Cosmology at radio frequencies with the SKA

Stefano Camera
Department of Physics, Alma Felix University of Turin, Italy

INFN TORINO
Istituto Nazionale di Fisica Nucleare
Sezione di Torino

UNIVERSITY of the WESTERN CAPE

Programma per Giovani Ricercatori
"Rita Levi Montalcini"

Physics Torino
Department of Excellence

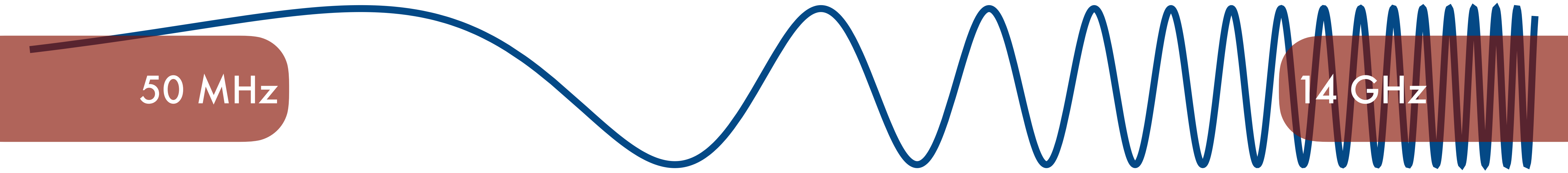
The SKA

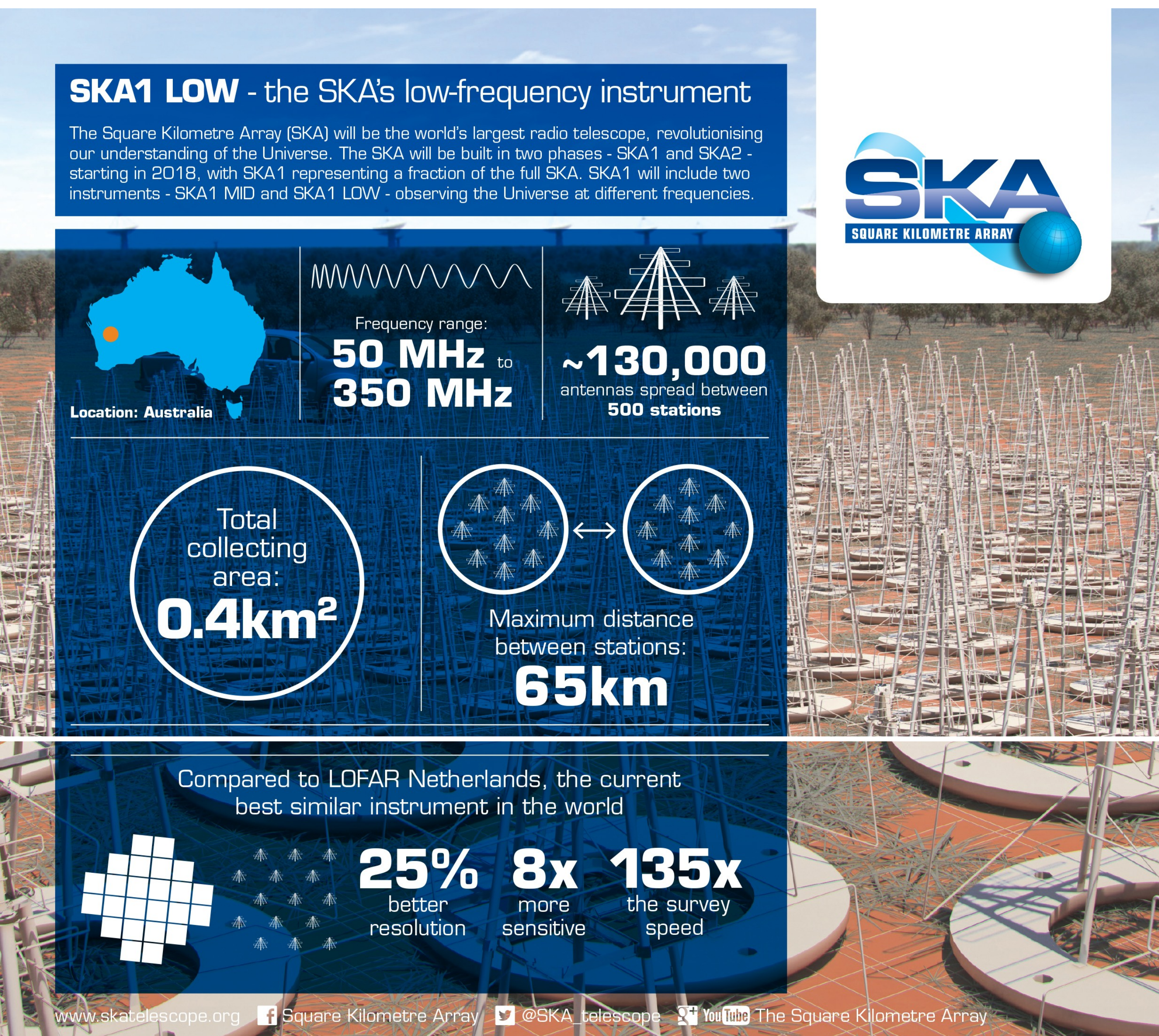
UNIVERSITÀ DEGLI STUDI DI TORINO
ALMA UNIVERSITAS TAURINENSIS

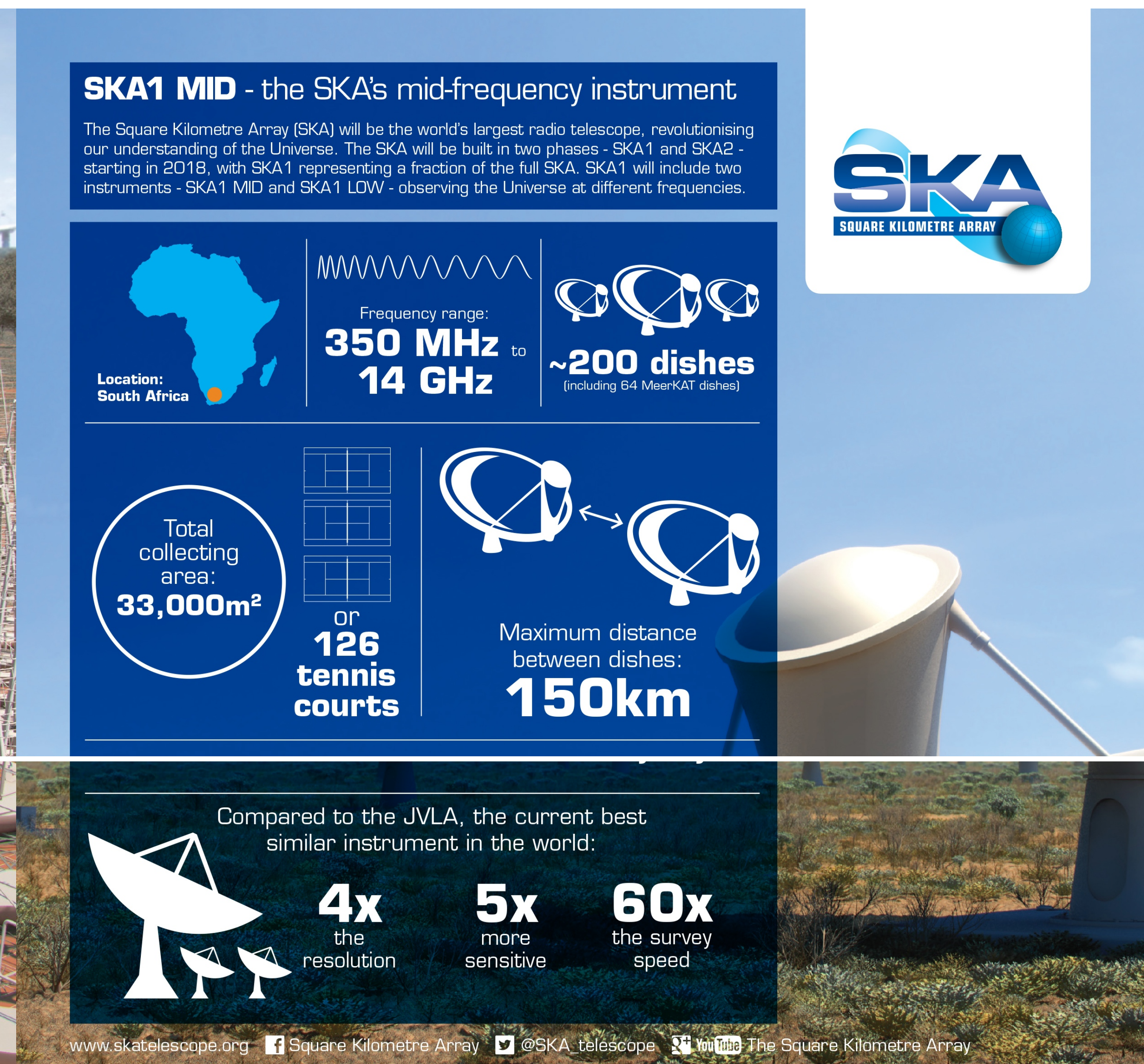
- The Square Kilometre Array (SKA) will be the largest radio-telescope on Earth and will be built in two locations

The SKA

UNIVERSITÀ DEGLI STUDI DI TORINO
ALMA UNIVERSITAS TAURINENSIS





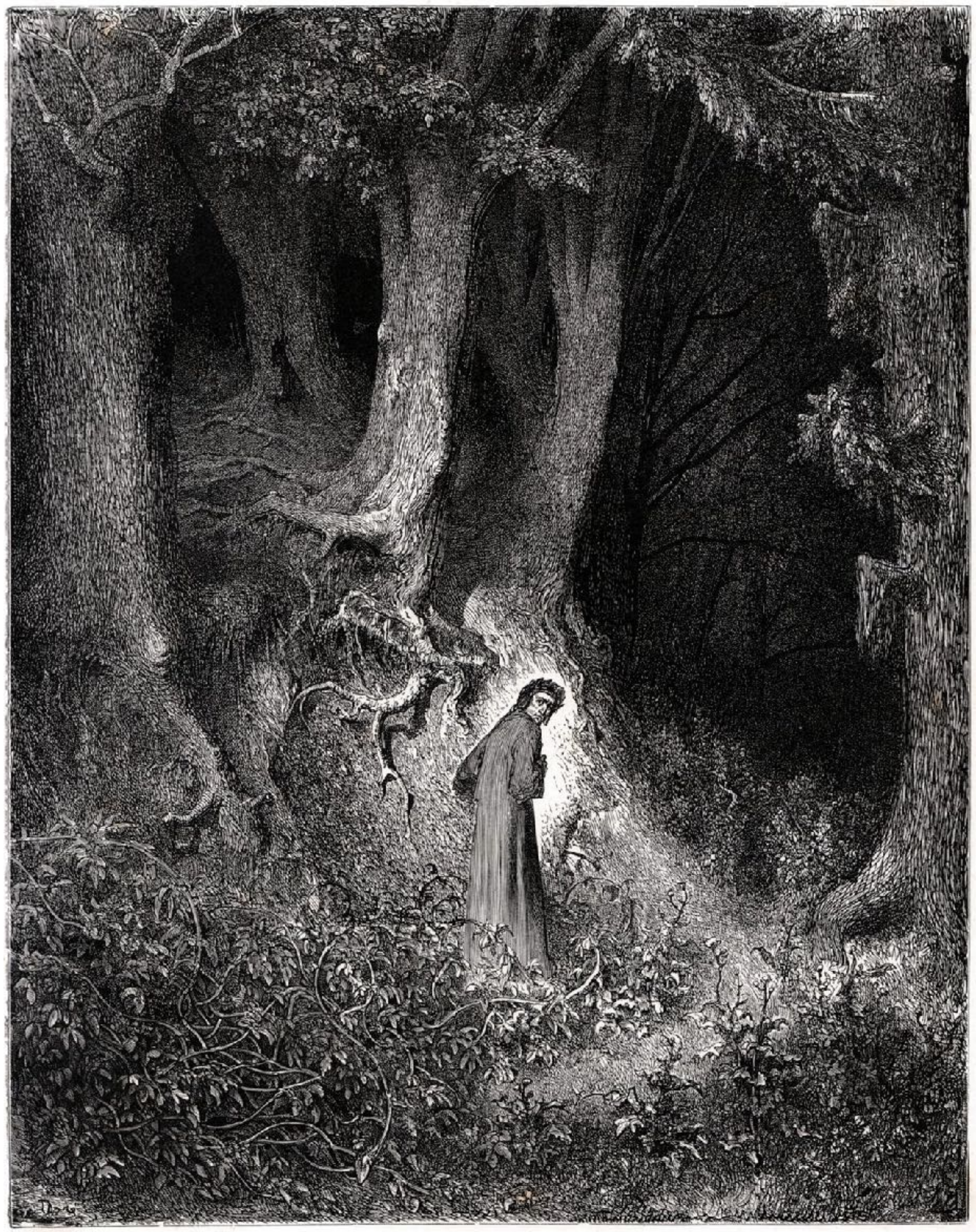


The SKA

UNIVERSITÀ
DEGLI STUDI
DI TORINO
ALMA UNIVERSITAS
TAURINENSIS

‘Within a forest dark’

UNIVERSITÀ DEGLI STUDI DI TORINO
ALMA UNIVERSITAS TAURINENSIS

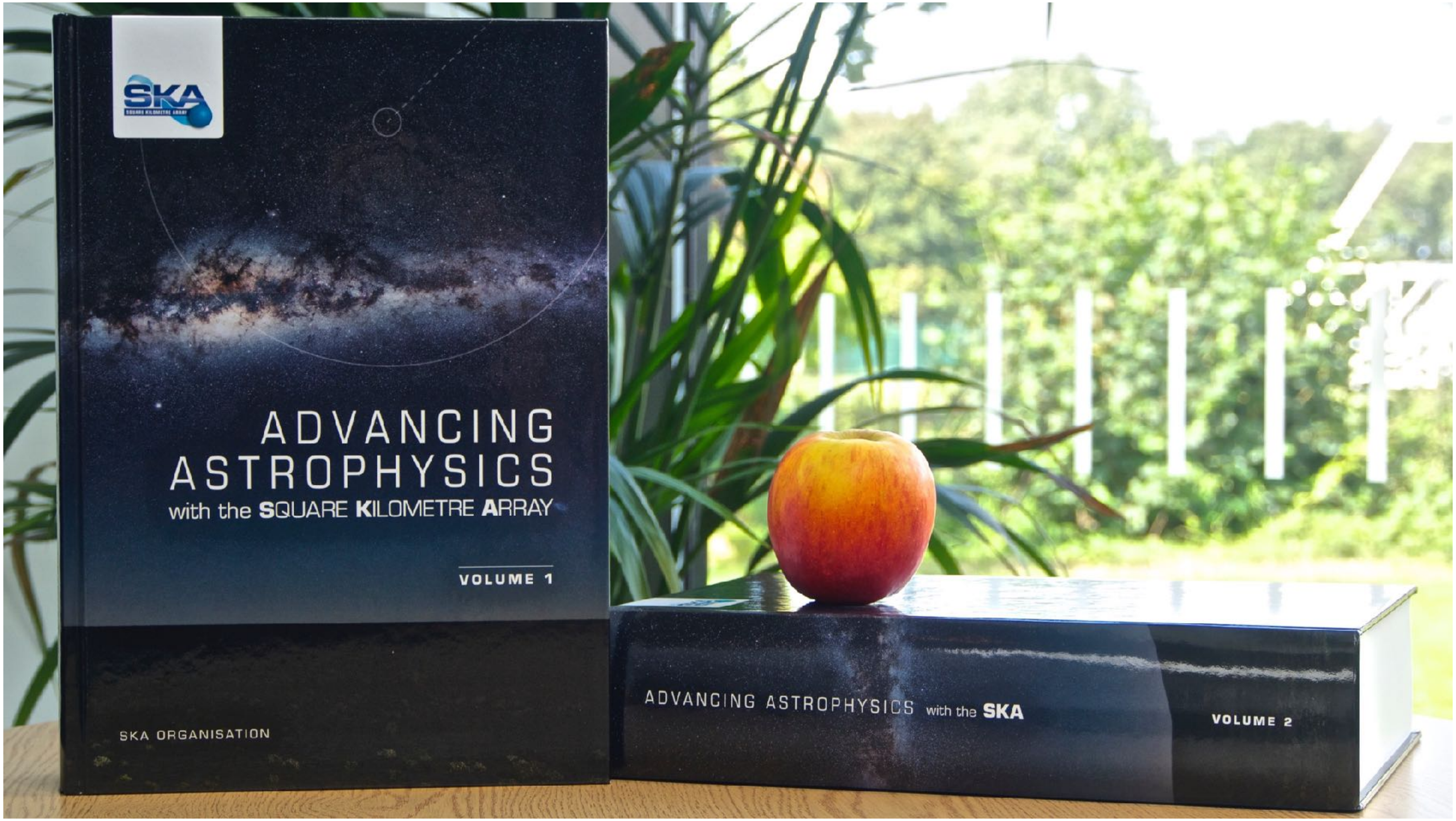


Dark matter

Dark energy

Inflation

SKA cosmology



SKA cosmology

UNIVERSITÀ DEGLI STUDI DI TORINO
ALMA UNIVERSITAS TAURINENSIS

[Bacon, SC et al. 2019 (in press)]

Cosmology with Phase 1 of the Square Kilometre Array

Red Book 2018: Technical specifications and performance forecasts

David J. Bacon[1], Richard A. Battye[2], Philip Bull[3,4,5], Stefano Camera[6,7,8,2], Pedro G. Ferreira[9], Ian Harrison[2,9], David Parkinson[10], Alkistis Pourtsidou[5,1], Mário G. Santos[11,12], Laura Wolz[13], Filipe Abdalla[14,15], Yashar Akrami[16], David Alonso[9], Sambatra Andrianomena[11,12,17], Mario Ballardini[11], José Luis Bernal[18,19], Daniele Bertacca[20,36], Carlos A.P. Bengaly[11], Anna Bonaldi[21], Camille Bonvin[22], Michael L. Brown[2], Emma Chapman[23], Song Chen[11], Xuelei Chen[24], Steven Cunnington[1], Tamara M. Davis[26], Clive Dickinson[2], José Fonseca[11], Keith Grainge[2], Stuart Harper[2], Matt J. Jarvis[9,11], Roy Maartens[1,11], Natasha Maddox[27], Hamsa Padmanabhan[28], Jonathan R. Pritchard[23], Alvise Raccanelli[18], Marzia Rivi[14,29], Sambit Roychowdhury[2], Martin Sahlén[30], Dominik J. Schwarz[31], Thilo M. Siewert[31], Matteo Viel[32], Francisco Villaescusa-Navarro[32], Yidong Xu[24], Daisuke Yamauchi[34], Joe Zuntz[35]

SKA cosmology

UNIVERSITÀ DEGLI STUDI DI TORINO
ALMA UNIVERSITAS TAURINENSIS

[Bull, SC et al. 2019 (in press)]

Fundamental Physics with the Square Kilometre Array

P. Bull,[*] S. Camera,[*] K. Kelley,[*] H. Padmanabhan,[*] J. Pritchard,[*] A. Raccanelli,[*] S. Riemer-Sørensen,[*] L. Shao,[*] S. Andrianomena, E. Athanassoula, D. Bacon, R. Barkana, G. Bertone, C. Bonvin, A. Bosma, M. Brüggen, C. Burigana, C. Bœhm, F. Calore, J. A. R. Cembranos, C. Clarkson, R. M. T. Connors, Á. de la Cruz-Dombriz, P. K. S. Dunsby, N. Fornengo, D. Gaggero, I. Harrison, J. Larena, Y.-Z. Ma, R. Maartens, M. Méndez-Isla, S. D. Mohanty, S. G. Murray, D. Parkinson, A. Pourtsidou, P. J. Quinn, M. Regis, P. Saha, M. Sahlén, M. Sakellariadou, J. Silk, T. Trombetti, F. Vazza, T. Venumadhav, F. Vidotto, F. Villaescusa-Navarro, Y. Wang, C. Weniger, L. Wolz, F. Zhang, B. M. Gaensler,[†] A. Weltman[†]

FUNDAMENTAL PHYSICS WITH THE SKA

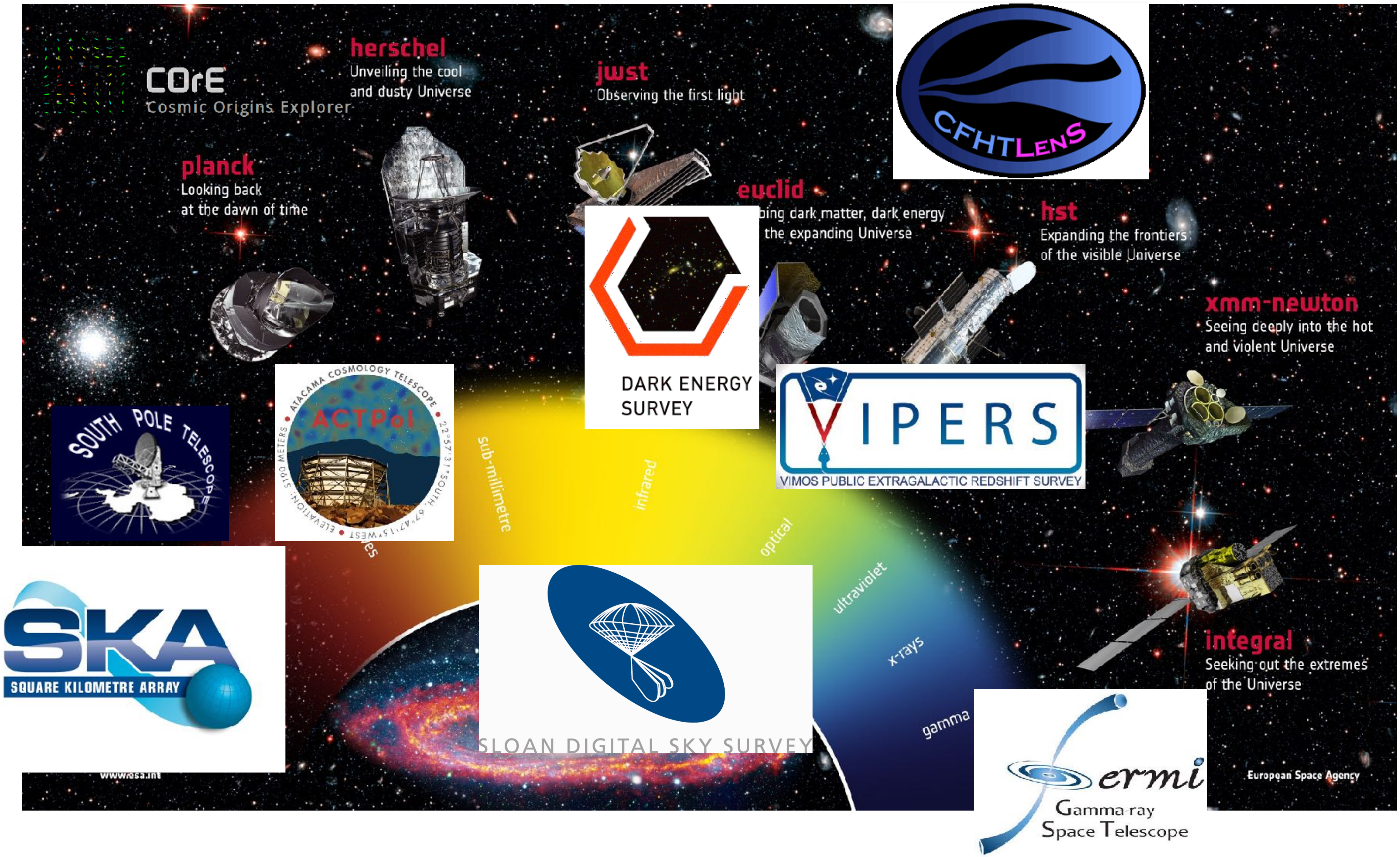
FUNDAMENTAL PHYSICS WITH THE SQUARE KILOMETRE ARRAY

CONFERENCE PRESENTATIONS NOW AVAILABLE HERE

1st-5th May 2017, La Pirogue Resort, Flic en Flac, Mauritius

Multi-wavelength cosmology

UNIVERSITÀ DEGLI STUDI DI TORINO
ALMA UNIVERSITAS TAURINENSIS



Correlations

UNIVERSITÀ DEGLI STUDI DI TORINO
ALMA UNIVERSITAS TAURINENSIS

- Cosmological perturbations $f(t, \boldsymbol{x})$
  [temperature anisotropies, density fluctuations...]

- Correlation function $\xi^f(t, |\boldsymbol{x} - \boldsymbol{y}|) = \langle f(t, \boldsymbol{x}) f(t, \boldsymbol{y}) \rangle$

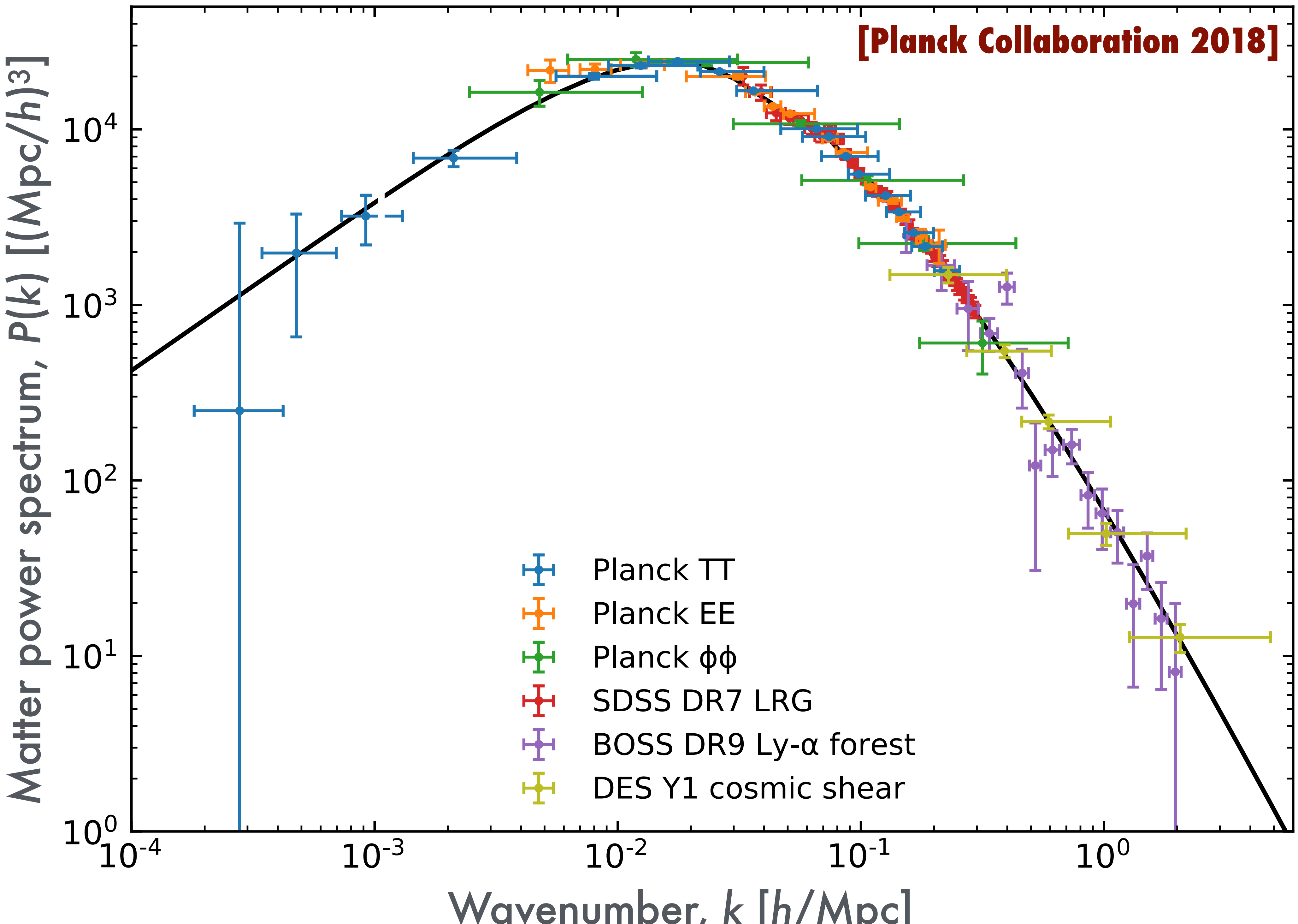
- Fourier-space power spectrum

$$\langle \hat{f}_{\boldsymbol{k}}(t) \hat{f}^\star_{\boldsymbol{k}'}(t) \rangle = (2\pi)^3 \delta_{\rm D}(\boldsymbol{k} - \boldsymbol{k}') P^f(k, t)$$

- *E.g. #1:* Matter 2-pt correlation function and power spectrum

$$f(t, \boldsymbol{x}) \to \delta(t, \boldsymbol{x}) \simeq \frac{\delta_{\rm g}(t, \boldsymbol{x})}{b_{\rm g}(t)}$$

Correlations



Correlations

UNIVERSITÀ DEGLI STUDI DI TORINO
ALMA UNIVERSITAS TAURINENSIS

- Cosmological perturbations $f(t,\boldsymbol{x})$
  [temperature anisotropies, density fluctuations...]

- Correlation function $\xi^f(t,|\boldsymbol{x}-\boldsymbol{y}|)=\langle f(t,\boldsymbol{x})f(t,\boldsymbol{y})\rangle$

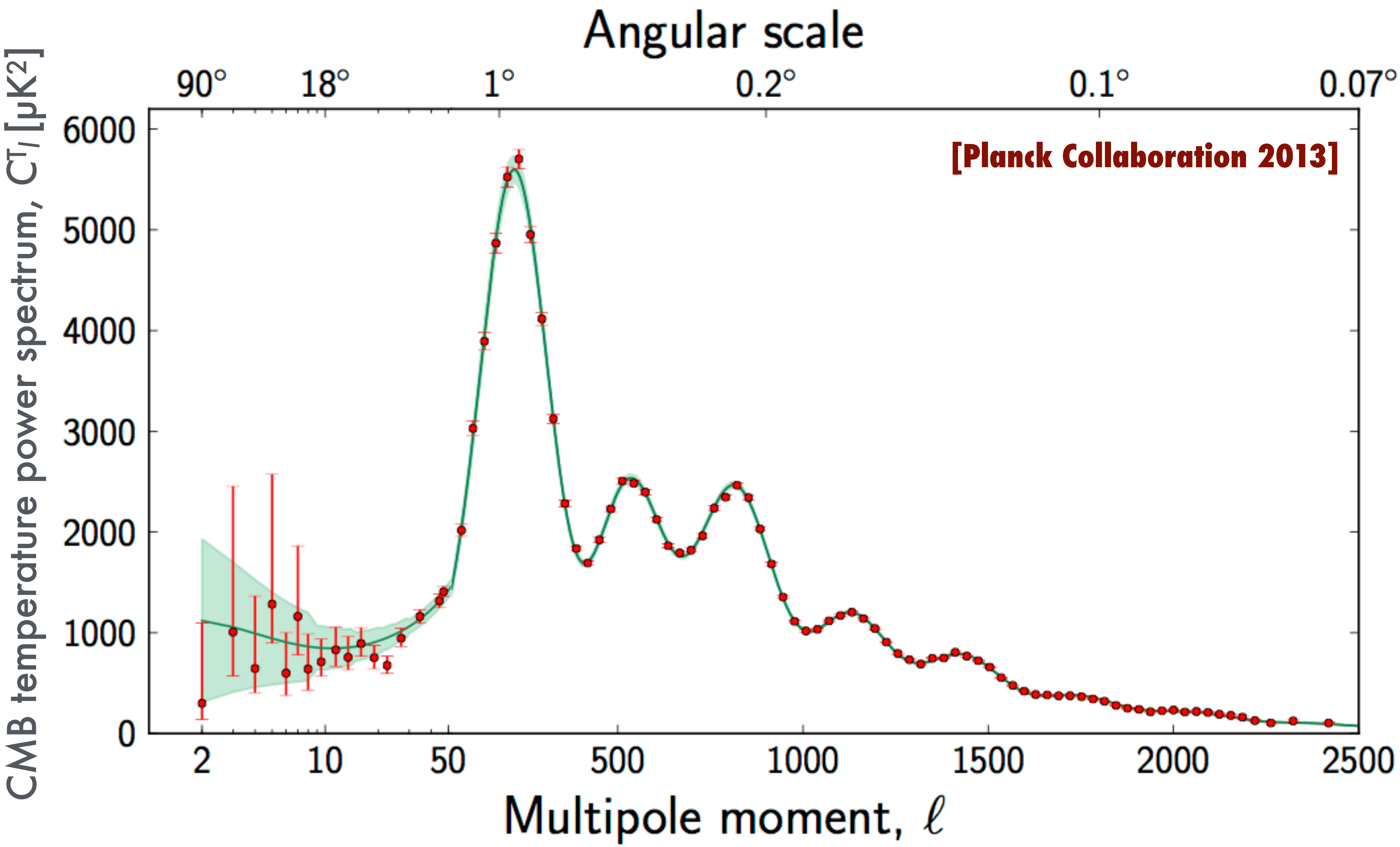
- Fourier-space power spectrum
$$\langle\hat{f}_{\boldsymbol{k}}(t)\hat{f}^\star_{\boldsymbol{k}'}(t)\rangle=(2\pi)^3\delta_{\rm D}(\boldsymbol{k}-\boldsymbol{k}')P^f(k,t)$$

- Harmonic-space power spectrum
$$\langle\hat{f}_{\ell m}(z)\hat{f}^\star_{\ell' m'}(z')\rangle=(2\pi)^2\delta^{\rm K}_{\ell\ell'}\delta^{\rm K}_{mm'}C^f_\ell(z,z')$$

- *E.g. #2:* CMB temperature anisotropies $f(t,\boldsymbol{x})\to T(t_{\rm rec},\vec{\theta})$

Correlations

UNIVERSITÀ DEGLI STUDI DI TORINO
ALMA UNIVERSITAS TAURINENSIS



Correlations

UNIVERSITÀ DEGLI STUDI DI TORINO
ALMA UNIVERSITAS TAURINENSIS

- Cosmological perturbations $f(t,\boldsymbol{x})$
  [temperature anisotropies, density fluctuations...]
- Correlation function $\xi^f(t,|\boldsymbol{x}-\boldsymbol{y}|)=\langle f(t,\boldsymbol{x})f(t,\boldsymbol{y})\rangle$
- Fourier-space power spectrum
  $$\langle \hat{f}_{\boldsymbol{k}}(t)\hat{f}^\star_{\boldsymbol{k}'}(t)\rangle=(2\pi)^3\delta_{\mathrm{D}}(\boldsymbol{k}-\boldsymbol{k}')P^f(k,t)$$
- Harmonic-space power spectrum
  $$C_\ell^{\mathcal{O}_f}=\frac{2}{\pi}\int\mathrm{d}k\,k^2\left[\mathcal{W}_\ell^{\mathcal{O}_f}(k)\right]^2P^f(k,t_0)$$

Cross-correlations

UNIVERSITÀ DEGLI STUDI DI TORINO
ALMA UNIVERSITAS TAURINENSIS

- Cosmological perturbations $f(t,\boldsymbol{x})$ $g(t,\vec{x})$
  [temperature anisotropies, density fluctuations…]

- Correlation function $\xi^{fg}(t,|\boldsymbol{x}-\boldsymbol{y}|)=\langle f(t,\boldsymbol{x})g(t,\boldsymbol{y})\rangle$

- Fourier-space power spectrum

$$\langle\hat{f}_{\boldsymbol{k}}(t)\hat{g}^\star_{\boldsymbol{k}'}(t)\rangle=(2\pi)^3\delta_{\rm D}(\boldsymbol{k}-\boldsymbol{k}')P^{fg}(k,t)$$

- Harmonic-space power spectrum

$$\mathcal{W}_\ell^{\mathcal{O}_g}(k)$$

$$C_\ell^{\mathcal{O}_f\mathcal{O}_g}=\frac{2}{\pi}\int\mathrm{d}k\,k^2\left[\mathcal{W}_\ell^{\mathcal{O}_f}(k)\right]^{\cancel{2}}P^{fg}(k,t_0)$$

Radio cosmology

UNIVERSITÀ
DEGLI STUDI
DI TORINO
ALMA UNIVERSITAS
TAURINENSIS

- Radio surveys and observables
  - Continuum galaxy surveys
  - HI-line galaxy surveys
  - HI intensity mapping
  - Radio weak lensing
- Multi-wavelength synergies

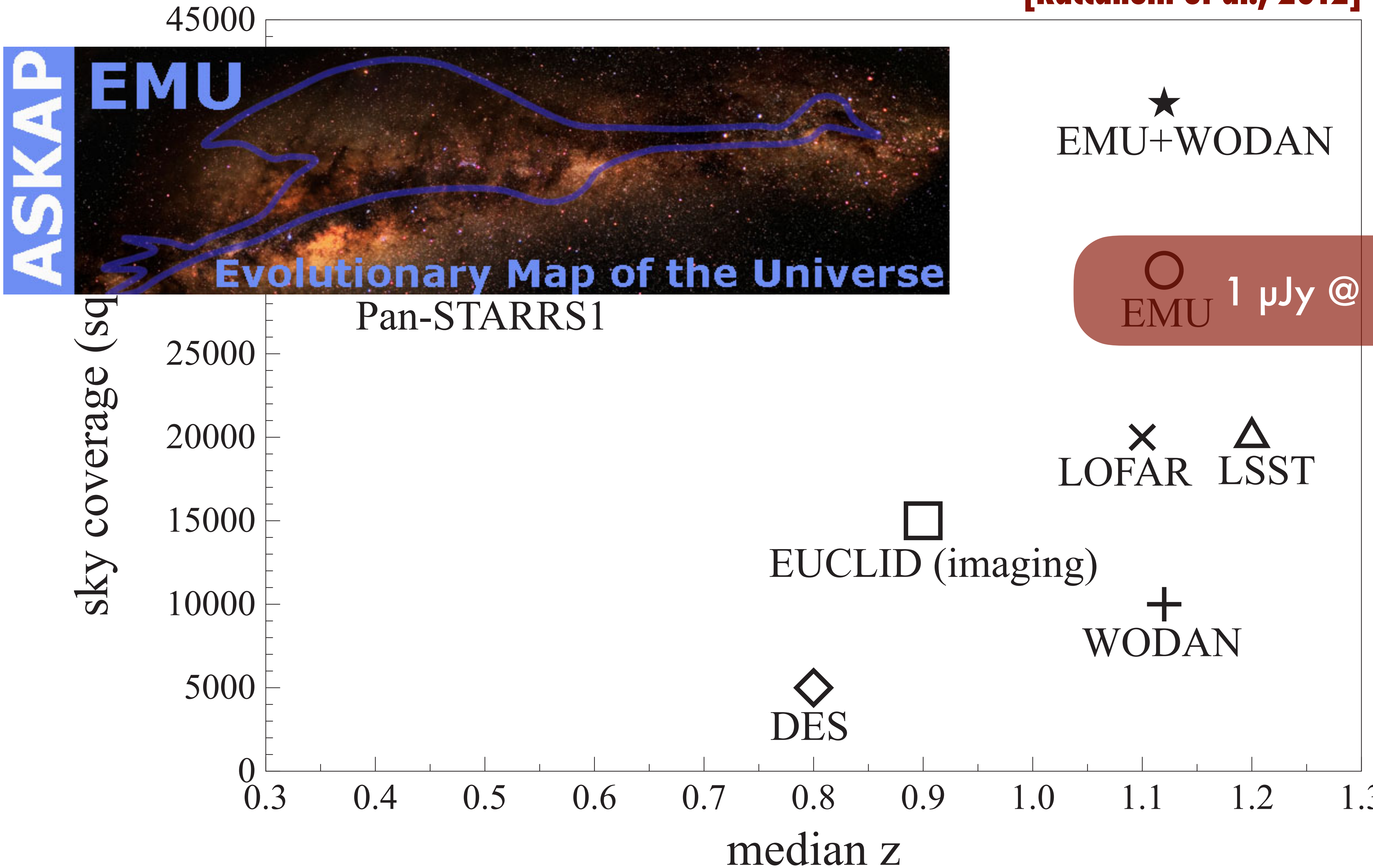
Radio continuum

UNIVERSITÀ DEGLI STUDI DI TORINO
ALMA UNIVERSITAS TAURINENSIS

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

Radio continuum

[Raccanelli et al., 2012]



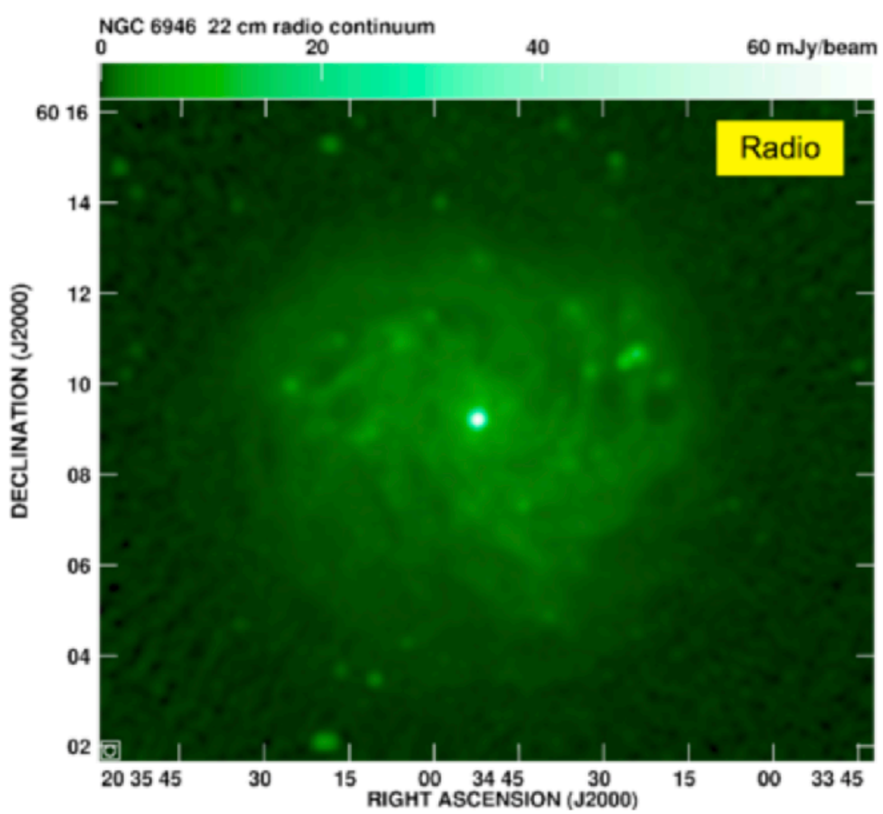
1 μJy @ 1.4 GHz

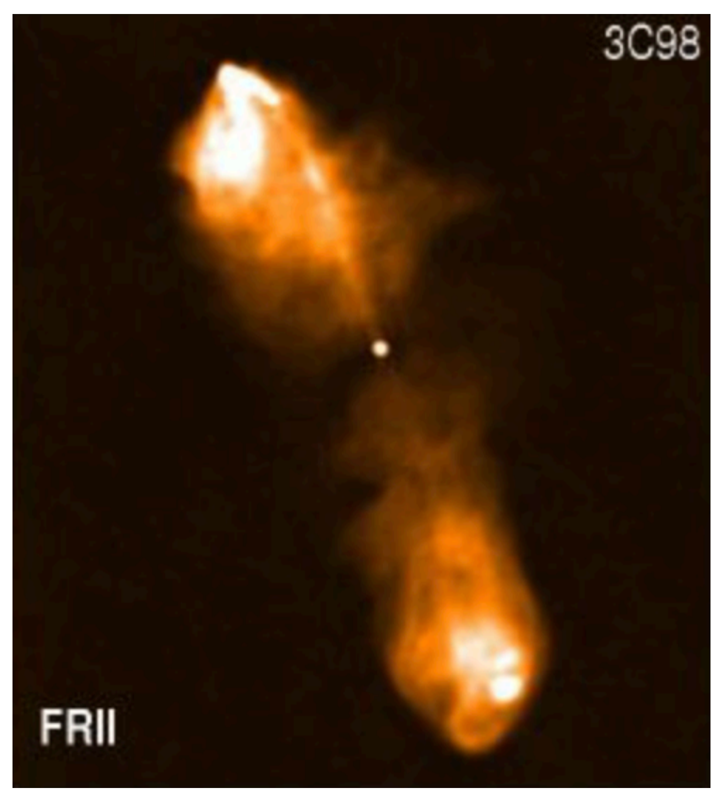
Radio continuum

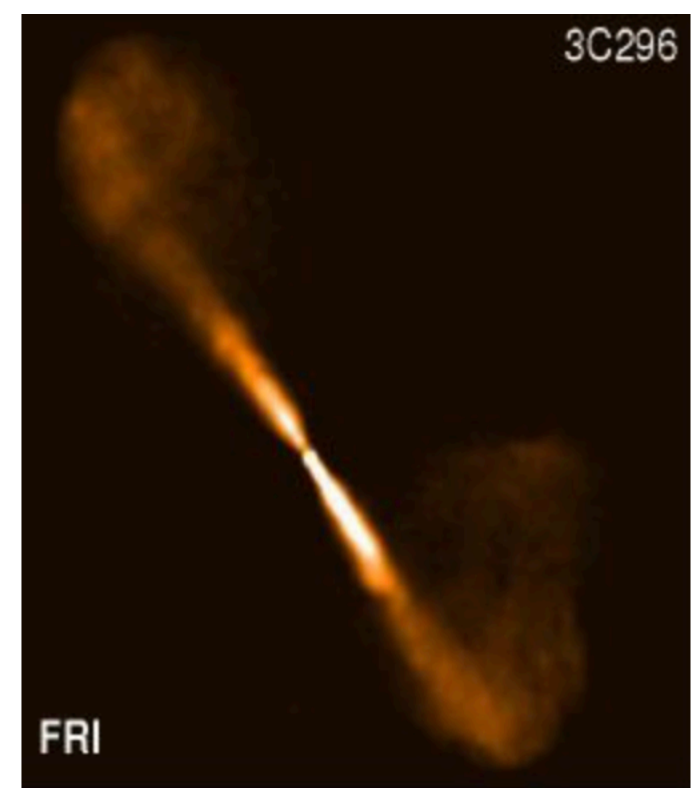
- Various populations of radio galaxies (e.g. SFGs and AGNs)

- Radio galaxy populations related to dark matter halo mass

[Wilman et al. 2008]

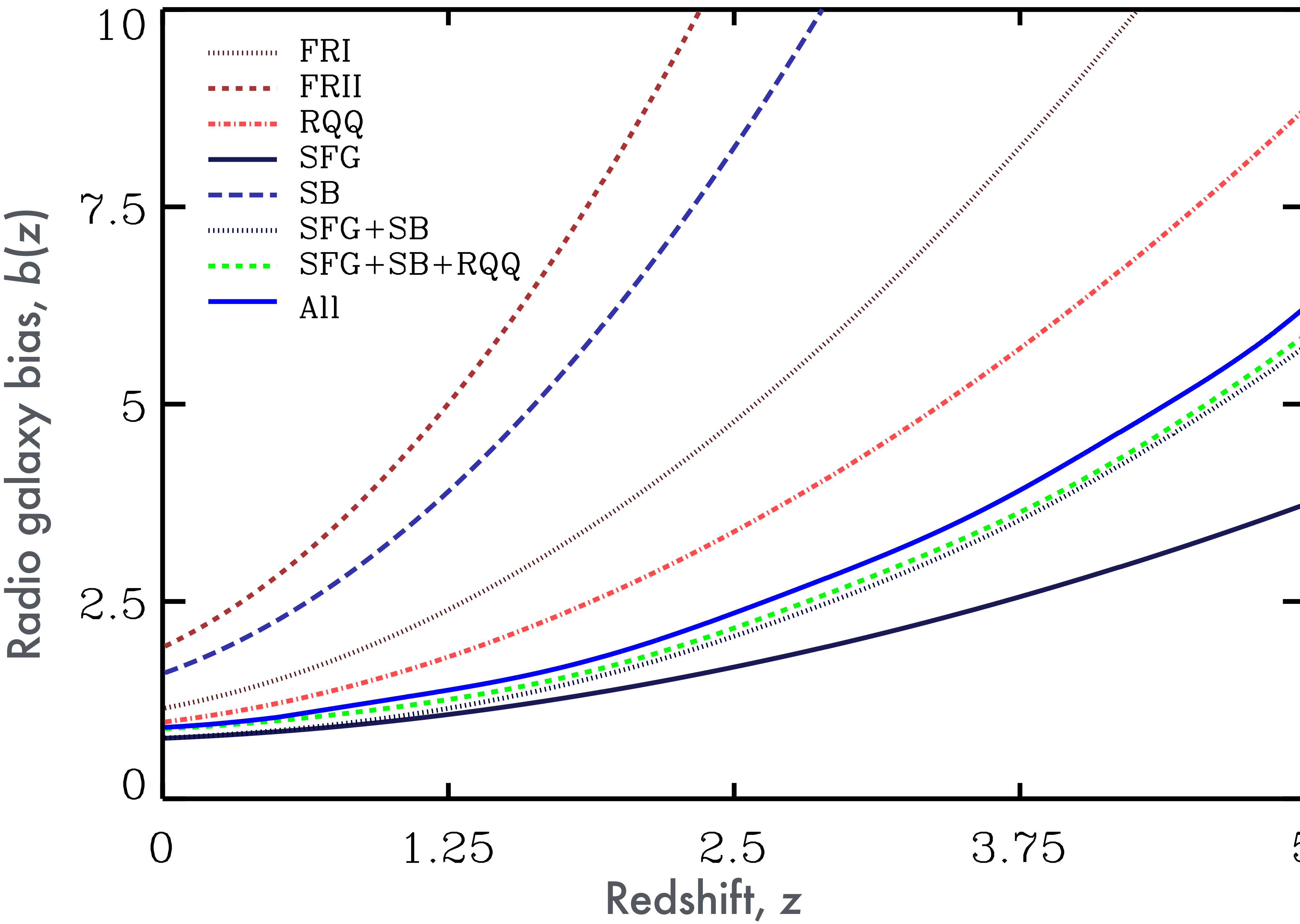






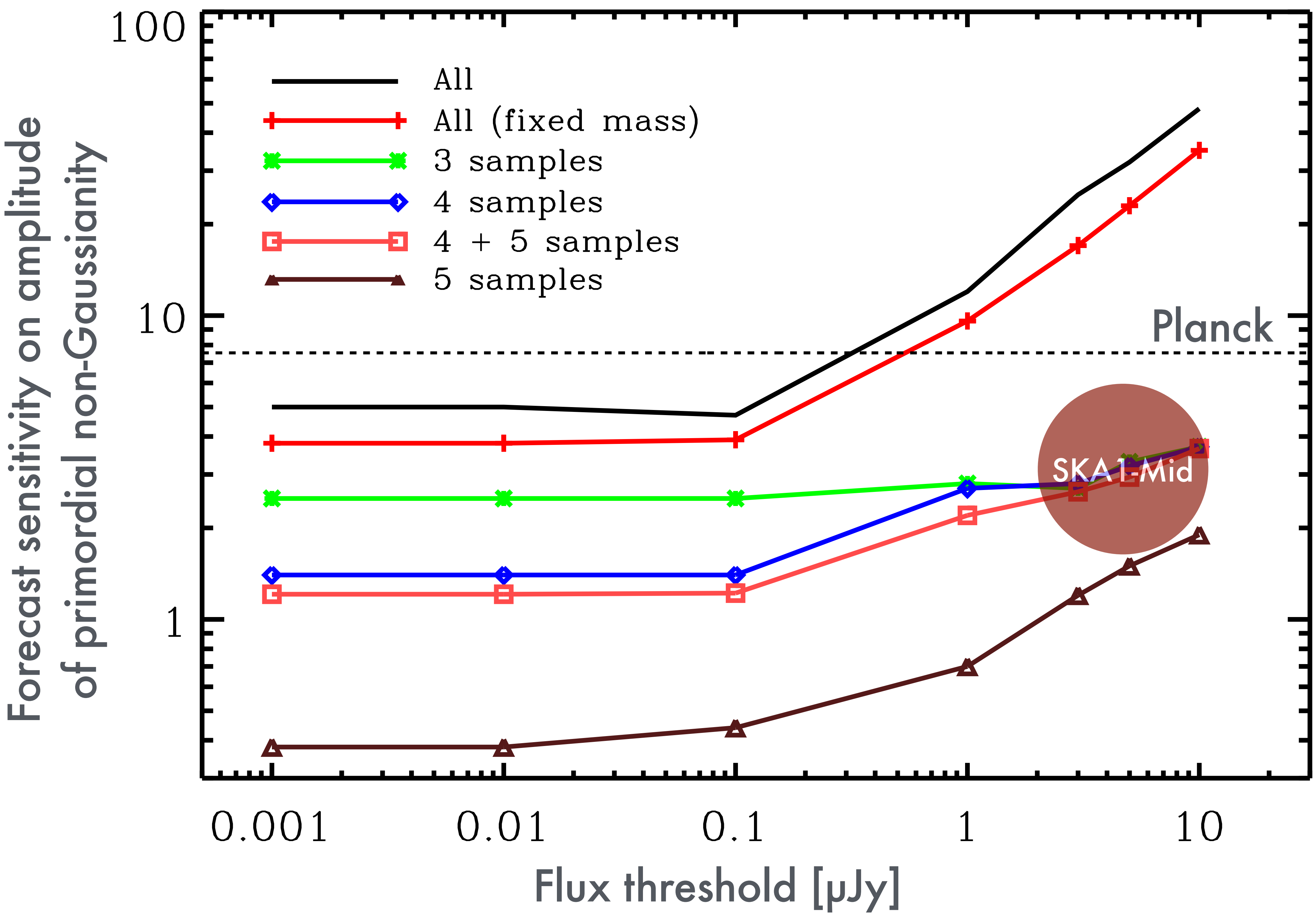
Radio continuum

[Ferramacho, SC et al. 2014]



Radio continuum

[Ferramacho, SC et al. 2014]



Inflation

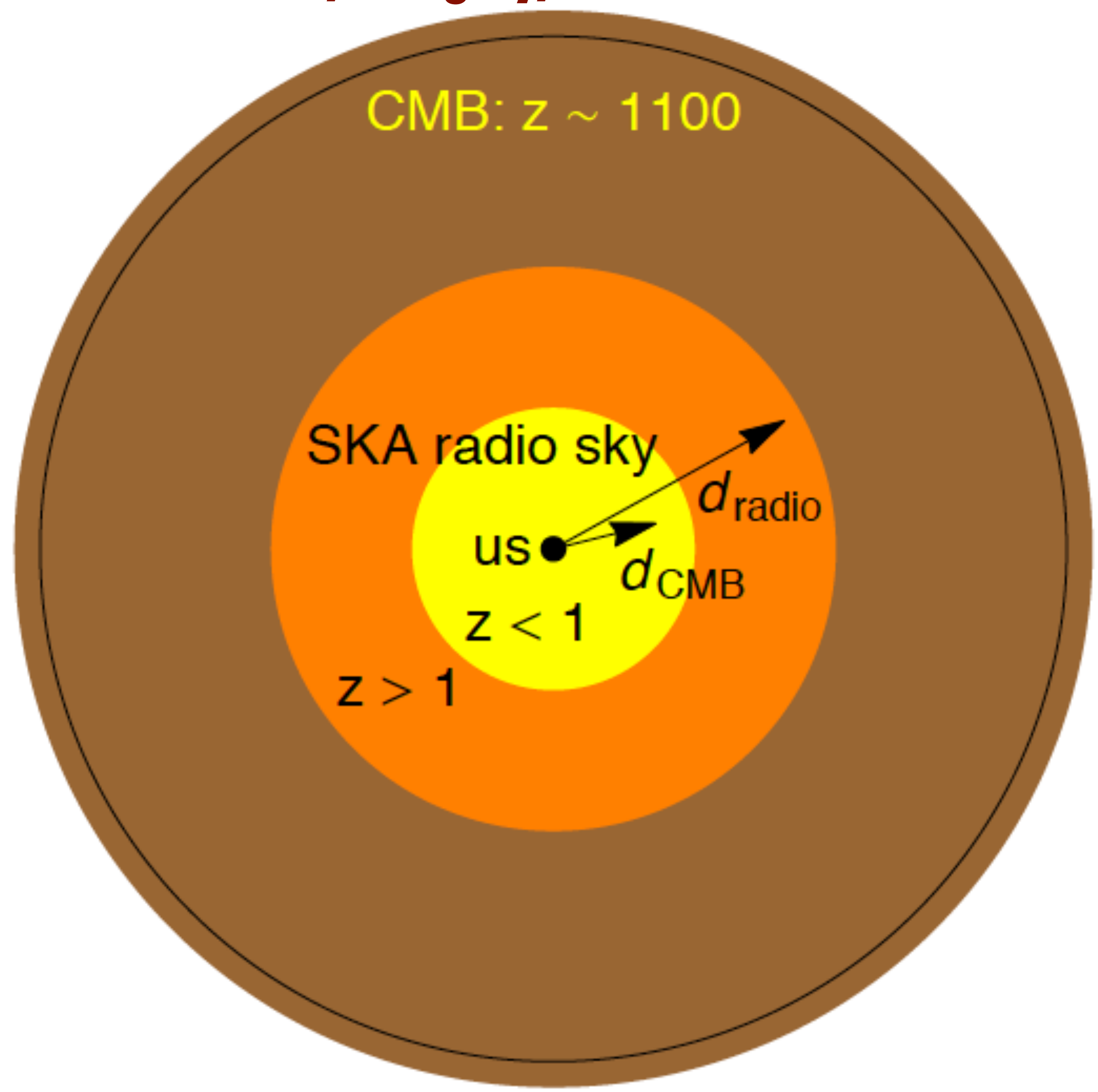
Radio continuum

UNIVERSITÀ
DEGLI STUDI
DI TORINO
ALMA UNIVERSITAS
TAURINENSIS

- Testing the cosmological and the Copernican principles

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

  - SKA galaxy survey angular correlation function will be able to detect dipole:
  - Within 5° (SKA1)
  - Within 1° (SKA2)



HI galaxies

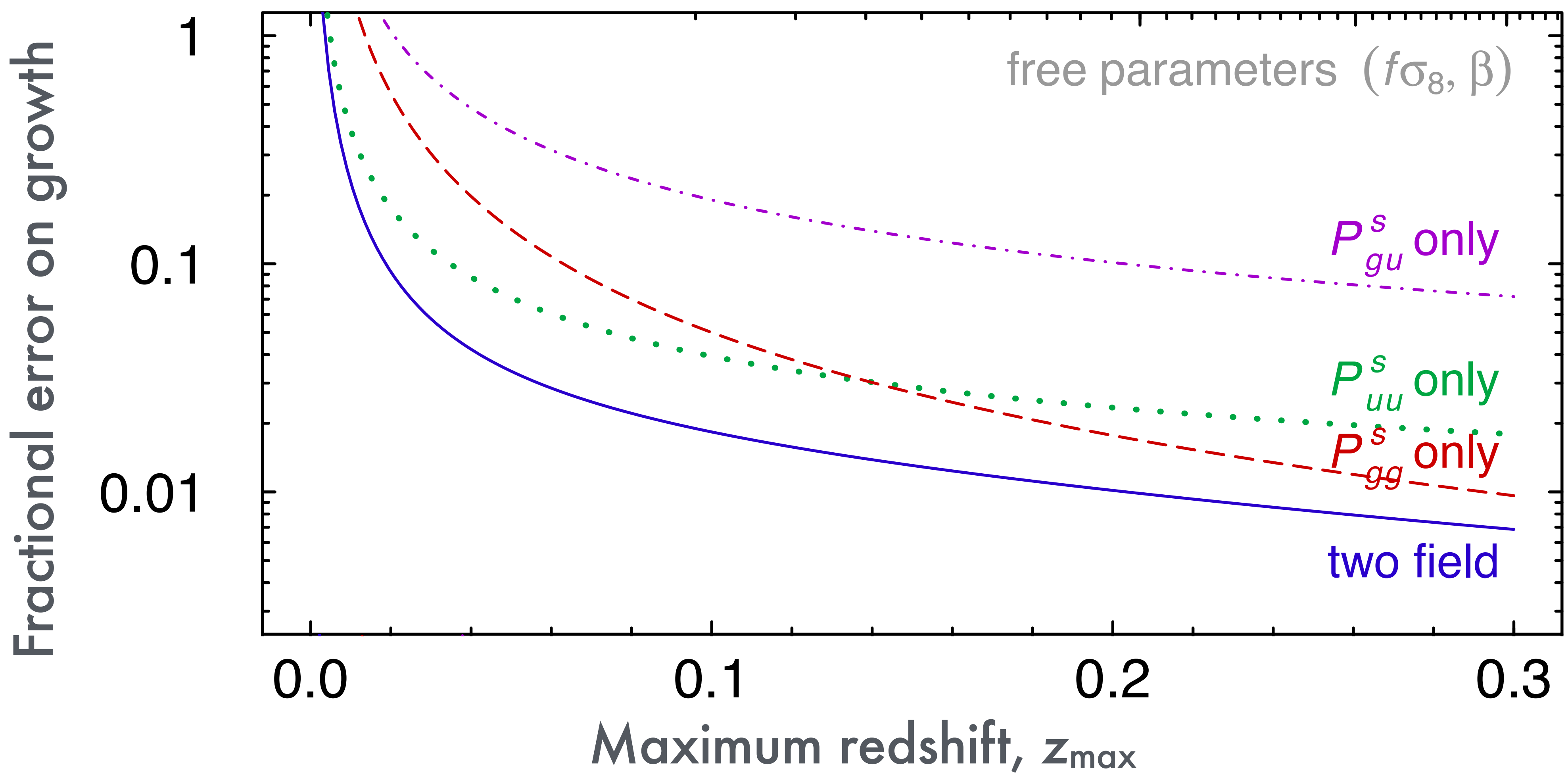
UNIVERSITÀ DEGLI STUDI DI TORINO
ALMA UNIVERSITAS TAURINENSIS

- **Origin:** HI (neutral hydrogen) emission line in galaxies
- **Pros:** spectroscopic redshift accuracy, peculiar velocities
- **Cons:** fewer galaxies, 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 galaxies

- HI 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.

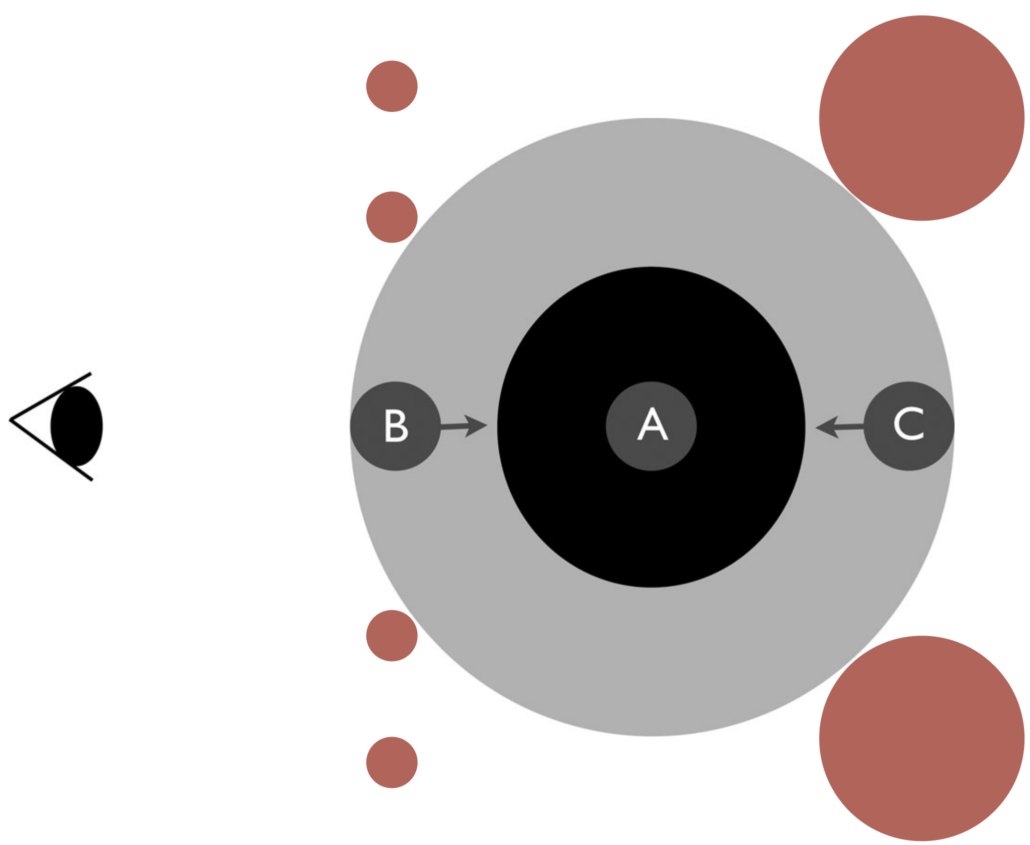
[Koda et al. 2014]

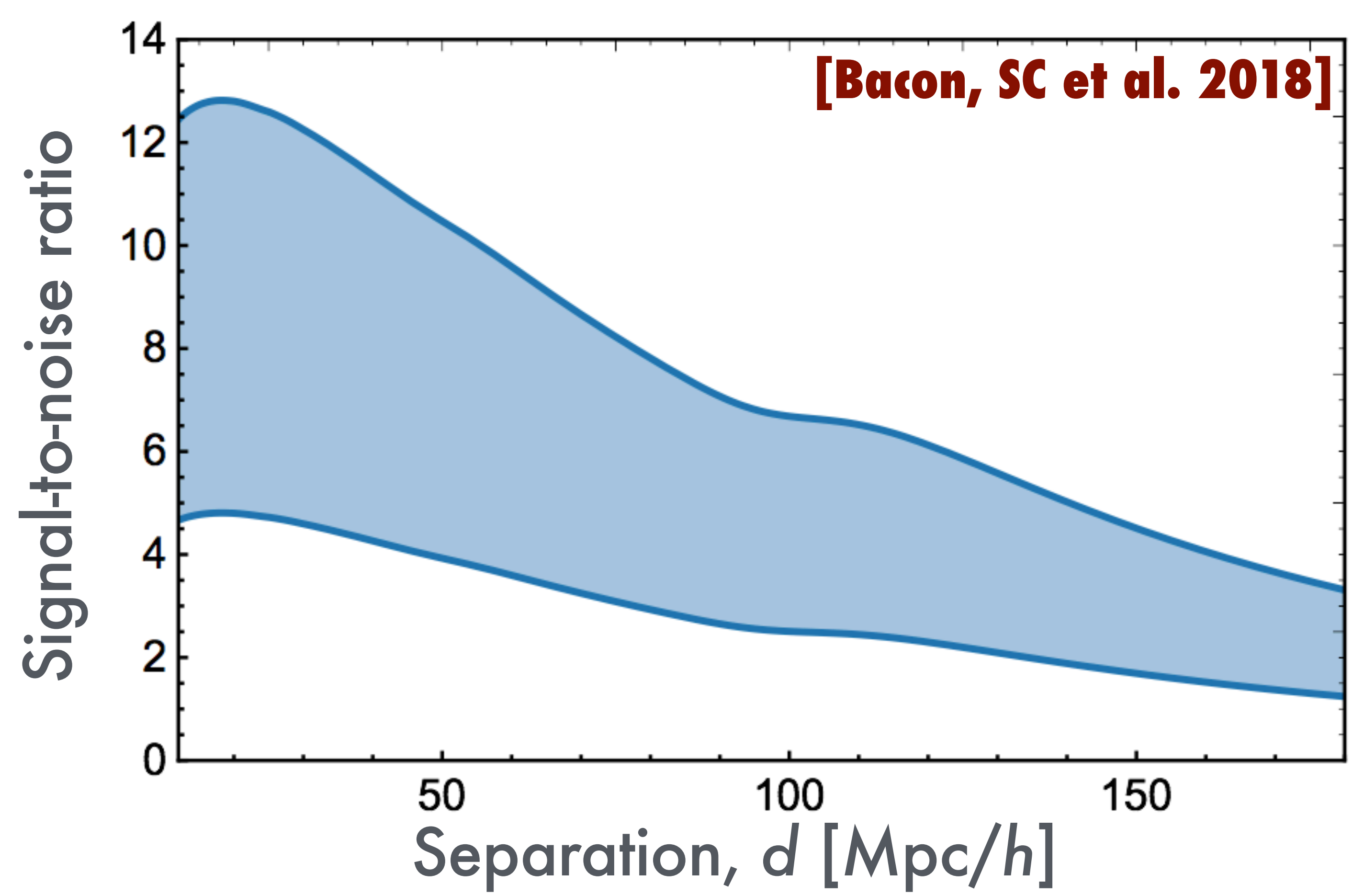


HI galaxies

- Doppler magnification
  - A galaxy moving away from us will maintain fixed angular size while appearing to be further away than it really is (and thus 'bigger').

[Bacon et al. 2014; Bonvin et al. 2017]





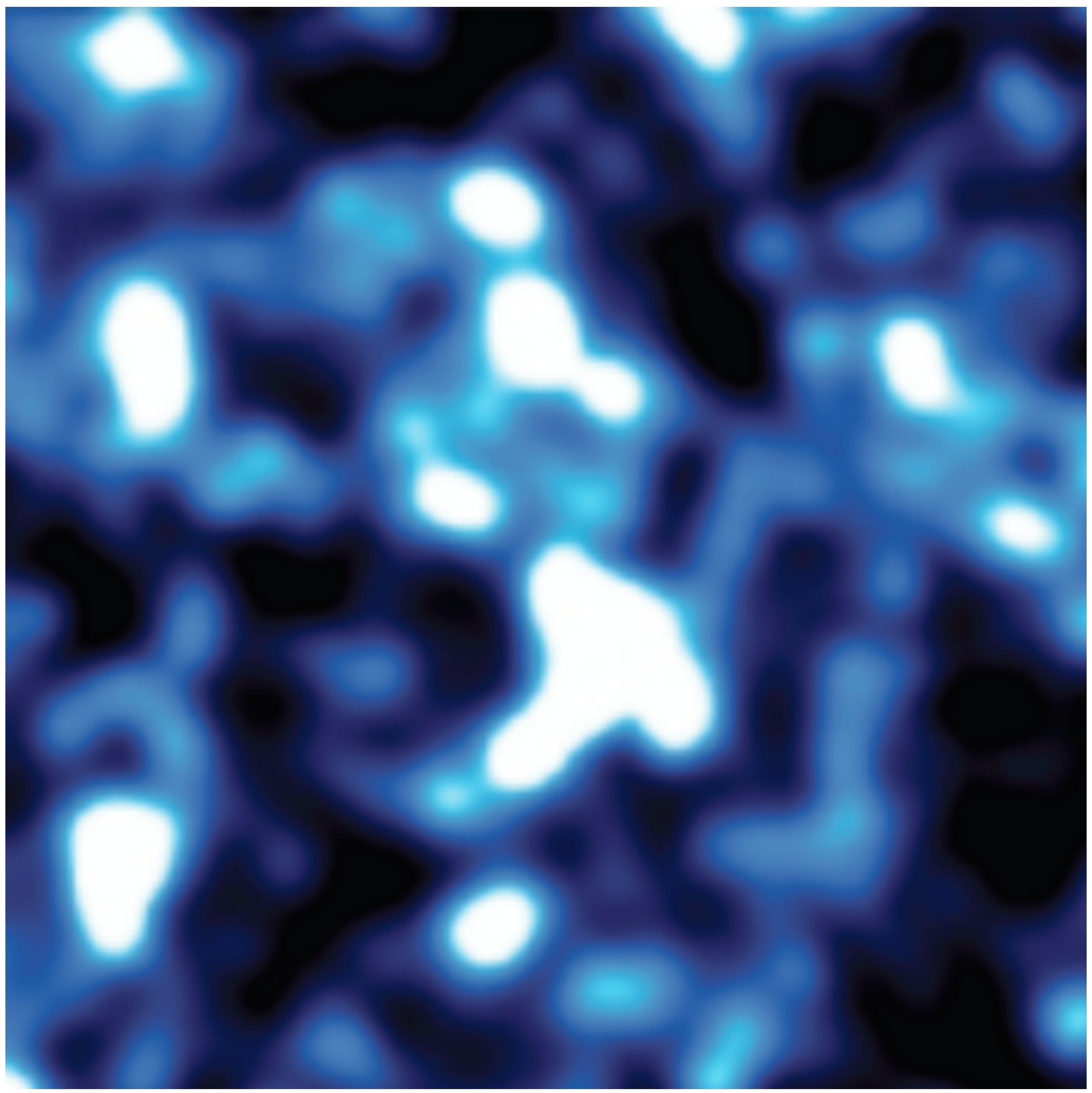
HI intensity mapping

UNIVERSITÀ DEGLI STUDI DI TORINO
ALMA UNIVERSITAS TAURINENSIS

- **Origin:** brightness temperature of 21cm sky (after EoR ends)
- **Pros:** no photon lost, better-than-spectro-z accuracy
- **Cons:** poor angular resolution, (huge) foregrounds
- **Examples:**
  - GBT (~1 sq. deg. in X-corr. w/ WiggleZ @ $0.53 < z < 1.12$)
    [Chang et al., Nature 2010; Masui et al. 2012; Switzer et al. 2013]
  - Parkes (1.3k sq. deg. in X-corr. w/ 2dFGRS @ $0.057 < z < 0.098$)
    [Anderson et al. 2018]

HI intensity mapping

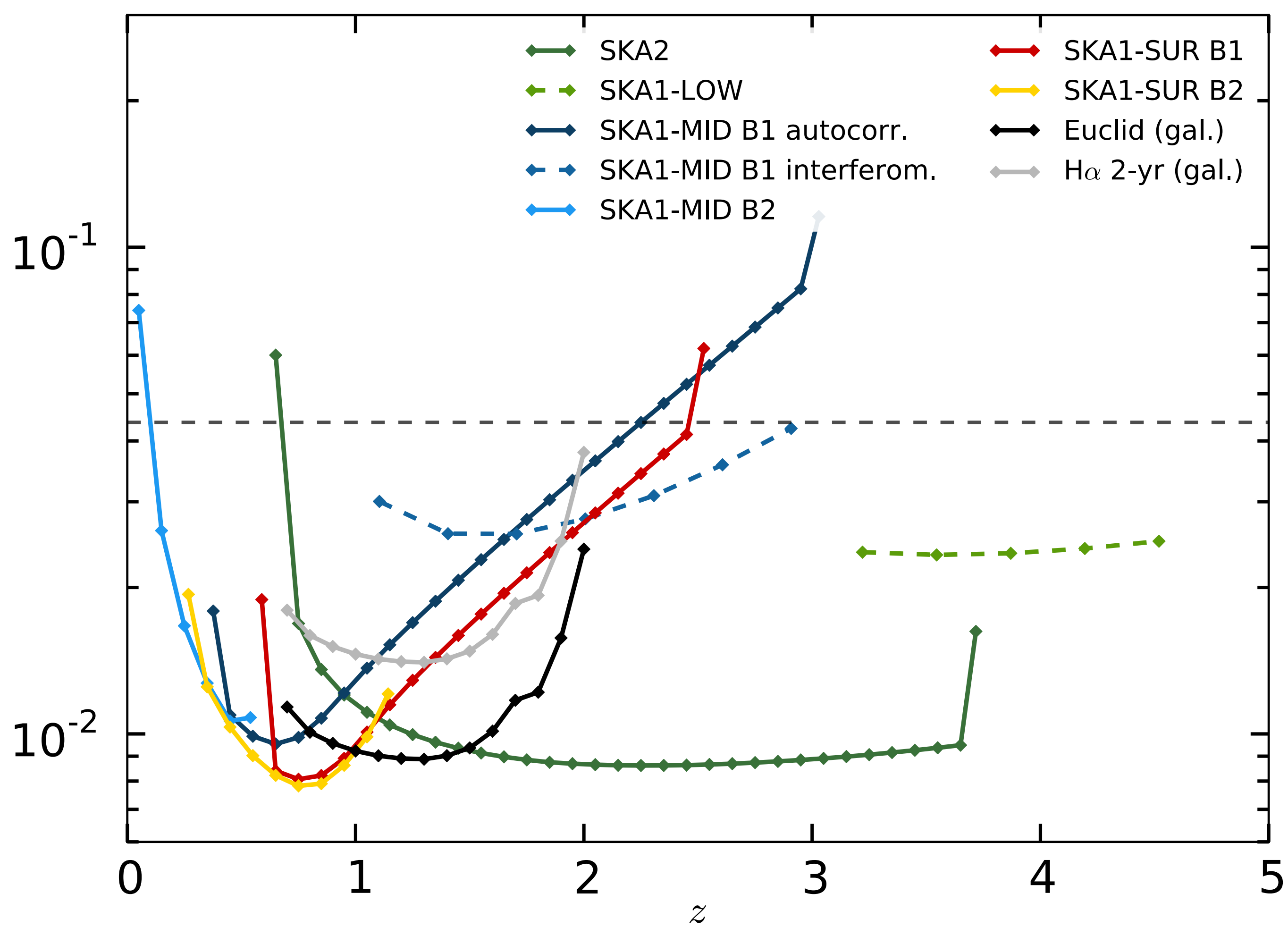
[Bharadwaj et al. 2001; Battye et al. 2004; Loeb & Whyte 2008]



- Redshift for free: ν_{obs} = 1420 MHz / (1+z)

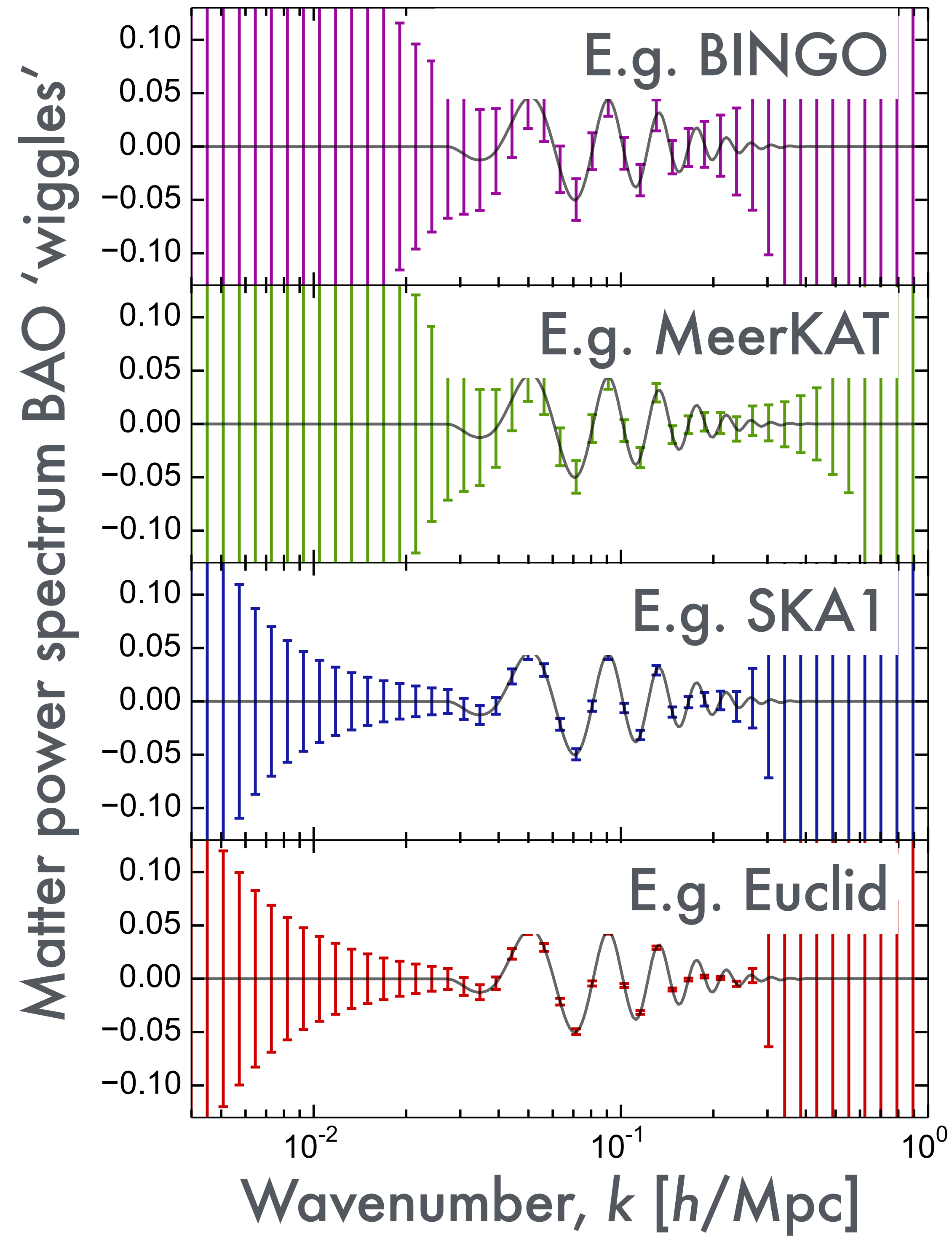
HI intensity mapping

[Santos, SC et al. 2015]



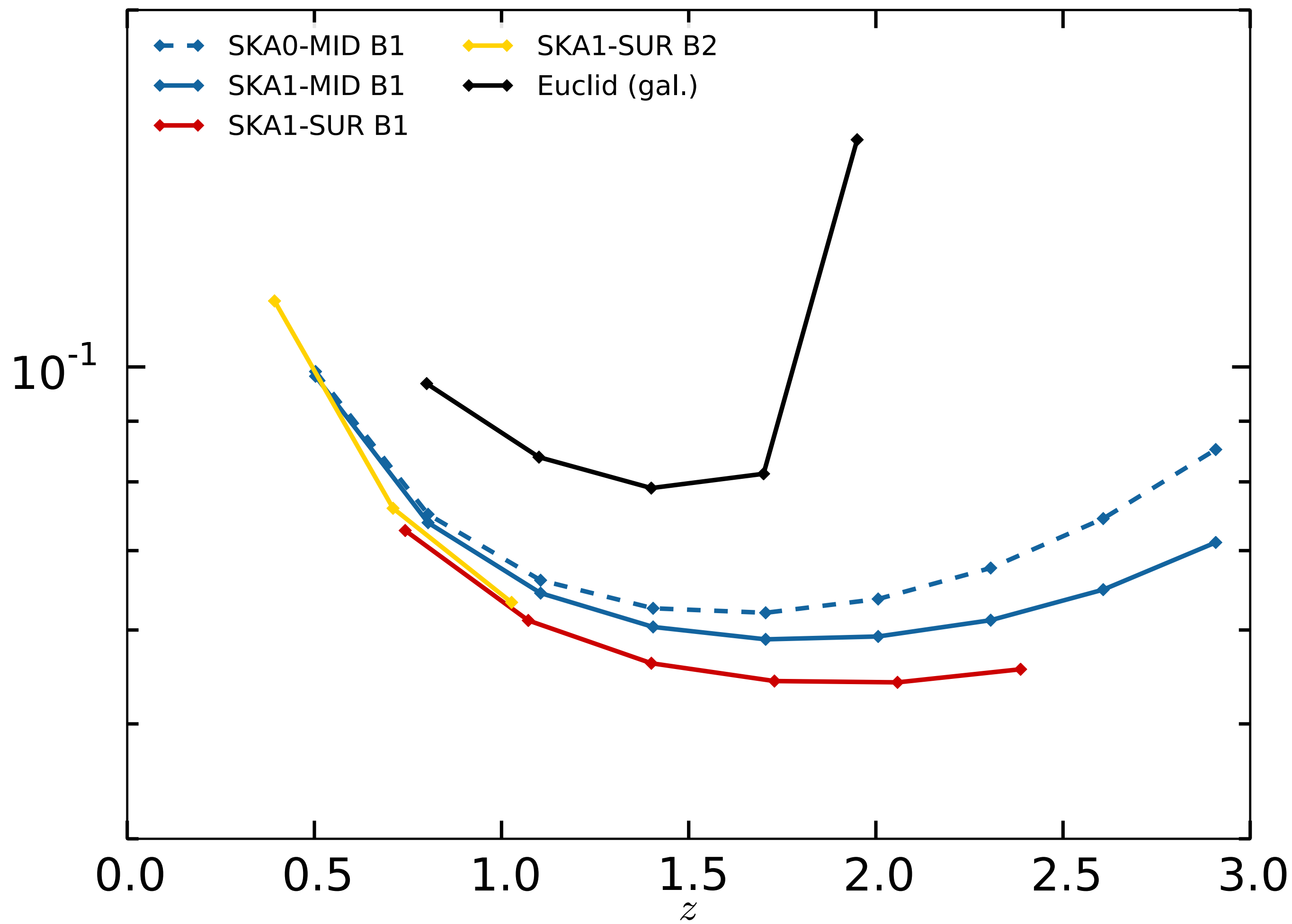
Noise-to-signal at BAO scales
$k \approx 0.074$ Mpc^{-1}

[Bull et al. 2015]

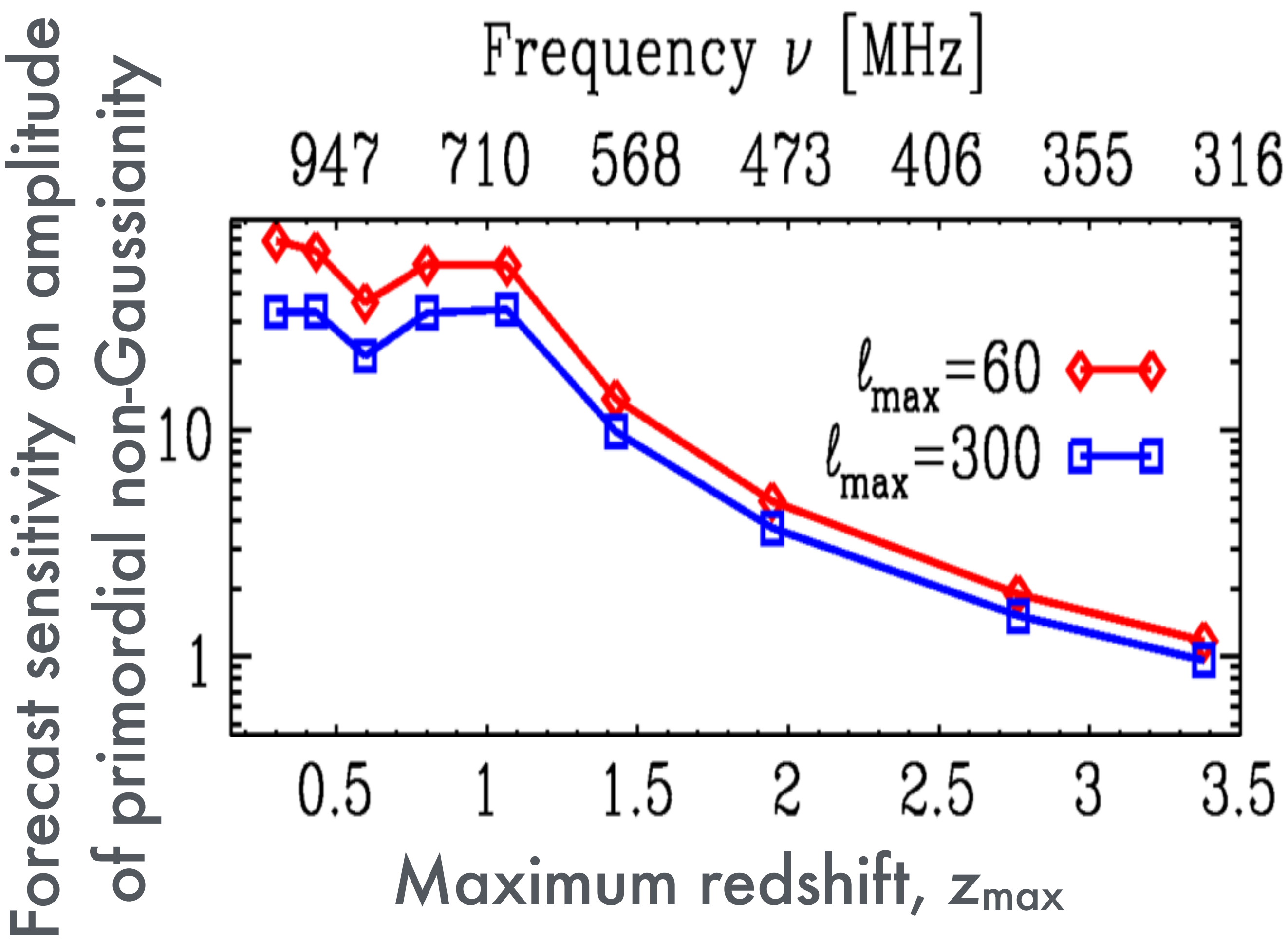


HI intensity mapping

[Santos, SC et al. 2015]



[SC et al., PRL 2013]

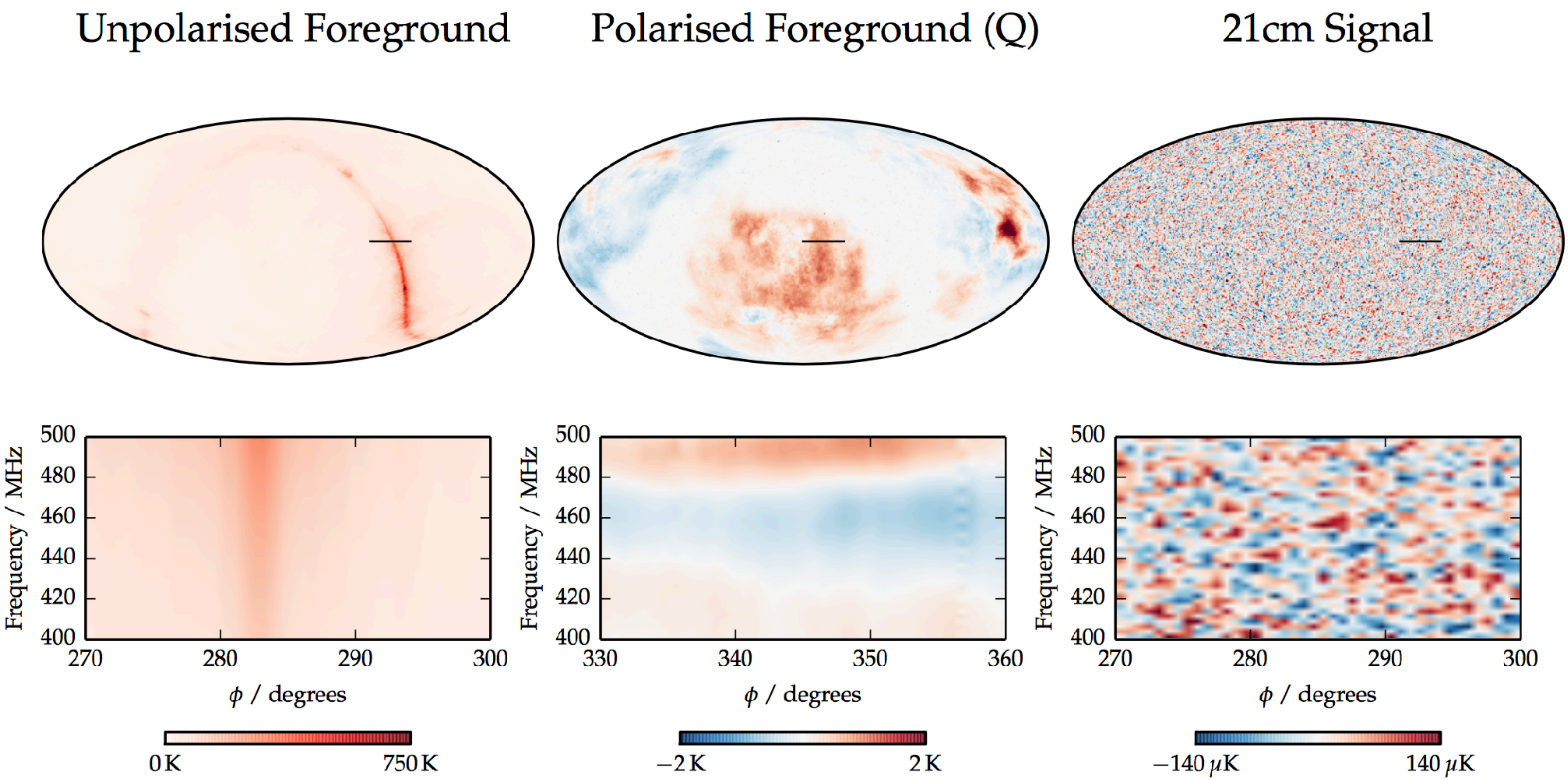


Noise-to-signal at large scales
$k \approx 0.01\ \mathrm{Mpc}^{-1}$

HI intensity mapping

UNIVERSITÀ DEGLI STUDI DI TORINO
ALMA UNIVERSITAS TAURINENSIS

[Credits: R. Shaw]



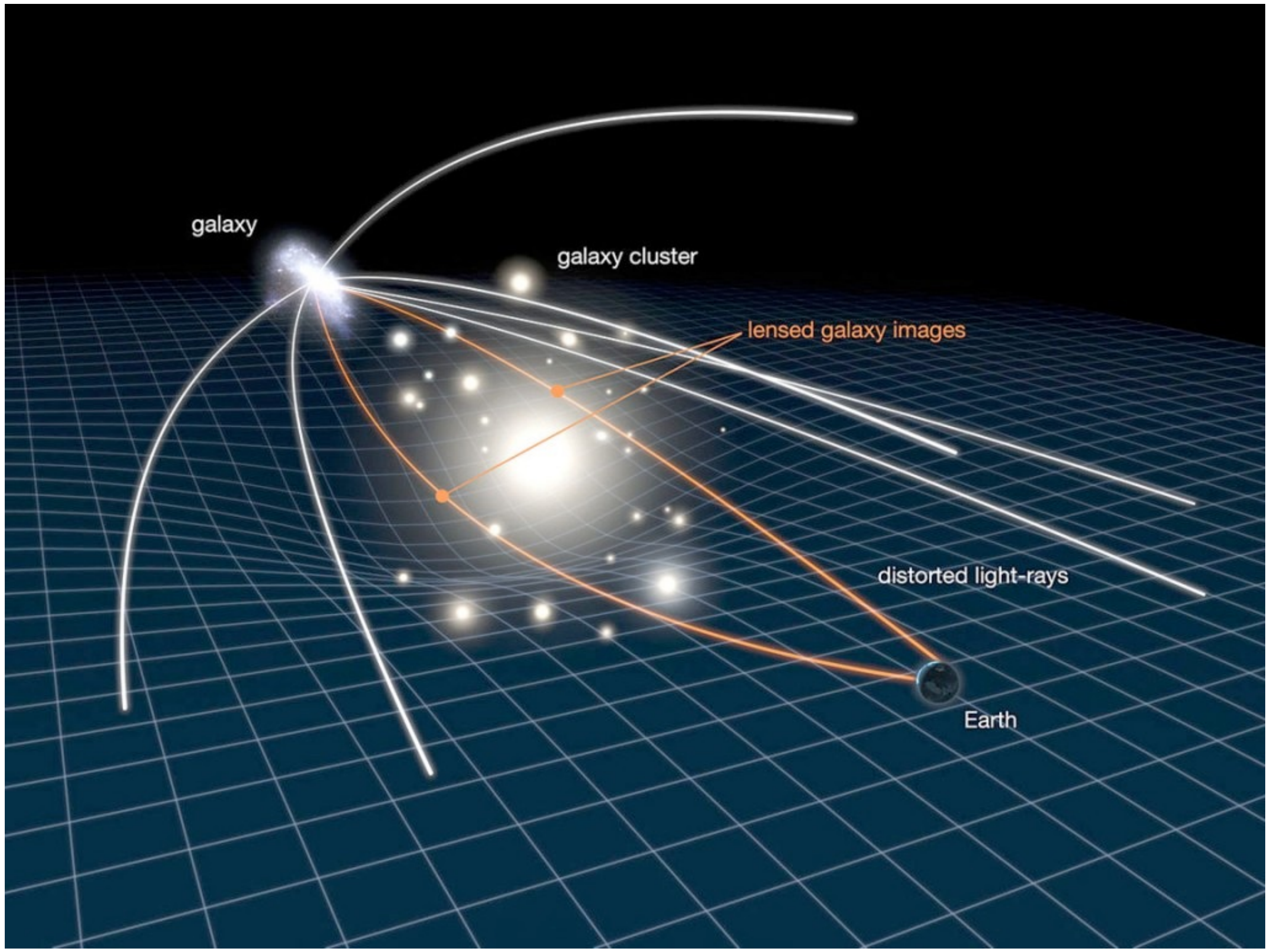
[see also works by C. Dickinson; M. Santos; L. Wolz; F. Villaescusa-Navarro; D. Alonso]

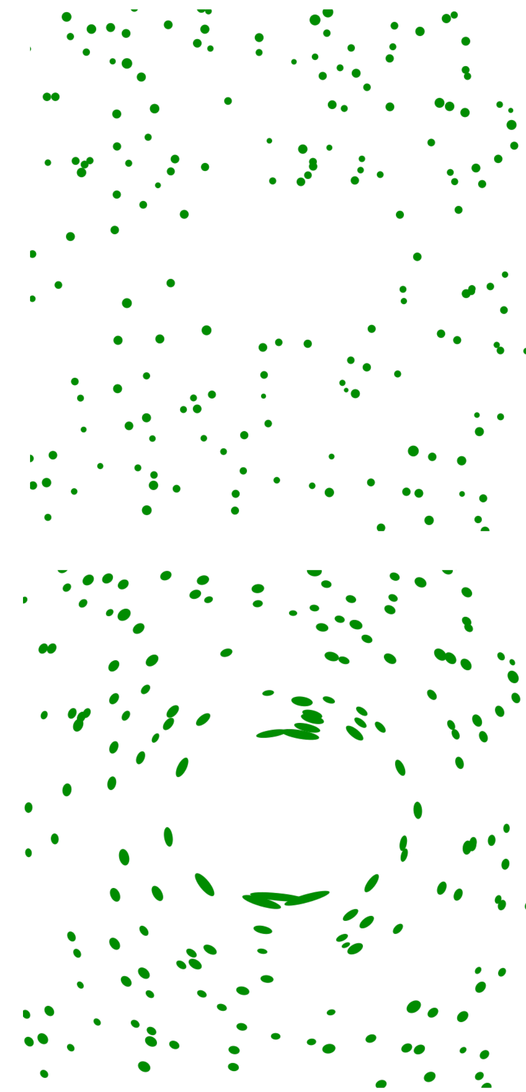
Radio weak lensing

UNIVERSITÀ DEGLI STUDI DI TORINO
ALMA UNIVERSITAS TAURINENSIS

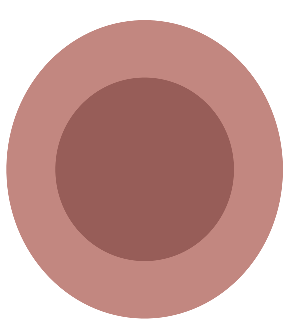
- Origin: weak lensing shearing of galaxy images' ellipticities
- Pros: complementary to clustering, not biased
- Cons: difficult to measure, needs (?) imaging
- Examples:
  - VLA FIRST (~90 sources per sq. deg. vs to ~10 per sq. arcmin. in opt.)
    [Chang et al., Nature 2004]
  - VLA+MERLIN (also in cross-correlation w/ optical shear estimates)
    [Patel et al. 2010]

Cosmic shear

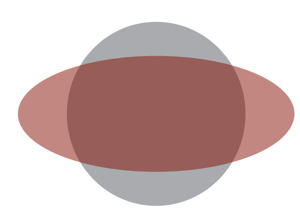




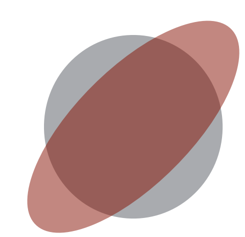
convergence



shear +



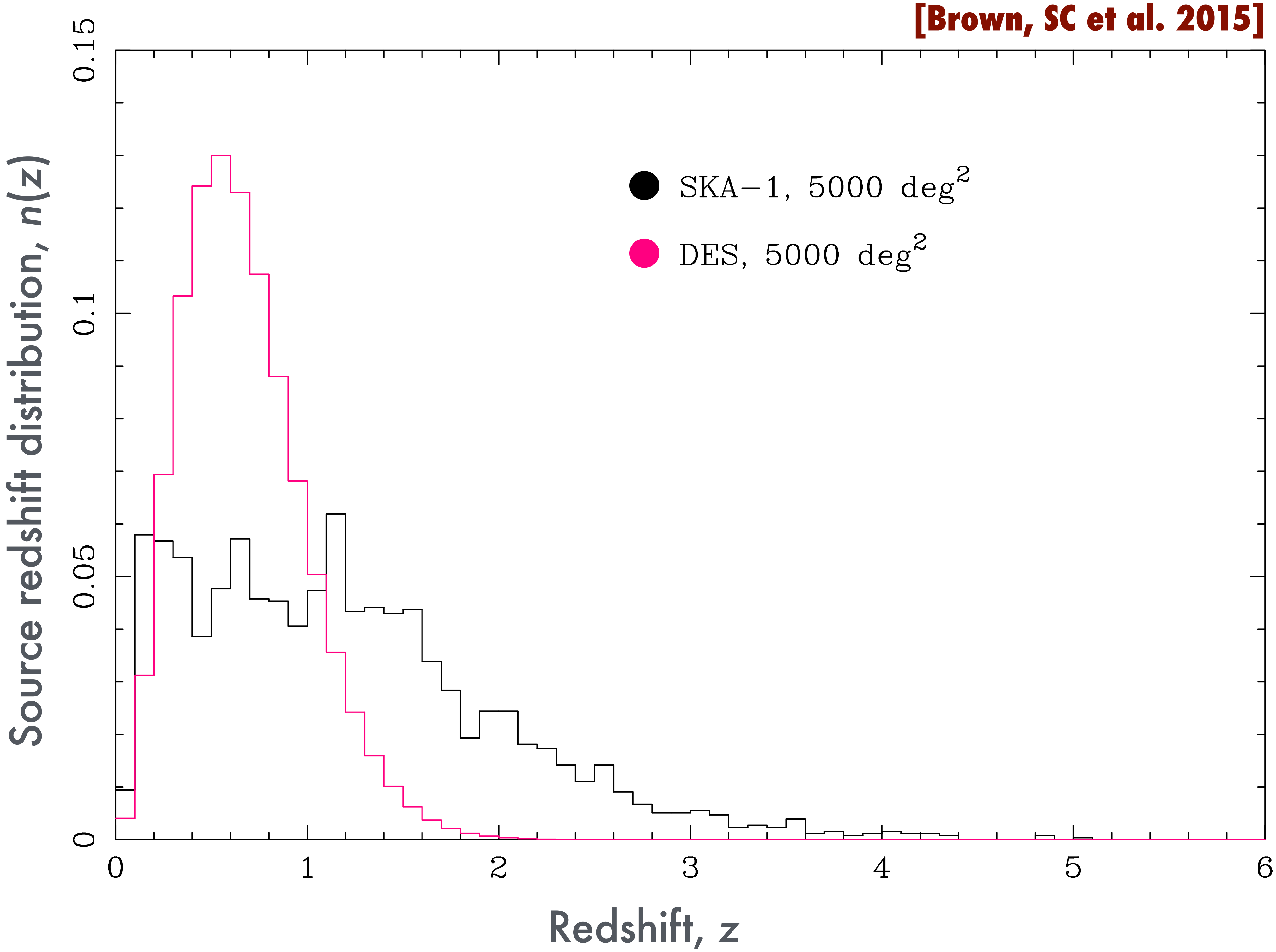
shear ×



Radio weak lensing

UNIVERSITÀ DEGLI STUDI DI TORINO
ALMA UNIVERSITAS TAURINENSIS

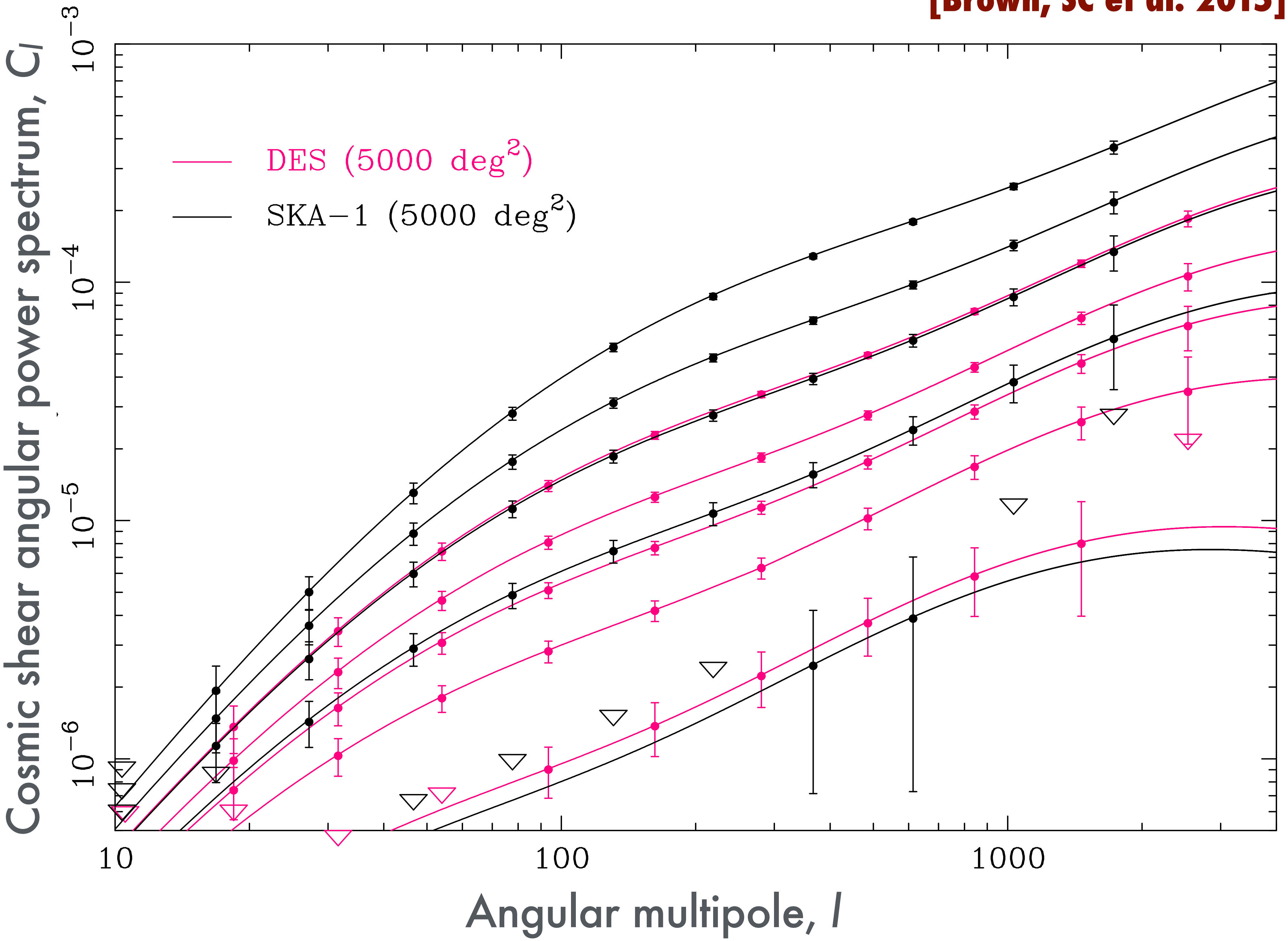
[Brown, SC et al. 2015]



Radio weak lensing

UNIVERSITÀ DEGLI STUDI DI TORINO
ALMA UNIVERSITAS TAURINENSIS

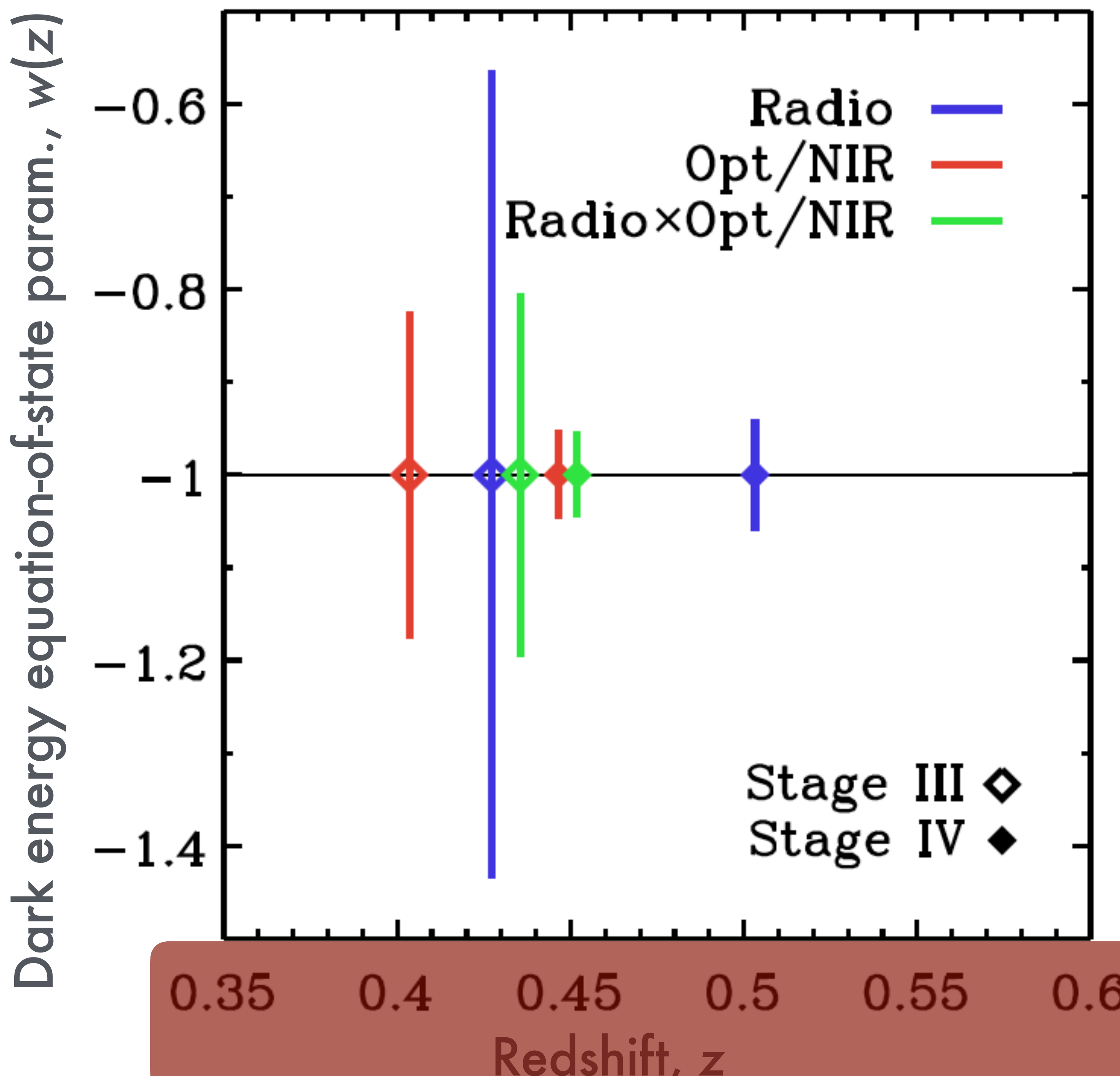
[Brown, SC et al. 2015]



Radio weak lensing

UNIVERSITÀ
DEGLI STUDI
DI TORINO
ALMA UNIVERSITAS
TAURINENSIS

[SC et al. 2017]



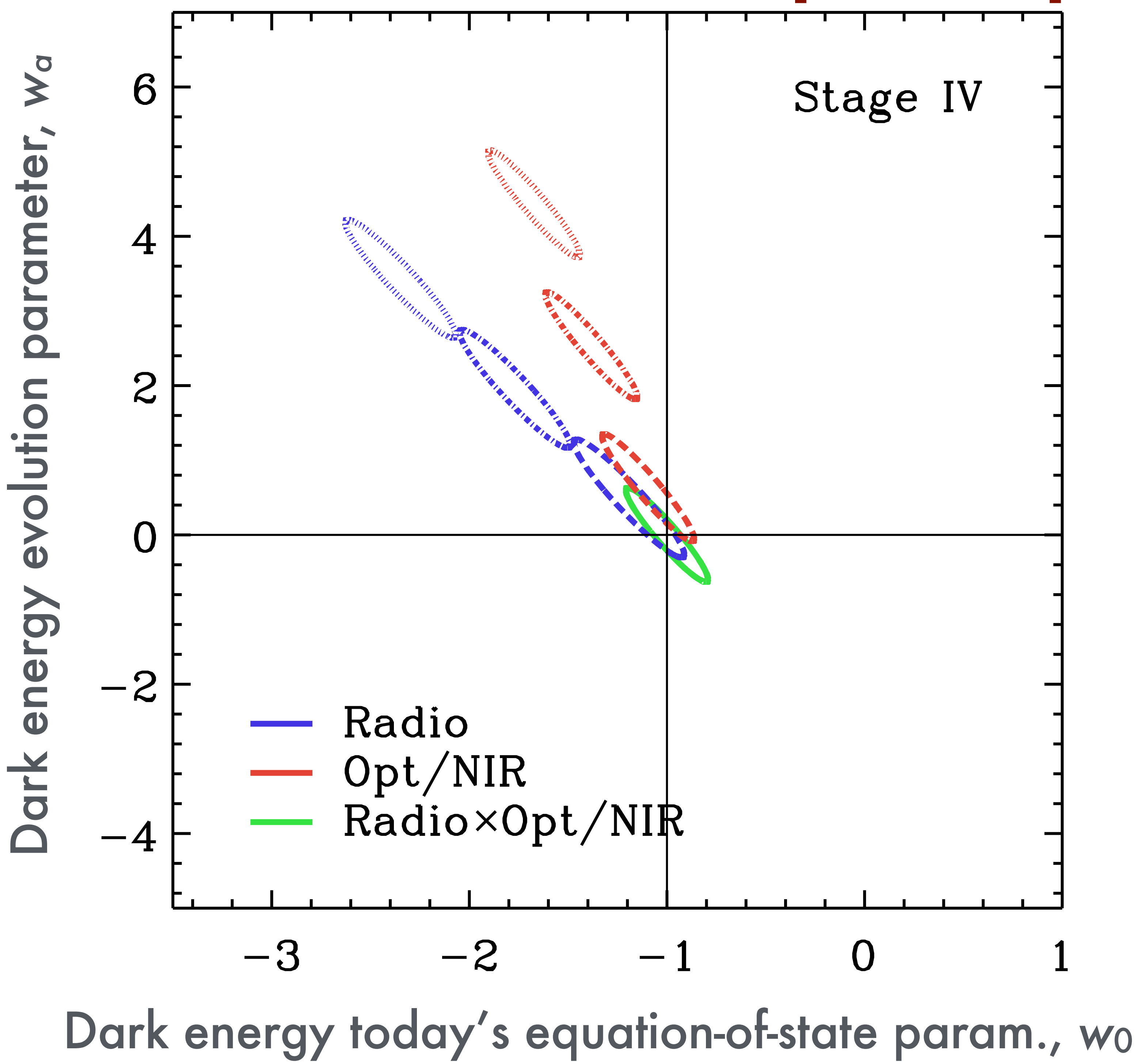
>1 billion years

Dark energy

Radio weak lensing

UNIVERSITÀ DEGLI STUDI DI TORINO
ALMA UNIVERSITAS TAURINENSIS

[SC et al. 2017]

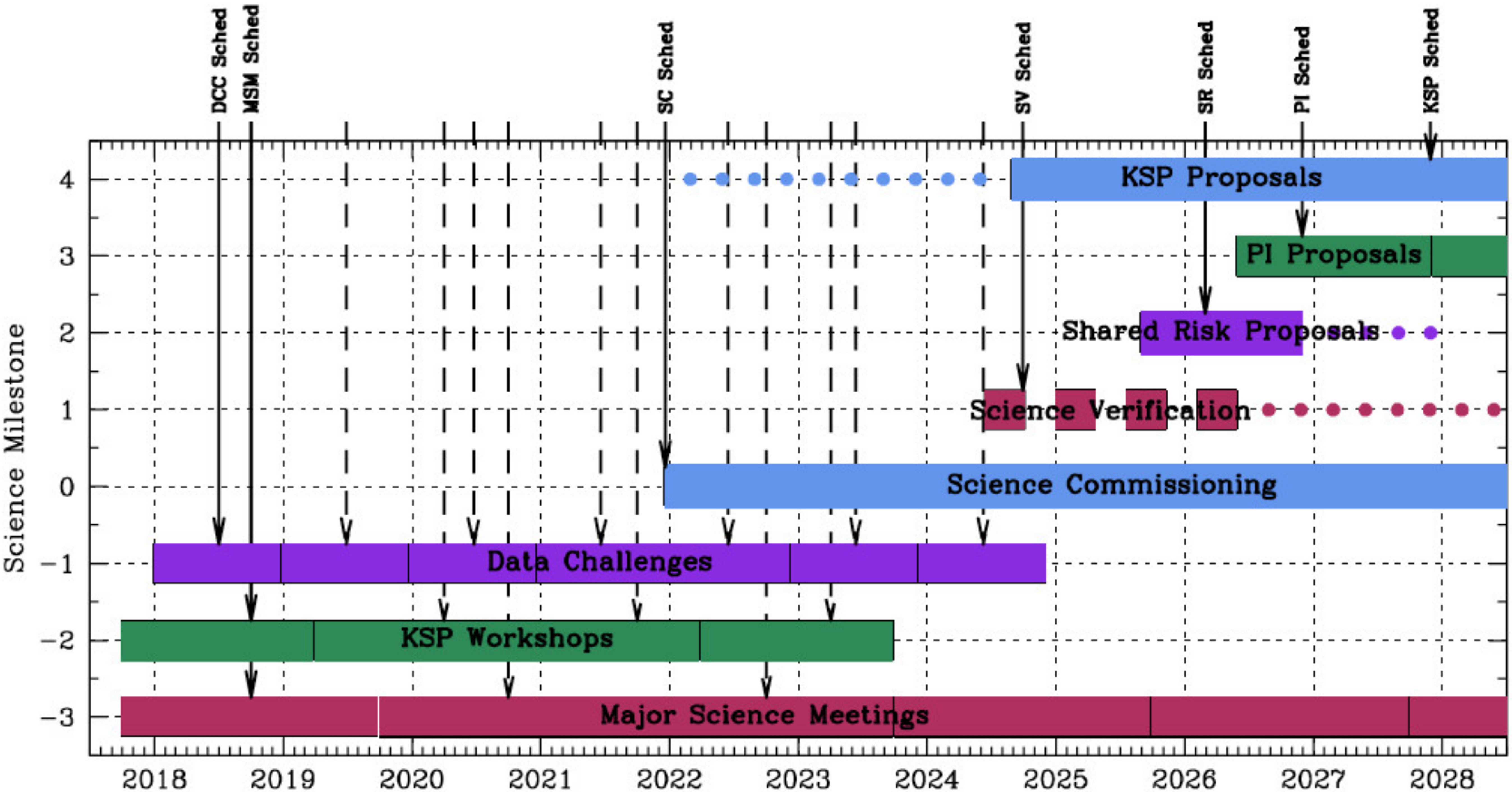


euclid

Dark energy

SKA timescale

UNIVERSITÀ
DEGLI STUDI
DI TORINO
ALMA UNIVERSITAS
TAURINENSIS



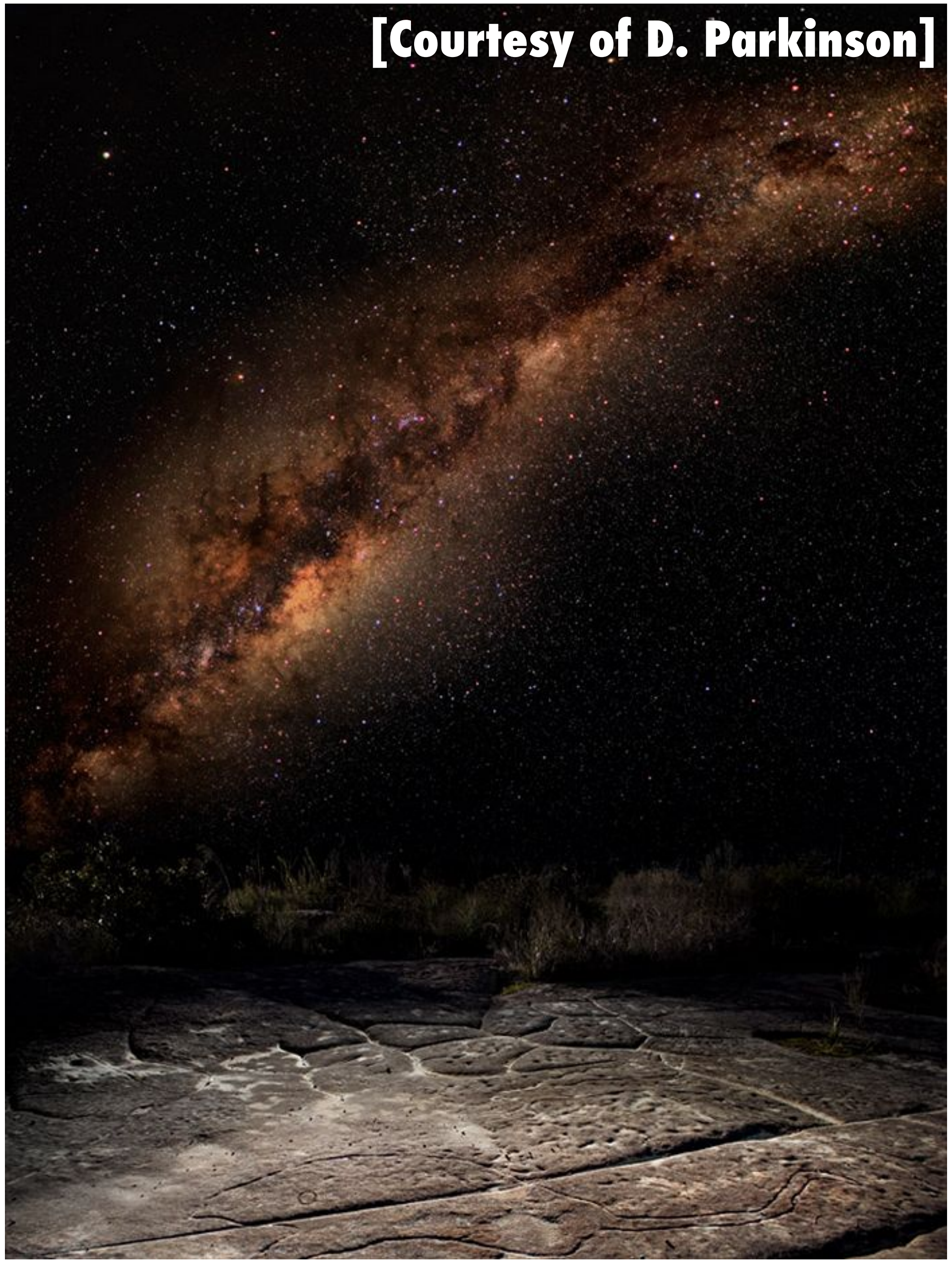
[Credits: R. Braun 2018]

SKA pathfinders

- Continuum galaxy surveys
  - Evolutionary Map of the Universe (EMU)
- HI intensity mapping
  - MeerKAT Large Area Synoptic Survey (MeerKLASS)
- Radio weak lensing
  - Super CLuster Assisted Shear Survey (SuperCLASS)

EMU

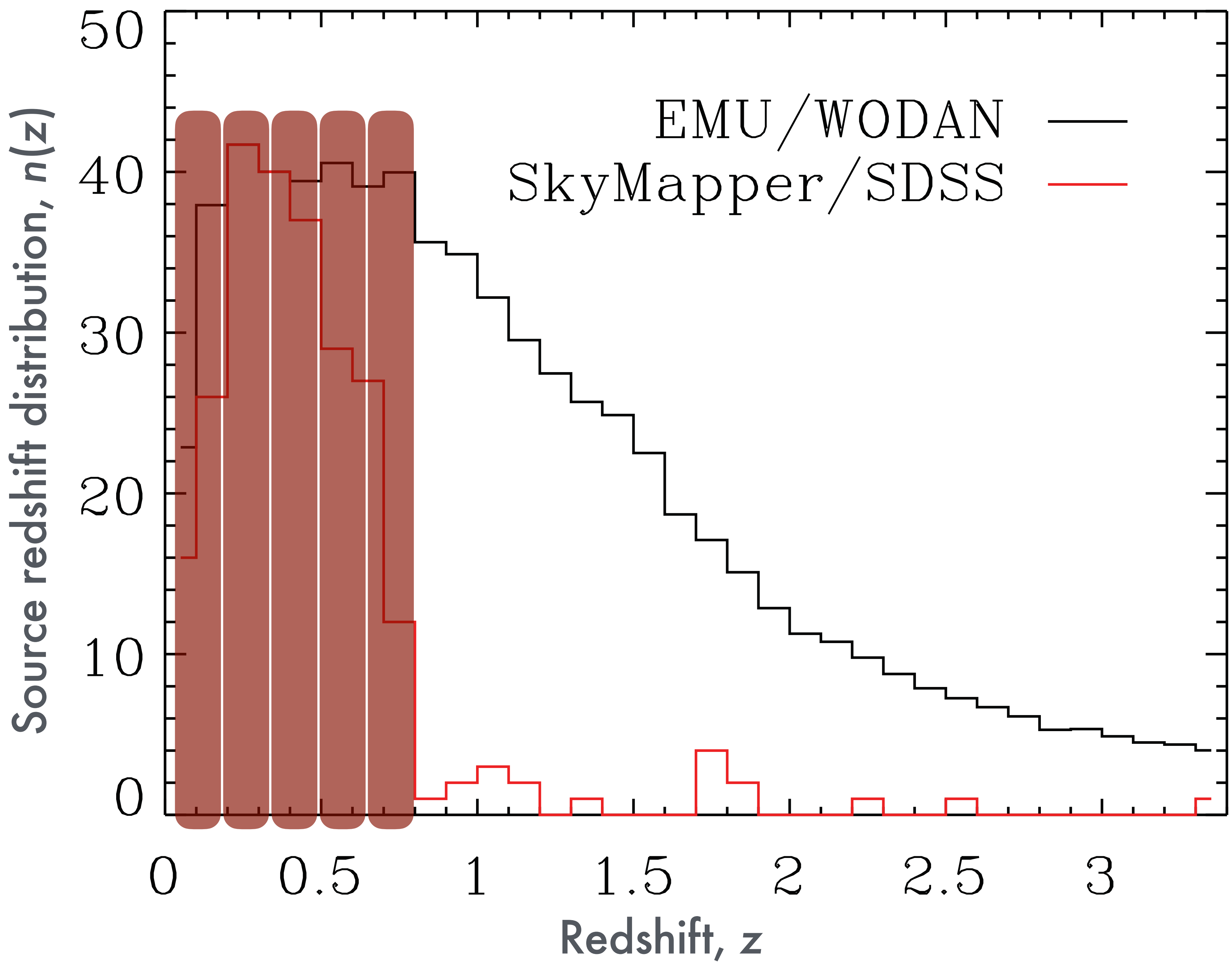
- The Evolutionary Map of the Universe (EMU)
  - All-sky radio survey w/ ASKAP
  - 1100-1400 MHz in radio continuum
  - 40x deeper than NVSS (10 μJy rms)
  - 5x ang. resolution of NVSS (10 arcsec)
  - ~70 million galaxies
  - Images, catalogues, cross-IDs: public!
  - Survey starts end-2019
    - Early science observations taken with ASKAP-12 in 2018
  - Total integration time: ~1.5 years



EMU

UNIVERSITÀ DEGLI STUDI DI TORINO
ALMA UNIVERSITAS TAURINENSIS

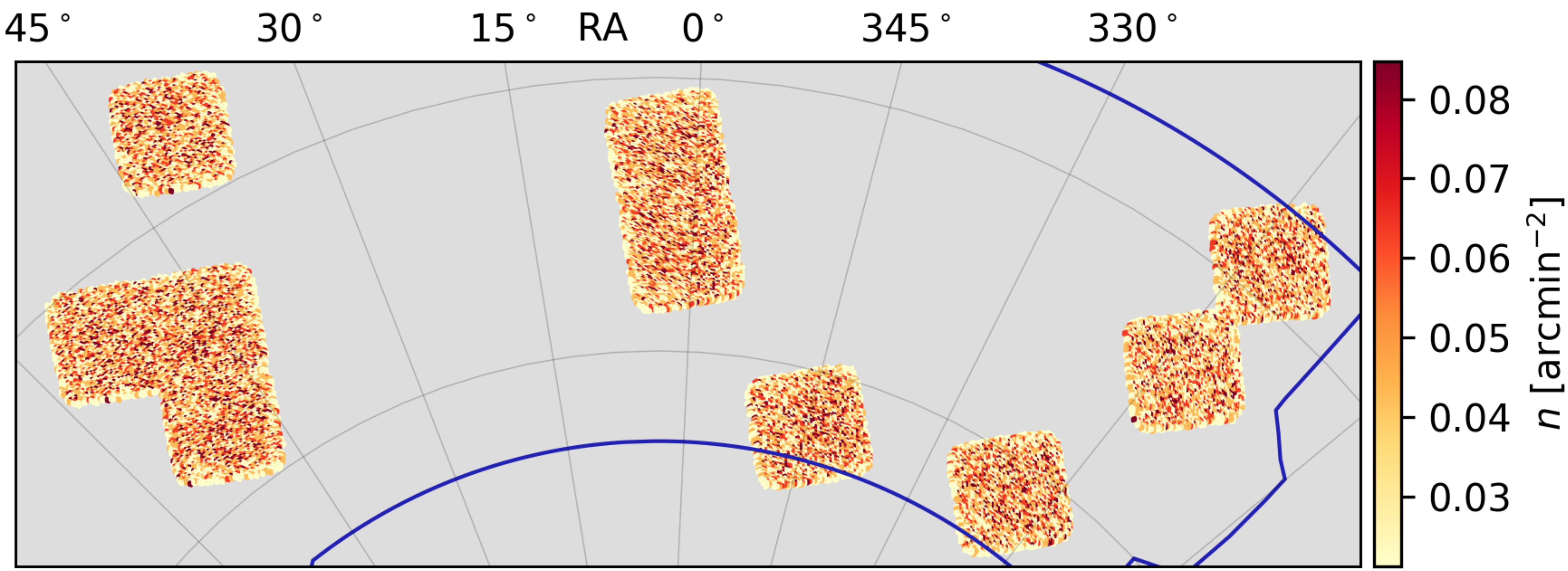
[SC et al. 2012]



EMU

- Constraining power on dark energy (FoM):
  [EMU+SNeIa+CMB] **[SC et al. 2012]**
  - EMU sources (no redshift): <100
  - EMU cross-ID sources (opt. redshift): ~300
  - EMU cross-IDs + high-redshift tail: >500

EMU



[Sevilla-Noarbe et al., in prep.]

MeerKLASS

UNIVERSITÀ DEGLI STUDI DI TORINO
ALMA UNIVERSITAS TAURINENSIS

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

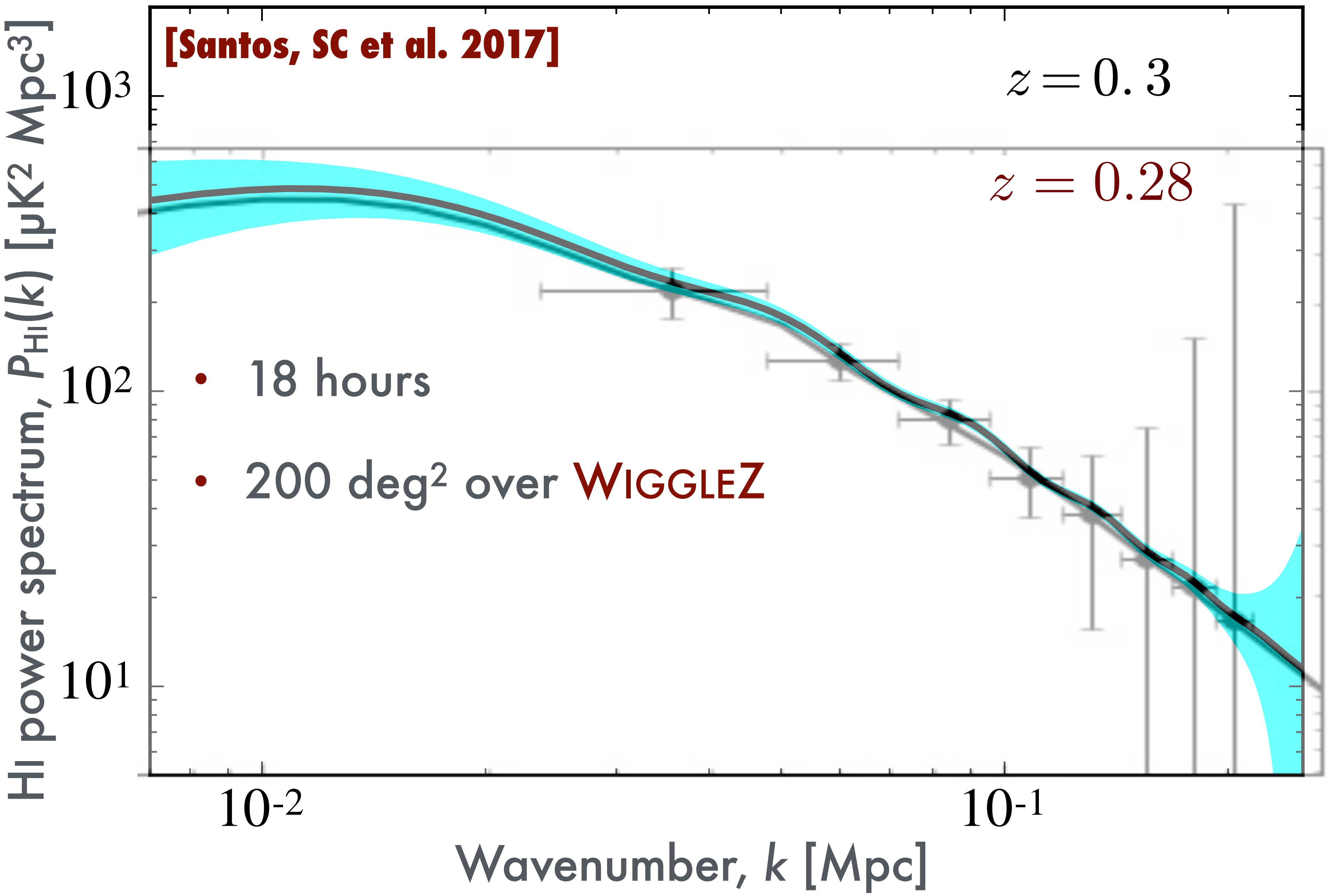
PoS PROCEEDINGS OF SCIENCE

A large sky survey with MeerKAT

Mário G. Santos*[a,b] Philip Bull,[c,d] Stefano Camera,[e] Song Chen,[a] José Fonseca,[a] Ian Heywood,[f] Matt Hilton,[g] Matt Jarvis,[a,f] Gyula I. G. Józsa[b,h,i], Kenda Knowles,[g] Lerothodi Leeuw,[j] Roy Maartens,[a,k] Eliab Malefahlo,[a] Kim McAlpine,[a] Kavilan Moodley,[g] Prina Patel,[a,b] Alkistis Pourtsidou,[k] Matthew Prescott,[a] Kristine Spekkens,[l] Russ Taylor,[a,m] Amadeus Witzemann[a] and Imogen Whittam[a]

MeerKLASS

- Detection of Baryon Acoustic Oscillations using HI



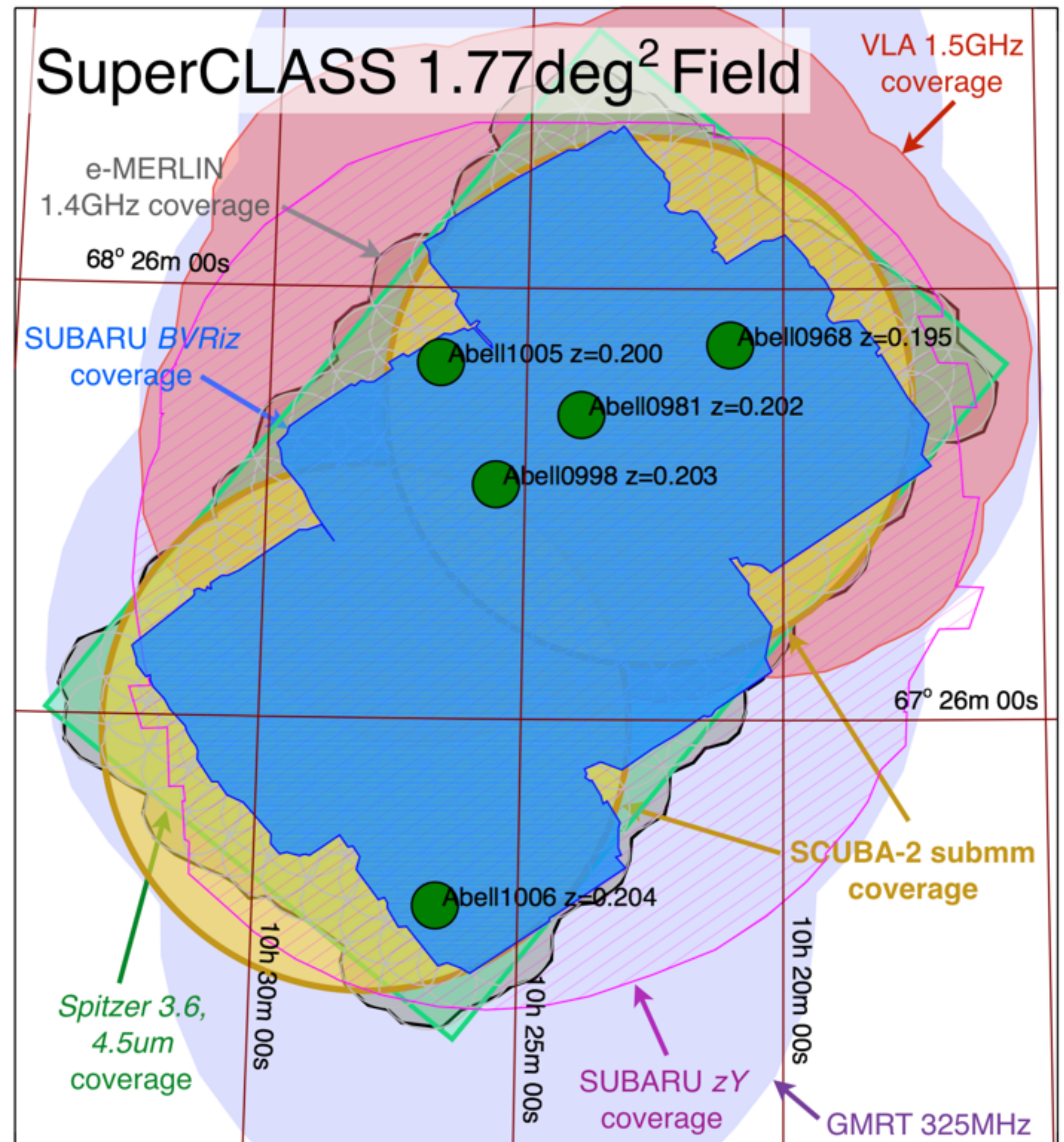
- 18 hours
- 200 deg² over WiggleZ

SuperCLASS

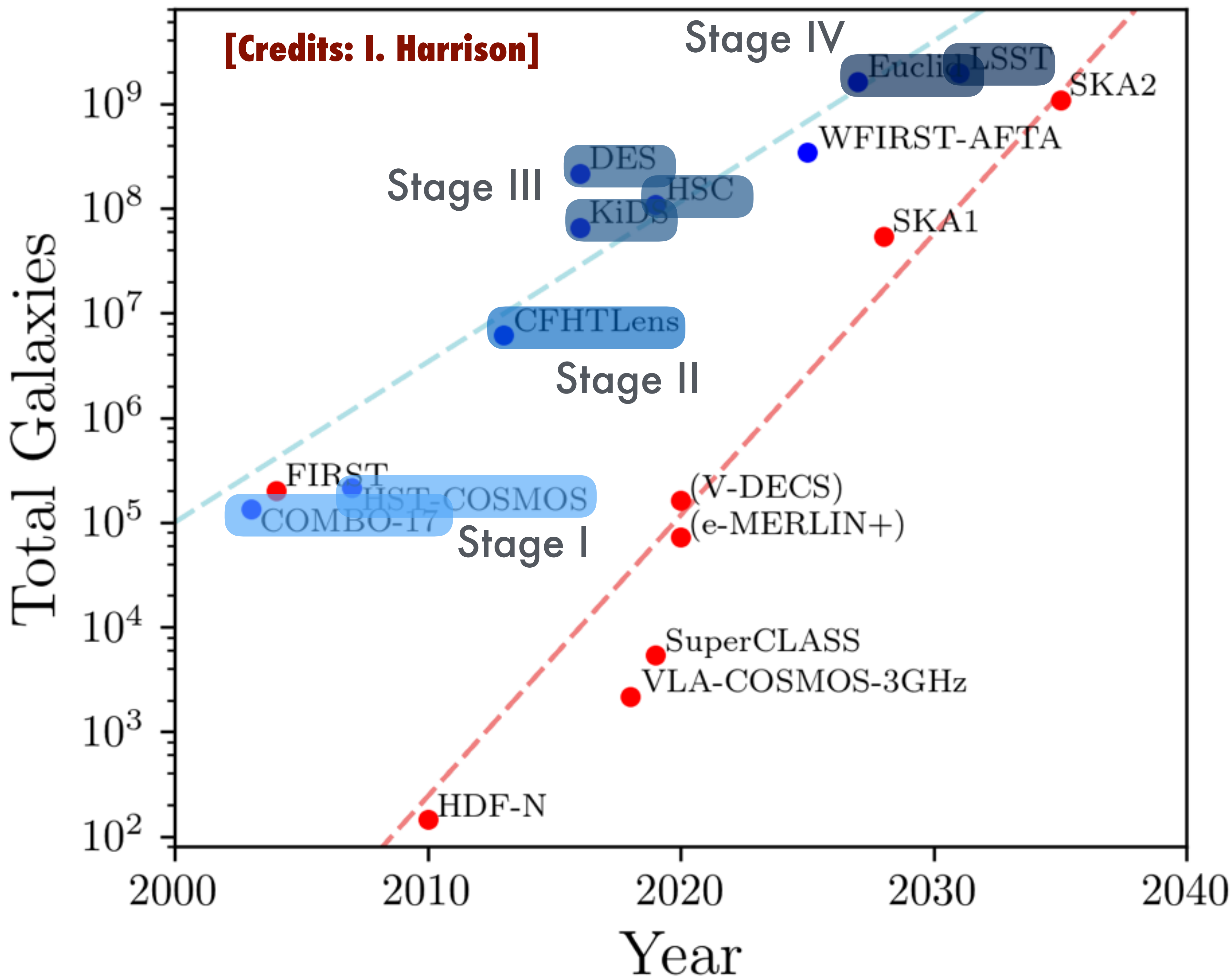
- The Super CLuster Assisted Shear Survey (SuperCLASS)

[Credits: C. Casey]

- Aiming for the first solid detection of cosmic shear in the radio band
- ~1 gal. arcmin^{-2} (detected, resolved, and at high redshift)
- ~1.77 deg^2
- Multi-wavelength



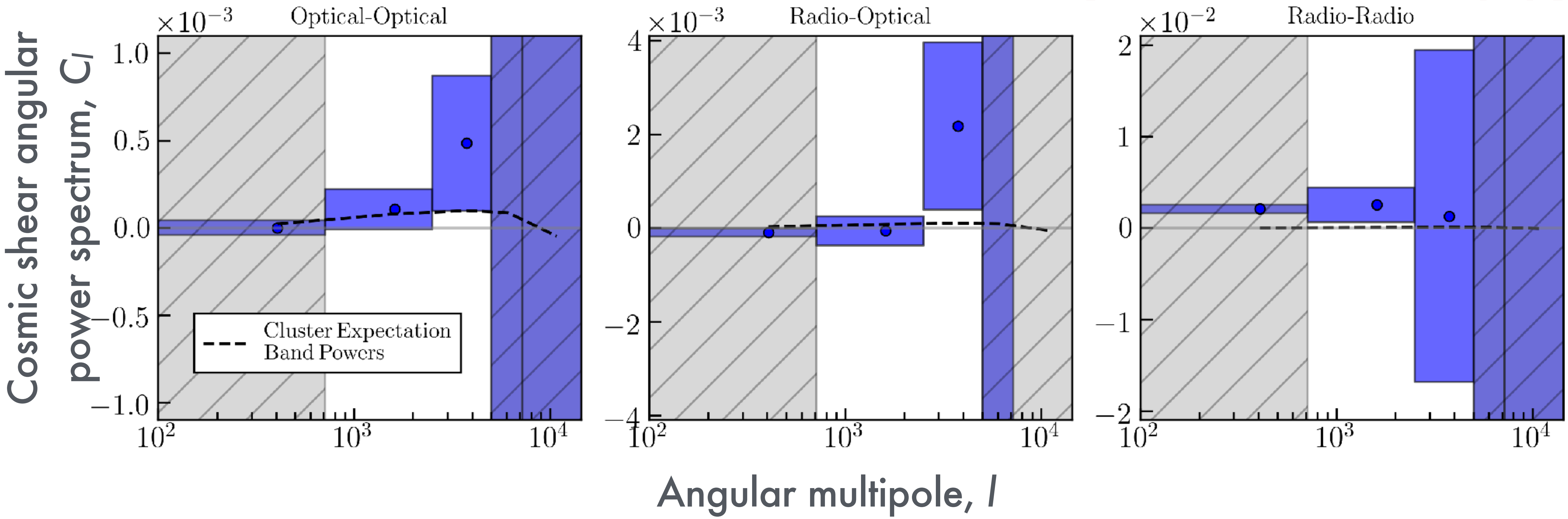
SuperCLASS



[Credits: I. Harrison]
Stage IV
Euclid
LSST
SKA2
WFIRST-AFTA
Stage III
DES
HSC
KiDS
SKA1
CFHTLens
Stage II
FIRST
HST-COSMOS
COMBO-17
Stage I
(V-DECS)
(e-MERLIN+)
SuperCLASS
VLA-COSMOS-3GHz
HDF-N
Total Galaxies
10^9
10^8
10^7
10^6
10^5
10^4
10^3
10^2
2000
2010
2020
2030
2040
Year

SuperCLASS

[Harrison, SC et al. 2019, in prep.]

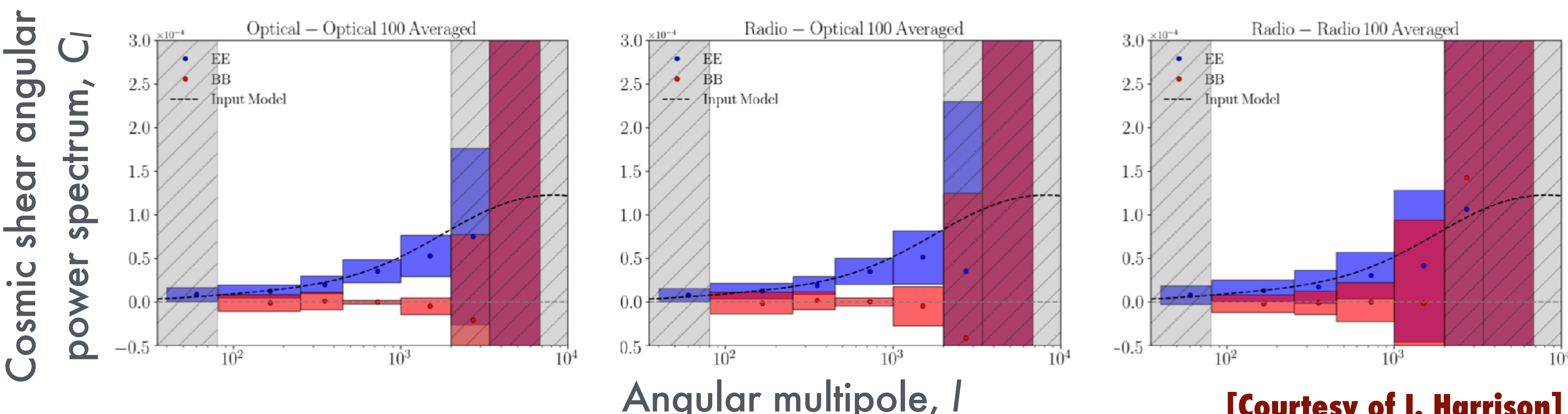


SuperCLASS

- The VLA Deep Extragalactic Cosmology Survey (V-DECS)

  - ~3 gal. arcmin^{-2} (detected, resolved, and at high redshift)

  - ~10 deg^2



[Courtesy of I. Harrison]

Radio cosmology

- Radio cosmology era is nigh!
  - Great time for cosmological synergies at various wavelengths
- Cross-correlations crucial for:
- Cross-checking validity of cosmological results
- Accessing signal buried in noise or cosmic variance
  [e.g. particle dark matter, multi-tracing for non-Gaussianity]
- Removing/alleviating contamination from systematic effects
  [e.g. radio-optical cosmic shear]