# Probing Fundamental Physics with the Radio Sky

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science & technology
Department: Science and Technology
REPUBLIC OF SOUTH AFRICA

NRF National Research Foundation

COSMOLOGY & GRAVITY GROUP

QGaSlab
The laboratory for Quantum Gravity & Strings

# Motivation

- Connection between high energy physics, small scale physics and large scale observations
- Imprints of the early universe
- Cosmological Constant problem
- Observe accelerated expansion - slightly far off
- Tension in Hubble measurements - theory explanation?
- Dark matter observed
- many particle physics theories - no direct detection
- the sky is a fabulous experimental play ground for high energy physics

Nobeyama 45m Radio telescope

# Radio Astronomy

- Discovered by Jansky in 1930's to get rid of noise to improve telephones for Bell labs
- Extremely weak - Add them all up (except solar) - not enough to melt a snowflake!
- Low Frequencies, long wavelengths ~ 10 MHz —> 1 THz
- Large wavelengths - good because goes straight through dust
- Low energy —> hyperfine splitting ——> 21 cm HI line.
- Optical and radio - ground based. Atmosphere absorbs IR, UV, X-ray, Gamma-ray.

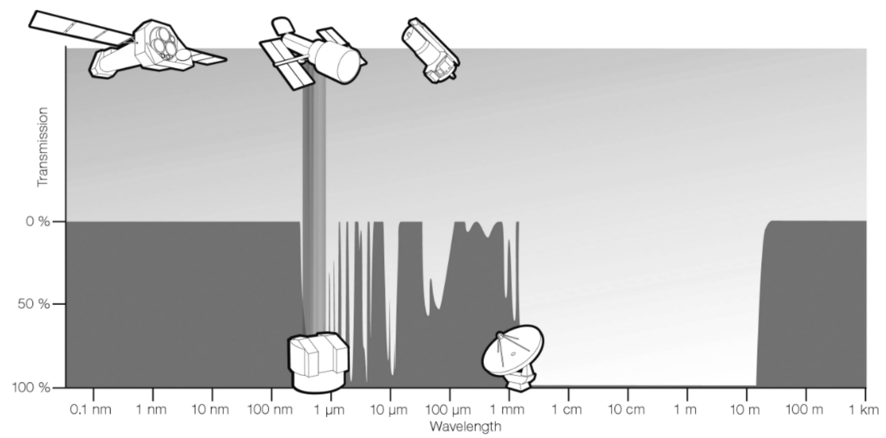



Figure 1.1: Ground-based astronomy is confined to the visible and radio **atmospheric windows**, wavelength ranges in which the atmosphere is nearly transparent. The radio window is much wider than the visible window when plotted on logarithmic wavelength or frequency scales, so it includes a wide range of astronomical sources and emission mechanisms. Radio astronomers usually measure (and think in terms of) frequencies $\nu = c/\lambda$ instead of wavelengths $\lambda$. Thus $\lambda = 0.3$ mm corresponds to $\nu = 1$ THz, the highest frequency accessible from the best terrestrial sites. The Earth's ionosphere reflects radio waves longer than $\lambda \sim 30$ m ($\nu \sim 10$ MHz). Abscissa: Wavelength. Ordinate: Atmospheric transmission. Image Credit: ESA/Hubble (F. Granato).

CMB, pulsars, quasars, radio galaxies, neutron stars, evidence for DM, indirect evidence for gravitational radiation, strong lensing, exoplanets ——- What is next?

# Radio Astronomy

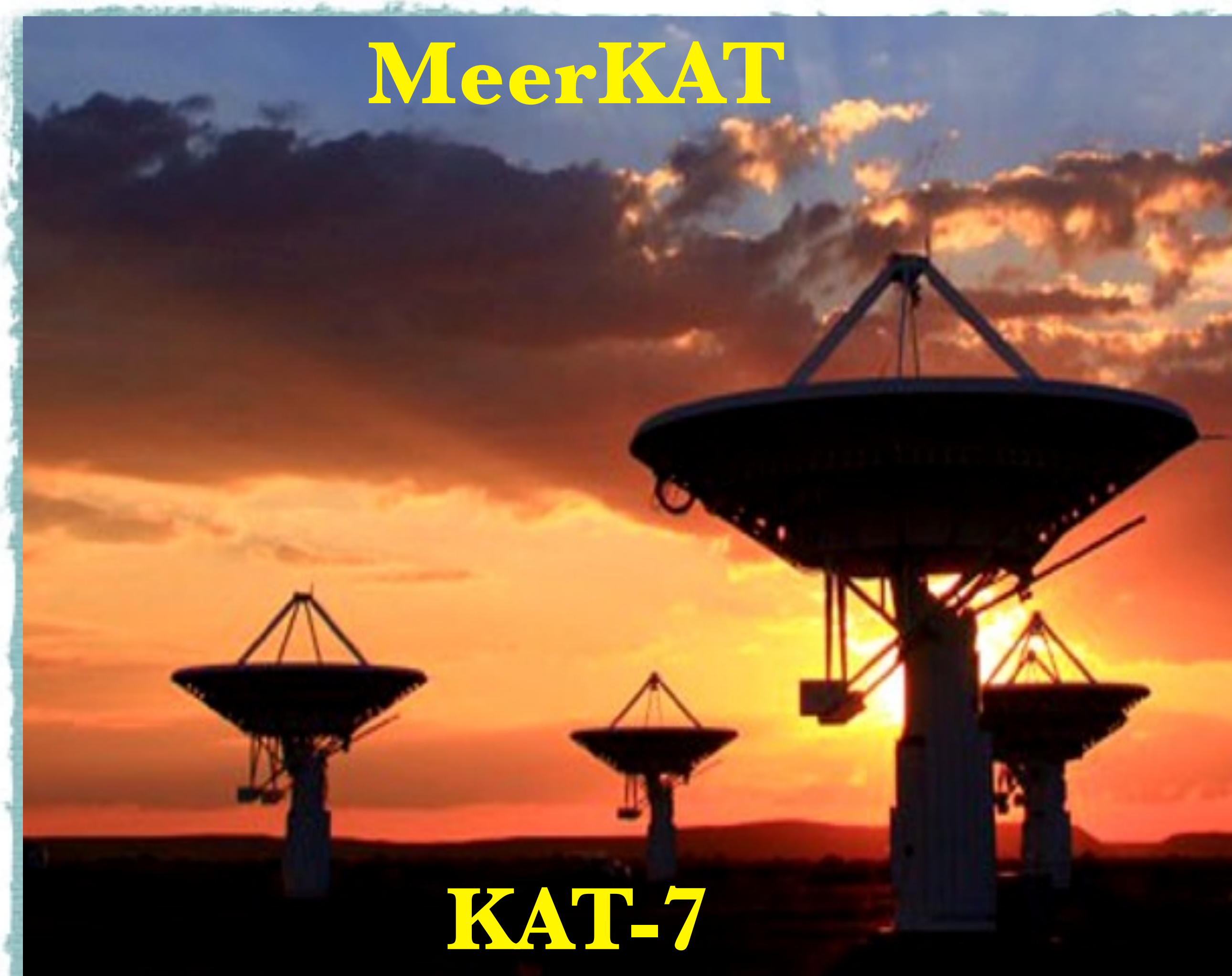
# HIRAX

## Hydrogen Intensity and Real time Analysis eXperiment

L. Newburgh, **AW** et.al 2016

- 1024 6 m dish array
- 400 - 800 MHz radio interferometer
- Intensity mapping of BAO at z ~ 0.8 - 2.5
- ideal to probe dark energy
- constrain dynamical dark energy
- constrain curvature
- Transients - pulsars and fast radio bursts
- FRBs - short (~ms), bright ( ~Jy), radio transients, likely cosmological
- complementary to CHIME - South, lower RFI, no snow

**http://www.acru.ukzn.ac.za/~hirax**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HIRAX


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# Intensity Mapping

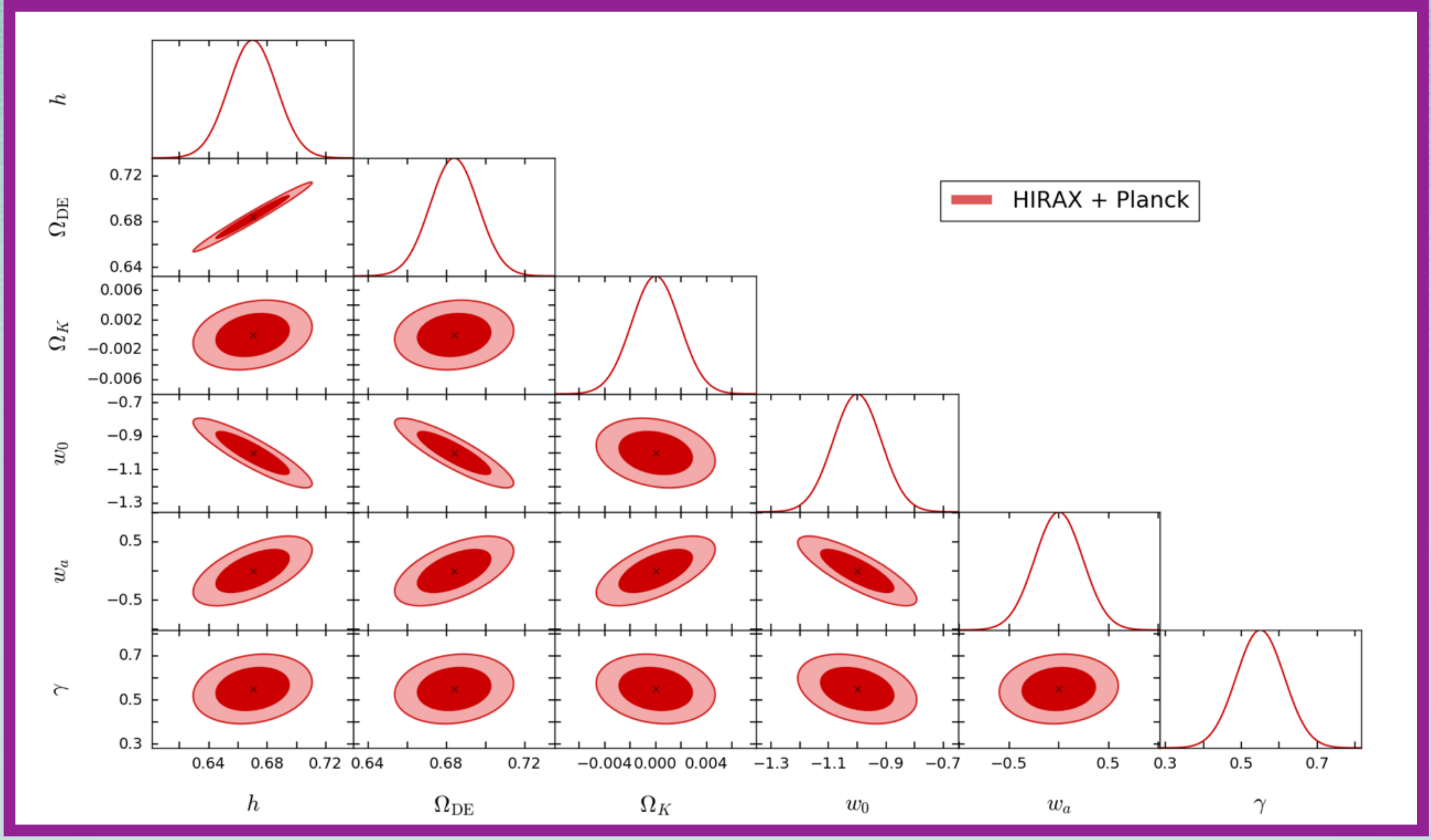
- Goal: measure baryon acoustic oscillations with HI intensity mapping
- How: observe unresolved sources via their redshifted 21 cm line
- What: produce maps of large scale structure to measure BAO
- Why: BAO are a preferential length scale 150 Mpc

→ characterize the expansion history of the universe

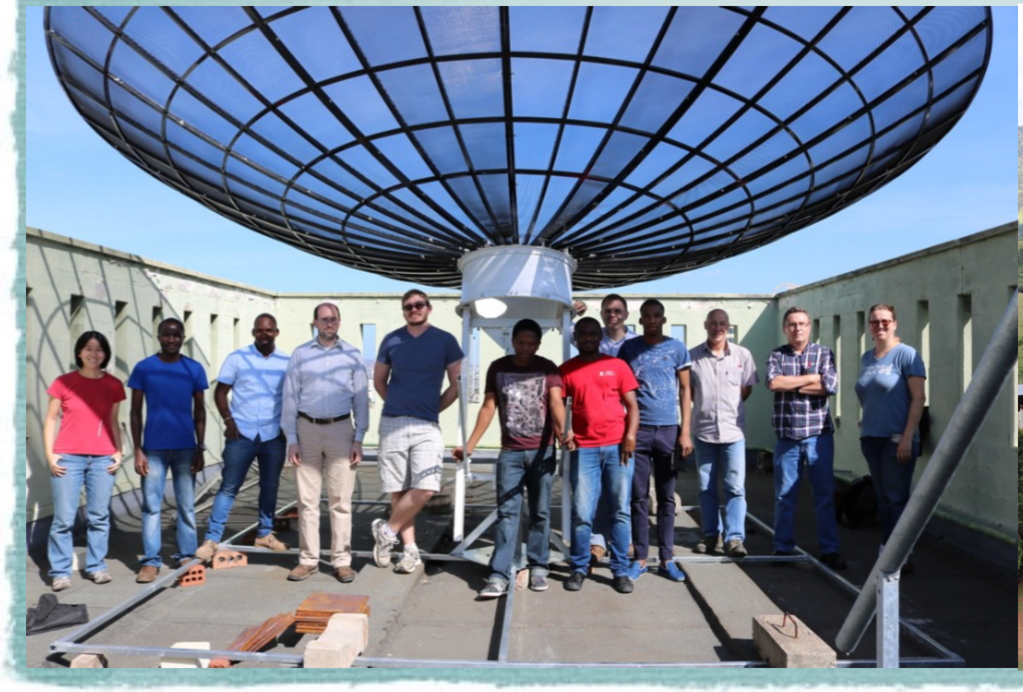
→ dark energy

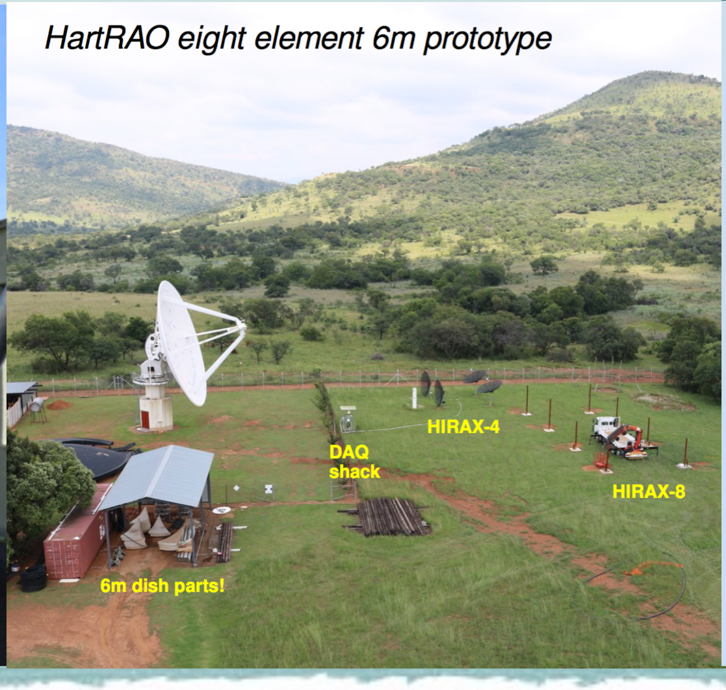
A Sunday on La Grande Jatte, Seurat, 1884

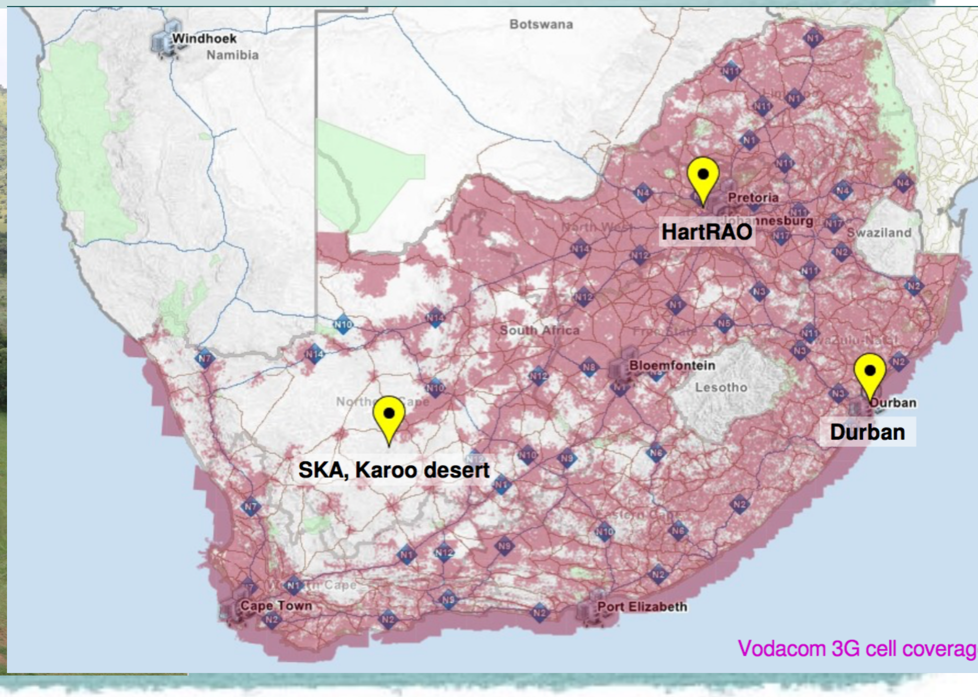
# Forecasts




L. Newburgh, **AW** et.al 2016





# Constraining the Multiverse

Curvature matters!

Guth and Nomura, 2012
Kleban and Schillo, 2012

Measurement of positive curvature $\Omega_k < -10^{-4}$

→ Eternally inflating multiverse is ruled out

Measurement of negative curvature $\Omega_k > 10^{-4}$

→ Bubble nucleation happened, excludes some pre-inflation histories

Measurement of curvature $|\Omega_k| > 10^{-4}$

→ Slow-roll eternal inflation ruled out

Planck bound $|\Omega_K| < 5 \times 10^{-3}$ assumes $w = -1$

Cosmic variance bound $\Omega_k \sim 10^{-4}$

Leonard, Bull & Allison 2016

Improve bounds by order of magnitude. Close to absolute bound.

Break curvature dark energy degeneracy to improve these constraints

# How?

- Combined 21cm spectral line emission from many unresolved galaxies in each pixel
- Survey large cosmological volumes, retain cosmological info, sacrifice resolution
- galaxy distribution traces matter distribution —> so make intensity maps

→ measure distances out to higher redshift than optical galaxy survey

Use 21 cm IM to do large, high redshift cosmological survey

**Two approaches**

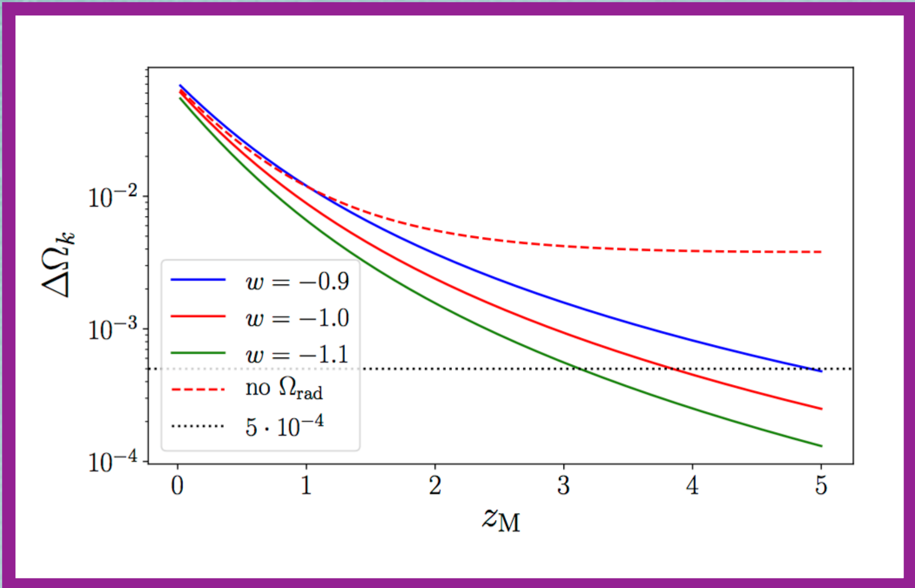
Technique of Knox et al 2006

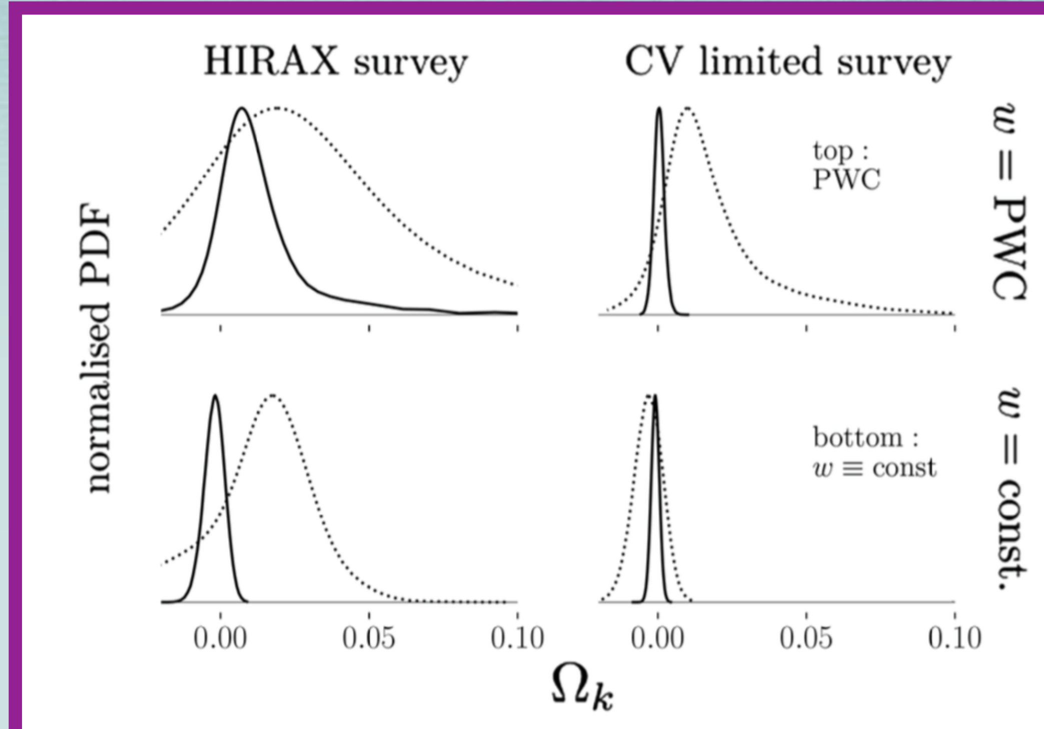
Consider constant w and skip DE dominated era

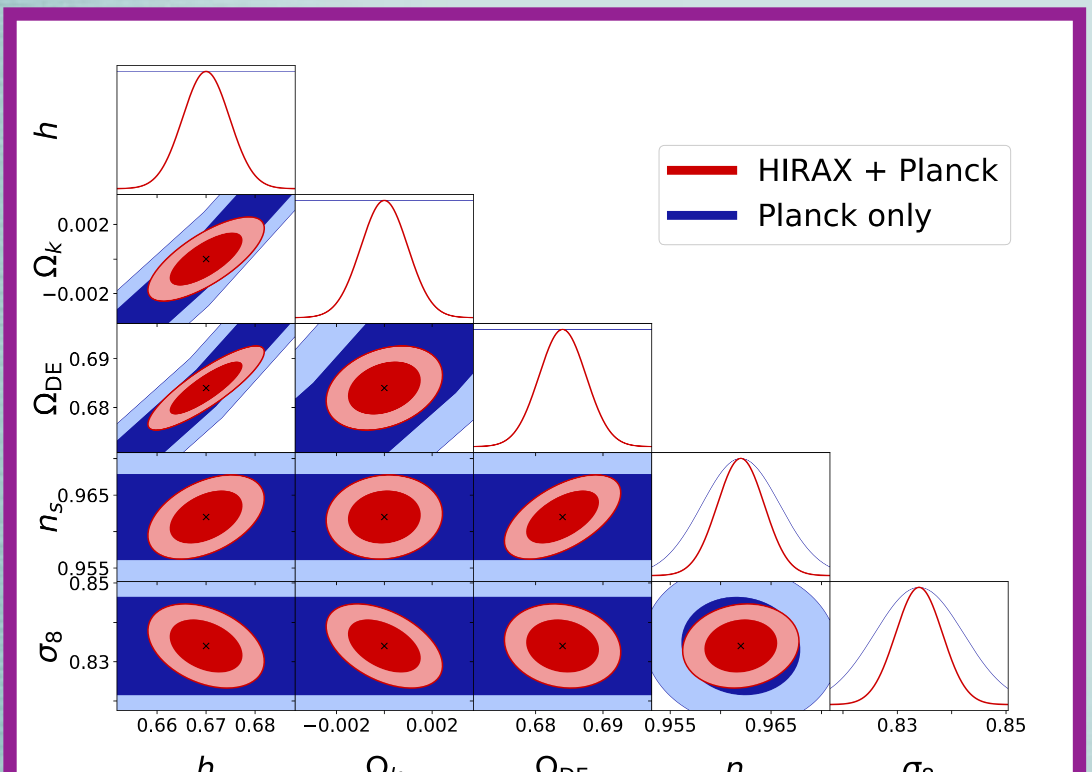
Consider piecewise constant w(z), use MCMC to sample from posterior $\Omega_k$ ,

marginalise over w(z) in each bin. Results converge with enough bins.

# Model Independent $\Omega_k$ Constraints




| $\Omega_k \times 10^{-3}$ | Avoidance | $w \equiv$ const | $w_0 w_a$ | Piecewise |
|---|---|---|---|---|
| Planck | — | $-52^{+49}_{-55}$ | — | — |
| SDSS | — | $+39^{+29}_{-70}$ | — | $+76^{+65}_{-50}$ |
| HIRAX 1 yr | $0.0^{+2.0}_{-2.0}$ | $-2.0^{+3.3}_{-3.6}$ | $-1.3^{+6.2}_{-7.0}$ | $+9.35^{+13.9}_{-7.76}$ |
| HIRAX 2 yr | $0.0^{+1.4}_{-1.4}$ | $-2.0^{+2.8}_{-2.9}$ | $-2.0^{+5.3}_{-6.0}$ | $7.6^{+10.3}_{-6.6}$ |
| CV1 | $0.0^{+0.07}_{-0.07}$ | $-0.9^{+1.4}_{-1.4}$ | $-0.9^{+1.4}_{-1.4}$ | $+0.4^{+1.7}_{-1.7}$ |
| CV2 | $0.0^{+0.07}_{-0.07}$ | $-1.1^{+1.6}_{-1.6}$ | $-1.1^{+1.6}_{-1.6}$ | $-0.1^{+2.1}_{-1.9}$ |

Proof of principle for HIRAX, but true for IM experiments in general

Witzemann, Bull, Clarkson, Santos, Spinelli & **AW** 2017

# Fast Radio Bursts

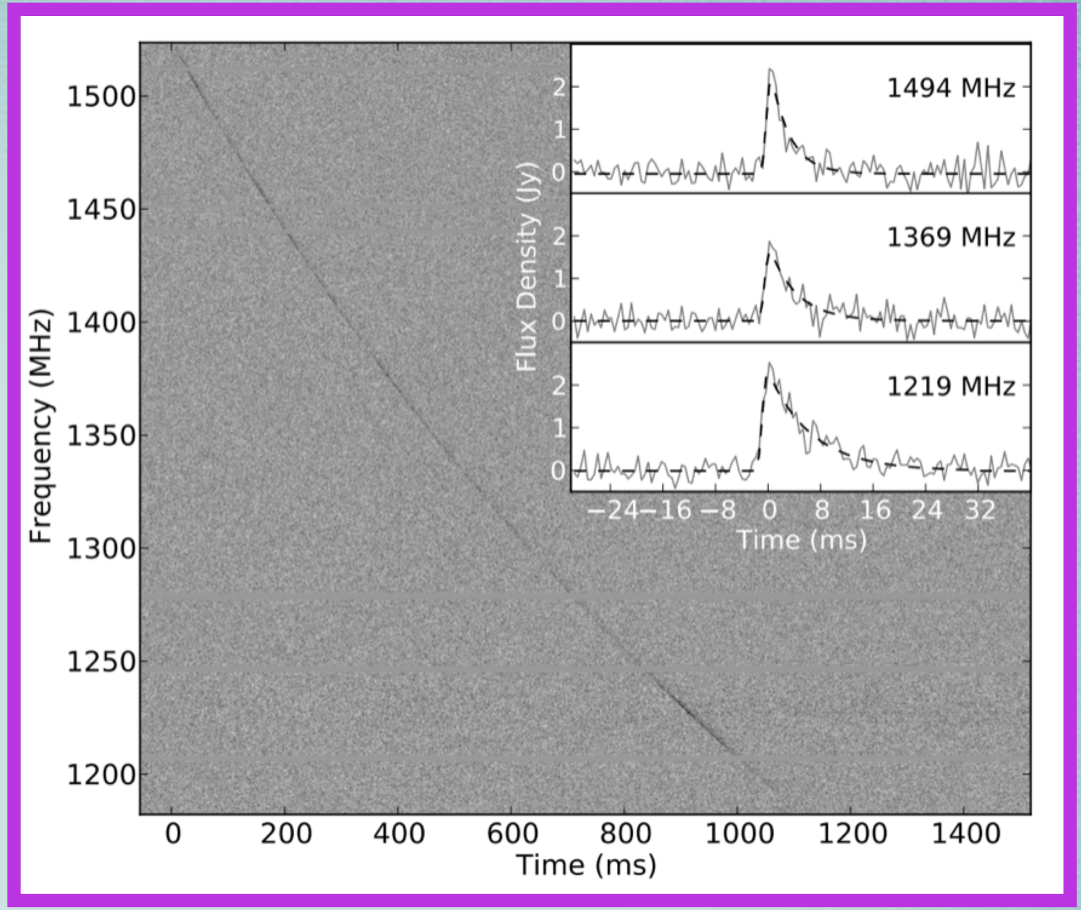
- Transients, recently discovered (2007), only 20+ observed so far
- Progenitor mechanism is currently unknown
- Number of classes is unknown. 1 has been observed to repeat
- Very bright (~Jy) and brief (~ms)

Possibility for new science and discovery!

- Figure out the progenitor theory - possibilities include cosmic strings
  Cai, Sabancilar, Vachaspati 2016
  Brandenberger, Cyr, Iyer 2017
- Catalogue of predictions of theories
  Platts, Gordin, da Costa Santos, Kandhai, Walters and **AW** in progress
- Use FRBs as cosmological yardsticks
  Walters, **AW**, Gaensler, & Ma, 2017
  Walters, Sievers, **AW** in progress

# Dispersion Measure

- Brief pulse in the radio (ms)
- Delay in arrival time ~ $\nu^{-2}$
- Propagation through cold plasma




- Dispersion Measure contains info about the distribution of electrons from source to observer

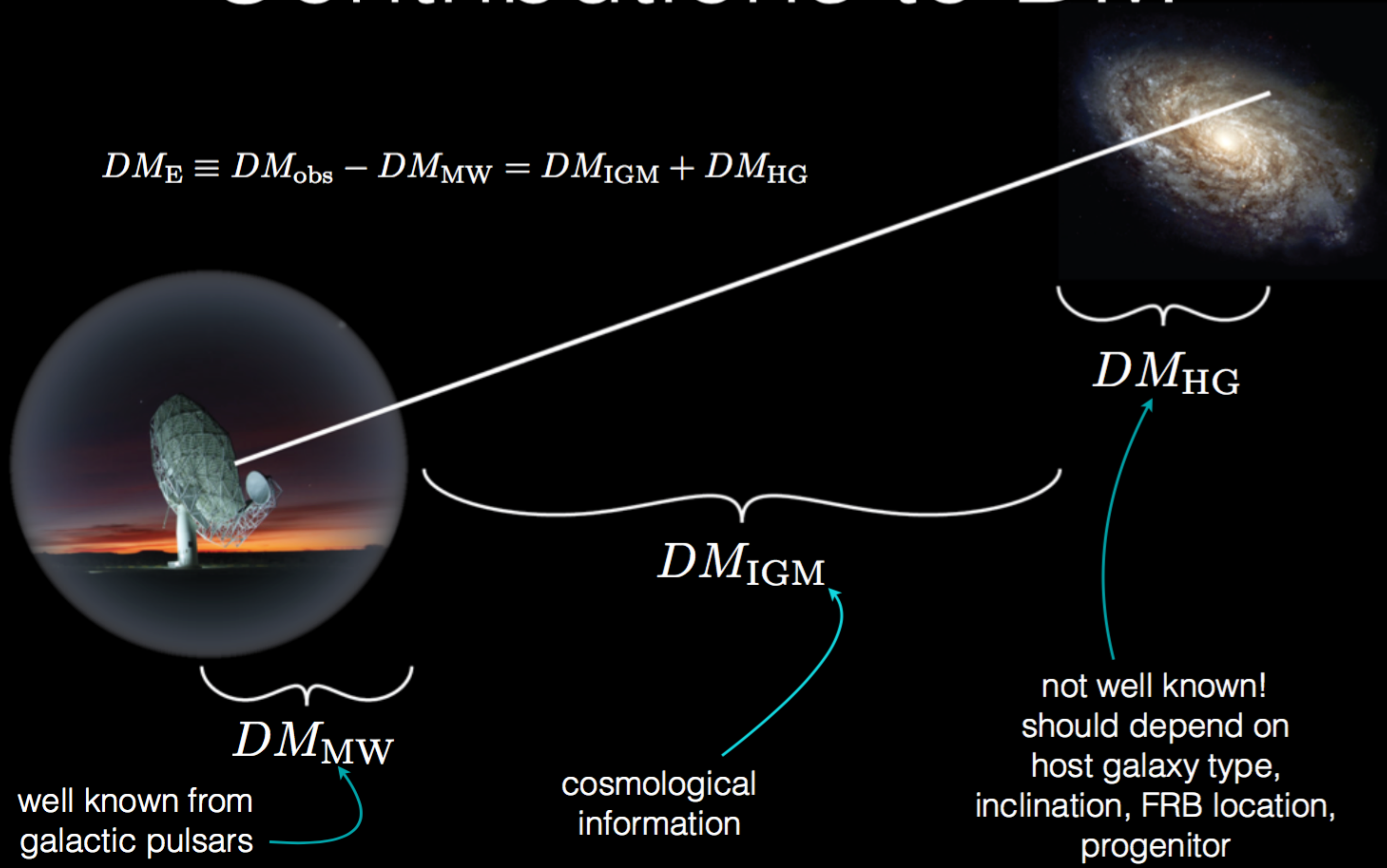
$$DM \sim \int n_e dl$$

- Large DM —-> Source must be extragalactic
- So far FRBs appear to have a host galaxy

Tendulkar et. al. 2017

# Contributions to DM

$$DM_{\rm E} \equiv DM_{\rm obs} - DM_{\rm MW} = DM_{\rm IGM} + DM_{\rm HG}$$



# Cosmology with FRBs

Walters, **AW**, Gaensler, & Ma, 2017

Yang & Zhang, 2017

- DM(z) as a probe of cosmology?
- Question - Can we get better low redshift curvature constraints?
- SN1a alone give $\Omega_k \sim 0.2$
- Average DM to deal with inhomogeneous IGM

$$< DM_{\rm IGM}(z) >= K_{\rm IGM} \int_0^z \frac{\chi(z')(1+z')dz'}{E(z')}$$

$$E(z) = [(1+z)^3\Omega_m + f(z)\Omega_{DE} + (1+z)^2\Omega_k]^{\frac{1}{2}}$$

$$K_{\rm IGM} \equiv \frac{3cH_0\Omega_b f_{\rm IGM}}{8\pi G m_p}$$

$$\chi(z) = \frac{3}{4}y_1\chi_{e,H}(z) + \frac{1}{8}y_2\chi_{e,He}(z)$$

$$f(z) = e^{3\int_0^z \frac{1+w(z'')dz''}{(1+z'')}}$$

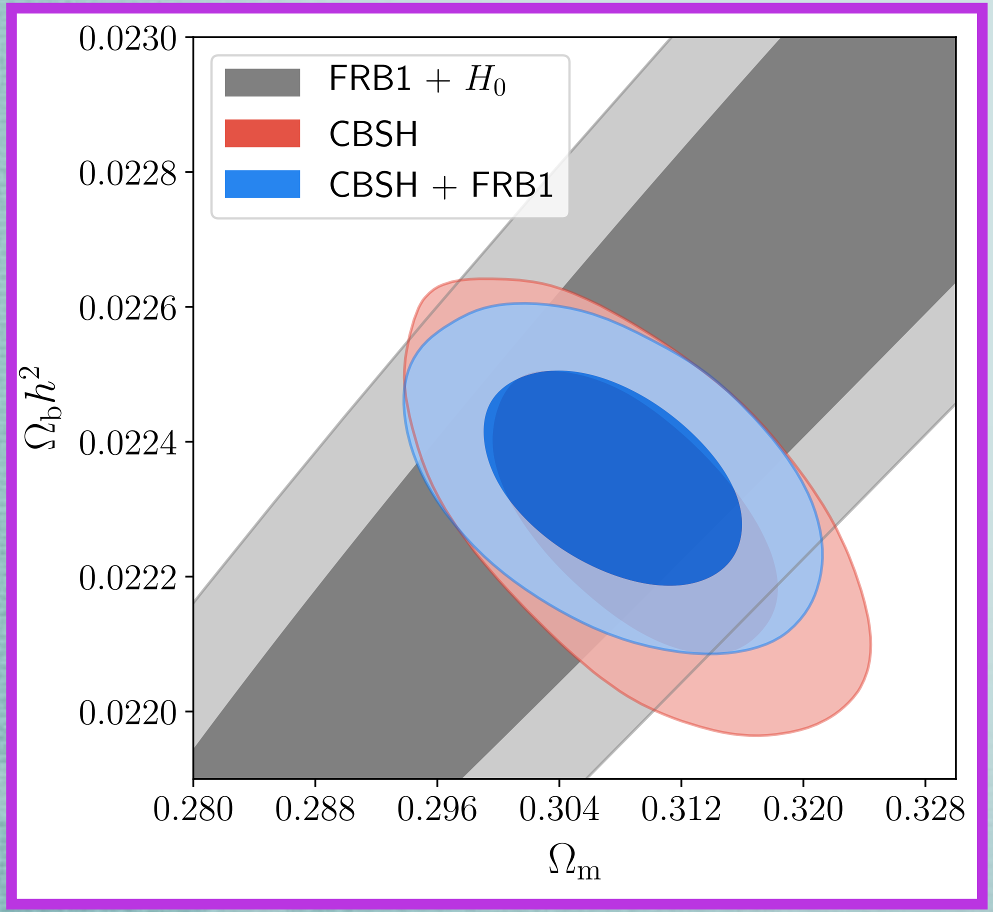
**growth depends on DE EOS**

**Parametrise Equation of State :** $w = w_0 + w_a \frac{z}{1+z}$

# Cosmology with FRBs

- Simulate an FRB catalogue with errors from a HIRAX-like survey
- Consider ~ 1000 FRBs with associated redshift 0<z<3
- Forecast using MCMC
- combine with CMB, BAO, SNe, H0

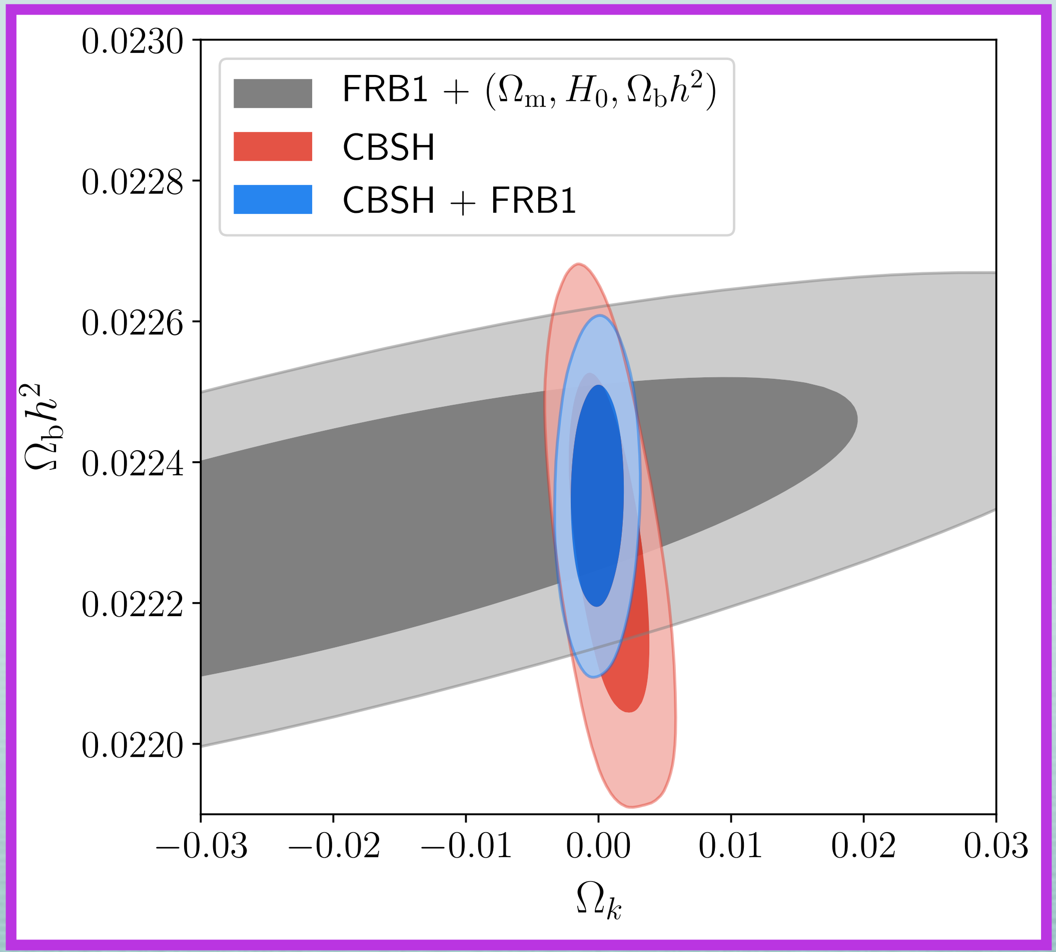
**Flat ΛCDM**




- FRBs alone, don't constrain - need priors
- Biggest improvement over CBSH is $\Omega_b h^2$
- Limited by HG and IGM uncertainties

- Curvature unconstrained by FRBs alone
- FRBs alone, don't constrain - need priors
- Including CBSH covariance improves $\Omega_b h^2$ and $\Omega_k$
- Novel constraint of $\Omega_b h^2$ independent of high redshift (CMB/BBN)
- Limited by HG and IGM uncertainties

**Non-Flat $\Lambda$ CDM**



# Find BSM particles in the Radio?

Light Scalar fields are abundant in BSM and string theories.

Typically, gravitational strength, long range forces, coupled to everything … yet unobservable in the solar system?

Hide from our view - Screening mechanisms.

- Set the coupling to be small. By hand or environmentally small - e.g. Symmetron
- Allow the mass of the field to be environmentally dependent - Chameleon screening. All f(R) models.
- Consider a kinetic coupling - effectively reduces matter coupling - Vainshtein screening. DGP, massive gravity and galileons.

Rethink known observations and future ones

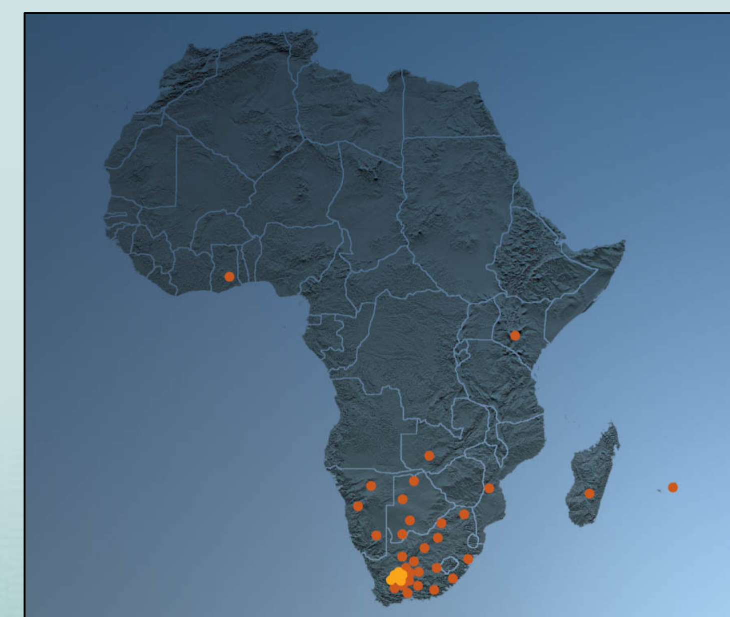
# Next Frontier

The SKA project is an array of radio telescopes - ostensibly Astronomy but in reality it can be a fundamental physics machine

- Curvature
- Dark Energy
- Dark Matter
- Astroparticle physics
- Pulsars
- Pulsar timing arrays
- Gravitational waves
- Magnetism

- Early universe
- Late universe
- General Relativity
- Primordial Non-Gaussianity
- ALPS

http://www.ska.ac.za/media/gigapans.php



KAT-7 SKA South Africa

# Conclusions

- HI line Intensity Mapping - a potentially powerful new tool
- FRB detection is on the brink of explosion
- Cosmology with FRB + BAO - useful for baryon constraints
- Obstacles - Host galaxy DM unknown, IGM uncertainties, redshift follow up takes time.

- Possible solution
- HIRAX outrigger - possibly identify candidates near edge of HG
- Machine learning algorithm- neural network to identify best case
- Limit redshift followup
- Explain origins of FRBs

Platts, Shock, **AW** in progress

Radio telescope arrays can serve as fundamental physics machines