Strong gravitational lensing with the SKA

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(The SKA strong lensing working group)
• First gravitational lens found in radio from large area survey at 900 MHz (Walsh et al. 1979, *Nature*).
• VLA based systematic surveys have found \(~36\) radio-loud gravitational lenses.

• Large area imaging and spec. surveys from SDSS have found \(~10^2\) star-forming galaxies and quasars.

• Steep source counts will lead to \(~10^2s\) lenses in the mm and sub-mm, and detected by ALMA.
Key application: **Mass**

- The most precise (few percent) measurement mass,
  1. Black holes
  2. Galaxies (baryonic and dark)
  3. Clusters (dark)

\[ \theta_E = \left[ \frac{4GM(\theta_E)}{c^2} \frac{D_{ls}}{D_lD_s} \right]^{1/2} \]

- Combine with kinematics to determine mass density profiles.

\[ \rho(r) \propto r^{\gamma'} \]

- Sample of 58 elliptical lenses at \( z \sim 0.2 \) selected from SDSS finds inner mass profiles consistent with isothermal (Koopmans et al. 2009).

As a function of galaxy type, environment, mass?
Key application: **Magnification**

**Sensitivity:**

- Identify a population of objects too faint to be directly detected.
- Study a population of objects below the confusion limit.
- Magnifications of 10-100 reduce $t_{\text{exp}}$ by factors of $\sim 10^{2-4}$.

**Resolution:**

- Resolve the structure of distant sources.
- Magnifications of 10-100 increase the effective resolution by similar factors.

Take your target (HI, AGN, star-forming galaxy) and put it behind a gravitational lens for SKA$_2$ science results with SKA$_1$.
Lensing statistics using **SKADS**

How many gravitational lenses in the SKA sky?

$$\tau(z_s) = \int_0^{z_s} n(z) \sigma_x \frac{cdt}{dz} dz = 10^{-3}$$

Gravitational lenses are rare, and the flat source number counts require shallow and wide-field surveys as opposed to deep and narrow-field (x 14 more efficient).

For 1 square degree,

**360 with** $S_{1.4 \text{ GHz}} > 1 \text{ uJy}$ (Deep)

**50 with** $S_{1.4 \text{ GHz}} > 10 \text{ uJy}$

**8 with** $S_{1.4 \text{ GHz}} > 50 \text{ uJy}$ (Shallow)

Statistics from a deep survey would directly constrain the SKA$_2$ number counts.
Identifying gravitational lenses

How many gravitational lenses found with SKA\textsubscript{1}? 

- Resolution (> 0.3 arcsec).
- Sensitivity (~3 uJy rms for 15 sigma at ~50 uJy).
- Band 2 (0.95-1.76 GHz) for survey
- Band 5 (4.6-13.8 GHz) for follow-up
~few per square degree (~1 per SKA MID pointing).

CLASS (McKean et al. 2005)

Conservative: 1 per 4 square degrees with S\textsubscript{0.5} arcsec. This will give ~10
Confirming gravitational lenses

Challenges:

1. False positives
   A. Higher angular resolution imaging.
   B. Spectral information.
   C. Polarisation information.

2. Modelling large numbers of candidates.

3. Lens and source redshifts.

Optical / Infrared cross correlation from Euclid and LSST are vital.
Unique science goals

• Galaxy formation
  • Mass density profiles over mass, redshift and environment *(0.3 arcsec imaging, lens kinematics from HI)*.
  • Weak lensing to measure outer haloes *(0.3 arcsec imaging)*.
  • Mass substructure in lensing haloes over mass, redshift and environment *(1 to 50 mas “VLBI” imaging)*.
  • Measuring central images and supermassive black hole masses *(1 to 50 mas “VLBI” imaging)*.
  • Scattering/free-free absorption/polarisation due to the lens *(wide band imaging from 1 to 15 GHz)*.

• Cosmology
  • Tests of dark energy using gravitational lens time-delays *(monitoring over several months with 0.3 arcsec imaging)*.
  • Tests of dark energy using multiple-plane lensing *(0.3 arcsec imaging)*.

• Source science
  • Probing the CD and EoR through magnified CO / HI detections *(imaging at 0.1 to 15 GHz)*.
Testing models for dark matter

Imaging of two bright (~500 and 200 mJy) lenses with global VLBI 10% collecting area of the SKA

(McKean et al., in prep)
Testing models for dark energy

Constraints from CMB+two lenses competitive with other methods (Suyu et al. 2013).

Collett & Auger 2014 – constraints on $w$ from one 2-source-plane lens (blue) – loose, but orthogonal to Planck (grey)

Currently ~20 time-delay lenses, not all suitable for detailed modelling
~1 double source-plane lens
Need a factor of 10 more lenses to get the rare and valuable cases – SKA will provide (especially in combination with Euclid/LSST)
Measuring black hole masses

- Faint central images (magn. \( \sim 10^{-3} \)) tightly probe the inner mass distributions.
- Image splitting of the central image by \( 10^{7-9} M_{\text{sol}} \) black holes predicted.
- Requires large bandwidth to identify images and mas-imaging.
Summary

• The SKA will transform studies of the Universe with gravitational lenses by increasing sample sizes from a few 10s to a few $10^4$s.

• We find that an all-sky survey with SKA MID in Band 2 (0.3-0.5 arcsec resolution) down to 3 uJy beam$^{-1}$ sensitivity with follow-up at Band 5 (preferred) is needed.

• A VLBI component to SKA phase 1 is vital for the most exciting science uses of gravitational lenses.

• The magnification provided by gravitational lenses will allow studies of the population of sources that will only be accessible with SKA Phase 2 (both in sensitivity and angular resolution).