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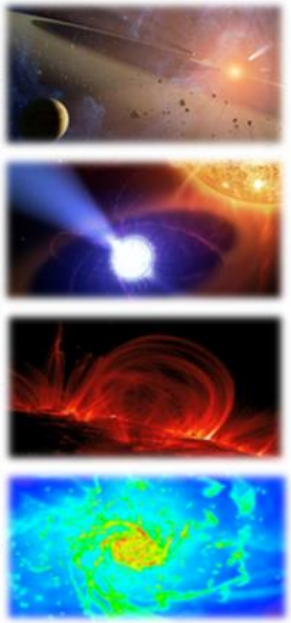
# Extragalactic Science: Role of Radio Facilities

Paul Alexander

# Scope and approach

- Personal View, not Intended to be complete
- Concentrate on e-MERLIN role in SKA experiments explicitly (extragalactic science)

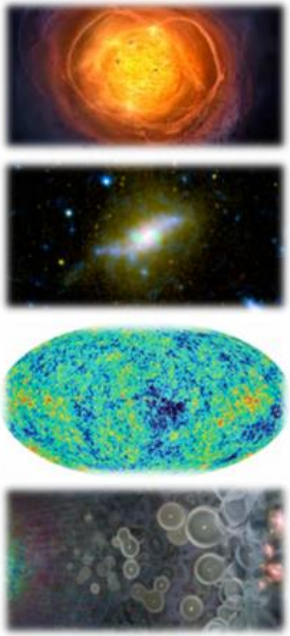
| | SKA1 | SKA2 |
|---|---|---|
| **The Cradle of Life & Astrobiology** | Proto-planetary disks; imaging inside the snow/ice line (@ < 100pc), Searches for amino acids. | Proto-planetary disks; sub-AU imaging (@ < 150 pc), Studies of amino acids. |
| | Targeted SETI: airport radar 10^4 nearby stars. | Ultra-sensitive SETI: airport radar 10^5 nearby star, TV ~10 stars. |
| **Strong-field Tests of Gravity with Pulsars and Black Holes** | 1st detection of nHz-stochastic gravitational wave background. | Gravitational wave astronomy of discrete sources: constraining galaxy evolution, cosmological GWs and cosmic strings. |
| | Discover and use NS-NS and PSR-BH binaries to provide the best tests of gravity theories and General Relativity. | Find all ~40,000 visible pulsars in the Galaxy, use the most relativistic systems to test cosmic censorship and the no-hair theorem. |
| **The Origin and Evolution of Cosmic Magnetism** | The role of magnetism from sub-galactic to Cosmic Web scales, the RM-grid @ 300/deg2. | The origin and amplification of cosmic magnetic fields, the RM-grid @ 5000/deg2. |
| | Faraday tomography of extended sources, 100pc resolution at 14Mpc, 1 kpc @ z ≈ 0.04. | Faraday tomography of extended sources, 100pc resolution at 50Mpc, 1 kpc @ z ≈ 0.13. |
| **Galaxy Evolution probed by Neutral Hydrogen** | Gas properties of 10^7 galaxies, <z> ≈ 0.3, evolution to z ≈ 1, BAO complement to Euclid. | Gas properties of 10^9 galaxies, <z> ≈ 1, evolution to z ≈ 5, world-class precision cosmology. |
| | Detailed interstellar medium of nearby galaxies (3 Mpc) at 50pc resolution, diffuse IGM down to N_H < 10^17 at 1 kpc. | Detailed interstellar medium of nearby galaxies (10 Mpc) at 50pc resolution, diffuse IGM down to N_H < 10^17 at 1 kpc. |



# Scope and approach

- Personal View, not Intended to be complete
- Concentrate on e-MERLIN role in SKA experiments explicitly (extragalactic science)

| | SKA1 | SKA2 |
|---|---|---|
| **The Transient Radio Sky** | Use fast radio bursts to uncover the missing "normal" matter in the universe. | Fast radio bursts as unique probes of fundamental cosmological parameters and intergalactic magnetic fields. |
| | Study feedback from the most energetic cosmic explosions and the disruption of stars by super-massive black holes. | Exploring the unknown: new exotic astrophysical phenomena in discovery phase space. |
| **Galaxy Evolution probed in the Radio Continuum** | Star formation rates (10 M_Sun/yr to z ~ 4). | Star formation rates (10 M_Sun/yr to z ~ 10). |
| | Resolved star formation astrophysics (sub-kpc active regions at z ~ 1). | Resolved star formation astrophysics (sub-kpc active regions at z ~ 6). |
| **Cosmology & Dark Energy** | Constraints on DE, modified gravity, the distribution & evolution of matter on super-horizon scales: competitive to Euclid. | Constraints on DE, modified gravity, the distribution & evolution of matter on super-horizon scales: redefines state-of-art. |
| | Primordial non-Gaussianity and the matter dipole: 2x Euclid. | Primordial non-Gaussianity and the matter dipole: 10x Euclid. |
| **Cosmic Dawn and the Epoch of Reionization** | Direct imaging of EoR structures (z = 6 - 12). | Direct imaging of Cosmic Dawn structures (z = 12 - 30). |
| | Power spectra of Cosmic Dawn down to arcmin scales, possible imaging at 10 arcmin. | First glimpse of the Dark Ages (z > 30). |



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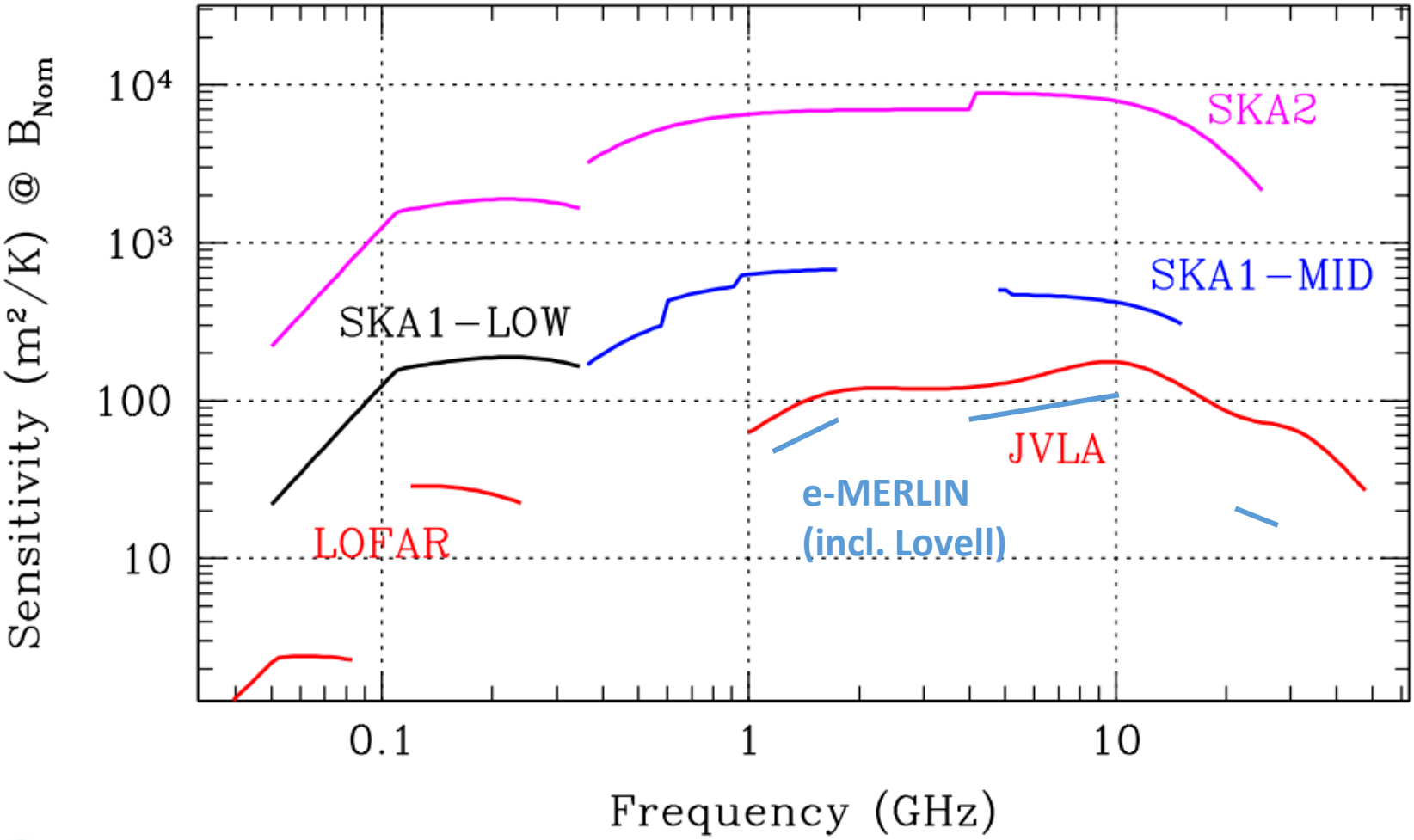
# Consider E-MERLIN Science roles in these SKA Science Areas

- Magnetic Universe
- Galaxy Evolution
  - Star Formation history **[eMerge]**
  - Star Formation and accretion in detail **[Lemmings, LIRGI]**
  - Feedback **[LIRGI, eMerge, AGATE]**
- AGN Physics **[Extragalactic Jets]**
- Transient / Changing Universe
  - Detailed observations on detected objects
- Cosmology
  - Weak and strong lensing **[Gravitational Lensing, SuperCLASS]**
  - Variation in fundamental constants
  - First galaxies

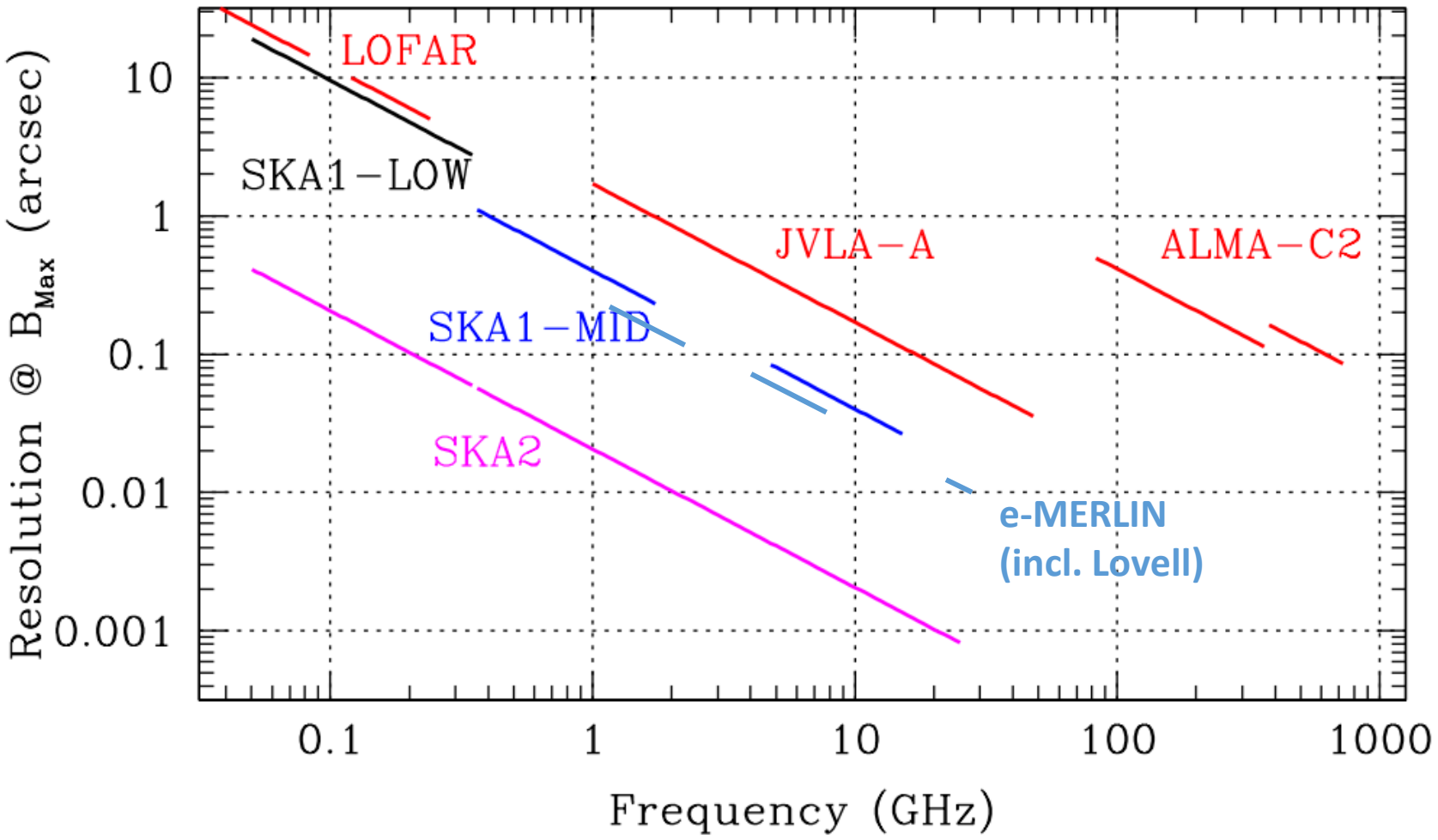
# Facility Comparison to SKA

| Parameters for Comparable Telescopes | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | eMERLIN | JVLA | GBT | GMRT | Parkes MB | LOFAR | FAST | MeerKAT | WSRT | Arecibo | ASKAP | SKA1-low | SKA-mid |
| $A_{eff}/T_{sys}$ | $m^2/K$ | 60 | 265 | 276 | 250 | 100 | 61 | 1250 | 321 | 124 | 1150 | 65 | 559 | 1560 |
| FoV | $deg^2$ | 0.25 | 0.25 | 0.015 | 0.13 | 0.65 | 14 | 0.0017 | 0.86 | 0.25 | 0.003 | 30 | 20.77 | 0.49 |
| Receptor Size | m | 25 | 25 | 101 | 45 | 64 | 39 | 300 | 13.5 | 25 | 225 | 12 | 35 | 15 |
| Fiducial frequency | GHz | 1.4 | 1.4 | 1.4 | 1.4 | 1.4 | 0.12 | 1.4 | 1.4 | 1.4 | 1.4 | 1.4 | 0.11 | 1.67 |
| Survey Speed FoM | $deg^2\ m^4\ K^{-2}$ | $9.00\times10^2$ | $1.76\times10^4$ | $1.14\times10^3$ | $8.13\times10^3$ | $6.50\times10^3$ | $5.21\times10^4$ | $2.66\times10^3$ | $8.86\times10^4$ | $3.84\times10^3$ | $3.97\times10^3$ | $1.27\times10^5$ | $6.49\times10^6$ | $1.19\times10^6$ |
| Resolution | arcsec | $10\text{-}150 \times 10^{-3}$ | 1.4 - 44 | 420 | 2 | 660 | 5 | 88 | 11 | 16 | 192 | 7 | 7 | 0.25 |
| Baseline or Size | km | 217 | 1 - 35 | 0.1 | 27 | 0.064 | 100 | 0.5 | 4 | 2.7 | 225 | 6 | 80 | 150 |
| Frequency Range | GHz | 1.3-1.8, 4-8, 22-24 | 1 - 50 | 0.2 - 50+ | 0.15, 0.23, 0.33, 0.61, 1.4 | 0.44 to 24 | 0.03 – 0.22 | 0.1 – 3 | 0.7 - 2.5, 0.7 - 10 | 0.3 – 8.6 | 0.3 - 10 | 0.7-1.8 | 0.050 – 0.350 | 0.35-14 |
| Bandwidth | MHz | 400 | 1000 | 400 | 450 | 400 | 4 | 800 | 1000 | 160 | 1000 | 300 | 300 | 770 |
| Cont. Sensitivity | $\mu Jy\text{-}hr^{-1/2}$ | 27.11 | 3.88 | 5.89 | 6.13 | 16.26 | 266.61 | 0.92 | 3.20 | 20.74 | 0.89 | 28.89 | 3.36 | 0.75 |
| Sensitivity, 100 kHz | $\mu Jy\text{-}hr^{-1/2}$ | 1714 | 388 | 373 | 411 | 1029 | 1686 | 82 | 320 | 830 | 89 | 1582 | 184 | 66 |
| SEFD | Jy | 46.0 | 10.4 | 10.0 | 11.0 | 27.6 | 45.2 | 2.2 | 8.6 | 22.3 | 2.4 | 42.5 | 4.9 | 1.8 |

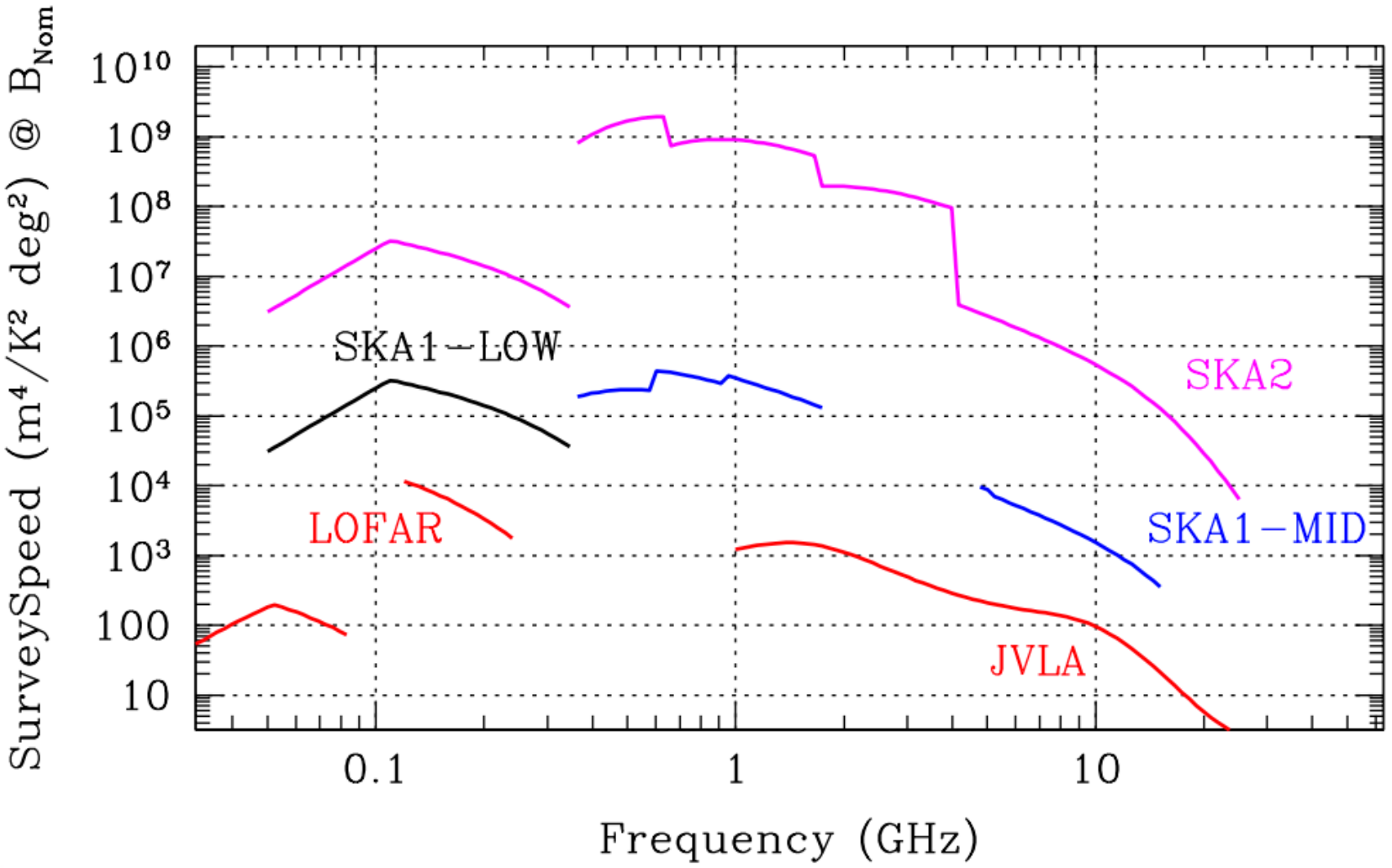
# Basic Comparison: Sensitivity



# Basic Comparison: Resolution



# Basic Comparison: Survey Speed



# SKA High Priority Science

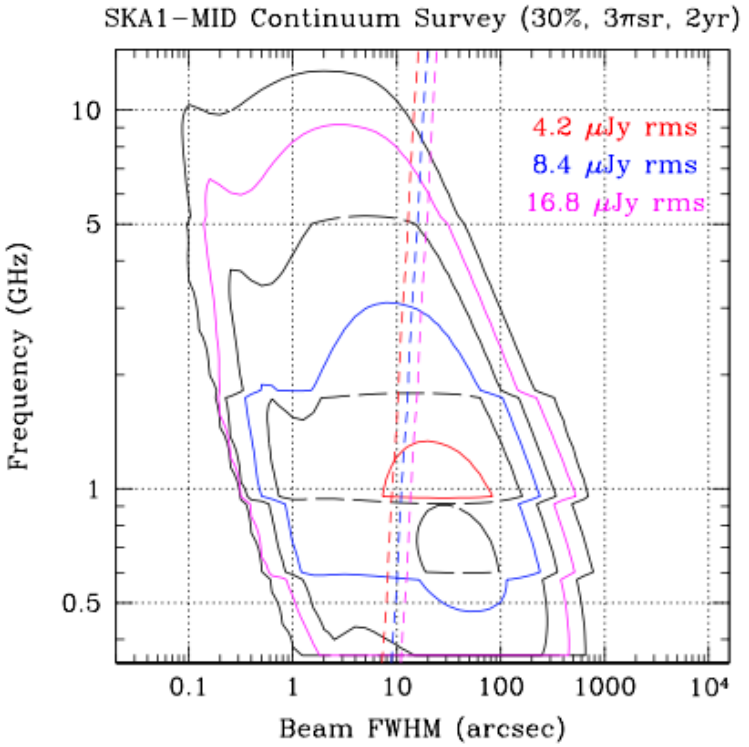
| SWG | Objective |
|---|---|
| *CD/EoR* | Physics of the early universe IGM - I. Imaging |
| *CD/EoR* | Physics of the early universe IGM - II. Power spectrum |
| *Pulsars* | Reveal pulsar population and MSPs for gravity tests and Gravitational Wave detection |
| *Pulsars* | High precision timing for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

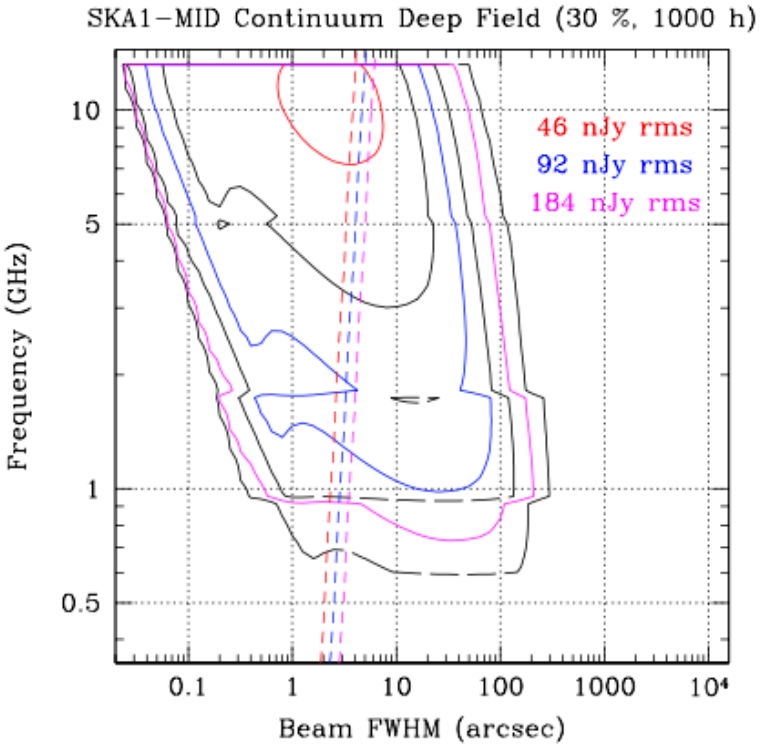
- Relevant Question is how deep are these surveys and how important is e-MERLIN for complementary observations?

- **Assertion: e-MERLIN will provide a unique and powerful followup / complimentary instrument for SKA1**

- Consider e-MERLIN in (my view) best mode – full synthesis imaging with Lovell in L- and C- band
- Incl. Lovell similar sensitivity to JVLA in full synthesis and e-MERLIN sensitivity within a factor of 4 of limiting sensitivity of wide area surveys
- Should consider SKA+e-MERLIN science (survey detailed imaging)

# More relevant consideration




E-MERLIN imaging sensitivity with Lovell, full synthesis:

L-band 5-6 μJy/Beam
C-band 1.8 – 2.3 μJy/Beam

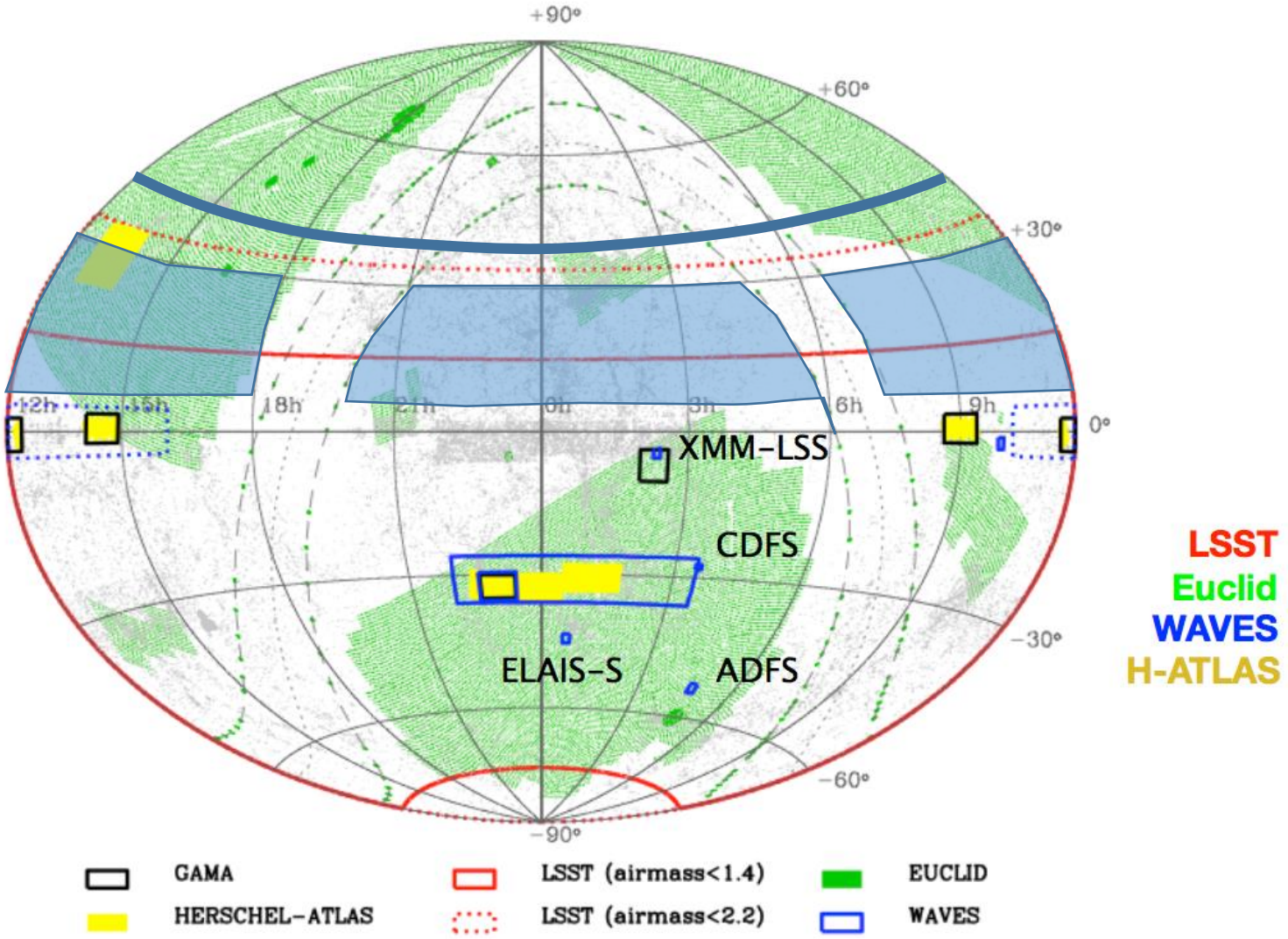
Comparable to survey depth for wide area survey

# SKA: High Priority Science

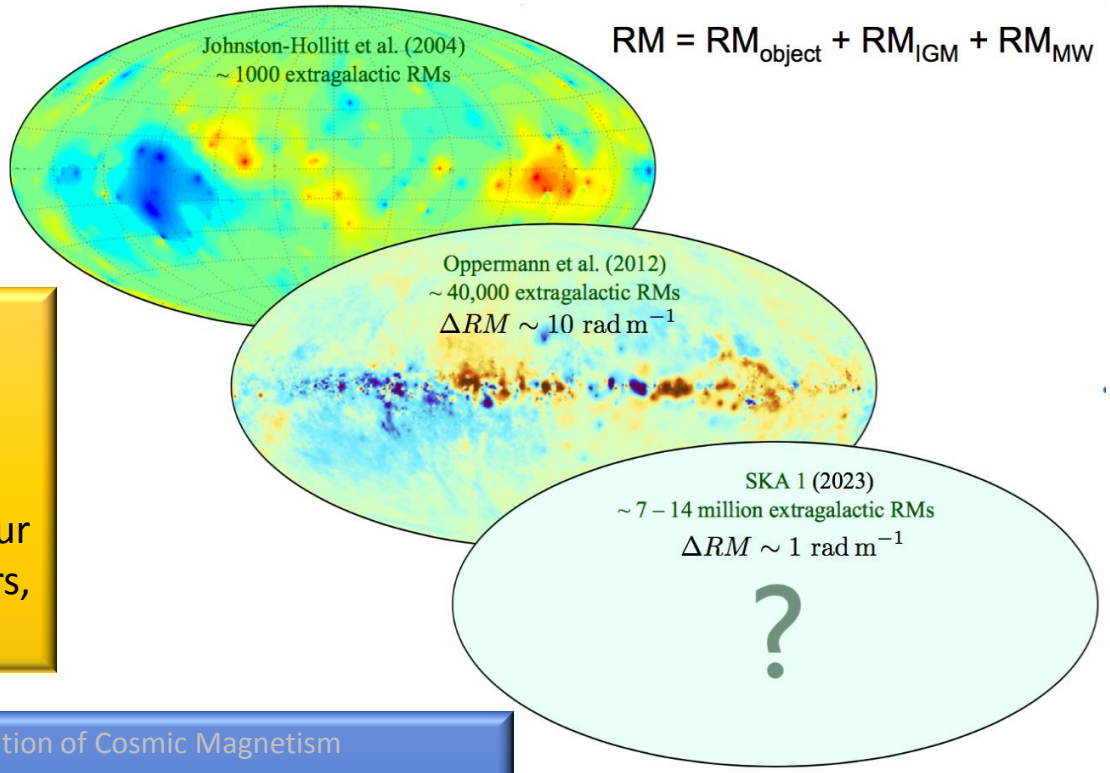
| Science Objective | SWG | High Priority Science Objective Number | SKA1 Component | Band | Mode | Frequency | | | Sensitivity | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Range Low - High | Resolution Initial:Cal:Final | Spectral Dynamic Range (I_max/ I_min) | RMS Noise Min:Max @ Beam @ Bandwidth | Brightness Dynamic Range (I_max/ I_min) | Polarisation Dynamic Range (I_max/ P_min ) |
| EoR - Imaging AASKA14:001 | CD/EoR | 1 | SKA1-LOW | N/A | Imaging | 50 - 200 MHz | 4:4:1000 kHz | 50 dB | 1.4:100 mK @ 300 arcsec @ 1 MHz | 50 dB | 45 dB |
| EoR - Power Spectra AASKA14:001 | CD/EoR | 2 | SKA1-LOW | N/A | imaging/Power Spectrum | 50 - 200 MHz | 4:4:1000 kHz | 50 dB | 4.6:330 mK @ 300 arcsec @ 1 MHz | 50 dB | 40 dB |
| | | | SKA1-LOW | N/A | imaging/Power Spectrum | 50 - 200 MHz | 4:4:1000 kHz | 50 dB | 14:1000 mK @ 300 arcsec @ 1 MHz | 50 dB | 35 dB |
| Pulsar Searching AASKA14:040 | Pulsars | 4 | SKA1-LOW | N/A | Non-Imaging | 150 - 350 MHz | 20:20:75 kHz | 30 dB | 20 μJy/Beam @ 145 arcsec Cont | 30 dB | 25 dB |
| | | | SKA1-MID | SPF1 | Non-Imaging | 650 - 950 MHz | 20:20:75 kHz | 30 dB | 13 μJy/Beam @ 65 arcsec Cont | 30 dB | 25 dB |
| | | | SKA1-MID | SPF2 | Non-Imaging | 1250 - 1550 MHz | 20:20:75 kHz | 30 dB | 7 μJy/Beam @ 45 arcsec Cont | 30 dB | 25 dB |
| Pulsar Timing AASKA14:037 | Pulsars | 5 | SKA1-LOW | N/A | Non-Imaging | 150 - 350 MHz | 20:20:75 kHz | 30 dB | 10 μJy/Beam @ 8 arcsec Cont | 30 dB | 40 dB |
| | | | SKA1-MID | SPF2 | Non-Imaging | 950 - 1760 MHz | 20:20:75 kHz | 30 dB | 3 μJy/Beam @ 7 arcsec Cont | 30 dB | 40 dB |
| HI - High z AASKA14:128 | HI | 13 | SKA1-MID | SPF1 | Imaging | 790 - 950 MHz | 4:50 kHz | 30 dB | 16 μJy/Beam @2-10 arcsec Line | 50 dB | 35 dB |
| HI - Low z AASKA14:129 | HI | 14 | SKA1-MID | SPF2 | Imaging | 1300 - 1400 MHz | 4:15:20 kHz | 30 dB | 14 μJy/Beam @2-10 arcsec Line | 50 dB | 30 dB |
| HI - Galaxy AASKA14:130 | HI | 15 | SKA1-MID | SPF2 | Imaging | 1415 - 1425 MHz | 0.5:4 kHz | 30 dB | 75 μJy/Beam @2-10 arcsec Line | 45 dB | 30 dB |
| Transients - FRB AASKA14:055 | Transients | 18 | SKA1-MID | SPF1 | Non-imaging/ Commensal | 650 - 950 MHz | 20:20:75 kHz | 30 dB | 7 mJy/Beam @ 65 arcsec Cont | 30 dB | 25 dB |
| CoL - Planet formation AASKA14:117 | Cradle of Life | 22 | SKA1-MID | SPF5 | Imaging | 8 - 12 GHz | 80:80:4000 kHz | 30 dB | 80 nJy/Beam @ 0.04 arcsec Cont | 40 dB | 25 dB |
| Magnetism - RM-grid AASKA14:092 | Magnetism | 27 | SKA1-MID | SPF2 | Imaging | 1000 - 1700 MHz | 10:1000 kHz | 30 dB | 7 μJy/Beam @ 2 arcsec Cont | 45 dB | 30 dB |
| Cosmology - High z IM AASKA14:019 | Cosmology | 32 | SKA1-MID | SPF1 | Auto-correlations | 350 - 1050 MHz | 10:300 kHz | 45 dB | 3.3 mJy/Beam @ 1.7 deg Line | 40 dB | 40 dB |
| Cosmology - ISW, Dipole AASKA14:018, 032 | Cosmology | 33 | SKA1-MID | SPF2 | Imaging | 1000 - 1700 MHz | 10:1000 kHz | 30 dB | 7 μJy/Beam @ 2 arcsec Cont | 45 dB | 30 dB |
| Continuum - SFR(z) AASKA14:067 | Continuum | 37 + 38 | SKA1-MID | SPF2 | Imaging | 1000 - 1700 MHz | 10:1000 kHz | 30 dB | 1.3 μJy/Beam @ 0.5 arcsec Cont | 60 dB | 30 dB |
| | | | SKA1-MID | SPF2 | Imaging | 1000 - 1700 MHz | 10:10:1000 kHz | 30 dB | 0.25 μJy/Beam @ 0.5 arcsec Cont | 60 dB | 30 dB |
| | | | SKA1-MID | SPF2 | Imaging | 1000 - 1700 MHz | 10:10:1000 kHz | 30 dB | 65 nJy/Beam @ 0.5 arcsec Cont | 60 dB | 30 dB |
| | | | SKA1-MID | SPF5 | Imaging | 7 - 11 GHz | 80:80:4000 kHz | 25 dB | 400 nJy/Beam @ 0.05 arcsec Cont | 45 dB | 30 dB |
| | | | SKA1-MID | SPF5 | Imaging | 7 - 11 GHz | 80:80:4000 kHz | 25 dB | 50 nJy/Beam @ 0.05 arcsec Cont | 45 dB | 30 dB |
| L0 Requirements | | | 001, 002, 004, 005 | | 047, 048, 049, 050, 051, 052 | 024, 025, 026, 028 | 026, 028 | 022, 023 | 003, 006, 007, 008, 009, 010, 011, 012, 013, 014, 015, 033, 034, 035, 036, 037, 038, 043, 044, 045, 046 | 018, 019, 039, 040, 041, 042 | 020, 021 |

| Science Objective | SWG | High Priority Science Objective Number | Observing Area | | | | | Integration | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Total Area | Area of Single Pointing/ Beam | Angular Resolution Min:Max | Targets/ Beams | Tracking | Total | Per Pointing | Dump Rate / Temporal Resolution | Epochs | Cadence Min:Max | # Sessions per Interval | Time per Session |
| EoR - Imaging AASKA14:001 | CD/EoR | 1 | 100 deg2 | 20 deg2 | 10:1000 arcsec | 5 Fields/ 2 StationBeams | Sidereal | 5000 hr | 2000 hr | 0.4 s | | | 1000 | 5 hr |
| EoR - Power Spectra AASKA14:001 | CD/EoR | 2 | 1000 deg2 | 20 deg2 | 10:1000 arcsec | 50 Fields/ 2 StationBeams | Sidereal | 5000 hr | 200 hr | 0.4 s | | | 1000 | 5 hr |
| | | | 10000 deg2 | 20 deg2 | 10:1000 arcsec | 500 Fields/ 2 StationBeams | Drift | 5000 hr | 20 hr | 0.4 s | | | 1000 | 5 hr |
| Pulsar Searching AASKA14:040 | Pulsars | 4 | 30000 deg2 | 11.3 arcmin2 | 320 arcsec | 1 Target/ 500 Tied-Array Beams | Sidereal | 12750 hr | 40 mn | 50 μs | | | 3200 | 4 hr |
| | | | 2400 deg2 | 1.2 arcmin2 | 105 arcsec | 1 Target/ 1500 Tied-Array Beams | Sidereal | 800 hr | 10 mn | 50 μs | | | 100 | 8 hr |
| | | | 2400 deg2 | 0.39 arcmin2 | 60 arcsec | 1 Target/ 1500 Tied-Array Beams | Sidereal | 2400 hr | 10 mn | 50 μs | | | 300 | 8 hr |
| Pulsar Timing AASKA14:037 | Pulsars | 5 | 0.9 arcmin2 | 65 arcsec2 | 8 arcsec | 50 Targets/ 1 Tied-Array Beam | Sidereal | 4300 hr | 40 mn | 100 ns | 130 | 2 wks | 1075 | 4 hr |
| | | | 0.7 arcmin2 | 50 arcsec2 | 7 arcsec | 50 Targets/ 1 Tied-Array Beam | Sidereal | 1600 hr | 15 mn | 100 ns | 130 | 2 wks | 200 | 8 hr |
| HI - High z AASKA14:128 | HI | 13 | 5.4 deg2 | 1.1 deg2 | 3:5 arcsec | 5 Fields | Sidereal | 5000 hr | 1000 hr | 0.15 s | | | 625 | 8 hr |
| HI - Low z AASKA14:129 | HI | 14 | 3.8 deg2 | 0.38 deg2 | 3:5 arcsec | 10 Targets | Sidereal | 2000 hr | 200 hr | 0.15 s | | | 250 | 8 hr |
| HI - Galaxy AASKA14:130 | HI | 15 | 1080 deg2 | 0.38 deg2 | 5:60 arcsec | 2840 Pointings | Sidereal | 12600 hr | 4.4 hr | 0.15 s | | | 1575 | 8 hr |
| Transients - FRB AASKA14:055 | Transients | 18 | 30000 deg2 | 1.2 arcmin2 | 105 arcsec | 1 Target/ 1500 Tied-Array Beams | Sidereal | 10000 hr | 2 msec | 50 μs | 1.20E+06 | 2 msec | 1250 | 8 hr |
| CoL - Planet formation AASKA14:117 | Cradle of Life | 22 | 0.05 deg2 | 0.005 deg2 | 0.04:1 arcsec | 10 Targets | Sidereal | 6000 hr | 600 hr | 0.15 s | | | 750 | 8 hr |
| Magnetism - RM-grid AASKA14:092 | Magnetism | 27 | 31000 deg2 | 0.38 deg2 | 2 arcsec | 81600 Pointings | Sidereal | 10000 hr | 7.4 mn | 0.15 s | | | 1250 | 8 hr |
| Cosmology - High z IM AASKA14:019 | Cosmology | 32 | 30000 deg2 | 1.4 deg2 | 1.7 deg | 21500 Pointings | Drift | 10000 hr | 2.2 hr @ 190 Dishes | 0.15 s | | | 1250 | 8 hr |
| Cosmology - ISW, Dipole AASKA14:018, 032 | Cosmology | 33 | 31000 deg2 | 0.38 deg2 | 2 arcsec | 81600 Pointings | Sidereal | 10000 hr | 7.4 mn | 0.15 s | | | 1250 | 8 hr |
| Continuum - SFR(z) AASKA14:067 | Continuum | 37 + 38 | 1000 deg2 | 0.38 deg2 | 0.5:1 arcsec | 2600 Pointings | Sidereal | 10000 hr | 3.8 hr | 0.15 s | | | 1250 | 8 hr |
| | | | 7.8 deg2 | 0.38 deg2 | 0.5:1 arcsec | 21 Pointings | Sidereal | 2000 hr | 95 hr | 0.15 s | | | 250 | 8 hr |
| | | | 0.38 deg2 | 0.38 deg2 | 0.5:1 arcsec | 1 Pointings | Sidereal | 2000 hr | 2000 hr | 0.15 s | | | 250 | 8 hr |
| | | | 0.5 deg2 | 30 arcmin2 | 0.05:1 arcsec | 61 Pointings | Sidereal | 1000 hr | 16.4 hr | 0.15 s | | | 125 | 8 hr |
| | | | 30 arcmin2 | 30 arcmin2 | 0.05:1 arcsec | 1 Pointing | Sidereal | 1000 hr | 1000 hr | 0.15 s | | | 125 | 8 hr |
| L0 Requirements | | | 043, 044 | | 037, 038 | 27, 031, 032 | | 043, 044 | 045, 046 | | 016, 017 | 016, 017 | | 031, 032, 033, 034 |

# Common Sky Coverage



# Magnetic Universe

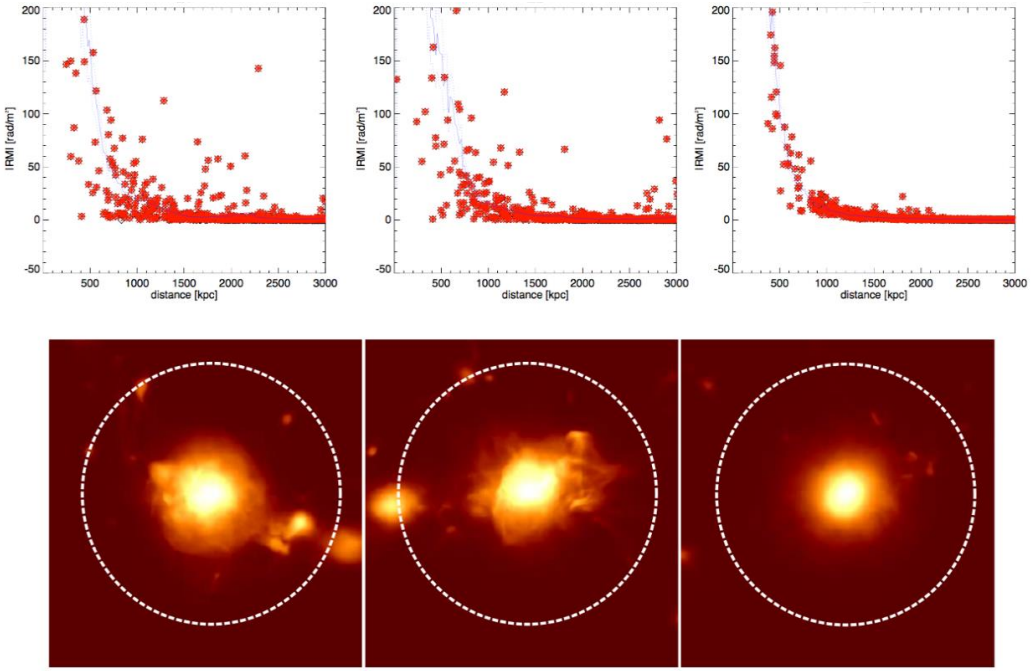



$RM = RM_{object} + RM_{IGM} + RM_{MW}$

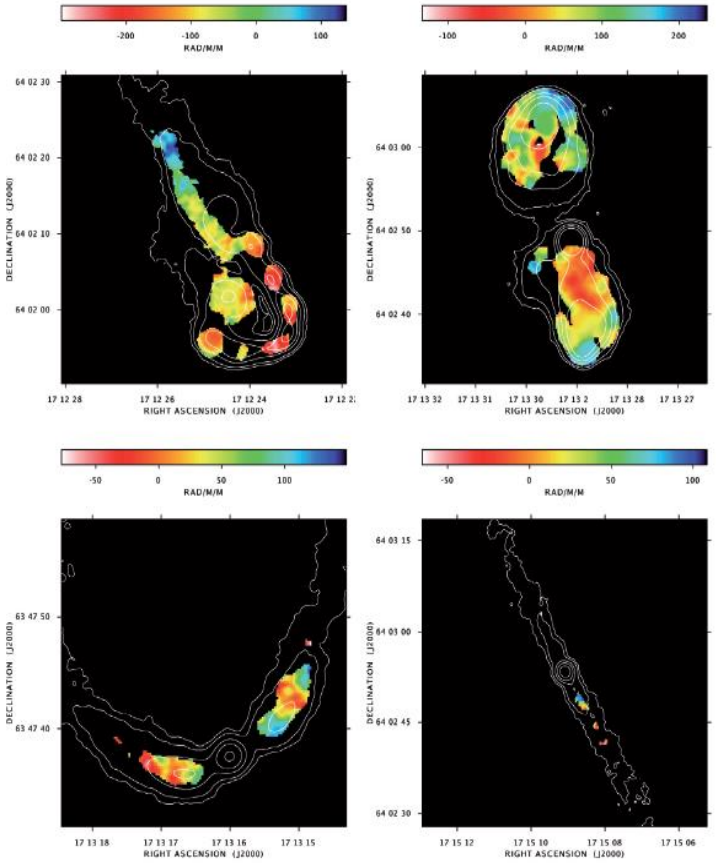
- Key SKA HPSO is to construct a detailed RM grid
- Measure RM against as many sources as possible
- Probe foreground structure in our galaxy and other objects, clusters, large nearby galaxies ….

- Line of sight probes of Evolution of Cosmic Magnetism
- The Magnetic cosmic web
- Broad-band polarimetry as a probe of AGN and Galaxy Physics
- Magnetic fields in AGN at all redshifts and luminosities
- Magnetic field in clusters and filaments
- Magnetic field in nearby galaxies
- Magnetic fields in the heart of the Milky Way
- Emergence and Evolution of magnetic fields in galaxy disks
- Probing the nature of Dark Matter
- Multi-scale magnetism in the Milky Way
- Imaging of Diffuse Polarization Features in the Milky Way

# Magnetic Universe: Clusters



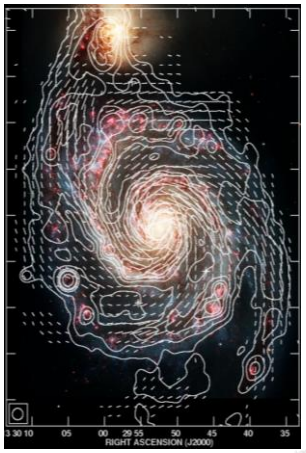

*Vazzaet al. 2010*



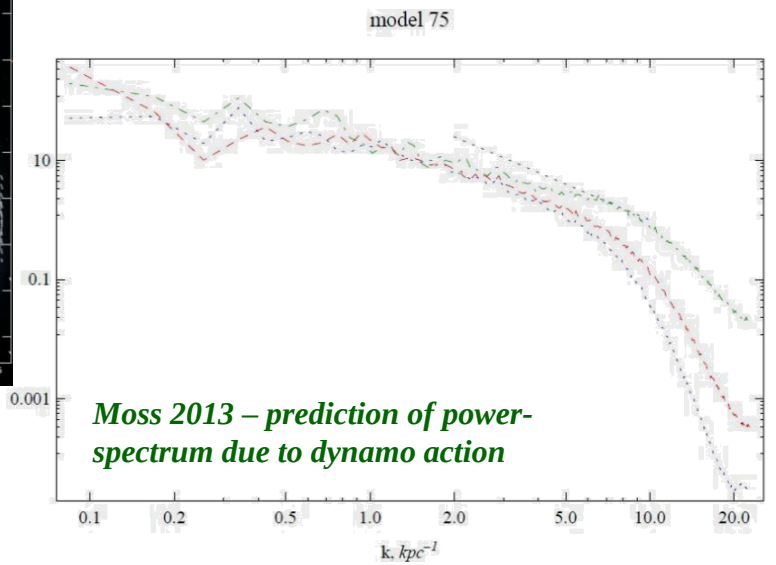

*Govoni et al. 2006*

- Use RM Grid to probe evolution of field in clusters
- Simulation shows evolution during merging clusters
- Probe smallest scales by detailed RM studies across resolved background objects or embedded radio sources within the cluster

# Magnetic Universe: Galaxies

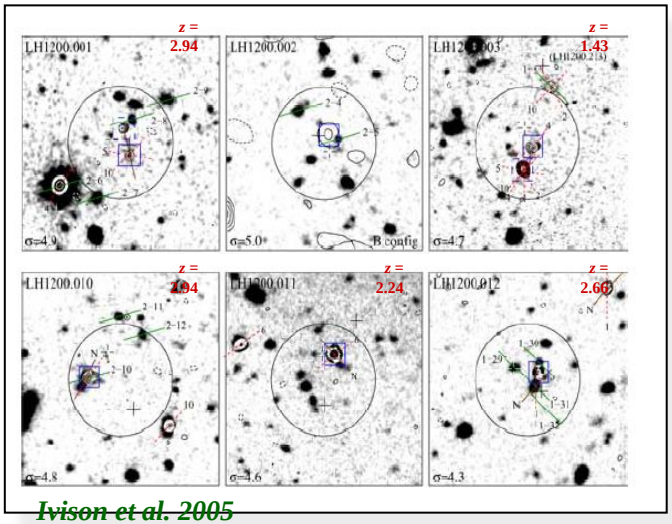


*M51: Fletcher et al. 2006*

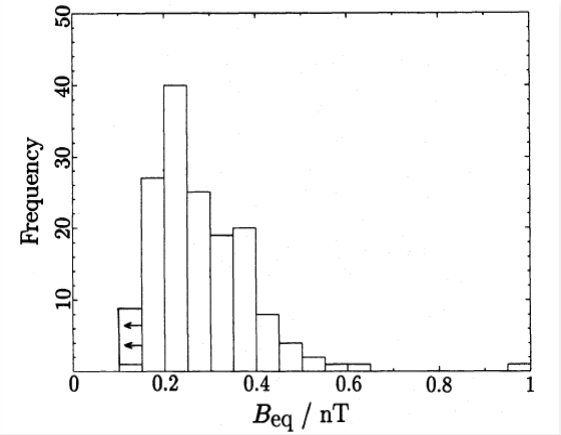



*Moss 2013 – prediction of power-spectrum due to dynamo action*

- Nearby galaxies map field structure on multiple scales
  - E-MERLIN in galactic centres …
  - Power-spectra test models of field generation
- Synchrotron detection → B-fields
  - Need to resolve discs for accurate estimates of $B_{eq}$
  - Evolution of $B_{eq}$ with redshift




*Ivison et al. 2005*



# Possible SKA1 Continuum Survey Strategy

**Deep / Multi-tier**

- Star formation & BH accretion history
- Role of AGN feedback over cosmic Time
- Evolution of FIR-Radio correlation
- Role of environment

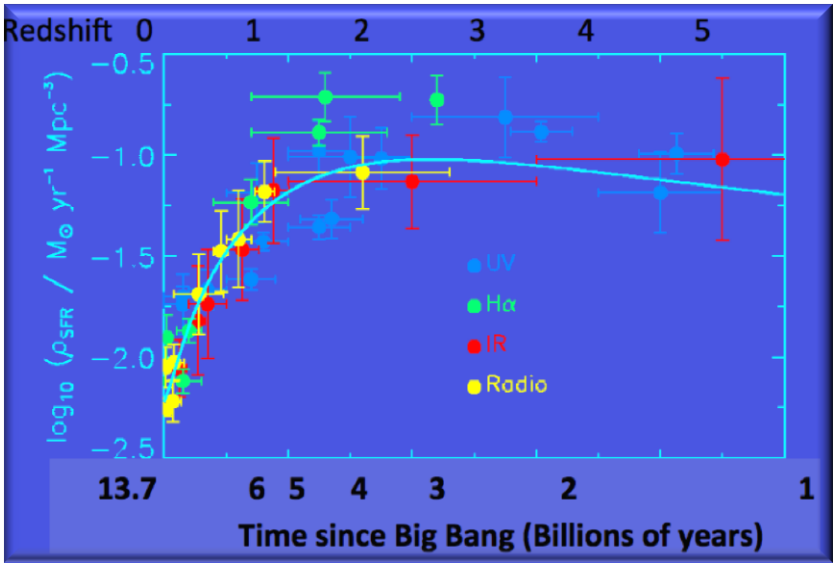
**Wide / All Sky**

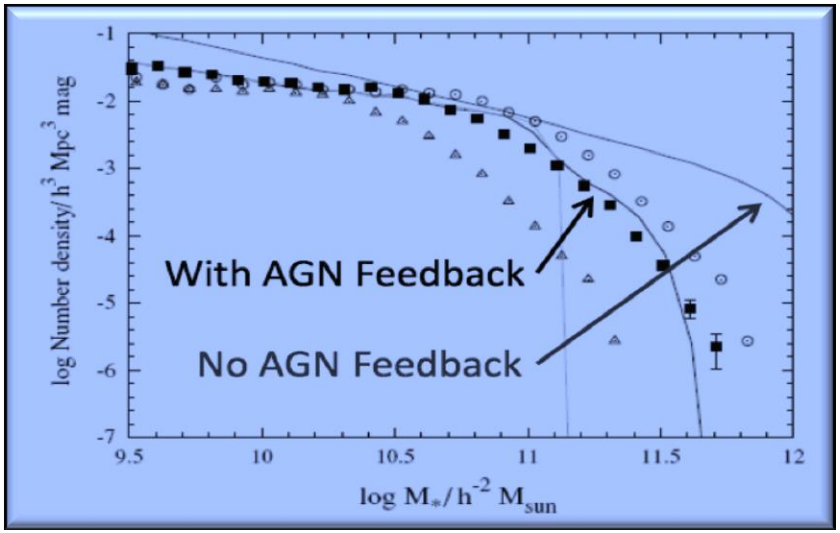
- First galaxies, BHs & protoclusters
- Galaxy clusters, cosmic web
- RL AGN physics/lifecycle
- RQ/RL AGN dichotomy
- ISM and SF physics in nearby galaxies
- Origin of FIR-Radio correlation
- Stro ng lensing

| Science Drivers | Freq. | Tier | Rms (full BW) | Area | Res. | Science/ Commensality |
|---|---|---|---|---|---|---|
| **SFHU Non-thermal** (gal/AGN co-evol.) | ~1 GHz Band 1/2 | Ultra Deep | 50 nJy | 1 deg2 | ~0.5" | AGN/gal co-evol. |
| | | Deep | 200 nJy | 10-30 deg2 | ~0.5" | AGN/gal co-evol.<br>**High-z Magnetism**<br>HI deep field (B1) |
| | | Wide | 1 uJy | 1000 deg2 | ~0.5" | Weak/Strong Lensing |
| **SFHU Thermal** (gal/AGN co-evol.) | ~10 GHz Band 5 | Ultra Deep | 40 nJy | 0.008 deg2 | ~0.1" | AGN/gal co-evol. |
| | | Deep | 300 nJy | 1 deg2 | ~0.1" | AGN/gal co-evol. |
| **Legacy Strong Lensing** (rare populations) | ~1 GHz Band 2 | All-sky | 4 uJy | 31000 deg2 | ~2"<br>0.5" | **Magnetism**<br>Cosmology tests<br>Transients (beam forming)<br>HI surveys<br>Our Galaxy |
| **Clusters** (RL AGNs) | ~120 MHz | All-sky | 20 uJy (confusion) | 31000 deg2 | 8" | **EoR** |

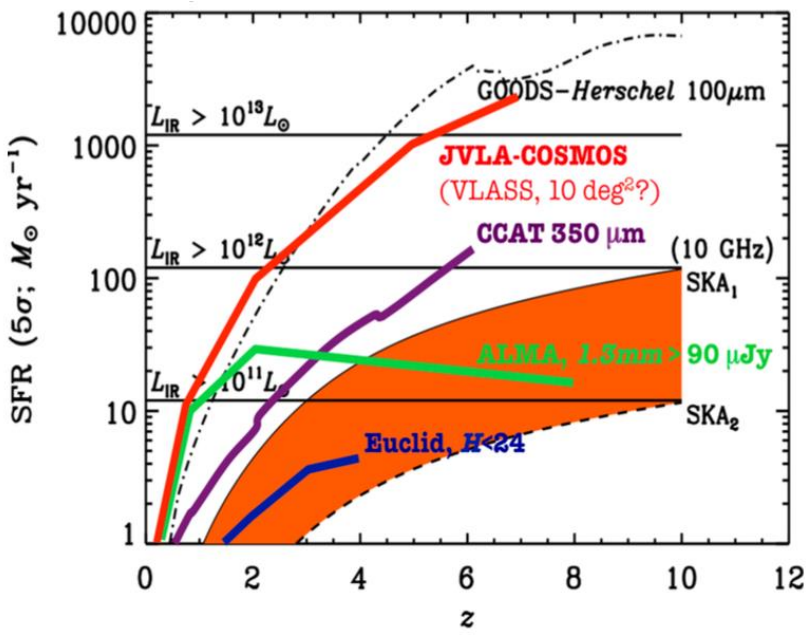
# Galaxy Evolution: Star formation and feedback

*Hopkins et al. 2004*



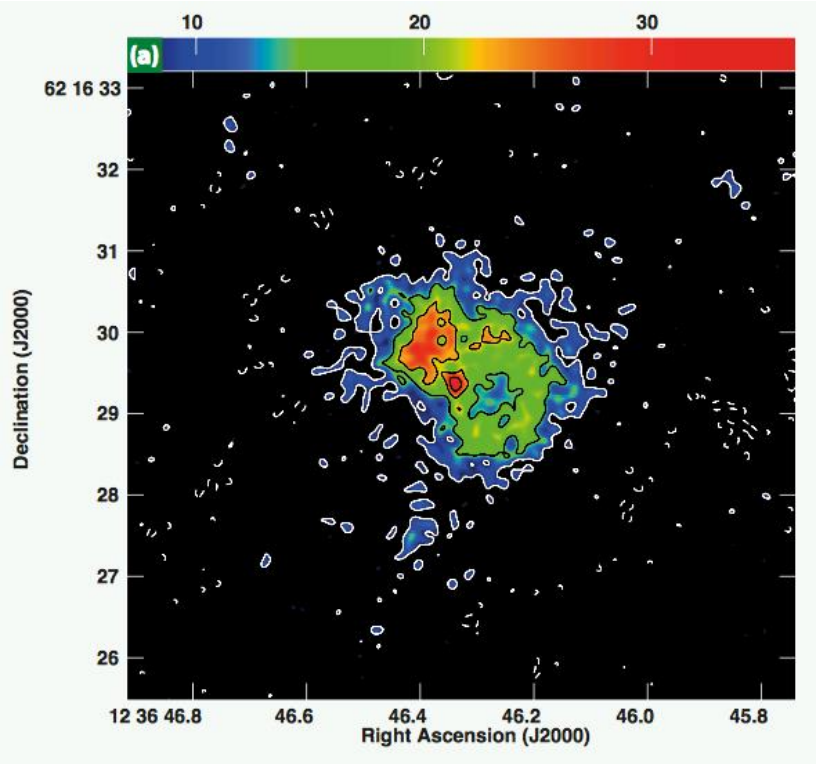




*Murphy, Sargent et al 2015*

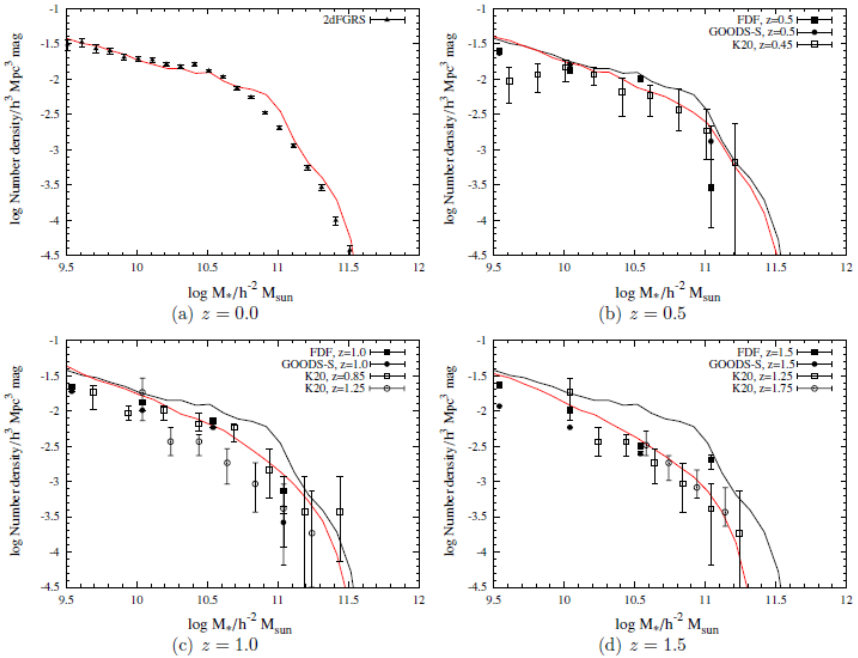



- Radio continuum excellent tracer of SF in SKA era
- AGN Feedback radio essential

# Galaxy Evolution: Star formation and feedback

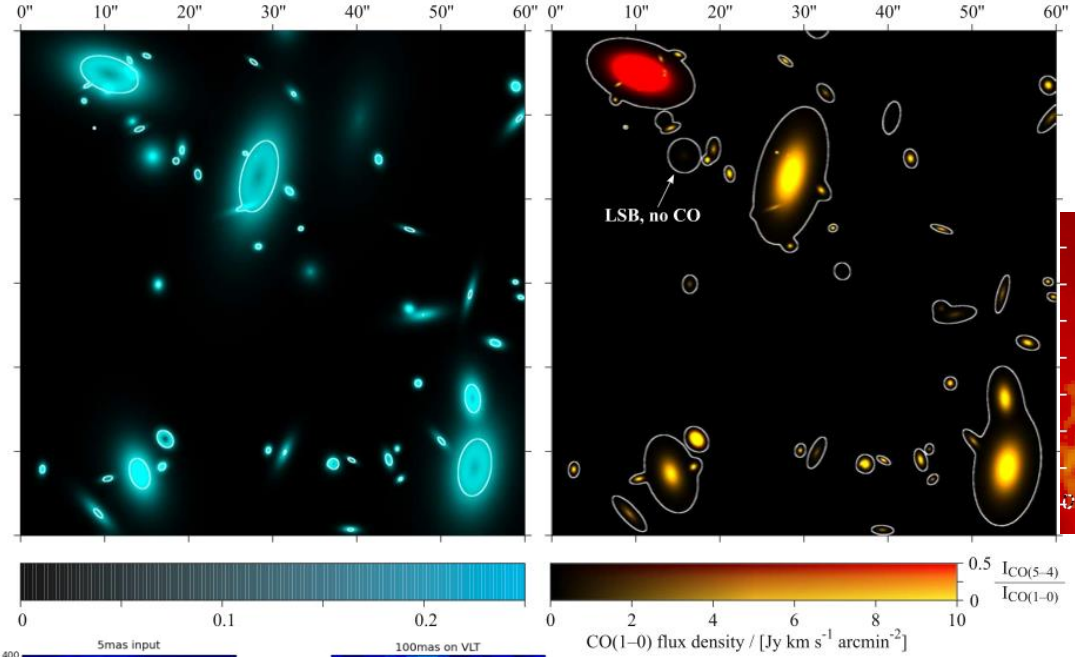



***One source from e-MERGE showing embedded AGN and ring of star formation across massive spheroidal***

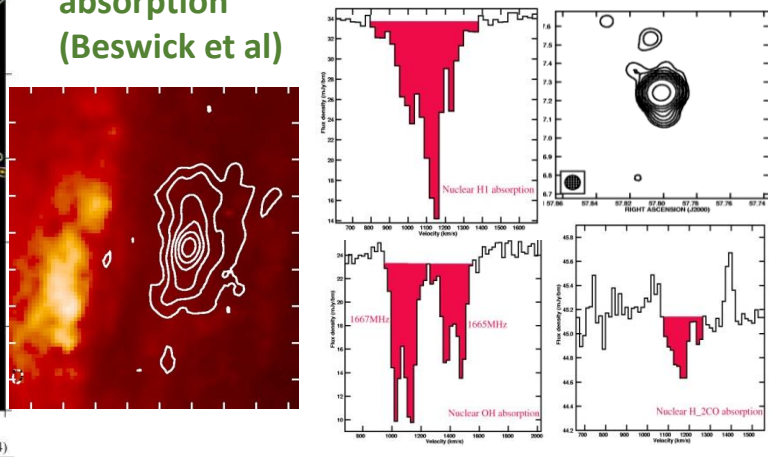


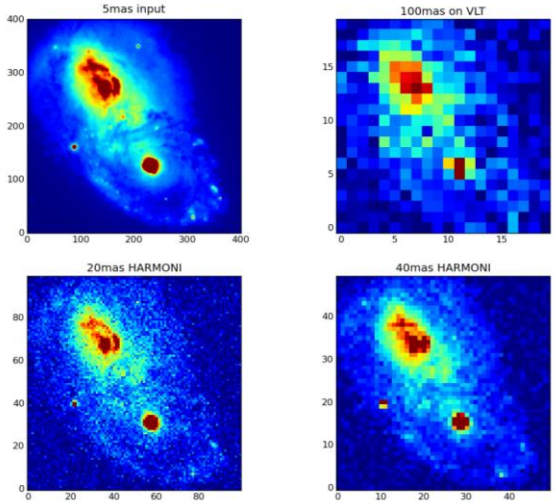

- e-MERLIN demonstrated the power of resolving AGN and star-forming contributions
- e-MERLIN follow up of brighter galaxies to probe detailed star-formation / AGN interactions and feedback
- Large fraction of wide-field sample will be accessible to e-MERLIN

# Galaxy Evolution: SKA / ALMA / E-ELT /e-MERLIN synergy



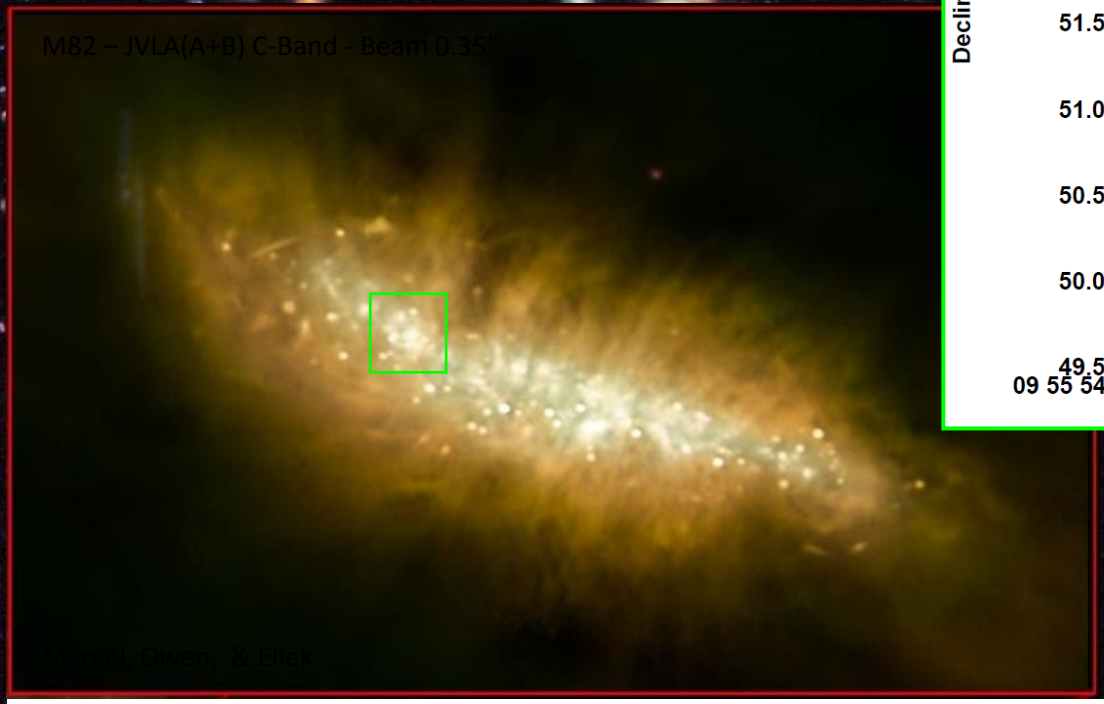

NGC3079 HI, OH and $H_2CO$ absorption (Beswick et al)

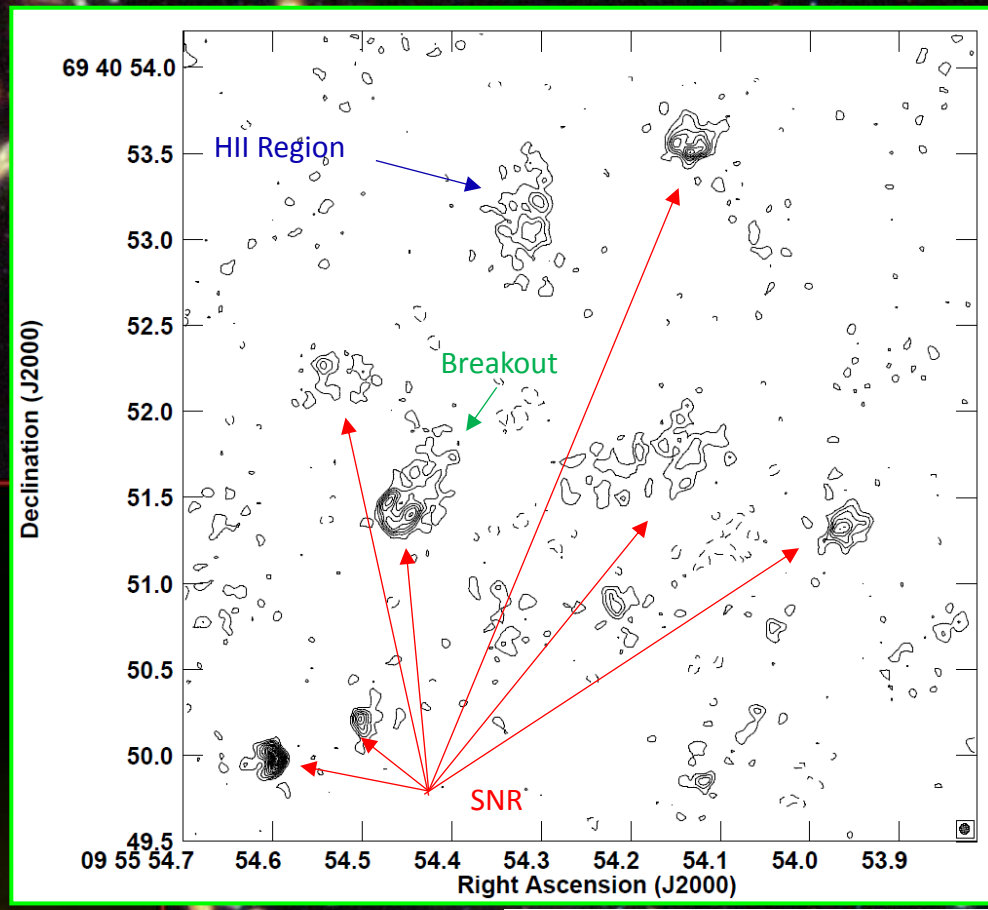


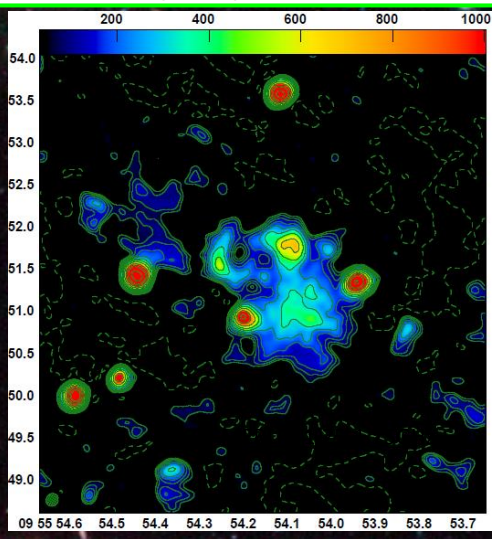




- ALMA, SKA and e-MERLIN are natural IFUs at different scales and transitions
- E-ELT IFU maps, e.g. Halpha
- Continuum imaging e-MERLIN + VLBI

Tom Muxlow/Rob Beswick: Star-formation
Across Cosmic Time: M82



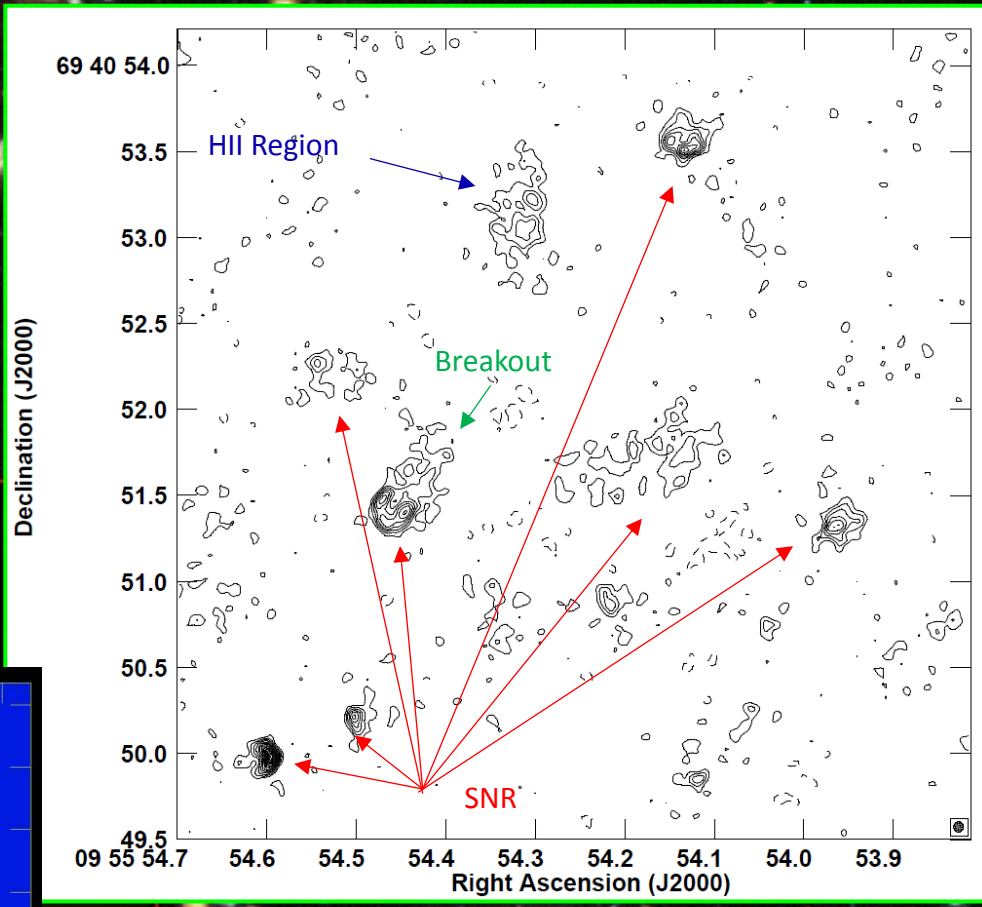



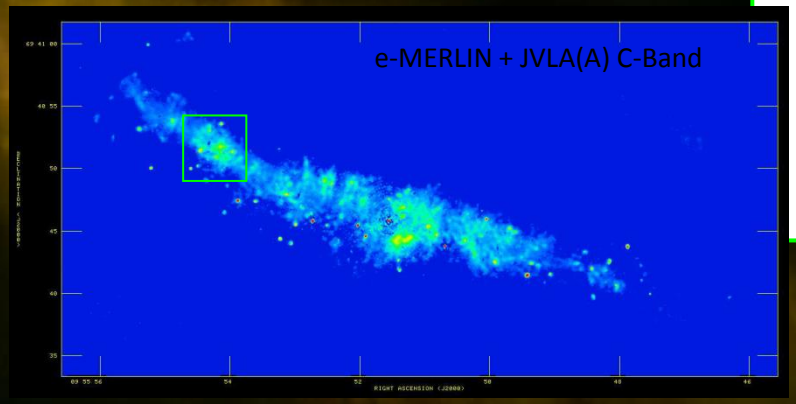

Calibrate star-formation rate derivation on nearby galaxies like M82

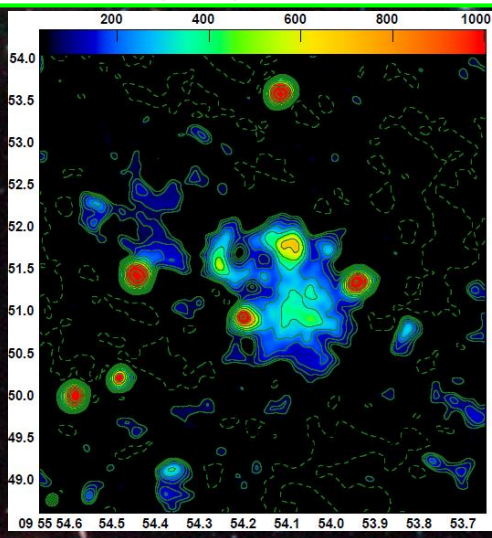
Separate AGN / S-F (& SNR from HII) by sensitive high resolution imaging at C- & L-Band

Extend to distant galaxies 1000 times further away and 1 million times fainter

Tom Muxlow/Rob Beswick: Star-formation
Across Cosmic Time: M82



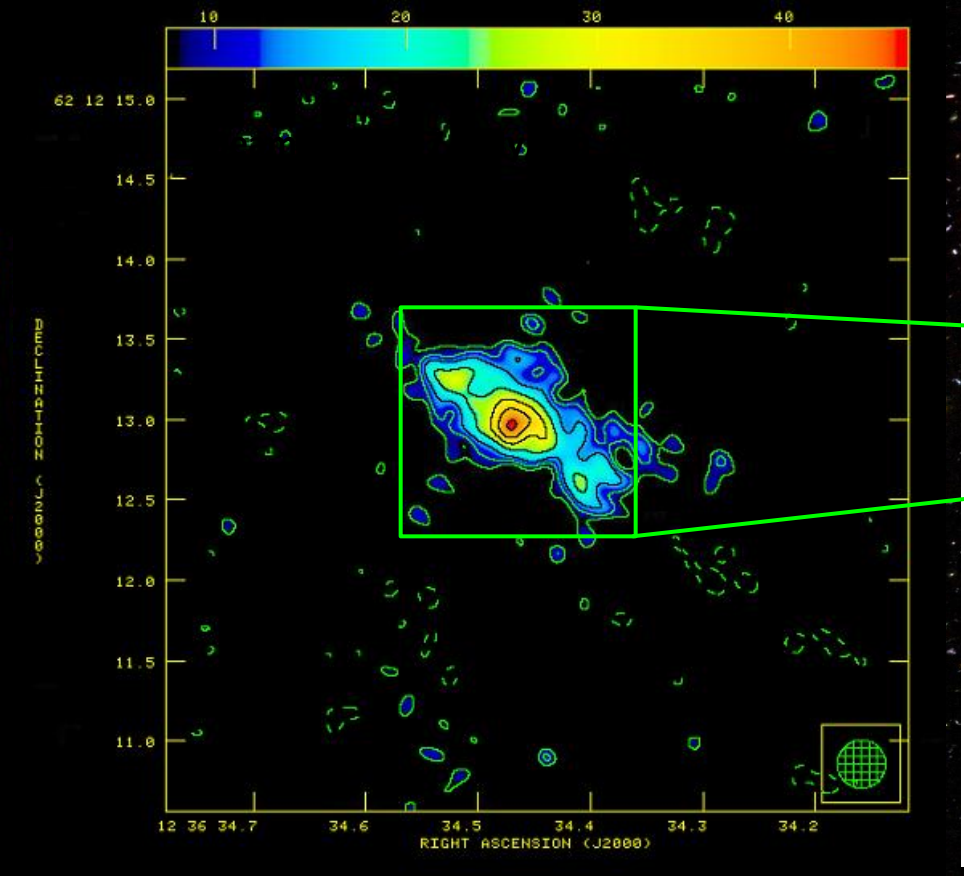

Calibrate star-formation rate derivation on nearby galaxies like M82

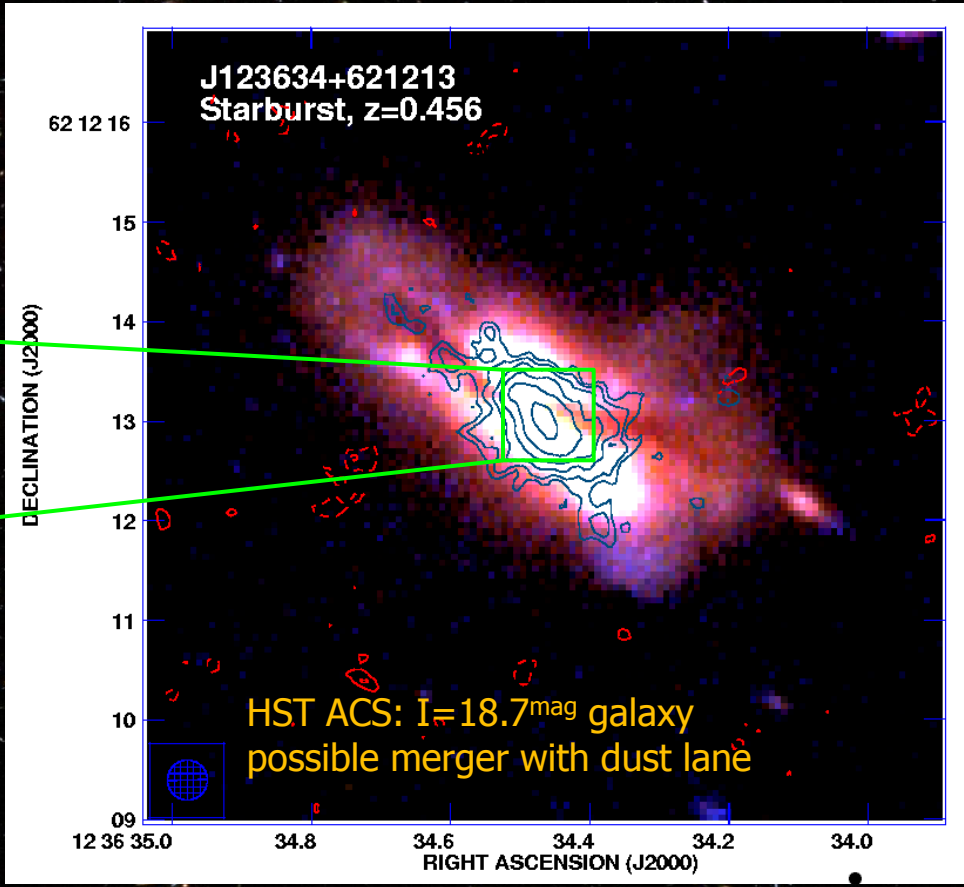
Separate AGN / S-F (& SNR from HII) by sensitive high resolution imaging at C- & L-Band

Extend to distant galaxies 1000 times further away and 1 million times fainter

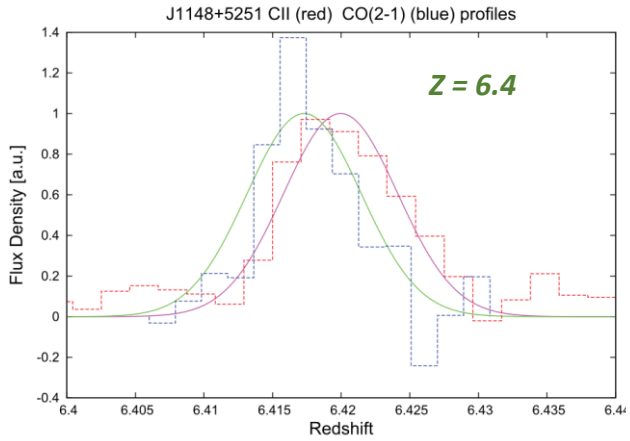
# Star-formation Across Cosmic Time: *e*-MERGE Tier 1

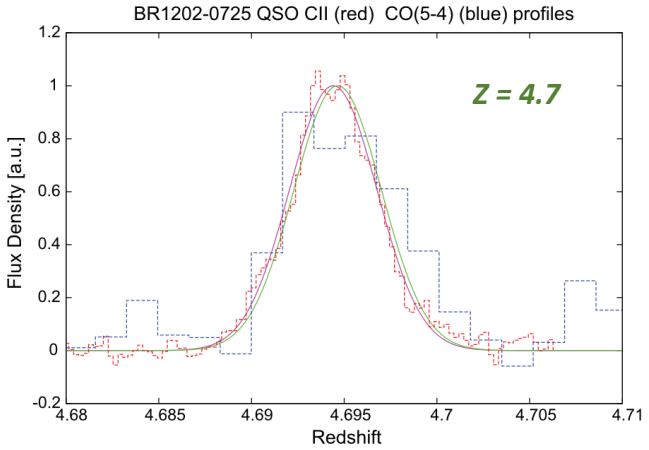
J123634+621213:



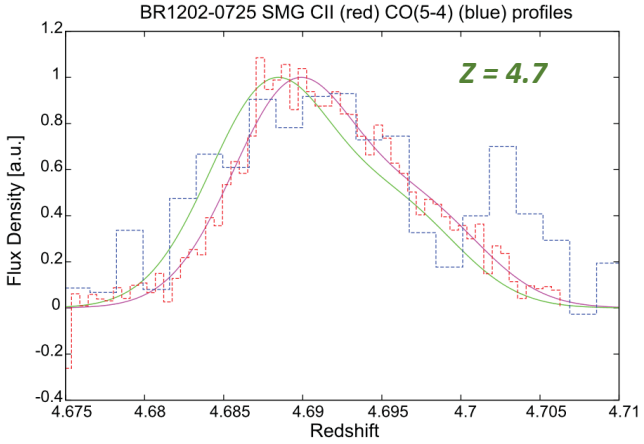



# Cosmology: Variation of fundamental constants?




$$F = \frac{\alpha^2}{m_p/m_e}$$



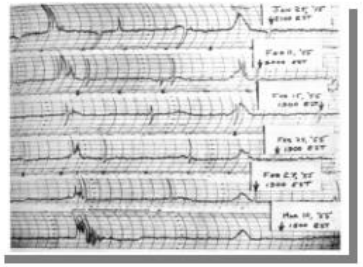

$$\frac{\Delta F}{F} = -3.3 \pm 2.3 \times 10^{-4} \text{ (12.9 Gyr)}$$

*Lentati et al 2013*

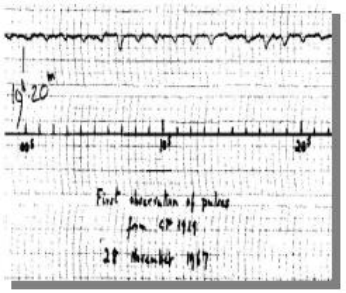
*DF/F = -3.3*

- Observe different types of transitions (e.g. electronic vs rotational) in galaxies at range of z
- Use differences in inferred redshits of the lines to look for evidence of variation in fundamental constants
- Problem
  - Are we tracing same gas in the two transitions?
  - Do we observe astrophysics or physics?
- Here resolution of e-MERLIN very helpful
  - HI / OH
  - More transitions

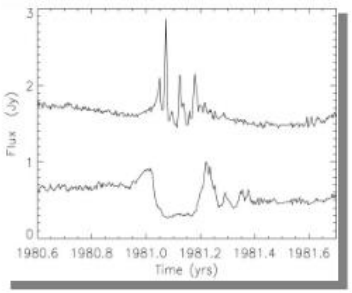
# Transient Universe



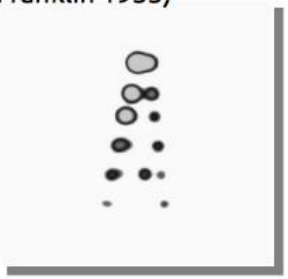
Radio Bursts from Jupiter (Burke & Franklin 1955)



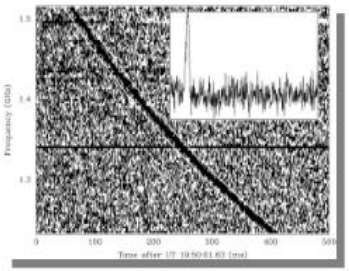
Pulsars (Hewish et al. 1968)



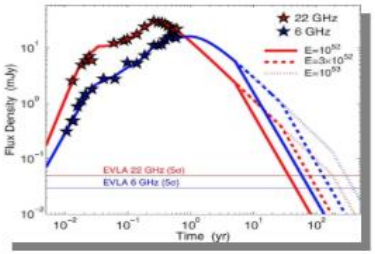

Extreme scattering events (Fiedler et al. 1987)



A superluminal source in our galaxy (Mirabel & Rodriguez 1994)



Fast radio bursts Lorimer et al. (2007)




A relativistic jet from a tidal disruption event (Zauderer et al. 2011)

- Traditional area of big impact e-MERLIN science
- SKA1 Discovery +
  - Power of responsive observing
  - Resolution
  - Link to EVN

# Transient Universe

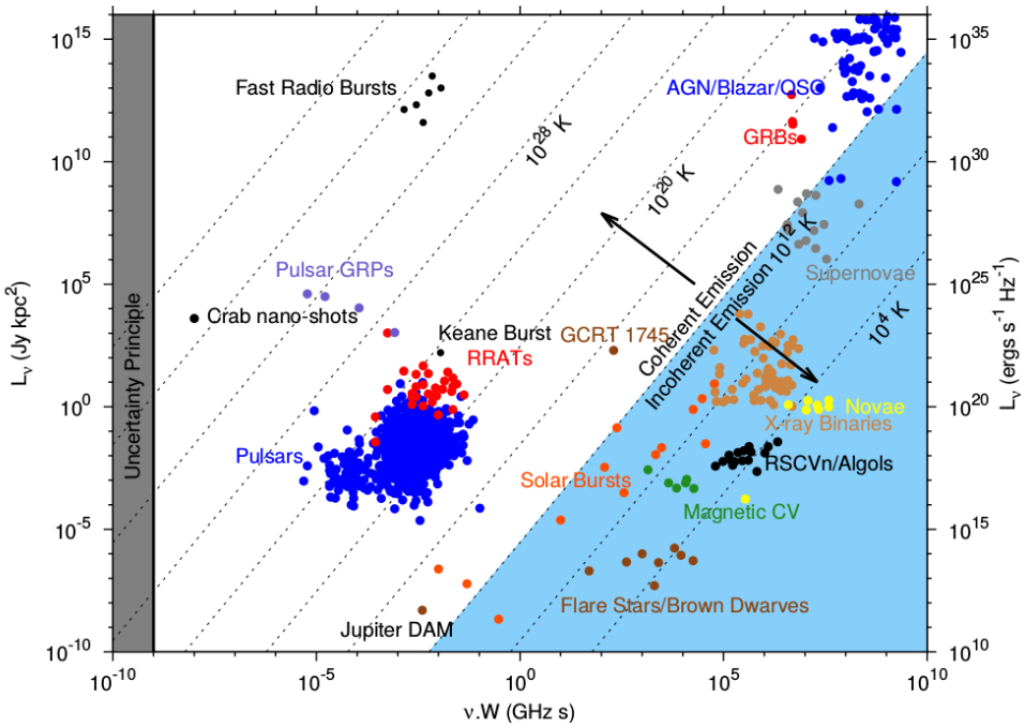
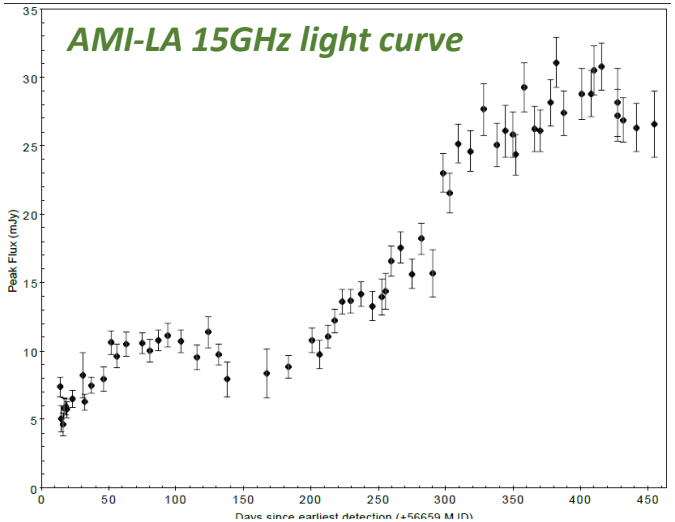



**Figure 4:** Transients parameter space expanded to include coherent sources. From Pietka, Fender & Keane (2015), following a long line of similar plots (e.g. Cordes, Lazio & McLaughlin 2004).

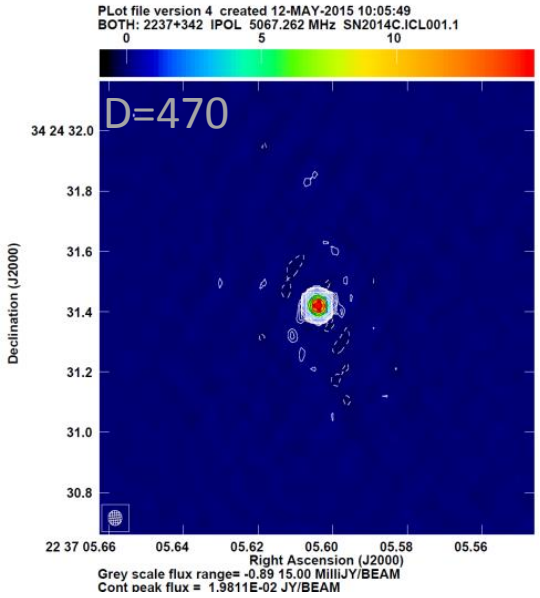
- Traditional area of big impact e-MERLIN science
- SKA1 Discovery +
  - Power of responsive observing
  - Resolution
  - Link to EVN

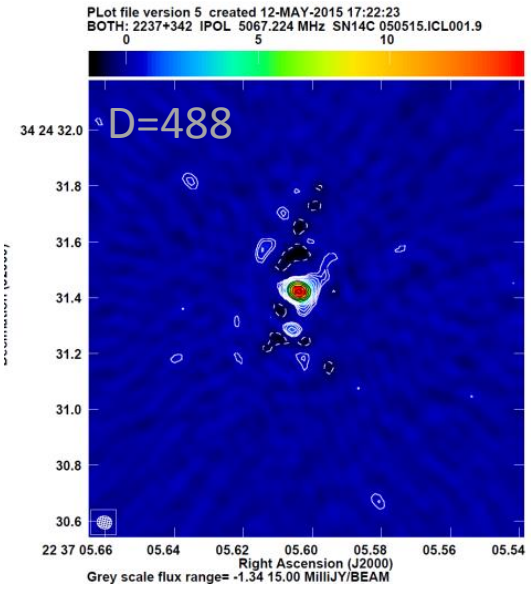
# Transient Universe: SN2014C

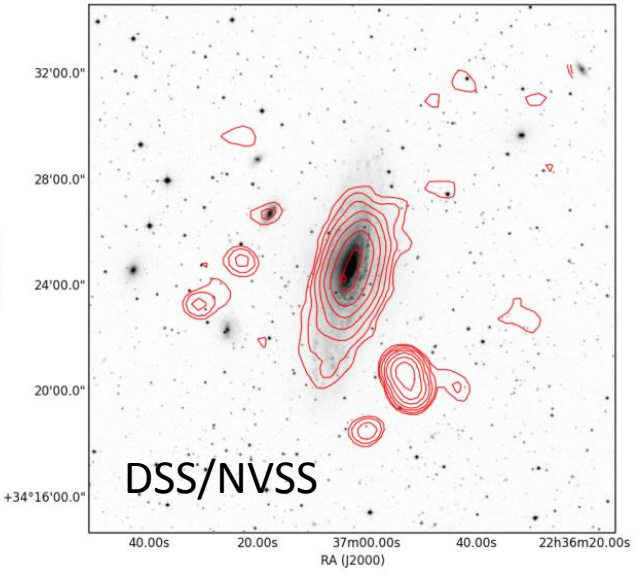



SN2014C (Lick discovery)

- D=15.1Mpc in NGC7731
- Unusual double peak
- Indicative of shell interaction with dense CSM
- Possibly radio bright SN1b
- *Now trigger VLBI follow-up pending*
- e-MERLIN resolution vital to remove confusion



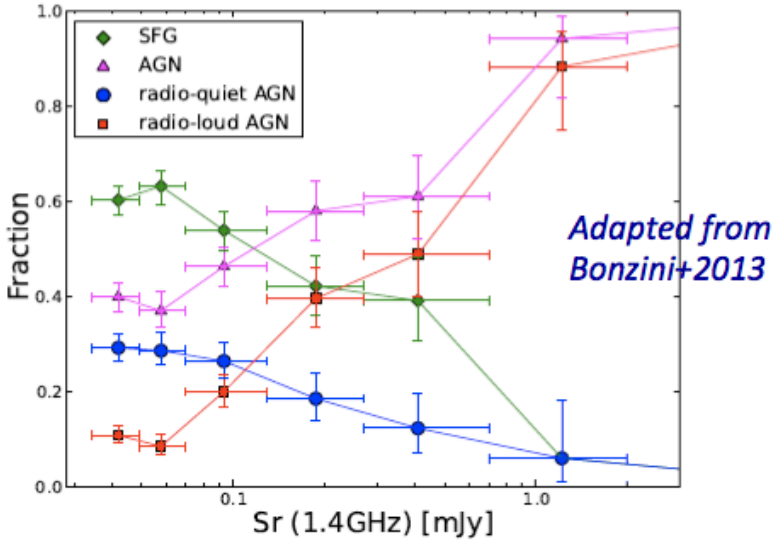



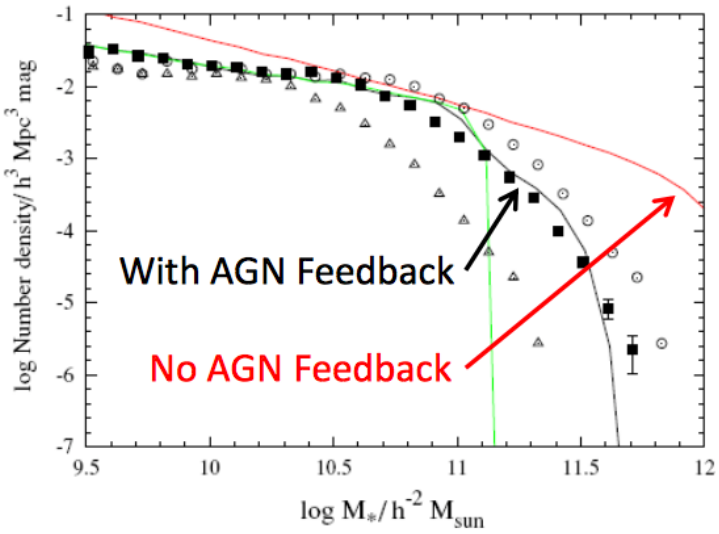

*Anderson, Fender et al*

# AGN Physics

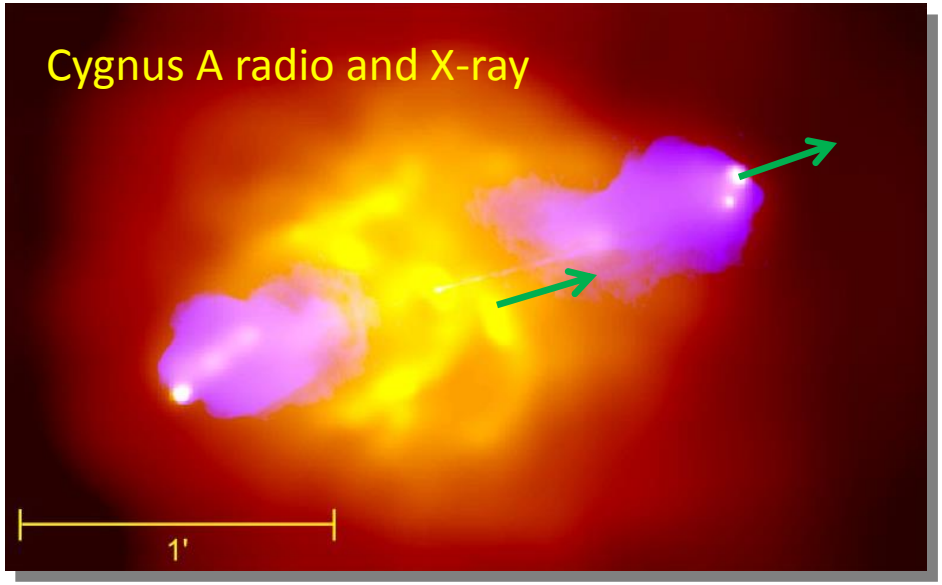
- Physics of RL AGN physics/lifecycle
- Physics of RQ/RL AGN dichotomy
- How do RL / RQ AGN provide feedback
- Jet Physics: origin and propagation

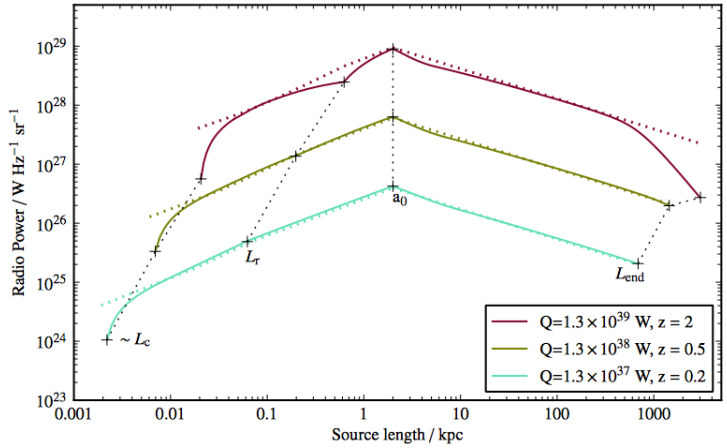


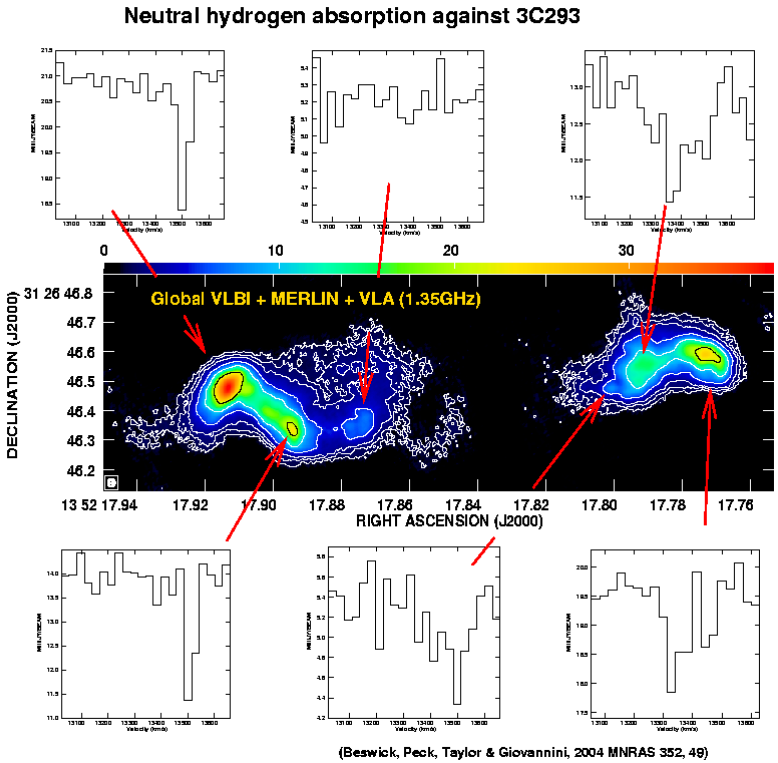

- Radio Astronomy and AGN Physics !!
- Much progress but still many unsolved problems
- Interesting in own right as well as importance in overall galaxy evolution
- AGN physics is interesting



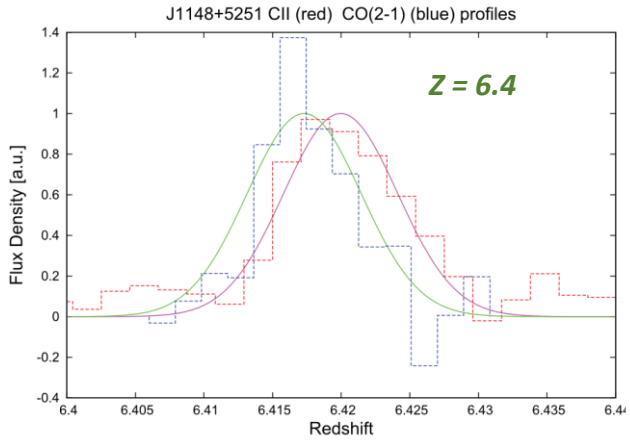
# AGN Physics

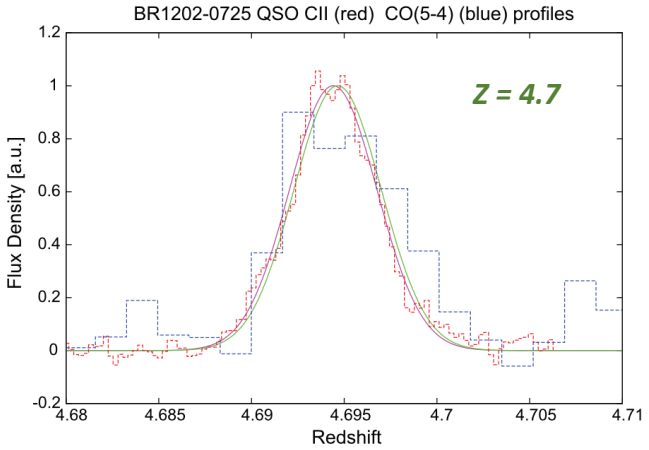

Cygnus A radio and X-ray
1'


Radio Power / W Hz$^{-1}$ sr$^{-1}$
Source length / kpc
$a_0$
$L_r$
$L_{end}$
$\sim L_c$
Q=1.3×10$^{39}$ W, z = 2
Q=1.3×10$^{38}$ W, z = 0.5
Q=1.3×10$^{37}$ W, z = 0.2

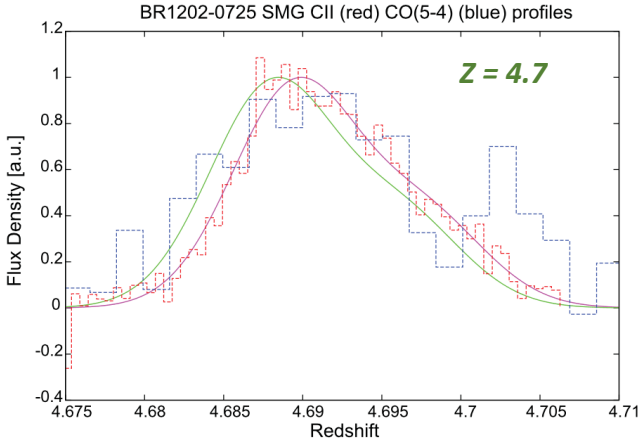

Neutral hydrogen absorption against 3C293
Global VLBI + MERLIN + VLA (1.35GHz)
DECLINATION (J2000)
RIGHT ASCENSION (J2000)
(Beswick, Peck, Taylor & Giovannini, 2004 MNRAS 352, 49)

# Cosmology: Variation of fundamental constants?




$$F = \frac{\alpha^2}{m_p/m_e}$$




$$\frac{\Delta F}{F} = -3.3 \pm 2.3 \times 10^{-4} \text{ (12.9 Gyr)}$$

*Lentati et al 2013*

*DF/F = -3.3*

- Observe different types of transitions (e.g. electronic vs rotational) in galaxies at range of z
- Use differences in inferred redshits of the lines to look for evidence of variation in fundamental constants
- Problem
  - Are we tracing same gas in the two transitions?
  - Do we observe astrophysics or physics?
- Here resolution of e-MERLIN very helpful
  - HI / OH
  - More transitions

# Conclusions and thoughts

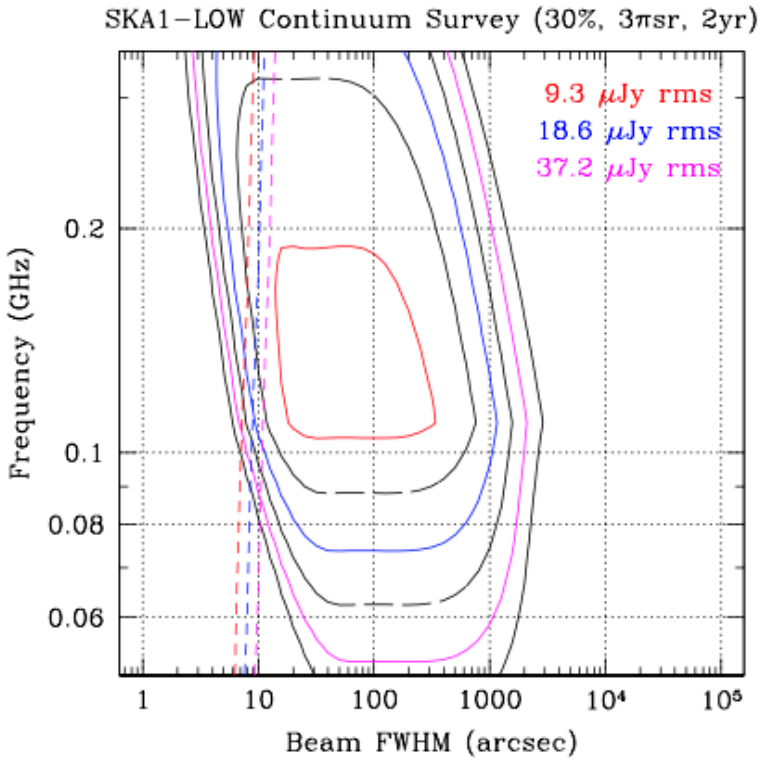
SKA is a brilliant facility, but it will be fully occupied through to at least 2030 with HPSO planned science
Major role for other observatories
e-MERLIN has unique capabilities in this regard

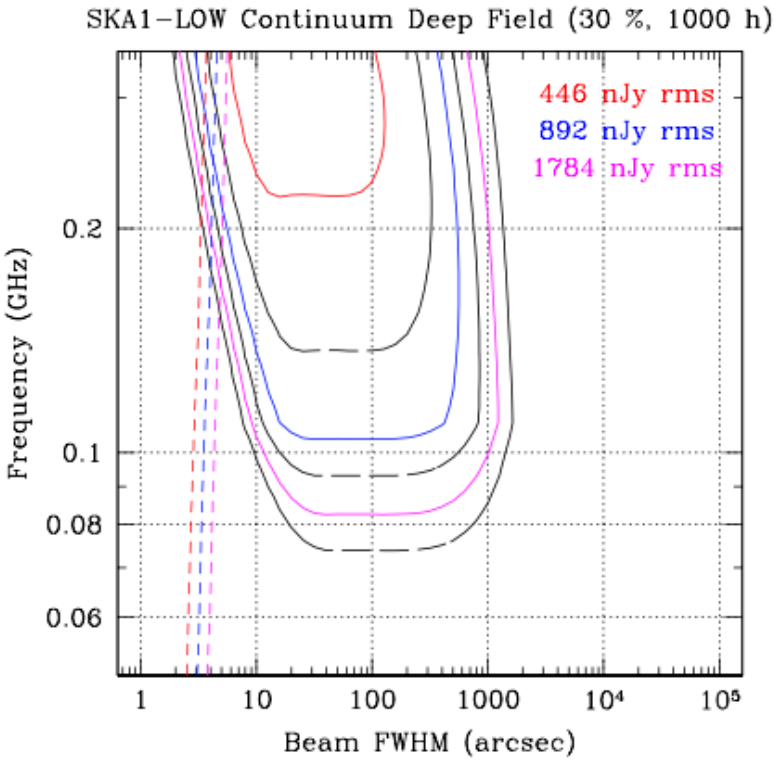
Discussion thoughts on e-MERLIN upgrades in context of extregalactic science

- **Fully integrated Lovell and e-MERLIN operations**
  - **Critical importance to have sensitivity to followup SKA1 surveys**
- **Phased Array Feed for the Lovell telescope – factor 4 increase in survey speed**
  - **Useful to get full field of view, but mainly to do followup fields**
- **New Receiver Bands – matching SKA1-Mid coverage**
  - **Mostly important for spectroscopy?**
  - **Competition with SKA1?**
  - **Of course fully justified by experiments to do evolution of fundamental constants** ☺
- **Increased bandwidth data transmission –for increased sensitivity and band coverage**
  - **Not clear it will give enough sensitivity improvement to justify?**
- **Rapid trigger for transient and variable observations**
  - **Yes – follow up science to SKA very important**
- **Tied-array operations for time-domain astrophysics**
  - **Not competitive to SKA?**
- **New telescopes and combined VLBI/e-MERLIN arcsecond-to-milliarcsecond imaging**
  - **Yes if targeted at better imaging in sky overlap area with SKA**

  ?
- **Advanced imaging and non-imaging analysis techniques** ?
- **A UK test-bed for SKA science and technology**

# Simple (but more relevant) consideration



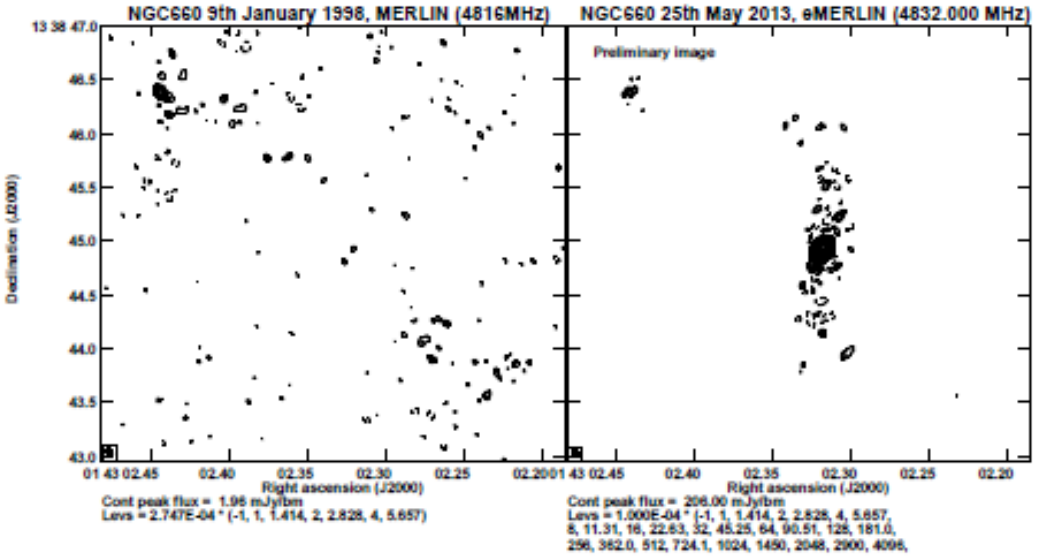



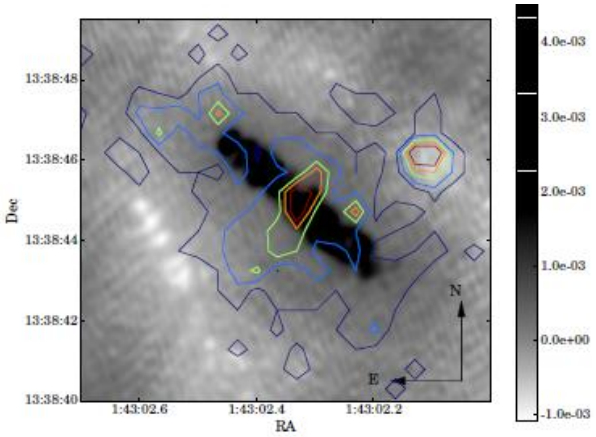
# A new period of activity in NGC660

Witnessing the **(re-)birth** of an AGN

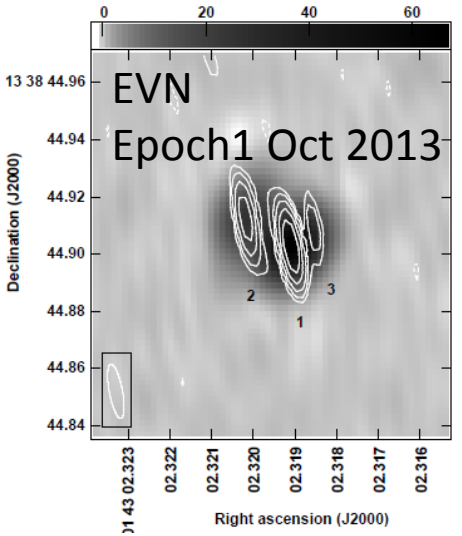
Joint eMERLIN/EVN/WSRT study of spectral lines and continuum

- New source discovered in Arecibo monitoring (2008-2010)
- Nuclear continuum source peaked at ~0.5Jy – now in steady decline



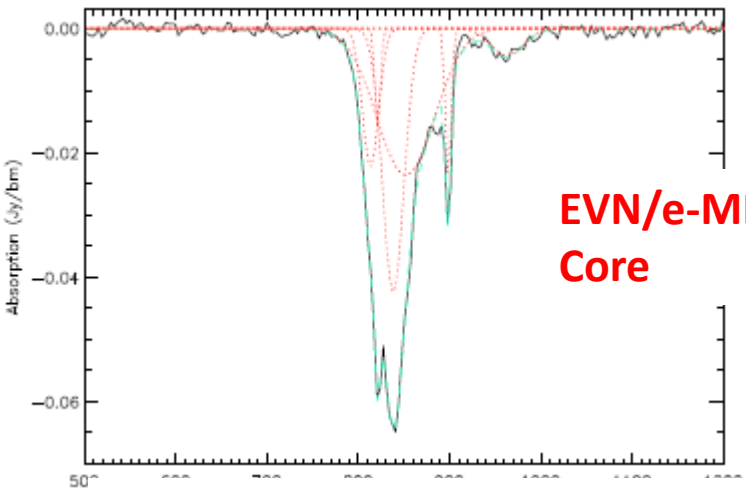

Pre-outburst MERLIN L-band and post outburst X-ray (Chandra)



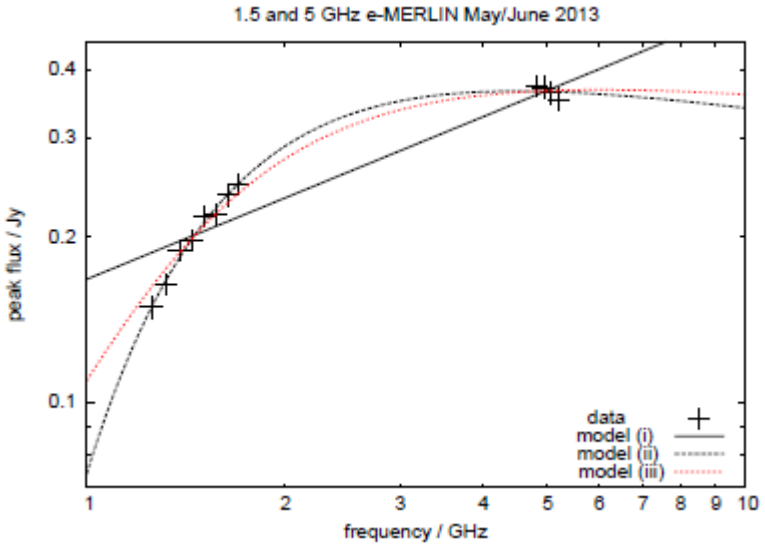
# Nuclear source & Gas?

- Outburst provide chance of high-res/sen line observations of neutral molecular ISM
- Wide-band continuum SED

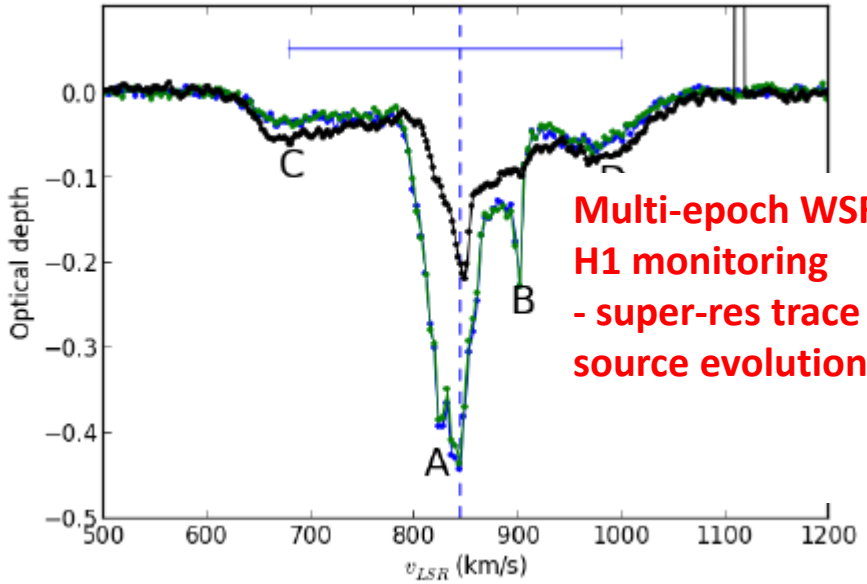
- New GPS source




**EVN/e-MERLIN H1 against Core**




*Argo et al MNRAS in press*




**Multi-epoch WSRT H1 monitoring**
**- super-res trace of source evolution**

*van Bemmel in prep*