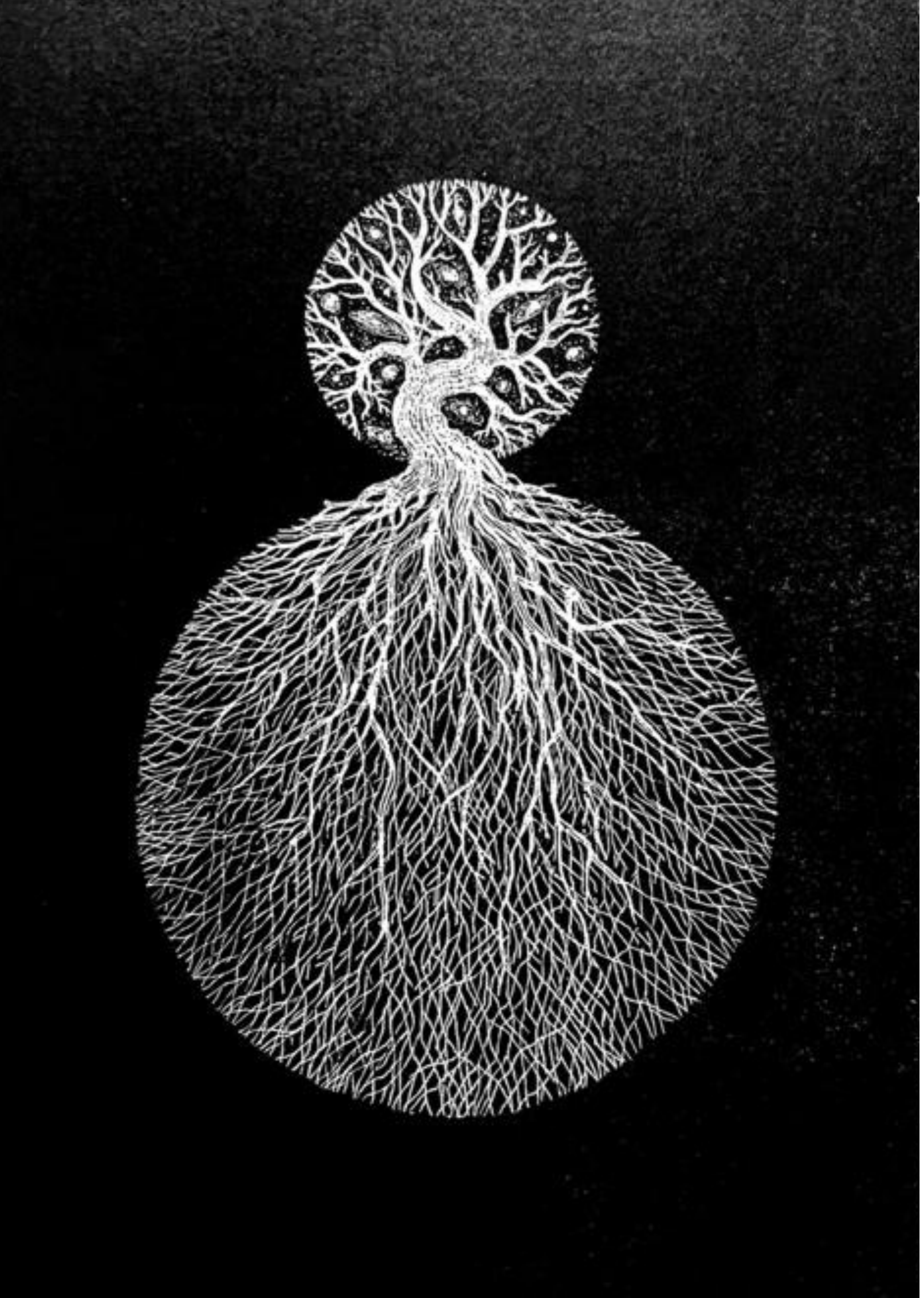

Cosmology with the SKA Observatory

Stefano Camera

Department of Physics, Alma Felix University of Turin, Italy

The SKA Observatory

- The SKA Observatory (Inter-Governmental Organisation) was born on 15th Jan 2021!

The SKA Observatory

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The SKA Observatory

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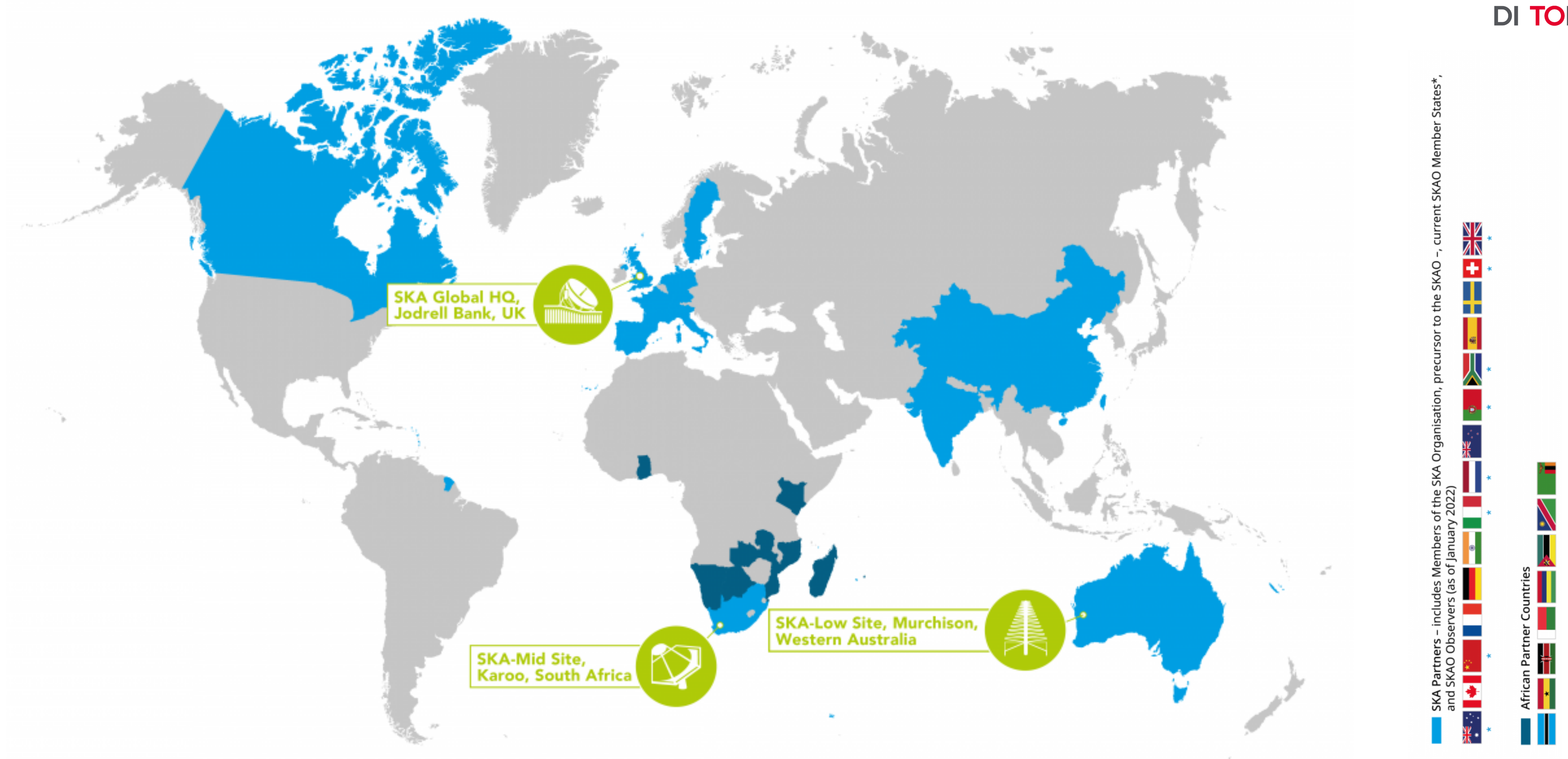
The SKA Observatory



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The SKA Project

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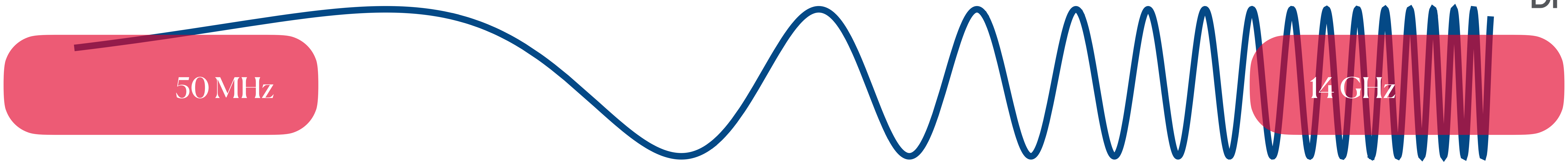
- The SKA (formerly known as 'Square Kilometre Array') will be the largest radio-telescope on Earth and will be built in two locations

The SKA Project



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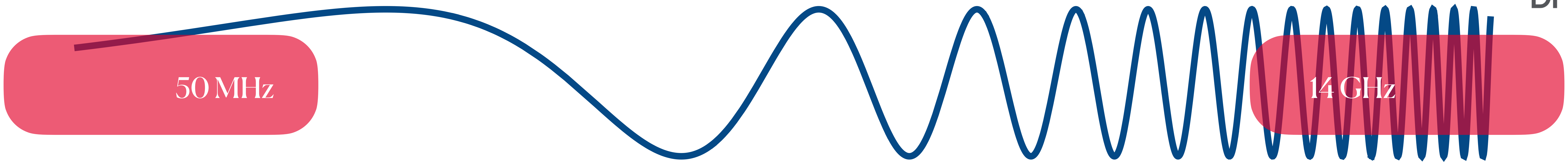
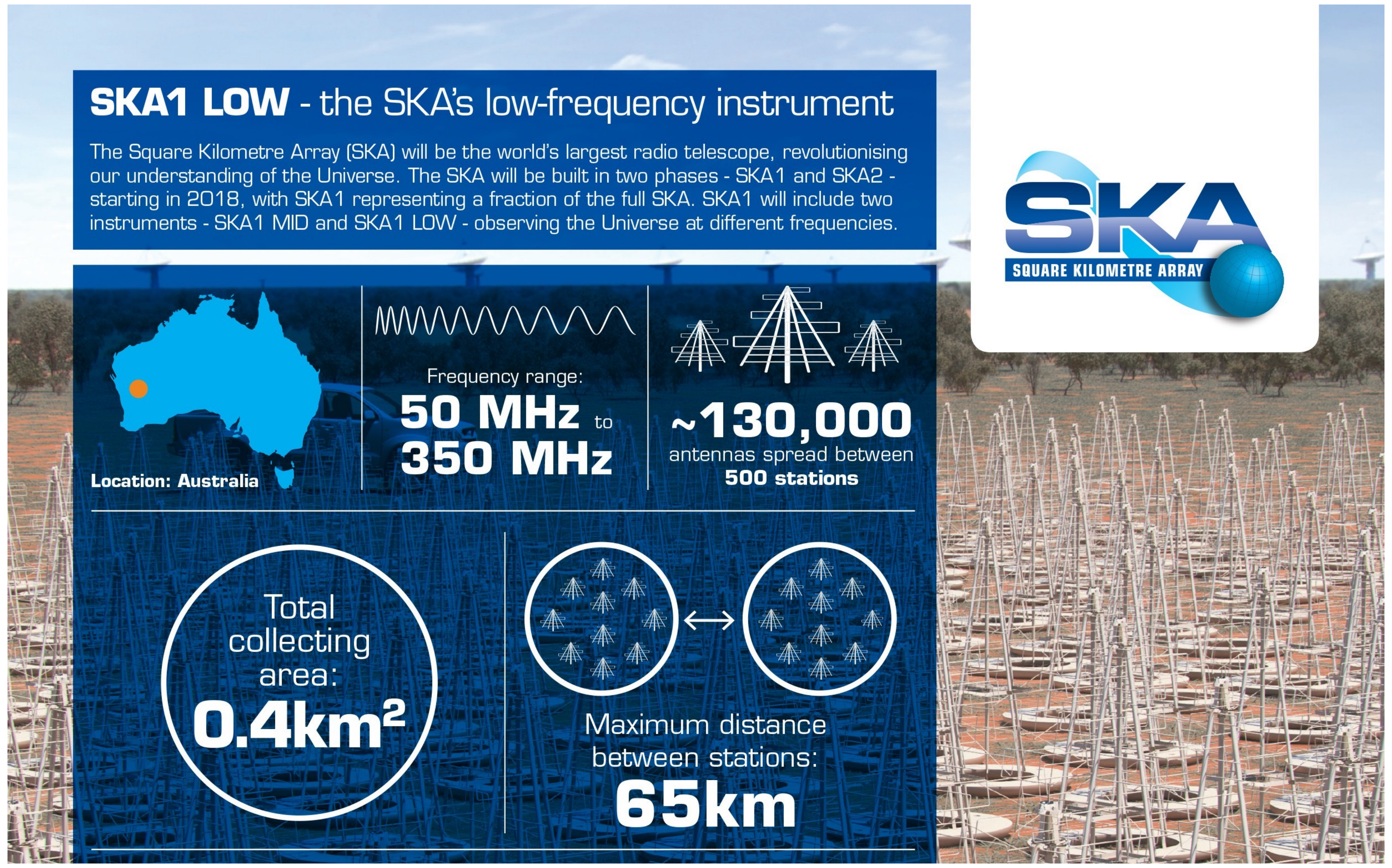
The SKA Project





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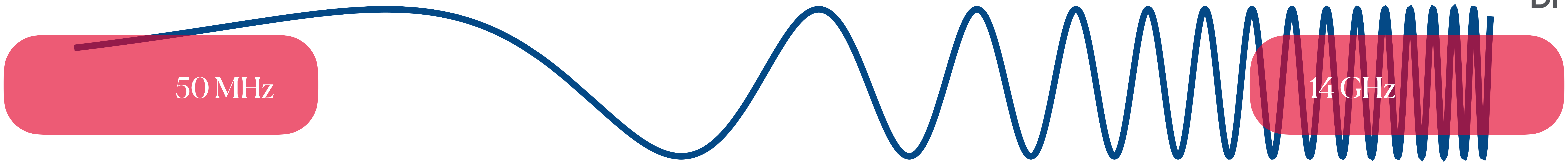
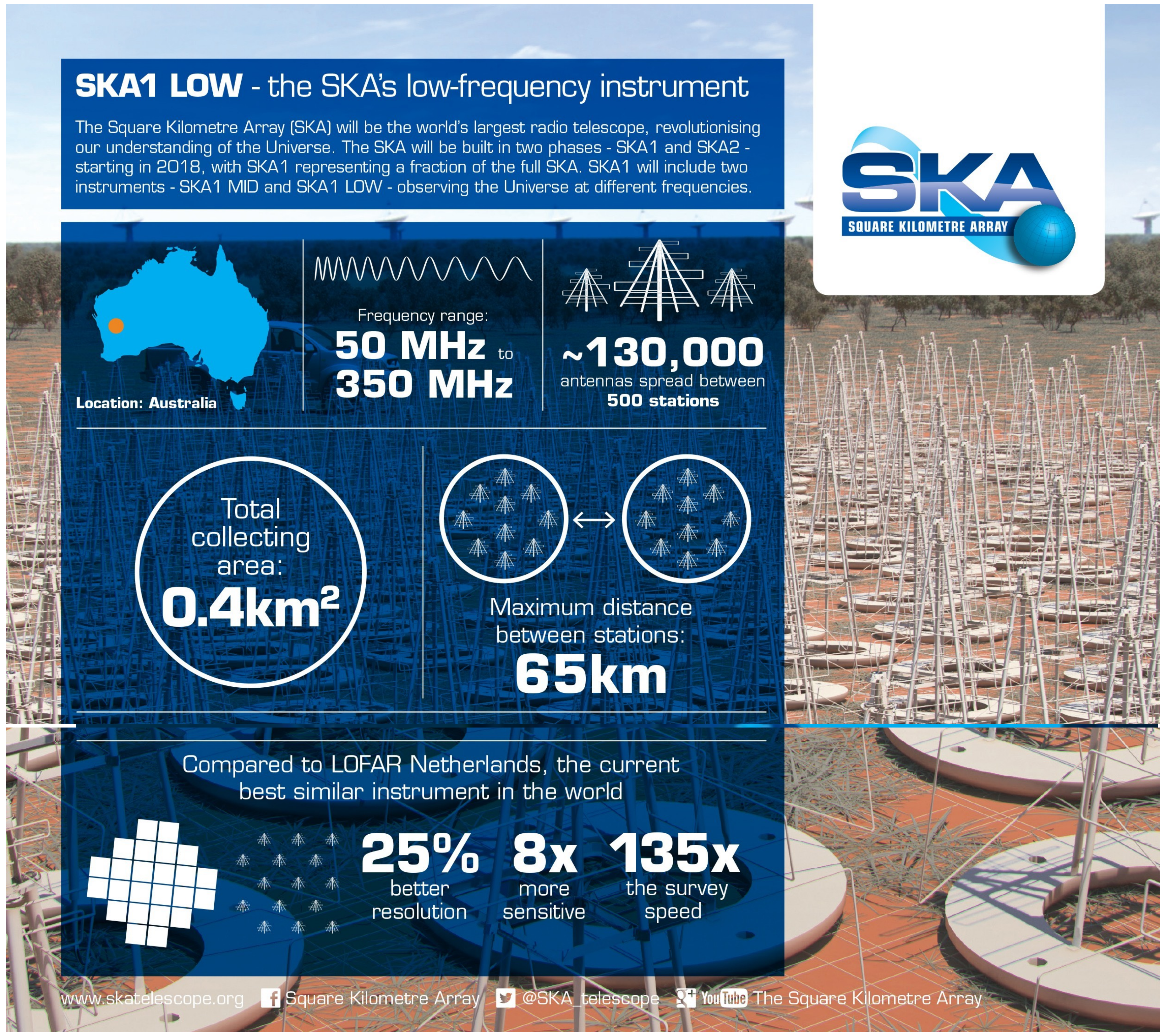
Cosmology with the SKA Observatory

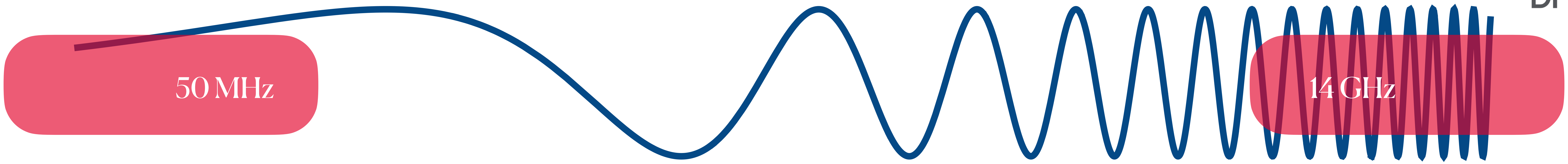
Stefano Camera

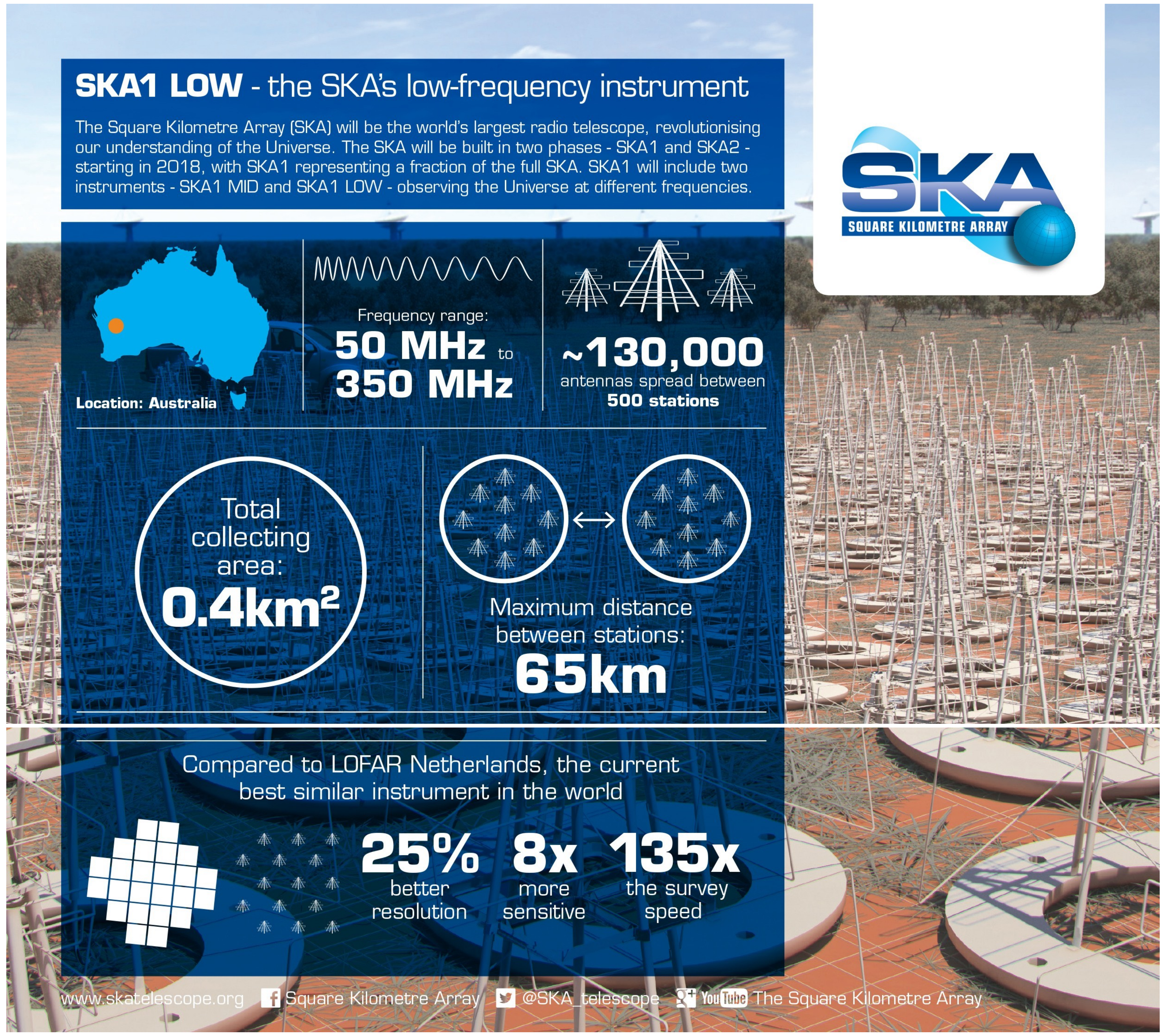
The SKA Project

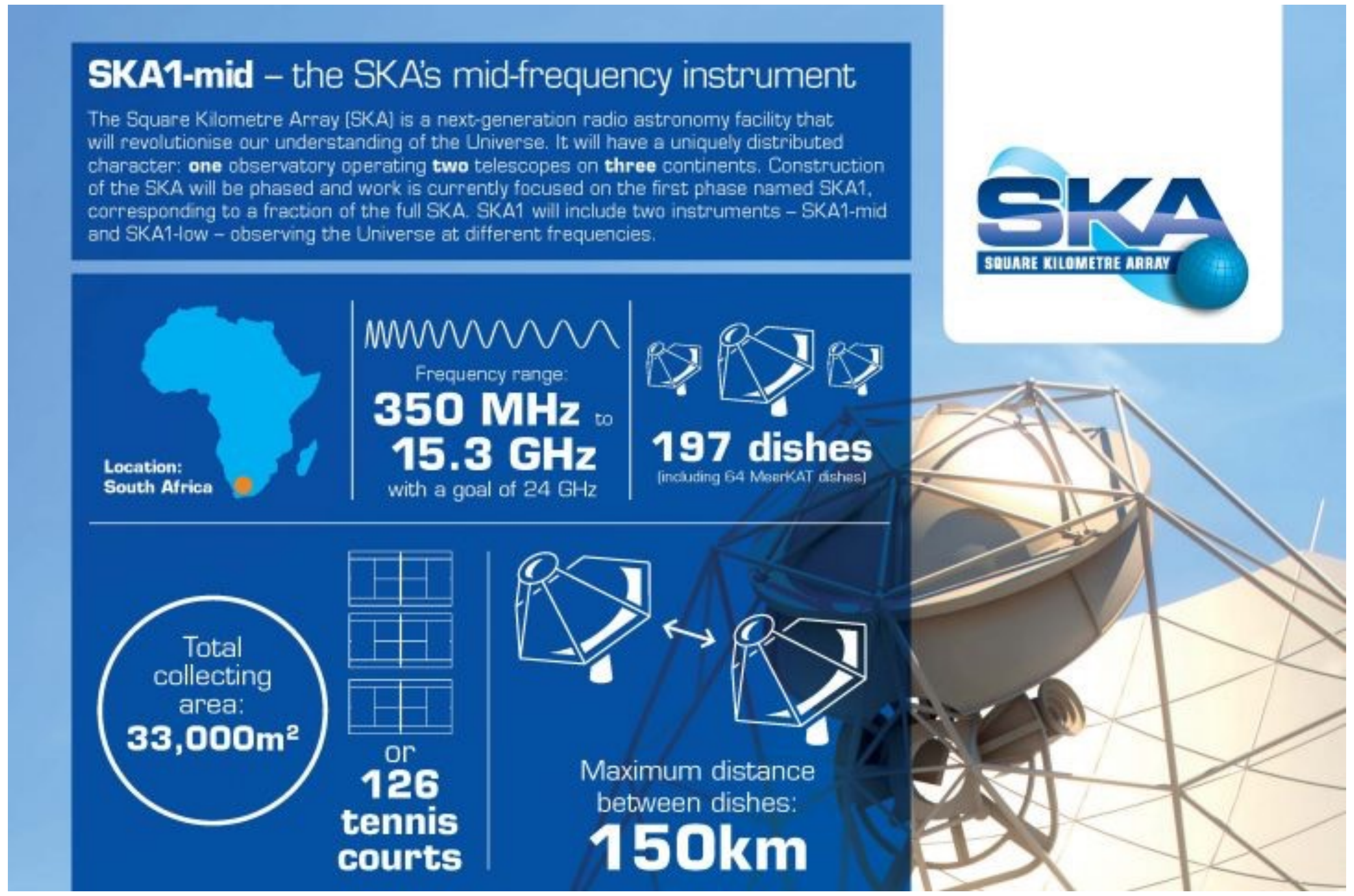




The SKA Project







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Cosmology with the SKA Observatory

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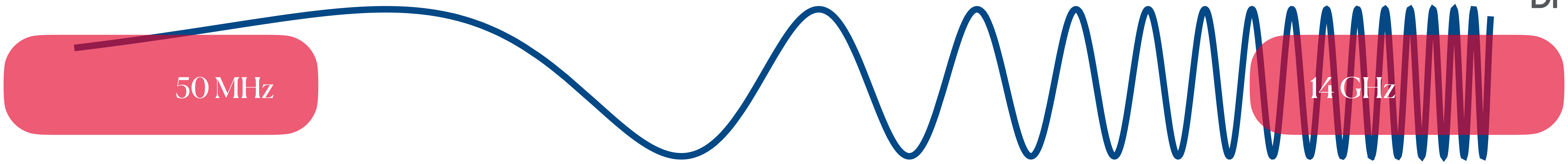

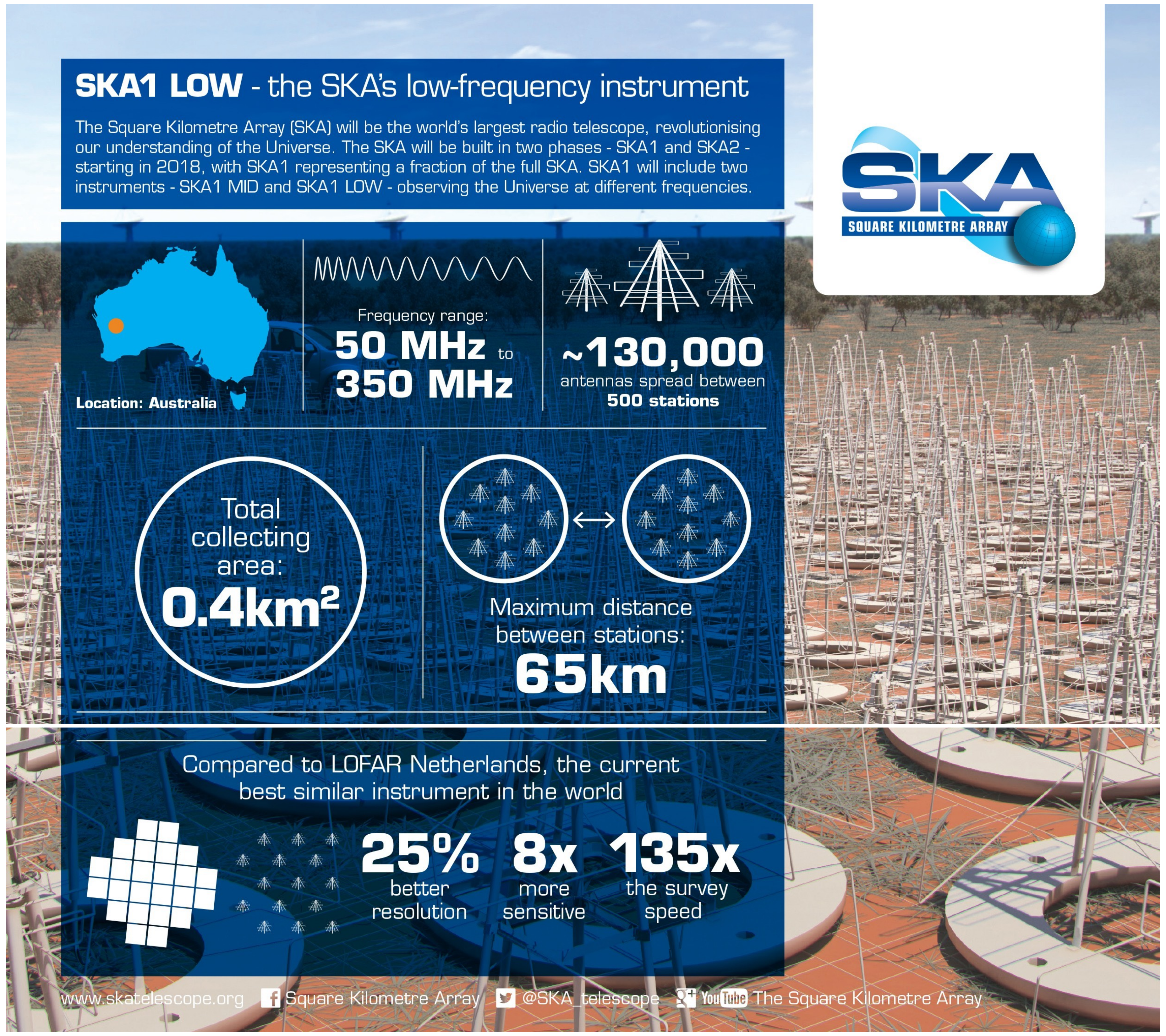

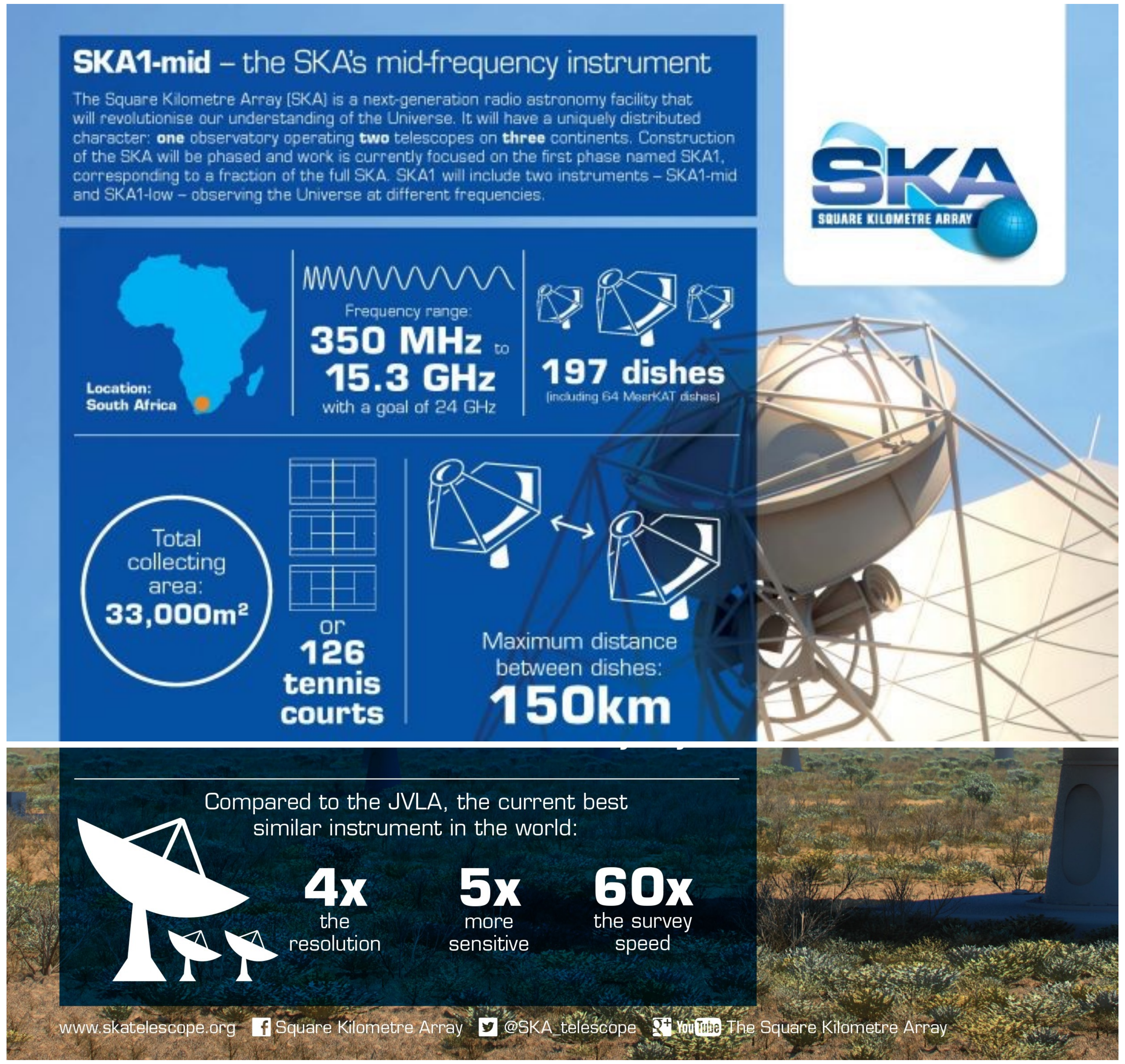

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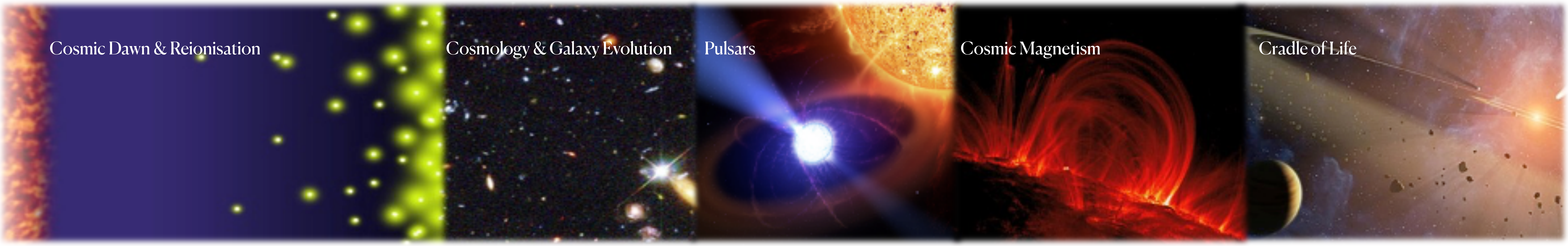
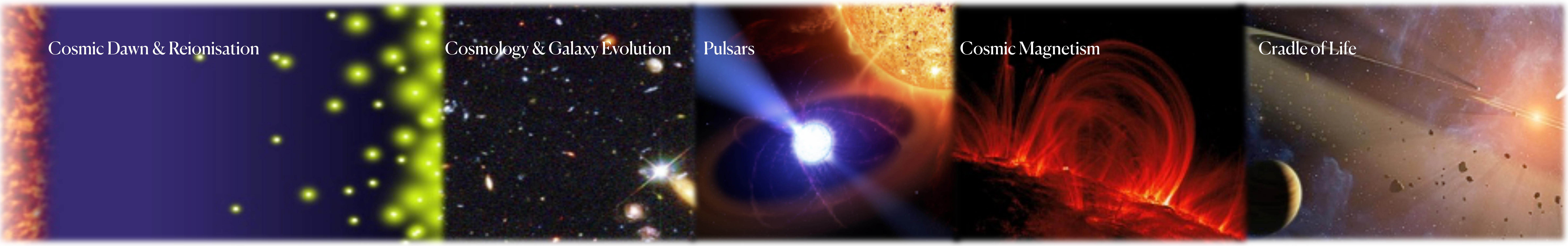
SKAO Science



SKAO Science



SKAO's Low telescope

SKAO's Mid telescope

50-350 MHz

Band 1
0.35-1.05 GHz

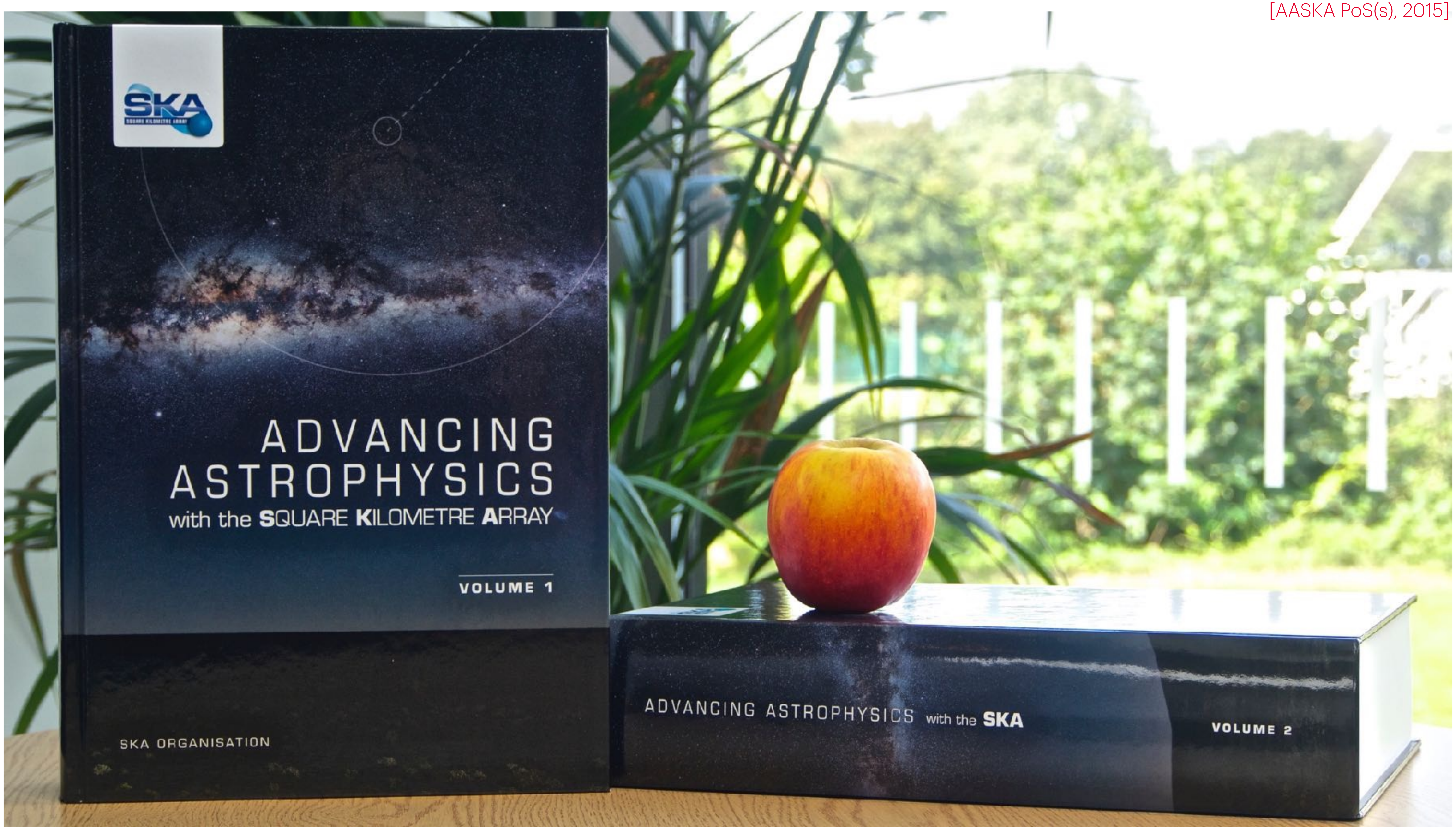
Band 2
0.95-1.76 GHz

Band 3
1.65-3.05 GHz

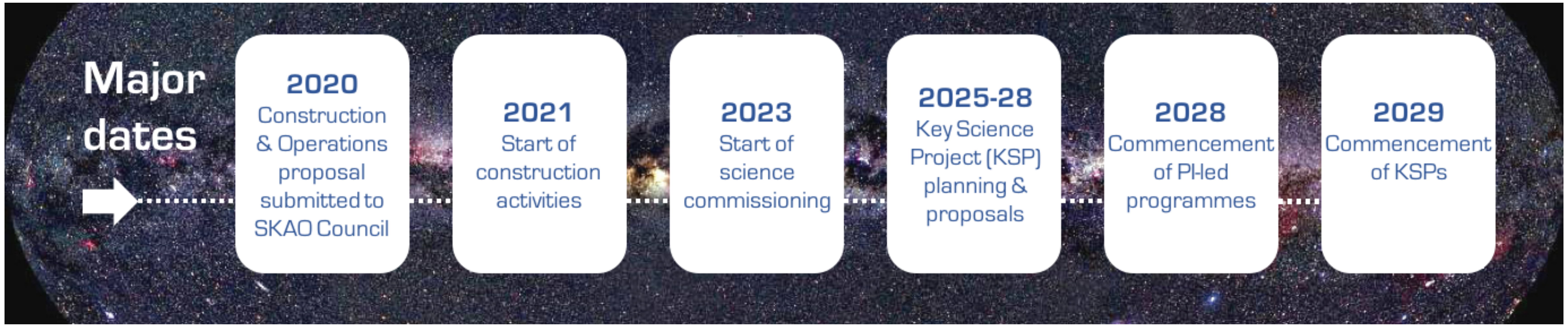
Band 5
4.6-24 GHz

SKAO Science

[AASKA PoS(s), 2015]



SKAO Science



SKAO Science

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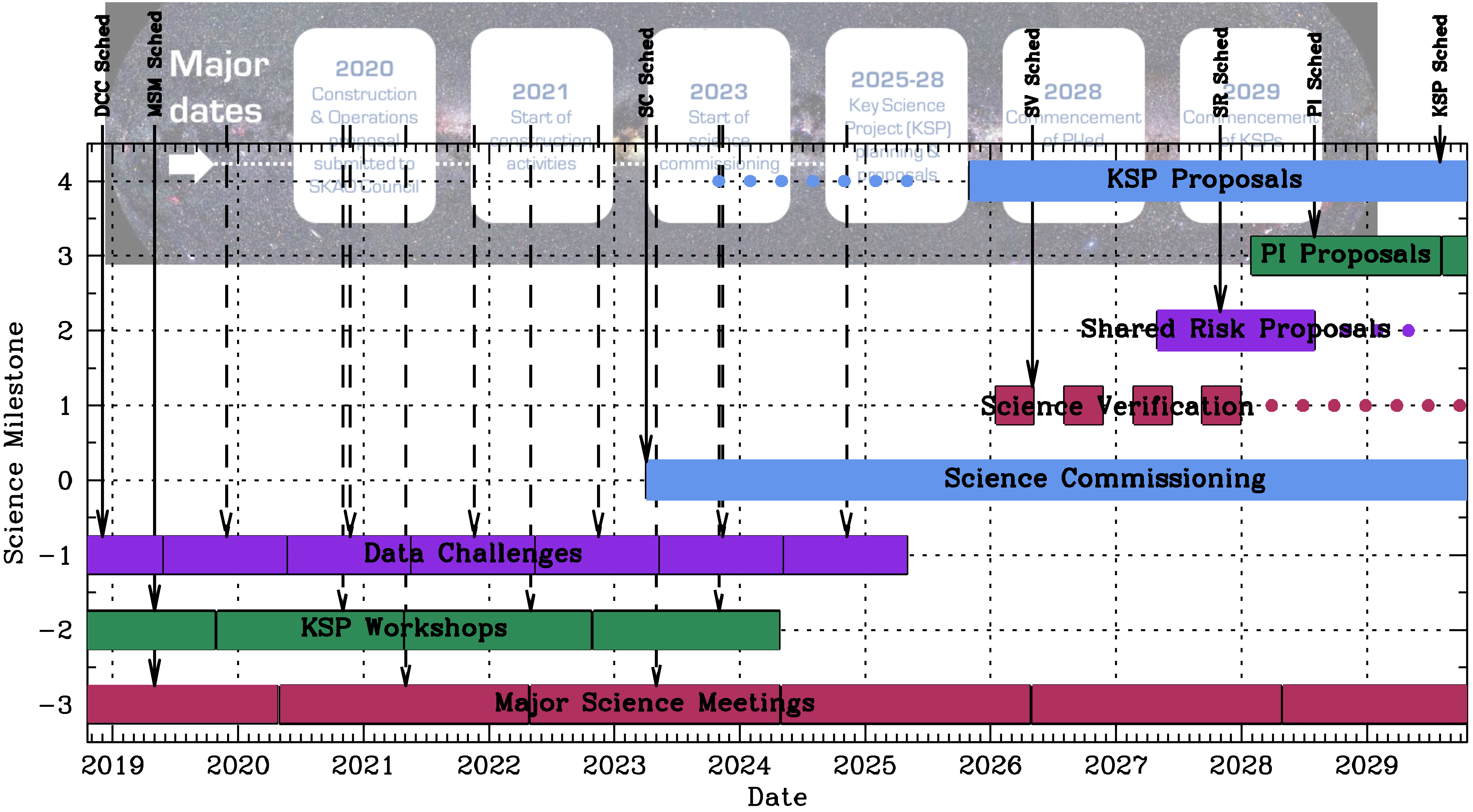
[Credits: R. Braun]



SKAO Cosmology

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Publications of the Astronomical Society of Australia (2020), **37**, e007, 31 pages
doi:10.1017/pasa.2019.51

CAMBRIDGE UNIVERSITY PRESS

[Bacon, SC et al. (2020)]

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]

SKAO Cosmology

Publications of the Astronomical Society of Australia (2020), **37**, e002, 52 pages
doi:10.1017/pasa.2019.42

CAMBRIDGE UNIVERSITY PRESS

[Weltman, SC et al. (2020)]

Review (unsolicited)

Fundamental physics with the Square Kilometre Array

A. Weltman[1,#], P. Bull[2,*], S. Camera[3,4,5,*], K. Kelley[6,*], H. Padmanabhan[7,8,*], J. Pritchard[9,*], A. Raccanelli[10,*], S. Riemer-Sørensen[11,*], L. Shao[12,*], S. Andrianomena[13,14], E. Athanassoula[15], D. Bacon[16], R. Barkana[17], G. Bertone[18], C. Bœhm[19], C. Bonvin[20], A. Bosma[15], M. Brüggen[21], C. Burigana[22,23,24], F. Calore[18,25], J. A. R. Cembranos[26], C. Clarkson[1,14,27], R. M. T. Connors[28], Á. de la Cruz-Dombriz[29], P. K. S. Dunsby[29,30], J. Fonseca[31], N. Fornengo[4,32], D. Gaggero[18], I. Harrison[33], J. Larena[1], Y.-Z. Ma[34,35,36], R. Maartens[14,16], M. Méndez-Isla[29], S. D. Mohanty[37], S. Murray[38], D. Parkinson[39], A. Pourtsidou[16,27], P. J. Quinn[6], M. Regis[4,32], P. Saha[40,41], M. Sahlén[42], M. Sakellariadou[43], J. Silk[44,45,46,47], T. Trombetti[22,23,48], F. Vazza[21,22,49], T. Venumadhav[50], F. Vidotto[51], F. Villaescusa-Navarro[52], Y. Wang[53], C. Weniger[18], L. Wolz[54], F. Zhang[55] and B. M. Gaensler[56,†]

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SKAO Cosmology

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- Surveys carried out at radio wavelengths:
  - HI-line galaxy surveys
  - Continuum galaxy surveys
  - HI intensity mapping surveys
  - Radio weak lensing surveys
- Multi-wavelength synergies

HI-line galaxies

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- Origin: HI (neutral hydrogen) emission line in galaxies
- Pros: spectroscopic redshift accuracy, peculiar velocities
- Cons: few galaxies (faint signal), threshold experiment
- Examples:
  - HIPASS (4.5k galaxies; 5σ detection limit 5.6 Jy km s–1 @ 200 km s–1)
  - ALFALFA (>20k galaxies; 5σ detection limit 0.72 Jy km s–1 @ 200 km s–1)

HI-line galaxies

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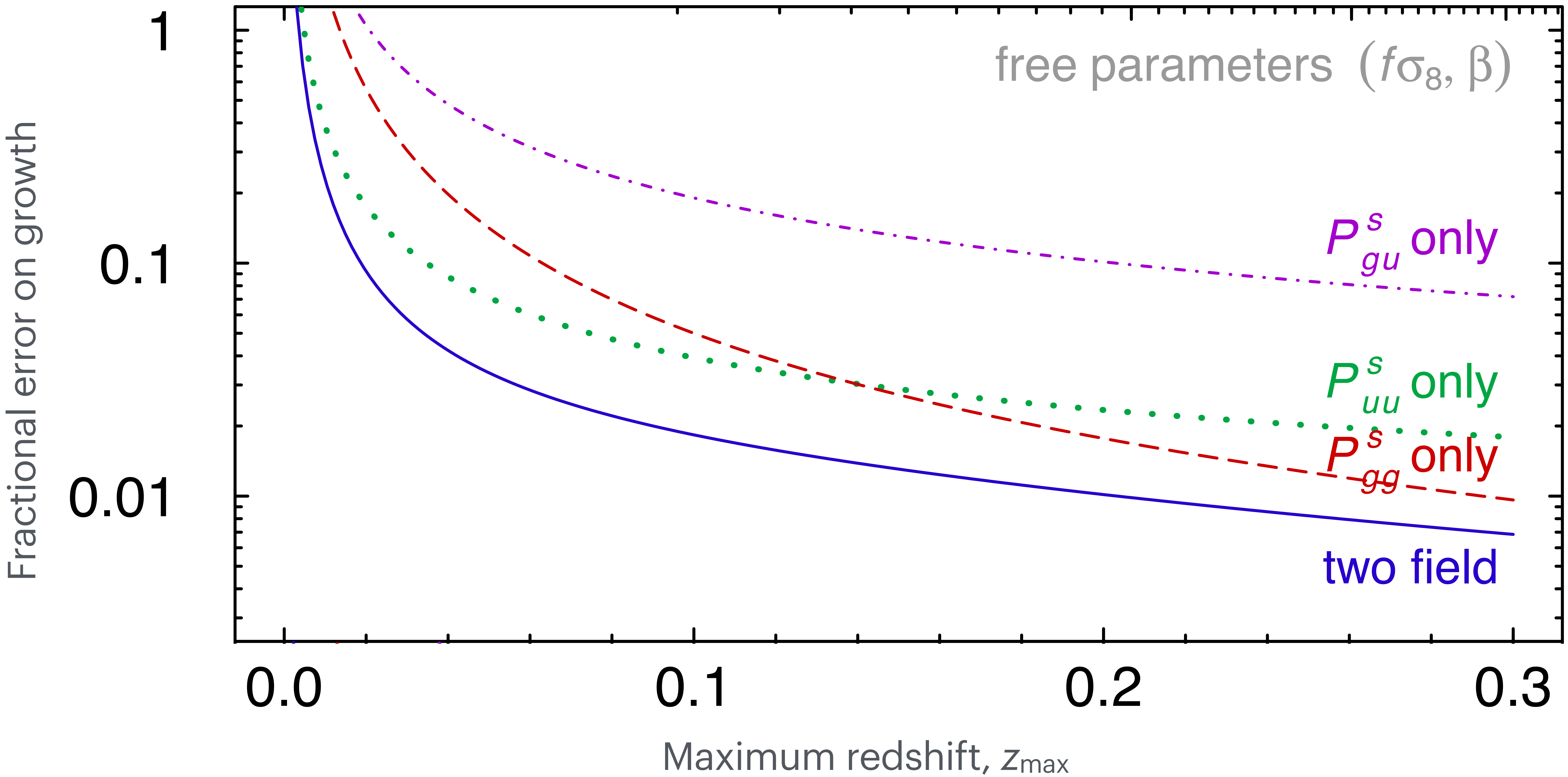
- HI-line galaxy surveys are ‘Tully-Fisher’ surveys
  - The intrinsic luminosity of a galaxy (from 21cm line width) combined with its measured redshift, gives peculiar velocity of the galaxy.

HI-line galaxies

- HI-line galaxy surveys are ‘Tully-Fisher’ surveys

[Koda et al. (2004)]



Continuum galaxies

- Origin: synchrotron emission of charged particles within galaxies
- Pros: large number of galaxies (strong signal)
- Cons: (almost) no redshift information
- Examples:
  - VLA FIRST (10k sq. deg.; 900k galaxies)
  - NVSS (>34k sq. deg.; 2M galaxies; I, Q and U polarisation maps)

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Continuum galaxies

- Testing the cosmological and the Copernican principles

[Schwarz et al. (2015, 2018); Bengaly et al. (2017); Pant et al. (2019); Bengaly, Larena & Maartens (2019)]

  - SKAO continuum galaxy angular correlation function will be able to detect dipole:
    - Within 5º (SKAO)
    - Within 1º (Futuristic SKAO)

[Courtesy of R. Maartens]

HI intensity mapping

- Origin: integrated emission of 21-cm photons in galaxies (after the EoR ends)
- Pros: no photon lost, better than spectroscopic redshift accuracy
- Cons: poor angular resolution, huge foreground contamination
- Examples:
  - GBT (~1 sq. deg. in cross-correlation w/ WiggleZ @ $0.53 < z < 1.12$) [Chang et al. (Nature 2010)]
    (~100 sq. deg. in cross-correlation w/ eBOSS & WiggleZ @ $0.6 < z < 1.0$) [Wolz et al. (2021)]
  - Parkes (1.3k sq. deg. in cross-correlation w/ 2dFGRS @ $0.057 < z < 0.098$) [Andeson et al. (2018)]
  - MeerKAT (~200 sq. deg. in cross-correlation w/ WiggleZ @ $0.400 < z < 0.459$) [Cunnington et al. (2022)]
  - CHIME (three fields stacked against eBOSS LRGs, ELGs, QSOs @ $0.78 < z < 1.43$)

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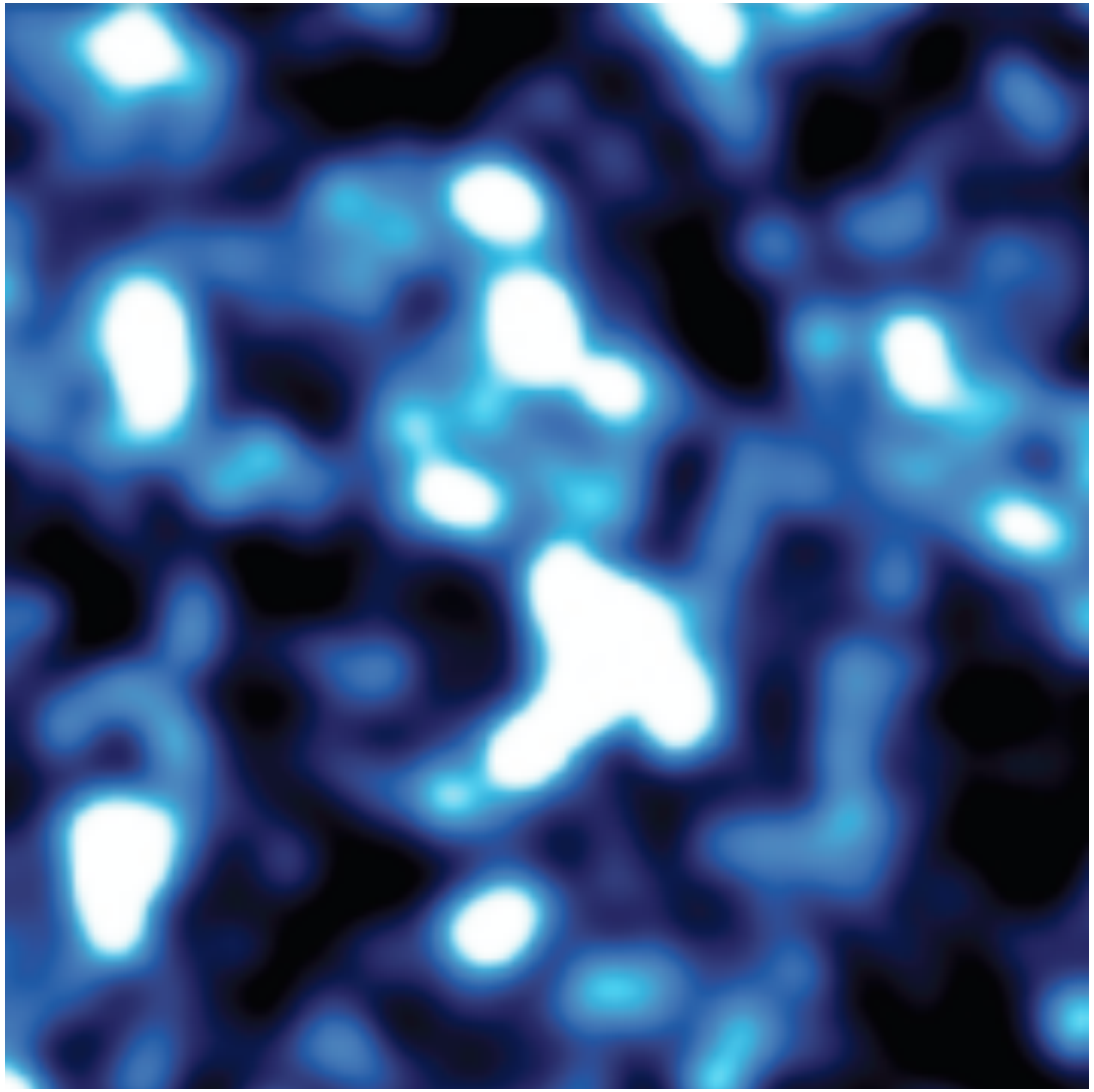
HI intensity mapping

HI intensity mapping



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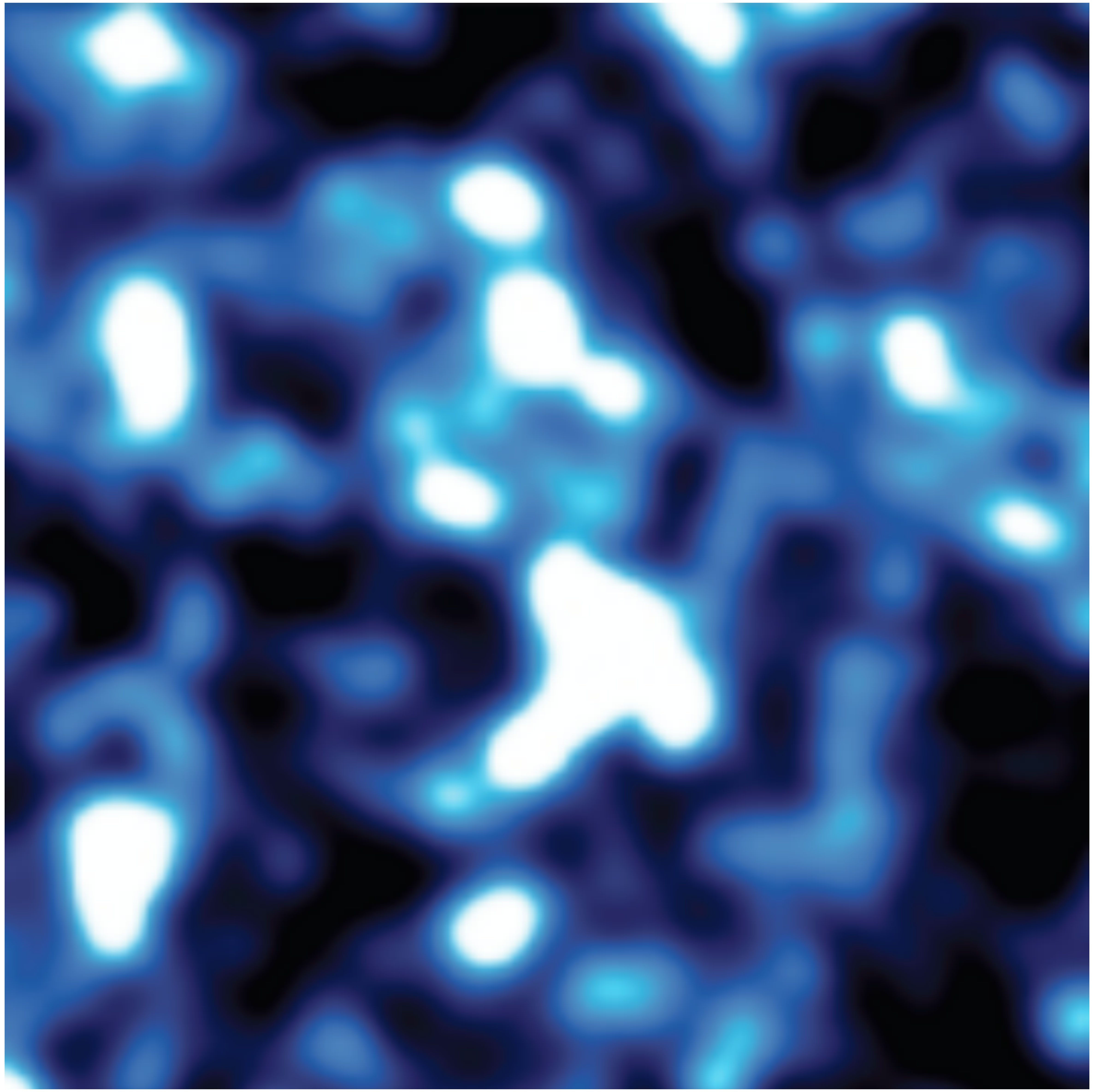
HI intensity mapping



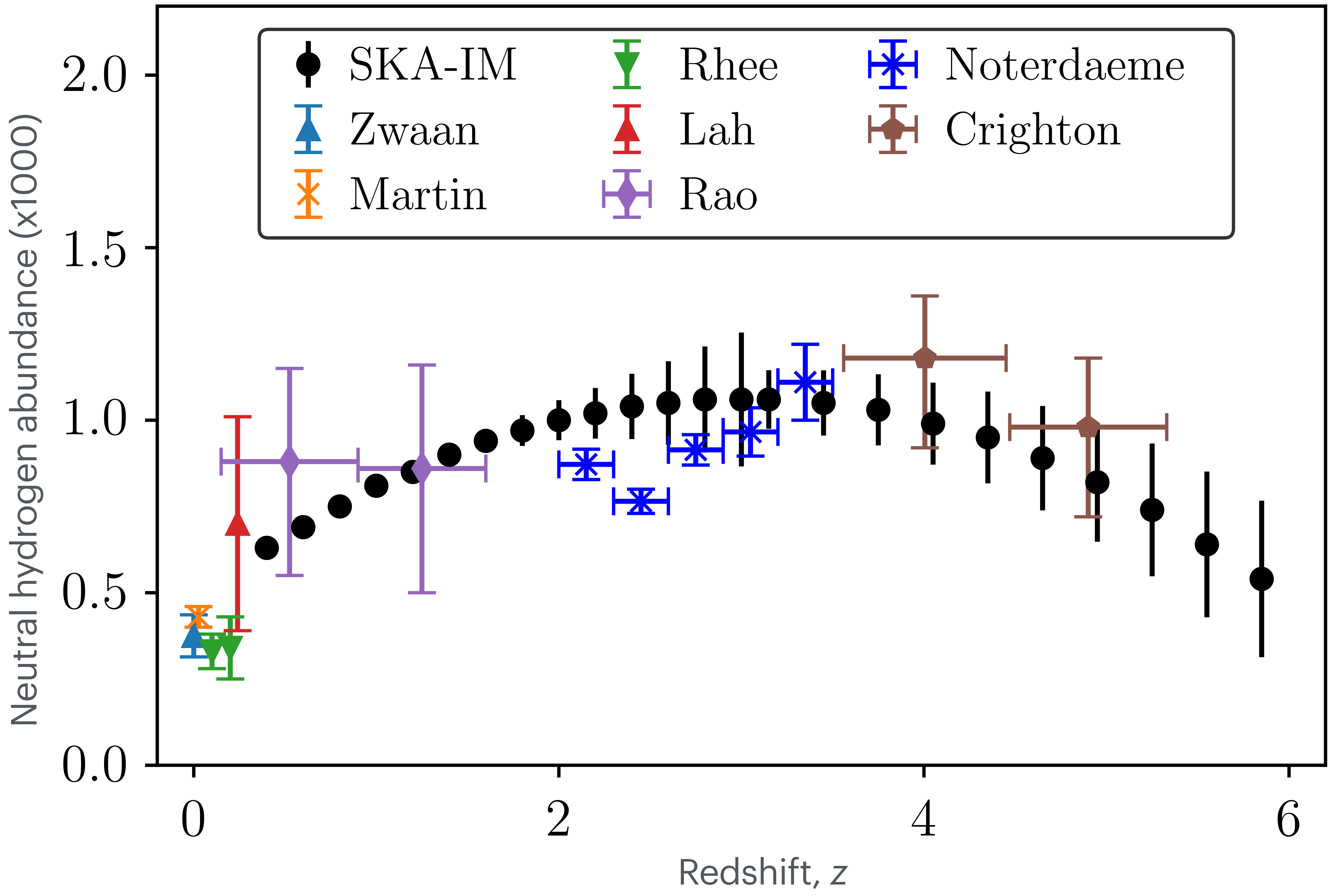
Redshift for free:

ν_{obs} = 1420 MHz / (1+z)

[Bharadwaj et al. (2001); Battye et al. (2004); Loeb & Whyte (2008)]

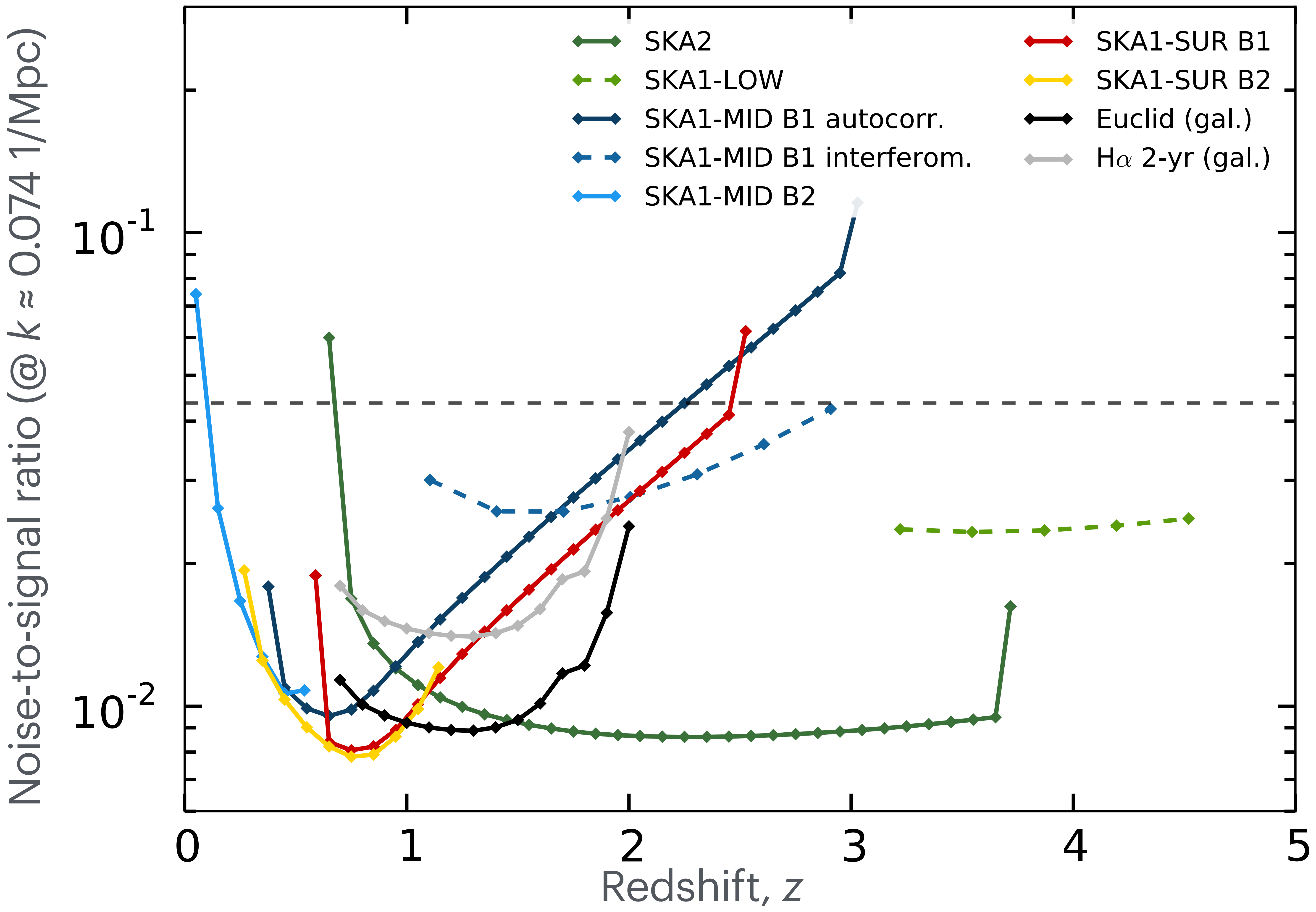
HI intensity mapping

[Bacon, SC et al. (2020)]



HI intensity mapping

[Santos, SC et al. (2015)]



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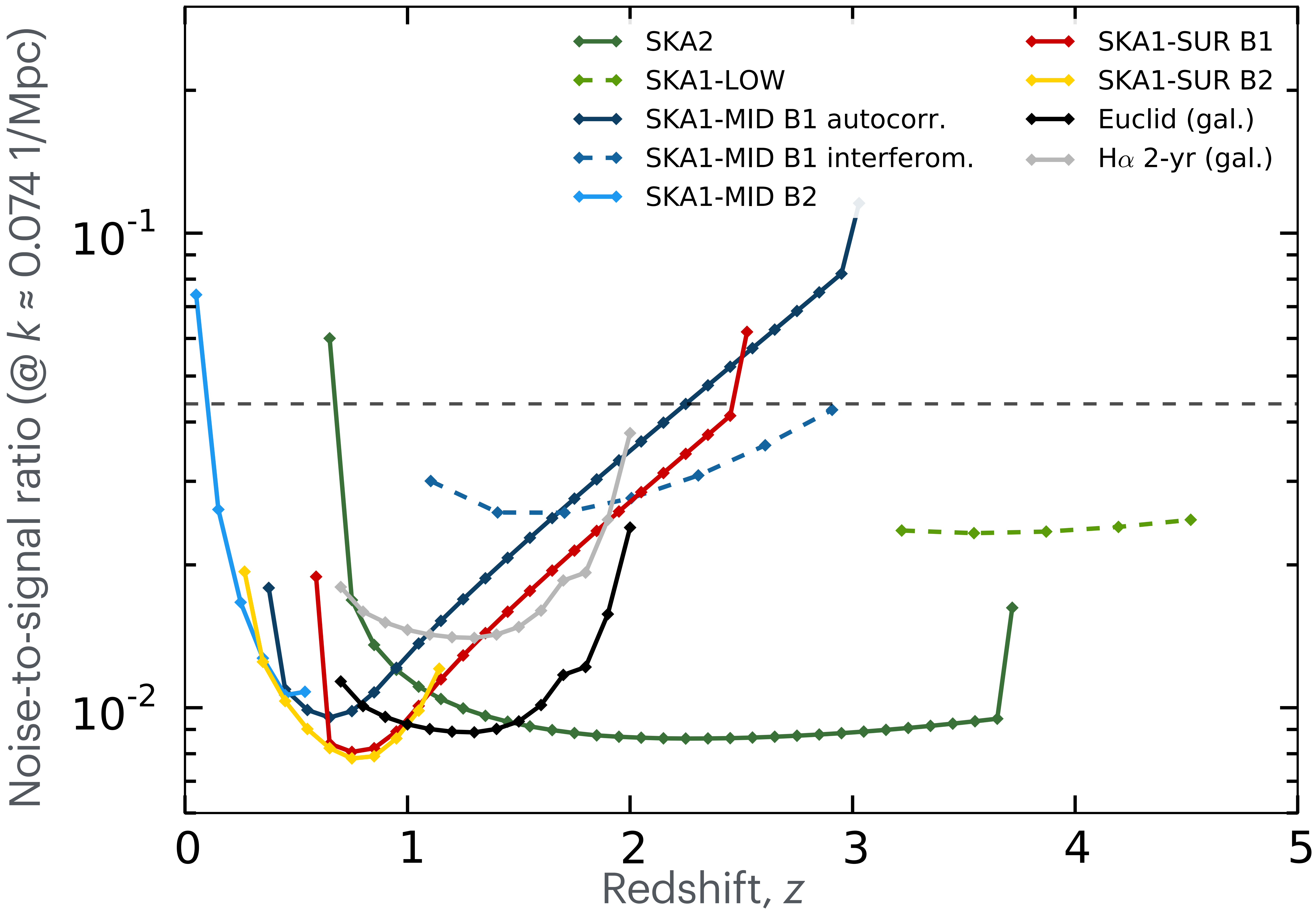
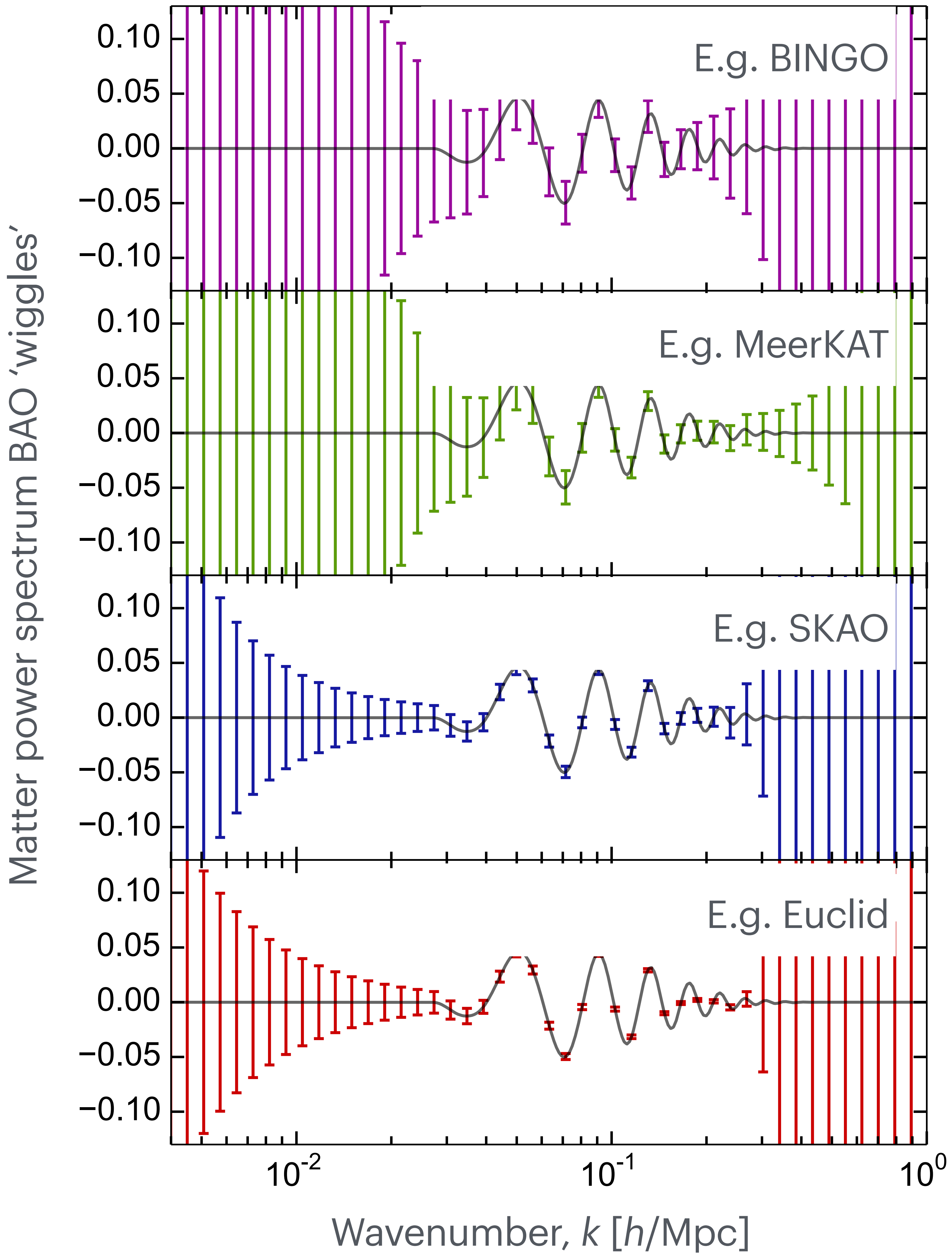
HI intensity mapping

[Santos, SC et al. (2015)]

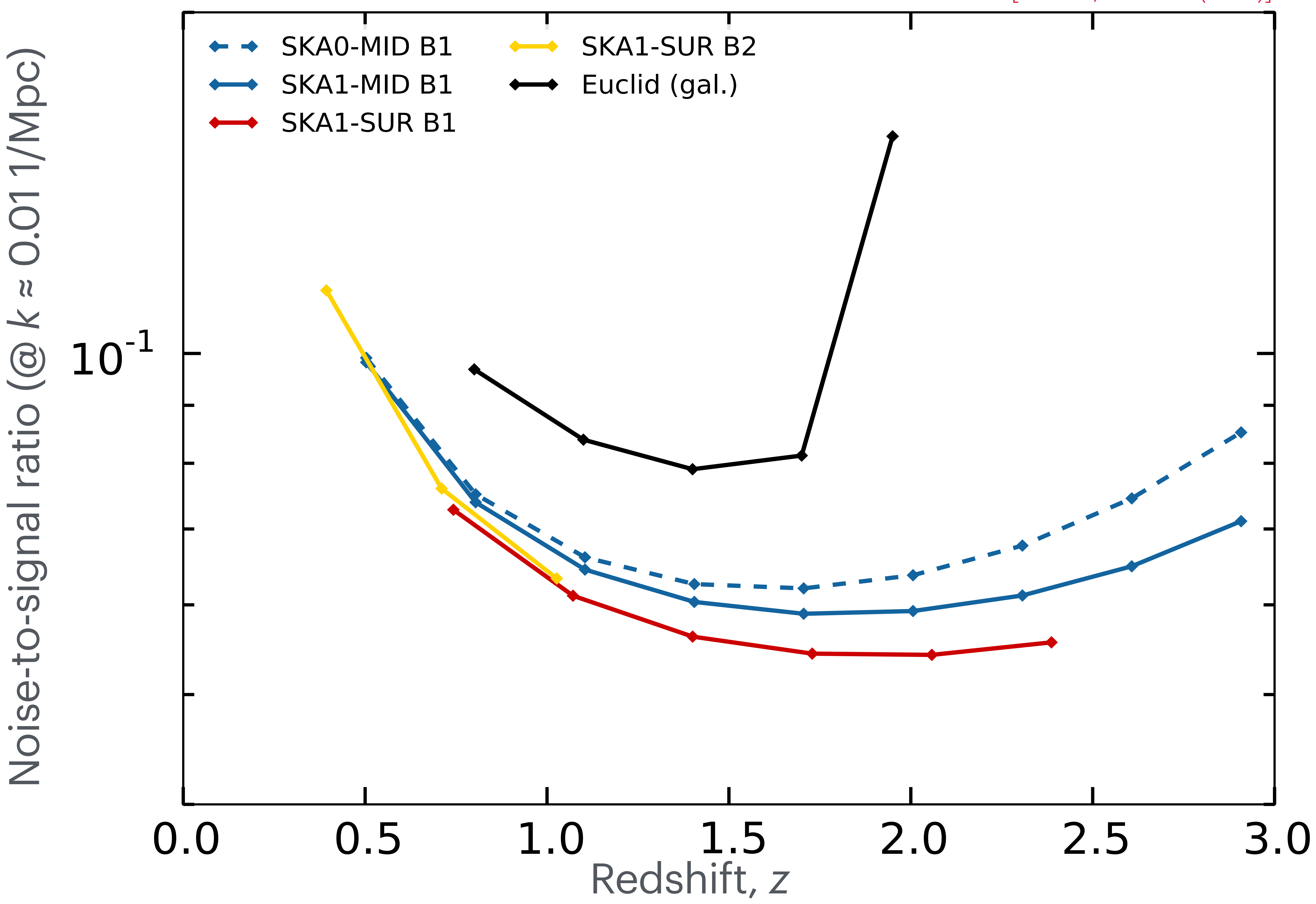


[Bull et al. (2015)]



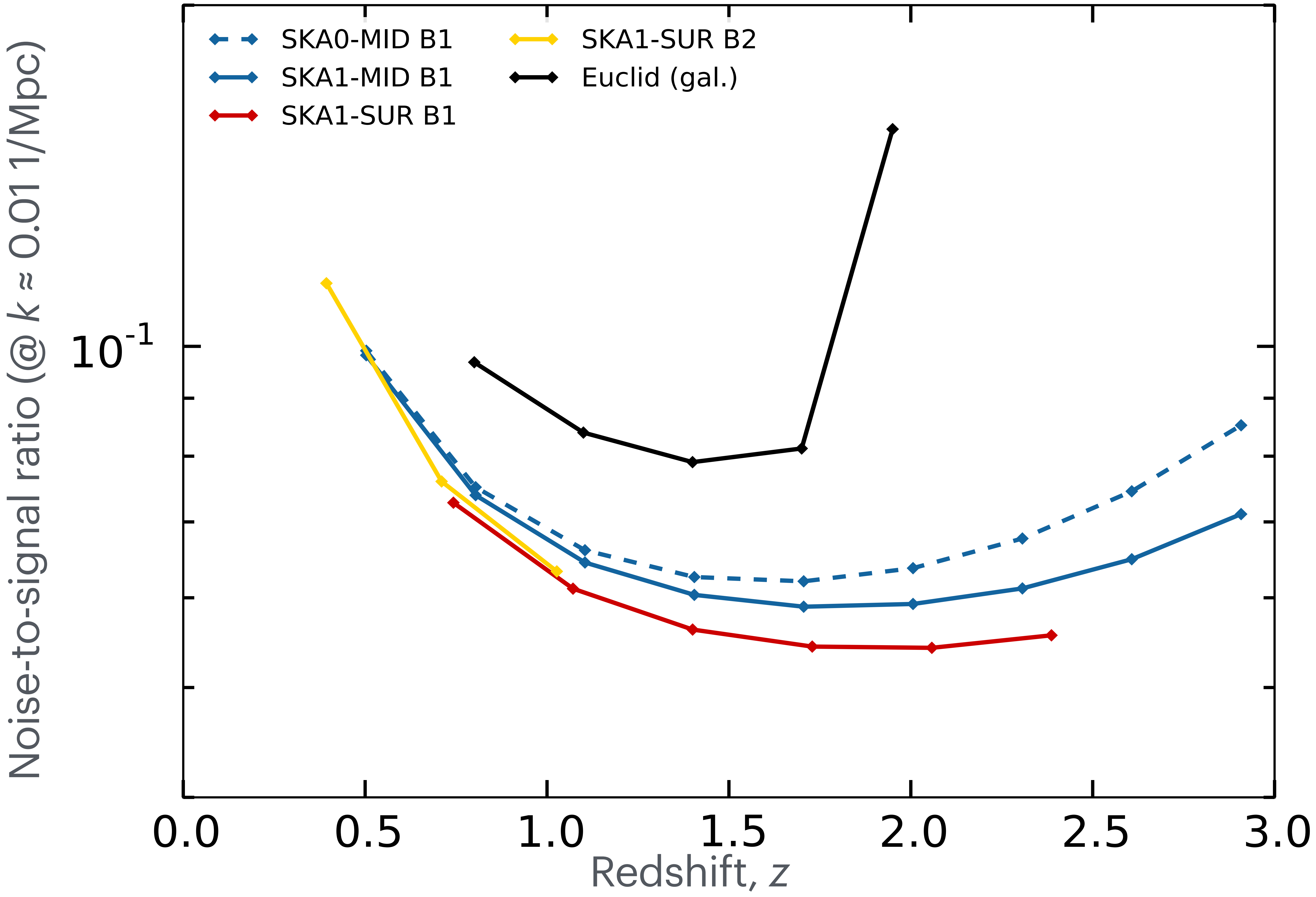
Hɪ intensity mapping

[Santos, SC et al. (2015)]



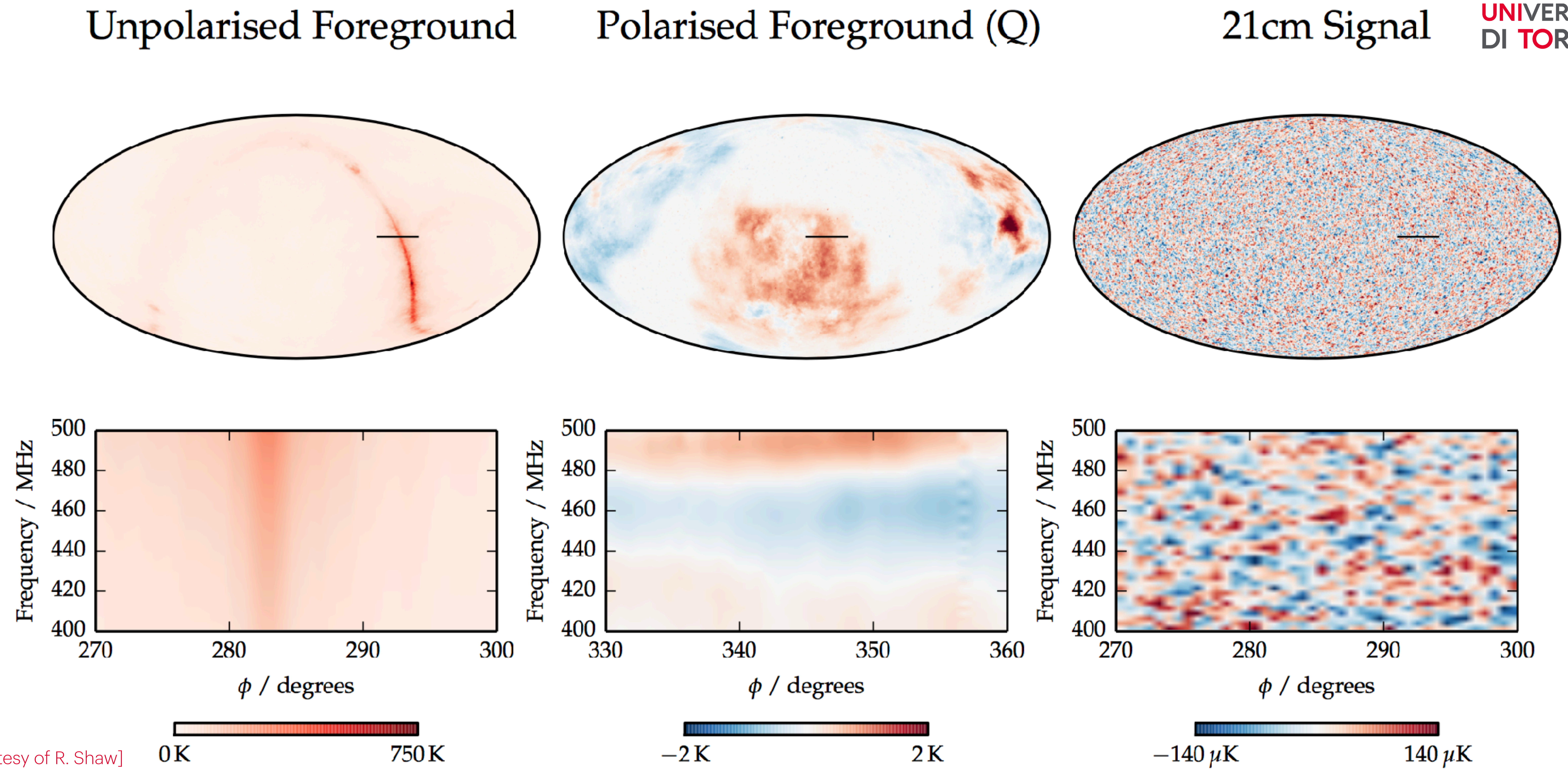
HI intensity mapping

[Santos, SC et al. (2015)]



- Sensitivity to ultra-large scale effects
  - Primordial non-Gaussianity (for inflation)
  - Relativistic, light-cone projection effects (for modified gravity)

HI intensity mapping



[Courtesy of R. Shaw]

Radio weak lensing

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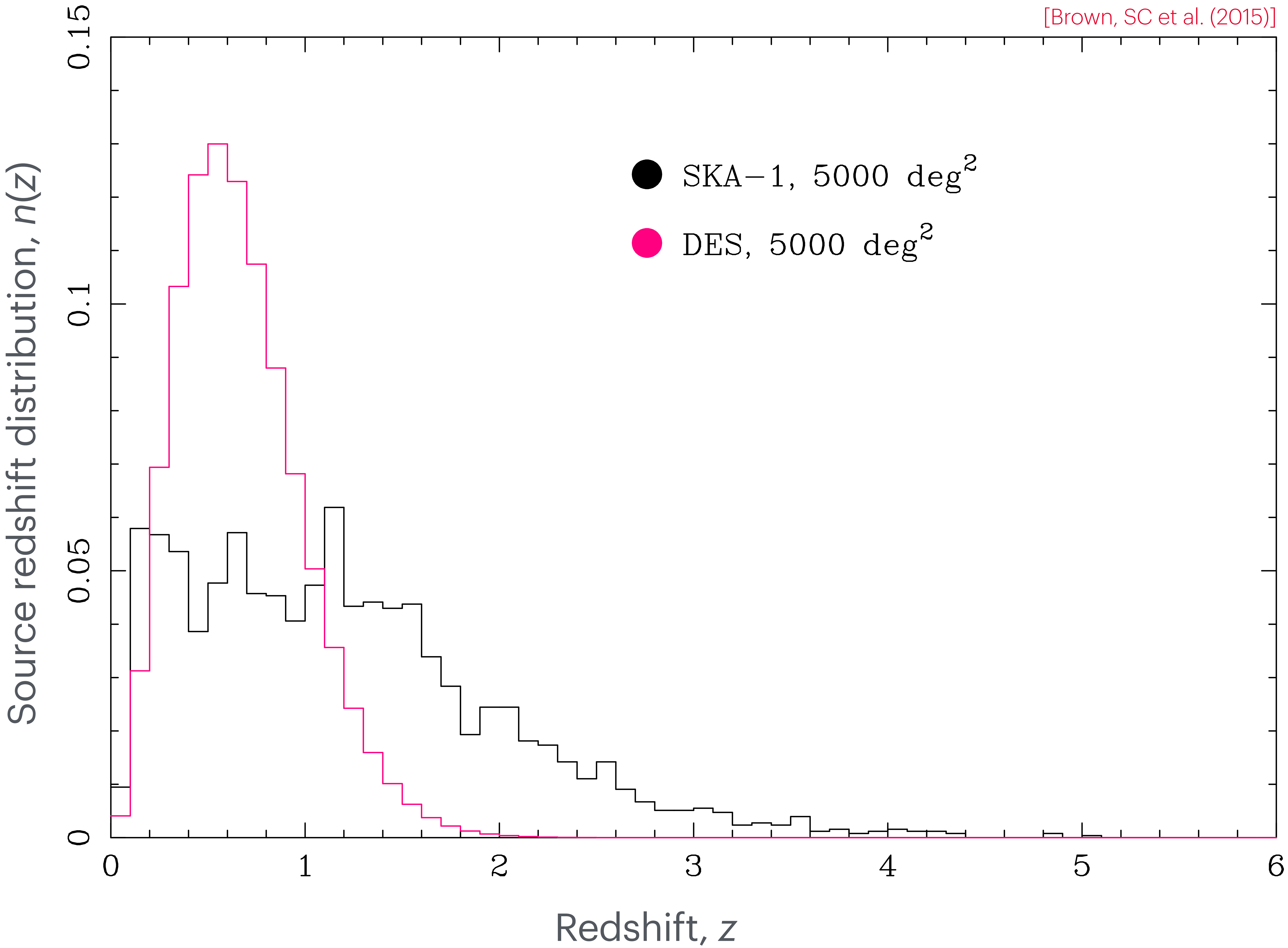
- Origin: weak lensing shearing of imaged galaxy ellipticities
- Pros: complementary to clustering, insensitive to galaxy bias
- Cons: low signal to noise, needs (?) imaging
- Examples:
  - VLA FIRST (~90 sources per sq. deg. vs to ~10 per sq. arcmin. in opt.)
    [Chang et al. (Nature 2004)]
  - VLA+MERLIN (also in cross-correlation w/ optical shear estimates)
    [Patel et al. (2010)]

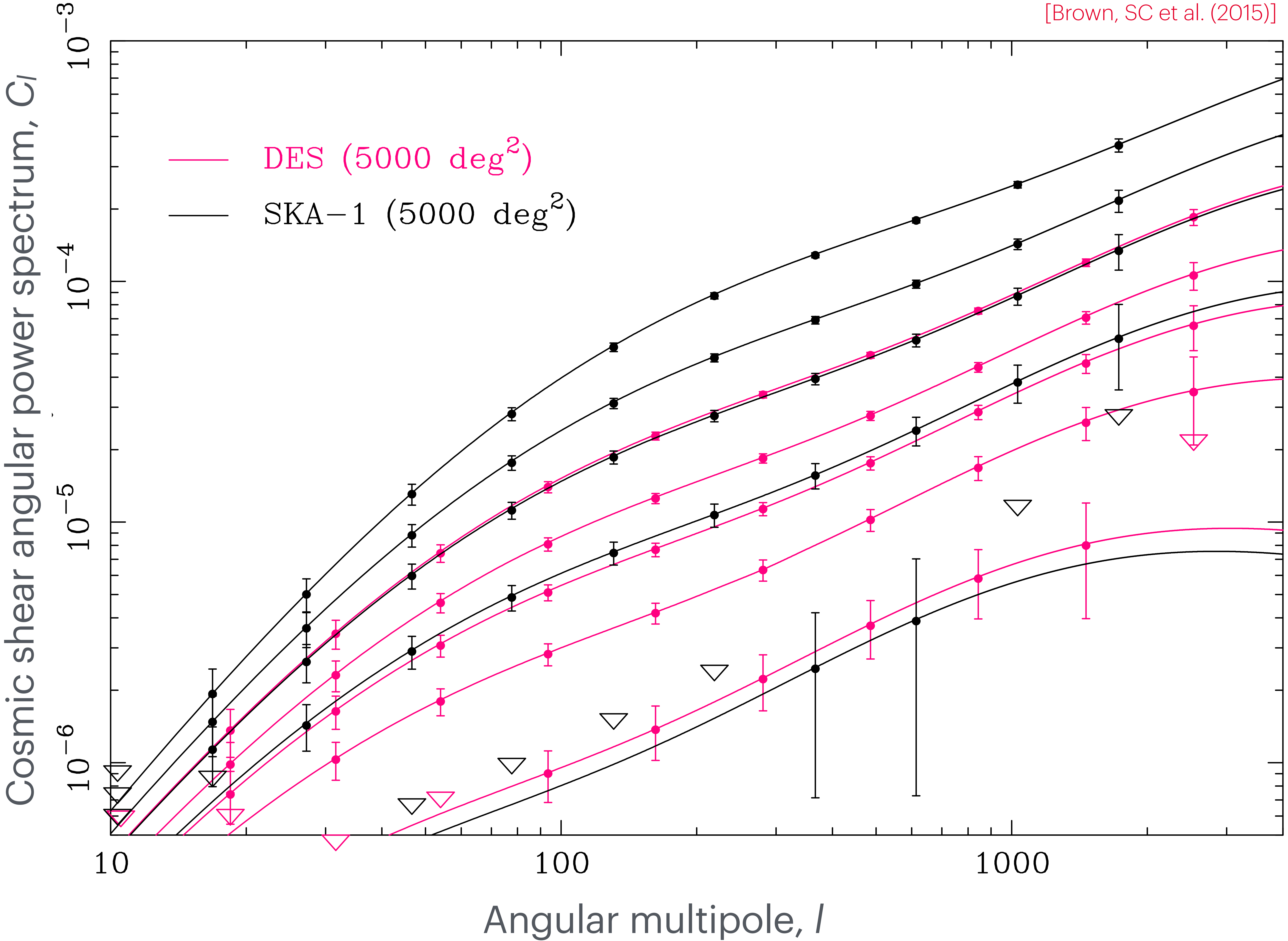
Radio weak lensing

[Brown, SC et al. (2015)]



Radio weak lensing

[Brown, SC et al. (2015)]



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Radio weak lensing

$$\gamma^{\rm obs}(z,\vec{\theta}) = \gamma(z,\vec{\theta}) + \gamma^{\rm sys}(z,\vec{\theta})$$

Radio weak lensing

$$\gamma^{\rm obs}(z,\vec{\theta}) = \gamma(z,\vec{\theta}) + \gamma^{\rm sys}(z,\vec{\theta})$$

$$\langle\gamma^{\rm obs}\gamma^{\rm obs}\rangle = \langle\gamma\gamma\rangle + 2\langle\gamma^{\rm sys}\gamma\rangle + \langle\gamma^{\rm sys}\gamma^{\rm sys}\rangle$$

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Radio weak lensing

$$\gamma^{\mathrm{obs}}(z,\vec{\theta}) = \gamma(z,\vec{\theta}) + \gamma^{\mathrm{sys}}(z,\vec{\theta})$$

$$\langle\gamma^{\mathrm{obs}}\gamma^{\mathrm{obs}}\rangle = \langle\gamma\gamma\rangle + \xcancel{2\langle\gamma^{\mathrm{sys}}\gamma\rangle} + \langle\gamma^{\mathrm{sys}}\gamma^{\mathrm{sys}}\rangle$$

Radio weak lensing

$$\gamma^{\rm obs}(z,\vec{\theta}) = \gamma(z,\vec{\theta}) + \gamma^{\rm sys}(z,\vec{\theta})$$

$$\langle\gamma^{\rm obs}\gamma^{\rm obs}\rangle = \langle\gamma\gamma\rangle + \cancel{2\langle\gamma^{\rm sys}\gamma\rangle} + \langle\gamma^{\rm sys}\gamma^{\rm sys}\rangle$$

$$\langle\gamma^{\rm obs}_{(o)}\gamma^{\rm obs}_{(r)}\rangle = \langle\gamma\gamma\rangle + \langle\gamma^{\rm sys}_{(o)}\gamma_{(r)}\rangle + \langle\gamma_{(o)}\gamma^{\rm sys}_{(r)}\rangle + \langle\gamma^{\rm sys}_{(o)}\gamma^{\rm sys}_{(r)}\rangle$$

Radio weak lensing

$$\gamma^{\mathrm{obs}}(z,\vec{\theta}) = \gamma(z,\vec{\theta}) + \gamma^{\mathrm{sys}}(z,\vec{\theta})$$

$$\langle\gamma^{\mathrm{obs}}\gamma^{\mathrm{obs}}\rangle = \langle\gamma\gamma\rangle + \cancel{2\langle\gamma^{\mathrm{sys}}\gamma\rangle} + \langle\gamma^{\mathrm{sys}}\gamma^{\mathrm{sys}}\rangle$$

$$\langle\gamma^{\mathrm{obs}}_{(o)}\gamma^{\mathrm{obs}}_{(r)}\rangle = \langle\gamma\gamma\rangle + \cancel{\langle\gamma^{\mathrm{sys}}_{(o)}\gamma_{(r)}\rangle} + \cancel{\langle\gamma_{(o)}\gamma^{\mathrm{sys}}_{(r)}\rangle} + \langle\gamma^{\mathrm{sys}}_{(o)}\gamma^{\mathrm{sys}}_{(r)}\rangle$$

Radio weak lensing

$$\gamma^{\mathrm{obs}}(z,\vec{\theta}) = \gamma(z,\vec{\theta}) + \gamma^{\mathrm{sys}}(z,\vec{\theta})$$

$$\langle\gamma^{\mathrm{obs}}\gamma^{\mathrm{obs}}\rangle = \langle\gamma\gamma\rangle + \cancel{2\langle\gamma^{\mathrm{sys}}\gamma\rangle} + \langle\gamma^{\mathrm{sys}}\gamma^{\mathrm{sys}}\rangle$$

$$\langle\gamma^{\mathrm{obs}}_{(o)}\gamma^{\mathrm{obs}}_{(r)}\rangle = \langle\gamma\gamma\rangle + \cancel{\langle\gamma^{\mathrm{sys}}_{(o)}\gamma_{(r)}\rangle} + \cancel{\langle\gamma_{(o)}\gamma^{\mathrm{sys}}_{(r)}\rangle} + \cancel{\langle\gamma^{\mathrm{sys}}_{(o)}\gamma^{\mathrm{sys}}_{(r)}\rangle}$$

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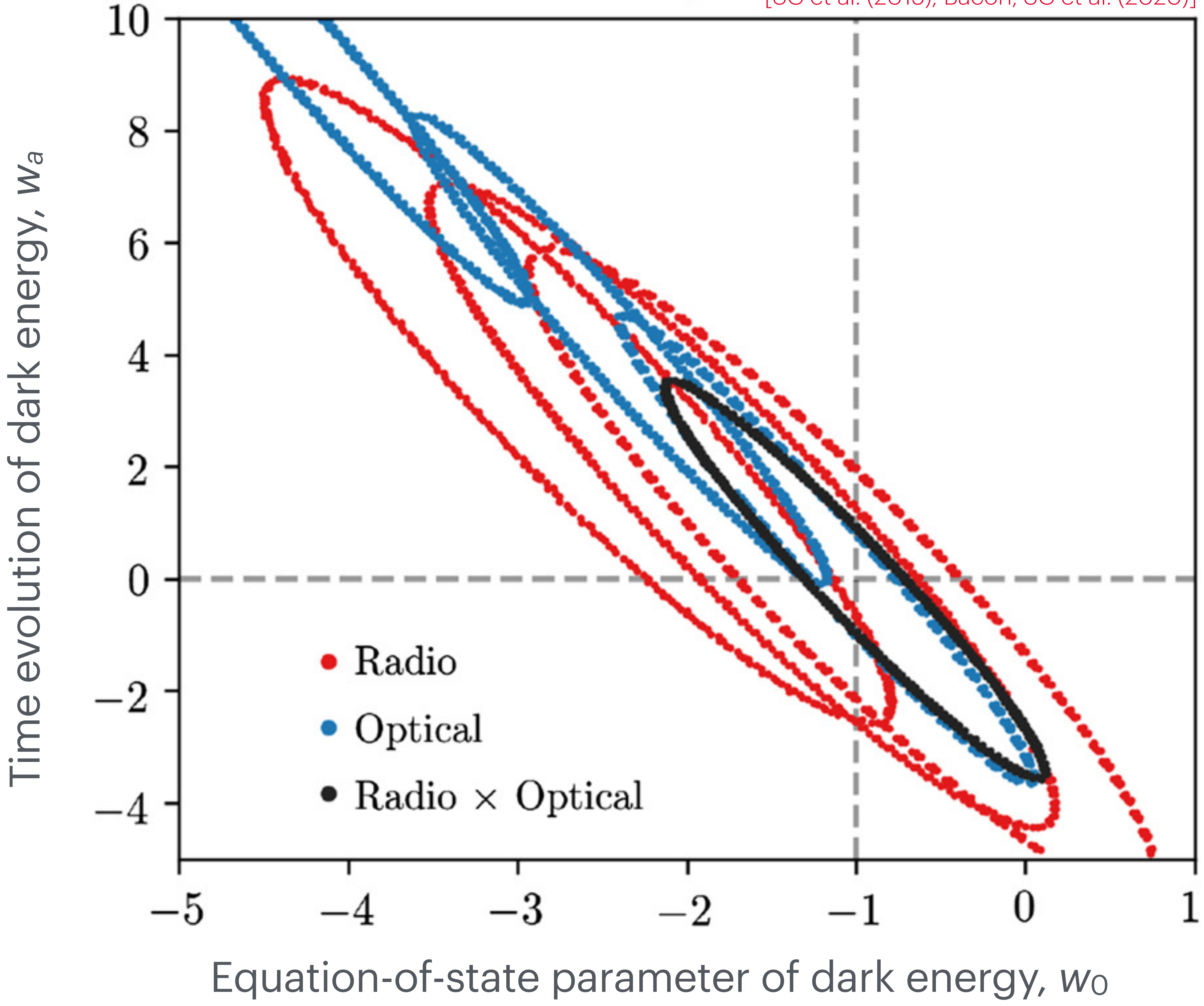
Radio weak lensing

[SC et al. (2015); Bacon, SC et al. (2020)]



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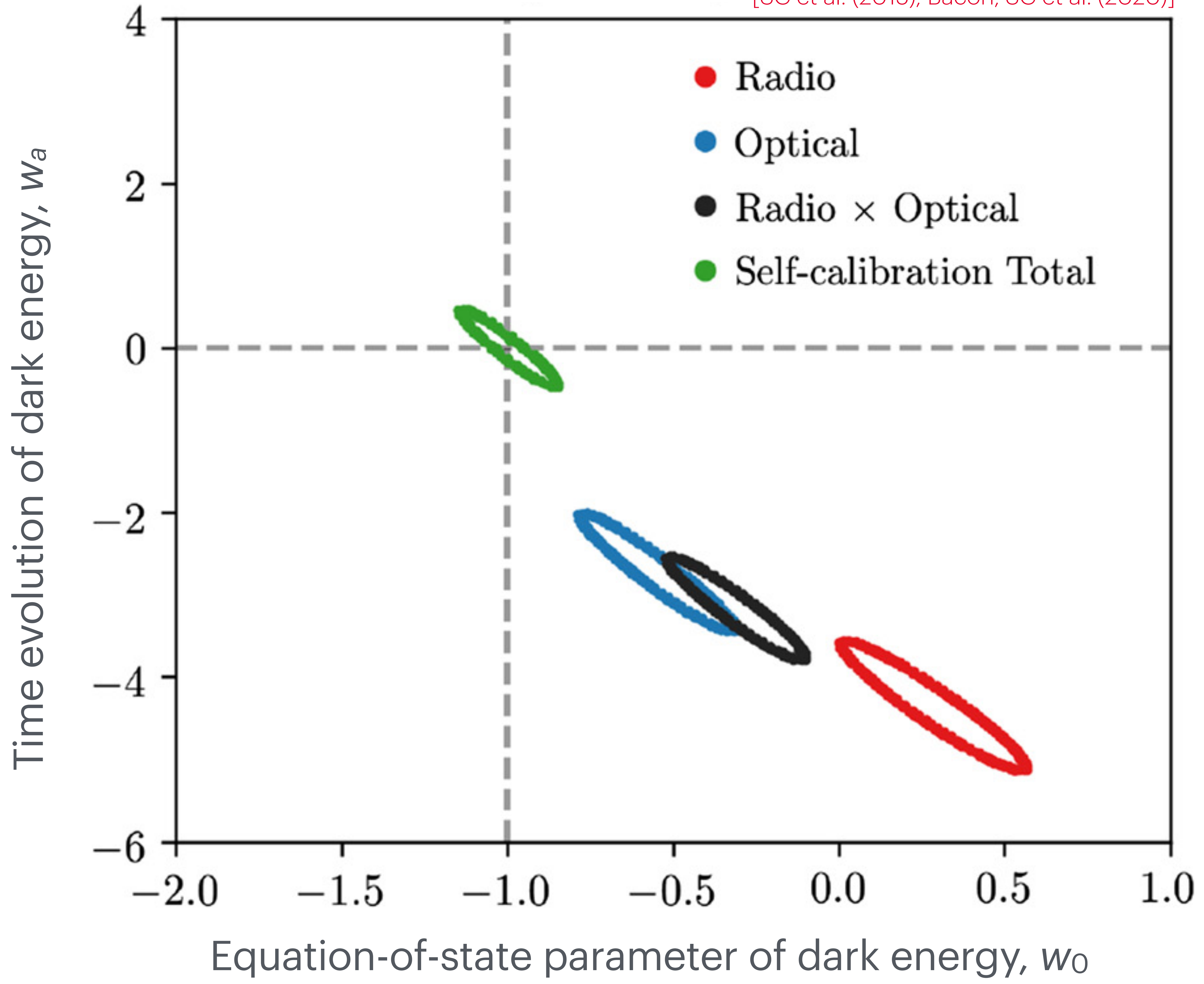
Radio weak lensing

[SC et al. (2015); Bacon, SC et al. (2020)]



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Towards the SKAO

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[Courtesy of A. Bonaldi]

Precursors

Located at future SKA sites (South Africa and Australia)

Pathfinders

Engaged in SKA related technology and science studies