SPICA at the Highest Redshifts

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UK SPICA meeting, 3 December 2018

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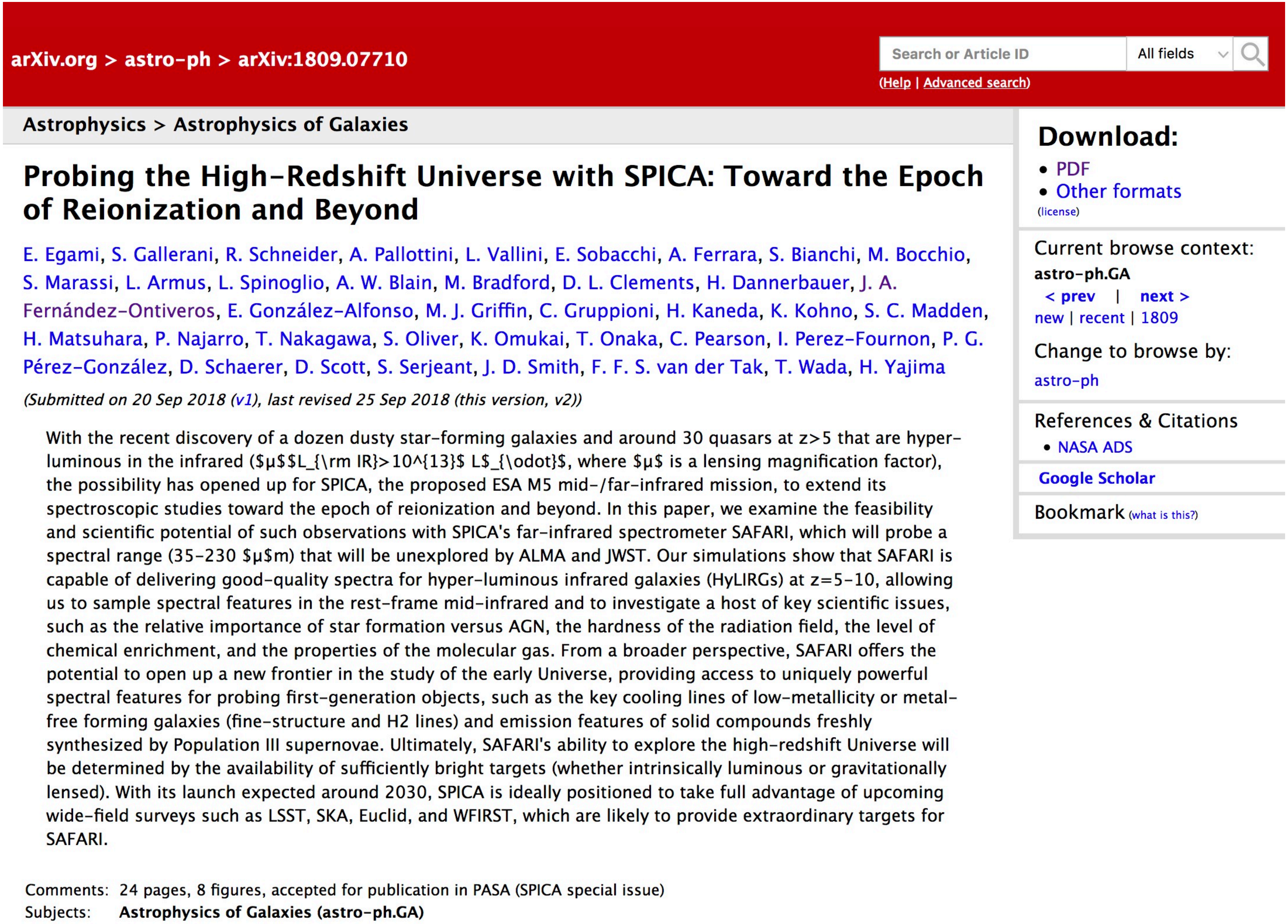

Astrophysics > Astrophysics of Galaxies

Probing the High-Redshift Universe with SPICA: Toward the Epoch of Reionization and Beyond

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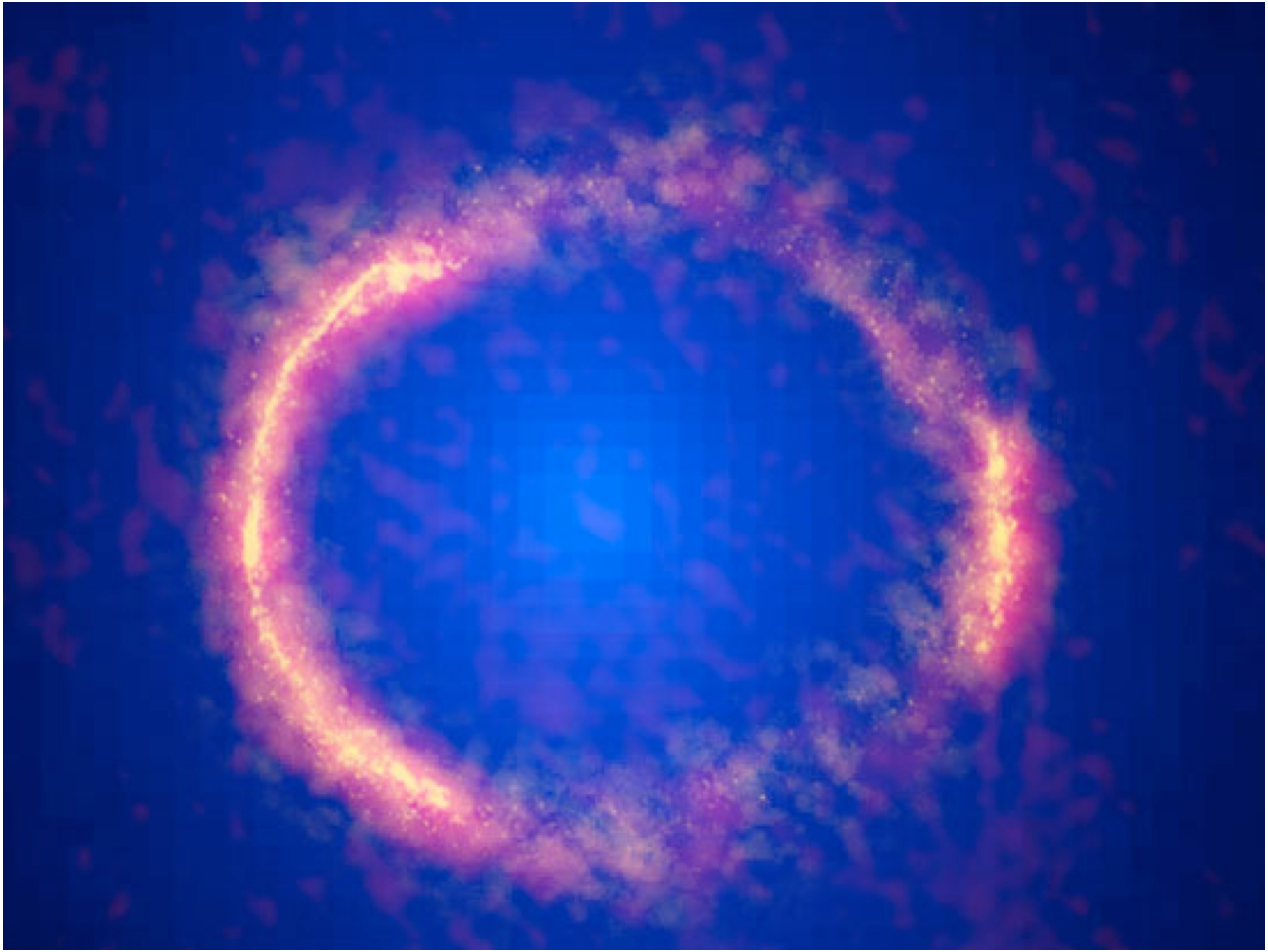
With the recent discovery of a dozen dusty star-forming galaxies and around 30 quasars at z>5 that are hyper-luminous in the infrared ($µ$$L_{\rm IR}>10^{13}$ L$_{\odot}$, where $µ$ is a lensing magnification factor), the possibility has opened up for SPICA, the proposed ESA M5 mid-/far-infrared mission, to extend its spectroscopic studies toward the epoch of reionization and beyond. In this paper, we examine the feasibility and scientific potential of such observations with SPICA's far-infrared spectrometer SAFARI, which will probe a spectral range (35-230 $µ$m) that will be unexplored by ALMA and JWST. Our simulations show that SAFARI is capable of delivering good-quality spectra for hyper-luminous infrared galaxies (HyLIRGs) at z=5-10, allowing us to sample spectral features in the rest-frame mid-infrared and to investigate a host of key scientific issues, such as the relative importance of star formation versus AGN, the hardness of the radiation field, the level of chemical enrichment, and the properties of the molecular gas. From a broader perspective, SAFARI offers the potential to open up a new frontier in the study of the early Universe, providing access to uniquely powerful spectral features for probing first-generation objects, such as the key cooling lines of low-metallicity or metal-free forming galaxies (fine-structure and H2 lines) and emission features of solid compounds freshly synthesized by Population III supernovae. Ultimately, SAFARI's ability to explore the high-redshift Universe will be determined by the availability of sufficiently bright targets (whether intrinsically luminous or gravitationally lensed). With its launch expected around 2030, SPICA is ideally positioned to take full advantage of upcoming wide-field surveys such as LSST, SKA, Euclid, and WFIRST, which are likely to provide extraordinary targets for SAFARI.

Comments:	24 pages, 8 figures, accepted for publication in PASA (SPICA special issue)
Subjects:	**Astrophysics of Galaxies (astro-ph.GA)**

The 2030 landscape

- Post-JWST (nearly?)
- ELT first light 2024+
- SKA key projects from ~2025+
- ALMA 2030 Development Plan



The 2030 landscape

ORIGINS OF GALAXIES

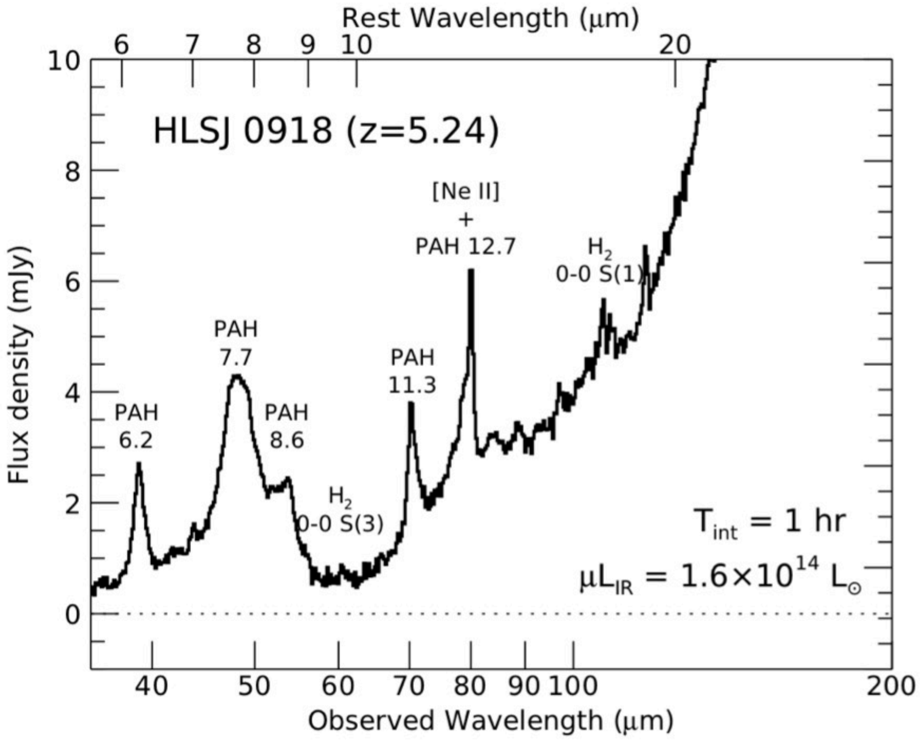
Trace the cosmic evolution of key elements from the first galaxies (z>10) through the peak of star formation (z=2–4) by detecting their cooling lines, both atomic ([CII], [OIII]) and molecular (CO), and dust continuum, at a rate of 1-2 galaxies per hour.

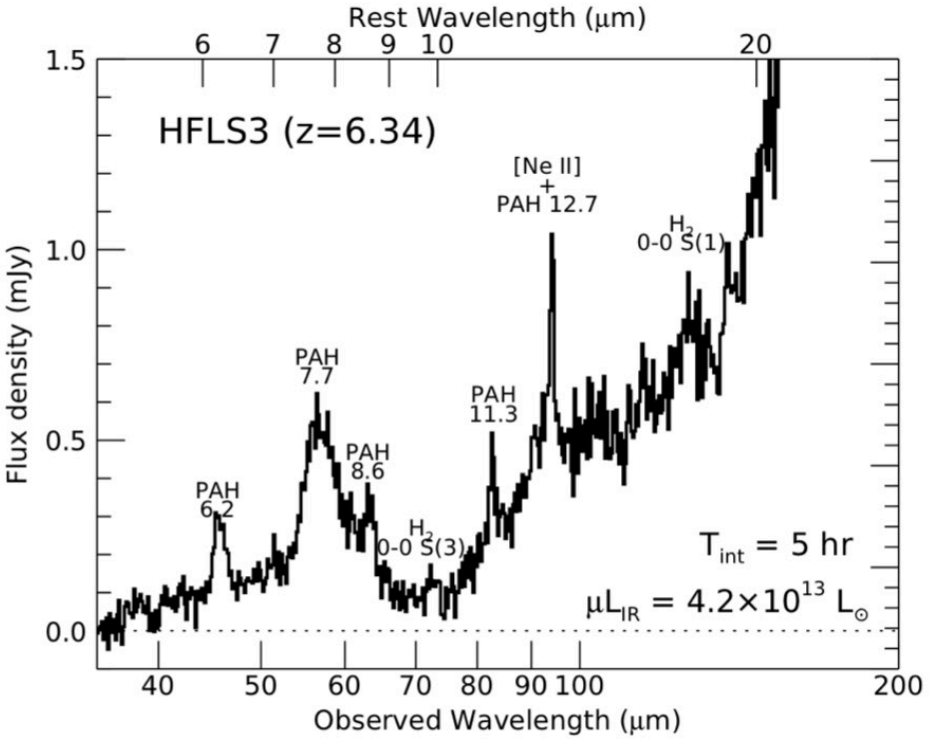
Provocative statement

We will not care much about $z=2$ in 2030

Dusty star-forming galaxies at z>5

- PAH, continuum ⇒ SB, AGN
- [NeII(12.8μm)]/[NeIII(15.6μm)] ⇒ U
- H_2 0–0 S(1) /0–0 S(3) 17.0/9.66 μm ⇒ T, M_{gas}





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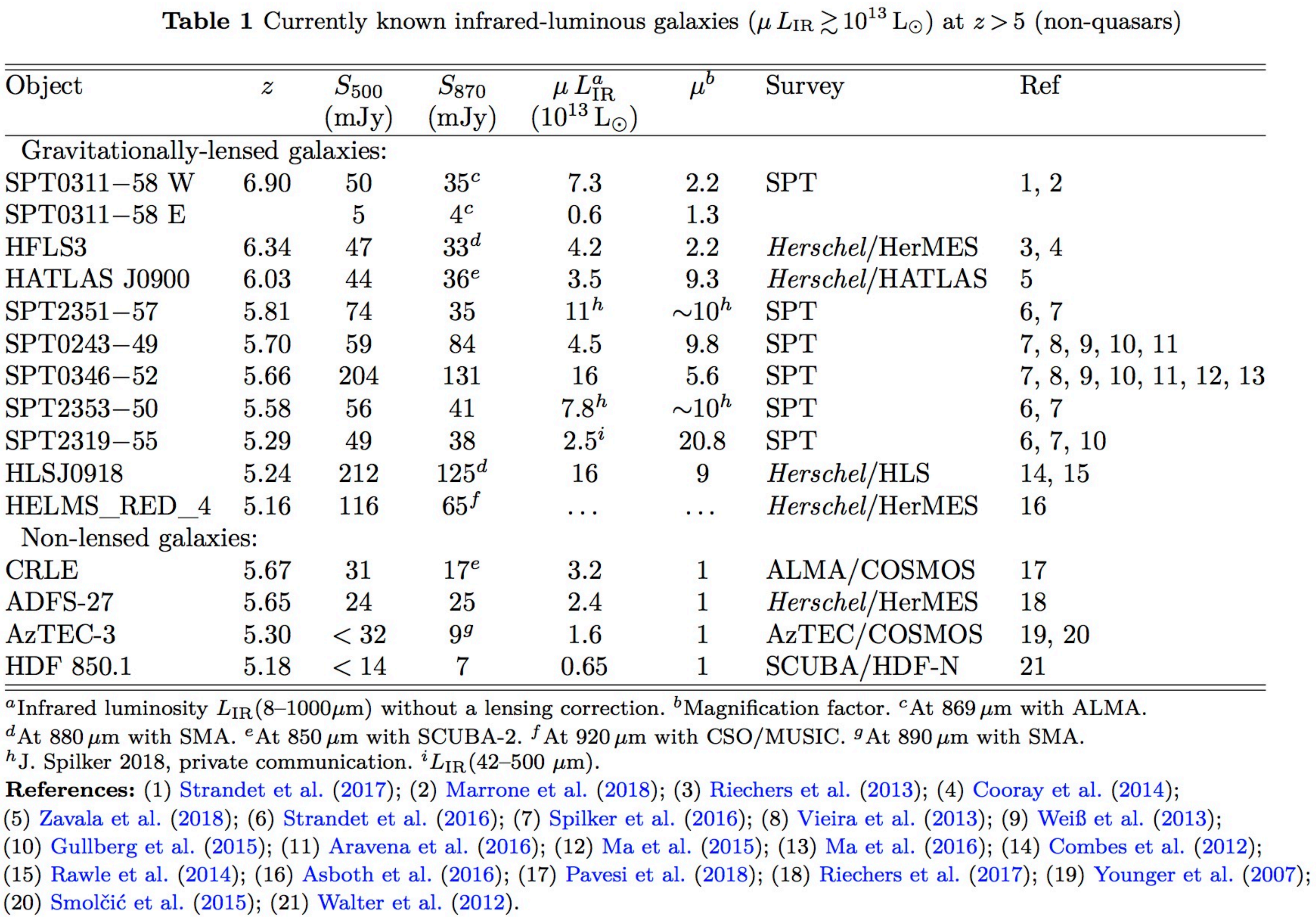

Table 1 Currently known infrared-luminous galaxies ($\mu\,L_{\rm IR} \gtrsim 10^{13}\,{\rm L}_\odot$) at $z > 5$ (non-quasars)

Object	z	S_{500} (mJy)	S_{870} (mJy)	$\mu\,L_{\rm IR}^{a}$ ($10^{13}\,{\rm L}_\odot$)	μ^{b}	Survey	Ref
Gravitationally-lensed galaxies:							
SPT0311−58 W	6.90	50	35^{c}	7.3	2.2	SPT	1, 2
SPT0311−58 E		5	4^{c}	0.6	1.3		
HFLS3	6.34	47	33^{d}	4.2	2.2	*Herschel*/HerMES	3, 4
HATLAS J0900	6.03	44	36^{e}	3.5	9.3	*Herschel*/HATLAS	5
SPT2351−57	5.81	74	35	11^{h}	$\sim 10^{h}$	SPT	6, 7
SPT0243−49	5.70	59	84	4.5	9.8	SPT	7, 8, 9, 10, 11
SPT0346−52	5.66	204	131	16	5.6	SPT	7, 8, 9, 10, 11, 12, 13
SPT2353−50	5.58	56	41	7.8^{h}	$\sim 10^{h}$	SPT	6, 7
SPT2319−55	5.29	49	38	2.5^{i}	20.8	SPT	6, 7, 10
HLSJ0918	5.24	212	125^{d}	16	9	*Herschel*/HLS	14, 15
HELMS_RED_4	5.16	116	65^{f}	…	…	*Herschel*/HerMES	16
Non-lensed galaxies:							
CRLE	5.67	31	17^{e}	3.2	1	ALMA/COSMOS	17
ADFS-27	5.65	24	25	2.4	1	*Herschel*/HerMES	18
AzTEC-3	5.30	< 32	9^{g}	1.6	1	AzTEC/COSMOS	19, 20
HDF 850.1	5.18	< 14	7	0.65	1	SCUBA/HDF-N	21

[a] Infrared luminosity $L_{\rm IR}$(8–1000μm) without a lensing correction. [b] Magnification factor. [c] At 869 μm with ALMA.
[d] At 880 μm with SMA. [e] At 850 μm with SCUBA-2. [f] At 920 μm with CSO/MUSIC. [g] At 890 μm with SMA.
[h] J. Spilker 2018, private communication. [i] $L_{\rm IR}$(42–500 μm).

References: (1) Strandet et al. (2017); (2) Marrone et al. (2018); (3) Riechers et al. (2013); (4) Cooray et al. (2014); (5) Zavala et al. (2018); (6) Strandet et al. (2016); (7) Spilker et al. (2016); (8) Vieira et al. (2013); (9) Weiß et al. (2013); (10) Gullberg et al. (2015); (11) Aravena et al. (2016); (12) Ma et al. (2015); (13) Ma et al. (2016); (14) Combes et al. (2012); (15) Rawle et al. (2014); (16) Asboth et al. (2016); (17) Pavesi et al. (2018); (18) Riechers et al. (2017); (19) Younger et al. (2007); (20) Smolčić et al. (2015); (21) Walter et al. (2012).

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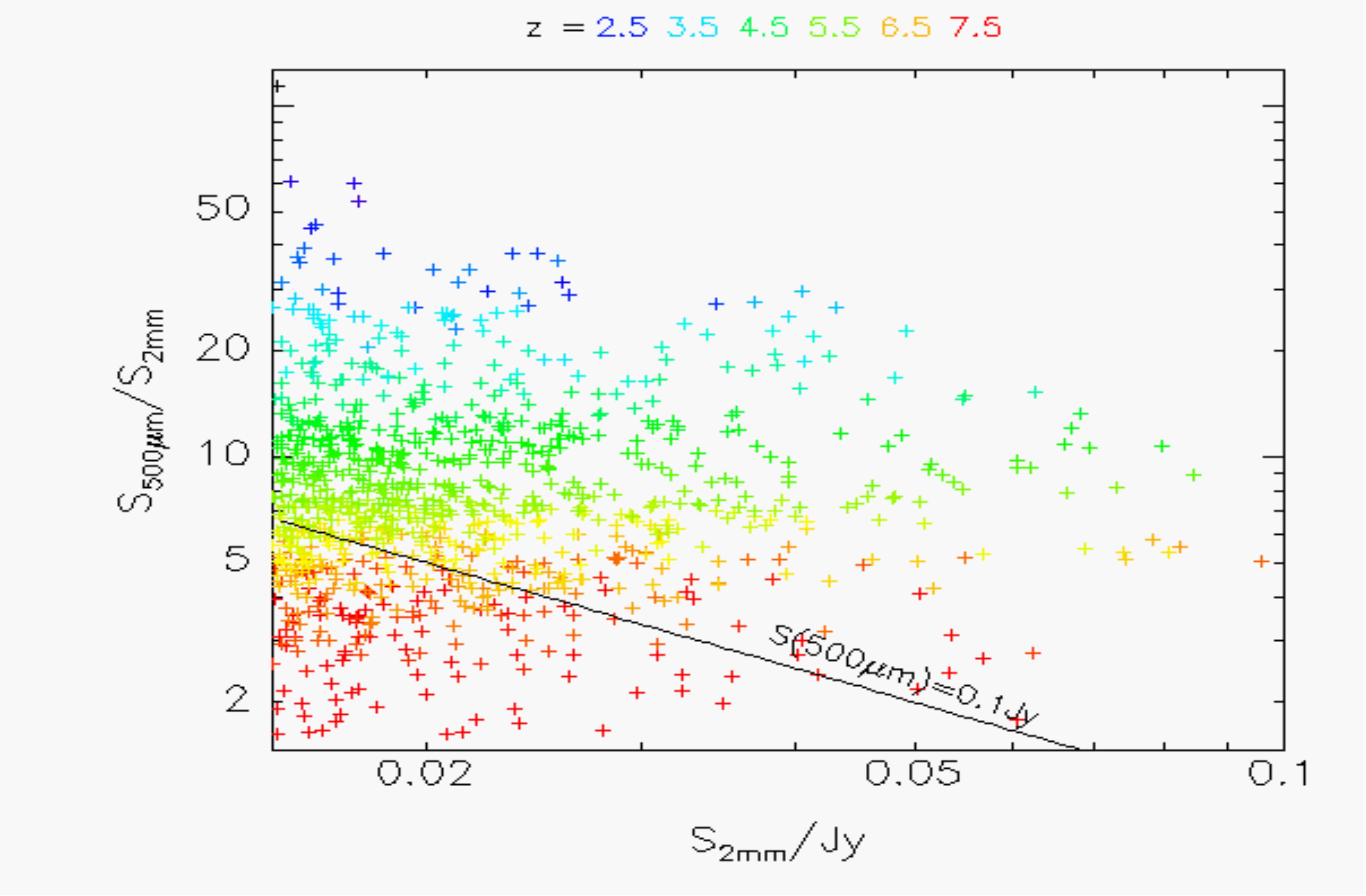
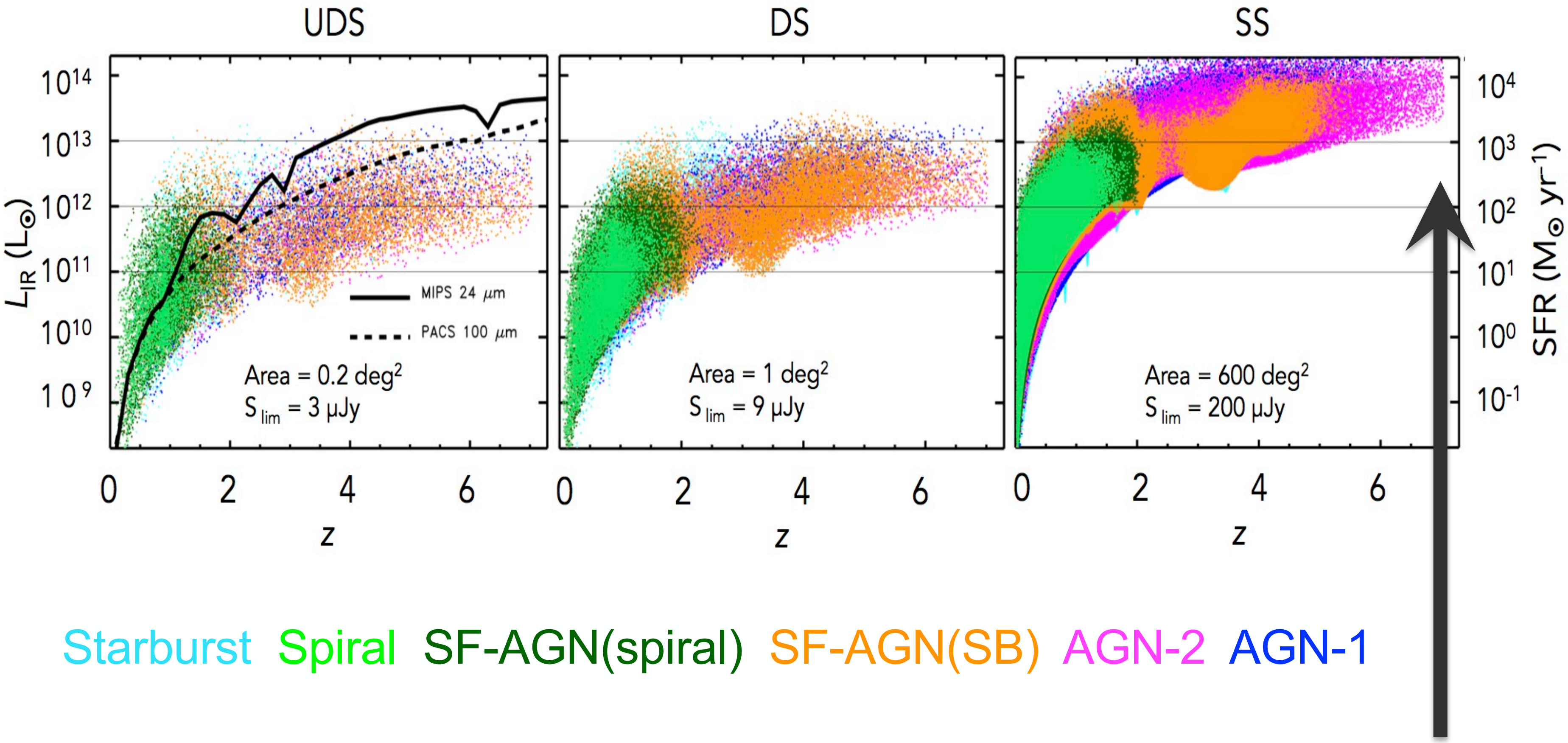
Dusty star-forming galaxies at z>5



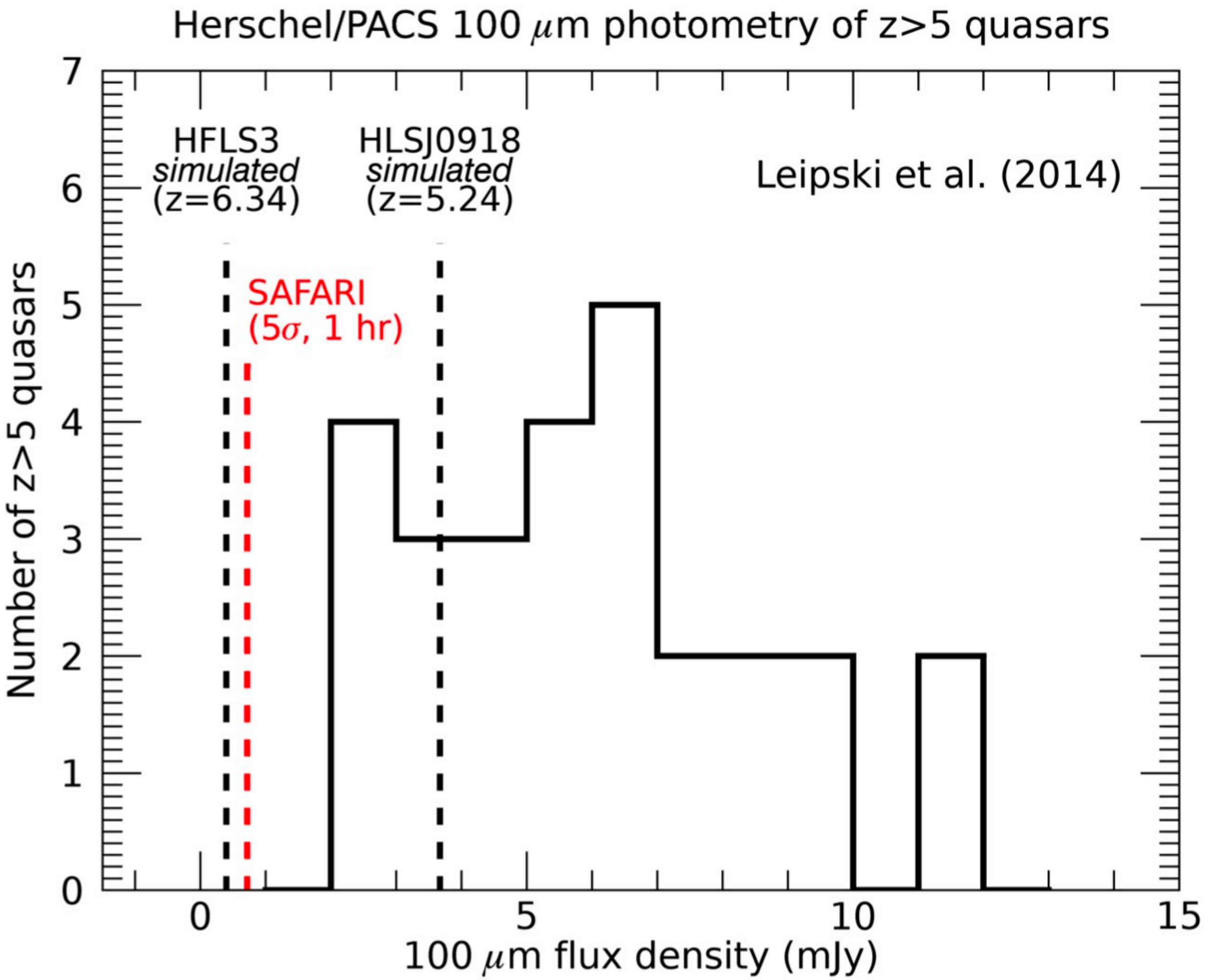
Dusty star-forming galaxies at z>5



Starburst Spiral SF-AGN(spiral) SF-AGN(SB) AGN-2 AGN-1

Gruppioni+ 17

Dusty star-forming galaxies at z>5



Does the torus exist at z>7?

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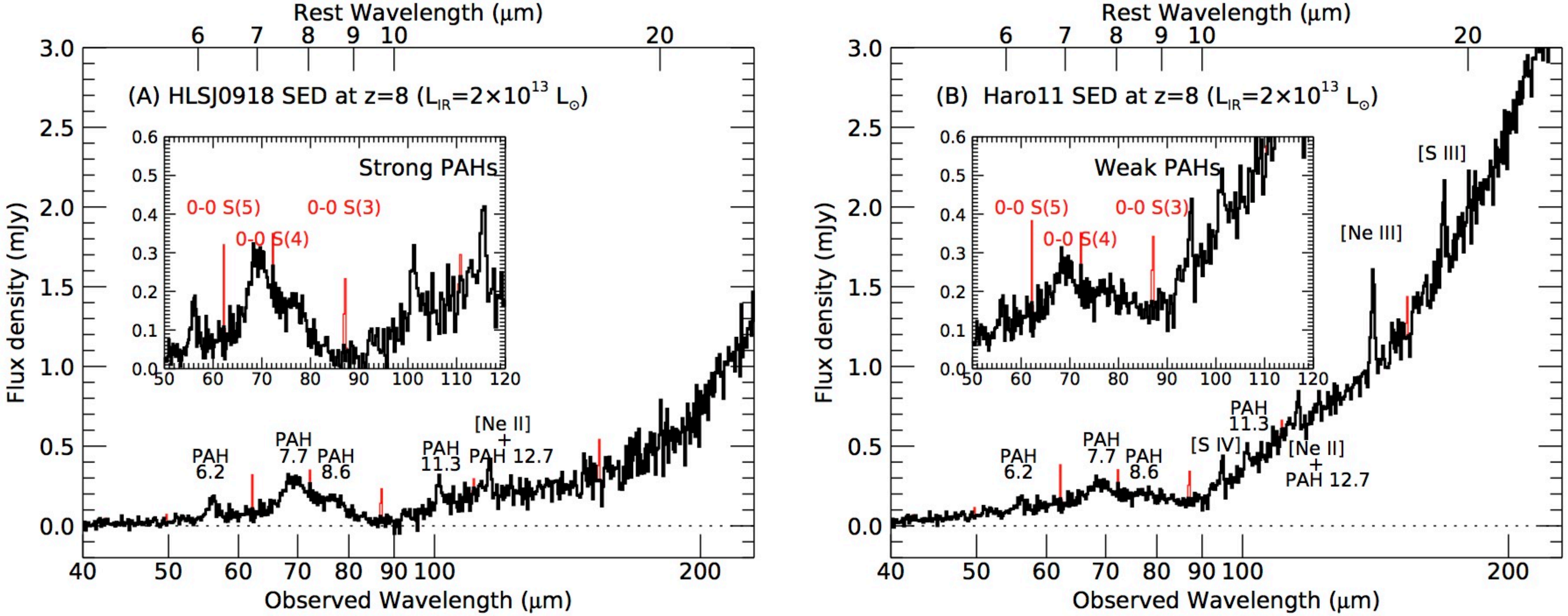
What we need: more source count model predictions for IR-luminous starbursts/AGN at z>6

What we need: Multi-wavelength survey strategies for z>6

Pushing into reionization

PAHs, continuum shapes, ionic lines

- **HLSJ0918**: z=5.24 gravitationally-lensed ULIRG
- **Haro11**: Local BCD: D ≈ 90 Mpc, $L_{IR} \approx 2\times10^{11}\ L_{\odot}$, $Z \approx 1/3\ Z_{\odot}$
- **II Zw 40**: Local BCD: D ≈ 10 Mpc, $Z \approx 1/5\ Z_{\odot}$, $L_{IR} \approx 3\times10^{9}\ L_{\odot}$.



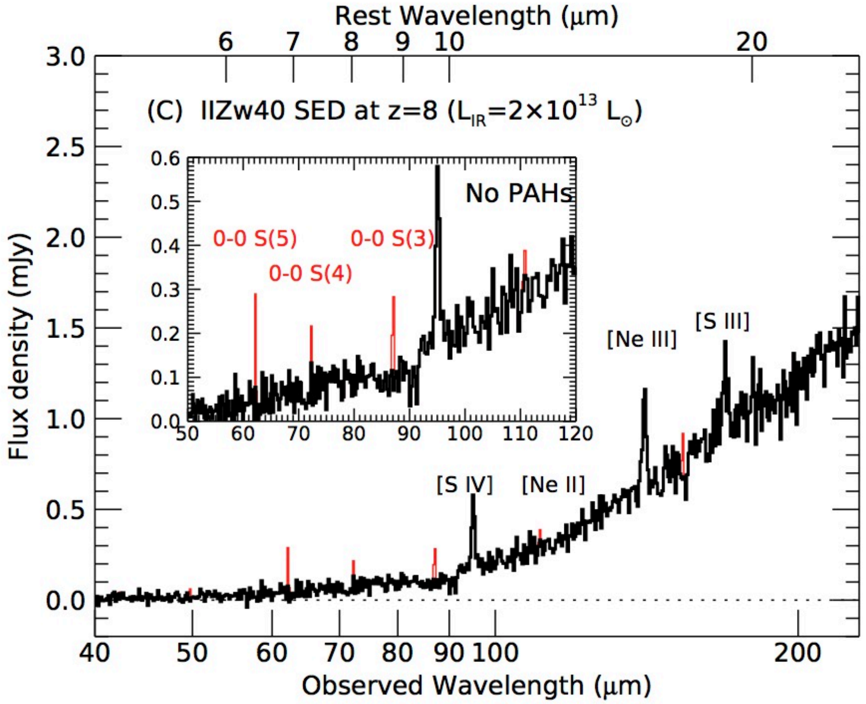


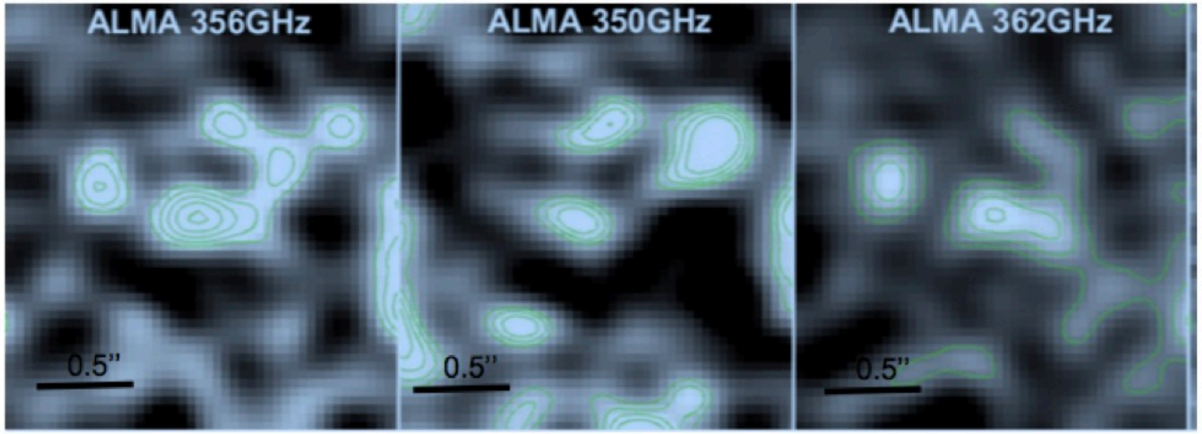
Figure 3. SAFARI 10-hr LR ($R = 300$) spectra for $z = 8$ galaxies simulated for the following three-types of galaxies: (A) HLSJ0918, a HyLIRG at $z = 5.24$ (see Figure 1 and Table 1); (B) Haro 11, a low-metallicity infrared-luminous local BCD; and (C) II Zw 40, another low-metallicity local BCD that is not infrared-luminous. For HLSJ0918, the $L_{\rm IR} = 10^{11.75}$ $L_\odot$ LIRG SED from Rieke et al. (2009) was used as in Figure 1, while for the two BCDs, the fully-processed *Spitzer*/IRS low-resolution spectra were obtained from the Combined Atlas of Sources with *Spitzer* IRS Spectra (CASSIS; Lebouteiller et al. 2011). The infrared luminosities of these SEDs have been scaled to 2×10^{13} $L_\odot$, comparable to the intrinsic luminosity of HFLS3. See the caption of Figure 1 for how these SAFARI spectra were simulated. The red lines show simulated H_2 emission lines (assumed to be unresolved) produced by 2×10^{10} $M_\odot$ of $T = 200$ K gas and 2×10^8 $M_\odot$ of $T = 1000$ K gas under the LTE assumption (an ortho-to-para ratio of 3:1 is also assumed). These H_2 lines are hardly visible in the original galaxy spectra.

Egami +18

Pushing into reionization

PAHs, continuum shapes, ionic lines

- Are z=8 galaxies scaled-up local BCDs?
- Lower metallicity ⇒ stronger [OIII] 88μm line and weaker PAHs



Laporte et al. 2017:
ALMA OBSERVATIONS OF A Z =8.38 GRAVITATIONALLY-LENSED GALAXY

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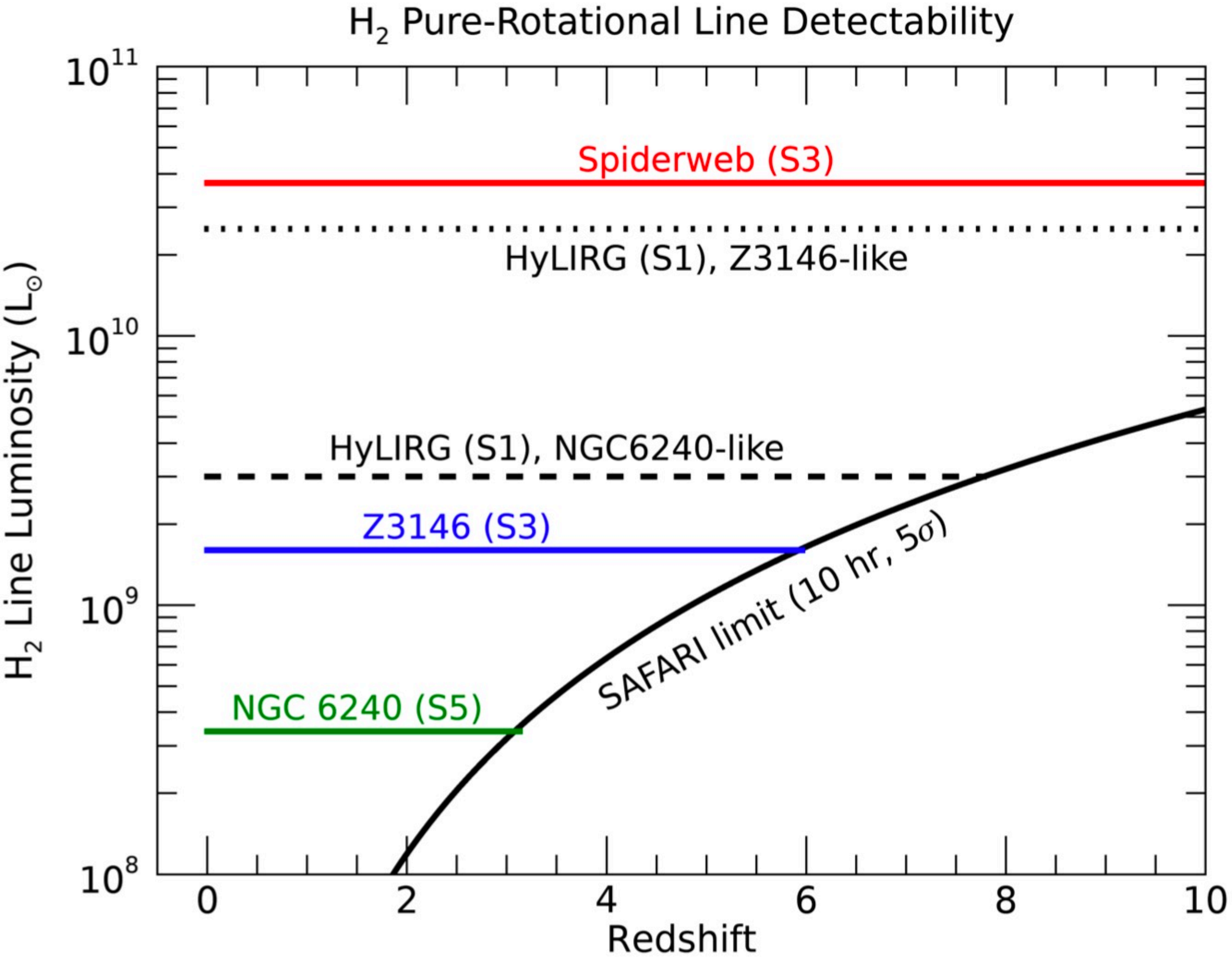
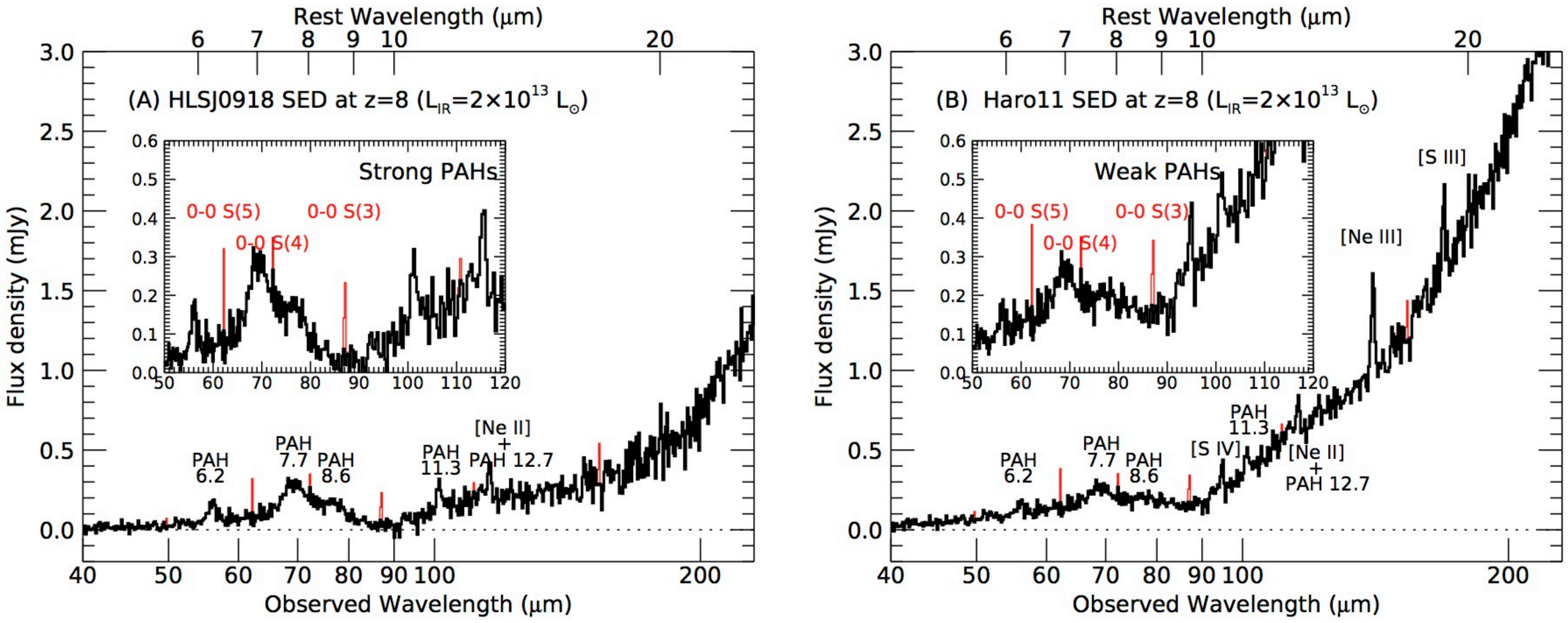
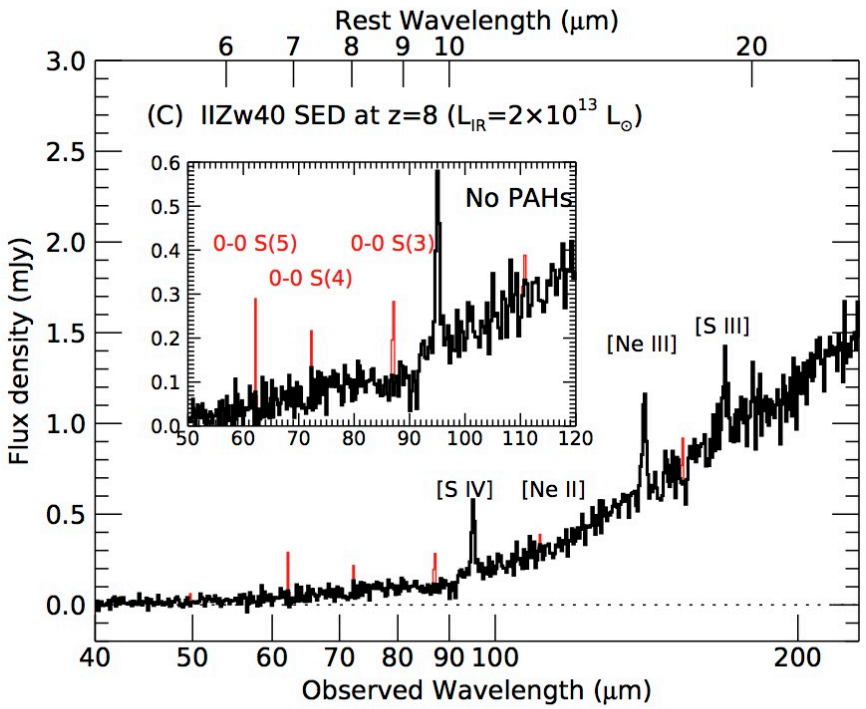

H_2 Pure-Rotational Line Detectability
H_2 Line Luminosity ($L_\odot$)
10^{11}
10^{10}
10^{9}
10^{8}
Spiderweb (S3)
HyLIRG (S1), Z3146-like
HyLIRG (S1), NGC6240-like
Z3146 (S3)
NGC 6240 (S5)
SAFARI limit (10 hr, 5σ)
0
2
4
6
8
10
Redshift





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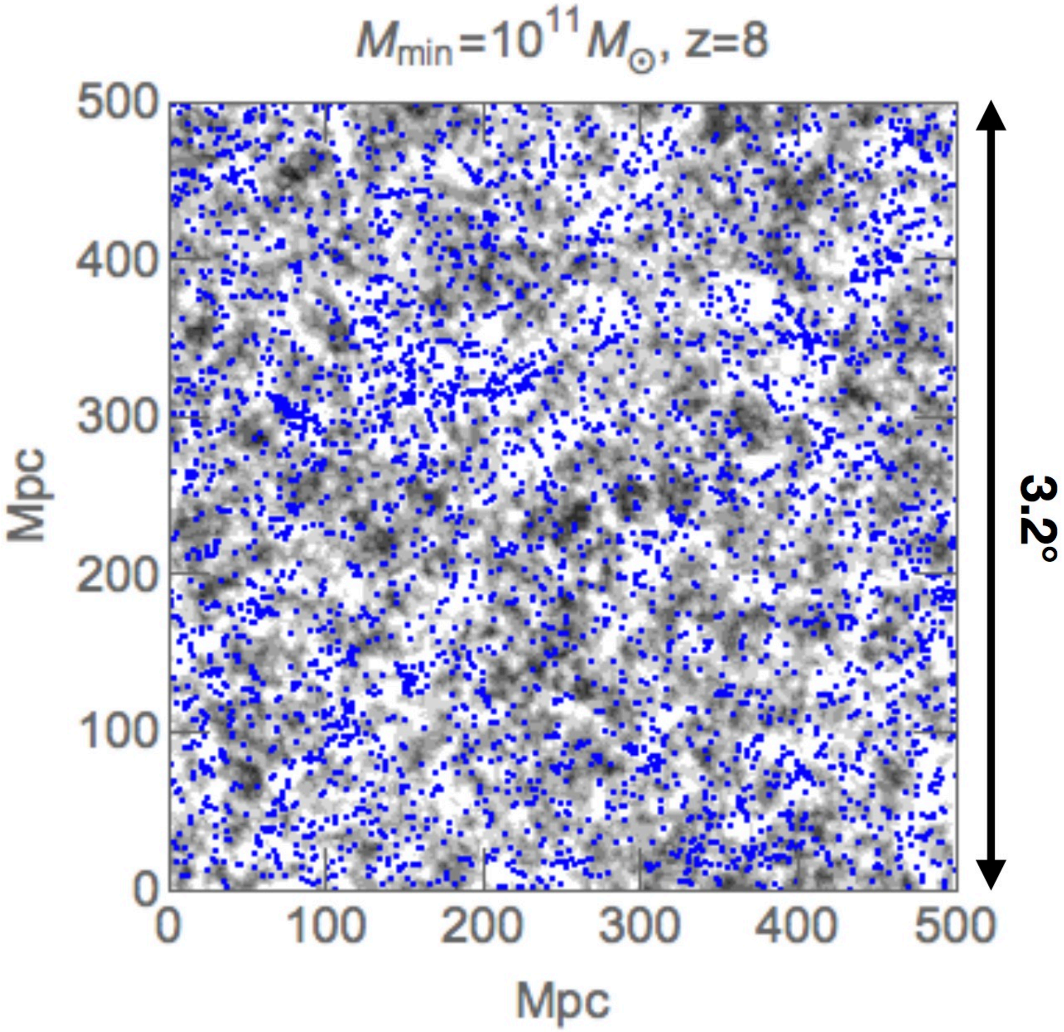
Egami +18

Pushing into reionization

SKA, WFIRST & Euclid synergies

- Are there HLIRGs in the HII bubbles?
- Are there Pop-III systems on the edges of HII bubbles?



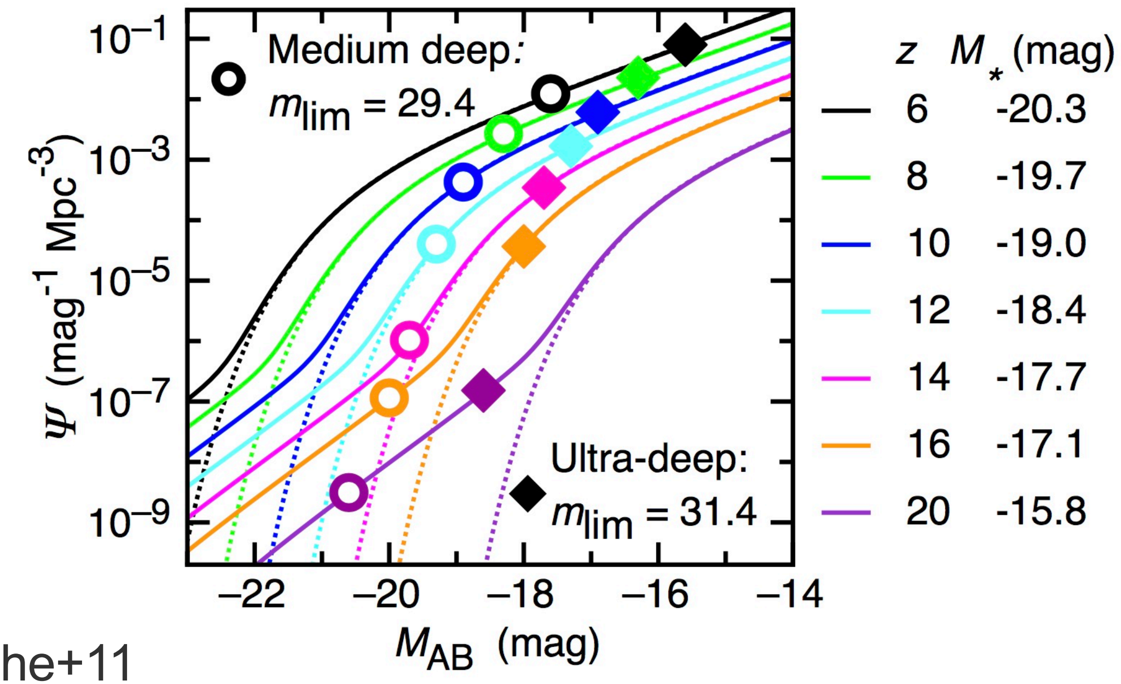
Egami+18

What we need: simulations of Pop-2 and Pop-3 environments in reionization

Pushing into reionization

SKA, WFIRST & Euclid synergies

- WFIRST High-Latitude Survey: 100 bright ($m_{160,AB}<26$) galaxies at $z>10$ over 2200 deg^2



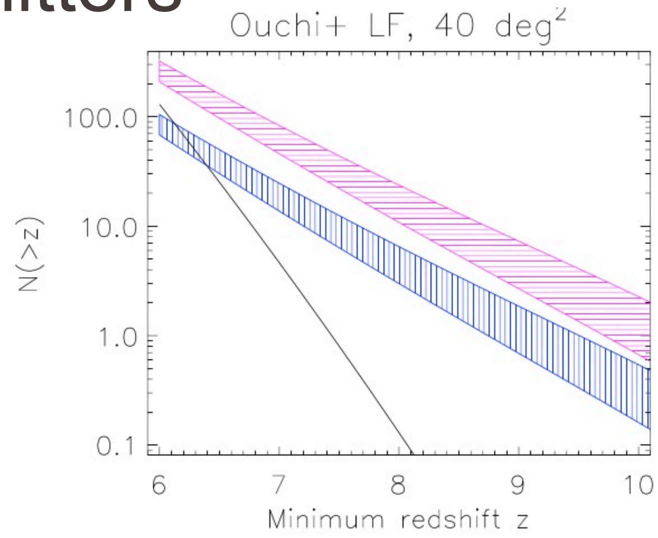
Wyithe+11

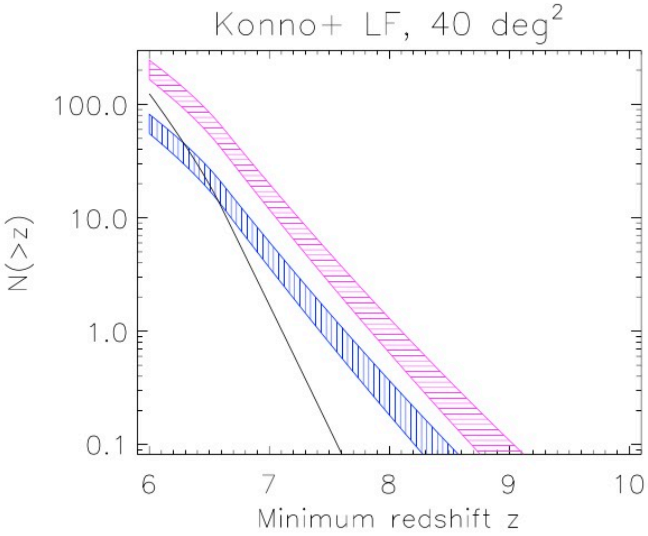
Marchetti+ 17, Egami+18

Pushing into reionization

SKA, WFIRST & Euclid synergies

- WFIRST High-Latitude Survey: 100 bright ($m_{160,AB}<26$) galaxies at z>10 over 2200 deg^2
- Euclid-Deep: tens of strongly lensed Lyα emitters





Marchetti+ 17, Egami+18

What we need: SPICA light cone simulations into reionization including strong lensing

Pushing into reionization

Pop-III SNe (Pair-Instability SNe)

- Detectable out to z=7 with LSST
- Detectable out to z=15-20 with WFIRST
- Detectable out to z~30 with JWST
- 100-day transient becomes 3 years long at z=10
- What is the optimum SPICA SMA survey strategy?

Egami +18

What we need: SPICA SMI survey recommendations for Pop-III PISNe

Summary

A SPICA case for z>8 would look different to our current science case.

We need:

- More z>6 source count predictions
- Multi-wavelength survey strategies for z>6
- Simulations of Pop-2 and Pop-3 environments in reionization
- SPICA light cone simulations into reionization including strong lensing
- Pop-III PISNe survey strategies