Next Generation Radio-continuum Extra-galactic Radio Surveys & Deep fields

Probing AGN activity down to the radio-quiet regime

Isabella Prandoni

INAF - IRA

Science-driven Requirements for the SKA

Based on
SKA Science Book
(Carilli & Rawlings Eds. 2004)

•Sensitivity ≈ 1-2 10^4 m^2 K^{-1}
(low T_{sys} receivers)

•Survey speed
≈ 0.2-60 10^8 deg^4 m^4 K^{-2}
(large FOV, up to 1 deg^2)

•Resolution ≈ 1-100 mas
(long baselines, up to 4500 km)

	Description of Key Science Project	Frequency Range (GHz)	FoV	Sensitivity	Survey Speed	Resn.	Baseline	Dyn. Range Driver	Poln. Driver
		.1 .3 1.0 3.0 10 30	deg^2	m^2/K	$deg^2 m^4 K^{-2}$	mas*	Km		
1	**The Dark Ages**								
1a	EoR				>~3x10^7		10	√	√
1b	First Metals		0.003	15,000		50	125		
1c	First Galaxies & BHs			20,000		10	4500	√	√
2	**Galaxy Evolution, Cosmology & Dark Energy**								
2a	Dark Energy				6x10^9		5		
2b	Galaxy Evolution			20,000	1x10^9		10		
2c	Local Cosmic Web				2x10^7		0.5		
3	**Cosmic Magnetism**								
3a	Rotation Measure Sky				2x10^8		10-30		√
3b	Cosmic Web				1x10^8		5		√
4	**GR using Pulsars & Black Holes**								
	Search				1x10^8		< 1		
4a	Gravitational Waves		-	>15,000		1	200		√
4b	BH Spin		1	10,000			-		√
4c	Theories of Gravity			>15,000		1	200		√
5	**Cradle of Life**								
5a	Proto-planetary Disks		0.003	10,000		2	1000		
5b	Prebiotic Molecules		0.5-1	10,000		100	60		
5c	SETI		1						
6	**Exploration of the Unknown**		Large	Large	Large				

*milli-arcseconds of angular resolution

From Dewdney et al. 2009

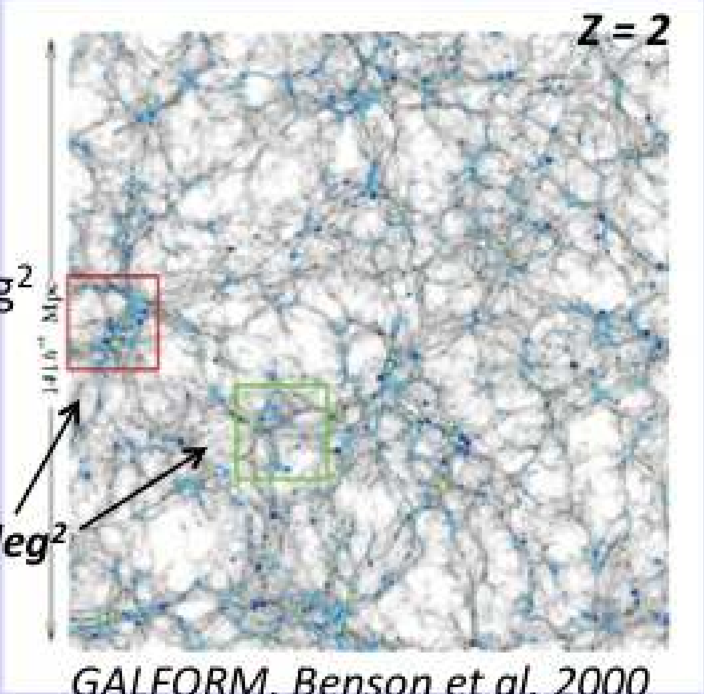
Radio Continuum Extragalactic Survey Science

- Evolution of galaxies and clusters (in combination with HI + multi-λ information)
  - Star formation & BH accretion history
  - Role of AGN feedback over cosmic time
  - Interplay between SF and AGN activity
  - Origin of FIR-Radio correlation

  } Deep fields ~10-100 deg^2

  - diffuse non-thermal emission in clusters
  - first galaxies, BHs & protoclusters
- Cosmology (in combination with HI/redshift surveys)
  - Baryonic Acoustic Oscillations
  - Integrated Sachs-Wolfe Effect
  - Magnification Bias
  - Weak lensing
- Magnetism (in combination with polarization)
  - Formation & evolution of magnetic fields

} Shallower wide-area surveys >1/4 sky



GALFORM, Benson et al. 2000

- Commensality between line/continuum/polarization surveys
- Synergy with surveys in other wave-bands

Next Generation Radio Telescopes/ Instrumentation

Radioastronomy (from m to sub-mm λs) is making a major leap forward. Triggered by *SKA*, a number of new facilities, or major upgrades of existing facilities, are coming on-line

They are referred to as *SKA pathfinders* and *precursors*

Pathfinders: Apertif, Arecibo, ATA, eEVN, EMBRACE, e-MERLIN, JVLA, LOFAR, LWA, SKAMP

Precursors: ASKAP, Meerkat, MWA

SKA Pathfinders: Upgrades

- **JVLA:** VLA major upgrade (27 dishes ~30 km max. bs.)

	VLA	JVLA	Factor
Continuum Sensitivity (1-σ, 1 hr.)	30 μJy	3 μJy	10

Call for observations & obs. ongoing

- **eMERLIN:** array of 7 UK radio telescopes operated as a radio interferometer (220 km max. baseline)

Parameter	1.5 GHz L	5 GHz C	22 GHz K
Resolution (mas)	150	40	12
Sensitivity (μJy/b) 1σ, 12 hr, w. Lovell	5-6	1.8-2.3	~15

Commissioning ongoing
First shared risk call early 2012

- **Apertif:** major upgrade of WSRT (3 km max. baseline). New PAF receivers. Optimized for (HI) surveys. Working frequency 1.4 GHz

SKA Pathfinders: LOFAR

- Low Frequency Array:

  10-240 MHz (LBA, HBA)

  40 NL stations + 8 International

  First operational Cycle Dec. 2012

  (23% Open) 33/36 NL + 5 IS

International stations increase resolution:

High spatial resolution important to beat confusion

Max Baseline (km)	Freq. (MHz)	Angular resol. (")	Confusion Limit (3s) (μJy)
150	240	2.	13
500	240	0.6	5
1000	240	0.3	1

VLSS: 74 MHz, 100 mJy rms, 80" res (500x)

TGSS (ongoing): 150 MHz, 7-9 mJy rms, 20" res. (500-700x)

SKA Precursors: ASKAP

Main characteristics:

- Array of 36 *12-m* antennas over region of 6km in diameter
- Phased array feeds (focal plane arrays)
- Wide FoV and High dynamic range imaging capability
- Observing Band: L-band (1.4 GHz)
- Bandwidth: 300 MHz
- FoV = 30 sq. degr

- Site: *Murchison Radio-astronomy Observatory (MRO),* Western Australia. Remarkably radio quiet site, chosen as site for Australian component of *SKA-1*

- Timeline:
  - Start of operations: 2013

- Performance:
  - Continuum Sensitivity (12h, 1σ): 10 μJy /beam
  - Line Sensitivity (12h, 100 kHz res., 1σ): 0.6 mJy /beam
  - Continuum Survey Speed (10 μJy /beam) : 2.2 sq. degr. /hour
  - Line survey speed (0.6 mJy/beam) : 2.6 sq. degr. /hour

SKA Precursors: Meerkat

Main characteristics:

Number of dishes[a]	80 (central array) + 7 (spur)
Dish diameter	12 m
Aperture efficiency	0.7
System temperature	30 K
Low frequency range[a]	0.58–2.5 GHz
High frequency range[a]	8–14.5 GHz
Field of view	1 deg^2 at 1.4 GHz 6 deg^2 at 580 MHz 0.5 deg^2 at 2 GHz
A_e/T_{sys}	200 m^2/K
Continuum imaging dynamic range[b]	1:10^5
Spectral dynamic range[b]	1:10^5
Instrumental linear polarisation purity	−25 dB across field
Minimum and maximum bandwidth per polarization[a]	8 MHz–4 GHz
Number of channels	16384
Minimum sample time	0.1 ms
Minimum baseline	20 m
Maximum baseline	8 km (without spur) 60 km (with spur)

Notes: a: *Final values. See Table 2 for roll-out schedule.*
b: *Dynamic range defined as rms/maximum.*

Timeline:

	KAT-7 2010	Phase 1 2013	Phase 2 2014	Phase 3 2015	Phase 4 2016
Number of dishes	7	80	80	87	87
Low freq. range (GHz)	1.2–1.95	0.9–1.75	0.9–1.75	0.9–1.75	0.58–2.5
High freq. range (GHz)	—	—	8–14.5	8–14.5	8–14.5
Maximum processed bandwidth (GHz)	0.256	0.850	2	2	4
Min. baseline (m)	20	20	20	20	20
Max. baseline (km)	0.2	8	8	60	60

SKA_1 – Dual Site Implementation

Incremental approach confirmed by dual site implementation

- SKA1_Low: Western Australia (ANZ) → Sparse AA (50 stations)
- SKA1_Mid: South Africa (RSA) + '*survey instrument*' in WA
  - RSA: ~250 dishes w. low-Tsys SPF (incl. MeerKAT, 64 *13.5-m* antennas)
    high A/T (1000 m^2/K) lower SS (1 10^6 deg^4 m^4 K^{-2})
    [FOV(1 GHz)=1 deg^2]
  - ANZ: ~100 dishes w. PAF (incl. ASKAP, 36 *12-m* antennas)
    lower A/T (275 m^2/K), higher SS (3 10^6 deg^4 m^4 K^{-2})
    [FOV(1 GHz)=30 deg^2]

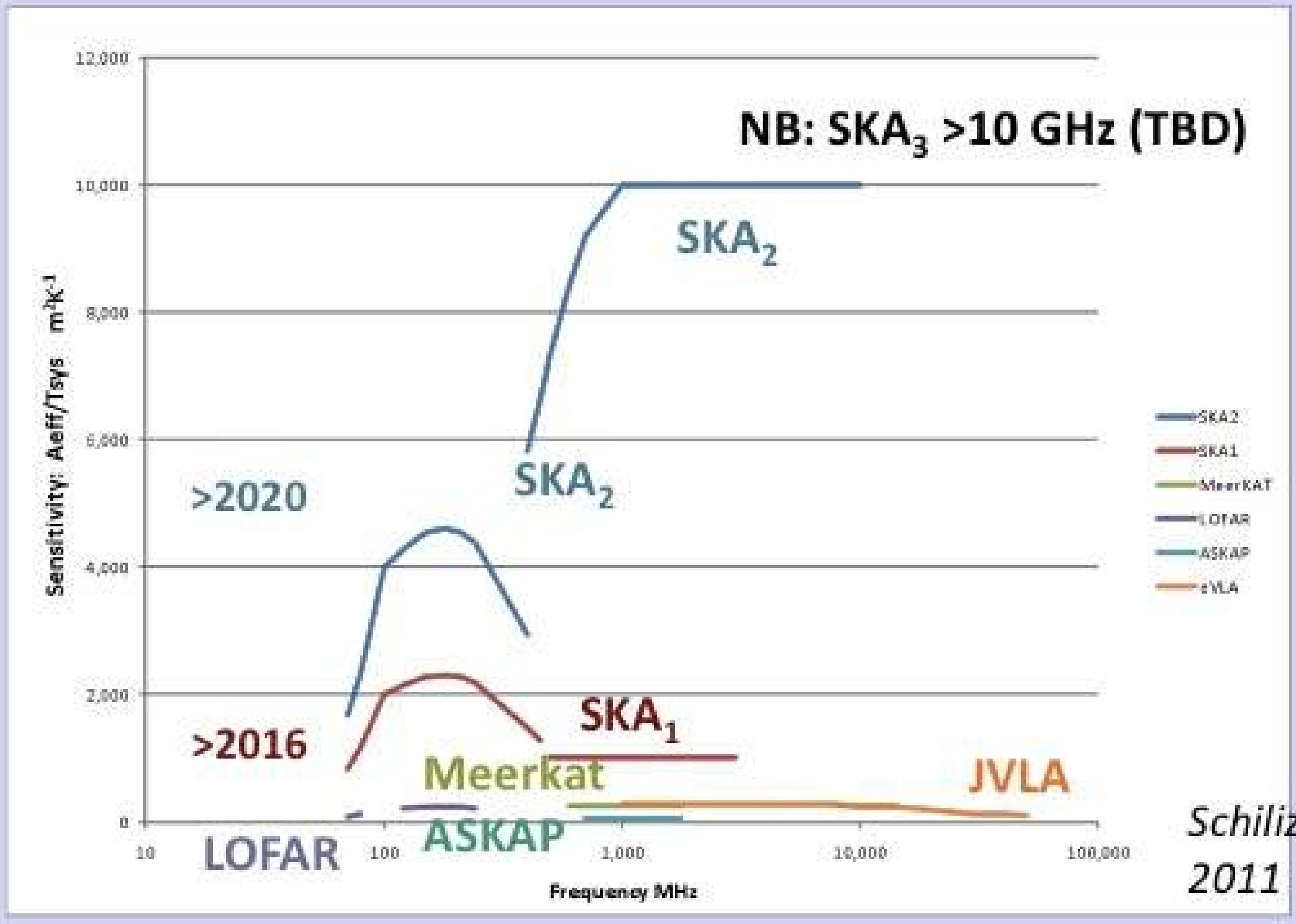
Implications for surveys: all-sky → ANZ; deep → RSA

Construction phase from 2016

The SKA in steps: Sensitivity Comparison

Phased construction allows maximum use of advances in technology and incremental **fine-tuning of** science drivers/technical requirements

- Building on precursors & pathfinders (mainly JVLA & Meerkat) for SKA_1
- Building on SKA_1 (mainly SPF) for SKA_2

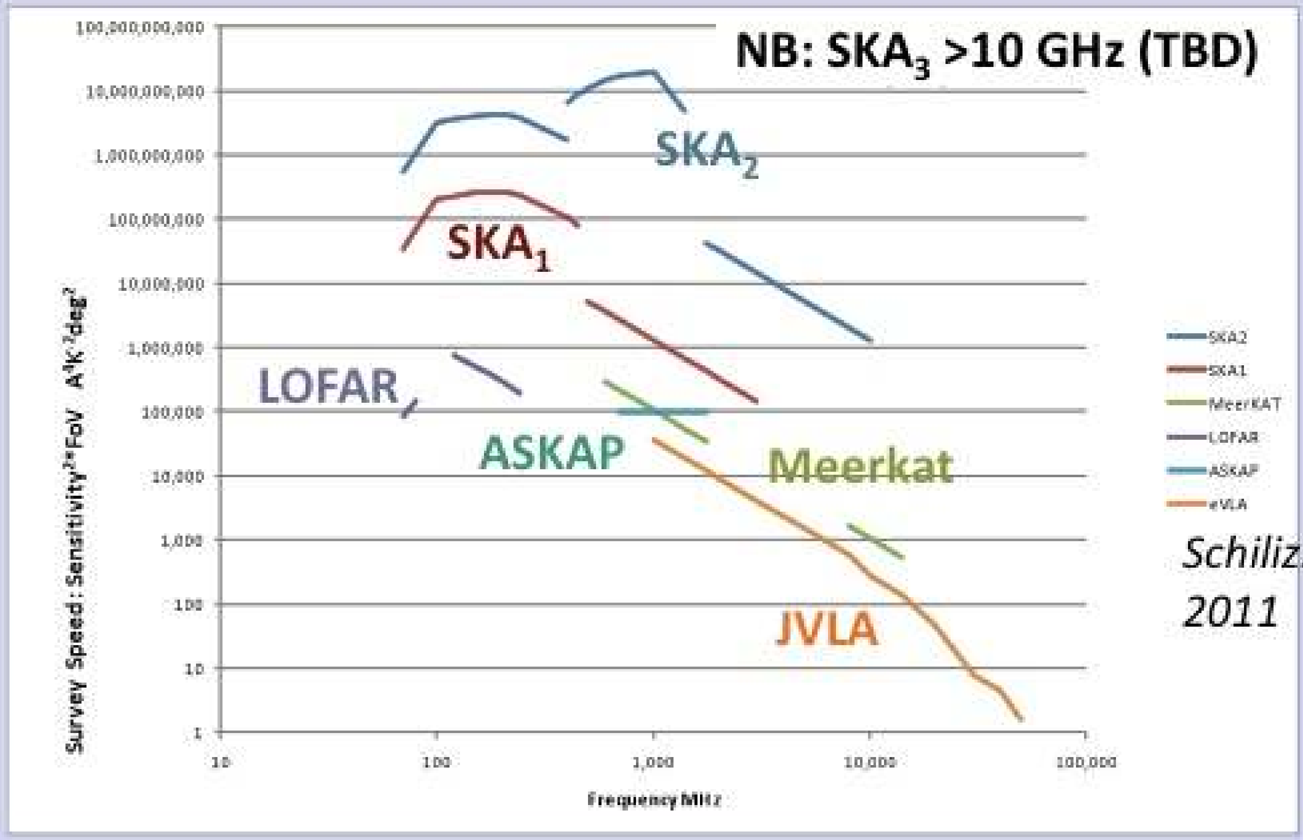


Schilizzi, 2011

The SKA in steps: Survey Speed Comparison

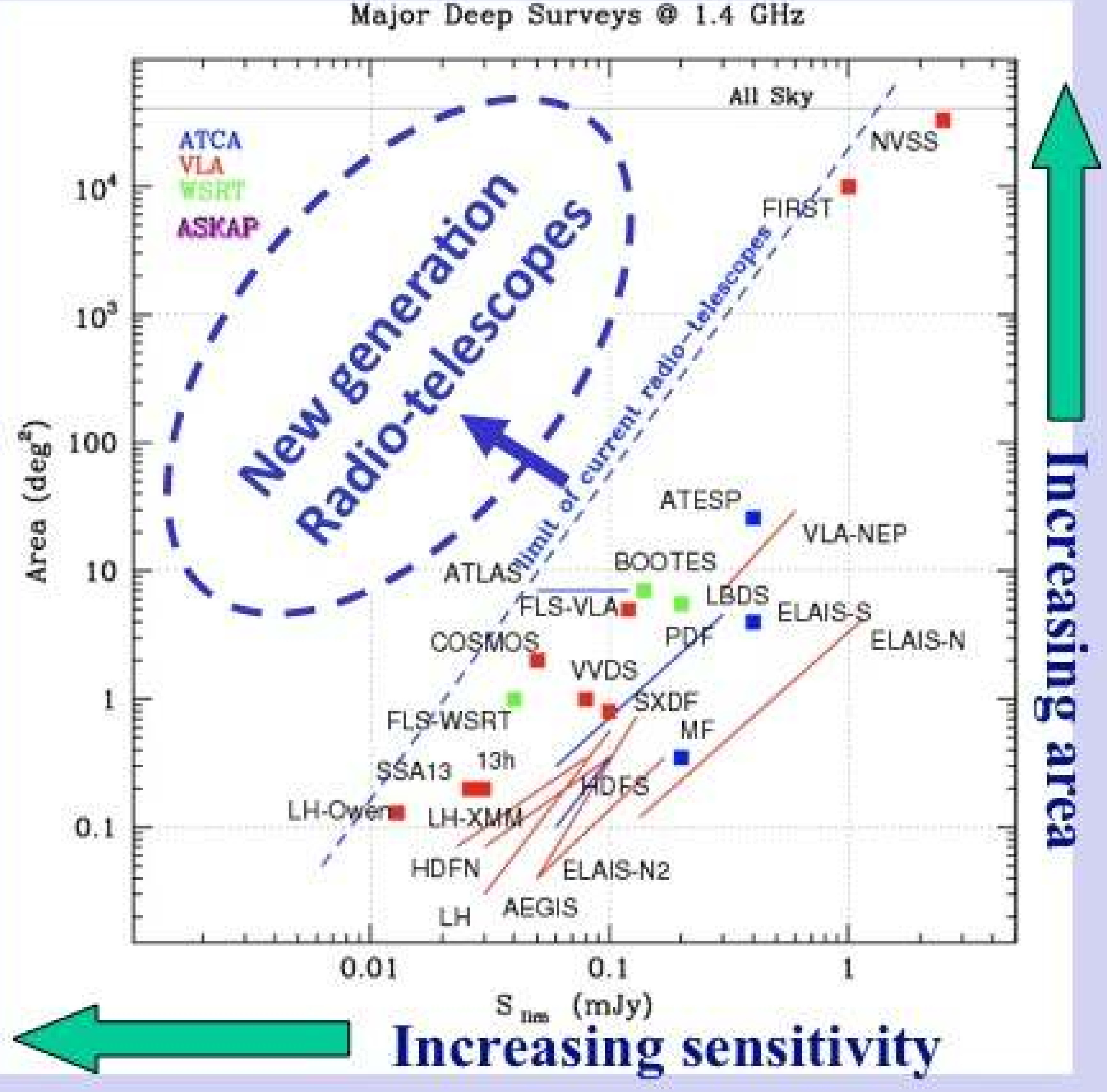
Phased construction allows maximum use of advances in technology and incremental **fine-tuning of** science drivers/technical requirements

- Building on precursors & pathfinders (mainly LOFAR & ASKAP) for SKA_1
- Building on SKA_1 (mainly AA & PAF) for SKA_2



Radio Continuum extra-galactic surveys

- Available extragalactic surveys & deep fields with current facilities
- Next generation radio telescopes will push the boundary by a factor of 10-1000
- Need of high sensitivity, together with high survey speed and high spatial resolution to beat confusion
- New region of parameter space will be explored, new discoveries expected



Next Radio-continuum extra-galactic legacy surveys

All-sky (rms 14 μJy)

- ASKAP: EMU (δ<+30°)

[+ APERTIF: WOODAN] (δ>+30°)

Deep fields

- Meerkat: MIGHTEE

Tier 1: 35 deg^2 rms 1 μJy

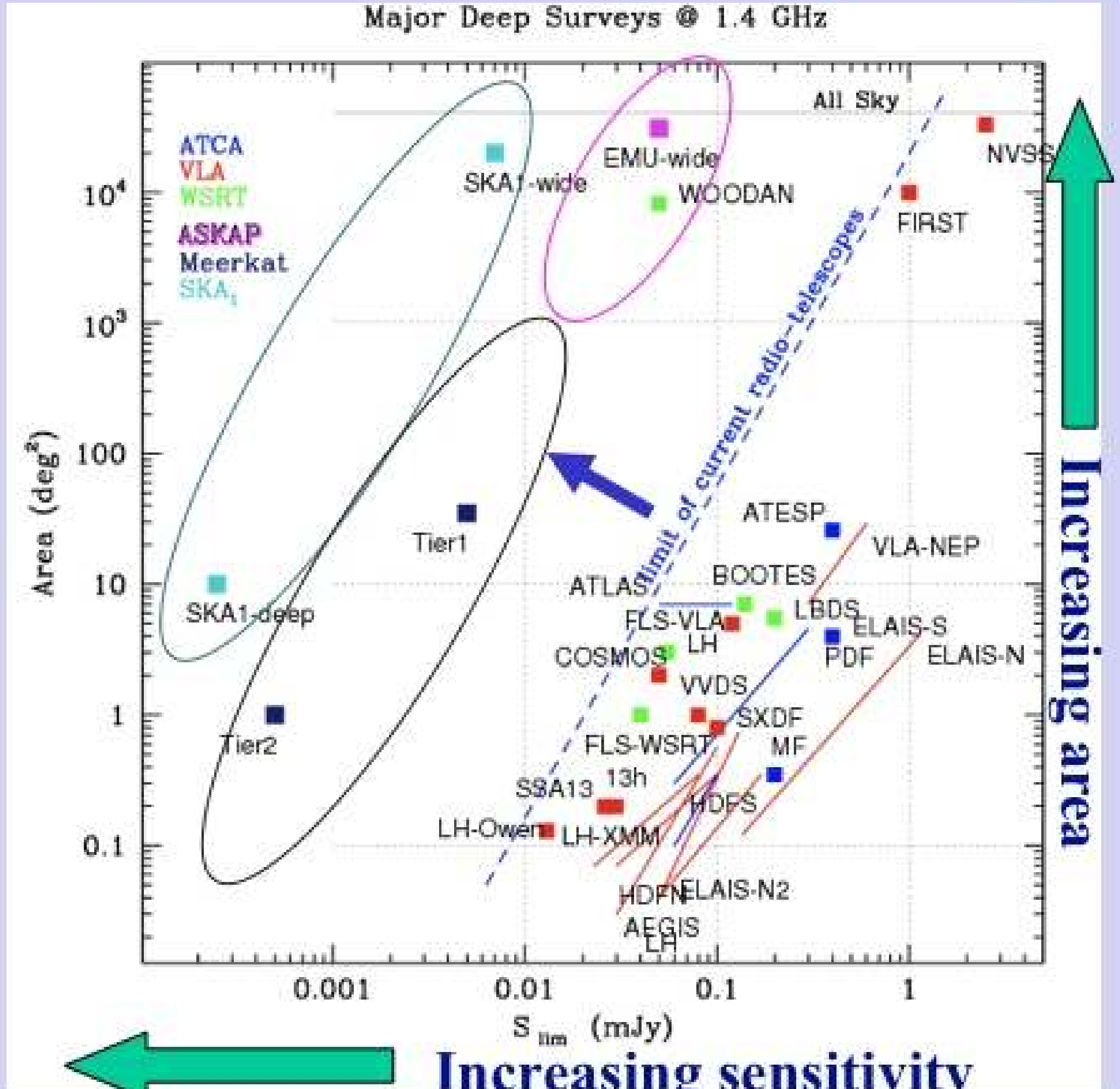
Tier 2: 1 deg^2 rms 0.1 μJy

Factor 50 deeper

SKA$_1$ Killer survey:

[Huynh+, work in progress]

Factor 10 deeper



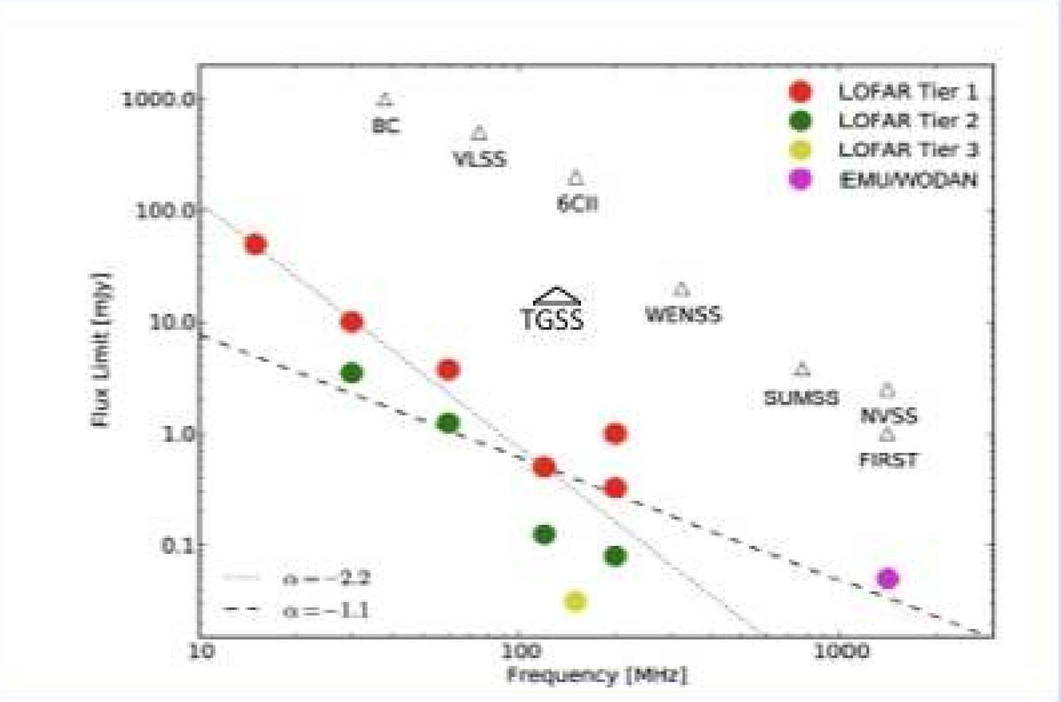
Next Radio-continuum extra-galactic legacy surveys

LOFAR Survey Key-Project

- ➔ Extension to low frequency for Northern Sky
- ➔ Spectral index info

Multi-freq. (15-200 MHz) and Tiered (Large, Deep & Ultra-deep) approach

Factor >50 deeper



Revised Proposal (2012):

Table 2: *Proposed LOFAR surveys*

f MHz	Area deg^2	thermal rms[1] mJy	Int. time[1] hrs	Number pointings	Days[2]	Total[3] sources	Key[4] Topic	Main[4] Topic
Tier 1: The "Large Area" survey								
15 - 40[5]	20626	2.0	20	307	64	3e6	1,2	5,7,10
40 - 65	20626	1.0	20	190	40	5e6	1,2	5,7,10
120 - 180	20626	0.07	3	1942	121	3e7	1,2	5,7,8,9,10
Tier 2: The "Deep" survey								
15 - 40	975	0.9	100	15	31	1e6	2,3	5,6,7
40- 65	1575	0.3	100	15	31	1e6	2,3	5,6,7
120 - 180	566	0.015	50	55	57	3e6	2,3	5,6,7
Tier 3: The "Ultra Deep" survey								
120 - 180	83	0.007	220	5	23	2e6	3	5,6

(Many) AGN science cases to be addressed

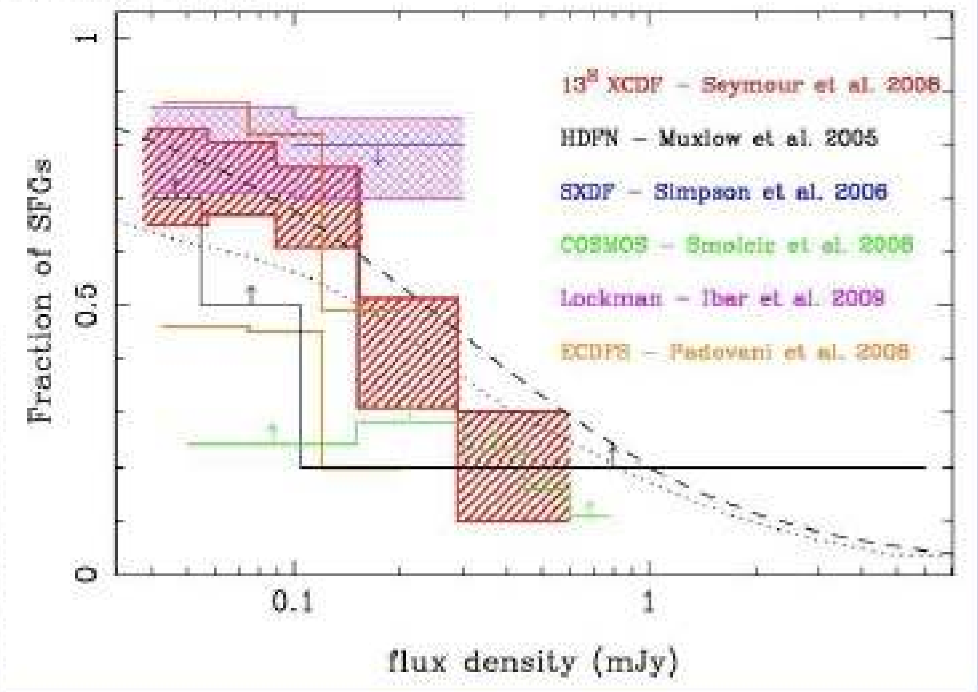
1. AGN Evolution & BH Accretion History down to radio-quiet regime
   AGN component seen in radio fields down to deepest sensitivities
   → physics & evolution of AGN possibly down to the radio-quiet regime **(not affected by obscuration!)** LOFAR Tier 2: 10^5 RQ-AGN (50% @ z>1)
2. Role of AGN feedback in galaxy evolution (different accretion modes)
   Radio + multi-band studies of host galaxies → role of AGN feedback (radio/QSO modes).
   LOFAR Tier 2: Local studies of Low-P RL-AGN up to z~2
   Very high res. deep radio imaging → co-existence of SF & AGN activity *within* galaxies (see eMERGE KP)
3. Growth and duty cycle of radio sources, and role of IGM
   What determines the FRI/II dichotomy? Is it possible to directly determine DC from detection of old very steep-spectrum outbursts ? (LOFAR crucial here)
4. Highest redshift (z>6) AGN searches and studies
   see USS (LOFAR), IFRS,… (multi-λ+ large area needed)
5. Influence of galaxy environment on AGN activity and feedback

…

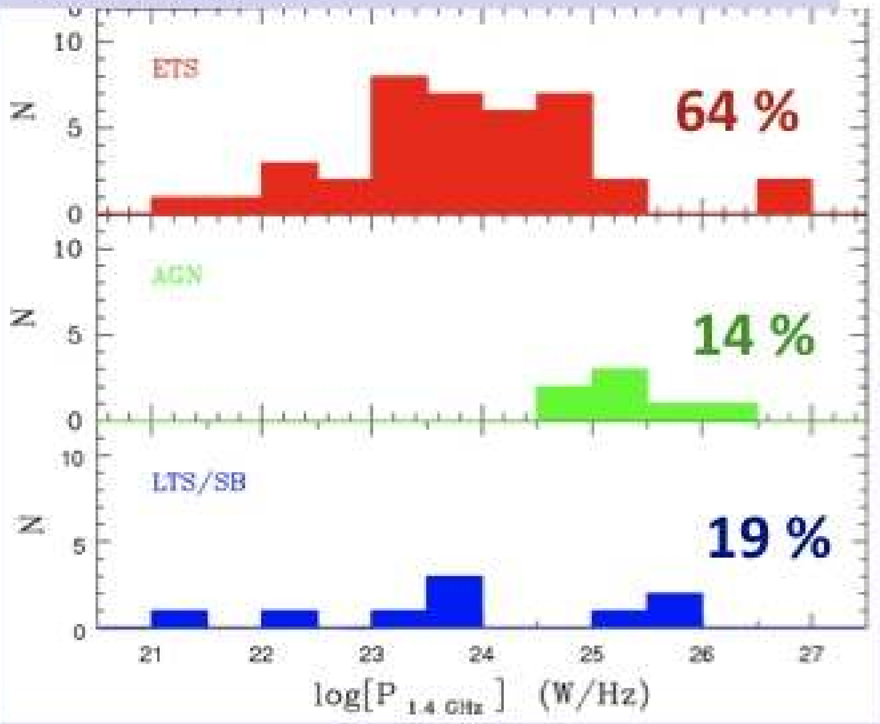
AGN Component in deep fields

Difficult to securely disentangle AGN from SFG, however…

Seymour+ 08



Mignano,IP+ 08



At S >400-500 μJy:

SFG contribution ~ 10-20%

AGN contribution ~ 80%

(65% ETS + 15% Type 1 AGN)

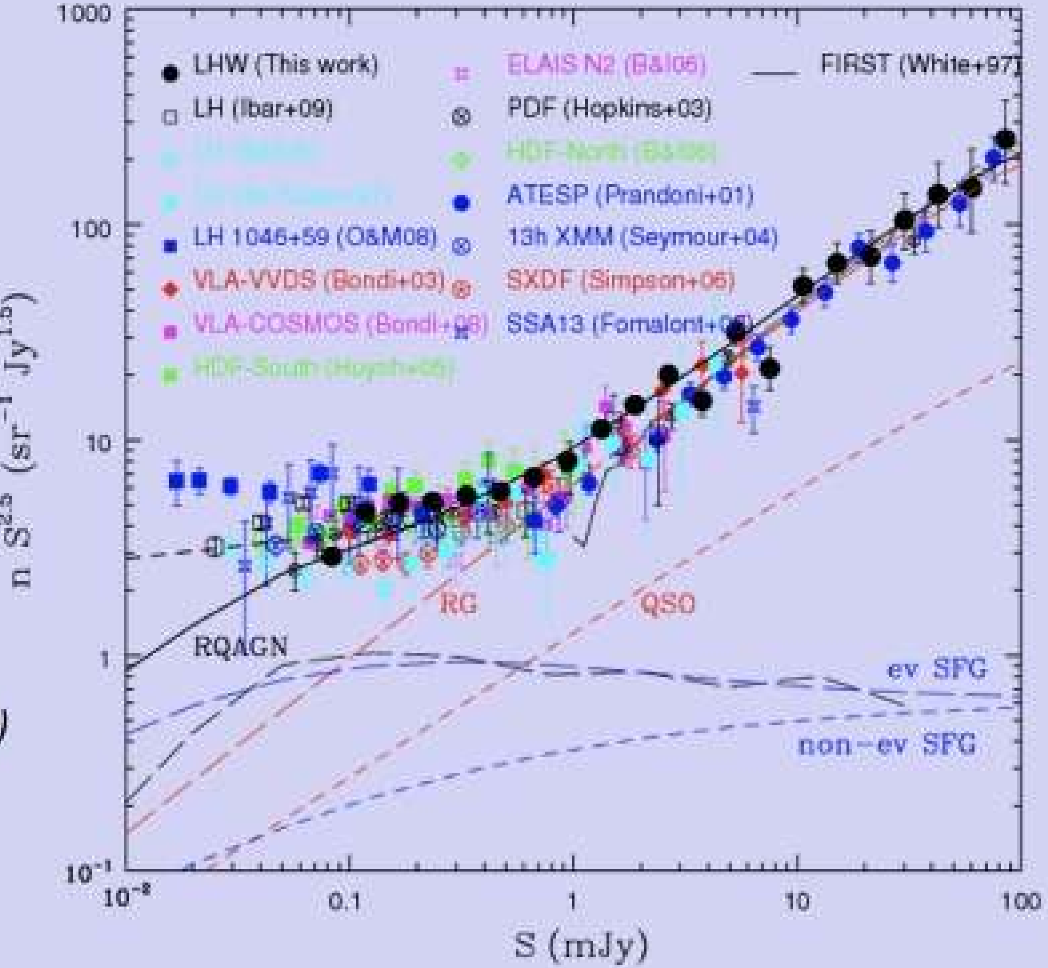
Modeling the faint radio sources

Classical RL-AGNs → PLE
→steep/flat *(e.g. Dunlop & Peacock 80)*
→FRI/FRII *(e.g. Willott+ 01, Clewley & Jarvis 04, Sadler+ 06)*

SF gals. → PLE
→ local F(L) + L ~ $(1+z)^p$ p~3
(*e.g. Condon 89, Saunders+ 90, Machalski & Godlowski 00, Yun+ 01, Sadler+ 02)*

RQ-AGN: (*Jarvis & Rawlings 04, Wilman+ 08)*

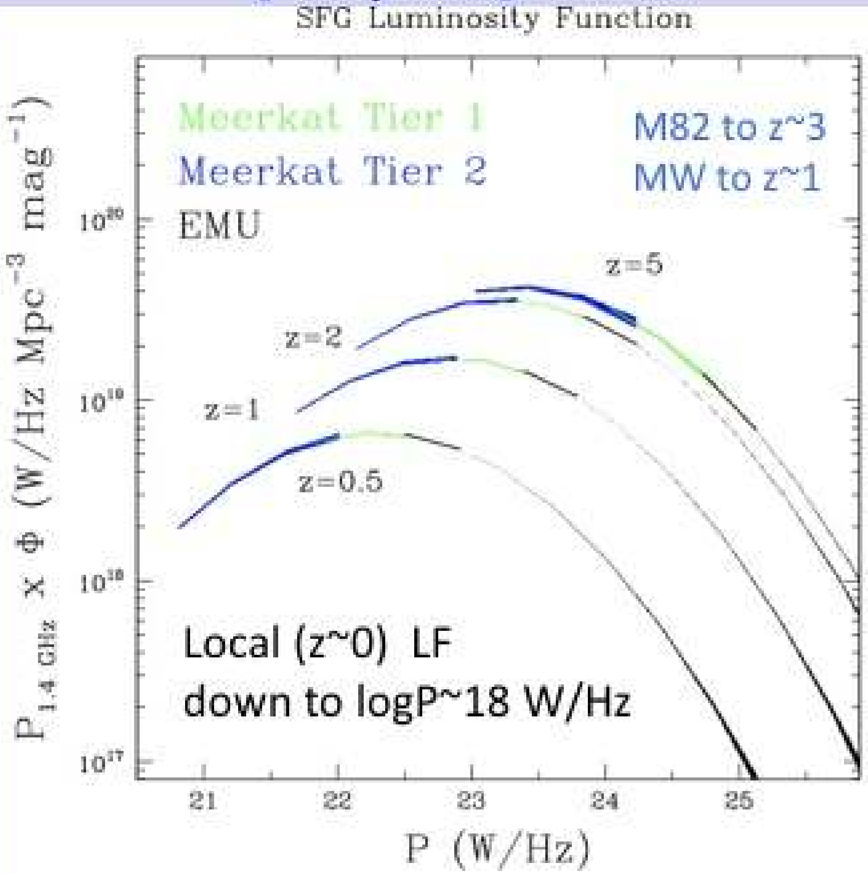
→LDDE [largest comp. at z<1
RS →compact & steep (<<10 kpc)
22< logP <24
host galaxy → (em. line spectrum)



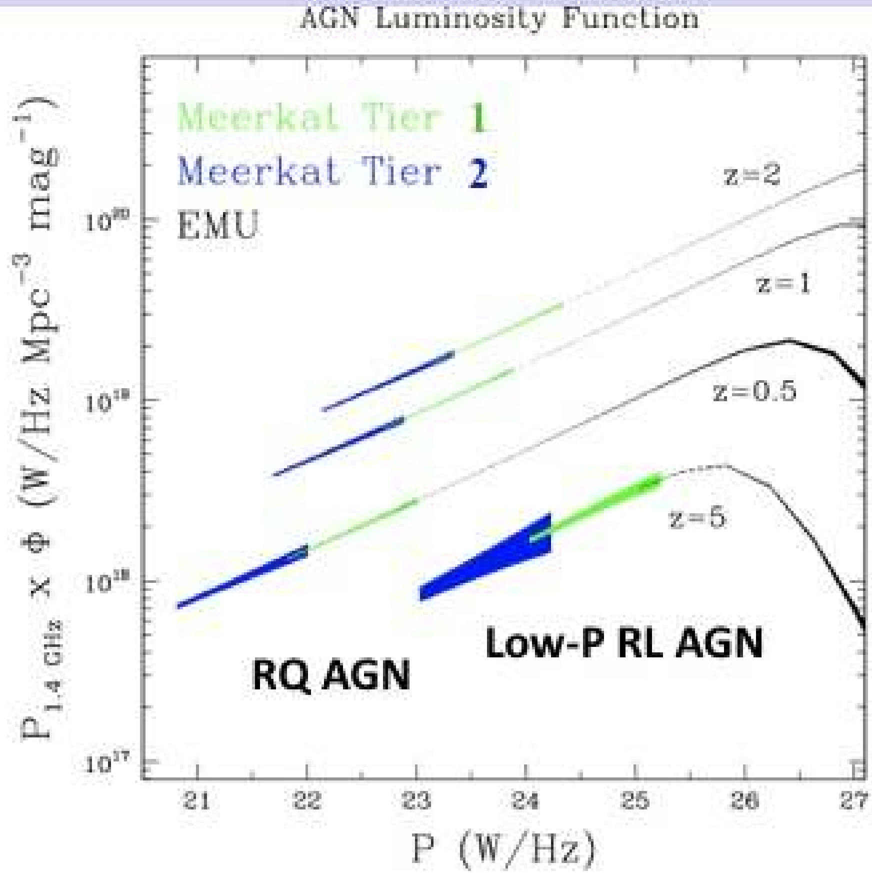
1.4 GHz Source Counts

EMU+MIGHTEE: SFG/AGN LF

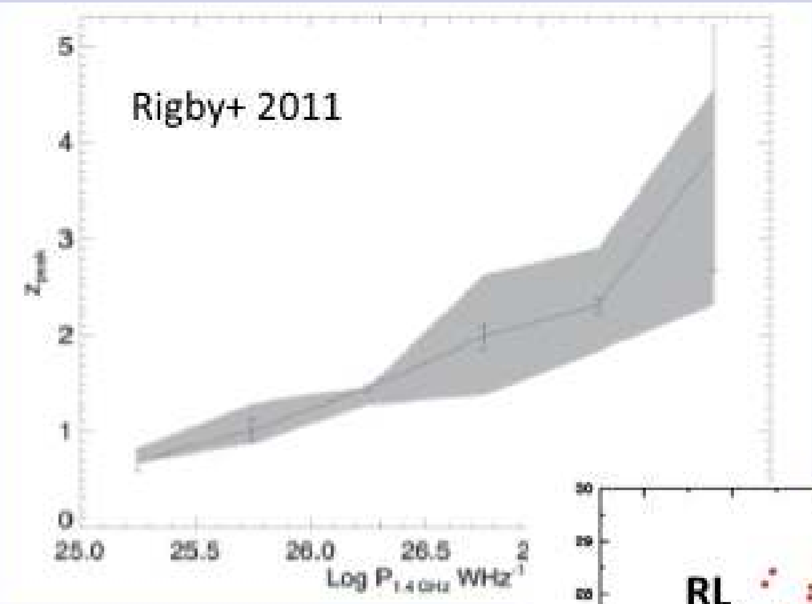
SFG Luminosity Function [no hybrids]



AGN Luminosity Function [no downsising, no hybrids]



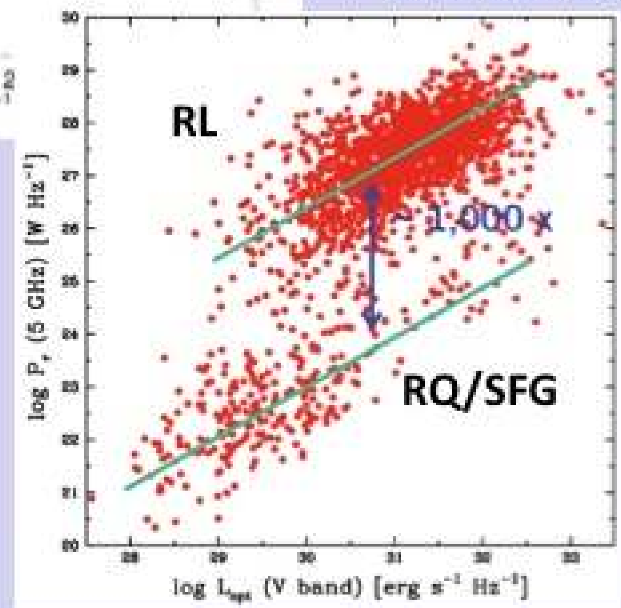
AGN evolution/BH Accretion History



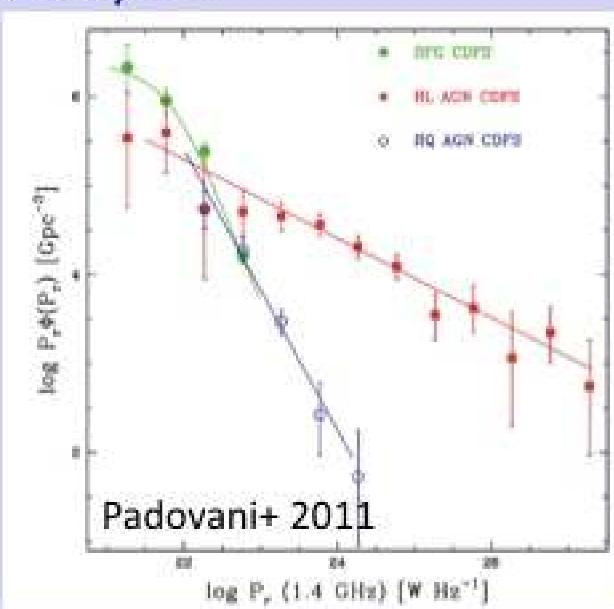
- Probe downsizing for low-P radio AGN: most powerful RS peak at the highest z Evolution at P<<10^{25} W/Hz?

- Evolution of radio-selected RQ-AGN: they start to appear at μJy levels & share many properties with SFGs → radio em. dominated by SF?

- Interplay between AGN and SF activity in galaxies?



CDFS



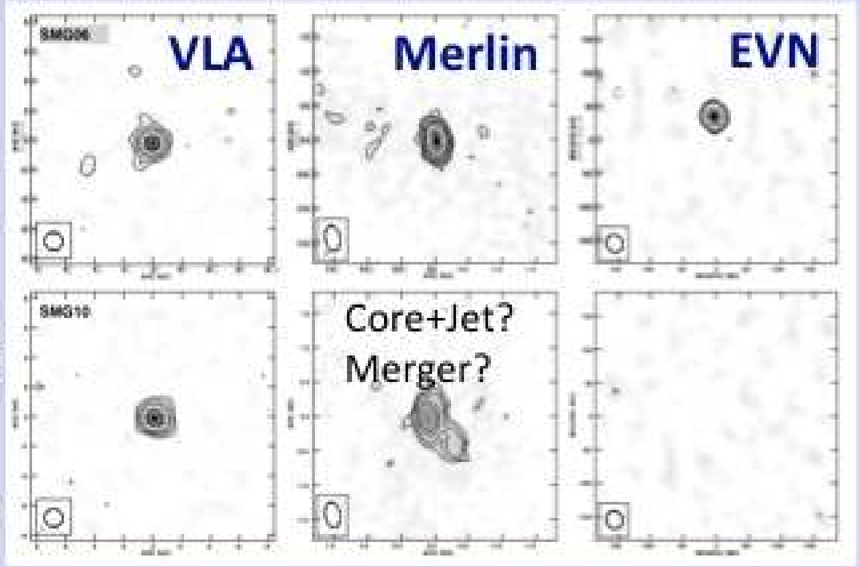
Composite sources: Separating AGN/SF activity

High resolution sensitive radio observations is the most direct and neat way to securely pinpoint AGN radio emission in deep radio fields

z=2.7
S=246 μJy

z=1.2
S=295 μJy

HDFN
Biggs+ 2010



High spatial resolution allows to separate AGN/SF contributions in *hybrid* sources

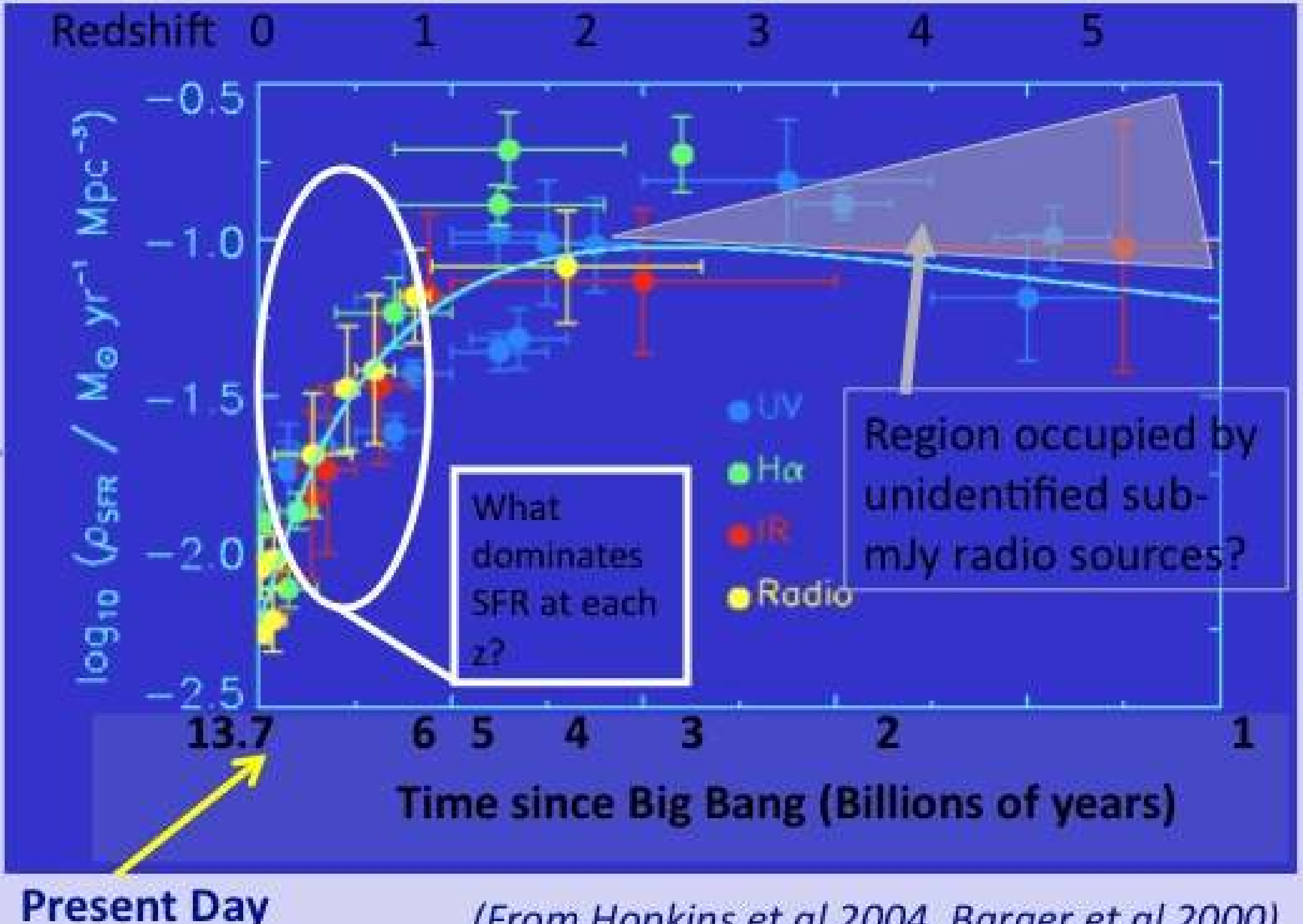
- Unbiased estimation of SF/BH History especially at high-z
- Overall Energy budget of gals (balance of fusion vs. accretion)
- Interplay between AGN and SF

Star Formation History

• Radio is sensitive tracer of star formation rates unaffected by dust or gas (at ν>> 1 GHz it traces thermal emission)

- SFRD vs redshift [Dust enshrouded SFH up to high z]

- SFRD as a function of mass (downsizing) (need of very sensitive radio observations



(From Hopkins et al 2004, Barger et al 2000)

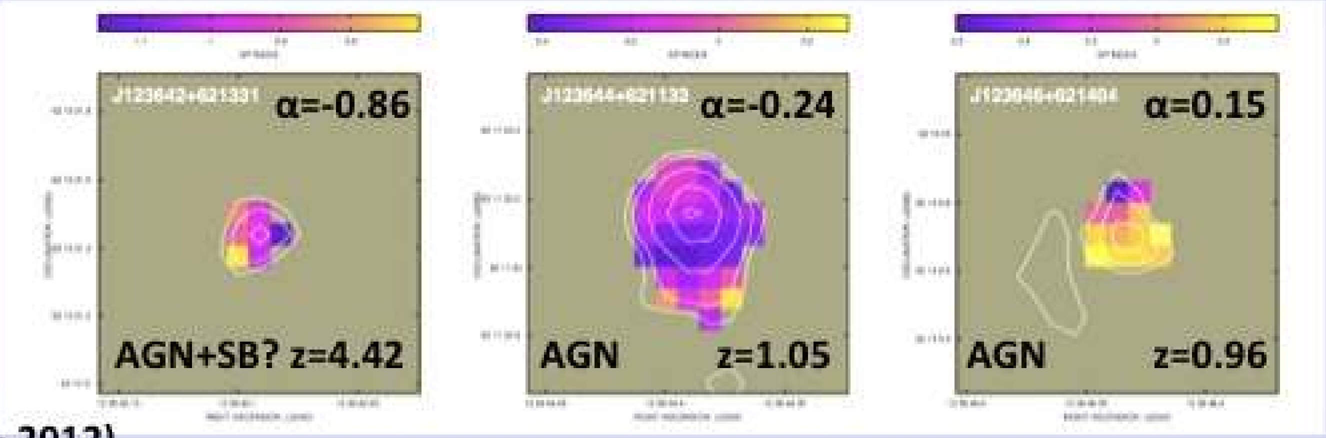
e-MERLIN Galaxy Evolution (*e*-MERGE) legacy survey

- *e-Merlin's* unique combination of sensitivity and spatial resolution

- 900 hours allocated (about 30% of the total amount of time available): deepest high resolution radio imaging of two well studied extragalactic fields → to be combined with JVLA

- GOODS-N (L + C bands) → SFR & AGN evolution at 1<z<4, with special focus on possible co-existence and co-evolution of the two phenomena

- Abell Cluster (L band)
  → lensed pop (z>5)



(Guidetti, Bondi, IP+ 2012)

- Resolution of 50-200 mas in C- & L-Bands respectively (<0.5-1.5 kpc at z>1)
→ disentangle the contributions of AGN and SF, an essential step given the apparently simultaneous growth of the black holes and stellar populations in galaxies.

Open Issues for next-generation survey design

All expected results stronly based on simulations and/or extrapolations of current observations

Strong role of precursors & pathfinders (also in synergy with studies at other λ)

Fine-tuning necessary to better design SKA_1/SKA_2 surveys. For instance:

- **Better SFG/AGN Modeling** (including composite AGN/SF sources)
  - radio SED (spectral index of faint radio sources)
  - number counts at microJy levels (cosmic variance)
  - size evolution (implications on natural confusion)

Galaxy/AGN Evolution – Modeling

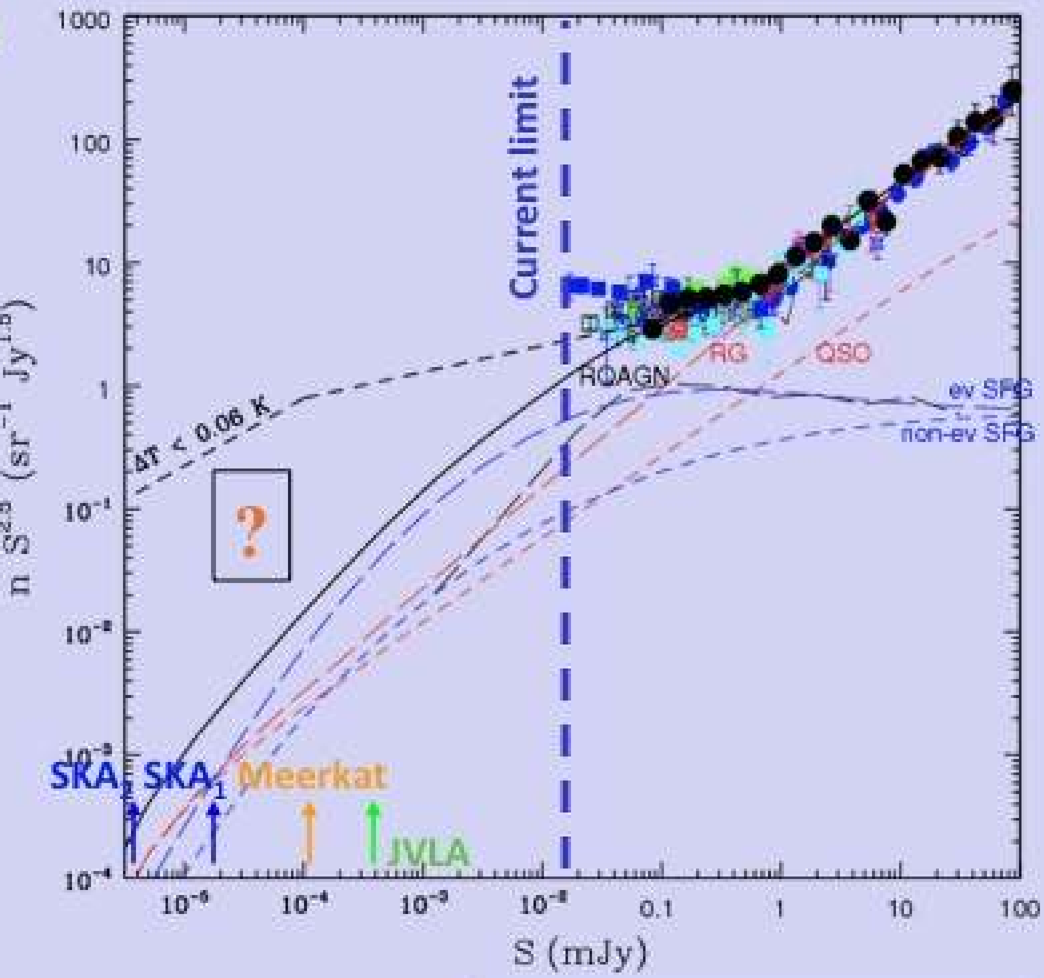
Need of Fine-tuning source models

- Classical RL-AGNs
- SF gals.
- RQ-AGN
- Other classes?

Some Critical Issues for pathfinders/precursors:

➢ ev. of Low-P AGNs (Meerkat)

➢ extrapolation of local LF of SF & AGN to lower powers (ASKAP)



1.4 GHz Source Counts

BUT see Condon+ 2012….

Conclusions

- Valuable (AGN) science expected in all phases to the full SKA:
  - from Pathfinders to Precursors to SKA1 & SKA2

- Previous phases will provide valuable constraints (both scientific & technological) to better fine-tune following phases
  - Better sky modeling + technology advances

- We don't need to wait for the full SKA. A lot of work can be done already now!