Galaxy Evolution
with
SKA Precursors & Pathfinders

Isabella Prandoni
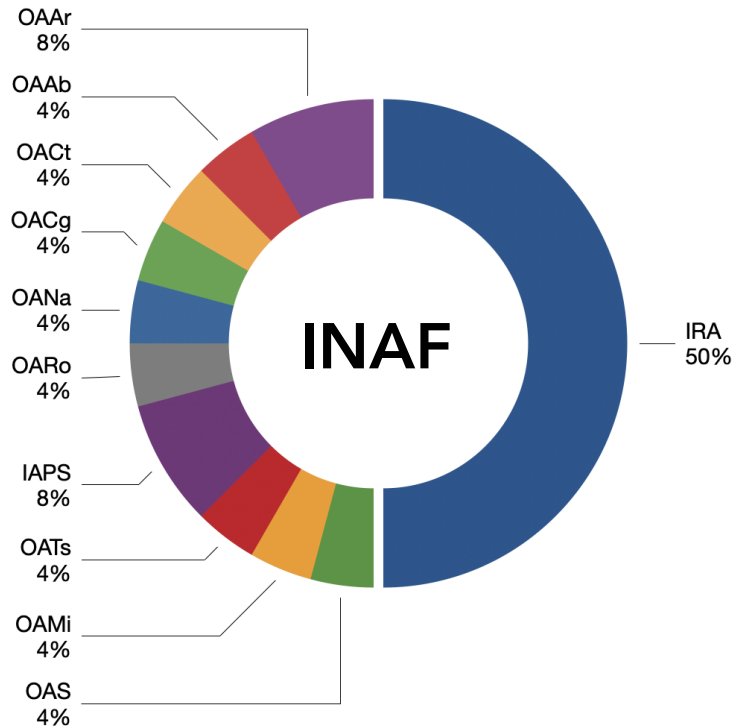
in collaboration with the SKA_Galev Team

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
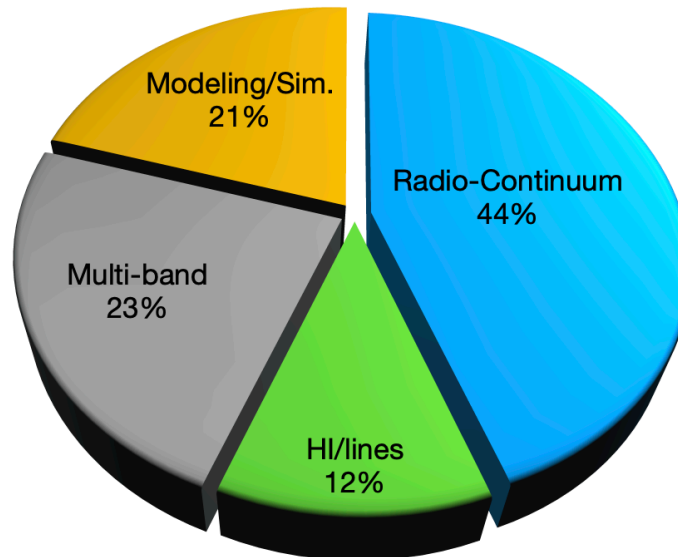Massardi
Paladino
Casasola
Burigana
Mack
Zanichelli

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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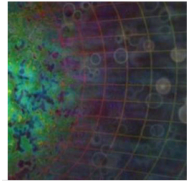Paladino
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The Pathway to the SKA

Science Drivers

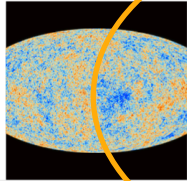**RC surveys** **HI surveys**

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?

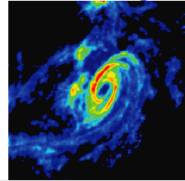The SKA will fundamentally advance our understanding of the mysterious dark

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?
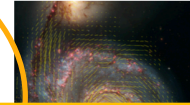
There is evidence that star formation

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?

> ➢ Sensitivity to both SF and AGN, to high-z and down to RQ regime
> ➢ no dust extinction/gas obscuration effects
> ➢ high spatial resolution → resolved studies
> ➢ role of jet-induced AGN feedback:
>   • radio duty cycles
>   • physics of radio emission in RQ AGN
> ➢ Simultaneous information on RC and HI line emission:
>   • HI accretion → H_2 → SF cycle
>   • AGN fueling/feedback & link with radio jets

MeerKAT ASKAP LOFAR

SKA
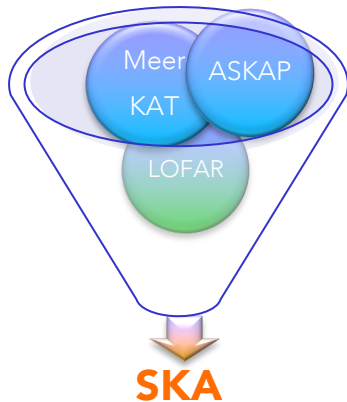
- **Exploit SKA precursors/pathfinders in preparaton to the SKA**
  - Definition of SKA Key Science Projects (KSP)
  - Development new data analysis skills
  - Formation of international KSP teams and leaderships

- **High level Project Goals:**
  - Maintain and possibly increase scientific visibility of Italian community
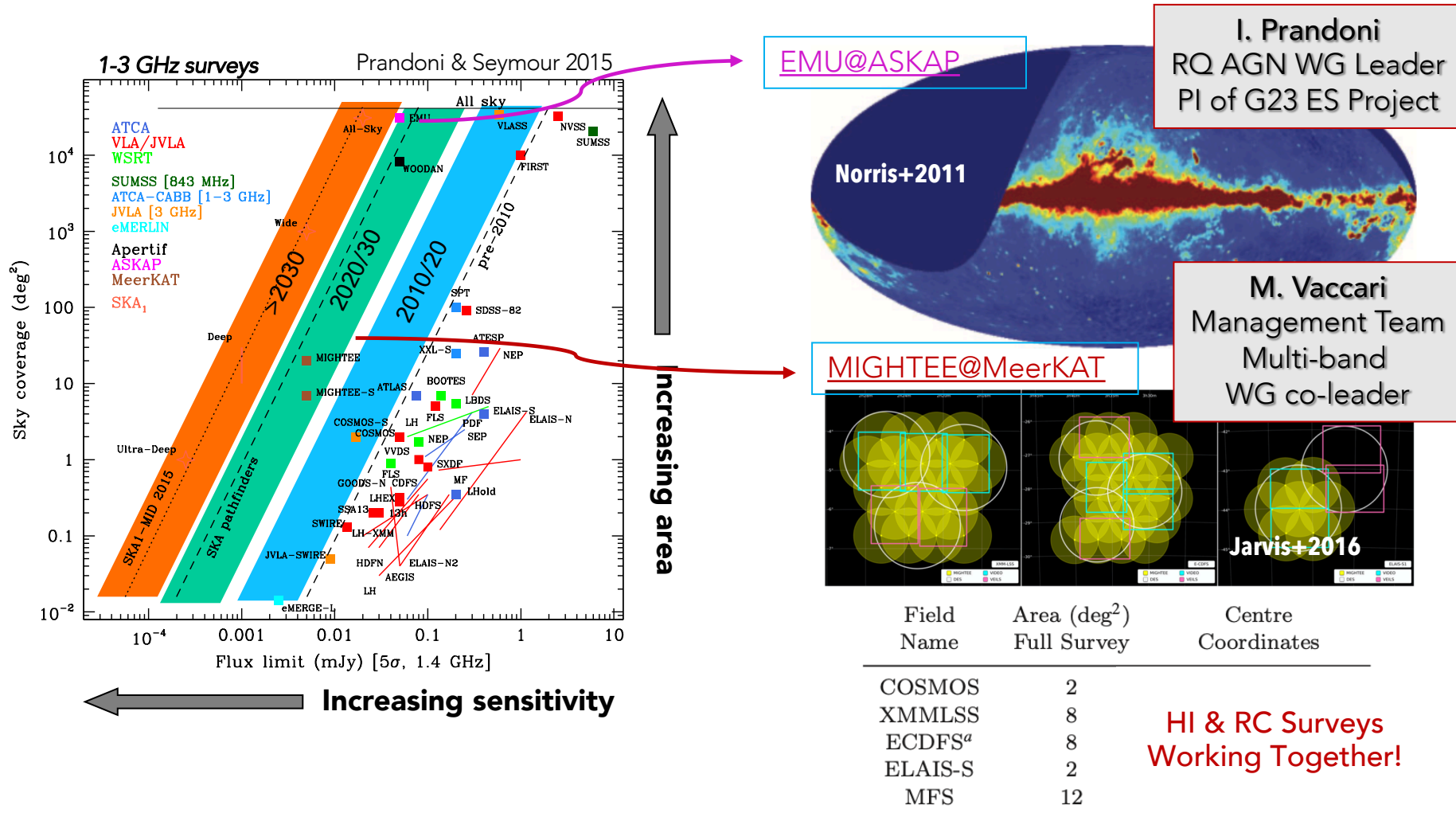 - Build over the years national teams able to get leadership roles in SKA KSPs

Survey Membership & Leadership
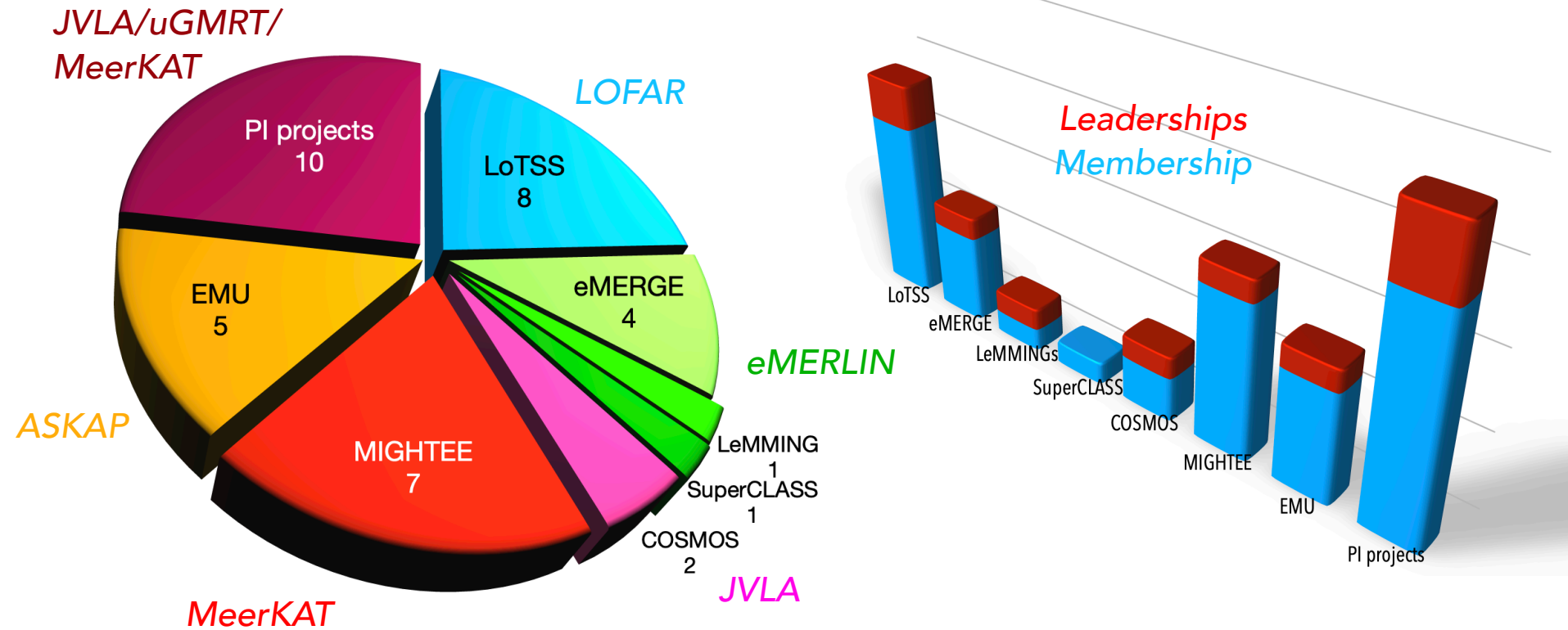
Modeling Expertise/Leaderships:
L. Hunt (BaryonicCycling) – Baryonic Cycle / Scaling relations
G. De Lucia (GAEA) – galaxy formation and evolution - HI simulations
A. Lapi – galaxy formation and evolution – RC modeling

Pre-SKA Legacy Surveys

EMU@ASKAP

I. Prandoni
RQ AGN WG Leader
PI of G23 ES Project

MIGHTEE@MeerKAT

M. Vaccari
Management Team
Multi-band
WG co-leader

Norris+2011

Jarvis+2016

| Field Name	Area (deg²) Full Survey	Centre Coordinates
COSMOS	2	
XMMLSS	8	
ECDFS[a]	8	
ELAIS-S	2	
MFS	12	

HI & RC Surveys
Working Together!

LOFAR Two-Metre Sky Survey (LoTSS)

I. Prandoni
Deep Fields
core team member

M. Bondi
EDF North
data analysis
coordination

- LoTSS: All-sky δ>0° at 150 MHz
  100 uJy/b rms @ 6″ res. (8hr / pointing)

- LoTSS-Deep: ~500h / pointing → 10 uJy/b rms
  Several 'famous' extragalactic fields targeted,
  incl. equatorial fields (COSMOS, XMM-LSS)

All sky/wide area surveys

Shimwell+2019

Tasse+2021 (α=-0.7)

LoTSS-Deep DR1
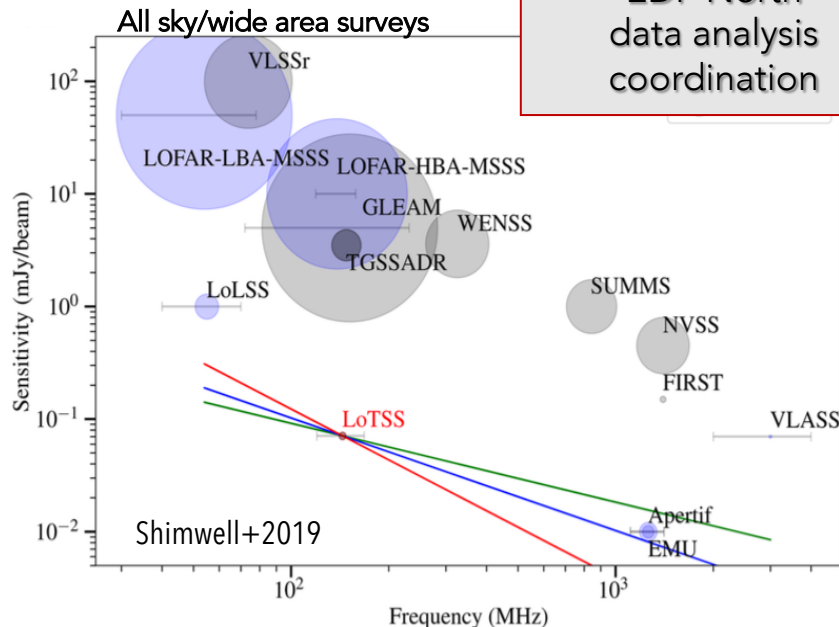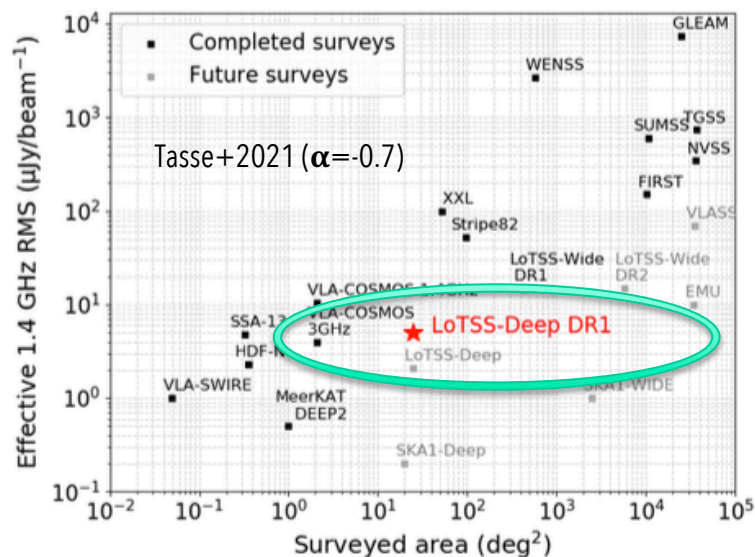
- DR1 All Sky (424 deg^2): **A&A Special issue (2019)**
- DR1 Deep : Focus on 3 fields at high decl.:
  - ➤ ELAIS-N1 (δ>+55°): 164 hrs, σ_c ~17 uJy/b
  - ➤ Lockman (δ>+58°): 112 hrs, σ_c ~22 uJy/b
  - ➤ Bootes (δ>+34°): 80 hrs, σ_c ~32 uJy/b

A&A Special Issue (April 2021)

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

I. Prandoni – May 2021

High-resolution radio surveys

Prandoni & Seymour 2015

Increasing sensitivity

Higher resolution
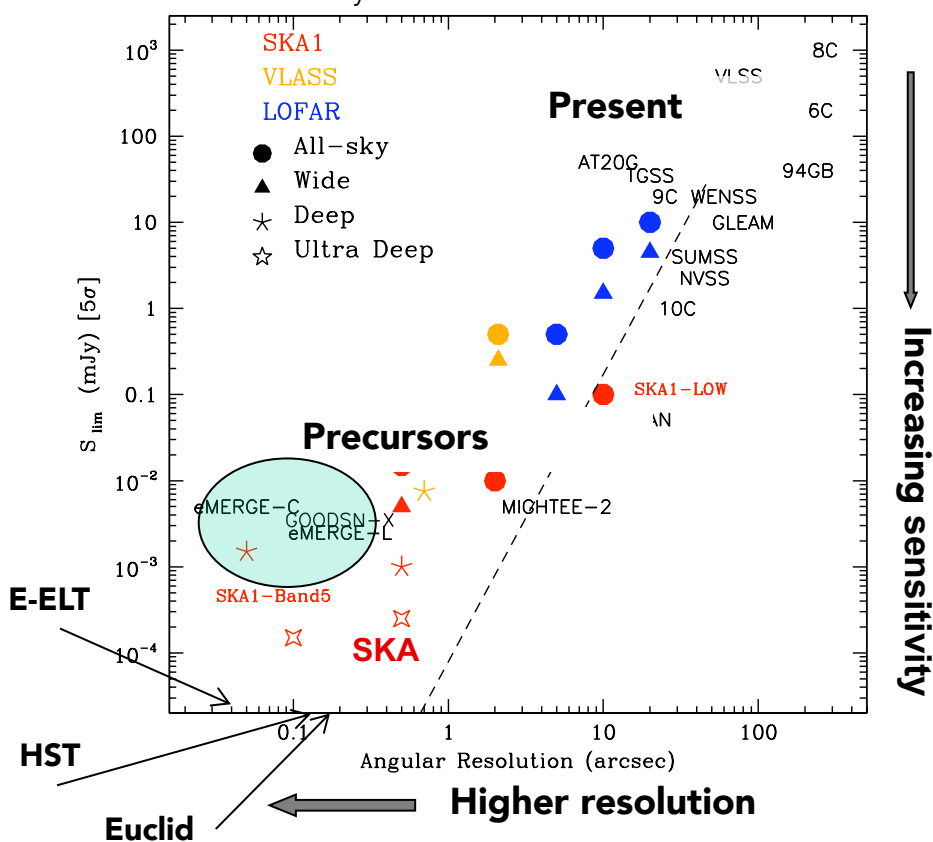
A resolved view of the radio Universe

Credit: Jack Radcliffe and Cristina Garcia-Miro
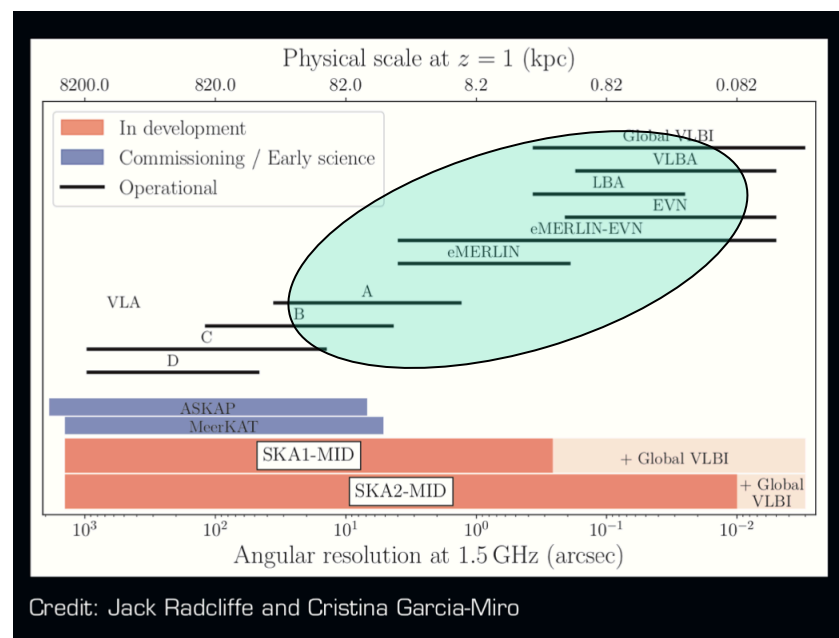
Pilots experiments with
JVLA+eMERLIN + VLBI follow-ups

LeMMINGs: Resolving the Local Universe

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

R. Baldi
Survey Coordination

NGC4151   HST [OIII] line + eMERLIN

Williams et al (2017)

- 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 uJy/beam
- Aims:
  - Studying low-luminosity AGN at the low end of the radio luminosity function (< 10^{18} 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

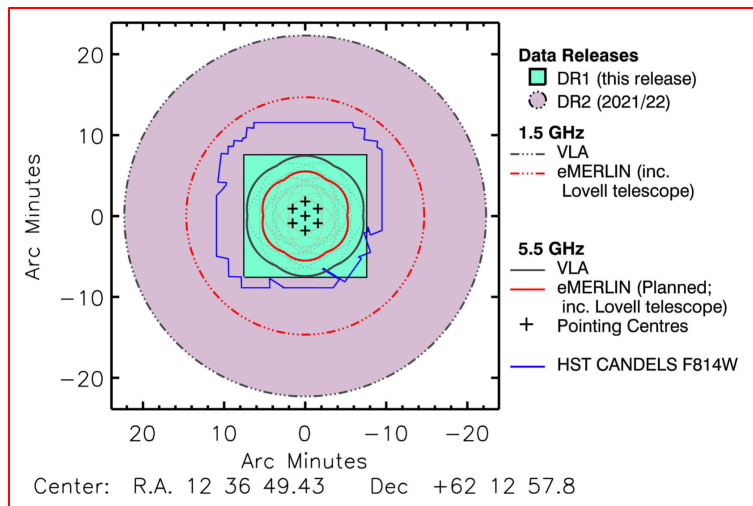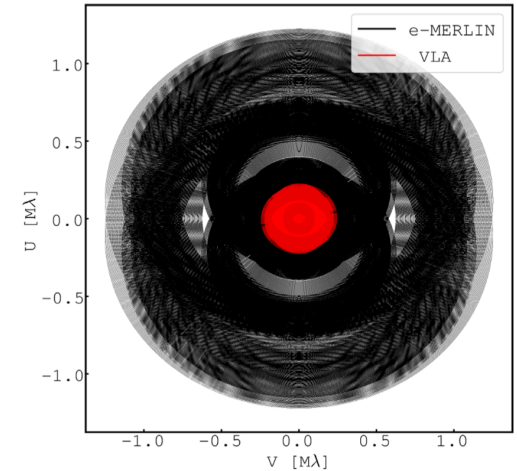- Scheda INAF 'The origin of the radio emission in radio-quiet AGN' – TORQUA PI: Panessa
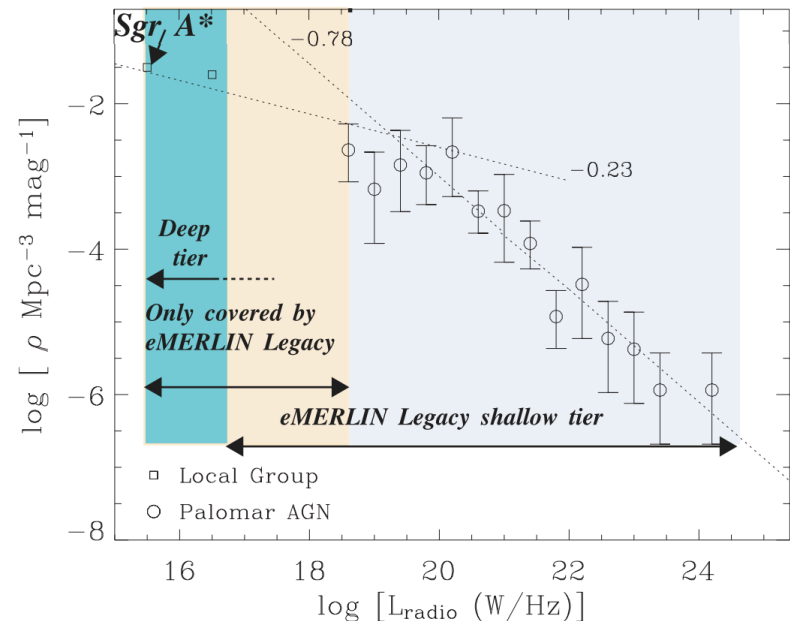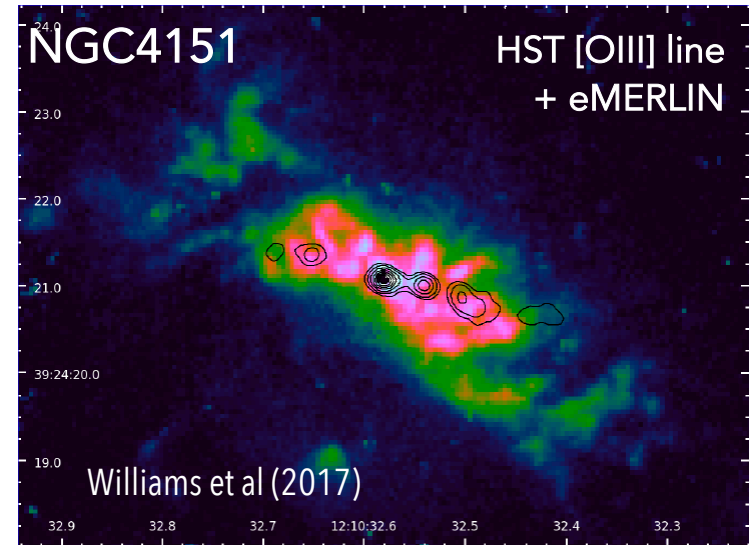
eMERGE: Resolving the high-z Universe

I. Prandoni
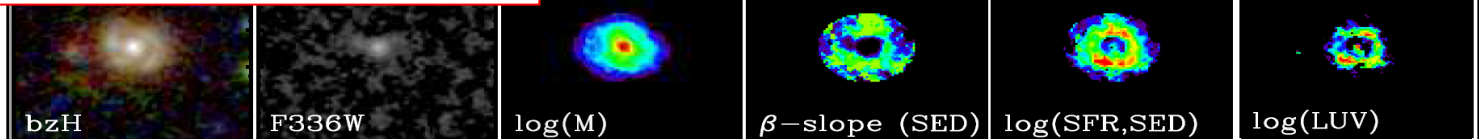Management team
Leader of C-band survey

GOODS-N field

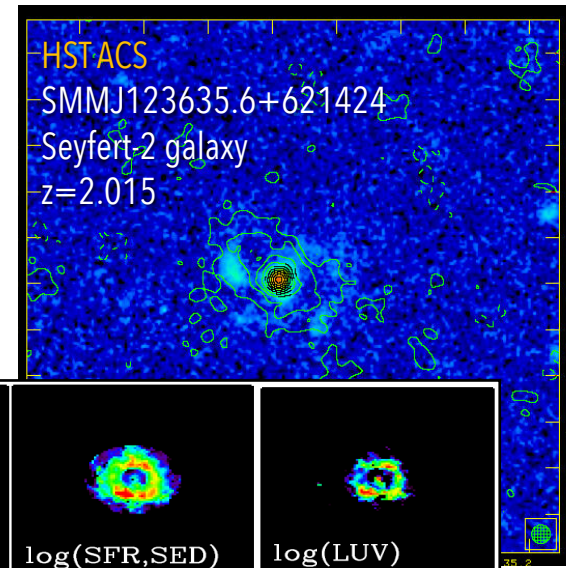- sub-uJy rms L-Band imaging of 30′ field (200mas)

- 1 uJy rms C-Band mosaic of the inner 12′ field (50mas)

→ DR1: 1.5 uJy rms L-band [**Muxlow+2020**] 140h

    +JVLA 7 pointing mosaic C Band [**Guidetti+17**]
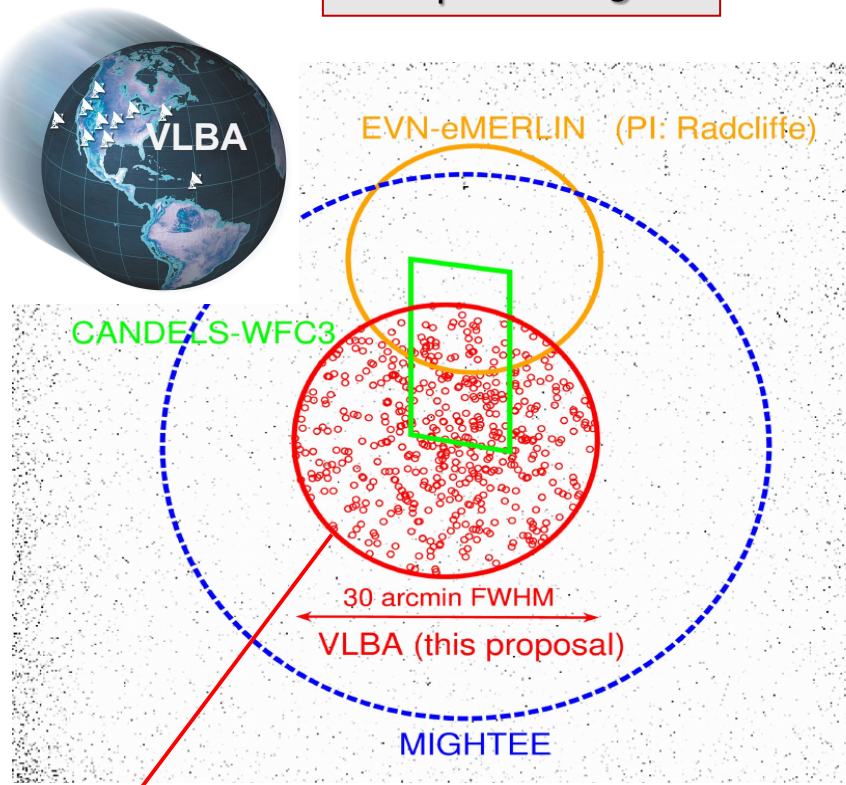

bright ring of SF + bright core

Obscured Nuclear SB or AGN?

HST ACS
SMMJ123635.6+621424
Seyfert-2 galaxy
z=2.015

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

A deep VLBA survey in COSMOS

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

- ❑ 120 hr on-going (80% done)
- ❑ 542 star-forming galaxies at redshift 0.5<z<5
- ❑ rms ~ 3.7 μJy/beam at 1.4 GHz
- ❑ resolution: 0.01" FWHM (~85 pc at z=2)

Goals:

- Genuine census of radio-faint AGN at high-z
- Calibrating AGN-corrected radio-SFR relations
- Realistic sub-μJy 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**
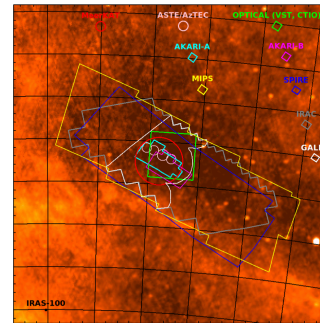
❖ J1030 Field (R. Gilli coordinator) – scheda INAF J1030

  ➢ **R. Gilli – PI of LOFAR follow-up**

  ➢ **I. Prandoni – PI of JVLA follow-up**

  ➢ **M. Brienza – PI of uGMRT follow-up**
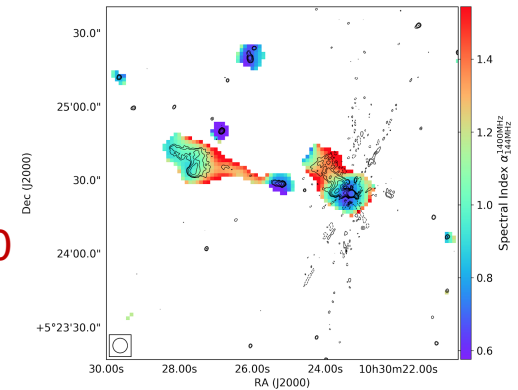
❖ Spiderweb (P. Tozzi coordinator) – scheda INAF Spiderweb

  ➢ **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

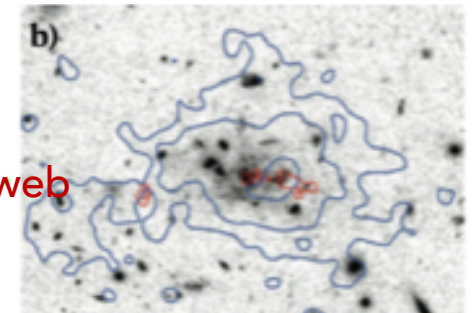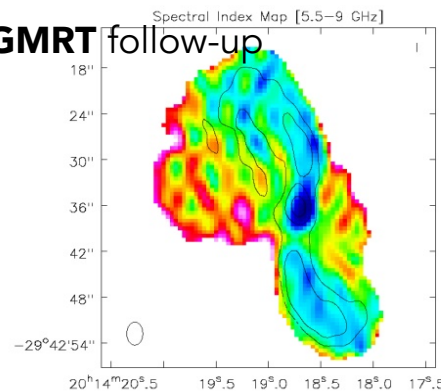1. Galaxy/AGN co-evolution at radio band
   – novel radio source evolutionary models & state-of-the-art SKA radio sky predictions (**Mancuso+17; Bonato+17; Bonaldi+19**) based on state-of-the-art observational constraints (**Prandoni+18; Bonato+21; Mandal+21)**

2. Physics of Radio-FIR correlation and its dependence on galaxy parameters
   – Robust evidence that it may depend on stellar mass (**Smith+21; Delvecchio+2**1)

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:
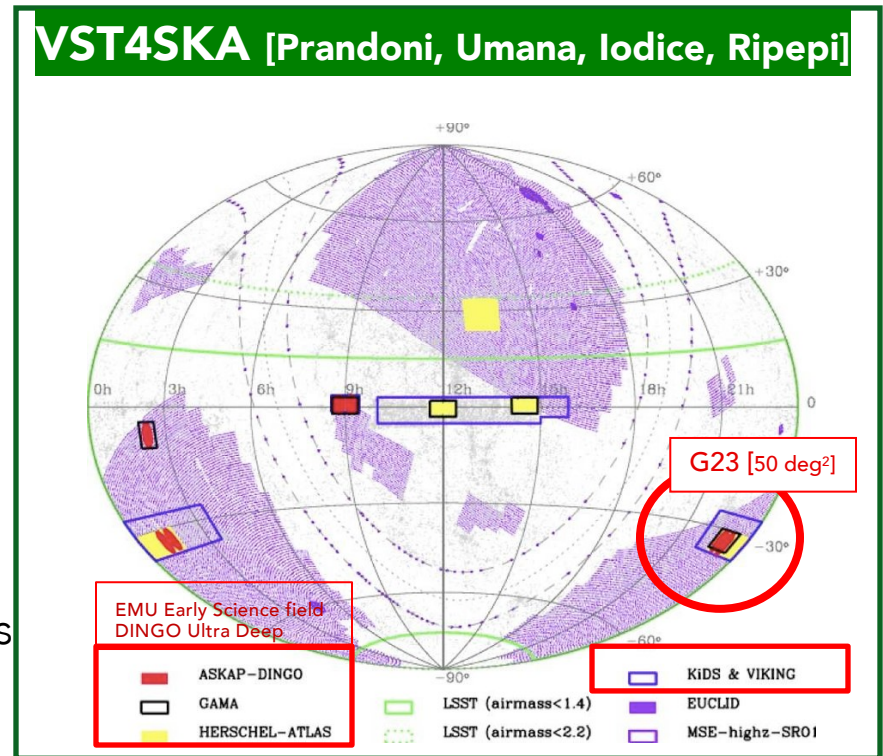- LOFAR VLBI pipeline (see scheda INAF LOFAR-It)

Exploit existing overlapping scientific interests and complementary expertise to tighten collaborations in view of SKA KSPs:
- Starting from linked projects (e.g. schede 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: Spectrocopy 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?

VST4SKA [Prandoni, Umana, Iodice, Ripepi]

G23 [50 deg²]

EMU Early Science field
DINGO Ultra Deep

ASKAP-DINGO	LSST (airmass<1.4)	EUCLID
GAMA	LSST (airmass<2.2)	MSE-highz-SR01
HERSCHEL-ATLAS		

KiDS & VIKING

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

- <u>Adequate level of funding is strategic in preparation to the SKA KSPs</u>
  - **next 5 years** will be **critical fo**r 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**.
- <u>Need to hire and train young postdocs</u>, who will constitute the next SKA generation
- <u>Need to retain postdocs</u> with a solid SKA-related know-how and already engaged in ongoing projects/activities
- <u>Critical is the availability of computing power and data analysis e-infrastructures</u> able to deal with the data volume produced by SKA precursors.
- <u>Ability to handle these data in house critical in view of SKA KSPs.</u>