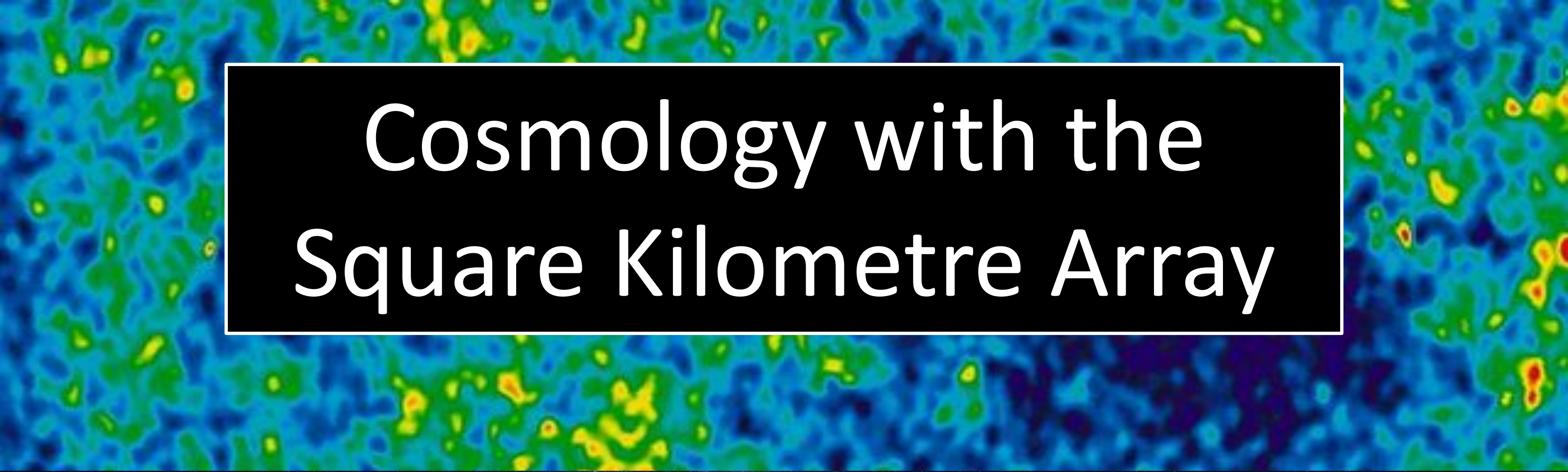
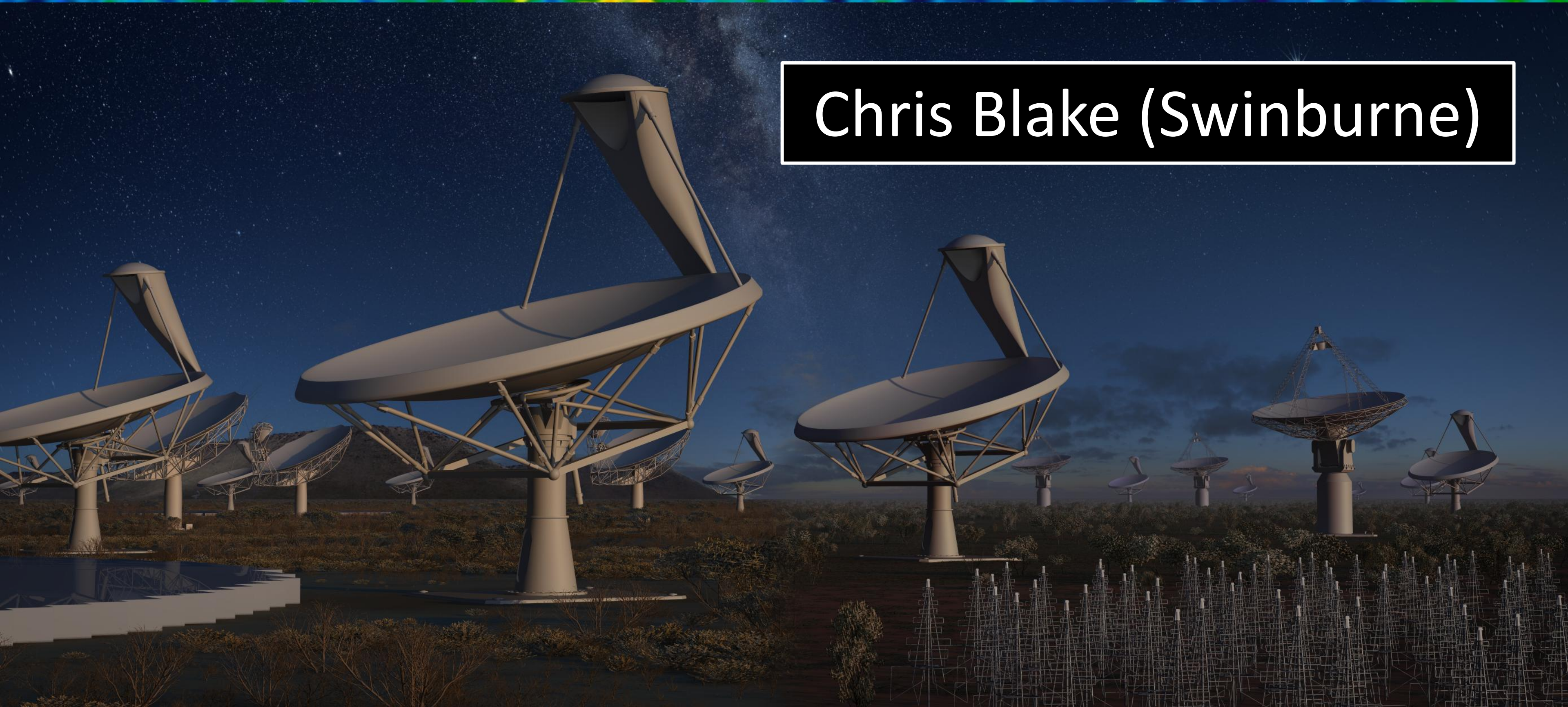
Cosmology with the Square Kilometre Array

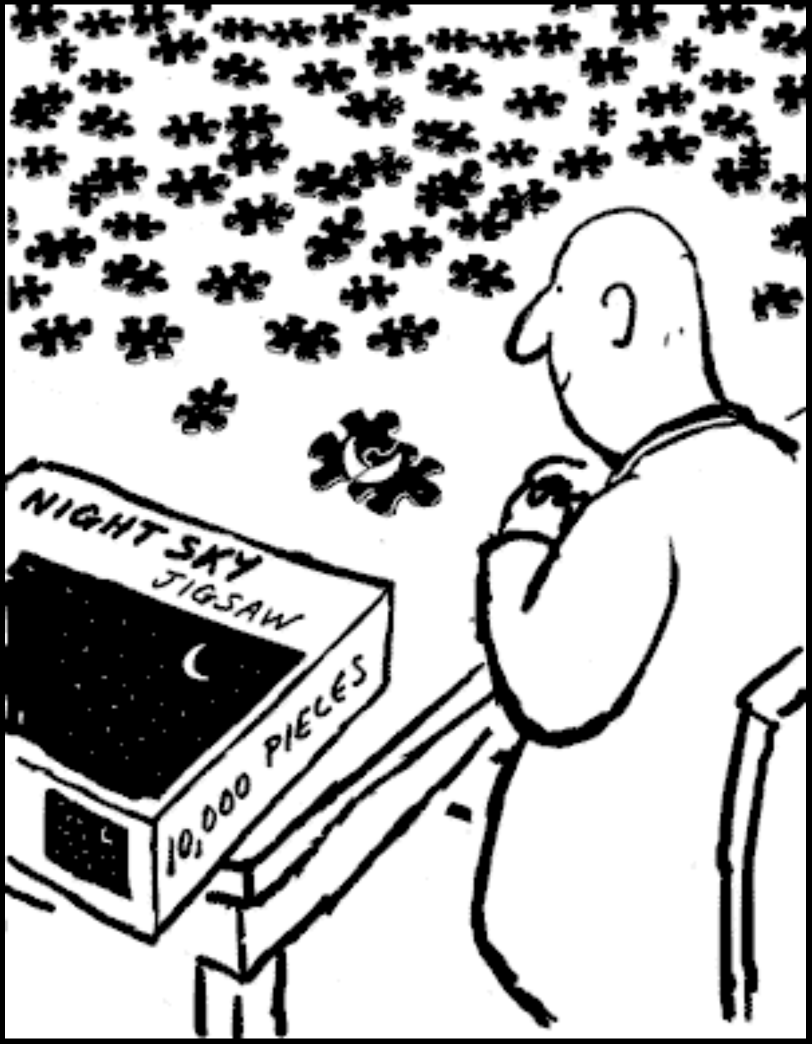


Chris Blake (Swinburne)

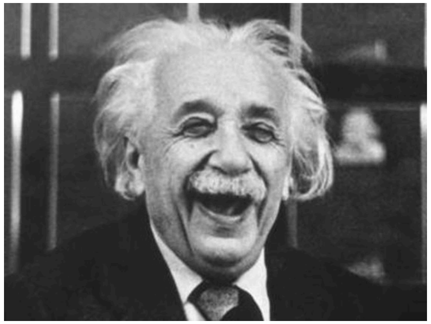


Why cosmology?

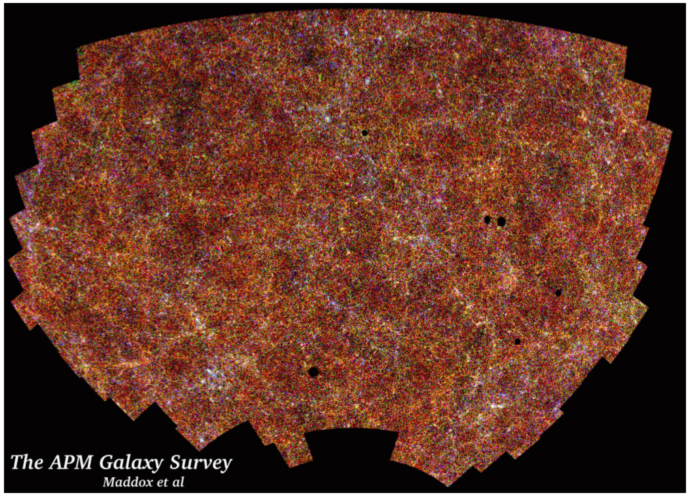
- Dark matter and energy show that our understanding of physics is incomplete
- Astronomy can provide fundamental physical insights into quantum theory, gravity and particle physics
- We are working in a breakthrough era where new data might be revolutionary!

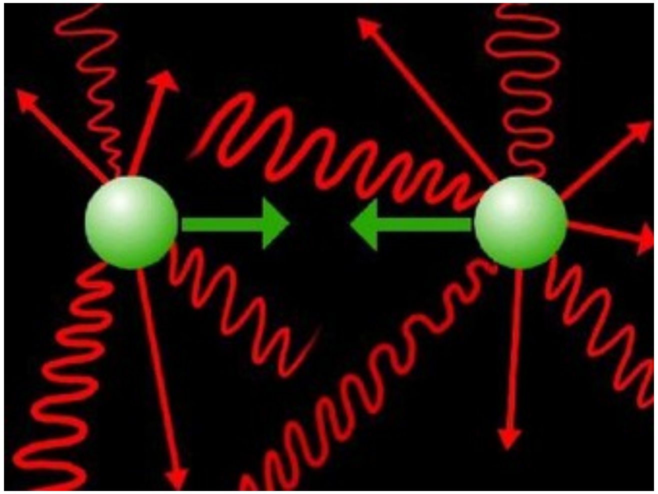


The cosmic expansion is accelerating!



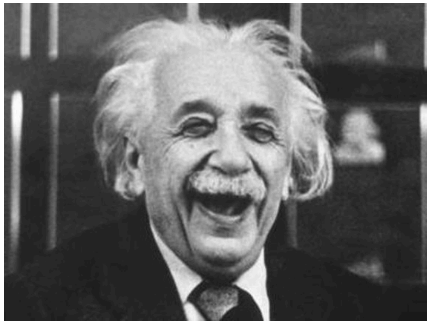
$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$





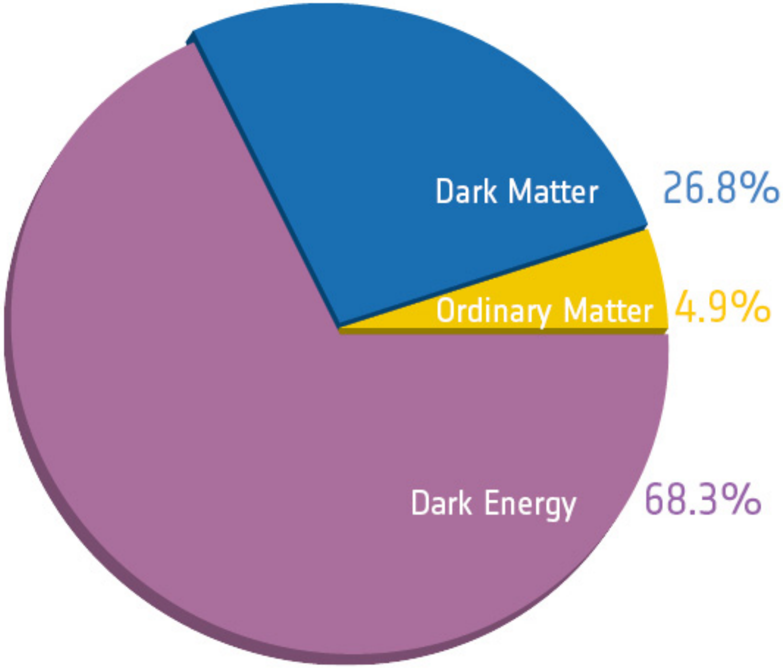
- The accelerating cosmic expansion cannot be produced by applying **General Relativity** to a **homogeneous and isotropic** Universe containing **matter and radiation**

The cosmic expansion is accelerating!



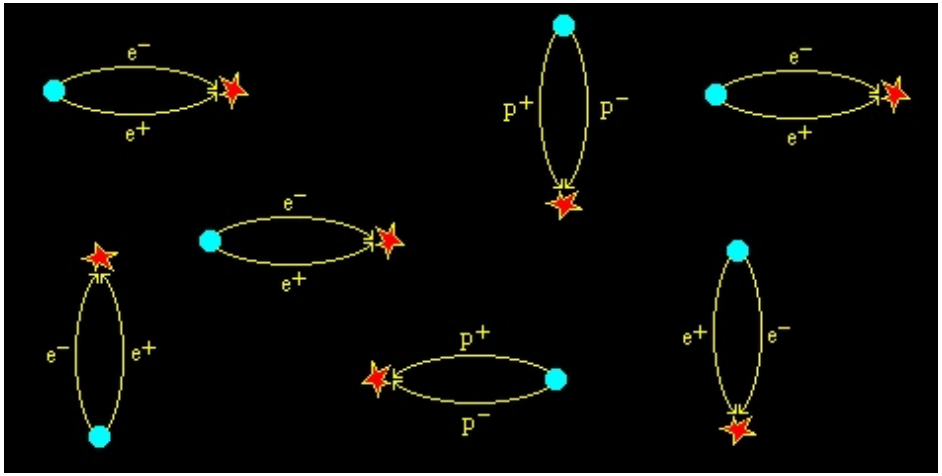
$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu} - \Lambda g_{\mu\nu}$$

- Accelerating expansion can be produced by adding a **cosmological constant** term
- A wide range of data is consistent with a Universe where the current energy density is **$\sim 70\%$ cosmological constant and $\sim 30\%$ matter**



Why is this a problem?

$$\Lambda_{\text{obs}} \sim (10^{-30}\, M_{\text{Planck}})^4$$



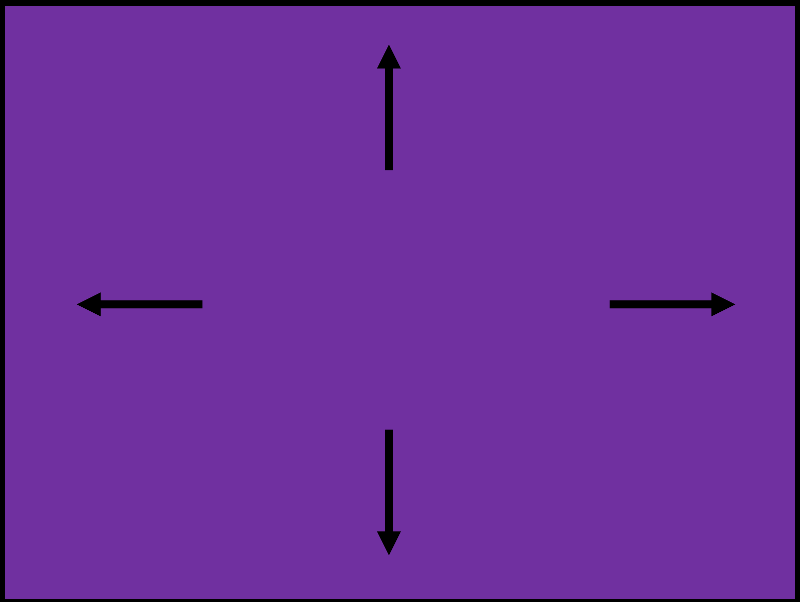
- Why is the energy density in the cosmological constant "unnaturally low"? [many tens of orders of magnitude lower than expected from quantum mechanical processes involving standard particles]
- Why are the energy densities in cosmological constant and matter roughly equal today? ["coincidence problem"]
- **Is the cosmological constant a sign of new physics?**

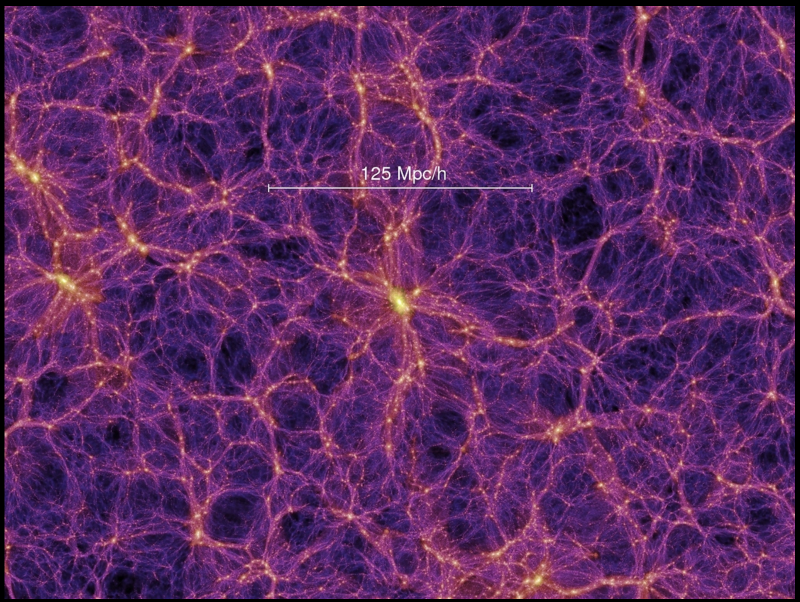
Other explanations?

Let's not worry about cosmological constant and seek another solution!

- *"Accelerating cosmic expansion cannot be produced applying GR to a homogeneous/isotropic Universe containing matter and radiation"*
- Modify gravitational physics? [e.g. Einstein-Hilbert action]
- Allow for effects of inhomogeneity? [very hard!]
- Add extra "source"? [e.g. dynamical scalar field]

Cosmological observations

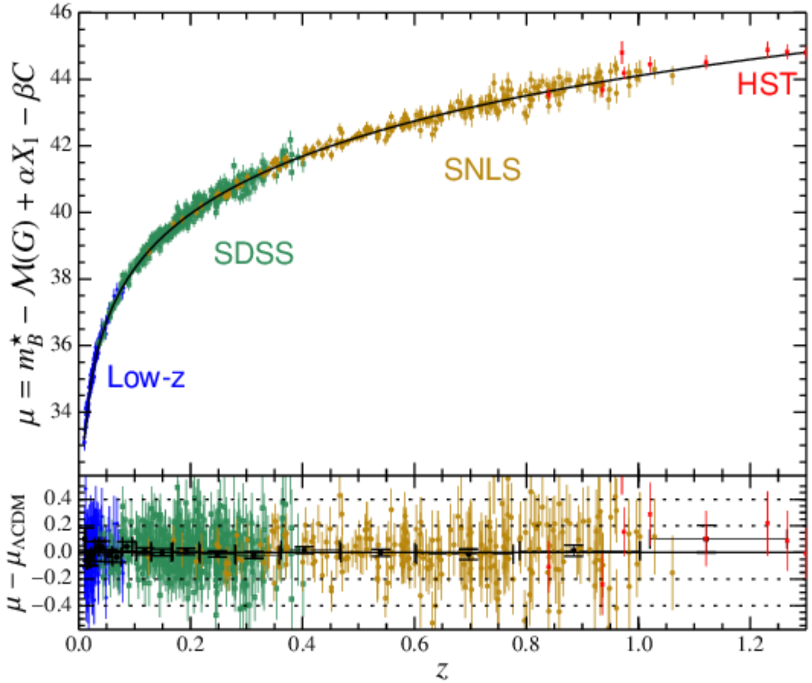


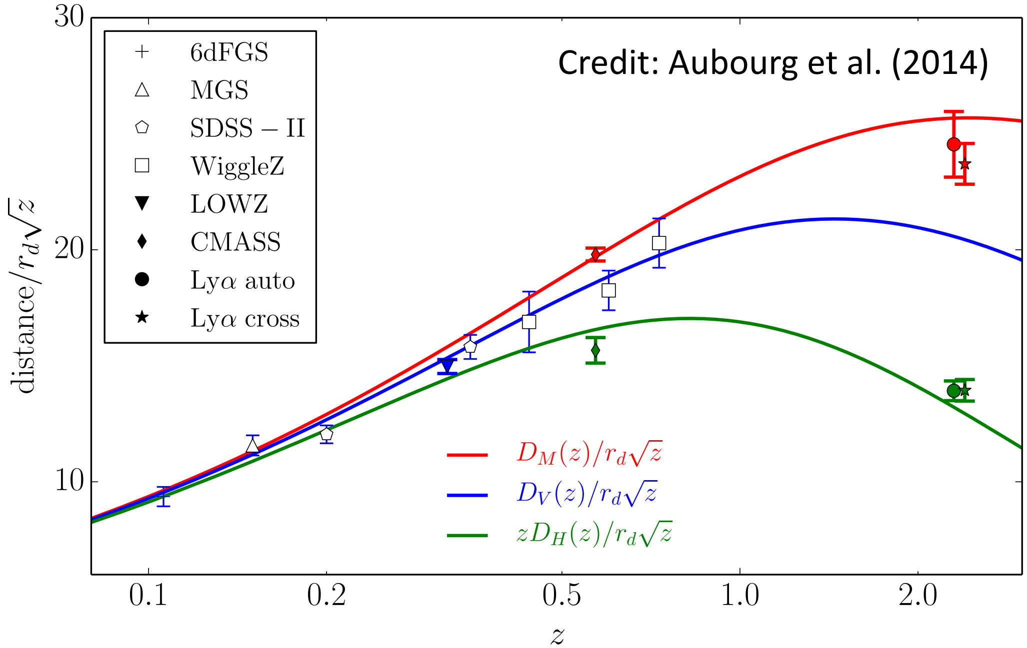


Homogeneous expansion of the Universe

Growth of perturbations within the expanding background

Cosmological observations

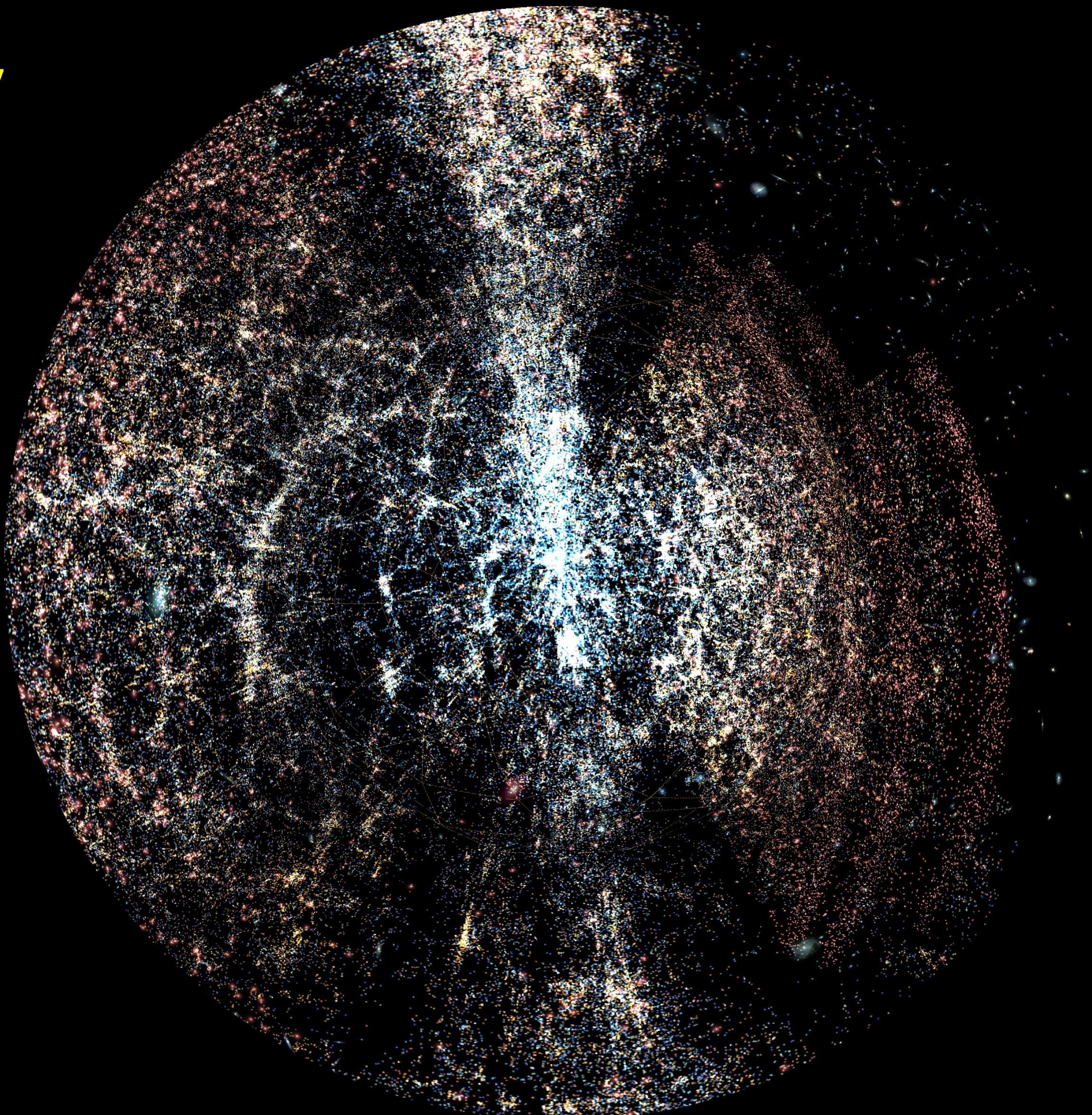




- The **cosmic expansion history** has been measured with ~1% accuracy using supernovae and baryon acoustic oscillations
- The **cosmic growth history** has not yet been measured as accurately, but is crucial for distinguishing physics

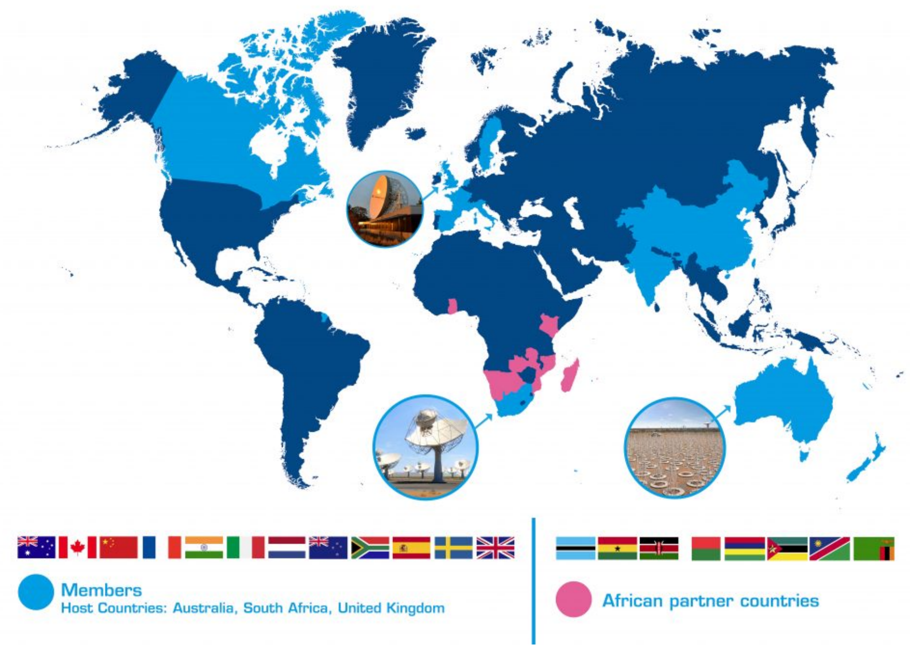
Cosmological observations

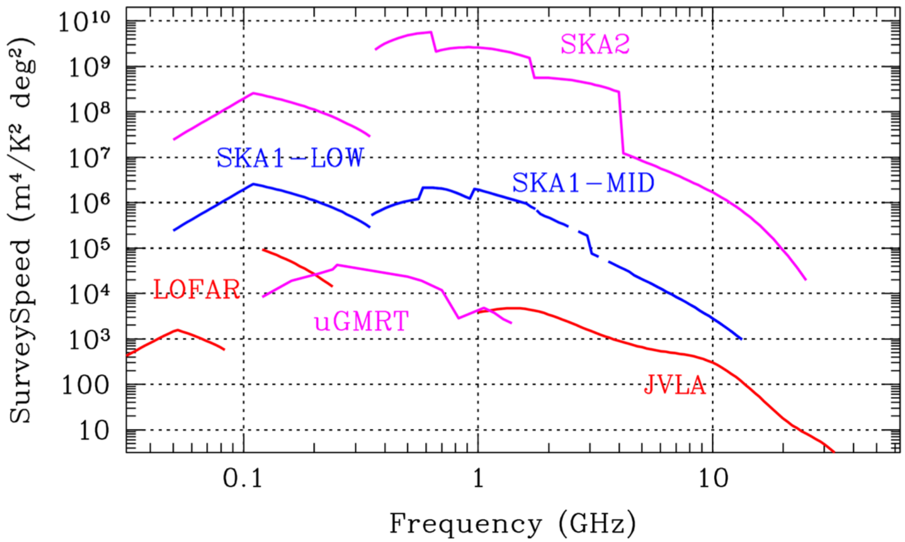
- There are a rich variety of observable signatures of the clumpy Universe …
- Clustering of galaxies
- Velocities of objects
- Gravitational lensing
- Abundance/properties of objects
- Environmental effects



What is the SKA project?

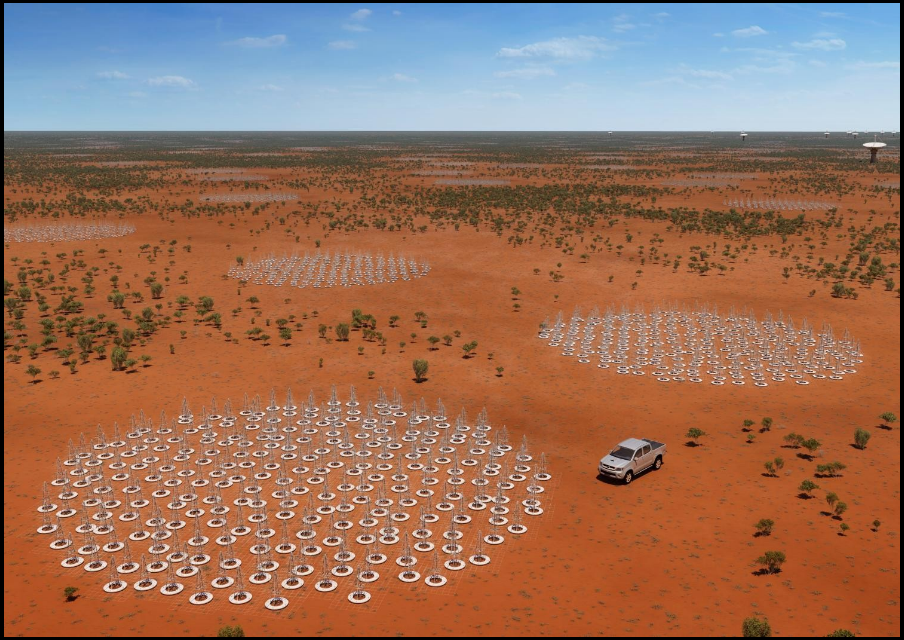
- An international effort to build the **world's largest radio telescope**, with (eventually) $\sim 1\ km^2$ of collecting area
- Increased resolution and sensitivity, and **vastly increased survey speed**, compared to current instruments
- Can detect airport radar on a planet 10 light years away, Milky Way at $z \sim 1$!





Two telescopes!

SKA1 LOW (Australia)



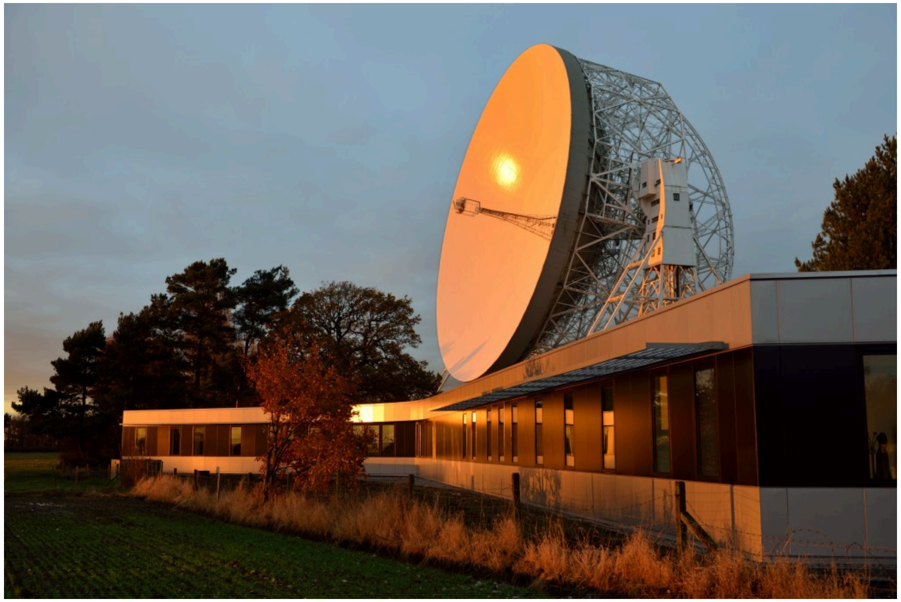
- 50-350 MHz
- $\sim$130,000 antennae
- Collecting area $\sim 0.4\ km^2$
- Max. baseline $\sim 65\ km$

SKA1 MID (South Africa)

- 350 MHz – 14 GHz
- $\sim$200 dishes
- Collecting area $\sim 33{,}000\ m^2$
- Max. baseline $\sim 150\ km$

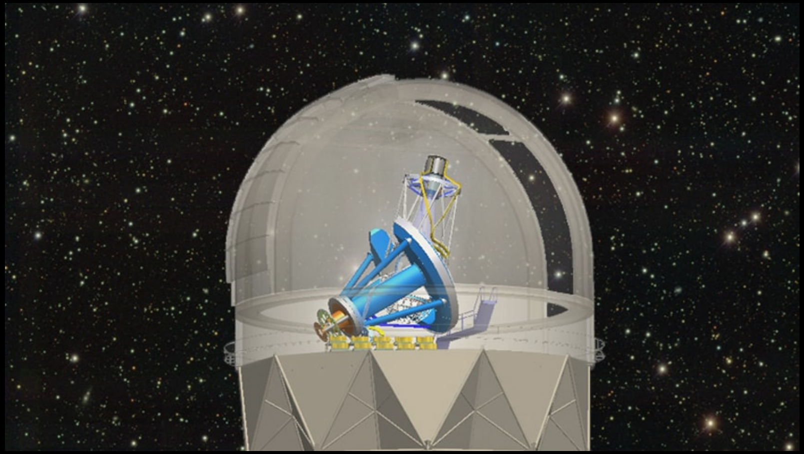
A brief timeline …

- 1990s: SKA development begins
- 2000: International SKA steering committee established
- 2011: SKA Organization established
- July 2018: MeerKAT inaugurated
- **2018-2024: SKA Phase 1 (SKA1) construction (650M Euro)**
- 2022: SKA1 commissioning
- 2025-: SKA1 Key Science Projects
- mid-2020: Phase 2 upgrades (?)

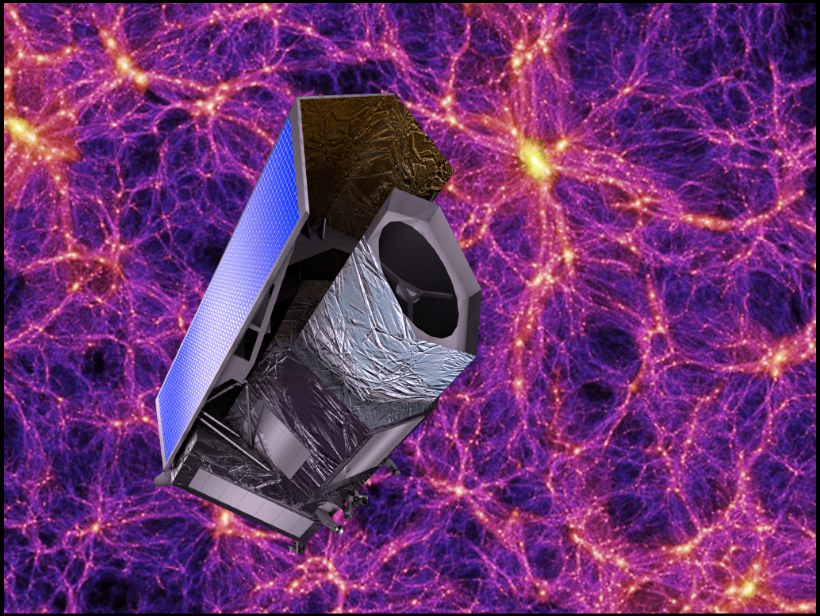


Other major facilities on the way!

Dark Energy Spectroscopic Instrument (DESI)



Euclid satellite



Large Synoptic Survey Telescope (LSST)

What is the SKA cosmology case?

Publications of the Astronomical Society of Australia (PASA)
doi: 10.1017/pas.2018.xxx.

See https://arxiv.org/pdf/1811.02743.pdf

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[4,5,6,2], 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

(For the purposes of this talk I'll exclude studies of the Epoch of Reionization, although it's also a key SKA science goal.)

What is the SKA cosmology case?

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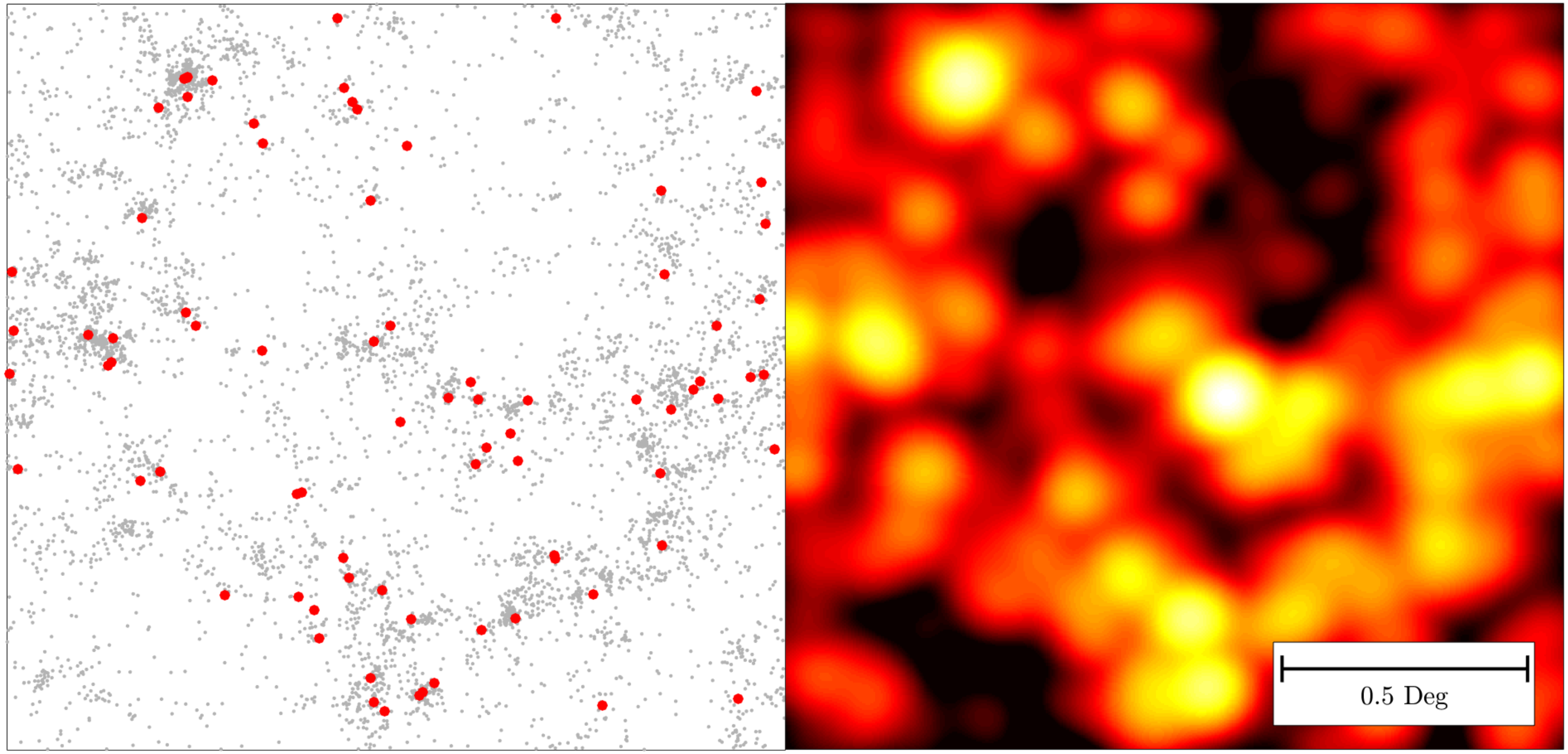
- Medium-deep ~1 GHz continuum weak lensing survey and low-z spectroscopic HI galaxy survey over 5000 sq deg
- Deep continuum / HI intensity mapping survey (350 MHz – 1 GHz, $0.35 < z < 3$) over 20,000 sq deg
- High-z ($3 < z < 6$) intensity mapping survey over 100 sq deg

HI intensity mapping

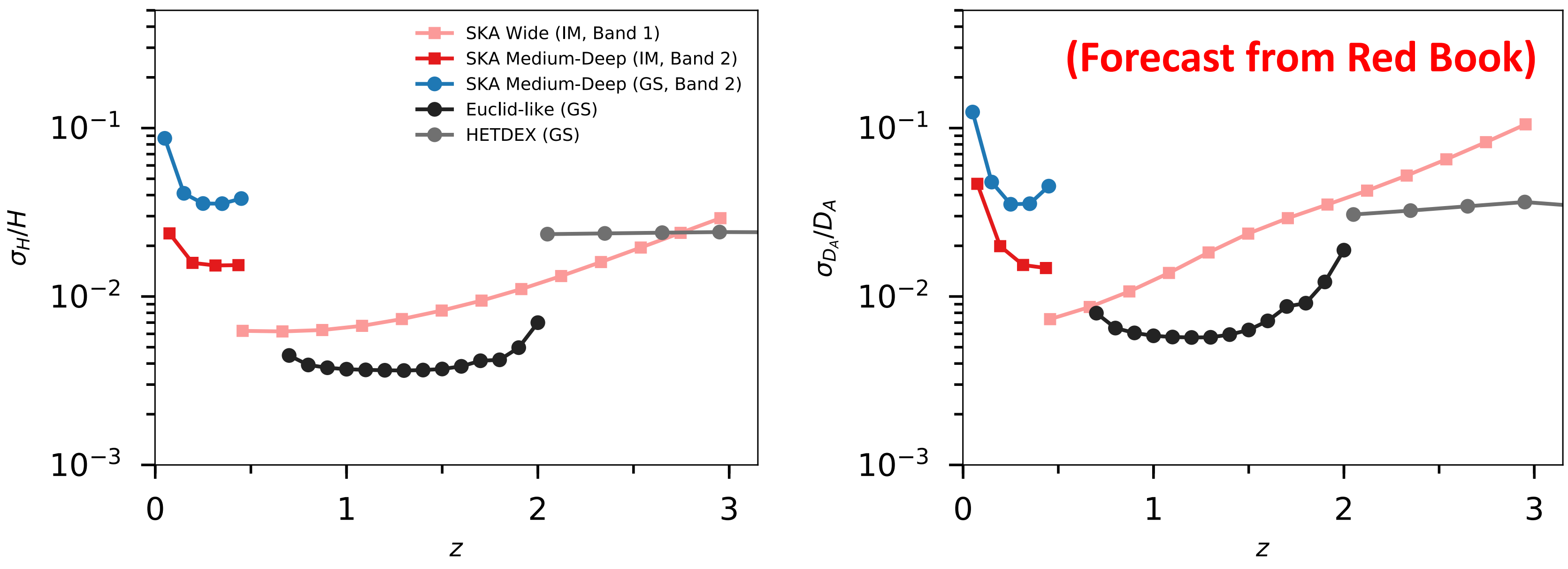
- 21 cm surveys which do not resolve individual galaxies, but the **integrated emission in each pixel** of a datacube



Credit: Kovetz et al., arXiv:1709.09066

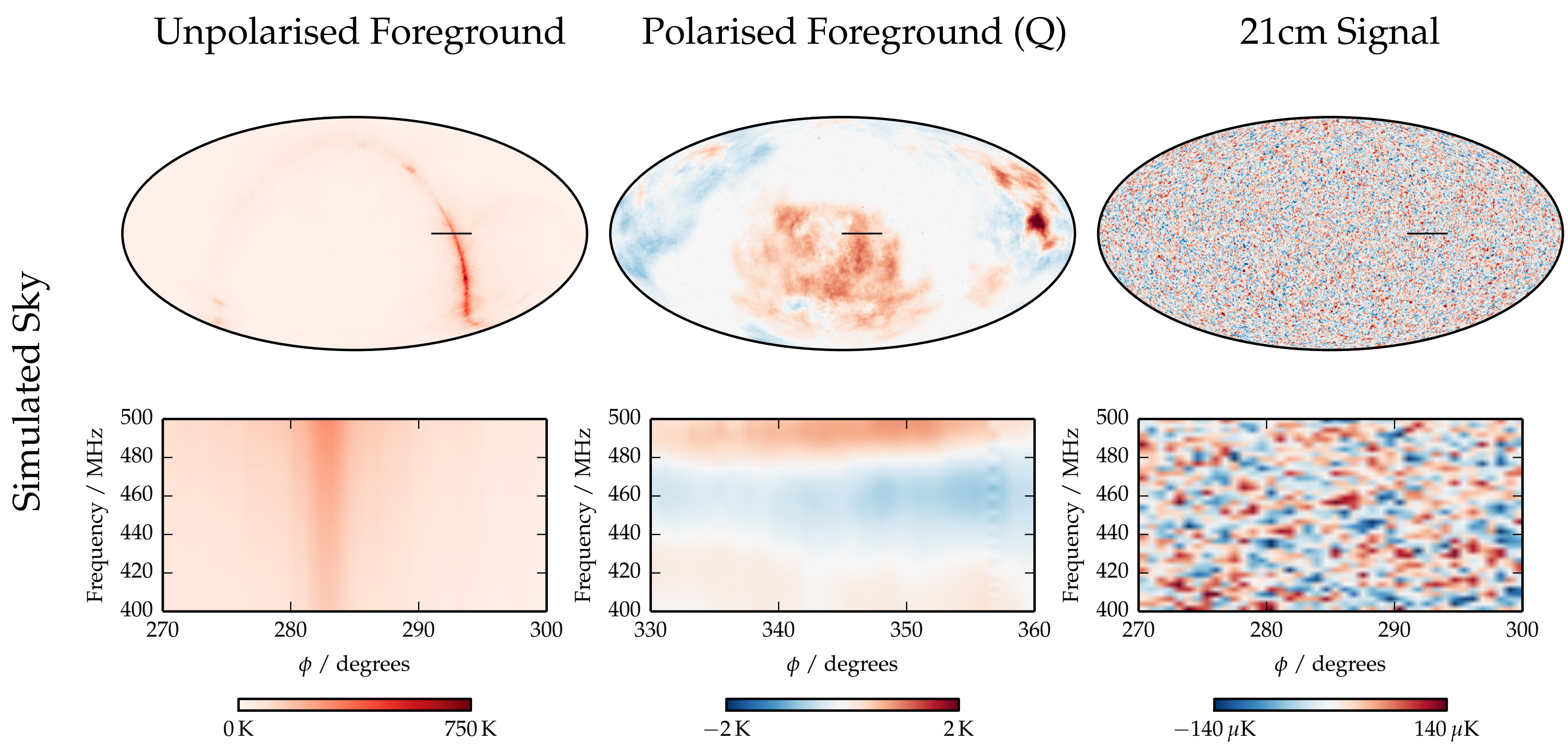
HI intensity mapping

- 21 cm surveys which do not resolve individual galaxies, but the **integrated emission in each pixel** of a datacube
- Enables mapping of **large cosmological volumes**, potential accurate measurement of large-scale features such as **baryon acoustic oscillations**, **non-Gaussianity**, etc.



HI intensity mapping

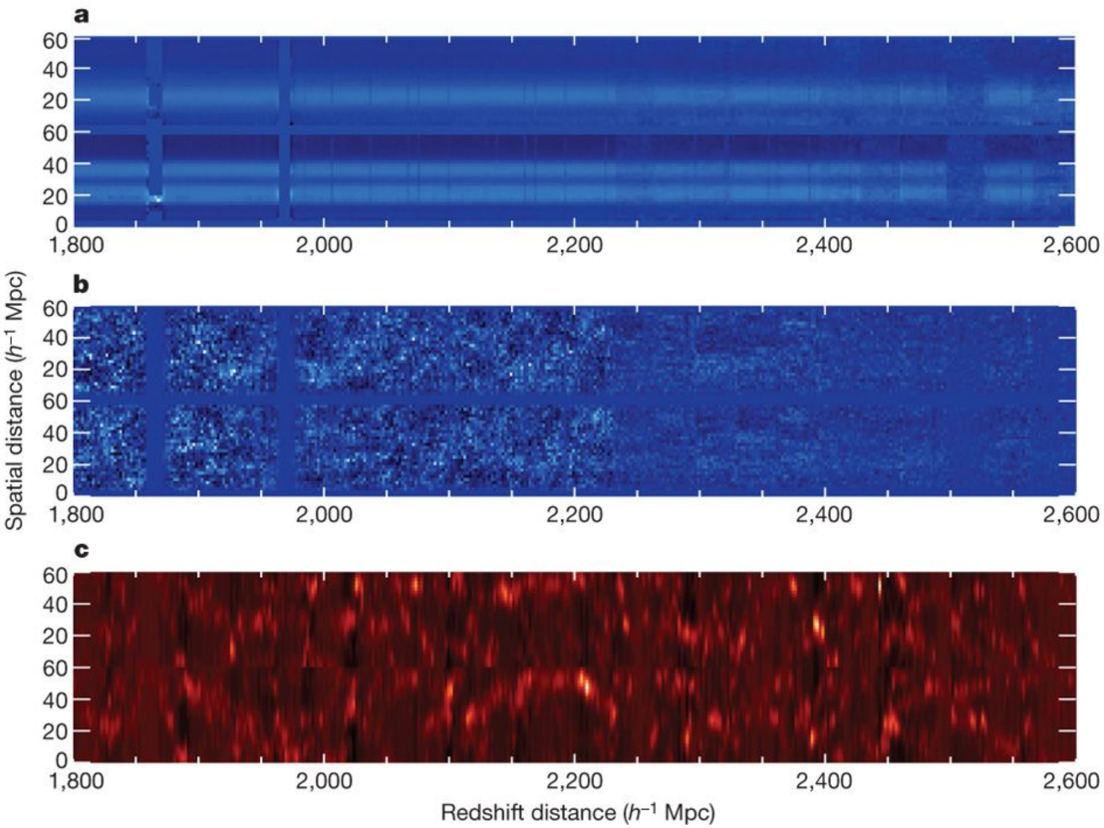
- Main issue is subtracting the **foreground emission**, which is orders of magnitude larger than the HI signal

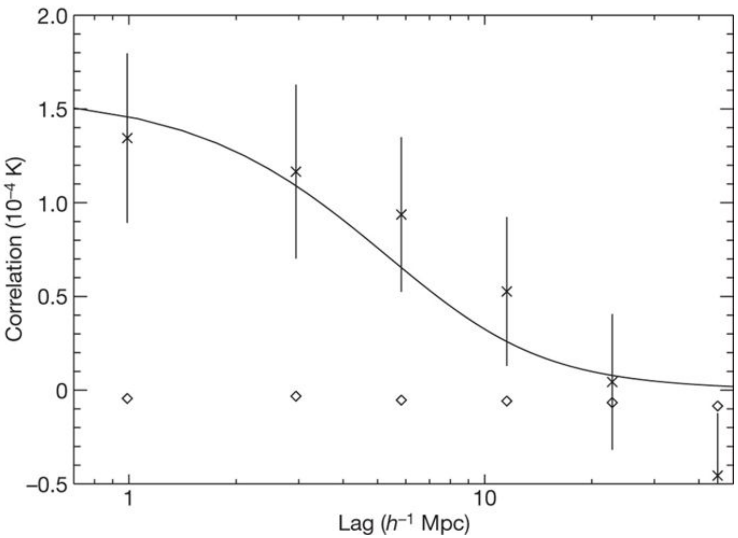


Credit: Bandura et al. (CHIME), arXiv:1406.2288

HI intensity mapping

- Even in the presence of foregrounds, **cross-correlations between HI maps and optical datasets** allow the neutral hydrogen content of galaxies to be mapped over redshift

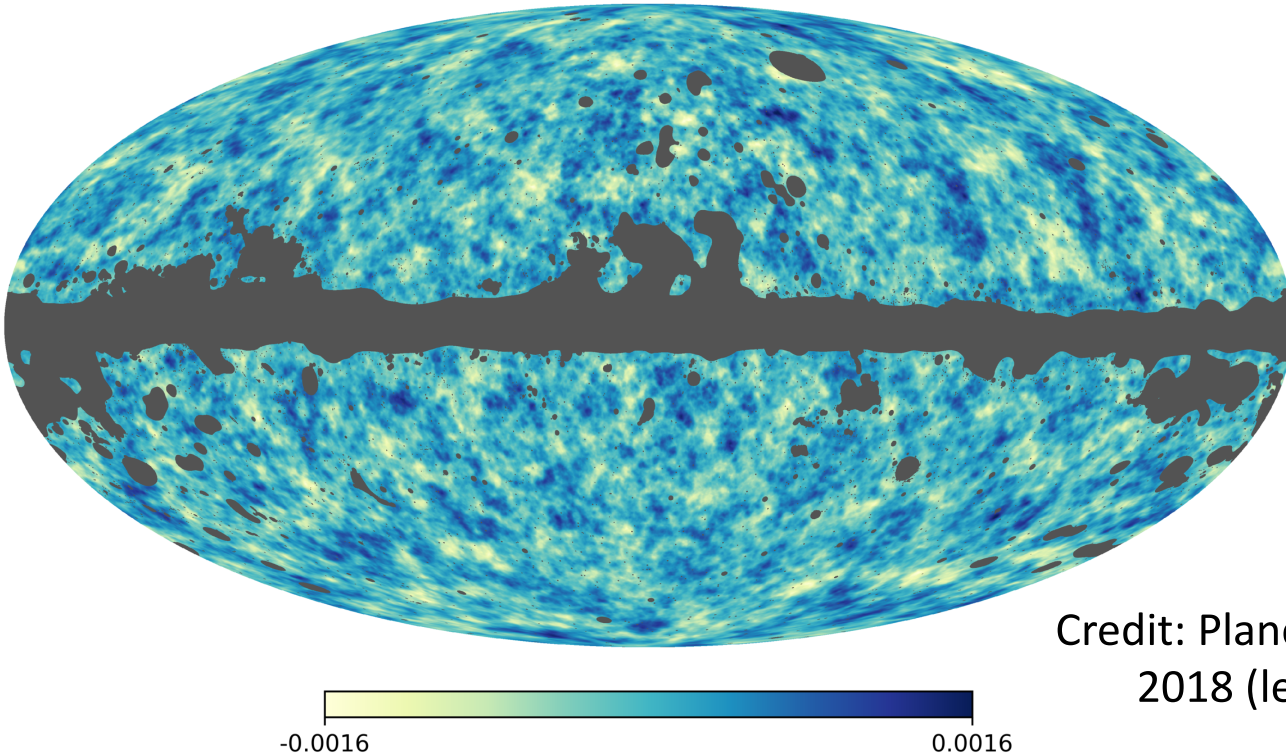




Credit: Chang et al., arXiv:1007.3709

Continuum surveys: cross-correlations

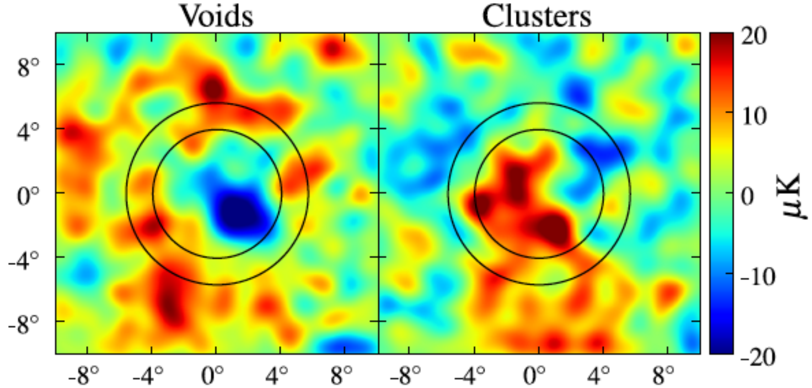
- **Radio continuum surveys trace the high-z density field**
- Expect correlations with the CMB (**late-time ISW effect, lensing**) and low-redshift galaxies (**cosmic magnification**)

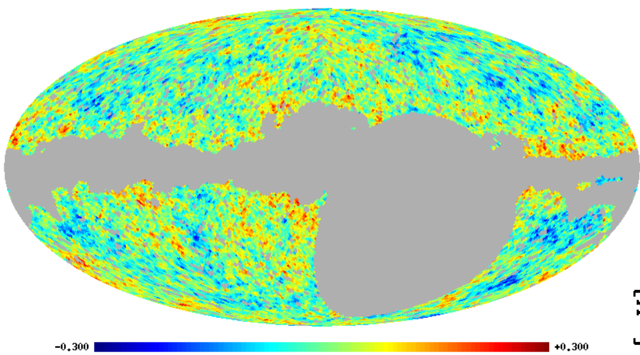


Credit: Planck collaboration 2018 (lensing map)

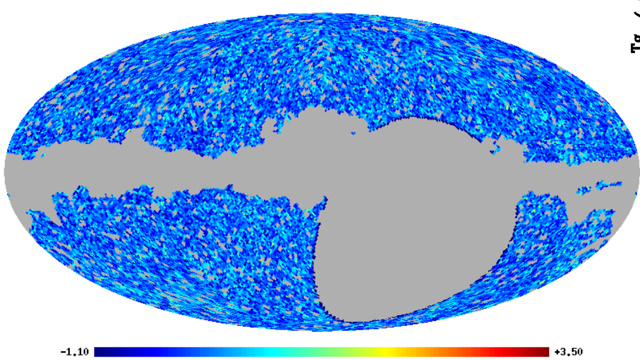
Continuum surveys: cross-correlations

- The **integrated Sachs-Wolfe effect** is physical evidence of dark energy, but not a precise probe of its properties

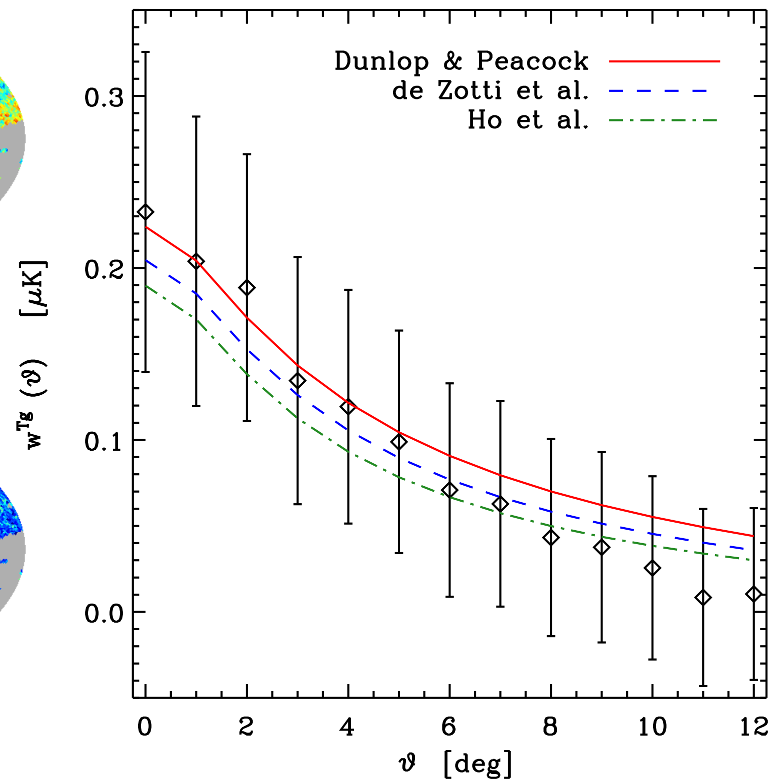




(a) WMAP



(b) NVSS



Nolta et al., astro-ph/0305097

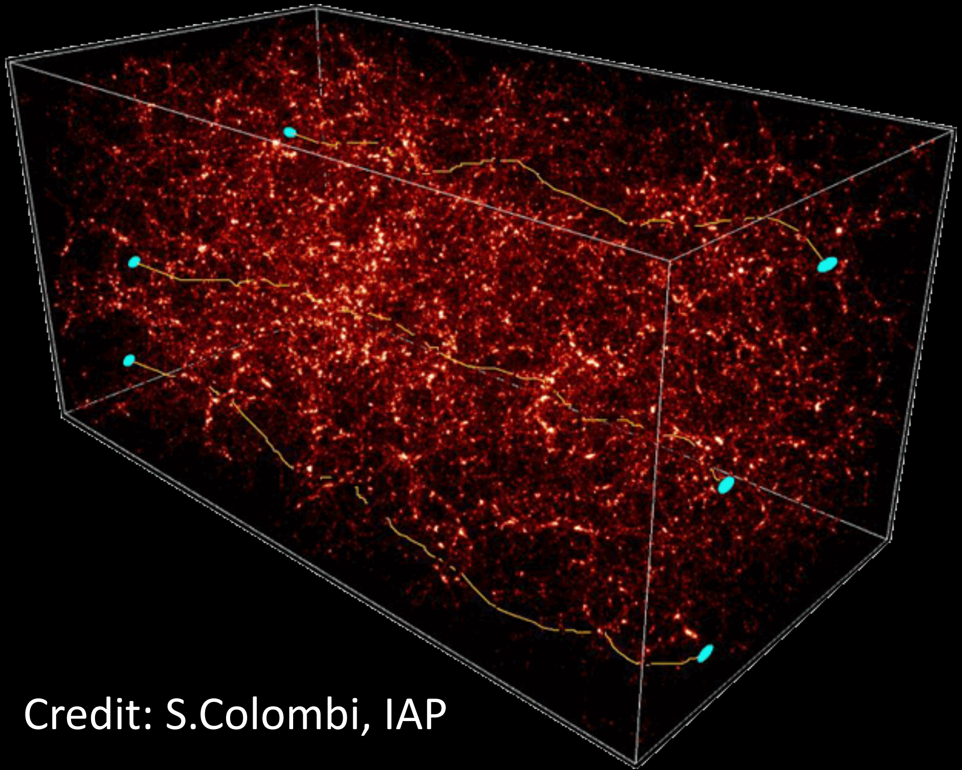
Granett et al., arXiv:0805.3695

McEwen et al., arXiv:0704.0626

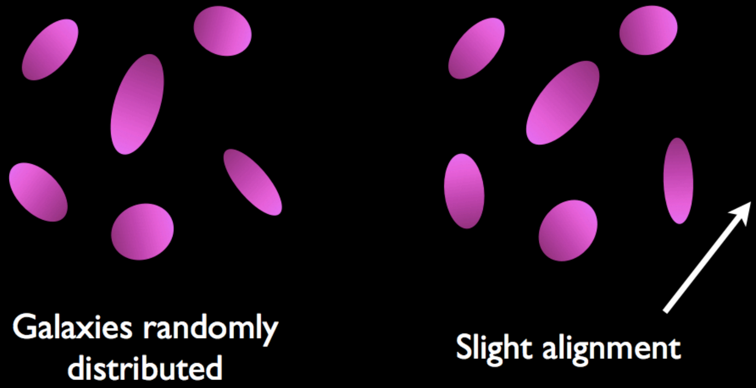
Giannantonio et al., arXiv:1209.2125

Continuum surveys: weak lensing

- Weak lensing refers to the **tiny, correlated distortions imprinted in the shapes of distant galaxies**, as their light travels to us through the cosmic web of large-scale structure
- It probes the mass distribution, geometry and gravity



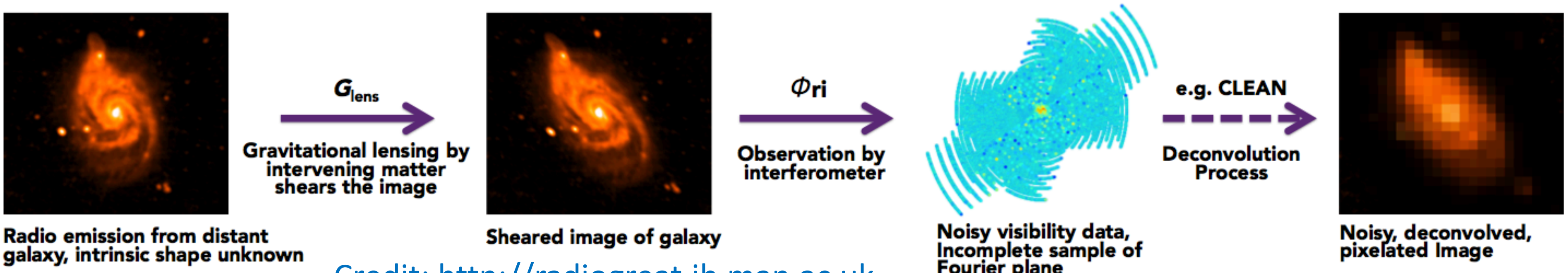
Credit: S.Colombi, IAP



Credit: E.Grocutt, Edinburgh

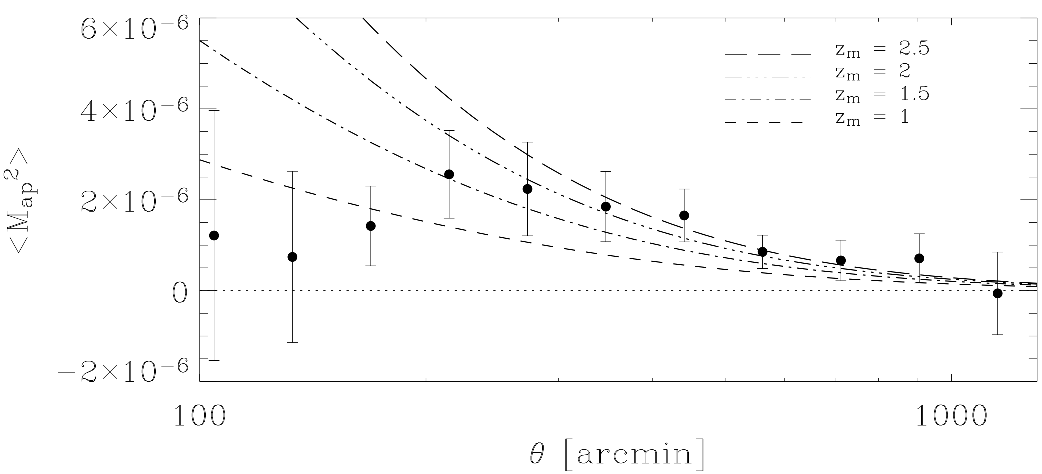
Continuum surveys: weak lensing

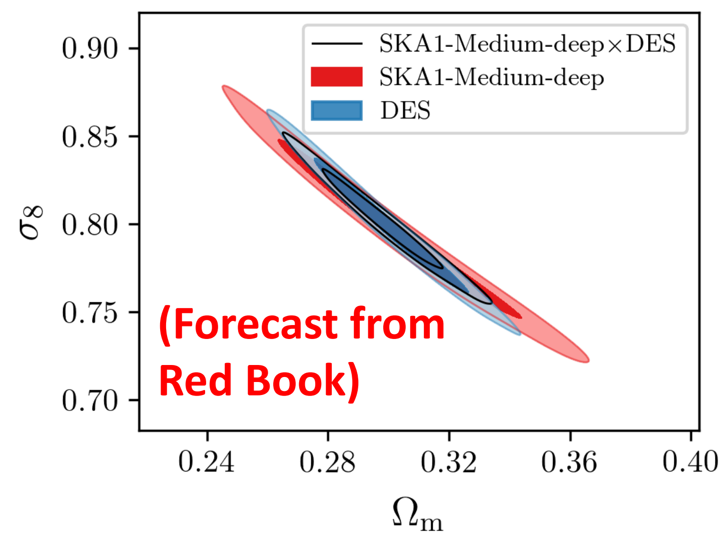
- Radio surveys probe the high-z Universe and could allow galaxy shapes to be measured with **independent systematics**



Credit: http://radiogreat.jb.man.ac.uk

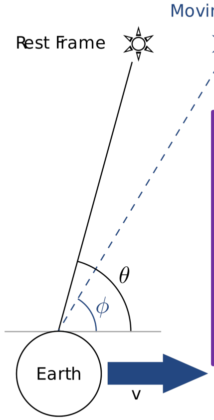
Detection from Chang et al. (astro-ph/0408548)



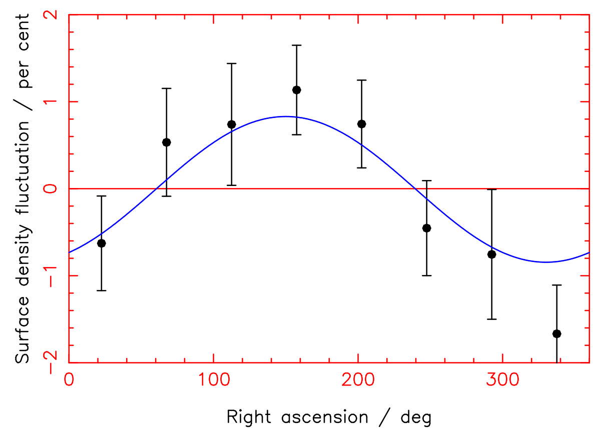


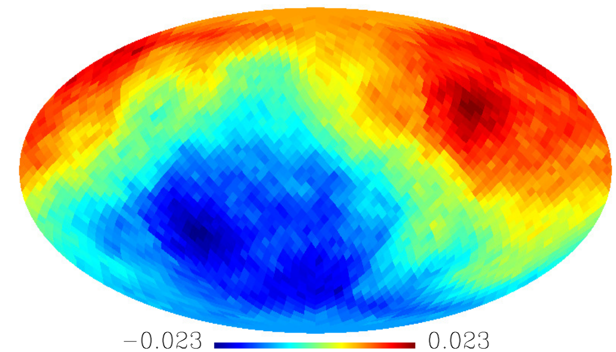
Continuum surveys: dipoles!

- Faint source counts over the sky allow cosmological tests of isotropy and homogeneity, such as the **velocity dipole**

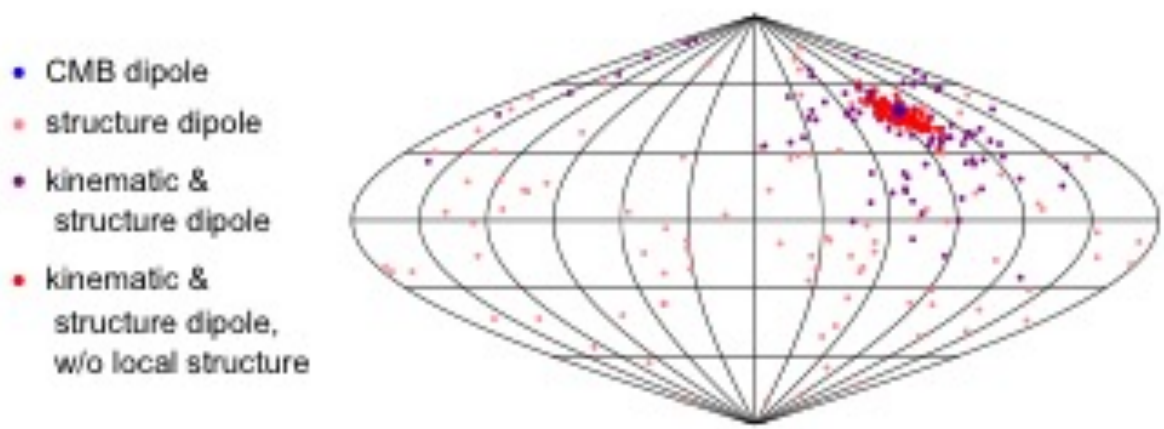


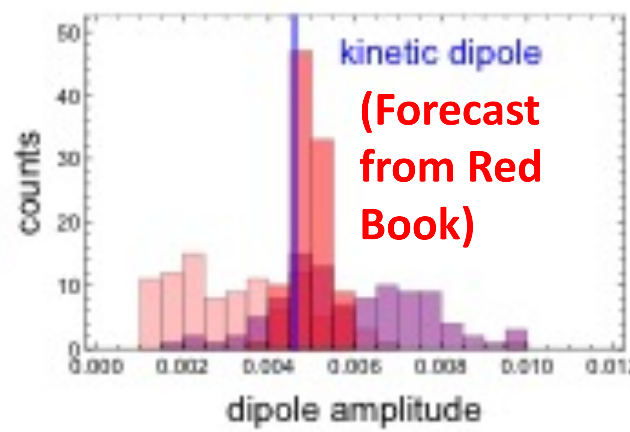
Detected by Blake & Wall (astro-ph/0203385)





Bengaly & Santos, arXiv:1710.08804





Challenges

- The data challenges! (e.g. data output of SKA1 LOW is 5 zettabytes per year, or 35,000 DVDs per second!)
- The systematics challenges! (all measurements in cosmology will be limited by systematics, not statistics)
- The sociological challenges! (science in huge teams)

Summary

- Some important cosmological mysteries remain to be uncovered, such as the physics represented by dark energy
- We are entering the era of large cosmological surveys
- SKA1 will be operational from the mid-2020s, performing cosmology over $0 < z < 6$ with two telescope arrays
- This will bring unique capabilities (e.g. intensity mapping) and complementarity with optical surveys
- Multiple pathfinders are already operational (e.g. MeerKAT, CHIME, ASKAP, LOFAR, MWA, etc.)