Cosmological forecasts using 21cm Intensity Mapping

with

HIRAX: Hydrogen Intensity mapping and Real time Analysis eXperiment

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Outline

- Introduction:
  Dark Energy and Baryon Acoustic Oscillations
- 21cm Intensity Mapping → HIRAX
- HIRAX Forecasts
- Cosmology Simulations
- Conclusions and Ongoing work

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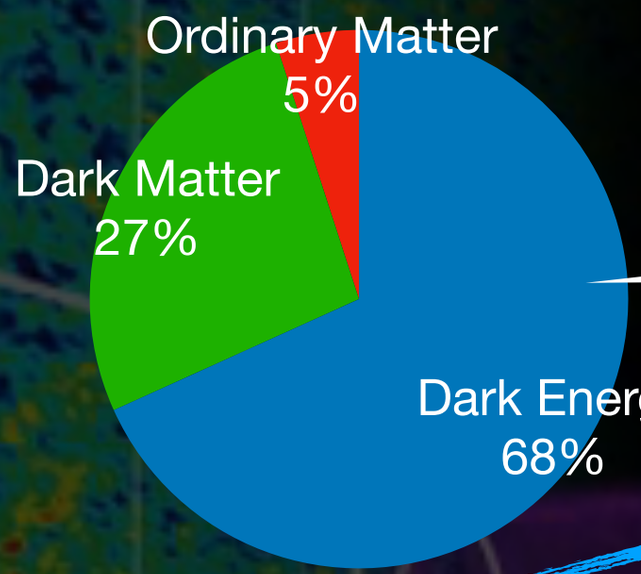
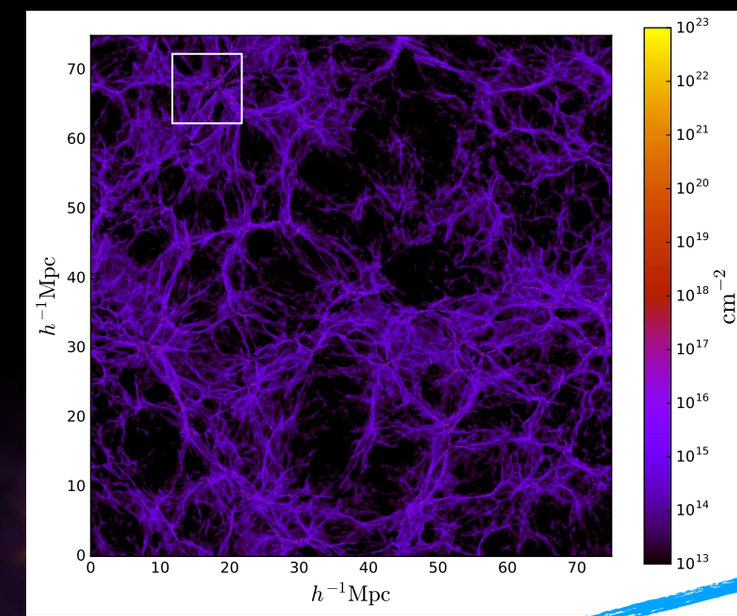
Dark Energy with 21cm radiation

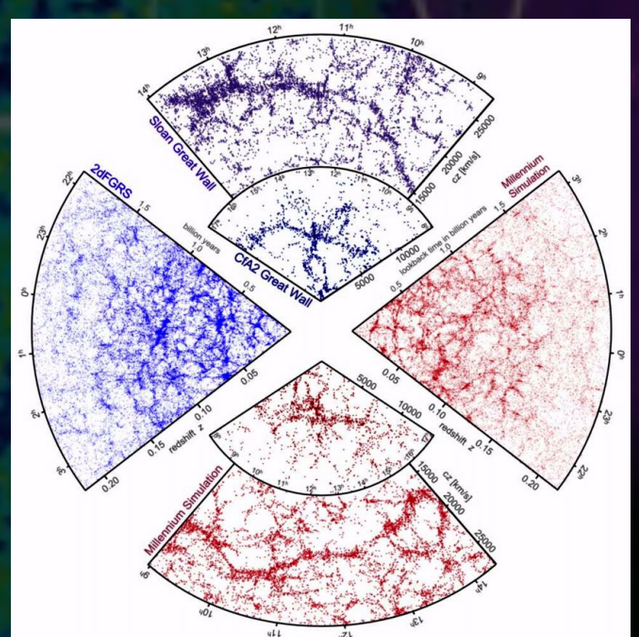


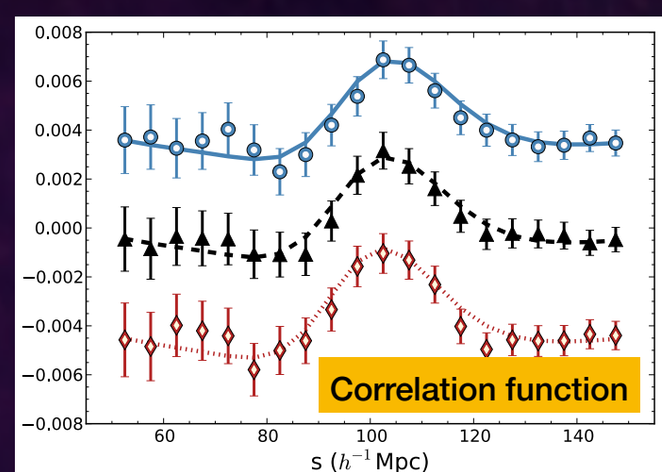
Baryon Acoustic Oscillations

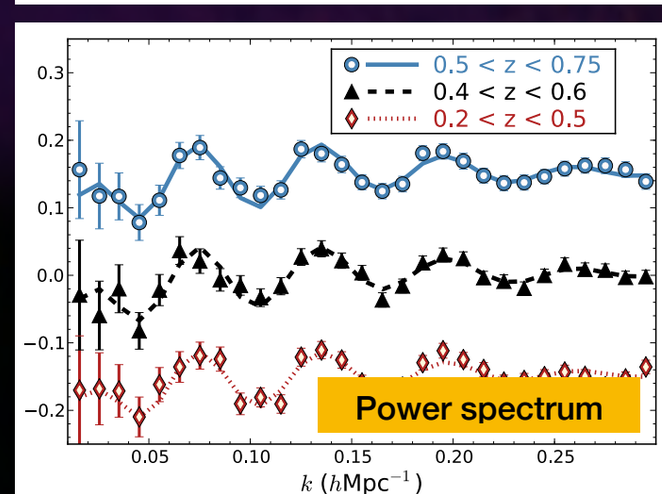
$D_A(z)$,
$H(z)$



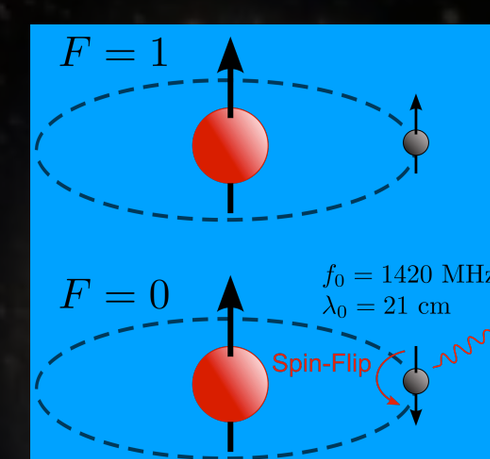
Neutral Hydrogen



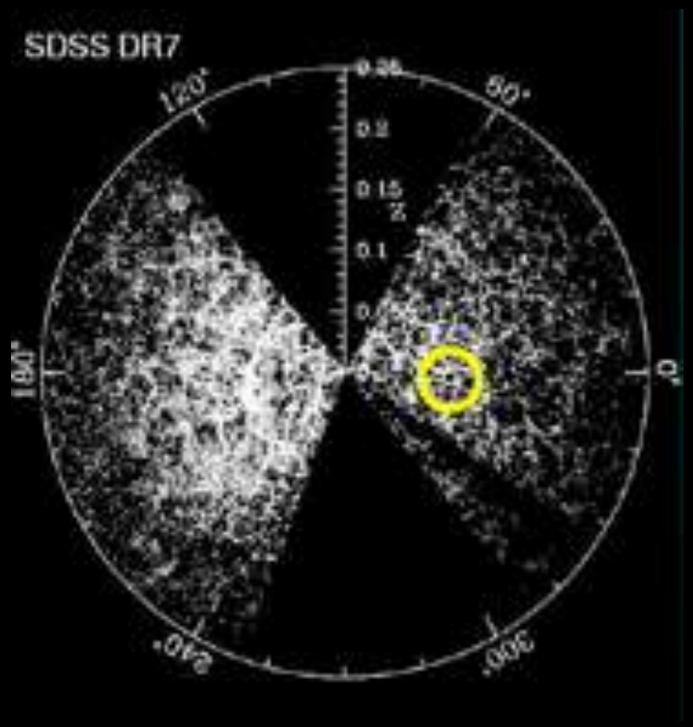


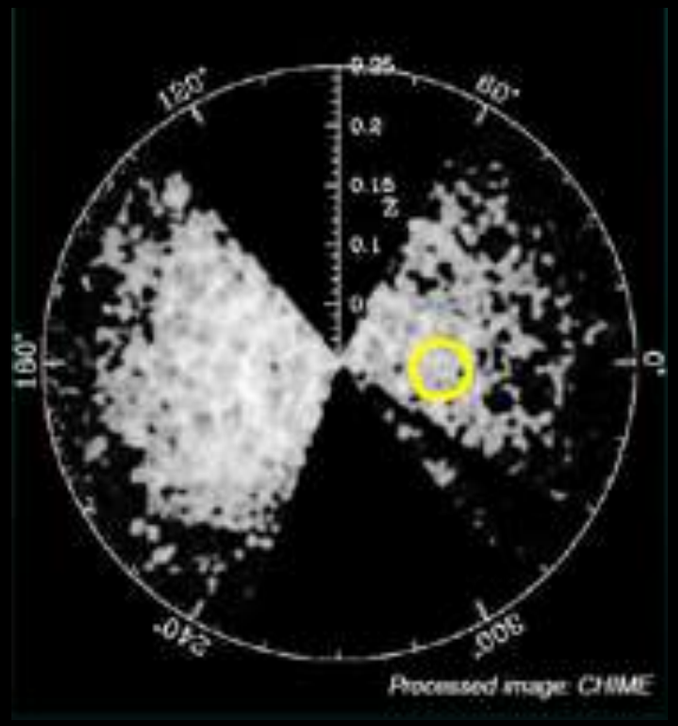


- Hyperfine splitting of the 1S ground state due to the interaction of the magnetic moments of the proton and the electron
- Neutral hydrogen is abundant in galaxies (and IGM)
- Observations: redshifted 21cm line



BAOs with 21cm IM





- Sound wave imprint from recombination: characteristic 150 Mpc scale (1 degree) - large!
- Requires large volume (large sky area and z range)
- Counting individual galaxies and getting to high z is challenging

- Ignore spatial resolution: use HI intensity mapping to measure matter distribution AND obtain redshift information
- Use BAO peak as a standard ruler for charting the expansion history

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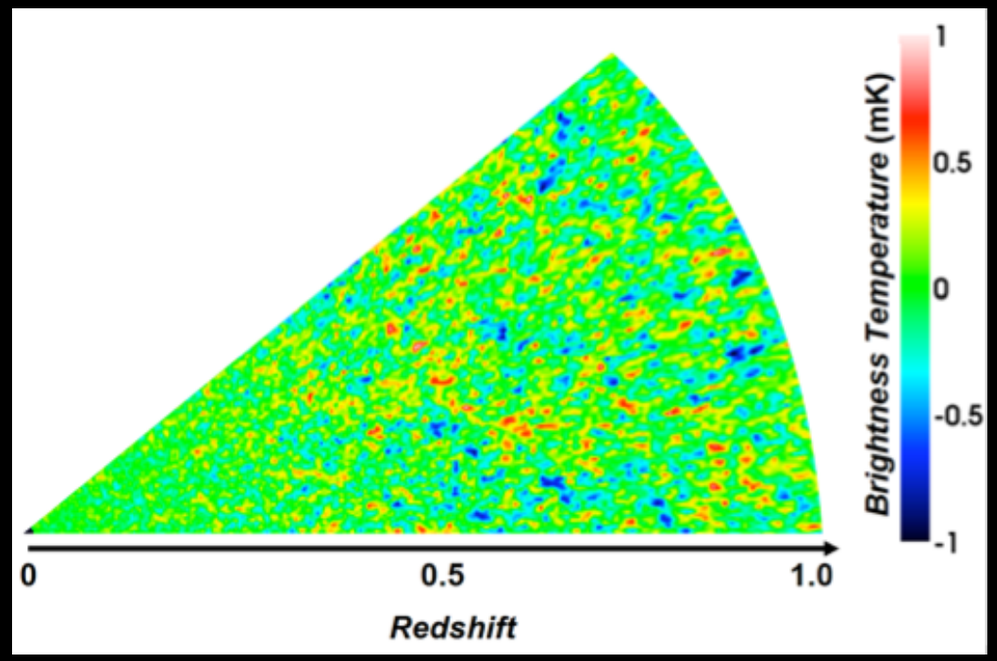
Challenges

for 21cm Intensity Detection

- **Weak signal** - needs a lot of collecting area and sensitive receivers
- **Large volume** to reduced cosmic variance
- **Precise calibration** - need for a very stable instrument
- **Foregrounds** (galactic and extragalactic) significantly larger than 21cm signal - need an extremely well characterised instrument to limit foreground leakage



0902.3091

HIRAX

Crichton et al (2021)

Parameter	Value
Number of dishes	256
Dish diameter	6 m
Dish focal ratio	0.23
Collecting area	7200 m^2
Frequency range	400–800 MHz
Frequency resolution	1024 channels, 390 kHz
Field of view	$5°$–$10°$
Resolution	$0.2°$–$0.4°$
Target system temperature	50 K

- Compact array of 1024 6m dishes operating at 400-800 MHz
- Scalable array built in stages: 128 (funded), 256 (funded), then 1024 - operate full array for 4 years
- Dishes stationary, but can tilt for more sky area
- Back-end: overlap with CHIME - channelize with FGPA ICE boards, correlation with GPUs

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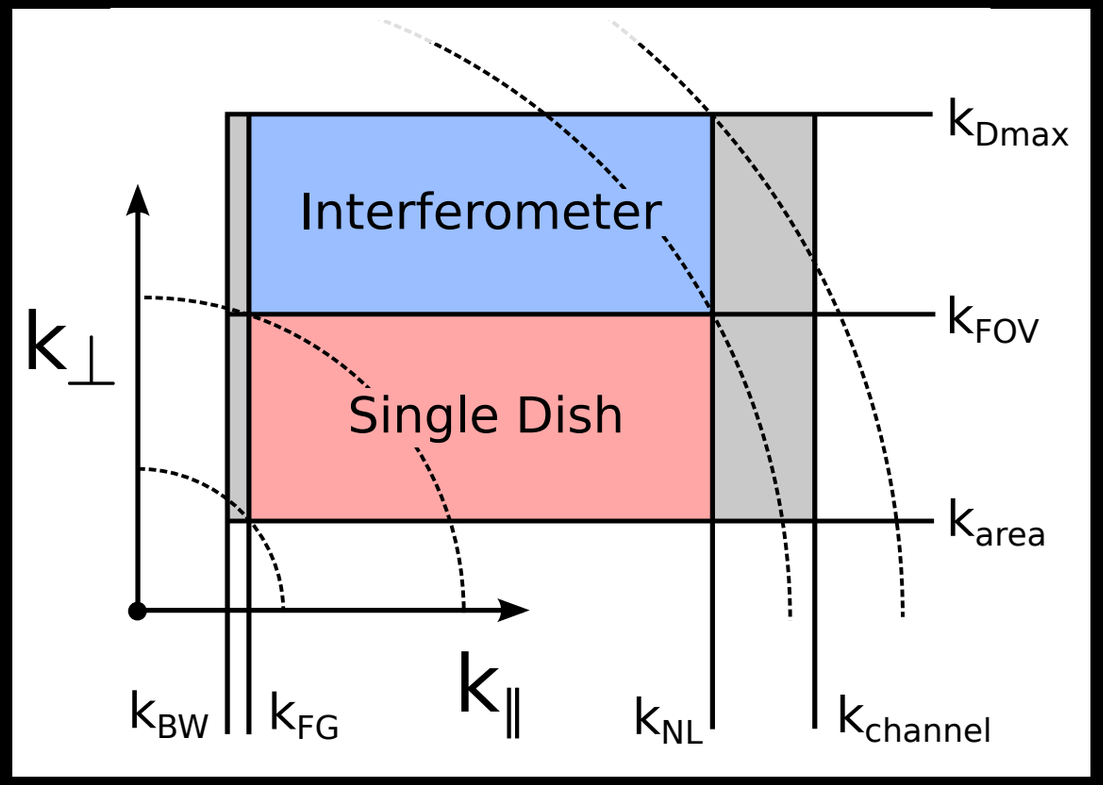
HIRAX

21cm IM survey

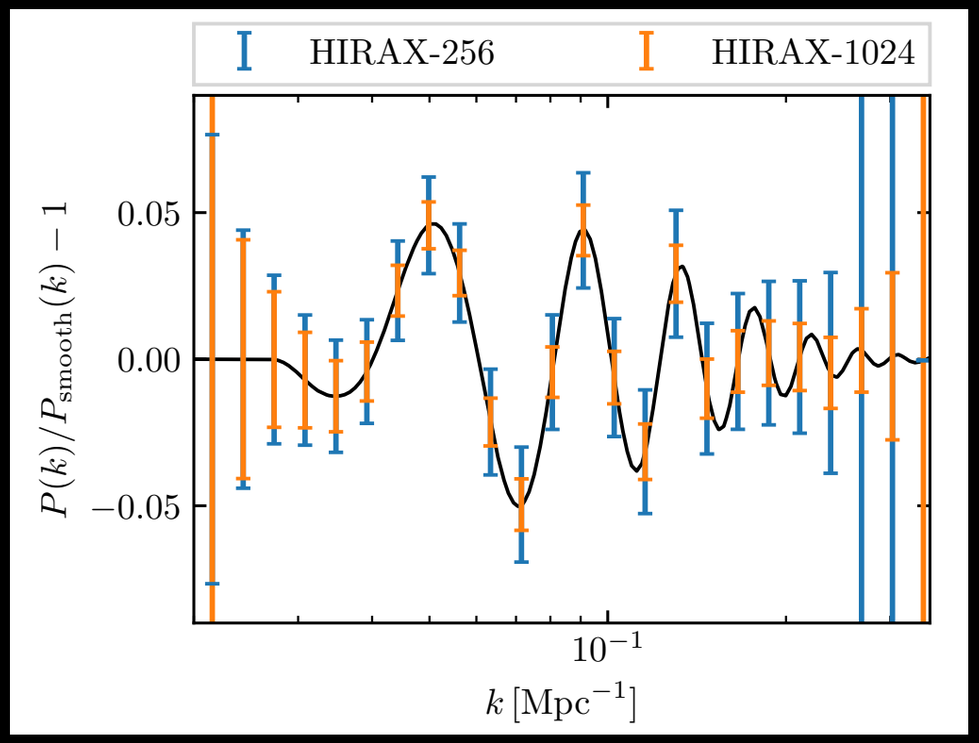


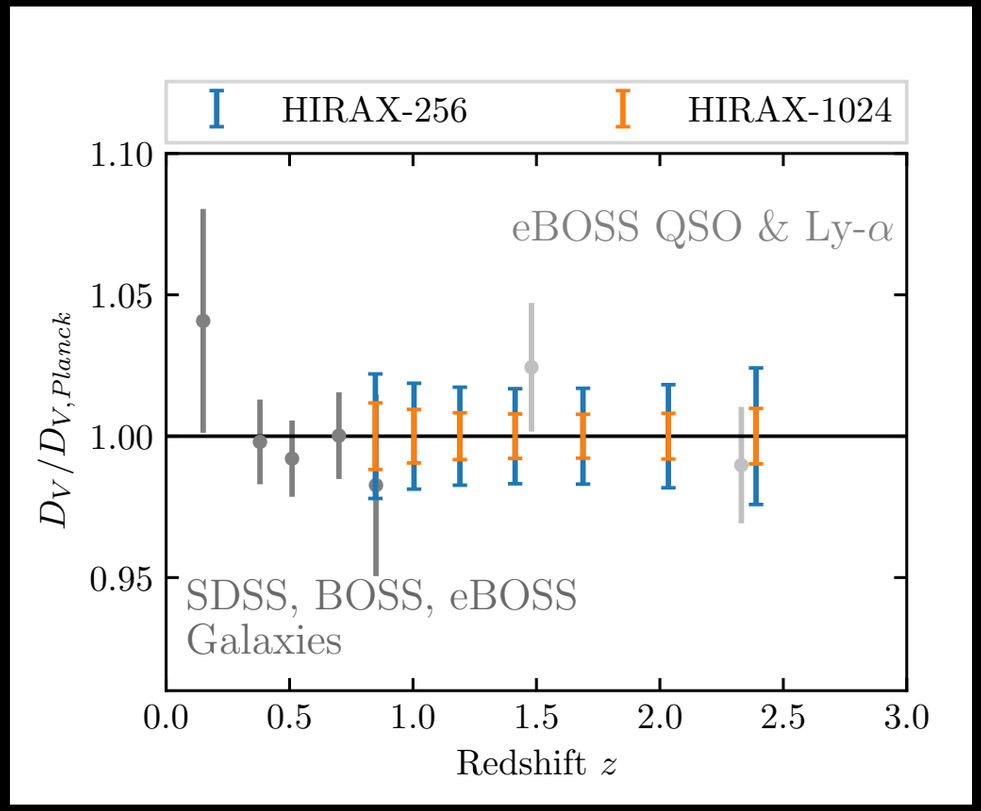
Bull et al (1405.1452)

- z ~ 0.8 - 2.5
- SA: ~15,000 deg^2
- Angular coverage: ℓ ~ 40 - 2000 gives
  $k_\perp \sim [10^{-2}, 1]\,\mathrm{h\,Mpc^{-1}}$ at $z \sim 1$;
  limited by primary beam and maximum baseline
- Frequency coverage: $y \sim 20 - 2000$ gives
  $k_\parallel \sim [10^{-3}, 1]\,\mathrm{h\,Mpc^{-1}}$;
  limited by foregrounds and nonlinearities

BAO forecast
with HIRAX

Crichton et al (2021)





- Precise measurement in a number of z-bins from $z = 0.77$ to $z = 2.55$
- SHOWN: HIRAX-256, HIRAX-1024
- 4-year survey with $50\,\%$ effeciency.
- PS $\rightarrow D_v$
  → constrains at percent level out to high-z (HIRAX-1024)

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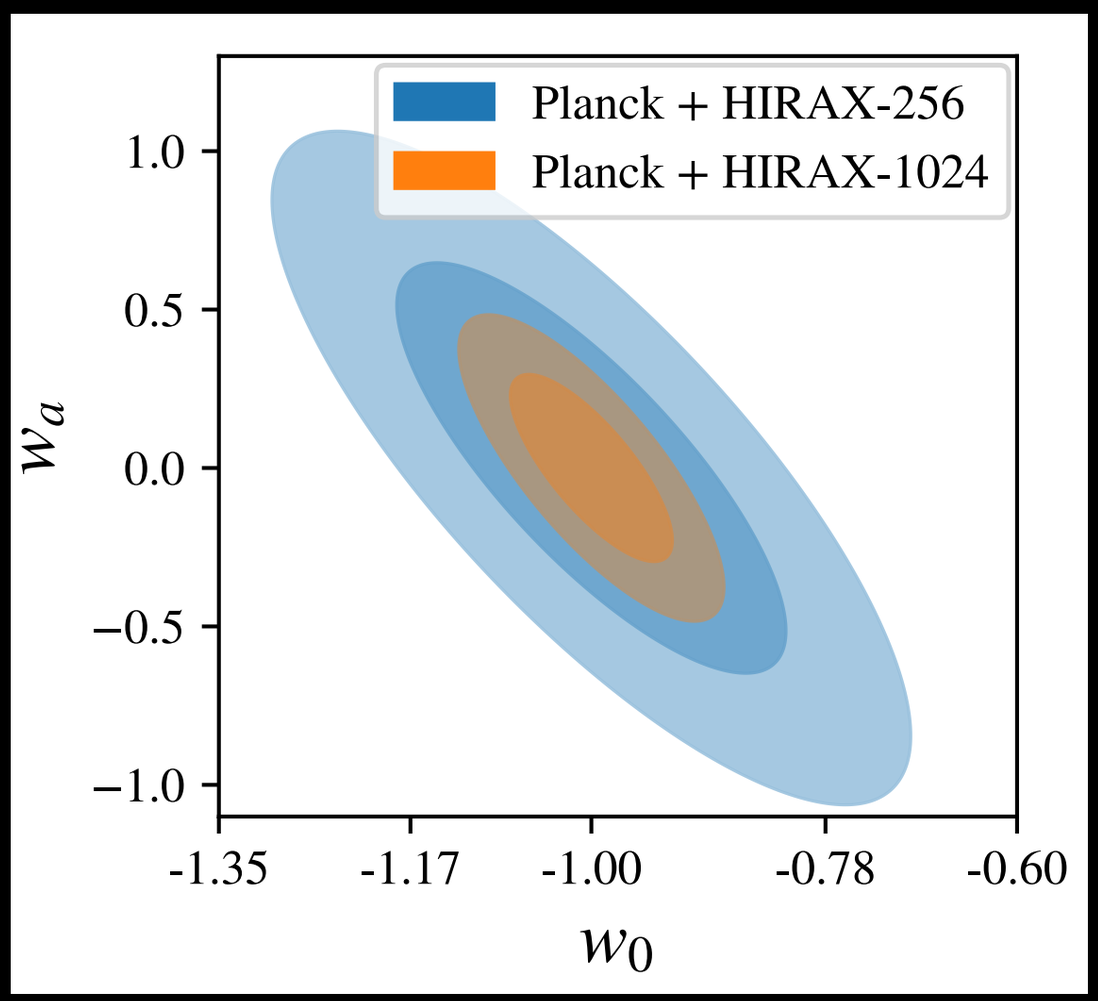
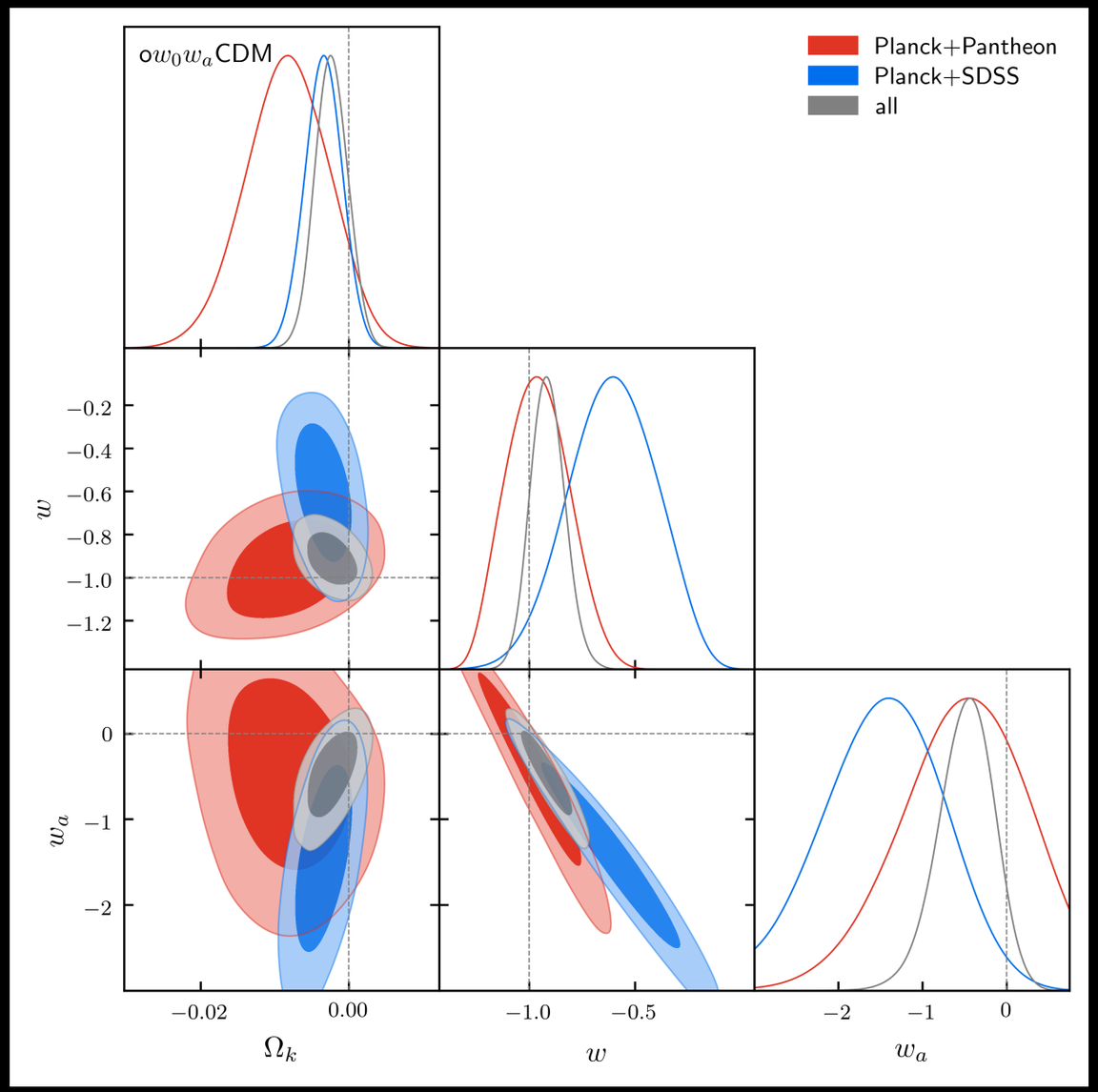
DE constraints

- Tight constraints in combination with CMB priors
- HIRAX-1024 FoM ~300 approaching DETF stage IV class galaxy surveys ~400



Crichton et al (2021)

eBOSS 2020



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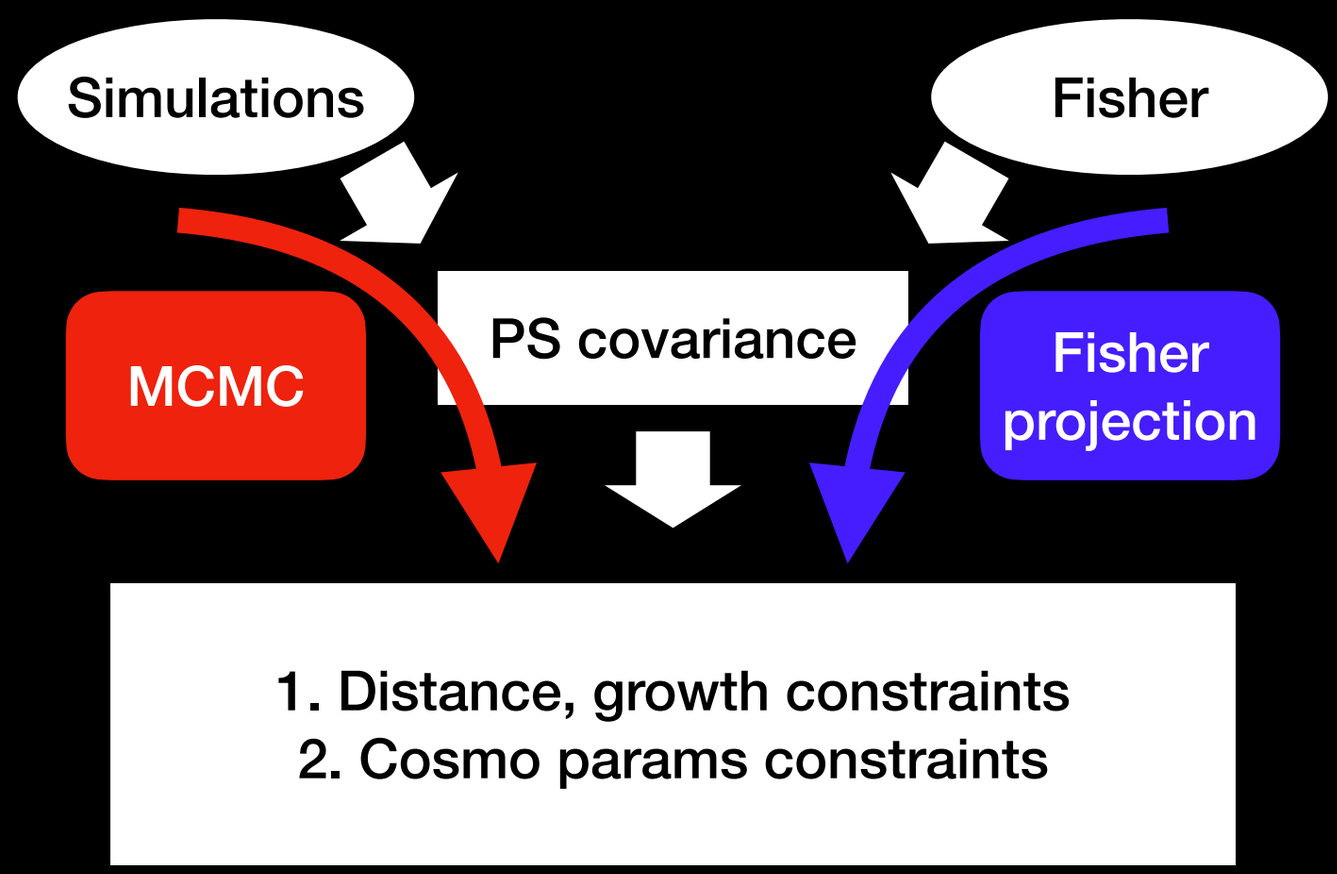
Constraining cosmology

Different methods

- Constraining cosmological parameters using end-to-end simulations: a sophisticated approach

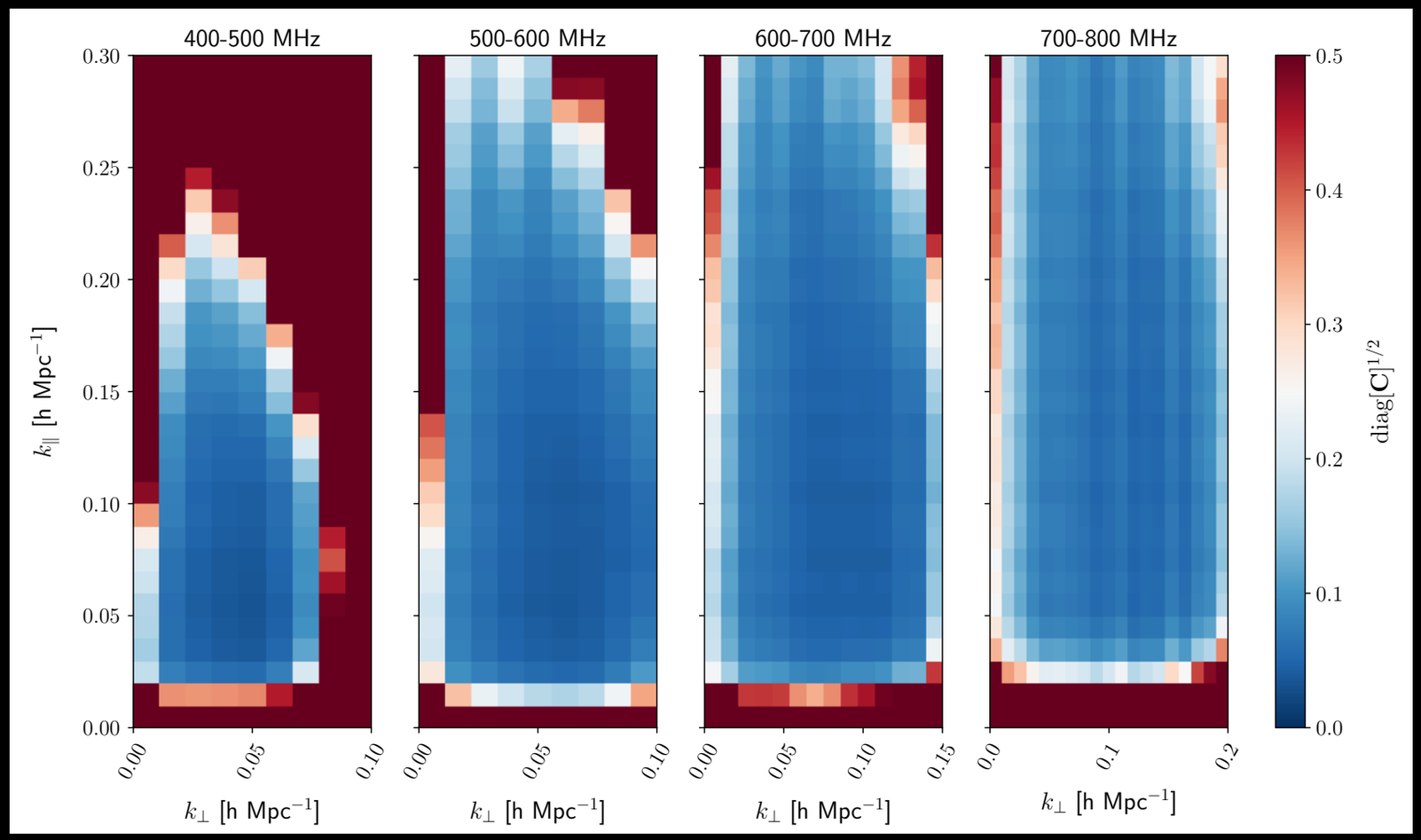


Simulations for Instrument Design

PS estimation - results

- Estimated PS errors using Gaussian beam
- Here shown: **autocovariance** between k-bins = diag of Cov
  - Total 9×30 bins
  - Cov: 270×270

Crichton et al (2021)



with FG

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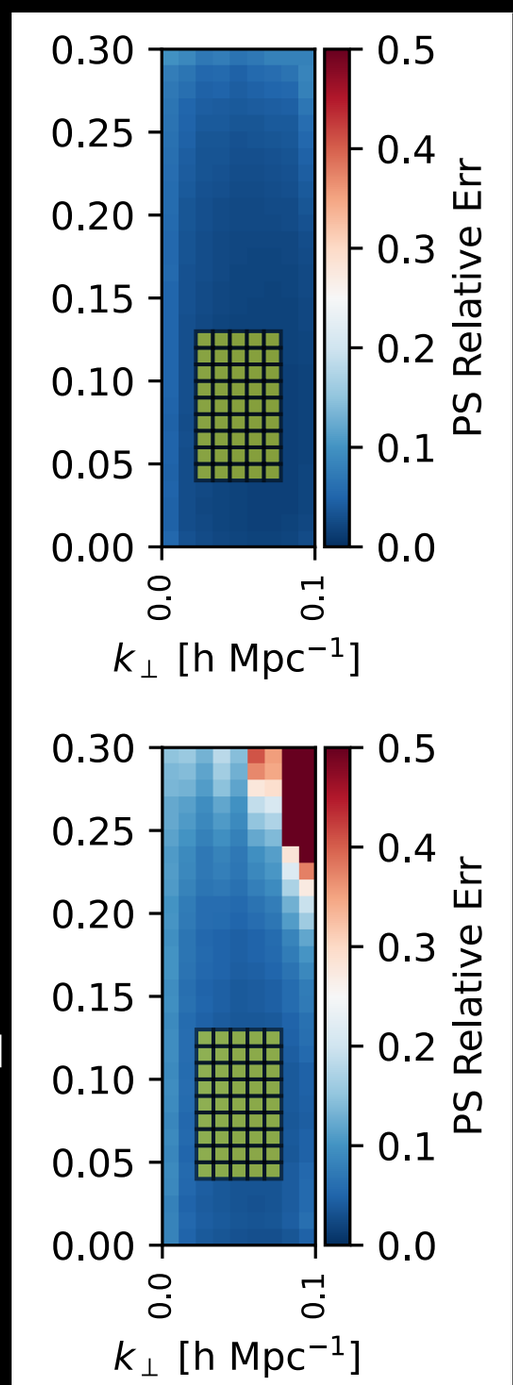
Power spectrum covariance

m-mode VS Fisher

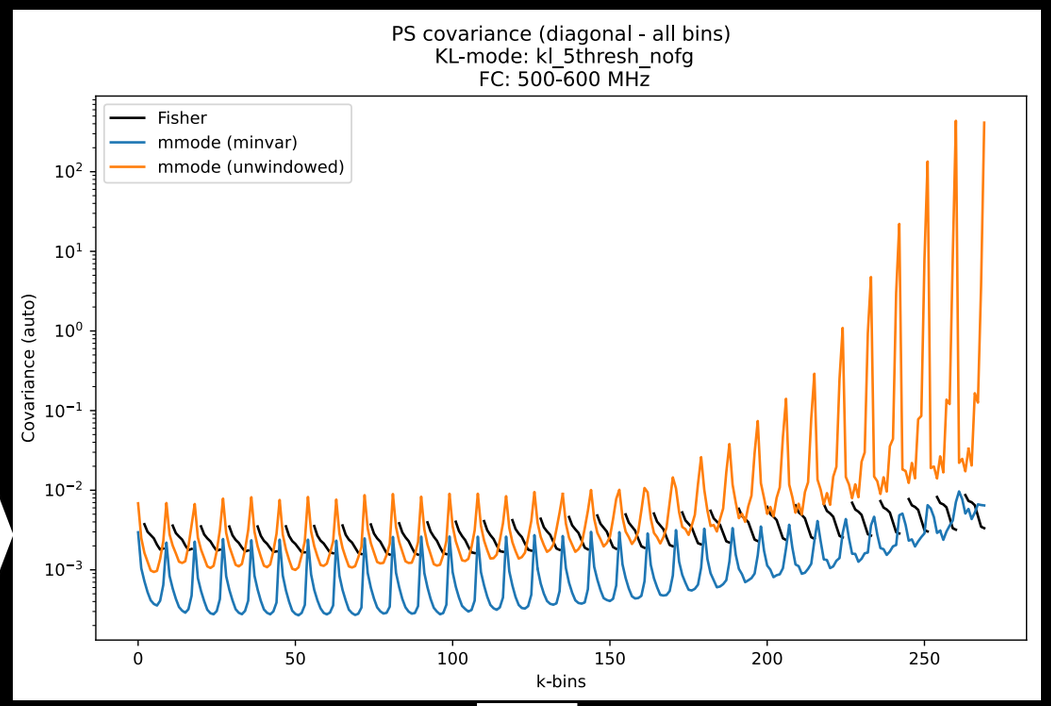
Minimum Variance Estimator

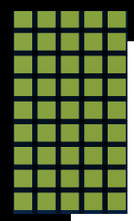
500-600 MHz w/o FG

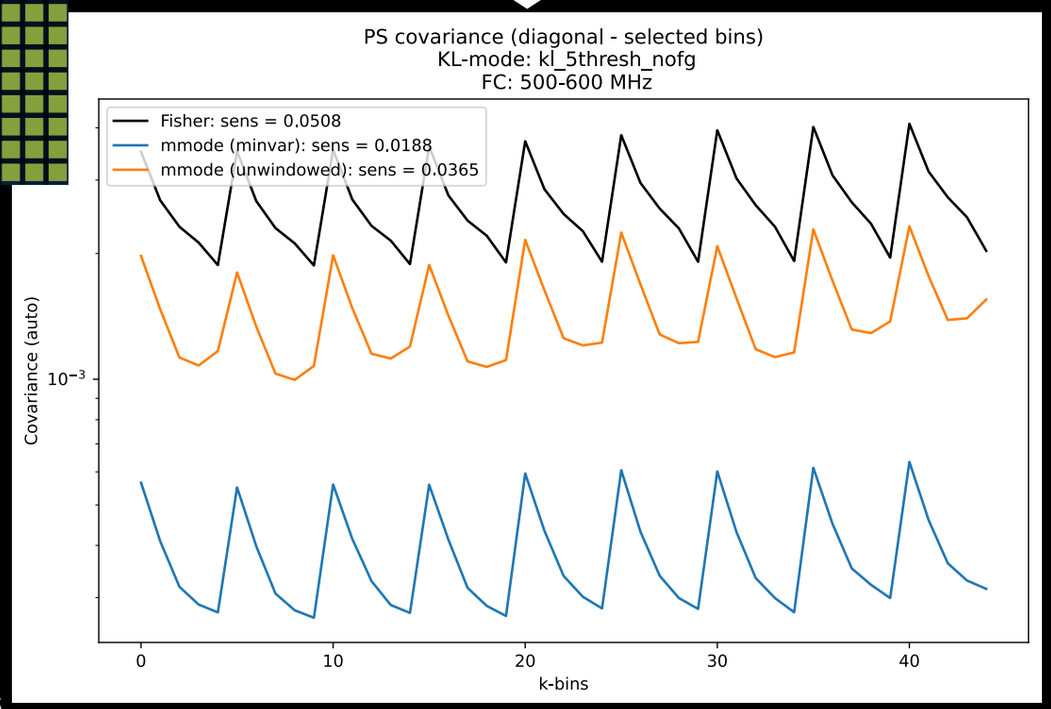
Unwindowed Estimator



diag x 1D







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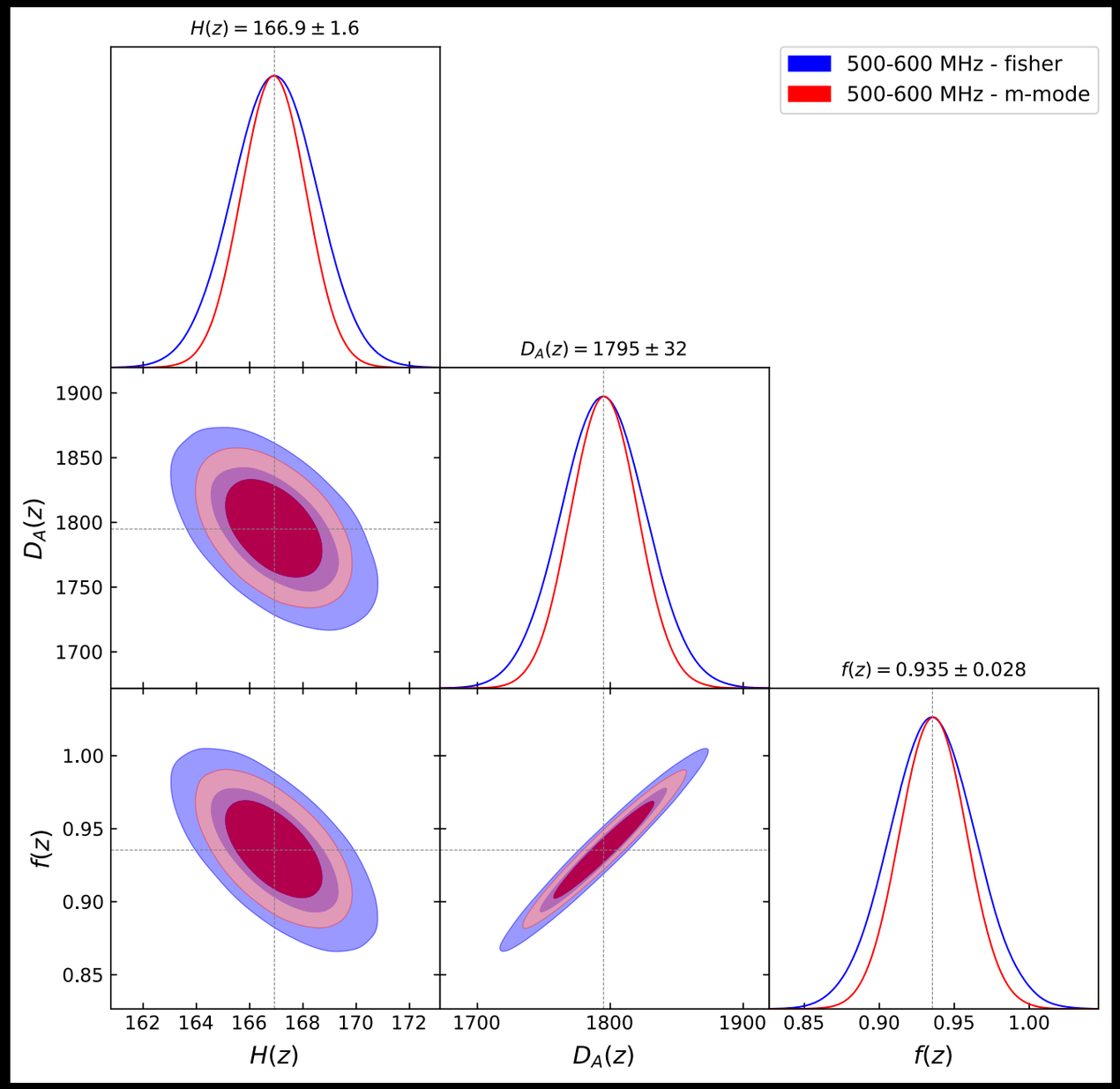
Constraints

$H(z), D_A(z), f(z)$ - distance parameters and growth factor

- Freq dependent parameteres
- Shown: 500-600 MHz (Unwindowed PSE in MCMC)



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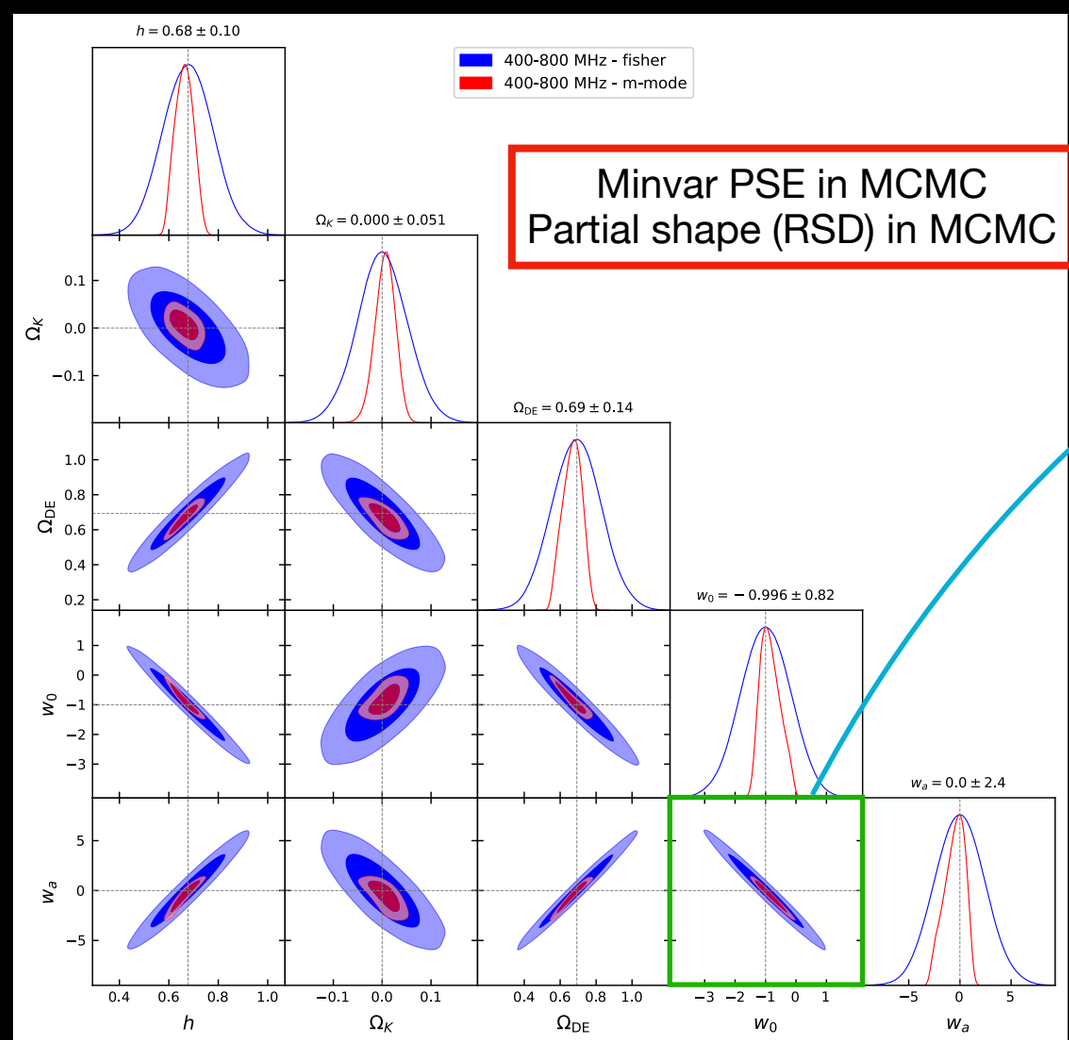
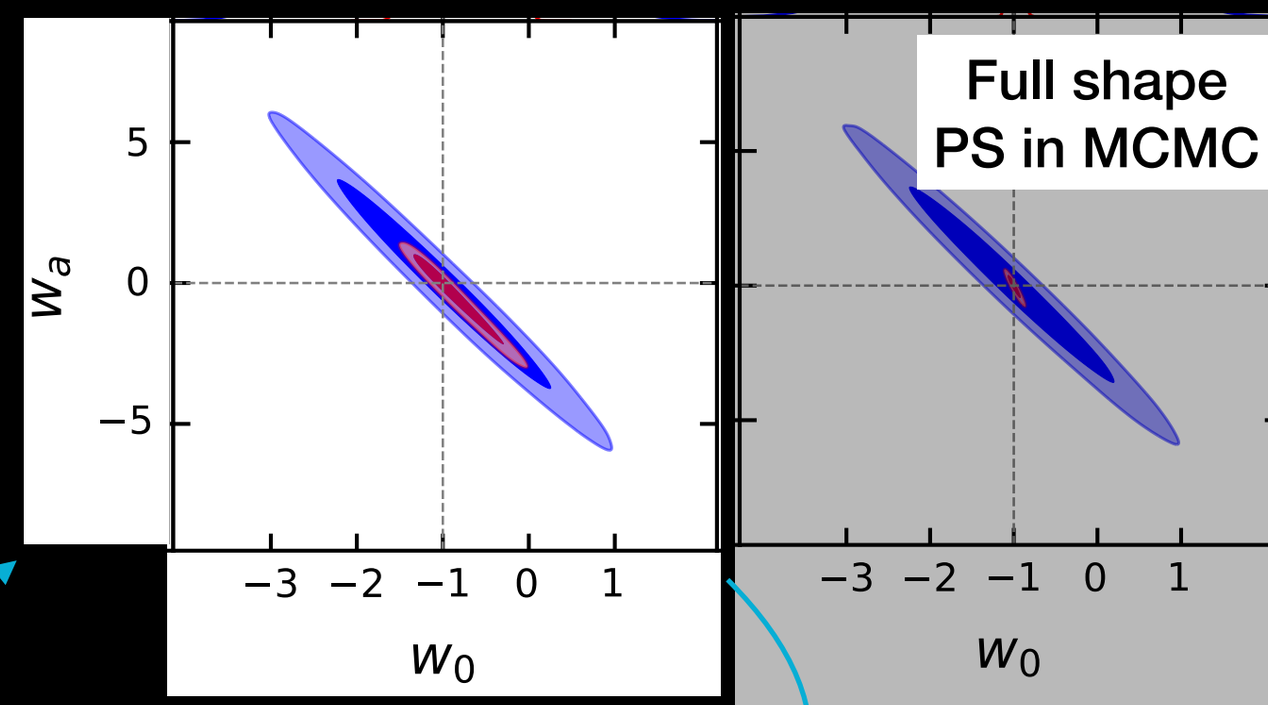
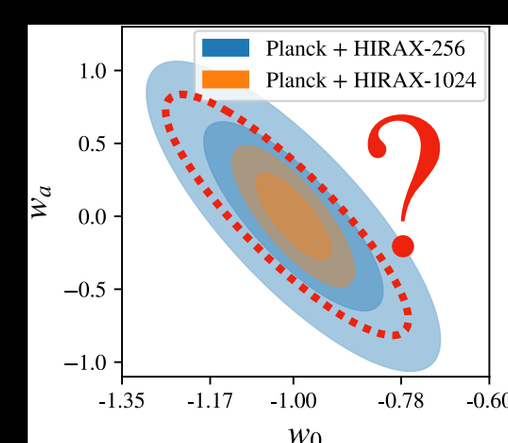
Constraints

h, Ω_K, Ω_{DE}, w_0, w_a - cosmological parameters





+ Planck



Crichton et al (2021)

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Conclusions/Ongoing Work

- FoM around 300 expected from full scale experiment (comparable to galaxy surveys)
- Sophisticated approach available with m-mode simulations to compare Fisher forecasts
- Different experiment configurables to be compared
  - Beams
  - PSEs
  - Pointings

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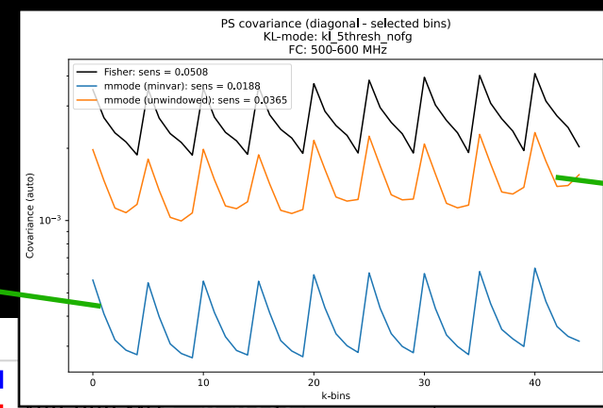
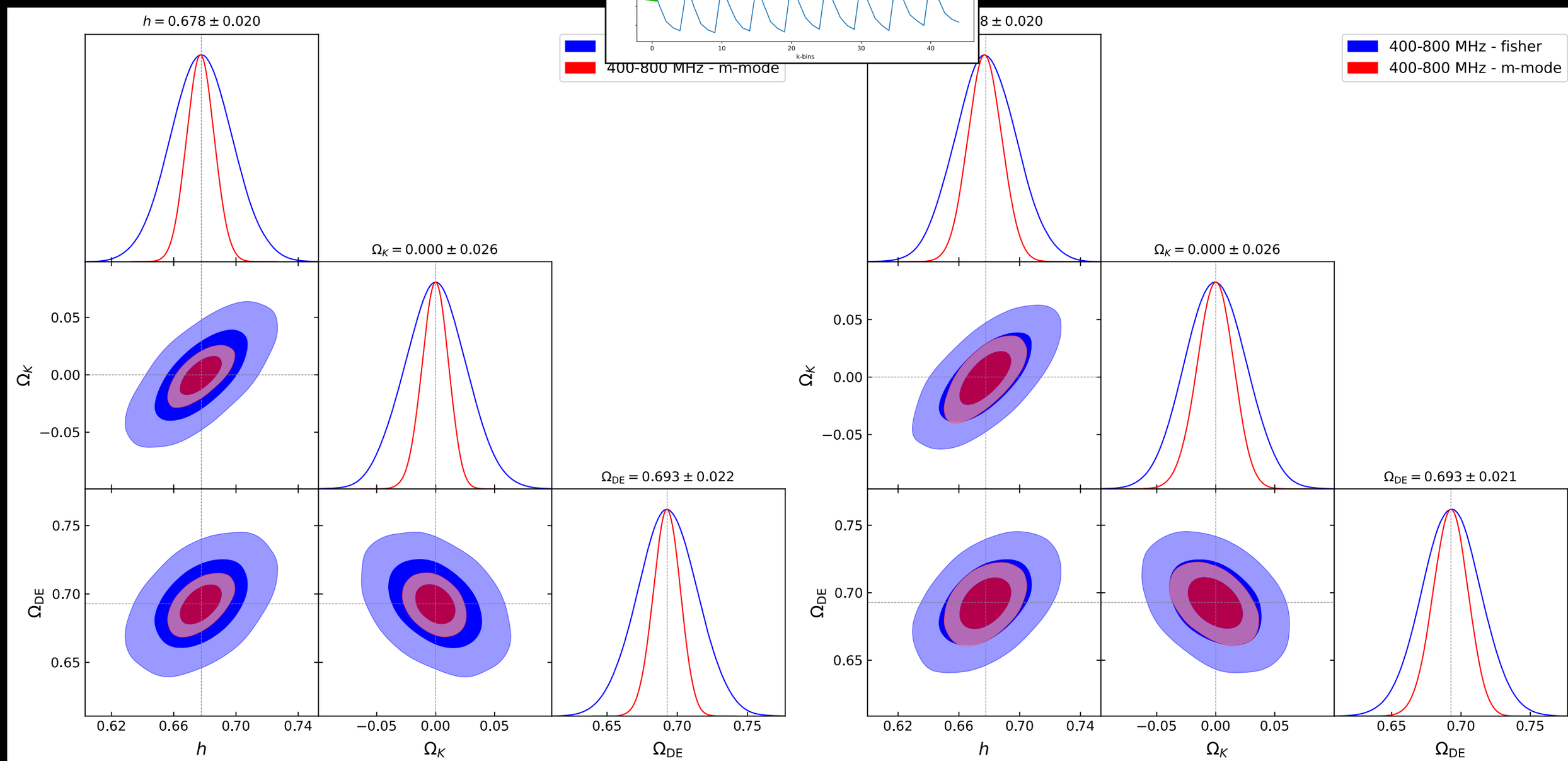
Constraints

h, Ω_K, Ω_{DE} - cosmological parameters



Minvar PSE in MCMC

Unwindowed PSE in MCMC

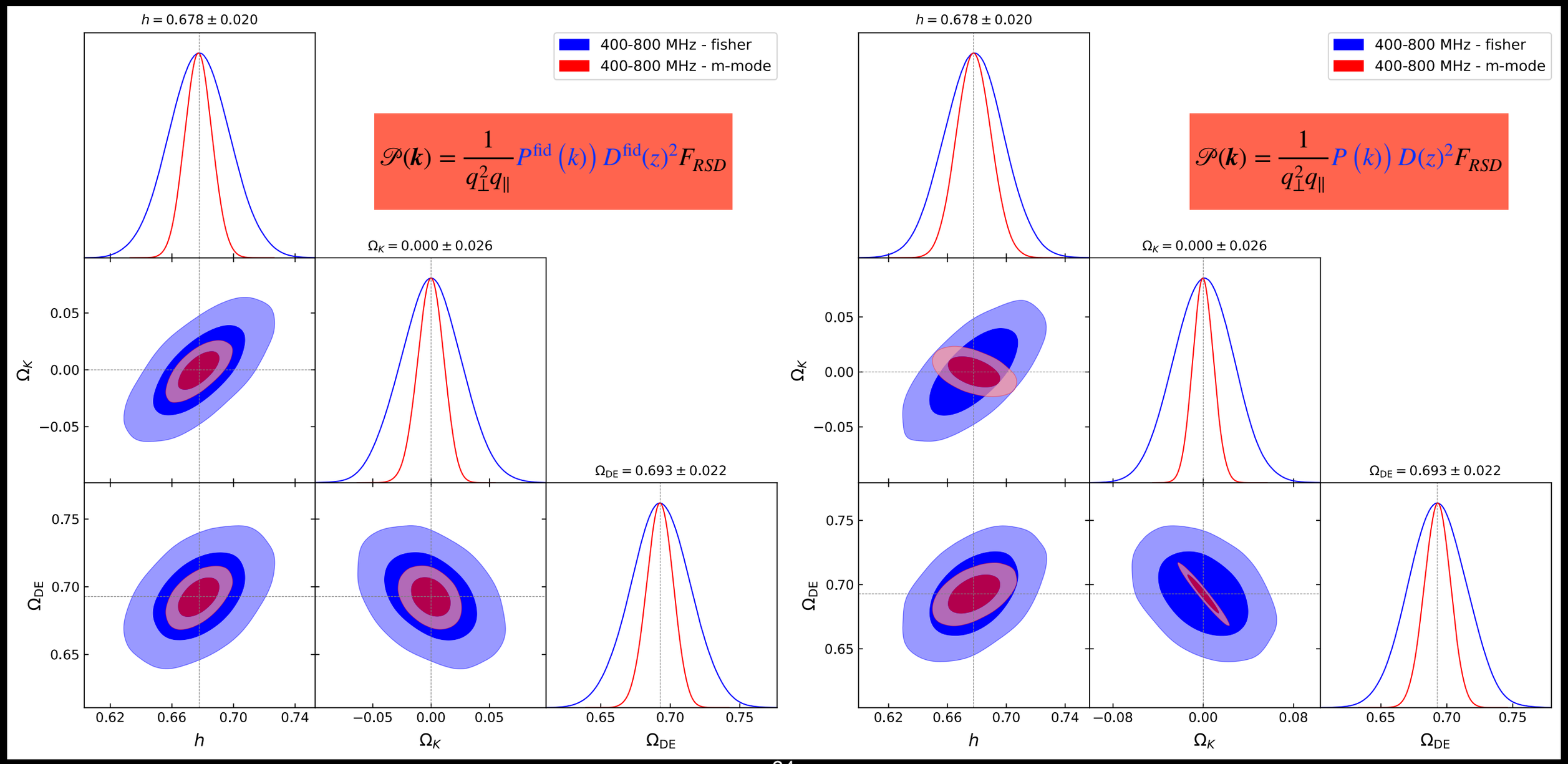


Constraints

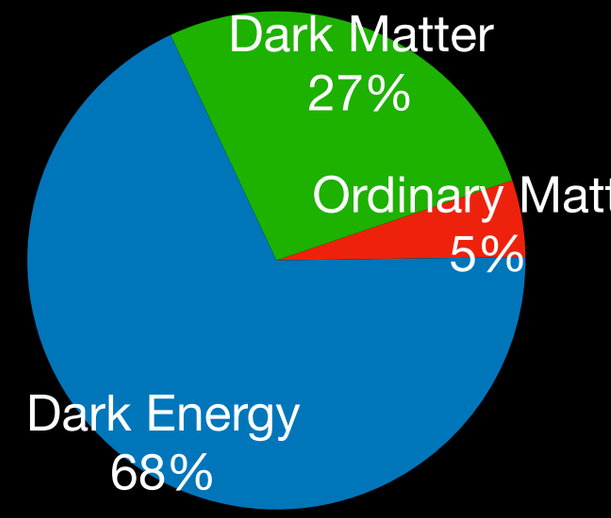
h, Ω_K, Ω_{DE} - cosmological parameters

Partial shape (RSD) in MCMC

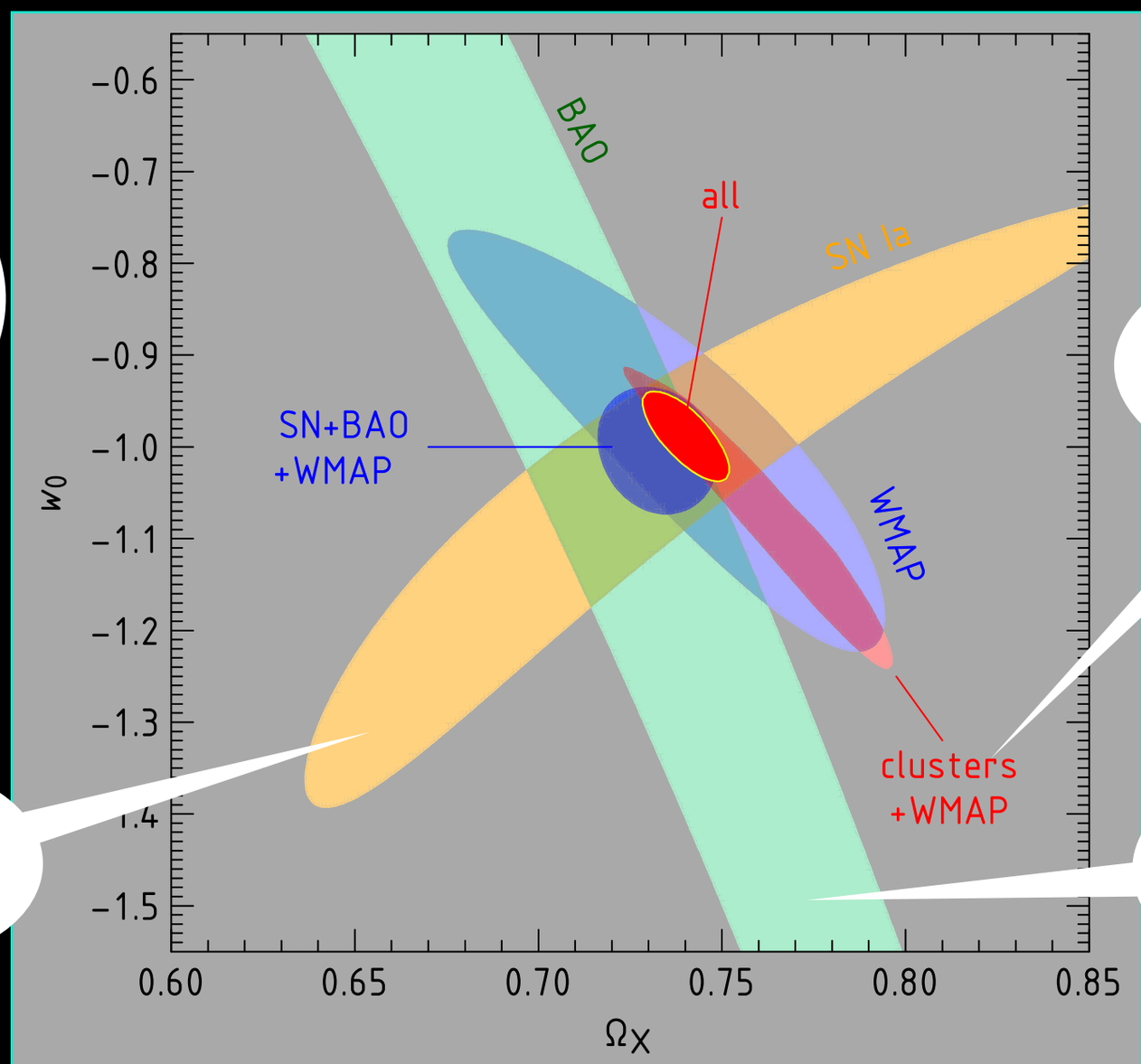
Full shape PS in MCMC



Cosmic Concordance
and Dark Energy



Key probes of DE



Cosmic Lensing

$G(z)$,
$D_A(z)$

clusters

$G(z)$,
$dV(z) \sim D_A^2(z)/H(z)$

SN1a

$D_L(z)$

BAO

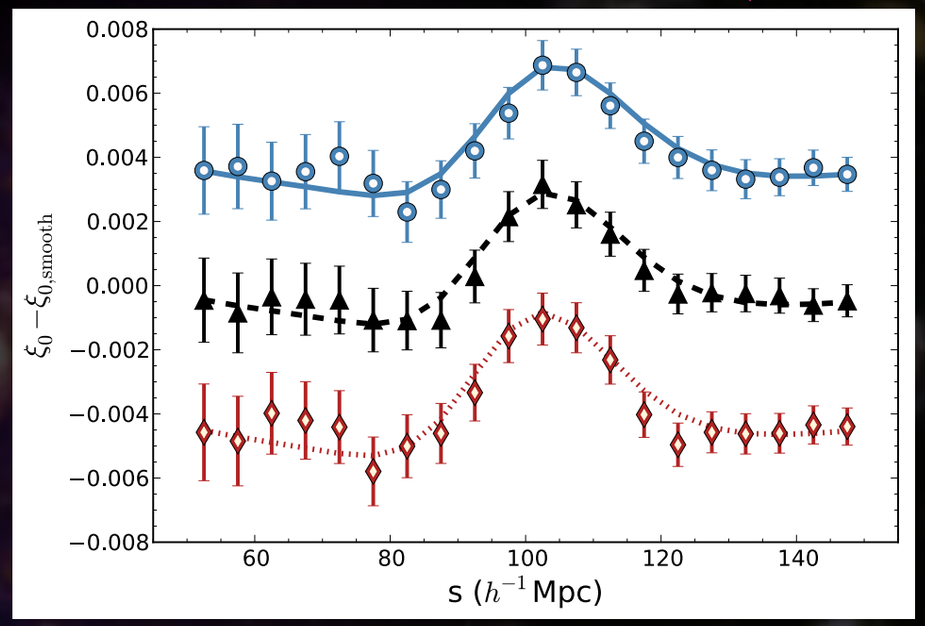
$D_A(z)$,
$H(z)$

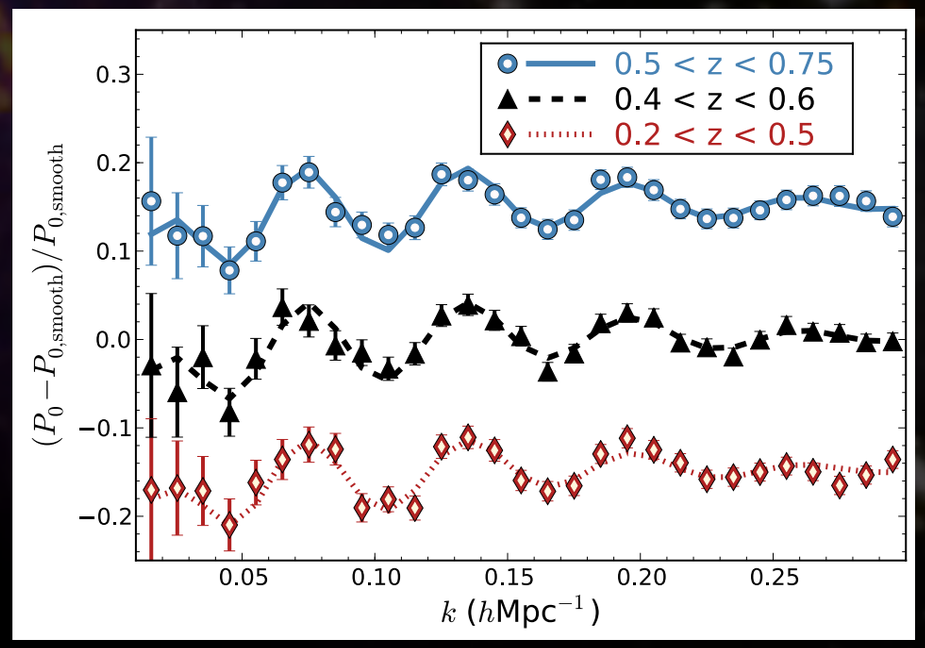
Baryon Acoustic Oscillations

and Dark Energy

- Galaxy positions trace acoustic waves from the early universe: sound horizon sets characteristic 150 Mpc scale
- Measure galaxy positions → peak in correlation function ↔ ripples in power spectrum
- DR12 release from SDSS-III shown here, $0.2 < z < 0.75$

Alam et al, 1607.03155

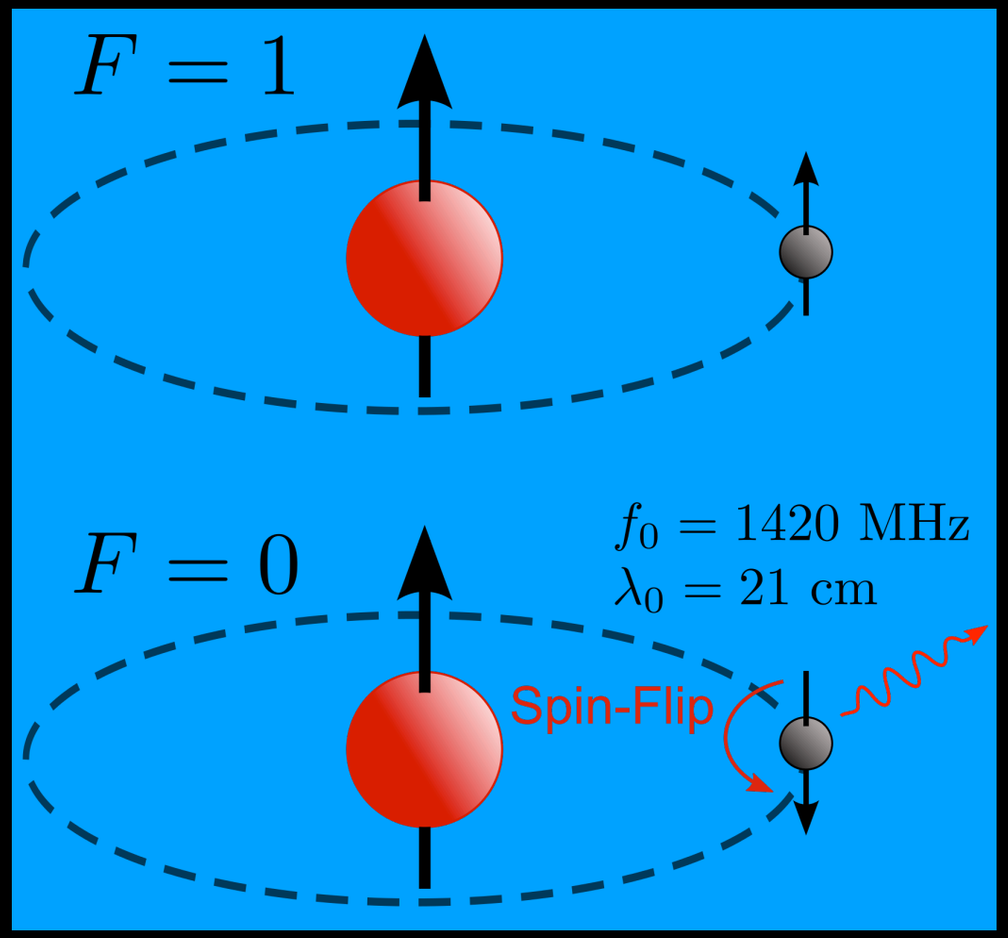




Credit: SDSSIII

Tracking Hydrogen?

21cm line



- Hyperfine splitting of the 1S ground state due to the interaction of the magnetic moments of the proton and the electron
- Neutral hydrogen is abundant in galaxies (and IGM)
- Observations: redshifted 21cm line

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HIRAX Schedule

- Develop HIRAX Karoo main site by Q3 2023
- Commision 2-element qualification dishes at Karoo Klerefontein site by Q2/3 2023
- Commision 8-element prototype at Karoo Swartfontein site by Q2 2023
- Commision 128-element pathfinder at HIRAX Karoo Swartfontein site by Q1/2 2024

Complementarity with CHIME

- HIRAX dishes || CHIME cylinders

  different systematics,
  larger collecting area

- Lower RFI at SKA-SA Karoo site

- CHIME sees whole (accessible) sky each day ||

  HIRAX can integrate deep on narrow strips

- HIRAX observes southern sky

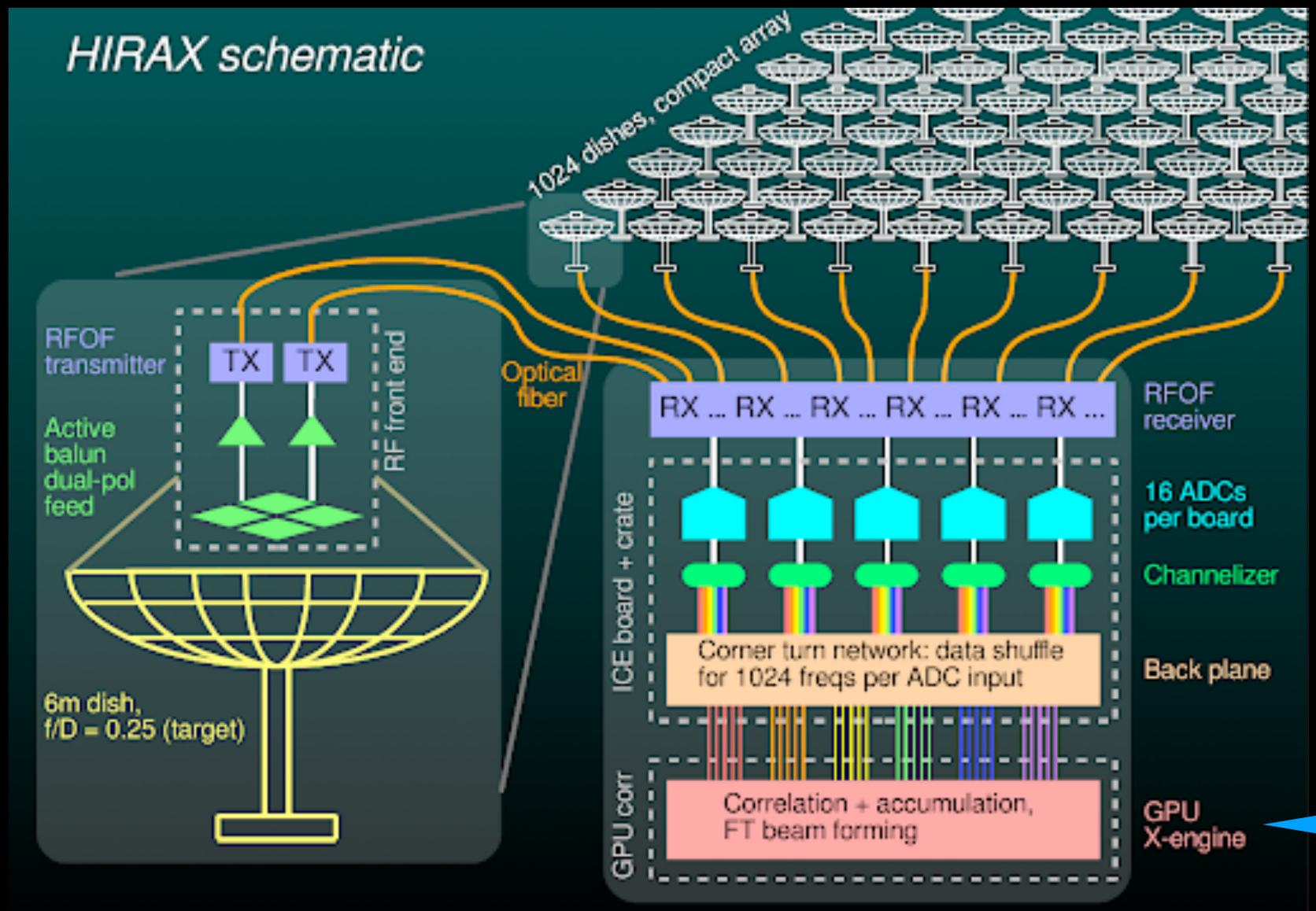
  - Optical surveys: cross-correlation science and foreground mitigation

  - More pulsars in south

Credit: CHIME

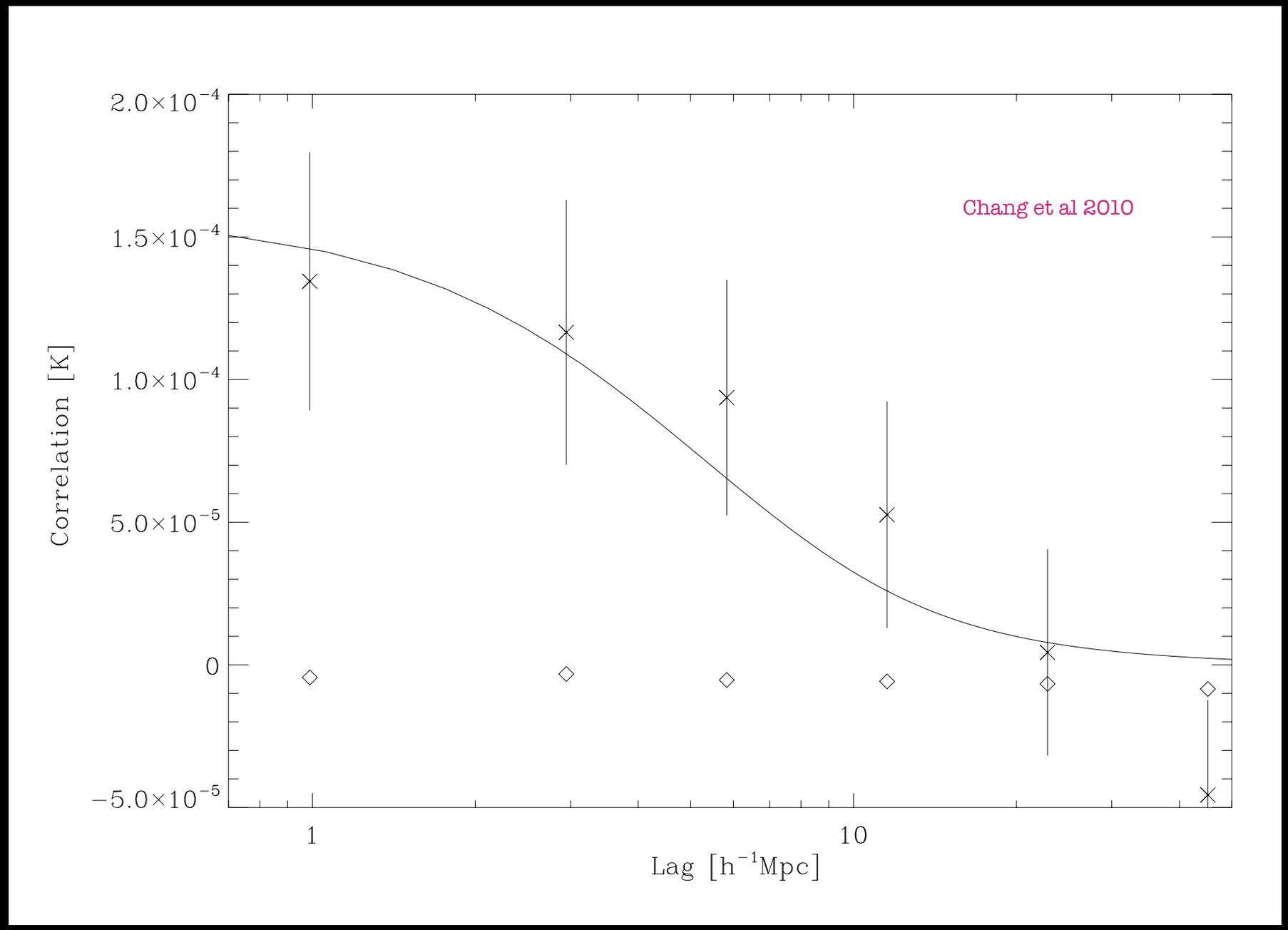
	CHIME	HIRAX
Site	DRAO, Canada	Karoo (lower RFI, no snow)
Telescope	Cylinder array	Dish array
FOV	100° NS, $1^\circ - 2^\circ$ EW	$5^\circ - 10^\circ$
Beam size	$0.23^\circ - 0.53^\circ$	$0.1^\circ - 0.2^\circ$
Collecting area	$8{,}000\ \mathrm{m}^2$	$28{,}000\ \mathrm{m}^2$
Sky coverage	North	South

HIRAX design



HI signal x galaxies

cross-correlation



Simulations for Instrument Design

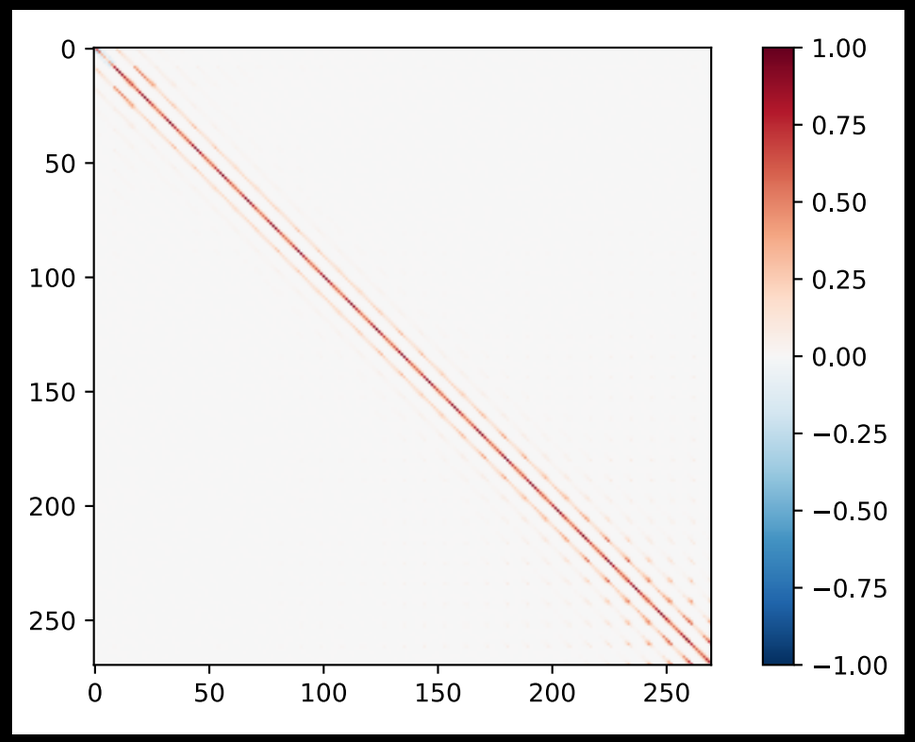
Off-diagonal correlations

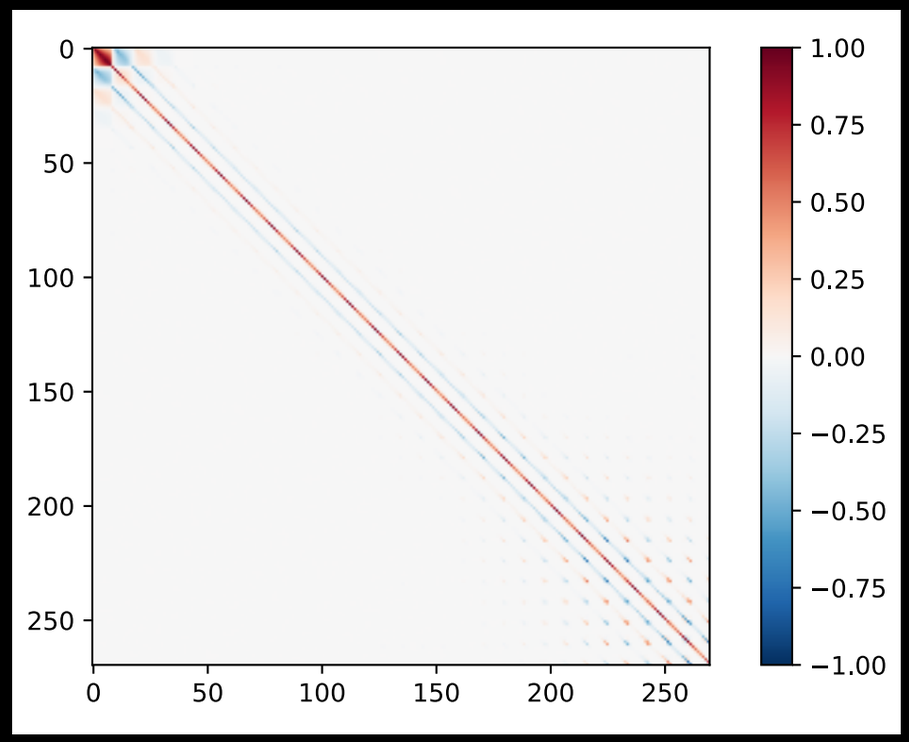
- The covariance has almost 0 off-diagonal correlation; hence, off-diagonal elements can be neglected

$$\mathrm{Corr}_{ij} = \frac{C_{ij}}{\sqrt{C_{ii}C_{jj}}}$$

500-600 MHz

minvar





unwindowed

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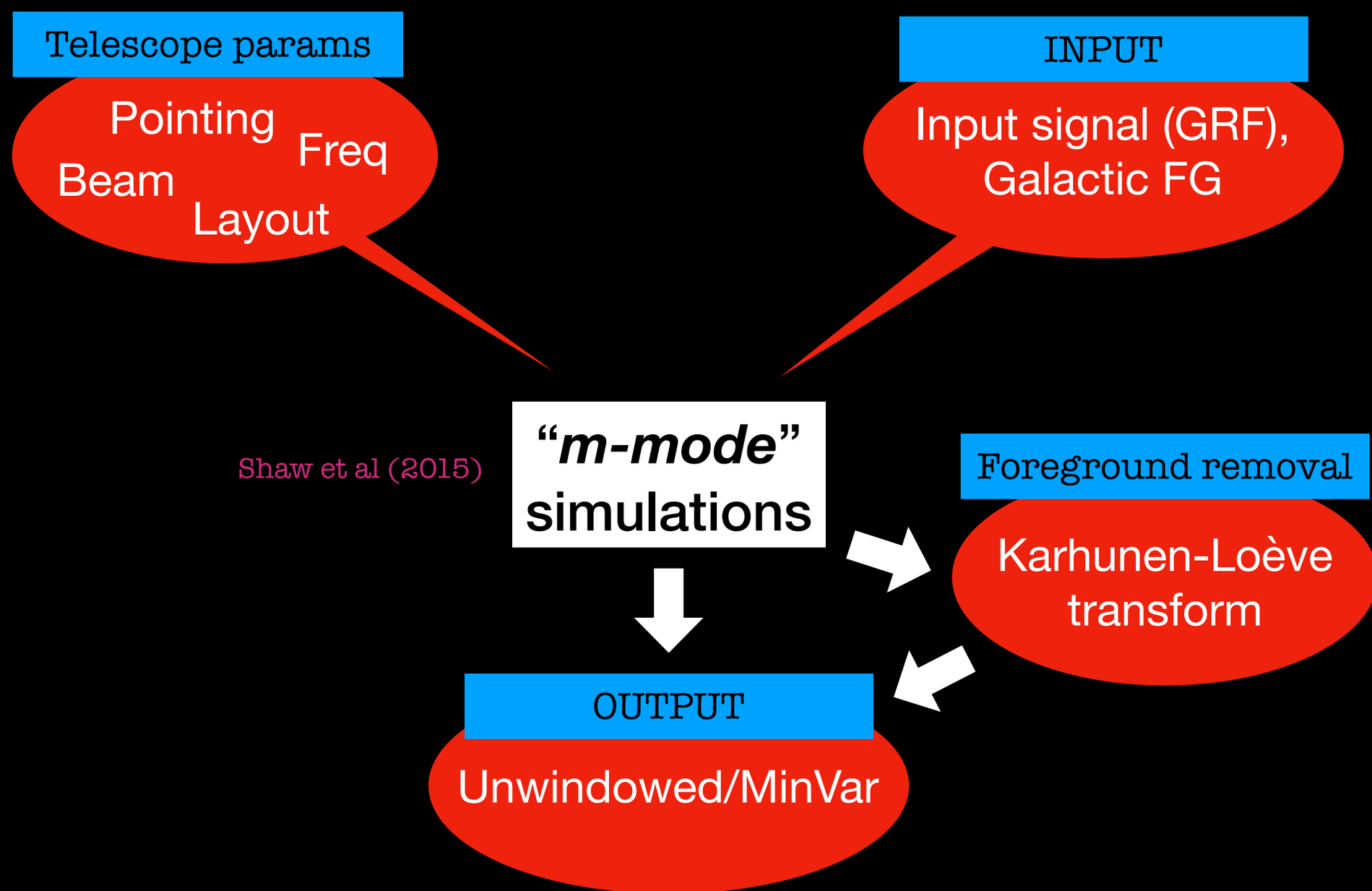
Simulations for Instrument Design



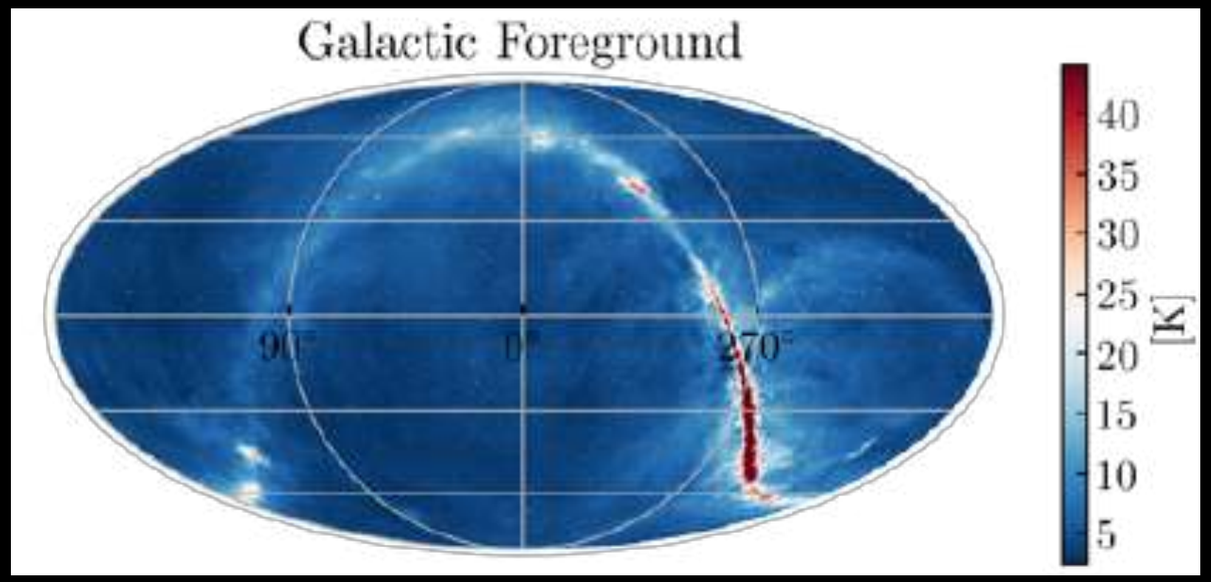
Simulations for Instrument Design

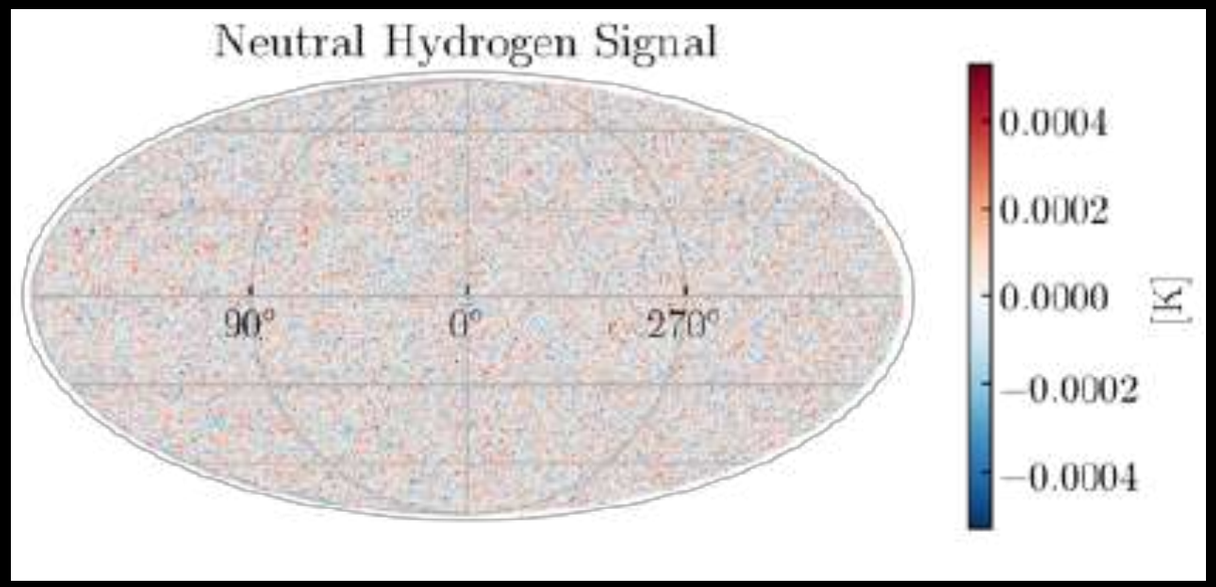
Input, Purpose

Credit: Devin Crichton

- End-to-end cosmology simulations pipeline that incorporates beams from full EM simulations
- Simulations used to set instrument design

  ➡ Control errors in beam shape, pointing, geometric delay that result in non-redundancies.





Simulations for Instrument Design

(Algorithm?)

Simulated Instrument $\left(B_m\right)_{(\alpha\nu)(l\nu')}$	$\times$	Simulated Sky $\left(a_m\right)_{(l\nu)}$	$\rightarrow$	Simulated Data $\left(v_m\right)_{(\alpha\nu)}$
Include Systematics				

Add solved for or unsolved for systematics to recovery pipeline and evaluate relative quality of results

Inverse Instrument $\left(B_m\right)_{(\alpha\nu)(l\nu')}$	$\times$	Simulated Data+Noise $\left(v_m\right)_{(\alpha\nu)} + n$	$\rightarrow$	Recovered Sky $\left(a_m\right)_{(l\nu)}$
Include known Systematics		Include calibrated solution		