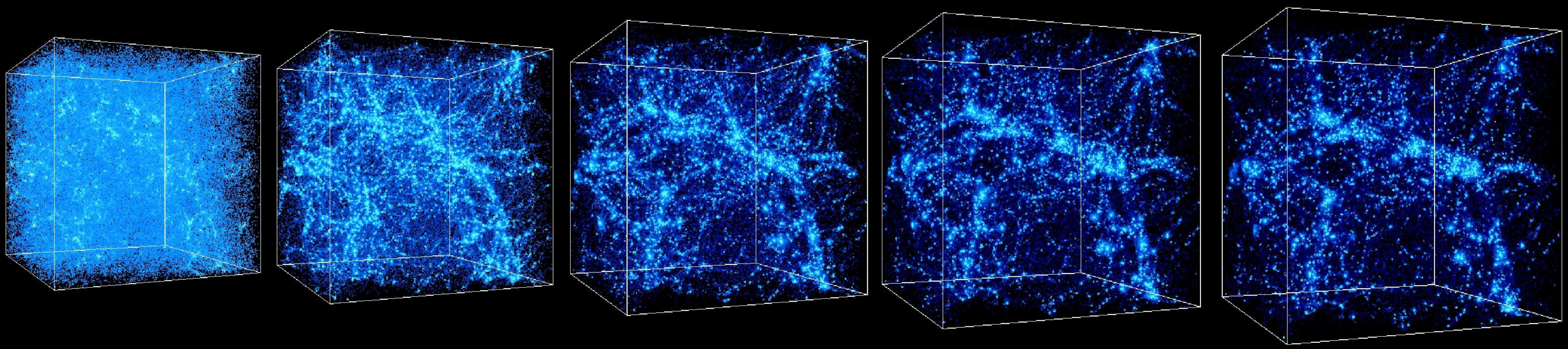
Galaxy Evolution & Cosmology with the SKA

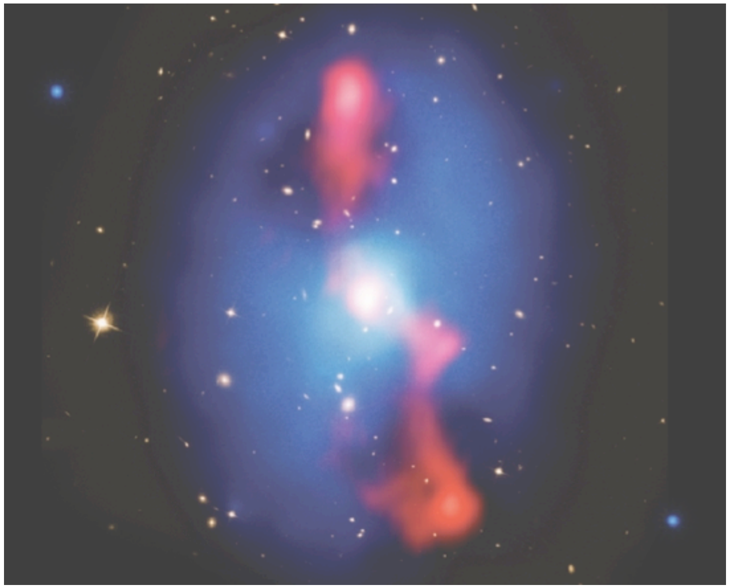


Matt Jarvis

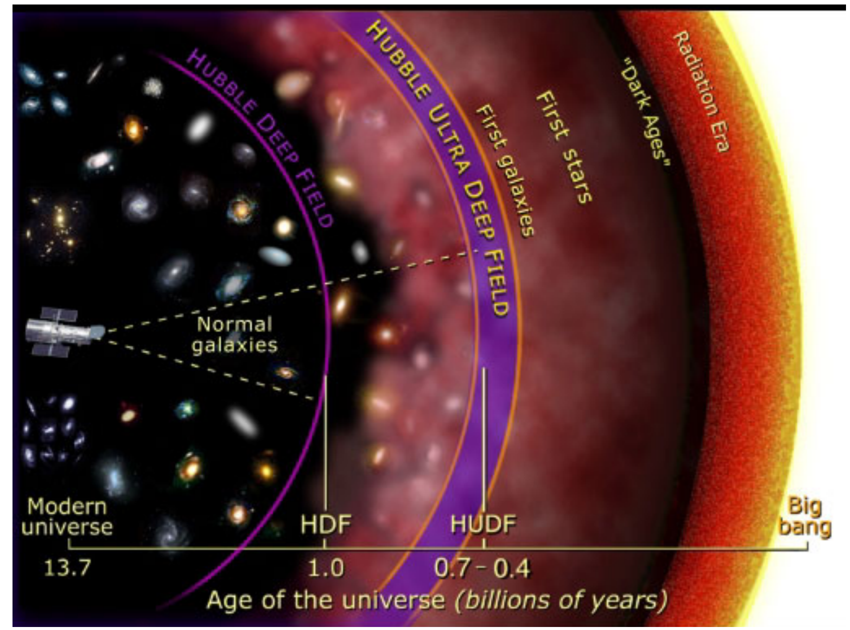
University of Oxford &
University of the Western Cape

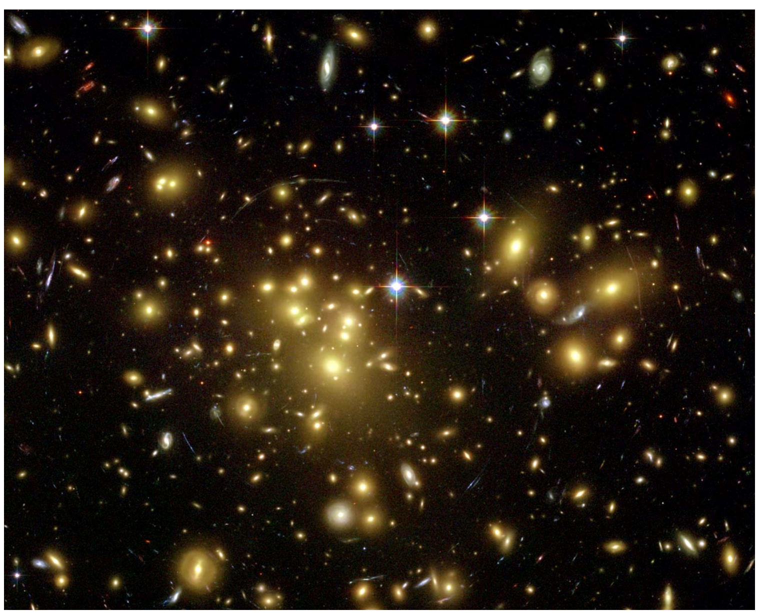
Galaxy Formation and Evolution with the SKA

How does accretion onto black holes affect the evolution of galaxies?



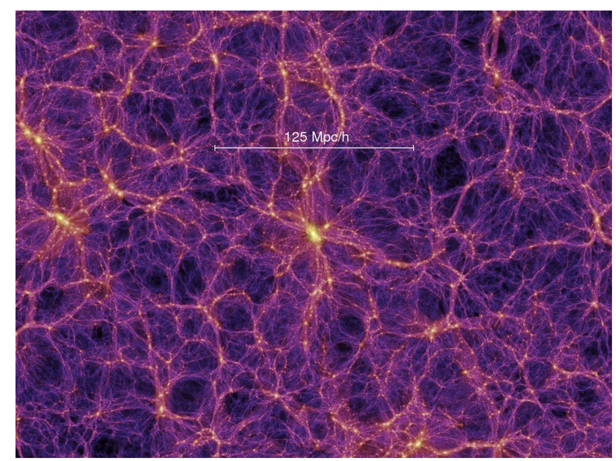
How and when were the first galaxies formed?



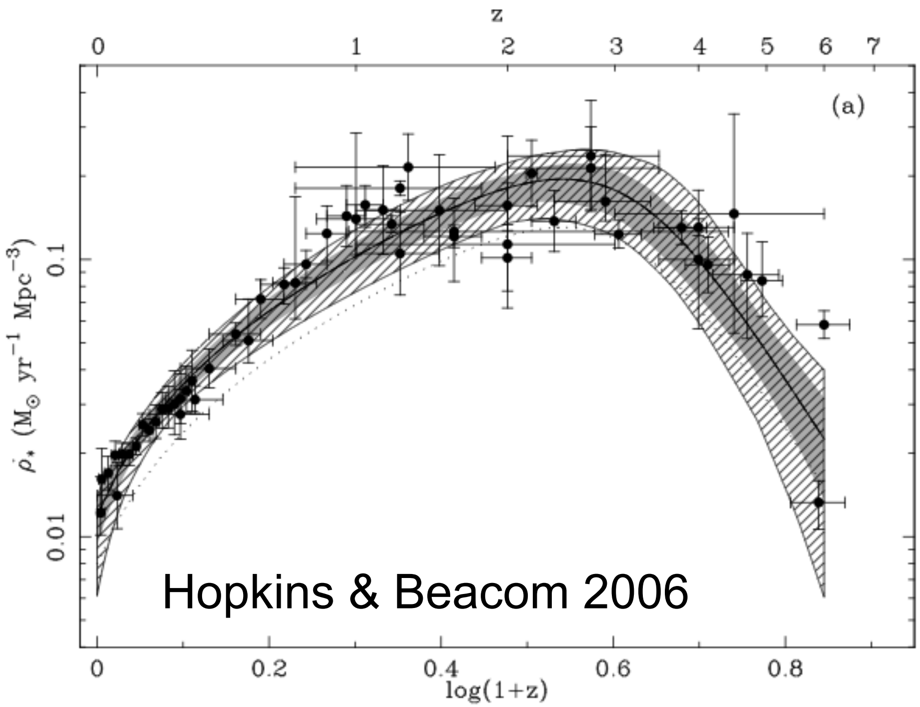


What is the environmental influence?

How do Baryons trace and affect the Dark Matter distribution?



Evolution of the star-formation rate density



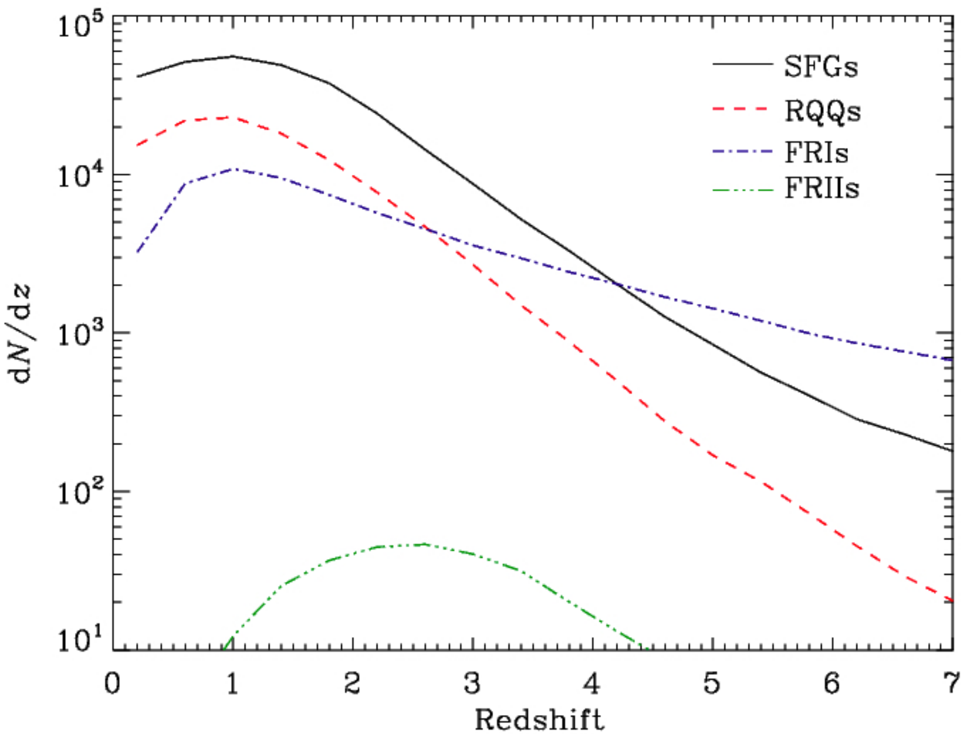
Hopkins & Beacom 2006

UV/Optical – dust extinction

Far-IR – poor resolution means confusion

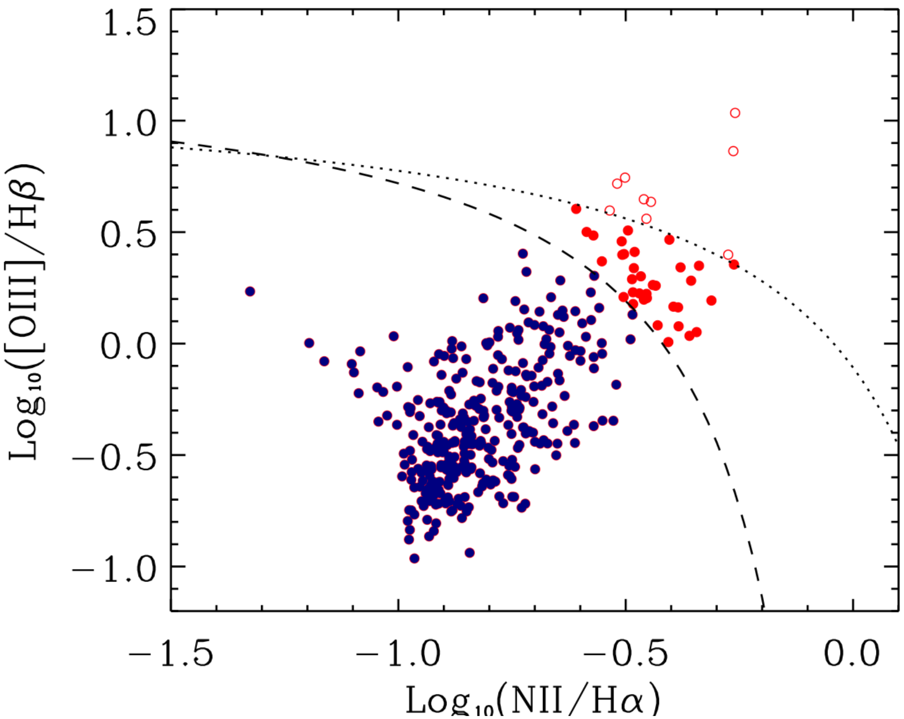
Radio – unaffected by dust, high-resolution

*AGN contamination in all at varying degrees



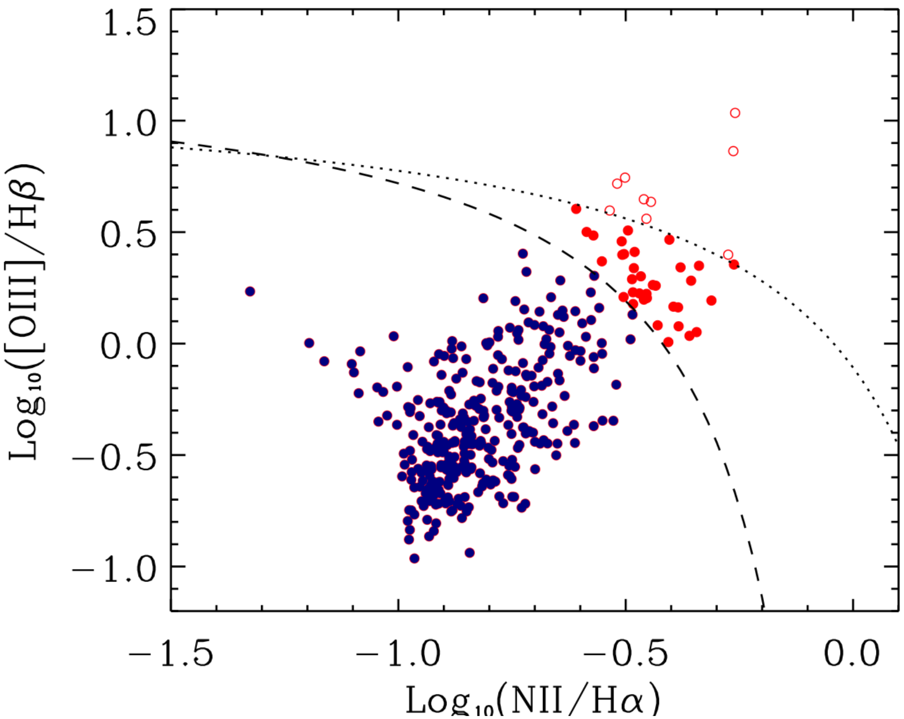
The dominance of star-forming galaxies in the new radio continuum surveys. Wilman & MJJ et al. 2008,2010

The new radio continuum surveys & the evolution of activity



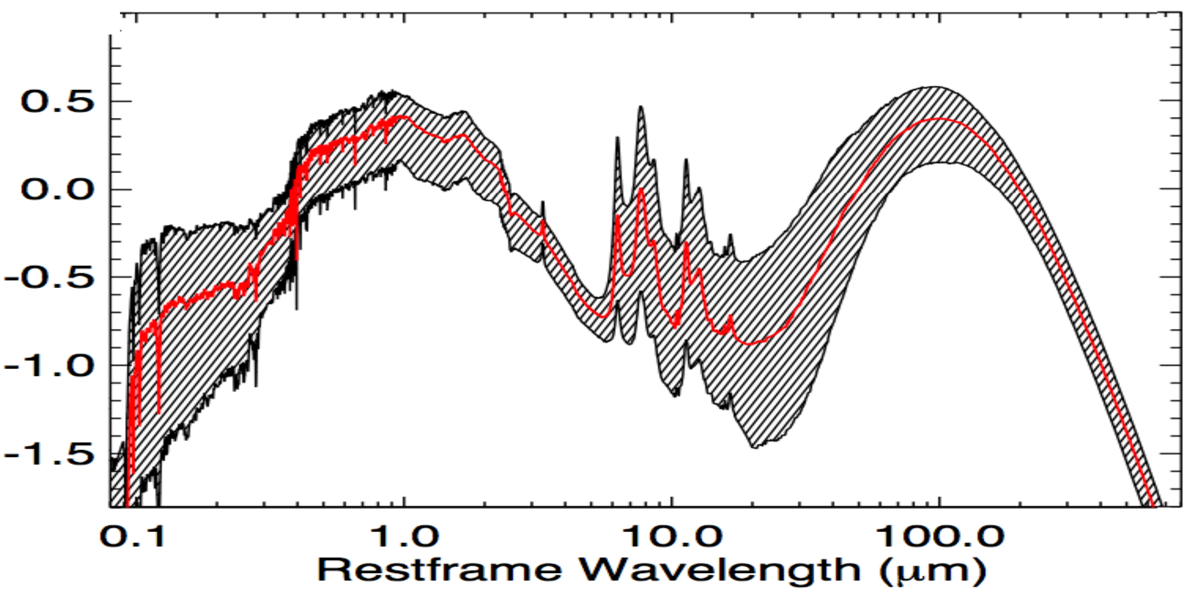
SFR – radio correlation from H-ATLAS (Jarvis et al. in prep.)

The new radio continuum surveys & the evolution of activity



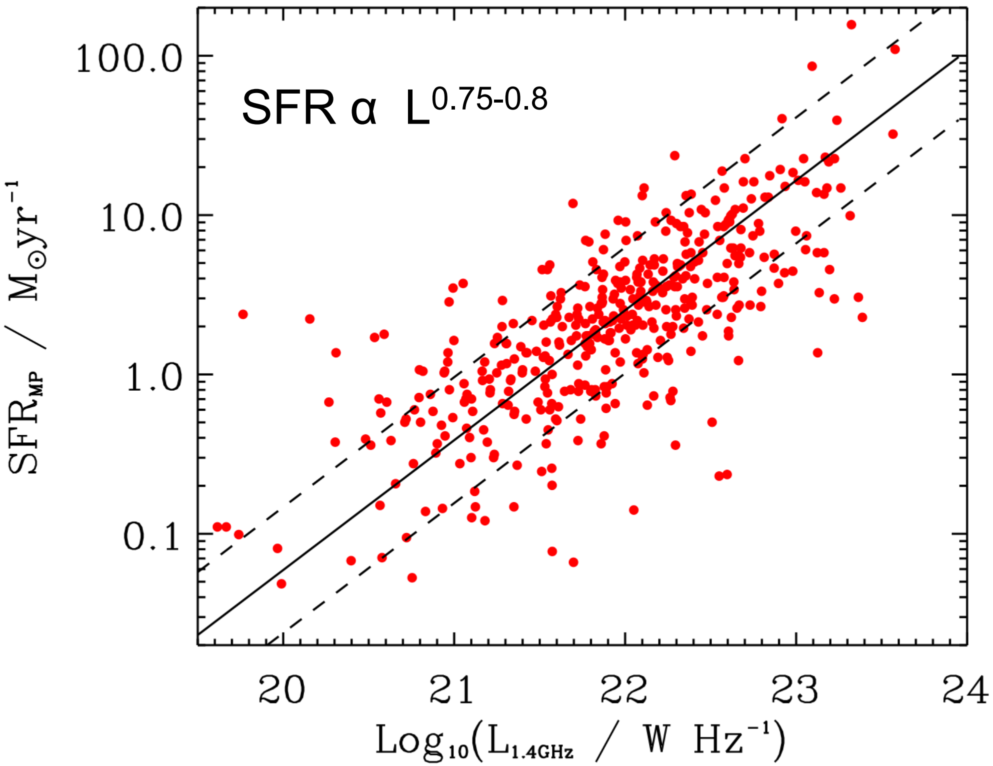
SED fits using the energy-balance models of da Cunha et al. 2008

SFR – radio correlation from H-ATLAS (Jarvis et al. in prep.)



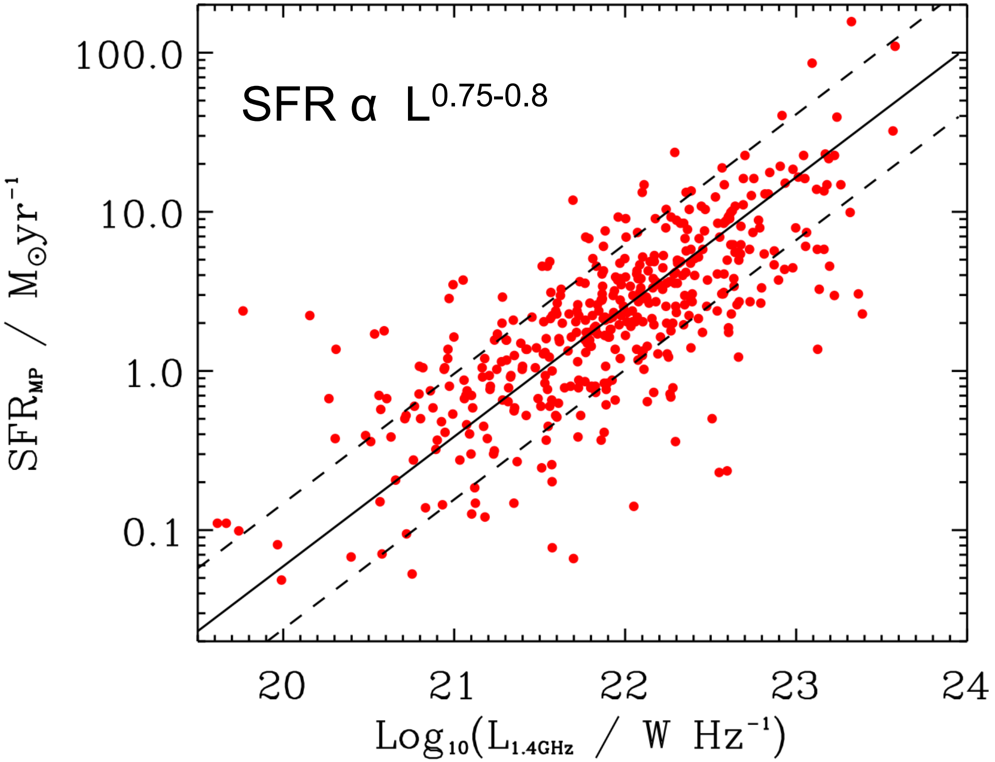
The new radio continuum surveys & the evolution of activity

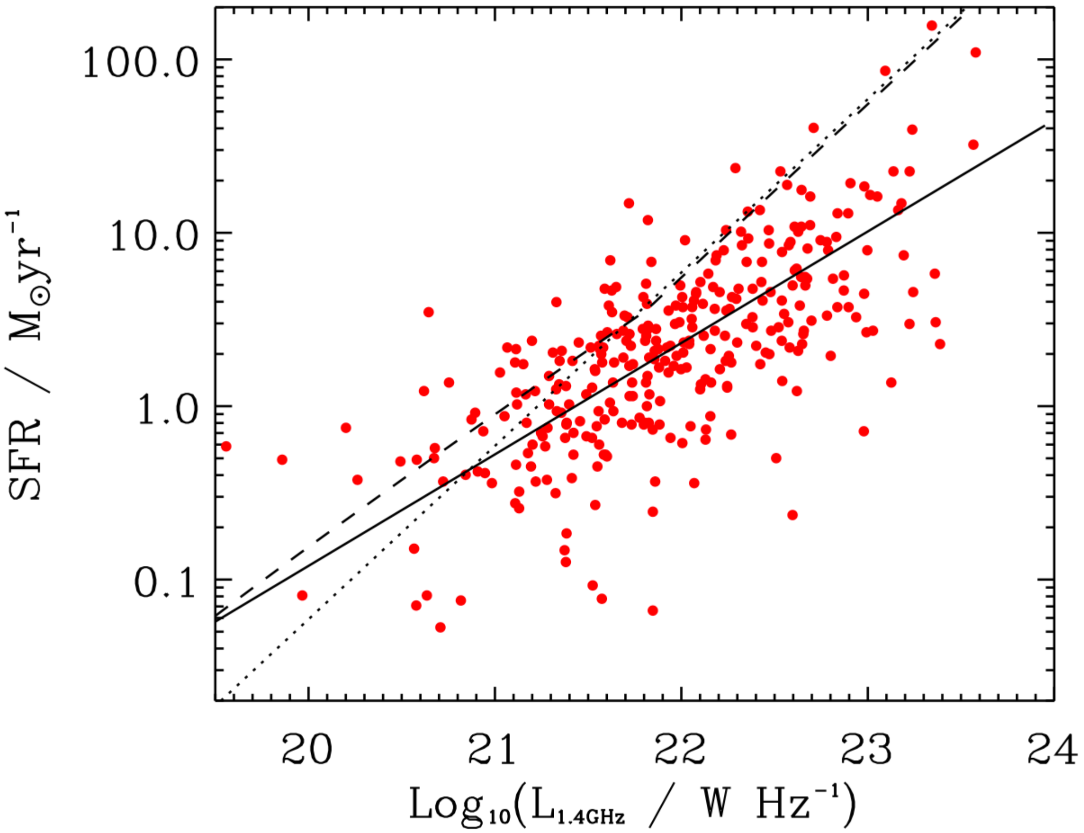
SFR – radio correlation from H-ATLAS (Jarvis et al. in prep.)



The new radio continuum surveys & the evolution of activity

SFR – radio correlation from H-ATLAS (Jarvis et al. in prep.)

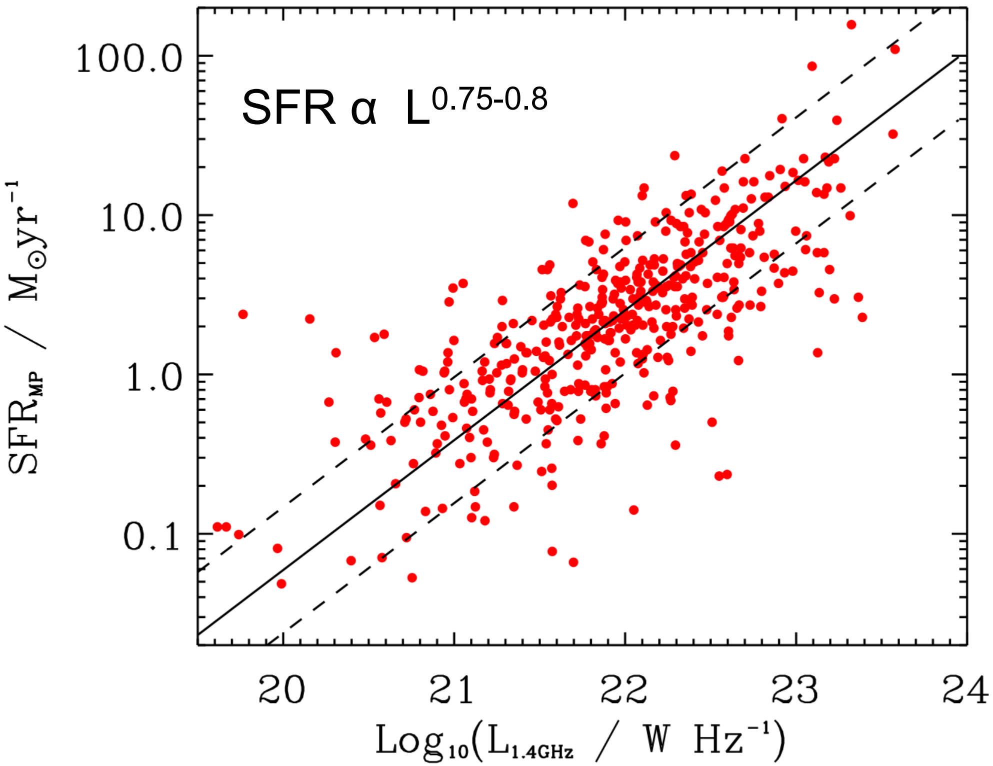




SFR-Radio Luminosity relation shallower that previous determinations.
Up to an order of magnitude difference at high-SFRs

The new radio continuum surveys & the evolution of activity

SFR – radio correlation from H-ATLAS (Jarvis et al. in prep.)



Taking various relations from the literature…

Schmidt-Kennicutt

Σ_{SFR} α $\Sigma_g^{1.4\text{-}1.7}$ (Kennicutt 1998; Bouche et al. 2007)

B α $\Sigma_g^{0.7\text{-}0.8}$ (Lacki et al. 2010)

Assuming equipartition

L_{sync} α $B_{eq}^{\alpha+3}$, where α≈0.8-0.9 (Heesen et al. 2011)

Then

SFR α $L_{sync}^{0.61\text{-}0.74}$ for SFR α $\rho^{1.4}$

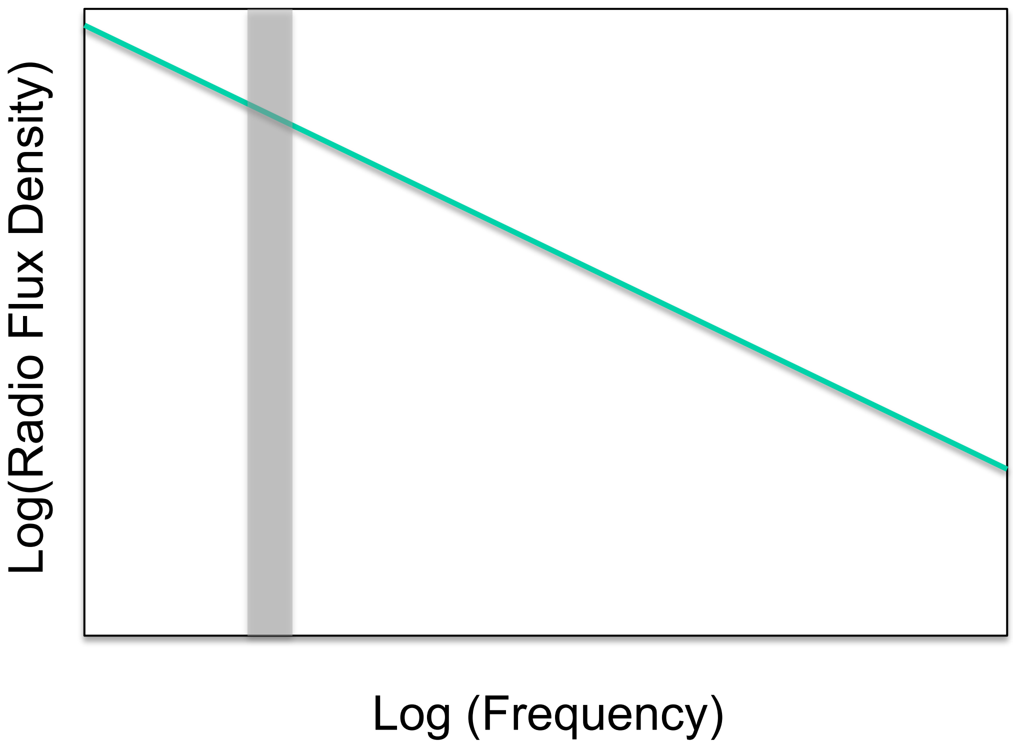
SFR α $L_{sync}^{0.75\text{-}0.89}$ for SFR α $\rho^{1.7}$

In line with our results

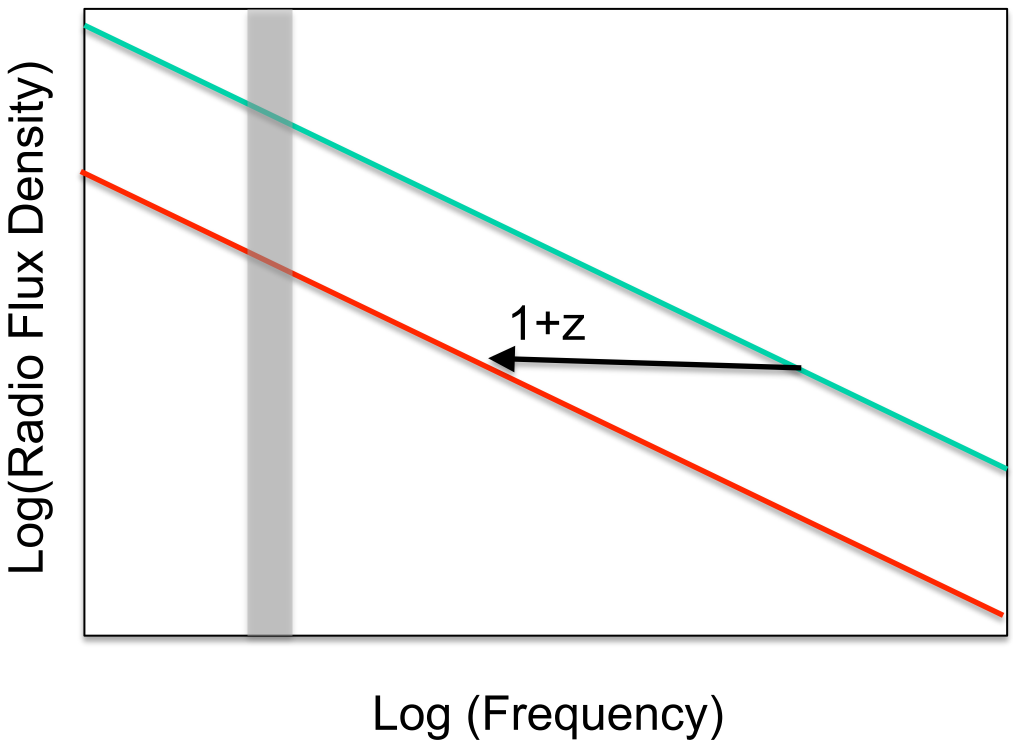
There is nothing as useless as a radio source…

- Jim Condon 2013

The new radio continuum surveys & the evolution of activity

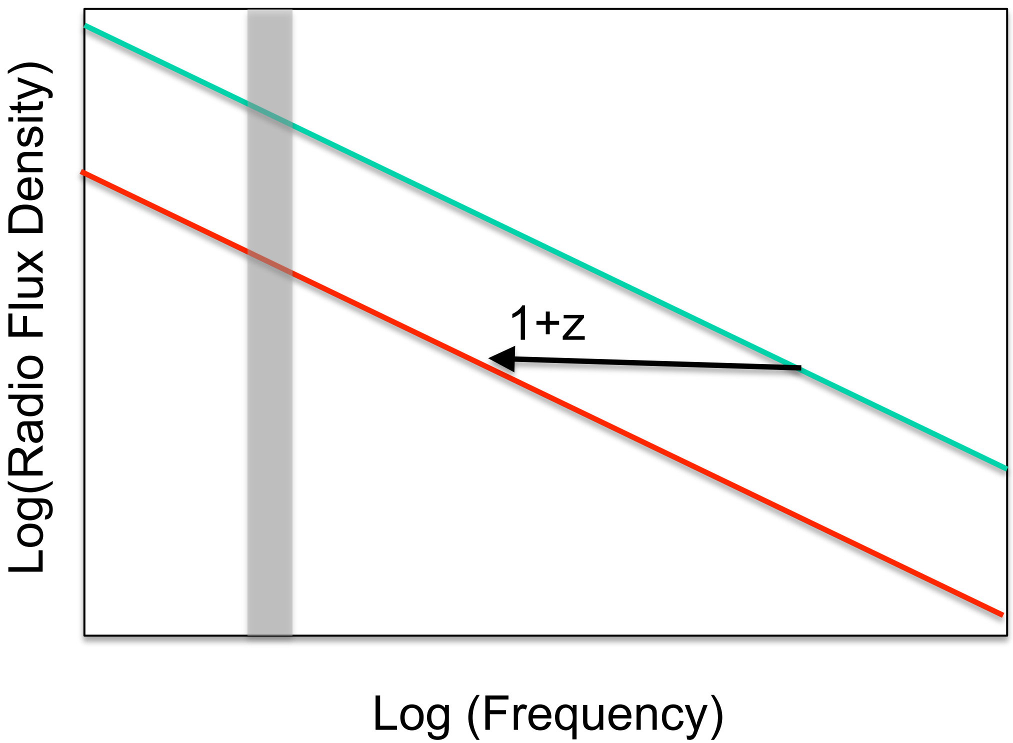


There's nothing as useless as a radio source

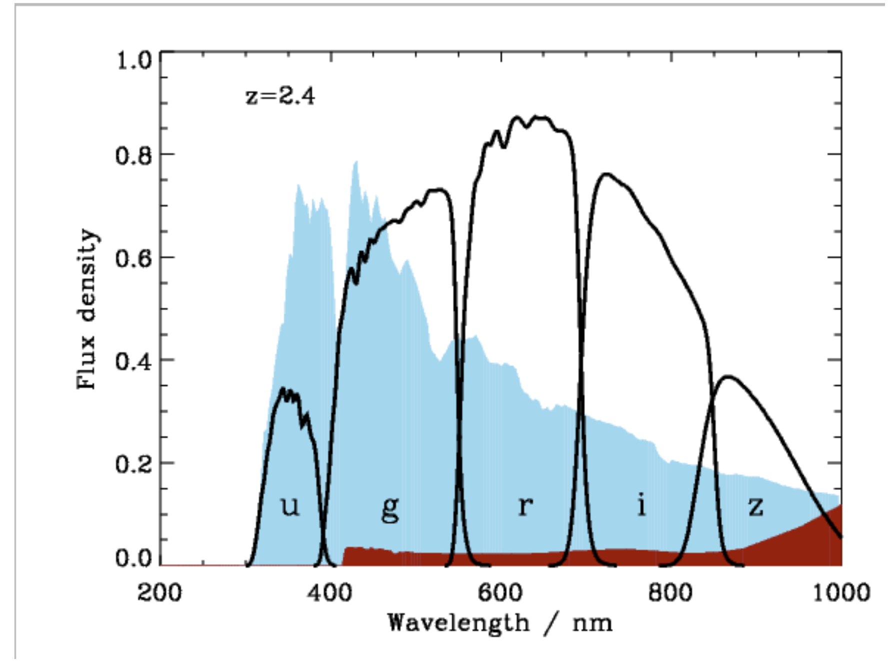


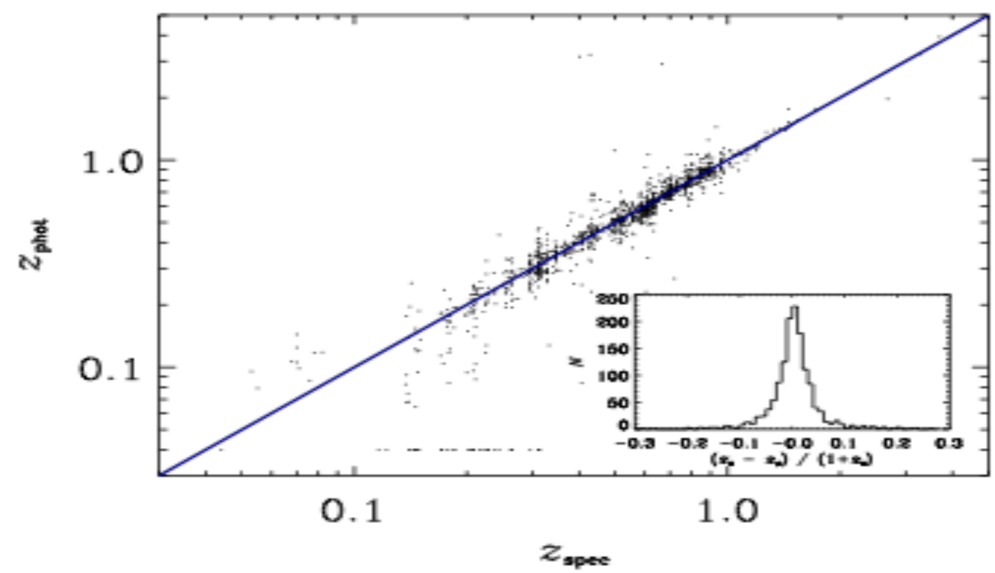
No redshift information!

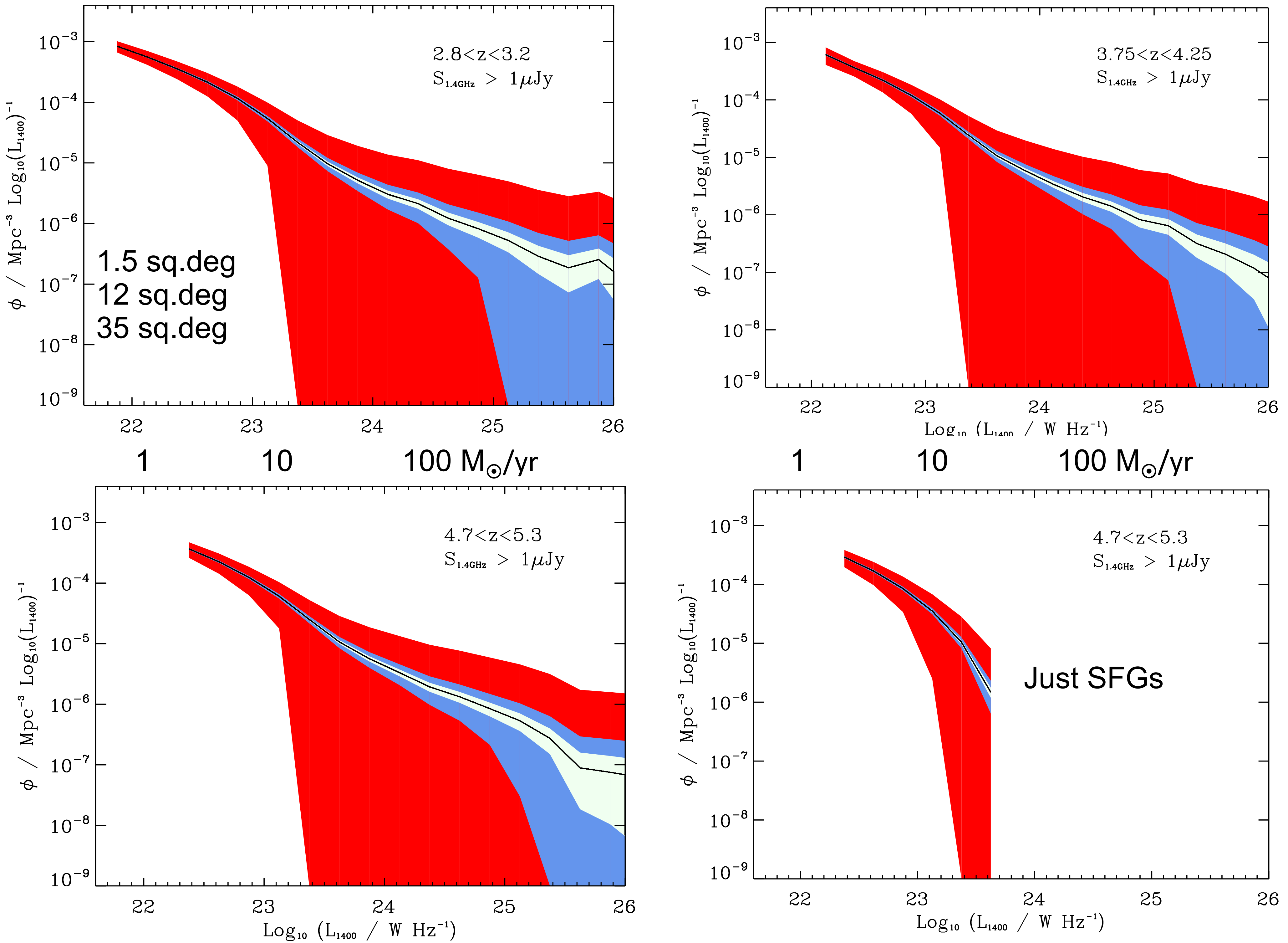
There’s nothing as useless as a radio source



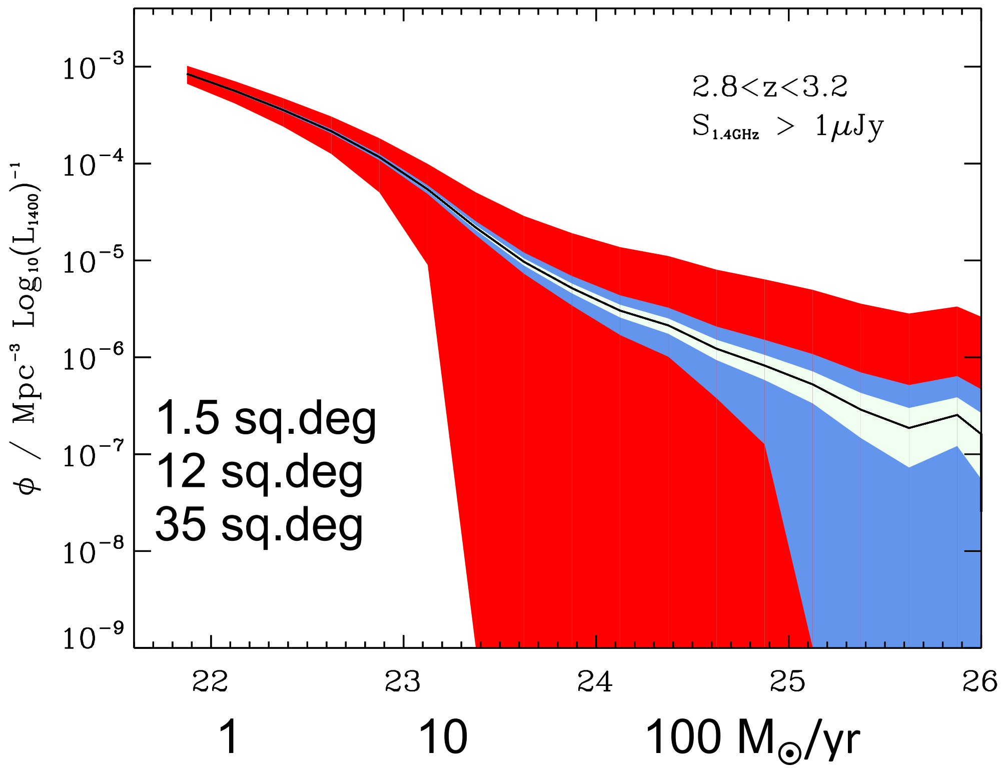
No redshift information!

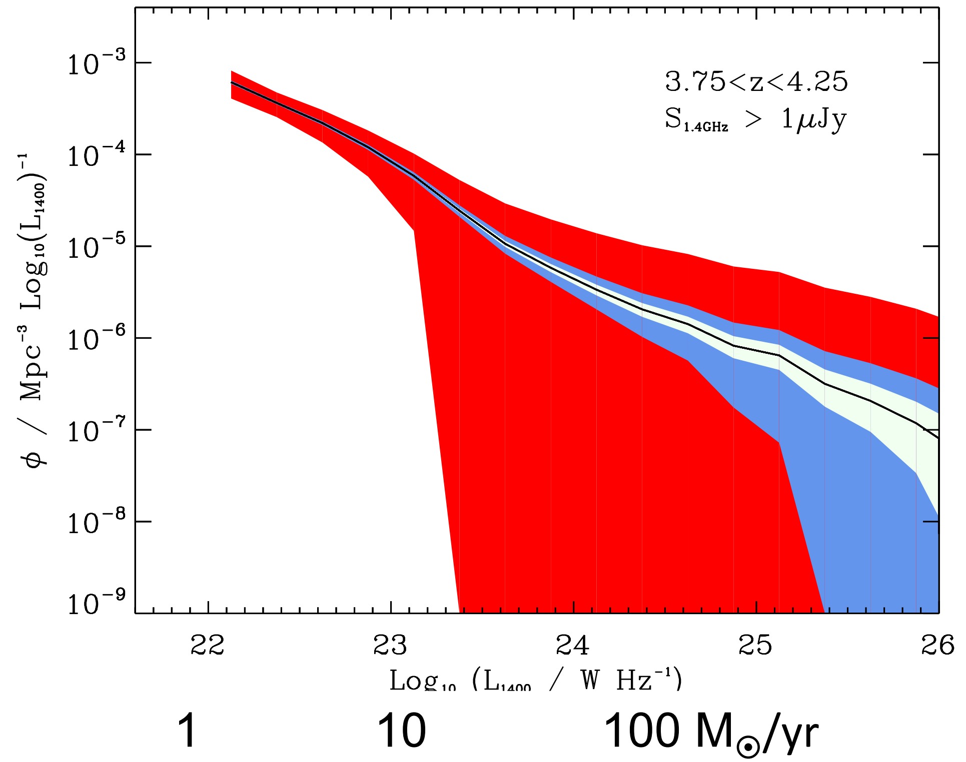






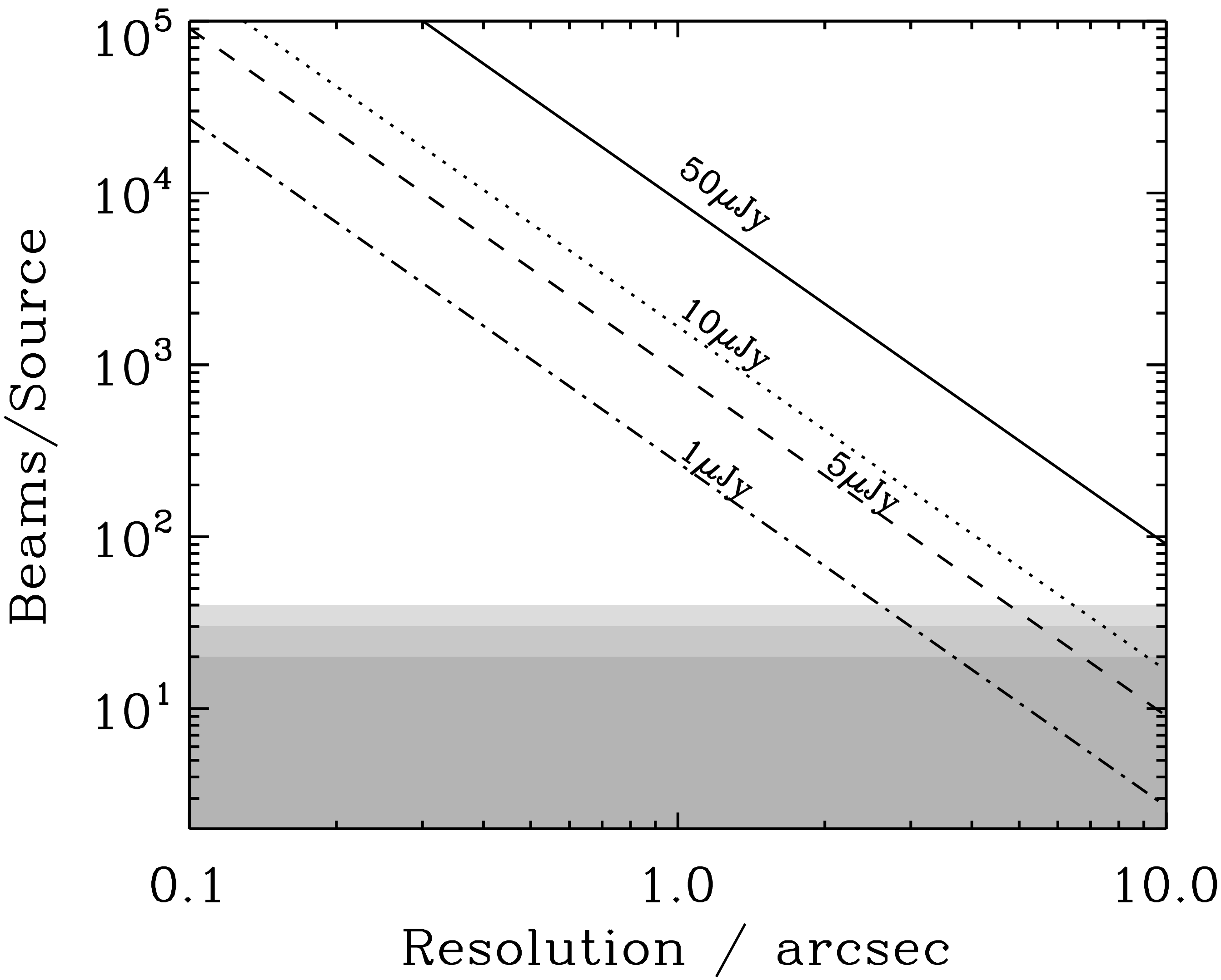
2.8<z<3.2
$S_{1.4GHz}$ > 1μJy
1.5 sq.deg
12 sq.deg
35 sq.deg
ϕ / Mpc^{-3} $Log_{10}(L_{1400})^{-1}$
1
10
100 M⊙/yr
3.75<z<4.25
$S_{1.4GHz}$ > 1μJy
Log_{10} (L_{1400} / W Hz^{-1})
1
10
100 M⊙/yr
4.7<z<5.3
$S_{1.4GHz}$ > 1μJy
Log_{10} (L_{1400} / W Hz^{-1})
4.7<z<5.3
$S_{1.4GHz}$ > 1μJy
Just SFGs
Log_{10} (L_{1400} / W Hz^{-1})





Can also map out the cosmic magnetic field through Rotation Measures along all lines of sight to distant polarised sources – Magnetism SWG

Confusion & Sensitivity trade-offs



With the baseline design we are confused at 1uJy rms depth

In SKA1, we cannot afford to be confused at 50nJy!

Properly distributed baselines all the way to AT LEAST 80km to allow sub-arcsec resolution at 1GHz

But you get a factor of 2 more “real” sensitivity to extragalactic sources at 700MHz compared to 1.4GHz

Or save a factor of 2.6 in time!!

SKA1 and HI

	WSRT	EVLA	SKA1 Mid	SKA1 Survey
FoV ($z = 0$)	0.25	0.25	0.6	18
FoV ($z = 0.5$)	–	–	1.4	18
FoV ($z = 1$)	–	–	2.4	61
SEFD ($0 < z < 0.5$)	22.3	10.4	1.7	7.1
rel. EVLA	0.5	1	6	1.5
SEFD ($0.5 < z < 1$)	–	–	2.8	7.1
SEFD ($1 < z < 3$)	–	–	2.8	12
SSpeed ($0 < z < 0.5$) (10^6)	0.0038	0.018-0.04	1.8-4.0	2.8
SSpeed ($0.5 < z < 1$) (10^6)	–	–	2.4-4.3	2.8
SSpeed ($1 < z < 3$) (10^6)	–	–	4.3-9.9	3.4
Resolution (H I emission)	15	6	*4-2.5*	*8-5*
Resolution (H I absorption)	<11	<1	*<0.4*	*<0.8*

This looks great!!!
- 100x the survey speed of the EVLA
- a telescope 6x more sensitive (36x faster) than the EVLA
- better sensitivity (and less RFI) down to low frequencies (high z)

Stolen from Tom Oosterloo

Key HI Science

- **HI and galaxy evolution**

  Resolved studies of HI emission in and around galaxies out to z ~ 1, i.e. from Now to ~8 Gyr ago. Current work is out to z=0.2.
  Pathfinders will cover this redshift range, but will not resolve galaxies.
  Unresolved statistical studies (emission & absorption) beyond 8 Gyr

  Will provide, for large part of the life span of the Universe, information about the cold-gas in galaxies and their environment for multi-wavelength, multi-archive studies of galaxies evolution.

- Star formation declined factor 10 over this period

  WHY???

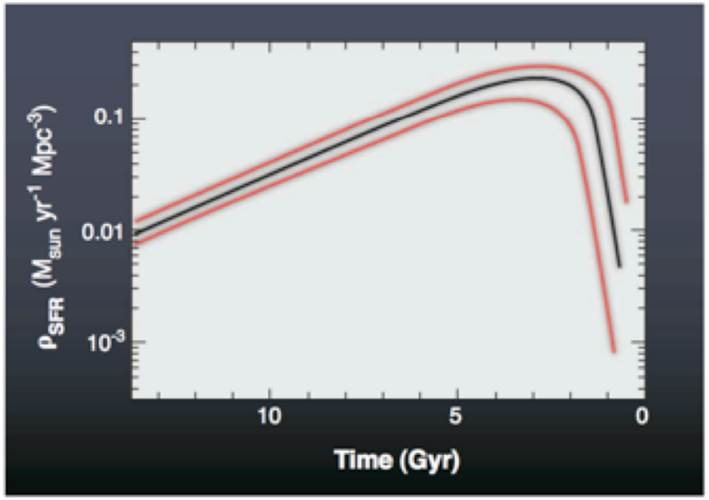


Fig. 2. A simple representation of our current knowledge of the rise and fall of globally averaged star-formation activity over the 13.7 billion years of cosmic history.

Stolen from Tom Oosterloo

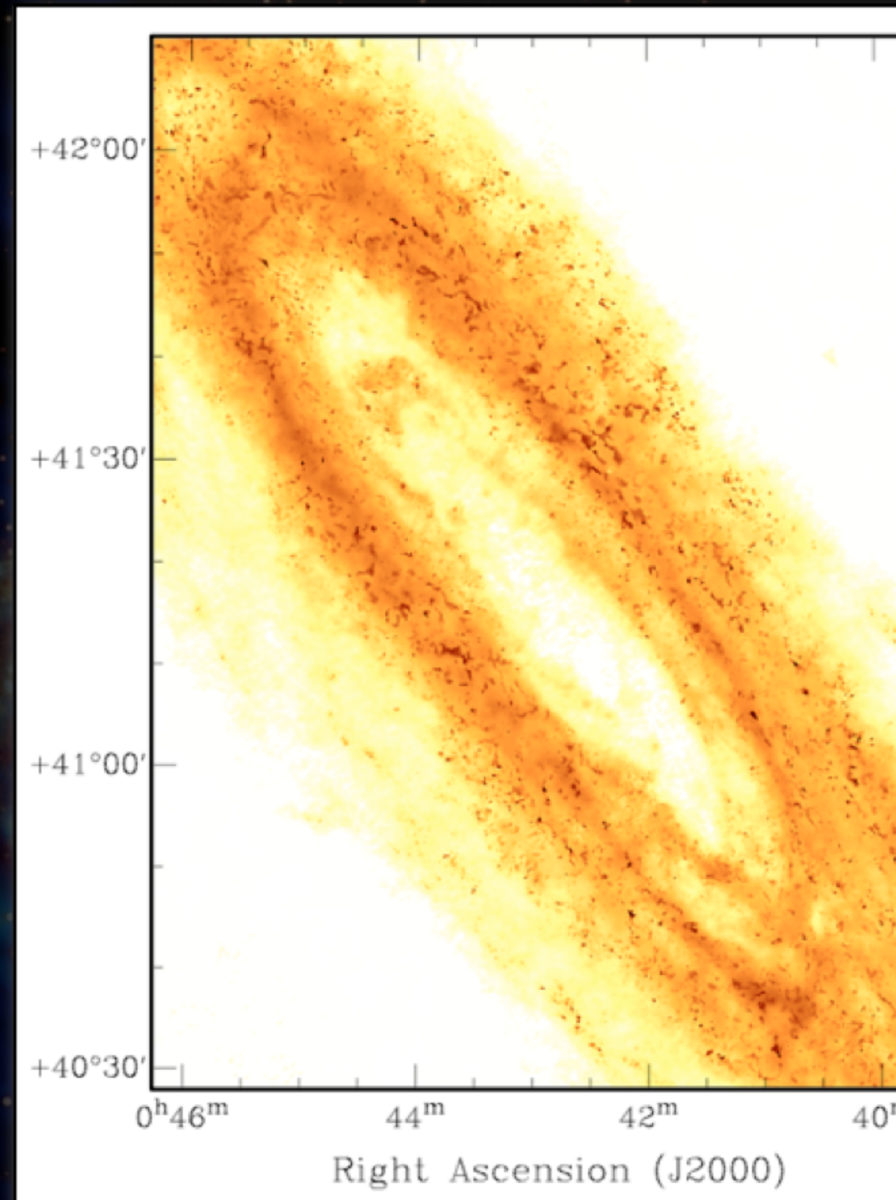
Key HI science

- **ISM in nearby galaxies**

  at high-spatial resolution (< 500 pc) to study the physics of the ISM and star formation below scales where statistical relations (KS-law) break down and simulations cannot (yet) go.

  Approach optical resolution.

  The synergy with ALMA for this kind of work is very exciting



HI in M31 with 100 pc resoution (WSRT) Braun 2013

Stolen from Tom Oosterloo

Other Key HI Science

- HI absorption studies to study the role of AGN feedback in galaxy evolution over large redshift ranges.

- HI studies of the Galaxy and of the Magellanic Coulds down to sub-pc scales

- Low-resolution (~1 arcmin) observations of low-column density HI around nearby galaxies to study the gaseous interface (cold accretion) between galaxies and the IGM. Search for the smallest galaxies.

  SKA1-Mid offers the first possibility to probe the column densities of the IGM.

- Baryonic-acoustic oscillations through Intensity Mapping up to high redshift

Stolen from Tom Oosterloo

Cosmology - Key Questions…

- What is the Equation of state of Dark Energy?
  - Cosmological constant or evolving scalar field
- Does General Relativity break down on cosmological scales?
- What kind of inflation?
  - Non-Gaussianity from non-vanilla inflation
- The nature of Dark Matter
- Neutrino mass

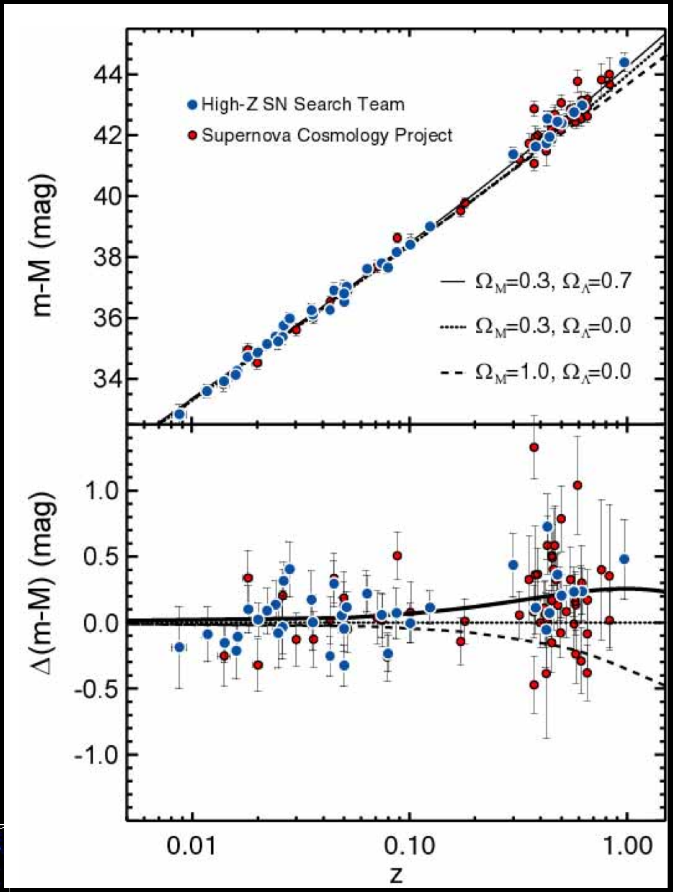
Key Questions…

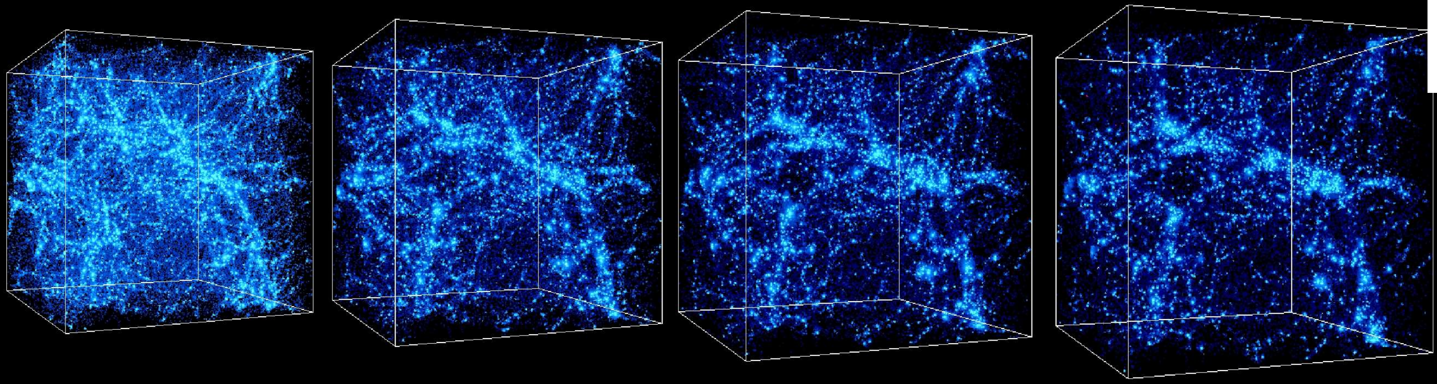
- What is the Equation of state of Dark Energy?
  - Cosmological constant or evolving scalar field
- Does General Relativity break down on cosmological scales?
- What kind of inflation?
  - Non-Gaussianity from non-vanilla inflation
- The nature of Dark Matter
- Neutrino mass

Can be addressed by both continuum and HI spectral line surveys with SKA

How do we answer these questions?

- Need to measure the expansion history (geometrical measurements)
- Need to measure the growth of structure (trace where the mass is as a function of redshift)
- Obviously these are linked!





How do we answer these questions?

- To measure the expansion history
  - *Type Ia Sne*
  - *Baryon Acoustic Oscillations*
  - *Gravitational Lensing*

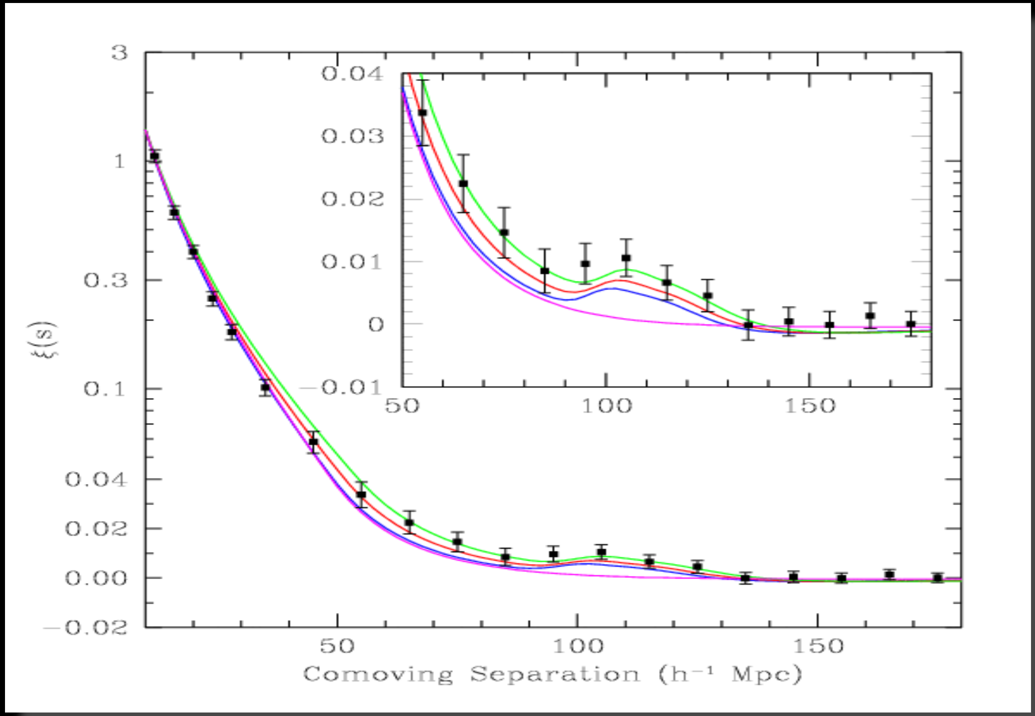
- To find departures from GR on cosmological scales, need to measure the influence of gravity on these scales
  - *Gravitational Lensing*
  - *Redshift Space Distortions*
  - *Integrated Sachs-Wolfe*

What can we do with spectral line surveys?

Baryon Acoustic Oscillations (BAO)

- Oscillations of coupled baryons & photons in early universe
- *Outward* photon pressure vs. *Inward* gravitational attraction
- Preferred distance scale frozen at decoupling
- Cosmological "standard ruler" (~100 h^{-1} Mpc)

Test: Autocorrelation function and/or power spectrum

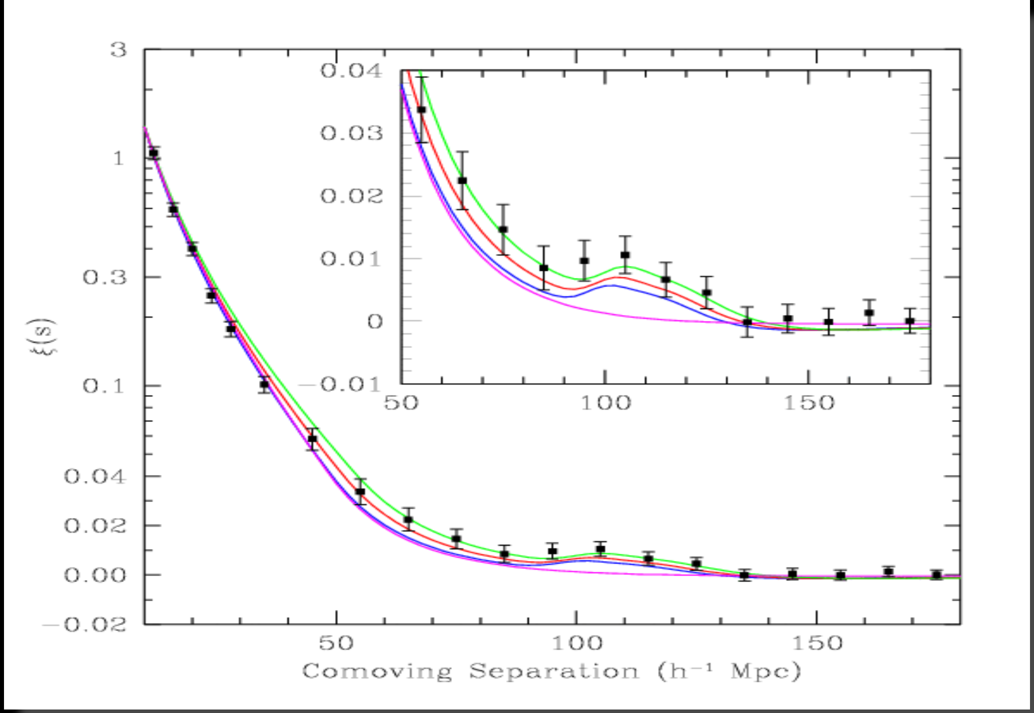


- Original cosmology science case for the SKA
- "The Billion Galaxy Redshift Survey"
  (Abdalla & Rawlings 200*)
- Phase 1 restricted to "proof of concept" type science at low-z
- The first non-optical detection of BAO

Baryon Acoustic Oscillations (BAO)

- Oscillations of coupled baryons & photons in early universe
- *Outward* photon pressure vs. *Inward* gravitational attraction
- Preferred distance scale frozen at decoupling
- Cosmological "standard ruler" (~100 h^{-1} Mpc)

Test: Autocorrelation function and/or power spectrum



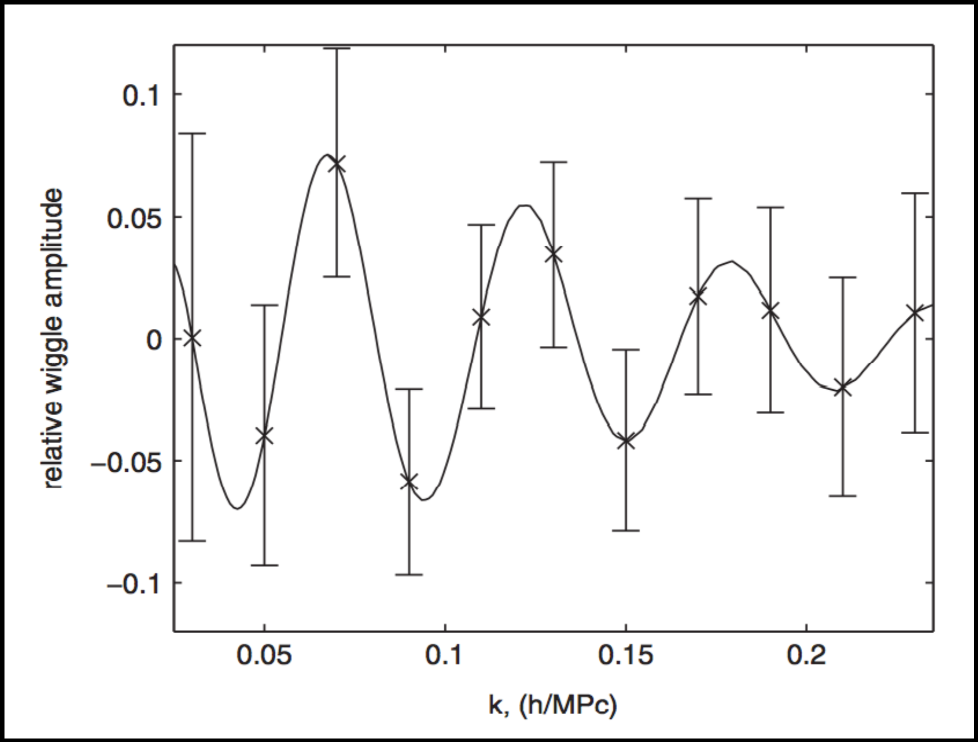
- However BAO is a large-scale effect, therefore no real need to resolve individual galaxies
- Could do with Intensity Mapping…

Intensity Mapping

- "Intensity Mapping" (instead of HI associated with galaxies, interested in HI associated with large-scale structure)
- measure the collective HI emission from a large region, more massive and luminous, without spatially resolving down to galaxy scales.
- Measurement of spatially diffused spectral line, in the confusion-limited regime, but redshift information is retained.
- Brightness temperature fluctuations on the sky: just like CMB temperature field, but in 3D
- Low-angular resolution redshift surveys: LSS science, economical

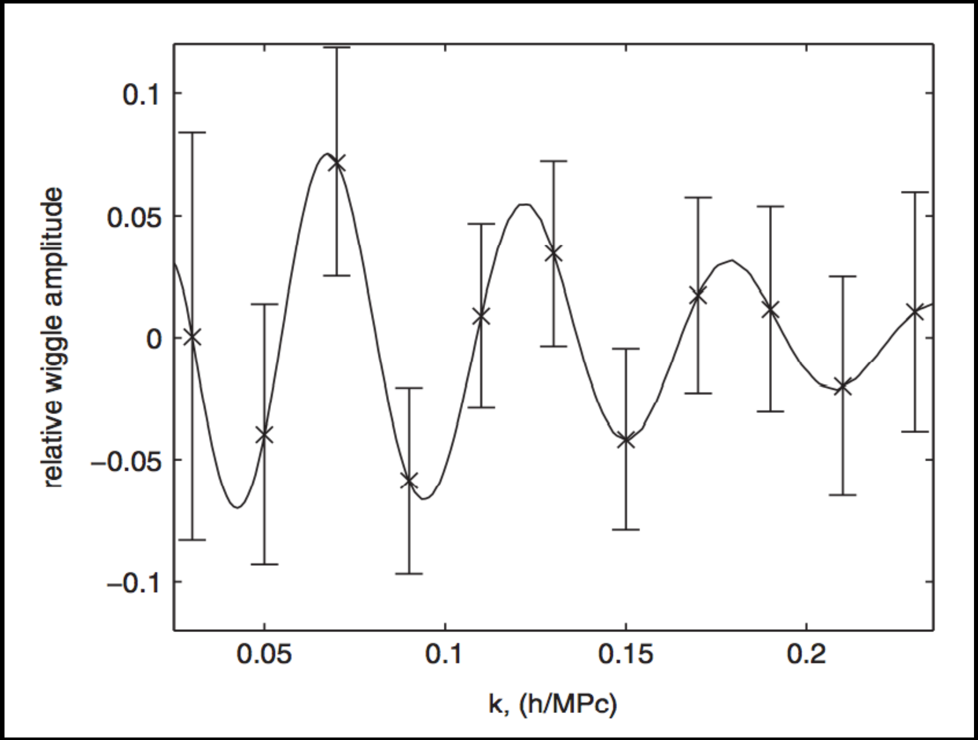
see e.g. Wyithe & Loeb 2008, Chang et al 2008

Intensity Mapping



- Signal is on large scales (150 comoving Mpc)
- Signals are weak - ~100uK (z)
- Need high surface-brightness sensitivity in the core, similar to EoR requirements

Intensity Mapping



- Signal is on large scales (150 comoving Mpc)
- Signals are weak - ~100uK (z)
- Need high surface-brightness sensitivity in the core, similar to EoR requirements

- Need to subtract foregrounds to high accuracy (better than 0.1%)
- Requires high degree of polarization purity (polarized foregrounds don't leak into I
- No bandpass structures that can mimic HI signal (>MHz scales)
- Large instantaneous field of view (similar to EoR)

How do we answer these questions?

- To measure the expansion history
  - *Type Ia Sne*
  - *Baryon Acoustic Oscillations*
  - *Gravitational Lensing*

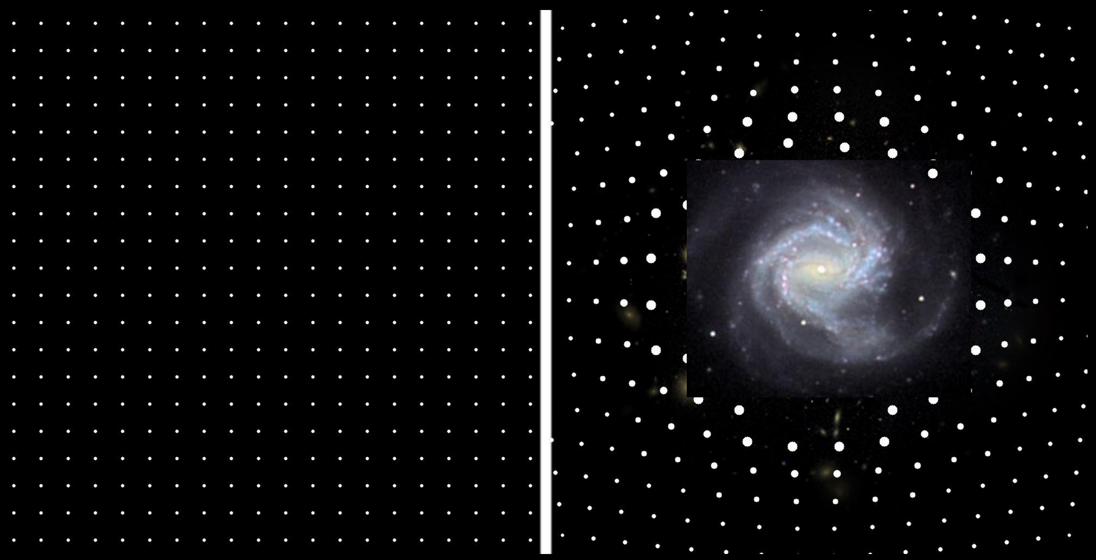
- To find departures from GR on cosmological scales, need to measure the influence of gravity on these scales
  - *Gravitational Lensing*
  - *Redshift Space Distortions*
  - *Integrated Sachs-Wolfe*

What can we do with continuum surveys?

Cosmic Magnification

Background sources (high-z) lensed by massive foreground (low-z) sources:

- Background area appears stretched
  → *decreased surface density*
- Fainter background sources appear brighter
  → *increased surface density*

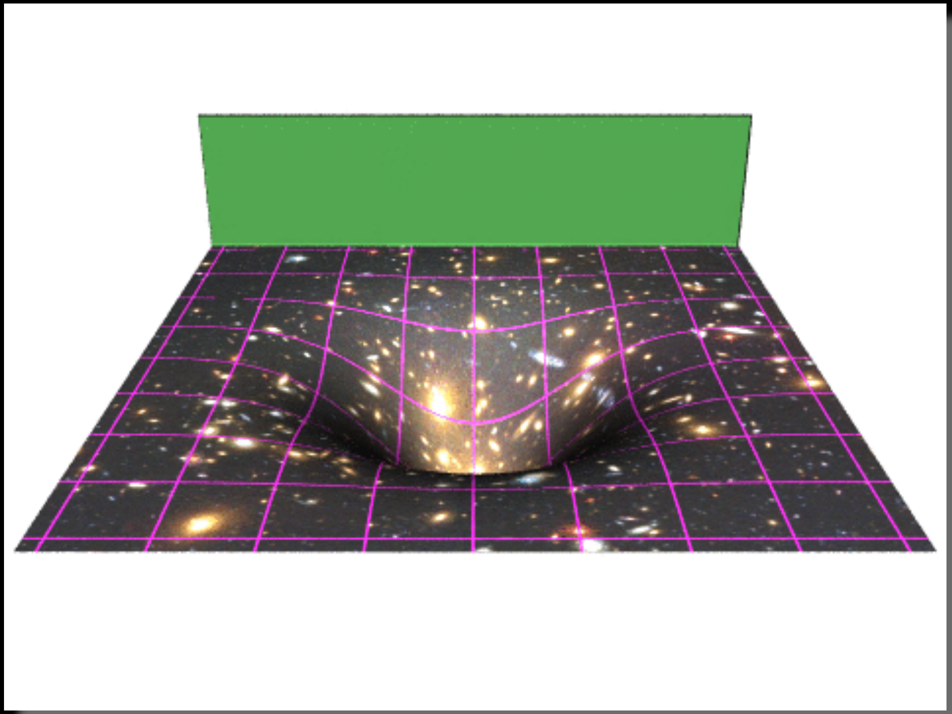


Joerg Colberg, Ryan Scranton, Robert Lupton, SDSS

Test: Cross-correlation of foreground and background objects

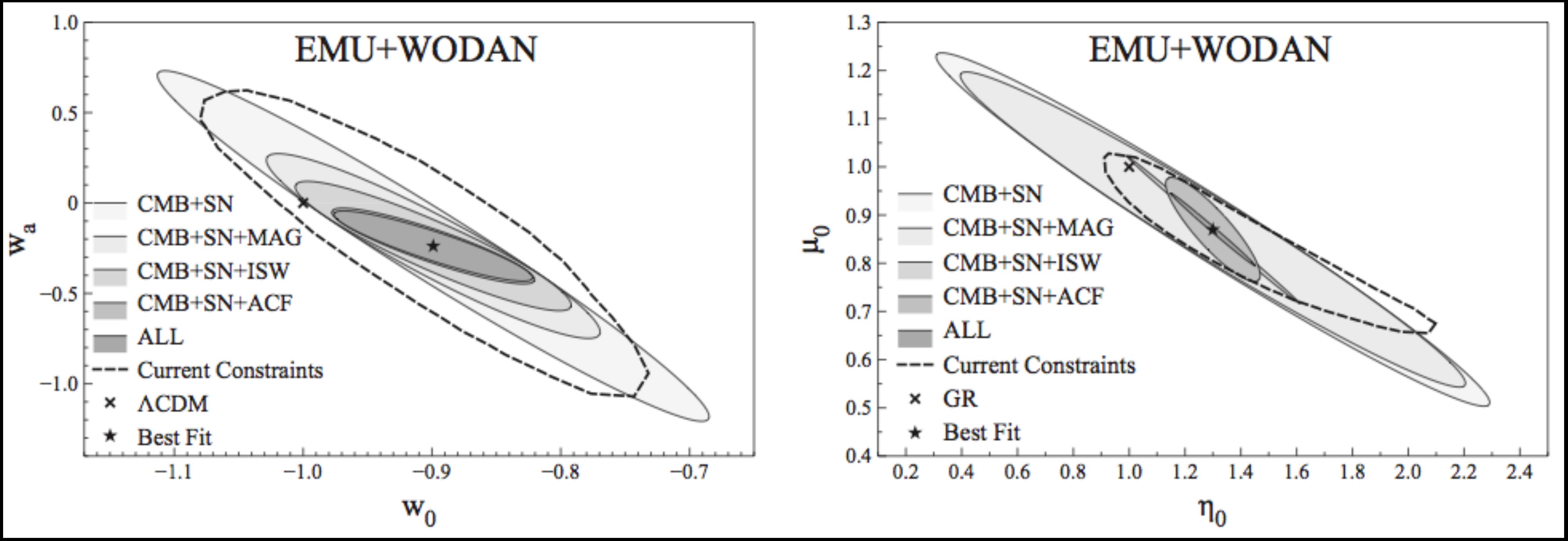
Integrated Sachs-Wolfe (ISW) effect

- CMB photons gain energy entering a deep gravitational potential well
- Universe undergoes accelerated expansion
- Photons lose less energy upon exit



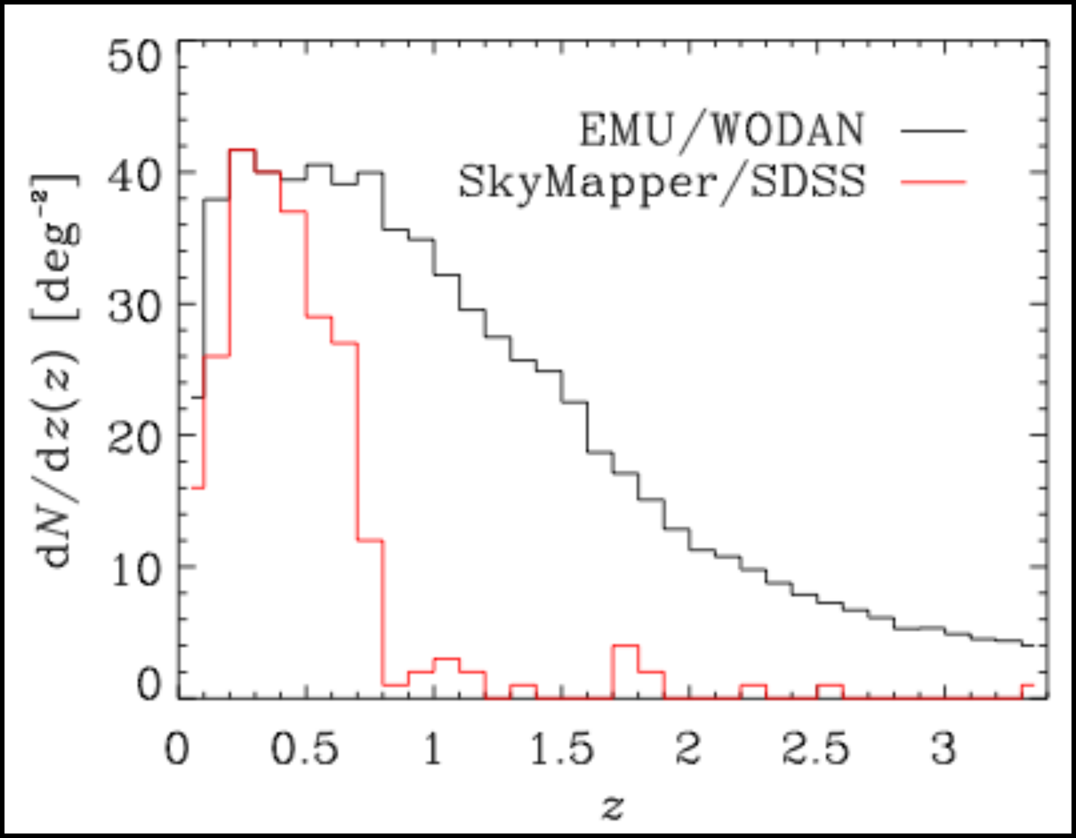
Test: Cross-correlation of large structures with CMB

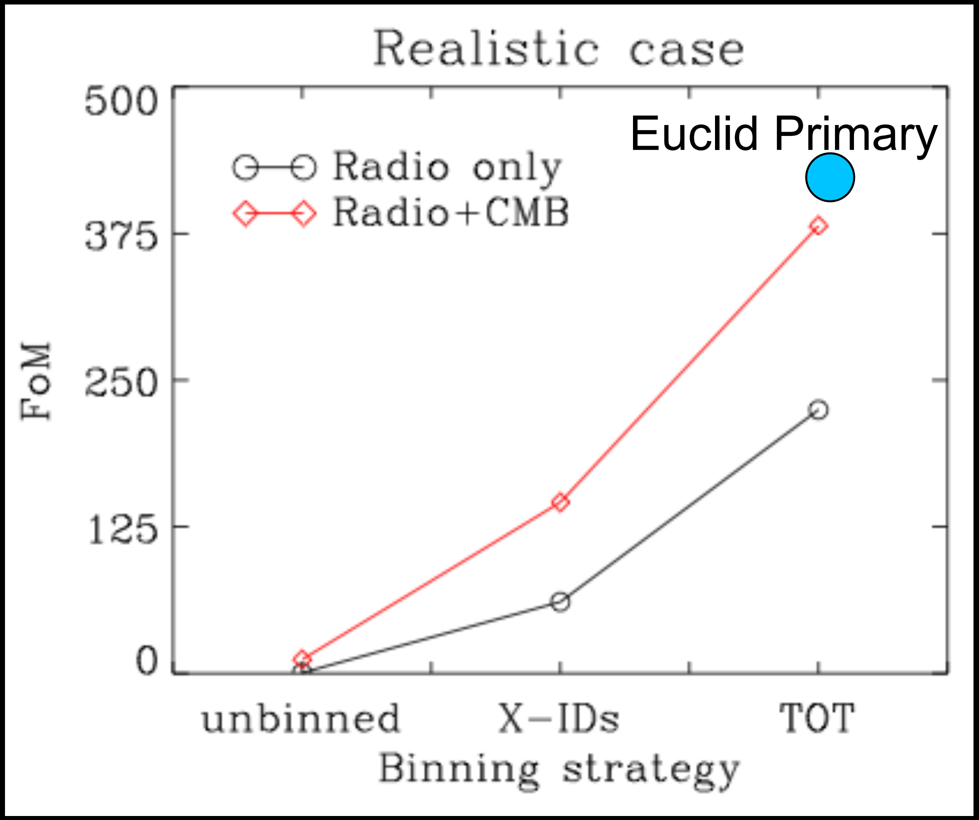
Dark Energy & Modified Gravity



Raccanelli et al. 2012

With redshifts





Camera et al. 2012

- With minimal photo-zs for radio sources at z<1 ish you get much improved constraints on the evolution of DE.
- ~5 years earlier than Euclid

Weak Gravitational Lensing

- Measurement of the distortion in galaxy shapes due to the dark matter distribution along the line of sight allows the reconstruction of the density field.

- Combining the continuum measurement with redshift allows lensing tomography, which measures a combination of geometry and the growth of structure

- Key to success
  - source density (40 sources/arcmin^2 with Euclid)
  - Shape measurement of distant galaxies (~1arcsec in size)
  - **resolution required ~0.5"**

- Why do this in the radio when you only get 5 sources arcmin for a 1.4GHz sensitivity of 0.5uJy rms per total flux – or **0.35uJy/beam!**

Weak Gravitational Lensing

- Radio Interferometers have a determinable and stable PSF
- You can “pick” the important spatial modes as a default
- Radio spectra are smooth and vary little across a galaxy
  - (cf optical imaging which have stellar absorption/emission features along with bulge and disk components of different colours)
  - Colour dependent shape biases can be much better controlled in the radio (frequency information available)
- Polarization can be used to measure the intrinsic orientation (Brown & Battye 2011a,b)

The combination of optical and radio surveys is greater than the sum of the parts!

Moving to the SKA…

- Weak lensing requirements in the radio…

  - Source density of ~5 /arcmin^2 (frequency independent)
  - Resolution (synthesised beam) of ~0.5”

    - Sensitivity needed is ~0.35uJy/beam at 1.4GHz
      - (scale as freq^-0.8 for required depth at other frequencies)

  - Area required to probe the large-scale power that you are sensitive to with 5 sources / arcmin^2 is ~5000 sq.deg

  - Less area would still help control systematics of other facilities

- Strong lensing

  - Weak lensing survey could find many of the expected strong lenses

  - With 0.5” resolution at 1GHz, we would get <0.2” resolution at 3GHz – good enough for studying the lens systems

Summary – Spectral Line

- HI cosmology with Intensity Mapping should be high-priority for SKA1
  - Compact configuration at all frequencies (SKA-Low too sparse at high-freq)

- SKA-Low is too sparse at >200MHz for Intensity Mapping at z>3

- SKA-Mid may be good enough with a denser core
  - 50 antennae within 100m radius would result in a filling factor f of ~0.3,
  - 25 antennae within 50m radius will have a f of ~0.6
  - Other possibility to gain a “single disk” experiment with a projected filled core
  - Extending frequency coverage to as low as possible would be advantageous (no need for > 800MHz for IM)
  - 250-single dish experiment also worth pursuing

  - More work on feasibility and competitiveness is still required

- Low-redshift BAO and Redshift Space Distortions will still be useful
  - provide confirmation of results from optical/nearIR surveys
  - reduce systematics
  - overcome cosmic variance with multiple tracers of the density field

  - Multi-bias tracer
    - HI less biased tracer of the density field – Good for low-z Redshift Space Distortions (growth of structure)
    - less prone to finger of God effect

Summary - Continuum

- Radio continuum surveys have potential to do cosmology

- Three tests that need area can be done well with 2 arcsec, 1uJy/beam all-sky survey
    - ISW
    - Power Spectrum
    - Cosmic Magnification bias

  - all need very high-precision calibration over 3pi sr (~1%)

Just about possible with baseline design (with weighting -> more time needed)

But…

- If SKA1 can combine resolution (0.5”) and sensitivity(0.35uJy/beam) then weak lensing surveys are within reach.
    - Unique and groundbreaking science for SKA1
    - Very complementary to optical/nearIR surveys
    - Key to accounting for systematics at different wavelengths
    - Polarization – would like large ~1GHz bandwidth

- With this resolution can also utilise multiple tracers to overcome cosmic variance
    - Distinguish FRII,FRI,RQQ, SFGs – possibly leading to tight(est) constraints on f_{NL}