Opportunities for maser studies with the Square Kilometre Array

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Outline of talk

- What is the Square Kilometre Array? The concept of the Reference Design.
- A progress report: Where will it be located and what is the timeline?
- What are the capabilities?
- What are the key science opportunities involving masers?

What is the SKA?

- The Square Kilometre Aray (SKA) is a paradigm-shifting radio telescope for the next generation, a truly global machine, to operate for ~50 years.

- Aim: a unique instrument to answer many of the “big” questions in astronomy e.g. what is the nature of Dark Energy, are we alone in the Universe, how did galaxies and black holes form, what is the origin & evolution of magnetism, can pulsars and black holes detect gravity waves – was Einstein right?

Organisation of the SKA Project

- Global project from the start : >50 institutes in 17 countries
- International Steering Committee leads the project development: ISPO, 6 working groups
- Engagement with inter-government agencies to establish governance model, funding strategy
- International collaborations – technology demonstrators & preparation for key science projects in progress

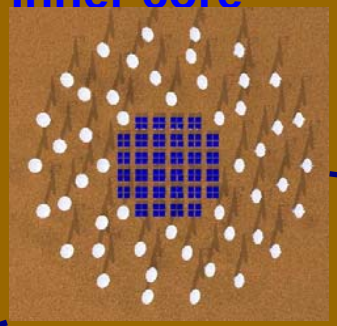
The Concept of the SKA

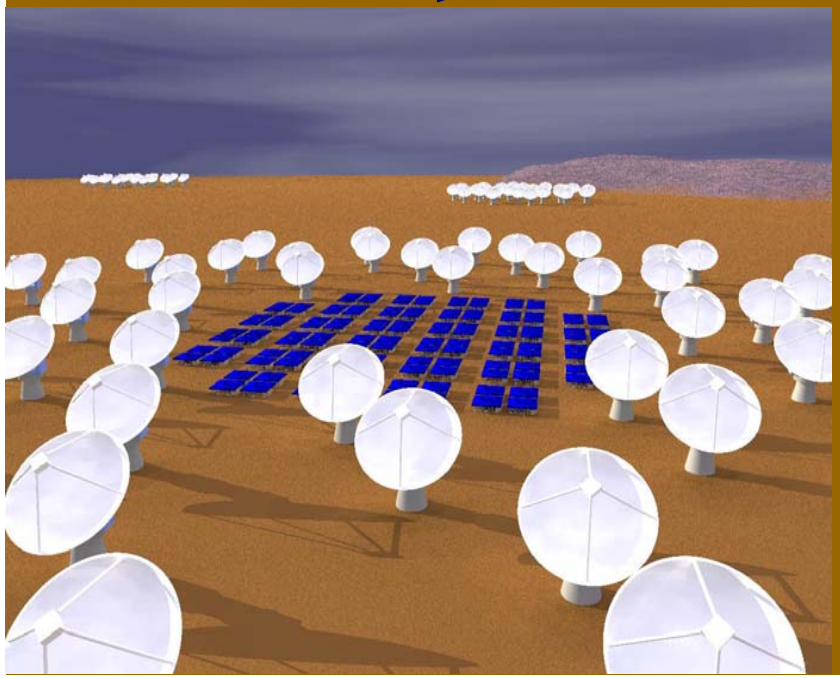
- Data network connecting sensors of the incident electromagnetic field to a correlator → interferometer array
- Sensing antennas highly concentrated in the central 5 km and further distributed in stations at distances up to ≥3000 km
- Antennas and stations connected via wide-band fibre links (100 Gbit/s) to the central data processor (10 – 100 Pflop/s)
- Small dishes + smart feeds and aperture arrays cover the frequency range 0.1 – 25 GHz
- Telescope to be built in stages - Phase 1 will be 10% of the full collecting area, at the array centre, able to do unique science

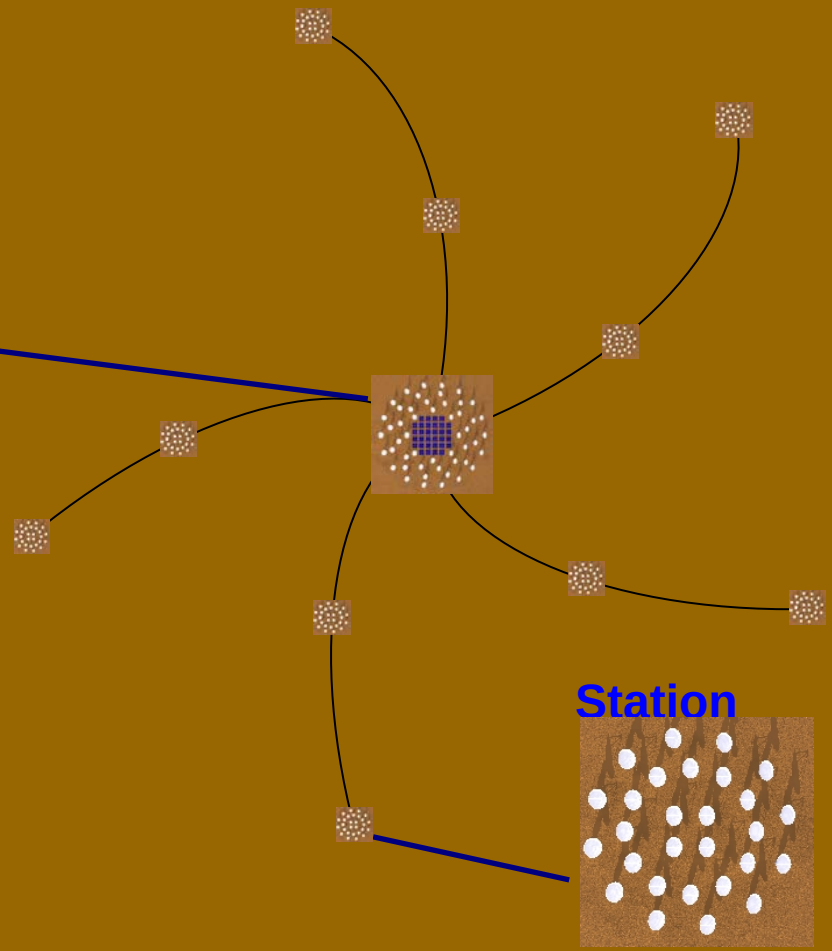
Status at March 2007

- Two sites short-listed for consideration:
  - Australia & New Zealand
  - South Africa + 7 countries
- Key issues: very low RFI, large site, low ionospheric & tropospheric turbulence
- Reference Design developed to:
  - Focus engineering & science efforts
  - Provide basis for detailed costing
  - Provide recognizable image for SKA

Reference Design

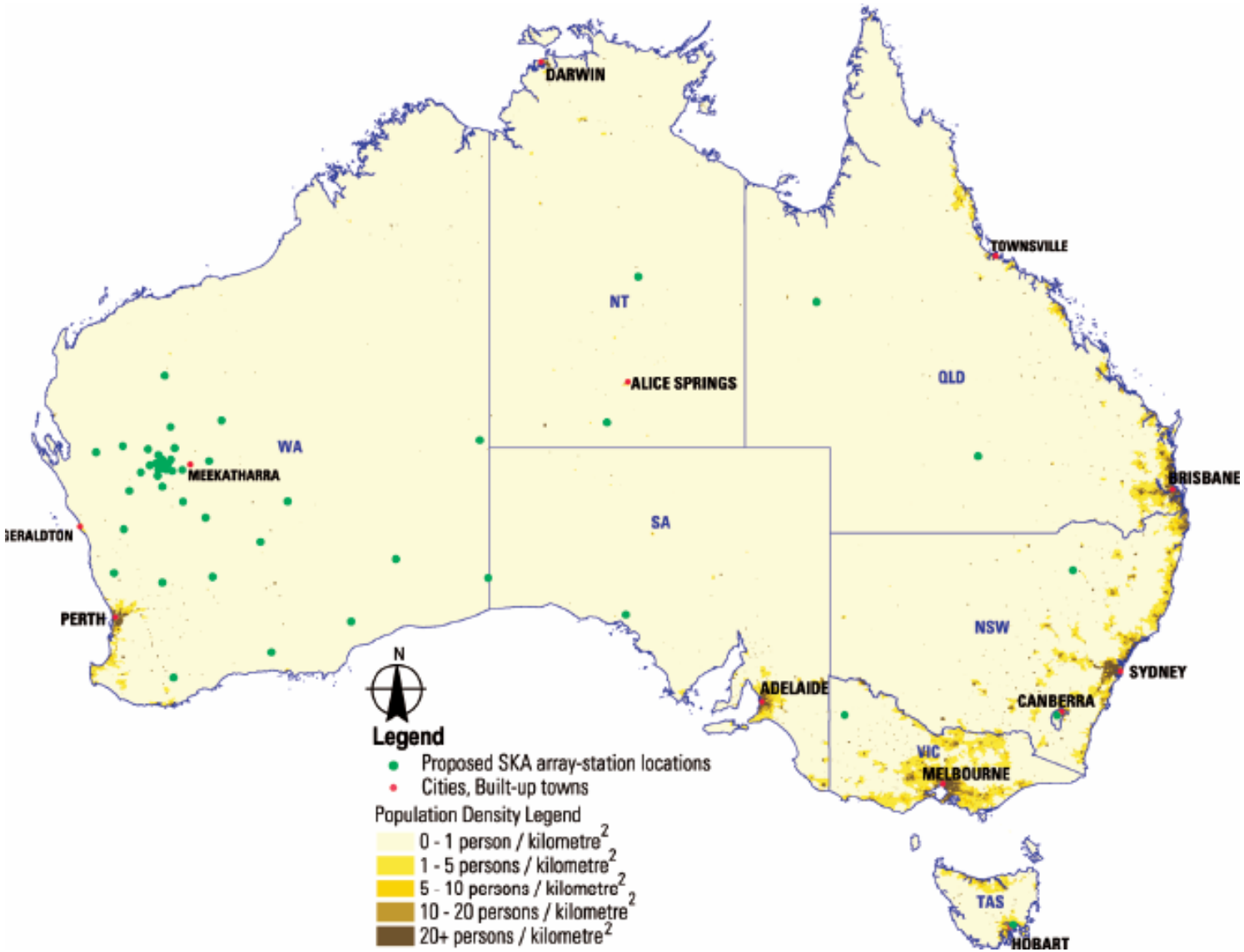




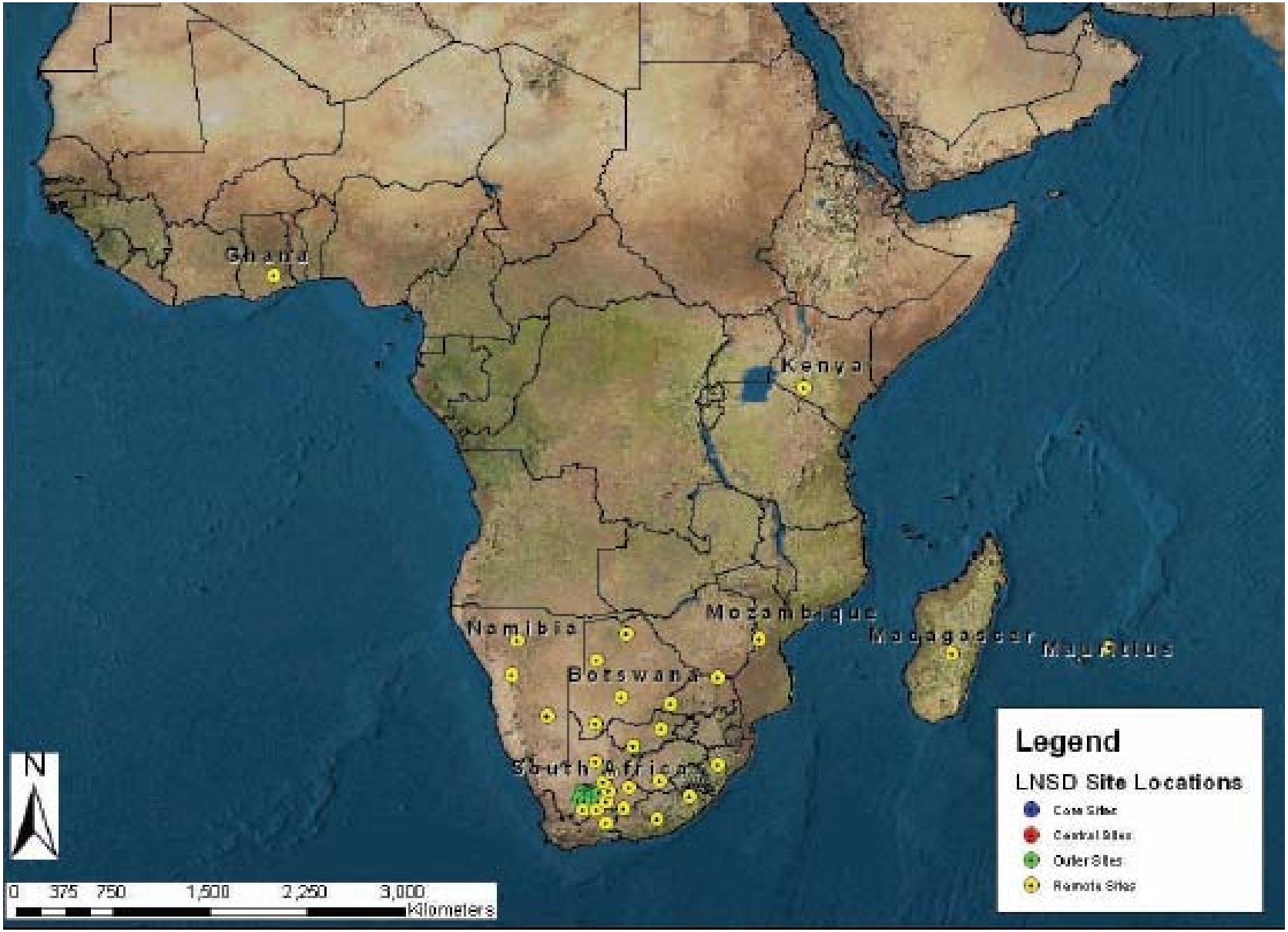


Wide-angle radio camera +
radio “fish-eye lens”

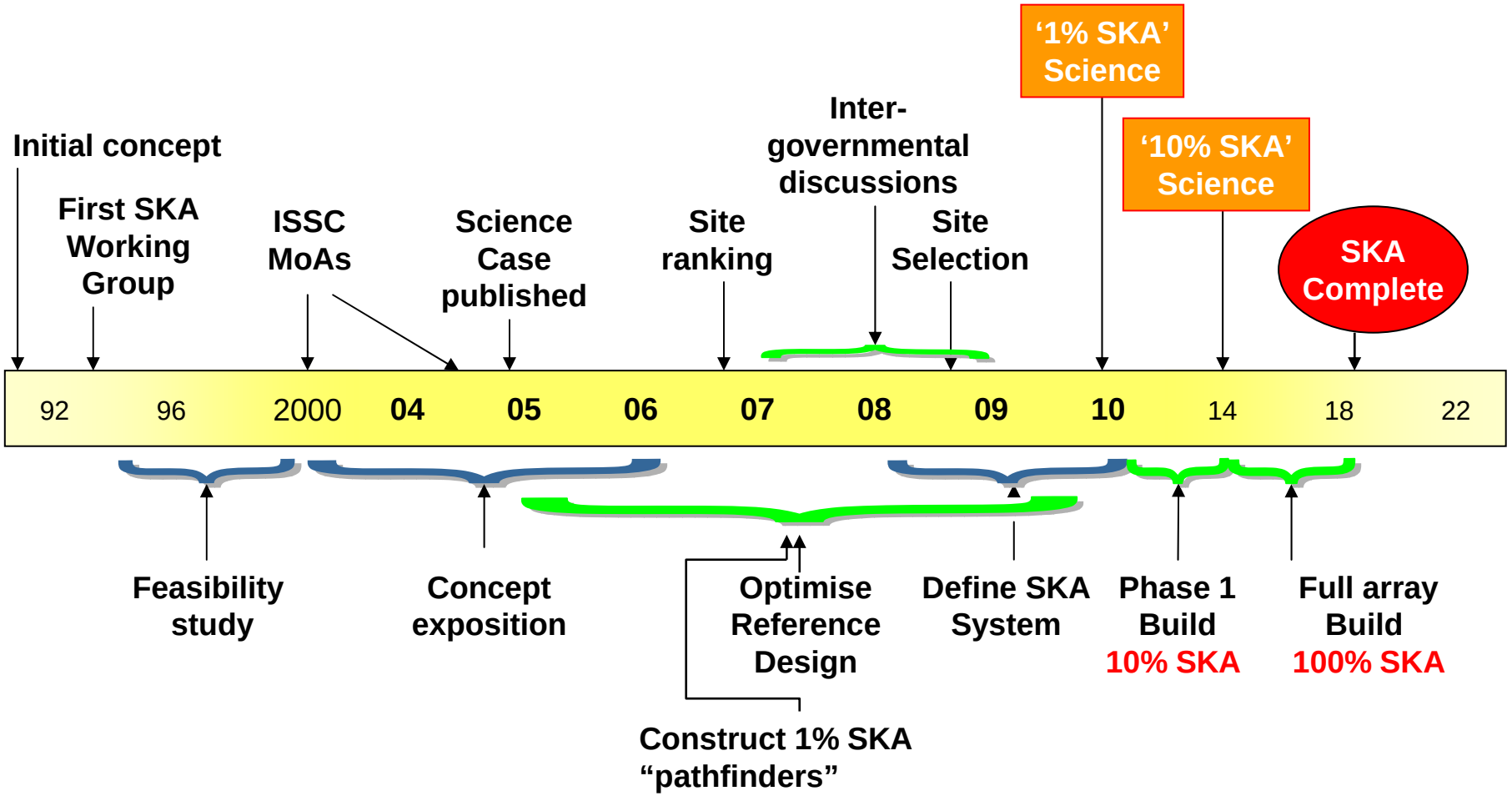
Australia + NZ



South Africa + 7 countries



SKA timeline



What capabilities we can expect?

- Sensitivity to detect and image atomic hydrogen & other molecules at the edge of the universe → *very large collecting area (~1 km^2)*
  line detectability ~50 times improvement on current telescopes

- Fast surveying capability over the whole sky → *very large field of view (1 square degree at 1.4 GHz)* FoV =18 sq arcmin @ 20 GHz

- Angular resolution to make detailed images of the structures of disks, planetary gaps and how they change → *large physical extent (baselines > 3000 km)* $\Theta = 20/f_{GHz}$ mas

- *A wide frequency range (0.1 – 25 GHz)* to handle the science goals

SQUARE KILOMETRE ARRAY
Total Cost 1 B€; projected operating cost 70 M€ p.a.

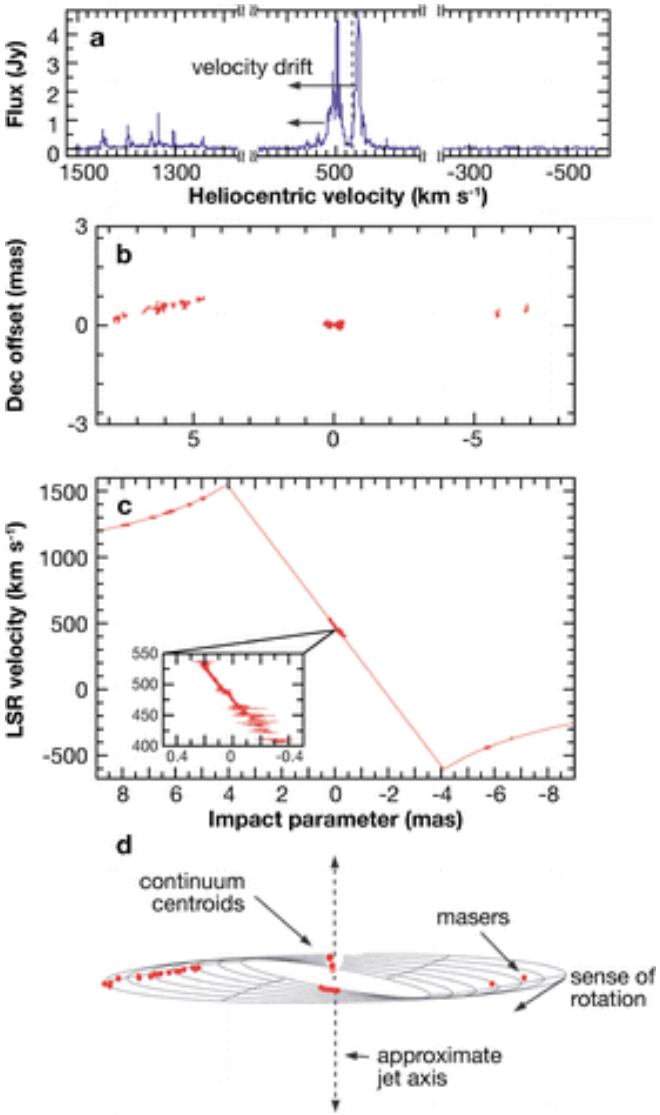
Science goals for masers

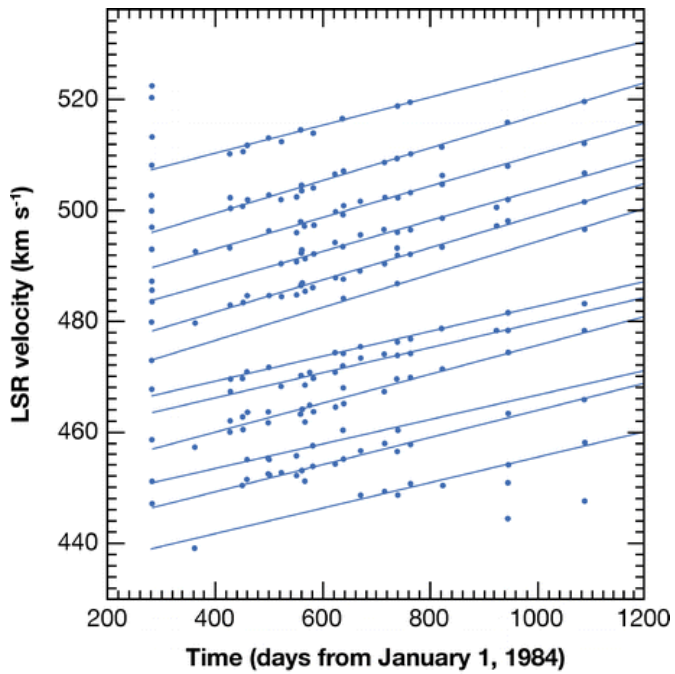
- Early Universe (Dark Energy, H_o & BH evolution):
  H_2O megamasers in AGNs
  OH megamasers in starburst galaxies
  OH masers in supernova remnants

- Our Galaxy (star formation & dynamics):
  Multiple maser species to image disks, outflows, young massive protostellar objects
  Masers to probe spiral structure

Strength of the SKA – great sensitivity & wide field of view (angular resolution limited if assume a real-time connected array)

1. NGC 4258 – nuclear disk H_20 masers

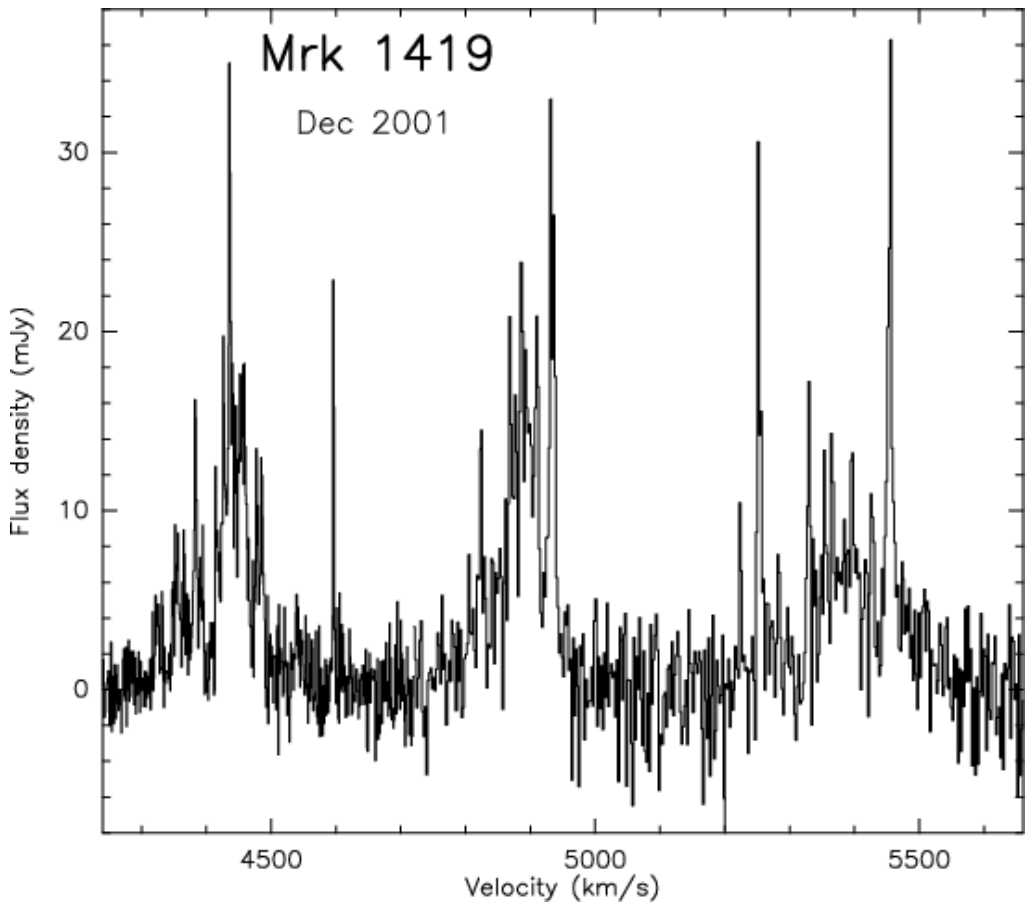




Seyfert 2/LINER galaxy
z = 0.0017
D = 7.2±0.5 Mpc
Thin, warped Keplerian disk (diam ~0.6 pc)

Claussen et al. (1984)
Herrnstein et al. (1999)
Nakai et al. (1993) etc

2. MK 1419 – a distant nuclear disk



Henkel et al. (2002)

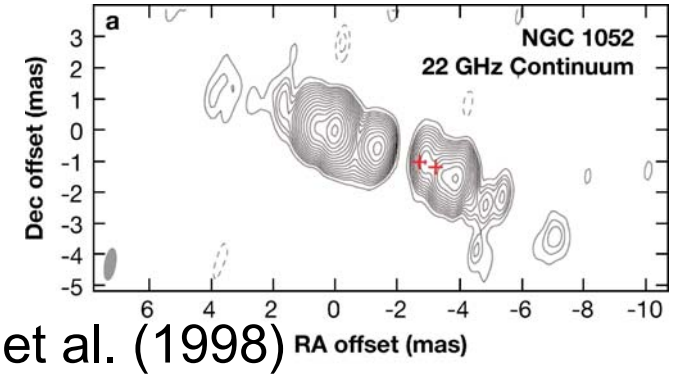
MK 1419 (NGC 2960)
LINER galaxy
z = 0.016
D = 69 Mpc
Disk scale 0.33 pc/mas

3 groups H_2O masers
Only systemic velocity drifts

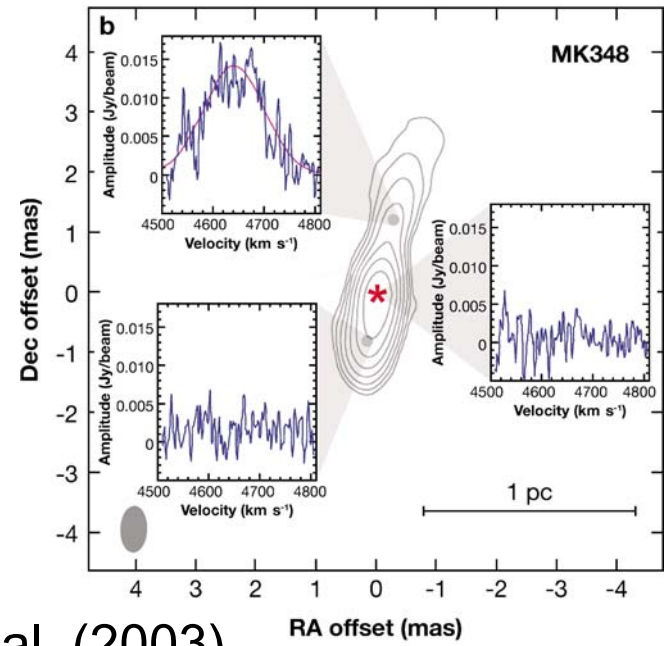
How predict new targets?

Current low detection rate is sensitivity limited

3. H_2O jet masers



Claussen et al. (1998)



Peck et al. (2003)

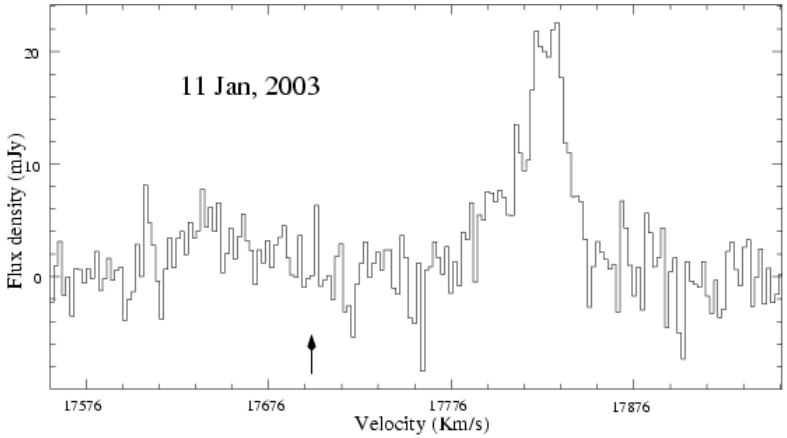
Interaction between radio jet & encroaching molecular cloud

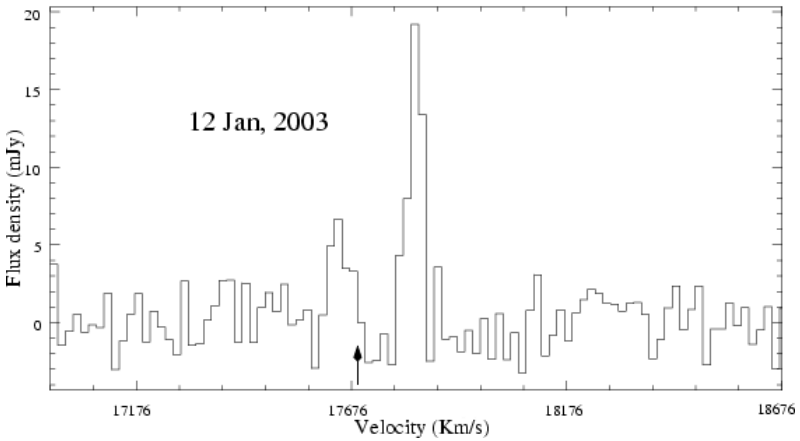
Variability and correlation with continuum suggest emission from shocked region at interface rather than simple amplification of radio jet

See velocity shifts from systemic value
Gas entrained by jet outflows?

More examples in Henkel et al. (2005)
e.g. Mrk 34 @ D = 205 Mpc

4. Another class of H_2O masers





Tarchi et al. (2003)

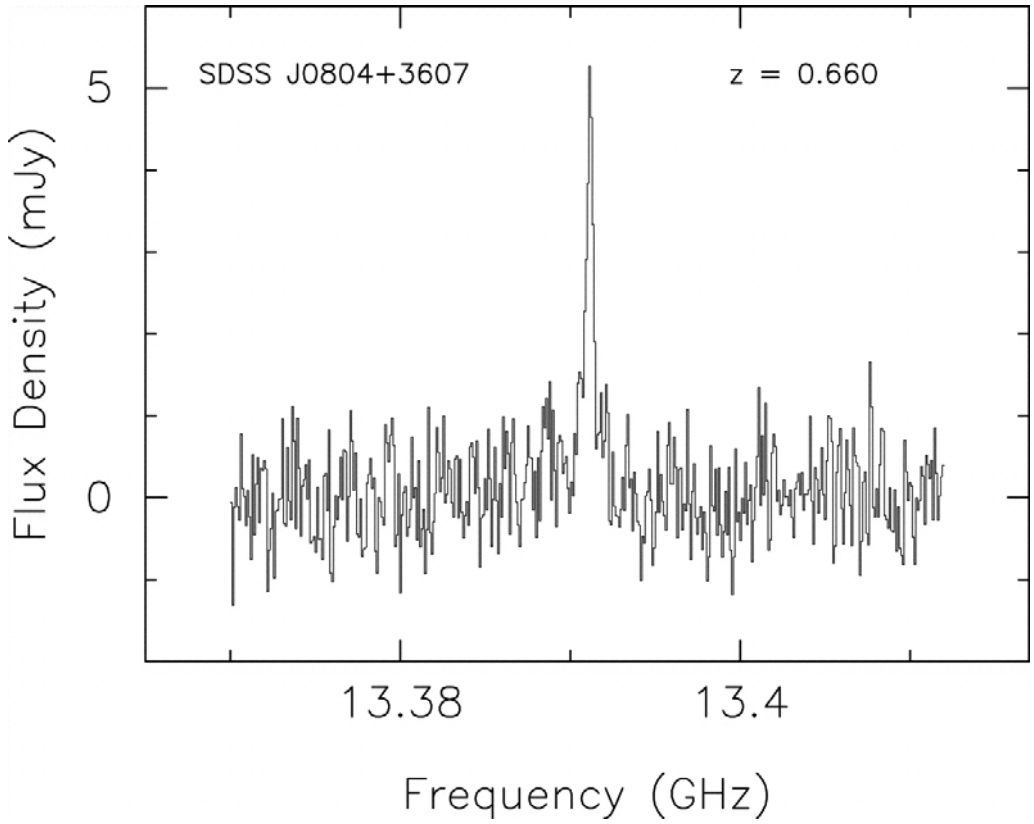
First detection of FRII in radio loud galaxy: 3C 403
z = 0.06

Masers could indicate accretion disk or jet interaction

Evidence that dense molecular gas is present ($>10^7$ cm^{-3}) in thick molecular torus

Disk can extend up to 100 pc from AGN

5. Type 2 quasar at z = 0.66



Barvainis & Antonucci (2005)

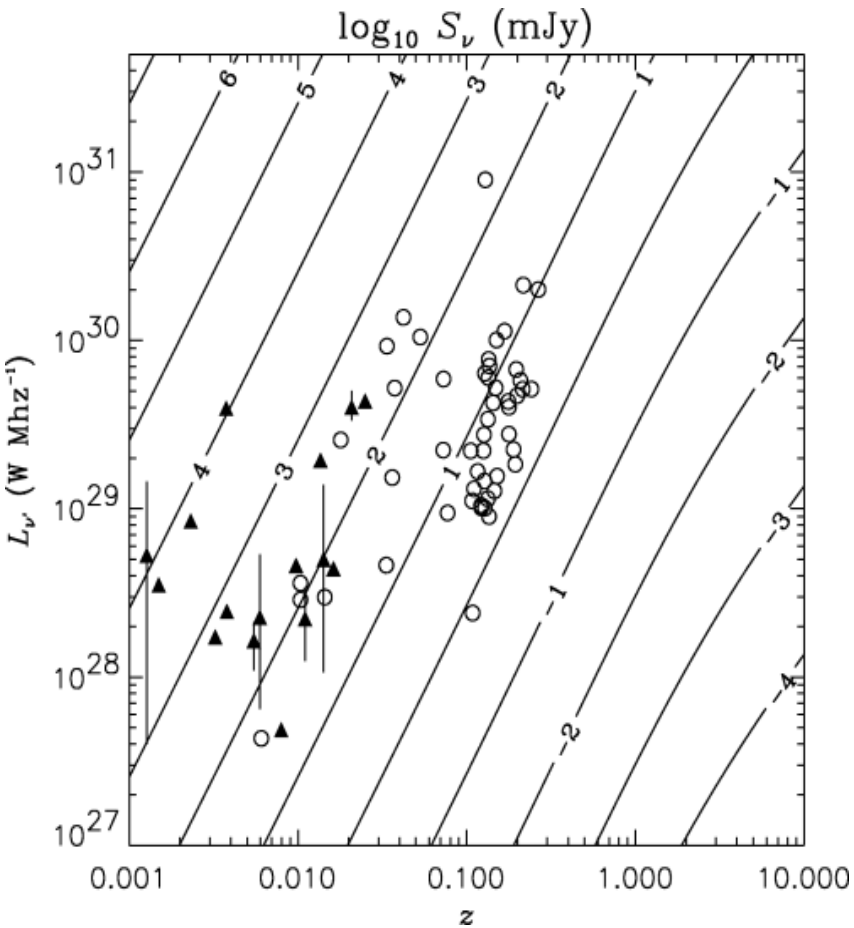
Most distant water maser known to date
D = 2.4 Gpc
Size scale = 10 pc/mas
L = 23,000 $L_\odot$

Only 1 component – no evidence of disk geometry

Molecular gas exists at large redshifts – CO observations

Distances to similar objects in the Hubble flow enables a direct measure of H_0 and a test of cosmological models and dark energy.

6. Masers & dusty star formation history



Townsend et al. (2001)

OH and H_2O masers are found in many ULIRGs. Maser luminosity ~correlates with FIR luminosity – analogues of Milky Way massive star-forming regions?
(Henkel et al. 2005)

Determine redshift distribution of distant dusty starburst galaxies using masers.
e.g. at z~3, expected S_{OH} = 0.4 mJy
H_2O for z~1-10 is in range 2-11 GHz

For HLIRGs, OH maser flux ~1 mJy at z ≥4

Separation (OH @ higher z & luminosity) may be real or selection effects

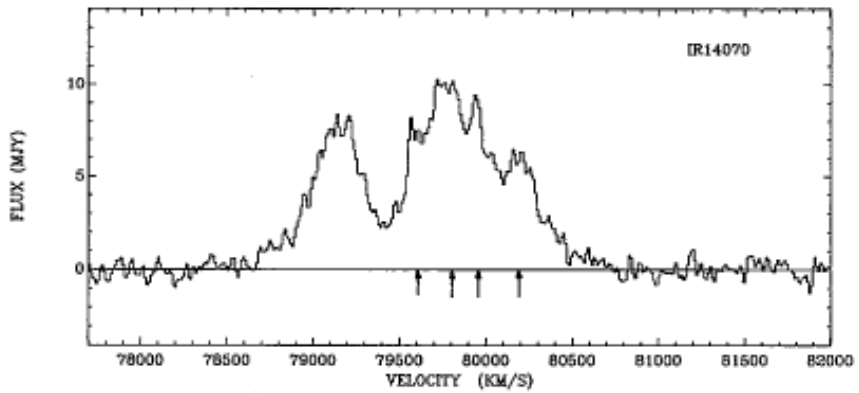
7. OH megamasers in starburst galaxies

OH megamasers ↔ starburst galaxies – undetected in some LIRGs?

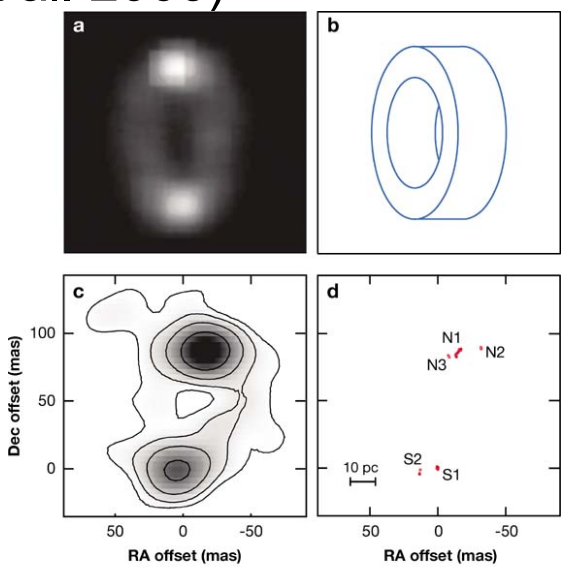
Some in extreme starbursts: ≤ 100 pc in central regions, with high concentration of molecular gas; H_2CO also in a few sources

IRAS 14070+0525 most distant OH megamaser to date (z = 0.265)

Major mergers: III Zw 35 is interacting pair (Parra et al. 2005)

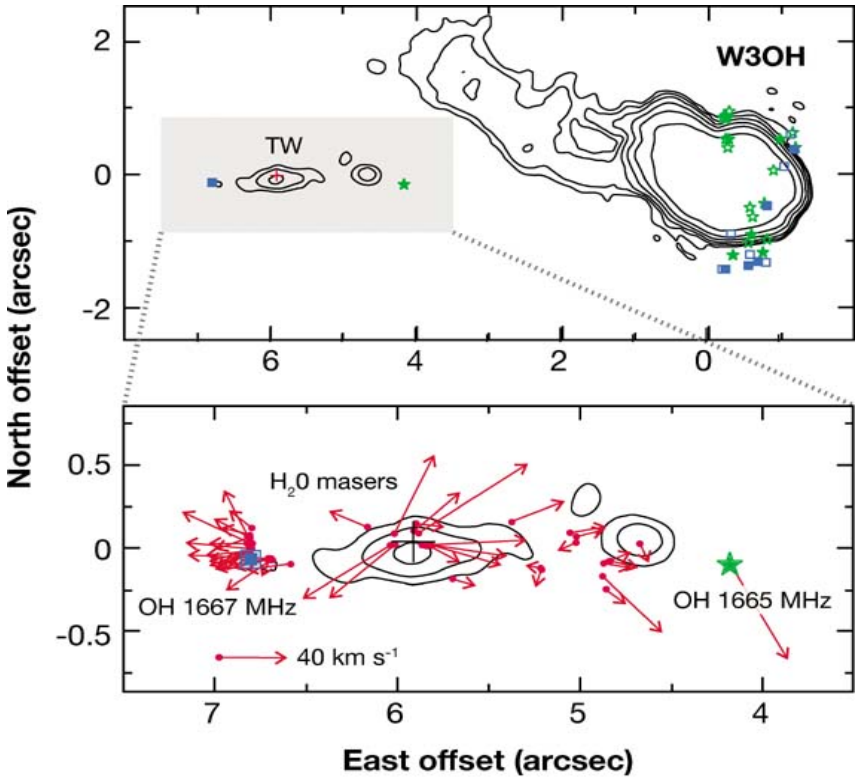


Baan et al. (1992)



Pihlstrom et al. (2001), Diamond et al. (1999)

8. Galactic masers of many flavours



Argon, Reid & Menten (2003)

Are extragalactic H_2O kilomasers associated with nuclear activity (i.e. weak megamasers) or with star-forming regions (the Galaxy)?

e.g. NGC 2146 (Tarchi et al. 2002)

Massive stars are distant – SKA has sensitivity to find protostellar Keplerian disks, outflows

UCHII regions detected to 50 Mpc

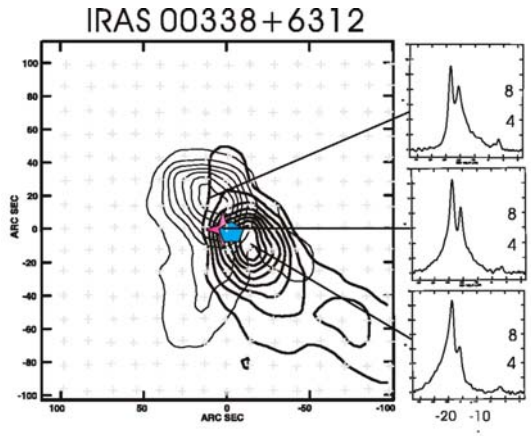
Spectral resolution: ≥4000 channels dual polarisation, 4 GHz BW max

Angular resolution: 1 mas (H_2O) up to 15 mas (OH)

Galactic options continued

- More YSOs – OH, H2O, methanol, (no SiO); add clarity to disk versus outflow issue
- Test methanol Class II absence near low mass star-forming regions
- Extragalactic 1720 MHz OH masers in SNRs; expect 3 mJy detection at M33 (1 Mpc)
- Image stellar photosphere & winds in AGB stars – eclipsing planets?
- Distance precision – proper motions, parallax, Galactic structure (SKA ++)

Molecular ouflow around a YSO
Xu et al. (2006)



Summary – what masers gain with the SKA

- Increased numbers of sub-parsec disks around AGNs for disk physics & BH mass studies – big improvement in sensitivity but distance may be limited to ~500 Mpc; complete local sample.
- Detect high density gas in parsec nuclear regions of high redshift galaxies – no distance limit. For resolved disks, precise distances & better H_0 estimate, insights into dark energy.
- Find gigamasers to get redshifts for luminous, dusty starburst galaxies → star-formation history.
- Many more disks & outflows in star-forming regions & dusty protostars; image CSEs around evolved stars; shock interactions (SNRs) in nearby galaxies; proper motions; magnetic fields everywhere.

Read more ….

"Science with the Square Kilometre Array"

New Astronomy Reviews (2004) volume 48

edited by Carilli & Rawlings