

Galaxy formation, evolution, feedback and VLBI...

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Outline

What has VLBI ever done for Galaxy Formation, Evolution, Feedback...?

What could/should VLBI do??

caveats... & disclaimers...

This is not (in any way) a comprehensive review...

- But rather a subjective collection of thoughts..
- focus VLBI/high res radio aspects ...
 - Where impact has occurred?
 - Where impact will occur?
 - What is required for this impact?

(lots and lots of things missing here)...

e.g. Binary SMBHs, CSS, GPS, DOGs, CONs etc etc ...

What has VLBI ever done for... Galaxy
Formation, evolution or feedback?

What could VLBI do?? - future

An 'incomplete' set of personal radio-centric thoughts

Key areas for high-resolution radio...

- SF/AGN compact component census - local
 - local universe studies – single targets or surveys
 - Clean census of compact radio sources – accretion or SF products
 - ... *VLBI filtering of confusing diffuse 'weather'...*
 - ... *linear resolutions to match 'Our Galaxy' studies*

Source surveys
- AGN demographics/populations/feedback
 - e.g. VLBI roles: -
 - Single / small number target observations of sources
 - 'Wide' area VLBI surveys of high-z galaxies
 - .. *VLBI resolution → clearer picture + resolved structures*

Source surveys / WF-VLBI / Follow-ups
- Influence on ISM/gas
 - VLBI – probe of mechanical/jet influence on gas - e.g. H1/molecular absorption/maser
 - ... *high resolution to study influence of AGN on ISM...*

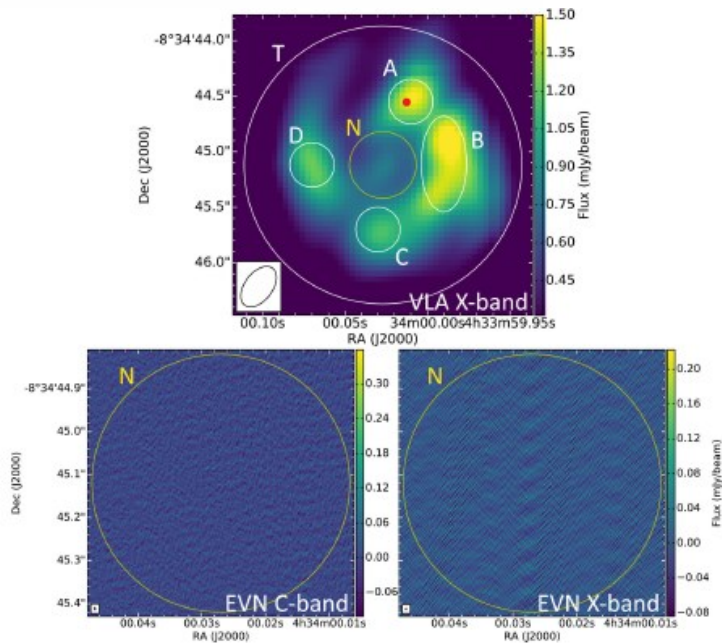
Single sources / surveys / Follow-ups

Influences of activity on galaxy evolution & feedback - local Universe – radio view

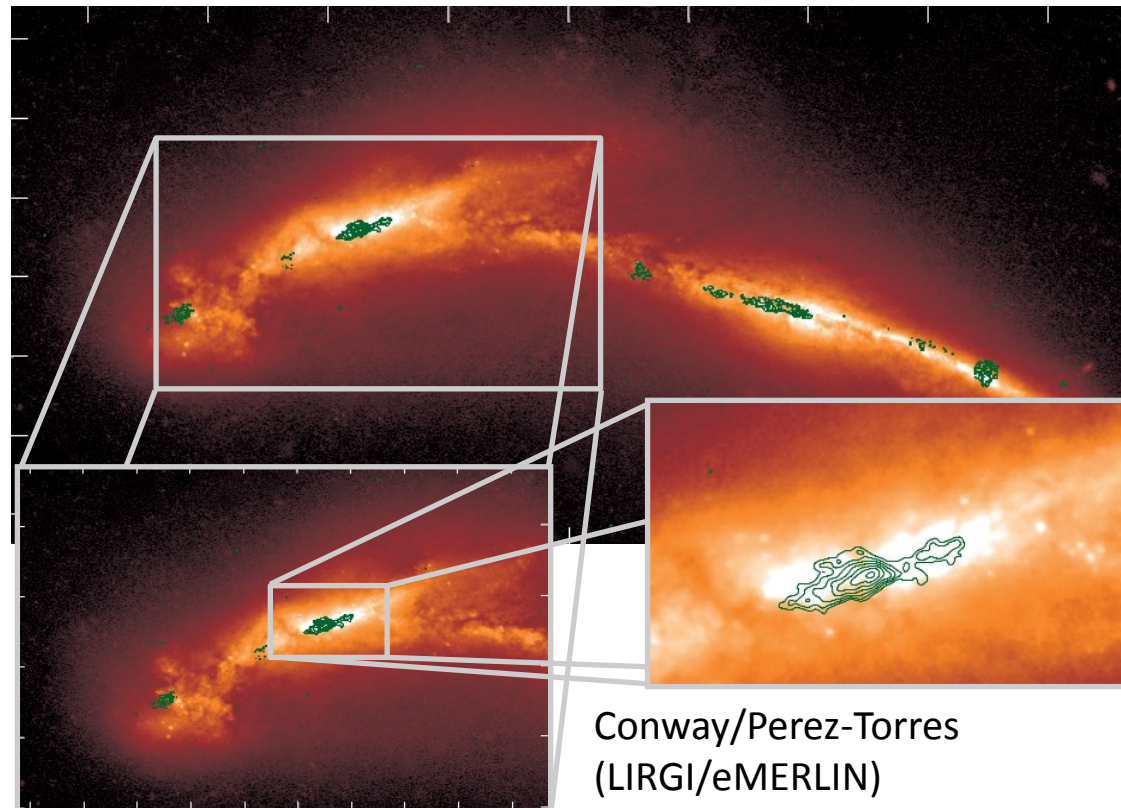
Role of SF and accretion in local to moderate redshift Universe

VLBI - pin-point obscured activity (or not)

... 'clean' census of obscured activity...



Herrero-Illana+ 2017



Conway/Perez-Torres
(LIRGI/eMERLIN)

Influences of activity on galaxy evolution & feedback - local Universe – radio view

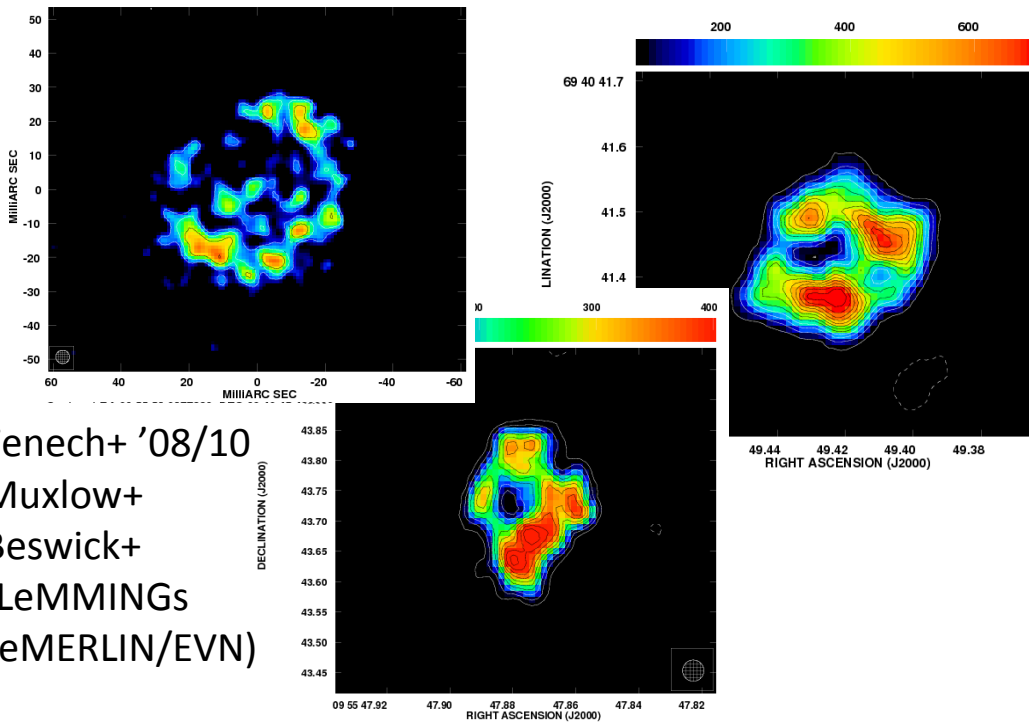
Role of SF and accretion in local to moderate redshift Universe

VLBI - Resolve on sub-pc scales

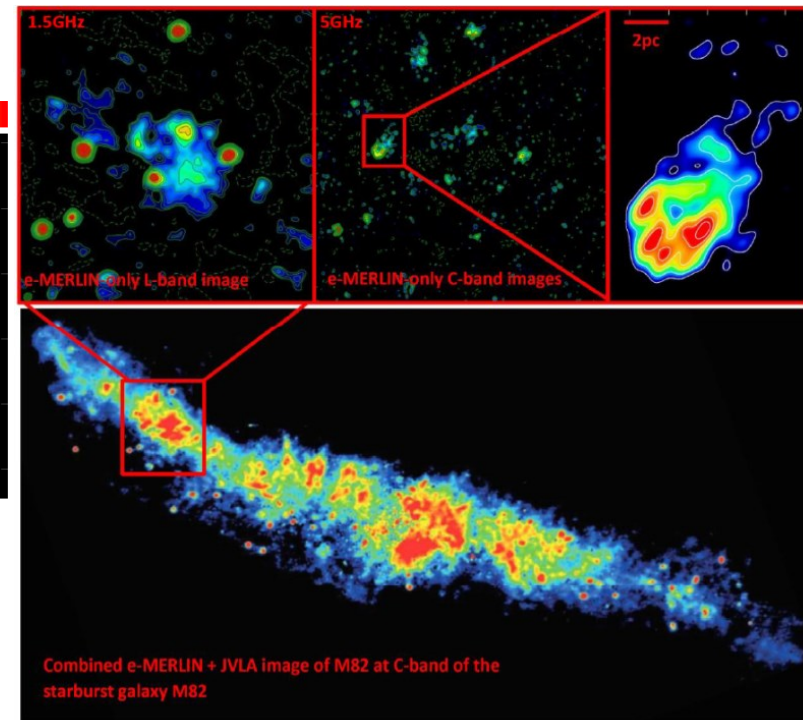
... SFR indicators ...

... details of influence/feedback on ISM ...

... Galactic-style physics in galaxies of all environments and classifications ...



Fenech+ '08/10
Muxlow+
Beswick+
(LeMMINGs
/eMERLIN/EVN)



jVLA/e-MERLIN/EVN/gVLBI

Influences of activity on galaxy evolution & feedback - local Universe – radio view

Role of SF and accretion in local to moderate redshift Universe

VLBI - Measure accretion activity

...Fundamental plane...

...Clean measure of accretion rates...

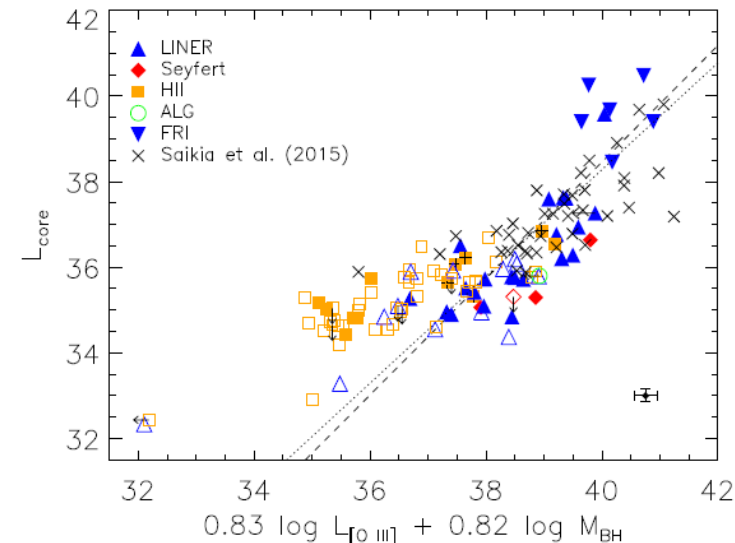
... LLAGN...

Determining core radio luminosity contribution (even in 'jetted' HII gals)

– remove 'troublesome' SF..

... VLBI advantage...

Resolution, sensitivity, surveys...



Baldi+2018

(LeMMINGs/eMERLIN)

- Core typically provides $\sim 24\%$ of total emission expected correlation with $L_{[\text{OIII}]}$
- Core power indicative of $M_{\text{BH}} > 10^7 M_{\text{sun}}$
- Slight separations as function of class becoming evident

Current surveys limited to few to tens of sources only..

Charting activity at higher-z

Characterising the sub-mJy/ μ Jy radio source population

SF & AGN co-evolve in galaxies

...peak of AGN/SF activity between $z \sim 1 - 3$

Crucial to

...separate SF & AGN emission

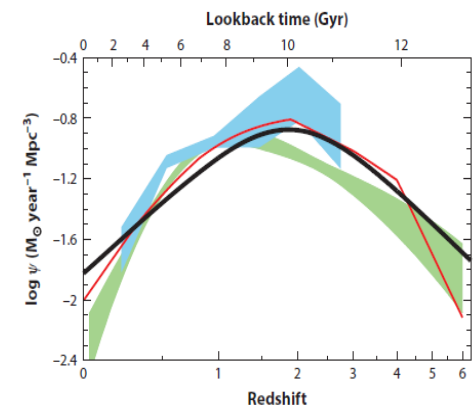
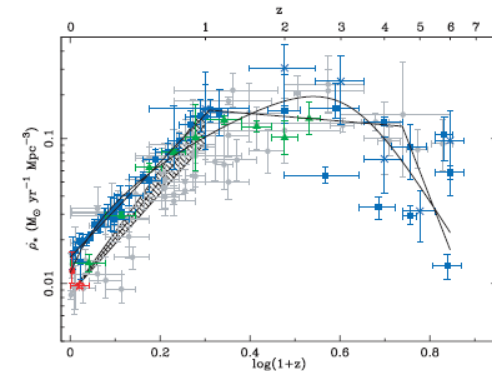
... probe obscured activity...

<<arcsec resolution required in radio to do this.

- VLBI direct probe of High T_B sources...(AGN)

- only e-MERLIN/VLBI resolution scales can

Spatially resolve SF & AGN emission..



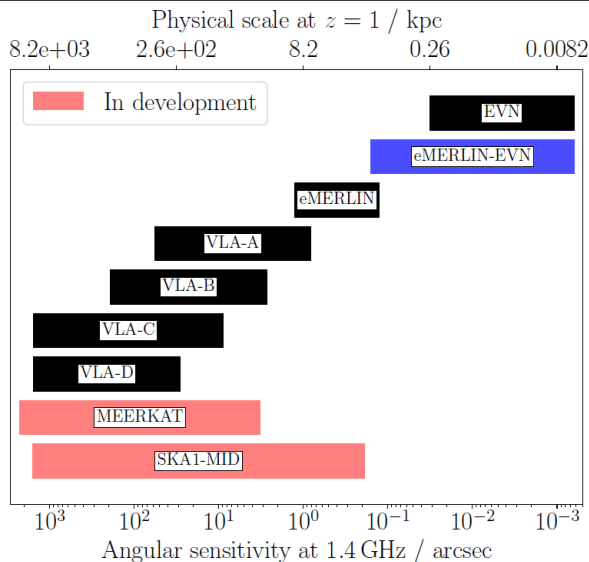
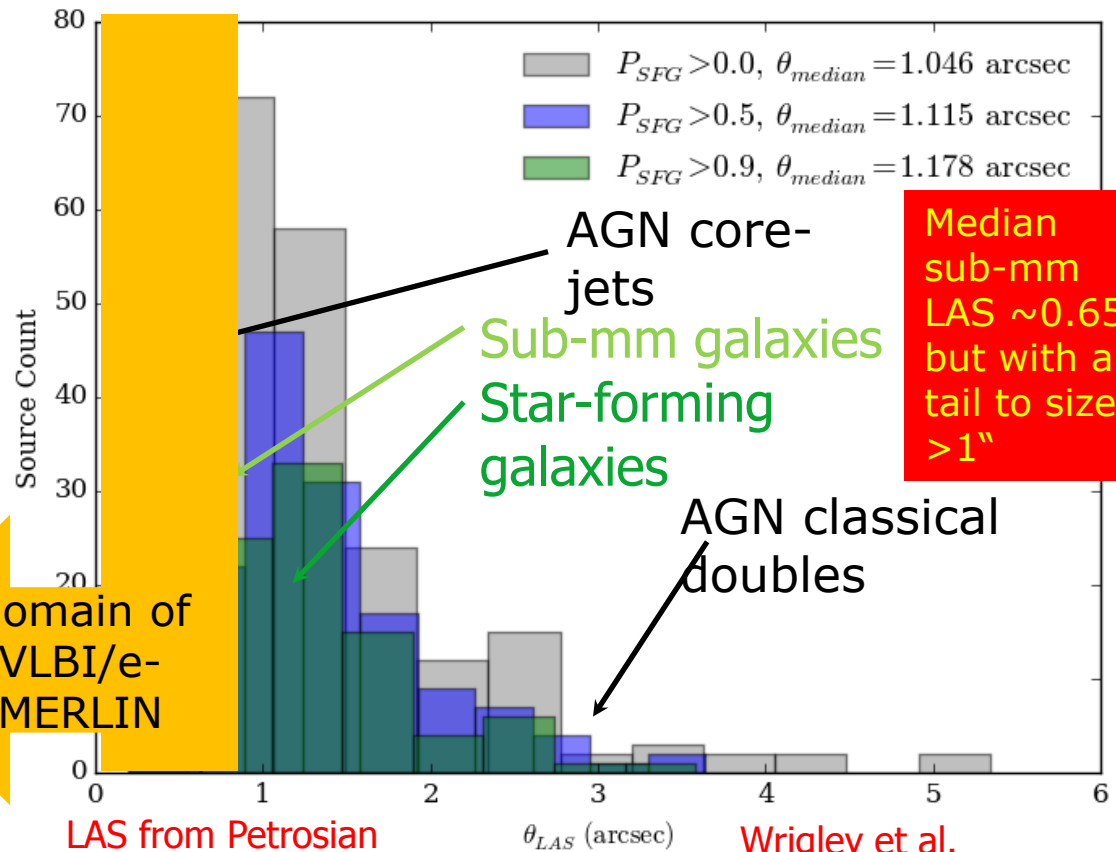
Madau & Dickinson '14

Size of the faint radio source populations

MANCHESTER
1824

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...



Domain of VLBI/e-MERLIN

LAS from Petrosian Radii

Wrigley et al.

(from e-MERGE - SVM - Support Vector Machine - classifications)

Star-formation & accretion across cosmic time: deep fields

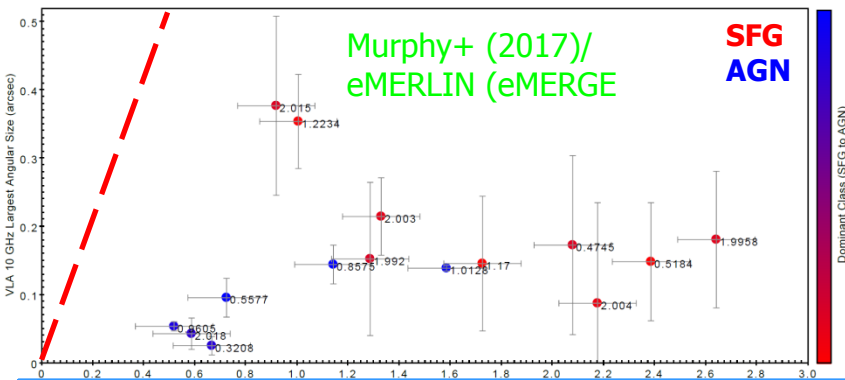
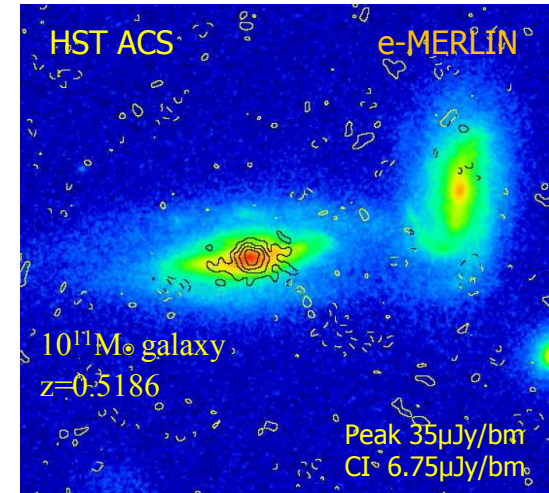
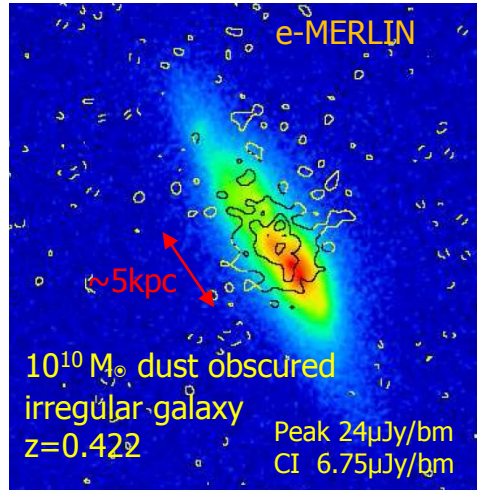
MANCHESTER
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e-MERGE (e-MERLIN key science project deep field)
Extragalactic Deep field imaging

~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

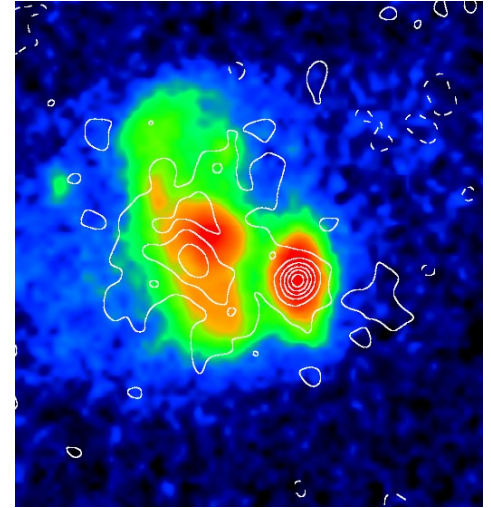
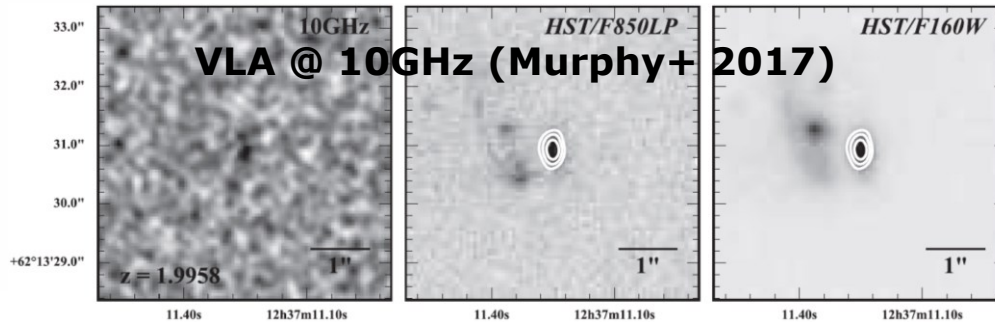
JVLA 10GHz (~200mas) show LAS up to x10 smaller



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

- and the inner core-jet structures in AGN systems

Star-formation & accretion across cosmic time: deep fields



→ Steep-spectrum ($\alpha = -0.69$) 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 VLBI/e-MERLIN resolutions and sensitivities can fully detect and resolve.

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

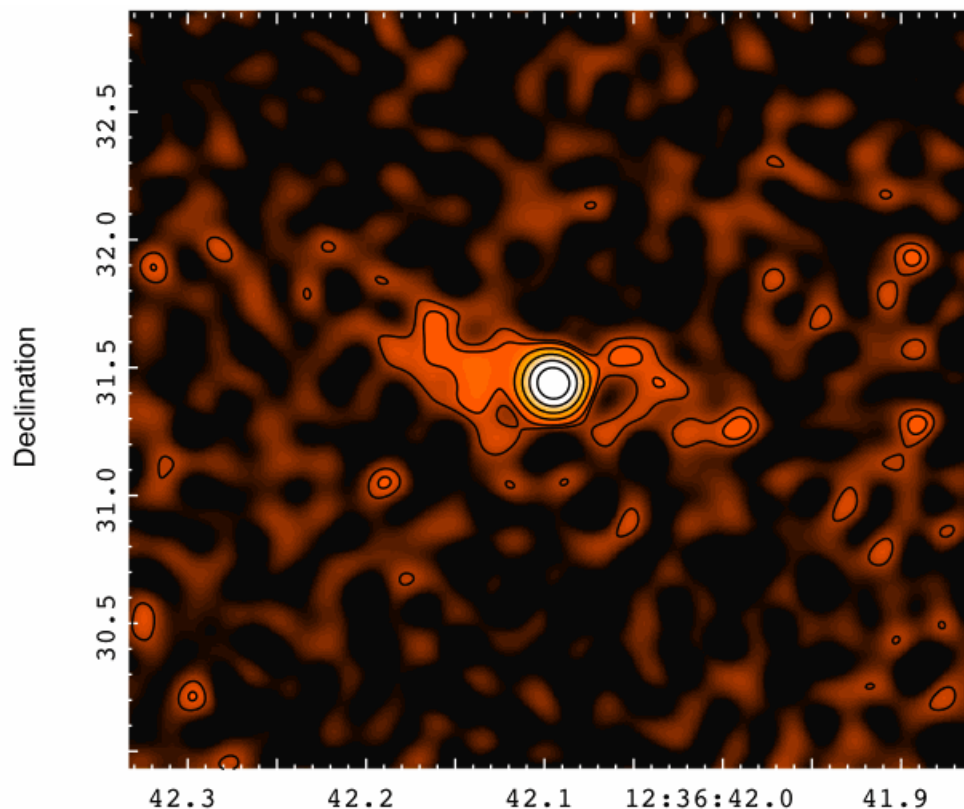
Unique window on the co-evolution of accretion and star-formation from $z \sim 0.2 \rightarrow 5$

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

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J123642+621331 – GOODS-N – part of e-MERGE legacy

(Radcliffe et al)



J123642+621331 – high- z ($z=4.4$) AGN/starburst composite source – e-MERLIN to EVN resolution scales.

...VLBI uniquely pin-points the AGN contributions...

Samples=impact

AGN demographics – deep, wide & distant

VLBI resolves out diffuse emission and only detects **bright** ($T_B > 10^6\text{K}$) and **compact** objects (e.g. SNR & AGN)

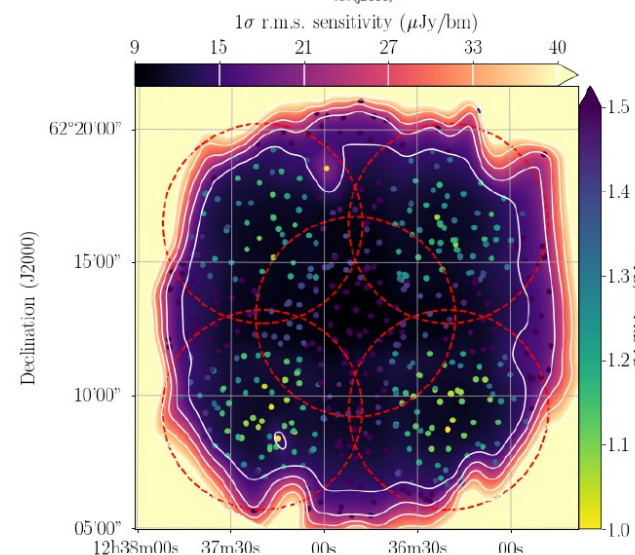
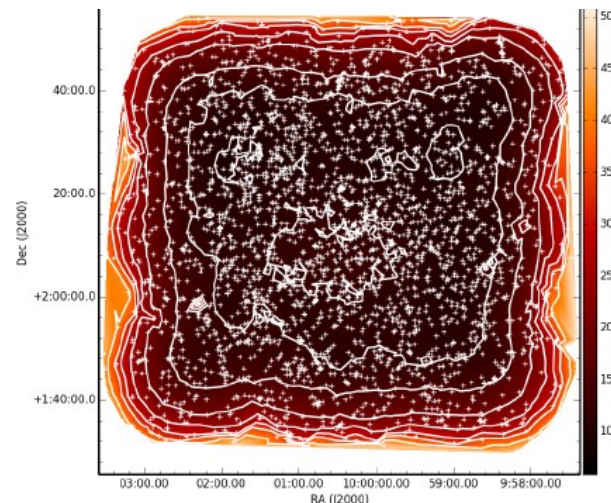
WF-VLBI can detect multiple compact sources within the primary beam of a VLBI telescope in one observation.

→ Disentangle radio quiet AGN emission from star formation in distant galaxies.

“Radio-AGN that are detected in VLBI observations are not special, but form a representative sample of the radio-loud AGN population.”

... era of wide field VLBI surveys ...

COSMOS – Herrera-Ruiz+'17



GOODS-N – Radcliffe+'18a

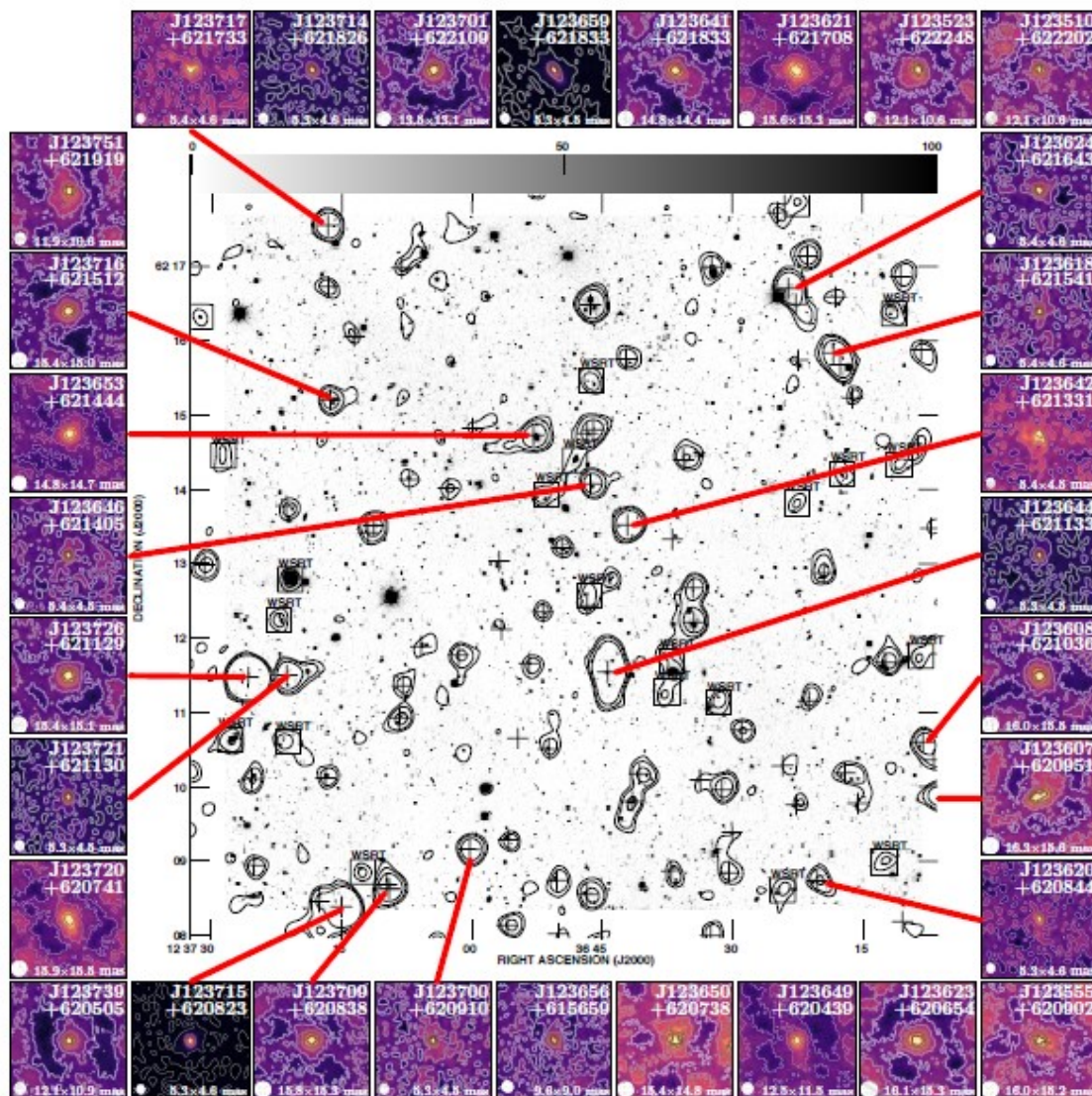
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Excellent AGN finder..

... era of wide field VLBI surveys...



Samples=impact

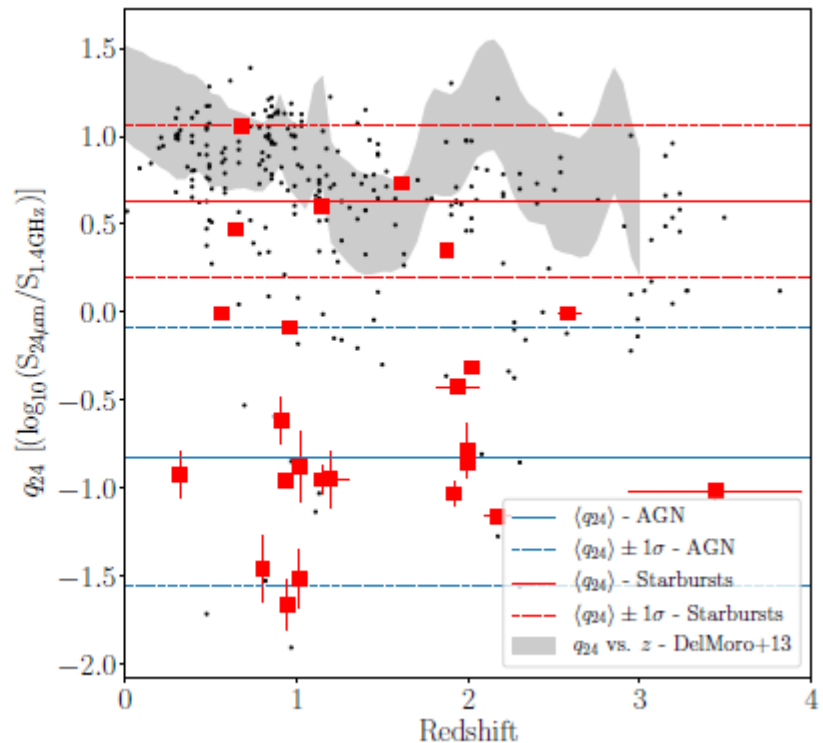
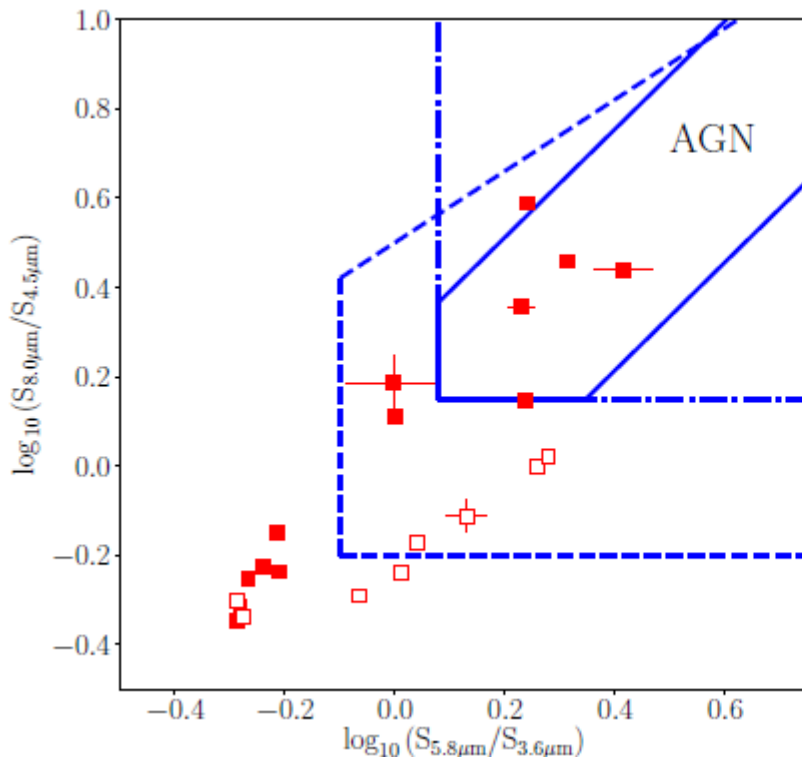
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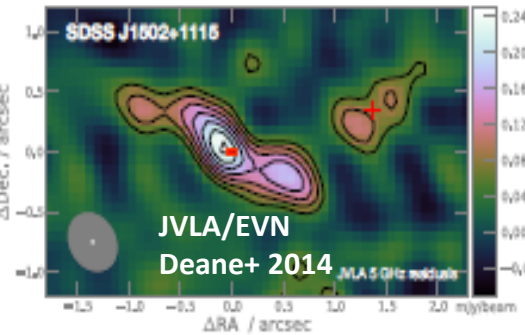
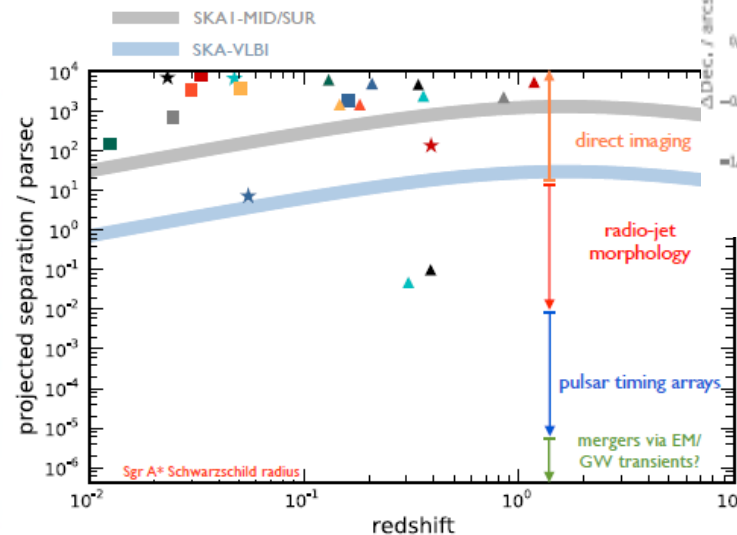
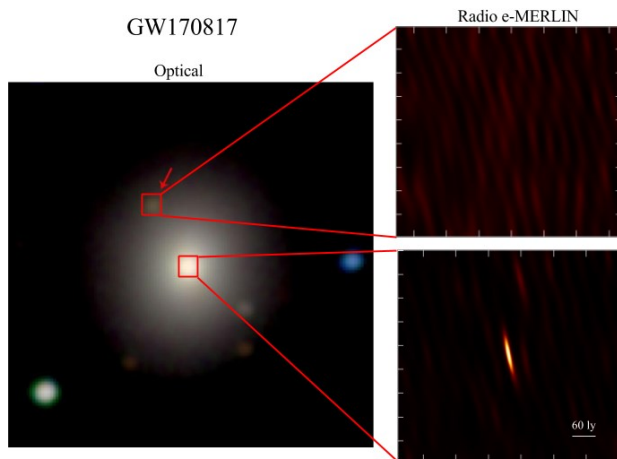
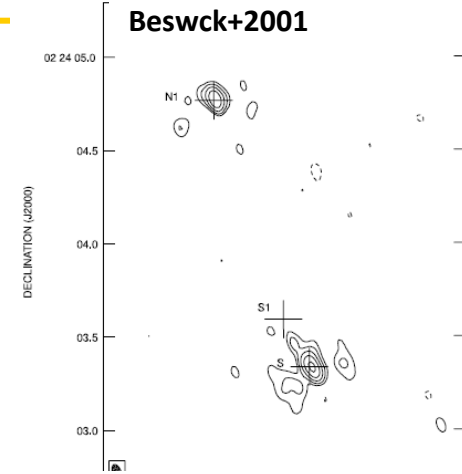
GOODS-N – Radcliffe+'18b



SM(BH)-Binaries

VLBI can uniquely 'see' and resolve
 Important stage of galaxy evolution
 VLBI is needed to understand
 populations
... now in an era of GW astronomy ...
 (& *GW-EM astronomy*)

MERLIN/VLBA
 Gallimore & Beswick 2004
 Beswick+2001

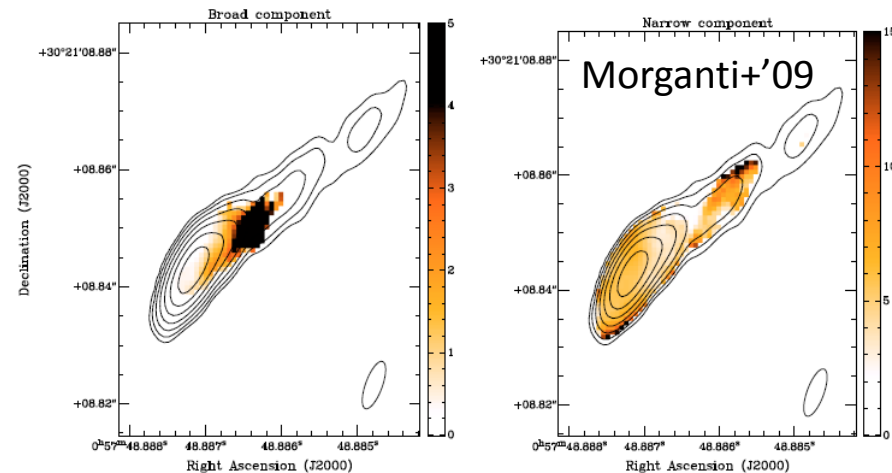


Influence on ISM/gas Feedback and fuelling

... VLBI tracing interplay of jets/AGN and ISM...

Absorption and Maser studies
domain of VLBI.

Only VLBI can resolve
the interaction/action.



Key techniques needed to follow-up 1000s of new SKA-
pathfinder project detections e.g. MALS, FLASH etc..

*e.g. FLASH expects to >1000 HI absorption detections
VLBI will be the only follow-up route to resolve these..*

What has VLBI ever done for Galaxy Formation,
evolution, feedback?

The future – what next??

Recap: An 'incomplete' set of personal radio-centric thoughts

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 - ... *high resolution to study influence of AGN on ISM...*
- VLBI Legacy Survey-mode Short-spacings
- SKA, AVN WF-VLBI routine
- VLBI follow-ups MALS/FLASH/SHARP

New landscape – new opportunities

Science requires:

- Capacity of large samples – both multiple pointed and multi-phase centre
- Lower surface brightness sensitivity
ie ++e-MERLIN, ++more sensitivity (SKA-VLBI)
- Access south → AVN, SKA-MID, MeerKat-VLBI
- Frequency coverage (and agility)...
- Survey-mode

Landscape:

- must be ready to exploit and follow-up discoveries with new SKA & pathfinder experiments – e.g. MIGHTEE, MALS, FLASH, WODAN, EMU, VLASS.. Then SKA-mid itself
- Development of AVN will bridge N-S ... (EVN – SKA-Mid)

... next ...

(yes, yes... as always more sensitivity, more capabilities, more telescopes etc)

- GO-WIDE: Wide-field capabilities (Multi-phase centre, PAF??)
 - Important to allow wide field VLBI surveys – key to understanding role/fraction of AGN at high-z...
- GO-SOUTH(-EAST-or-WEST): SKA (& MeerKAT) - AVN
 - Complementarity of observation... as well as combined sensitive observations
 - Inc. better southerly coverage (e.g. AVN)
- GO-DIFFUSE: Wider-range of spatial scale (especially 10s-100s km – e-MERLIN)
- GO-BIG: EVN/VLBI – Large programmes (EVN-lite)??

Summary

- Must increase in VLBI impact
 - New opportunities such as WF-VLBI part of this.
 - But must convert modes like this to 'common/accessible to use'. (need to make things like EVN PBs reliable)
 - Lots of areas not covered here that need to be included in white paper
- Next 10yrs – 'growth of SKA and its pathfinders'
 - Landscape is evolving
 - VLBI will always have a key role in 'follow-up' (as well as discovery)
 - Must provide the infrastructure/capabilities.. (go-south)
 - **AVN** (both infrastructure and people) plus linkage with SKA is critical

