Synergistic Study of High-z Strongly Lensed Dusty Star-Forming Galaxies with ALMA: Insights into Galaxy/AGN Co-evolution

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Main collaborators

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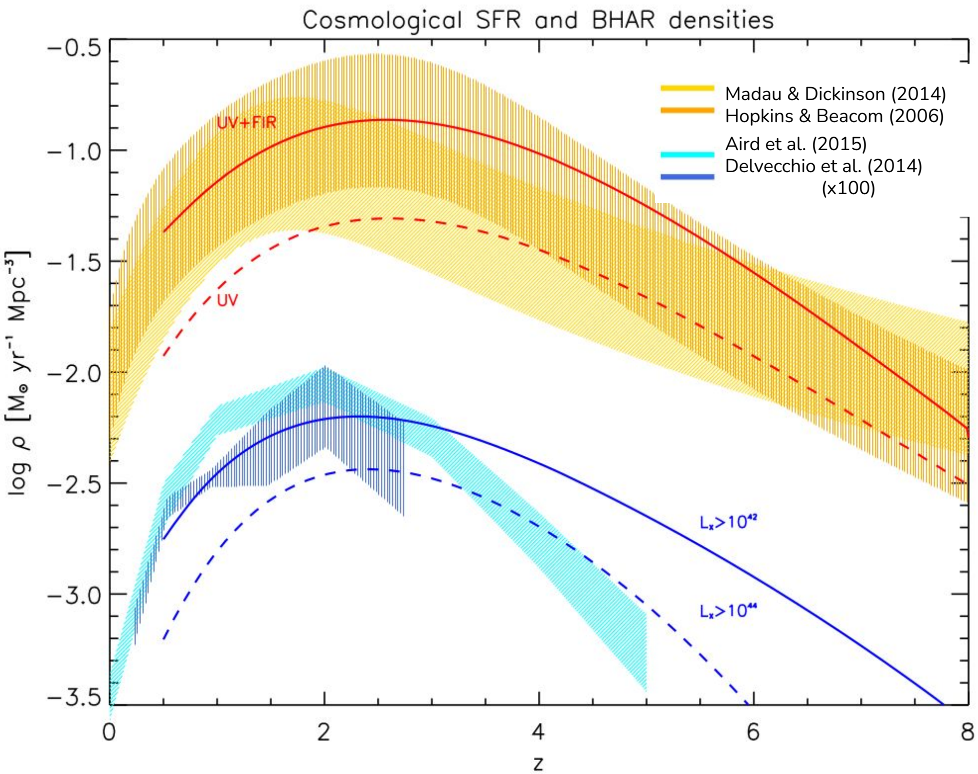
Fifth Workshop on Millimetre Astronomy in Italy
Bologna, 14/06/2023

Dusty star-forming galaxies

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



Credits: Mancuso+2016

- SFR≳100-1000 $M_{\odot}$ yr^{-1}

- z≳1

-Heavily **dust-obscured**

- DSFGs strongly contribute to the Star Formation History at 2<z<4.

- Progenitors of quiescent early-type galaxies

The cosmic BH accretion rate and SFR densities feature a similar evolution → **important to test co-evolutionary models.** (1)

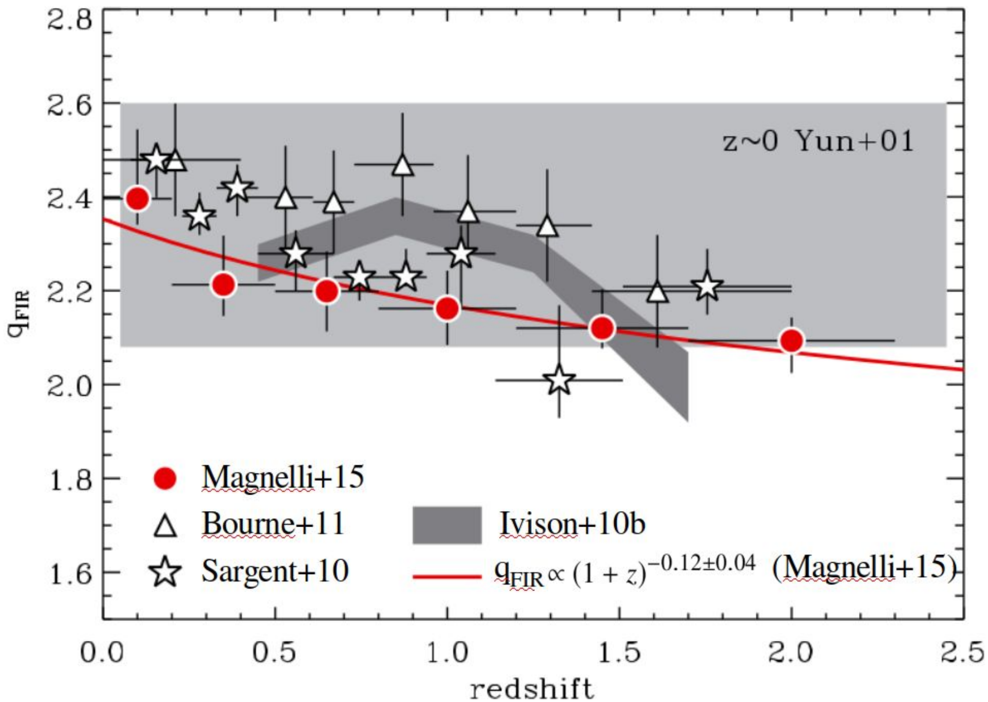
High-quality multi-band data are needed to investigate DSFGs' structure in different evolutionary phases.

The FIR/Radio-correlation (FIRRC)

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

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

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



Credit: Magnelli+15

Redshift evolution? e.g. Murphy+09, Lacki & Thompson 2010, Sargent+10, Delhaize+17, Delvecchio+21

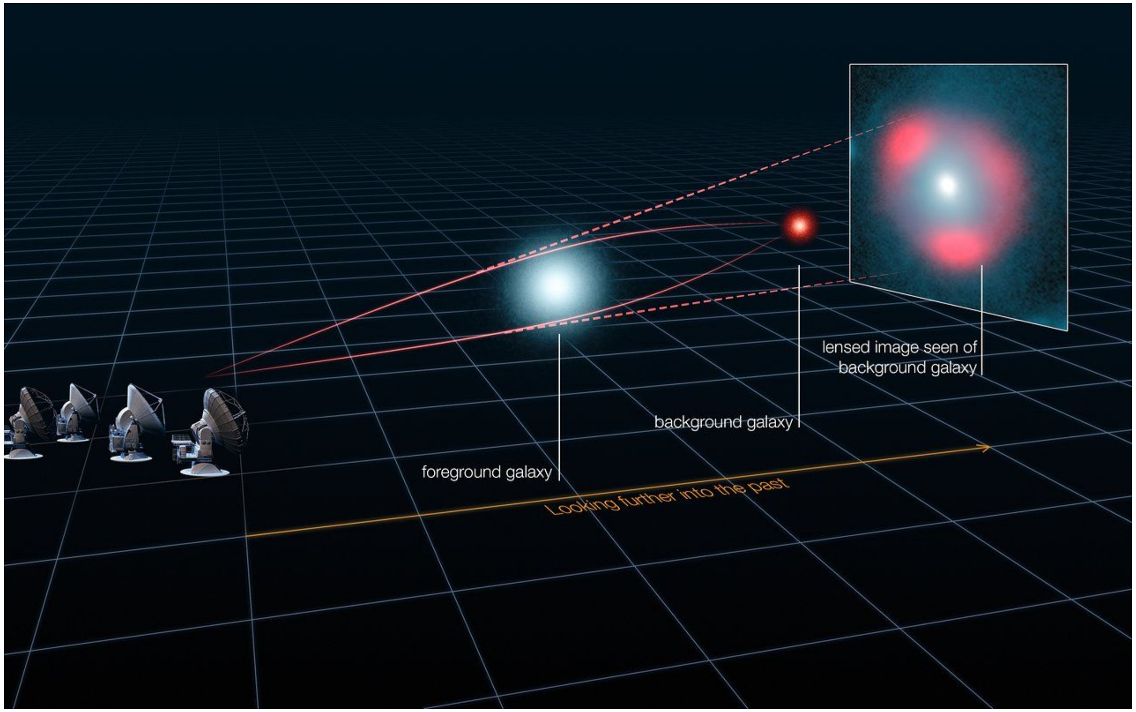
Presence of AGN:

Outliers in $q_{\rm FIR}$ are indicative of nuclear activity (i.e $q_{\rm FIR} \lesssim 1.8$, Condon+02)

How to overcome limits in sensitivity/angular resolution?

High-z DSFGs are compact: typical intrinsic sizes of few ~ kpc, corresponding to a few tenths of an arcsec at z~2 (e.g. Pantoni+21) → **very hard to resolve!**

→Gravitational lensing



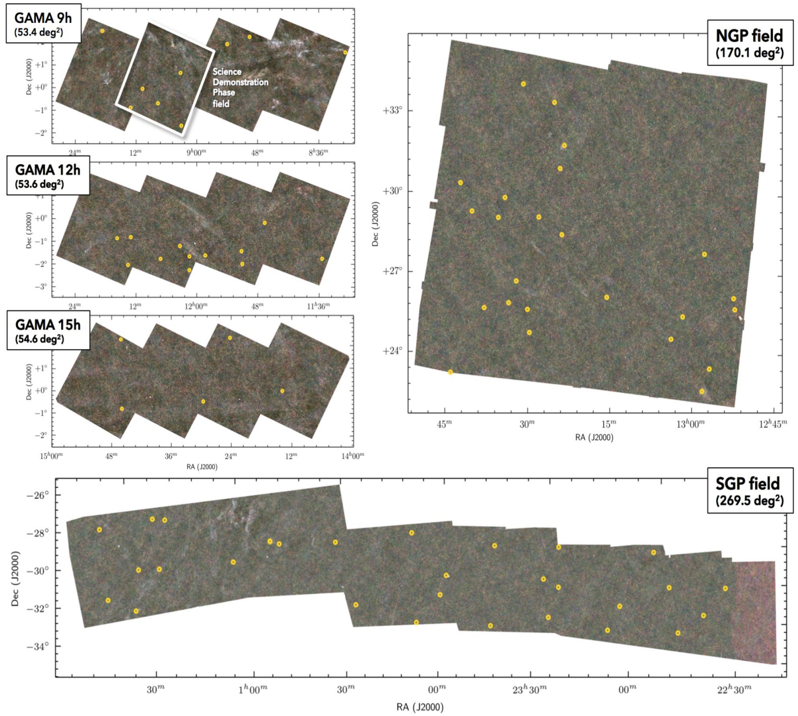
Gravity of massive objects can work the fabric of space-time. The path of photons from distant sources is affected by gravity.

- Apparent luminosity increased by a factor **μ**.

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

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

Lensed galaxies in the *Herschel*-ATLAS survey



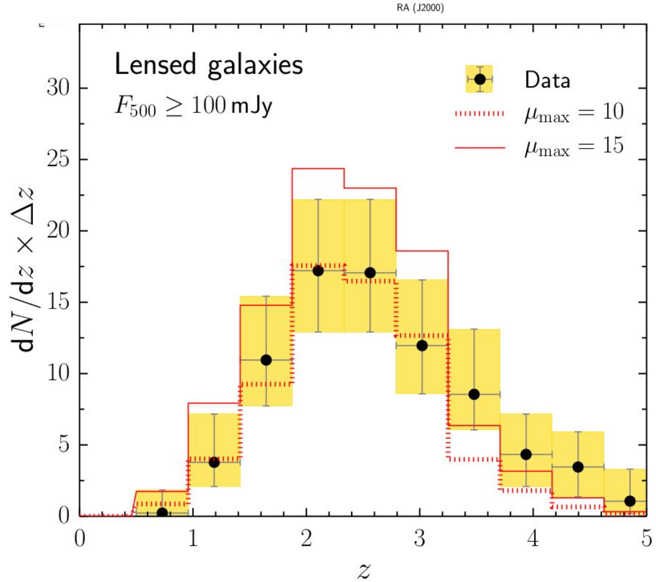
(Eales et al. 2010)

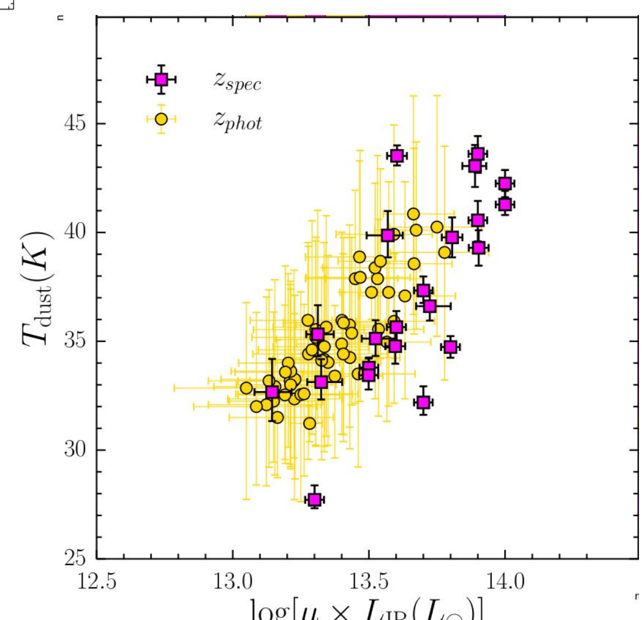
Candidate strongly lensed galaxies:
80 (Negrello+17) + 11 (Ward+22)

Selection criteria: $S_{500\ \mu m} \gtrsim 100$ mJy.

22 strong lensing events **confirmed** to date

See also HerBS and BEARS samples (Bakx+18, Urquhart+22, Bendo+23, Hagimoto+23)





Credits: Negrello+17

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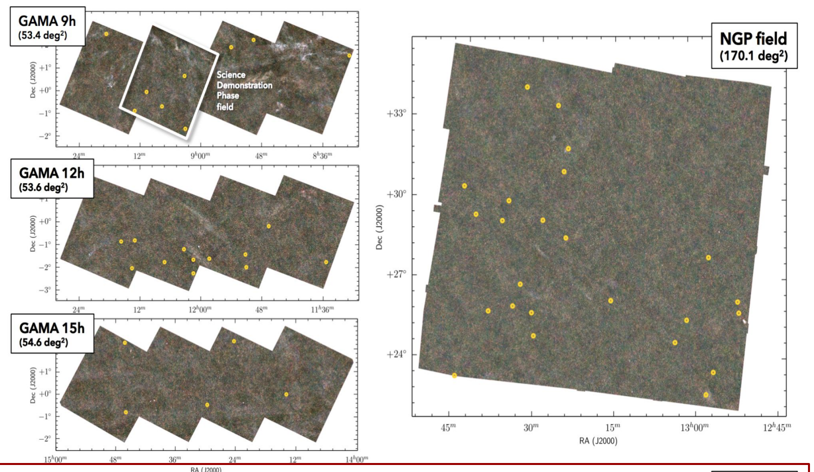

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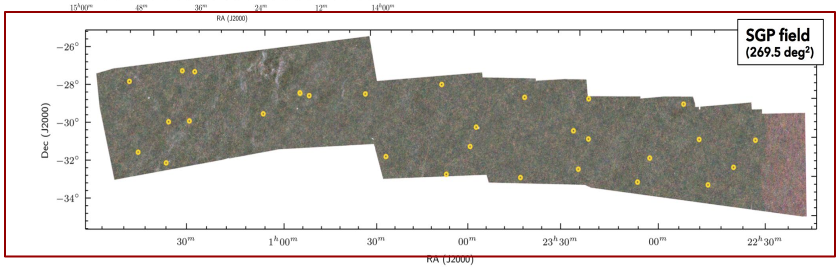
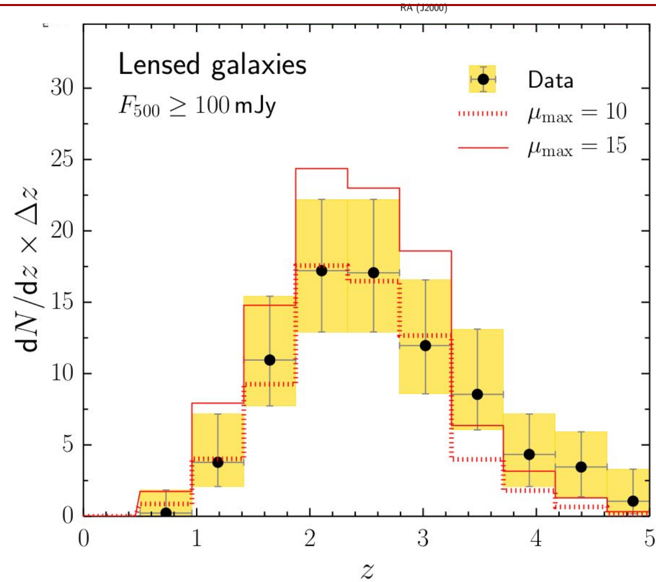
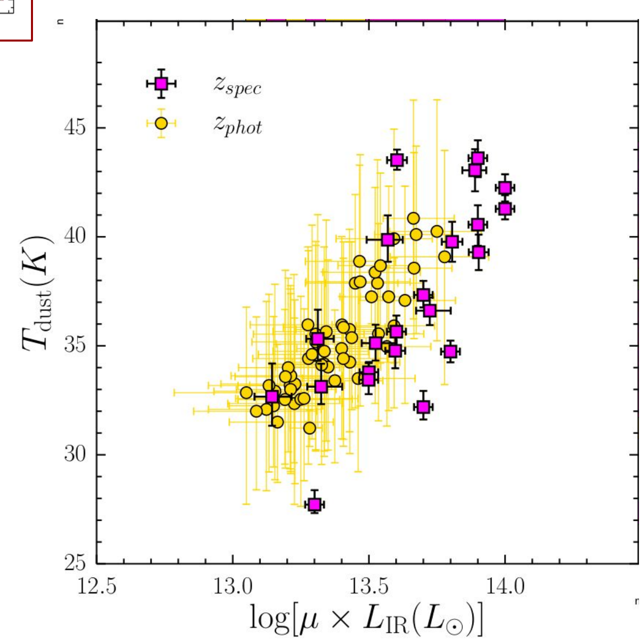


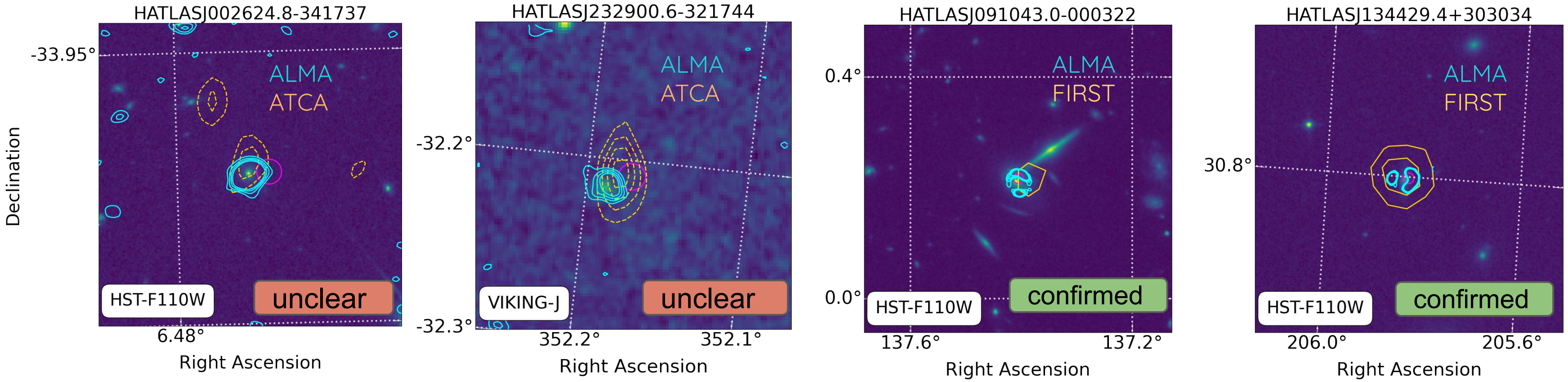
Sample observed by SHORES (see also M. Behiri poster)





Credits: Negrello+17

The Far-Infrared/Radio Correlation for strongly-lensed galaxies



Final sample of radio counterparts:
28 (candidate) strongly-lensed sources
<u>12 confirmed to be lensed</u>

Giulietti et al. (2022), MNRAS

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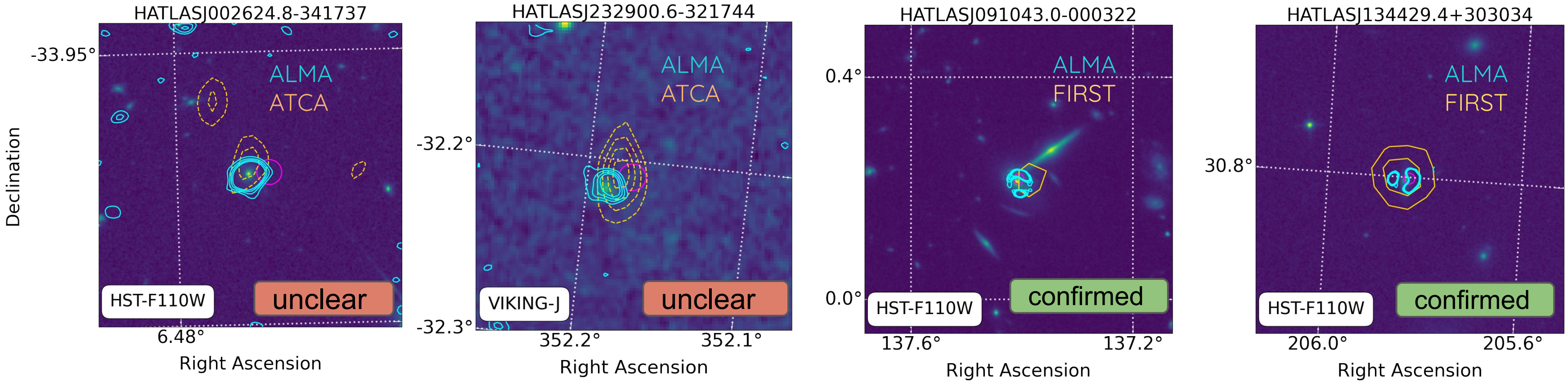

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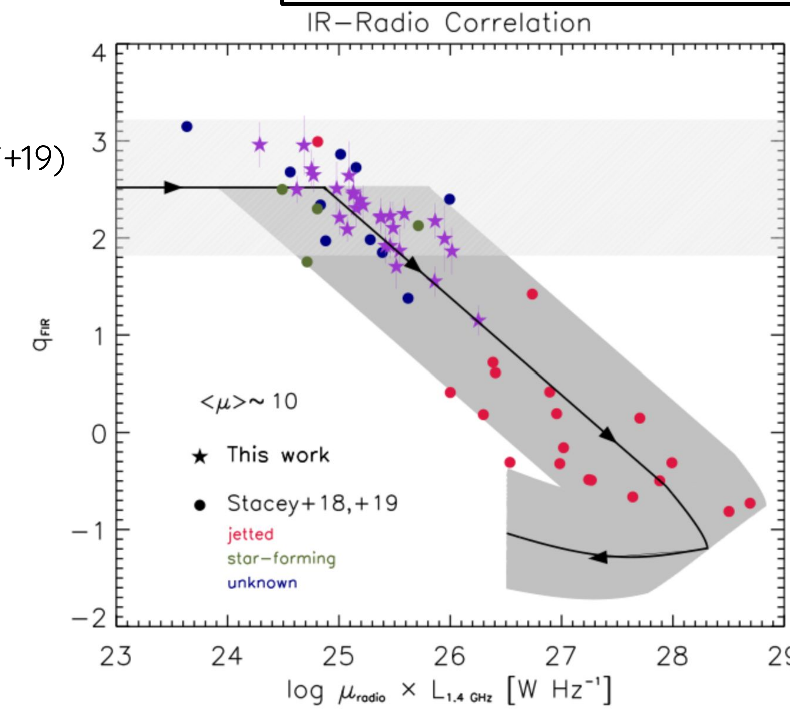
Testing the in-situ model (Lapi+14,+18; Mancuso+17, Pantoni+19)

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).



Study individual sources

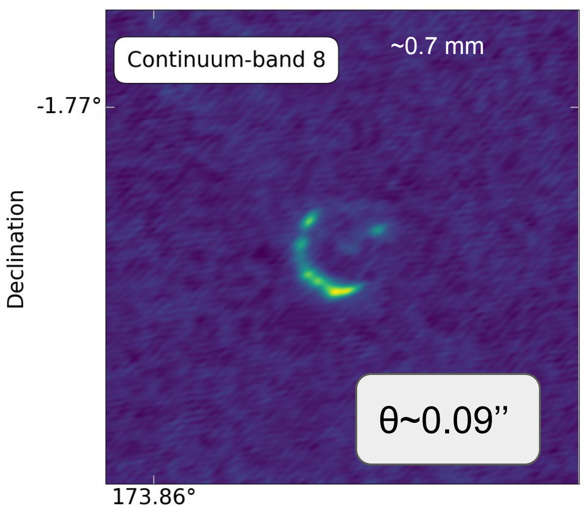
<u>HATLASJ113526.3-014605 (or G12v2.43 or G12H43)</u>

Source redshift: 3.1276±0.0005, spectroscopic
Lens redshift: unknown
μL_{FIR} ~1.2×10^{14} $L_{\odot}$

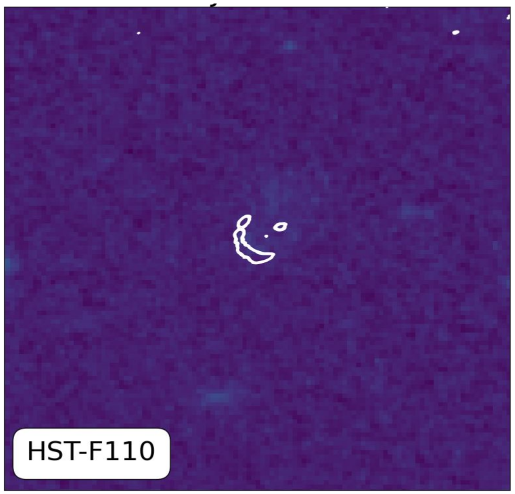
Previous works (debated lensing nature):
Harris et al. (2011)
Yang et al. (2016)
Vishwas et al. (2018)

Marginally resolved in Sub-mm Array (SMA) observations at 0.8" (*Bussmann et al. 2013*).

Strong lensing event confirmed by ALMA Observations



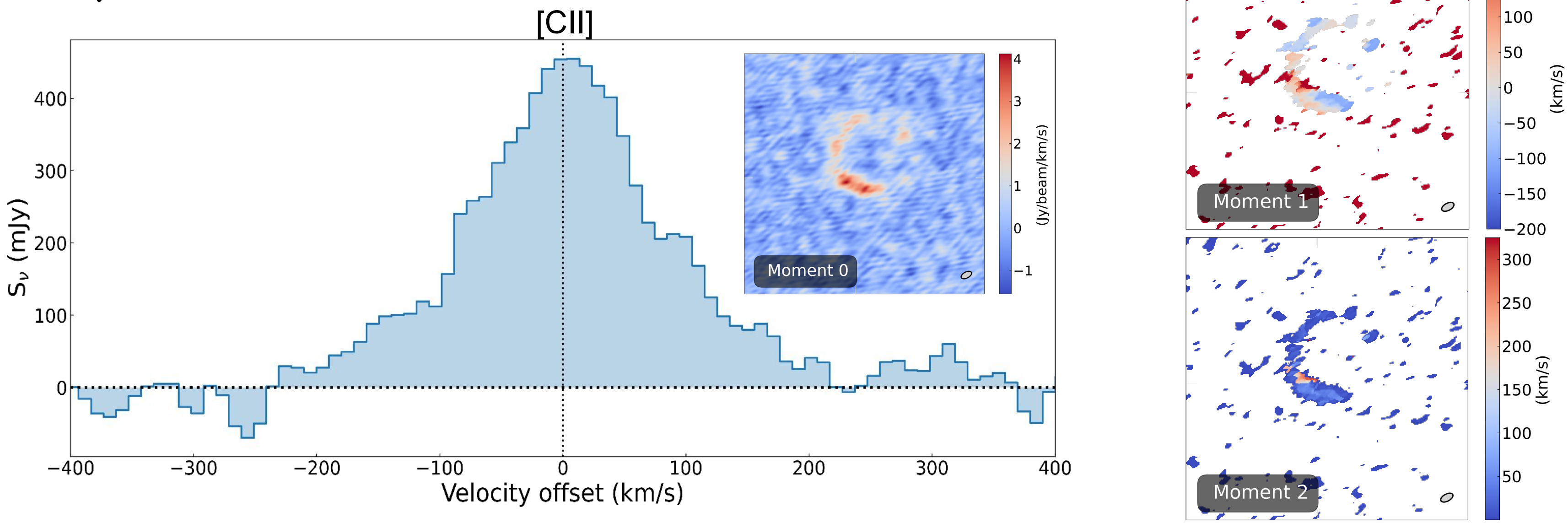
No previous lens modelling

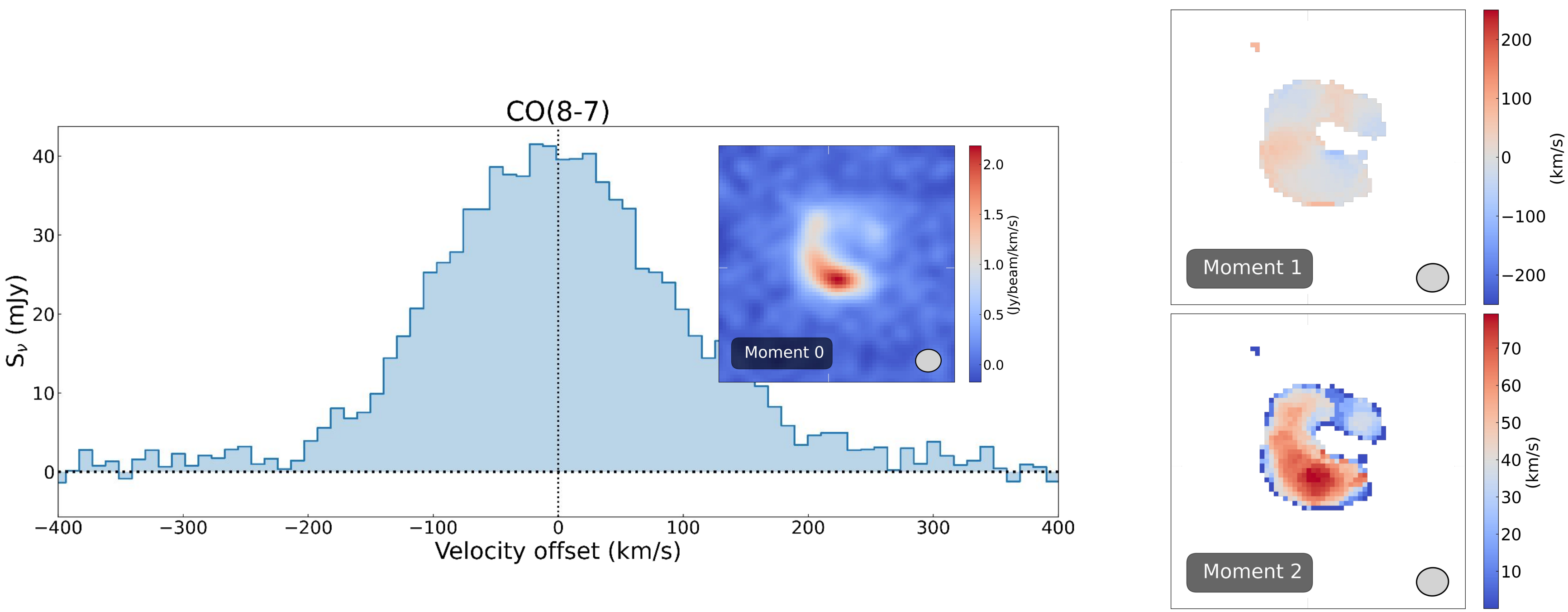


No clear NIR counterpart

See also F. Gentile's poster on Rs-NIR Dark galaxies!

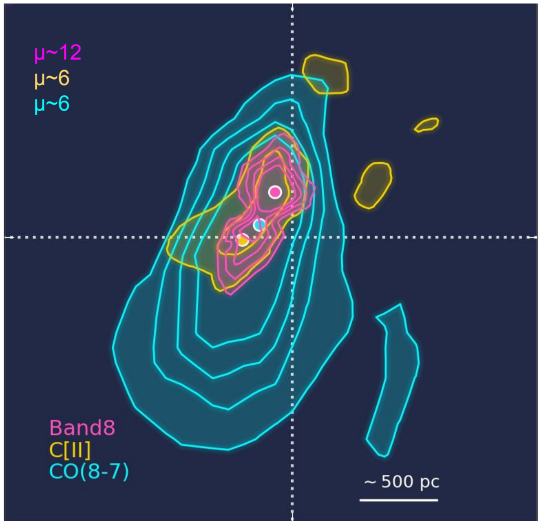
Spectral lines

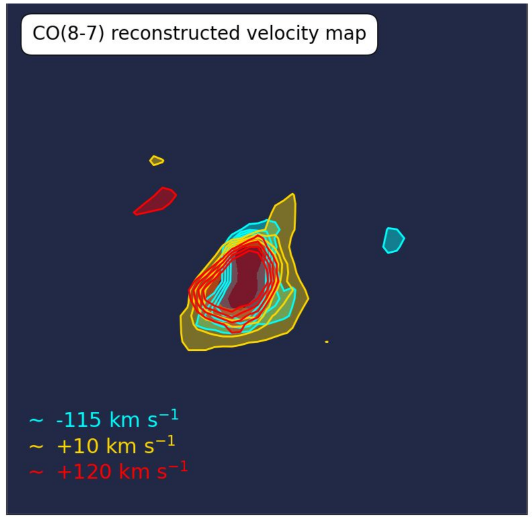




Results - lens modeling and physical properties

Lens Modeling: `PyAutoLens`, open source Python 3.6+ package for strong gravitational lensing (*Nightingale+2021*)





- Compact dust emission

- Source reconstruction of the CO(8-7) emission in 3 different velocity bins
→ **No clear evidence of strong rotation/outflows**

Giulietti et al. (2023), ApJ

SED-fitting results	
$\log L_{dust}$ $(L_\odot)$	13.03 ± 0.06
$\log M_{dust}$ $(M_\odot)$	9.06 ± 0.04
$\log SFR$ $(M_\odot\ yr^{-1})$	2.97 ± 0.08
$\log M_\star$ $(M_\odot)$	$\lesssim 11.75$
q_{IR}	2.84 ± 0.09

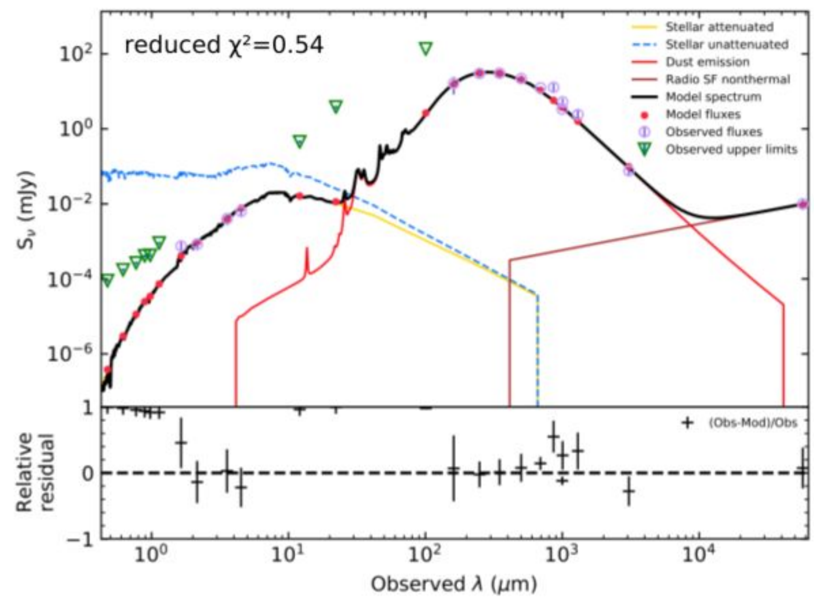
Gas Masses

$M_{gas,\ C[II]} \sim 10^{11}\ M_\odot$

$M_{gas,\ CO} \sim (2\text{-}8) \times 10^{10}\ M_\odot$

$M_{gas,DGR} \sim (3\text{-}11) \times 10^{10}\ M_\odot$

CIGALE (Boquien et al. 2019) :



Results - evolutionary interpretation

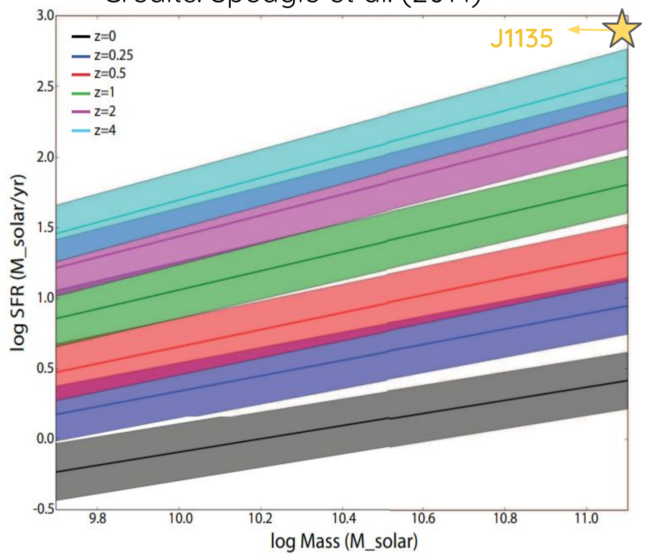
$\rho_{SFR} \simeq 1153.8\ M_\odot\ yr^{-1}\ kpc^{-2}$ **> Eddington limit for a radiation pressure supported starburst**

$t_{depl} = M_{gas}/SFR \simeq 10^8$ yr

$t_{SFR} = M_\star/SFR \simeq 10^8$ yr

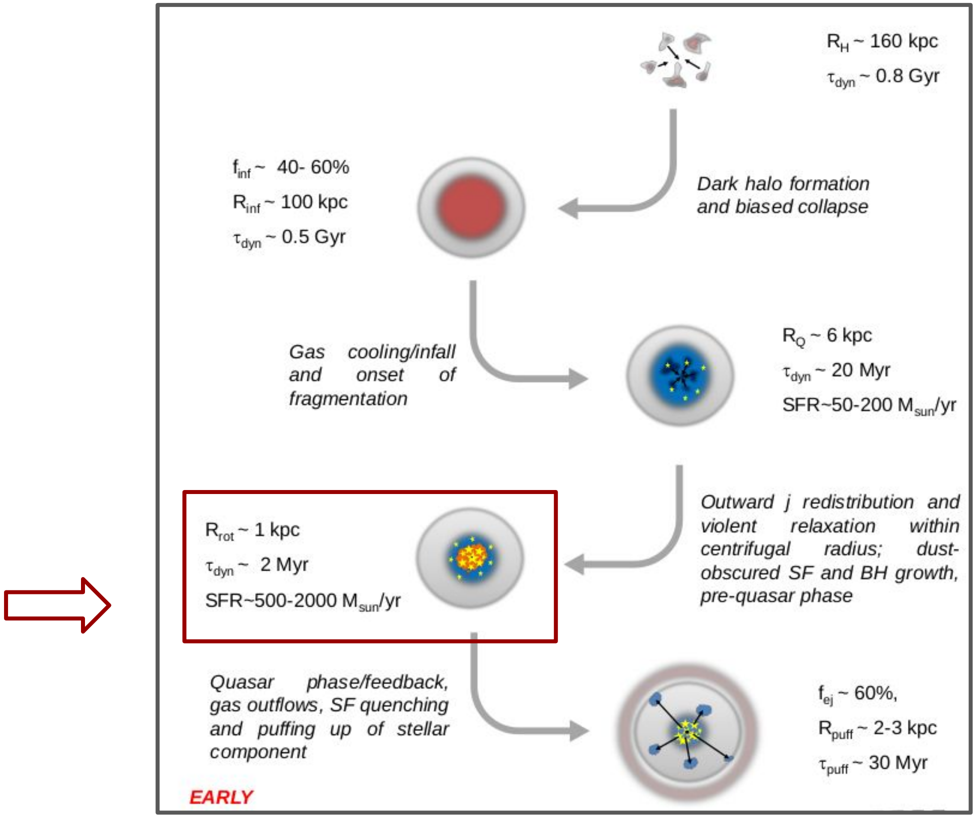
→ off main sequence, **young compact starburst**

Credits: Speagle et al. (2014)



Compatible with the **compaction stage** predicted by the in-situ scenario.

in-situ model



Credits: Lapi et al. (2018)

Summary and conclusions

- Exploiting **high-sensitivity radio data + millimetric ALMA observations** we have reconstructed the FIRRC for a sample of 28 (candidate + confirmed) strongly lensed galaxies selected in the sub-mm H-ATLAS survey (up to z~4).

- Thanks to **ALMA high resolution observations** (continuum + CO(8-7) and [CII]) we were able to perform the lens modelling of a previously unconfirmed peculiar strongly lensed DSFGs.

    - Our analysis in compatible with J1135 being a compact starburst object triggered by in situ processes at the early stages of its evolution.

- The combination of high sensitivity/angular resolution multi-wavelength data of lensed sources are a powerful tool to investigate AGN/galaxy co-evolution.

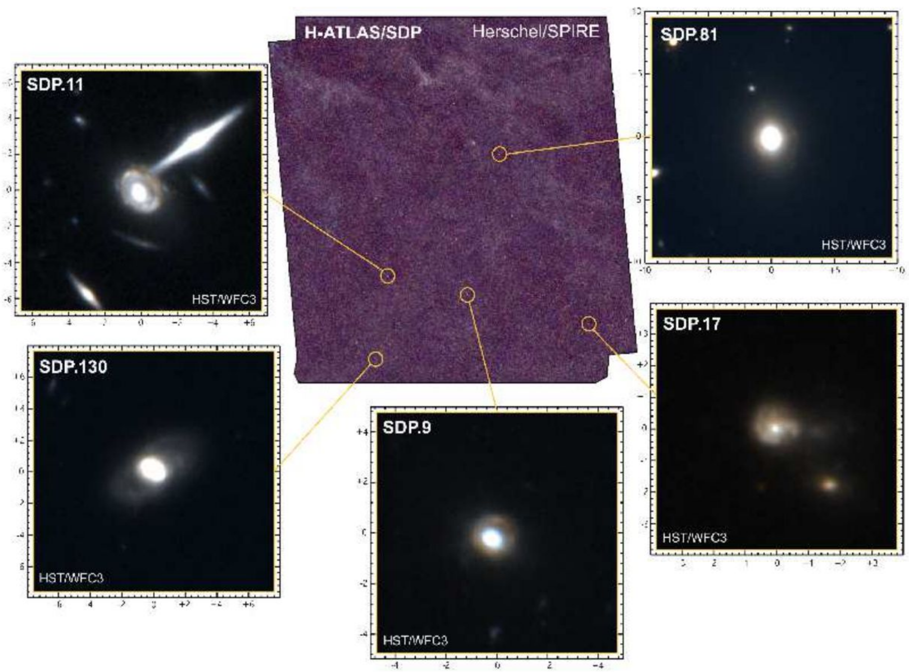
Thank you!

Backup slides

Results - what about the lens?

Expectations

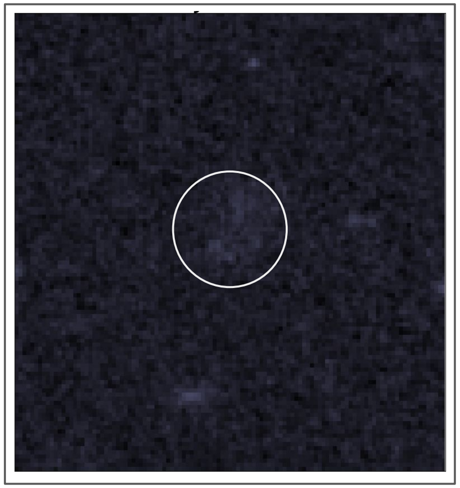
Other strongly lensed galaxies in H-ATLAS



Credits: Negrello et al. (2010)

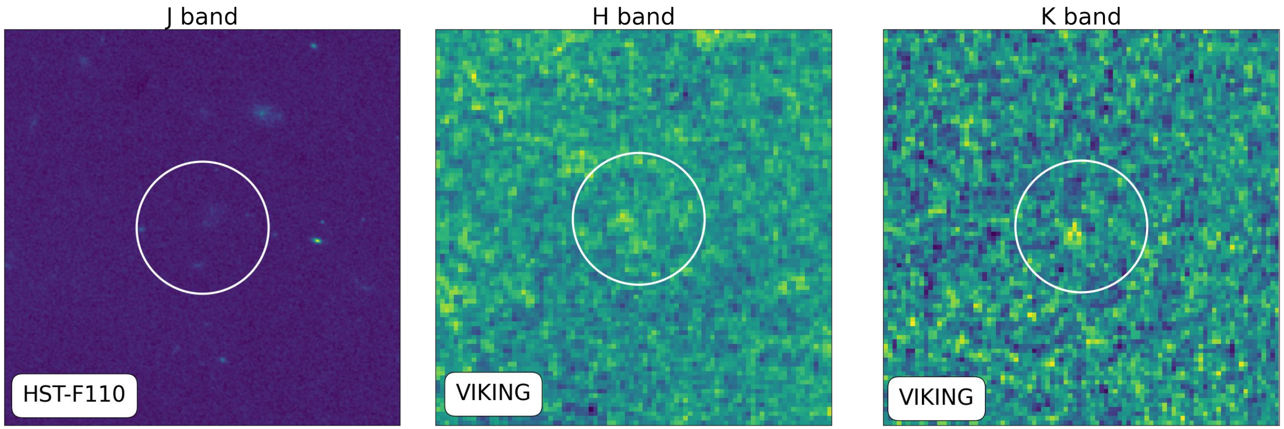
Reality

J1135



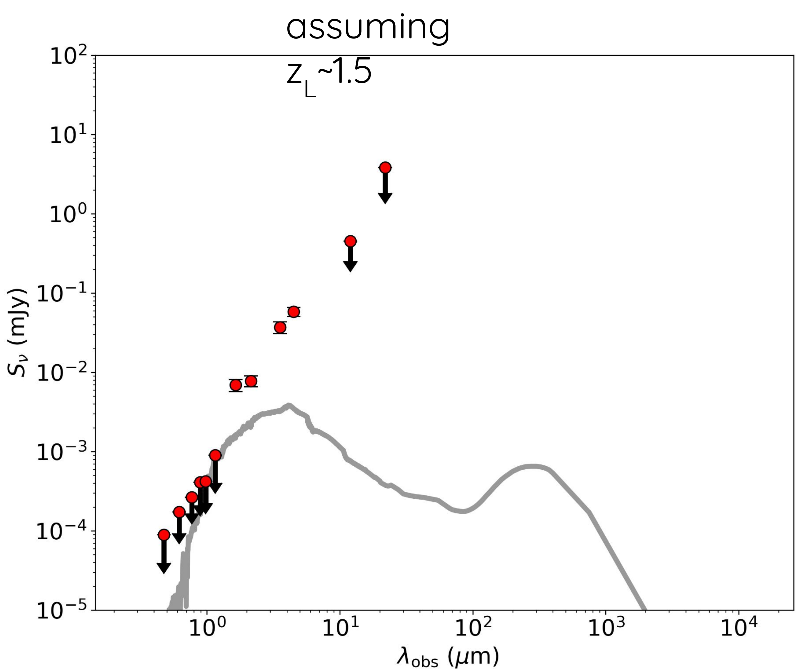
No clear counterpart in J-band (HST/WFC3) high resolution image.

Results - what about the lens?



No redshift measurement.

No clear counterpart in optical/NIR images.



Constrain from lens modelling: M_E~1.2 x 10^{11} $M_\odot$

→No significant contribution from the foreground lens to the overall SED

→No need for lens subtraction

Further observations needed → JWST (NIRCam+MIRI)