SKA challenges

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TITAN meeting

Orme de Merisiers - February 2023

- SKA : Next Generation Radio Telescope
  - Science with SKA
- Radio interferometry
- Cosmology with SKA
  - H_I redshift survey
  - Intensity mapping
- Summary

SKA - Next Generation Radio Telescope

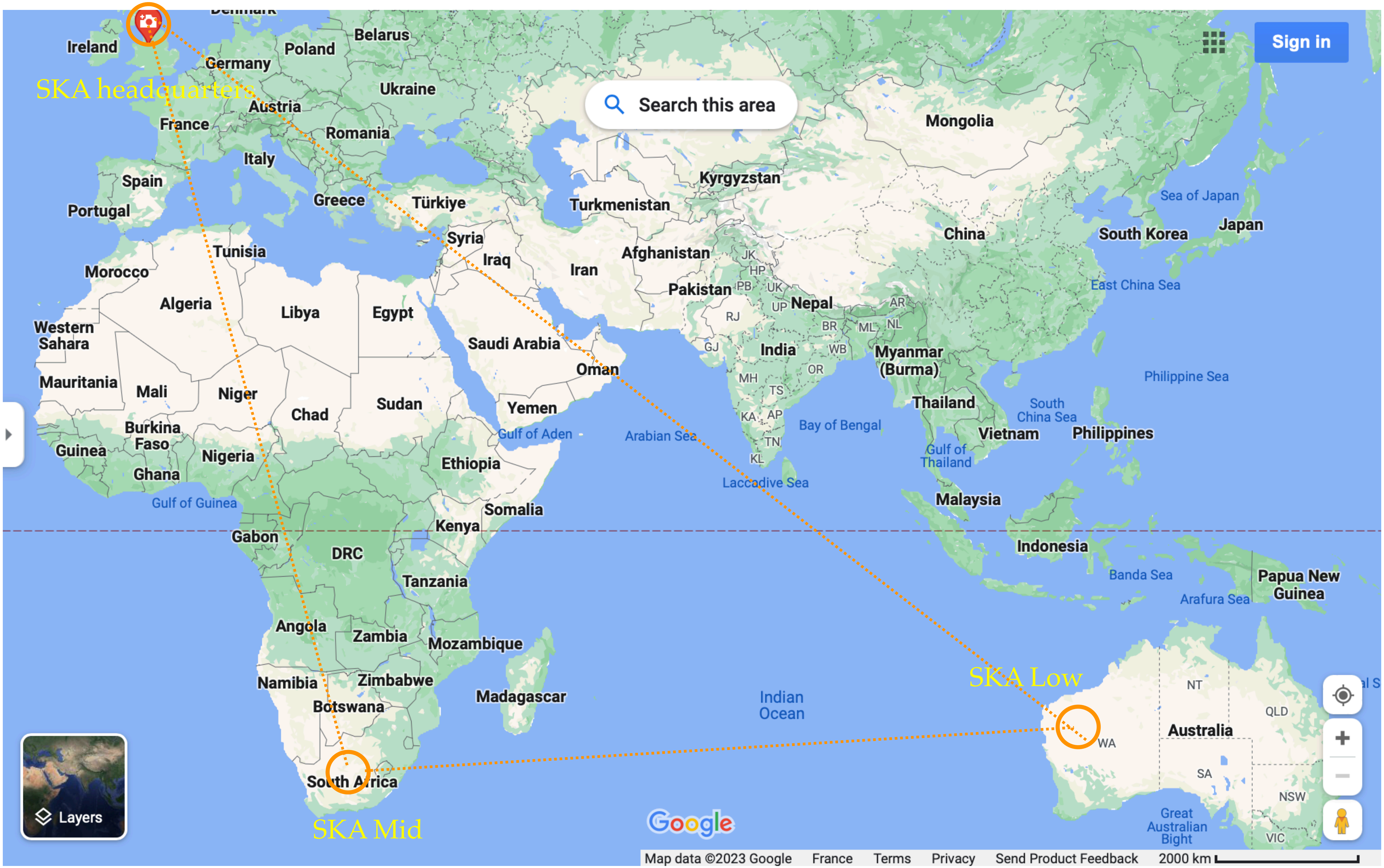
SKA : Next generation radio telescope

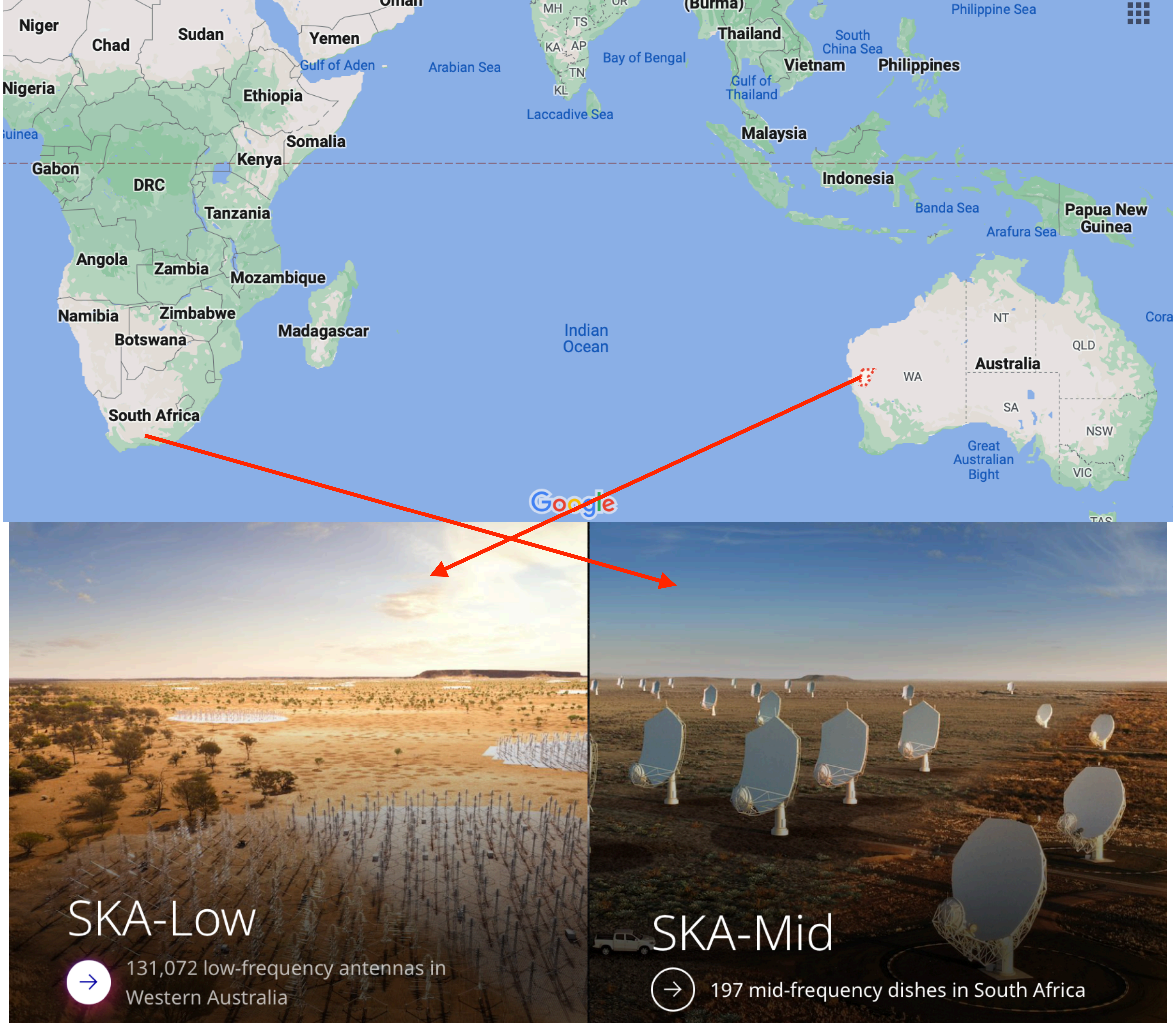
Large FOV, high resolution, large bandwidth , digital radio interferometer

- SKA-Low (50-350 MHz) in Murchinson area in Australia , using phased array of antenna
  - 512 stations, each with 256 antennae (total=131072 antenna), maximum baseline ≃ 74 km , total collecting area about **400 000 m^2**
- SKA-Mid, (0,35-15.4 GHz) - in Karoo region in South Africa, using 197 steerable dishes, off axis design, cryogenic receiver
  - 133 × D=15m diameter dishes + 64 × D=13.5m MeerKAT dishes, 5 receivers (selectable) to cover 6 frequency bands , max baseline ≃ 150 km, total collecting area about **30 000 m^2**
- SKAO headquarters at Jodrell-Bank, Manchester, UK

https://www.skao.int/en/explore/telescopes/ska-low

https://www.skao.int/index.php/en/explore/telescopes/ska-mid


SKA headquarters
SKA Low
SKA Mid


Niger
Chad
Sudan
Yemen
Nigeria
Ethiopia
Gulf of Aden
Arabian Sea
Bay of Bengal
Thailand
Vietnam
Philippines
South China Sea
Philippine Sea
Gulf of Thailand
Laccadive Sea
Malaysia
Somalia
Kenya
Gabon
DRC
Indonesia
Tanzania
Banda Sea
Arafura Sea
Papua New Guinea
Angola
Zambia
Mozambique
Namibia
Zimbabwe
Botswana
Madagascar
Indian Ocean
NT
QLD
Australia
WA
SA
NSW
VIC
Great Australian Bight
South Africa
Google
SKA-Low
131,072 low-frequency antennas in Western Australia
SKA-Mid
197 mid-frequency dishes in South Africa

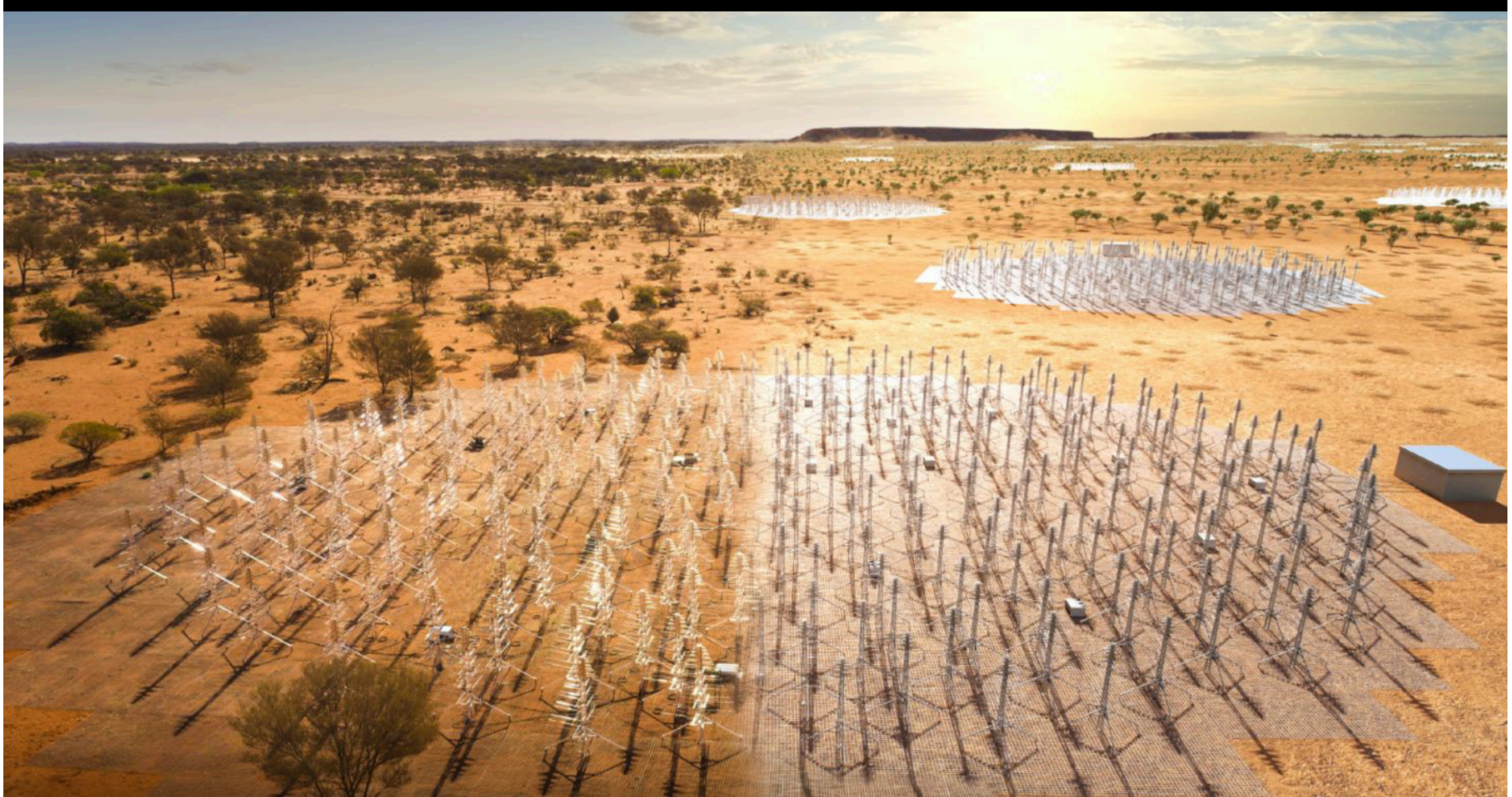
SKA-low 131072 antennae, organised into
512 stations, each with 256 antenna
Total collecting area ~ 400 000 m^2

50 - 350 MHz

Maximum baseline : 74 km

How does SKA-Low compare?

Compared to the LOFAR telescope in the Netherlands, which is currently the best similar instrument in the world, SKA-Low will have 25% better resolution, eight times the sensitivity, and will be able to survey the sky 135 times faster.



Composite of SKA-Low prototype antennas on site (left) blending with an artist's impression of the array.

https://www.skao.int/en/explore/telescopes/ska-low

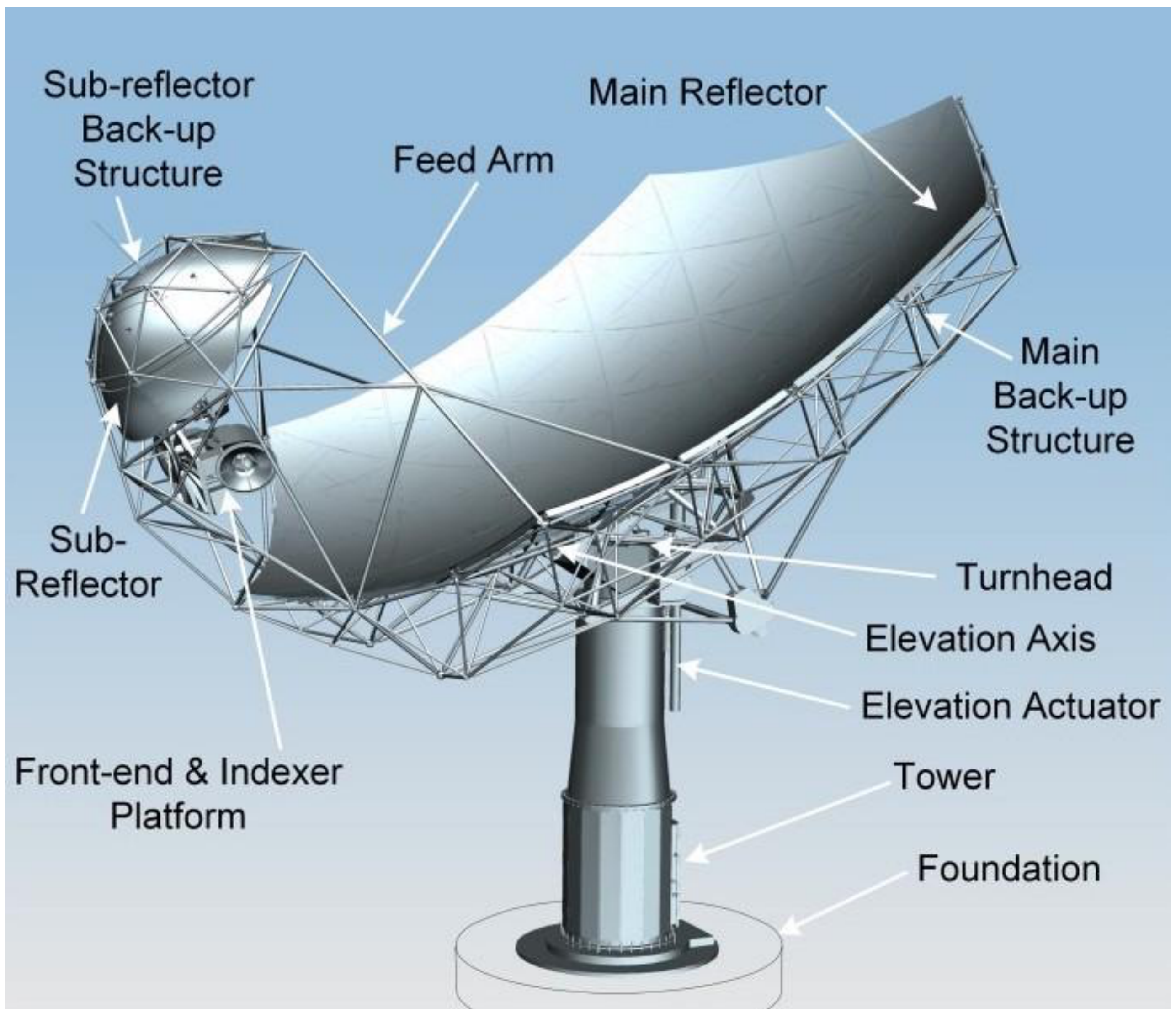
SKA-mid dish (15 m)

133 x 15 m dishes + 64 MeerKAT 13.6 m dishes

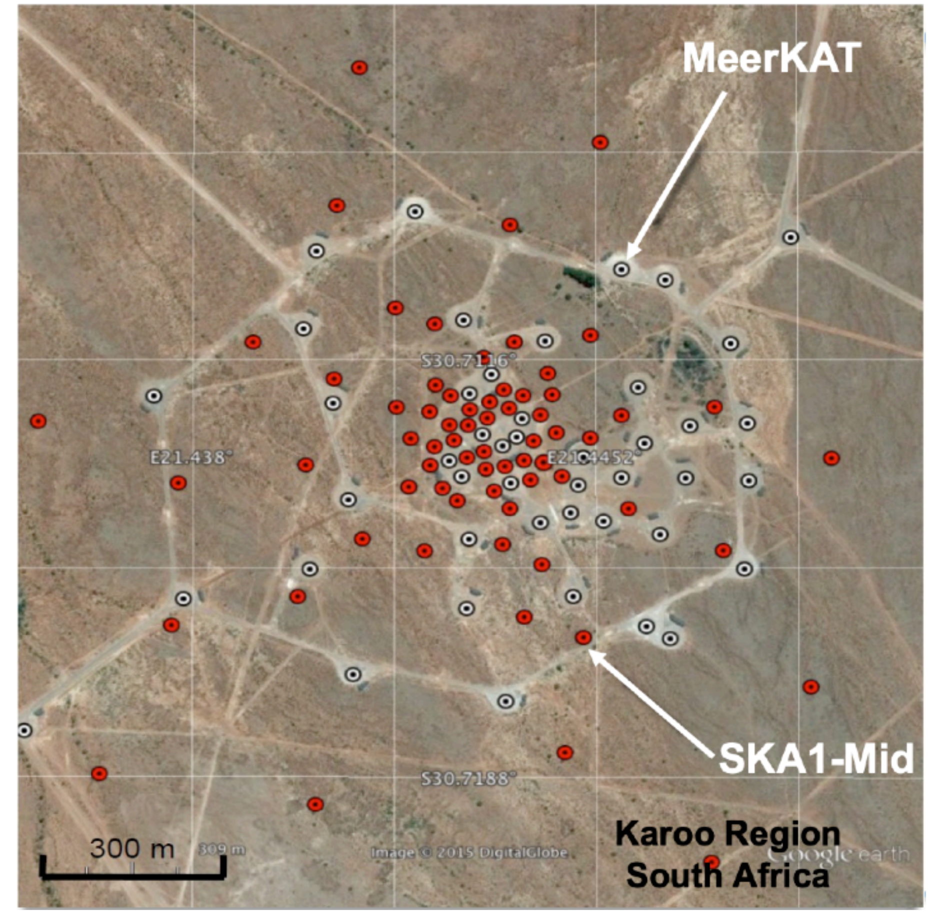
Total collecting area ~ 30 000 m²

350 MHz - 15.4 GHz

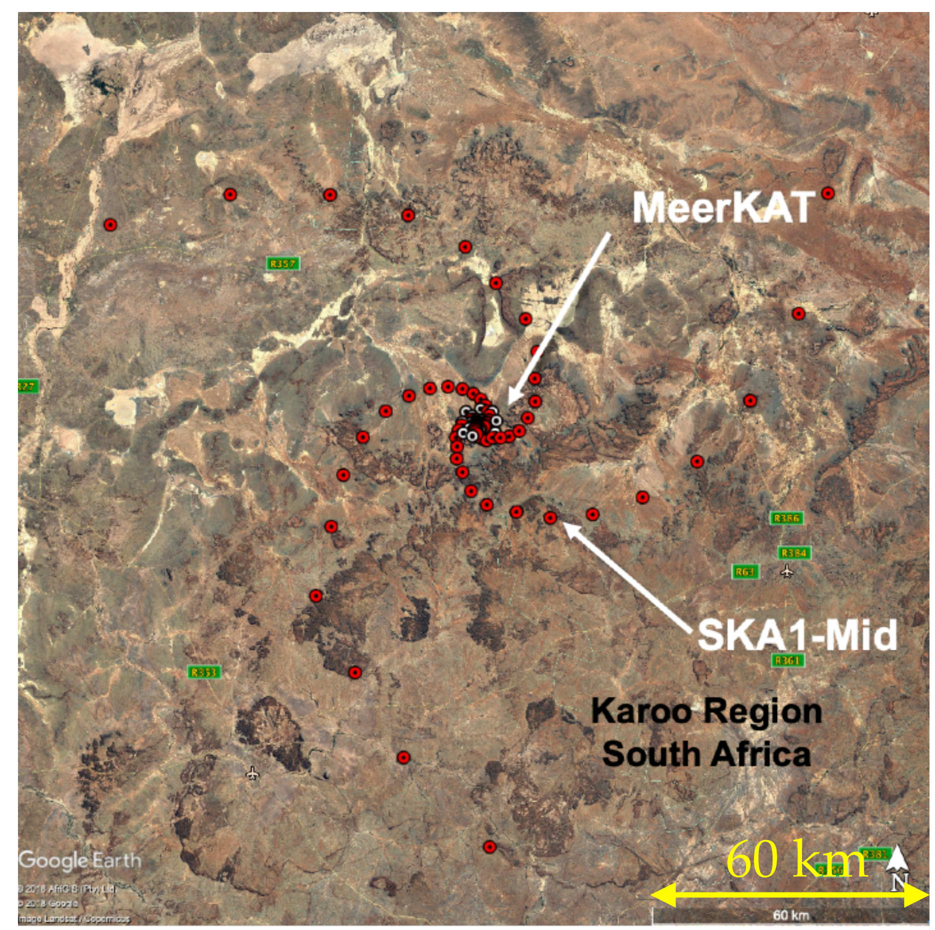
Maximum baseline : 150 km



SKA1-Mid core



SKA1-Mid full array



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

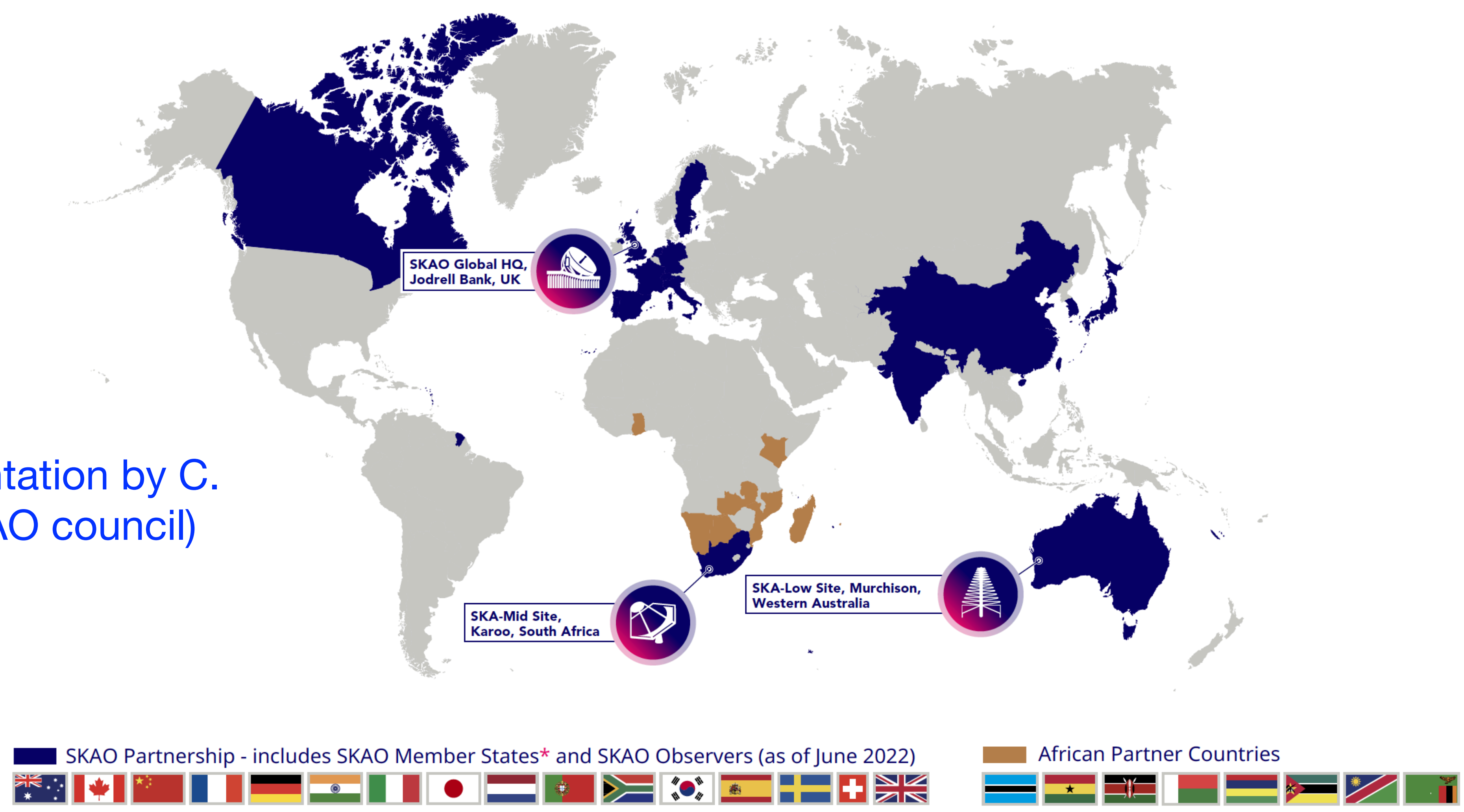
Who are we?

The Square Kilometre Array Observatory (SKAO)

An inter-governmental organization, governed by a treaty. SKAO was born in January 2021.

Members	Australia, China, Italy, Netherlands, Portugal, South Africa, Switzerland, UK
Accession stage	France, Spain, Germany
Membership negotiations	Canada
Interim agreements	India, Sweden
Early stages	Japan, South Korea

Slide borrowed from a presentation by C. Cesarsky (chair person, SKAO council)



SKA-I construction strategy / planning

Construction Strategy

- Target: build the SKA Baseline Design (197 Mid dishes; 512 Low stations: AA4)
- Not all funding yet secured, therefore following Staged Delivery Plan (AA*)
- Develop the earliest possible working demonstration of the architecture and supply chain (AA0.5).
- Then maintain a continuously working and expanding facility that demonstrates the full performance capabilities of the SKA Design.

Milestone Event (earliest)		SKA-Mid (end date)	SKA-Low (end date)
AA0.5	4 dishes 6 stations	2024 Dec	2024 Aug
AA1	8 dishes 18 stations	2025 Nov	2025 Oct
AA2	64 dishes 64 stations	2026 Oct	2026 Sep
AA*	144 dishes 307 stations	2027 Aug	2028 Jan
Operations Readiness Review		2027 Nov	2028 Apr
End of Construction		2028 Jul	2028 Jul

- **Best argument for further investment is a working system!**

First science expected in 2026/27

Slide borrowed from a presentation by C. Cesarsky (chair person, SKAO council)

SKA-1 Cost ≳ 650 M€

SKA total Cost ≳ 2100 M€

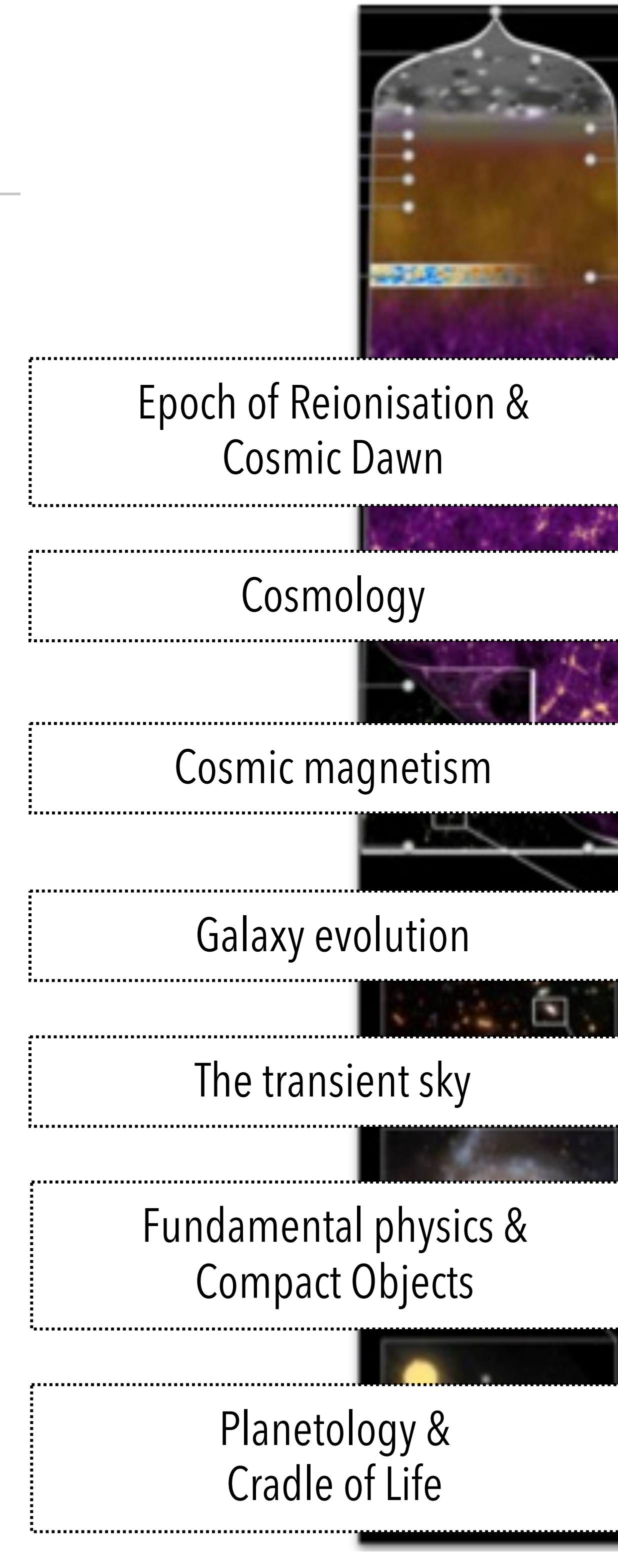
SKA science

Very broad coverage in astrophysics, cosmology and physics

SKA-Low

SKA-Mid

- Study the Epoch of Reionisation (EoR) at z ~ 6-12 and explore the Cosmic Dawn, up to z <~ 30
- **Cosmology, dark matter and dark energy**
- Galaxy evolution, cosmic history of baryons
- Cosmic magnetism: magnetic field and their impact on structure formation
- The transient sky in radio, stellar explosions and influence of compact objects on their environment
- Gravity, Gravitational waves and compact objects
- Formation of stars and planetary systems, search for complex molecules in close planetary nebulae



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

Illustration from a slide by C. Ferrari

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

$0.35<z<3$

$0<z<0.35$

SKA1 Band	Frequency Range	Available Bandwidth
Low	50 – 350 MHz	300 MHz
Mid Band 1	0.35 – 1.05 GHz	700 MHz
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. Bandwidth [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

Radio interferometers

Radio-telescopes / Interferometers

$\lambda = 21$ cm ; $\nu = 1420$ MHz

Radio observation: spectro-photometry
Single dish diffraction limited : λ/D
Interferometer resolution : λ/Baseline
Interferometer FOV : λ/D
Sensitivity limited by receiver / environment noise : T_{sys}

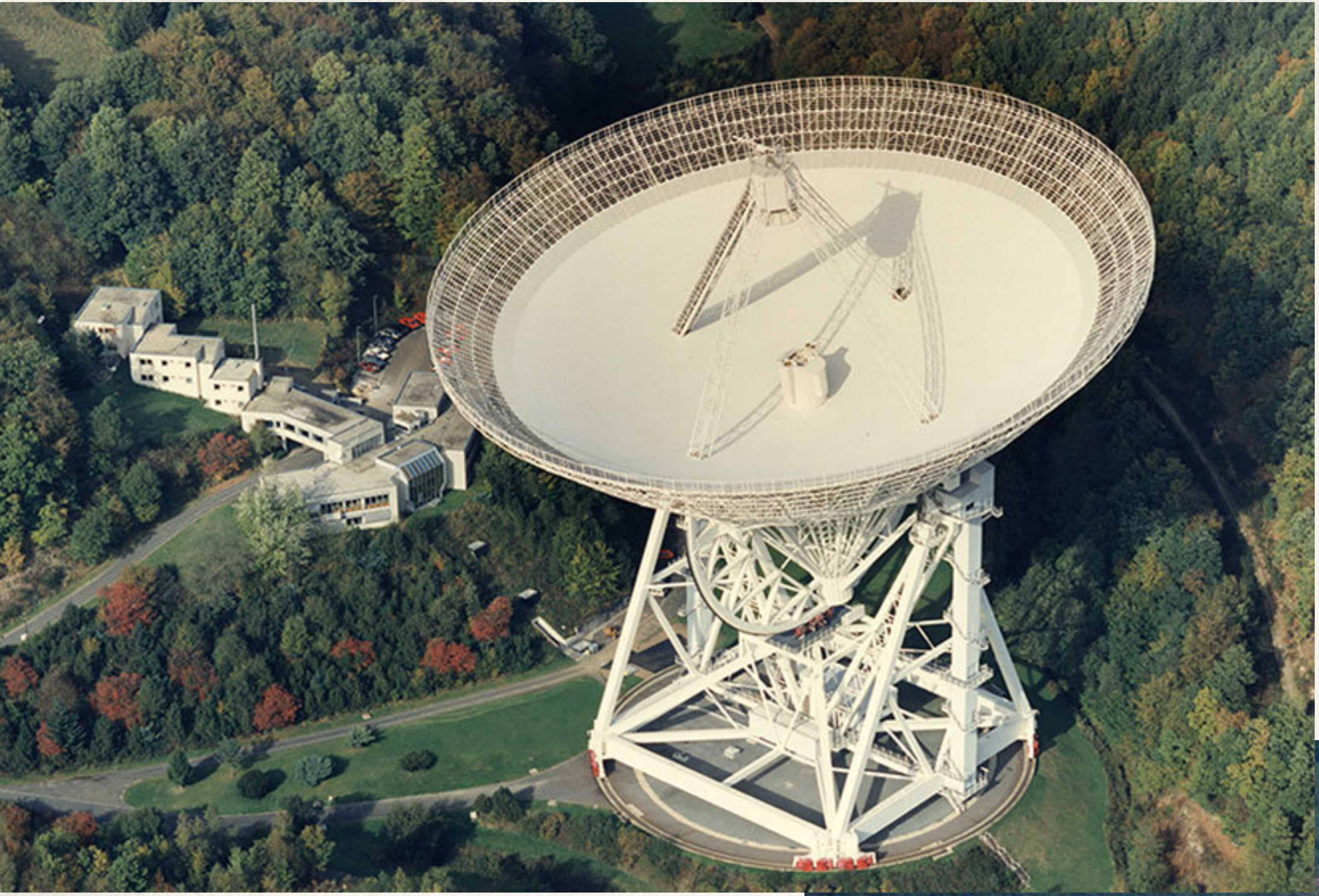
D	S	λ/D
10 m	78.5 m^2	1.2 deg
50 m	2000 m^2	15′
300 m	70 000 m^2	2.5′

$$S_* = \frac{T_{sys}}{A_e \sqrt{t_{int}\,\delta\nu}}$$

Large collecting area for sensitivity

High angular resolution through interferometry with long baselines

- Single reflector - single receiver (feed)
- Single reflector - multiple receivers (feeds) in the focal plane (10 - 100)
- Single reflector and phased array in the focal plane
- **Several antenna : interferometry**
- Dense array of antenna (no reflector) : aperture synthesis



Effelsberg 100 meter radiotelescope, Germany

https://www.mpifr-bonn.mpg.de/en/effelsberg

NRT, (Nançay, France)

https://www.obs-nancay.fr

FAST (Chine)

Photo : © Jeff Dai - https://apod.nasa.gov/apod/ap160929.html

FAST (Five hundred meter Spherical Radio Telescope) https://fast.bao.ac.cn

From visibilities to maps

$$s_i(\nu) = \iint d\hat{n}\; E(\hat{n},\nu) D_i(\hat{n},\lambda) e^{i(\vec{k}_{EM}.\vec{r})}$$

$$\mathcal{V}_{ij}(\nu) = < s_i(\nu) s_j(\nu)^* >$$

$$L(\hat{n},\nu) = D_i(\hat{n},\nu) D_j^*(\hat{n},\nu)$$

$$I(\hat{n},\nu) = E(\hat{n},\nu) E^*(\hat{n},\nu)$$

$$\mathcal{V}_{ij}(\nu) = \iint d\hat{n}\; I(\hat{n},\nu) L(\hat{n},\nu) e^{i(\vec{k}_{EM}.\vec{\Delta r}_{ij})}$$

Visibility

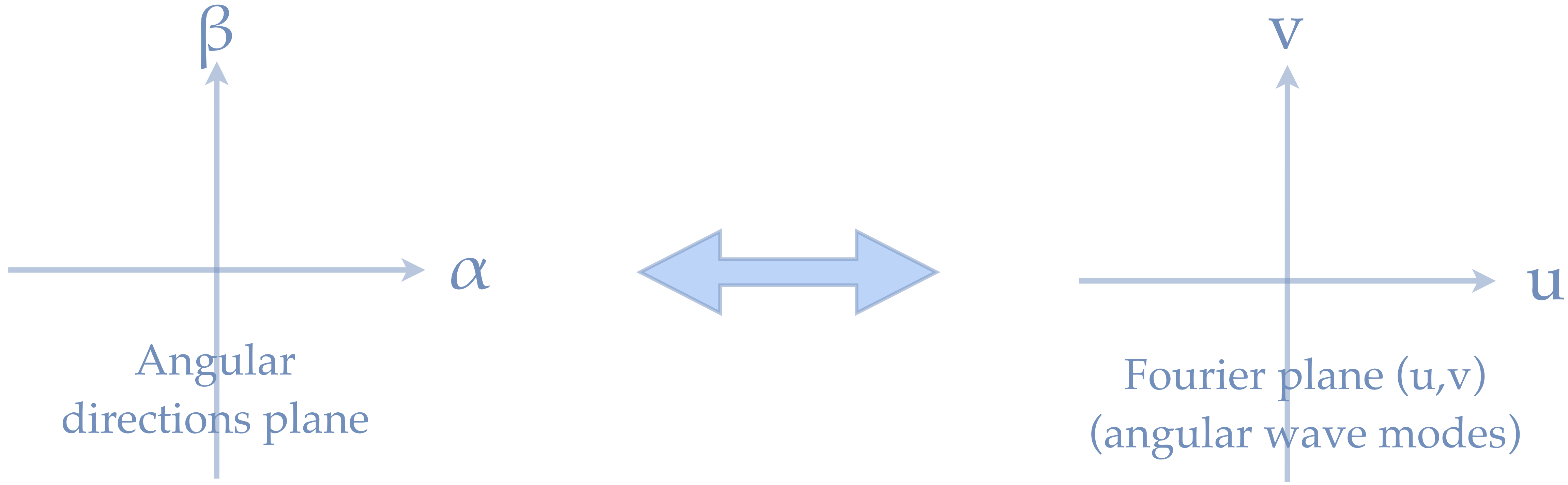
Sky signal **Antenna response**

Angular domain		Angular frequency (u,v) plane
$\hat{n} \rightarrow (\alpha,\beta)$	$\longrightarrow$	(u,v)
$I(\alpha,\beta,\nu)$	$\longrightarrow$	$\mathcal{I}((u,v),\nu)$
$L(\alpha,\beta,\nu)$	$\longrightarrow$	$\mathcal{L}((u,v),\nu)$

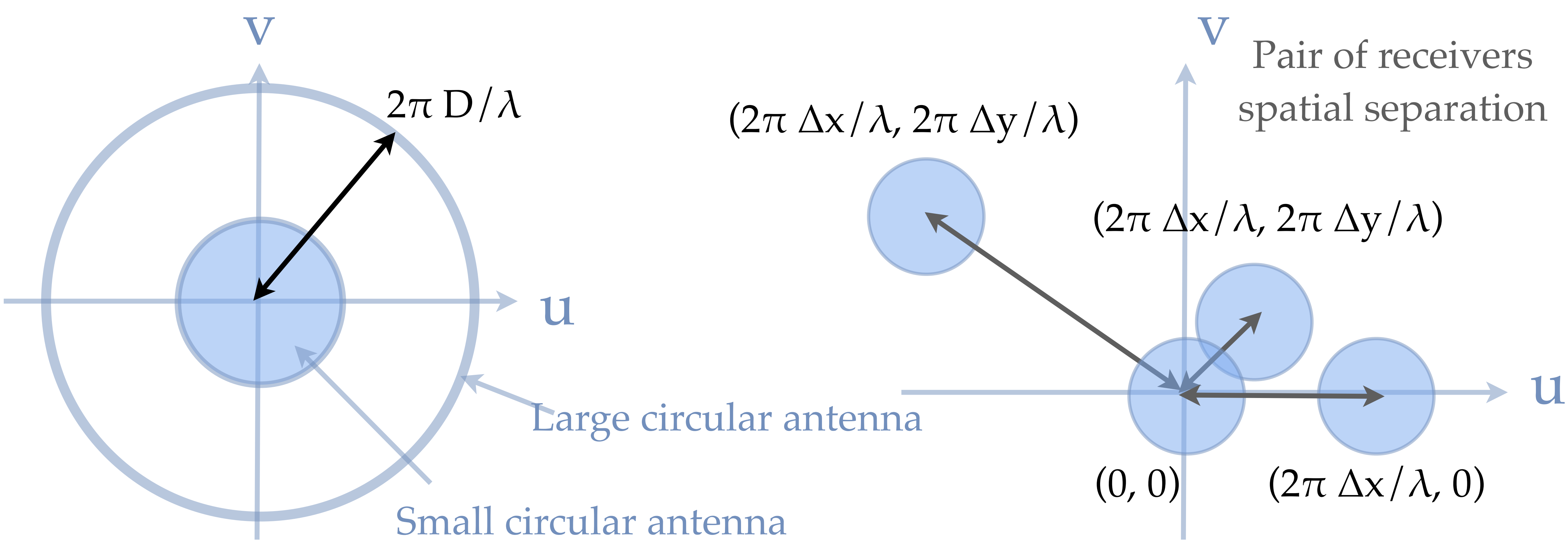
$$\mathcal{V}_{ij}(\nu \rightarrow \lambda) \simeq \iint dudv\, \mathcal{I}((u,v),\nu)\, \mathcal{L}(u - \frac{\Delta x_{ij}}{\lambda}, v - \frac{\Delta y_{ij}}{\lambda}, \nu)$$

A visibility corresponds approximately to a weighted measurement in the Fourier (u,v) plane

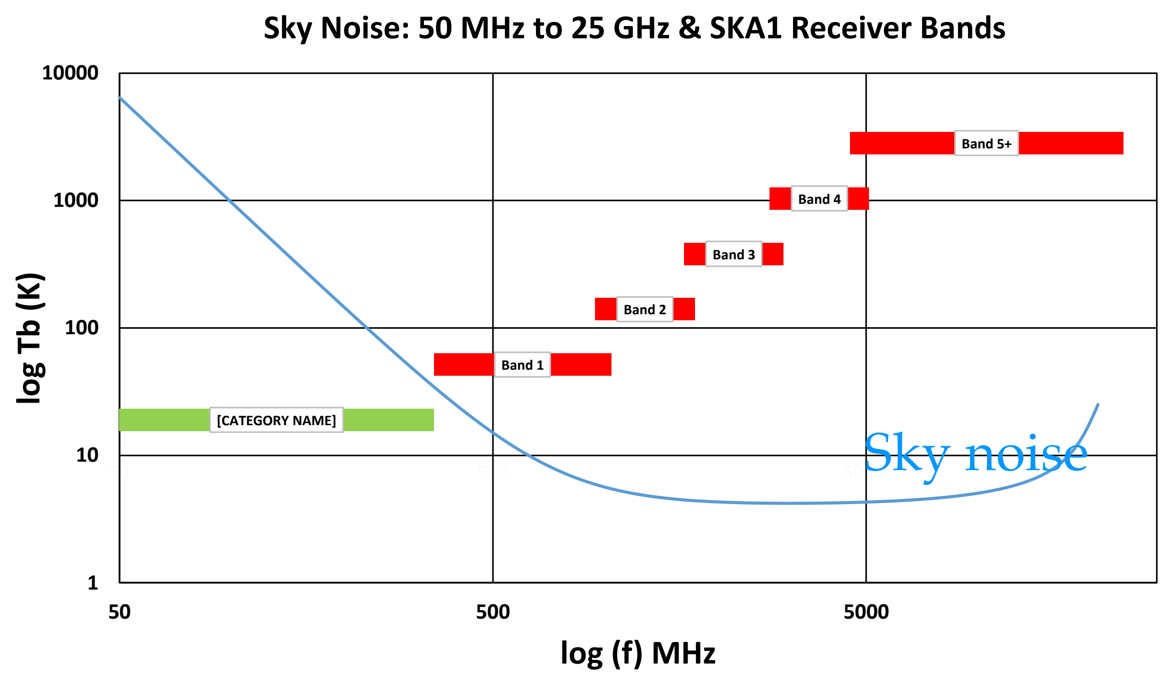
➠ **Use of FFT for map reconstruction, but the relation is not exact and (u,v) plane coverage is incomplete**

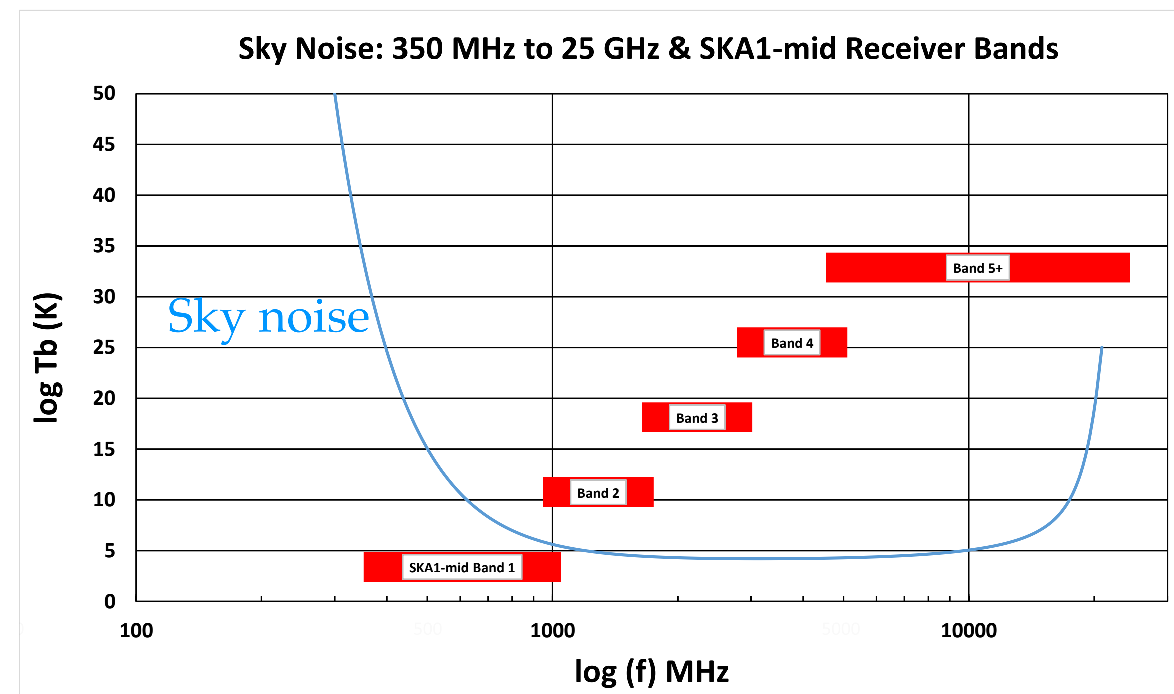


(u,v) plane response

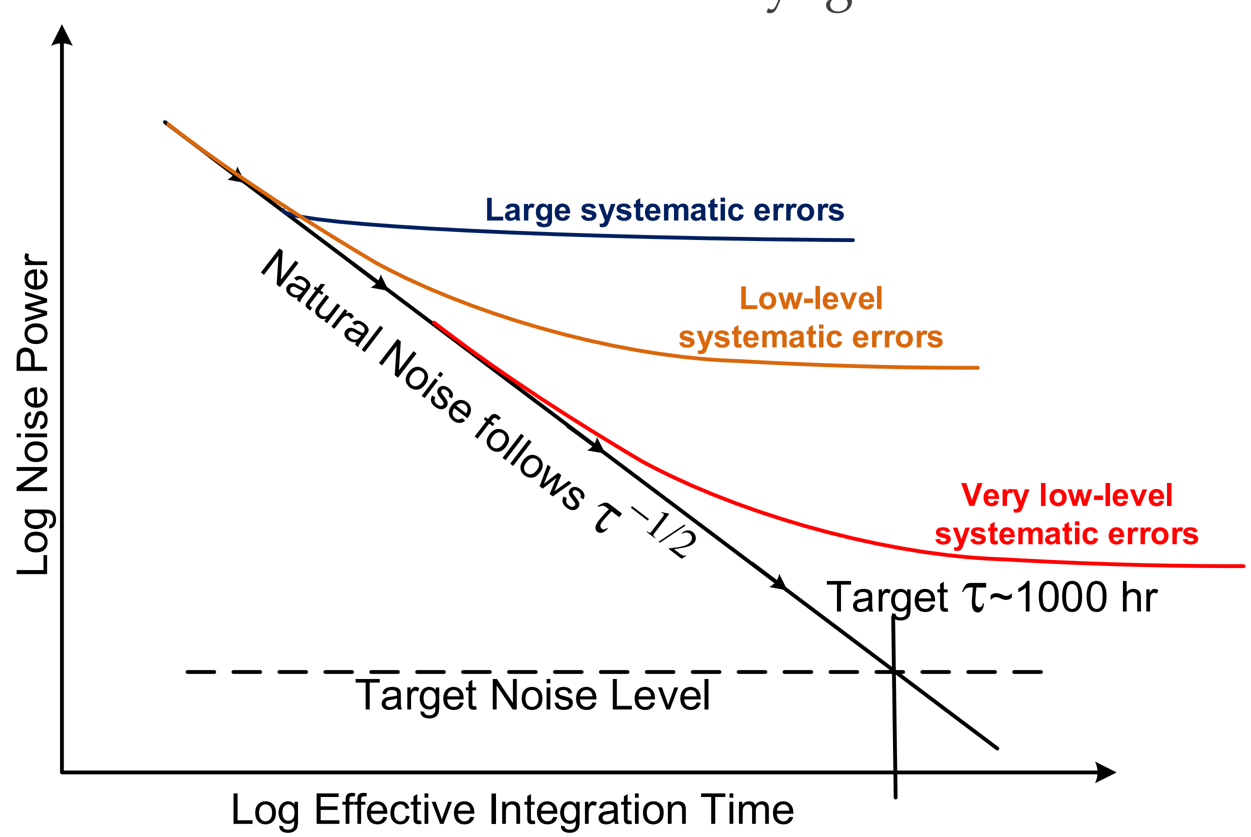


SKA bands , noise level





➠ Cryogenic receivers for SKA-Mid



Systematic errors are the limits, as often

SKA-I system design baseline V2 report , *P. Dewdney* (2016)

https://www.skao.int/sites/default/files/documents/d1-SKA-TEL-SKO-0000002_03_SKA1SystemBaselineDesignV2_1.pdf

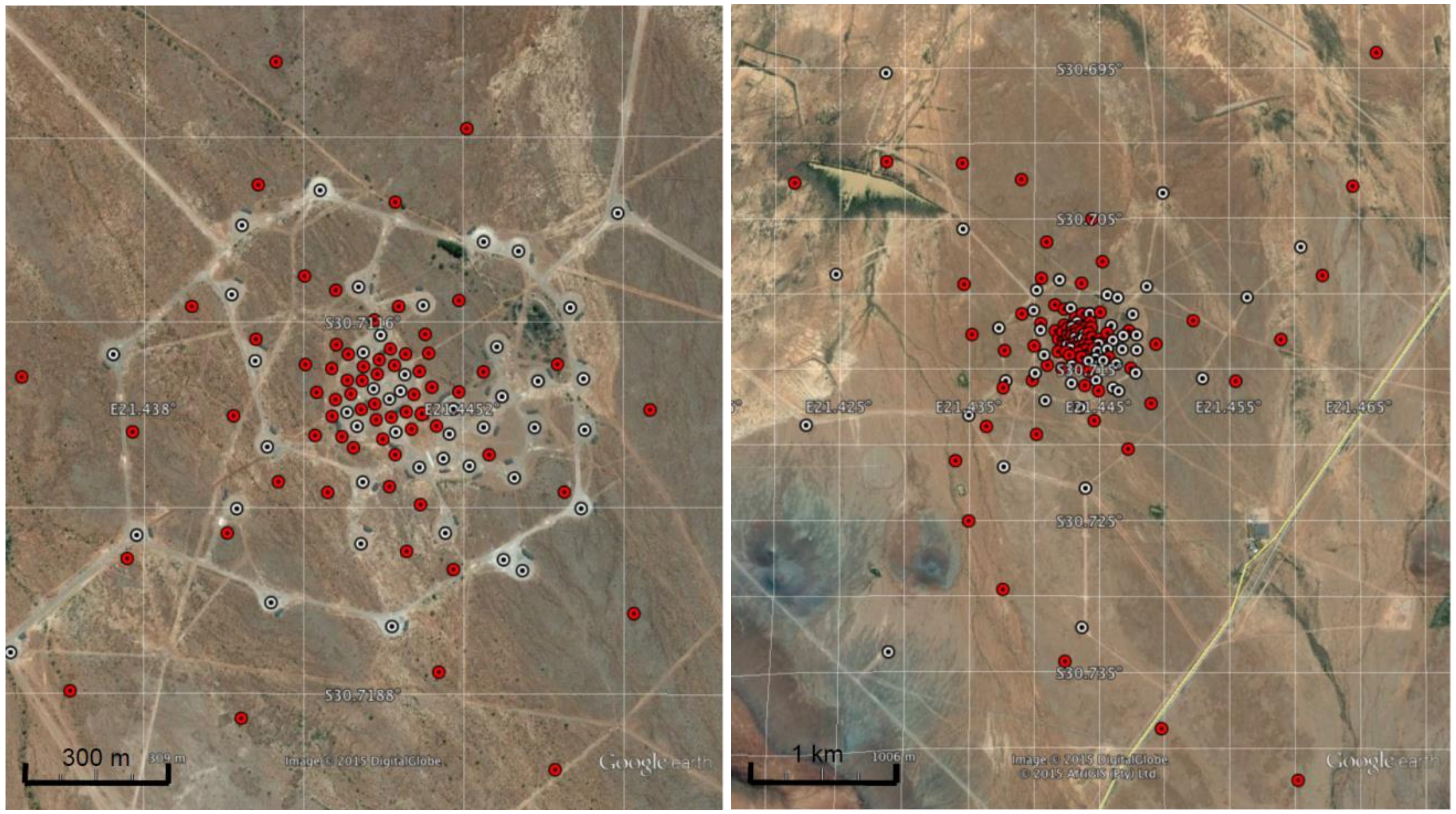


Figure 11: Location of SKA1-mid dishes (red dots) on the ground in the central area of the Karoo SKA site at two different scales

The black and white circles show the location of the MeerKAT antennas. The background is from Google Earth.

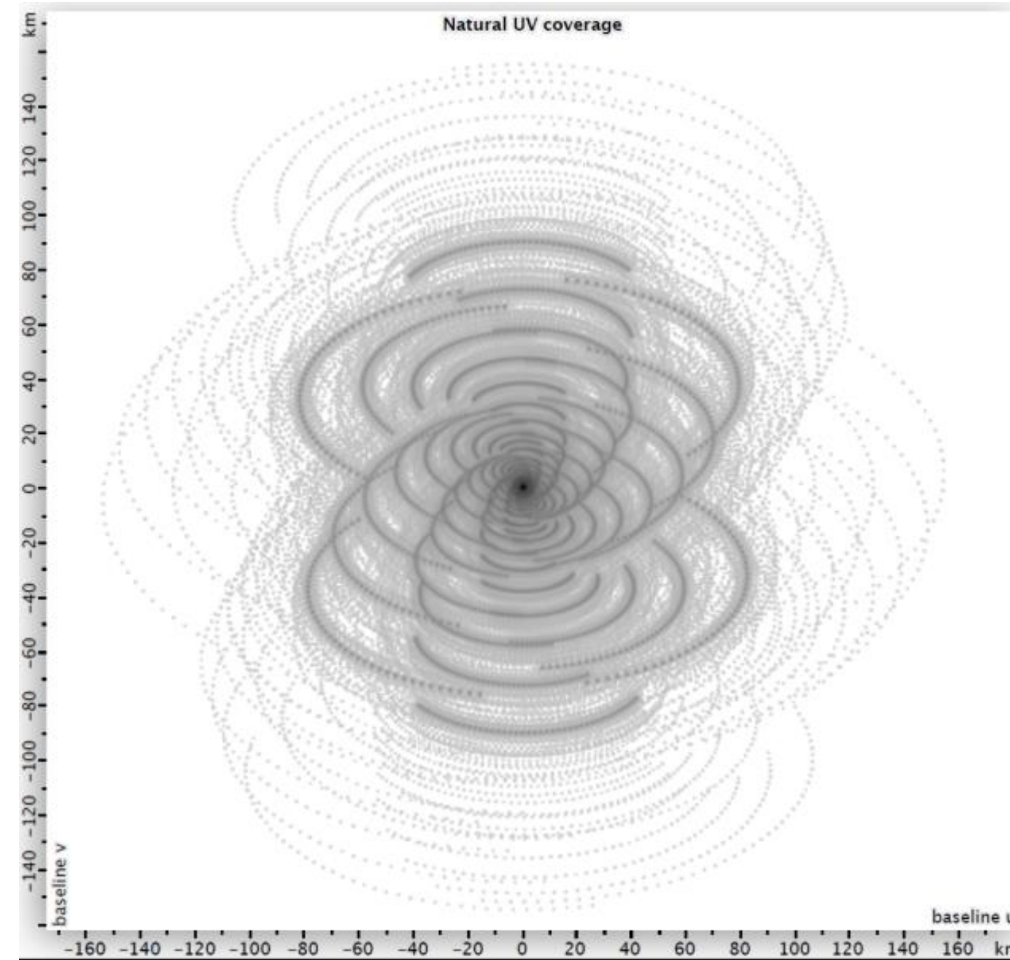


Figure 10: Naturally-weighted u-v coverage of SKA1-mid for an 8 hour track at Declination -30deg, using only a single frequency channel

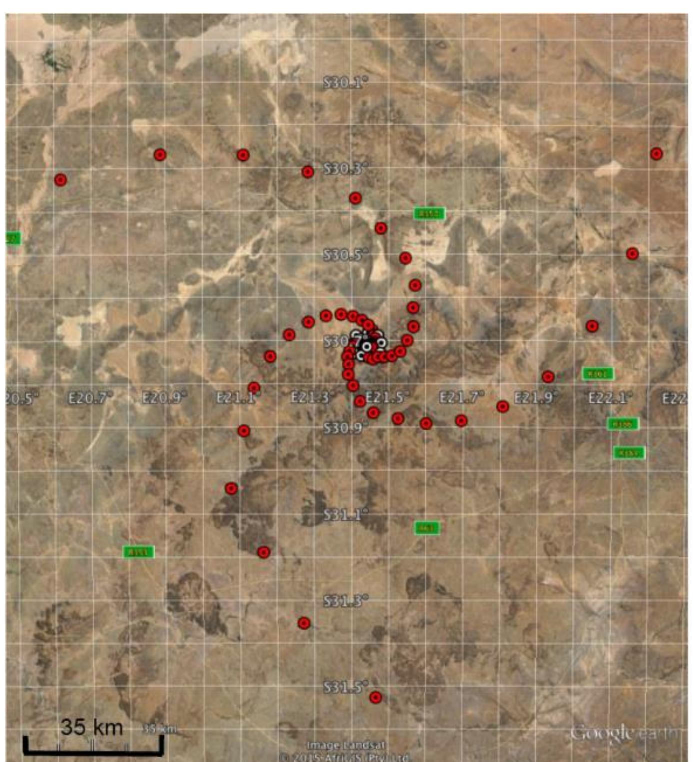


Figure 12: Location of entire SKA1-mid antenna array on the ground

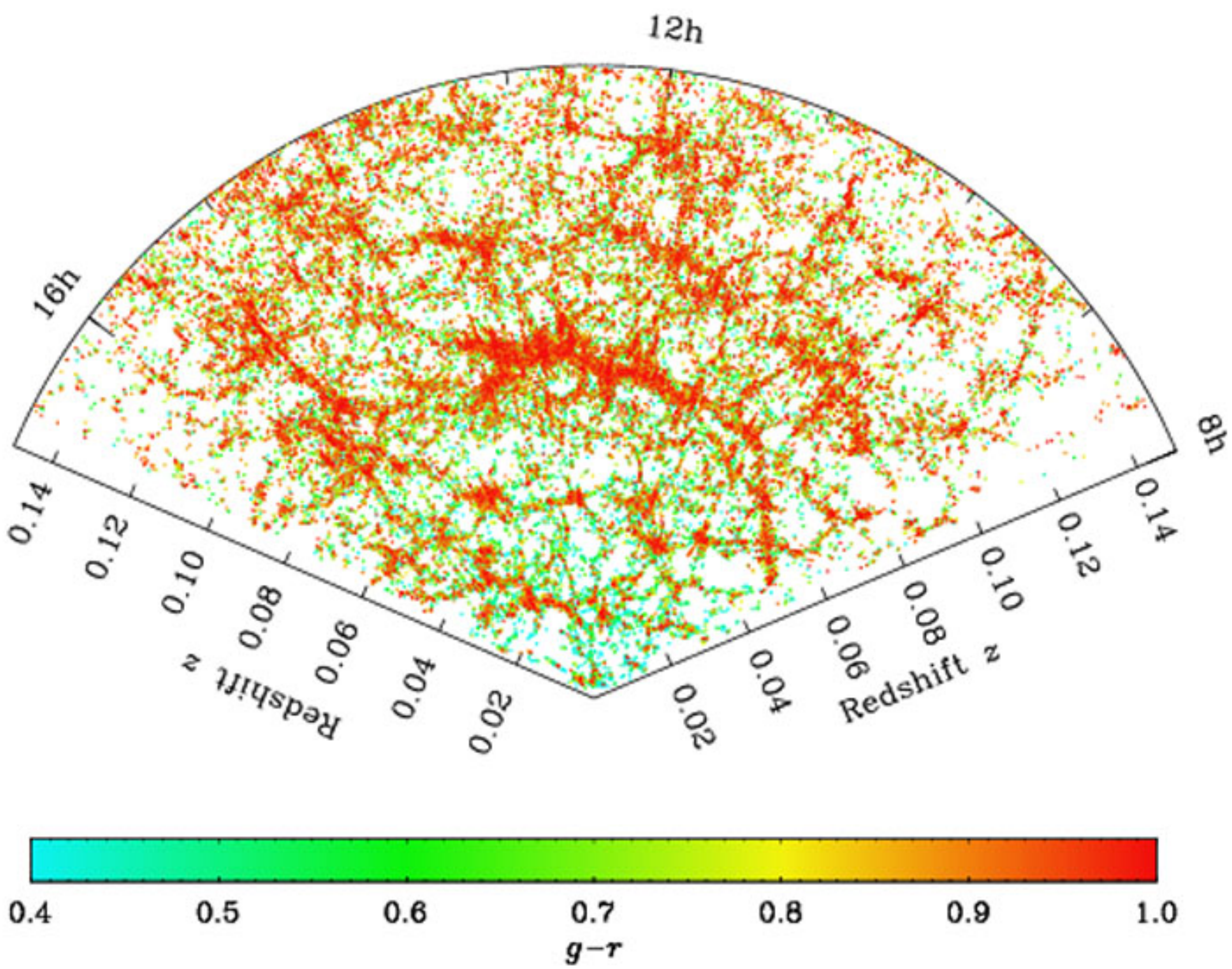
SKA-1 configuration

SKA-1 system design baseline V2 report , *P. Dewdney* (2016)

https://www.skao.int/sites/default/files/documents/d1-SKA-TEL-SKO-0000002_03_SKA1SystemBaselineDesignV2_1.pdf

Cosmology with H_I redshift survey

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

Optical surveys:
SDSS - DES -
LSST - Euclid - DESI …

- Supernovae (SN)
- Galaxy Clusters (CL)
- Weak Lensing (WL) — **SKA**
- Galaxy clustering (LSS / GC)
- BAO → $d_A(z)$, $H(z)$
- BAO/RSD — **21cm IM**
- …

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

A galaxy at z=0.3 , D_L =1500 Mpc

- 21 cm Radio emission
  - 10^9 $M_\odot$ de H_I → 3 10^{27} watts (total emitted power)
  - Received power ≲ 10^{-24} W/m² spread over ~ 1 MHz (few photons / m^2 /s)
  - ≲ (10^{-30} W/m²/Hz = 100 μ Jy)

Jansky : $1\text{Jy} = 10^{-26}\ \text{W/Hz/m}^2$

- Optical / visible light
  - 10^9 - 10^{10} $L_\odot$ → ≳ 10^{35} watts (total emitted power)
  - Received power ≲ 10^{-16} W/m²
  - Or 10^{-17} W/m² in given photometric band (~ 10 photons / m²/s)

21cm signal from a H_I rich galaxy at cosmological distances

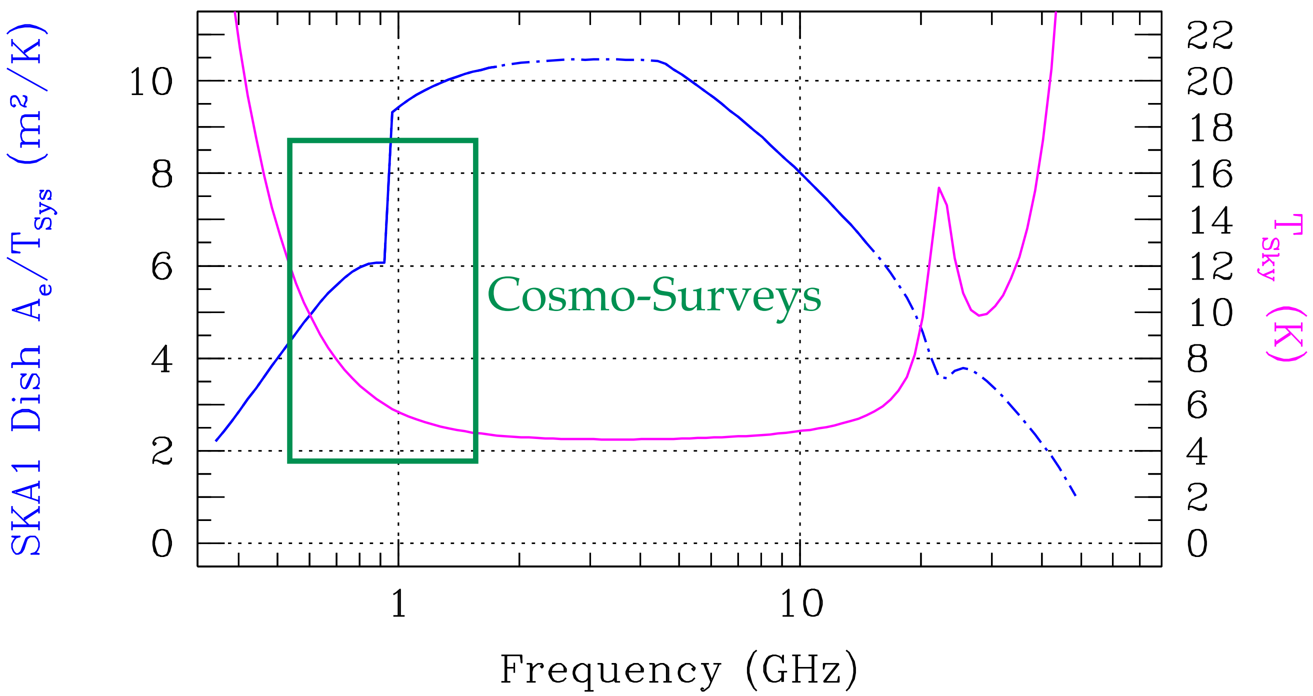
A (m²)	Tsys (K)	S_{lim} (μJy)
5000	50	66
5000	25	33
100000	50	3,5
100000	25	1,7

S_* in μJy for :
$t_{integ} = 24\,\text{hours}\ \delta\nu = 1\,\text{MHz}$

z	S_{21} (μJy)
0,25	175
0,5	40
1	9,6
1,5	3,5
2	2,5

S_{21} in μJy for $10^{10}\ M_\odot$

SKA1 single dish sensitivity A_e/T_{sys}



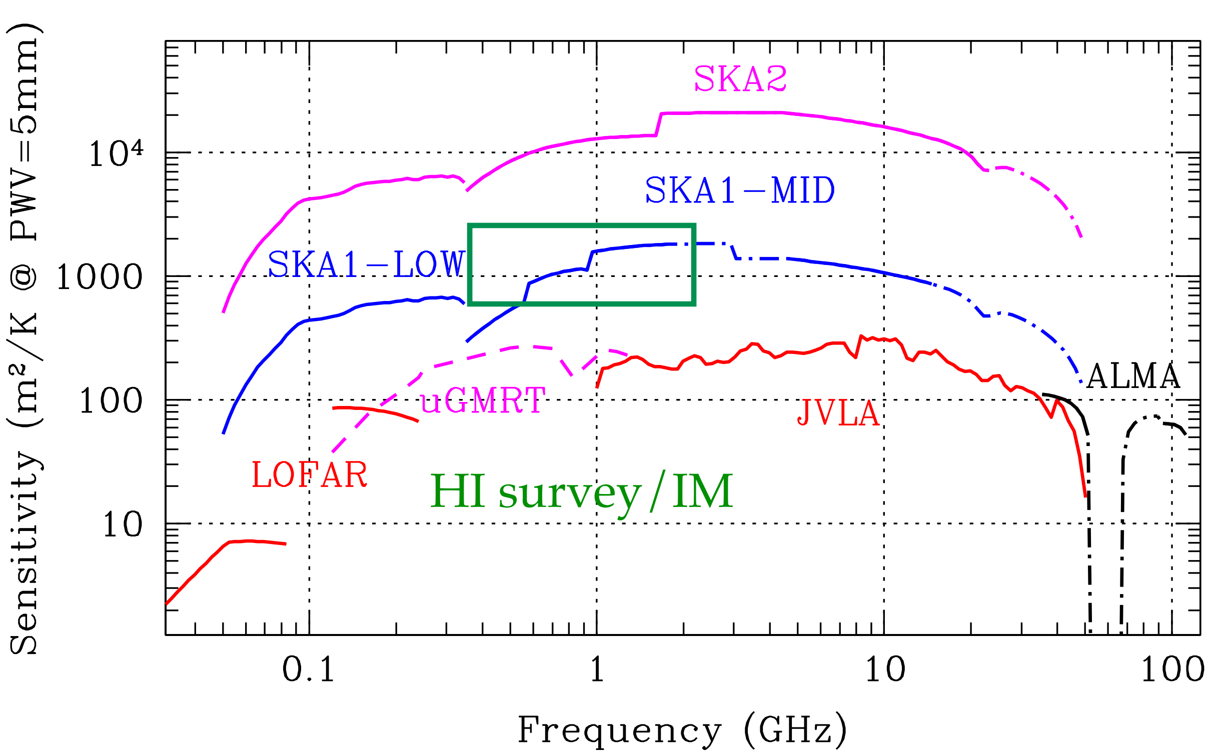
$$S_{\rm lim} \propto \frac{T_{\rm sys}}{A_e} \frac{1}{\sqrt{t_{\rm int}\delta\nu}}$$

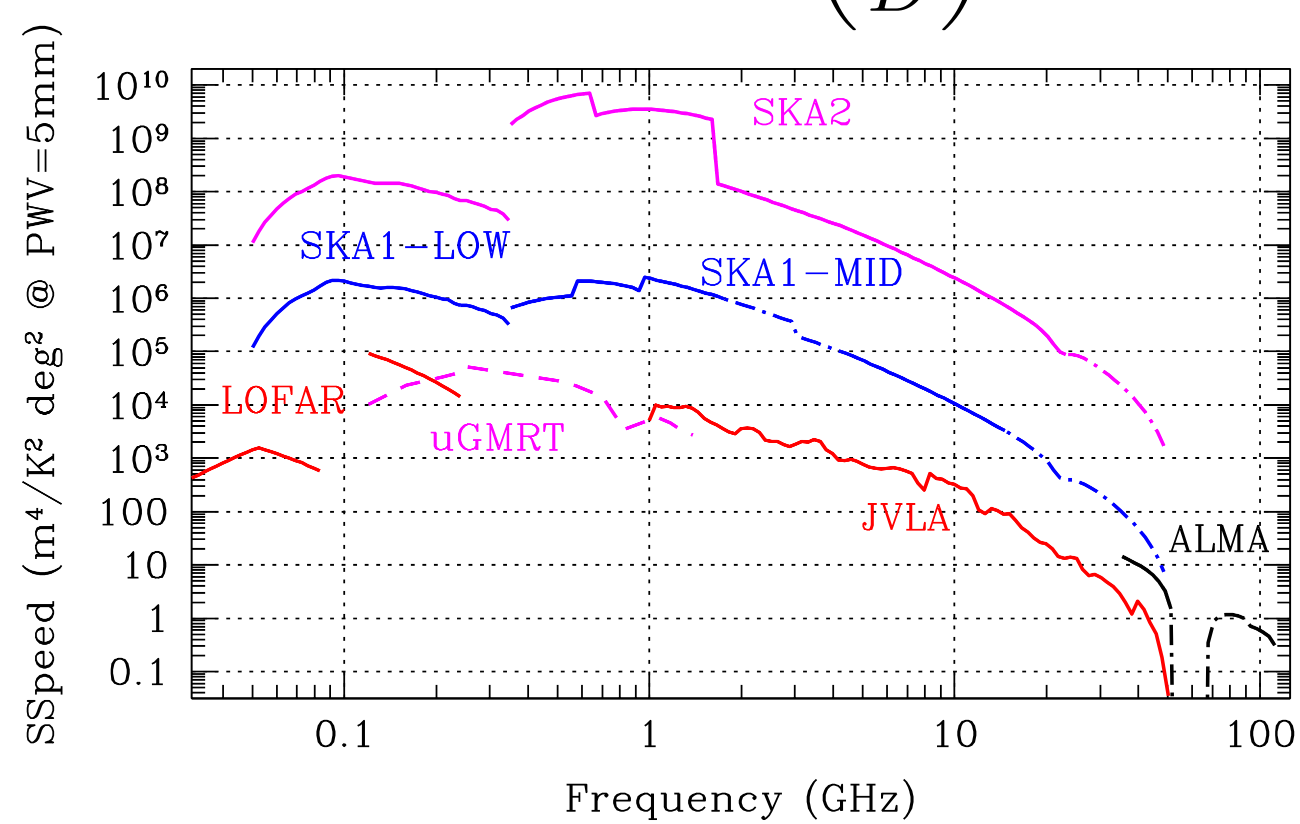
$$\rightarrow t_{\rm int} \propto \left(\frac{A_e}{T_{\rm sys}}\right)^2$$

Survey Speed Figure of Merit SS_{FoM}

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

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





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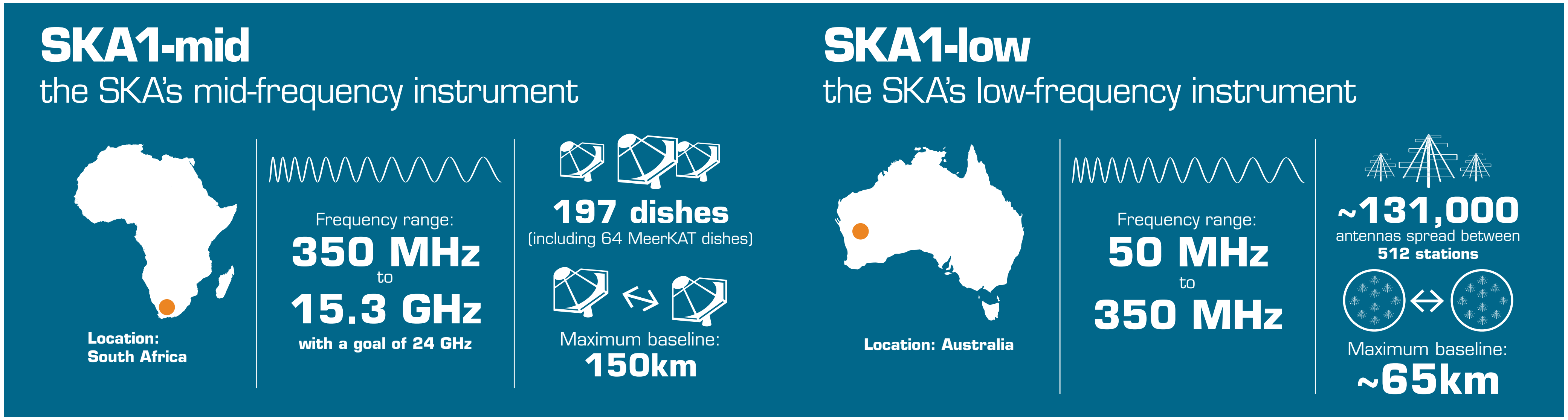
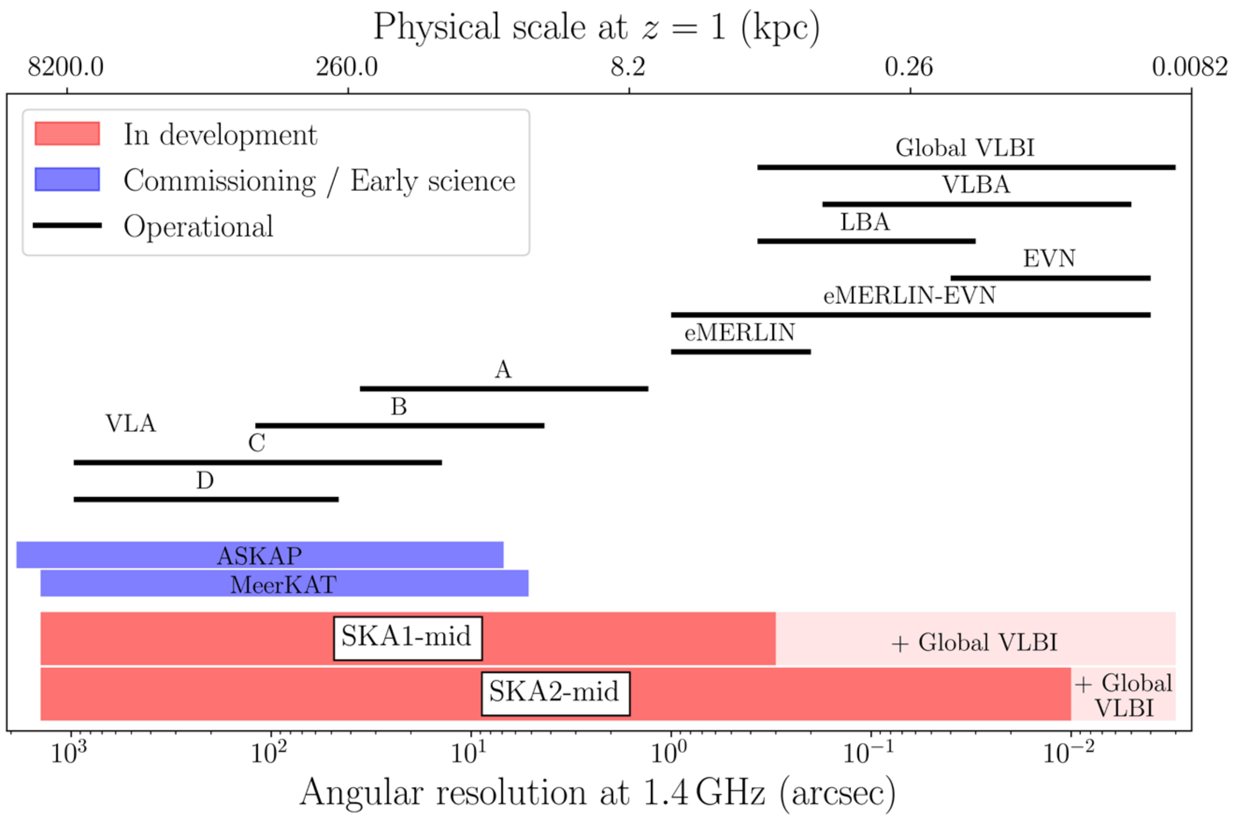
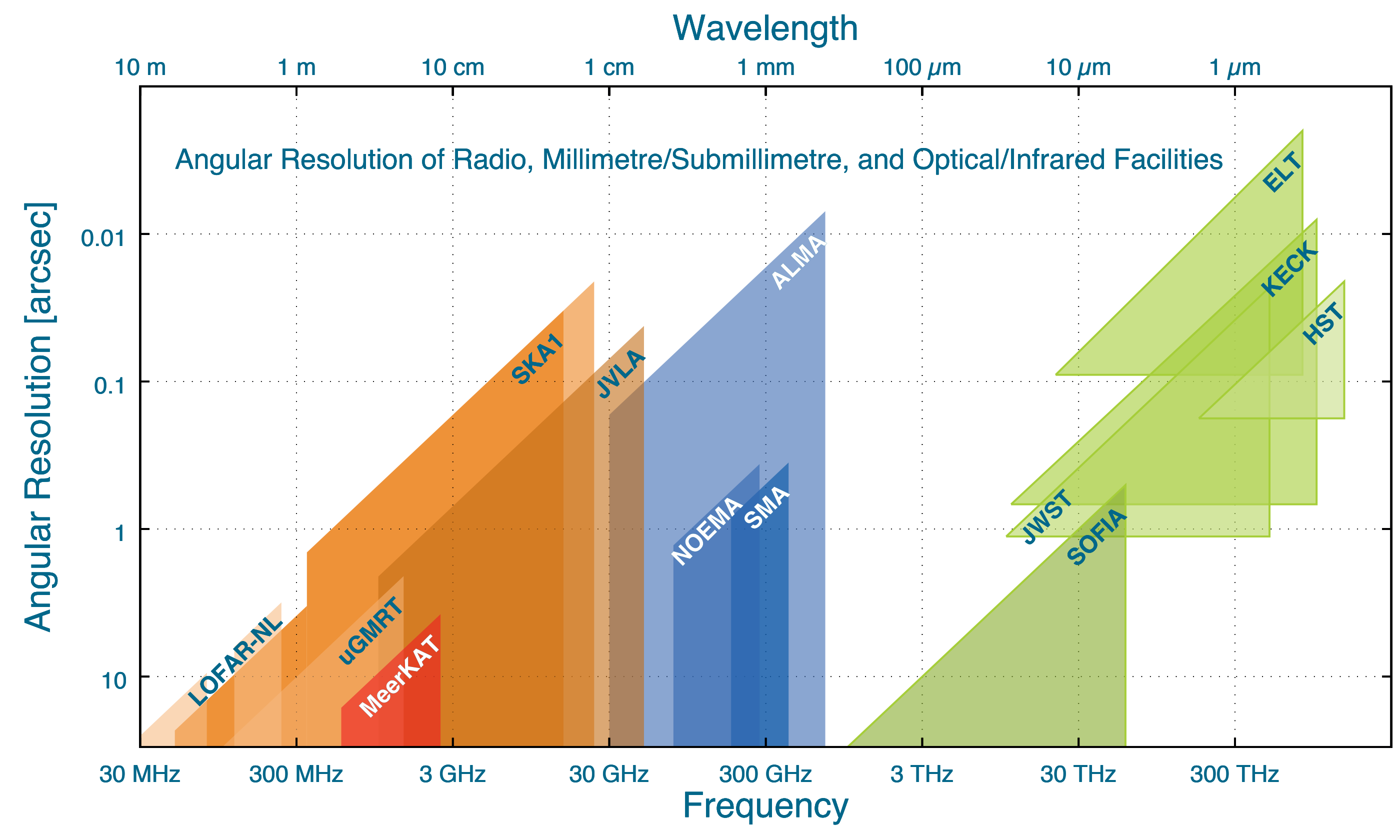






SKA-Observatory (Square Kilometer Array) https://www.skatelescope.org/

SKA HI galaxy redshift survey

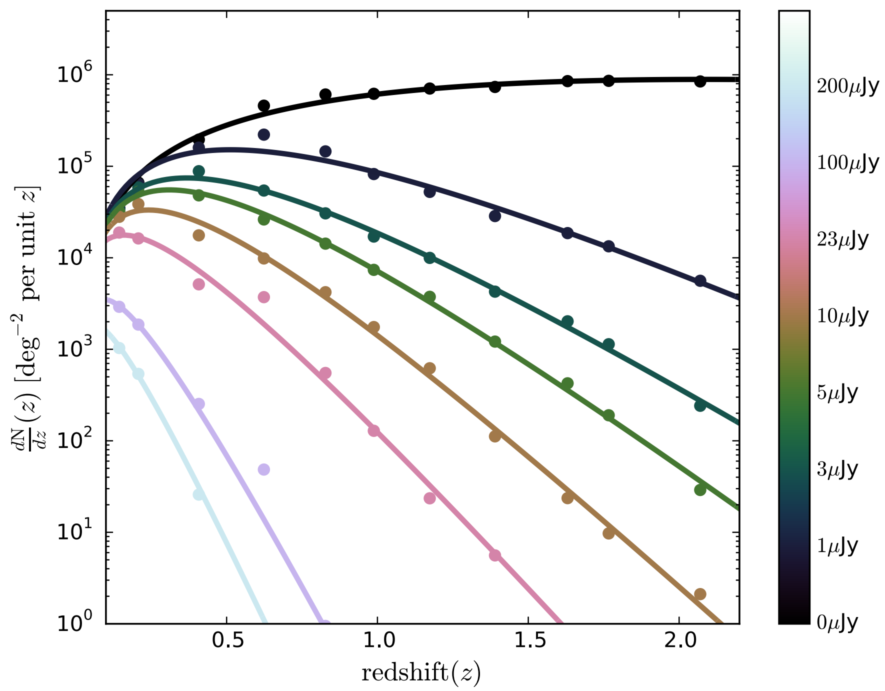
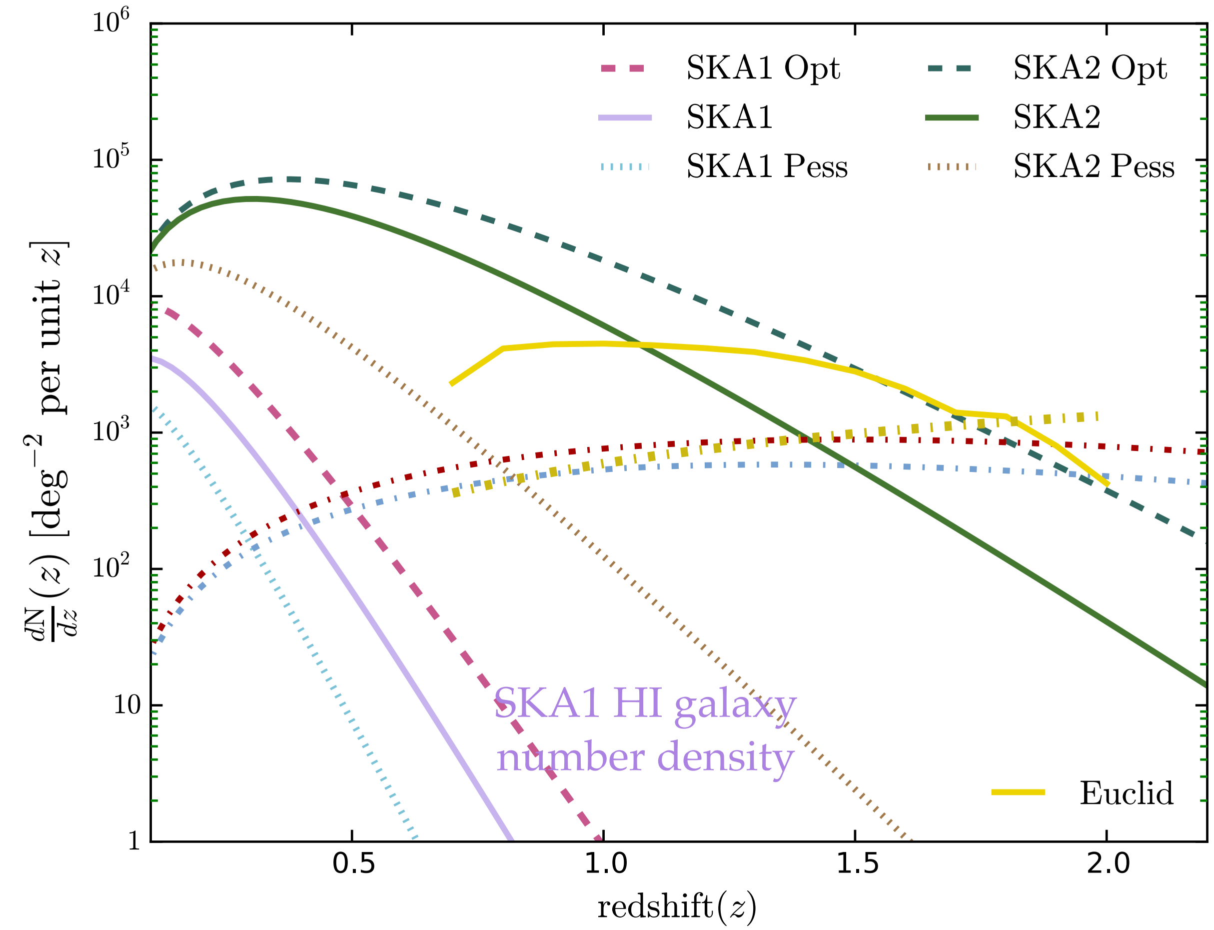
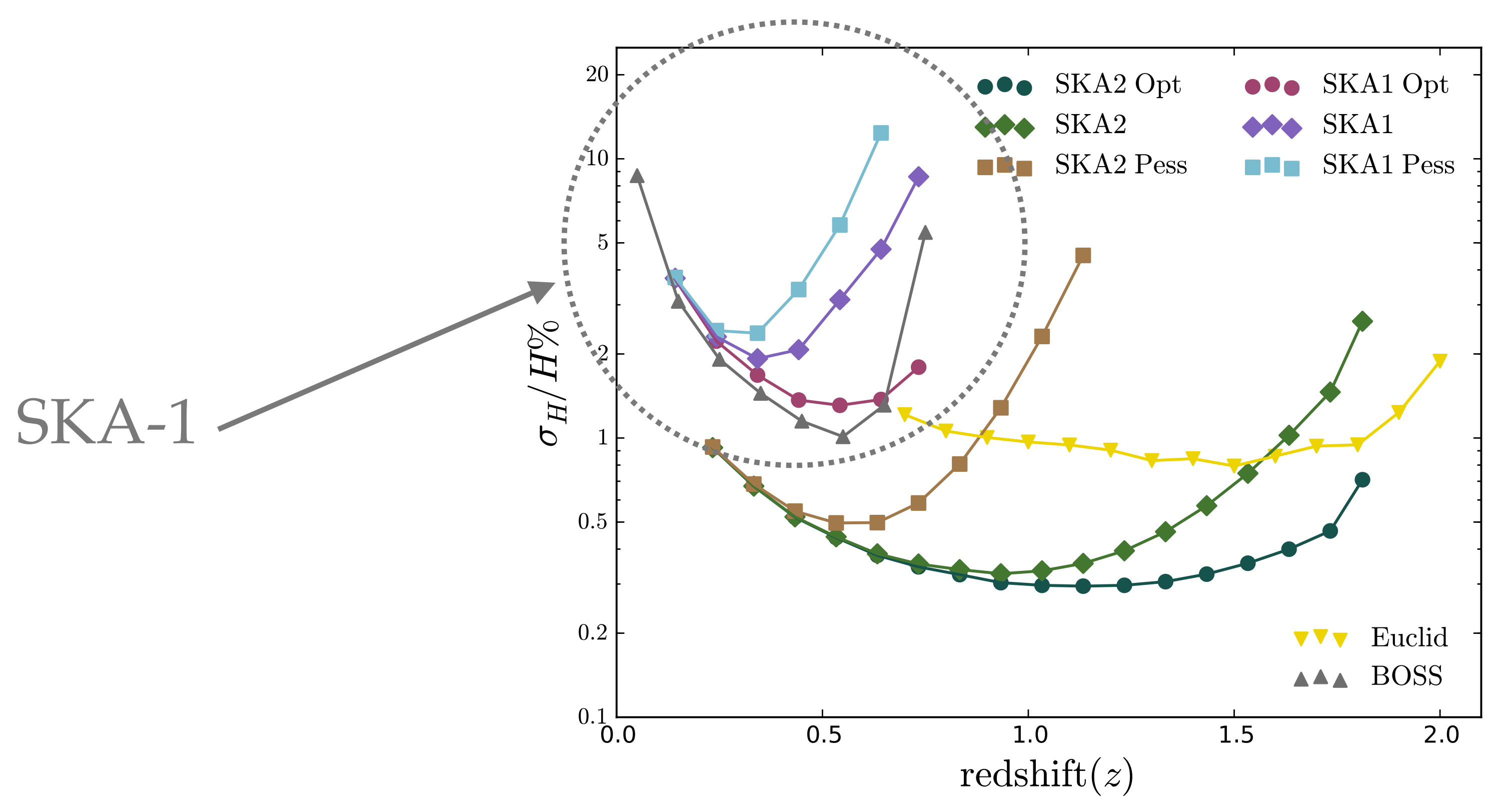


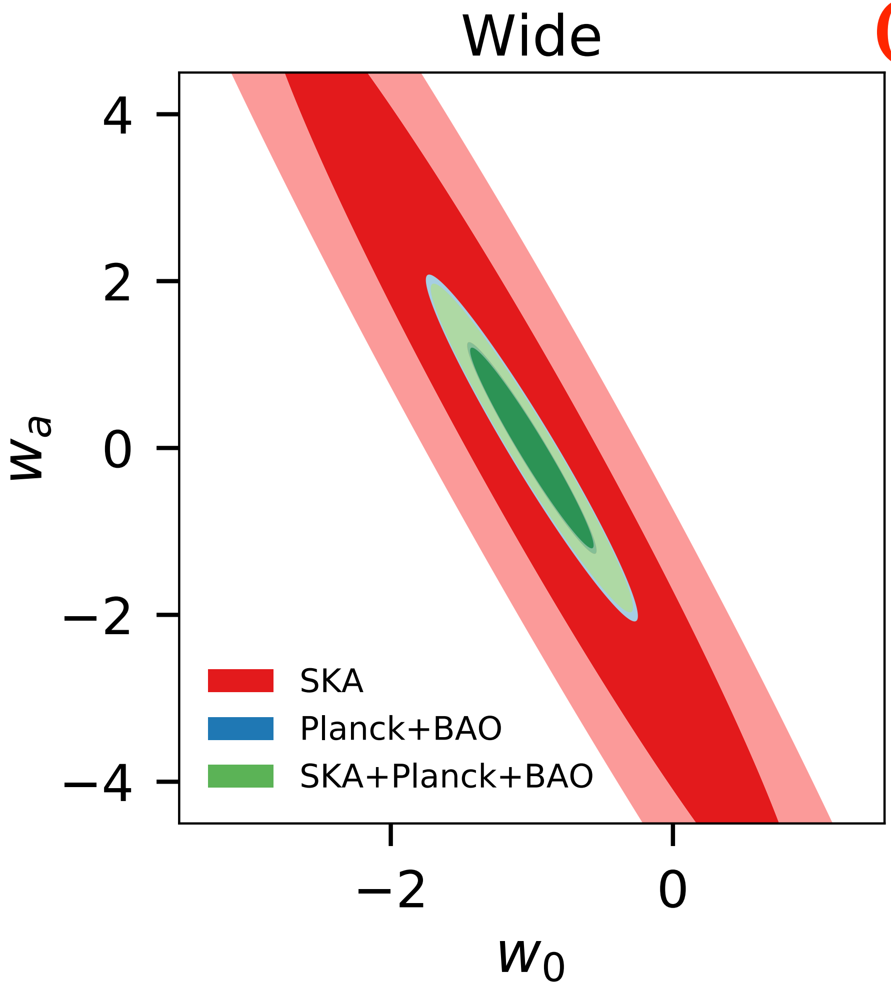
Figure 2. H I galaxy redshift distribution, dN/dz, calculated from simulations (filled circles) and the corresponding fitting function, equation (5). From top to bottom, the curves shown correspond to flux sensitivities $S_{\rm rms}$ = (0, 1, 3, 5, 10, 23, 100, 200) μJy (colour-coded according to the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





https://arxiv.org/abs/1412.4700

Constraints on DE and MG from SKA1 (forecasts)



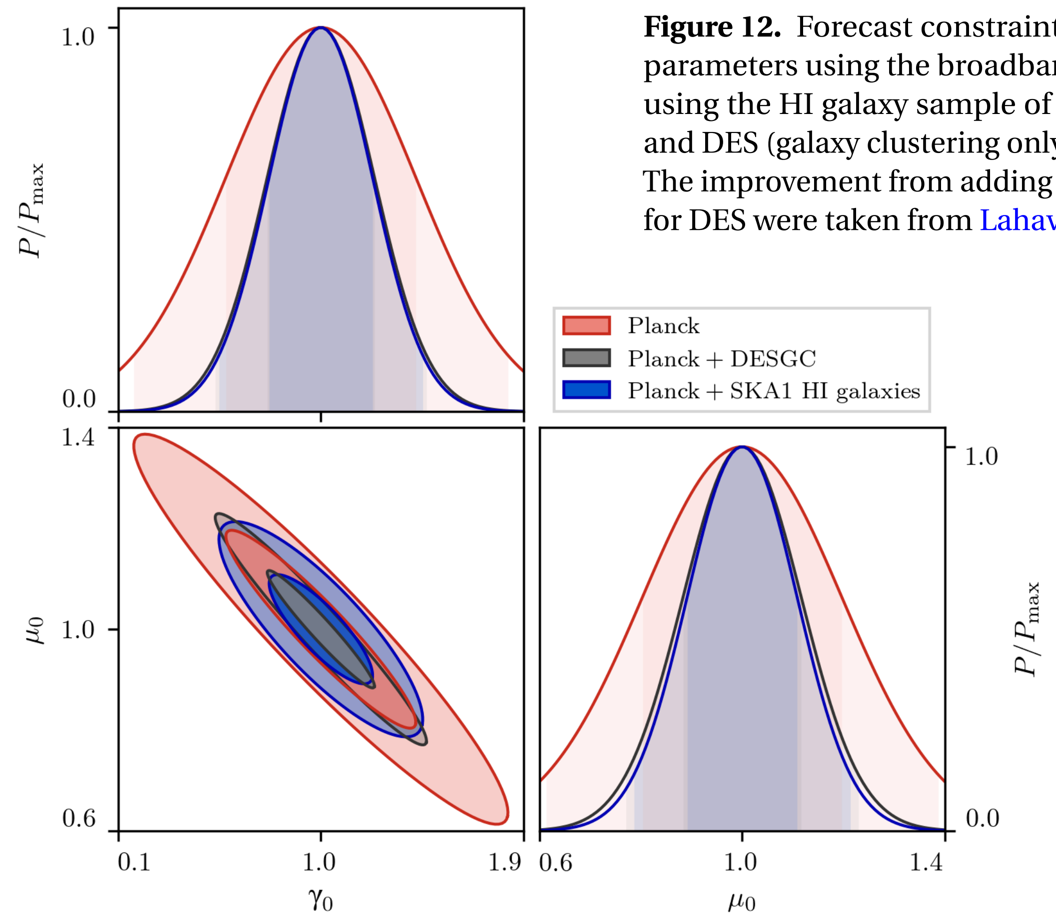
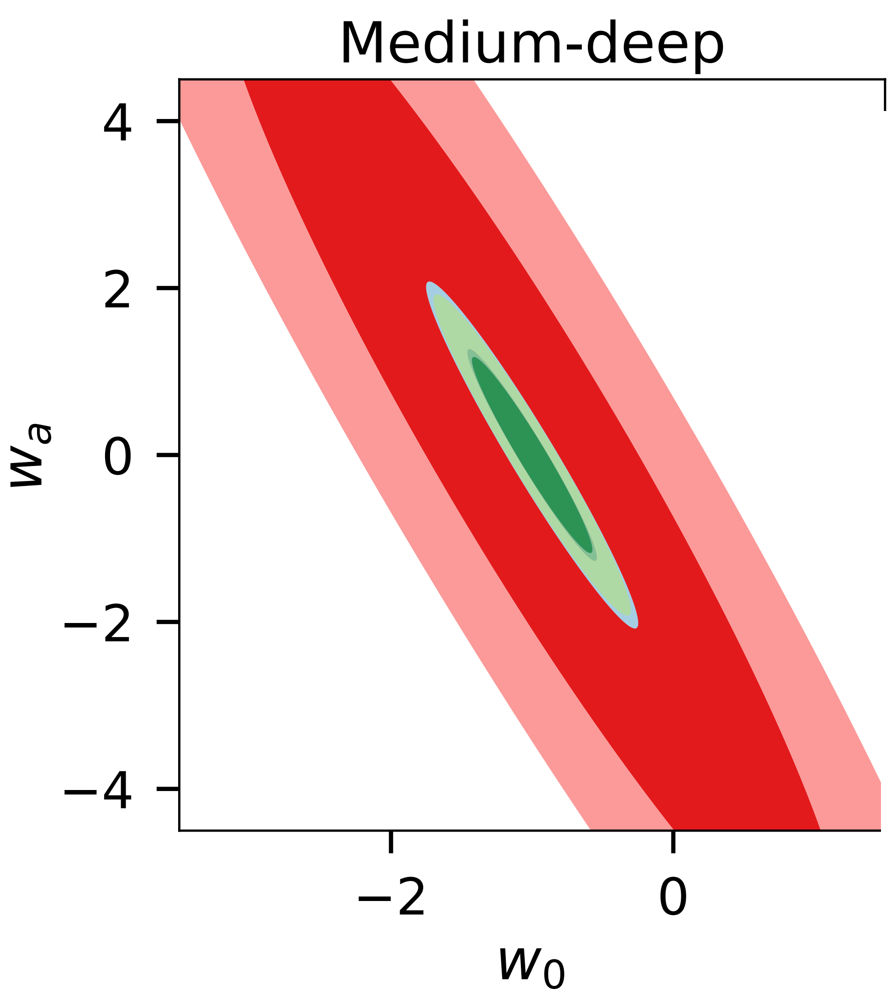
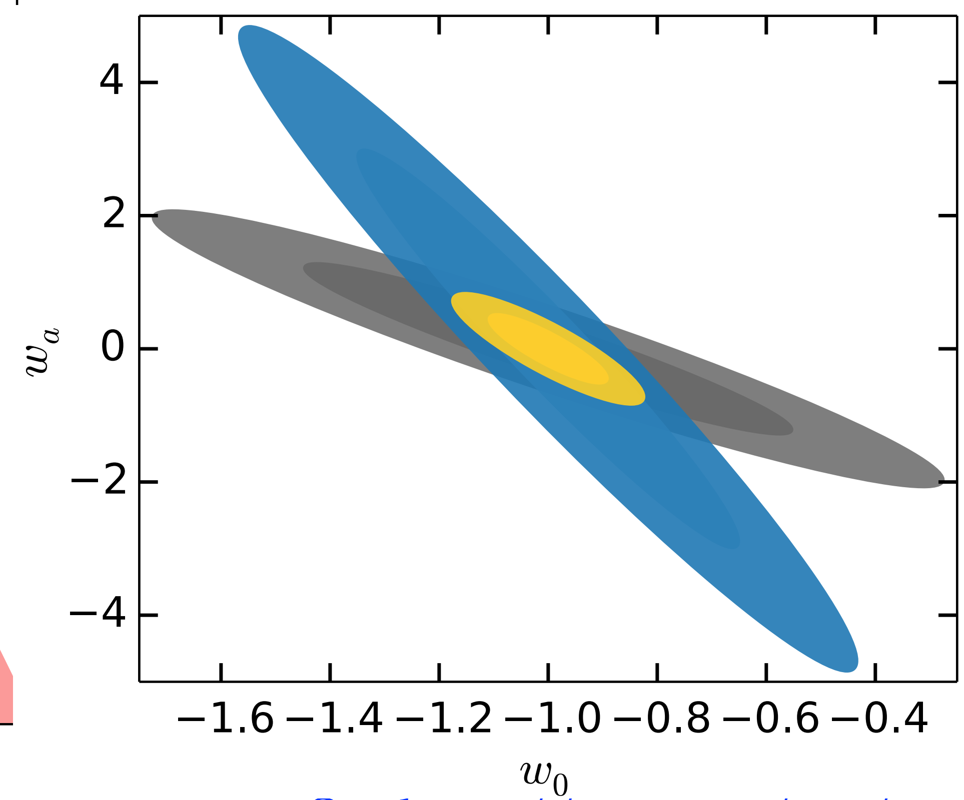


Figure 12. Forecast constraints on phenomenological modified gravity parameters using the broadband shape of the power spectrum, detected using the HI galaxy sample of the *Medium-Deep Band 2 Survey*. *Planck* and DES (galaxy clustering only) constraints are included for comparison. The improvement from 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).

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

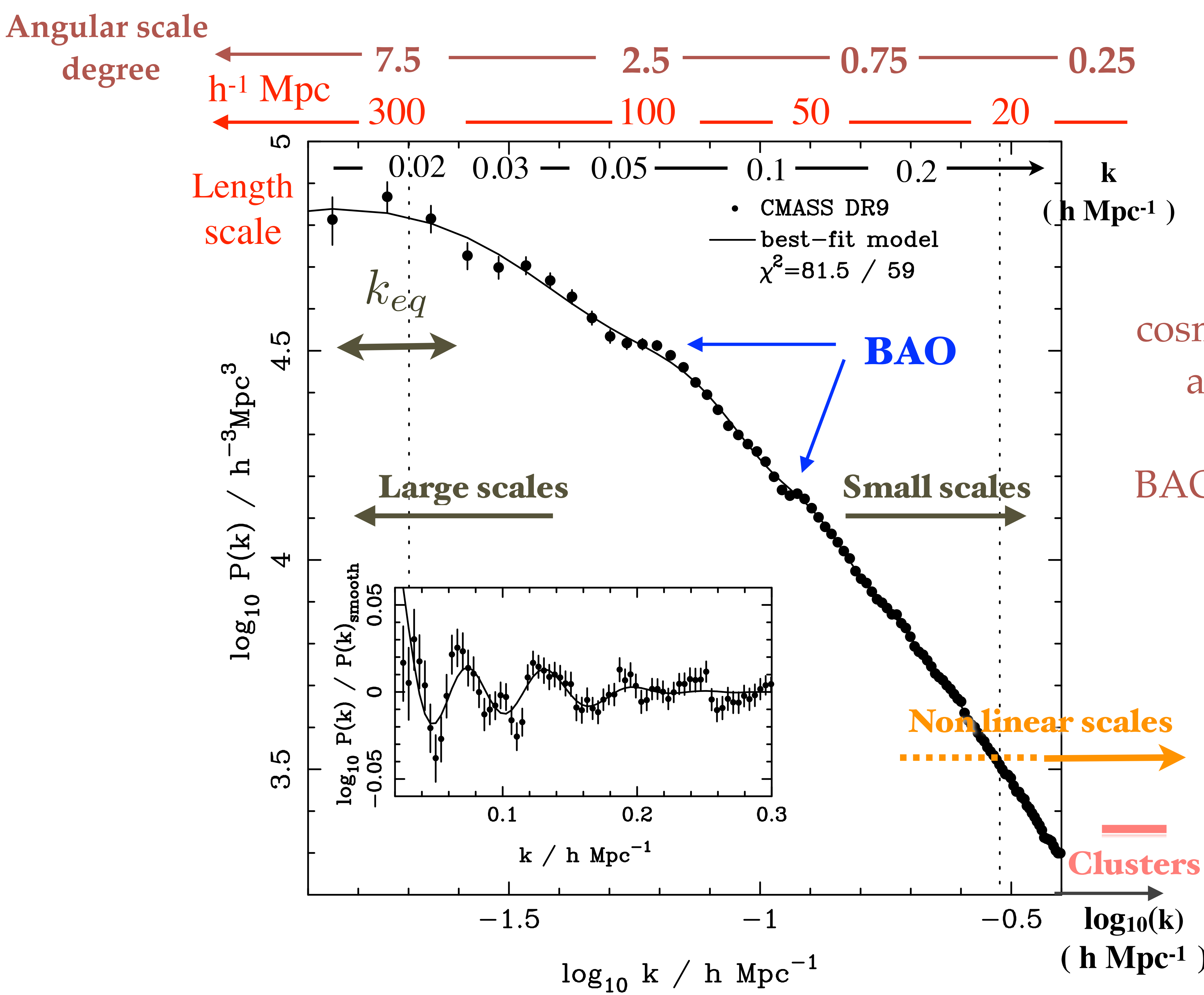
See https://arxiv.org/abs/1811.02743 and its reference list

Post EoR
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

LSS : Power spectrum and different scales



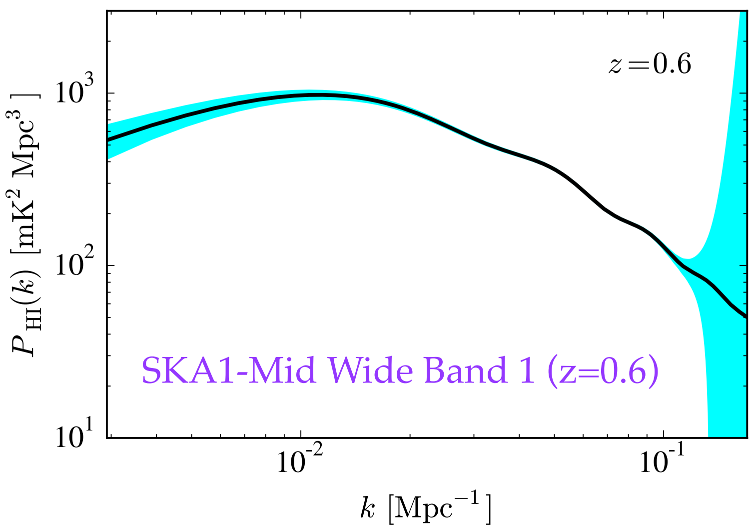
Most of the LSS cosmological information at scales larger than few arc minutes

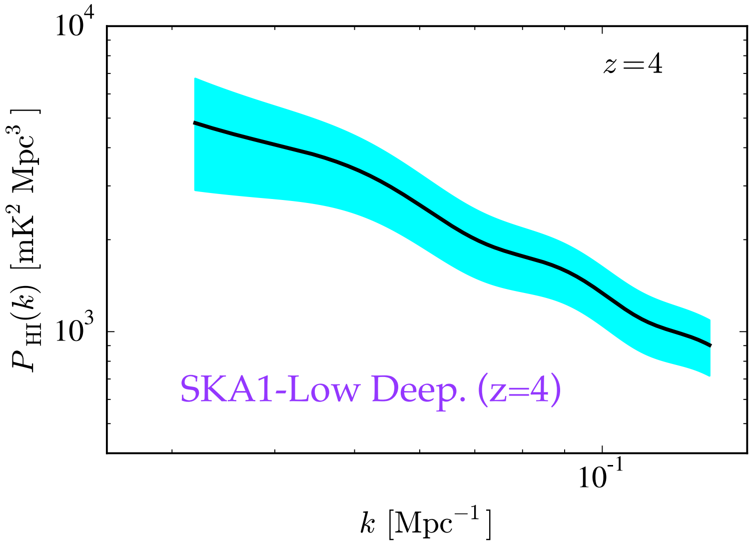
BAO: 0.5 to a few degrees

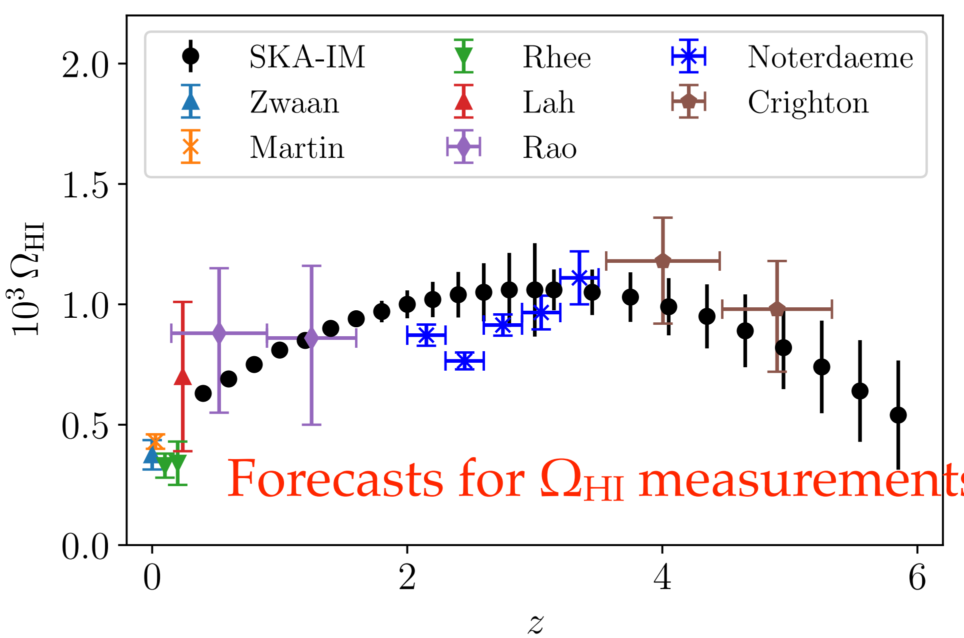
SDSS-DR9 , Anderson et al et al. 2012, arXiv:1203.6594

Constraints on Cosmology from SKA-1 IM survey

HI auto-correlation P(k) from SKA1 IM

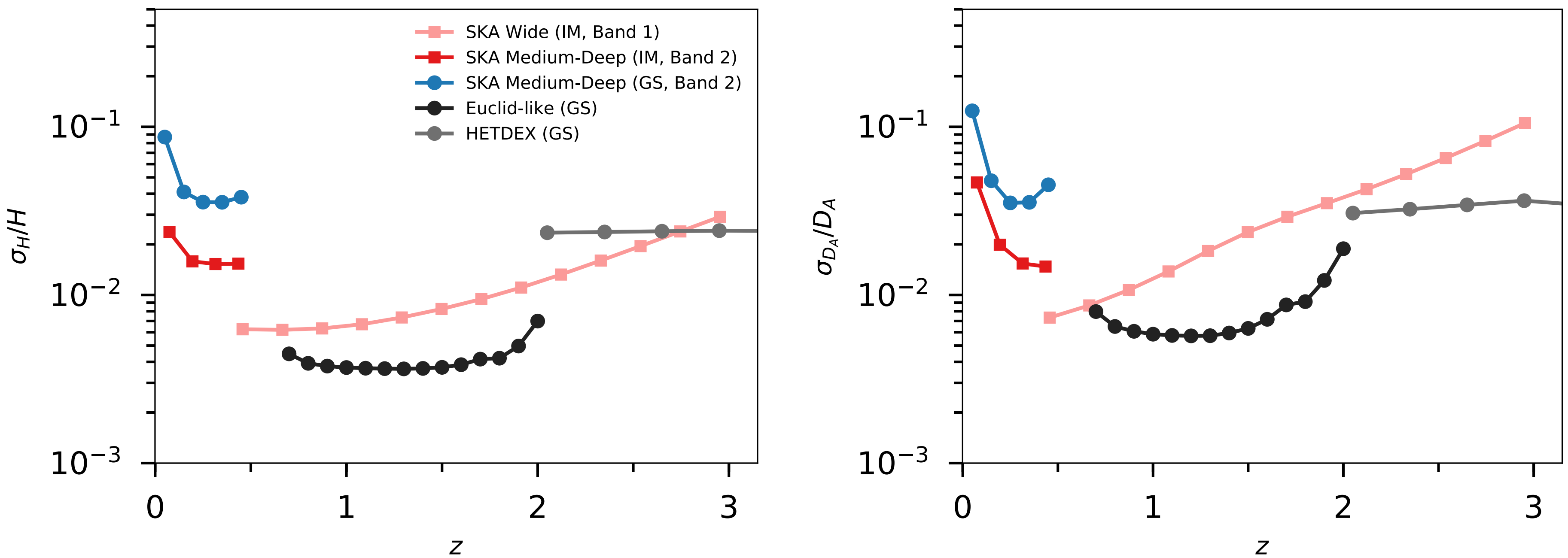


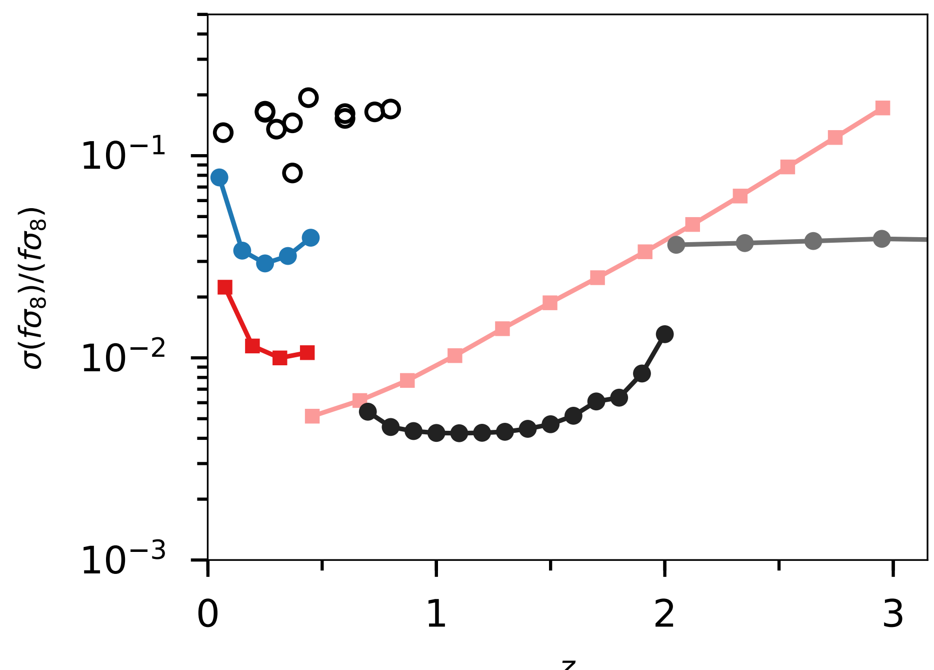




Forecasts for Ω_{HI} measurements

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

The price to pay …

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)

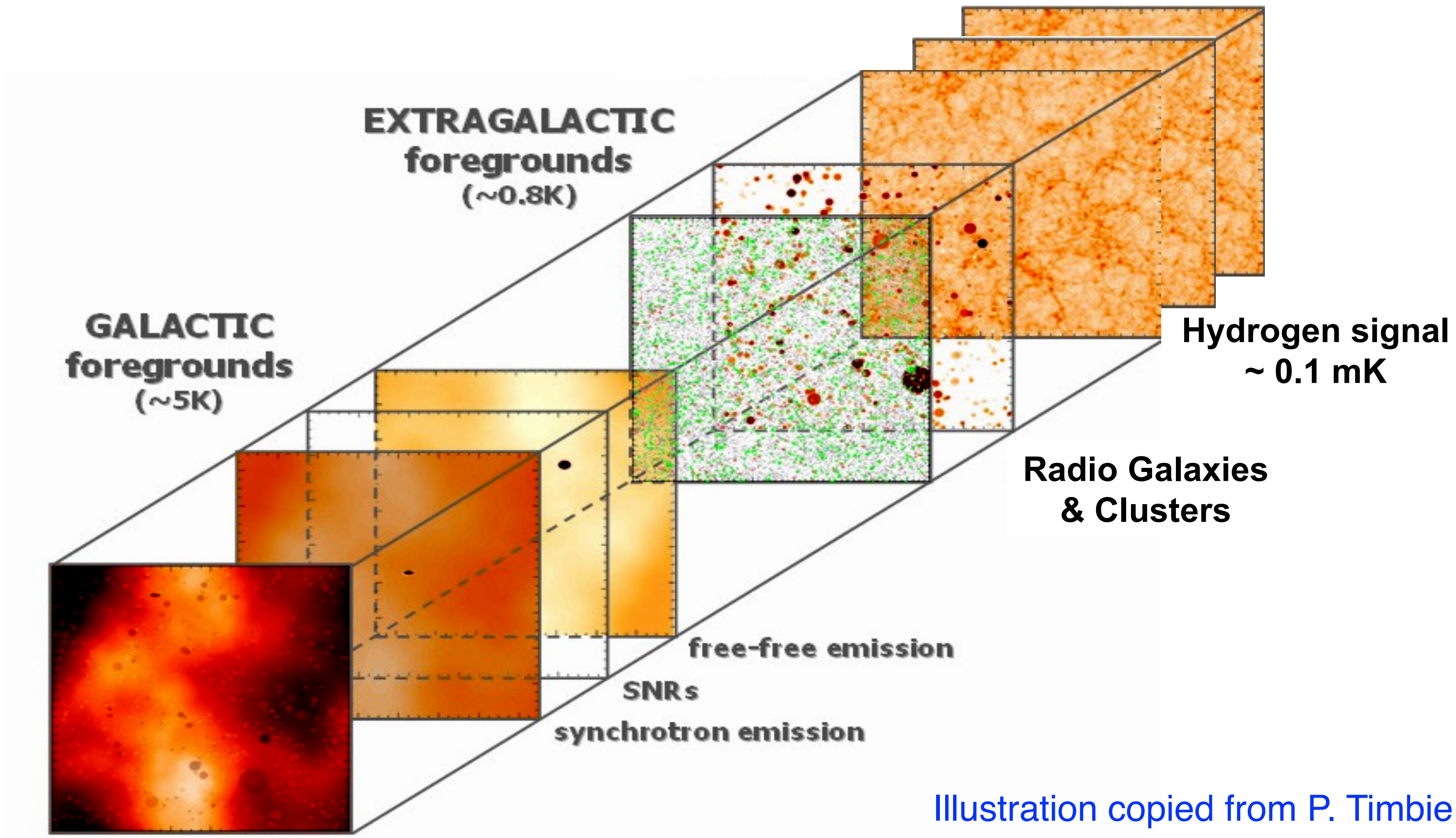
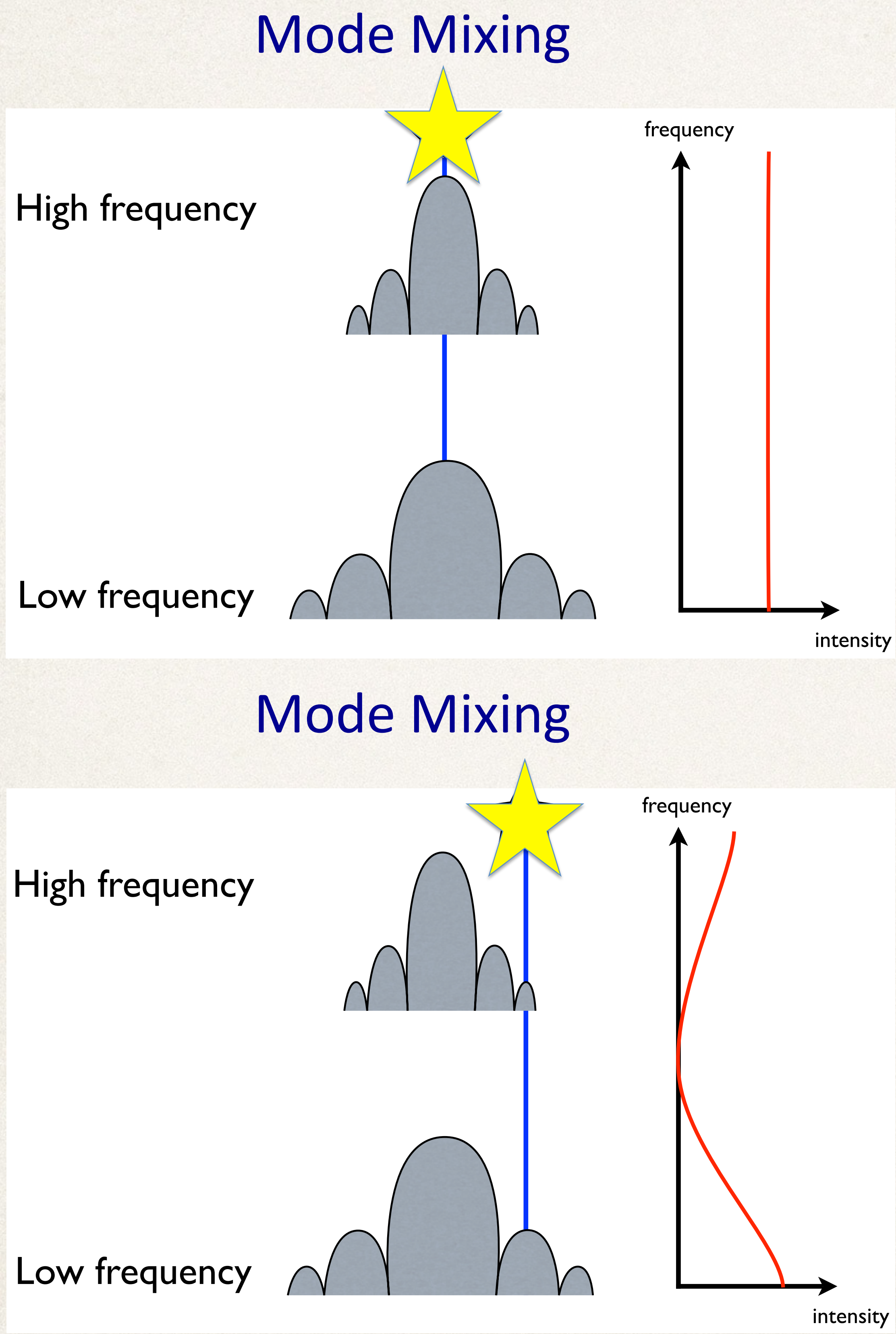
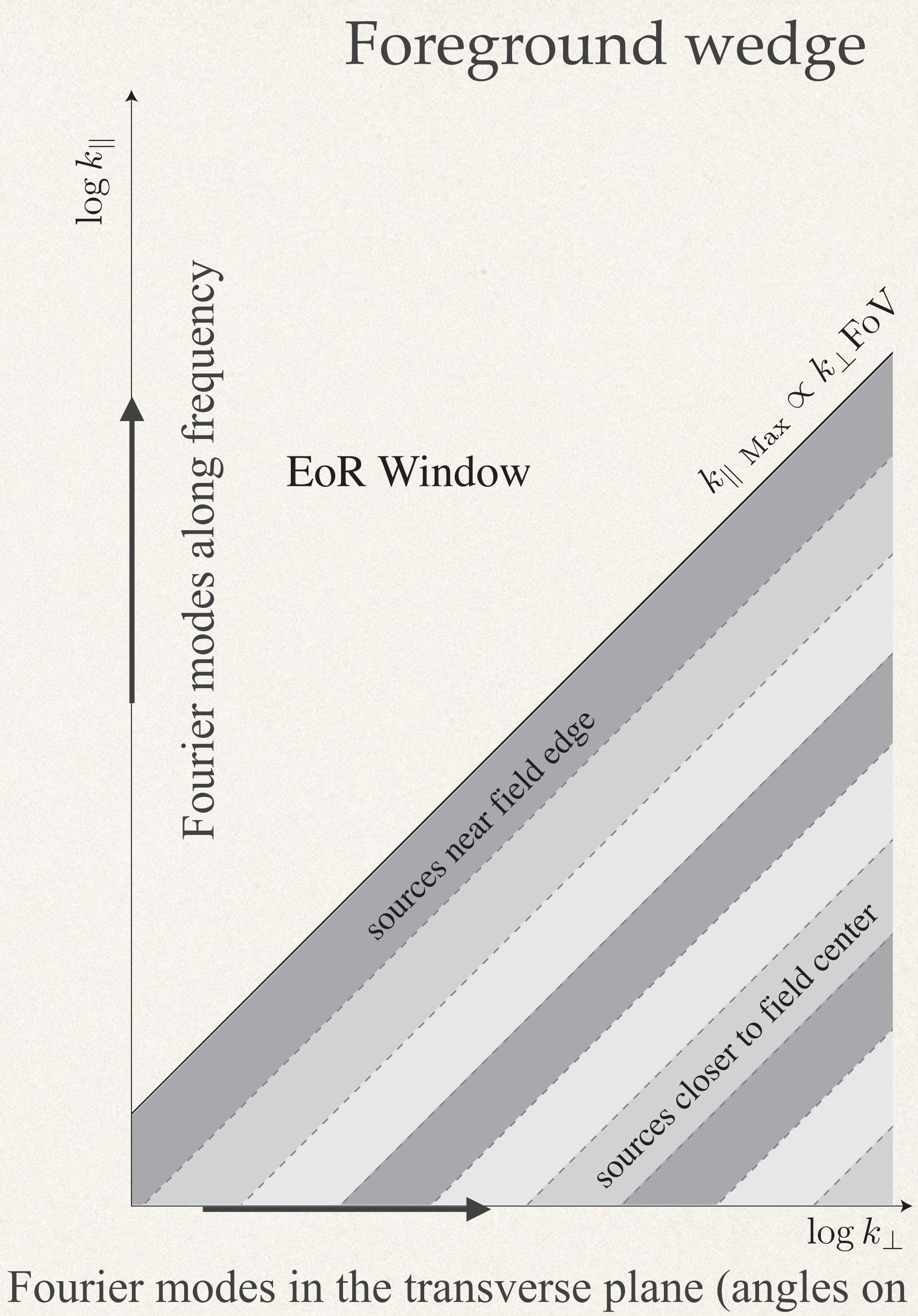


Illustration copied from P. Timbie slides

Mode mixing / foregrounds

Illustration : K. Sigurdson



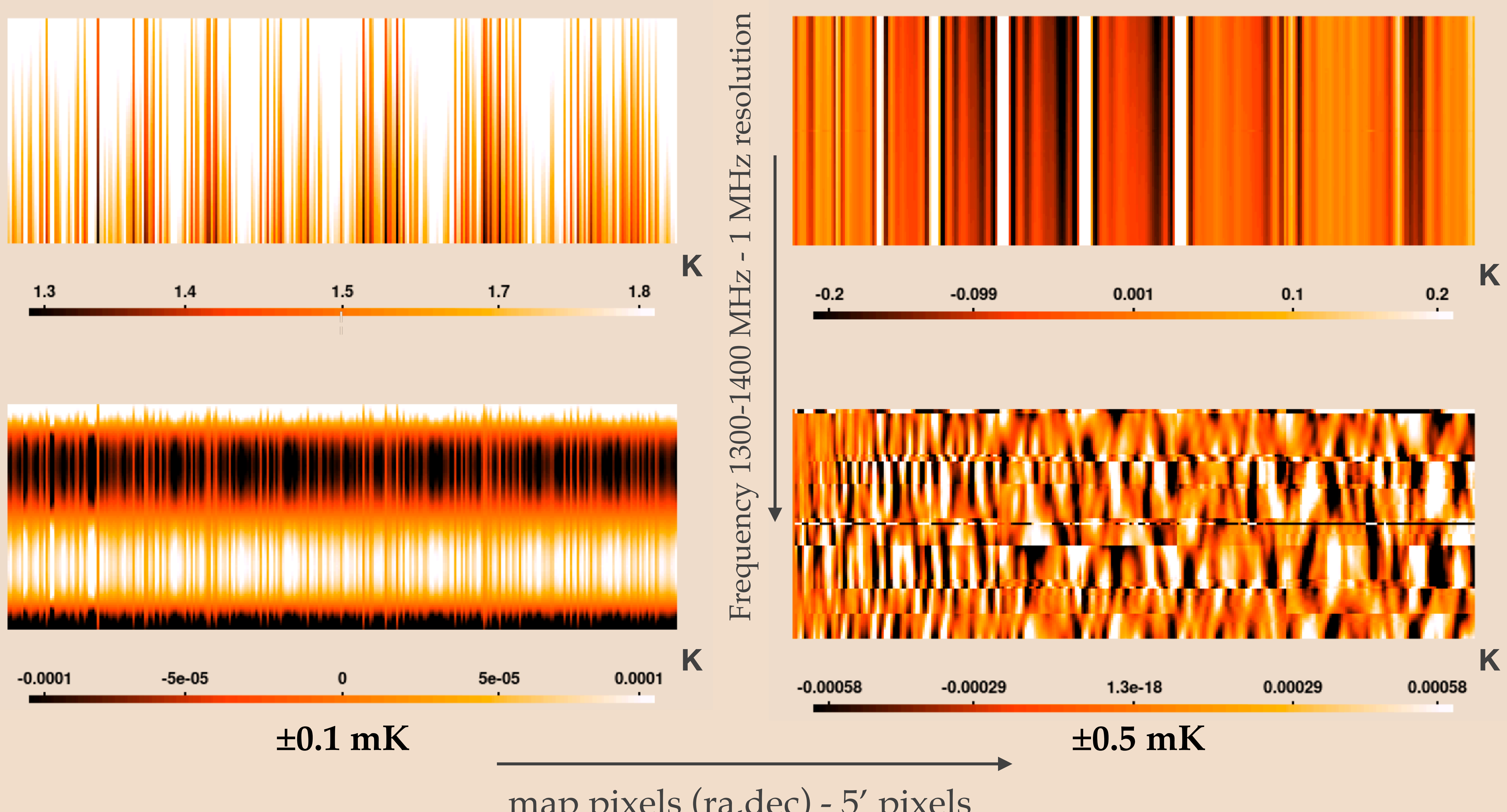


Mode mixing - A realistic illustration

Top: reconstructed 3D maps - bottom After simple 2nd order polynomial subtraction

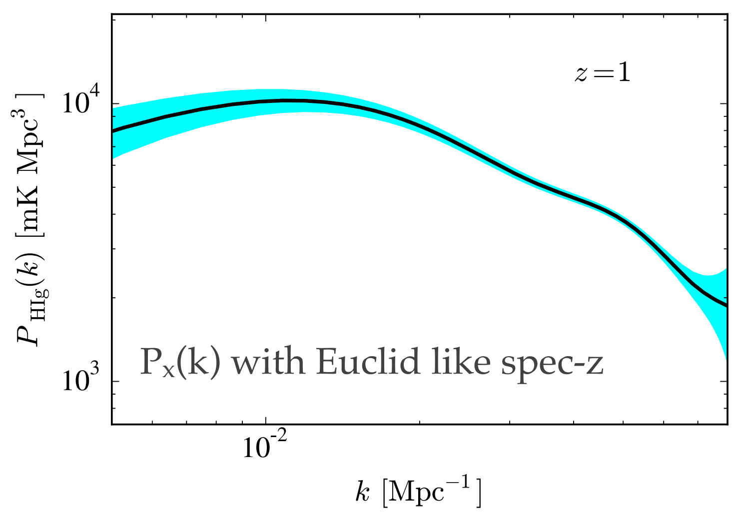
Perfect instrument - frequency independent gaussian beam
Imperfect foreground model

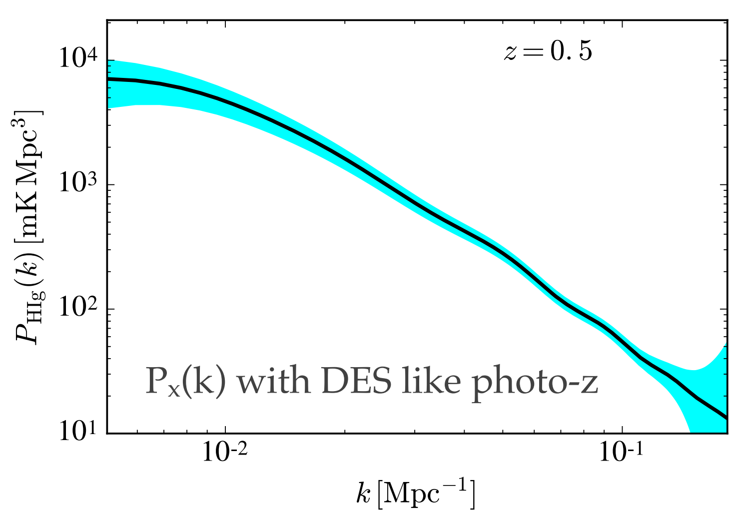
Tianlai T16D - NCP survey
Residual mode mixing



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





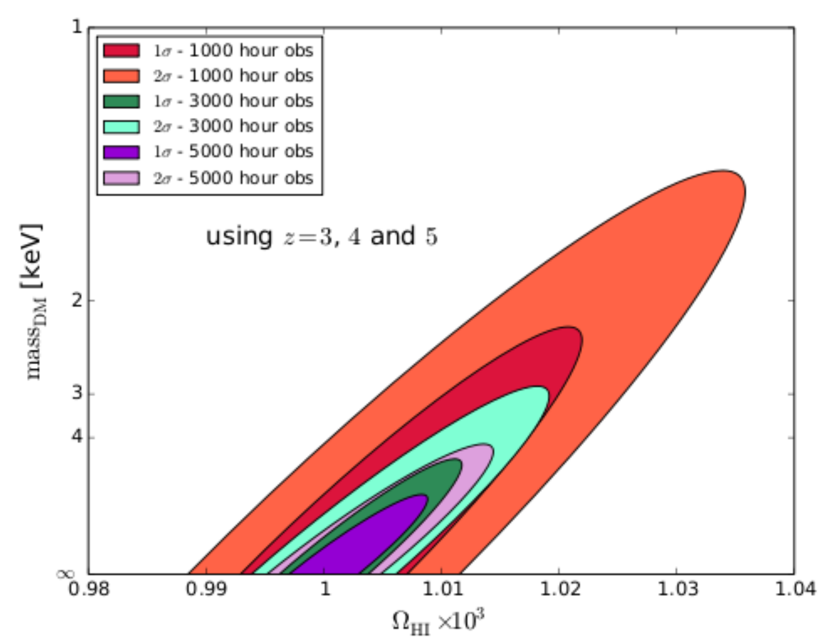


Figure 25. 1σ and 2σ contours (dark and light areas) of the values of Ω_{HI} and m_{WDM} determined using the HI power spectrum measured by SKA1-LOW with three different observation times: 1,000, 3,000 and 5,000 hours (red, green and violet) and using a field-of-view between 2.7-6 deg^2. The Fisher matrix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

HI 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

Summary

- Outstanding technical challenges for building the two instruments : infrastructure, optics, mechanics, cryogenic, electronics
- SKA is a digital interferometer, with great many numerical challenges, well beyond other large astronomical instruments
- The complexity of interferometric data analysis (RFI, calibration, map making …) makes it an ideal application domain for state of the art algorithms, from the sparse representation, inverse problems, statistics and deep learning
- Component separation, to extract 21cm cosmological signal is another major challenge for the intensity mapping
- But SKA will open / or widen the observation window in radio of the universe, including the unique possibility of exploring the EoR

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

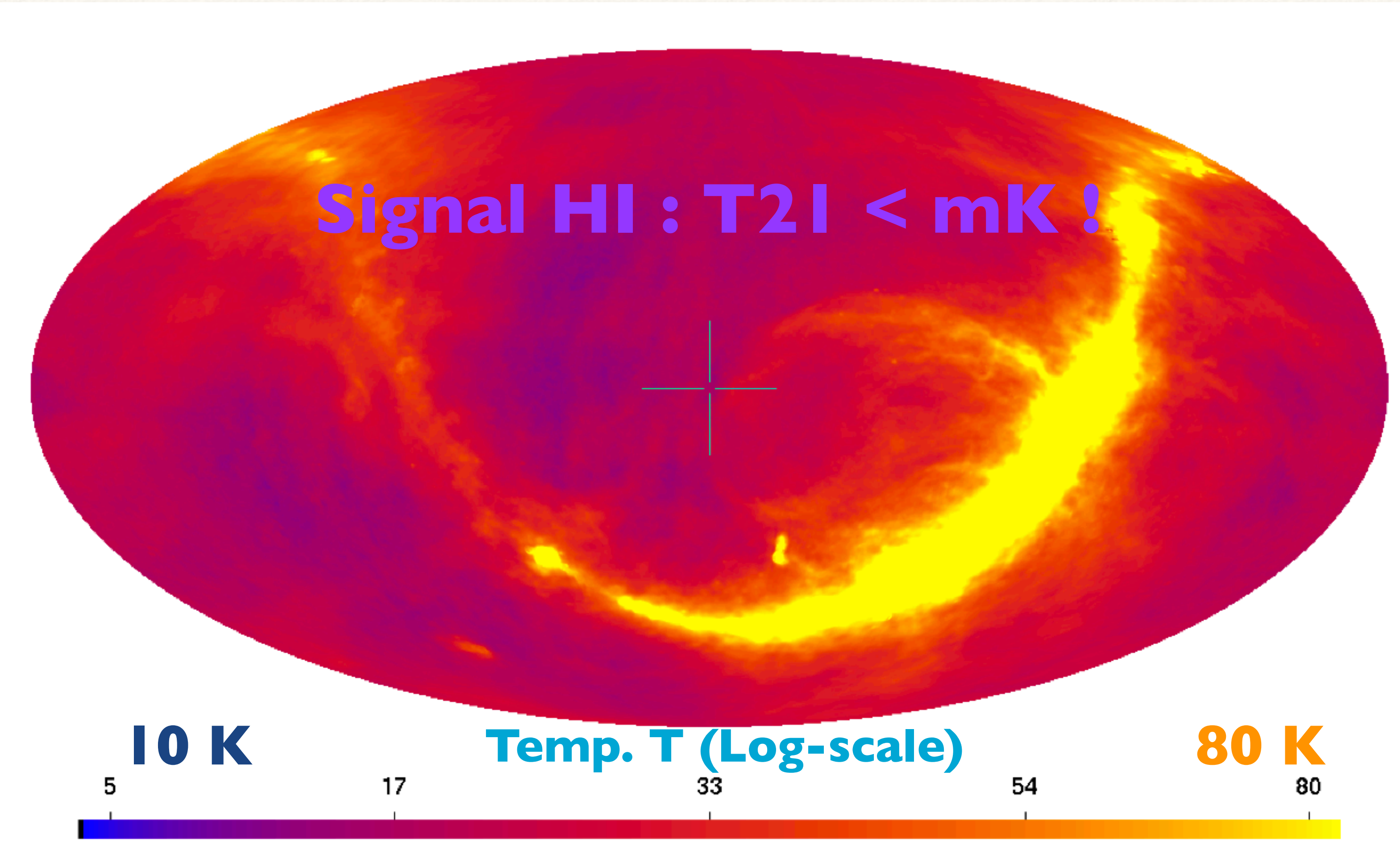
Cosmological probes and Dark energy (I)

- 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 → $d_A(z)$, $H(z)$
- Supernovae (**SN**) : Measure of apparent SNIa luminosity as a function of → $d_L(z)$
- Weak lensing (**WL**) : Measure of preferred orientation of galaxies → $d_A(z)$, growth of inhomogeneities (structures / LSS)
- Galaxy Clusters (**CL**) : number count and distribution of clusters → $d_A(z)$, $H(z)$, Structure formation (LSS)
- Integrated Sachs Wolf (**ISW**) effect : effect of evolving gravitational potential in large scale structures (with redshift)

Cosmological probes (II)

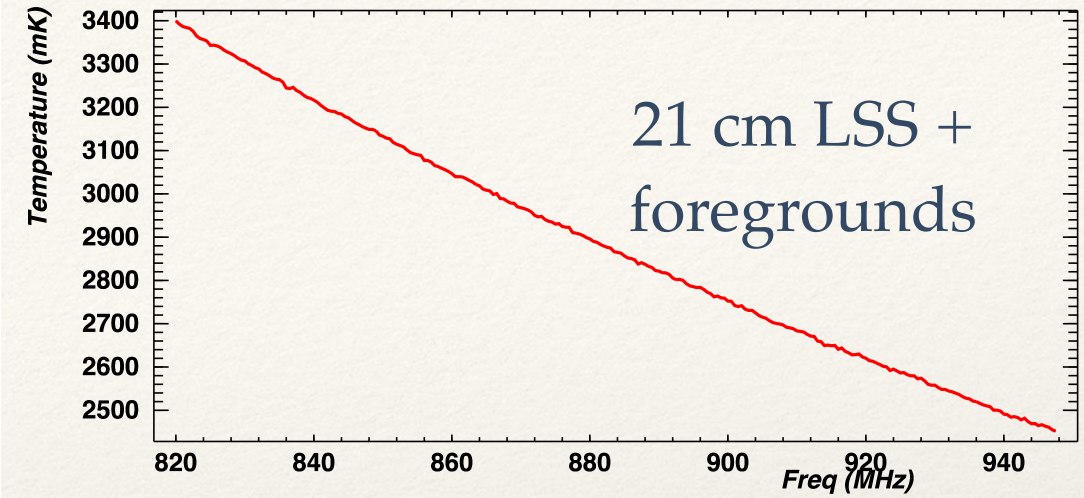
- 1- Study the geometry of the universe (FLRW metric) - with a distance-redshift relation depending on the cosmological parameters (energy-matter densities)
  - Standard candles : SNIa , gravitational sirenes (GW)…
  - Standard ruler probes : BAO
- 2- Study the dynamics of structure formation : observe 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) …

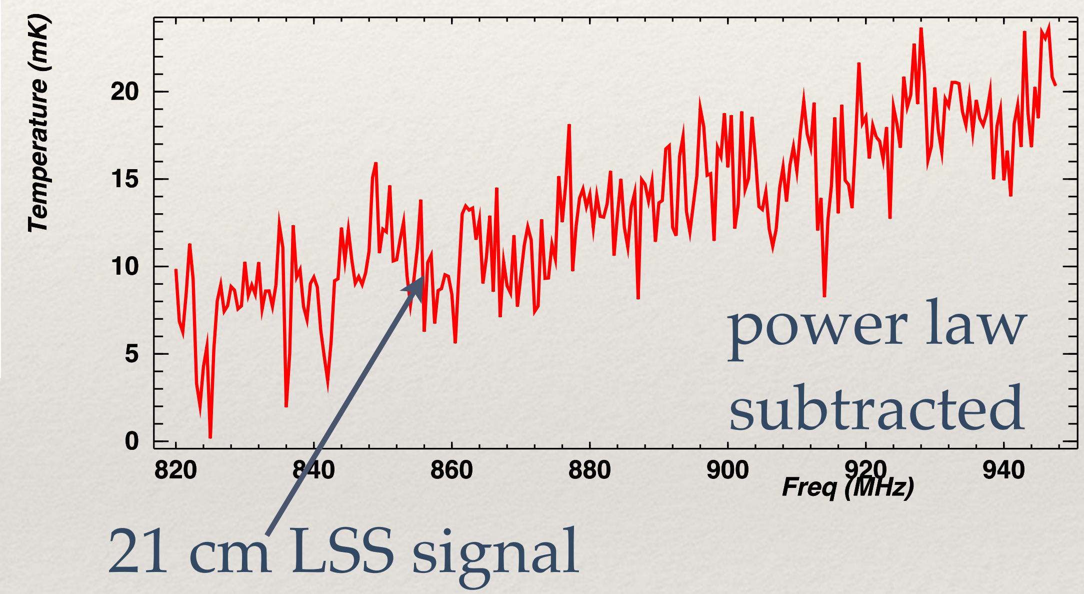
Foregrounds



Galactic synchrotron emission

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



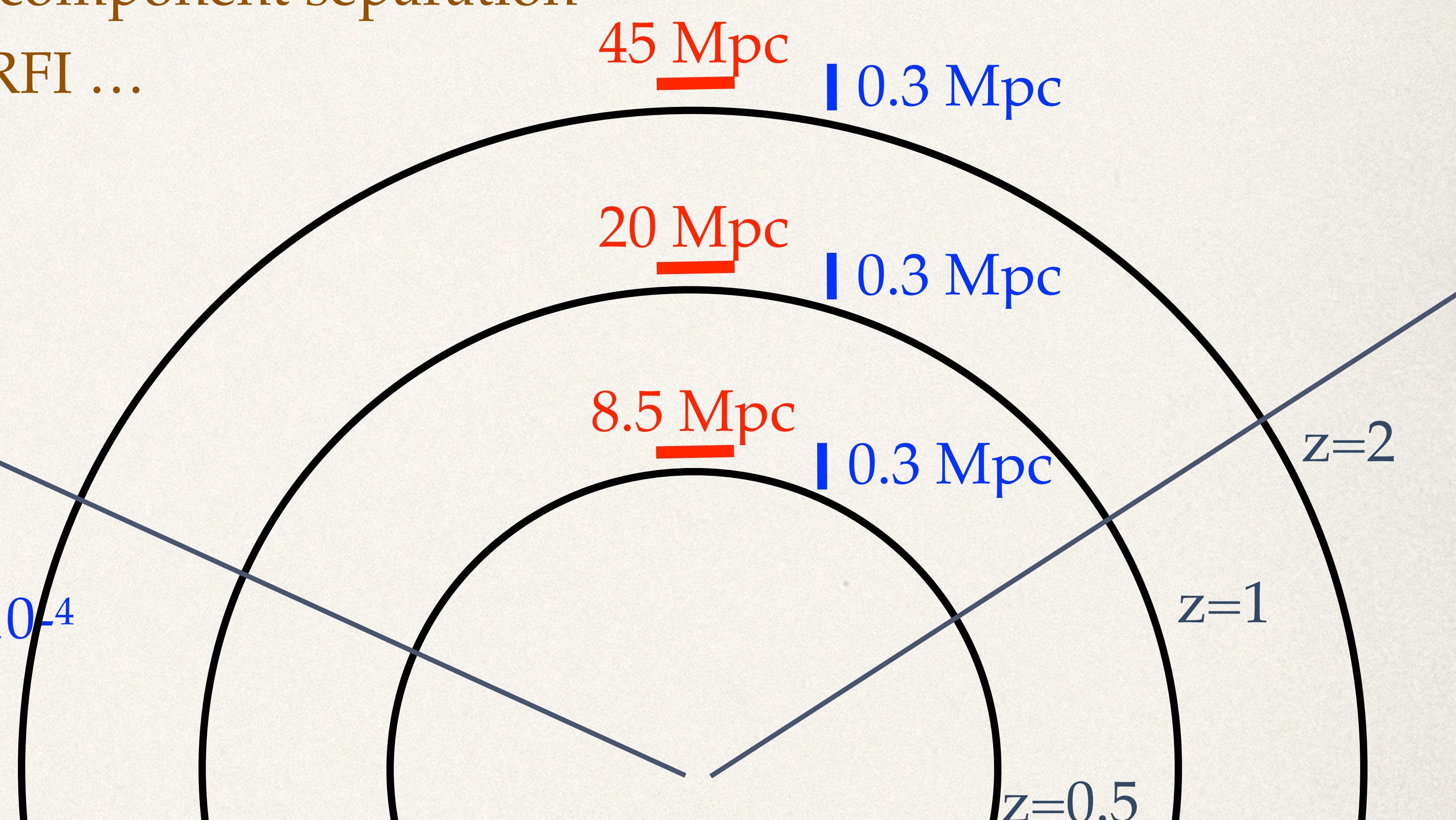


- Exploit foregrounds smooth frequency dependence (power law ∝ ν^β) for Galactic synchrotron and radio sources
- Instrumental effects (mode mixing), Polarisation leakage /Faraday rotation …

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 …

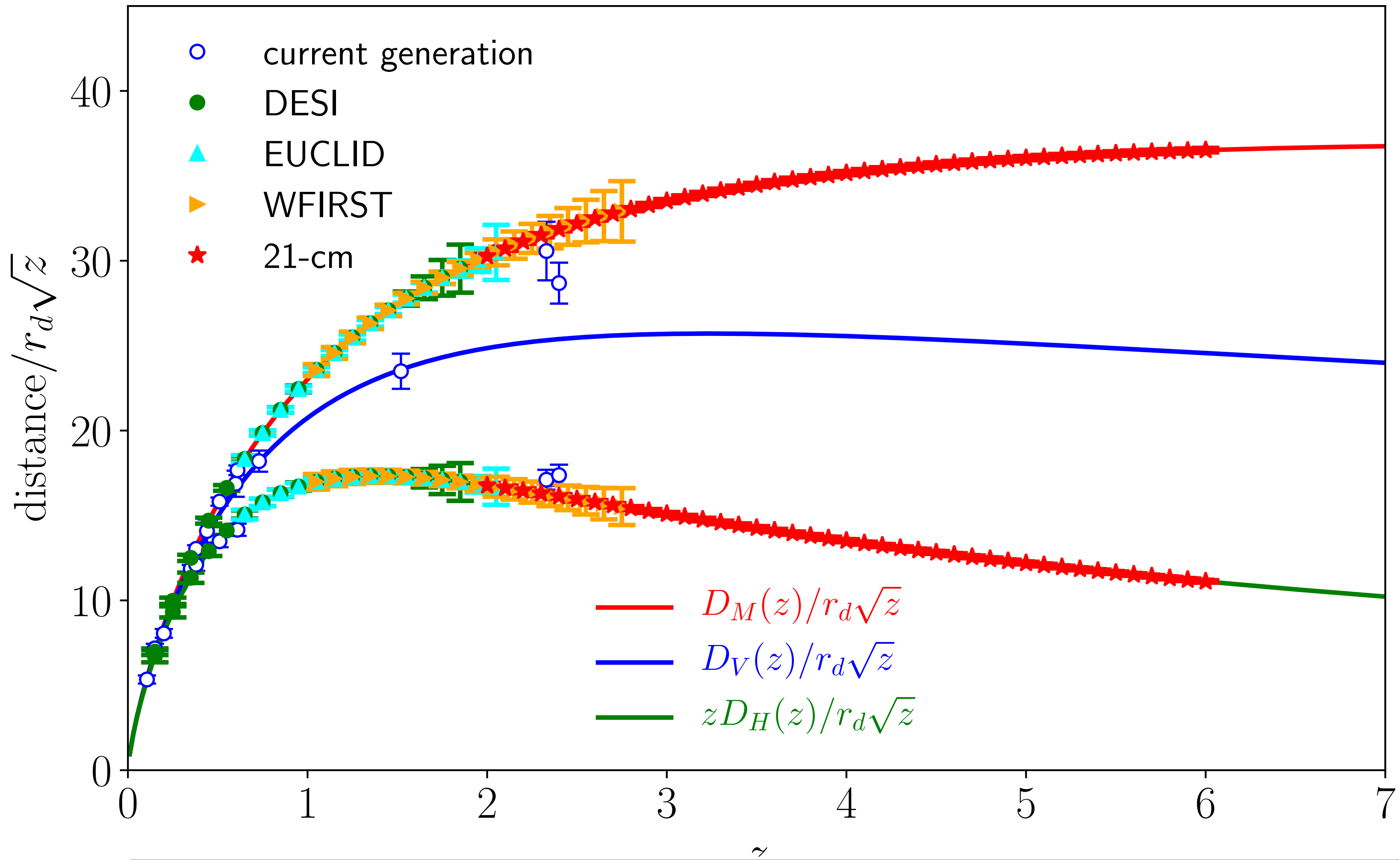
L=100 m array radio instrument
➝ ang. resolution $\delta\theta \sim \lambda/L$
deteriorating with redshift z
Spectral resolution 100 kHz
➝ excellent redshift precision $\delta z/z \sim 10^{-4}$

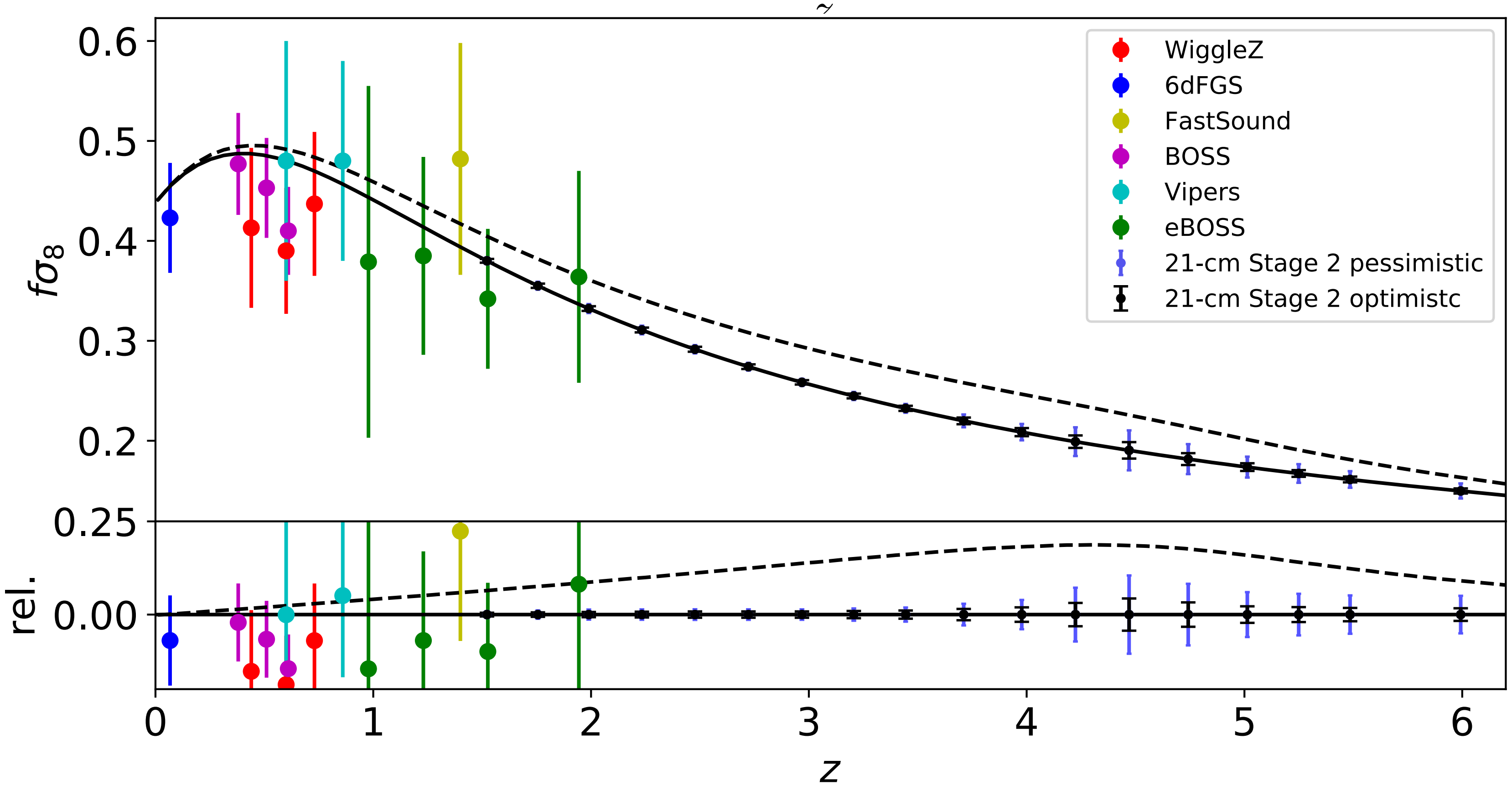


z	$\delta\theta$	d_{LOS} (Mpc)	H	$\delta d_\perp$ (Mpc)	$\delta d_\parallel$ (Mpc)
0,5	15′	1945	90	8,5	~0.3
1	20′	3400	120	20	~0.3
2	30′	5320	200	45	~0.3
3	40′	6320	300	75	~0.3

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

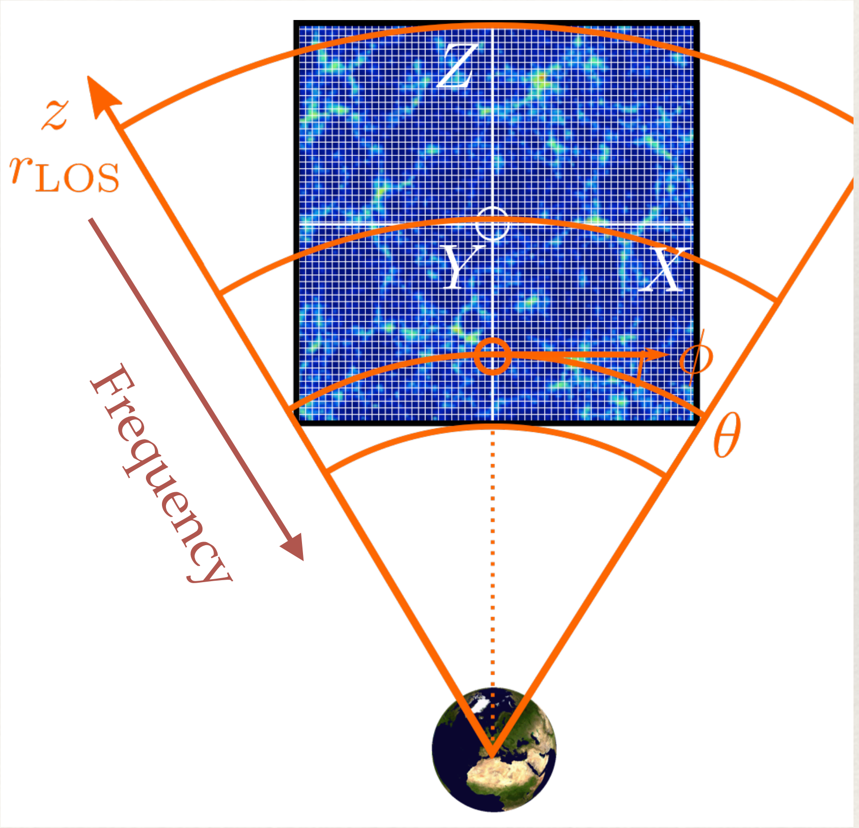
Chen et al, arXiv:2010.07985

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**



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

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

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

SKA Science Working Groups & Focus groups

The Science Working Groups (SWGs) and Focus Groups (FGs) are scientific advisory bodies that provide input to the SKA Organisation on issues related to the design, construction, and future operations of the SKA that are likely to affect the Observatory's scientific capability, productivity and user relations. In addition, the FGs have a more specific, technical focus.

If you are interested in participating in any of the groups, please contact the current chairs or corresponding project scientists via the website link below.

- **Cosmology**
- **Cradle of Life**
- **Epoch of Reionization**
- **Extragalactic Continuum (galaxies/AGN, galaxy clusters)**
- **Extragalactic Spectral Line**
- **HI galaxy science**
- **High Energy Cosmic Particles (FG)**
- **Magnetism**
- **Our Galaxy**
- **Pulsars**
- **Solar, Heliospheric & Ionospheric Physics**
- **Transients**
- **VLBI (FG)**

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Square Kilometre Array

YouTube The Square Kilometre Array

For more, visit

astronomers.skatelescope.org/science-working-groups