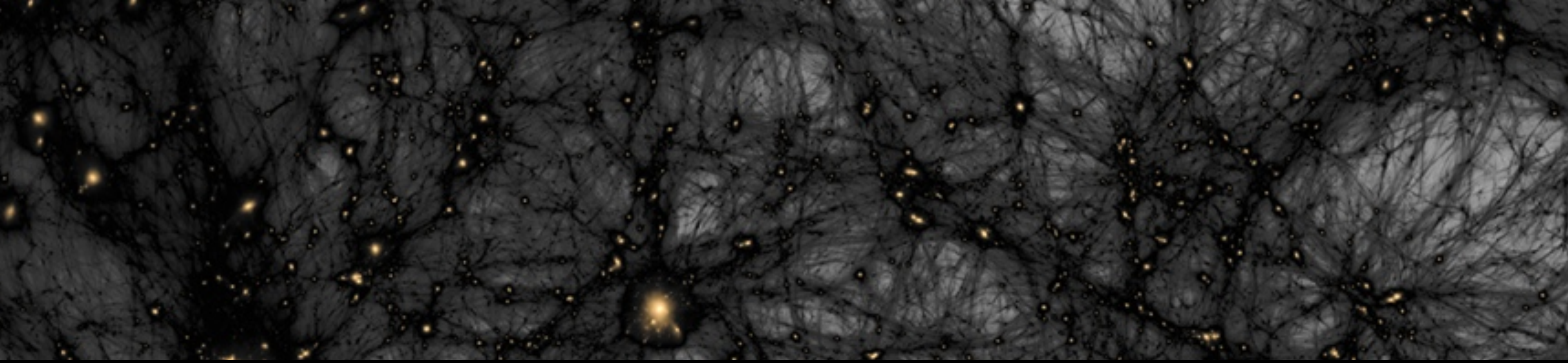


LECTURE II: RADIO ASTRONOMY & COSMOLOGY

Alkistis Pourtsidou

Queen Mary University of London

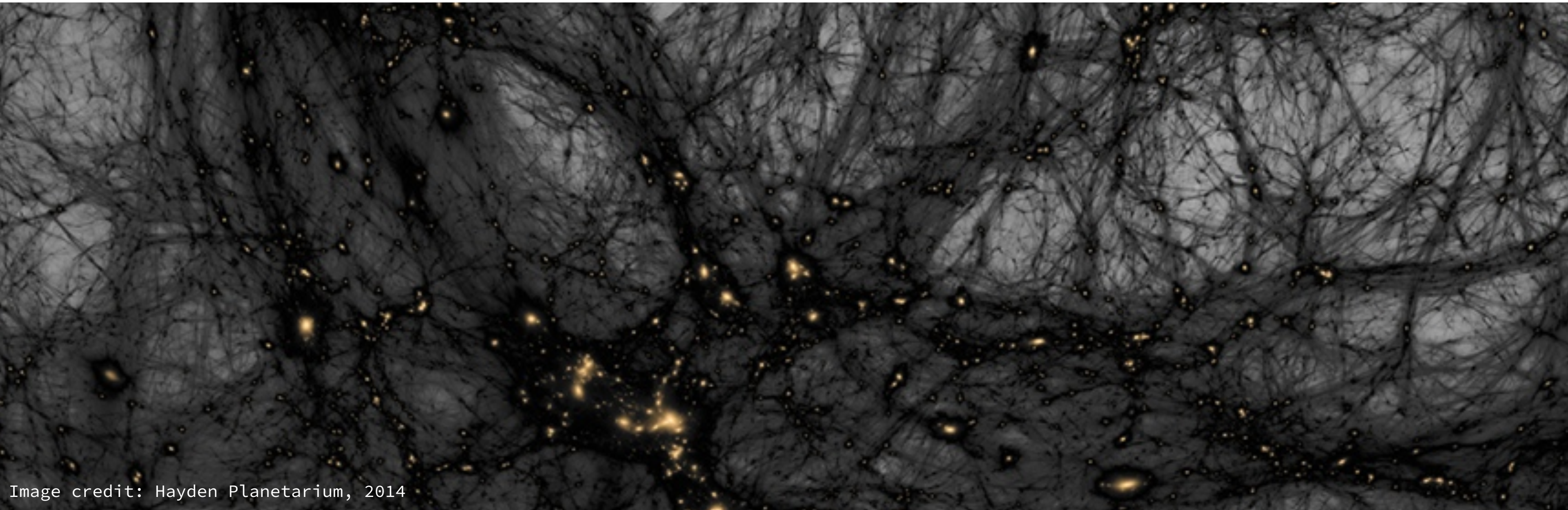
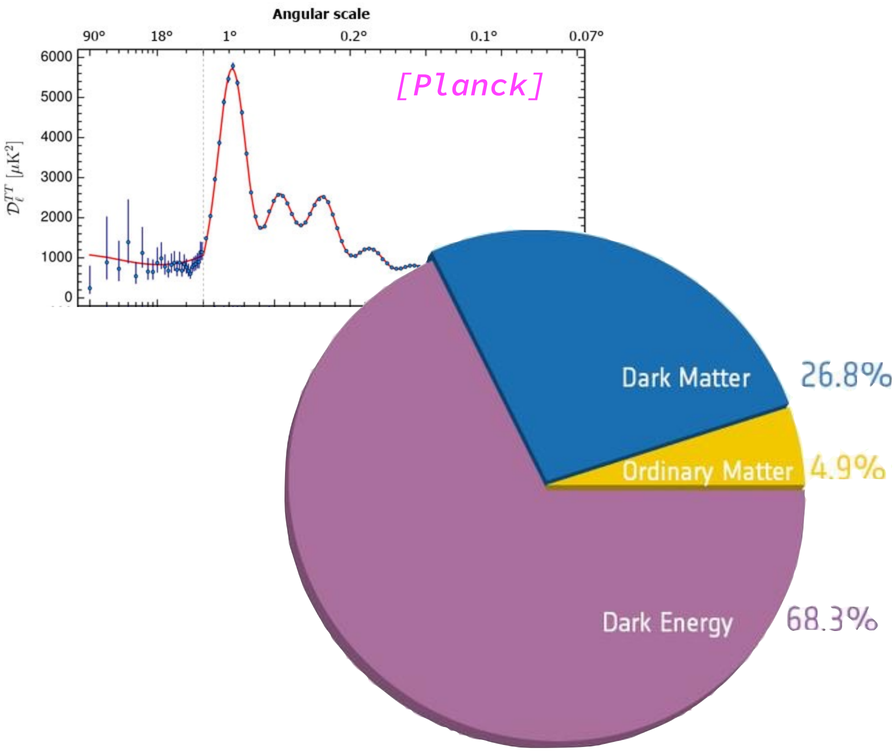
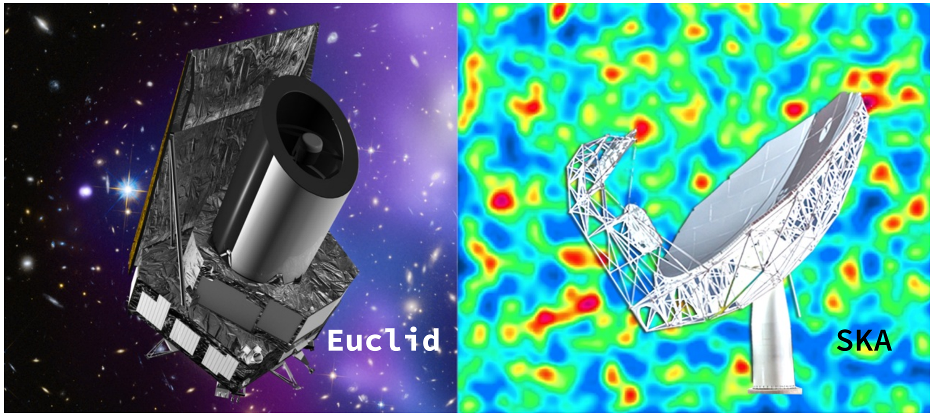


Image credit: Hayden Planetarium, 2014

New Frontiers in Observational Cosmology

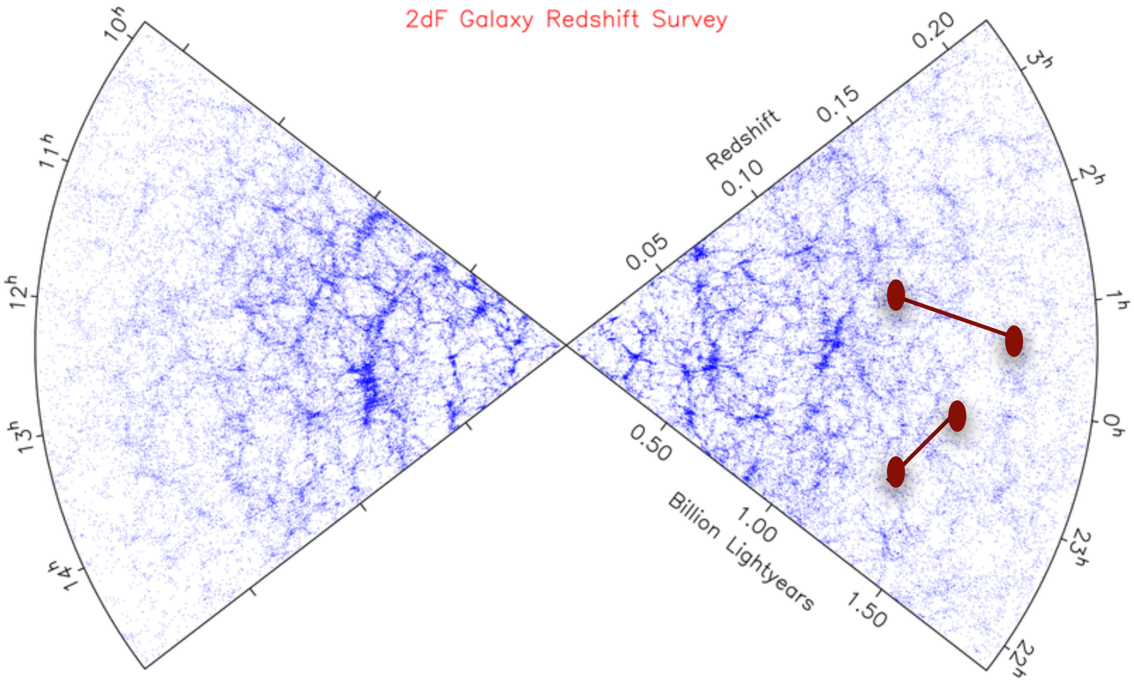


- ✦ 95% of our Universe is very strange - new physics!
- ✦ Use **large scale structure surveys**, multiple wavelengths, and multiple probes
- ✦ Invest in pathfinders
- ✦ Exploit synergies



WHAT IS LARGE SCALE STRUCTURE?

We use the positions of galaxies as tracers for the underlying dark matter distribution (as a function of time).



Galaxy Clustering

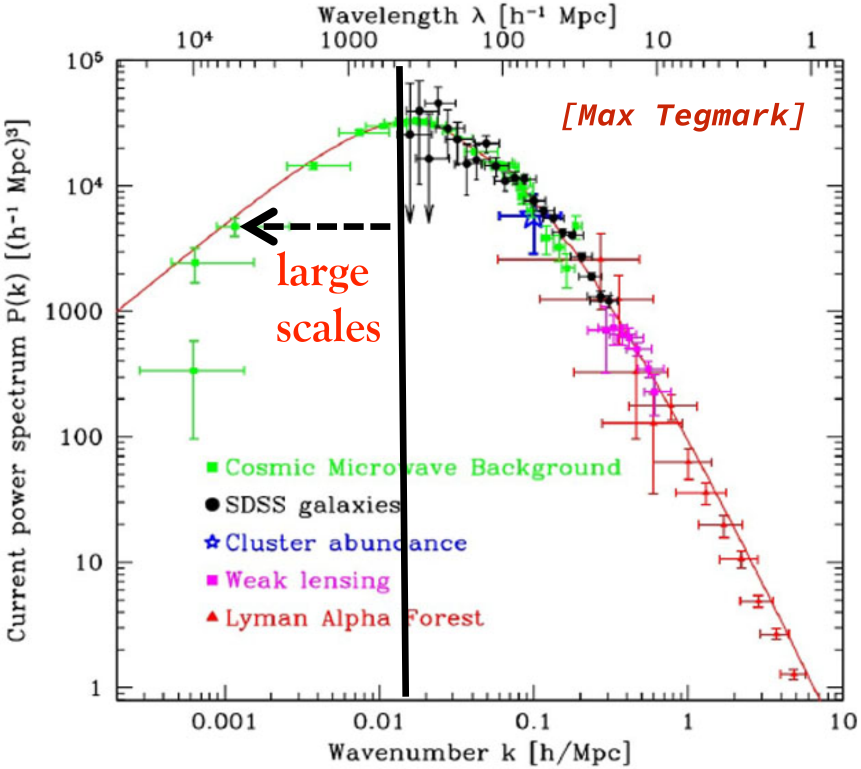
# of pairs as a function of distance w.r.t pairs distributed randomly

We are interested in density fluctuations. We characterise those statistically through correlation functions / power spectra.

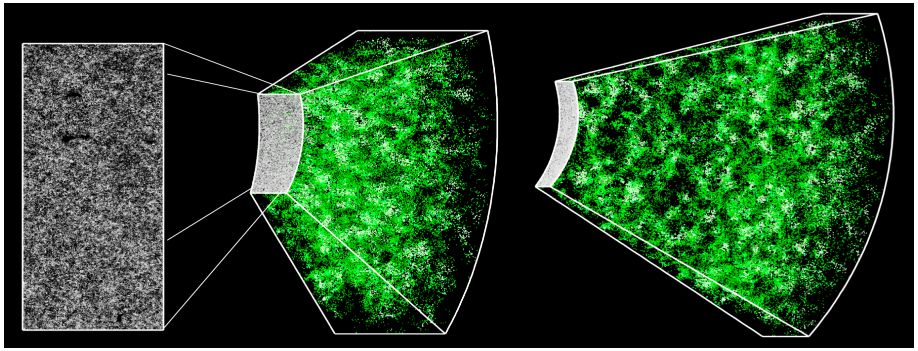
Adapted slide from Martin Crocce

OPTICAL GALAXY SURVEYS

Galaxies trace the underlying dark matter distribution – statistical sampling, more volume and more galaxies, better precision!



- **Spectroscopic:** Very precise redshifts [BOSS/DESI/Euclid]



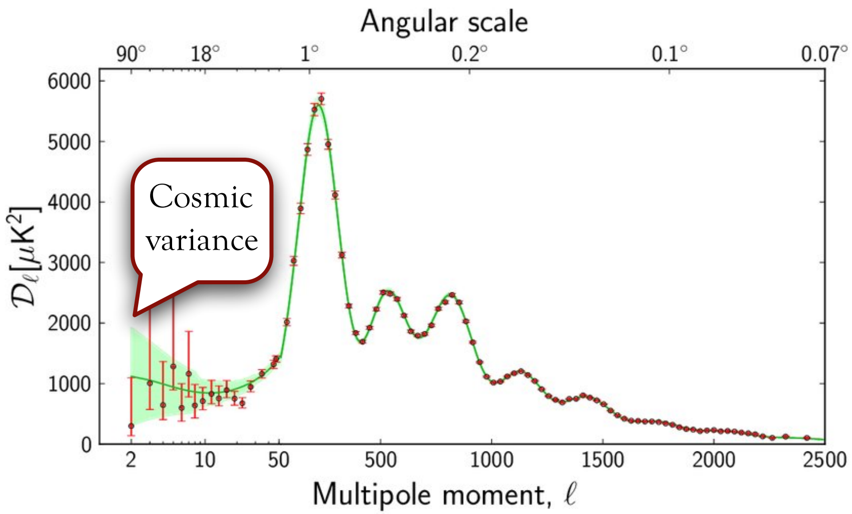
BOSS

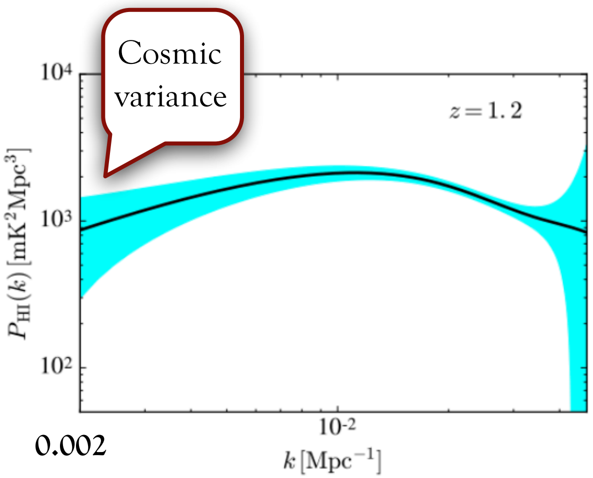
- **Photometric:** Large sky, many galaxies, uncertain redshifts [DES/LSST]

LSST

Optical measurements

Two sources of statistical noise: (1) cosmic variance (2) shot noise

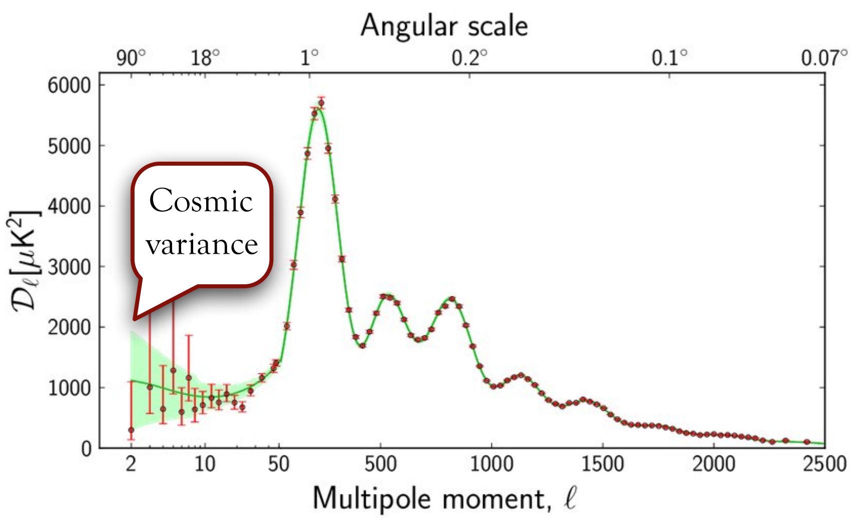


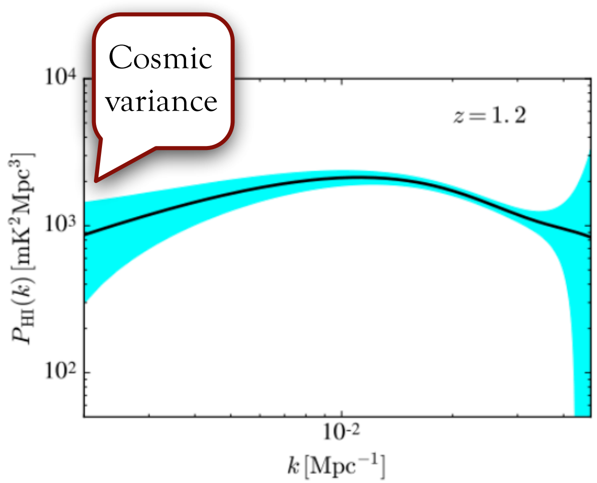


- Cosmic variance is an inherent statistical uncertainty
- Can't get rid of it! (but see later...)
- It's a *sample variance* because the volume of the observable Universe is finite
- Finite number of observable modes: $N_{\rm modes}$

Optical measurements

Two sources of statistical noise: (1) cosmic variance (2) shot noise





- Cosmic variance is an inherent statistical uncertainty
- Can't get rid of it! (but see later…)
- It's a *sample variance* because the volume of the observable Universe is finite

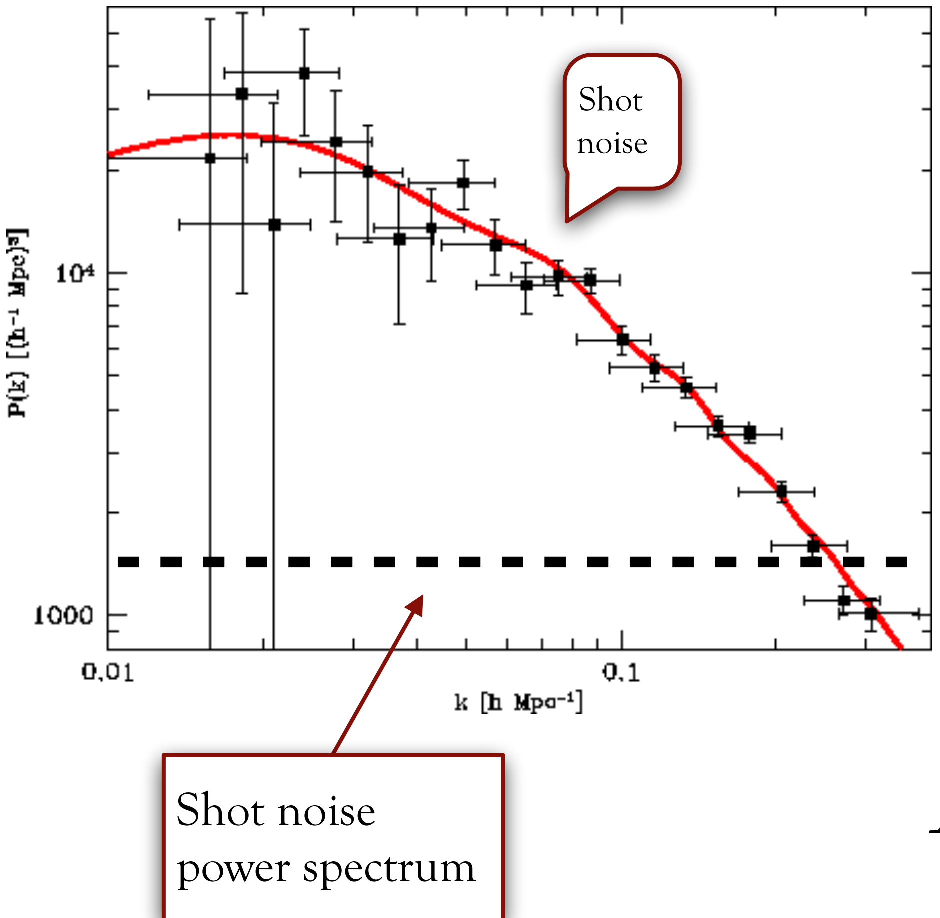
$$\sigma_P \propto \sqrt{1/N_{\rm modes}}$$

- Finite number of observable modes
- Dominates on the largest scales

Optical measurements

Two sources of statistical noise: (1) cosmic variance (2) shot noise [note we also need to worry about systematic effects, more about that in the next lecture]

[Max Tegmark]



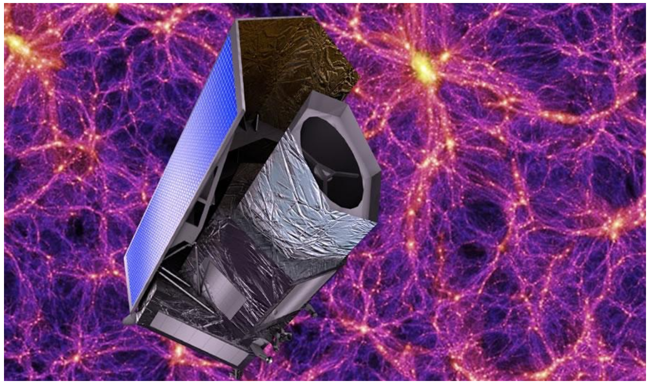
- Shot noise comes from sampling with discrete sources (galaxies)
- Discrete (Poisson) distribution
- The more galaxies the better

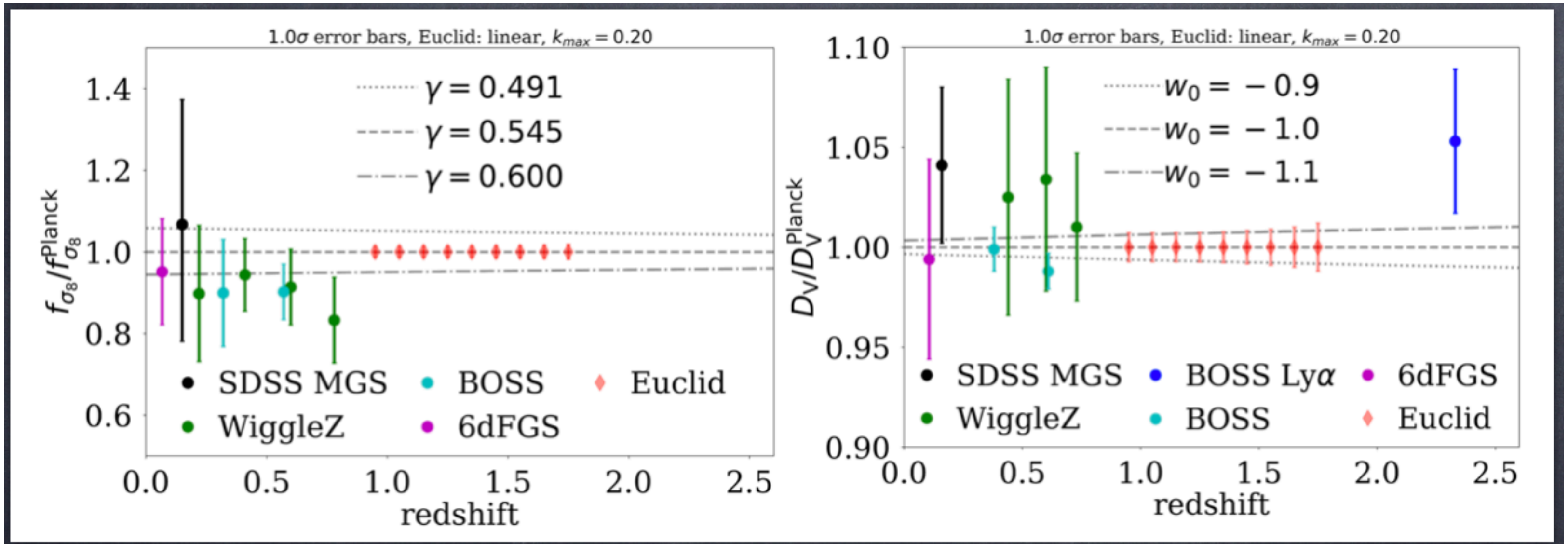
$$\sigma_P \propto \sqrt{1/N_{\rm gals}}$$

$$P^{\rm shot} = \frac{V_{\rm sur}}{N_{\rm gals}}$$

Example: The Euclid satellite

- ESA cosmic visions programme, launch late 2020
- 15,000 deg^2, millions of galaxies in $0.7<z<2$, galaxy clustering and weak lensing





Euclid-like forecasts

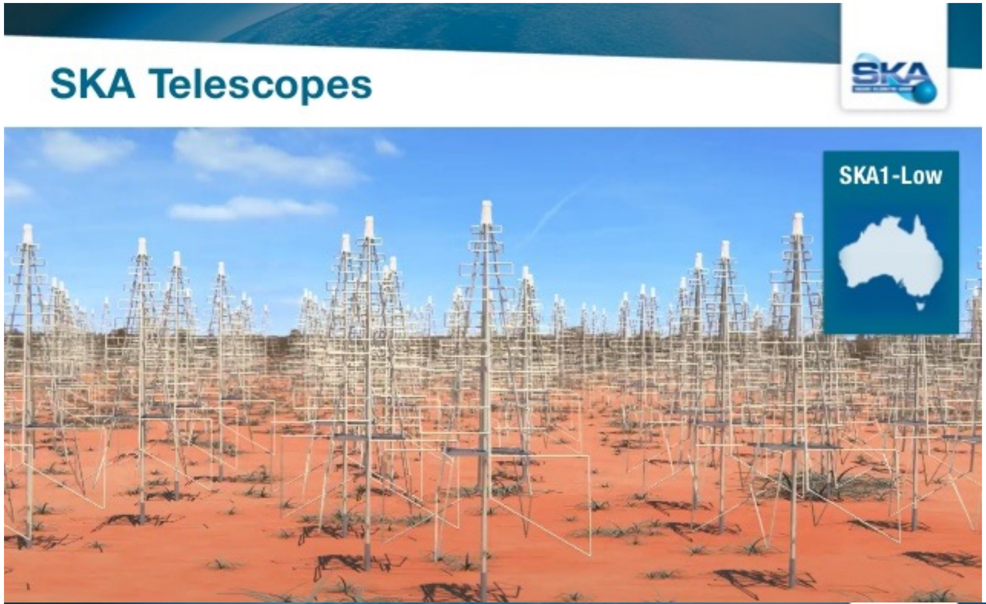
[AP and Dida Markovic]

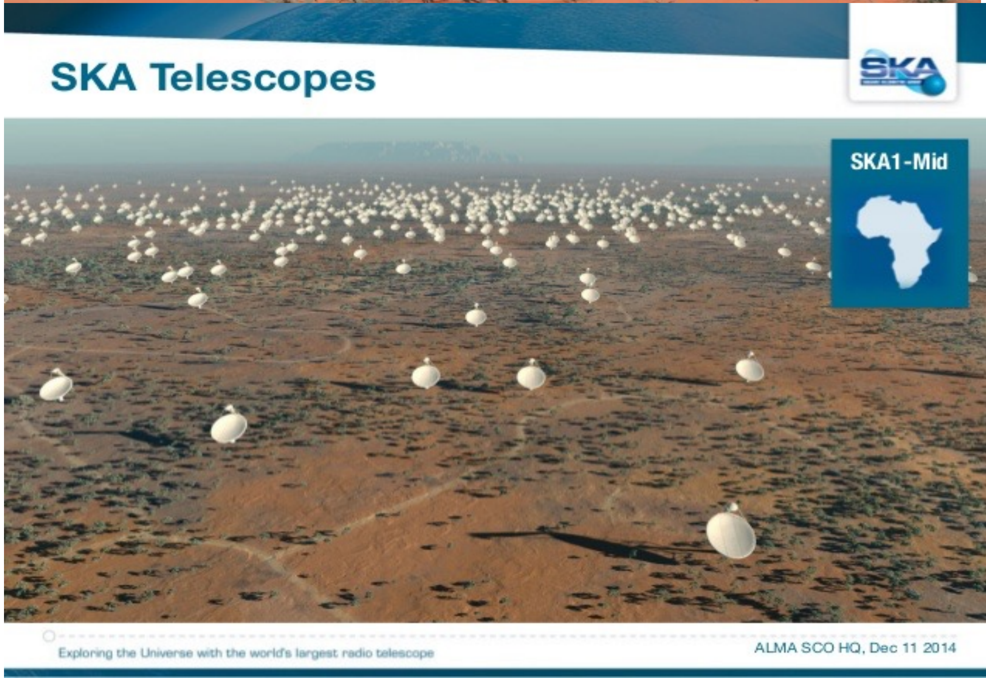
THE SQUARE KILOMETRE ARRAY (SKA)

- Series of radio telescopes, very sensitive to a wide range of frequencies (redshifts)
- **SKA Phase 1**: 2024+
- **MeerKAT** live now!

MeerKAT/SKA-Mid will complement and compete with optical galaxy surveys (0<z<3)

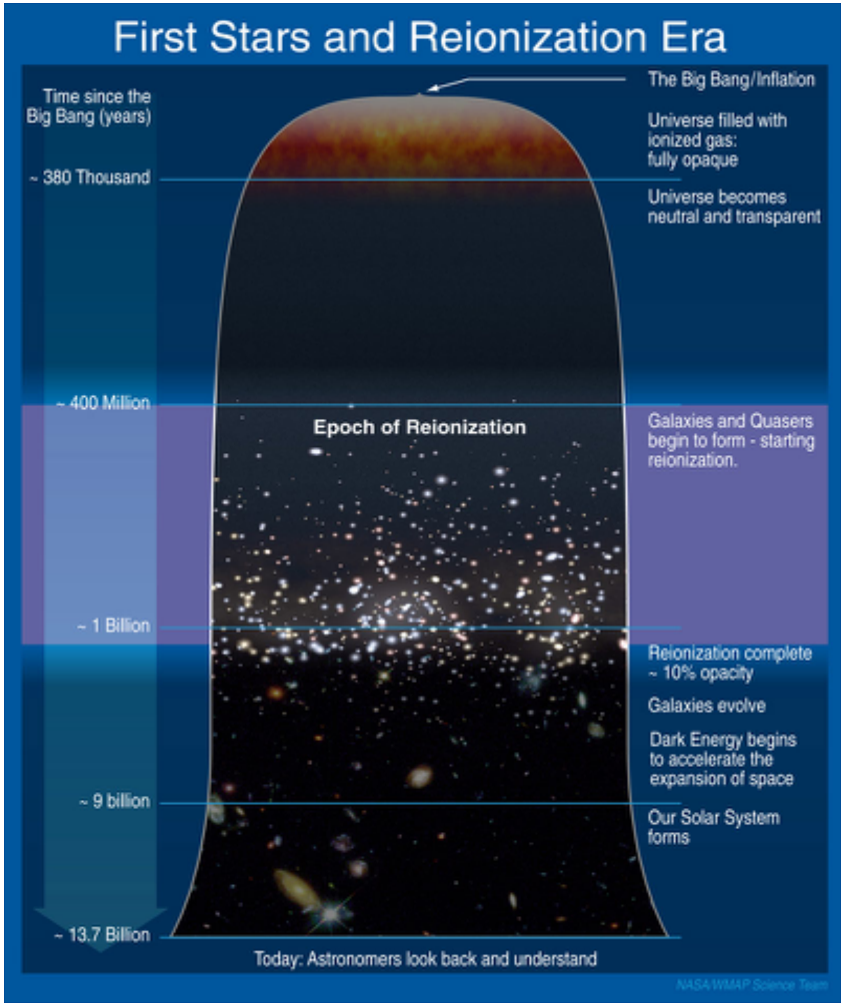
SKA-Low will explore the unknown! (3<z<25)



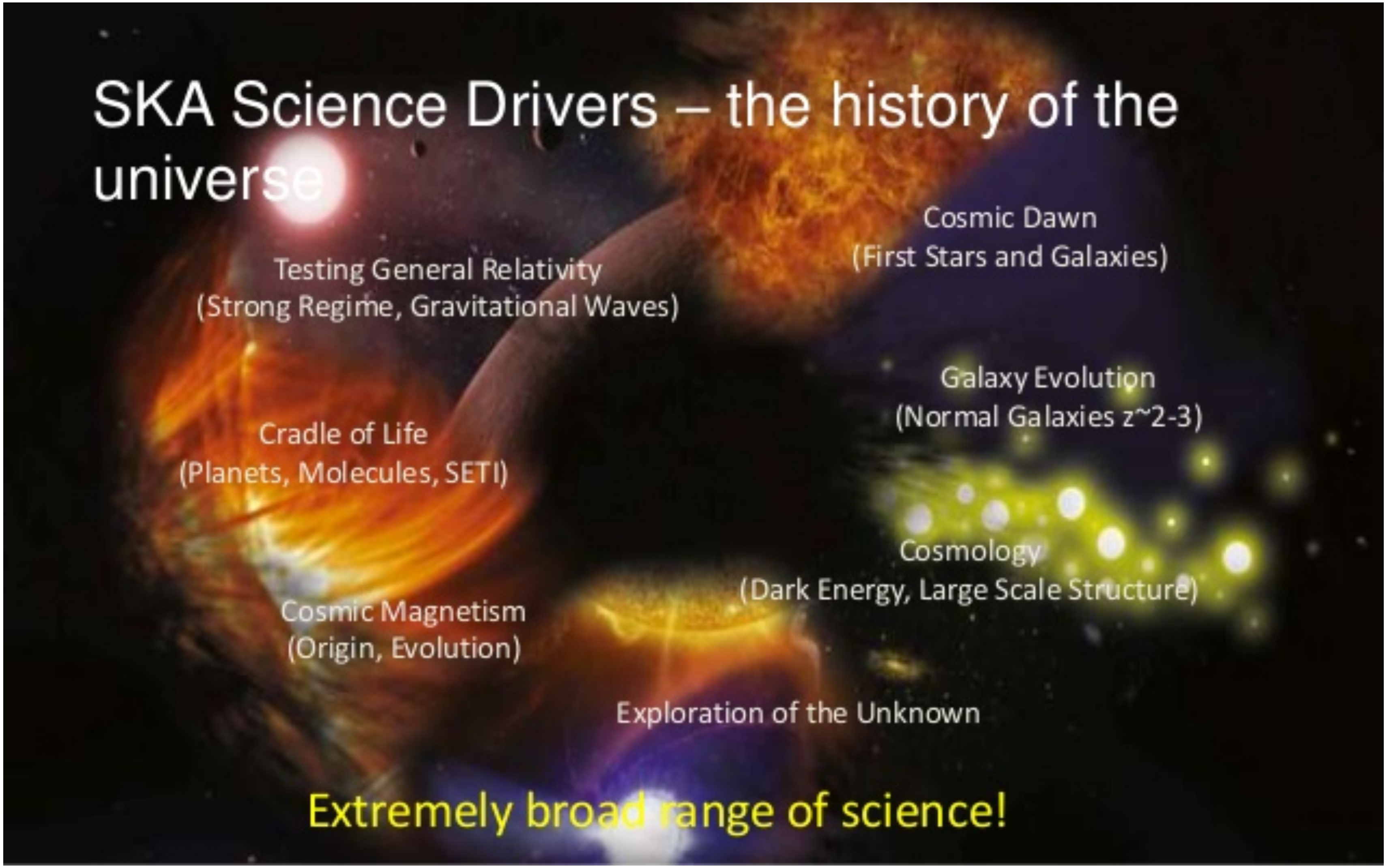


Brief history of the HI universe

- Radio surveys detect neutral hydrogen (HI)



SKA SCIENCE



SKA Office / A. Bonaldi

WHY DO WE BUILD RADIO ARRAYS? AREN'T SINGLE DISHES GOOD ENOUGH?

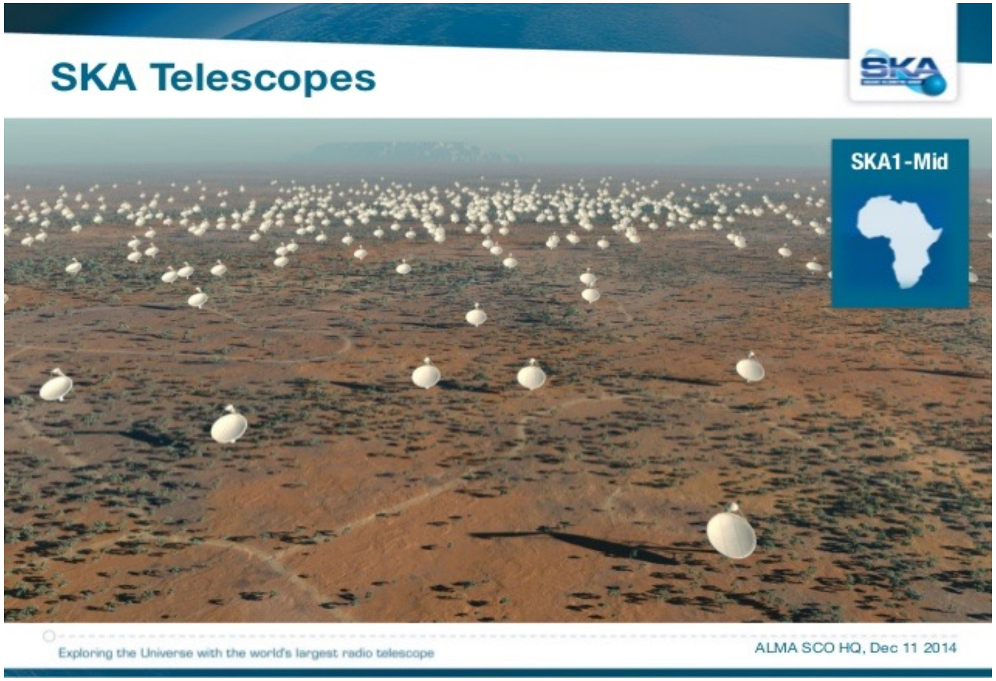
- In the early days of radio astronomy, single dishes were the norm
- Resolution $\theta_B = \lambda / D_{\text{dish}}$
- For precision astronomy, we need to distinguish fine detail on the sky… we need **sub-arcsecond resolution**

- But with a single dish, at about $D_{\text{dish}}=100$ m, we're done - and that's about as good resolution as our eyes (even with the shortest wavelengths)
- **Note:** the Green Bank Telescope (GBT) has 100 m diameter and its fully steerable - we'll talk more about it later on

https://public.nrao.edu/telescopes/radio-telescopes/

RADIO INTERFEROMETRY

- We simply cannot build or operate a single radio dish of 1 square kilometre collecting area
- **Idea:** combine the views of a group of dishes/antennae spread over a large area
- Operate them together as a single, gigantic telescope!

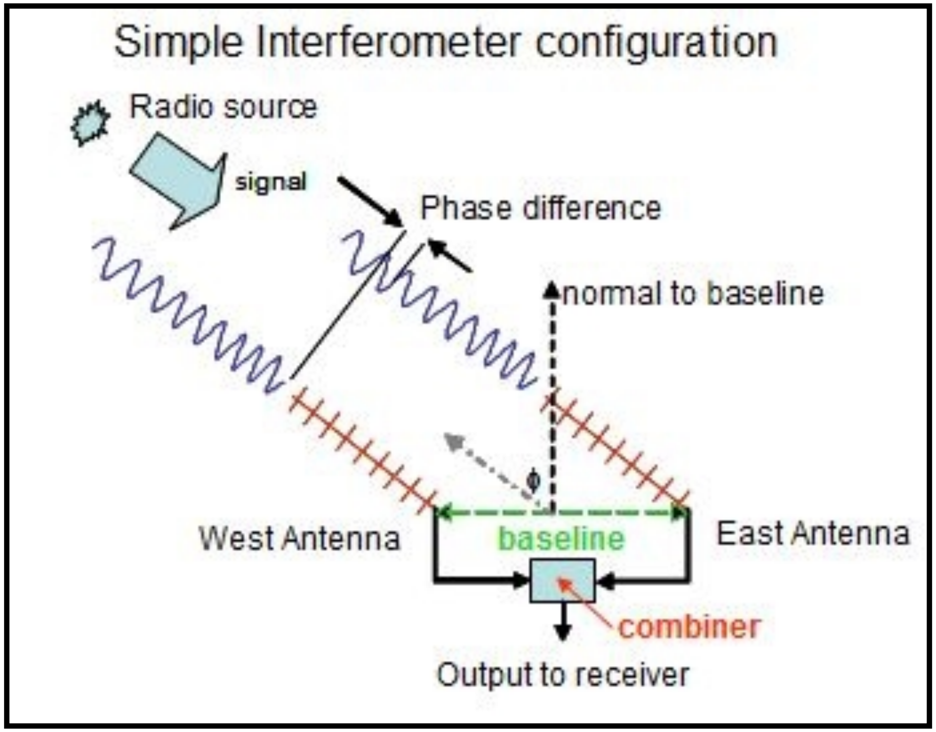


https://public.nrao.edu/telescopes/radio-telescopes/

RADIO INTERFEROMETRY

- Say that 2 dishes observe the same galaxy
- They are separated by a known distance on the ground (the baseline)
- The radio waves will arrive at them with a slight time delay in the phase of the wave
- When we combine, there is no perfect overlap and this creates "*interference fringes*"
- The longer we observe, the more variations we get - the more variations, the more perspective
- The longer the baseline, the sharper the view becomes

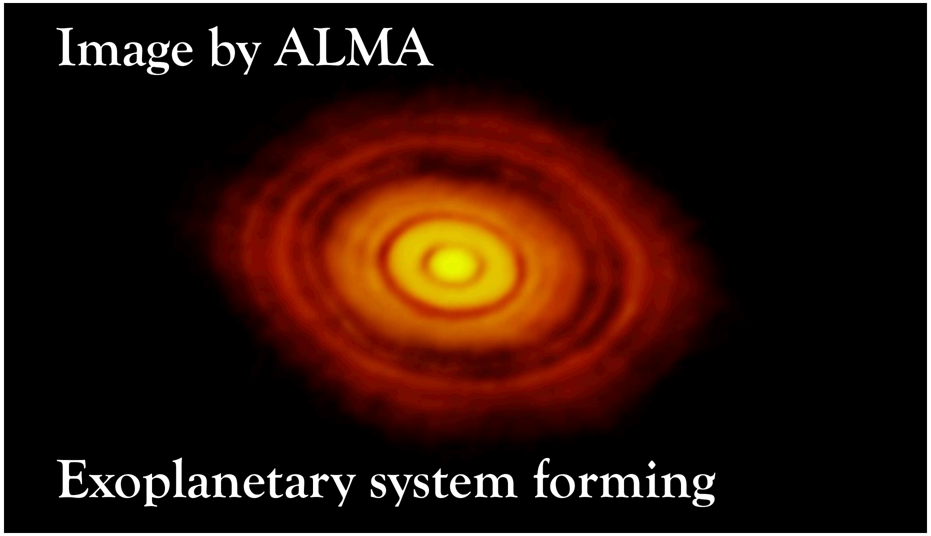
https://public.nrao.edu/telescopes/radio-telescopes/



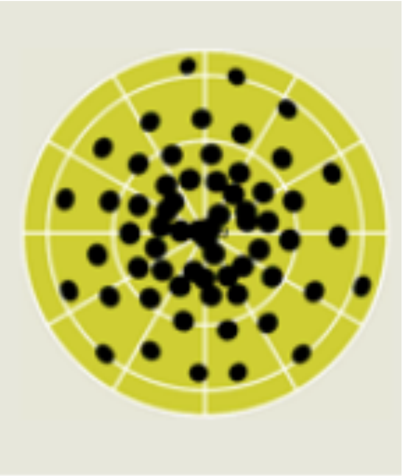
https://sites.google.com/site/radioastronomydm2/interferometry

Aperture synthesis

https://briankoberlein.com/2015/10/14/how-does-interferometry-work/



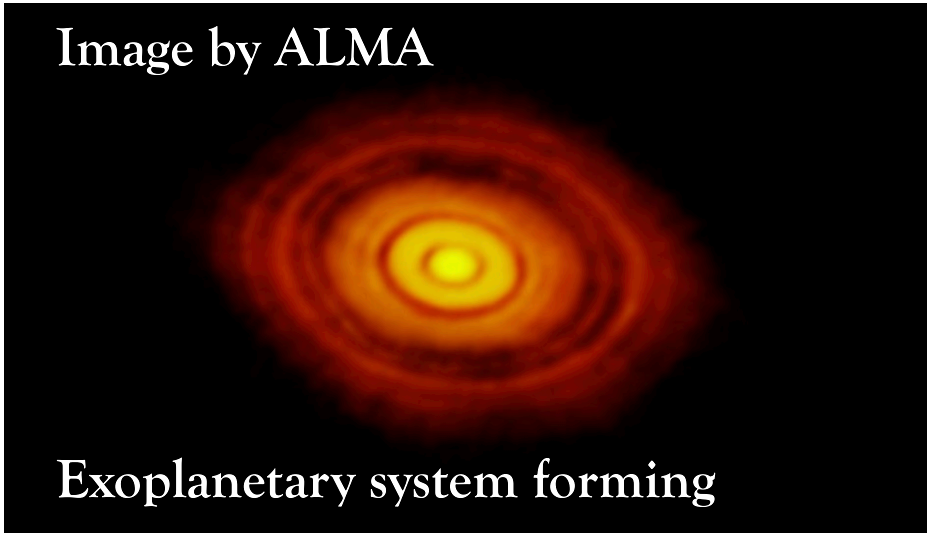
- 2 dishes/antennas will give you one point in the sky
- Dozens of antennas give lots of points, one for each pairing of antennas.

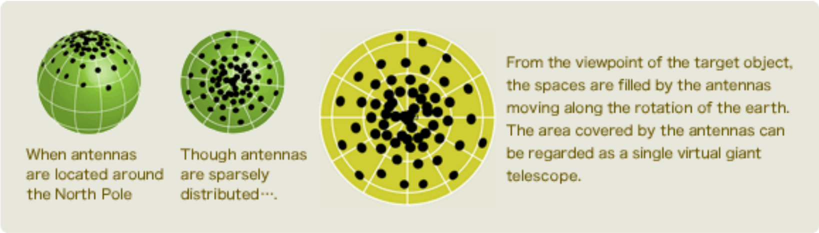


Aperture Synthesis

https://briankoberlein.com/2015/10/14/how-does-interferometry-work/

- 2 dishes/antennas will give you one point in the sky
- Dozens of antennas give lots of points, one for each pairing of antennas.
- Earth's rotation helps fill in the gaps (Earth Aperture Synthesis)
- The results are spectacular!

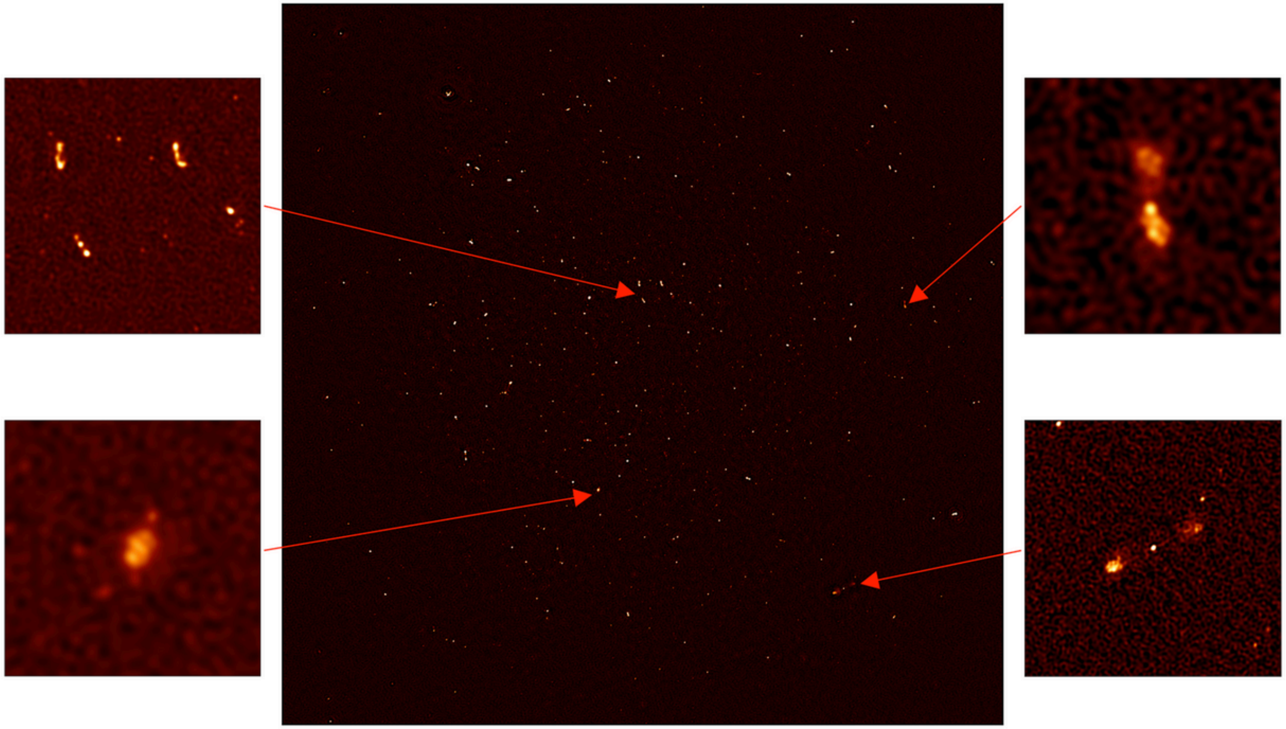




*The actual ALMA antenna location differs from the figure above. The figure is a conceptual illustration to explain the principle of the "aperture synthesis" technique (interferometric imaging method) in a very simple way.

MEERKAT-16 FIRST LIGHT: SIMPLY AWESOME

At only a quarter of its eventual capacity, the MeerKat radio telescope captures 1,300 galaxies in tiny corner of universe where only 70 were known before

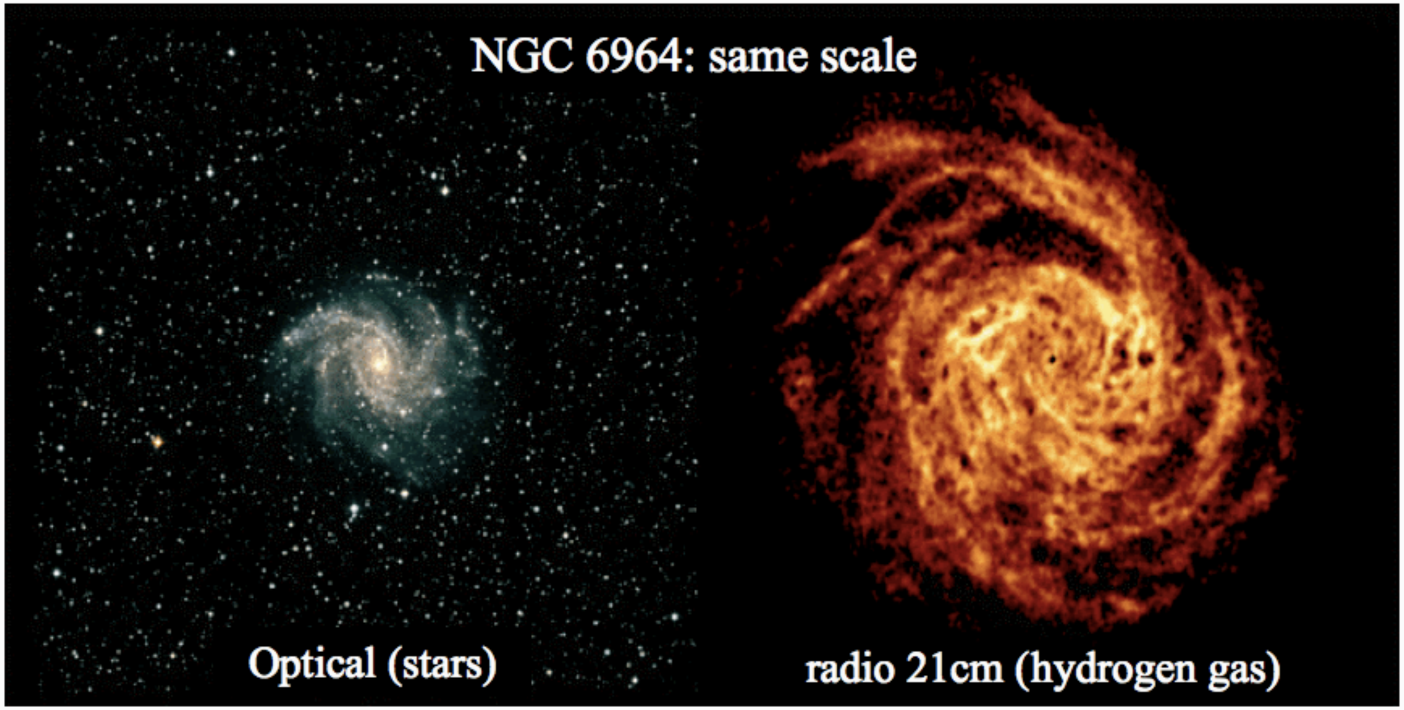


▲ A montage of the MeerKat radio telescope's First Light image with four zoomed-in insets – the two panels to the right show distant galaxies with massive black holes at their centres; at lower left is a galaxy approximately 200m light years away where hydrogen gas is being used up to form stars in large numbers. Photograph: MeerKat/SKA South Africa

From The Guardian, 17 July 2016

RADIO VS OPTICAL: GALAXIES

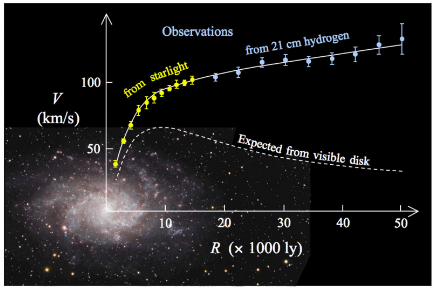
- HI in galaxies more extended than the stellar light distribution
- HI disk much larger than the stellar disk

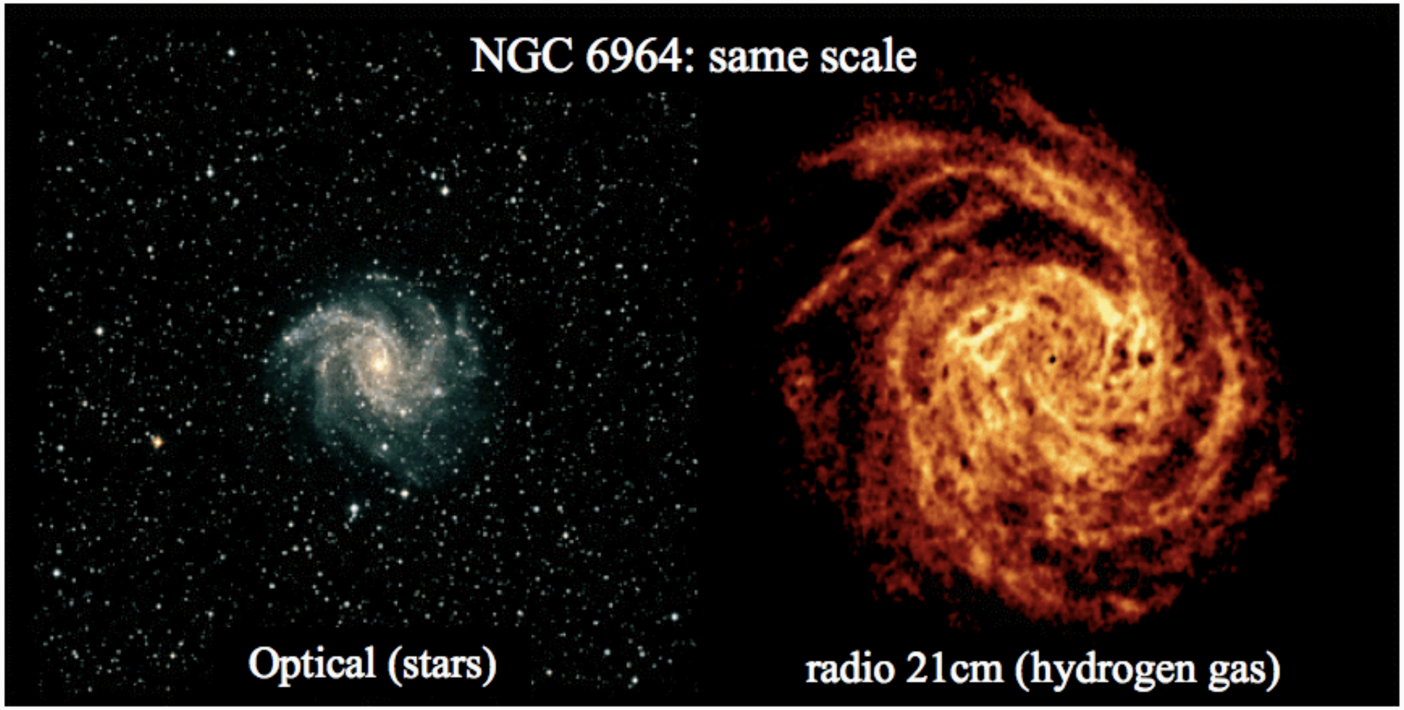


https://www.skatelescope.org/galaxyevolution/

RADIO VS OPTICAL: GALAXIES

- HI in galaxies more extended than the stellar light distribution
- HI disk much larger than the stellar disk
- HI velocity fields can be used to calculate rotation curves and trace the total mass distribution to very large radii





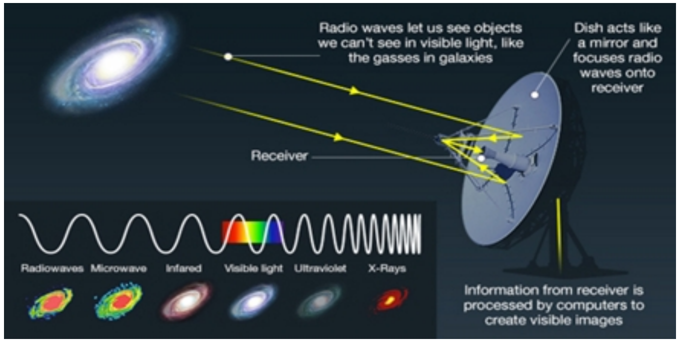
https://www.skatelescope.org/galaxyevolution/

HOW DOES A RADIO ARRAY WORK? THE MEERKAT CASE

- An array of 64 interlinked receptors
- Each receptor contains: **1.** The antenna positioner, which is a steerable dish on a pedestal **2.** A set of radio receivers **3.** A set of digitisers
- 13.5 effective diameter main reflector, and a smaller sub-reflector
- Excellent sensitivity and imaging quality
- The steerable antenna positioner can point the main reflector with an accuracy of 5 arc seconds

https://www.ska.ac.za/science-engineering/meerkat/about-meerkat/

HOW DOES A RADIO ARRAY WORK? THE MEERKAT CASE



- E/M waves from radio sources bounce of the reflector and sub-reflector and then focused in the feed horn (part of the receiver)

- The receiver captures the E/M radiation and converts it to a voltage signal that is then amplified

- The first 2 receivers are L-band (0<z<0.5) and UHF-band (0.6<z<1.4)

- 4 digitisers convert the radio frequency voltage signal into digital signals via an analogue to digital converter

- The amount of data generated is equivalent to to 1 DVD per second

https://www.ska.ac.za/science-engineering/meerkat/about-meerkat/

HOW DOES A RADIO ARRAY WORK? THE MEERKAT CASE

- Once the signal is converted to digital data, the digitiser sends this data via buried fibre optic cables to the correlator, in the Karoo Array Processor Building

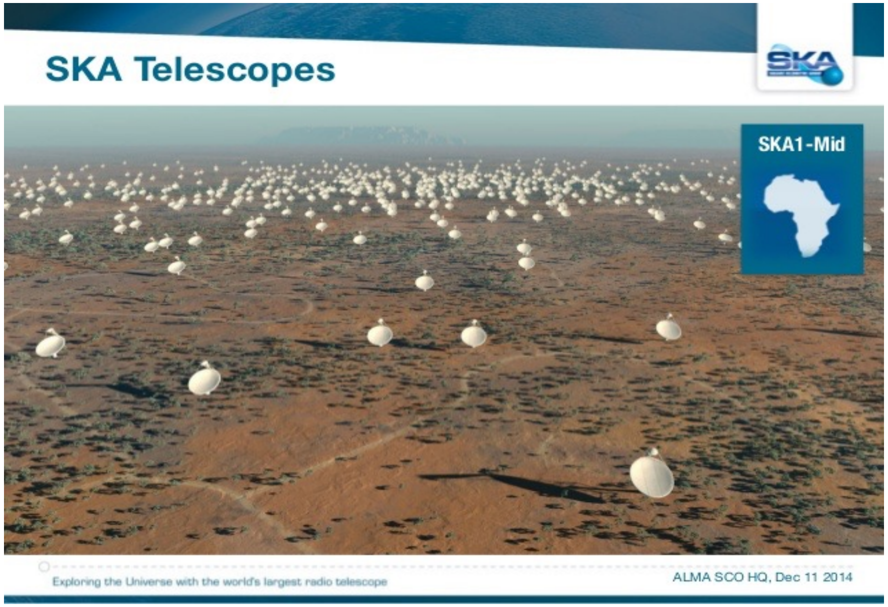
- Total of 170 km buried fibre cables!

- At the KAPB, the digital processing happens, e.g. correlation - which combines all the signals from all the receptors to form an image of the area of the sky to which the antennas are pointing

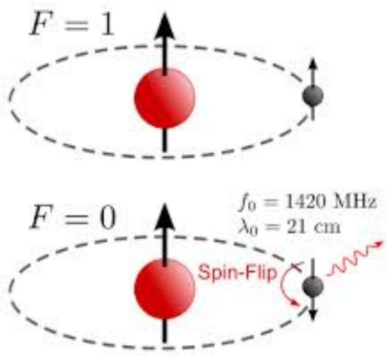
https://www.ska.ac.za/science-engineering/meerkat/about-meerkat/

WHAT ABOUT COSMOLOGY?

- Wrap-up: with interferometers, we can do high resolution radio astronomy
- But what about precision large scale cosmology?
- Detecting millions of galaxies in the radio is still very difficult
- We would need the **full SKA Phase 2, performing a billion galaxy survey in the radio**, to be competitive with optical surveys like *Euclid*
- Can we do something sooner? **Yes! With HI intensity mapping**.



The HI spin-flip transition

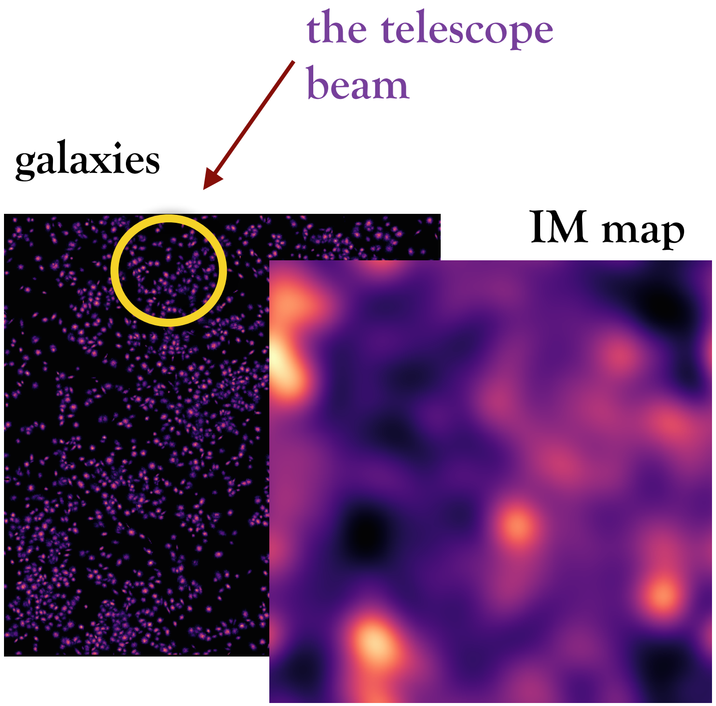


- HI makes the bulk of cold interstellar gas (which does not emit at visible wavelengths)
- HI can be detected observing the **spin-flip transition**

- HI in its lowest energy state has *p* and *e* spins antiparallel
- But can acquire energy from collisions and go in the excited state (parallel spins)
- This is just slightly higher, so when it returns to the low state it emits a very long wavelength (21cm) photon
- This is a rare transition but HI is abundant in the Universe (e.g. dark ages, EoR).
- After reionization: HI within galaxies.

RADIO PRECISION COSMOLOGY: THE INTENSITY MAPPING METHOD

[Battye et al 2004, Chang et al 2008, Peterson et al 2009, Seo et al 2010, …]



[Simulations by S. Cunnington]

- Detecting HI (neutral hydrogen) galaxies via their 21cm emission line is very expensive
- But cosmological information is on large scales
- Get intensity map of the HI 21cm emission line - like CMB but 3D!
- Excellent redshift resolution
- **Signal of the order 0.1 mK – foregrounds much bigger**

21cm IM surveys: GBT, CHIME, HIRAX, MeerKAT, SKA!

GOALS: Probe HI evolution, dark energy, gravity, inflation, …