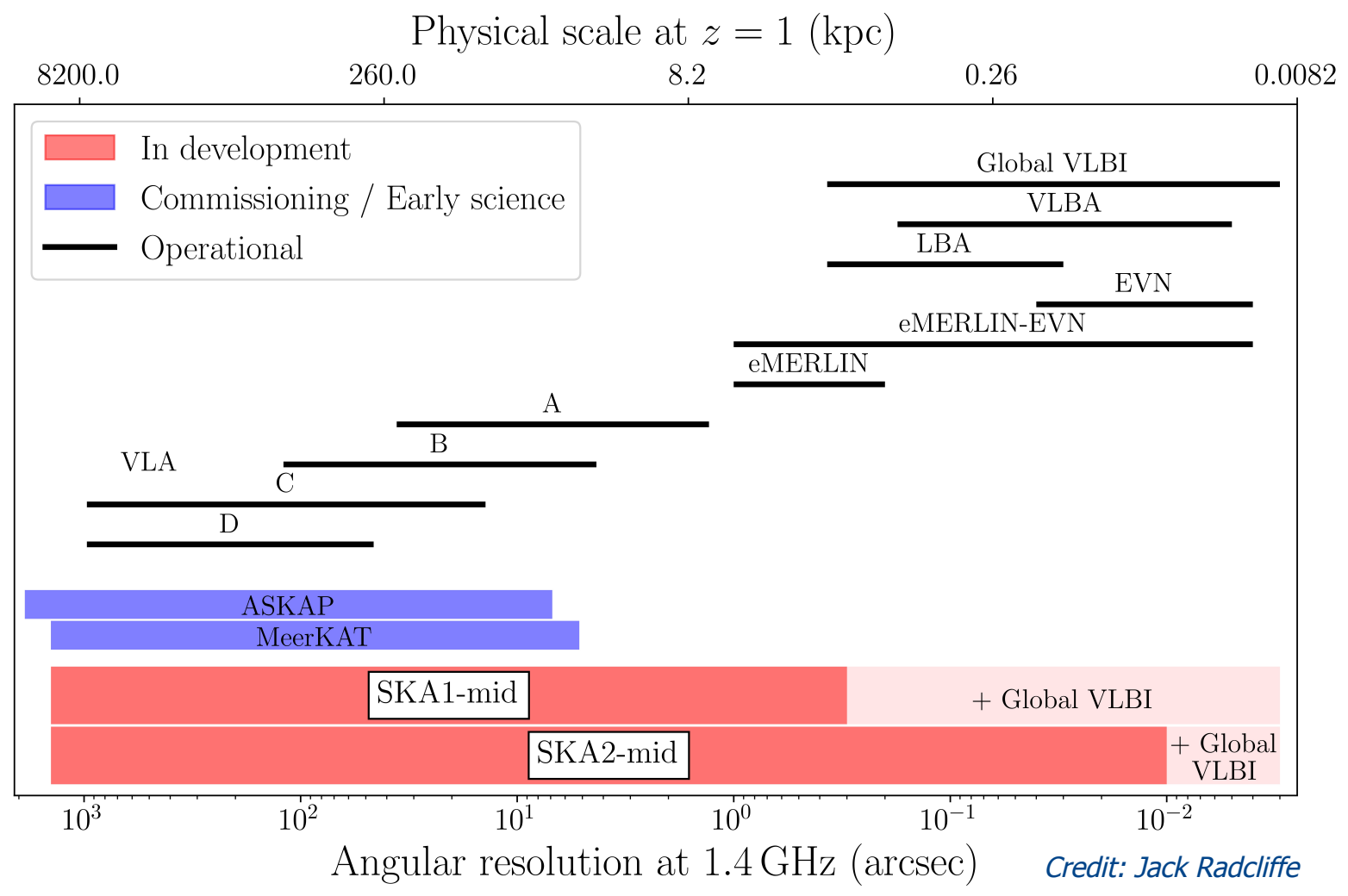
SKA-VLBI Key Science Programmes

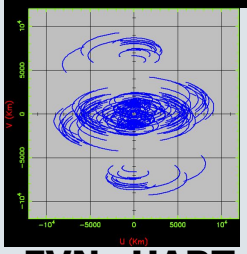
Zsolt Paragi
JIVE

Why VLBI with the SKA?

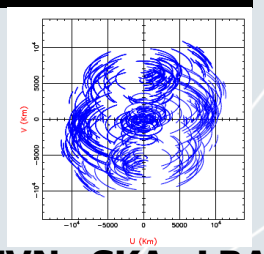


Credit: Jack Radcliffe

Why is SKA-VLBI important?



EVN+HART

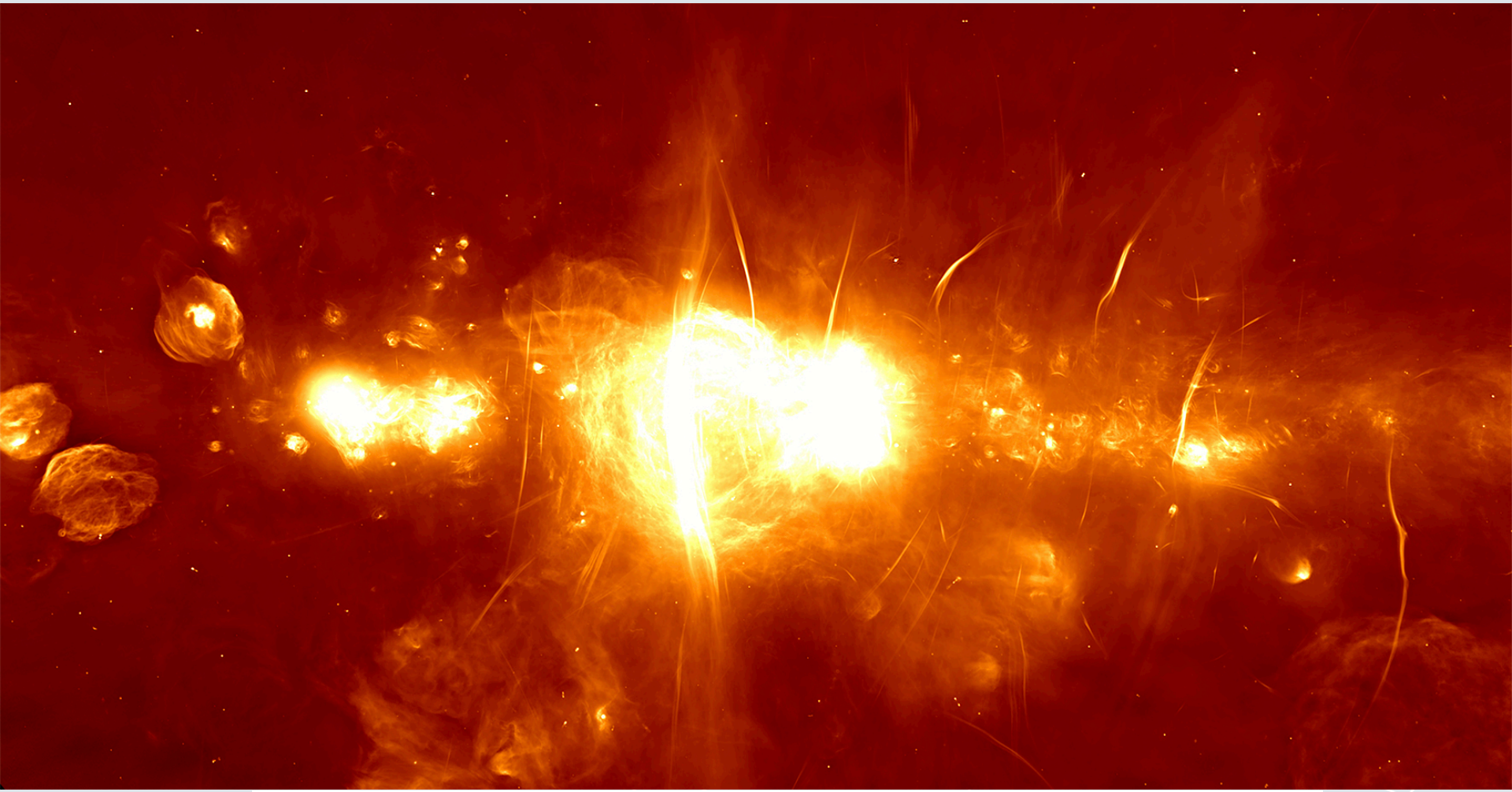


EVN+SKA+LBA

- **Improved imaging capability**
  - GC region of high interest
  - Denser sampling of the "u-v" plane
- **Boost in sensitivity**
  - VLBI Survey of sub-mJy source population (fields of interest)
  - Individual sources in the μJy regime
- **Improved Calibration**
  - Make use of SKA superior amplitude and polarization calibration
  - Multiple beams for VLBI phase calibration over the target region

"Very Long Baseline Interferometry with the SKA", Paragi et al. 2015, SKA Science book

SKA1 will change radio astronomy



- **First publicly released MeerKAT image**
- **Part of SKA1-MID is already here!**

https://www.ska.ac.za

SKA High Priority Science Objectives

Science Goal	SWG	Objective	SWG Rank
1	CD/EoR	Physics of the early universe IGM - I. Imaging	1/3
2	CD/EoR	Physics of the early universe IGM - II. Power spectrum	2/3
3	CD/EoR	Physics of the early universe IGM - III. HI absorption line spectra (21cm forest)	3/3
4	Pulsars	Reveal pulsar population and MSPs for gravity tests and Gravitational Wave detection	1/3
5	Pulsars	High precision timing for testing gravity and GW detection	1/3
6	Pulsars	Characterising the pulsar population	2/3
7	Pulsars	Finding and using (Millisecond) Pulsars in Globular Clusters and External Galaxies	2/3
8	Pulsars	Finding pulsars in the Galactic Centre	2/3
9	Pulsars	Astrometric measurements of pulsars to enable improved tests of GR	2/3
10	Pulsars	Mapping the pulsar beam	3/3
11	Pulsars	Understanding pulsars and their environments through their interactions	3/3
12	Pulsars	Mapping the Galactic Structure	3/3
13	HI	Resolved HI kinematics and morphology of ~10^10 M_sol mass galaxies out to z~0.8	1/5
14	HI	High spatial resolution studies of the ISM in the nearby Universe.	2/5
15	HI	Multi-resolution mapping studies of the ISM in our Galaxy	3/5
16	HI	HI absorption studies out to the highest redshifts.	4/5
17	HI	The gaseous interface and accretion physics between galaxies and the IGM	5/5
18	Transients	Solve missing baryon problem at z~2 and determine the Dark Energy Equation of State	=1/4
19	Transients	Accessing New Physics using Ultra-Luminous Cosmic Explosions	=1/4
20	Transients	Galaxy growth through measurements of Black Hole accretion, growth and feedback	3/4
21	Transients	Detect the Electromagnetic Counterparts to Gravitational Wave Events	4/4
22	Cradle of Life	Map dust grain growth in the terrestrial planet forming zones at a distance of 100 pc	1/5
23	Cradle of Life	Characterise exo-planet magnetic fields and rotational periods	2/5
24	Cradle of Life	Survey all nearby (~100 pc) stars for radio emission from technological civilizations.	3/5
25	Cradle of Life	The detection of pre-biotic molecules in pre-stellar cores at distance of 100 pc.	4/5
26	Cradle of Life	Mapping of the sub-structure and dynamics of nearby clusters using maser emission.	5/5
27	Magnetism	The resolved all-Sky characterisation of the interstellar and intergalactic magnetic fields	1/5
28	Magnetism	Determine origin, maintenance and amplification of magnetic fields at high redshifts - I.	2/5
29	Magnetism	Detection of polarised emission in Cosmic Web filaments	3/5
30	Magnetism	Determine origin, maintenance and amplification of magnetic fields at high redshifts - II.	4/5
31	Magnetism	Intrinsic properties of polarised sources	5/5
32	Cosmology	Constraints on primordial non-Gaussianity and tests of gravity on super-horizon scales.	1/5
33	Cosmology	Angular correlation functions to probe non-Gaussianity and the matter dipole	2/5
34	Cosmology	Map the dark Universe with a completely new kind of weak lensing survey - in the radio.	3/5
35	Cosmology	Dark energy & GR via power spectrum, BAO, redshift-space distortions and topology.	4/5
36	Cosmology	Test dark energy & general relativity with fore-runner of the 'billion galaxy' survey.	5/5
37	Continuum	Measure the Star formation history of the Universe (SFHU) - I. Non-thermal processes	1/8
38	Continuum	Measure the Star formation history of the Universe (SFHU) - II. Thermal processes	2/8
39	Continuum	Probe the role of black holes in galaxy evolution - I.	3/8
40	Continuum	Probe the role of black holes in galaxy evolution - II.	4/8
41	Continuum	Probe cosmic rays and magnetic fields in ICM and cosmic filaments.	5/8
42	Continuum	Study the detailed astrophysics of star-formation and accretion processes - I.	6/8
43	Continuum	Probing dark matter and the high redshift Universe with strong gravitational lensing.	7/8
44	Continuum	Legacy/Serendipity/Rare.	8/8

- **Science working groups are organized around the HPOs identified by the community**

  VLBI WG
  co-chair: Cormac Reynolds (CSIRO)
  co-chair: Zsolt Paragi (JIVE – till end 2017)
  co-chair: An Tao (ShAO – since end 2017)
  office contact: Evan Keane

- **Very high resolution VLBI science is not a single topic, but it is related to several HPOs**

https://astronomers.skatelescope.org/science-working-groups/

Highest-ranked HPSOs and VLBI

	Science Goal	SWG	Objective	SWG Rank	VLBI with:
	1	*CD/EoR*	Physics of the early universe IGM - I. Imaging	1/3	
	2	*CD/EoR*	Physics of the early universe IGM - II. Power spectrum	2/3	
	4	*Pulsars*	Reveal pulsar population and MSPs for gravity tests and Gravitational Wave detection	1/3	
→	5	*Pulsars*	High precision timing for testing gravity and GW detection	1/3	**LOW/MID**
(→)	13	*HI*	Resolved HI kinematics and morphology of ~10^10 M_sol mass galaxies out to z~0.8	1/5	**LOW/MID**
	14	*HI*	High spatial resolution studies of the ISM in the nearby Universe.	2/5	
	15	*HI*	Multi-resolution mapping studies of the ISM in our Galaxy	3/5	
→	18	*Transients*	Solve missing baryon problem at z~2 and determine the Dark Energy Equation of State	=1/4	**MID**
(→)	22	*Cradle of Life*	Map dust grain growth in the terrestrial planet forming zones at a distance of 100 pc	1/5	**MID**
	27	*Magnetism*	The resolved all-Sky characterisation of the interstellar and intergalactic magnetic fields	1/5	
	32	*Cosmology*	Constraints on primordial non-Gaussianity and tests of gravity on super-horizon scales.	1/5	
	33	*Cosmology*	Angular correlation functions to probe non-Gaussianity and the matter dipole	2/5	
→	37 + 38	*Continuum*	Star formation history of the Universe (SFHU) – I+II. Non-thermal & Thermal processes	1+2/8	**MID**

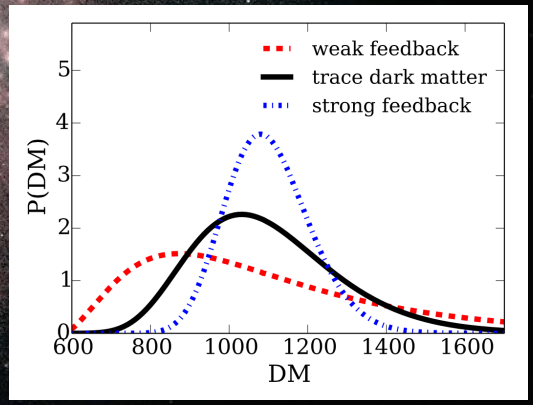
Also note: VLBI science = SKA2 science!

Highlight: Fast Radio Bursts

FRB

The distance must be known: localization!

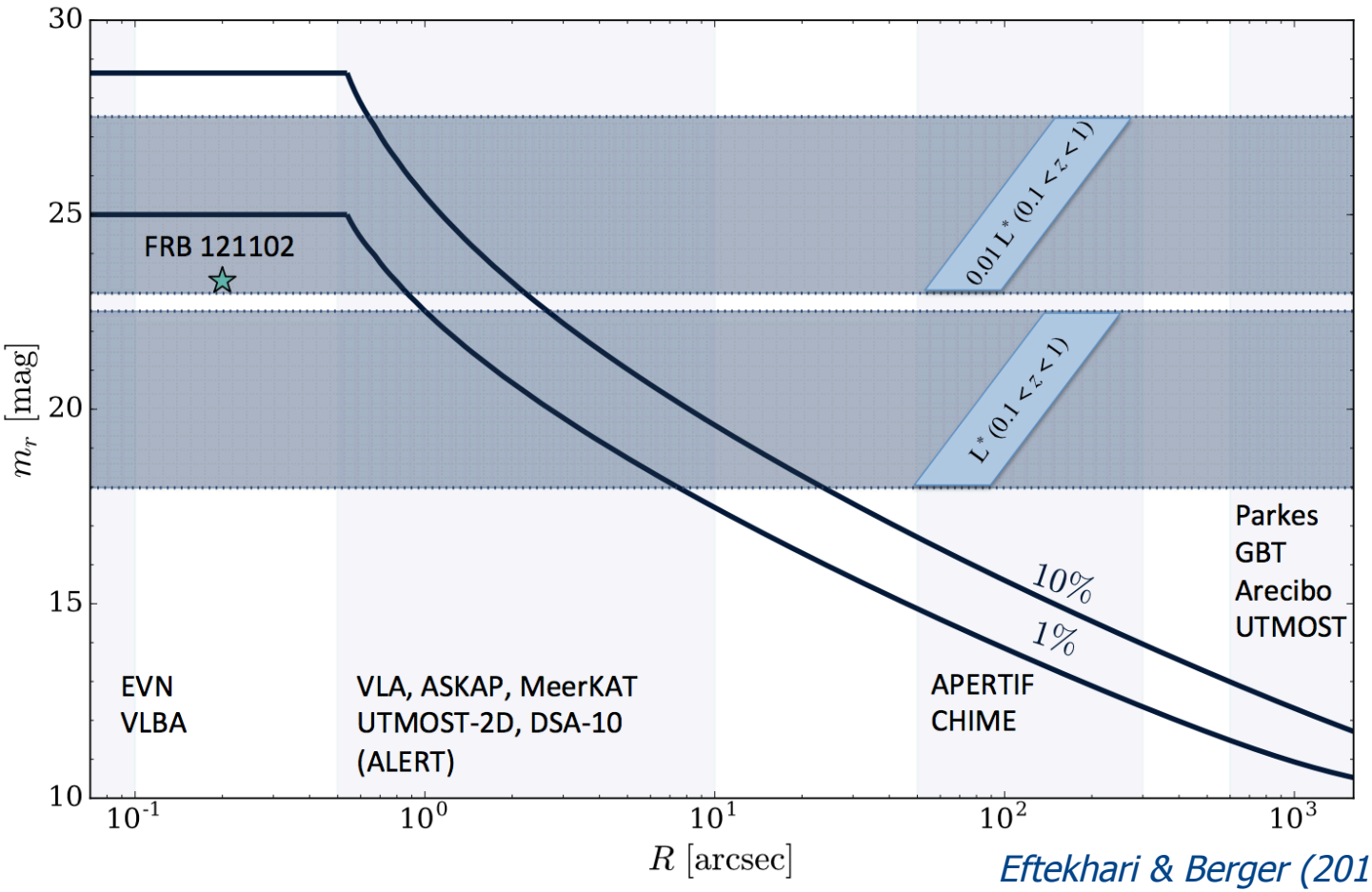
Measurement on Earth



- **A tool to study the cosmic web: the distribution of matter in the Universe**
- **Most of this matter within the galaxies is invisible otherwise**

Bourke, Crain and Duffy

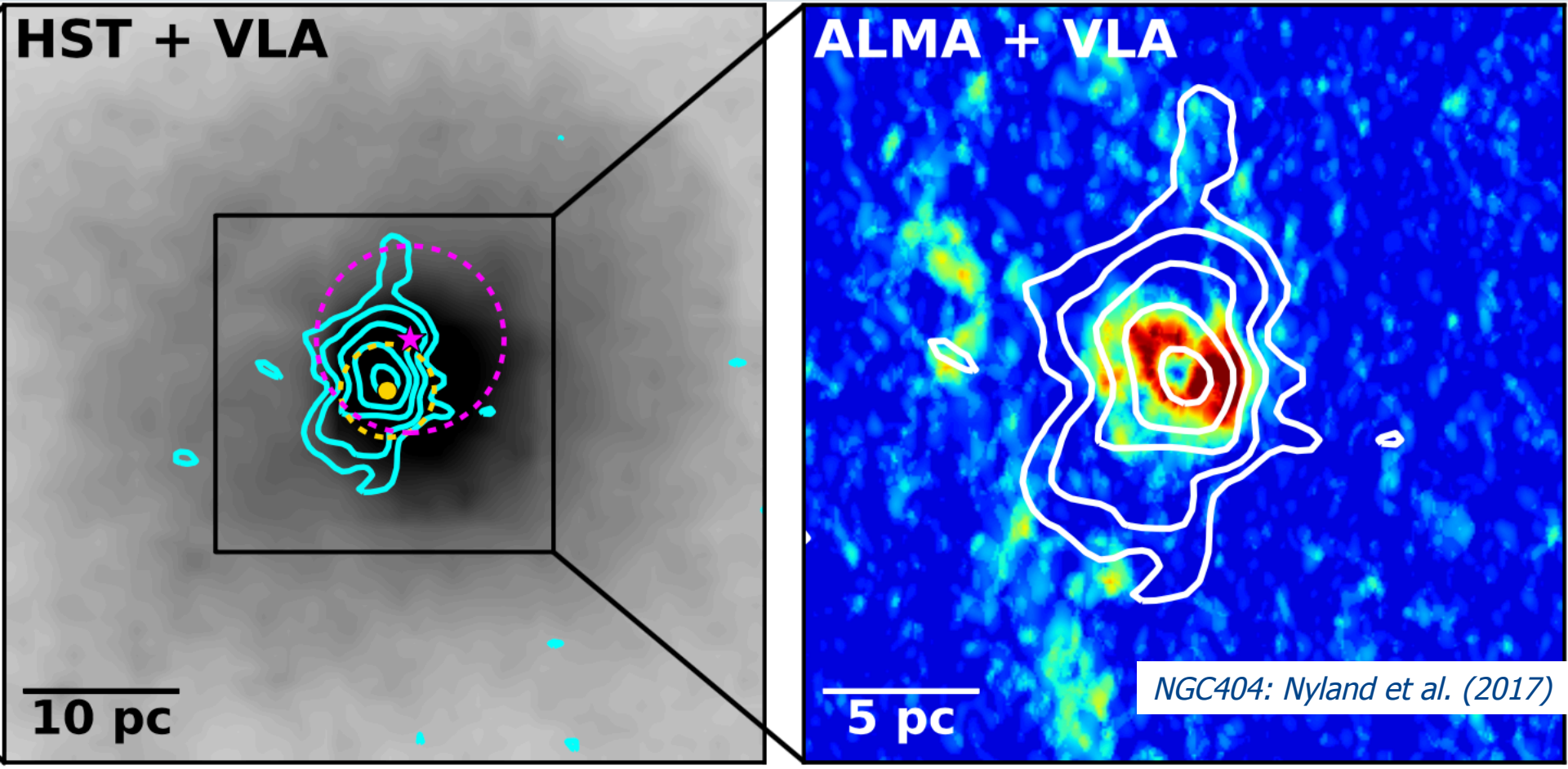
FRBs: sub-arcsec localization is essential!



Eftekhari & Berger (2017)

- **<0.5" localizations are necessary for secure dwarf gx host identifications at *z* >0.1**
- **Progenitor environments (position within host gx) as well as high redshift localizations will require SKA1-MID and VLBI!**

Nucelar activity in dwarf galaxies

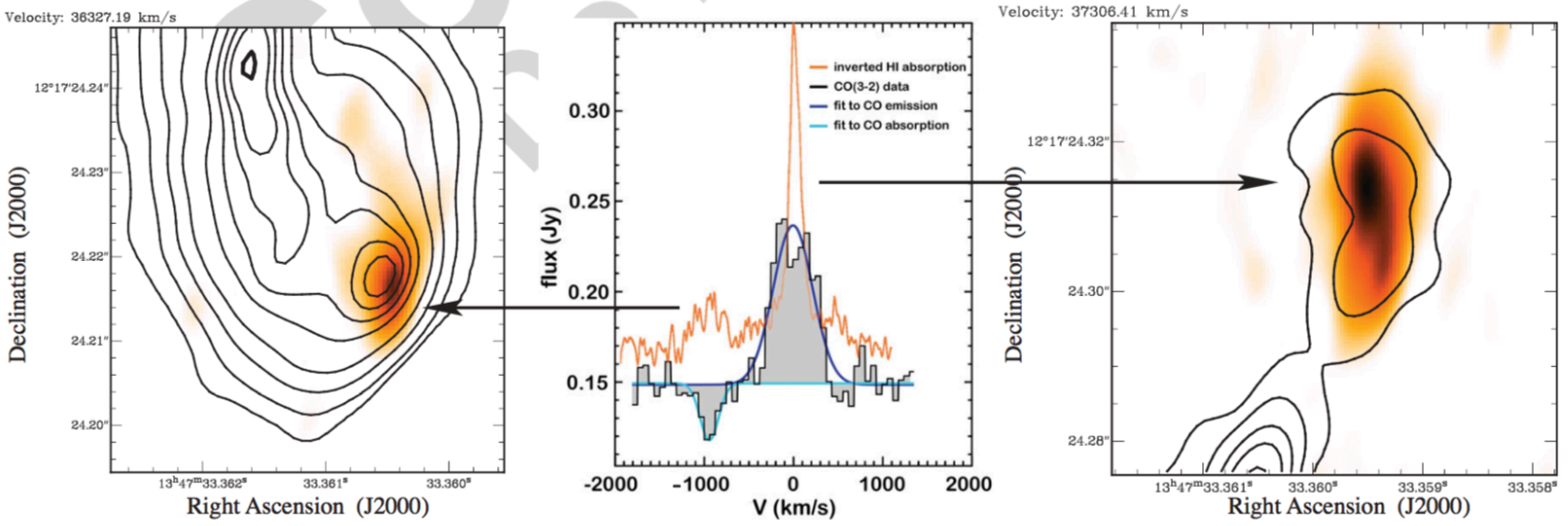


- **Classic AGN/SF indicators do not (always) work in dwarfs/LLAGN…**
  - Requires multi-band approach
  - Requires high frequencies (Band 5) and long baselines for SKA1-MID

HI VLBI: pushing the limits

$N_{HI} = 1.8\times10^{18}\ T_{spin}\ \tau_{peak}\ FWHM_{line}$ (100 K; 0.02-0.05; 100 km/s) ➔ few 10^{20} – 10^{21} cm^{-2} (4.6×10^{21} cm^{-2} in 4C 12.50)

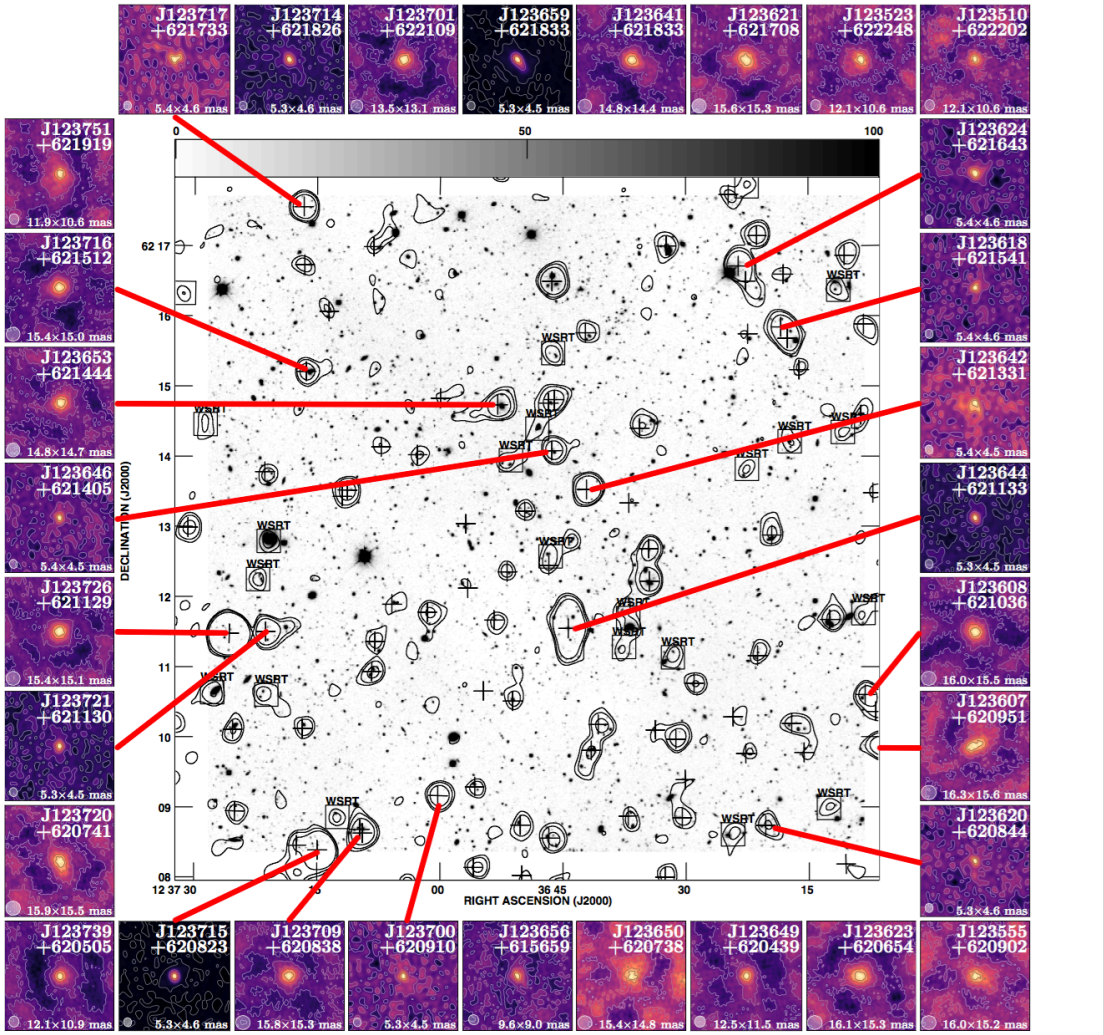
[N_{HI} detection limit using sensitivities of EVN and EVN+FAST or EVN+SKA1-MID]



Young radio source in an ULIRG, 4C12.50 at z=0.1217 Morganti et al., Science, 341, 1082, 2013

- **Need massive increase in collecting area to reach beyond N_{HI} limit of ~10^{20} cm^{-2}**
- **Must improve ν<1.2–1.3 GHz coverage to reach beyond z ~ 0.1–0.2**
- **Use e-MERLIN/MeerKAT/SKA1-MID short spacings to map extended outflows**

Piggybacking on SKA1-MID surveys?



Radcliffe et al. (2018)

- **Besides HI, continuum surveys will reveal a new population of Jy sources**
- **What is the best strategy to very high resolution follow-up?**

Key Science Projects with SKA1

- **Projects that require 1000+h over a few year**
- **What fraction of time will be available for VLBI?**
- **How many hours of support will come from other networks?**
- **Min. 240h/yr EVN & LBA support should be possible, making it >1000h for 5yr duration (KSP domain, but not per science proposals)**
- **African VLBI Network (AVN) may support even more, but only a few telescopes will be there initially – commensal VLBI?**

Discussions Stockholm KSP meeting (2015)

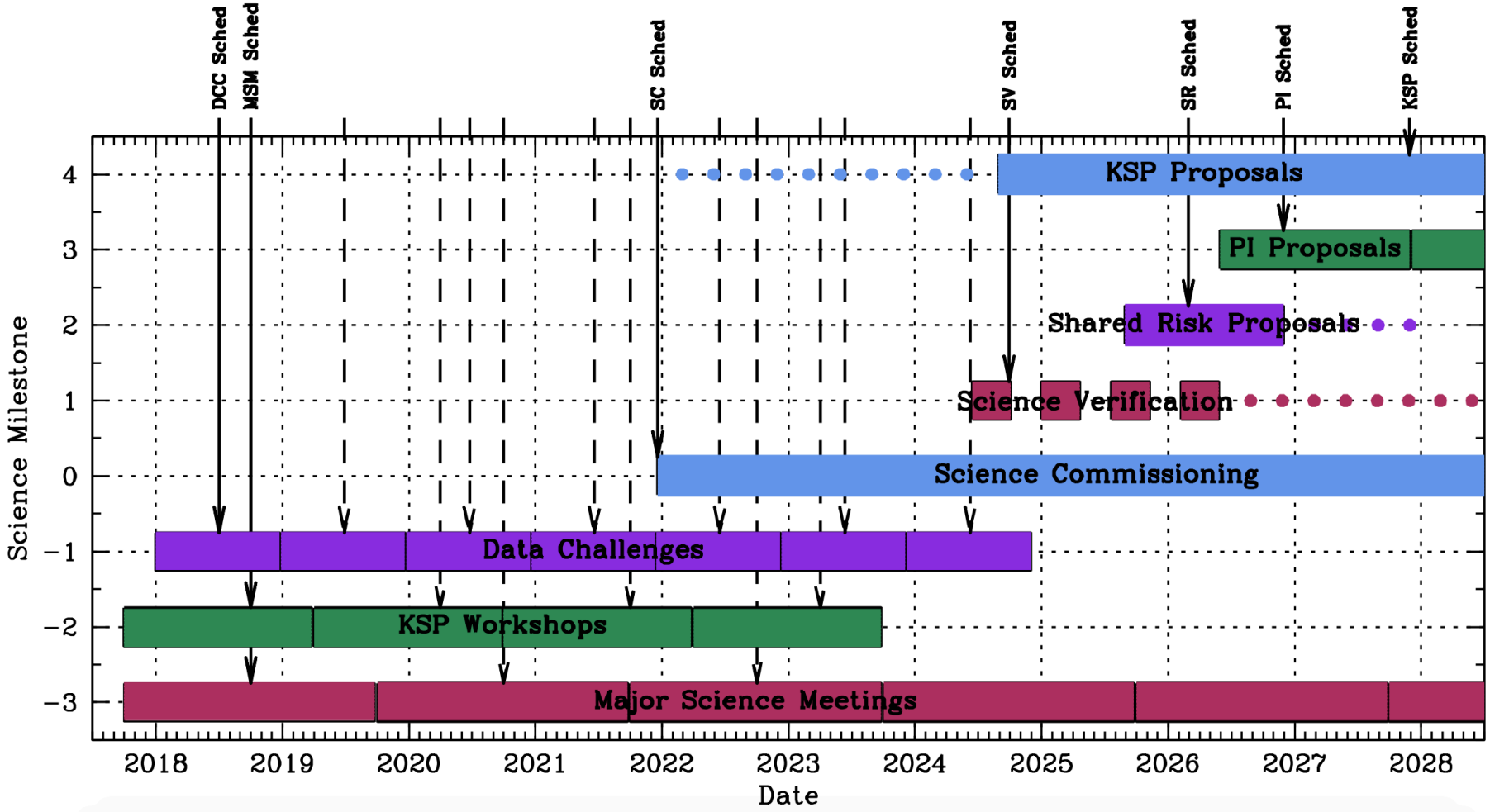
We need an operational model for SKA-VLBI

- **KSPs, GOTs, TOOs, "OOS" (not TOO, but time coordinated with other facilities for multi-band projects), triggered, and commensal observations**
- **Will be part of our KSPs absorbed by other groups of the relevant scientific interest?**
- **What are the outstanding science cases?**

Is commensal VLBI possible?

Band	VLBI + coarse Vis	Imaging	PSS	PST	Zoom
Band 1 (0.35-1.05GHz)	**4b full** (8 FSP)	Full (4 FSP)	1500b 300MHz (8 FSP)	16b (4 FSP)	2 (2 FSP)
	4b 512MHz (6 FSP)	Full (4 FSP)	1500b 300MHz (8 FSP)	16b (4 FSP)	4 (4 FSP)
Band 2 (0.95-1.76GHz)	**4b full** (10 FSP)	Full (5 FSP)	1500b 300MHz (8 FSP)	16b 600 MHz (3 FSP)	⛔
	4b 512MHz (6 FSP)	Full (5 FSP)	1500b 300MHz (8 FSP)	16b (5 FSP)	2 (2 FSP)
Band 5a/b (4.6-8.5 GHz & 8.3-15.3 GHz)	2b 5GHz (26 FSP)	⛔	⛔	⛔	⛔
	4b 2.5GHz (26 FSP)	⛔	⛔	⛔	⛔
	4b 512MHz (6 FSP)	512MHz (3 FSP)	1500b 300MHz (8 FSP)	16b 512 MHz (3 FSP)	6 (6 FSP)

SKA1 Milestones



- Time for brainstorming to start – community must self-organize
- Note there are plans for an Early Production Array – must do VLBI!

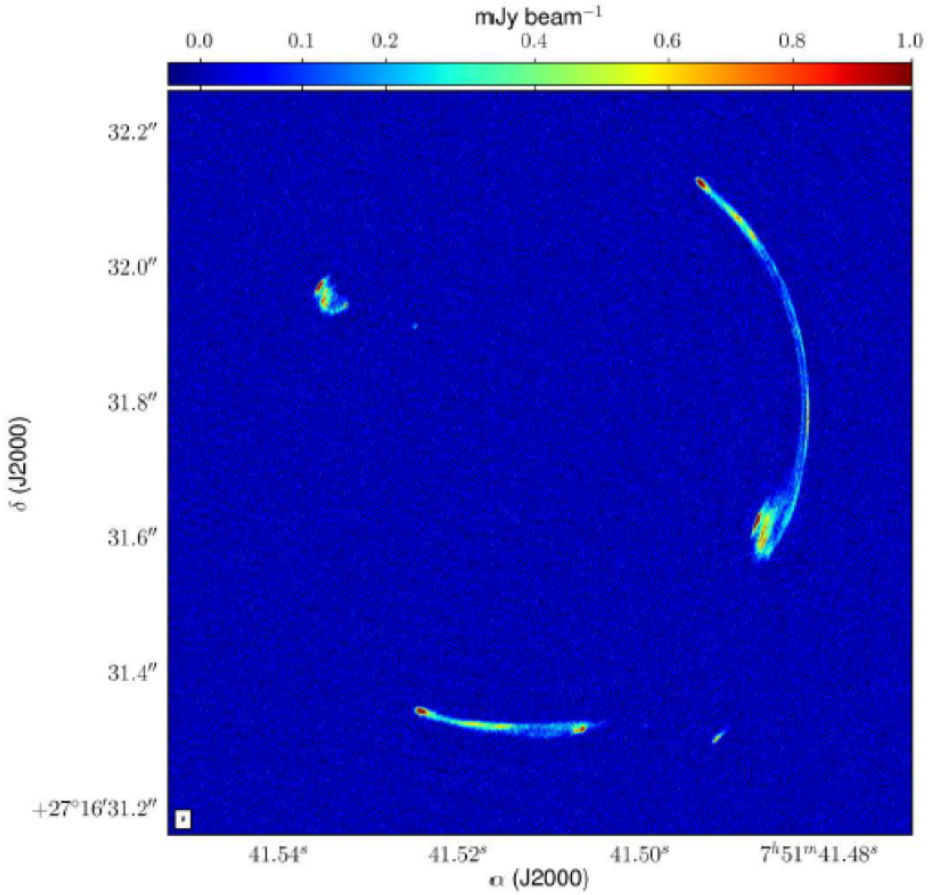
SKA General Science Meeting and Key Science Workshop 2019

VLBI KSP and Operations meeting

- **Location: SKA HQ, Jodrell Bank, fall 2019**
- **JUMPING JIVE WP10 initiative**
- **SOC**
  - Antonio Chrysostomou, Zsolt Paragi (conveners)
  - An Tao (ShAO, CN)
  - … (TBC)
  - Francisco Colomer (JIVE, NL)
  - John Conway (OSO, SE)
  - … (TBC)
  - Roger Deane (Rhodes, SA)
  - Preeti Kharb (NCRA, IN)
  - Mar Mezcua (ICE, SP)
  - Chris Phillips (CSIRO, AU)
  - … (TBC)
  - Kazi Rygl (INAF, IT)
  - … (TBC)
- **LOC**
  - Cristina García-Miró
  - …

End

- **What will you do to make sure there is a bright future for (SKA-)VLBI in the coming 5-10+ years?**



Spingola et al. (2018)