IGM theory
Dark Age, Cosmic Dawn, & Epoch of Reionization

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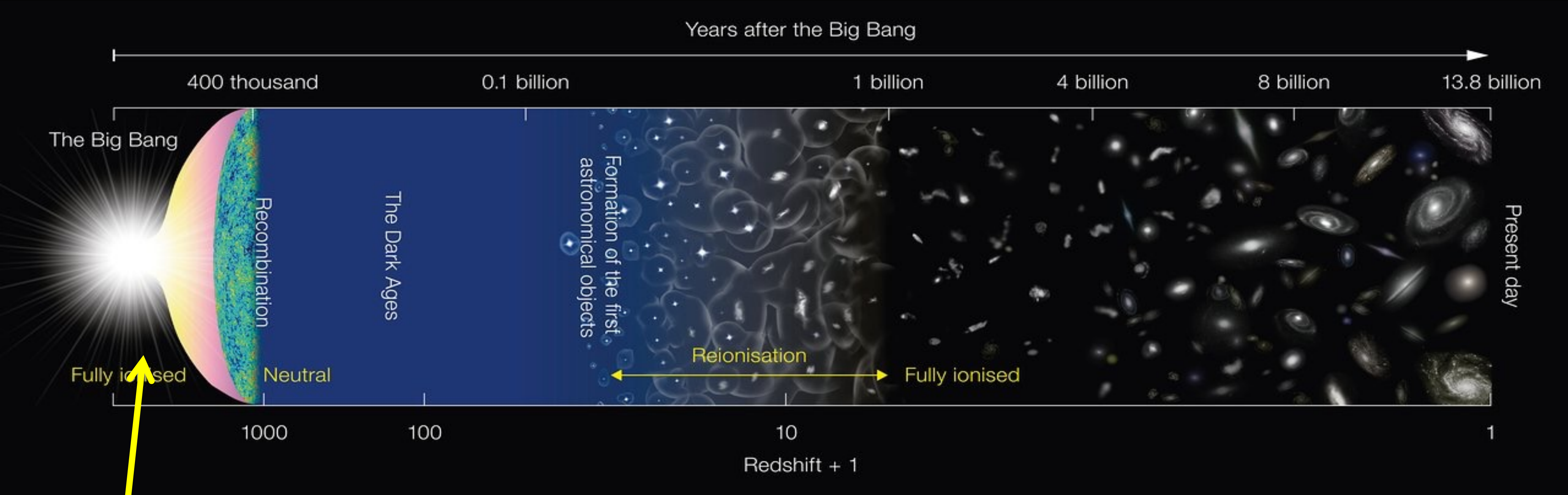
contents

1. history of the universe

history of the universe

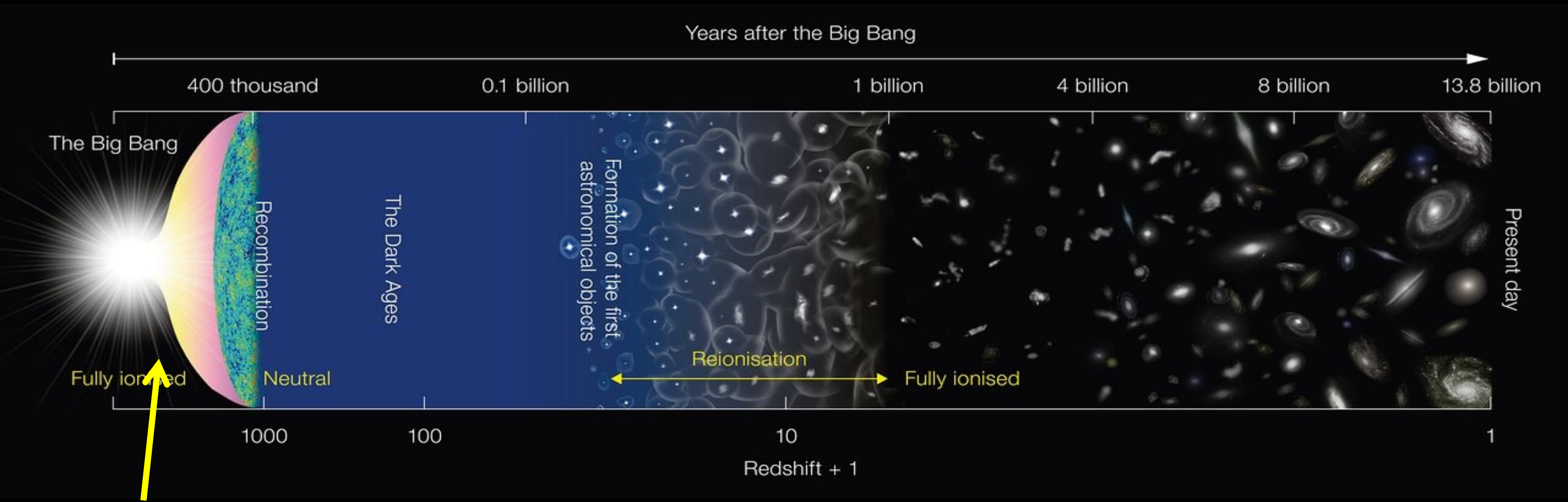
NAOJ



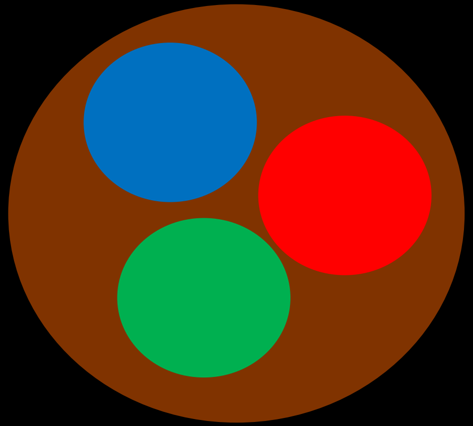
beginning of the universe: Big Bang
- high density, high temperature
- soup of elementary particles
- cools as it expands

history of the universe

NAOJ

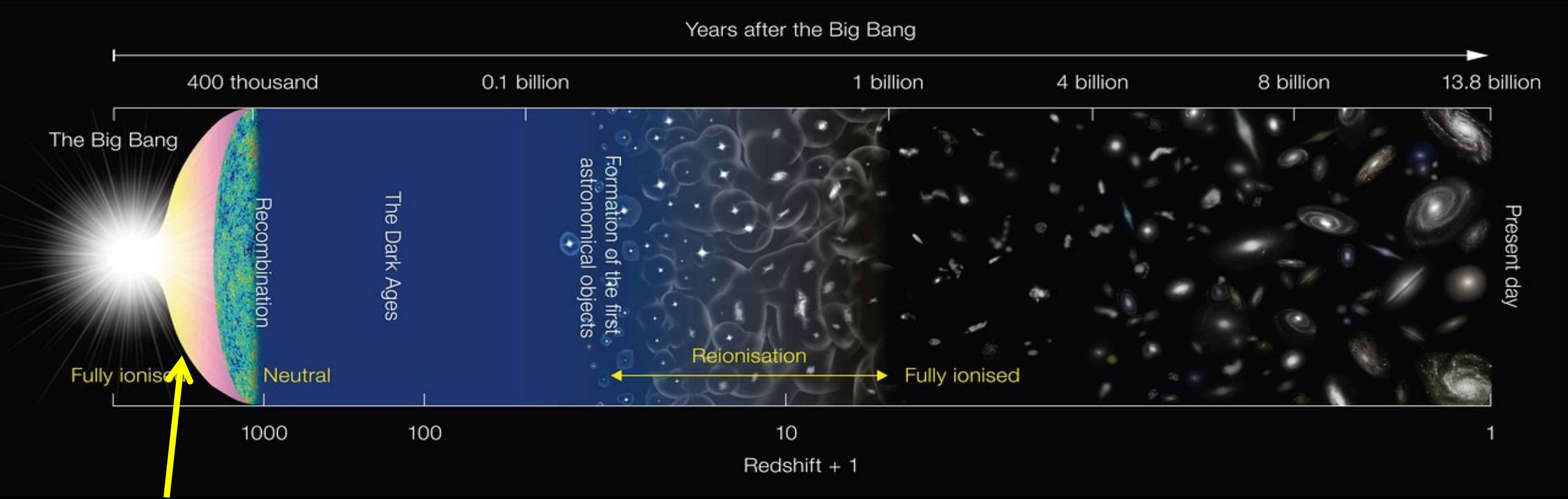


0.000001 sec after Big Bang
- temperature ~ 10^{13}K
- protons & neutrons formed from quarks

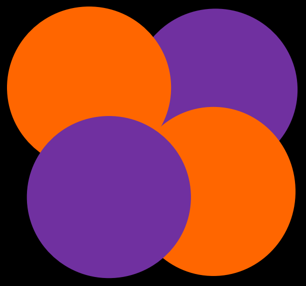


history of the universe

NAOJ



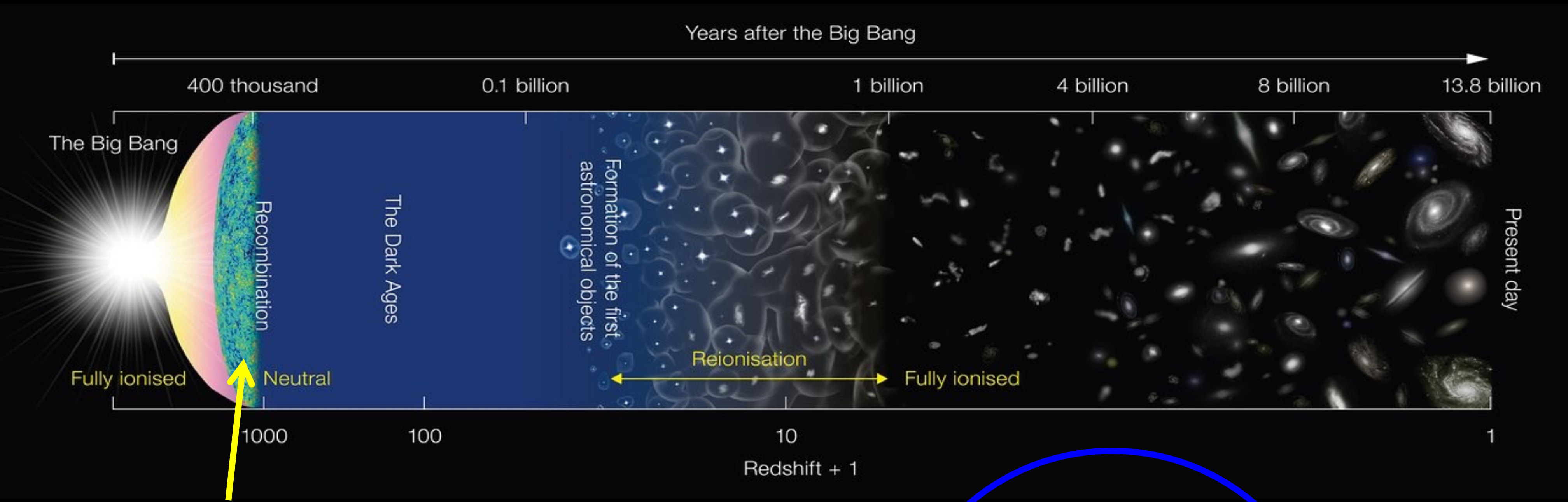
3 mins
- temperature ~ 10^9K
- synthesis of light elements (Big Bang Nucleosynthesis)



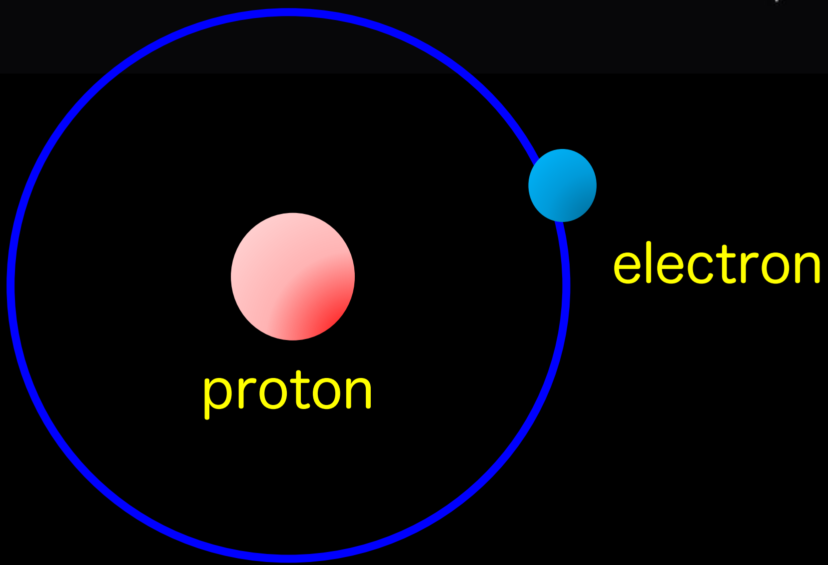
^{4}He = 2p + 2n

history of the universe

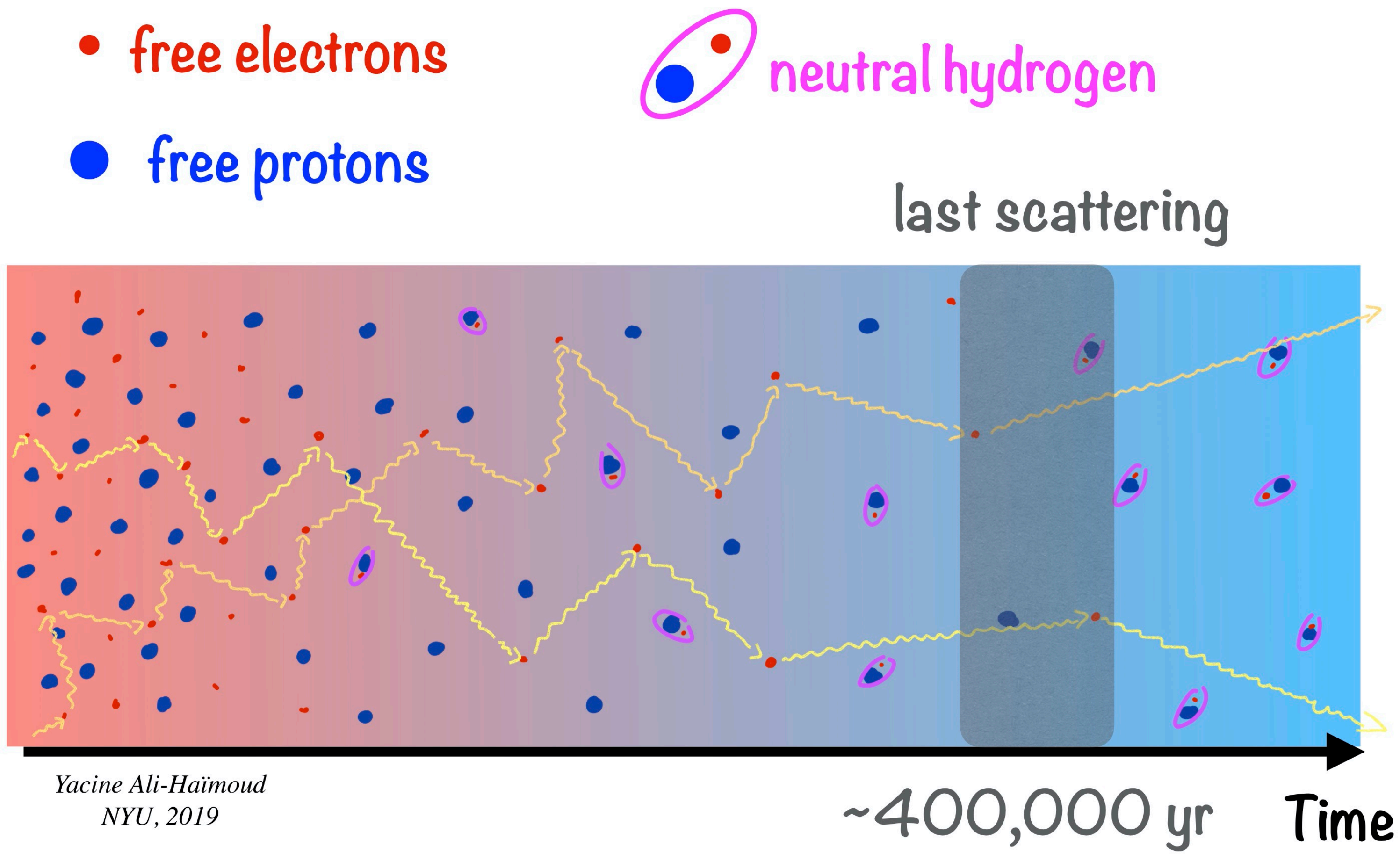
NAOJ



400,000yrs (z=1100)
- temperature = 3,000K
- recombination
  (formation of H atom)
  → less interaction between
  matter & radiation



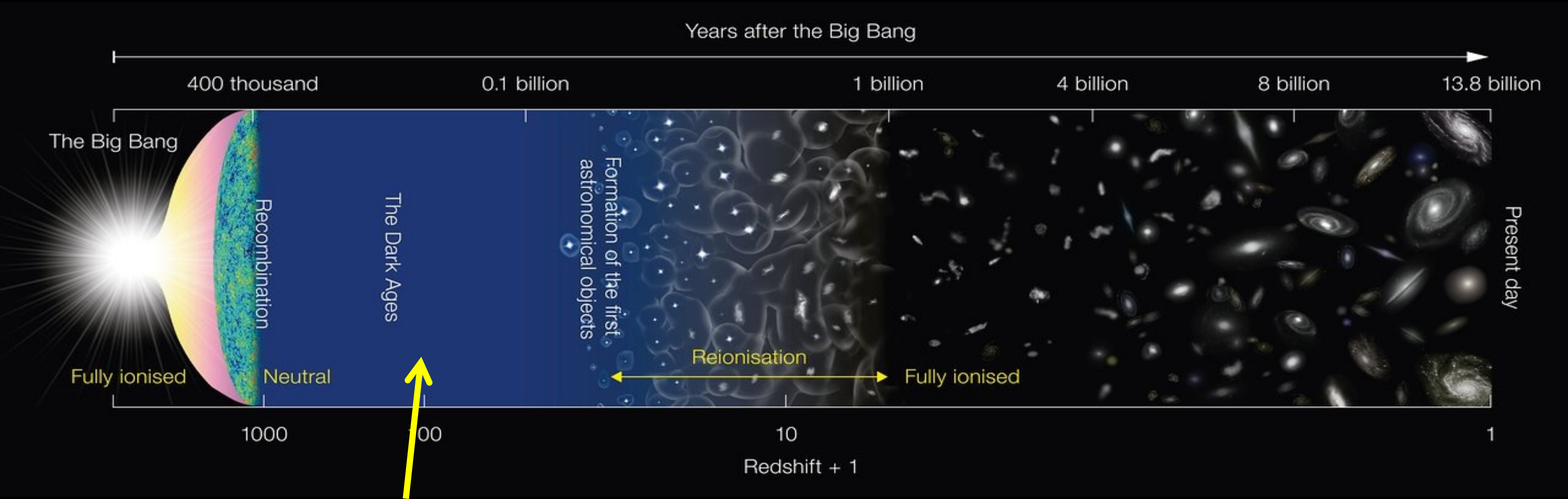
CMB production



- optical depth decreases significantly
- photons move freely after last scattering around z~1100
  → CMB photons

history of the universe

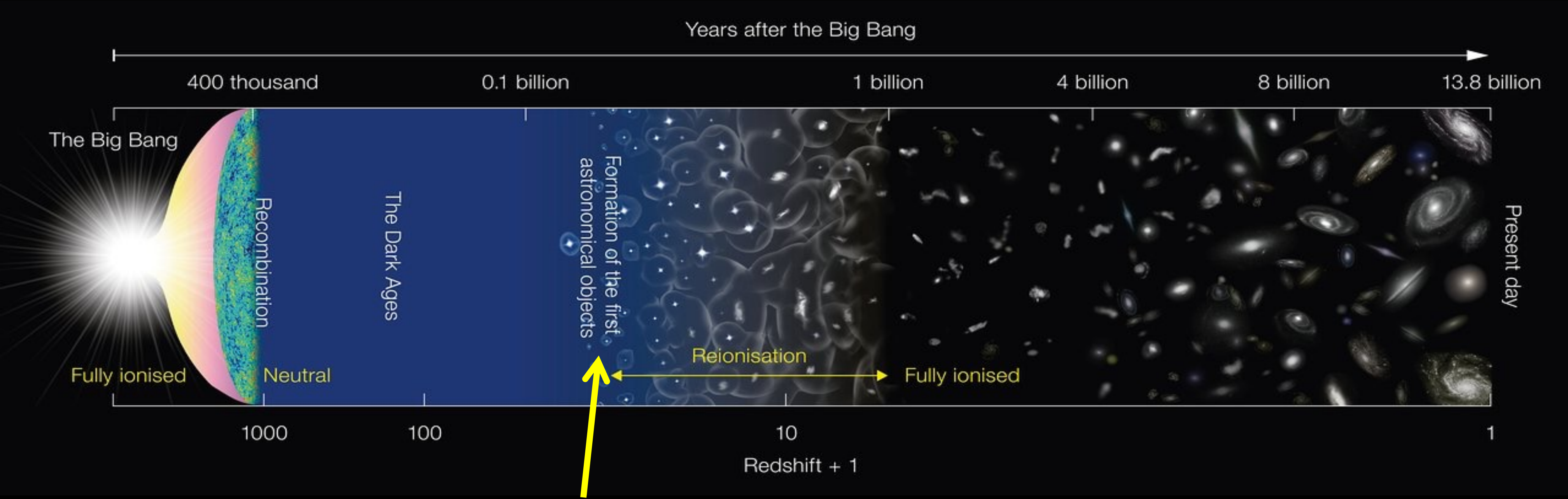
NAOJ



Dark Age
- low temperature
- no astronomical objects yet

history of the universe

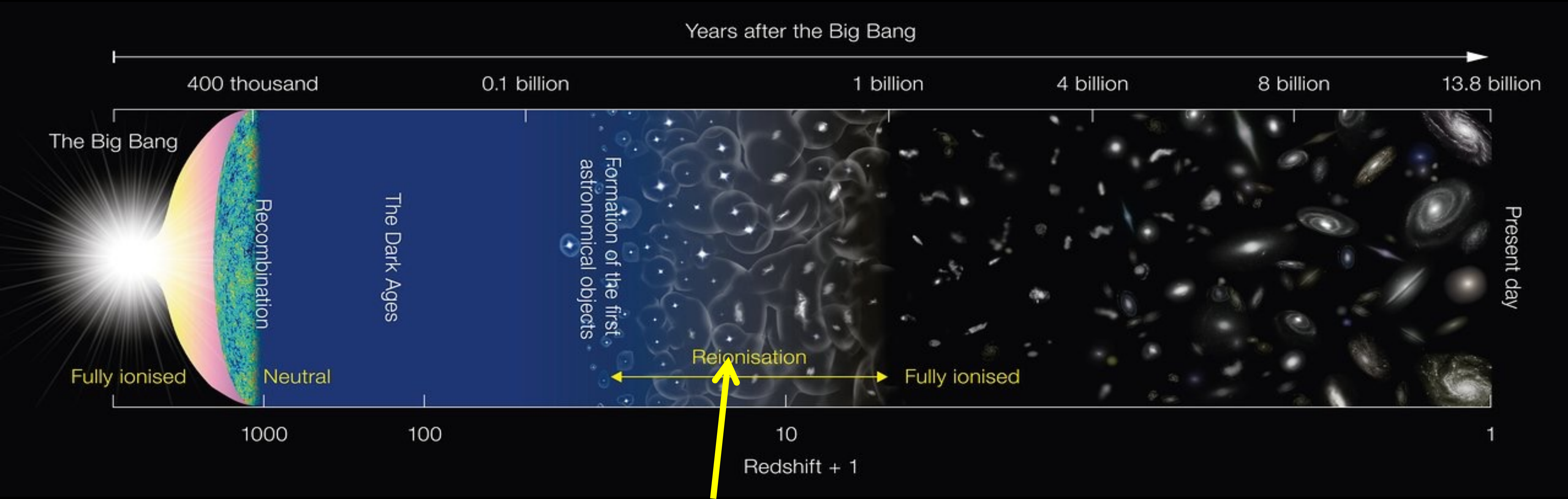
NAOJ



Cosmic Dawn (0.1 Gyr?, z~30?)
- first stars (PopIII)
- first galaxies
- first black holes

history of the universe

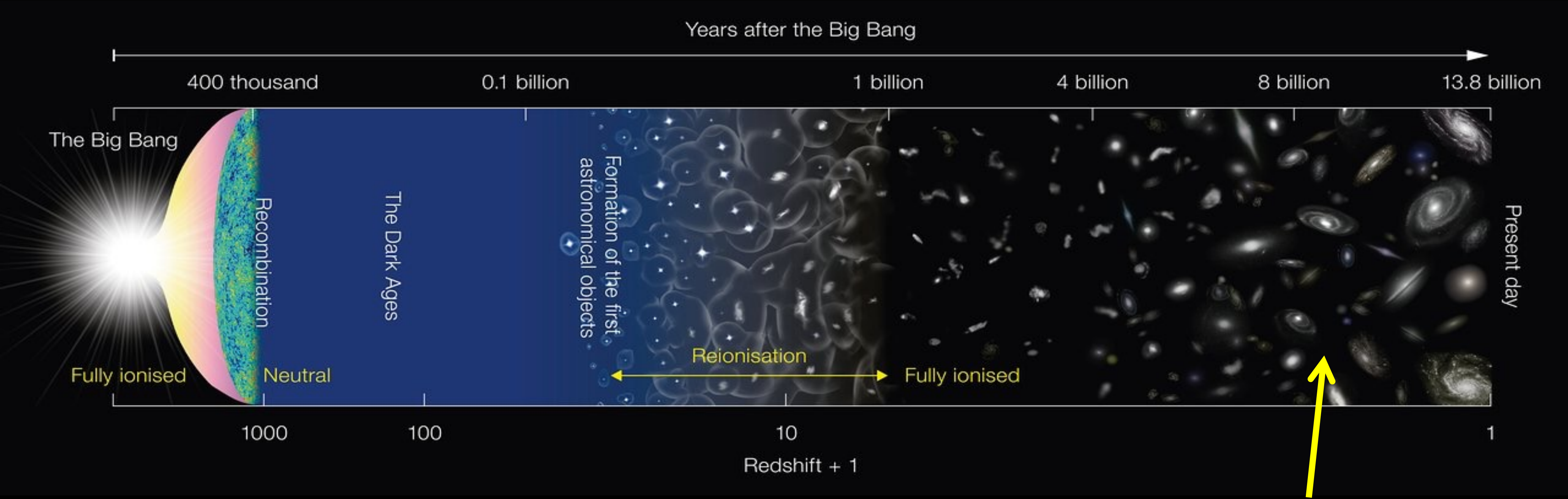
NAOJ



Epoch of Reionization (1 Gyr, z~6)
reionization of intergalactic
hydrogen atoms by UV & X
from stars & BHs

history of the universe

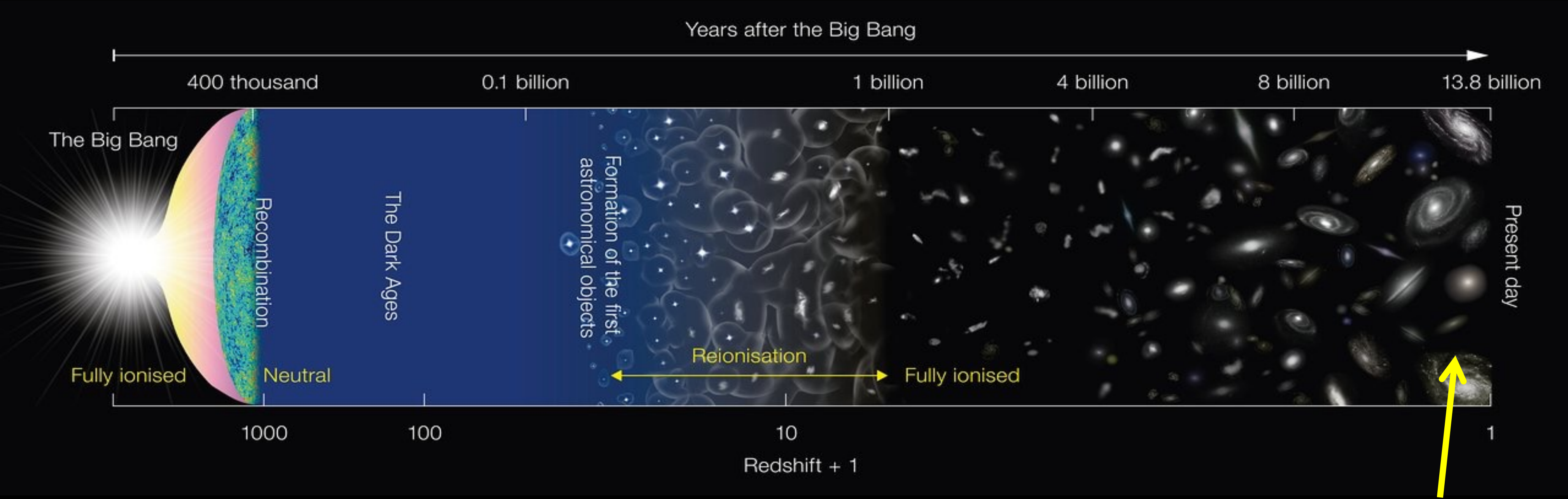
NAOJ



10 Gyr (z~0.5)
- dark energy
- Sun & Earth

history of the universe

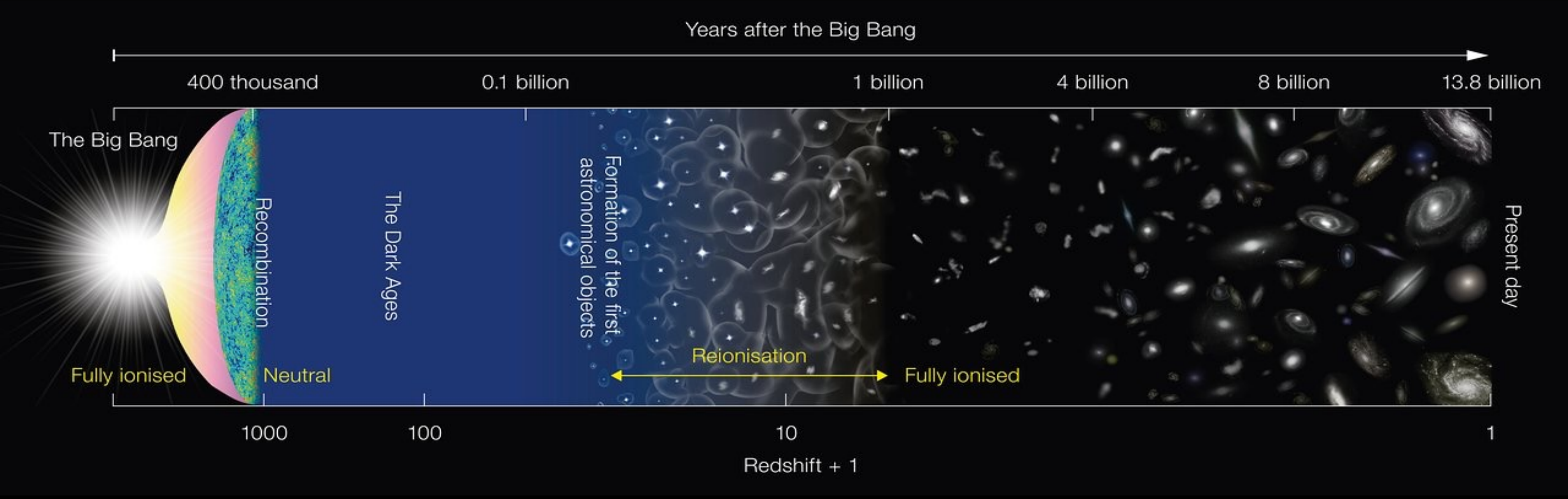
NAOJ



13.8 Gyr
present time

history of the universe

NAOJ

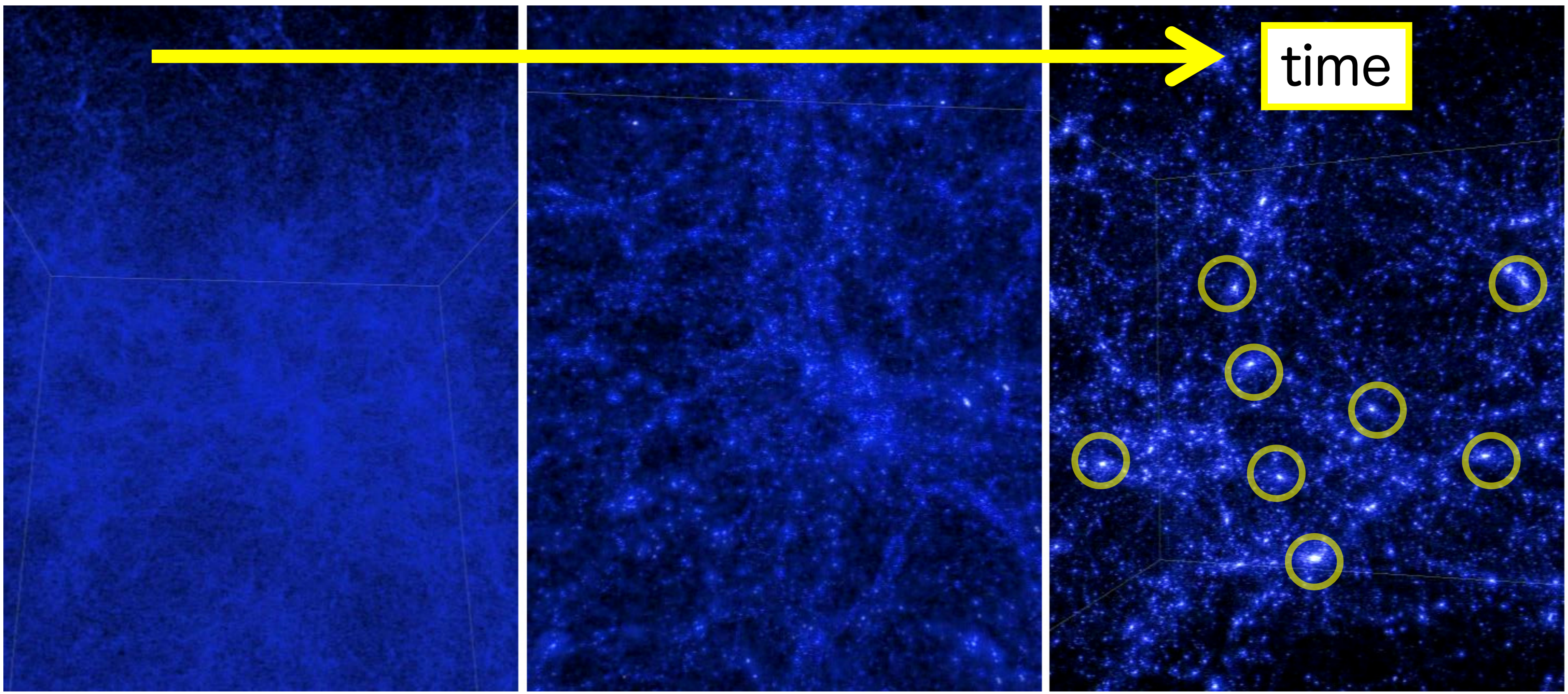


Dark Age (DA, 1100 < z < 30)
Cosmic Dawn (CD, 30 < z < 10)
Epoch of Reionization (EoR 10 < z < 6)

2. Epoch of Reionization

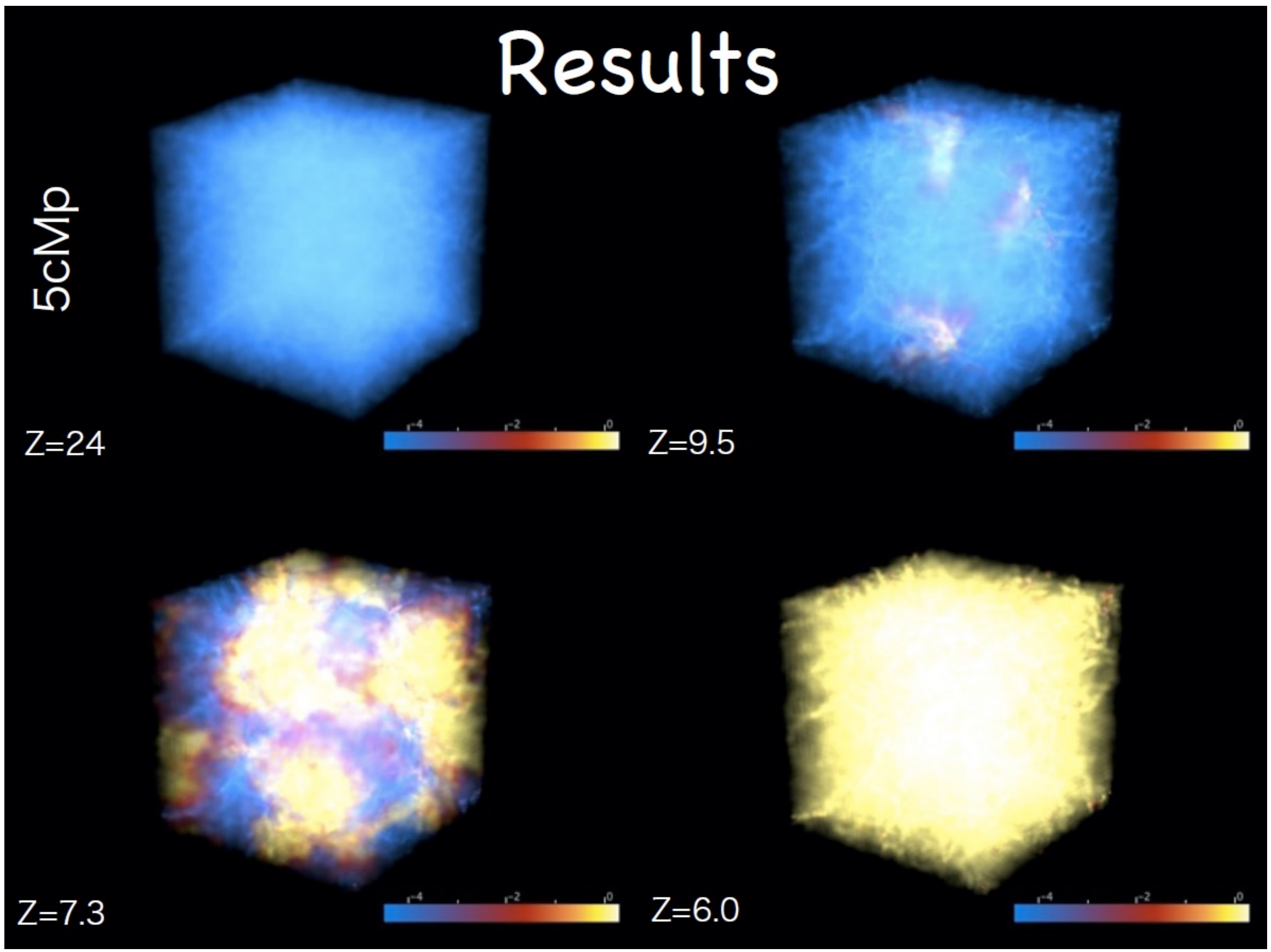
structure formation

- density fluctuations generated during inflation
- structure formation due to gravity
- dense regions become more dense
  $\rightarrow$ galaxy formation

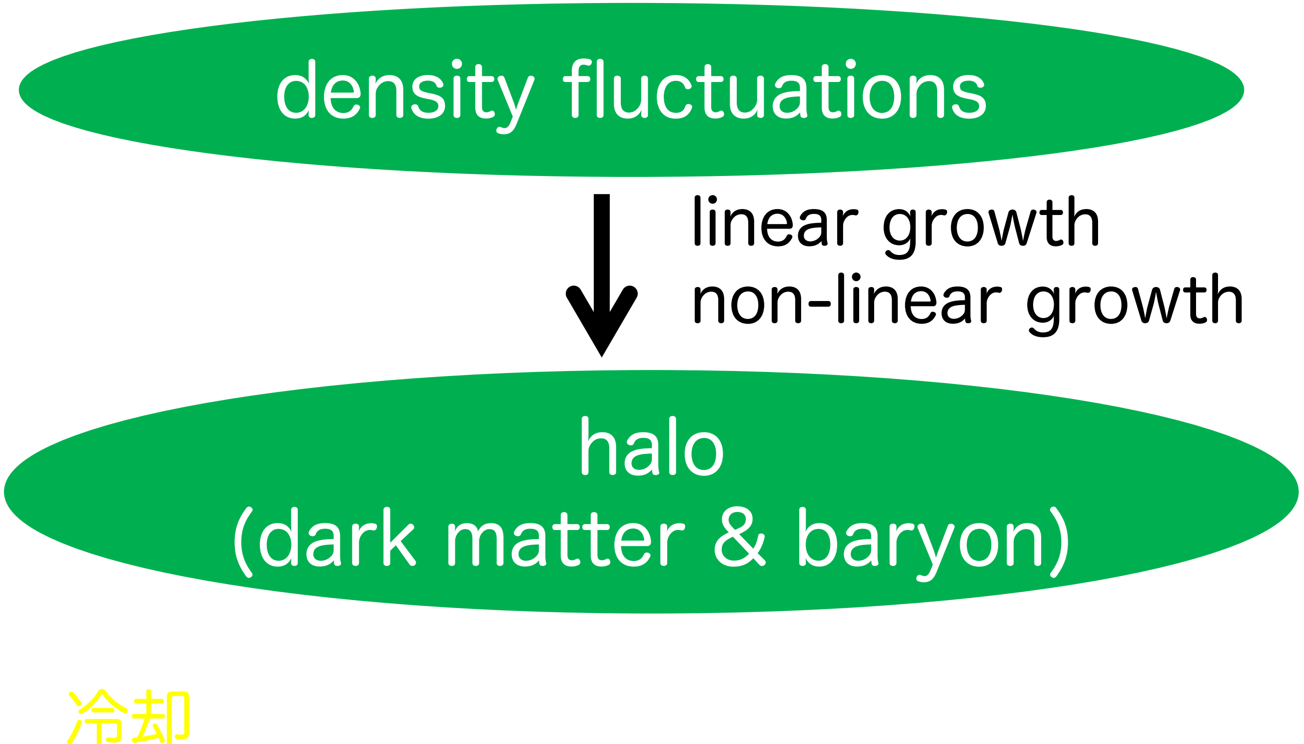


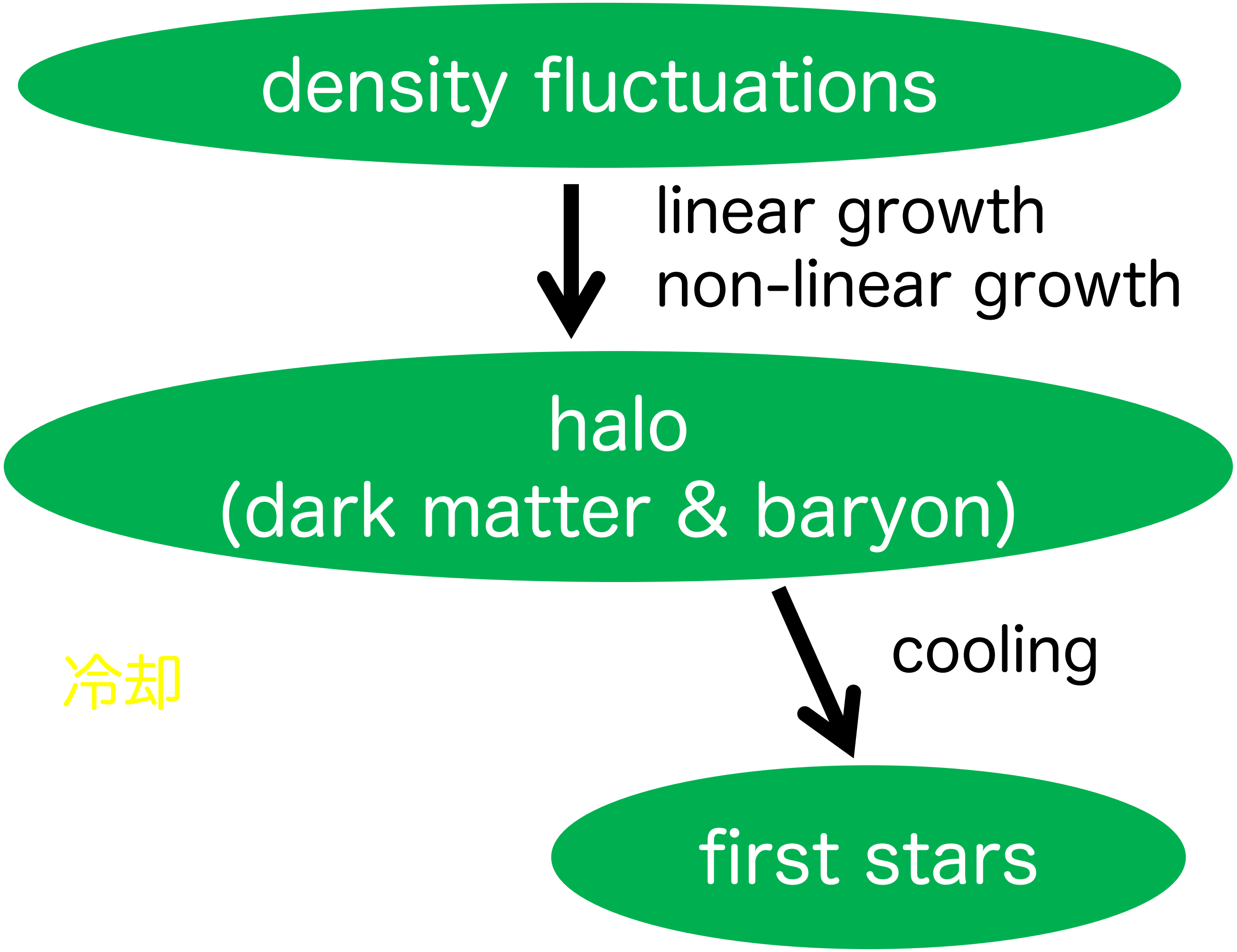
DA - CD - EoR

z~30 first star formation
z~10 start of reionization
z~6   completion of reionization



K. Hasegawa

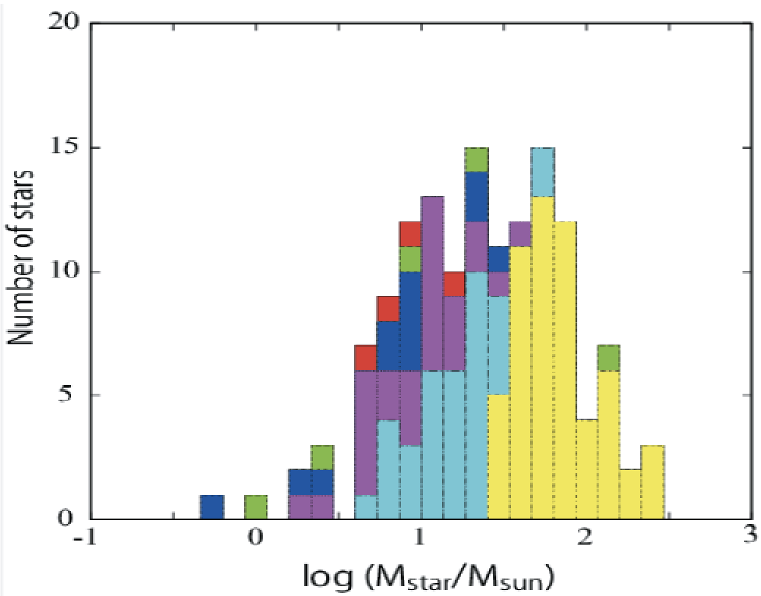

density fluctuations
linear growth
non-linear growth
halo
(dark matter & baryon)
冷却


density fluctuations
linear growth
non-linear growth
halo
(dark matter & baryon)
冷却
cooling
first stars

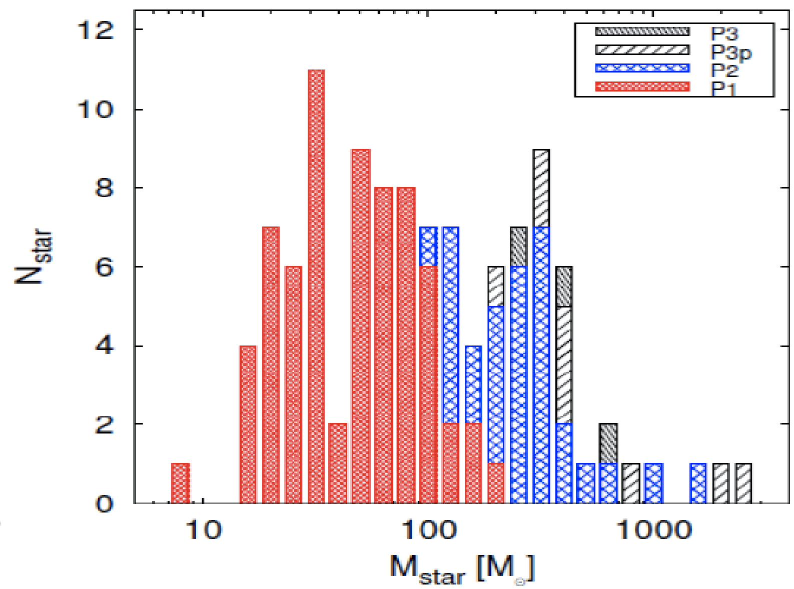
mass of first stars

first stars are very massive?
- less effective cooling without metal
- uncertainty in radiative feedback & fragmentation

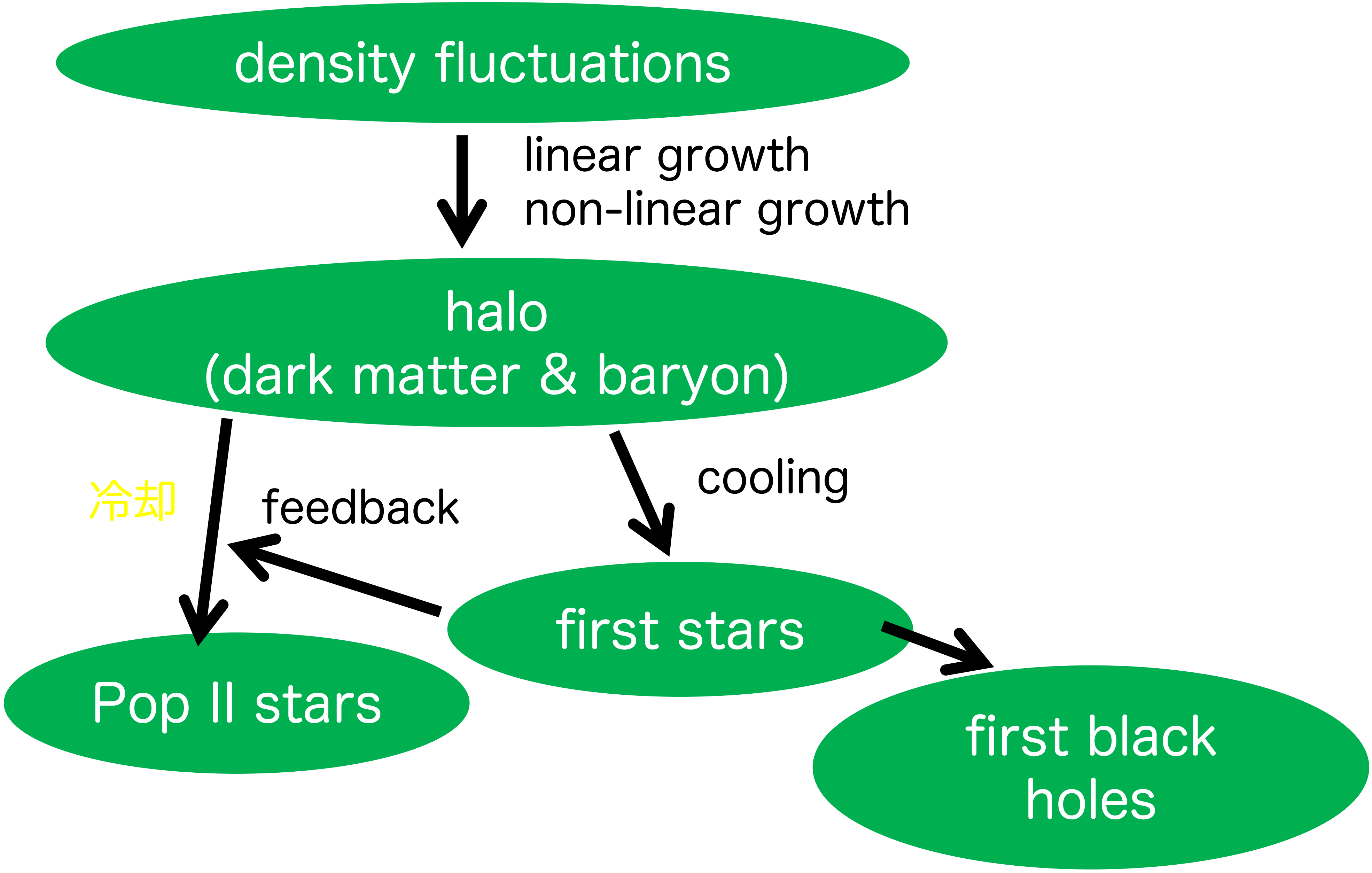
Susa et al. (2014)

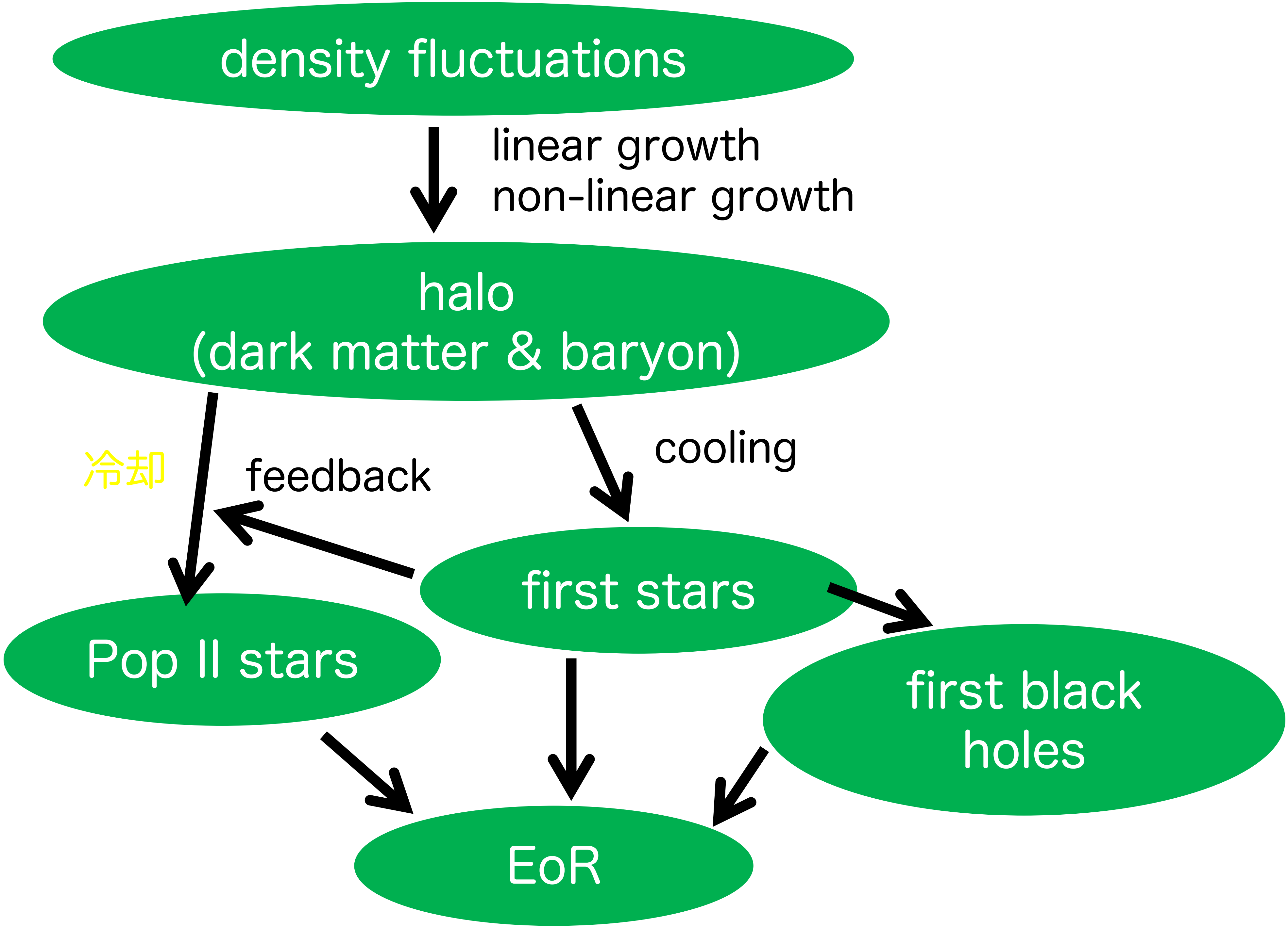


Hirano et al. (2014)



140 – 260 M_{sun} → pair-instability supernova
> 260 M_{sun} → black hole


density fluctuations
linear growth
non-linear growth
halo
(dark matter & baryon)
冷却
feedback
cooling
first stars
Pop II stars
first black
holes



density fluctuations
linear growth
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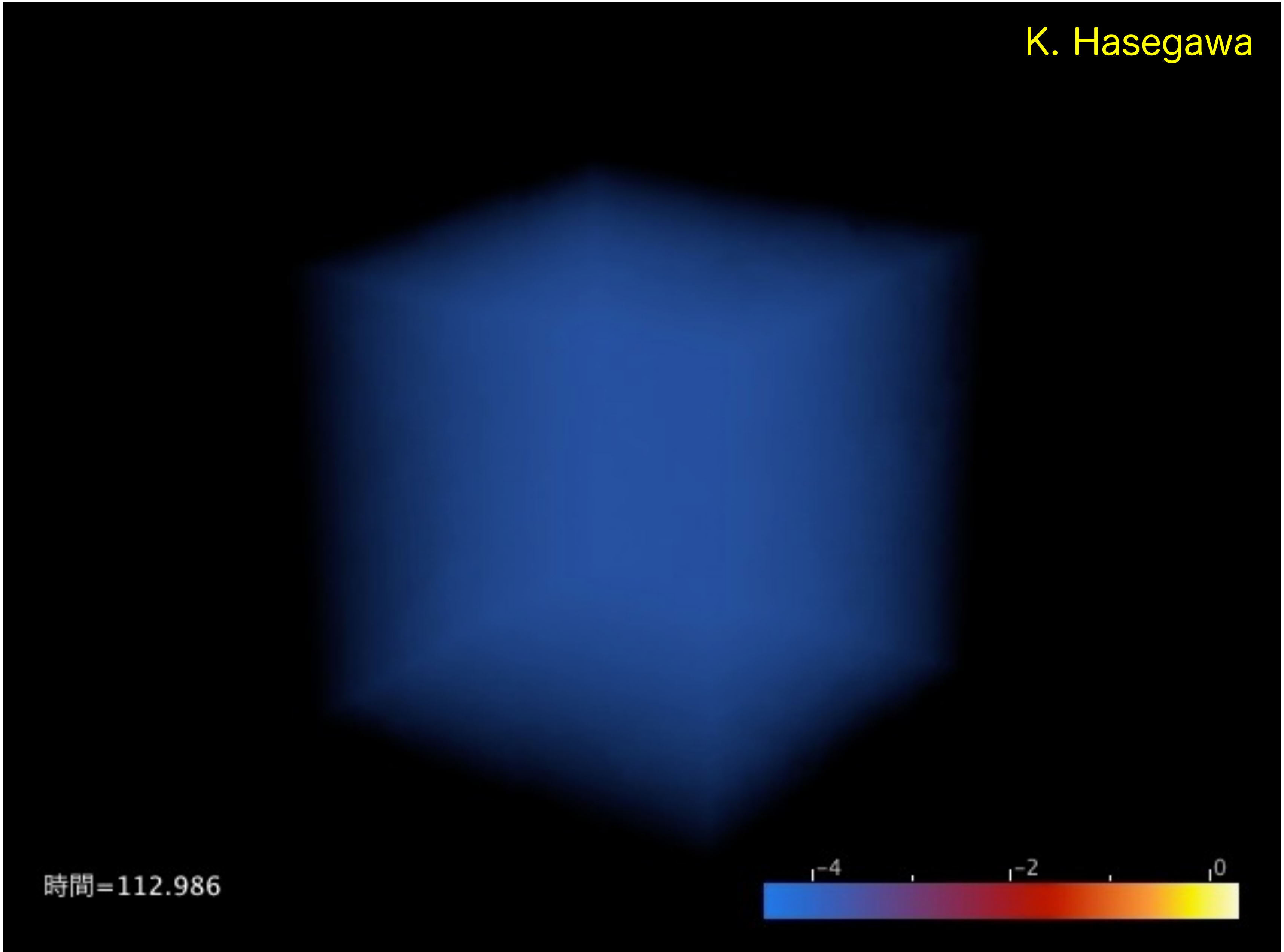
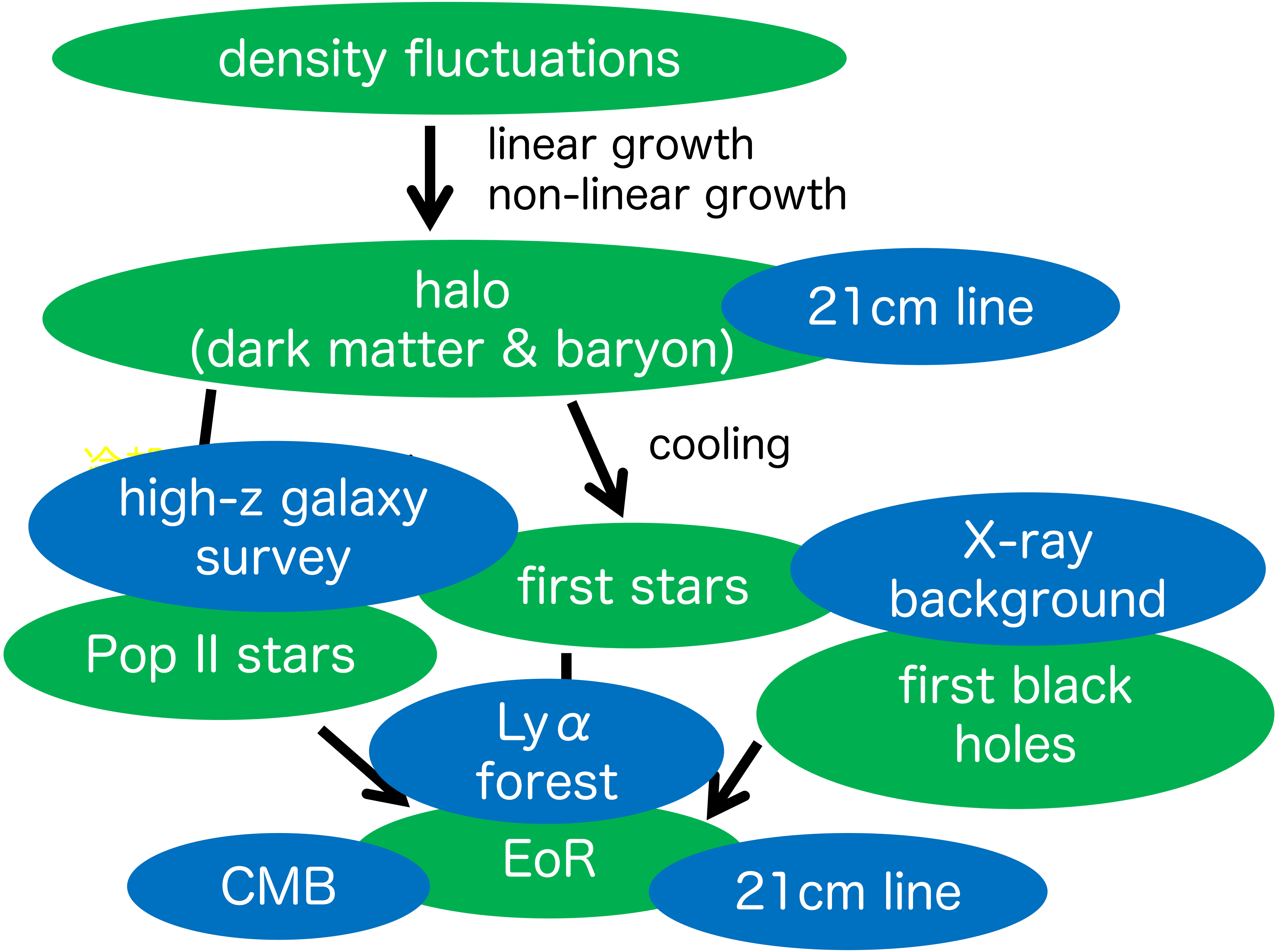
(dark matter & baryon)
冷却
feedback
cooling
first stars
Pop II stars
first black
holes
EoR

DA - CD – EoR: simulation

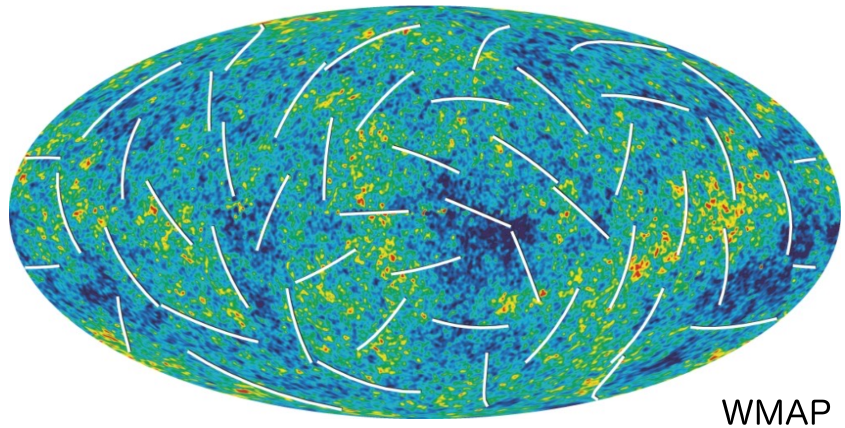



density fluctuations
linear growth
non-linear growth
halo
(dark matter & baryon)
21cm line
cooling
high-z galaxy
survey
first stars
X-ray
background
Pop II stars
first black
holes
Lyα
forest
EoR
CMB
21cm line

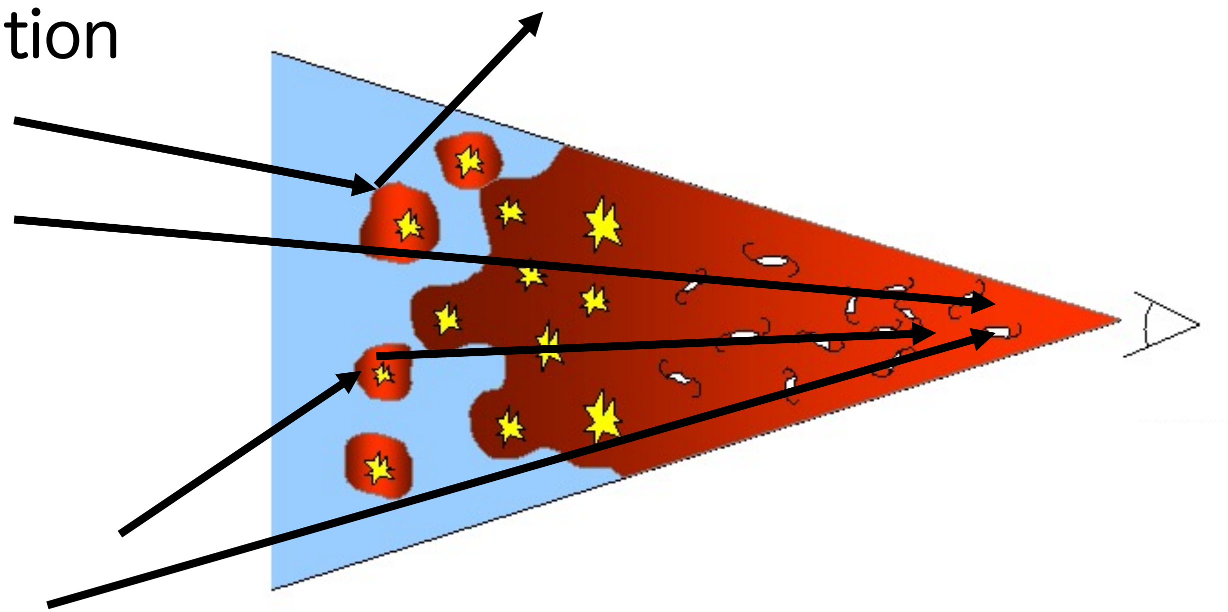
observation of EoR: CMB

CMB is polarized by several %
→ mostly due to EoR

z=1100: generation of CMB
z~10: EoR
- CMB photons are
  scattered by free electrons
- polarization generation

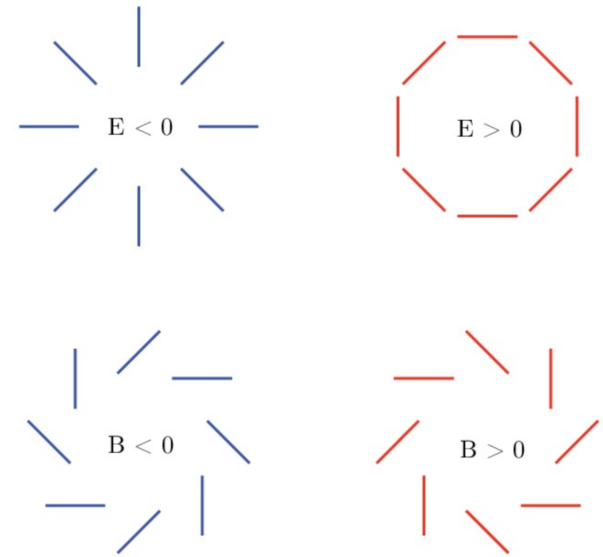


WMAP



observation of EoR: CMB

large-scale E mode polarization is generated by scattering after EoR

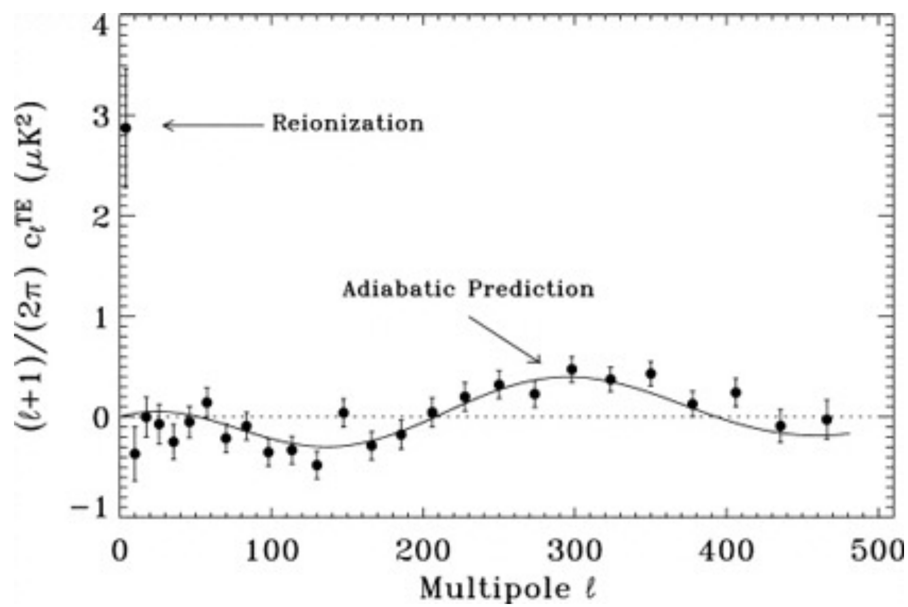


polarization amplitude
→ optical depth

$$\tau = c\sigma_T \int n_e(t)dt$$

τ < 0.1 (WMAP, Planck)

- integral of electron density
- no information on the time evolution
- instantaneous reionization → z ~ 10



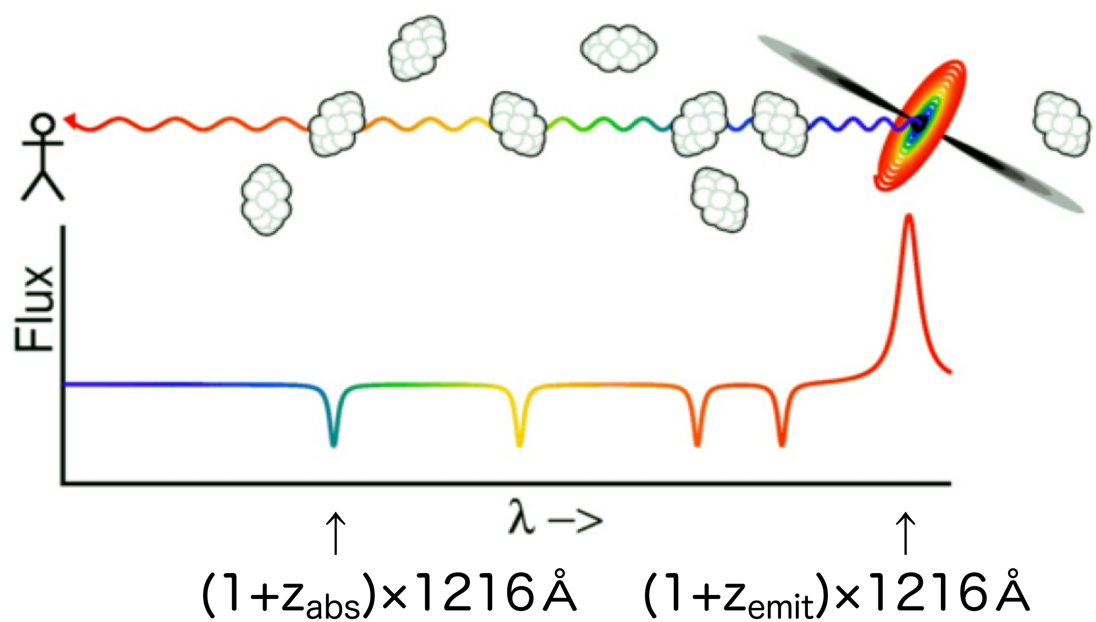
observation of EoR: Ly-α forest

Gunn-Peterson test

- probe IGM ionization rate from HI absorption lines
- large optical depth

$$\tau_{Ly\alpha} \approx 5\times10^5 x_{HI}\left(\frac{1+z}{10}\right)^{3/2}$$

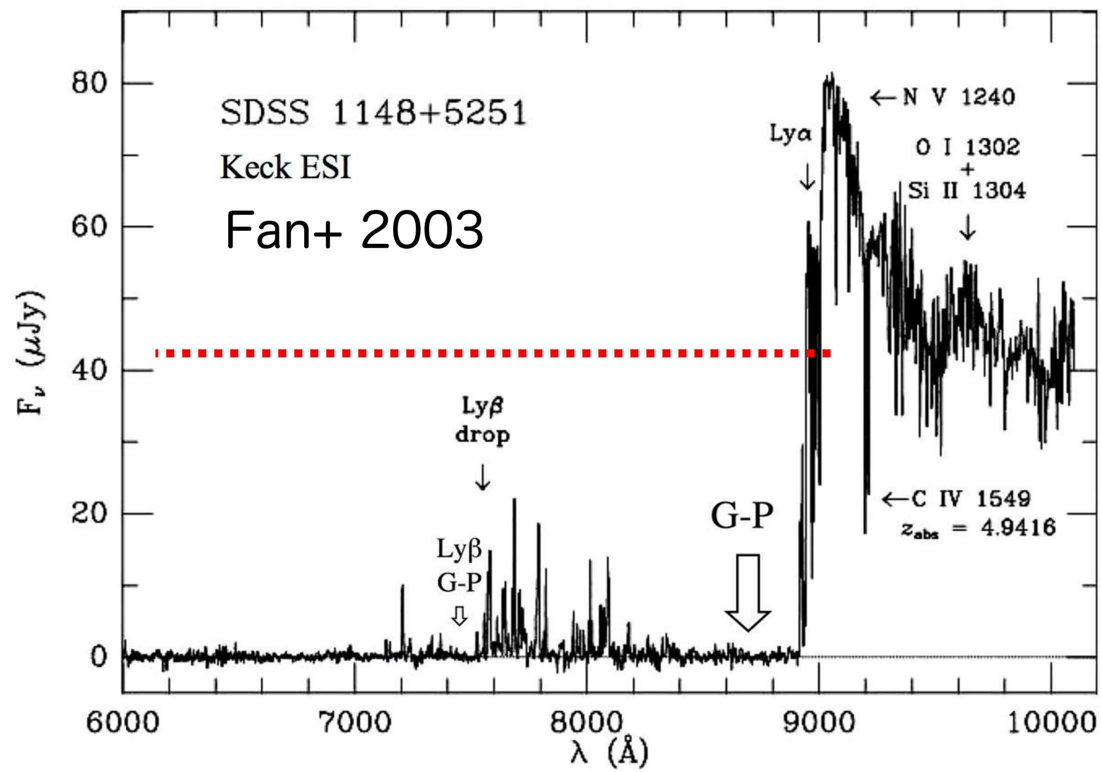
- tiny neutral fraction leads to significant absorption
- presence of radiation implies that the region was almost completely ionized

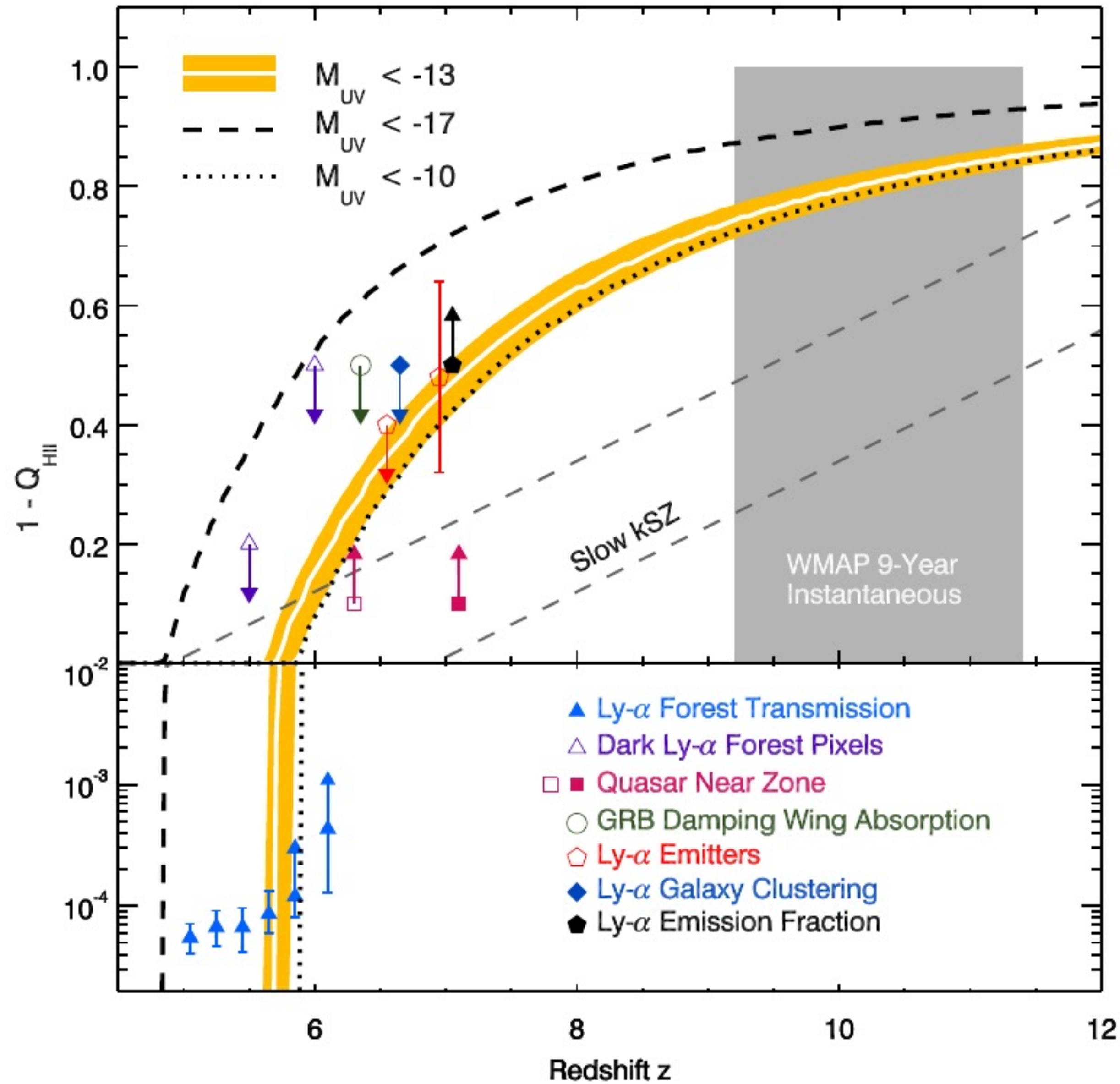


observation of EoR: Ly-α forest

SDSS 1148+5251

- Lyα emission ~ 9000Å → z~7.4
- complete absorption at 8400Å < λ < 9000Å
  → HI existed at z > 5.9
- some radiation
  at λ < 8400Å
  → no HI at z < 5.9
- reionization was
  completed at z ~ 6





M_{UV} < -13
M_{UV} < -17
M_{UV} < -10
1.0
0.8
0.6
0.4
0.2
10^{-2}
10^{-3}
10^{-4}
1 - Q_{HII}
Slow kSZ
WMAP 9-Year
Instantaneous
Ly-α Forest Transmission
Dark Ly-α Forest Pixels
Quasar Near Zone
GRB Damping Wing Absorption
Ly-α Emitters
Ly-α Galaxy Clustering
Ly-α Emission Fraction
6
8
10
12
Redshift z

current status of EoR study

what we know

- reionization proceeded around z=10
- completed z~6
- residual neutral fraction is ~ 10^{-4}

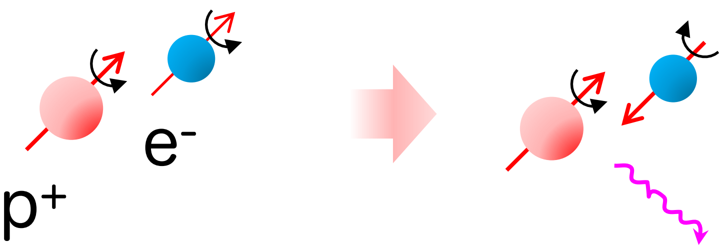
what we don't know

- what kind of objects contributed to reionization?
  PopIII? PopII? AGN?
- time evolution of ionization fraction
- when first stars formed? how massive?
- first black holes?

3. 21cm line

21cm line

hyper-fine structure of H atom



21cm line (1.4GHz)

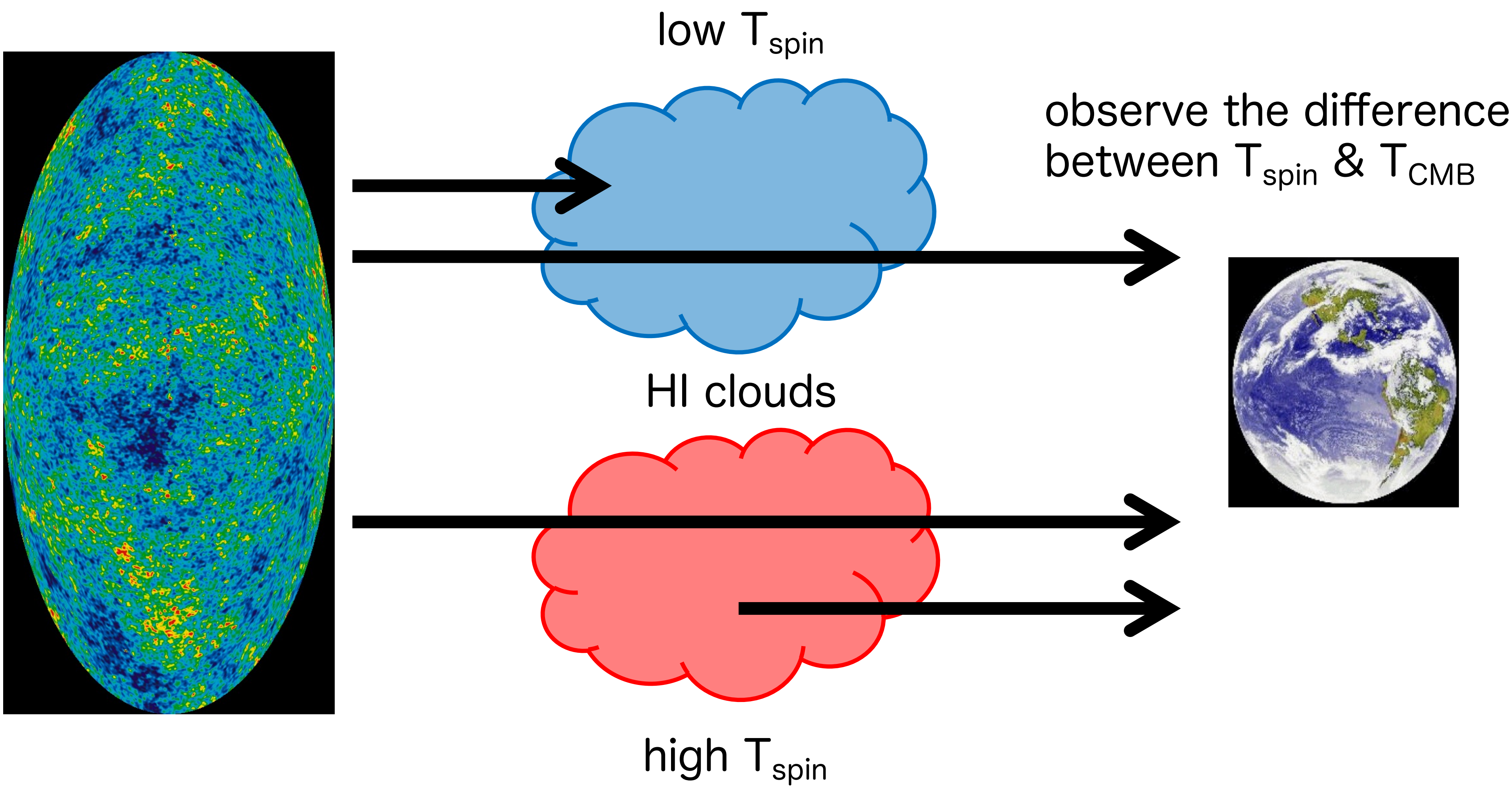
◯neutral hydrogen
✖ionized hydrogen
redshifted 21cm line
$z = 6 \rightarrow 200$MHz
$z = 20 \rightarrow 70$MHz

with ~100MHz radio waves, we can observe CD/EoR tomographically.

spin temperature

$$\frac{n_{\uparrow\uparrow}}{n_{\uparrow\downarrow}} = 3\exp\left[-\frac{h\nu_{21\mathrm{cm}}}{kT_{\mathrm{spin}}}\right]$$

abundance ratio between ground/excited states

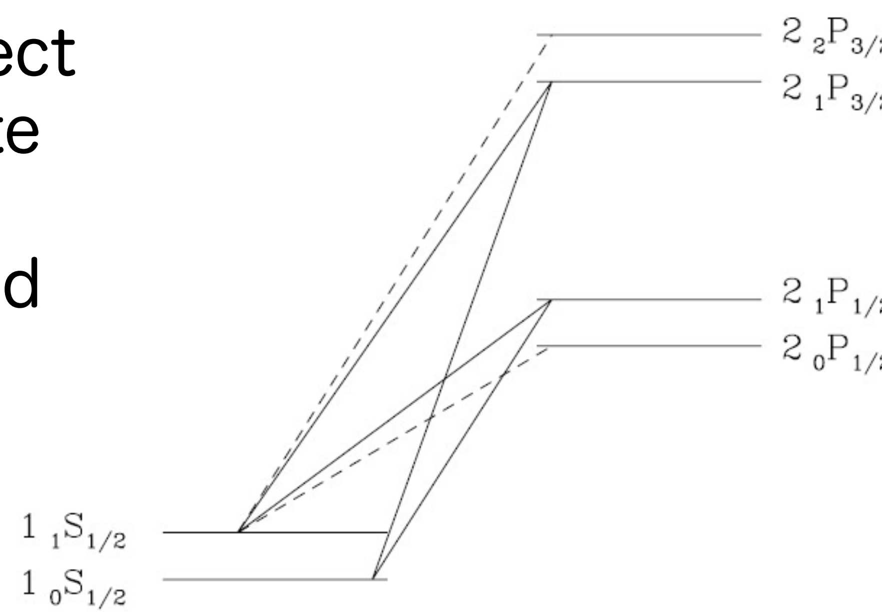


spin temperature

spin temperature is determined by
- interaction with CMB (CMB temperature T_γ)
- atomic collision (kinetic temperature T_K, x_C)
- interaction with ambient Lyα (color temperature T_C, x_α)

$$T_S^{-1} = \frac{T_\gamma^{-1} + x_c T_K^{-1} + x_\alpha T_c^{-1}}{1 + x_c + x_\alpha}$$

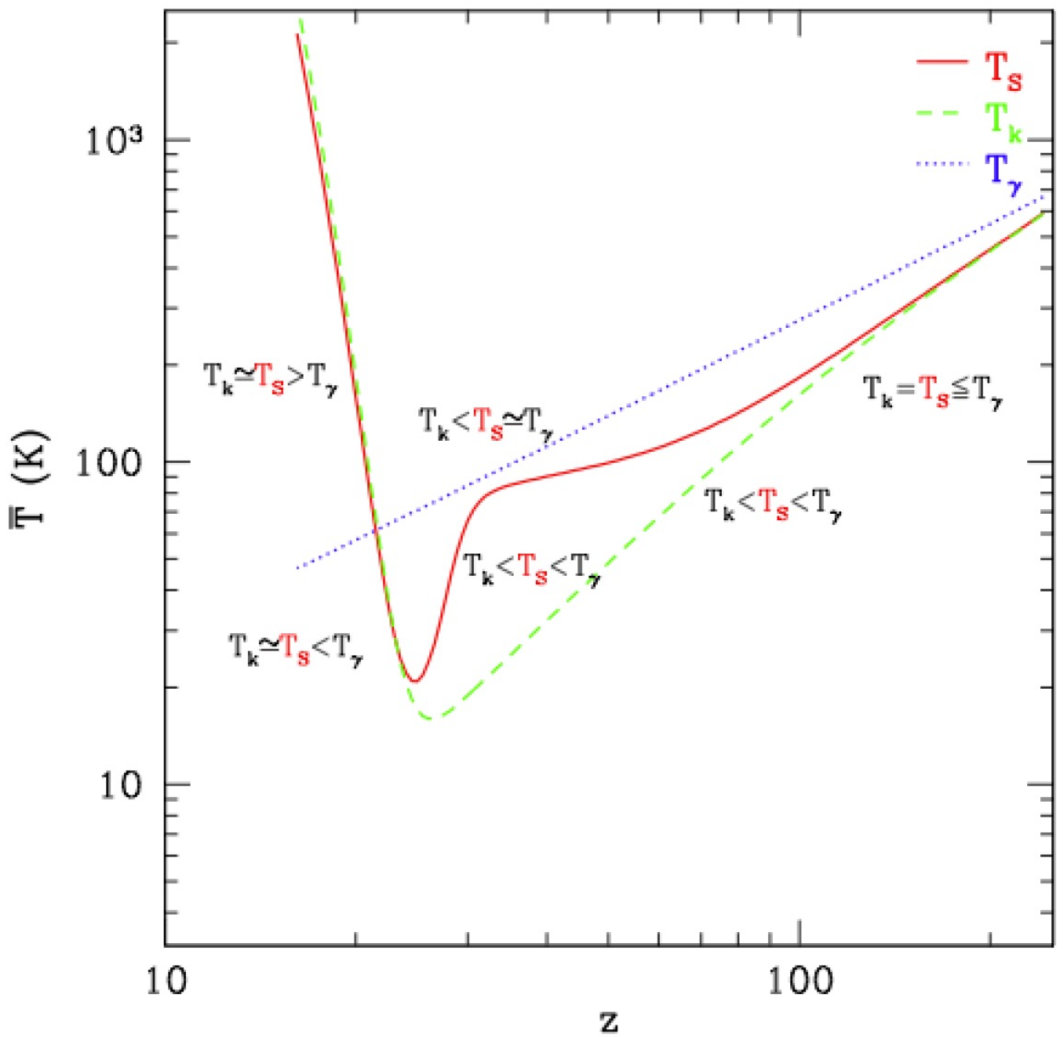
Wouthuysen-Field (WF) effect
- fall to 1S spin-excited state after excitation by Lyα
- the efficiency is determined by the amount of ambient Lyα (T_C)



evolution of spin temperature

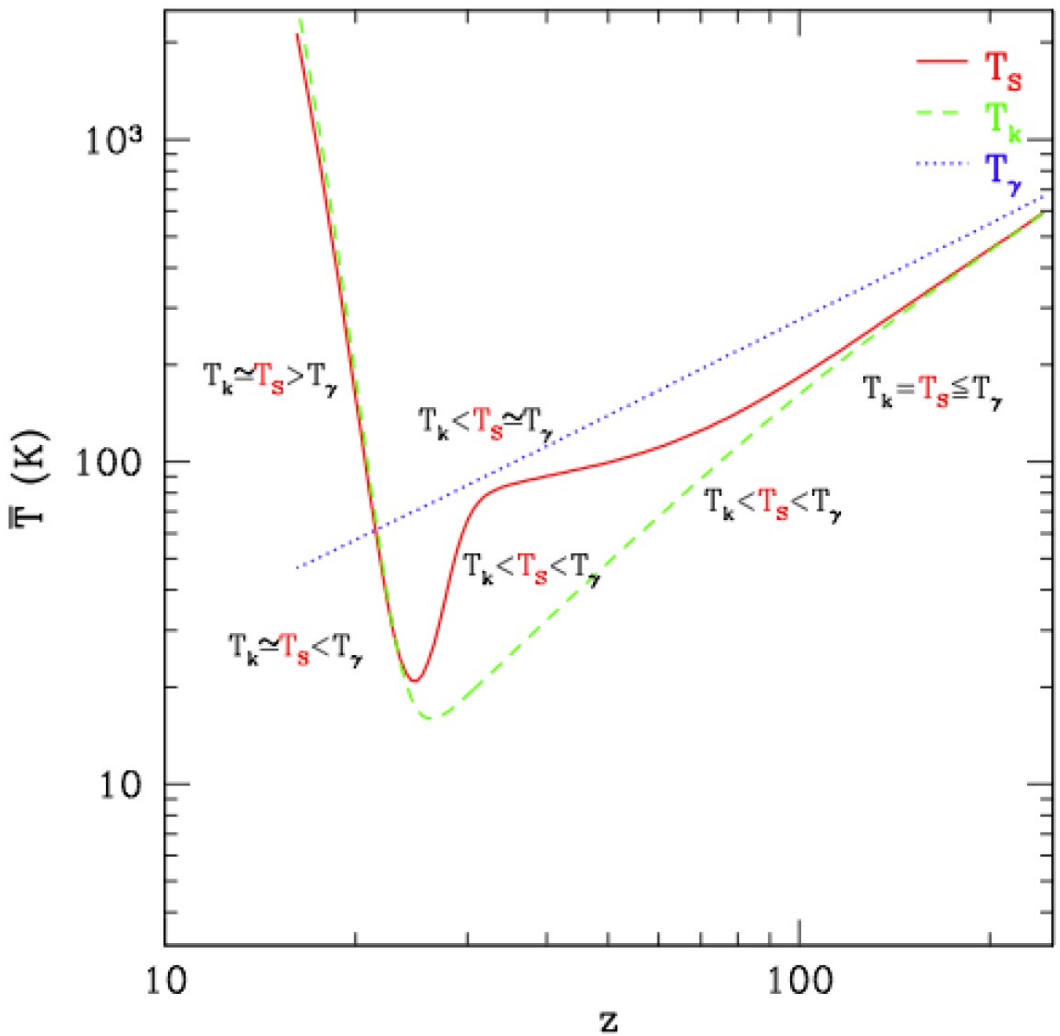
CMB temperature
- cool with expansion as a^{-1}

kinetic temperature
- cool with expansion as a^{-2} (non relativistic fluid)
- heated by X-rays from galaxies from some time (z~25)



evolution of spin temperature

Big Bang: thermal equi.
$z \sim 150$
  CMB & baryons decouple
  frequent atomic collision
$z \sim 70$
  atomic collision less
  frequent due to dilution
$z \sim 30$
  WF effect is turned on
  by Lyα from first stars
$z \sim 25$
  gas heating and T_{spin}
  exceeds T_{CMB}



evolution of spin temperature

Big Bang: thermal equi.

z ∼ 150

CMB & baryons decouple

frequent atomic collision

z ∼ 70

atomic collision less

frequent due to dilution

z ∼ 30

WF effect is turned on

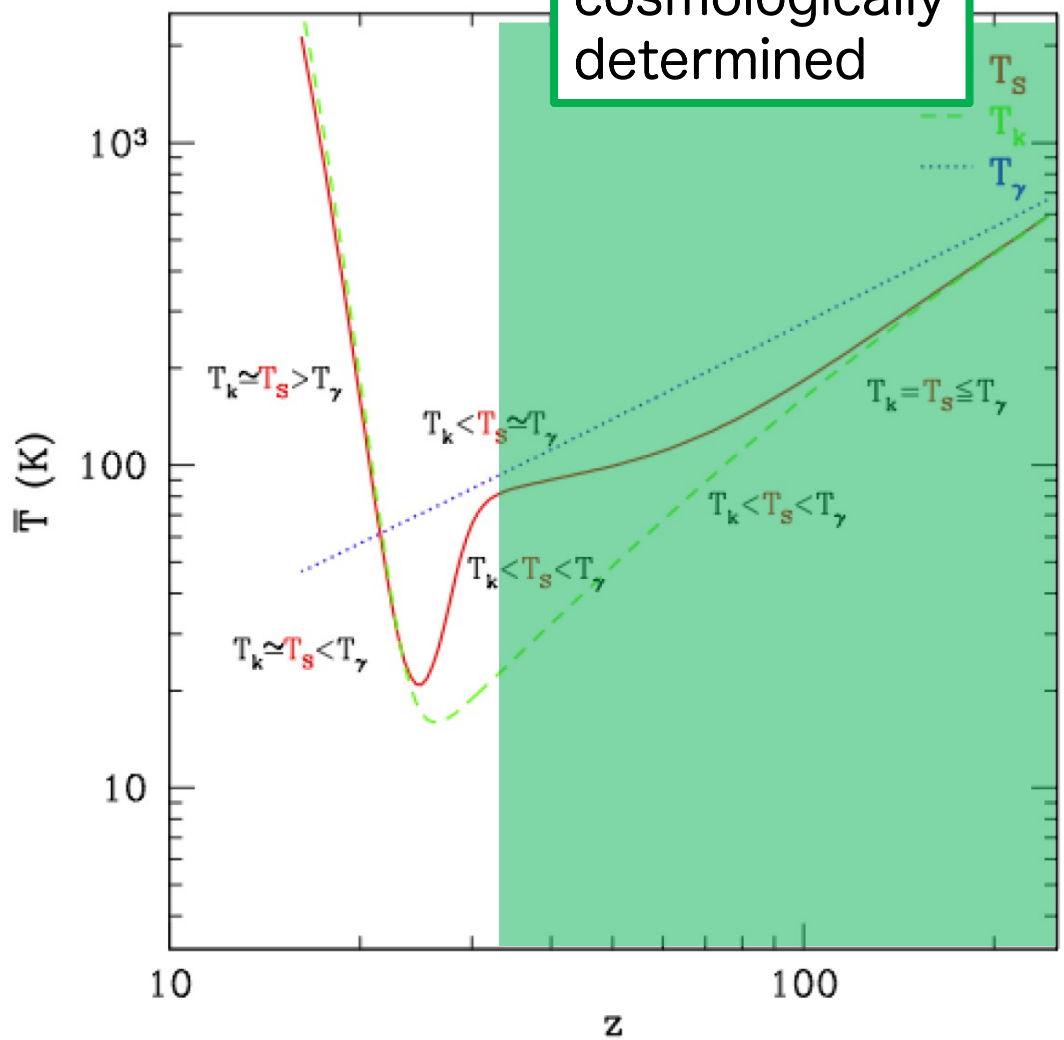
by Lyα from first stars

z ∼ 25

gas heating and T_{spin}

exceeds T_{CMB}

cosmologically determined



evolution of spin temperature

Big Bang: thermal equi.

z ∼ 150

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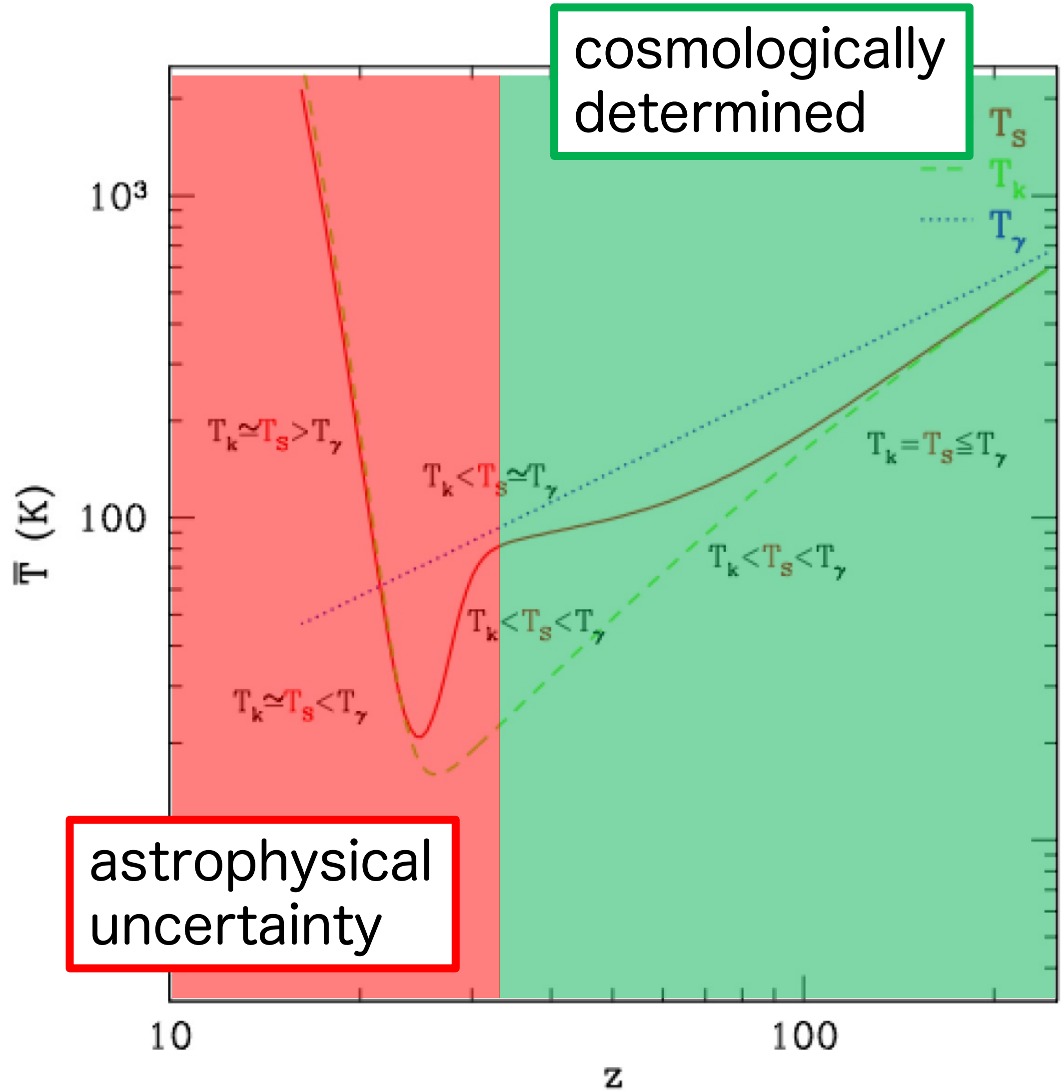
exceeds T_{CMB}

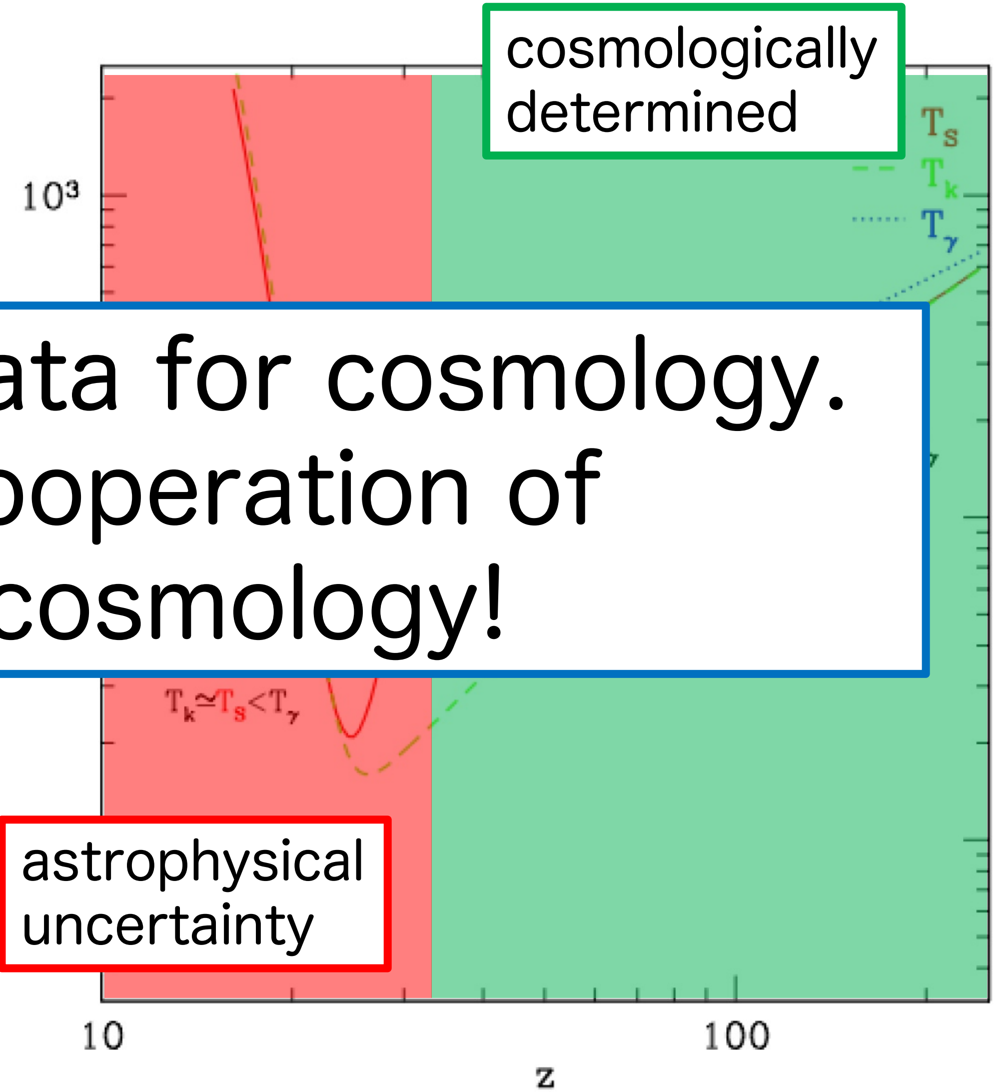


evolution of spin temperature

Big Bang: thermal equi.
$z \sim 150$
CMB & baryons decouple
frequent atomic collision

z
a
f

z
WF effect is turned on
by Lyα from first stars
$z \sim 25$
gas heating and T_{spin} exceeds T_{CMB}

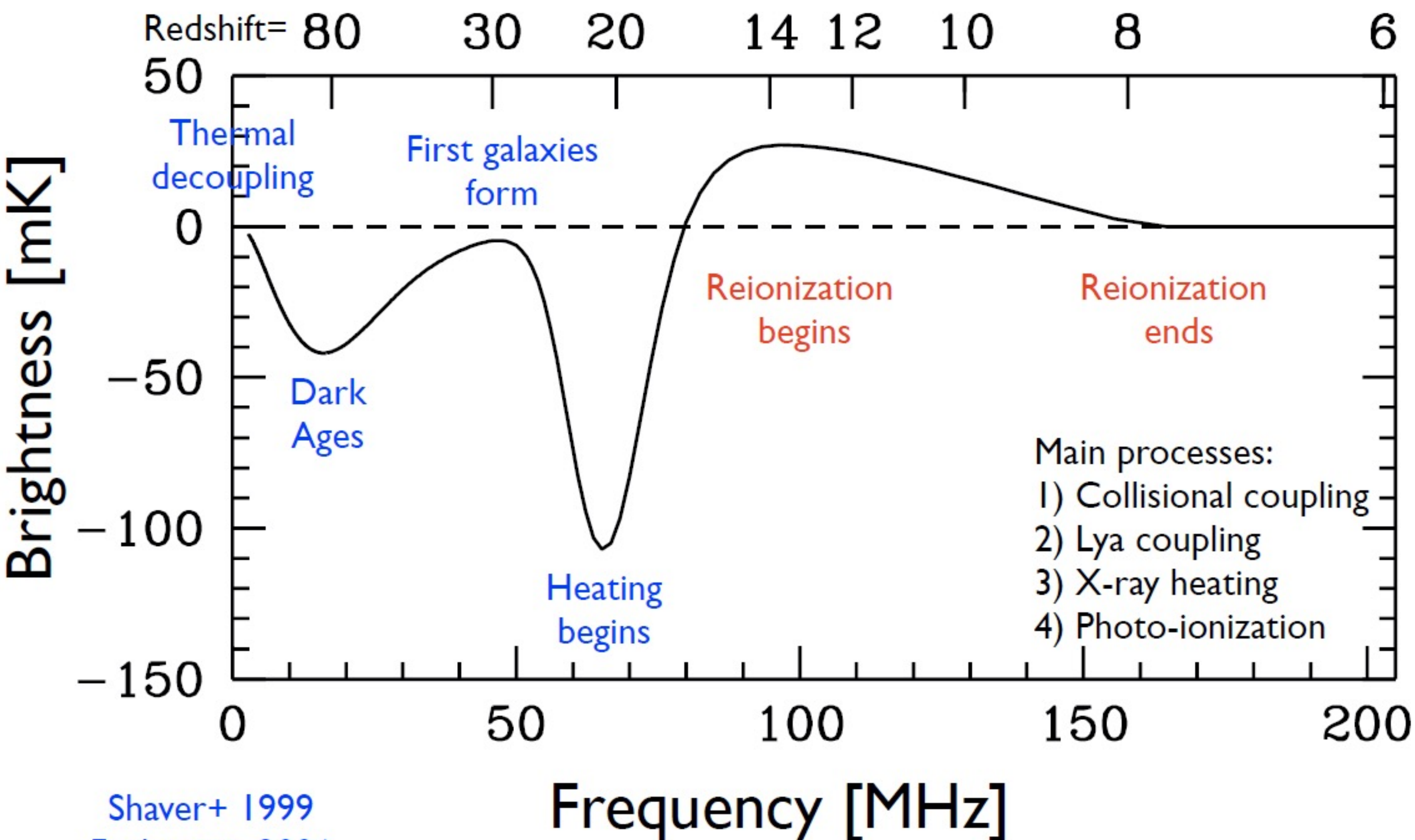


DA offers clean data for cosmology.
CD & EoR need cooperation of astrophysics and cosmology!

brightness temperature

difference between T_{spin} and T_{CMB}
+: emission, -: absorption

$$\delta T_b(\nu) = \frac{T_S - T_\gamma}{1+z}(1 - e^{-\tau_{\nu_0}})$$



Shaver+ 1999
Furlanetto 2006
Pritchard & Loeb 2010

brightness temperature

difference between T_{spin} and T_{CMB}

+: emission, -: absorption

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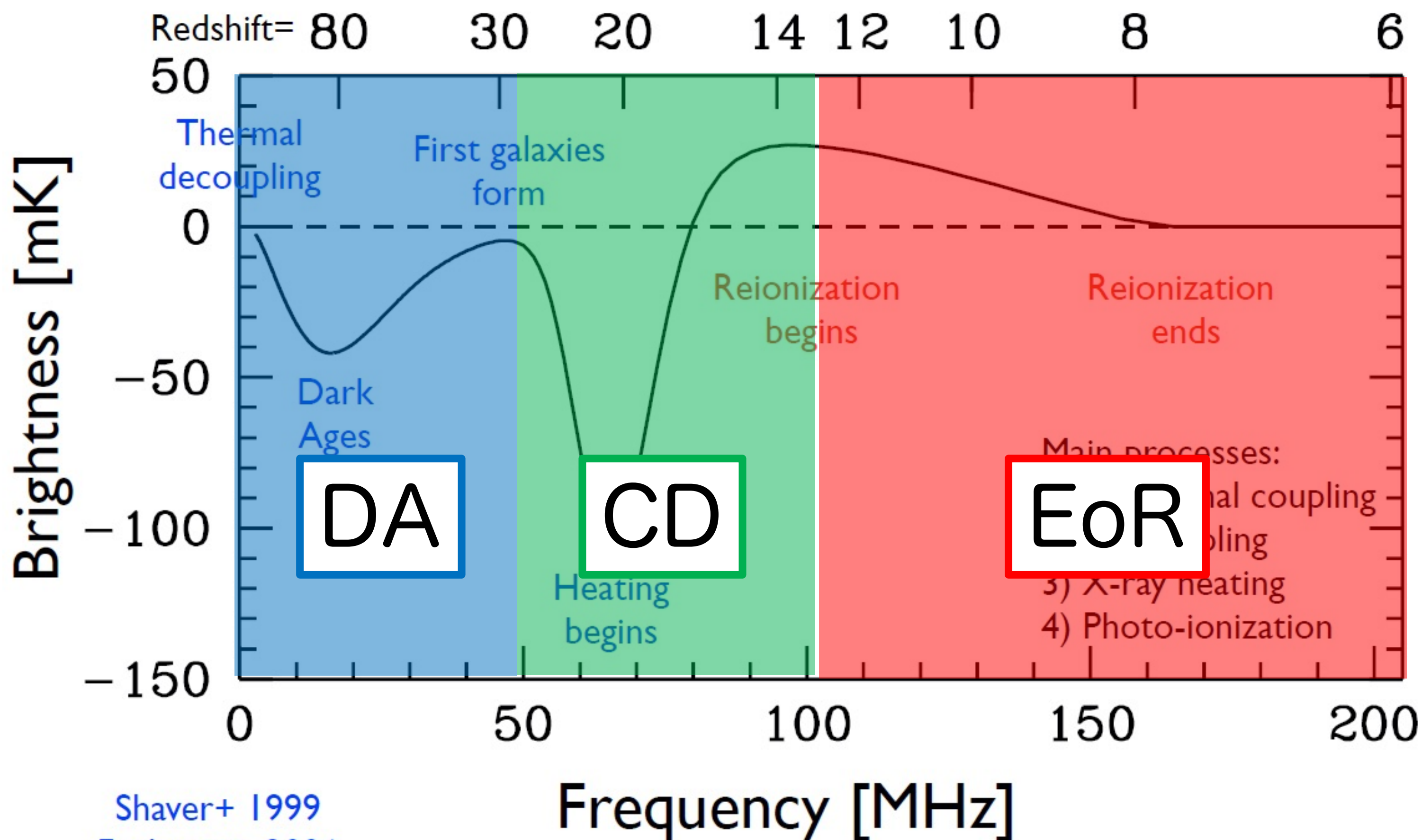
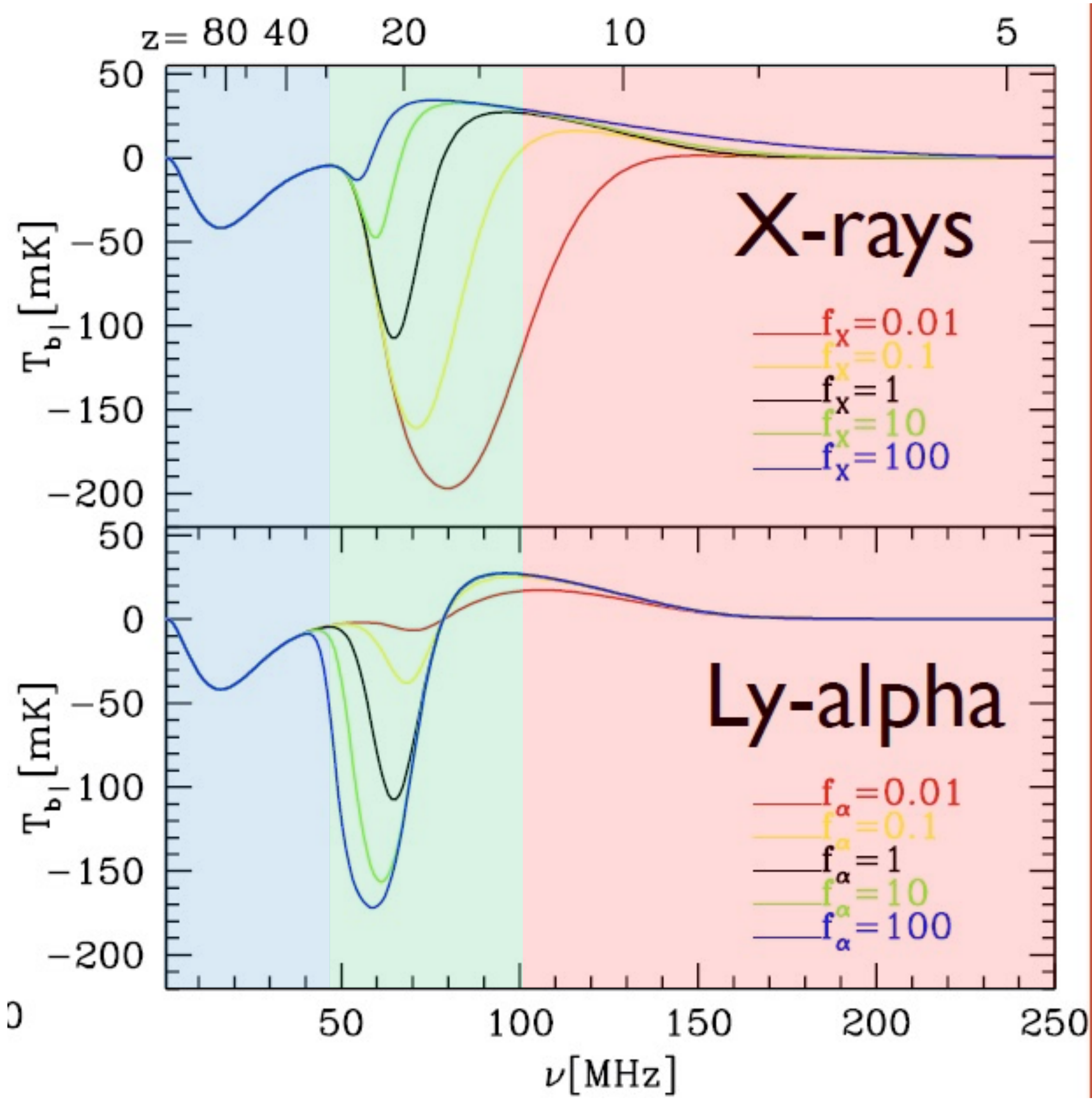


Shaver+ 1999
Furlanetto 2006
Pritchard & Loeb 2010

dependence

X-ray intensity
- heat IGM gas
- sources
  QSO, X-ray binary
  supernova
- depends on IMF, binary fraction, etc.

Lyα
- couples T_K and T_{spin}
- depends on IMF, star formation rate, etc.



Pritchard & Loeb 2010

21cm-line fluctuations

$$\delta T_b = 27[\mathrm{mK}]\, x_{\mathrm{HI}}(1+\delta_b)\left(\frac{T_S - T_\gamma}{T_S}\right)\left(\frac{1+z}{10}\right)^{1/2}\left[\frac{\partial_r v_r}{(1+z)H(z)}\right]^{-1}$$

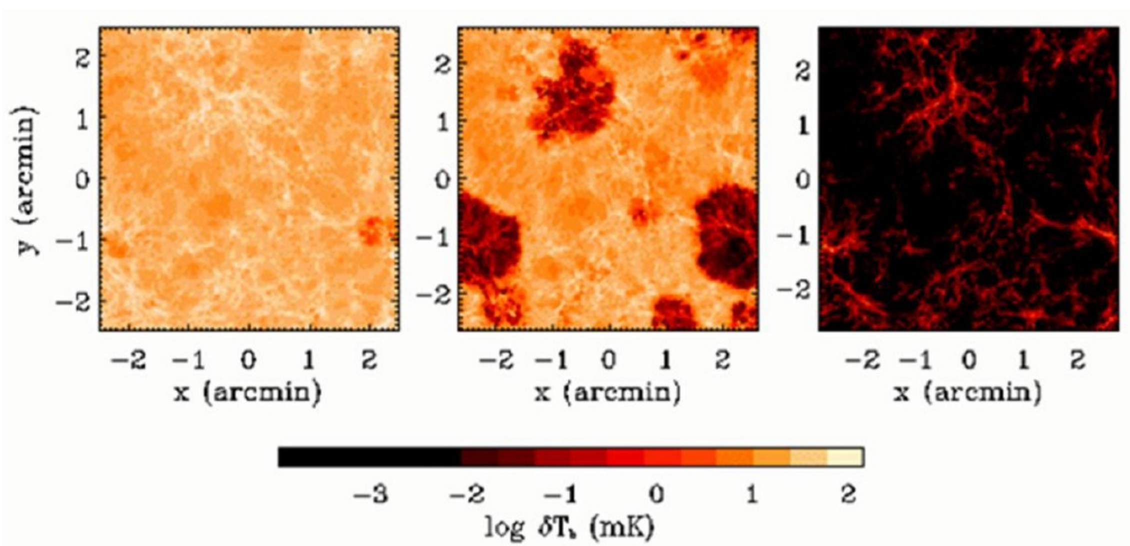
ionization fraction

baryon overdensity

spin temperature

peculiar velocity

simulated brightness temperature maps

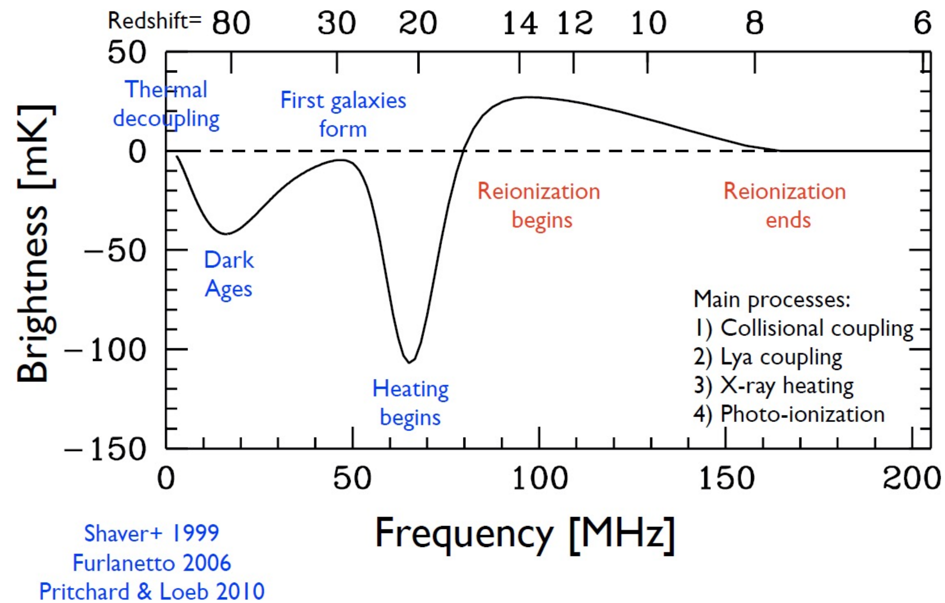


time evolution of HI distribution
- ionizing bubbles
  → sources inside!
- statistics

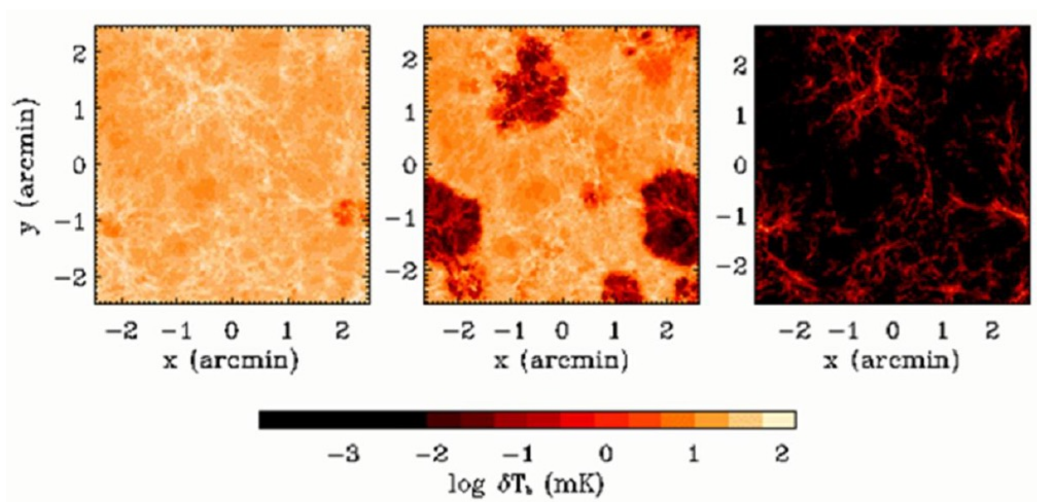
21cm-line observations

2 ways to observe

1. global signal
- average brightness temperature
- evolution of spin temperature



2. fluctuations
- fluctuations in ionization fraction, baryon density & spin temperature
- statistics
- ionization bubbles



21cm line for DA-CD-EoR study

new probe of DA/CD/EoR
- hydrogen hyperfine structure
- directly probe IGM
- spin temperature
- brightness temperature: presence of CMB
- global signal & fluctuations
- CD/EoR are mixture of cosmology & astrophysics

4. observation of 21cm line

observation of EoR 21cm line

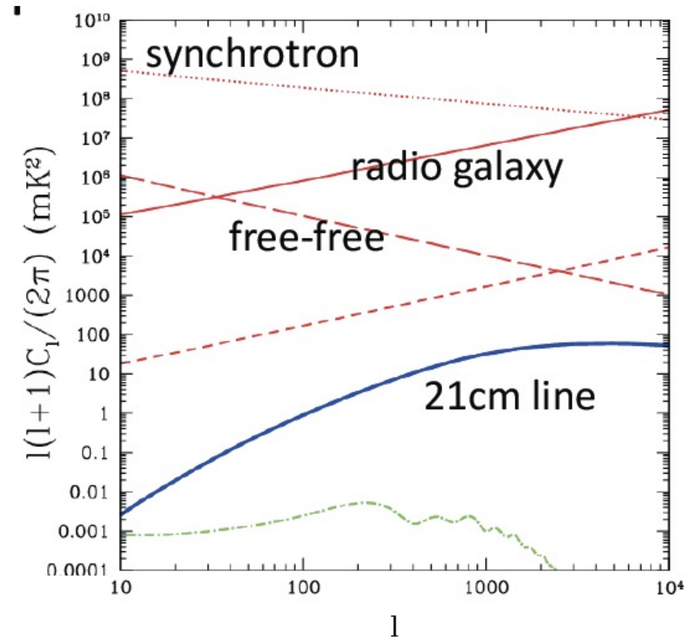
low frequency telescopes
- MWA (Australia)
- LOFAR (Europe)
- HERA (South Africa)

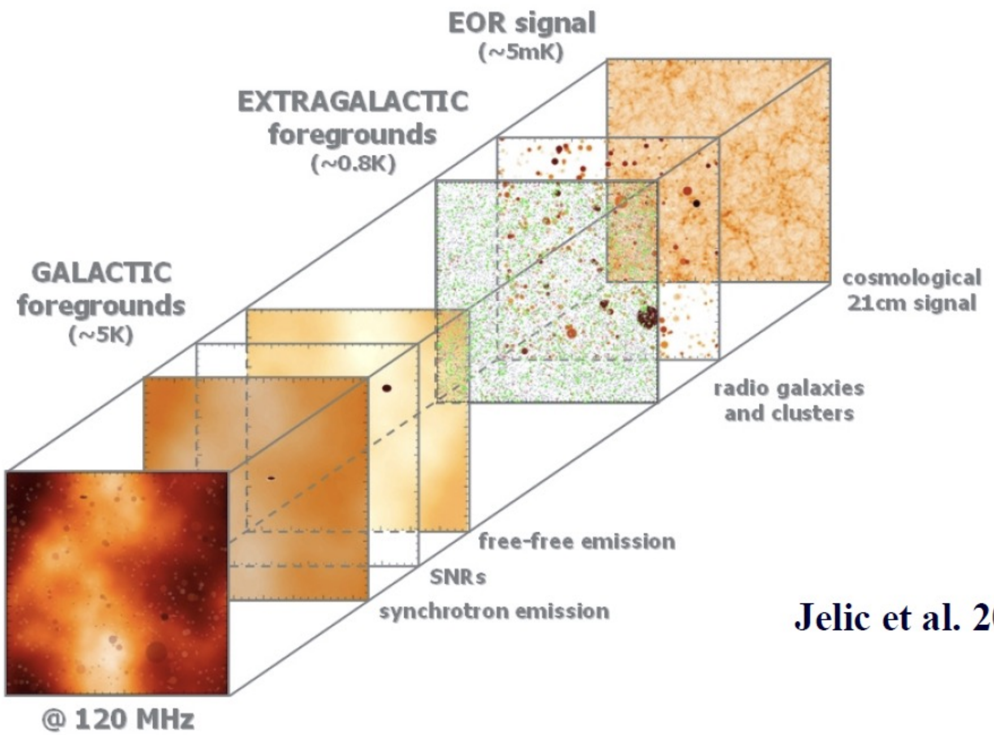
EoR 21cm line has never been detected yet!

foregrounds

bright foregrounds
- Galactic synchrotron
- extragalactic radio sources

>> EoR 21cm-line signal





Jelic et al. 2008

Foregrounds are larger than signal by 6 orders in terms of power spectrum.
Subtraction is vitally important.
Only upper limits.

detection of global signal?

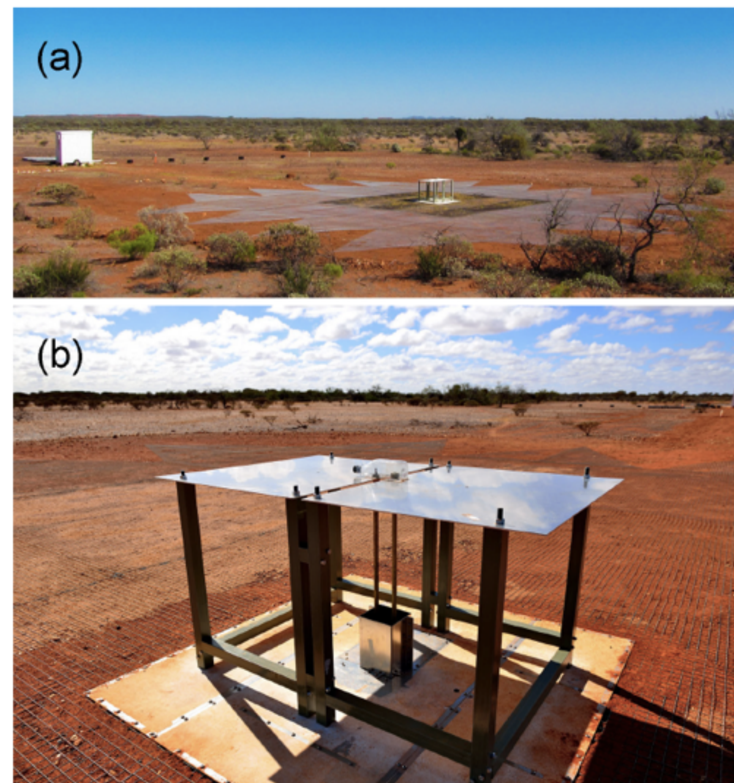
LETTER

doi:10.1038/nature25792

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

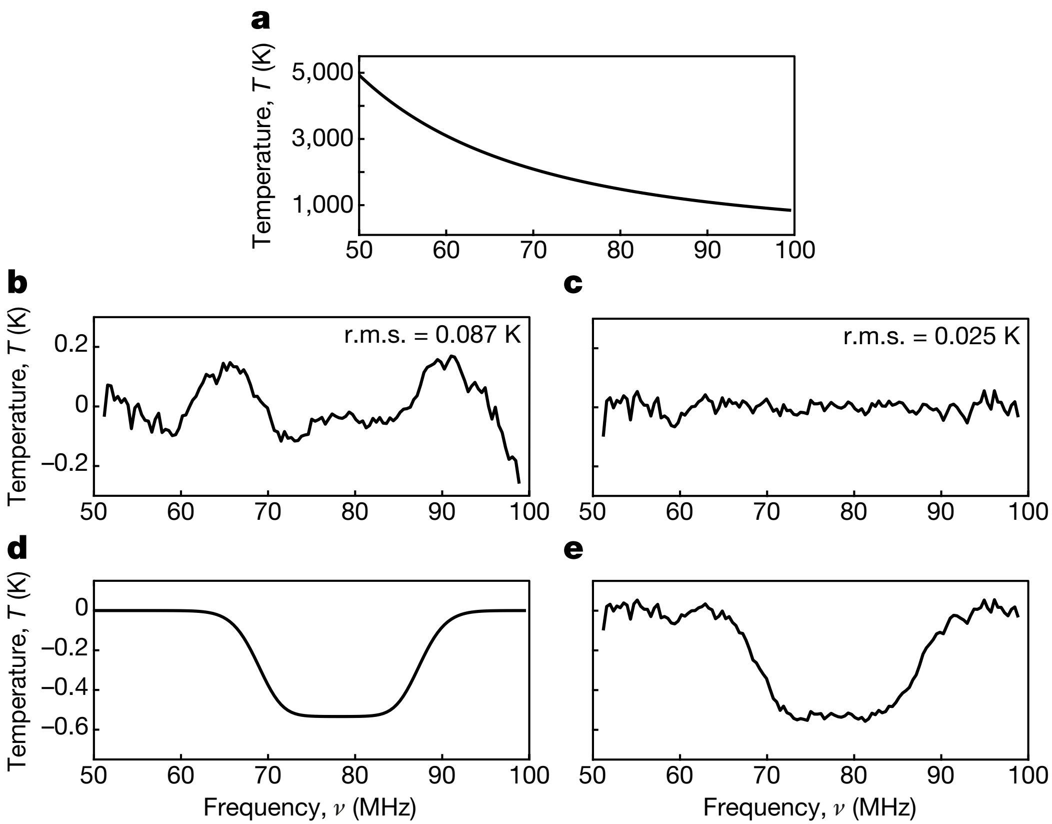
Judd D. Bowman[1], Alan E. E. Rogers[2], Raul A. Monsalve[1,3,4], Thomas J. Mozdzen[1] & Nivedita Mahesh[1]

Bowman et al. 2018
- EDGES
- absorption in global signal
- 70~80MHz
  → z = 15~20
  → cosmic dawn

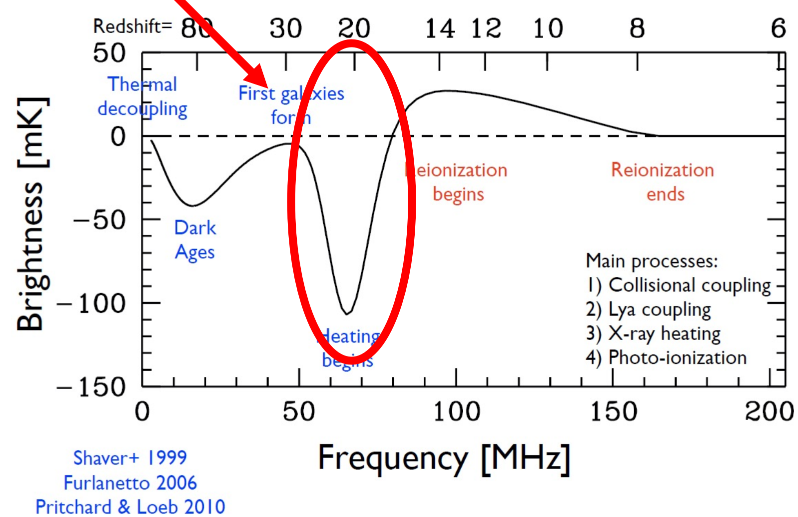


detection of global signal?

a: observed data
c: (observed data) – (power-law foreground)
– (absorption signal template)
d: obtained absorption feature

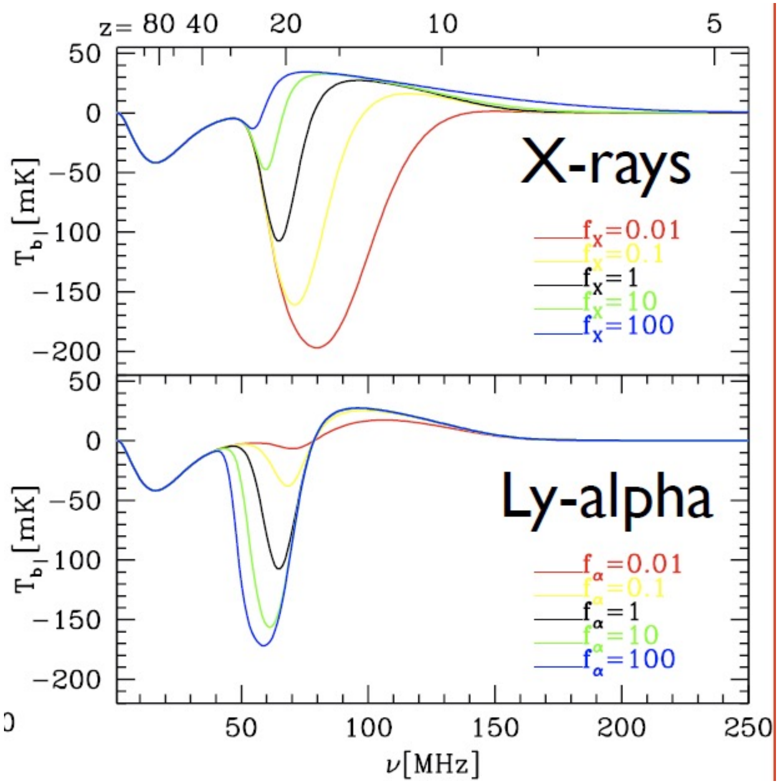


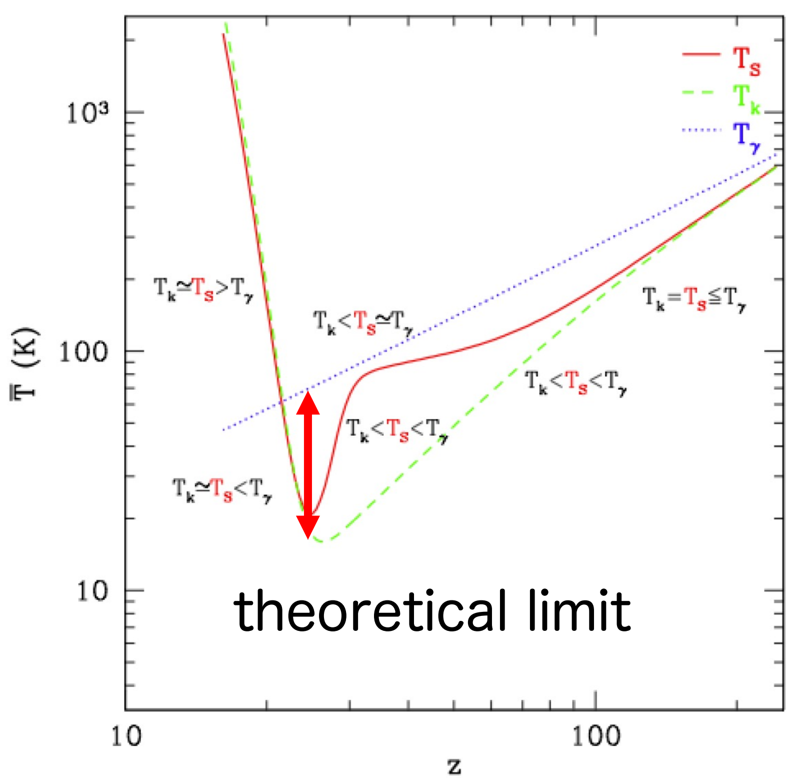
claimed to be this feature!



detection of global signal?

But the absorption depth is about 0.5K,
much larger than theoretical limit (~0.2K).
- systematic error? → needs confirmation
- (astro)physics beyond the standard model?

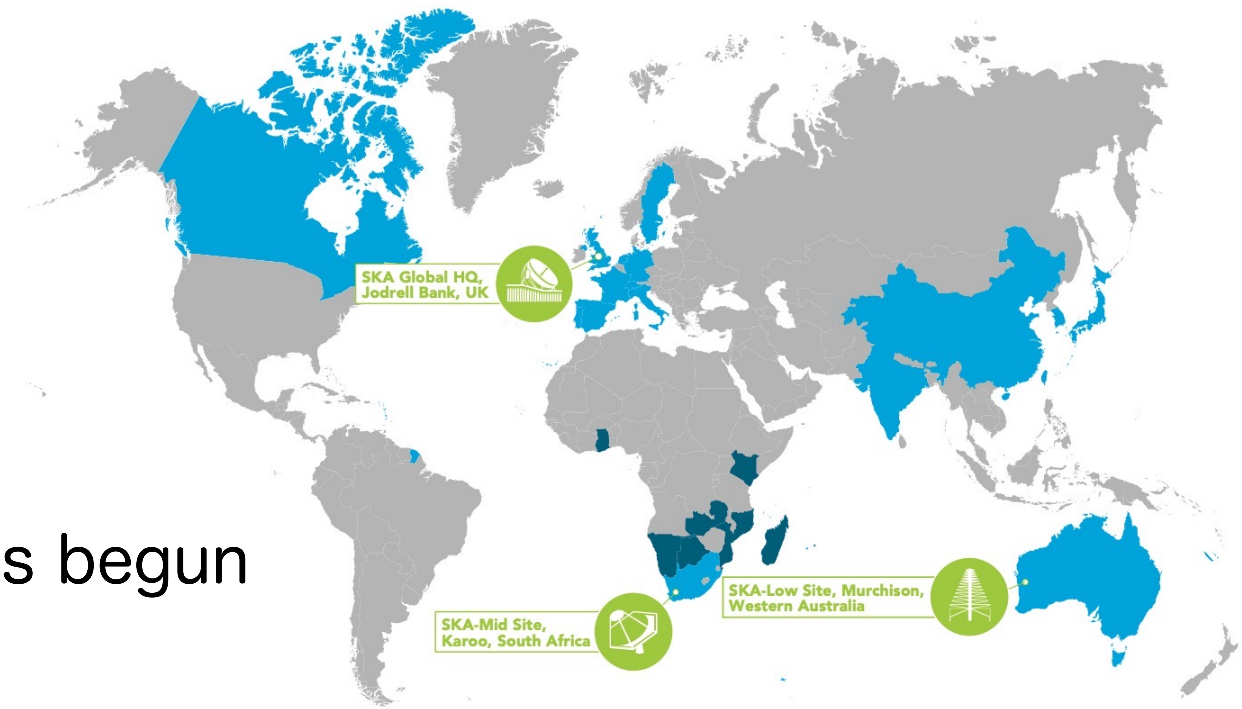




Square Kilometre Array

next-generation low-frequency radio telescope

- high sensitivity, wide field-of-view
  ultra-wideband, high angular resolution
- SKA1: 10% (2G€)
- SKA2: 100% (???)
- SKA-low: AU
- SKA-mid: SA
- HQ: UK

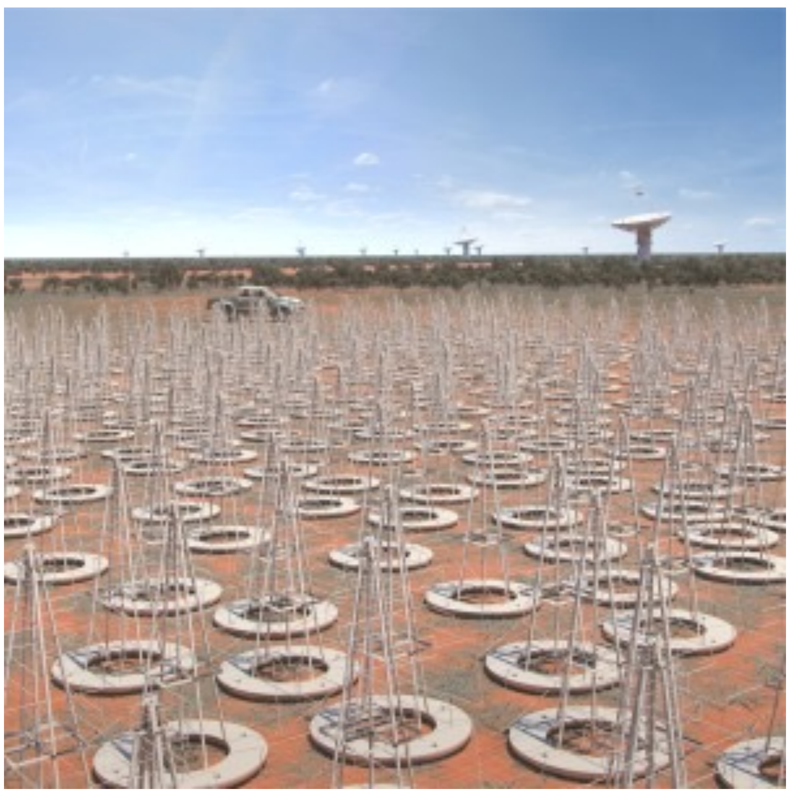


Construction has begun
in July/2021!

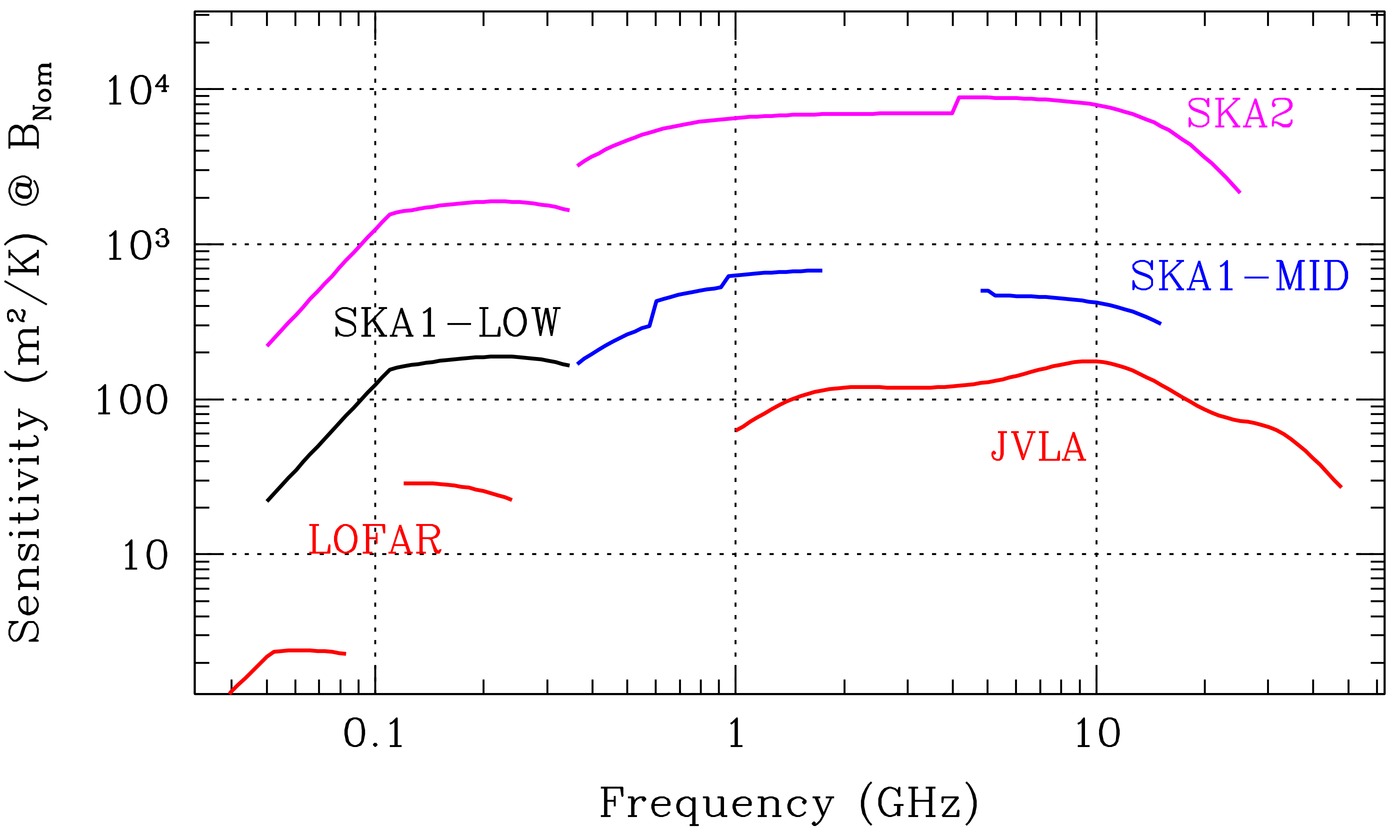
Square Kilometre Array

SKA-low
- Australia
- 50 - 350MHz
- 400,000 antennas

SKA-mid
- South Africa
- 350MHz - 24GHz
- 2,000 dishes



sensitivity



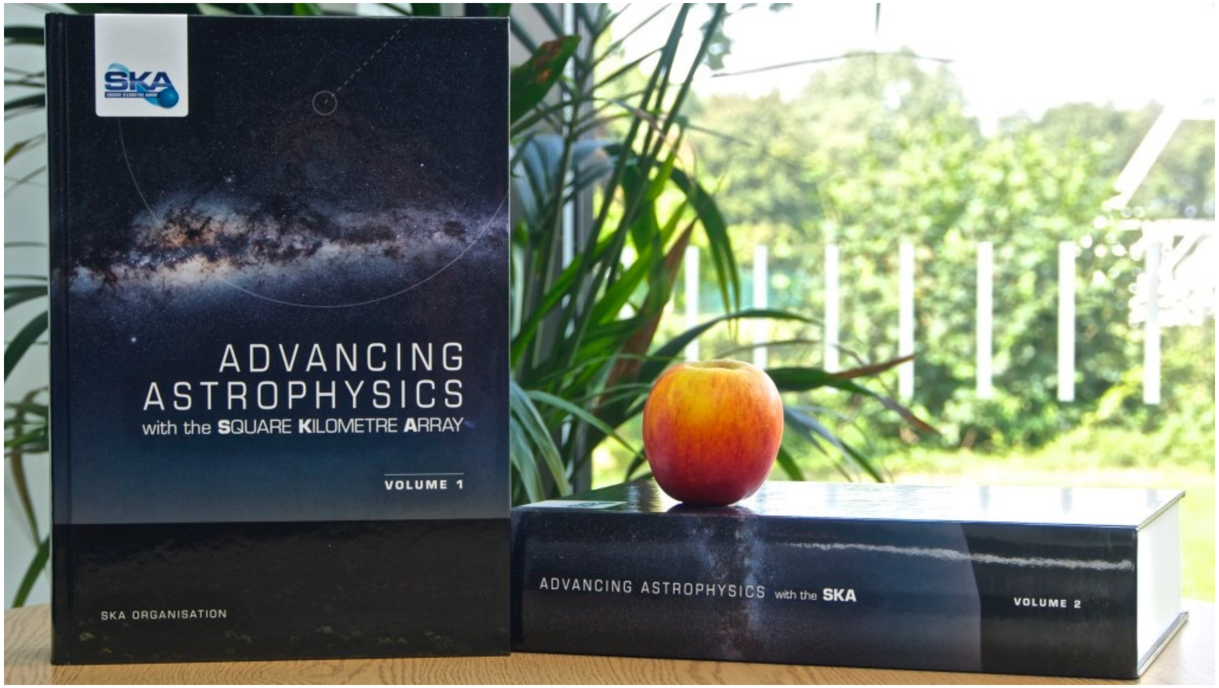
MWA, LOFAR, HERA: first detection
SKA1: precise statistics
SKA2: imaging

SKA science

Key Science

- cosmic dawn & epoch of reionization
- pulsar & gravitational waves
- cosmic magnetism
- galaxy evolution
- astrobiology
- transients
- cosmology

If you are interested, please let me know.



5. summary

summary

DA/CD/EoR

- last frontier of cosmology & astrophycs
- first stars, first galaxies, first black holes
- so far: CMB E mode, Lyα forest
- new probe: 21cm line

observations

- tiny signal, large foreground
- EDGES result: very interesting!
- MWA/LOFAR/HERA: first detection?
- SKA: new era of CD/EoR study

thank you!