

Next-generation radio continuum surveys

Exploring synergies between galaxy evolution and cosmology

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The SKA in a nutshell

SKA: Major radio facility of the 21st Century

Main parameters:

- **km² collecting area** → 100x sensitivity
- **Large FoVs** → 100x survey speed
- **3000+ km max baseline** → mas angular resolution
- **large frequency range [50 MHz – 24+ GHz]**

Multi-messenger science:

- Fundamental Physics: Gravity, DE, cosmic magnetism
- Astrophysics: Cosmic dawn & first gals, gal. assembly and evol., proto-planetary disks, biomolecules, etc.
- The Unknown: transients, SETI, ...



SKA Key Science



SKA Science Book – Updated in 2015!

- 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

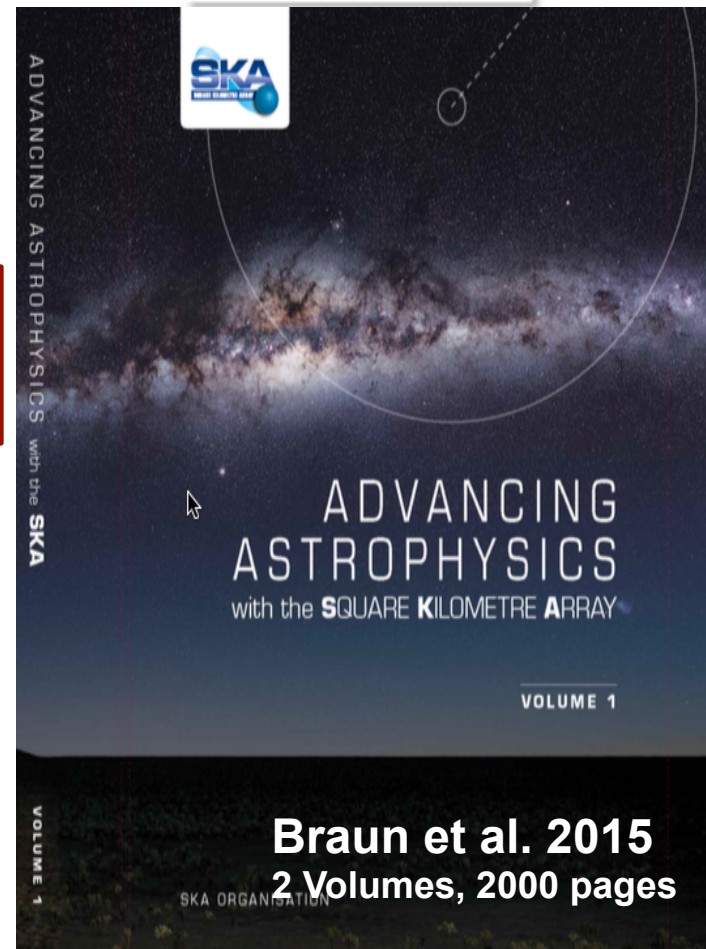
Phase 1 “H I through cosmic time” headline science

- The Cradle of Life & Astrobiology
- The Origin and Evolution of Cosmic Magnetism

With design philosophy of *Exploration of the Unknown*

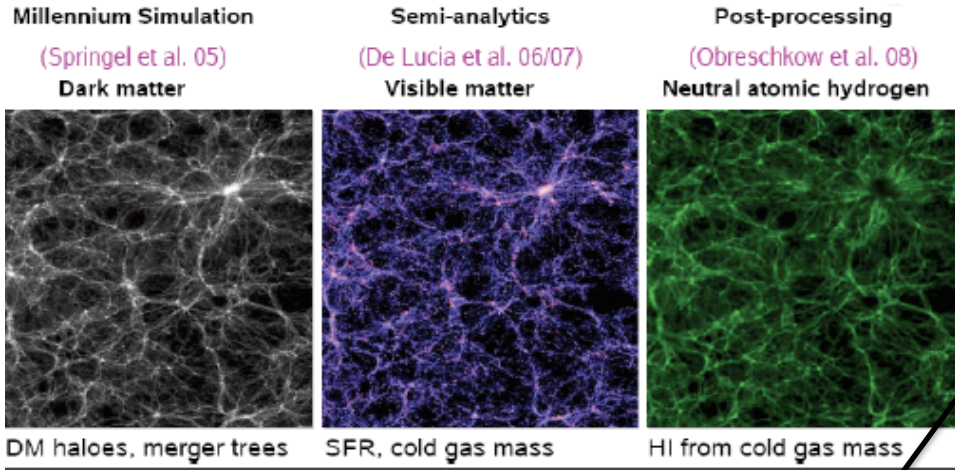
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I. Prandoni



Braun et al. 2015
2 Volumes, 2000 pages

Galaxy Assembly - Stars and Gas



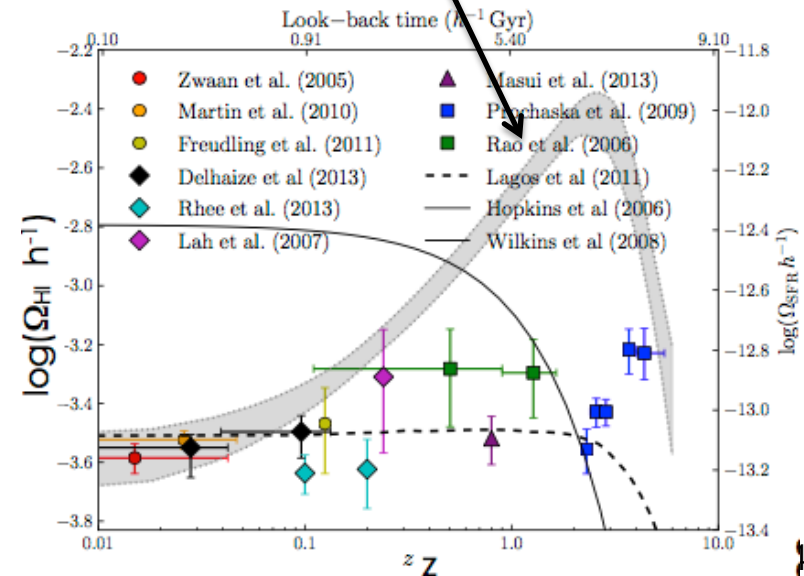
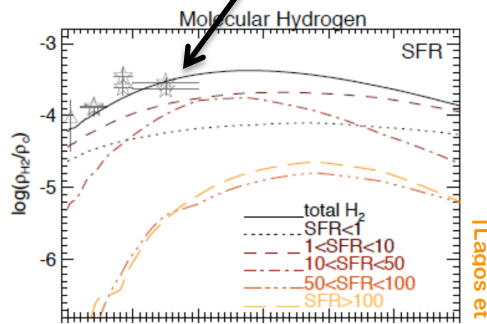
- HI density: weak evolution
- H₂ and SFR density: strong evolution

Blyth et al. 2015

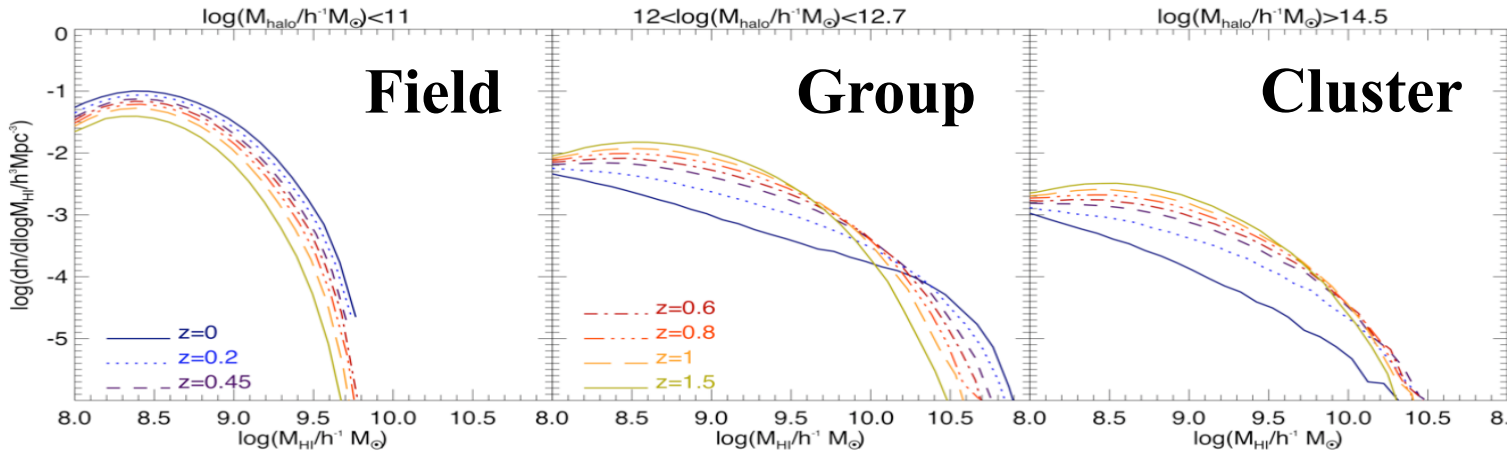
- Gas content and dynamics becoming critical part of simulations
- Blind surveys limited to local Universe
- Stacking ($z \sim 0.2$) and Damped Ly α ($z > 0.4$)

➔ Need HI surveys over cosmic time to understand galaxy formation!

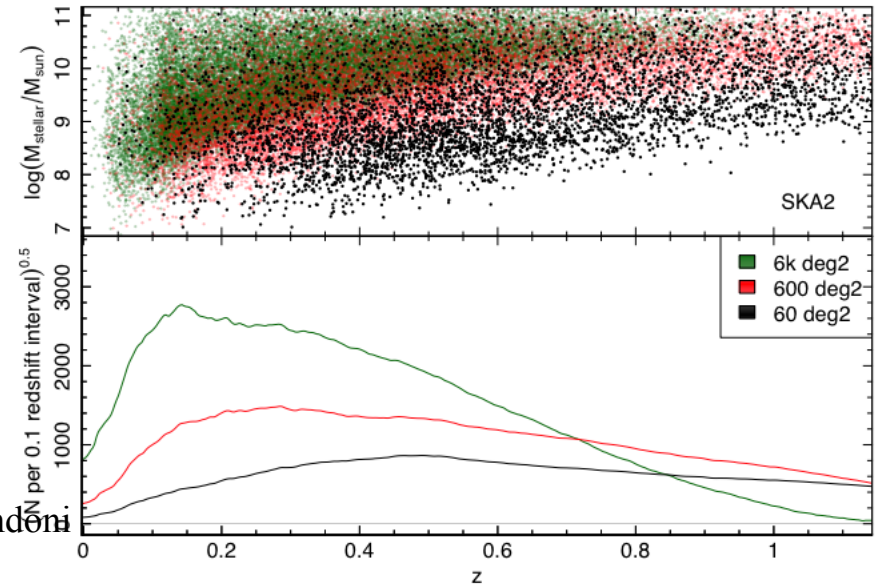
- Precursors will reach $z \sim 0.6$
- SKA1 will reach $z \sim 1$
- SKA2 will reach $z \sim 3$



Galaxy Assembly - Environment



- Role of environment on HIMF
- Need shallow large-area and deep narrow HI surveys



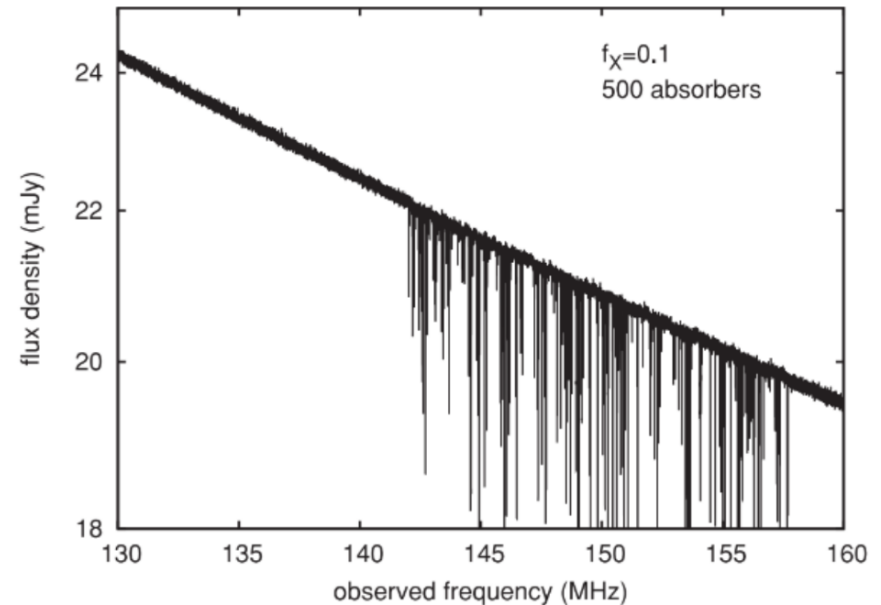
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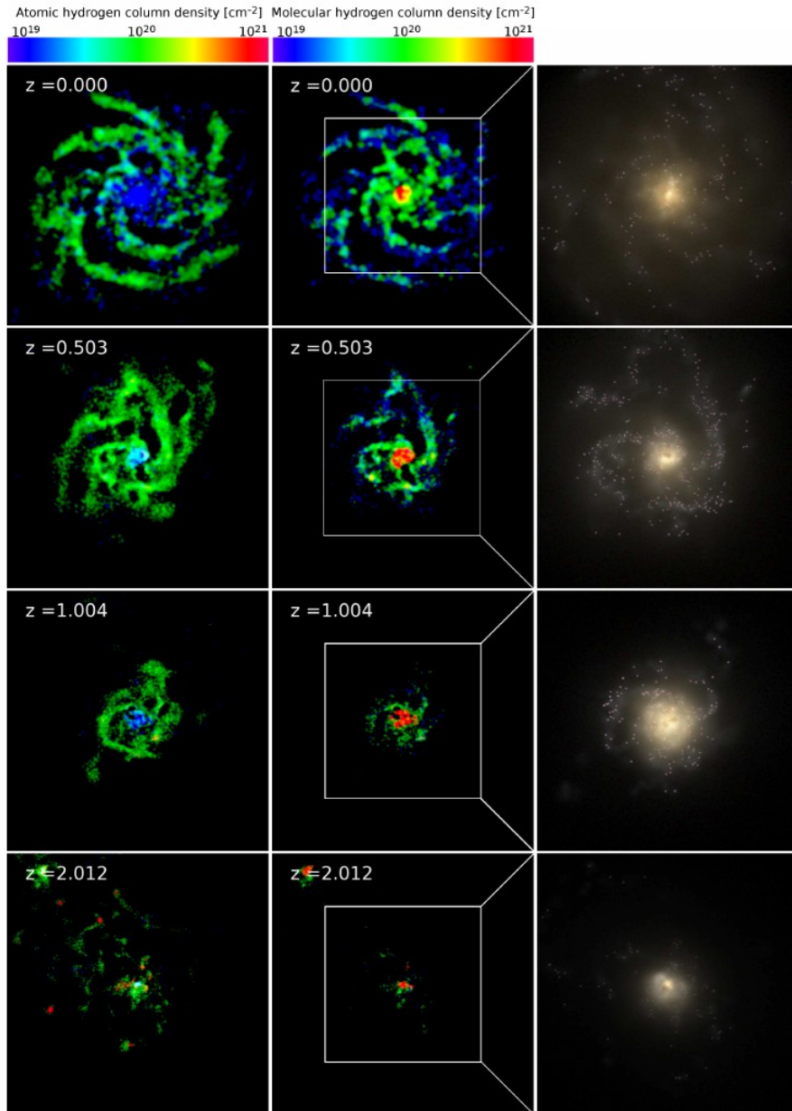
Galaxy Assembly – High-z

- **Intervening HI absorption against bright radio continuum sources**
powerful tool to constrain *evolution of cold gas in normal & active galaxie* along l.o.s of bright RC sources at $z \gg 3$ up to the EoR
- **HI optically thin at $z > 6$** [IGM becomes optically thick to Ly- α photons for neutral fractions $> 0.1\%$]
- **HI absorption not limited by sensitivity**, but by brightness of background source
- Extremely luminous RL-AGN are rare ($\sim 10^{27-29}$ W/Hz)
→ **All Sky surveys**

7.5 < z < 9 - Modeled by Mack+ 2012



Galaxy Assembly - Physics



Resolved HI surveys

- interplay between different gas phases and stars
- Feedback cycles

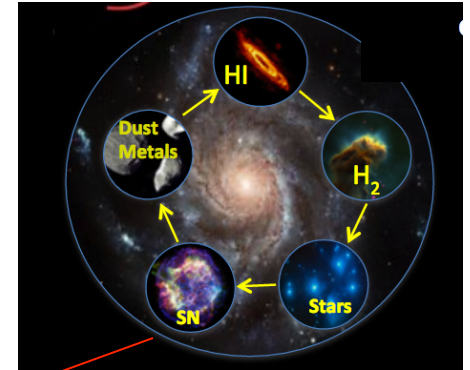
Galaxy & AGN Co-Evolution

Role of radio continuum surveys

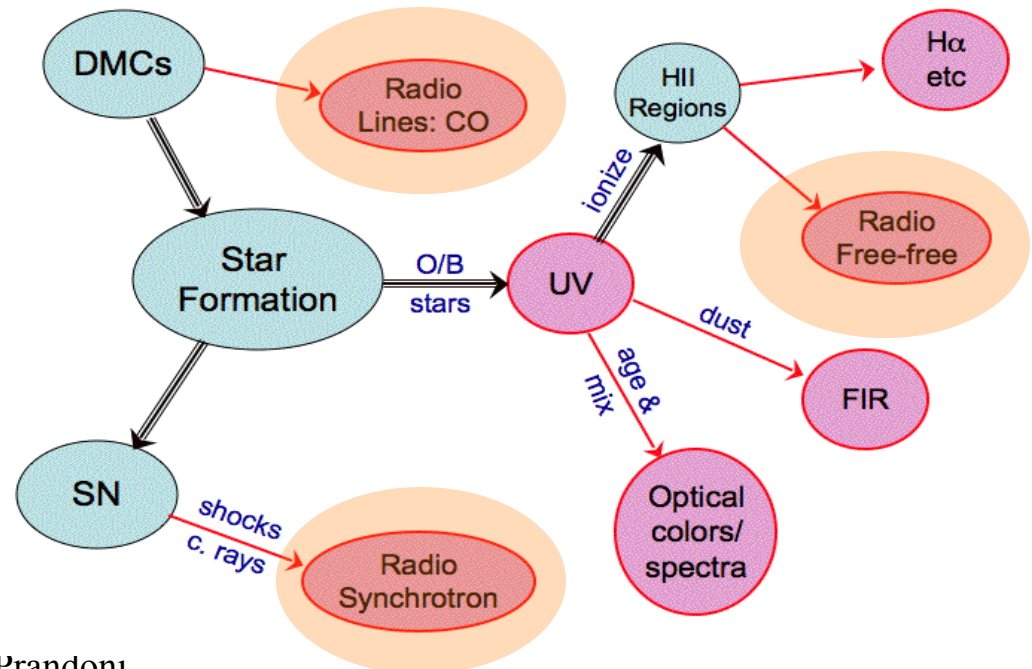
Radio continuum emission reliable tracer of star formation rates unaffected by dust (opt/UV/H α)

Less confused than IR surveys

SKA 1 can probe both synchrotron and free-free continuum radio emission



Emission from Star Formation Regions



Star Formation History

Deep Radio Fields dominated by SFGs

Murphy, Sargent et al 2015

Sensitivity is key

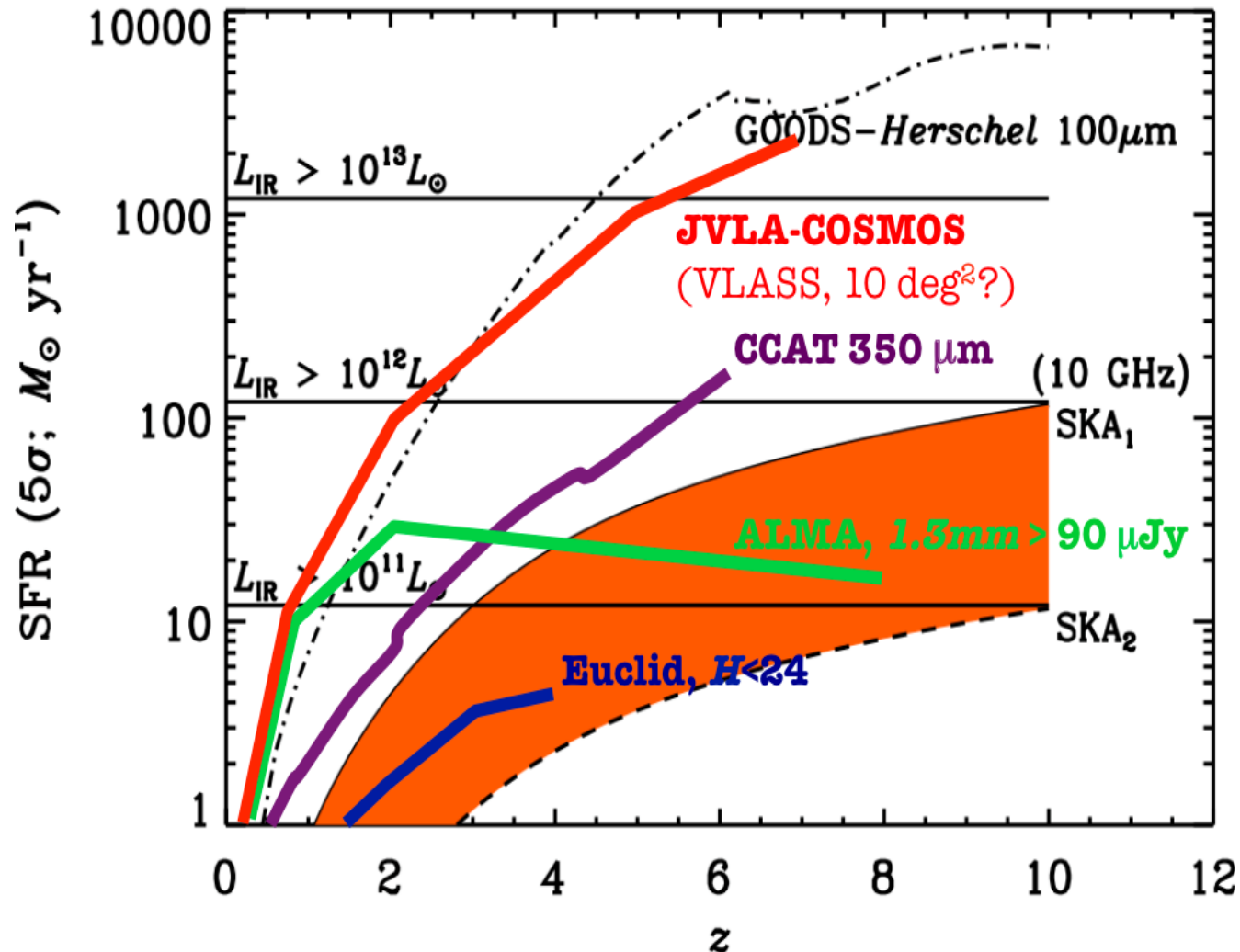
Requirement:
→ **sub-uJy rms**

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

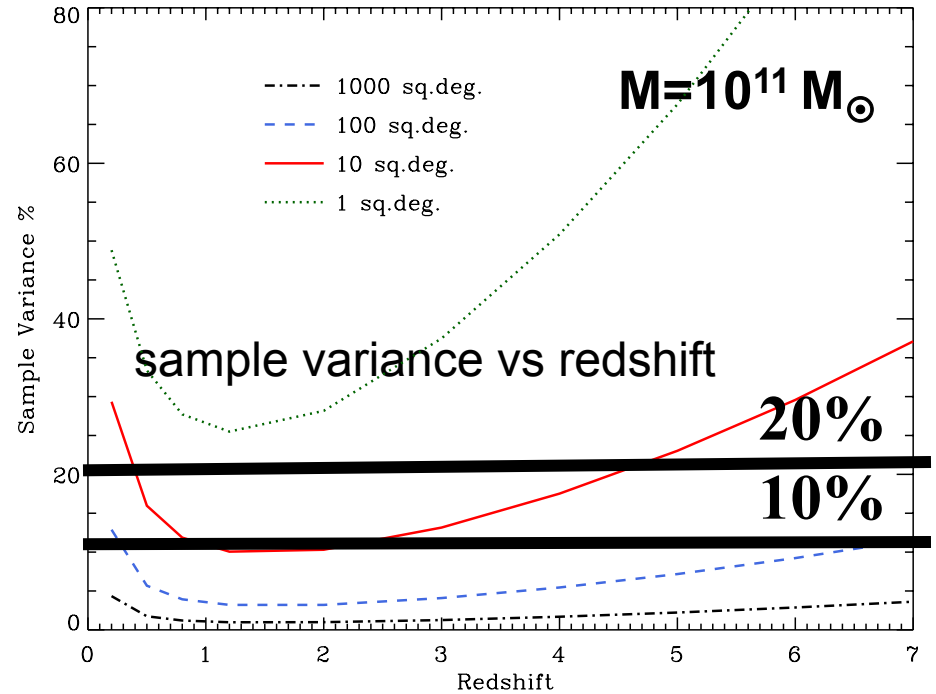
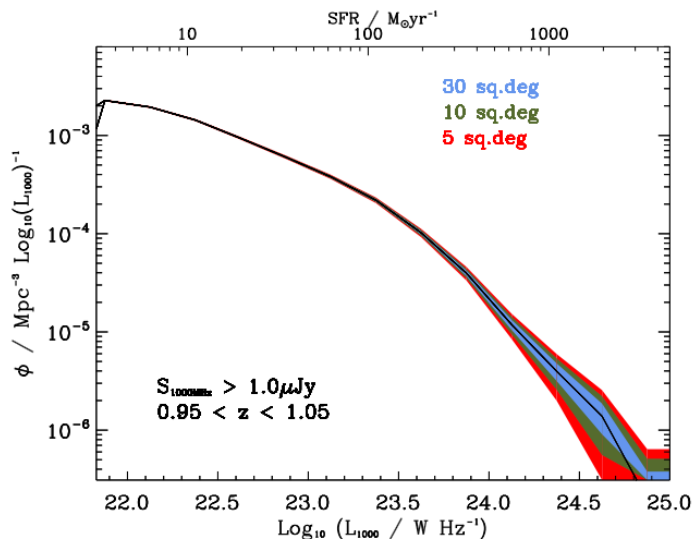
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SF vs Environment

Requirement:
10-1000 deg² 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

Detailed Astrophysics at high-z

At $z > 1$ H α merging systems with $< 1''$ size

- 0.5-1'' resolution (1 GHz) \rightarrow Resolve mergers
- 0.05-0.1'' resolution (10 GHz) \rightarrow Resolve disks

SKA-MID: ~ 150 km baselines

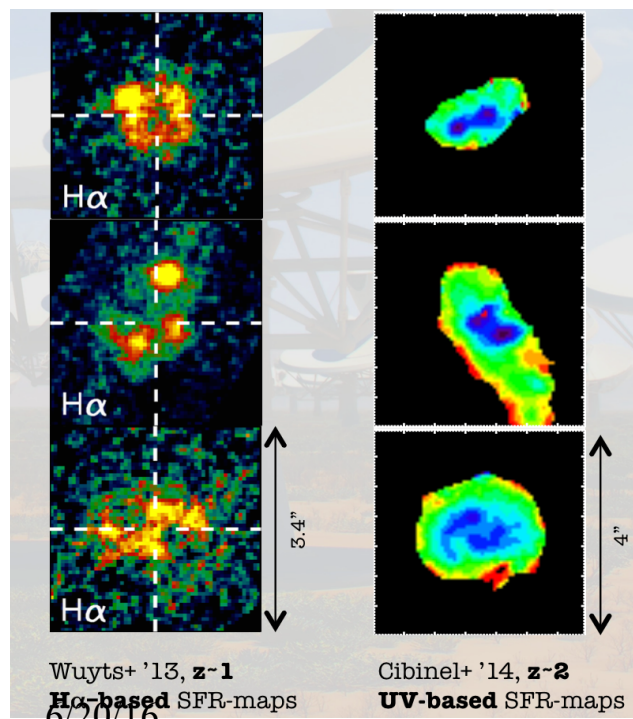
SKA1 \rightarrow resolve $100 M_{\odot}/\text{yr}$ SFGs

- to $z \sim 1$ on sub-kpc scales and
- to $z \sim 2$ on kpc scales

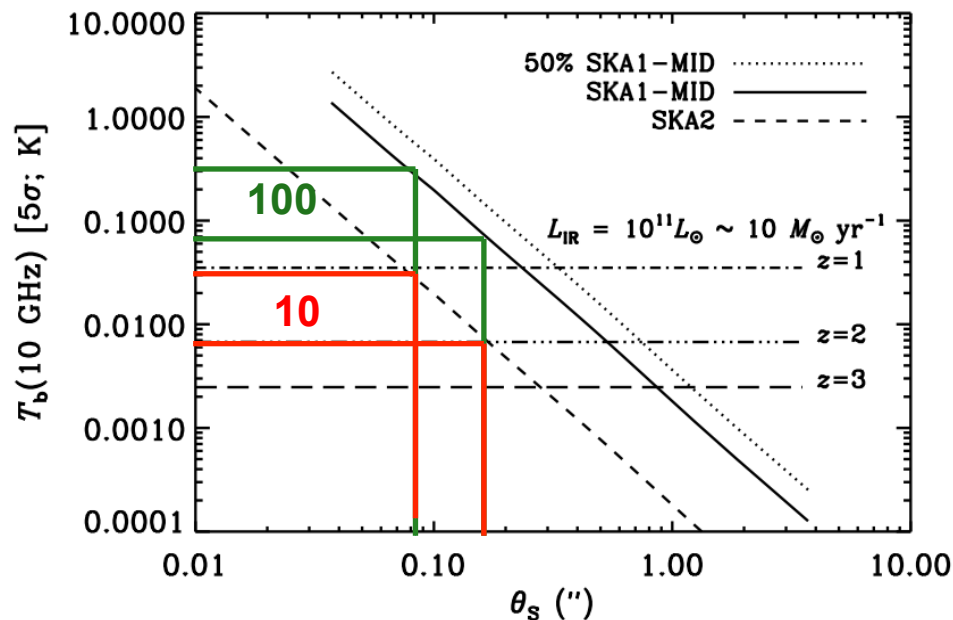
SKA2 \rightarrow push to $10 M_{\odot}/\text{yr}$ SFGs

5 kpc: $\sim 0.7''$ at $z > 1$

Nelson+13



Murphy, Sargent et al. et al 2015



Galaxy/AGN co-Evolution

Clear bimodality in galaxy population

- Blue galaxies/Star Forming MS
- Red Galaxies/Red Sequence
- Green Valley/AGN

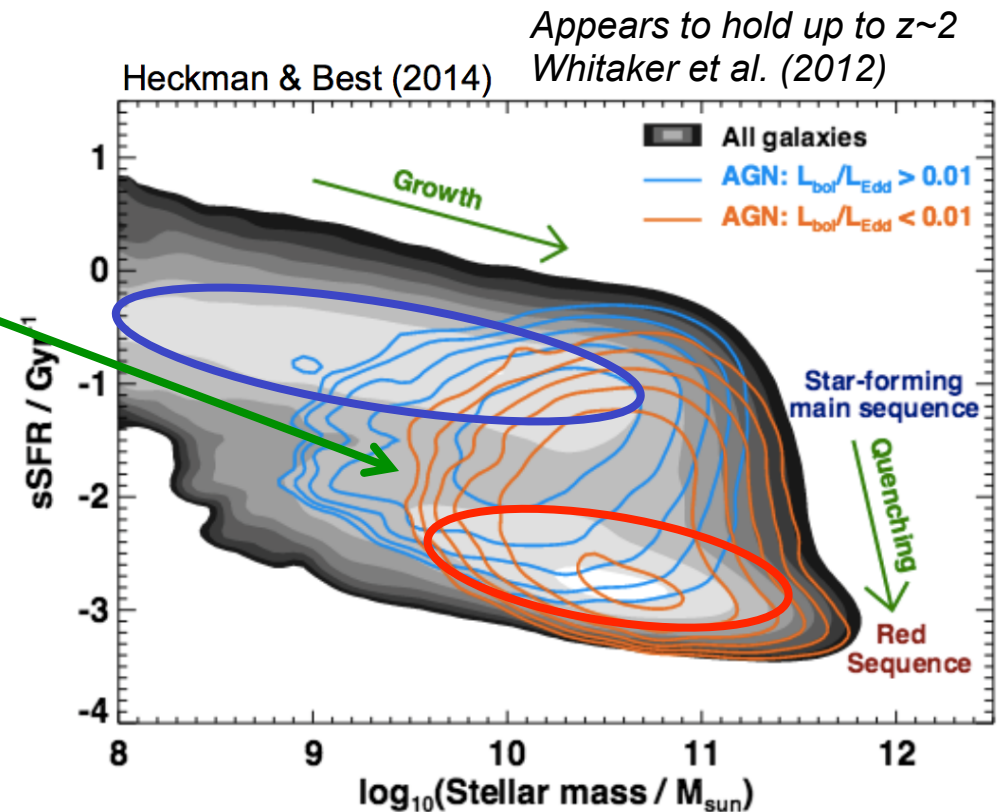
AGN feedback responsible for SF quenching and maintain galaxies “red and dead”

AGN feedback may be ubiquitous (winds, in addition to jets, seen in ionized, atomic, molecular gas)

SDSS: $z \sim 0$ (AGN $\sim 1\%$)

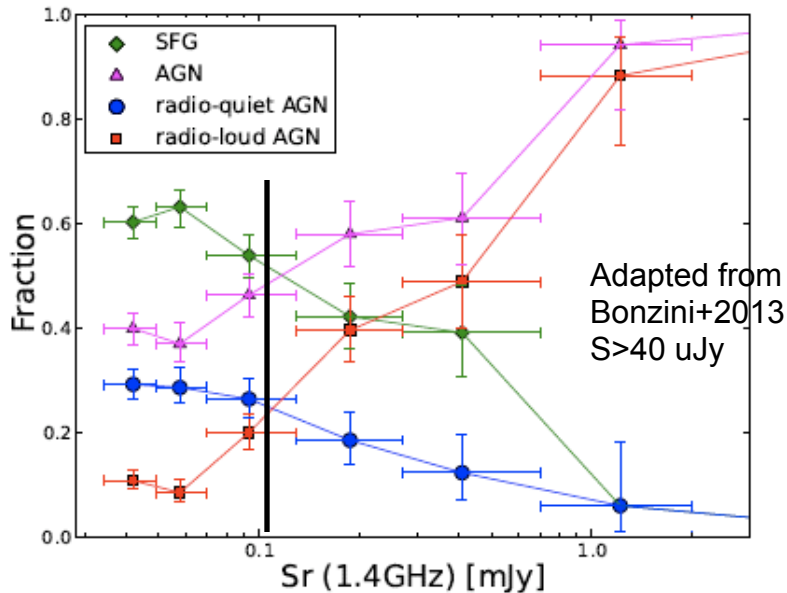
Push Feedback studies to

- Golden epoch of AGN/gal co-evolution ($z \sim 1-3$; AGN $\sim 10-30\%$)
- to epoch of formation of first galaxies ($z \sim 6-10$)



Galaxy/AGN co-Evolution

ECDFS: RQ-AGN $\sim 860/\text{deg}^2$!

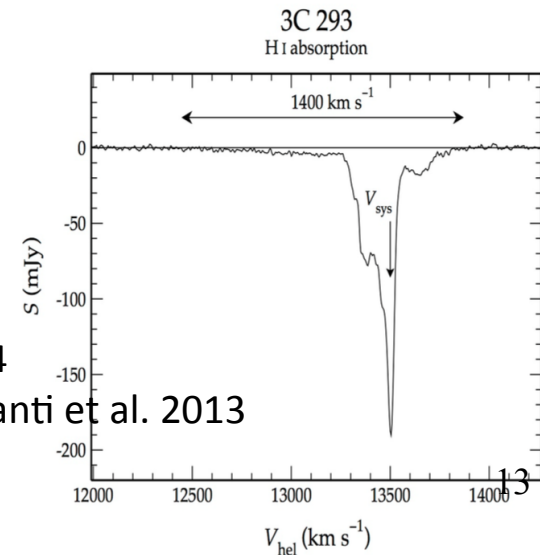


(sub-)uJy-level RC surveys can trace SFG, RL and RQ AGNs

→ complete view of SF and AGN activity & feedback to high-z and down to RQ regime, including role of environment

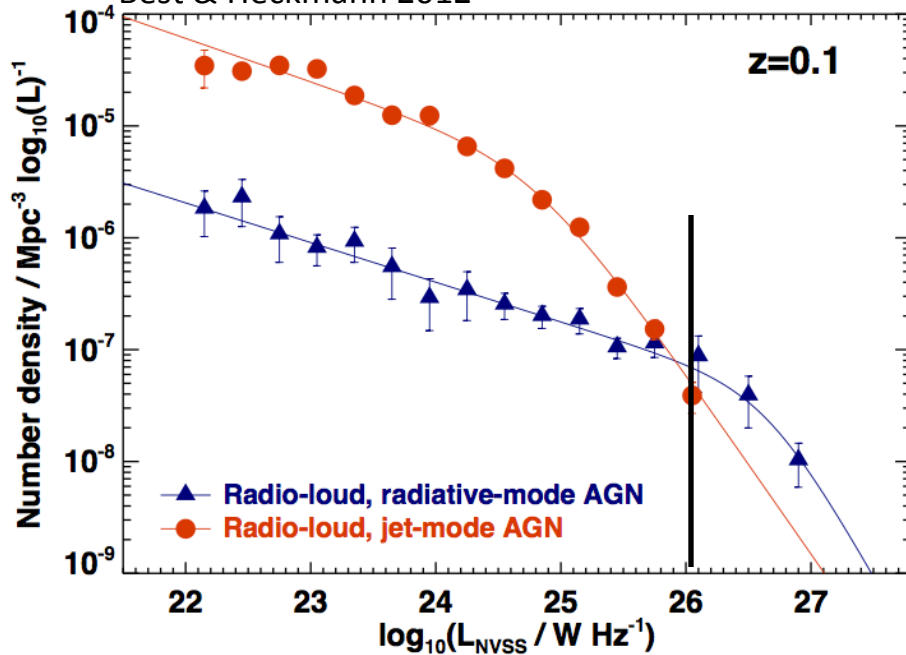
Not affected by dust extinction/gas obscuration

- **HI absorption in individual galaxies**
→ In-/out-flows directly probe AGN feeding/feedback in action



Galaxy/AGN co-Evolution

Heckmann & Best 2014; Gendre et al. 2013;
Best & Heckmann 2012



AGN Cosmic downsizing

(Hasinger et al. 2005):

RL-AGN: z_{peak} at $\sim 0.5-1$

RQ-AGN: z_{peak} at $0.5-2$, similar to SFG

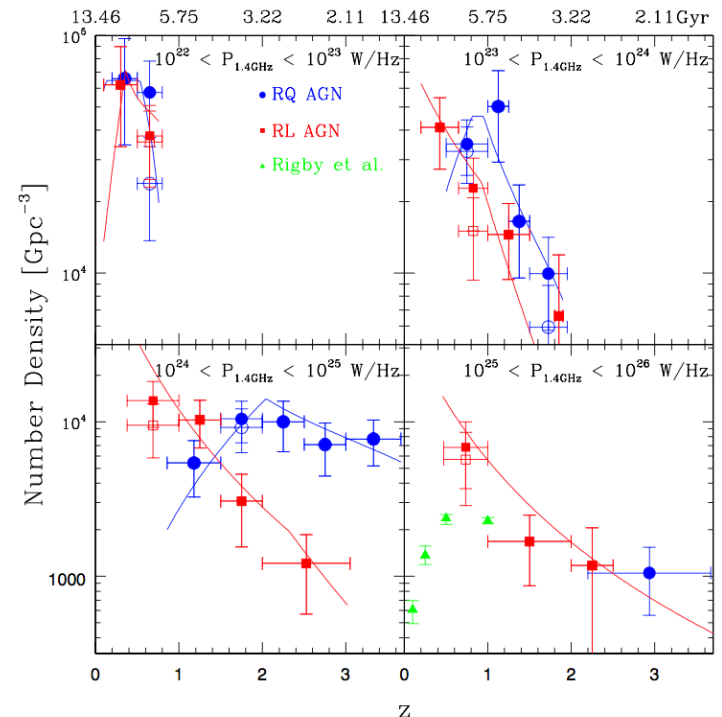
High-z dominated by radiative-mode AGN?

Local RL-AGN LF

Jet-Mode AGN dominant population

→ Not necessarily true at high redshift

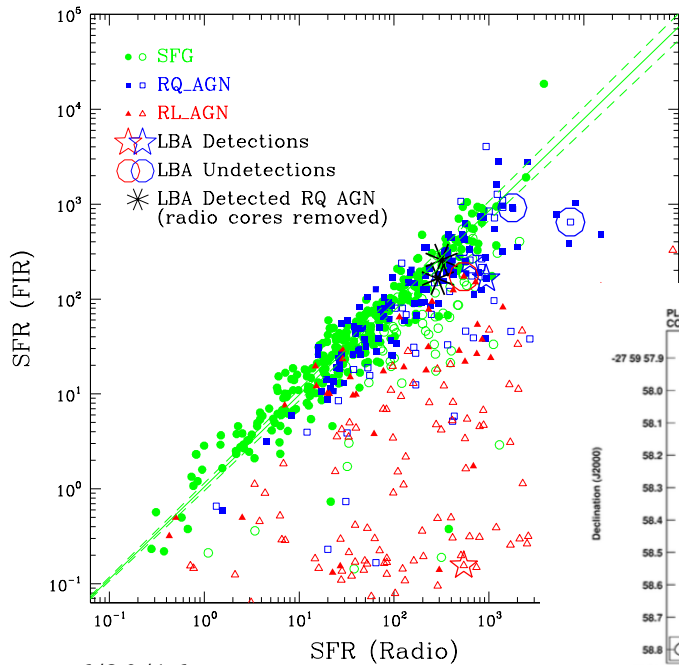
ECDFS Field: 0.3 deg^2 – Padovani+ 2015



Detailed Astrophysics at high-z

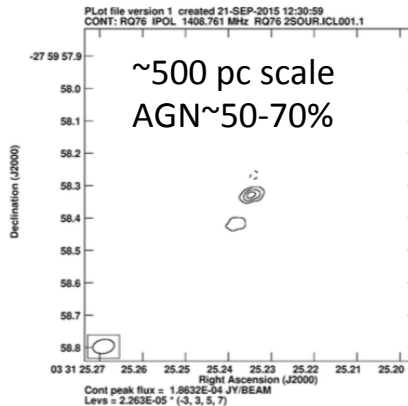
At $z \sim 1-3$ Golden era of AGN/galaxy co-evolution
 → 10-30% composite systems

- 0.05-0.1" resolution (10 GHz):
 - origin of radio emission
 - remove embedded radio cores
 - unbiased census of SFR and accretion

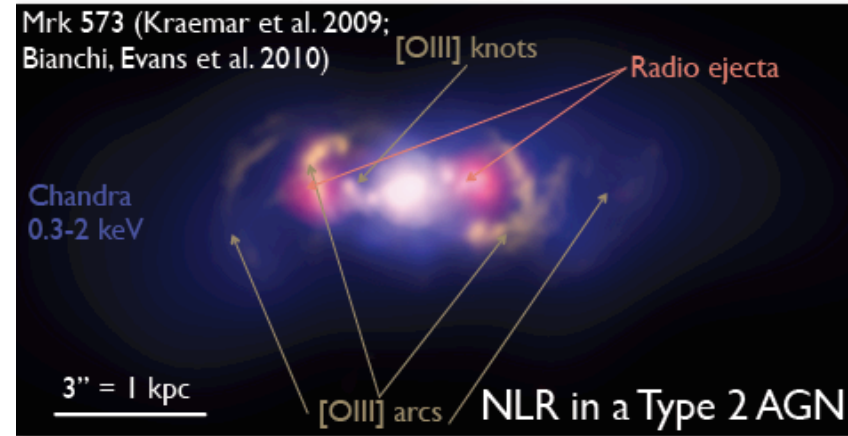


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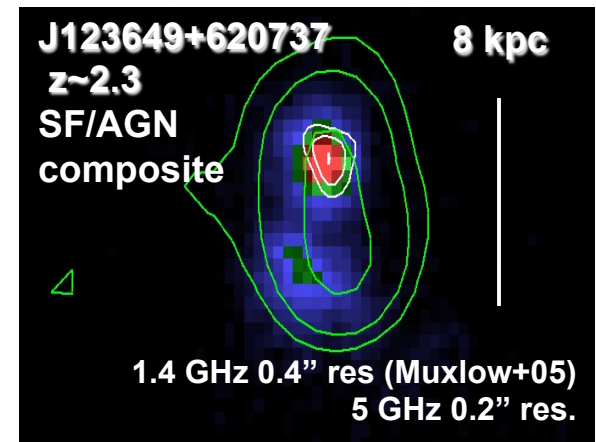
Maini, IP et al. 16



Mrk 573 - $z \sim 0$



Guidetti, Bondi, IP et al. 13



Cosmology vs. Galaxy surveys

S. Driver @ ASKAP16

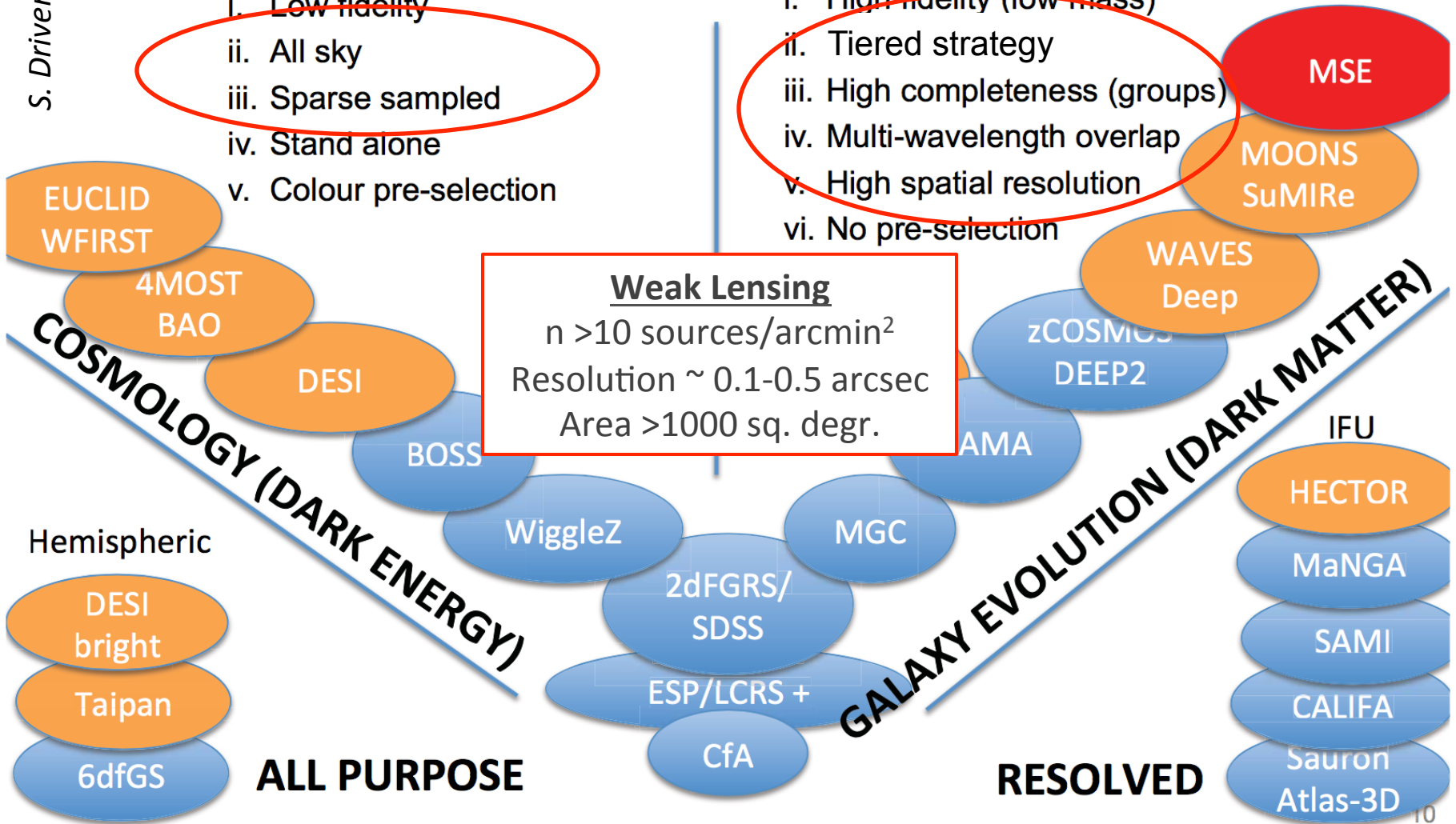
Optimal cosmology survey

- i. Low fidelity
- ii. All sky
- iii. Sparse sampled
- iv. Stand alone
- v. Colour pre-selection

Optimal galaxy survey

- i. High fidelity (low mass)
- ii. Tiered strategy
- iii. High completeness (groups)
- iv. Multi-wavelength overlap
- v. High spatial resolution
- vi. No pre-selection

Weak Lensing
 $n > 10$ sources/arcmin²
 Resolution $\sim 0.1-0.5$ arcsec
 Area > 1000 sq. degr.



ALL PURPOSE

RESOLVED

Cosmology vs. Galaxy Surveys

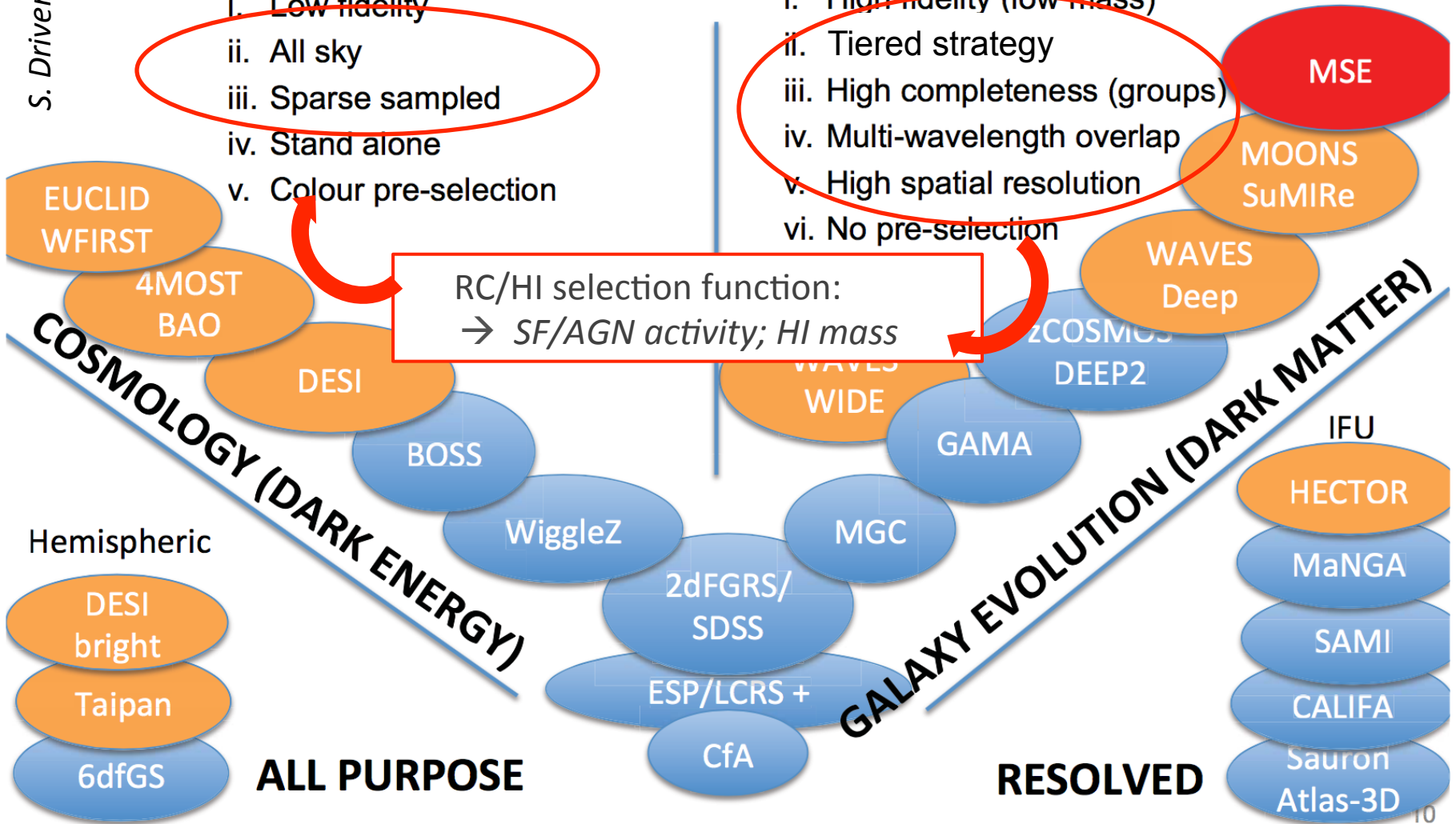
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EUCLID
WFIRST

4MOST
BAO

DESI

BOSS

WiggleZ

2dFGRS/
SDSS

ESP/LCRS +

CfA

Hemispheric

DESI
bright

Taipan

6dfGS

ALL PURPOSE

WAVES
WIDE

GAMA

MGC

ESP/LCRS +

CfA

RESOLVED

2COSMOS
DEEP2

WAVES
Deep

MOONS
SuMIRe

MSE

IFU
HECTOR

MaNGA

SAMI

CALIFA

Sauron
Atlas-3D

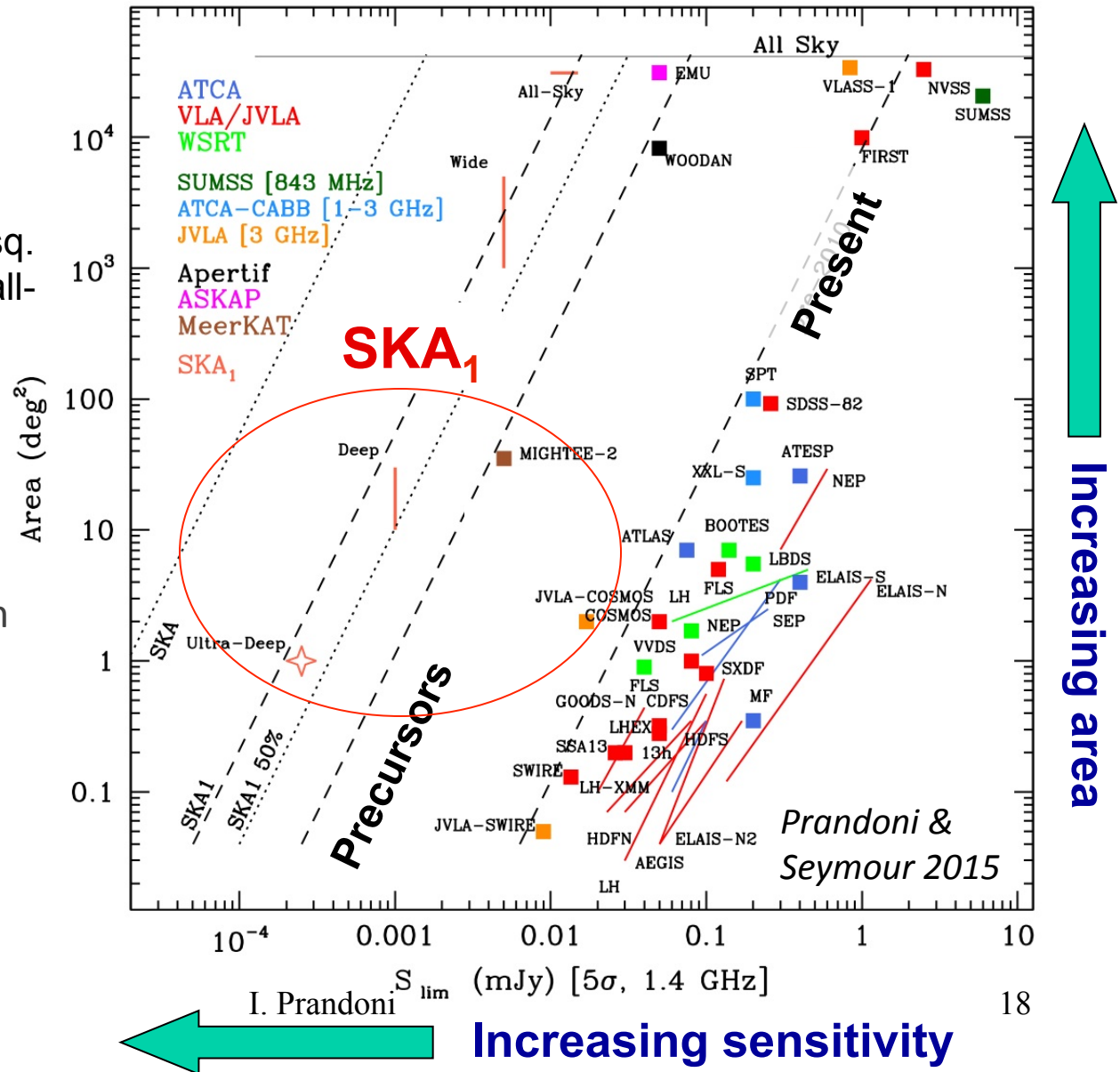
Next Generation Radio-continuum Surveys

The SKA as a survey machine

Surveys will probe from few sq. deg. (at sub-uJy rms) to all-sky (at uJy rms)

→ representative volumes at all redshifts

- Inform about source demographics & evolution at matched res. & depth
 - *bias vs source types, z environment*
 - *halo mass function*



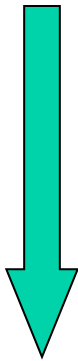
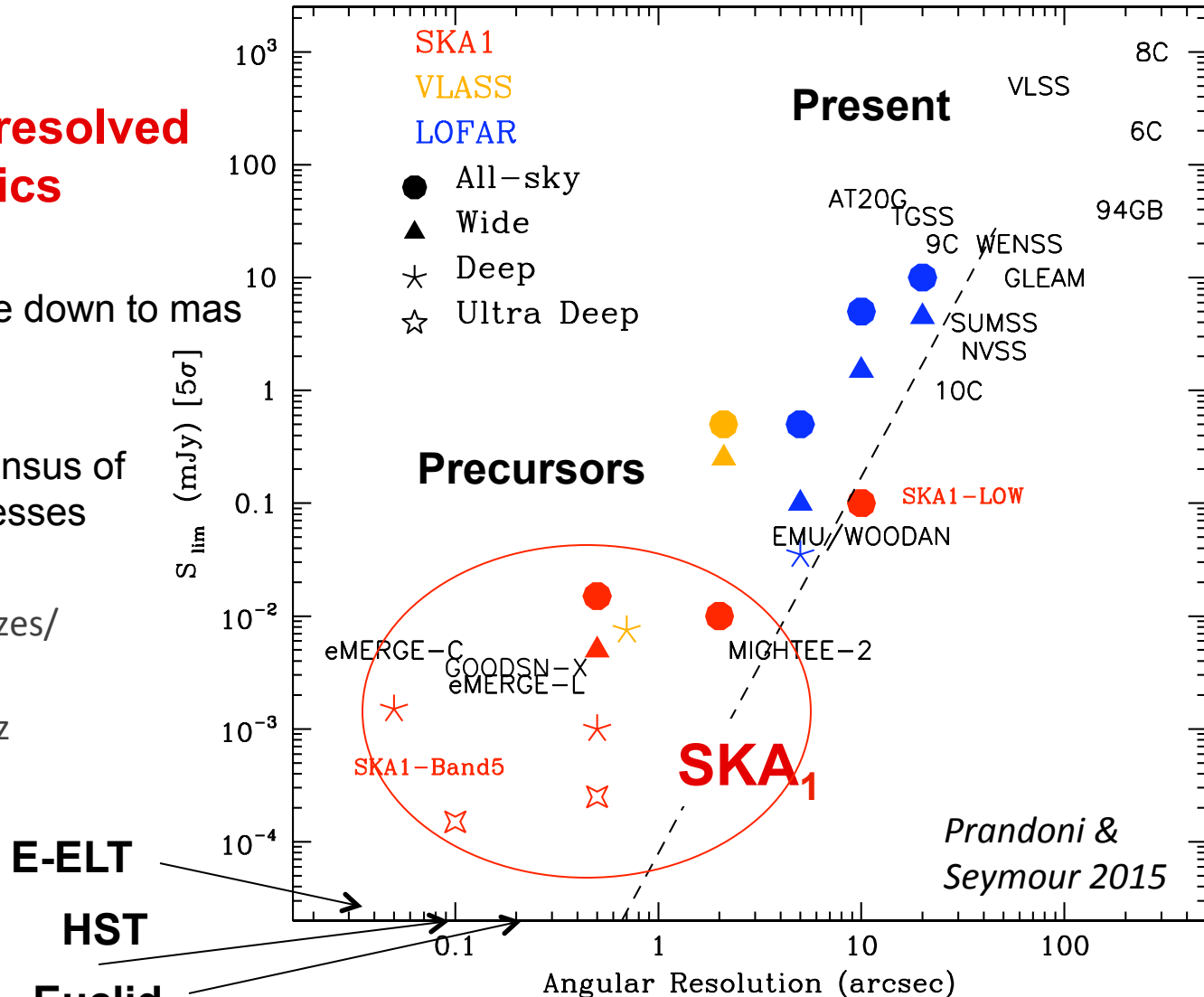
Next Generation Radio-continuum Surveys

The SKA for resolved astrophysics

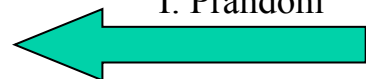
Surveys will probe down to mas resolutions

→ multi-scale census of sources/processes

→ Inform about sizes/morphologies vs source type, z



Increasing sensitivity



Higher resolution

eMERGE: New Ultra-Deep Study of GOODS-N

L-band: Single pointing + C-band 7-point mosaic

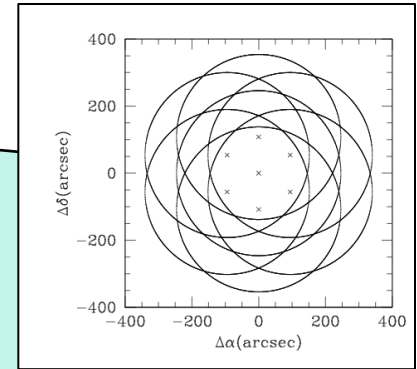
Central 12' field $1\sigma \sim 500\text{nJy/beam}$

Outer 30' field $1\sigma \sim 1\mu\text{Jy/beam}$

Resolution: 50-200 mas

+ ultra-deep EVN L-Band (PhD Radcliffe)

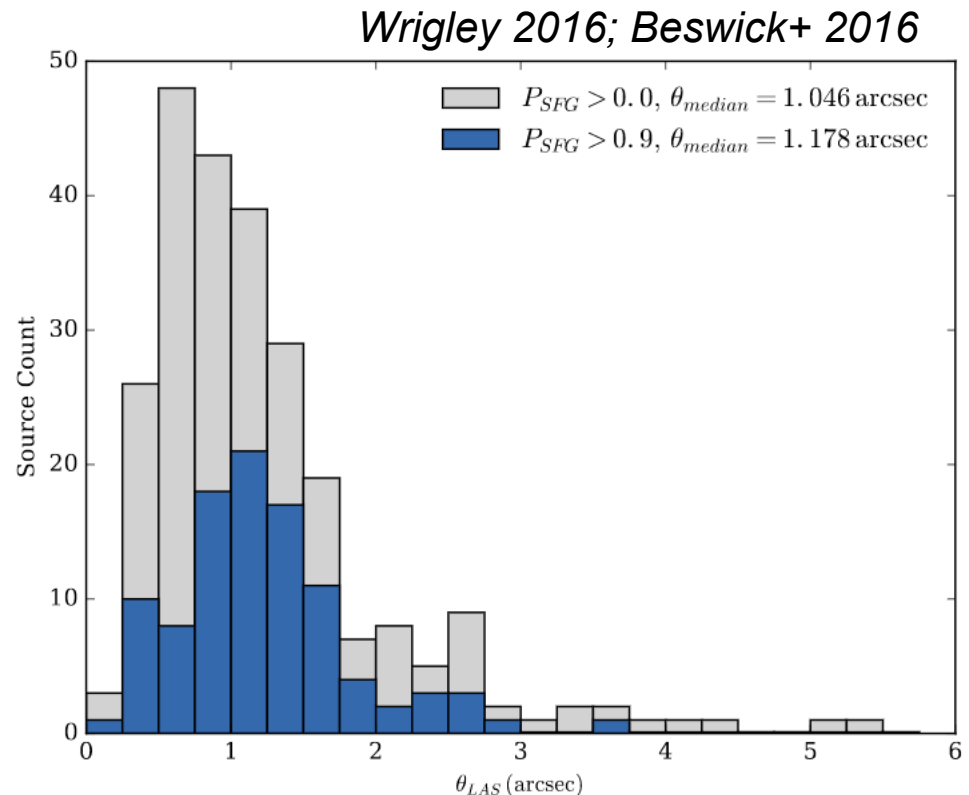
~5000 sources in 0.2 square degree field (~7 sources/arcmin²)



eMERGE: New Ultra-Deep Study of GOODS-N

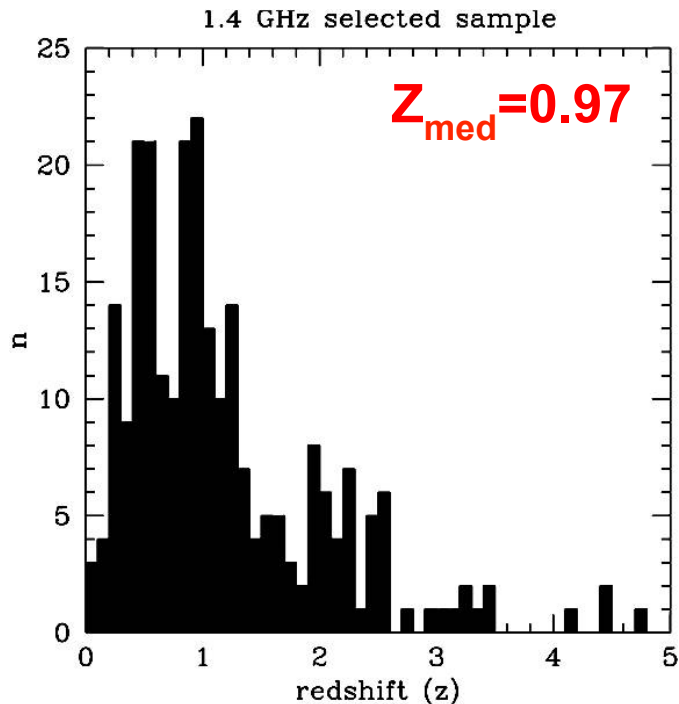
~250 sources >10-20 μ Jy separated by starburst/AGN contribution through a statistical approach based on source morphology parametrization

- Typical angular size of μ Jy SFGS \sim 1-1.2arcsec
- AGN more compact
- AGN contribution \sim 30%
- High resolution (<0.5arcsec) critical for component separation



eMERGE: New Ultra-Deep Study of GOODS-N

Preliminary C-band mosaic (rms ~ 1.5-2 μ Jy)



- 88% NIR identified (96% for SNR>5.5)
- 95% NIR counterparts with redshift
- $L_{1.4 \text{ GHz}} = 10^{21-26} \text{ WHz}^{-1}$
- 96% $L_{1.4 \text{ GHz}} < 10^{25} \text{ WHz}^{-1}$
- AGN/SFG separation based on IR colors, X-ray luminosity, radio loudness

eMERGE: New Ultra-Deep Study of GOODS-N

Preliminary C-band mosaic (rms ~ 1.5-2 uJy)

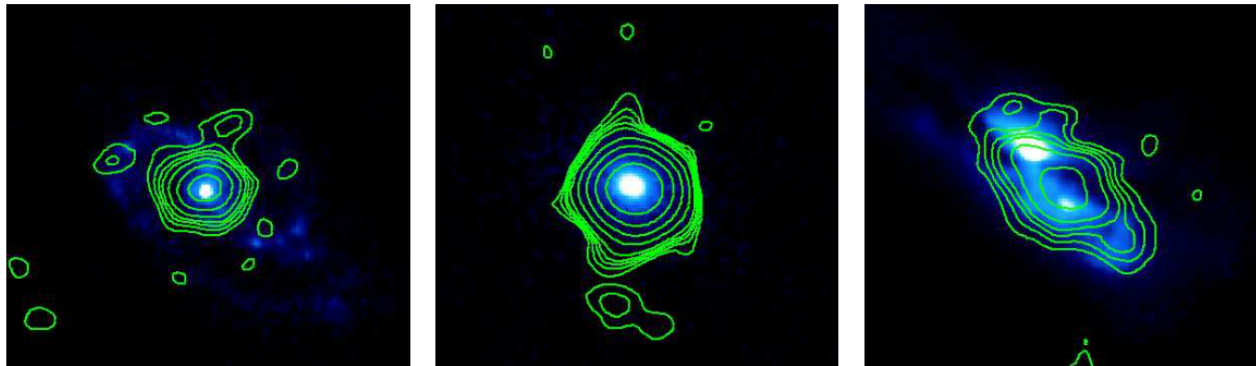
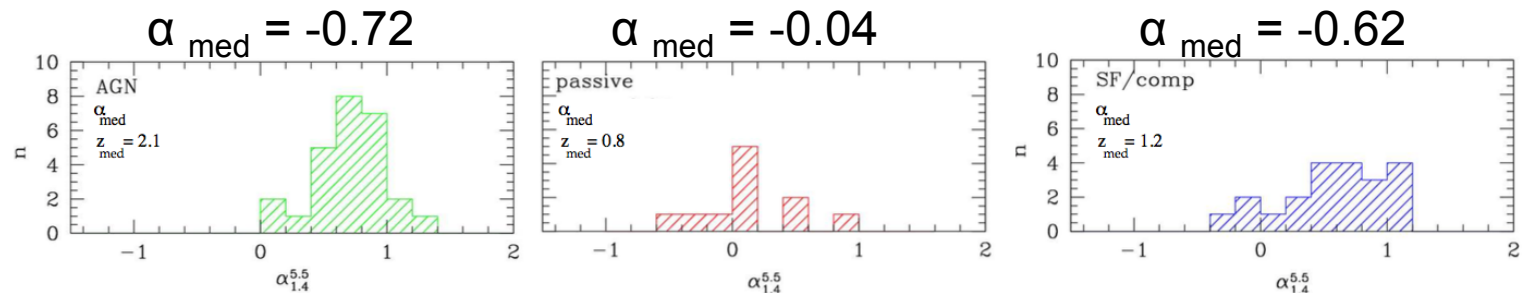


Figure 4: 5.5 GHz contours overlaid on the HST B-band images for an IR-AGN candidate (left), a passive galaxy (center) and a SF/Comp system (right).



Conclusions

- Next-generation radio surveys will play an unprecedented role in studying galaxy/AGN co-evolution (depth+large fields)
 - will inform on uJy population and radio selection function (different from optical surveys)
- High-resolution (sub-arcsec) will allow to get into the realm of detailed astrophysical studies at high-redshifts → pathfinders eMERLIN+JVLA
 - unbiased census of both SF and accretion and the interplay between AGN and SF activity
 - will inform on composite systems, galaxy shapes and sizes essential to reliably measure sizes of weak lensing radio population