Future (Extragalactic) Radio Surveys and Synergies with Spectroscopic Surveys

Isabella Prandoni
INAF - IRA

The SKA in a nutshell

SKA:

Main parameters:

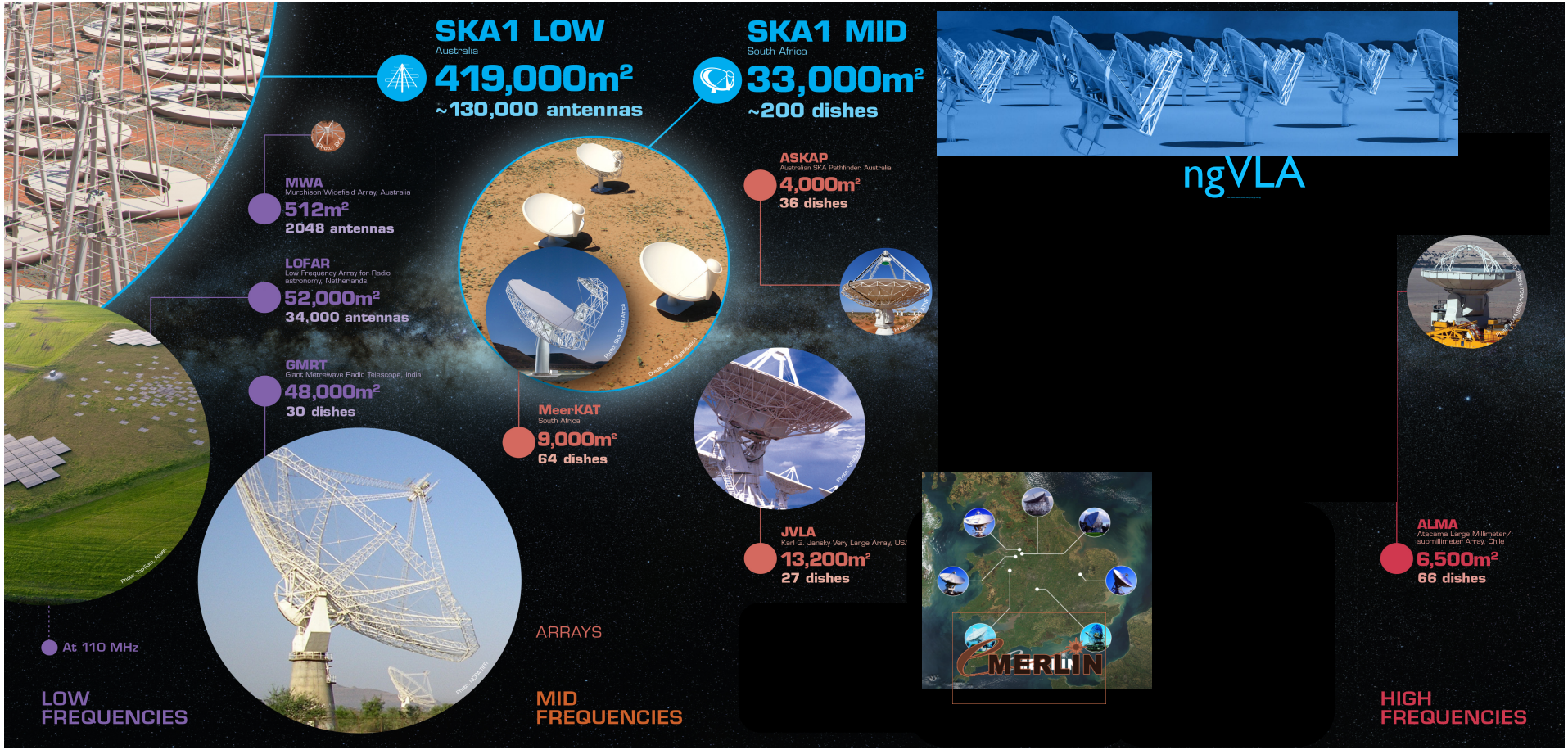
- **km^2 collecting area ➔ 100x sensitivity**
- **Large FoVs ➔ 100x survey speed**
- **3000+ km max baseline ➔ mas angular resolution**
- **large frequency range [50 MHz – 24+ GHz]**

SKA1 (650 MEu) Timeline:

- *Design & IGO: Q1-2 2019*
- *Construction begins: Q4 2020*
- *Commmissioning/SV starts: 2022/2024*
- *Full Operations: 2027*

Radioastronomy: a Golden Age

Adapted from SKAO image



50 MHz 350 MHz 15(24) GHz 100 GHz 1 THz

frequency

SKA– Key Science Drivers: The history of the Universe

Broadest science range of any facility on or off the Earth (Braun et al. 2015)
.....see also II National SKA Workshop talks...

SKA– Key Science Drivers:

FOCUS TODAY

Testing General Relativity
(Strong Regime, Gravitational Waves)

Cosmic Dawn
(First Stars and Galaxies)

Galaxy Evolution
(Normal Galaxies z~2-3)

Cradle of Life
(Planets, Molecules, SETI)

See Grazia's Talk

Cosmology
(Dark Matter, Large Scale Structure)

Cosmology with SKA1 - Red Book 2018

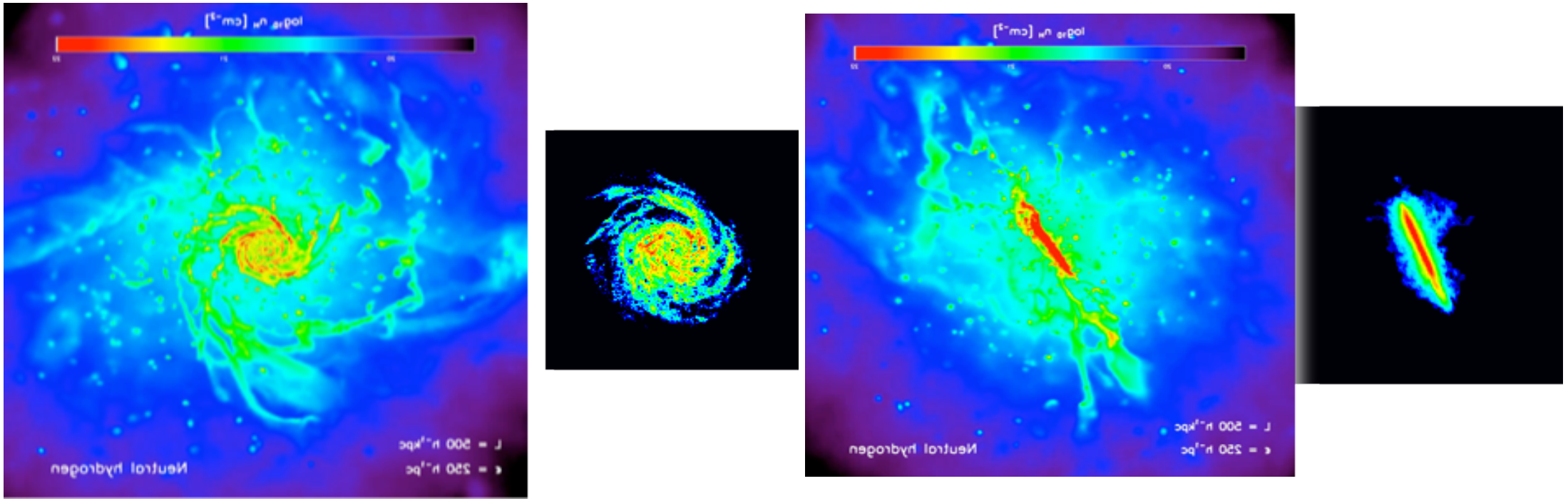
Cosmic Magnetism
(Origin, Evolution)

Exploration of the Unknown

Broadest science range of any facility on or off the Earth (Braun et al. 2015)

Galaxy HI Evolution:

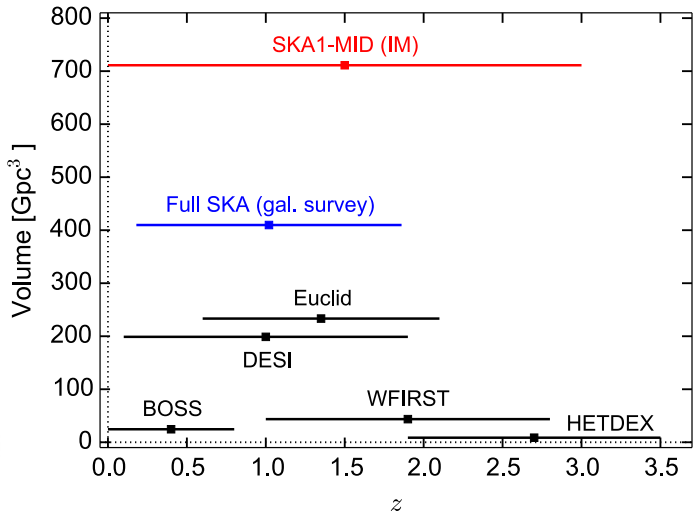
precursors to z~0.5; SKA1 out to z ~ 1 and SKA2 to z ~ 5



(Simulations: Schaye et al. 2010, Images: Oosterloo 2014)

- *Understanding galaxy assembly and the baryon cycle*
  - Determine the impact of galaxy environments
  - Probe gas inflow and removal, diffuse gas $N_{HI} < 10^{17}$ cm^{-2}
  - Measure angular momentum build-up

HI vs opt/NIR surveys



RC Surveys: Unbiased census of SF

Sensitivity is key

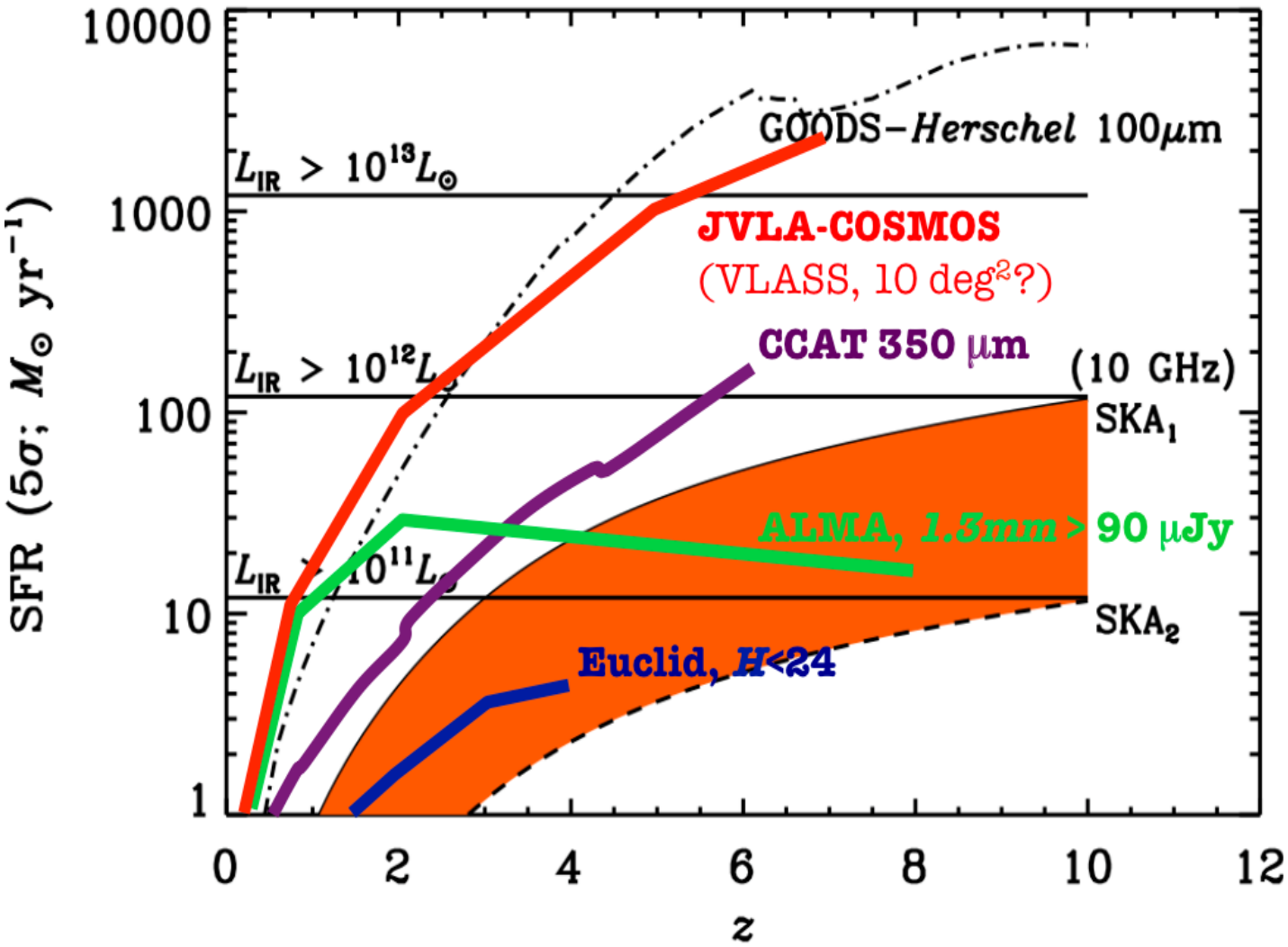
uJy → ULIRGs @ z>1.5-2 (Novak+2017)

Requirement:
→ sub-uJy rms

- SKA1: 10 M_{sun}/yr out to z~4
- SKA2: 10 M_{sun}/yr out to z~10

Band 5: 0.05-0.1" res.
Resolved kpc/sub-kpc imaging of star forming disks:
- SKA1 out to z~1
- SKA2 out to z~6

Murphy+ 2015: SKA Science Book



The role of high-resolution RC Surveys

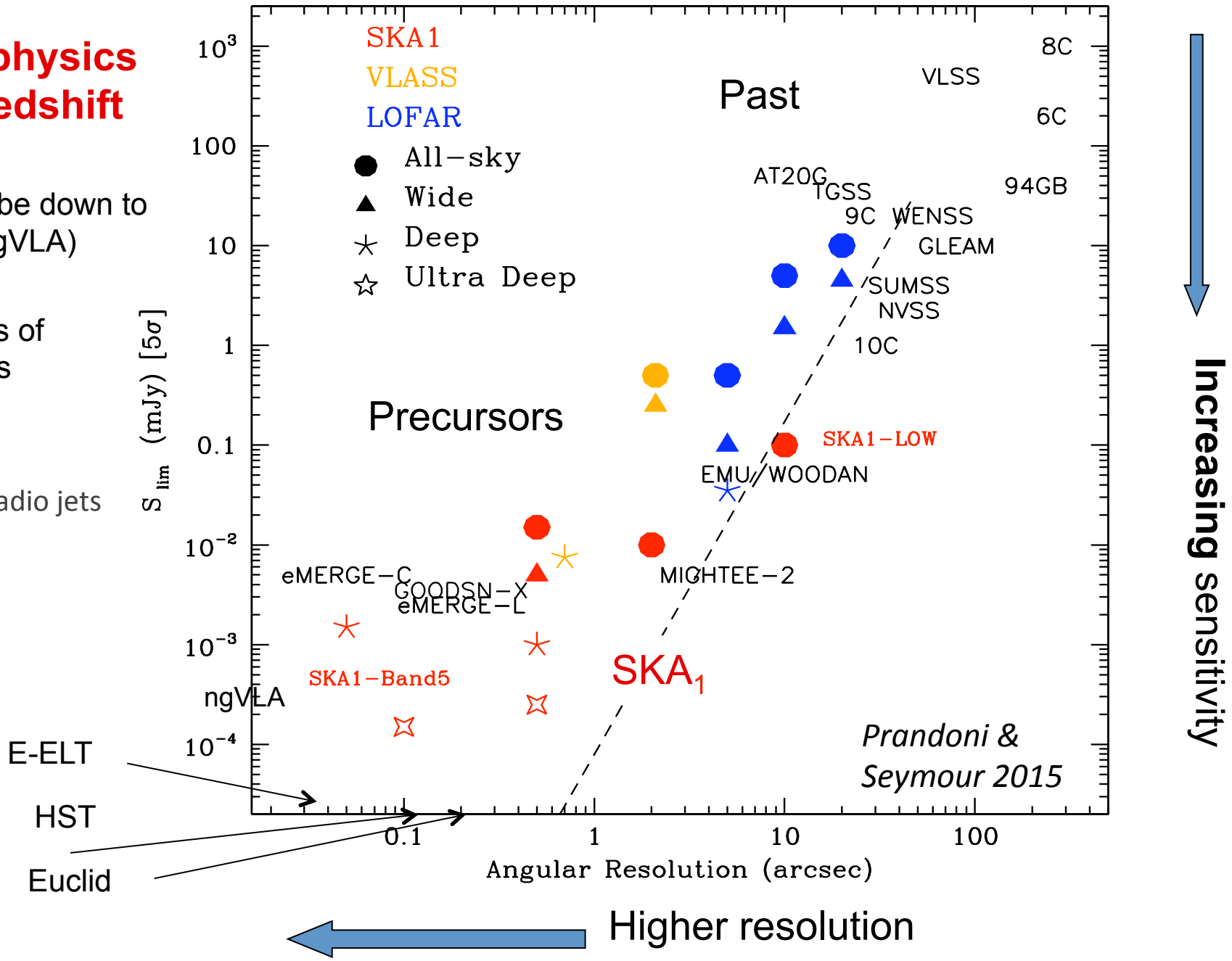
Resolved astrophysics out to high redshift

Radio surveys will probe down to mas resolution (ngVLA)

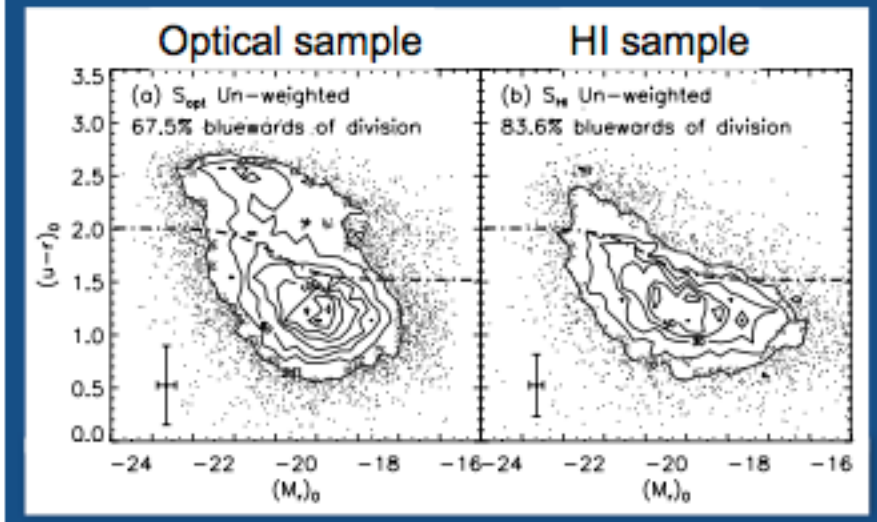
➔ multi-scale census of sources/processes

➔ Physics of RQ AGN:

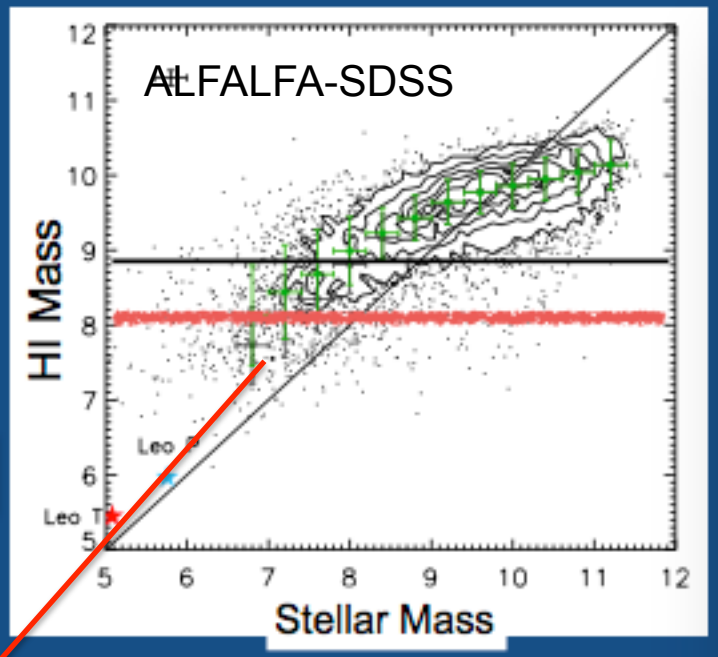
- incidence of radio jets
- SF



RC/HI/Opt selection functions



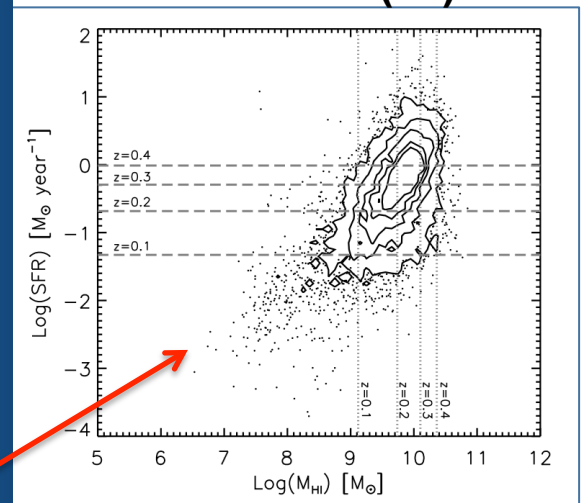
Huang et al (2012)



Maddox, Hess et al (2015)

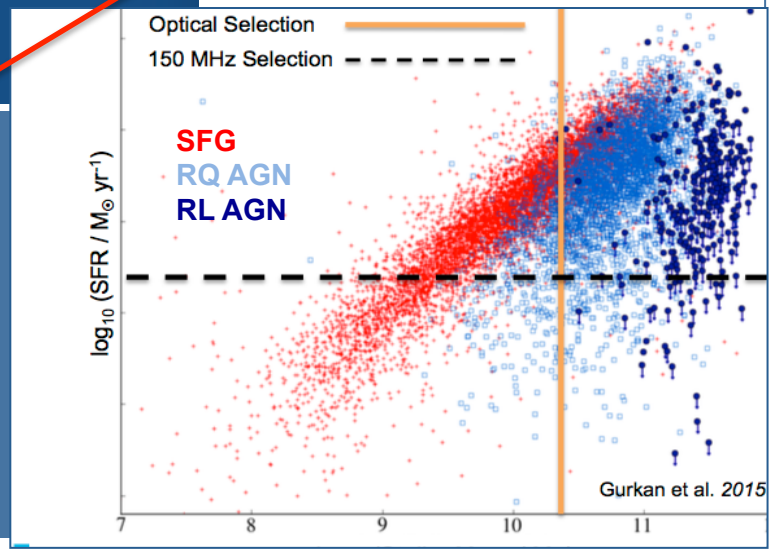
- Preferentially detect galaxies in the blue cloud
- HI mass and stellar mass are weakly correlated

SFR vs M(HI)



- Radio Continuum selects based on SFR **(unbiased tracer!)**
  P ÷ Star Formation Rate
- RC and HI are biased towards the same (blue) population BUT no 1:1 relation

➔ ideal to probe relation between HI, SFR, stellar mass (environment)



Panchromatic Approach is Key!

- **Source redshifts**: multi-band photometry [F(L,z)] + **spectra** (calibration, environment, spectral stacking)

- **AGN/SFG & RL/RQ AGN separation**:
  mid/far IR colors (WISE+Herschel)
  + X-ray (eROSITA, Athena), **high S/N spectroscopy**

- **AGN accretion physics:** HEG (Seyfert/QSO) vs LEG (Liners, ETS)
  X-ray (Athena), **High S/N optical spectra**
  (BPT diagnostic, TAIPAN, GAMA, WEAVE..)

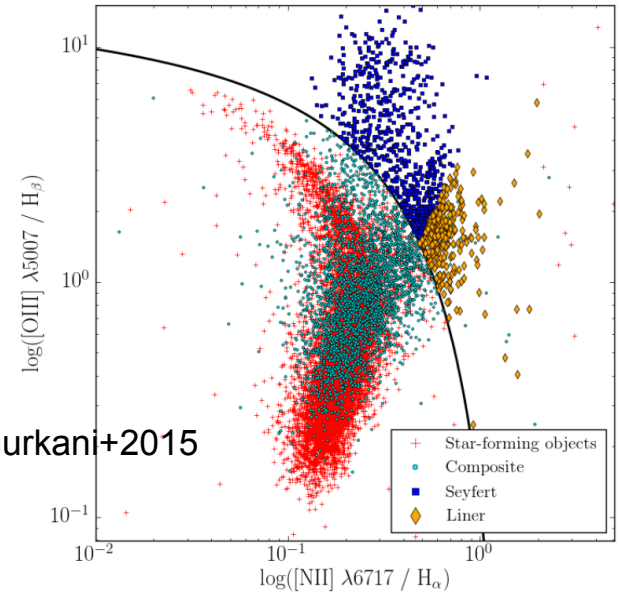
- Host galaxy properties (mass , color, SFR, etc.)

- Role of gas: HI + ALMA + Opt/NIR

- **Chemistry**: mm/sub-mm/opt **spectroscopy (high R)**

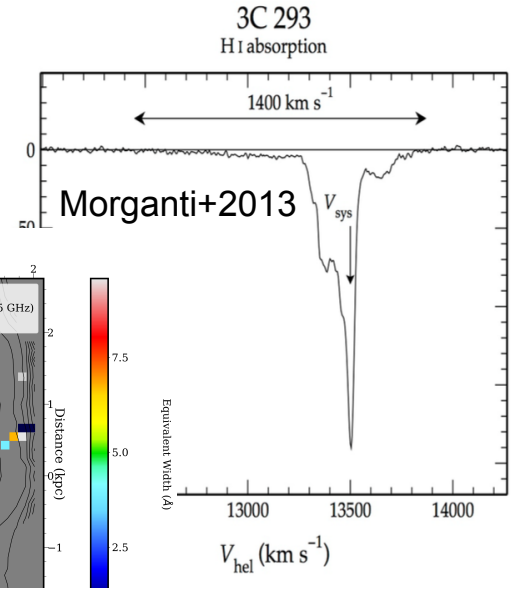
- **Dynamics: line fitting** (optical, near-IR, CO, HI, X-ray), spatially resolved (optical IFU,CO, HI)

- Morphology at high-z: High-res opt/NIR from space (HST, JWST, Euclid, ELT) + SKA-MID/VLBI

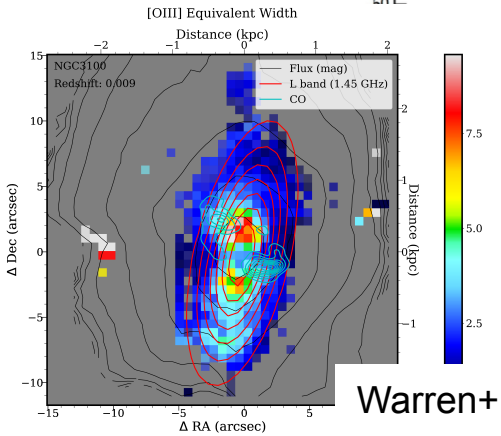


Gurkani+2015

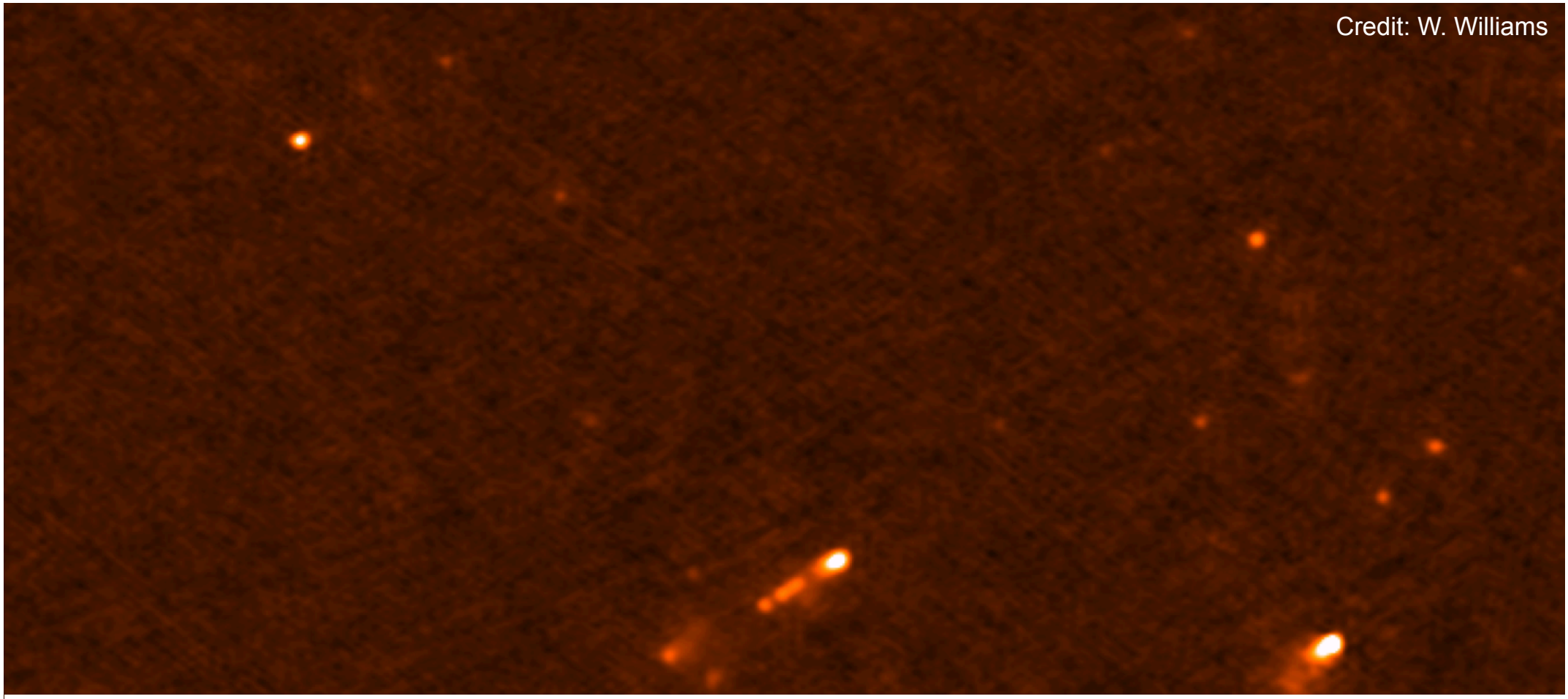
AGN feedback



Morganti+2013



Warren+in prep.



WEAVE-LOFAR

Currently finalising WEAVE-LOFAR & LOFAR KSP MoU

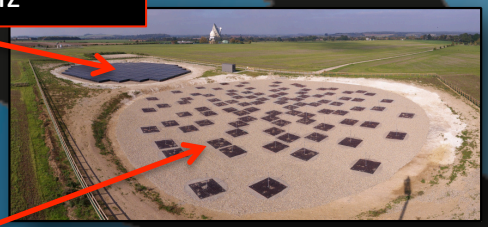
Italy both part of LOFAR & WEAVE Consortia

[ackn. Dan Smith – PI of WEAVE-LOFAR Science team]

International LOFAR Telescope (ILT)

Italy joined April 2018

High Band Array:
120-200 MHz



Low Band Array:
10-90 MHz

Onsala

Dutch stations

Norderstedt

Chilbolton

LOFAR Core (NL)

Potsdam

Bałdy

Borówiec

Jülich

Effelsberg

Tautenburg

Łazy

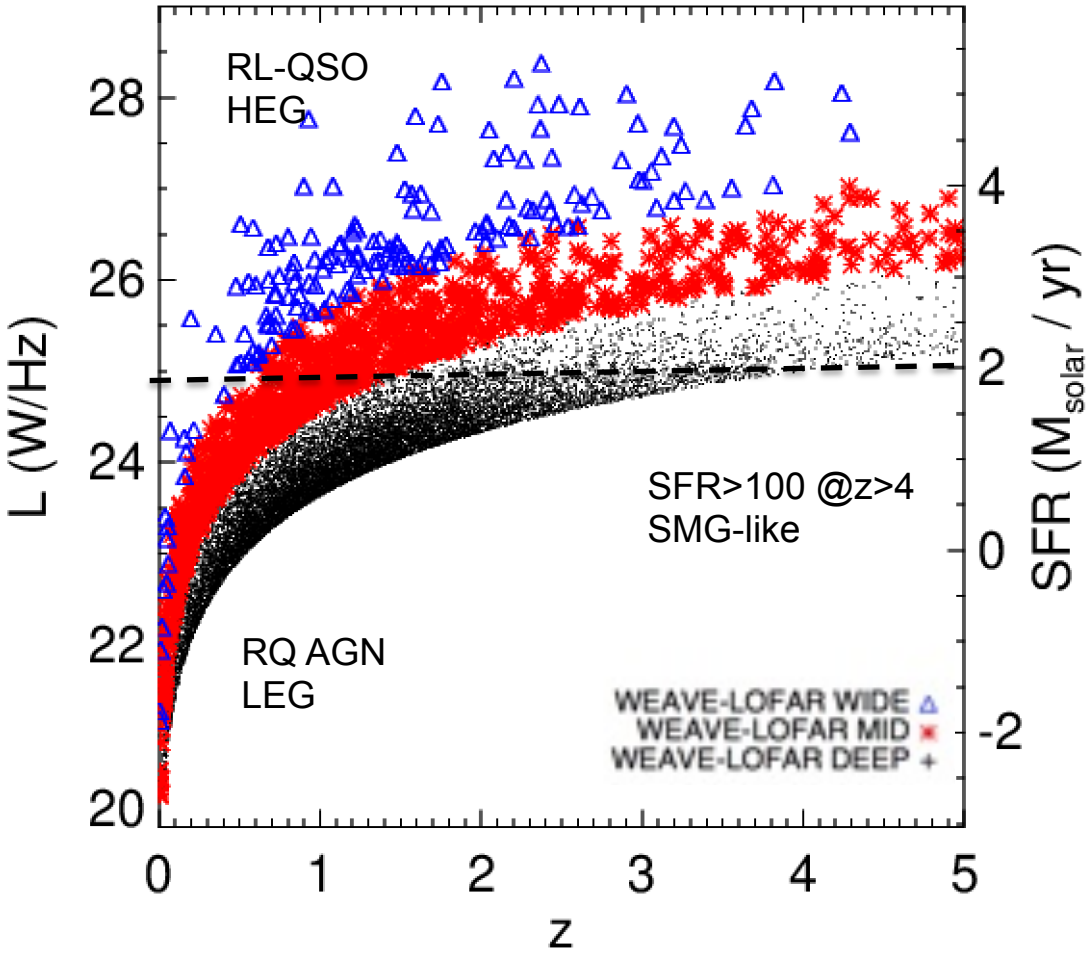
- **47 operational stations completed**
- **38 NL stations, 9 international stations**
- **3 new stations coming in Poland**

Nançay

Unterweilenbach

LOFAR

WEAVE-LOFAR
The MOS Survey - Current design [fiber hours < 1.6 million]



Deep (up to 100 deg²)
S>100 uJy → 5000/deg²
faint end of RLF & SFRF

t_{exp}≤5h

Mid (700-1250 deg²)
S>1 mJy → 500/deg²
SF/AGN co-evolution across cosmic history

t_{exp}=1h

Wide (up to 10000 deg²)
S>10 mJy → 55/deg²
rare objects e.g. bright EOR Radio Galaxies at z>6 for 21cm abs. experiments
(+local Volume)

Courtesy D. Smith

WEAVE-LOFAR
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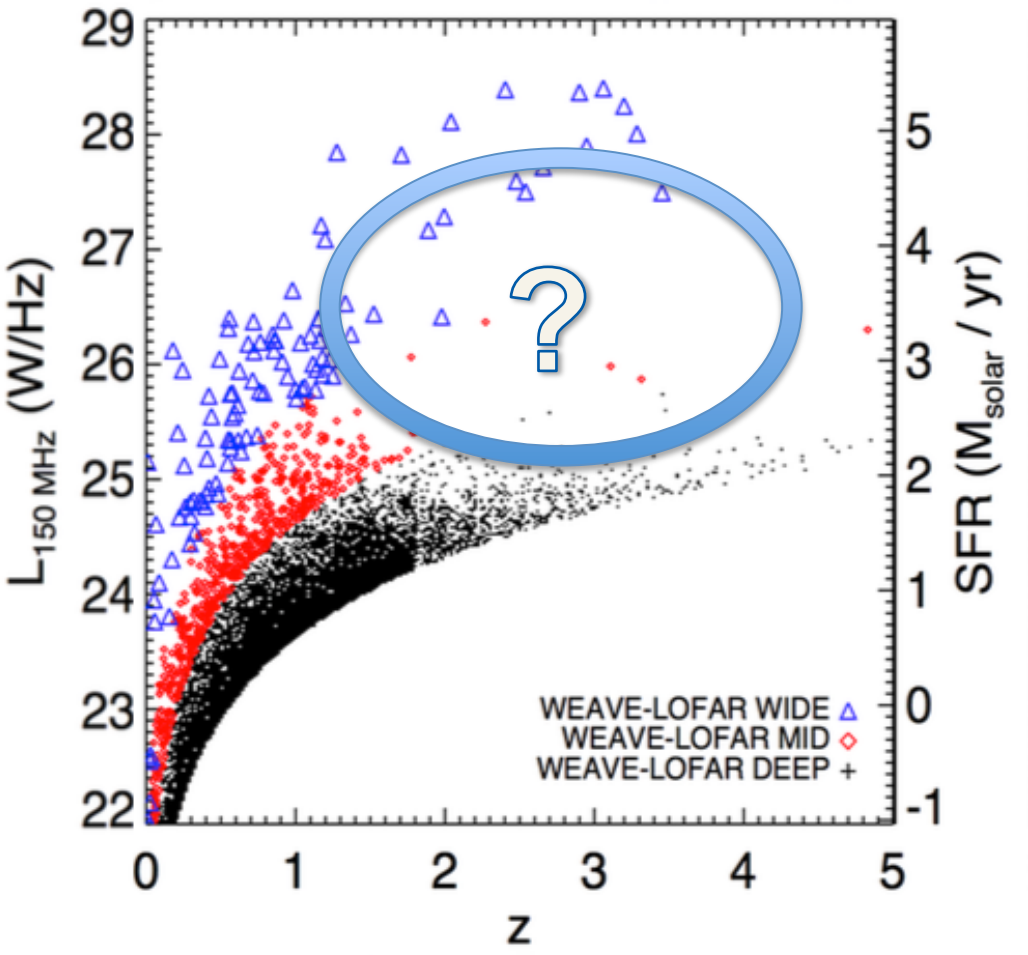

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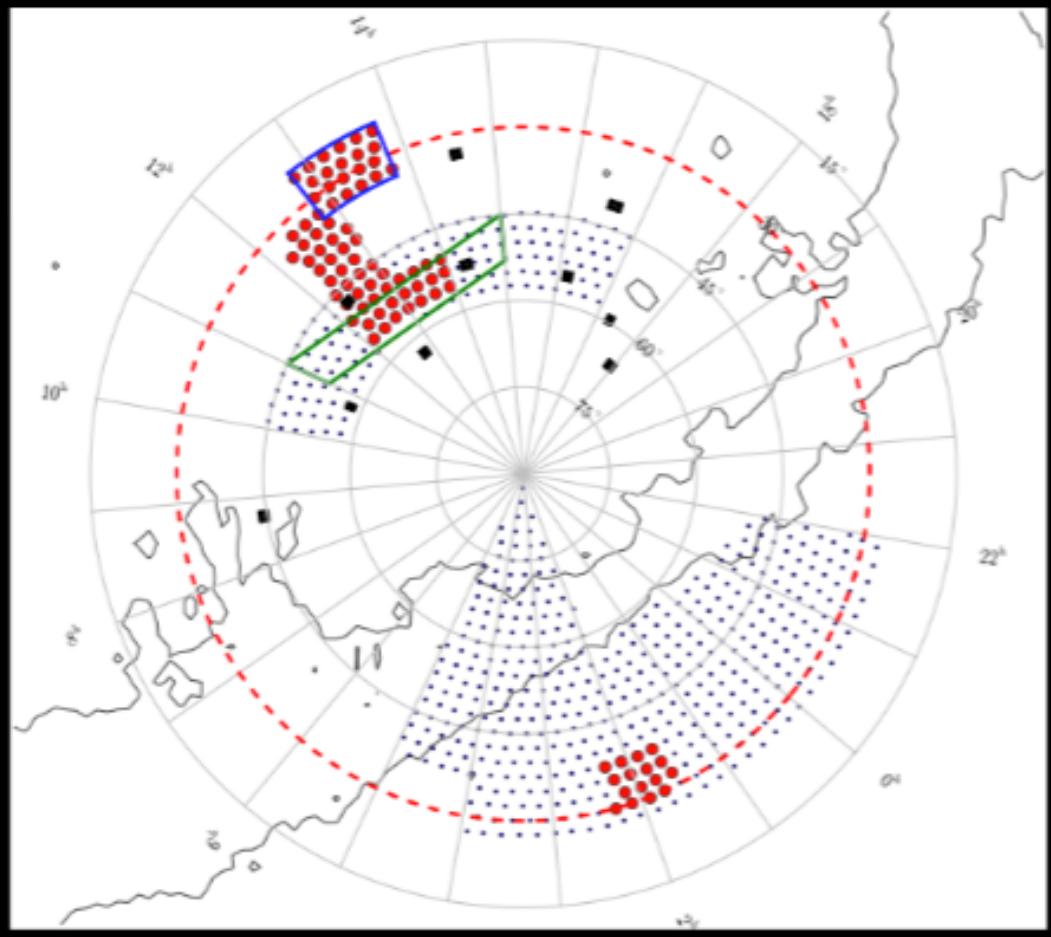
Courtesy D. Smith

WEAVE - APERTIF Survey

P.I. J. Falcon-Barroso (IAC)

includes Cagliari, Arcetri

IFU follow-up of a sample selected based on HI mass and HI morphology from APERTIF

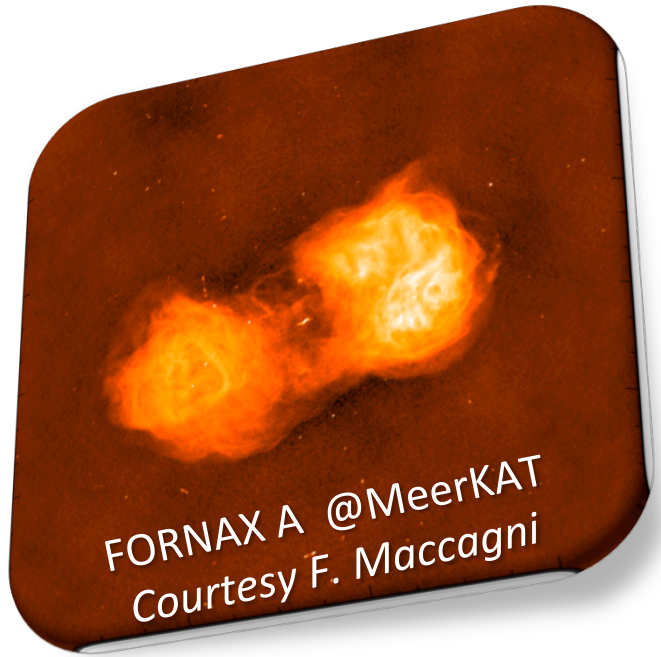


APERTIF
APERture Tile In Focus

Italy only part of WEAVE Consortia

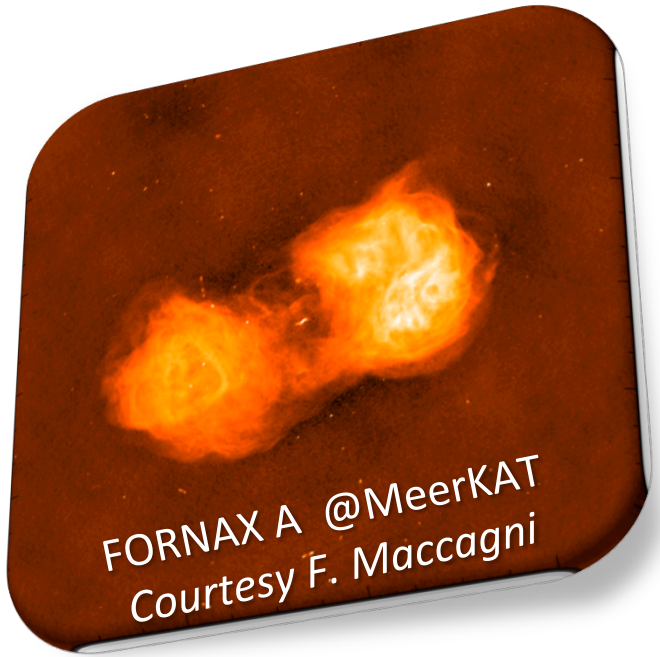
Courtesy P. Serra
Ackn. J. Falcon-Barroso

MeerKAT



- **64 Antennas, 13.5m → 1.7 deg FoV at 1.4 GHz**
  - dense core (<50m)
  - longer baselines (up to 8 km) –res. ~8" at 1.4 GHz
- **L-band:** 0.9-1.67 GHz → **HI 0<z<0.58**
  - wideband mode: 32K channels (20kHz ~ 5km/s)
  - zoom mode: 0.1 km/s
- **Key Projects + Open** (first *shared risk* call just issued; deadline 31 Jan. 19)
  - KP: MeerKAT Fornax Survey (PI Serra)

MeerKAT



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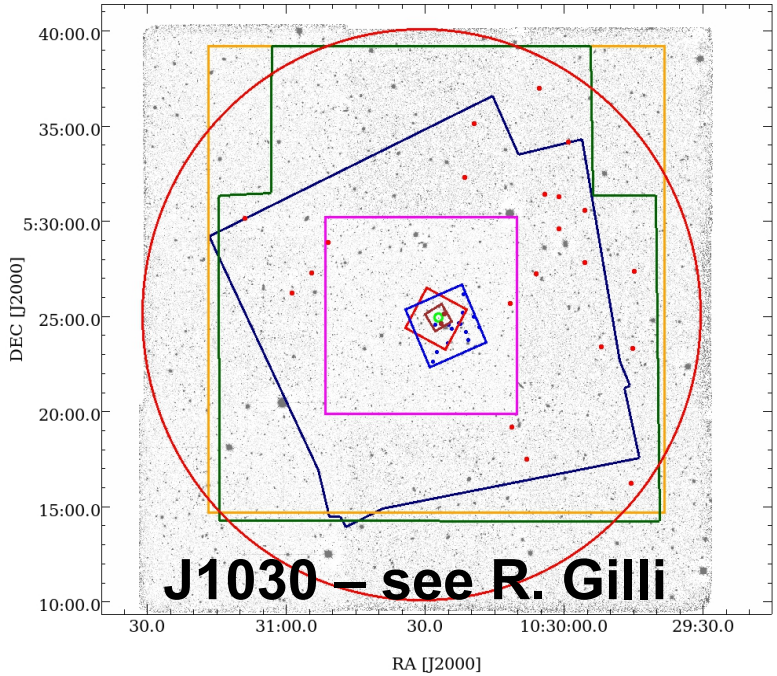
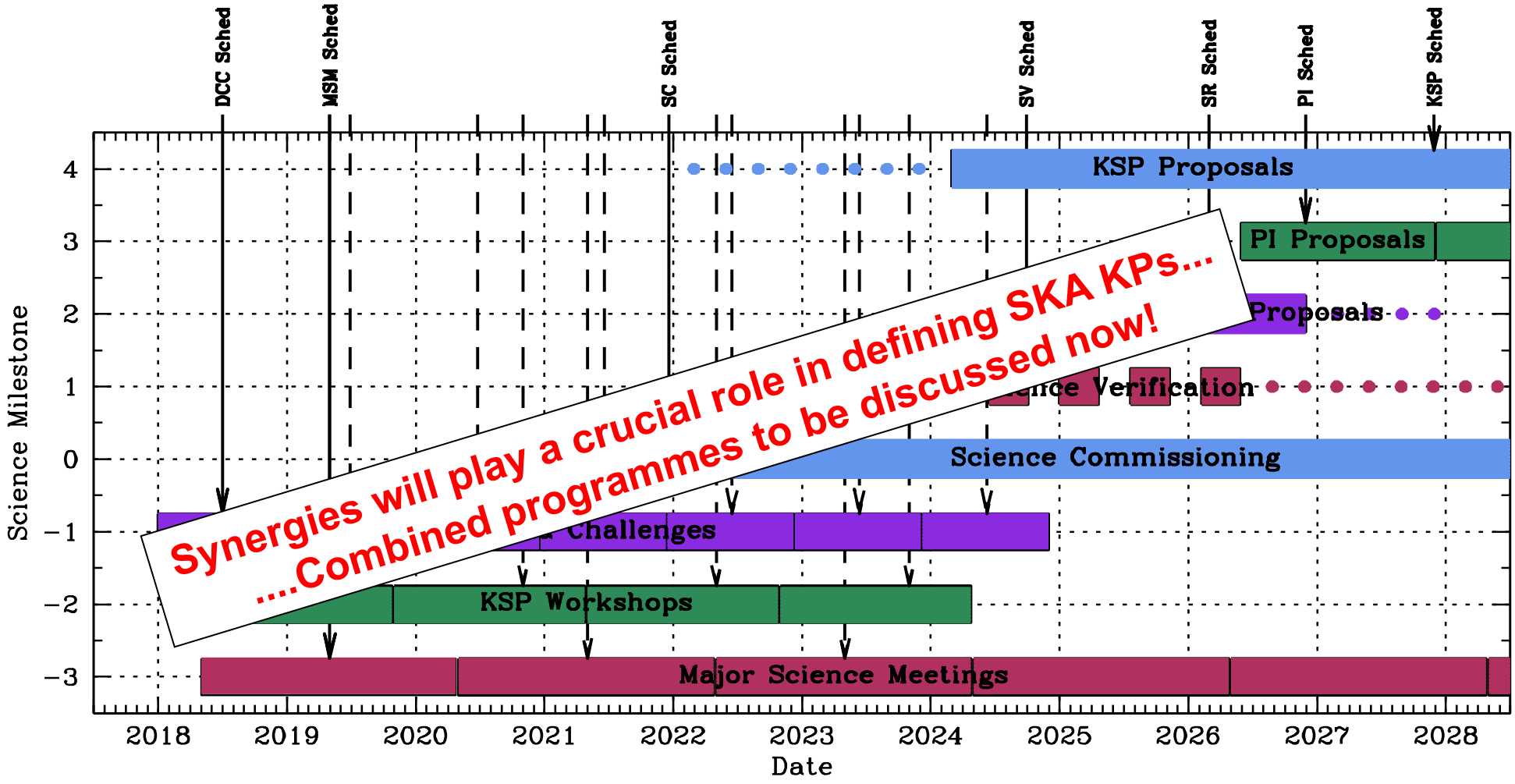


SKA1 Science Milestones (Doc #822)

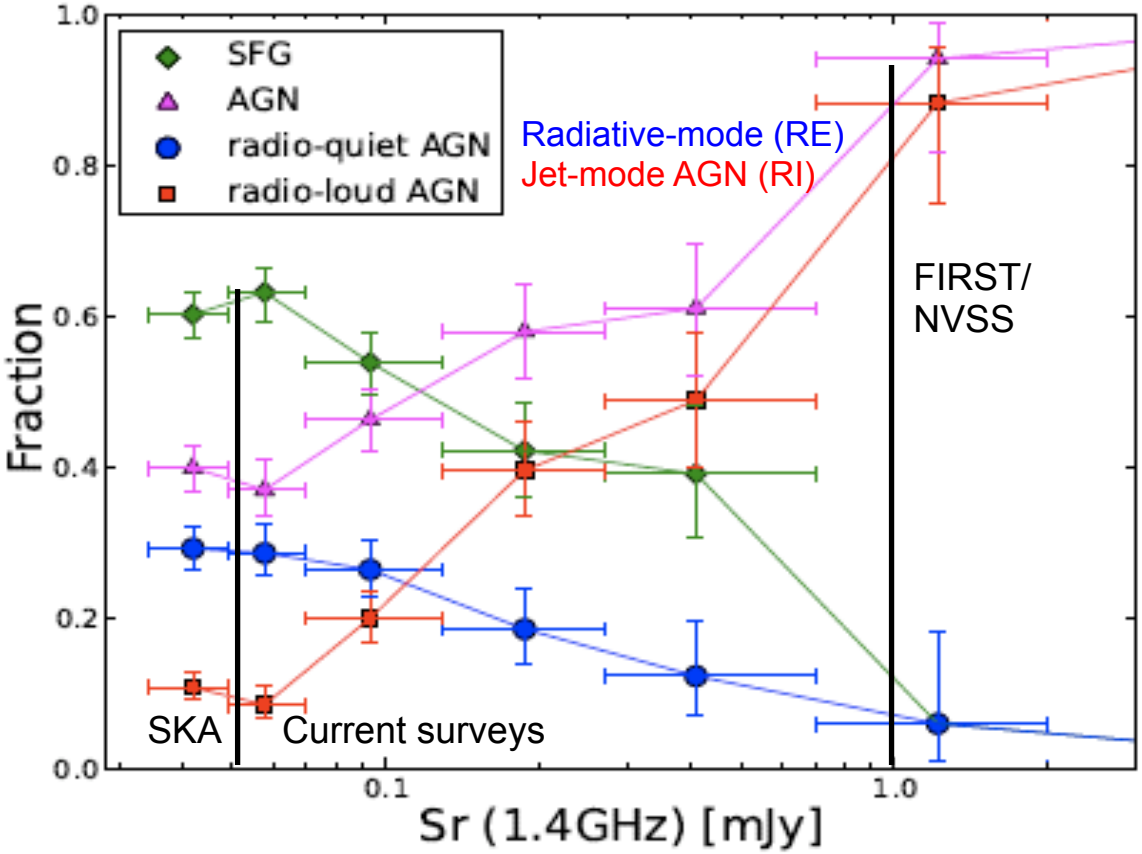


- Overview of preparatory and scientific observing activities
- Increasingly realistic Data Challenges every 6 months

Backup Slides

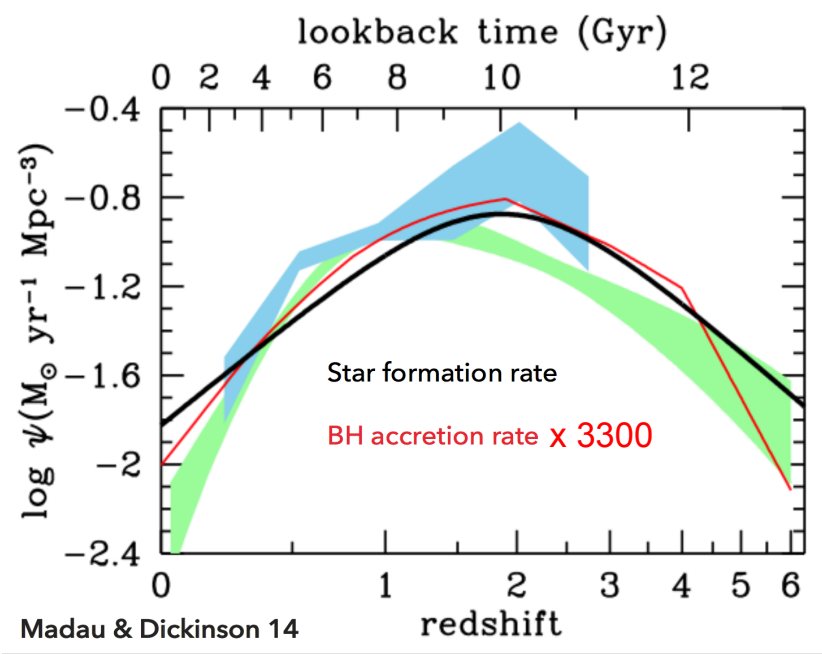
RC surveys: Unbiased census of SF galaxies and *whole* AGN population

ECDFS S>40 uJy (→ 200 uJy @ 150 MHz)
Adapted from Bonzini+2013



- Complete census of SF, AGN activity, up to high-z and down to RQ regime

- Co-evolution of SF AND AGN
- Role of AGN feedback [QSO winds & radio jets]
- not dust extinction/gas obscuration effects

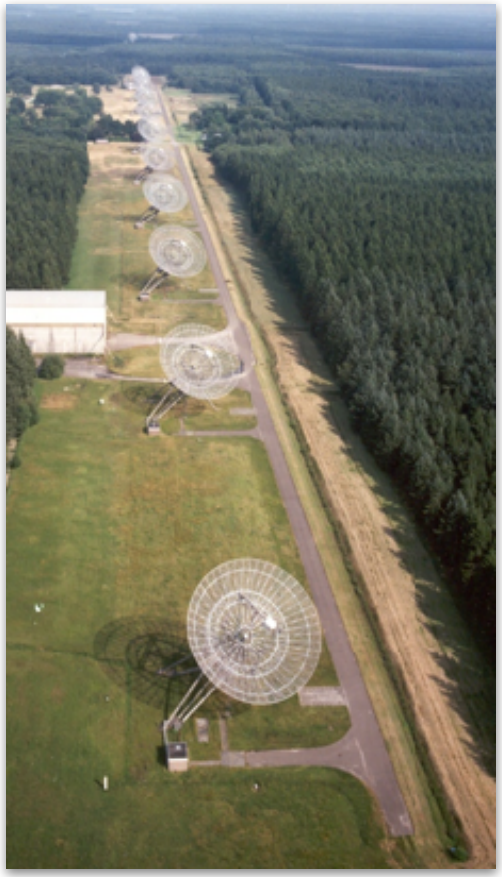


Apertif @ WSRT

- **Apertif** is the first working focal-plane array capable of full Westerbork resolution (~15”x15” beam) over a single, full 8 deg^2 pointing

- Operating in the frequency range 1000-1750 MHz with nearly the sensitivity of the present single-pixel WSRT frontend

- With **Apertif**, the WSRT can image an area on the sky about 25 times the size of the full moon



Courtesy J. Falcon-Barroso

WEAVE LOFAR - MOS

- **WEAVE-LOFAR** will be the **primary source of spectroscopic information for the LOFAR Surveys KSP**

- It will consist of **> 10^6 spectra of radio-selected sources** → multi-parameter analysis (mass, env., redshift, AGN type, SFG type, etc.)

- **We are hunting for redshifts**, so the "low"-resolution grating (R=5000, which provides complete wavelength coverage, 3700-9500 A) is essential

- **High S/N spectroscopy allow robust source classification:**
  - SF vs AGN spectra
  - HEG (Seyfert/QSO) vs LEG (Liners, Early Type)

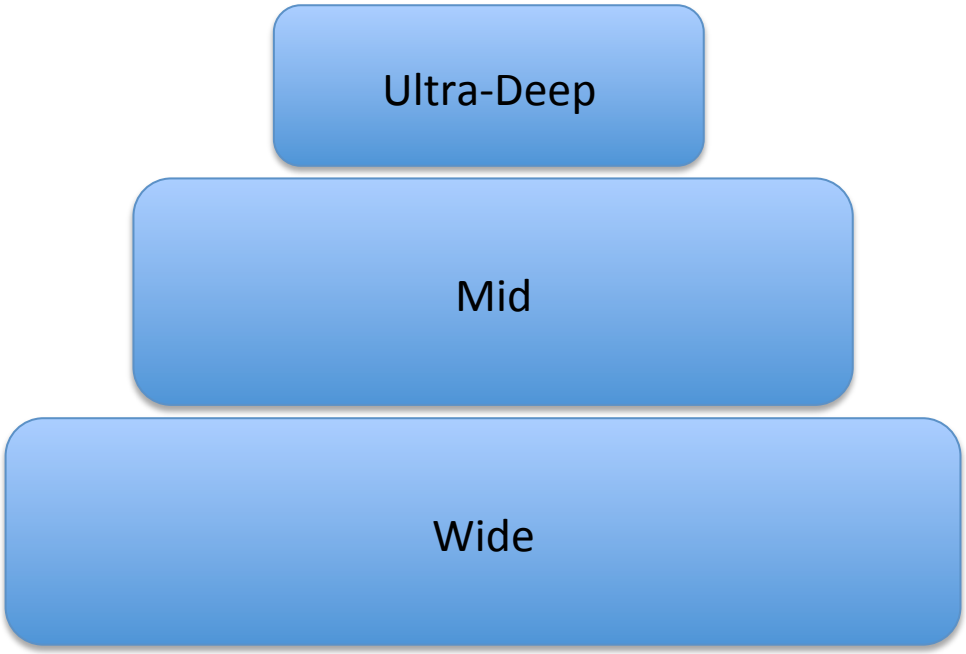
- Spectroscopy also enables ***a lot*** **more science**
  - velocity dispersions
  - metallicities
  - virial mass of BHs
  - etc.

Courtesy D. Smith

WEAVE-LOFAR
Survey Design

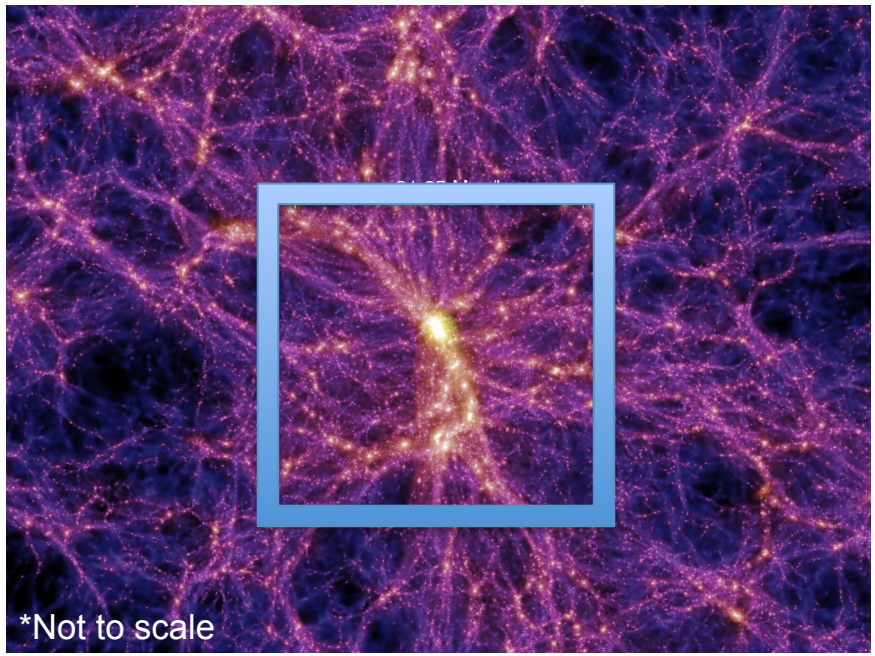
1) **MOS Survey:**

Spectroscopic follow-up of large numbers of LOFAR-selected sources in three tiers, to get *a* complete picture of SF and AGN co-evolution.



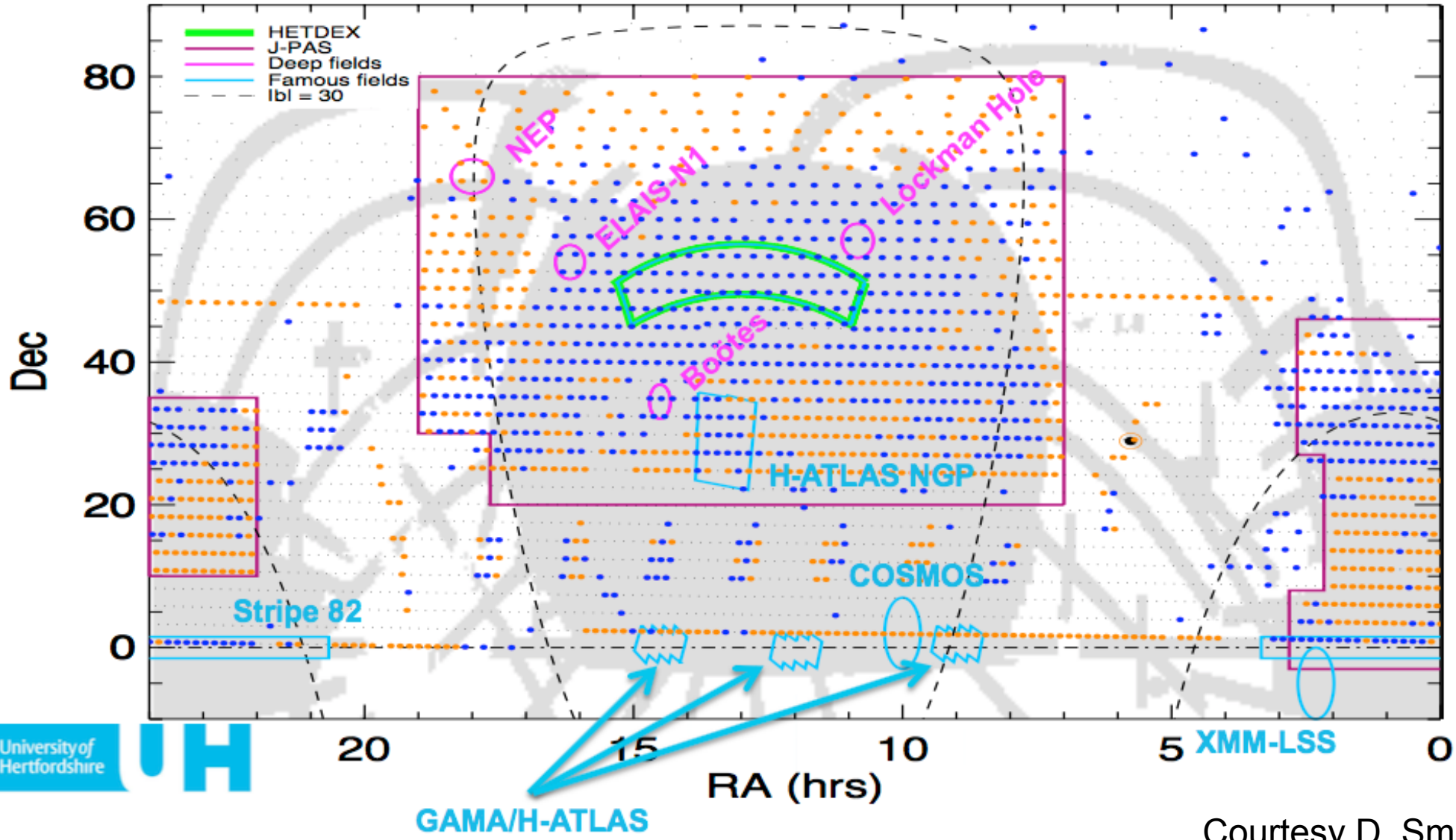
2) **Bad Weather IFU Survey:**

Resolved spectroscopy of large samples of sources of interest, incl. proto-clusters, targets with extended haloes, absorption systems, etc.



Courtesy D. Smith

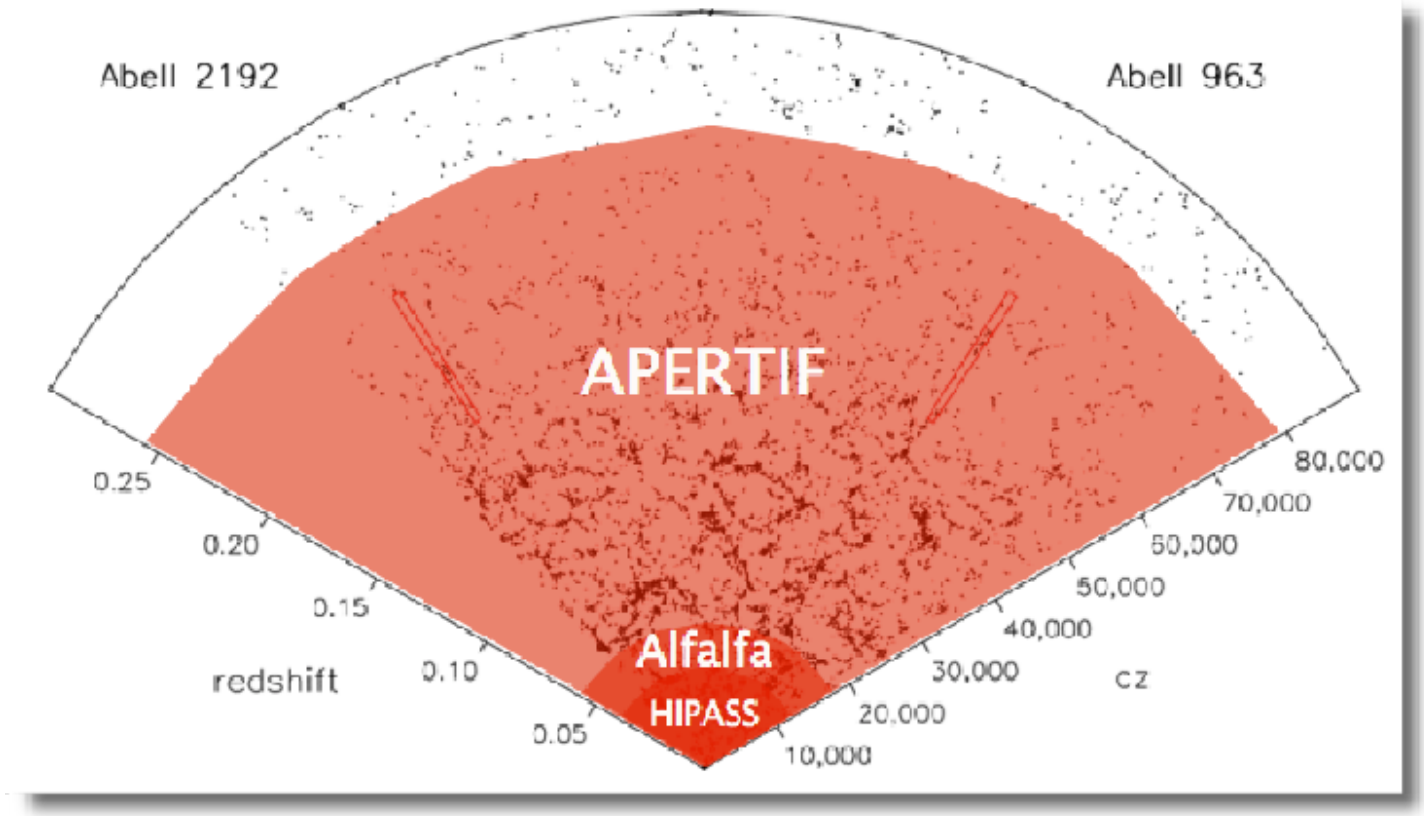
WEAVE-LOFAR Survey Fields
The best regions of every scale



University of Hertfordshire

Courtesy D. Smith

Apertif Footprint



Courtesy J. Falcon-Barroso

Synergy with WEAVE

- Provide a broader astrophysical context for HI detections

- Apertif provides resolved HI observations over a large FoV for many thousands of galaxies

- WEAVE provides the optical component on similar scales with the LIFU mode

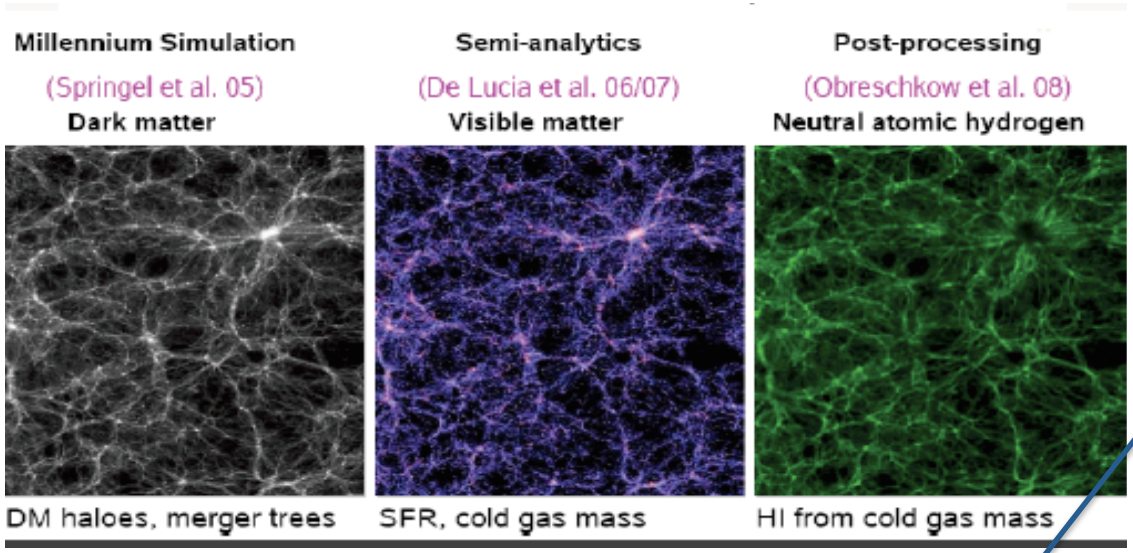
- It allows for a different way to define galaxy samples (based on HI properties and not optical ones)

- WEAVE-Apertif offers a combination of Optical+HI observations not possible with ongoing IFU surveys (e.g. large spatial coverage with high spectral resolution)

WEAVE-Apertif Science

- **Influence of HI accretion histories on spiral disk evolution**
  - Impact of HI accretion on chemo-dynamical properties of galaxies
- **Nature of galaxy bi-modality**
  - origin of gas feeding SF
  - how SF quenches
  - role of environment
- **Disc galaxy mass dissection**
  - dark matter: amount and distribution
  - dependence on environment & stellar mass

HI Surveys: Galaxy Assembly and Baryon Cycle

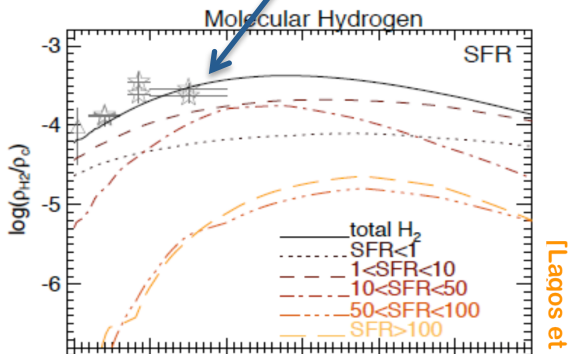


- HI density: weak evolution
- H_2 and SFR density: strong evolution

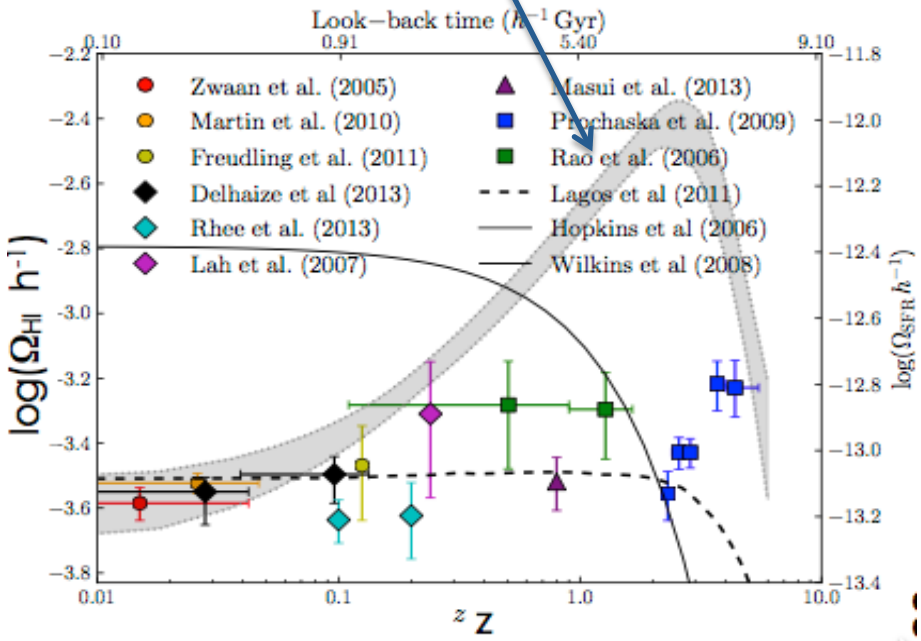
- Gas content and dynamics becoming critical part of simulations
- Blind surveys limited to local Universe
- Stacking (z~0.2) and Damped Lya (z>0.4)

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

- ➢ Precursors will reach z~0.6
- ➢ SKA1 will reach z~1
- ➢ SKA2 will reach z~5



Blyth et al. 2015



SKA – Surveys for Cosmology

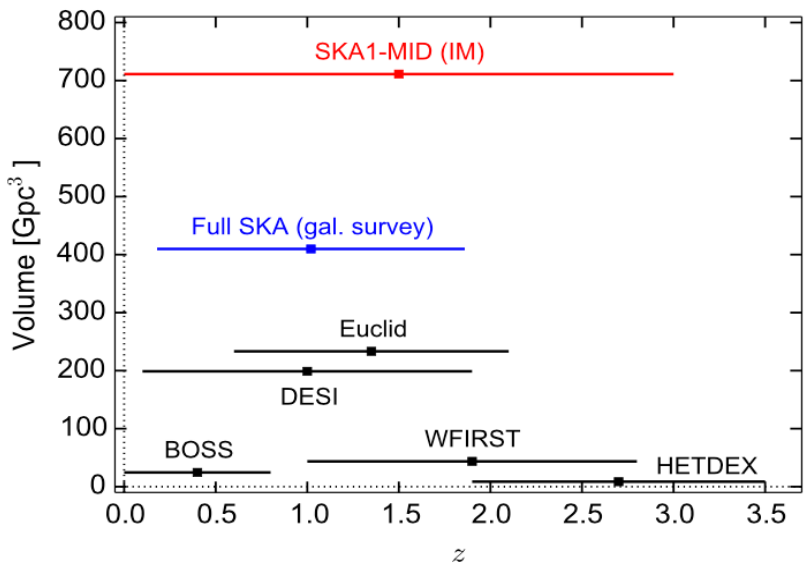
1. **HI Intensity Mapping** [BAO, super-horizon, etc.]
   All-sky (3π sr)**; low-resolution >30'**; 0<z<3

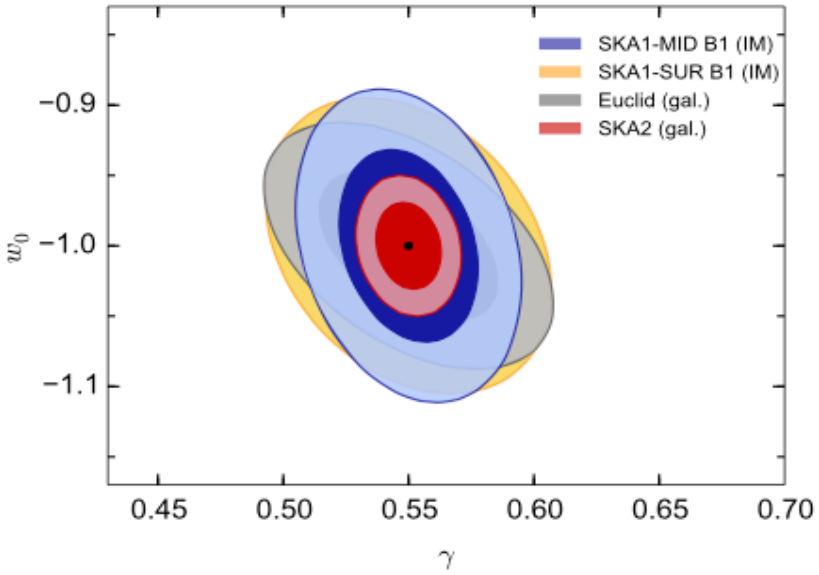
2. **HI Threshold:** galaxy redshift survey [BAO, RSD]
   SKA1: 5 10^6 gals @ z<0.5
   SKA2: ~10^9 gals @ z<2

3. **Continuum** [weak lensing, angular clustering, ISW]:
   - ➔ <u>All-Sky Survey</u> (~ 1-2" res.)
   - ➔ <u>Weak Lensing Survey</u> (0.5" res.):

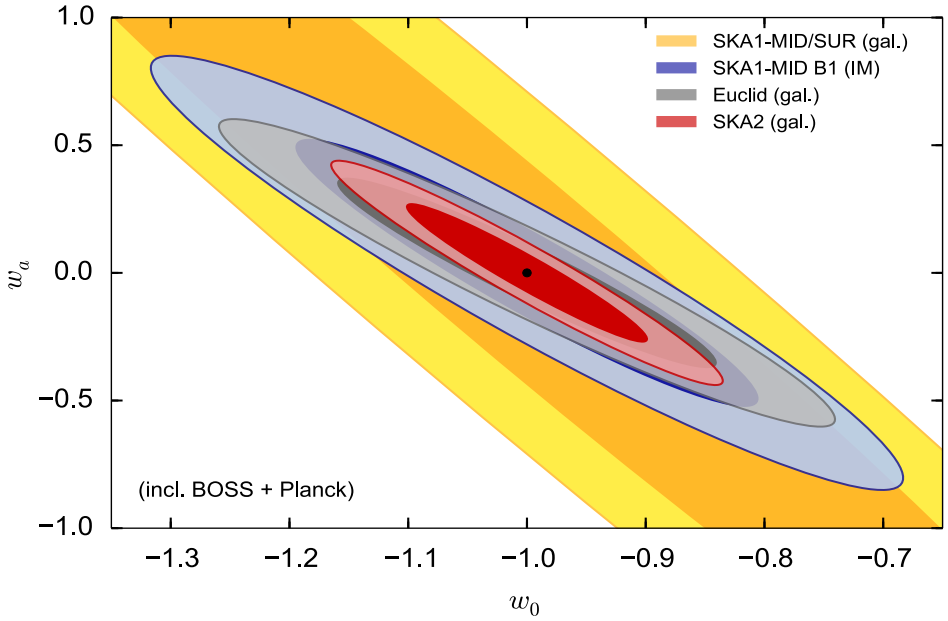
   NB: Commensality with HI/Continuum surveys for galaxy evolution

<u>Euclid + SKA: huge synergies</u>
➔ Scientific: smaller volume higher res. vs large volume low-res, complementary constraints, multi-tracers, etc.
➔ Programmatics: e.g. simulations, likelihood definitions and coding, etc.

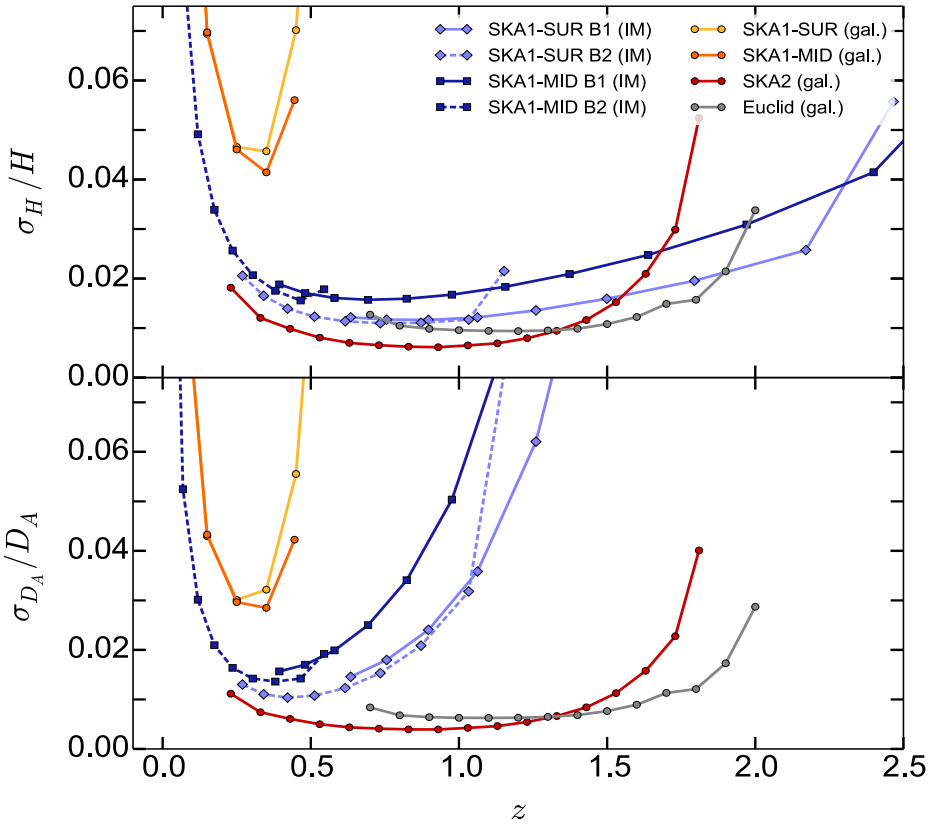




Cosmology with SKA: Baryon Acoustic Oscillations



(Bull et al 2014)



- Constraining Dark Energy models with redshift-resolved BAO measurements
  - Discrete detection is complementary with SKA1, cutting edge with SKA2
  - Intensity mapping is higher risk but world-class, even with SKA1

SKA – Surveys for Cosmology

1. **HI Intensity Mapping** [BAO, oscillations on super-horizon scales, etc.]
   - SKA1 (Auto-corr): All-sky (3π sr); ang. scales >30'; 0<z<3
   - SKA2 (Interferometry): similar, but optimized for high-z (z>1.5)

   SKA1 already competitive wrt Euclid
2. **HI threshold:** galaxy redshift survey [BAO, RSD, etc.]
   - SKA1: pilot [5000 deg^2, 5 10^6 gals w z<0.5];
   - SKA2: Billion Galaxy Survey [All-sky (3π sr), 9 10^8 gal with 0<z<2]

   SKA1 already competitive wrt Euclid at low redshift
3. **Continuum** [Weak Lensing, Power Spectrum, ISW Effect, Magnification Bias, etc.]:
   a. All-Sky Survey (~ 1-2" res.): [PS, ISW, MB, etc.]
      - SKA1: few μJy rms all sky + deeper tiers; SKA2: 1 μJy rms for all-sky

   b. Weak Lensing Survey (0.5" res.):
   - SKA1: pilot [5000 deg2, 10 gals/arcmin^2]
   - SKA2: All sky [3π sr, 75 gals/arcmin^2]

   Euclid + SKA → beat systematics and provide better constraints

NB: Commensality with SKA HI/Continuum surveys for galaxy evolution

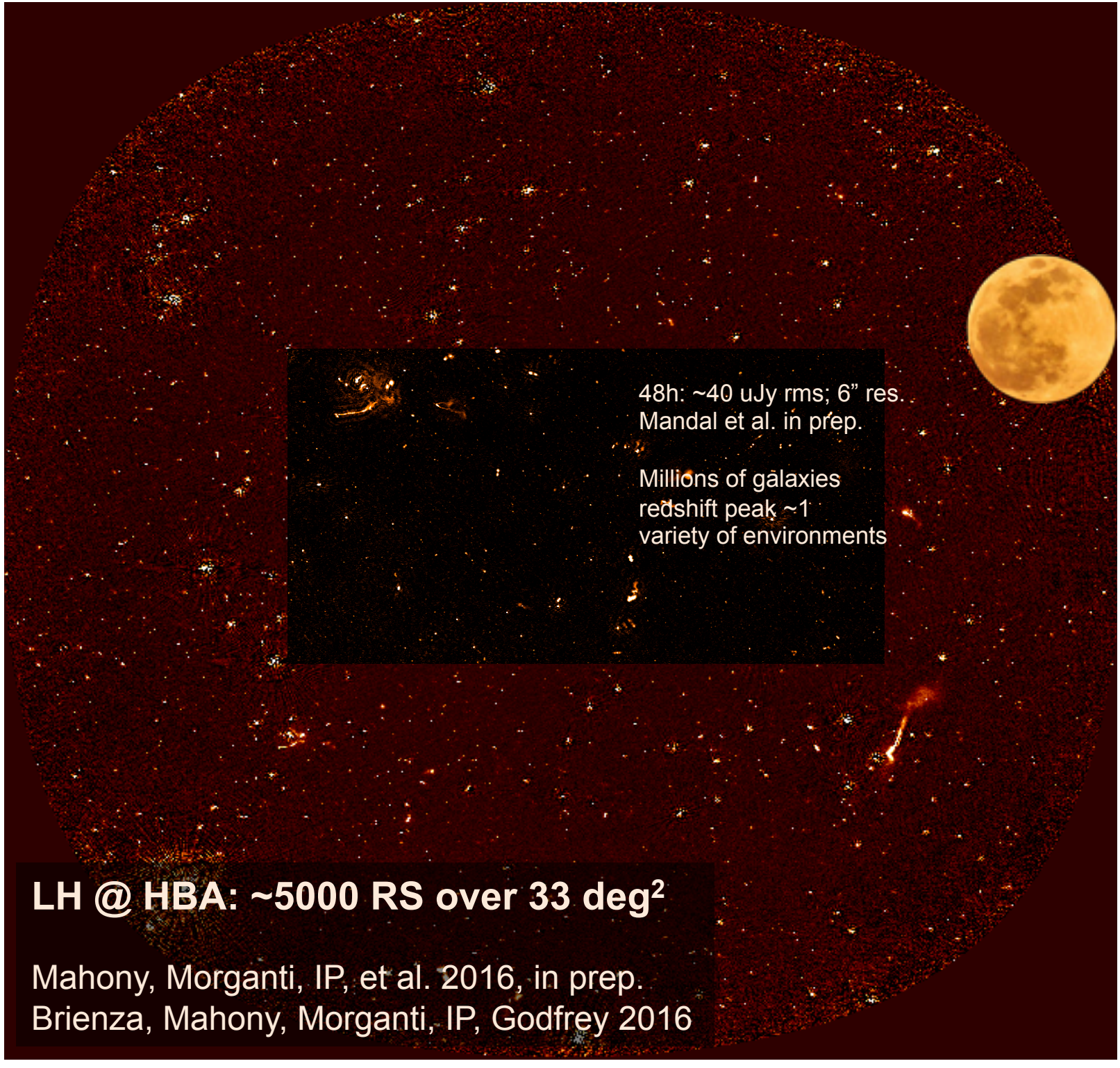
The (radio) pathway to SKA

Radio Surveys (relevant for Cosmology) planned for Pathfinders/ Precursors:

1. HI Intensity Mapping
   - Precursors: BINGO (Single Dish, South America); CHIME (Array, Canada); MeerKAT & ASKAP Autocorrelation (Single Dish mode)
2. HI threshold: galaxy redshift survey
   - ASKAP: WALLABY (all-sky, $z<0.25$), DINGO ($z_{med}<0.4$; 60/150 deg^2)
   - MeerKAT: LADUMA (1 pointing, $z>1$)
3. Continuum
   a. All-Sky Survey:
      - LOFAR; ASKAP (EMU);
      - JVLA (VLASS?)
      - MeerKAT (MIGHTEE, tiered strategy: wide/deep)
   b. Weak Lensing Continuum Survey (0.5” res. or better):
      - e-MERLIN (eMERGE; SuperCLASS)
      - JVLA (VLASS?)

Why LOFAR Surveys?

- Large FoV:
  >30 deg2 @ HBA
- Sensitivity:
  10h @ HBA
  →100 uJy rms
  [EMU: 10 uJy @1.4 GHz]
- Resolution:
  NL → 5” @ HBA
  ILT → 0.5” @ HBA
  [~100 pc scale @z~0
  few kpc scale @ z>1]
- New spectral window (+ Surface Brightness)
  → low-E e^- population



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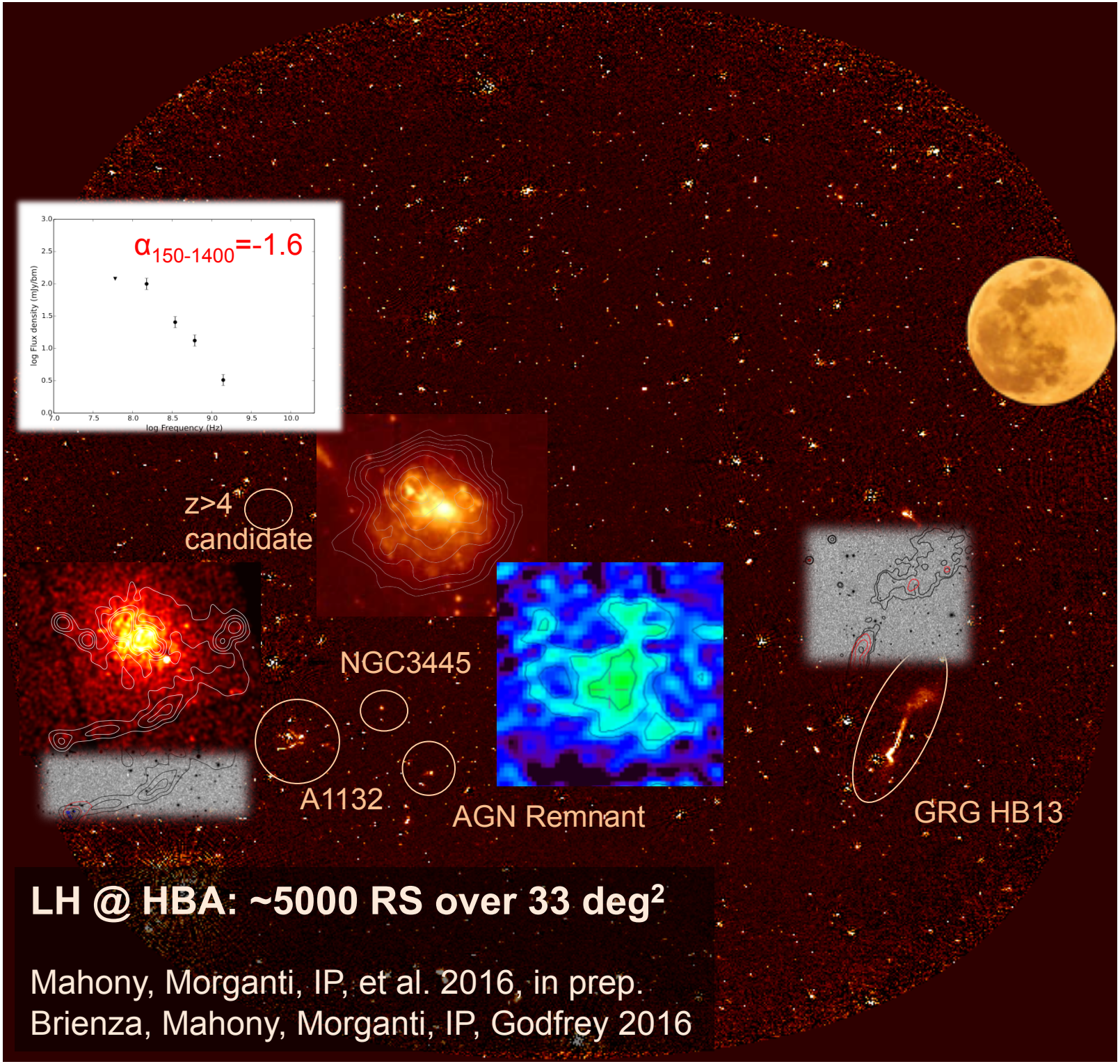
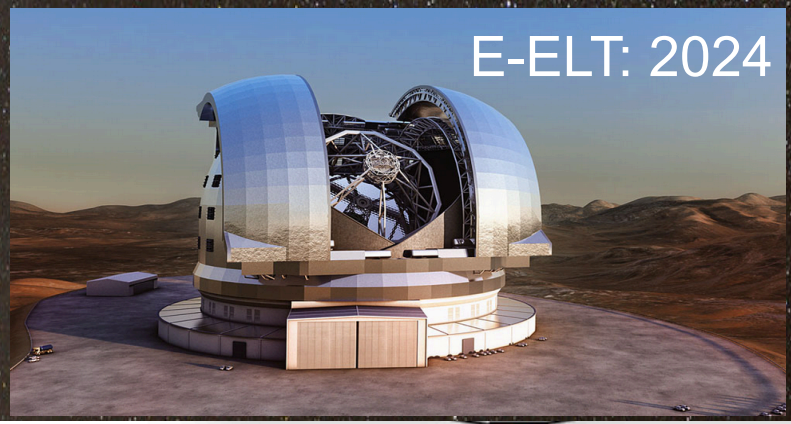
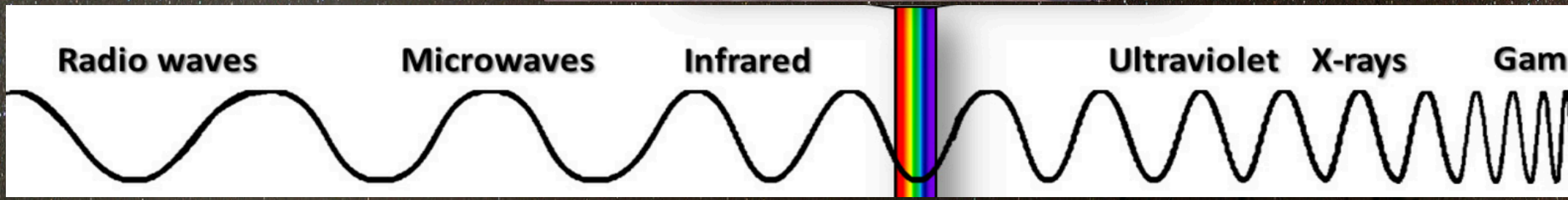


21st Century Observatories



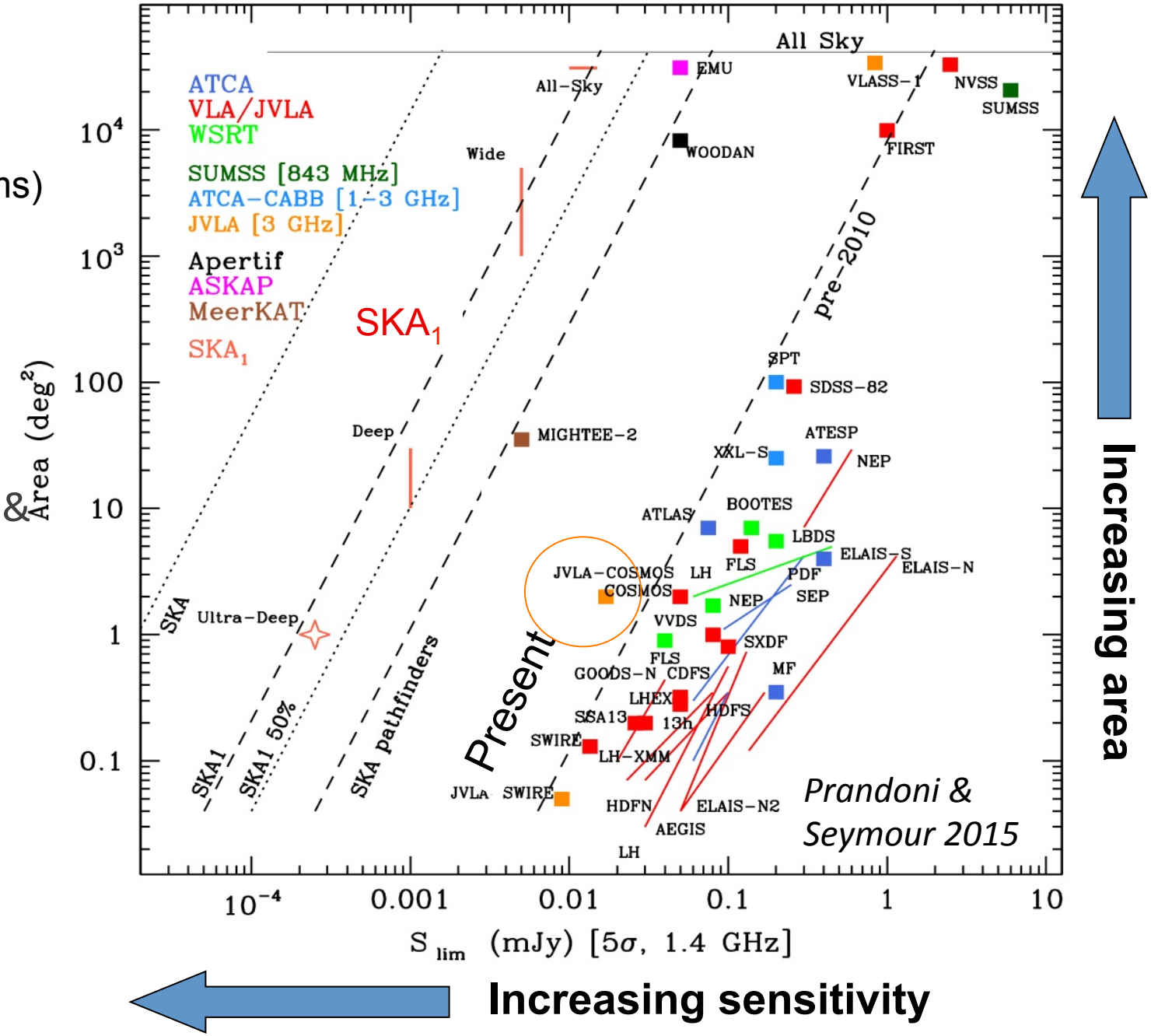


Next Generation RC Surveys

1-3 GHz surveys

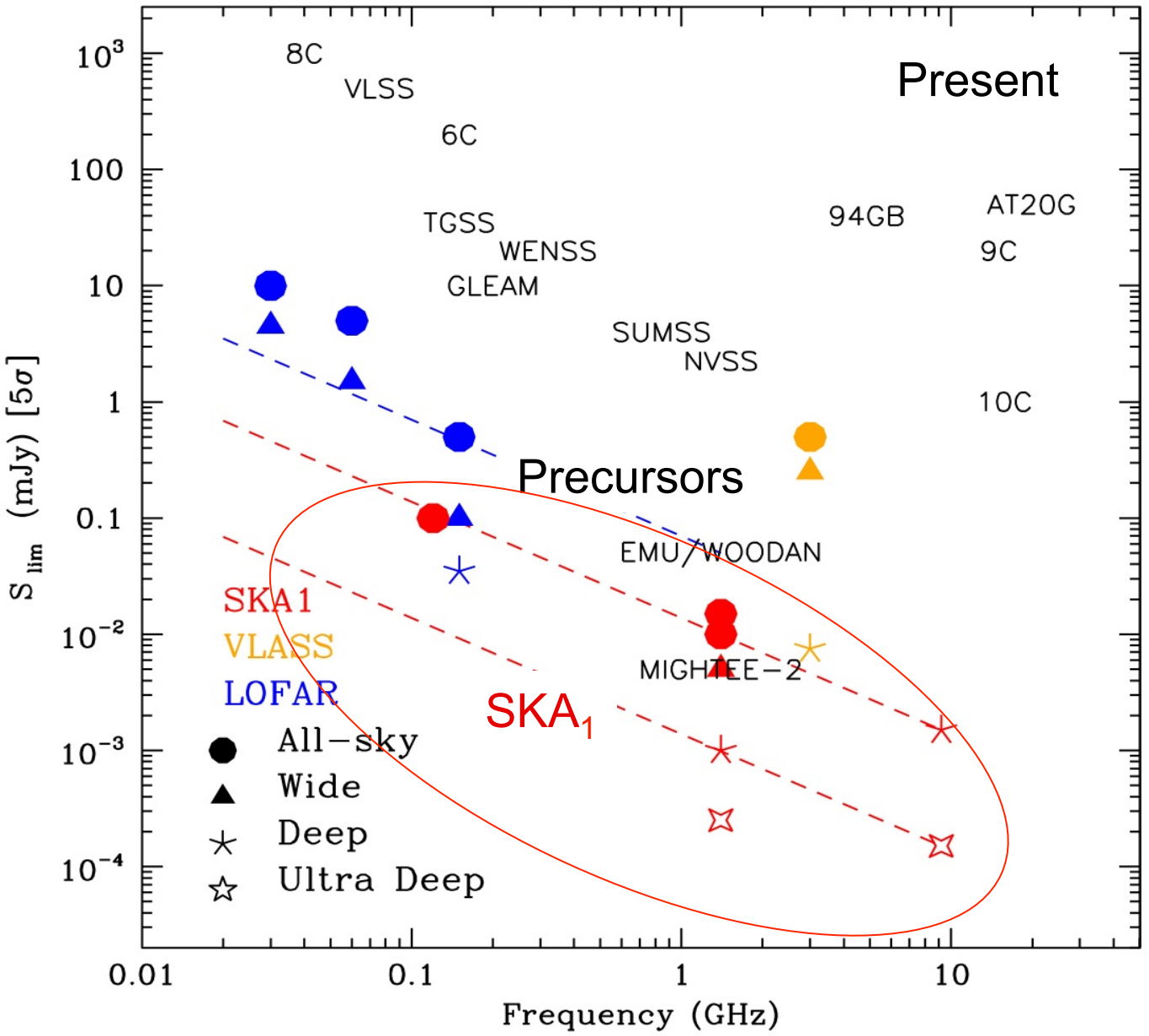
- RC surveys will probe from few sq. deg. (at sub-uJy rms) to all-sky (at uJy rms)
  ➔ representative volumes at all redshifts

- source demographics & evolution at matched res. & depth



Next Generation Radio-continuum Surveys

Multi-frequency surveys will probe from synchrotron to thermal process, including redshifted HI emission up to EoR



Increasing sensitivity

Decreasing frequency

.....but have a taste now!