Mapping the Universe on the pathway to the SKA

Galaxy Evolution and the role of AGN

Isabella Prandoni

INAF - IRA

Outline

1. The SKA Framework
   - Science drivers
   - The ramp-up to the SKA: precursors, SKA1, SKA2

2. Radio Continuum Extragalactic Survey Science
   - Cosmology/LSS
   - Galaxy Evolution
   - The role of AGN

3. Designing the best SKA
   - Current Activity in SKA WGs
   - Design Criticalities
   - How one can contribute

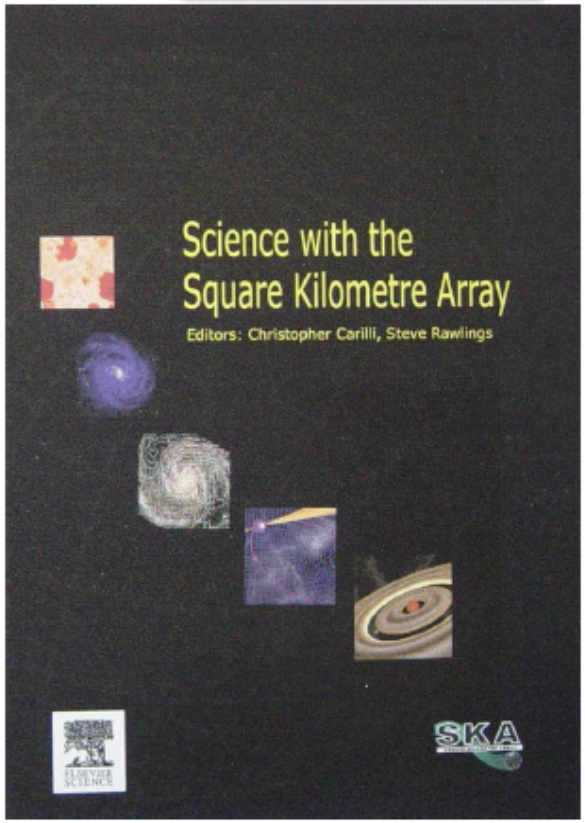
Courtesy R. Braun

SKA Key Science

SKA Science Book (now being update)

- Strong-field Tests of Gravity with Pulsars and Black Holes
  Phase 1 headline science
- Galaxy Evolution, Cosmology, & Dark Energy
  Phase 1 "H I through cosmic time" headline science
- Emerging from the Dark Ages and the Epoch of Reionization
  Phase 1 "H I through cosmic time" headline science
- The Cradle of Life & Astrobiology
- The Origin and Evolution of Cosmic Magnetism

With design philosophy of *Exploration of the Unknown*



Science with the Square Kilometre Array
(Carilli & Rawlings, 2004)

Courtesy R. Braun

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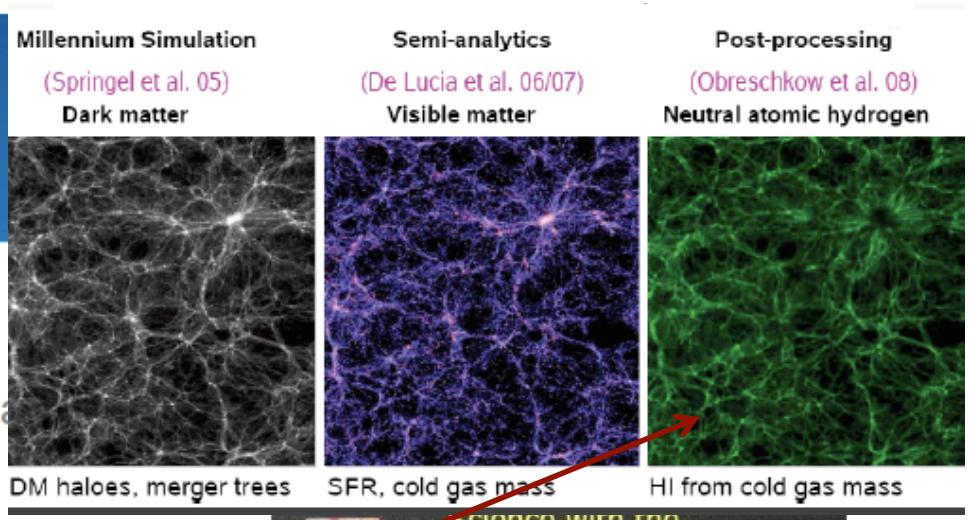

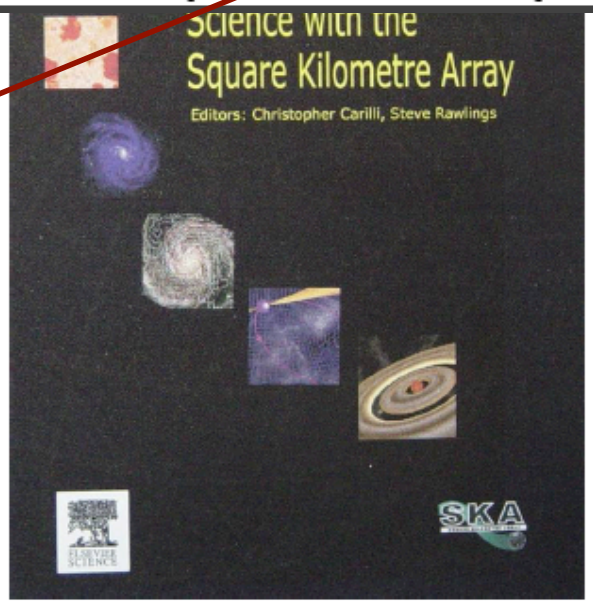

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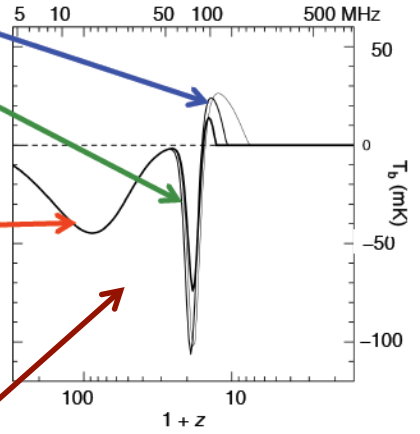
With design philosophy of *Exploration of the Unknown*

Neutral Hydrogen 21 cm spin-flip transition provides probe of neutral intergalactic medium before and during formation of first stars

EoR

Cosmic Dawn

Dark Ages



$\nu = 1420\ \text{MHz}/(1+z)$

$\lambda = 21\ \text{cm}\ (1+z)$

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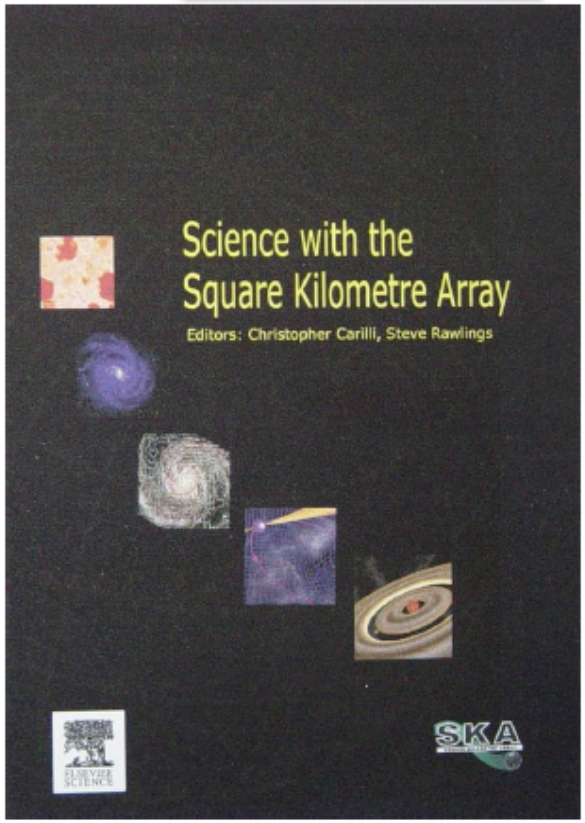


Science with the Square Kilometre Array
(Carilli & Rawlings, 2004)

Science-driven Requirements for the SKA

From Dewdney et al. 2009

- Large Frequency Range
  10 MHz - 30 GHz
  [different receivers: SKA LOW & MID]

- High Sensitivity ≈ 1-2 10^4 m^2 K^{-1}
  [low T_{sys} receivers]

- High Survey speed
  ≈ 0.2-60 10^8 deg^4 m^4 K^{-2}
  [large FOV, small dishes + PAF technology (1-10s deg^2)]

- High spatial resolution
  ≈ 10-100 mas
  [long baselines, >1000 km]

	Description of Key Science Project	Frequency Range (GHz)	FoV	Sens-itivity	Survey Speed	Resn.	Base-line	Dyn. Range Driver	Poln. Driver
		.1 0.3 1.0 3.0 10 30	deg^2	m^2/K	$deg^2m^4K^{-2}$	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				

The SKA in Phases

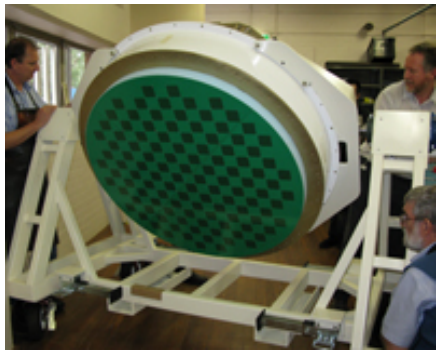
SKA will be implemented in phases:

- Precursors (Meerkat, ASKAP)
- SKA_1 subset (~10% area) of SKA_2

SKA1-low (sparse AA): Freq. Range: 70 - 350 MHz

SKA1-mid (dish+SPF): Freq. Range: 0.45 – 10 GHz (3 Bands)

SKA1-survey (dish+PAF) : Freq. Range: 0.7 – 1.7 GHz
PAF for Survey Speed



- SKA_2 : full SKA capability between 70 MHz and 10 GHz
- SKA_3 (TBD): extension of SKA_2 to 30 GHz

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

Courtesy P. Diamond

SKA Phase 1 (SKA1)
Cost: €650M, construction start 2017

SKA1_MID
254 Dishes including:
64 x MeerKAT dishes
190 x SKA dishes

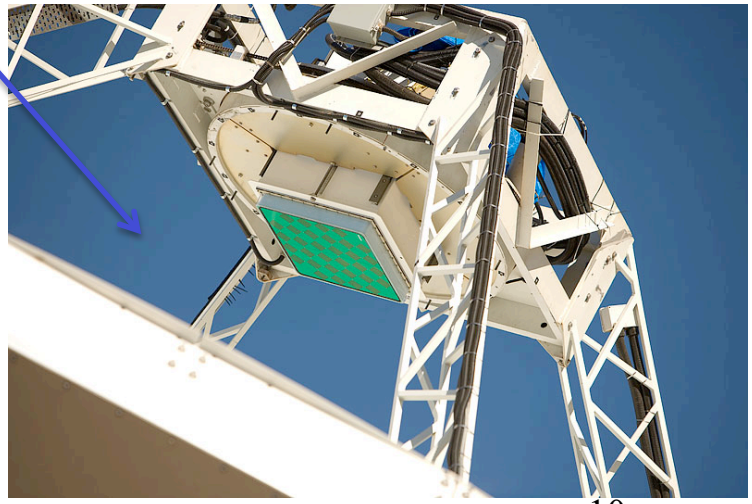
SKA1_LOW
Low Frequency Aperture Array Stations

SKA1_SURVEY
96 Dishes including:
36 x ASKAP
60 x SKA dishes

ASKAP – Australia's SKA Pathfinder

Main characteristics:

- Array of 36 *12-m* antennas
- Phased array feeds (36-feeds, focal plane array
- Wide FoV and High dynamic range imaging cap
- Observing Band: L-band (1.4 GHz)
- Maximum baseline ~8 km
- FoV = 30 sq. degr @ 1.4 GHz
- High survey speed: continuum (10 μJy /beam) 2.2 deg^2/h
- Site: *Murchison Radio-astronomy Observatory (MRO),* Western Australia. Remarkably radio quiet



Timeline:

- Beta Array: in operation + new MkII PAFs
- Early Science: 12 antennas (mid 2015)
- Full system: mid 2016

MeerKAT – South Africa's SKA Pathfinder

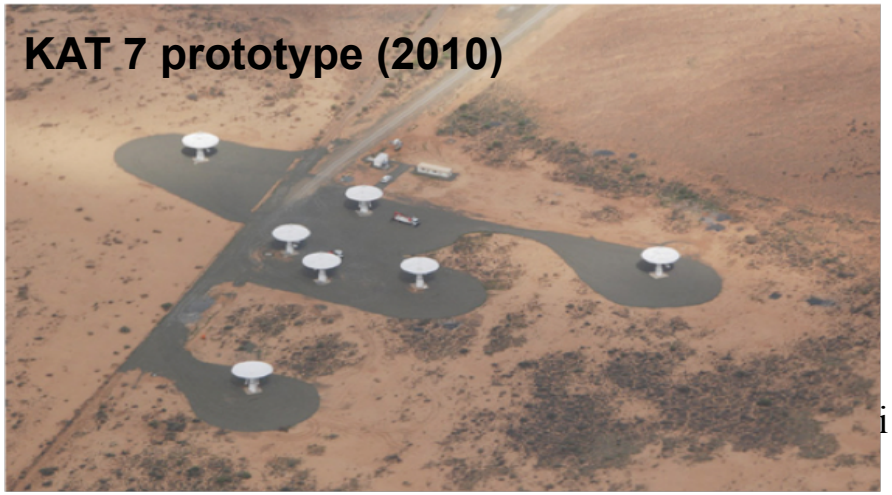
Main characteristics

- Array of 64 13.5m receptors
- 48 concentrated in the core area ~1 km in diameter.
- longest baseline 8 km
- Site: Karoo Region

- 0.58 - 1.015 GHz
- 1 - 1.75 GHz
- 8 - 14.5 GHz
- Single Pixel, high sensitivity (T_{sys}~20K)

Timeline

- End 2014: Four MeerKAT receptors fully assembled, integrated and verified
- End 2015: Array of 16 antennas commissioned and ready to do science
- End 2016: All 64 antenna positioners will be in place.
- Mid 2017: Full array ready to do science.

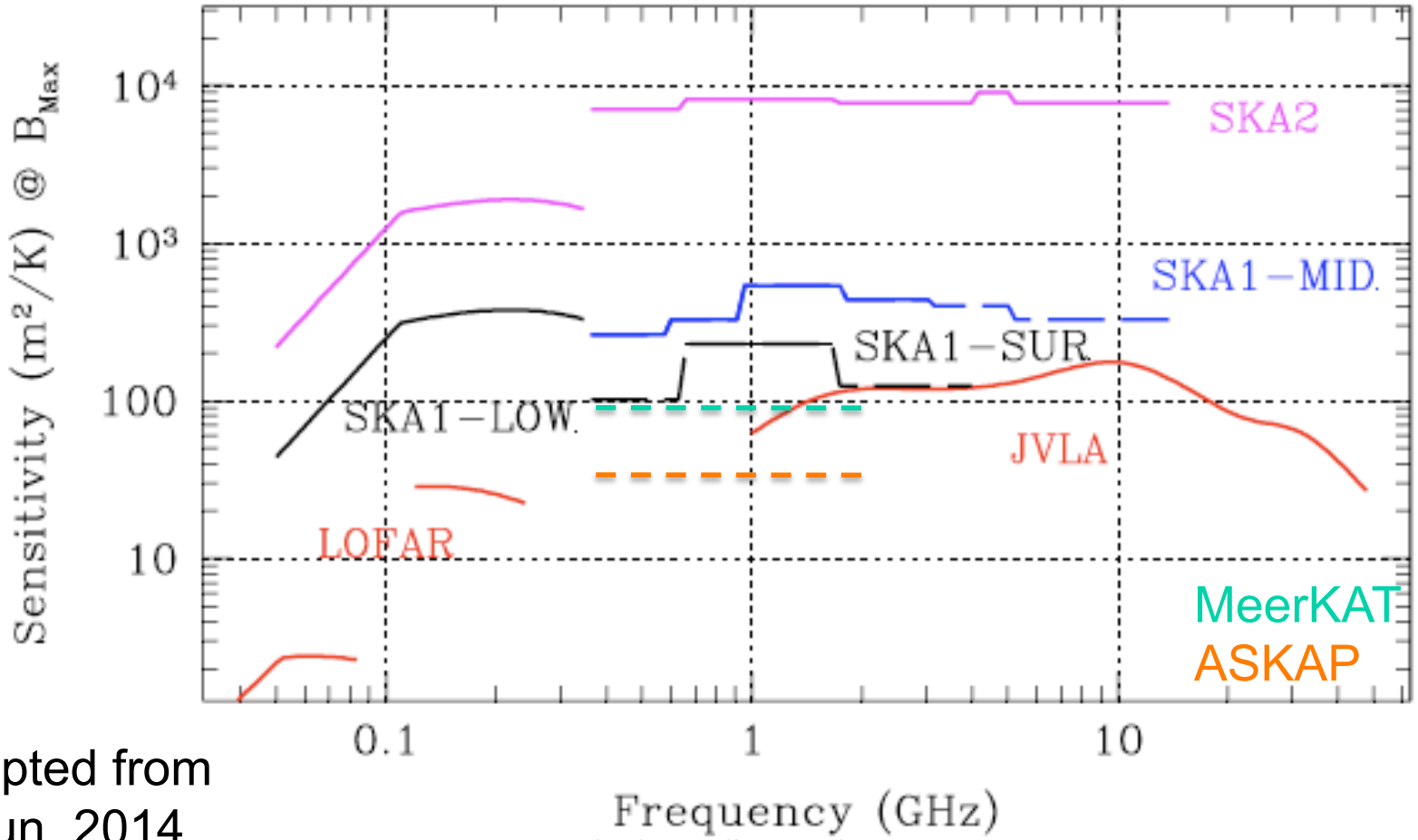


What's up now ?

SKA Pathfinders (1% SKA):

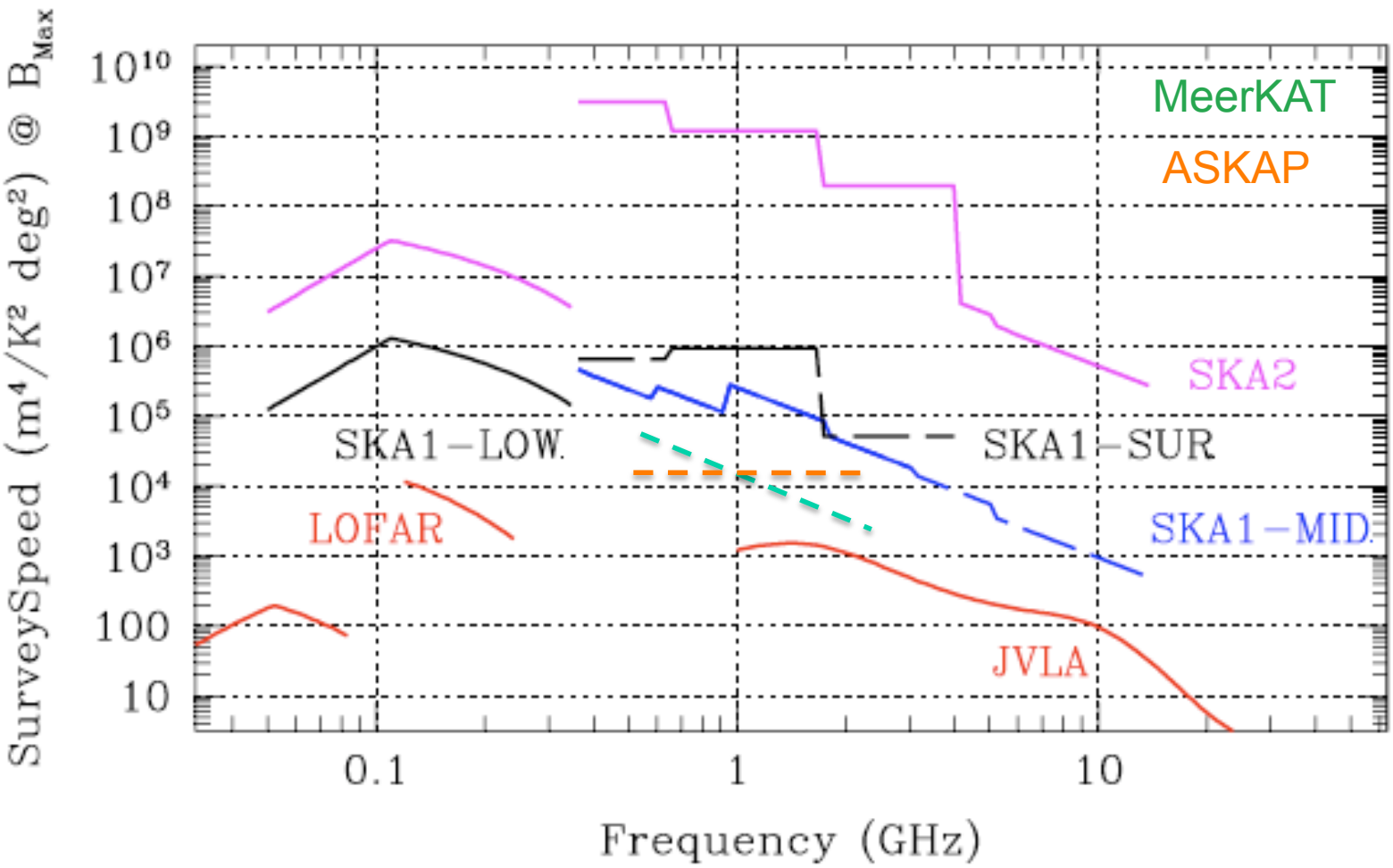
- JVLA: upgrade of the existing Very Large Array (VLA) - operational
- eMERLIN: deep high resolution imaging I,Q,U,V
  [Key Programmes approved in 2009 - started end 2013]
- Apertif: PAF mounted on the WSRT (L-band only).
  [Expression of interest for key projects (2010) – 2015]
- LOFAR (Key Projects: EoR, Continuum Tiered Survey, Magnetism, Transients, Pulsars)
  [operational (Cycle 0 – 2013; Cycle 1 & 2 – 2014)]
- MWA (Australia) – operational
- eEVN: real-time VLBI operations

Performance Comparison - Sensitivity



Adapted from Braun, 2014

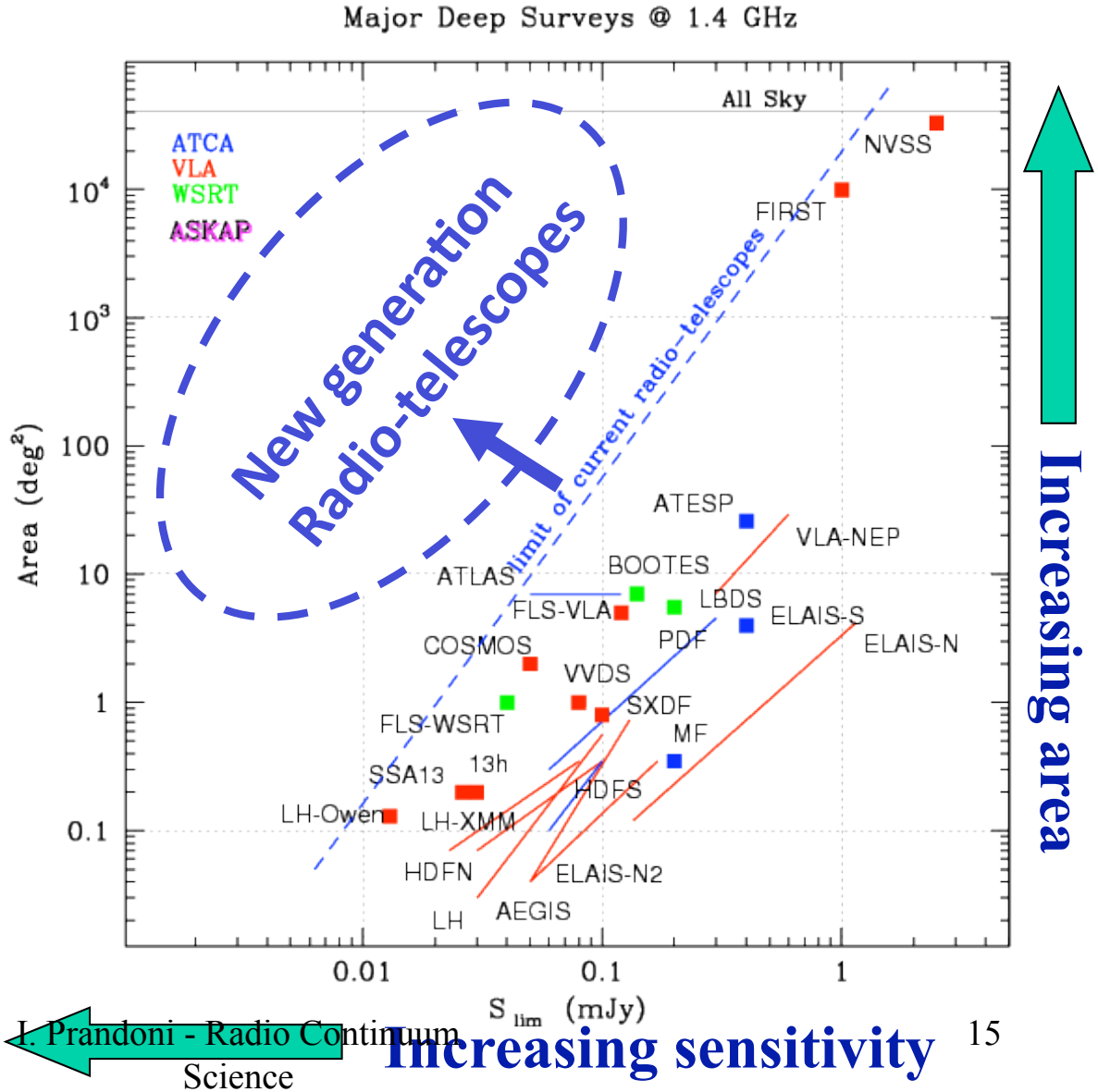
Performance Comparison - Survey Speed



Adapted from Braun, 2014

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 1 μJy rms

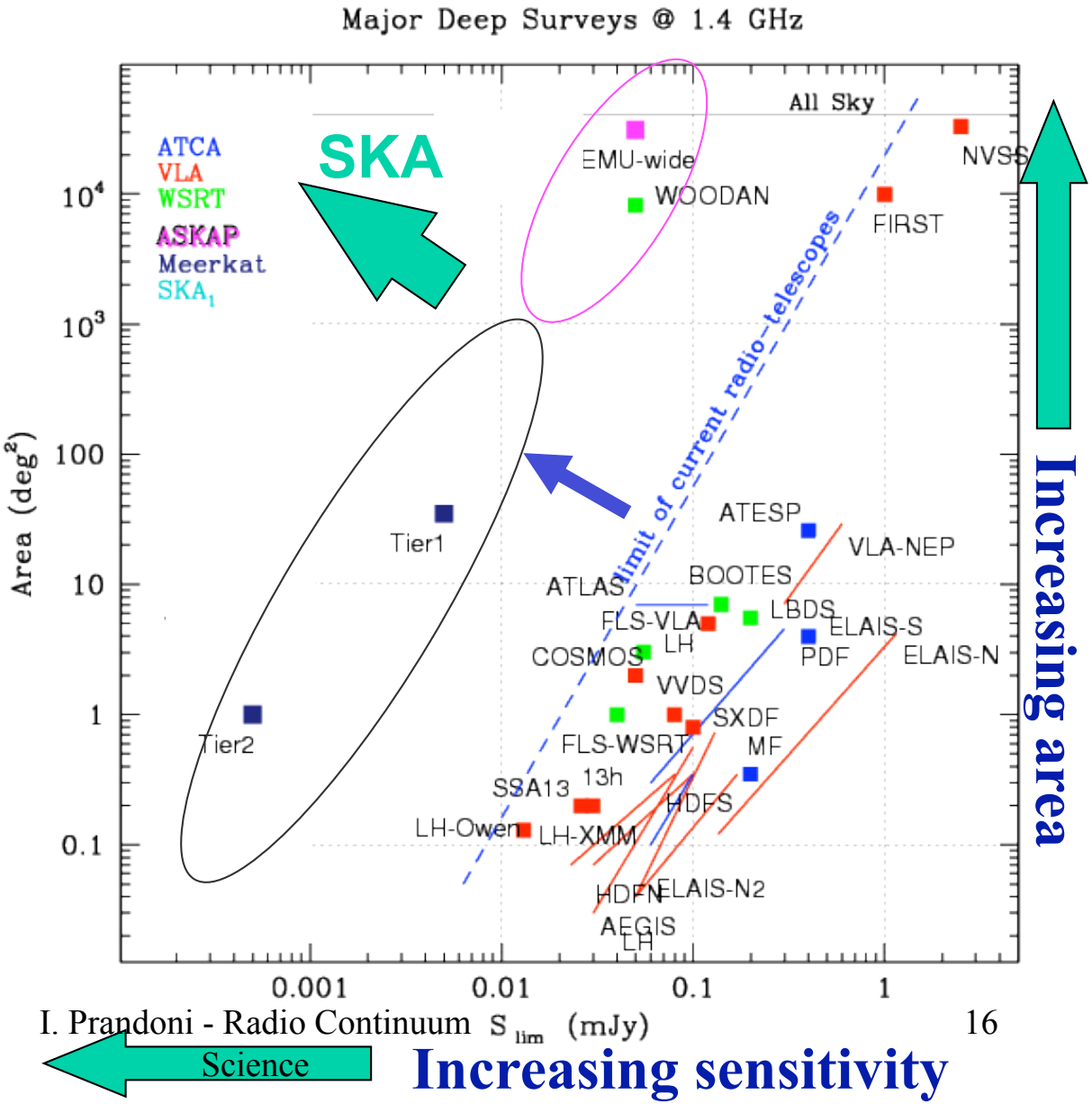
Tier 2: 1 deg^2 0.1 μJy rms

Factor 50 deeper

SKA$_1$ Killer survey:

[Huynh+, work in progress]

Factor 10 deeper



Astronomy Landscape in SKA Era

Pre-SKA (2015+):

• SKA precursors/pathfinders (1% SKA): LOFAR, JVLA, eMERLIN, ASKAP, Meerkat,…
➔SKA1 needs to make significant scientific advance over pathfinders

SKA1 (2020+):

• Euclid: 15k deg^2 HST image (0.2”) in optical and near IR, L* gals up to z=3, 0.7<z<2
• LSST: 18k deg^2 ugrizy (r<27.5; i<26.8; z<26.1), 4 Billion gals, <z>~1.2, photo-z to z~4
• JWST: sub-arcsec mid IR imaging + spectroscopy of z>5 galaxies

SKA2 (2025+)

• E-ELT: VLBI-like optical/MIR images + spectroscopy, internal dynamics of gals to z~4, spectroscopy of z>7 galaxies

Reference SKA 1 Continuum Surveys – mid frequency

Topics	Rms (μJy/b)	Area (deg2)	Resolution (“)	Freq. (GHz)	Science
Tier 1 (All sky)	1	20-30k	2	~1	**Cosmology tests** Low-z gal/AGN Cluster/diffuse Magnetism Galactic studies Legacy/Rare
Tier 2 (Wide) Feasible @ SKA_1?	0.34	5k	0.5	~1	**Weak lensing** Galaxy/AGN Cluster/diffuse Magnetism Galactic studies Strong lensing
Tier 3 (Deep)	0.05 0.1 feasible @ SKA_1	10s	0.5	~1	**Complete census of SFRD(z),** SFG/ AGN evolution, SF/AGN interplay

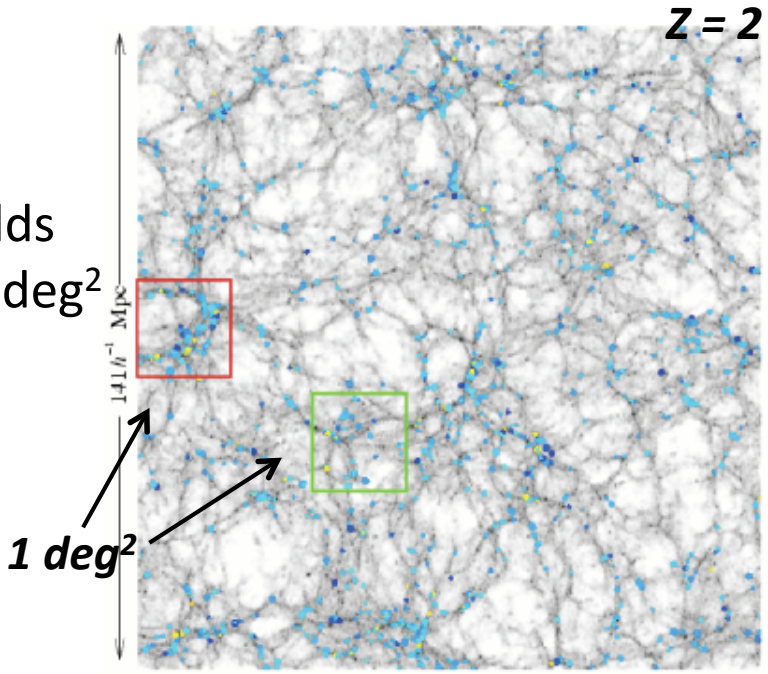
Radio Continuum Extragalactic Survey Science

•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
- diffuse non-thermal emission in clusters

Deep fields
~10-100 deg^2

- radio continuum emission from the cosmic web
- first galaxies, BHs & protoclusters
- Detailed study of ISM physics in nearby galaxies



GALFORM, Benson et al. 2000

•Cosmology (in combination with HI/redshift surveys)
(Constrain dark energy and non-Gaussianity)

- Baryonic Acoustic Oscillations
- Integrated Sachs-Wolfe Effect
- Magnification Bias
- Weak lensing
- HI Intensity Mapping

Shallower wide-area surveys
>1/4 sky

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

Next generation 1.4GHz Surveys

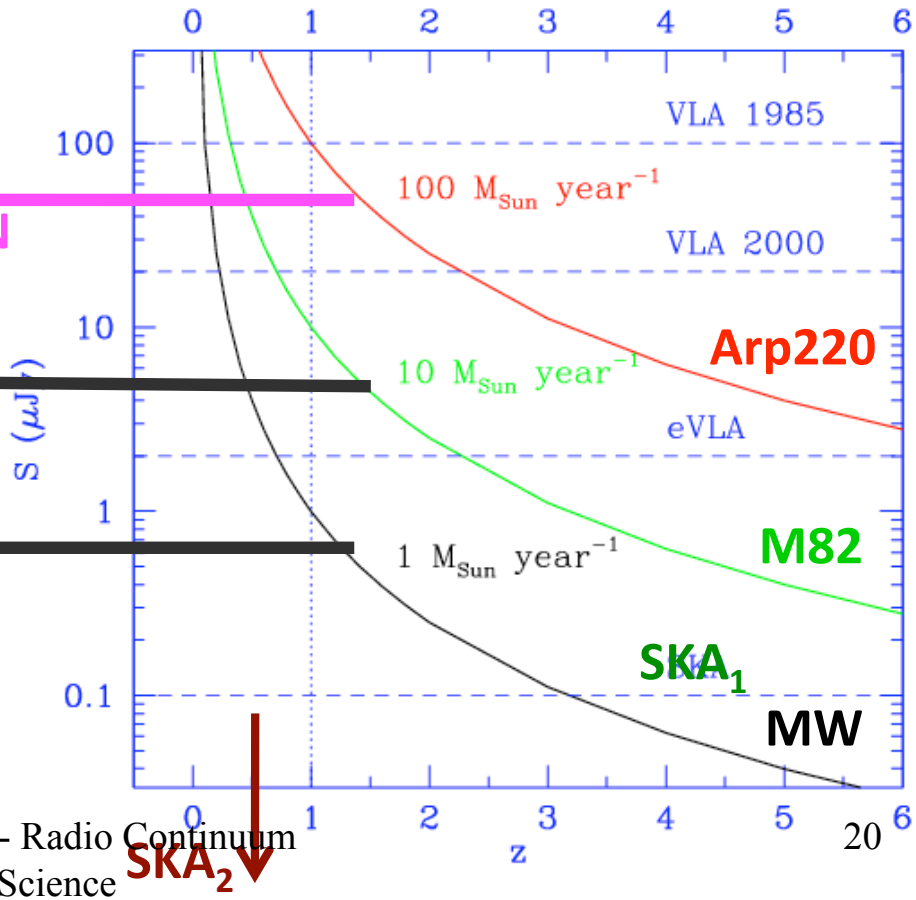
•SKA_1 Surveys designed to give a complete census of galaxies (including MW-like) up to z~3 and to probe more intense star-forming gals to z~6

•SKA_2 will give complete census of galaxies up to z~6, and will push galaxy studies into the realm of the EOR (z>>6) including RQ AGN

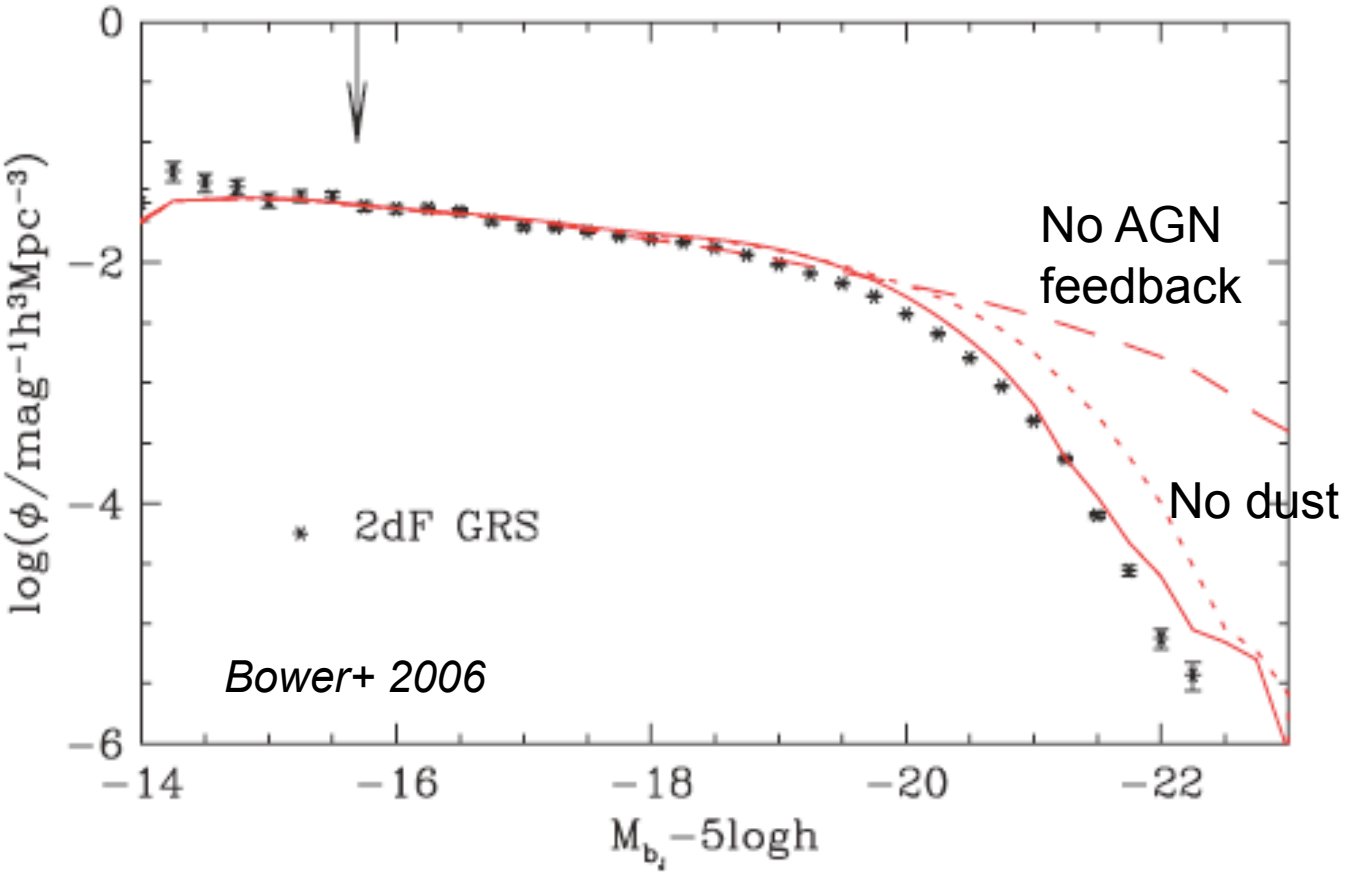
All sky EMU + WOODAN

Meerkat Tier 1 (35 deg²)

Meerkat Tier 2 (1 deg²)



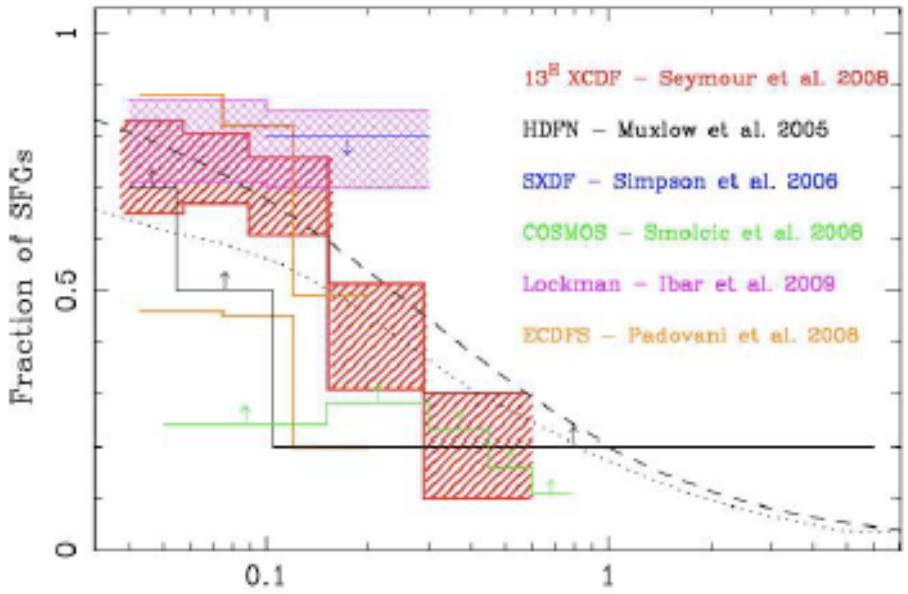
Galaxy evolution – SF and AGN feedback



Star Formation History

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

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



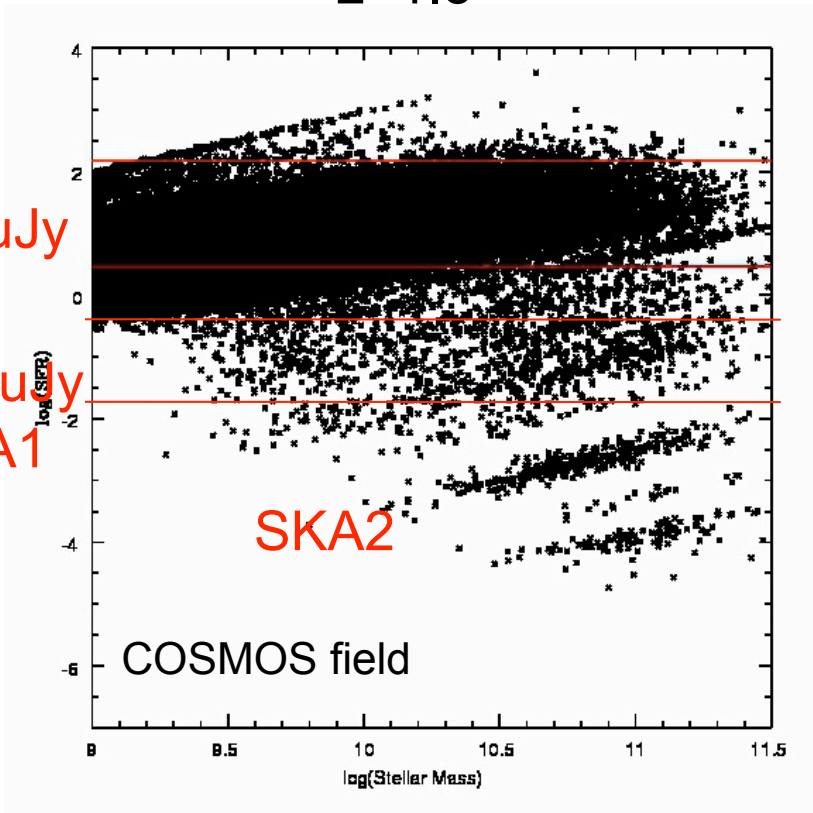
Seymour+08

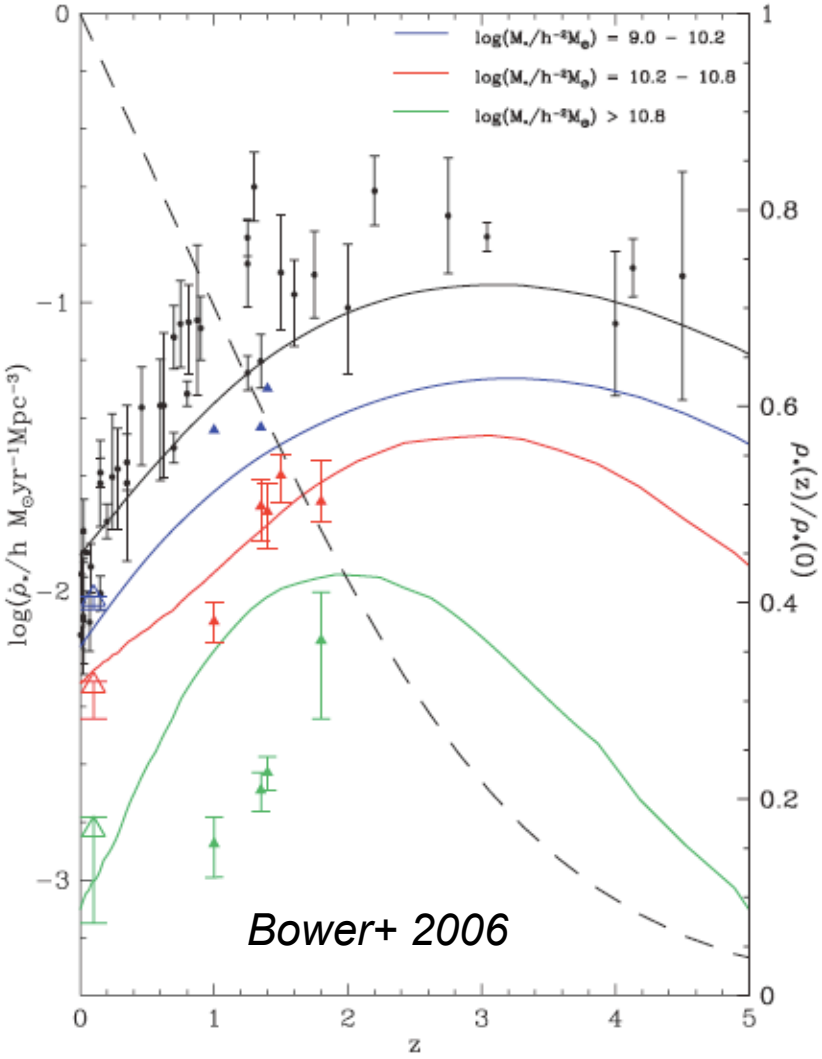
Present Day Science *(From Hopkins et al 2004, Barger et al 2000)*

SF vs Stellar Mass

What dominates SFR at each z?

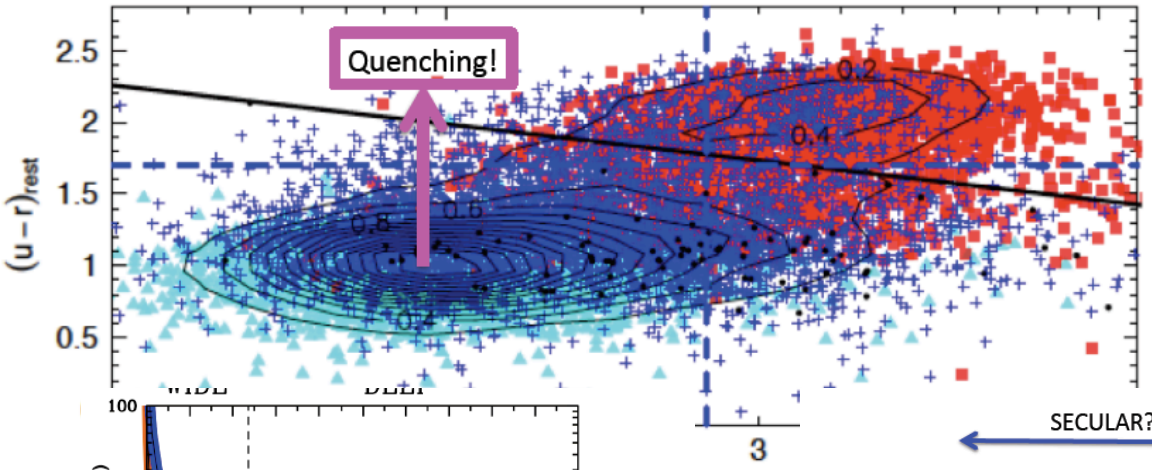
z=1.5

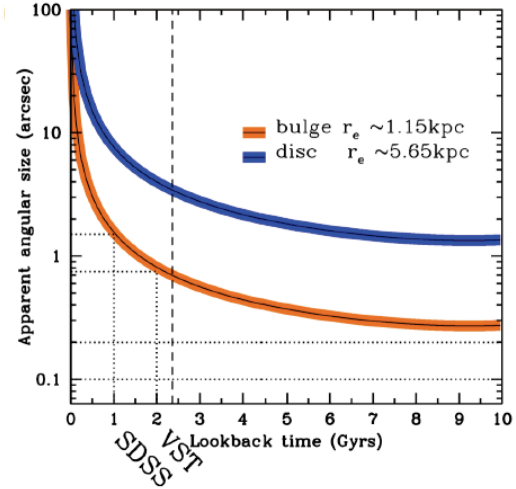




SF vs Galaxy Structure

Quenching SF cannot cause a galaxy to transition from blue cloud to red sequence





Euclid
HST

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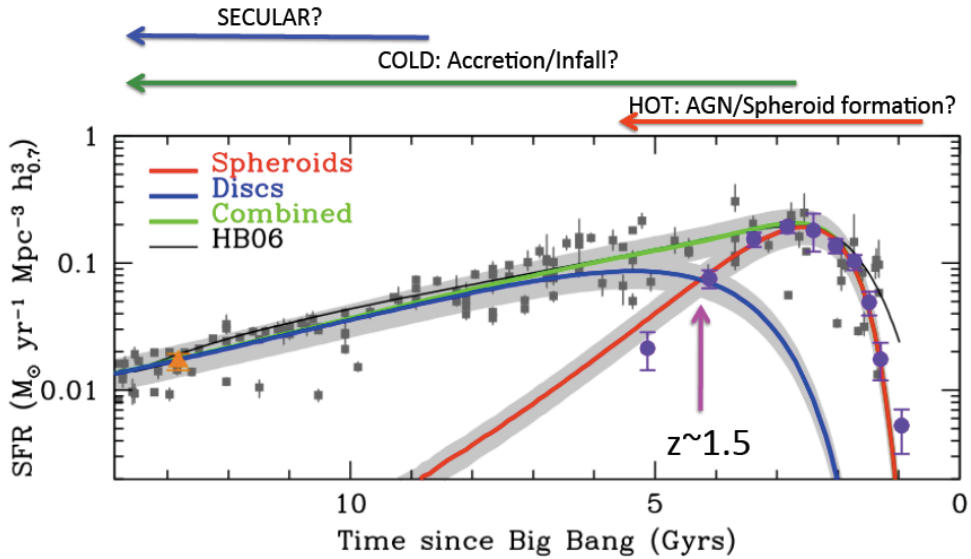
Do AGN play a role?

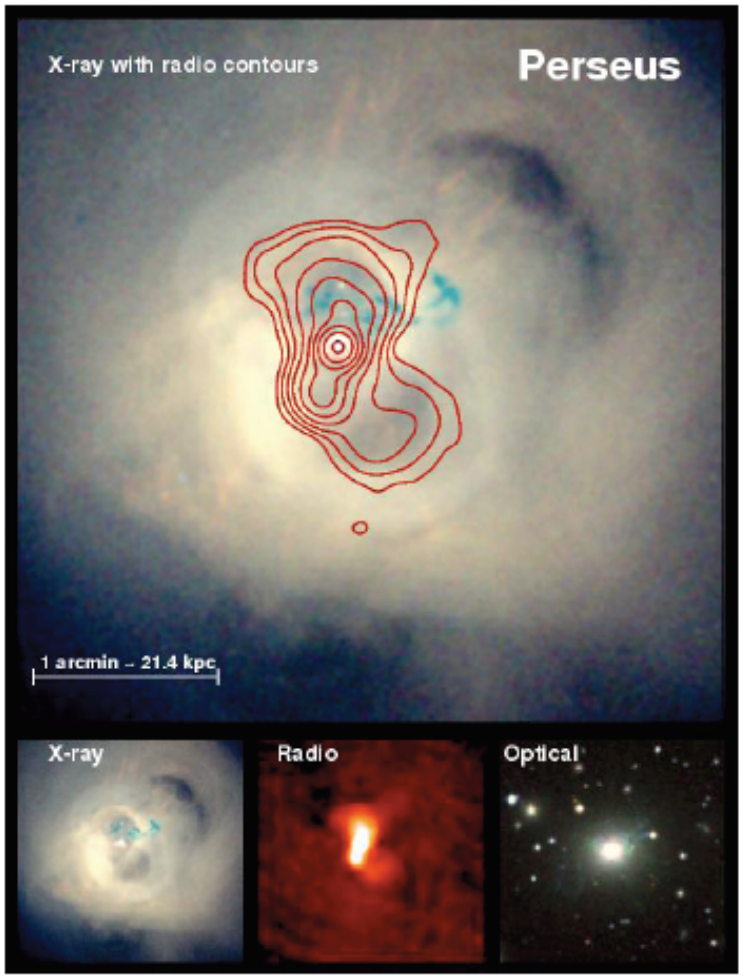


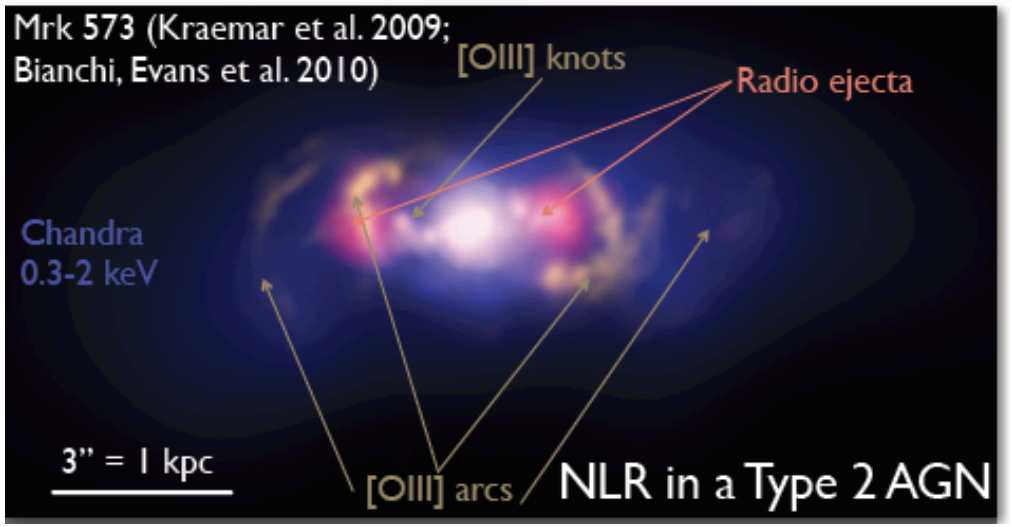
Need sub-arcsec spatial resolution

~0.5” → SKA1

AGN Radio-mode Feedback

From galaxy cluster to individual galaxy scales



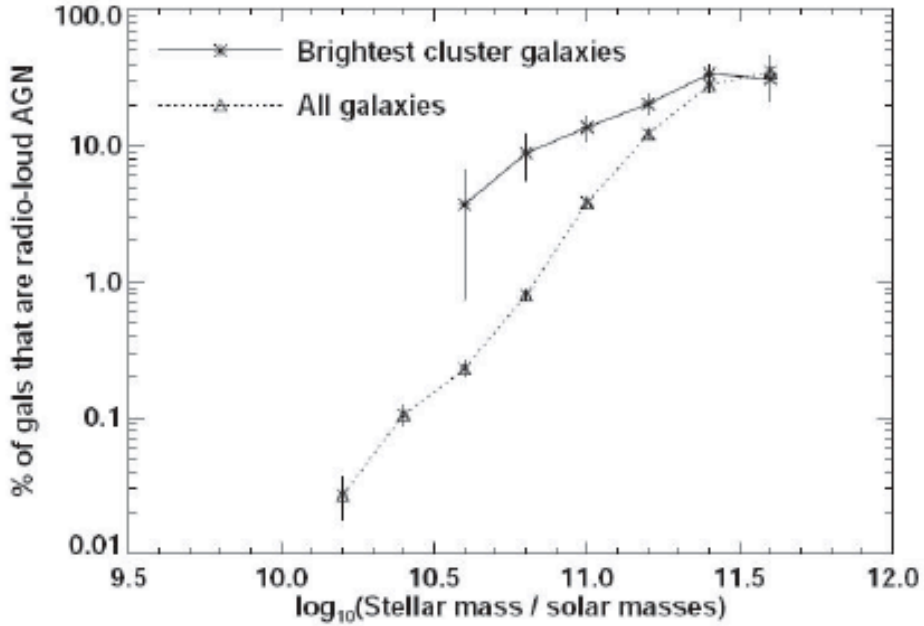


1. Spatial relationships between nucleus, jet, warm [OIII] gas and X-ray gas in kpc NLR

2. Some estimates of energy in the multiphase gas

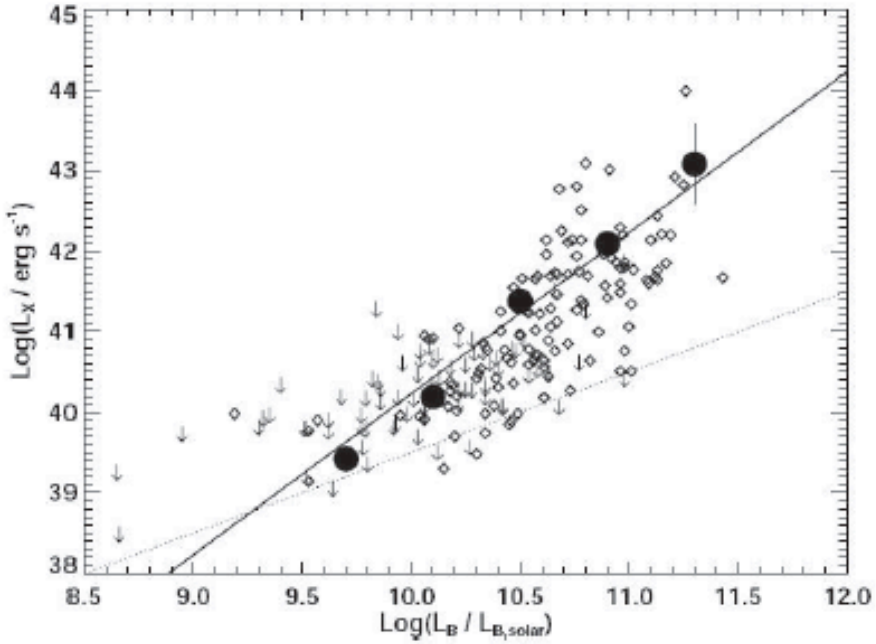
AGN Radio-mode Feedback

AGN radio mode feedback vs environment and stellar mass



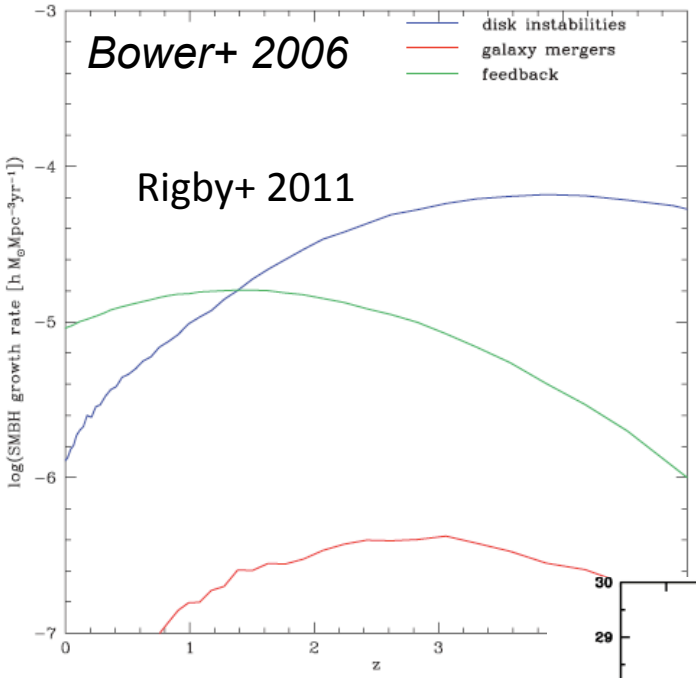
Best et al. 2005, 2006, 2007

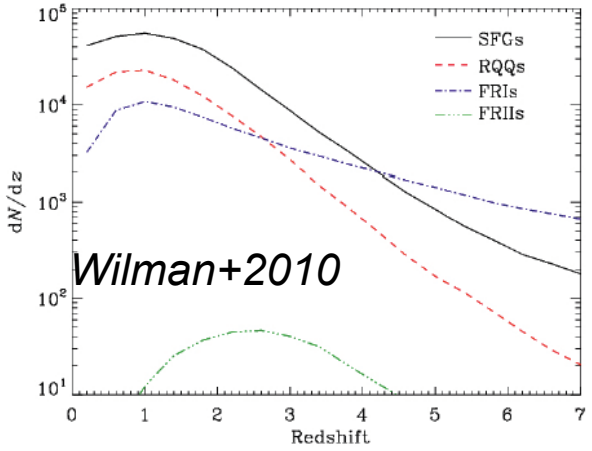
Radio-AGN heating versus radiative cooling balance in elliptical galaxies



RL-AGN~10% → jet-driven mechanical feedback or RQ-AGN radiation-driven feedback (winds) important for the overall galaxy evolution ?

BH Accretion Hystory

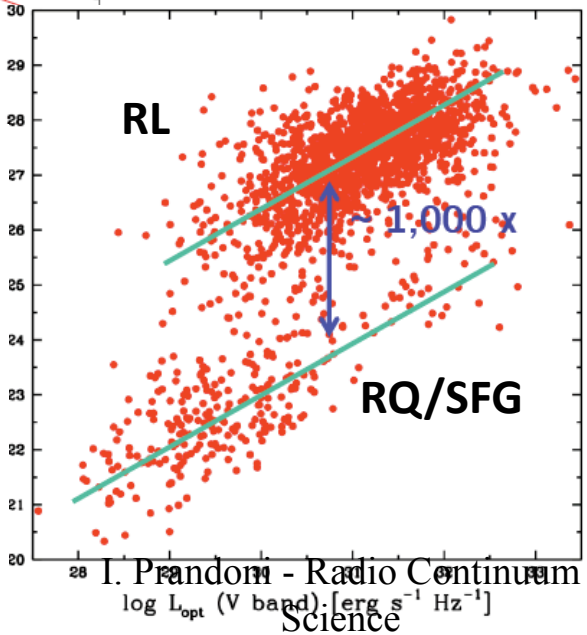


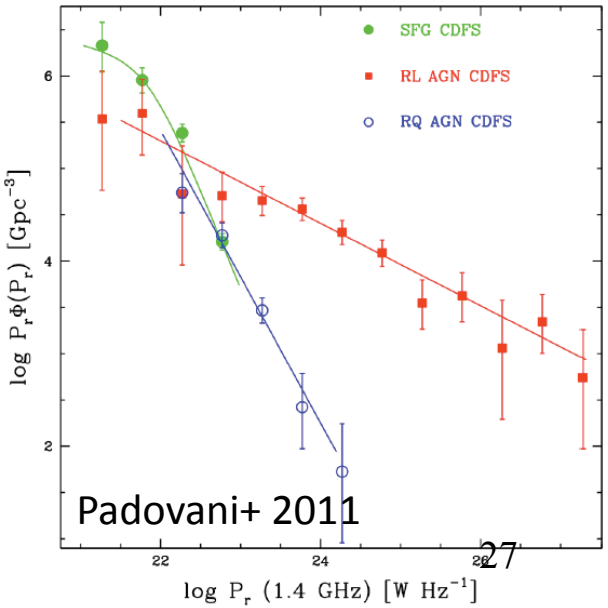


- RQ-AGN start to appear at uJy levels in deep radio fields
- SKA perspective: Evolution of radio-selected AGN down to RQ regime [P~10^{21} W/Hz]

- RQ-AGN share many properties with SFGs
→Mini-jets or SF? Or both?

- Interplay/co-existence of AGN and SF activity?





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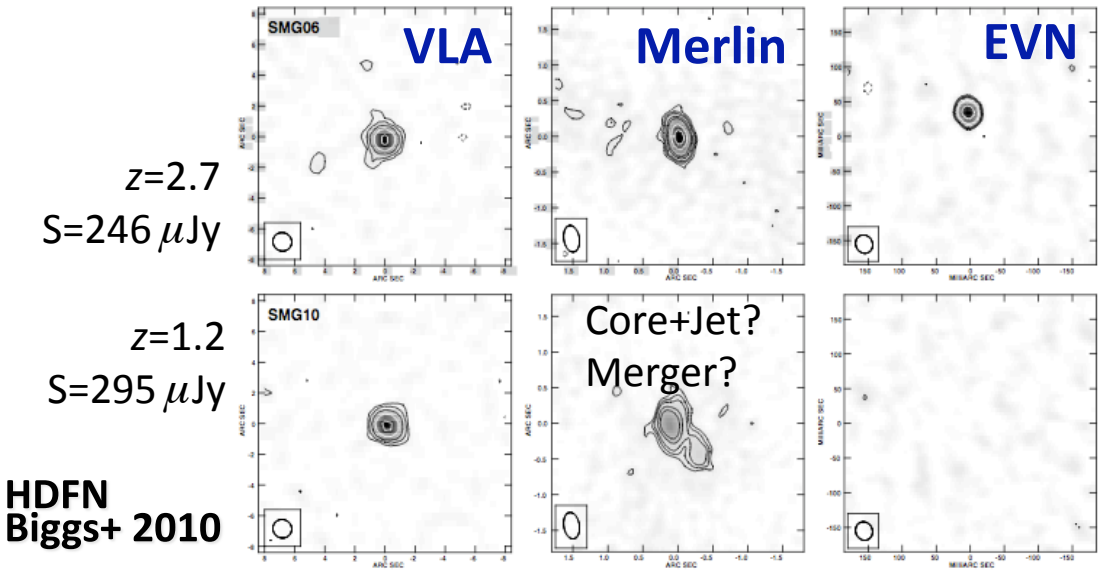
Separating AGN/SF activity

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

Need baselines >1000 km

(SKA2)



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

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)

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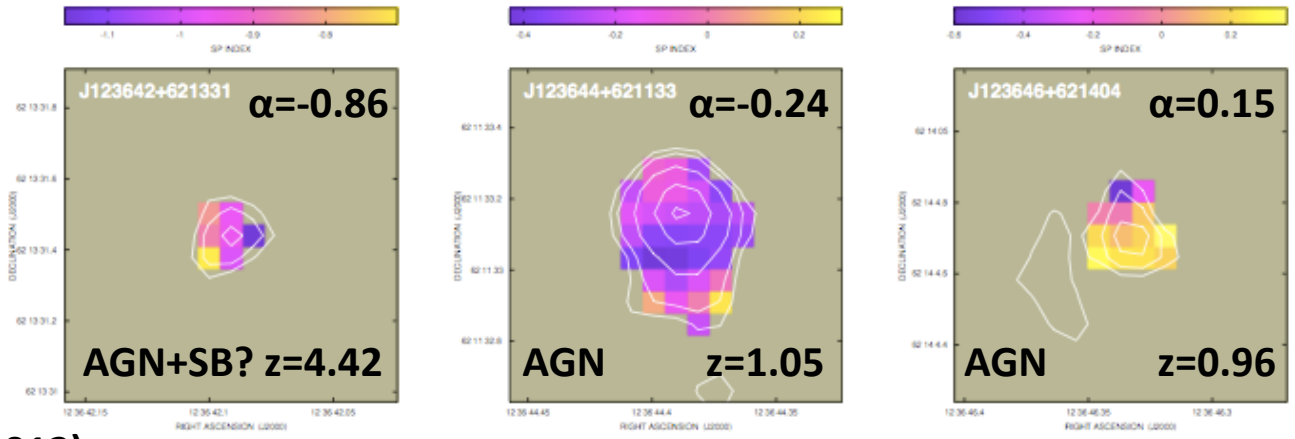


(Guidetti, Bondi, IP+ 2012)

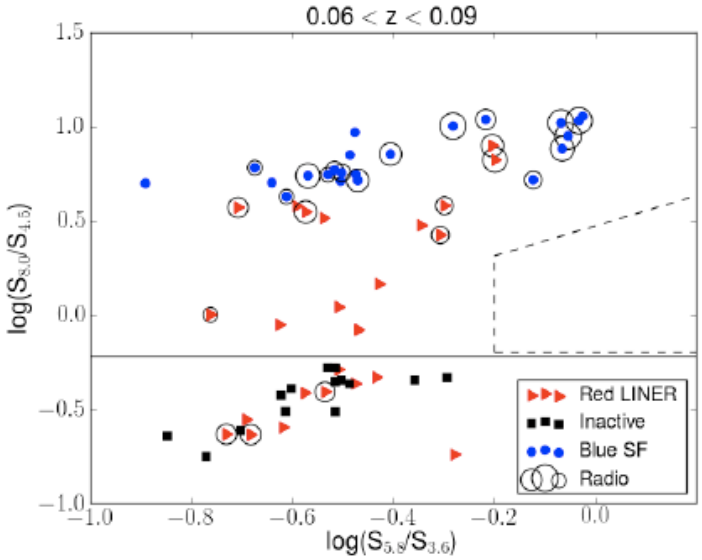
▪Resolution of 50-200 mas in C- & L-Bands respectively (<0.5-1.5 kpc at z>1)
➔ disentangle the contributions of AGN and SF, an essential step given the apparently simultaneous growth of the black holes and stellar populations in galaxies.

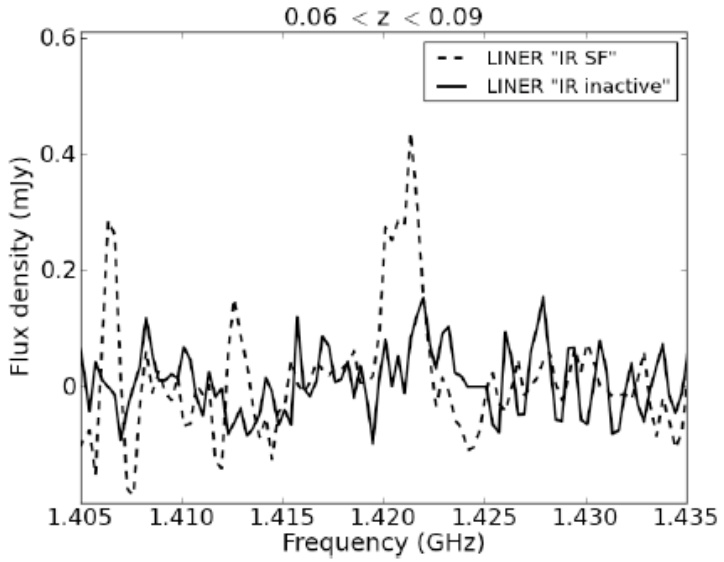
Separating SF/AGN Activity

- **Synergies with VLBI**

→ <u>will inform the SKA on the need of >1000 km bs</u>

- **Synergies with HI surveys** [see pilot work *Gereb, IP et al. 2013]*





Conclusions

- Valuable continuum 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!

- Need to address some critical issue in SKA1 design that may limit continuum science