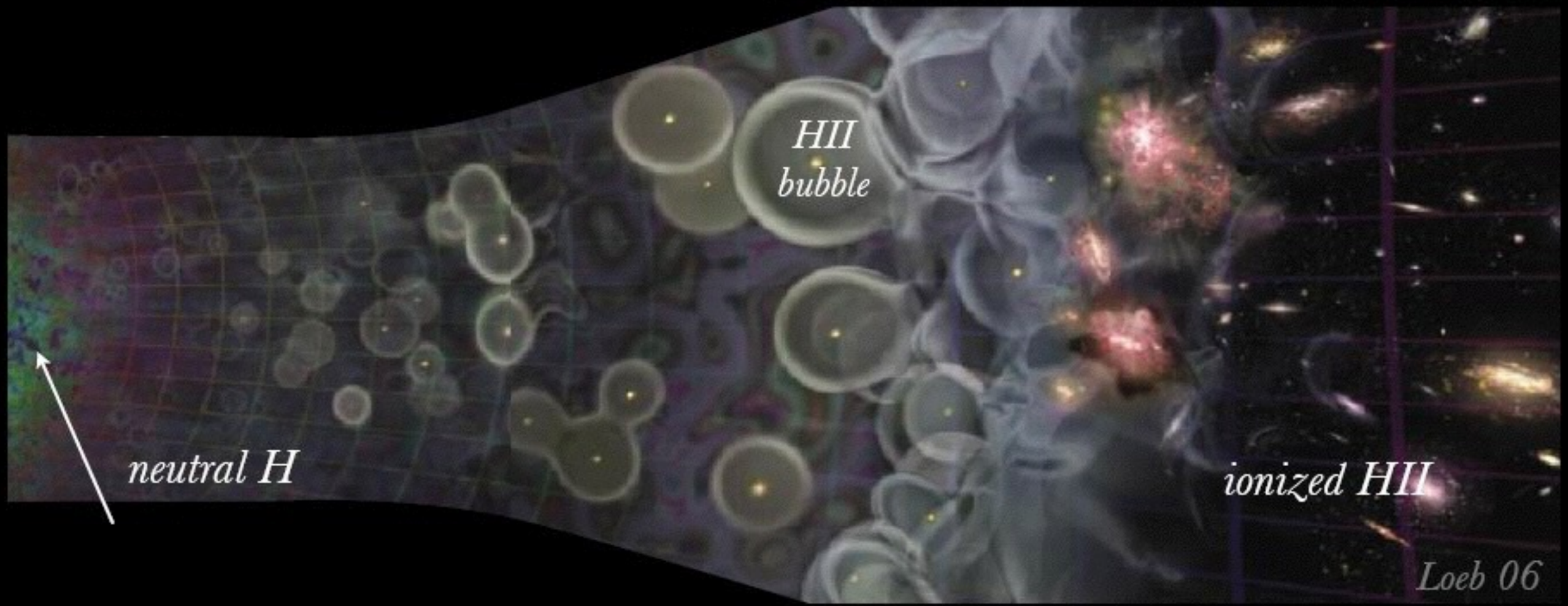


Cosmic dawn and Epoch of Reionization with 21cm line

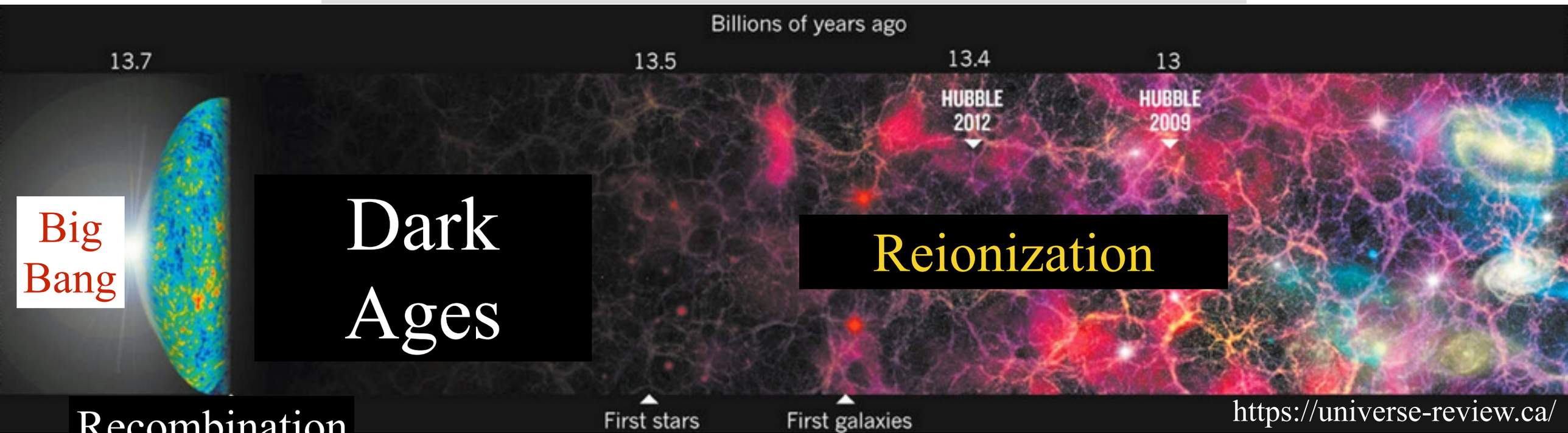
Hayato Shimabukuro (Tsinghua University)

Galaxy-IGM workshop (08/08/2018 ,Tsukuba)

Contents

- Introduction of cosmic dawn and reionization
- 21cm signal
- Observations of 21cm signal

History of the Universe



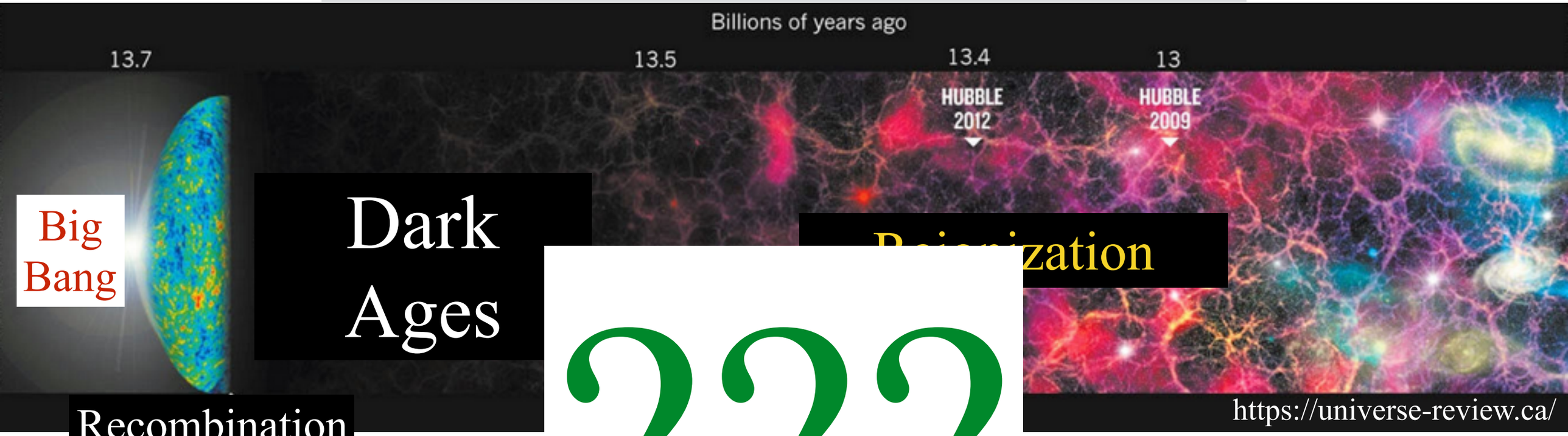
past ***present***

Dark Ages • • • No luminous object exists. (z>~30?)

Cosmic Dawn • • • First stars and galaxies form. (z~20-30?)

Reionization • • • UV photons by luminous objects ionize IGM. (z~6-15?)

History of the Universe



past *present*

Dark Ages • • • No luminous object exists. (z>~30?)

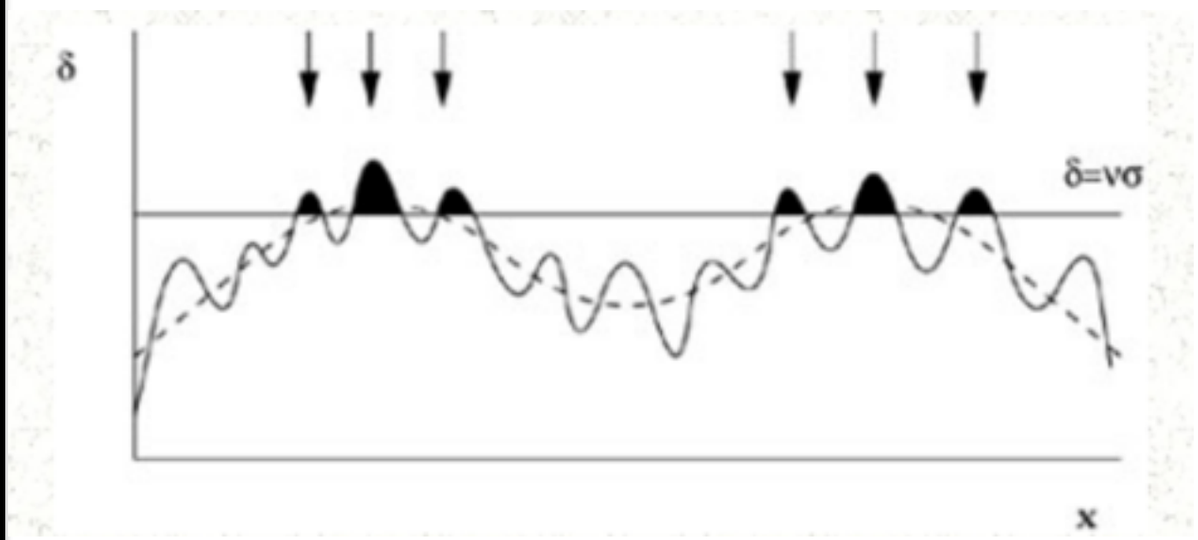
Cosmic Dawn • • • First stars and galaxies form. (z~20-30?)

Reionization • • • UV photons by luminous objects ionize IGM. (z~6-15?)

Hierarchical formation of first stars

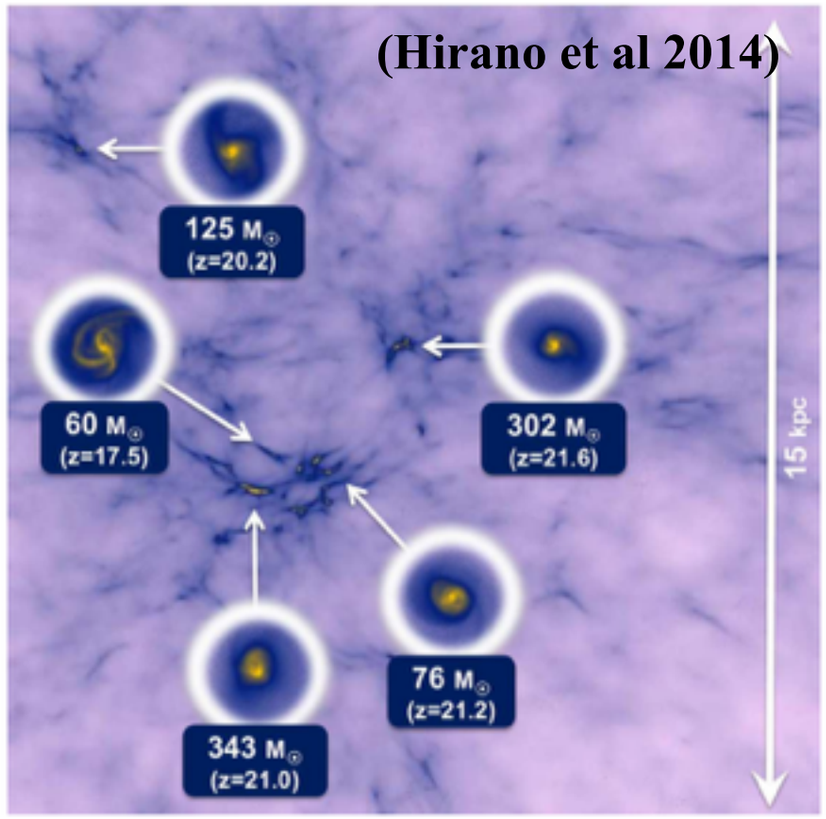
Λ-CDM cosmology

- Primordial density fluctuations
- Growth of fluctuations
- Dark matter halo

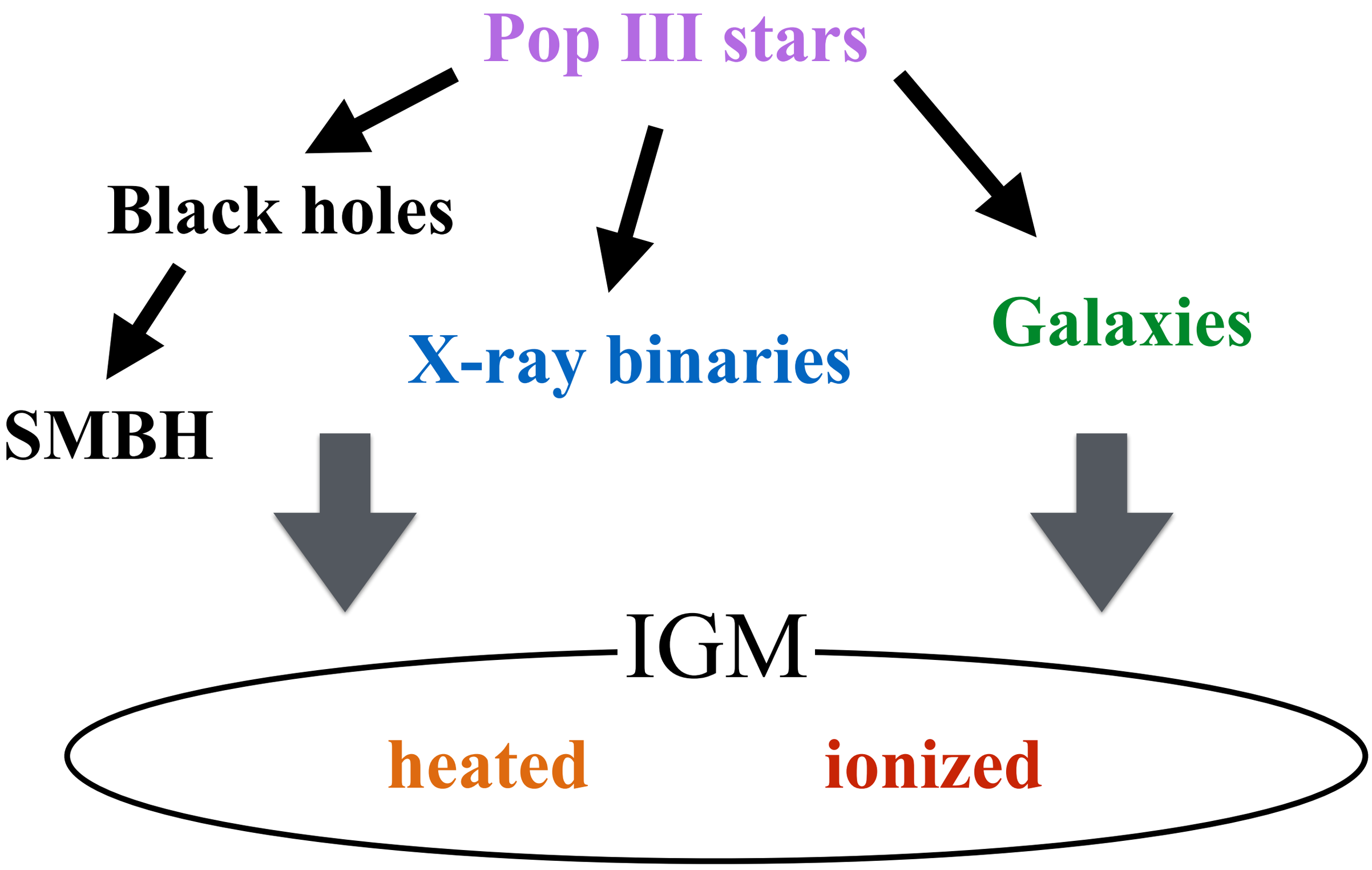


Baryon (gas) physics

- Molecular gas cloud
- Protostellar core
- First stars (Pop III)



Cosmic Dawn


Pop III stars
Black holes
SMBH
X-ray binaries
Galaxies
IGM
heated
ionized

Cosmic Dawn

After first luminous objects (**first stars**, **galaxies**, **black holes**) had formed • • •

IGM is • • •

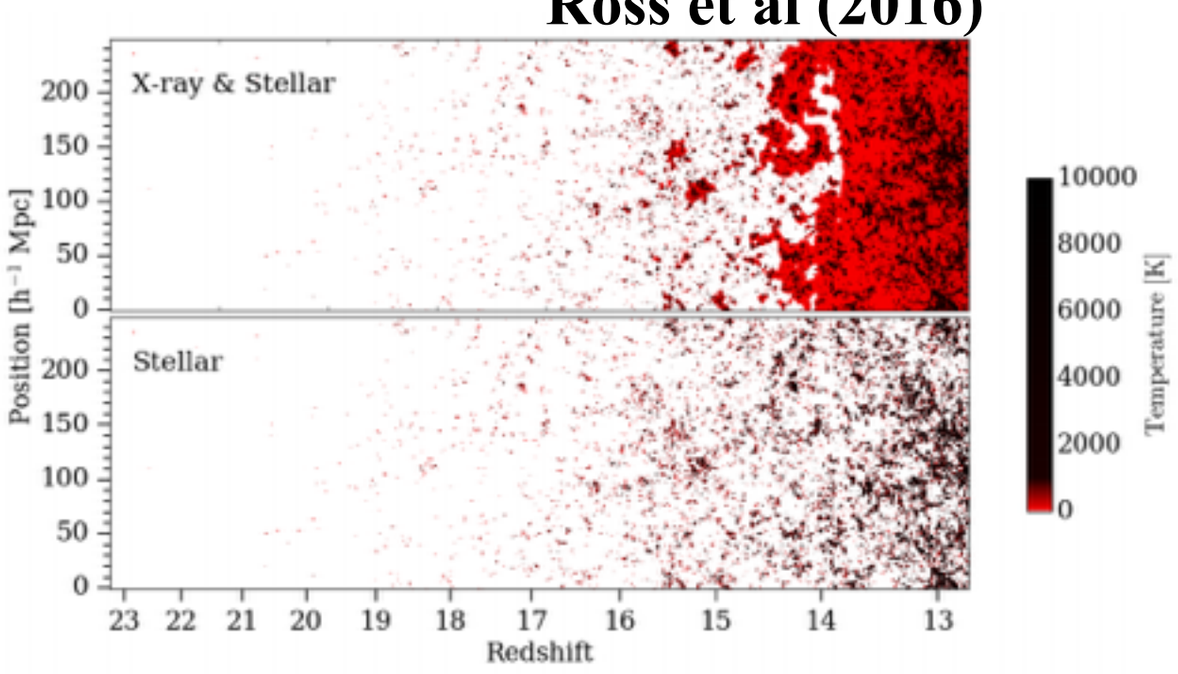
•heated

•(re) ionized

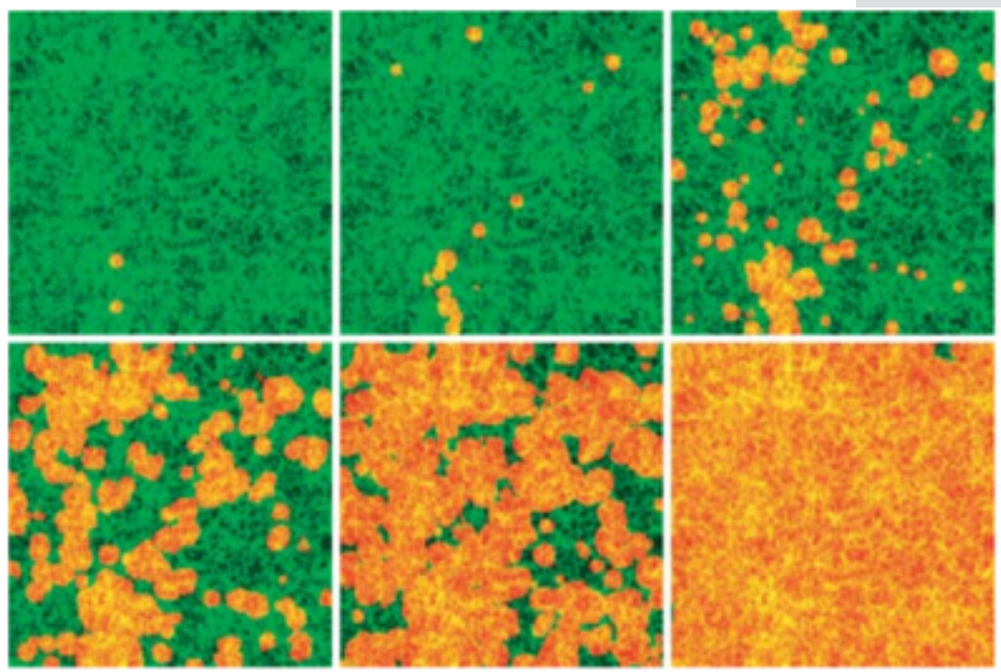
neutral

ionized

Ross et al (2016)



z



Iliev et al (2006)

z

Physics of IGM heating

The time evolution of gas temperature

Furlanetto et al (2006)

$$\frac{dT_K}{dt} = -2HT_K + \frac{2}{3k_{\rm B}} \sum_j \frac{\epsilon_j}{n}$$

adiabatic cooling of the gas

energy injection

ϵ_j : heating rate for the process j

IGM heating is mainly driven by **X-ray sources**
(X-ray binaries, supernovae remnant and so on).

Physics of reionization

Simple analytic reionization model

Barkana & Loeb (2001)

$$\frac{dQ_{\rm HII}}{dt} = \frac{1}{n_{\rm H}^0}\dot{n}_{\rm ion}^{\gamma} f_{\rm esc,ion} - \alpha_{\rm B} C (1+z)^3 n_{\rm H}^0 Q_{\rm HII}$$

ionizing .vs. **recombination**

$Q_{\rm HII}$: volume fraction of HII

$n_{\rm H}^0$: hydrogen number density

$\dot{n}_{\rm ion}^{\gamma}$: ionising photon number density

$f_{\rm esc,ion}$: escape fraction of ionising photon

$\alpha_{\rm B}$: case B recombination rate

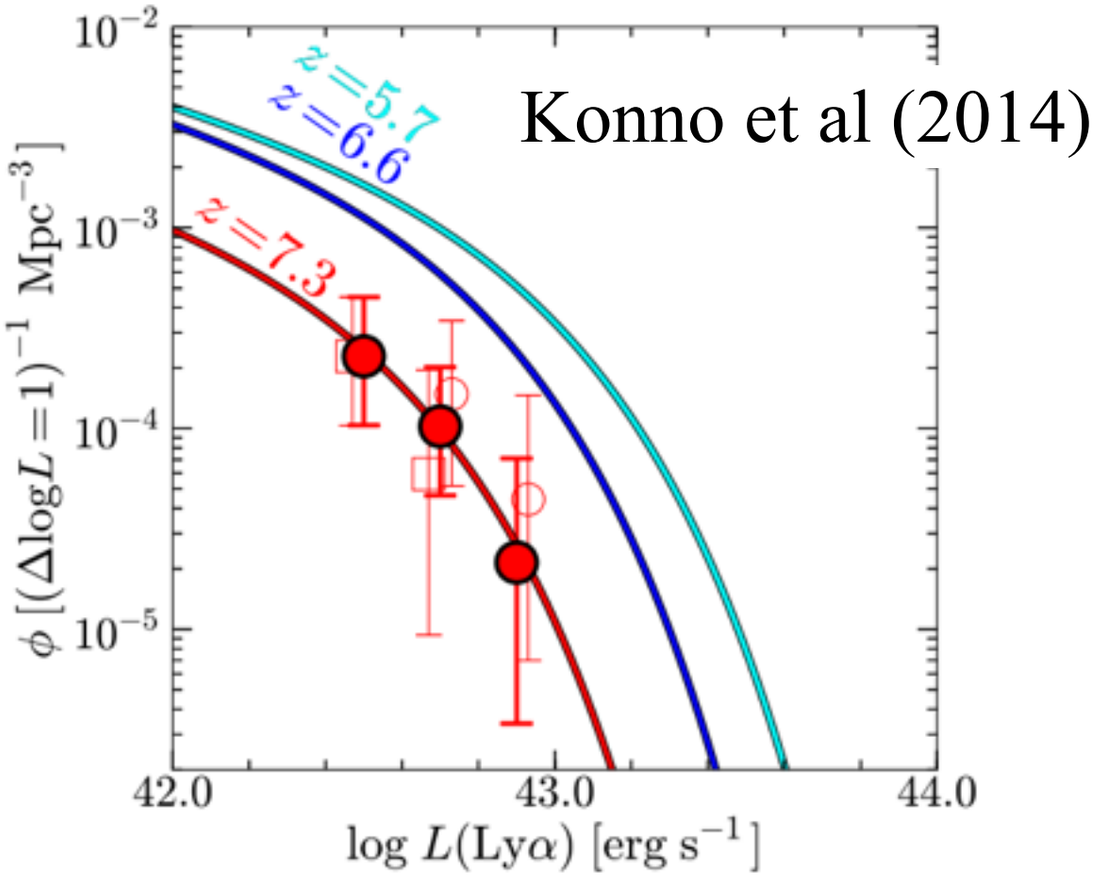
C : clumping factor

What do we want to know ?

- When did first generation objects (ex. first star, black hole) form ?
- What are the properties of first generation objects (ex. IMF of first stars, SED of X-ray sources) ?
- What is the environment of first galaxies (ex. escape fraction)
- When did reionization start?
- What is the main source of heating and reionization of the IGM?
- How do ionised regions evolve? …*etc*

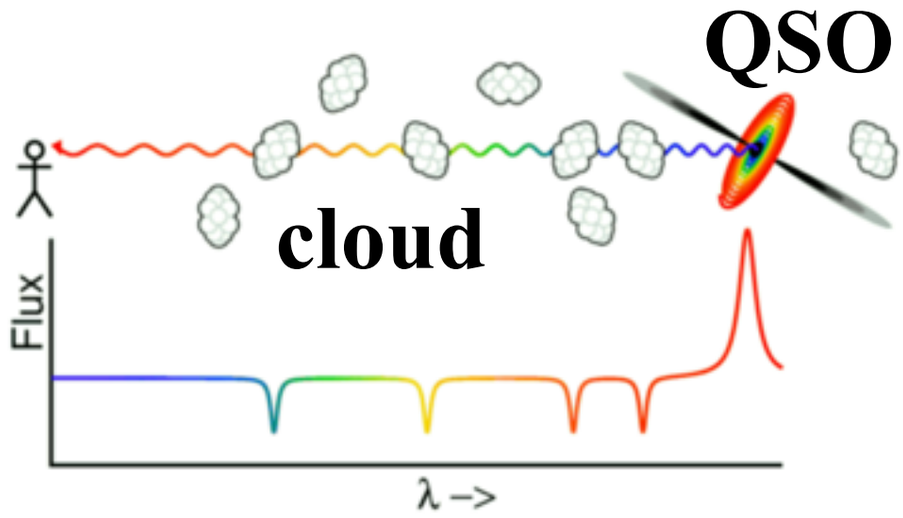
Current observations tell us

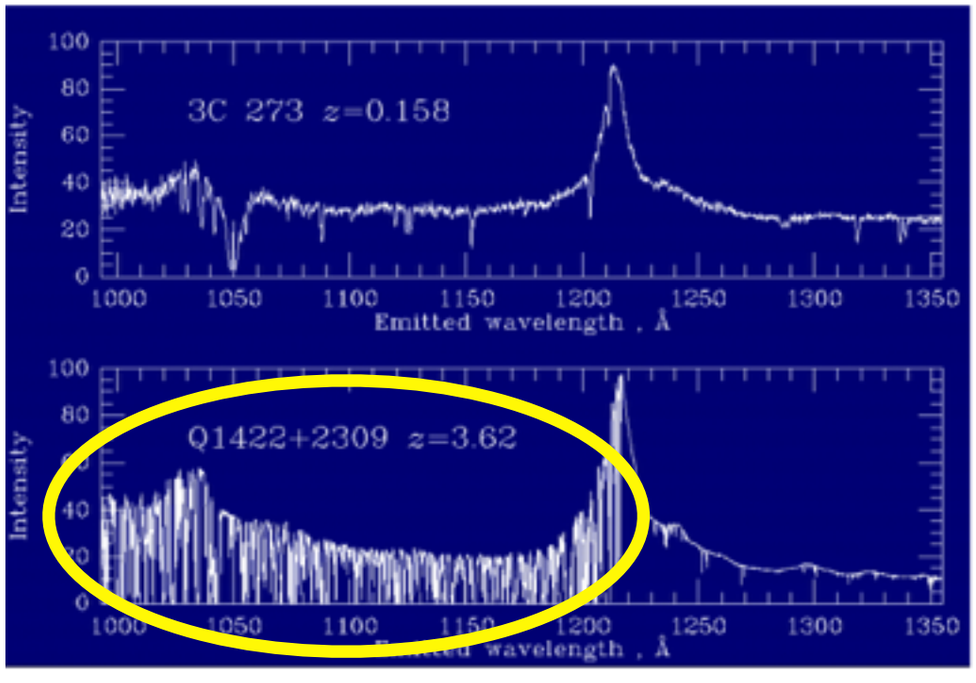
•Ly alpha emitter galaxies



• CMB-electron Thomson scattering

•Ly alpha forest

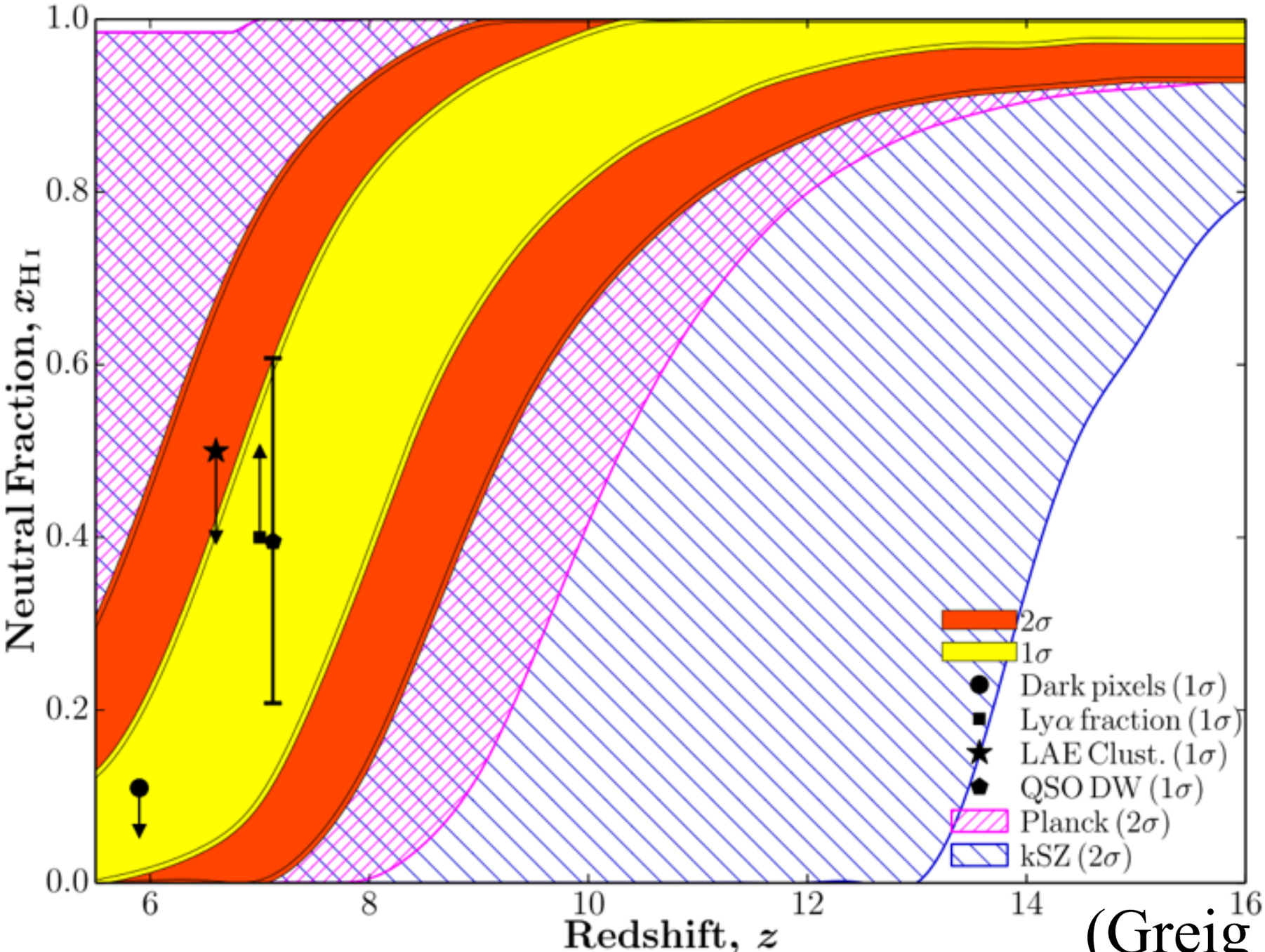




(http://pages.astronomy.ua.edu/keel/agn/forest.html)

Current observations tell us

ionisation history

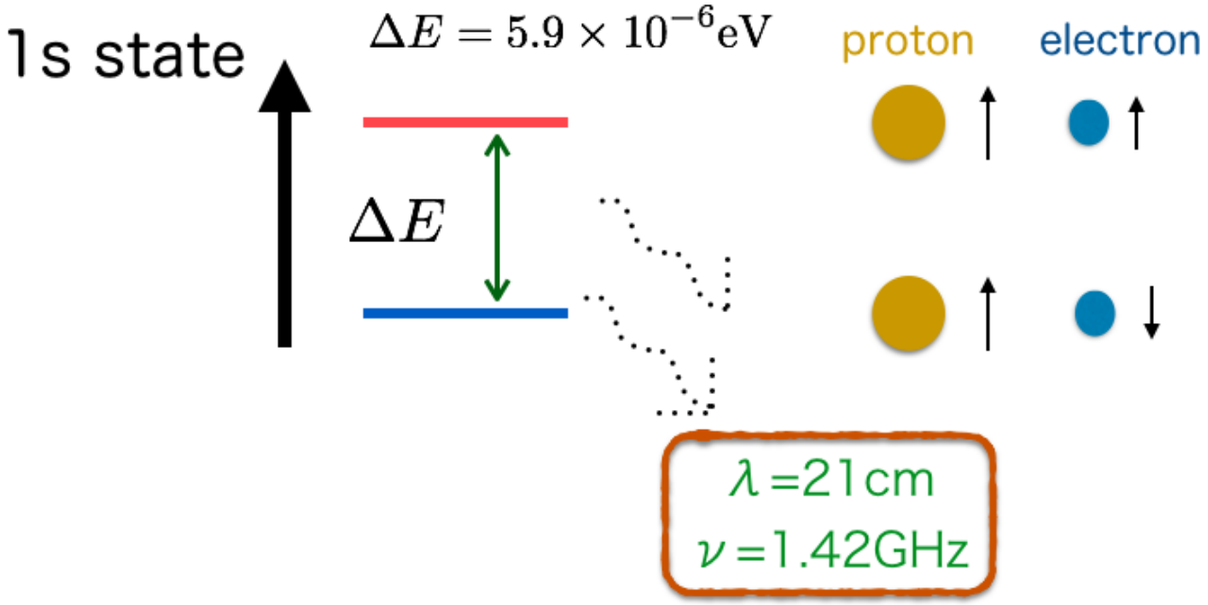


(Greig et al 2017)

How do we observe IGM at the EoR and cosmic dawn beyond current limits?

21cm line

•**21cm line radiation** : Neutral hydrogen emits the radiation due to the hyperfine structure.



z=6 → 202 MHz

z=20 → 68MHz

We can observe the distribution of neutral hydrogen atom in the IGM at the EoR and cosmic dawn as **3D tomography**.

Spin temperature

spin temperature

$$\frac{n_{\uparrow\uparrow}}{n_{\uparrow\downarrow}} = 3\exp\left(-\frac{h\nu_{21\mathrm{cm}}}{kT_{\mathrm{S}}}\right) \quad \Rightarrow \quad T_{\mathrm{S}}^{-1} = \frac{T_{\mathrm{CMB}}^{-1} + x_c T_{\mathrm{K}}^{-1} + x_\alpha T_c^{-1}}{1 + x_c + x_\alpha}$$

Spin temperature is determined by

- interaction with **CMB photons** (T_{CMB})
- collision with **hydrogen atom** (T_{K}, x_c) ⟷ X-ray sources
- interaction with **Ly-alpha photons** $(T_c \sim T_{\mathrm{K}}, x_\alpha)$ ⟷ Properties of PopIII (II) star.

Relevant astrophysics

Spin temperature

spin temperature

$$\frac{n_{\uparrow\uparrow}}{} = 3\exp\left(-\frac{h\nu_{21\mathrm{cm}}}{}\right) \quad \rightarrow \quad T_s^{-1} = \frac{T_{\mathrm{CMB}}^{-1} + x_c T_{\mathrm{K}}^{-1} + x_\alpha T_c^{-1}}{}$$

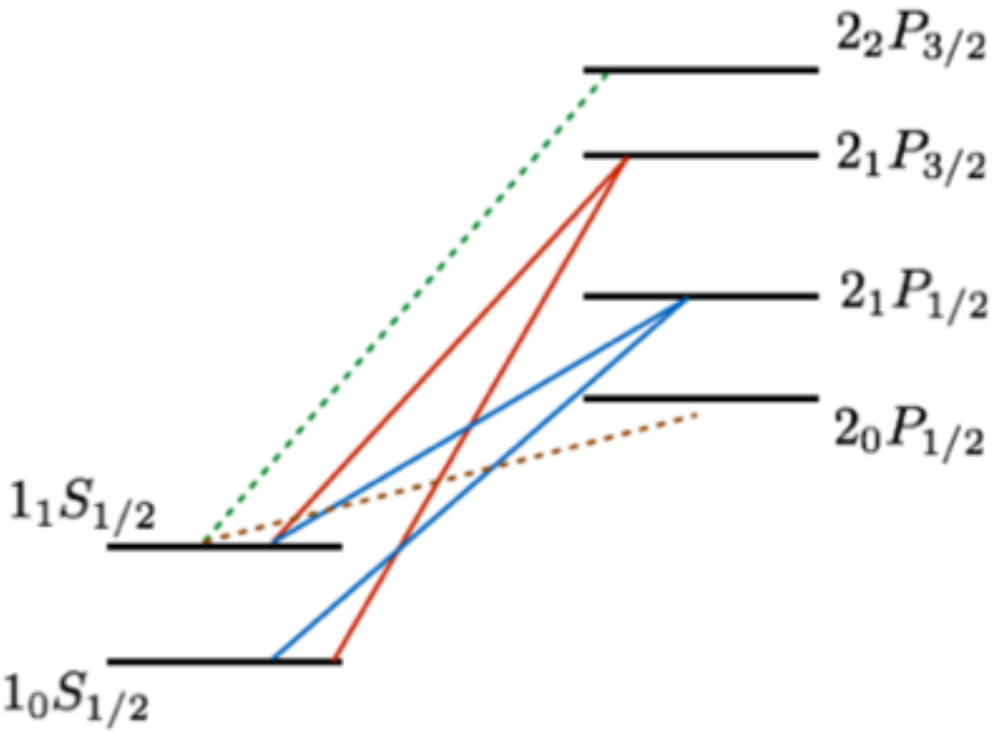
Spin temperature includes astrophysical information

S

- interaction with **CMB photons** (T_{CMB})
- collision with **hydrogen atom** (T_{K}, x_c) ⟷ X-ray sources
- interaction with **Ly-alpha photons** $(T_c \sim T_{\mathrm{K}}, x_\alpha)$ ⟷ Properties of PopIII (II) star.

WF effect

Wouthuysen-Field (WF) effect



Ly-alpha photon excites the 21cm line via transitions involving n=2 level

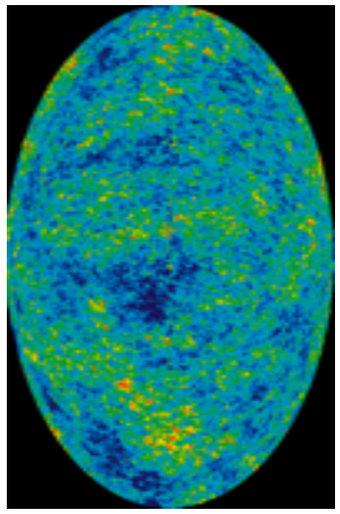
Solid line → Change spin state

Dashed line → Not change spin state

WF effect is related to $\mathcal{X}_\alpha$

Brightness temperature

We actually observe **brightness temperature**, **not** spin temperature.



$$T_\gamma \exp(-\tau_\nu) + T_{\rm S}[1 - \exp(-\tau_\nu)]$$

Brightness temperature

>0 :emission
<0 :absorption

against **CMB**

$$\delta T_b = \frac{T_{\rm S} - T_\gamma}{1+z}(1 - \exp(-\tau_\nu))$$

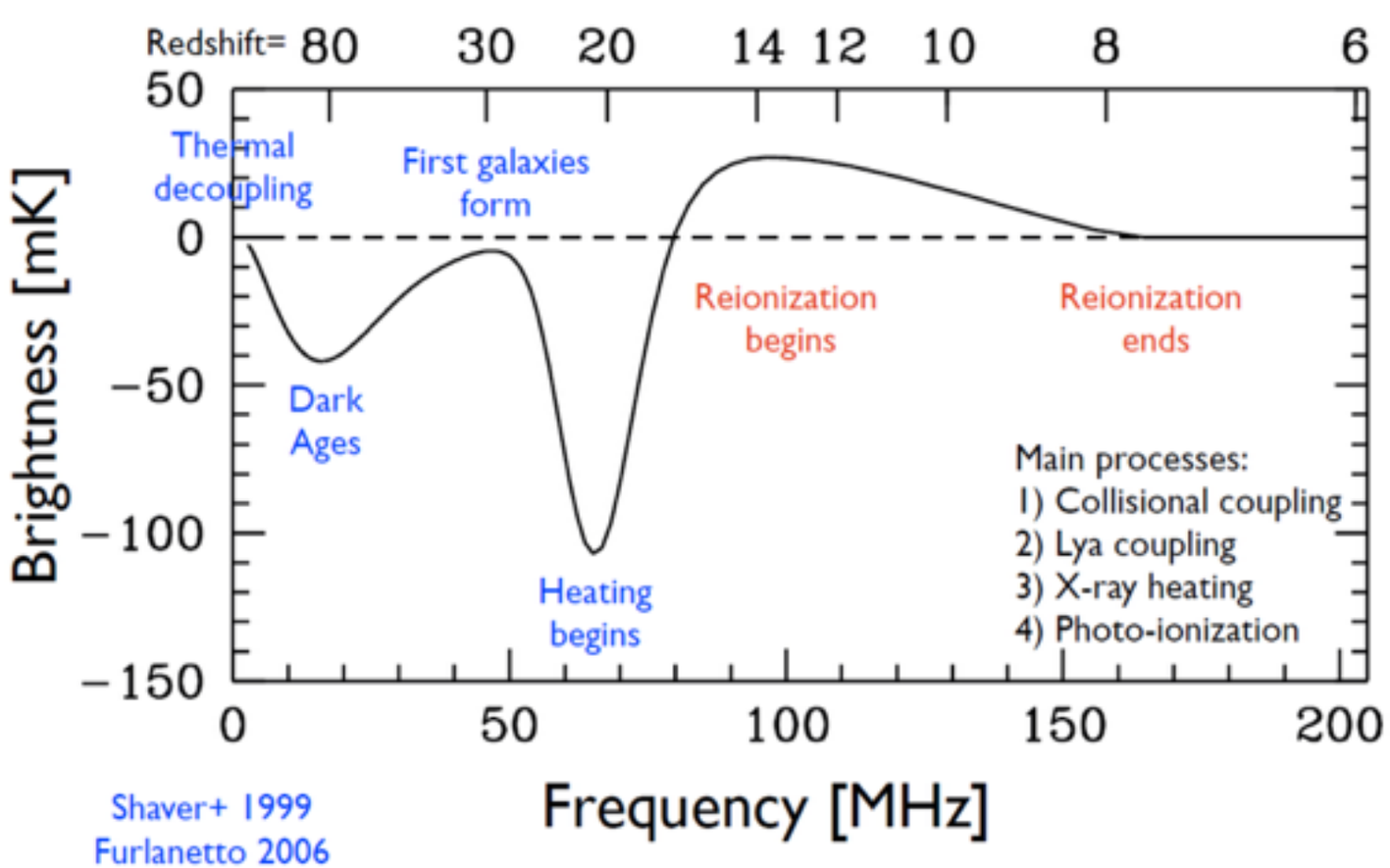
$$\sim 27 x_{\rm H}(1+\delta_m)\left(\frac{H}{dv_r/dr + H}\right)\left(1 - \frac{T_\gamma}{T_{\rm S}}\right)\left(\frac{1+z}{10}\frac{0.15}{\Omega_m h^2}\right)^{1/2}\left(\frac{\Omega_b h^2}{0.023}\right)\ [\rm mK]$$

Brightness temperature

$$\delta T_b = \frac{T_{\rm S} - T_\gamma}{1+z}(1 - \exp(-\tau_\nu))$$

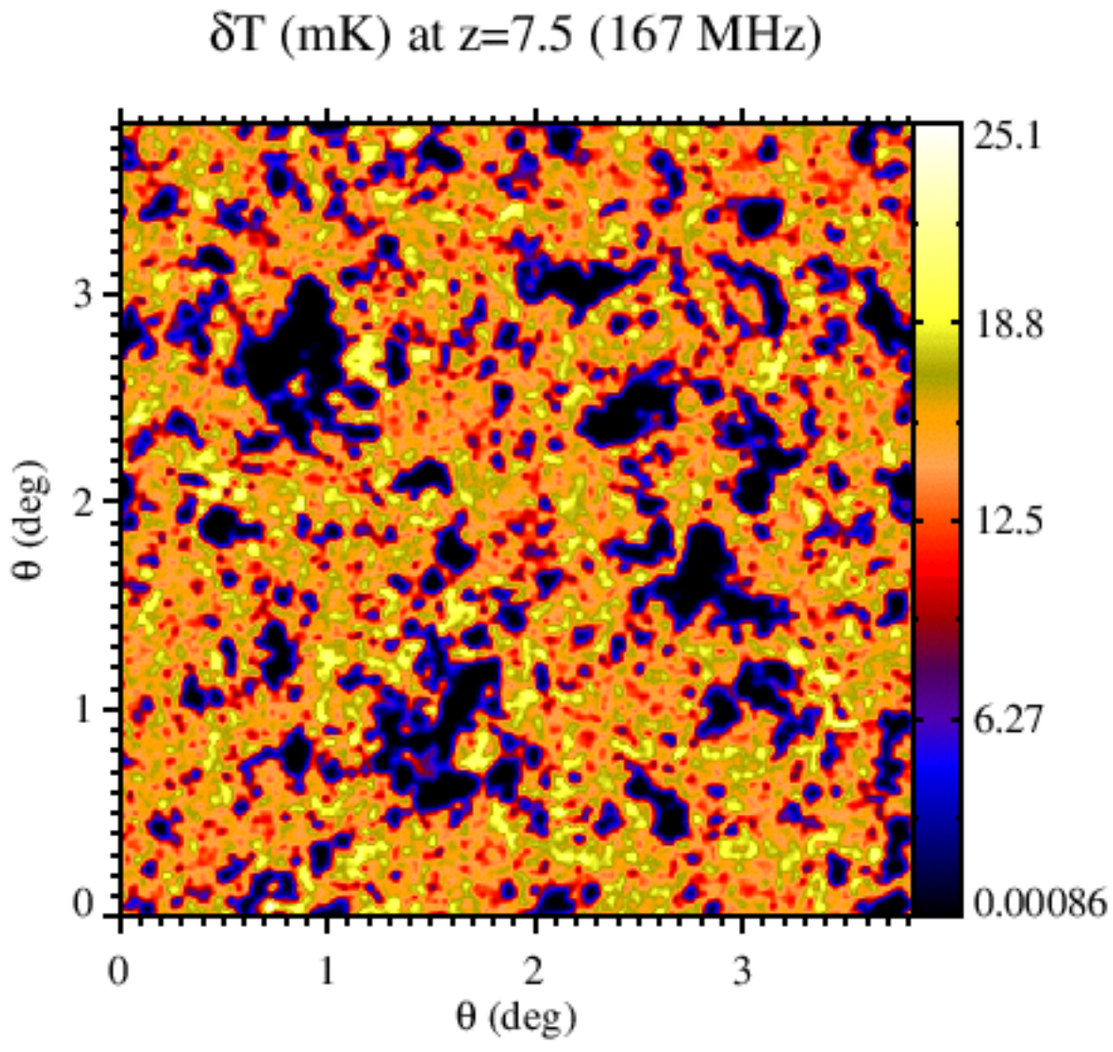
$$\sim 27 x_{\rm H}(1+\delta_m)\left(\frac{H}{dv_r/dr + H}\right)\left(1 - \frac{T_\gamma}{T_{\rm S}}\right)\left(\frac{1+z}{10}\frac{0.15}{\Omega_m h^2}\right)^{1/2}\left(\frac{\Omega_b h^2}{0.023}\right)\ [\mathrm{mK}]$$

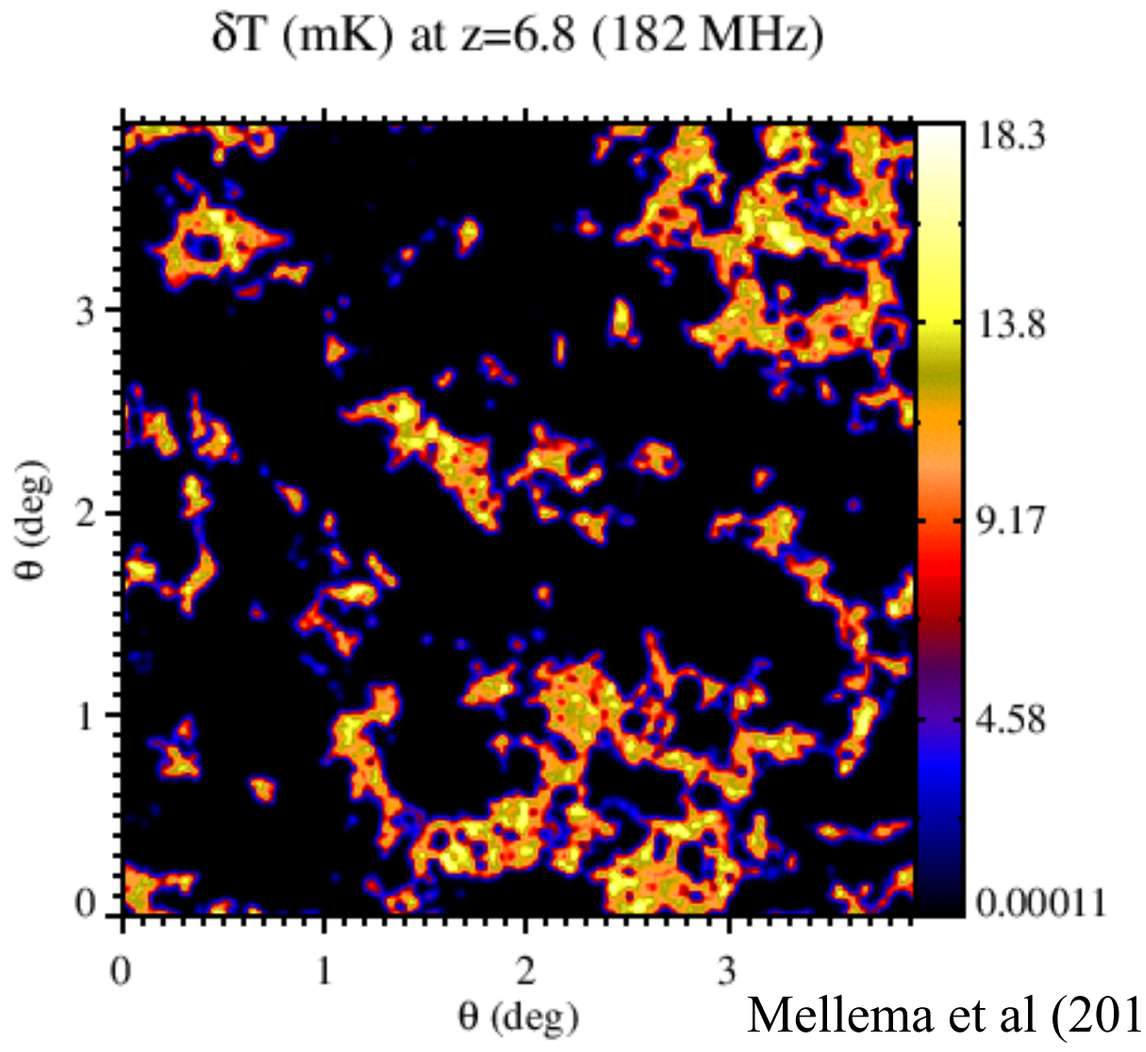
Red : **cosmology** Blue : **astrophysics**



Brightness temperature has characteristic peaks and troughs according to key epochs

Imaging with 21cm line



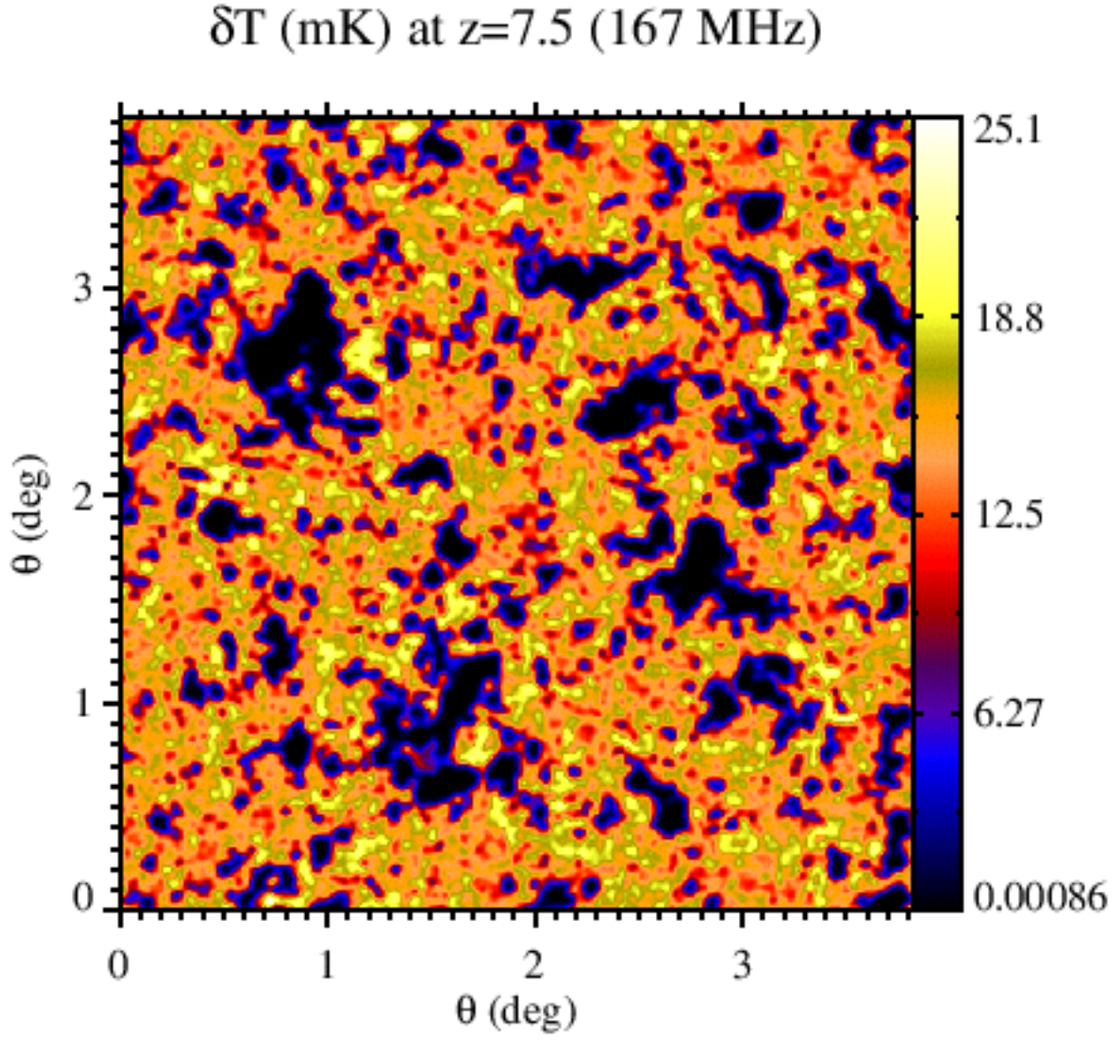


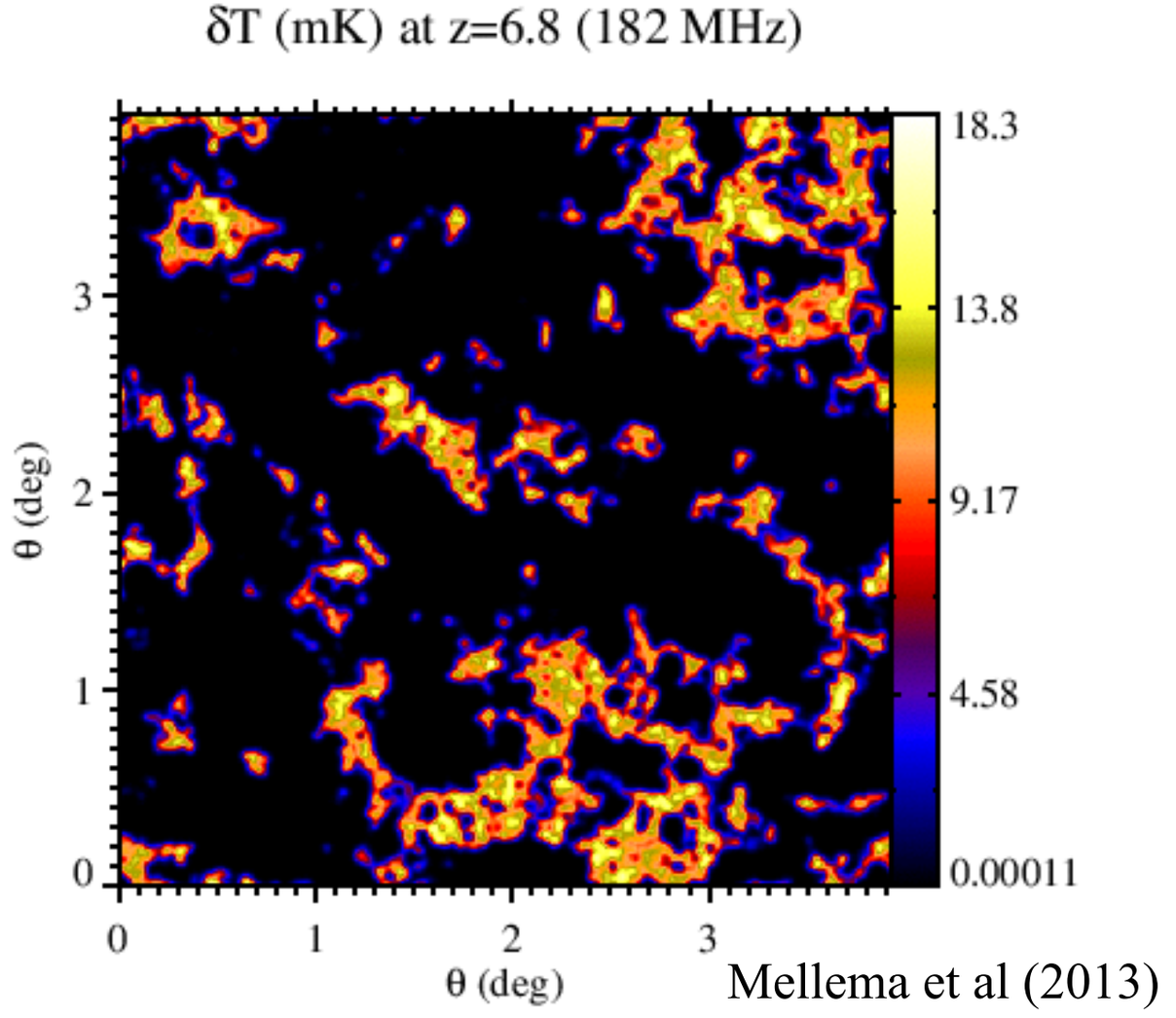
Mellema et al (2013)

We can see bubble topology with time evolution by 21cm imaging.

→ See bubble with other telescopes (ALMA, Subaru, JWST etc)

Imaging with 21cm line





Mellema et al (2013)

Required specification for imaging

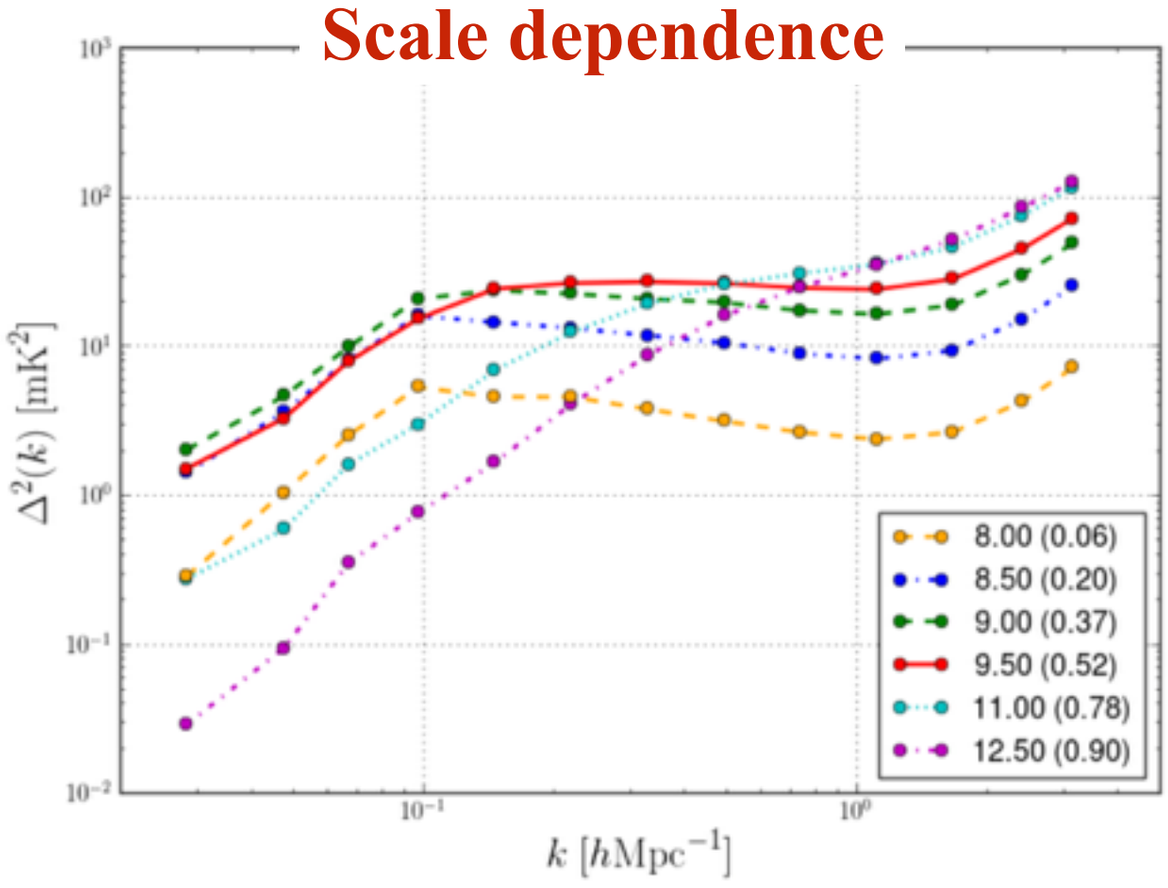
◯~ **a few arc-minutes resolution**

◯~ **a few degree FoV**

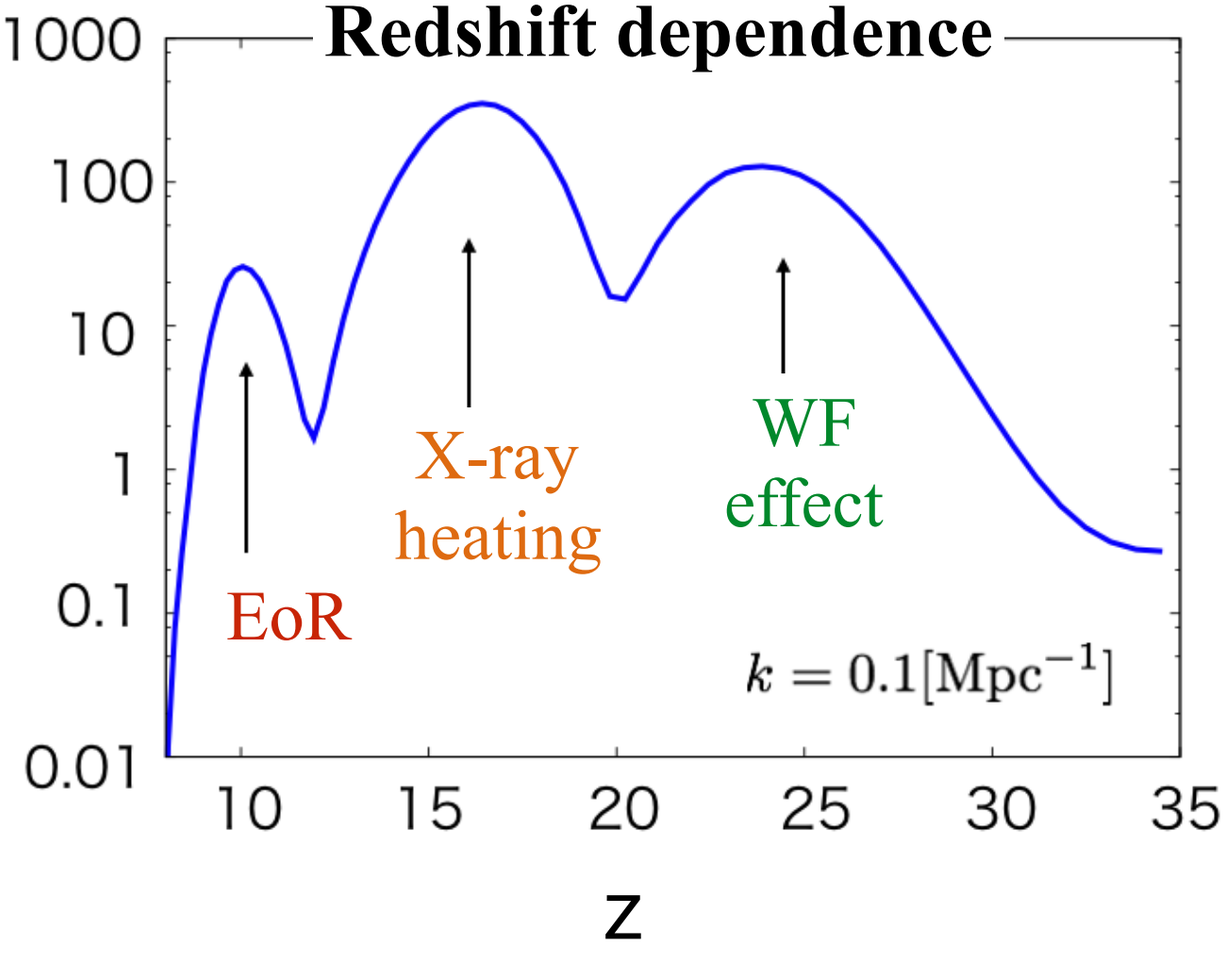
21cm power spectrum

We first aim to detect 21cm signal **statistically**.

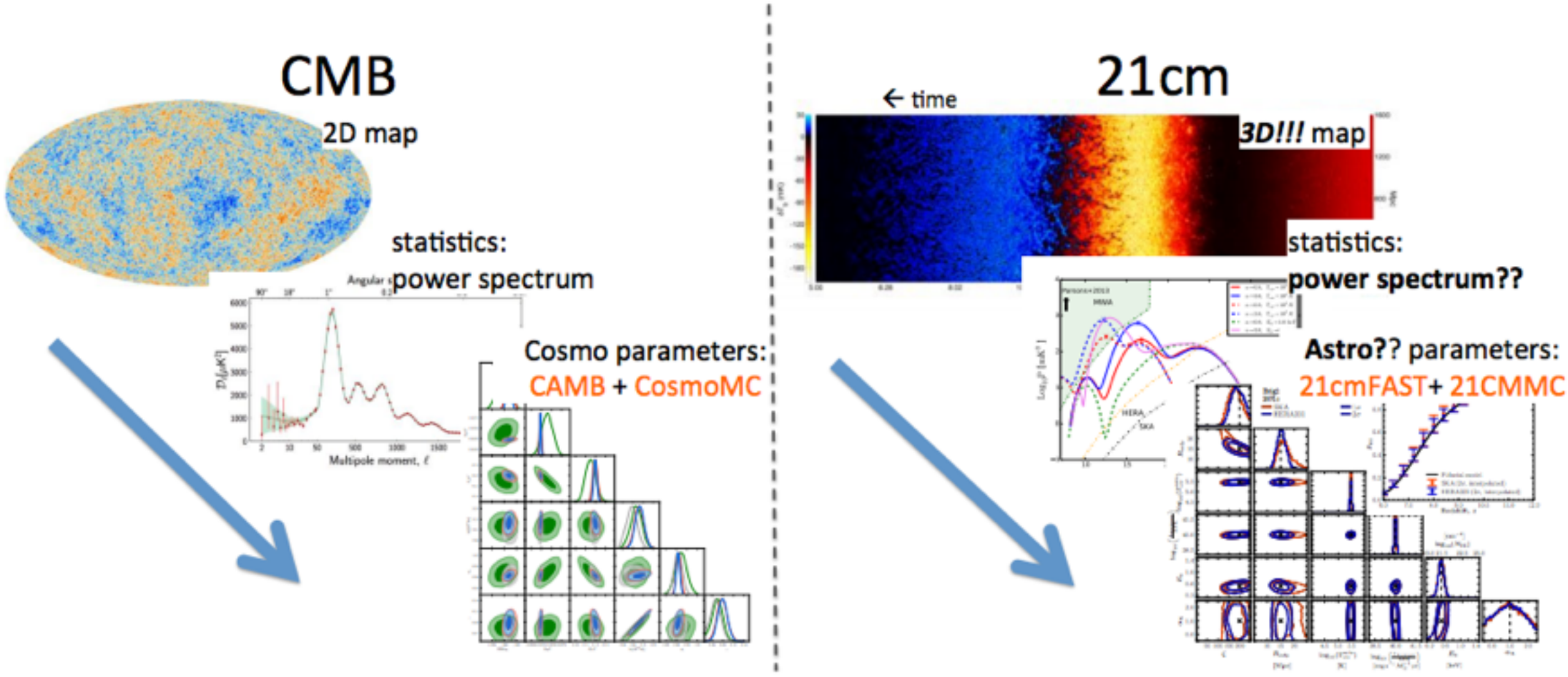
21cm power spectrum (PS) : $\langle \delta T_b(\mathbf{k}) \delta T_b(\mathbf{k}') \rangle = (2\pi)^3 \delta(\mathbf{k}+\mathbf{k}') P_{21}$



Pober et al (2014)



Statistical challenge



(Mesinger 2018)

Cosmology

CMB map → (angular) power spectrum → cosmological parameter

21cm

21cm 3D map → 21cm power spectrum → astrophysical parameter

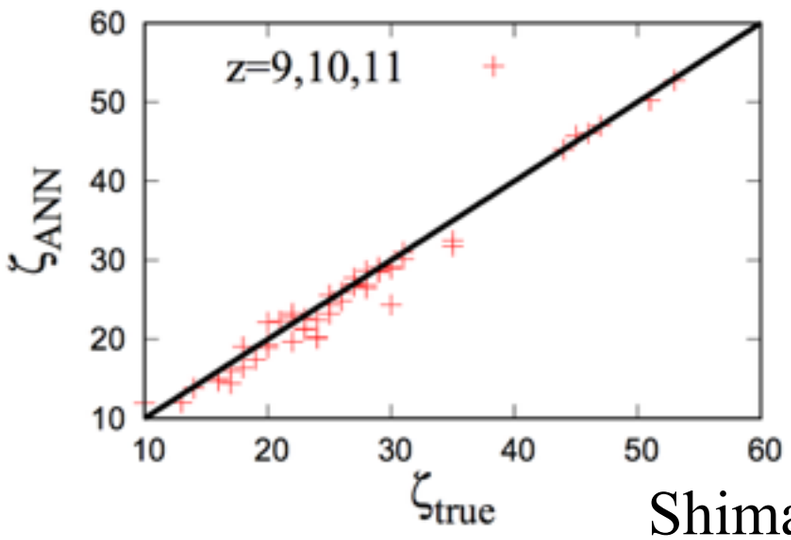
Machine learning with 21cm signal

Recently, some works have focused on **Artificial Neural Networks (ANNs)** with 21cm signal analysis.

○**Emulate 21cm power spectrum** (Kern et al 2017, Schmit et al 2018)

→ *We can quickly perform MCMC calculation.*

○**Parameter estimate** (Shimabukuro et al 2017, Gillet et al 2018)



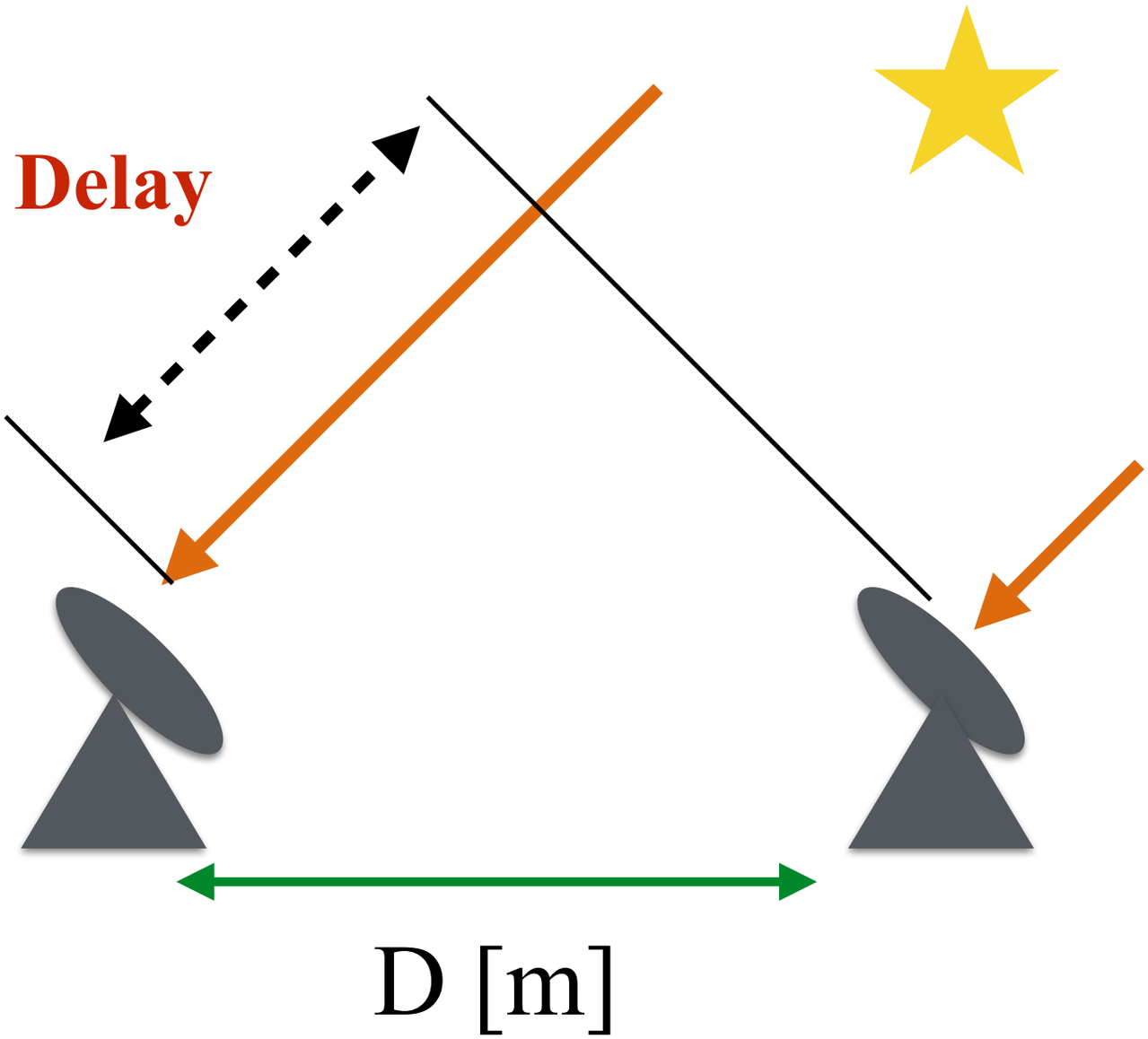
21cm signal → EoR parameters

Shimabukuro et al (2017)

How do we detect 21cm signal?

Radio interferometer

The measurement by radio interferometer is based on **time delay** between antennae.



We actually measure

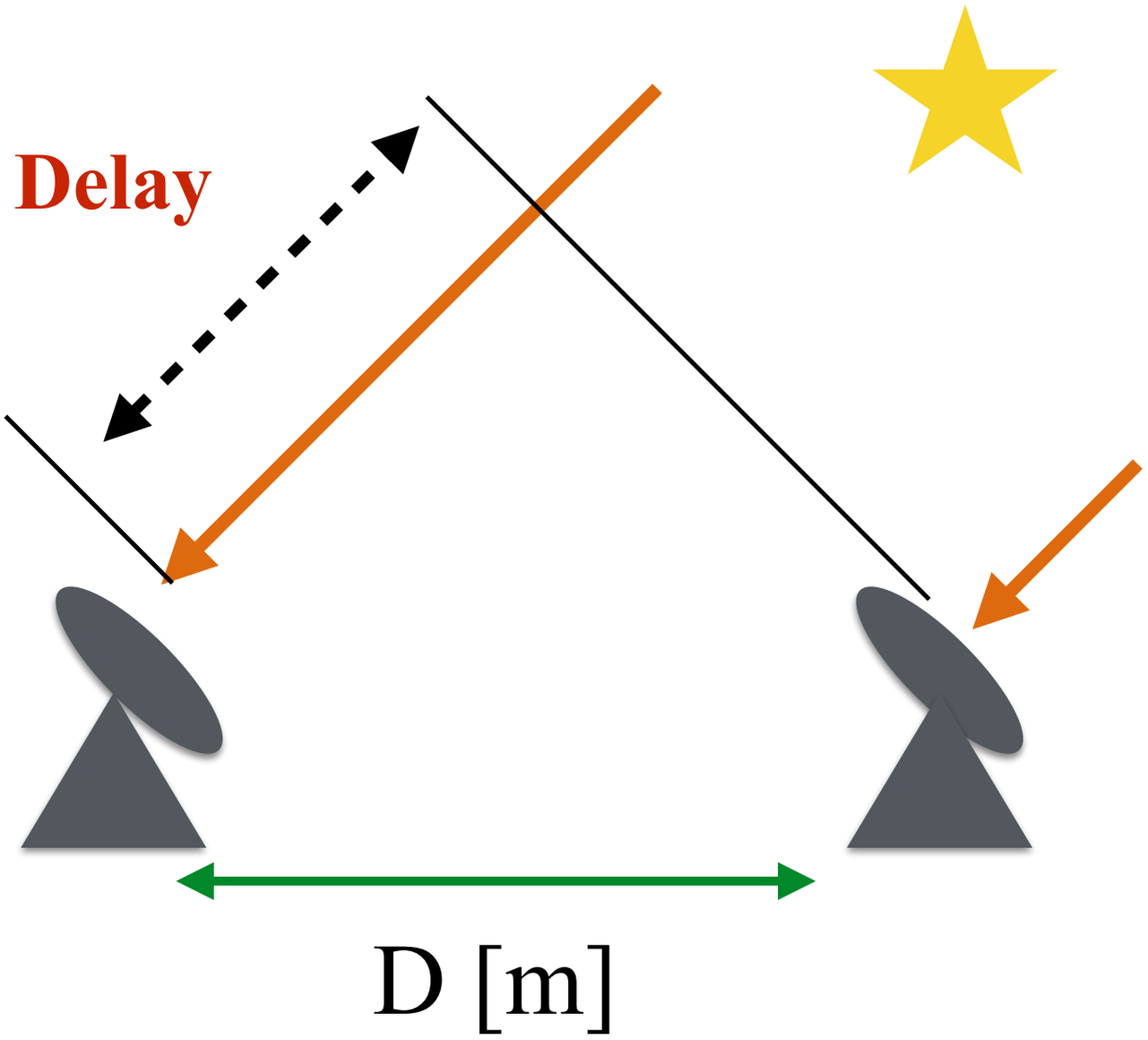
“Visibility”

↕ Fourier transform

“Brightness temperature”

Radio interferometer

The measurement by radio interferometer is based on **time delay** between antennae.



Resolution

$$\theta = \frac{\lambda}{D}$$

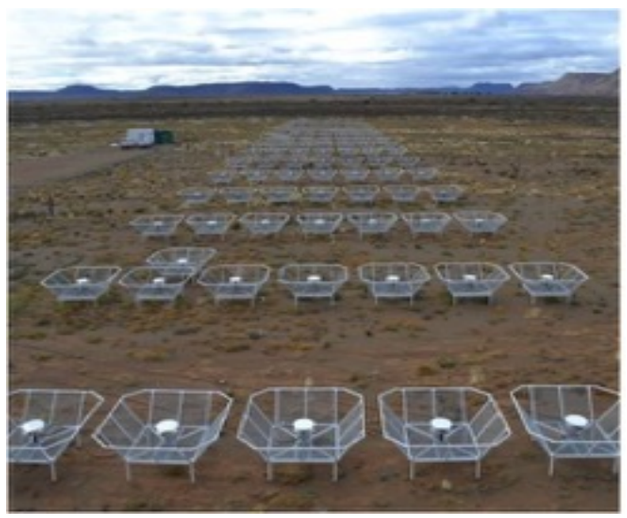
Sensitivity

$$\frac{\text{(effective collecting area)}}{\text{(thermal noise)}}$$

Current observations

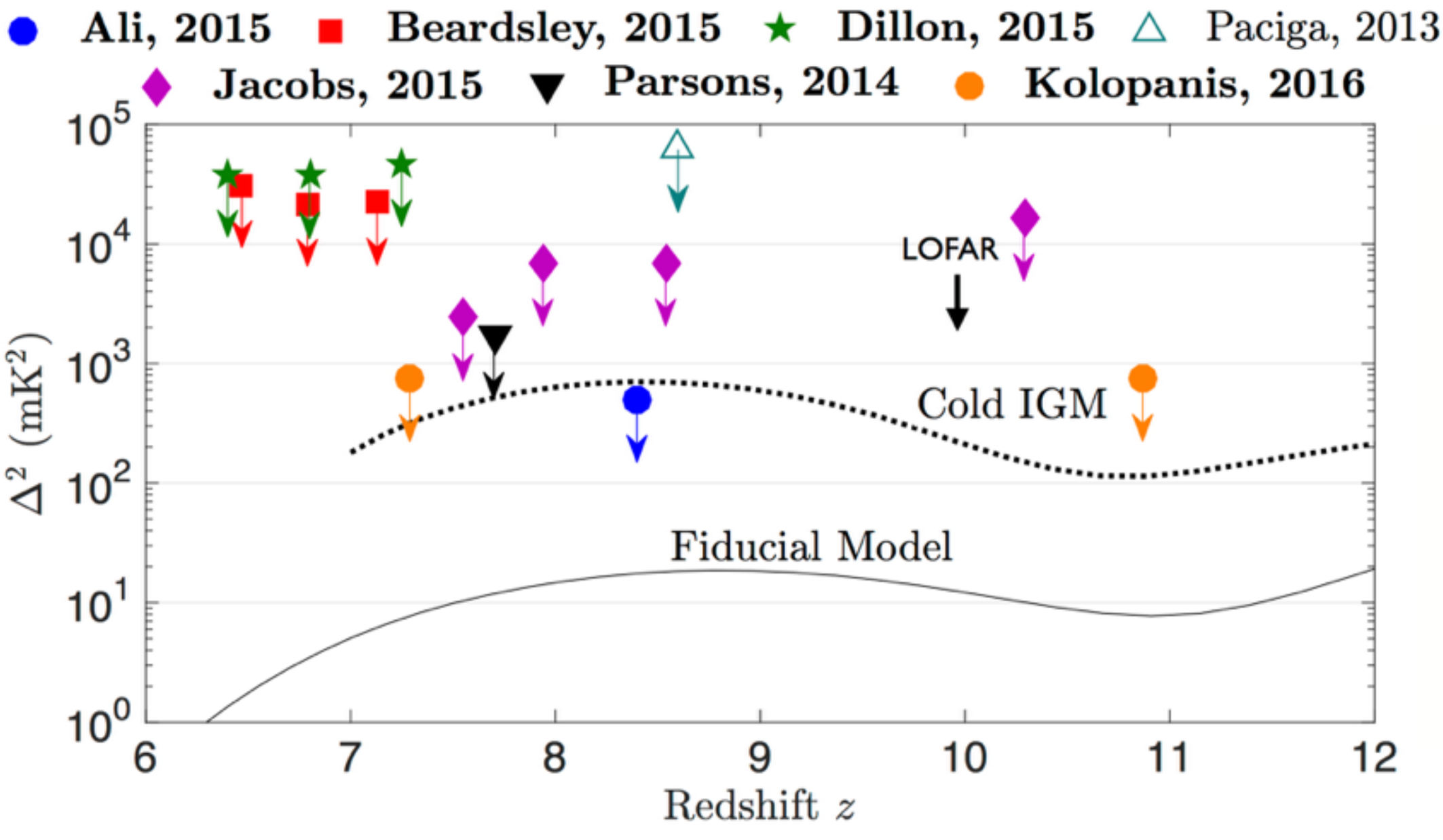
- **MWA** (Australia)
- z=6-11.4
- Resolution : 2 arcmin
- Array diameter : ~3km
- Effective collecting area : 3500 m^2

- **LOFAR** (Netherlands)
- z=7-12
- Resolution : 3 arcmin
- Array diameter : ~2km (core)
- Effective collecting area : 18000 m^2



- **PAPER** (South Africa, USA)
- z=7-12
- Resolution : 30 arcmin
- Array diameter : ~200m
- Effective collecting area : 1100 m^2

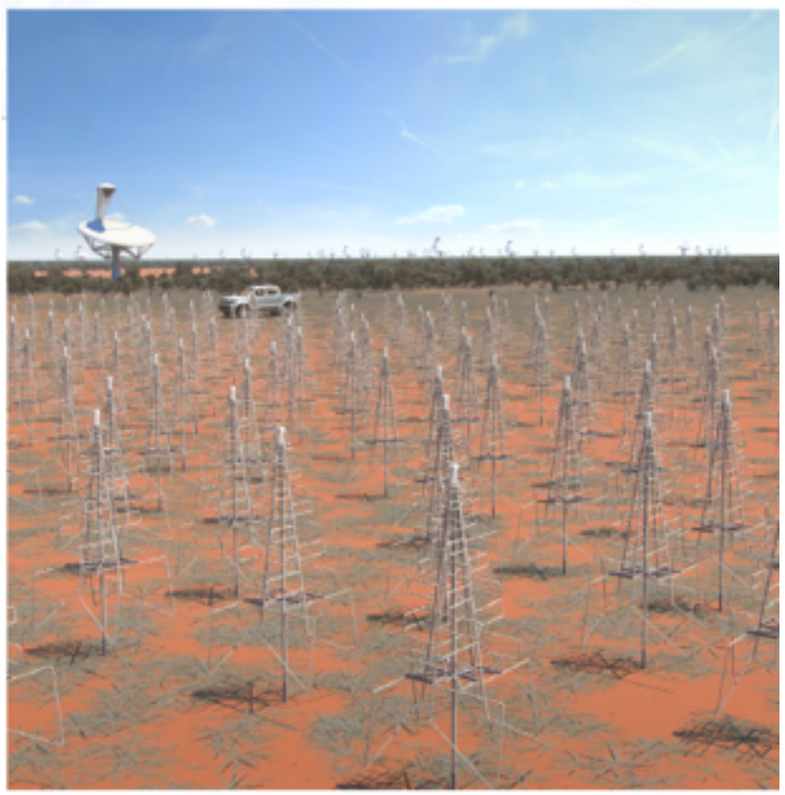
Current upper limits on 21cm PS



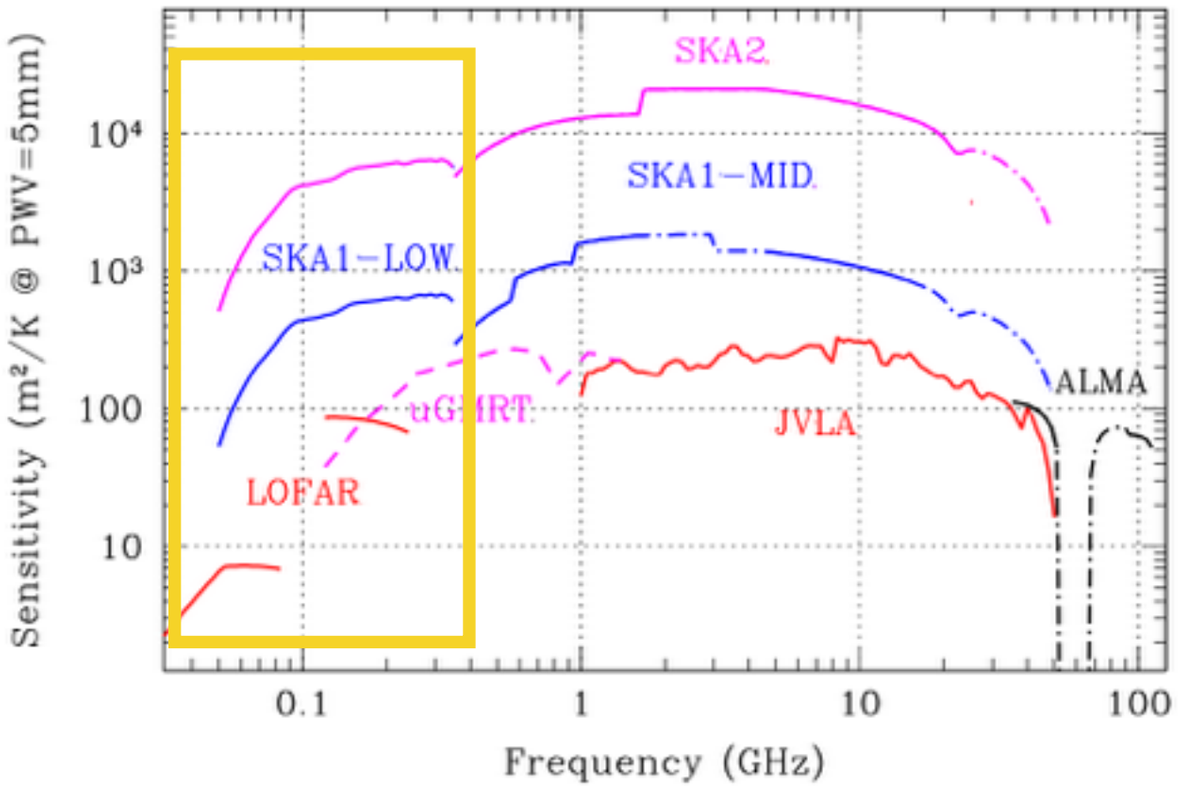
Pritchard's talk

$k \sim 0.2\mathrm{Mpc}^{-1}$

SKA



- **SKA** (Australia)
- z=6-28
- Resolution : ~7 arcsec
- Array diameter : ~80km
- Effective collecting area : ~300’000 m^2



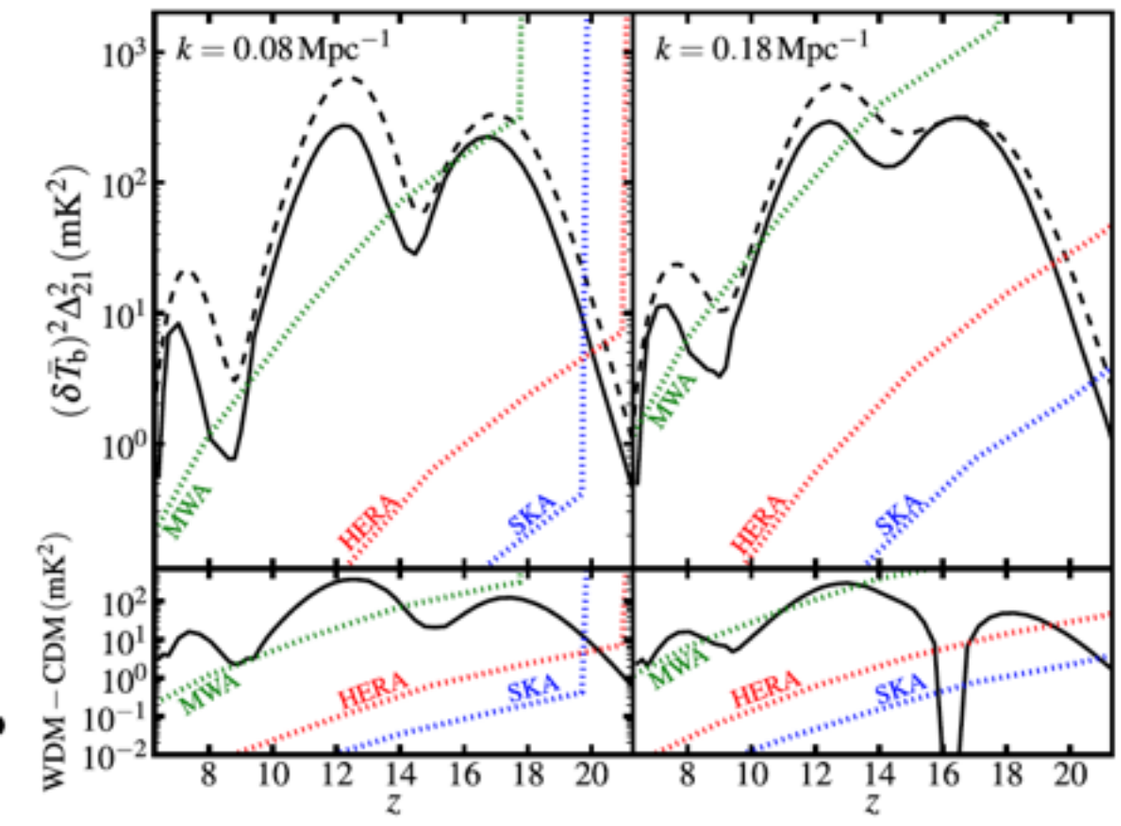
High resolution

&

High sensitivity

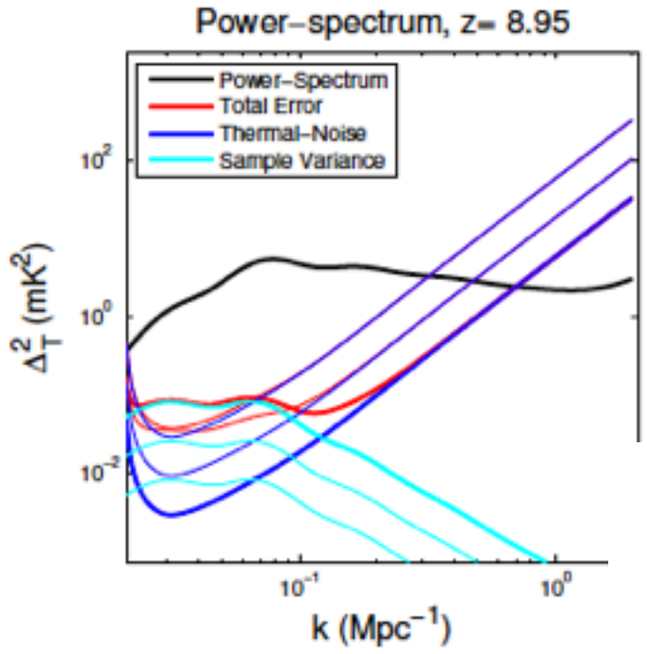
21cm PS with SKA

Redshift evolution



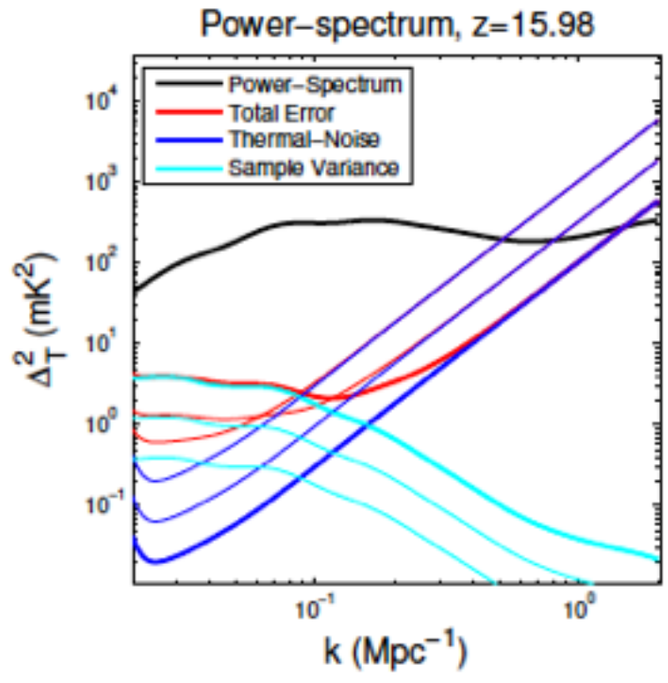
Pritchard et al. (2014)

Scale dependence



z=8.95

Koopmans et al. (2014)

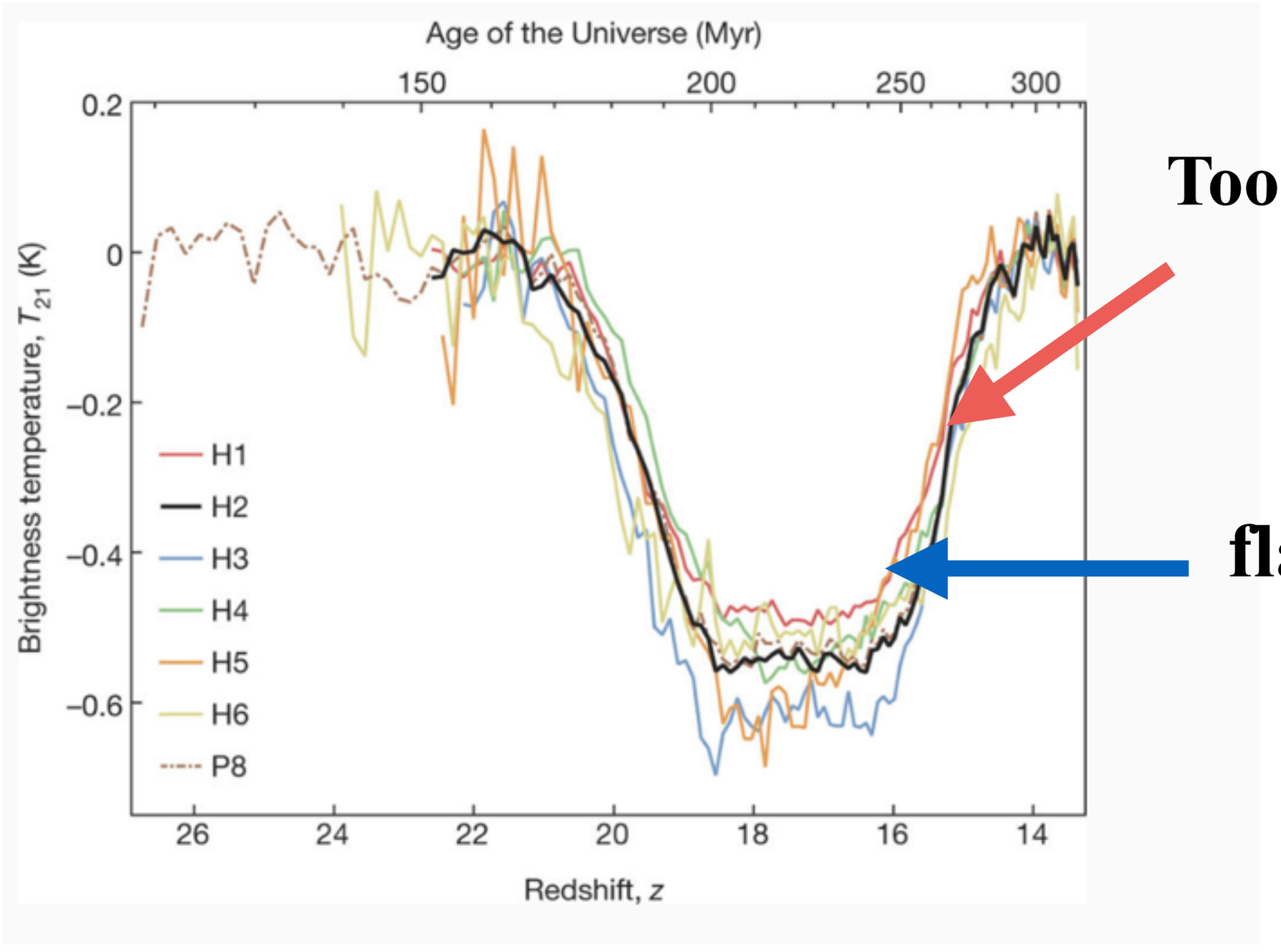


z=15.98

SKA covers wide epoch and range of the 21cm PS !!

We did it ?

EDGES (Bouman et al 2018)



Too deep trough

flatten trough

We did it ?

EDGES (Bouman et al 2018)

Exotic physics ?

Foreground?

Systematic error?

Did we detect the 21cm global signal ?

We need to wait for other experiment results, but….

We need to wait for other experiment results, but….

The era of 21cm cosmology is around the corner !

References

•SKA science books (https://www.skatelescope.org/books/)

• SKA-JAPAN science book (in JAPANESE) (http://ska-jp.org/science.html)

•Japanese Cosmic Dawn/Epoch of Reionization Science with the Square Kilometre Array (arxiv:1603.01961)

Summary

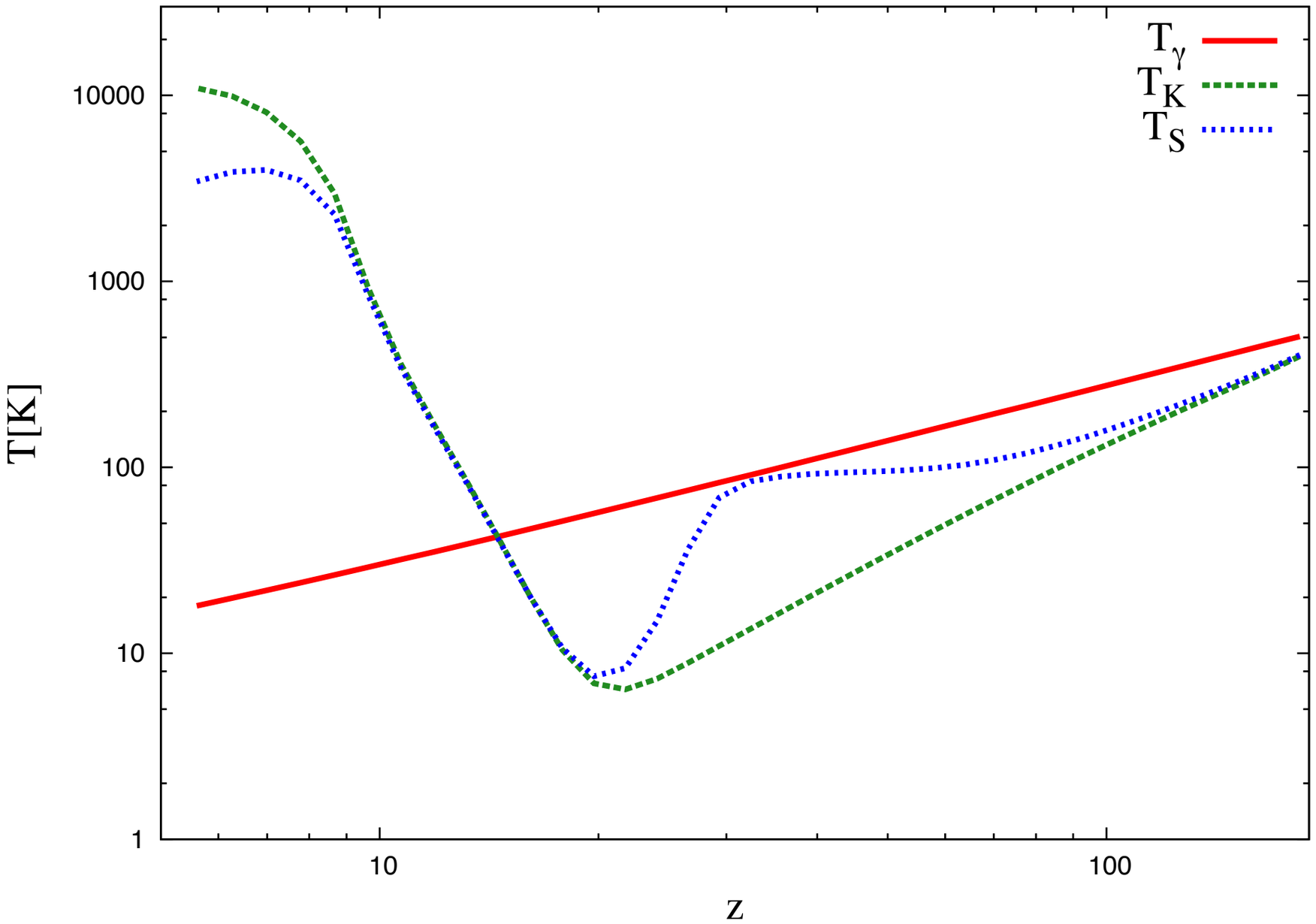
- **Cosmic dawn and EoR are milestones of the Universe.**

- **The 21cm signal will open the window and give fruitful information on cosmic dawn and EoR.**

- **Some on-going and future observations target to detect 21cm signal.**

Backup

Spin temperature



Component of 21cm PS