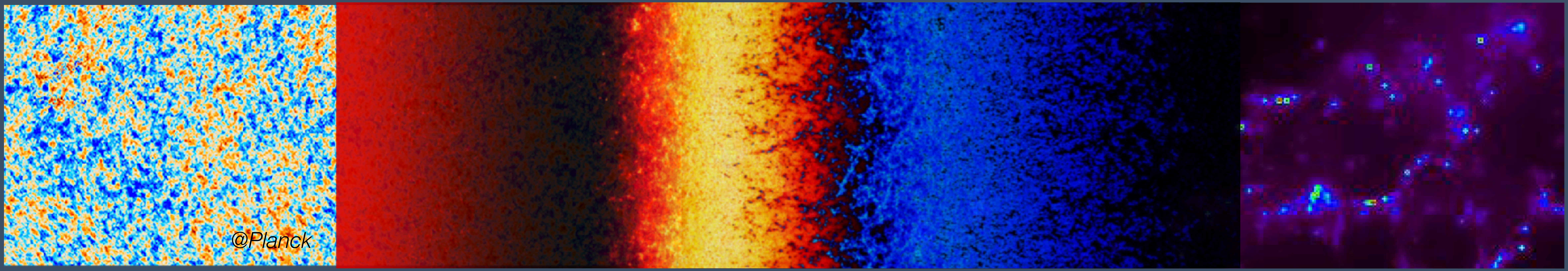


# Unveiling Cosmology through Cosmic Backgrounds

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Heidelberg University, Advanced Cosmology

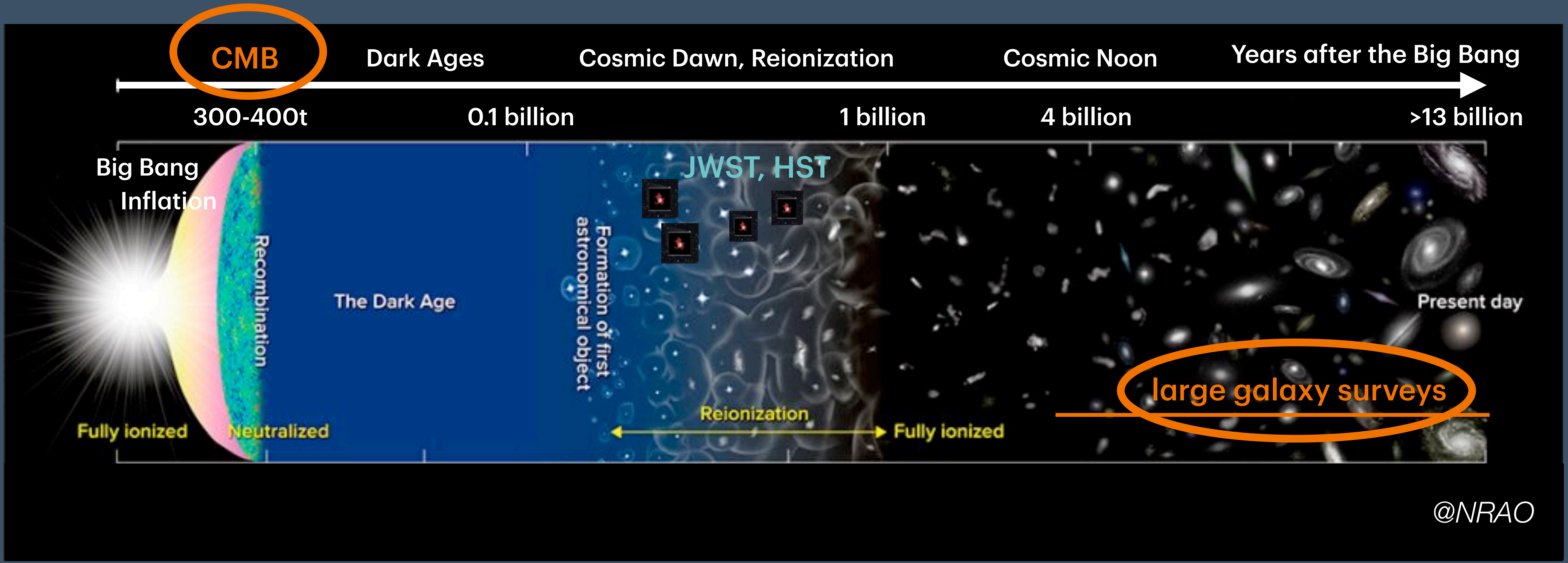
May 9th & May 16th 2025

**Cosmic Backgrounds**

- Microwave
- Gravitational Wave
- Neutrino
- Radio
- Emission Lines
- Infrared

I. Basics: LSS & Backgrounds
II. Basics: 21cm Background
III. 21cm Cosmology
IV. New methods: ML/AI
V. Outlook Line Mappings

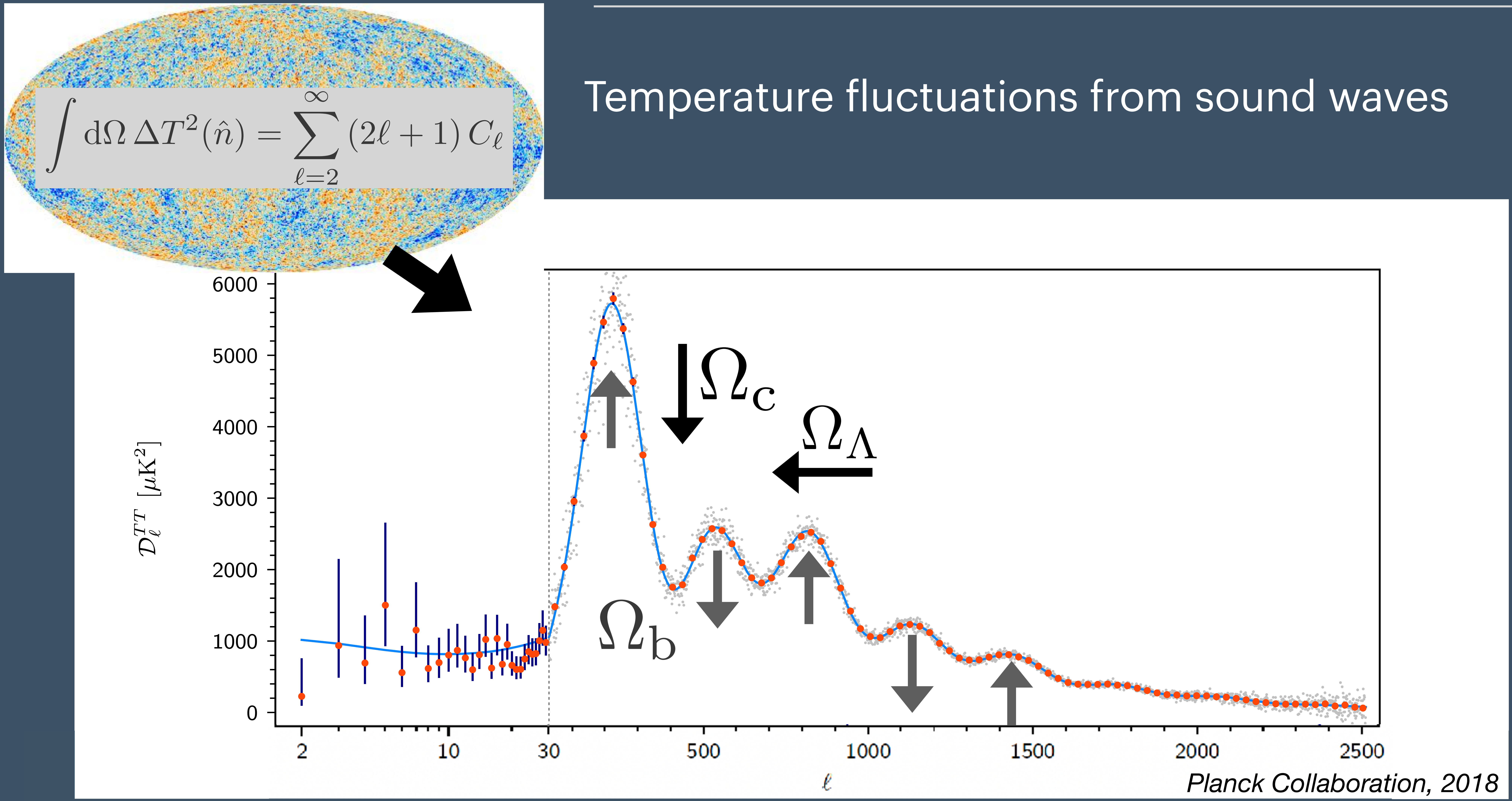
# I. Cosmic evolution




Where information on cosmology comes from.

Temperature fluctuations from sound waves

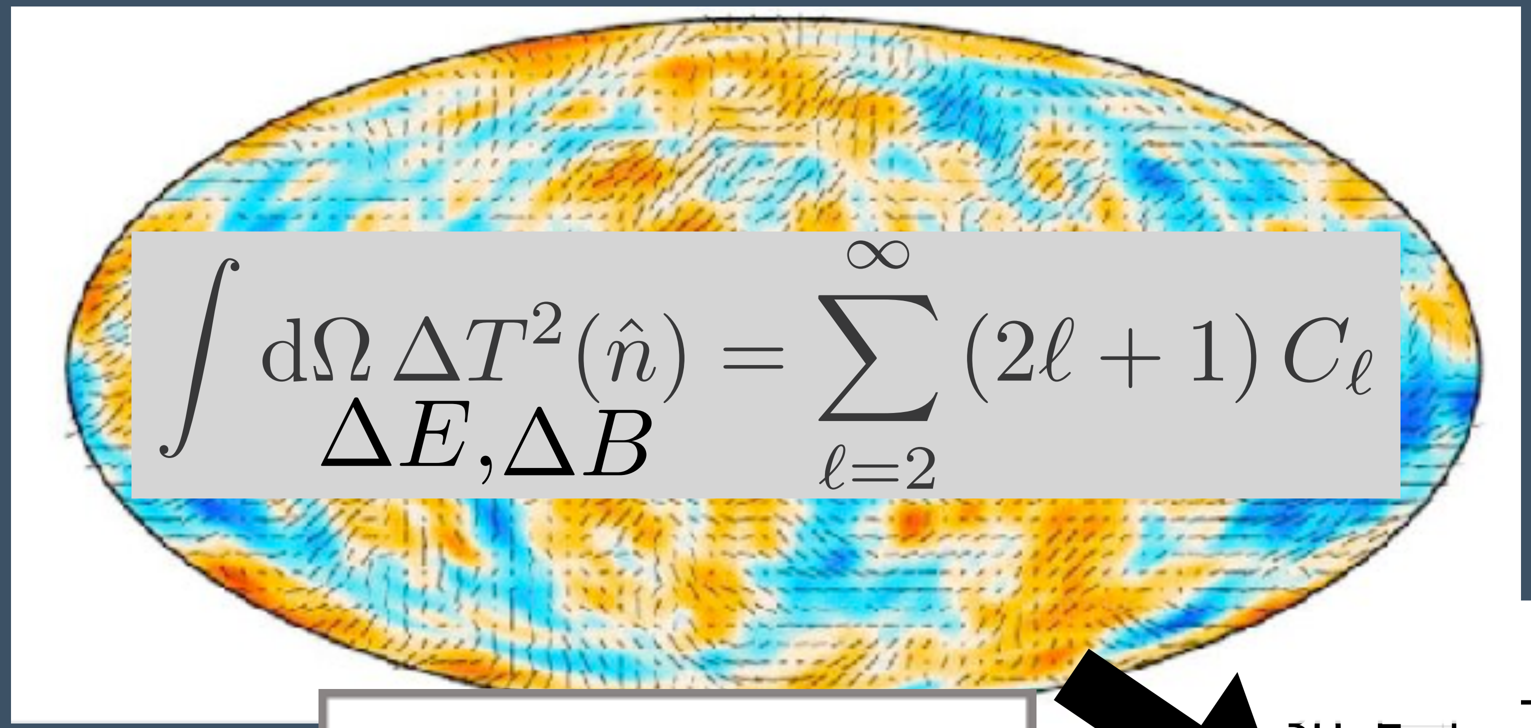
$$\int \mathrm{d}\Omega\, \Delta T^2(\hat{n}) = \sum_{\ell=2}^{\infty} (2\ell+1)\, C_\ell$$




*Planck Collaboration, 2018*

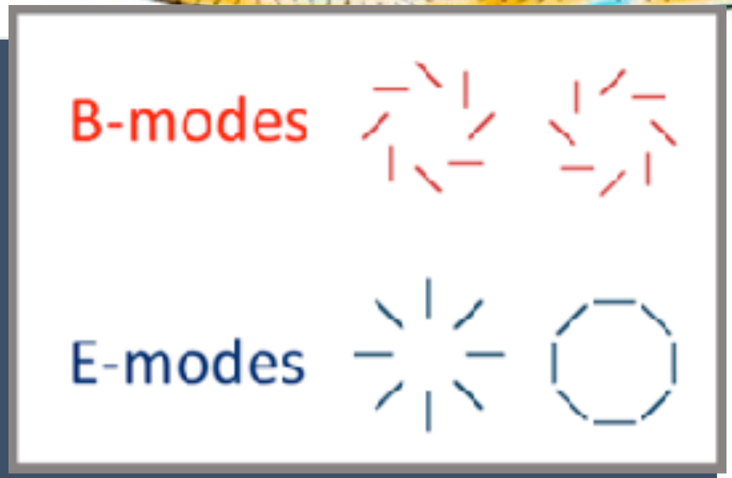
Cosmological parameters = $\Omega_\mathrm{b}, \Omega_\mathrm{c}, \Omega_\Lambda, \ldots$

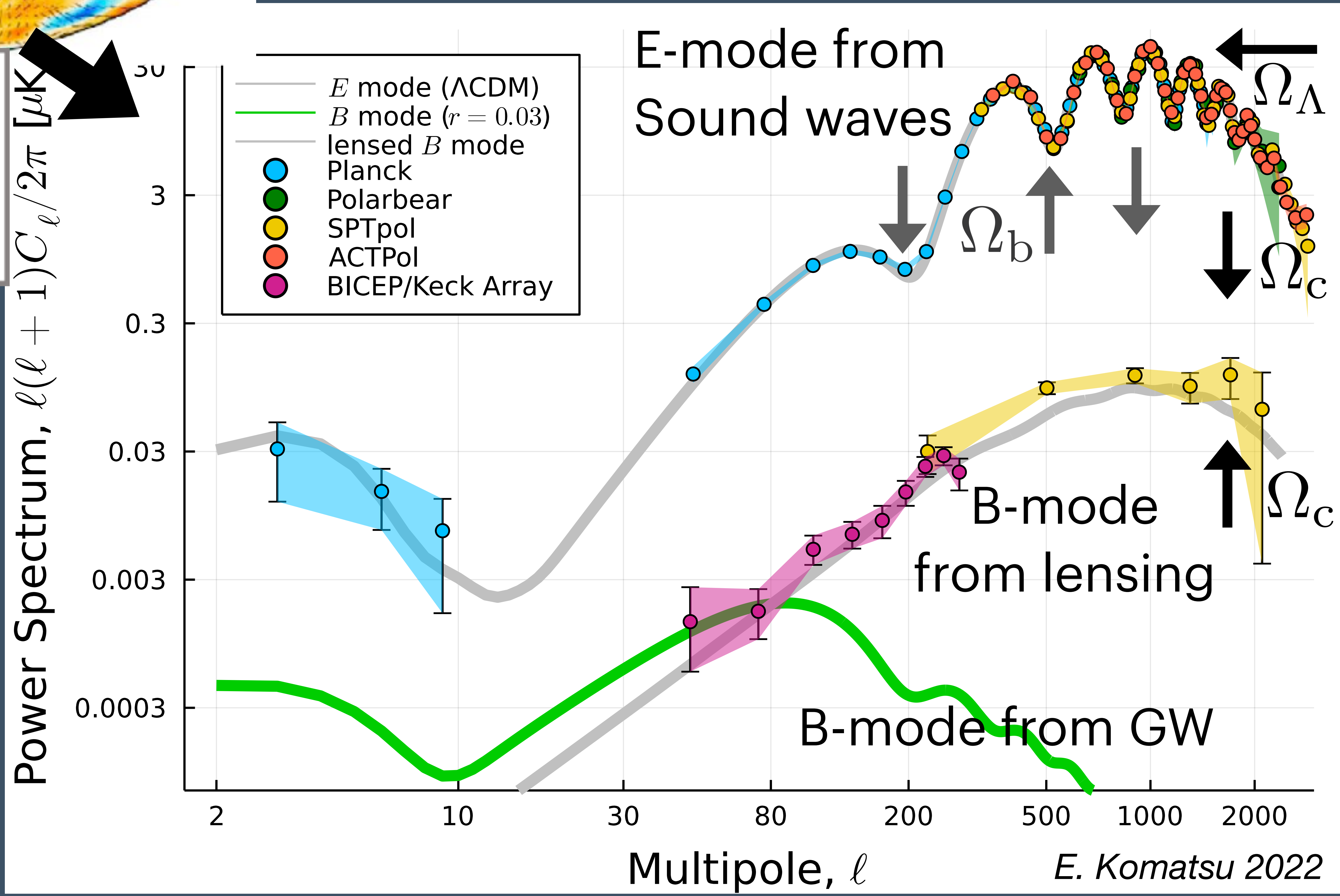
# I. Cosmic Microwave Background



$$\int_{\Delta E,\Delta B} \mathrm{d}\Omega\, \Delta T^2(\hat{n}) = \sum_{\ell=2}^{\infty} (2\ell+1)\, C_\ell$$

Polarisation fluctuations



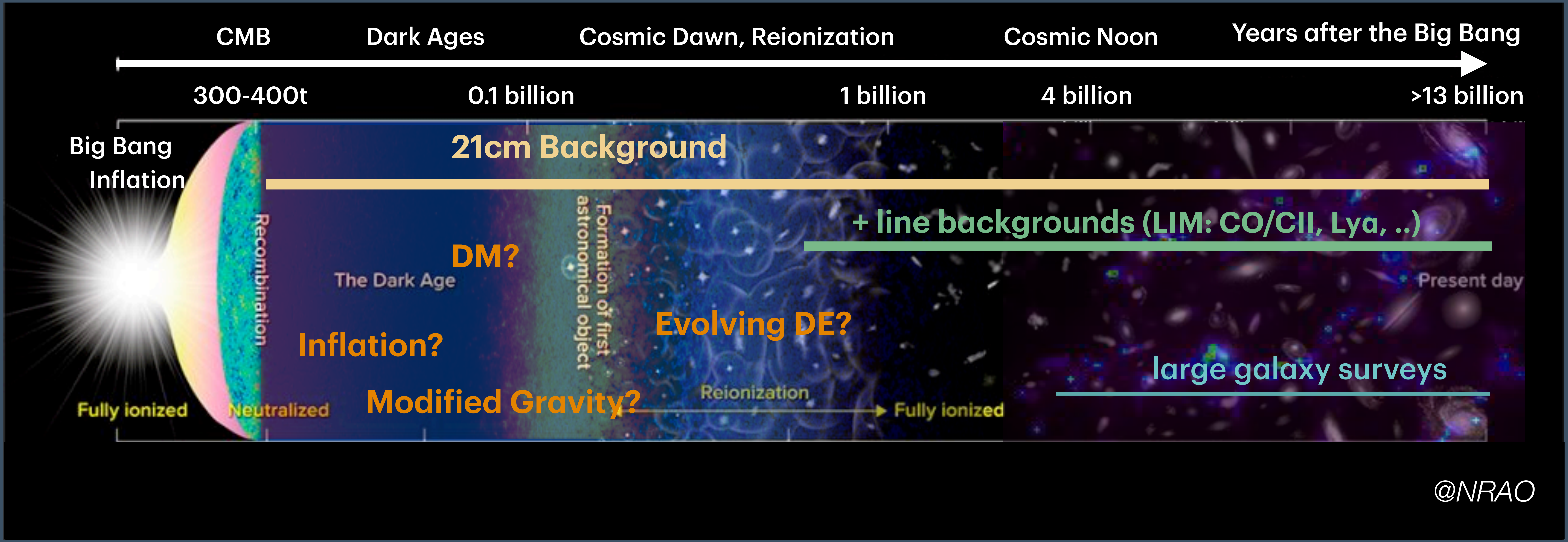




(+ integrated quantities)

**Cosmic Backgrounds**

- Microwave
  CMB
- Gravitational Wave
  GW
- Neutrino
  CvB
- Radio
  ~~CRB~~ 21cm
- Emission Lines
  LIM
- Infrared
  CIB

# I. Cosmic evolution & new backgrounds




Map up to 80% of the observable Universe.

What is the Large-Scale-Structure? Distribution of matter

It emerges due to gravitational instability and its evolution is governed by cosmology.

Background - Friedmann eqs:

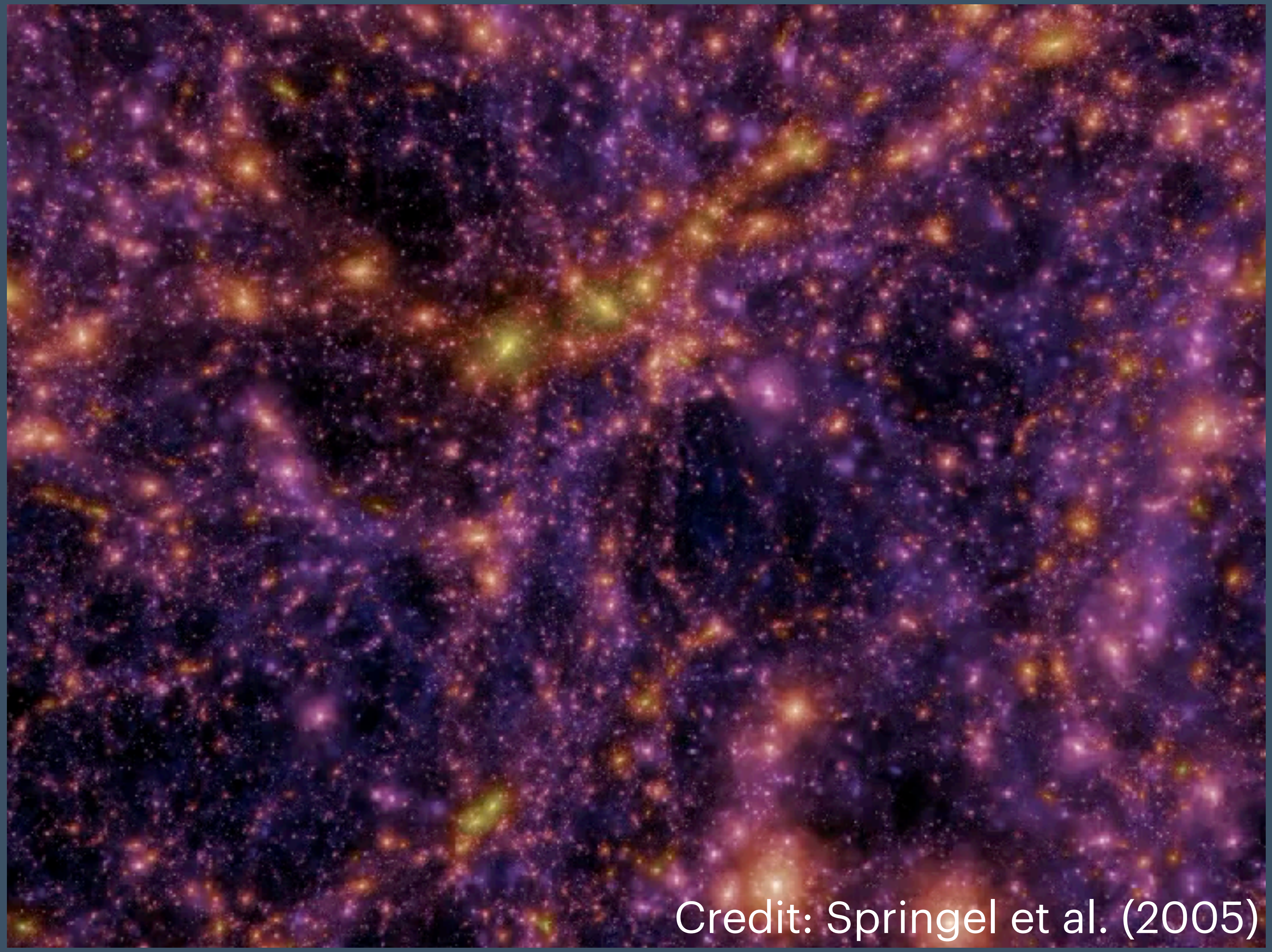
$$H^2(z) = \frac{8\pi G_{\rm eff}}{3}\rho_{\rm tot}(z)$$

Perturbations - fluctuations:

$$\frac{\partial \delta}{\partial t} + \nabla \cdot [(1+\delta)\mathbf{v}] = 0$$

$$\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v}\cdot\nabla)\mathbf{v} = -\frac{\nabla p}{\rho} - \nabla\Phi$$

$$\nabla^2\Phi = 4\pi G\rho\delta$$


Credit: Springel et al. (2005)

→ Key parameters:

$h_0, \Omega_{\rm b}, \Omega_{\rm c}, \Omega_{\rm r}, \Omega_\Lambda$

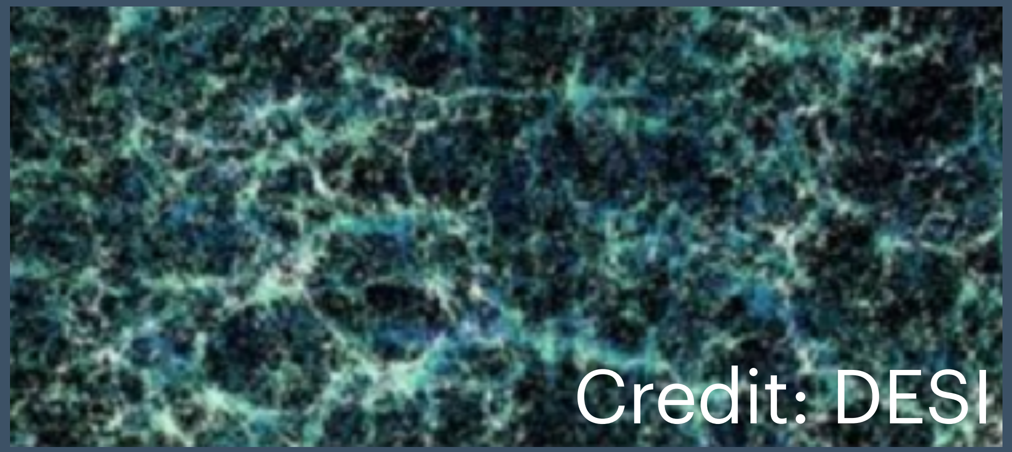
ΛCDM, $w_\Lambda = -1$

$w_0, w_a, G_{\rm eff}, Q, m_{\rm WDM}, \ldots$

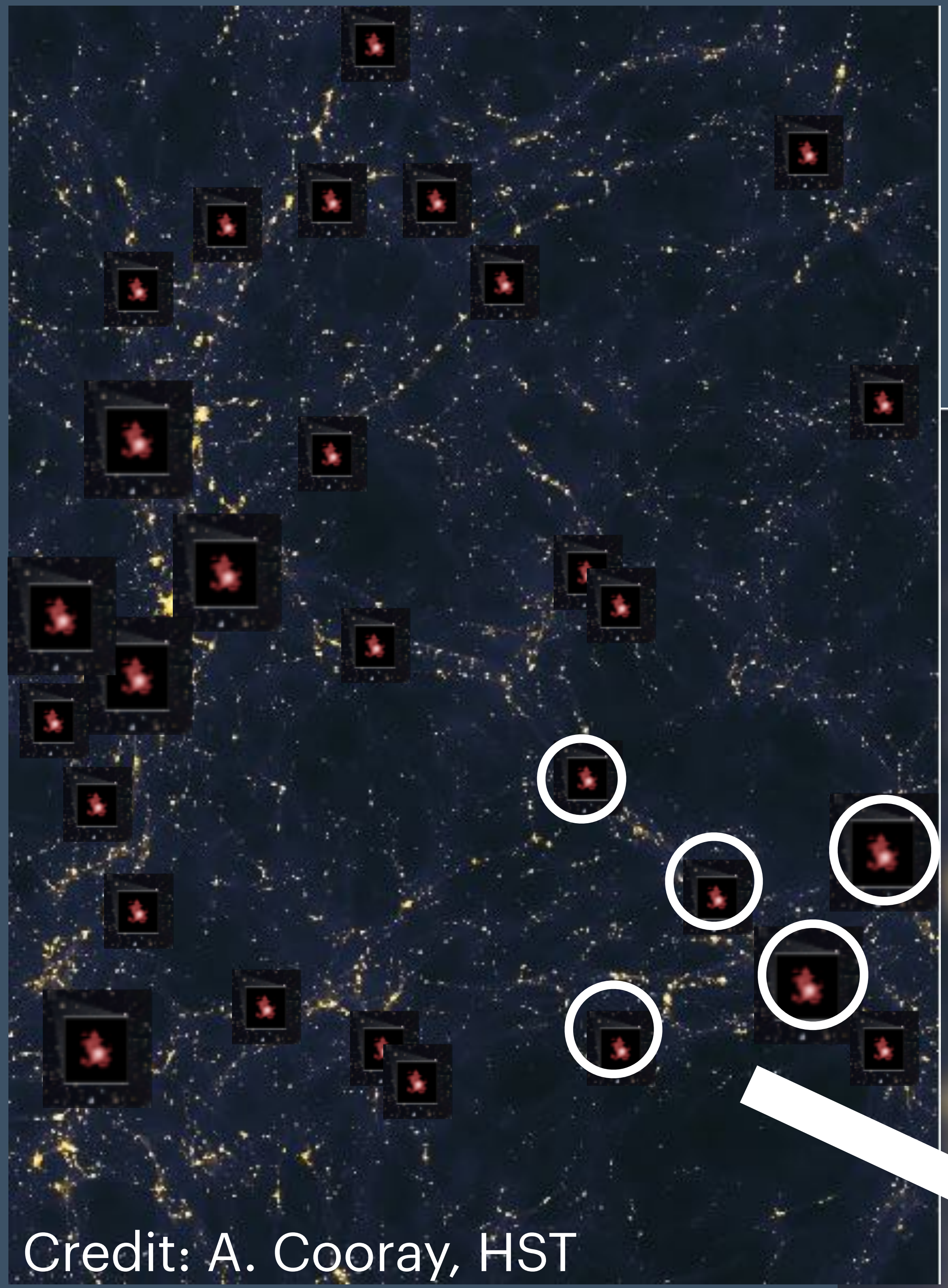
+ extensions: wCDM, MG, quintessence, warm DM, ...

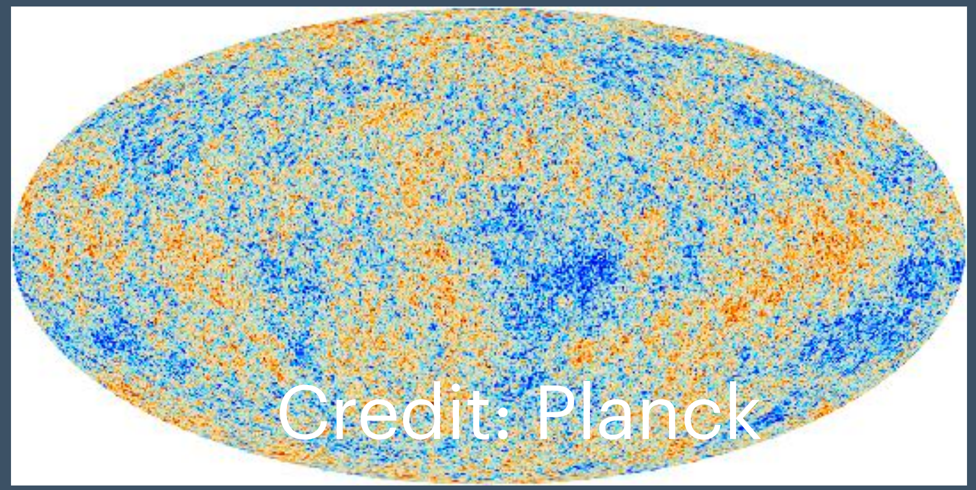
## What is the Large-Scale-Structure?

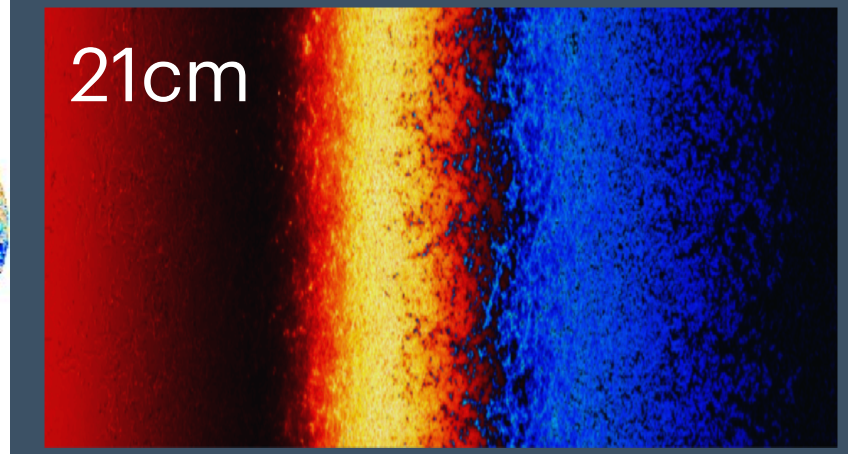
Distribution of gas + sources.


Credit: DESI

A) Individual sources
~ peaks in the DM field


Credit: A. Cooray, HST


Credit: Planck




B) Intensity Mapping
~ tracer of fluctuations

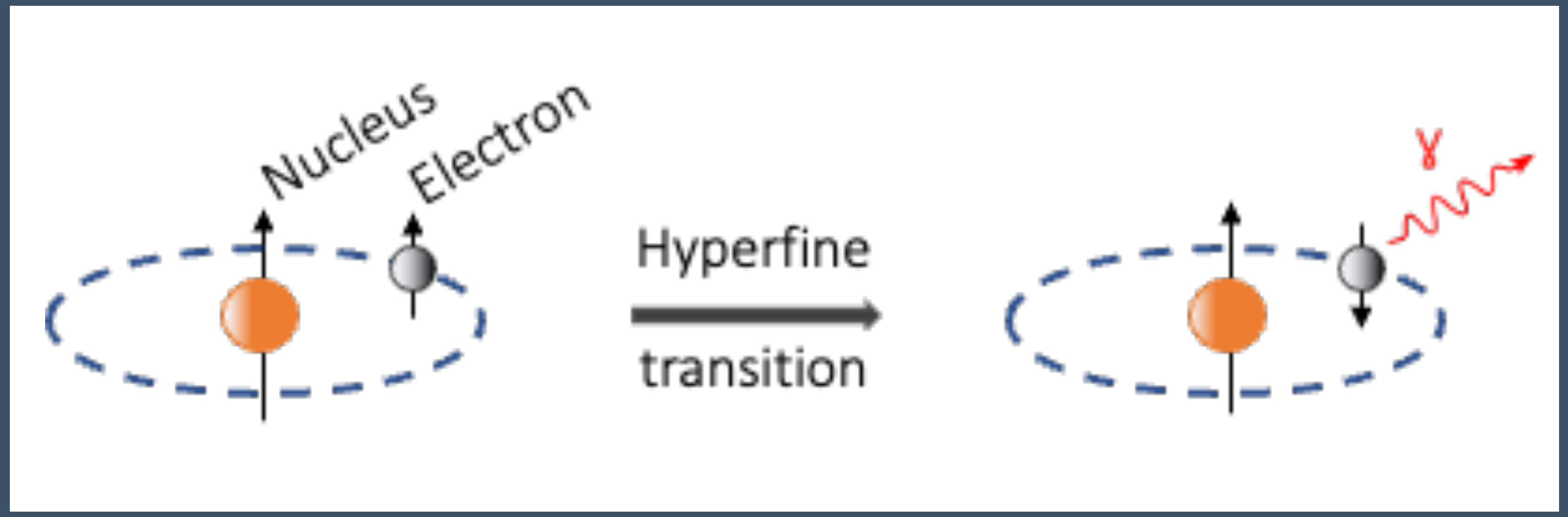

Credit: A. Cooray

Cosmic Backgrounds trace the LSS of the Universe.

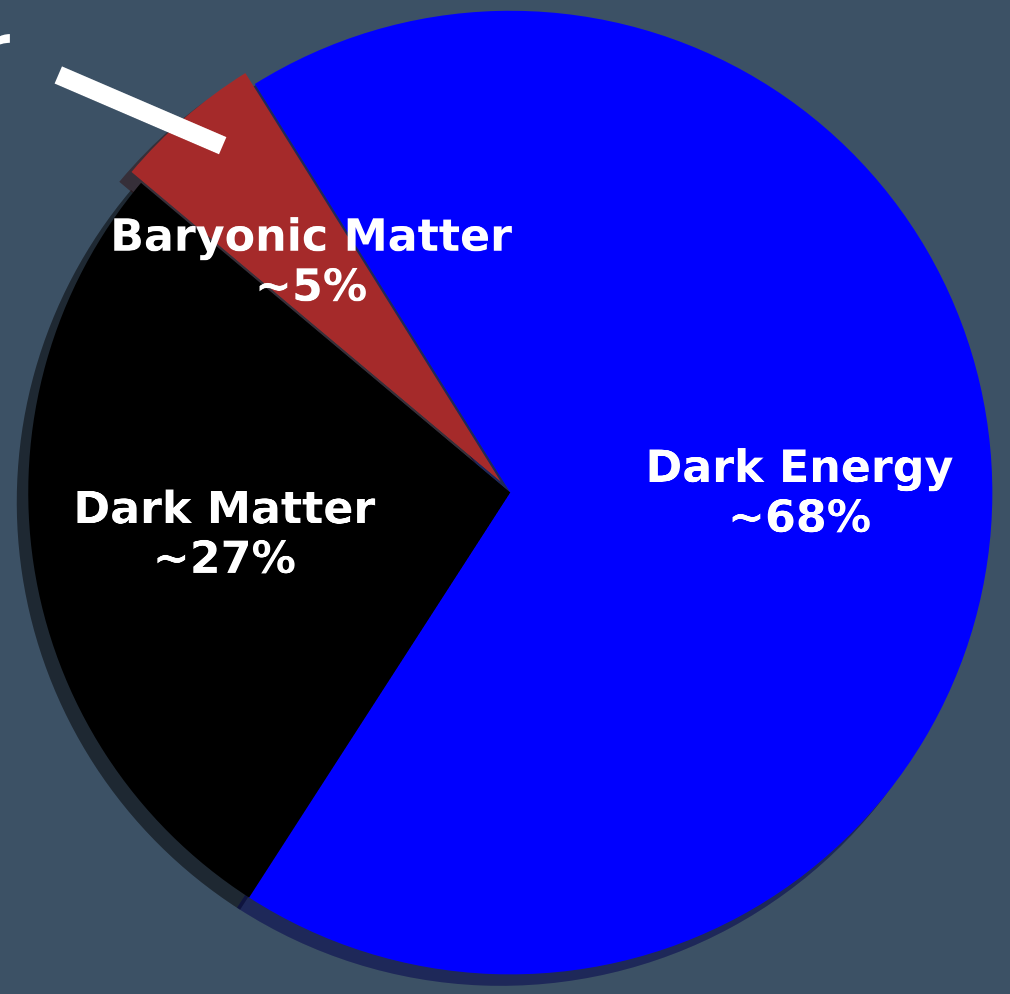
Their structure and evolution is sensitive to cosmology.

# The Cosmic 21cm Background

Hydrogen = 74% of baryonic matter

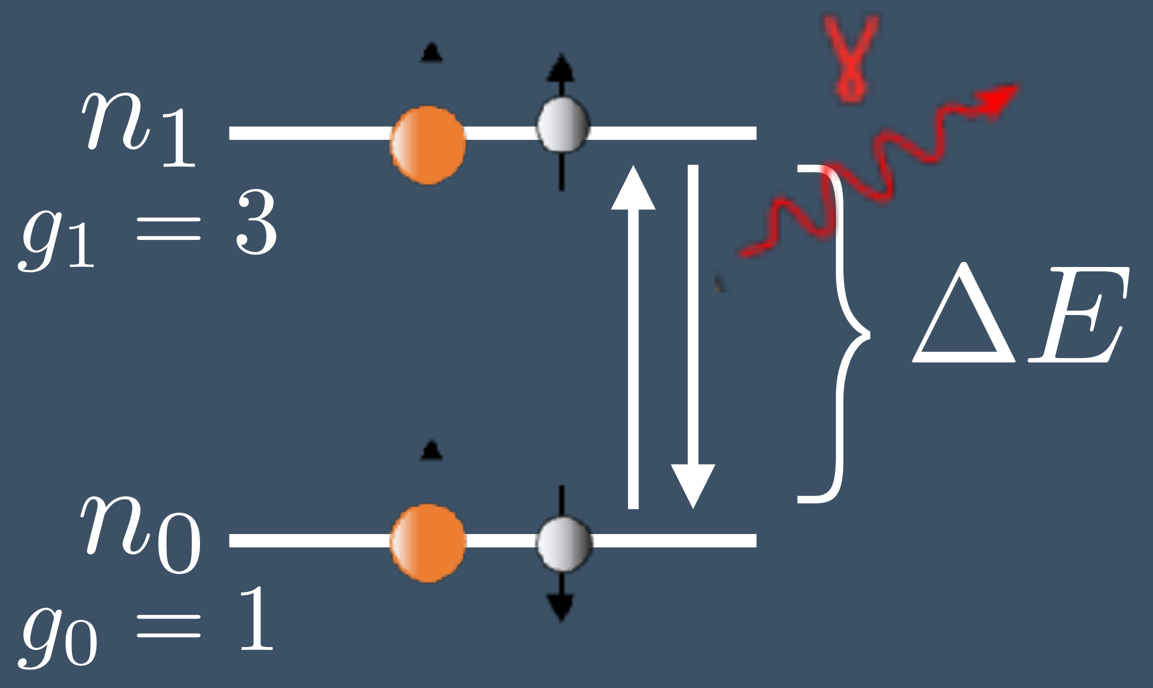



λ ~ 21 cm
ν ~ 1.42 GHz




Spin Temperature in thermodynamic equilibrium:

$$\frac{n_1}{n_0} = \underbrace{\frac{g_1}{g_0}}_{=3} \exp\left(-\frac{\Delta E}{k_\mathrm{B} T_\mathrm{S}}\right)$$



Cosmology

**3 main couplings:**

1. Absorption & stimulated emission γ's $\xrightarrow{\text{CMB}}$ $T_\gamma\ (\Omega_b h^2, \Omega_c h^2, \theta_s, \tau, n_s, \ln(10^{10} A_s))$
2. (De-)excitation (other HI, e⁻, p) via collisions $\longrightarrow$ $\rho_b, \delta_b, H(z)$
3. Lyman-alpha coupling (Wouthuysen 1952, Field 1959) $\longrightarrow$ $T_k\ (\rho_b, \delta_b, H(z), \delta_m)$

+ spontaneous emission 1 spin-flip per 10 Mio. years per hydrogen

$$(A_{10} = 2.85 \times 10^{-15}\,\mathrm{s}^{-1})$$

$$n_{\mathrm{H}}(z) = \frac{\boxed{\rho_{\mathrm{b}}}}{m_{\mathrm{p}}}(1 - Y_{\mathrm{He}})(1+z)^3 \approx 0.19\,(1+z)^3\ [\mathrm{atoms/m^3}]$$

In practice, 3 processes are important for the Ts evolution:

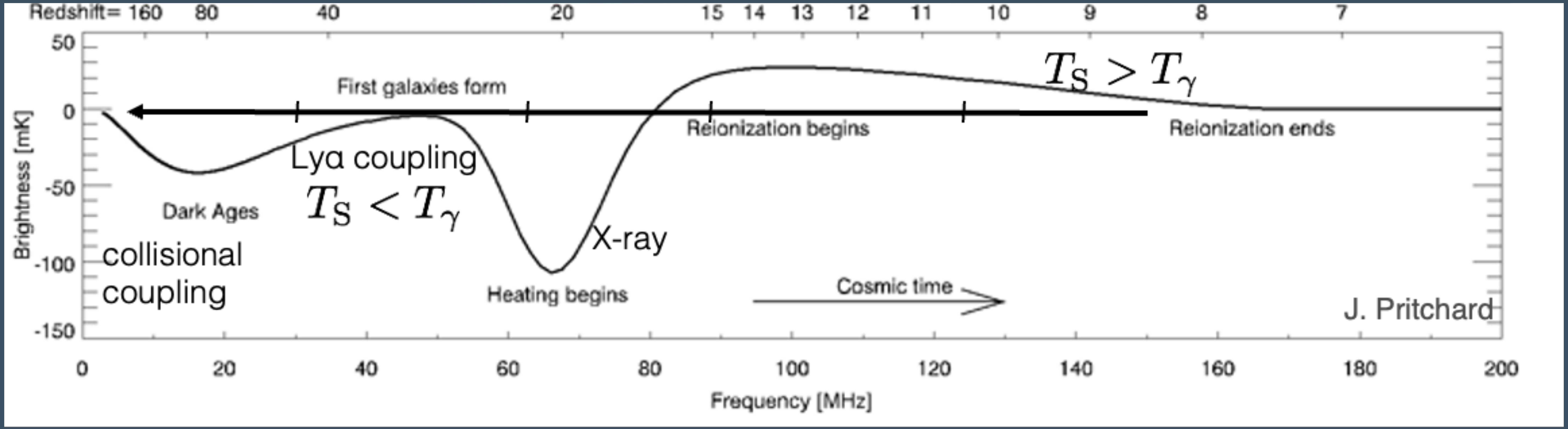
- Absorption & stimulated emission by CMB γ's
- Collisions for (de-)excitation (other HI, e$^-$, p)
- Lyman-alpha coupling (Wouthuysen 1952, Field 1959)

+ spontaneous emission: 1 spin-flip per 10 Mio. years

Reminder redshift:

$$\lambda(z) = \lambda_0(1+z)$$

$$\nu(z) = \frac{\nu_0}{(1+z)}$$



# All the spin-flips

How many spin-flips right now (~s) in the observable Universe?

A) >> Planck event rate of $1/t_{Pl} \sim 10^{43}$ events/s.

B) Well, which cosmology?

C) << Planck event rate of $1/t_{Pl} \sim 10^{43}$ events/s.

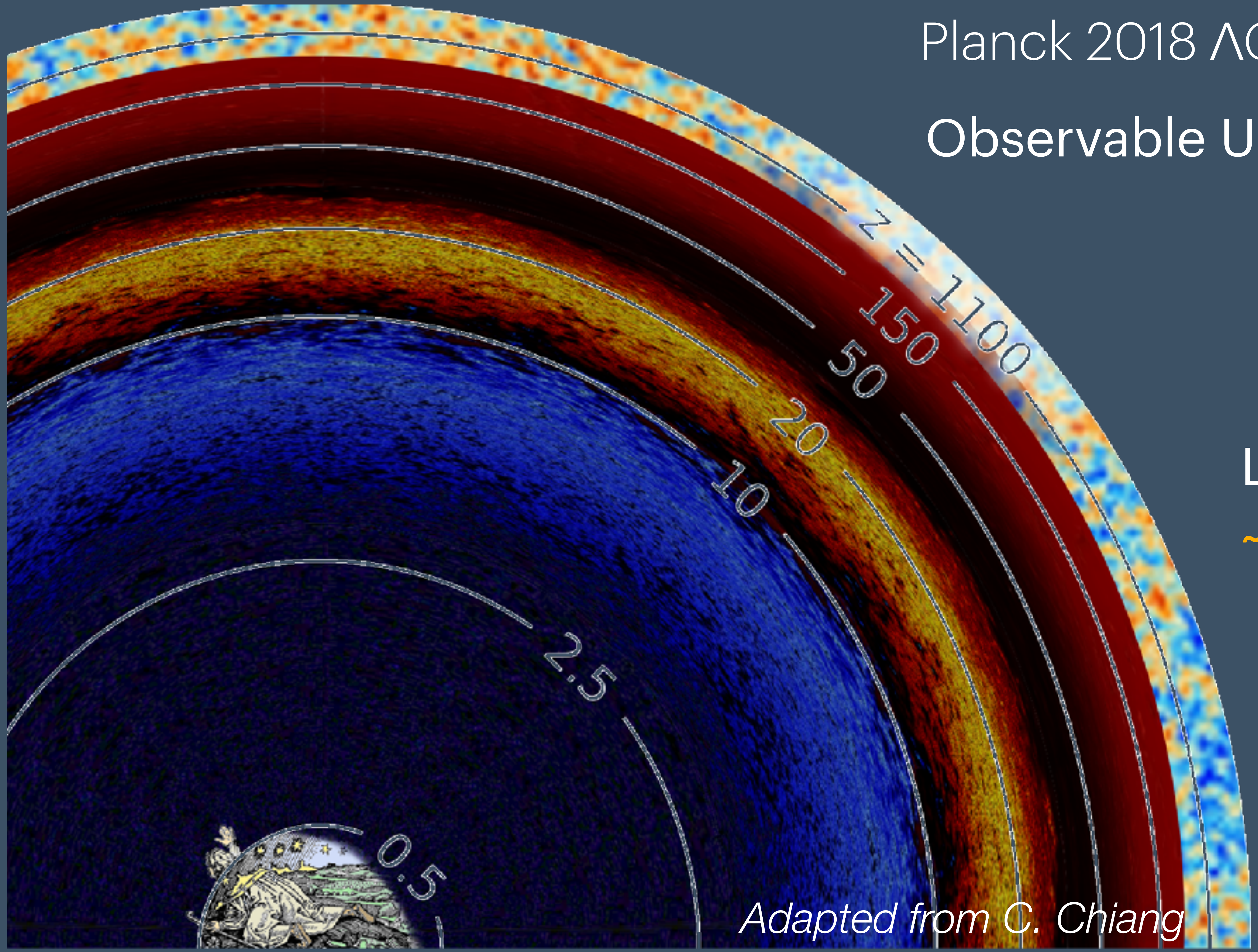
D) Not sure without the size of the observable Universe.

+ spontaneous emission ~$10^{-15}$ flips/atom/s:

$$n_{\mathrm{H}}(z) = \frac{\rho_{\mathrm{b}}}{m_{\mathrm{p}}}(1 - Y_{\mathrm{He}})(1+z)^3 \approx 0.19\,(1+z)^3 \;\; [\mathrm{atoms/m^3}]$$

# Size of the Universe

What does a map of ~80% of the observable Universe even mean?



Adapted from C. Chiang

Planck 2018 ΛCDM

Observable Universe d ~ 28 Gpc (~100 Gly)

1 ly ~ $10^{16}$ m

Let's say we resolve only Mpc:
~ $10^{9}$ - $10^{10}$ modes measured!

# All the spin-flips

How many spin-flips right now (~s) in the observable Universe?

A) >> Planck event rate of $1/t_{Pl} \sim 10^{43}$ events/s.

B) Well, which cosmology?

C) << Planck event rate of $1/t_{Pl} \sim 10^{43}$ events/s.

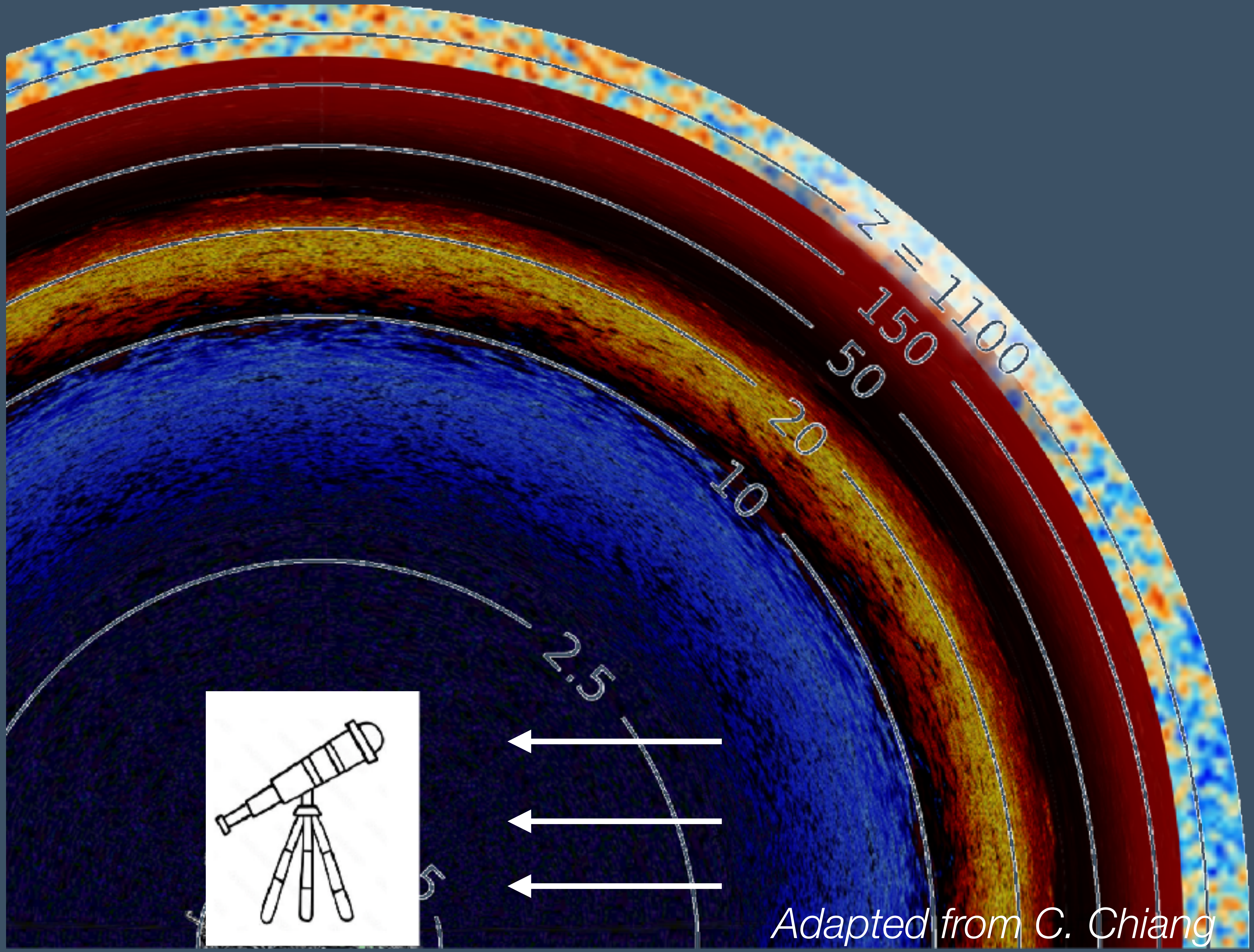
D) Not sure without the size of the observable Universe.

+ spontaneous emission $\sim 10^{-15}$ flips/atom/s:

$$n_{\rm H}(z) = \frac{\rho_{\rm b}}{m_{\rm p}}(1 - Y_{\rm He})(1+z)^3 \approx 0.19\,(1+z)^3\ \left[\underline{\rm atoms/m^3}\right]$$

How does the signal depend on cosmology?

... and how **much of it reaches us?**



21cm background: Tracer of neutral hydrogen (HI)

Which cosmological properties influence the 21cm Background?

A) Background $H(z)$.

B) Background $H(z)$, $\Omega_m$, and density fluctuations $\delta_b$.

C) Background $H(z)$ and matter density parameter $\Omega_m$.

D) Can't tell without cosmological model.

## 21cm background: Tracer of neutral hydrogen (HI)

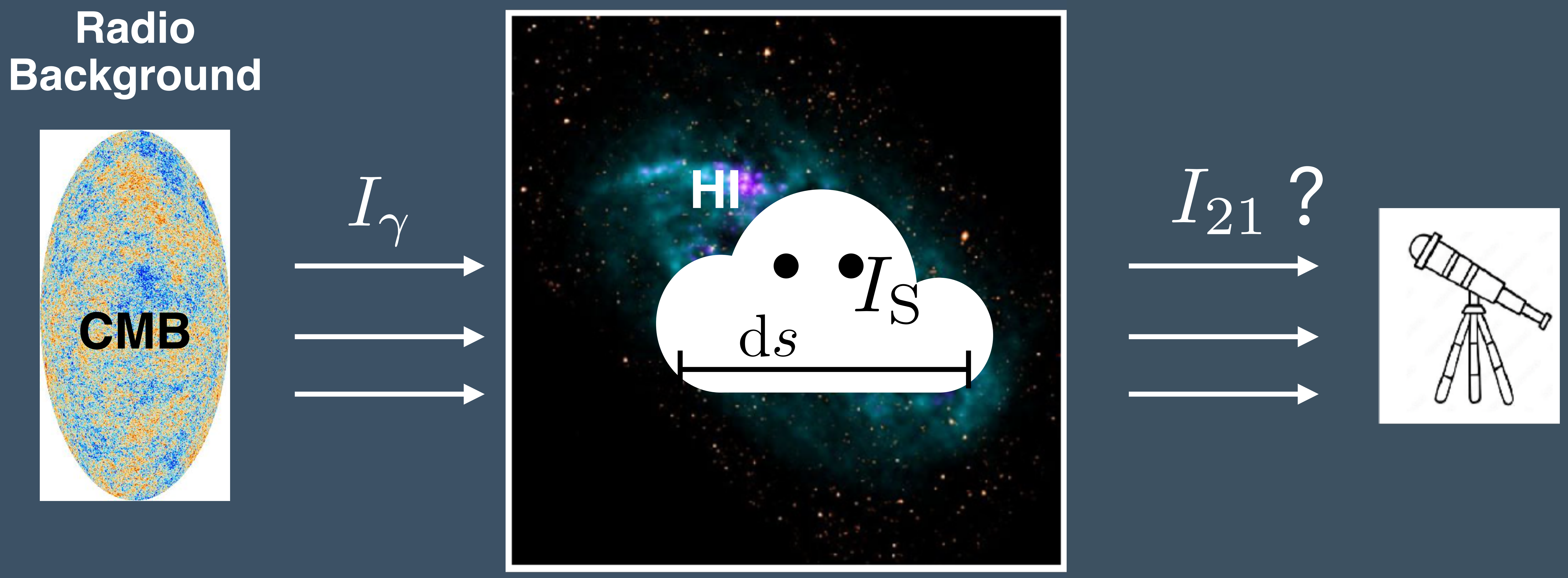

$I_\nu$ = specific intensity (spectral radiance) $[\mathrm{W/m^2/sr/Hz}]$

REMINDER

Rayleigh-Jeans law:

$$I_\nu(T) = \frac{2\nu^2 k_\mathrm{B} T}{c^2}$$

## Radiative transfer for brightness $I_{21}$

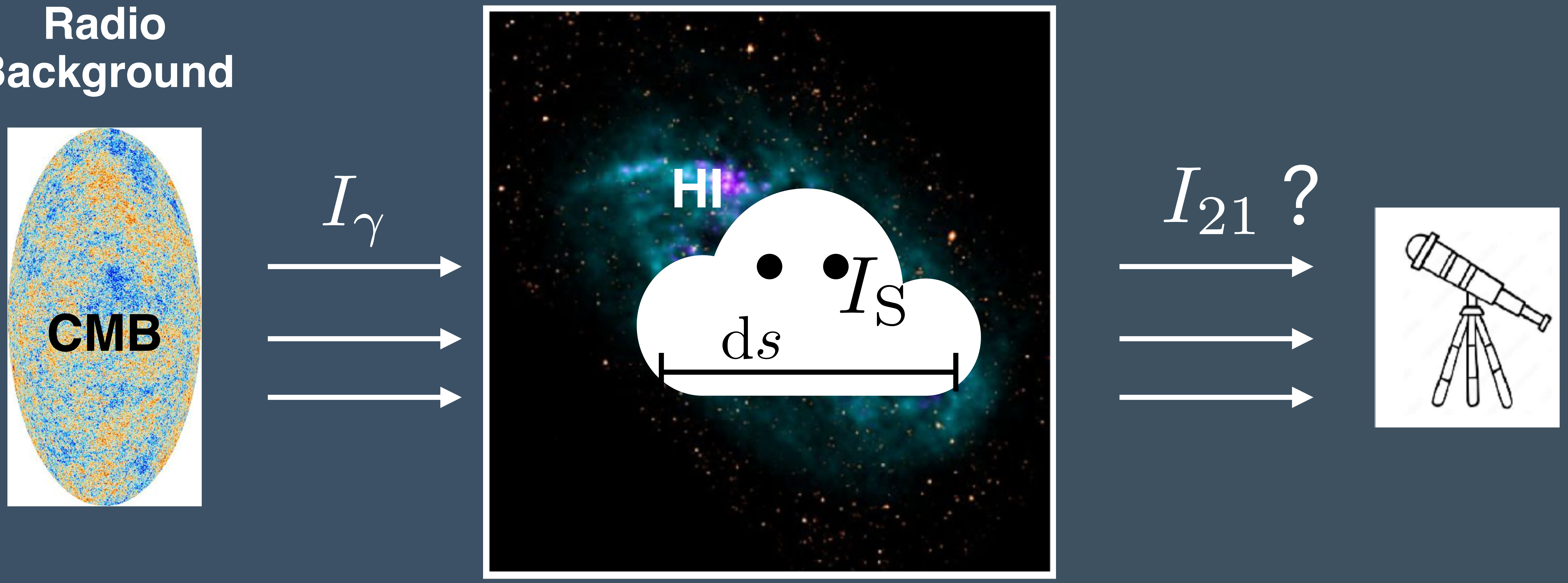



$$\boxed{\frac{\mathrm{d}I_{21}}{\mathrm{d}s} = -\alpha(\nu) I_\gamma + \alpha(\nu) I_\mathrm{S}}$$

$\alpha(\nu)$ net absorption/emission coefficient

$\boxed{\delta T_{21} = T_{21} - T_\gamma}$ = measured 21cm background

**Radio Background**




Homogenous medium

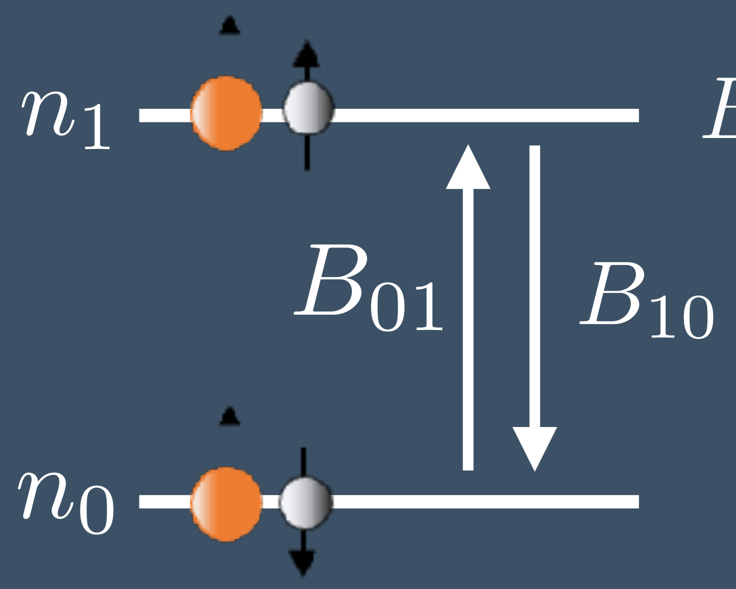
+Rayleigh-Jeans Law

$$\boxed{\delta T_{21} = \frac{T_S - T_\gamma}{1+z}\left(1 - e^{-\tau}\right)}$$

$$\tau = \int \alpha(\nu) \mathrm{d}s$$

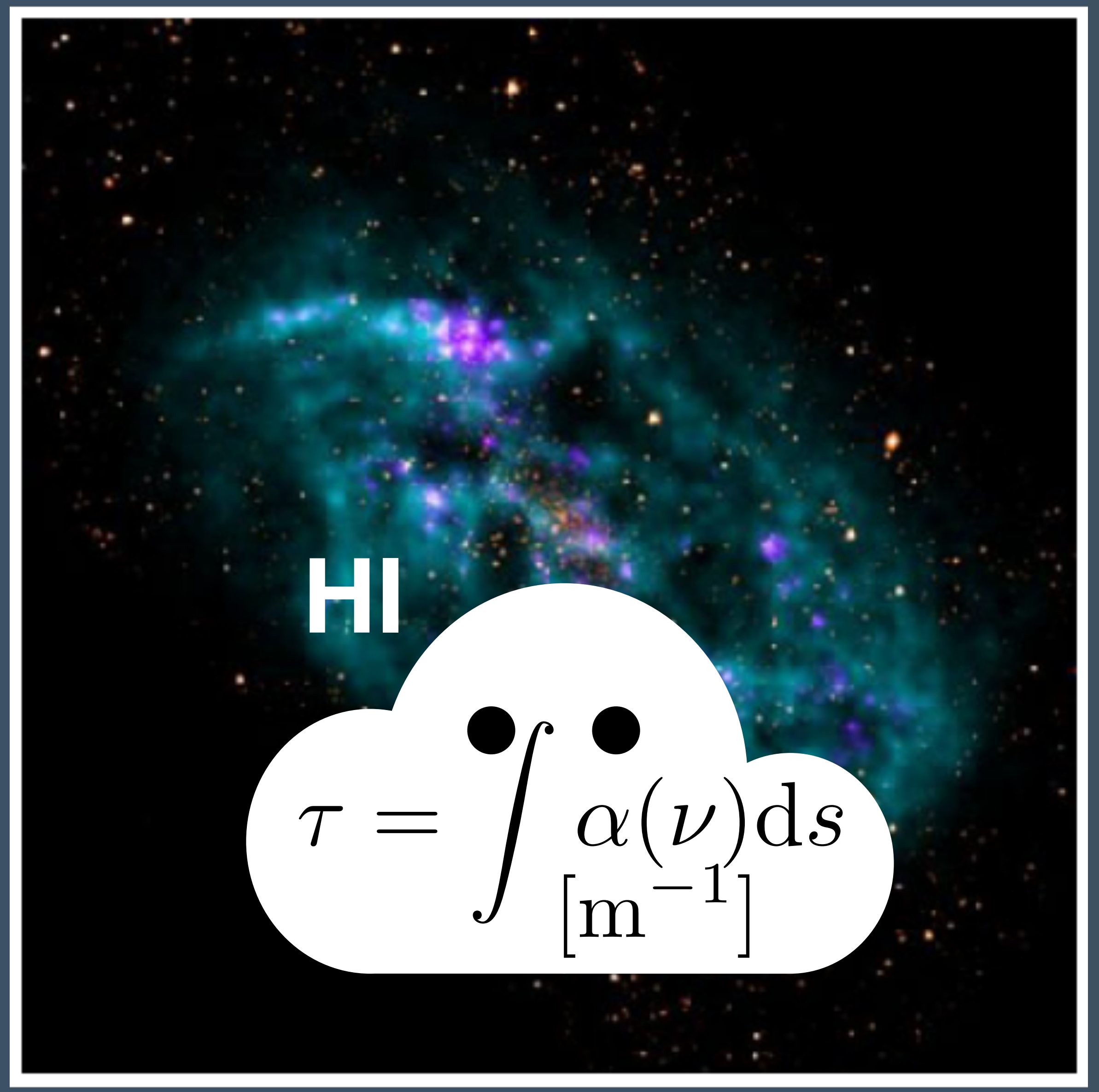
optical depth

## What is the optical depth τ?




$B_{01}/B_{10} = g_1/g_0$

= Einstein coefficient $[\mathrm{J^{-1}m^3s^{-2}}]$
Prob. / unit time / spectral energy density

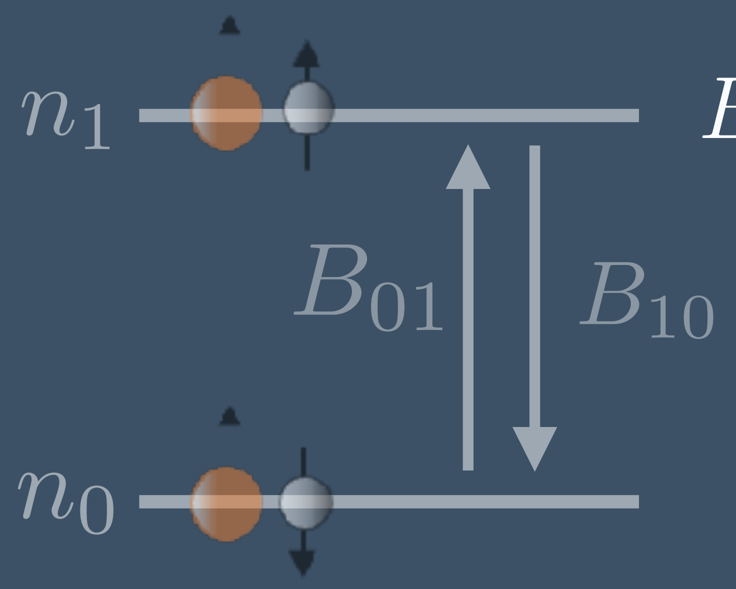



$\tau \ll 1$ : optically thin

**Net absorption/emission coefficient:**

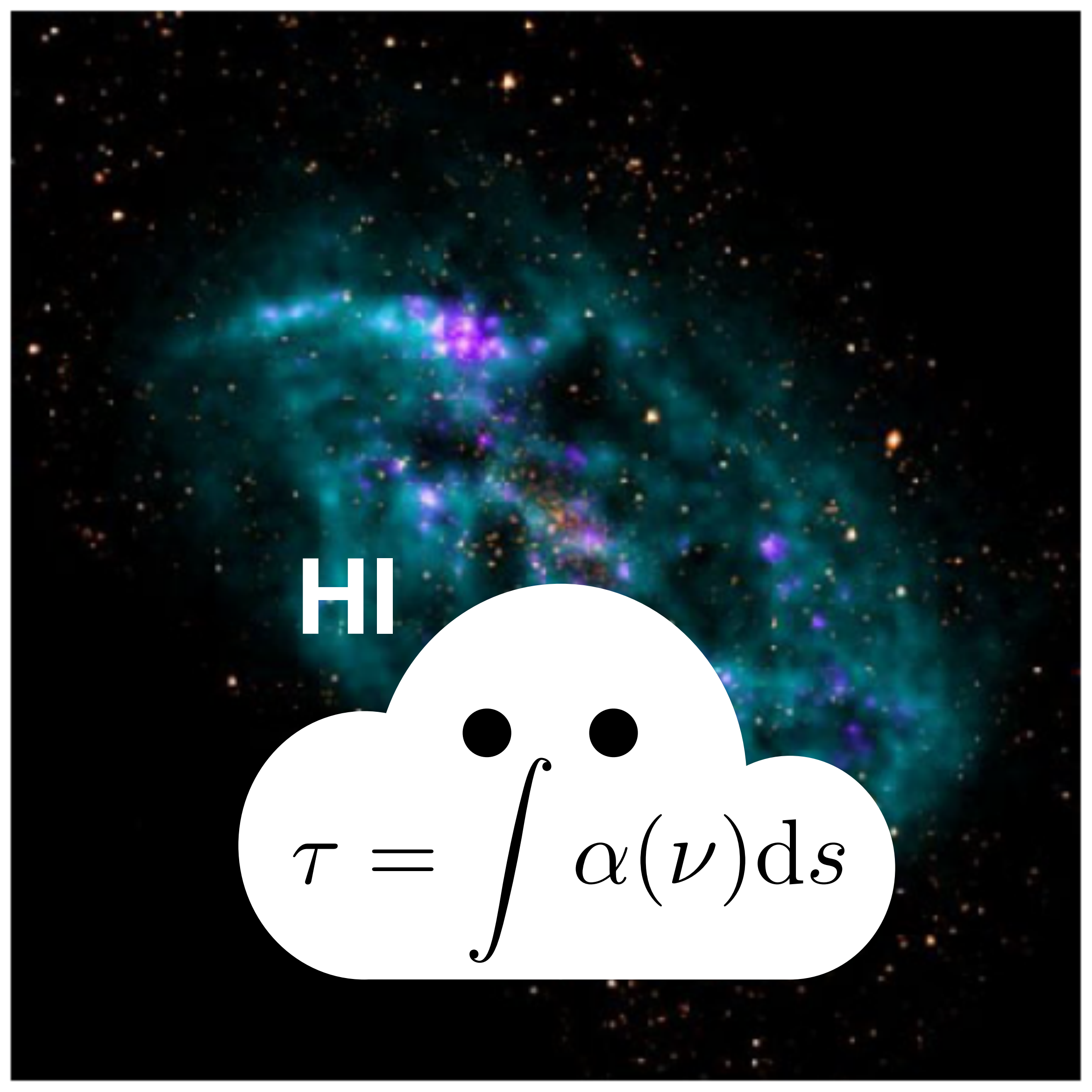
$$\alpha(\nu) = \frac{\mathrm{h}\nu}{c}\,(\underbrace{B_{01}n_0}_{\text{absorption}} - \underbrace{B_{10}n_1}_{\text{emission}})\,\phi(\nu)$$

## What is the optical depth τ and how does it depend on cosmology?




$B_{01}/B_{10} = g_1/g_0 = 3$

$B_{10}$ = Einstein coefficient $[\mathrm{J}^{-1}\mathrm{m}^3\mathrm{s}^{-2}]$
Prob. / unit time / spectral energy density




Net absorption/emission coefficient:

$$\alpha(\nu) = \frac{\mathrm{h}\nu}{c}\left(B_{01}n_0 - B_{10}n_1\right)\phi(\nu)$$

$$n_0 = x_{\mathrm{HI}} n_{\mathrm{H}}$$
$$\propto (1 + \boxed{\delta_{\mathrm{b}}})\boxed{\Omega_{\mathrm{b},0}}(1+z)^3\boxed{H_0^2}$$

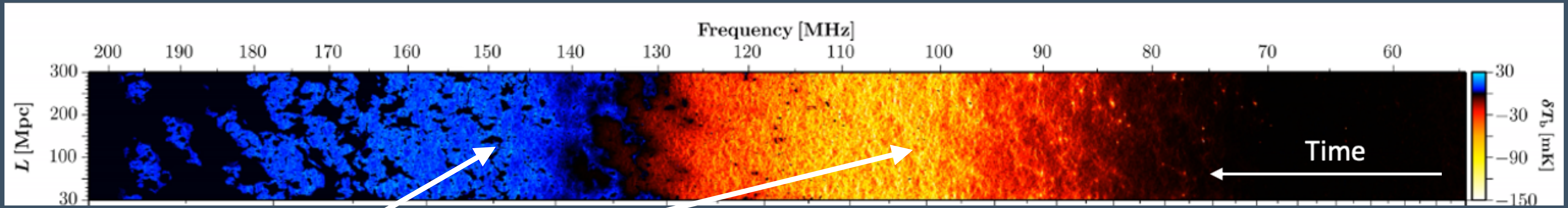
baryon density

+ background

$$\phi(\nu) = \frac{1}{\Delta\nu} \approx \frac{c}{s\nu}\frac{1}{\left(\underbrace{\boxed{H(z)}}_{\text{cosmological recession}} + \underbrace{\boxed{\mathrm{d}v_{\|}/\mathrm{d}r_{\|}}}_{\text{peculiar velocities}}\right)}$$

Putting it all together: $$\delta T_{21} = \frac{T_\mathrm{S} - T_\gamma}{1+z}\left(1 - e^{-\tau}\right) \quad \& \quad \tau(H(z), \delta_\mathrm{b}, \mathrm{d}v_\parallel/\mathrm{d}r_\parallel)$$

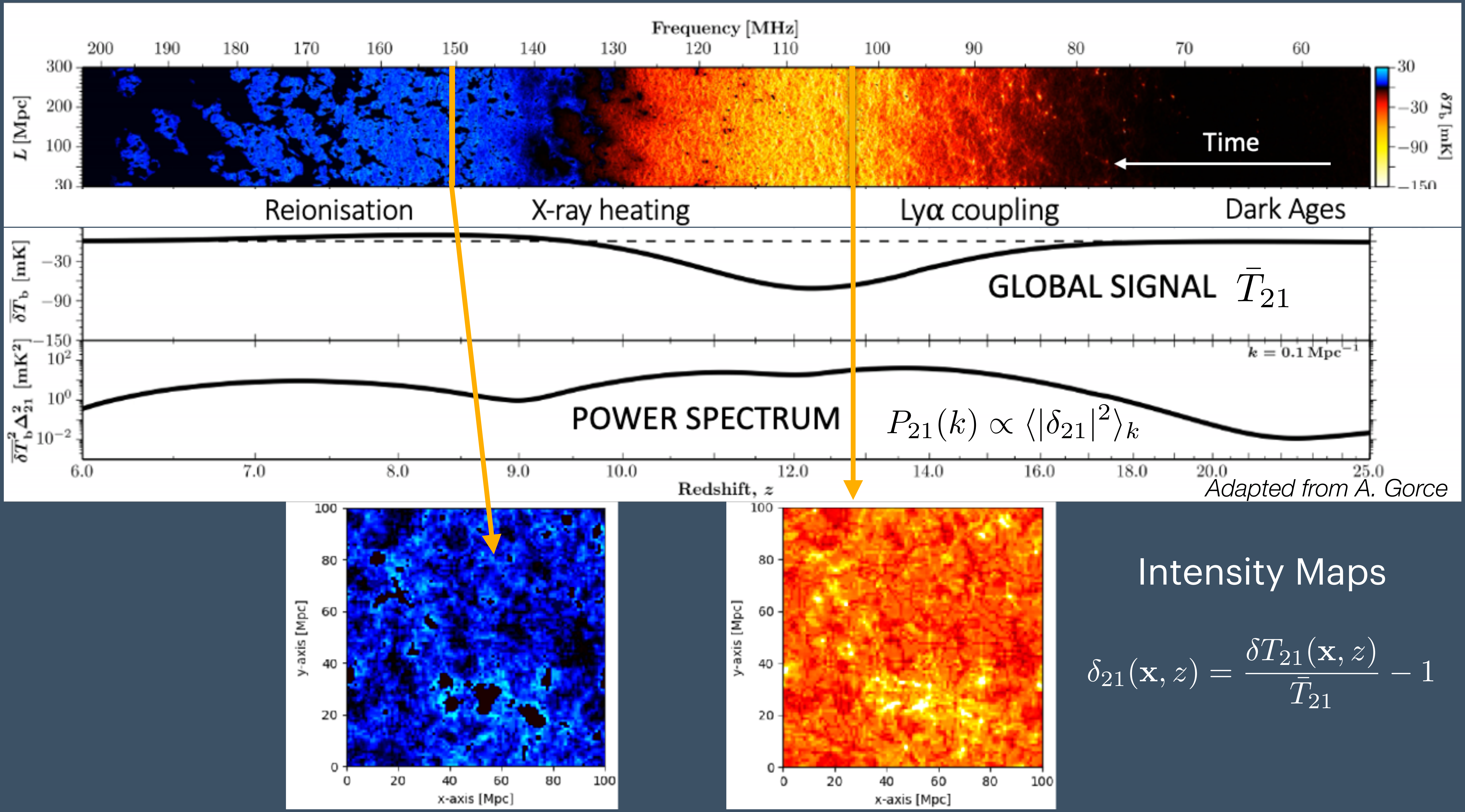
+ LSS distribution optical thin $\tau \ll 1$




*EoR* *CD* *Dark Ages*

$$\delta T_{21}(k,z) = T_0(z)\boxed{x_\mathrm{HI}}(1+\boxed{\delta_\mathrm{b}})\left(\frac{H(z)}{\boxed{\mathrm{d}v_\parallel/\mathrm{d}r_\parallel} + \boxed{H(z)}}\right)\left(1 - \frac{\boxed{T_\gamma}}{\boxed{T_\mathrm{S}}}\right)\ [\mathrm{mK}]$$

$$T_0(z) \approx 27\left(\frac{1+z}{10}\right)\left(\frac{0.15}{\Omega_{\mathrm{m},0}h^2}\right)^{1/2}\left(\frac{\Omega_{\mathrm{b},0}h^2}{0.023}\right)\ [\mathrm{mK}]$$

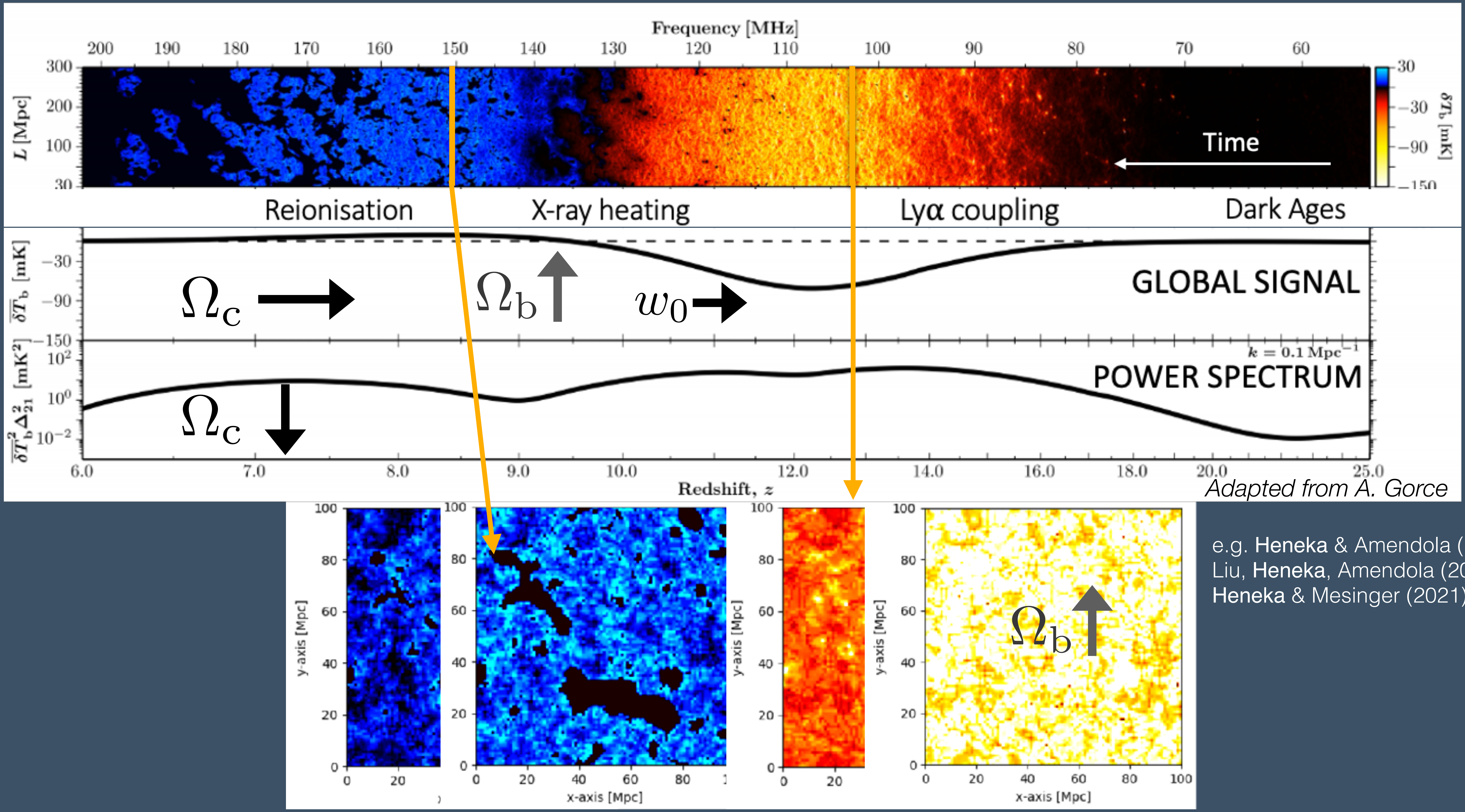



Adapted from A. Gorce

Intensity Maps

$$\delta_{21}(\mathbf{x}, z) = \frac{\delta T_{21}(\mathbf{x}, z)}{\bar{T}_{21}} - 1$$

# II. Basics of 21cm Cosmology




*Adapted from A. Gorce*

e.g. **Heneka** & Amendola (2018)
Liu, **Heneka**, Amendola (2020)
**Heneka** & Mesinger (2021)

Which cosmological properties influence the 21cm Background?

A) Background $H(z)$.

B) Background $H(z)$, $\Omega_m$, and density fluctuations $\delta_b$.

C) Background $H(z)$ and matter density parameter $\Omega_m$.

D) Can't tell without cosmological model.

Which cosmological properties influence the 21cm Background?

A) Background H(z).

B) Background H(z), $\Omega_m$, and density fluctuations $\delta_b$.

C) Background H(z) and matter density parameter $\Omega_m$.

D) Can't tell without cosmological model.

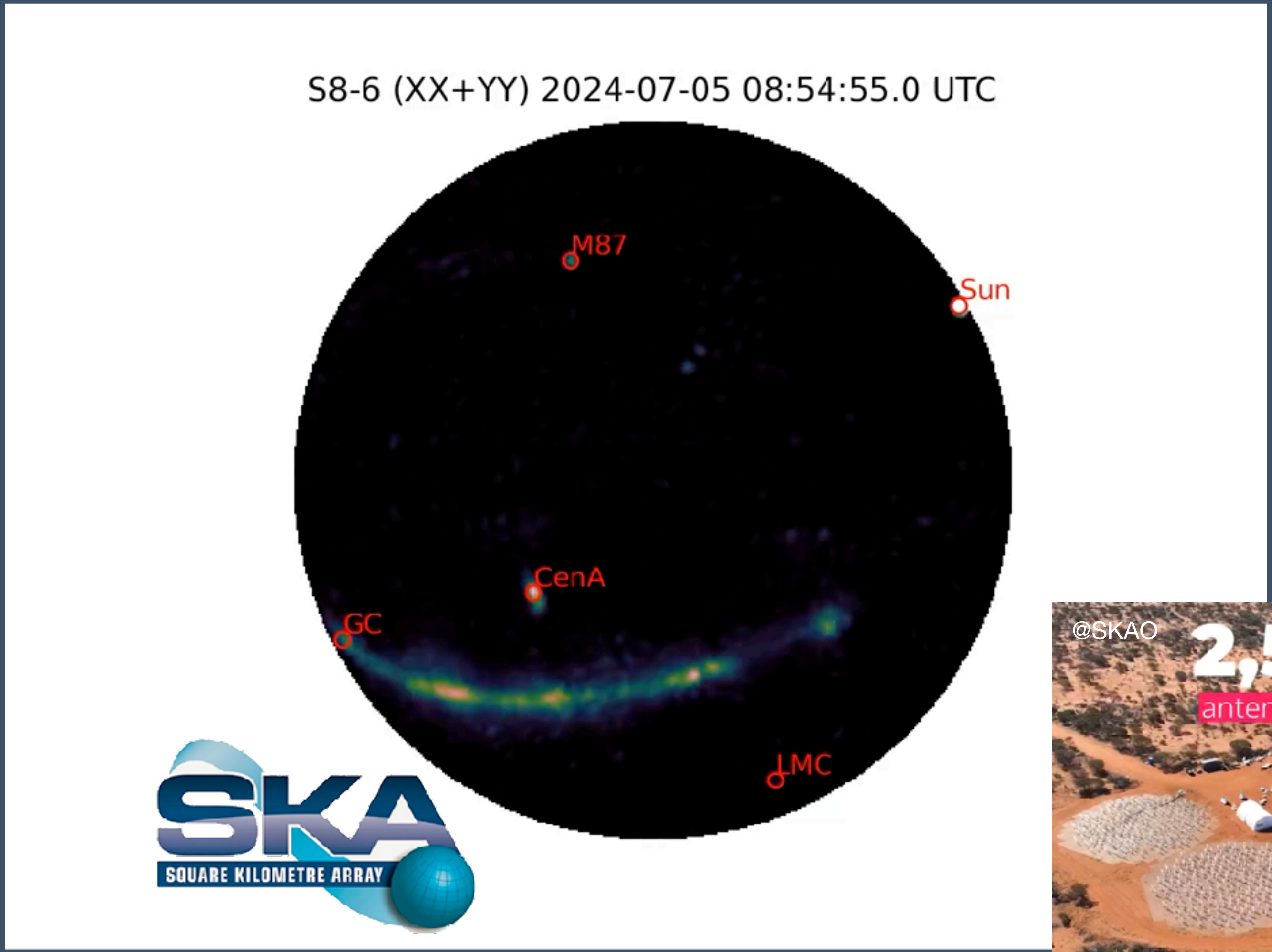
$$\delta T_{21}(k,z) = \boxed{T_0(z)}\, x_{\mathrm{HI}}\, (1+\boxed{\delta_{\mathrm{b}}}) \left( \frac{H(z)}{\boxed{\mathrm{d}v_{||}/\mathrm{d}r_{||}} + \boxed{H(z)}} \right) \left( 1 - \frac{\boxed{T_\gamma}}{T_{\mathrm{S}}} \right) [\mathrm{mK}]$$

The 21cm Background is sensitive to:

- Background expansion
- Density fluctuations
- Peculiar velocities

→ Wealth of cosmological information

# III. 21cm Cosmology
## *Why Now?*





*The SKAO Universe machine*

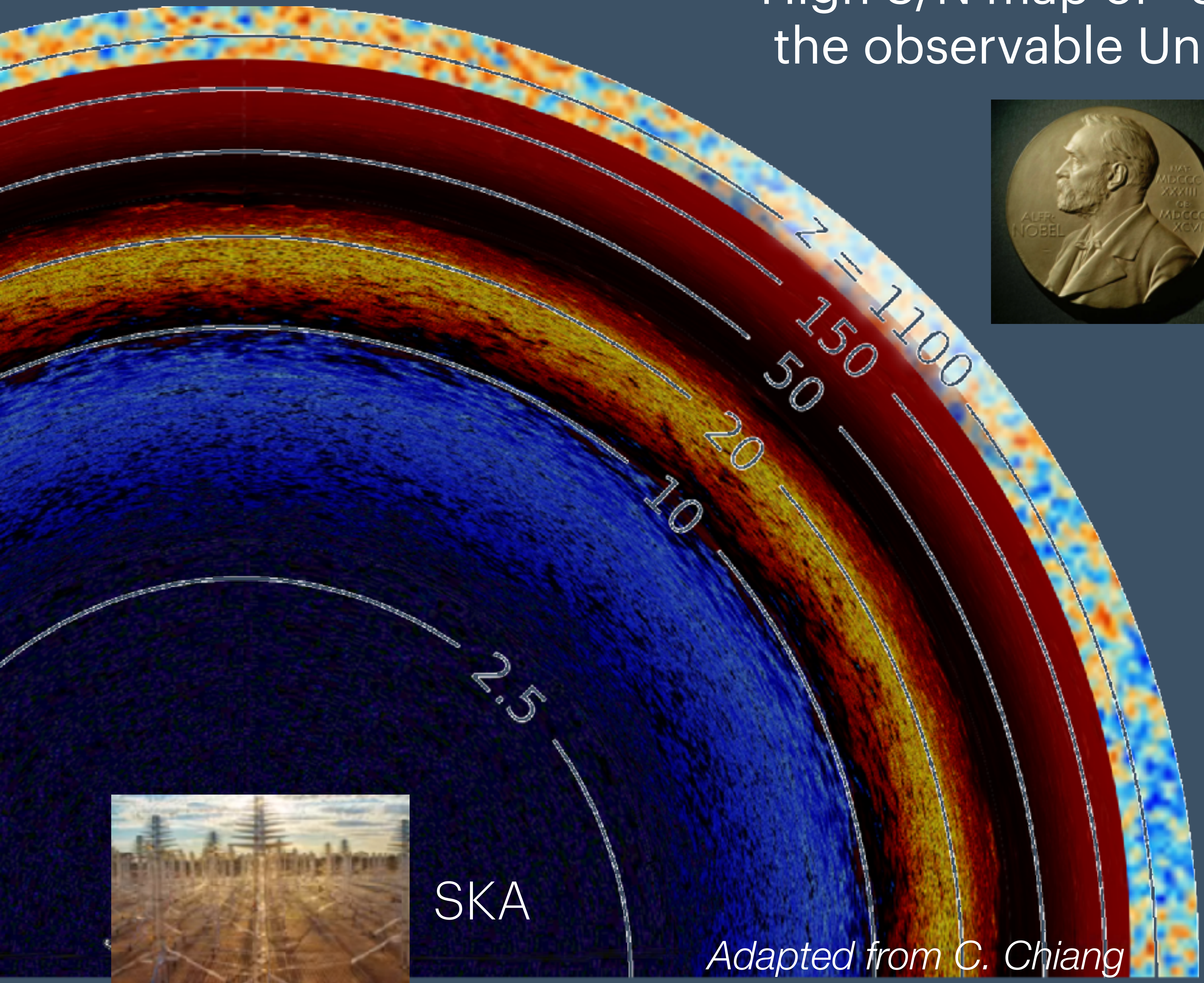
*+ precursors (LOFAR, MWA, HERA, ...)*


*> 100,000 antennae*
*Max. Baseline 150 km*
*50 MHz - 15.3 GHz*

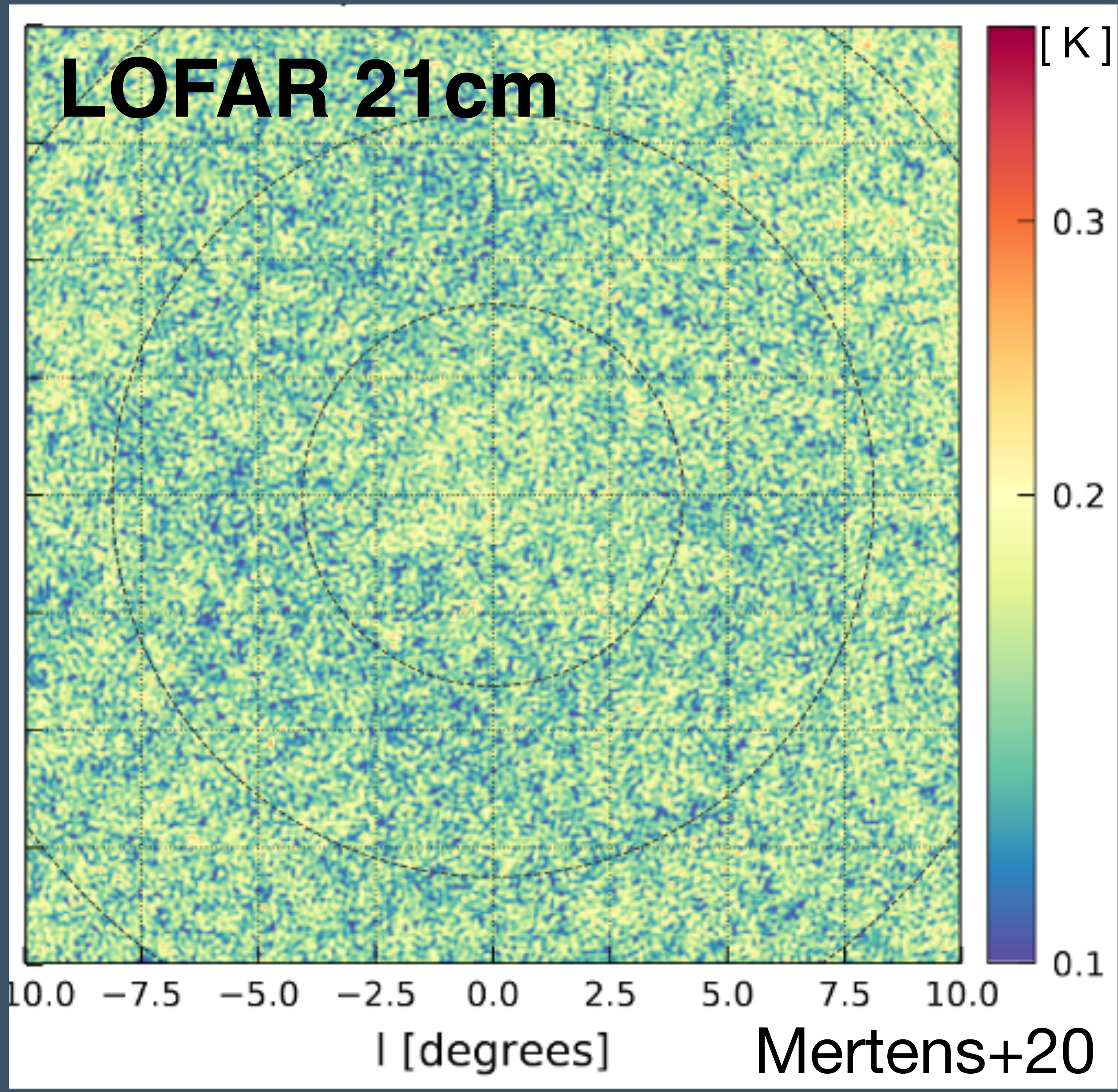
# III. 21cm Cosmology
## *Observable Universe Roadmap*

~2030-2040

High S/N map of >50% of the observable Universe




*Adapted from C. Chiang*




SKA

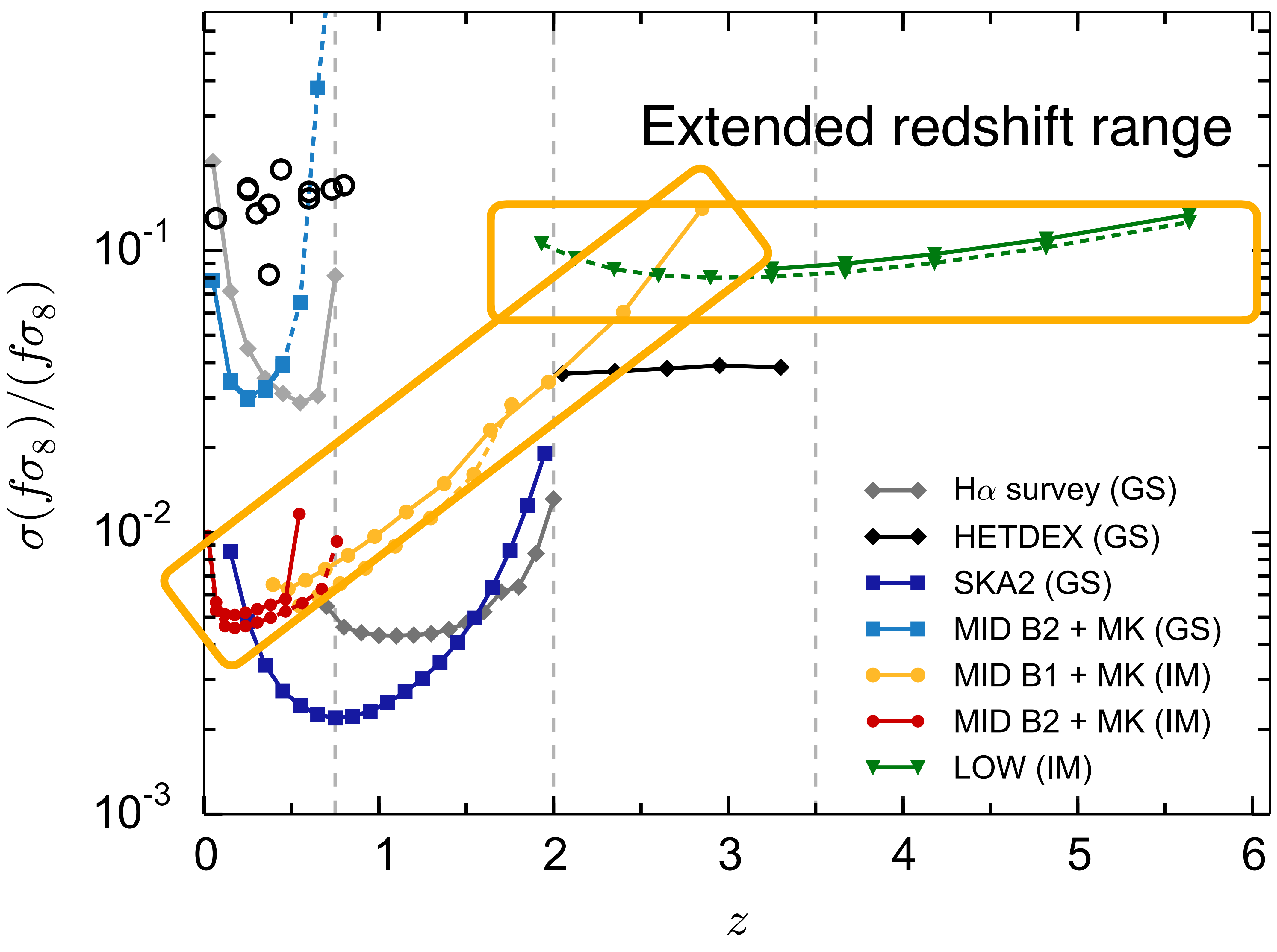
Now: upper limits on Power spectrum

Soon: Low S/N detection

# III. 21cm cosmology $0 < z < 6$

In halo model approach: $P_{21}(z,k,\mu) = \boxed{\bar{T}_{21}^2(z)}\left[b_{\rm HI}^2(z) + \boxed{f(z)}\mu^2\right]\boxed{P_{\rm m}(z,k)}$

HI bias Growth Matter Power + BAOs




Cosmology with Phase 1 of the SKA, Red Book 2018

Hubble expansion $H(z)$

Matter and baryon density $(\delta_m, \delta_b)$

…

# III. 21cm cosmology 0 < z < 6

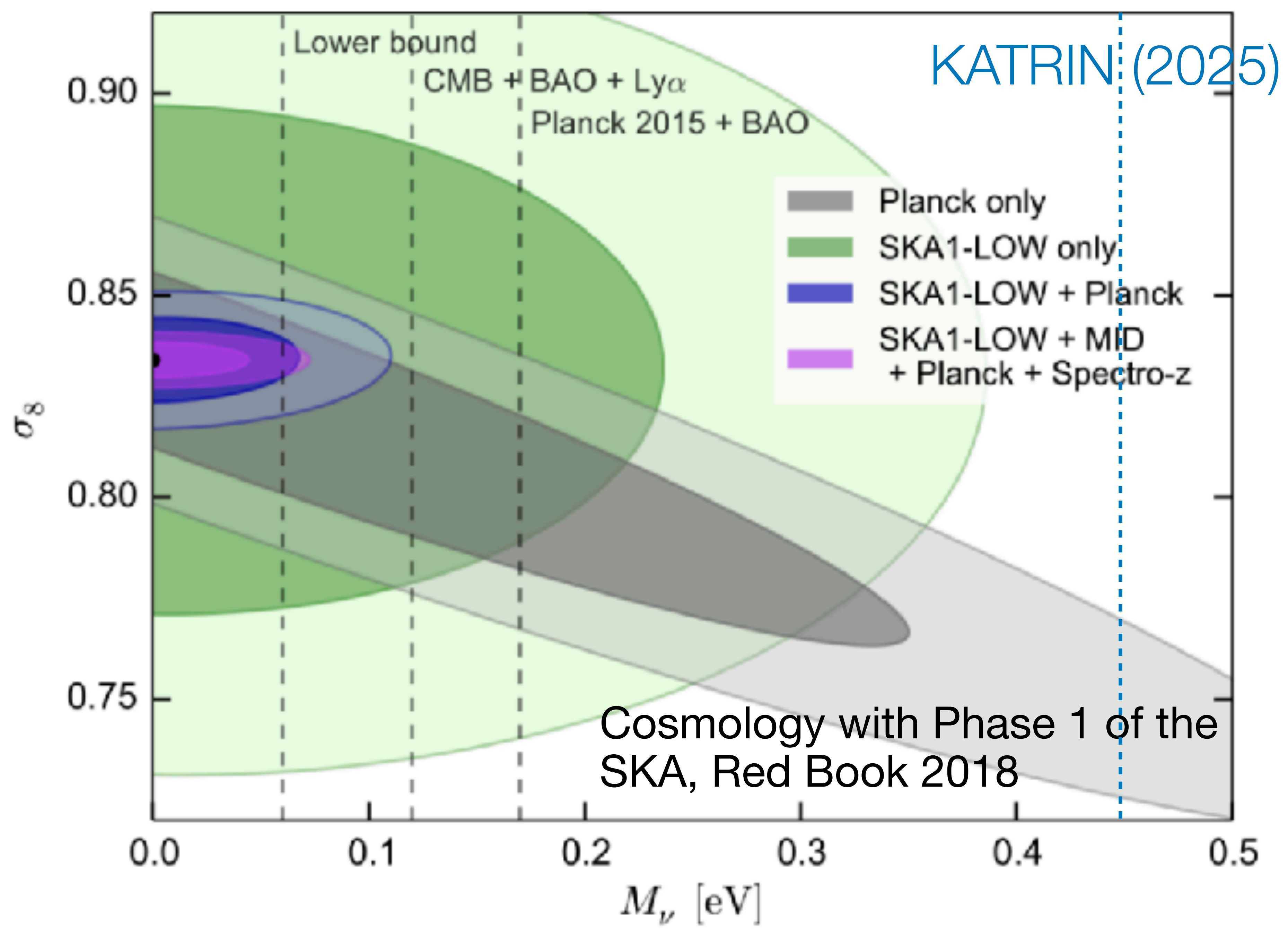
## Test ΛCDM

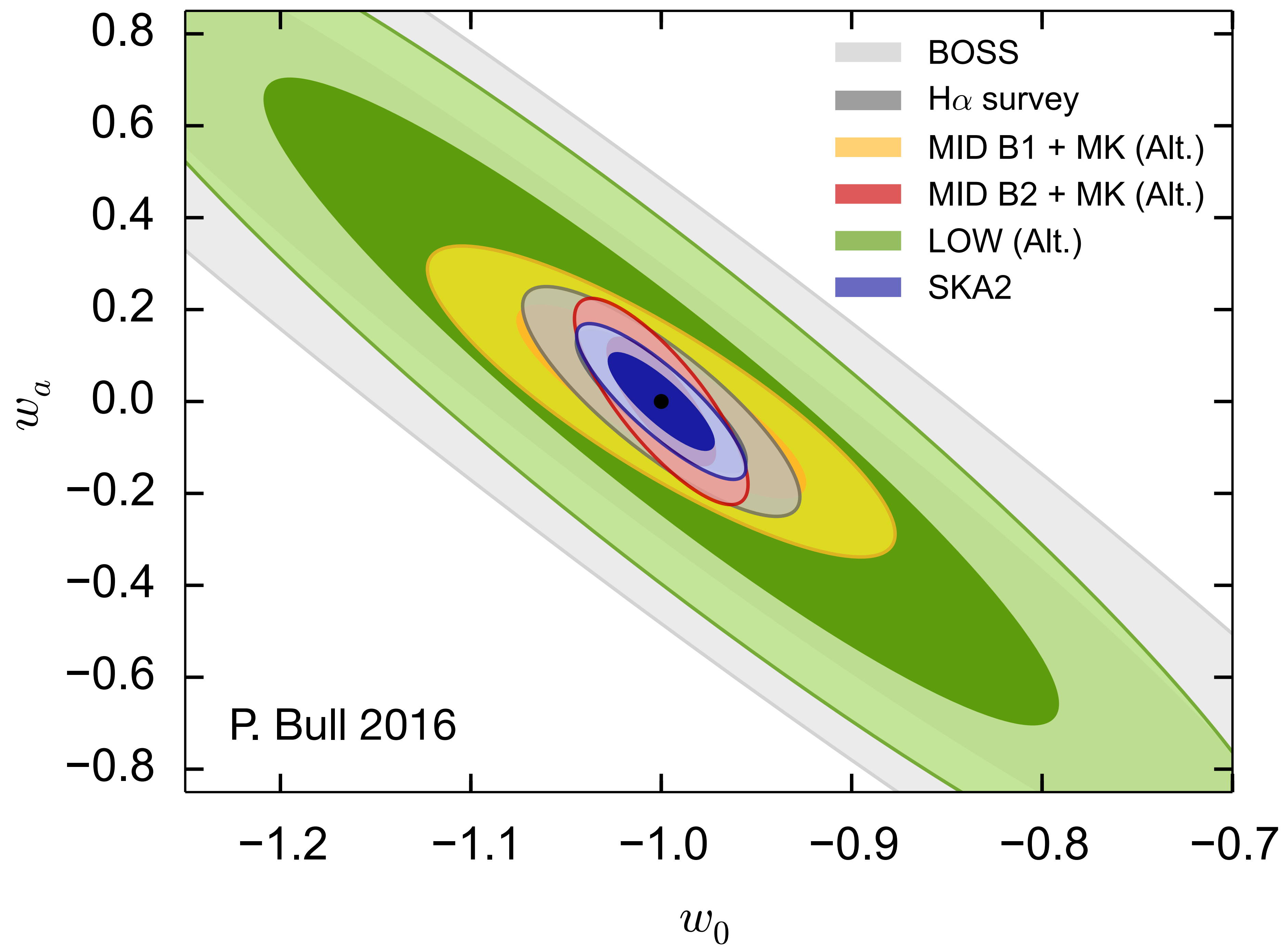
| New Physics | Expansion rate/ distance | Linear clustering | Non-linear/n-point clustering | Direct expansion | Weak lensing | CMB (T/P) | Solar System/ binary pulsars | Gravitational waves |
|---|---|---|---|---|---|---|---|---|
| **Cosmic acceleration** | | | | | | | | |
| Non-Λ equation of state | ▲ | △ | | | ▲ | △ | | |
| Tracking behavior / early DE | ▲ | △ | | | △ | ▲ | | |
| Apparent accel. / backreaction | △ | △ | | ▲ | △ | | | |
| **Modified gravity** | | | | | | | | |
| Time-dependent $G_N$ | | ▲ | ▲ | | ▲ | △ | △ | ▲ |
| Environment-dep. screening | | △ | ▲ | | | | ▲ | △ |
| Equivalence principle violation | | △ | ▲ | | | | ▲ | ▲ |
| Lorentz symmetry violation | | | | | △ | | | ▲ |
| Extra dimensions | △ | | | | | △ | | △ |
| Massive gravitons | △ | △ | △ | | △ | | | ▲ |
| **New particles** | | | | | | | | |
| Neutrinos (sum of masses) | △ | ▲ | ▲ | | △ | ▲ | | |
| Sterile neutrinos | | △ | △ | | △ | ▲ | | |
| Warm dark matter | | | △ | | | | | |
| Interacting dark matter | | | △ | | | | | |
| **Early universe** | | | | | | | | |
| Primordial non-Gaussianity | | △ | ▲ | | | △ | | |
| Features in primordial spectrum | | △ | ▲ | | | △ | | |
| | **Stage 2 intensity mapping** | | | | **Combined probes** | | **Other experiments** | |

**Legend:** ▲ Strongly constraining (discovery potential) △ Weakly constraining (improves current constraints)

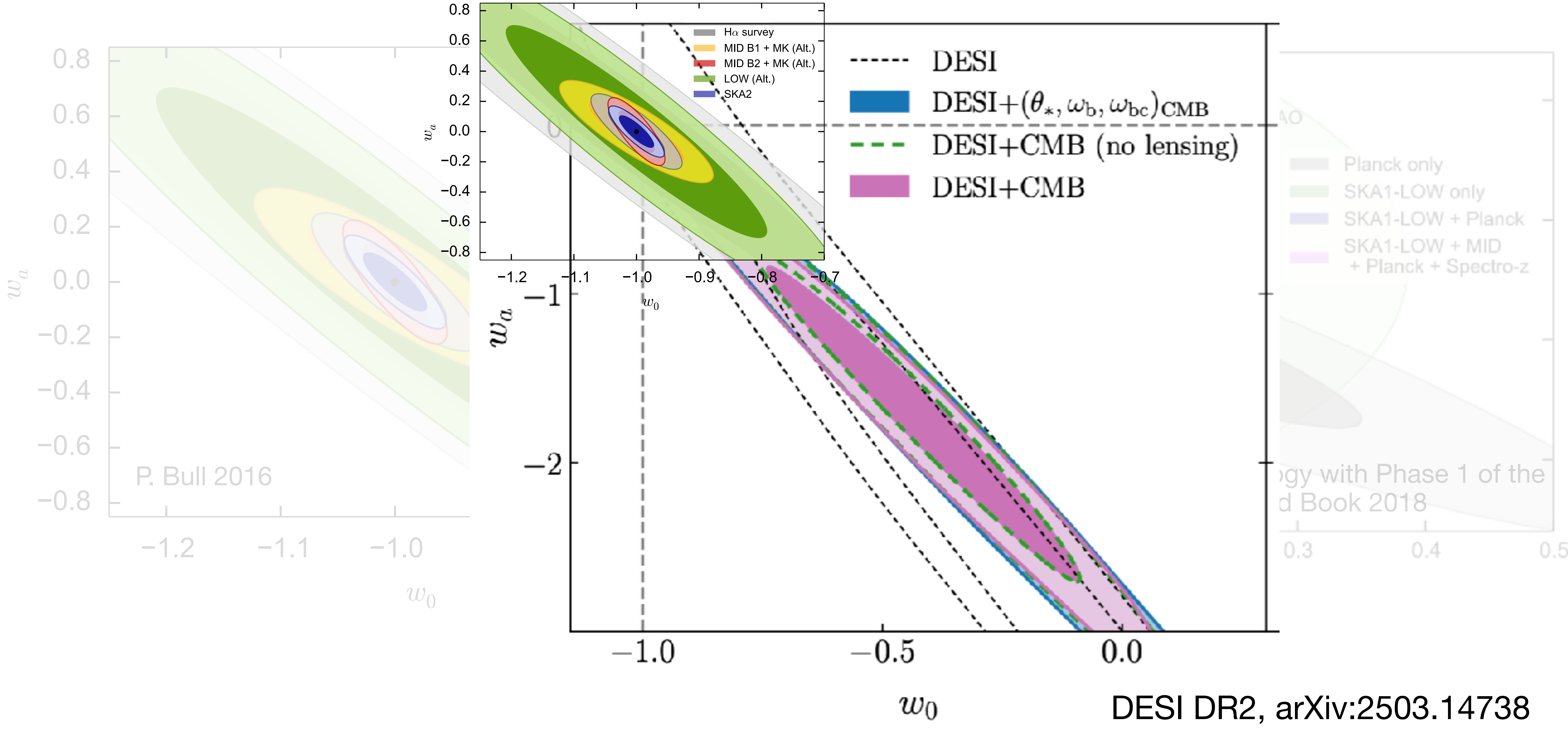
Cosmic Visions 21cm Collaboration 2019

Evolving DE and sum of neutrino mass



# III. 21cm cosmology 0 < z < 6




DESI DR2, arXiv:2503.14738