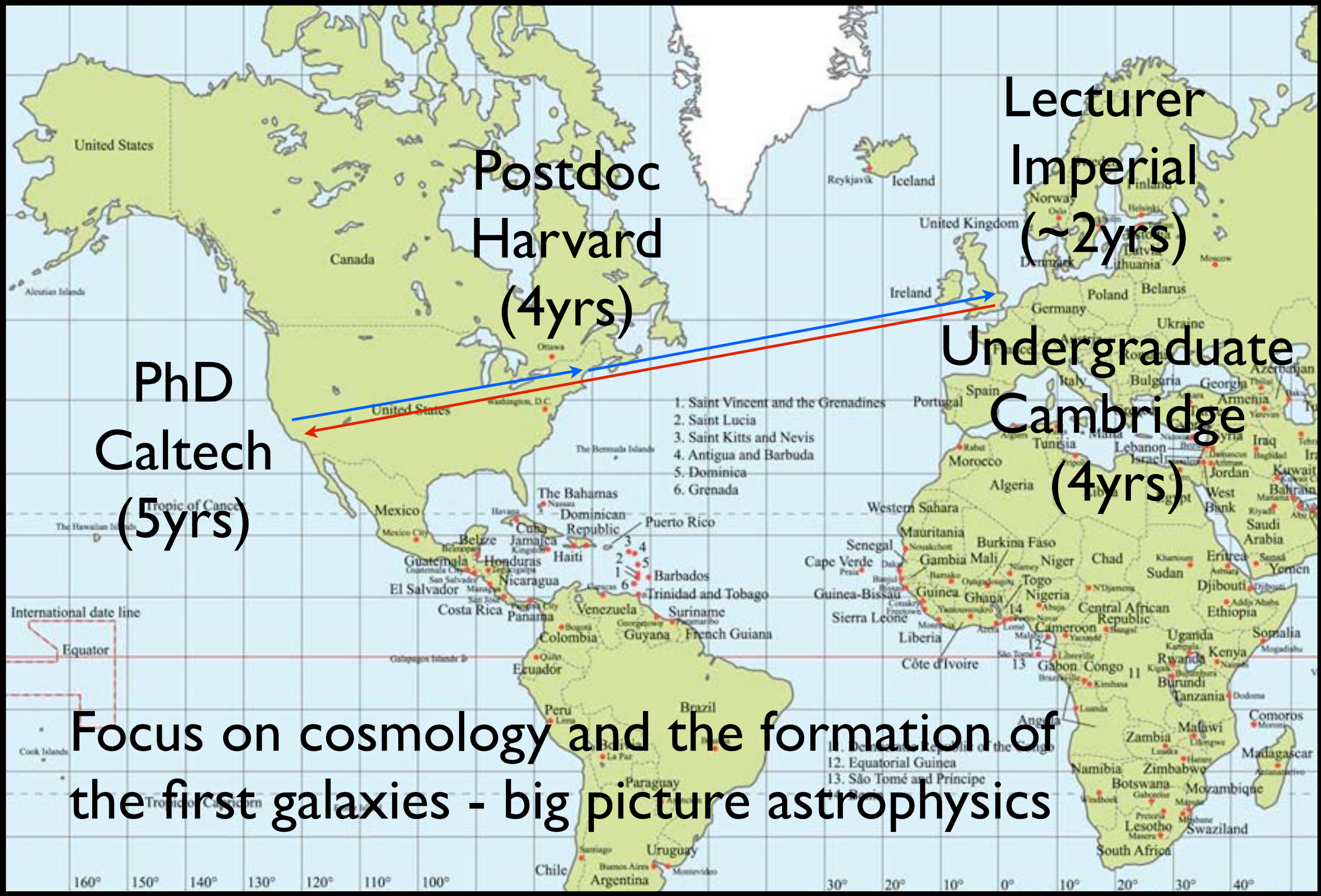
In the beginning of the Dark Ages, electrically neutral hydrogen gas filled the universe. As stars formed, they ionized the regions immediately around them, creating bubbles here and there. Eventually these bubbles merged together, and intergalactic gas became entirely ionized.

Cosmic Dawn & Square Kilometer Array

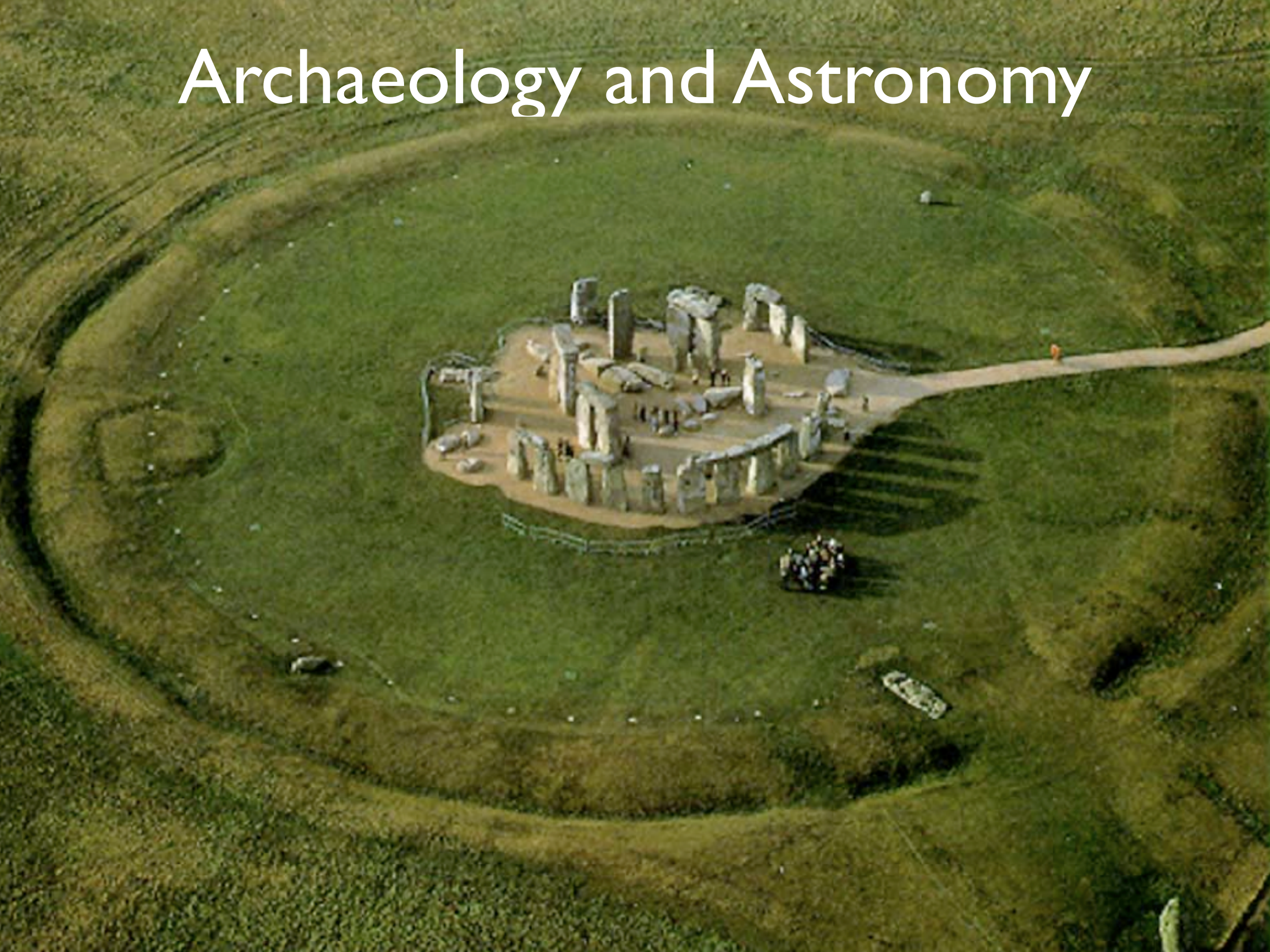
Jonathan Pritchard
(Astrophysics)


RADIO QUIET ZONE
SWITCH OFF
MOBILE PHONES
10

Who am I?


Postdoc
Harvard
(4yrs)
Lecturer
Imperial
(~2yrs)
PhD
Caltech
(5yrs)
Undergraduate
Cambridge
(4yrs)
Focus on cosmology and the formation of the first galaxies - big picture astrophysics

Archaeology and Astronomy

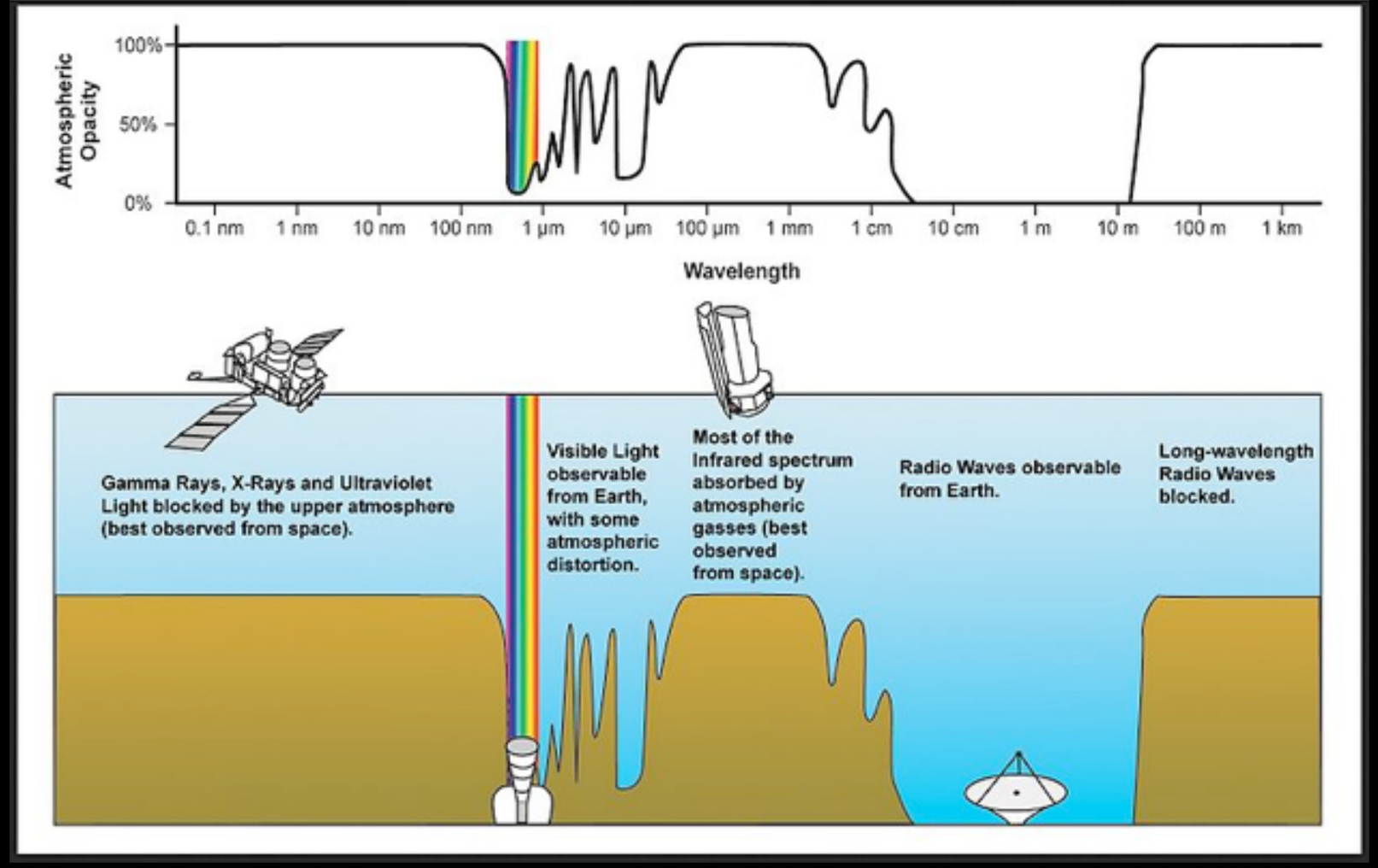


Seeing the past

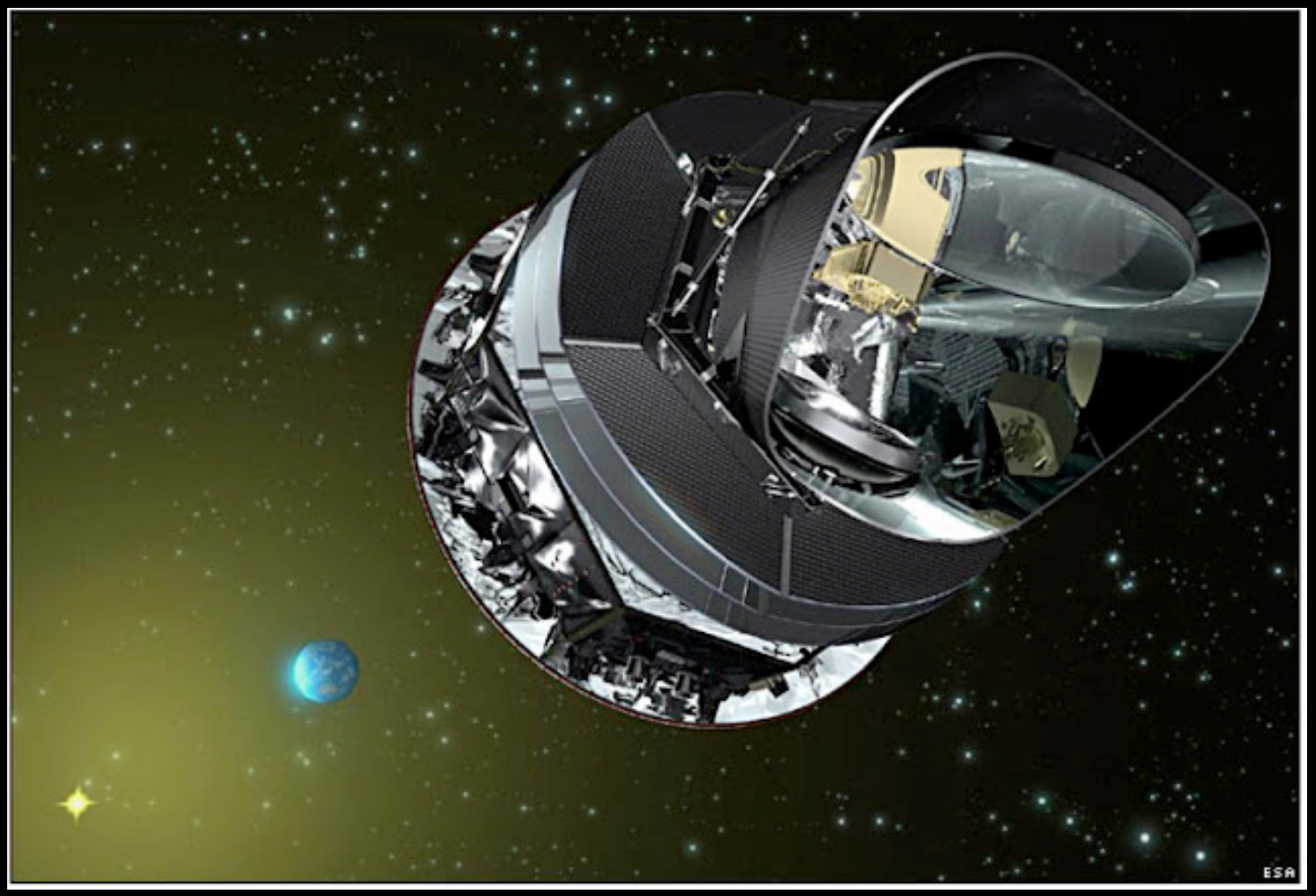
- Light travels at 300,000 km/s. Fast, but finite.
- When we see distant objects, we're seeing them as they were when that light was emitted
- We're seeing the past
- Moon is ~1 light seconds away
  Sun is ~8 light minutes away
- We don't get to choose when we see. Each distance corresponds to a specific time in cosmic history

What do we see?

- Different frequencies show us different objects at different distances.
- Limits set by technology and absorption along the line of sight

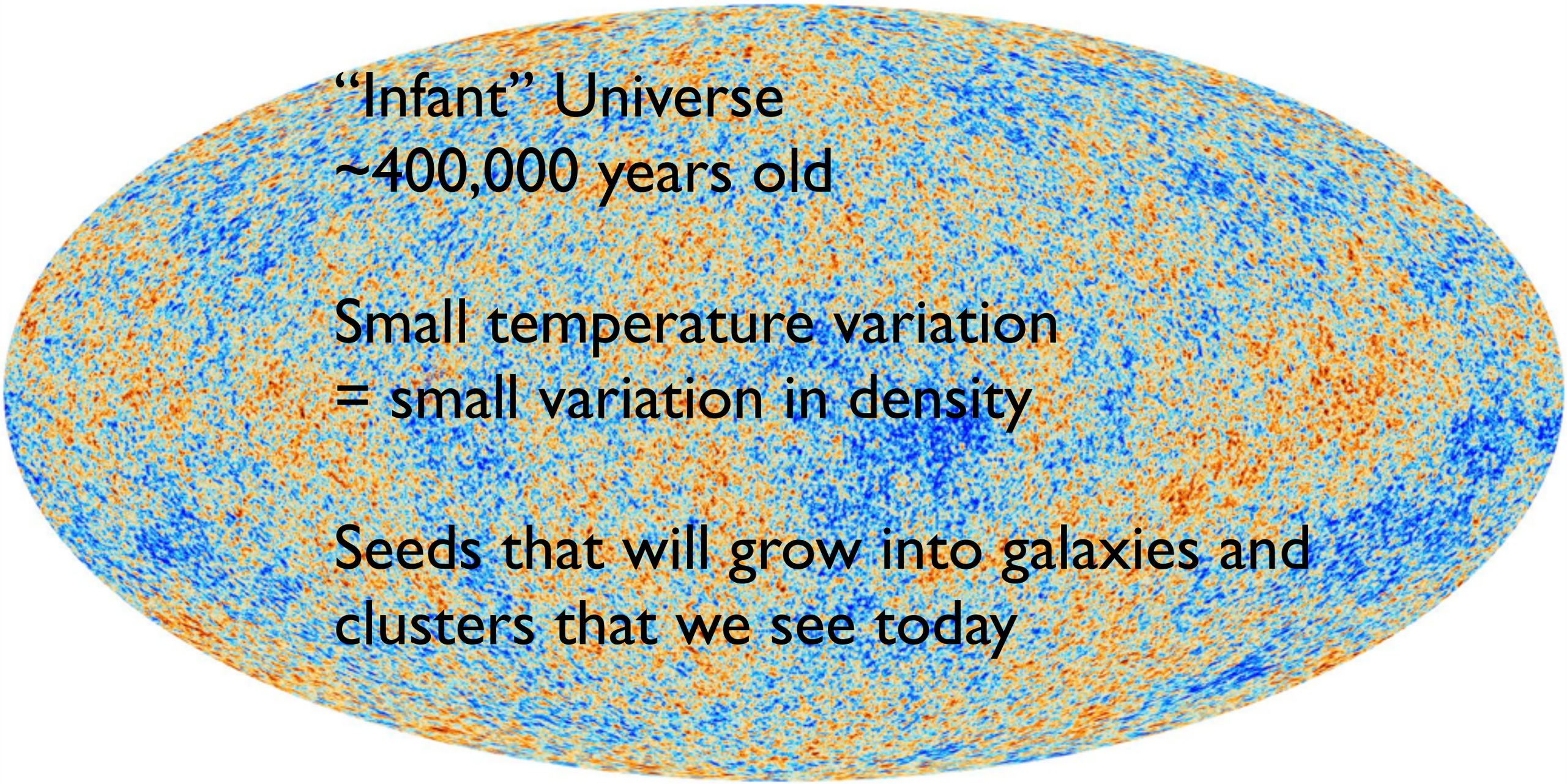


Cosmic Microwave Background



Planck satellite

Cosmic Microwave Background

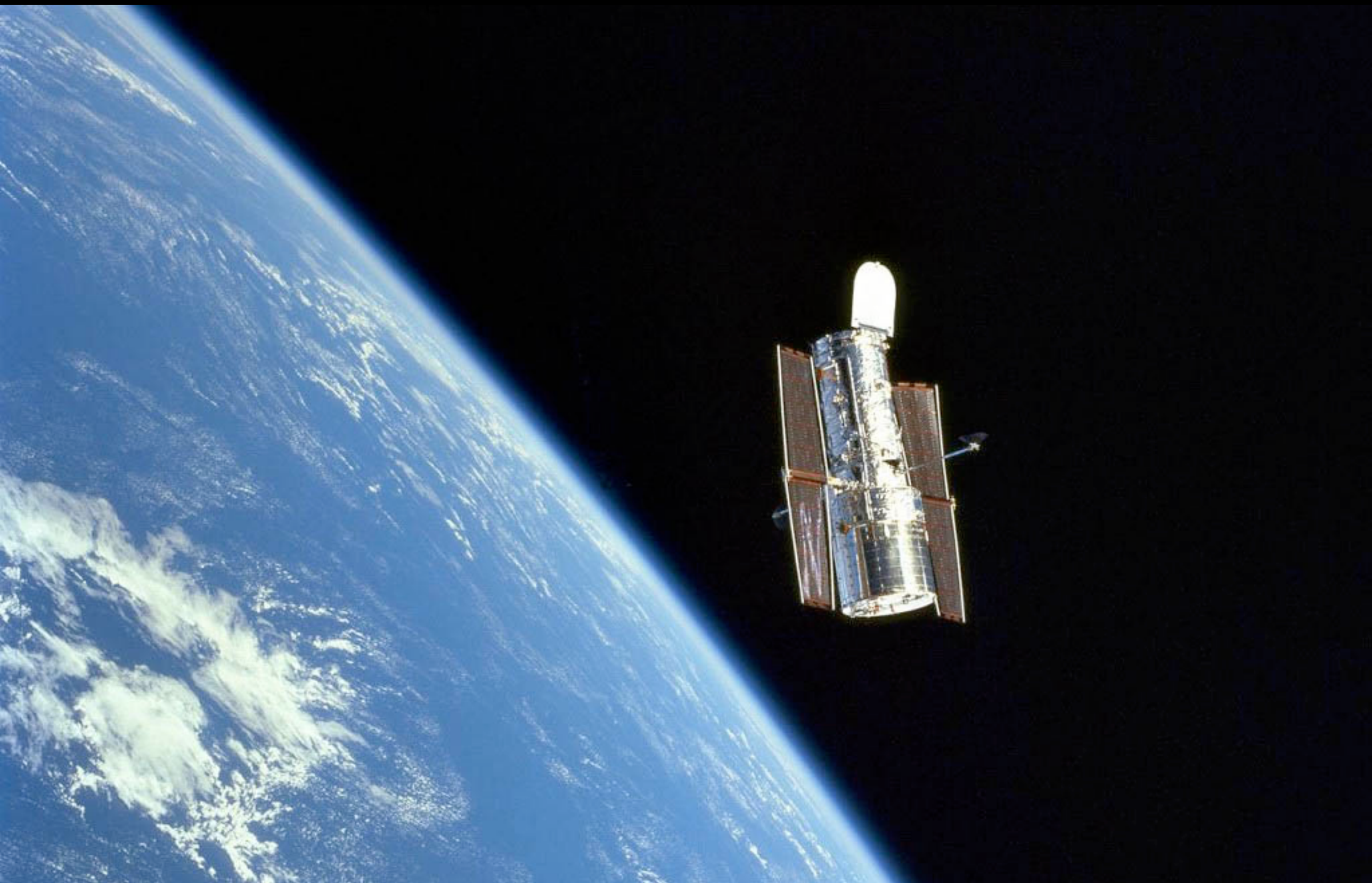


"Infant" Universe
~400,000 years old

Small temperature variation
= small variation in density

Seeds that will grow into galaxies and clusters that we see today

Hubble Space Telescope

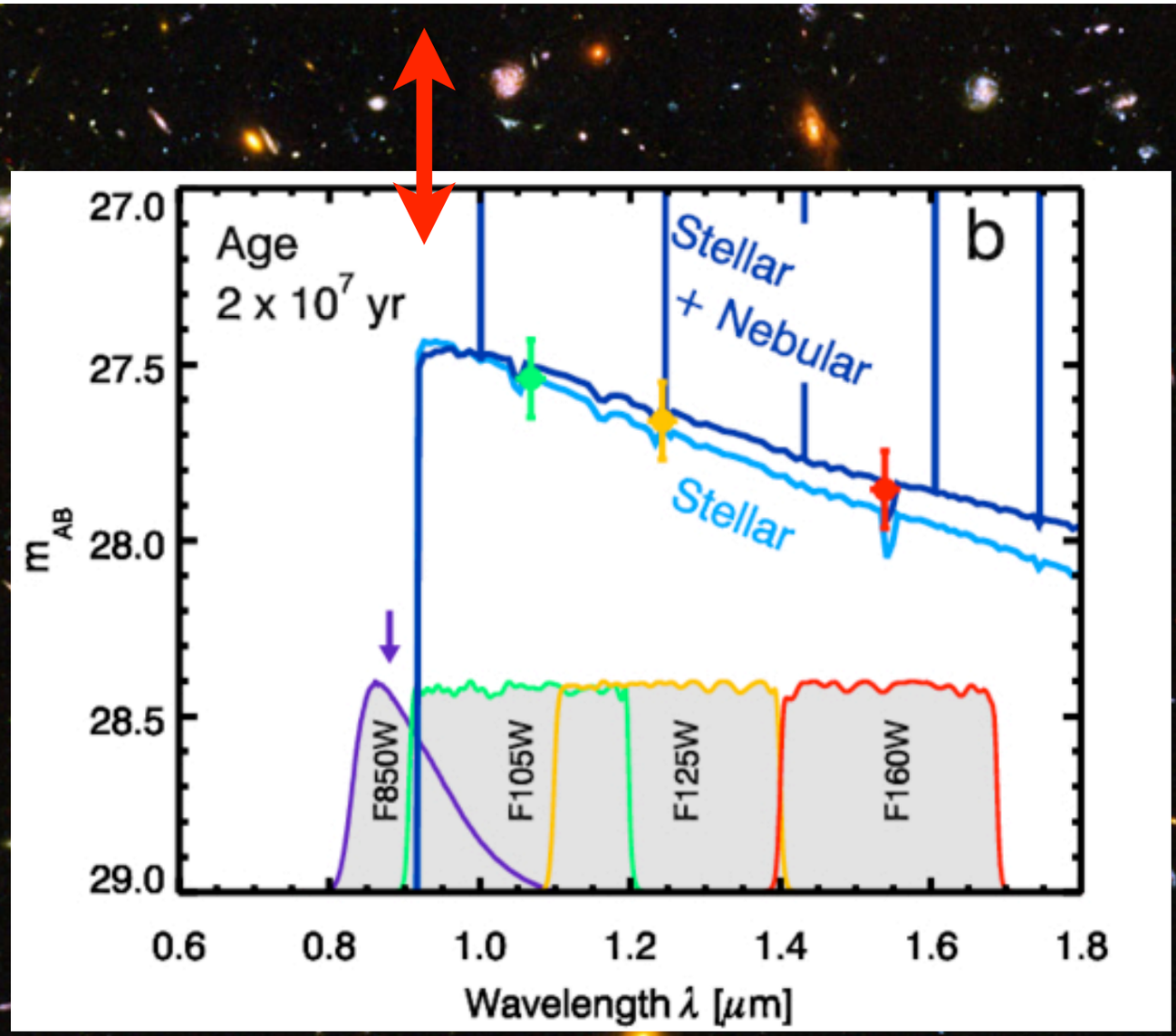


Hubble Ultra Deep Field

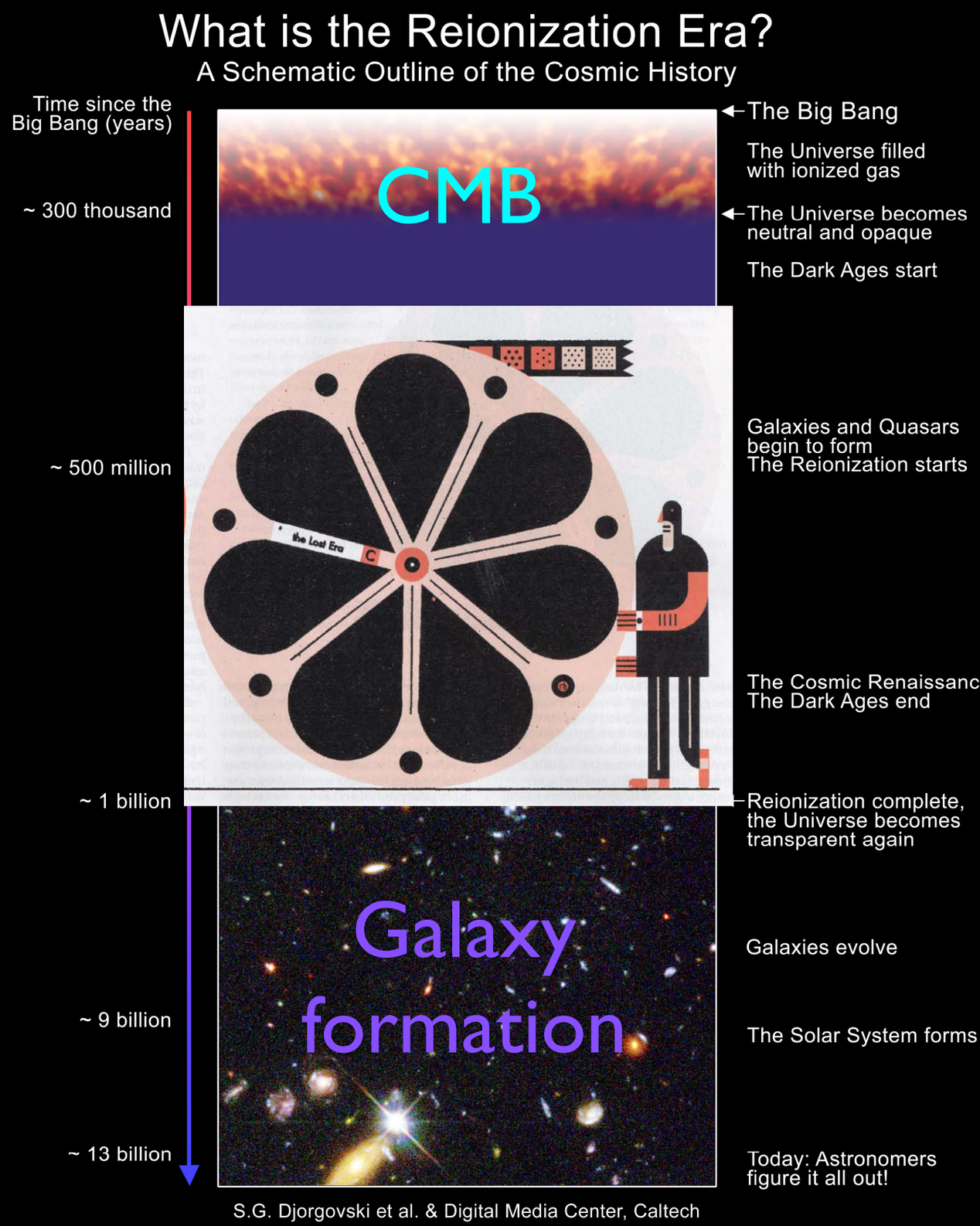
- Patch smaller than the moon on sky

- Furthest galaxies are located at distances when Universe was 1 billion years old
- “Mature” Universe

Hubble (and soon JWST) identify high redshift galaxies as "drop outs"



The Cosmic Timeline

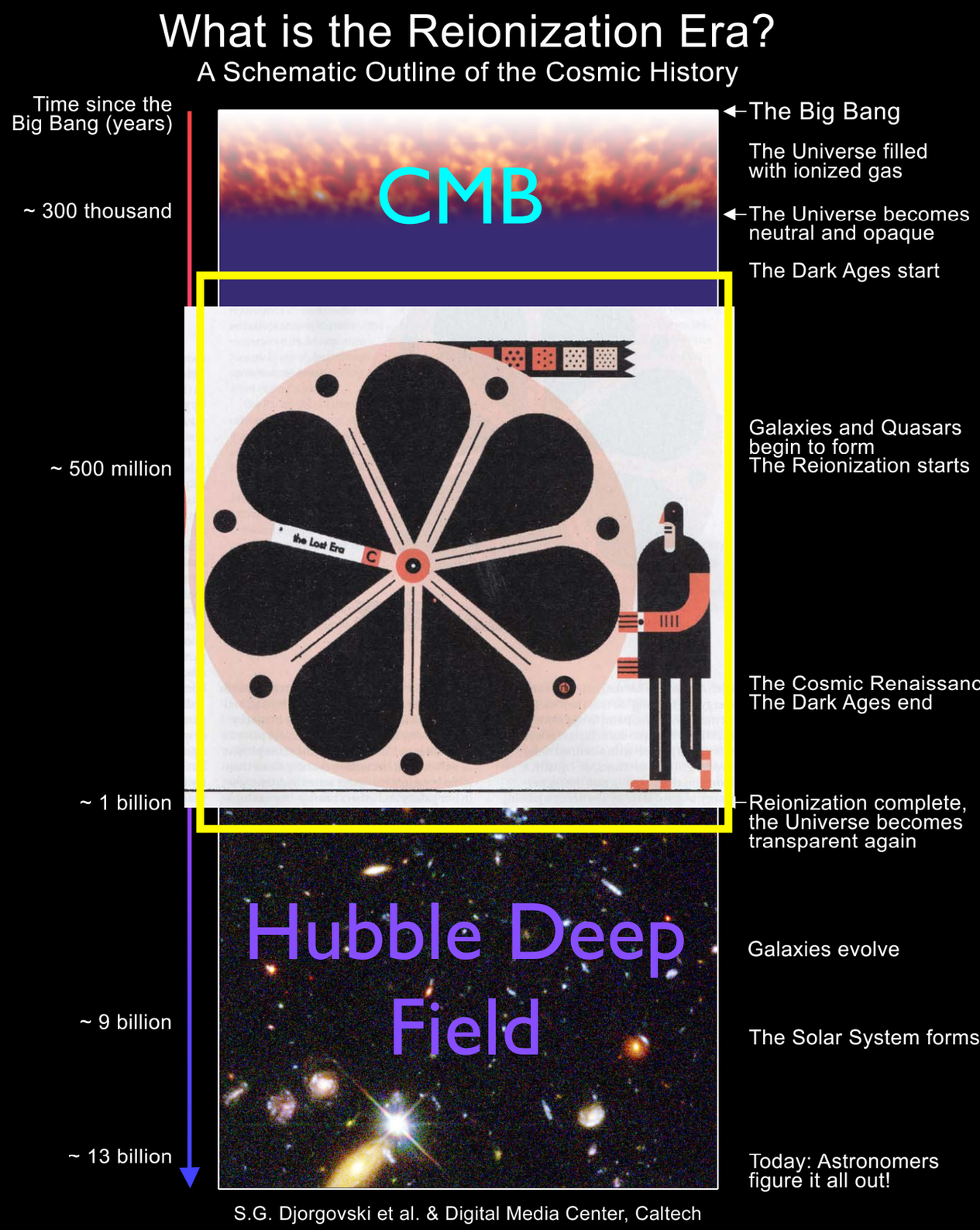


- CMB shows intial conditions
- Deep galaxy surveys show later galaxies
- What went on in between?
- Currently NO observations!

The Missing Reel

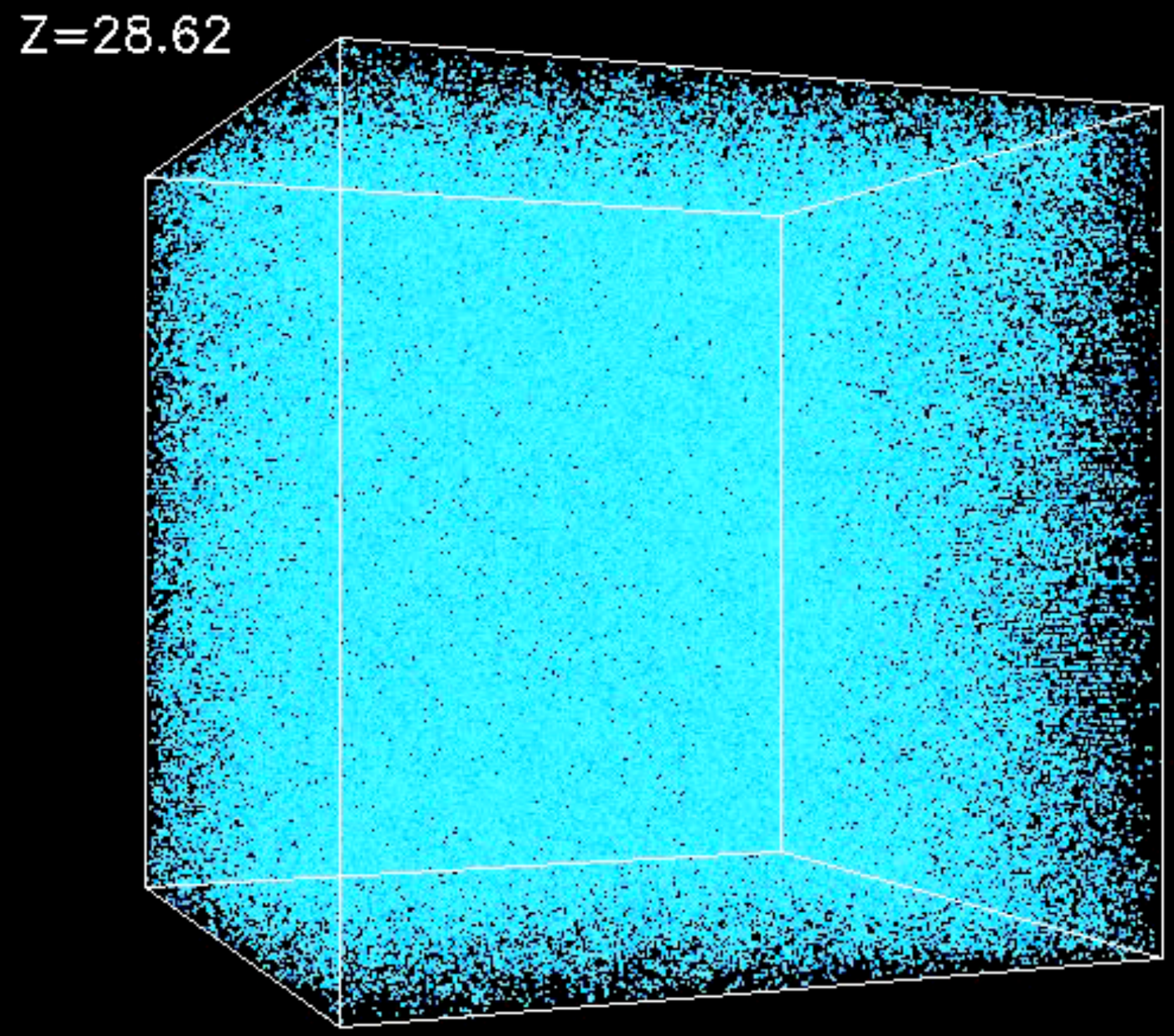
DIRECTOR	T. Universe	
CAMERAMAN	S.K.A.	
DATE	TAKE	SCENE
13.75 GYrABB	1	10^{51}

The Missing Reel



- Dark Ages
- Cosmic Dawn
- Reionization

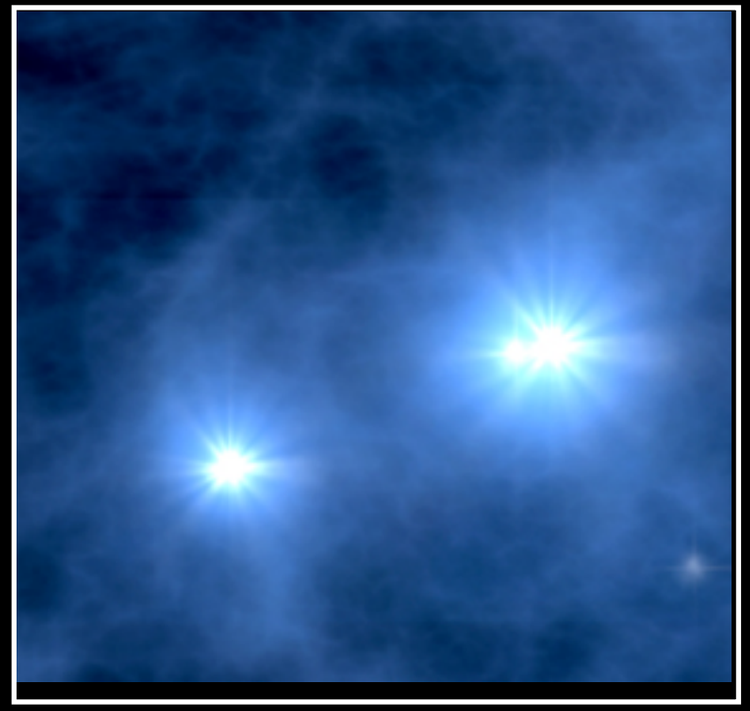
Dark sure, but interesting



Structures grow as gravity causes collapse

Fire breathing monsters?

- First stars formed from primordial gas - hydrogen and helium
- Later stars form from gas enriched with metals - carbon, oxygen, iron,...
- First stars may have been larger, hotter, brighter
  => live fast, die young (Pop III lifetime ~ 1 million years)

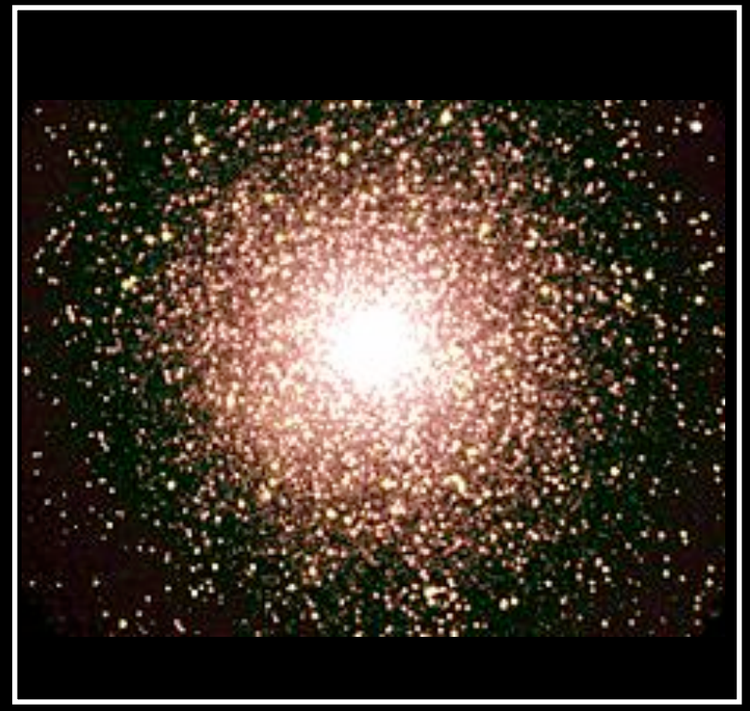


Population III

Metal-free

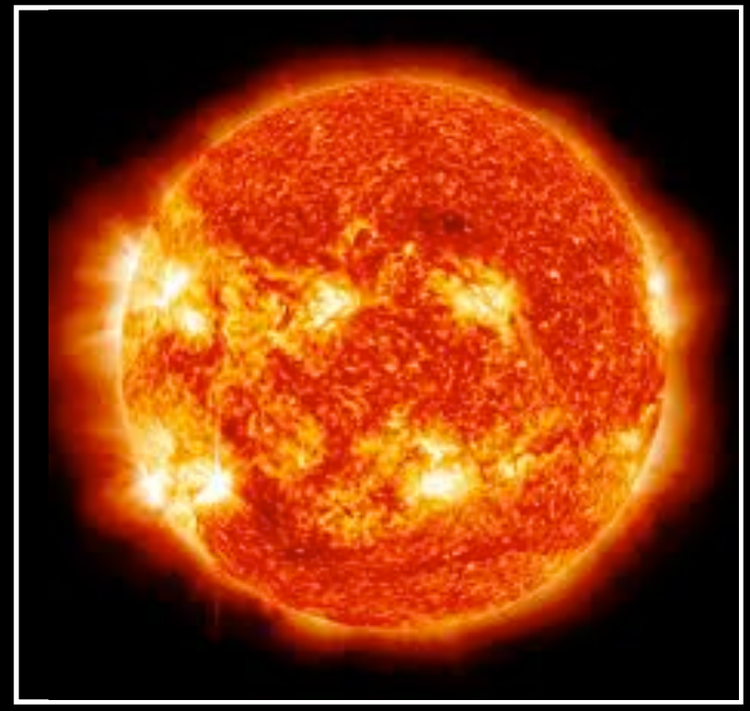
~100 Msol

~20 Lsol



Population II

Metal-poor
(galactic bulge/globular clusters)



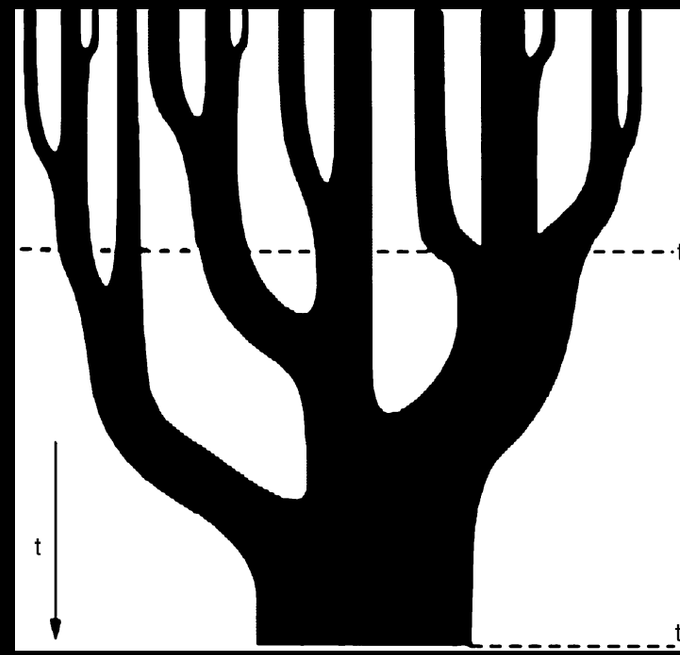
Population I

Metal-rich
(spiral arms of Milky way)
Our sun

First stars

Galactic archaeology

- "hierarchical structure formation"
  - small galaxies merge to form larger ones
- Can search for oldest stars in our galaxy as low-mass metal-poor stars
- Less fossils, more very old citizens of Universe

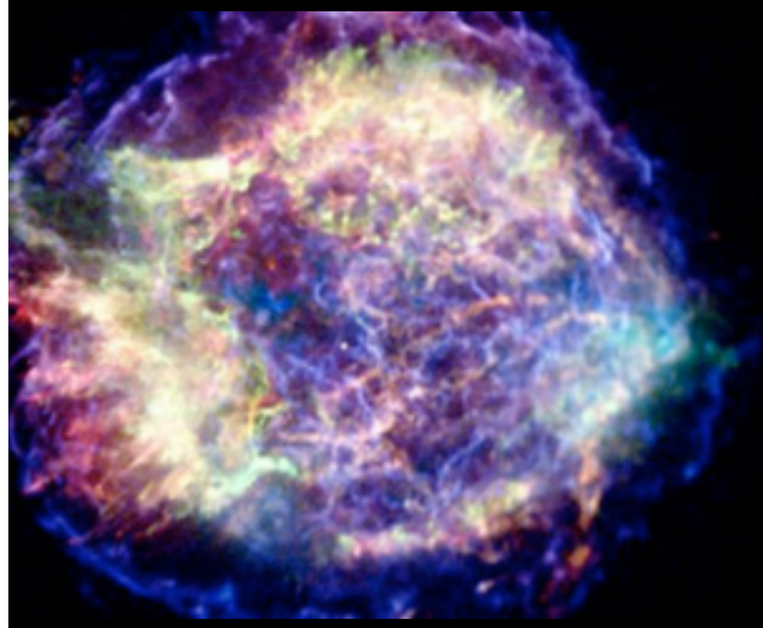


LETTER

doi:10.1038/nature12990

A single low-energy, iron-poor supernova as the source of metals in the star SMSS J031300.36−670839.3

S. C. Keller[1], M. S. Bessell[1], A. Frebel[2], A. R. Casey[1], M. Asplund[1], H. R. Jacobson[2], K. Lind[3], J. E. Norris[1], D. Yong[1], A. Heger[4], Z. Magic[1,5], G. S. Da Costa[1], B. P. Schmidt[1] & P. Tisserand[1]



First galaxies

- Galaxy is a collection of gravitationally bound stars
- First star to form altered surroundings
  - heating, ionization, metal enrichment, winds,...

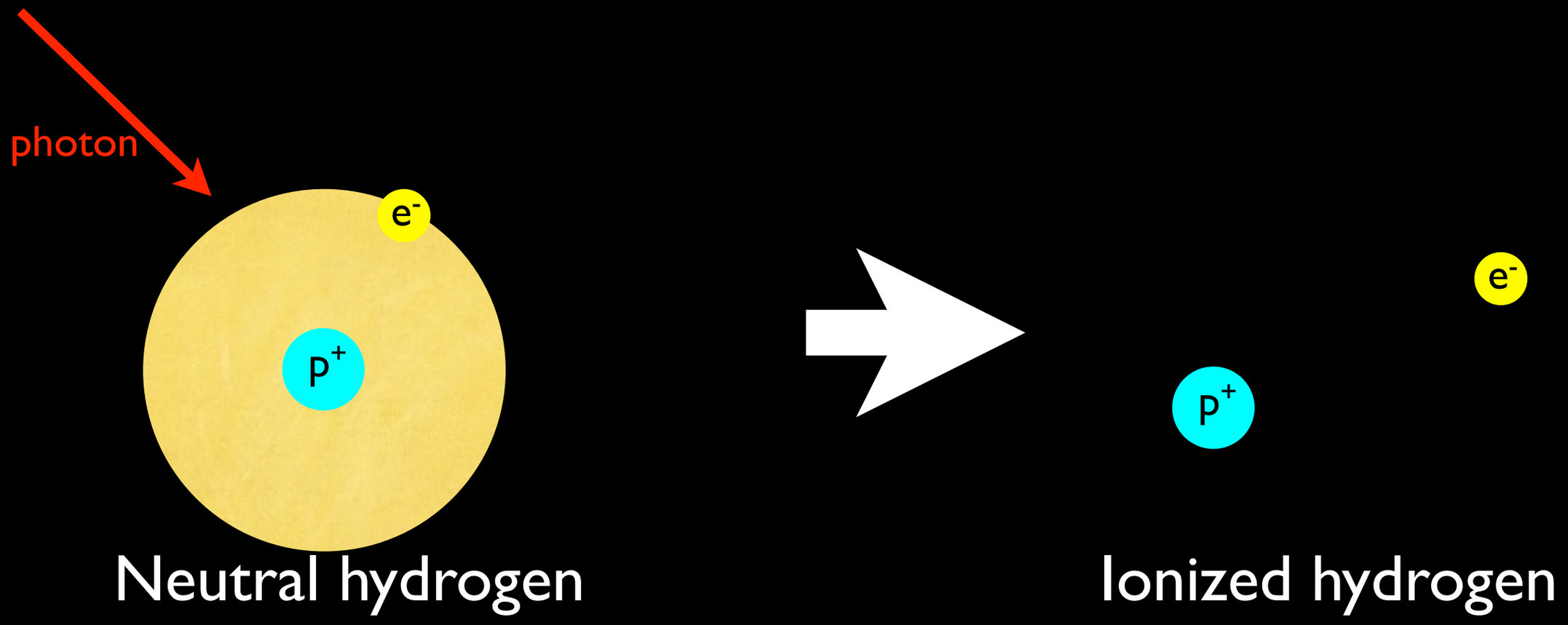
- IF feedback prevents star formation for a while then galaxies are “bursty” - 1 star at a time
- IF feedback mild then may get more continuous star formation
- Prima dona vs team players...

What sort of light?

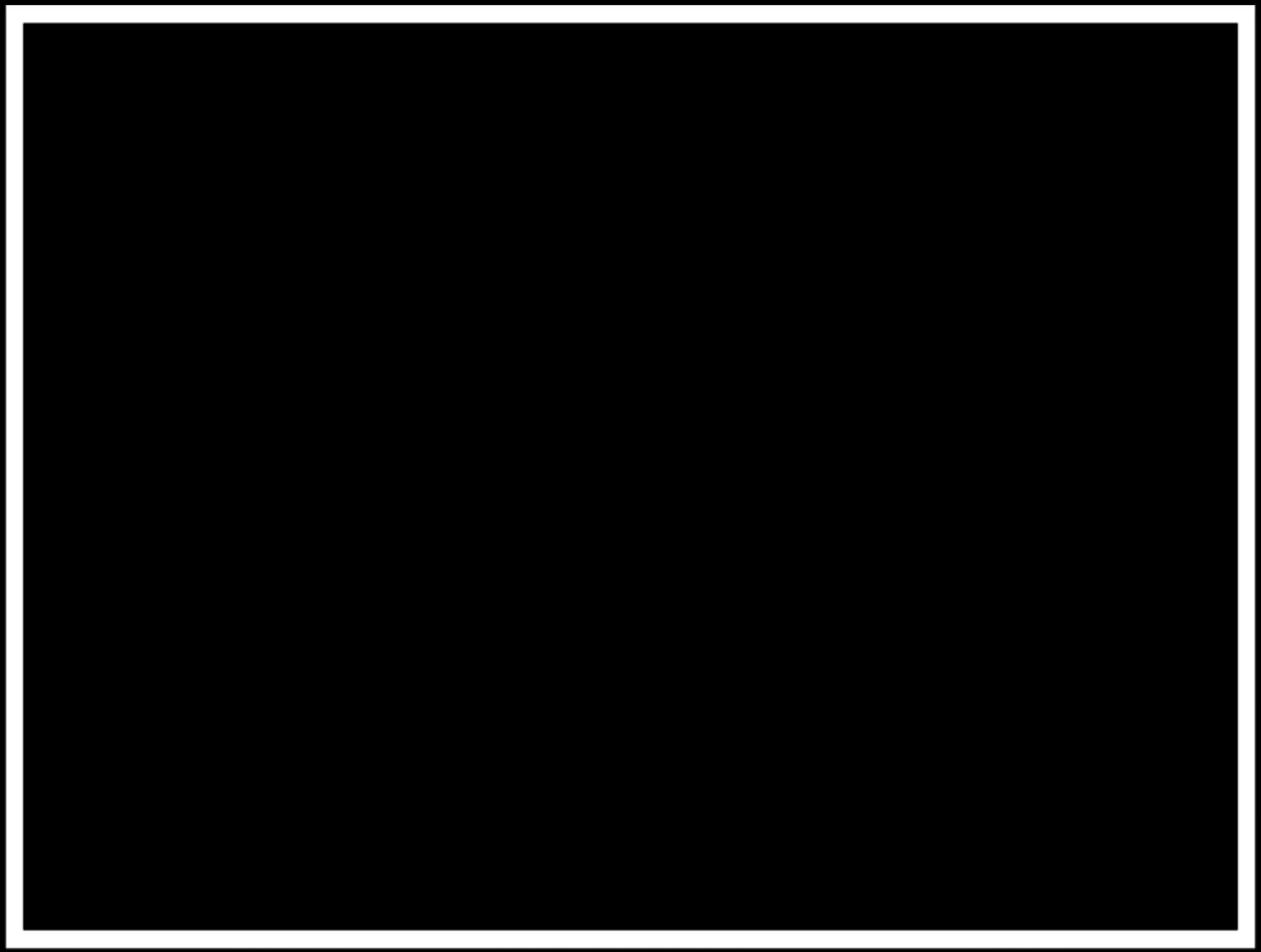
- As stars live and die they produce remnants - neutron stars, black holes
- Black holes can coalesce at center of galaxy and grow rapidly => supermassive black hole
- Accretion of gas onto black hole releases energy as radiation - can out shine galaxy
  = Active Galactic Nuclei (AGN)
- Jet of non-thermal emission + hot X-rays

Blowing bubbles

- Light more energetic than 13.6 eV can ionize hydrogen
- Ionized bubbles form around galaxies and grow, merging over time.
- Ultimately, the space between galaxies becomes entirely ionized



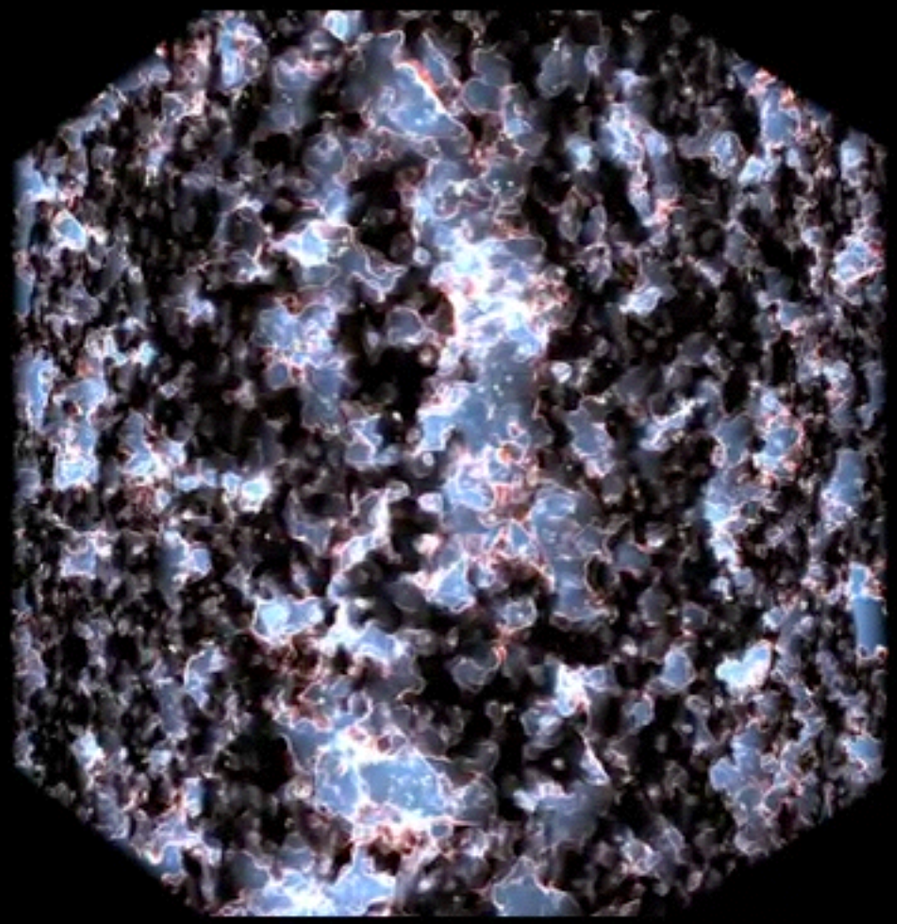
Reionization



The last phase transition???

- Reionization is the last major phase transition in the Universe from space being filled with cold, neutral gas to hot, ionized gas.
- When and how long did reionization take place?
- What were the sources that drove it?
  - Massive metal-free Population III stars
  - Many metal-poor Population II stars
  - Accretion onto supermassive black holes (AGN)
- How did ionized bubbles grow and merge?
  - small bubbles around individual galaxies
  - larger bubbles around groups of galaxies

What do we know?



Reionization

Reionization

Cast:
dark matter halos
Population III stars
Population II stars
Galaxies
Black holes
Dark stars
Miniquasar
...

Casablanca

Cast:
Taxi driver
Police man
Rick
Souk merchant
Lazlo
Ilsa
Man with camel
...

Know the cast, but
who are the leads and who the bit players?

Reionization

Plot:
Universe was neutral
Luminous sources form
Universe became ionized

Casablanca

Plot:
Boy meets girl
Boy falls for girl
Boy loses girl

Know the plot highlights,
but what are the details?

Cosmic movie making

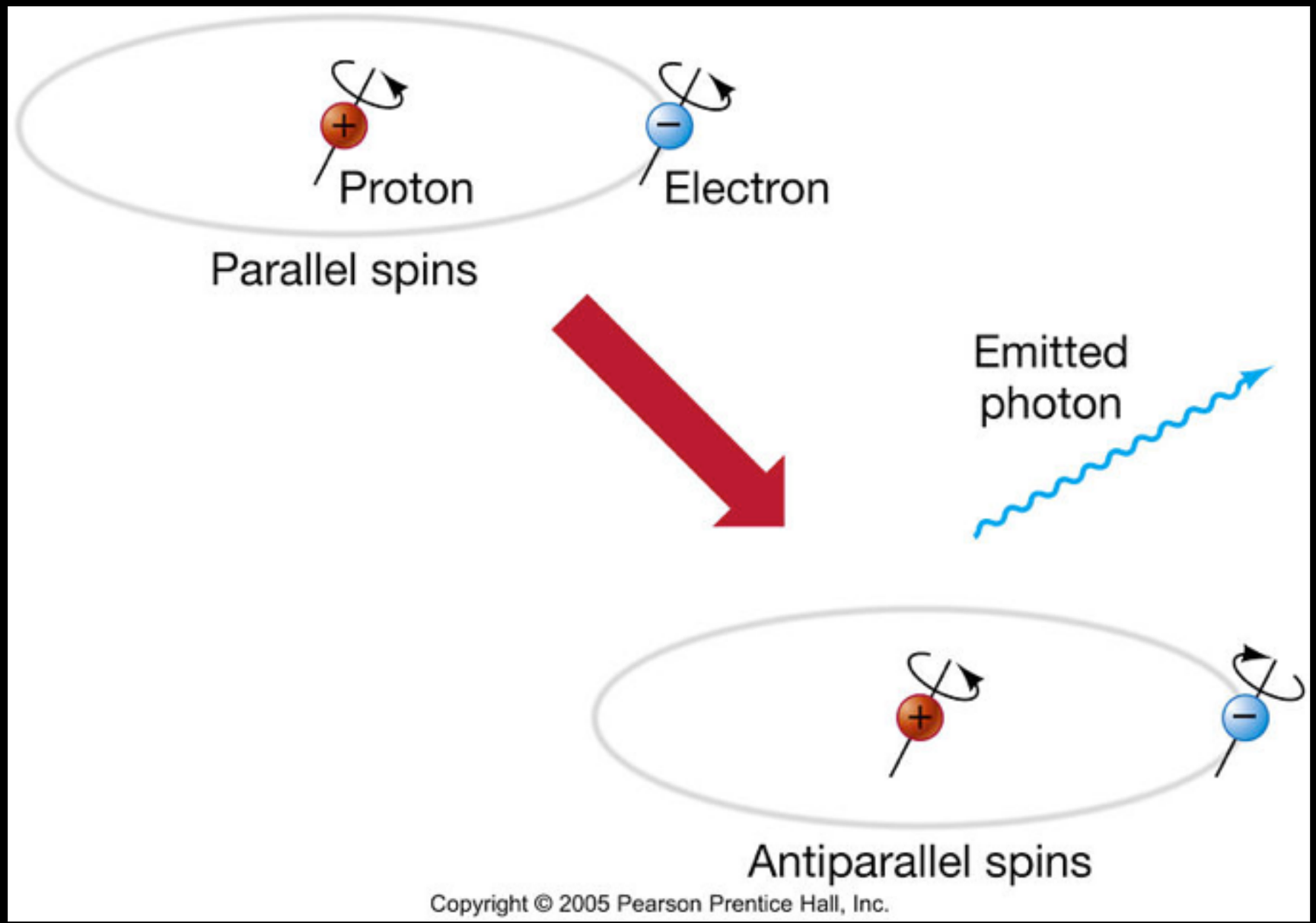
DIRECTOR	T. Universe	
CAMERAMAN	S.K.A.	
DATE	TAKE	SCENE
13.75 GYrABB	1	10^{51}

How to observe reionization?

- Should be able to see some of the bright galaxies with the James Webb Space Telescope
  BUT
  faint galaxies are too faint. Sad since they're numerous
- Really want to see the hydrogen gas that gets ionized
  BUT
  light from ionization and recombination of hydrogen gets blocked before it gets to us
- Need a new technique to map the hydrogen

The 21 cm line

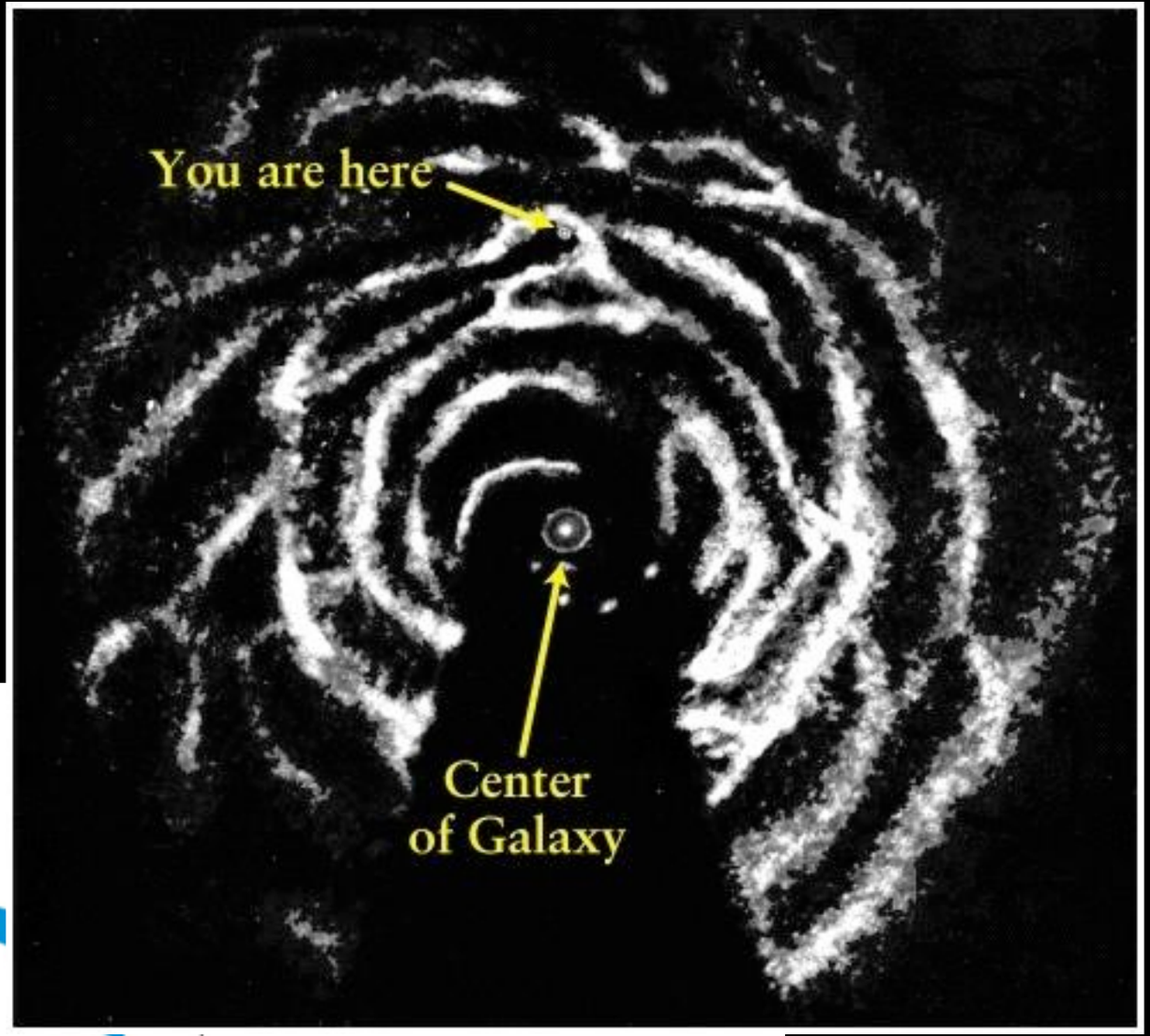
- Hydrogen can emit or absorb radio waves with wavelength of 21cm from spin flips
- These radio waves can propagate to us today

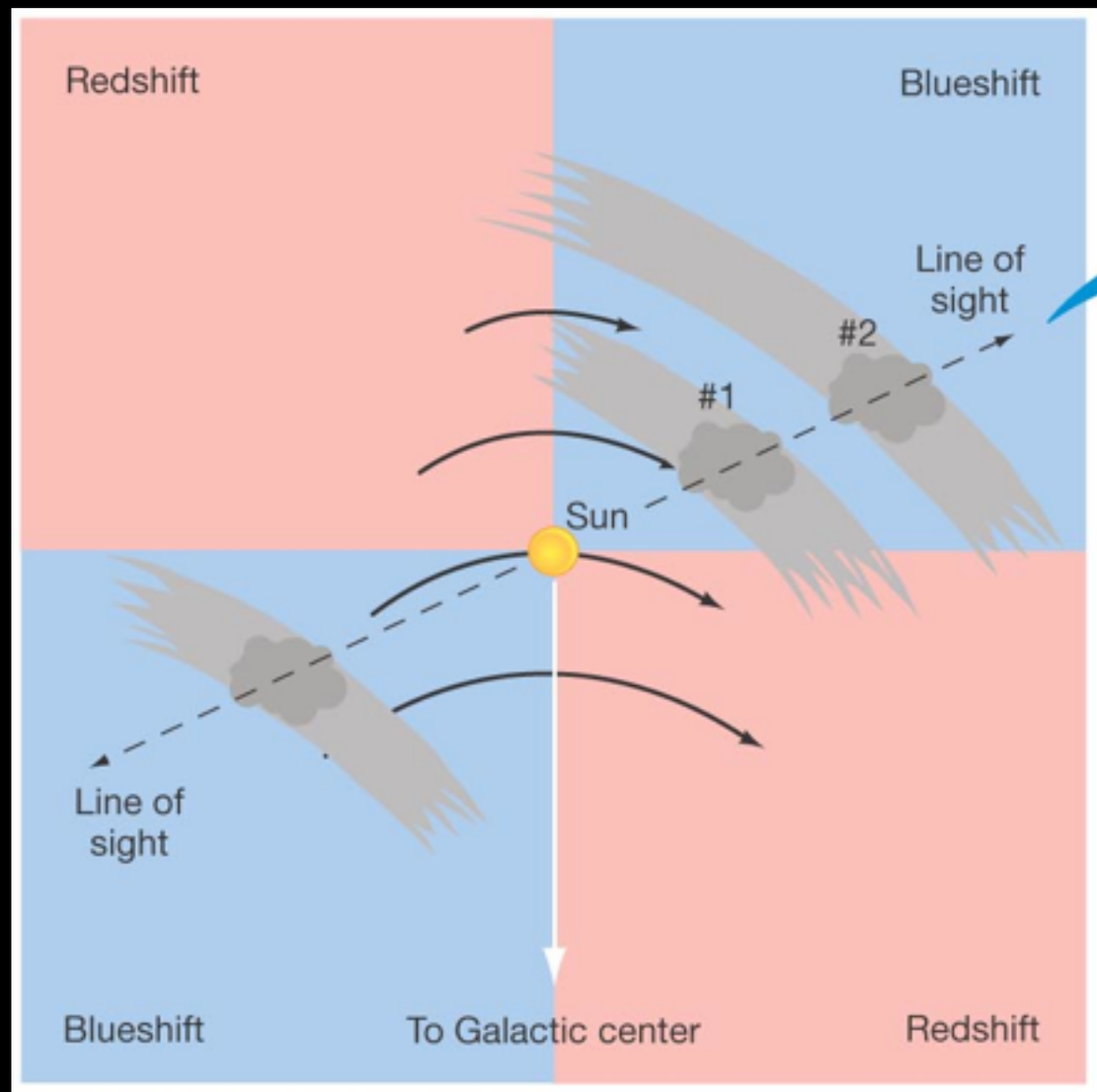


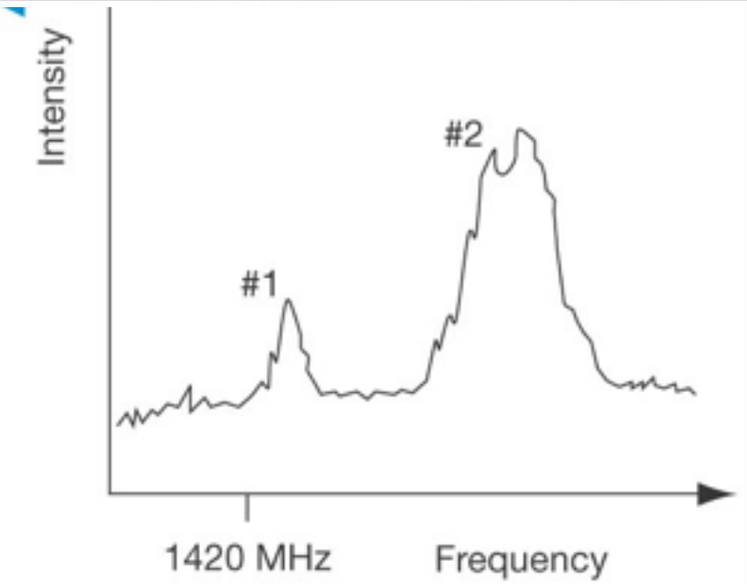
21cm = 1.4 GHz

Nearby 21 cm

- 21 cm light will be shifted in
- Used in nearby Universe to

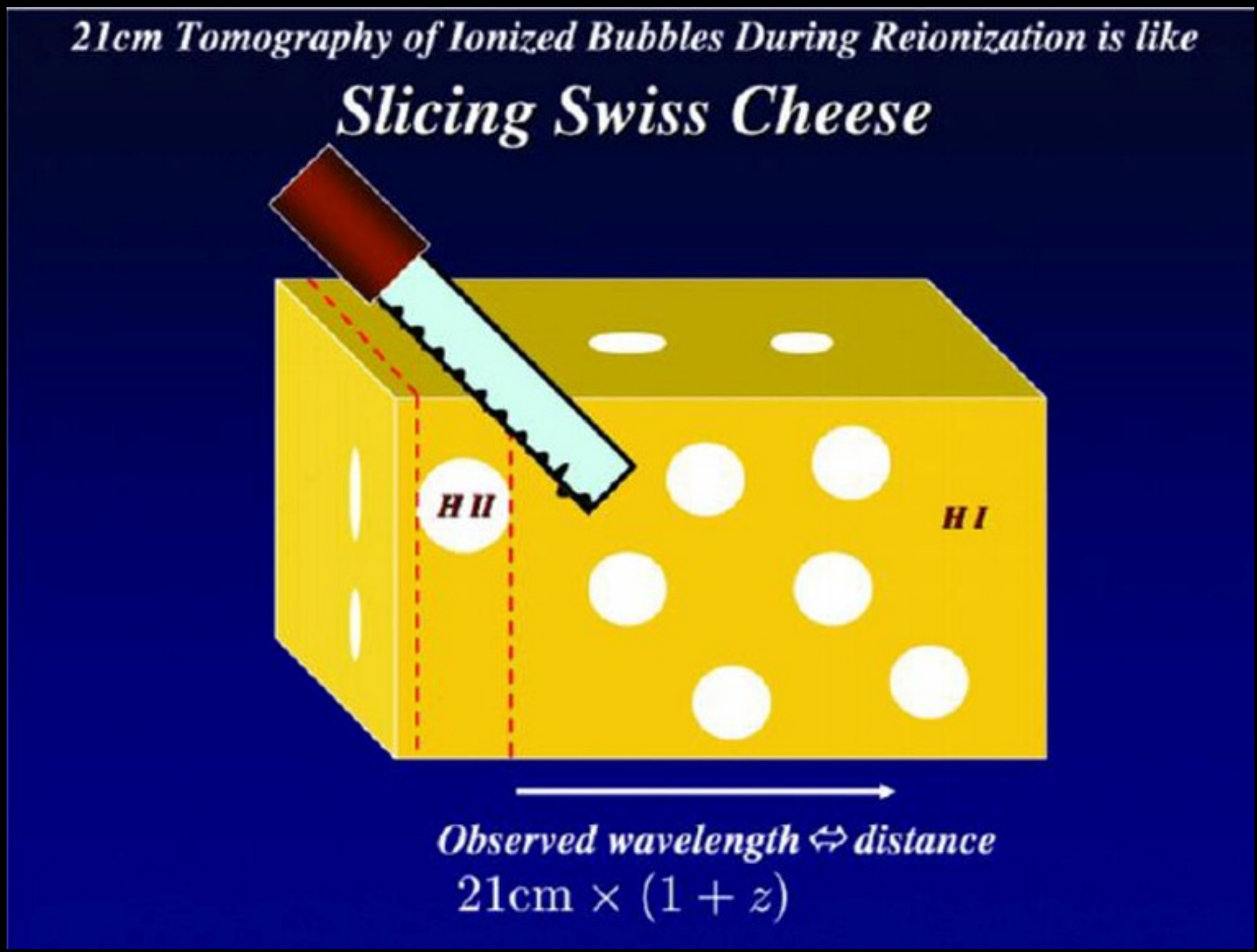






Cutting Swiss Cheese

- At cosmic distances, expansion of Universe produces Doppler shift = redshifting



Where should we look?

- Frequencies 40-200MHz correspond to 100million - 1billion years after the Big Bang

1420 MHz => z=0

$200\,\mathrm{MHz} \rightarrow z = 6$

$100\,\mathrm{MHz} \rightarrow z = 13$

$70\,\mathrm{MHz} \rightarrow z \approx 20$

50 MHz => z~27

t_{Age}(z=0) ~13.7 Gyr

$t_{\mathrm{Age}}(z = 6) \approx 1\,\mathrm{Gyr}$

$t_{\mathrm{Age}}(z = 10) \approx 500\,\mathrm{Myr}$

$t_{\mathrm{Age}}(z = 20) \approx 150\,\mathrm{Myr}$

t_{Age}(z=27) ~100 Myr

Radio telescopes of the past

NEW RADIO WAVES TRACED TO CENTRE OF THE MILKY WAY

Mysterious Static, Reported by K. G. Jansky, Held to Differ From Cosmic Ray.

DIRECTION IS UNCHANGING

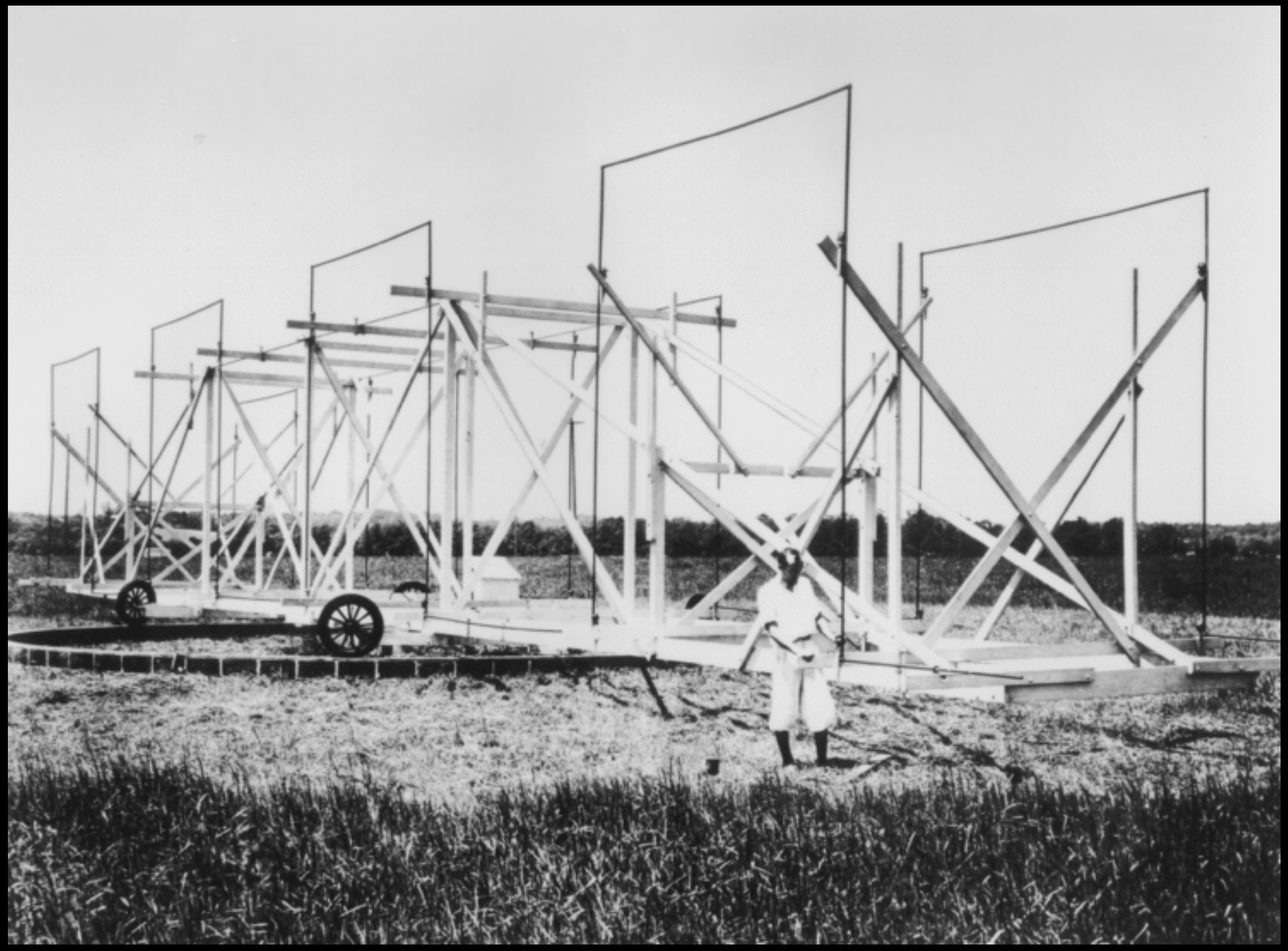
Recorded and Tested for More Than Year to Identify It as From Earth's Galaxy.

ITS INTENSITY IS LOW

Only Delicate Receiver Is Able to Register—No Evidence of Interstellar Signaling.

Discovery of mysterious radio waves which appear to come from the centre of the Milky Way galaxy was announced yesterday by the Bell Telephone Laboratories. The discovery was made during research studies on static by Karl G. Jansky of the radio research department at Holmdel, N. J., and was described by him in a paper delivered before the International Scientific Radio Union in Washington.

Front page
New York Times
May 3, 1933



Jansky with his 20.5 MHz telescope near Bell Labs

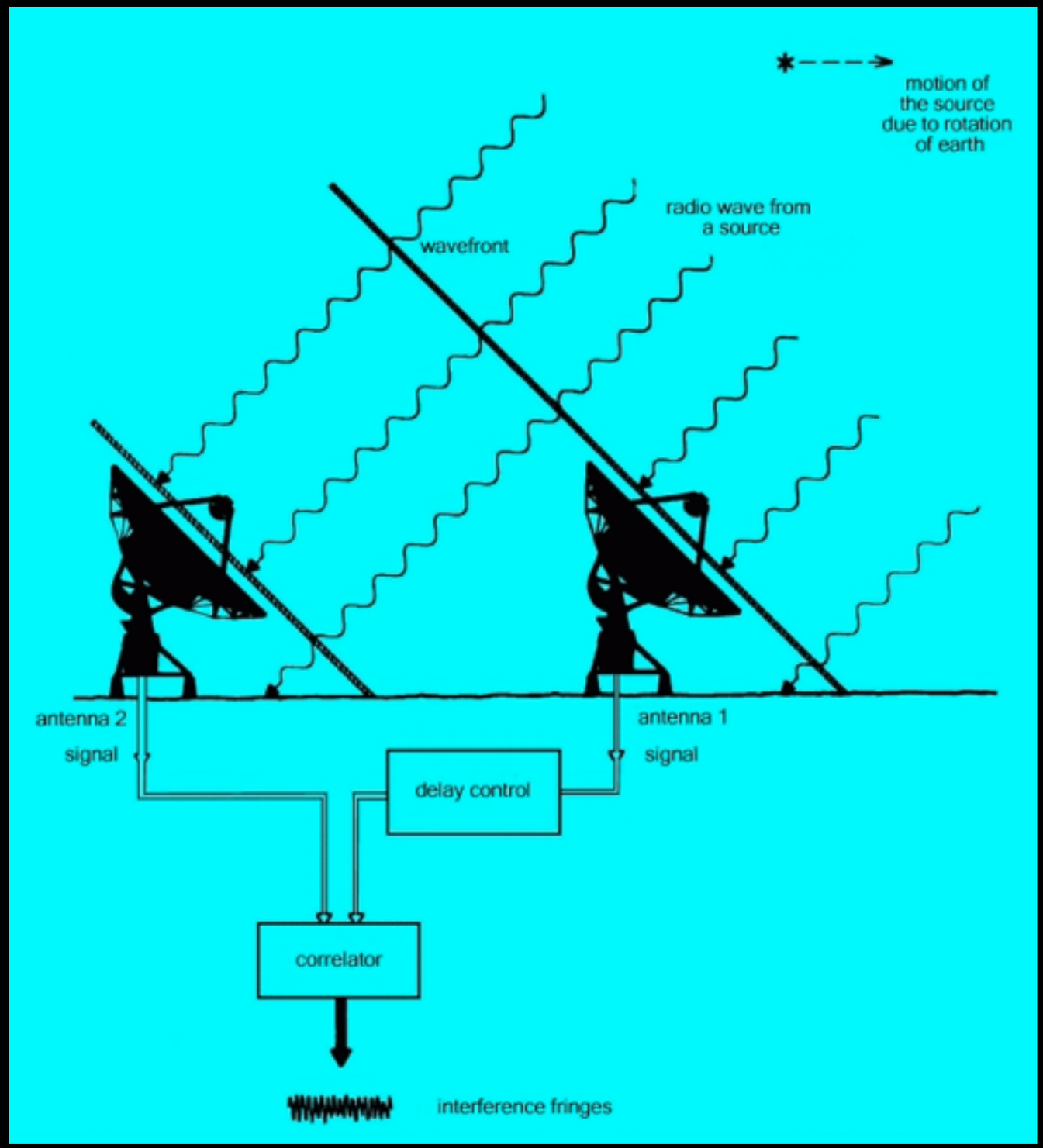
Bigger is better!

Green Bank 300ft telescope

Building big dishes is hard

Interferometry

- Radio telescope samples phase and amplitude of electromagnetic wave
- Combine signal from many elements to synthesise a bigger telescope
  = ‘interferometry’
- More elements
  = more collecting area
  & better quality image

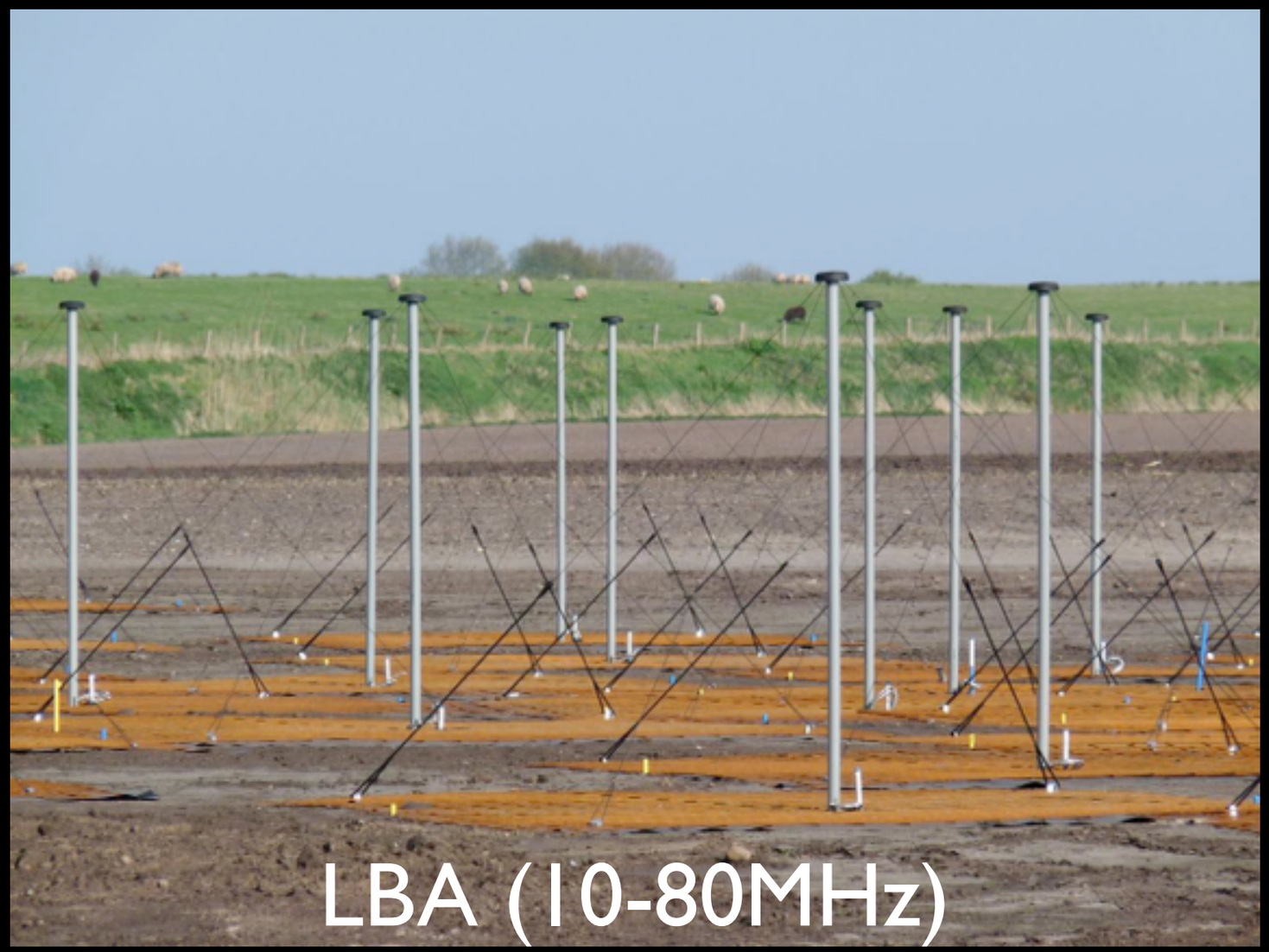


Giant Meter Radio Telescope

Built in 1995, 80 km from Pune, India
30 x 45m dishes. 50MHz-1500MHz

LOw Frequency ARray (LOFAR)

- First of modern arrays built to target cosmic 21cm signal
- Individual elements are simple antennae collected into ‘tiles’
- Plug into supercomputer and correlate = ‘Digital astronomy’



LBA (10-80MHz)

HBA (120-240 MHz)

LOFAR

- Core located in Netherlands
- Stations scattered over Europe
- Now looking for cosmic 21 cm signal

Square Kilometer Array

- Will have ~ 1 million antennae and 1 km^2 collecting area
- Distributed over core of ~ 1km to outlying stations ~ 100km away
- Located in South Africa and Australia
- First light ~2020
- International HQ at Jodrell Bank near Manchester
- Cost: €650 million for Phase 1
- BIG DATA!!! - SKA Phase 1 will produce today's internet per night

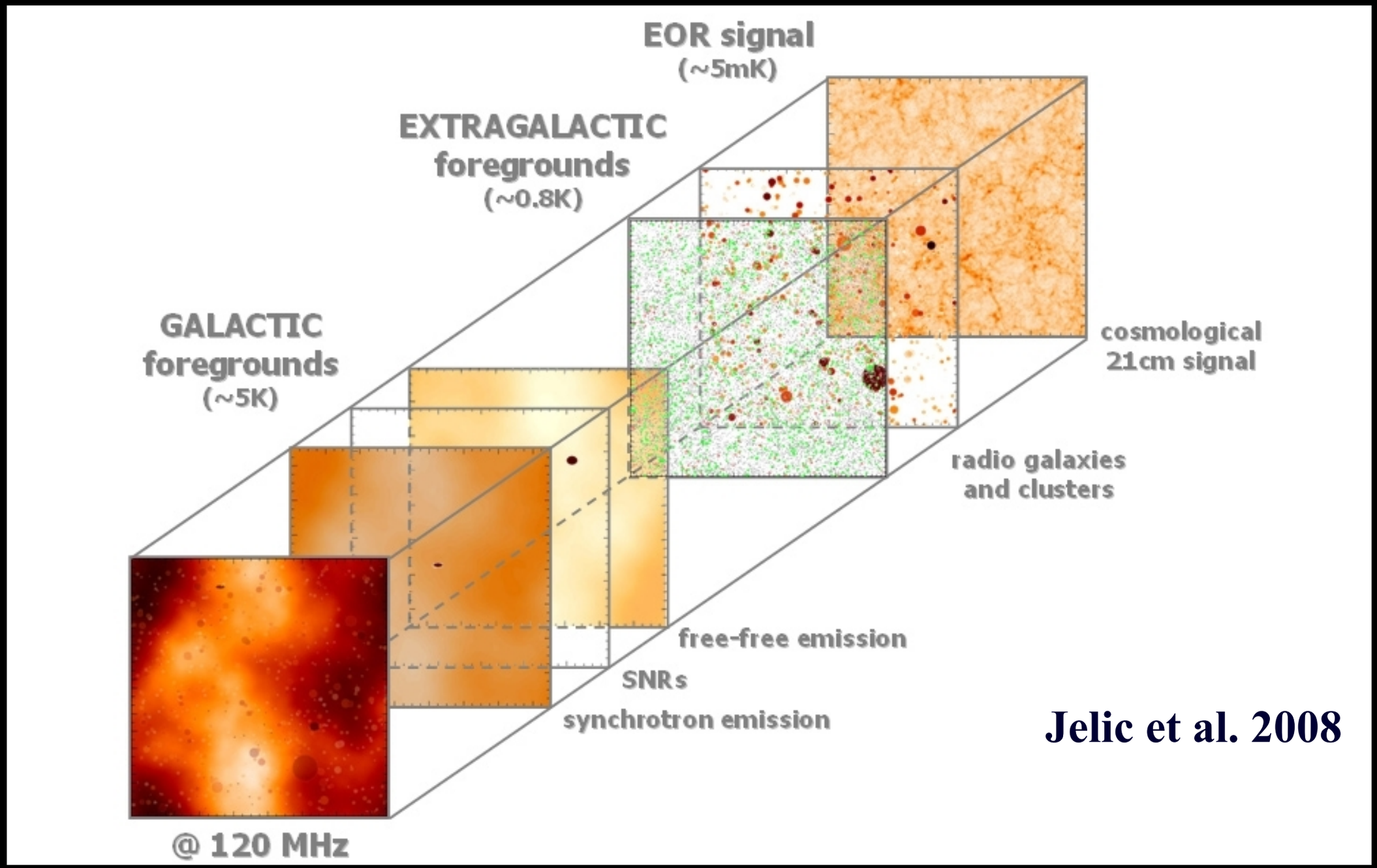
Square Kilometer Array

The Square Kilometre Array

Square Kilometer Array

Key challenges

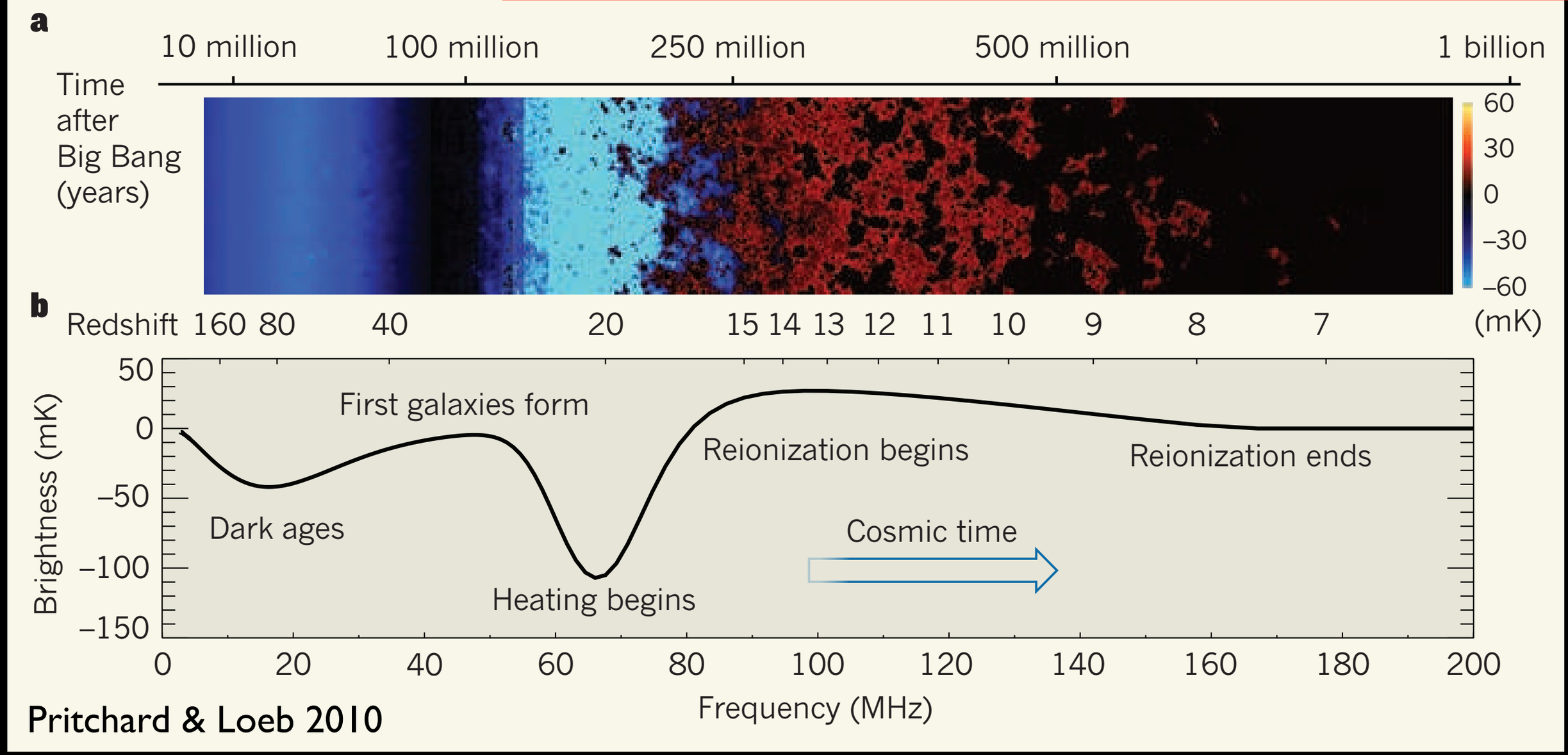
- Man made radio interference
- Astronomical foregrounds - 1000x larger than signal



Jelic et al. 2008

21 cm signal

Moon? | SKA | LOFAR/MWA/PAPER

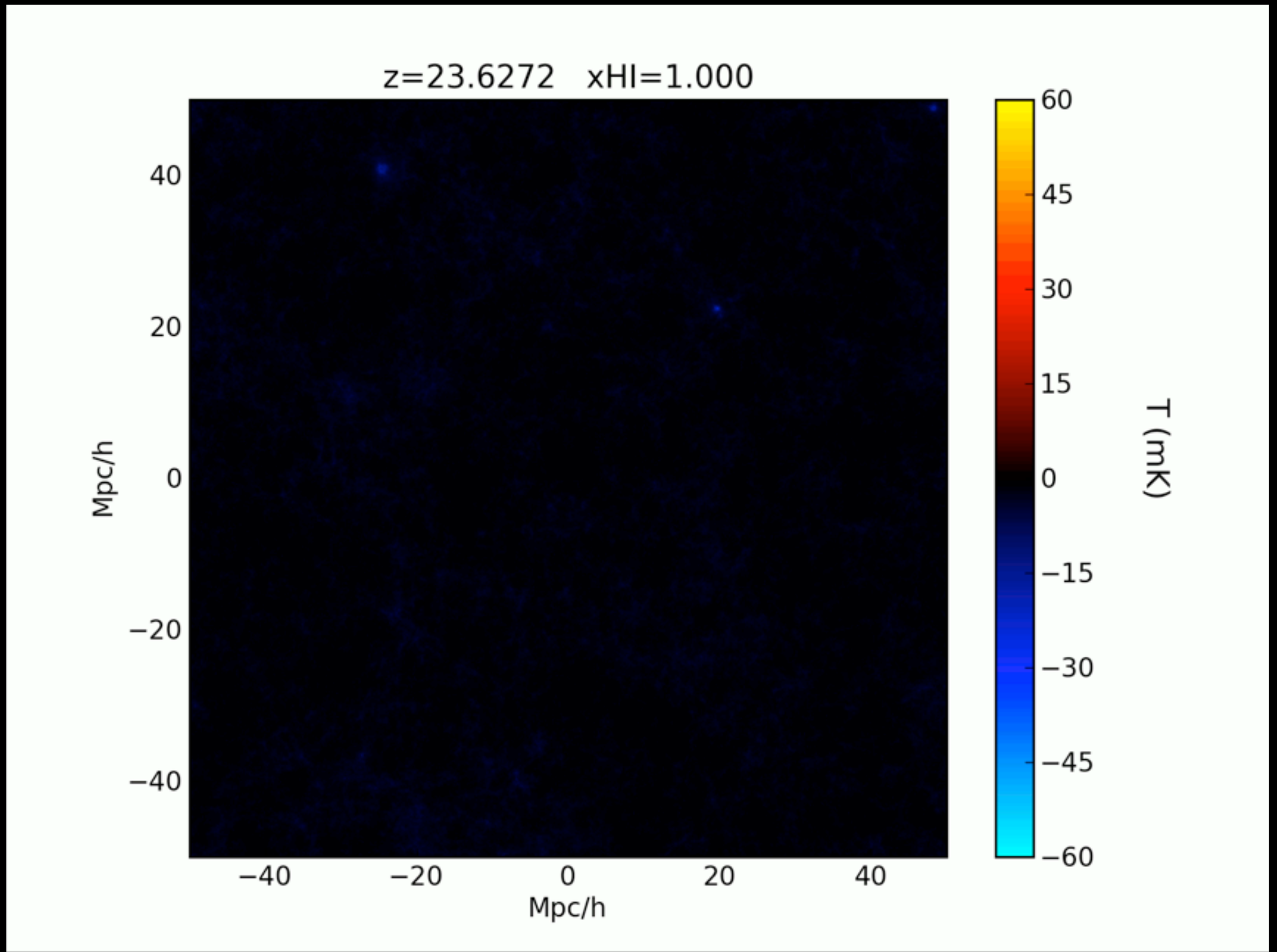


Pritchard & Loeb 2010

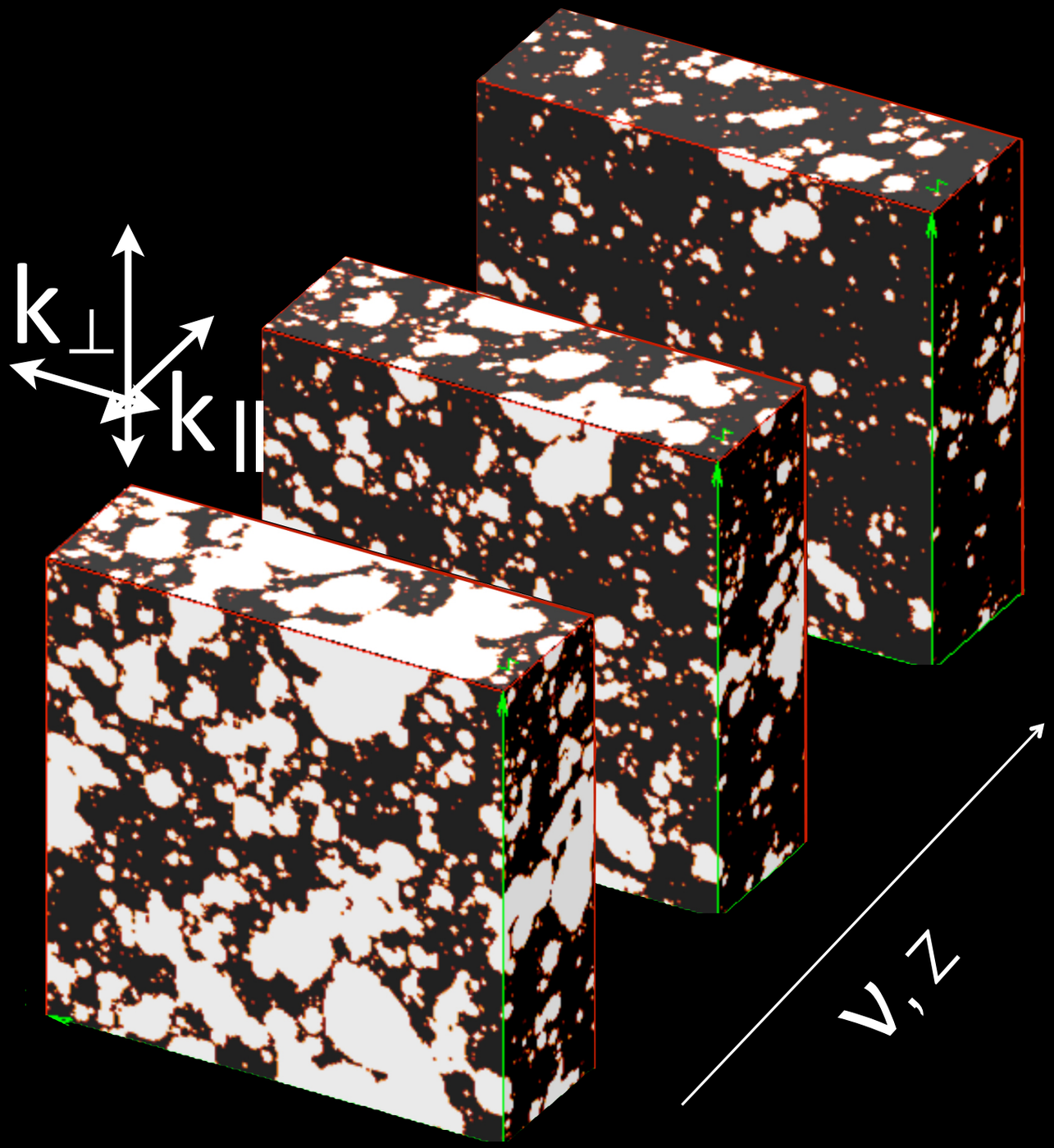
Where CMB is a photo; 21cm signal is a movie

Sensitive to key moments in cosmic history

Cosmic movies

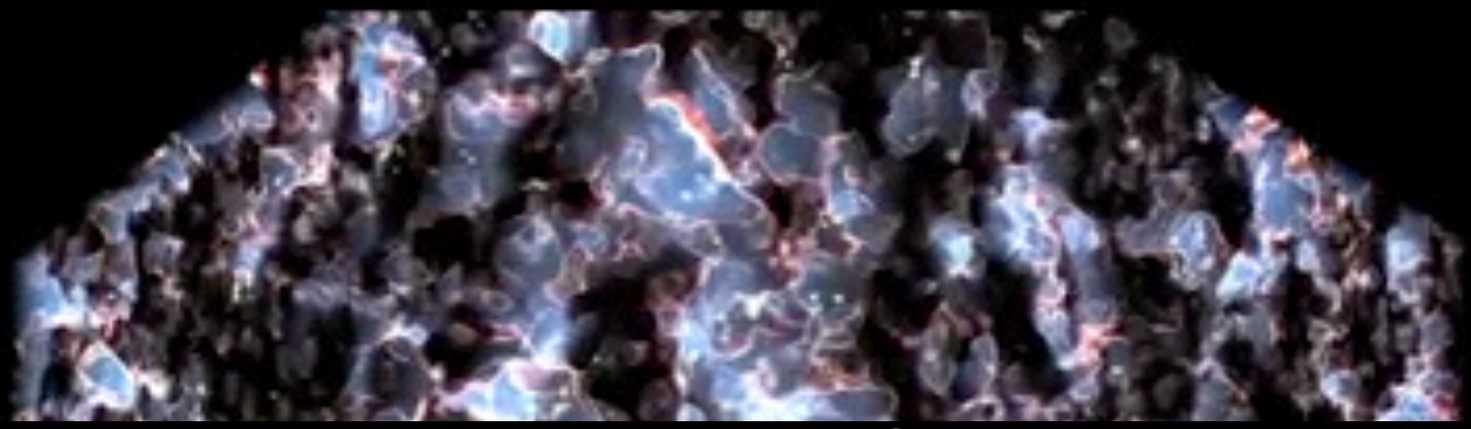


What might we learn?



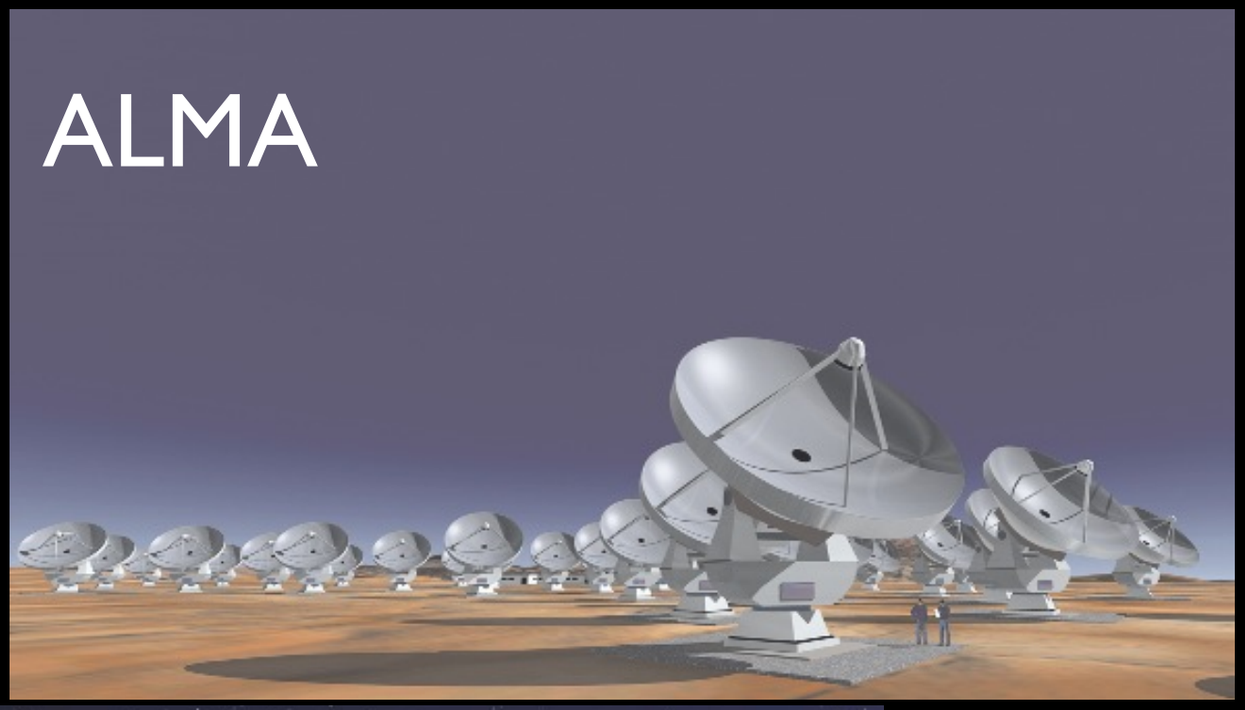
- When did first galaxies begin heating and ionizing the Universe.
- Sizes & number of bubbles linked to brightness and abundance of galaxies
- Temperature of hydrogen linked to X-ray emission from early black holes
- Map distribution of matter throughout Universe

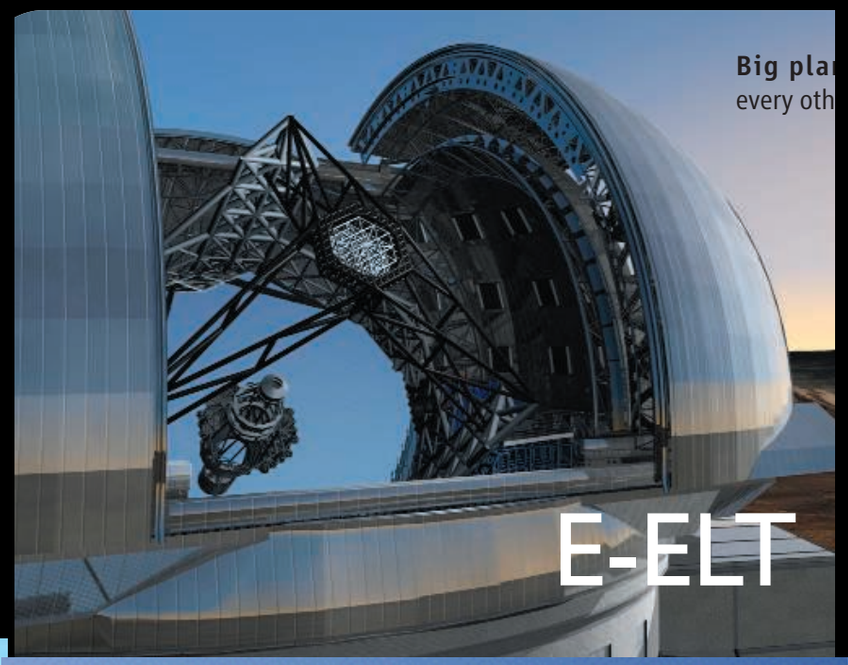
Things to watch out for

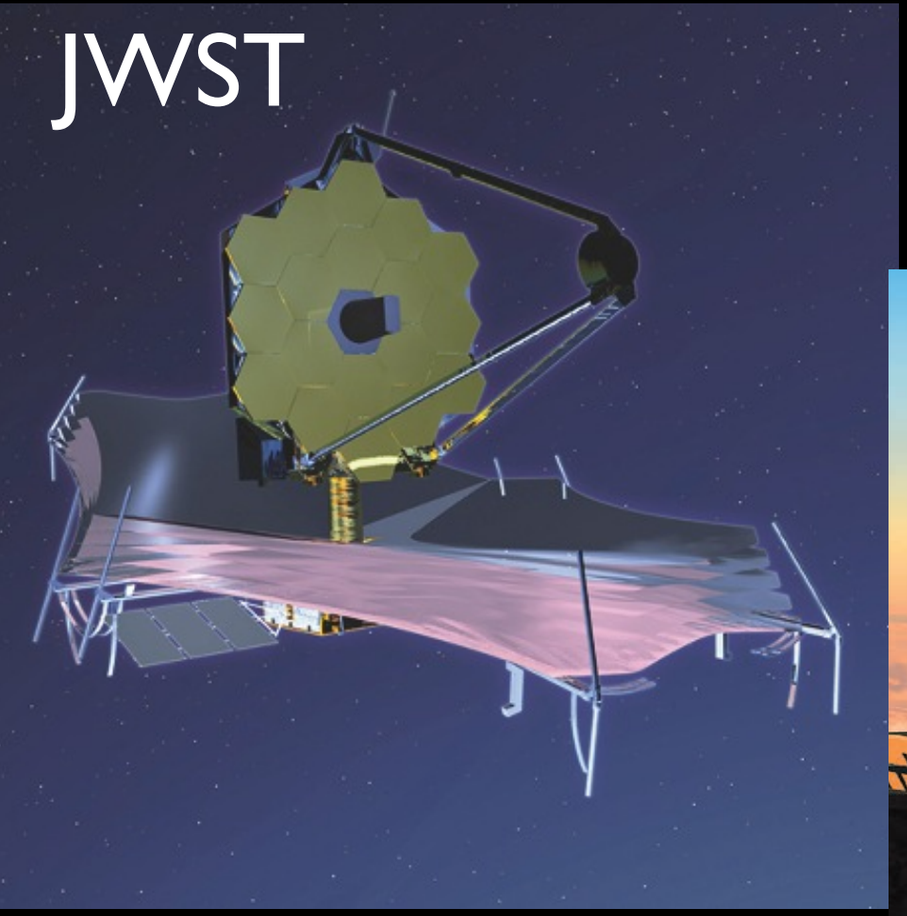


- Radio astronomy being transformed by computing power
- New instruments; new capabilities; new frontiers
- Big data; big computing challenges
  => new algorithms needed
- 21 cm studies will reveal Universe from 100 million years after the Big Bang through to today

Exciting times ahead!







We are listening - Diane Ackerman

As our metal eyes wake
to absolute night,
where whispers fly
from the beginning of time,
we cup our ears to the heavens.
We are listening

on the volcanic rim of Flagstaff
and in the fields beyond Boston,
in a great array that blooms
like coral from the desert floor,
on highwire webs patrolled
by computer spiders in Puerto Rico.

We are listening for a sound
beyond us, beyond sound,

searching for a lighthouse
in the breakwaters of our uncertainty,
an electronic murmur,
a bright, fragile *I am*.

Small as tree frogs
staking out one end
of an endless swamp,
we are listening
through the longest night
we imagine, which dawns
between the life and times of stars.

Our voice trembles
with its own electric,
we who mood like iguanas,
we who breathe sleep
for a third of our lives,
we who heat food
to the steaminess of fresh prey,
then feast with such
good manners it grows cold.

In mind gardens
and on real verandas
we are listening,
rapt among the Persian lilacs
and the crickets,
while radio telescopes
roll their heads, as if in anguish.

With our scurrying minds
and our lidless will
and our lank, floppy bodies
and our galloping yens
and our deep, cosmic loneliness
and our starboard hearts
where love careens,
we are listening,
the small bipeds
with the giant dreams.

In the beginning of the Dark Ages, electrically neutral hydrogen gas filled the universe. As stars formed, they ionized the regions immediately around them, creating bubbles here and there. Eventually these bubbles merged together, and intergalactic gas became entirely ionized.

Thank you for your consideration

SKA status

SKA director general - Phil Diamond

SKA sites: South Africa - Karoo
Australia - Western Outback

SKA-low: 50-350 MHz (Australia)
SKA-mid: 350MHz-3GHz (SA)

Baseline design currently under discussion

Current

SKA project office - Jodrell Bank, Manchester


FOR EXTRATERRESTRIAL INTELLIGENCE
WAIT
WETI

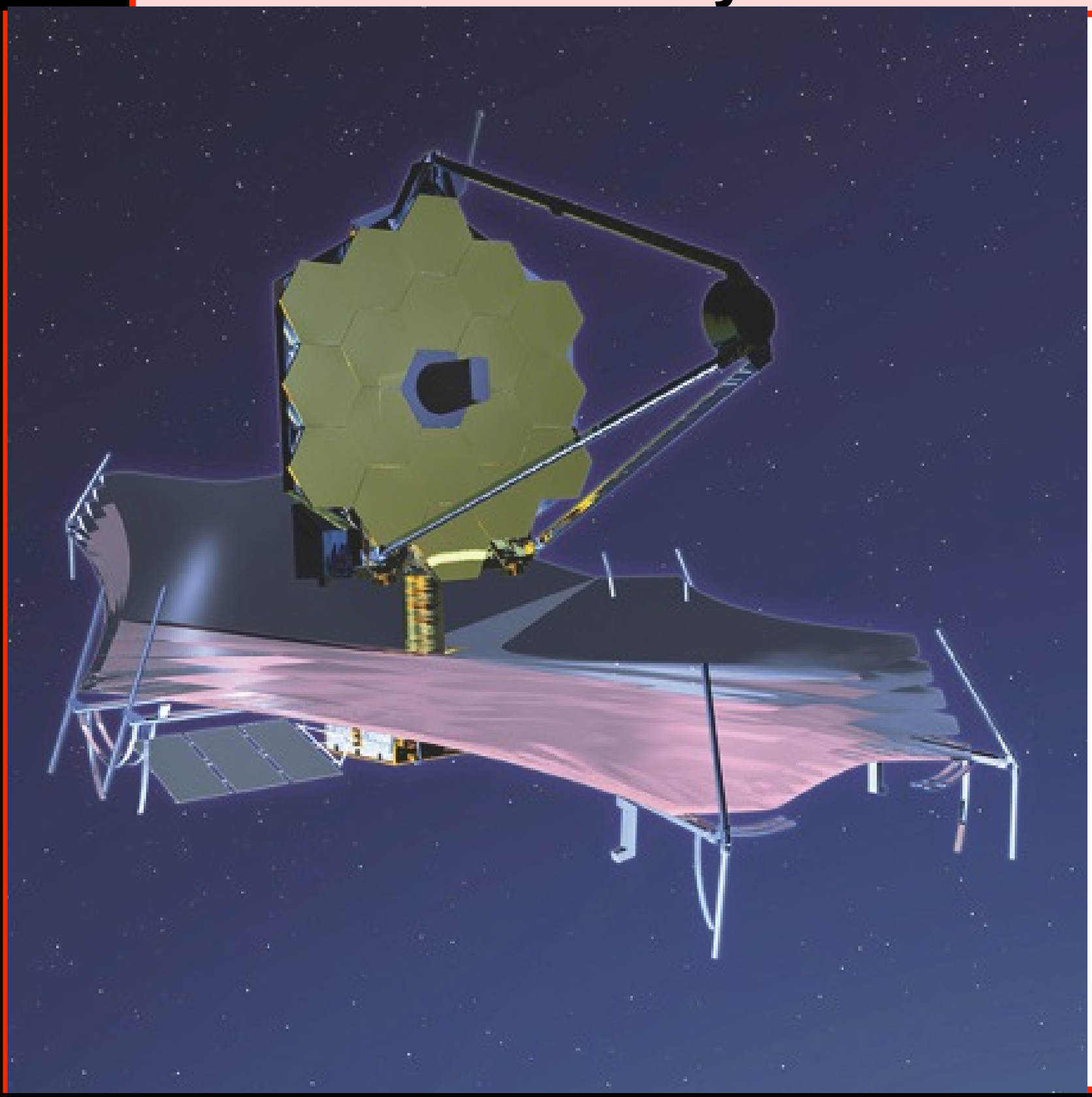
MWA

Arecibo

305m dish

VLA

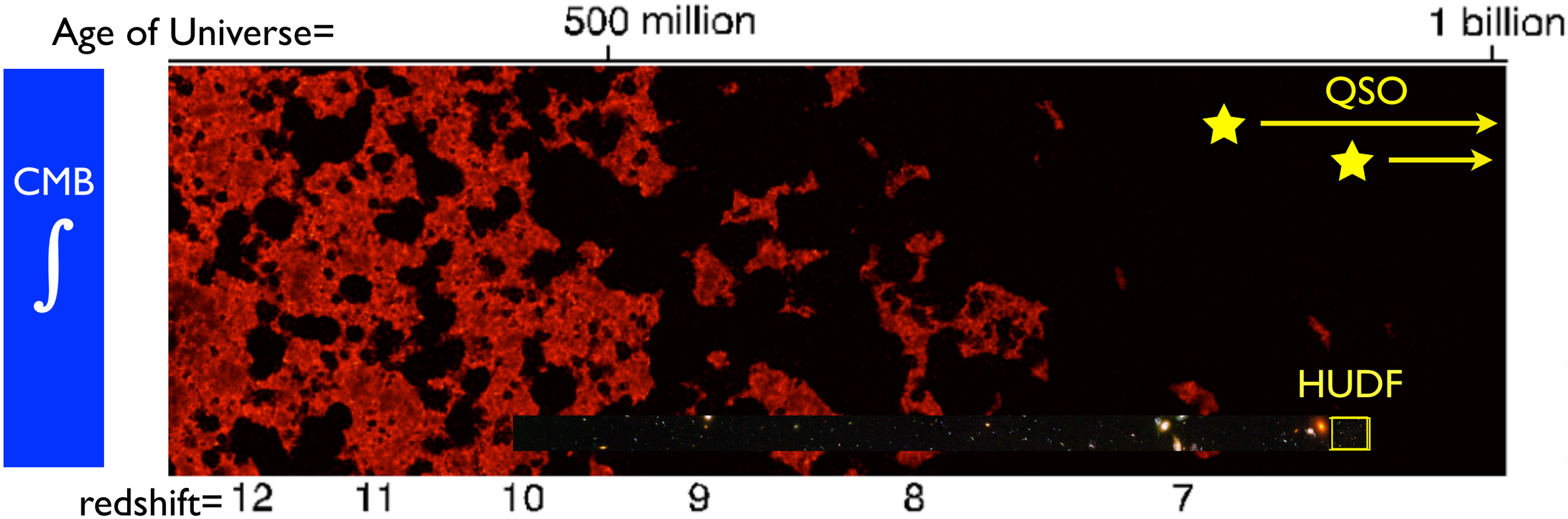
JWST



ALMA

DARE

More needed...



Existing observations leaves much unanswered:

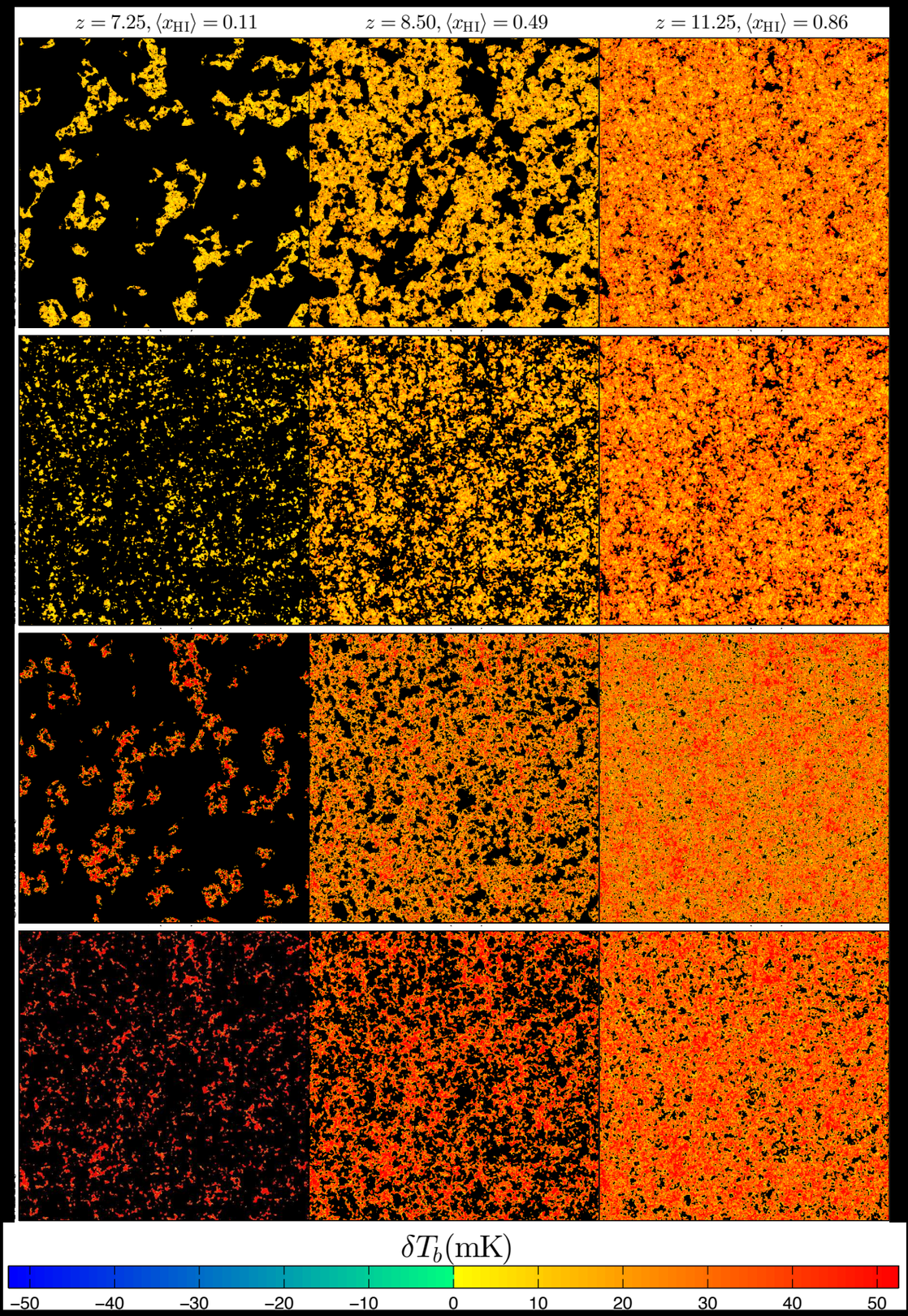
1) Lyman-alpha forest: end point $z>6.5$
2) CMB optical depth: mid point $z\sim11$
3) kSZ amplitude: duration $z<4.4$?

HST probes skewer much smaller than scale of ionized regions + only brightest sources

Large galaxy samples with LAE surveys or Euclid possible to $z\sim8$

Fundamental need for new types of observation to understand details of reionization

Simulation of galaxy formation


$z = 7.25, \langle x_{\rm HI} \rangle = 0.11$
$z = 8.50, \langle x_{\rm HI} \rangle = 0.49$
$z = 11.25, \langle x_{\rm HI} \rangle = 0.86$
$\delta T_b\,({\rm mK})$
−50
−40
−30
−20
−10
0
10
20
30
40
50

We could imagine that light moved more slowly
say 1km/year

Then 18000km to Wellington, NZ would take 18000years
we'd see back to the beginning of human history

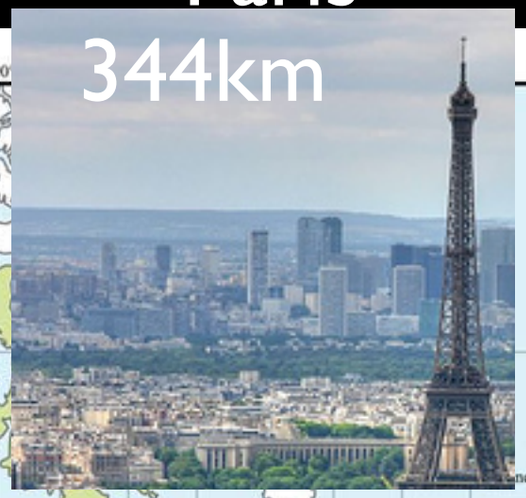
and you'd have to wait ~18 hours after hitting
a lightswitch to see the light

London

0km

Paris

344km

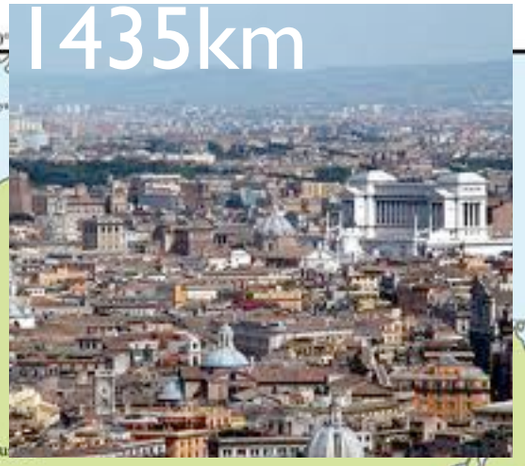


Berlin

932km

Rome

1435km



Cario

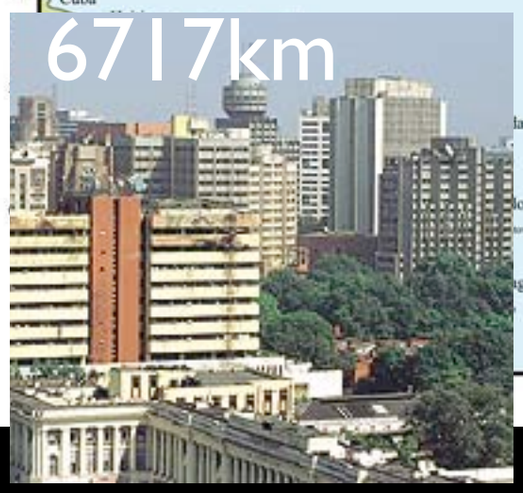
3515km

Baghdad

4097km

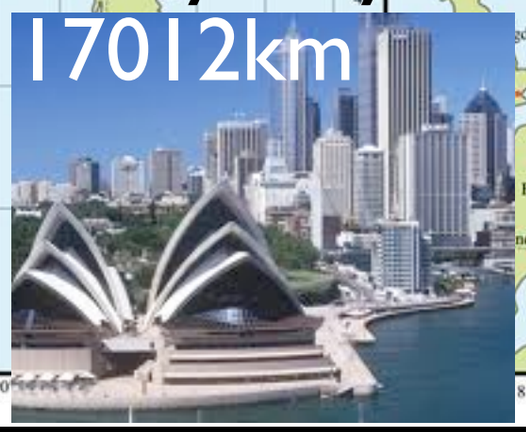
Delhi

6717km



Sydney

17012km



Wellington

18834km

London

2013AD

Paris

1669AD

Berlin

1081AD

Rome

578AD

Cario

1502BC

Baghdad

2084BC

Delhi

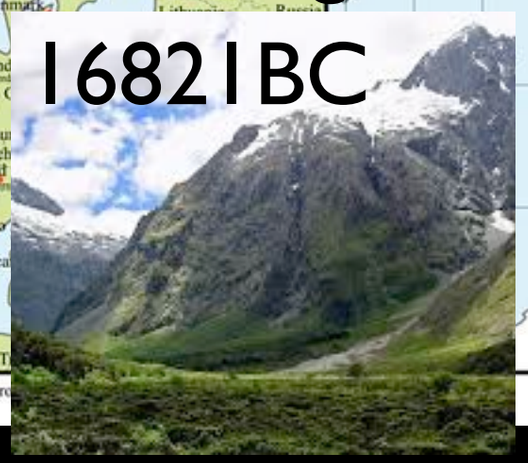
4500BC

Sydney

15000BC

Wellington

16821BC



Stellar Archeology

- Our galaxy has formed via mergers - “hierarchical structure formation” - smaller units form first then merger to form larger ones
- Some components were galaxies that formed long ago
- Low mass stars have lifetime> age universe so may be still around today
- Search for metal-poor and metal-free stars in our Milky way

LETTER

doi:10.1038/nature12990

A single low-energy, iron-poor supernova as the source of metals in the star SMSS J031300.36−670839.3

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