Image credits: ChatGPT

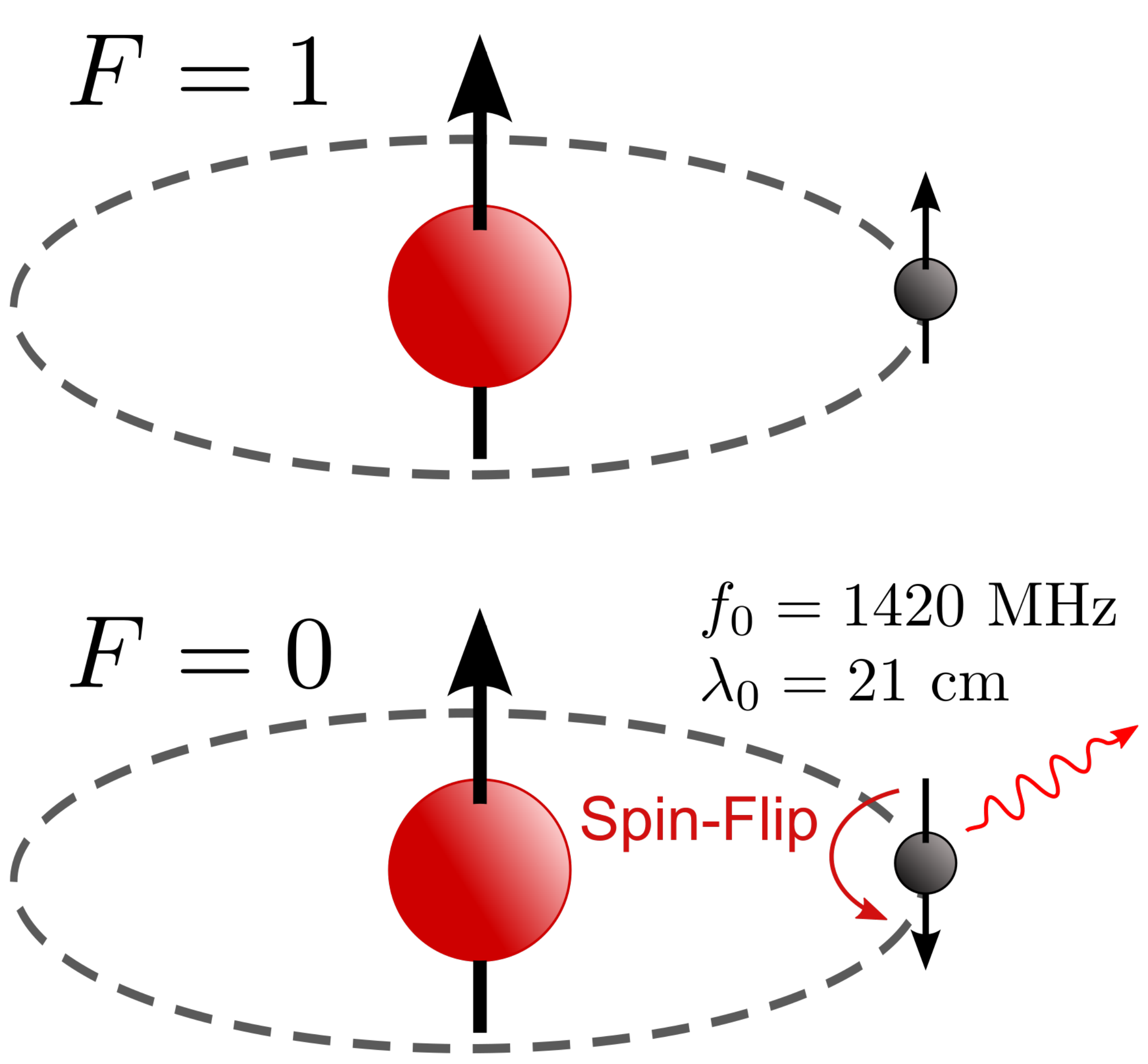
Weighing neutrinos with 21cm intensity mapping at the SKAO

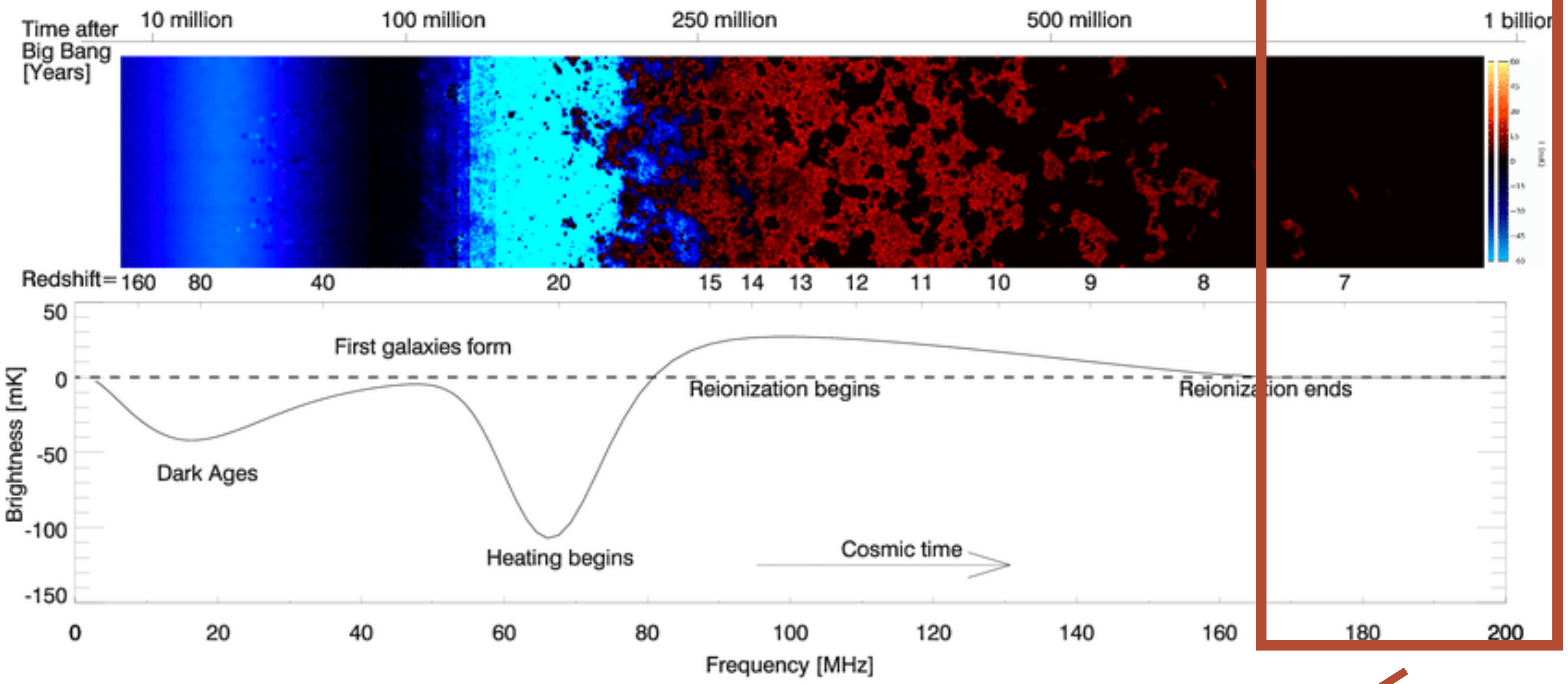
Gabriele Autieri, PhD student at SISSA (Trieste, Italy), Supervisor: Prof. Matteo Viel

Based on: arxiv 2504.18625, GA, M. Berti, B.S. Haridasu, M. Spinelli, M. Viel

21CM LINE – INTRODUCTION

[Pritchard & Loeb, 2011]



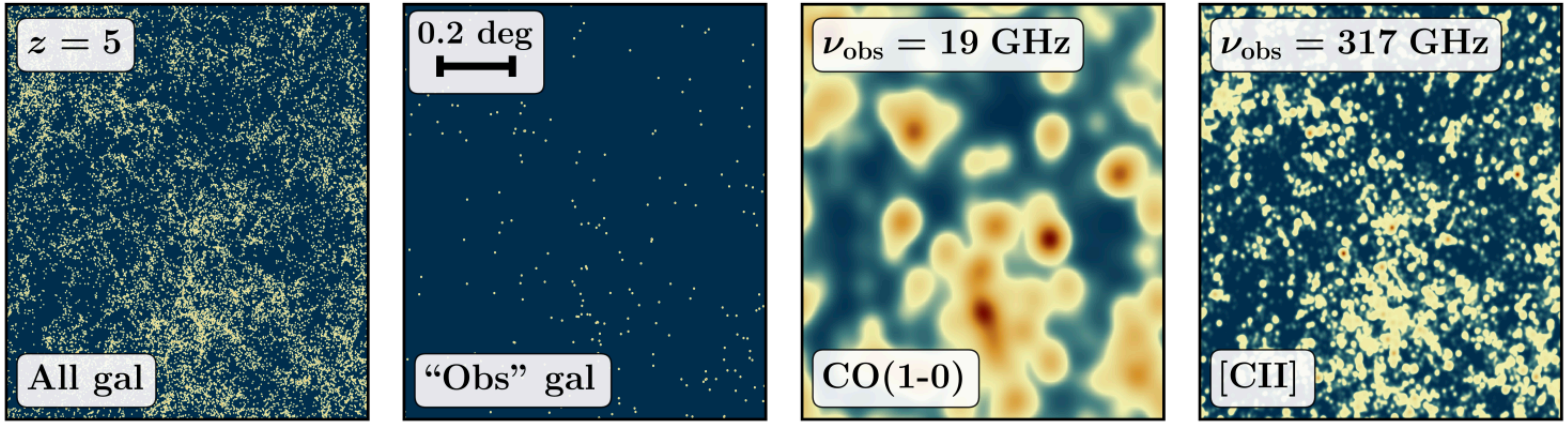


Neutral hydrogen (HI) line: hyperfine splitting of the ground state due to interaction between the magnetic moments of proton and electron.

After reionization:

- Most of the HI is in galaxies and in the intergalactic medium (IGM).
- The 21cm signal is a **biased tracer of the underlying matter field.**

LINE-INTENSITY MAPPING — THEORY



[Bernal+2022]

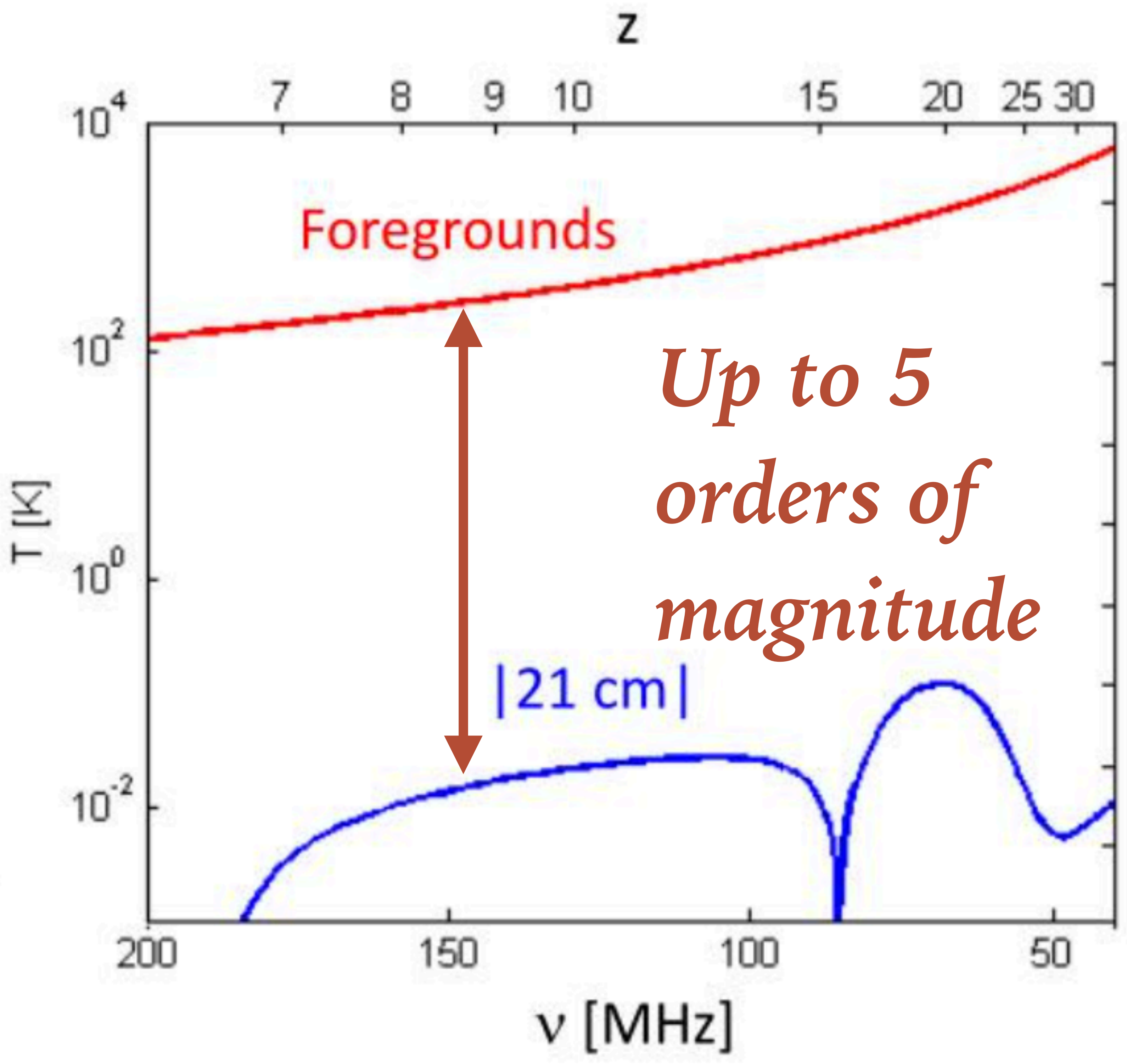
- **Intensity mapping (IM):** measures the integrated emission from individually unresolved galaxies and intergalactic medium (IGM).

- Probes **large volumes quickly** → **high potential of cross-correlations.**

21CM LINE – FOREGROUNDS

Main issue:
FOREGROUNDS

- ***Galaxy synchrotron emission***
- ***Detector noise***



Importance of cross-correlations:

Probe-specific systematics are uncorrelated

METHODOLOGY

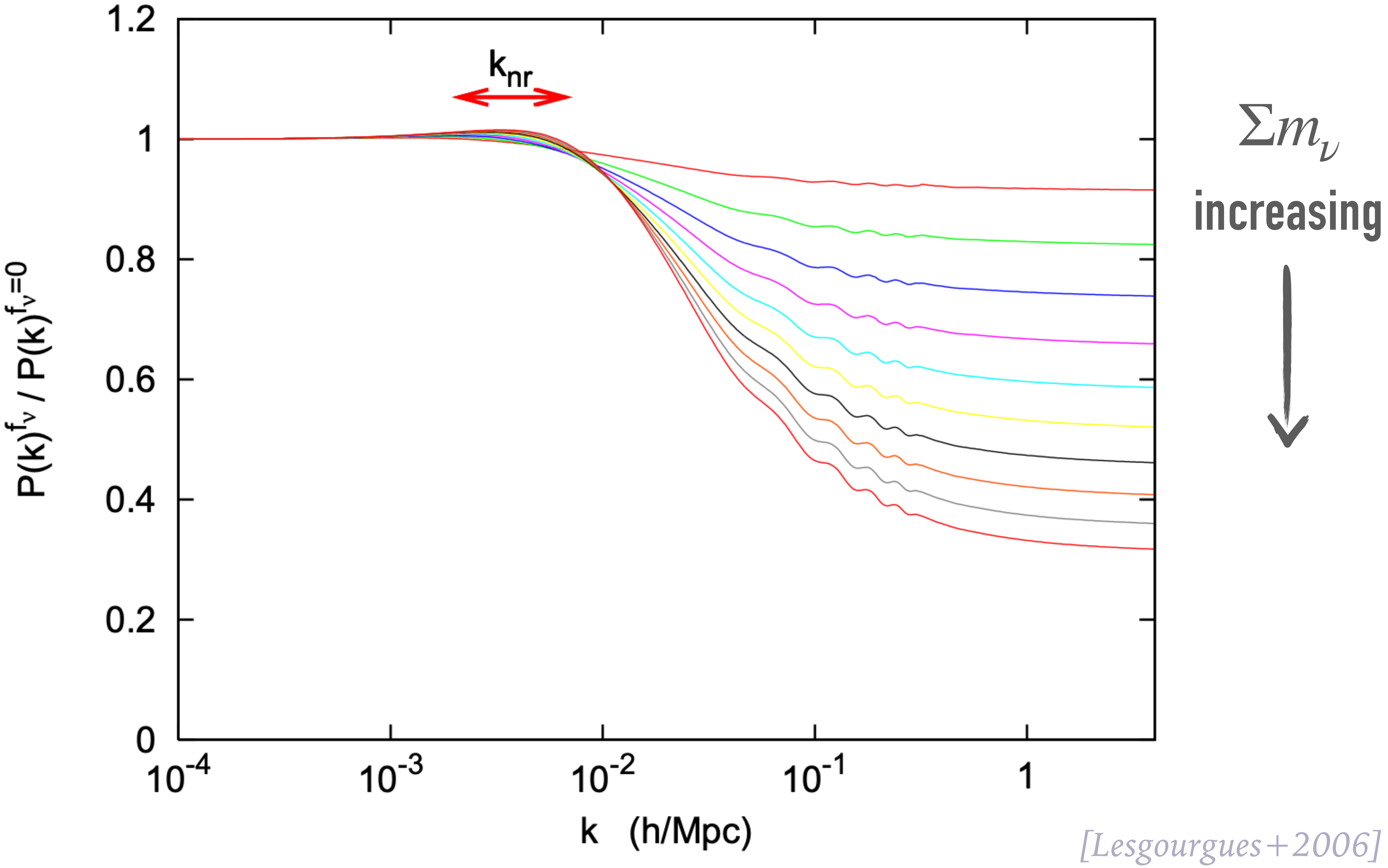
- The goal is to **forecast the constraining power of future 21cm intensity mapping with the SKAO** on the sum of neutrino masses, Σm_ν .

- Build **synthetic data sets** that mimic realistic observations that will be possible with the SKAO and forecast the constraining power with a Bayesian analysis.

- We focus on **21cm IM auto-power spectrum** and **21cm IM - galaxies cross-correlation power spectrum measurements.**

MASSIVE NEUTRINOS IN COSMOLOGY

Free-streaming*:** neutrinos ***free-stream out of high-density regions suppressing perturbations on small scales. The resulting suppression in the matter power spectrum provides a way to constrain neutrino masses.



[Lesgourgues+2006]

FORECASTING – SURVEYS TO BUILD SYNTHETIC DATA SETS

Surveys to build synthetic data sets

IM surveys

SKA1-Mid surveys in redshift range
$0 < z < 3$

Euclid-like survey

Euclid-like survey in redshift range
$0.9 < z < 1.8$

DESI-like survey

DESI ELG- like survey in redshift range
$0.7 < z < 1.7$

FORECASTING – BUILDING THE SYNTHETIC DATA SETS

For each redshift bin, the ***survey specifications fix the range of accessible scales***

z-bin volume

$$V_{\rm bin}(z_c) = \Omega_{\rm sur} \int_{z-\Delta z/2}^{z+\Delta z/2} {\rm d}z' \, \frac{c r(z')^2}{H(z')}$$

$$k_{\rm min}(z_c) = \frac{2\pi}{\sqrt[3]{V_{\rm bin}(z_c)}}$$

Dimension of the telescope beam

$$R_{\rm beam}(z_c) = \frac{\theta_{\rm FWHM}}{2\sqrt{2\ln 2}} r(z_c)$$

$$k_{\rm max}(z_c) = \frac{2\pi}{R_{\rm beam}(z_c)}$$

FORECASTING – POWER SPECTRUM MODEL

$$P_{21}(z,k,\mu) = \overline{T}_{\rm b}^2(z)\left[b_{\rm HI}(z) + f_{\rm CDM+b}(z,k)\,\mu^2\right]^2 P_{\rm CDM+b}(z,k) + P_{\rm SN}(z)$$

$$P_{21,\rm g}(z,k,\mu) = \overline{T}_{\rm b}(z)\left(b_{\rm HI}(z) + f_{\rm CDM+b}(k,z)\mu^2\right)\left(b_{\rm g}(z) + f_{\rm CDM+b}(k,z)\mu^2\right) P_{\rm CDM+b}(z,k,\mu)$$

Average brightness temperature

HI bias

Growth rate

Galaxy bias

Shot-noise

Nuisance parameters (either computed from theory or sampled)

FORECASTING – MIMICKING REALISTIC OBSERVATIONS

To ***mimic realistic observations*** we add ***two*** factors:

Gaussian beam smoothing

$$\tilde{B}(z,k,\mu) = \exp\left[\frac{-k^2 R^2_{\rm beam}(z)(1-\mu^2)}{2}\right]$$

Suppresses the power on small scales

Alcock-Paczynski (AP) effect

$$\alpha_\perp(z) = \frac{D_A(z)}{D_A^{\rm fid}(z)} \quad \text{and} \quad \alpha_\parallel(z) = \frac{H^{\rm fid}(z)}{H(z)}$$

$$q = \frac{k}{\alpha_\perp}\sqrt{1+\mu^2\left(\frac{\alpha_\perp^2}{\alpha_\parallel^2}-1\right)} \qquad \nu = \frac{\alpha_\perp \mu}{\alpha_\parallel\sqrt{1+\mu^2\left(\frac{\alpha_\perp^2}{\alpha_\parallel^2}-1\right)}}$$

FORECASTING – BUILDING THE SYNTHETIC DATA SETS – ERRORS

21cm IM variance

$$\sigma_{21}(z,k,\mu) = \frac{\hat{P}_{21}(z,k,\mu) + P_{\rm N}(z)}{N_{\rm modes}(z,k,\mu)}$$

Instrument noise

$$P_{\rm N}(z) = \frac{T_{\rm sys}^2\, 4\pi f_{\rm sky}}{N_{\rm dish}\, t_{\rm obs}\, \delta\nu} \frac{V_{\rm bin}(z)}{\Omega_{\rm sur}}$$

cross- correlation variance

$$\sigma_{21,\rm g}(z,k) = \frac{1}{\sqrt{2N_{\rm modes}(z,k)}} \sqrt{\hat{P}^2_{21,\rm g}(z,k) + \left(\hat{P}_{21}(z,k) + P_{\rm N}(z)\right)\left(\hat{P}_{\rm g}(z,k) + \frac{1}{\bar{n}_{\rm g}}(z)\right)}$$

Number of modes per k bin

$$N_{\rm modes}(z,k) = \frac{k^2 \Delta k(z_c)}{4\pi^2} V_{\rm bin}(z_c)$$

FORECASTING – FULL POWER SPECTRUM MODEL

Adding everything you get the ***21cm (observed) power spectrum*** model and similar for the cross

$$\hat{P}_{21}(z,\ k,\ \mu) = \frac{1}{\alpha_\perp^2 \alpha_\parallel} \tilde{B}^2(z, q, \nu) P_{21}(z, q, \nu) + P_\mathrm{N}(z)$$

- We can decompose the power spectrum using Legendre polynomials

$$\hat{P}_{\mathrm{X},\ell}(z, k) = \frac{(2\ell + 1)}{2} \int_{-1}^{1} \mathrm{d}\mu\, \mathcal{L}_\ell(\mu) \hat{P}_\mathrm{X}(z, k, \mu)$$

Power spectrum multipoles

$$C_{\ell,\ell'}(z, k) = \frac{(2\ell + 1)(2\ell' + 1)}{2} \int_{-1}^{1} \mathrm{d}\mu\, \mathcal{L}_\ell(\mu)\, \mathcal{L}_{\ell'}(\mu)\, \sigma^2(z, k, \mu)$$

Multipoles covariance

FORECASTING – DATA ANALYSIS

- We consider three values for $\Sigma m_\nu = 0.06, 0.1, 0.4$ eV, meaning that in total we have **9** data sets (**3** data sets for each of the **21cm IM auto-power spectrum**, the **SKAO×DESI cross-correlation** and the **SKAO×Euclid cross-correlation**)

- Additionally, we ***combine our mock data sets with Planck 2018.***

Gaussian likelihood

$$-\ln\left[\mathcal{L}\right] = \frac{1}{2}\sum_z \Delta\Theta(z)^{\mathrm{T}} C^{-1}(z)\Delta\Theta(z)$$

$$\Delta\Theta(z) = \Theta^{\mathrm{th}}(z) - \Theta^{\mathrm{obs}}(z)$$

LIKELIHOOD FUNCTION

- We built on Maria's works [Berti+2021, Berti+2022, Berti+2023] and built a ***Gaussian likelihood code*** fully integrated with the MCMC sampler **Cobaya** .

- This likelihood code, called **topk**, will be made ***publicly available*** on Maria's GitHub page at **github.com/mberti94**

- The likelihood code can handle the computation of:

→ ***21cm IM power spectrum*** multipoles

→ ***21cm and galaxies cross-correlation power spectrum*** multipoles

FORECASTING – RESULTS

21cm IM power spectrum results

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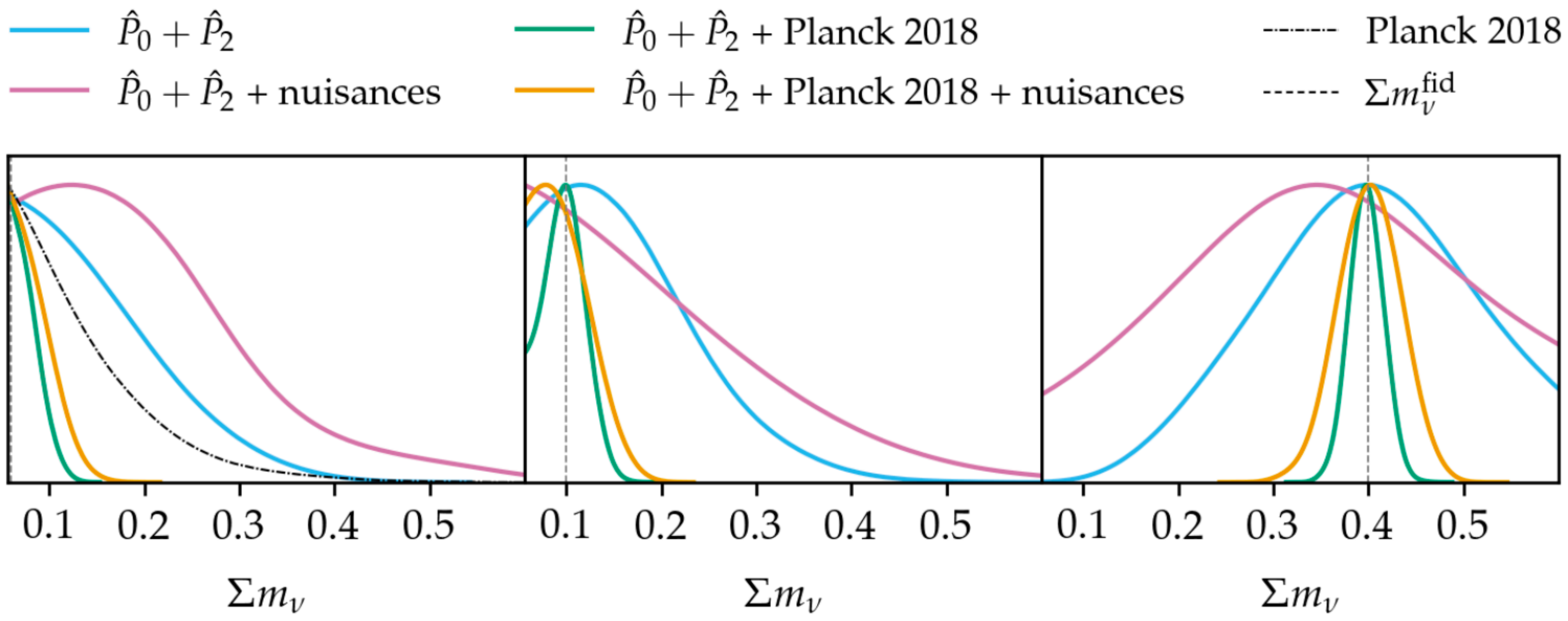
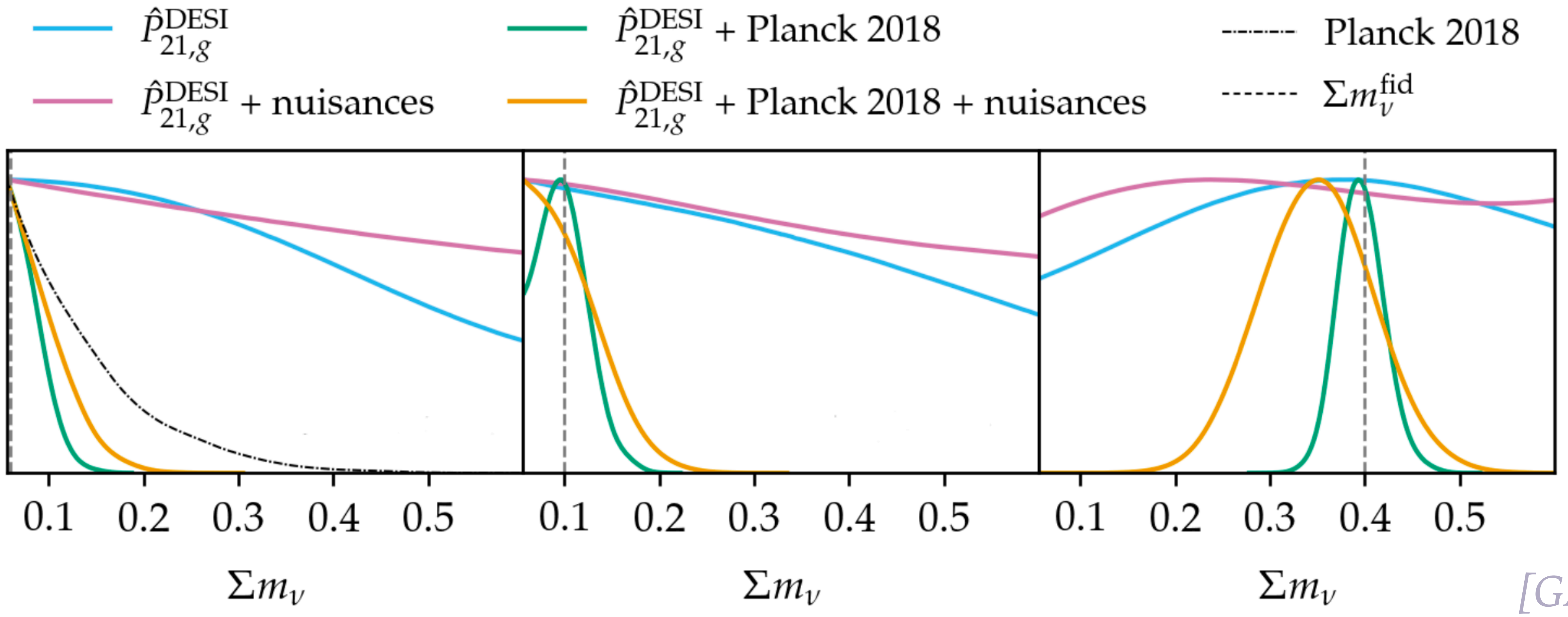


SKAOxDESI results (similar for SKAOxEuclid)

→



[GA et al., arxiv:2504.18625]

FORECASTING - RESULTS

Likelihoods	$\Sigma m_\nu^{\rm fid} = 0.06\,{\rm eV}$	$\Sigma m_\nu^{\rm fid} = 0.1\,{\rm eV}$	$\Sigma m_\nu^{\rm fid} = 0.4\,{\rm eV}$
$\hat{P}_0 + \hat{P}_2$	< 0.287	< 0.317	$0.41^{+0.11}_{-0.14}$
+ nuisances	< 0.425	< 0.452	$0.34^{+0.16}_{-0.14}$
Planck 2018			
$+ \hat{P}_0 + \hat{P}_2$	< 0.105	0.098 ± 0.022	0.398 ± 0.018
+ nuisances	< 0.126	< 0.151	0.401 ± 0.034
Planck 2018			
$+ \hat{P}_{21,\rm g}^{\rm DESI}$	< 0.116	$0.099^{+0.020}_{-0.033}$	$0.396^{+0.023}_{-0.026}$
+ nuisances	< 0.155	< 0.177	0.349 ± 0.060
Planck 2018			
$+ \hat{P}_{21,\rm g}^{\rm Euclid}$	< 0.117	$0.100^{+0.021}_{-0.032}$	$0.397^{+0.023}_{-0.026}$
+ nuisances	< 0.156	< 0.180	0.343 ± 0.062

- Cross-correlation data alone ***doesn't hold enough constraining power to improve the state of the art Σm_ν .***
- When ***combined with complementary CMB data***, gives constraints ***comparable*** to the ones obtained with auto-power.

[GA et al., arxiv:2504.18625]

Thank you for your attention!

Extra slides

THE 21CM POWER SPECTRUM

- $\overline{T}_b$ is the ***averaged brightness temperature of HI***, can be computed as

$$\bar{T}_{\rm b}(z) = 180\ \Omega_{\rm HI}(z)\,\frac{h\,H_0}{H(z)}\,(1+z)^2 {\rm mK}$$

[Battye+2013]

- The HI density $\Omega_{\rm HI}$ has mild redshift evolution

$$\Omega_{\rm HI}(z) = 4.\times 10^{-4}(1+z)^{0.6}$$

[Chrighton+2015]

THE 21CM POWER SPECTRUM

- We have no analytical models for HI bias and shot-noise, therefore we interpolate results from ***hydrodynamical simulations***

z	0	1	2	3	4	5
$b_{\rm HI}$	0.84	1.49	2.03	2.56	2.82	3.18
$P_{\rm HI}^{\rm SN}$ $[(h^{-1}{\rm Mpc})^3]$	104	124	65	39	14	7

[Villaescusa-Navarro+2018]

- The growth rate $f(z)$ and the matter power spectrum $P_m(z, k)$ are computed with a Boltzmann solver (CAMB) or an emulator. ***For massive neutrinos they are computed neglecting the contributions of neutrinos.***