Cosmology with the Square Kilometre Array

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Part Two

Intensity Mapping and the challenge of foregrounds

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Acknowledgments & References

The content of these slides is inspired by various lectures given by different experts in SKA Cosmology.
I would like to thank for letting me steal here and there:

Phil Bull (QMUL), Stefano Camera (UniTo), Alkistis Pourtsidou (Edinburgh), Laura Wolz (UNIMAN)

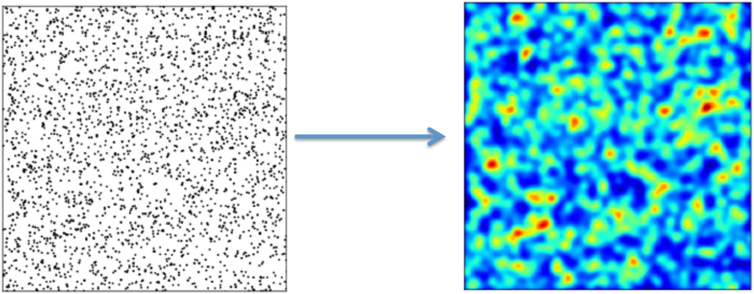
SKA specific material can be found at: `https://www.skatelescope.org` or `https://www.skaobservatory.org/`.

See also: Advancing Astrophysics with the Square Kilometre Array,

`https://pos.sissa.it/215/`

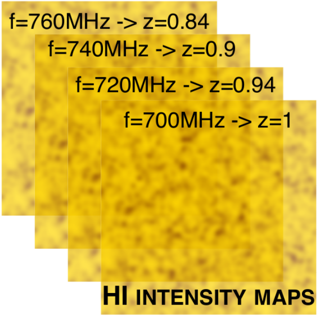
21 cm Intensity Mapping

- Look at the total intensity of the 21 cm emission line in a large 3d pixel (angle and frequency)
- Pixel will have joint emission from multiple galaxies
- Cheap for large volume



galaxies   Intensity map

21 cm Tomography

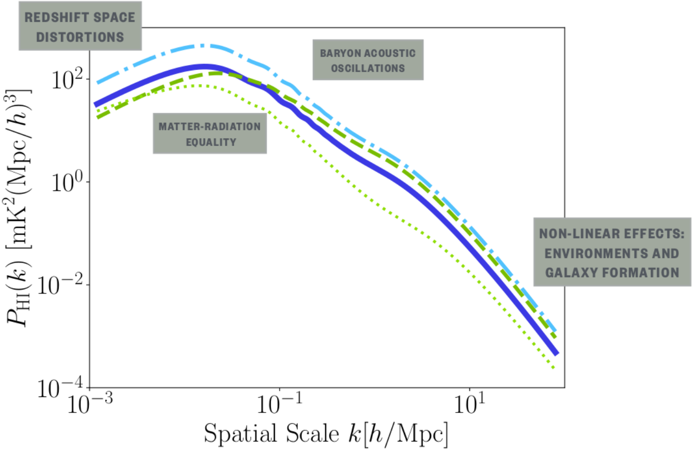


courtesy of Laura Wolz

- large volumes fundamental for cosmology (a.k.a cosmological volumes)
- tomographic maps of the Universe (in principle in the range $0 < z < 6$)
- measurement of LSS
- integrated line flux over entire HI mass function ... we are measuring baryons!
- high line-of-sight and low spatial resolution

21 cm Power Spectrum content

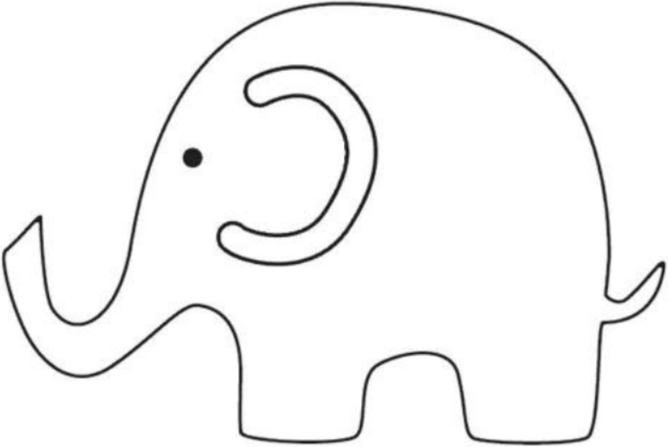
courtesy of Laura Wolz



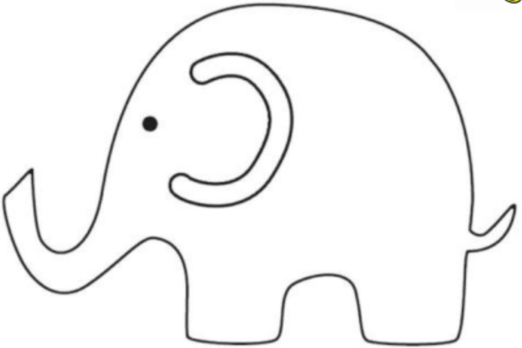
The foreground problem

A simple formulation...

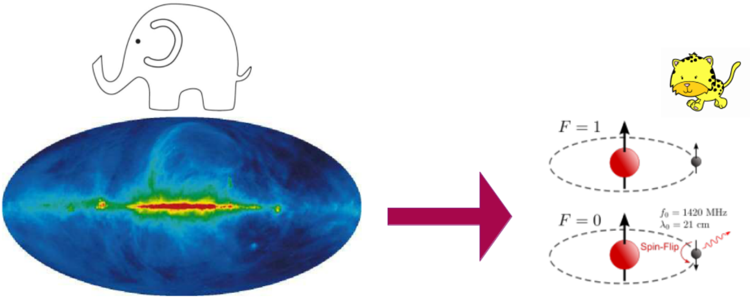
The foreground problem



The foreground problem

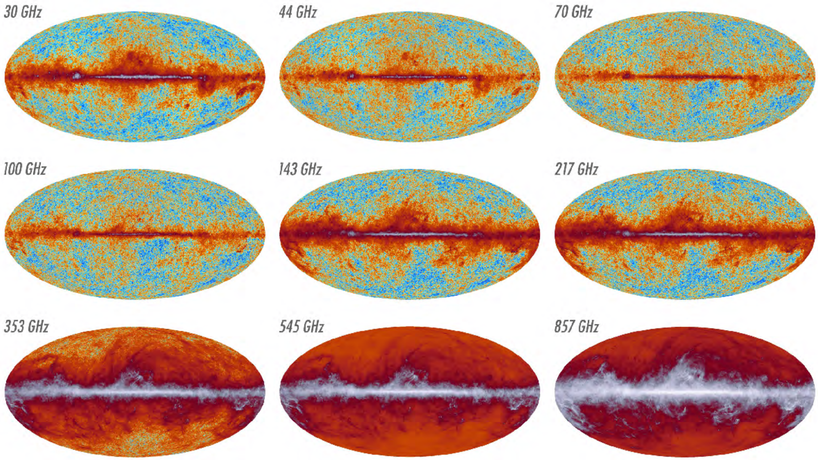


The foreground problem



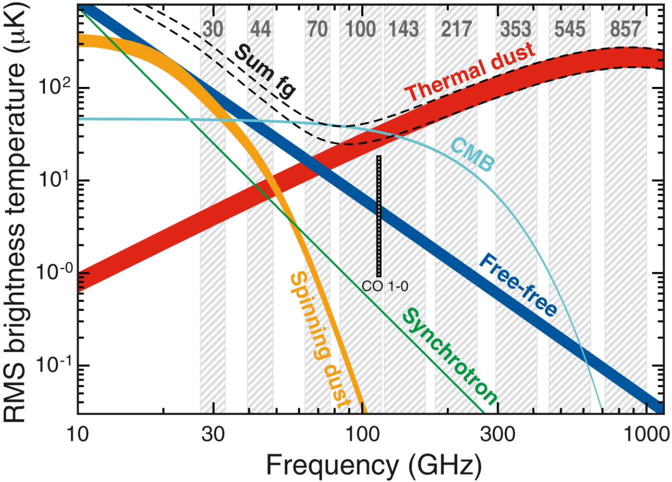
We need to understand the (most important) foreground properties to disentangle it from the cosmic signal!

An example from higher frequencies



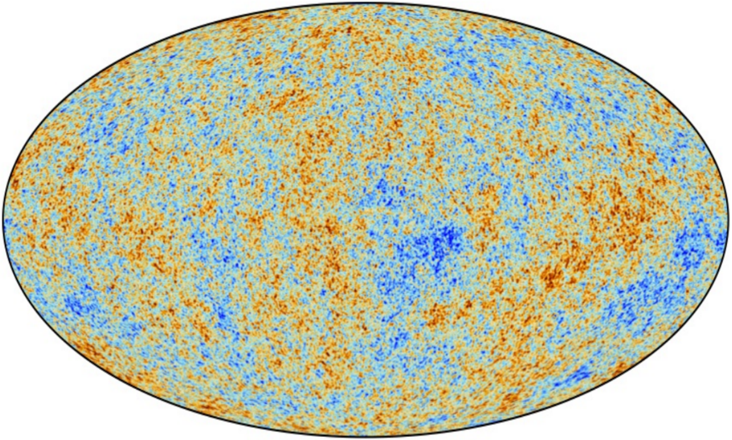
Planck Collaboration 2015

An example from higher frequencies



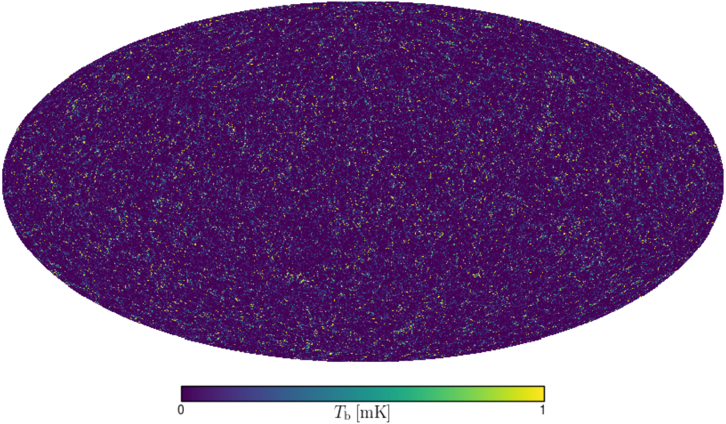
Planck Collaboration 2015

Cosmic Microwave Background

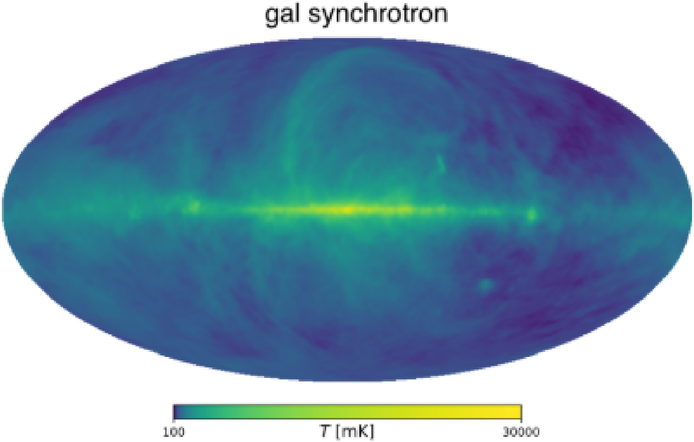


Planck Collaboration 2015

21 cm signal (simulation!)



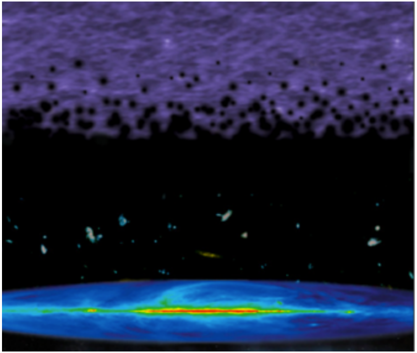
If we look at the sky



Below the GHz..

- Galactic synchrotron
  (dominant foreground) cosmic ray electrons interacting with the galactic magnetic field.
- Extragalactic Point Sources (PS)
  radio galaxies, AGNs, ..
- Galactic and Extragalactic free-free
  bremsstrahlung radiation from electron-ion collisions

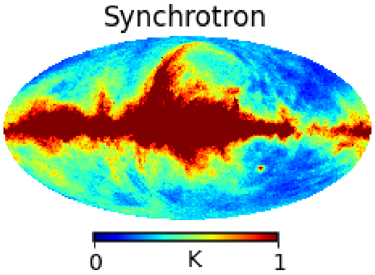
e.g. Santos et al 2005, Jelic et al 2008, Geil et al 2011

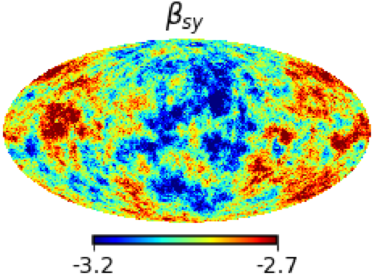


credit: LOFAR

Modeling foregrounds

$$T_{\rm sky}(\nu, \hat{\mathbf{n}}) = [T_{\rm H}(\hat{\mathbf{n}}) - T_{\rm cmb}] \left(\frac{\nu}{408\,\rm MHz}\right)^{\beta_{sy}(\hat{\mathbf{n}})} + T_{\rm cmb}$$





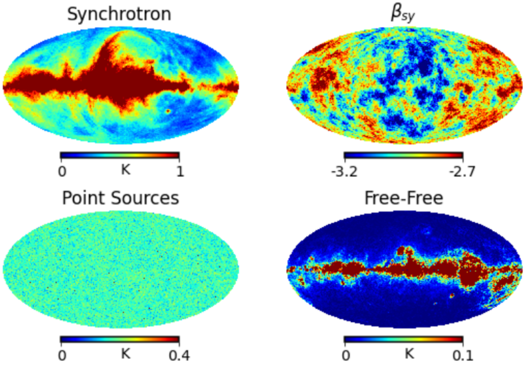
Haslam 408 MHz (Ramazeilles et al 2015)

Spectral index (Miville-Deschenes et al 2008)

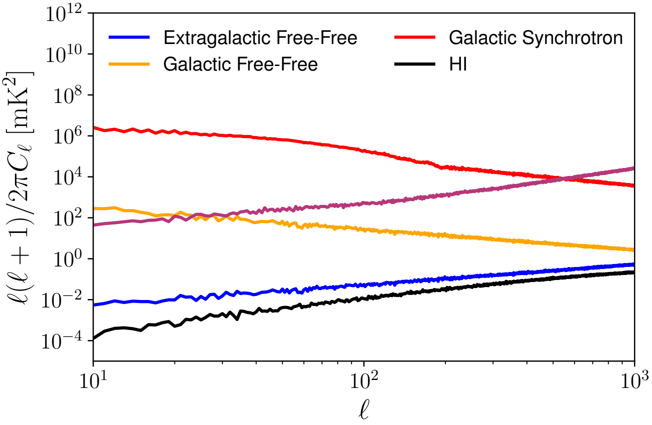
Modeling foregrounds

Typical choices:

- Haslam 408 MHz Ramazeilles et al (2015)
- Spatially varying synch spectral index Miville-Deschenes et al (2008)
- Free-Free from Planck Sky Model Delabruille et al (2013)
- Extragalactic PS Olivari (2018) (flux cut at 0.1 Jy)

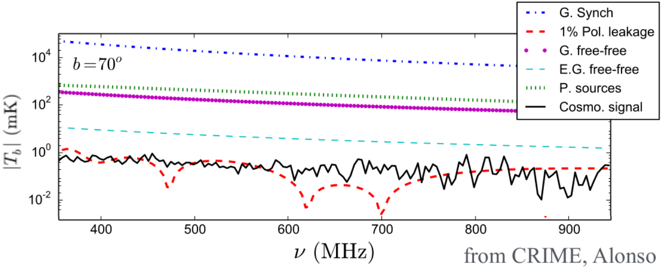


Foregrounds *vs* signal



Matshawule et al. (2021)

Foregrounds *vs* signal

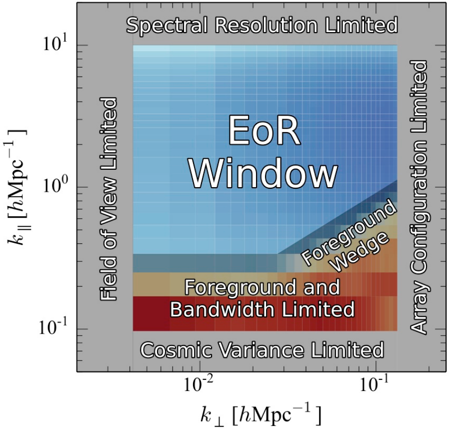


from CRIME, Alonso et al 2014

- foregrounds: smooth frequency structure means they are highly correlated along the line of sight
- very different behavior of the 21cm signal!

Two main strategy: attempt to clean or attempt avoid them

Foreground Avoidance



Liu et al. (2014)

- Smooth foregrounds are expected at small $k_\parallel$
- upper limit on $k_\parallel$ fixed by the spectral resolution of the instrument
- field of view limits the small $k_\perp$
- going to higher $k_\perp$, due to the instrument response, foregrounds leak out to higher $k_\parallel$ (foreground wedge)

Foreground cleaning

$$T = As + n + c$$

A mixing matrix of the foreground sources

Noise

21cm signal

Parametric Fitting:

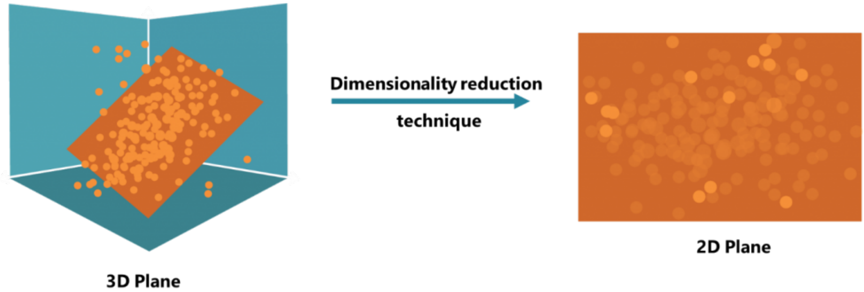
- Use known properties of foregrounds: synchrotron and free free (prior knowledge for the A)
- Ad-hoc smooth basis functions to model the foregrounds e.g. Alonso et al 2015

Blind foreground subtraction:

- Principal Component Analysis (PCA)
- Fast Independent Component Analysis (FastICA) e.g. Wolz et al. (2017), Cunnington et al. (2019)
- Generalized Morphological Component Analysis (GMCA) e.g. Carucci et al. (2020)

Principal Components Analysis (PCA)

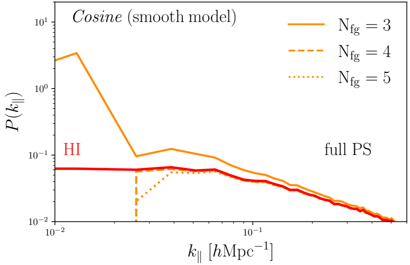
- from data-"cube" $(N_\nu \times N_{\hat{n}})$ one construct $C_{ij} = \frac{1}{N_{\hat{n}}} \sum_{p=1}^{N_{\hat{n}}} T(\nu_i, \hat{n}_p)\, T(\nu_j, \hat{n}_p)$
- compute eigenvectors and assume foregrounds can be described by the most important of them ($N_{\rm fg}$).



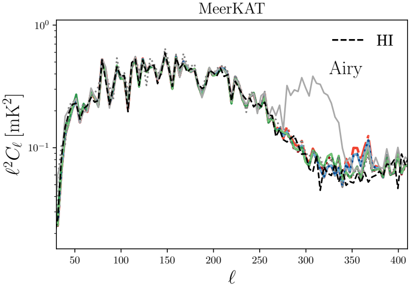
https://365datascience.com/

Does it work?

Performance of cleaning methods need to be checked (carefully!) against simulations

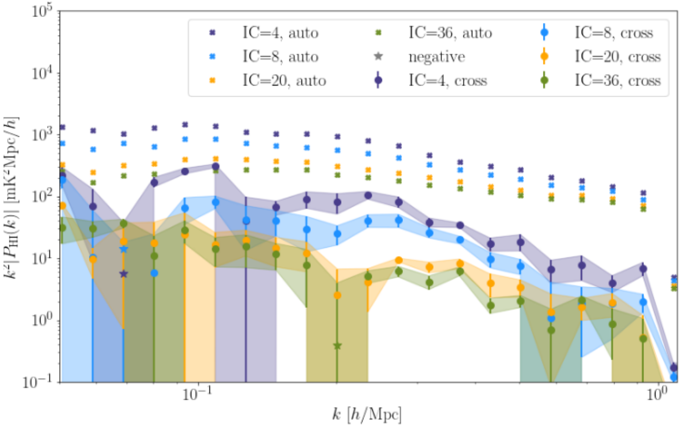


Matshawule et al. (2021)



SKAO IM Focus Group: *Blind Foreground challenge on realistic simulations*

In reality..



Wolz et al (2021)

Ways out

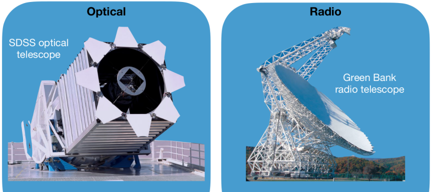
Understand Systematics

On the long run this is what we need, it takes time and getting to know the instrument very well.

Avoid Systematics

HI comes from the same DM density field of galaxy survey. You can try to correlate with optical galaxy surveys.

Mitigation of systematics with cross-correlation



$\mathbf{X}_{\rm opt} = \mathbf{S}_{\rm opt} + \mathbf{N}_{\rm opt}$ $\qquad$ $\mathbf{X}_{\rm rad} = \mathbf{S}_{\rm rad} + \mathbf{N}_{\rm rad}$

Auto Correlation:

uncorrelated

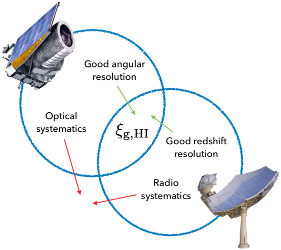
$$\langle \mathbf{X}_{\rm opt}\mathbf{X}_{\rm opt}\rangle = \langle \mathbf{S}_{\rm opt}\mathbf{S}_{\rm opt}\rangle + \cancel{2\langle \mathbf{S}_{\rm opt}\mathbf{N}_{\rm opt}\rangle} + \langle \mathbf{N}_{\rm opt}\mathbf{N}_{\rm opt}\rangle$$

$$\langle \mathbf{X}_{\rm opt}\mathbf{X}_{\rm opt}\rangle = \langle \mathbf{S}_{\rm opt}\mathbf{S}_{\rm opt}\rangle + \langle \mathbf{N}_{\rm opt}\mathbf{N}_{\rm opt}\rangle$$

signal you want $\qquad$ *noise you don't want*

Cross Correlation:

$$\langle \mathbf{X}_{\rm opt}\mathbf{X}_{\rm rad}\rangle = \langle \mathbf{S}_{\rm opt}\mathbf{S}_{\rm rad}\rangle + \cancel{\langle \mathbf{S}_{\rm opt}\mathbf{N}_{\rm rad}\rangle} + \cancel{\langle \mathbf{S}_{\rm rad}\mathbf{N}_{\rm opt}\rangle} + \cancel{\langle \mathbf{N}_{\rm opt}\mathbf{N}_{\rm rad}\rangle}$$



Thus, 21cm intensity mapping offers enormous potential for future cross-correlations

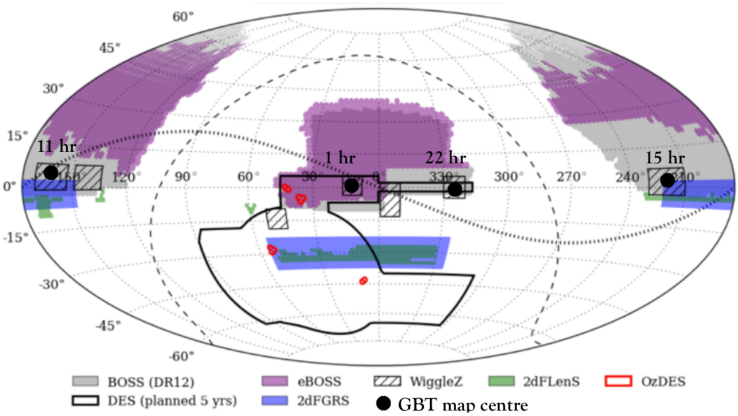
courtesy of Steve Cunnington

It worked with different cross-correlations

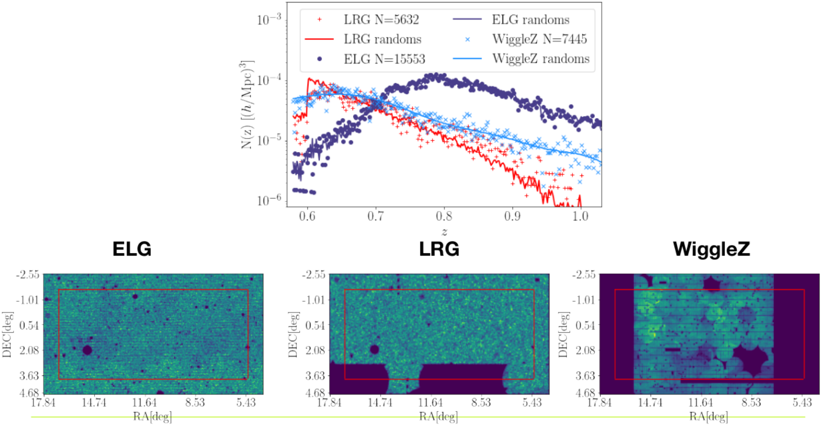
- DEEP2 x GBT
  Chang et al. (2010)
- WiggleZ x GBT
  Masui et al. (2013)
- 2dF x Parkes
  Anderson et al. (2018)
- eBOSS x GBT
  WiggleZ x GBT
  Wolz et al. (2021)

GBT/BOSS/WiggleZ: where in the sky

Wolz et al (2021)

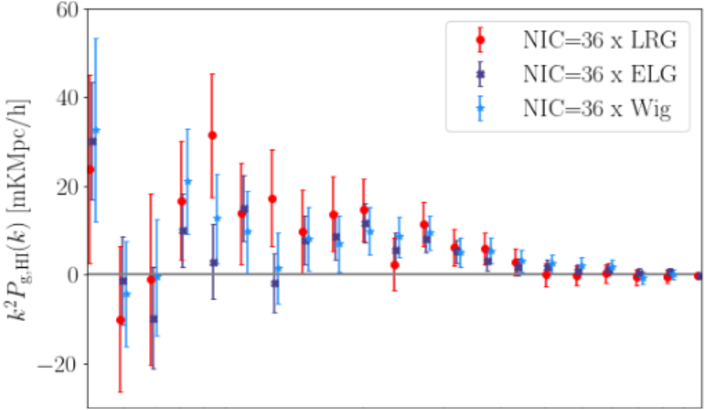


How the galaxy surveys look like



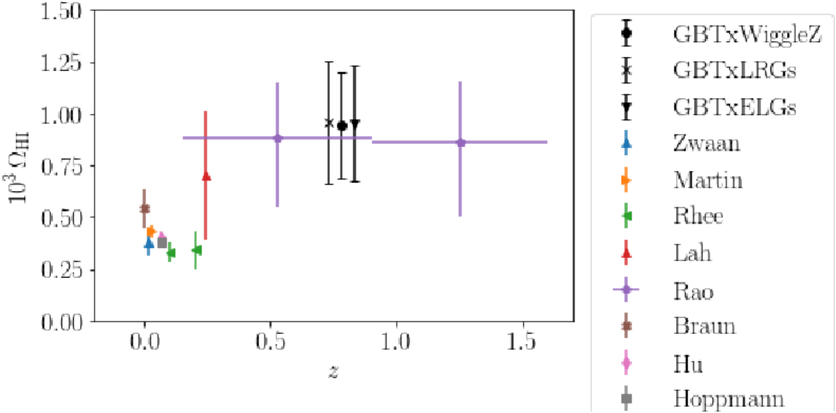
Wolz et al (2021)

Latest detection!



Wolz et al (2021)

What we can learn



Wolz et al (2021)