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SEMPER: a semi-empirical model for extragalactic radio emission

Insights and predictions with the SKA

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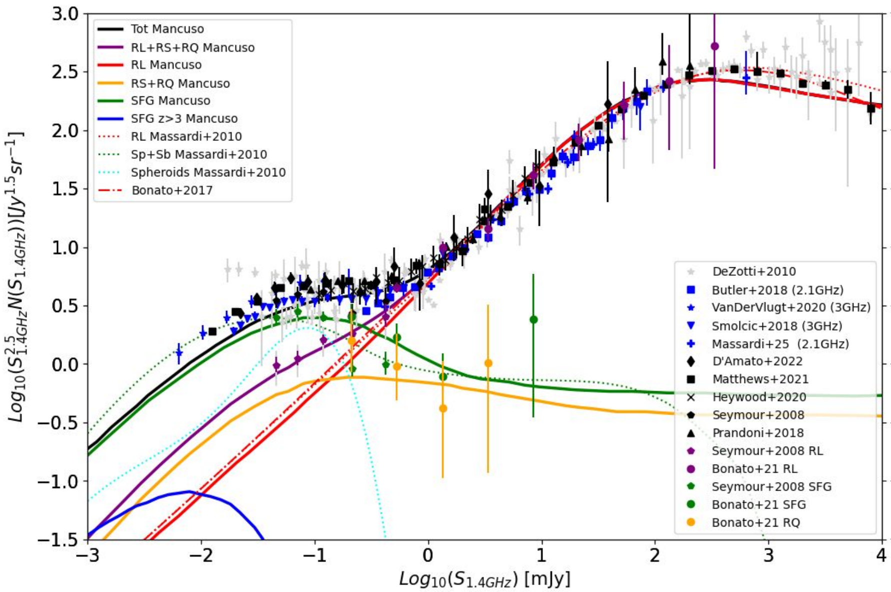
The Fifth National Workshop on the SKA Project – Bologna, Nov. 2025

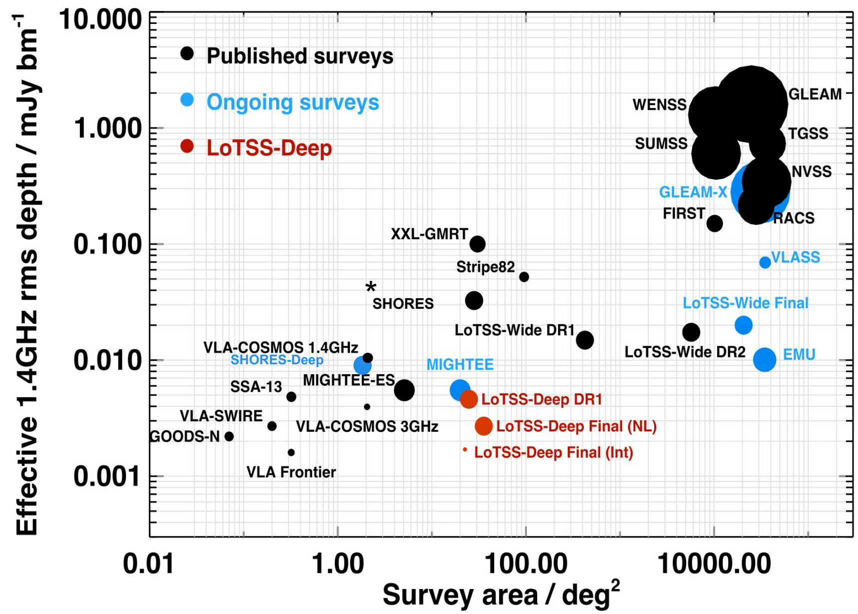
Radio emission as a SFR tracer

Radio continuum emission is an **unbiased tracer of star-formation:** synchrotron emission (supernovae remnants) + free-free emission (HII regions).



Galluzzi et al. 2025

*SHORES (Massardi+2025, Behiri+submitted)

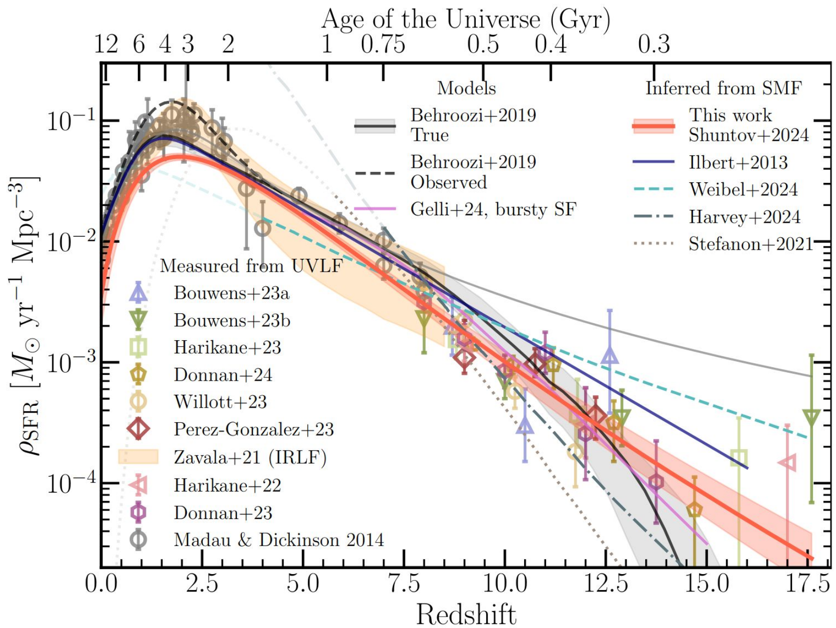


Best et al. (2023)

SFGs dominate the faint radio sky at $S_{1.4GHz} \lesssim 100$ μJy.

Significantly improved sensitivity of current deep and wide radio survey.

Selecting SFGs: a panchromatic approach



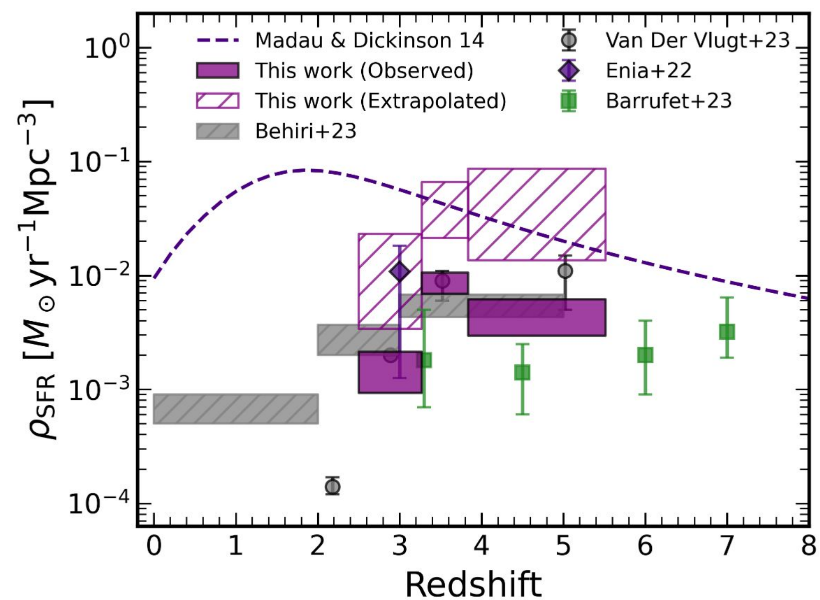
Shuntov et al. (2025)

Studying SFGs requires a panchromatic approach

Advancements in radio observations have mirrored those in the Optical/Near-IR bands.

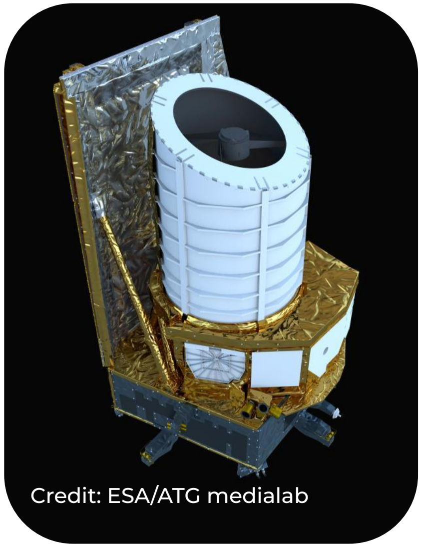
Optical/NIR dark (now faint with JWST) galaxies **significantly contribute to the cosmic SFRD** (see e.g. Simpson+2014, Wang+2019, Gruppioni+2020, Franco+2018; Williams+2024).

Radio-band selection (see e.g. Talia et al. 2021, Enia+2022, Behiri+2023, Van der Vlugt+2023, Gentile+2024a)



Gentile et al. (2025)

Selecting SFGs: a panchromatic approach



Need for a comprehensive view of processes driving SFGs and its evolution with z.

Semi-empirical models

- Use empirical relations between spatially averaged galaxy properties
- Do not model small-scale physics from first principles
- Minimize parameters and assumptions

Why semi-empirical models?

- Computationally efficient and easily expandable
- Useful for detecting dataset inconsistencies
- Enables predictions for future missions ←

SEMPER: Semi-EMPirical model for Extragalactic Radio emission

Goal: predictions for radio luminosity function and number counts for extragalactic sources

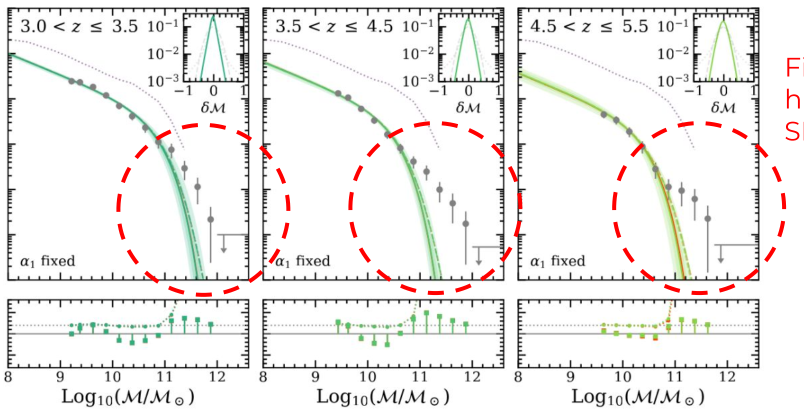
Main ingredients

- Redshift-dependent galaxy SMF
- Galaxy Main Sequence
- Mass-and redshift- dependent Far-Infrared/Radio Correlation

SEMPER- Stellar Mass Function

Data:

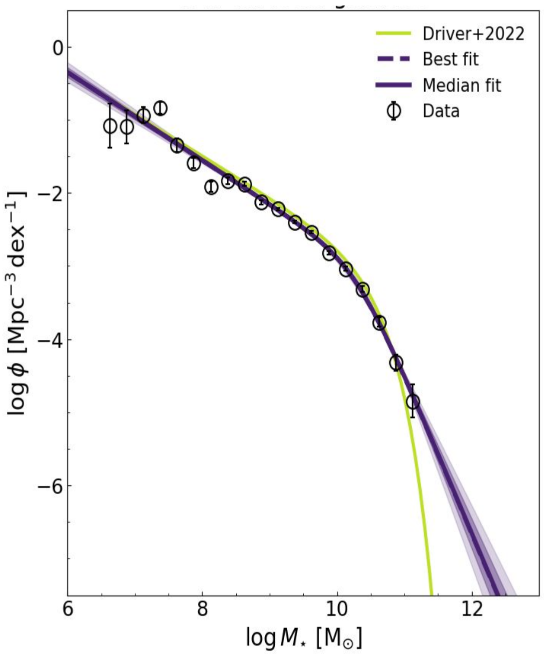
- 0.2<z<5.5 - Weaver et al. (2023), based on the COSMOS2020 catalogue (Weaver et al. 2022)
- z<0.1 - Driver et al. (2022), based on GAMA DR4.

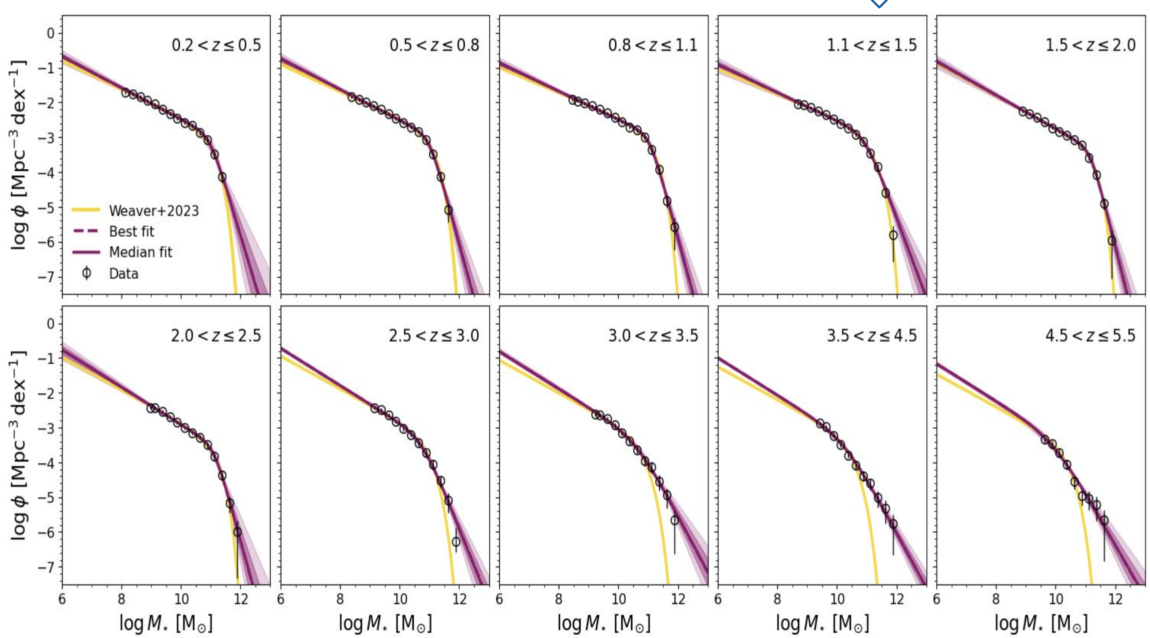


Fit fails to reproduce high-mass end of SMFs

New fit via **Double Power Law**:

$$\log \Phi d \log M = -\log\left(10^{(\log M - \log M_0)(\alpha+1)+\log \Phi_1} + 10^{(\log M - \log M_0)(\beta+1)+\log \Phi_2}\right) d \log M$$

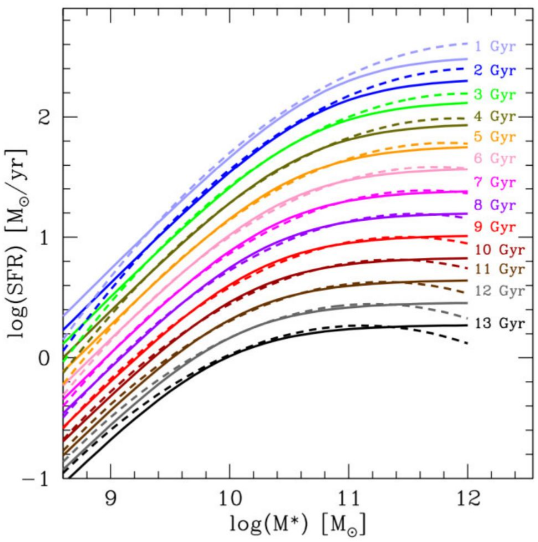




The double power law fit models the high-mass end of the SMF at z>3

SEMPER- Main Sequence & FIRRC

- Popesso et al. (2023)



Average relation between $M_\star$ and SFR→ presence of dispersion and outliers.

SFGs at fixed z and $M_\star$ assumed to be distributed in SFR following a double Gaussian shape (Sargent+2012):

Dominant population of MS Galaxies

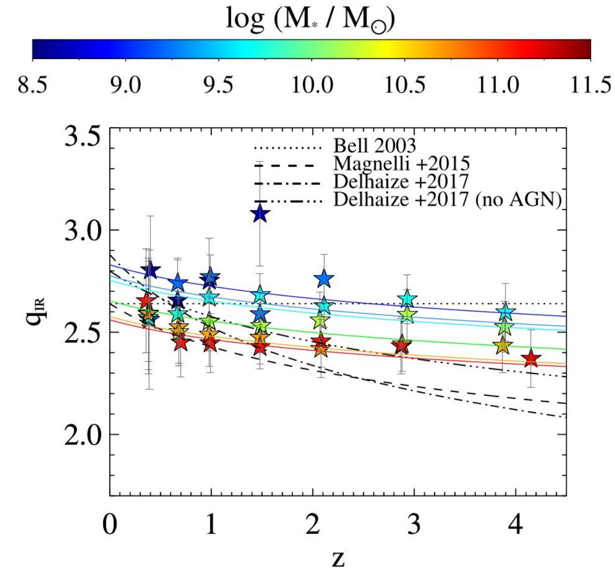
$$\frac{dp}{d\log\psi}(\psi \mid z, M_\star) = \left(\frac{A_{\rm MS}}{\sqrt{2\pi\sigma^2_{\rm MS}}}\right)\exp\left[-\frac{(\log\psi - \langle\log\psi\rangle_{\rm MS})^2}{2\sigma^2_{\rm MS}}\right]$$

Sub-population of Starburst galaxies

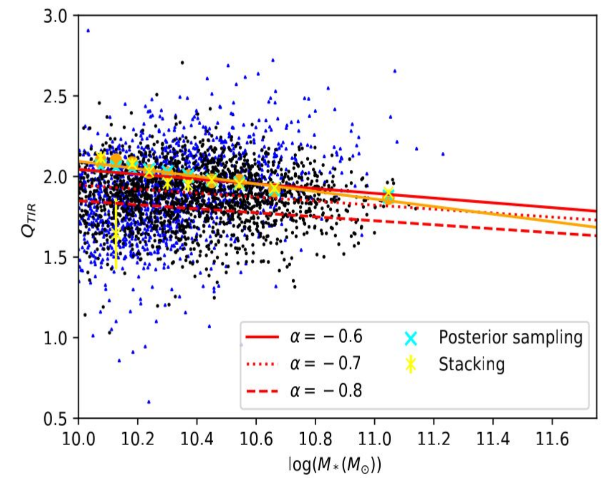
$$+\left(\frac{A_{\rm SB}}{\sqrt{2\pi\sigma^2_{\rm SB}}}\right)\exp\left[-\frac{(\log\psi - \langle\log\psi\rangle_{\rm SB})^2}{2\sigma^2_{\rm SB}}\right]$$

NEW: variable SB fraction (Bisigello+2018, Rinaldi+2024)

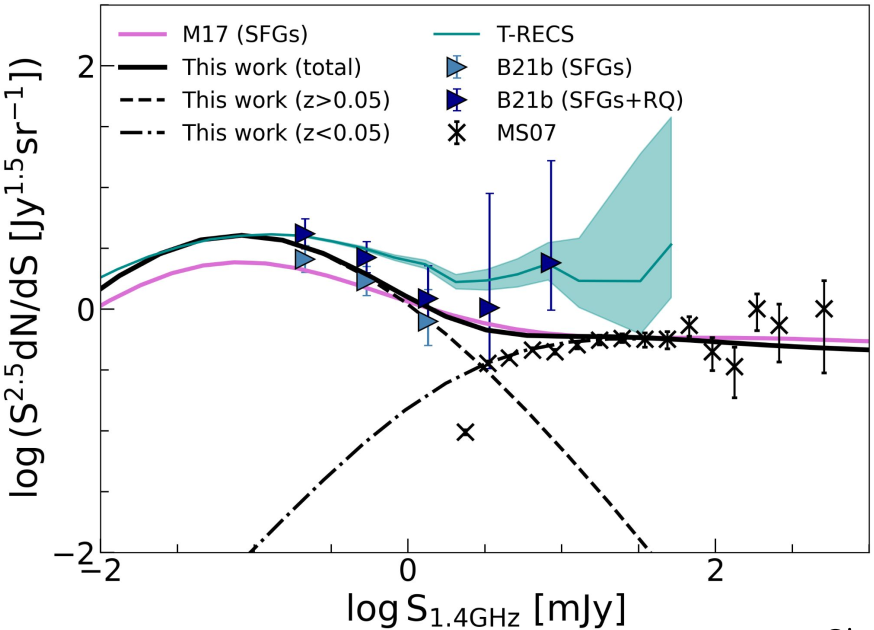
- Delvecchio et al. (2021) -1.4 GHz

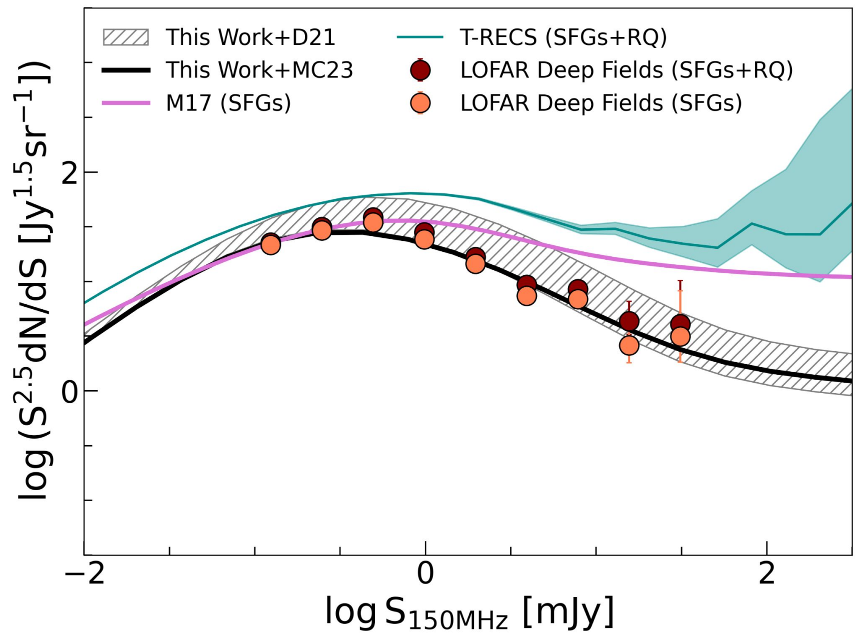


- McCheyne et al (2022) - 150 MHz



Results - Number Counts





Giulietti+2025

Comparison samples:

1.4 GHz:

- WSRT-Lockmann Hole (Bonato+2021)
- NVSS+ 6dFGS (Mauch & Sadler 2007)

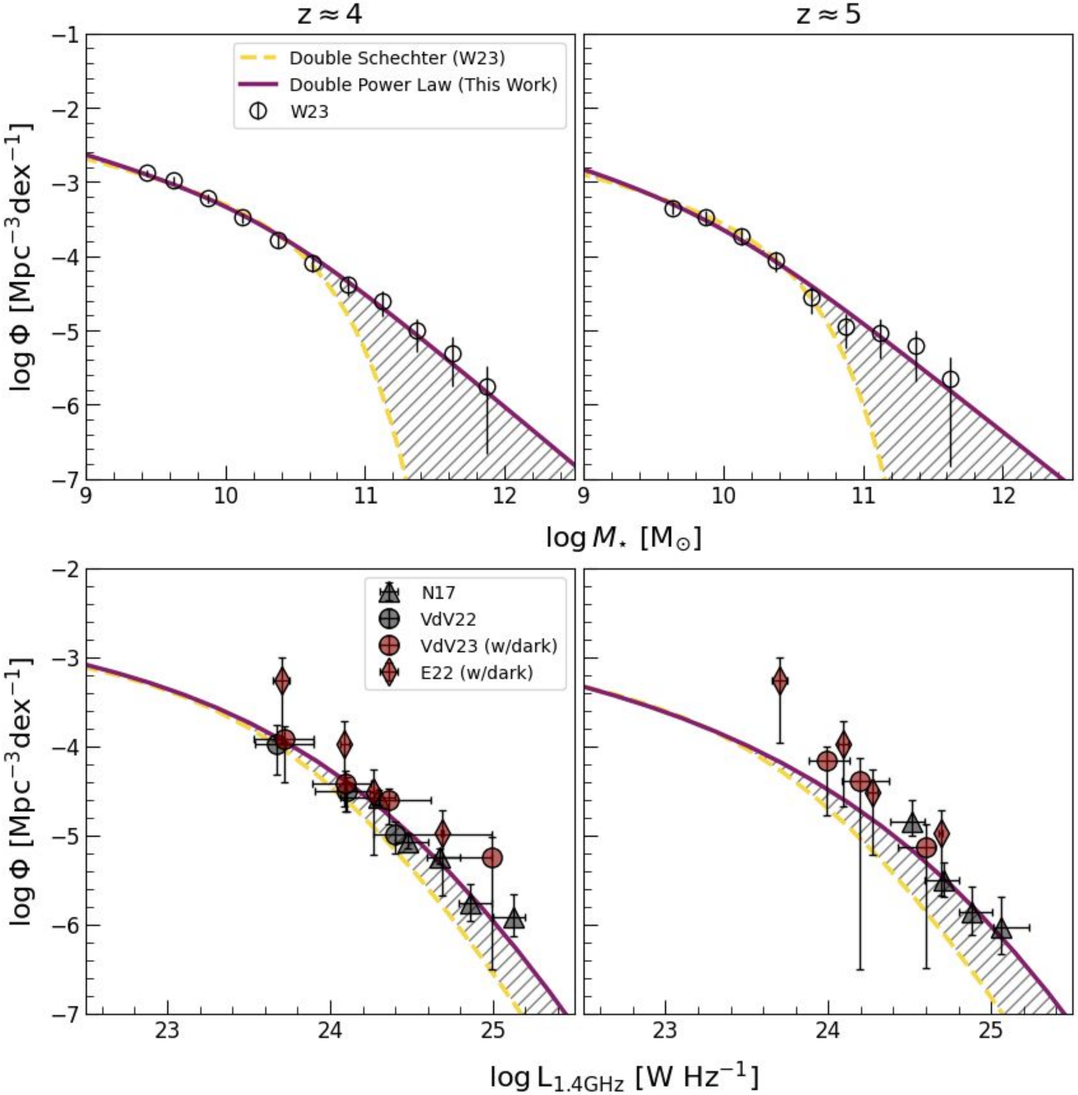
150 MHz:

- LoTSS Deep all fields DR1 (based on the classification of Best+2023)

All frequencies:

- Semi-empirical Model from Mancuso+2017
- T-RECS simulation

Results - Massive and Obscured Galaxies at high z

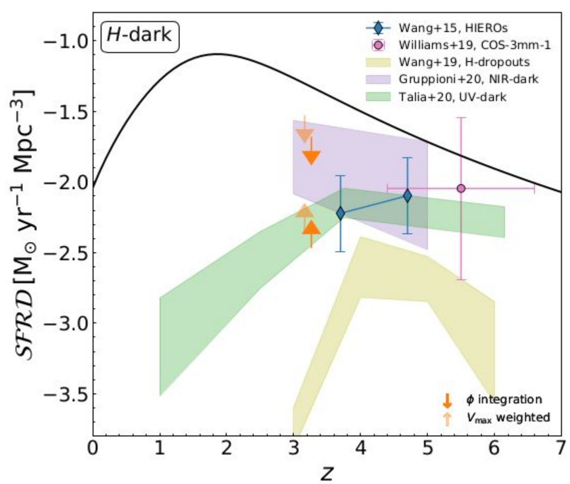


Giulietti+2025

High-z (z>3) massive ($M\star > 10^{11}$ M$_\odot$) and red objects detected in excess in the NIR and **missed by previous surveys** likely correspond to a population of bright radio sources at similar redshifts.

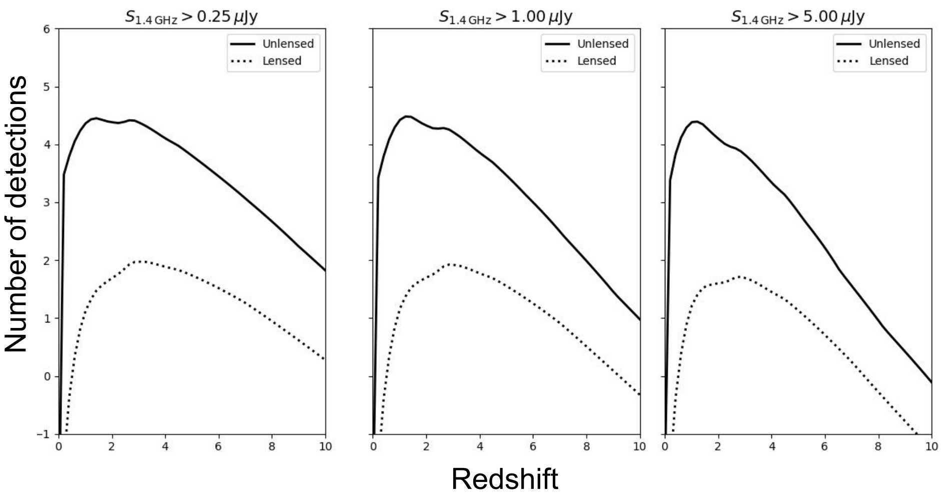
Radio band observations are sensitive to massive and obscured (Av~4) galaxies.

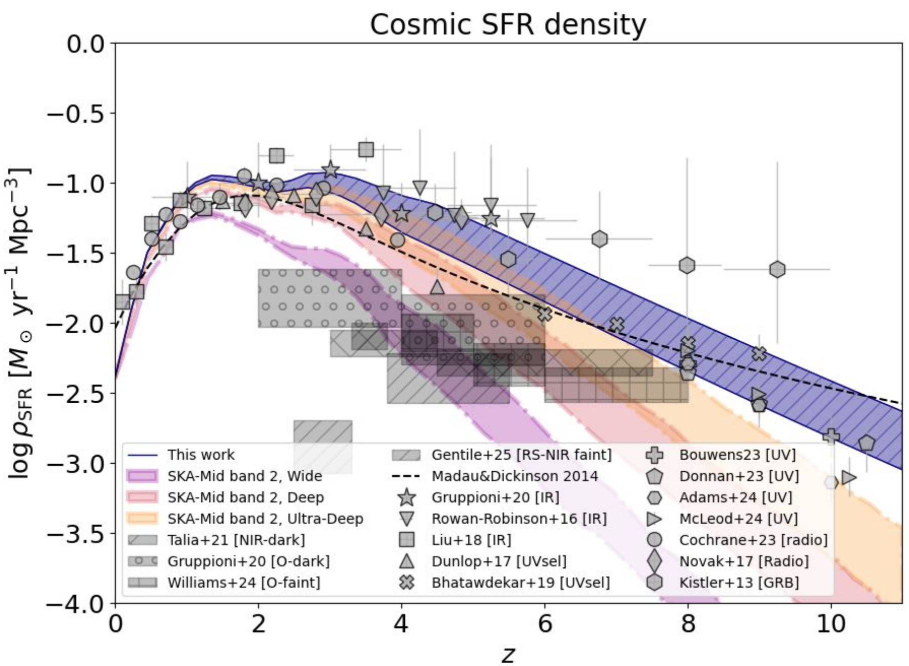
In agreement with observations of radio-selected NIR-dark galaxies (Talia+2021, Behiri+2023, van Der Vlugth+2023, Gentile+2024).



Credits: Enia+2022

Predictions for SKA





Draft contribution to **Advancing Astrophysics: Preparing for Science with the SKAO**

Semi-empirical Predictions for Ultra-deep Radio Counts of Star-forming Galaxies with the SKAO

Giulietti Marika,[1] Prandoni Isabella,[1] Bisigello Laura,[2] Bondi Marco,[1] Massardi Marcella,[3] Bonato Matteo[3] and Lapi Andrea[4]

SKA -Mid Band 2 continuum surveys (Prandoni+2015):
$\sigma \approx$ 0.05 μJy/beam (Wide)
$\sigma \approx$ 0.2 μJy/beam (Deep)
$\sigma \approx$ 1 μJy/beam (Ultra-Deep)

$S_{1.4GHz,MIN} \rightarrow L_{1.4GHz} \rightarrow \Upsilon_{MIN}$ as input for SEMPER.

With <20 hours of SKA Band 2 observations using the AA4 configuration, we can detect at least 20% of the total SFR density predicted by SEMPER, including the contribution from dark galaxies up to redshift ~6.

Conclusions

SEMPER
Semi-empirical model for extragalactic radio emission predicting radio luminosity function and number counts, with the goal of better understanding the radio properties of high-z, massive galaxy populations.

SEMPER combines the evolving SMFs for SFGs, from deep NIR data (COSMOS2020; Weaver+2023) with up-to-date observed scaling relations (galaxy main sequence & mass- and redshift-dependent FIRRC) .

Results:

- **SMF Reconstruction**: Double Power Law fit accurately reproduces observed massive galaxies at z>3.
- **Radio LFs:** SEMPER predictions match 1.4 GHz & 150 MHz data from JVLA, LOFAR, GMRT, WSRT, and ATCA.
- **Dust-Obscured SFGs:** the model successfully reproduces 1.4 GHz LFs for high-z radio-selected SFGs, linking them to dust obscured (even optically/NIR dark) galaxies.
- **Number Counts**: SEMPER's predictions match NVSS, WSRT, and recent LoTSS data; slight deviations from T-RECS & Mancuso+2017.

SKA predictions: SEMPER can be exploited to plan SKA follow-ups, e.g. for Rs-NIR dark/faint sources.

Future Work: JWST-based SMFs expansion, predictions for AGNs

SEMPER- All in all

1) SFR function

SMF

SFR distribution (from the MS)

$$\frac{d^2N_{\mathrm{SMF+MS}}}{d\log\psi dV}(z,\log\psi) = \int d\log M_\star \frac{d^2N}{d\log M_\star dV}(z,\log M_\star) \times \frac{dp}{d\log\psi}(\log\psi \mid z, M_\star)$$

2) Standard calibrators (Kennicutt & Evans 2012): $L_{\mathrm{FIR}} = k_{\mathrm{FIR}}\psi$

3) Probability of a given radio luminosity (L_ν) at fixed SFR(ψ), M⋆ and z:

$$\frac{dp}{d\log L_\nu}(\log L_\nu \mid \psi, M_\star, z) = \left(\frac{1}{\sqrt{2\pi\sigma^2_{\mathrm{FIRRC}}}}\right)\exp\left[-\frac{(\log L_\nu - \langle\log L_\nu\rangle)^2}{2\sigma^2_{\mathrm{FIRRC}}}\right]$$

Scatter in the FIRRC

4) Radio LF function:

$$\frac{d^2\mathrm{N}}{d\log L_\nu dV}(\log L_\nu, z) = \int d\log M_\star \frac{d^2N}{d\log M_\star dV}(\log M_\star \mid z) \times \int d\log\psi \frac{dp}{d\log\psi}(\psi \mid z, M_\star) \times \frac{dp}{d\log L_\nu}(\log L_\nu \mid \psi, M_\star, z)$$

5) Number Counts:

$$\frac{dN}{d\log S_\nu d\Omega}(S_\nu) = \int dz \frac{dV}{dz d\Omega}\frac{dN}{d\log L_\nu dV}(L_{\nu(1+z)}, z) \qquad \text{where} \qquad S_\nu = \frac{L_{\nu(1+z)}(1+z)}{4\pi D_L^2(z)}$$