
e-MERLIN updates (inc legacy surveys)
Rob Beswick
(JBCA/e-MERLIN,
University of Manchester)
e MERLIN

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e-MERLIN

Outline

e-MERLIN – background & capabilities

Overview of on-going e-MERLIN key projects

The future – what next??

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e-MERLIN (SKA-pathfinder) operating at cm-λ with μJy sensitivity and ~10-220km baselines

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e-MERLIN (SKA-pathfinder) operating at cm-λ with μJy sensitivity and ~10-220km baselines

Key/integral part of the EVN
- providing 'short' spacing baselines
- Now becoming fully integrated

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Northwest Regional Development Agency
University of Cambridge
Science & Technology Facilities Council
liverpool JMU

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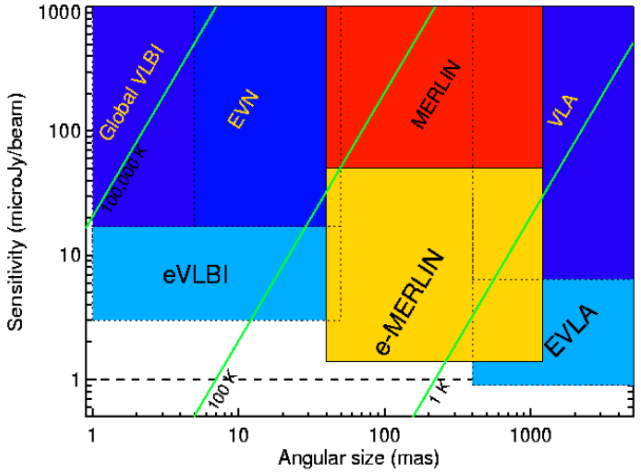
e-MERLIN

- Increase bandwidth to
  - 0.5 GHz (L-band)
  - 2 GHz (C-band)
- Include Lovell Telescope at C-band
- New telescope optics,feeds, receivers, IF, samplers
- Digital transmission system: 30 Gb/s from each telescope
- Dedicated optical fibre network
  - 100 km installed; 600km leased (total ~700km)
- H-maser freq (1 part in 10^{14})std over optical fibre network
- New correlator: wide field imaging; simultaneous line & continuum observations
- EVN recording/transmission for multiple telescopes



Basic capabilities

150, 40, 10 mas **resolution**

~10 uJy **sensitivity** in typical runs

Order of mag better than MERLIN performance

< uJy deep fields

Wide fields

[~7,27 arcmin]

Spectroscopy

Up to 16 sub-bands;>512 chan/pol; (More with Recirculation)

Mix line and continuum

Much improved aperture coverage

Via frequency coverage

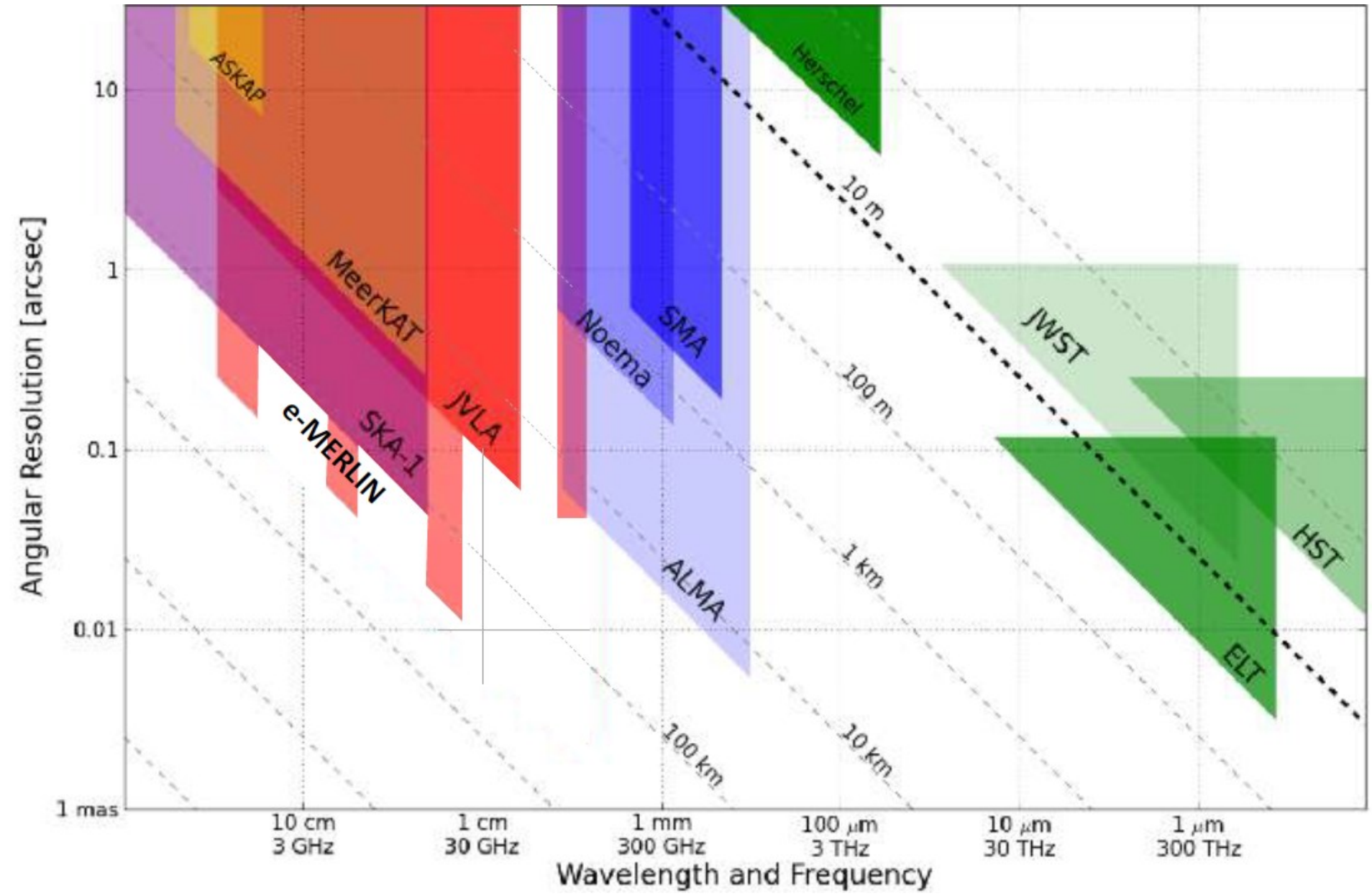
Spectral mapping

1.3-1.7; 5-7/4-8 GHz

Polarization (L,R → IQUV)

Astrometry

Goal is < 1 mas wrt ICRF


ASKAP
MeerKAT
SKA-1
e-MERLIN
JVLA
Noema
SMA
ALMA
Herschel
JWST
HST
ELT
10 m
100 m
1 km
10 km
100 km
10
1
0.1
0.01
1 mas
Angular Resolution [arcsec]
10 cm
3 GHz
1 cm
30 GHz
1 mm
300 GHz
100 μm
3 THz
10 μm
30 THz
1 μm
300 THz
Wavelength and Frequency

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e-MERLIN

Unique instrument covering particular resolutions scales..

Basic Capabilities - See www.e-merlin.ac.uk for more details

	1.5GHz (L-band)	5GHz (C-band)	22GHz (K-band)	Notes
Resolution (milliarcseconds)	150	40	12	Uniform weight at central frequency
Field of View (FoV) (arcmin)	30	7	2	FWHM of 25m dishes; reduced when the Lovell Telescope is included
Frequency range (GHz)	1.25-1.75	4-8	21-24	Tuneable frequency range
Bandwidth (GHz)	0.5	2	2	Max bandwidth per polarisation; at C or K-band, 4GHz is possible using a single polarisation.
Sensitivity (μJy/bm) in a full imaging run	6-7	4	15	Performance depends on usable bandwidth and observing conditions. Figures are for e-MERLIN with the Lovell telescope at L and C-band.
Surface brightness sensitivity (K)	190	~70	~530	
ICRF astrometric performance (mas)	2	~1	~2	With respect to the ICRF (assuming a typical 3^{o} target-calibrator separation)
Astrometric repeatability (mas)	~0.5	~0.2	~1	Day-to-day repeatability using surveyed or in-beam sources, and assuming a full imaging run
Amplitude calibration (%)	2	1	10	Targets for day-to-day repeatability

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Legacy & PATT Proposals

PATT proposals (aka PI-led proposals of all sizes)

- 6 monthly call cycle (spring/Autumn) – fully open
- Proposals accepted via Northstar proposals system

See www.e-merlin.man.ac.uk/observe/

- Online Simulator tools and exposure calculators available from e-MERLIN website
- Any use questions : **e-merlin@jb.man.ac.uk**

Typical oversubscription rates are

- 4-3:1 (all proposals)
- 8-5:1 (proposals requesting Lovell telescope inclusion)

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Existing Large Legacy projects

- Account for ~50% of available observing time
- Competatively allocated programme of 12 large projects
- Cover all science areas – planets to cosmology
- Long-term observing status – allowing large international teams to build resources and sustain projects.
- Opportunities for new projects will be available… soon!...

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Current e-MERLIN legacy programme:

Addressing the Key science challenges..

12 Large projects covering planet formation → cosmology

Galactic Science :

- eΠ - Pulsar astrometry – Vlemmings/Stappers et al. 160hrs*
- PEEBLES – planet formation - Greaves et al. 172hrs
- Feedback processes in Massive SF – Hoare/Vlemmings et al. 450hrs
- Thermal jets from low mass stars - Rodriguez et al 180hrs
- COBRaS – wide-field deep galactic survey - Prinja et al. 294hrs

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Extragalactic and cosmology :

- LEMMINGS – 300 nearby gals - Beswick/McHardy et al. 810hrs
- LIRGI – LIRGs/ULIRGs - Conway/Perez-Torres et al. 353hrs
- Extragalactic Jets – Laing/Hardcastle et al 375hrs
- AGATE – cluster fields - Simpson/Smail et al 330hrs
- e-MERGE – deep field - Muxlow/Smail/McHardy et al 918hrs
- Gravitational lenses – Jackson/Serjeant et al 228hrs *
- SuperCLASS - 1+deg^2 supercluster field - Battye et al 832hrs

* Additional allocations pending on-going reviews

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e-MERLIN/VLBI Legacy Science

- Pulsars, Gravity & Gravitational waves
- Time-domain & Transient astrophysics
- Planet & star-formation
- Galaxy formation & evolution
- Cosmic shear & Gravitational lensing

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e-MERLIN/VLBI Science

Pulsars, Gravity & Gravitational waves

Time-domain & Transient astrophysics

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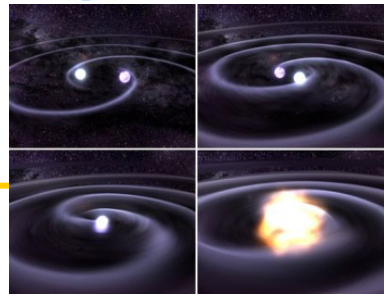
Time-Domain astrophysics

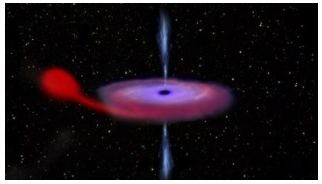
'rapid response, sensitivity and resolution'

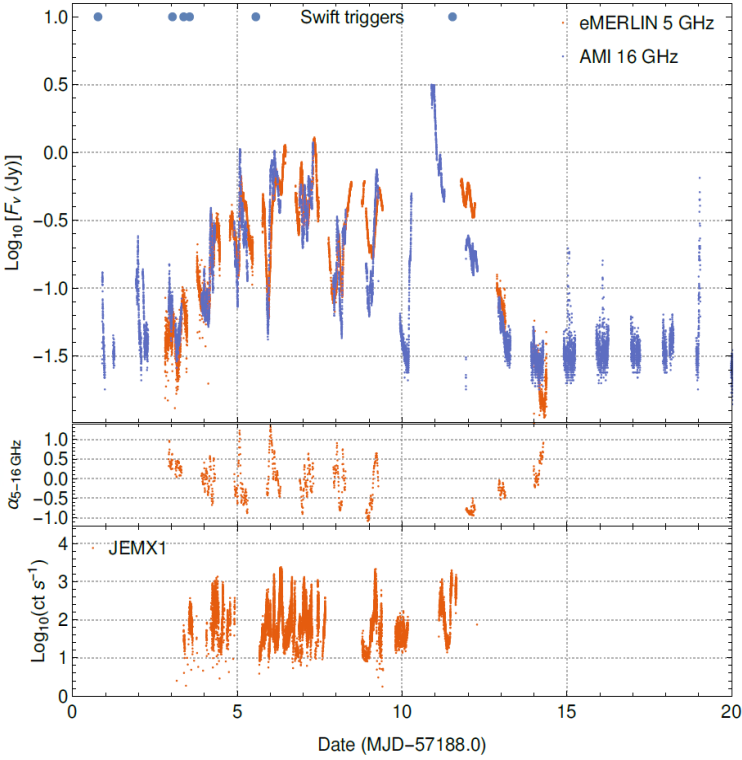


e-MERLIN provides high sensitivity, temporal imaging, mas-astrometry and monitoring of time variable objects.

Galactic objects such as XRB, novae through to SNe, TDEs, GRBs, FRBs etc

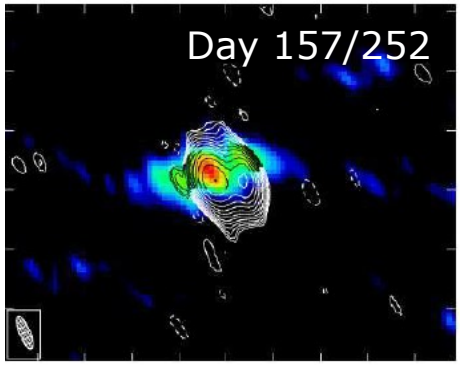
- Most energetic cosmic sources
- High energy particle accelerations
- Time-evolving structures

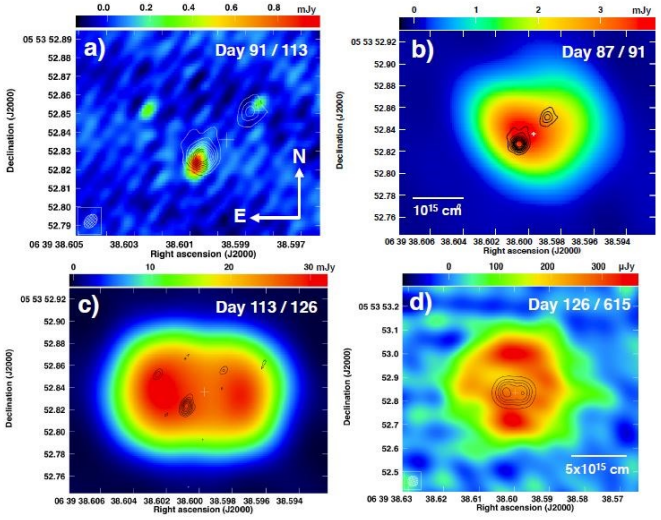




V404cyg 2015 outburst from stellar mass Black-Hole binary
- Unprecedented coverage of particle acceleration (Fender et al., in prep)

Evolution of the gamma ray nova (Nova mon)
EVN+e-MERLIN, jVLA
Chomiuk + 2014 Nature,
Healy+ 2017 MNRAS





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Time-Domain astrophysics

'rapid response, sensitivity and resolution'

X-ray peak

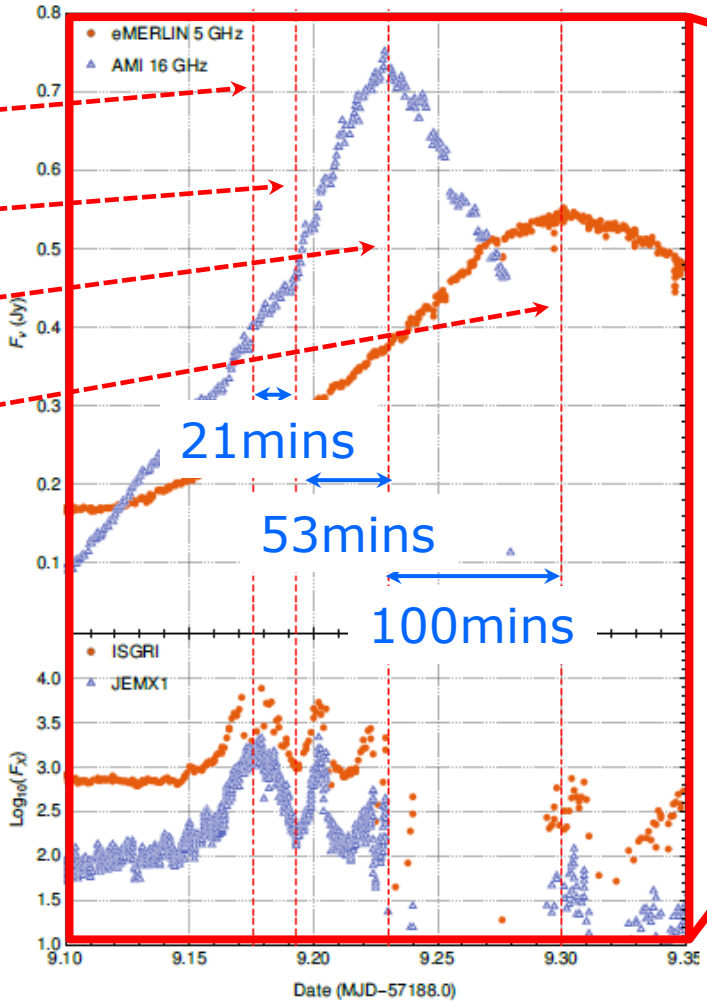
Radio spectral index change

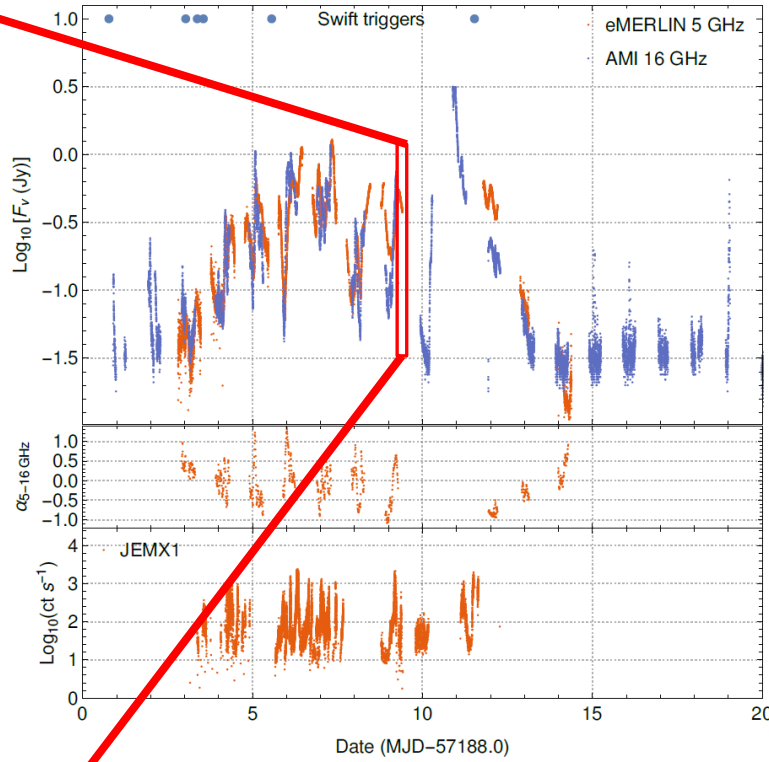
16GHz emission peak

5GHz emission peak

e-MERLIN plus multi-λ campaign

- Highest cadence radio observations
- No jet on e-MERLIN scales (>30mas scales)
- Mix of discrete impulsive particle acceleration injection and strong extended injection events .





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e-MERLIN/VLBI Science

Pulsars, Gravity & Gravitational waves

Time-domain & Transient astrophysics

Planet & star-formation

Galaxy formation & evolution

Cosmic shear & Gravitational lensing

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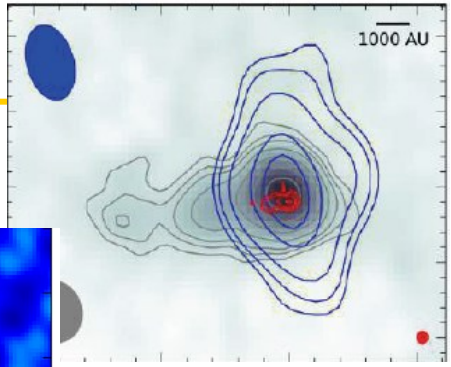
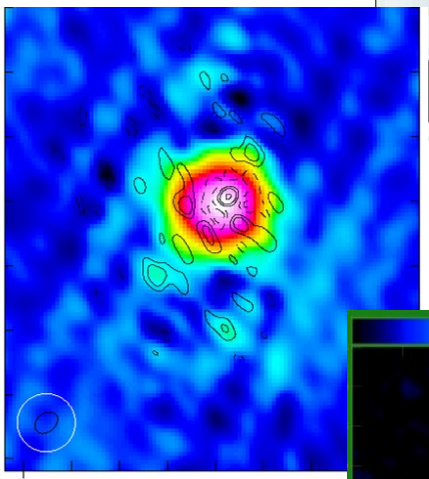
From stars to planets

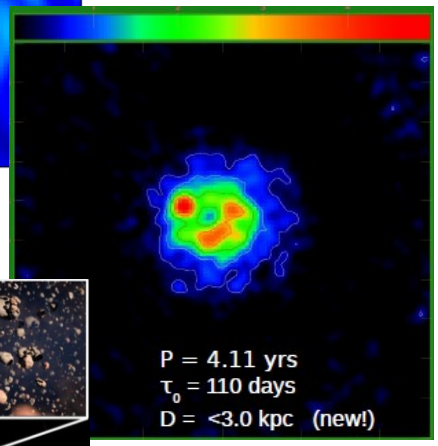
'sensitivity, resolution, spectral lines'

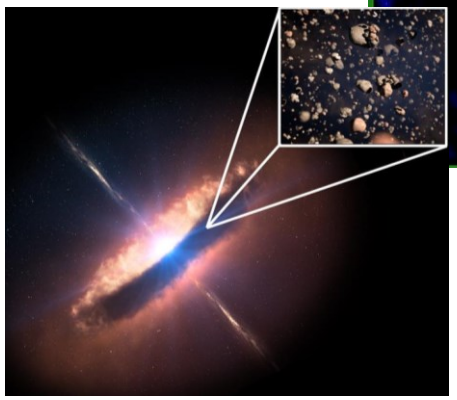
Probing full range of stellar evolution and planet formation

- cm-sized grain formation in protoplanetary disks
- YSOs to evolved stars to stellar end-points
- Stellar outflows
- Stellar evolution
- Molecular astrophysics
- Magnetic fields
- Fundamental physics









Multiple legacy programmes

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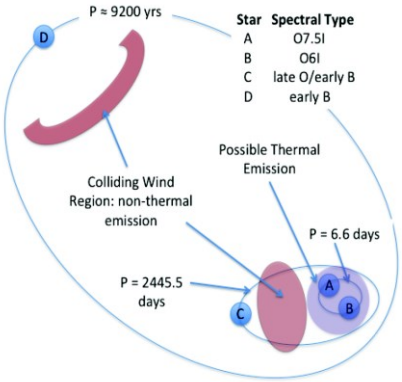
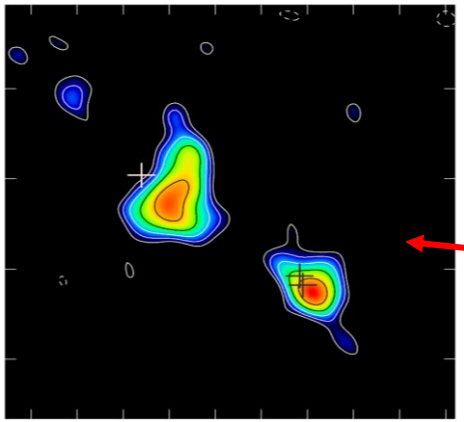
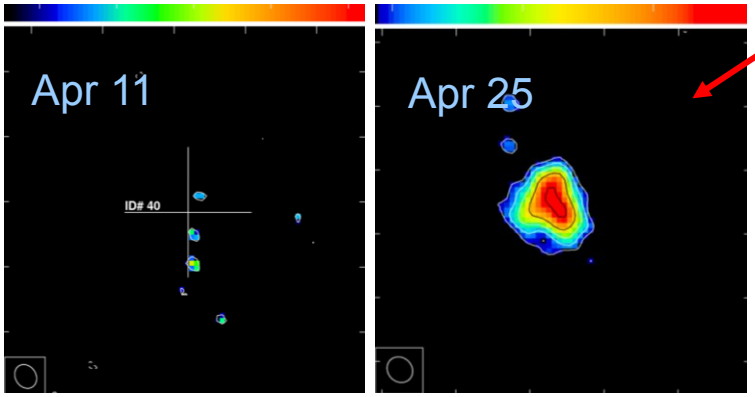
Galactic Star-formation – deep fields

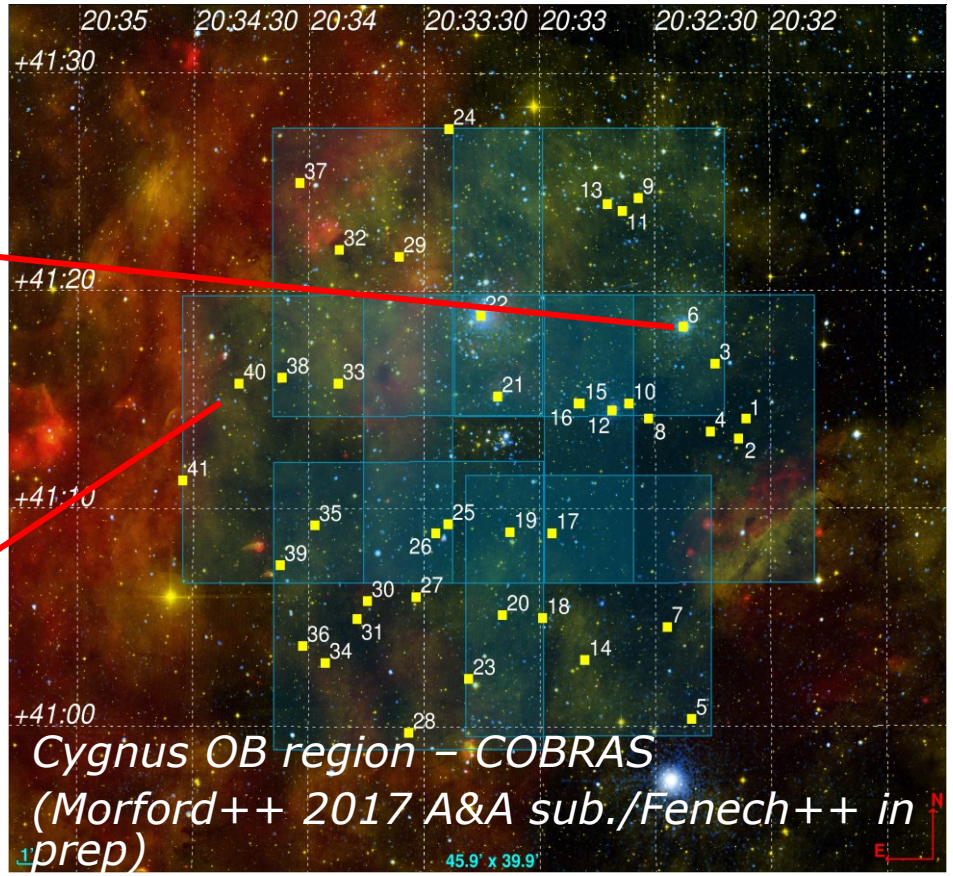




Quadruple star-system with colliding winds



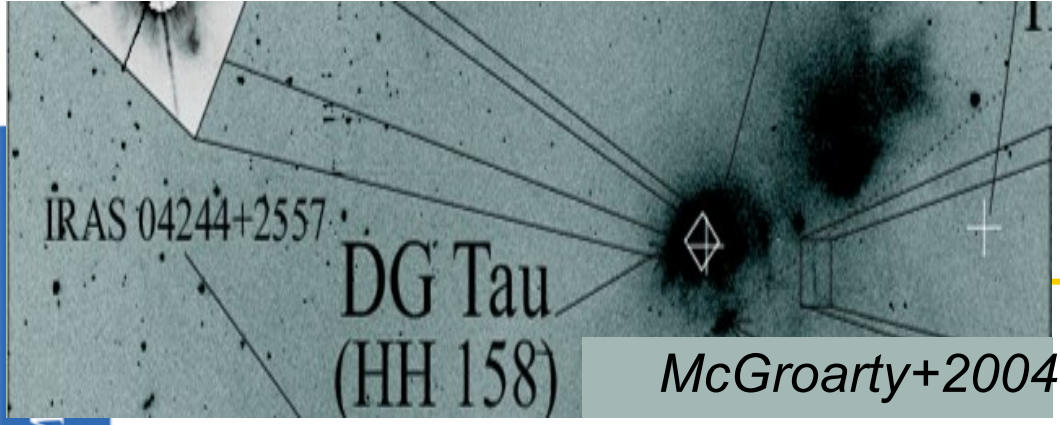
Previously unknown transient sources



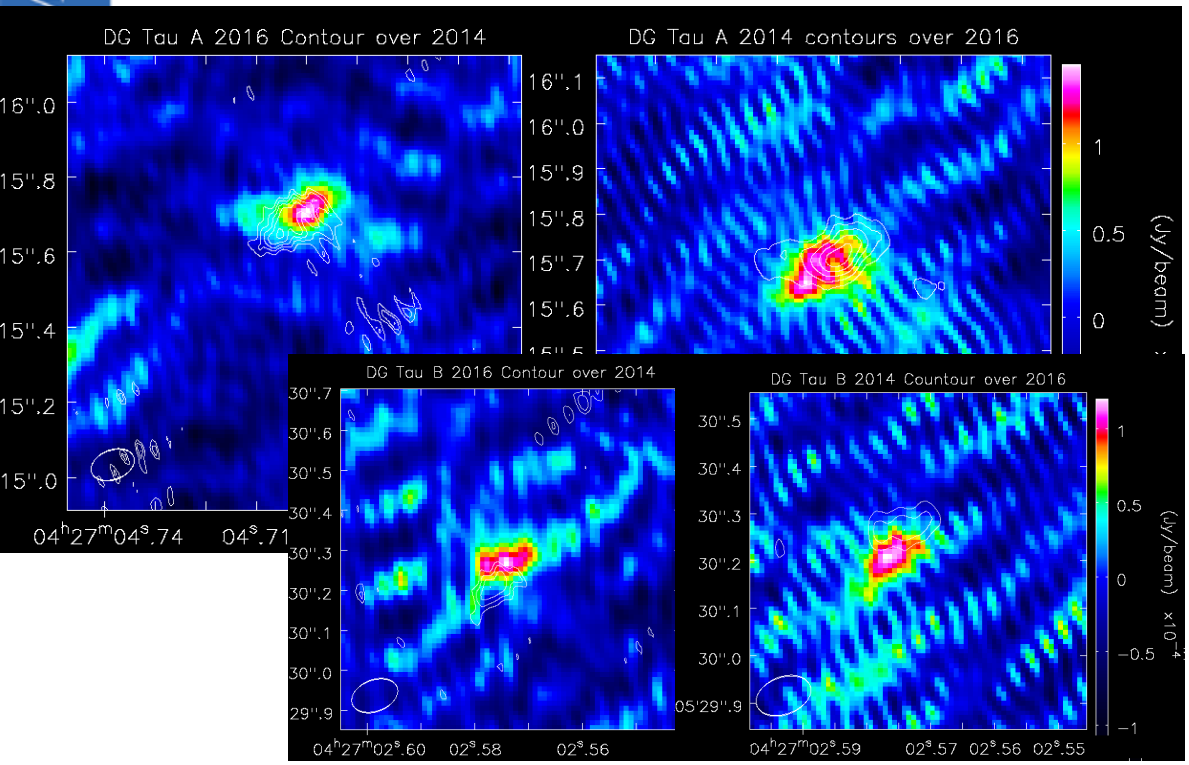
Lowest upper-limits of mass-loss rates for majority of these sources

CoBRAS legacy programme (Prinja et al)

Planet formation



McGroarty+2004



- Imaging protoplanetary discs
- DG Tau A (and younger B)
  - 2014 6.47 GHz
  - 2016 7.25 GHz
- Dusty discs detected
  - 10s au-scale
    - Resolve SED
    - Distinguish disc/jet

(Greaves et al. & Pebbles legacy project)

- More sensitivity, plus (new) X-band, 22 GHz will reveal any large grain clusters within few au of DG Tau A

PeBBLES legacy programme (Greaves et al)

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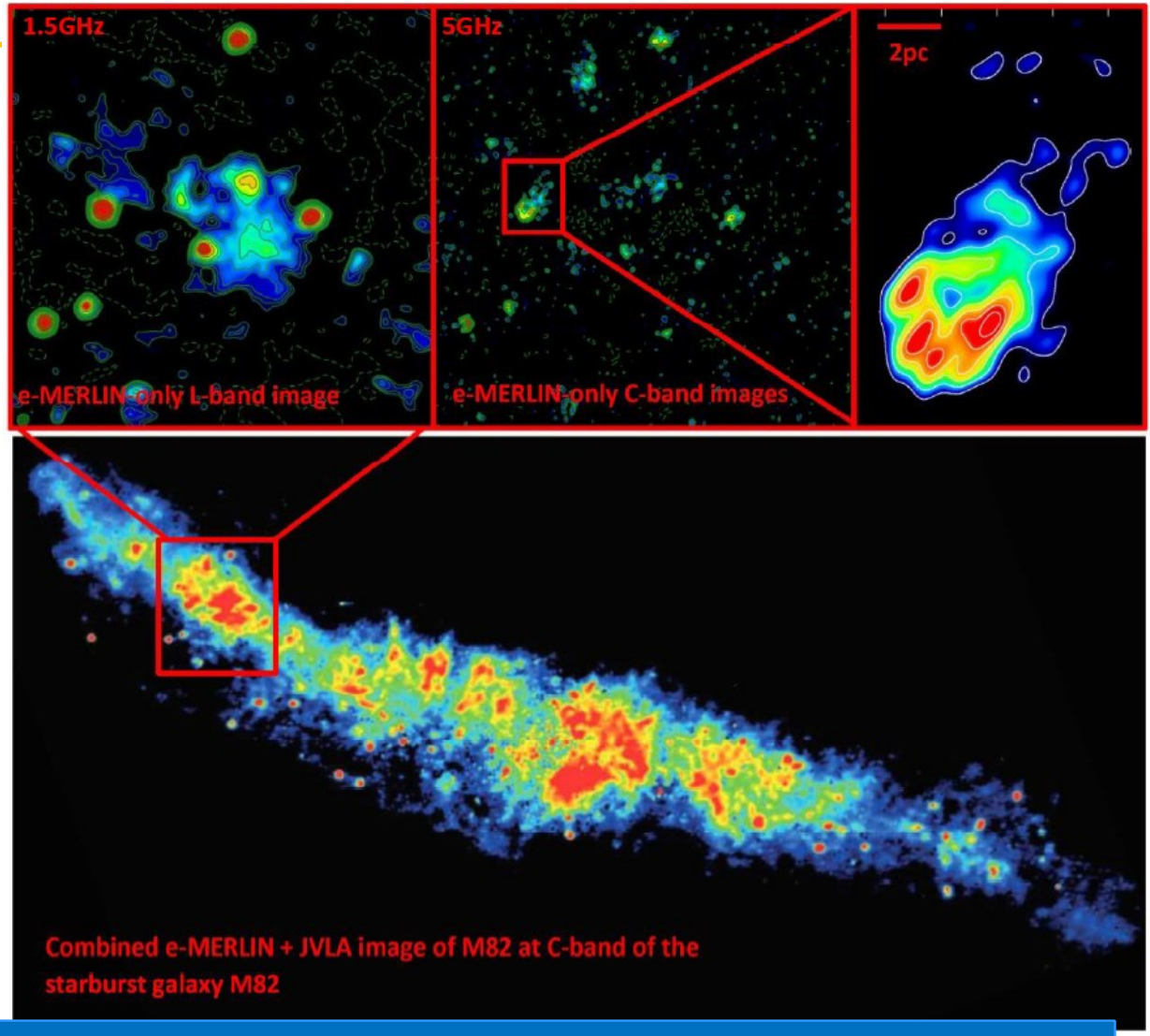
The Local Universe

Seeing through the dust

Decomposing individual galaxies into 100s of SF/accretion products – unique laboratories for galaxy evolution

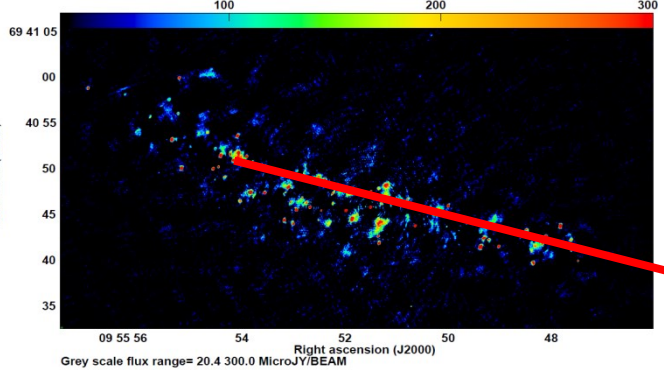
Physics of SF/accretion on sub-pc scales.

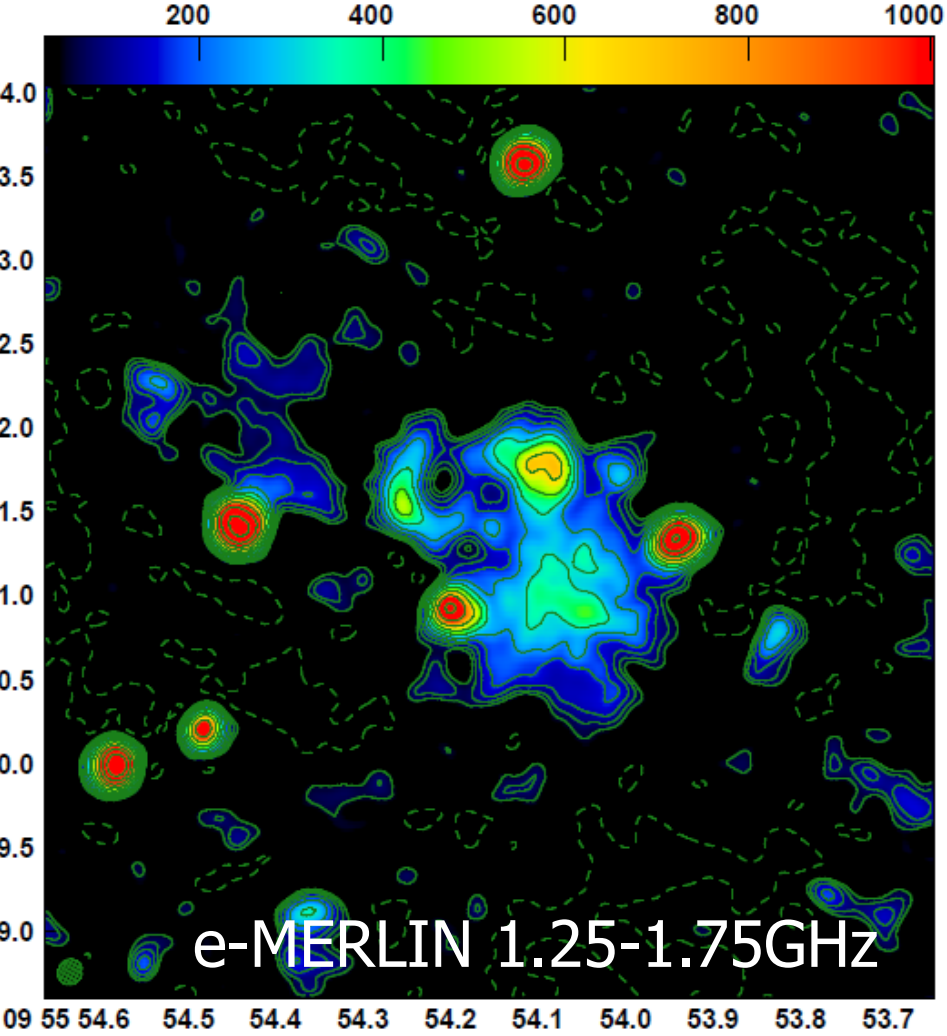
Galactic-style physics in galaxies of all environments and classifications

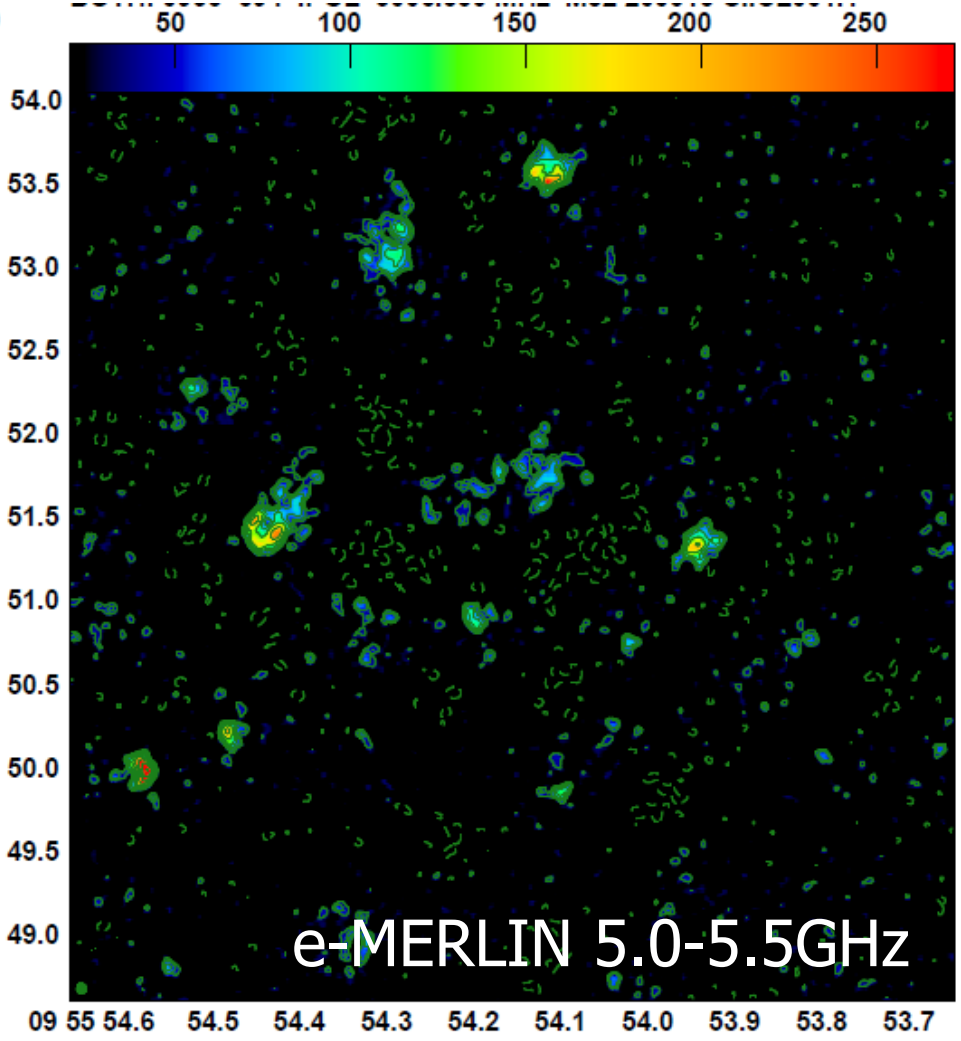


LeMMINGs legacy programme (Beswick/McHardy et al)

New SNR +
increasing fraction of HII regions
- Multiple SNR break-outs

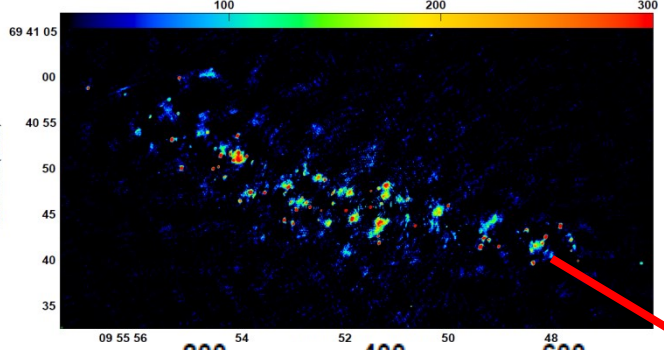


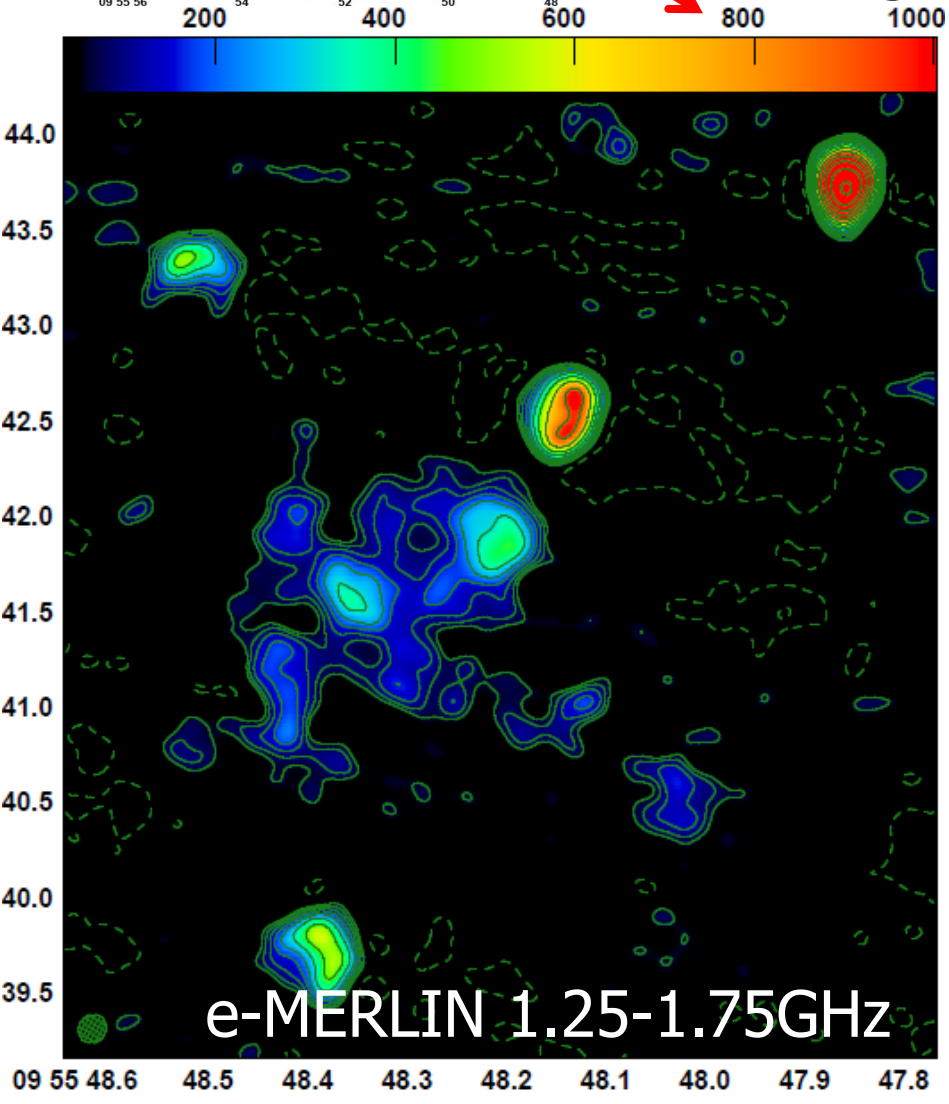


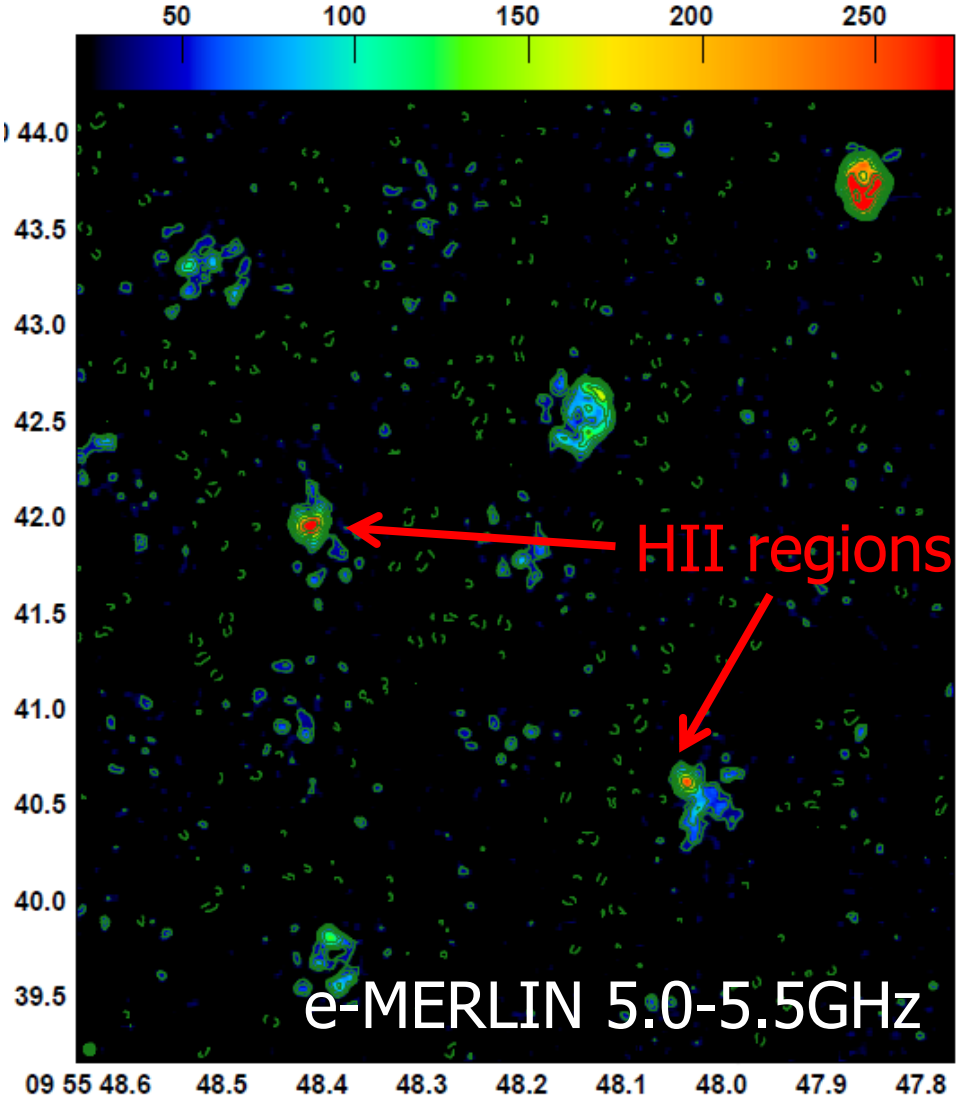


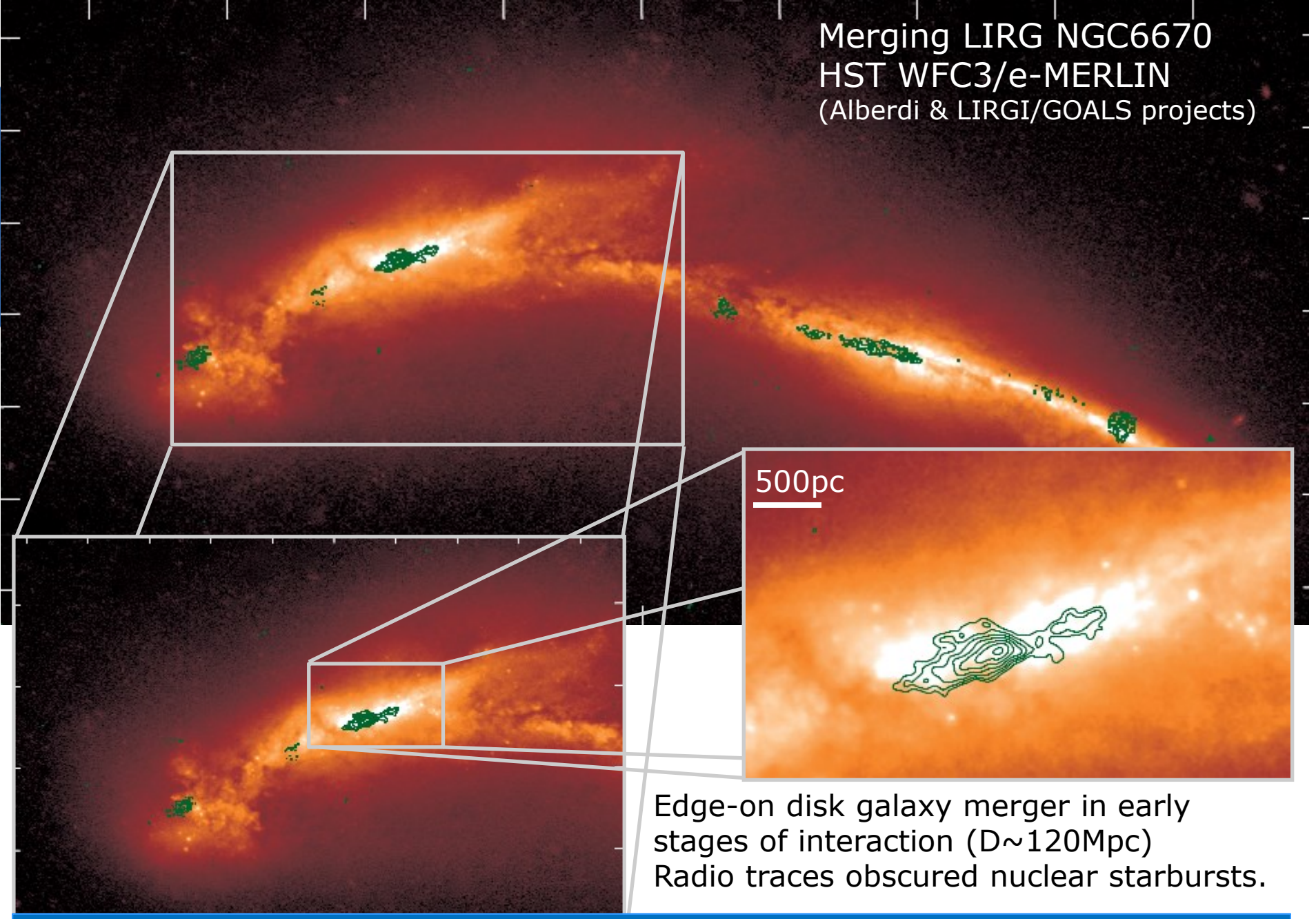
New SNR + Higher fraction of compact HII regions

- Multiple SNR break-outs – expansion into highly inhomogeneous ISM



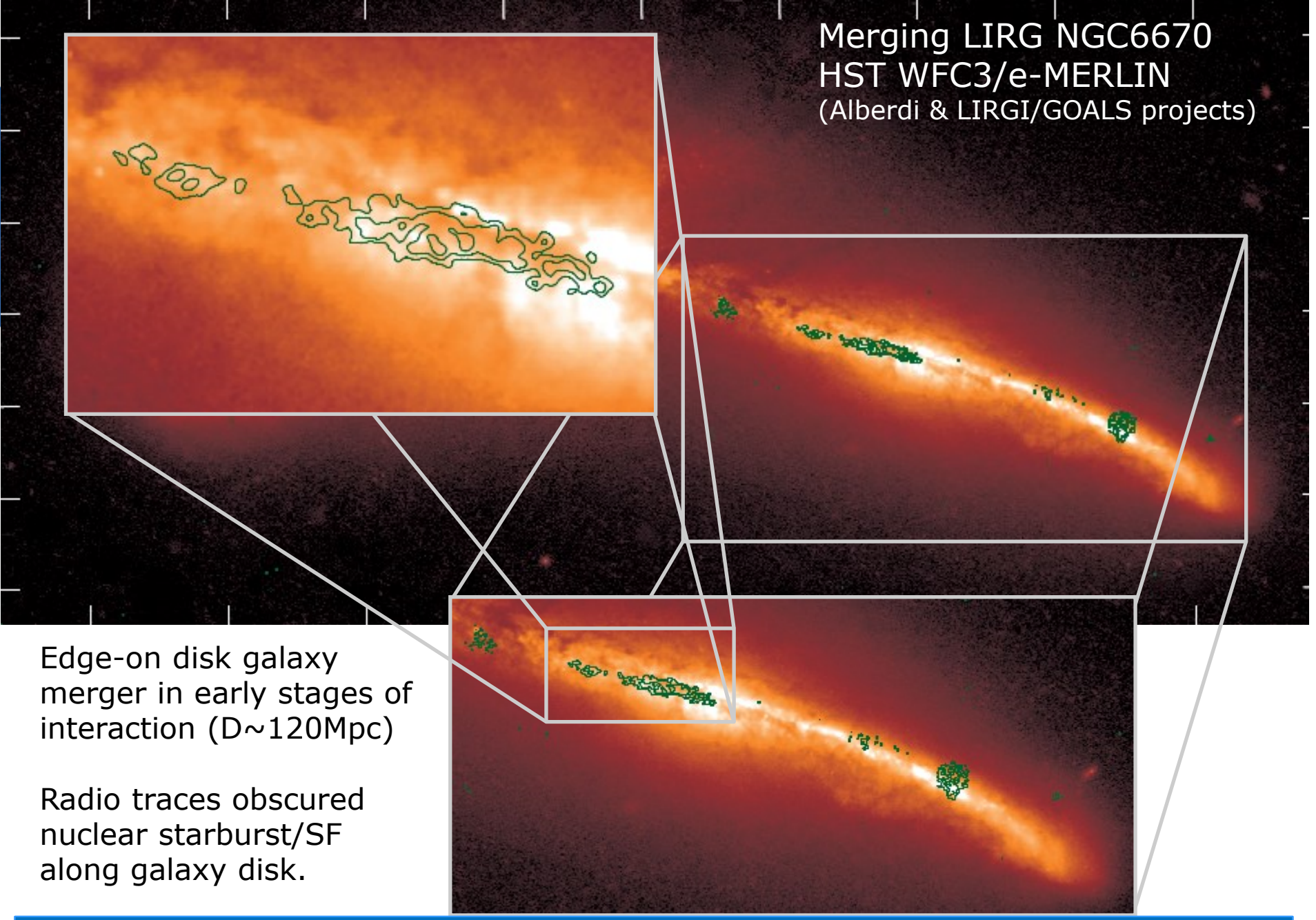






Edge-on disk galaxy merger in early stages of interaction (D~120Mpc)
Radio traces obscured nuclear starbursts.

LIRGI legacy programme (Perez-Torres/Conway et al)



Edge-on disk galaxy merger in early stages of interaction (D~120Mpc)

Radio traces obscured nuclear starburst/SF along galaxy disk.

LIRGI legacy programme (Perez-Torres/Conway et al)

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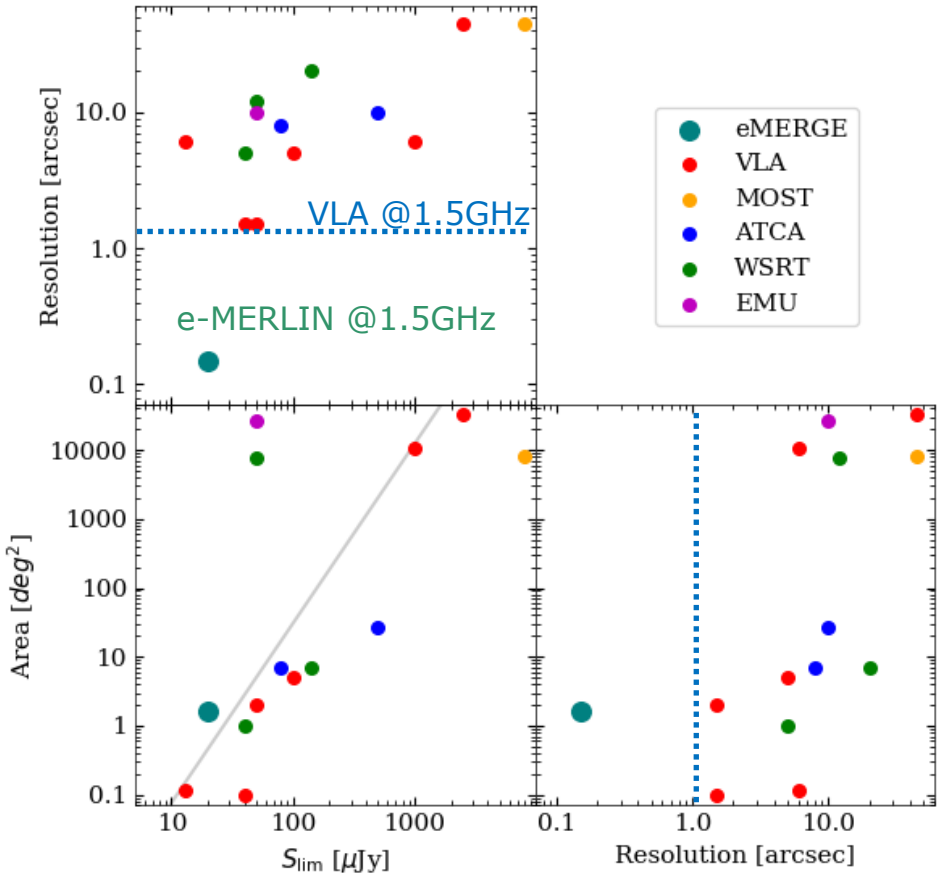
Area/Depth/Resolution..

Traditionally e-MERLIN 'more targeted' objected based programmes.

Large legacy surveys now targeting moderate areas

- eMERGE, AGATE, SuperCLASS & CoBRAS

- Not huge areas (typically degs^2)
- But different part of *resolution space*



e-MERLIN resolution – actually resolve <u>all</u> sources!!
- spatial separation of SF/AGN

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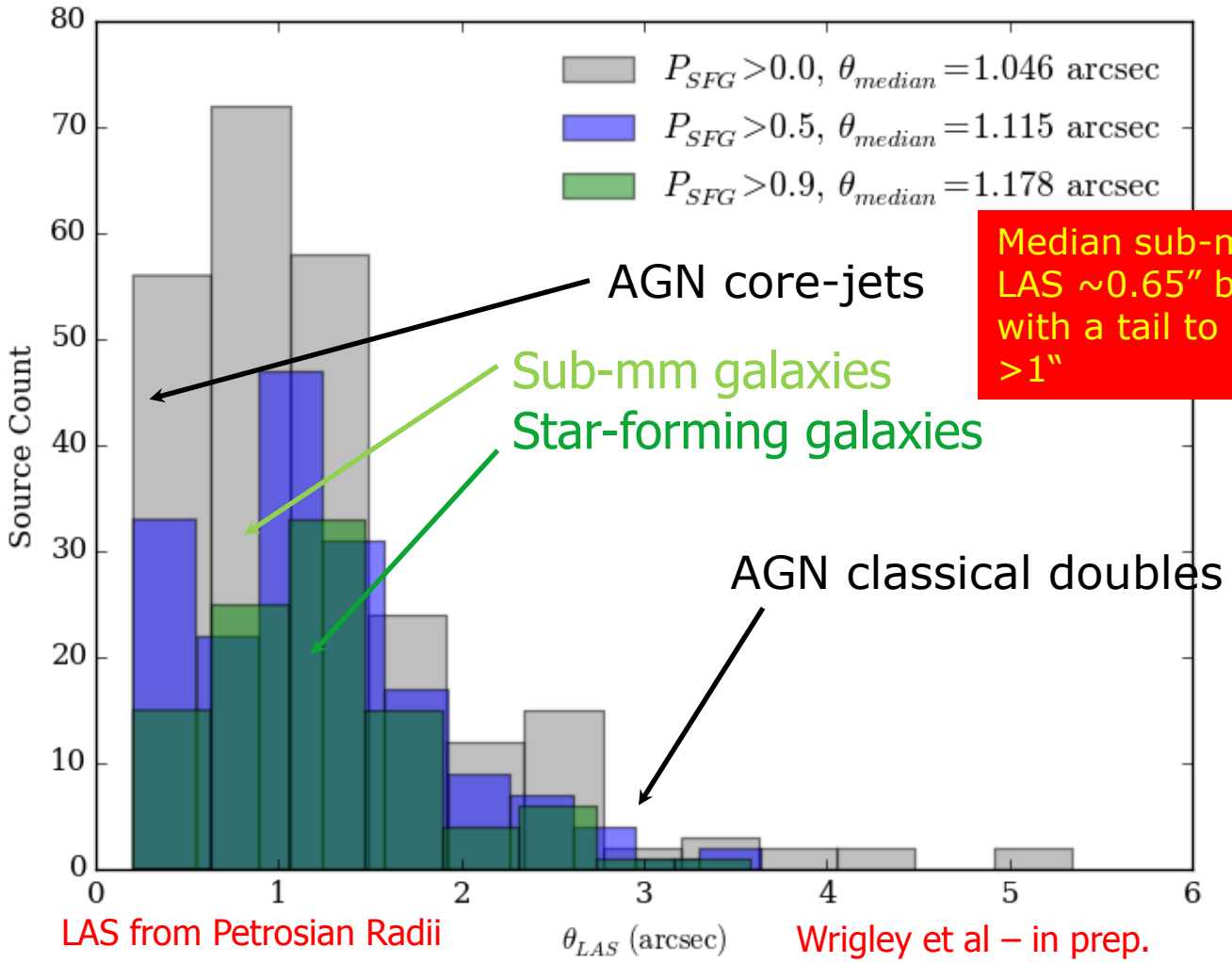
Size of the faint radio source populations

Sample of 248 detected sources within central 12' field from ~90 hrs of data.

Assign probabilities of being AGN or SF from radio structures and spectral properties...



Median sub-mm LAS ~0.65" but with a tail to sizes >1"

LAS from Petrosian Radii

Wrigley et al – in prep.

Machine-learning (SVM – Support Vector Machine)

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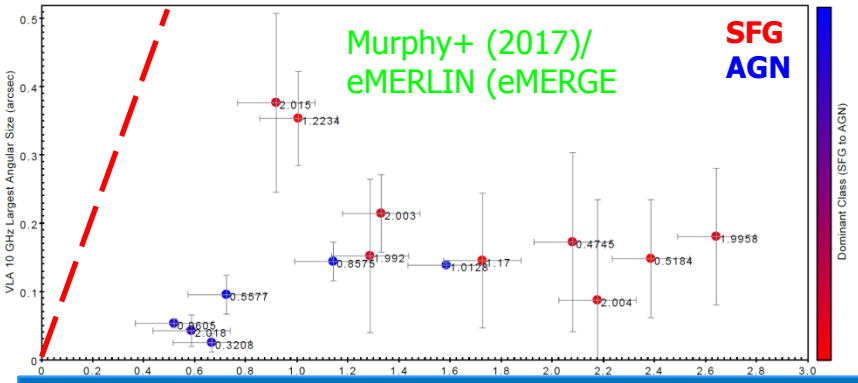
Star-formation across cosmic time: e-MERLIN deep fields

e-MERGE (e-MERLIN key science project deep field)
Extragalactic Deep field imaging

~200mas resolution separates SF and AGN activity and shows detailed feedback where present. SF galaxies dominate 1.5GHz number counts <100μJy

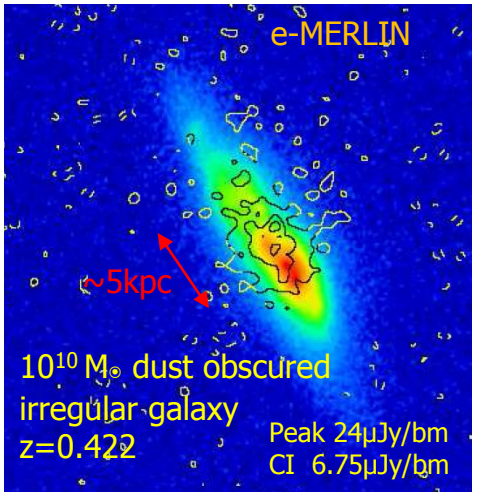
For z<0.5 – Extended starbursts aligned with major axis
For z>0.5 – Additional compact nuclear starburst components become more common

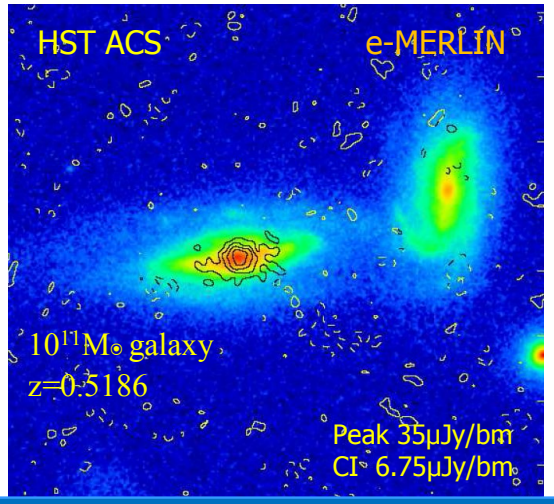
JVLA 10GHz (~200mas) show LAS up to x10 smaller



JVLA at 10GHz detects only the central nuclear starbursts in star-forming galaxies

- and the inner core-jet structures in AGN systems





eMERGE legacy programme (Muxlow/Smail/McHardy++)

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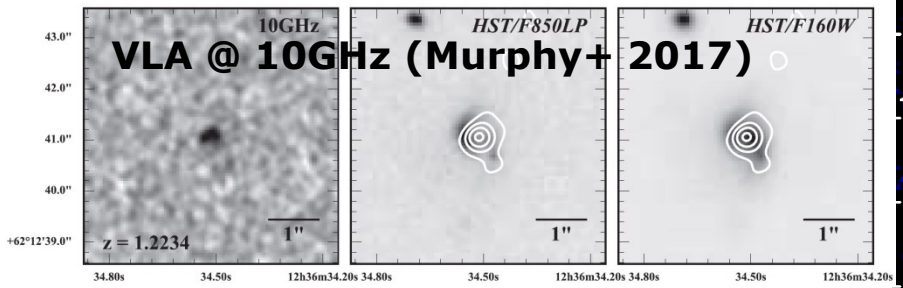
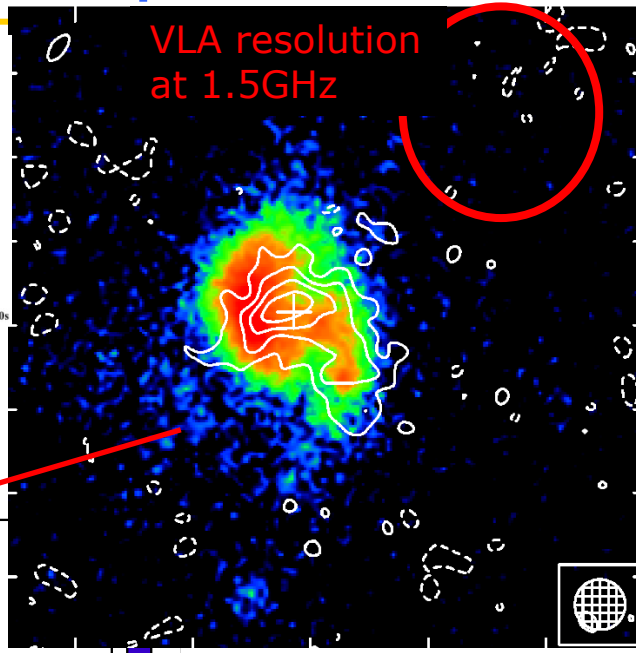
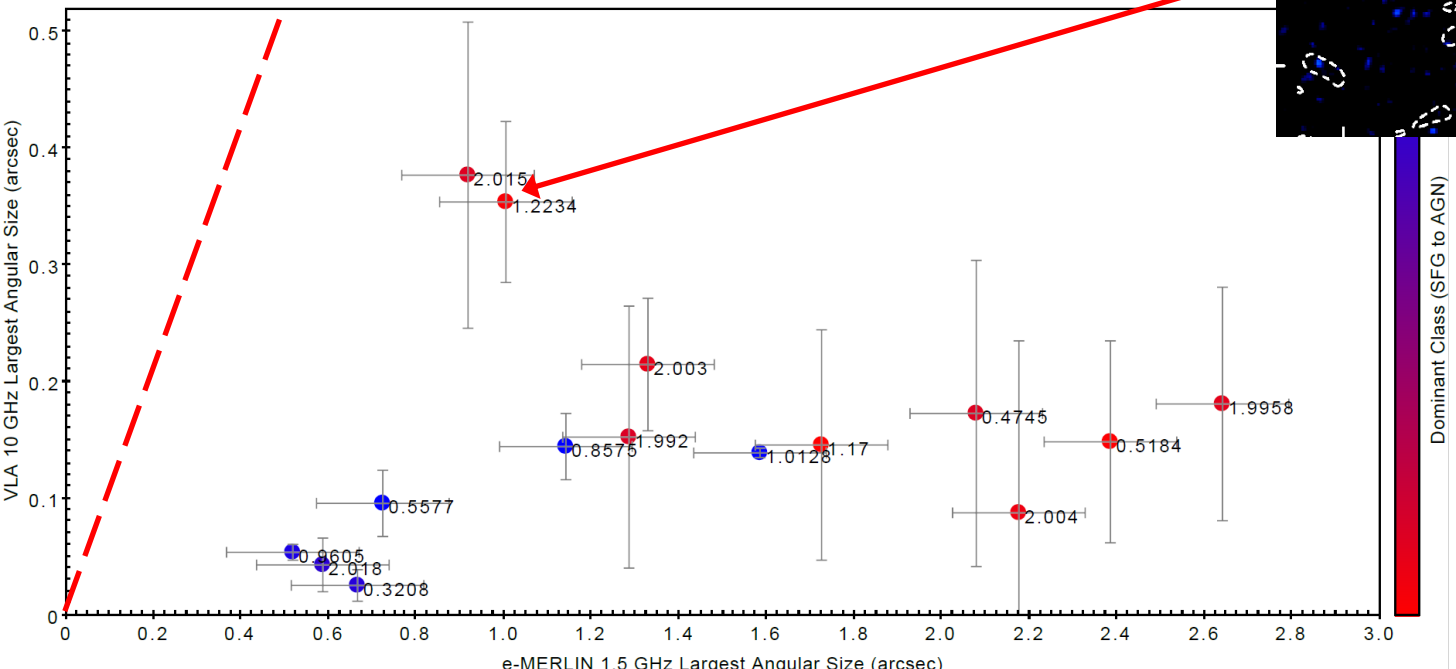
Star-formation across cosmic time: e-MERLIN deep fields





→ Star-formation rate ~960 $M_\odot$/yr

Merging Scd sub-mm galaxy with tidal tail - High redshift version of the 'Antennae'



JVLA at 10GHz detects only the central nuclear starbursts / merging cores in star-forming galaxies

- and the inner core-jet structures in AGN systems

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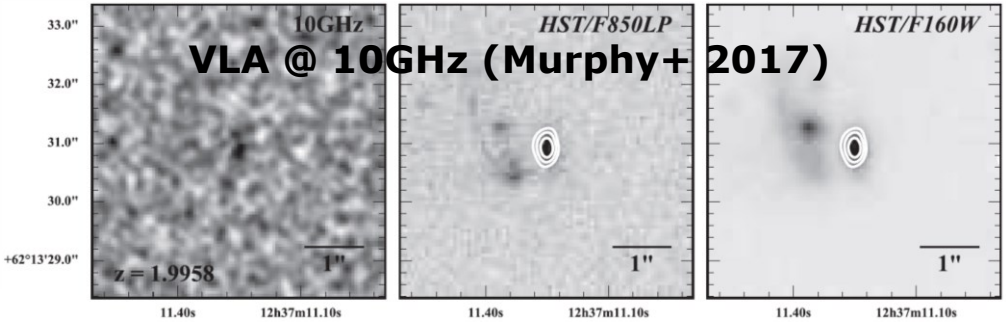
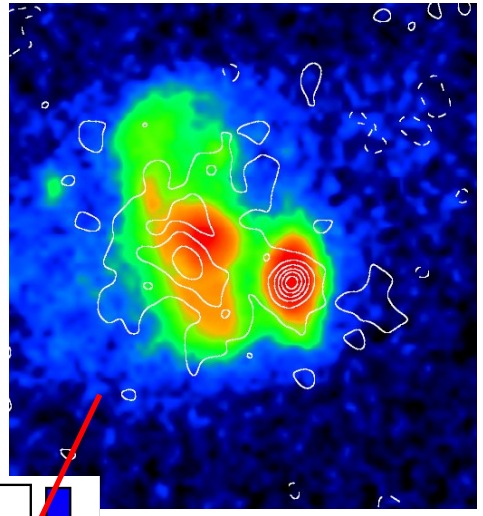
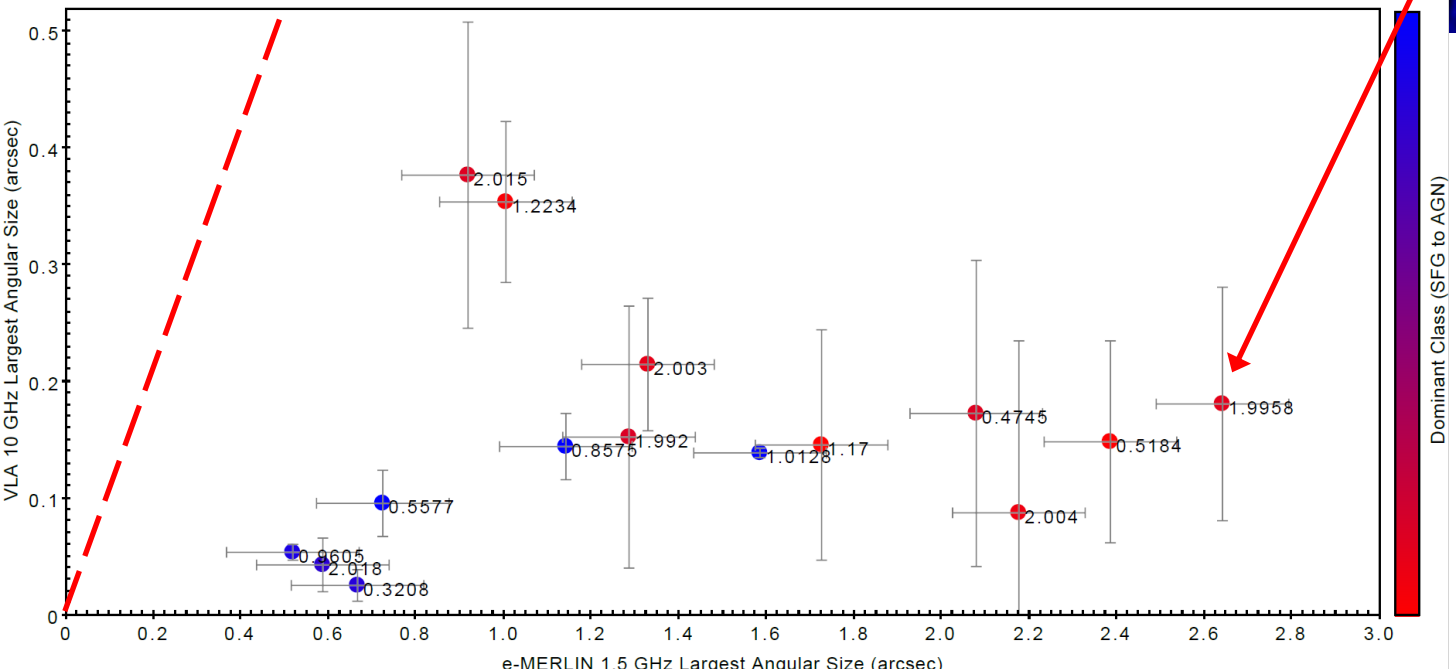




→ Steep-spectrum (α=-0.69) merging system with star-formation + a nuclear starburst (160x90mas)



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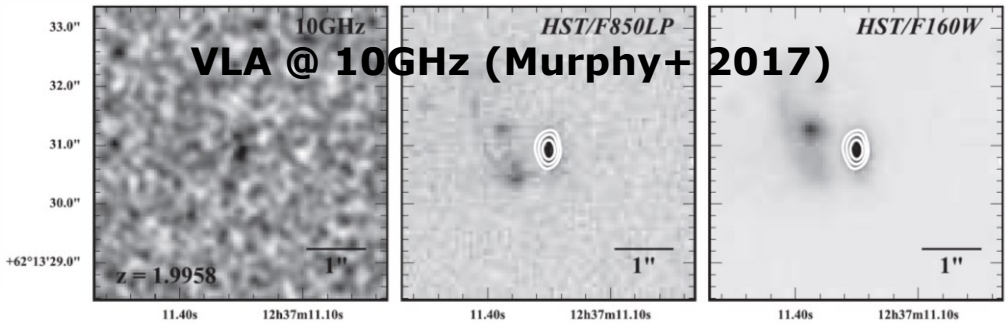
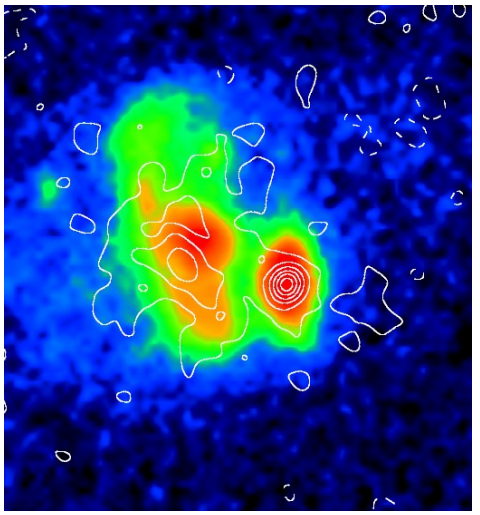


VLA @ 10GHz (Murphy+ 2017)



→ Steep-spectrum (α=-0.69) merging system with star-formation + a nuclear starburst (160x90mas)

Only at lower (few GHz) frequencies are the is the full extent of the star-formation detected.

- Higher frequencies see compact cores only.

ONLY at e-MERLIN resolutions and sensitivities can fully detect and resolve.

- Spatially separating emissions to providing a direct and unobscured measure AGN & star formation emission

Unique window on the co-evolution of accretion and star-formation from z~0.2 → 5

JVLA at 10GHz detects only the central nuclear starbursts / merging cores in star-forming galaxies

- and the inner core-jet structures in AGN systems

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e-MERLIN/VLBI Science

Pulsars, Gravity & Gravitational waves

Time-domain & Transient astrophysics

Planet & star-formation

Galaxy formation & evolution

Cosmic shear & Gravitational lensing

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Cosmic shear : radio weak lensing

Pioneering radio weak lensing surveys - aiming at first radio weak lensing detections. Pathfinder for SKA science

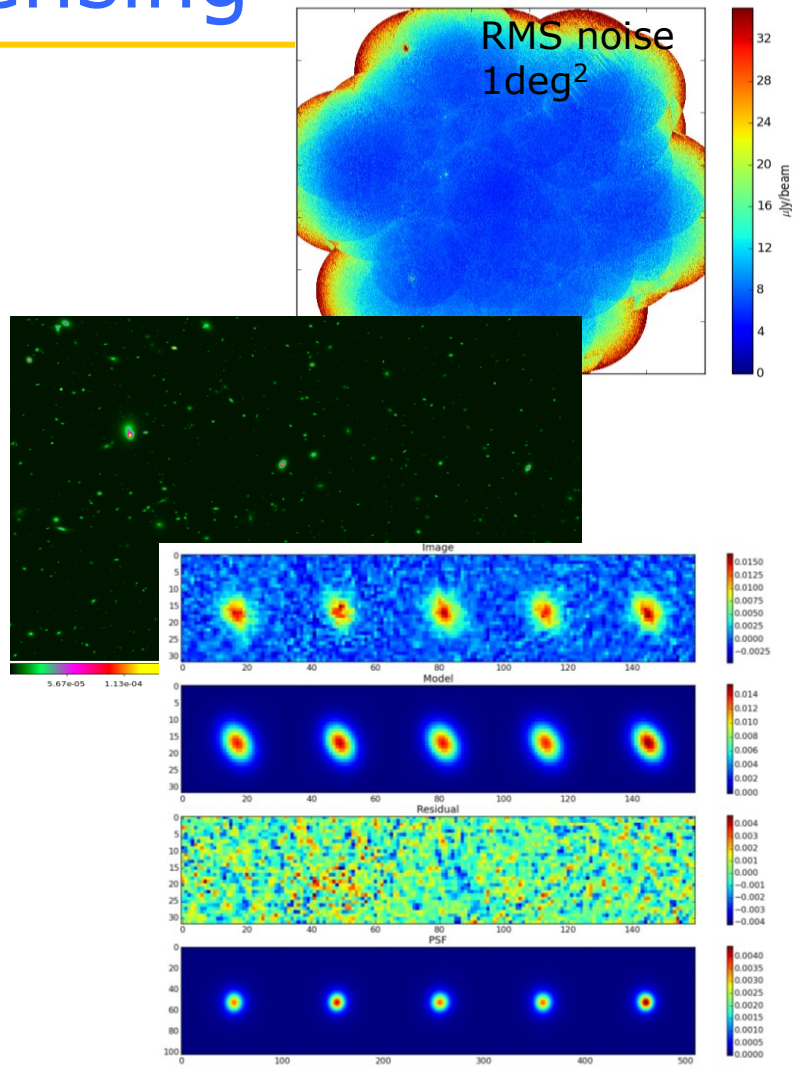
Exploiting e-MERLIN's unique ability to resolve high-z radio starbursts

- precisely defined, stable PSF

SuperCLASS field covering multiple supercluster fields

- combined Multi-λ programme

Radio + Optical weak lensing → powerful complementary constraints.



SuperCLASS legacy programme (Battye et al)

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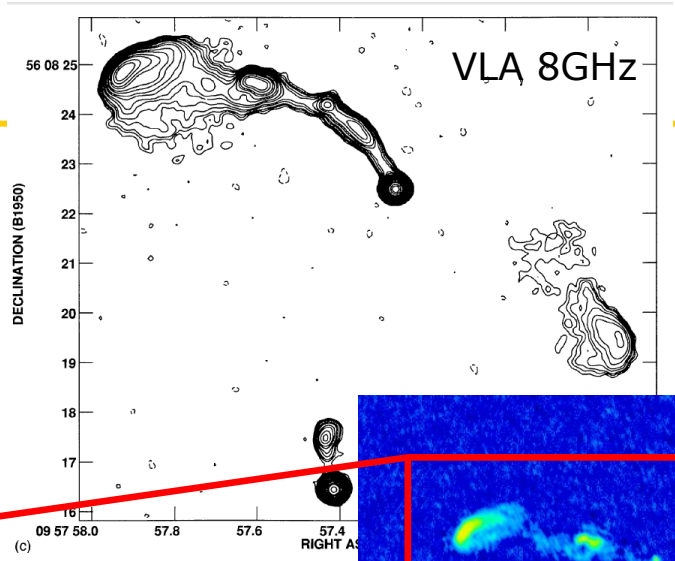
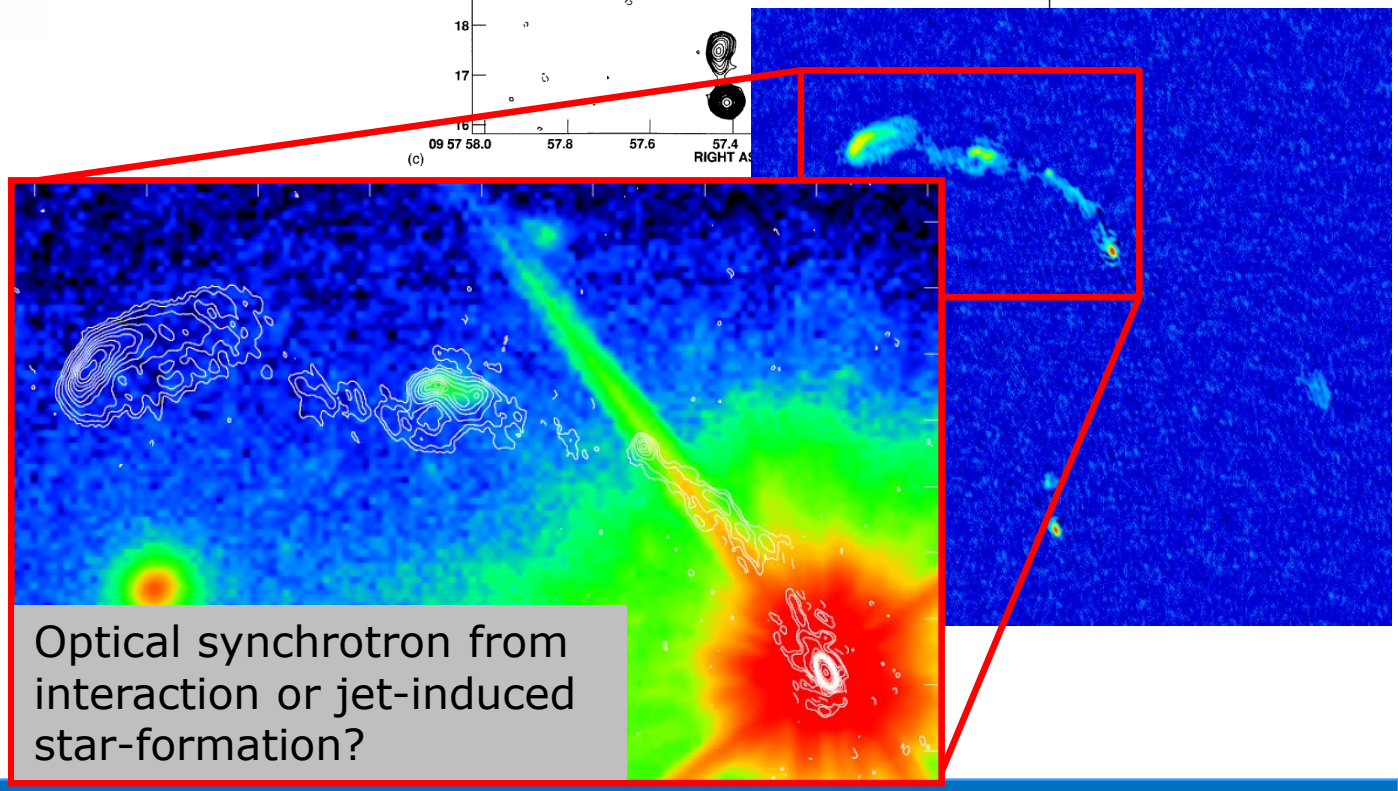
Strong lensing

e-MERLIN

On-going seep follow-up of lens

Known lens and new discoveries

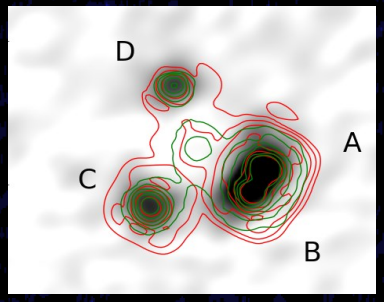




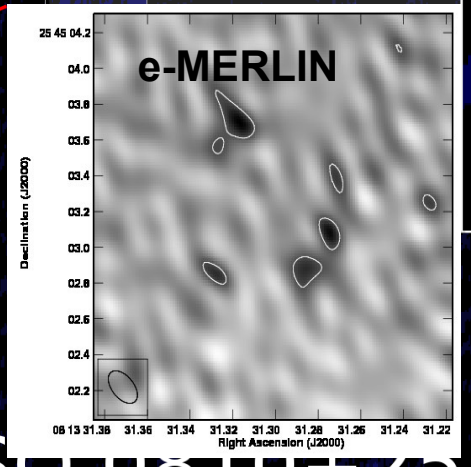
Strong lens legacy programme (Jackson/Serjent++)

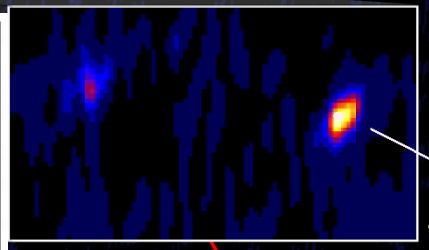
Probing the faintest 3μJy Radio-quiet quasars (SKA SCIENCE NOW)

Intrinsic flux density ~**3uJy**
r.m.s. = **7uJy**/beam



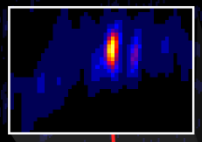
~0.1"



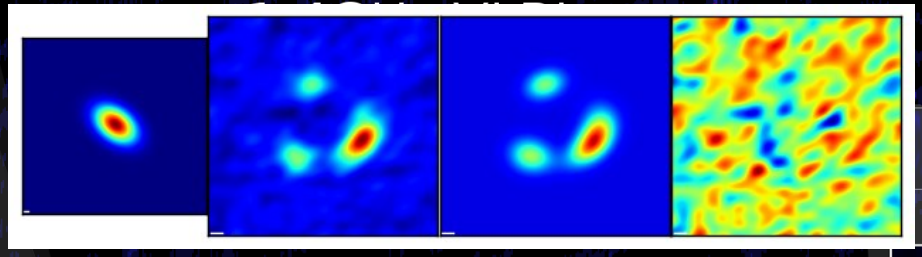


$T_B \sim 10^6$ K

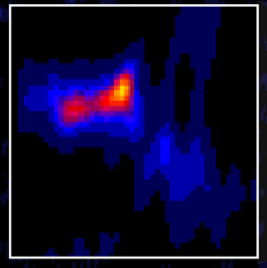
Multi-resolution → nature of radio emission (AGN-dominated) & Lens models →Probe galaxy Substructure

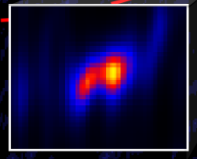


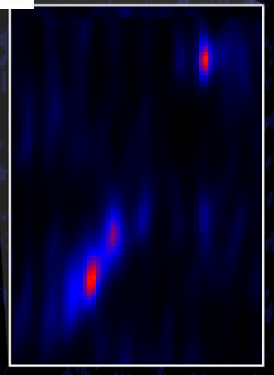
QSO 0810+2354



LENS MODEL







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What next…?

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What next…?

a) On-going Operational upgrades
- Final commissioning of 2GHz bandwidths (C/K-band)
- Phasing up of array – superb PSR/transient instruments ~equivalent to 110m dish
- Inclusion of new dishes – Goonhilly + other? – More resolution, more coverage
- PAF on LT
- e-MERLIN fully in EVN → baselines from 10 to 10,000s km

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b) An ambitious, yet cost-effective, series of major upgrades

- New SDP-like software pipelines – look, feel behave like SKA
- New Frequency bands - S-band and X-band (band 5b)
- Cyro-PAF (S-L-band)
- Replacement of Defford telescope (with SKA1-mid dish) – allow better performance at >~6GHz
- Digital upgrades → increase bandwidths

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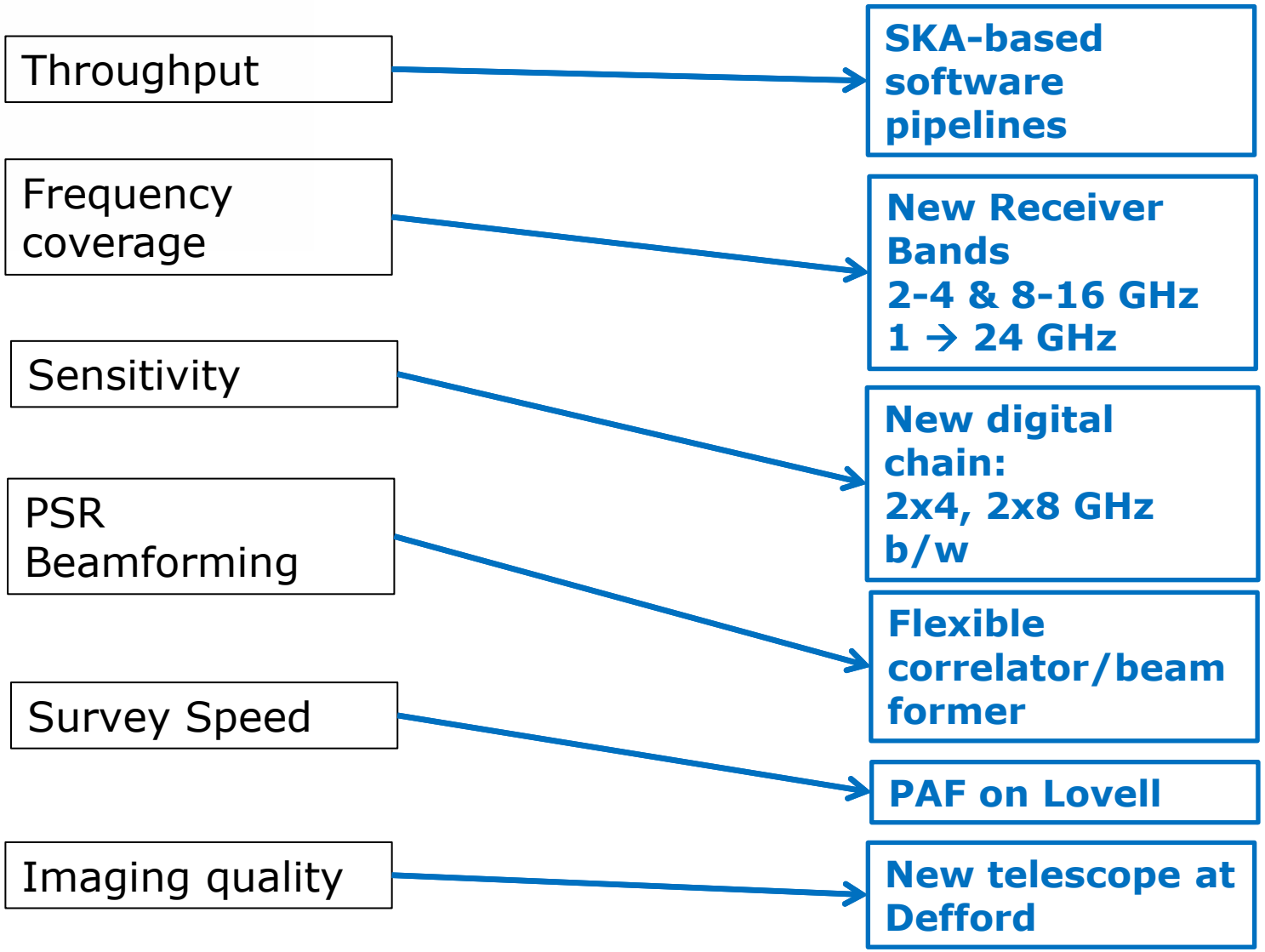
e-MERLIN Upgrades – science driven upgrades



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Upgraded capabilities

	1.5GHz (L-band)	3GHz (S-band)	5GHz (C-band)		10GHz (X-band)		22GHz (K-band)	Notes	
		WP3			WP4 & WP7				
Resolution (milliarcseconds)	150	-	40		-		12	(1) no Goonhilly	
	75	**75**	**20**		**20**		12	(2)	WP3,4
Field of View (arcmin)	LT (No-LT)11 (30)	-	LT (No-LT)3 (9)		-		2	(1)	
Field of View (arcmin)	**With LT PAF**	**With LT PAF**	LT	No-LT	LT	No-LT	No LT	(3)	WP5
	30	**15**	3	9	**1.5**	**4.5**	2		
Frequency range (GHz)	1.25-1.75	**2-4**	4-8		**8-15**		21-24	(4)	WP3,4
Bandwidth (GHz)	0.5	**2**	2		**2**		2	(5)	WP3,4
Sensitivity (μJy/bm) in a full imaging run	6-7	**3-4**	4-5		**4**		15	(6)	WP3,4
Bandwidth (GHz)	0.5	**2**	**4**		**4**		**4**	(5)	WP3,4, 6,7
Sensitivity (μJy/bm) in a full imaging run	6-7	**3-4**	**2-2.5**		**4**		**4**	(6)	WP3,4, 6,7

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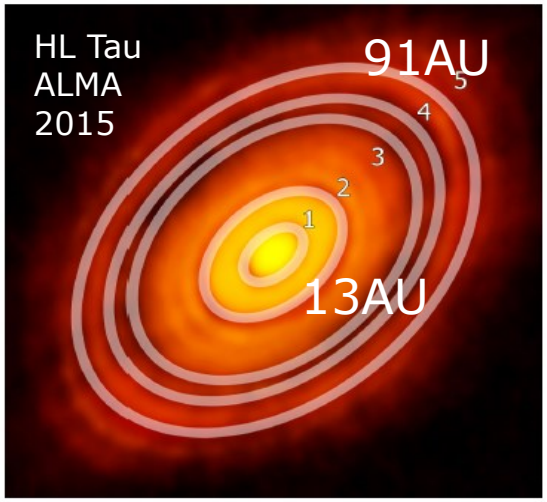
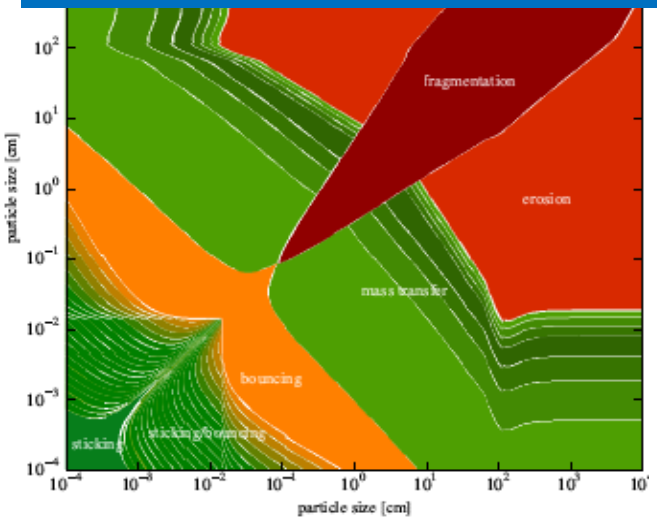
Science Examples:
Planet-forming disks



How to go from Dust → pebbles → planets?



Inner 10AU (Saturn) opaque to sub-mm [MMSN]

- Need cm wavelengths to see through dust & detect pebble material
- At 1AU need >~ 3 cm
- Jup: 40 mas, Mars 12 mas

→ e-MERLIN at 10 GHz is ideal:

1 uJy/b = 15 K (τ=0.15 T=100K)

20 mas resolution

use 5 GHz, 22 GHz to untangle emission

thermal jets, disk winds, synchrotron

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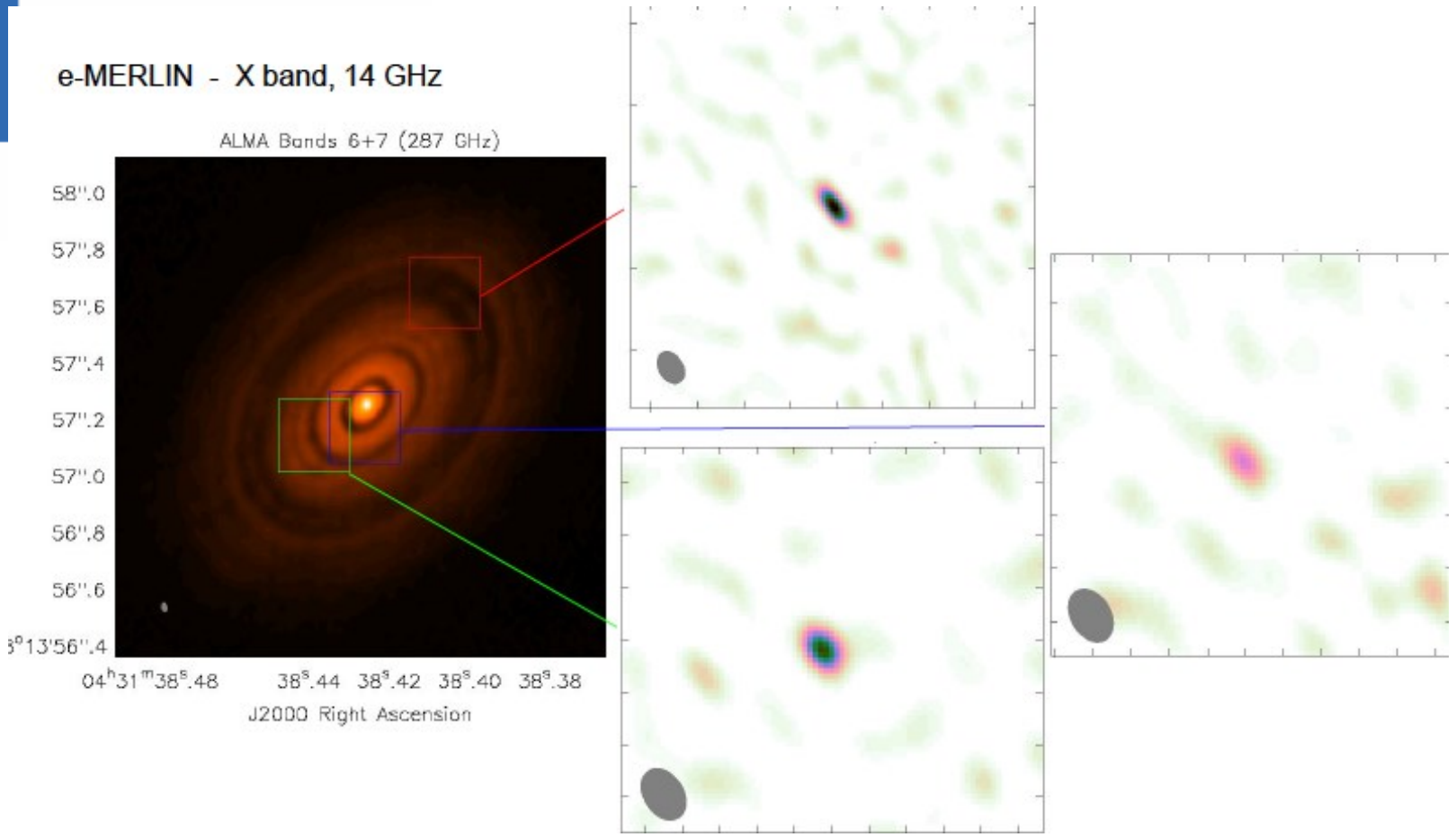
8-16 GHz simulations



Javier Moldon (e-MERLIN/JBO)

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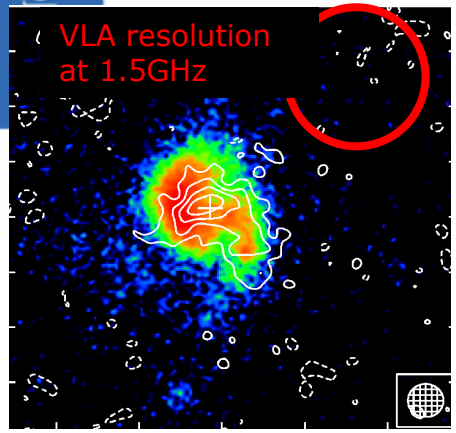
Science example: Galaxy evolution



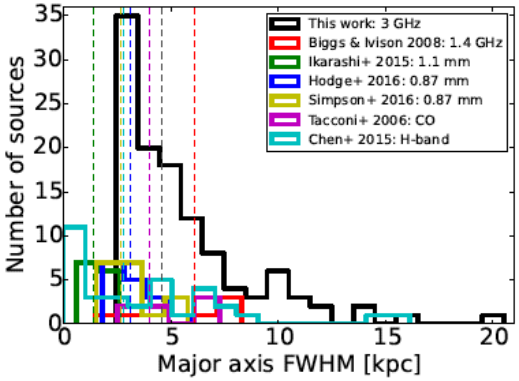


Fig. 9. Distributions of the SMG sizes (major axis FWHM) measured in radio, dust, CO, and stellar emissions. The black histogram shows the sizes of our COSMOS ASTE/AzTEC SMGs as seen at ν_{obs} = 3 GHz.

- Cosmic star-formation history
- Most star-formation obscured

-> radio (SNR, HII) or sub-mm (dust)

- Radio emission is very faint, steep spectrum, and extended ~ 1”

→ Need ~0.1” resolution, ~ 2 GHz

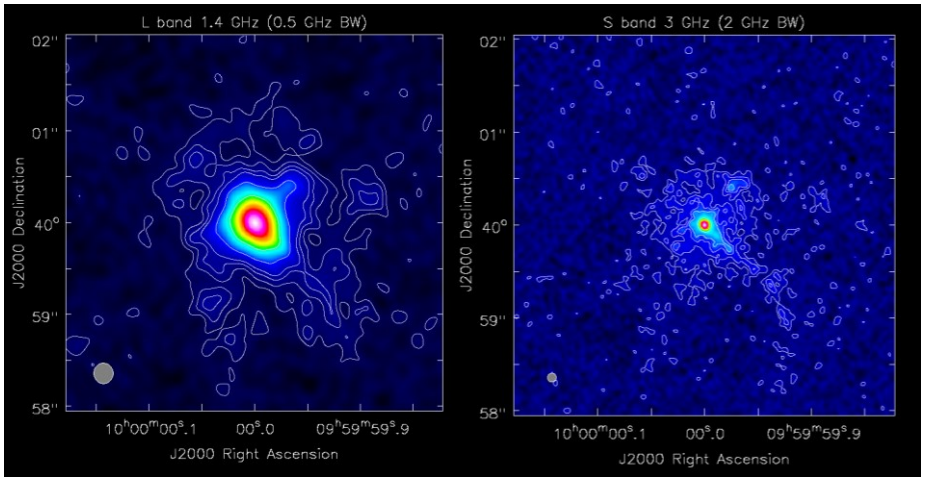
e-MERLIN S-band (2-4) GHz ideal

0.1” resolution, increased b/w

Where does star-formation occur?

Dust sizes < radio sizes

Separate AGN emission



2-4GHz Simulation examples

Summary

- e-MERLIN provides a unique set of capabilities
  - Providing the frequencies and baseline lengths of SKA1-Mid now.. Perfect for (pre-SKA) science demonstration and development..
- e-MERLIN legacy programme covering a wide range of science goals
  - Current programmes first sets of results coming out now
  - New programmes will be considered in future rounds
- Exciting range of new capabilities being considered to further enhance instrument (~15M£ programme)
  - Great capabilities and complementarities
  - ~25% SKA1-mid…, new RXs 1-26GHz…, enhanced survey speeds etc… etc…

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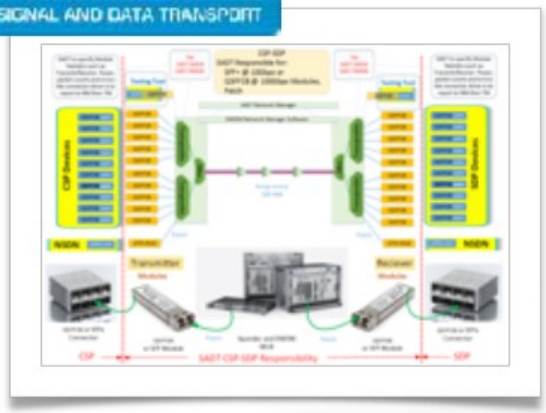
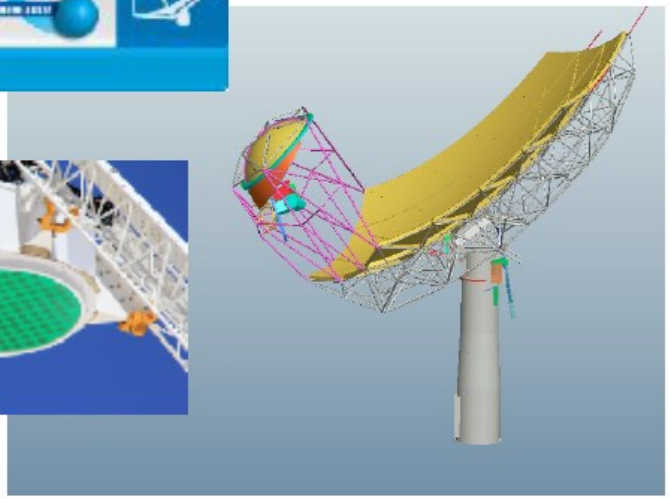
Building upon and leveraging SKA investments

SKA SIGNAL AND DATA TRANSPORT

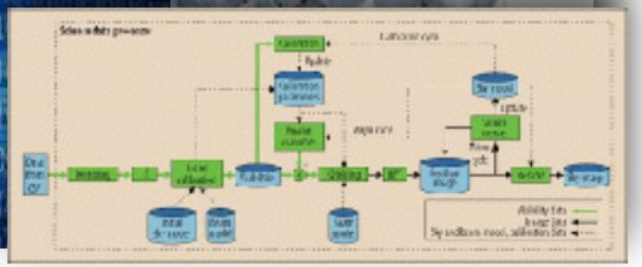


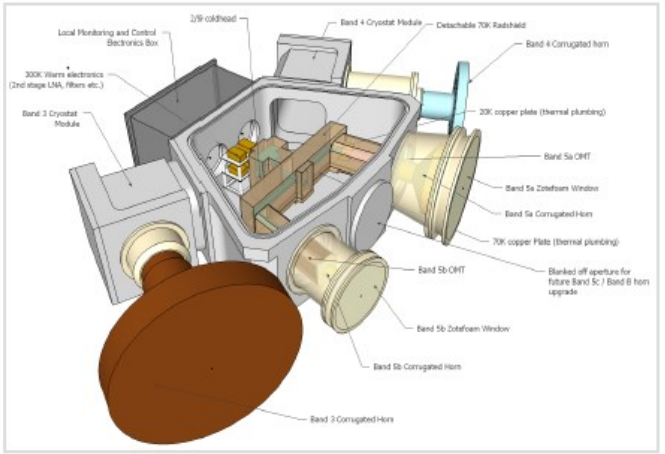
SKA DISH



SKA SDP SCIENCE DATA PROCESSOR

UK SKA Regional Science Node





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