

# Galaxy Evolution with SKA Precursors & Pathfinders

Isabella Prandoni

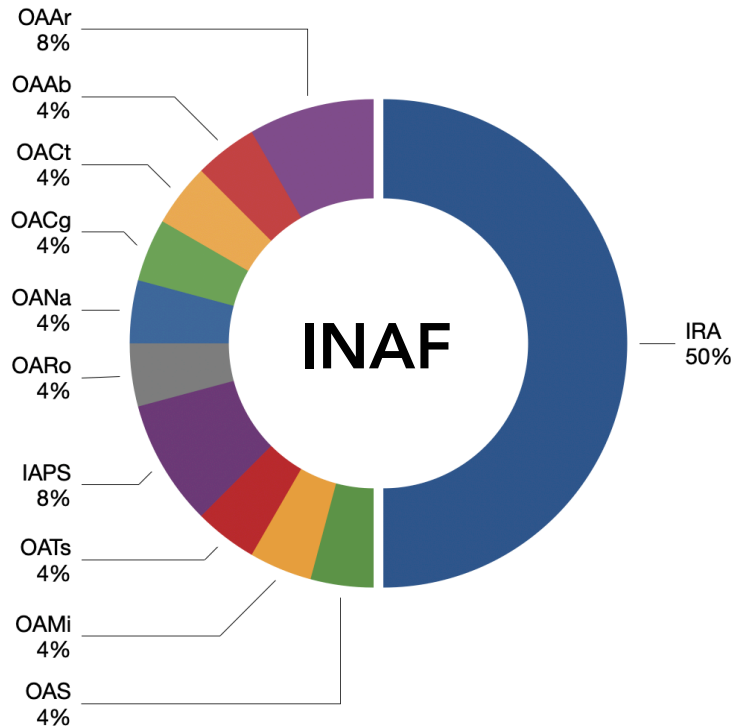
in collaboration with the SKA\_Galev Team



# Team

	INAF	Associati
TI	21	4
non-TI	3	9
All	24	13

**OAS**  
**Gilli**  
**OAMi**  
**Delvecchio**  
**IAPS**  
 Magliocchetti  
**Panessa**  
**OACg**  
 Maccagni  
**OANa**  
 Napolitano  
**OARo**  
 Pentericci  
**OAAr**  
**Hunt**  
**Tozzi**  
**OATs**  
**De Lucia**  
**OACt**  
 Antonuccio  
**OAAb**  
 Raimondo



**IRA**  
 Prandoni  
 Baldi  
 Bondi  
 Bonato  
 Guidetti  
 Liuzzo  
 Massardi  
 Paladino  
 Casasola  
 Burigana  
 Mack  
 Zanichelli

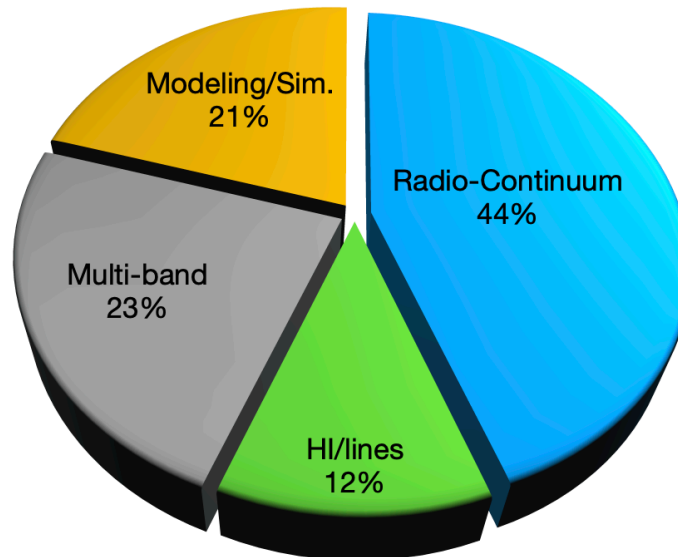
## ASSOCIATI

**UniBo**  
 Brienza  
 Bruno  
 D'Amato  
 Gitti  
 Vignali  
**SISSA**  
 Lapi  
**UniTs**  
 Pannella  
**UniModena/RE**  
 Rivi  
**UWC**  
 Vaccari  
**UCT**  
 Marchetti  
**IRA**  
 Giovannini  
 Gregorini  
**OAS**  
 Zamorani

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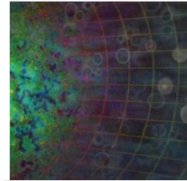
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# The Pathway to the SKA

SKA0 PROSPECTUS 2020

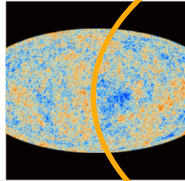
SKA0 PROSPECTUS 2020

## Science Drivers



### Cosmic Dawn and the epoch of reionisation

**WHERE DID IT ALL BEGIN?**  
HOW AND WHEN DID THE FIRST STARS, GALAXIES AND BLACK HOLES FORM?  
The SKA will uniquely enable the measurement of a complete time sequence



### Cosmology and dark energy

**CAN WE UNCOVER THE MYSTERIOUS NATURE OF DARK ENERGY?**  
HOW AND WHY HAS IT BECOME THE MAJOR PLAYER IN OUR UNIVERSE?  
The SKA will fundamentally advance our understanding of the mysterious dark

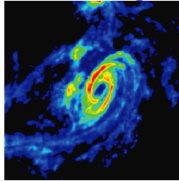
## RC surveys



### Forming stars through cosmic time

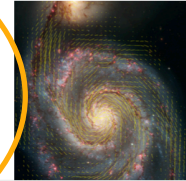
**HOW AND WHEN WERE THE FIRST STARS BORN?**  
HOW HAS THE RATE OF STAR FORMATION CHANGED OVER TIME, AND WHY?  
There is evidence that star formation

## HI surveys



### Galaxy evolution

**WHAT IS THE LIFE-CYCLE OF A GALAXY?**  
WHERE DO THEY COME FROM, WHERE DO THEY GO?  
WHAT ARE THE PROPERTIES OF THE MYSTERIOUS DARK ENERGY?



### Cosmic magnetism

**HOW DID THE UNIVERSE BECOME MAGNETIC?**  
WHERE AND WHEN DID MAGNETISM ORIGINATE?  
HOW HAS IT EVOLVED?



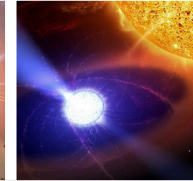
### The bursting sky

**WHAT ARE THE COUNTERPARTS OF THE FAST AND FURIOUS BURSTS OF RADIO WAVES?**  
WHAT CAN THEY TELL US ABOUT THE CONSTITUENTS OF THE UNIVERSE?



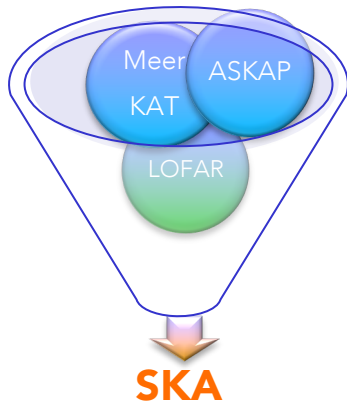
### The cradle of life

**HOW DO YOU MAKE A PLANET FROM SPACE PEBBLES?**  
ARE WE ALONE IN THE UNIVERSE?  
The SKA will have sufficient resolution to watch the assembly of planets in Earth-like orbits about their parent stars.



### Challenging Einstein: gravitational waves

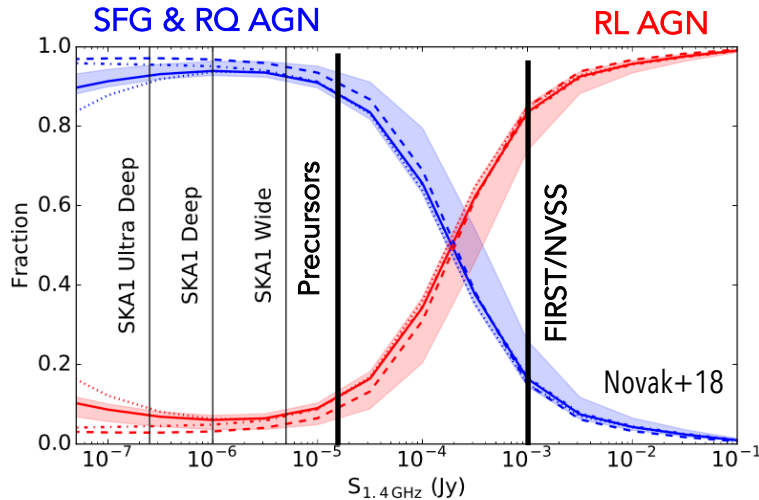
**WAS EINSTEIN RIGHT ABOUT GRAVITY?**  
CAN WE FIND AND UNDERSTAND WHERE GRAVITATIONAL WAVES COME FROM?  
The SKA will use our entire galaxy to



- **Exploit SKA precursors/pathfinders in preparation to the SKA**
  - Definition of SKA Key Science Projects (KSP)
  - Development new data analysis skills
  - Formation of international KSP teams and leaderships
- **High level Project Goals:**
  - Maintain and possibly increase scientific visibility of Italian community
  - Build over the years national teams able to get leadership roles in SKA KSPs

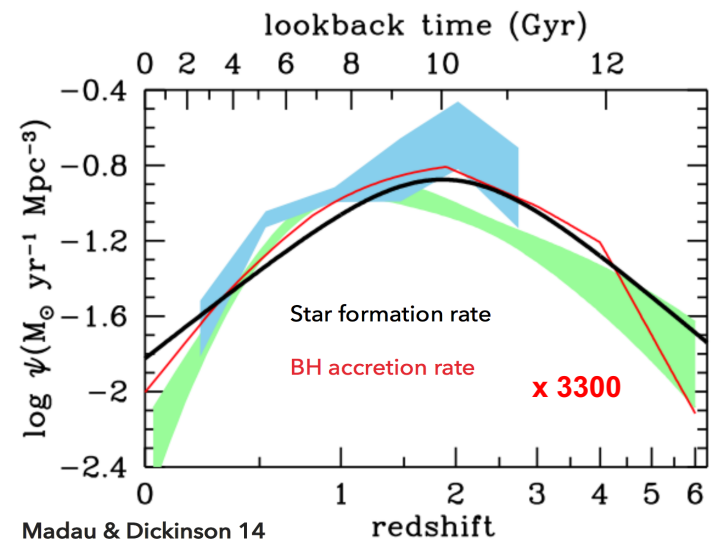


# The promise of next-generation radio surveys

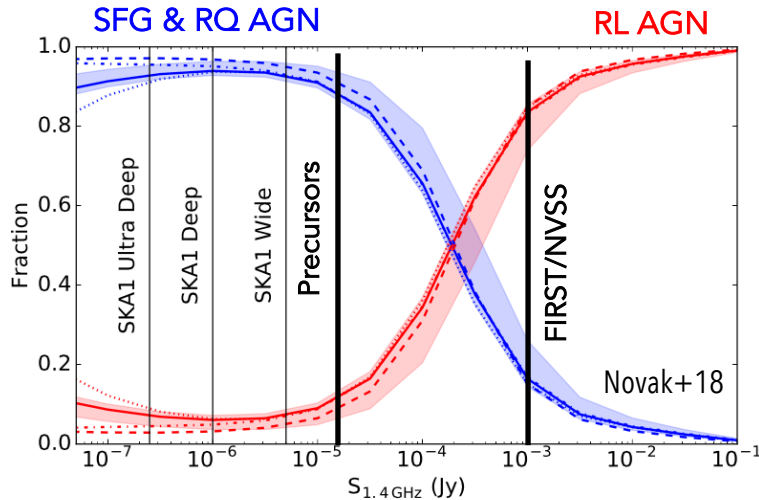


- Co-evolution of SF AND AGN
- Role of AGN feedback [radio jets]
- resolved studies → physics/interplay of SF/AGN

- Complete census of SF, AGN activity, up to high-z and down to RQ regime
- not dust extinction/gas obscuration effects
- long bs → high spatial resolution



# The promise of next-generation radio surveys

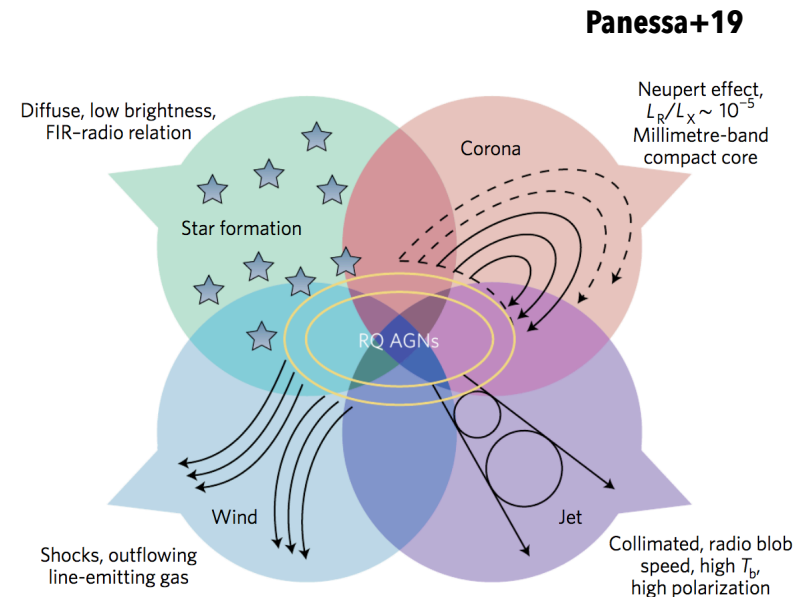


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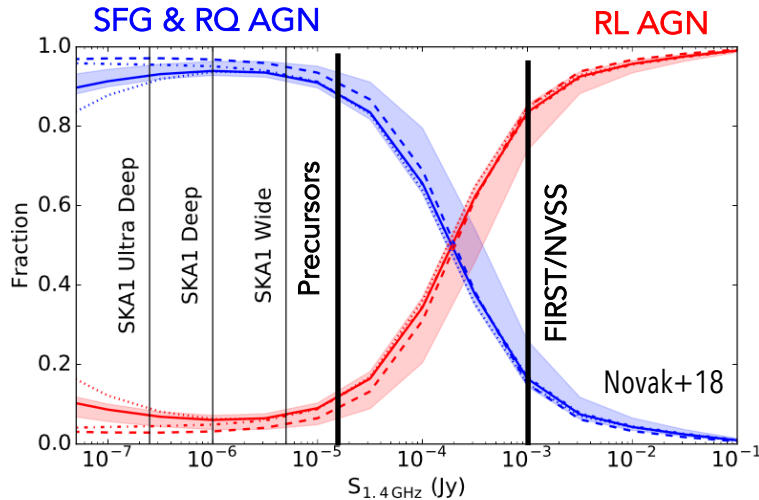
Physics of radio emission:

- radio duty cycles/feedback physics
- RQ/RL dichotomy;
- Origin of radio emission in RQ AGN

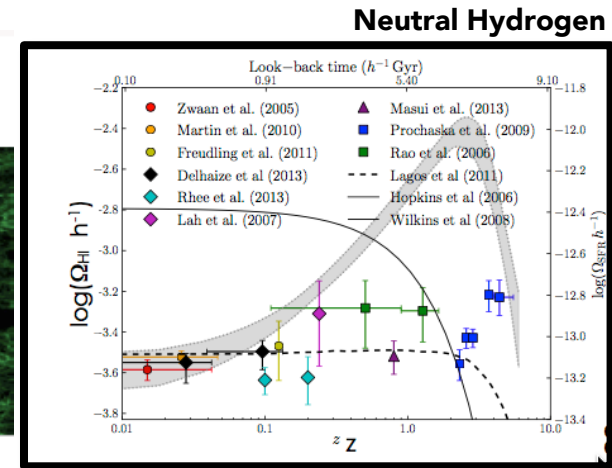
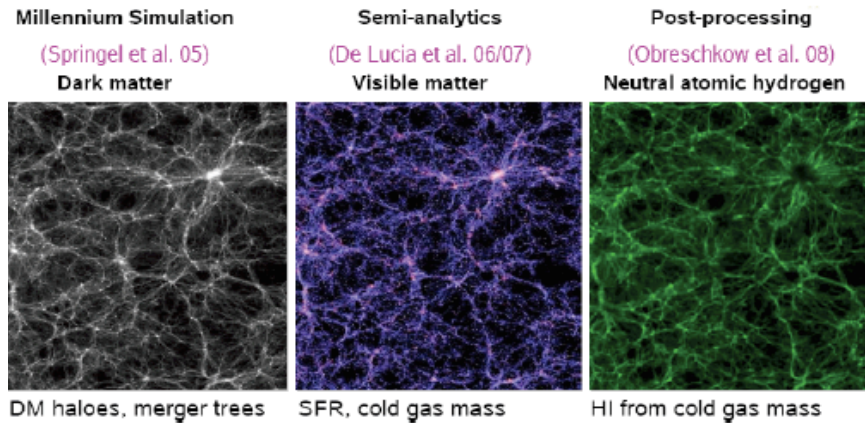
Scheda INAF 'TORQUA'



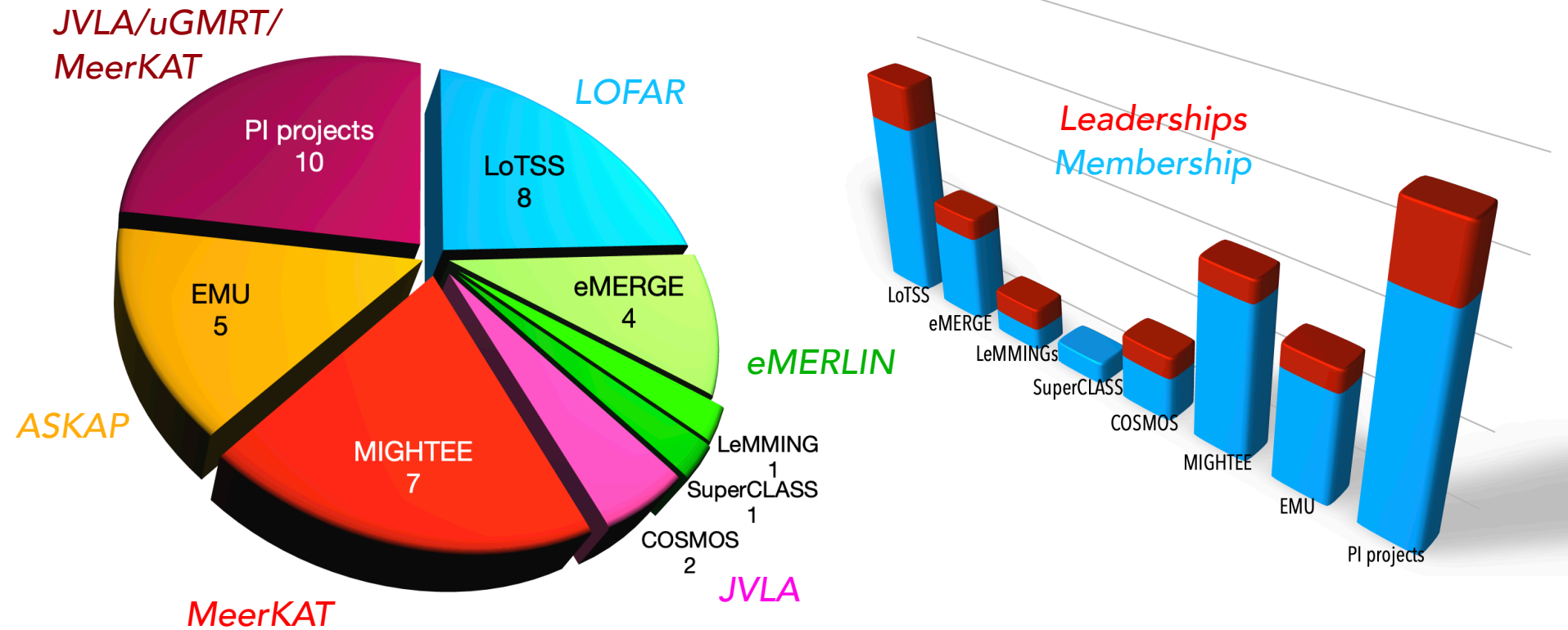
# The promise of next-generation radio surveys



- Simultaneous information on RC and HI line emission
- HI surveys over cosmic time needed to test predictions and understand galaxy formation
- RC+HI:
  - ❖ HI accretion  $\rightarrow$   $\text{H}_2 \rightarrow$  SF cycle
  - ❖ AGN fueling/feedback process & link with radio AGN duty cycle



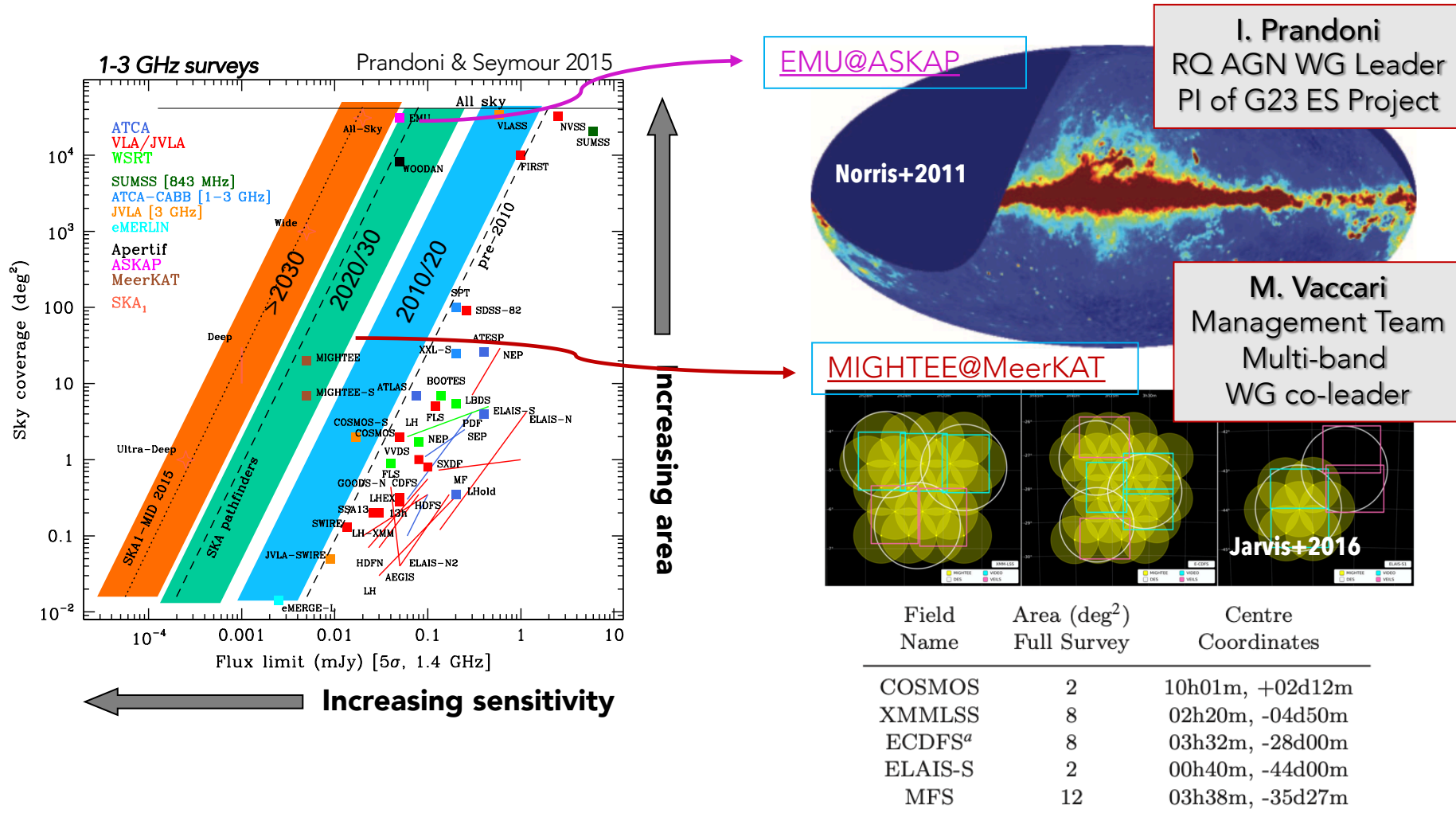
# Survey Membership & Leadership



## Modeling Expertise/Leaderships:

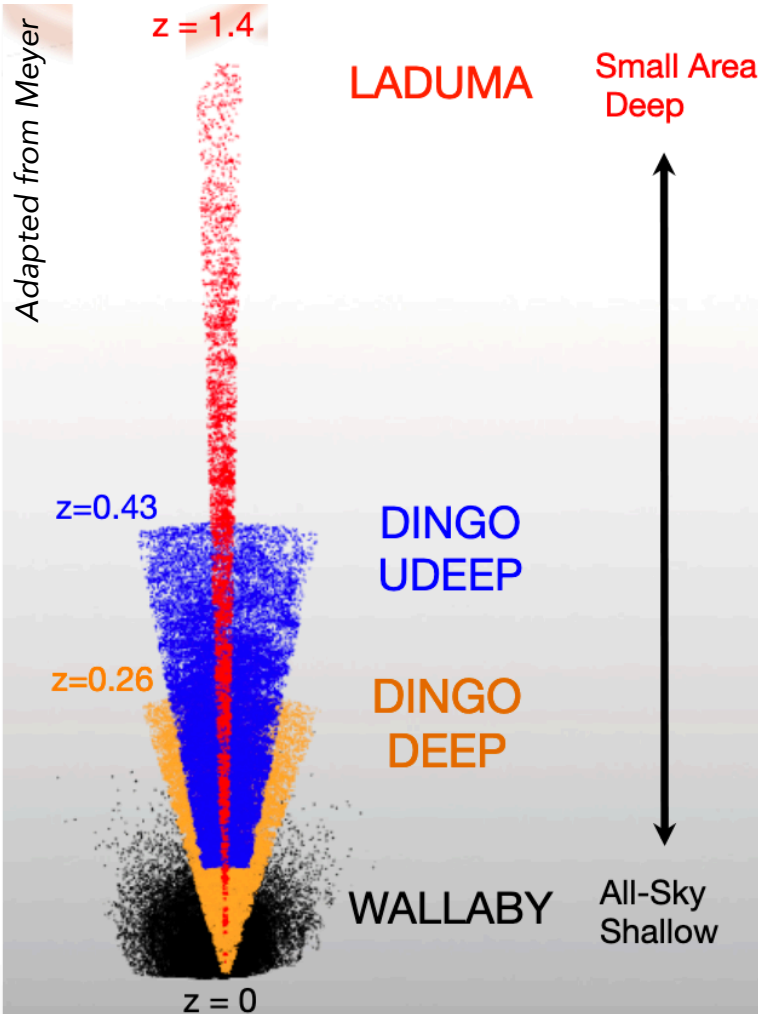
- L. Hunt (BaryonicCycling) – Baryonic Cycle / Scaling relations
- G. De Lucia (GAEA) – galaxy formation and evolution - HI simulations
- A. Lapi – galaxy formation and evolution – RC modeling

# Pre-SKA Legacy Surveys



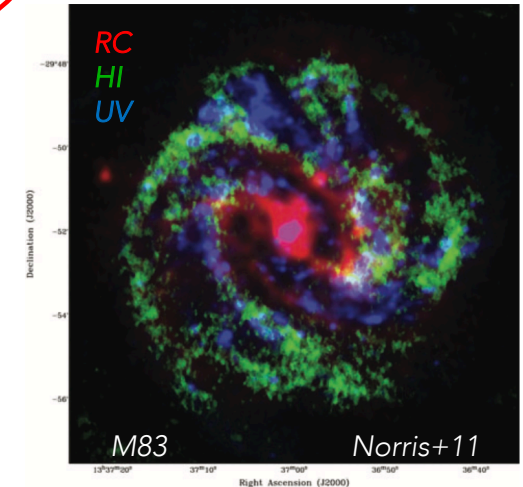
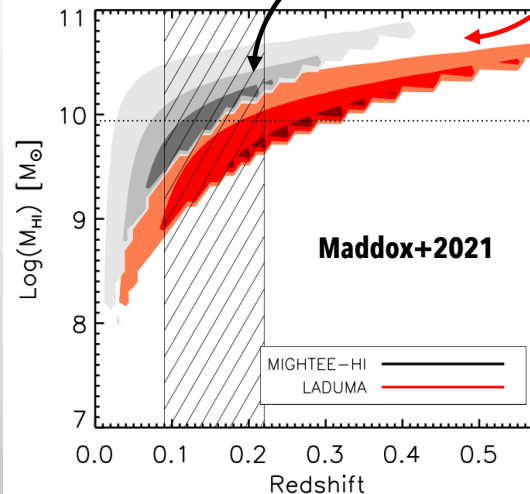


# HI & RC Surveys Working Together



- Availability of overlapping HI and RC surveys (e.g. **Wallaby/DINGO/EMU; MIGHTEE/LADUMA**)

→ Combined surveys / Single datasets can serve multiple science cases and allow scientific synergies to be exploited

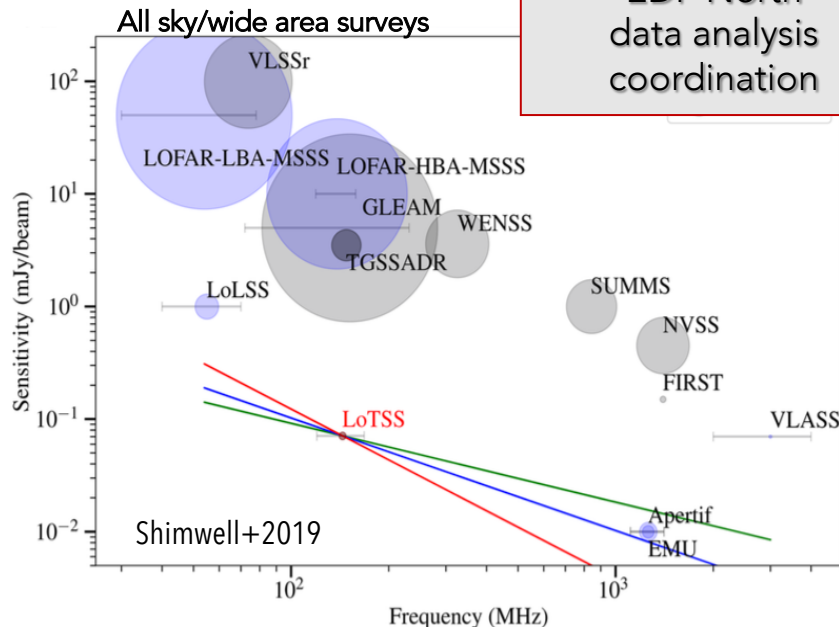
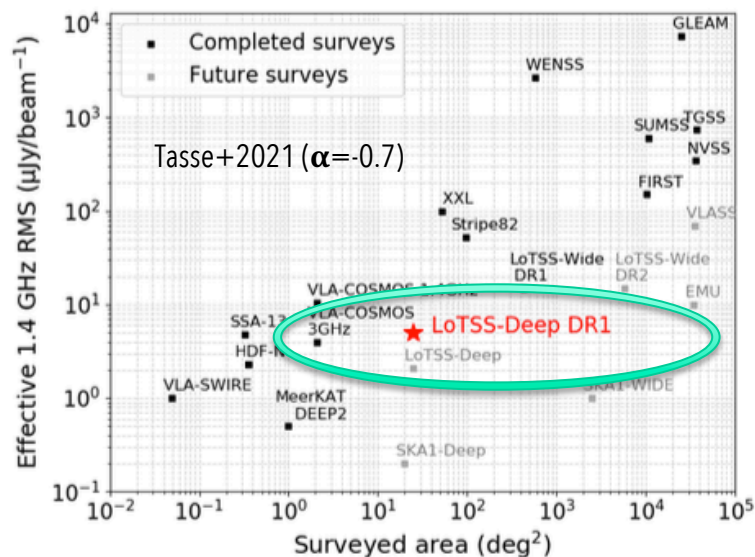


# LOFAR Two-Metre Sky Survey (LoTSS)

I. Prandoni  
Deep Fields  
core team member

M. Bondi  
EDF North  
data analysis  
coordination

- LoTSS: All-sky  $\delta > 0^\circ$  at 150 MHz  
100  $\mu\text{Jy}/\text{b}$  rms @ 6" res. (8hr / pointing)
- LoTSS-Deep:  $\sim 500\text{h}$  / pointing  $\rightarrow$  10  $\mu\text{Jy}/\text{b}$  rms  
Several 'famous' extragalactic fields targeted,  
incl. equatorial fields (COSMOS, XMM-LSS)



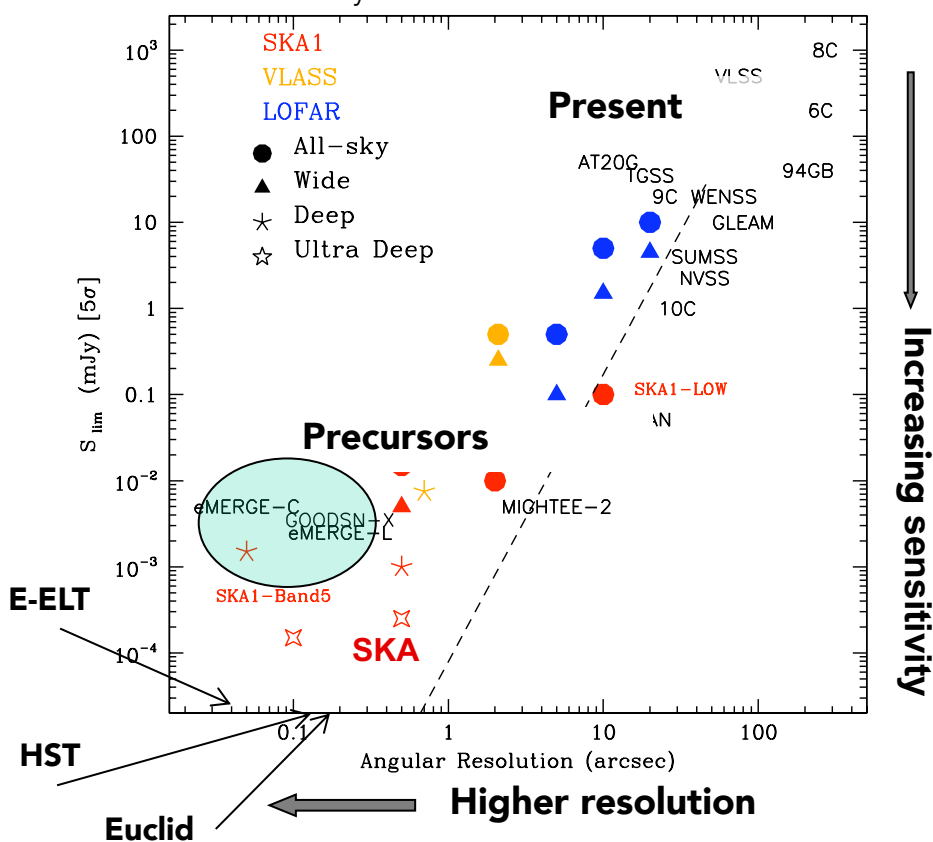
- DR1 All Sky (424 deg<sup>2</sup>): **A&A Special issue (2019)**
- DR1 Deep : Focus on 3 fields at high decl.:
  - ELAIS-N1 ( $\delta > +55^\circ$ ): 164 hrs,  $\sigma_c \sim 17$   $\mu\text{Jy}/\text{b}$
  - Lockman ( $\delta > +58^\circ$ ): 112 hrs,  $\sigma_c \sim 22$   $\mu\text{Jy}/\text{b}$
  - Bootes ( $\delta > +34^\circ$ ): 80 hrs,  $\sigma_c \sim 32$   $\mu\text{Jy}/\text{b}$

**A&A Special Issue (April 2021)**

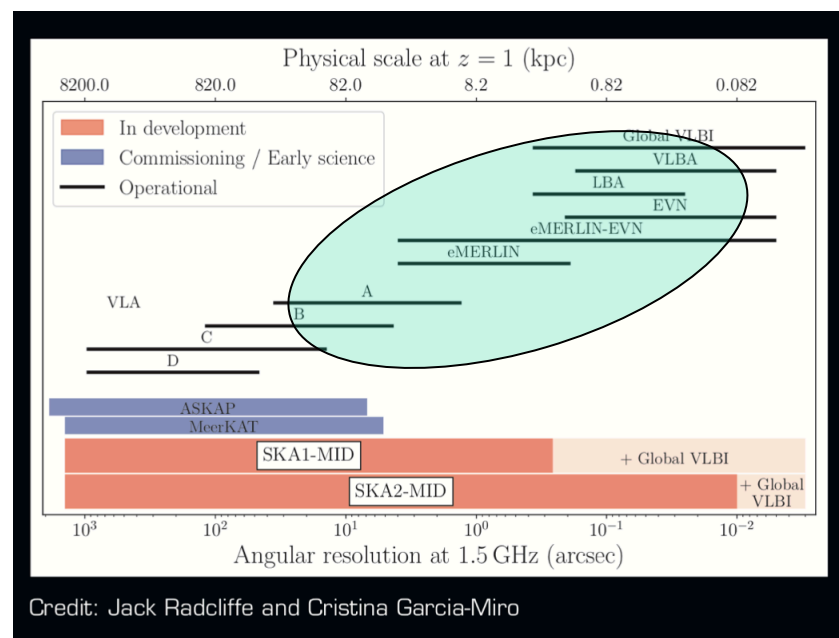
See also Scheda INAF 'LOFAR-It' PI: Brunetti

# High-resolution radio surveys

Prandoni & Seymour 2015



## A resolved view of the radio Universe



Pilots experiments with  
JVLA+eMERLIN + VLBI follow-ups

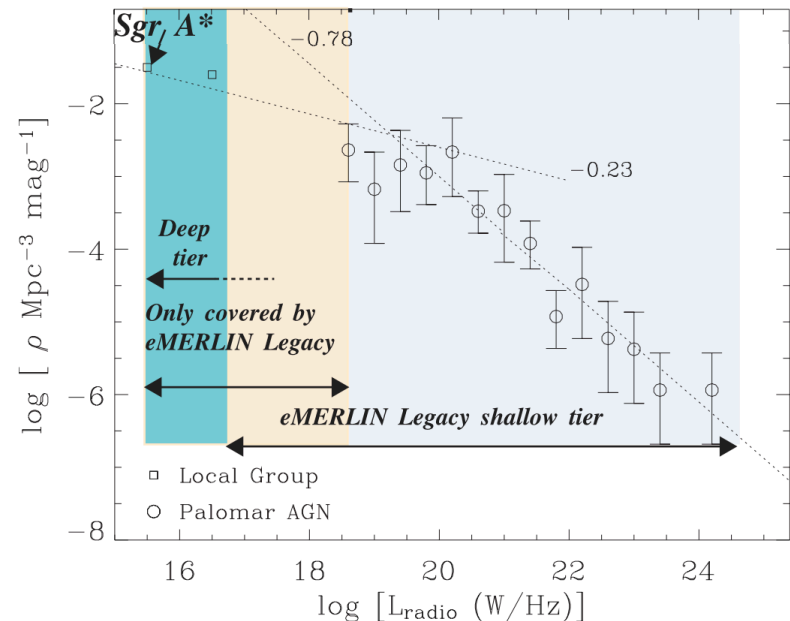
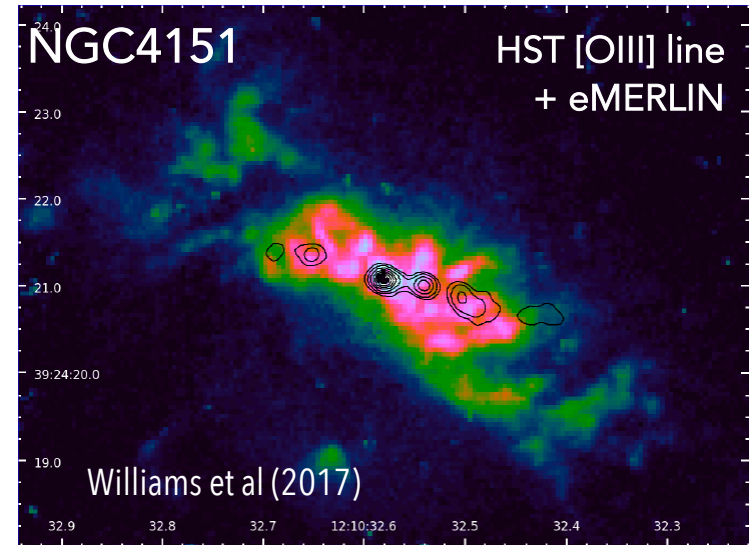
# LeMMINGs: Resolving the Local Universe



## Legacy e-MERLIN Multi-band Imaging of Nearby Galaxies survey

R. Baldi  
Survey Coordination

- Observations of Palomar active and inactive galaxies (<110 Mpc) at 1.5 GHz (**Baldi et al 2018, 2021**) and 5 GHz (in calibration):
  - Reaching angular resolutions of 150 mas and 50 mas respectively
  - Reaching sensitivities of 50-80  $\mu\text{Jy}/\text{beam}$
- Aims:
  - Studying low-luminosity AGN at the low end of the radio luminosity function ( $< 10^{18} \text{ W Hz}$ )
  - Star formation and Supernova remnants in local galaxies
- Two tiers: deep and shallow tier observations
- Multi-band study: complete Chandra and HST data to study the origin of the nuclear emission in local galaxies
- **Scheda INAF 'The origin of the radio emission in radio-quiet AGN' – TORQUA PI: Panessa**



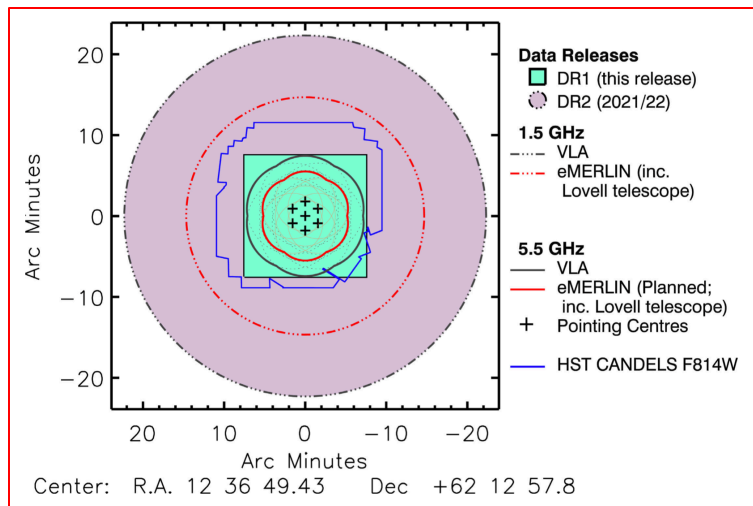
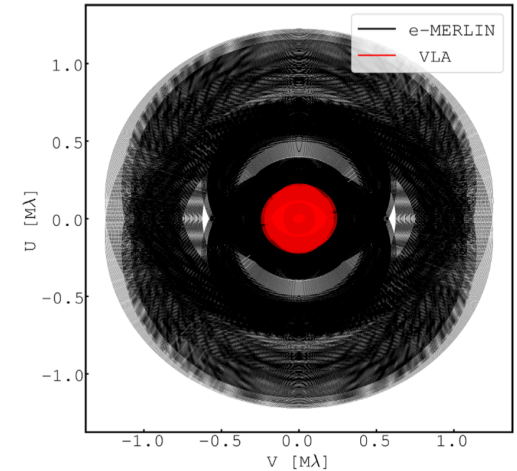
# eMERGE: Resolving the high-z Universe

I. Prandoni  
Management team  
Leader of C-band survey

GOODS-N field

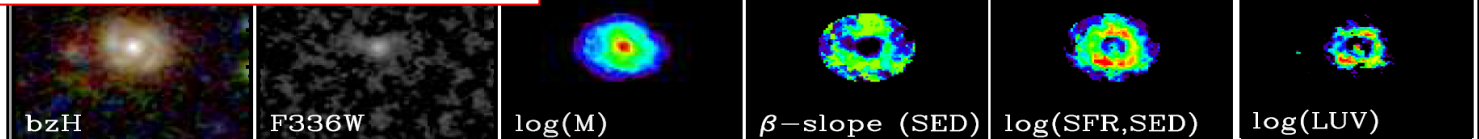
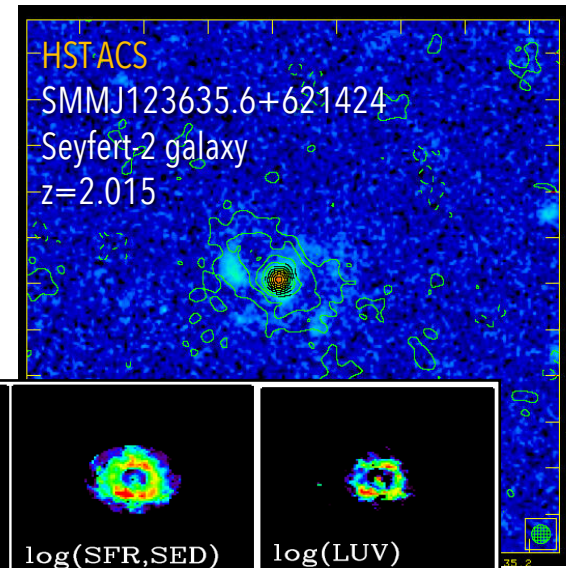
- sub- $\mu$ Jy rms L-Band imaging of 30' field (200mas)
- 1  $\mu$ Jy rms C-Band mosaic of the inner 12' field (50mas)

→ DR1: 1.5  $\mu$ Jy rms L-band [Muxlow+2020] 140h  
+JVLA 7 pointing mosaic C Band [Guidetti+17]



bright ring of SF +  
bright core

Obscured Nuclear SB  
or AGN?

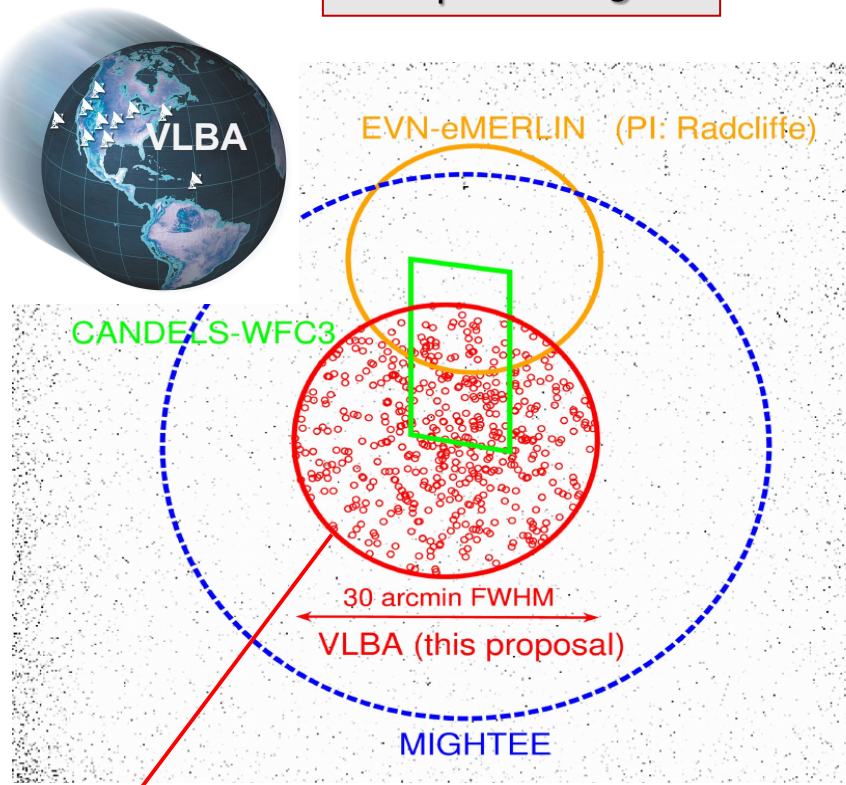


Anna Cibinel (Sussex) – private communication – multiband star-formation mapping

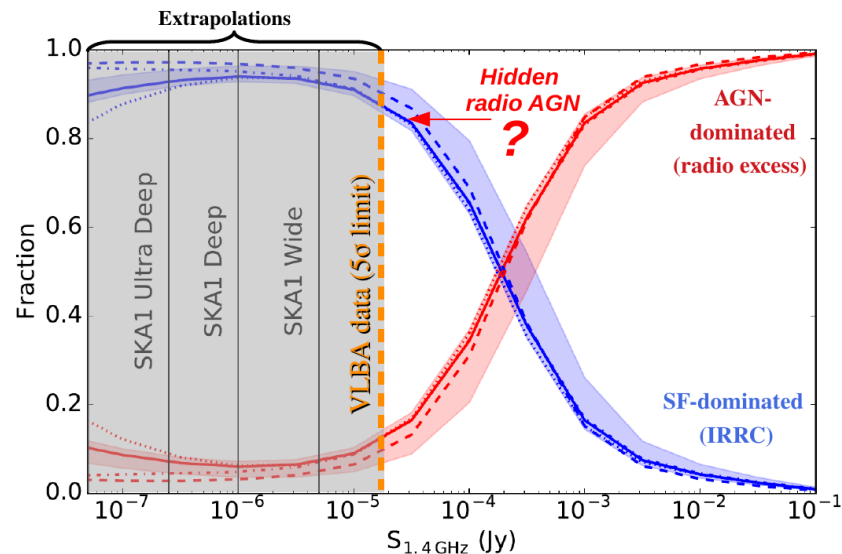


# A deep VLBA survey in COSMOS

I. Delvecchio  
Principal Investigator



- ❑ 120 hr on-going (80% done)
- ❑ 542 star-forming galaxies at redshift  $0.5 < z < 5$
- ❑ rms  $\sim 3.7 \mu\text{Jy/beam}$  at 1.4 GHz
- ❑ resolution:  $0.01''$  FWHM ( $\sim 85$  pc at  $z=2$ )



*This deep VLBA survey will provide radio morphological information required to separate star formation and AGN emission within individual high- $z$  galaxies.*

## Goals:

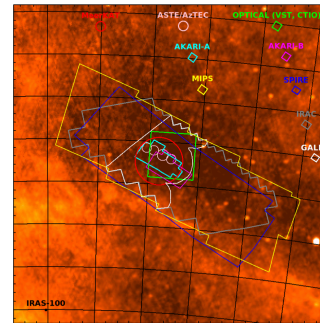
- Genuine census of radio-faint AGN at high- $z$
- Calibrating AGN-corrected radio-SFR relations
- Realistic sub- $\mu\text{Jy}$  extrapolations of AGN-vs-SFGs towards the upcoming SKA

Scheda INAF 'VLBA-COSMOS PI: Delvecchio

# Other PI Projects

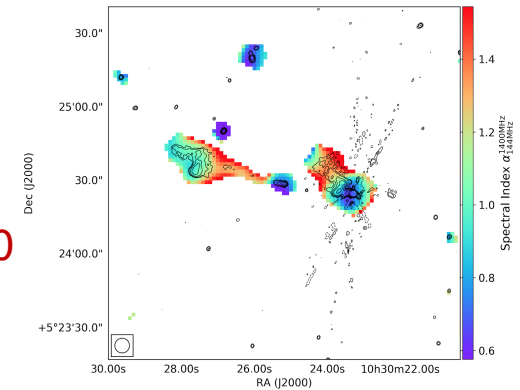
## ❖ AKARI Deep Field South (ADFS)

- M. Vaccari – PI of MeerKAT follow-up



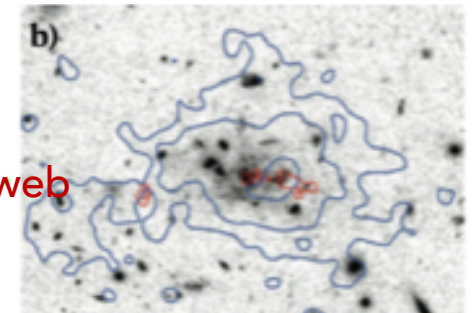
## ❖ J1030 Field (R. Gilli coordinator) – **scheda INAF J1030**

- R. Gilli – PI of LOFAR follow-up
- I. Prandoni – PI of JVLA follow-up
- M. Brienza – PI of uGMRT follow-up



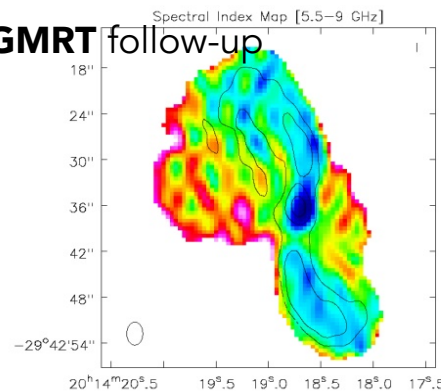
## ❖ Spiderweb (P. Tozzi coordinator) – **scheda INAF Spiderweb**

- M. Pannella – PI of MeerKAT and GMRT follow-up



## ❖ X-shaped RG sample

- L. Bruno - PI of uGMRT follow-up



# Scientific Impact - beyond state-of-the-art

1. Galaxy/AGN co-evolution at radio band
  - novel radio source evolutionary models & state-of-the-art SKA radio sky predictions (**Mancuso+17; Bonato+17; Bonaldi+19**) based on state-of-the-art observational constraints (**Prandoni+18; Bonato+21; Mandal+21**)
2. Physics of Radio-FIR correlation and its dependence on galaxy parameters
  - Robust evidence that it may depend on stellar mass (**Smith+21; Delvecchio+21**)
3. Origin of Radio emission in RQ AGN and LLAGN duty cycles
  - Growing evidence of AGN-induced radio emission in RQ AGN (**Delvecchio+17; Baldi+18,21**)
  - Exploration of possible mechanisms responsible for it (**Panessa+19**)

Scheda INAF 'TORQUA'
4. Role of environment in growth of galaxies and SMBHs
  - Example of positive feedback promoted by RG in J1030 protocluster (**Gilli+19**)

Scheda INAF 'J1030'
5. AGN fueling/feedback processes through HI studies
  - Survey of HI in absorption in radio AGN: outflow statistics and dependence on source parameters; SKA detections forecast (**Maccagni+17**)

# Ongoing Work & Future Perspectives - I

Ongoing legacy surveys at different levels of progress:

- Intense activity in the next 5 -10 years to get to full depth and full sky coverage
- Large scientific production expected also for the future

Strategic to invest on 'Italian' fields:

- Euclid Deep Field (EDF) – North @ LOFAR
- GAMA 23 @ ASKAP
- J1030 @ JVLA, uGMRT, LOFAR

... and Italian data analysis expertise:

- LOFAR VLBI pipeline (see [scheda INAF LOFAR-It](#))

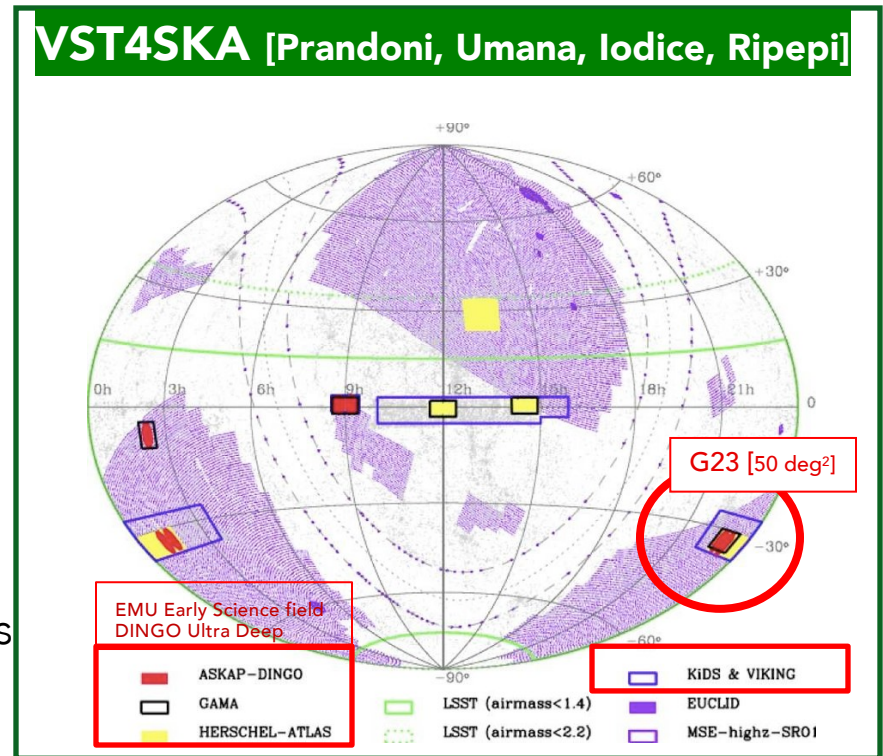
Exploit existing overlapping scientific interests and complementary expertise to tighten collaborations in view of SKA KSPs:

- Starting from linked projects (e.g. [scheda INAF TORQUA](#); [DUTYRAGA](#); [J1030](#); [Spiderweb](#); [GAEA](#); [BaryonicCycling](#))

# Ongoing Work & Future Perspectives - II

Exploit existing synergies with other next-generation facilities to expand Italian involvement in view of SKA KSPs:

- Weave LOFAR on WHT: Spectroscopy for a million LOFAR sources (→ **scheda INAF WEAVE**)
- Optical Imaging of G23 (VST Call for Interest 2020)
- Euclid Wide Survey & Deep Fields:
  - LOFAR + EMU Wide surveys
  - LOFAR EDF-N (w. VLBI)
  - MIGHTEE/FORNAX partial coverage of EDF Southern fields
 Exploit MeerKAT+/S-band?





# Funds

- This project is the result of collaborations established and/or grown in the framework of funded projects (**434 kEu in total**):
  - PRIN INAF 2009 (focused on eMERGE survey)
  - PRIN SKA/CTA 2016 "FoRECAST" (in particular its WP 2: Galaxy Formation and Evolution)
  - PRIN MAIN STREAM "SaUROS" (focused on modeling)
  - two bilateral projects funded by the MAECI aimed to cover traveling and support IT-SA scientific collaborations (like e.g. the MIGHTEE survey):
    - Esplorando il cielo in banda radio sulla via di SKA (PI Prandoni)
    - Radio SKY 2020 (PI Venturi)
- Residual funding (**32 kEu**) for 2021-2022 available from:
  - "FoRECAST" and "SaUROS" budget (extended to June 2022 due to the pandemic)
  - bilateral Italy-SA project "RADIO SKY 2020"

# Critical Issues

- Adequate level of funding is strategic in preparation to the SKA KSPs
  - **next 5 years** will be **critical for the scientific exploitation of the SKA precursors**, essential step in preparation of **SKA KSPs**
  - Essential that funding to support SKA-related science projects made available as **early** as possible, **and** distributed over the years **on a regular basis**.
- Need to hire and train young postdocs, who will constitute the next SKA generation
- Need to retain postdocs with a solid SKA-related know-how and already engaged in ongoing projects/activities
- Critical is the availability of computing power and data analysis e-infrastructures able to deal with the data volume produced by SKA precursors.
- Ability to handle these data in house critical in view of SKA KSPs.