Cosmology with SKA
H_I redshift survey and Intensity Mapping

Réza Ansari
Université Paris-Saclay & Irfu/DAp (CEA)

Journée SKA-DAp

Orme de Merisiers - Mai 2023

- Beyond ΛCDM : cosmological probes & SKA
  - Large Scale Structures, BAO …
- SKA configuration and surveys
  - Cosmology with H_I redshift survey
- Intensity mapping
  - The method
  - Expected performance of SKA1 IM survey

Cosmology beyond ΛCDM

FRONTIERS OF KNOWLEDGE

New fundamental physics, chemistry, and biology can be revealed by astronomical measurements, experiments, or theory and hence push the frontiers of human knowledge.

Science frontier questions in this category are:
- ***Why is the universe accelerating?***
- ***What is dark matter?***
- ***What are the properties of the neutrinos?***
- ***What controls the masses, spins and radii of compact stellar remnants?***

A number of large projects were imagined, mostly as optical surveys, and many of them are / will soon be / a reality

- DES (2013 - 2019)
- BOSS, eBOSS (2009 - 2019
- DESI (2020 - …)
- Euclid (2023 - …)
- Rubin/LSST (2024)

…

SKA-I : 2027 - …

New Worlds, New Horizons - Astro 2010 decadal survey
https://nap.nationalacademies.org/catalog/12951/new-worlds-new-horizons-in-astronomy-and-astrophysics

Few cosmological questions and probes

(i) Inflation : CMB , Non Gaussianities …

(ii) Flat or not flat , Curvature Ω_k : Expansion history (CMB, SNIa , BAO's ...)

(iii) Cosmological constant or dark energy , DE eq. of state $p/\varrho = w_0 + (1-a)\, w_a$

1. Map cosmic expansion history using standard candles : SNIa , gravitational sirenes (GW)…
2. Or using standard ruler probes : BAO
3. Study structure growth : LSS (GC), WL, clusters, voids …

(iv) Beyond GR / Modified gravity : study structure growth

1. Structure growth : LSS (GC), WL, clusters, voids …
2. Redshift space distorsions (RSD)
3. LSS (GC) broad band power spectrum shape

(v) Dark matter, does it exist really ? What is its nature ?

1. Dark matter clustering properties (sky surveys)
2. DM indirect detection / direct detection … (gamma/x/radio surveys, direct detection)

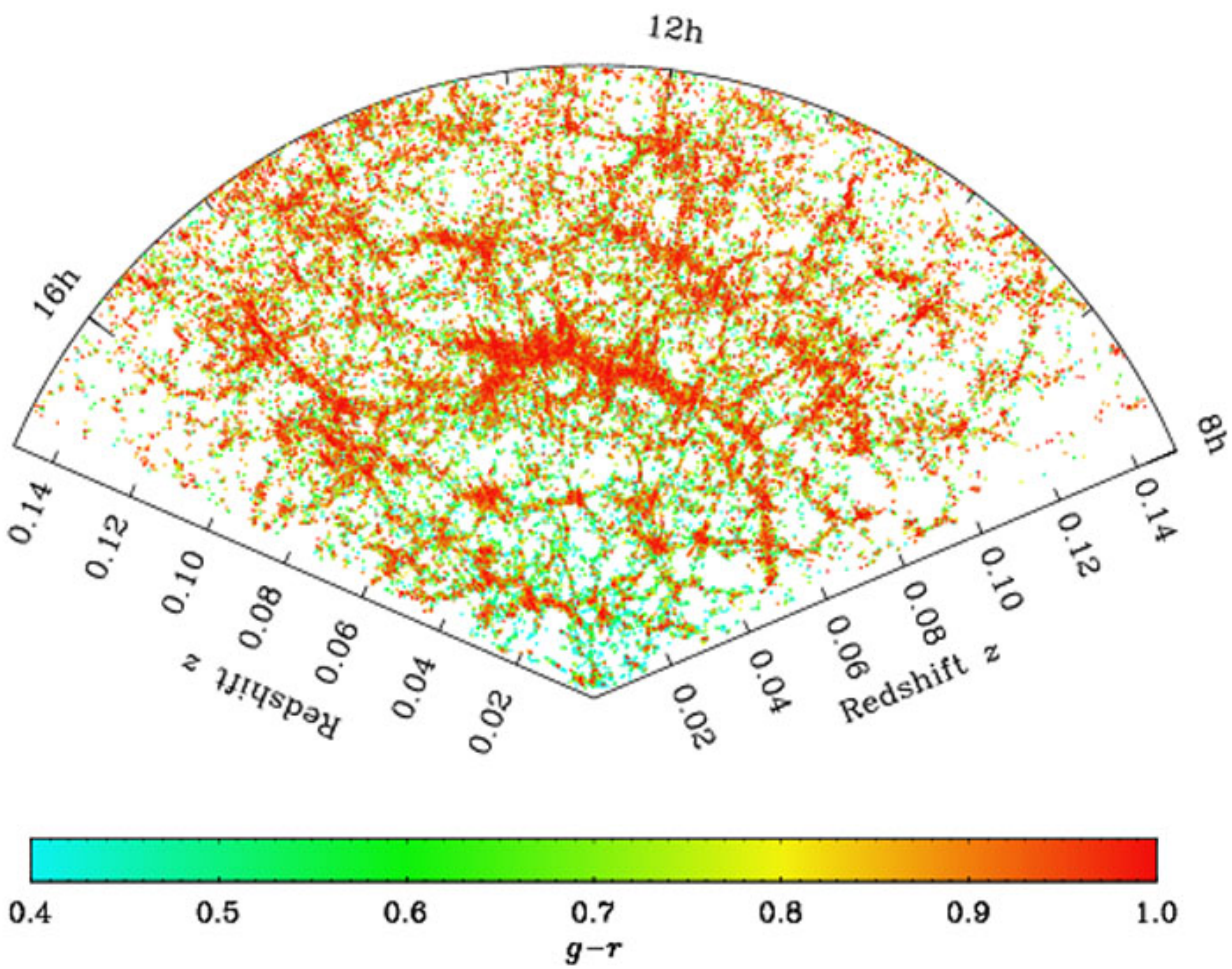
(vi) Neutrinos role and impact for structure formation : (GC) + WL + CMB

(vii) H0 value : standard candles (SNIa , gravitational sirenes (GW)…)

D. Weinberg et al. Phys.Rep. 2013, arXiv:1201.2434

L. Amendola et al. , Living Reviews in Relativity . 2018, arXiv:1606.00180

Structure formation and evolution : a cosmological probe



A slice through the SDSS galaxy 3D distribution

Zehavi et al. ApJ 2011, arXiv:1005.2413

Some major cosmological probes :

- Supernovae (SN)
- Galaxy Clusters (CL
- Weak lensing (WL)
- **Galaxy clustering (LSS / GC)**
- **BAO → $d_A(z)$, H(z)**
- **Redshift space distorsions (RSD)**
- **Void statistics**
- ISW (x CMB)
- Cosmic Dipole

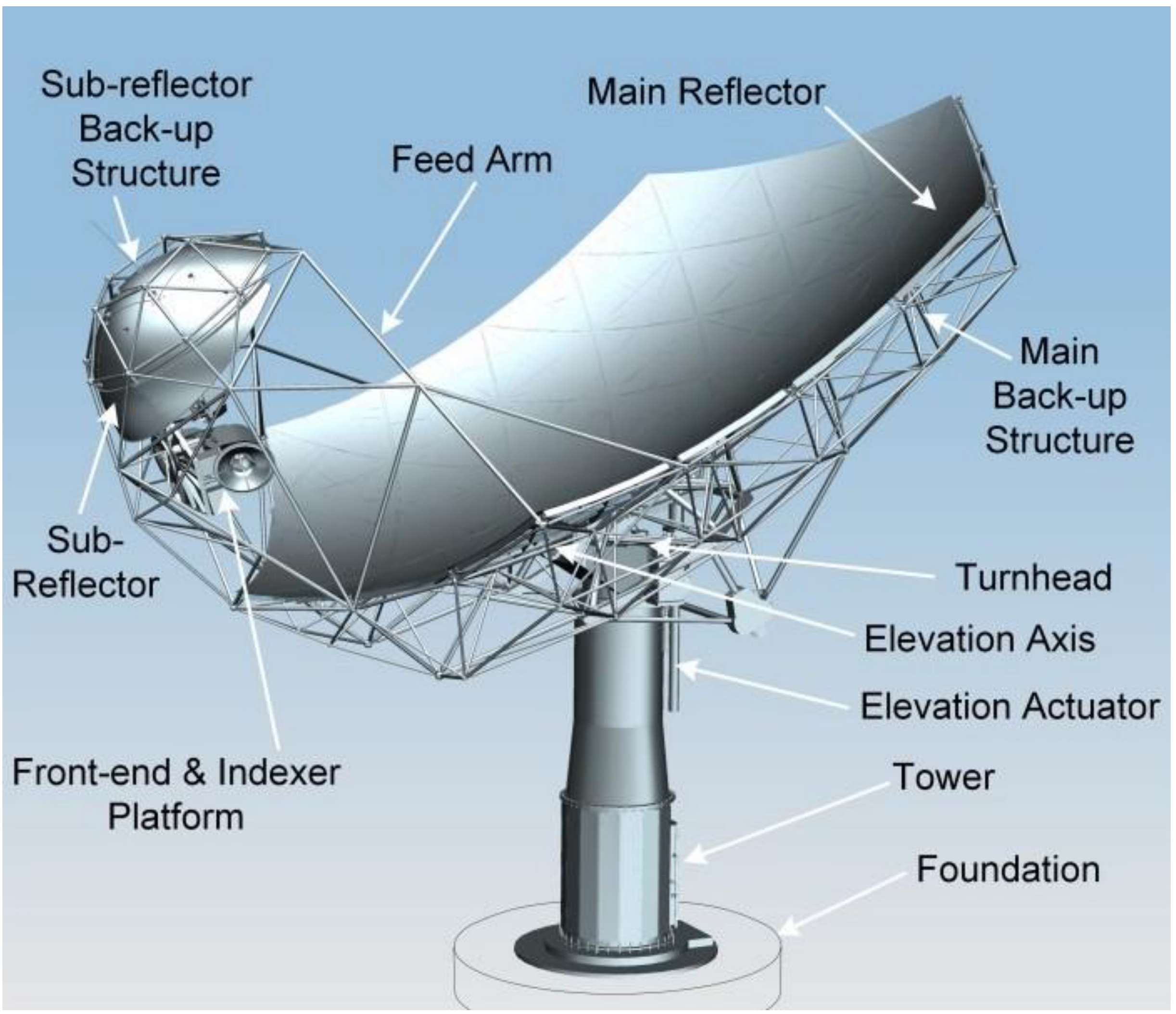
…

SKA

SKA-I configuration and surveys

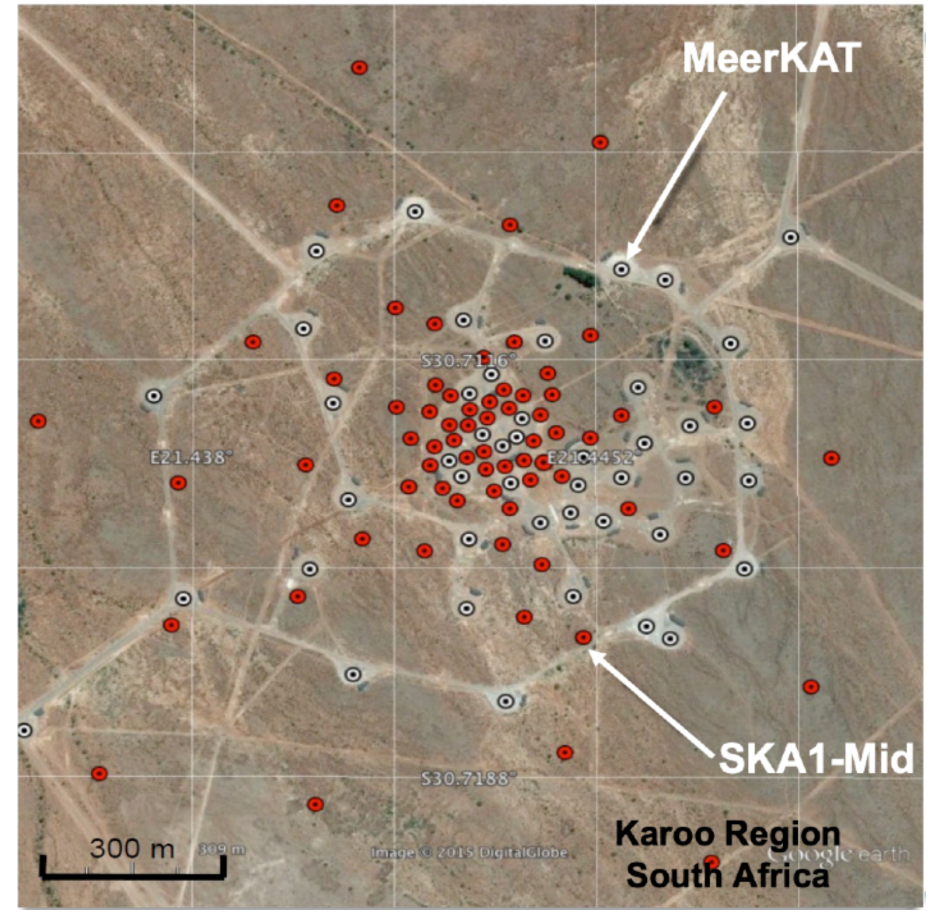
Cosmology with HI galaxy redshift survey

SKA-mid dish (15 m)
133 x 15 m dishes + 64 MeerKAT 13.6 m dishes

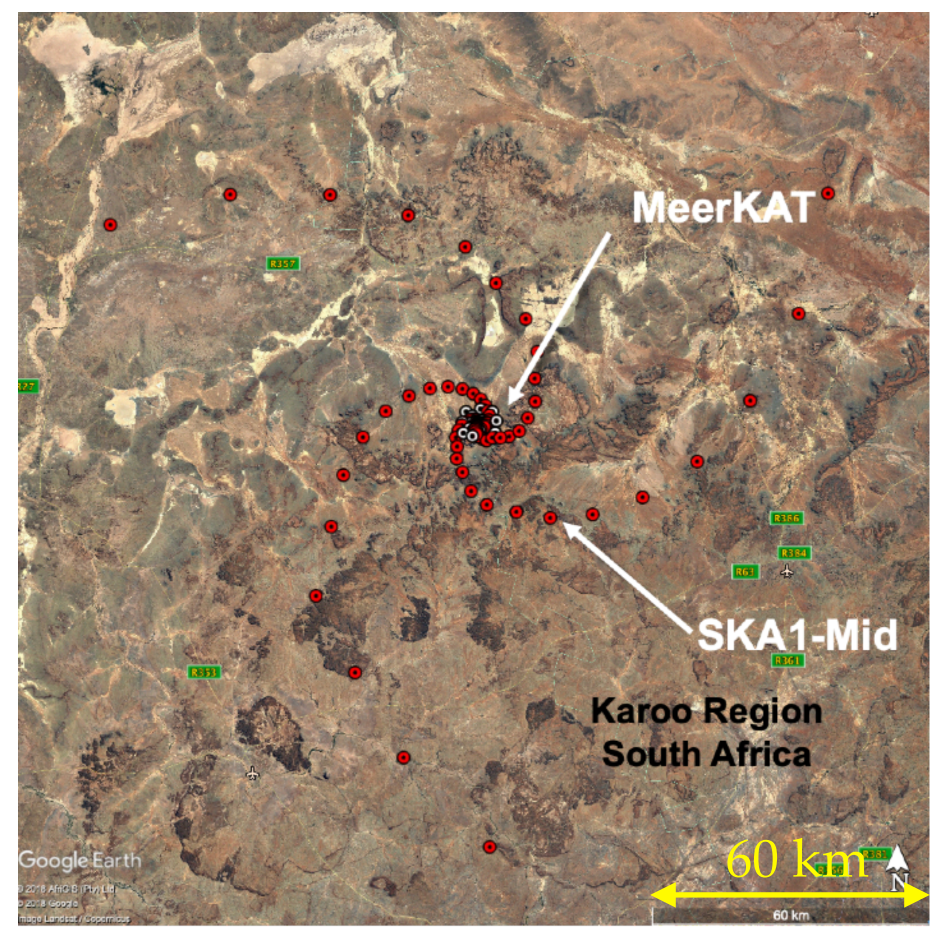


SKA-mid total collecting area ~ 30 000 m^2

SKA1-Mid core



SKA1-Mid full array



https://indico.skatelescope.org/event/551/attachments/5836/8583/7._SKA1-Mid_Telescope_Design_-_Gerhard_Swart.pdf

Table 1. Frequency coverage of SKA1 in the Design Baseline. Bands listed in bold will be deployed as part of the funded Design Baselines. While Bands 3 and 4 are part of the Design Baseline they are not funded at present.

Cosmology

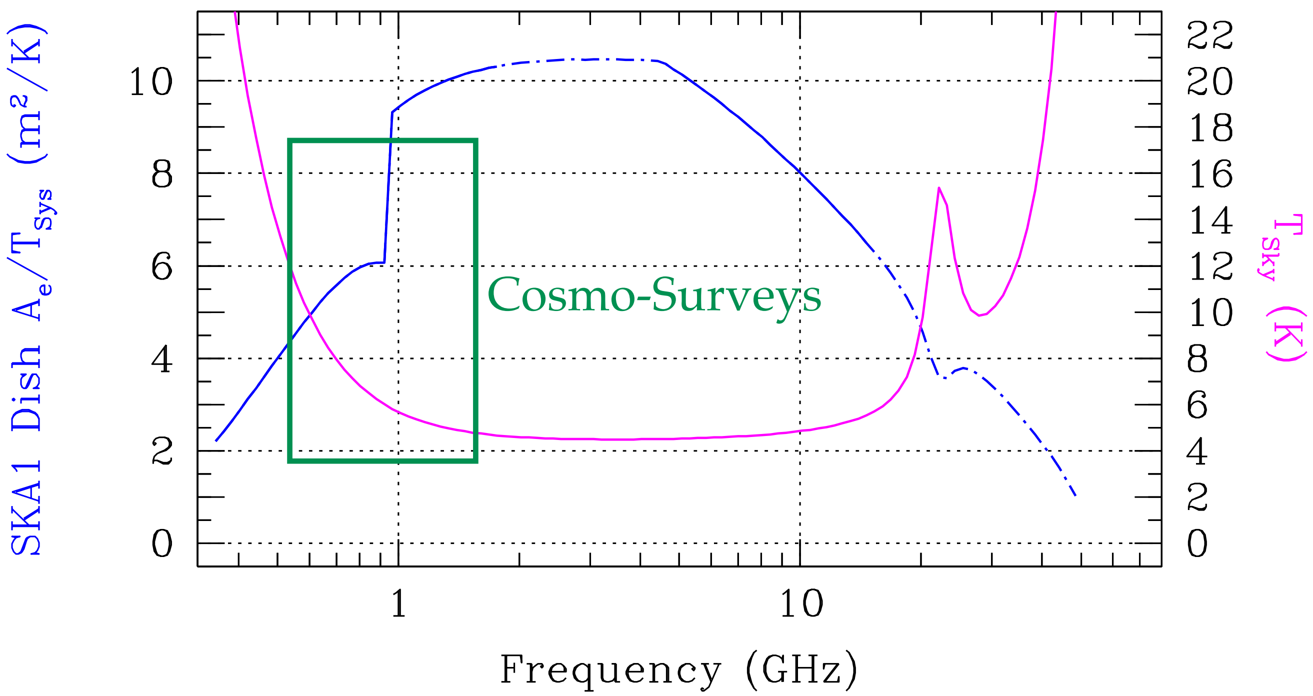
	SKA1 Band	Frequency Range	Available Bandwidth
	Low	50 – 350 MHz	300 MHz
0.35<z<3	**Mid Band 1**	0.35 – 1.05 GHz	700 MHz
0<z<0.35	**Mid Band 2**	0.95 – 1.76 GHz	810 MHz
	Mid Band 3	1.65 – 3.05 GHz	1.4 GHz
	Mid Band 4	2.80 – 5.18 GHz	2.38 GHz
	Mid Band 5a	4.6 – 8.5 GHz	3.9 GHz
	Mid Band 5b	8.3 – 15.3 GHz	2 x 2.5 GHz

Cosmo H_I surveys

Nominal Frequency	**110 MHz**	**300 MHz**	**770 MHz**	**1.4 GHz**	**6.7 GHz**	**12.5 GHz**
Range [GHz]	0.05-0.35	0.05-0.35	0.35-1.05	0.95-1.76	4.6-8.5	8.3-15.3
Telescope	Low	Low	Mid	Mid	Mid	Mid
FoV [arcmin]	327	120	109	60	12.5	6.7
Max. Resolution [arcsec]	11	4	0.7	0.4	0.08	0.04
Max. Bandwdith [MHz]	300	300	700	810	3900	2 x 2500
Cont. rms, 1 hr [μJy/beam][a]	26	14	4.4	2	1.3	1.2
Line rms, 1 hr [μJy/beam][b]	1850	800	300	140	90	85
Resolution Range for Cont. and Line rms [arcsec][c]	12–600	6–300	1–145	0.6–78	0.13–17	0.07–9
Channel width (uniform resolution across max. bandwidth) [kHz]	5.4	5.4	13.4	13.4	80.6	80.6
Spectral zoom windows x narrowest bandwidth [MHz]	4 x 3.9	4 x 3.9	4 x 3.1	4 x 3.1	4 x 3.1	4 x 3.1
Finest zoom channel width [Hz]	226	226	210	210	210	210

https://arxiv.org/pdf/1912.12699.pdf

SKA1 single dish sensitivity A_e/T_{sys}



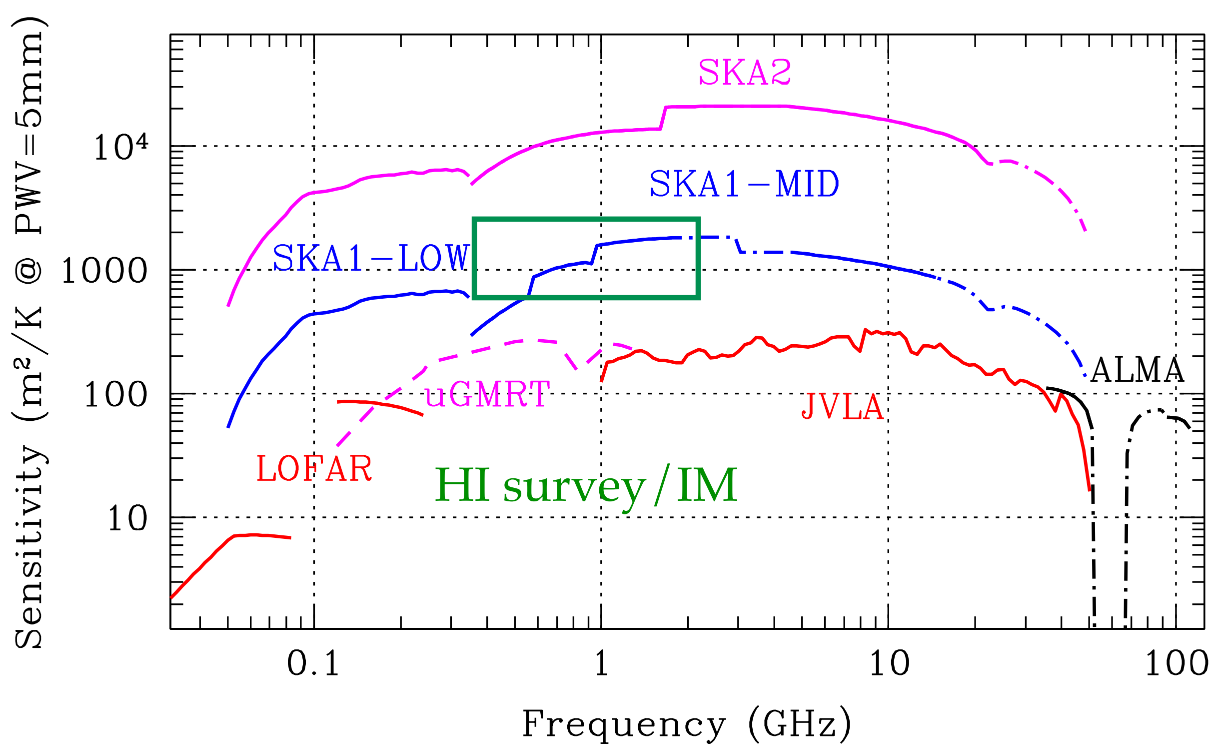
$$S_{lim} \propto \frac{T_{sys}}{A_e} \frac{1}{\sqrt{t_{int}\delta\nu}}$$

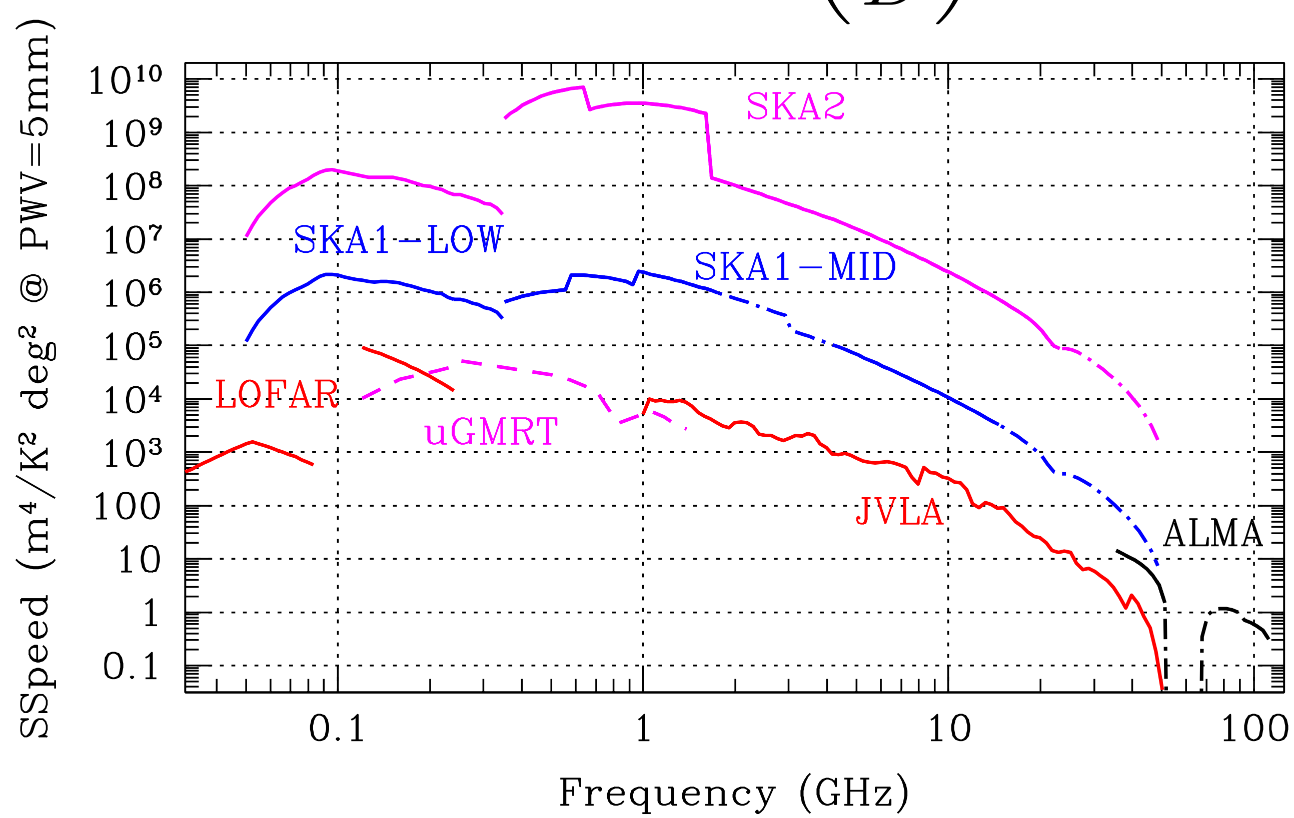
$$\rightarrow t_{int} \propto \left(\frac{A_e}{T_{sys}}\right)^2$$

Survey Speed Figure of Merit SS_{FoM}

$$SS_{FoM} = (A_e/T_{sys})^2 \times FoV_e$$

$$FoV_e \simeq 2000 \left(\frac{\lambda}{D}\right)^2 \deg^2$$





https://arxiv.org/pdf/1912.12699.pdf

Cosmo. related SKA1 surveys

- Medium-Deep Band 2 (0.95-1.75 GHz) SKA1-Mid survey, covering 5000 deg^2 with total 10 000 hours (few years) integ. time. Continuum Weak Lensing survey and H_I galaxy redshift survey $z \lesssim 0.4$
- Wide Band 1 (0.35-1.05 GHz) SKA1-Mid survey, covering 20000 deg^2 with total 10 000 hours (few years) integ. time. Continuum galaxy survey, H_I Intensity Mapping (IM) survey , $0.35 \lesssim z \lesssim 3$ redshift range
- Deep SKA1-Low survey - 100 deg^2 with total 5 000 hours, 200-350 MHz band , $3 \lesssim z \lesssim 6$

Red Book 2018 - SKA Cosmology Science WG
https://arxiv.org/abs/1811.02743

SKA HI galaxy redshift survey

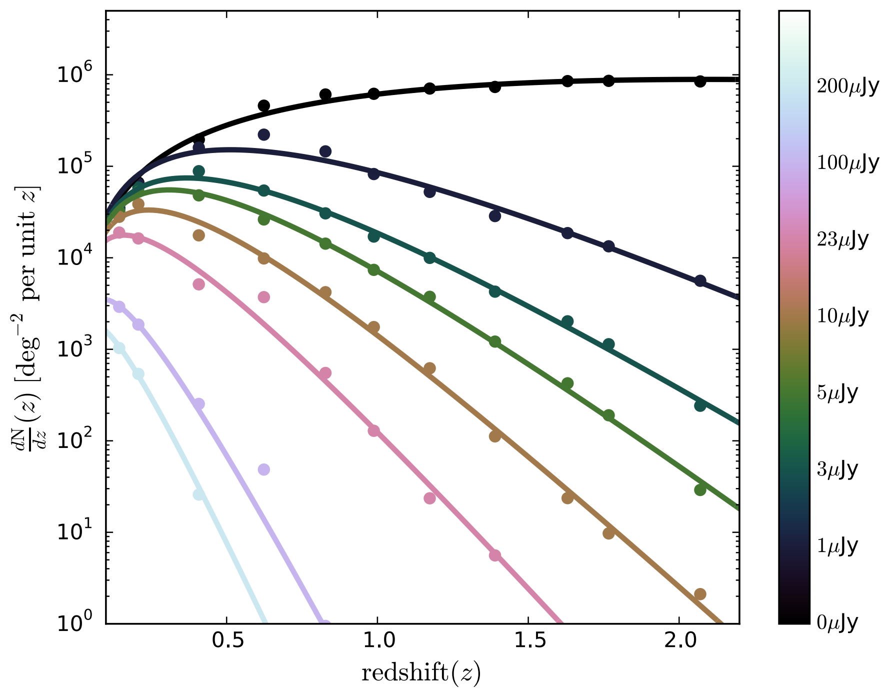
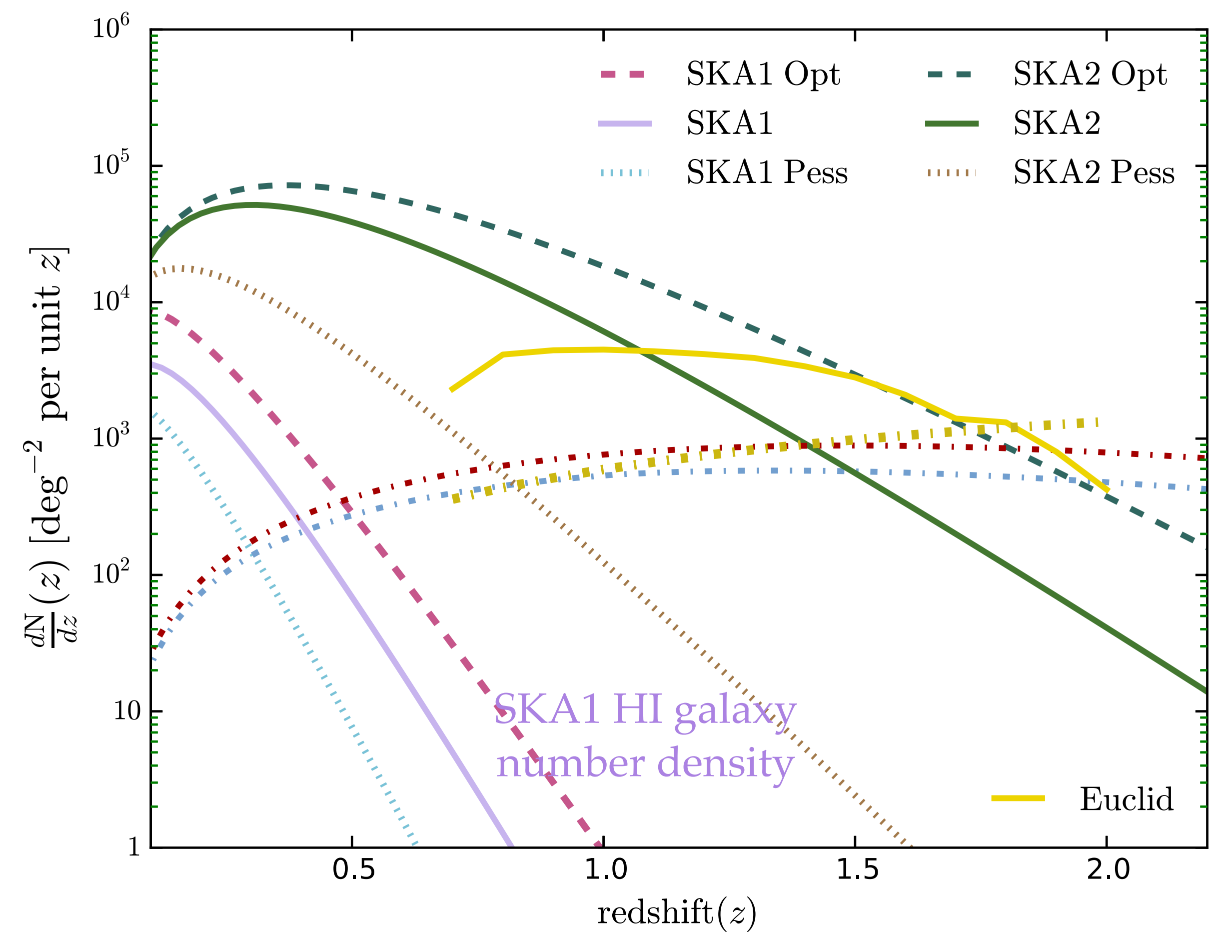
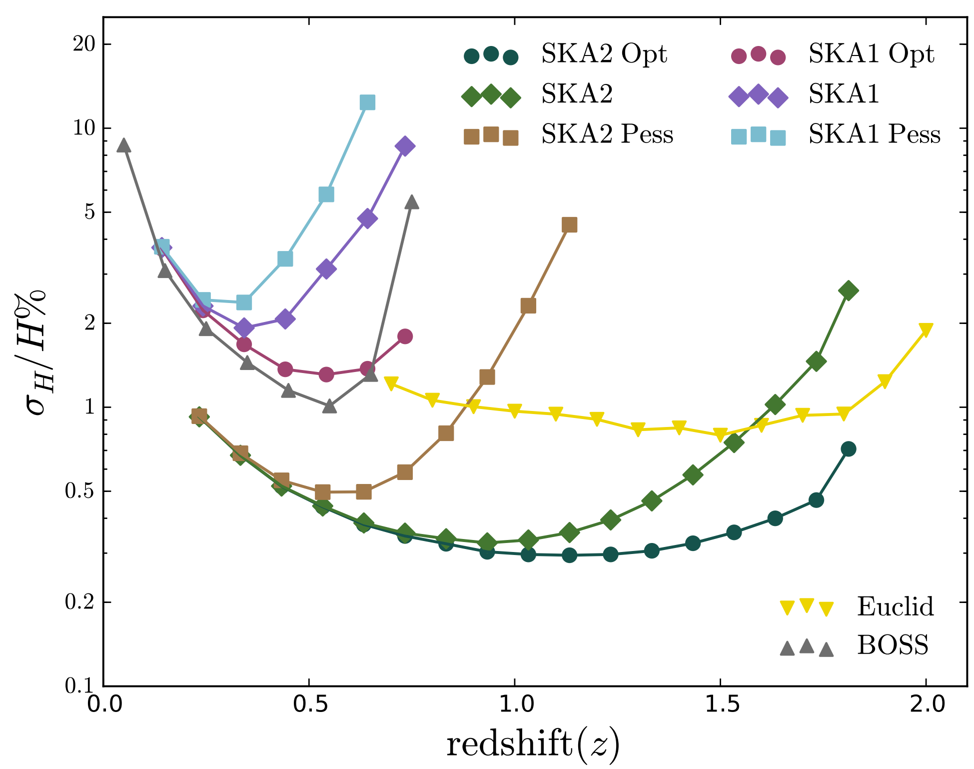


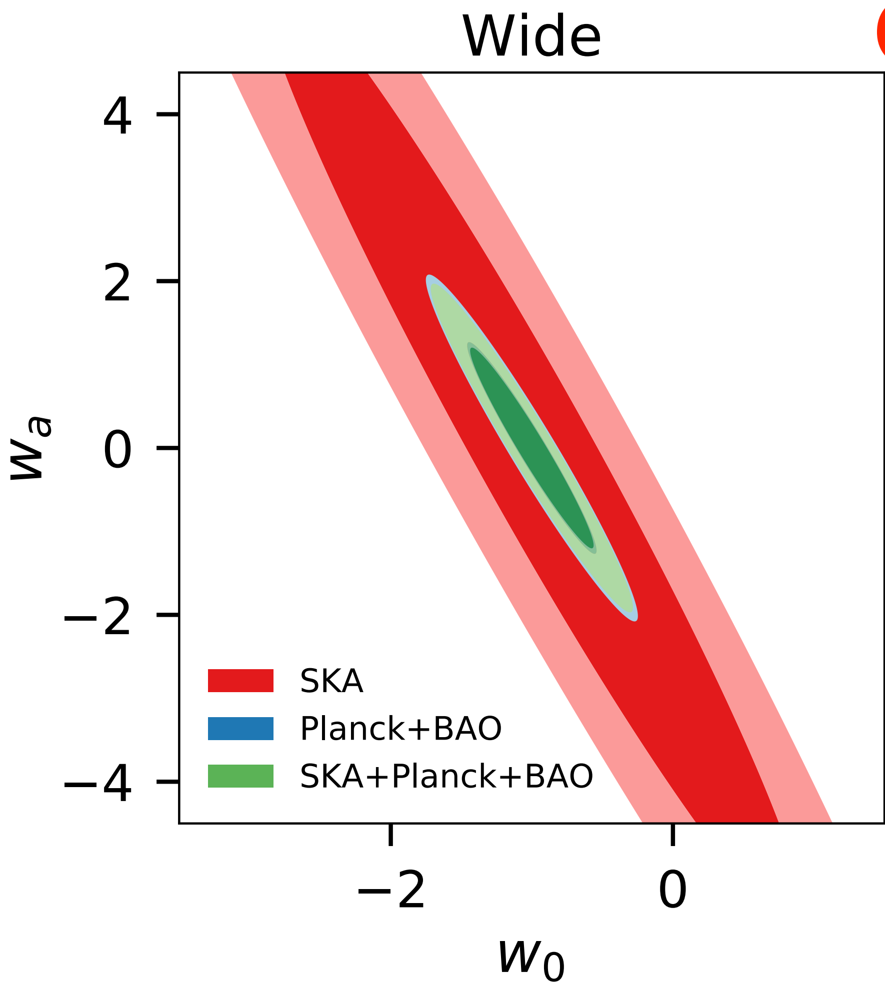
Figure 2. H I galaxy redshift distribution, dN/dz, calculated from simulations (filled circles) and the corresponding fitting function, equation (5). From top to bottom, the curves shown correspond to flux sensitivities $S_{\rm rms}$ = (0, 1, 3, 5, 10, 23, 100, 200) μJy (colour-coded according to the panel on the right).

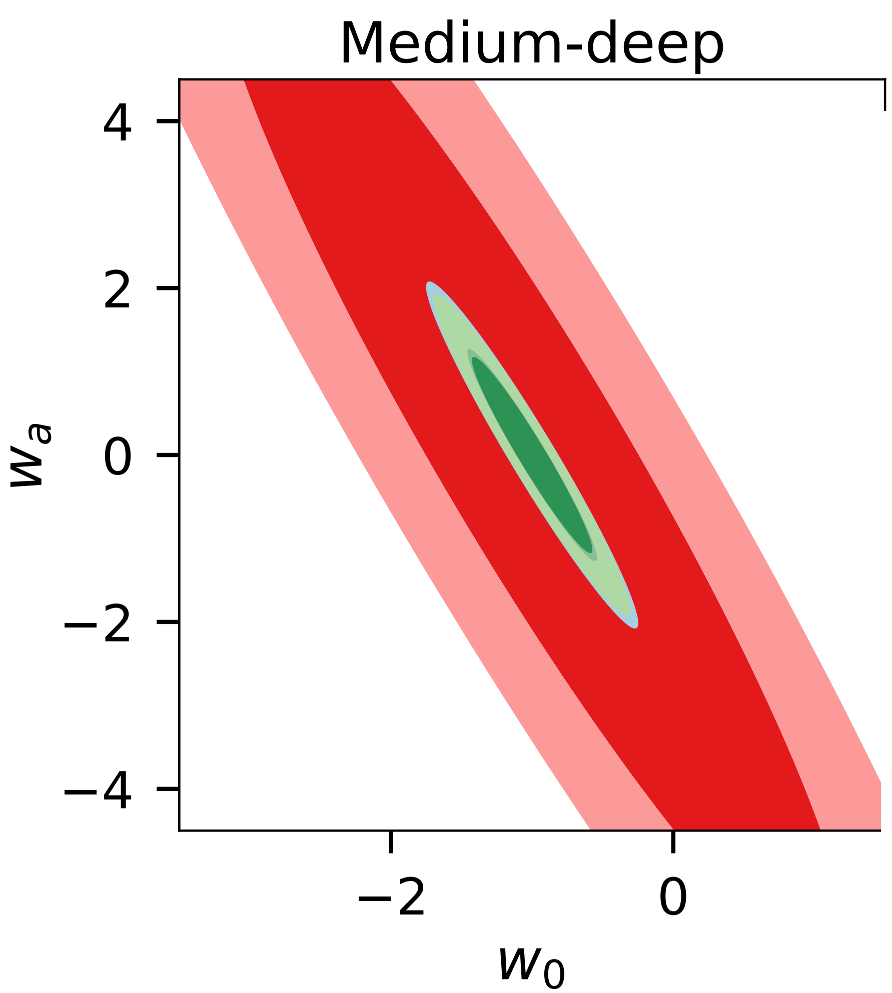




https://arxiv.org/abs/1412.4700

Constraints on DE and MG from SKA1 (forecasts)





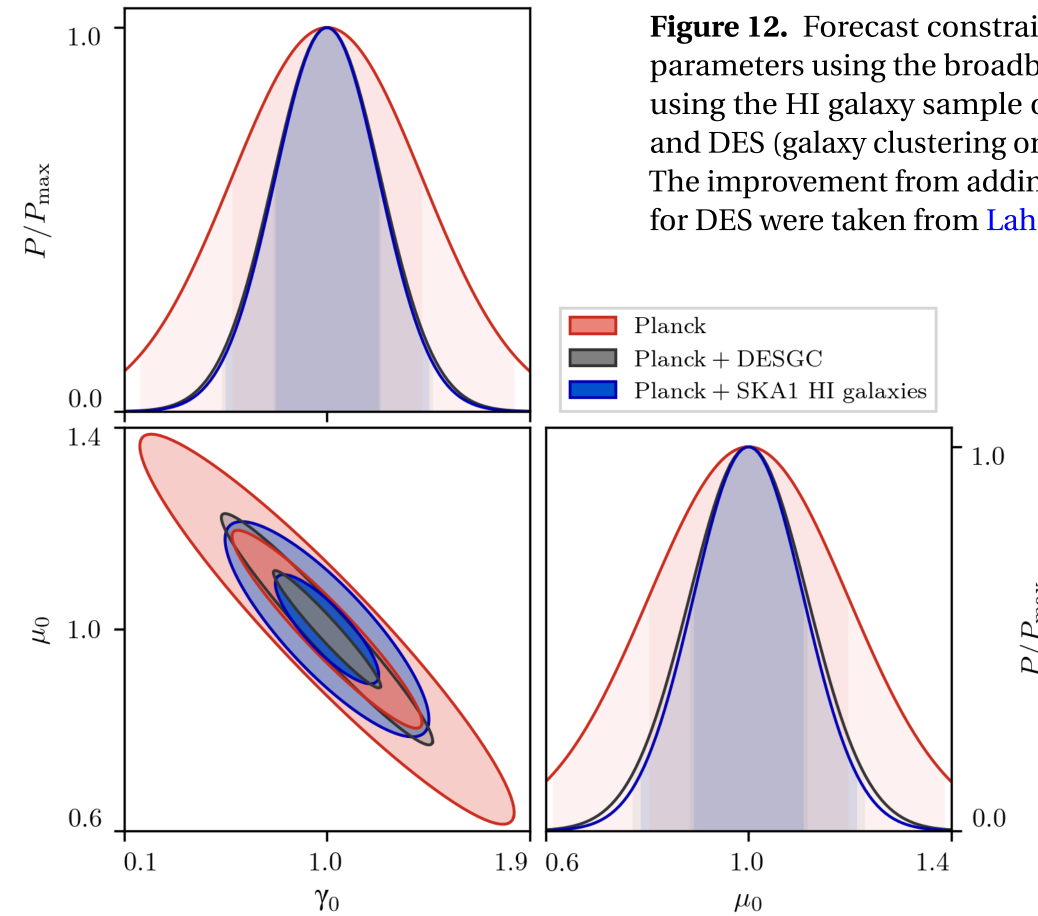
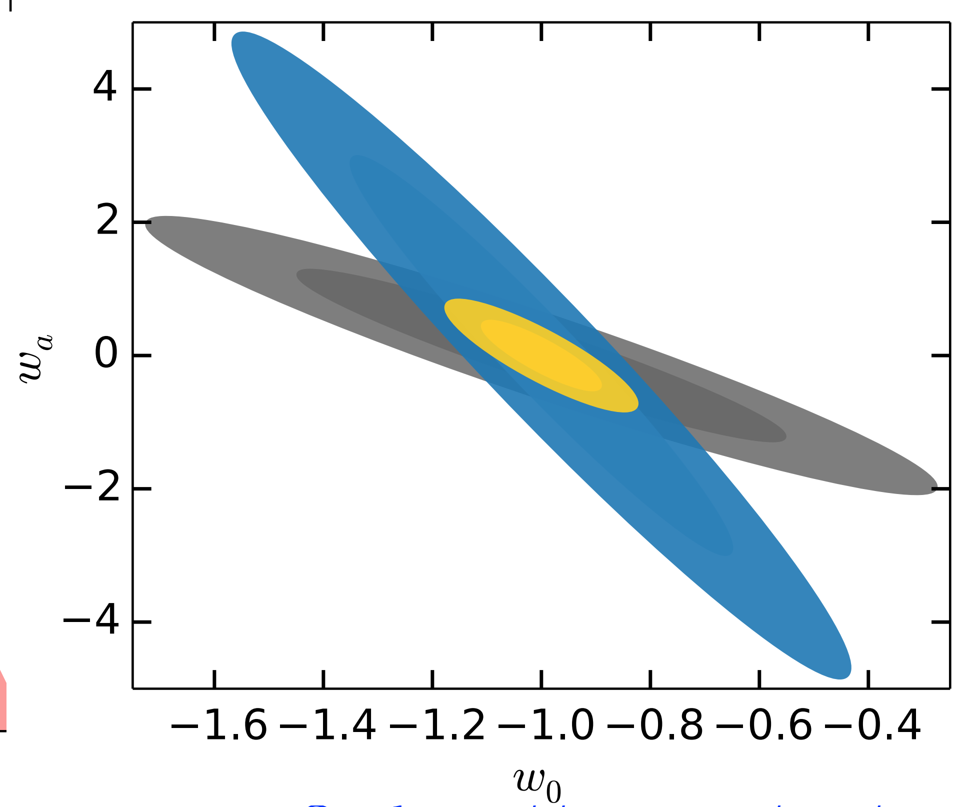


Figure 12. Forecast constraints on phenomenological modified gravity parameters using the broadband shape of the power spectrum, detected using the HI galaxy sample of the *Medium-Deep Band 2 Survey*. *Planck* and DES (galaxy clustering only) constraints are included for comparison. The improvement from adding SKA1 is comparable to DES. Specifications for DES were taken from Lahav et al. (2010).

Modified gravity



Void count

Figure 15. Forecast marginalized parameter constraints for w_0 and w_a from the void counts of the HI galaxy *Medium-Deep Band 2 Survey* (grey), *Planck* (blue), and both combined (yellow). Apart from the cosmological parameters, we have also marginalized over uncertainty in void radius (Sahlén & Silk, 2016), and in the theoretical void distribution function (Pisani et al., 2015).

$p/\varrho = w_0 + (1-a)\, w_a$

See https://arxiv.org/abs/1811.02743 and its reference list

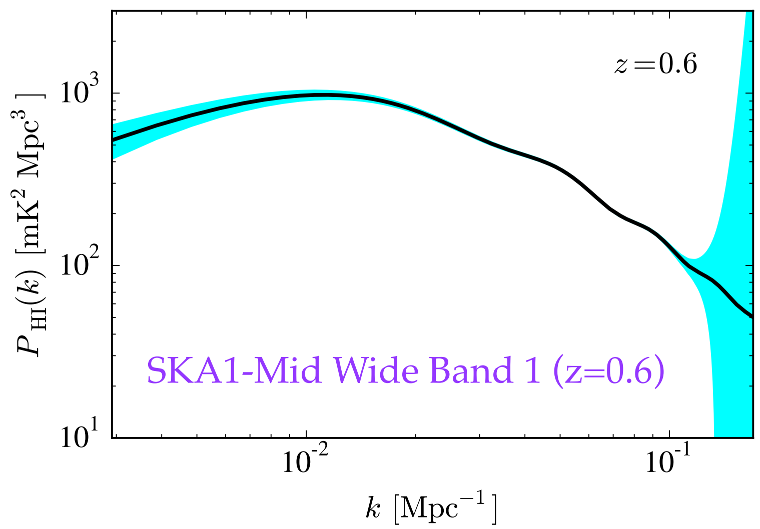
Intensity Mapping with SKA

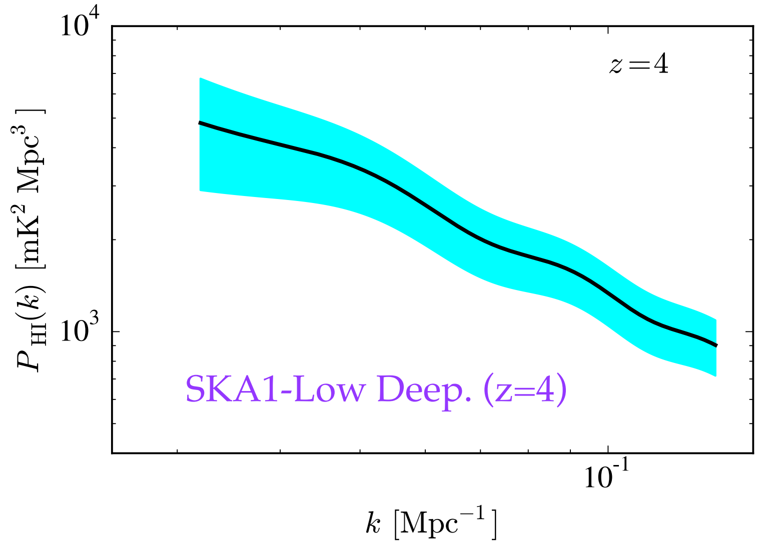
Intensity Mapping

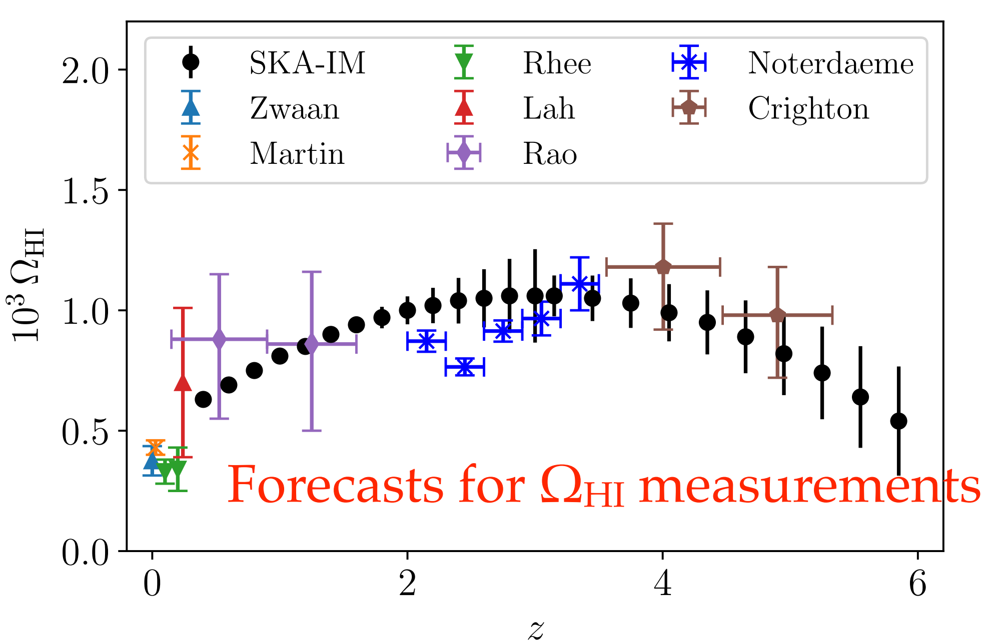
- SKA1 constraining power for cosmological parameters, DE EoS specially, is not competitive with optical surveys, due to the limited redshift reach of the H_I galaxy redshift survey
- Intensity Mapping allows to extend significantly the accessible redshift range
- However, the SKA1-Mid array configuration is not well suited to IM - Use of individual dishes - ***or possibly the central core in interferometric mode***
- 3D Intensity Mapping, similar to CMB
  - Measure integrated emission (brightness temperature) of HI - from IGM and gas in galaxies, in cells 10-1000 Mpc^3
  - Subtract foregrounds, and compute P(k,z) on 3D maps T21(α,δ,ν)
  - Possible to reach higher redshifts (z ~ 1-2) with SKA1-Mid
- Separating the cosmological signal from the foregrounds (Galactic synchrotron, radio-sources …) is a big challenge
- Residual fluctuations due to noise, specially in non interferometric mode is also a challenge

Constraints on Cosmology from SKA-1 IM survey

HI auto-correlation P(k) from SKA1 IM

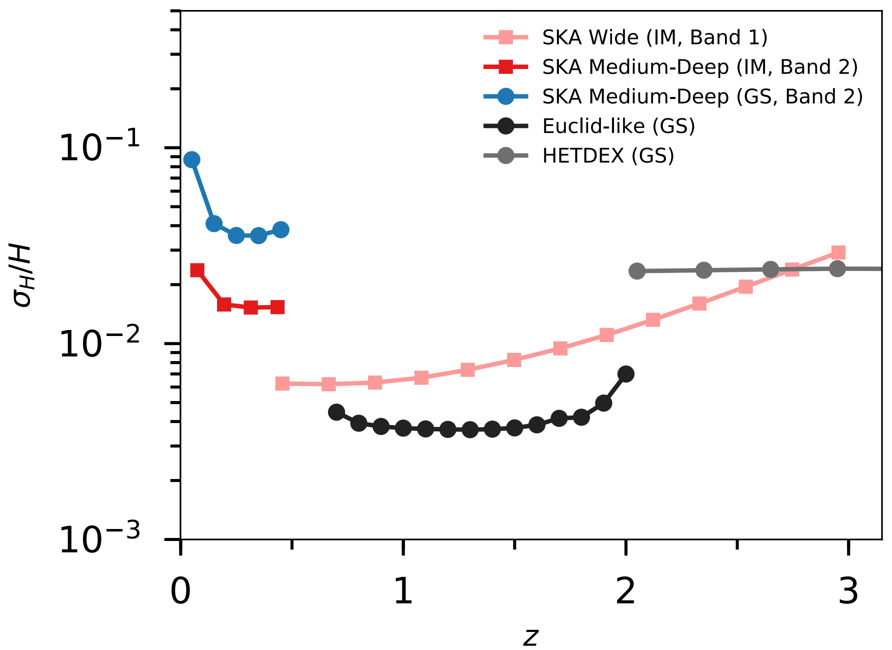


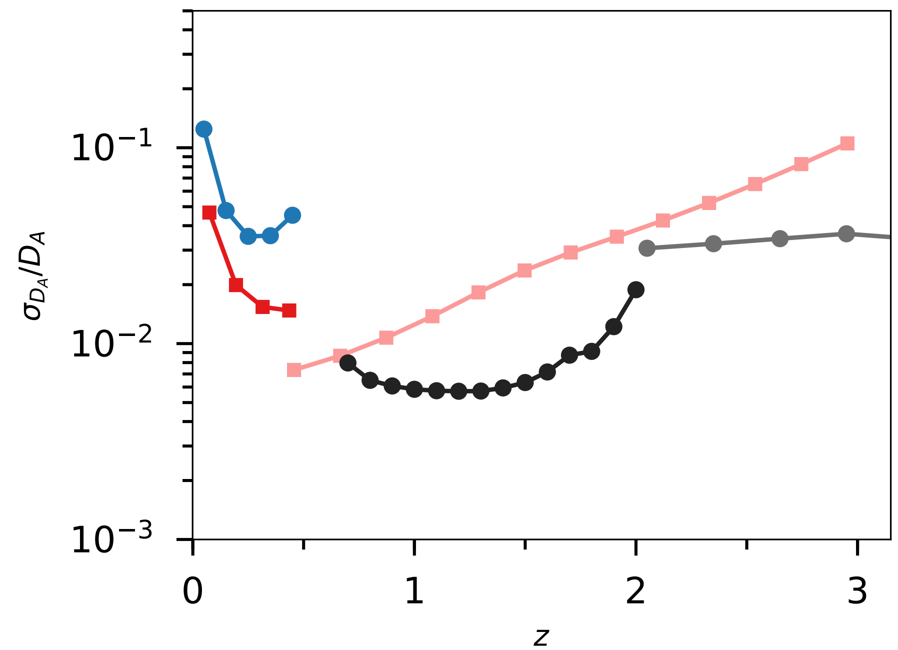


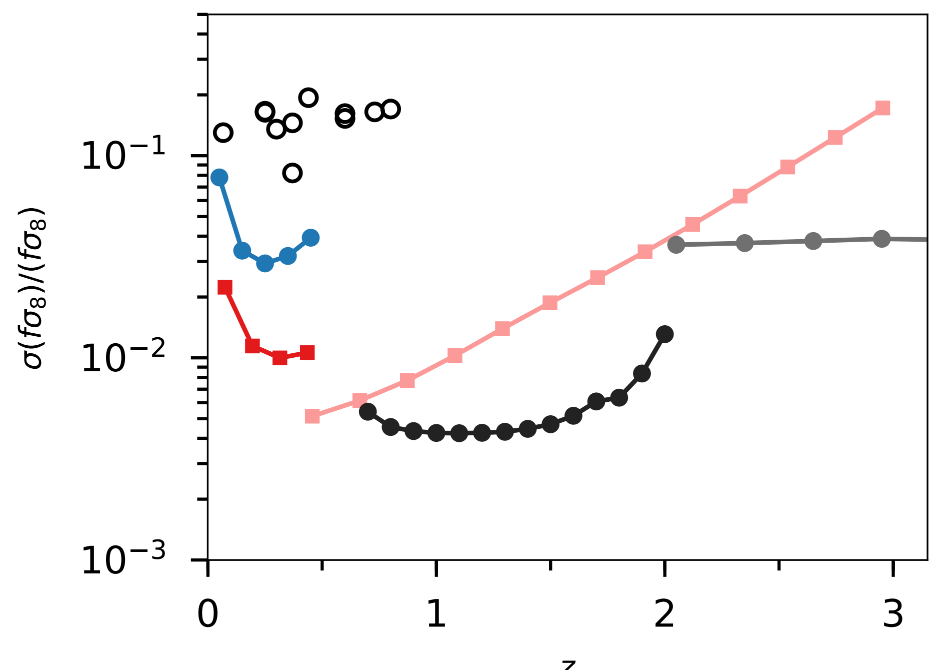


Forecasts for Ω_{HI} measurements

SKA1 IM constraining power for Cosmology, compared with HI Galaxy Survey (GS)





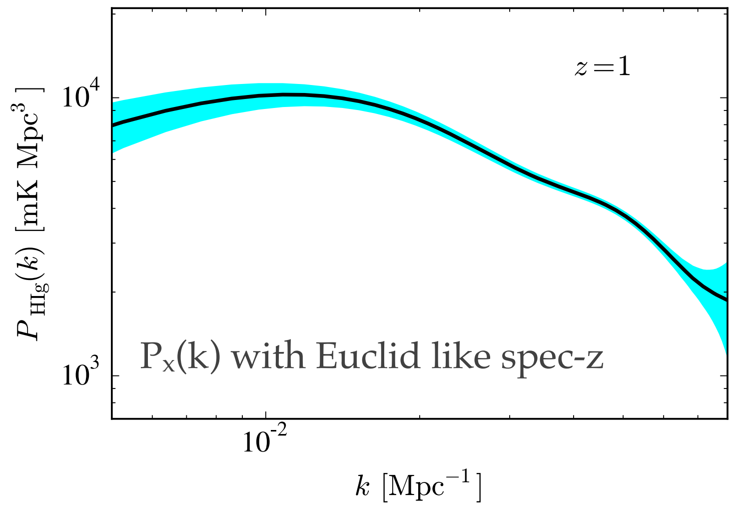


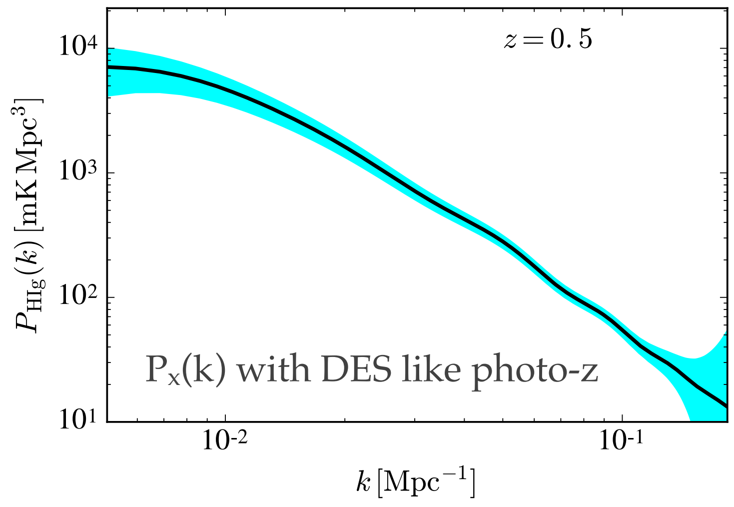
Structure growth factor from IM & GS

See https://arxiv.org/abs/1811.02743 and its reference list

Other probes / science goals - Synergy with optical surveys

- Particle DM search through H_I redshift survey cross-correlated with γ-ray maps
- Probing neutrinos masses , inflationary features
- Nature of DM (wdm …) using IM P(k) at small scales
- Cosmic dipole, using distribution of continuum radio-sources
- Cross-correlation with optical surveys :
    - Multi-tracer map of LSS : Control of systematics
    - Photometric redshift calibration , Photo-z for SKA continuum survey





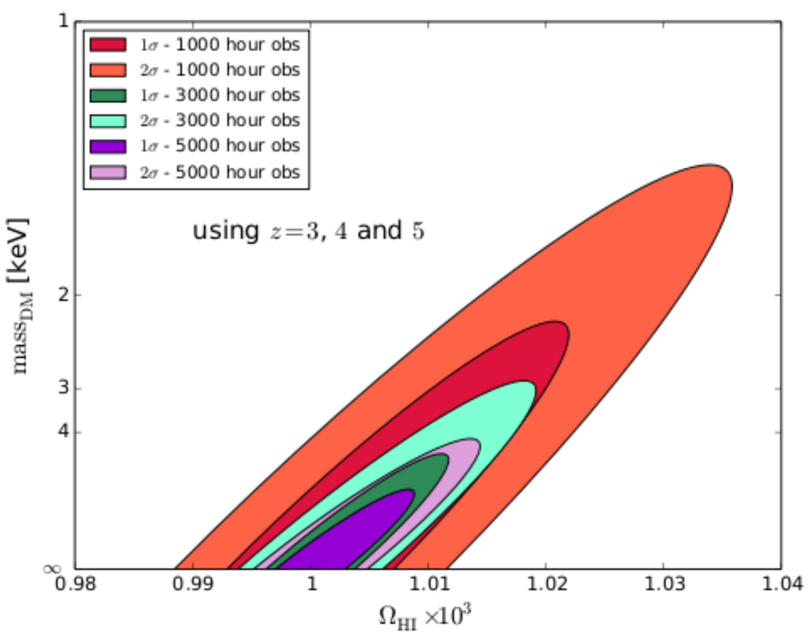


Figure 25. 1σ and 2σ contours (dark and light areas) of the values of Ω_{HI} and m_{WDM} determined using the HI power spectrum measured by SKA1-LOW with three different observation times: 1,000, 3,000 and 5,000 hours (red, green and violet) and using a field-of-view between 2.7-6 deg^2. The Fisher matrix analysis is performed using information coming from redshift $z = 3, 4$ and 5.

Summary (highlighting some of the conclusions of the SKA Cosmology WG Red Book)

H_I galaxy redshift survey

- The HI galaxy sample will reach extremely high number densities at $z \lesssim 0.2$, making it possible to reliably identify even small cosmic voids, and obtain high-SNR cross-correlations with γ-ray maps. The resulting void sample can be used as a complementary probe of matter clustering that is particularly sensitive to modified gravity effects, while the γ-ray cross-correlations can be used to detect dark matter annihilation.

Synergy with other surveys/instruments

- Using the SKA with other telescopes can provide complementary physical constraints, e.g. from the combination of optical weak lensing with radio intensity mapping, and vital cross-checks of results by comparing dark energy constraints from optical surveys to those from the SKA. Cross-correlations of probes can measure signatures which would otherwise be buried in noise.

Intensity Mapping

- Synergies of the intensity mapping surveys with optical surveys such as LSST and *Euclid* are crucial for multi-wavelength cosmology and systematics mitigation (see more detailed discussion below). In particular, they will provide ground breaking constraints on ultra-large scale effects such as primordial non-Gaussianity, potentially a factor of 10 better than current measurements.

https://arxiv.org/abs/1811.02743

END

Backup slides

Swiss SKA Days 2022 -
https://indico.skatelescope.org/event/936/timetable/?view=standard

Planning for Science with SKA @ Swiss SKA Days
https://indico.skatelescope.org/event/936/contributions/8818/attachments/8184/13487/SwissDays2022_Bourke.pdf

Un papier forecast pour DE models with IM/Tianlai
https://iopscience.iop.org/article/10.3847/1538-4357/ac0ef5/pdf

Cross correlating 21cm with optical Padmanabhan , refregier & Amara
https://arxiv.org/pdf/1909.11104.pdf

Cosmic Radio dipole
https://arxiv.org/pdf/1810.04960.pdf

Another cosmic dipole
https://arxiv.org/pdf/1606.06751.pdf

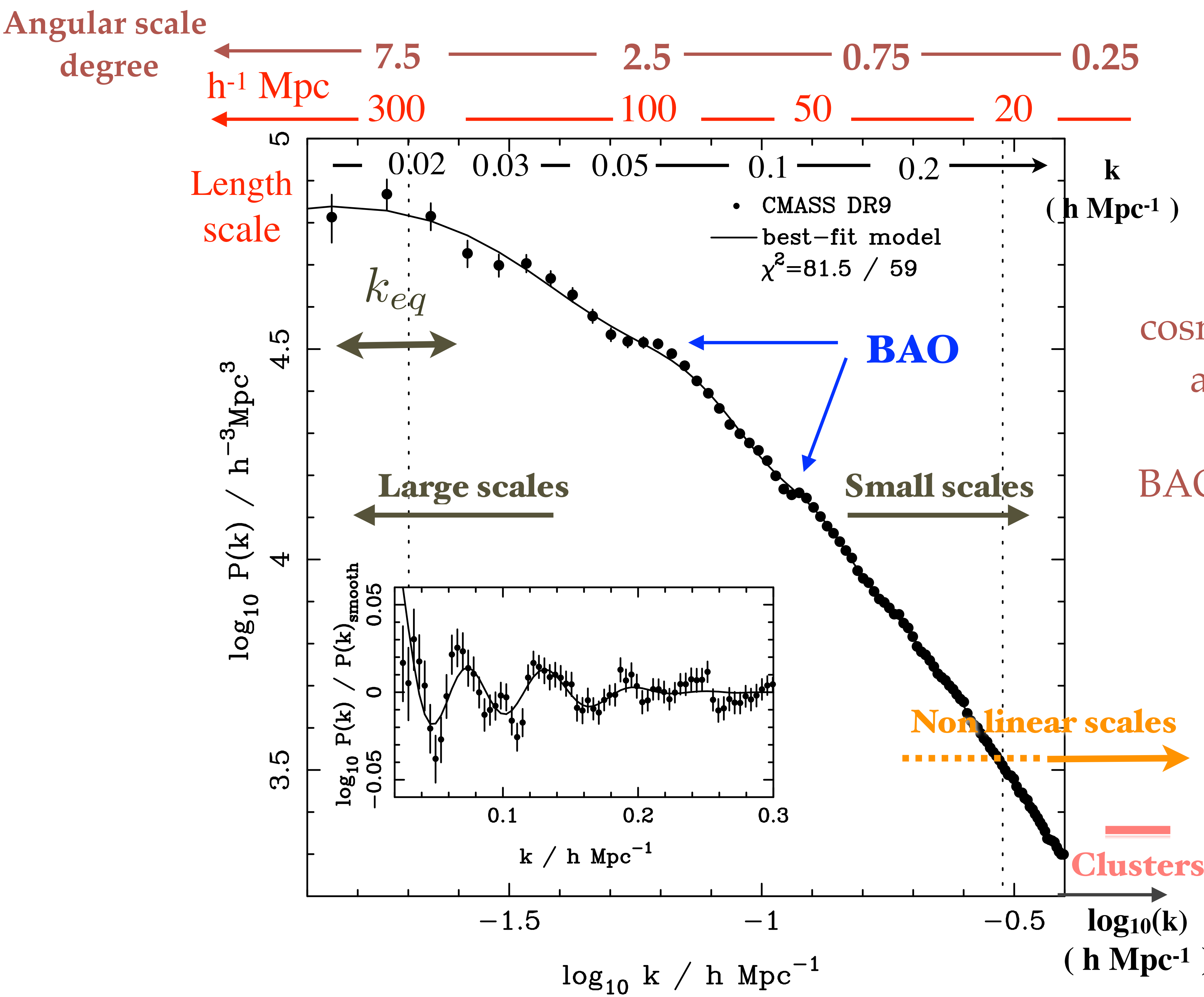
Cosmological probes and Dark energy (I)

- Large Scale Structure (**LSS**) : shape (power spectrum or correlation function) and its evolution with redshift is a powerful cosmological probe - in particular the BAO feature in the LSS
- Baryon Acoustic Oscillations (**BAO**) : Measurement of characteristic scales $\rightarrow$ $d_A(z)$, $H(z)$
- Supernovae (**SN**) : Measure of apparent SNIa luminosity as a function of $\rightarrow$ $d_L(z)$
- Weak lensing (**WL**) : Measure of preferred orientation of galaxies $\rightarrow$ $d_A(z)$, growth of inhomogeneities (structures / LSS)
- Galaxy Clusters (**CL**) : number count and distribution of clusters $\rightarrow$ $d_A(z)$, $H(z)$, Structure formation (LSS)
- Integrated Sachs Wolf (**ISW**) effect : effect of evolving gravitational potential in large scale structures (with redshift)

Cosmological probes (II)

- 1- Study the geometry of the universe (FLRW metric) - with a distance-redshift relation depending on the cosmological parameters (energy-matter densities)
  - Standard candles : SNIa , gravitational sirenes (GW)…
  - Standard ruler probes : BAO
- 2- Study the dynamics of structure formation : observe the LSS form and evolve through cosmic time (redshift)
  - Matter distribution using tracers (LSS) or the gravitational potential through lensing
- Statistical properties of matter distribution in the universe and its evolution with time (redshift) is one of the major tools/probes to test the cosmological model, determine its parameters: Dark matter and dark energy properties, neutrinos masses …
- The analysis is often carried out using the correlation function (or the spatial or angular power spectrum P(k) , C(l) …

LSS : Power spectrum and different scales



Most of the LSS cosmological information at scales larger than few arc minutes

BAO: 0.5 to a few degrees

SDSS-DR9 , Anderson et al et al. 2012, arXiv:1203.6594

Foregrounds: Extracting cosmological signal

- Foregrounds, dominated by Milky Way synchrotron emission and radio sources are 1000-10000 brighter than the cosmological signal (1-10 K in cold parts of the sky, compared to <0.1 mK for the cosmological 21cm)

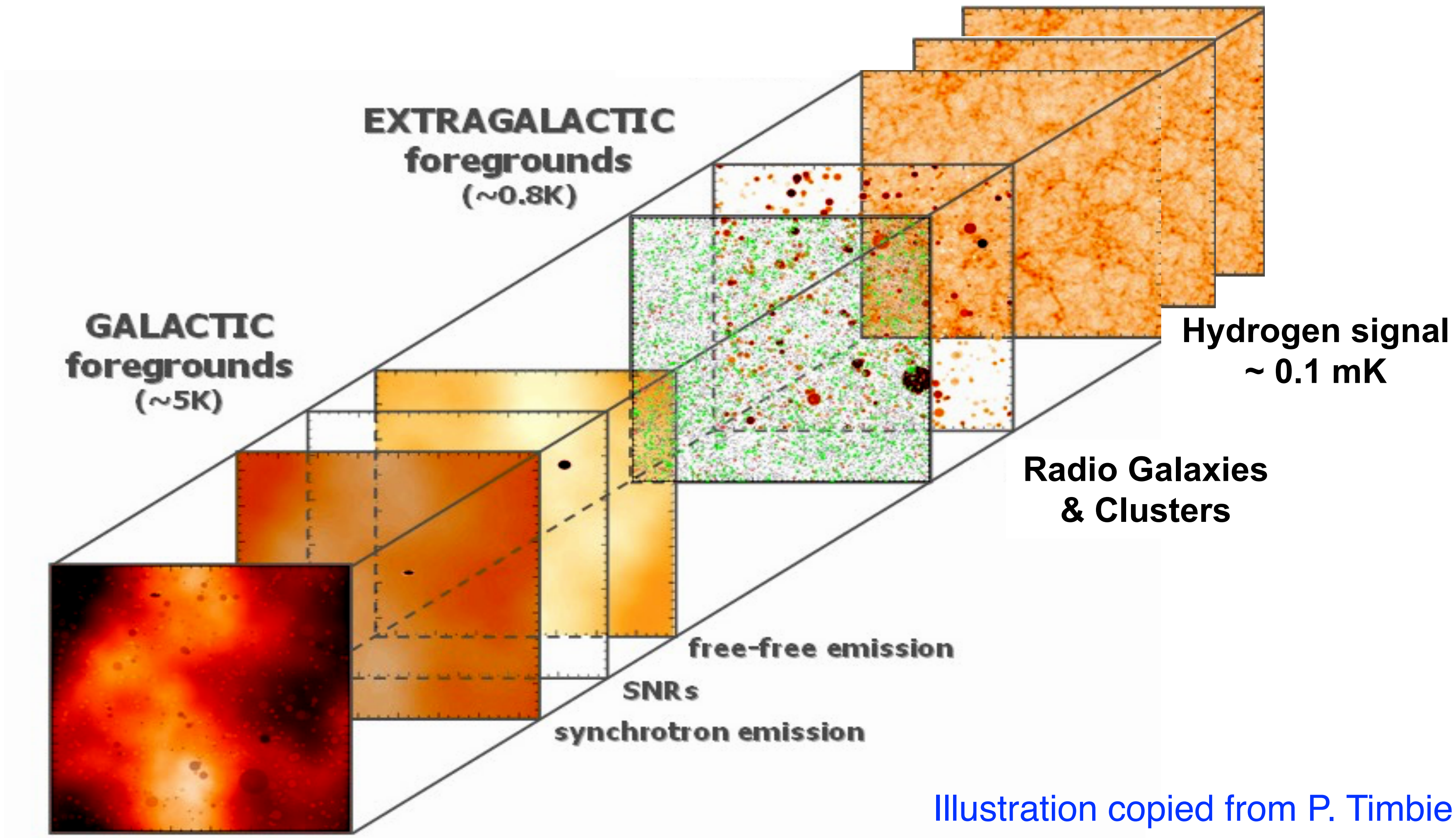
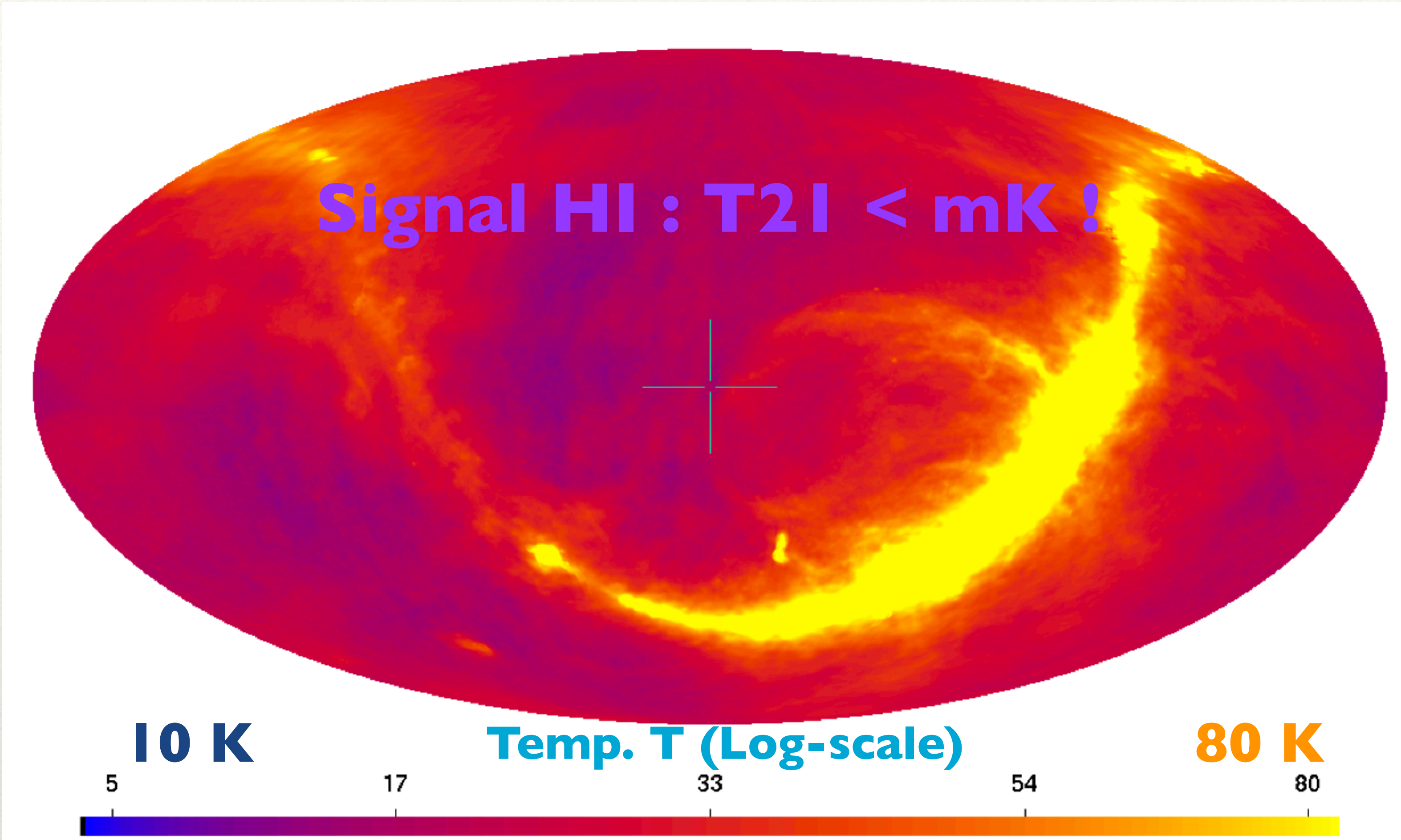


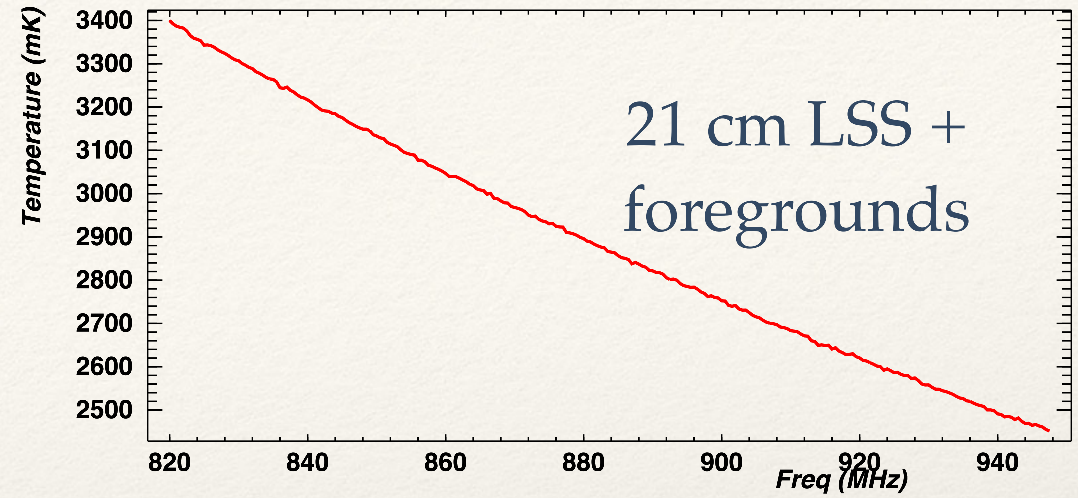
Illustration copied from P. Timbie slides

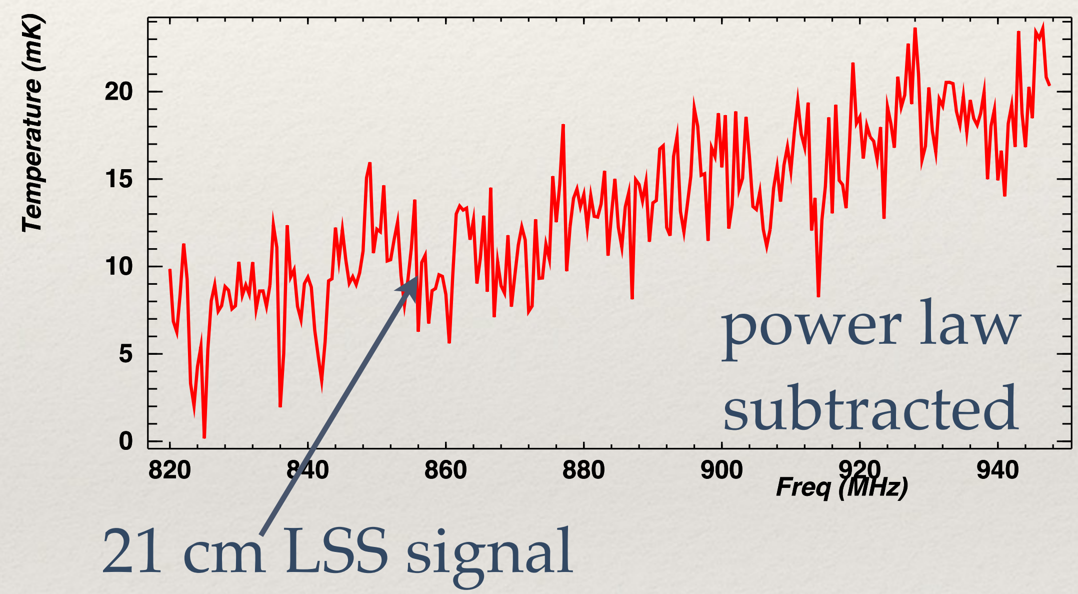
Foregrounds



Galactic synchrotron emission

http://lambda.gsfc.nasa.gov/



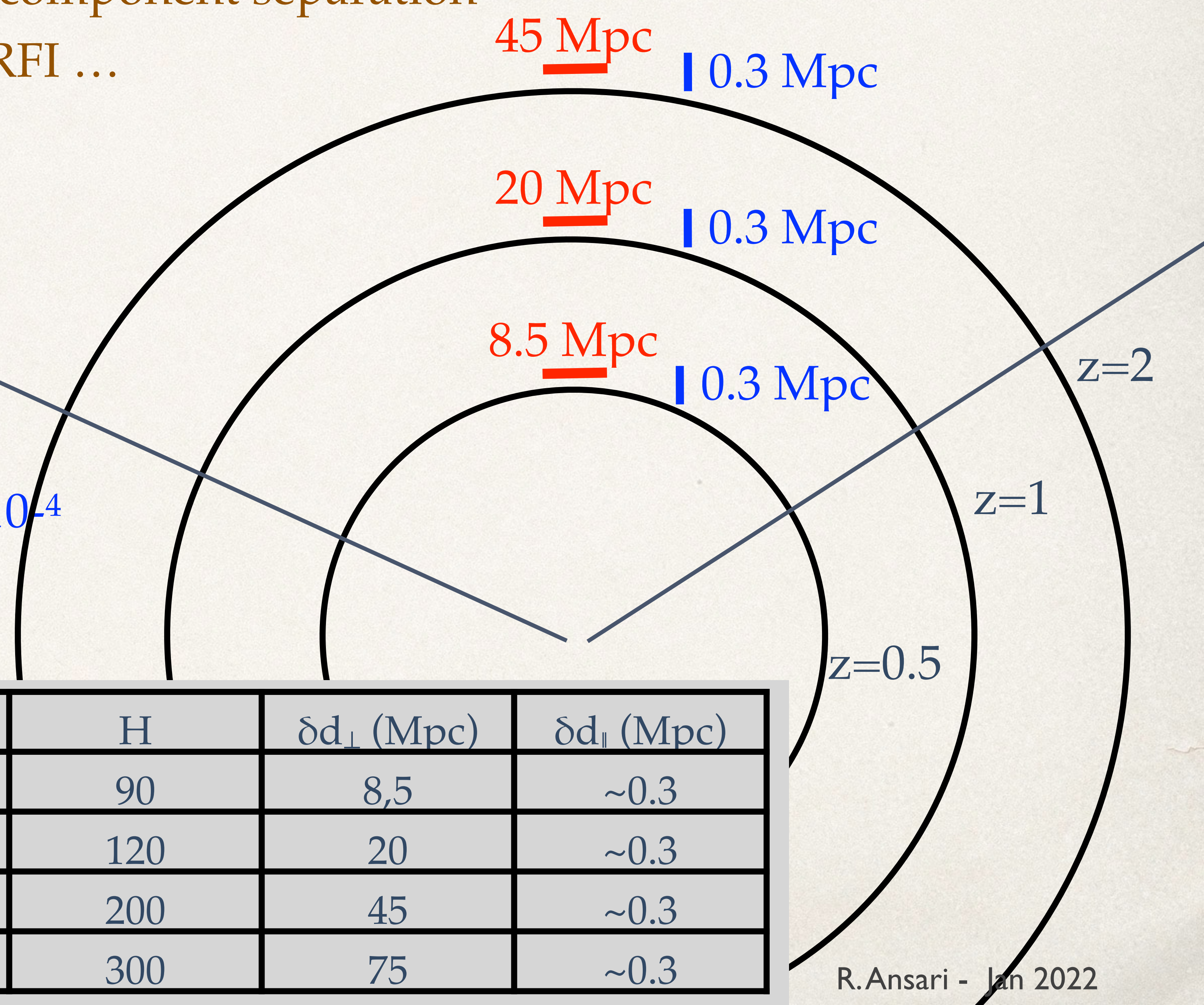


- Exploit foregrounds smooth frequency dependence (power law ∝ ν^β) for Galactic synchrotron and radio sources
- Instrumental effects (mode mixing), Polarisation leakage / Faraday rotation …

Wang et al. 2006 (EoR)
Ansari et al. (2012) - A&A
Shaw et al (2015) ApJ
Wolz et al. (2016) - MNRAS
Zuo et al. (2019) - AJ
+ many more !

- Mapping LSS with 21cmIM ➙ few arc min resolution is sufficient
- ➙ Large instantaneous field of view (FOV>few deg) and bandwidth (BW > 100 MHz)
- Use of dense interferometric arrays (small size reflectors) to insure high sensitivity to low k and large instantaneous FOV
- Or a single dish with multi-beam focal plane receivers
- Instrument noise (Tsys)
- Foregrounds / radio sources and component separation
- Calibration, instrument stability, RFI …

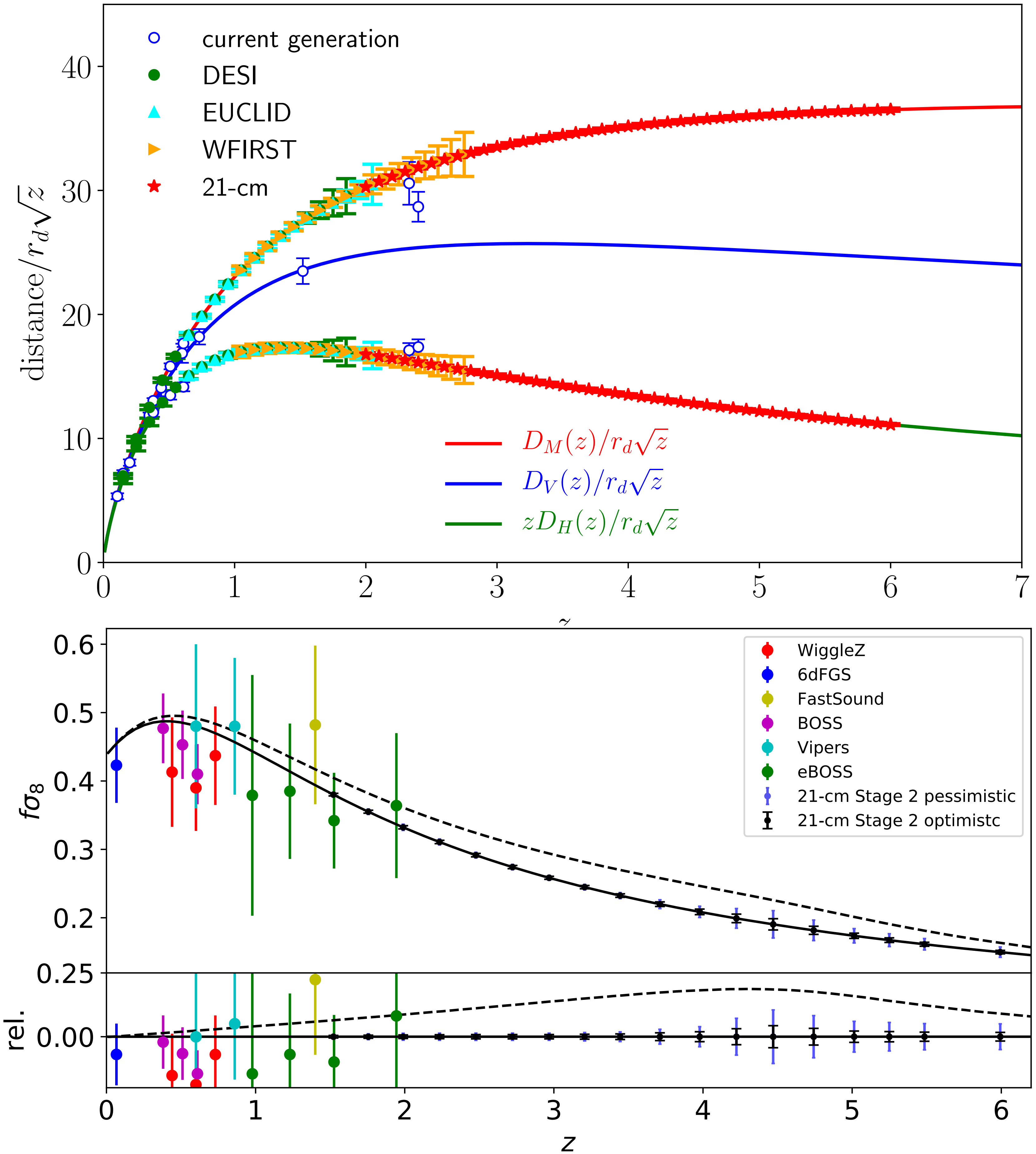
L=100 m array radio instrument
➙ ang. resolution $\delta\theta \sim \lambda/L$
deteriorating with redshift z
Spectral resolution 100 kHz
➙ excellent redshift precision $\delta z/z \sim 10^{-4}$



z	δθ	d_{LOS} (Mpc)	H	$\delta d_{\perp}$ (Mpc)	$\delta d_{\parallel}$ (Mpc)
0,5	15′	1945	90	8,5	~0.3
1	20′	3400	120	20	~0.3
2	30′	5320	200	45	~0.3
3	40′	6320	300	75	~0.3

IM instrumental challenges (incomplete summary)

- **Packed array transit interferometer** (chosen for most of the dedicated projects)
- Large instantaneous field of view → small individual reflector size (few meters)
- Large instantaneous bandwidth (400 MHz … 1 GHz)
- Large number of feeds: few hundreds to few thousands feeds and long observation (integration) time ➙ decrease projected noise level on sky
- technological challenge : cost effective design and construction of large number of feeds and associated electronics, while maintaining uniformity, construction quality and performance
- **Digital interferometry with such large arrays, technologically feasible through the use of FPGA + CPU/GPU's**
- Feed cross-couplings and correlated noise
- Instrument stability - bandpass smoothness and calibration
- Phase calibration - Interferometry / beam forming
- Individual feed beam response (simulation + on site measurements) - side lobe issues
- Array calibration : redundant baselines an advantage for calibration ✔
- Array grating lobes : disadvantage of regular arrays which perform poorly in terms of mode mixing ✘



Cosmic Visions A. Slosar et al &RA , arXiv:1810.09572

Many others (forecasts, phenomenology …)
Random selection

Karagiannis et al, arXiv:1911.03964

Santos et al, arXiv:1501.03989

Villaescusa et al, arXiv:1609.00019

Villaescusa et al, arXiv:1804.09180

Witzemann et al, arXiv:1711.02179

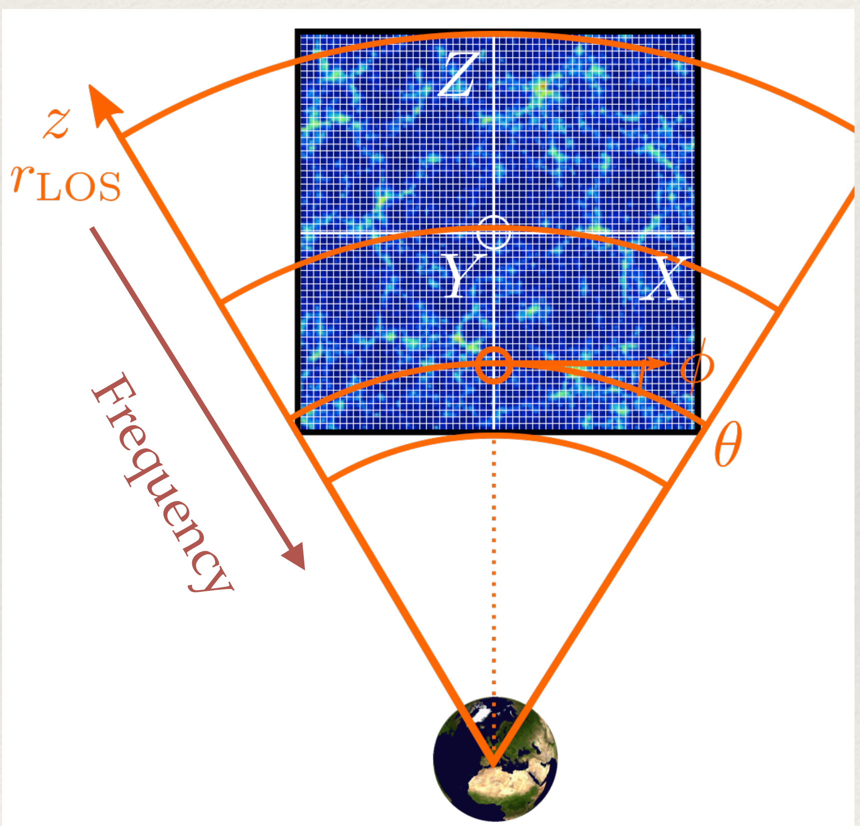
Chen et al, arXiv:2010.07985

SKA-WG , Bacon et al. arXiv:1811.02743

21 cm 3D Intensity Mapping

Dense Array Transit Interferometers

- Map the sky through drift-scan
- Reconstruct sky map from visibilities
- Visibilities correspond to transverse Fourier modes $k_\perp$
- **m-mode decomposition / map making with full EW scan**



$$P_{21}(k) \sim \left(\bar{T}_{21}\right)^2 \times P_{LSS}(k)$$

$$\bar{T}_{21} \simeq 4.7\,\mathrm{mK}\,\frac{\Omega_{H_I}}{10^{-3}}\,\frac{H_0(1+z)^2}{H(z)}$$

Single Dish

- Map the sky through drift-scan or by active scanning

- Sys ~ 50 K , Foreground ~10K for an LSS signal ≲ 1 mK (ratio 10^4 - 10^5)
- Stage I : 10^4 m^2 , 10^3 feeds
- Stage II : 10^5 m^2 , 10^4 feeds
- 10 GB/s … 1000 GB/s raw visibility data @ 1 sec averaging