# Cosmology with single-dish intensity mapping

Isabella Paola Carucci (INAF - Trieste)

neutral hydrogen through its 21cm line

- strongly forbidden: $t_{1/2} \sim 10^7$ years …

- … but VERY abundant — all galaxies have some (even *clouds?*)

- Spectrally isolated ⟶ no confusion/ interlopers!

- Small obscuration ⟶ no atmospheric effects!

- All the way up to EoR (and beyond?)

$\lambda = 21 \, cm$

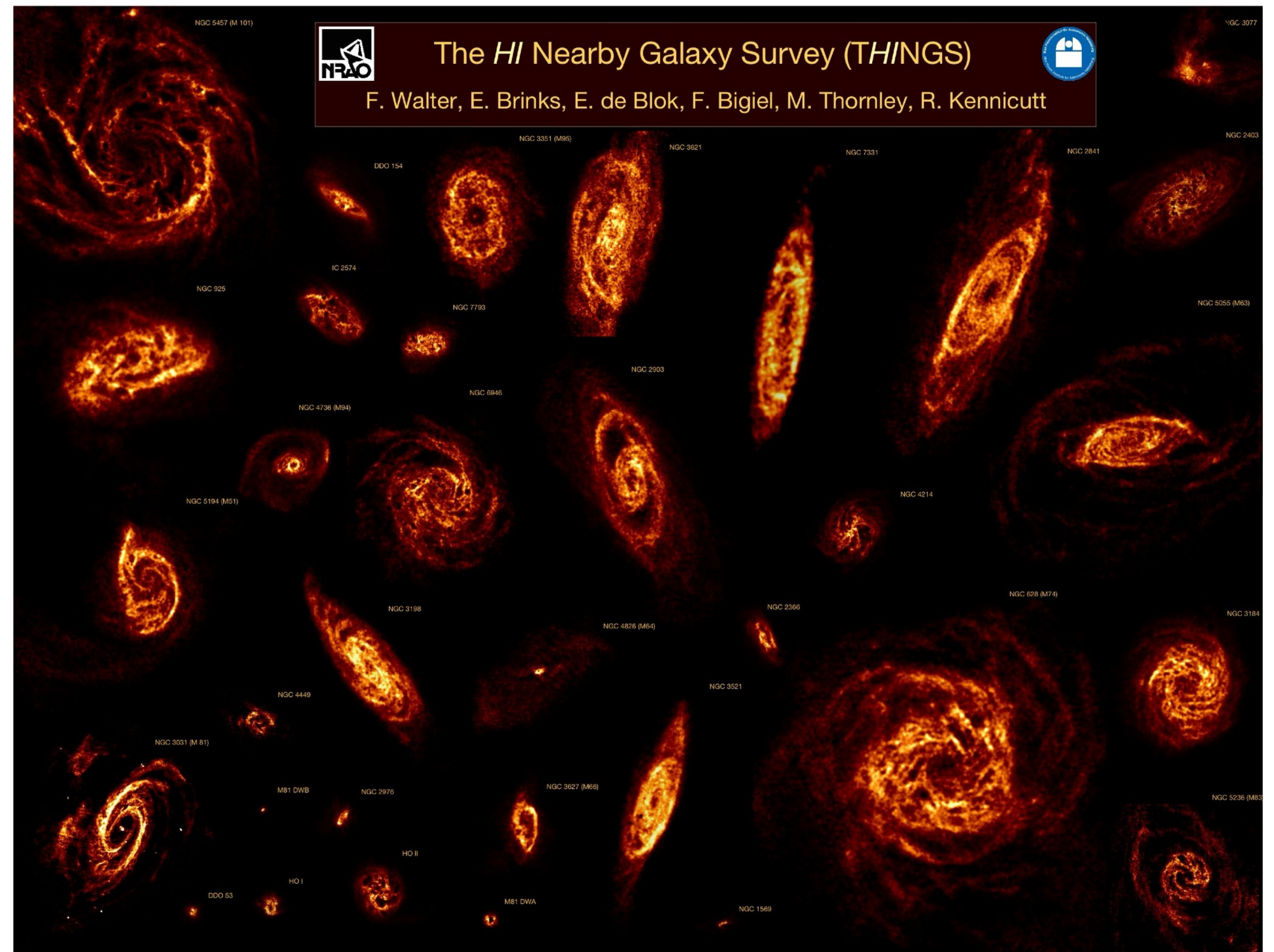the radio sky is *clean* to look at!

Isabella P. Carucci (INAF)

HIPASS
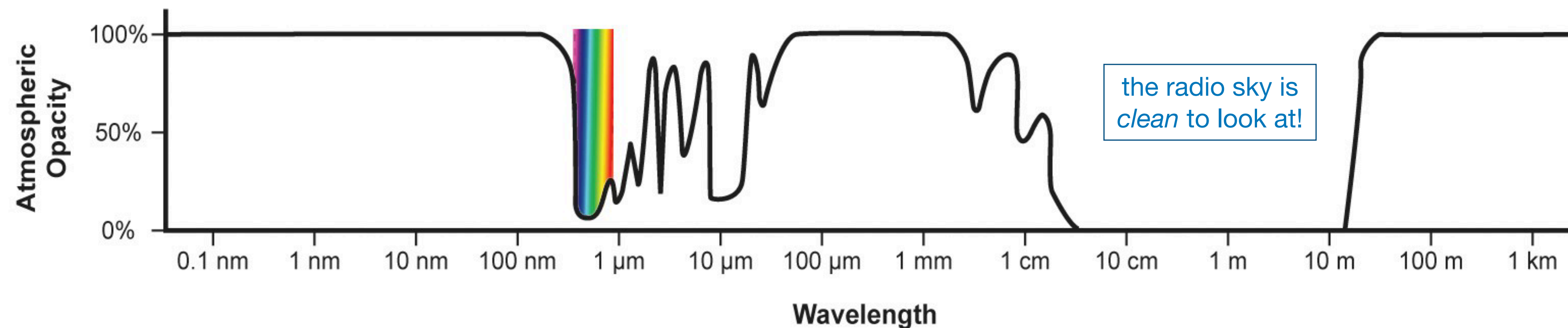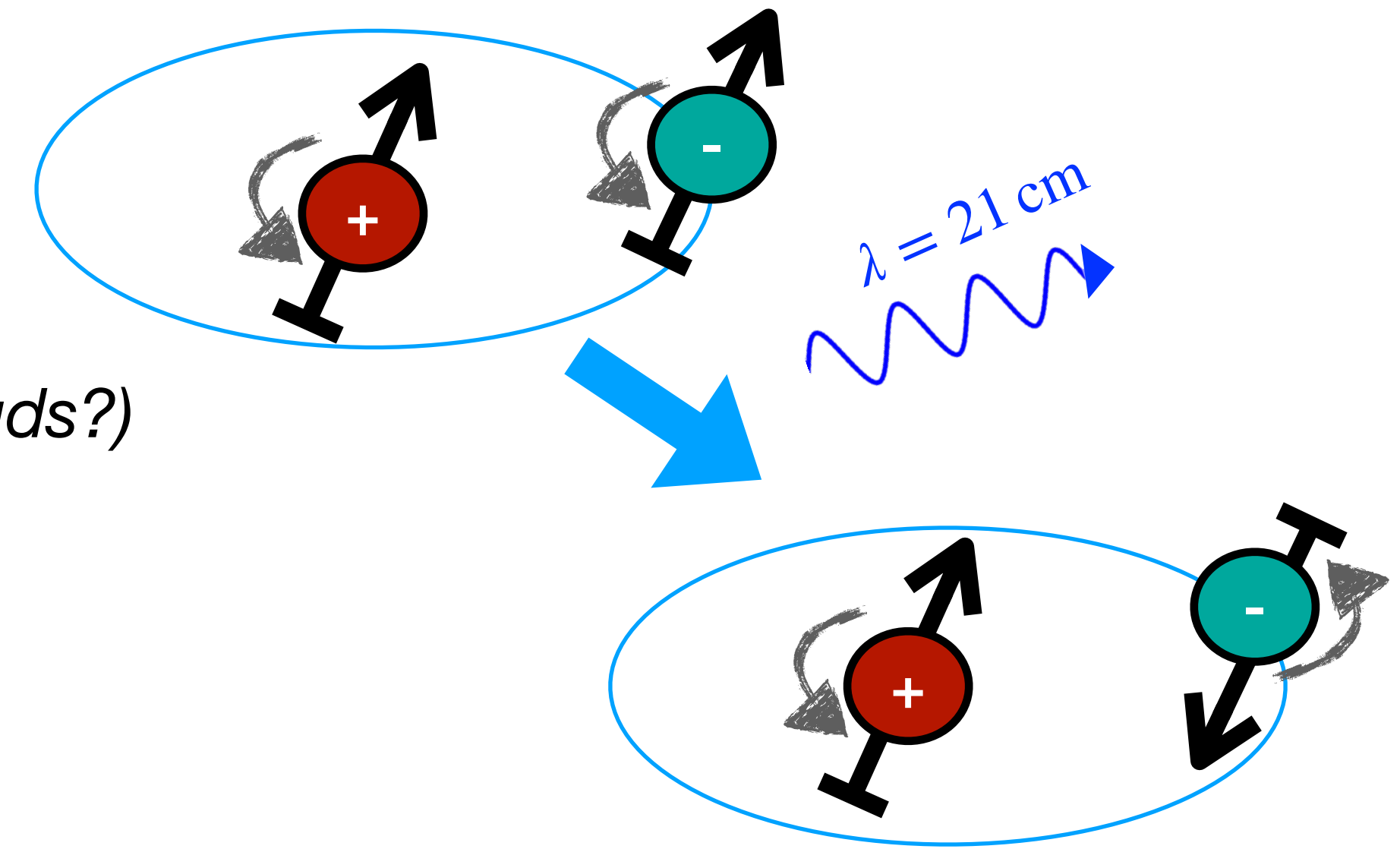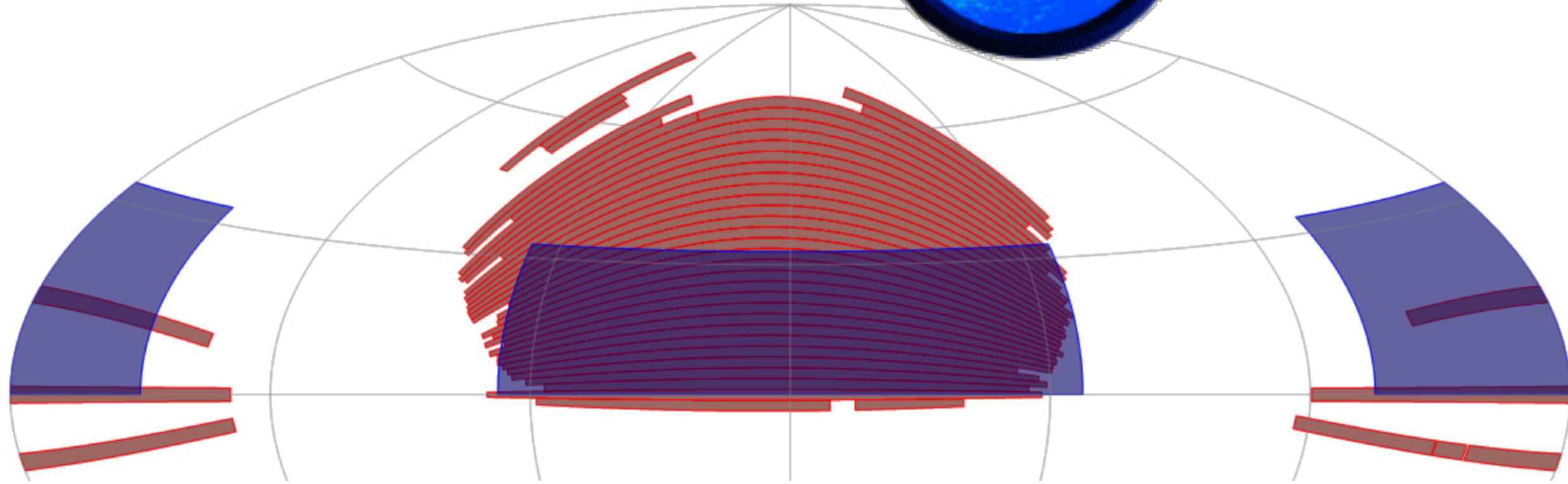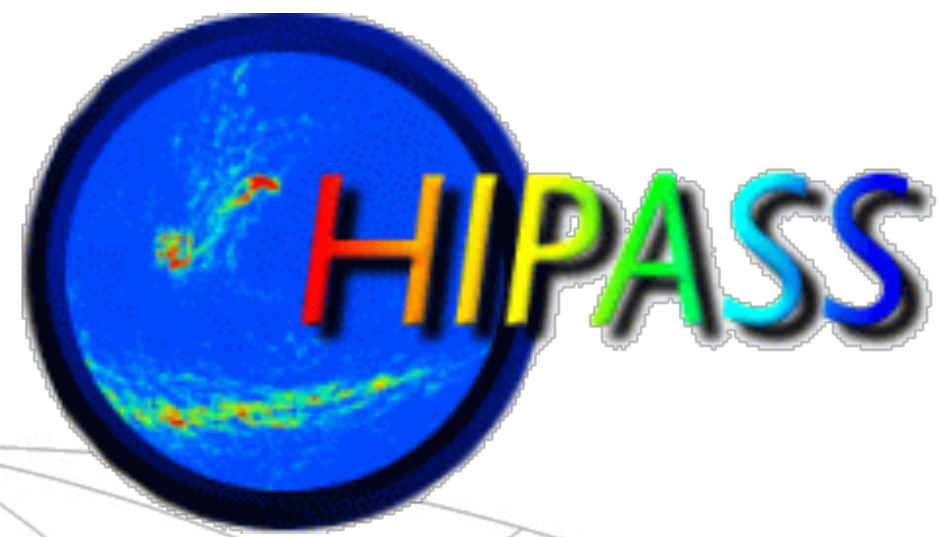
The **A**recibo **L**egacy **F**ast **ALFA** Survey
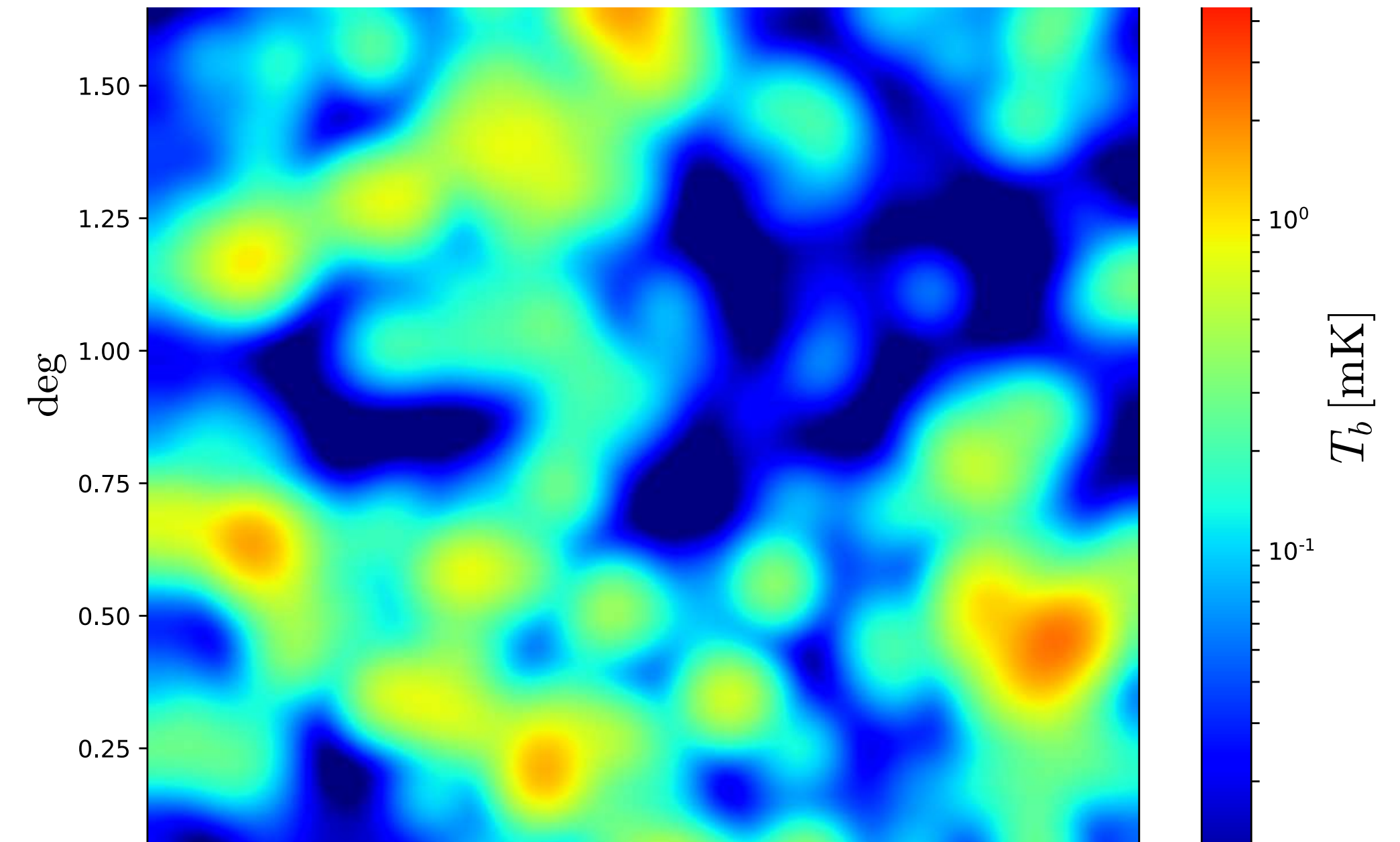
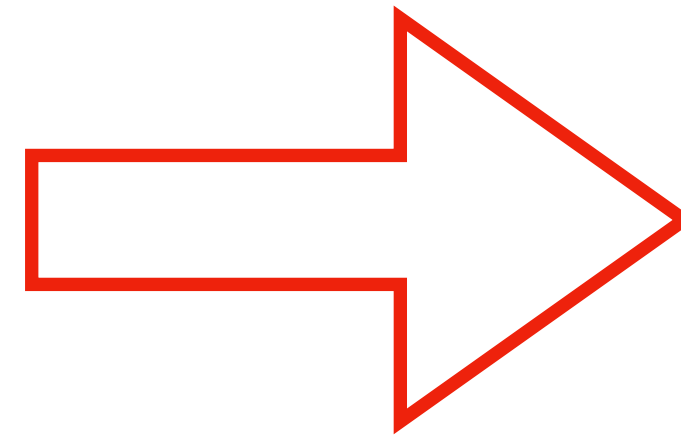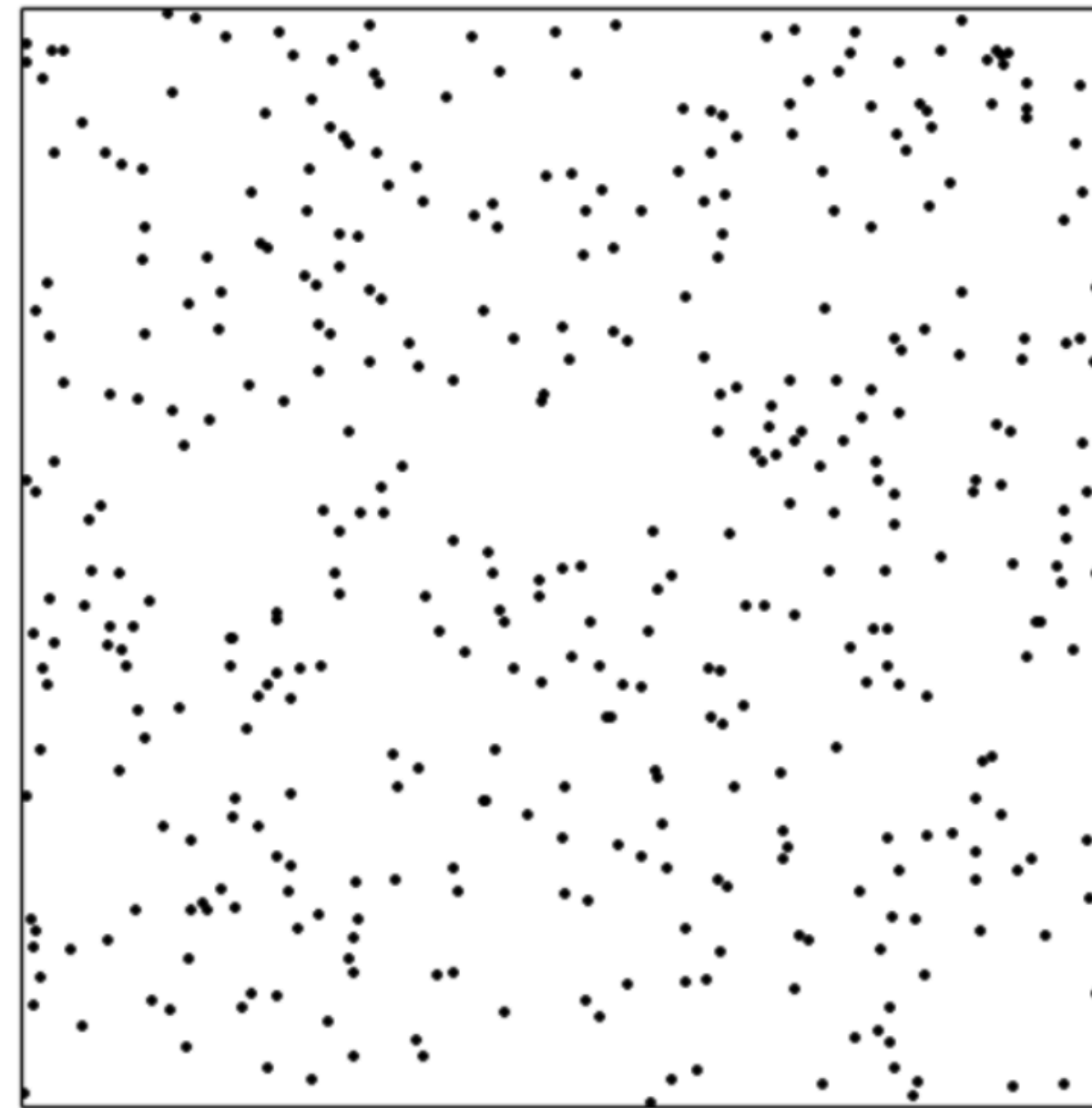The *HI* Nearby Galaxy Survey (T*HI*NGS)
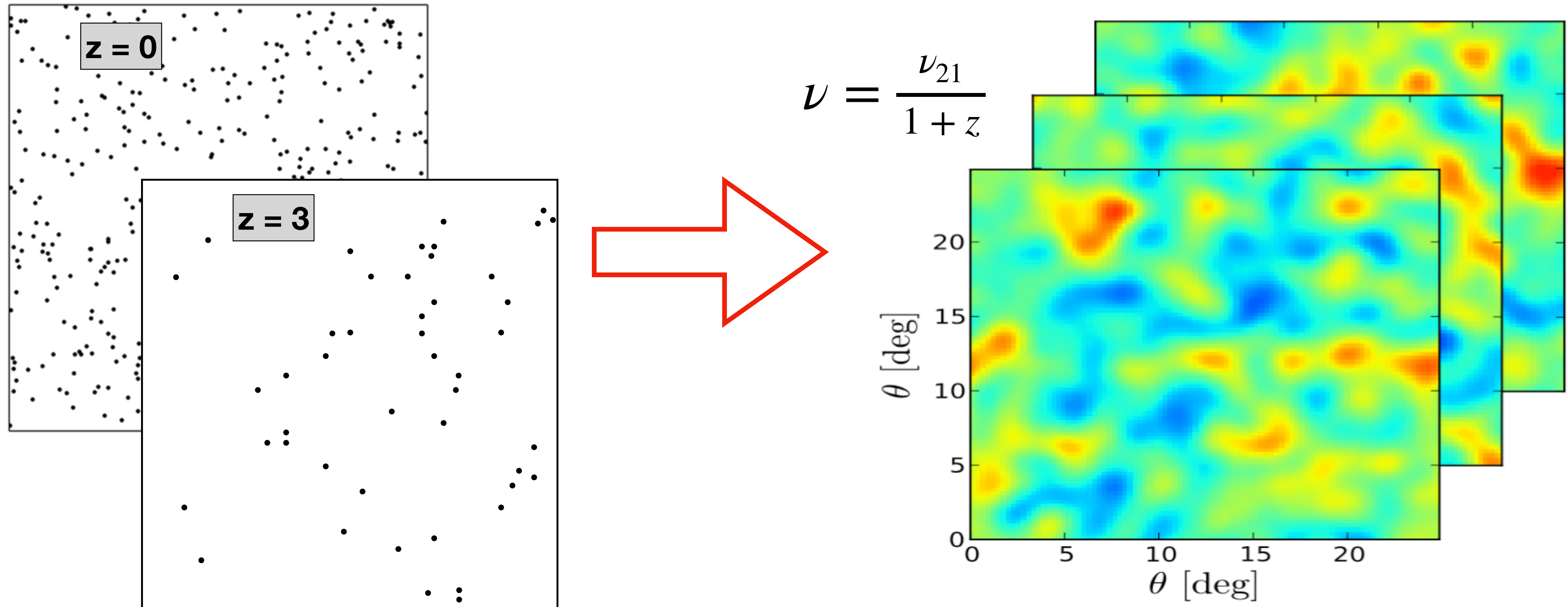F. Walter, E. Brinks, E. de Blok, F. Bigiel, M. Thornley, R. Kennicutt

Record **z = 0.376** detection of 21cm emitting galaxy with **178 hours** from VLA [Fernández et al, 2016]

intensity mapping

Put signal-to-noise where you really need it: **linear large scale modes**

intensity mapping

z = 0

z = 3

$$\nu = \frac{\nu_{21}}{1 + z}$$

Big volumes (for cheap) and high redshift resolution

A large-scale structure scientist's wish list:

✅ 1. Large areas

✅ 2. Deep and accurate redshifts (distances)

✅ 3. Better coverage of the Universe epochs

HI intensity mapping with the SKAO

Research Paper

Cosmology with Phase 1 of the Square Kilometre Array Red Book 2018: Technical specifications and performance forecasts

Square Kilometre Array Cosmology Science Working Group: David J. Bacon [1], Richard A. Battye [2], Philip Bull [3], Stefano Camera [2,4,5,6], Pedro G. Ferreira [7], Ian Harrison [2,7], David Parkinson [8], Alkistis Pourtsidou [3], Mário G. Santos [9,10,11], Laura Wolz [12], Filipe Abdalla [13,14], Yashar Akrami [15,16], David Alonso [7], Sambatra Andrianomena [9,10,17], Mario Ballardini [9,18], José Luis Bernal [19,20], Daniele Bertacca [21,22], Carlos A. P. Bengaly [9], Anna Bonaldi [23], Camille Bonvin [24], Michael L. Brown [2], Emma Chapman [25], Song Chen [9], Xuelei Chen [26], Steven Cunnington [1], Tamara M. Davis [27], Clive Dickinson [2], José Fonseca [9,22], Keith Grainge [2], Stuart Harper [2], Matt J. Jarvis [7,9], Roy Maartens [1,9], Natasha Maddox [28], Hamsa Padmanabhan [29], Jonathan R. Pritchard [25], Alvise Raccanelli [19], Marzia Rivi [13,18], Sambit Roychowdhury [2], Martin Sahlén [30], Dominik J. Schwarz [31], Thilo M. Siewert [31], Matteo Viel [32], Francisco Villaescusa-Navarro [33], Yidong Xu [26], Daisuke Yamauchi [34] and Joe Zuntz [35]

HI intensity mapping with the SKAO

Cosmology with Phase 1 of the Square Kilometre Array Red Book 2020: Technical specifications and performance forecasts

Proposed SKA1 Cosmology Surveys

a) Medium–Deep Survey of 5,000 deg² at 0.95-1.4 GHz for
- HI galaxy redshift survey with 3.5 million objects
- Weak Lensing shape measurements with ~50 million objects
- Continuum galaxy survey with ~60 million objects

b) Wide Survey of 20,000 deg² at 0.35-1.05 GHz for
- Continuum galaxy survey with ~100 million objects
- HI intensity maps for $0.35 < z < 3$

c) Deep Survey 100 deg² at 200-350 MHz for
- HI intensity maps for $3 < z < 6$

Forecasts assume AA4 !

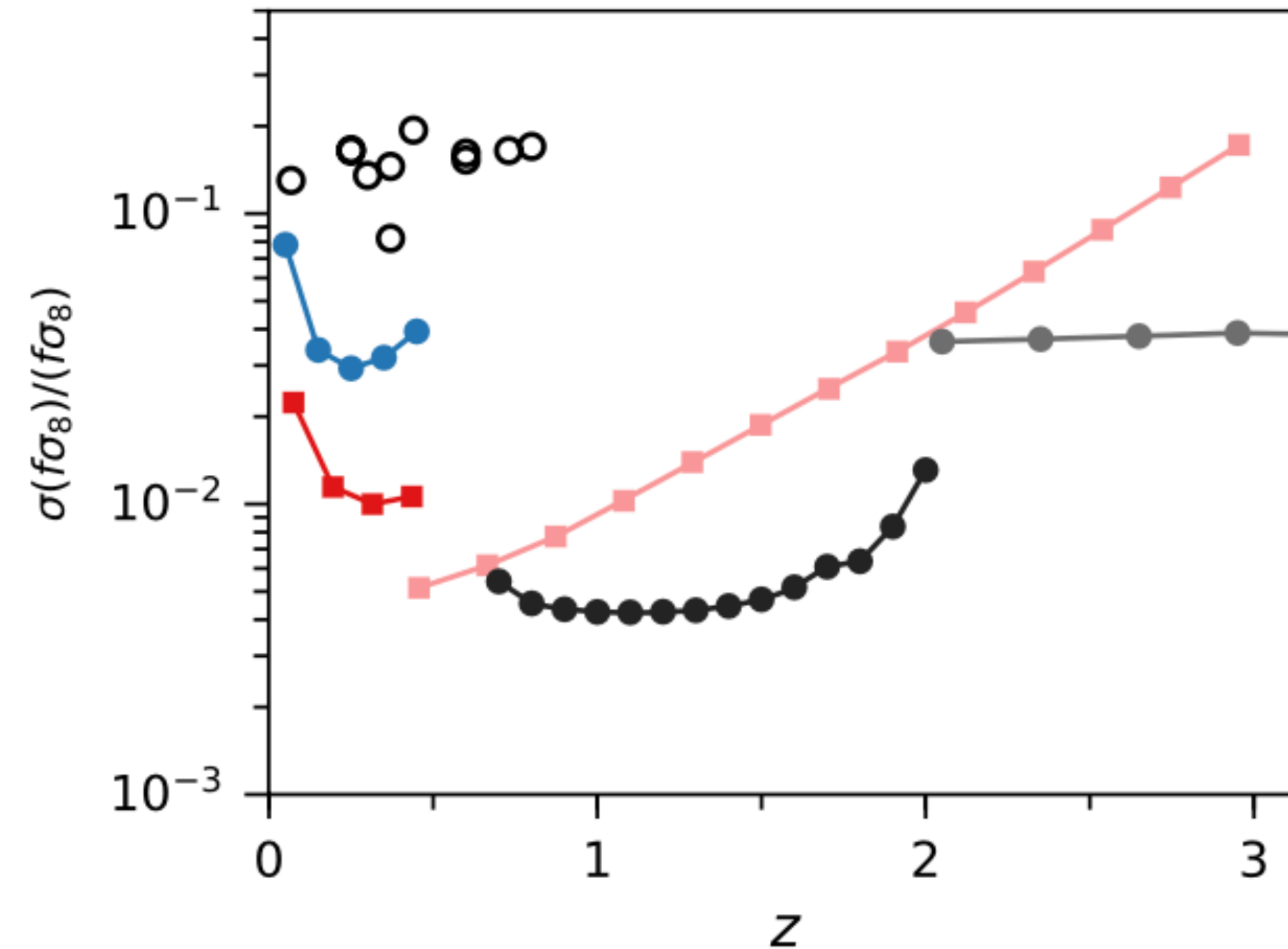# HI intensity mapping with the SKAO

1. Very large areas

- constraints on the power spectrum on **ultra-large scales** (past the equality peak)

- primordial non-gaussianity (**PNG**)

- general relativistic effects (**GR**)

- **inflation**ary effects

- in general, complementary to e.g., galaxy surveys for **multi-tracing technique** (to beat cosmic variance)
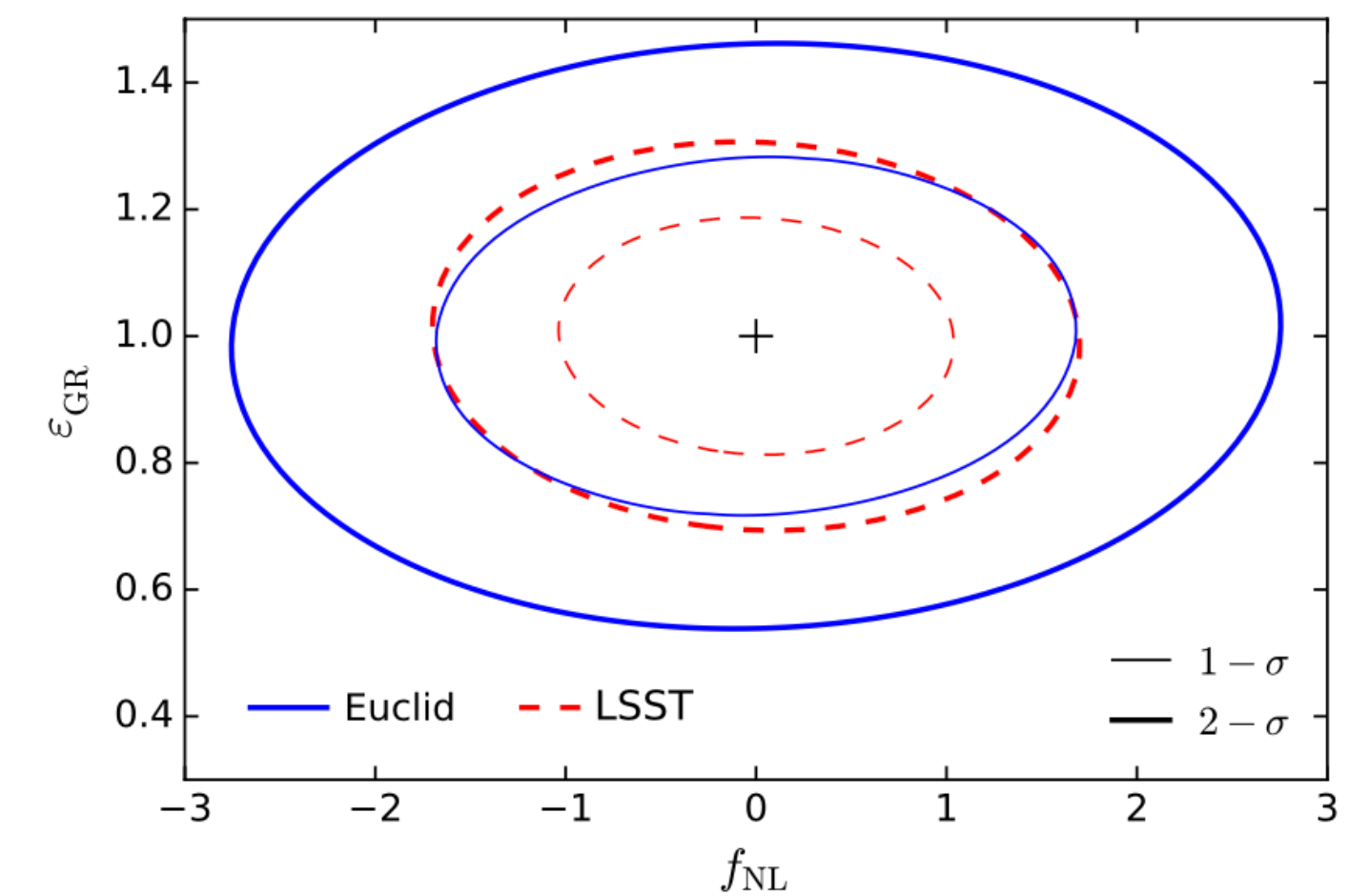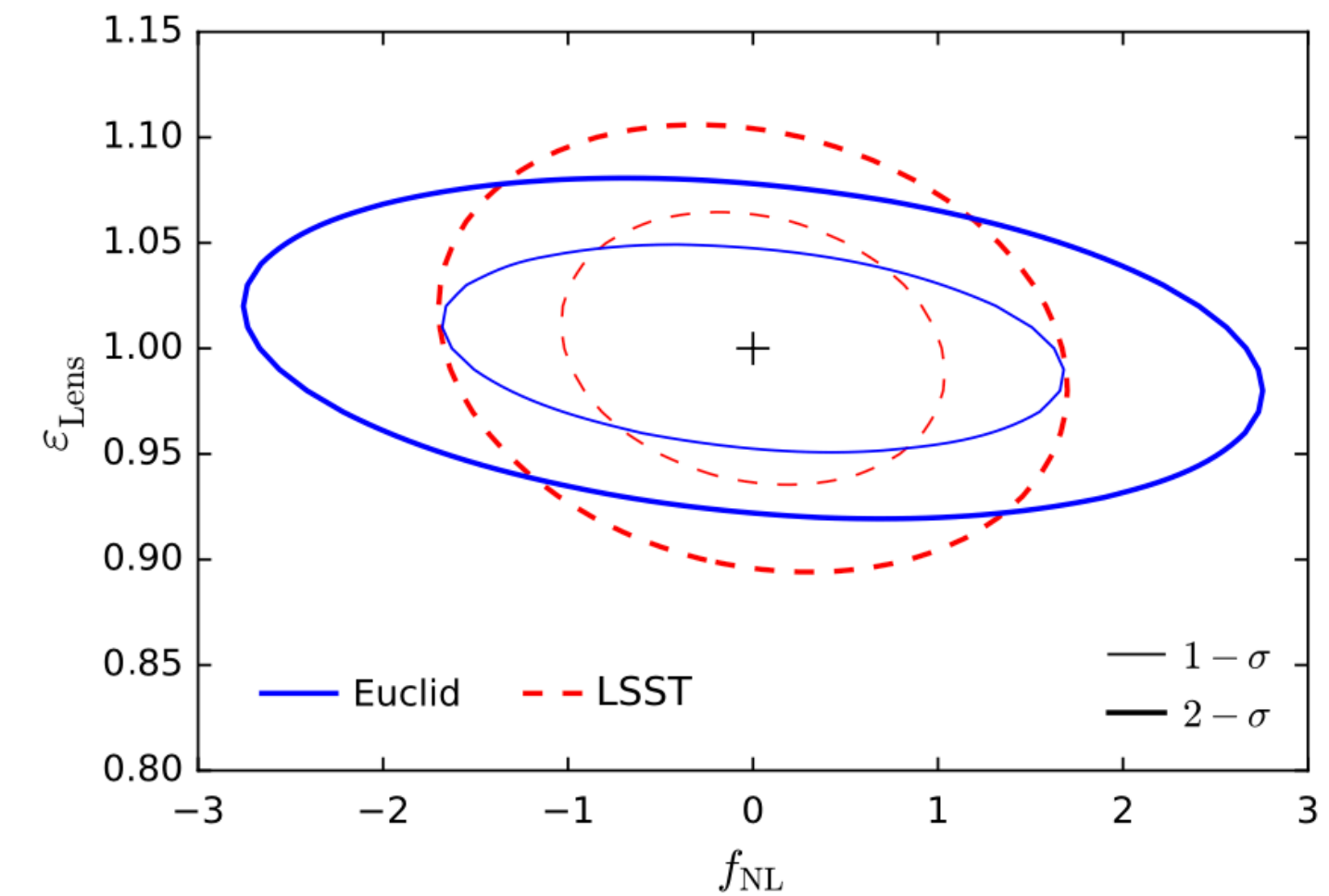
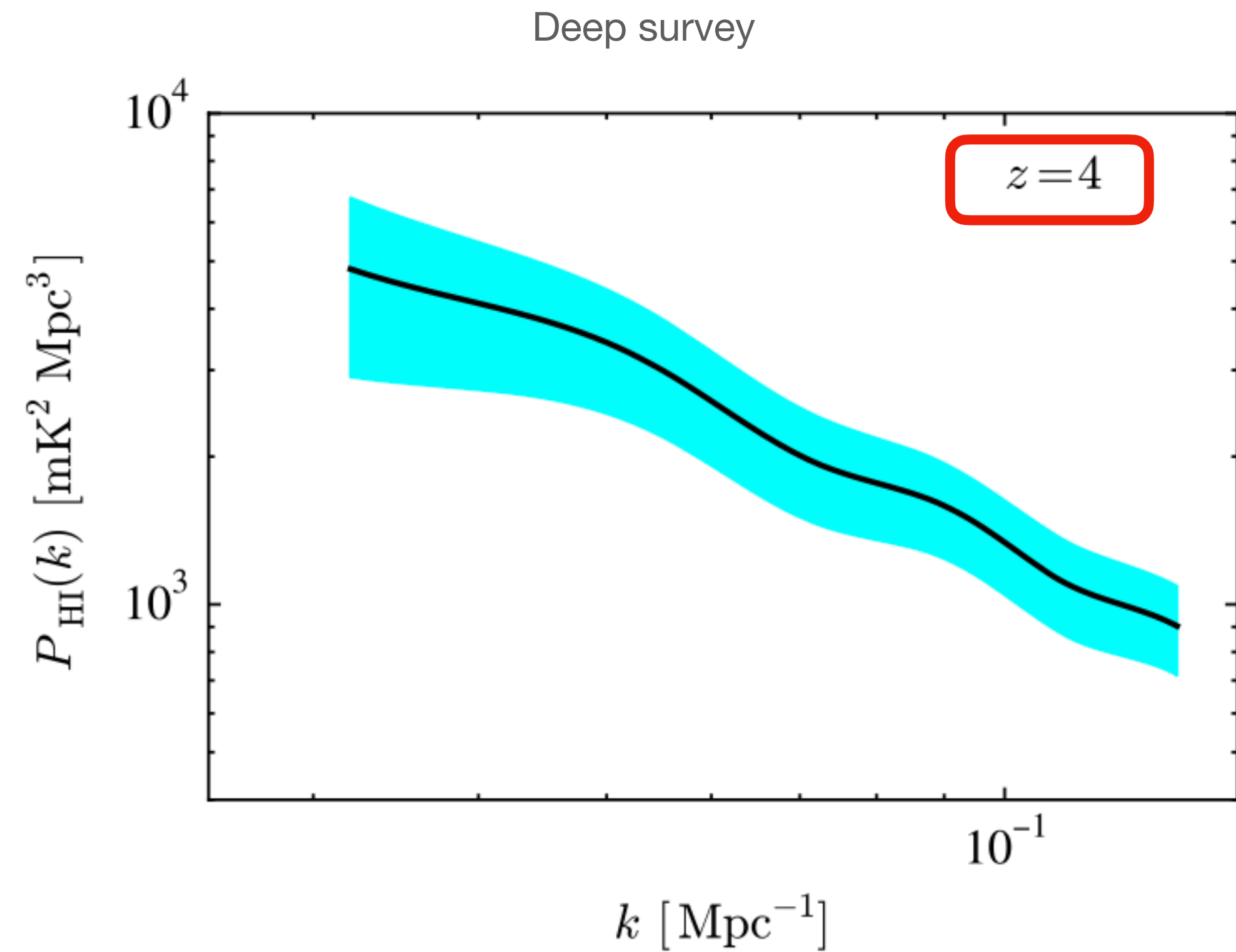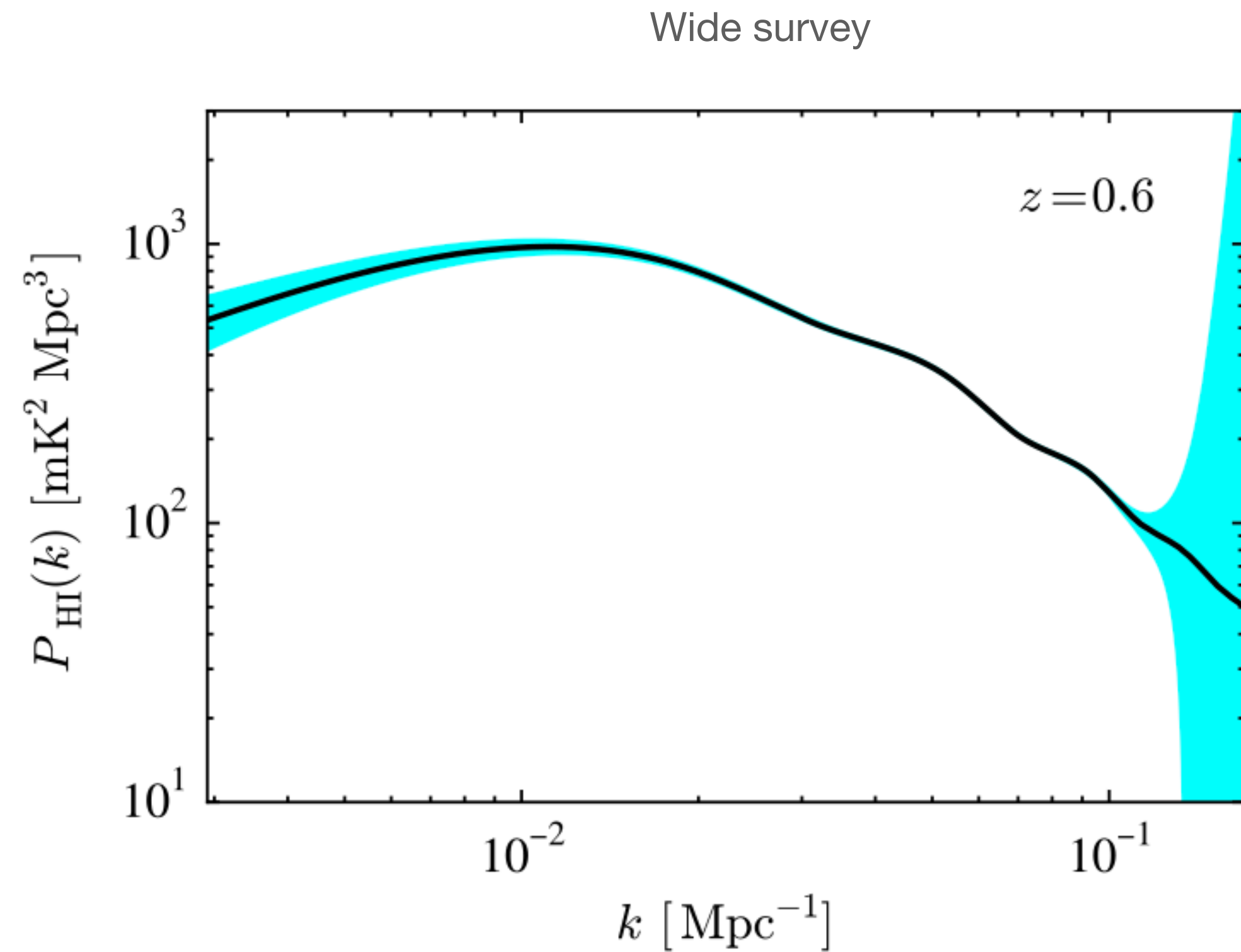# HI intensity mapping with the SKAO

2. Deep & accurate redshift: Tomographic probe!

constraints on the **expansion history** and **growth of structure** (hence, dark energy)
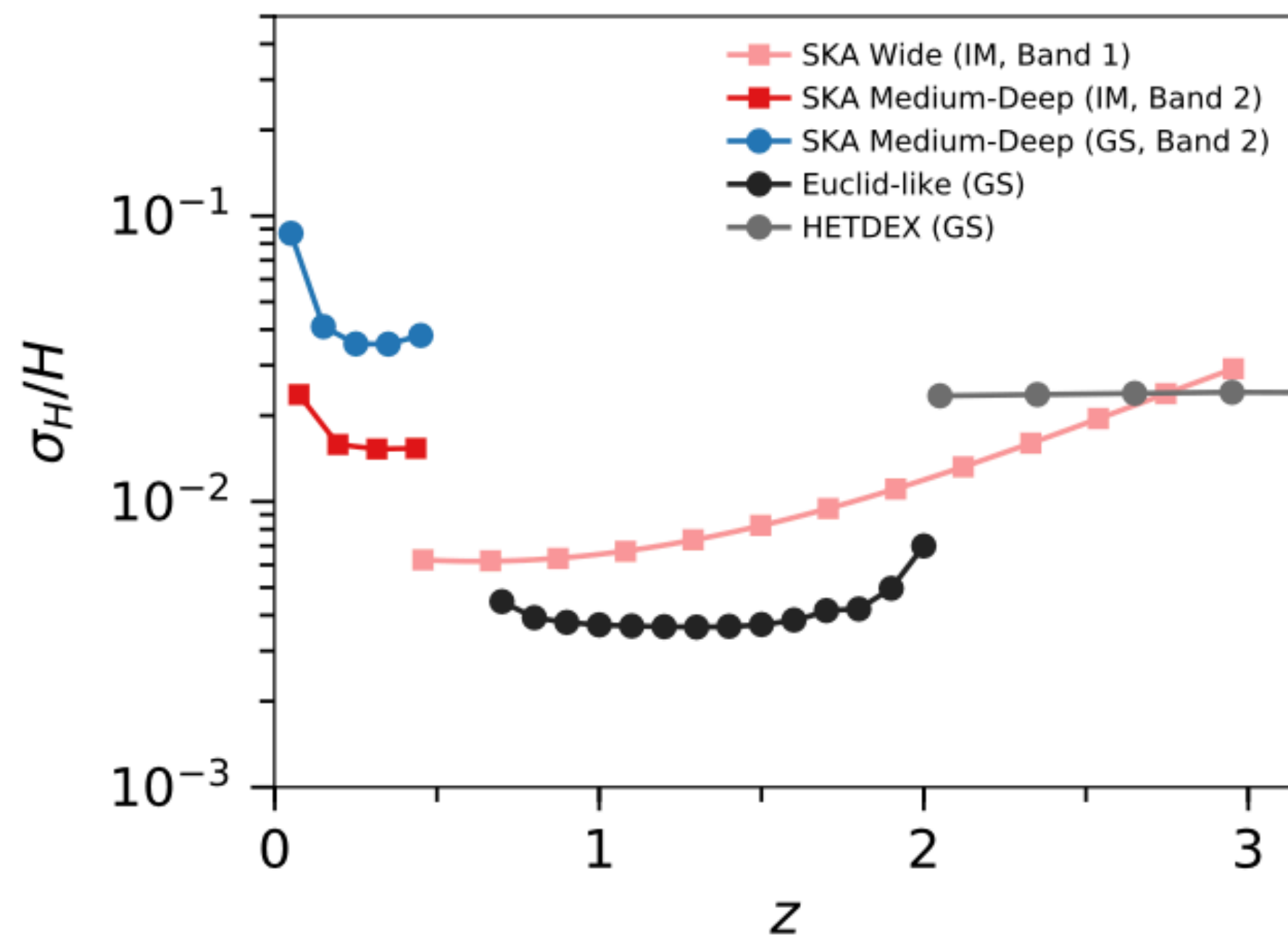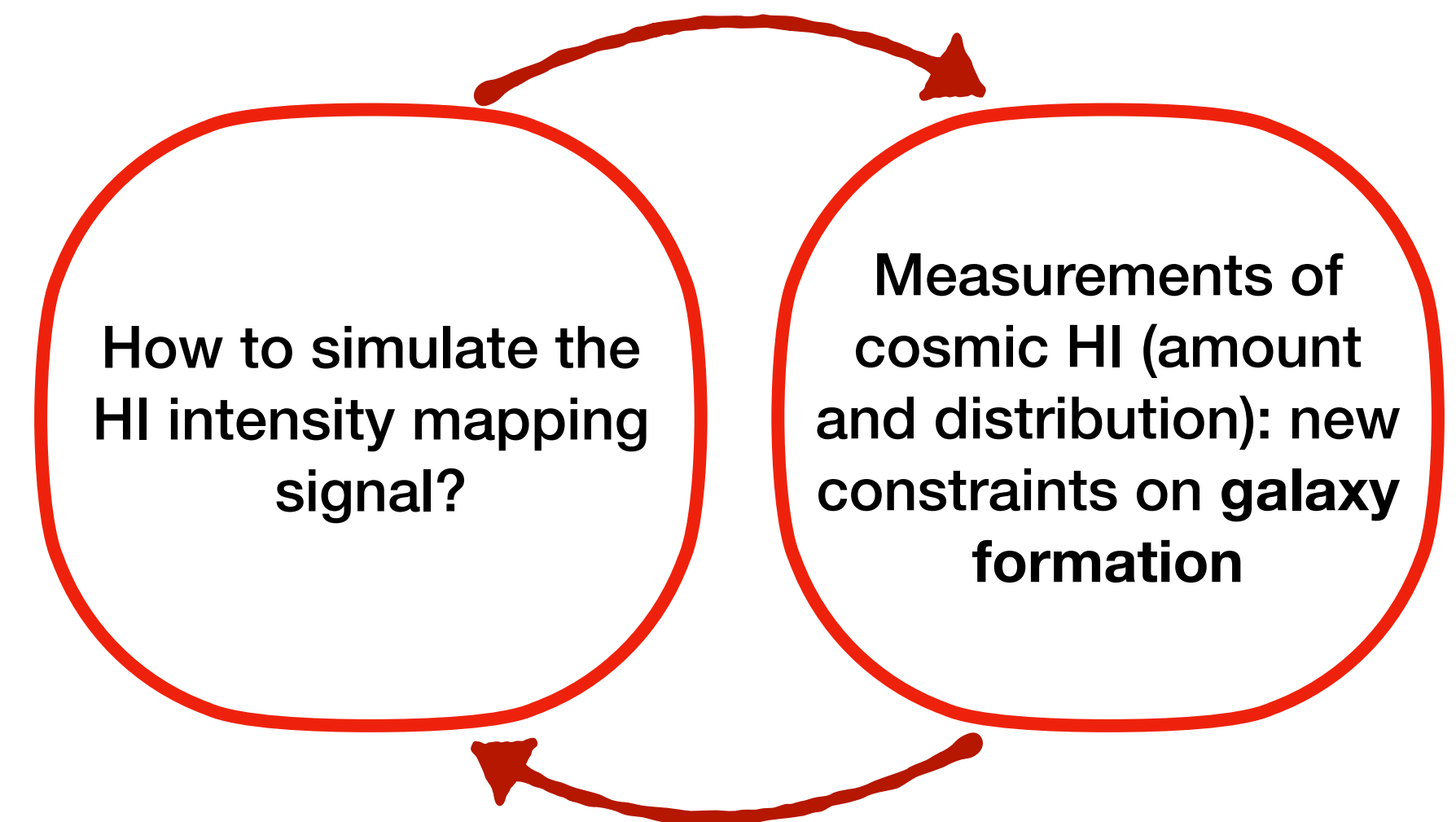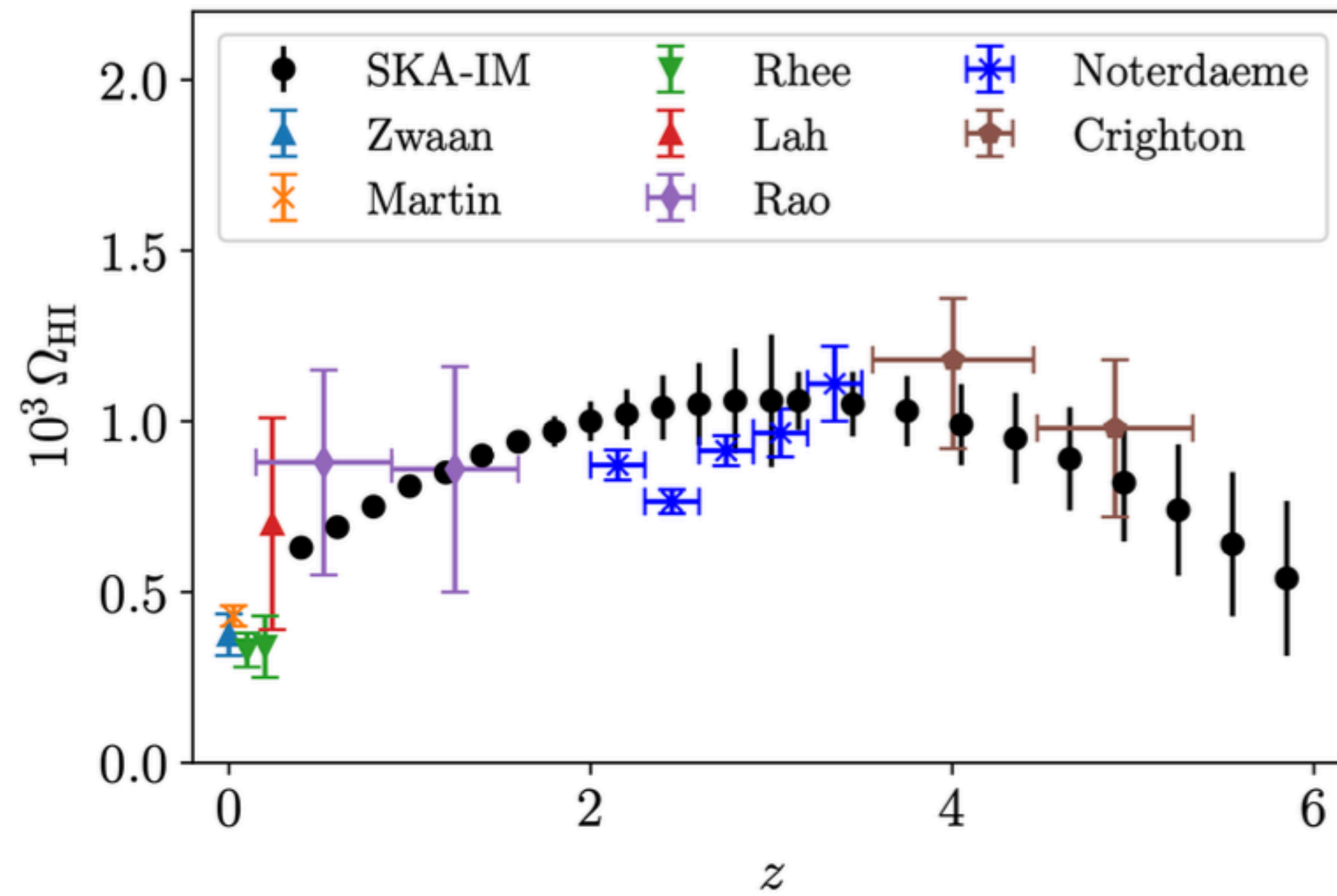
HI intensity mapping with the SKAO

3. Better coverage of the universe epochs

Wide survey

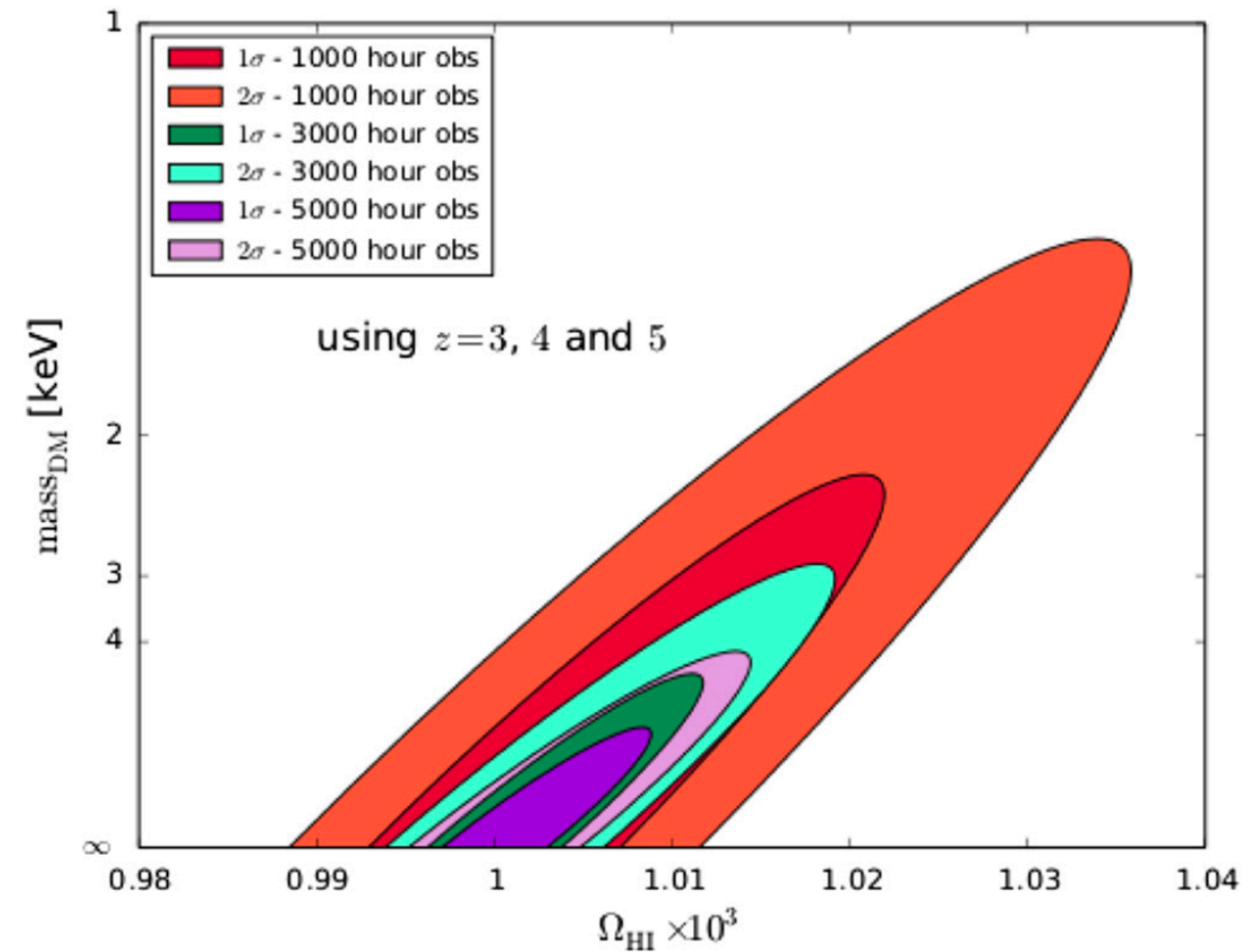Deep survey

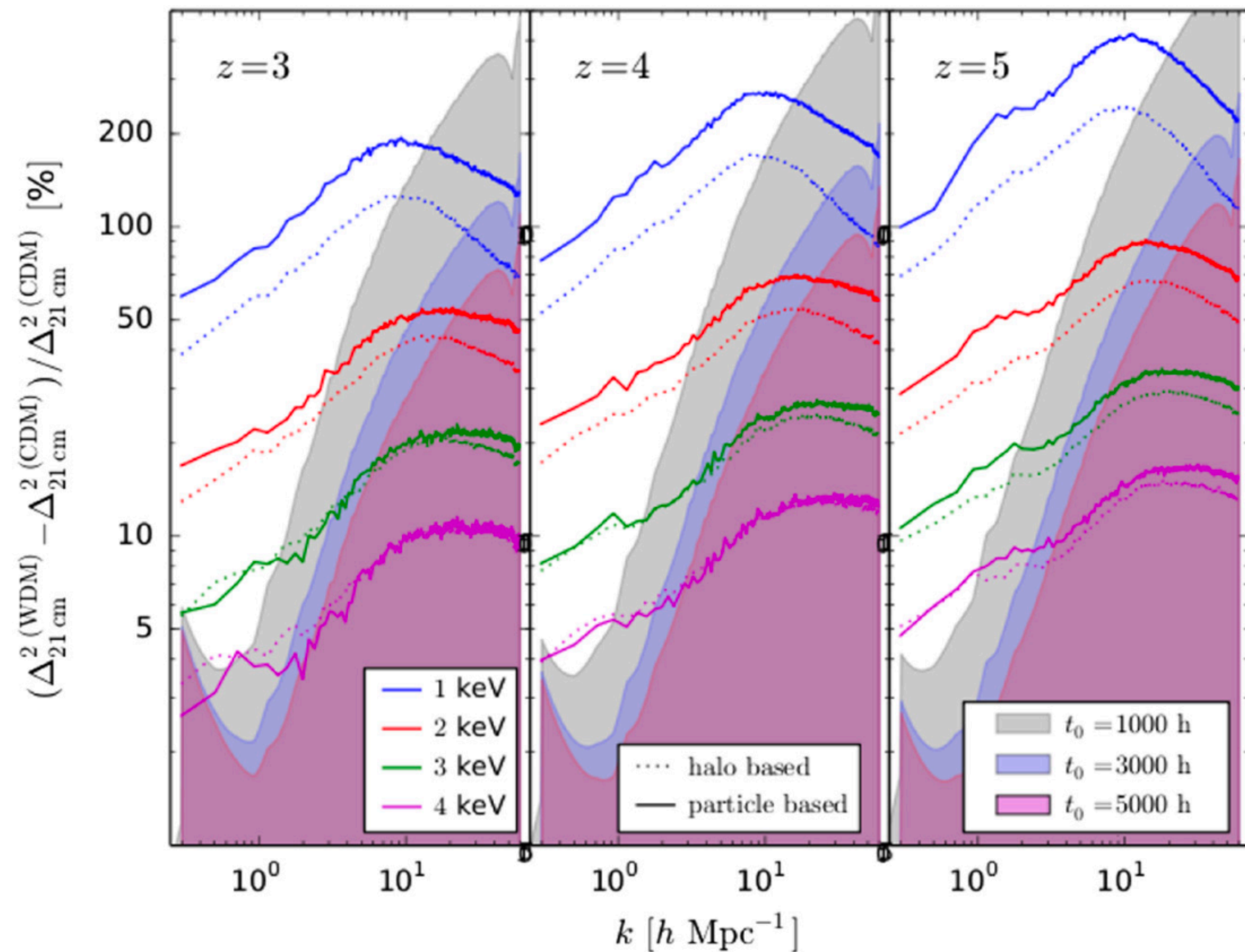# HI intensity mapping with the SKAO

Distribution and cosmic amount of neutral hydrogen (cold gas)

HI intensity mapping with the SKAO

"No photon left behind"

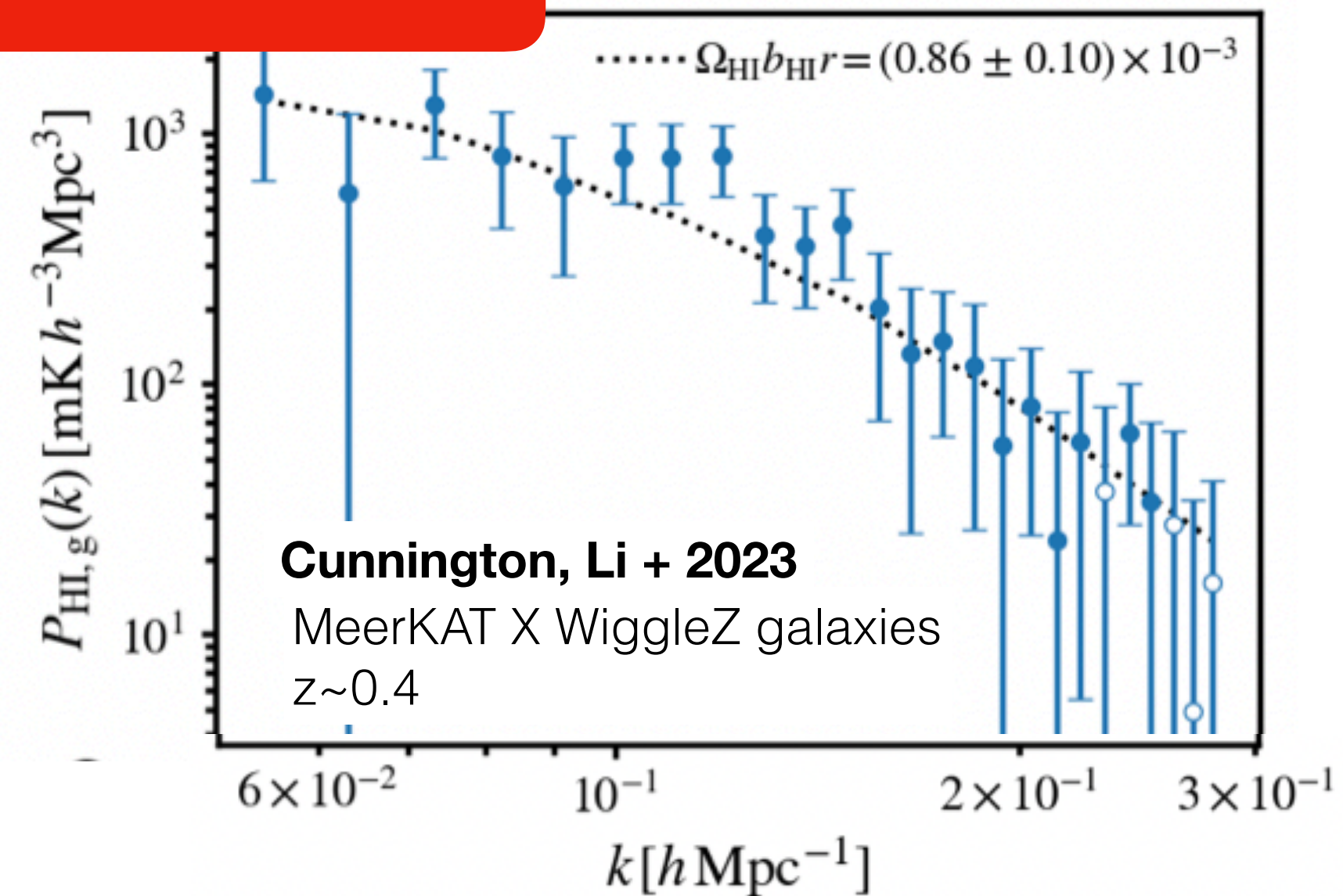Sensitive to smallest haloes*: dark matter and dark energy models

*that can host some baryon, though

is this even possible?

HI intensity mapping
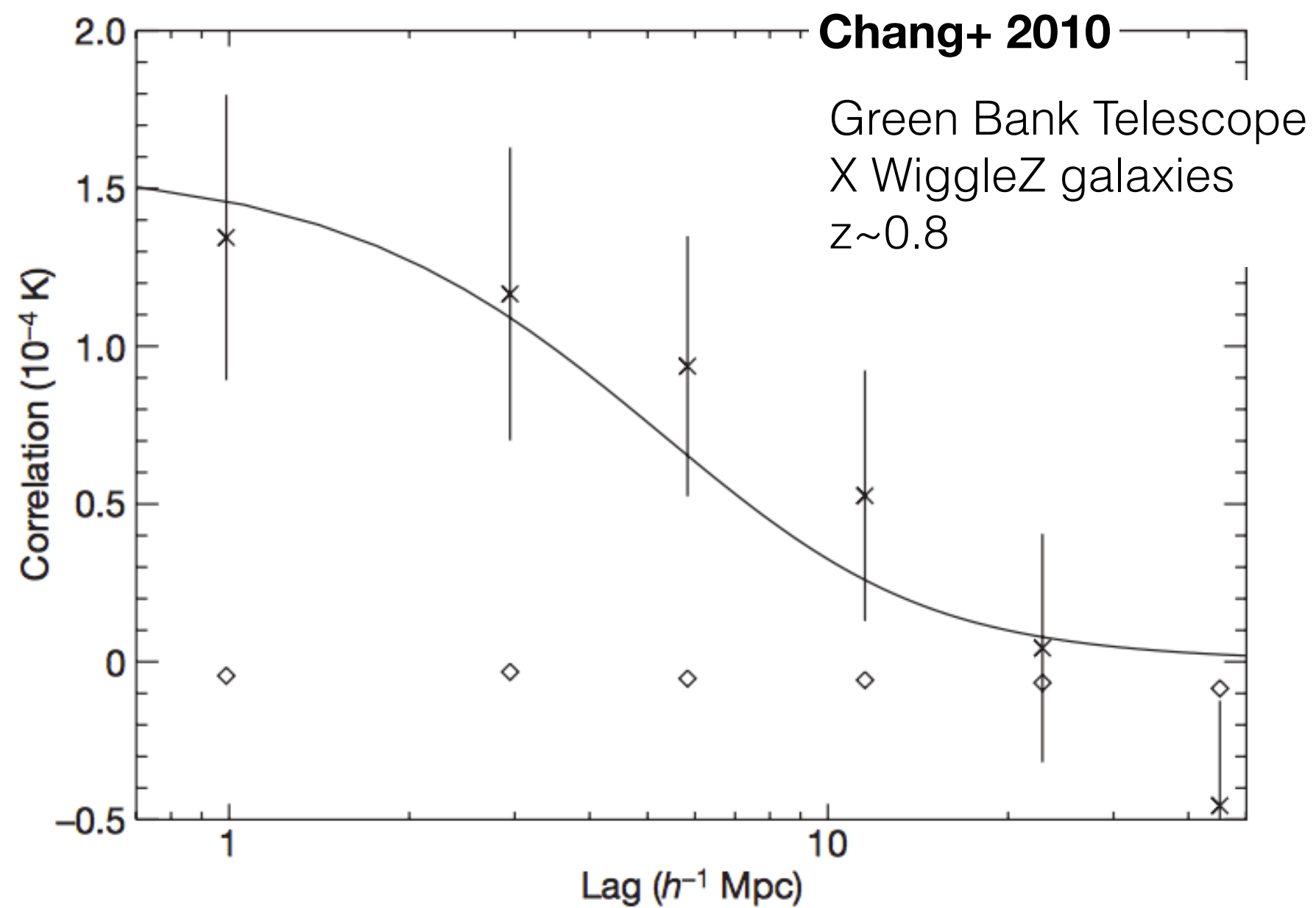## State-of-the-art

Steve's talk

$$\Omega_{\rm HI}b_{\rm HI}r = (0.86 \pm 0.10) \times 10^{-3}$$

Cunnington, Li + 2023
MeerKAT X WiggleZ galaxies
z~0.4

also MeerKLASS coll. 2024
(cross w/ GAMA galaxies + stacking)

Low-frequency cosmology is hard, but we are getting there!

HI intensity mapping
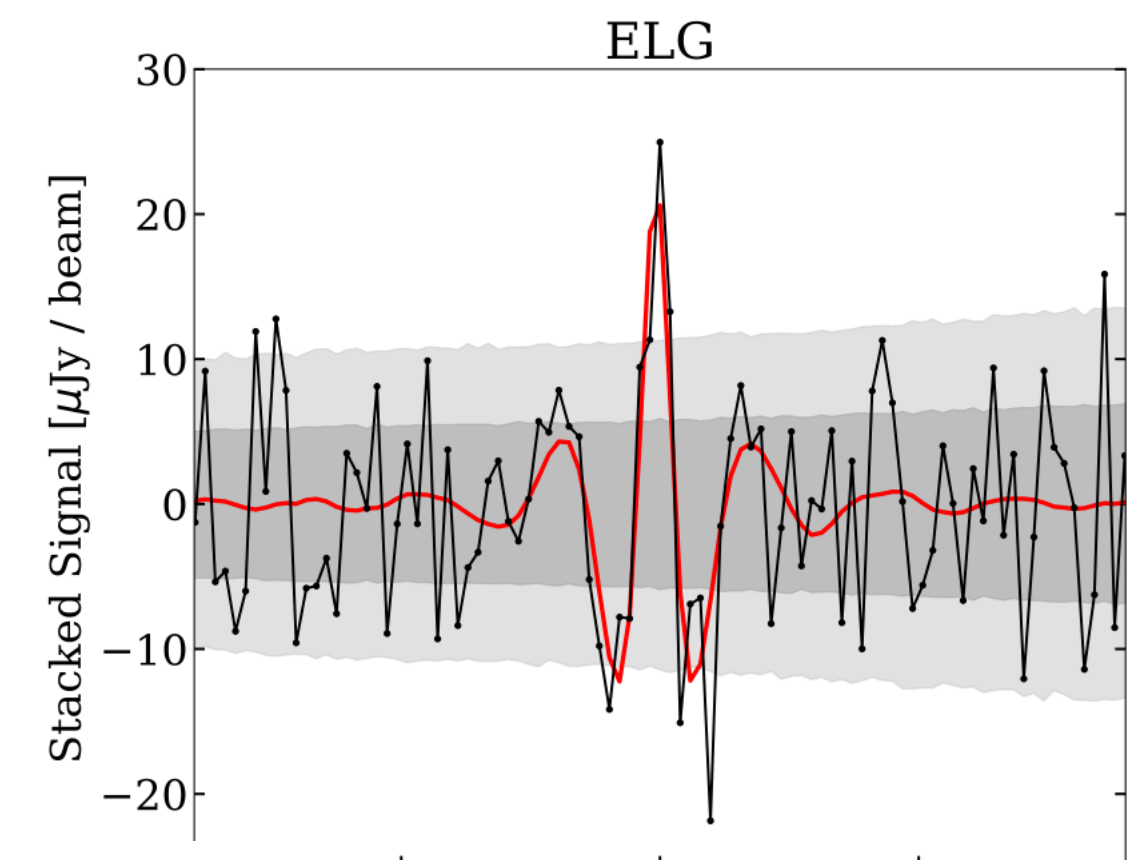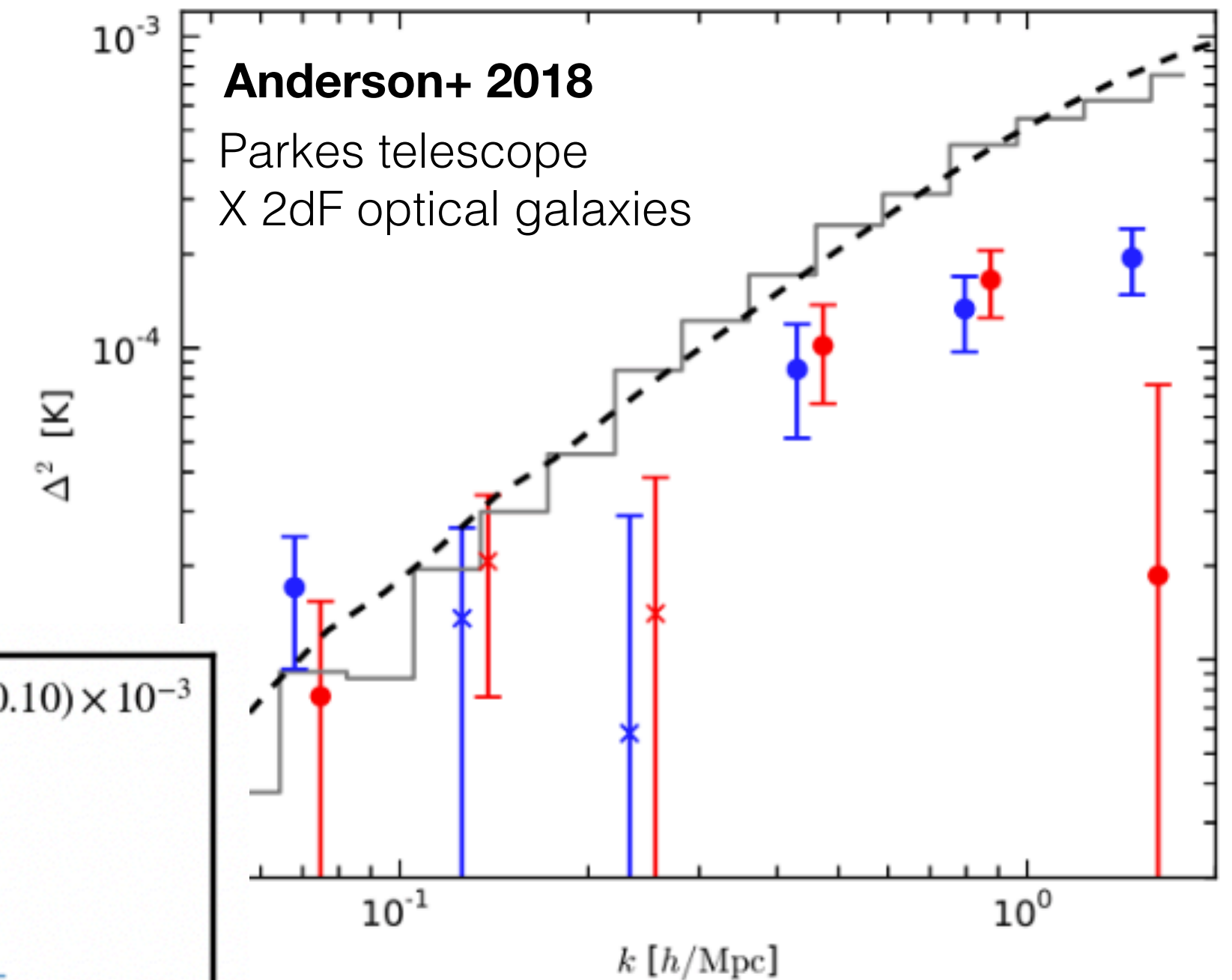## State-of-the-art

Anderson+ 2018

Parkes telescope
X 2dF optical galaxies

Chang+ 2010

Green Bank Telescope
X WiggleZ galaxies
z~0.8

$\Omega_{HI} b_{HI} r = (0.86 \pm 0.10) \times 10^{-3}$

Cunnington, Li + 2023

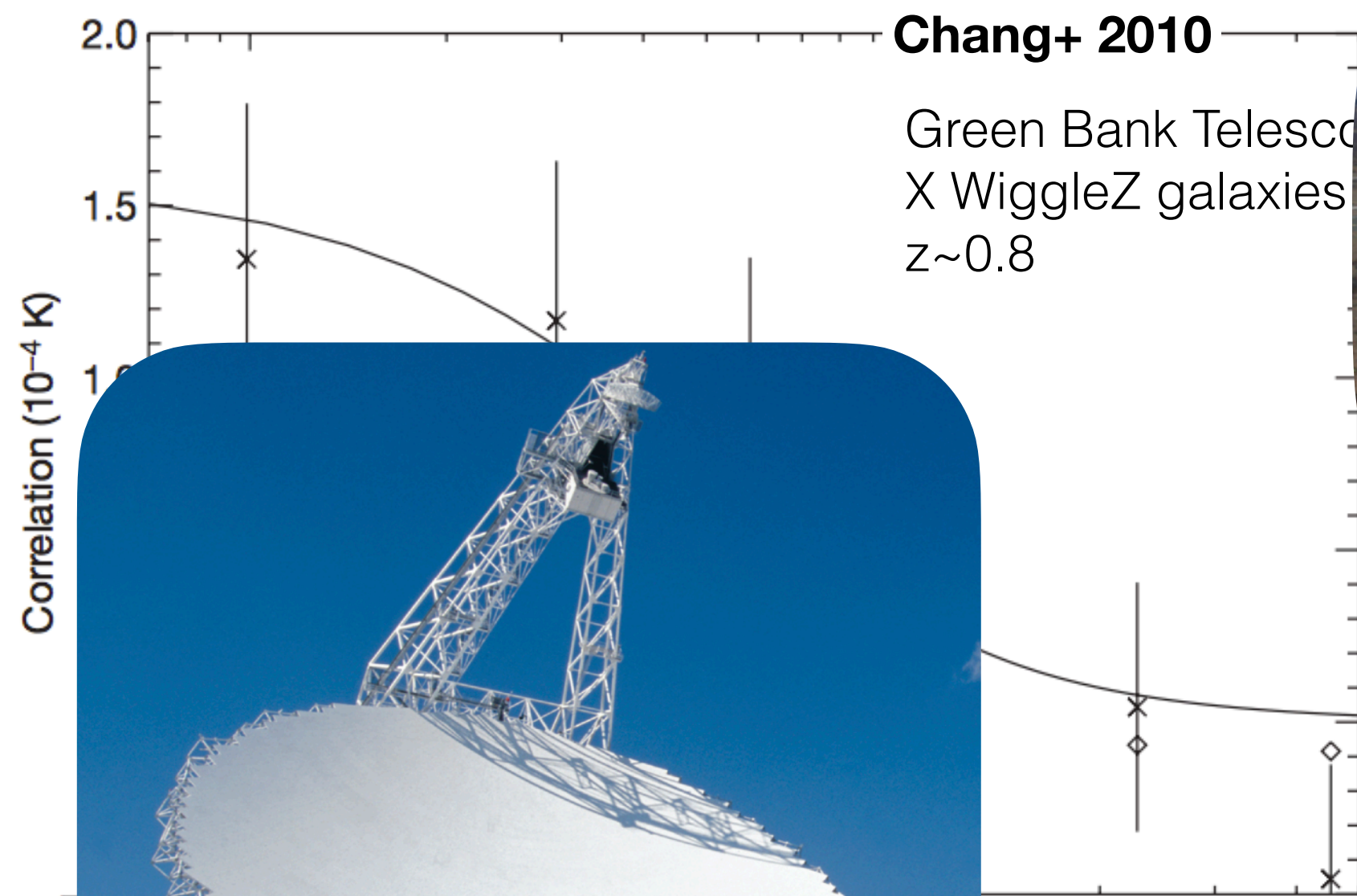MeerKAT X WiggleZ galaxies
z~0.4

also Masui+ 2013, Switzer+ 2013,
Wolz+ 2017,2022
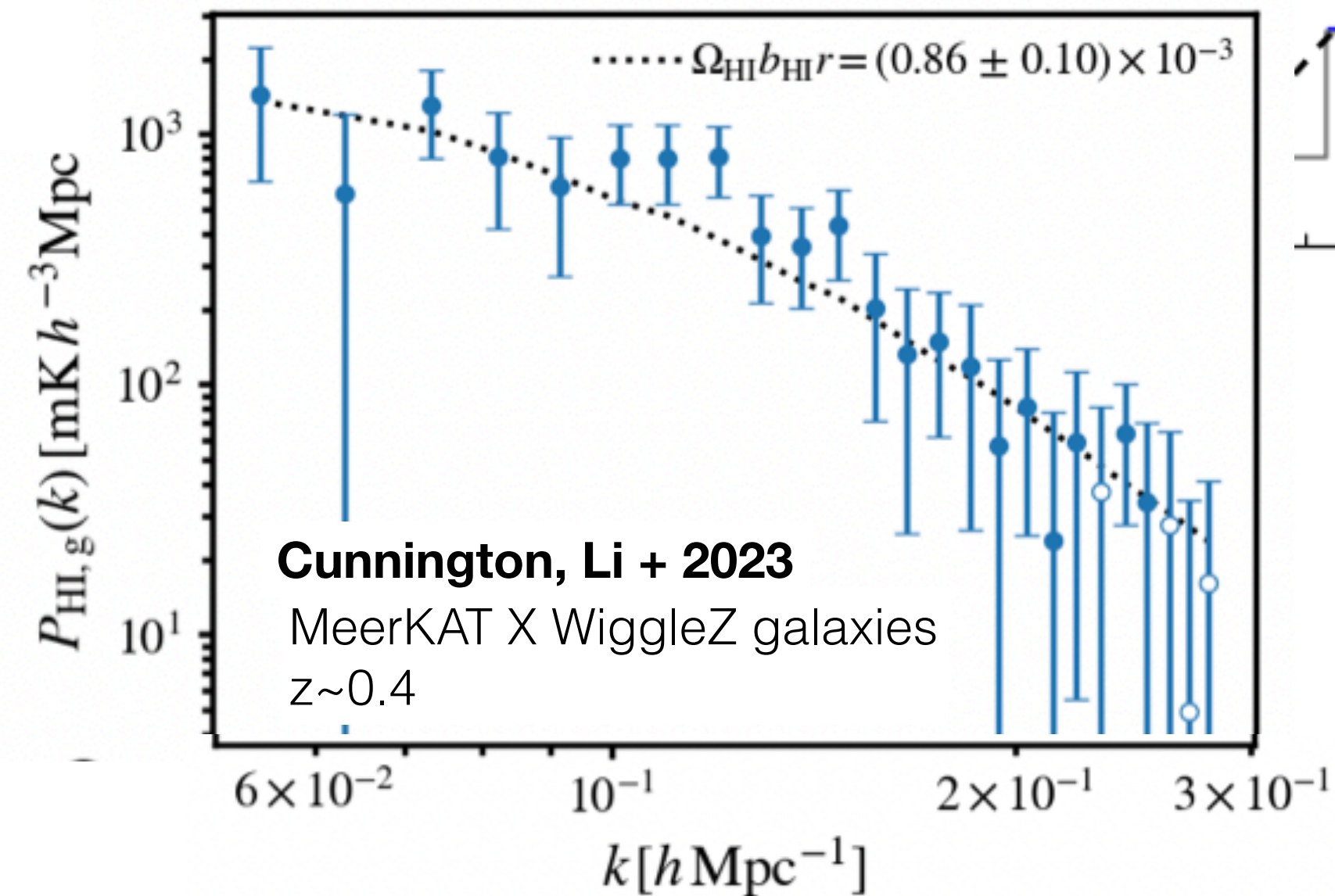
also MeerKLASS coll. 2024
(cross w/ GAMA galaxies + stacking)

ELG

CHIME collaboration, 2022
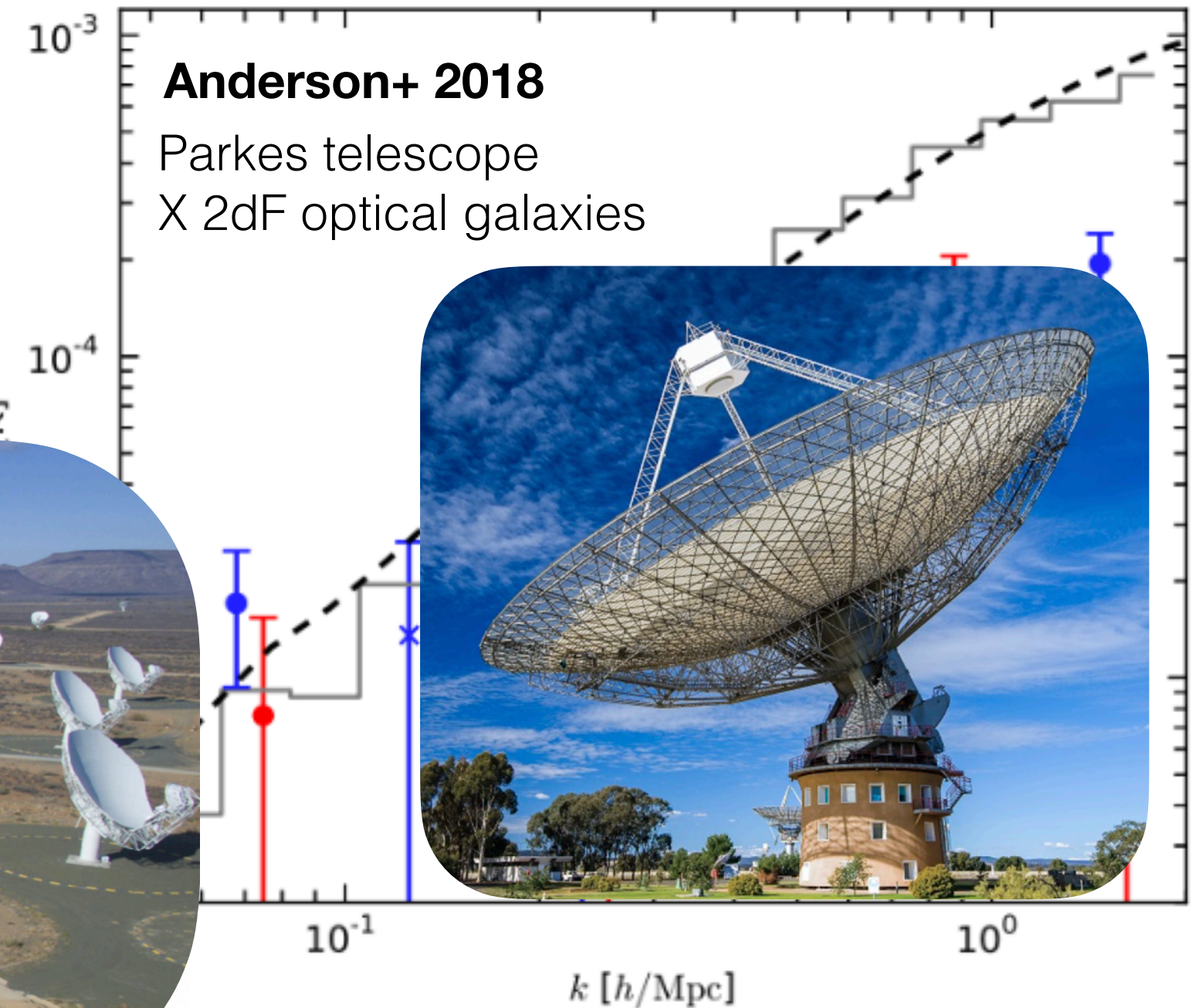
stacking LRGs, ELG and QSOs from eBOSS
0.8<z<1.5

HI intensity mapping

State-of-the-art

Anderson+ 2018
Parkes telescope
X 2dF optical galaxies

Chang+ 2010
Green Bank Telesc[ope]
X WiggleZ galaxies
z~0.8

Cunnington, Li + 2023
MeerKAT X WiggleZ galaxie[s]
z~0.4
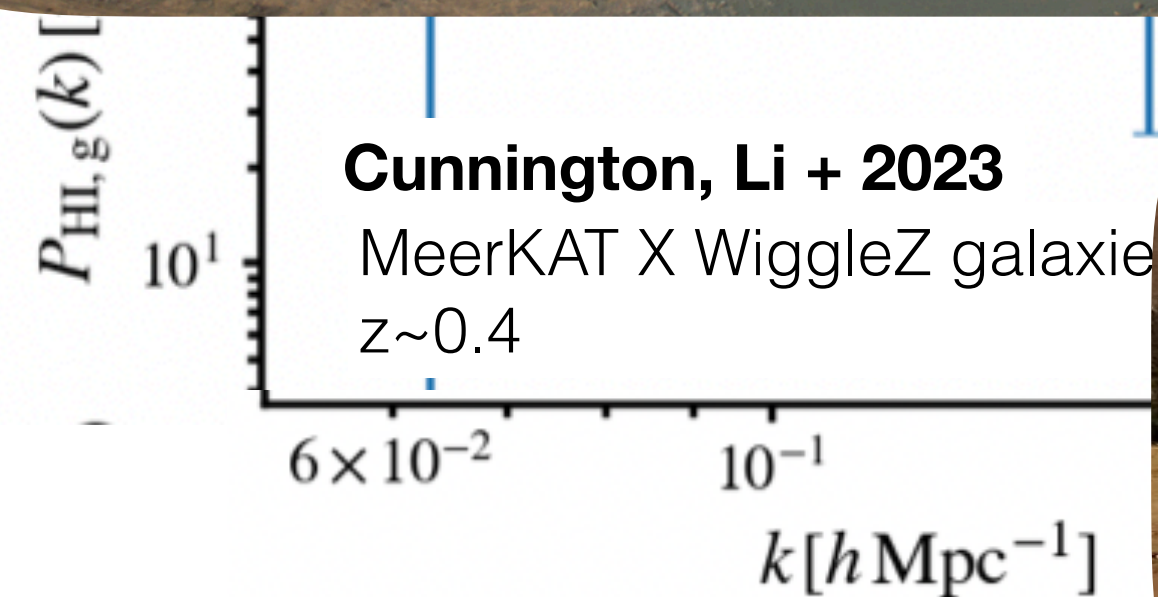
also MeerKLASS coll. 2024
(cross w/ GAMA galaxies + stacking)

CHIME collaboration, 2022
stacking LRGs, ELG and QSOs from eBOSS
0.8<z<1.5

HI intensity mapping

buried under the contaminants

Carucci+ 2020

CHALLENGES:
- Foregrounds
- Systematics

21 cm

Intrinsic foregrounds

$k_\parallel$

$k_\perp$

Line-of-sight / Frequency

Transverse direction 2D

?
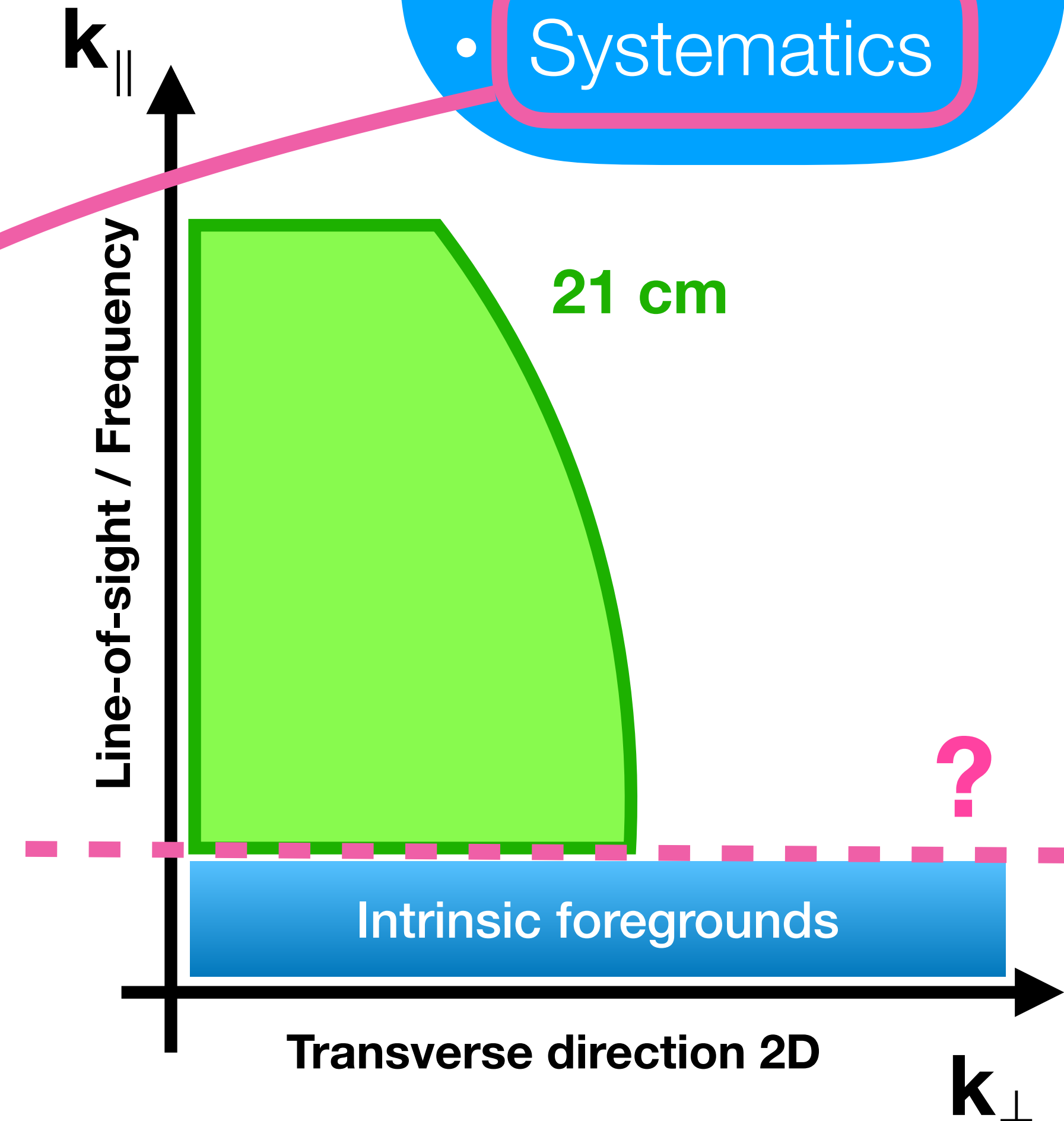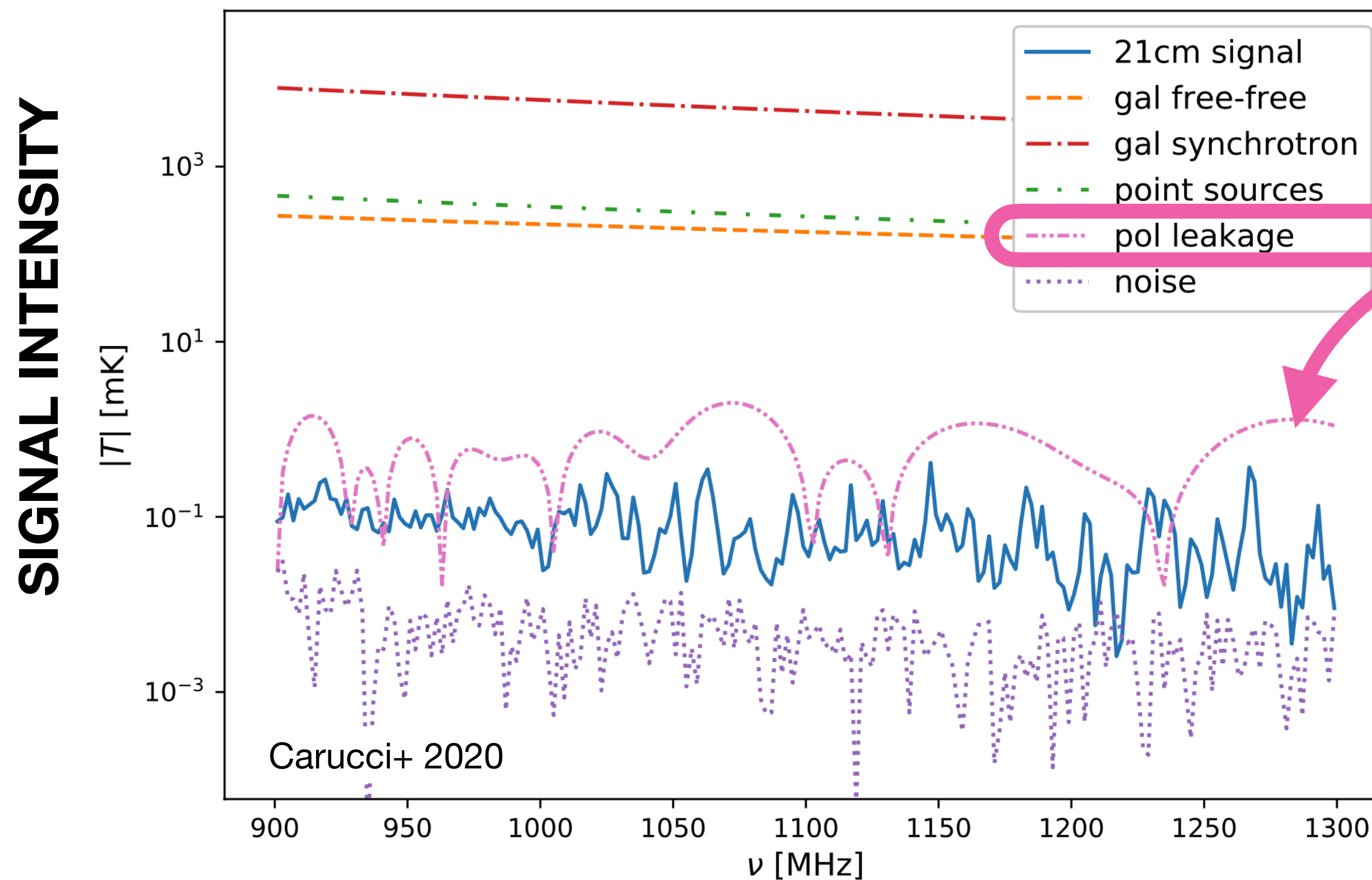
Q: if we were given SKA-mid IM data today, what could we achieve in terms of contaminants subtraction?

SKAO HI Intensity Mapping: Blind Foreground Subtraction Challenge

Marta Spinelli,[1,2,3]* Isabella P. Carucci,[4,5,6]† Steven Cunnington,[7] Stuart E. Harper,[8] Melis O. Irfan,[3,7] José Fonseca,[7,3,9,10] Alkistis Pourtsidou,[7,3] Laura Wolz[8]
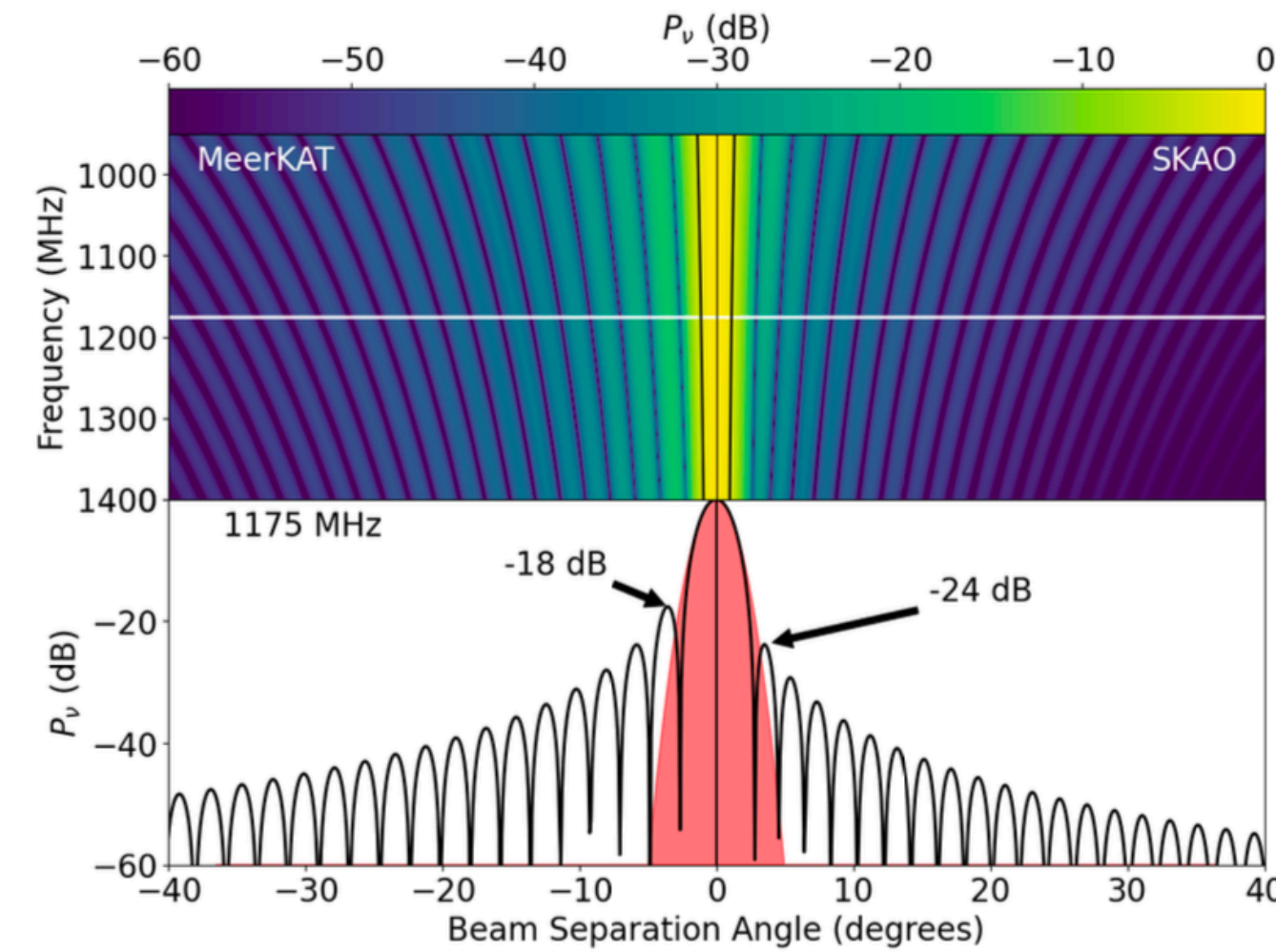
Simulating all we could
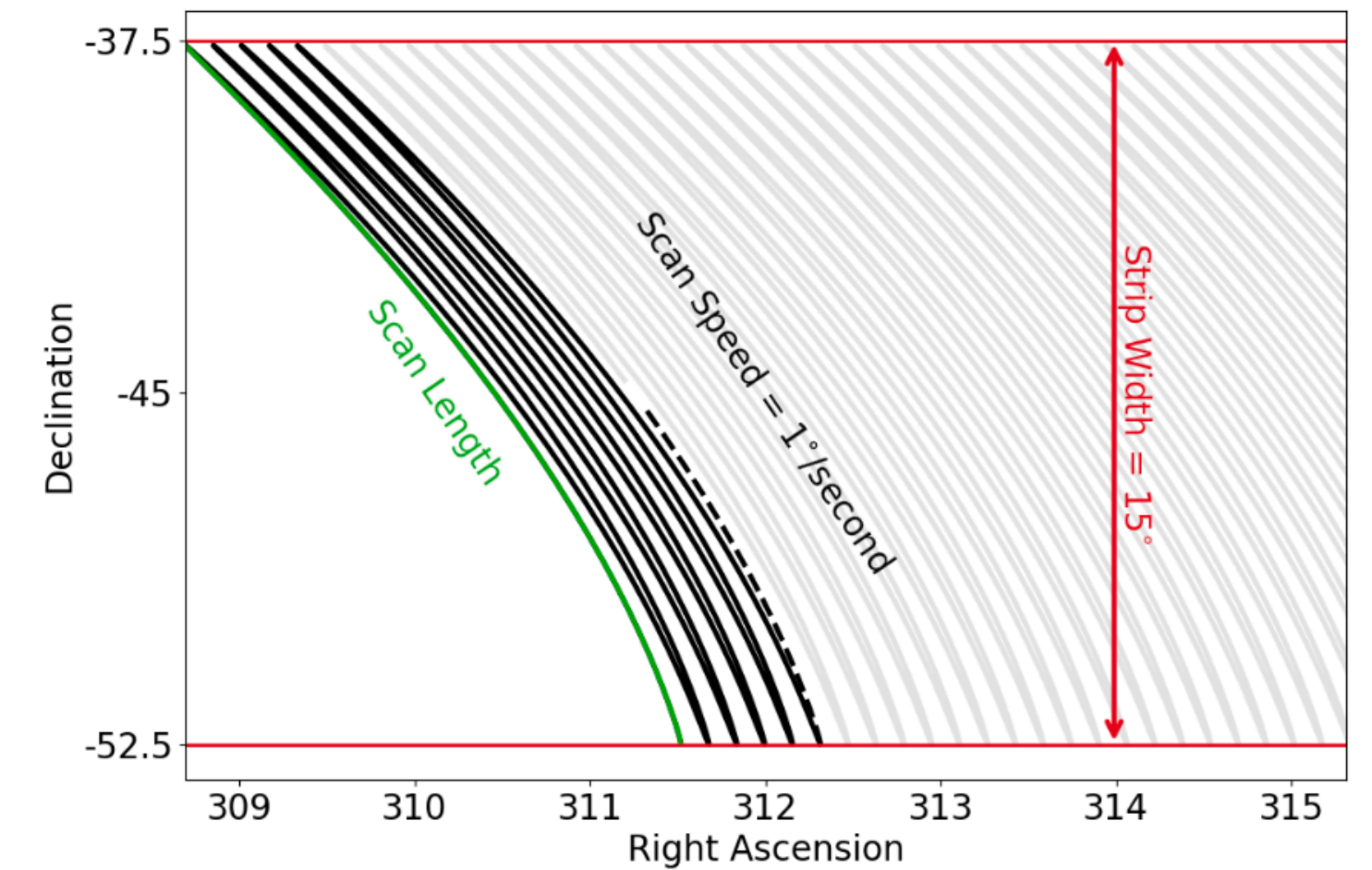
Sky components:

1. HI
(SAM coupled to halo
catalogue/merger tree)

2. Astrophysical Foregrounds

   - Galactic synchrotron

   - Galactic Free-Free

   - Extragalactic background

   - Point Sources

+

Telescope beam

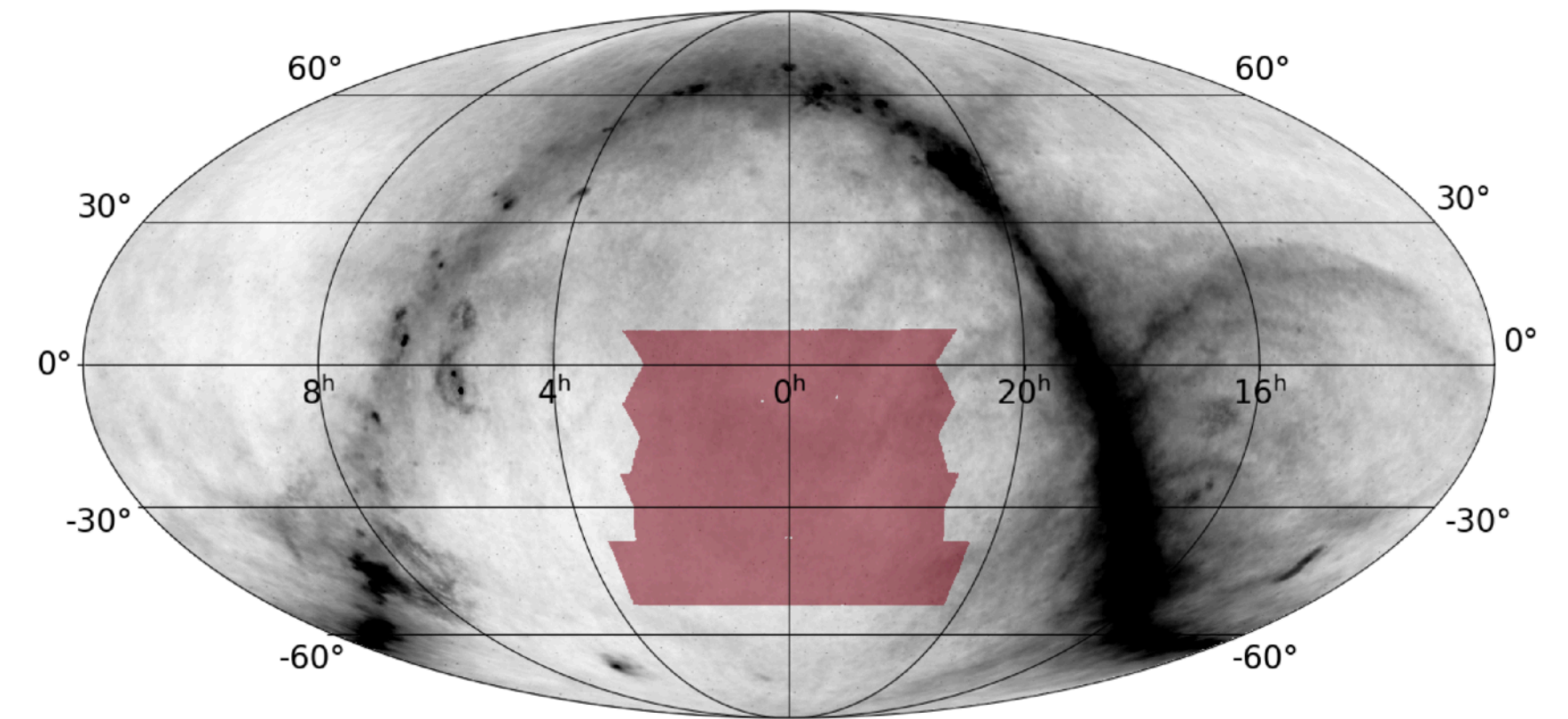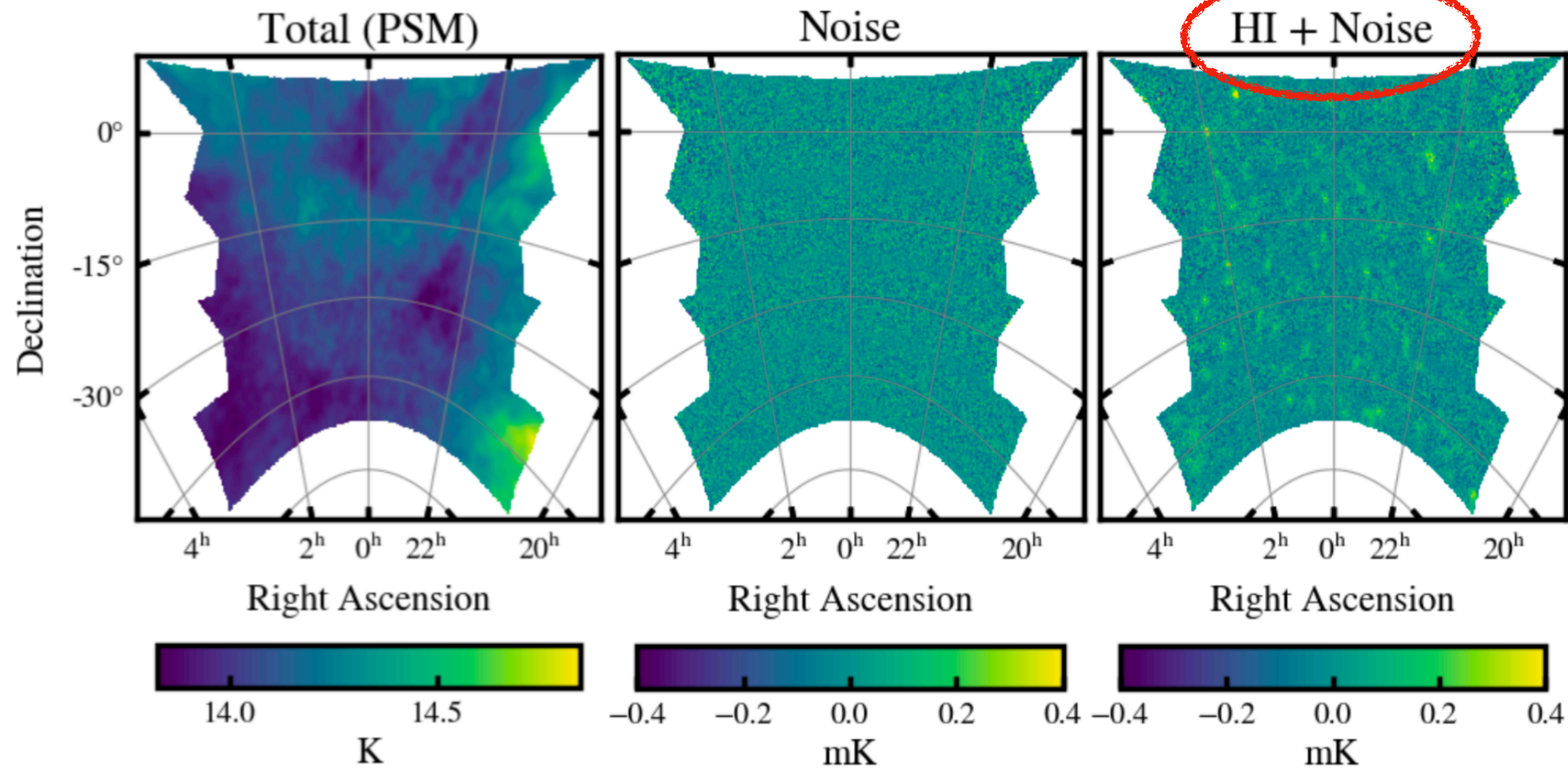**+**

Scanning strategy (non-uniform noise)

2 FGs models x 2 Beam Models
x 2 Instruments x 2 Deconvolution strategies

= 16 data cubes to clean

Simulating all we could

Unknown to participants!

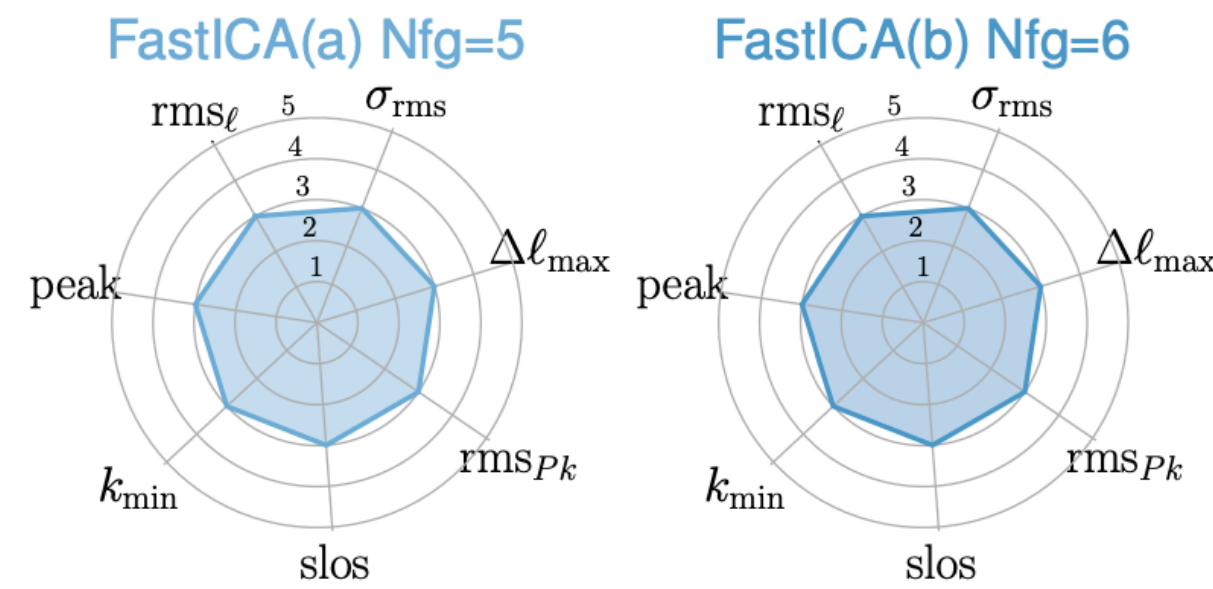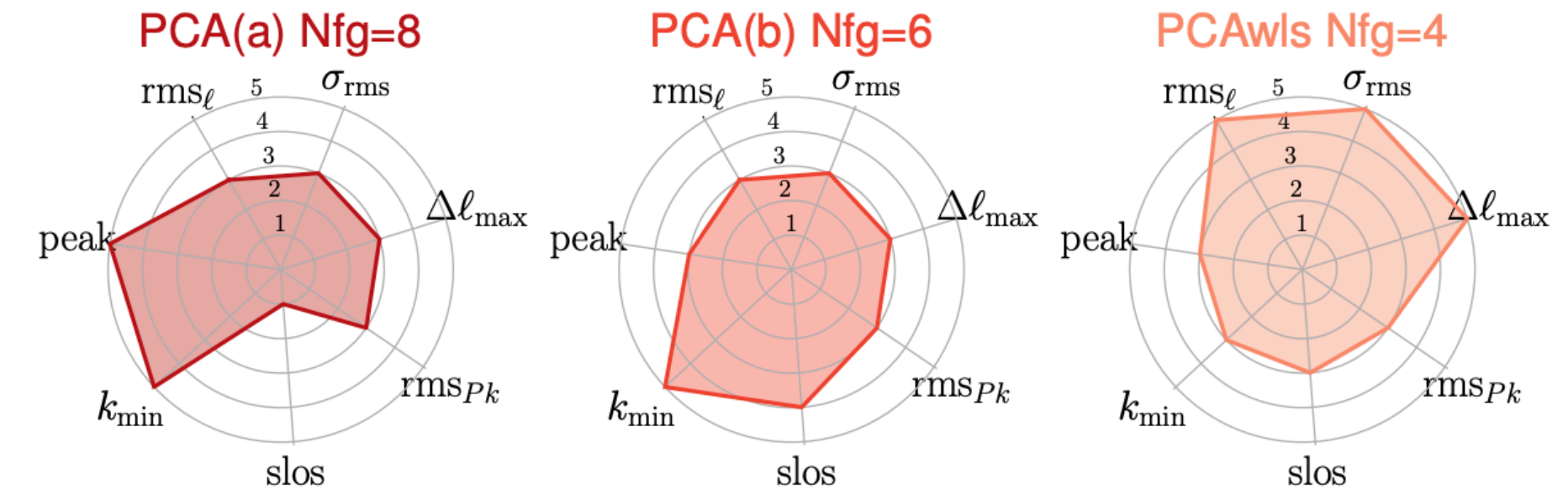Total (PSM) Noise HI + Noise
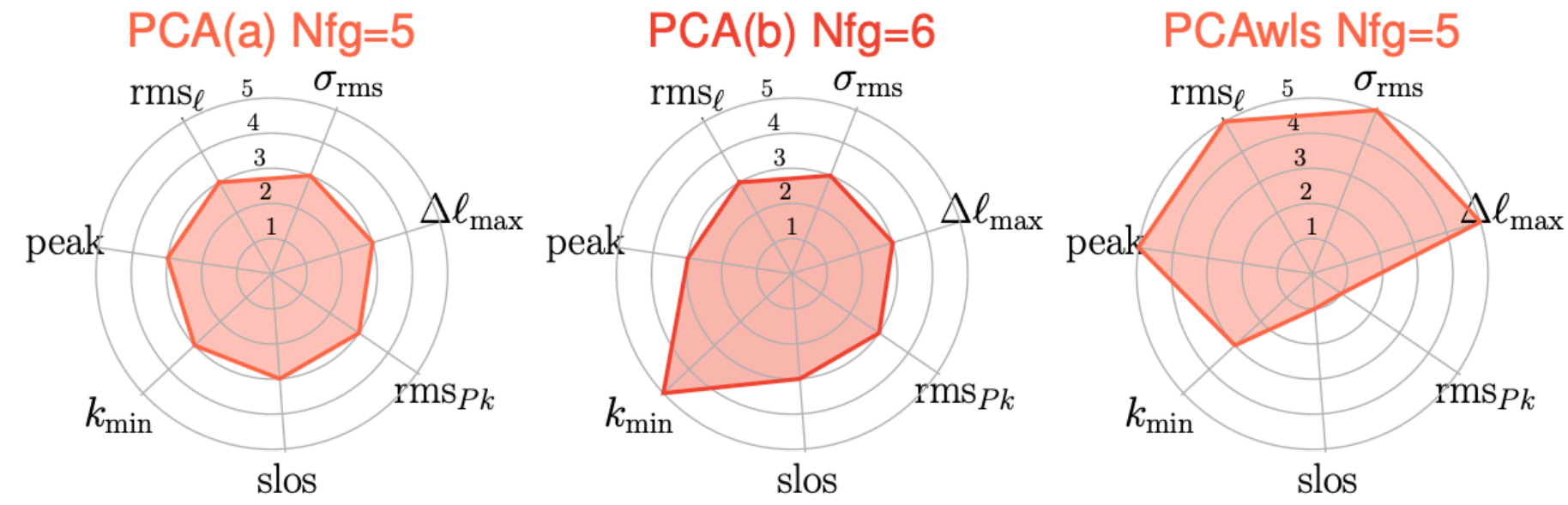
L-band: 950-1400 MHz

Single-dish mode

N_{dish}: 133 (SKAO) and 64 (MeerKAT)
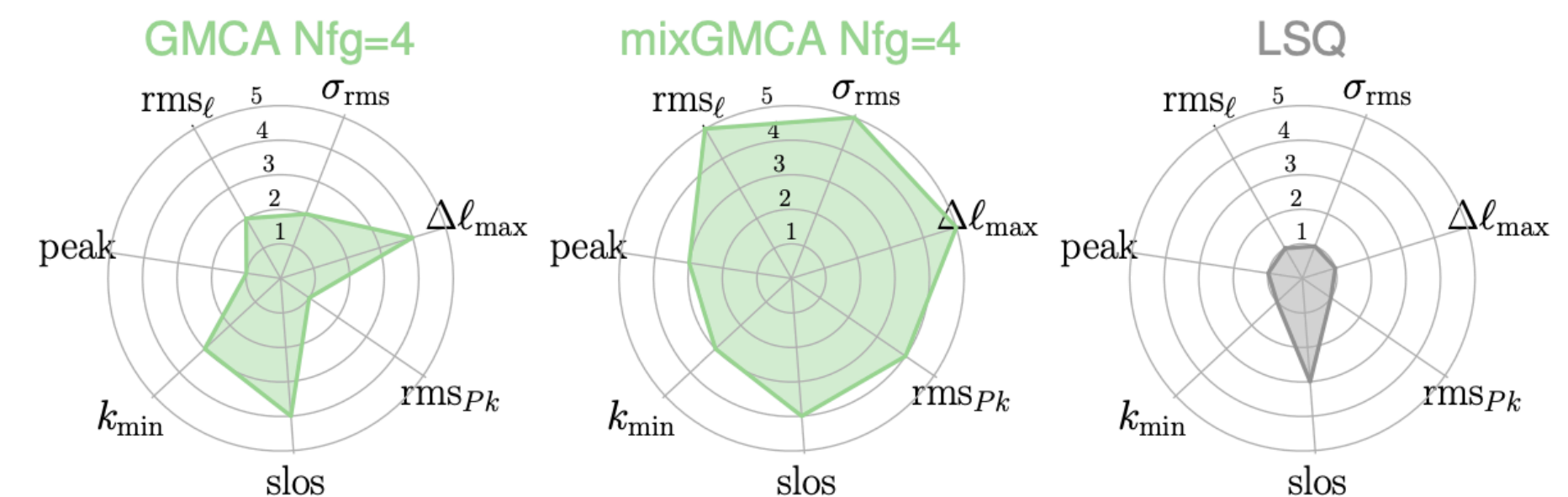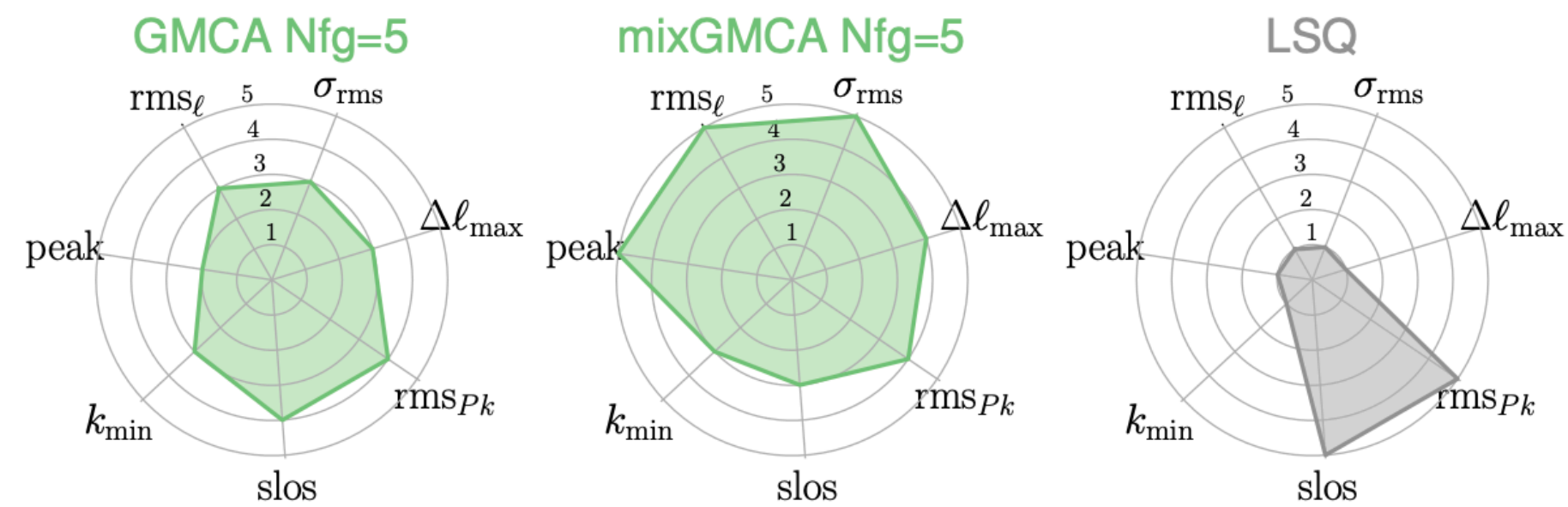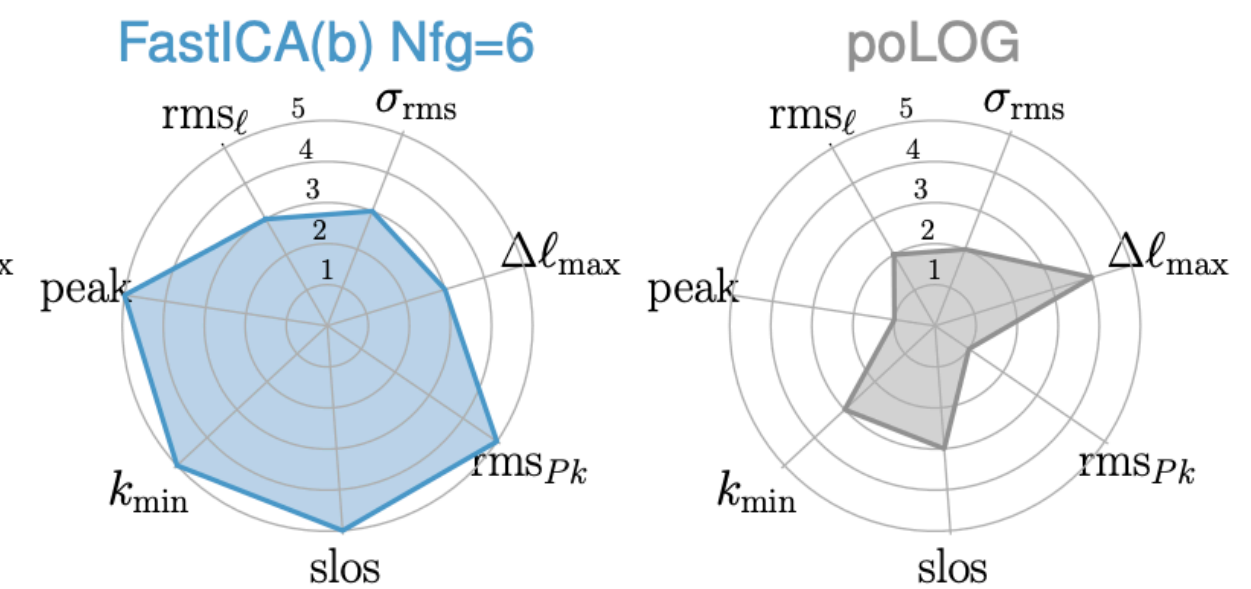
x 512 channels

Results

SKAO Airy Beam

MeerKAT Airy Beam

Ongoing efforts for foreground removal in MeerKLASSS are based on this

HI intensity mapping with the SKAO

- **Red Book is a great starting point for the Science Book**, especially for the proposed Chapter 1.

  - Of course forecasts should be updated, revised. (Newer forecasts exist, didn't mention them for brevity).

  - E.g., better xEuclid?

  - And new science cases (and people's expertise) included

- All things with real data: **MeerKLASS** (wait for Steve's talk), testbed for methods, systematics… and scientific results!

  - It should be properly showcased, in the proposed Chapter 2?