HIRAX Science Goals

- Measure baryon acoustic oscillations with 21cm intensity mapping: characterise dark energy
- Cross-correlation with other cosmological surveys
- Radio transient searches, fast (FRBs) and slow
- Pulsar searches: 15 uJy/scan - search in each of 10-20 beams, galactic centre searches
- Neutral hydrogen absorbers: upres frequency in beam-formed data (FFTs on GPUs)
- Diffuse galactic polarization
Dark energy with baryon acoustic oscillations (BAO$\mathrm{s}$)

- Galaxy positions trace acoustic waves from the early universe: sound horizon sets characteristic 150 Mpc scale.
- Measure galaxy positions -> see ripples in the power spectrum, peak in the correlation function.
- DR12 release from SDSS-III shown below, redshift range $0.2 < z < 0.75$.
BAOs with 21cm intensity mapping

Throw away spatial resolution: use HI intensity mapping to measure matter distribution AND obtain redshift information.

Use the BAO peak as a standard ruler for charting the expansion history.

Sound wave imprint from recombination has a characteristic 150 Mpc (degree) scale, which is large.

Require large volumes (large sky area and z range) for precision cosmology

Counting individual galaxies is hard and getting to high z is challenging.
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Designing a 21cm intensity mapping dark energy telescope

- Maximise sensitivity on scales of interest
  - Use compact array geometry
- Redshift range: $0.8 < z < 2.5$ to capture dark energy domination at $z \sim 1$ and sufficient volume
  - Required frequencies: 400 - 800 MHz
- BAO 150 Mpc angular scale: 3 - 1.3 degrees at $0.8 < z < 2.5$
  - Required interferometer baseline lengths: 15 - 60 metres
- BAO scale along line of sight: 20 - 12 MHz at $0.8 < z < 2.5$
  - Required frequency resolution: 100 channels, more for foregrounds and higher order peaks
- BAO signal level: $\sim 0.1$ mK
  - Low system temperature, large collecting area (lots of elements)
The **Hydrogen Intensity mapping and Real time Analysis eXperiment (HIRAX)**

- A compact array of 1024 six metre dishes operating at 400-800 MHz
- Scalable array built in stages: 128 (2020), 512 (2021) and 1024 (2022) elements and operate full array for 3-4 years
- Dishes stationary but can tilt for more sky area, fabrication in South Africa
- Back-end: working closely with CHIME - channelize with FPGA ICE boards, correlation with GPUs

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**Table 1: Table of instrumental parameters for HIRAX.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency Range</td>
<td>400–800 MHz</td>
</tr>
<tr>
<td>Frequency Resolution</td>
<td>390 kHz, 1024 channels</td>
</tr>
<tr>
<td>Dish size</td>
<td>6 m diameter, $f/D=0.25$</td>
</tr>
<tr>
<td>Interferometric layout</td>
<td>32×32 square grid, 7 m spacing</td>
</tr>
<tr>
<td>Field of View</td>
<td>$15 \text{ deg}^2$–$56 \text{ deg}^2$</td>
</tr>
<tr>
<td>Resolution</td>
<td>$\sim 5'–10'$</td>
</tr>
<tr>
<td>Beam Crossing Time</td>
<td>17–32 minutes</td>
</tr>
<tr>
<td>System Temperature</td>
<td>50 K</td>
</tr>
</tbody>
</table>

*Newburgh et al (1607.02059)*
HIRAX 21cm intensity mapping survey

- Wide redshift coverage: \( z \sim 0.8 - 2.5 \)
- Survey area: target \( \sim 15,000 \text{ deg}^2 \)
- Angular coverage: \( \ell \sim 40 - 2000 \)
gives \( k_{\text{perp}} \sim [10^{-2}, 1] \) h Mpc\(^{-1} \) at \( z \sim 1 \)
- Frequency coverage: \( y \sim 20 - 20,000 \)
gives \( k_{\text{par}} \sim [10^{-3}, 1] \) h Mpc\(^{-1} \); limited by foregrounds and nonlinearities.
- Sensitivity: 15 uJy/beam daily, 1 uJy/beam full survey
Collaboration and funding

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

- Multi-institutional global collaboration

- UKZN and South African NRF flagship funding secured for site infrastructure and pathfinder array. SARAO providing site, power and data.

- Swiss SNF funding secured for 512-element (512 channels) X-engine (GPU correlator).

- Canadian CFI funding submitted for 512-element F-engine (ICE boards, outcome July 2019).

- NRF strategic research equipment funding application in July 2019 to expand pathfinder array.
Location, location, location …

- SKA South Africa Karoo site - MoA signed
- Existing infrastructure (roads, power, data)
- Low levels of RFI (protected)
- Access to southern skies

RFI at HIRAX site

The nearest hotel, and food store is over an hour from the proposed site. It took us about 11 hours driving from HartRao. Once in operation we should stage vehicles on site and fly in on the twin engine charter flight from Capetown.
Design plan

- 1024 close-packed 6m dishes. Built fibre-glass and metal prototypes, fabrication in South Africa.
- Cloverleaf dual-pol feed, RF over fibre
- Operate between 400-800 MHz, 1000 channels
- Channelizing on FPGA ICE boards
- Correlation on GPUs
While significantly reducing the expense of circuit board parts, A 400-800 MHz prototype LNA built with the device produced a gain of 18 dB and a noise figure of 3 dB. We are currently planning to use an Avago MGA-16116 GaAs MMIC LNA because it meets our noise specification.

Amplification: including the amplification circuitry directly on the balun and backboard (a prototype of the feed amplification) is shown in Figure 3b. The feed with low noise amplifiers (LNAs). The gain specification is set by the required input level to the ADC: the total gain. As noted below, 50 dB of that gain must come before the Radio-Frequency over Fiber (RFoF) system.

Optimization also includes choke size: while wider chokes are more effective at reducing spillover, they also increase the blockage of the center of the dish. For the system noise to be dominated by the LNA noise figure. We are investigating two alternatives for the feed. The primary benefit of amplifying directly on the feed is a reduction in system noise. Even with a low-loss optical chain as described above, this requires amplifying the signal either on or directly behind the dish.

For the system noise to be dominated by the LNA noise figure, we need to digitize that signal such that its level is -21 dBm across the 400 MHz bandwidth. The total input power from the average 35 K sky and 50 K system temperature would be -93 dBm across the entire band, leading us to require 50 dB of that gain must come before the Radio-Frequency over Fiber (RFoF) system.

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The HIRAX Project
Kavilan Moodley, UKZN
Swiss SKA Days 2019, Bern
Complementarity with CHIME

<table>
<thead>
<tr>
<th></th>
<th>CHIME</th>
<th>HIRAX</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site</td>
<td>DRAO, Canada</td>
<td>Karoo (lower RFI, no snow)</td>
</tr>
<tr>
<td>Telescope</td>
<td>Cylinder array</td>
<td>Dish array (different systematics)</td>
</tr>
<tr>
<td>Field of view</td>
<td>100° NS, 1° – 2° EW</td>
<td>5° – 10° deg</td>
</tr>
<tr>
<td>Beam size</td>
<td>0.23° – 0.53°</td>
<td>0.1° – 0.2°</td>
</tr>
<tr>
<td>Collecting area</td>
<td>8000 m²</td>
<td>28,000 m²</td>
</tr>
<tr>
<td>Sky coverage</td>
<td>North</td>
<td>South</td>
</tr>
</tbody>
</table>

- 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
• 8-element prototype at Hartebeeshoek Radio Observatory (outside Johannesburg)

• Informing design, analysis and systematics

• Eight “off-the-shelf” f/0.38 dishes fully instrumented

• Fully functional scaled-down digital backend with single ICE board and GPU correlator

• Metal and fibreglass f/0.25 dishes to be installed in July 2019, currently preparing site

• Adding and testing RFoF system
HartRAO prototype commissioning

- Currently characterising instrumental properties from the data
- Poor RFI environment at HartRAO limits high-precision characterisation, analyse narrow subset of full bandwidth
- We see fringes. Can fit basic beam and gain models.
- Instrument characterisation on DRAO 3m dishes and shift to (low RFI) Karoo site in early 2020 with selected 6m dishes
Localising FRBs with Outrigger Arrays

- 8-element prototype array located at HartRAO
- Main site hosting the full array on the Swartfontein farm at the SKA Karoo site.
- Outrigger arrays in African partner countries provide very long baselines for FRB sub-arcsec localisation.
Swiss Involvement

- Swiss SNF FLARE grant:
  - Secured by HIRAX partner institutions - ETH-Zurich (Alex Refregier and Thierry Viant) and U-Geneva (Martin Kunz) - to build 512-element (512 channel) GPU correlator. Opportunity to expand the correlator to full array/bandwidth once demonstrated.
  - Collaborating with Keith Vanderlinde’s group at Toronto (built CHIME correlator)
  - EPFL in process of joining HIRAX collaboration
Swiss Involvement

- Swiss-South Africa bilateral grant:
  - Supporting collaboration on astronomy big data between UKZN/UWC/UCT/AIMS on South African side and U-Geneva/ETH-Zurich on Swiss side
  - Key focus on HIRAX simulations platform, data analysis platform and drone calibration.
  - Collaboration on 21cm intensity mapping cross-correlation science (see Mona Jalilvand’s talk tomorrow).
**HIRAX Simulations & Design**

- Extended m-mode cosmology pipeline for HIRAX; electromagnetic simulations of beams and S parameters using CST; telescope beams fed into cosmology pipeline

- Workshop at ETH-Zurich next week to advance HIRAX simulations pipeline and tie down design choices e.g. array layout, instrument tolerances. Supported by Swiss-SA big data bilateral grant.

- Also using simulations to develop analysis tools (calibration, foreground removal, power spectrum estimation) and cosmological forecasts
Some cosmology ...
HIRAX dark energy forecasts

- HIRAX will make a precise measurement of the matter power spectrum in the BAO regime.

- Convert power spectrum BAO constraints into constraints on $D_v$ in each redshift bin - constrain the BAO scale at the few percent level out to high redshift with HIRAX-1024
HIRAX dark energy forecasts

- HIRAX measurements of $D_v$ will provide tight constraints on dark energy equation of state parameters

- HIRAX-1024 FoM ~ 300 approaching DETF Stage IV class galaxy surveys ~400
HIRAX cross-correlation cosmology

- HIRAX intensity mapping survey will have good redshift overlap with other large-area cosmological surveys, primarily in the southern sky
  - Photometric: DES, LSST (Swiss)
  - Spectroscopic: DESI, Euclid (Swiss) and WFIRST
  - CMB: ACT, SPT, Simons Observatory

- HIRAX has excellent noise over cosmologically interesting scales, complementary to MeerKAT and SKA

- Cross-correlations ideal for testing systematics and joint science

Alonso et al 1704.01941
LSST photo-z calibration

- Cross-correlation with the LSST photometric survey can provide photo-z calibration via the clustering redshifts method (Alonso et al, 1704.01941) and improve parameter constraints.

![Figure 1: Constraints on the equation of state of dark energy](image1.png)

![Figure 2: Cross-correlation with the LSST photo-z calibration](image2.png)

![Figure 3: Impact of non-linearities on lower values of redshift](image3.png)

![Figure 4: Using the formalism described above, and in the simulations](image4.png)

![Figure 5: Forecast constraints on the LSST photo-z calibration](image5.png)

![Figure 6: With foreground removal](image6.png)
Correlation with CMB lensing

- Direct 21cm-CMB lensing correlation vanishes because of loss of low $k_{\text{par}}$ 21cm modes in foreground subtraction.

- Construct a bispectrum estimator that uses two copies of the 21cm intensity field and one copy of the CMB lensing field.

- Estimator relies on modulation of small-scale 21cm modes by large-scale (super-sample) modes to recover the line-of-sight long wavelength modes that are required for correlation with CMB lensing.

\[ \delta_L > 0 \]
\[ \delta_L < 0 \]
Correlation with CMB lensing

- Independently constrain growth function and clustering amplitude
- Improve dark energy constraints
- Provide tight constraints on HI bias parameters
Correlation with CMB lensing

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Upcoming schedule

- Inform instrument design and layout through cosmology and EM sims in Q2/Q3 2019
- HartRAO programme in Q3/Q4 2019:
  - Test f/0.25 fibreglass and metal dishes, finalise dish requirements and put out dish tender by Q4 2019
  - Test RFoF and feeds on f/0.25 dishes
  - Develop drone beam calibration system
- Develop HIRAX Karoo site by Q1 2020
- 8-element prototype at HIRAX Karoo site by Q2 2020
- 128-element pathfinder at HIRAX Karoo site by Q3 2020
Thank you!