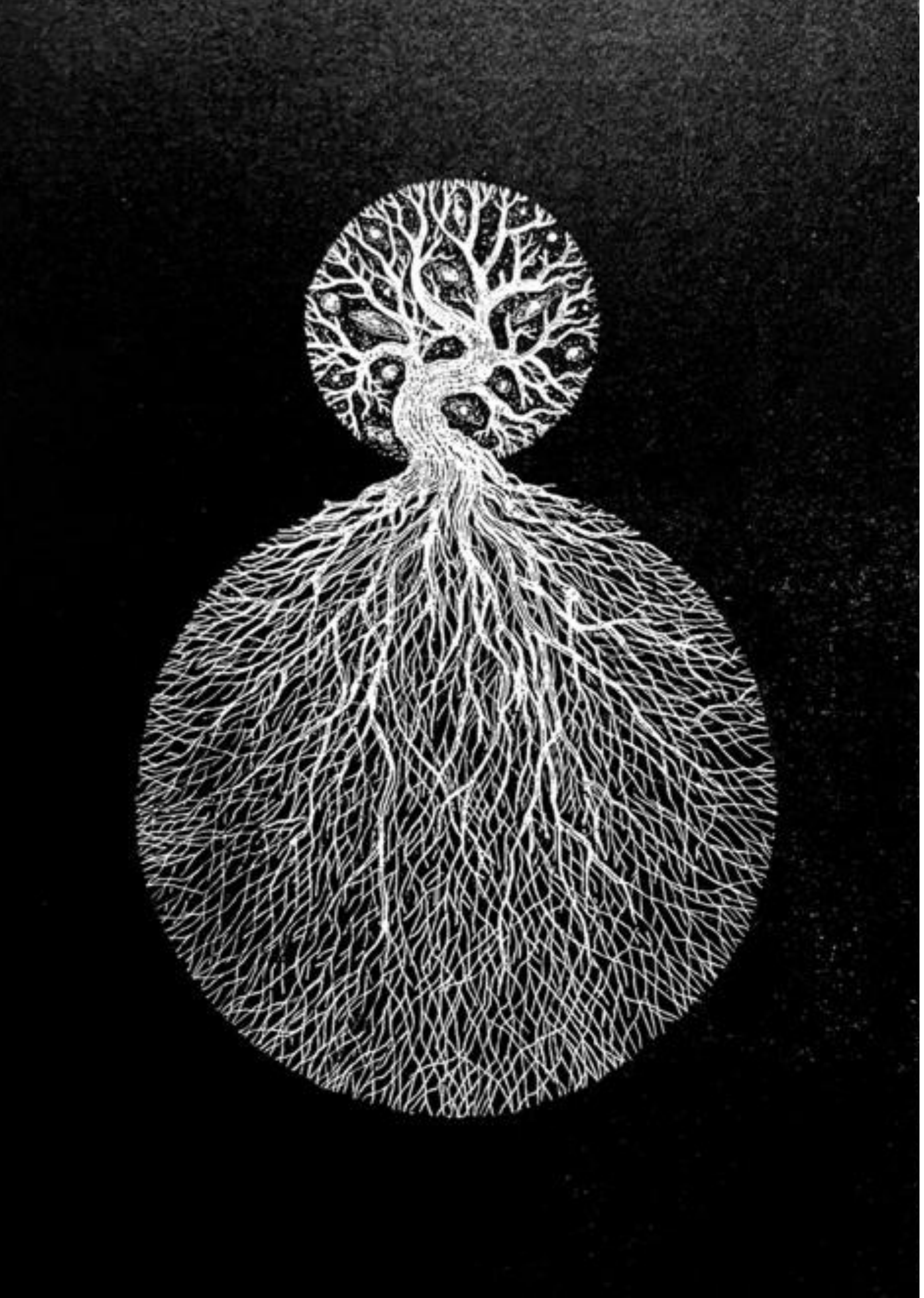


Dark energy with the SKA Observatory

Stefano Camera

Department of Physics, Alma Felix University of Turin, Italy

Physics Torino Department of Excellence

INFN TORINO Istituto Nazionale di Fisica Nucleare Sezione di Torino

INAF Istituto Nazionale di Astrofisica Osservatorio Astrofisico di Torino

University of the Western Cape

Università di Torino

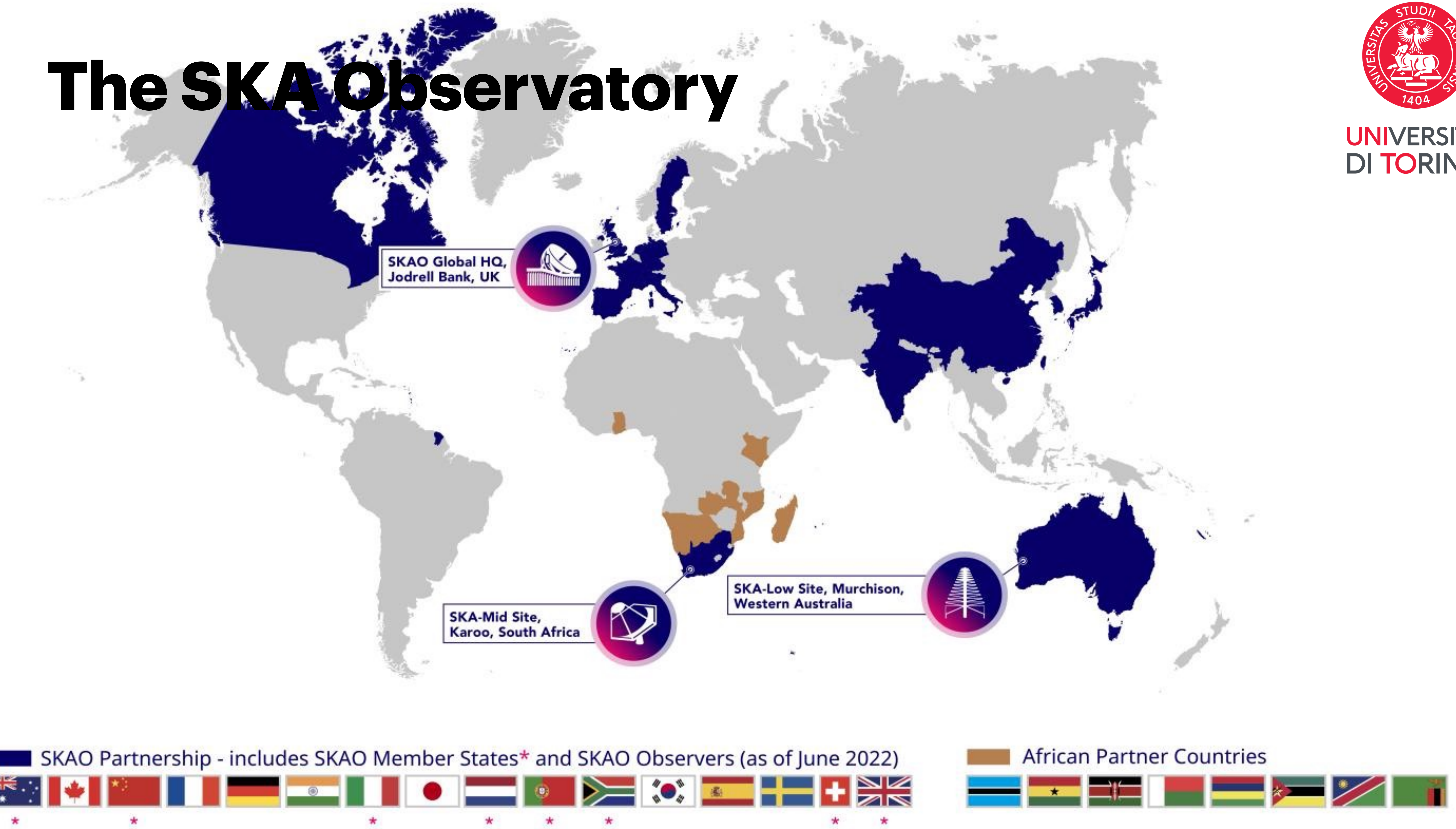
The SKA Observatory

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

The SKA Observatory

The SKA Observatory

The SKA Observatory



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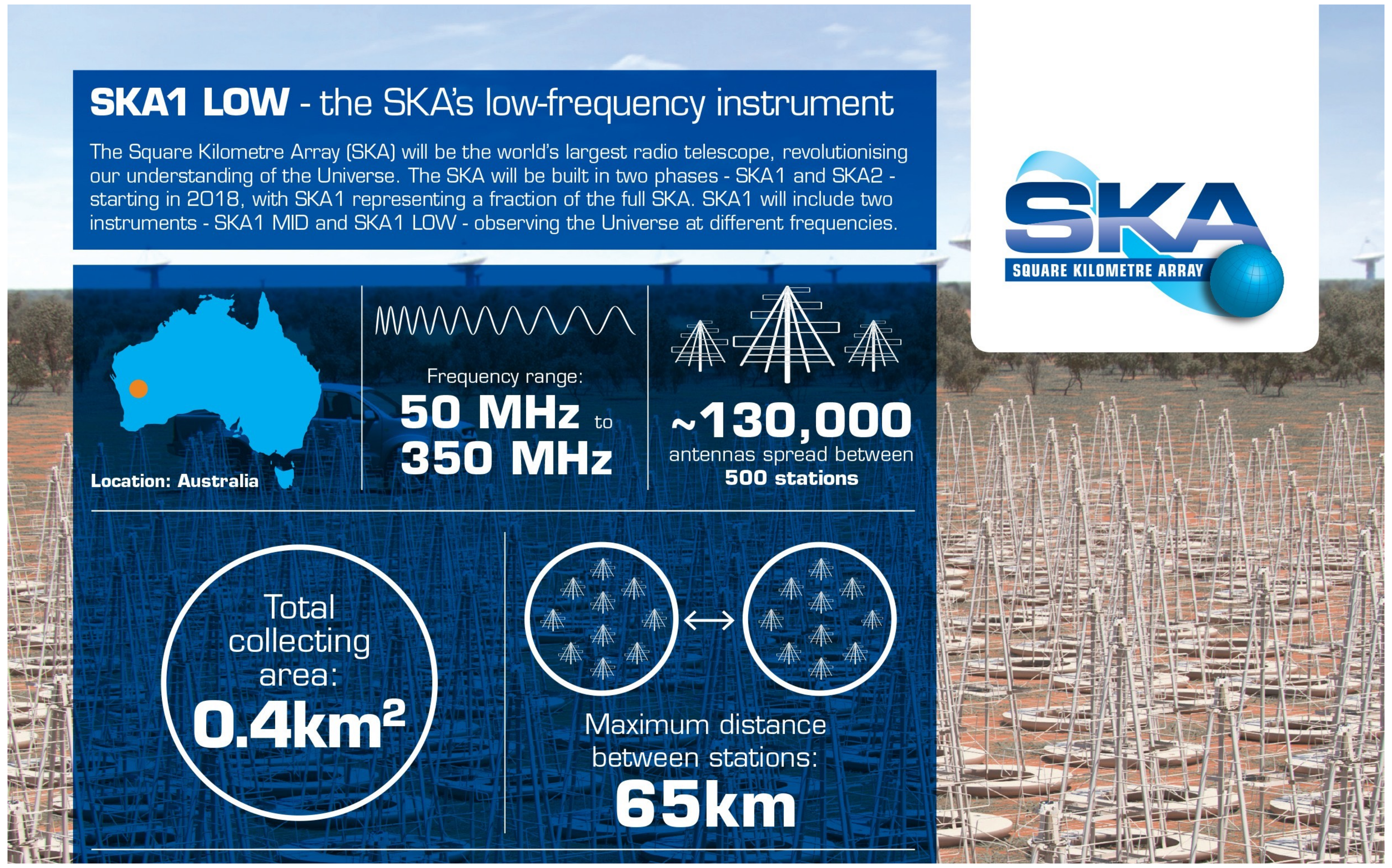
The SKA Project

- 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

The SKA Project

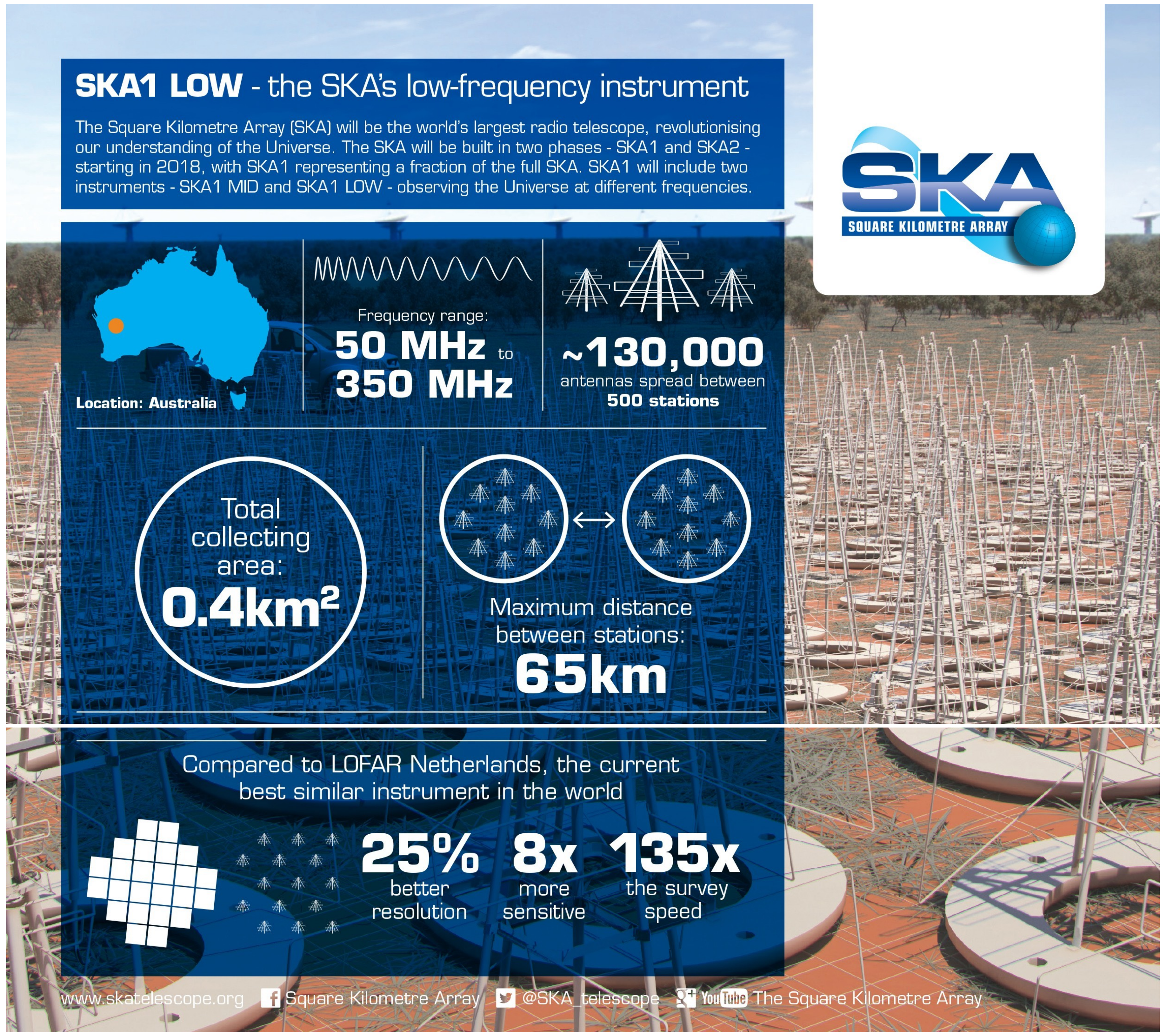


12 · IX · 2023

Dark energy with the SKAO

Stefano Camera

The SKA Project



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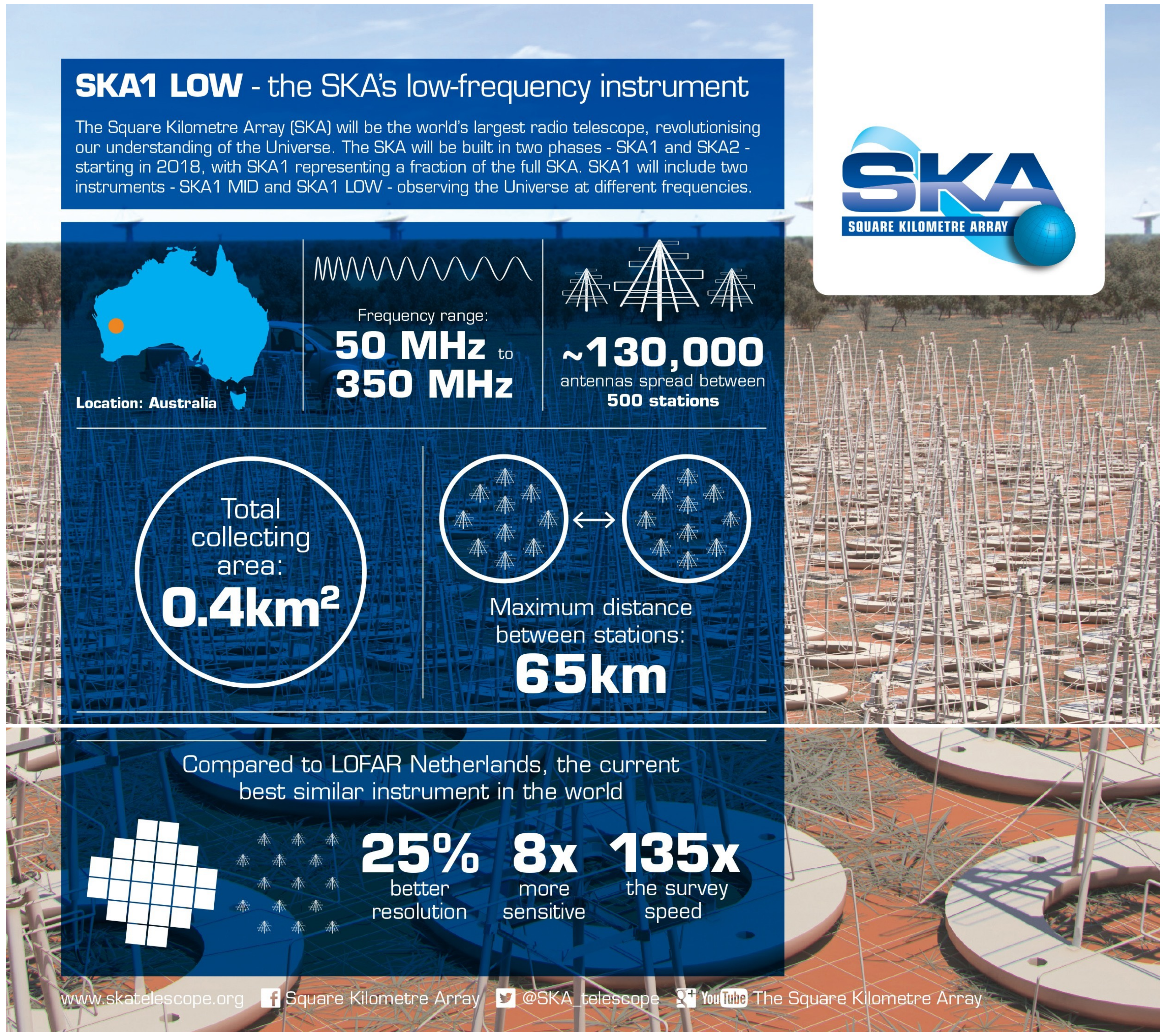

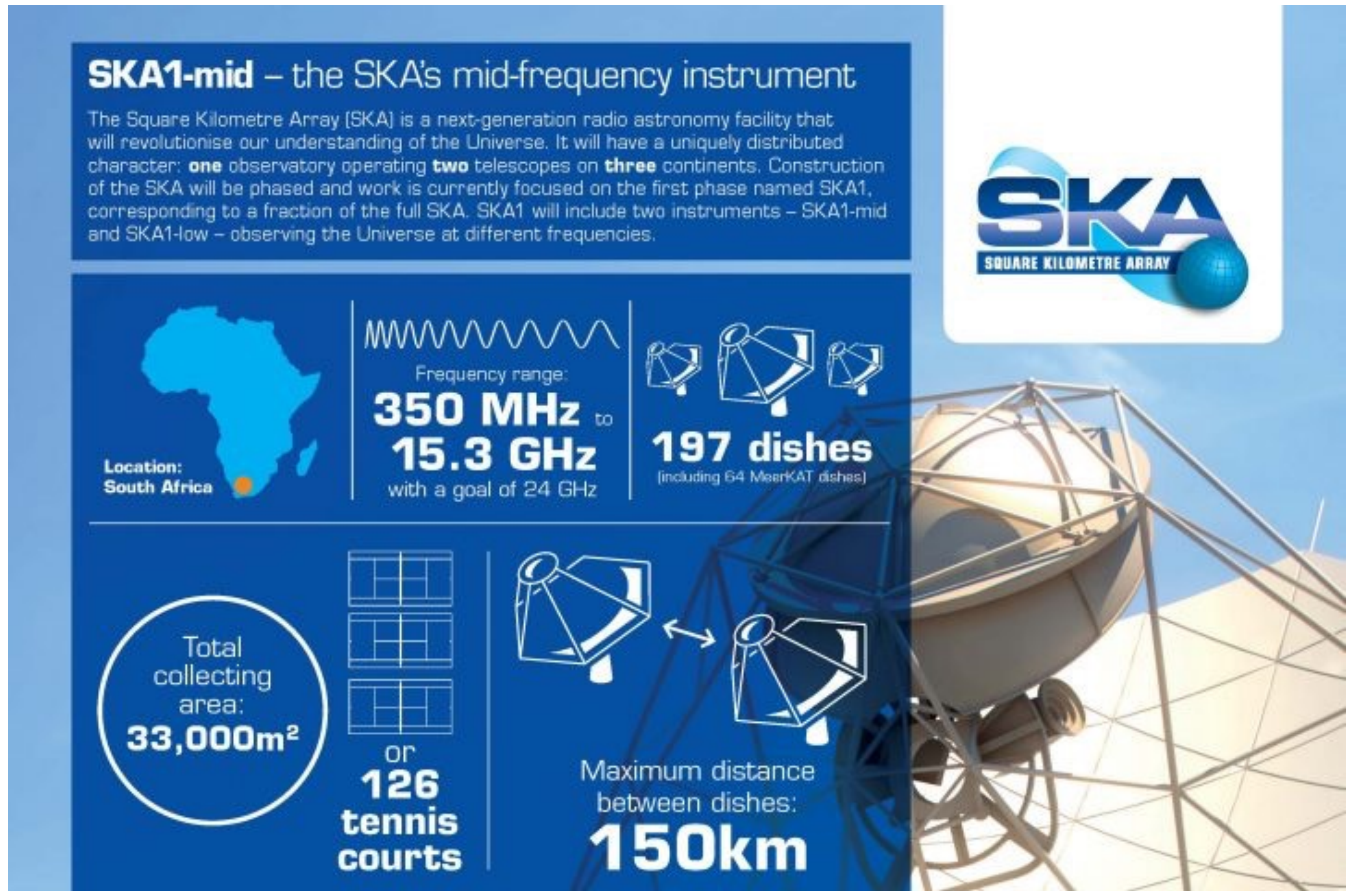

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Dark energy with the SKAO

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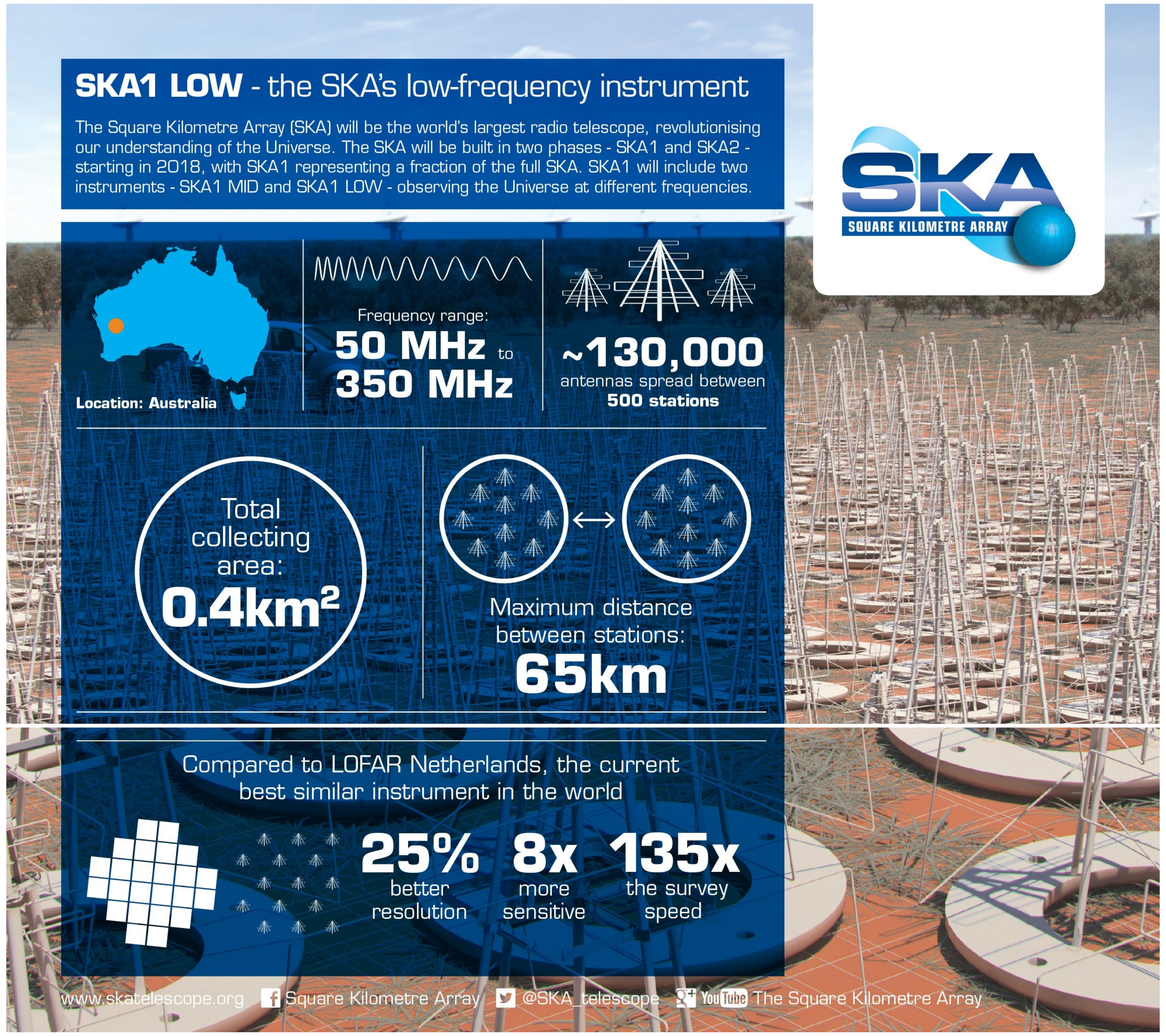

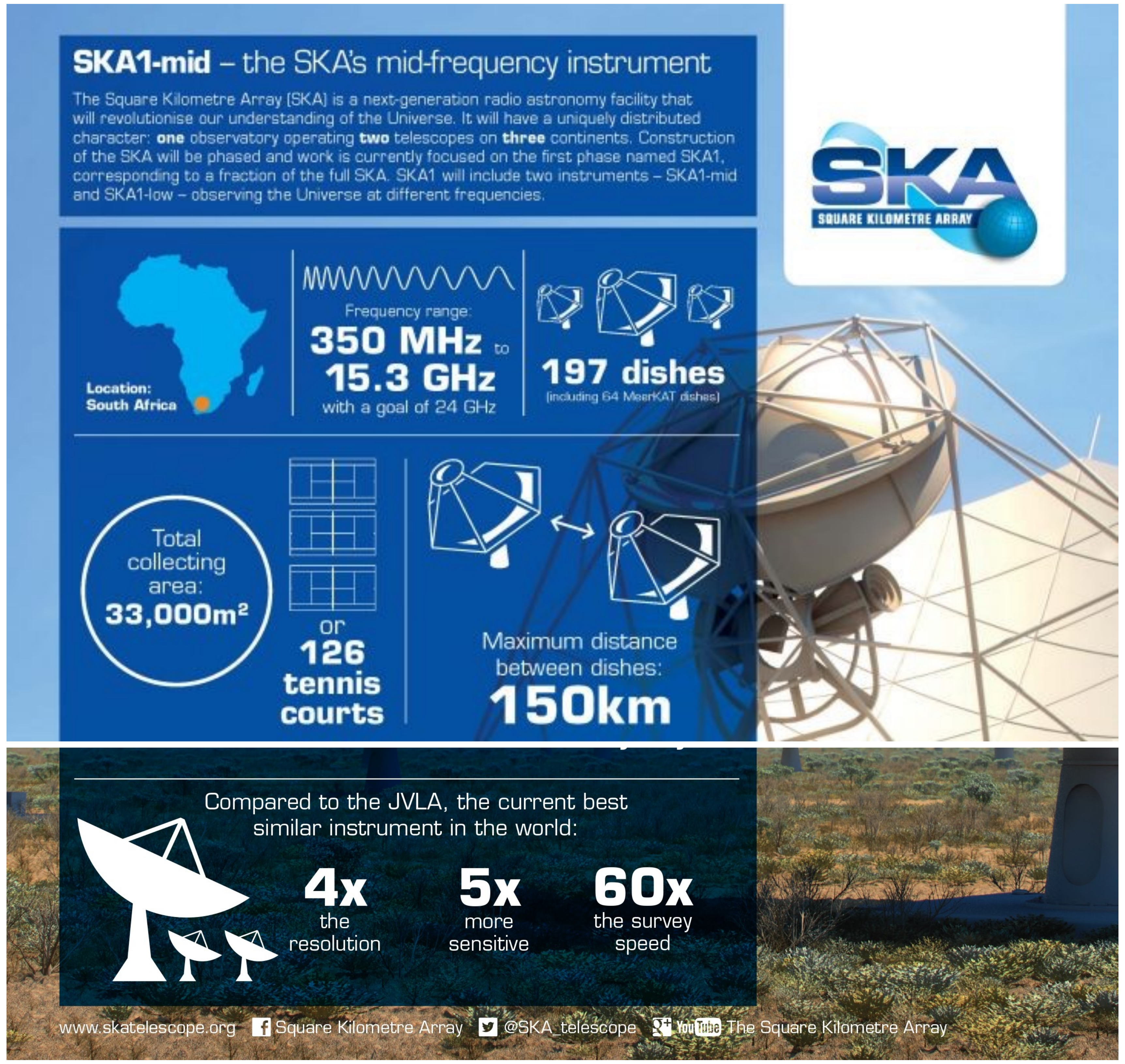

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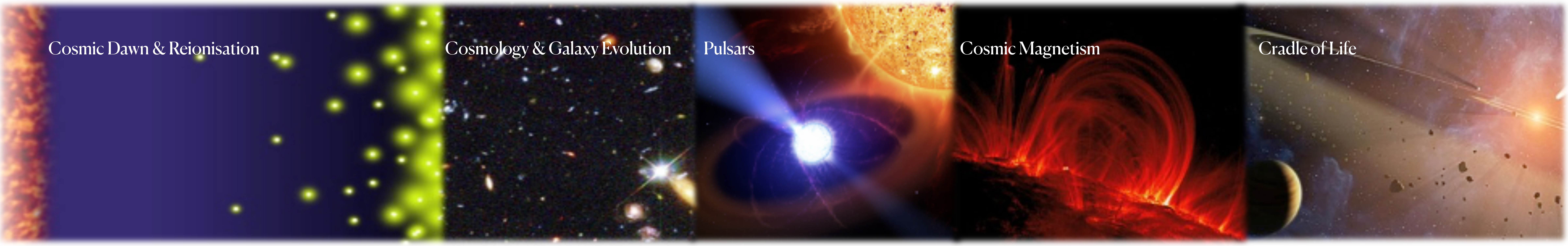
SKAO Science



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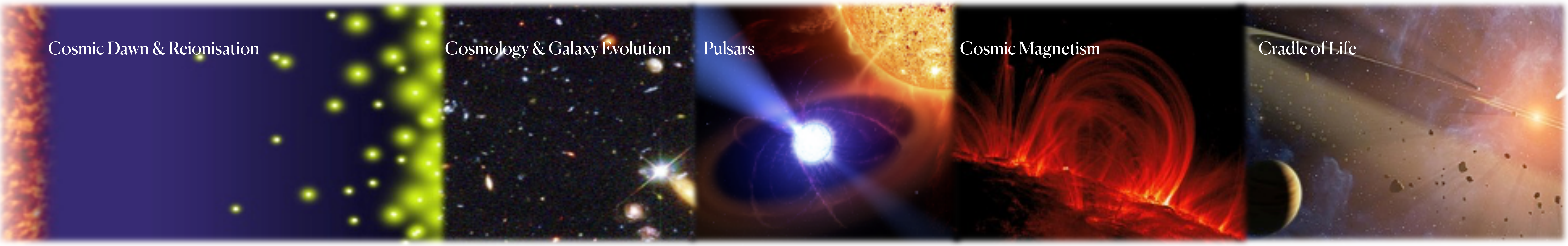

SKAO's Low telescope

50-350 MHz

SKAO's Mid telescope

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]

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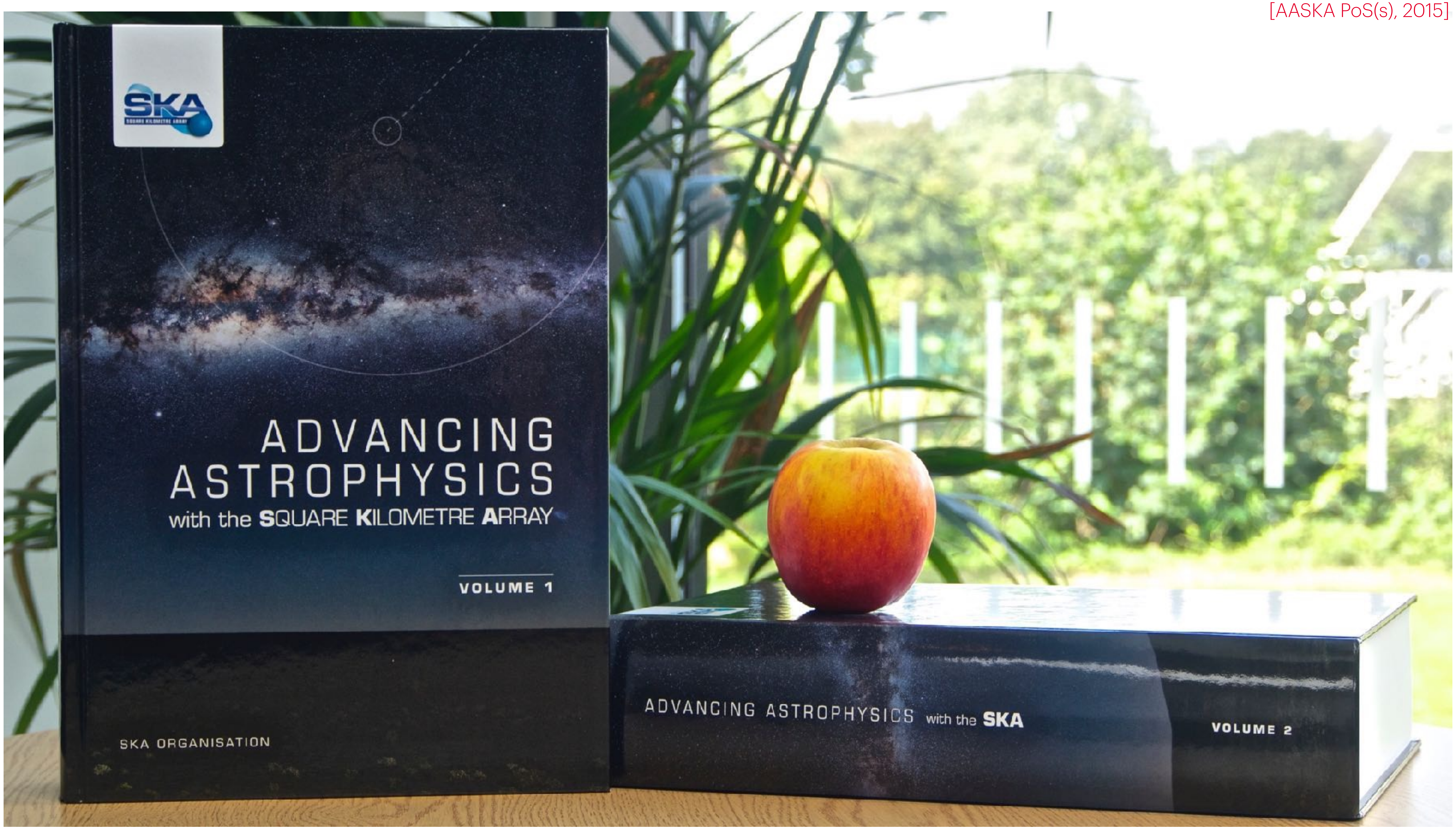

SKAO Cosmology

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

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[SKA Cosmology SWG ⊃ SC (2020)]

Research Paper

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

SKAO Cosmology

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

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[SKA Cosmology SWG ⊃ SC, 2020]

Research Paper

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

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

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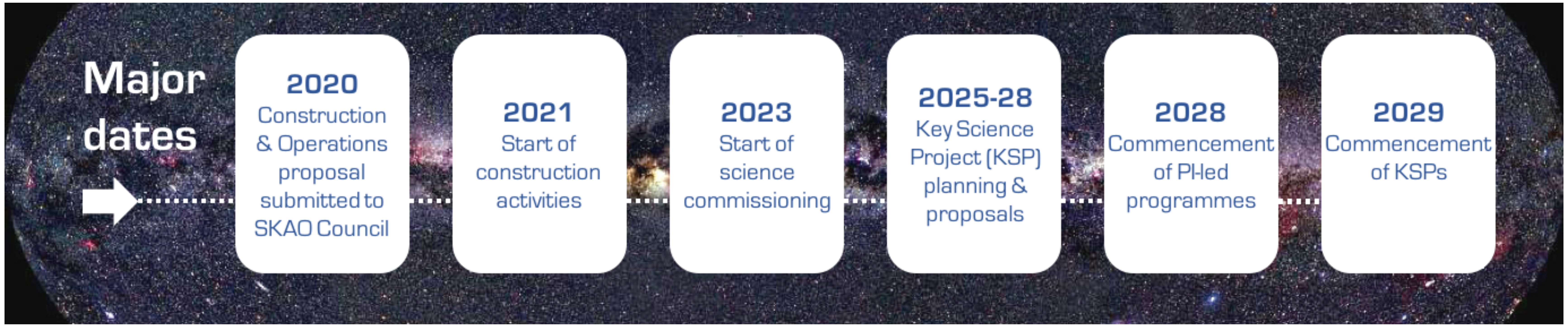
[Weltman et al. ⊃ SC, 2020]

Review (unsolicited)

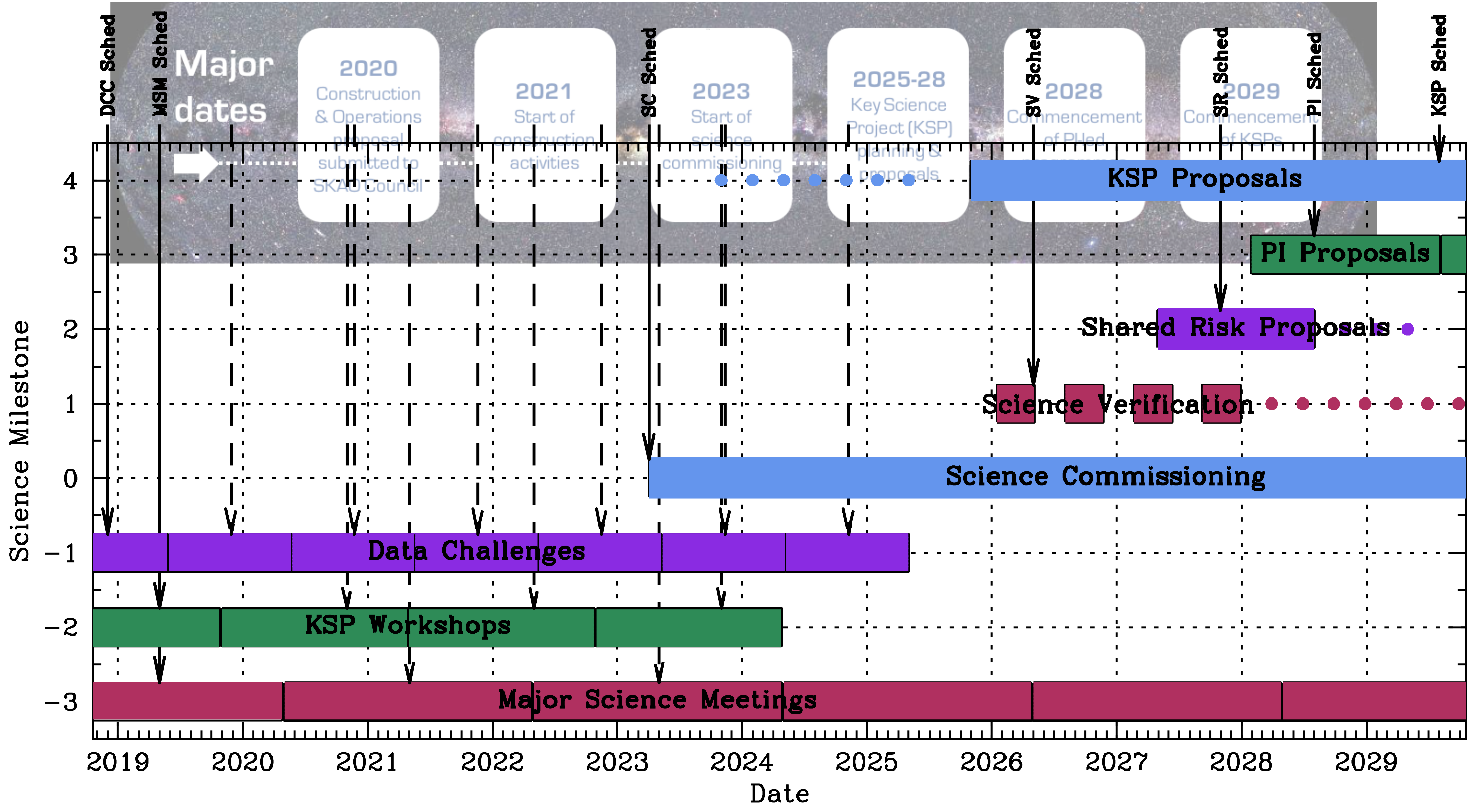
Fundamental physics with the Square Kilometre Array

Towards the SKAO



Towards the SKAO

[Credits: R. Braun]



Towards the SKAO

[Courtesy of A. Bonaldi]

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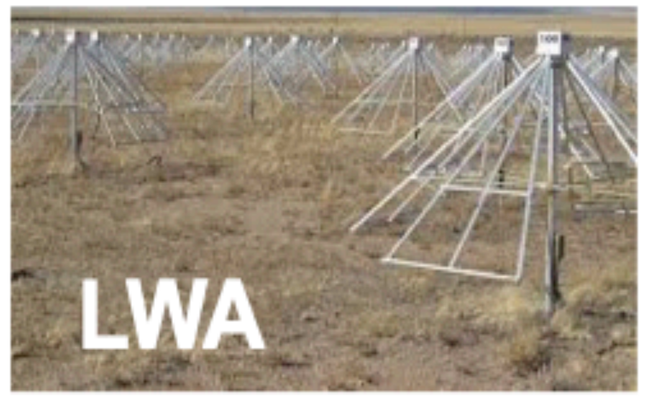
Precursors

Located at future SKA sites (South Africa and Australia)

Pathfinders

Engaged in SKA related technology and science studies



Towards the SKAO

[Courtesy of A. Bonaldi]

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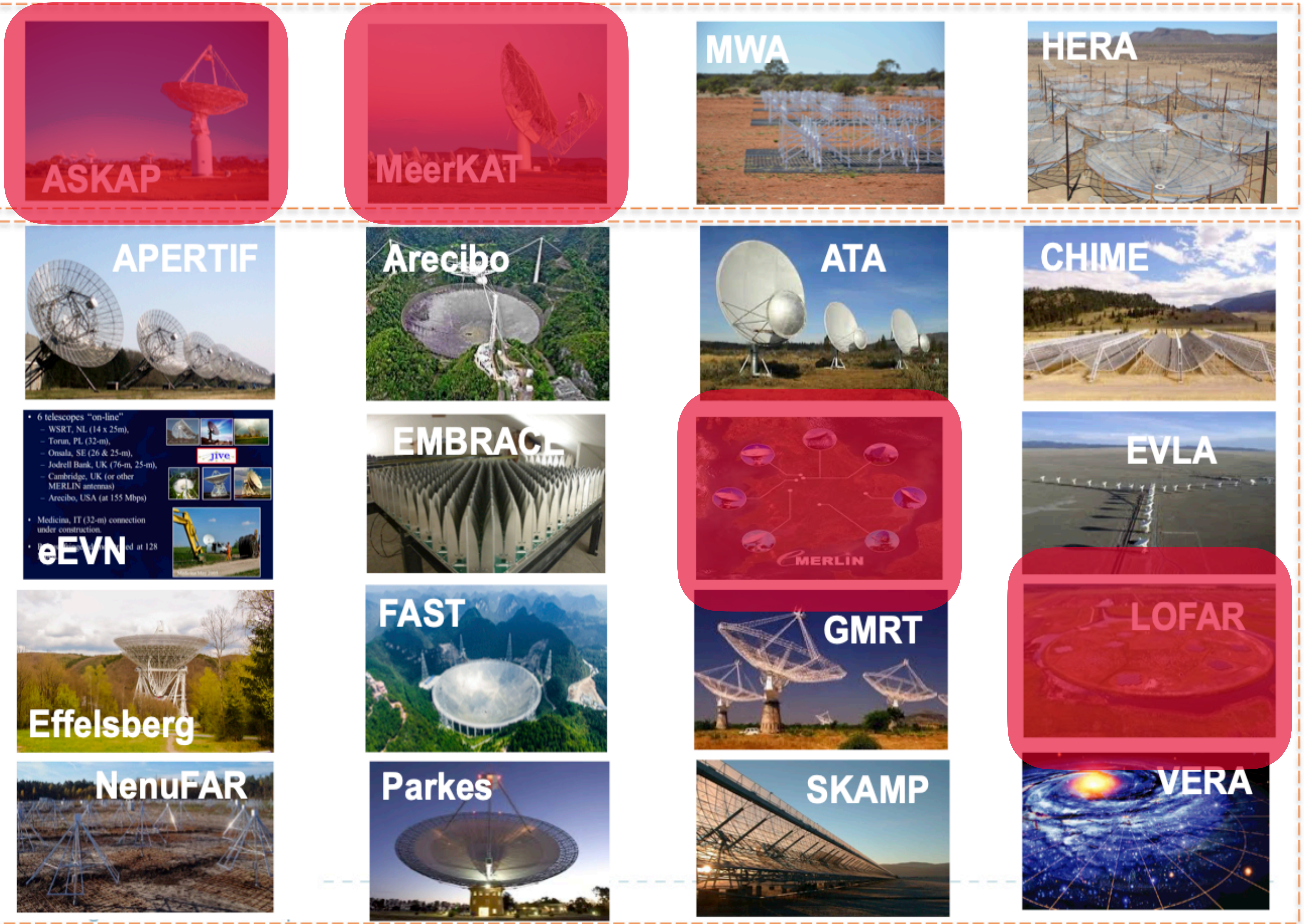

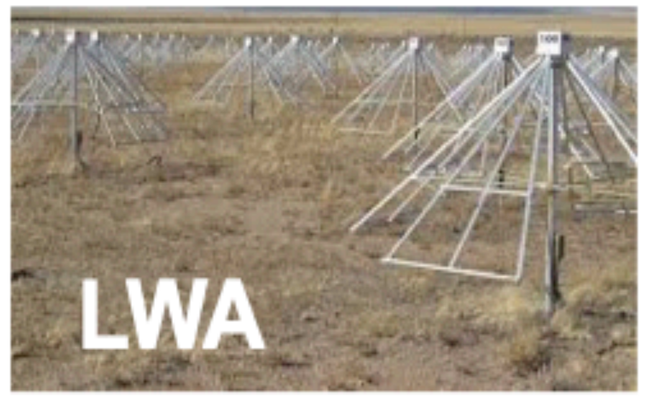

Cosmology at radio wavelengths

- 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: 21-cm emission line of HI (neutral hydrogen) 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})
  - MIGHTEE-HI (20 sq. deg.; ~3k galaxies; $z < 0.4$) [Maddox al. 2021]
  - WALLABY (~30k sq. deg.; ~0.5M galaxies; $z < 0.26$) [Koribalski et al. 2020]

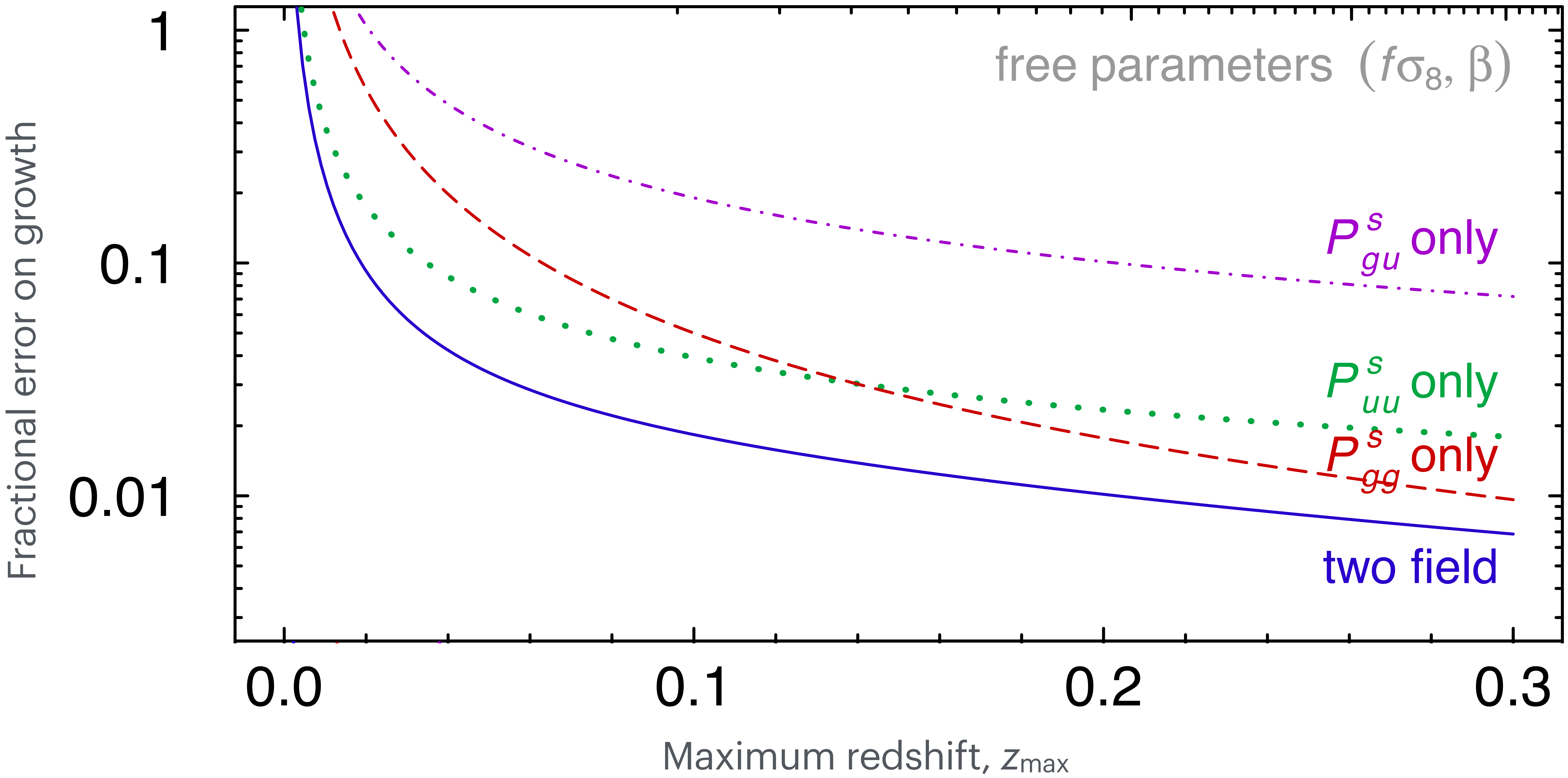
HI-line galaxies

- 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]



HI-line galaxies

- HI-line galaxy surveys are 'Tully-Fisher' surveys

$$f(z) := -\frac{\mathrm{d}D(z)}{\mathrm{d}(1+z)} \simeq [\Omega_\mathrm{m}(z)]^\gamma$$

See Martin's talk about DE/MG!

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HI-line galaxies

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$$f(z) := -\frac{\mathrm{d}D(z)}{\mathrm{d}(1+z)} \simeq [\Omega_\mathrm{m}(z)]^\gamma$$

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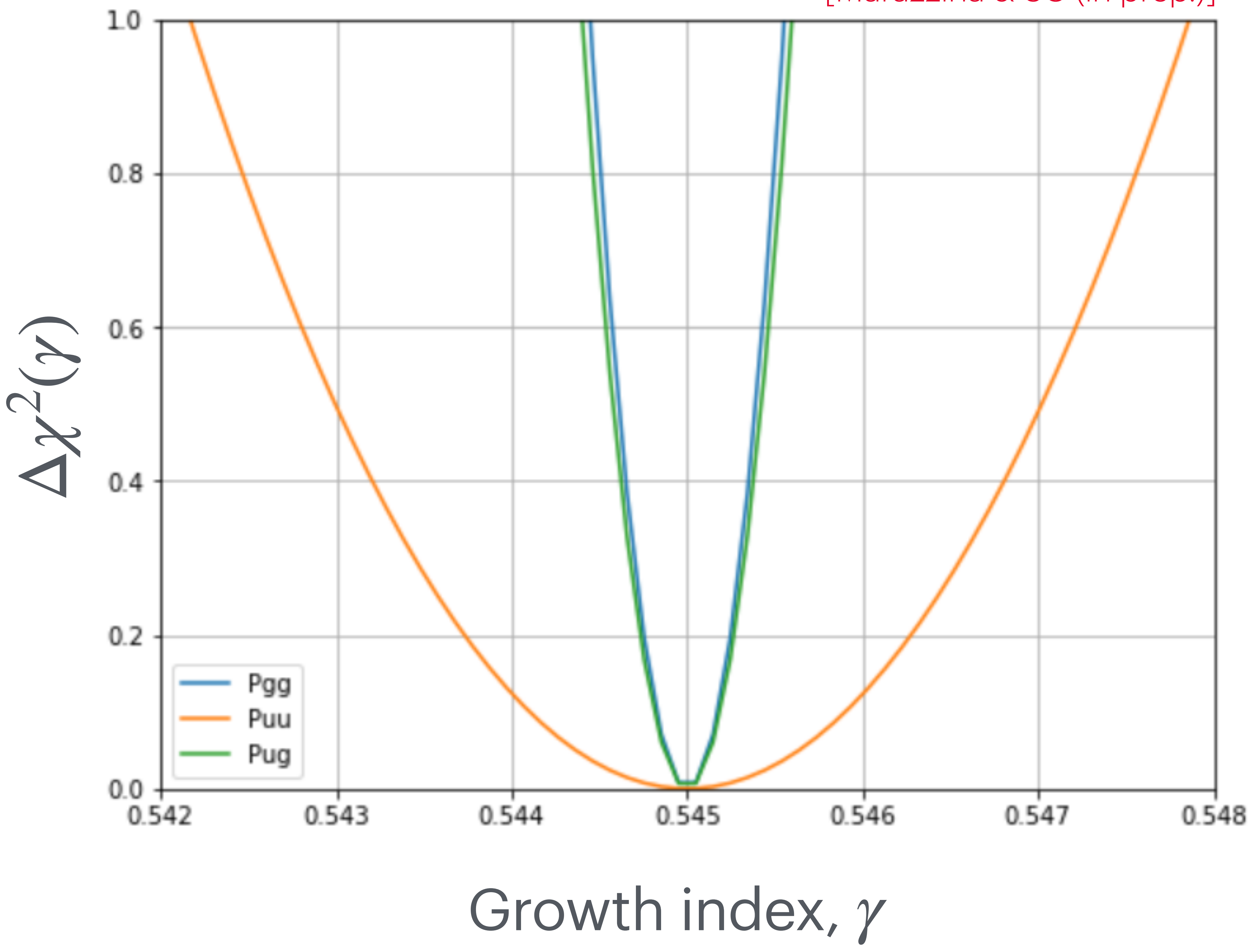
[Marazzina & SC (in prep.)]



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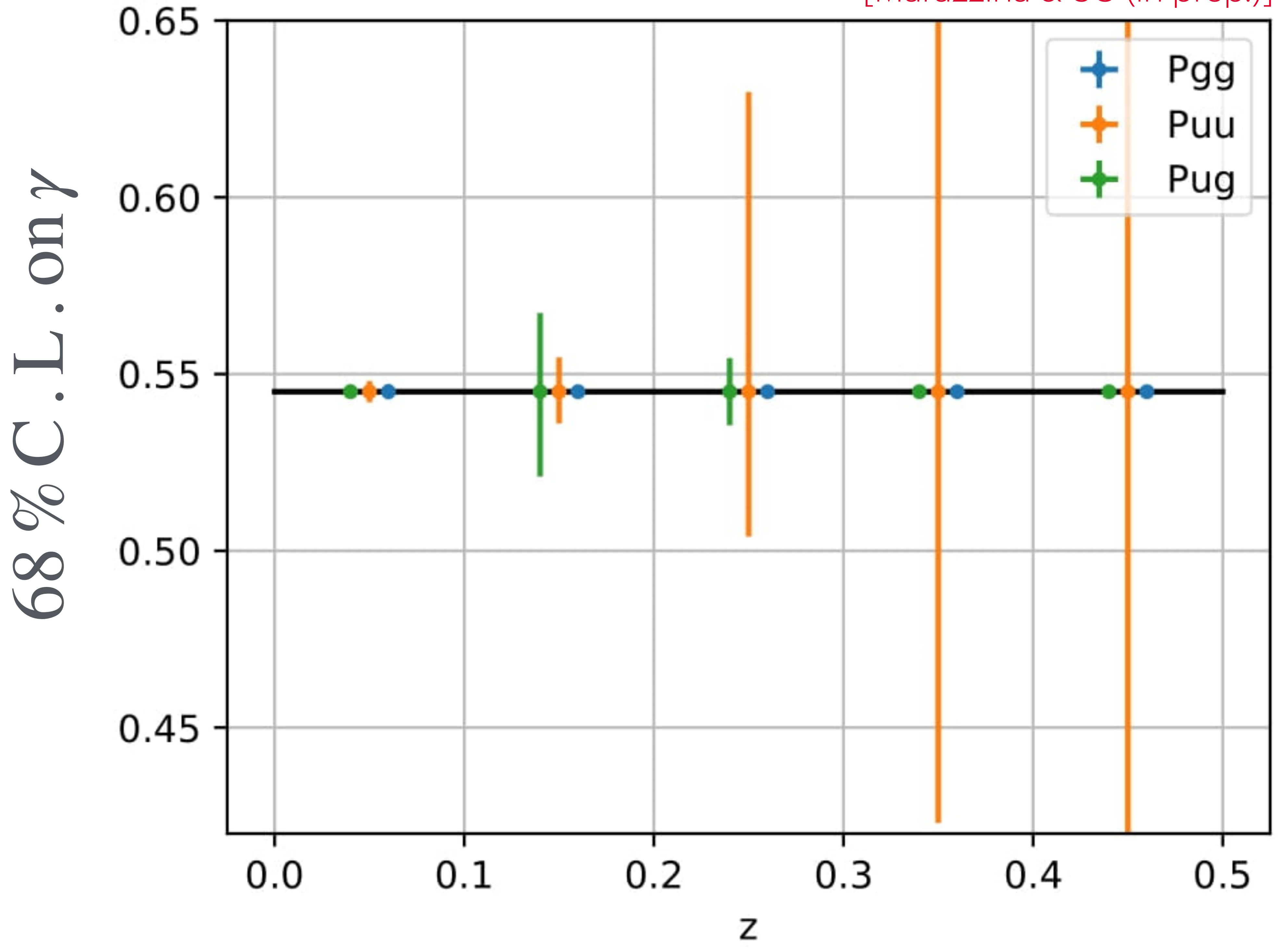

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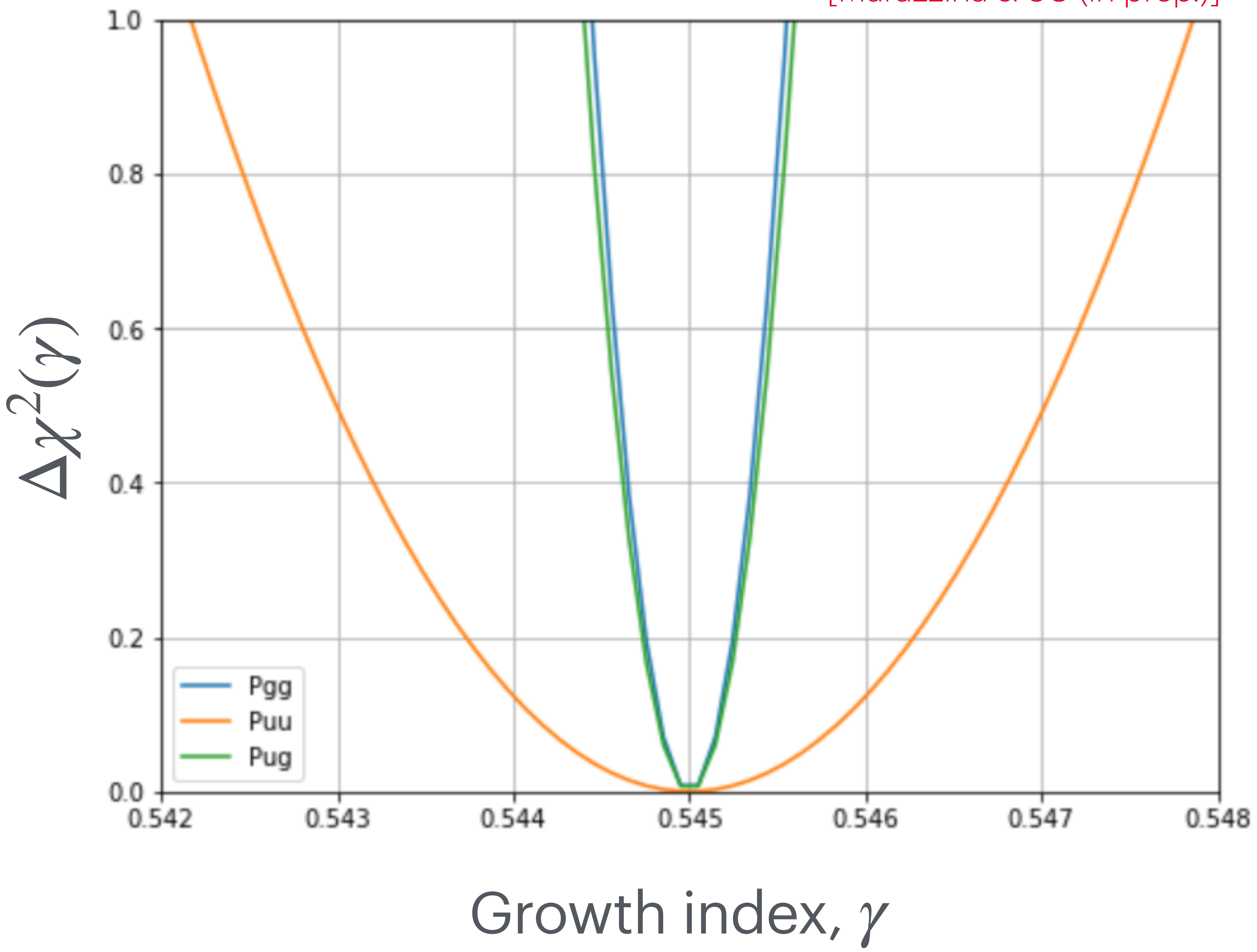

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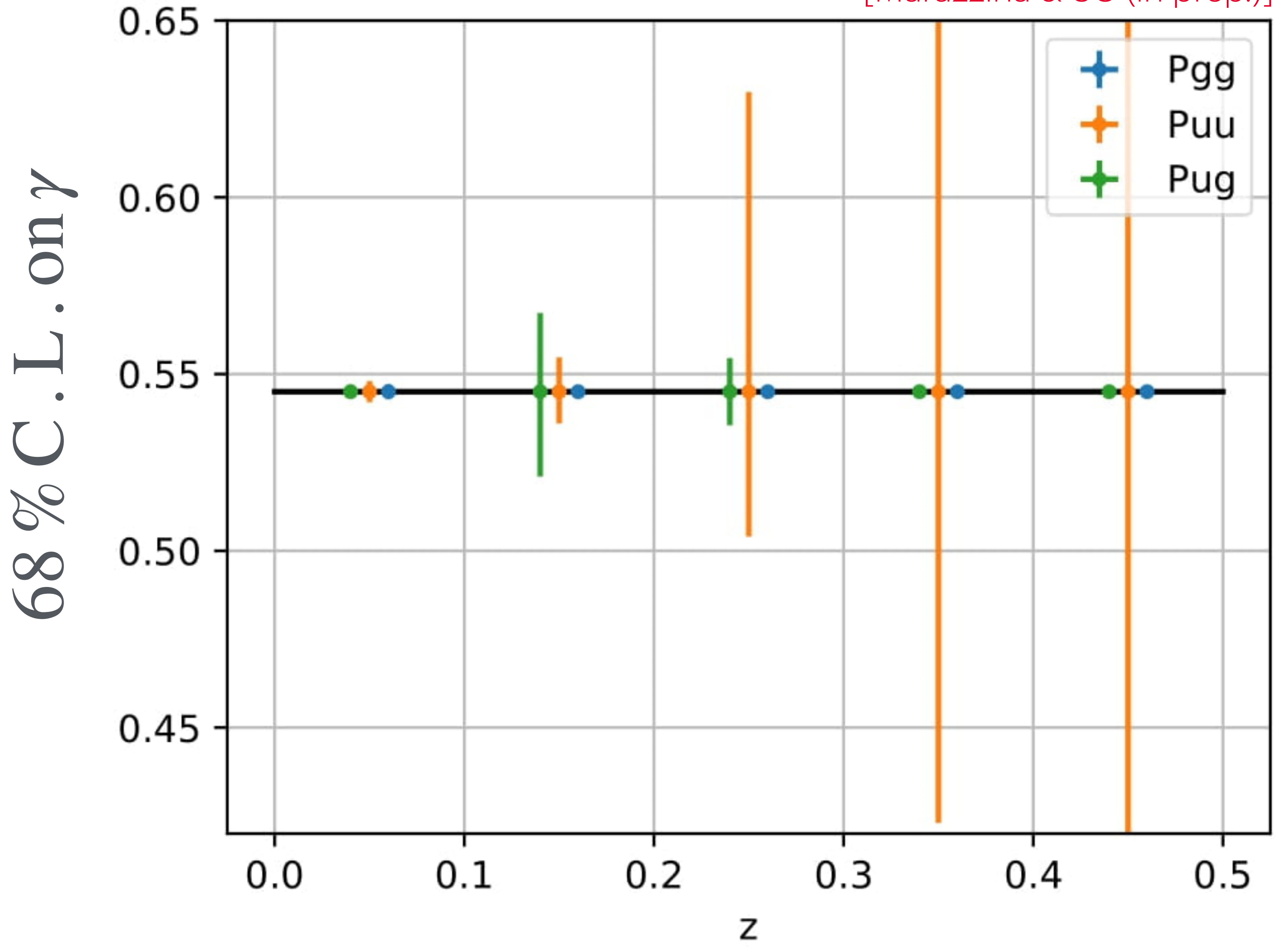

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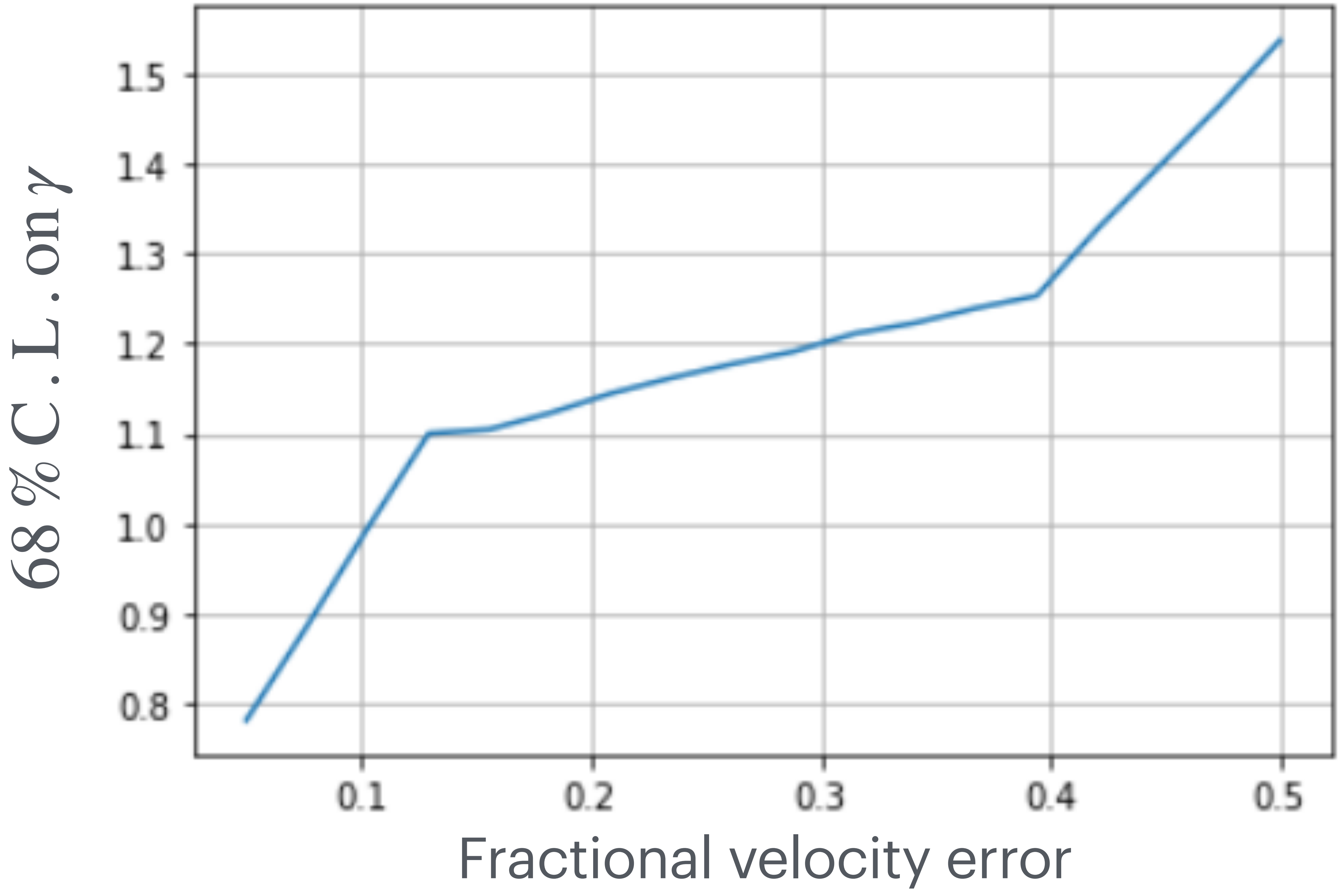


Continuum galaxies

- 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)
  - RACS (~34k sq. deg.; 2.5M galaxies)
  - LoTSS Deep Field DR1 (~26 sq. deg.; 80k galaxies)
  - LoTSS DR2 (5600 sq. deg.; 4.4M galaxies)

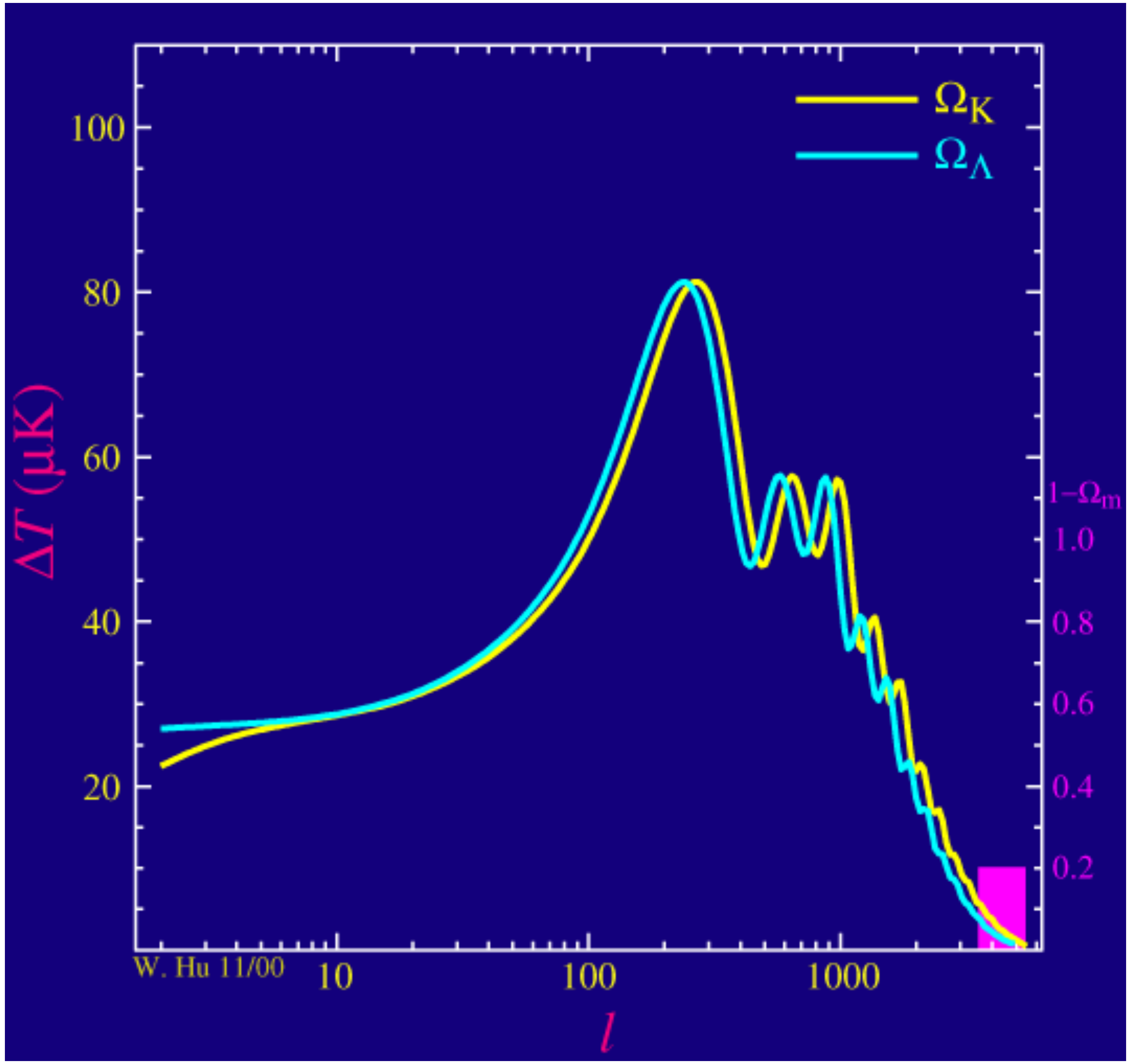
[McConnel et al. 2020; Hale et al. 2021]

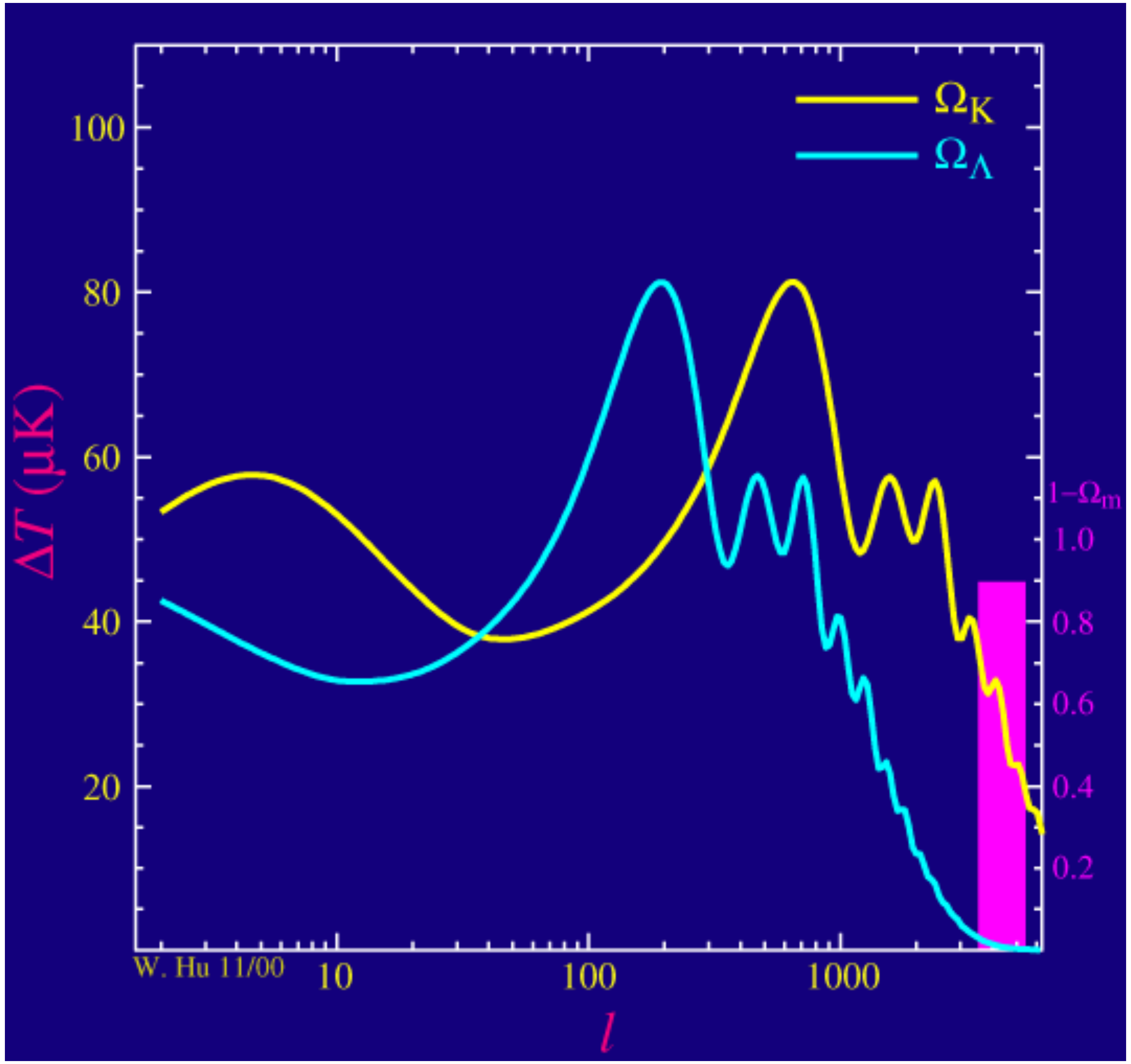
[Tessa et al. 2021, Sabater et al. 2021, Kondapally et al. 2021]

[Shimwell et al. 2022, Bhardwaj et al. (in prep.), Hale et al. (in prep.)]

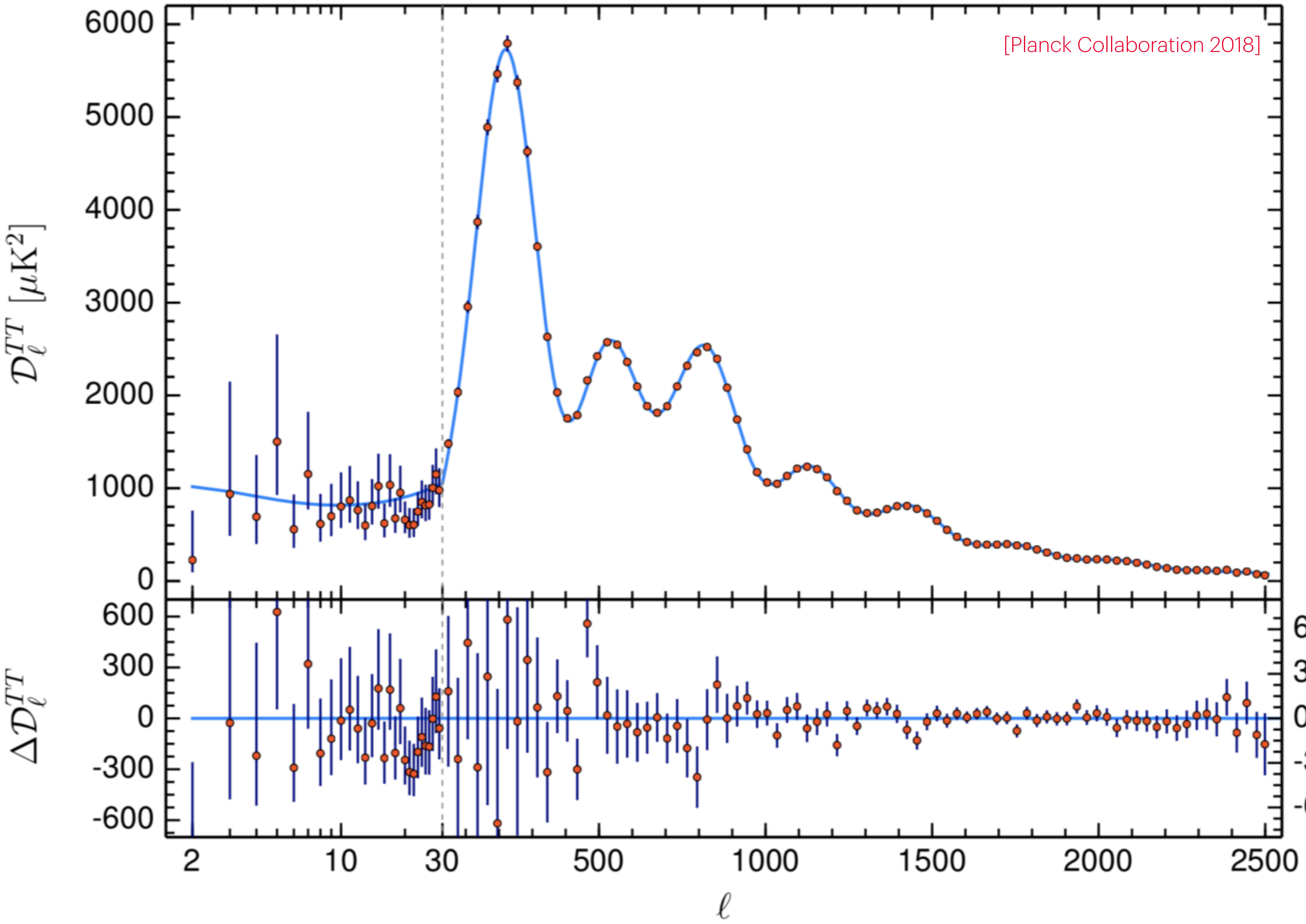
Continuum galaxies

[Credits: W. Hu]





Continuum galaxies



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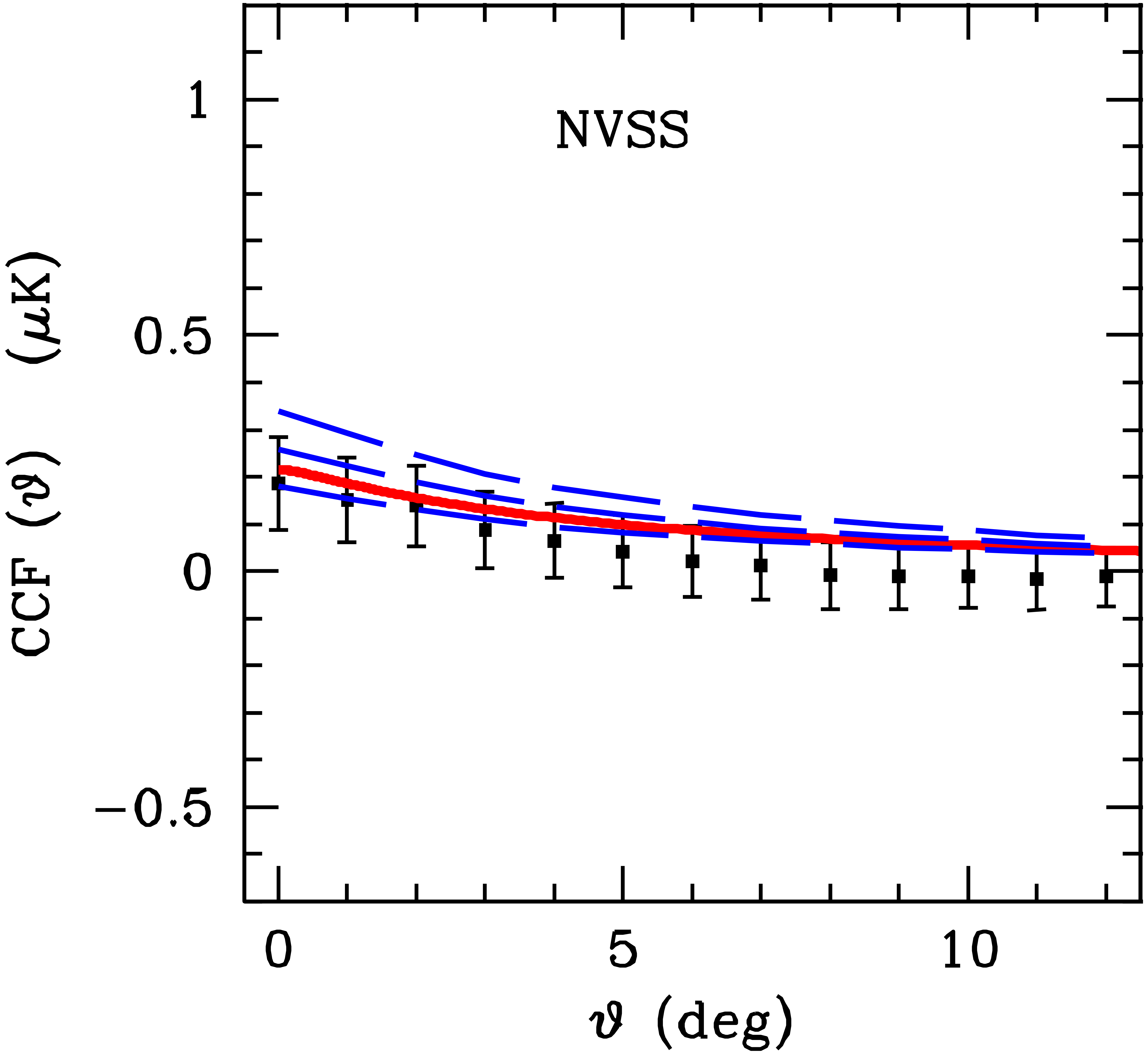
Continuum galaxies

[Giannantonio et al. 2008]



Continuum galaxies

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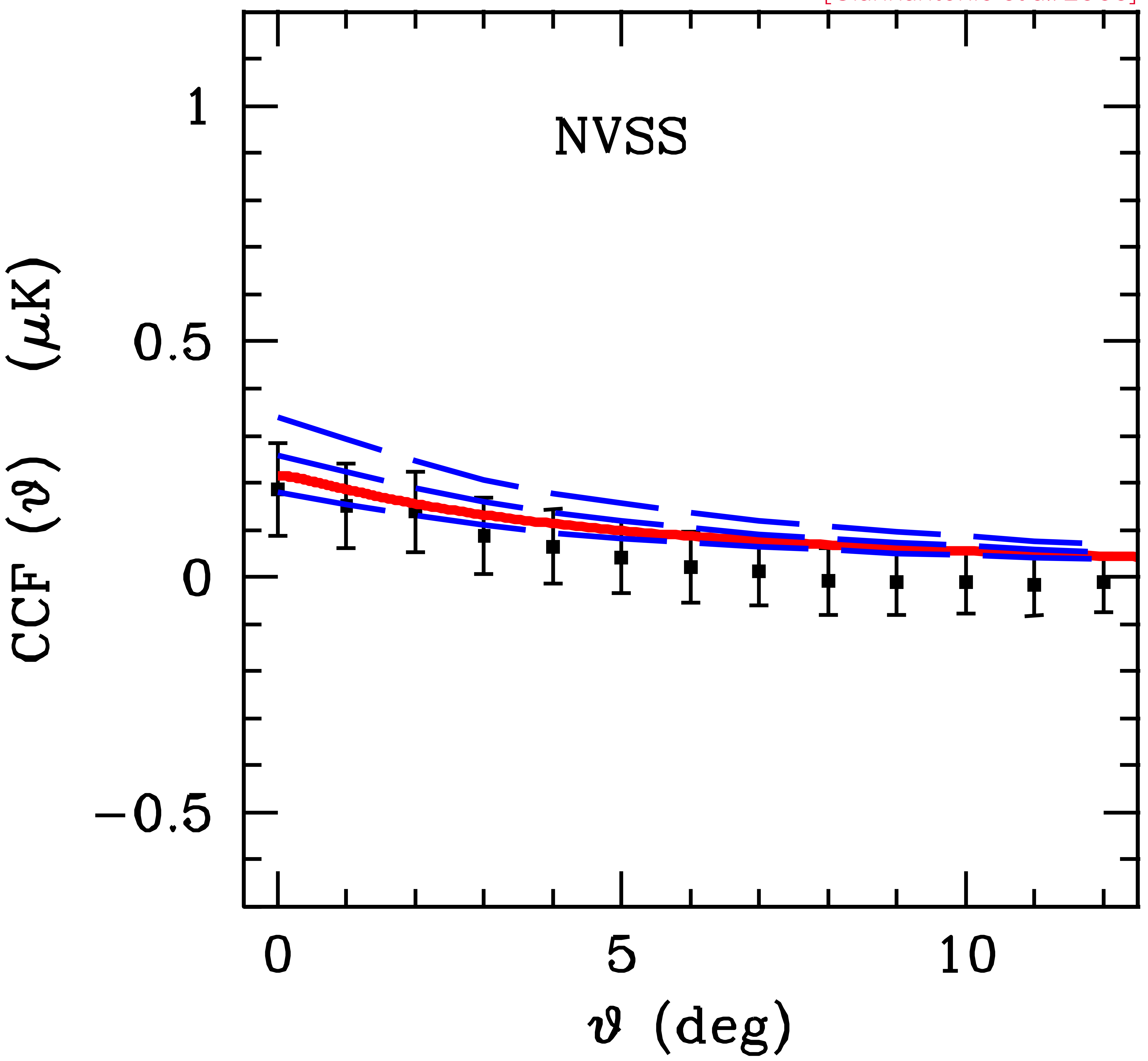
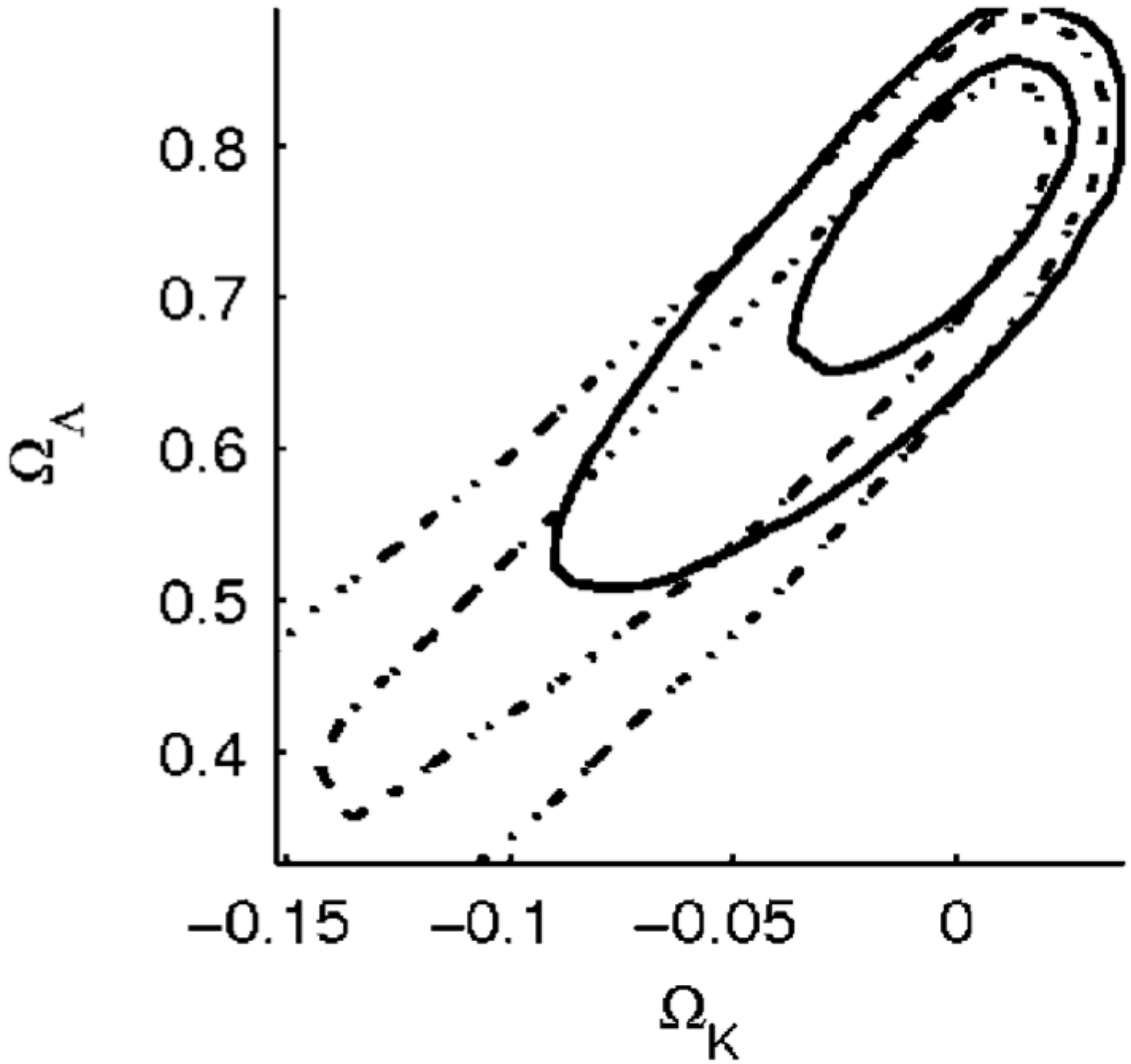


[Ho et al. 2008]



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Continuum galaxies

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- The Rapid ASKAP Continuum Survey (RACS)
  - Deepest radio survey of the Southern sky to date (central frequency 887.5 MHz)
  - Large instantaneous field of view ~31 deg² (~900 pointings with 15 min observations)
  - About 2.1M galaxies (cutting Galactic plane at ±5°)

Publications of the Astronomical Society of Australia (2021), **38**, e058, 25 pages
doi:10.1017/pasa.2021.47

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Research Paper

The Rapid ASKAP Continuum Survey Paper II: First Stokes I Source Catalogue Data Release

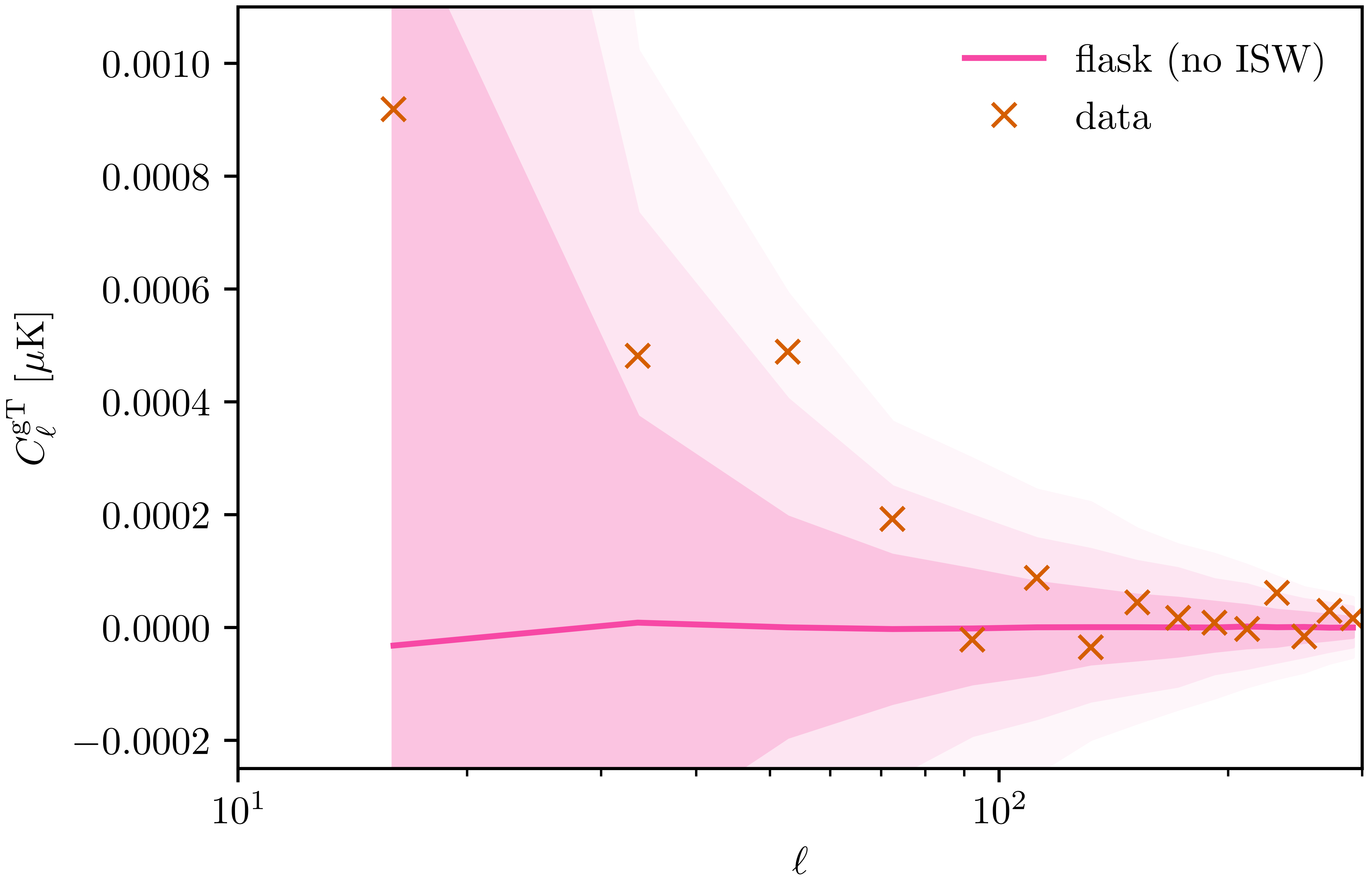
Catherine L. Hale[1,2], D. McConnell[3], A. J. M. Thomson[1], E. Lenc[3], G. H. Heald[1], A. W. Hotan[1], J. K. Leung[3,4], V. A. Moss[3], T. Murphy[4], J. Pritchard[4,3], E. M. Sadler[3,4], A. J. Stewart[4] and M. T. Whiting[3]

[1]CSIRO Space and Astronomy, PO Box 1130, Bentley WA 6102, Australia,[2]School of Physics and Astronomy, University of Edinburgh, Institute for Astronomy, Royal Observatory Edinburgh, Blackford Hill, Edinburgh EH9 3HJ, UK,[3]CSIRO Space and Astronomy, PO Box 76, Epping, NSW, 1710, Australia and [4]Sydney Institute for Astronomy, School of Physics, University of Sydney, NSW 2006, Australia

Continuum galaxies

- Cross-correlation between RACS galaxies and CMB temperature

[Bahr-Kalus ⊃ SC et al. (2022)]



Continuum galaxies

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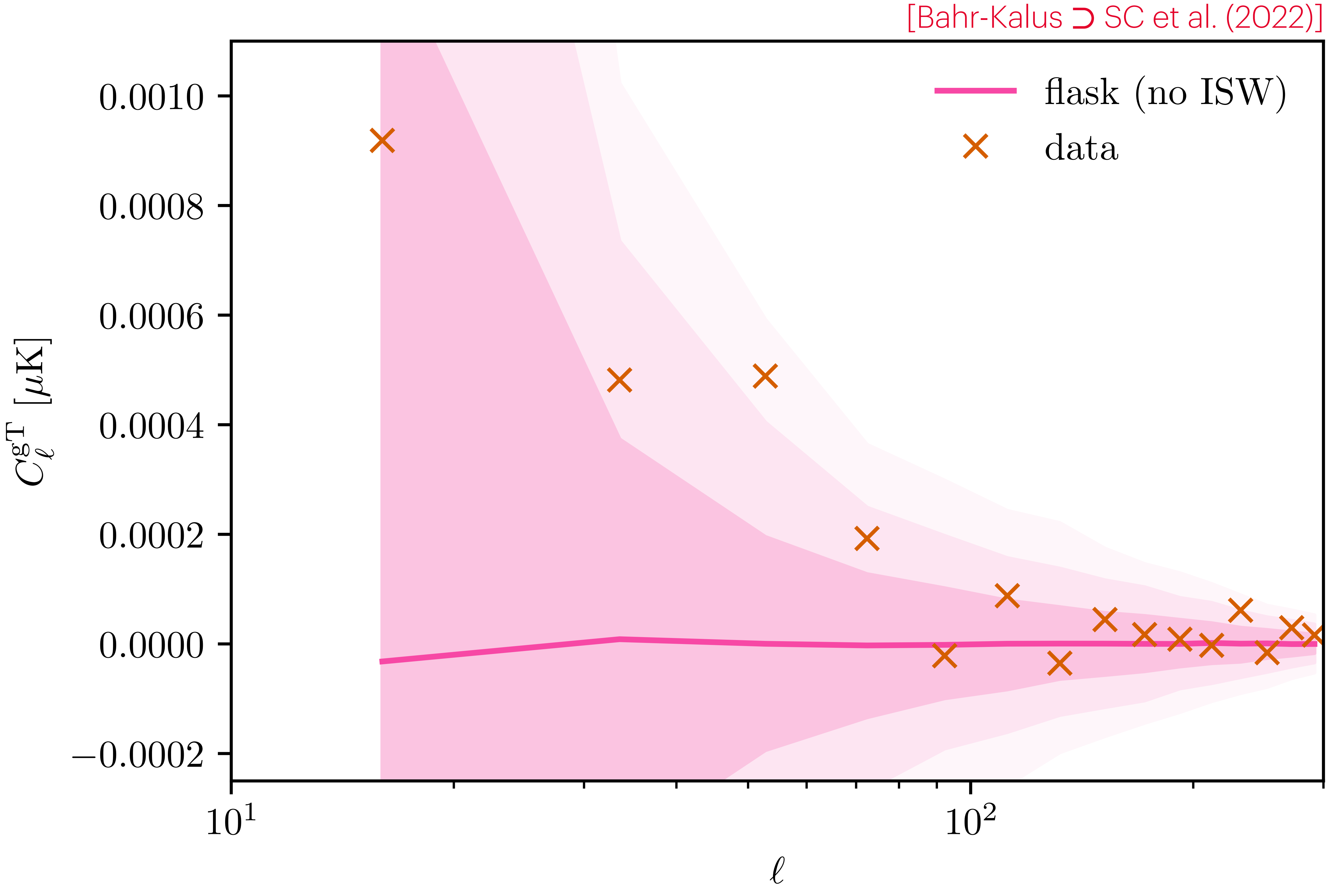

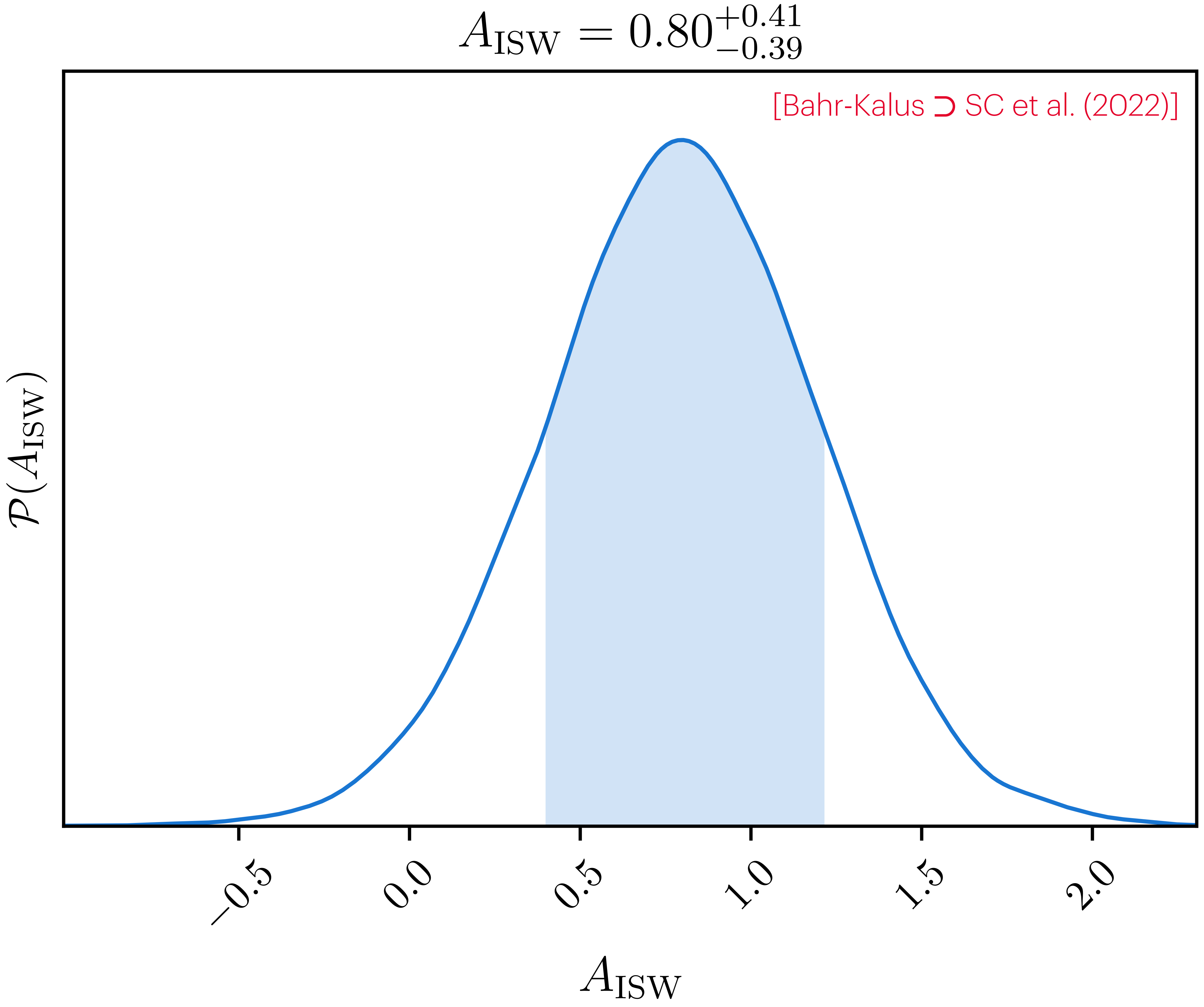

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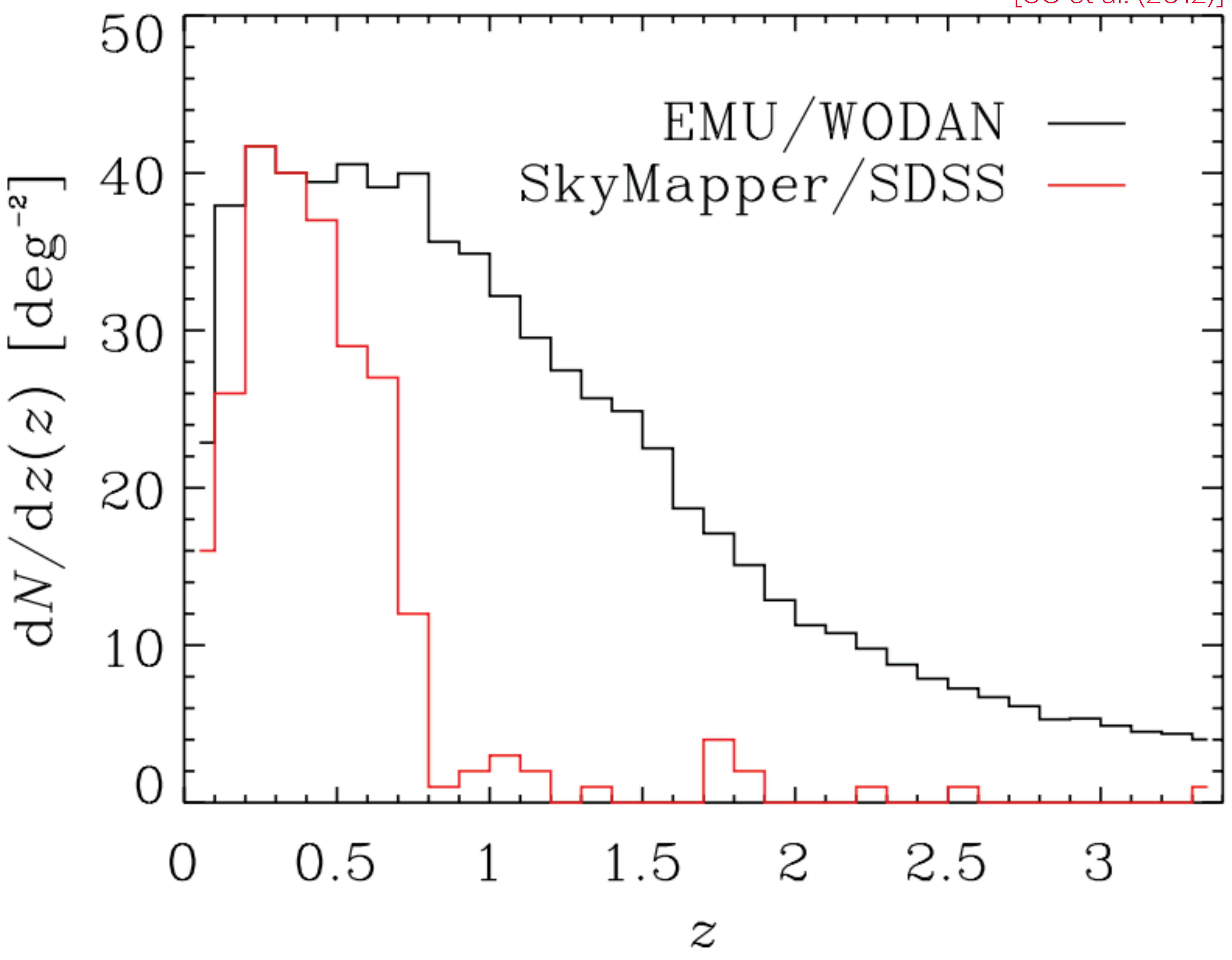
Continuum galaxies

- Synergies between radio-continuum and optical/near-IR galaxy surveys

[SC et al. (2012)]



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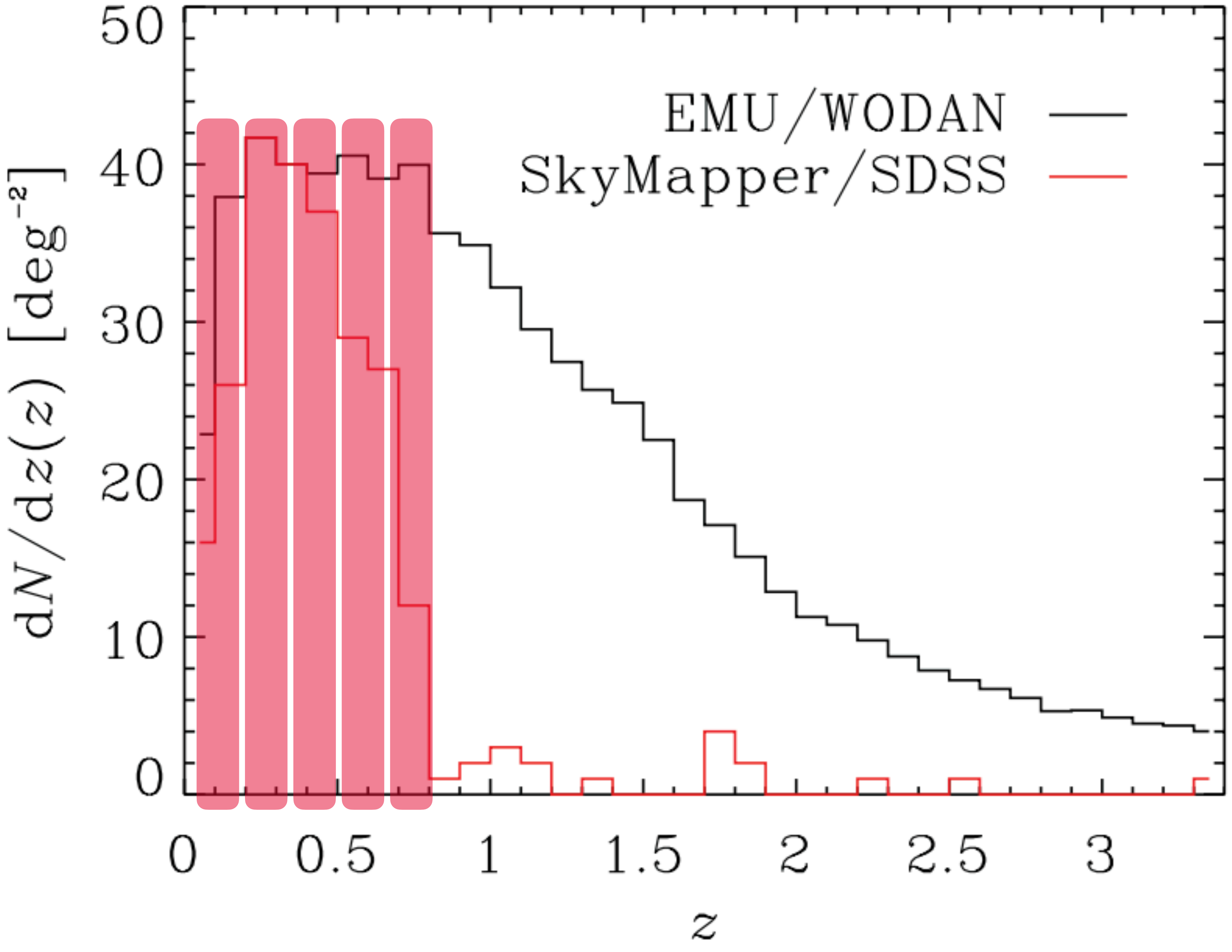
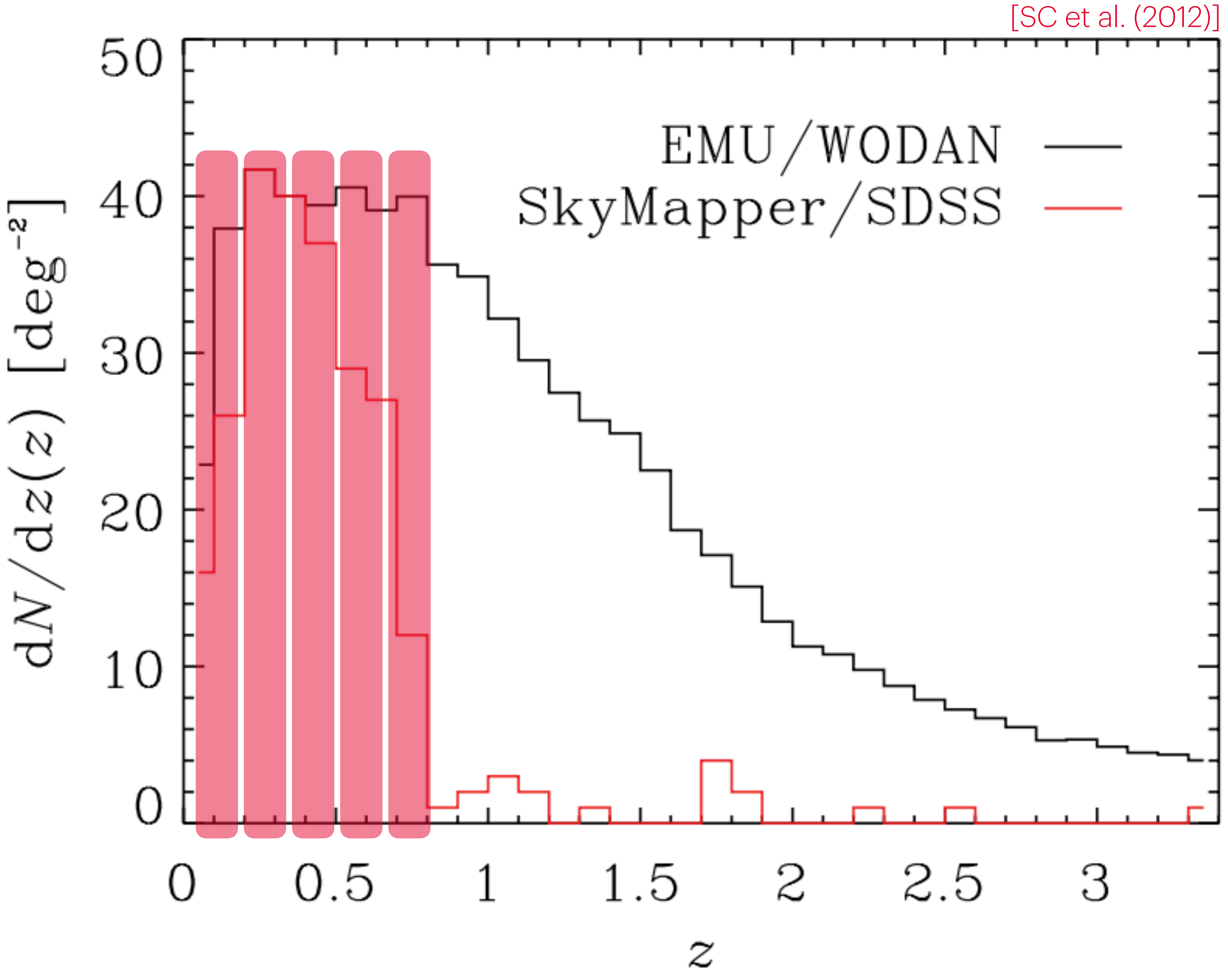
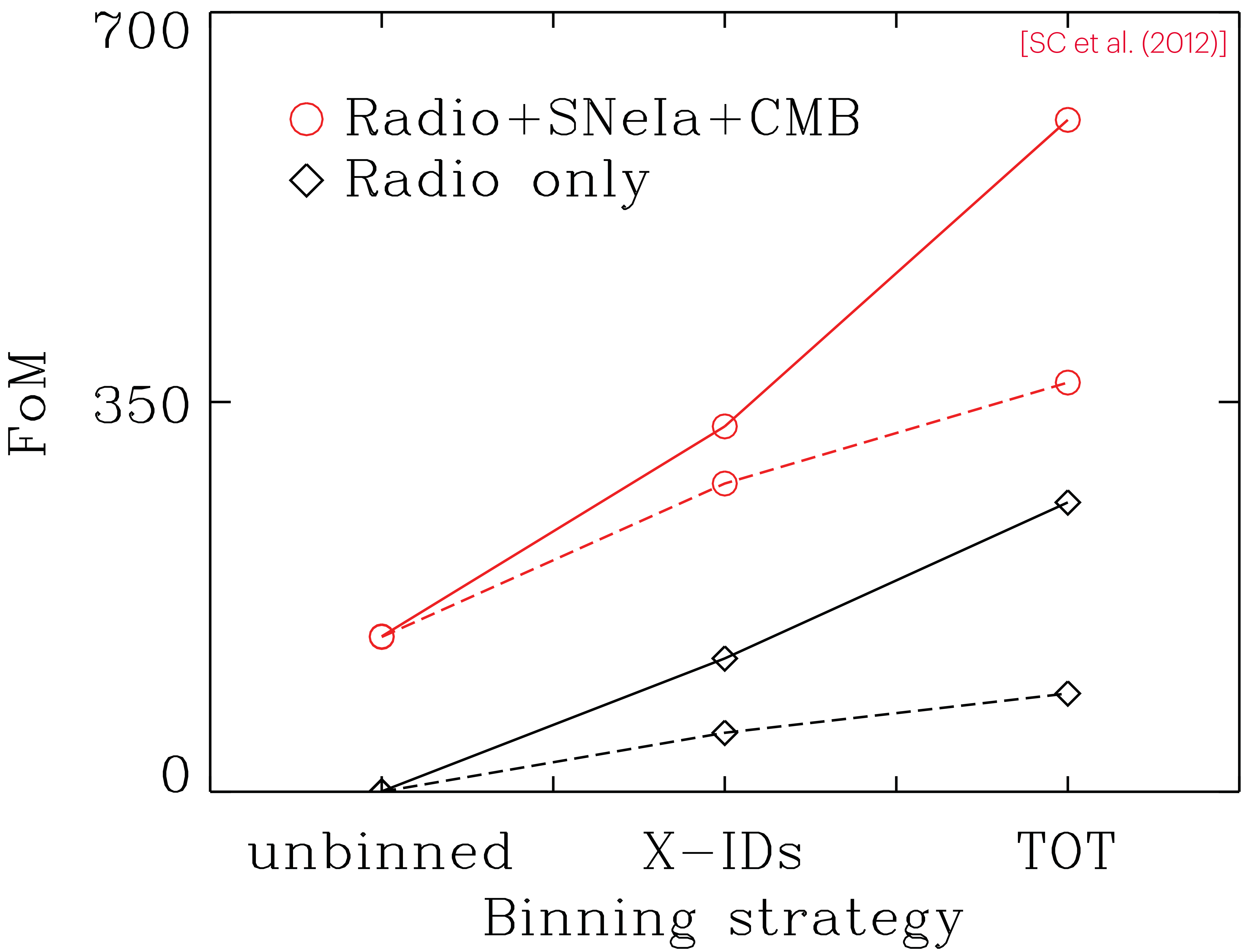


See Melita's talk about Euclid!

Continuum galaxies

- Synergies between radio-continuum and optical/near-IR galaxy surveys





HI intensity mapping

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- 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. 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 @ $0.400 < z < 0.459$) [MeerKLASS Collaboration 2022]
  - CHIME (three fields stacked against eBOSS LRGs, ELGs, QSOs @ $0.78 < z < 1.43$) [CHIME Collaboration 2022]

HI intensity mapping

- Examples:
  - MeerKAT (96 obs. hrs; 2 sq. deg. @ 986 MHz | $z \approx 0.44$ and @ 1077.5 MHz | $z \approx 0.32$)

[Sourabh et al. 2022]

HI intensity mapping

- Examples:
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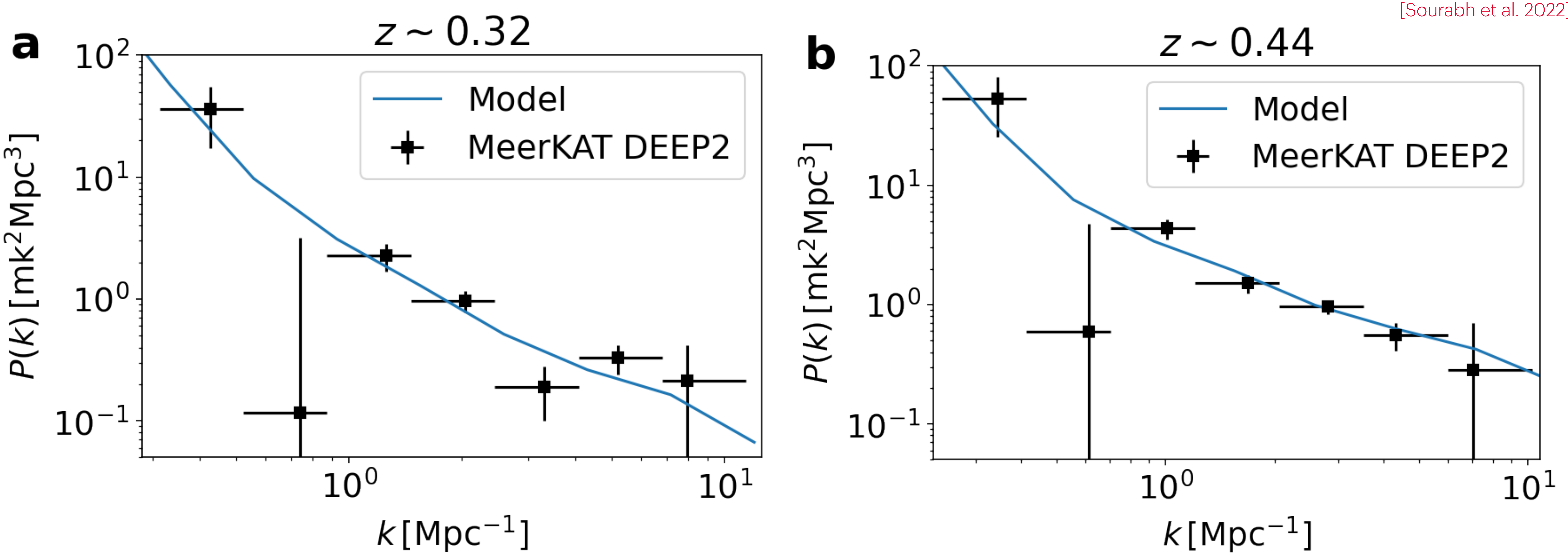
[Sourabh et al. 2022]



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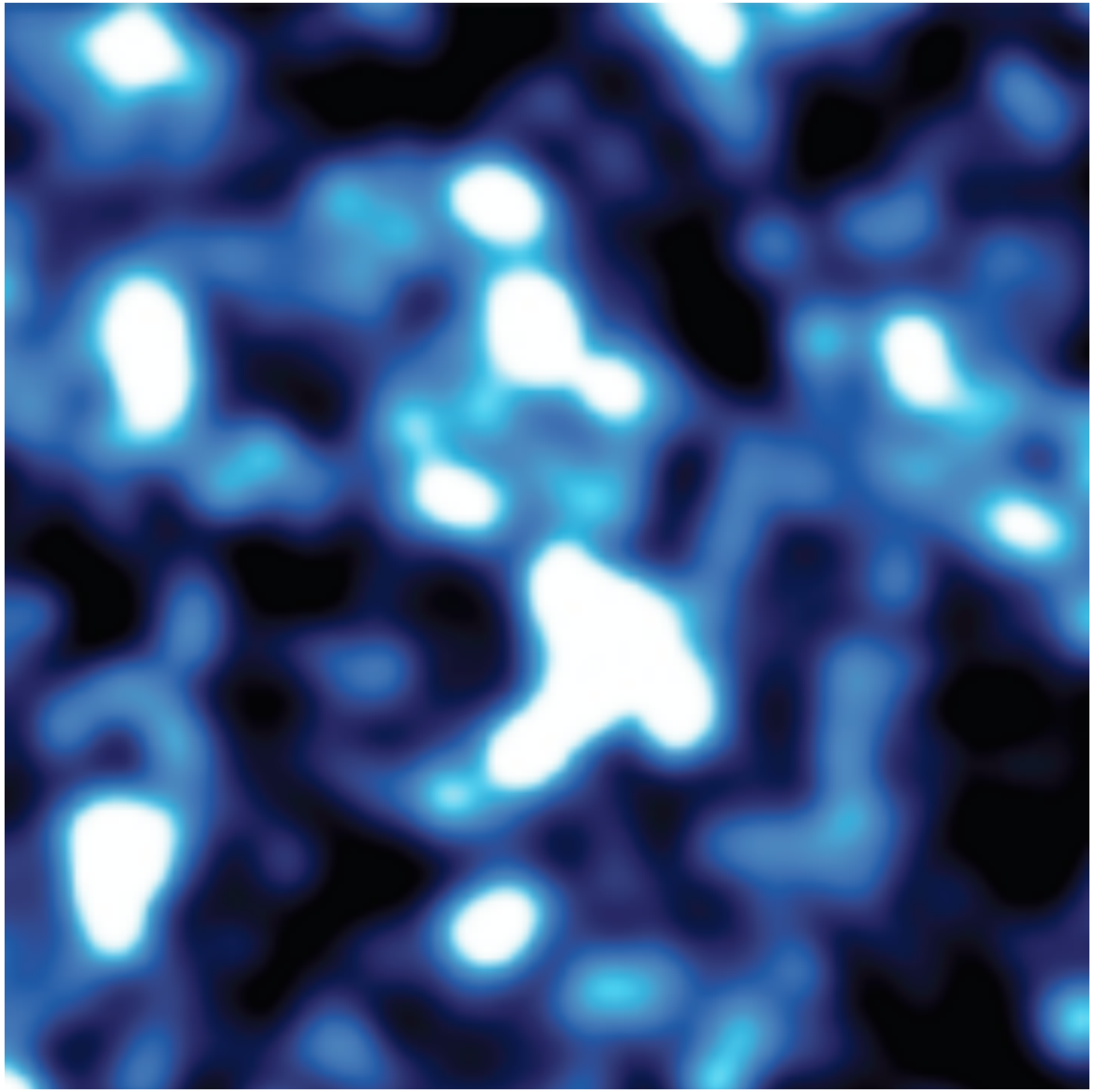
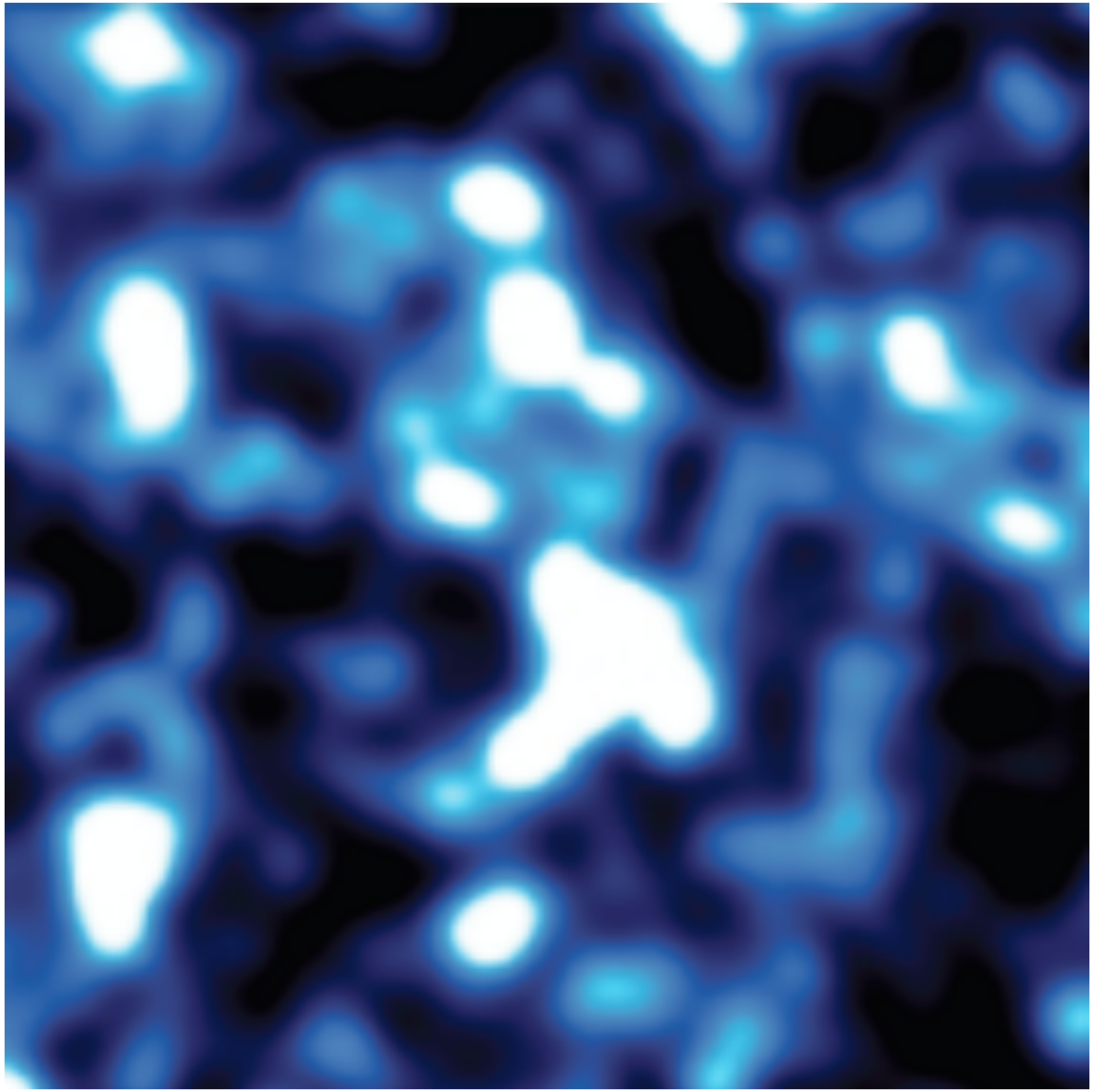


[Bharadwaj et al. (2001);
Battye et al. (2004);
Loeb & Whyte (2008)]

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

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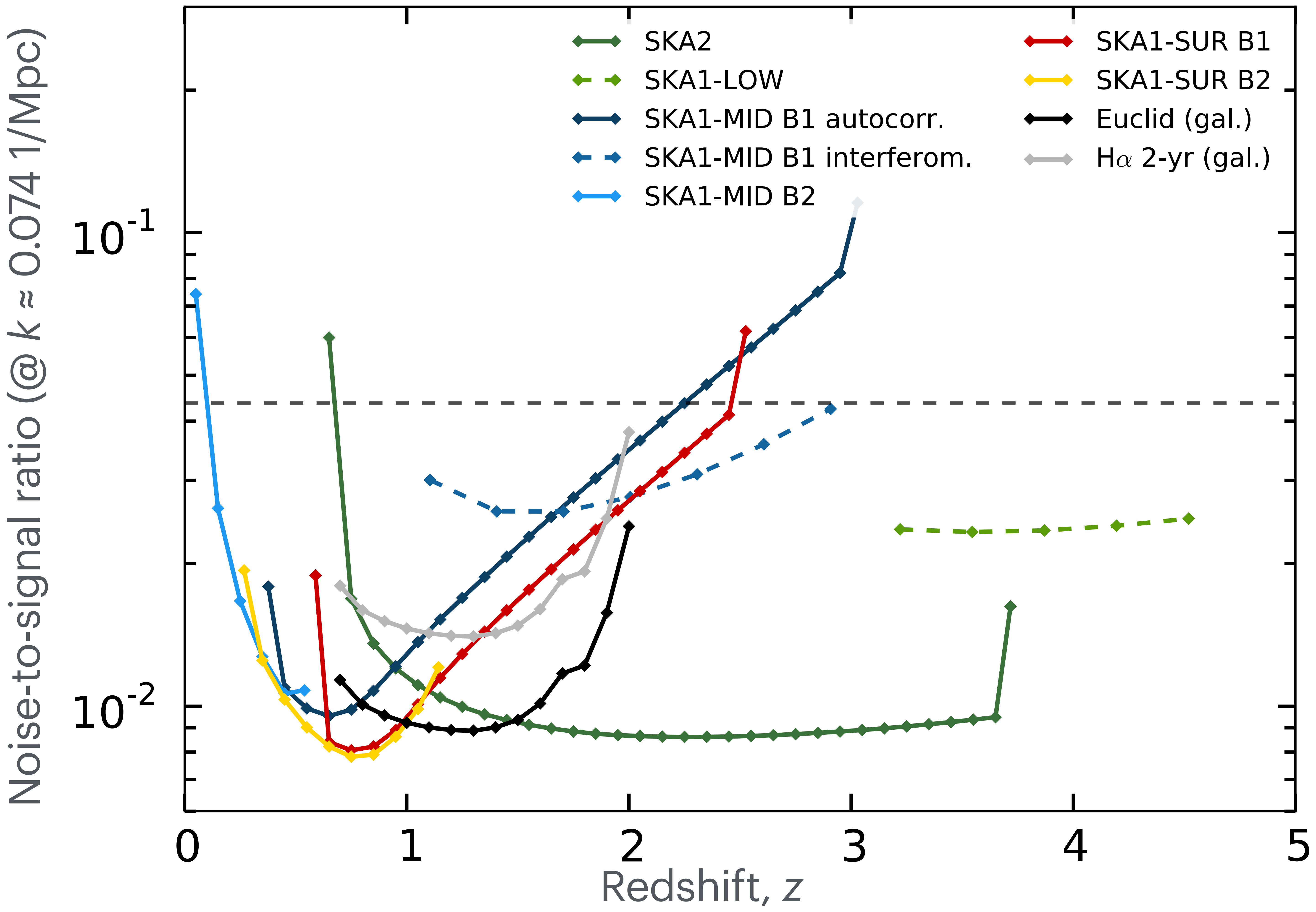
[Santos ⊃ SC et al. 2015]



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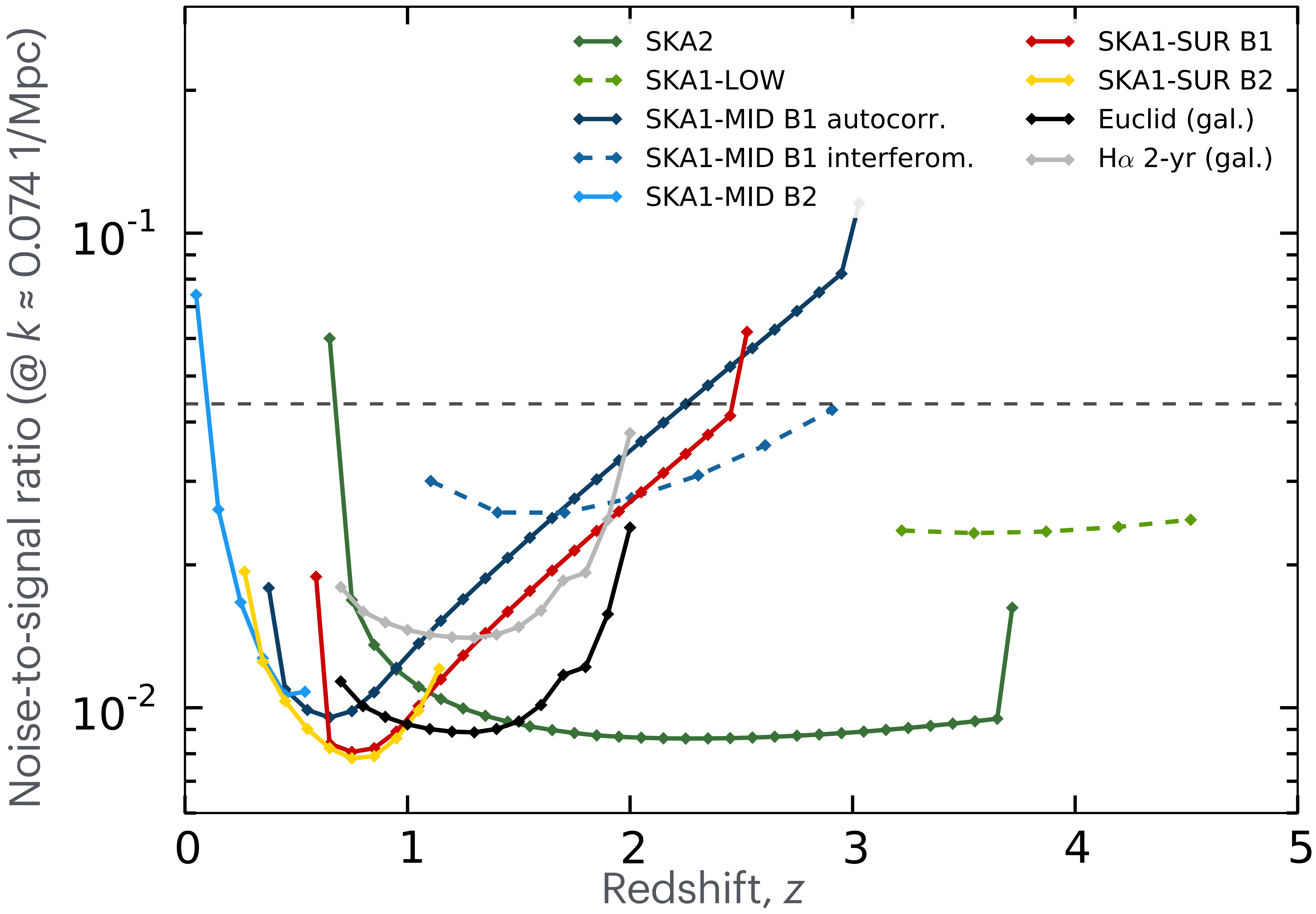
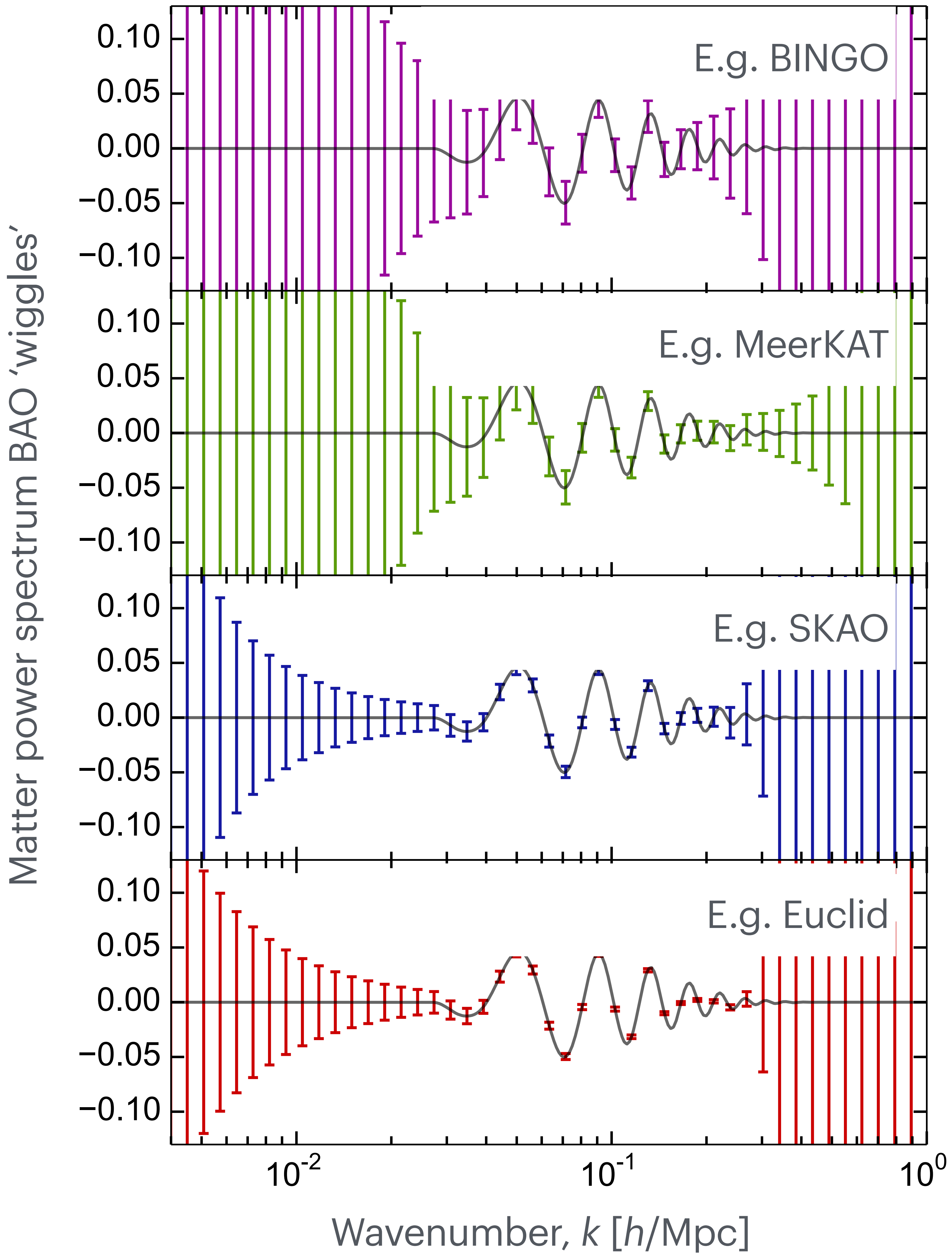
[Santos ⊃ SC et al. 2015]



[Bull ⊃ et al. 2015]



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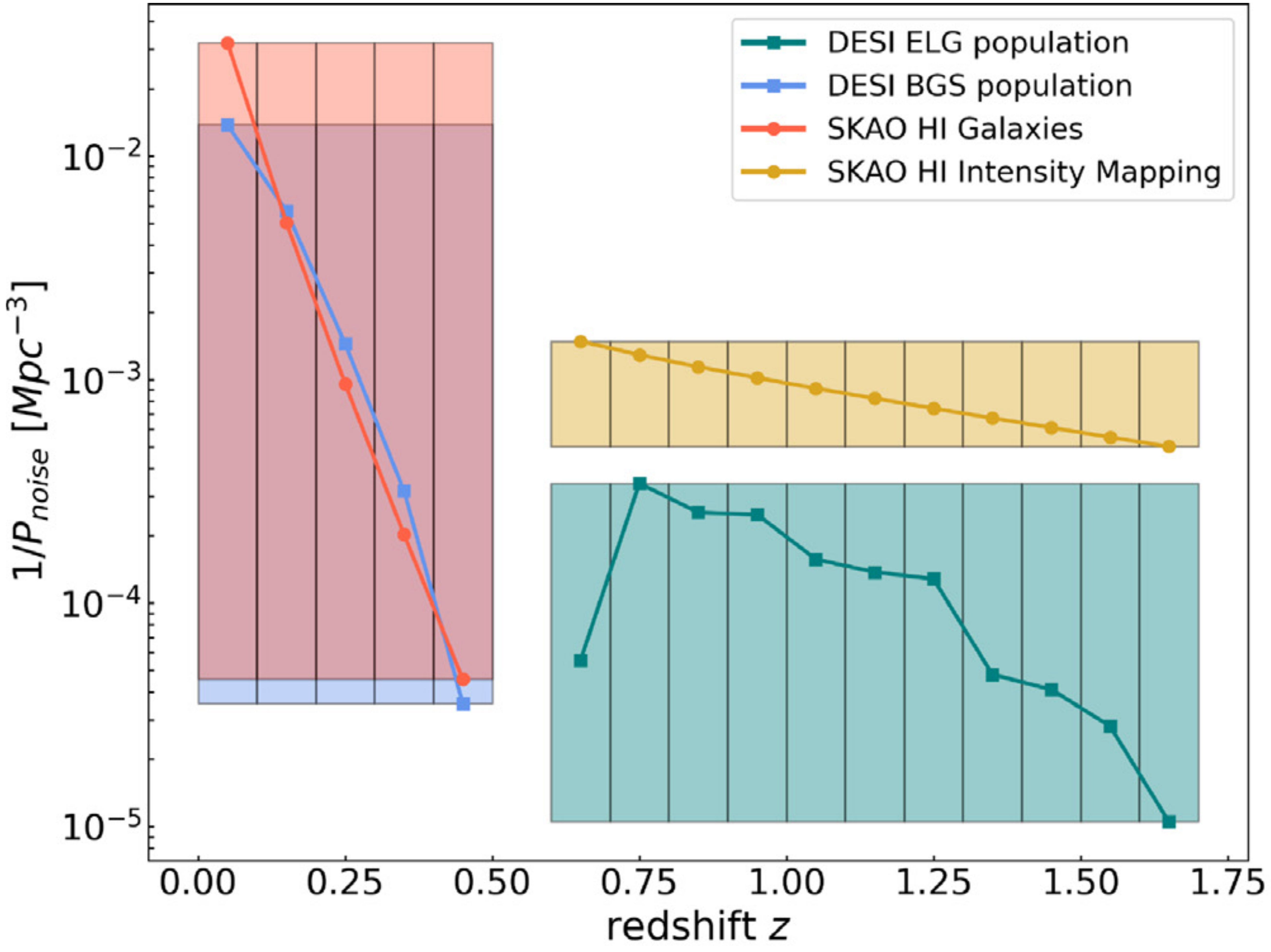
HI intensity mapping

[Casas ⊃ SC et al. (2015)]



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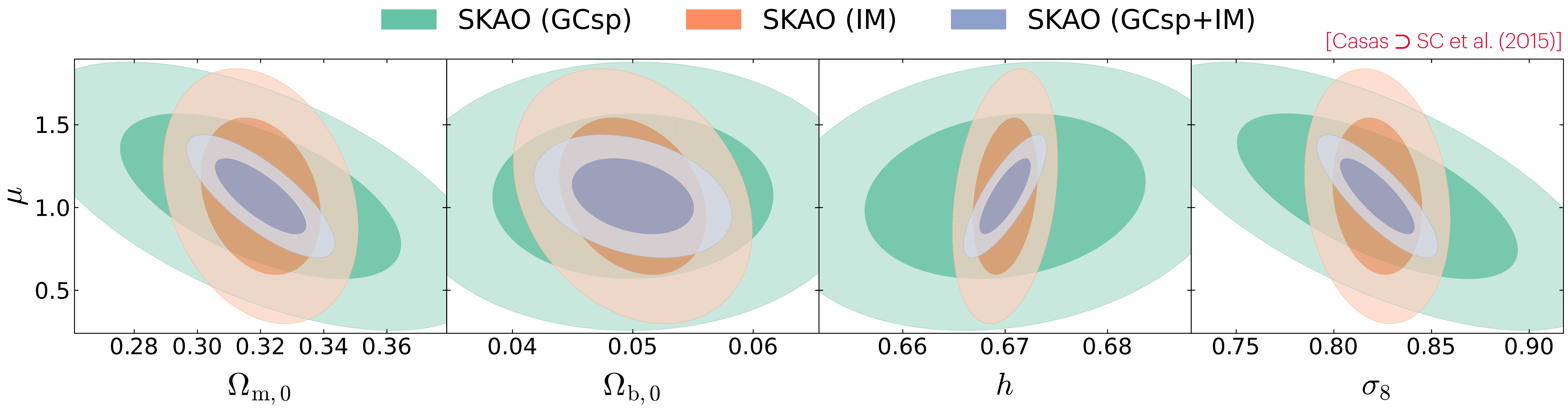

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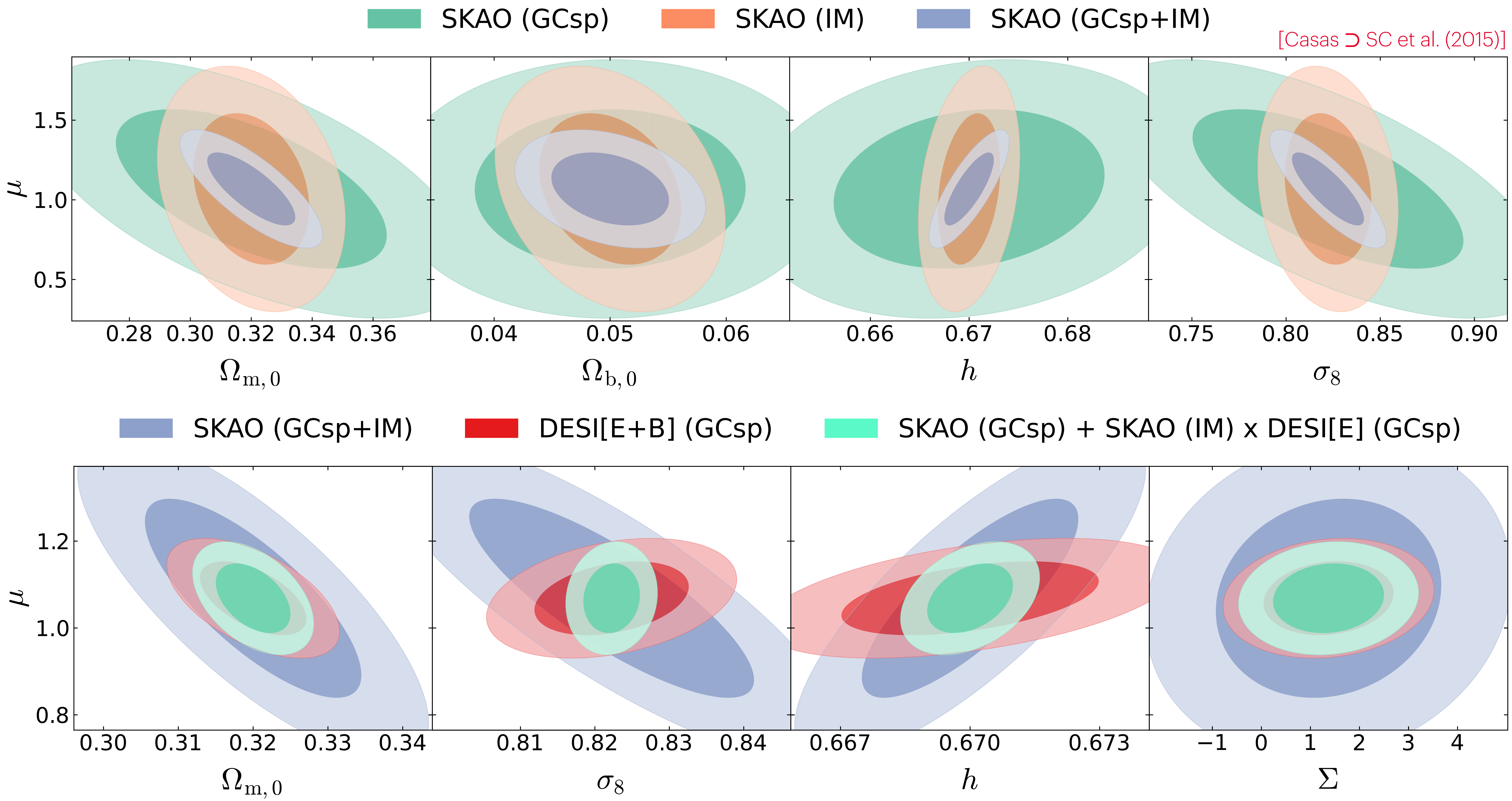

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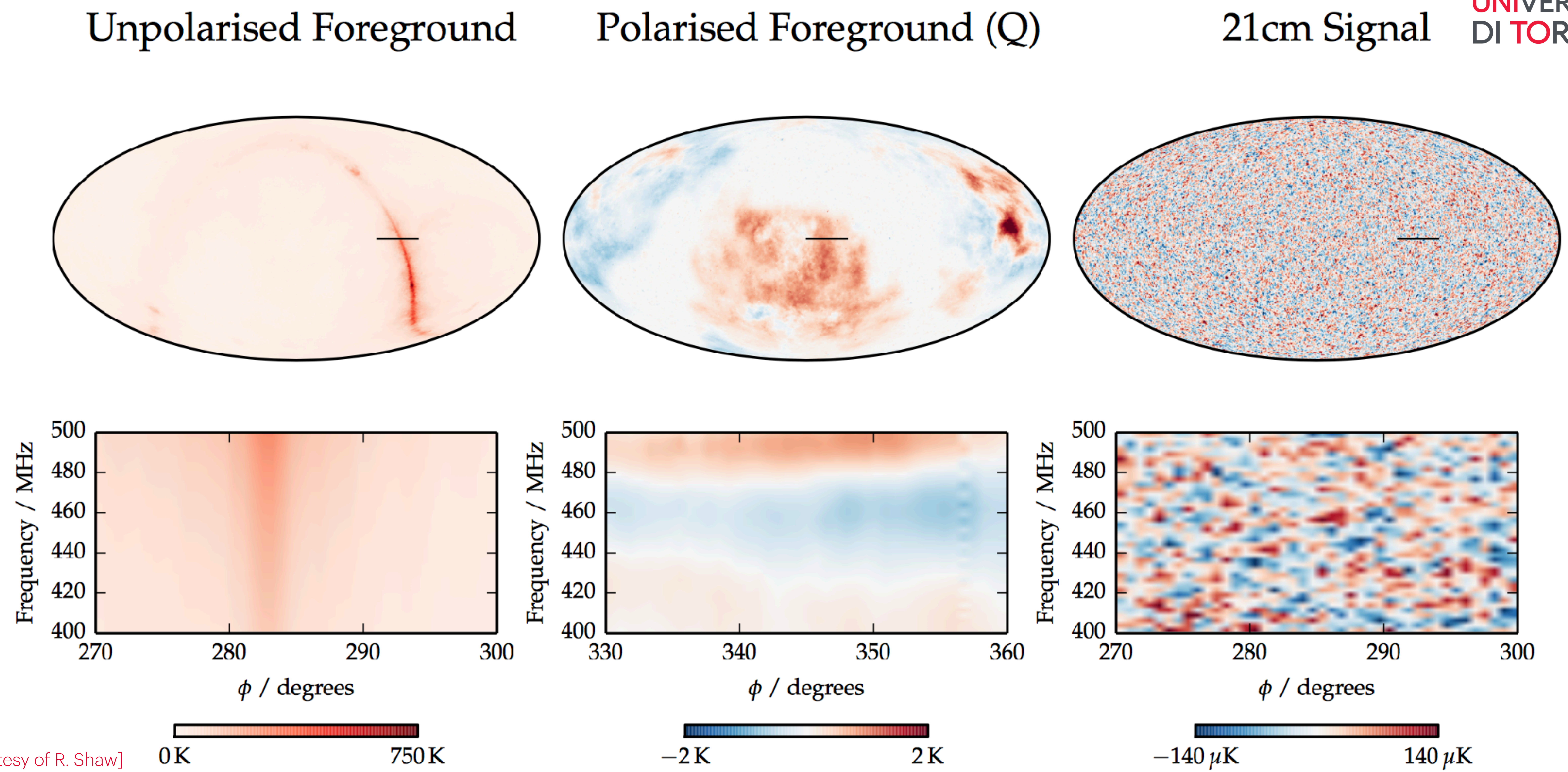

[Courtesy of R. Shaw]

Radio weak lensing

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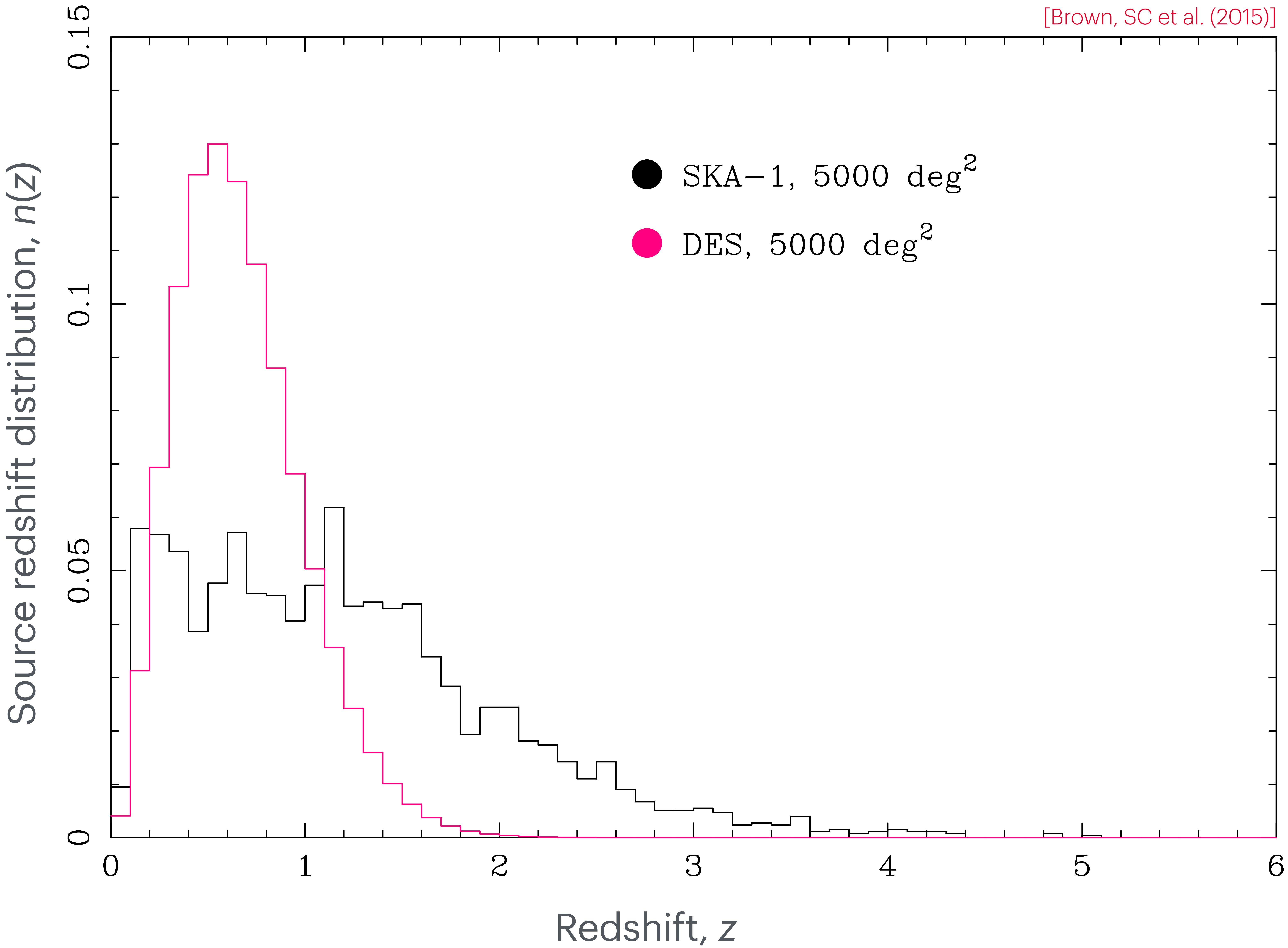
- Origin: weak lensing shearing of imaged galaxy ellipticities
- Pros: complementary to clustering, insensitive to galaxy bias
- Cons: low signal to noise, needs (?) imaging
- Examples:
    - VLA FIRST (~90 sources per sq. deg. vs to ~10 per sq. arcmin. in opt.)

      [Chang et al. (Nature 2004)]
    - VLA+MERLIN (in cross-correlation w/ optical shear)
      VLA+SDSS (in cross-correlation w/ optical galaxy and cluster clustering)
      VLA+COSMOS (in cross-correlation w/ optical shear)

      [Patel et al. (2010); Demetroullas & Brown (2018); Hillier et al. (2019)]

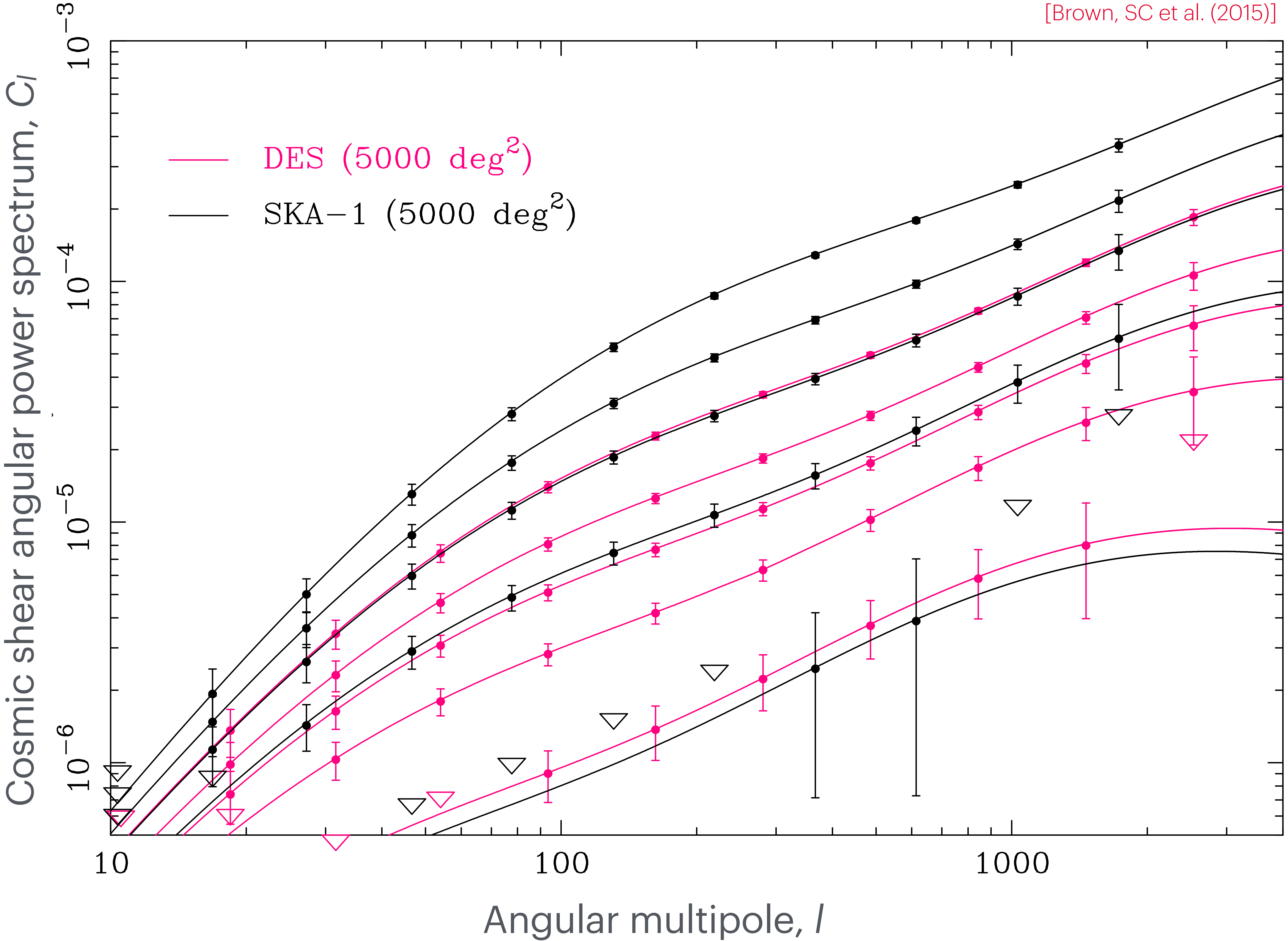
Radio weak lensing

[Brown, SC et al. (2015)]



Radio weak lensing

[Brown, SC et al. (2015)]



Radio weak lensing

$$\epsilon(z,\hat{\boldsymbol{n}})=\gamma(z,\hat{\boldsymbol{n}})+\epsilon^{\rm sys}(z,\hat{\boldsymbol{n}})$$

See Vincenzo's talk about weak lensing!

Radio weak lensing

$$\epsilon(z,\hat{\boldsymbol{n}}) = \gamma(z,\hat{\boldsymbol{n}}) + \epsilon^{\rm sys}(z,\hat{\boldsymbol{n}})$$

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

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Radio weak lensing

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$$\langle\epsilon_{(\mathrm{o})}\,\epsilon_{(\mathrm{r})}\rangle = \langle\gamma\,\gamma\rangle + \langle\gamma\,\epsilon^{\mathrm{sys}}_{(\mathrm{r})}\rangle + \langle\gamma\,\epsilon^{\mathrm{sys}}_{(\mathrm{r})}\rangle + \langle\epsilon^{\mathrm{sys}}_{(\mathrm{o})}\,\epsilon^{\mathrm{sys}}_{(\mathrm{r})}\rangle$$

Radio weak lensing

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$$\langle\epsilon_{\rm (o)}\,\epsilon_{\rm (r)}\rangle = \langle\gamma\,\gamma\rangle + \cancel{\langle\gamma\,\epsilon^{\rm sys}_{\rm (r)}\rangle} + \cancel{\langle\gamma\,\epsilon^{\rm sys}_{\rm (r)}\rangle} + \langle\epsilon^{\rm sys}_{\rm (o)}\,\epsilon^{\rm sys}_{\rm (r)}\rangle$$

Radio weak lensing

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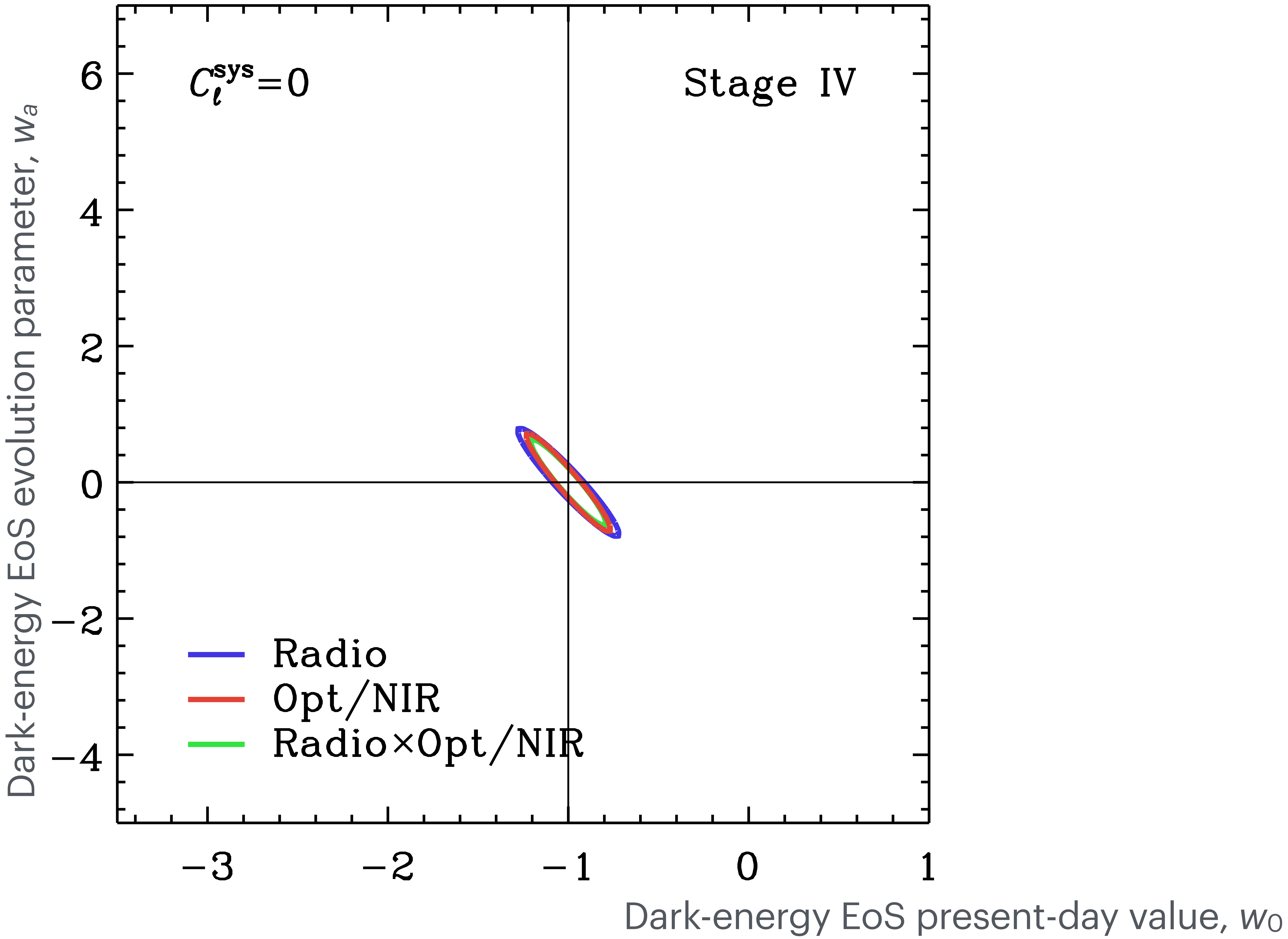
$$\langle\epsilon_{(\rm o)}\,\epsilon_{(\rm r)}\rangle = \langle\gamma\,\gamma\rangle + \cancel{\langle\gamma\,\epsilon^{\rm sys}_{(\rm r)}\rangle} + \cancel{\langle\gamma\,\epsilon^{\rm sys}_{(\rm r)}\rangle} + \cancel{\langle\epsilon^{\rm sys}_{(\rm o)}\,\epsilon^{\rm sys}_{(\rm r)}\rangle}$$

Radio-optical cosmic shear

[SC et al. 2015; Bacon ⊃ SC et al. 2020]



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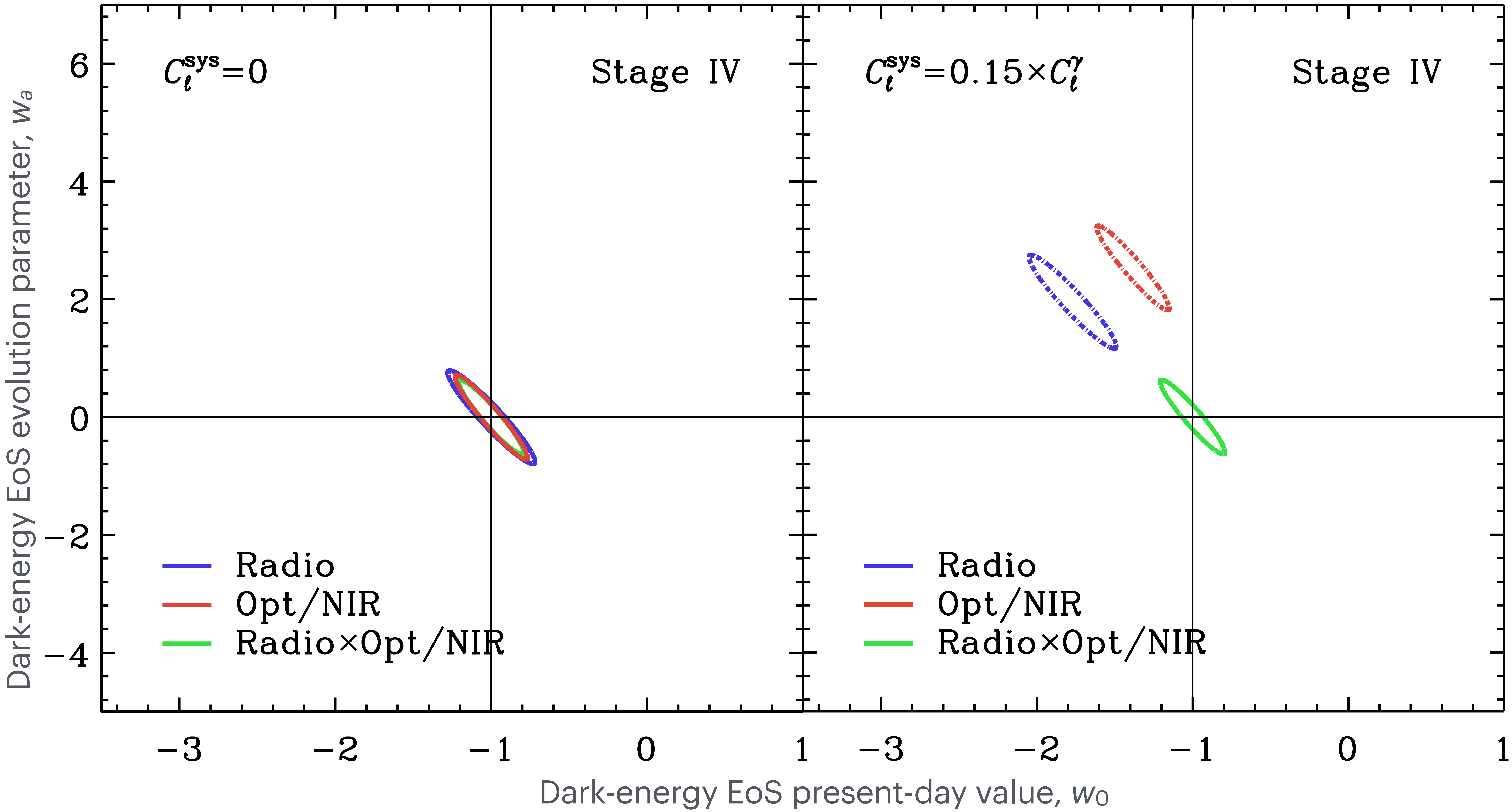
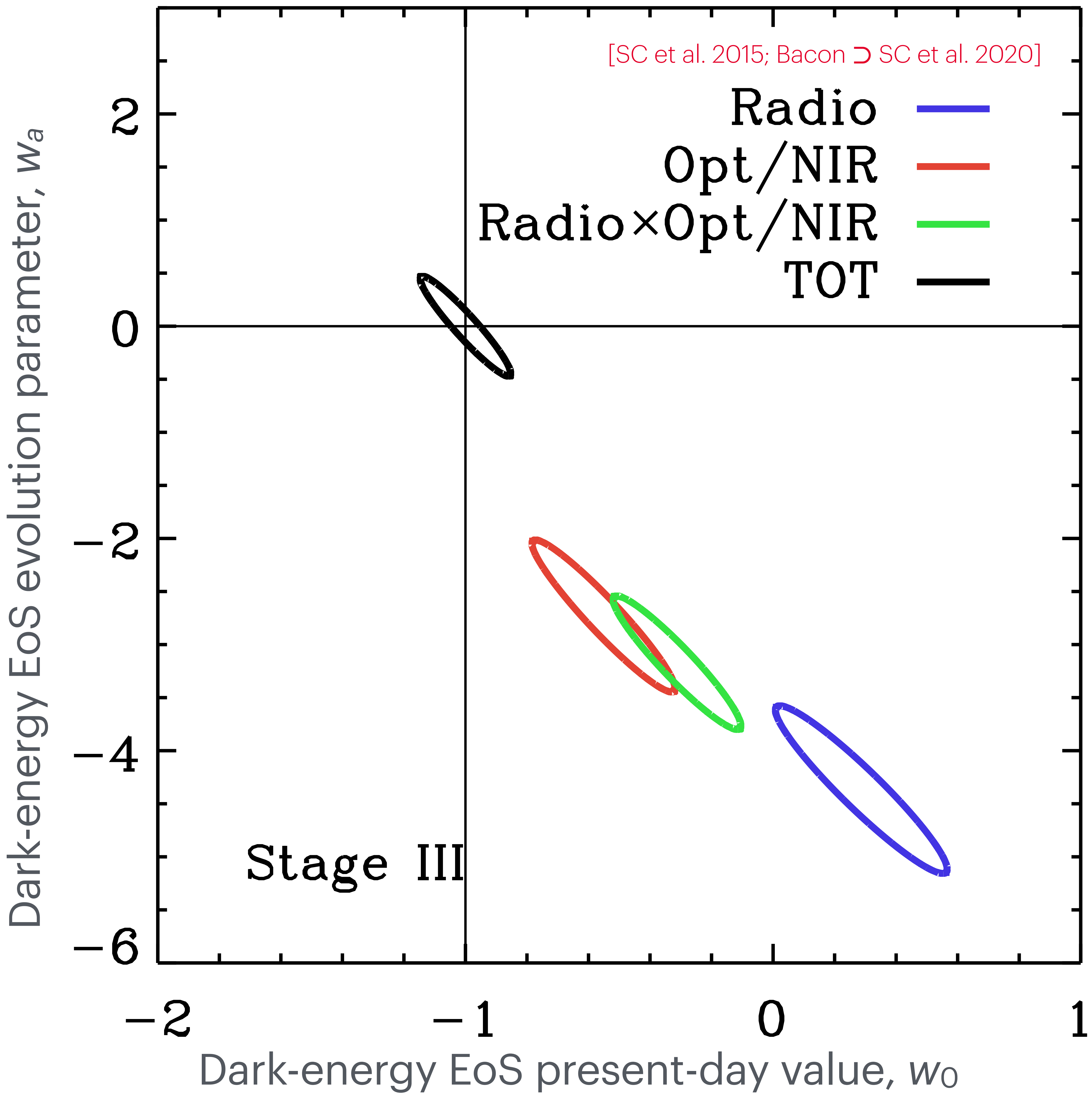
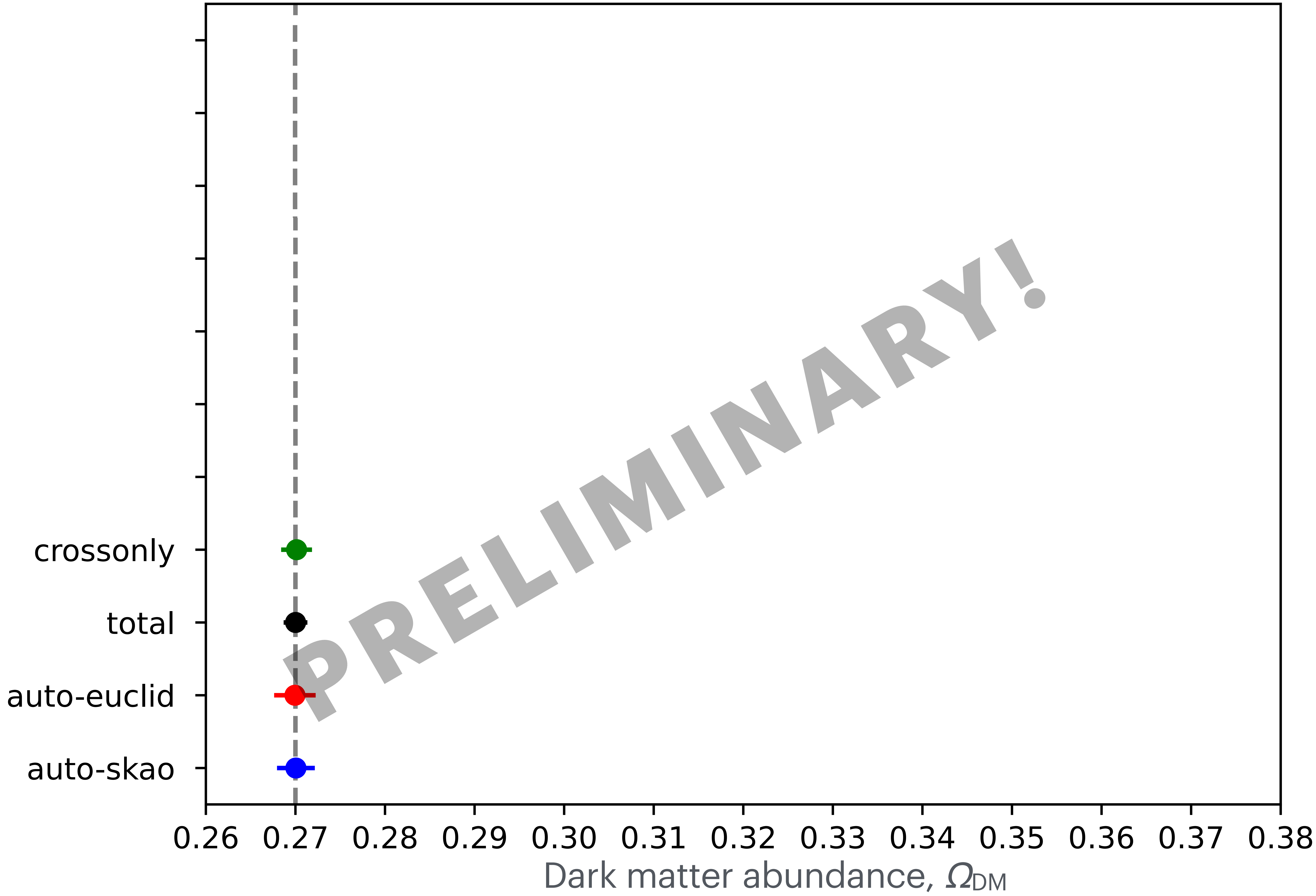


Radio-optical cosmic shear



Radio-optical cosmic shear

[Ingrao, SC et al. (in prep.)]



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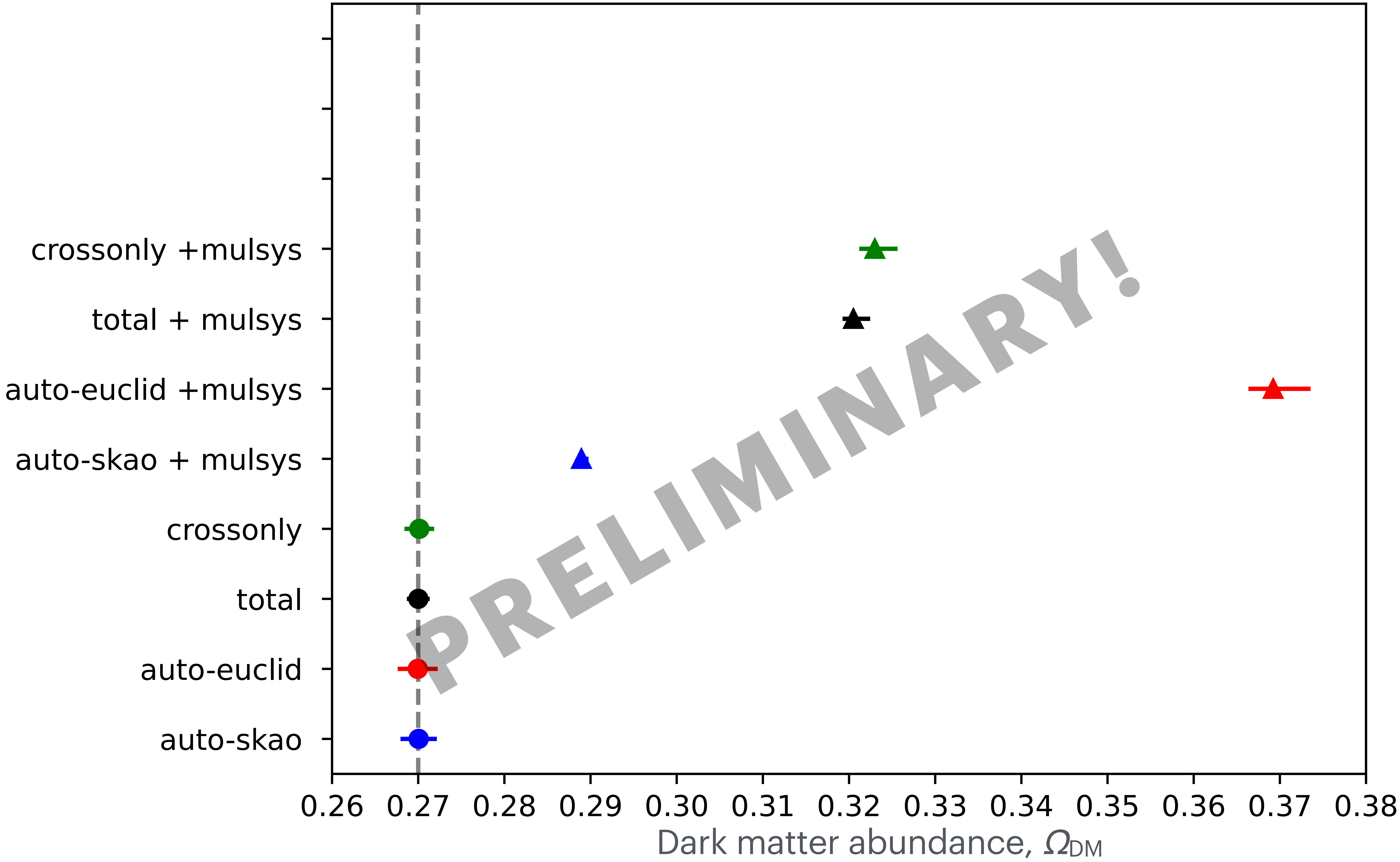

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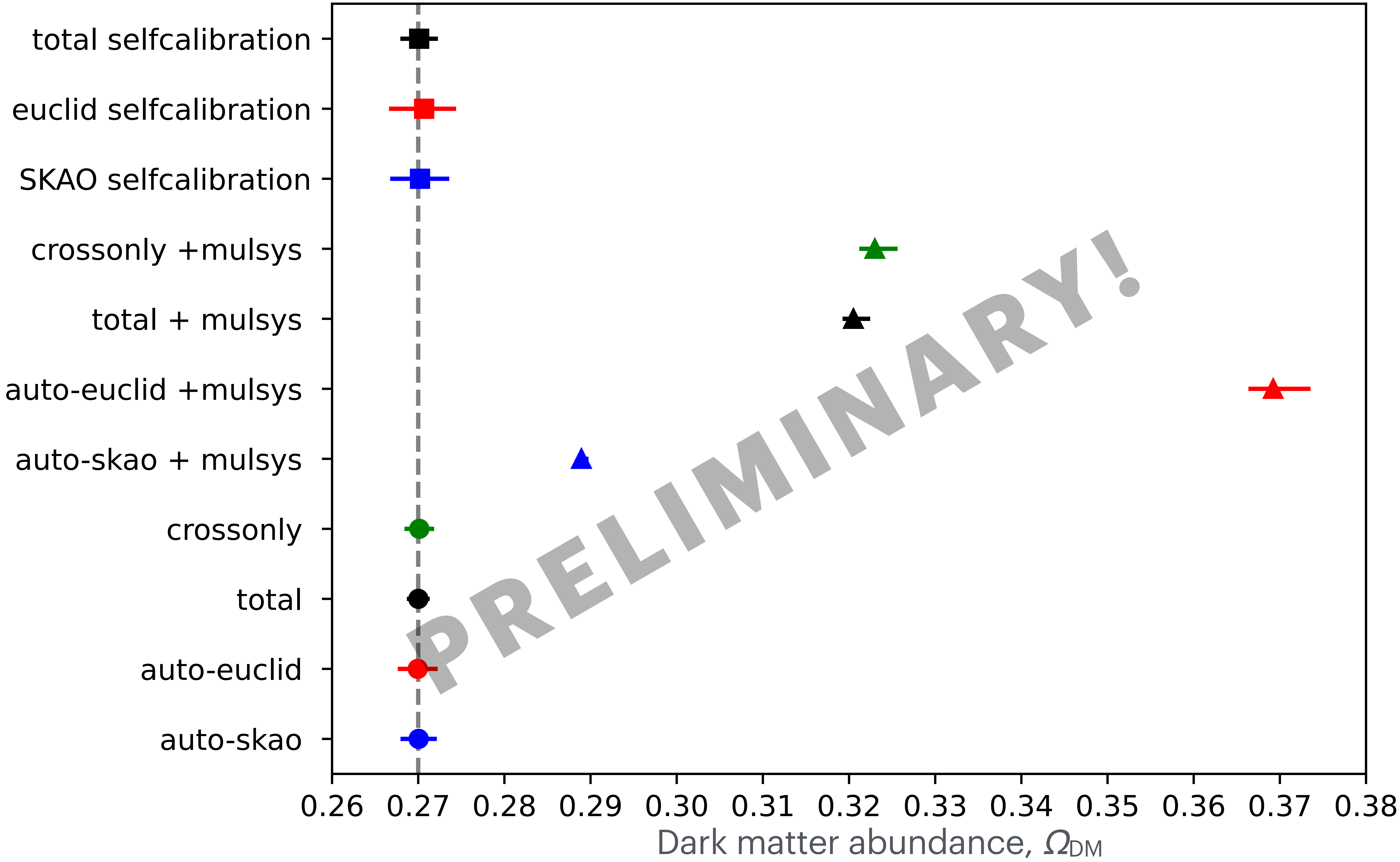

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Conclusions

- The SKA Observatory and its precursors/pathfinders are ushering in the era of cosmology at radio wavelengths

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See Licia's talk about reproducibility!

Conclusions

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Conclusions

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- Conventional cosmological probes (galaxy clustering and cosmic shear) available to cross-validate results from e.g. *Euclid*, DESI, DES
- Cross-correlations and other synergies will allow us to remove/alleviate observational and theoretical systematic effects
- Data from precursors and pathfinders already available (e.g. LOFAR, CHIME, ASKAP [RACS, EMU], MeerKAT [MeerKLASS, MIGHTEE-HI])