Very Long Baseline Interferometry in the SKA era

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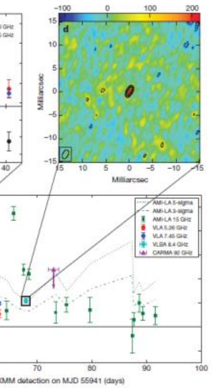
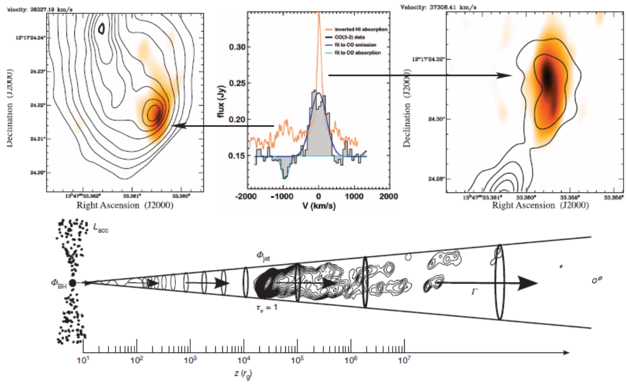
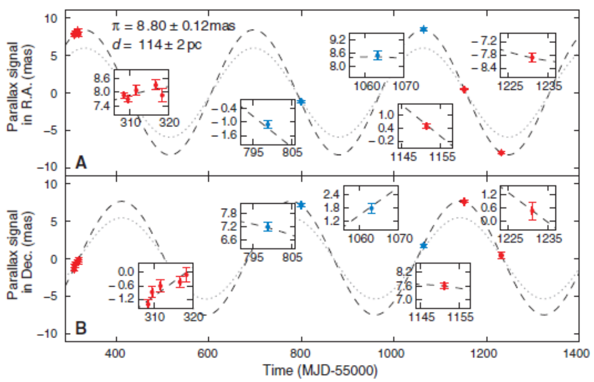
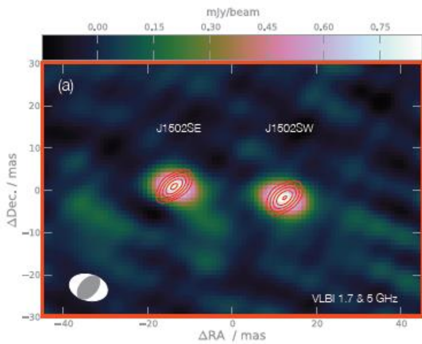
and many more…





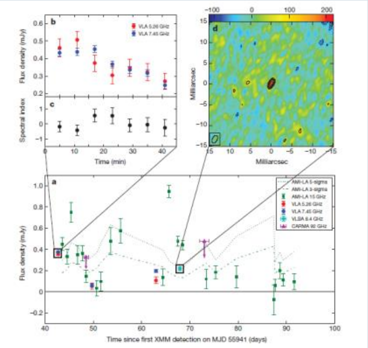




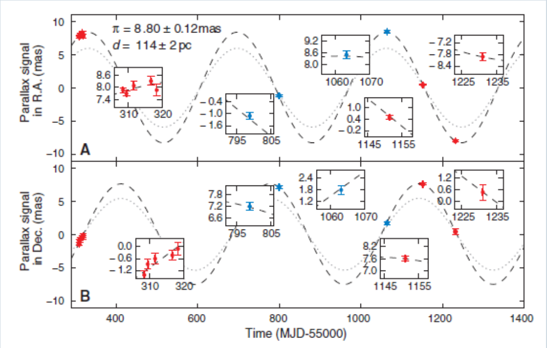
Some VLBI highlights 2013-2014

- VLBI is not only “jet science” – some science highlights
- How to do VLBI with the SKA (SKA1-MID)
- Example SKA-VLBI applications – astrometry, surveys and explosive outflows (as time allows)

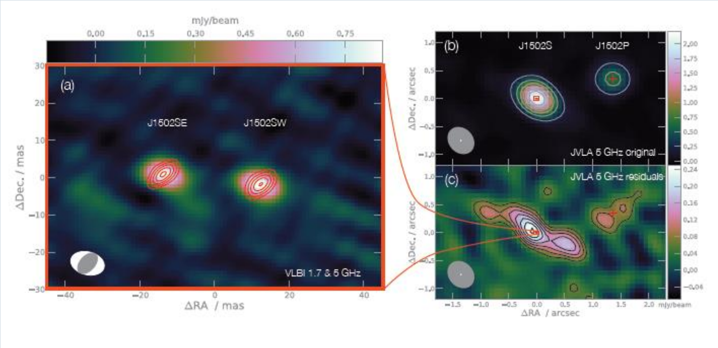
Middleton et al., Nature, 493, 187, 2013

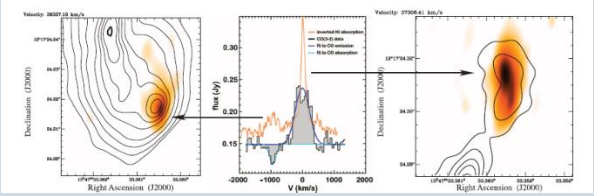


Miller-Jones et al., Science, 340, 950, 2013

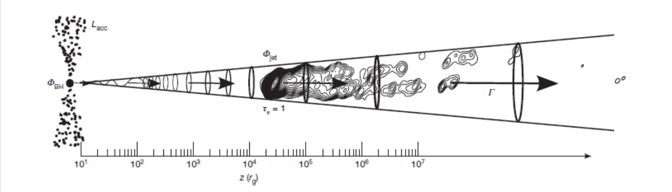


Deane et al., Nature, 511, 57, 2014



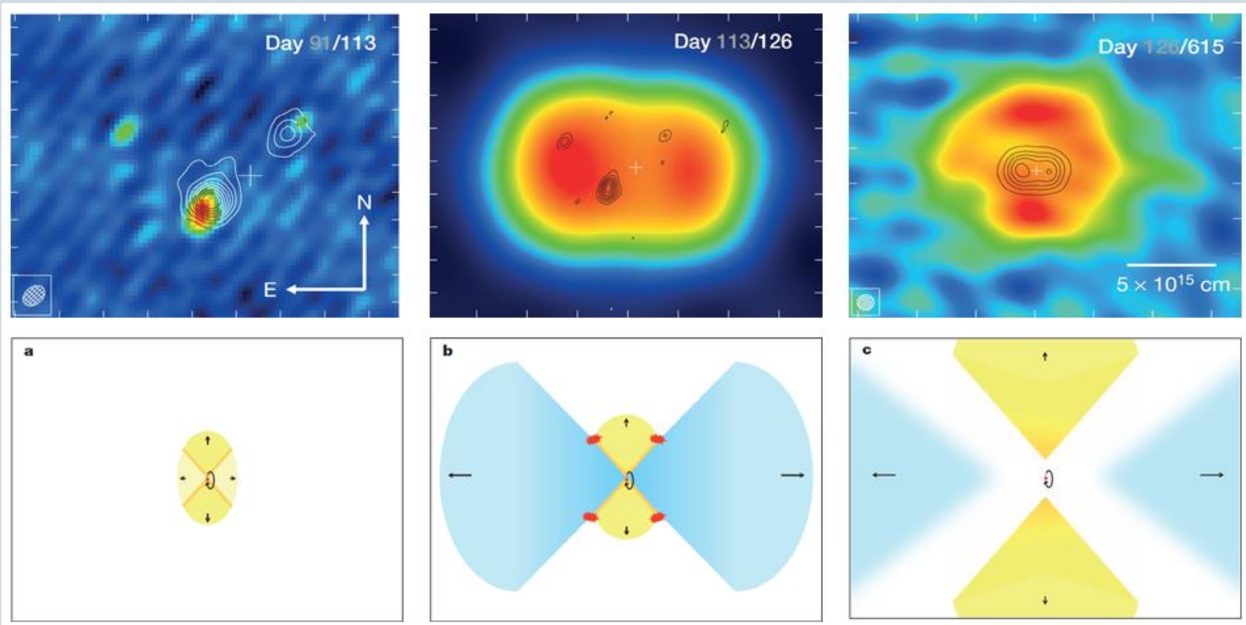


Morganti et al., Science, 341, 1082, 2013



Zamaninasab et al., Nature, 510, 126, 2014

Two more since June …

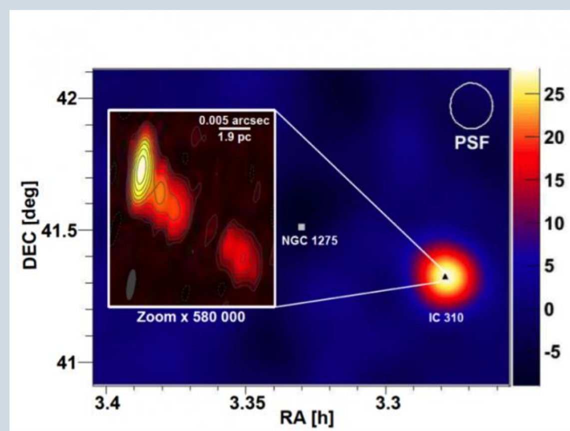


Chomiuk et al., Nature, 514, 339, 2014

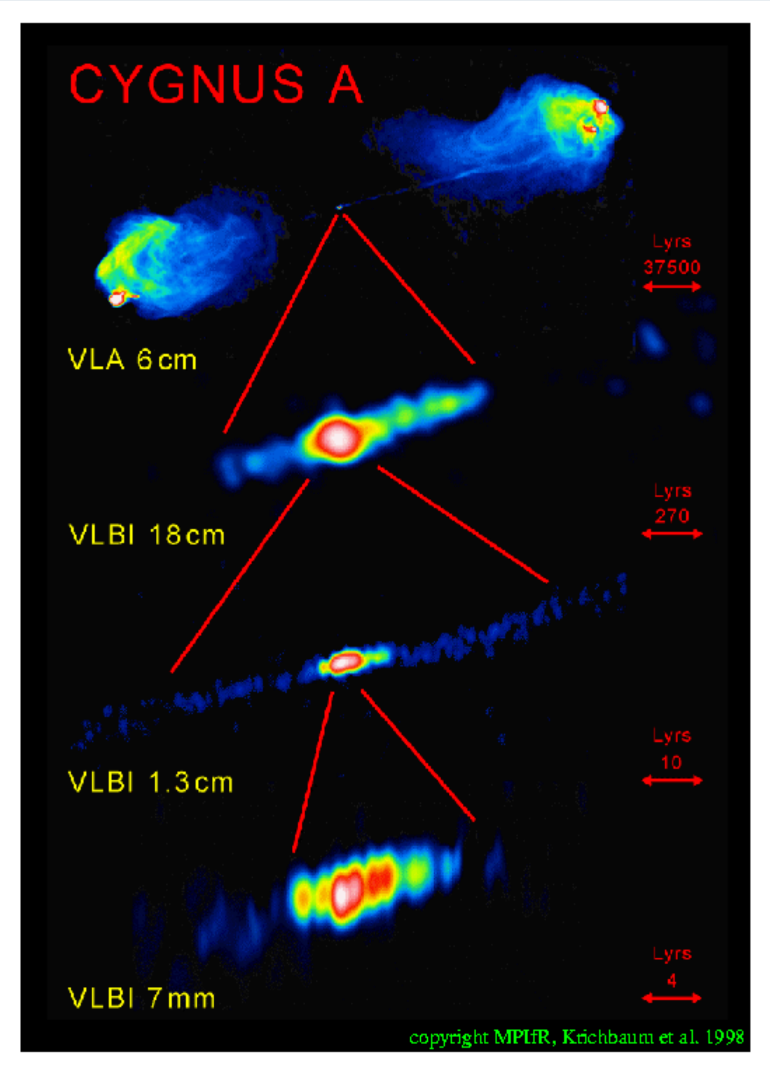
e-EVN, JVLA, VLBA, e-Merlin

Aleksić et al., Science (last week) DOI:10.1126/science.1256183

MAGIC+EVN



Angular scales probed by VLBI



- VLBI probes angular scales <1 mas to 100 mas

  10^{14} – 10^{16} cm (or 5 – 500 AU) @ 5 kpc
  1 – 100 parsec @ 200 Mpc (redshift of 0.05)
  7 – 700 parsec @ $z = 4$

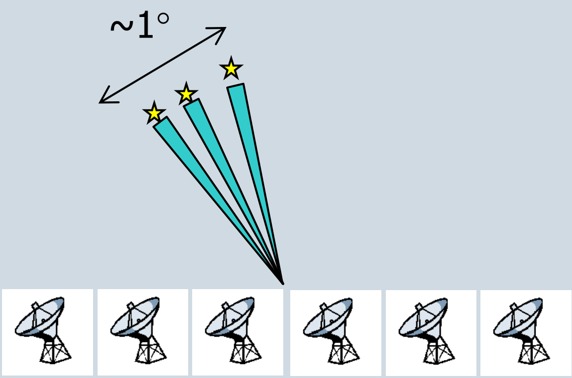
- There is a gap in angular resolution between VLBI arrays and connected element interferometers, the ~0.1 – 1 arcsec (only probed by e-MERLIN at ~GHz frequencies)

- In a typical VLBI observation we probe a region ~10^9 times smaller than the FoV of the individual telescopes

- Modern VLBI techniques address the second point (see later); a next generation radio instrument will have to address both

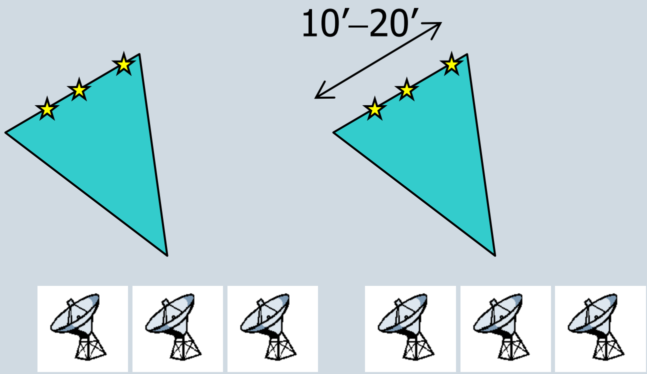
Figure: Krichbaum et al. (1998)

SKA-VLBI configurations



Full core (<4000m), 4 beams (~1″ each)

OR:



~~Form several sub-arrays, ~50-100m each~~

- SKA-VLBI in phase 1: phase-up the full core (left) **or** form a number of sub-arrays (right).
- If phasing up, form a number of tied-array beams within the telescope beam (~1°)
- Observe together with existing VLBI telescopes, correlate data in one of the correlators
- The full SKA: elements distributed over hundreds to thousands of km (possibly merging existing VLBI telescopes); use SKA correlator

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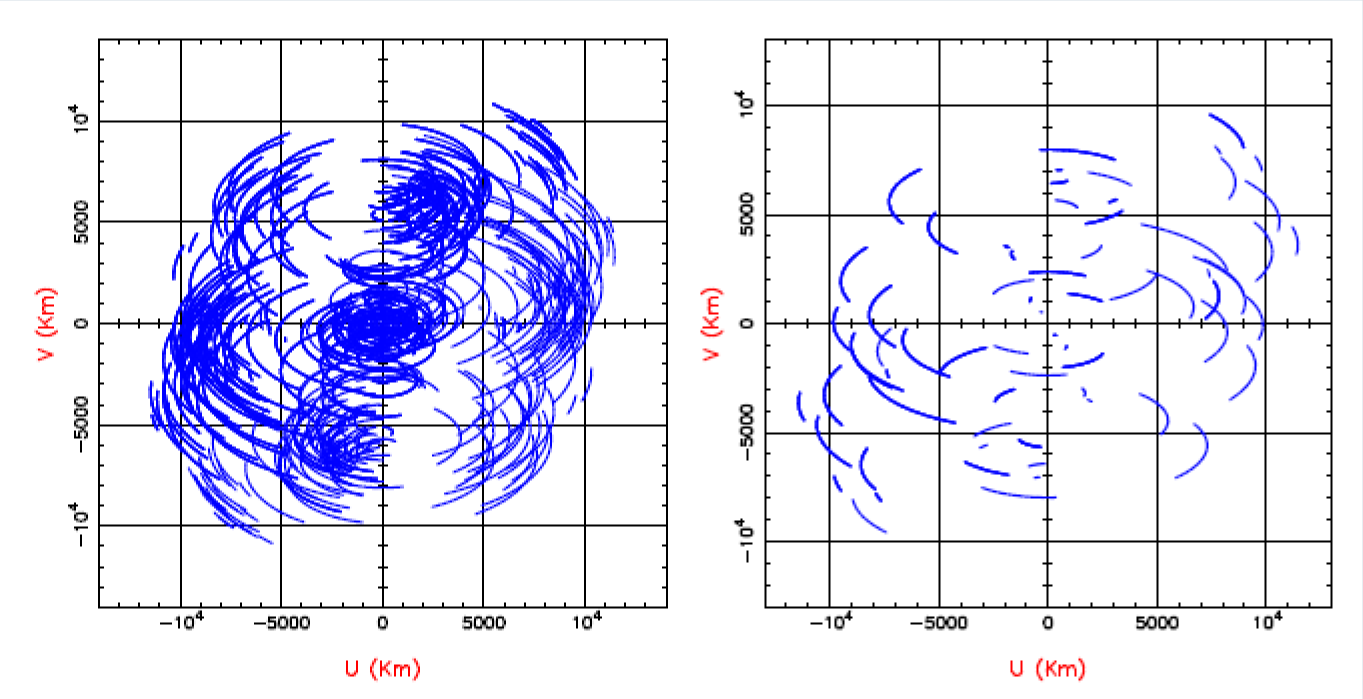
SKA-VLBI configurations



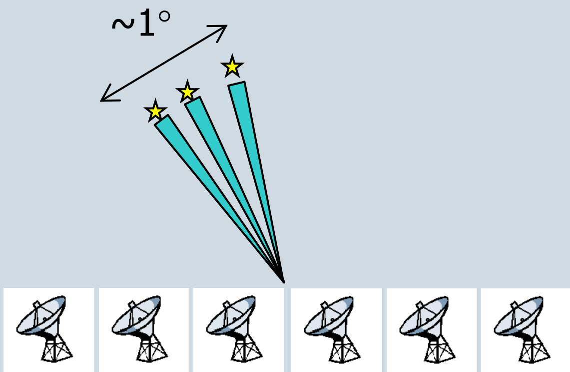
- Left: *uv*–coverage for a full-track observations of Sgr A* with all available VLBI telescopes in the EVN, CVN, LBA and planned AVN telescopes (*uv*–tracks for the central frequency only)
- Right: likely more typical 4h SKA-VLBI observation of a –20° declination source with a few telescopes selected from the same networks.
- SKA-VLBI limitations include: SKA1-mid antenna elevation limit, shadowing, and time available for VLBI-mode operations

SKA-VLBI configurations

SKA Band	SKA-core SEFD [Jy]	Bandwidth [MHz]	Remote tel. SEFD [Jy]	Baseline sens. 60s [μJy]	Image noise 1hr [μJy/beam]
50% SKA1-MID	5.2	256	20	82	9
SKA1-MID	2.6	1024	20	29	3
Full SKA	0.26	2048	20	3	0.05

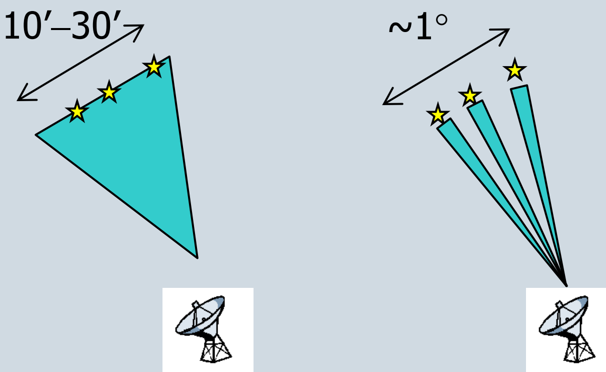
- Expected sensitivities for a more "typical" configuration (SKA1-mid + large telescope +3-4 small telescopes)
- In the early science operations SKA-VLBI will already compete/supercede the current e-EVN and will significantly improve the coverage of the Southern sky

SKA-VLBI calibration



SKA1-mid: <u>simultaneous</u> "MultiView" calibration

Use in-beam calibrators / fast switching

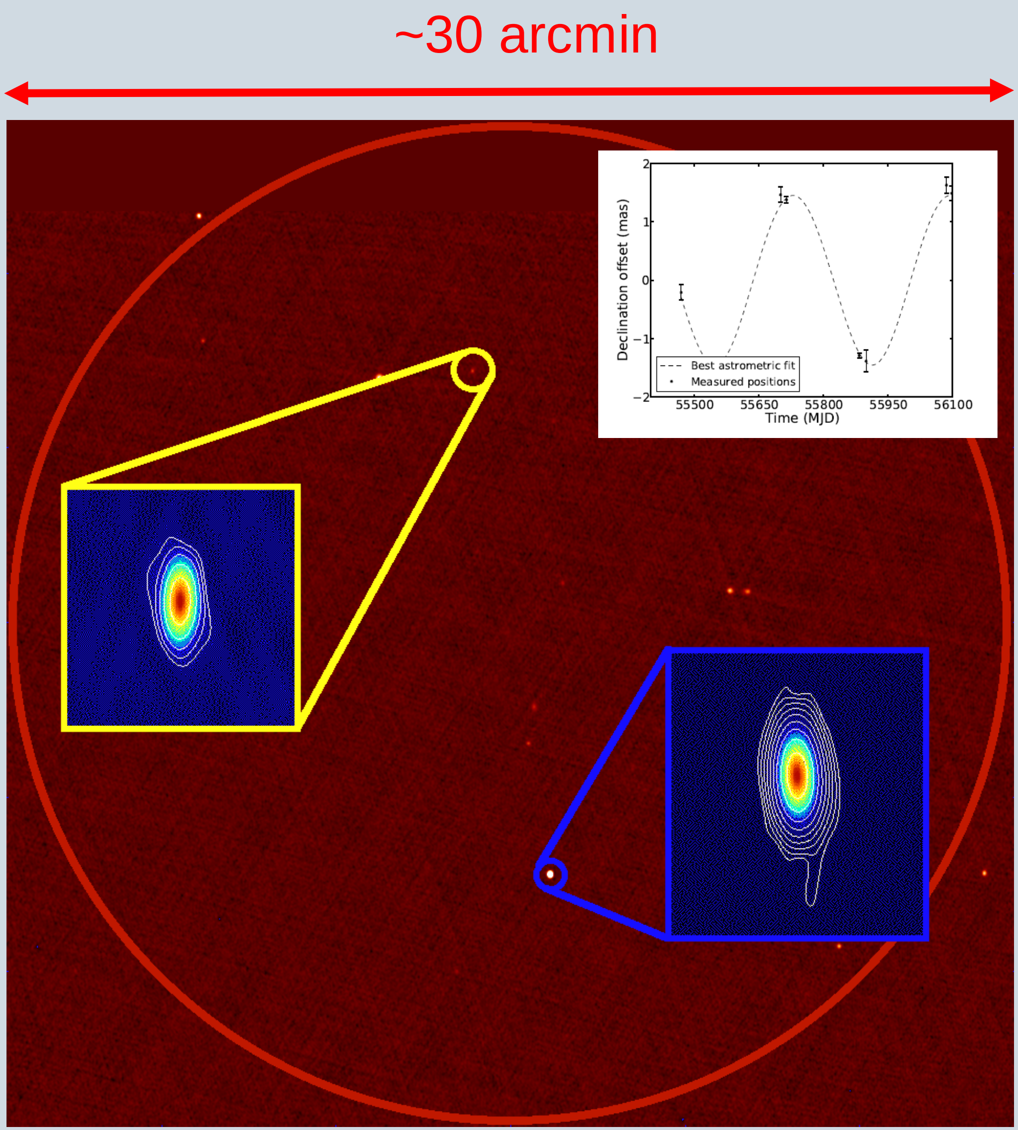


Matching resources: 30–100m telescopes

- SKA-VLBI a-priori calibration: metadata – T_{sys}, gains, weather, GPS…
- Use nearby calibrators for delay, delay rate and phase calibration (see above)
- Need <u>simultaneous</u> SKA tied-array (for VLBI) and local interferometer data
- Above is important for accurate SKA-VLBI amplitude and polarization calibration, as well as for scientific applications

SKA-VLBI astrometry

- SKA headline science: pulsar astrometry
- For delay and phase calibration use nearby calibrators
- Current VLBI can provide ~10 μas accuracy (e.g. in-beam cals)
- Further improvements: use multiple (min. 3) calibrators, solve for 2D phase slope across the beam
- Which frequency is best for SKA?

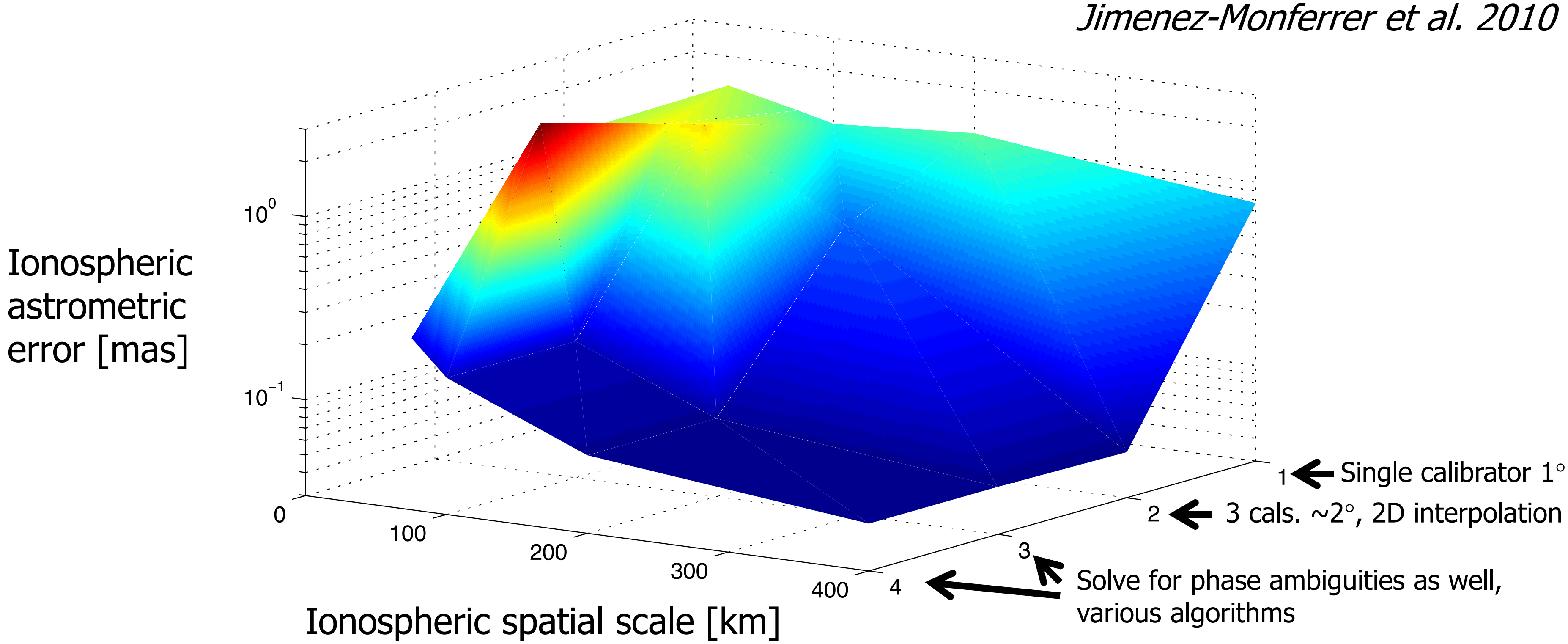


Deller et al. 2013

SKA-VLBI astrometry

Astrometric error vs. calibration scheme vs. fluctuations spatial scale
(Sinusoidal model, 1.4 GHz)

Jimenez-Monferrer et al. 2010

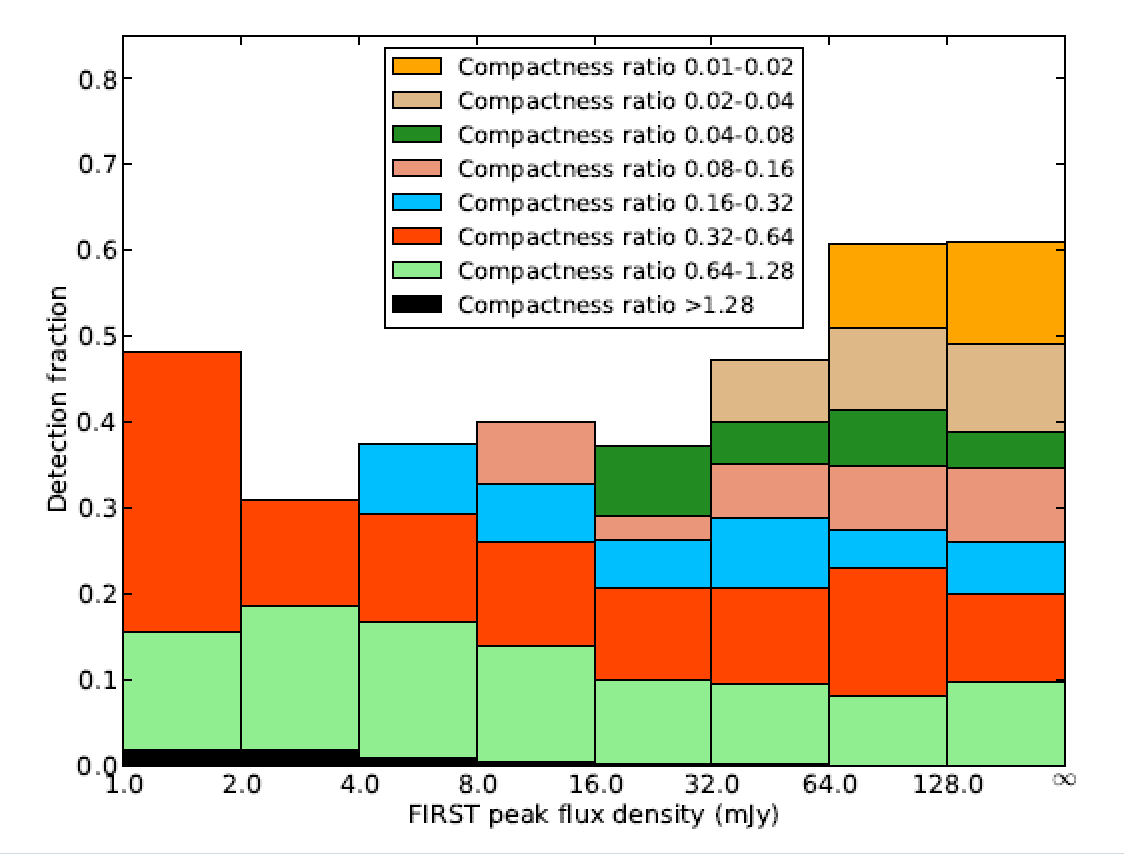


- At 1.4 GHz 10-15 μas accuracy may be achieved; <u>going to ~3 μas requires higher frequencies (~>3 GHz)</u>
- Several compact ~1 mJy sources within a few arcmin will work (5–8 GHz source counts TBC)

SKA-VLBI astrometry

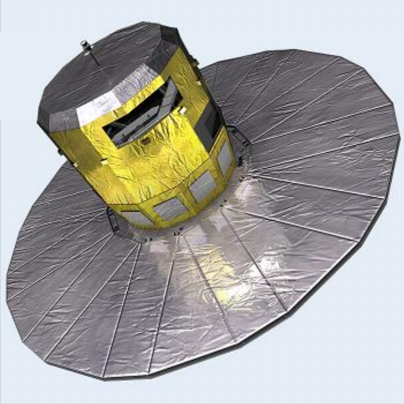
Will we have enough calibrators within a few arcminutes?

Deller & Middelberg 2014



- We need ~1 mJy sources, these provide good enough SNR (cf. baseline sensitivity ~30 μJy in phase 1)
- Fraction of compat sources at low flux density levels are higher – promising

Synergies with *Gaia*



Calibrating *Gaia* parallaxes

- *Gaia* vs. *Hipparcos* – similar technology and software

  Periodic variations in the "basic angle" between fields of view may introduce a systematic error

  The Pleiades distance controversy:

  Hipparcos – 122±2 pc

  Others (e.g. VLBI) – 133±3 pc

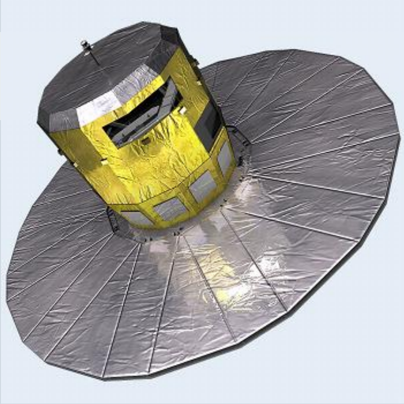
- For the *Gaia* mission, a bias ~ 0.1 μas will have a significant impact!

  Independent parallax measurements of a sample of *Gaia* targets in the radio will be very important to verify *Gaia* parallaxes.

  Will need ~500 stellar parallaxes with 10 μas uncertainty to push down any bias well below 1 μas.

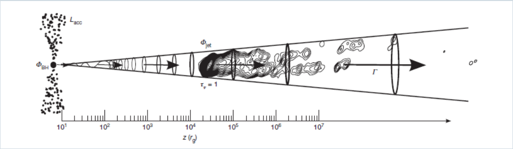
- <u>Only SKA-VLBI can do this</u>!

Synergies with *Gaia*



Gaia & SKA-VLBI: new opportunities

- Comparison of optical and radio positions of AGN: tie ICRF and the *Gaia* reference frames (find SNe progenitors!!!)
- Combine radio, optical and pulsar timing data for pulsar-WD binary systems: tie the radio, optical, and the Solar System dynamical frame as well
- AGN *and* microquasar core-shifts: study accretion/magnetic fields/jets from stellar to supermassive BH



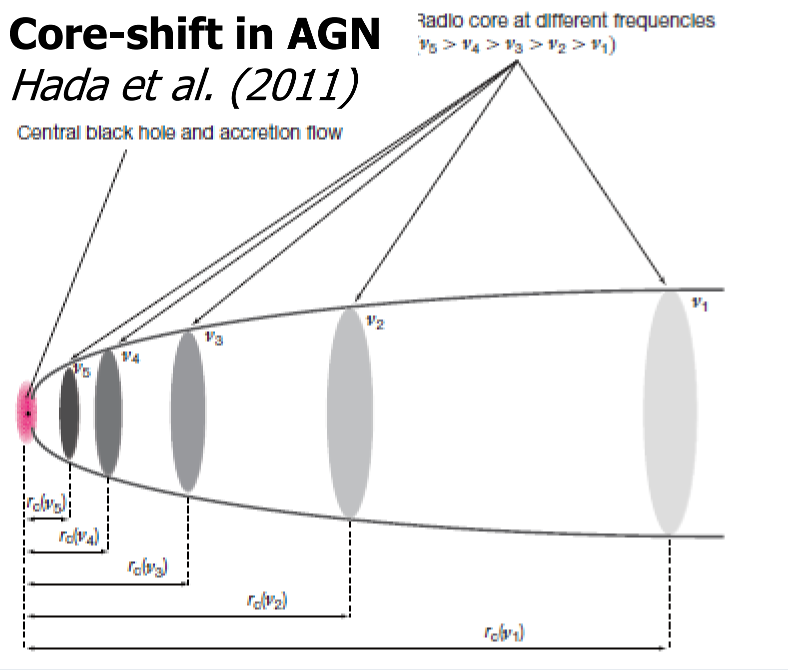
- Off-centre AGN:

  recoiling BH or

  radio-quiet/radio-loud pair of minor merger **dual/multiple AGN**

Core-shift in AGN

Hada et al. (2011)



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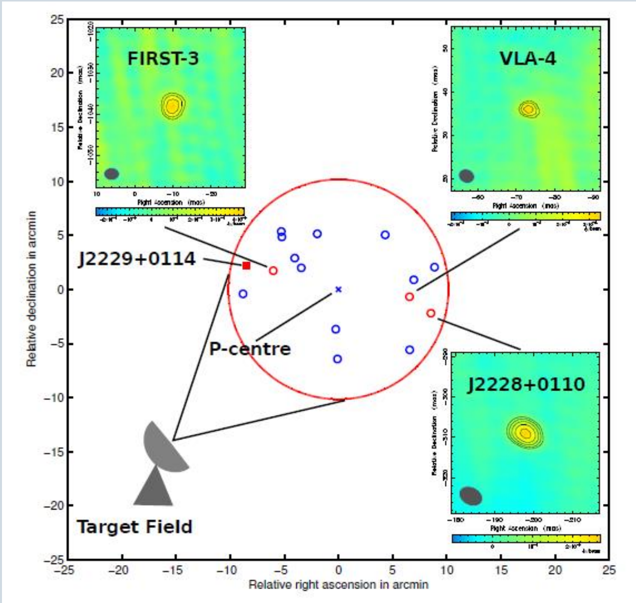
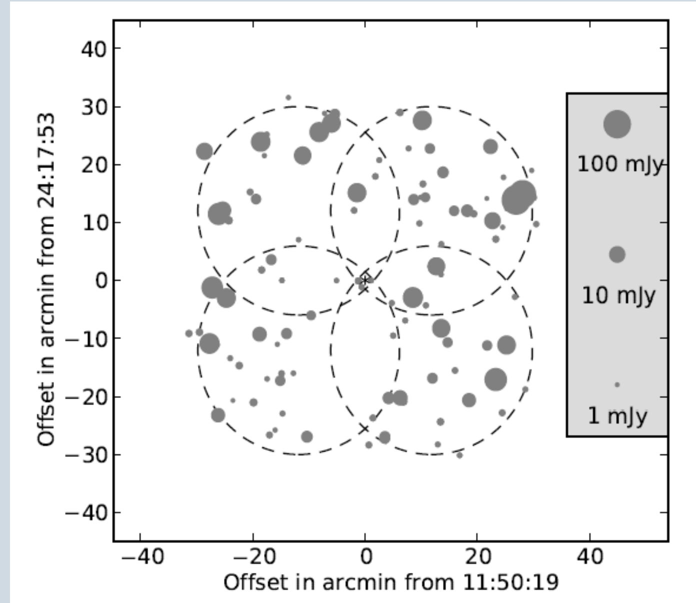
SKA-VLBI surveys

EVN
Cao et al. (2014)





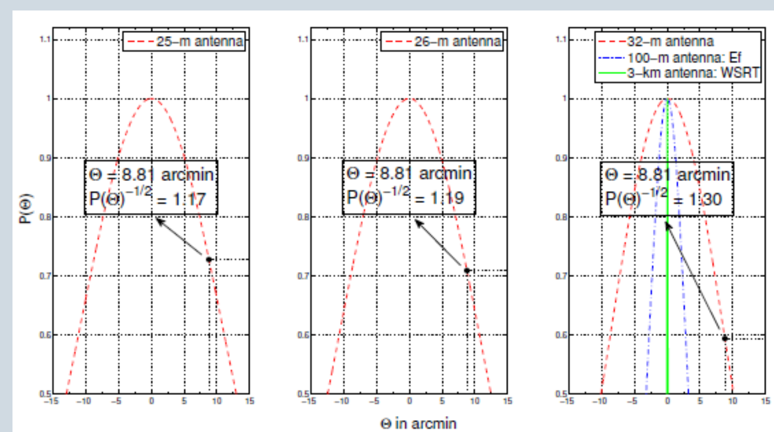
VLBA – mJIVE

Deller & Middelberg (2014)

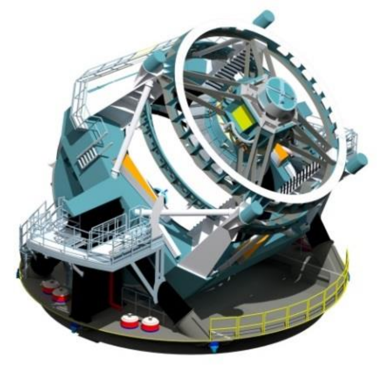
- Wide FoV VLBI efficient with modern S/W correlators
- Phasing-up SKA1-mid limits the FoV!!!

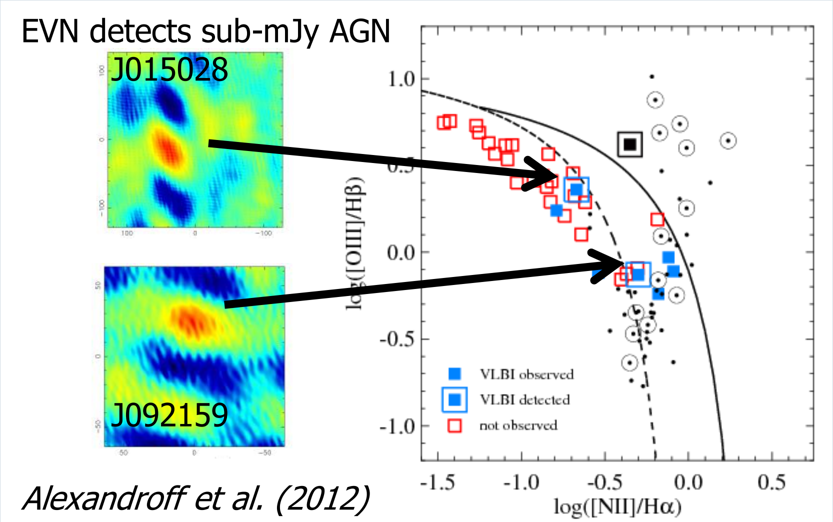
  ~~1) sub-arrays help but only a very small fraction of the core could be used~~

  2) rapid source switching of 4 tied-array beams – moderate loss of sensitivity
- Eventually need the full SKA…



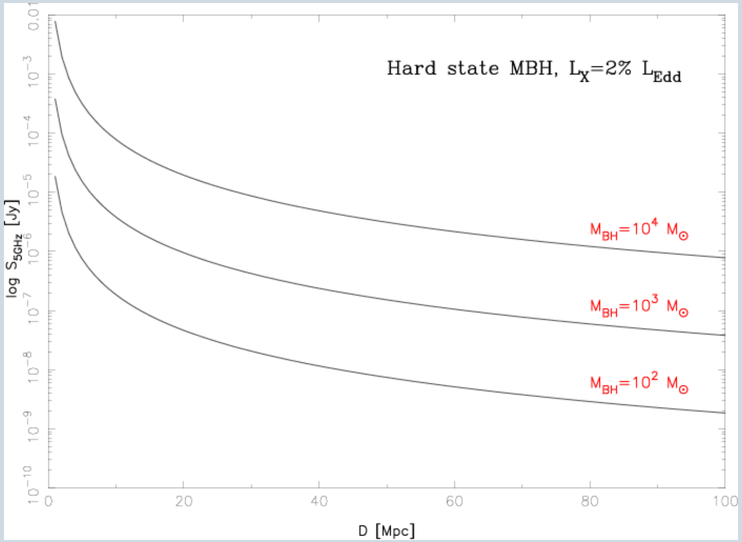
SKA-VLBI surveys





- Sub-mJy population:
  SKA-VLBI will be the most powerful way to detect AGN
  (at low accretion rates AGN are more radio-loud)

- Synergy with LSST



- Structure formation/ BH growth: find <u>local analogs</u> of $10^2 - 10^5\ M_{SUN}$ seed BH

- SKA1 will see all high/hard state MBH down to at least $10^4\ M_{SUN}$ within ~100 Mpc

  If these flare (e.g. tidal disruption events), detection is possible up to cosmological distances *(Donnarumma et al. 2014)*

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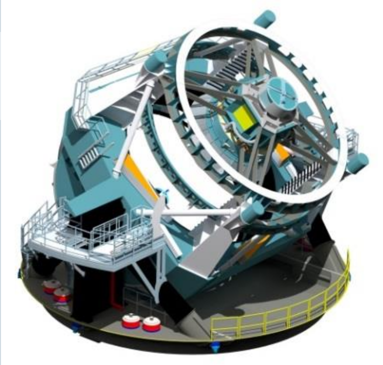
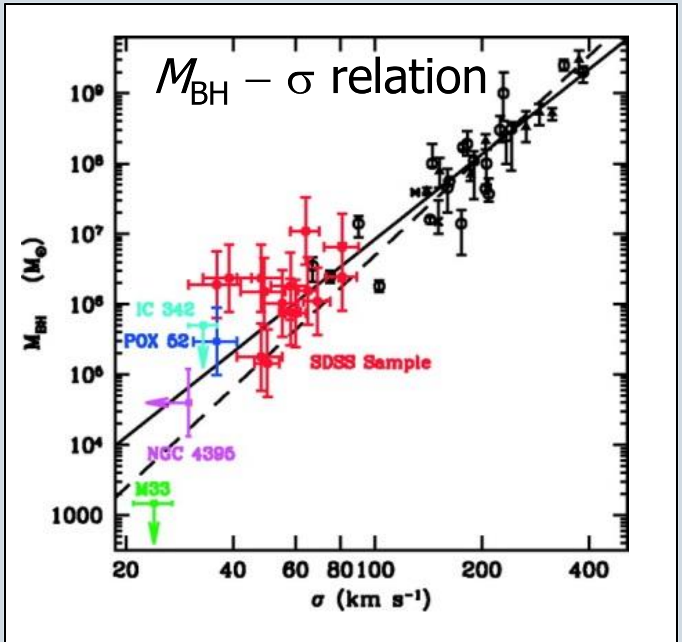
Finding active MBH in the Local Universe





Barth, Greene & Ho (2005)

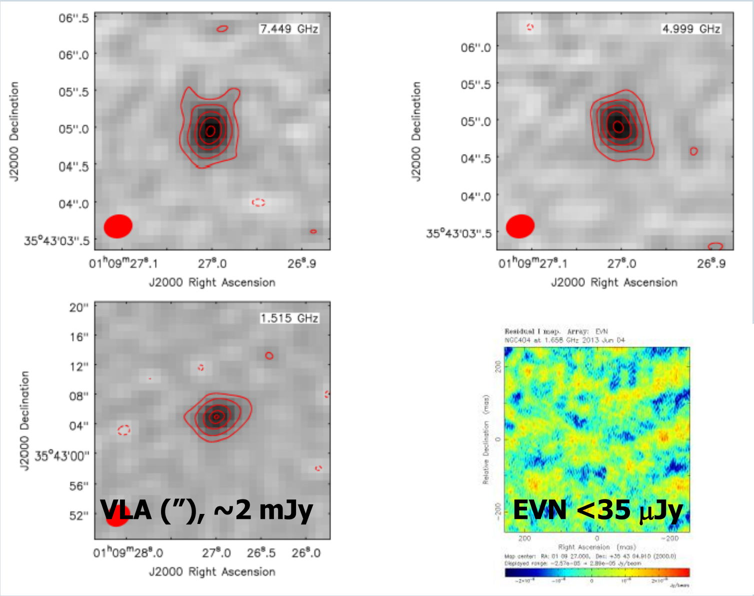
Supermassive BHs in the centre of galaxies

- Important role in host galaxy evolution
- The low-mass population of central SMBHs is little known (MBH, 10^4–10^5 M_{SUN})
- Where are the left-over seed BH required by structure formation models? How do they grow?

- Resolution well below arcsecond is needed to clarify the nature of radio emission in MBH at low accretion rates

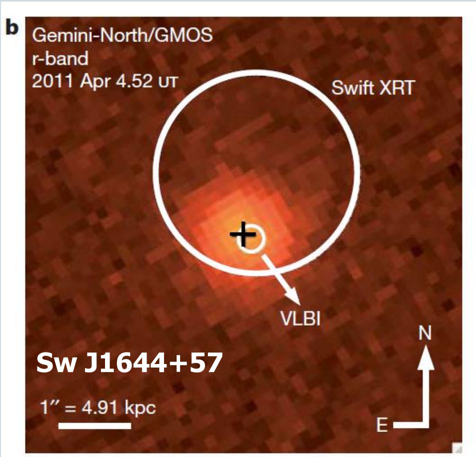
<u>(simultaneous SKA-VLBI and local interferometer data!)</u>

NGC404, 4.5×10^5 M_{SUN}, quiescent, L_{Edd} ~10^{-6}

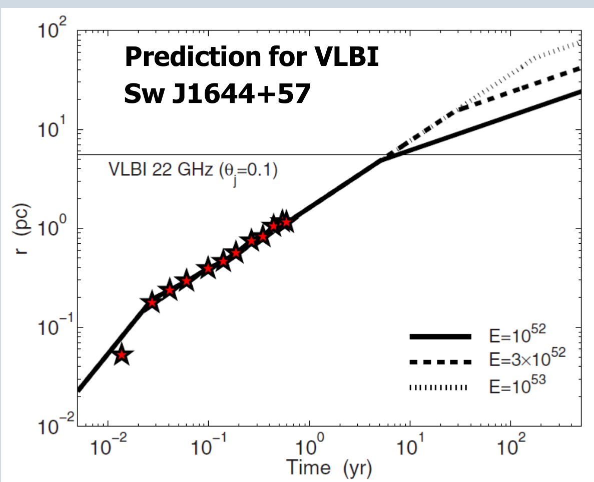


VLA: Nyland et al. (2012); VLBI: Paragi et al., ApJ accepted

Resolving explosive outflows



Zauderer et al. (2011)

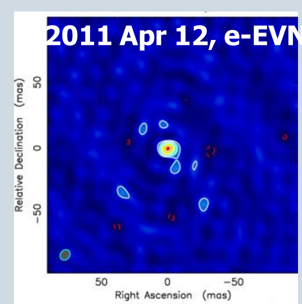


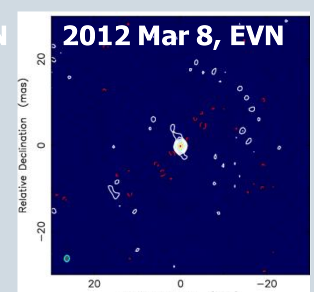
Berger et al. (2012)

Resolving jetted-TDE with SKA-VLBI

- SKA-VLBI will provide superior localization
- Sub-milliarcsecond resolution is needed to measure the source expansion and its deceleration. This will give clues on the "pristine" environment the jet is expanding to.
- SKA-VLBI, – if operating at ~5–8 GHz – will measure accurate sub-mas source sizes down to ~0.1 mJy level which is not possible today.
- SKA-VLBI will routinely provide astrometry accurate at the ≤ 10 μas level to measure jet ejecta proper motions

Right:
In-beam phase-referencing monitoring project, aiming for ~10 μas accuracy, 5 GHz (Jun Yang et al.)

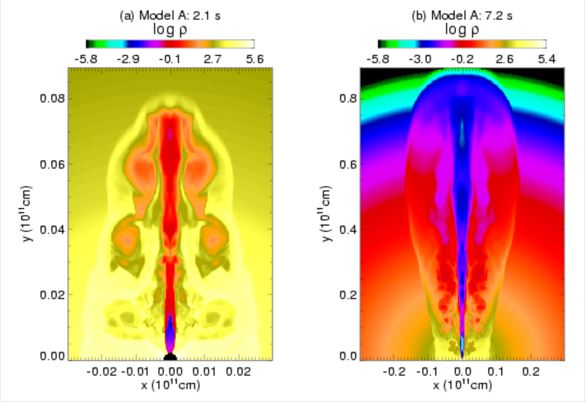




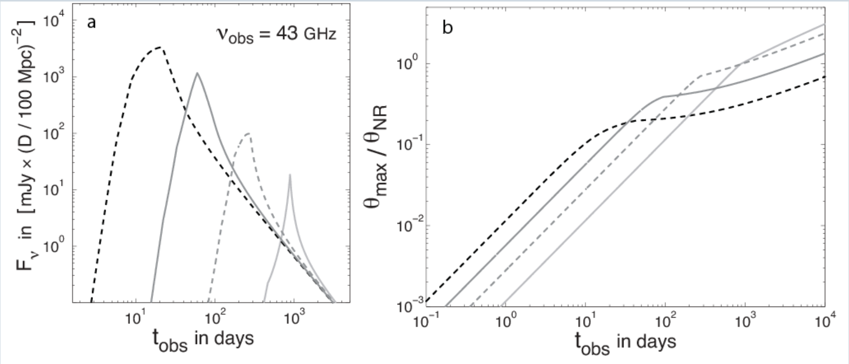
Resolving explosive outflows

Relativistic SNe, long-GRBs

- Death of massive stars: Collapsar model
- VLBI confirmed for only GRB030329 *(Taylor et al. 2004, …)*
- **SKA-VLBI: model independent probe of expansion for all "radio-loud" long-GRBs**

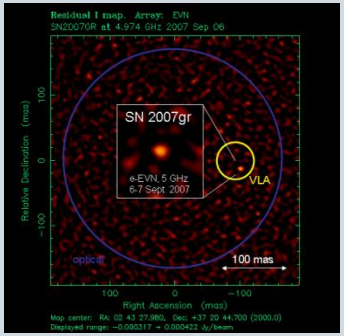


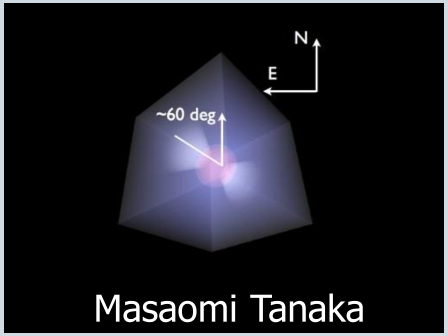
Woosley (1993)
MacFadyan & Woosley (1999)

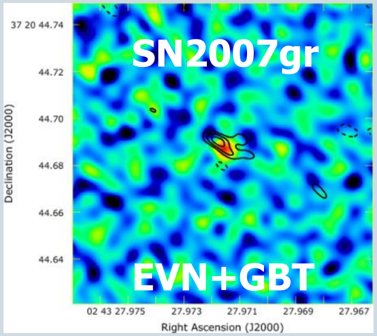


Granot & Loeb (2003)

- Mildly relativistic jets in the more powerful Ib/c SNe – no model-independent evidence yet, in spite of claims by *Paragi et al. (2010)*

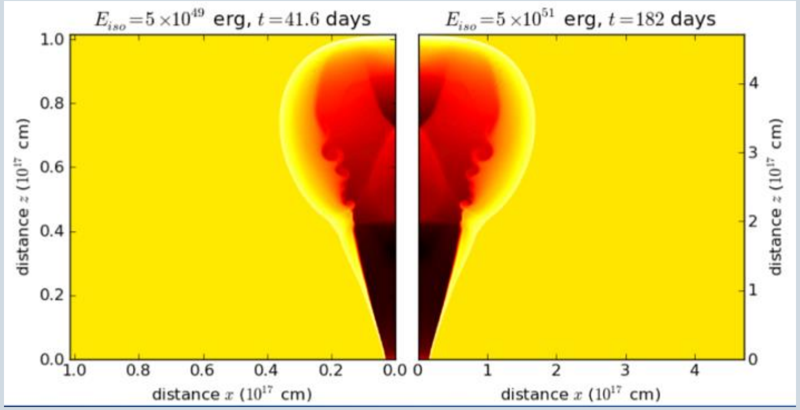






Resolving explosive outflows

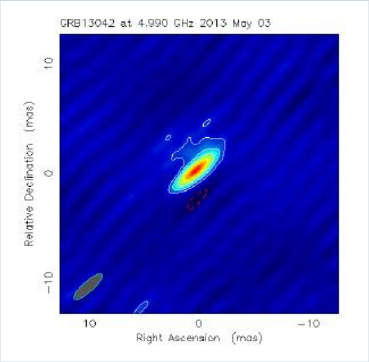
- It is now possible to model flux and size evolution simultaneosly by fitting data directly to simulations (thanks to scale invariance)
- Sensitivity, calibration: significant improvement on source size measurements
- Early observations: constraining expansion while GRB still in the ultra-reletavistic phase?
  – need a flexible array with trigger mechanism!
- SKA1 could start to probe that regime for sources like GRB130427A (in Band 4–5)

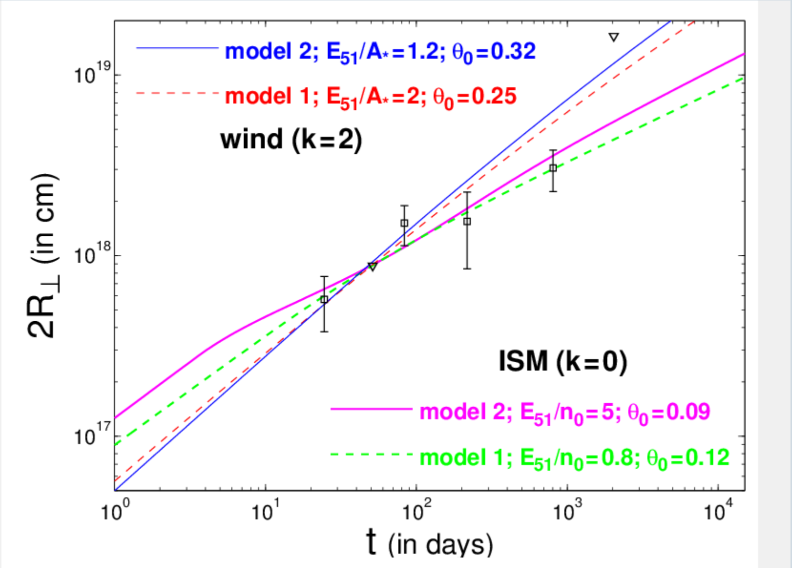


van Eerten, van der Horst & MacFadyen (2012)

e-EVN detection of the highest fluence GRB in 29 years

Paragi et al., ATel, #5242, 2013





Granot & van der Horst (2014)

Conclusions

- SKA-VLBI: broad range of science
- Phase 1:
  i. Sensitive, single-target pointed observations
  ii. Multiple beams & SNR – pushing beyond current astrometry limits (~>3 GHz)
  iii. Some VLBI survey capability
- Full SKA:
  i. Efficient VLBI surveys (~1.4 GHz)
  ii. Truly high resolution science (>>3 GHz)