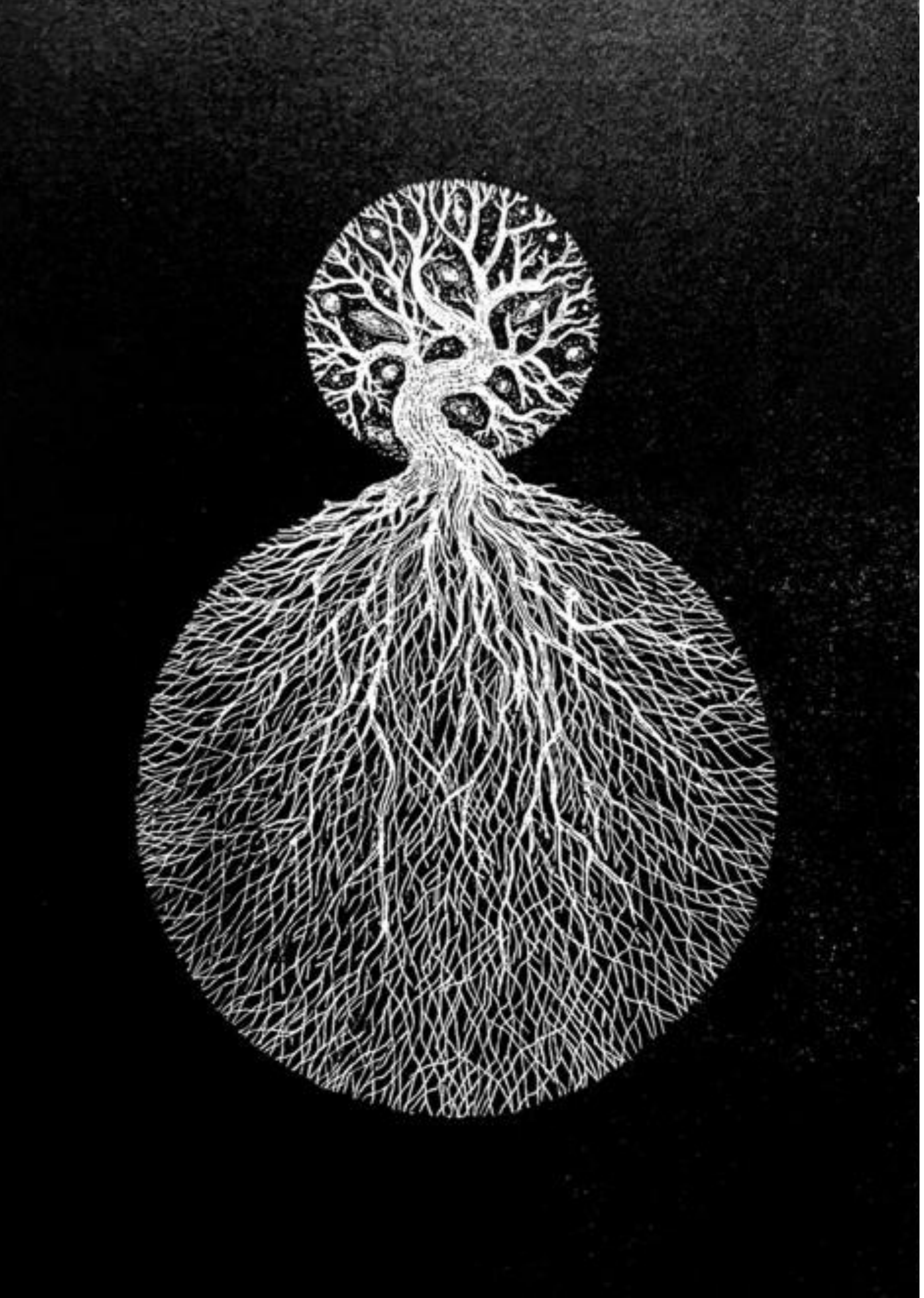

Radio cosmology and the impact of low frequencies

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
Osservatorio Astrofisico di Torino INAF Istituto Nazionale di Astrofisica
University of the Western Cape
Università di Torino

The concordance cosmological model

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Definition of **cosmology noun** from the Oxford Advanced Learner's Dictionary

cosmology *noun*

/kɒz'mɒlədʒi/

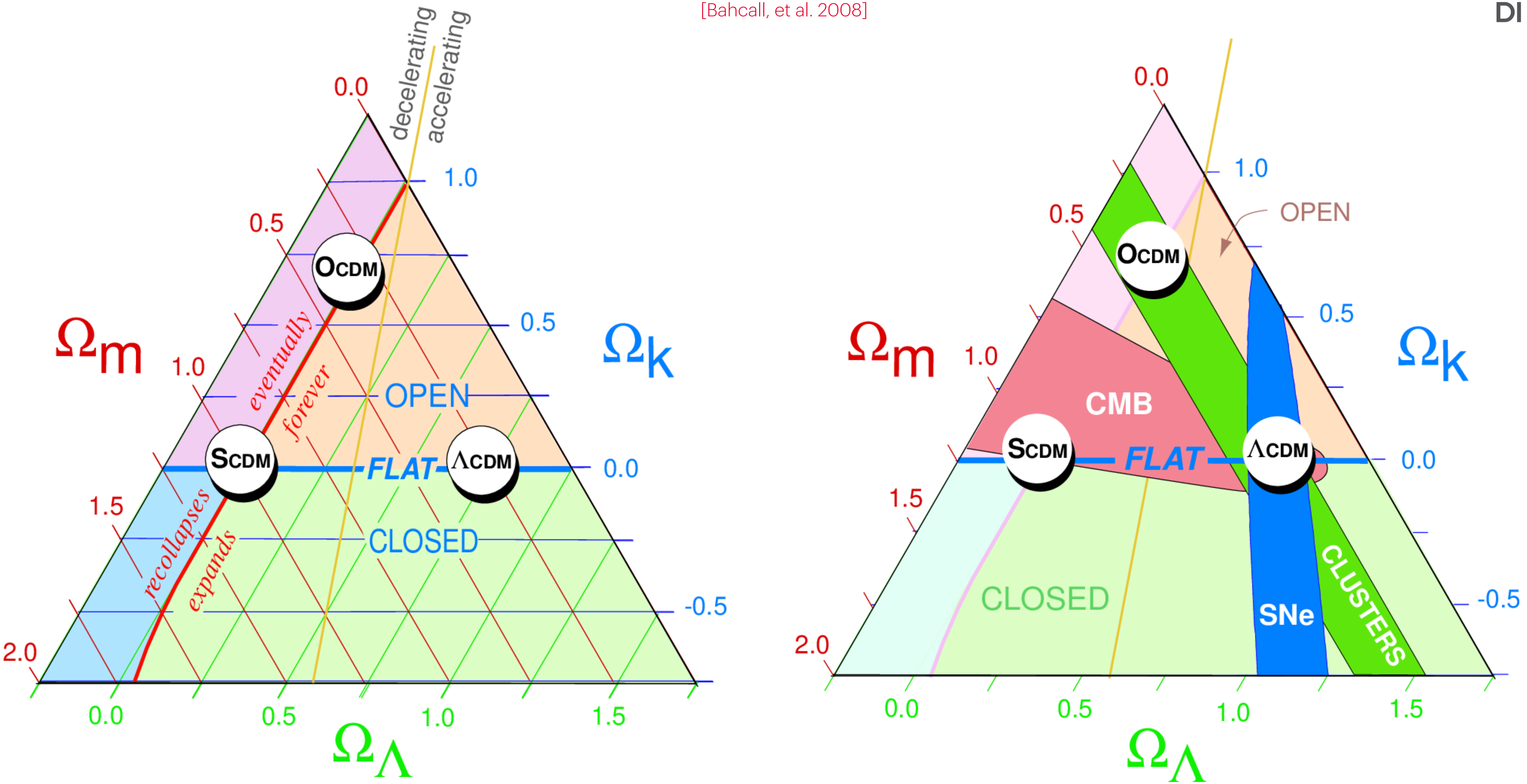
/kɑːz'mɑːlədʒi/

[uncountable]

the scientific study of the universe and its origin and development

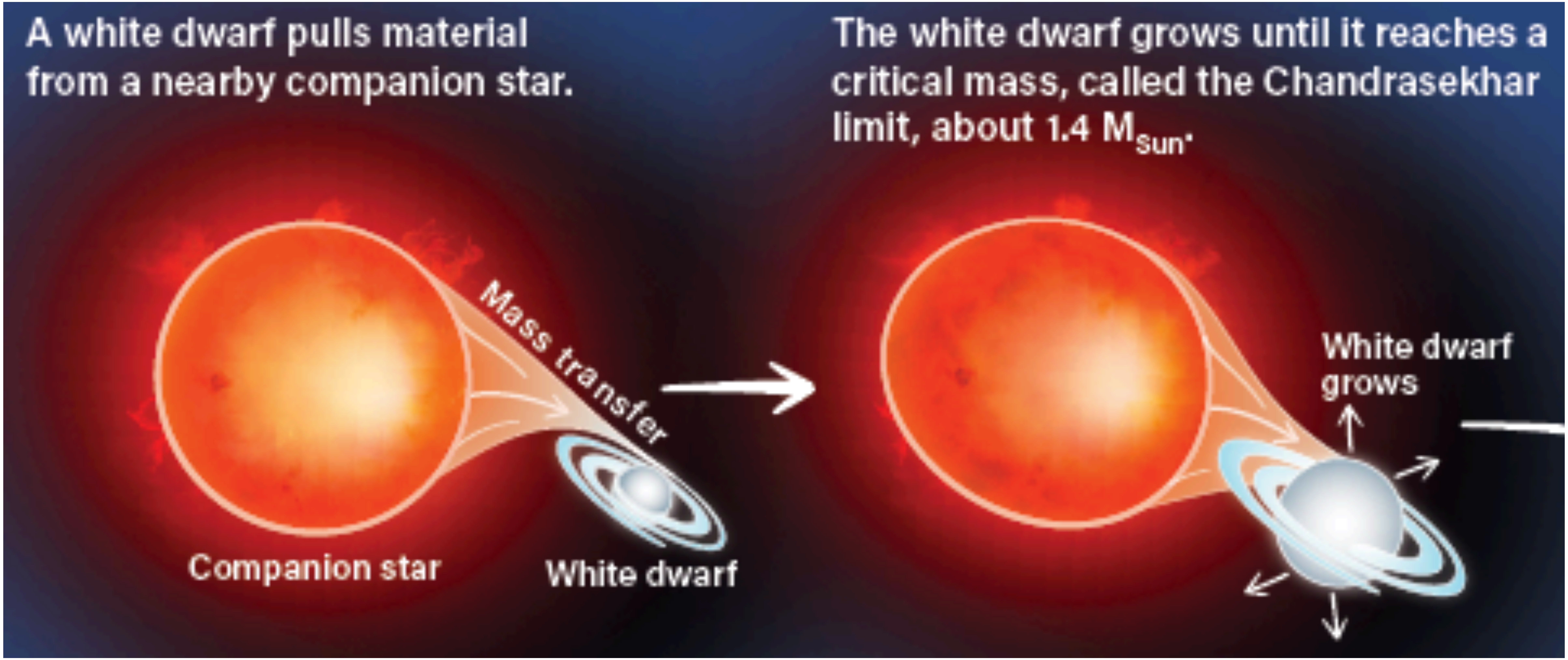
The concordance cosmological model

[Bahcall, et al. 2008]



Type Ia Supernovæ

[Perlmutter & Schmidt 2003]



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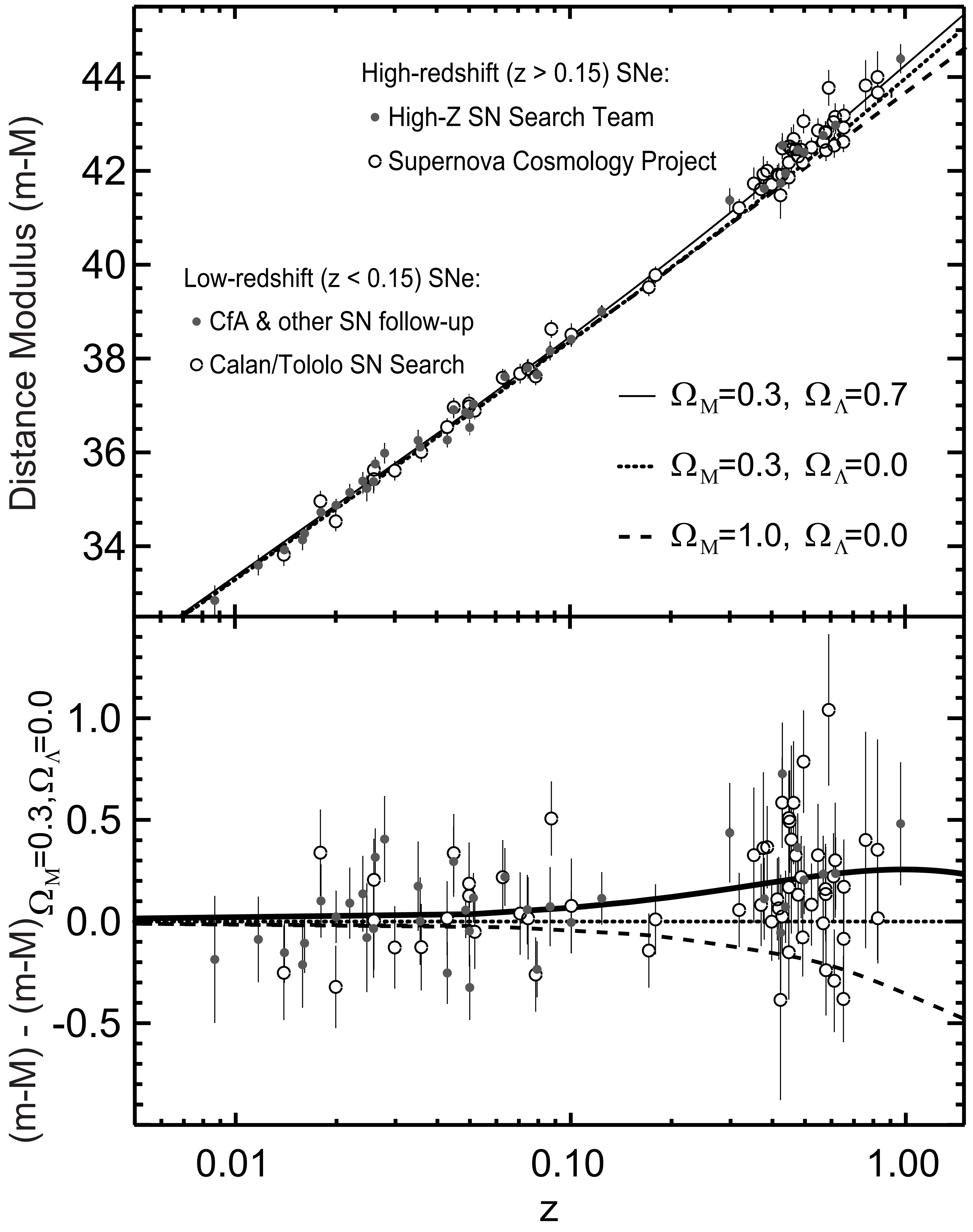
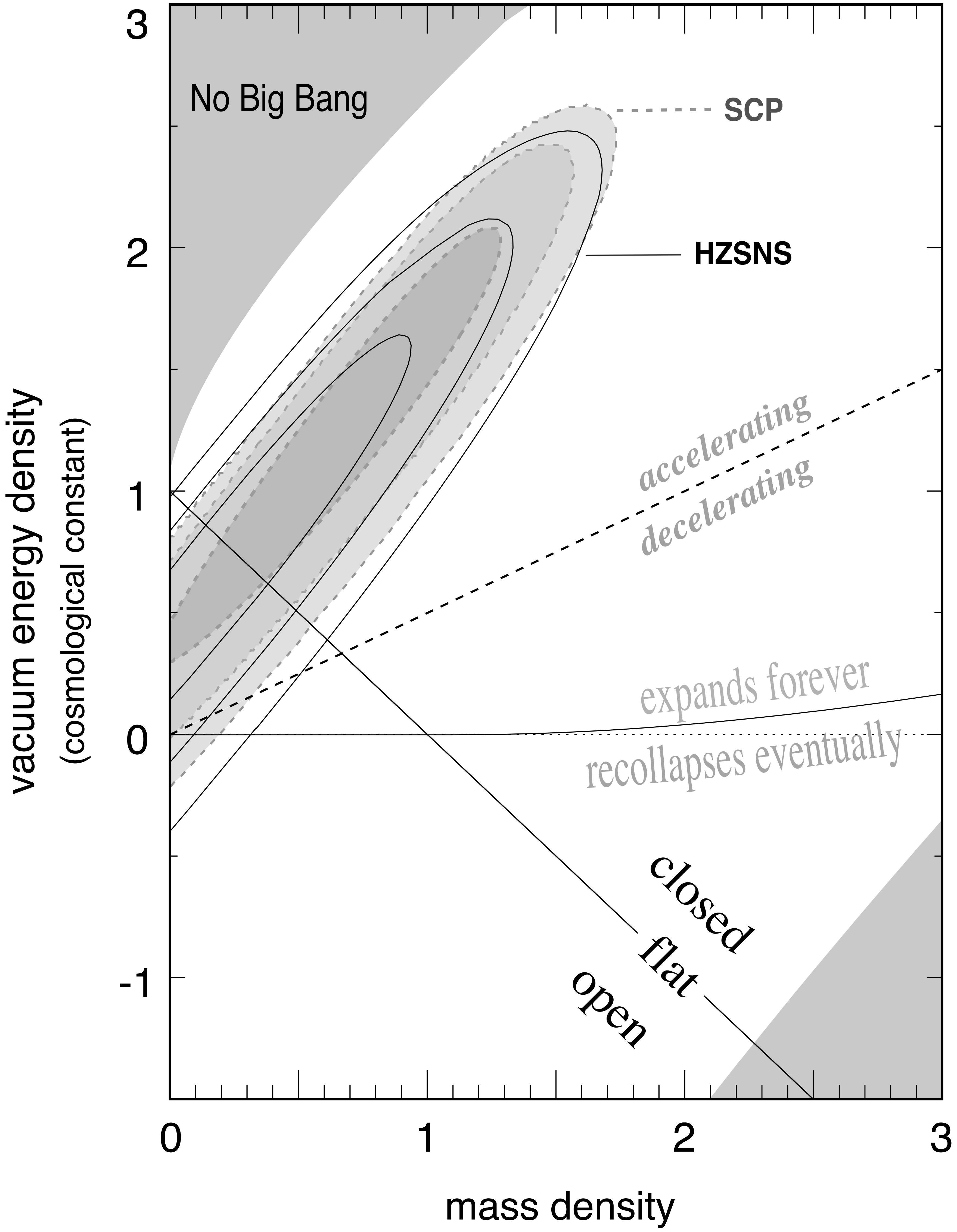
Type Ia Supernovæ

[Perlmutter & Schmidt 2003]





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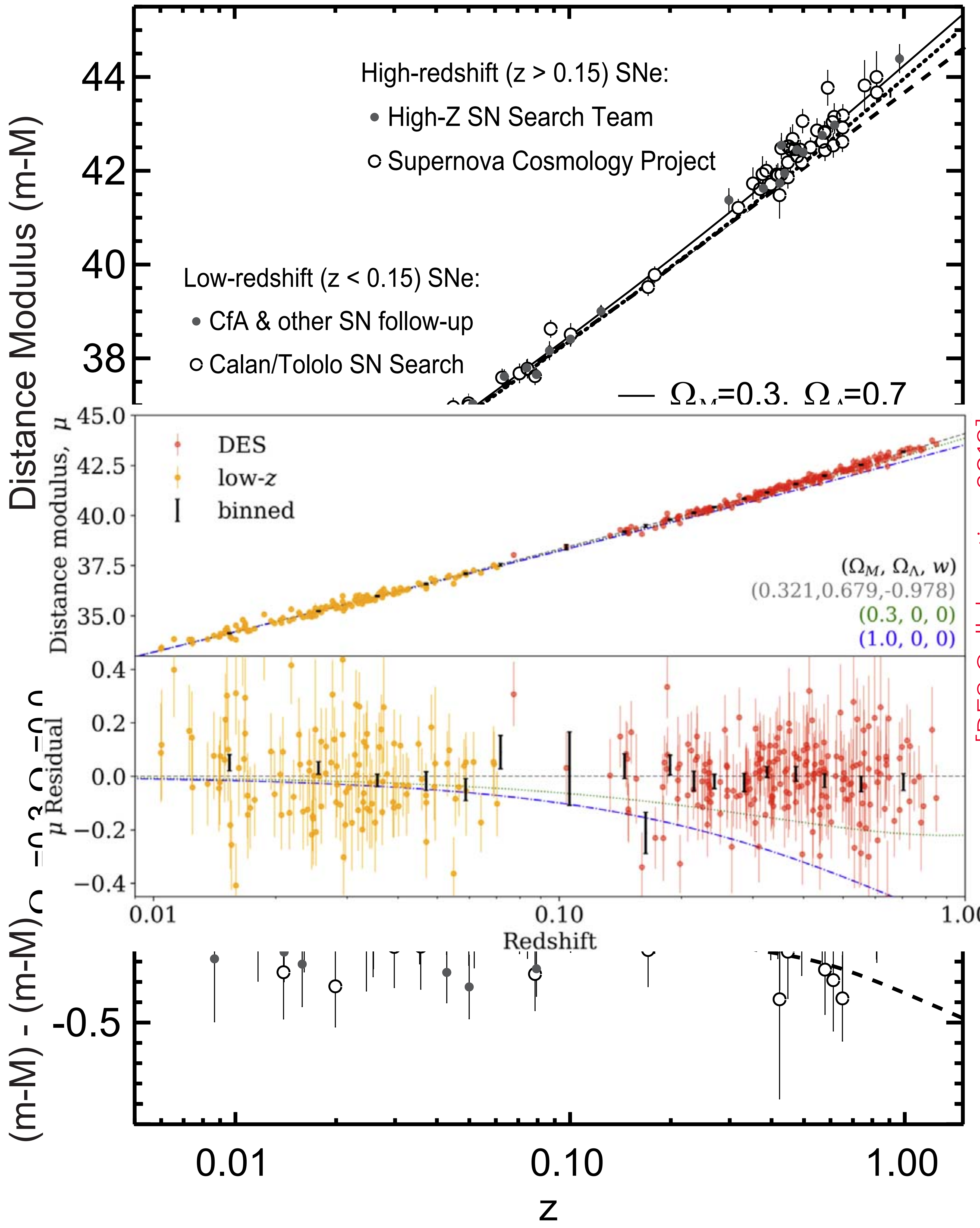
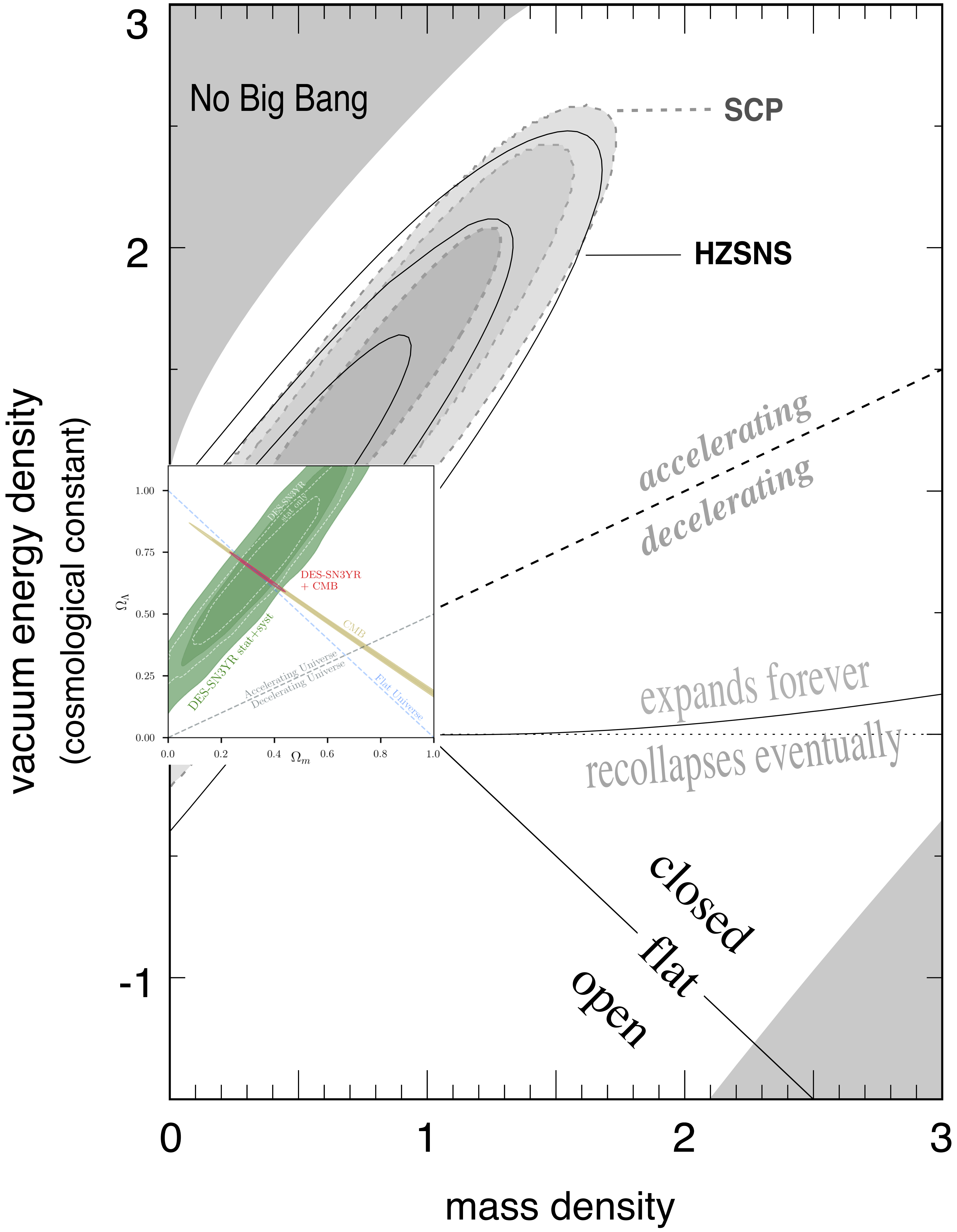
Type Ia Supernovæ

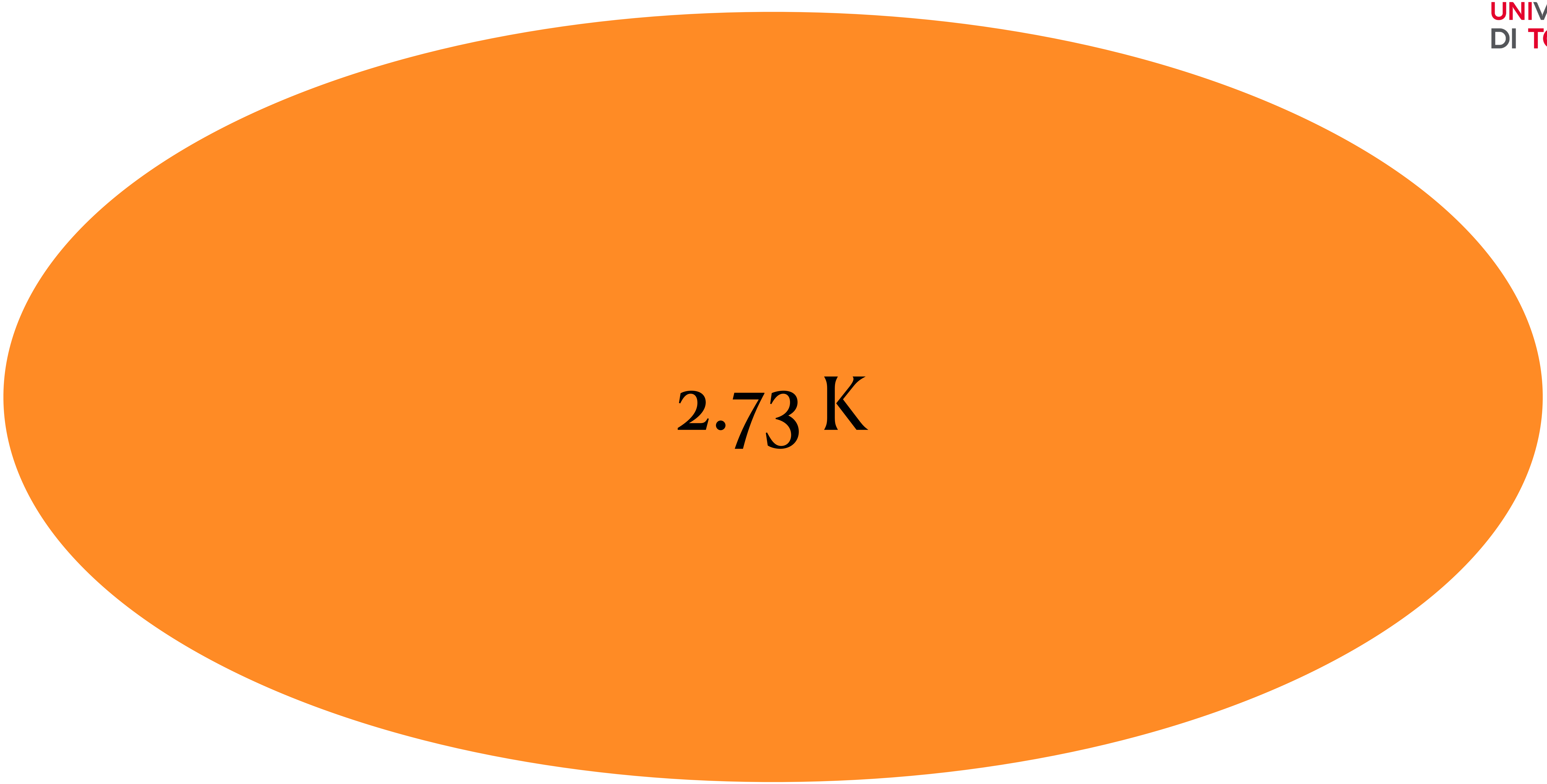
[Perlmutter & Schmidt 2003]



[DES Collaboration 2019]

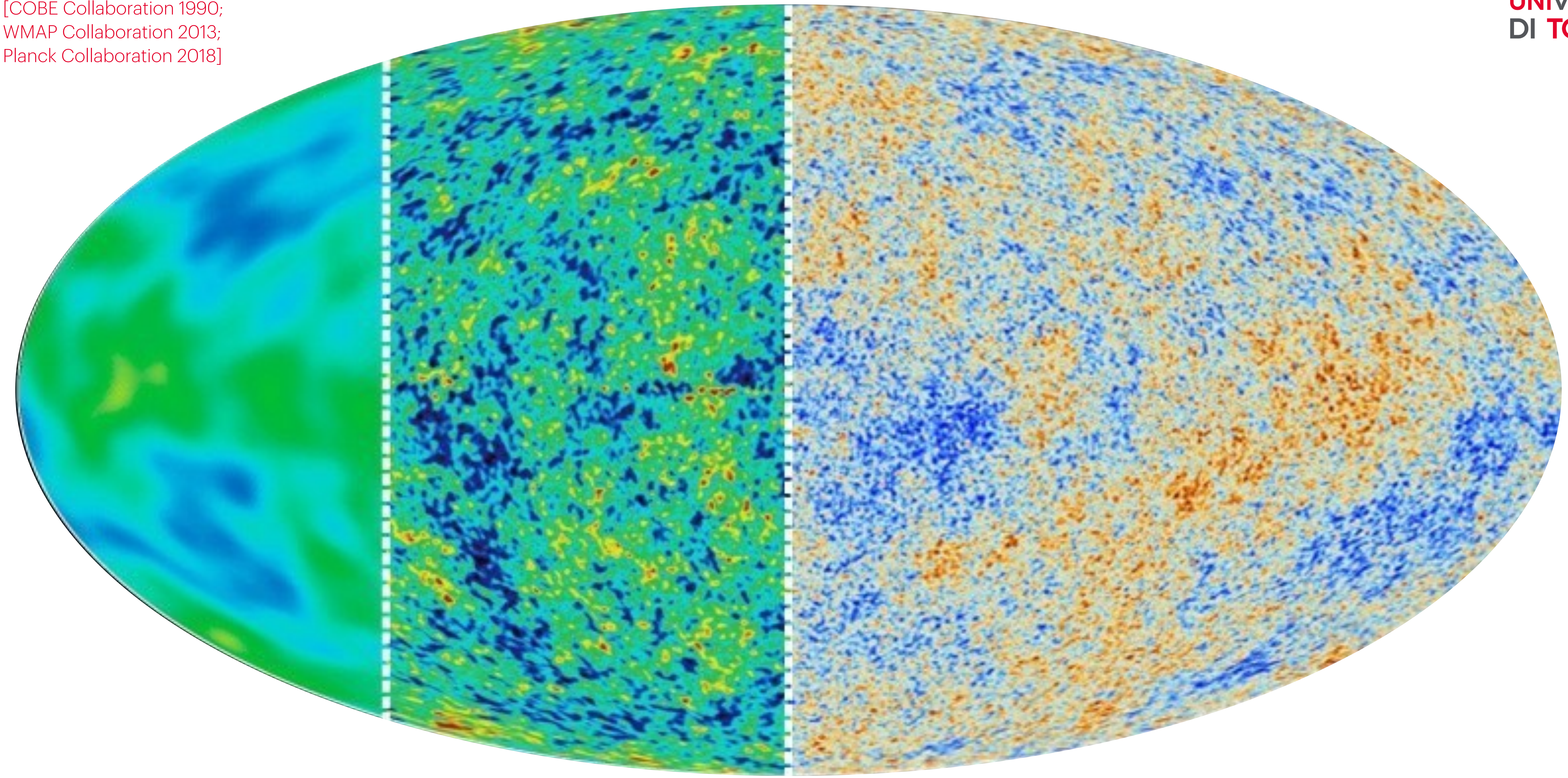


Cosmic microwave background

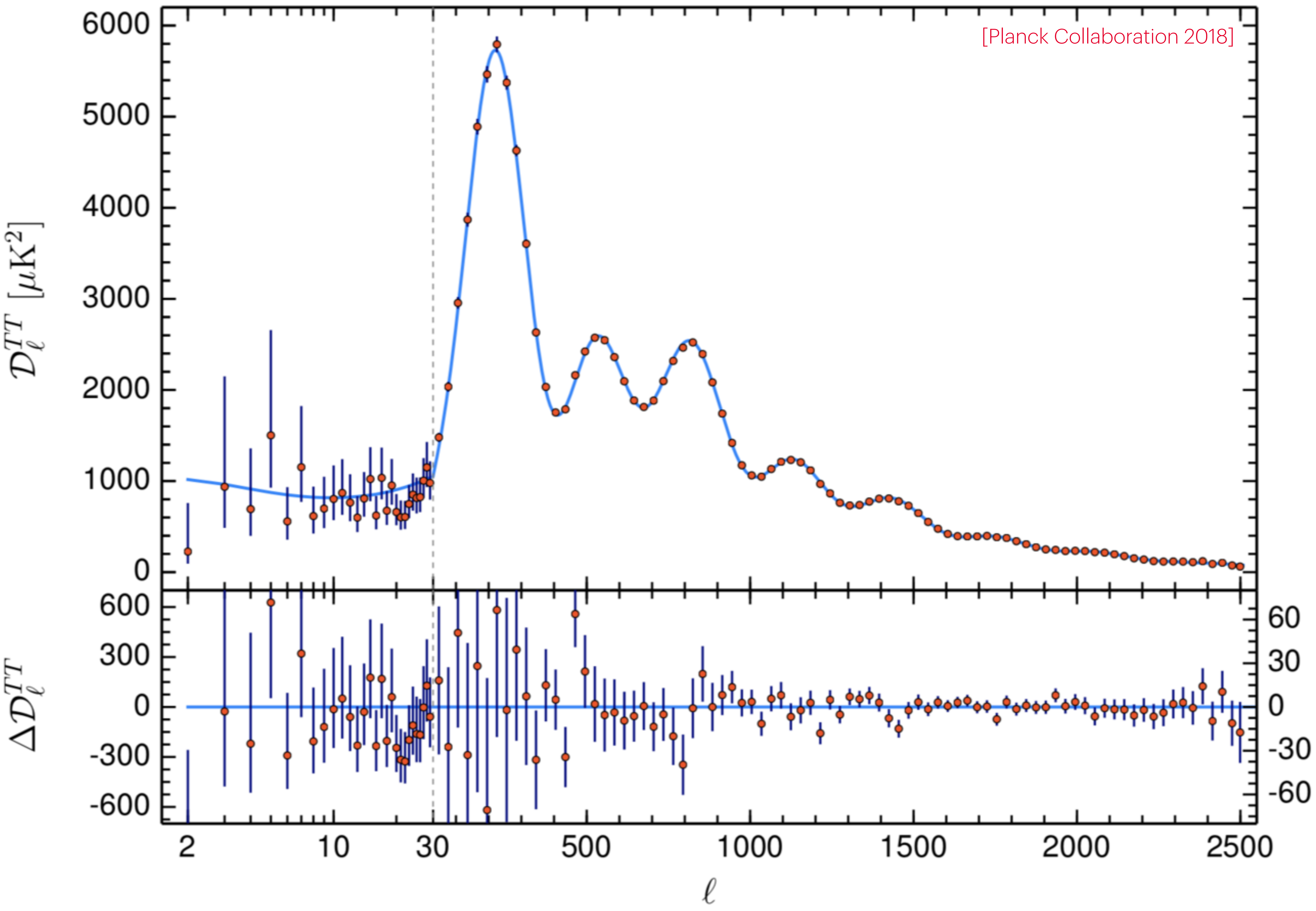


Cosmic microwave background

[COBE Collaboration 1990;
WMAP Collaboration 2013;
Planck Collaboration 2018]



Cosmic microwave background



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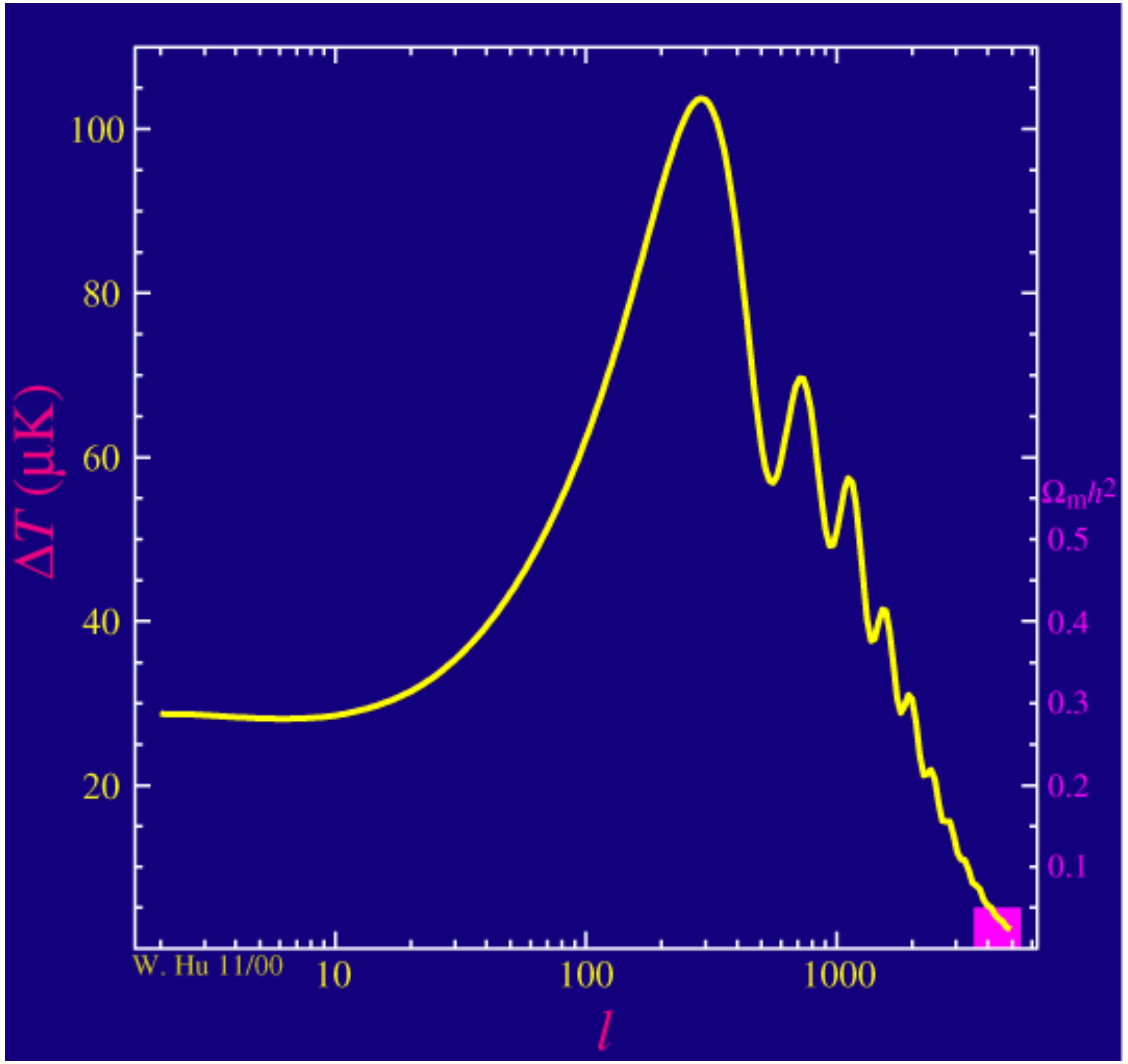
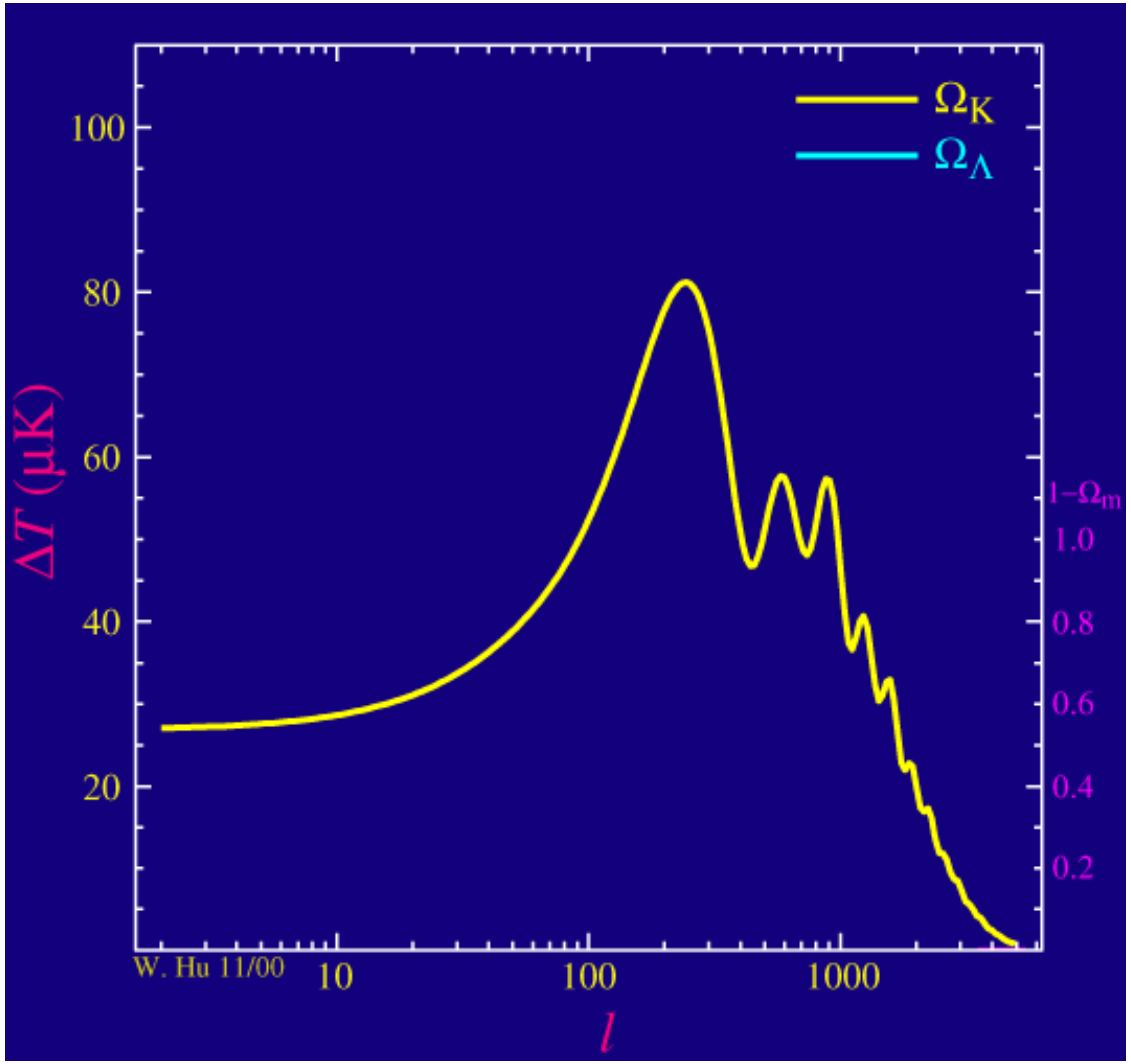
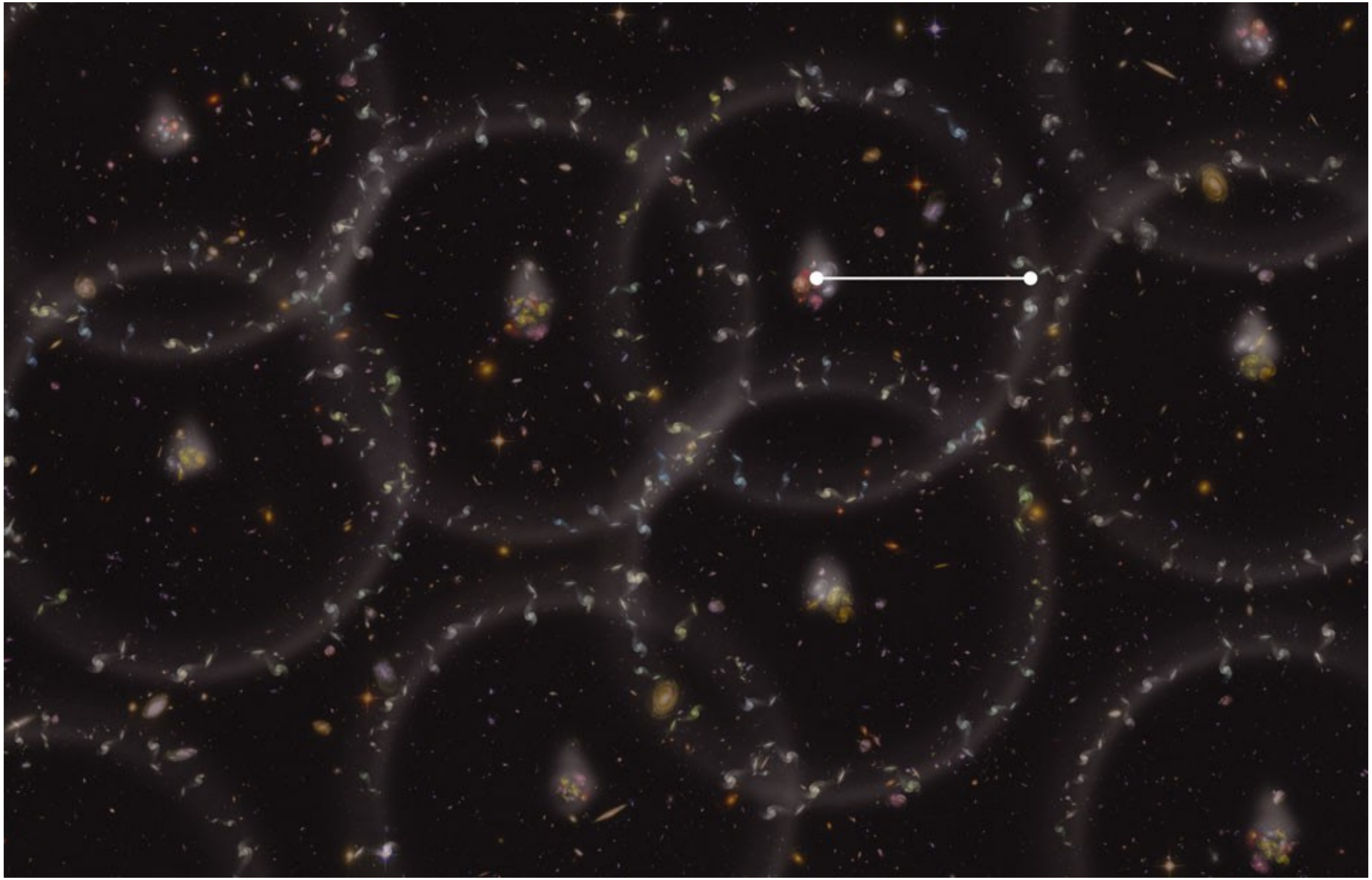
Cosmic microwave background

[Planck Collaboration 2018]





Baryon acoustic oscillations



[Credits: Z. Rostomian]

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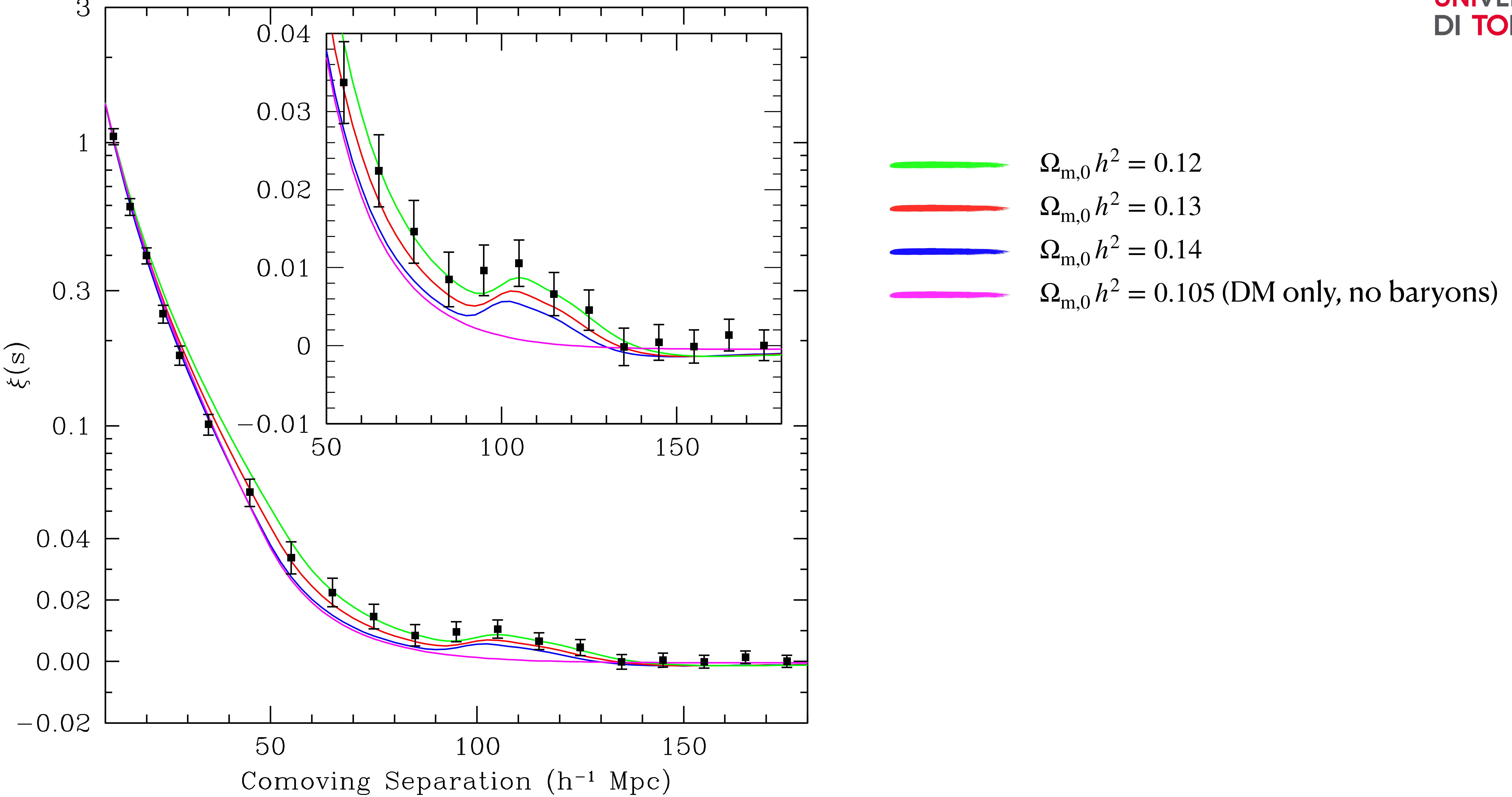
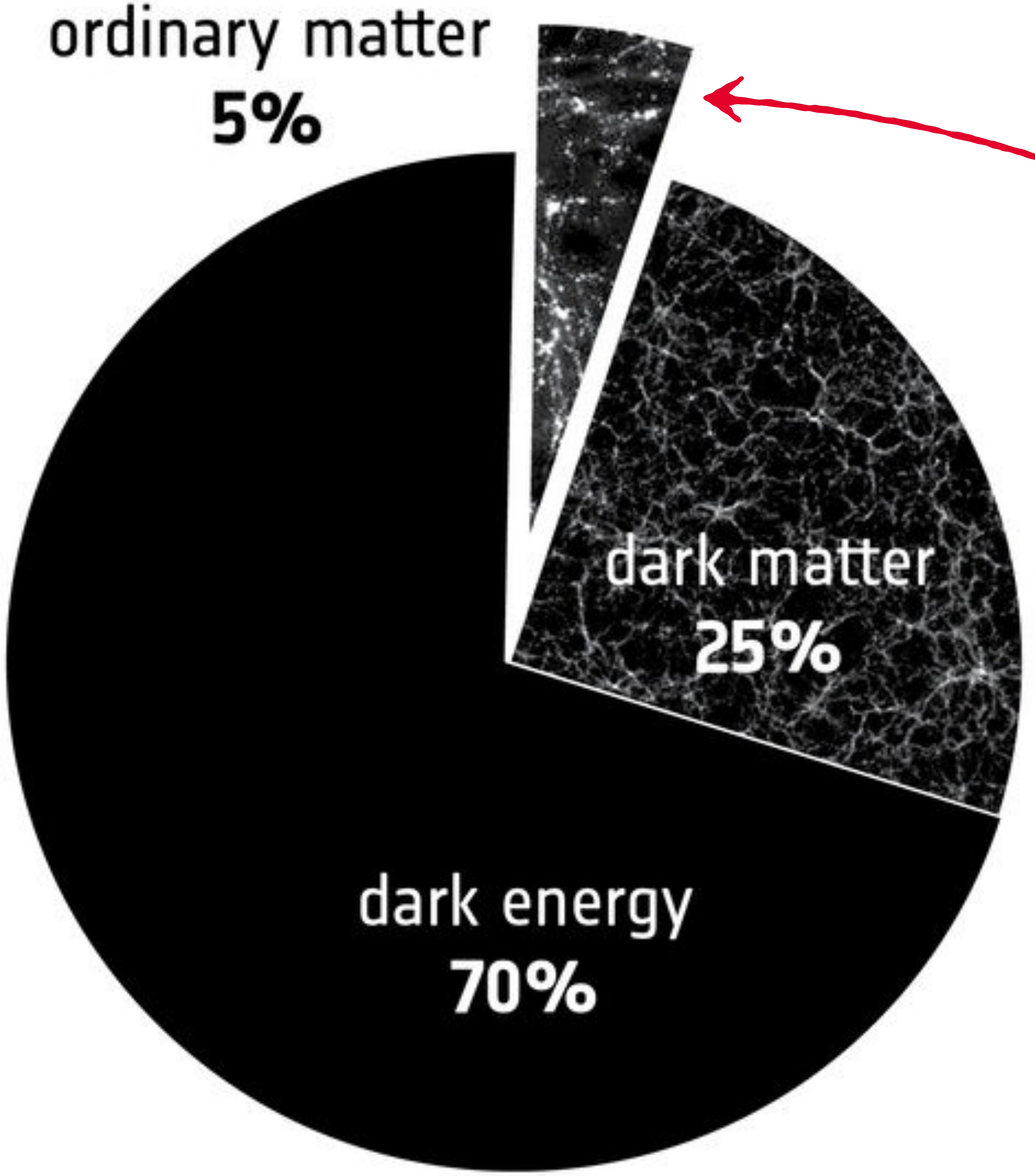
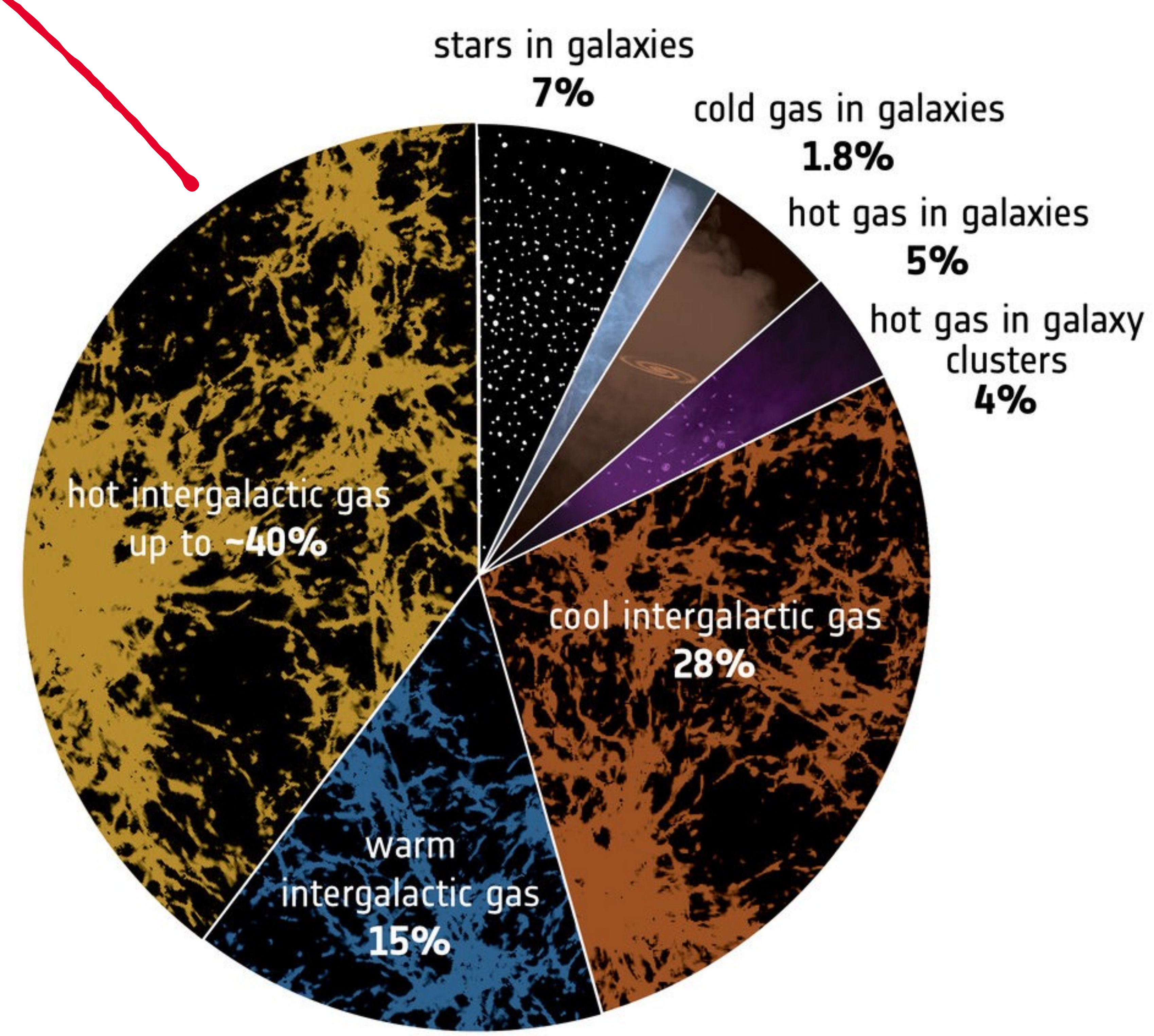
Baryon acoustic oscillations

[Eisenstein et al. 2005]



The concordance cosmological model





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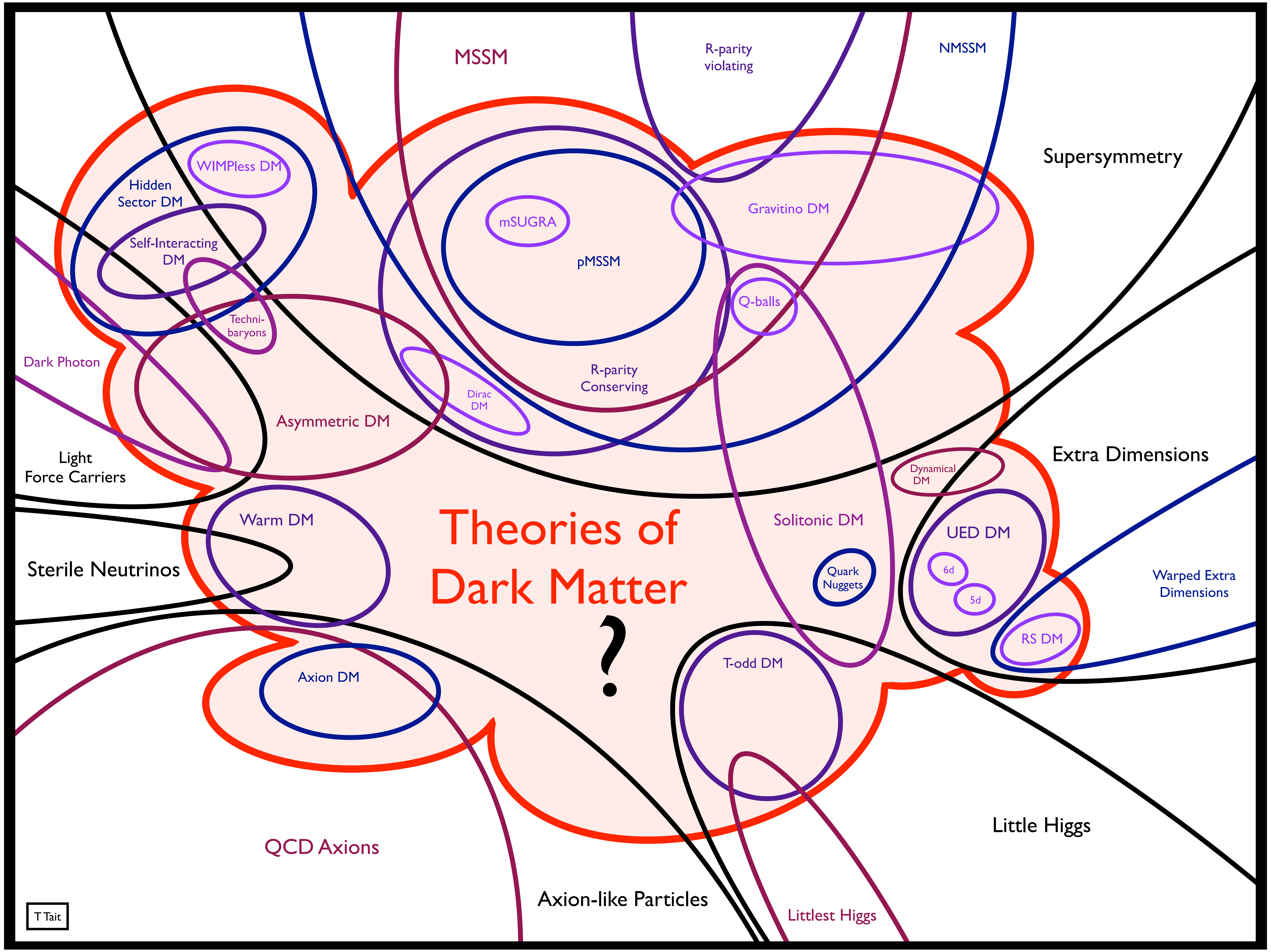
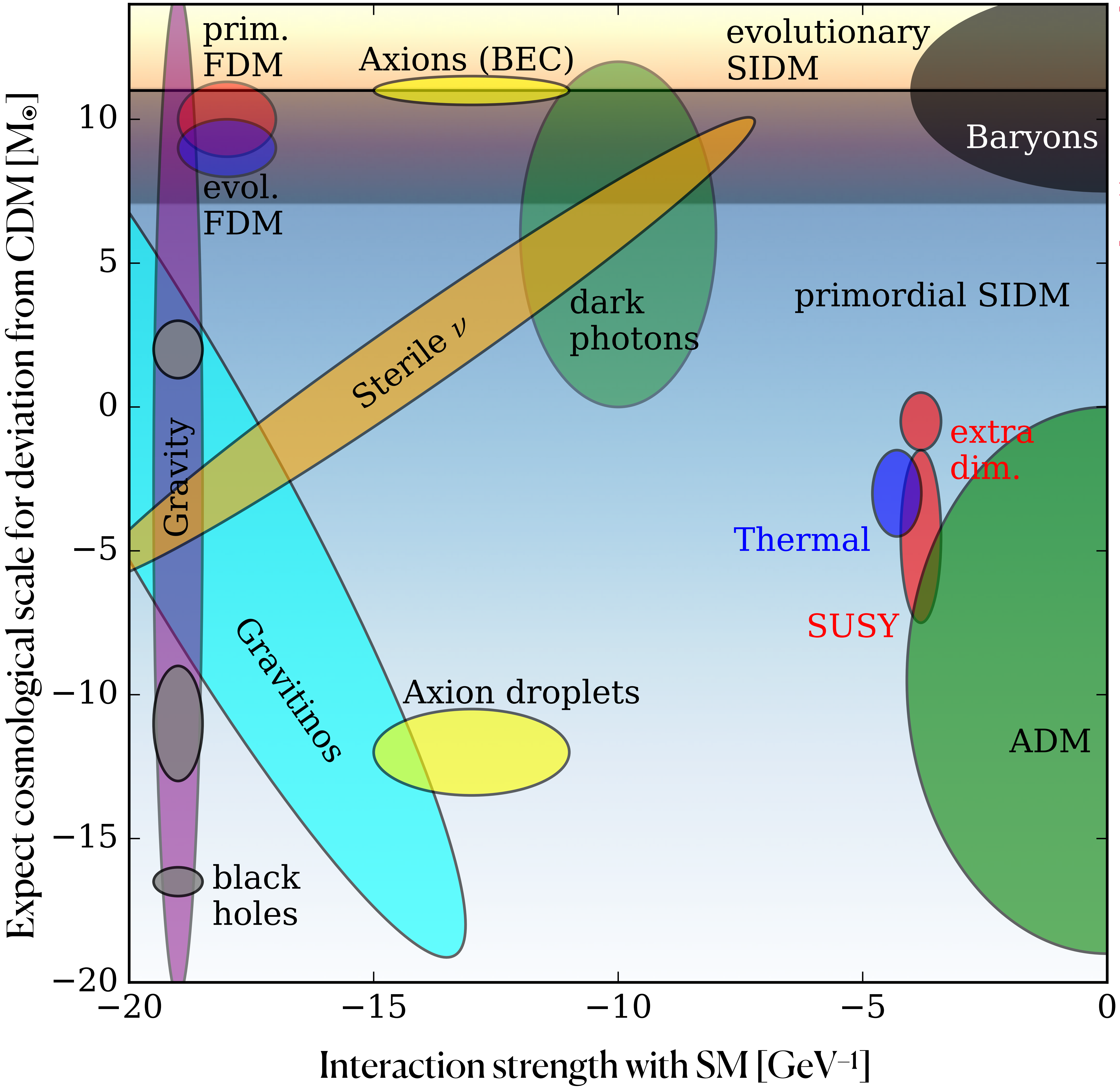
Dark matter (for particle physicists)



[Credits: T. Tait]

Dark matter (for cosmologists)



[Buckley & Peter 2017]

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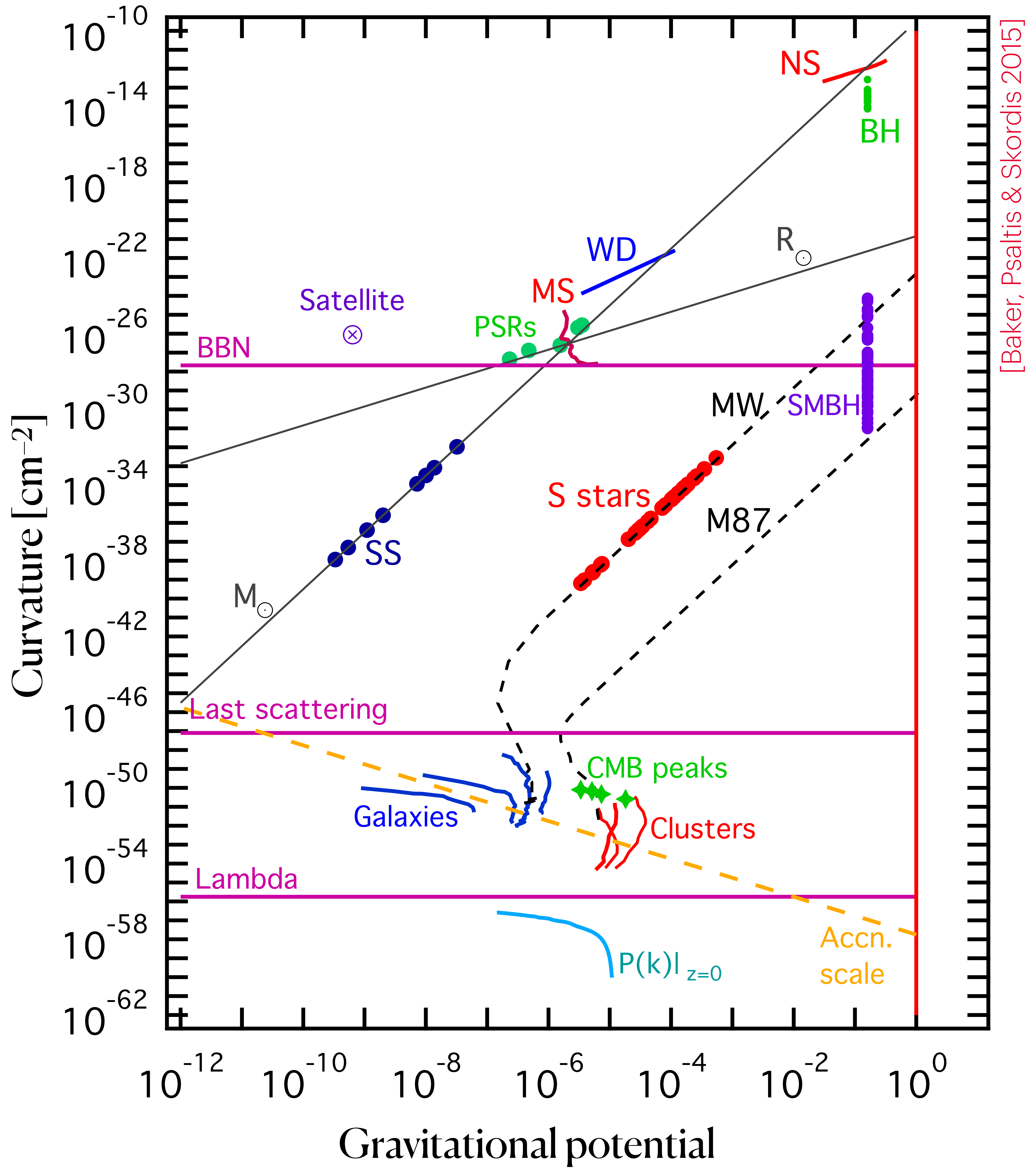
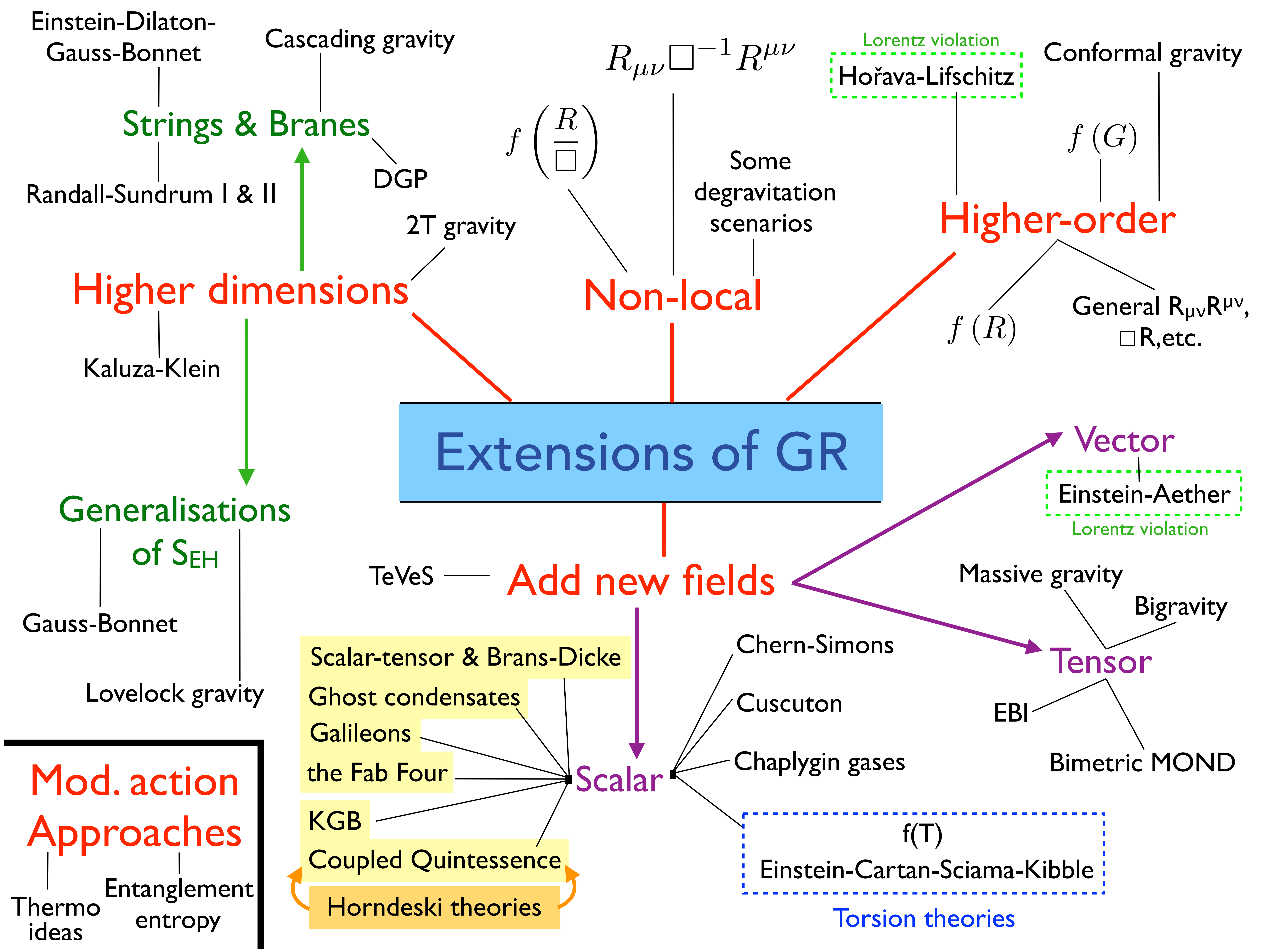
Dark energy (for astronomers)



Dark energy (for relativists)



[Credits: T. Baker]

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Correlations 101

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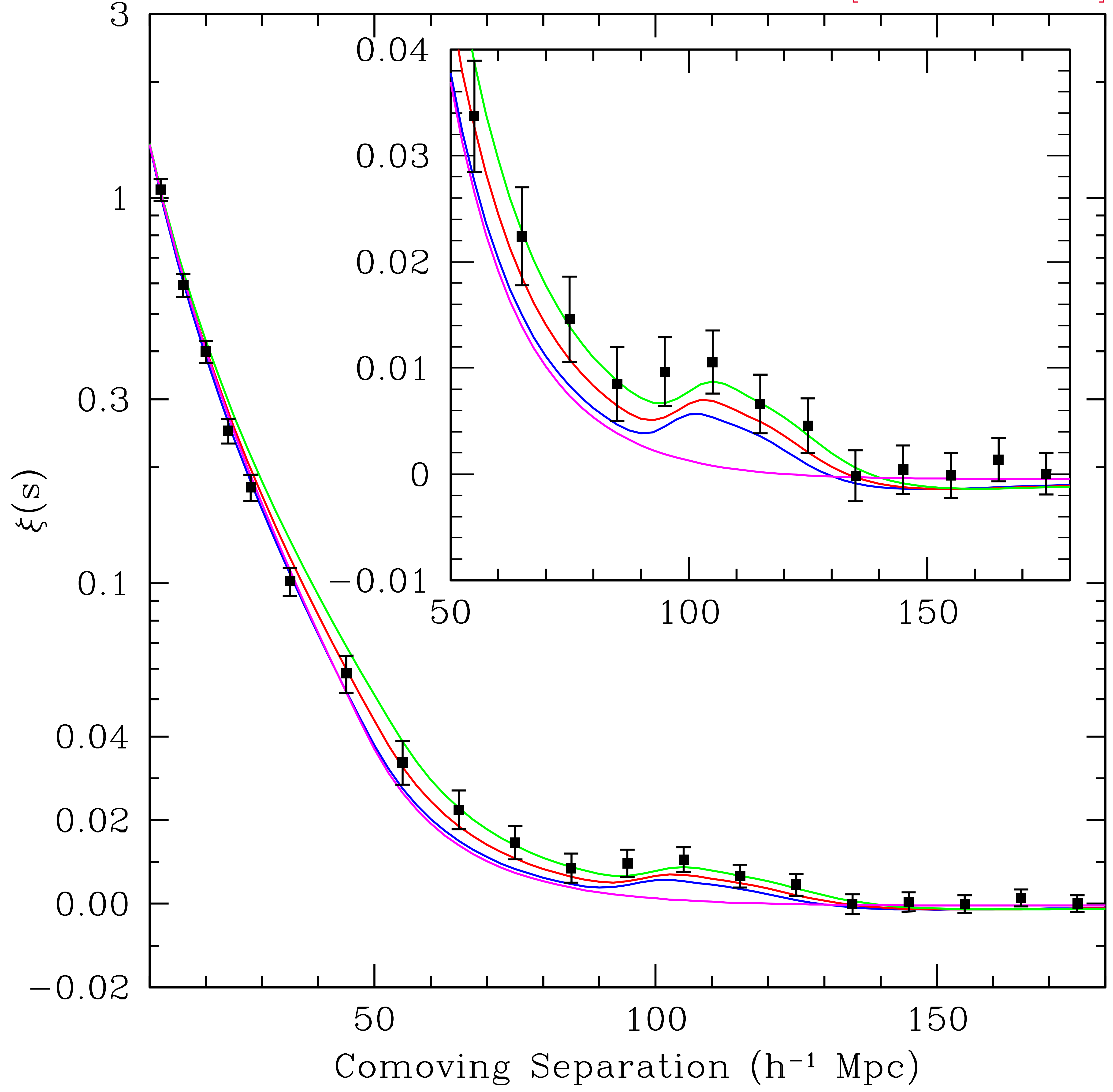
- Cosmological perturbation $f(t,\boldsymbol{x})$
  [temperature fluctuations, density perturbations, ...]
- Two-point correlation function $\langle f(z,\boldsymbol{x})\, f(z,\boldsymbol{y})\rangle = \xi_{ff}(z,|\boldsymbol{x}-\boldsymbol{y}|)$
- *Example no. 1:* Galaxy correlation function

$$f(t,\boldsymbol{x}) \to \Delta(z,\boldsymbol{x}) \equiv \frac{n_{\rm g}(z,\boldsymbol{x}) - \bar{n}_{\rm g}(z)}{\bar{n}_{\rm g}(z)}$$

Correlations 101

[Eisenstein et al. 2005]



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Correlations 101

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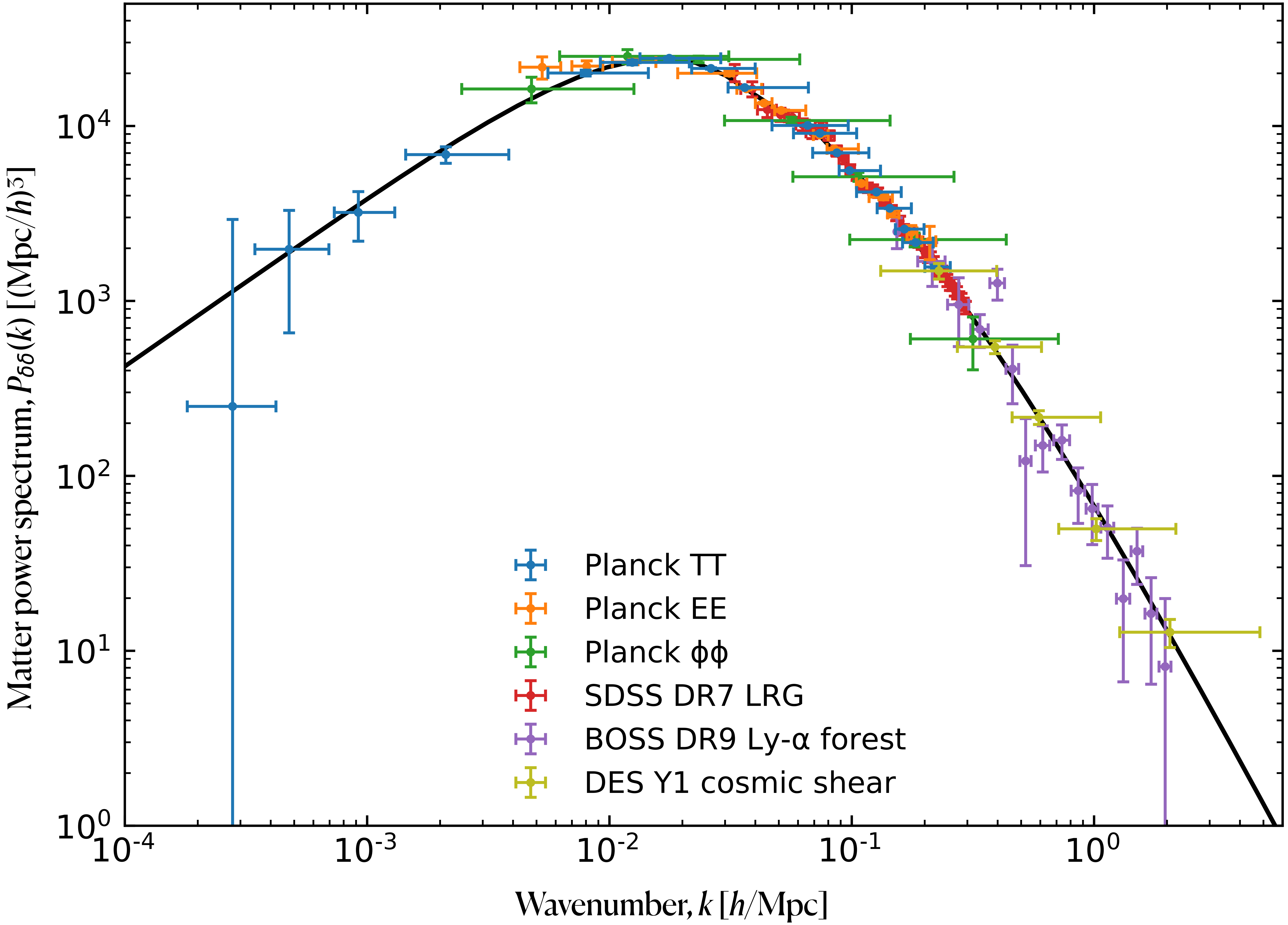
- Cosmological perturbation $f(t,\boldsymbol{x})$
  [temperature fluctuations, density perturbations, ...]
- Two-point correlation function $\langle f(z,\boldsymbol{x})\,f(z,\boldsymbol{y})\rangle = \xi_{ff}(z,|\boldsymbol{x}-\boldsymbol{y}|)$
- Fourier-space power spectrum $\langle \hat{f}(z,\boldsymbol{k})\,\hat{f}(z,\boldsymbol{k}')\rangle = (2\,\pi)^3\,\delta_{(\mathrm{D})}(\boldsymbol{k}+\boldsymbol{k}')\,P_{ff}(z,k)$
- *Example no. 2:* Matter power spectrum

$$f(t,\boldsymbol{x}) \to \delta(z,\boldsymbol{x}) \equiv \frac{\rho(z,\boldsymbol{x})-\bar{\rho}(z)}{\bar{\rho}(z)}$$

Correlations 101

[Planck Collaboration 2018]



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Correlations 101

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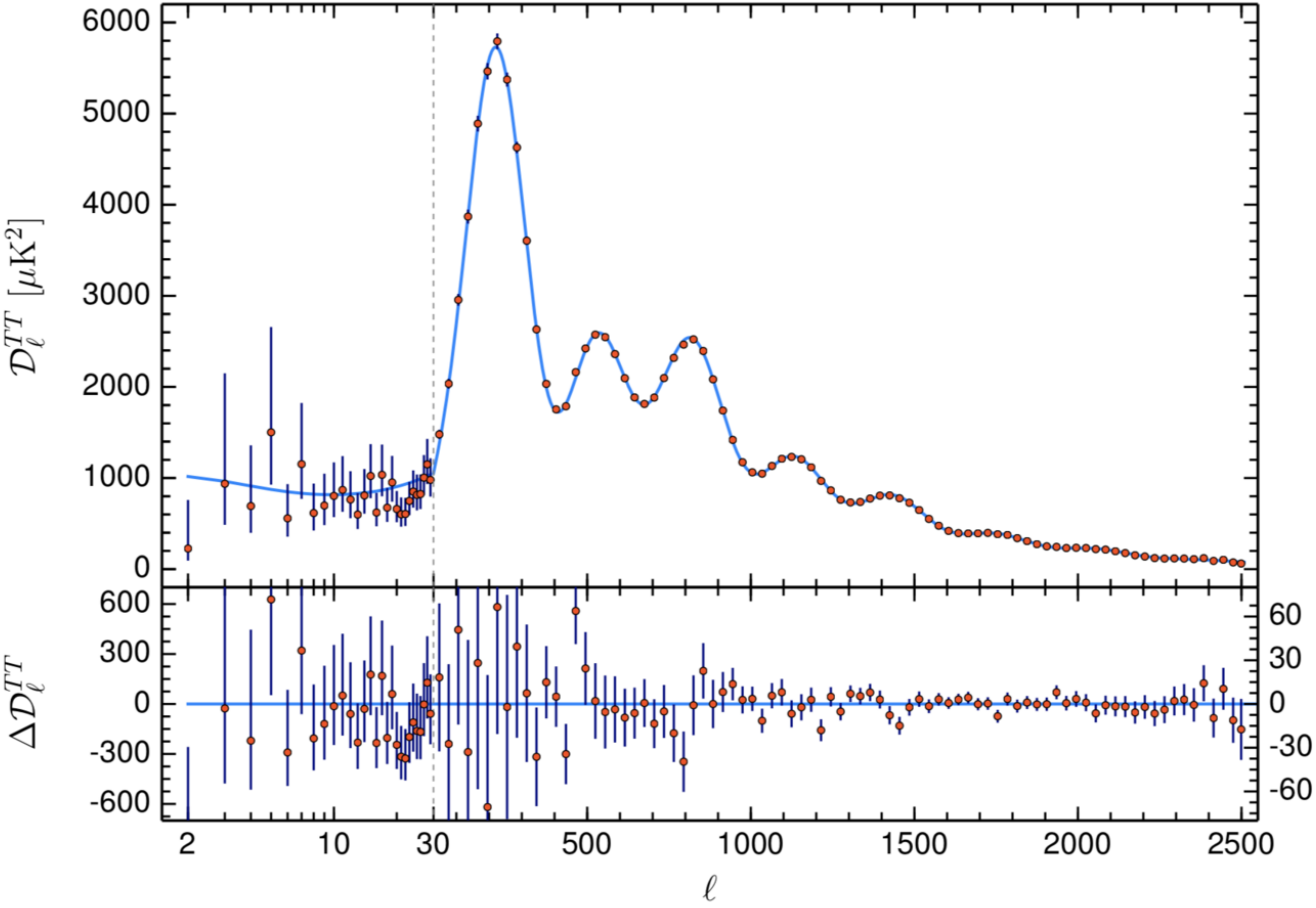
- Cosmological perturbation $f(t, \boldsymbol{x})$
  [temperature fluctuations, density perturbations, ...]
- Two-point correlation function $\langle f(z, \boldsymbol{x})\, f(z, \boldsymbol{y})\rangle = \xi_{ff}(z, |\boldsymbol{x} - \boldsymbol{y}|)$
- Fourier-space power spectrum $\langle \hat{f}(z, \boldsymbol{k})\, \hat{f}(z, \boldsymbol{k}')\rangle = (2\,\pi)^3\, \delta_{(\mathrm{D})}(\boldsymbol{k} + \boldsymbol{k}')\, P_{ff}(z, k)$
- Harmonic-space power spectrum $\langle \tilde{f}_{\ell m}(z)\, \tilde{f}_{\ell' m'}(z')\rangle = \delta^{\ell\ell'}_{(\mathrm{K})}\, \delta^{mm'}_{(\mathrm{K})}\, C^{ff}_{\ell}(z, z')$
- *Example no. 3:* CMB temperature power spectrum

$$f(t, \boldsymbol{x}) \to \Theta(\hat{\boldsymbol{n}}) \equiv \frac{T(t_0, \hat{\boldsymbol{n}}) - \bar{T}(t_0)}{\bar{T}(t_0)}$$

Correlations 101

[Planck Collaboration 2018]



Correlations 101

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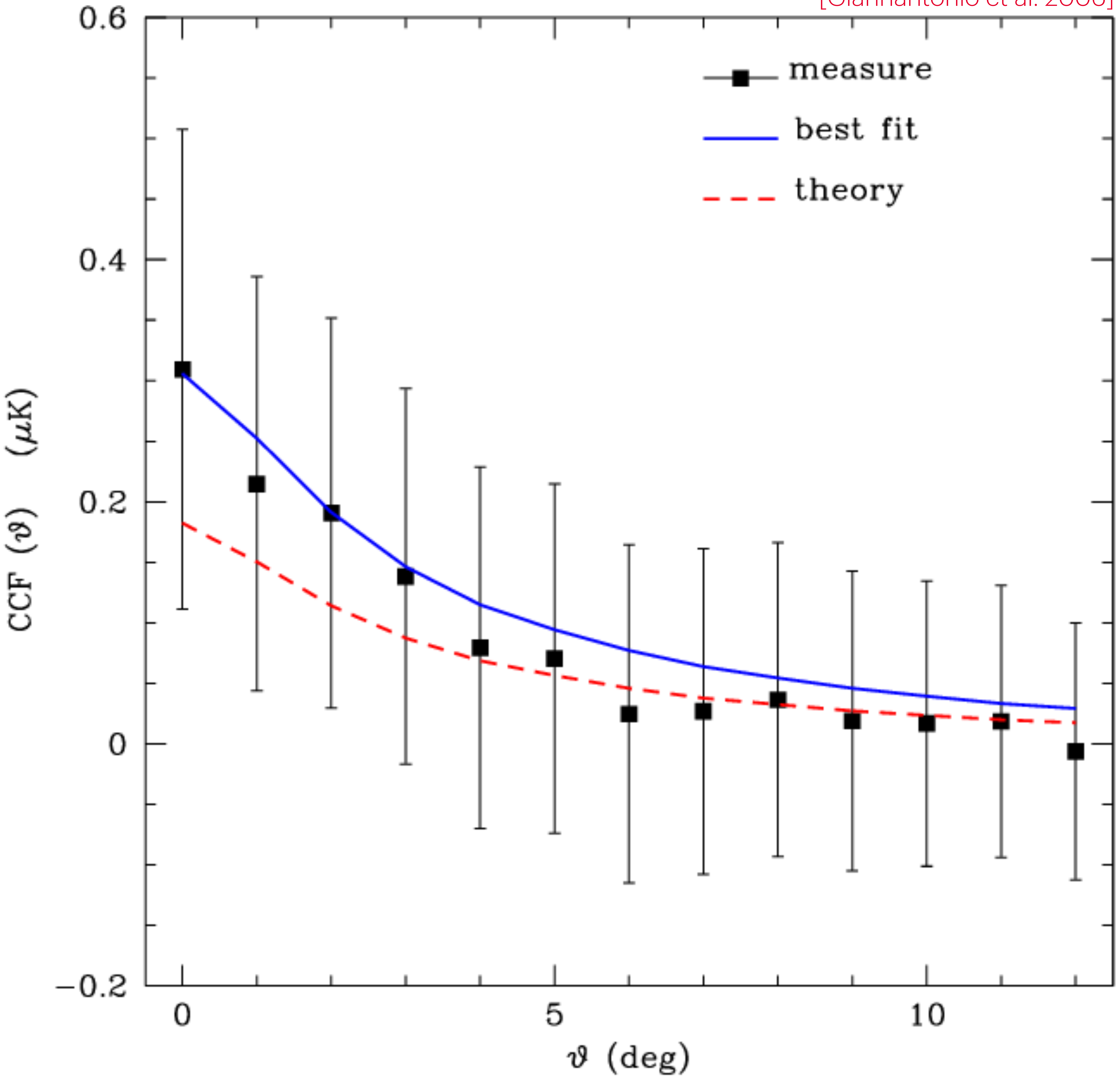
- Cosmological perturbation $f(z,\boldsymbol{x}), g(z,\boldsymbol{x})$
  [temperature fluctuations, density perturbations, …]
- Two-point correlation function $\langle f(z,\boldsymbol{x})\,g(z,\boldsymbol{y})\rangle = \xi_{fg}(z,|\boldsymbol{x}-\boldsymbol{y}|)$
- Fourier-space power spectrum $\langle \hat{f}(z,\boldsymbol{k})\,\hat{g}(z,\boldsymbol{k}')\rangle = (2\,\pi)^3\,\delta_{(\mathrm{D})}(\boldsymbol{k}+\boldsymbol{k}')\,P_{fg}(z,k)$
- Harmonic-space power spectrum $\langle \tilde{f}_{\ell m}(z)\,\tilde{g}_{\ell' m'}(z')\rangle = \delta^{\ell\ell'}_{(\mathrm{K})}\,\delta^{mm'}_{(\mathrm{K})}\,C^{fg}_\ell(z,z')$
- *Example no. 4:* galaxy-CMB temperature power spectrum

$$f(t,\boldsymbol{x}) \to \Theta(\hat{\boldsymbol{n}}) \equiv \frac{T(t_0,\hat{\boldsymbol{n}})-\bar{T}(t_0)}{\bar{T}(t_0)} \qquad g(t,\boldsymbol{x}) \to \varDelta(z,\boldsymbol{x}) \equiv \frac{n_\mathrm{g}(z,\boldsymbol{x})-\bar{n}_\mathrm{g}(z)}{\bar{n}_\mathrm{g}(z)}$$

Correlations 101

[Giannantonio et al. 2006]



Present and future data

Cosmology at radio wavelengths

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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

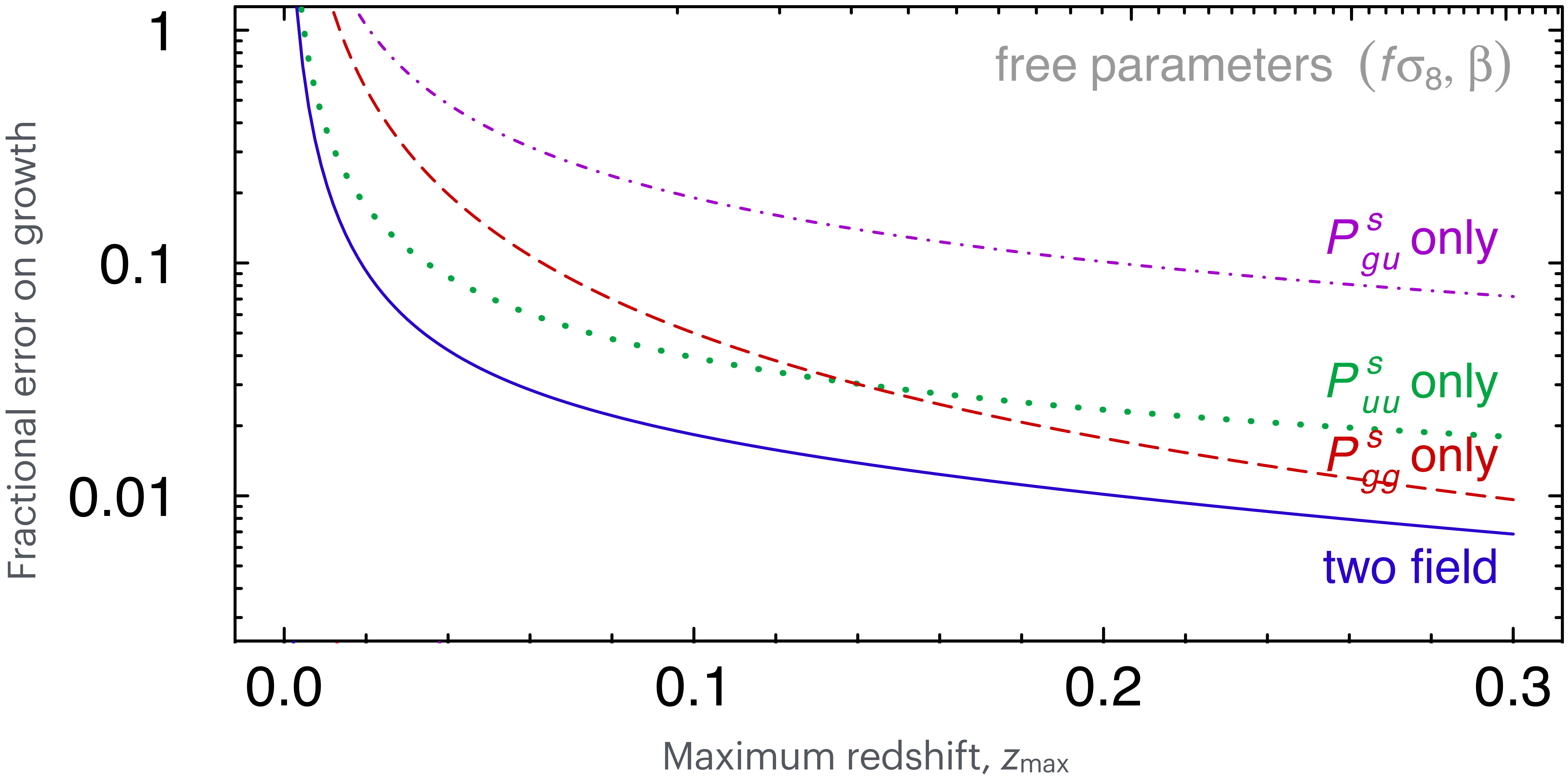
HI-line galaxies

- 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

[Koda et al. 2004]



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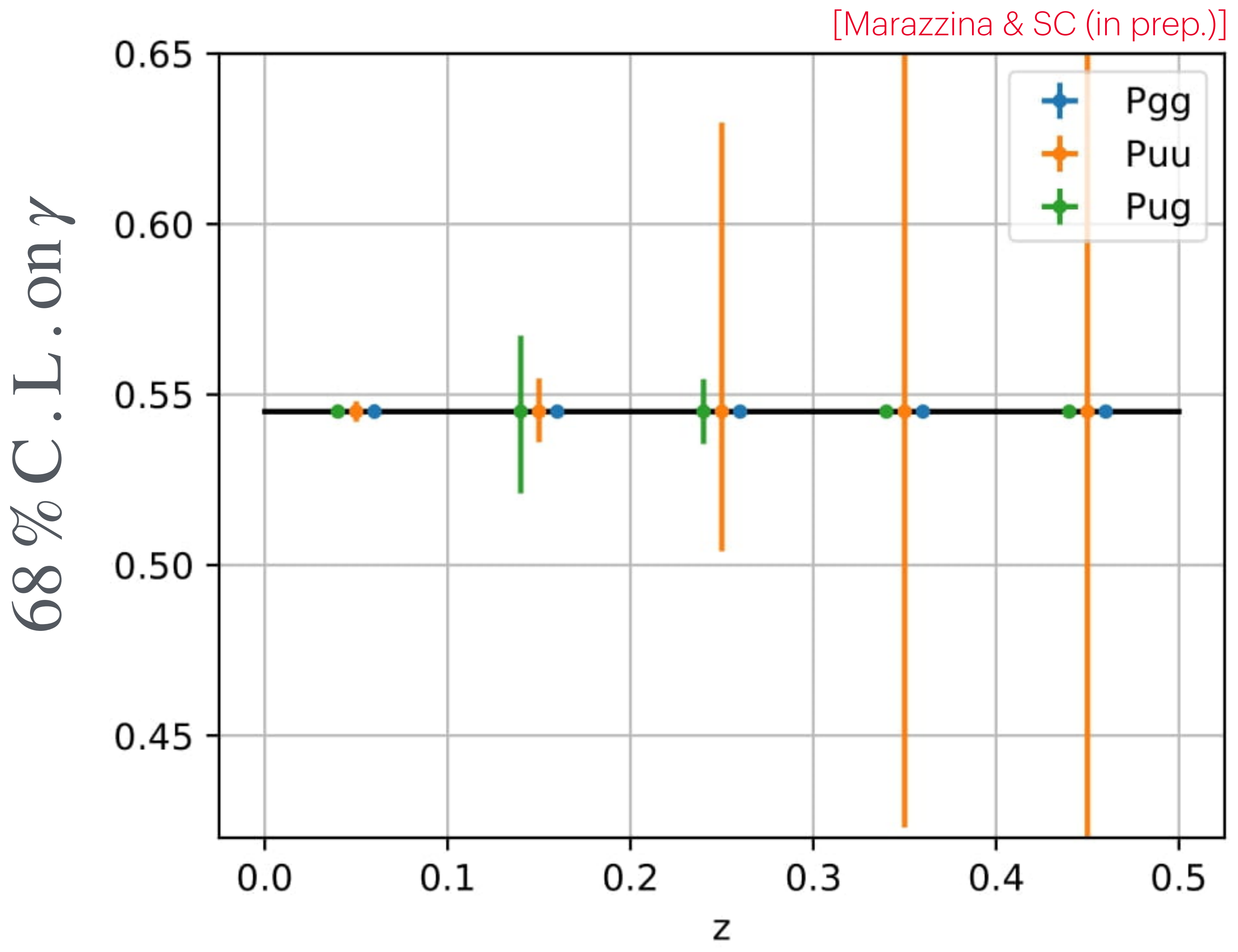
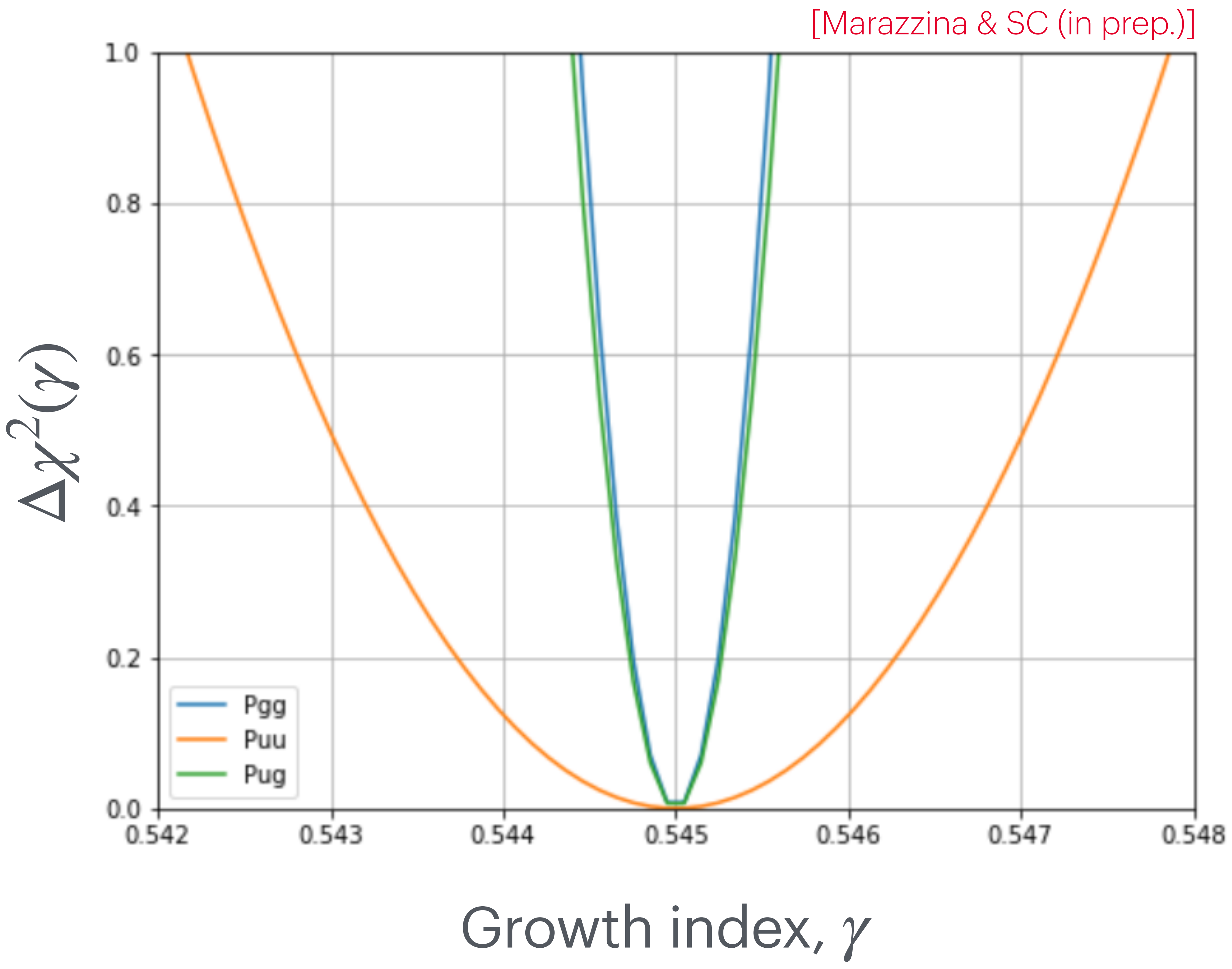
HI-line galaxies

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





Continuum galaxies

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- 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) [McConnel et al. 2020; Hale et al. 2021]
  - LoTSS Deep Field DR1 (~26 sq. deg.; 80k galaxies) [Tessa et al. 2021, Sabater et al. 2021, Kondapally et al. 2021]
  - LoTSS DR2 (5600 sq. deg.; 4.4M galaxies) [Shimwell et al. 2022, Bhardwaj et al. (in prep.), Hale et al. (in prep.)]

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)]

[Credits: D. Schwarz]

- Assumptions:
  1. Preferred rest frame and comoving observers
  2. Same at different redshifts
  3. Same for all probes

- Questions:
  - Is the CMB dipole kinematic?
  - And the other dipoles?
  - Can we establish a cosmic rest frame?
  - Can we link dipoles to local structure(s)?
  - Can we measure non-kinematic contributions?

[Courtesy of R. Maartens]

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 5° (SKAO)
    - Within 1° (Futuristic SKAO)

[Courtesy of R. Maartens]

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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

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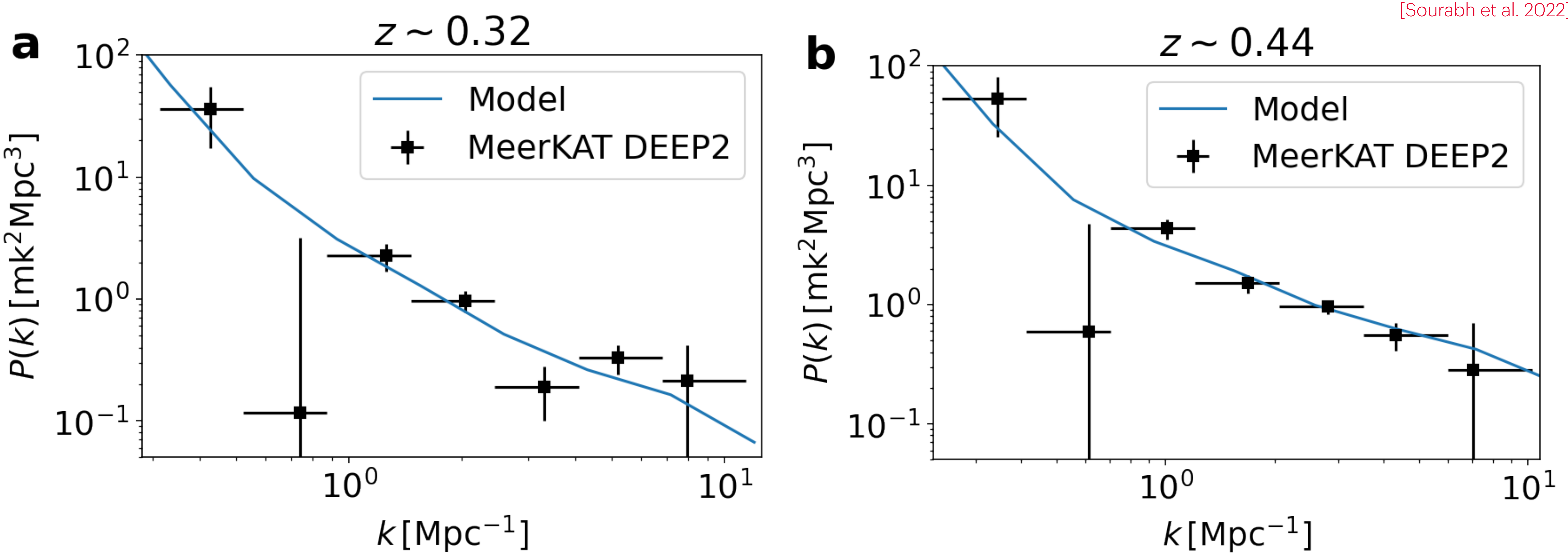
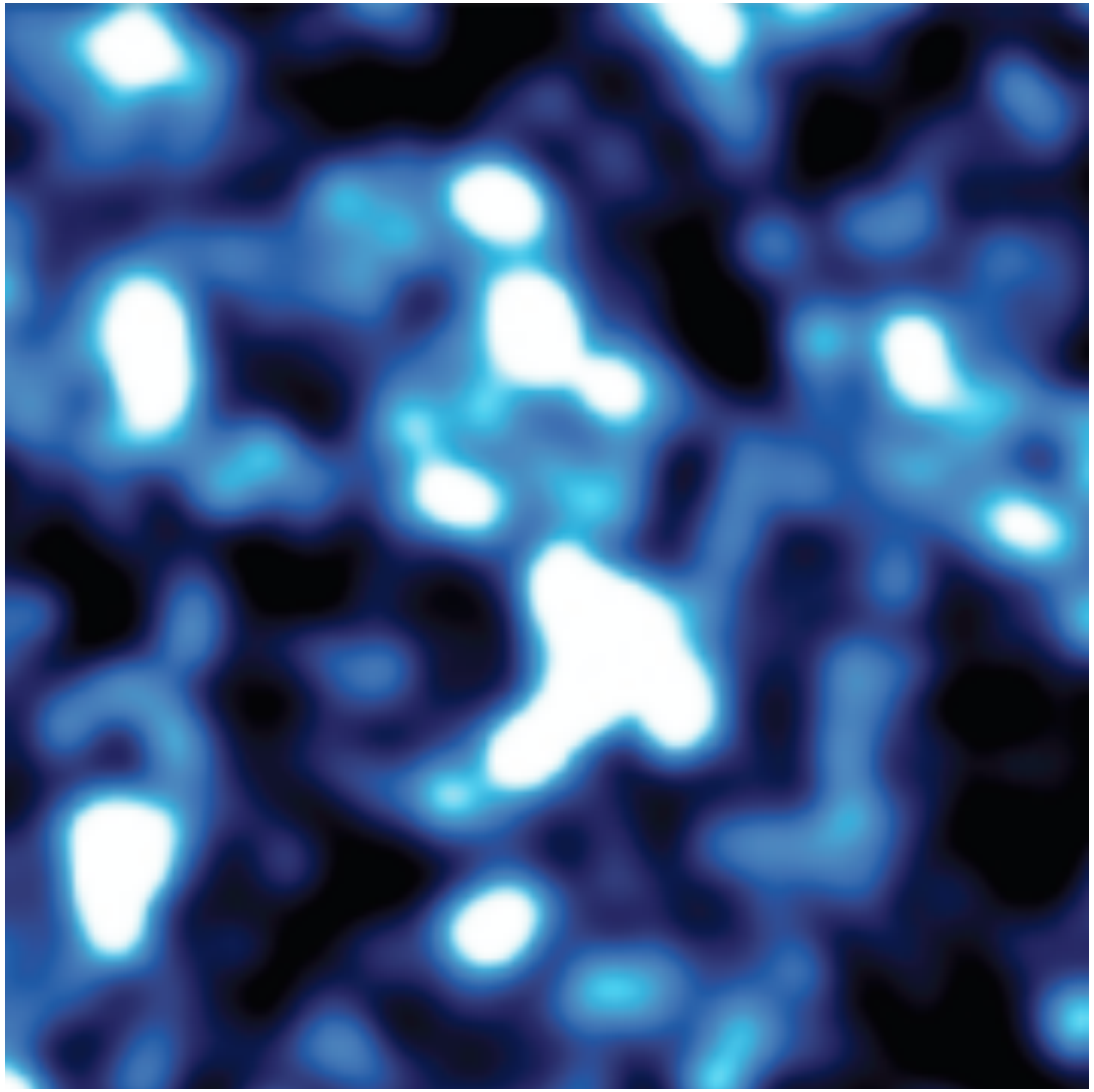
- Examples:
  - MeerKAT (96 obs. hrs; 2 sq. deg. @ 986 MHz | $z \approx 0.44$ and @ 1077.5 MHz | $z \approx 0.32$)

[Sourabh et al. 2022]



HI intensity mapping



Redshift for free:

ν_{obs} = 1420 MHz / (1+z)

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

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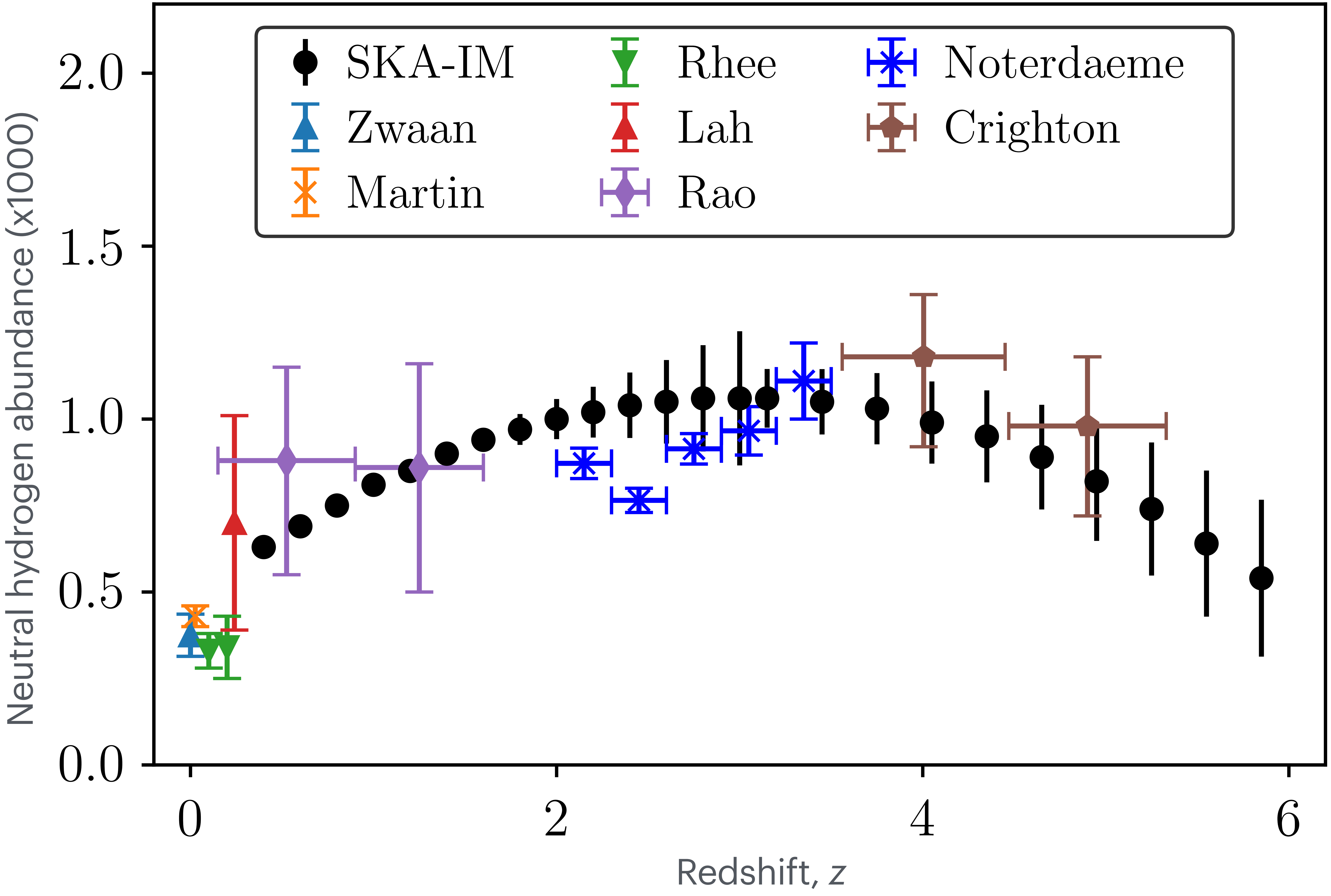
HI intensity mapping

[Bacon, SC et al. (2020)]



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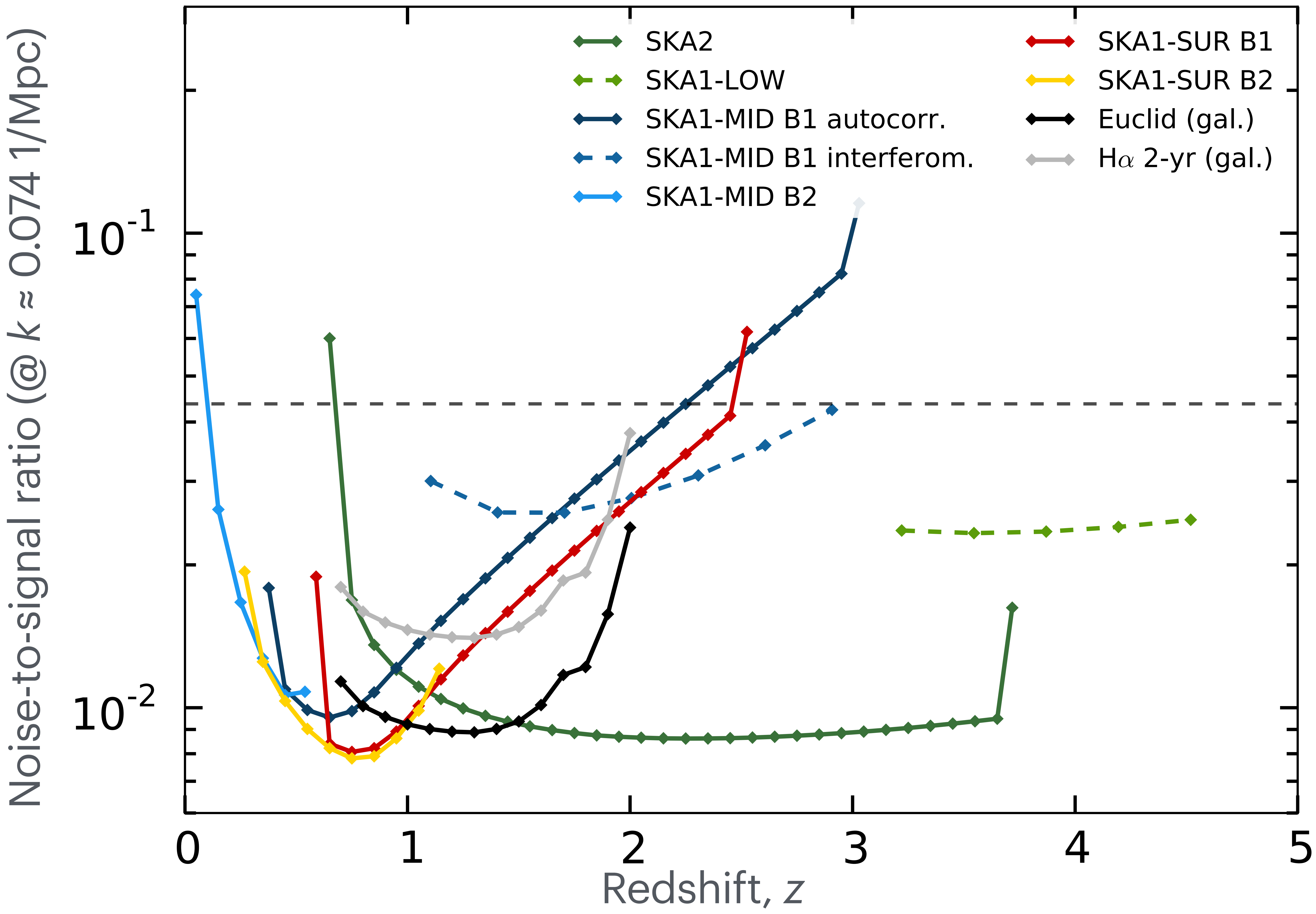
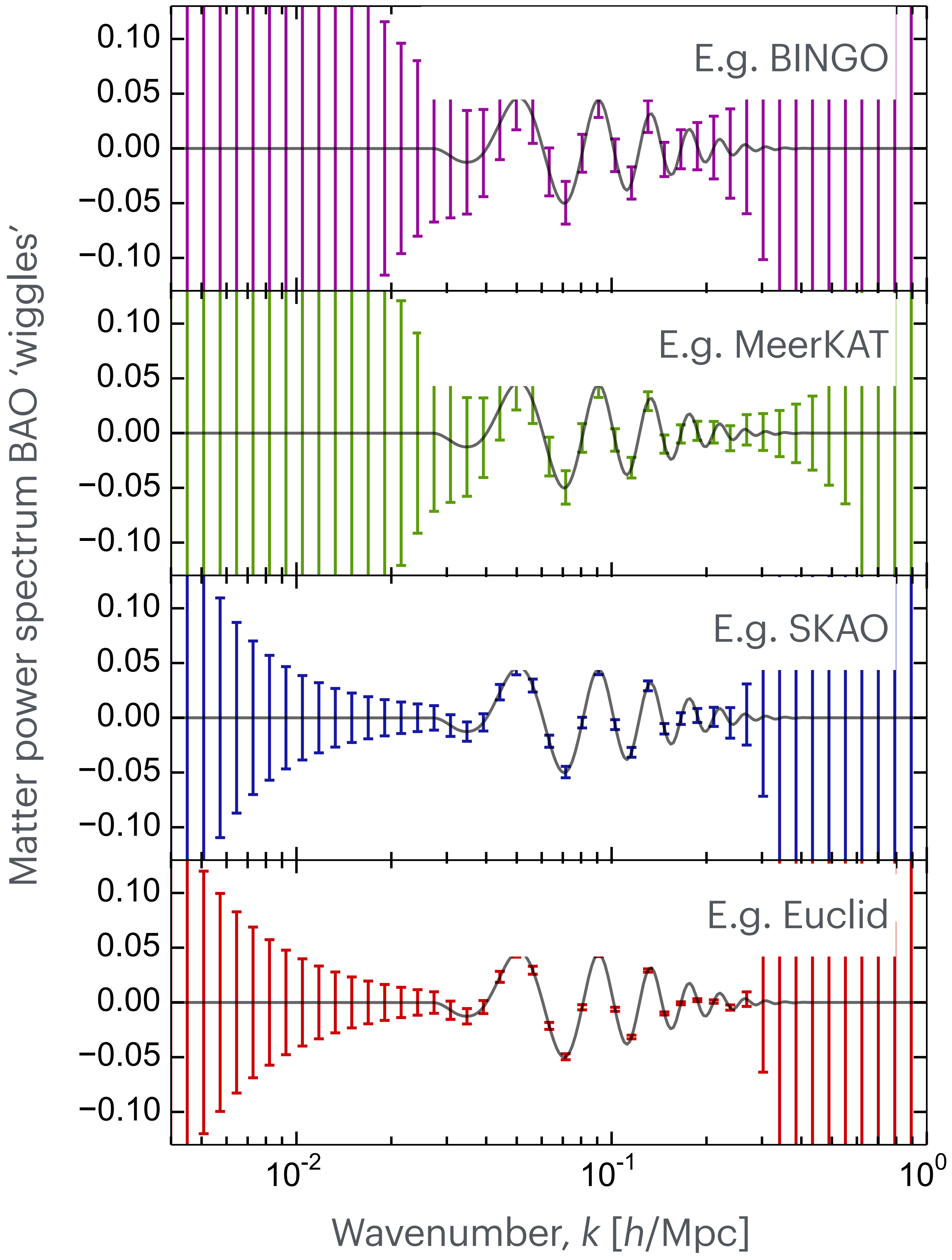
HI intensity mapping

[Santos, SC et al. (2015)]

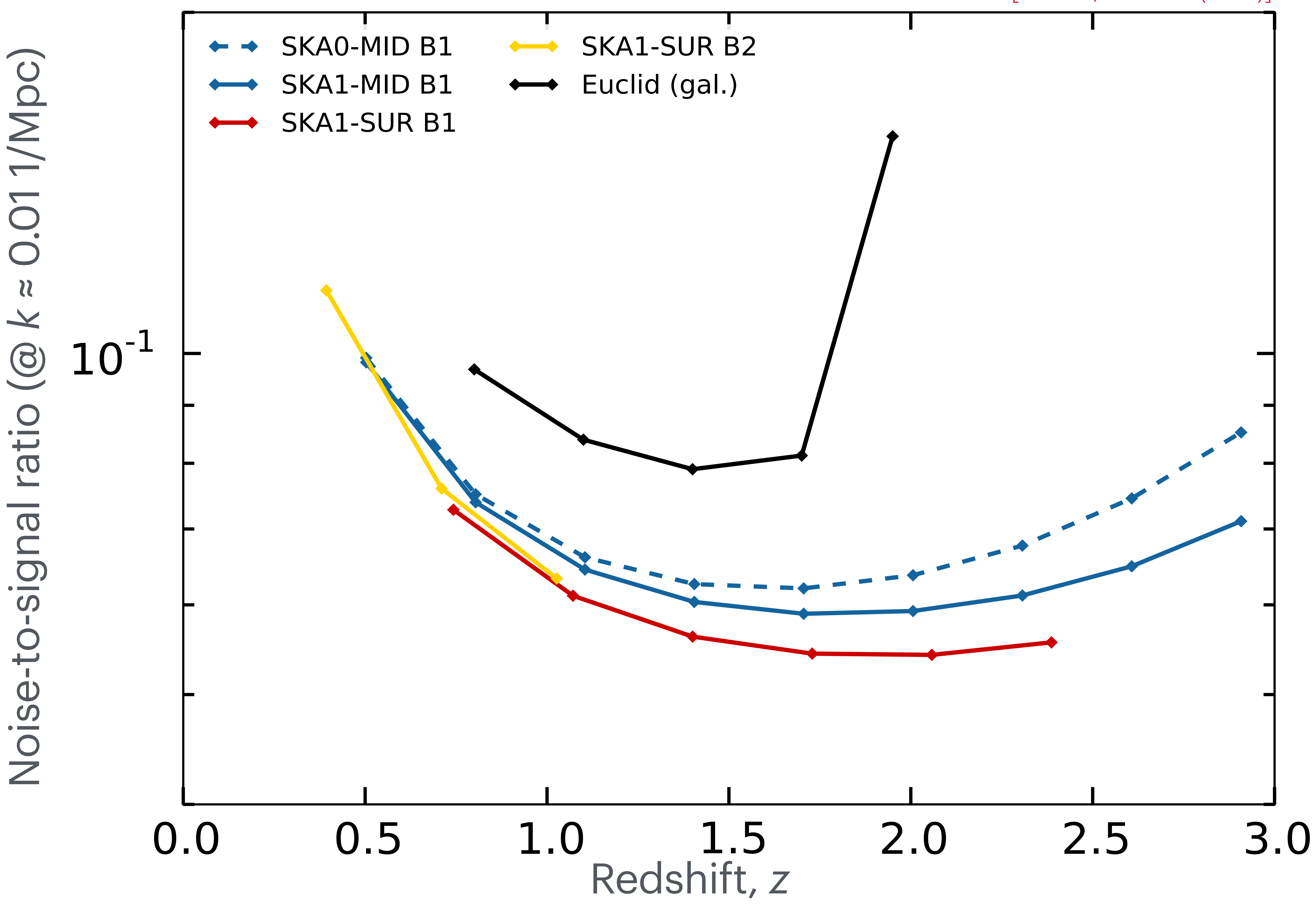


[Bull et al. (2015)]



HI intensity mapping

[Santos, SC et al. (2015)]



- Sensitivity to ultra-large scale effects
  - Primordial non-Gaussianity (for inflation)

    [SC et al. (PRL 2013)]
  - Relativistic, light-cone projection effects (for modified gravity)

    [Fonseca, SC et al. (2015); Alonso & Ferreira (2015)]

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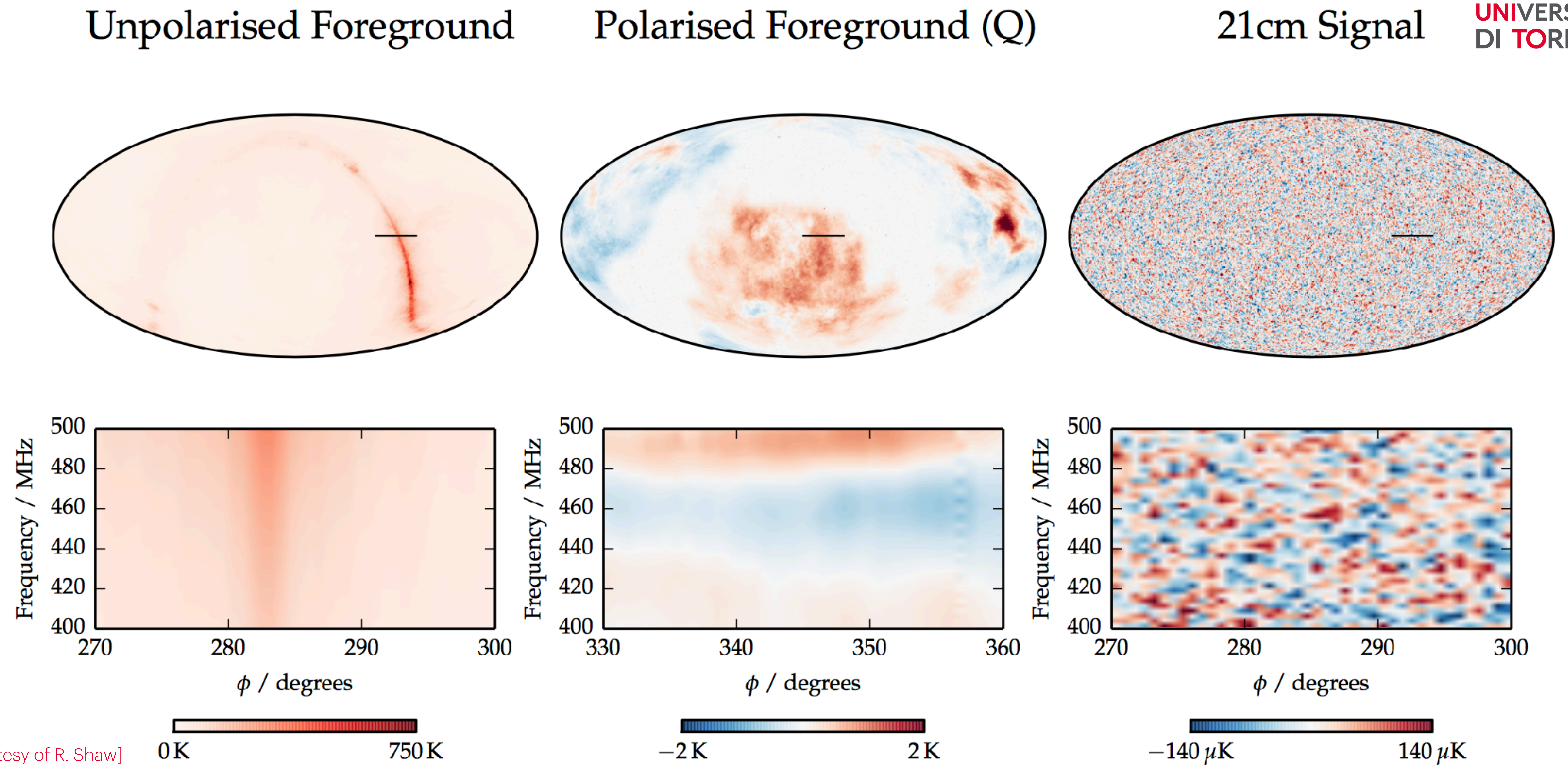
HI intensity mapping



[Courtesy of R. Shaw]

Radio weak lensing

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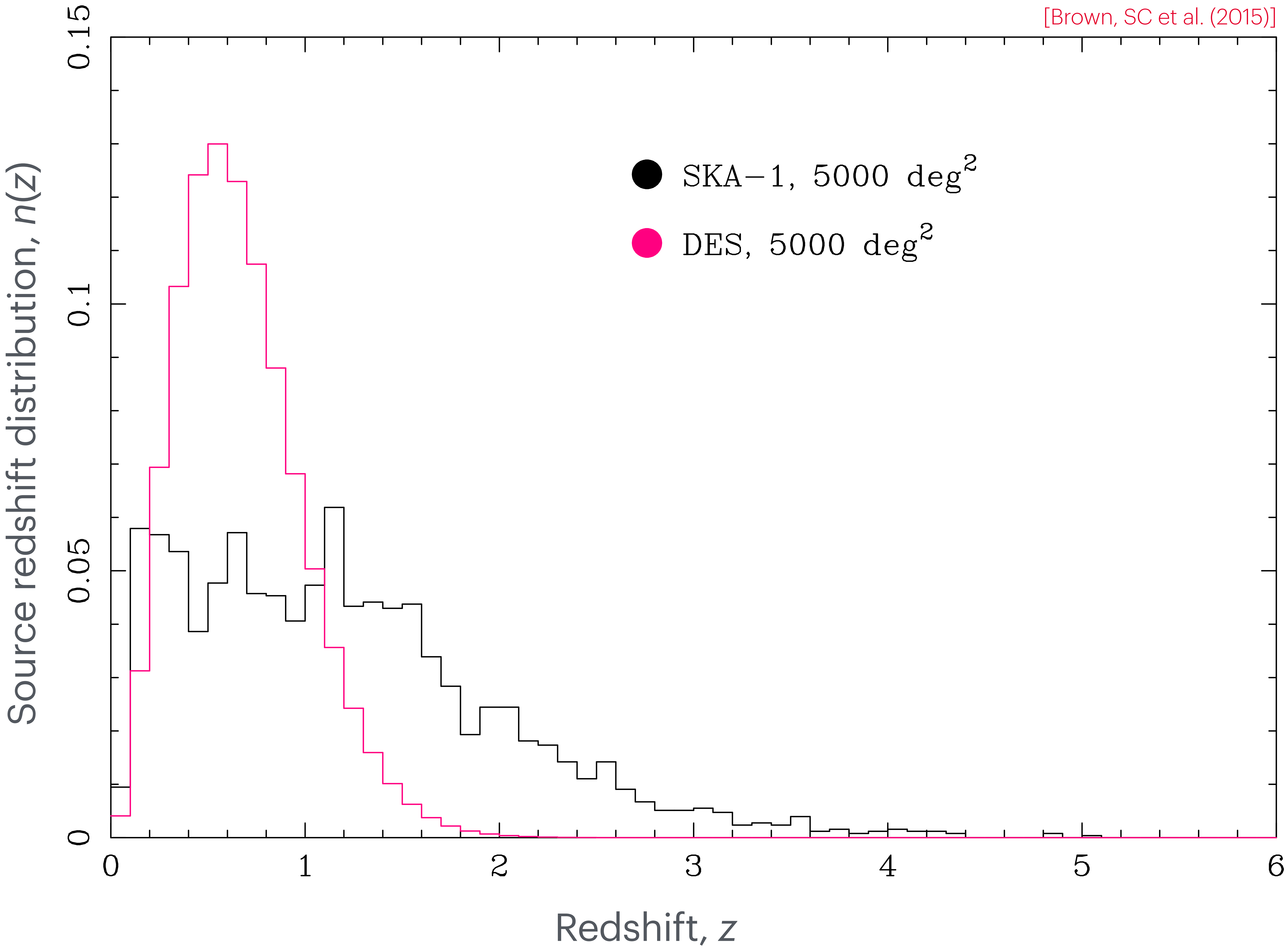
- Origin: weak lensing shearing of imaged galaxy ellipticities
- Pros: complementary to clustering, insensitive to galaxy bias
- Cons: low signal to noise, needs (?) imaging
- Examples:
  - VLA FIRST (~90 sources per sq. deg. vs to ~10 per sq. arcmin. in opt.)

    [Chang et al. (Nature 2004)]
  - VLA+MERLIN (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



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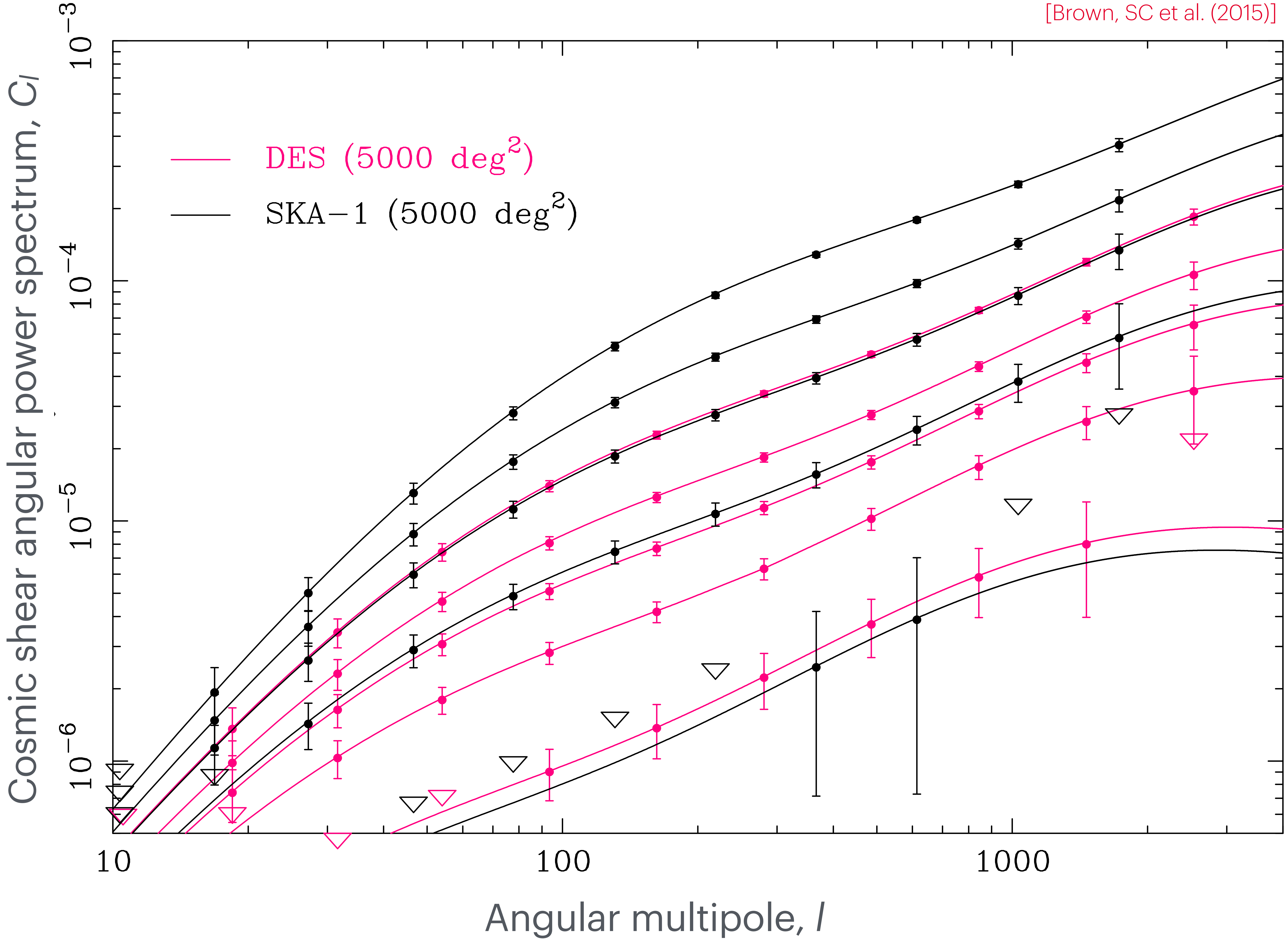
Radio weak lensing

[Brown, SC et al. (2015)]



Radio weak lensing

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

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

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

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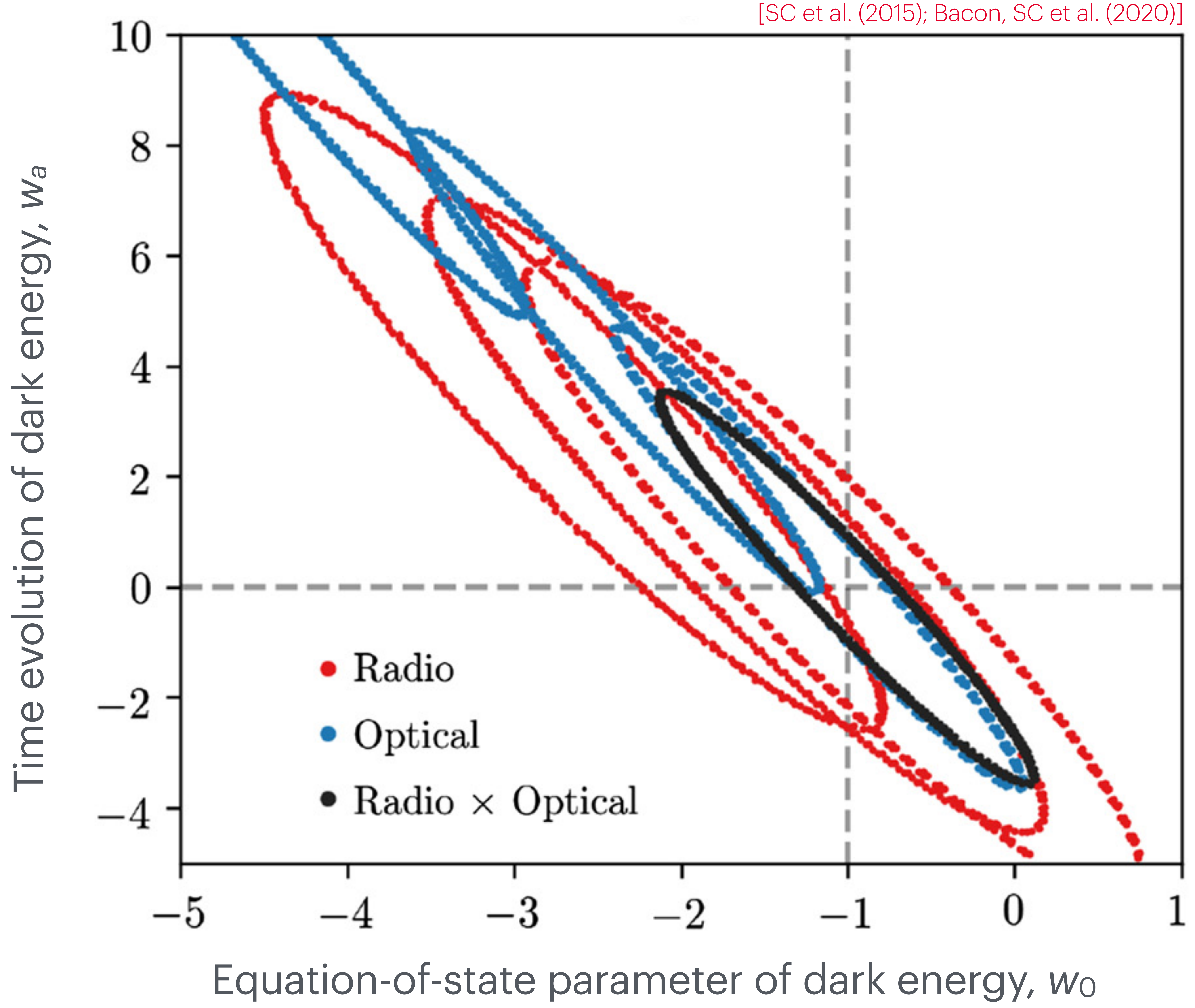
Radio weak lensing

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



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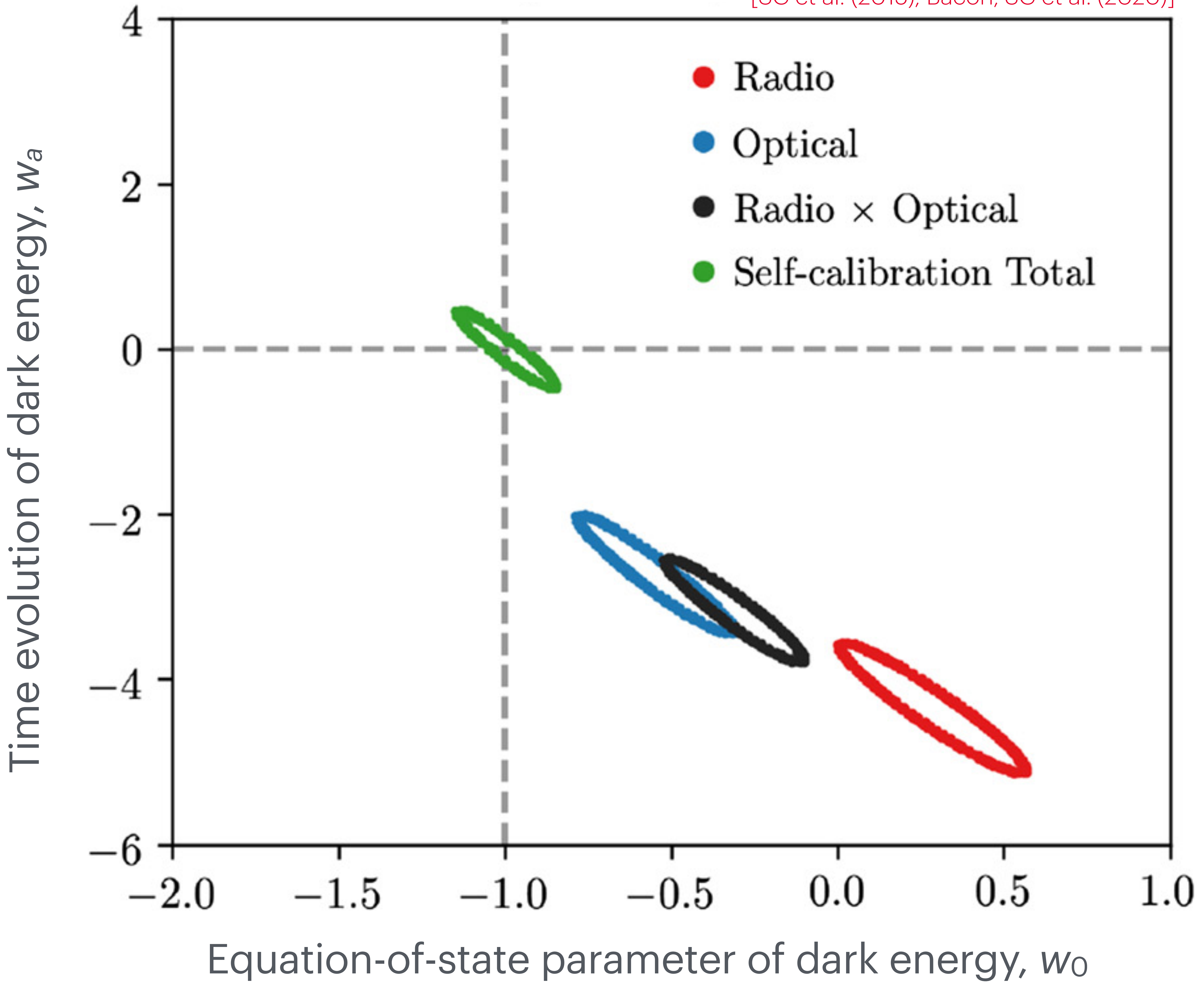
Radio weak lensing

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



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The SKA Observatory

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

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The SKA Observatory

The SKA Observatory

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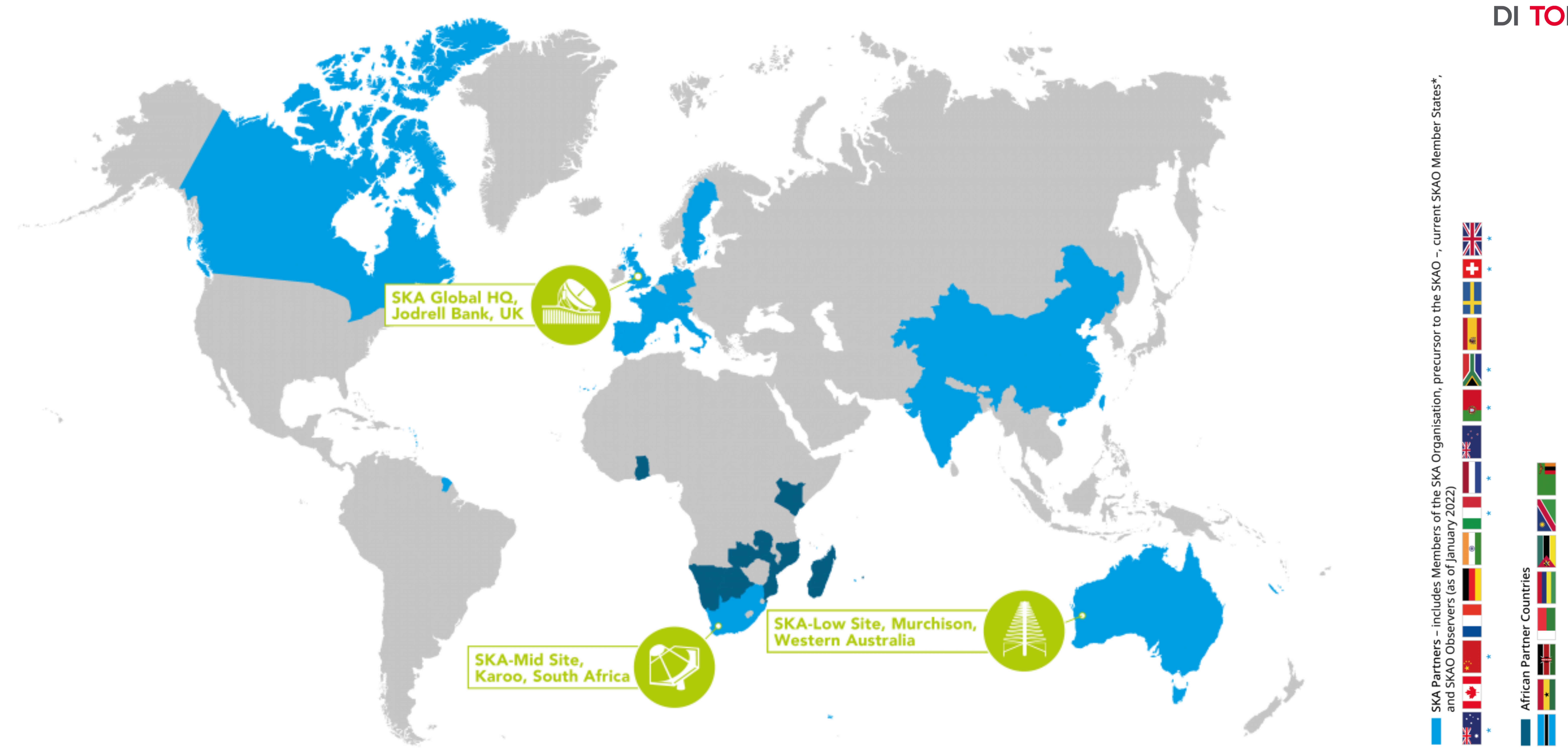
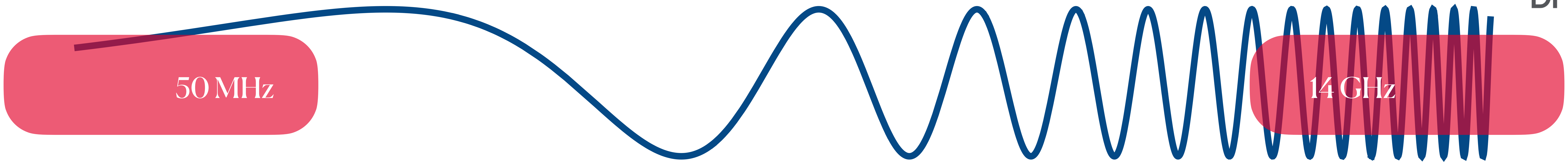
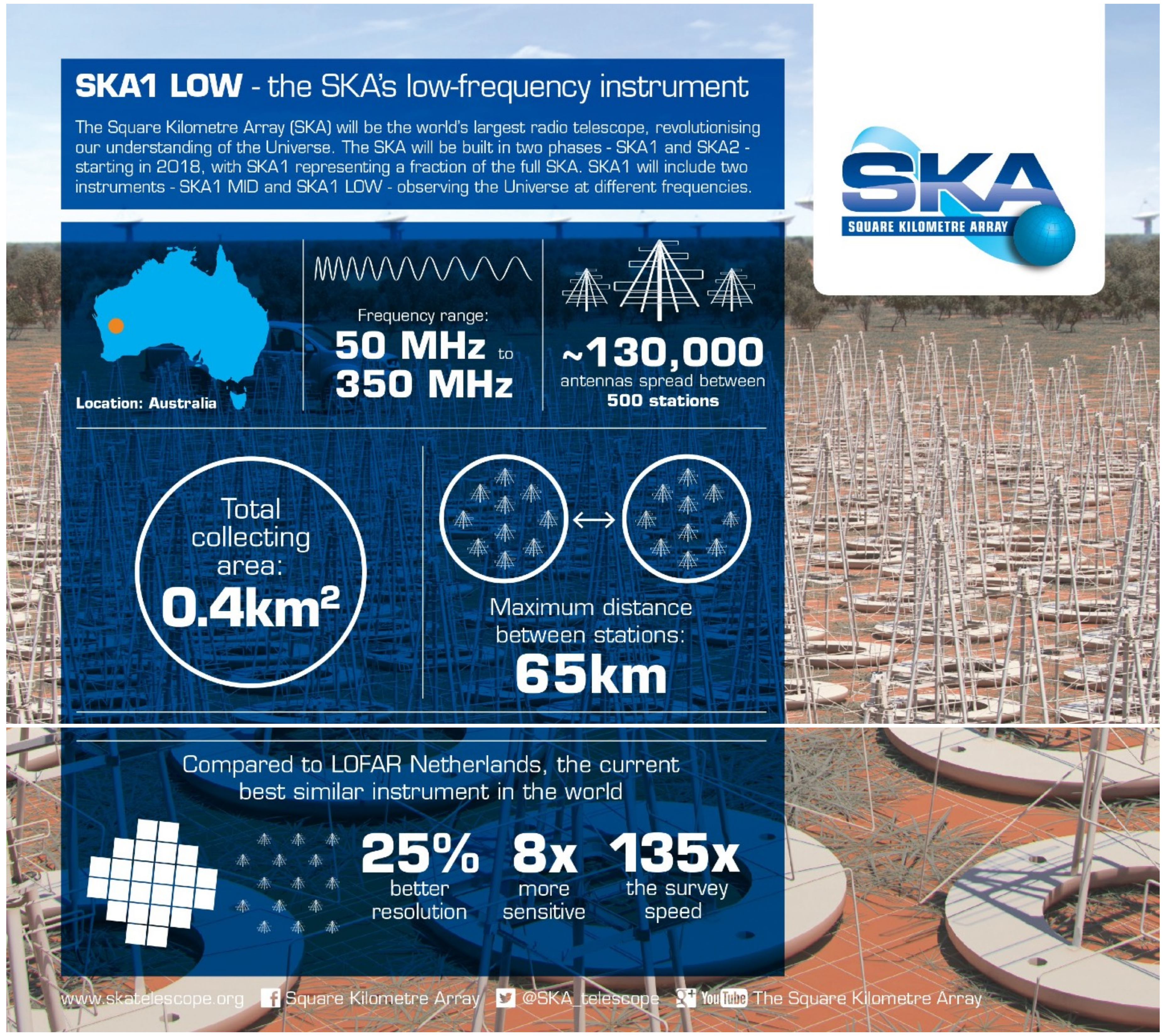
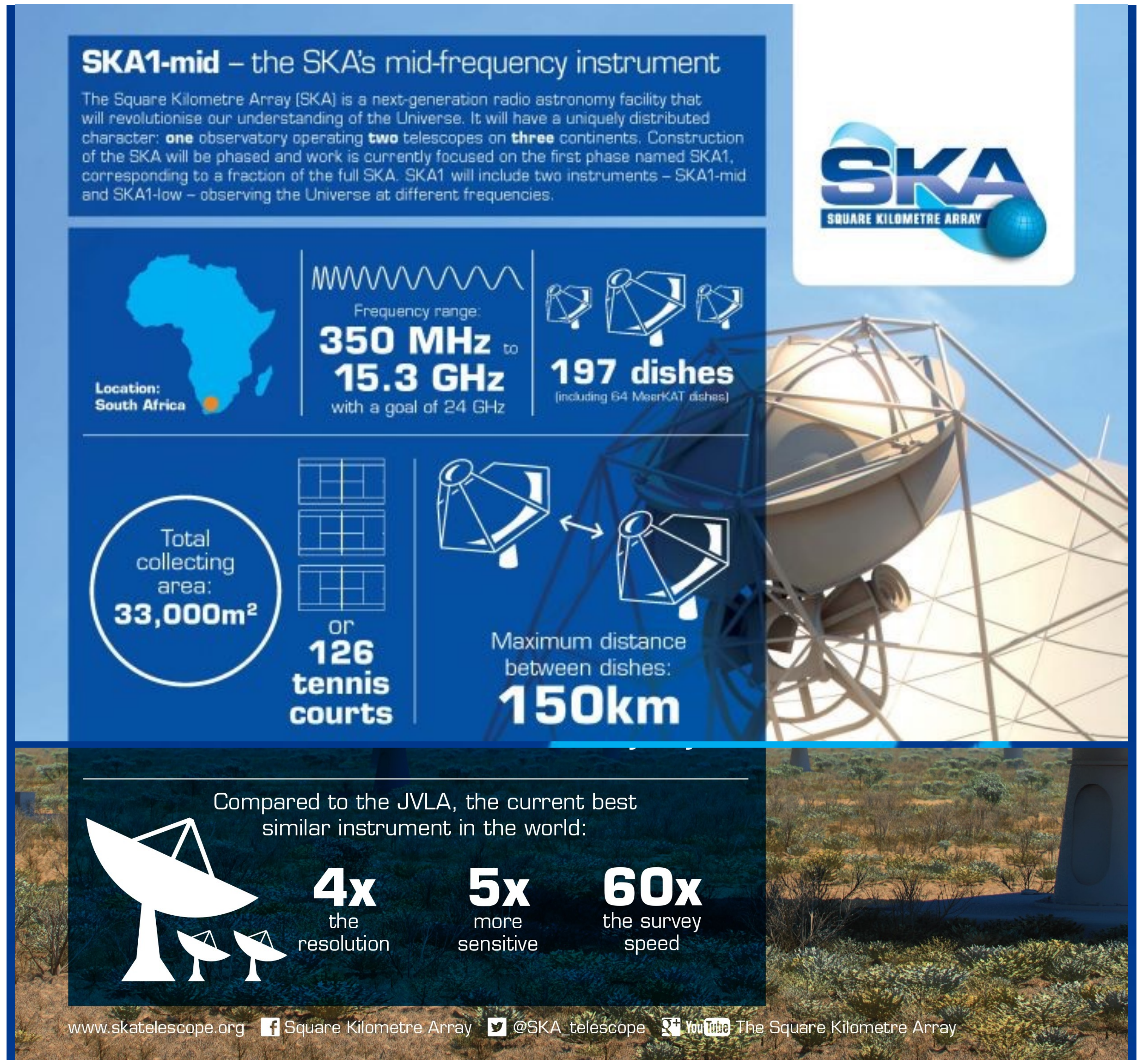


The SKA Project







SKAO Science

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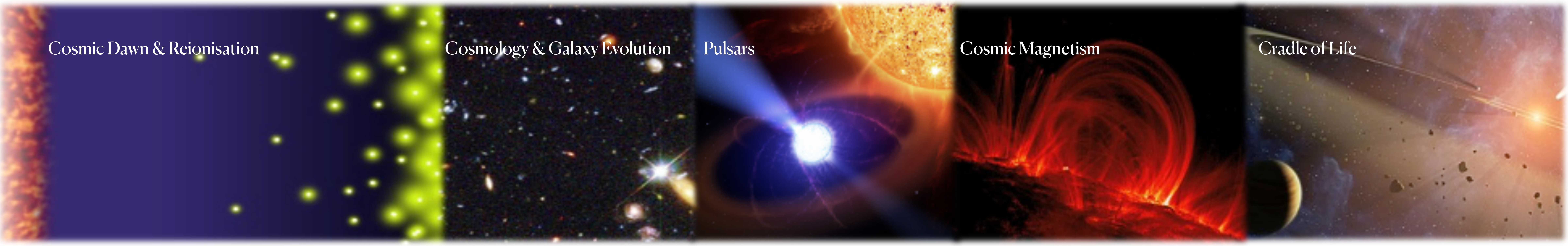


SKAO's Low telescope

50-350 MHz

SKAO's Mid telescope

Band 1
0.35-1.05 GHz

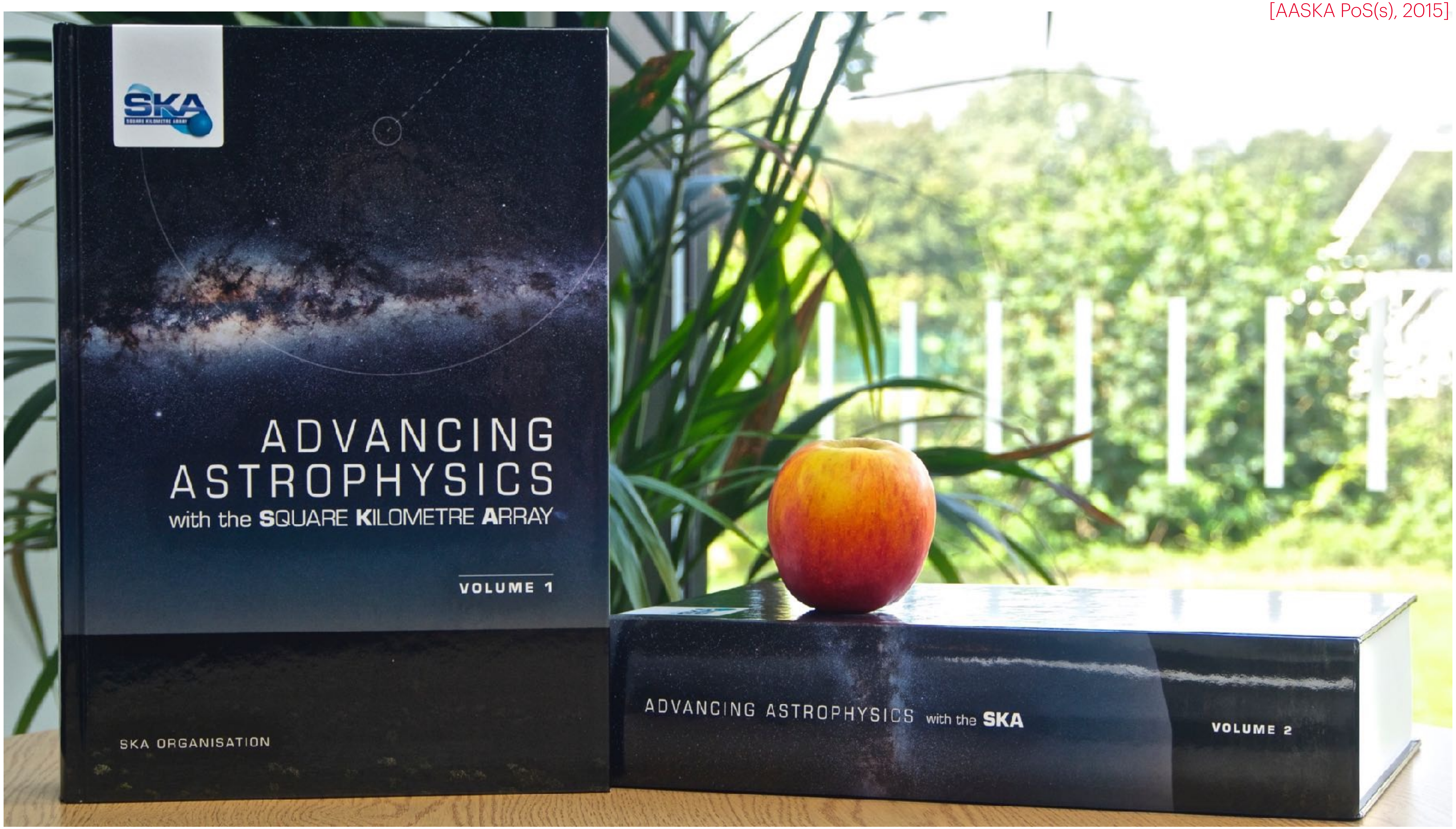
Band 2
0.95-1.76 GHz

Band 3
1.65-3.05 GHz

Band 5
4.6-24 GHz

SKAO Science

[AASKA PoS(s), 2015]



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)]

7 • IV • 2023

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]

International School in Space Science

Stefano Camera

SKAO Cosmology

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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)]

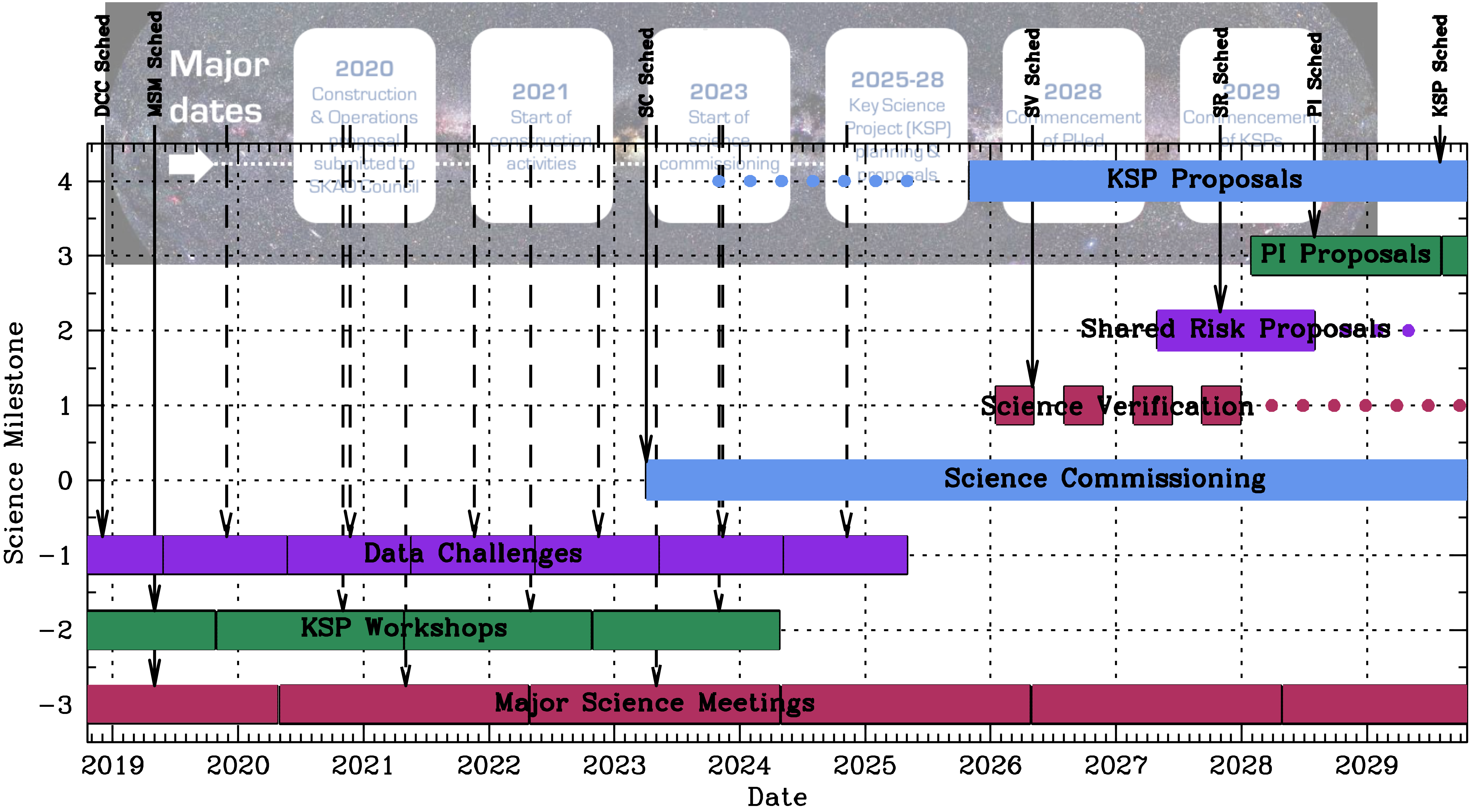
Review (unsolicited)

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,†]

Towards the SKAO

[Credits: R. Braun]



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Towards the SKAO

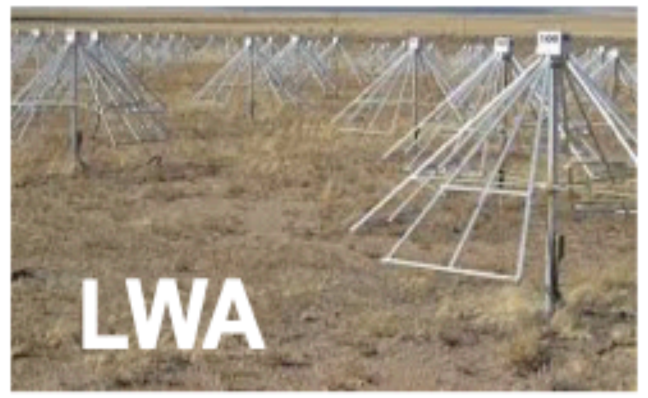
[Courtesy of A. Bonaldi]

Precursors

Located at future SKA sites (South Africa and Australia)

Pathfinders

Engaged in SKA related technology and science studies



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LOFAR

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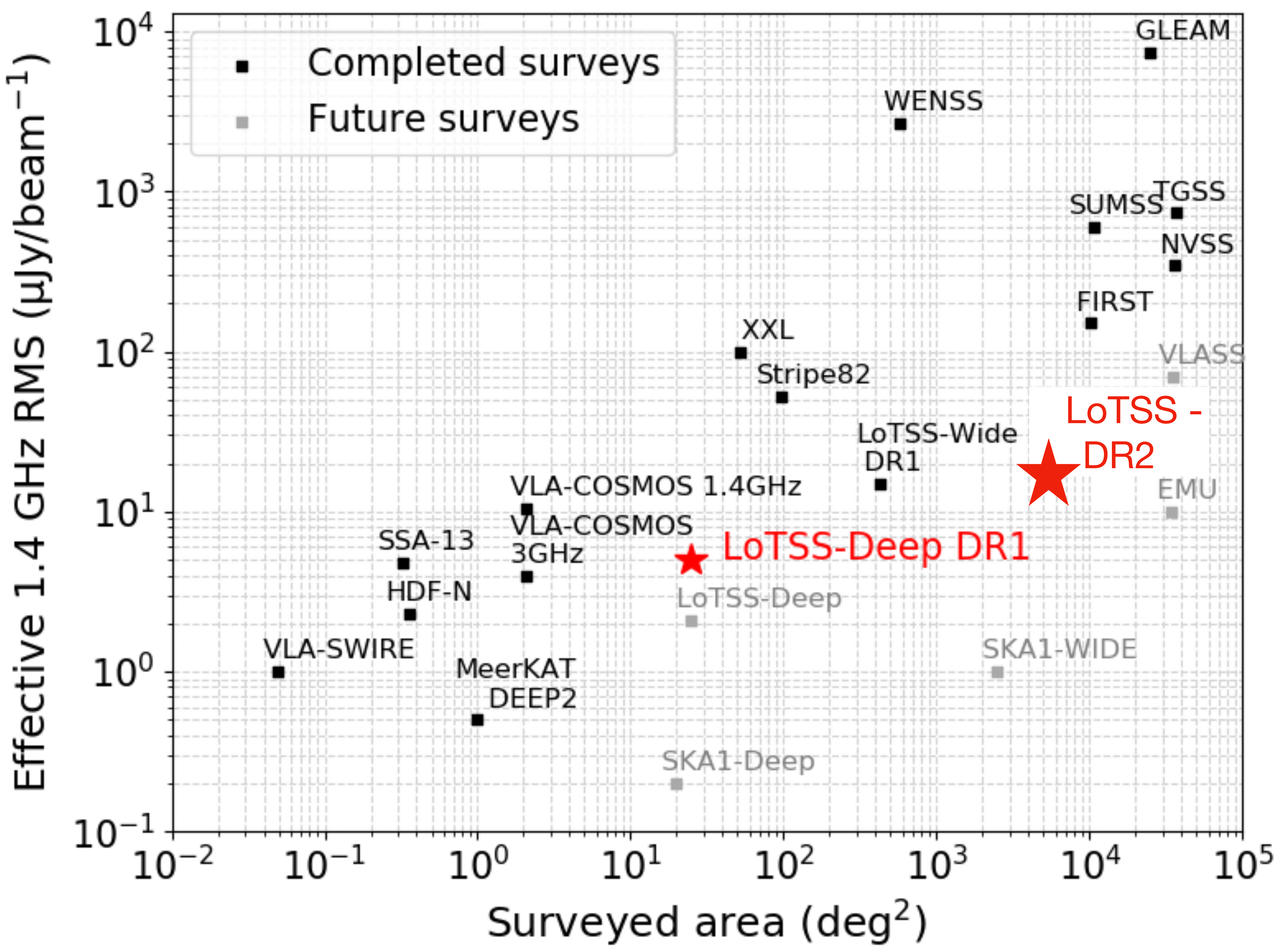
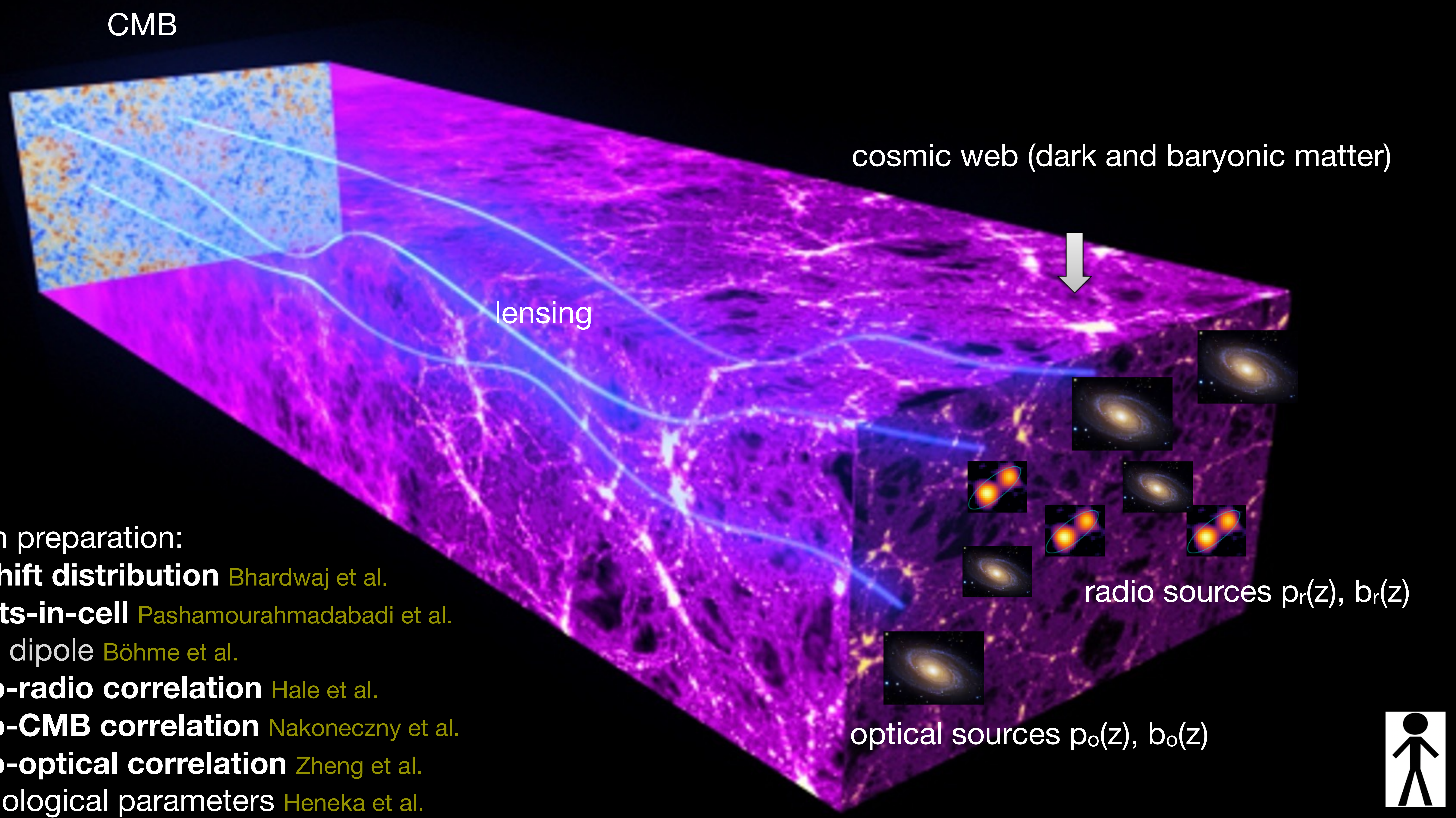
- The LOFAR Two-metre Sky Survey (LoTSS)



- LoTSS-Deep DR1:
  - Boötes, Lockman & Elias N1 fields w/ ~80 μJy/beam rms
  - Multi-frequency coverage leading to ~80k radio sources (~0.9/arcmin^2)
- LoTSS DR2:
  - Core and remote station HBA obs: @ 144 MHz, 841 pointings, 5600 sq. deg.
  - Direction dependent calibration: 6” resolution, ~80 μJy/beam rms
  - 4.4M radio sources (~0.2/arcmin^2)



Works in preparation:

- **Redshift distribution** Bhardwaj et al.
- **Counts-in-cell** Pashamourahmadabadi et al.
- Radio dipole Böhme et al.
- **Radio-radio correlation** Hale et al.
- **Radio-CMB correlation** Nakoneczny et al.
- **Radio-optical correlation** Zheng et al.
- Cosmological parameters Heneka et al.

Credit: ESA and Planck Collaboration

ASKAP

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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 deg^2 (~900 pointings with 15 min observations)
  - About 2.1M galaxies (cutting Galactic plane at $\pm 5^\circ$)

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

CAMBRIDGE UNIVERSITY PRESS

Research Paper

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

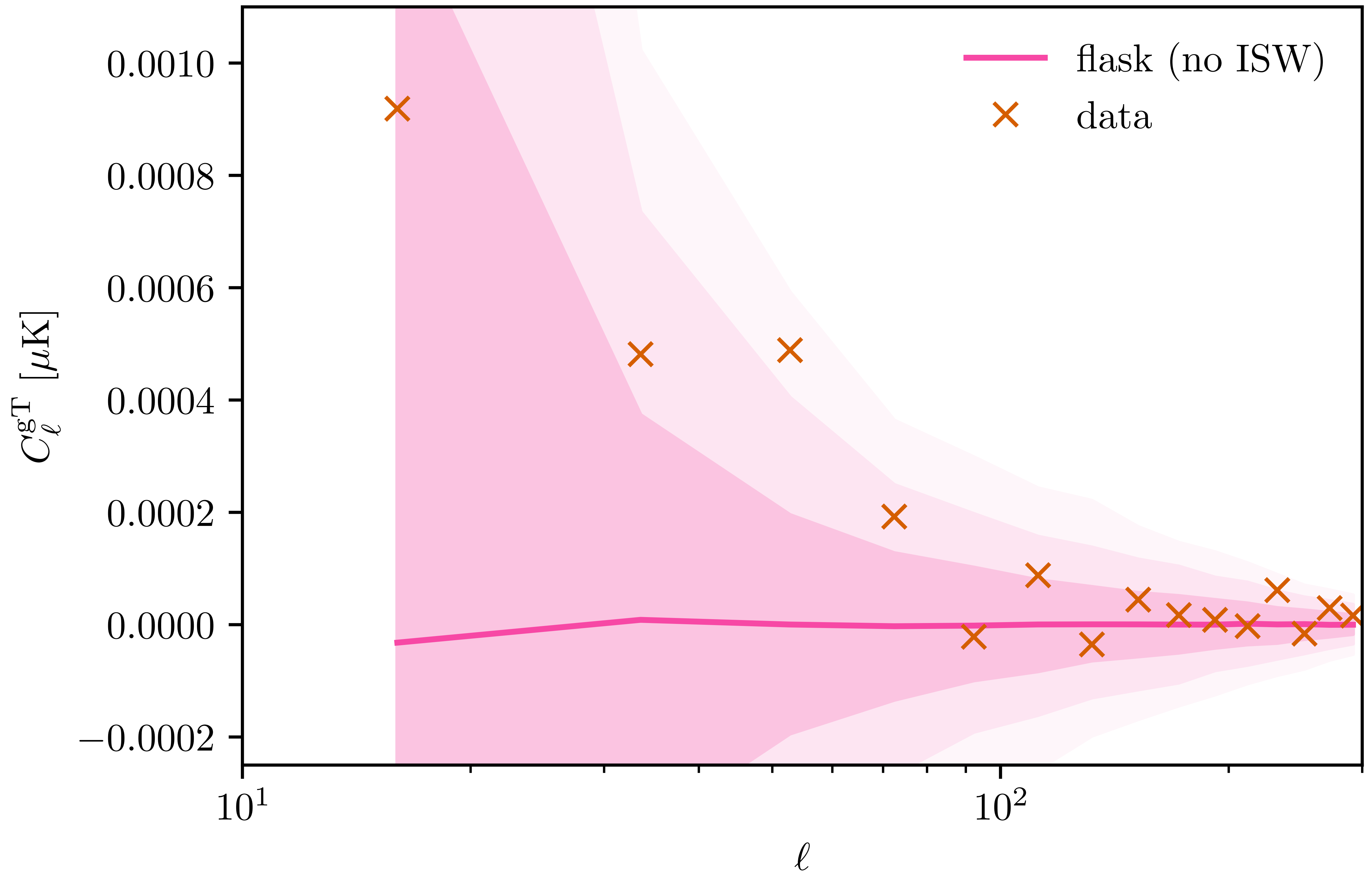
Catherine L. Hale[1,2], D. McConnell[3], A. J. M. Thomson[1], E. Lenc[3], G. H. Heald[1], A. W. Hotan[1], J. K. Leung[3,4], V. A. Moss[3], T. Murphy[4], J. Pritchard[4,3], E. M. Sadler[3,4], A. J. Stewart[4] and M. T. Whiting[3]

[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

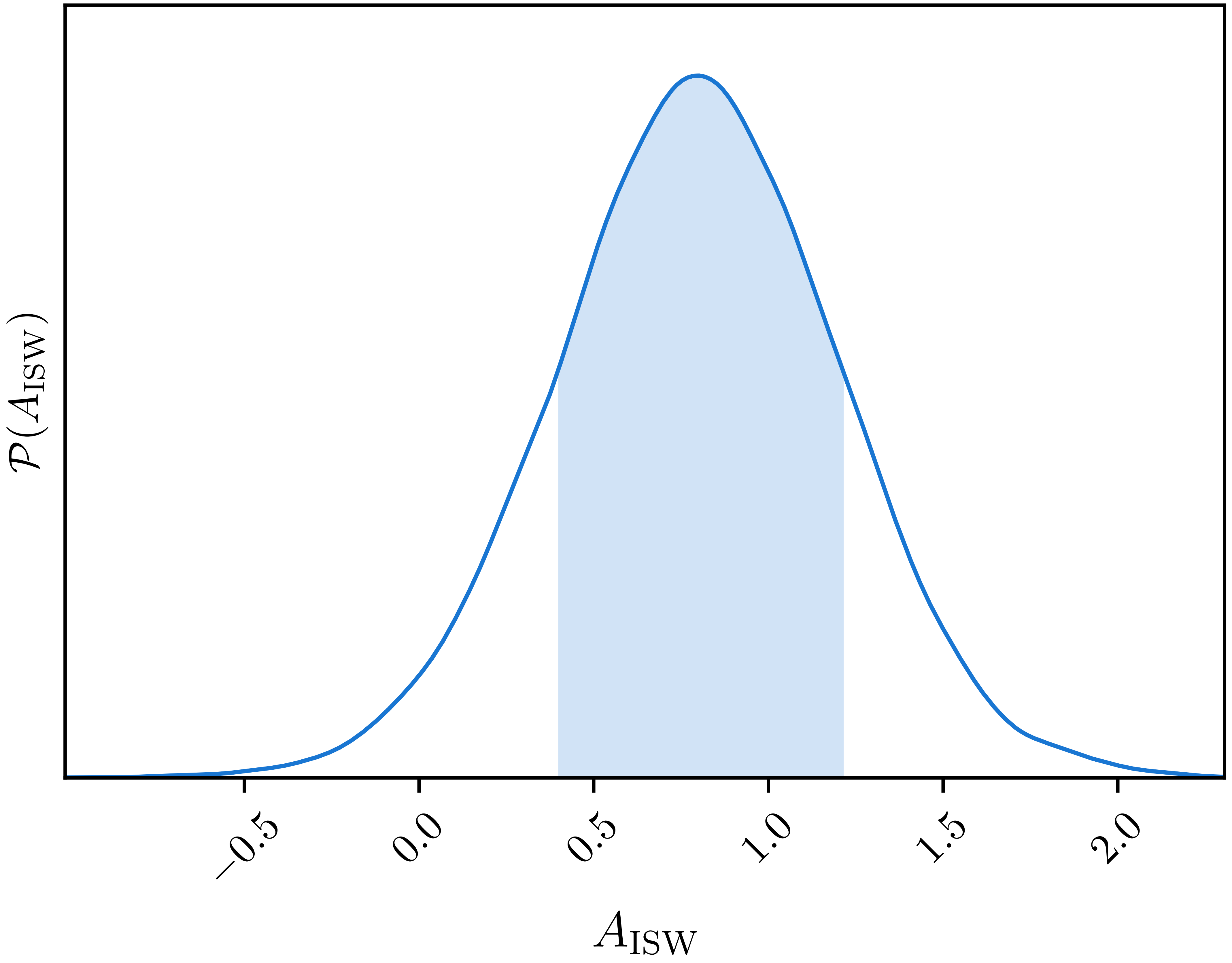
ASKAP

- Cross-correlation between RACS galaxies and CMB temperature

[Bahr-Kalus, SC et al. (2022)]



$A_{ISW} = 0.80^{+0.41}_{-0.39}$



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MeerKAT

- The MeerKAT Large Area Synoptic Survey (MeerKLASS)
  - Aiming at HI intensity mapping and continuum cosmology (lots of commensality)
  - Focus of sky patches with multi-wavelength data for cross-correlations
  - L-band: 900-1670 MHz ($z < 0.58$)

[Santos, SC et al. (2016)]

PoS PROCEEDINGS OF SCIENCE

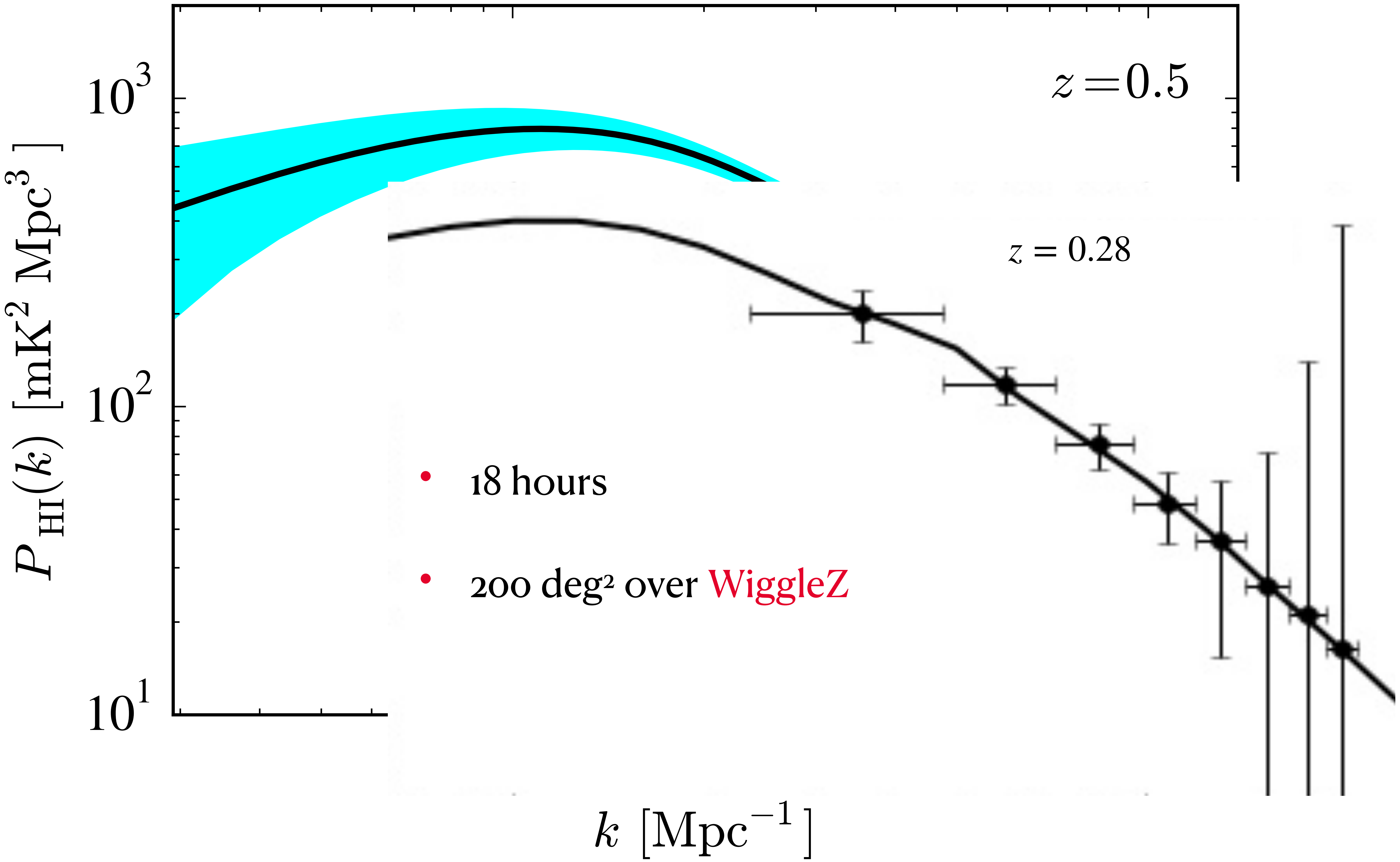
A Large Sky Survey with MeerKAT

Mário G. Santos*,[1,2] Philip Bull,[3,4] Stefano Camera,[5] Song Chen,[1] José Fonseca,[1] Ian Heywood,[6] Matt Hilton,[7] Matt Jarvis,[1,6] Gyula I. G. Józsa[2,8,9], Kenda Knowles,[7] Lerothodi Leeuw,[10] Roy Maartens,[1,11] Eliab Malefahlo,[1] Kim McAlpine,[1] Kavilan Moodley,[7] Prina Patel,[1,2] Alkistis Pourtsidou,[11] Matthew Prescott,[1] Kristine Spekkens,[12] Russ Taylor,[1,13] Amadeus Witzemann[1] and Imogen Whittam[1]

MeerKAT

- Detection of baryon acoustic oscillations using HI

[Santos, SC et al. (2016)]



- 18 hours
- 200 deg² over WiggleZ

MeerKAT

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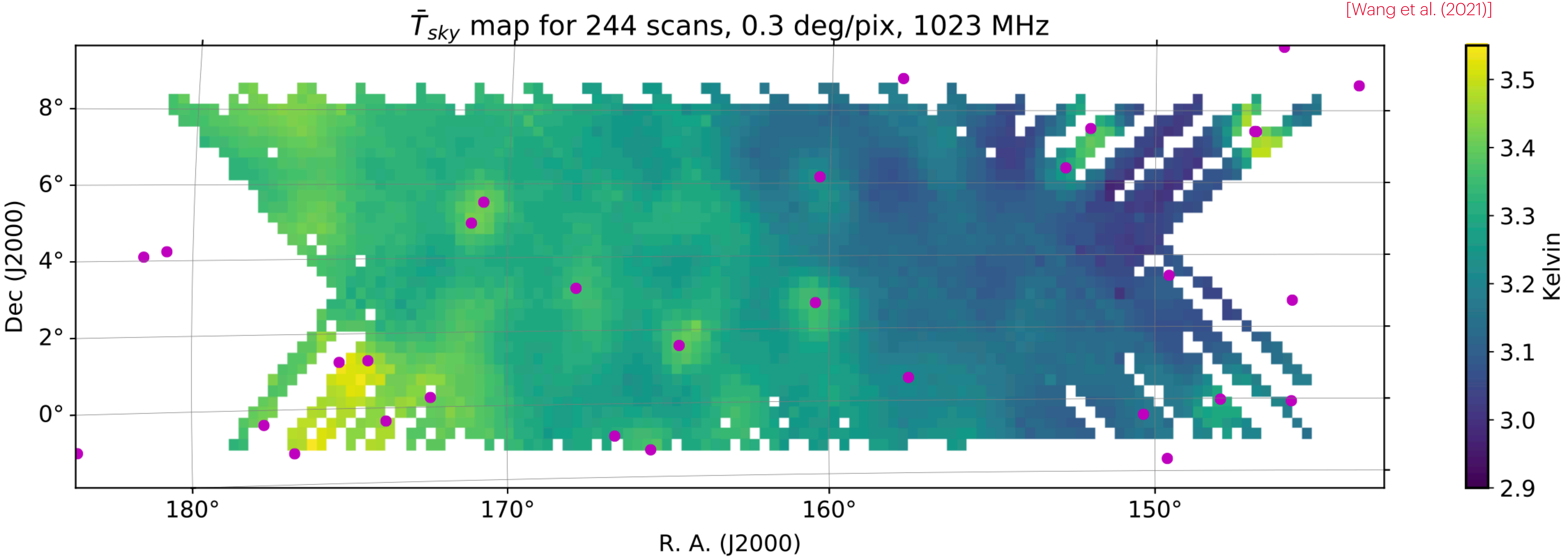
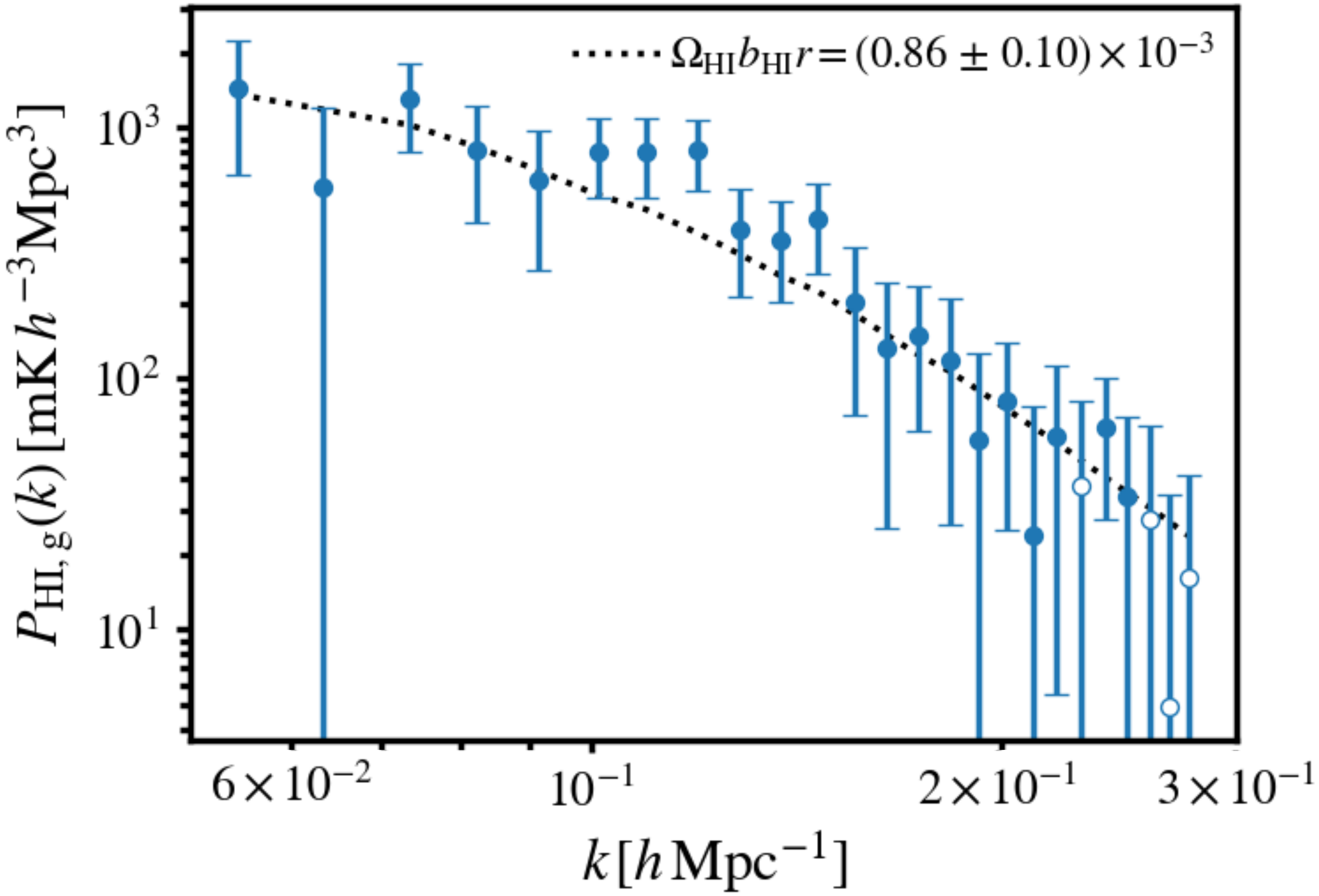
[Wang et al. (2021)]

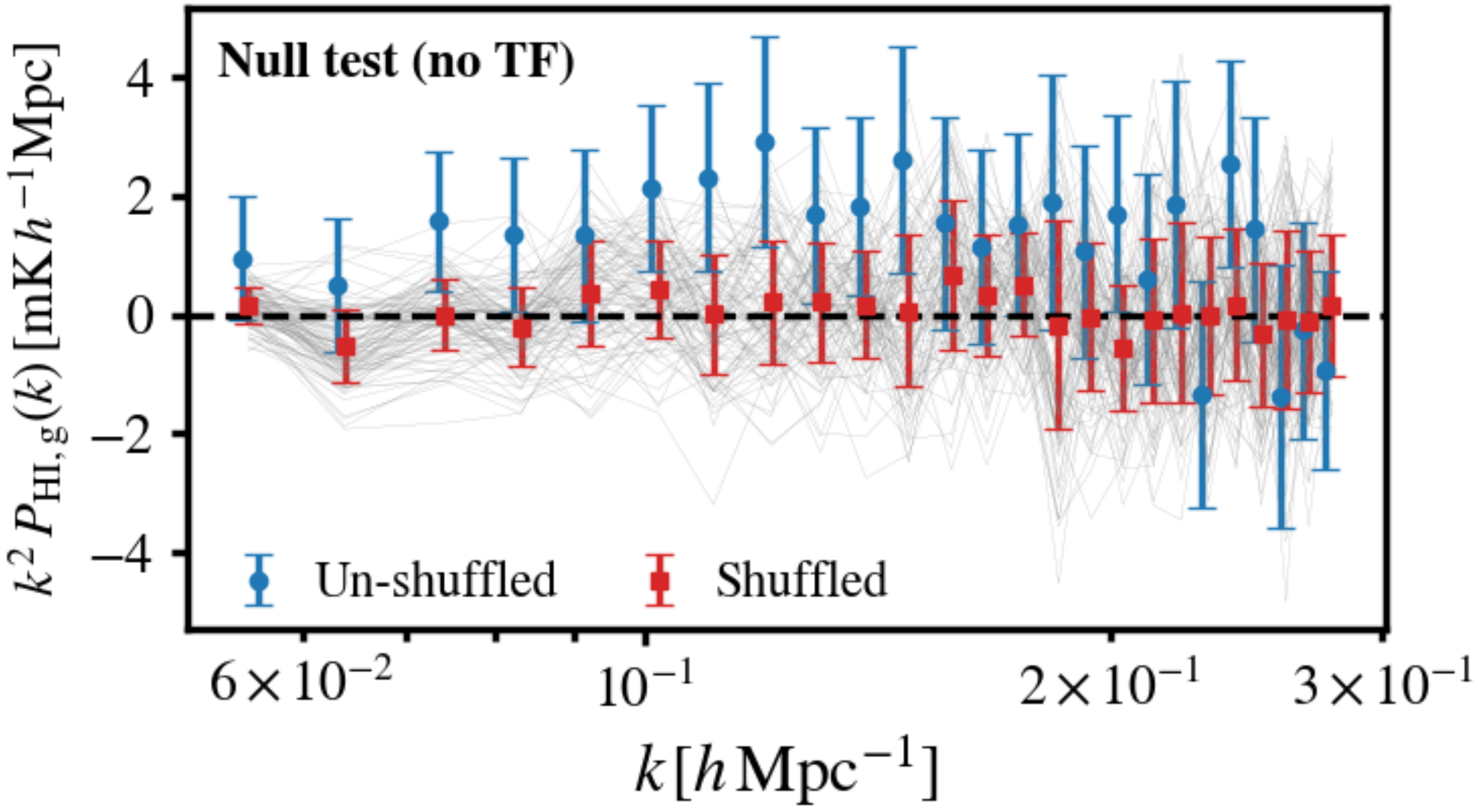


MeerKAT

- Detection in cross-correlation with WiggleZ galaxies @ $0.400 < z < 0.459$

[Cunnington et al. (2022)]





e-MERLIN

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- The Super Cluster Assisted Shear Survey (SuperCLASS)
  - Paving the road to detecting cosmic shear in the radio band
  - 0.06 gal/arcmin^2 (detected, resolved, and at high redshift)
  - ~0.26 deg^2

[Battye, SC et al. (2020)]

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

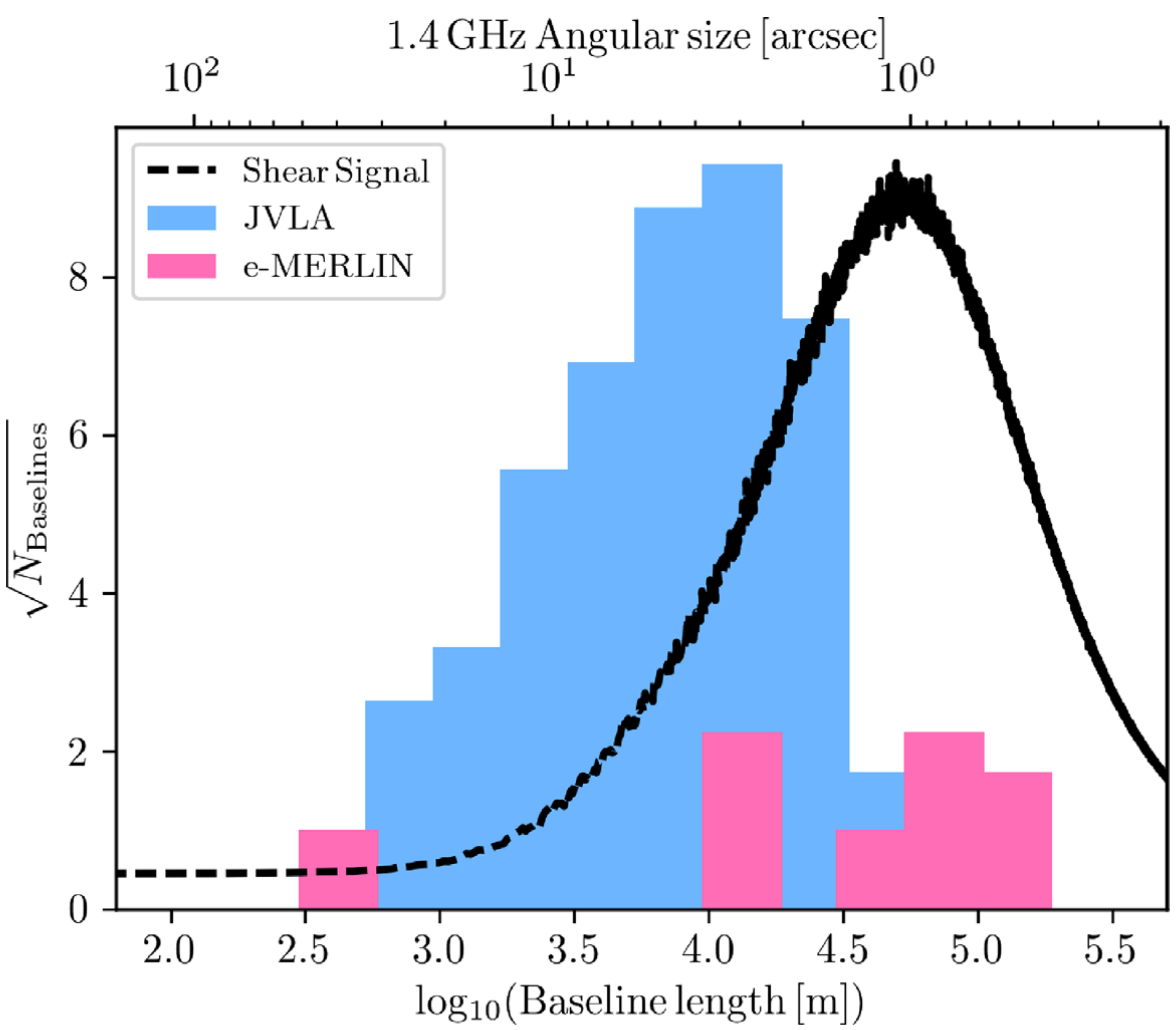
MNRAS **495,** 1706–1723 (2020) doi:10.1093/mnras/staa709
Advance Access publication 2020 April 2

SuperCLASS – I. The super cluster assisted shear survey: Project overview and data release 1

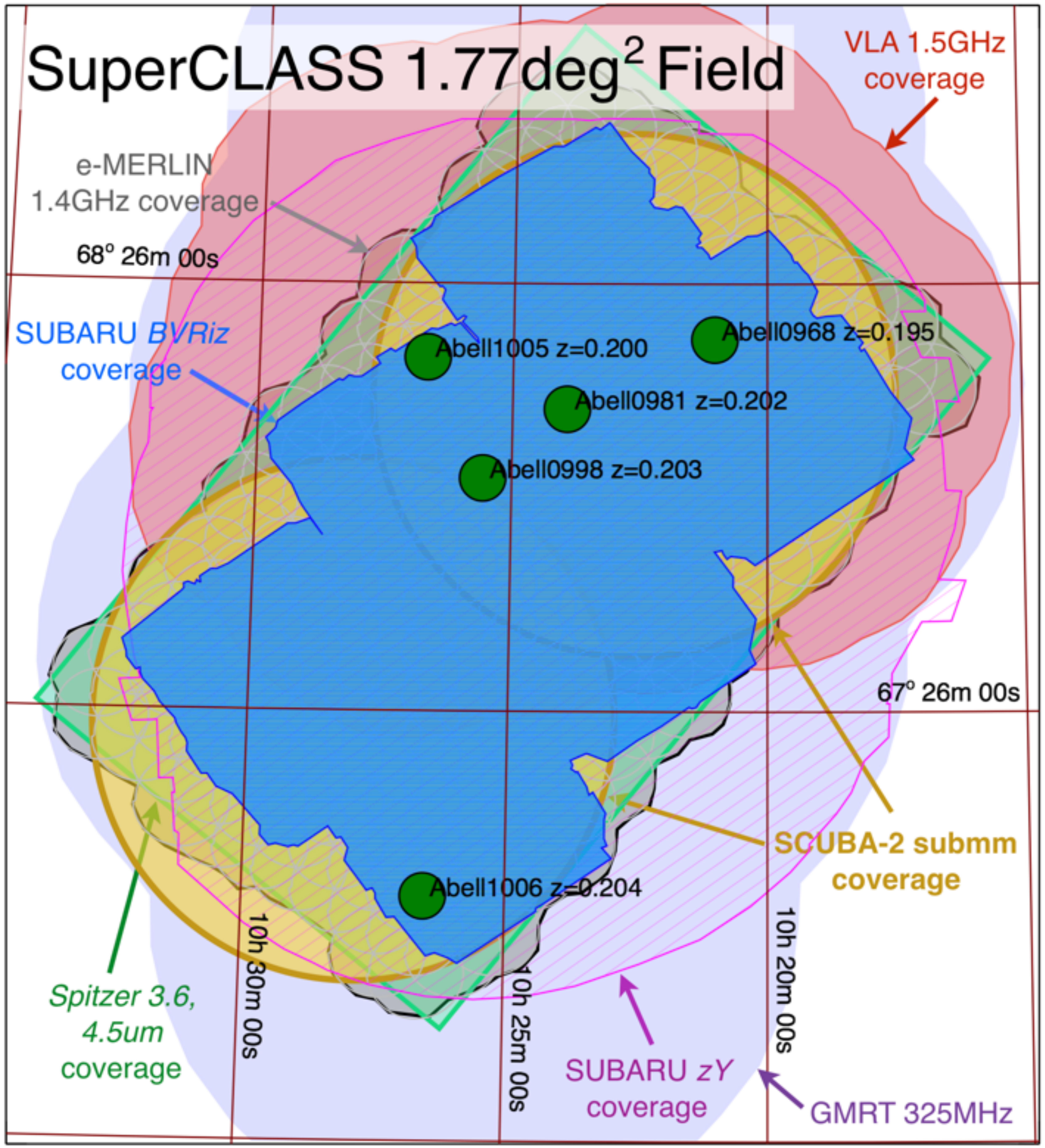
Richard A. Battye,[1★] Michael L. Brown,[1] Caitlin M. Casey,[2] Ian Harrison,[1,3] Neal J. Jackson,[1] Ian Smail,[4] Robert A. Watson,[1] Christopher A. Hales,[5,6] Sinclaire M. Manning,[2] Chao-Ling Hung,[2] Christopher J. Riseley,[7,8,9] Filipe B. Abdalla,[10] Mark Birkinshaw,[11] Constantinos Demetroullas,[1,12] Scott Chapman,[13] Robert J. Beswick,[1] Tom W. B. Muxlow,[1] Anna Bonaldi,[1,14] Stefano Camera,[1,15,16] Tom Hillier,[1] Scott T. Kay,[1] Aaron Peters,[1] David B. Sanders,[17] Daniel B. Thomas,[1] A. P. Thomson,[1] Ben Tunbridge,[1] and Lee Whittaker[1,10] (SuperCLASS Collaboration)

e-MERLIN

- Fully multi-wavelength!



[Courtesy of C. Casey]



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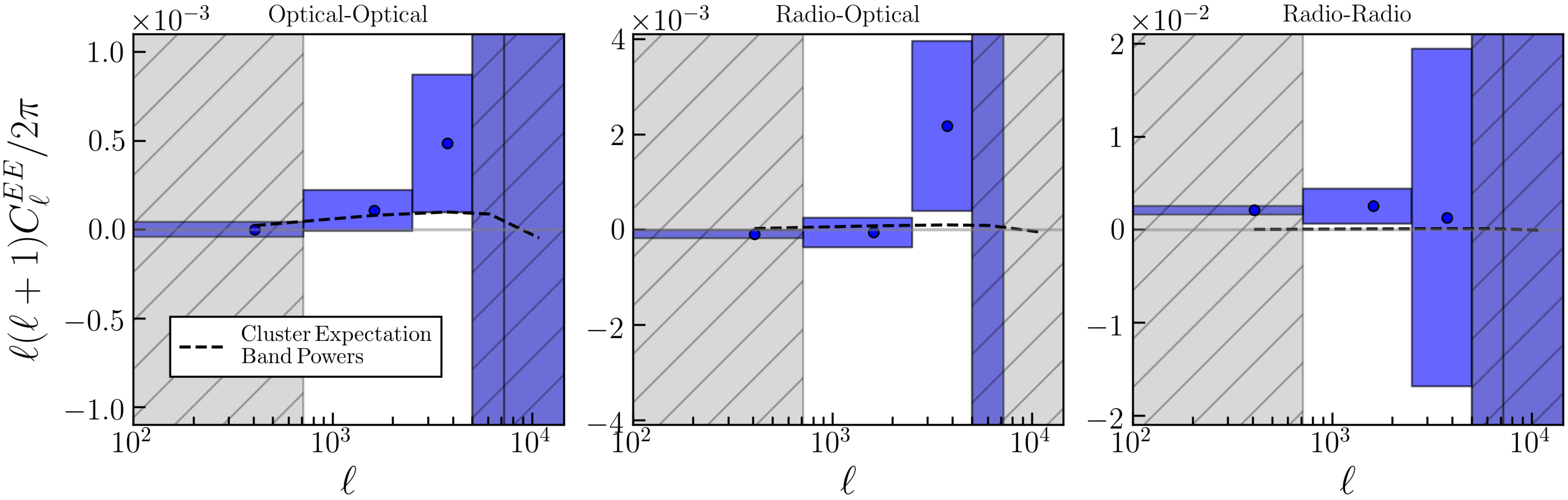
[Harrison, SC et al. (2020)]



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[Courtesy of I. Harrison]