Revealing the Physics and Evolution of Galaxies and Galaxy Clusters with SKA Continuum Surveys*

I. Prandoni

on behalf of the SKA Continuum Extragalactic Science WG

*based on the ***Continuum Science Chapters of new SKA Science Book***
[see chapter index at arXiv:1412.6942]

SKA Radio Continuum Extragalactic Surveys Science Drivers

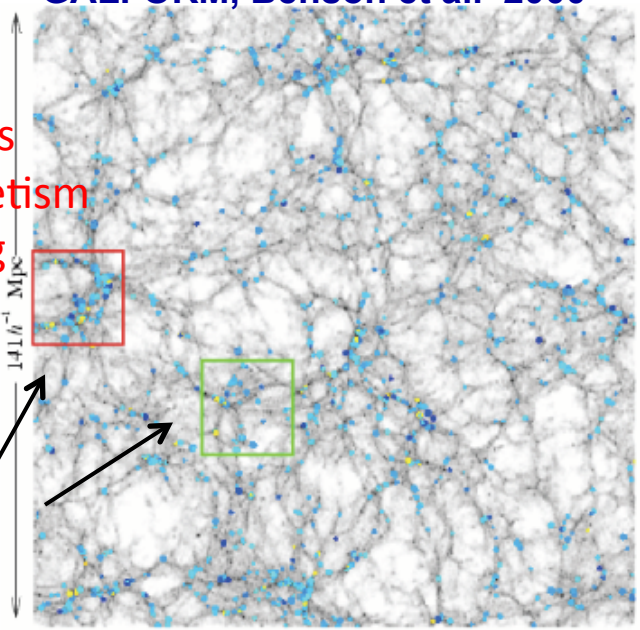
- **Deep Fields/Multi-Tier surveys (1-1000 deg^2)**

(in combination with redshift/multi-λ info)

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

Commensality:
- HI Deep Fields
- High-z Magnetism
- Weak Lensing

GALFORM, Benson et al. 2000



- **Wide/All-sky Shallower Surveys (1k-30k deg^2)**

(in combination with redshift/multi-λ information)

- **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**
- **Strong lensing**

Commensality:
- Magnetism All-Sky Survey
- Cosmology tests (ISW, MB, etc.)
- Our Galaxy
- HI shallow surveys
- Transients

Synergy with LSST, Euclid, JWST, eROSITA

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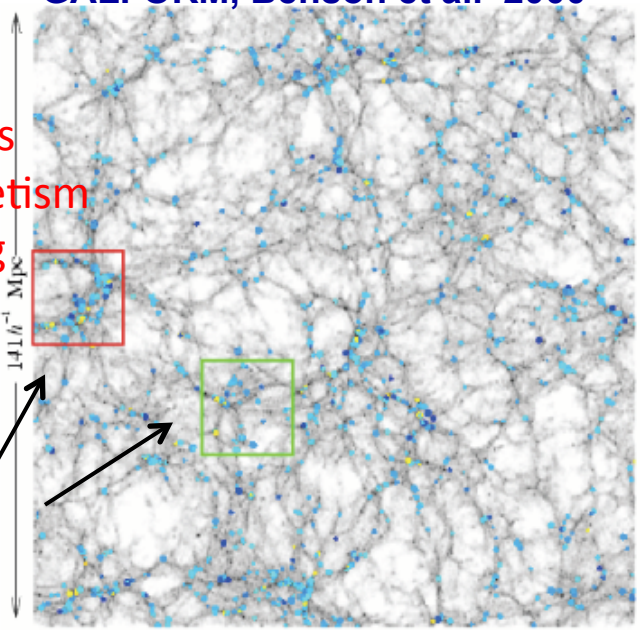

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Gal Evol.
Gal Physics, LSS
+Rare Populations

Synergy with LSST, Euclid, JWST, eROSITA

SKA1 Key Science Goals

Top Priority Objectives for SKA1 selected by SKA Office in consultation with ad hoc Science Review Panel and SEAC → *Notional Key Science Projects*

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
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
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
18	*Transients*	Solve missing baryon problem at z~2 and determine the Dark Energy Equation of State	=1/4
22	*Cradle of Life*	Map dust grain growth in the terrestrial planet forming zones at a distance of 100 pc	1/5
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

Table 2. List of highest priority SKA1 science objectives, grouped by SWG, but otherwise in arbitrary order.

(Ultra-)Deep Fields

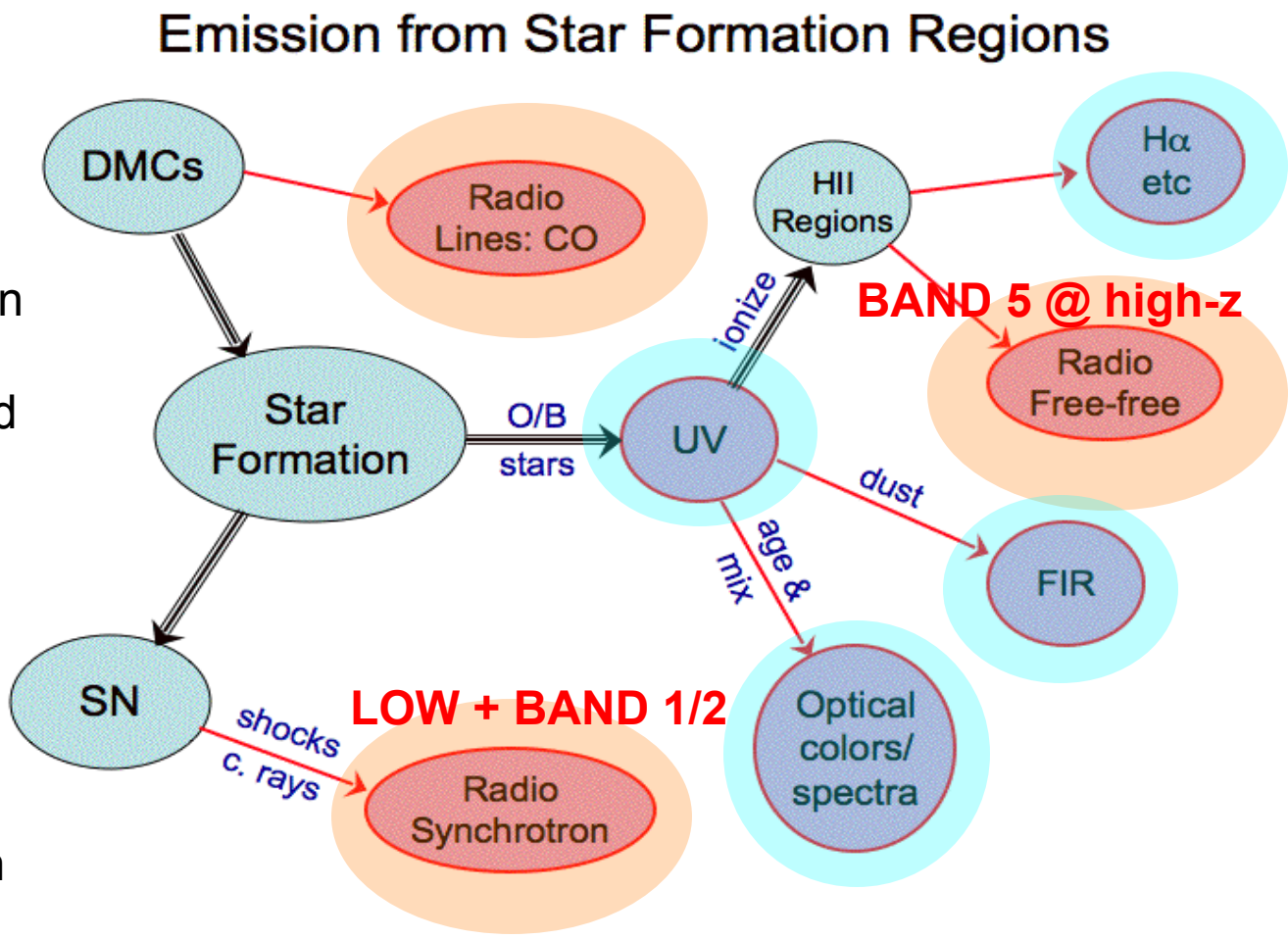
Star Formation History

Why radio surveys?

Radio continuum emission reliable tracer of star formation rates unaffected by dust (opt/UV/Hα)

Less confused than IR surveys

SKA 1 can probe both synchrotron and free-free continuum radio emission + redshifted CO lines



(Ultra-)Deep Fields

Star Formation History

Deep Radio Fields dominated by SFGs

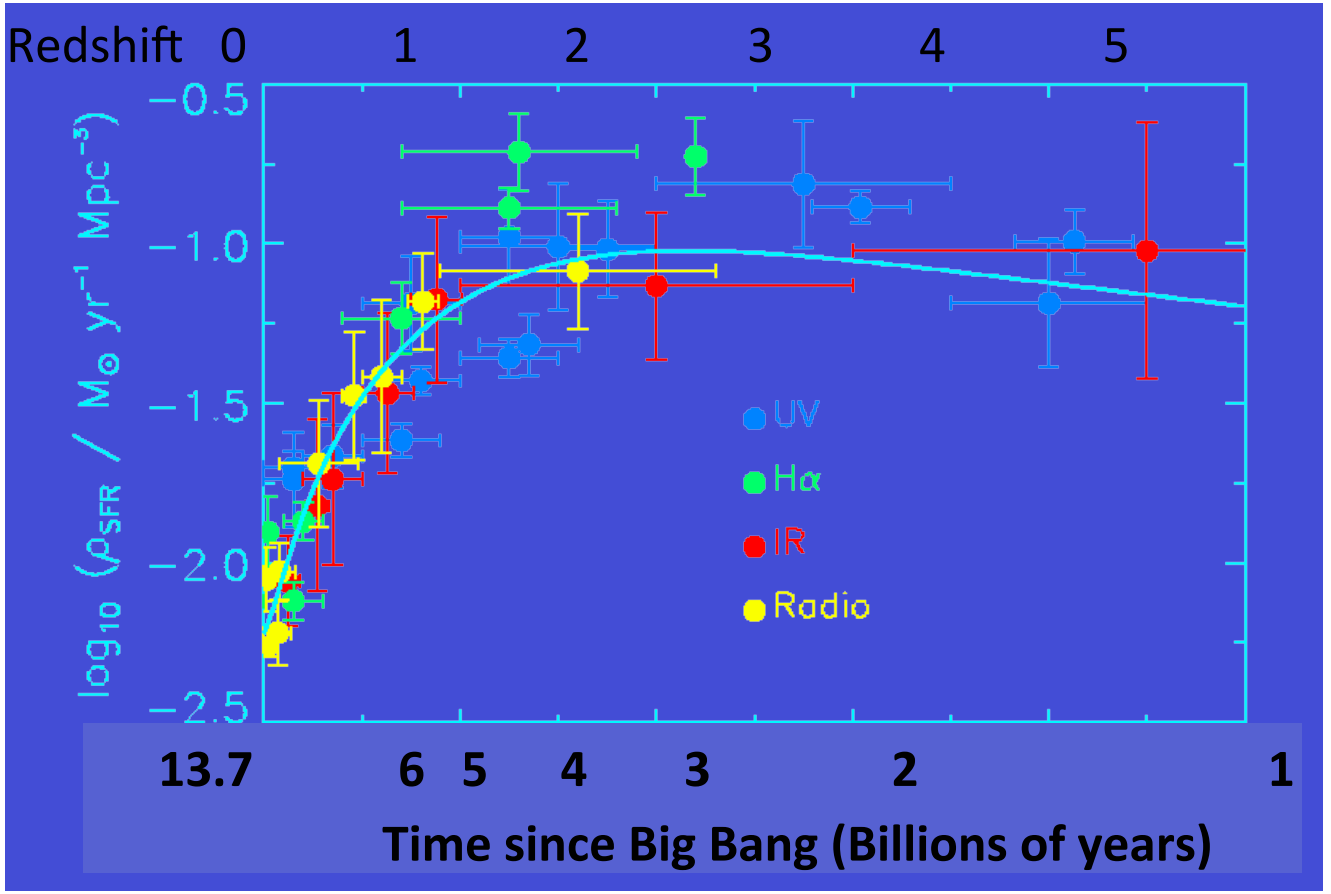
Sensitivity is key

Requirement:
→ sub-uJy rms

SKA competitive with opt/IR facilities !

When does SF occur?
What dominates SFRD at each z?

SFH vs gal type
SFH vs gal mass
SFH vs environment
…



(Hopkins et al 2004)

(Ultra-)Deep Fields

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Deep Radio Fields dominated by SFGs

Murphy, Sargent et al 2015

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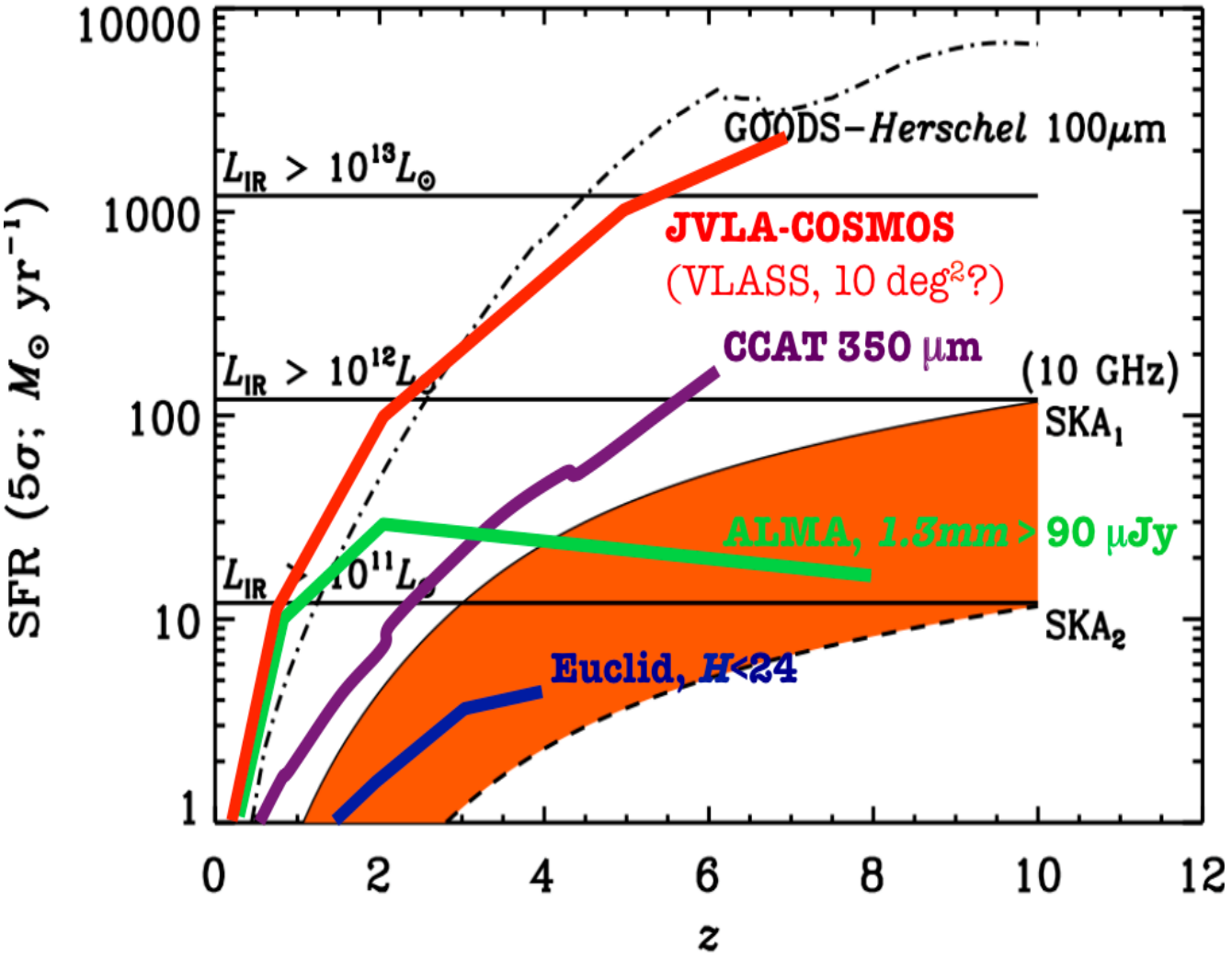


(Ultra-)Deep Fields

SF vs Stellar Mass

SFH vs galaxy mass [sSFRD]

➔ SF Main Sequence
SFR=f(Mass)

➔ to be constrained at high z

Requirement:

→ sub-uJy flux limits

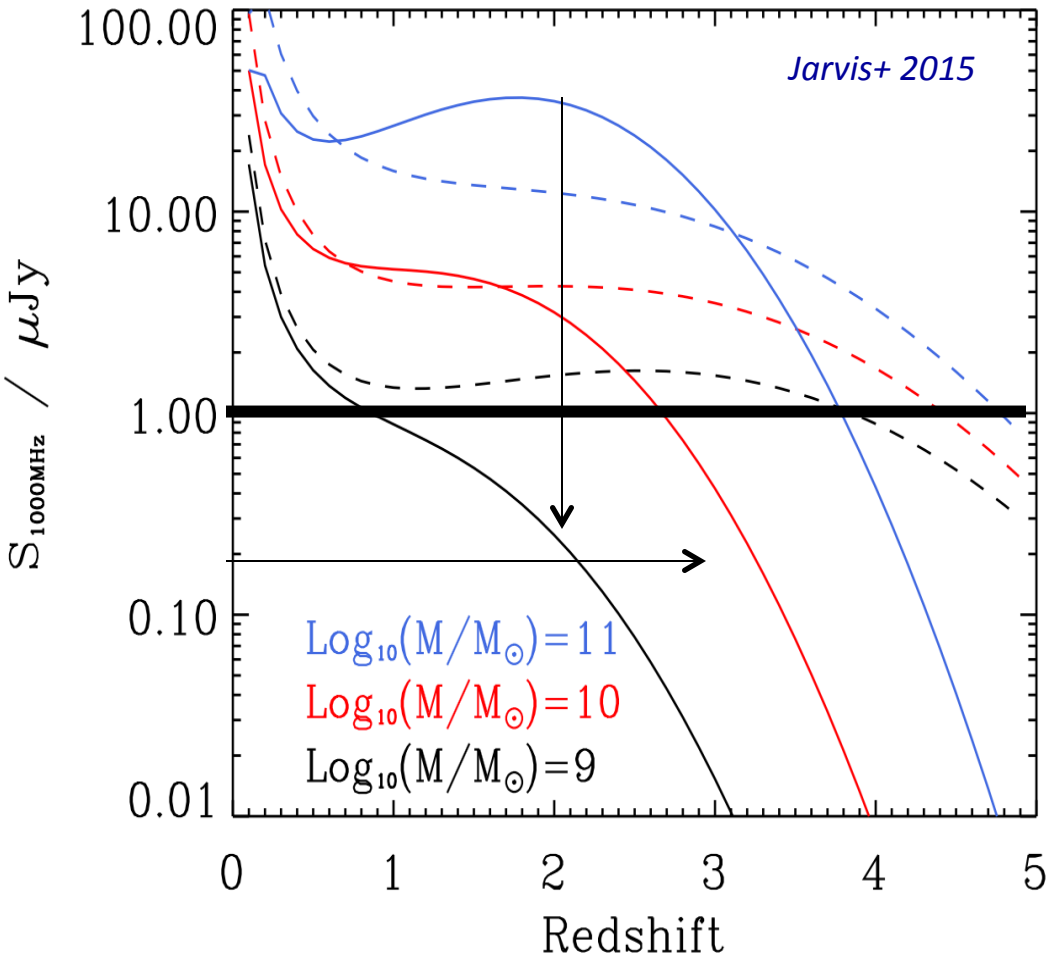
[sensitive to low SFR/low mass systems at high redshift]

1 GHz [BAND 1/2]

Deep (rms 0.2 uJy): lg(M/M$_\odot$) ~ 9
@ z~1-2 peak of SFH

Ultra Deep (50 nJy): ~lg(M/M$_\odot$) ~ 10
@ z~3-4

Full SKA → lg(M/M$_\odot$) @ z>5

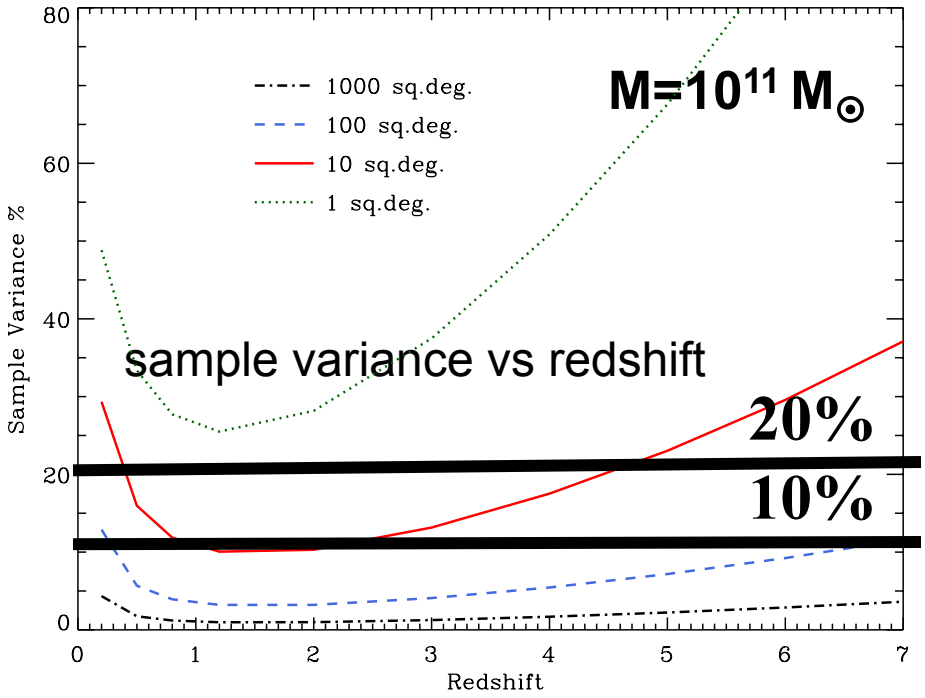


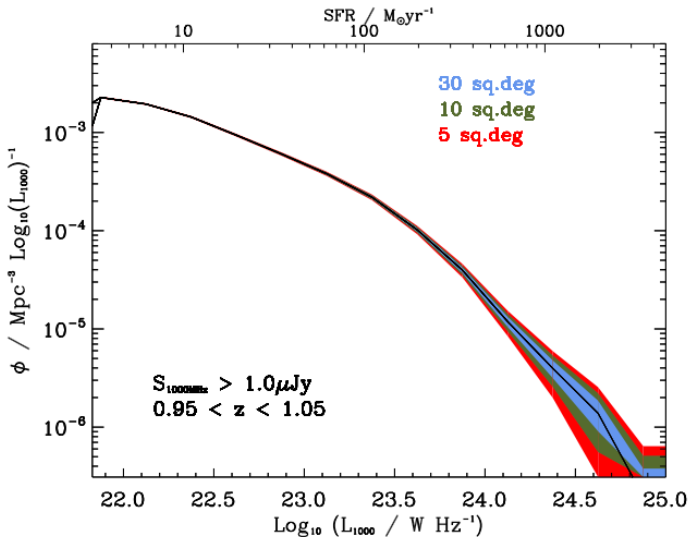
Deep+Wide Fields

SF vs Environment

Requirement:
10-1000 deg^2 survey coverage
(also relevant for AGN studies)

a) Large samples → good statistics
→ **accurate f(L,z) for different source parameters**
→ **sample variance under control**



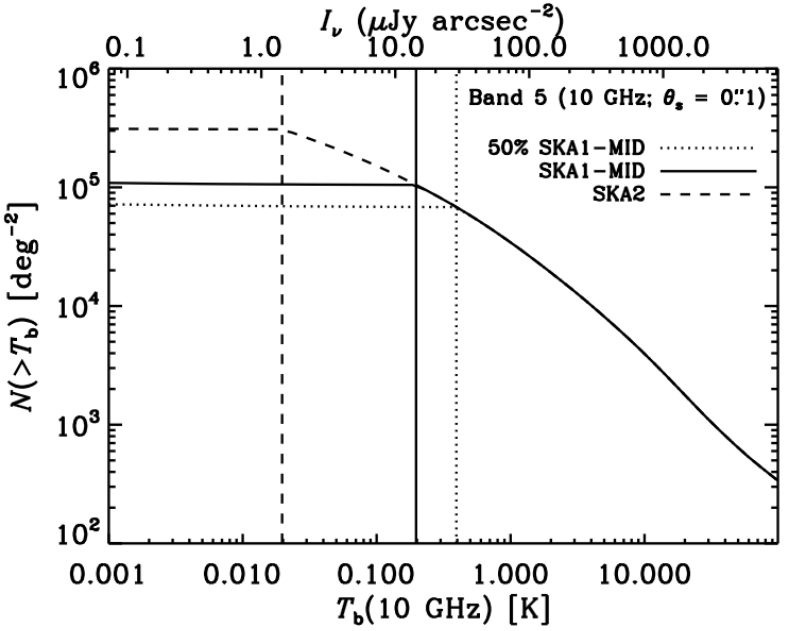


Jarvis et al 2015

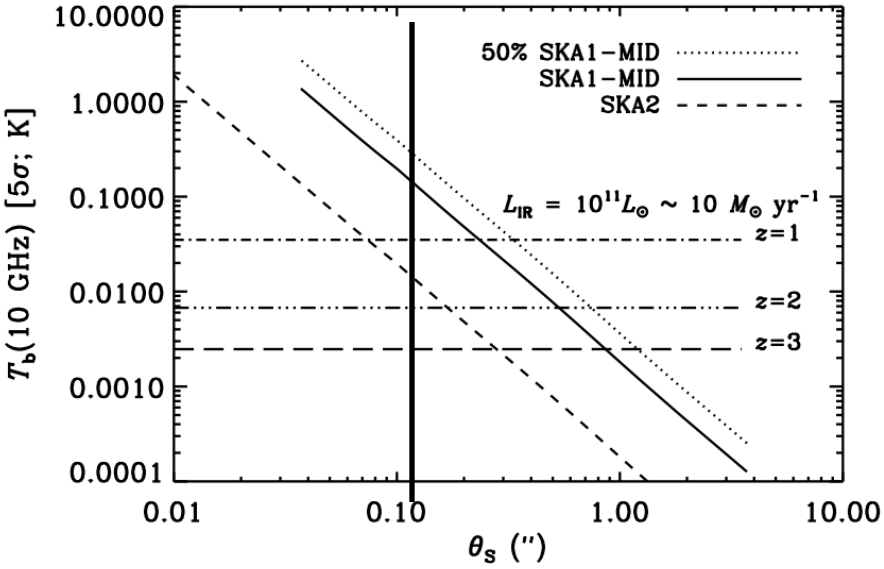
b) Study **environment effects**
→ **link between SF activity & Dark Matter Halo underlying distribution**

Band 5 Deep Fields

Detailed Astrophysics of SF



Murphy, Sargent et al. et al 2015



Band 5 → ~0.1” spatial resolution (**150km bs**) → **Spatially resolved SF** **(synergy Euclid 0.2”)**

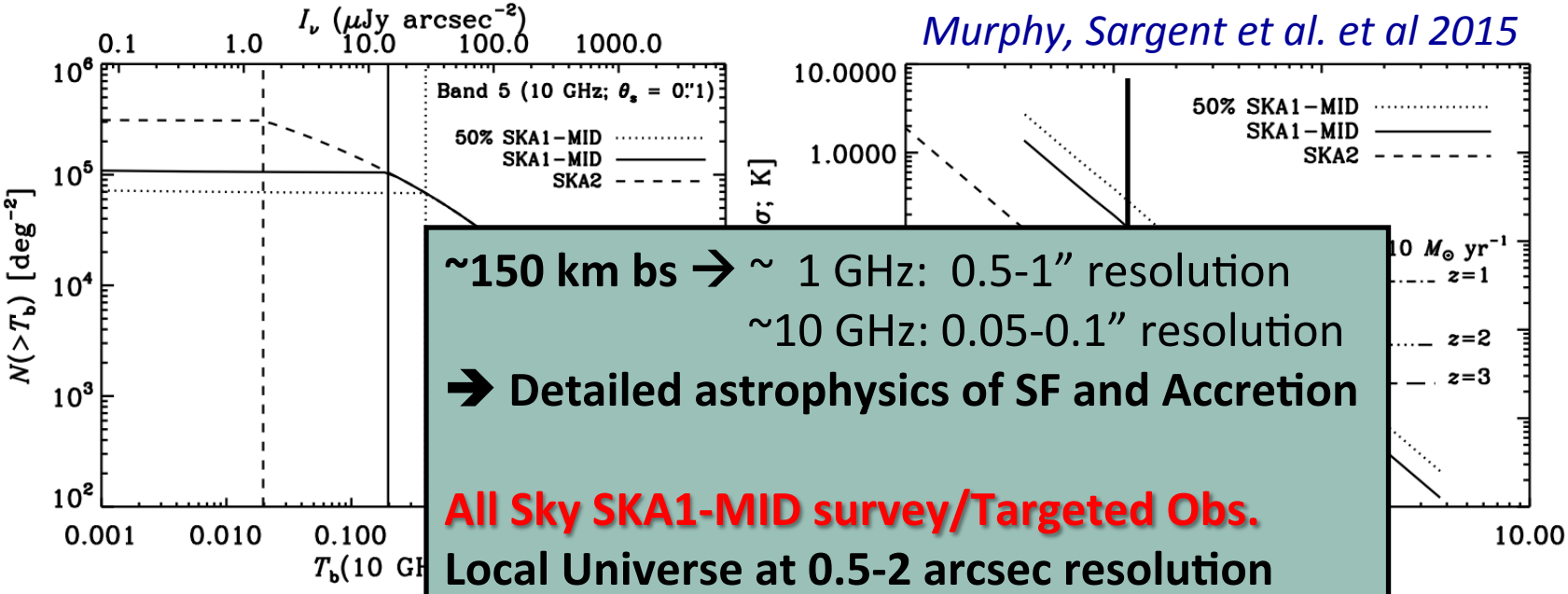
SKA1 → can resolve **100 $M_\odot$/yr** SFGs **to z~1 on sub-kpc scales** and **to z~2 on kpc scales**

SKA2 → can push high-z resolved studies to **10 $M_\odot$/yr** SFGs

→ **But also unbiased SFR (**resolution is key to identify and remove embedded AGN cores…**)**

Band 5 Deep Fields

Detailed Astrophysics of SF



Murphy, Sargent et al. et al 2015

~150 km bs → ~ 1 GHz: 0.5-1” resolution
~10 GHz: 0.05-0.1” resolution

→ Detailed astrophysics of SF and Accretion

All Sky SKA1-MID survey/Targeted Obs.

Local Universe at 0.5-2 arcsec resolution to resolve galaxies on several scales

VLBI-mode added value

Band 5 → ~0.1” spatial re **gy Euclid 0.2”)**

SKA1 → can resolve **100 kpc scales**

SKA2 → can push high-z

→ But also unbiased SFR (resolution is key to identify and remove embedded AGN cores…)

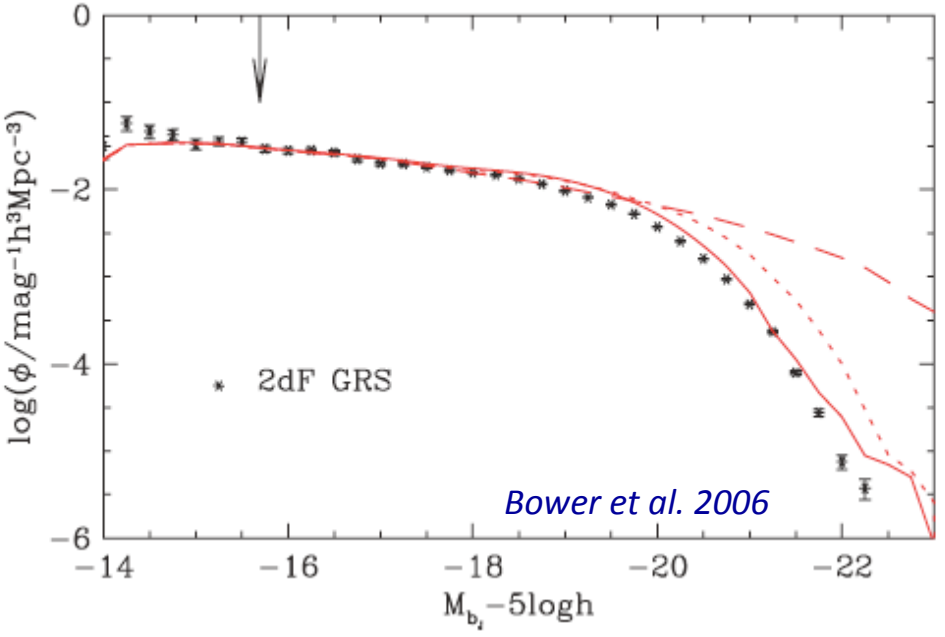
Deep+Wide Fields

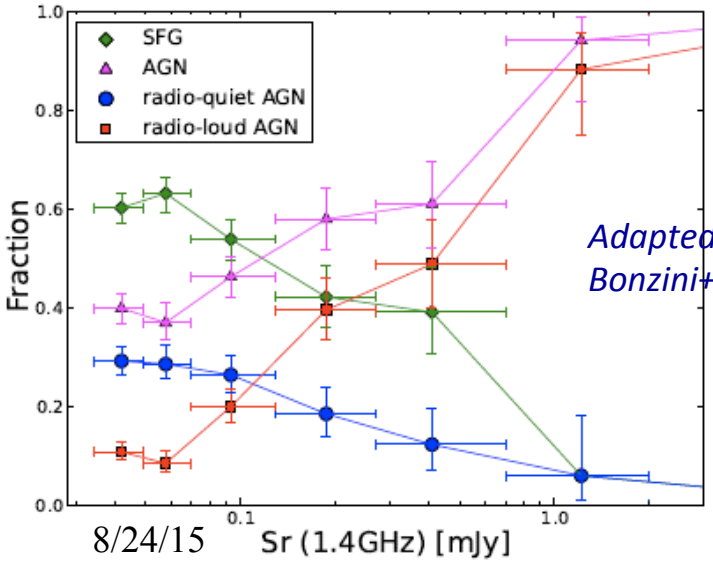
AGN Feedback

Important ingredient in galaxy formation and evolution models

RL AGN – Radio/Hot Mode
→jet-driven mechanical feedback

RQ-AGN – QSO/Cold Mode
→radiation-driven feedback (winds)





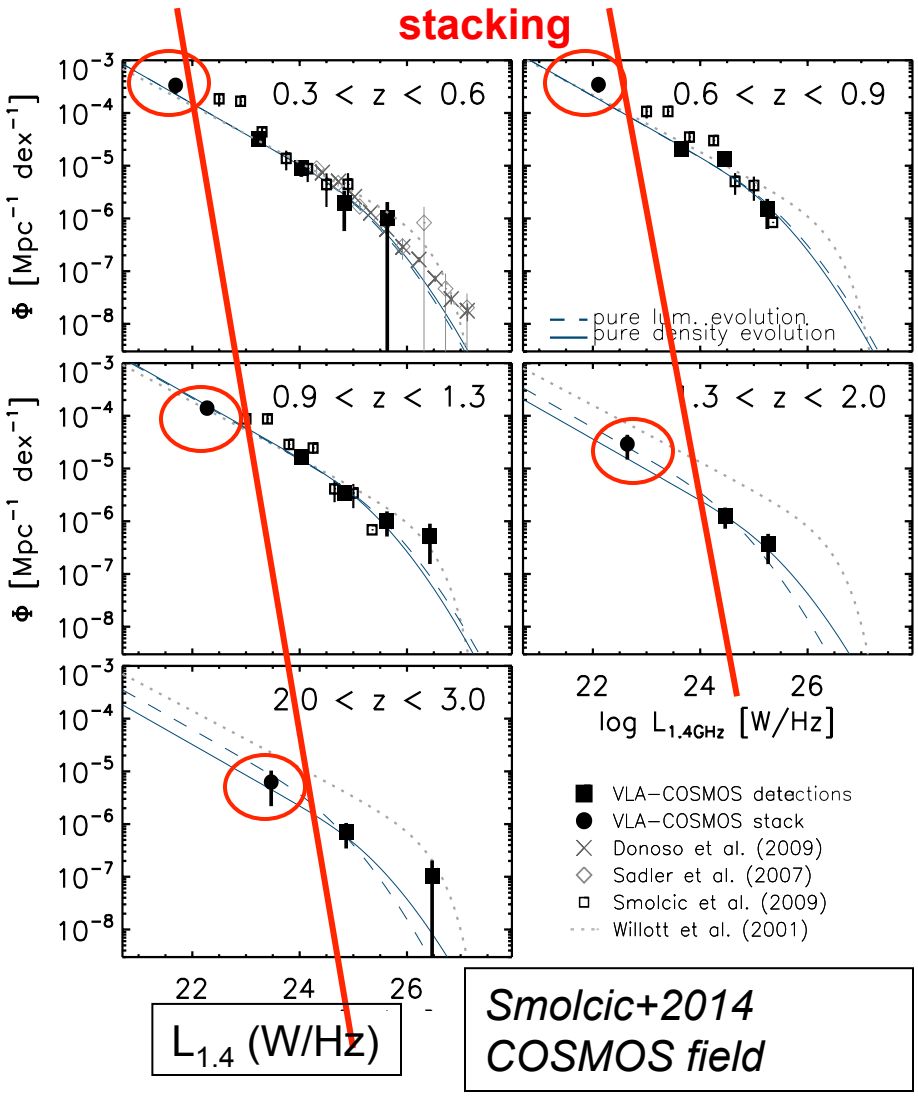
Adapted from Bonzini+2013

RQ-AGN start to appear at uJy levels in deep radio fields → hosted by disk galaxies

Complete census of RL and RQ AGNs
→ complete view of AGN feedback
→ Role of AGN feedback in gal. evol.

Deep+Wide Fields

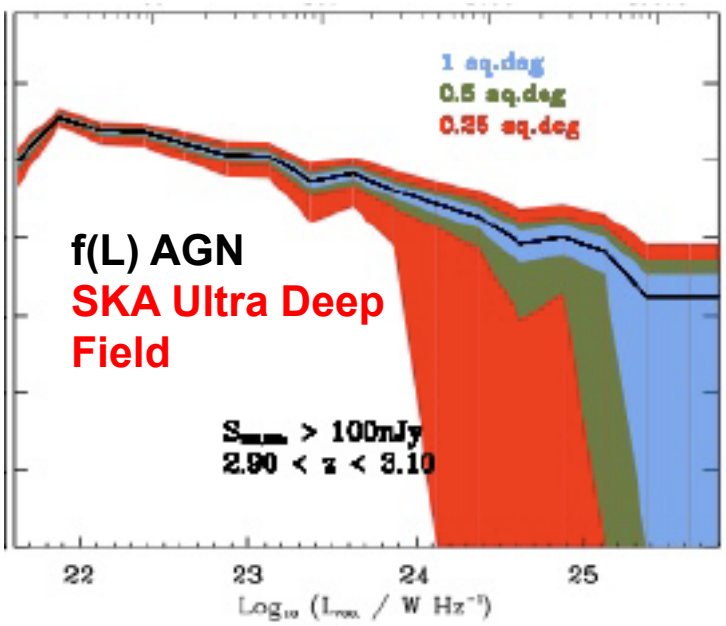
RL/RQ AGN Evolution



Evolution of RL AGN at z>1
& $L<10^{24\text{-}25}$ W/Hz → poorly constrained

$L<10^{24\text{-}25}$ W/Hz dominated by LERG
→ Role of radio feedback in gal. evol.

RQ AGNs span a similar radio lum. range



RL/RQ AGNs – Physical Processes

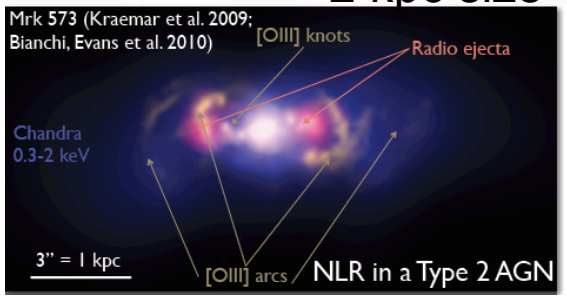
- **What determine RQ/RL dichotomy?**
- **What triggers radio emission in RQ AGNs?**

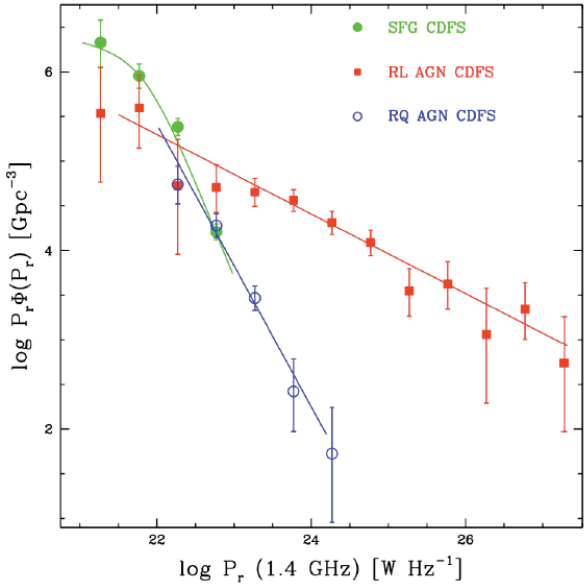
- Synchrotron radiation from mildly relativistic mini-jets?
- thermal cyclo-synchrotron emission from ADAF/ADIOS?
- thermal free-free emission from the X-ray heated corona or wind

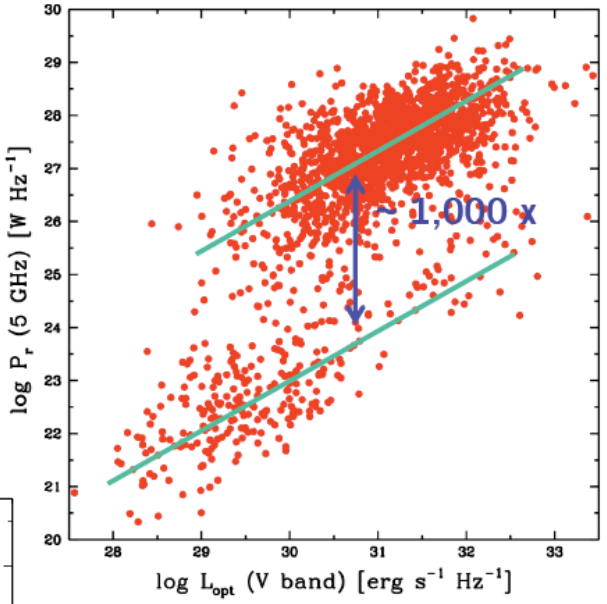
SF and AGN related emission do co-exist

Radio AGN cores
Difficult to detect at uJy levels

~2 kpc size







Padovani+ 2011

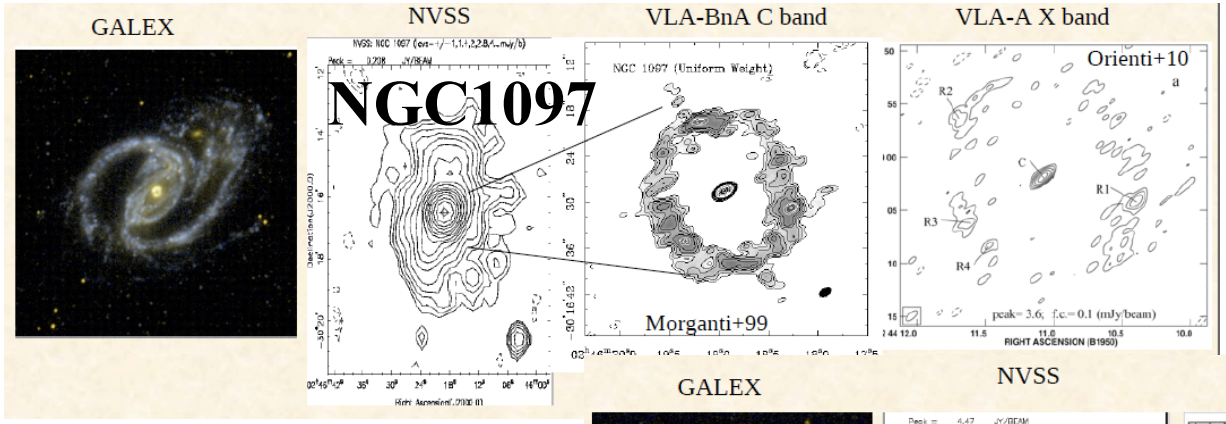
Requirements:
Multi-band information & Multi-frequency info

Radio-band:
Spatial Resolution & sub-uJy sensitivity

Separating AGN/SF activity in RQ AGN

RQ-AGN often associated to disk galaxies → Need to separate AGN from SF radio emission → unbiased and complete AGN demography

Requirements: sub-arcsec resolution + uJy/sub-uJy sensitivity

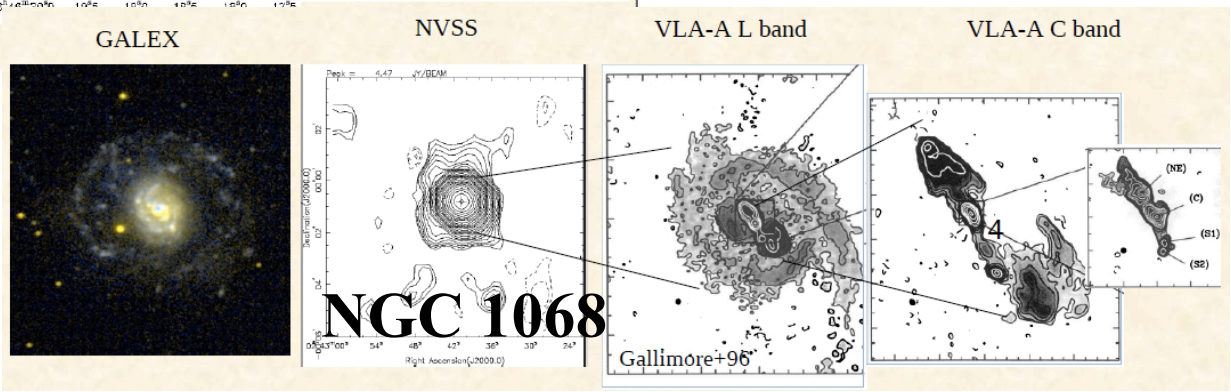


Now possible for small samples in local Universe

Courtesy Orienti

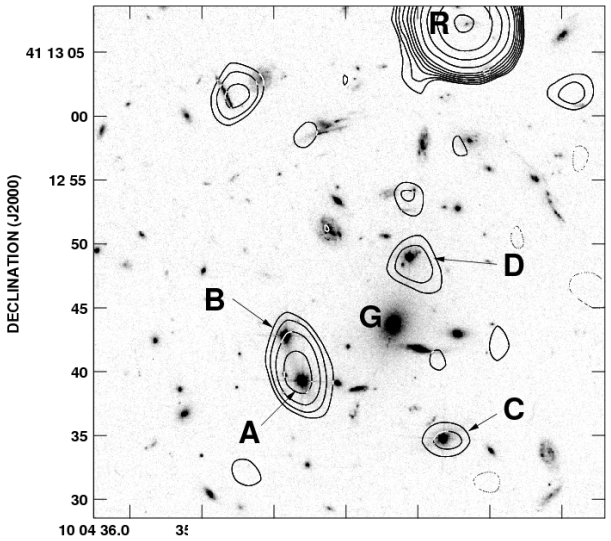
SKA → larger samples & higher redshift

Multi-frequency/Polarization disentangle thermal vs non-thermal emission



Wide/All-Sky Surveys

Core emission from high-z RQ QSO

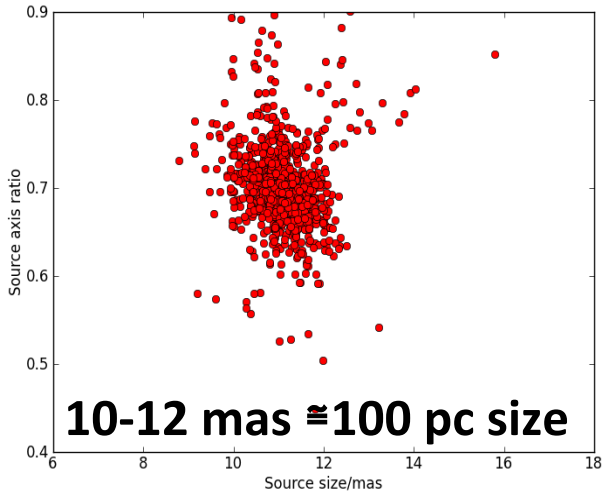


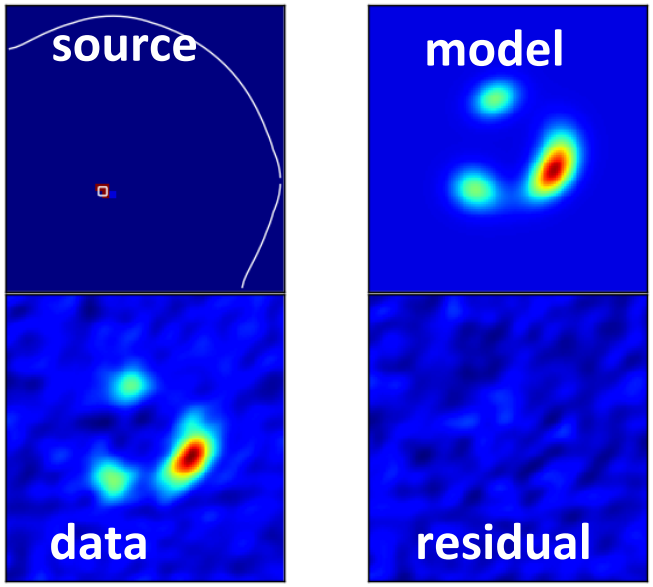
Gravitational lensing to study intrinsically faint sources
Requirement: sub-arcsec resolution at ~1 GHz

Left: SDSS J1004+4112 (z=1.7; 6hr JVLA 5GHz , C conf.); quad-imaged radio-quiet quasar of ~1 uJy intrinsic flux

Below: HS0810+2445 (z=1.5, 3hr JVLA 5GHz, C conf.): similarly faint RQ quasar → modelling shows intrinsic extent of RQQ

Courtesy N. Jackson





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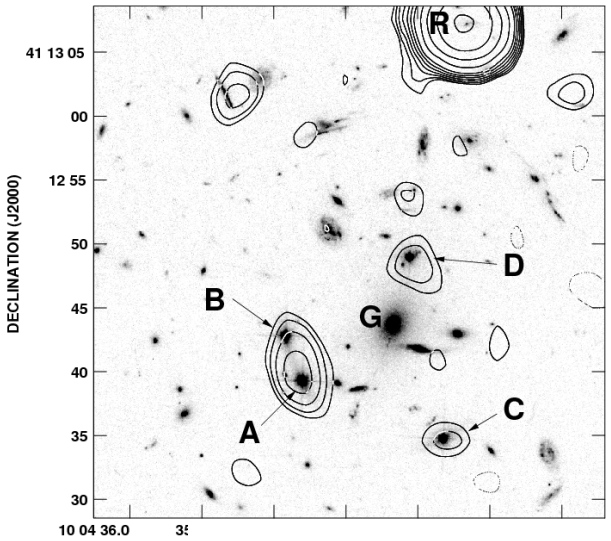

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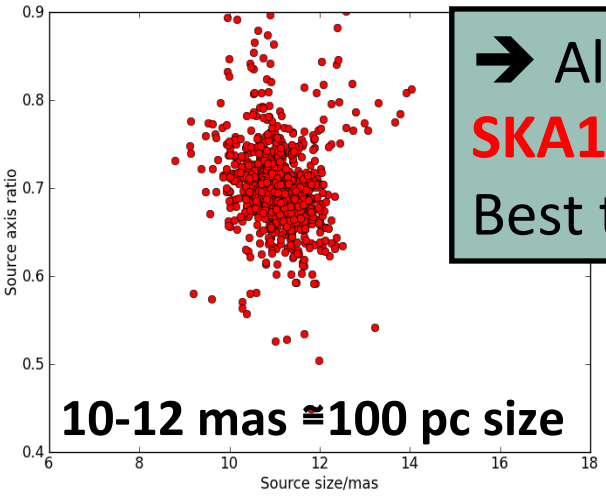
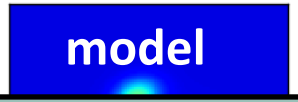
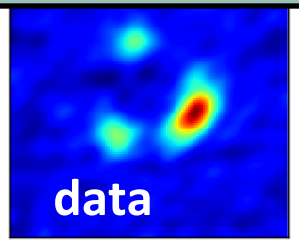
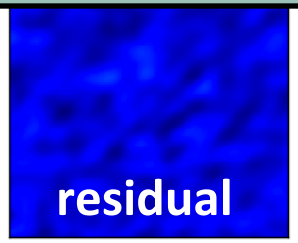


Courtesy N. Jackson



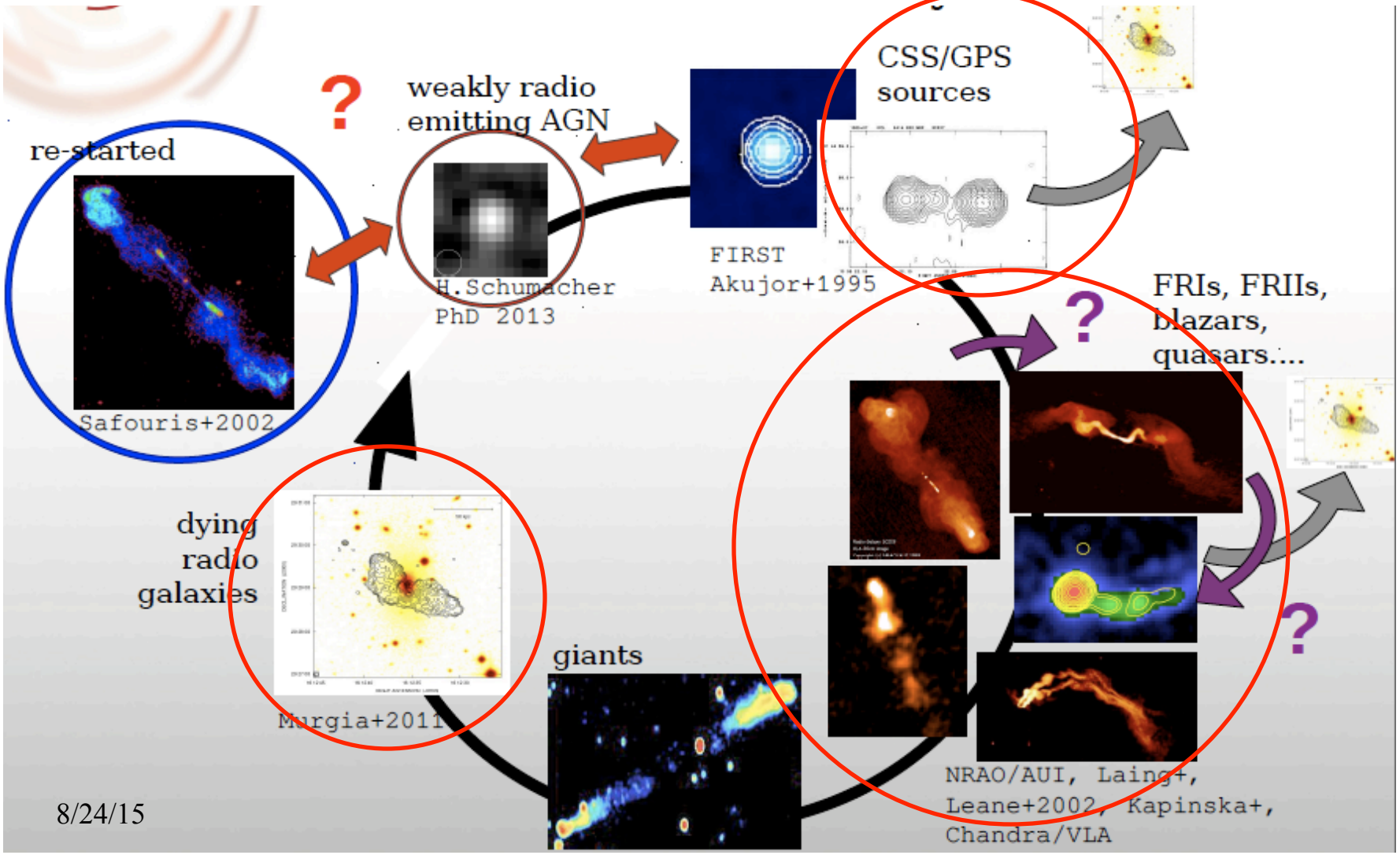
→ All Sky sub-arcsec resolution surveys
SKA1 @ 0.5" → **~7000 lens candidates**
Best to be followed up at Band 5/VLBI





SKA1-LOW All-Sky Surveys

Physics & Life Cycle of RL AGNs



SKA-LOW
All Sky

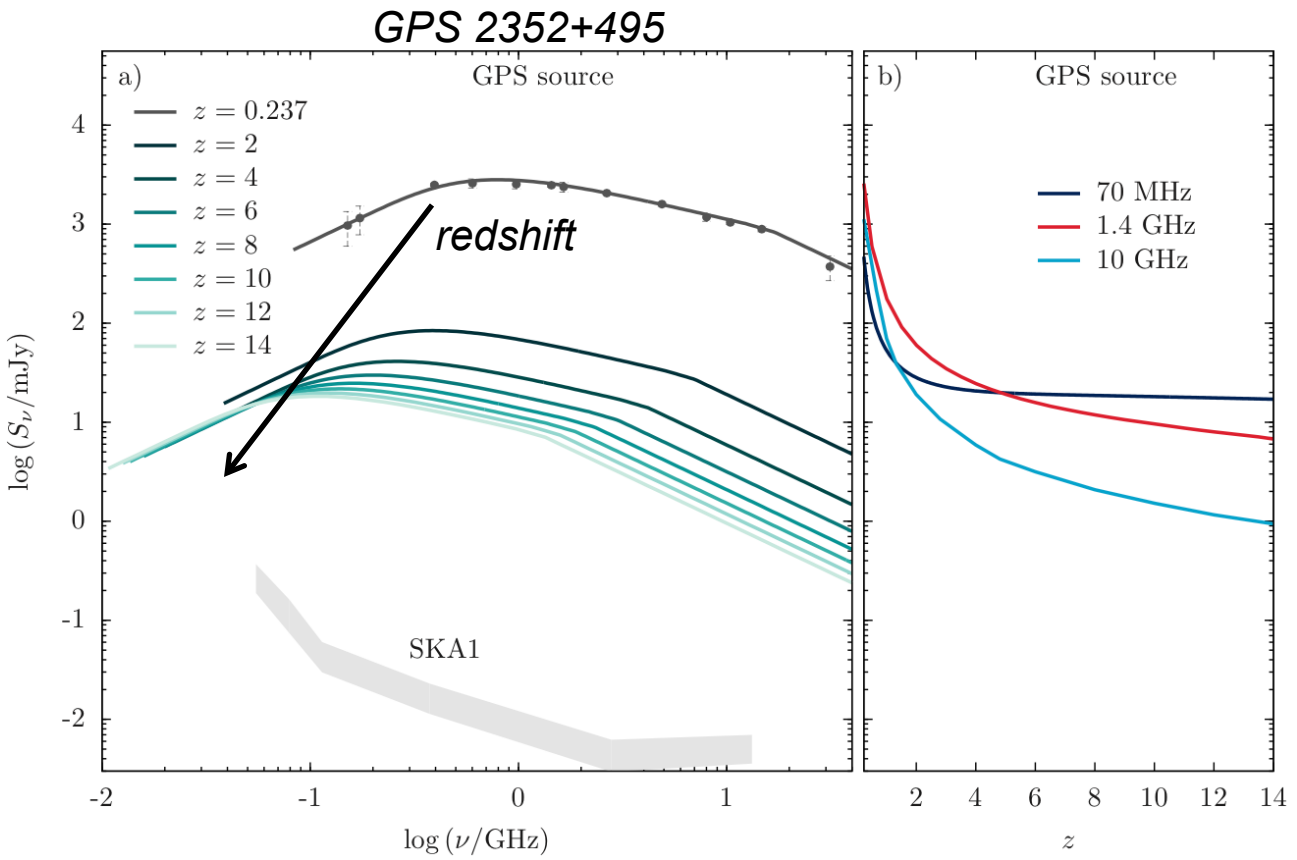
Census of High-z Young Radio Galaxies

1st generation RL AGNs (z>6)

GPS/CSS thought to be the progenitors of extended RGs

Low frequency emission less affected by radiative losses

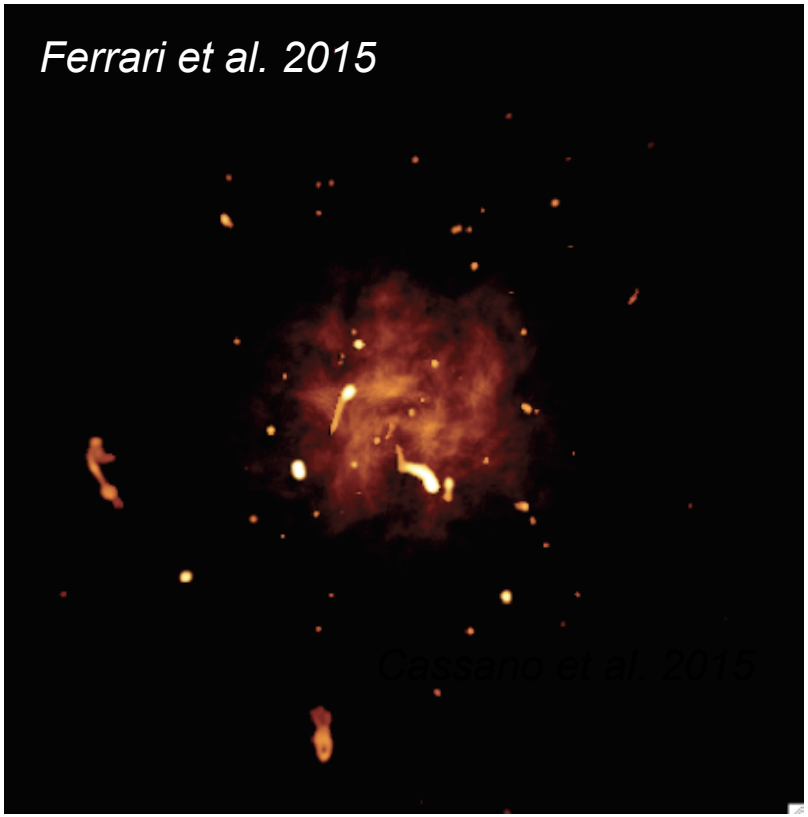
Peak moves to low frequency with redshift (150 MHz @z~6)



Afonso et al. 2015

SKA-LOW All Sky Survey

Galaxy Clusters



SKA1-LOW:
Confusion limited @ ~20 uJy/b rms (120 MHz, 10" res.)

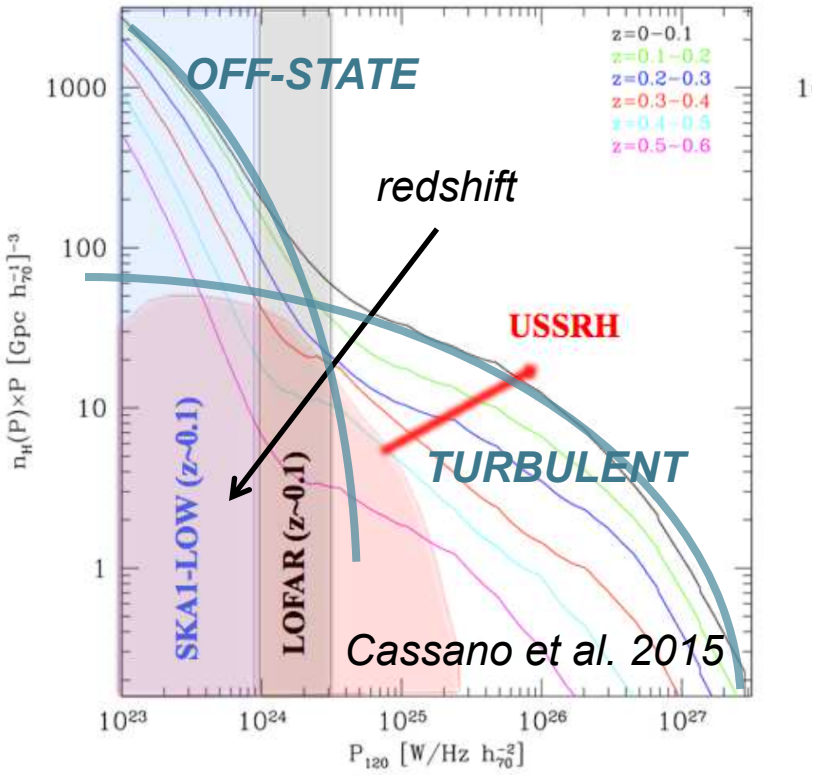
Exploit excellent surface brightness Sensitivity of SKA-LOW in synergy with eROSITA, up to z~0.5

SKA will be sensitive to **turbulent USSRHs** (low-mass mergers) and **"off-state" hadronic RHs** (relaxed clusters)

SKA2:
For higher-z needs <10" resolution to remove foreground galaxies

SKA-LOW All Sky Survey

Galaxy Clusters



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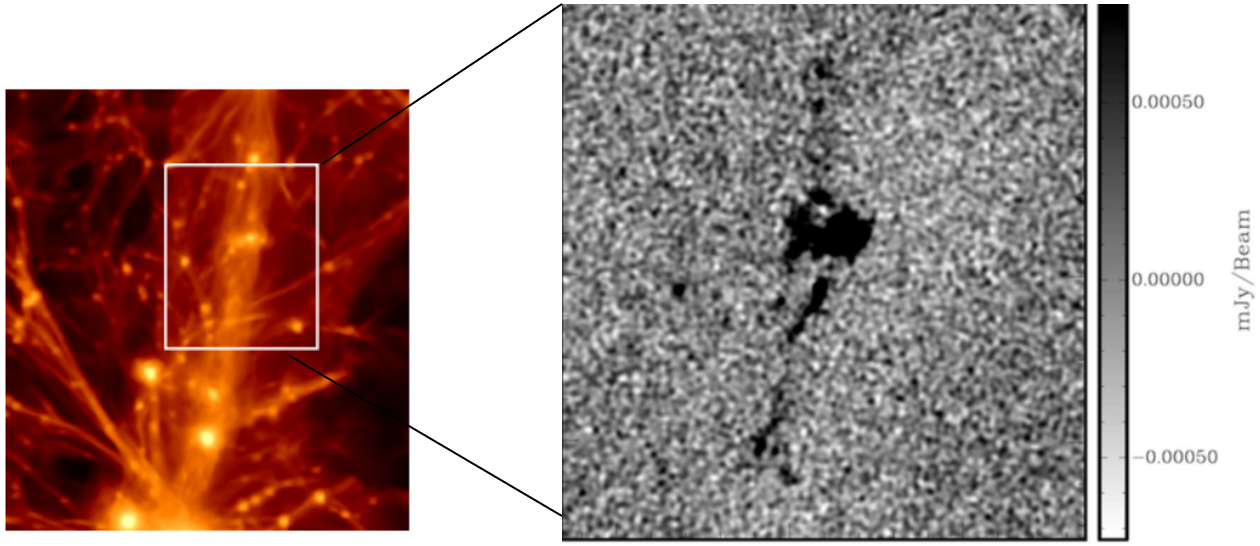
SKA-LOW
All-Sky Survey

Diffuse Emission in Cosmic Web

SKA can potentially detect non-thermal emission associated to steady-shocks in cosmic web filaments

z~0.02
B=0.1 μG
Vazza et al. 2015



Outline of SKA1 Key Reference Surveys

Prandoni & Seymour 2015

Revisited after rebaselining (March 2015)

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. **High-z Magnetism** 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” 0.5”	**Magnetism** Cosmology tests Transients (beam forming) HI surveys Our Galaxy
Clusters (RL AGNs)	~120 MHz	All-sky	20 uJy (confusion)	31000 deg2	8”	**EoR**

What's Next: Definition of KSP

Tasks for this meeting and next future:

- **Start defining actual KSPs**
- **Identification of useful ECPs**
- **Identification of Synergies and Commensality with other SKA WGs**
- **Exploiting synergies with other upoming facilities** (e.g. LSST, Euclid, JWST, eROSITA, etc.)

- **Observational Setup:** Frequency, BW, Area Coverage, rms, observing startegy, etc.
- **Choice of Region/Fields**
- **Pipelines/Data Products:** Stokes parameters (IQUV), image/catalogue parameters → **spatial/spectral resolution**, etc.
- **Resources/Expertise** (strong role played by Precursors)

Commensality: Examples

- **All-Sky Surveys:** All-Sky RM / Local Universe/ Legacy/Rare Cosmology tests / HI Intensity Mapping/ Our Galay
- **Wide Fields**: SFHU/AGN Evolution / Weak Lensing (MID) / HI Surveys (MID)
- **Deep Fields:** SFHU/AGN Evolution /HI deep surveys (MID) / Deep Polarization Fields (MID)
- **Mid Ultra Deep:** SFHU/AGN Evolution /HI deep surveys

To be fully exploited:

→data processing of all I,Q,U,V Stokes parameters,

→data processing with different setups, eg:

angular resolution: 0.5" – 2"

spectral resolution: full BW, ~MHz channels for RMs/spectral index, kHz for line

→ different data products, eg:

2D continuum I,Q,U,V + 3D HI images/catalogues

Summary

- **Continuum Radio surveys provide a valuable dust-extinction/gas-obscuration-free tool** to study thermal and non-thermal emission from galaxies and galaxy clusters

- **SKA sub-uJy sensitivity will make it possible to study high-z SFG and *all types* of AGN**: both the RL and the most common RQ component
  → Added value: sub-arcsec resolution and Band 5

- **SKA continuum surveys will be competitive with upcoming IR, optical and X-ray surveys** [will become important component of multi-band studies and useful to a very broad community]
  → Strong synergies to be exploited with other facilities

- **Existing commensality/synergy with other WGs should be explored.** To be fully exploited:
  → different obs. modes to be implemented in parallel (e.g. full Stokes, beam-forming, etc.)
  → data processing of all I,Q,U,V Stokes parameters, and with different setups:
    - Angular resolution/weighting scheme: from arcsec to sub-arcsec
    - Spectral resolution: from kHz (for line surveys) to ~MHz (for RMs/in-band spectral index) to ~GHz (for detection experiments)

THANKS!