The far-infrared/radio correlation for a sample of strongly lensed dusty star-forming galaxies detected by *Herschel*

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INAF-IASF, Milano
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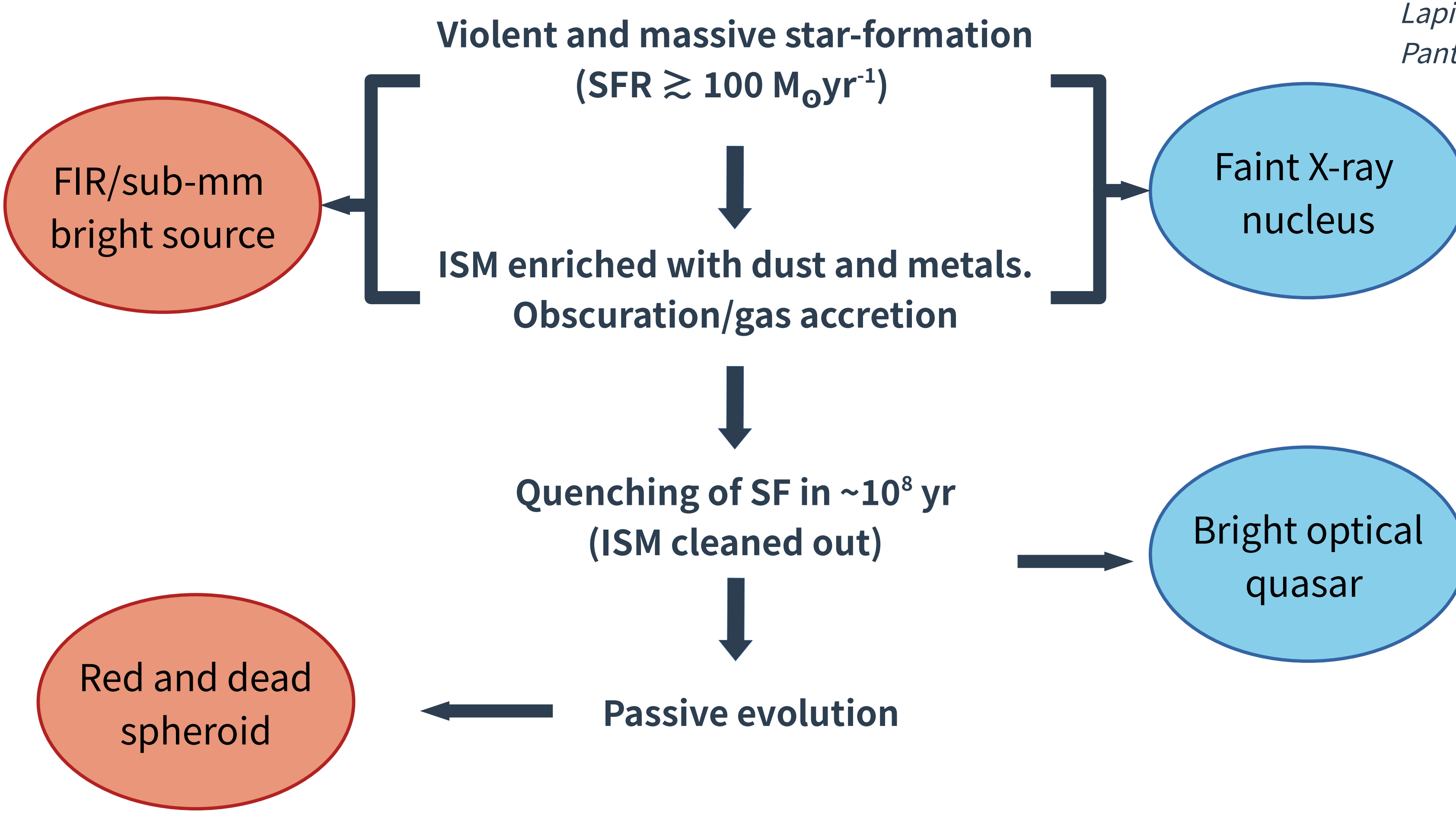
Image credits: ESO

Introduction

The in situ scenario[1]

Processes at early stages of galaxy formation (i.e. nuclear activity, star formation) are strictly related and coordinated in time (in situ).

[1] *Mancuso et al (2016a,b), Lapi et al. (2018), Pantoni et al. (2019).*



Introduction

The role of Dusty Star-Forming galaxies in co-evolutionary models

→ The interplay between star formation and nuclear activity can be studied through the dusty star-forming (DSFGs) galaxies at high z.

- **High star formation rate (SFR) : from $\gtrsim$100 $M_{\odot} yr^{-1}$**
- **Abundant at high redshift : $z \gtrsim 1$**
- **Progenitors of quiescent early-type galaxies**
- **Heavily obscured by dust**

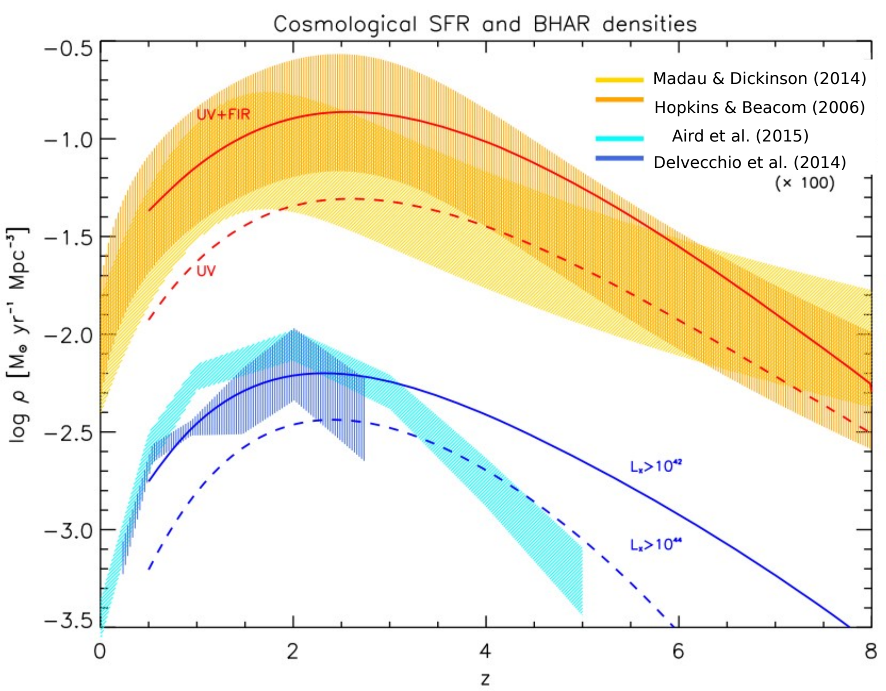
➡ **Bright in Far-Infrared (FIR)/ sub-millimeter (sub-mm).**

➡ **(Almost) invisible in optical bands.**

Introduction

The role of Dusty Star-Forming galaxies in co-evolutionary models

Credit: Mancuso et al. (2016):



The cosmic BH accretion rate and SFR densities feature a similar evolution:

- Peak around z ~ 2–3
- Decline at higher redshift

→ DSFGs are the main contributors to the Star Formation History at 1<z<4, (detected up to z~6).

High-quality multi-band data are needed to investigate DSFGs' structure in different evolutionary phases.

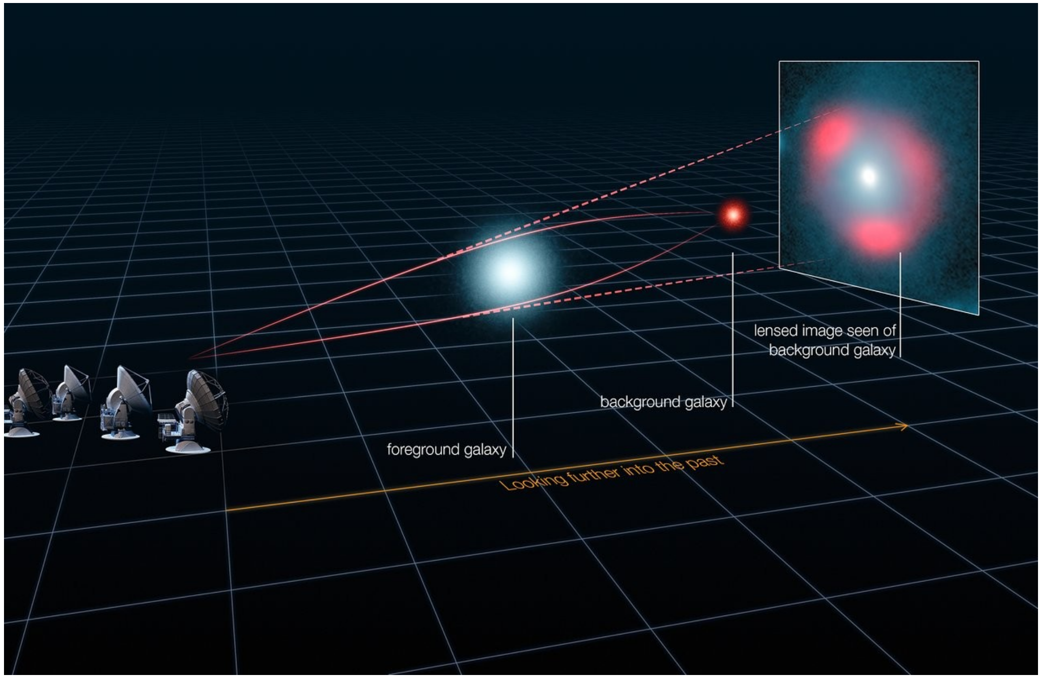
Issue:

High-z DSFGs are compact: typical intrinsic sizes of few ~ kpc, corresponding to a few tenths of an arcsec at z~2 (see e.g. *Pantoni et al., 2021*) → **very hard to resolve!**

→ **Gravitational lensing**

Introduction

Gravitational Lensing



Credits: *ALMA (ESO/NRAO/NAOJ), L. Calçada (ESO), Y. Hezaveh et al.*

Gravity of massive objects can work the fabric of space-time.

The path of photons from distant sources is affected by gravity.

- Apparent luminosity increased.

- Multiple images of the background object → sizes are "stretched" by a factor $\mu^{1/2}$.

Strong gravitational lensing as powerful astrophysical tool:

- Morphological and physical properties of high redshift sources
- Probe Dark Matter distribution of the Universe.

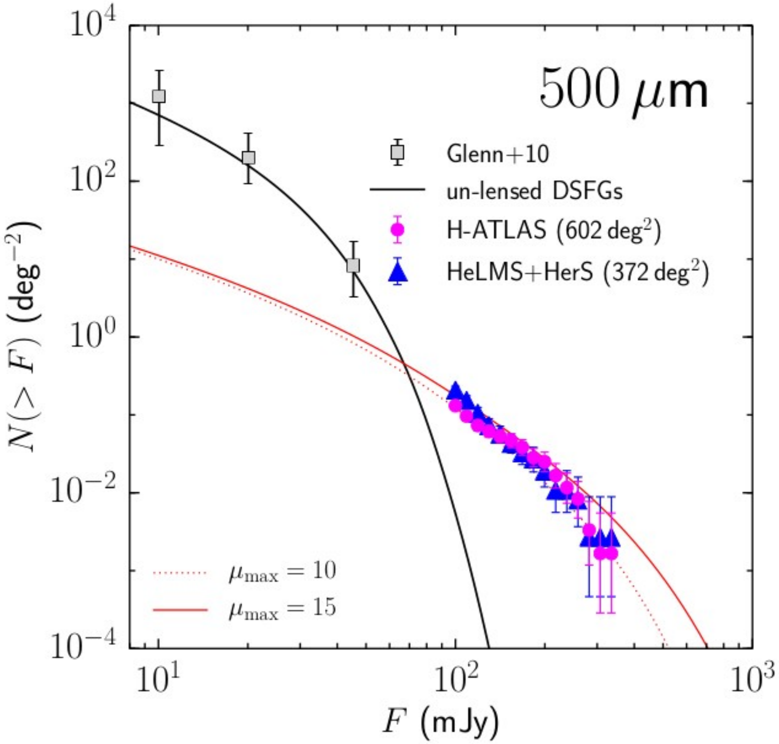
BUT: strong lensing events are rare.

Introduction

Wide-area sub-mm surveys

[(2)] *Blain (1996), Lapi et al. (2011), Negrello et al. (2007, 2010).*

Why sub-mm survey?



Credit: Negrello et al. (2017)

Models predict a drop in the number counts of un-lensed DSFGs at 500μm ≥ 100mJy. [(2)]

Main advantages of sub-mm observations:

Negative K-correction
Not affected by dust obscuration.

Sub-mm selected lensed galaxies:

No contamination from foreground lens (often an elliptical passive galaxy)→ advantage in the source reconstruction.

Lensing is necessary to overcome the **limited spatial resolution of FIR/sub-mm bands.**

Unique possibility to study the details of morphological and dynamical properties of individual giant molecular clouds (down to sub-kpc scales).

Introduction

Wide-area sub-mm surveys

[3] *Wardlow et al. (2013), Nayyeri et al. (2016),* ***Negrello et al. (2017).***
[4] *Ward et al. (2022)*

Discovery of several lensed DSFGs at high redshift (z>1).

Herschel **Space Observatory**

(FIR-to-sub-mm→ 100-500 µm)

Credit: *ESA*

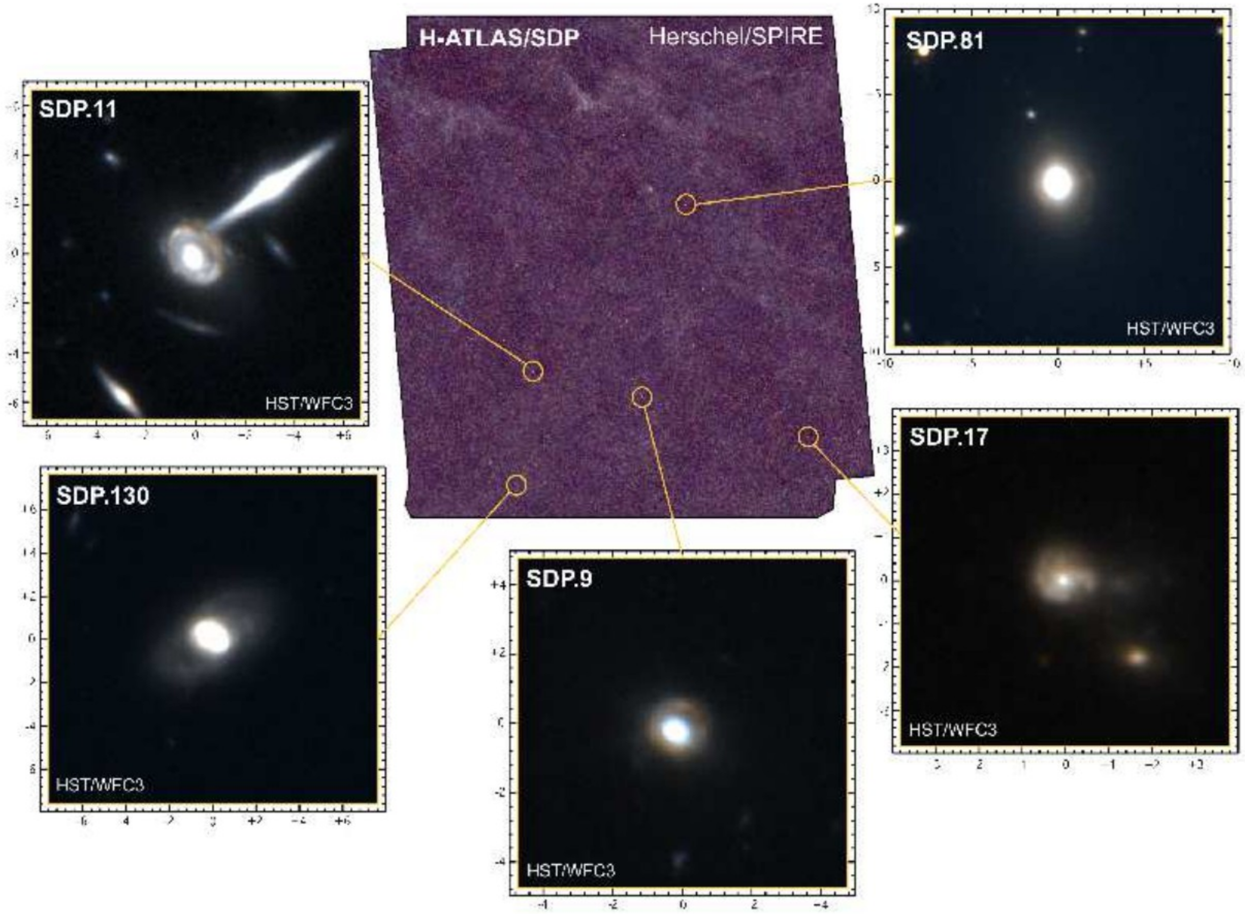
Lensing events detected by *Herschel* [3]

Herschel Multi-tiered Extragalactic Survey (**HerMES**): **11 lensed galaxies**	Her-MES Large Mode survey (**HeLMS**) + *Herschel* Stripe 82 Survey (**HerS**): **77 candidates**	*Herschel* Astrophysical Terahertz Large Area Survey (**H-ATLAS**) **80 candidates +11** [4]

The H-ATLAS survey

Overview

- Widest area survey undertaken with *Herschel* (600 deg^2)
- 5 FIR-to-sub-mm bands (100, 160, 250, 350 and 500 µm) PACS+SPIRE.
- Covered by other photometric/ spectroscopic surveys from optical to radio.
- **First sample of 5 strongly lensed galaxies discovered during the Science Demonstration Phase** [(4)] (SDP).



Credit: Negrello et al. (2010)

The H-ATLAS survey

Overview

80 candidate strongly lensed galaxies with flux 500 µm $\gtrsim$ 100 mJy.

- $13 \lesssim log(L_{TIR}/L_{\odot}) \lesssim 14$

(8-1000 µm, uncorrected for magnification).

- $1 \lesssim z \lesssim 4.5$ (z_{med}~2.5).

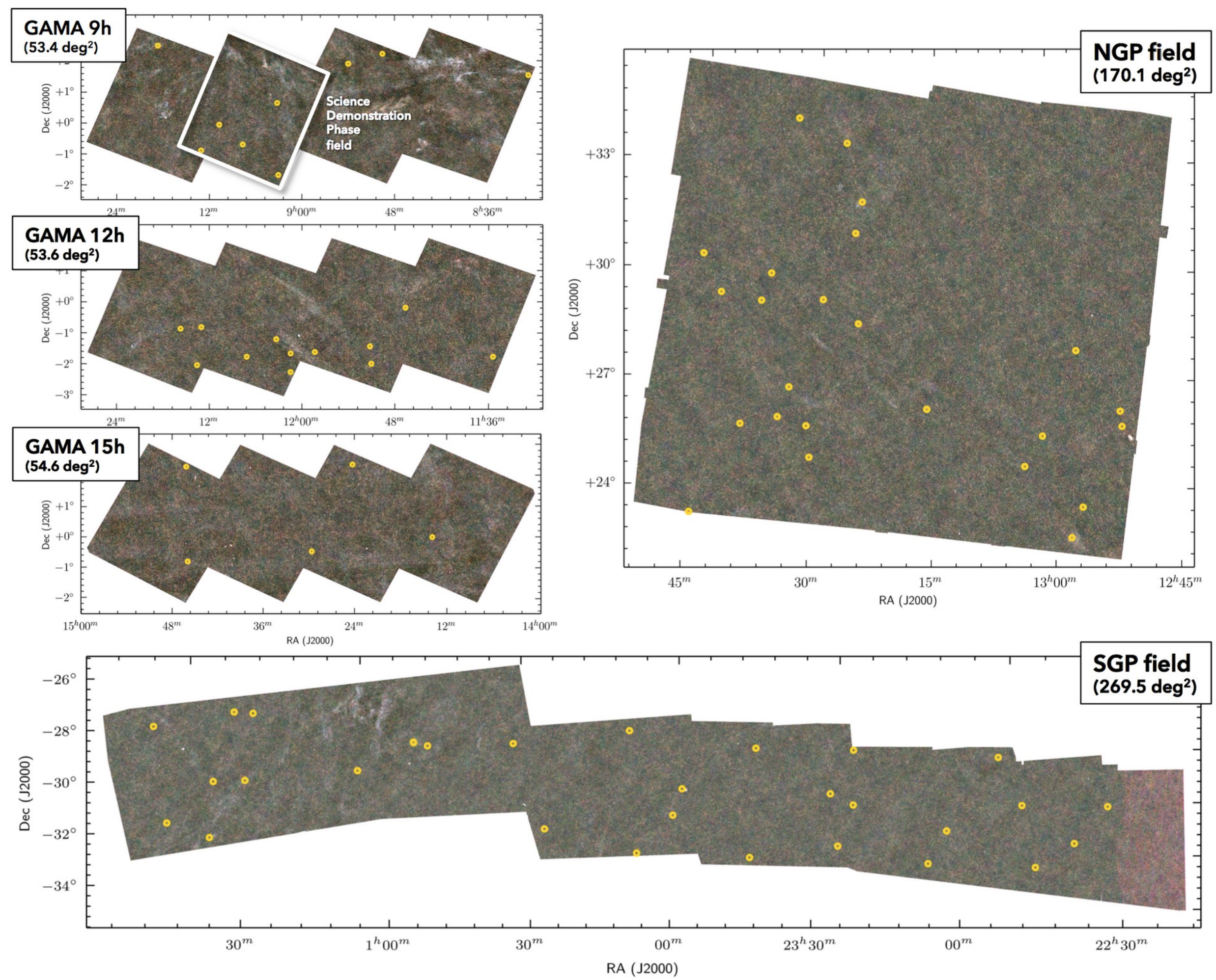
(A) 21 strong lensing events confirmed to date.

High resolution images: NIR (Hubble Space Telescope, HST and Keck/AO) or sub-mm/mm (Sub-millimetre Array, SMA)**+ two different z measures along the same line of sight.**

(B) 8 sources likely to be lensed.

(C) 50 objects still wait for confirmation.

(D) 1 source not (strongly) lensed.



Credit: Negrello et al. (2017)

The Far-Infrared/Radio Correlation (FIRRC)

[5] *Yun et al. (2001)*
[6] *Condon et al. (2002).*

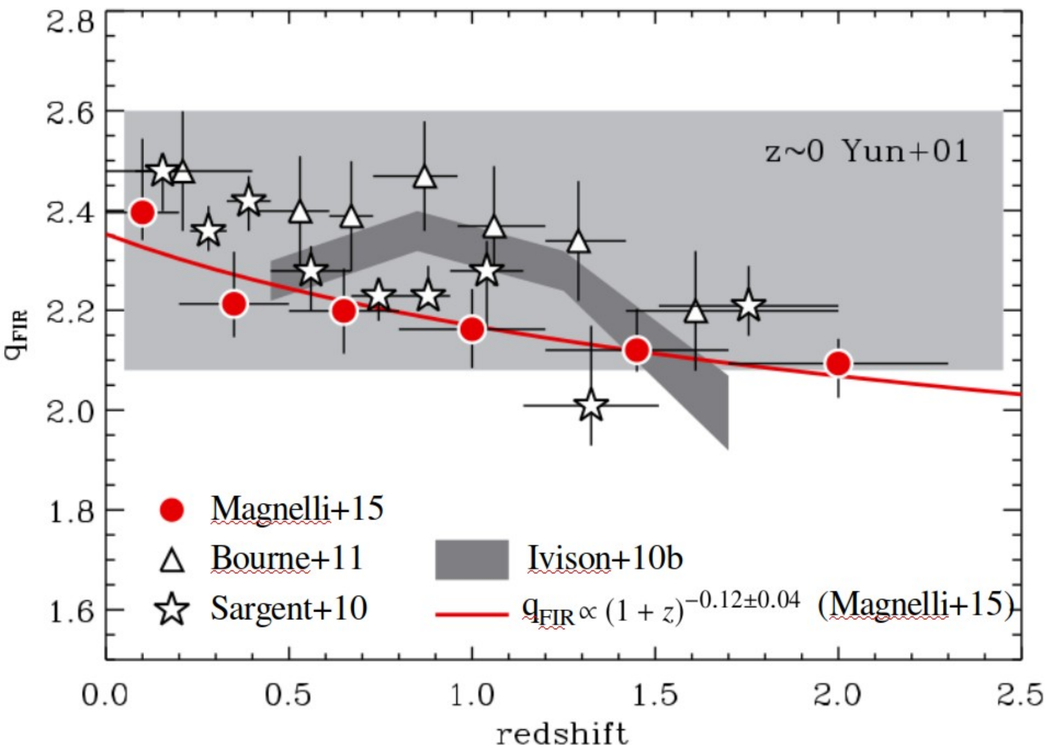
Empirical relation between radio and FIR luminosity of star-forming galaxies.

Parameterized via the FIR-to-radio luminosity ratio (q_{FIR}):

$$q_{FIR} = \log\left(\frac{L_{FIR}[\mathrm{W}]/3.75\times10^{12}}{L_{1.4\,\mathrm{GHz}}[\mathrm{W\,Hz^{-1}}]}\right)$$

Roughly linear across ~3 orders of magnitude in luminosity: $9 \lesssim \log(L_{IR}/L_{\odot}) \lesssim 12.5$ in the local Universe.
→ **Strictly linked to star-formation activity** [5]

Credit: Magnelli et al (2015)



→ **Radio continuum emission can be used as an unbiased tracer of SF**

Redshift evolution? (see also *Delvecchio et al., 2021*)

Presence of AGN:
Outliers in q_{FIR} are indicative of nuclear activity (i.e $q_{FIR} \lesssim 1.8$ [6])

The Sample

[7] *Becker et al., 1995*

Reconstruction of the FIRRC among the sample of 80 (candidate) lensed galaxies

Search for radio counterparts:

- NGP and GAMA fields are covered by the **FIRST** [7] (Faint Images of the Radio Sky at Twenty-cm) survey, performed with the VLA (NRAO Very Large Array) .

RMS~0.15 mJy

Angular resolution ~5 arcsec

- Radio counterparts available in literature
- The Southern Field (SGP)

Australia Telescope Compact Array (ATCA) 16 cm observations

Observations covering **30 positions** (22:30 <RA < 02:00 ; $-36 < \delta < -28$)

Project: C3215; PI: M. Massardi

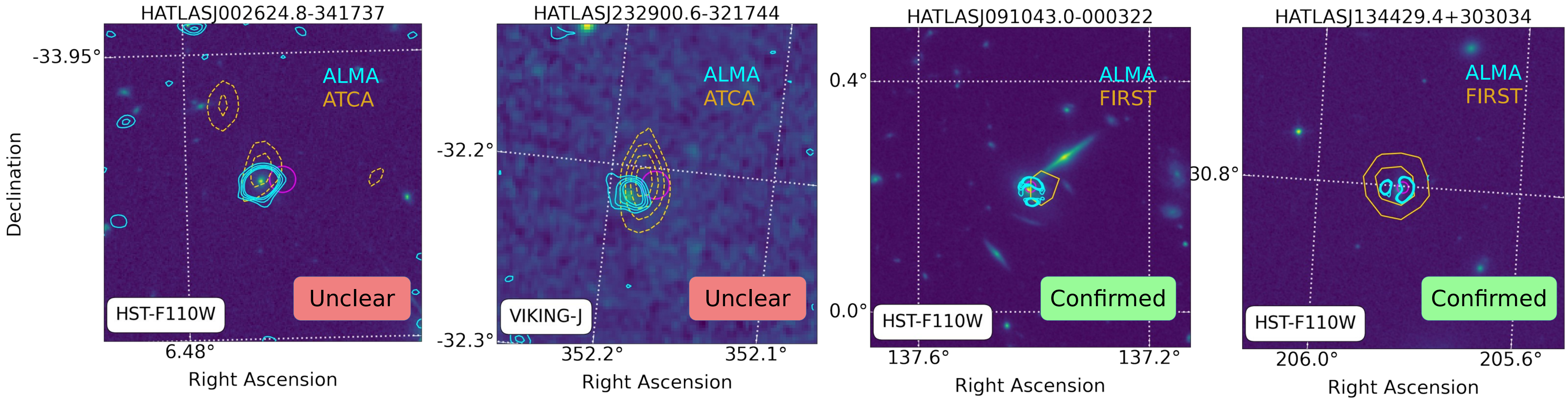
RMS~0.05 mJy

Angular resolution ~5 arcsec

The Sample

Counterpart association

Overlap between radio emission and high resolution images from NIR (HST, VIKING, UKIDSS) + mm (ALMA, where available).



ALMA: bands 4, 6, 7
θ~1.2 to $\lesssim$ 0.1 arcsec

Giulietti et al. (2022)

Final sample:
28 counterparts
12 confirmed to be lensed

General properties of our sample (uncorrected for magnification):

$1.9 \times 10^{24} \lesssim L_{1.4\,GHz}\,[WHz^{-1}] \lesssim 1.8 \times 10^{26}$

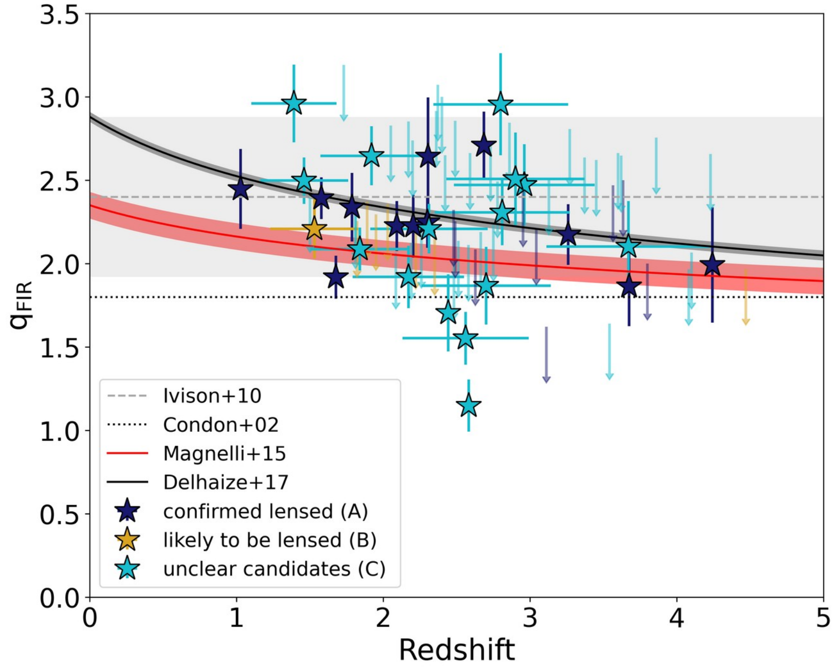
$1.3 \times 10^{13} \lesssim L_{FIR}/L_{\odot} \lesssim 1.1 \times 10^{14}$

Results

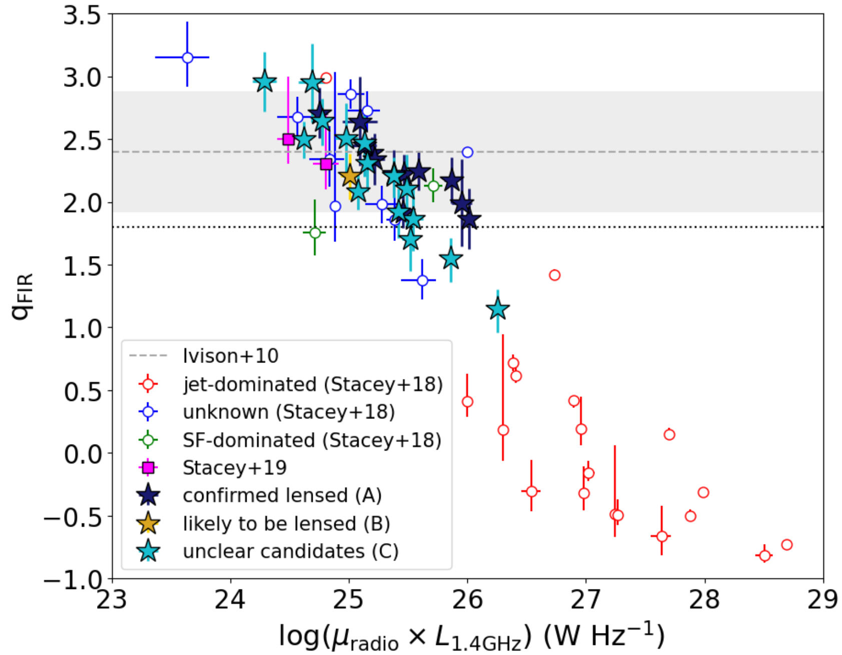
q_{FIR} was computed for the total 28 sources with a radio counterpart.

Giulietti et al. (2022)

Redshift evolution



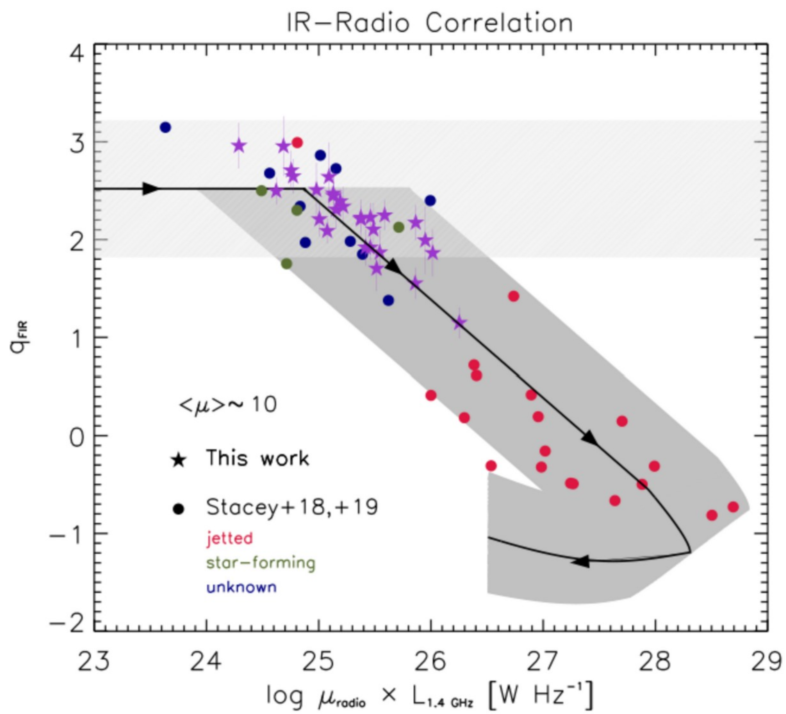
Comparison with *Stacey et al. (2018, 2019)*: sample of radio-selected lensed QSOs.



Weak evolution with redshift out to z $\lesssim$ 4.
Radio excess compatible with AGN presence (q_{FIR}<1.8).

Results

Possible physical interpretation



Giulietti et al. (2022)

- Early stages: small central BH and limited nuclear power → radio associated to star-formation activity ($q_{FIR} \approx 2.5$).
- Increasing of BH mass: nuclear radio emission > star formation (q_{FIR}<2.5).
- Late stage evolution: jets production (q_{FIR}<1.8).

Future perspectives

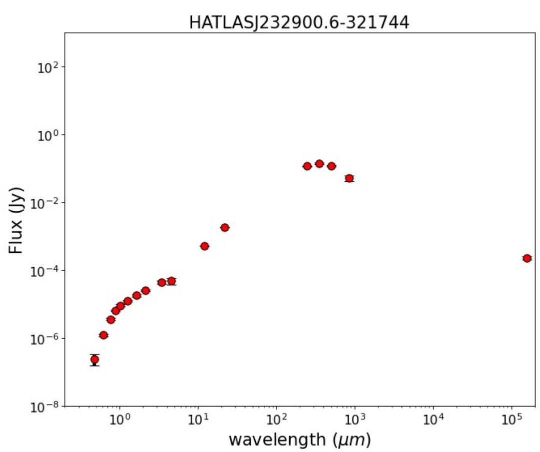
Multi-band observations of the 80 (candidate) lensed galaxies

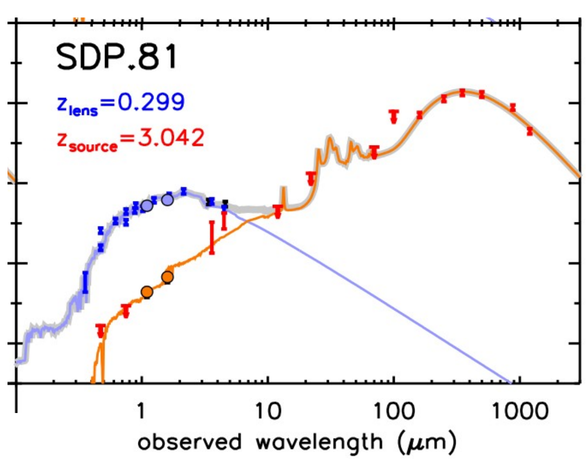
1) Reconstruction of the SEDs for the entire sample of the 80 candidate lensed galaxies.

Available photometric data

UV/ Optical	Near-IR/ Mid-IR	Far-IR/ sub-mm	mm/Radio
SDSS KiDS HSC	HST KiDS VIKING WISE	*Herschel* SCUBA SMA **ALMA**	**ALMA** FIRST ATCA

2) SED fitting→ Physical properties (SFR, M_{dust}, A_V, M_{star}, T_{dust} etc…)





Credit: Negrello et al. (2014)

Future perspectives

ALMA follow ups

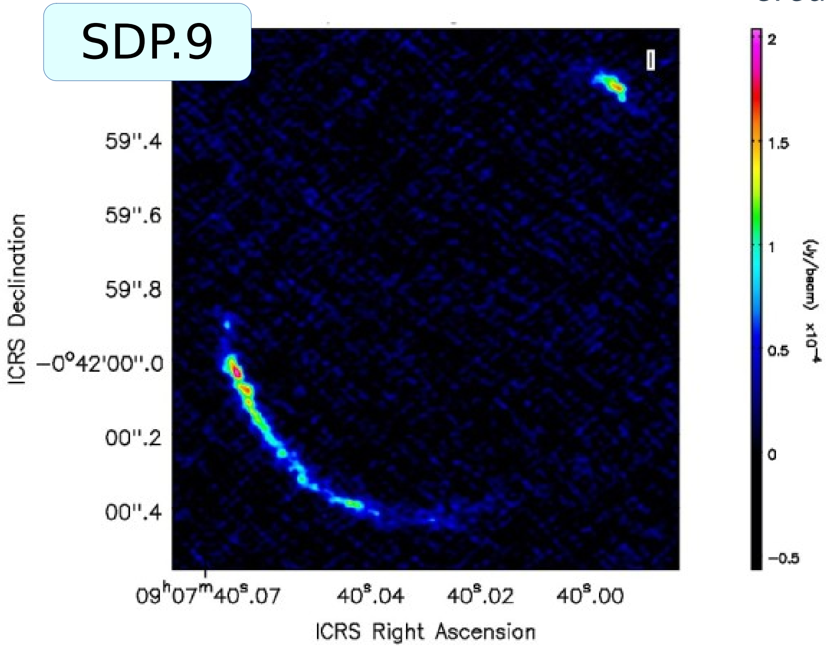
[12] *ALMA partnership (2015)*

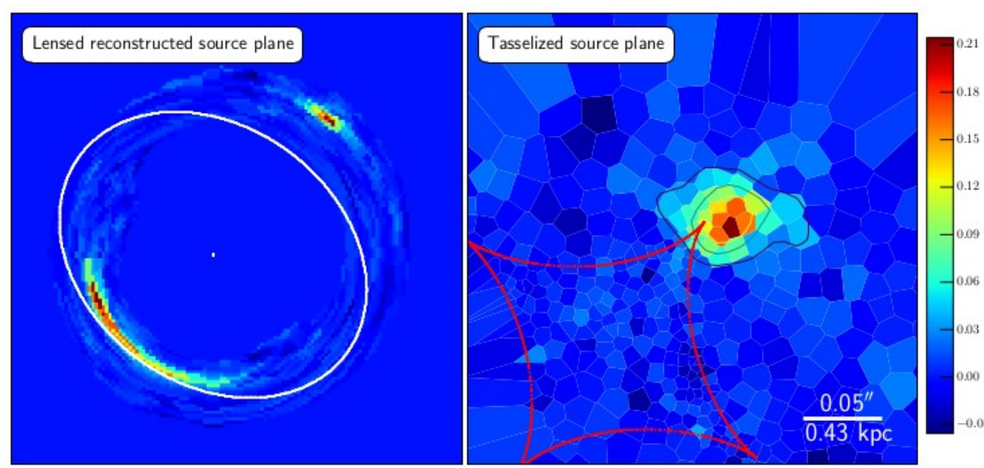
Observations at higher angular resolution and sensitivity are needed to:

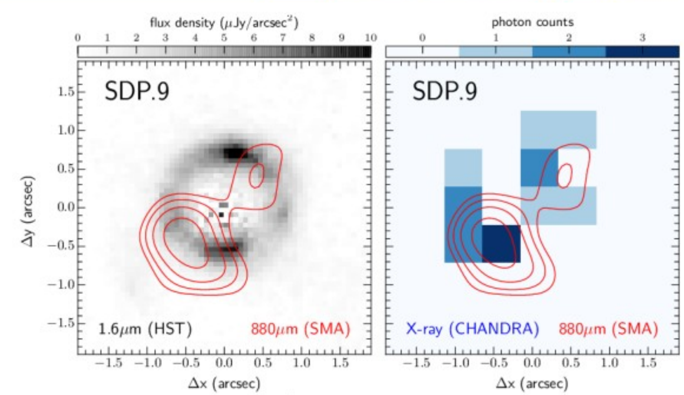
- Unveil the nature of unclear candidates.
- Identify the dust and gas properties associated with both the star formation process and tracing the nuclear feeding and feedback processes dynamics.

Credits: Massardi et al. (2018)

SDP.9







Continuum + CO(6-5) spectroscopic data: morphology reconstruction.

Multi-band observations: X-Ray emission as an AGN tracer.

Conclusions

- **Lensed DSFGs** selected in **sub-mm** are ideal targets for follow-up multi-band observations aimed at understanding the detailed properties of starburst phenomena in distant galaxies and the link with the AGN activity.
- Exploiting high-sensitivity radio data **we have reconstructed the FIRRC for a sample of 28 (candidate + confirmed) strong lensed galaxies** selected in the sub-mm H-ATLAS survey.
- We found a weak evolution with redshift, out to $z \lesssim 4$
- The decline in the qIR parameter vs $L_{1.4GHz}$ relation is compatible with the FIRRC found for a sample of lensed quasars and can be interpreted according to an in-situ galaxy evolution scenario.
- Some objects display a clear radio excess, signature of AGN presence → ideal candidates for testing co-evolutionary models.

Thank you!

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