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Slides available at http://bit.ly/ianh_tosca24

The Pathway to Radio Weak Lensing

Ian Harrison

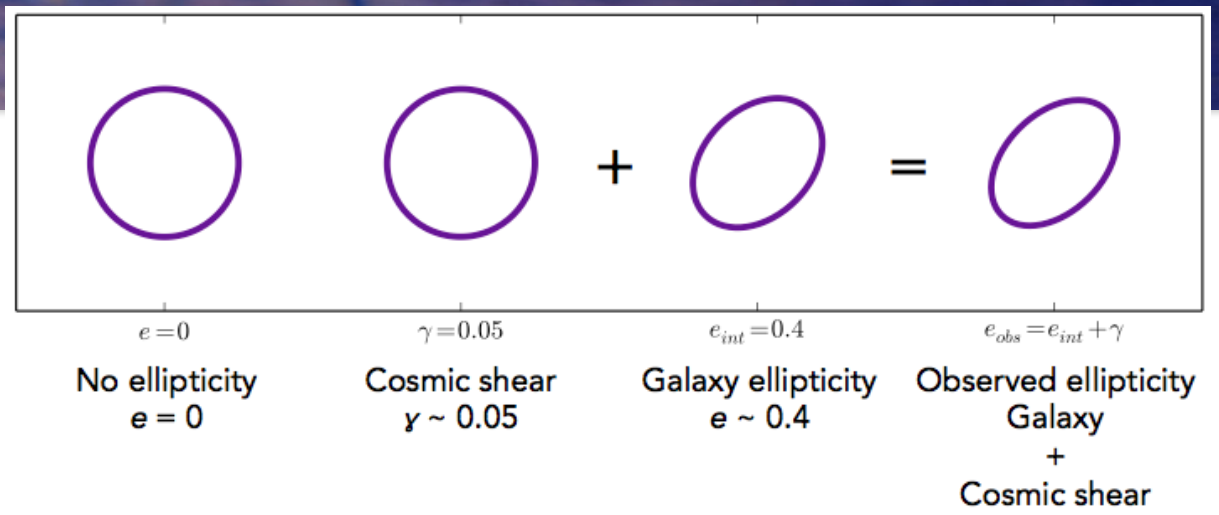
TOSCA Meeting

7 November 2024

Slides at:
bit.ly/ianh_tosca24

Introduction
Weak Lensing Cosmology

- Requires:
  - Exquisite systematics control
  - 1+ galaxies per arcmin^2 over 000s deg^2
- Therefore optical / near-IR experiments



$$e_{\mathrm{obs}} = e_{\mathrm{intrinsic}} + \gamma$$
$$\langle e_{\mathrm{obs}} \rangle = \hat{\gamma}$$

HSC KiDS euclid consortium LSST DESC Dark Energy Science Collaboration THE DARK ENERGY SURVEY

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Radio Weak Lensing

Motivation from SKA(0)

- Number density of resolved galaxies in current radio surveys too low
- SKA will do surveys capable of WL cosmology
  - 3-10 galaxies arcmin^{-2} over 5k-30k deg^2

Surveys close to these will be done with SKA anyway, although there are optimisations for weak lensing

Radio Weak Lensing
Motivation from SKA(O)

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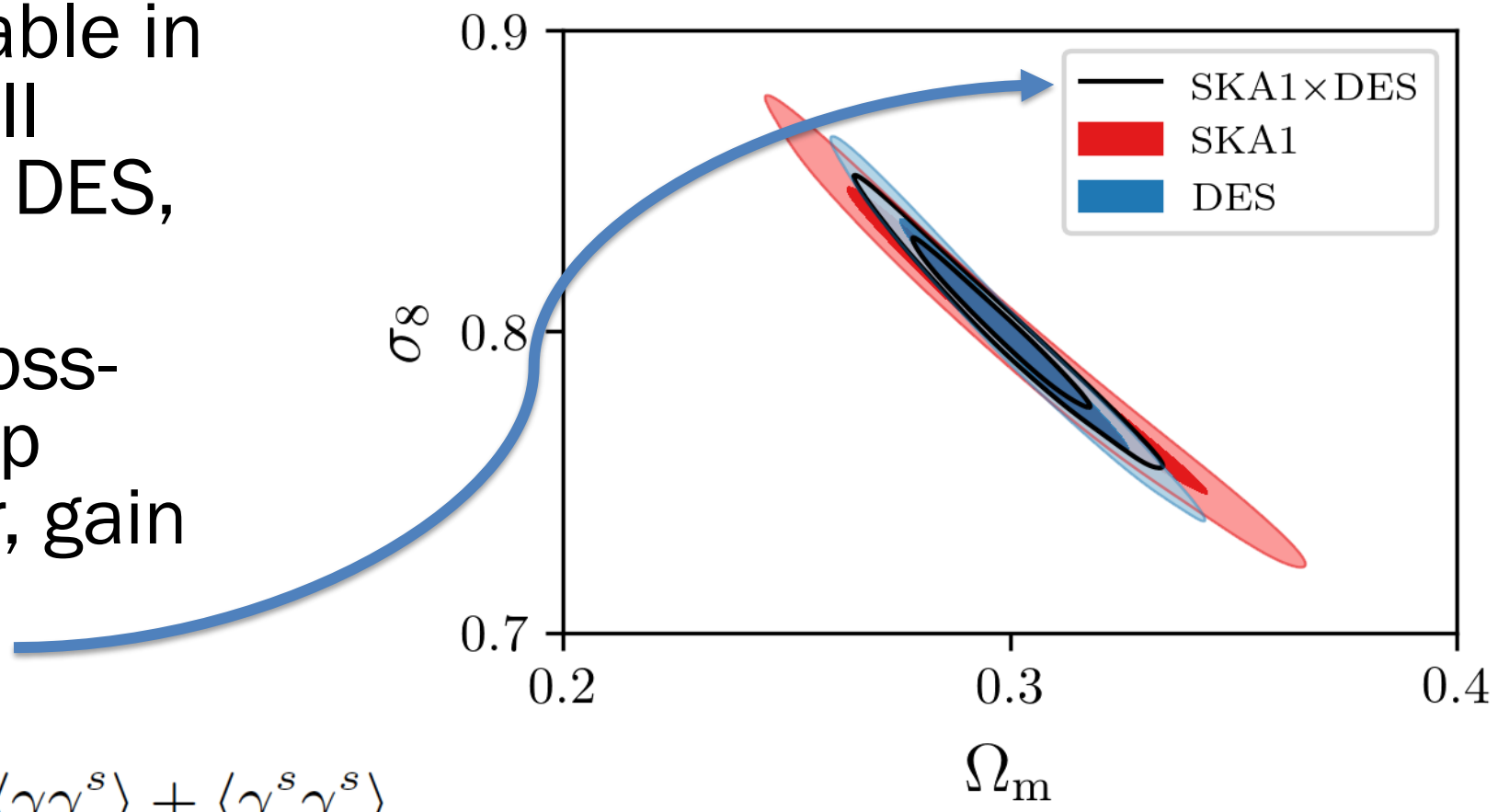
- Weak lensing will use SKA-MID
- 350-1760 MHz frequencies
- ‘Resolution’ of ~0.1 arcsec
- SKA Phase 1
  - Cost cap € 600m
  - First idea ~1990, design solidified 2017
  - Collaboration of 14 countries
  - Construction has begun!
    ~2030 large surveys
  - 194 15m dishes
- 🦄 The full SKA🦄
  - ~2035+
  - ~2000 dishes
  - Longer baselines across Africa

Full cosmology science case:
SKA Cosmology Science Working Group + IH (2020)

Radio Weak Lensing

SKAO Cosmology Forecasts

- SKA Phase I weak lensing comparable in power to Stage III surveys such as DES, KiDS, HSC
- Radio-optical cross-correlations keep statistical power, gain robustness to systematics

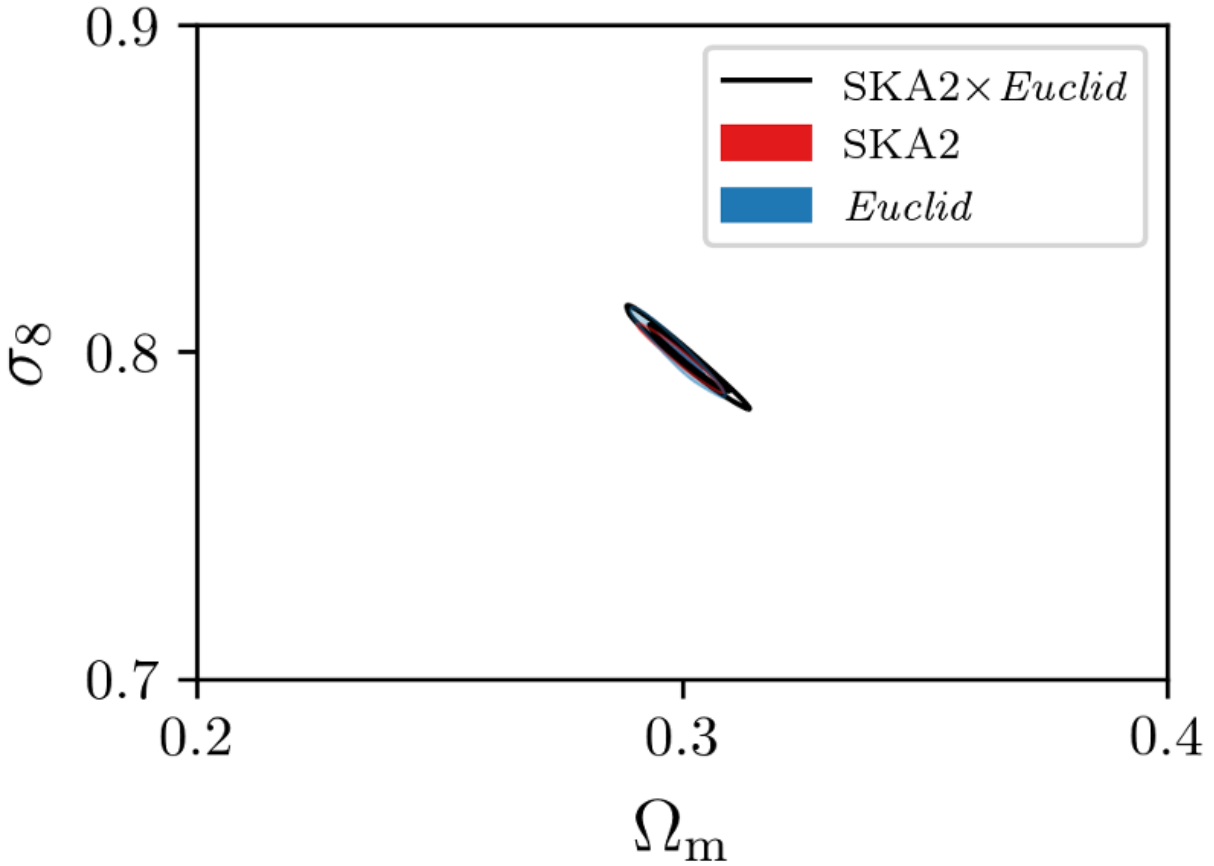


$$\langle \tilde{\gamma}_o \tilde{\gamma}_r \rangle = \langle \gamma\gamma \rangle + \langle \gamma\gamma_o^s \rangle + \langle \gamma\gamma_r^s \rangle + \langle \gamma_o^s \gamma_r^s \rangle$$

IH et al (2016)
SKA Cosmology Science Working Group + IH (2020)

Radio Weak Lensing
SKAO Cosmology Forecasts

- Full SKA (SKA2) comparable in power to Stage IV surveys such as *Euclid*, LSST



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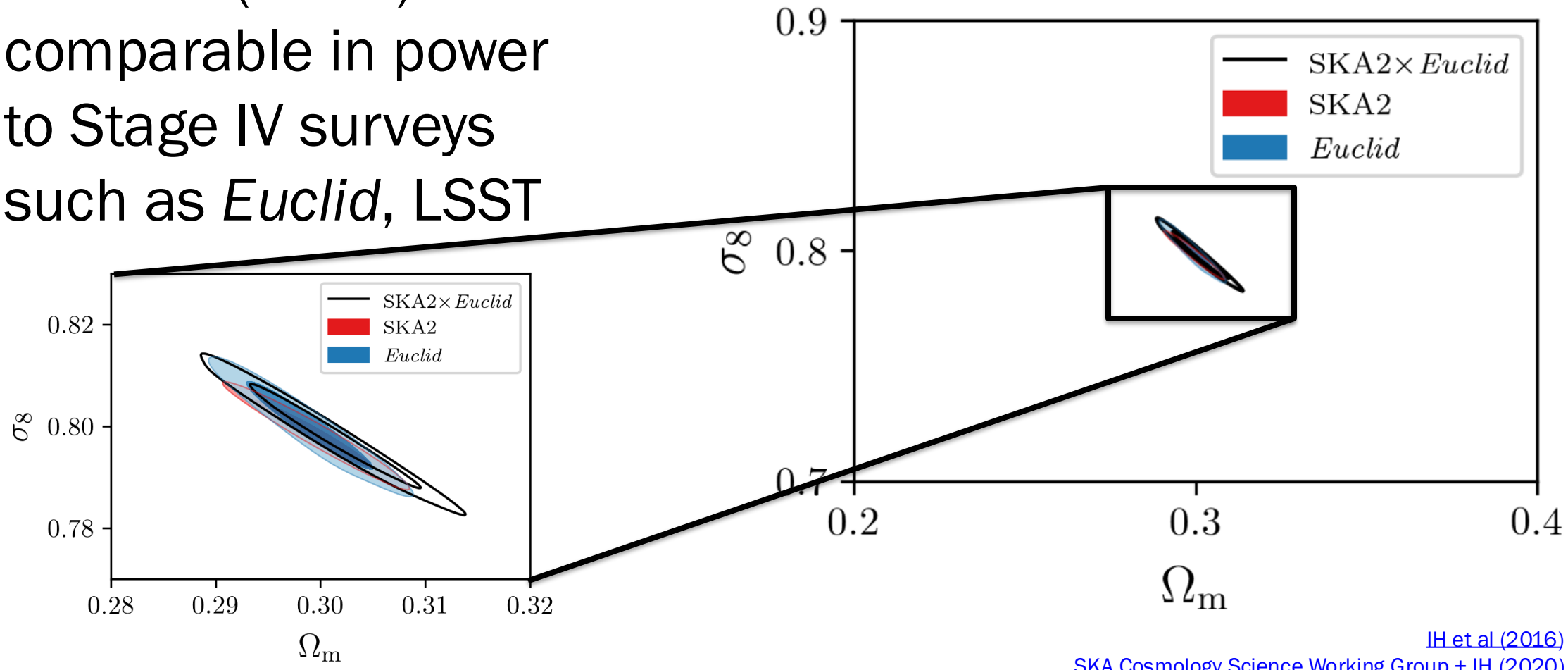
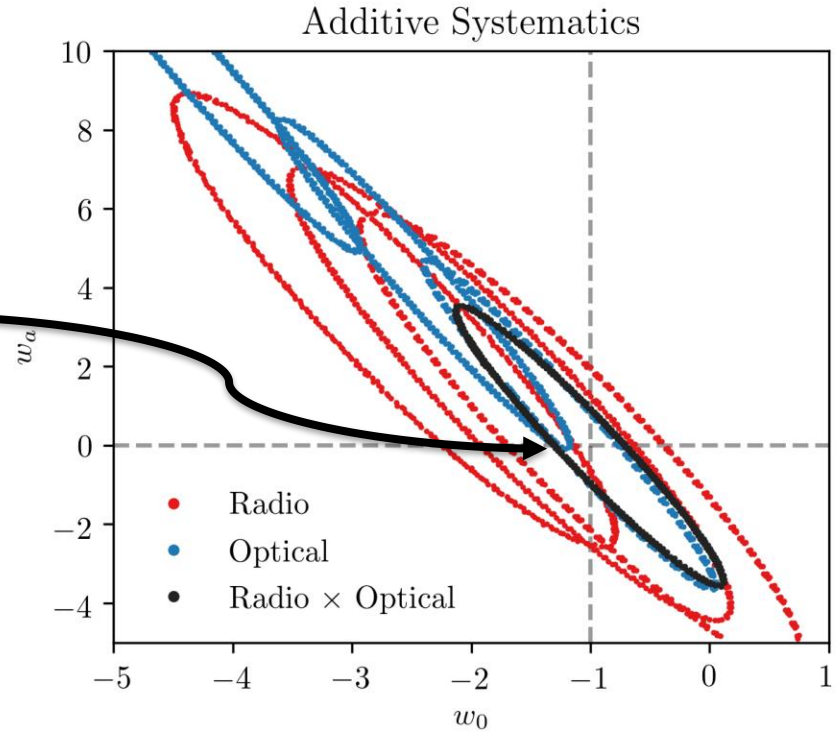


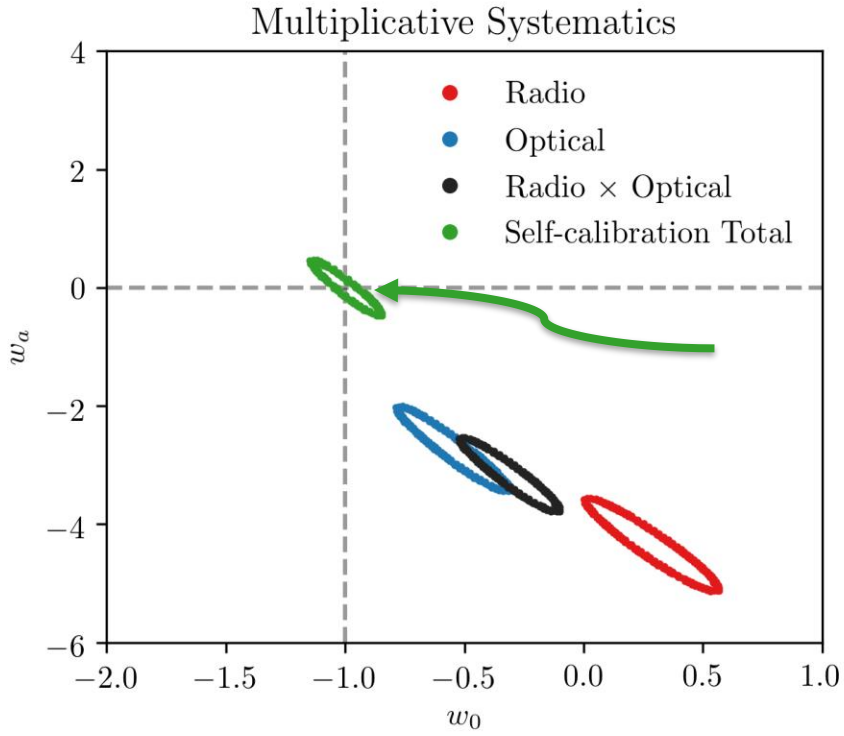
IH et al (2016)
SKA Cosmology Science Working Group + IH (2020)

Radio Weak Lensing
SKAO Cosmology Forecasts

- Radio-optical cross-correlations keep statistical power, gain robustness to systematics

Cross-correlation remains at input cosmology





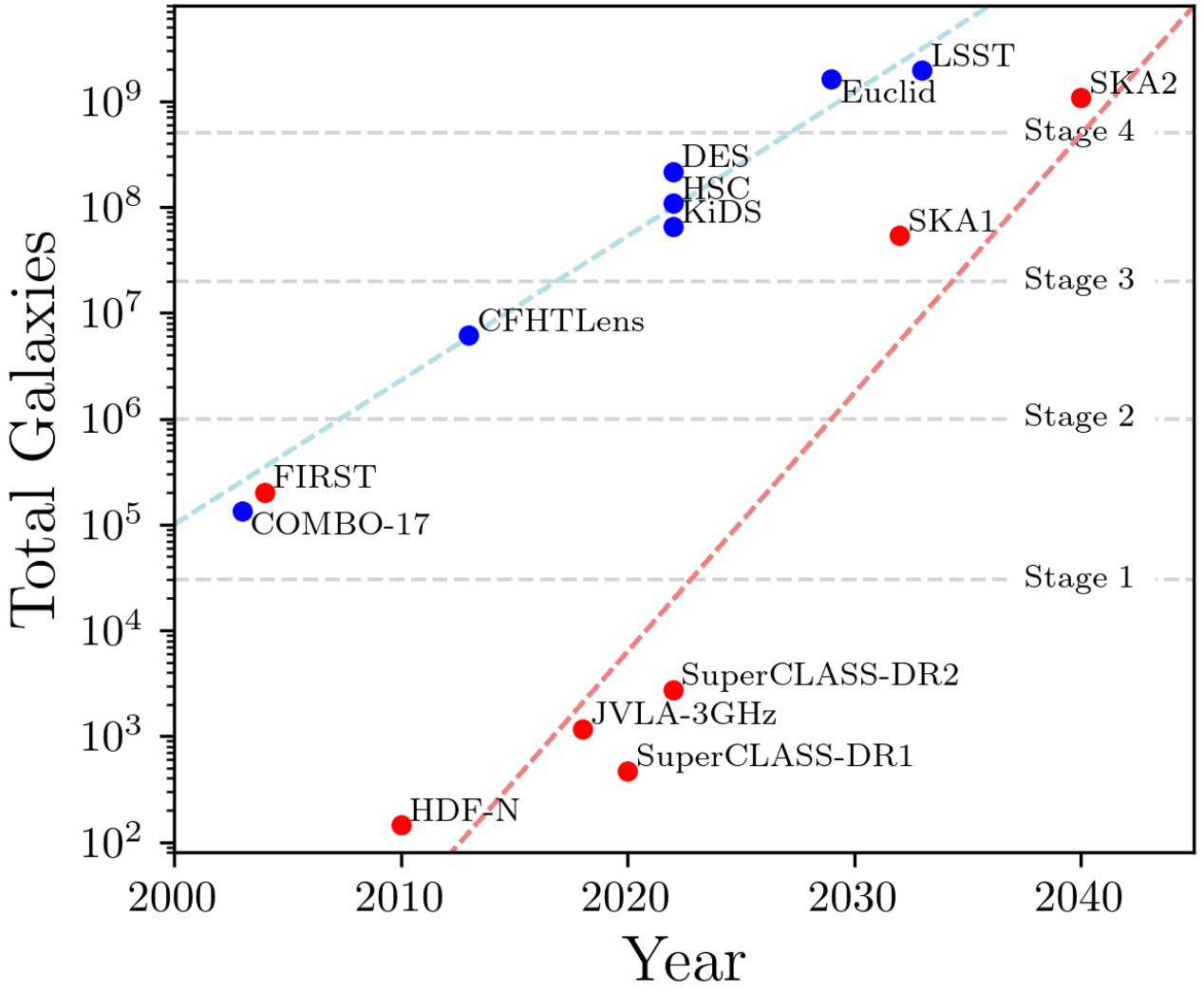
Radio-radio + optical-optical + radio-optical allows for self-calibration

Camera + IH et al (2017)
SKA Cosmology Science Working Group + IH (2020)

Radio Weak Lensing
A Brief History

- Big leap from tentative detections to Stage 4 ‘precision cosmology’ surveys

- Pre 2010, design a bespoke Stage 1 ‘discovery’ survey: SuperCLASS



Radio Weak Lensing
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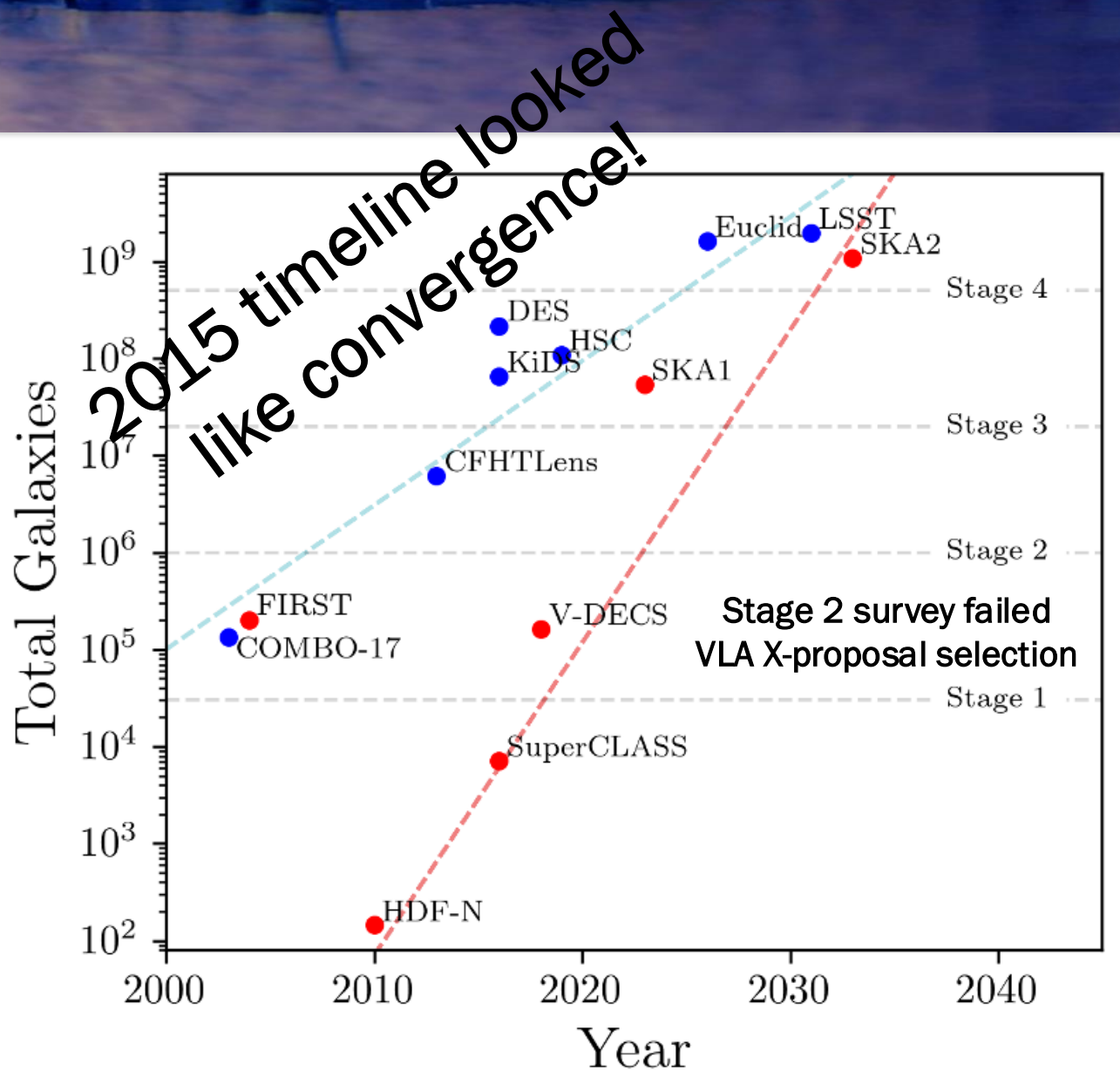
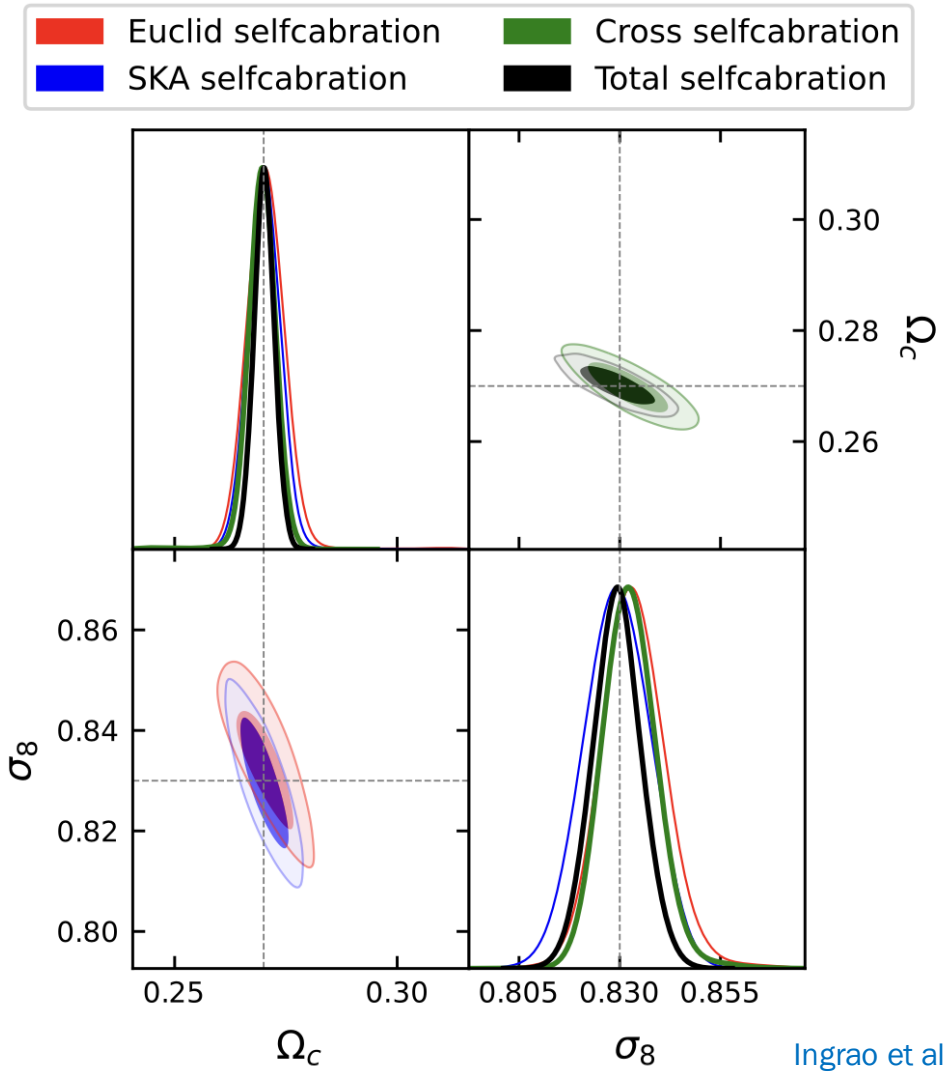


New – Forecast updates

- Re-done 2016 forecasts with SKA1(AA4) x *Euclid*
- Cross-correlations calibrate additive *and* multiplicative systematics
  - Show explicitly with MCMC chains (previously by construction with Fishers)



Ingrao et al (in prep.)

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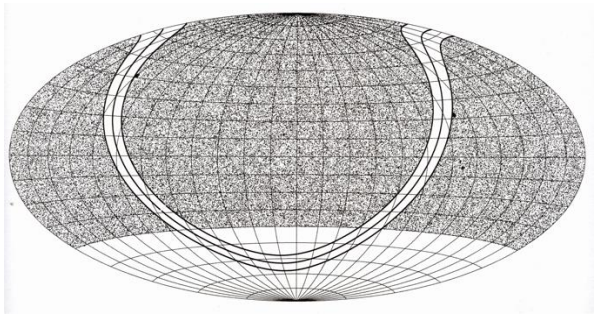
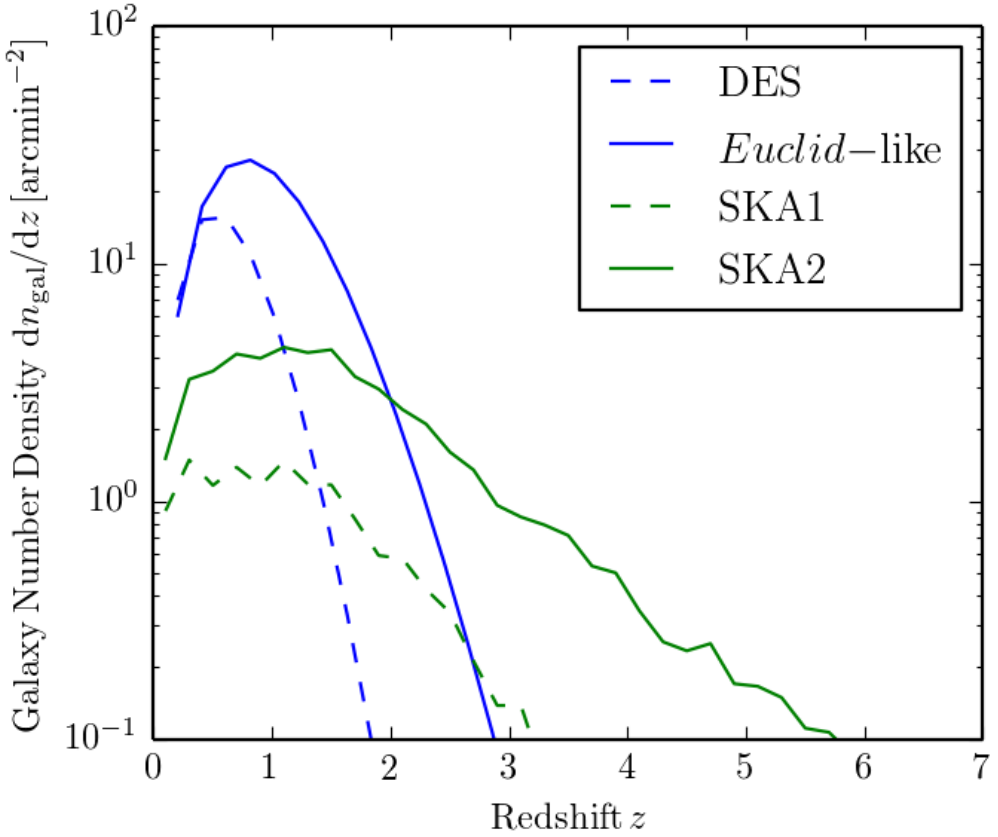
Radio Weak Lensing

PROMISES

Radio Weak Lensing Promises

- Highly deterministic PSF
- Long tail in source redshift distribution
- Large sky areas accessible from the ground



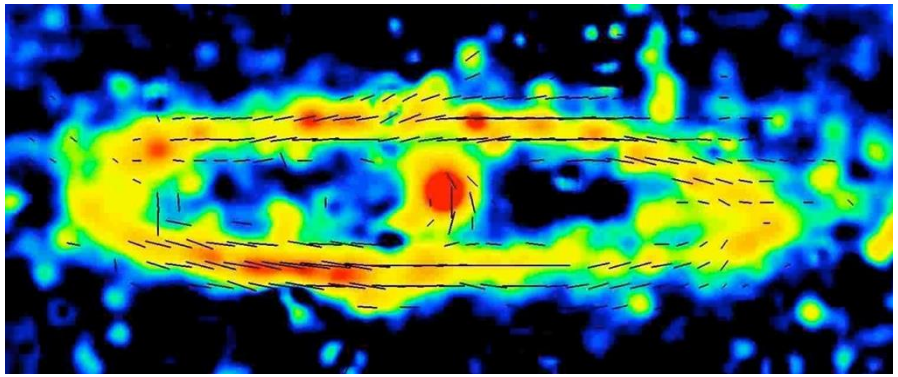


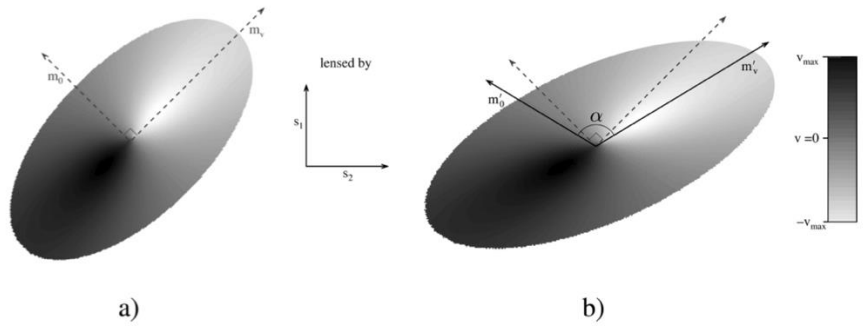
For a full list see Brown + IH et al (2015)

Radio Weak Lensing

Promises

- Extra information in the radio can mitigate intrinsic alignments
  - Polarisation Brown & Battye (2011), Whittaker et al (2015)
  - HI rotational velocities Morales (2006), Huff et al (2015)





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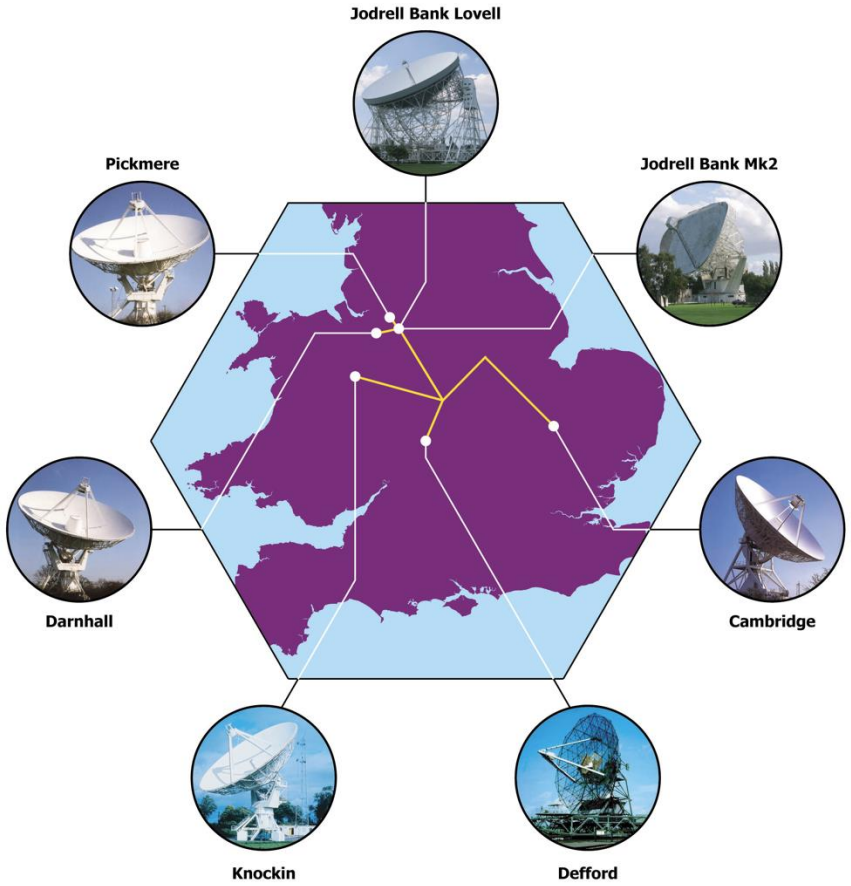
Radio Weak Lensing

CHALLENGES

• Interferometer data: PSF highly complicated

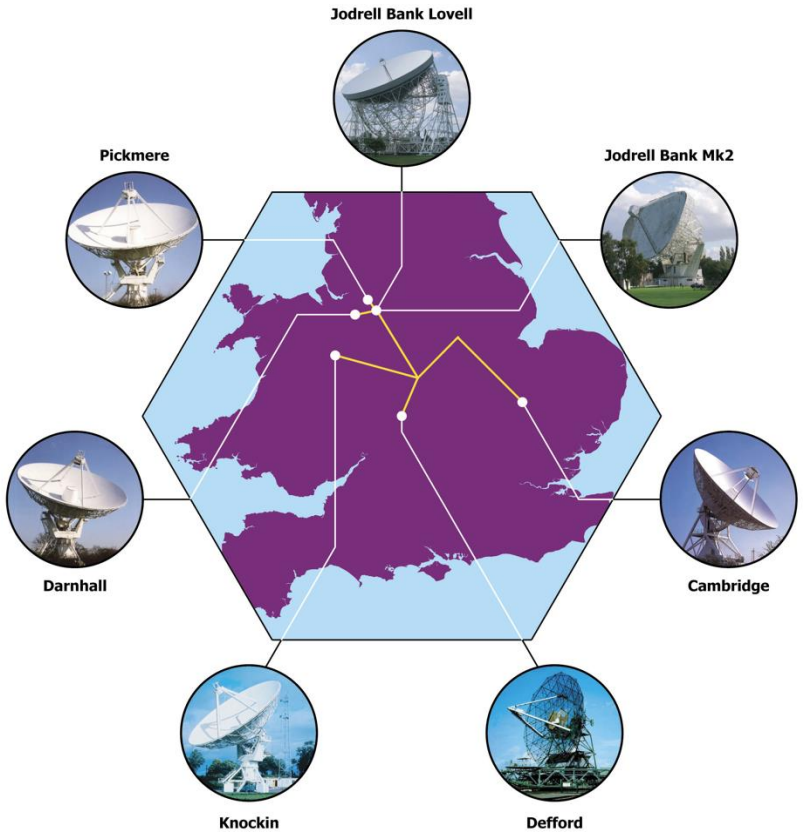
- λ/d ~0.1 arcsec implies d ~100 km
- Instead correlate signals from dishes ~100 km apart
- Each combination gives one Fourier mode
  - d large gives small scales in image
  - d small gives large scales in image
- $N(N\text{-}1)$ combinations and Earth rotation gives many samples of Fourier plane



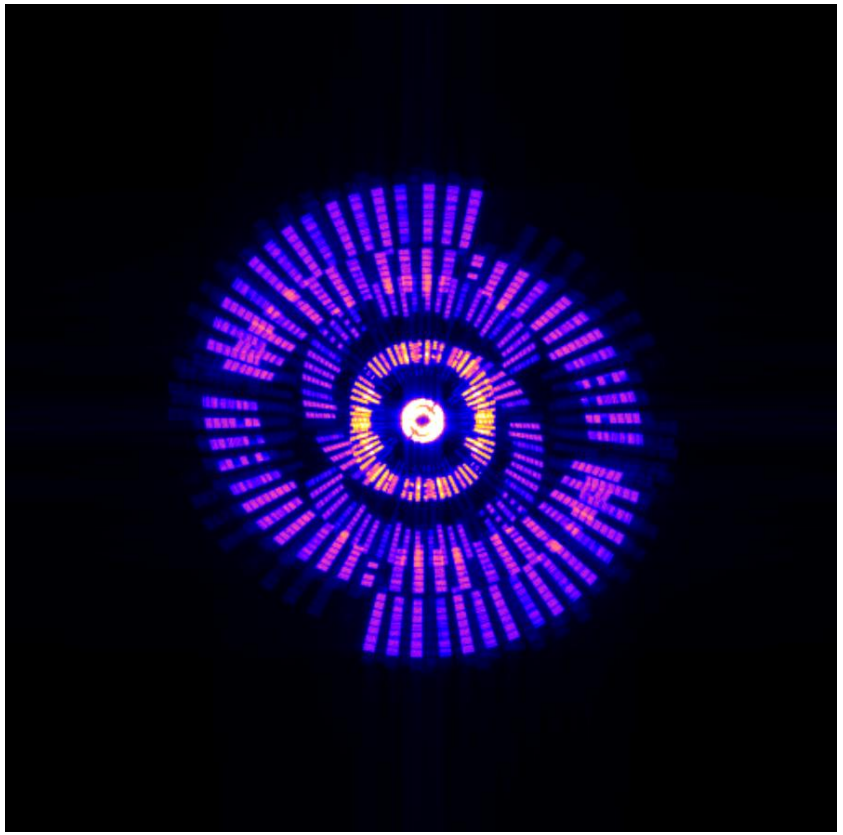
Radio Weak Lensing Challenges

Slides available at http://bit.ly/ianh_tosca24

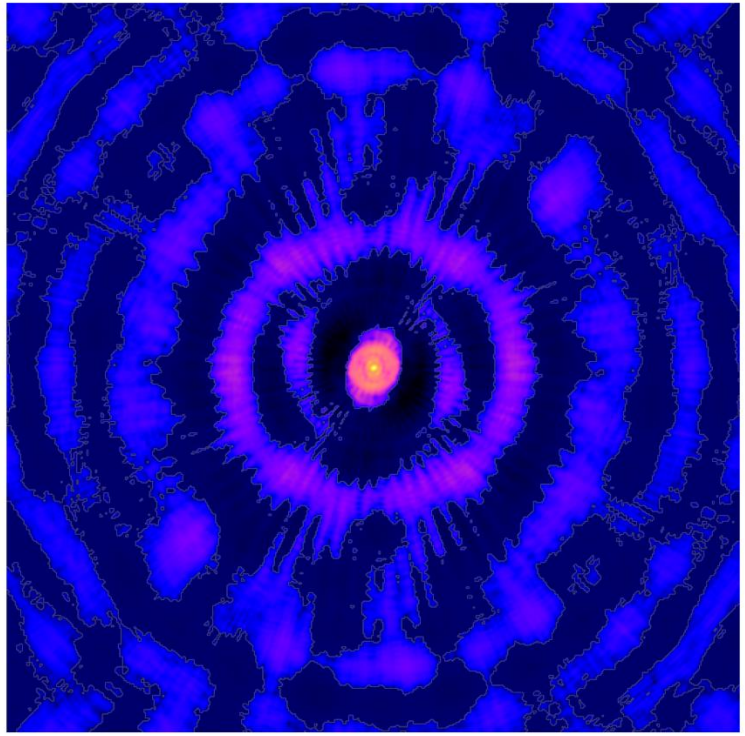
Observe with these dishes in real space



Get data at these locations in Fourier space



Get this PSF in real space (log scale)



Radio Weak Lensing Challenges

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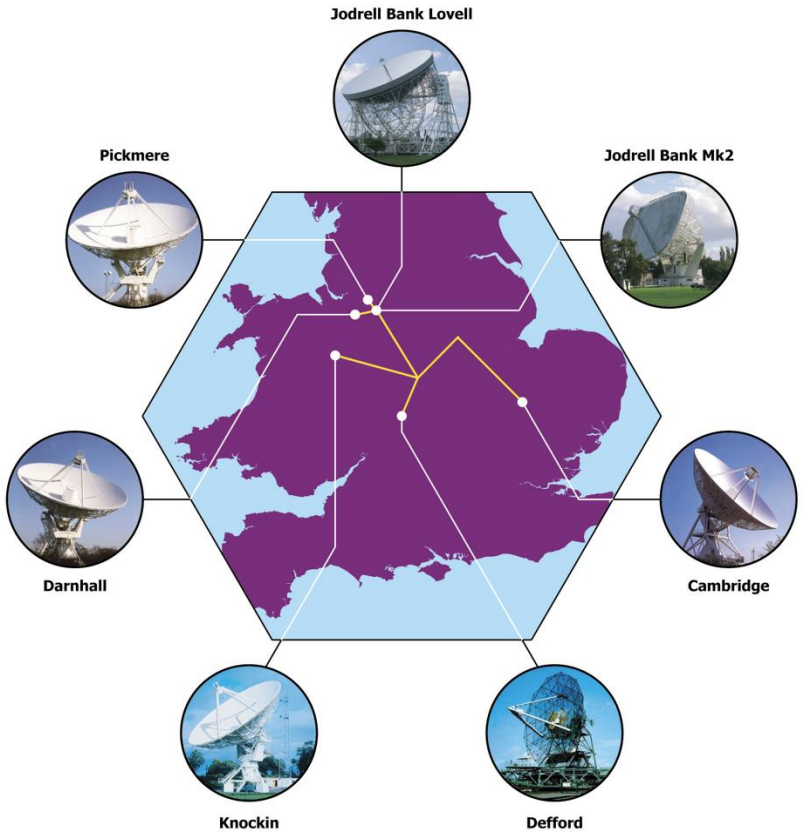

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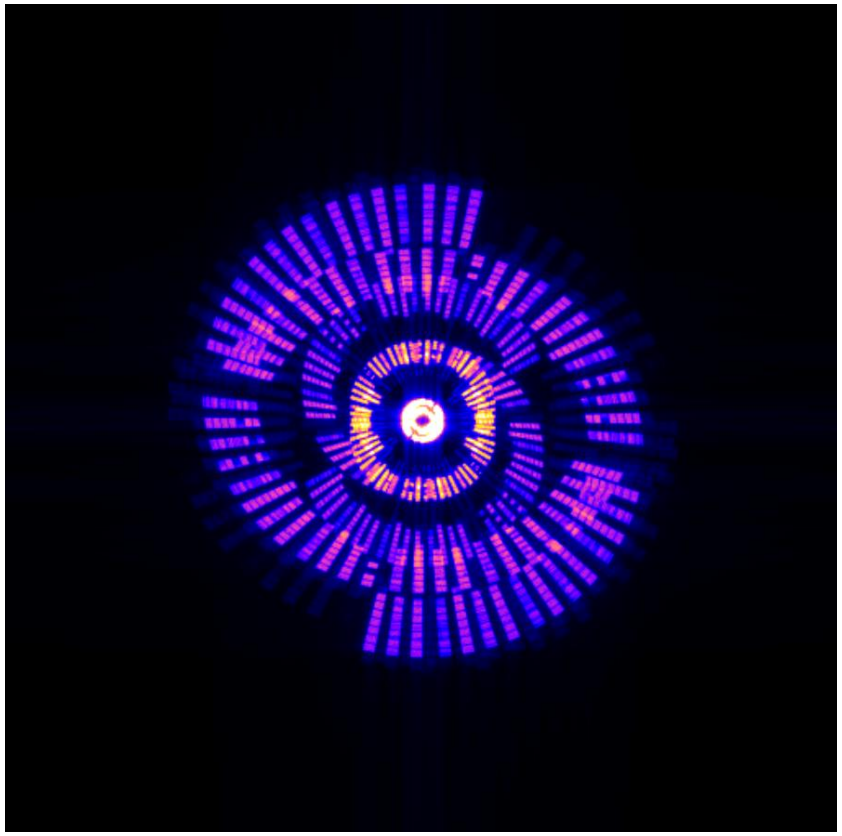
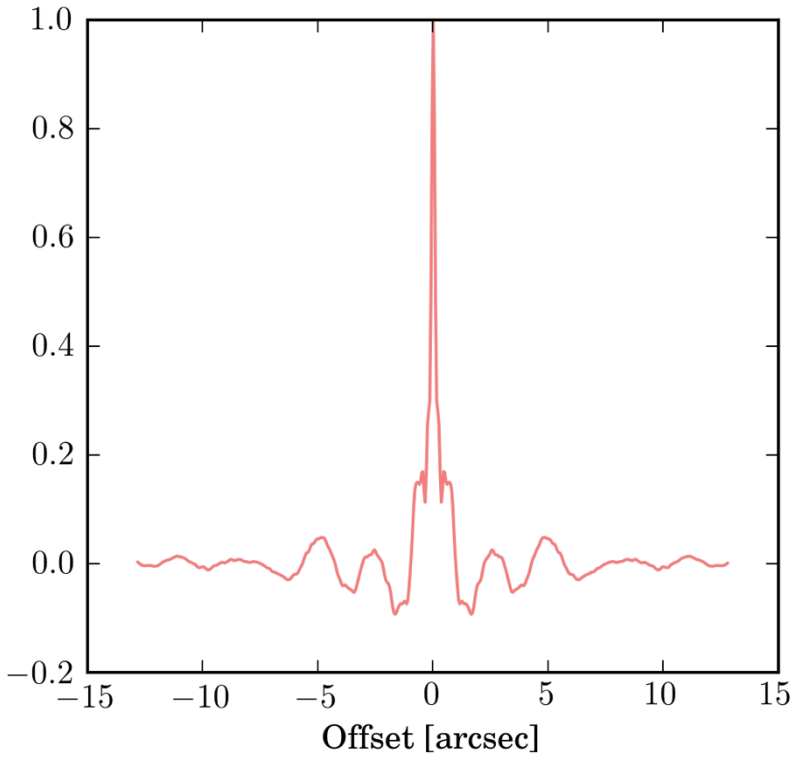


Get this PSF in real space



Radio Weak Lensing Challenges

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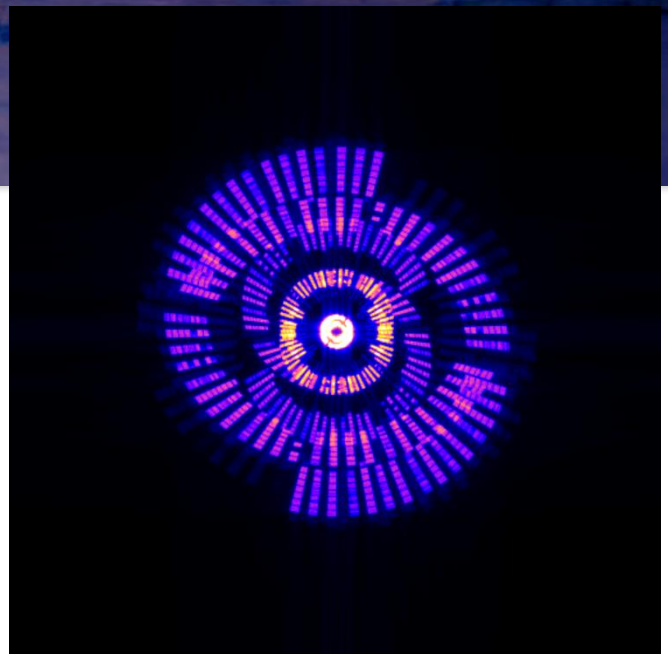
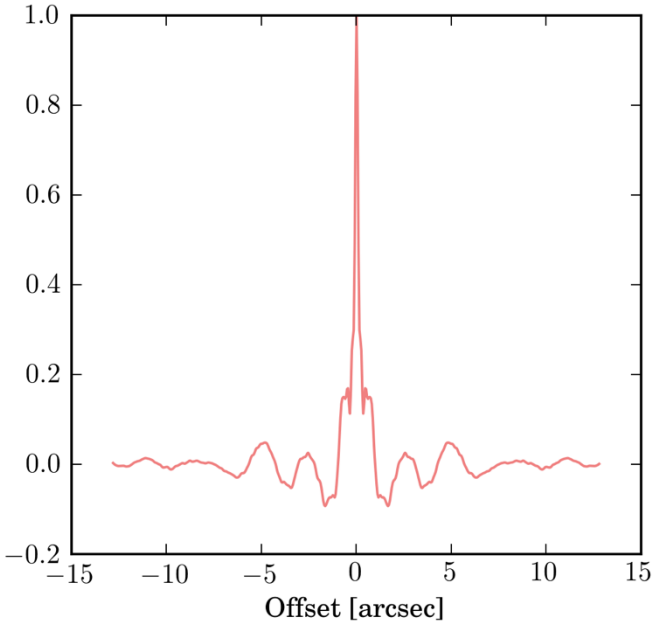
- True sky is unknown and under-constrained
  - PSF sidelobes extend across sky
  - flux from all sources mixed together
  - local in image non-local in Fourier
- Deconvolution algorithms exist but are non-linear, so true PSF hard to determine

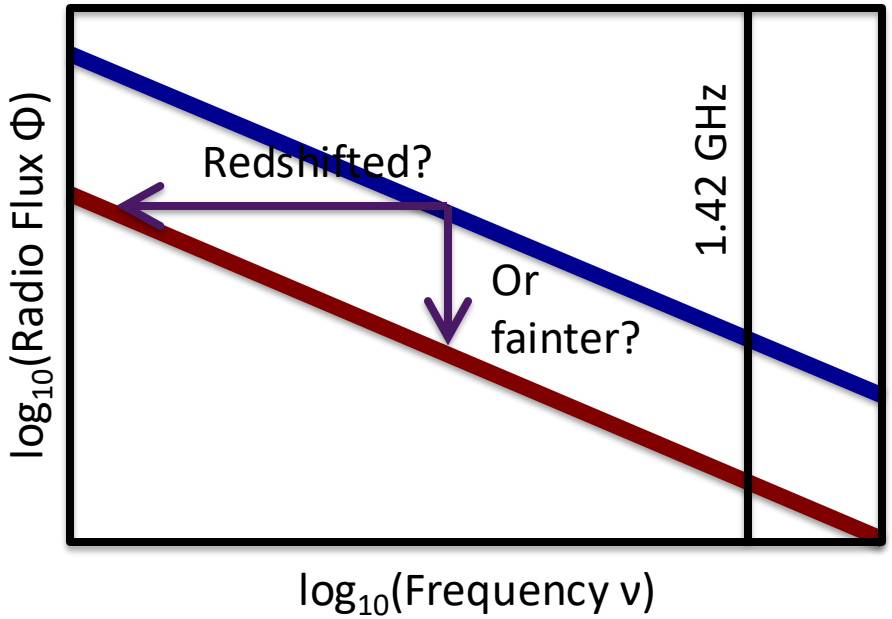
Precision weak lensing shape measurement will be hard!





Radio Weak Lensing Challenges

- Source redshifts are hard due to (nearly) featureless spectrum
  - Without tomography lose lots of constraining power!
  - Synchrotron emission from star forming galaxies
  - Could try ‘forced’ fitting of HI lines IH et al (2017)
  - Otherwise rely on cross-matches in near-IR, optical



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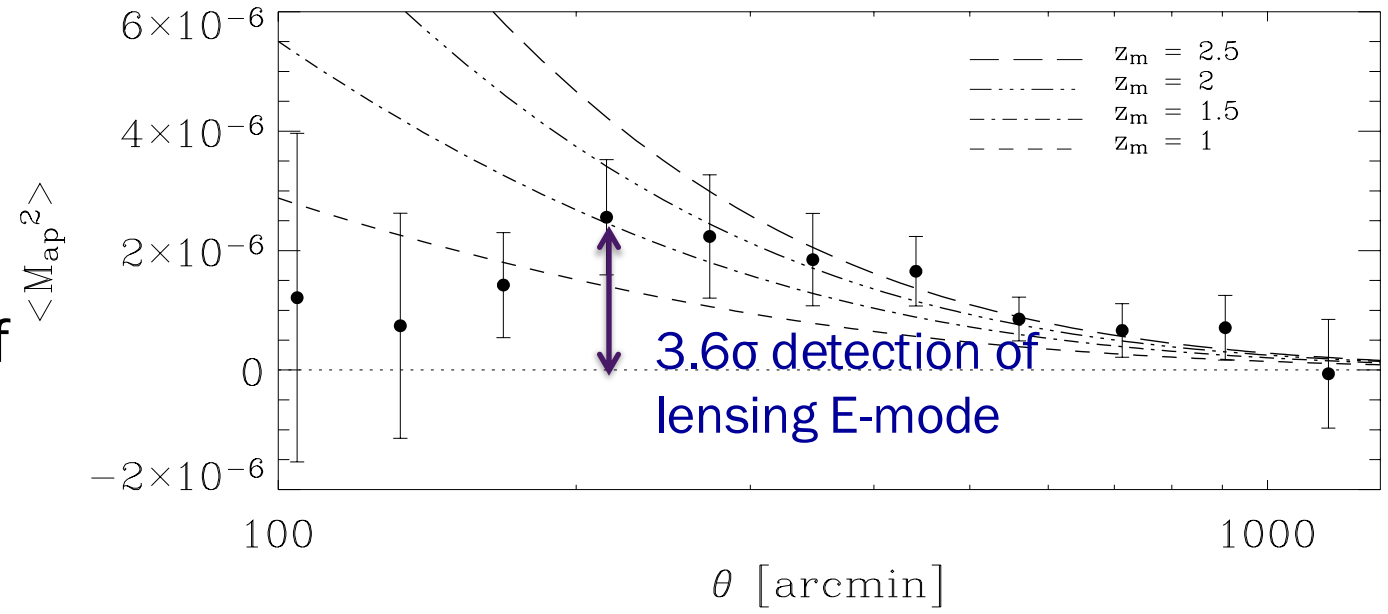
Radio Weak Lensing

PAST EFFORTS

Radio Weak Lensing
A Brief History

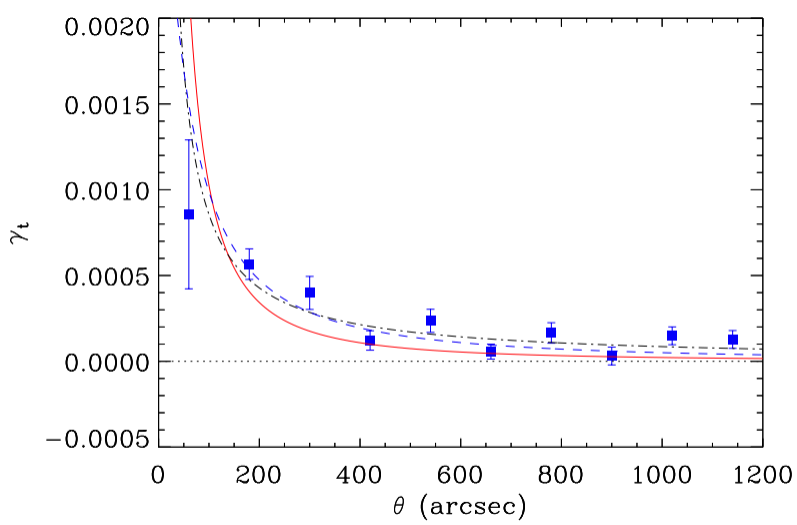
- Sole radio weak lensing detection in 2004
- Measure shapes in Fourier plane from VLA FIRST survey
  - Not designed as a weak lensing survey
  - Low number density, but very wide
- Make a 3.0σ to 3.6σ detection of an aperture mass variance across survey
- Detection significance increases when low-redshift sources removed



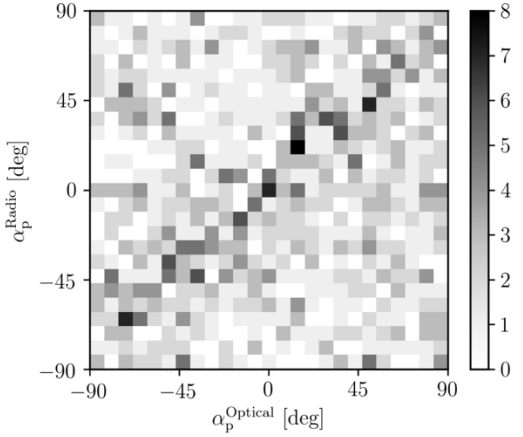
(Chang Refregier & Helfand 2004)

Developments – Observations

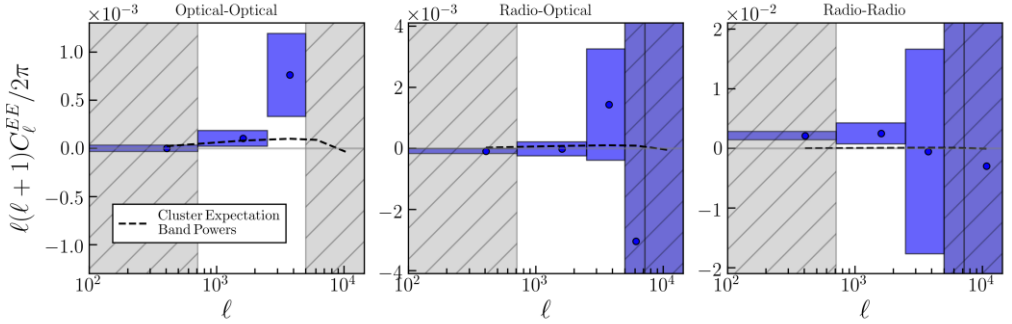
- SDSSxFIRST
  - 2.7σ on cross-power spectrum (Demetroullas & Brown 2016)
  - 10σ on galaxy-galaxy lensing (Demetroullas & Brown 2017)



- JVLA-COSMOS
  - 4.7σ on radio-optical shape correlation (Tunbridge et al 2016; Hillier et al 2019)



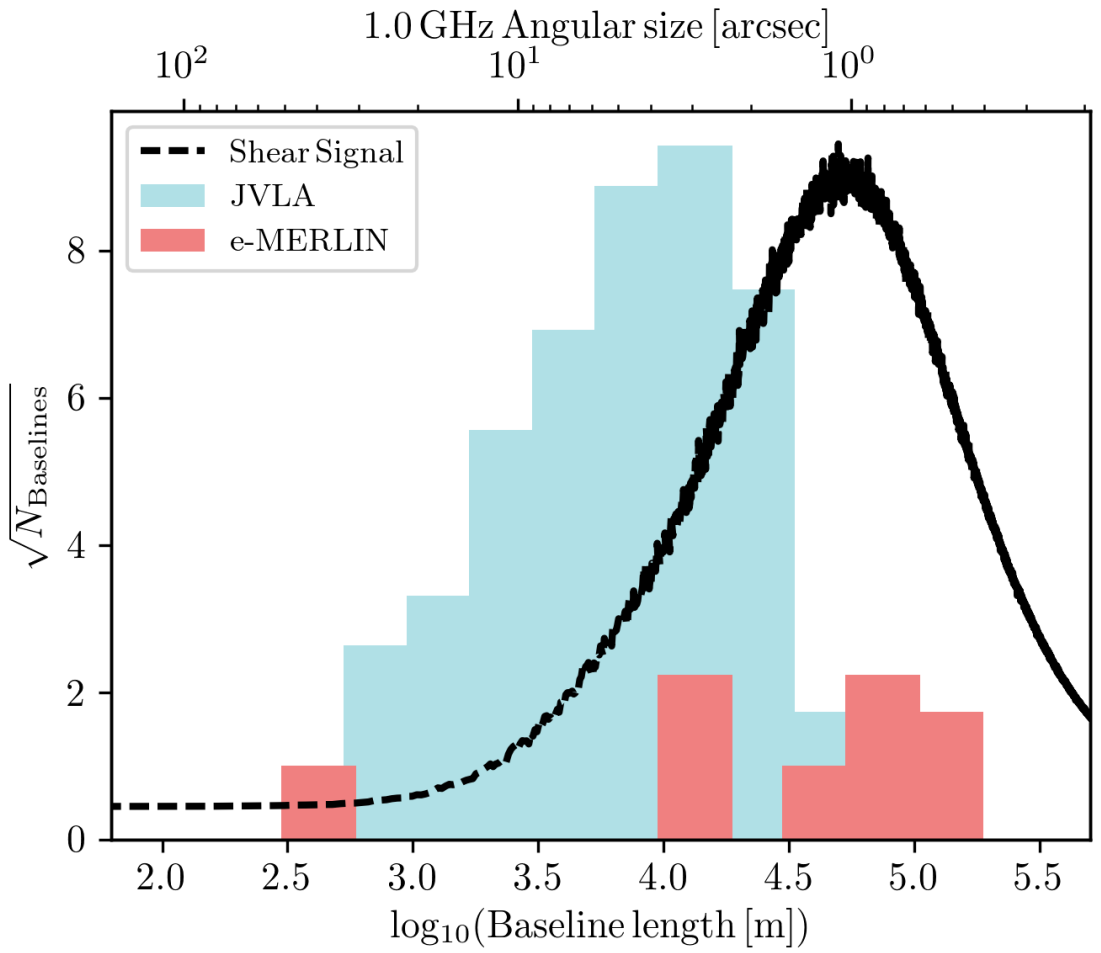
- SuperCLASS DR1
  - Upper limit on cluster lensing (Harrison et al 2020)



The SuperCLASS Survey

Survey Design

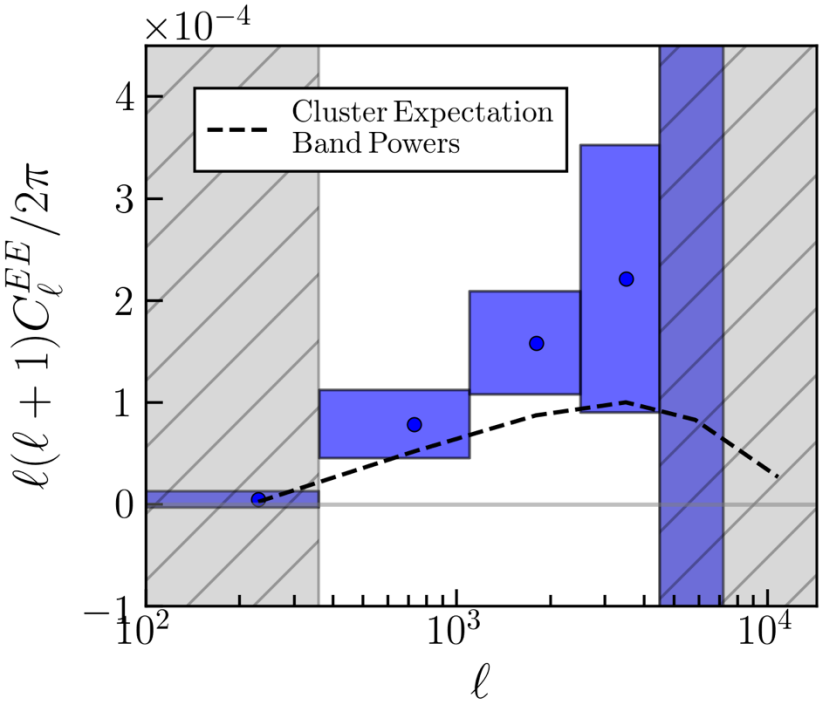
- Observe field at same frequencies with US-based JVLA telescope, UK-based e-MERLIN
- Complementary baseline lengths
- Cover relevant parts of the Fourier plane for weak lensing shear signal
- Ideally, would combine data in Fourier space
  - This is hard due to real world foibles with the data

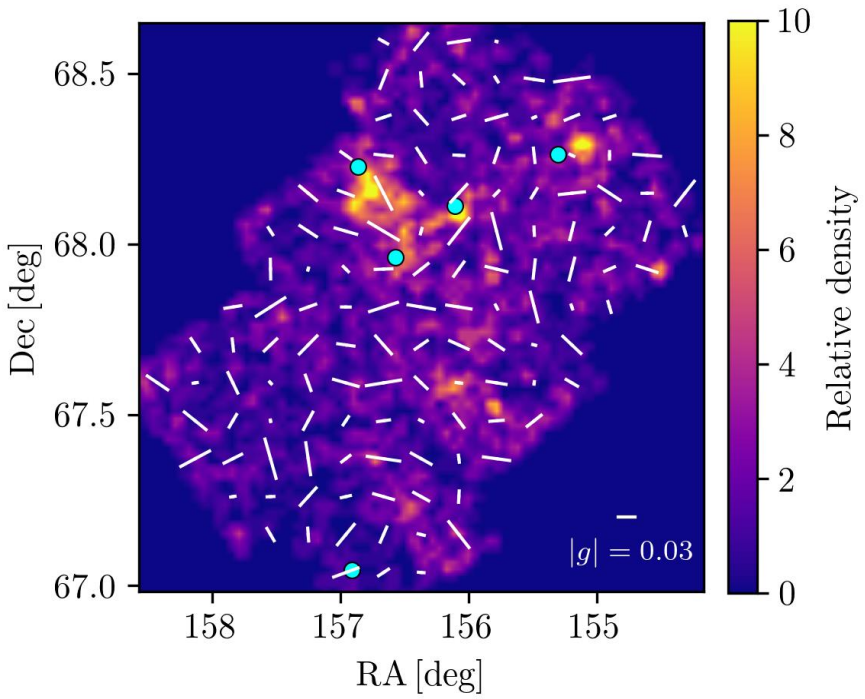


Battye + IH et al (2020)

The SuperCLASS Survey
DR1 Results

- Optical data allows detection of clusters and weak lensing signal





IH et al (2020)

The SuperCLASS Survey
DR1 Results

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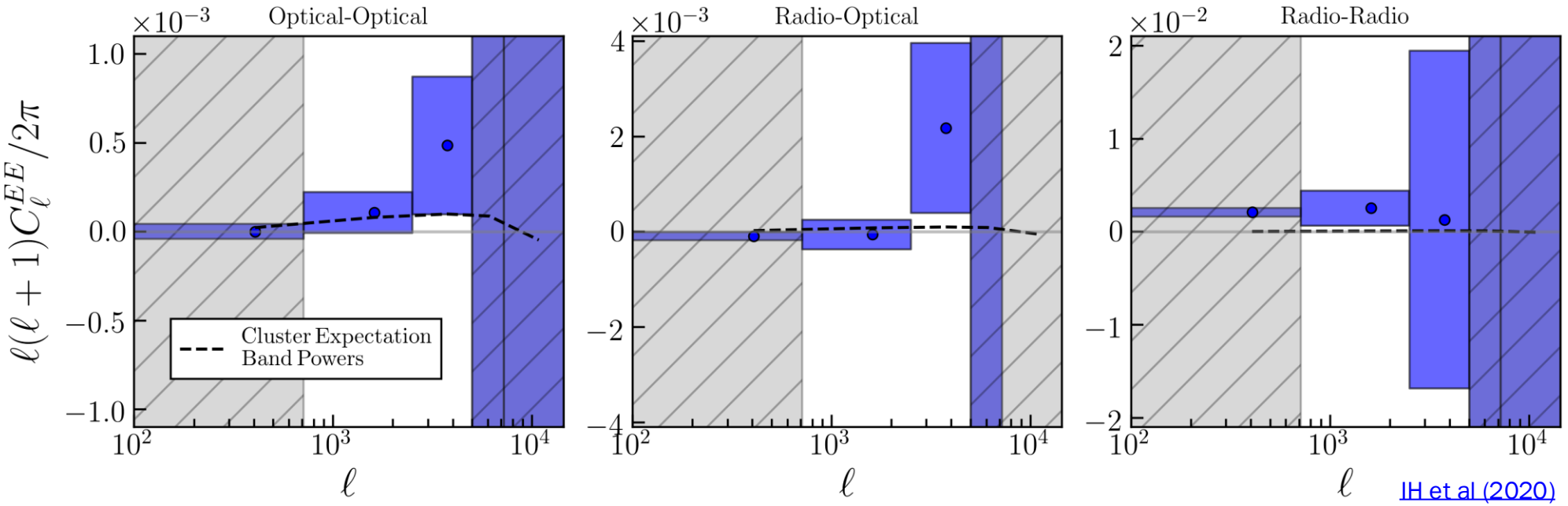
- Radio shapes for 440 sources in the 0.26 deg^2 (~0.47 arcmin^{-2})
- ...too much shape noise for detection of radio or radio-optical shear power spectrum

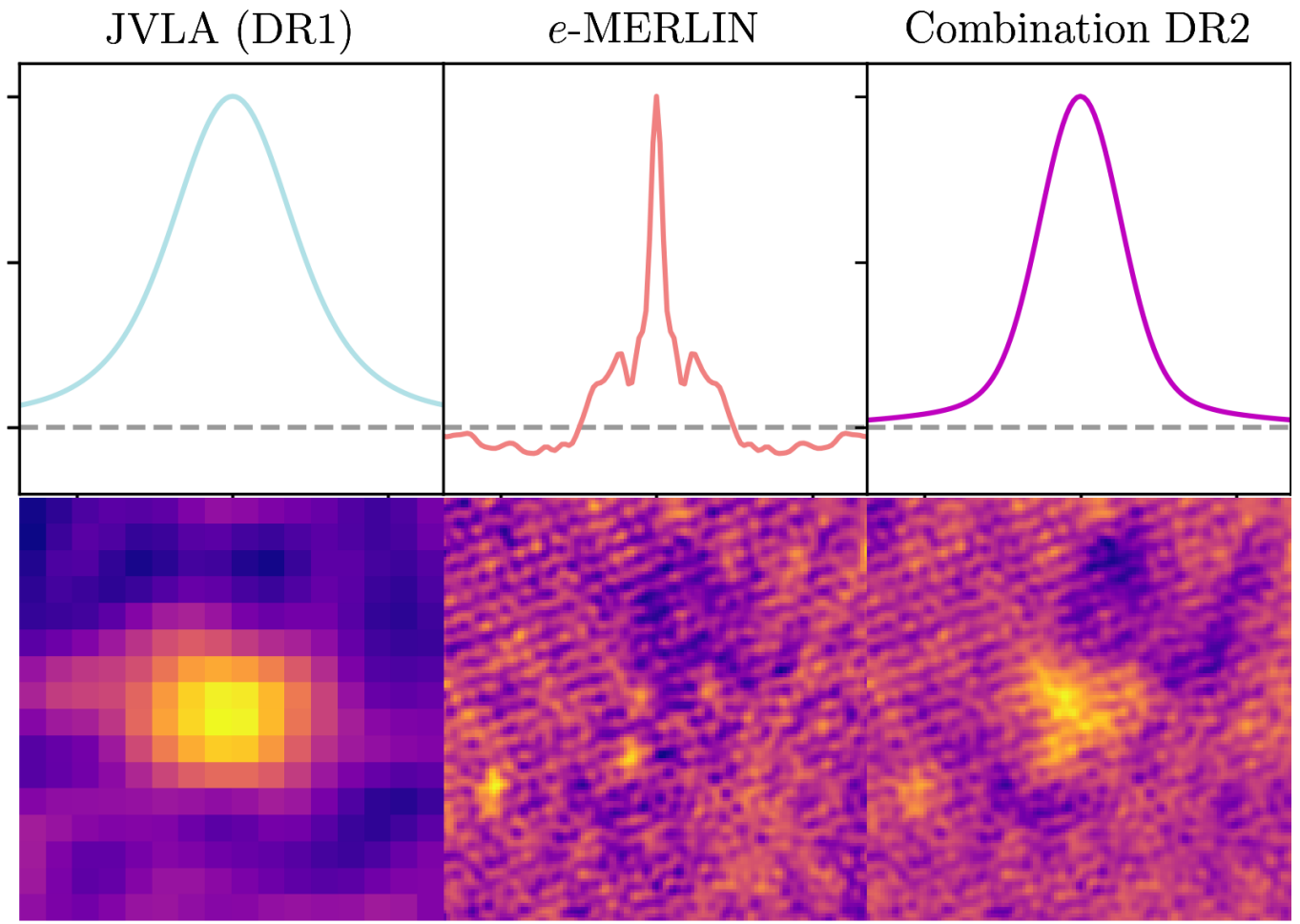


IH et al (2020)

The SuperCLASS Survey
Progress on DR2

Slides available at http://bit.ly/ianh_tosca24

- DR2 data combination between JVLA and *e*-Merlin adds sensitivity to small scales and improves PSF
- Looks like improve to ~0.7 gal arcmin^{-2} over 0.75 deg^2



IH et al (2020)

Radio Weak Lensing
Precursor & Pathfinder Surveys

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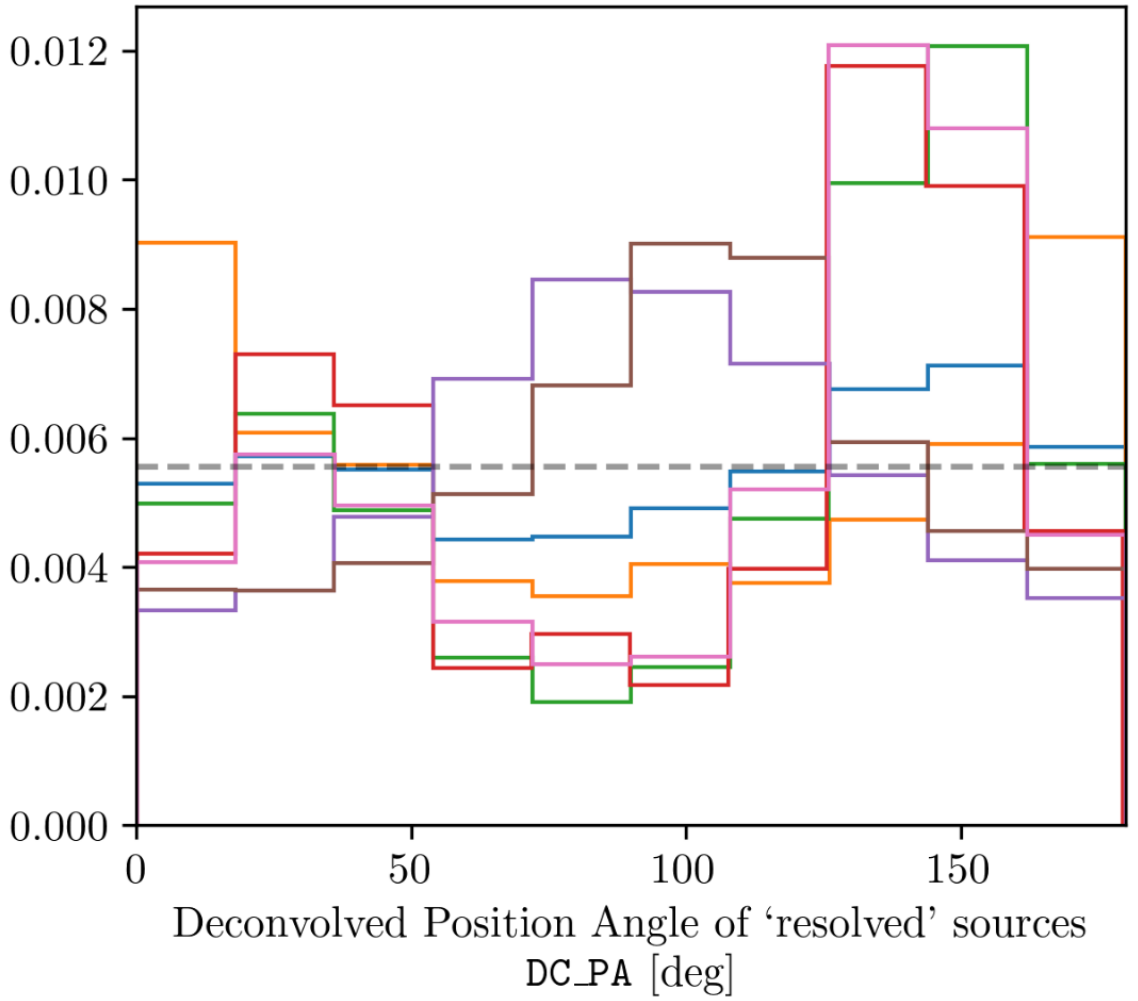
- Can we do weak lensing with other surveys?
- Images do not appear reliable enough(?)

racs_dr1_sources_galacticcut_v2
racs_mid_sources_v01
MIGHTEE_Continuum_Early_Science_COSMOS_r0p0
MIGHTEE_Continuum_Early_Science_COSMOS_r-1p2
LoTSS_DR2_v110_masked
LoLSS_DR1_v1
MIGHTEE_Continuum_Early_Science_XMMLSS_r0p0_circ

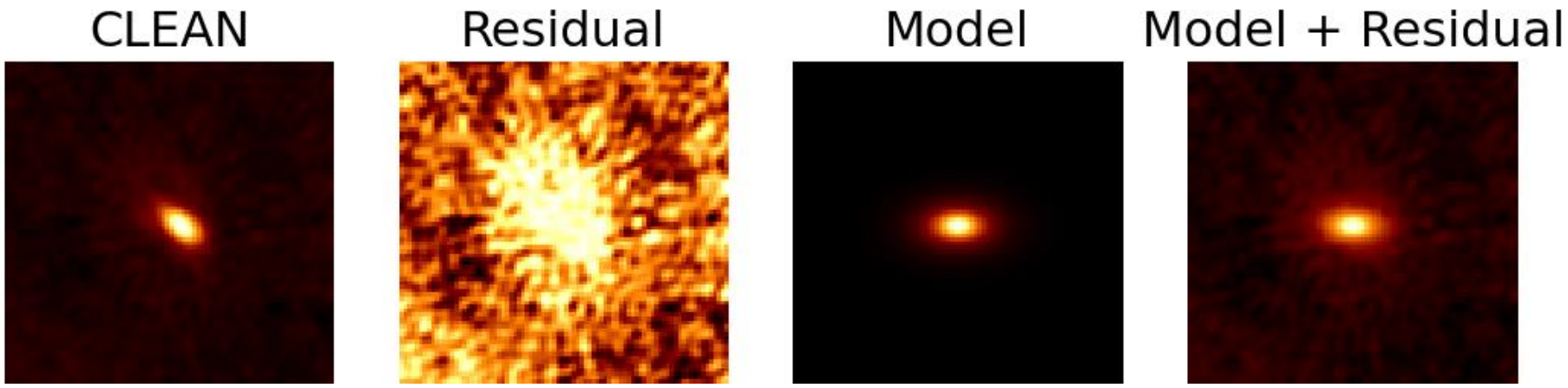


Shape Measurement

- Patel et al 2015 looked at SKA1-Mid simulations
- Find *m*, *c* biases factor >10 too large from images made using traditional deconvolution methods
  - Some promise of uv-plane shapelet methods used in Chang et al 2004

Shape Measurement

- SuperCLASS shapes measured in real space JVLA-only images using ‘SuperCALS’
  - Calibration simulations on a source-by-source basis
  - Inject ‘ring test’ of simulated sources onto CLEAN residual image
  - Measure recovered linear bias model
  - Apply correction to shape measured in real image



The SuperCLASS Survey
Progress on DR2

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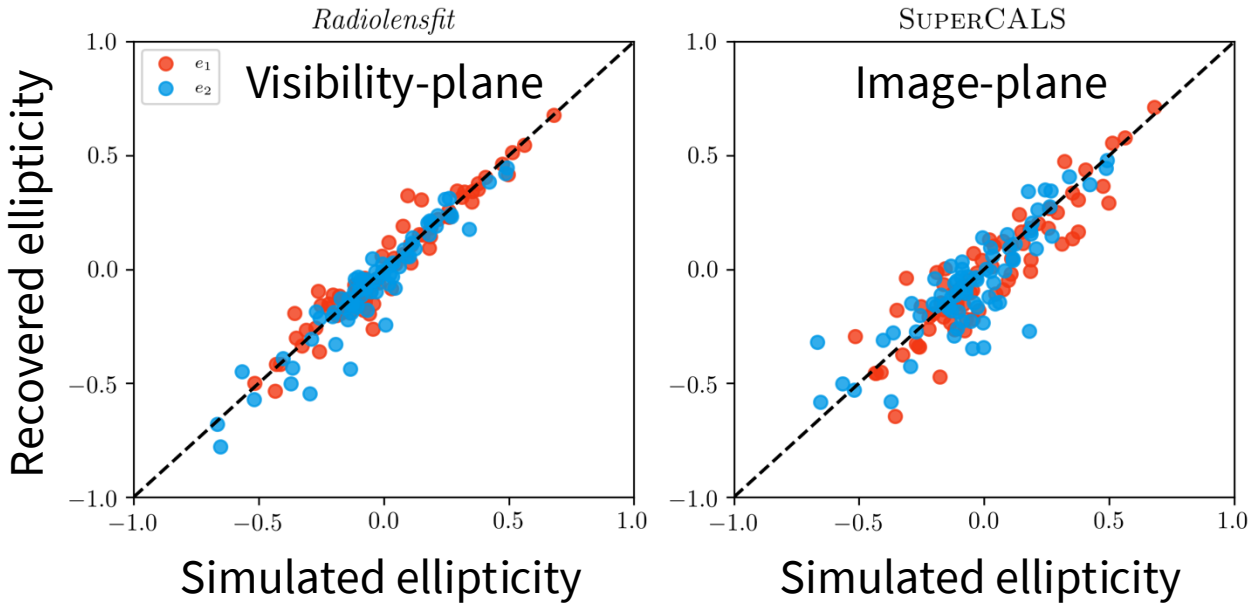
- Rivi & Miller since produced uv-plane fitting methods
  (as well as image-plane method from DR1)
  - Faceting to reduce necessary number of simultaneous fits
    Rivi & Miller (2018)
  - *lensfit*-style marginalisation over nuisance parameters
  - See also Hamiltonian Monte Carlo approach
    Rivi + IH et al (2019)
- Have compared on the same simulations with SuperCALS for SuperCLASS DR2



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Radio Weak Lensing

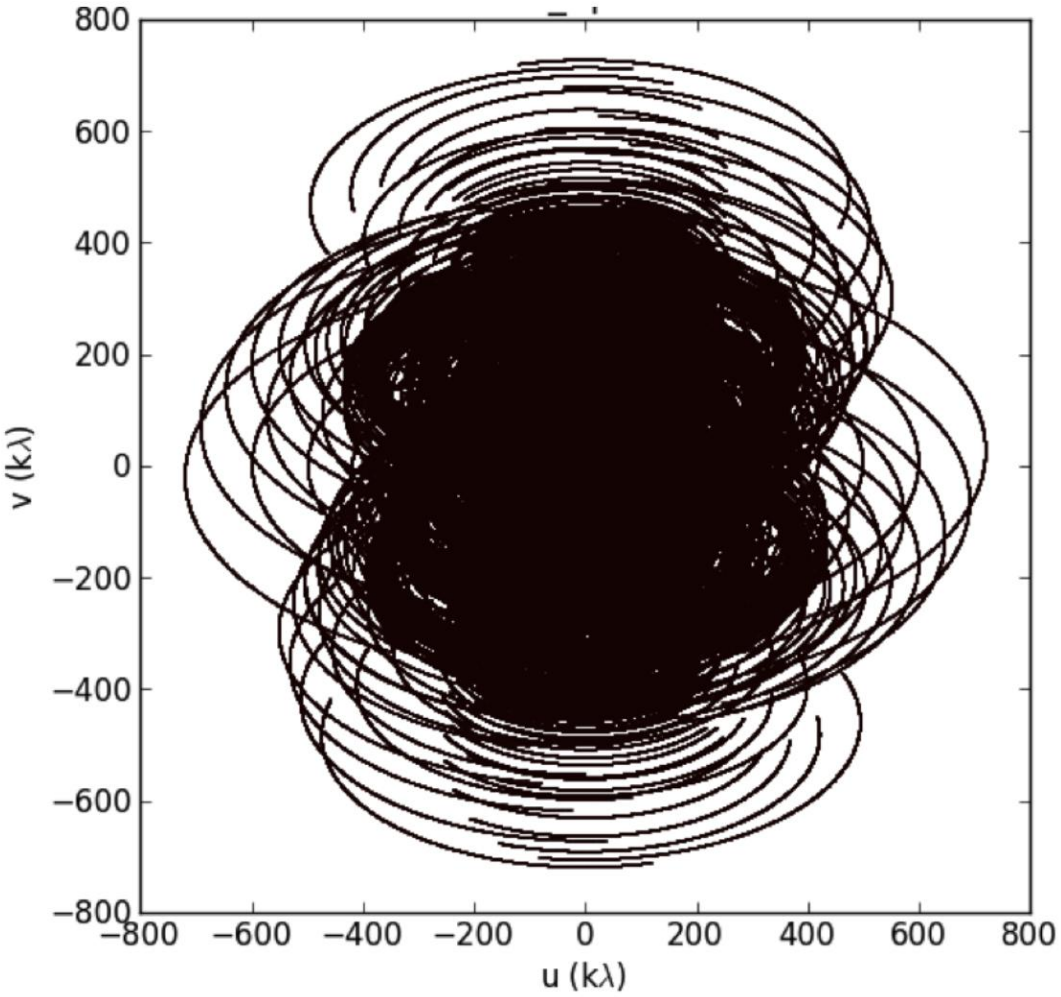
FUTURE WORK

2025 Science Book

- Propose 2 RWL chapters
  - Cosmic Shear Forecasts
    - Could also include WL beyond 2pt, beyond total intensity shape measurements, more?
    - A comparison of multiple RWL shape measurement algorithms on the same simulations
- Deadline:
  - A broad kernel from 28 February 2025 to “late 2025”

Simulation Configuration

- uv coverage of Rivi et al 2019
  - SKA1-Mid (AA4)
  - 8h track, ~zenith, 1.4GHz, 1 broad channel
  - 6.4Gb per measurement set
- Source catalogue from T-RECS (Bonaldi et al 2019) cut to be nice (“Nice Cut”?)
  - SFGs only
  - Realistic ellipticity, size distributions
  - Dynamic range 10 (i.e. SNR 10-100)
- Simulation of visibilities via simuclass / CASA
  - Verified to match Marzia’s own simulations
- Noise regimes
  - Low noise SNR 100-1000
  - ‘Realistic’ noise SNR 10-100
- Provide as a measurement set
- Provide truth catalogue

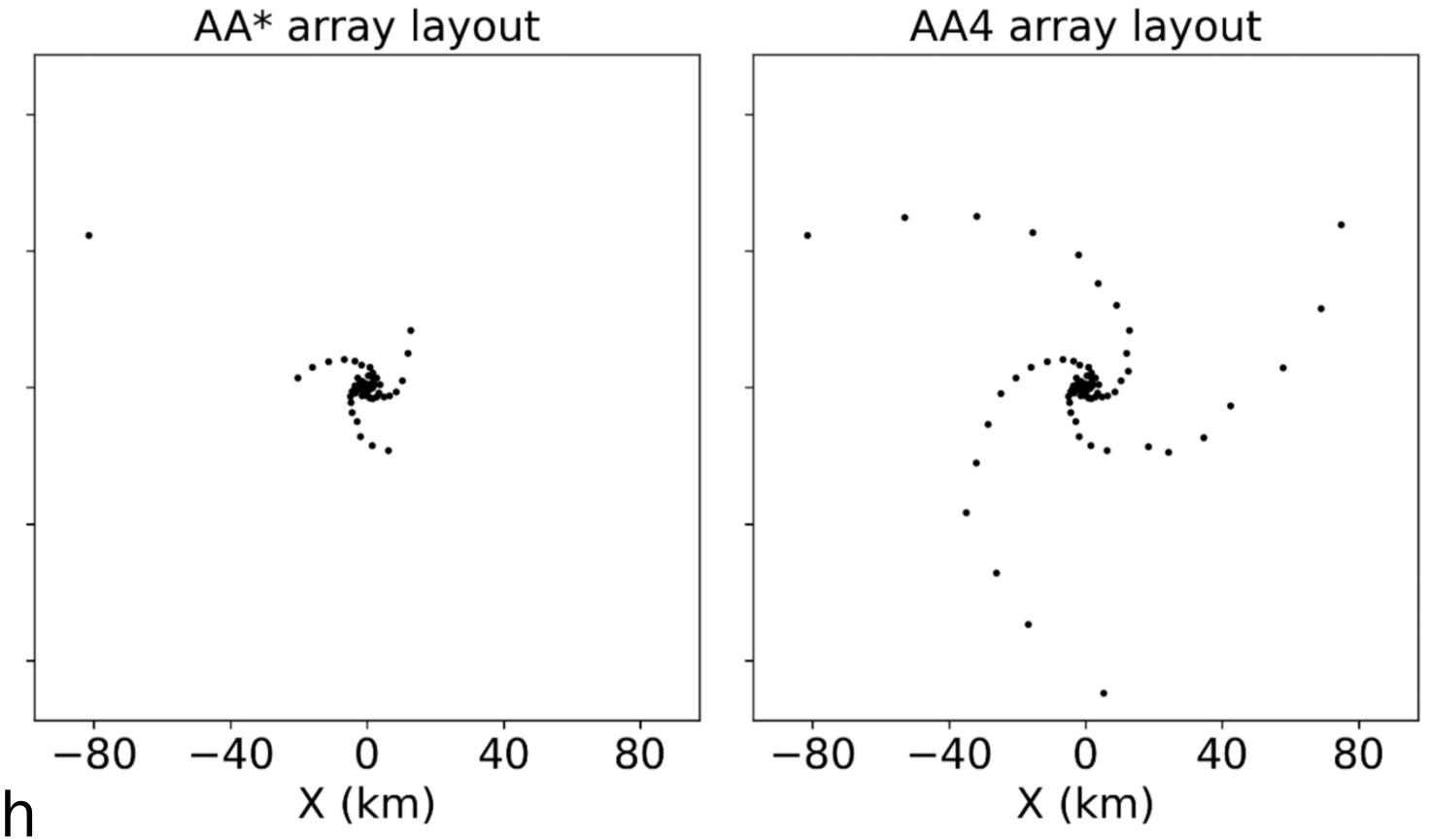


SKA Weak Lensing

AA* Array

Slides available at http://bit.ly/ianh_tosca24

- Nov 23 SKAO "Staged Delivery Memo"
- New AA* deployment configuration
  - Fewer antennae than AA4 design configuration
  - Particularly on >40km baselines
- AA* not good(!) for weak lensing
- *AND* any science case which requires source classification



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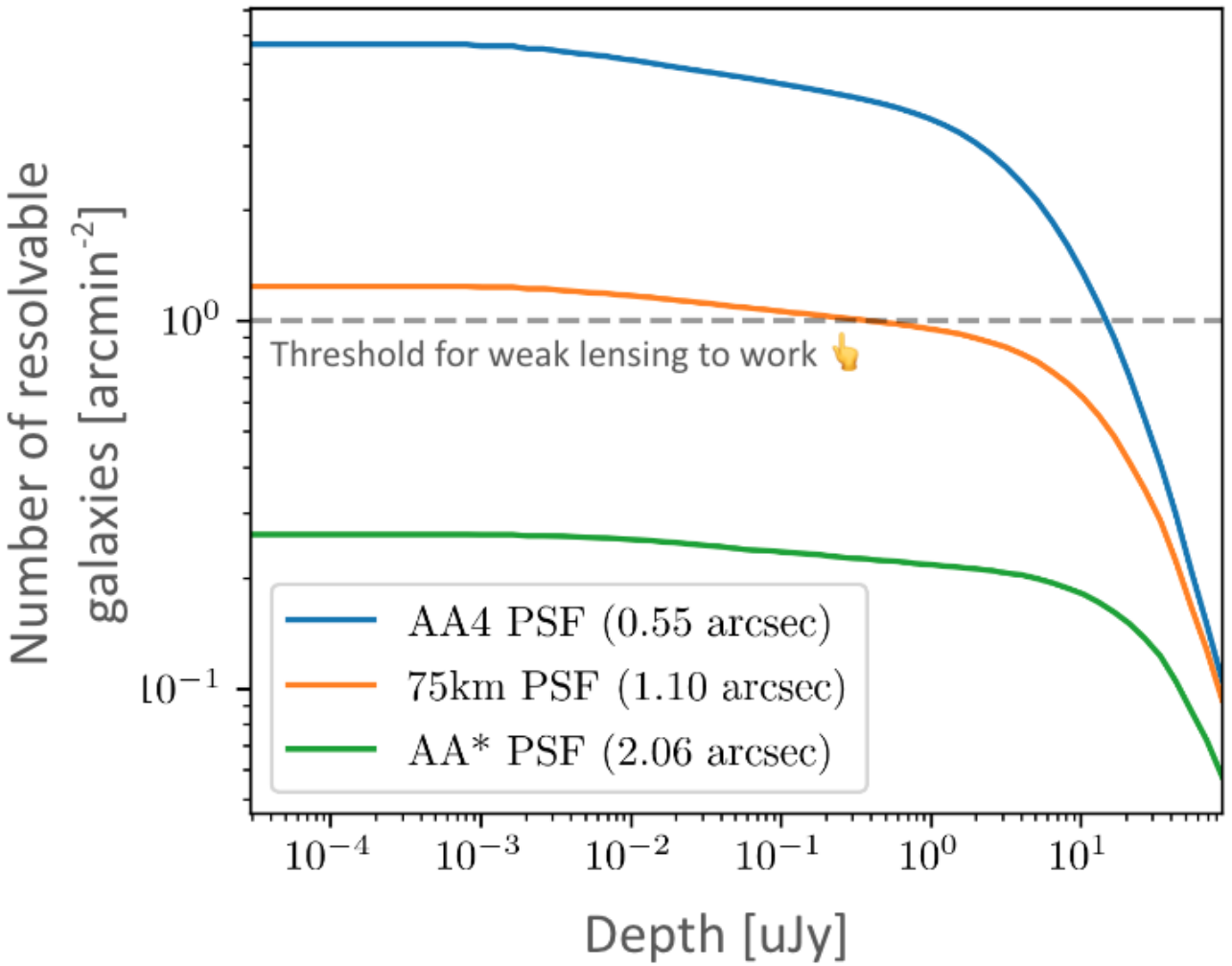

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Summary

Slides available at http://bit.ly/ianh_tosca24

- Radio weak lensing with SKA ≈ DES-Y6
  - Complete ~2033 at best
  - Cross-correlations have same statistical power but remove systematics
  - Can reduce IA, shape noise with polarisation, kinematics
- Shape measurement from interferometers is hard
- For 2025 SKA Science Book, expect a shape measurement on simulations chapter
  - Happy to circulate common simulations