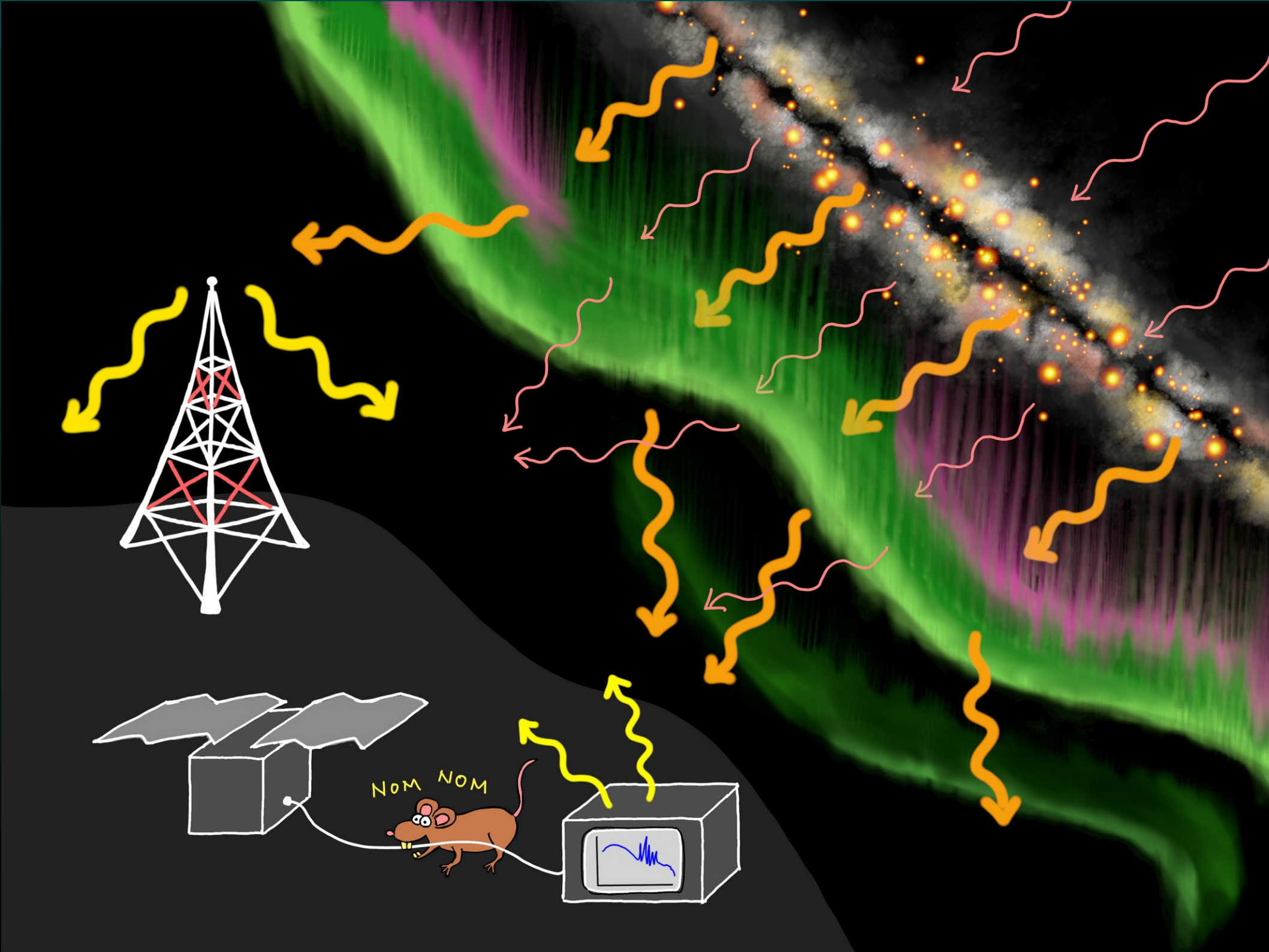


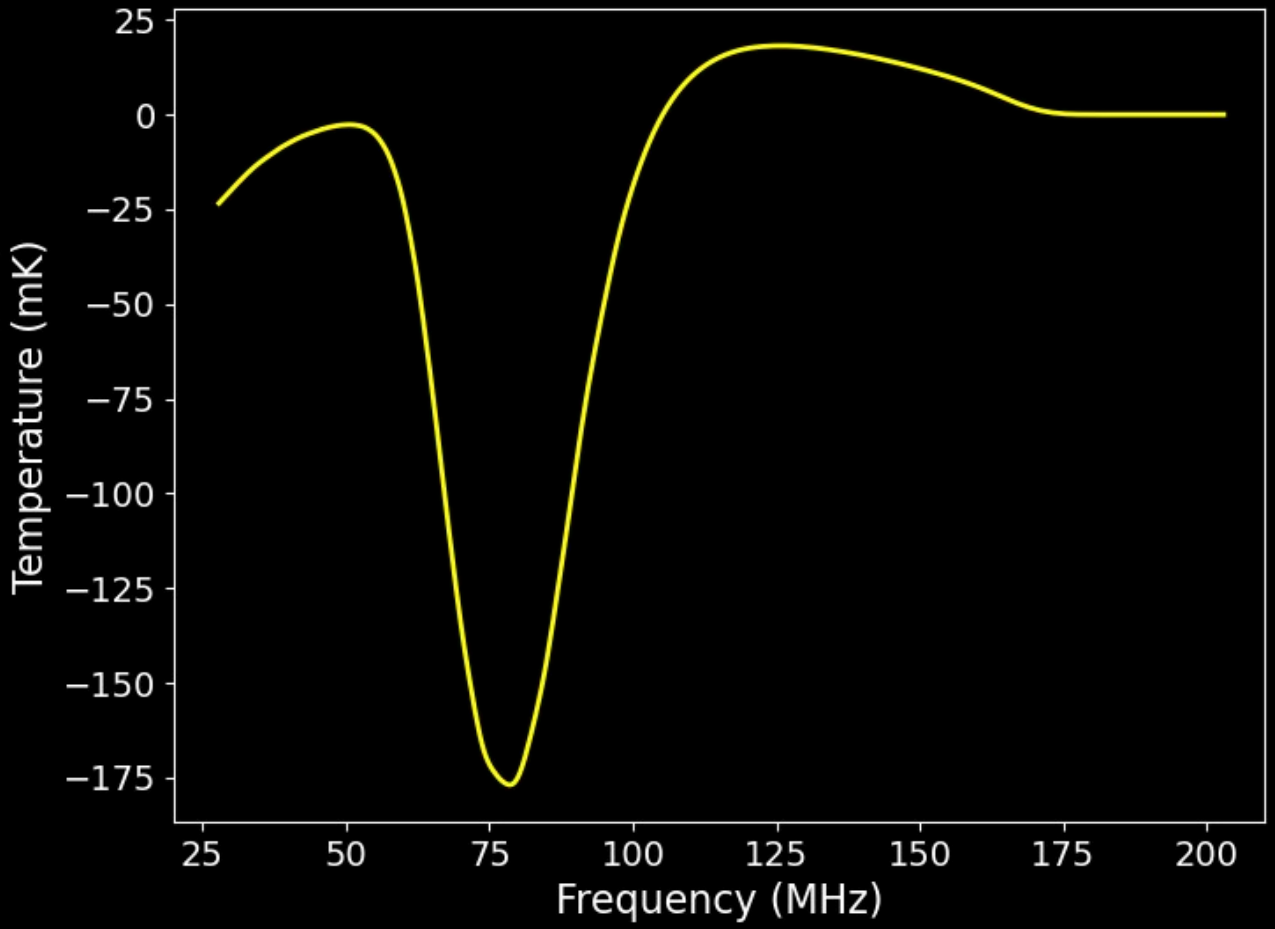


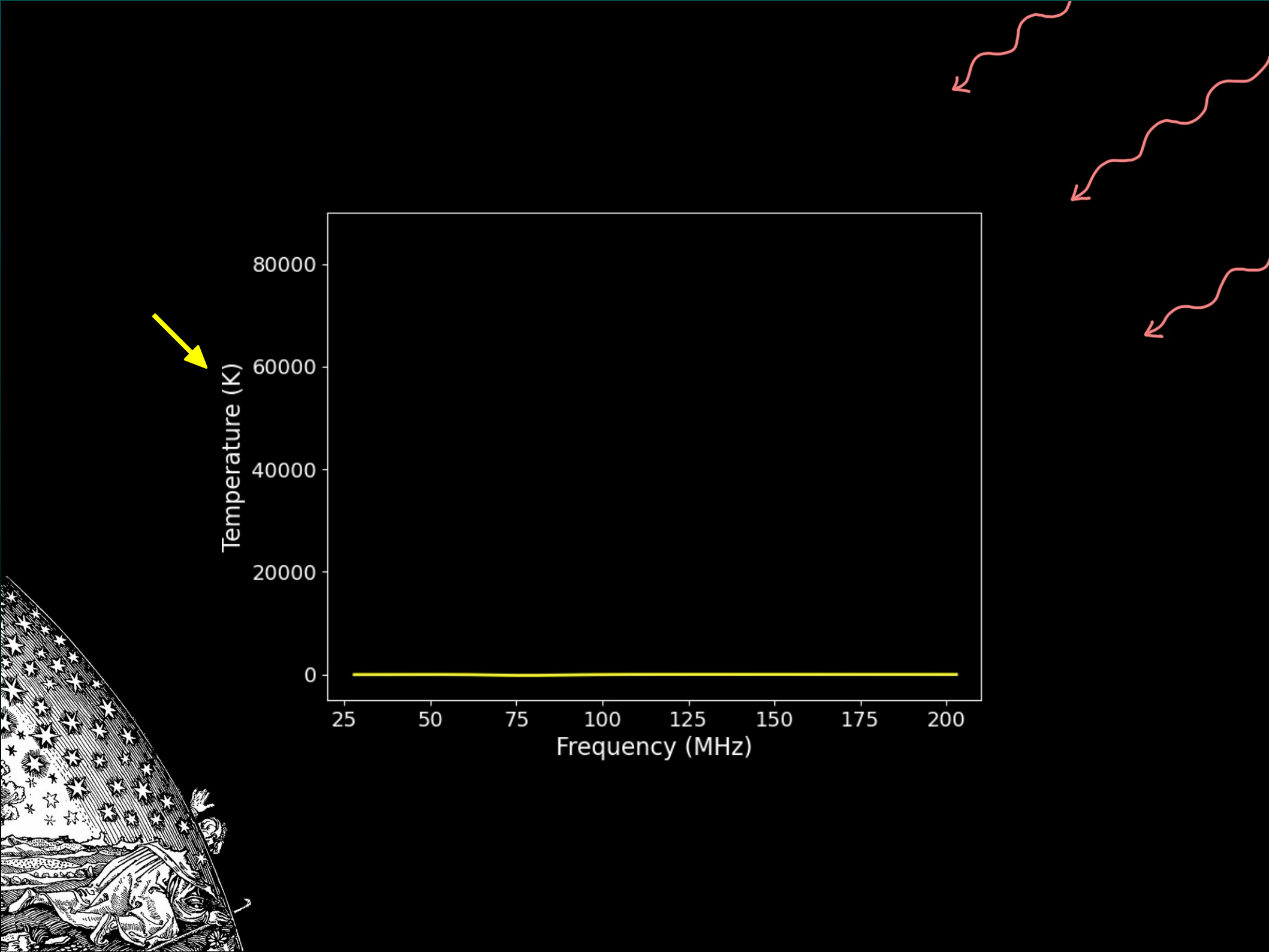


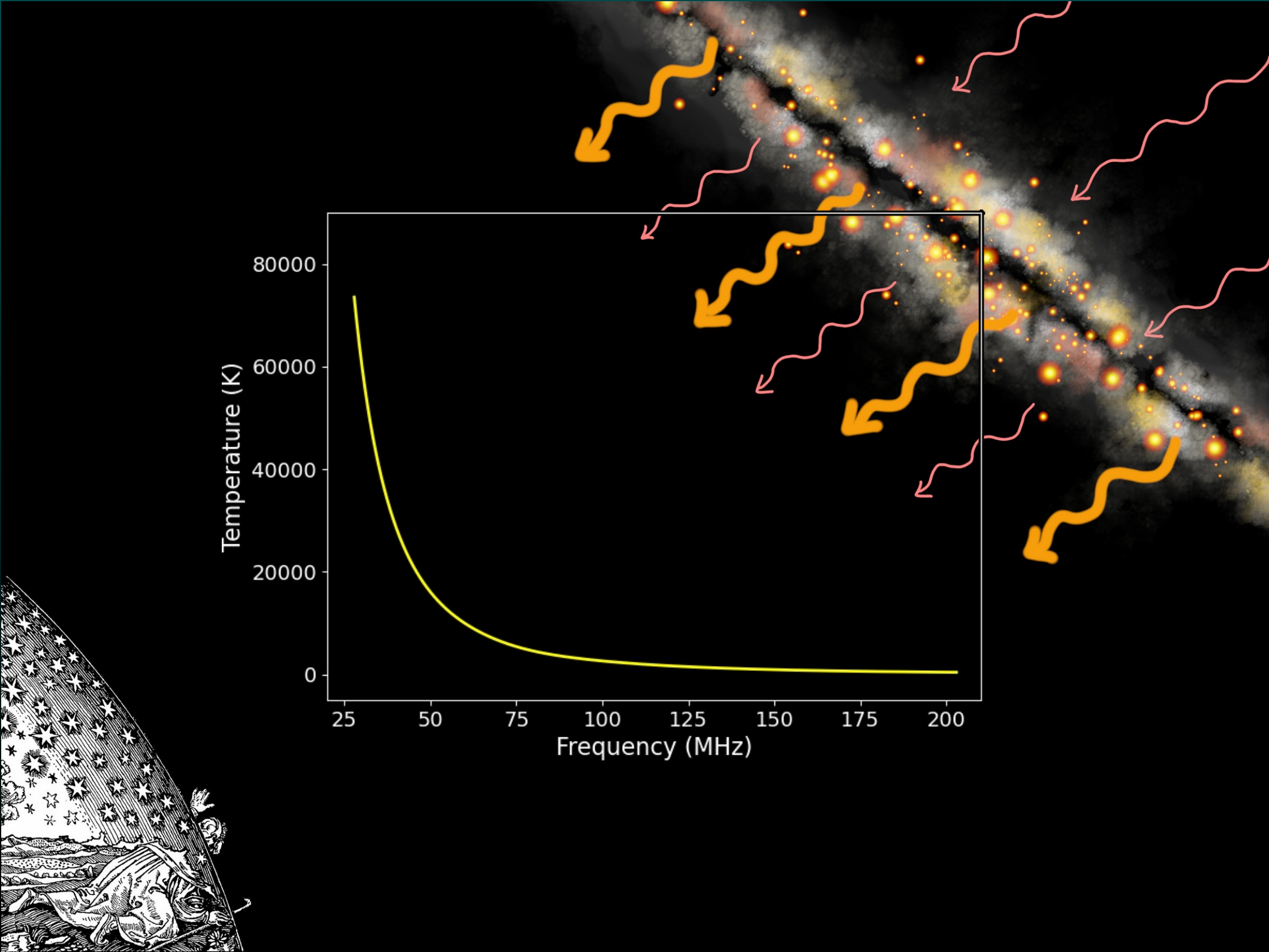


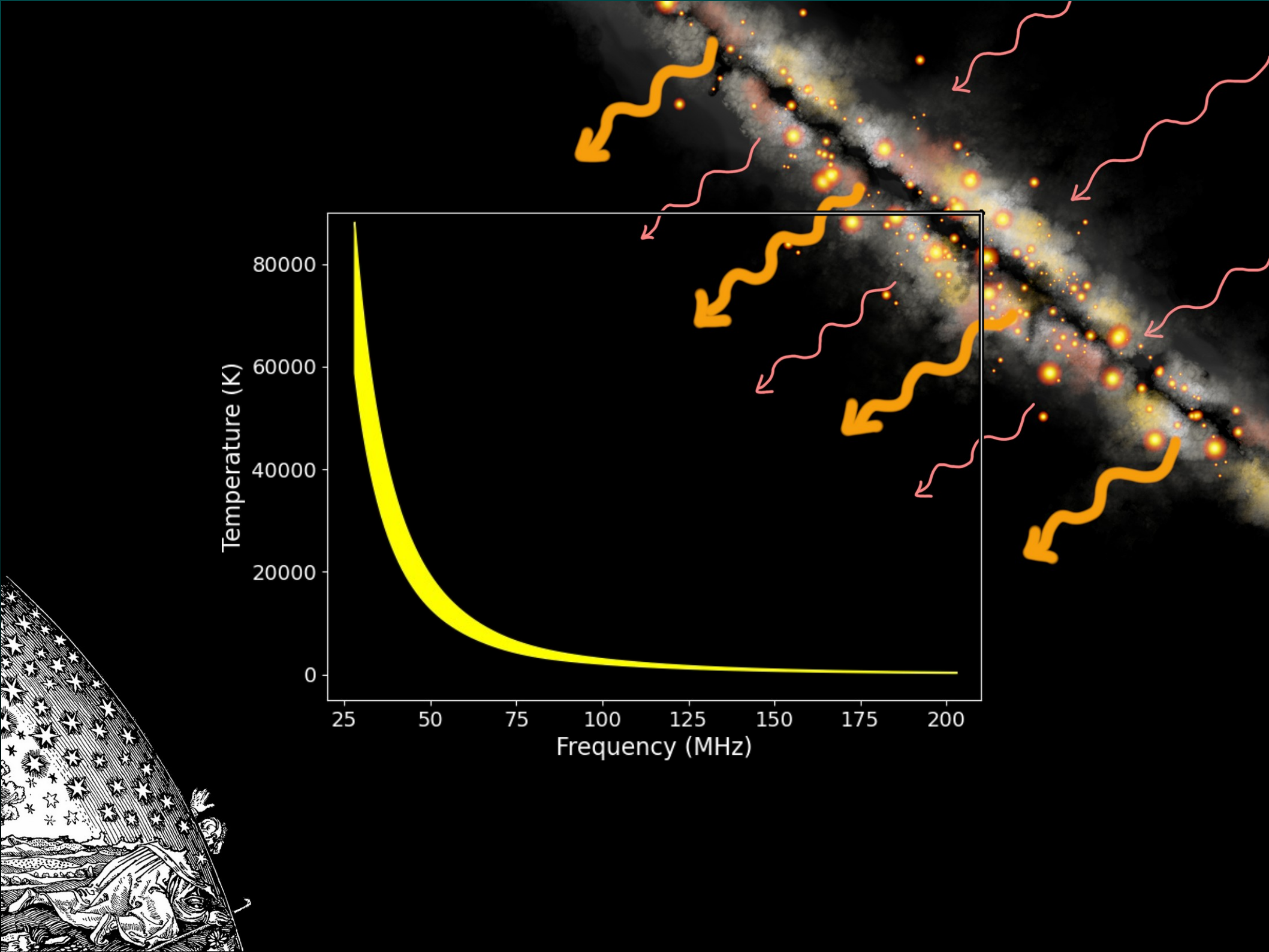


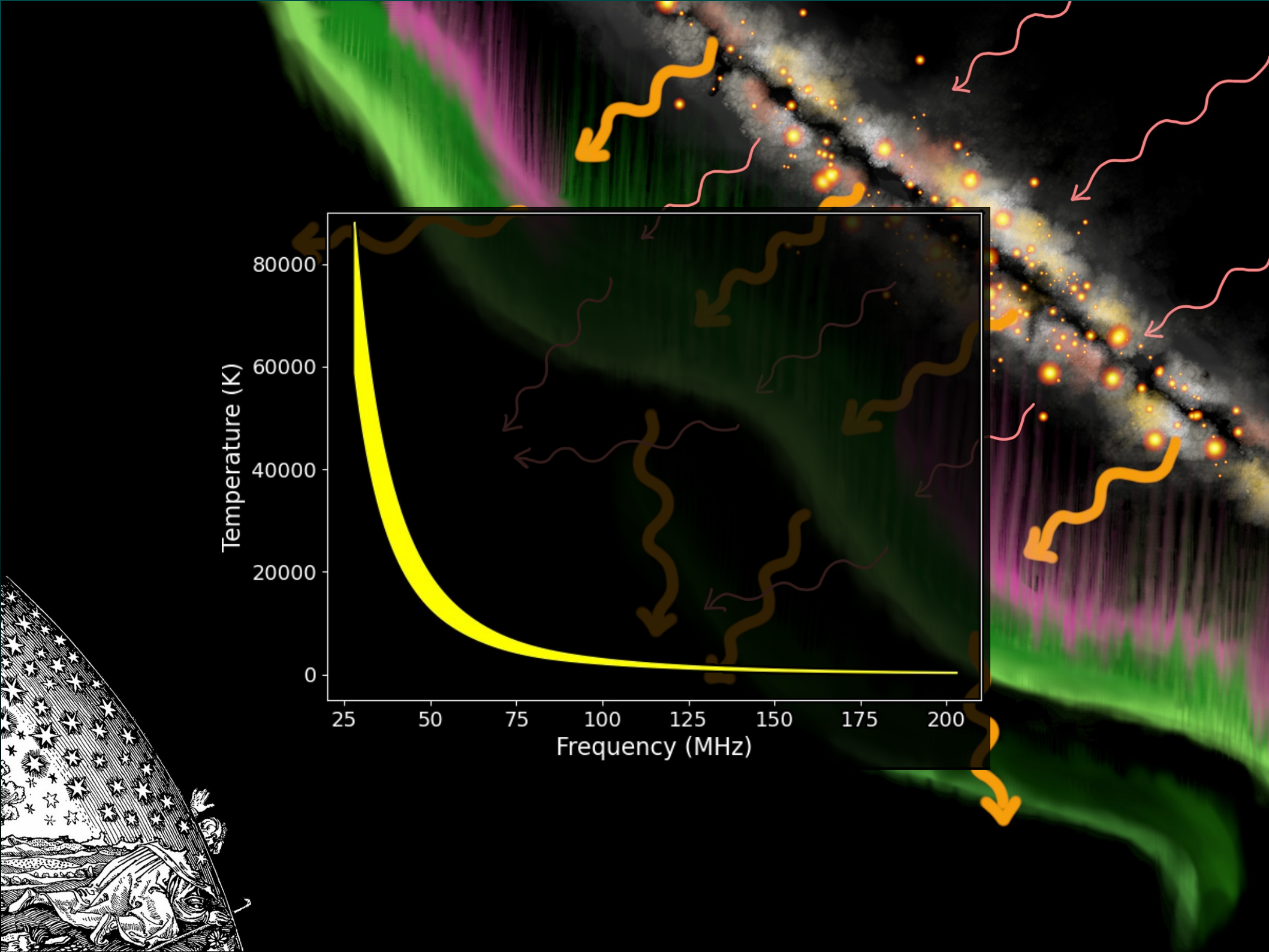

NOM NOM

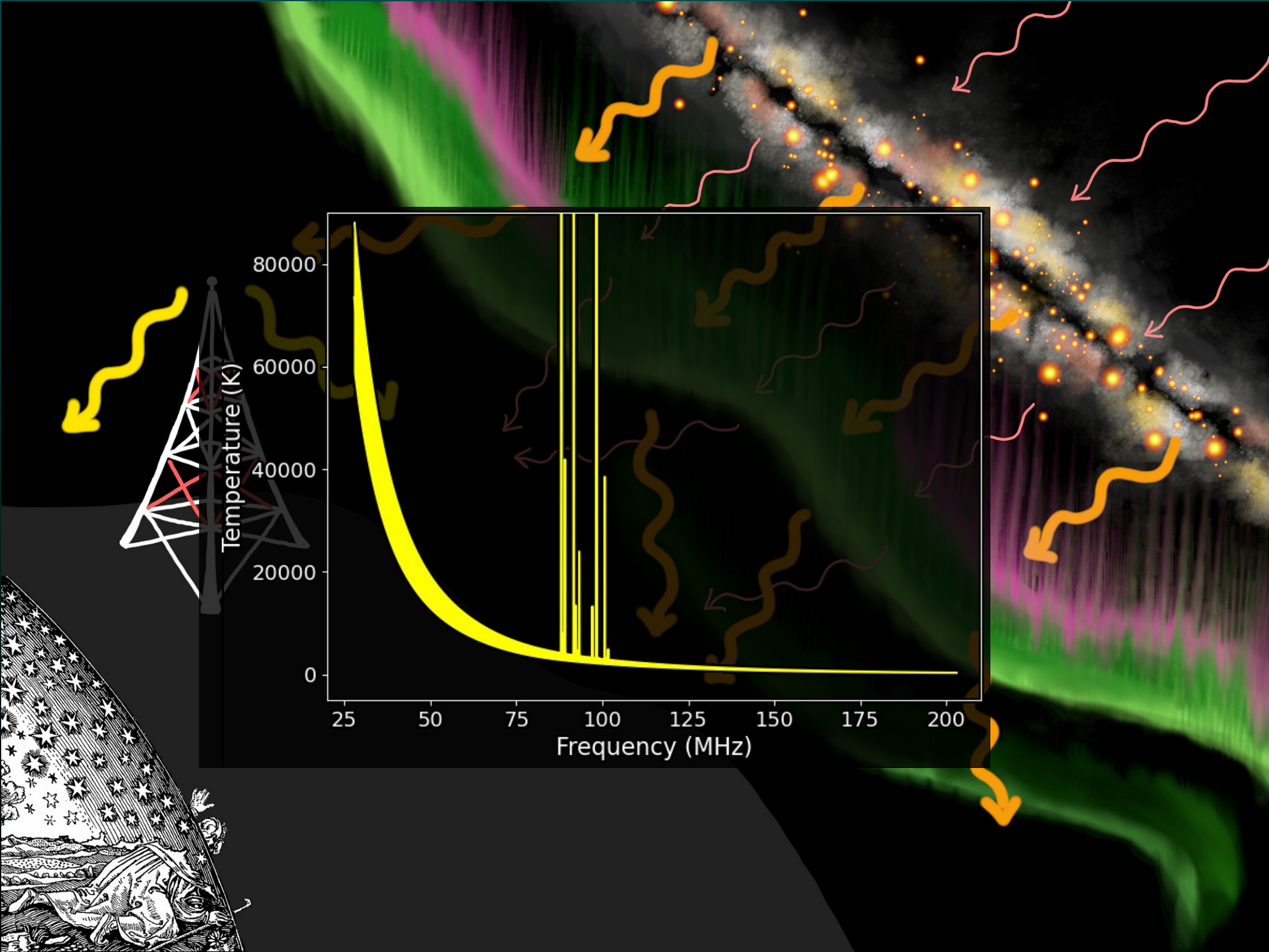

25
0
−25
−50
−75
−100
−125
−150
−175
Temperature (mK)
25
50
75
100
125
150
175
200
Frequency (MHz)

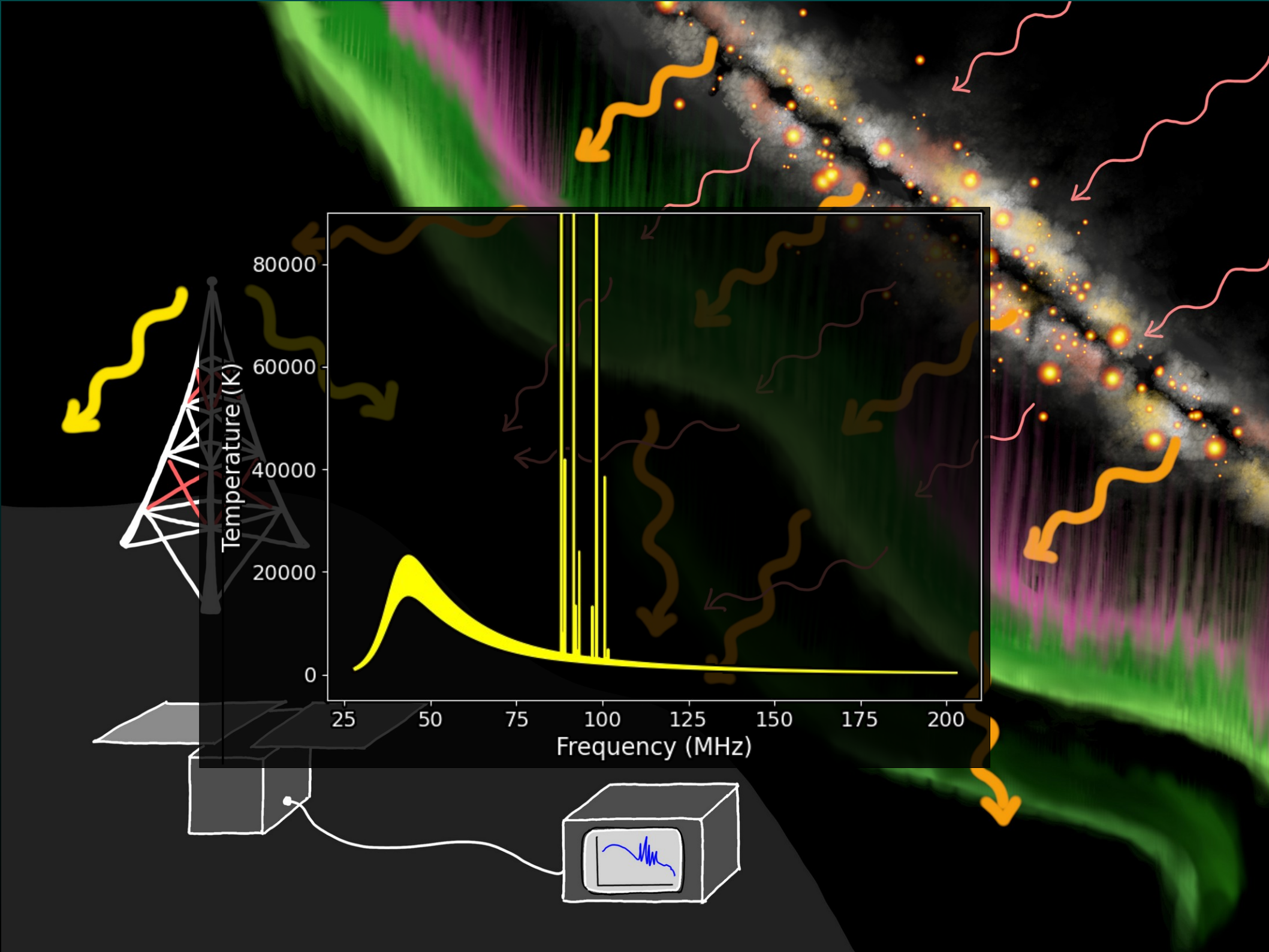

80000
60000
40000
20000
0
Temperature (K)
25
50
75
100
125
150
175
200
Frequency (MHz)

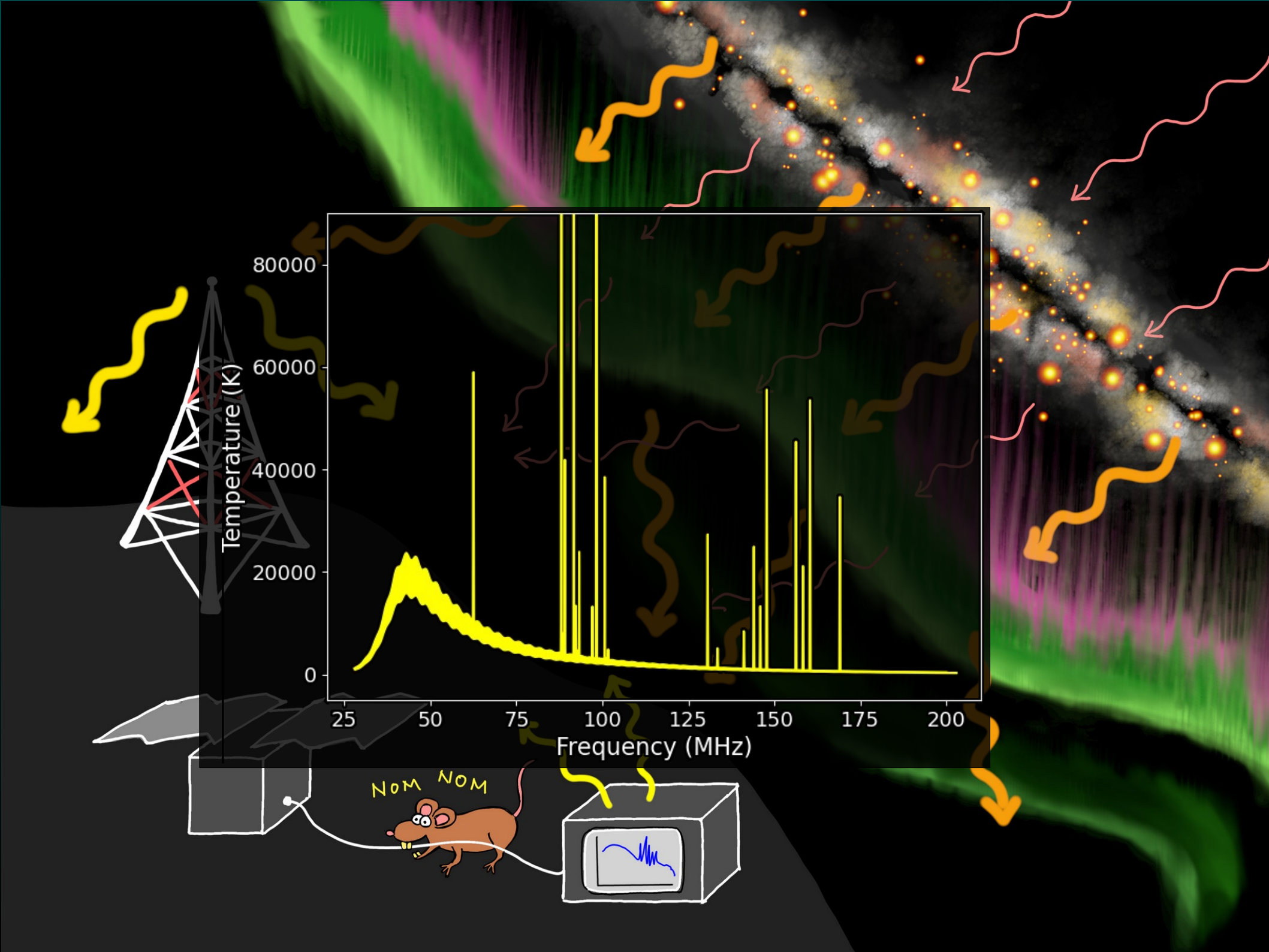

80000
60000
40000
20000
0
Temperature (K)
25
50
75
100
125
150
175
200
Frequency (MHz)


80000
60000
40000
20000
0
Temperature (K)
25
50
75
100
125
150
175
200
Frequency (MHz)


80000
60000
40000
20000
0
Temperature (K)
25
50
75
100
125
150
175
200
Frequency (MHz)


80000
60000
40000
20000
0
Temperature (K)
25
50
75
100
125
150
175
200
Frequency (MHz)


80000
60000
40000
20000
0
Temperature (K)
25
50
75
100
125
150
175
200
Frequency (MHz)


80000
60000
40000
20000
0
Temperature (K)
25
50
75
100
125
150
175
200
Frequency (MHz)
NOM NOM

Global 21cm experiments

Ground-based single antenna	Ground-based antenna array	Space-based
EDGES	ASSASSIN	Cosmocube
EIGSEP	LWA-Sevilleta	Hongmeng
HighZ	MWA w/ moon blockage	LuSEE-Night
LEDA	SITARA	Pratush
MIST		
PRI^{Z}M		
REACH		
SAFARI		
SARAS3		

Global 21cm experiments

	Ground-based single antenna	Ground-based antenna array	Space-based
Instrument access	“Easy”	”Easy”	Hard
Instrument systematics	Medium	Medium	Hard
Terrestrial RFI	Medium/hard	Medium/hard	”Easy”
Self-gen RFI	“Easy”	Medium	Hard
Ionosphere	Medium/hard	Medium/hard	Easy (none)

Ground-based, single-antenna experiments

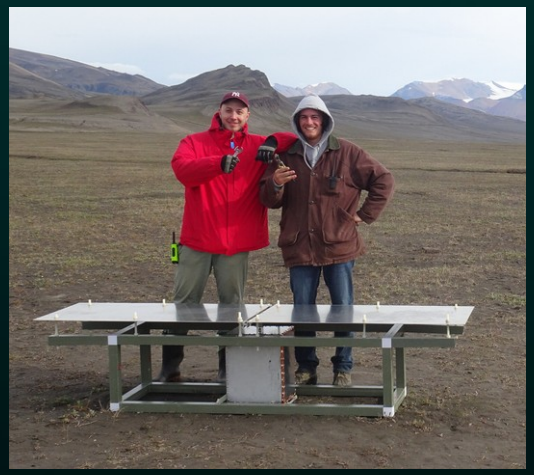
EDGES

SARAS3

LEDA

PRI^{Z}M

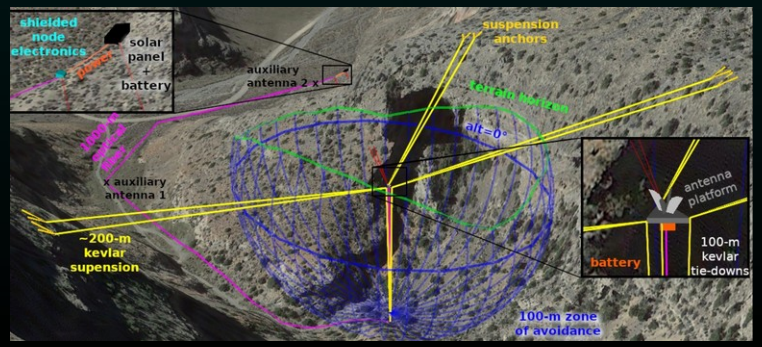
MIST



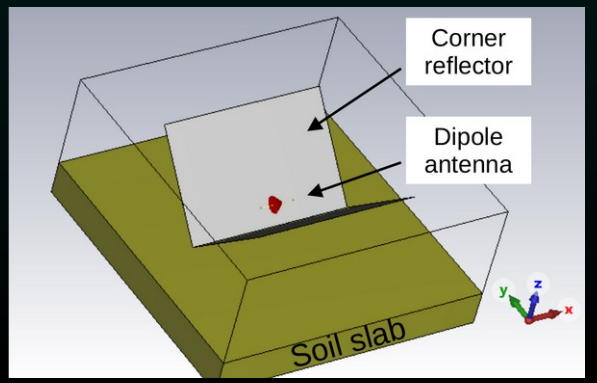
HighZ

REACH

EIGSEP



SAFARI



EDGES detection: February 2018

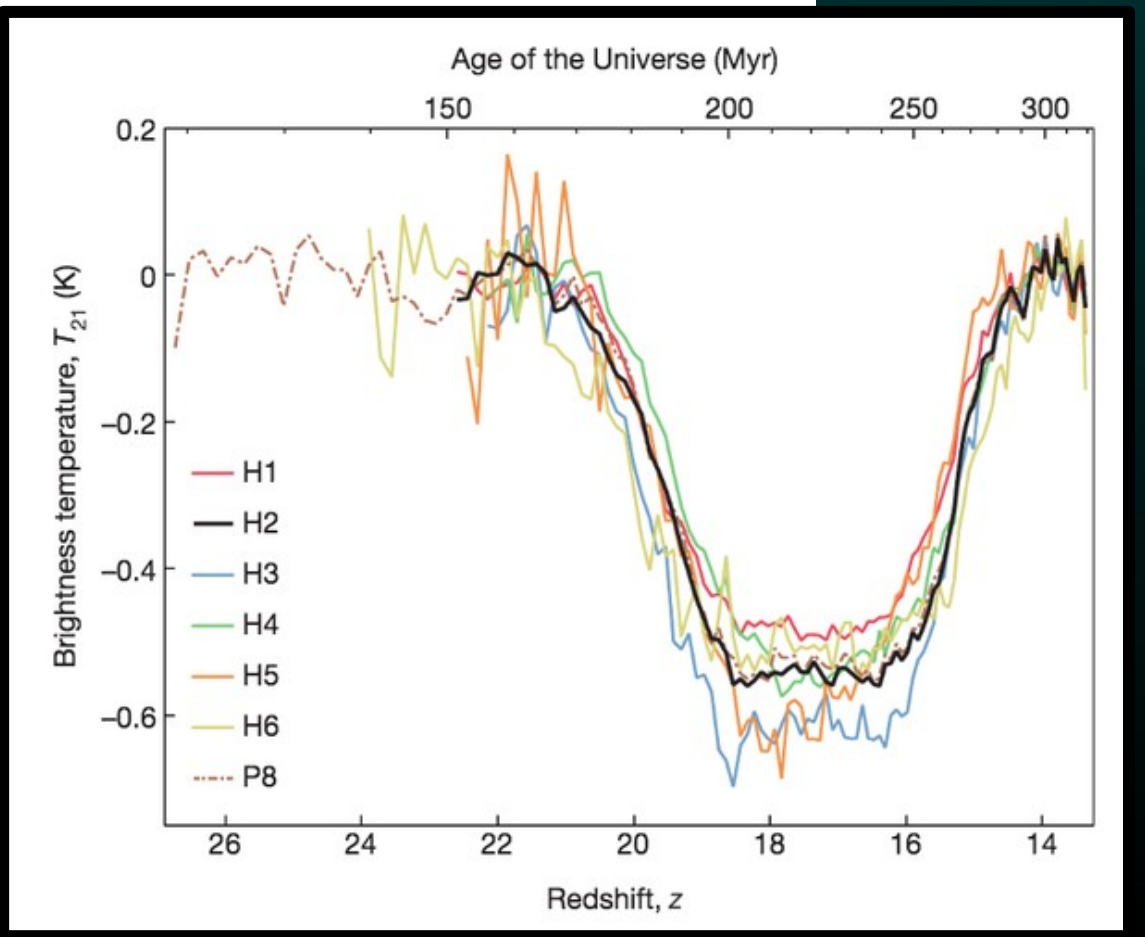
LETTER

doi:10.1038/nature25792

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

Judd D. Bowman[1], Alan E. E. Rogers[2], Raul A. Monsalve[1,3,4], Thomas J. Mozdzen[1] & Nivedita Mahesh[1]

After stars formed in the early Universe, their ultraviolet light is expected, eventually, to have penetrated the primordial hydrogen gas and altered the excitation state of its 21-centimetre hyperfine line. This alteration would cause the gas to absorb photons from the cosmic microwave background, producing a spectral distortion that should be observable today at radio frequencies of less than 200 megahertz[1]. Here we report the detection of a flattened absorption profile in the sky-averaged radio spectrum, which is centred at a frequency of 78 megahertz and has a best-fitting full-width at half-maximum of 19 megahertz and an amplitude of 0.5 kelvin. The profile is largely consistent with expectations for the 21-centimetre signal induced by early stars; however, the best-fitting amplitude of the profile is more than a factor of two greater than the largest predictions[2]. This discrepancy suggests that either the primordial gas was much colder than expected or the background radiation temperature was hotter than expected. Astrophysical phenomena (such as radiation from stars and stellar remnants) are unlikely to account for this discrepancy; of the proposed extensions to the standard model of cosmology and particle physics, only cooling of the gas as a result of interactions between dark matter and baryons seems to explain the observed amplitude[3]. The low-frequency edge of the observed profile indicates that stars existed and had produced a background of Lyman-α photons by 180 million years after the Big Bang. The high-frequency edge indicates that the gas was heated to above the radiation temperature less than 100 million years later.



EDGES instrument and data

Single dipole sitting on a reflective ground plane

Site: Murchison Radio Observatory, western Australia

Low-band instruments: 50 – 100 MHz

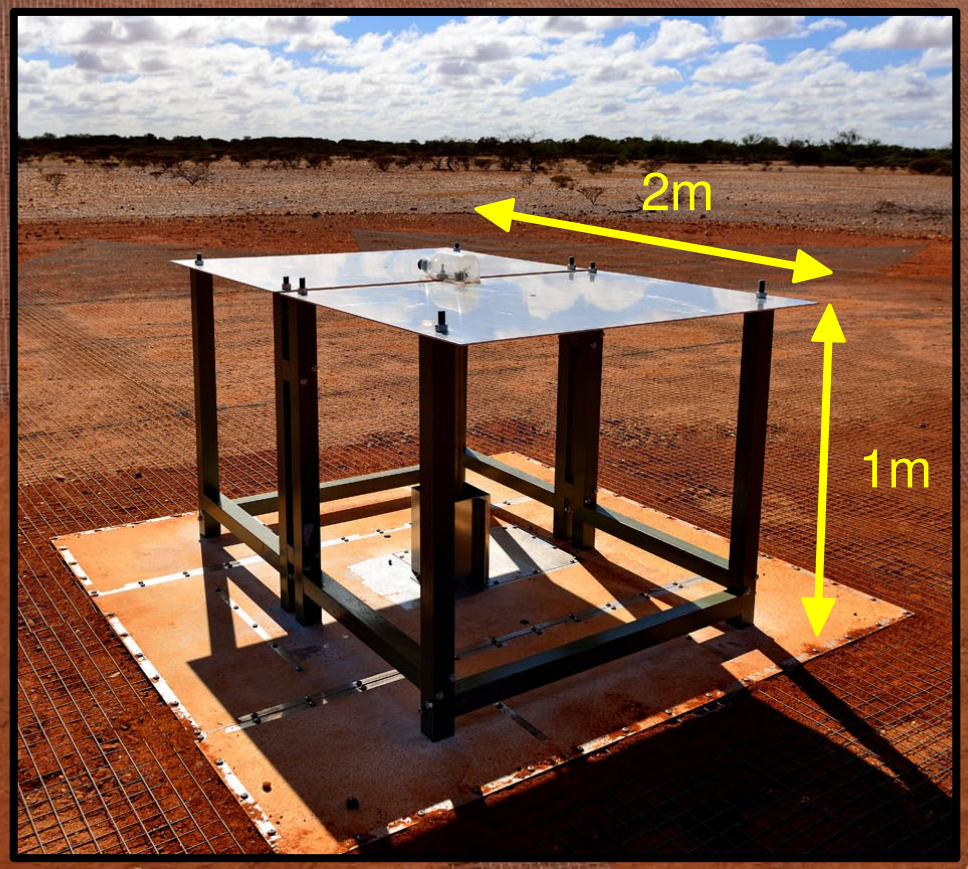
~430 hours of data

5-term foreground polynomial removal

~10 years of instrument development prior to 2018 results

Extensive tests for instrumental systematics, including a separate mid-band antenna (25% smaller)

EDGES-3 in progress



Notable features of the detection

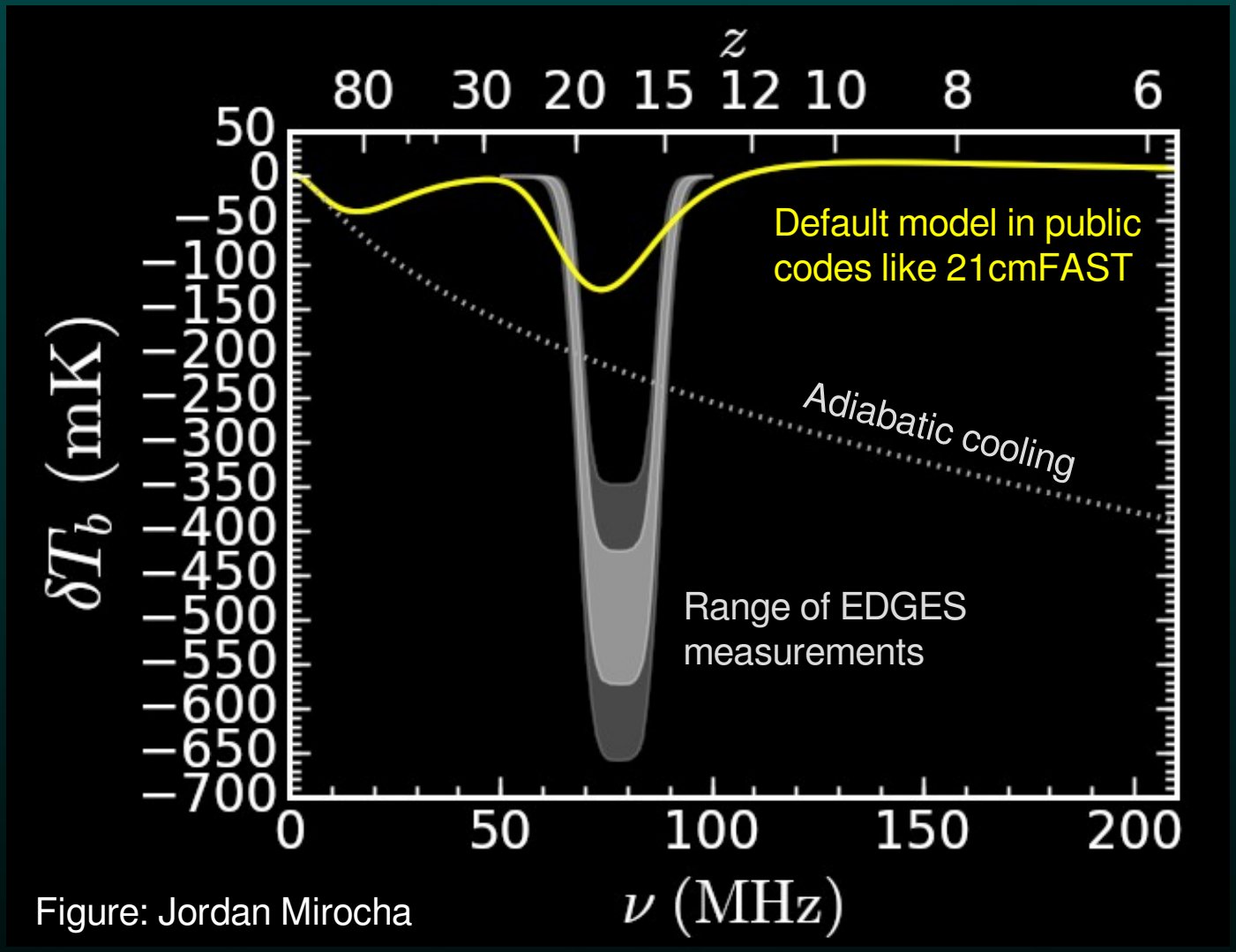


Figure: Jordan Mirocha

(1) How can we amplify the signal by a factor of 2–3?

(2) Why is the signal centered at 78 MHz?

(3) How can we explain the shape of the signal?

Challenges in explaining the EDGES signal

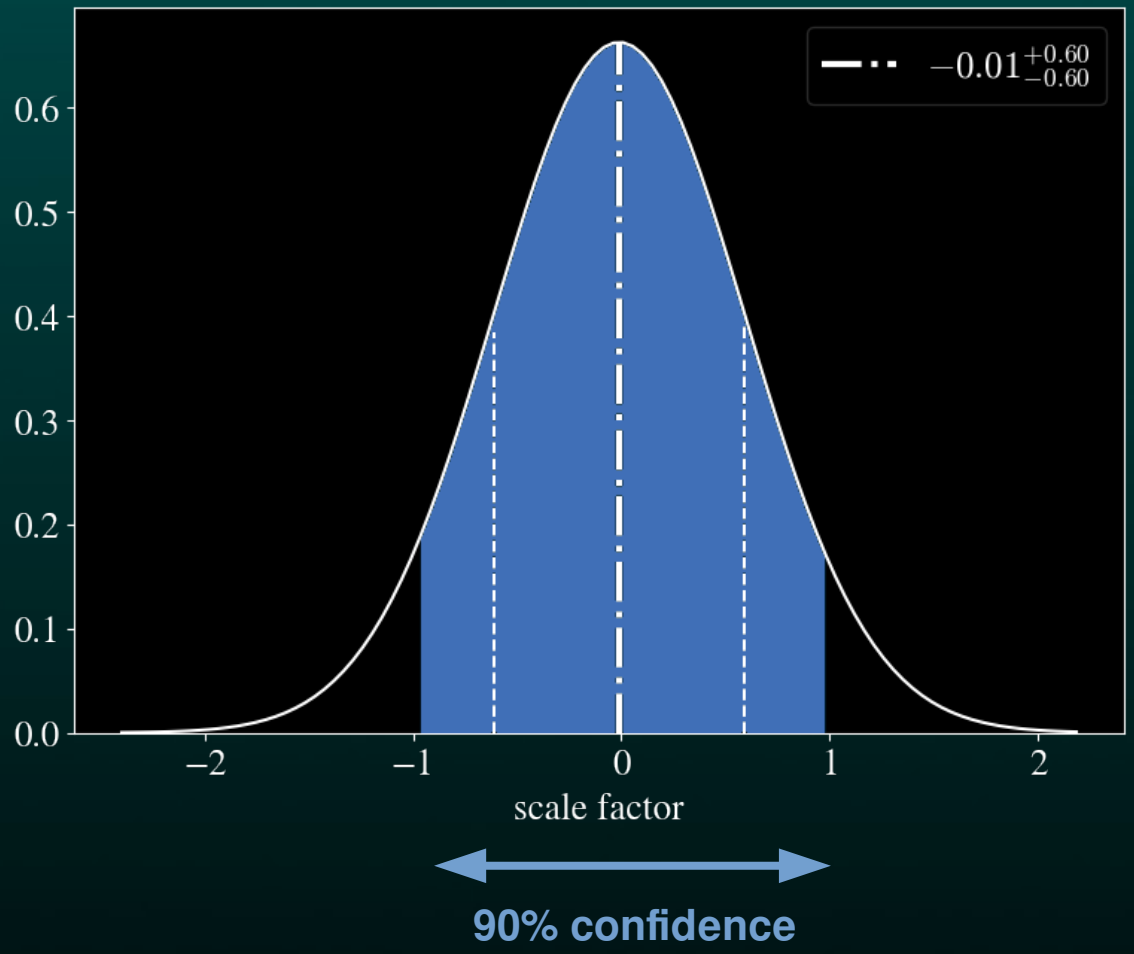
$$\delta T_b \simeq 27 x_{\rm HI}(1+\delta)\left(\frac{\Omega_{b,0}h^2}{0.023}\right)\left(\frac{0.15}{\Omega_{m,0}h^2}\frac{1+z}{10}\right)^{1/2}\left(1-\frac{T_R}{T_S}\right)$$

- Decrease T_S via interactions between baryons and dark matter
  Barkana, Munoz & Loeb, Fialkov et al., Berlin et al., Slayter & Wu
- Increase T_R via dark matter decay or synchrotron from black holes, first galaxies
  Feng & Holder, Ewall-Wice et al., Fraser et al., Mirocha & Furlanetto, Sharma
- Alter the cosmology
  McGaugh, Costa et al., Hill et al.
- Timing and shape: see e.g. Mirocha & Furlanetto 2018

> *"Although we have performed many tests to be confident that the observed profile is from a global absorption … we still seek confirmation observations from other instruments."* – EDGES Nature paper

Player two has entered the game: SARAS3

S. Singh et al., Nature Astronomy, 6, 2022

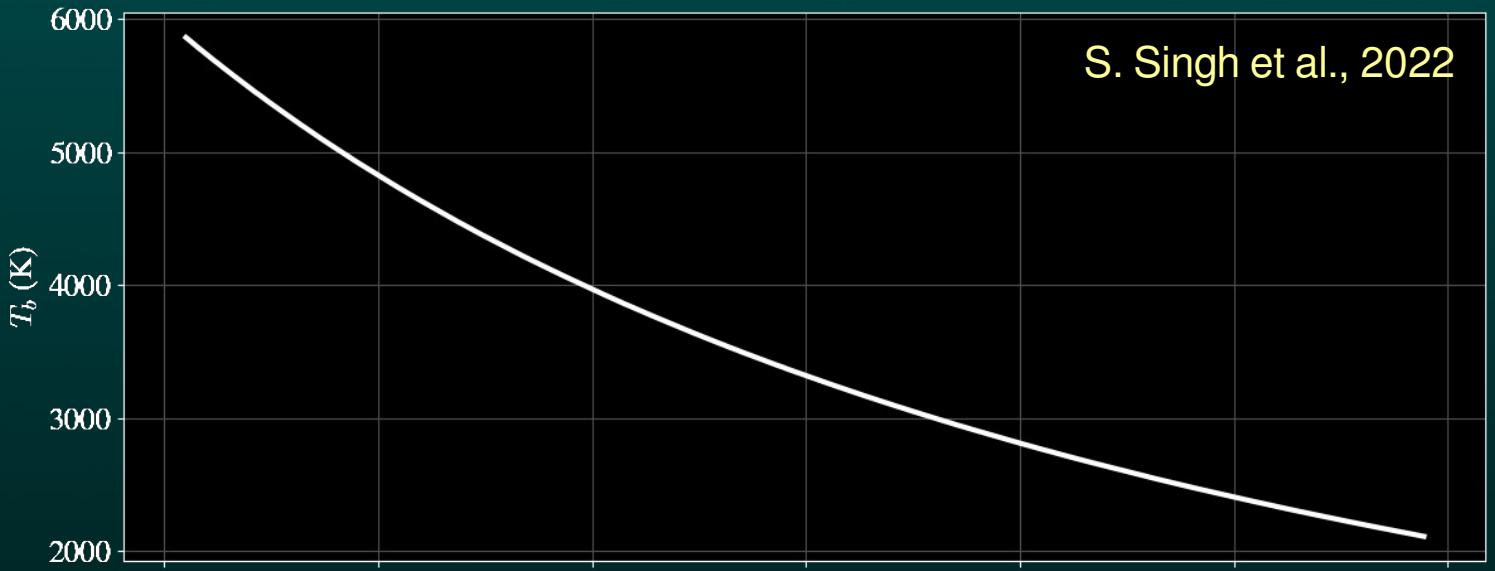


Monopole antenna floating on a lake in India, 55 – 85 MHz, ~3 nights of data

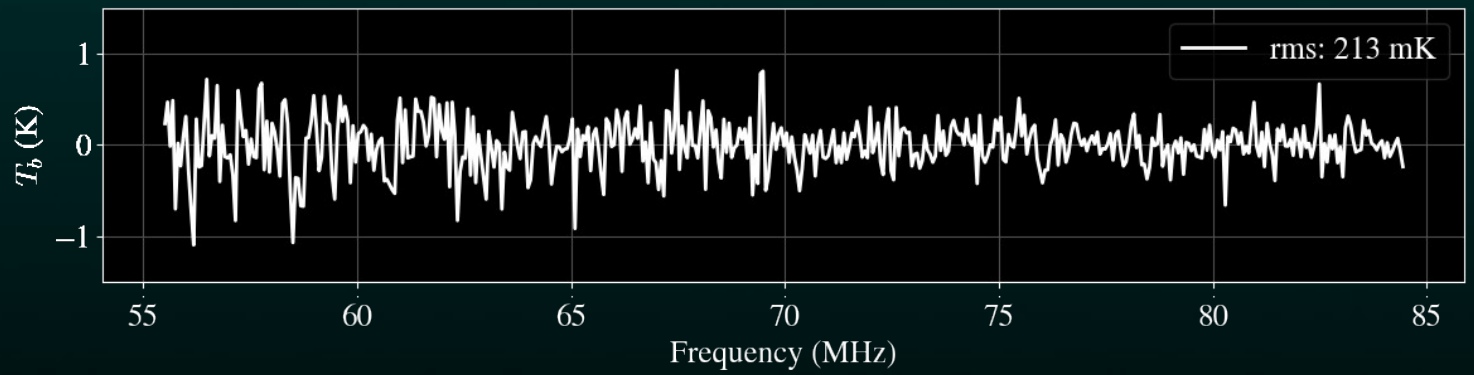
Fit for 7 foreground terms + 1 scale term for best-fit EDGES signal

Scale term consistent with zero, rules out nominal EDGES signal at ~2 sigma, but significance drops if reported EDGES uncertainties are included

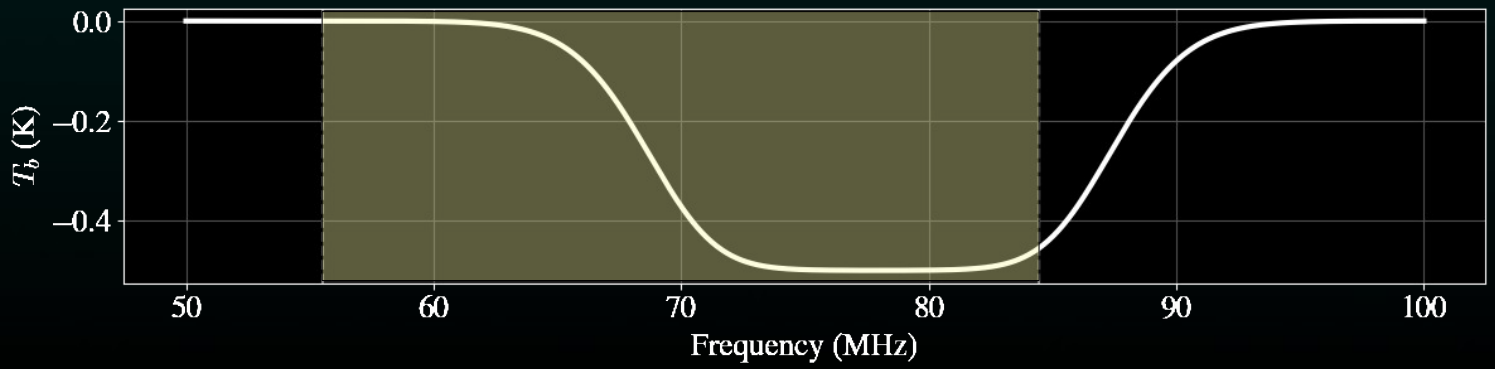
Player two has entered the game: SARAS3



Time-averaged sky spectrum measurement



Residuals after removing 6th order polynomial



Nominal EDGES profile with SARAS3 band highlighted

** *FM band starts at 88 MHz*

So what do we do now?

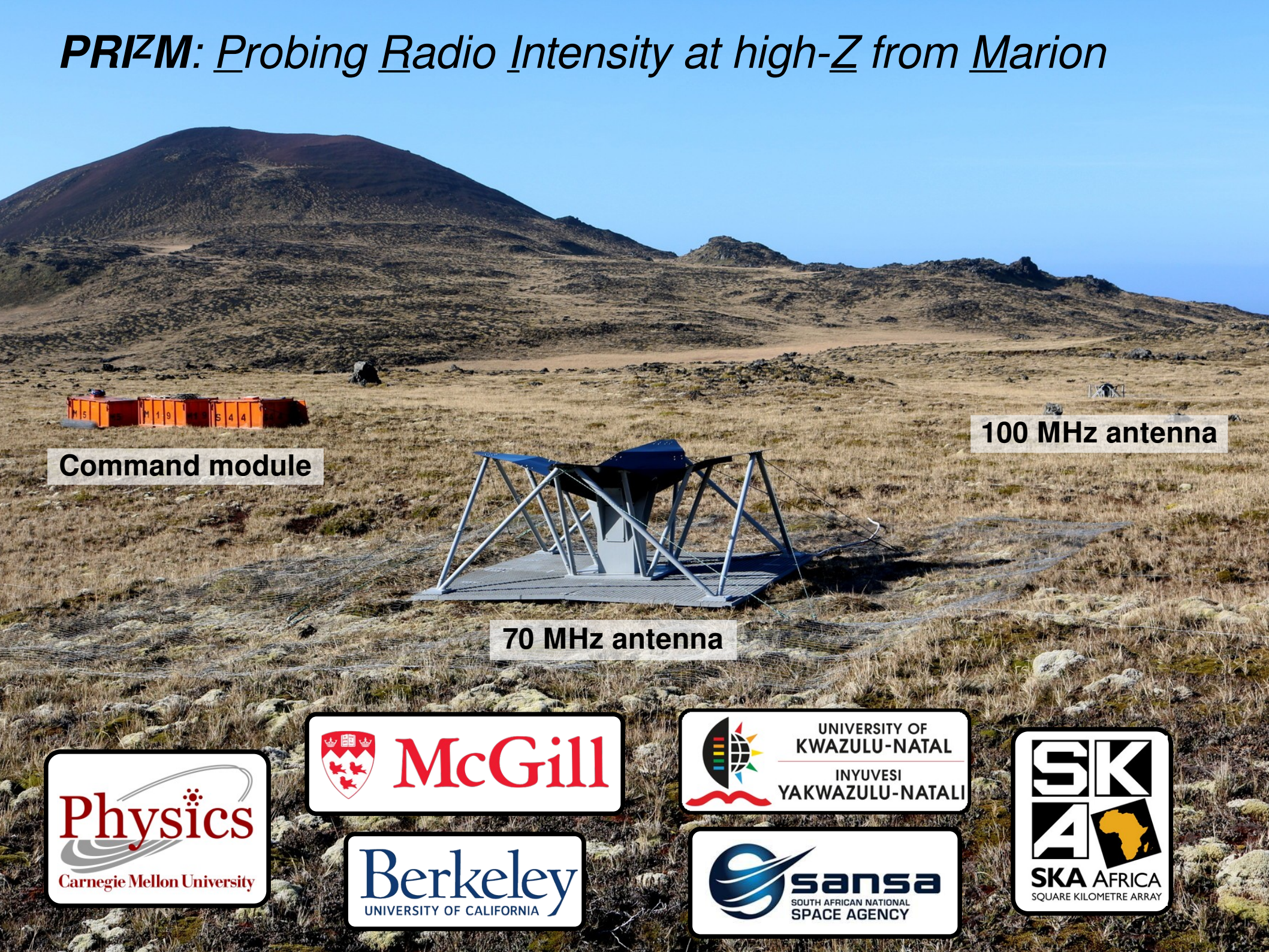
EDGES and SARAS3 results disagree at ~2 sigma, too early to say that one is “right” vs “wrong”

Tension underscores the importance of multiple experimental efforts with contrasting systematic effects

Theorists: please keep coming up with creative explanations for the EDGES absorption feature!

Experimentalists: we have new instruments in progress to probe systematics from different angles

PRIZM: Probing Radio Intensity at high-Z from Marion

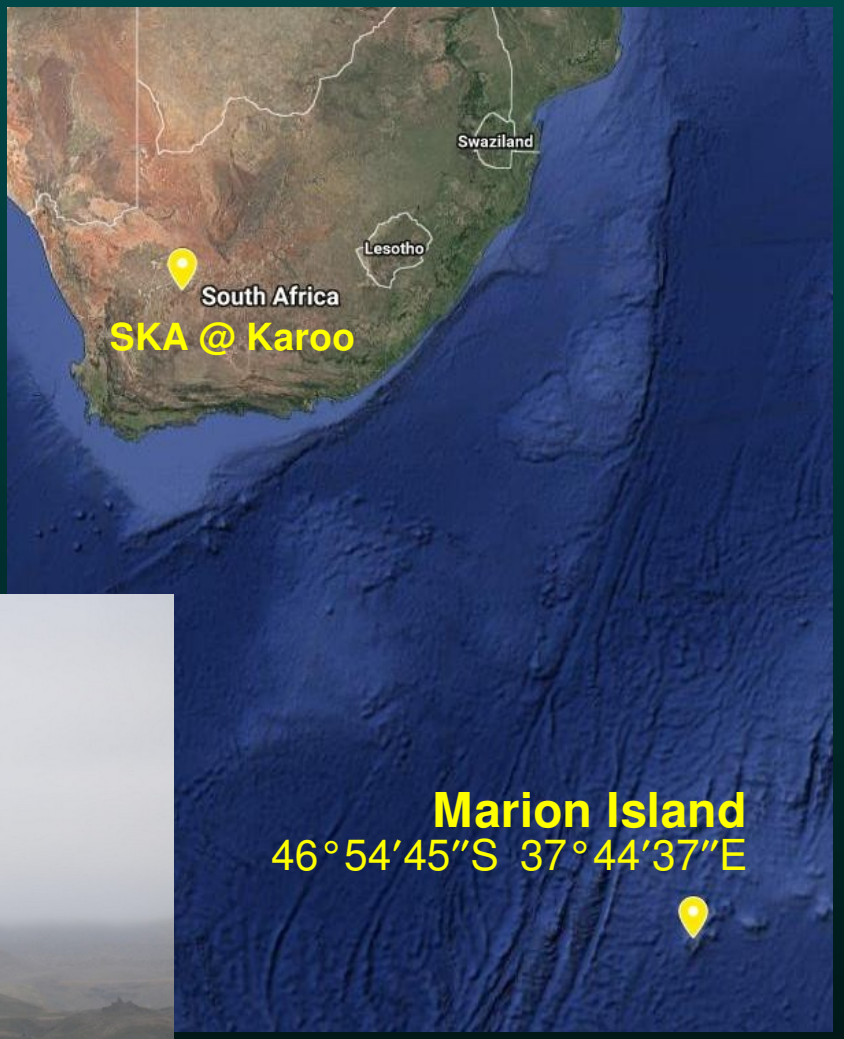


Marion Island

Marion Island base is operated by the South African National Antarctic Programme

2000 km from nearest continental landmass

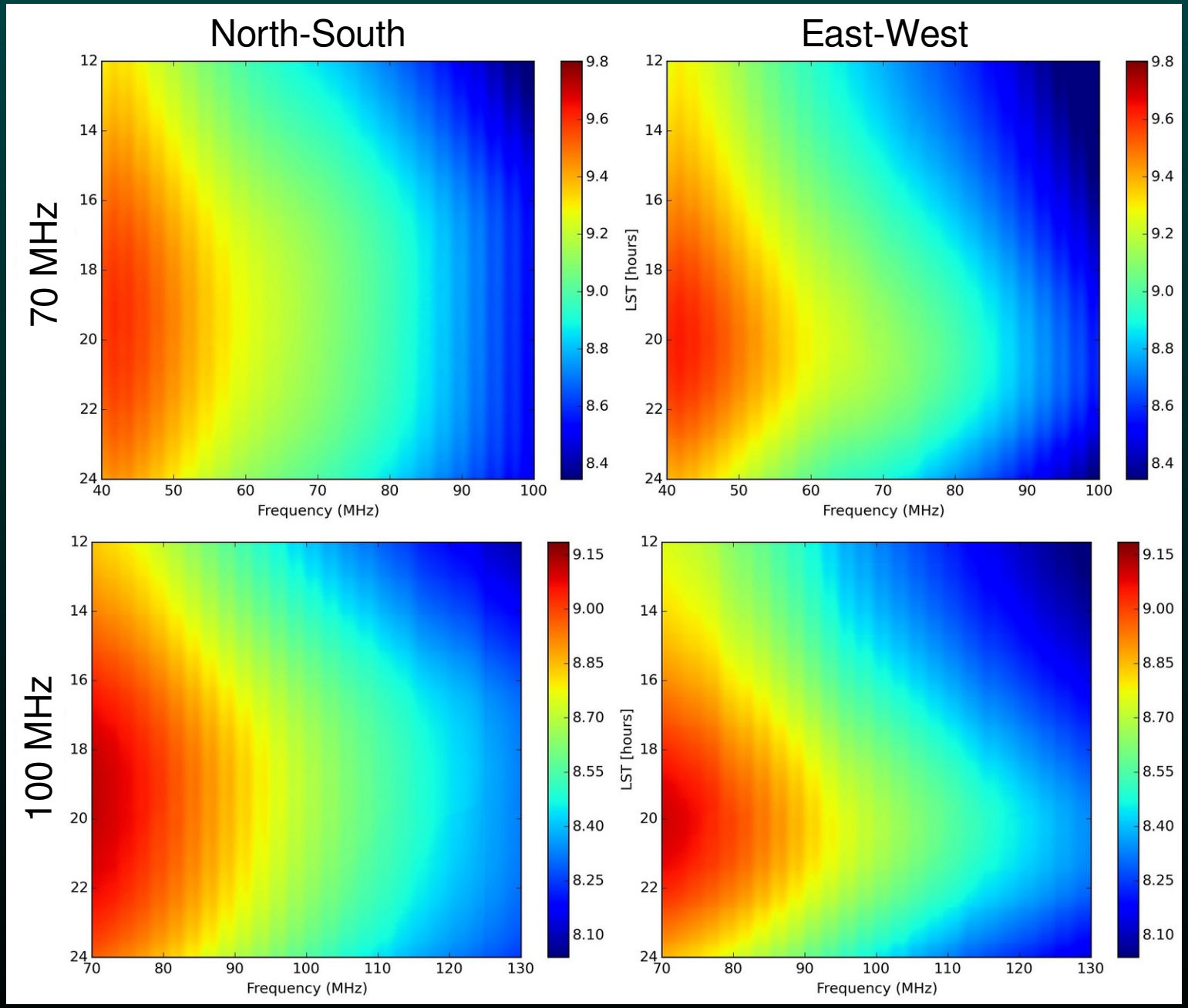
PRIZM = first astro experiment on Marion!
2016 engineering run, science ops since 2017



Superbly clean RFI environment, no visible FM contamination

...but very difficult access, harsh environmental conditions

Preliminary PRIZM raw data



MIST: *Mapper of the IGM Spin Temperature*

McGill Arctic Research Station

79°26′N 90°46′W

MIST highlights

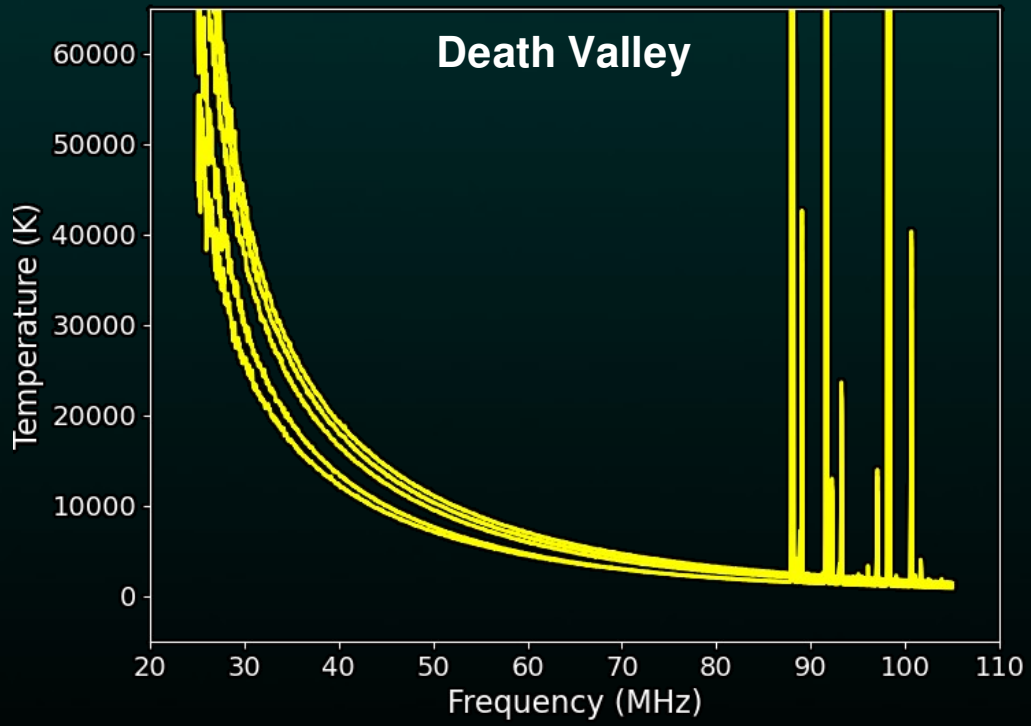
Dipole antenna with design heritage from EDGES

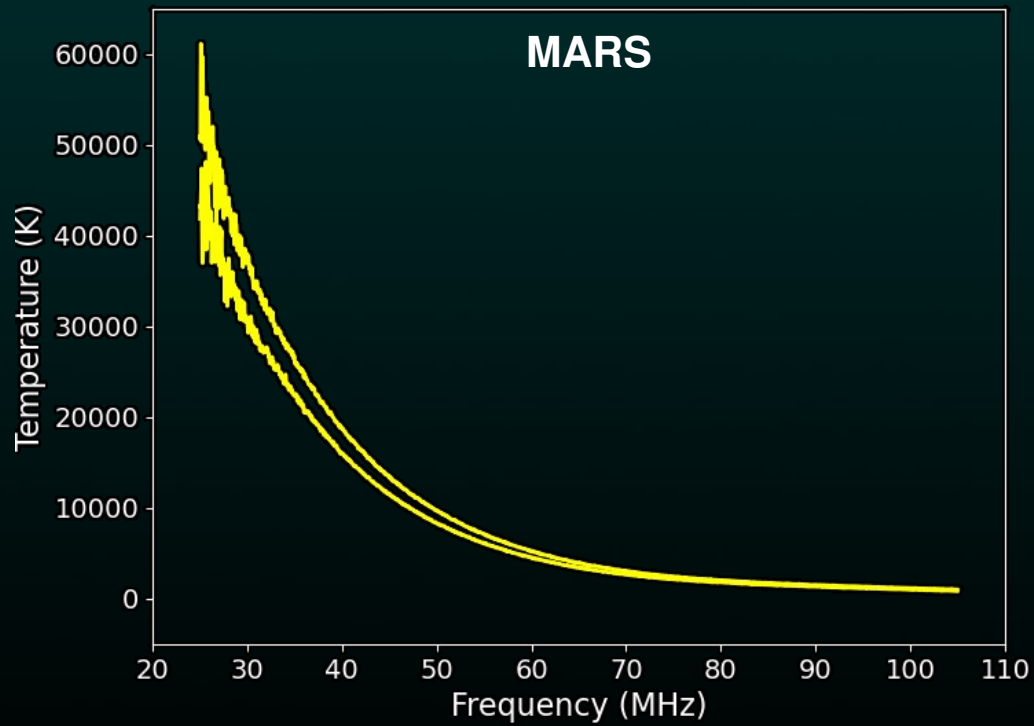
No metal ground plane: no systematics from electrical discontinuities, standing waves, etc.
Tradeoff: earth becomes part of the instrument.

Small, portable, low power consumption, battery powered

Readout electronics directly underneath the antenna, no long cables impacting performance

Observations at multiple sites with different foregrounds, terrain, and RFI conditions





Data: Raul Monsalve

Summary & future prospects

- Globally averaged redshifted 21cm emission is a promising tool for exploring cosmic dawn
- This subfield is young and exciting, with EDGES reporting the first (and only) detection in 2018. If the EDGES signal is real, we could have new physics.
- Plot has thickened with 2022 SARAS3 results, which are in tension with EDGES
- We need 1) continued creative theoretical explanations for the EDGES signal, and 2) continued independent experimental efforts
- New physics that affects the cosmic dawn signal may also affect dark ages cosmology. There will be even more fun things to calculate and observe.