Witnessing Galaxy Formation at High Redshift

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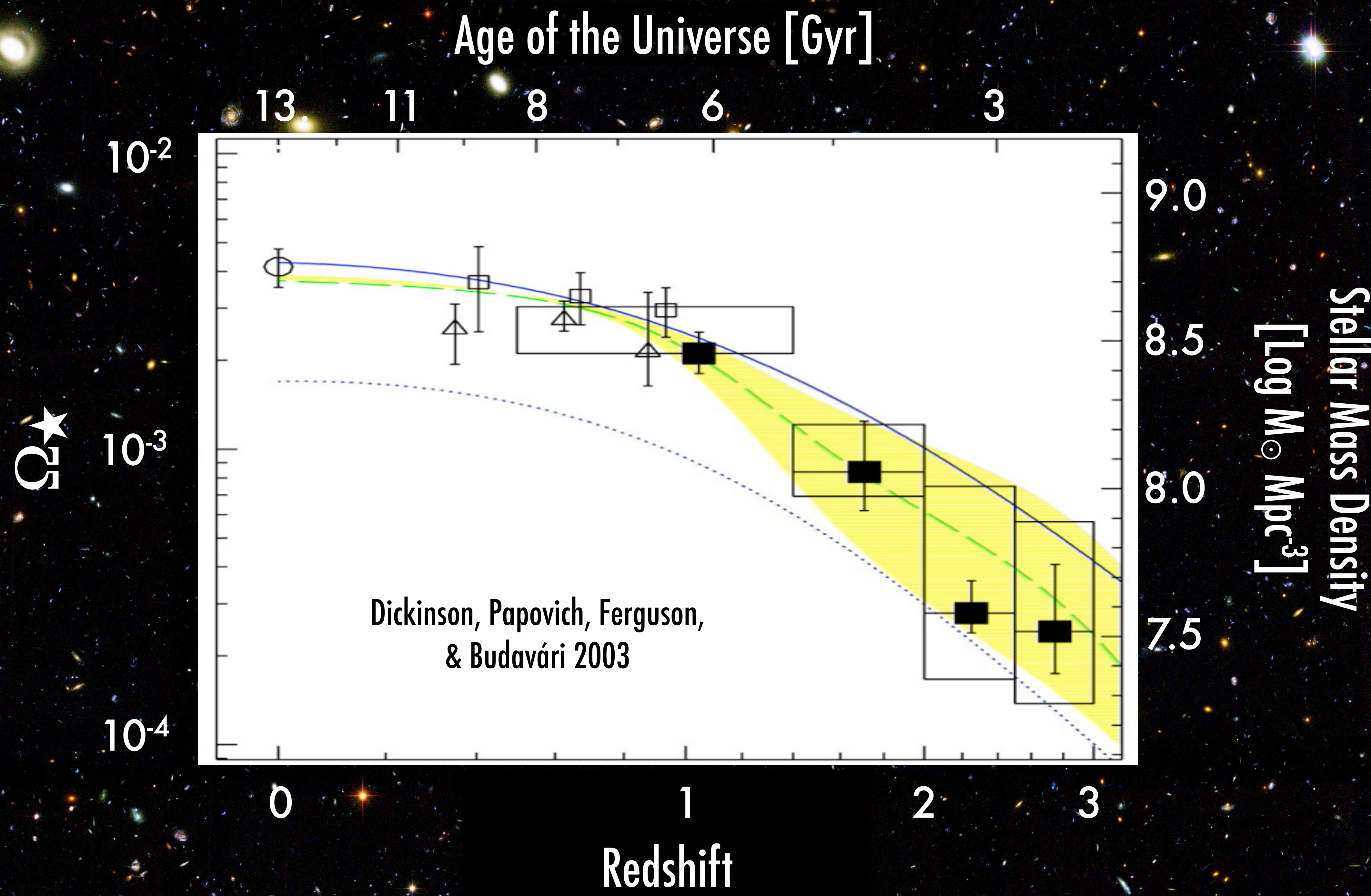
Berkeley Cosmology Group Seminar, 17 Mar 2009

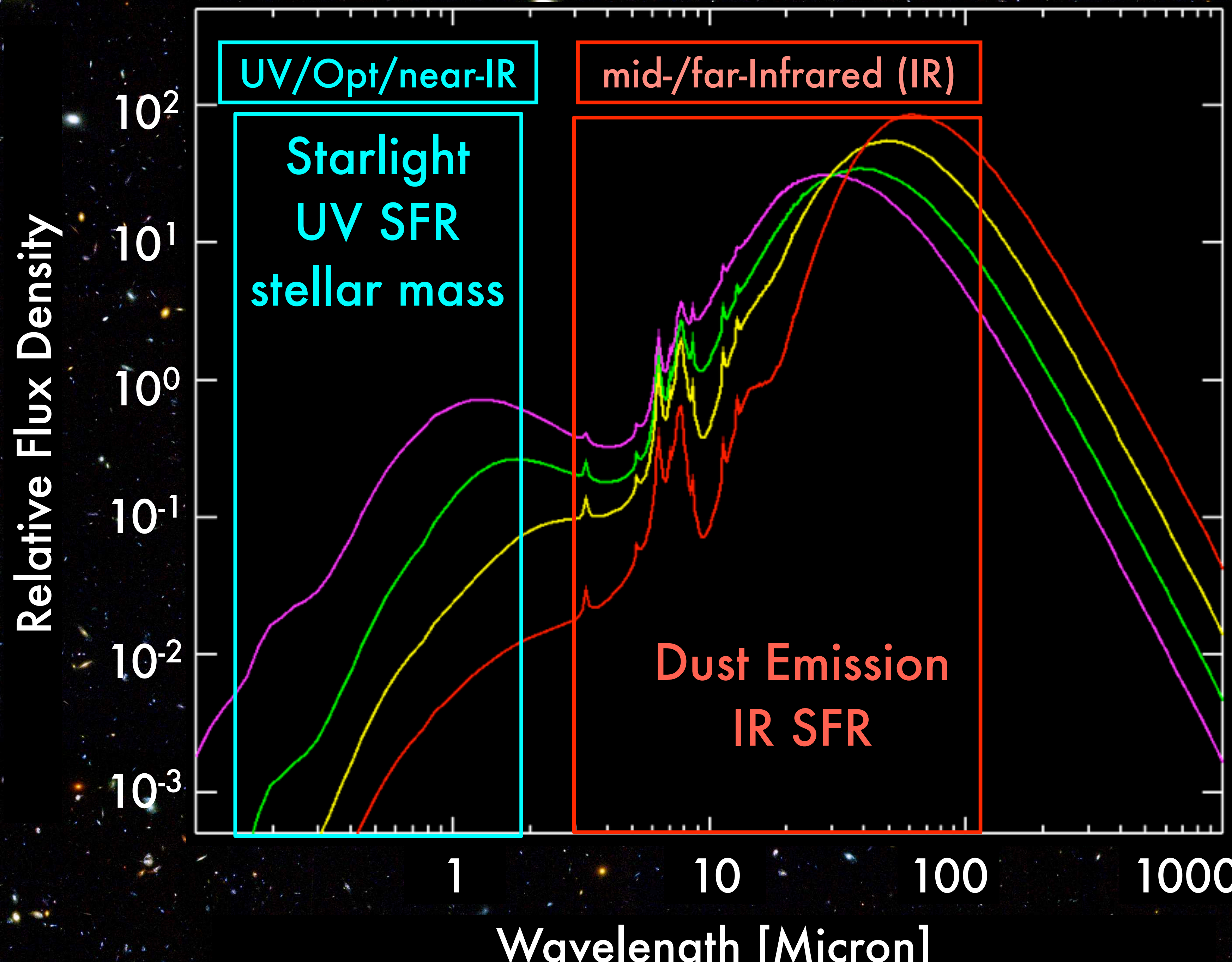
Evolution of Cosmic Stellar Mass Density over Past 12 Gyr



Outline and Summary

- Using multiwavelength data, in particular infrared data from Spitzer, probes the bolometric emission from distant galaxies.
- At high redshift, $1.5 < z < 3$, *majority* (>50%) of galaxies emit intensively at IR wavelengths. Implies vigorous star-formation in massive galaxies.
- At least 25% of massive galaxies at $1.5 < z < 3$ show indications of SMBH accretion. Simultaneous build-up of SMBHs and galaxies.
- Spitzer data provide only minimal constraints on the IR emission from distant galaxies.
  - How well do we measure quantities such as SFRs ?

Galaxy Diagnostics: The Spectral Energy Distribution



Models from Siebenmorgen & Kruegel (2006)

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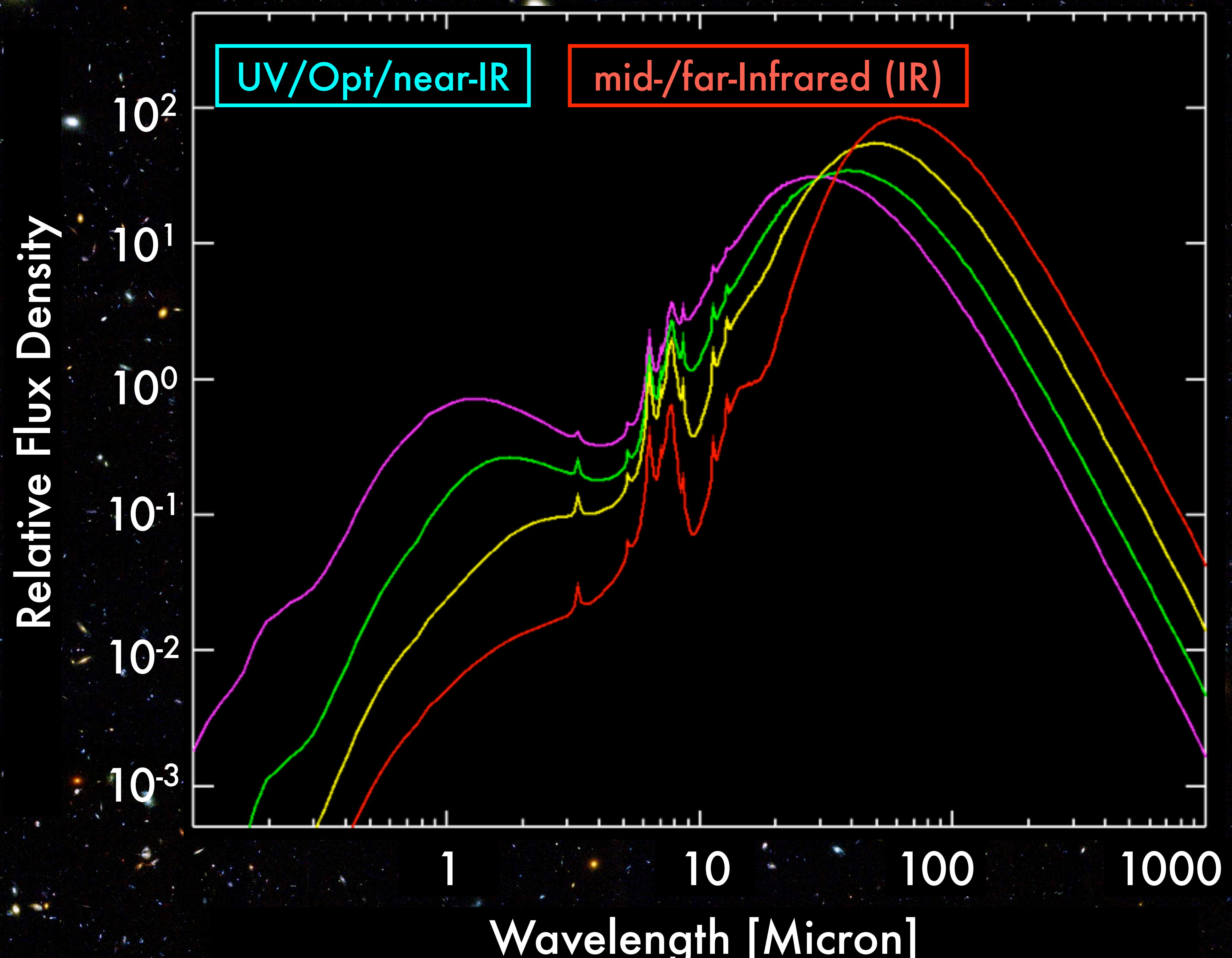

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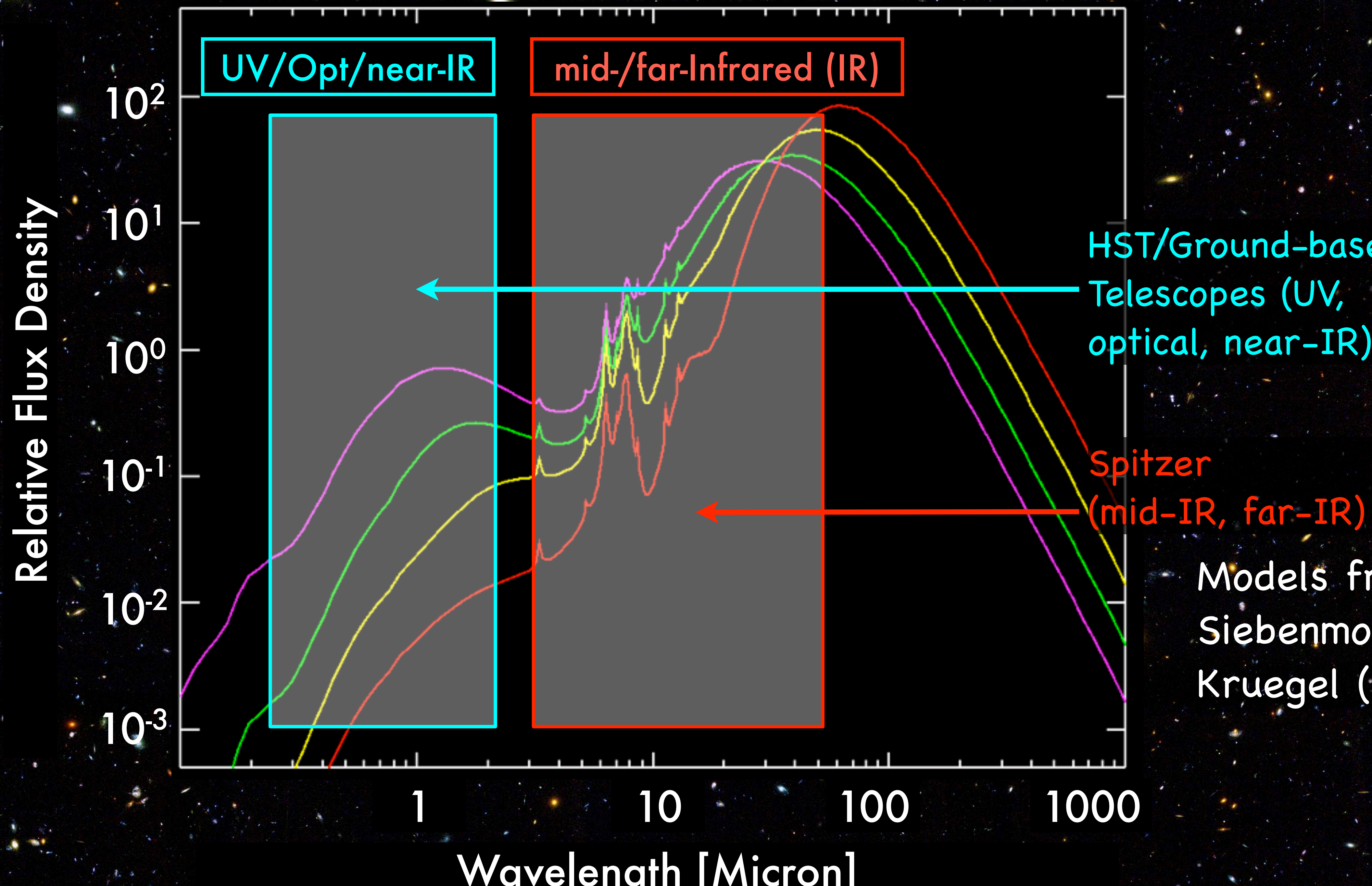
Galaxy Diagnostics: The Spectral Energy Distribution



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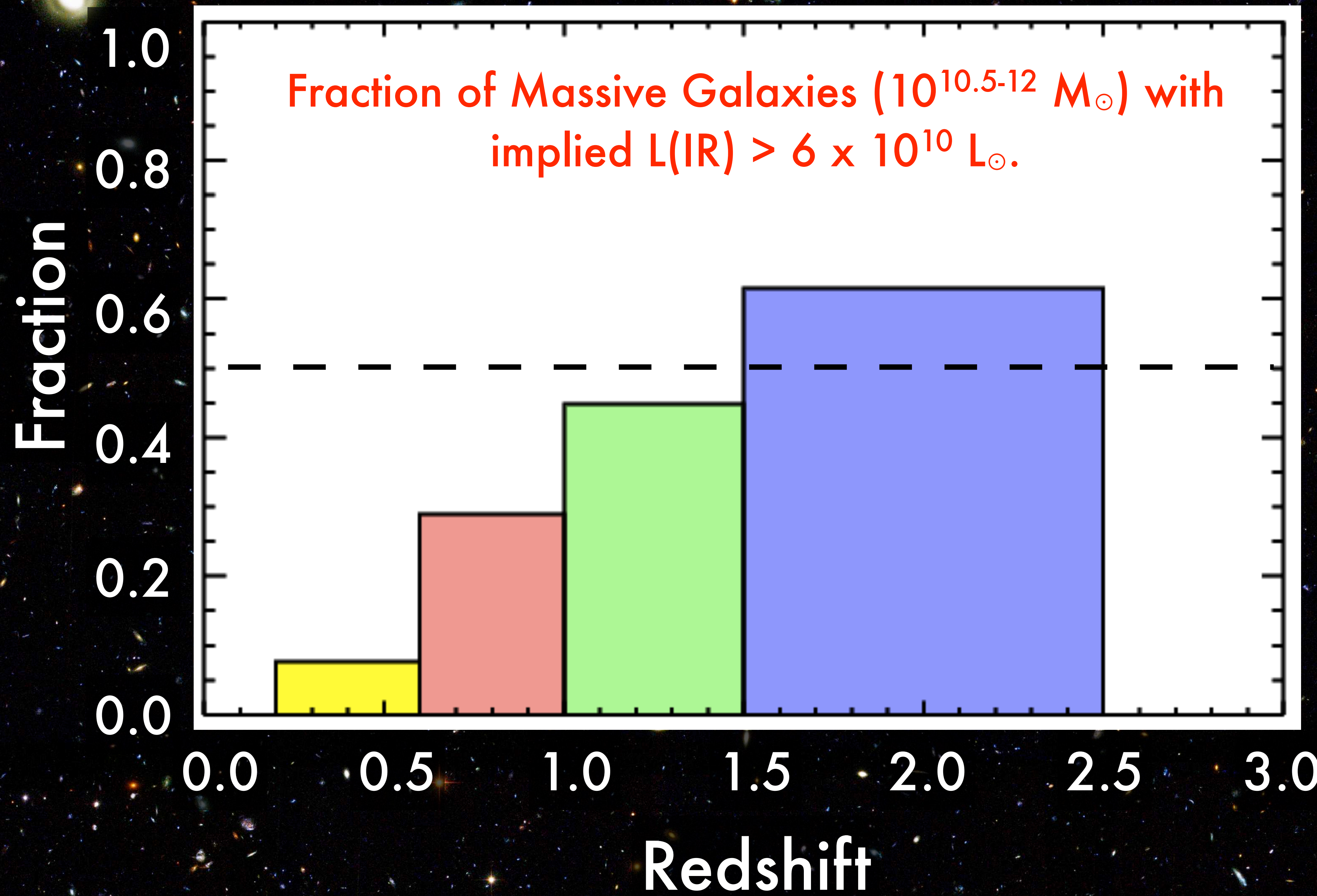
Spitzer IR Observations of High-z Galaxies



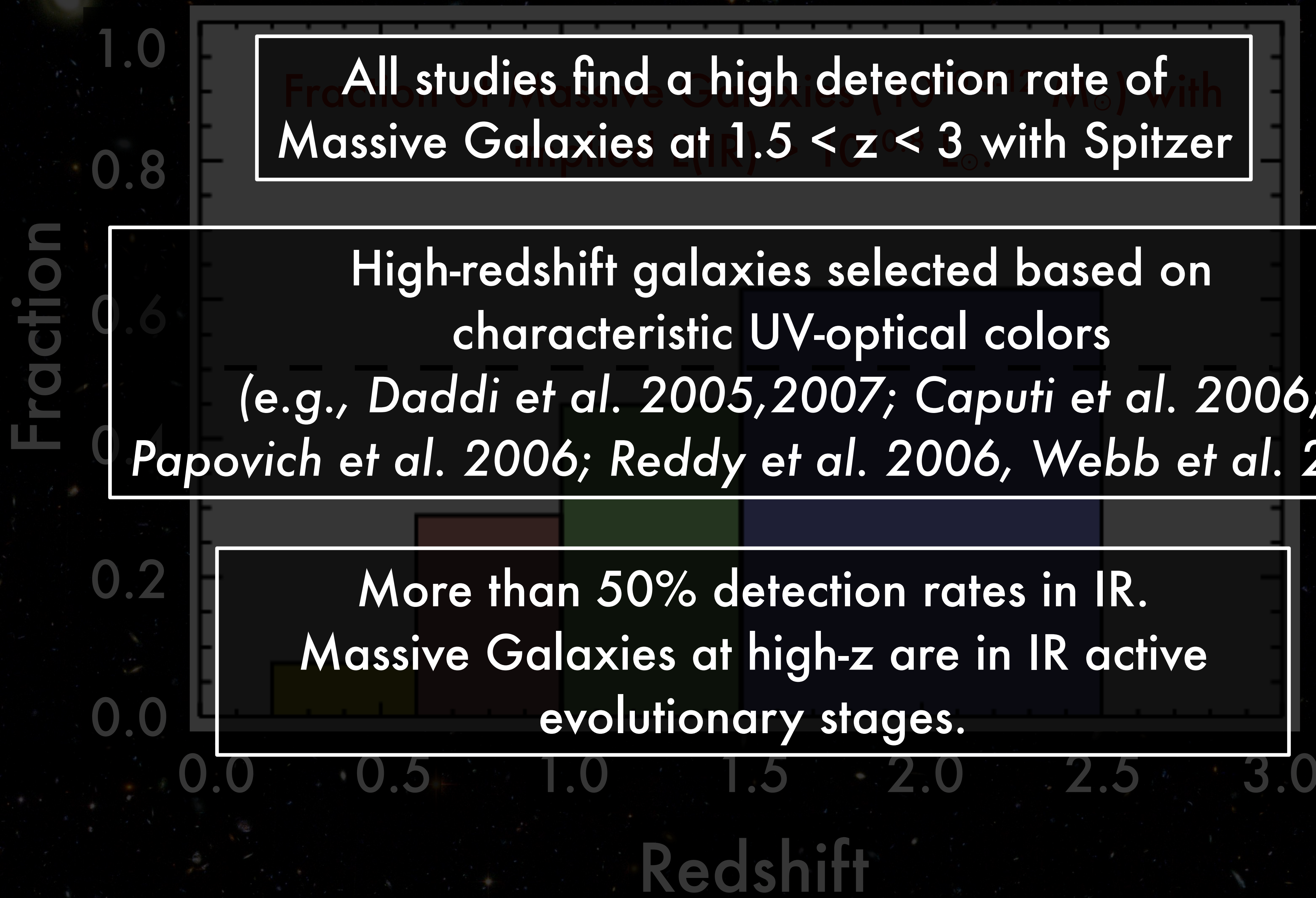
Distribution from galaxies in GOODS-S

Spitzer IR Observations of High-z Galaxies

All studies find a high detection rate of Massive Galaxies at 1.5 < z < 3 with Spitzer

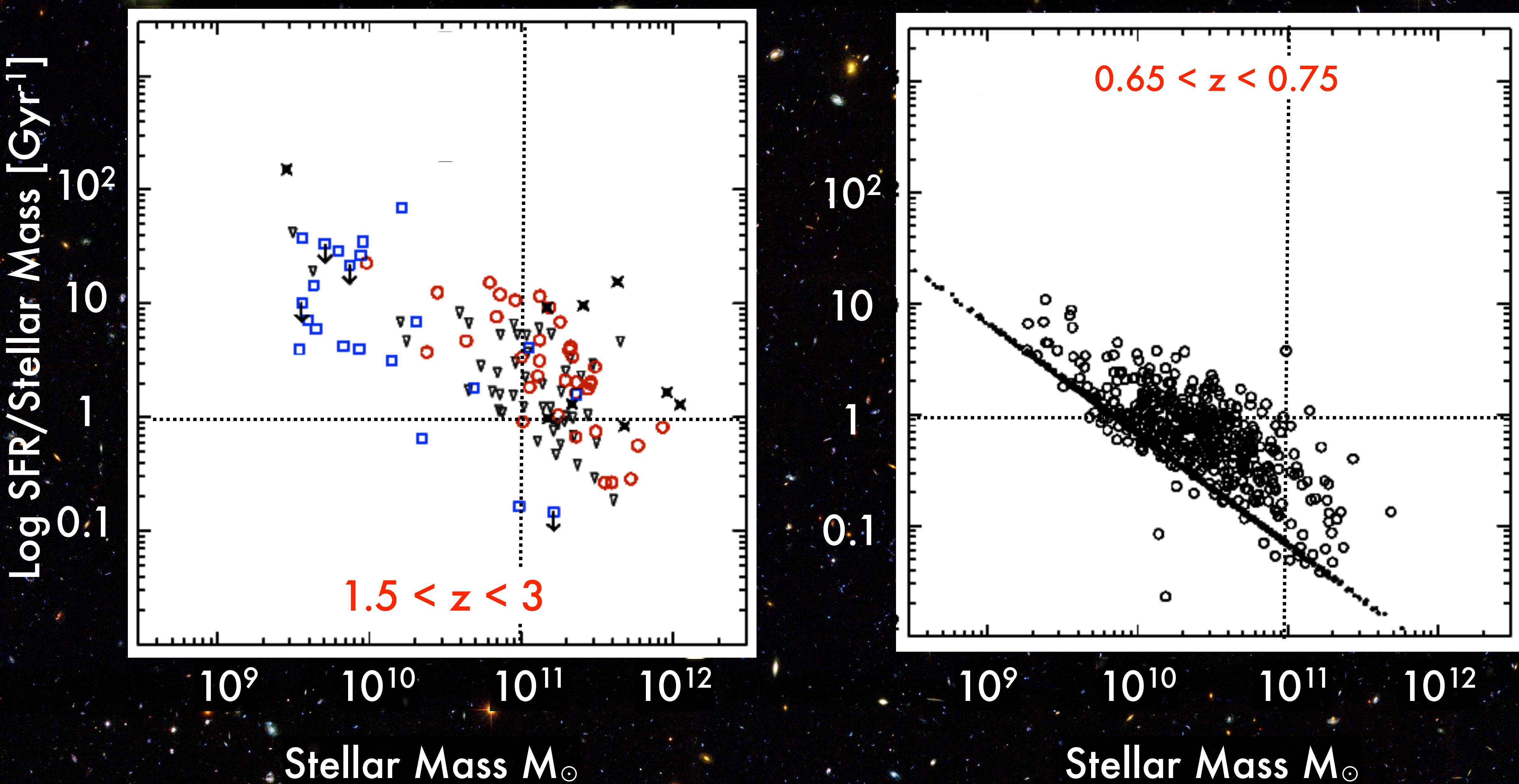
High-redshift galaxies selected based on characteristic UV-optical colors (*e.g., Daddi et al. 2005,2007; Caputi et al. 2006; Papovich et al. 2006; Reddy et al. 2006, Webb et al. 2006*)

More than 50% detection rates in IR. Massive Galaxies at high-z are in IR active evolutionary stages.



Distribution from galaxies in GOODS-S

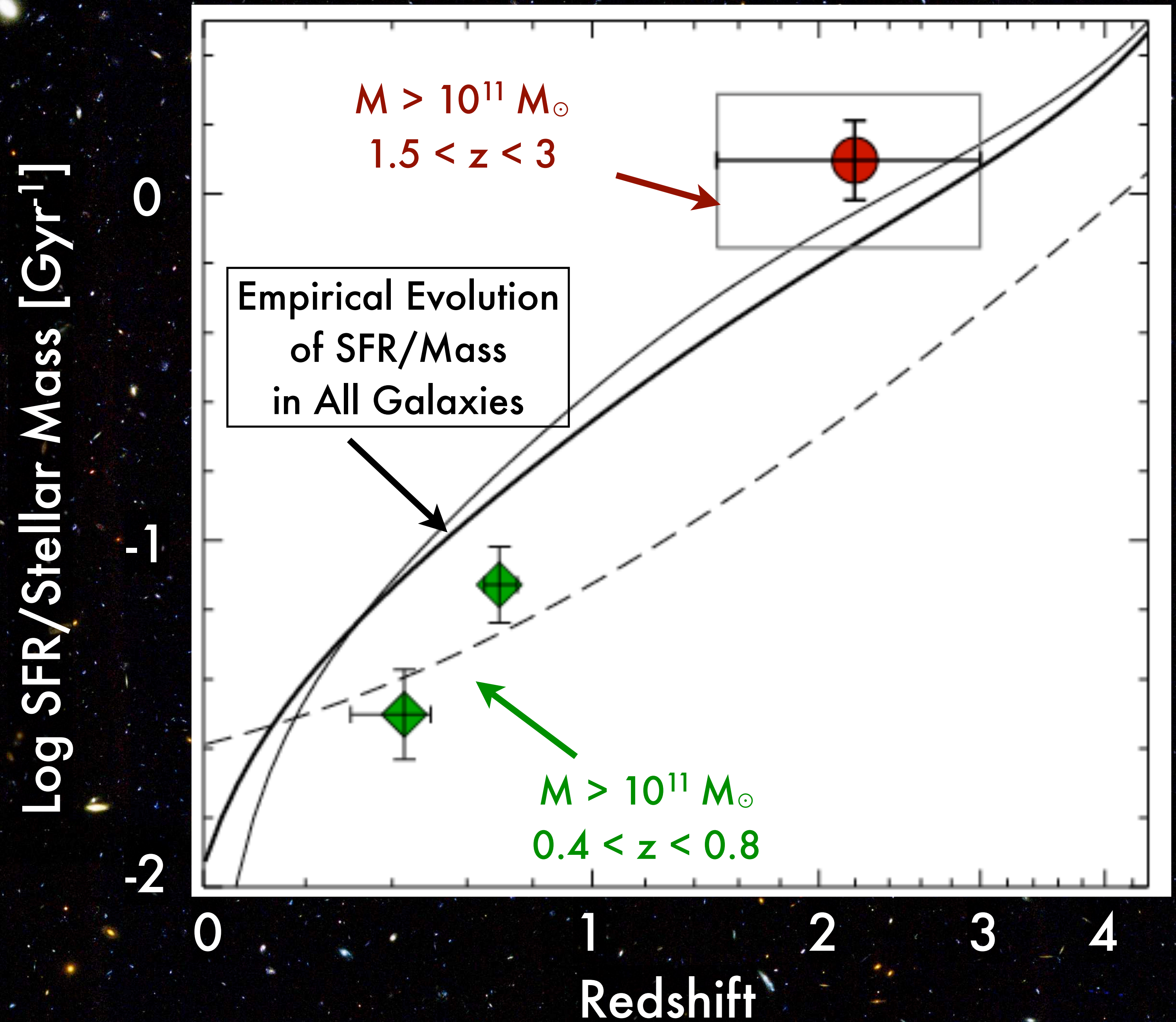
Evolution of SFR in Massive Galaxies



Papovich, Moustakas, Dickinson, Le Floc'h, Rieke, et al. (2006, ApJ, 640, 92)

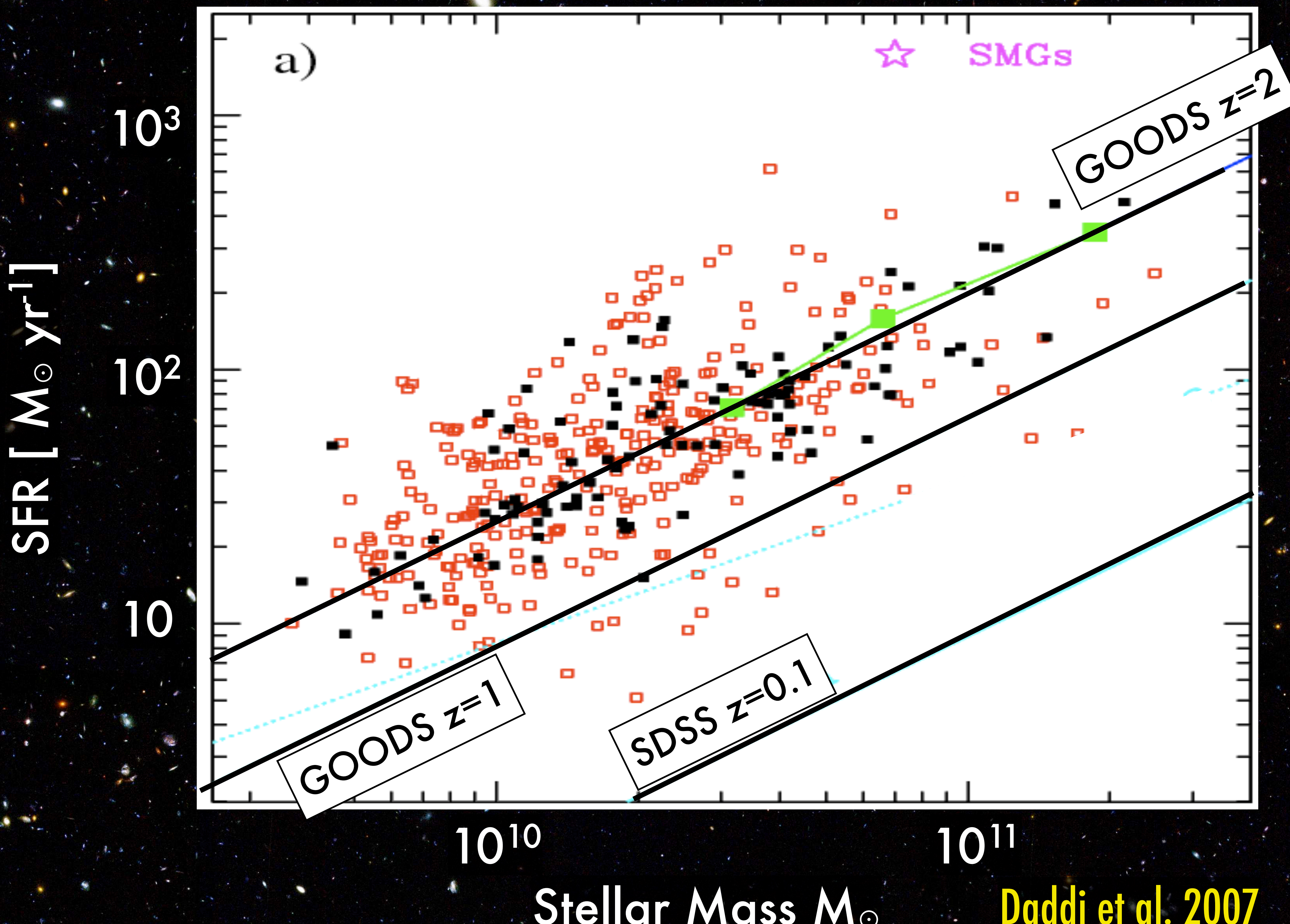
Evolution of SFR in Massive Galaxies

- At $1.5 < z < 3$ massive galaxies ($>10^{11}$ $M_\odot$) form stars as fast or faster than cosmic average.
- At $z < 1$, massive galaxies have formed most of their stellar mass and have lower SFR per stellar mass.



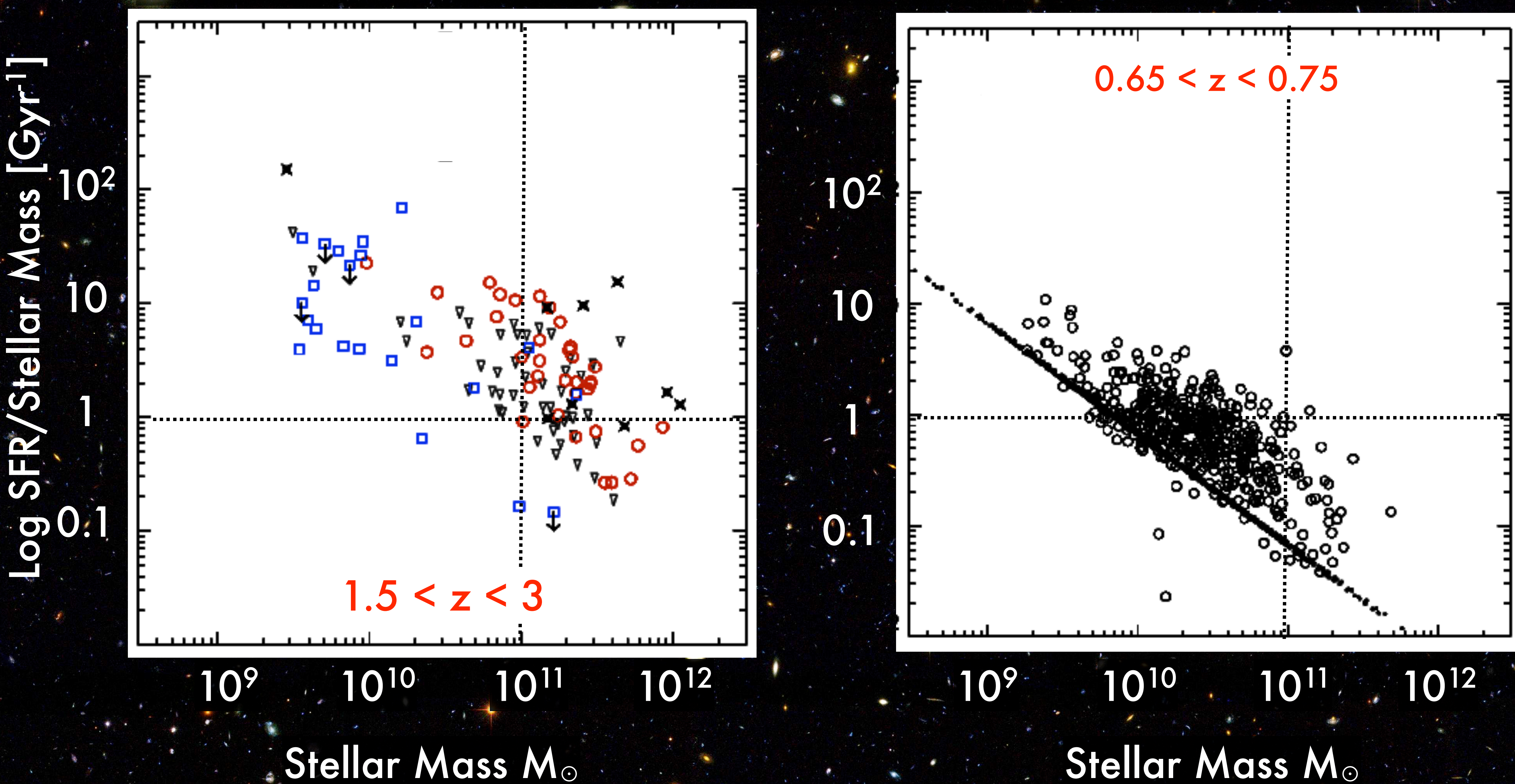
Papovich et al. (2006)

Evolution of SFR in Massive Galaxies



Daddi et al. 2007

Evolution of SFR in Massive Galaxies



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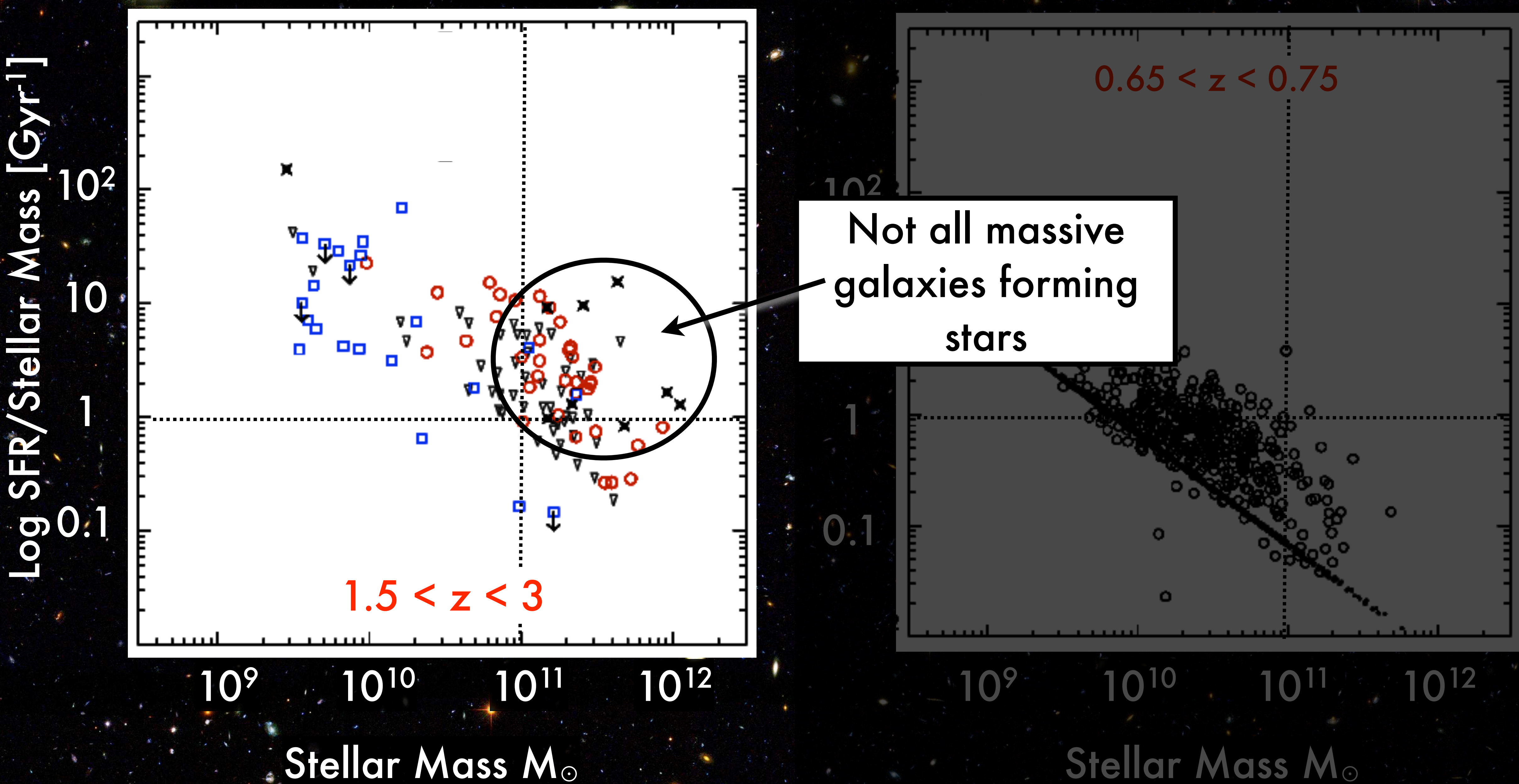

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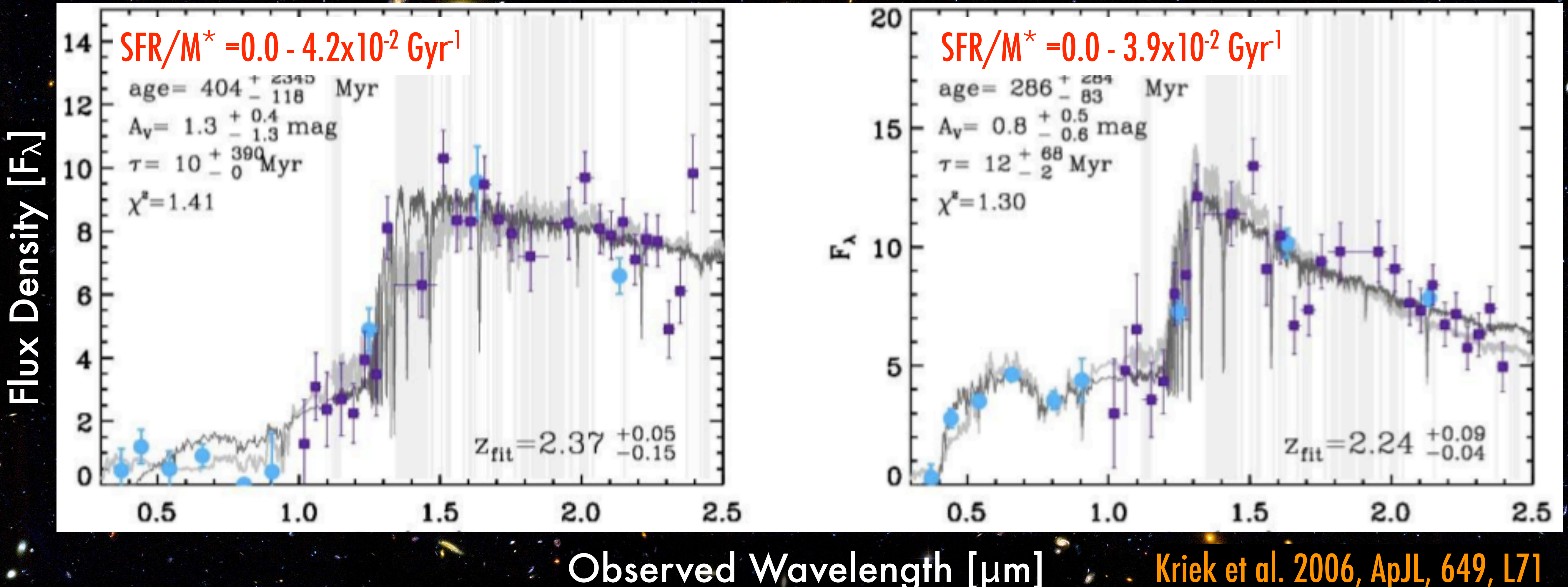
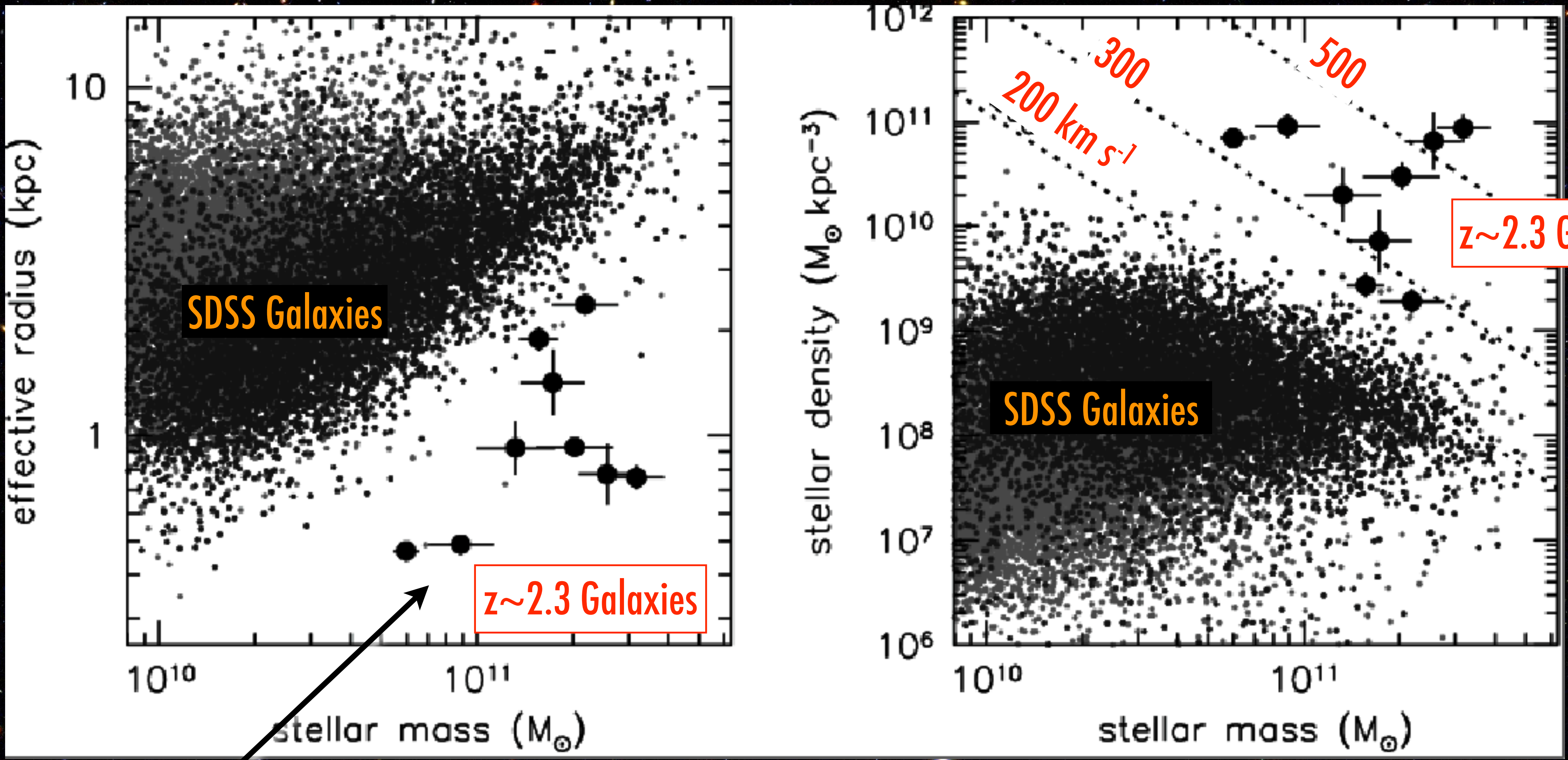
Massive z~2-3 Galaxies with Suppressed SFRs

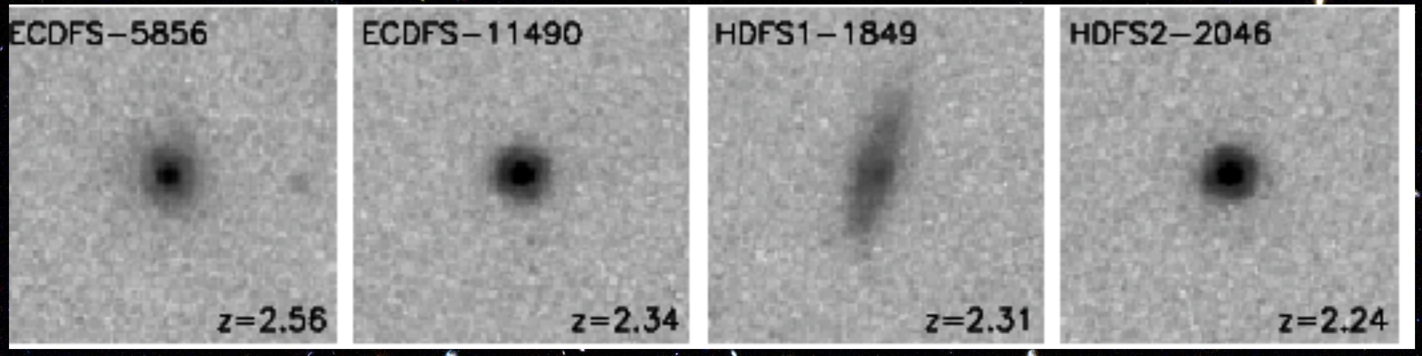


Kriek et al. 2006, ApJL, 649, L71

some of the most massive galaxies ($>10^{11.2}$ $M_\odot$) at z~2-3 not strongly forming stars.

Massive z~2-3 Galaxies with Suppressed SFRs





van Dokkum et al. (2008)
[see also Zirm et al. 2007,
Cimatti et al. 2008, Franx et al. 2008]

Compact High-Redshift Galaxies Are the Cores of Present-Day Massive Spheroids

Philip F. Hopkins[1]*, Kevin Bundy[1], Norman Murray[2,3], Eliot Quataert[1], Tod Lauer[4], Chung-Pei Ma[1]

[1] Department of Astronomy, University of California Berkeley, Berkeley, CA 94720
[2] Can
[3] Can
[4] Nat

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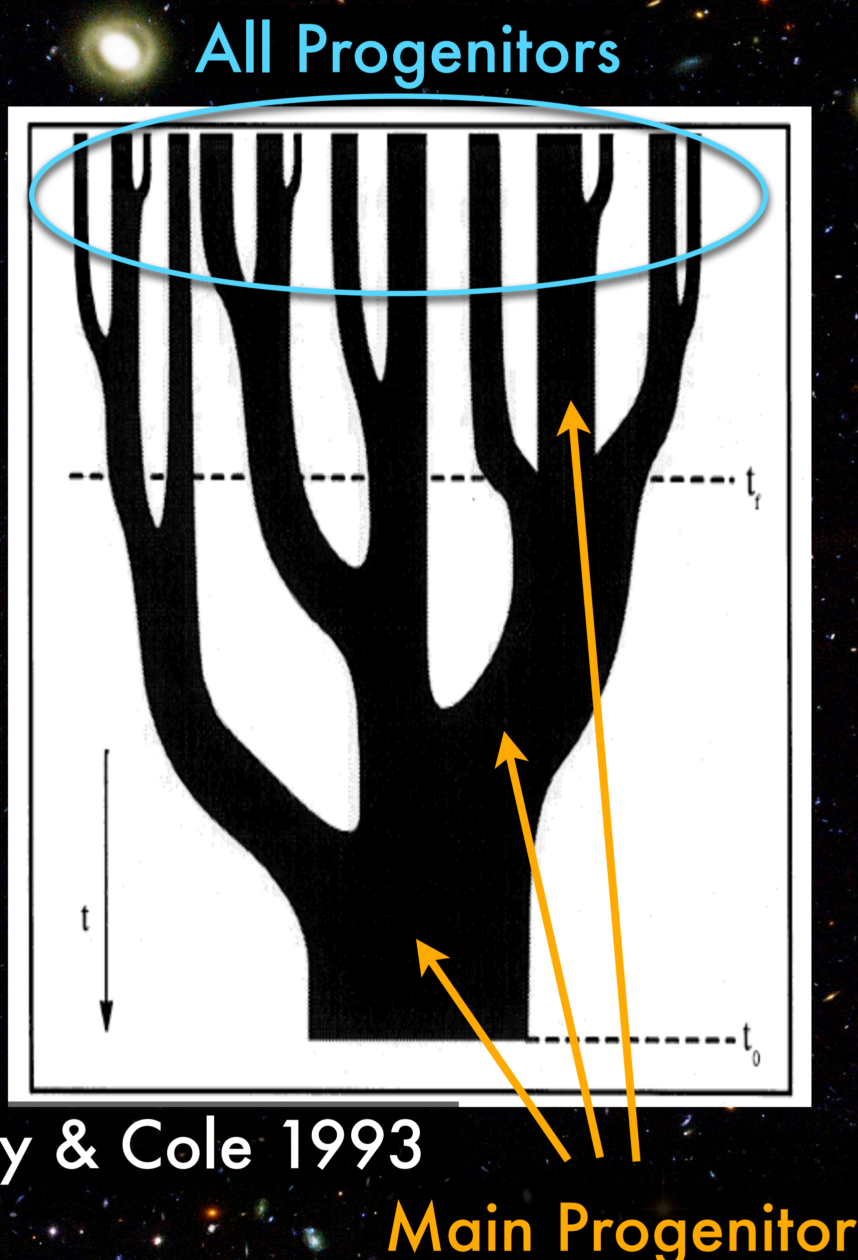
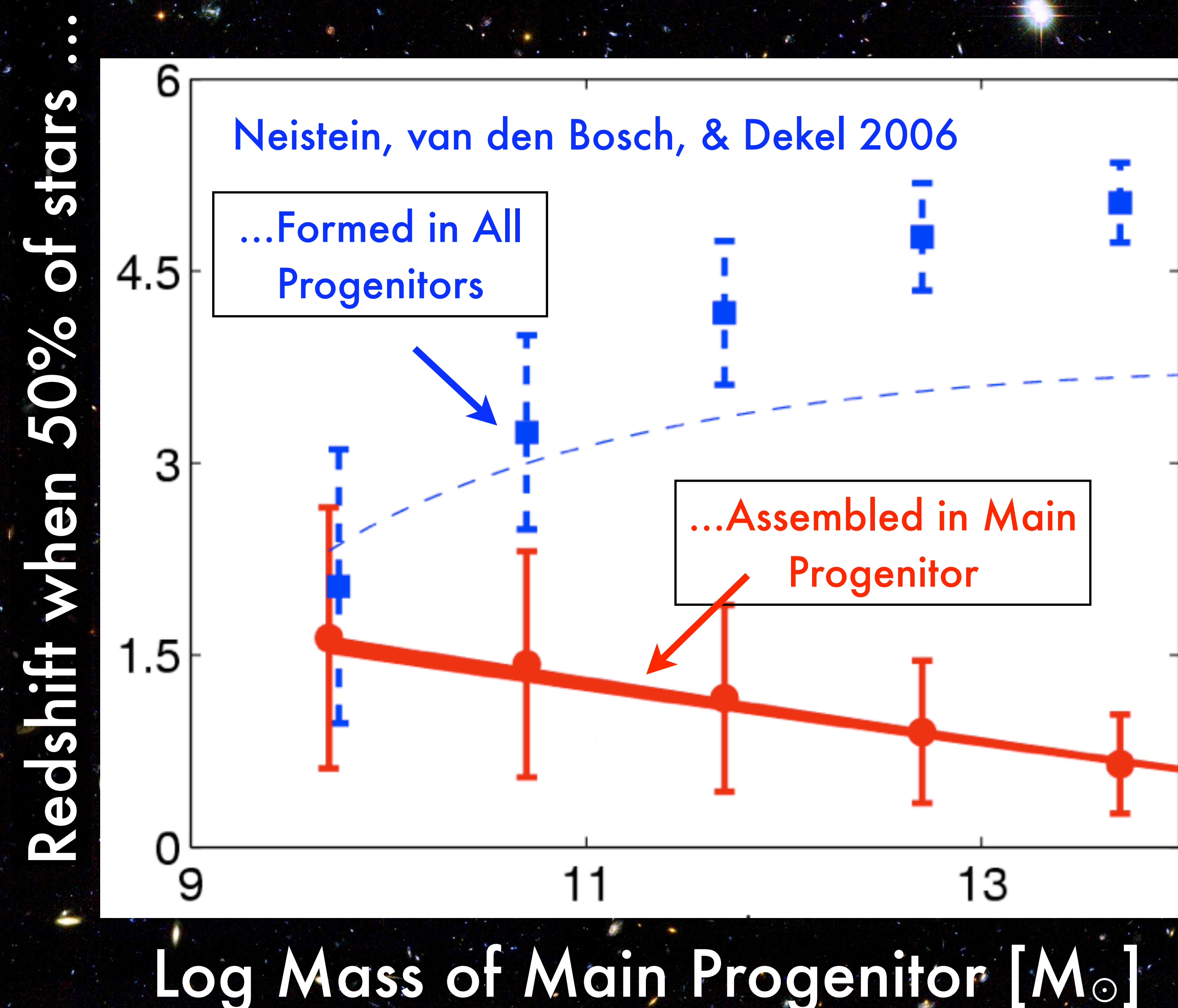
ABSTRACT

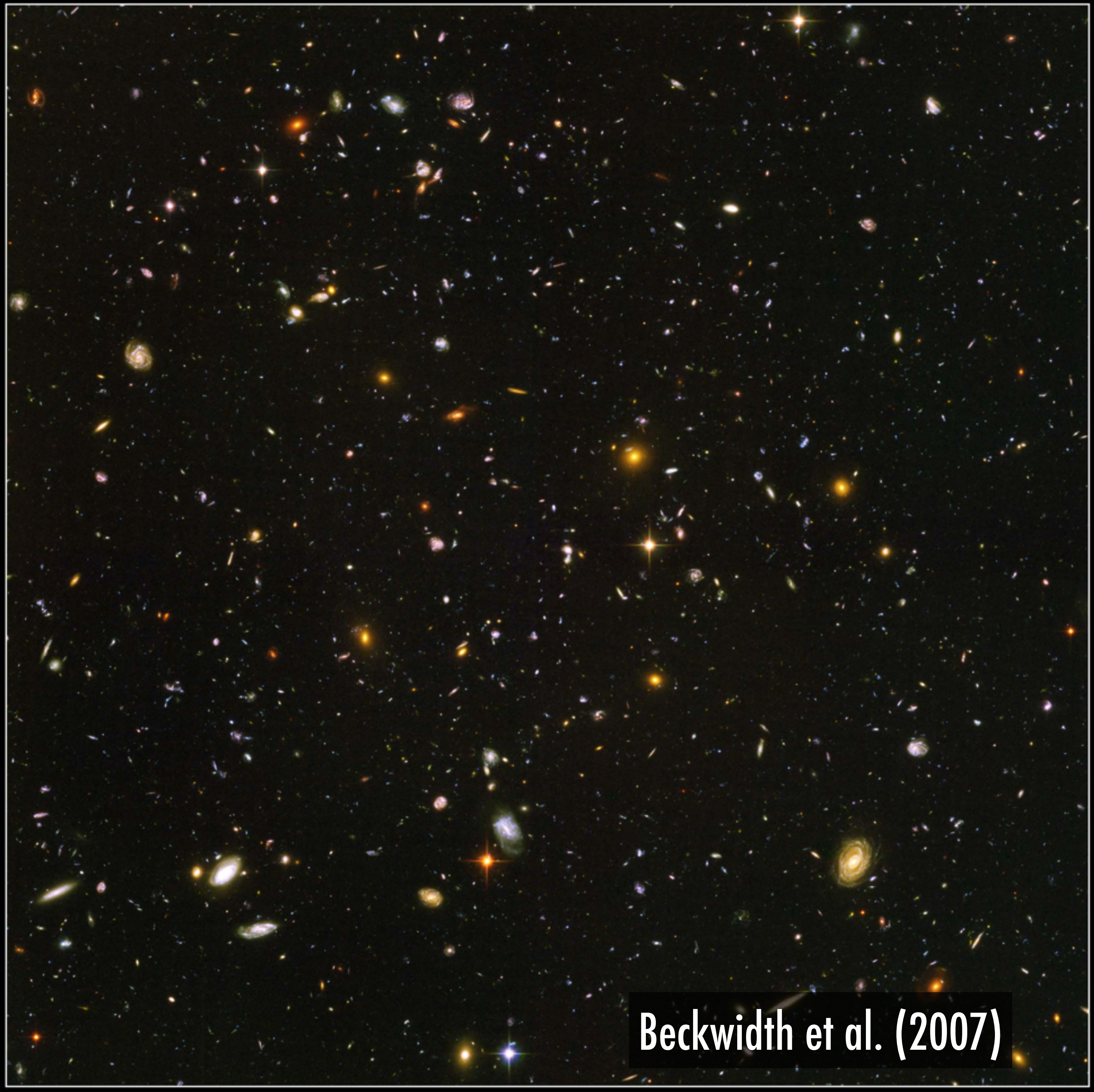
Observations suggest that the effective radii of high-redshift massive spheroids are as much as a factor ~ 6 smaller than low-redshift galaxies of comparable mass. Given the apparent absence of low-redshift counterparts, this has often been interpreted as indicating that the high density, compact red galaxies must be "puffed up" by some mechanism. We compare the ensemble of high-redshift observations with large samples of well-observed low-redshift ellipticals. At the same physical radii, the stellar surface mass densities of low and high-redshift systems are comparable. Moreover, the abundance of high surface density material at low redshift is comparable to or larger than that observed at $z > 1-2$, consistent with the continuous buildup of spheroids over this time. The entire population of compact, high-redshift red galaxies may be the progenitors of the high-density cores of present-day ellipticals, with no need for a decrease in stellar density from $z = 2$ to $z = 0$. The primary difference between low and high-redshift systems is thus the observed low-density material at large radii in low-redshift spheroids (rather than the high-density material in high-redshift spheroids). Such low-density material may either (1) assemble at $z < 2$ or (2) be present, but not yet detected, at $z > 2$. Mock observations of low-redshift massive systems show that the high-redshift observations do not yet probe sufficiently low surface brightness material to detect the low surface density "wings" (if present). Thus, if the high-redshift galaxies resemble the most massive systems today, their inferred effective radii could be under-estimated by factors $\sim 2-4$. This difference arises because massive systems at low redshift are not well-fit by single Sersic profiles. We discuss the implications of our results for physical models of galaxy evolution.

Theoretical Expectations

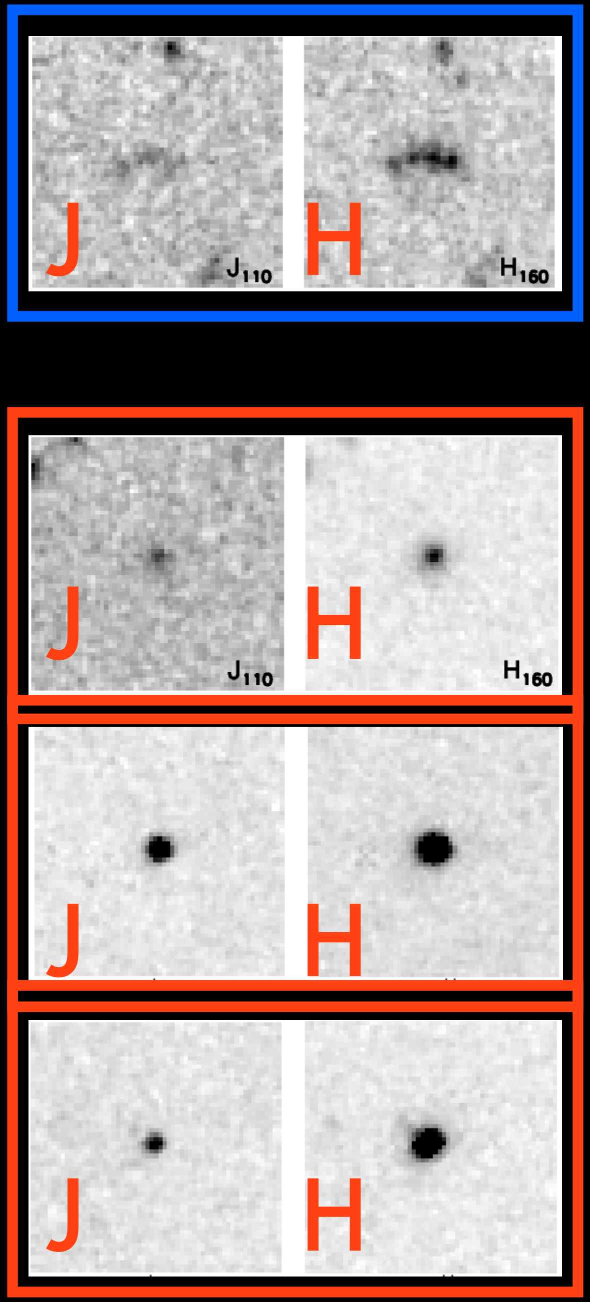




Faint, Red High-z Galaxies in the Hubble Ultra-deep Field



Search for galaxies with J - H > 1.0 mag using NICMOS data (J & H < 27 mag; R. Thompson et al.)



Stutz, Papovich, & Eisenstein (2008, ApJ, 677, 828)

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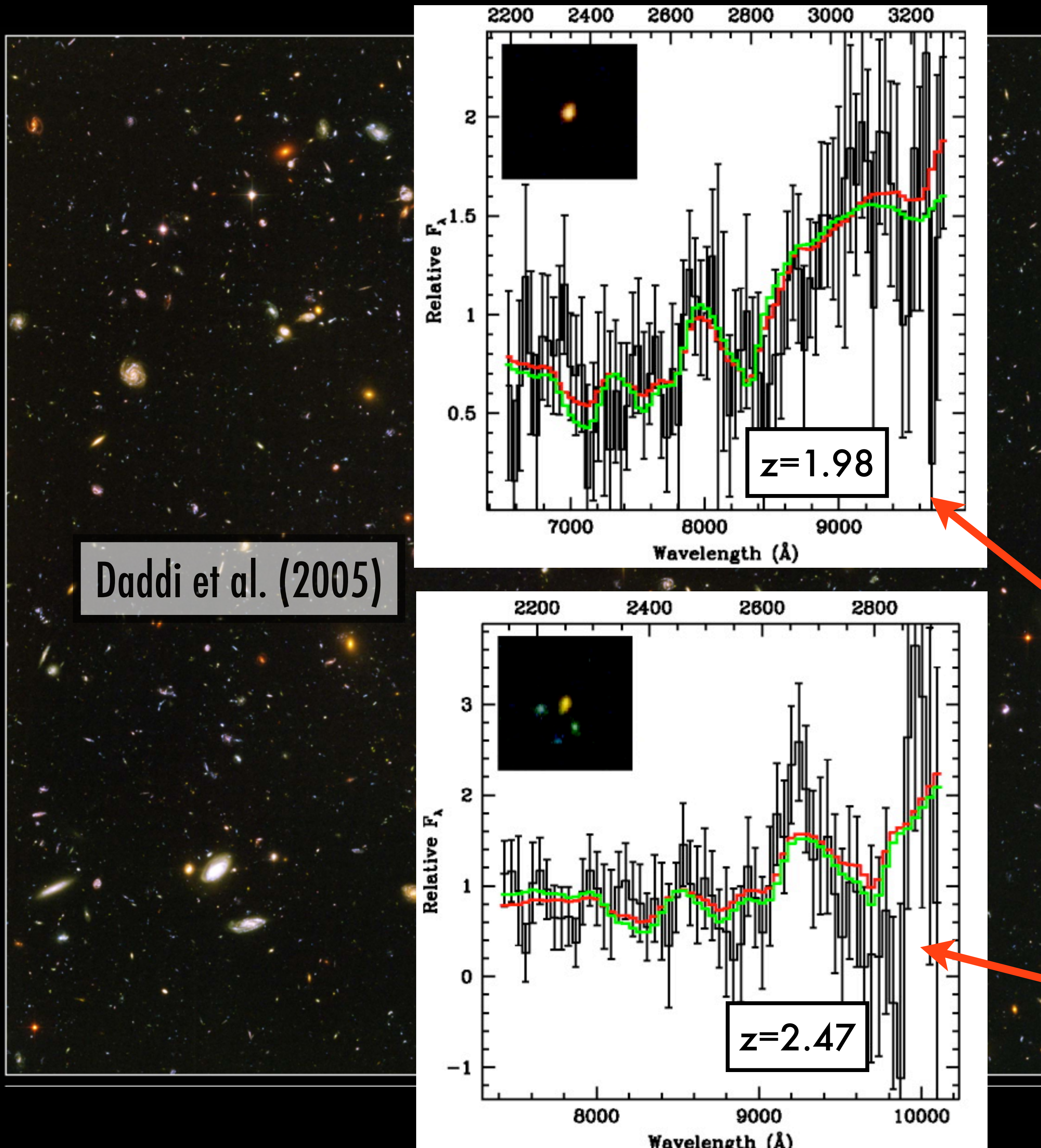

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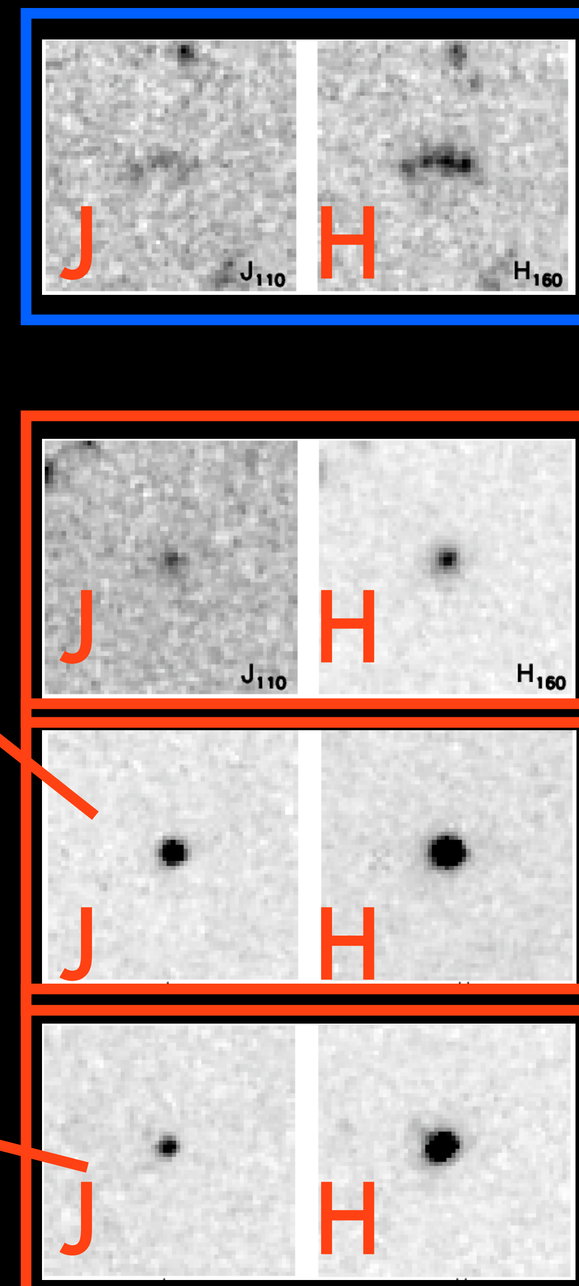

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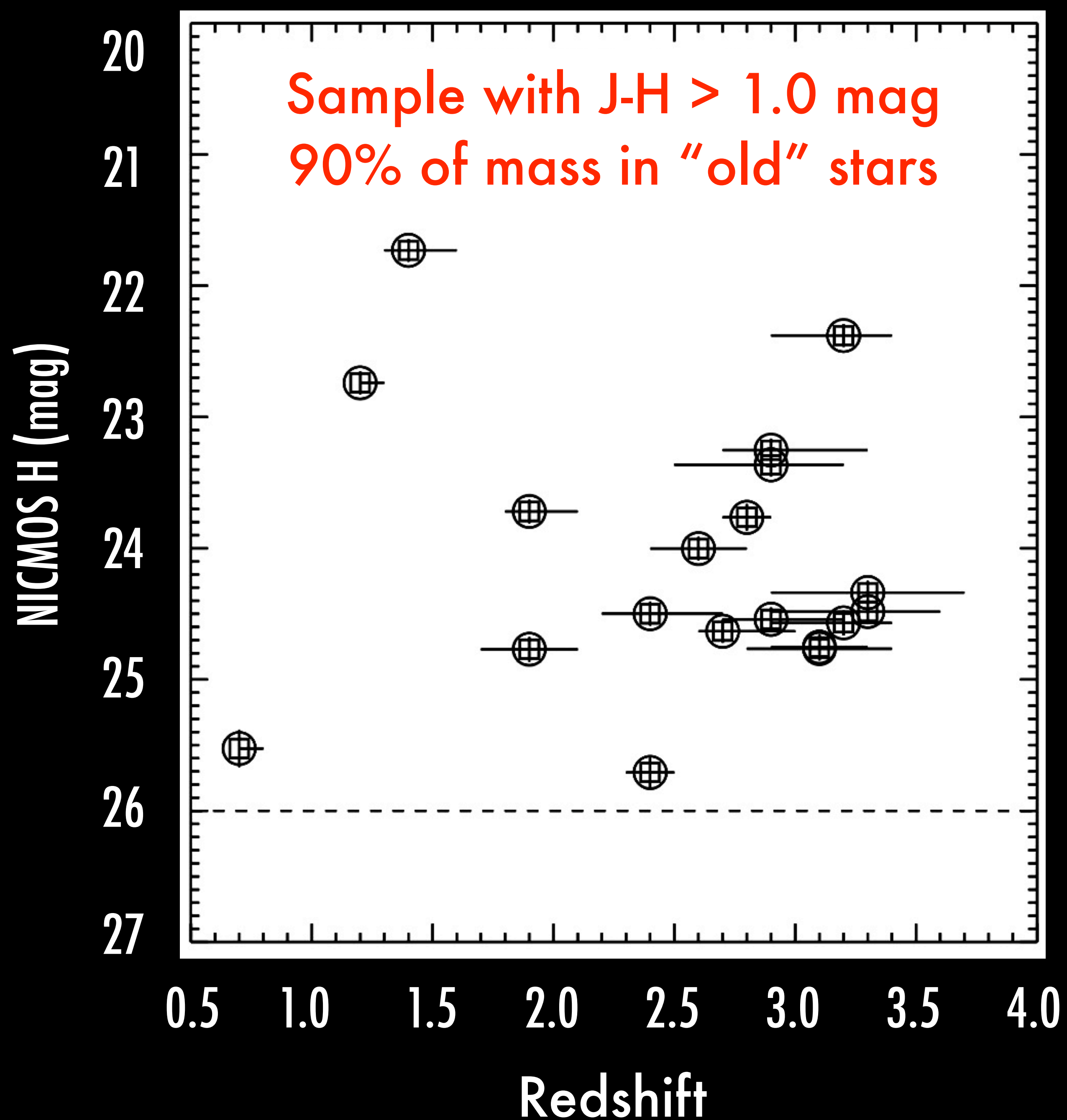

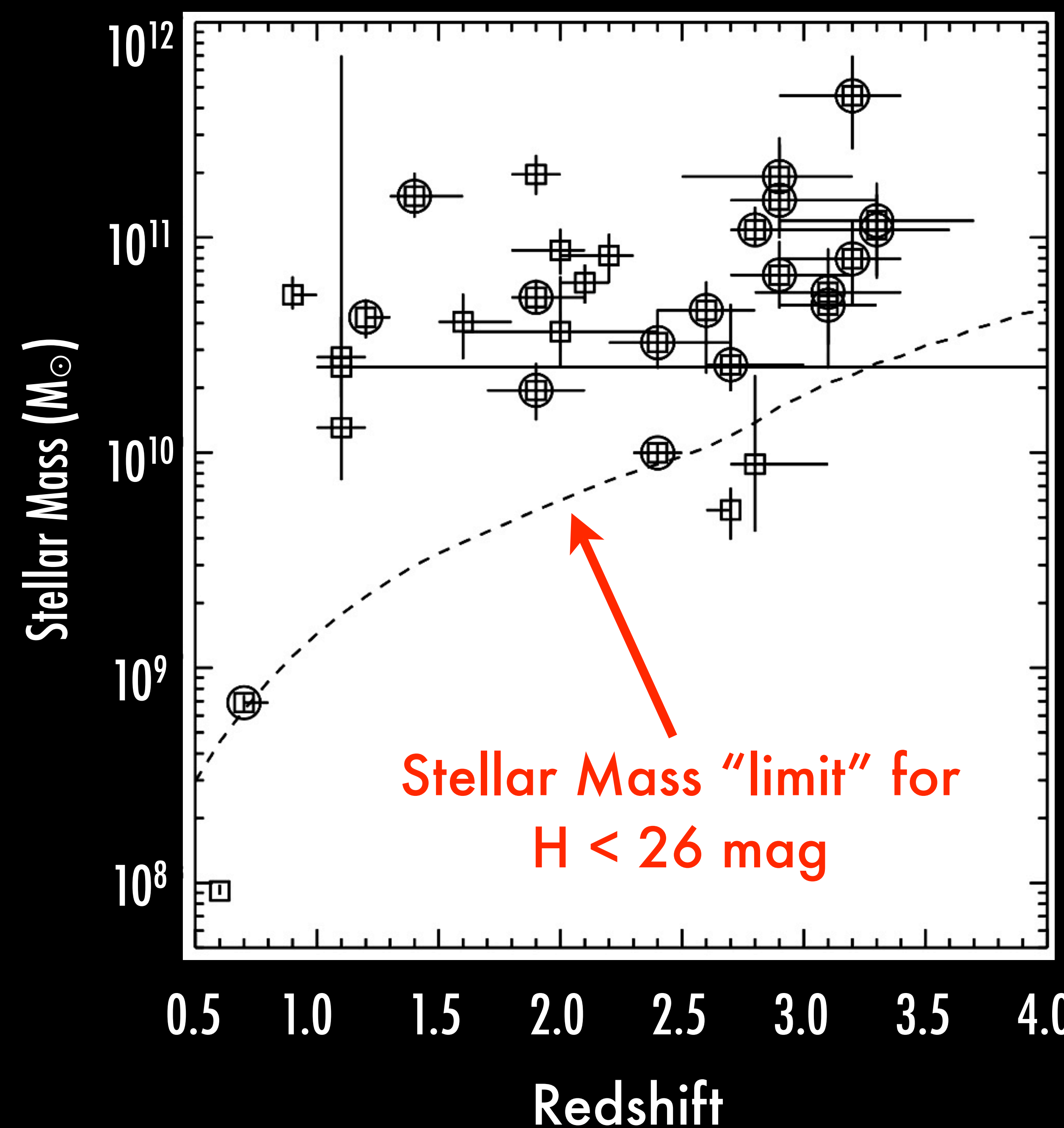

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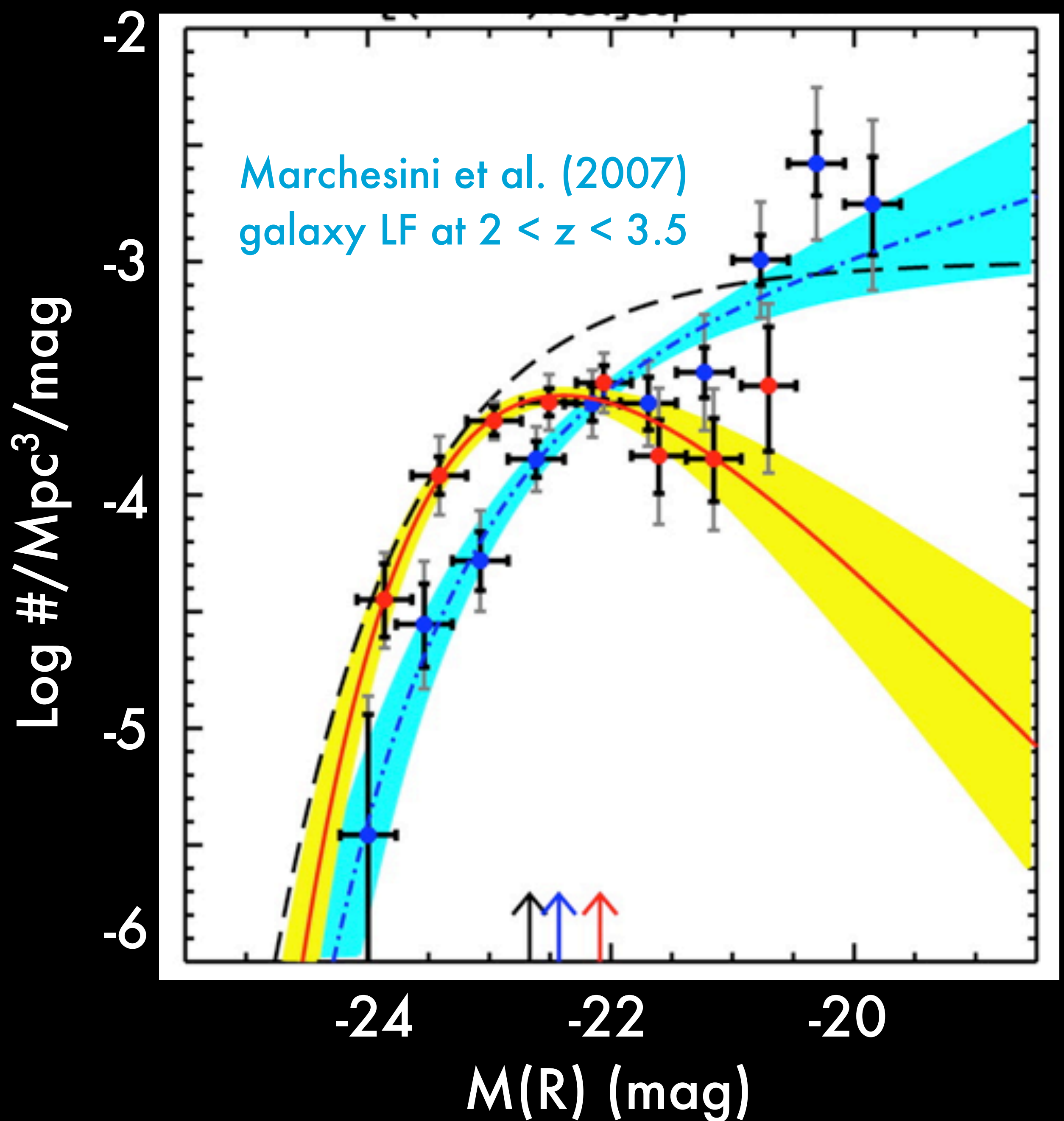

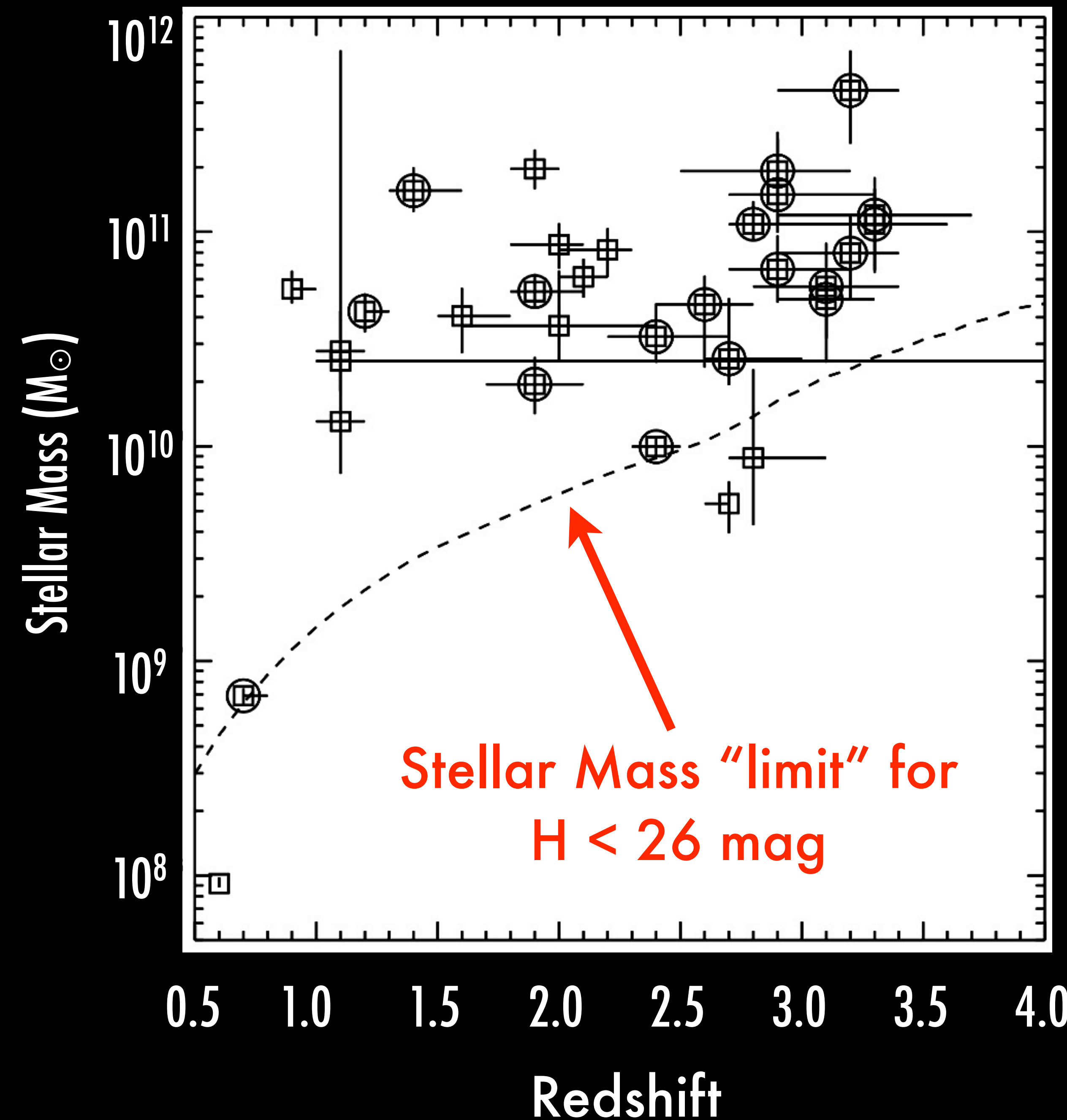

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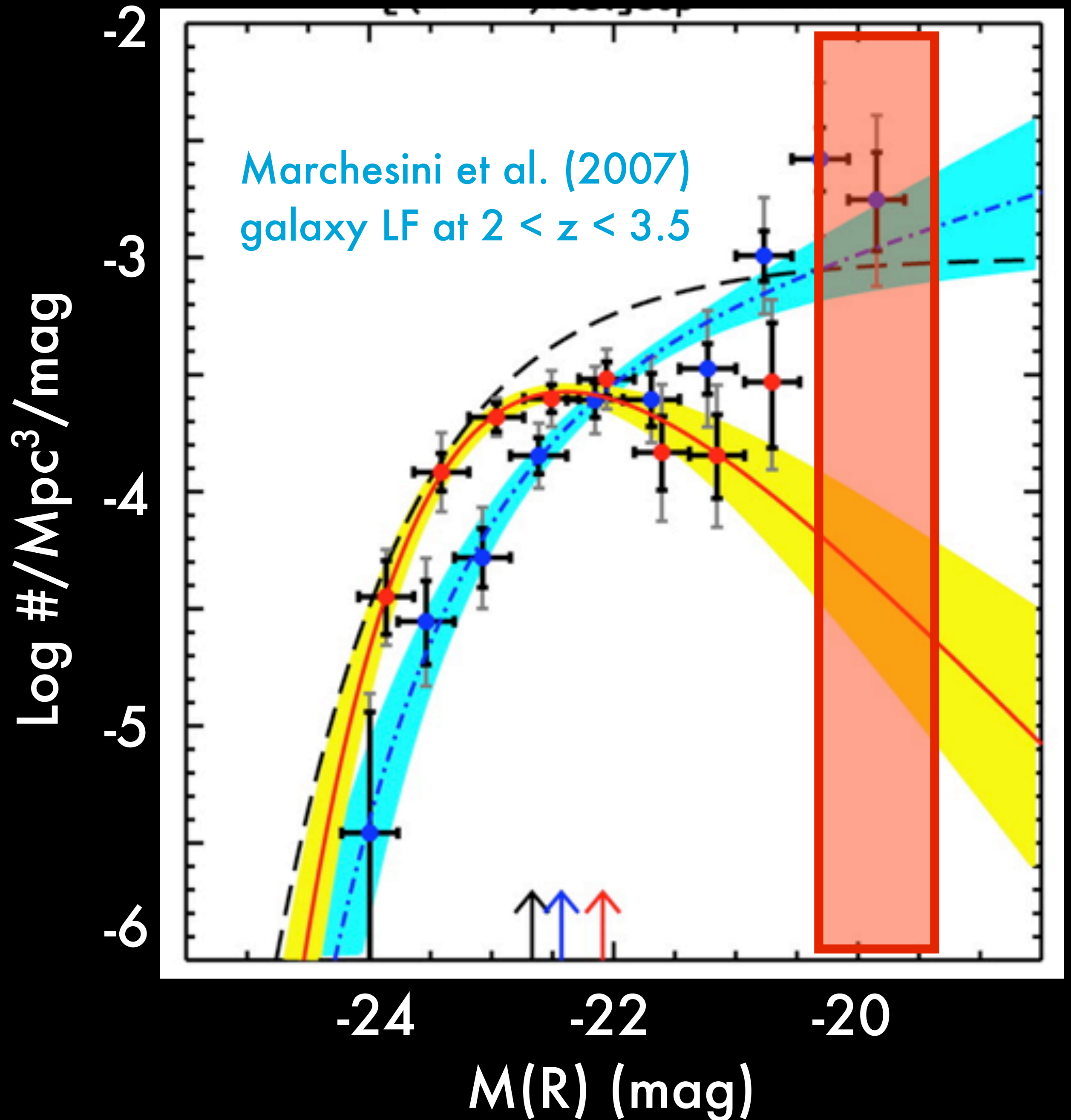

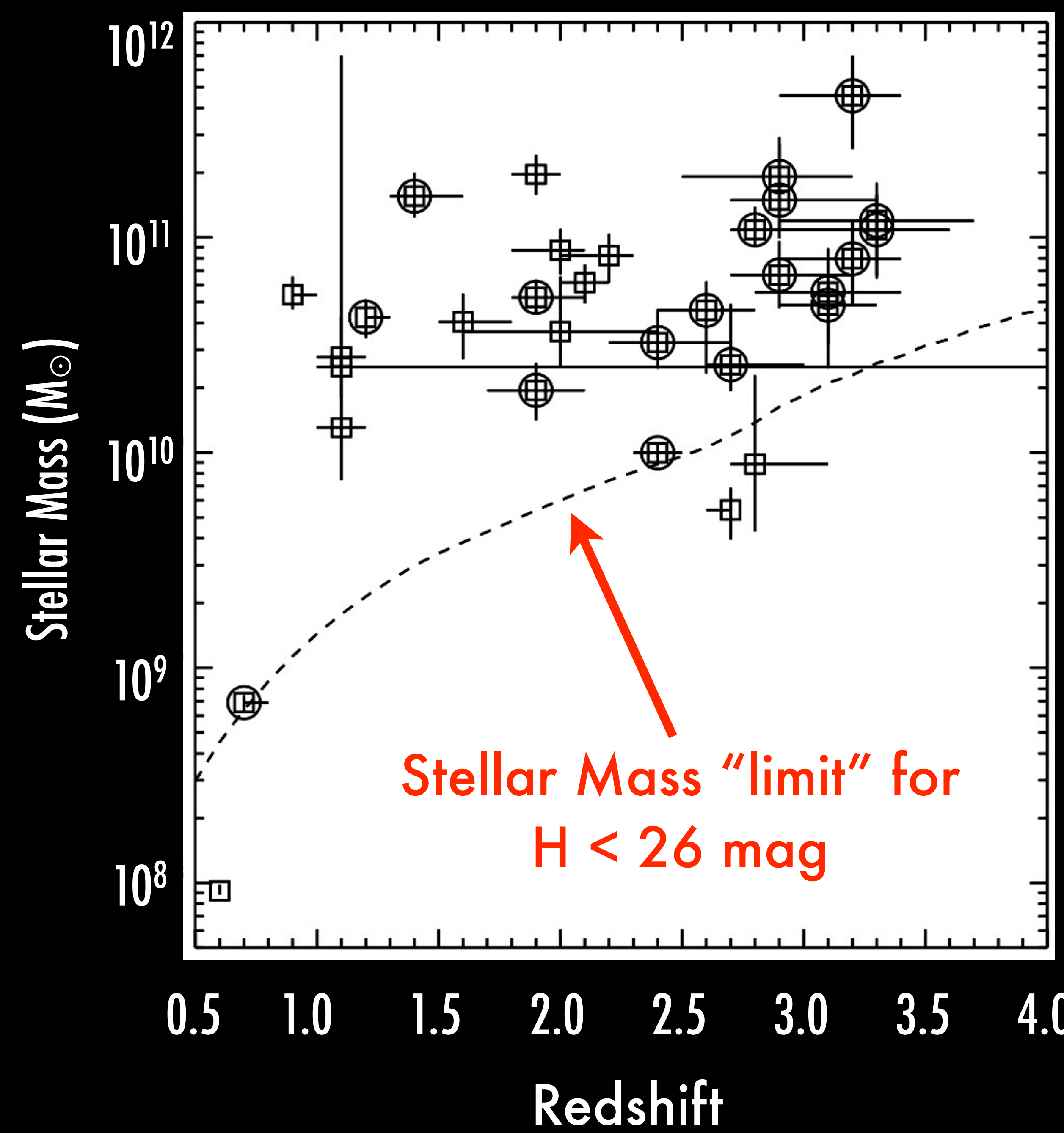

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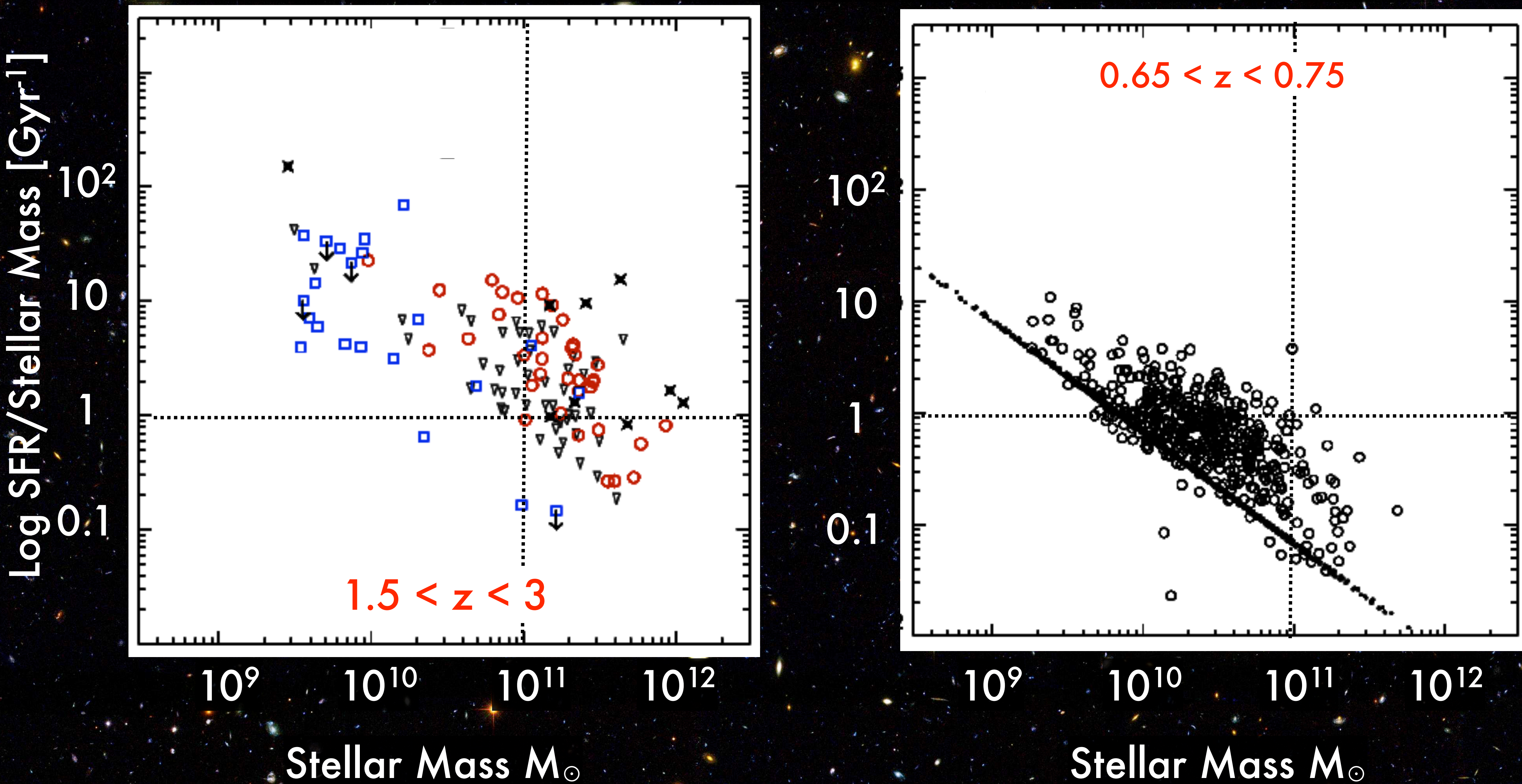
Evolution of SFR in Massive Galaxies



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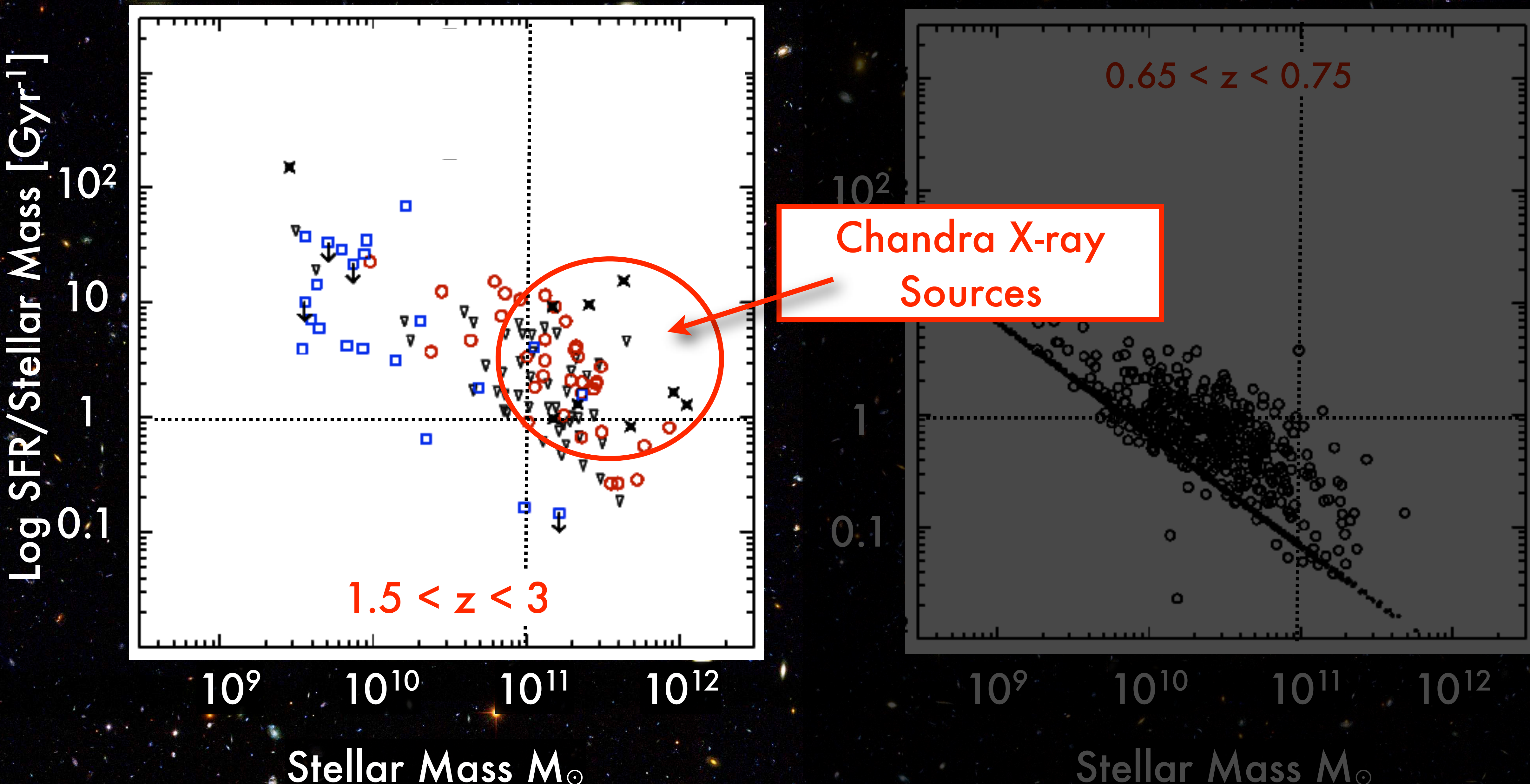

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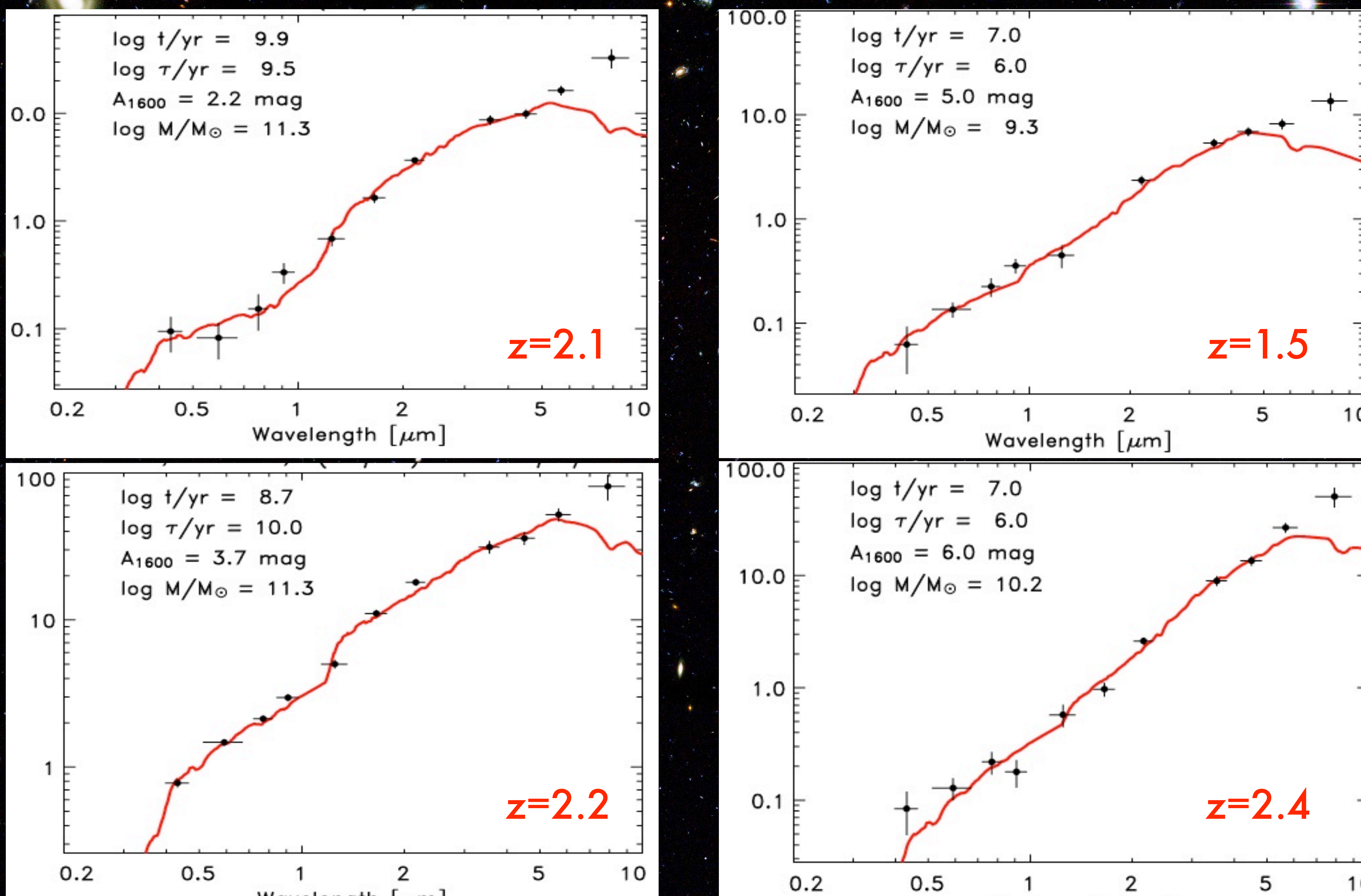
Near-IR Color Selection of AGN

(see also, Lacy+04; Stern+05; Barmby+06; Alonso-Herrero+06; Donley+07,08)

X-ray Sources

Non-X-ray Sources



Log Fν [μJy]

Log Wavelength

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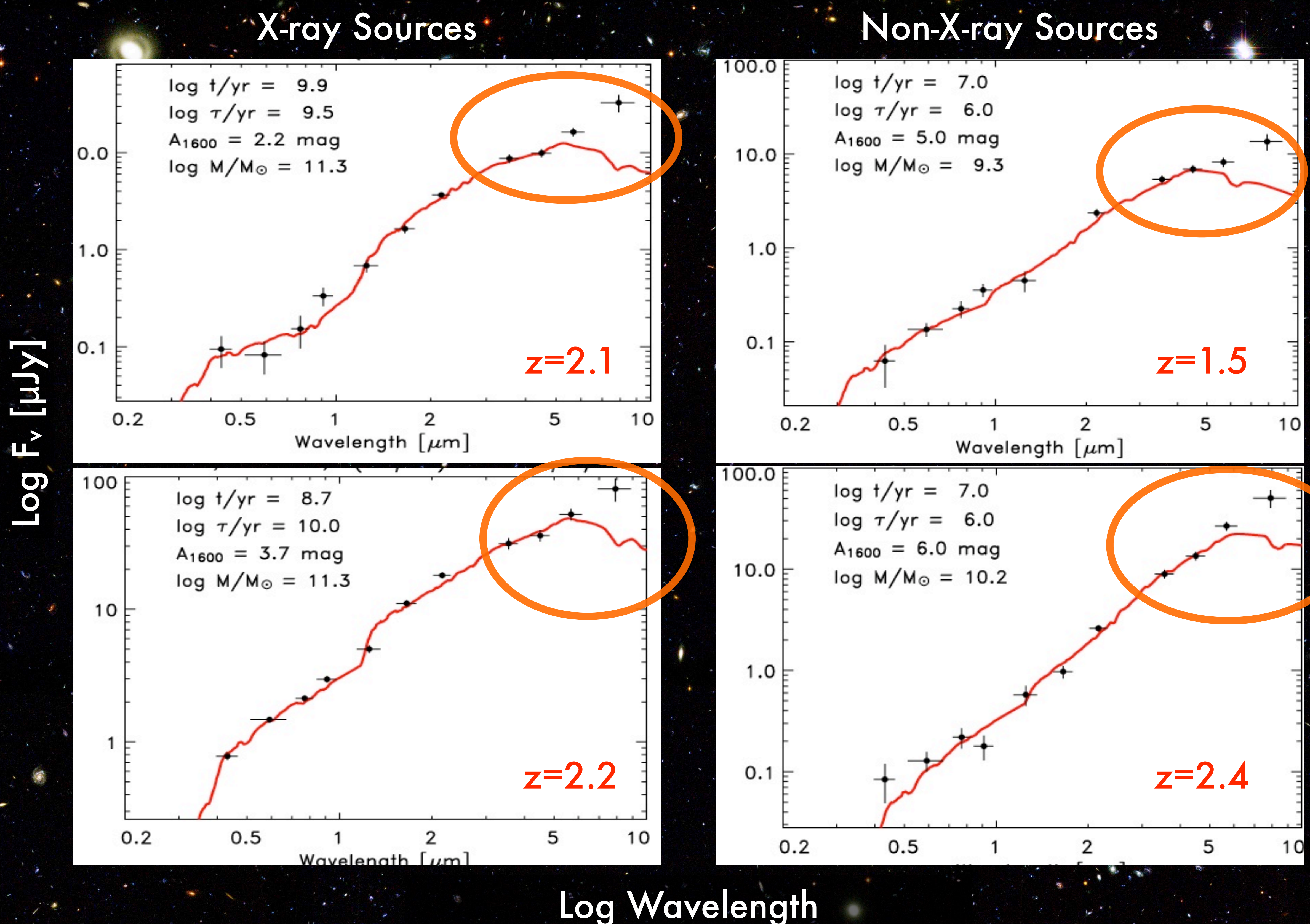

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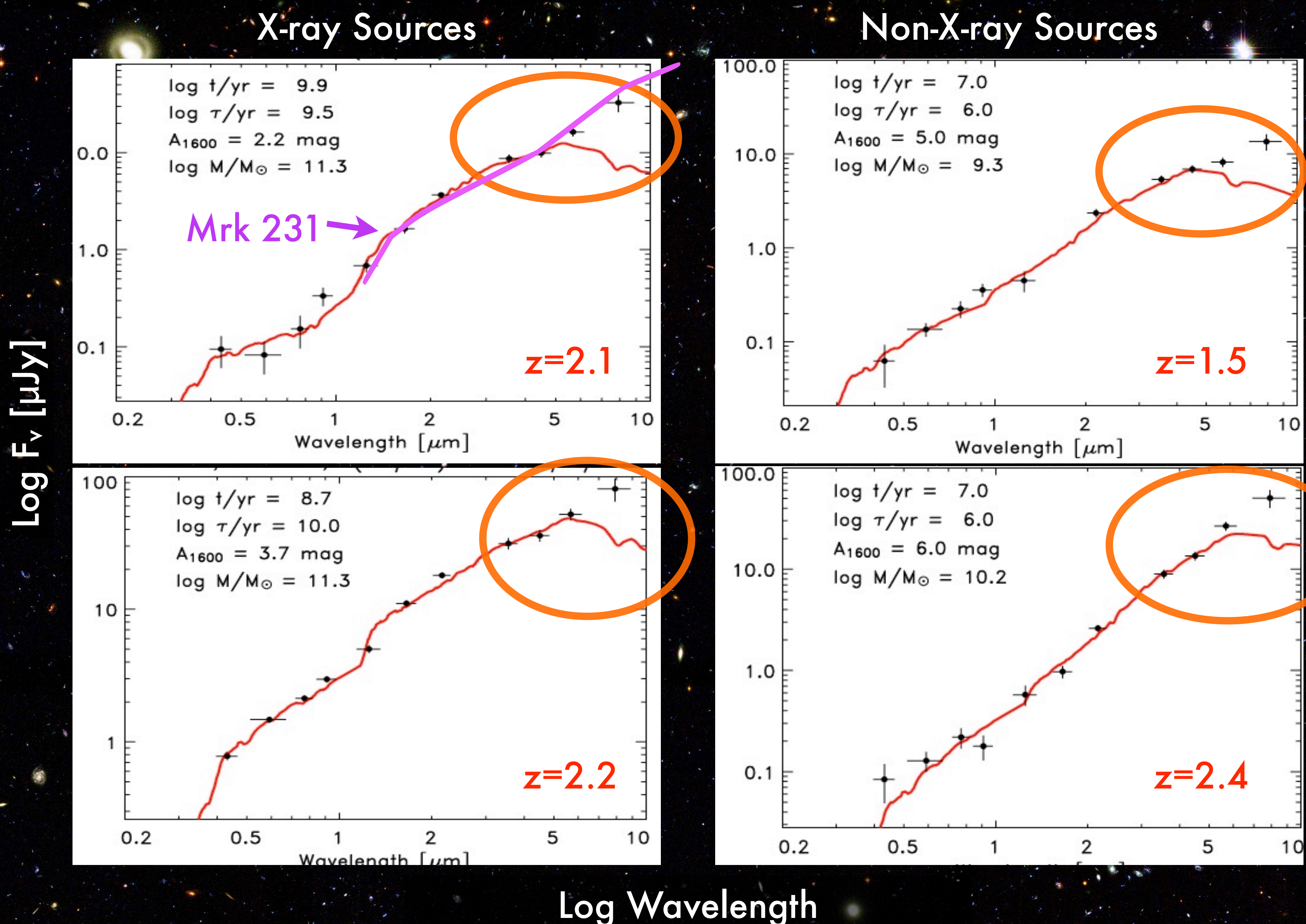


Near-IR Color Selection of AGN

(see also, Lacy+04; Stern+05; Barmby+06; Alonso-Herrero+06; Donley+07,08)

X-ray Sources

Non-X-ray Sources

+10% of massive galaxies at 1.5 < z < 3 are X-ray sources

+15% have IR Spectral Energy Distributions suggestive of dust heated by blackhole accretion processes.

At least ~ 25% of massive galaxies at z ~ 1.5 - 3 host accreting SMBHs

Similar conclusions by
Kriek et al. (2007) and Daddi et al. (2007).

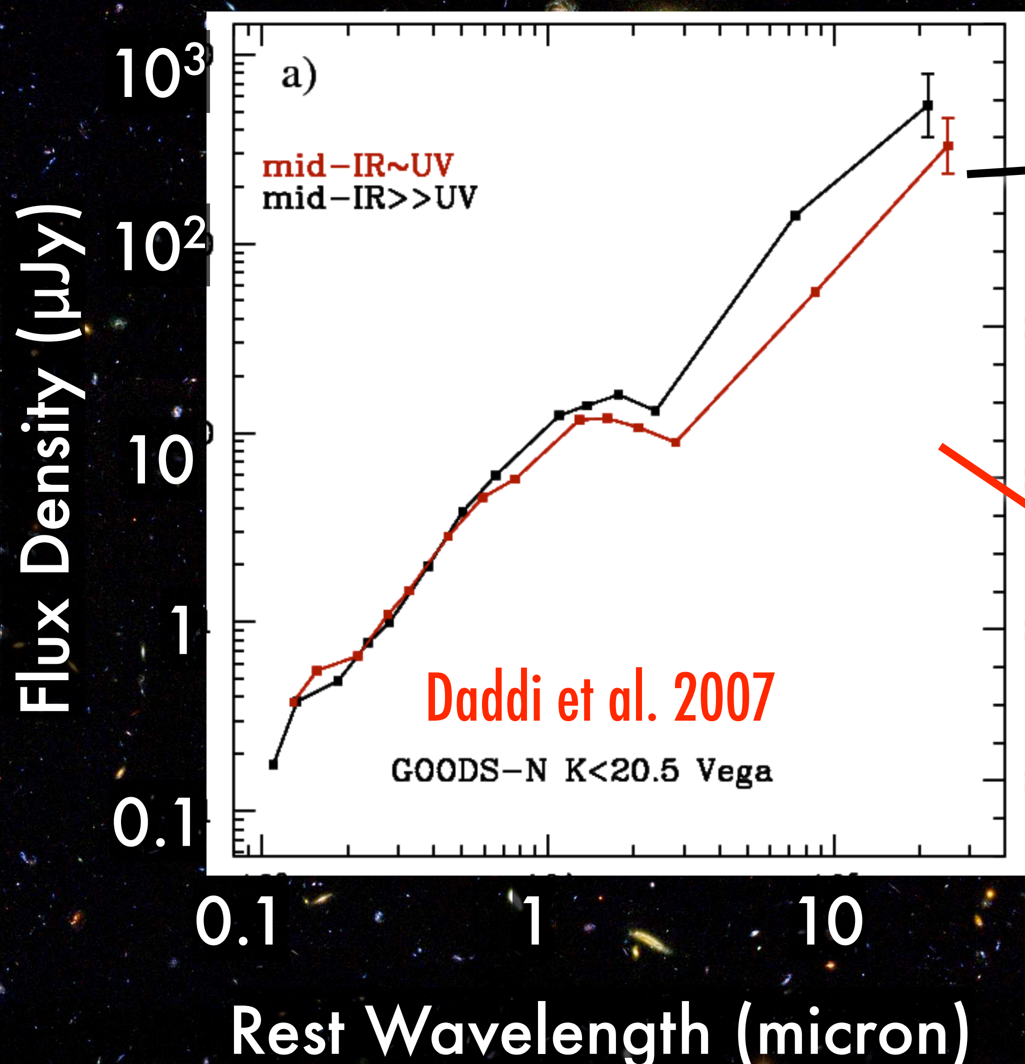
Interpretation of IR emission (AGN versus SF) is complicated and debated (Daddi+07; Alexander+08; Pope+08; Donley+08).

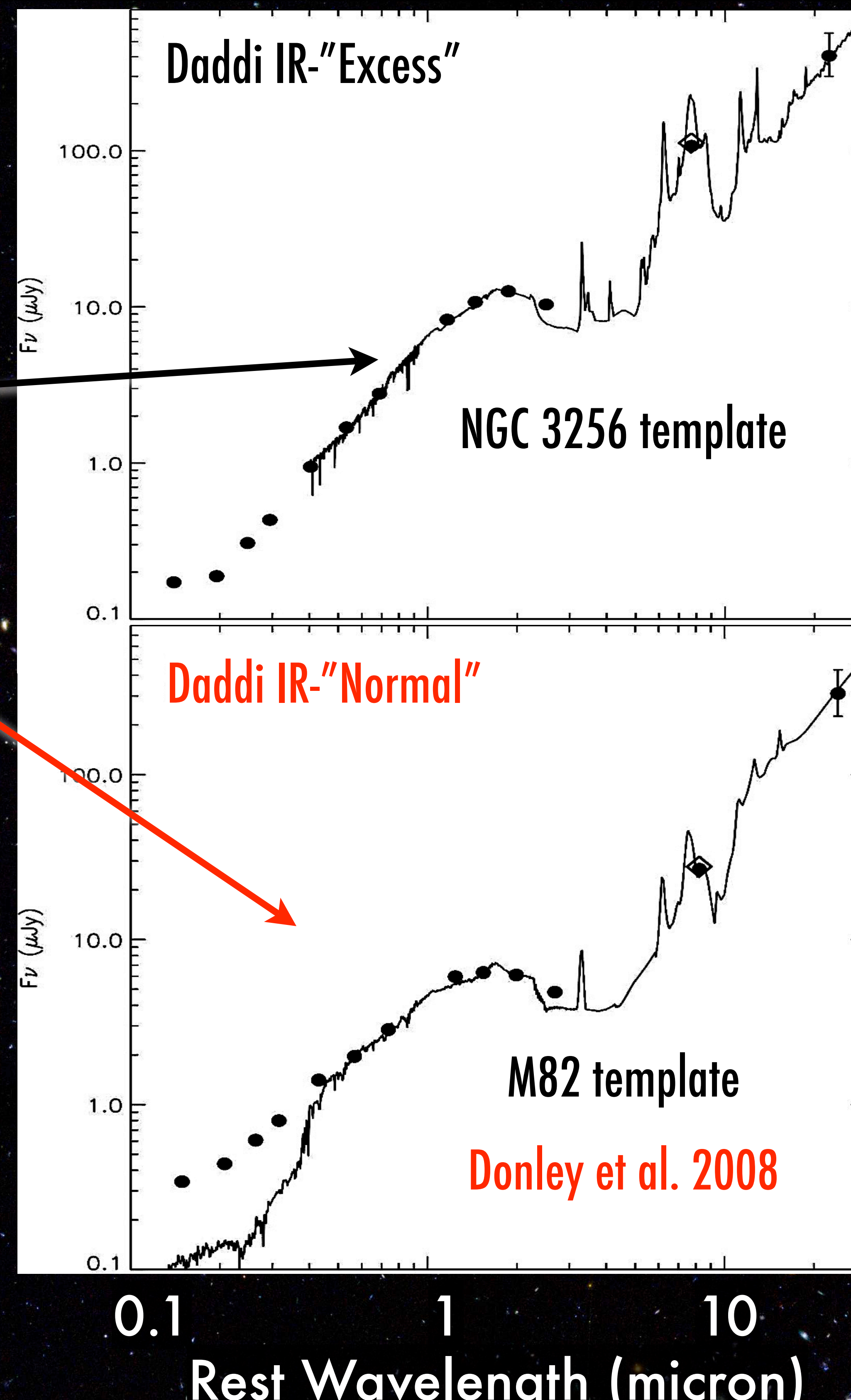
Suggestive that a relation exists between
SMBH and galaxy growth.

Log F_ν [μJy]

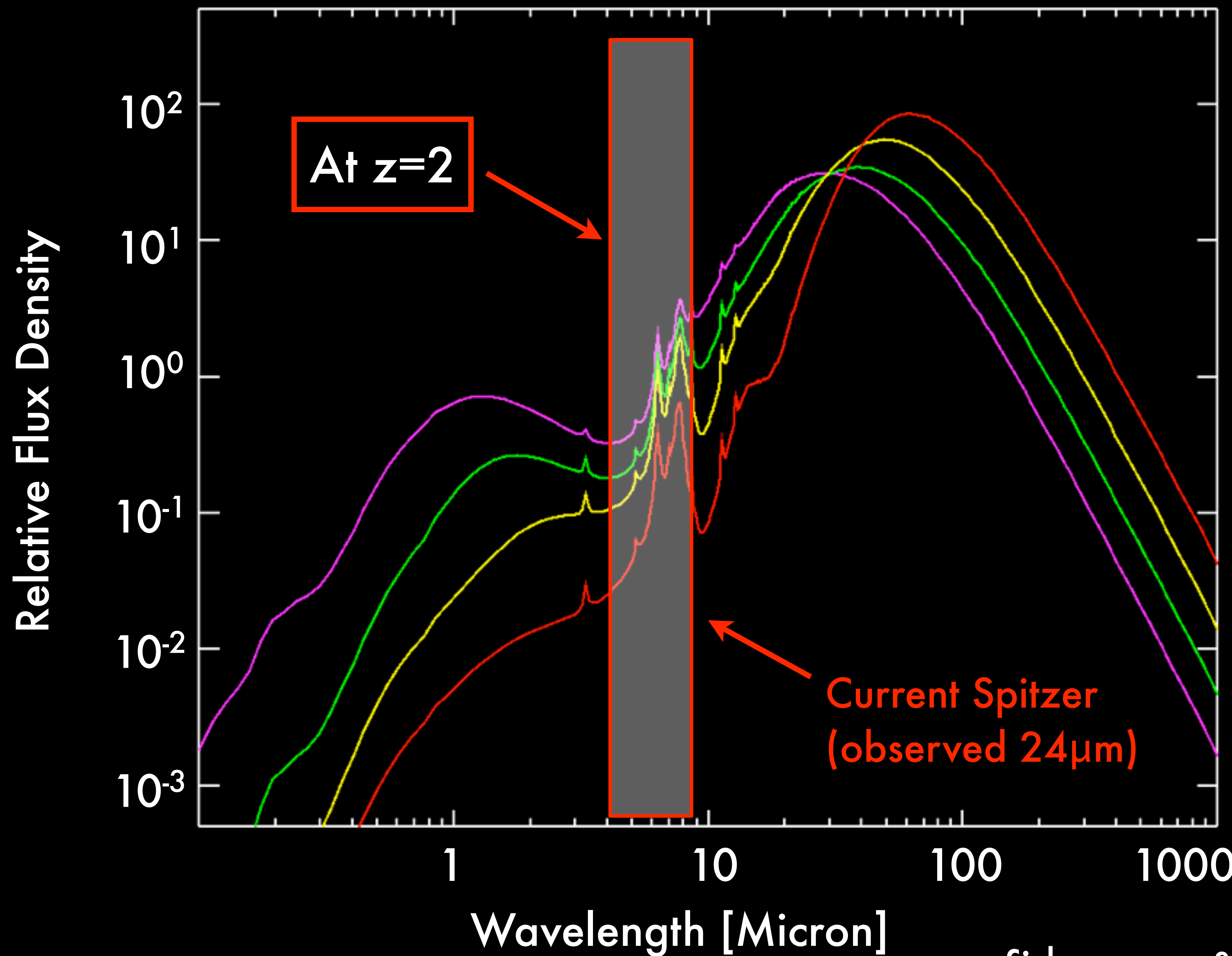
Log Wavelength

Interpretation of IR Emission: Star Formation vs. AGN





Relation between mid-IR and total IR Emission



Siebenmorgen & Krügel (2008) Models

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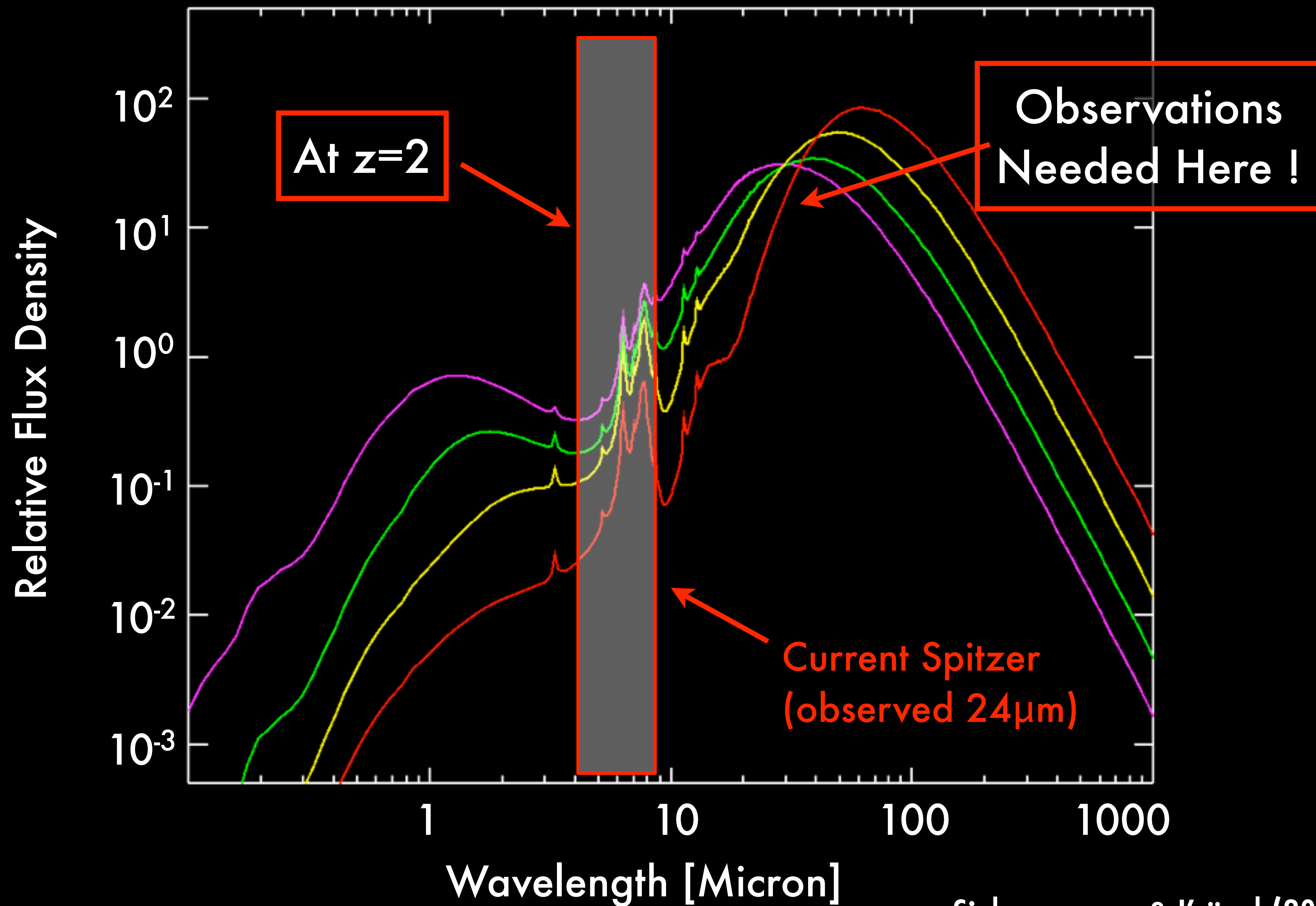
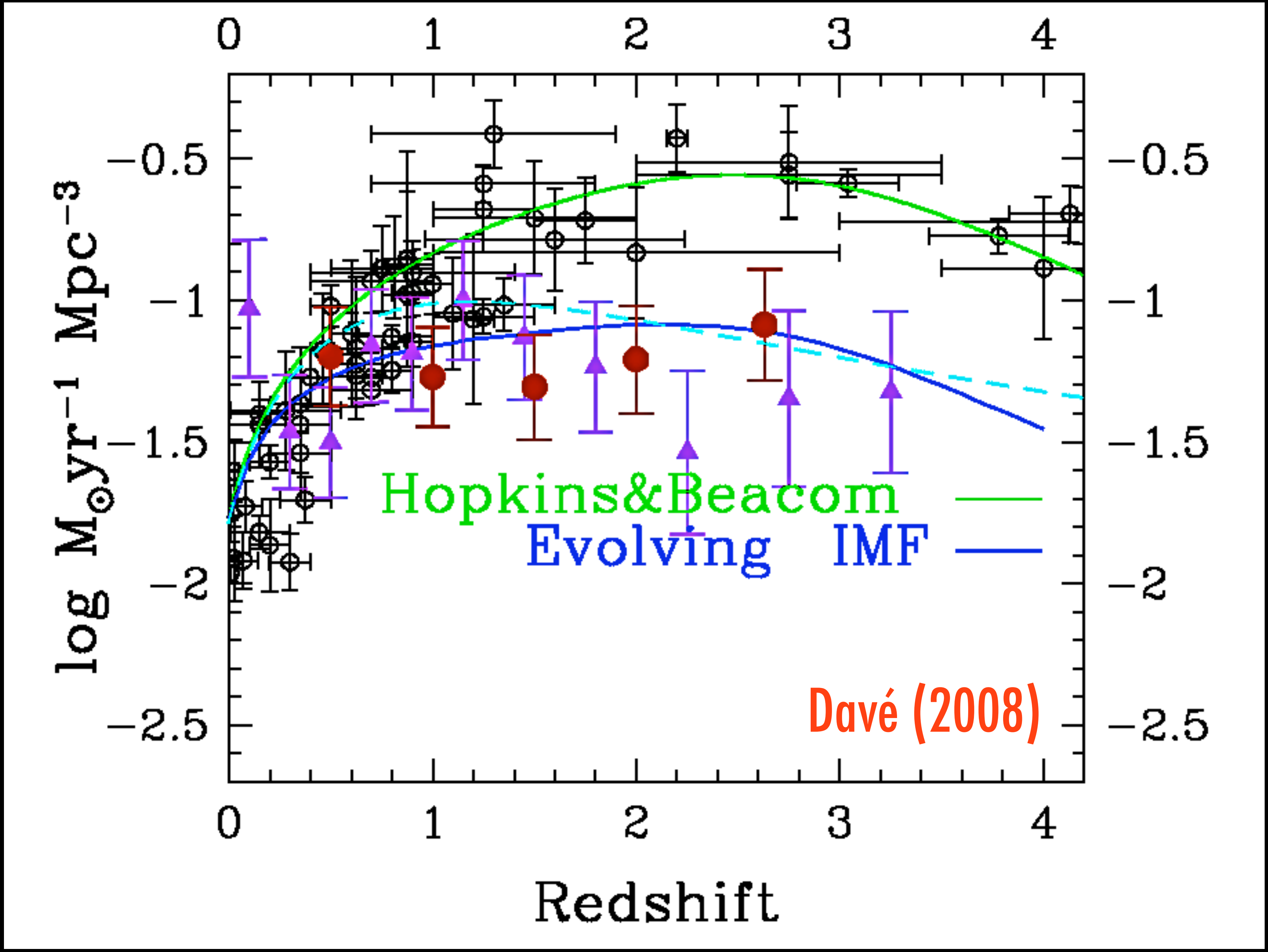


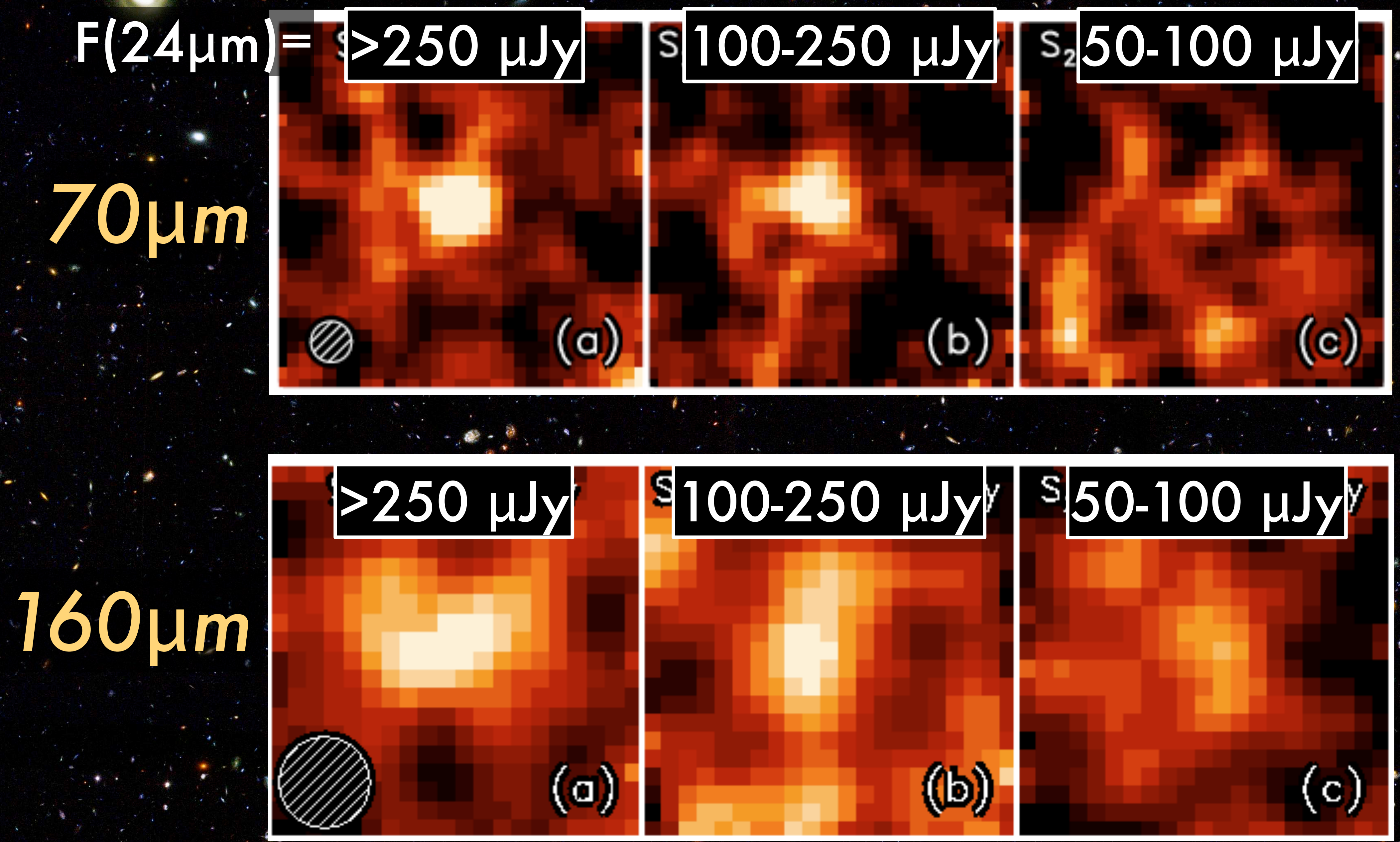
Siebenmorgen & Krügel (2008) Models

Evolution of Star Formation and Stellar Mass

Star Formation Rate Density



Stacked 70 and 160 μm for 24 μm Sources at 1.5<z<2.5



Papovich et al. (2007, ApJ, 668, 45)

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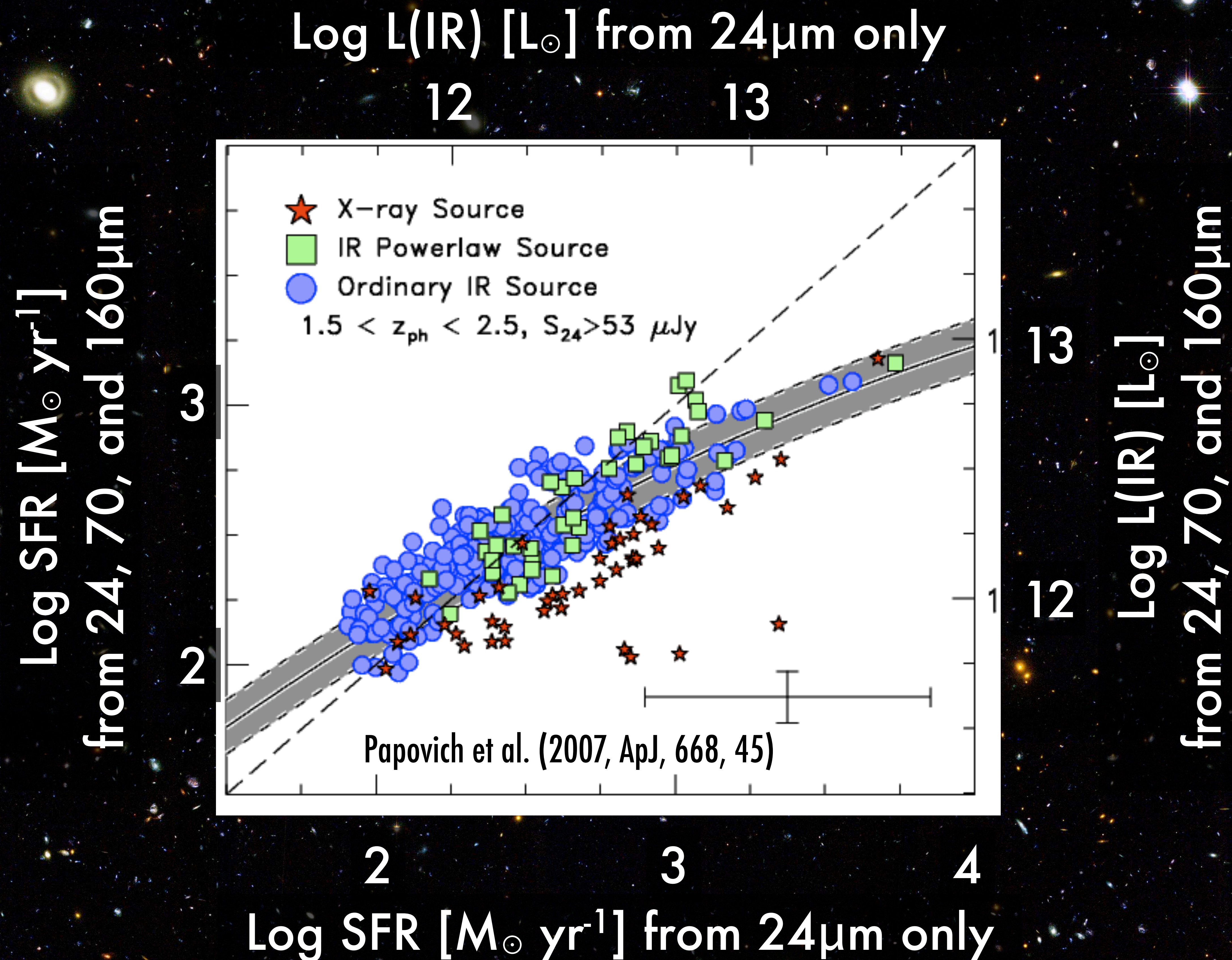
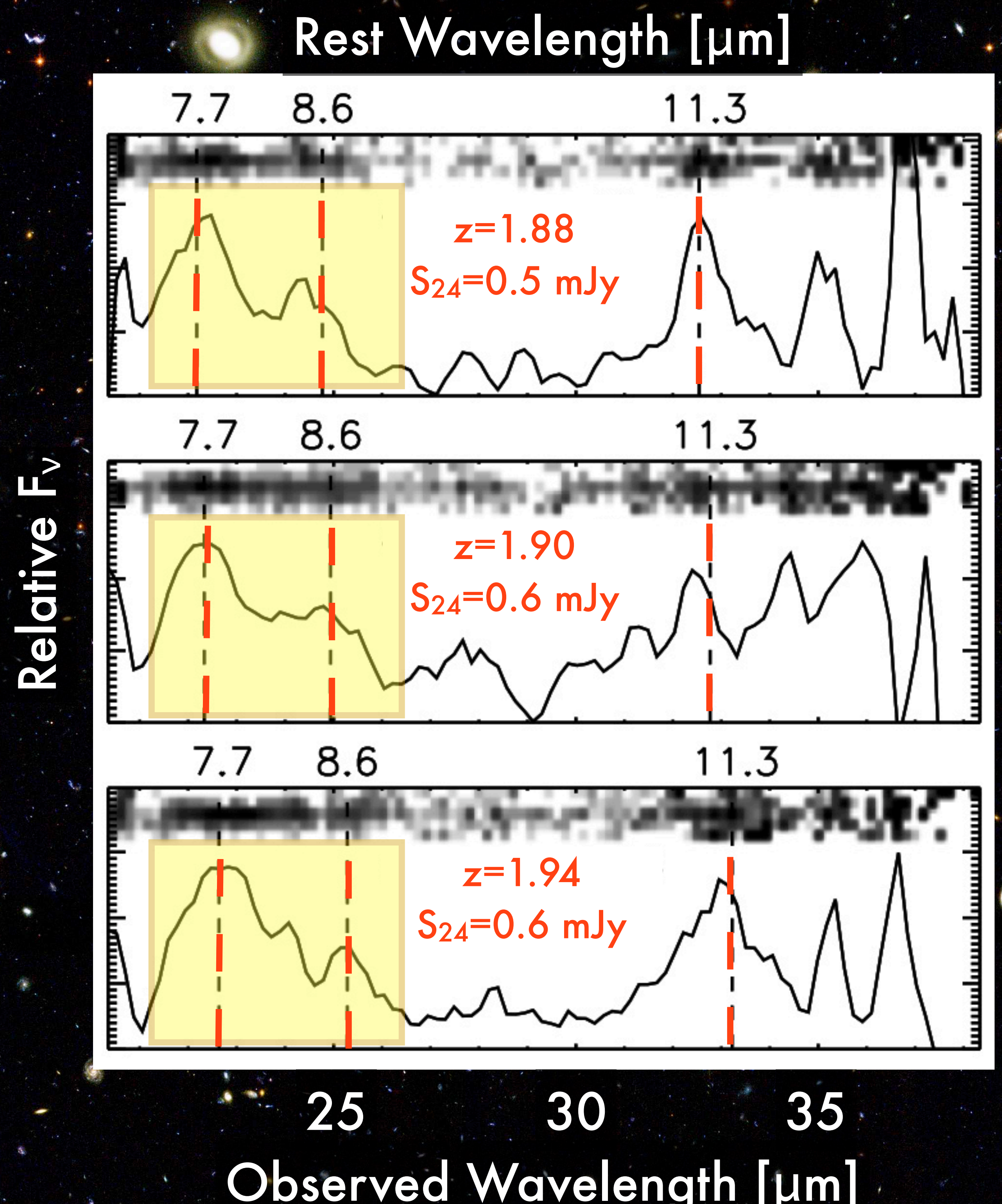
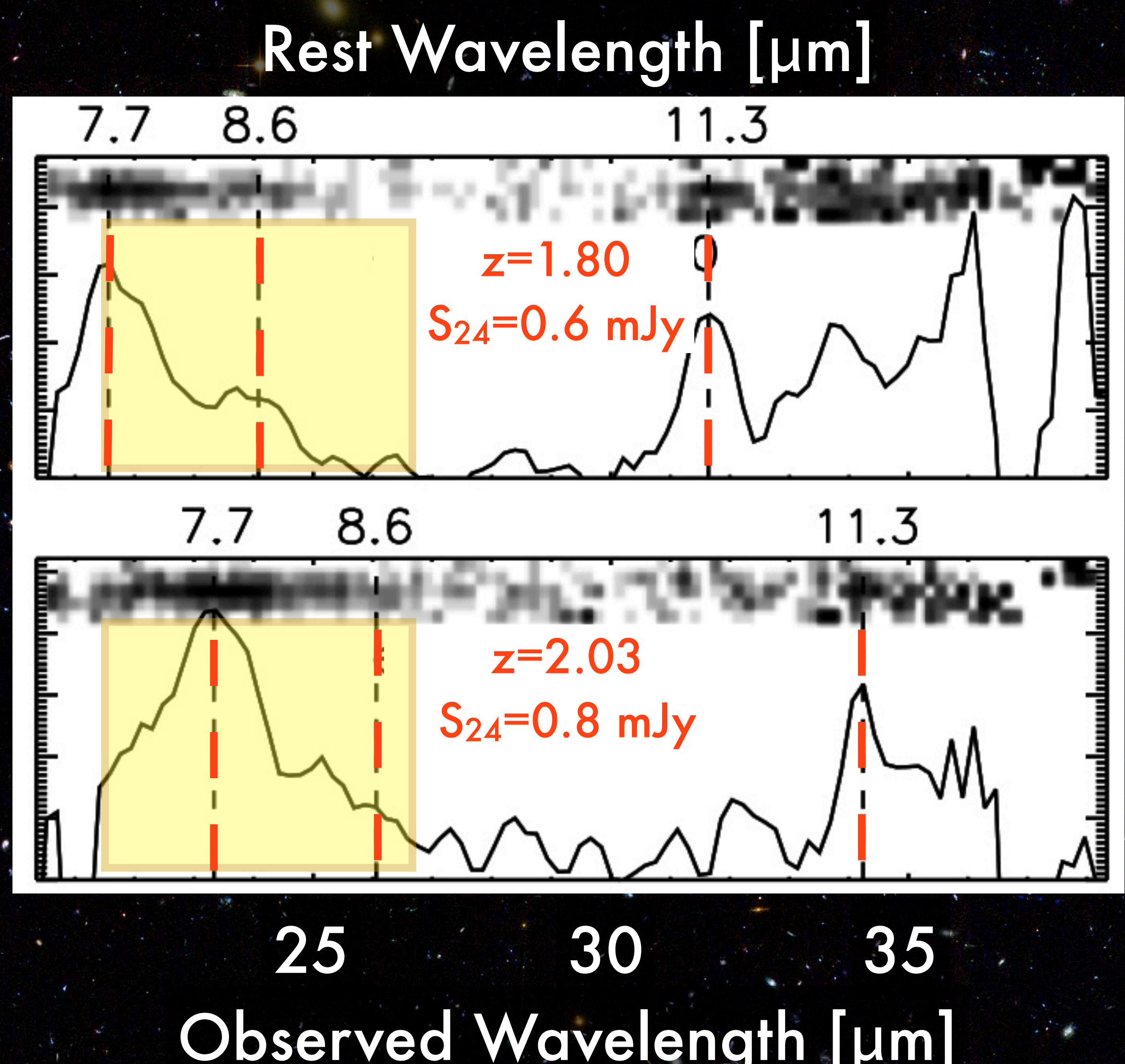


Spitzer Spectroscopy of High-z, Bright 24μm Sources

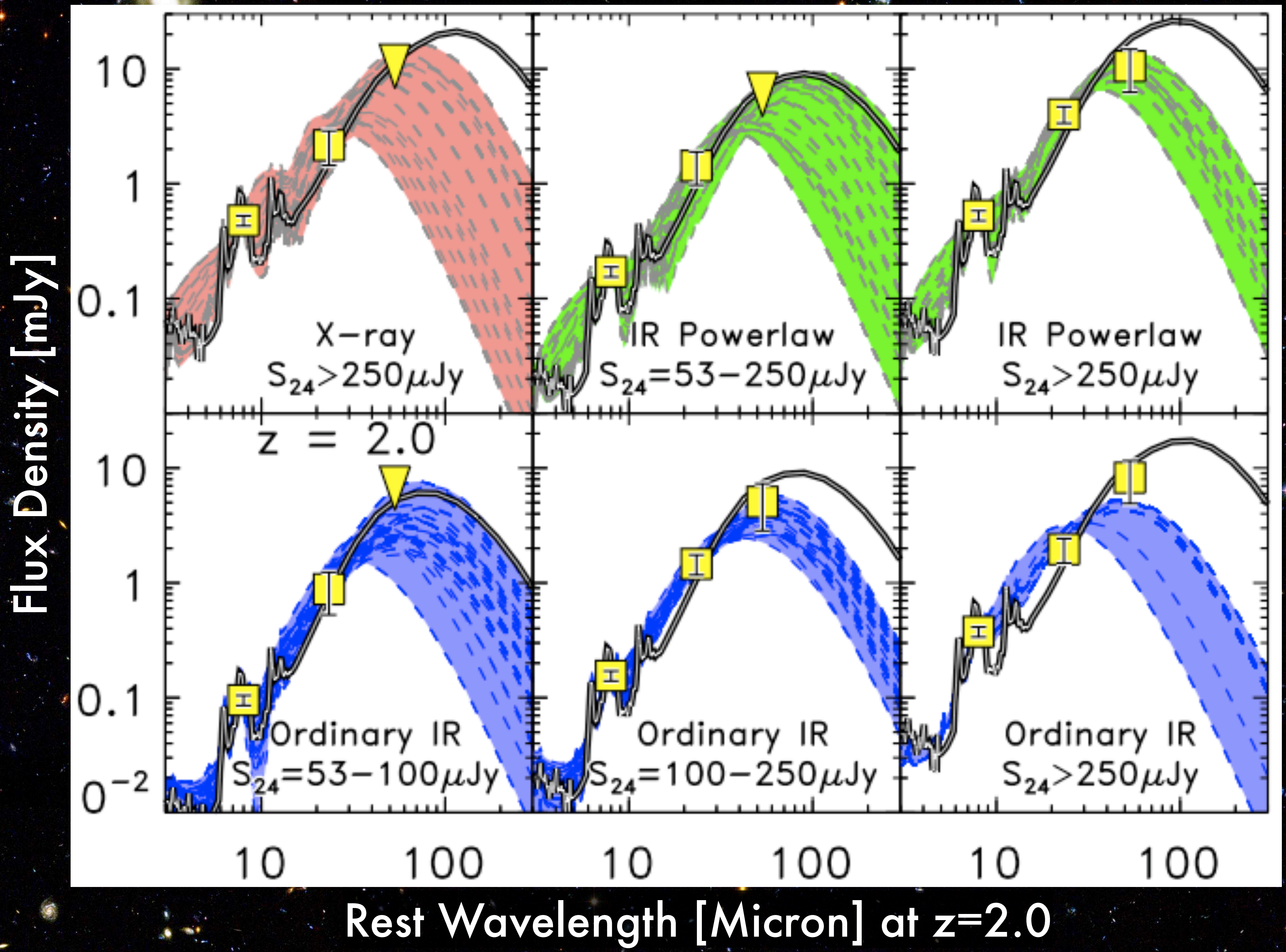
IRS/LL spectra of sources with stellar-dominated SEDs at z > 1.5 and S(24) > 0.5 mJy.
J.-S. Huang et al., in prep

Similar results found by Farrah et al. (2008) and Pope et al. (2008)





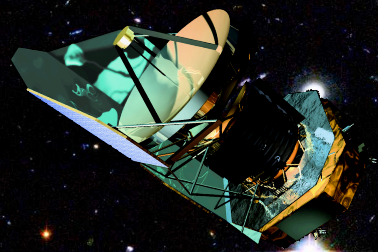
The Future: the Herschel Space Observatory

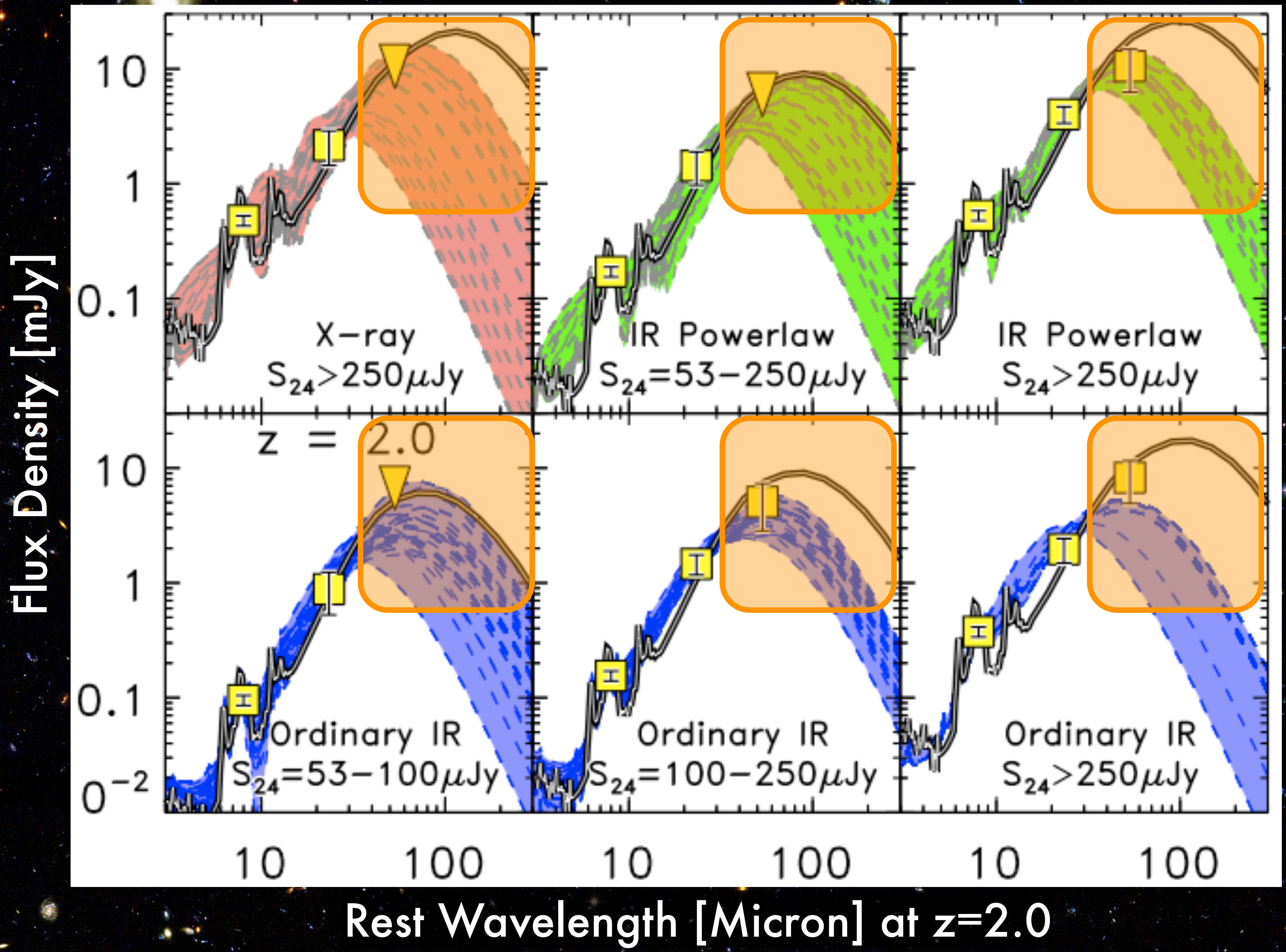


Stacked 24 - 160μm of $1.5 < z < 2.5$ galaxies, with model fits.

Papovich et al. (2007, ApJ, 668, 45)

The Future: the Herschel Space Observatory



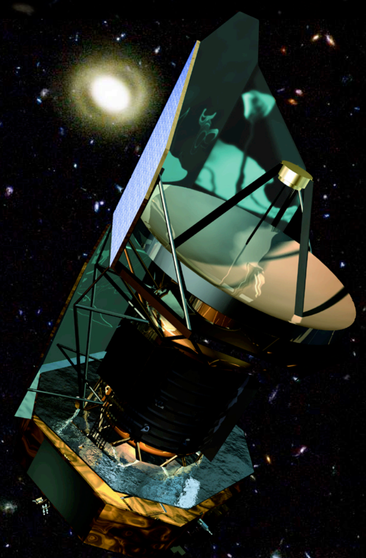


Herschel will probe 70-500 μm, measuring the shape of the IR Spectral Energy Distribution

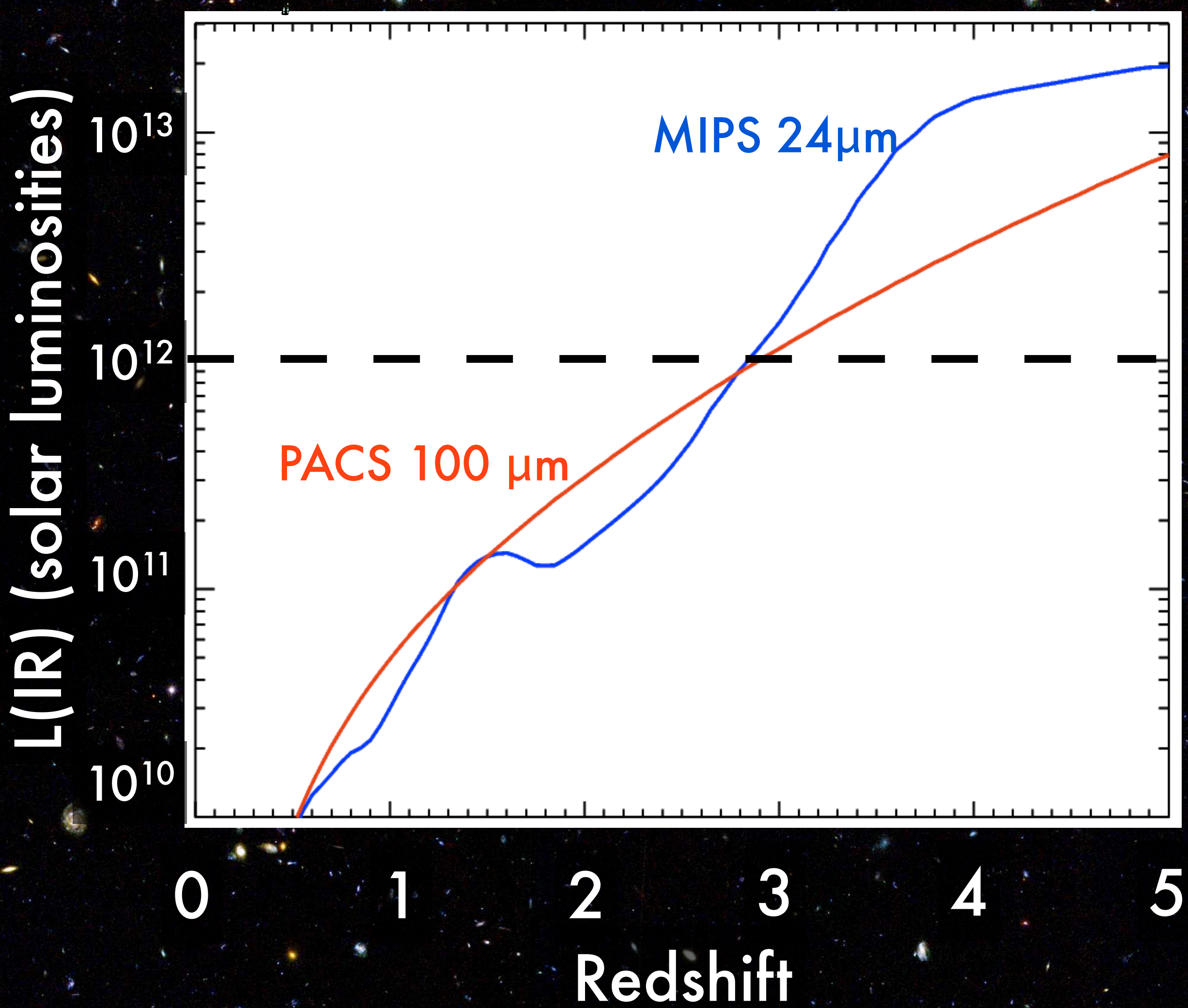
Papovich et al. (2007, ApJ, 668, 45)

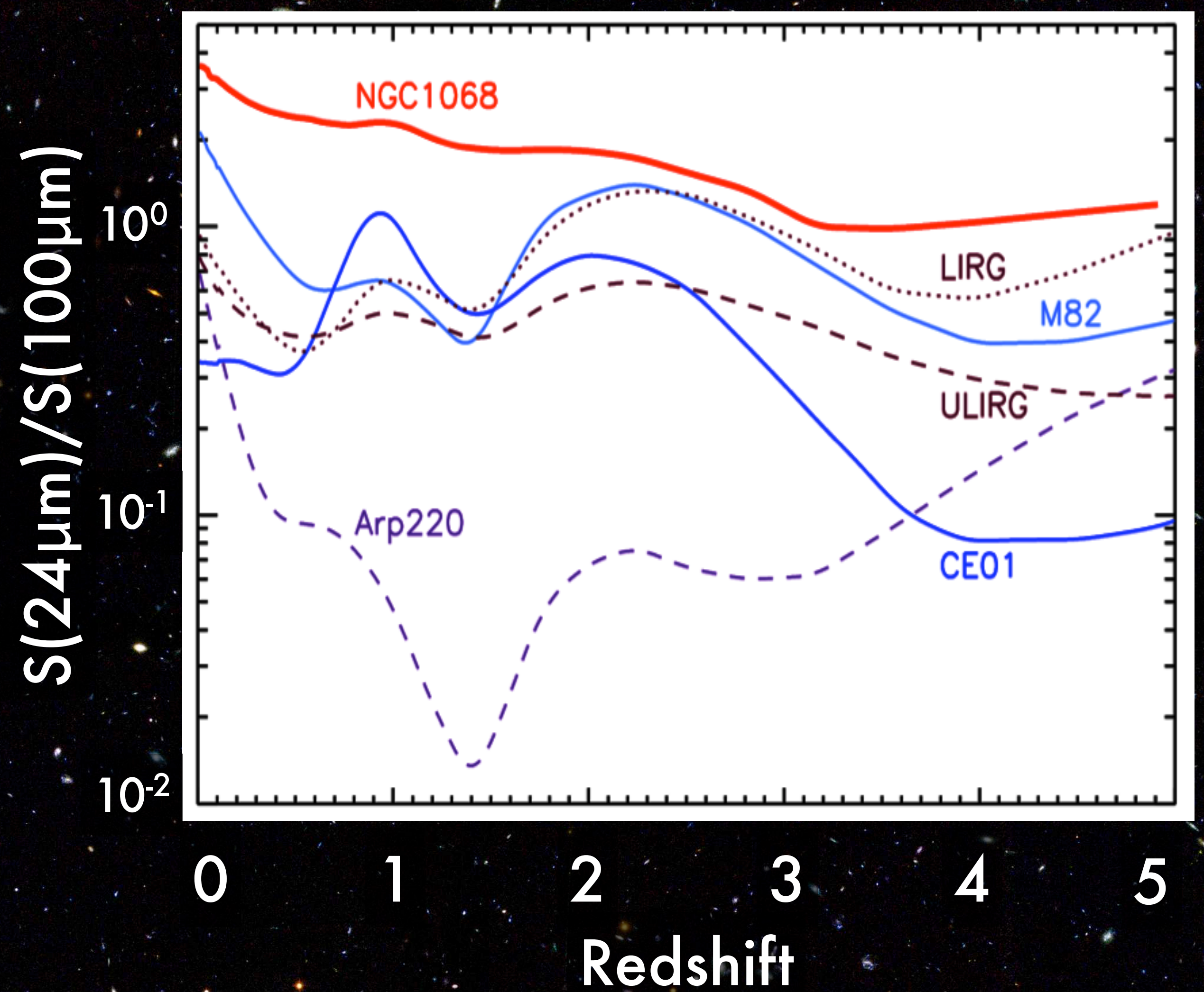
Improved Measurements of the IR Luminosity of Galaxies

Herschel Observations of the Great Observatories Origins Deep Survey (GOODS-H)



- Selected as Herschel Key Project (PI: D. Elbaz, CEA Saclay)
- Deepest PACS imaging, reaching 0.6 mJy (5σ) at 100 micron. Complements deep SPIRE imaging (250-500 micron) from GT.
- Far-IR study of starburst galaxies and AGN at high redshift using rest-frame 30-50 μm wavelength emission.





Comparison of Star-Formation Rate Indicators in Gravitationally Lensed Galaxies

Best SFR indicators: HI - recombination lines.

Paschen-α (1.875μm) observable by Spitzer/IRS (5.5 -38 μm) at $z > 2$.

Spitzer programs (PI: Papovich) to measure Pa-α in 12 gravitationally lensed $2 < z < 3$ galaxies.

with S. Finkelstein (Texas A&M), G. Rudnick (KU),
C. Willmer, E. Egami, S. Sivanadam, M. Rieke (UA), & J. Rigby (OCIW)
and also J.-D. Smith (Toledo), C. Kulesa & D. McCarthy (UA)

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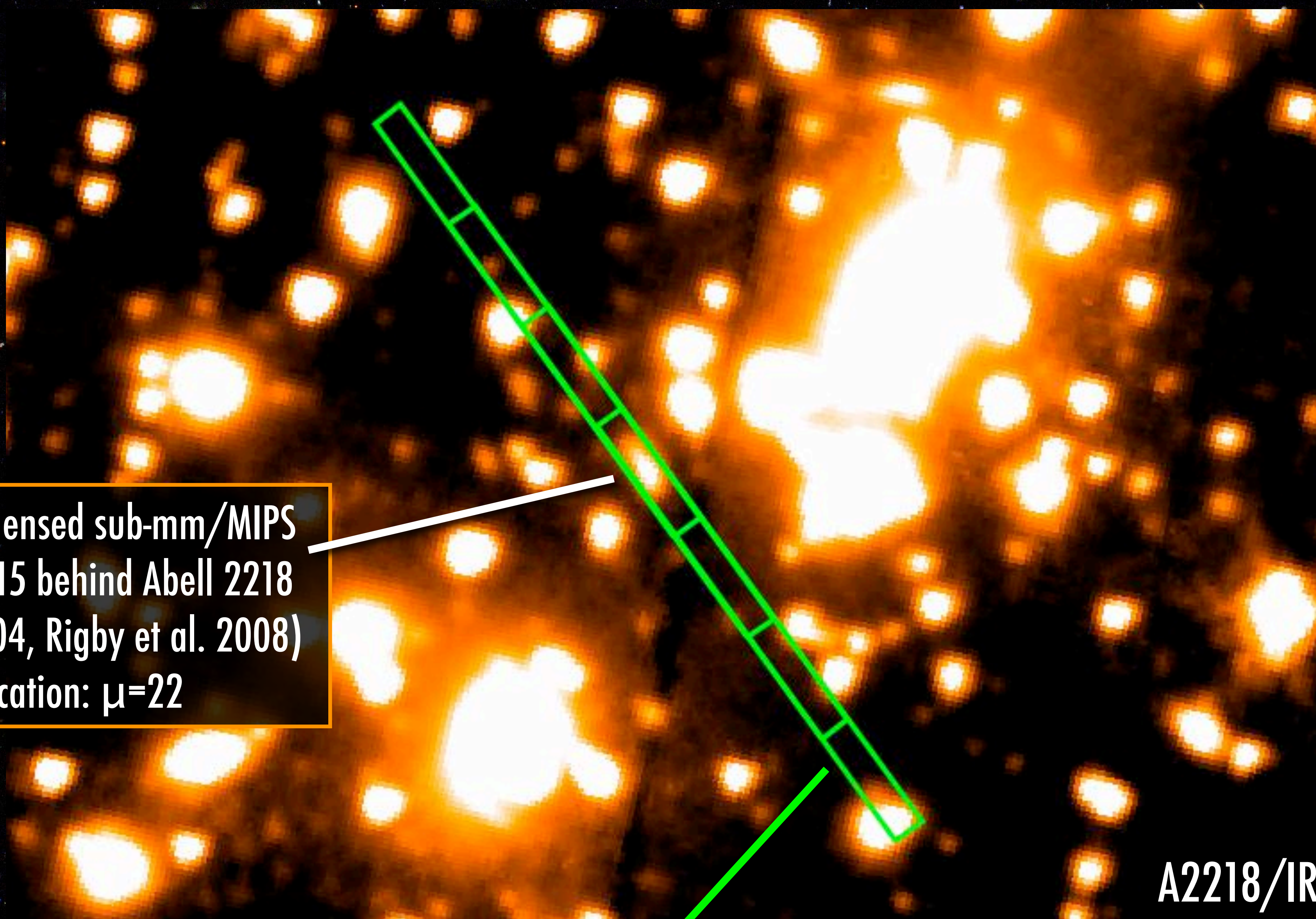

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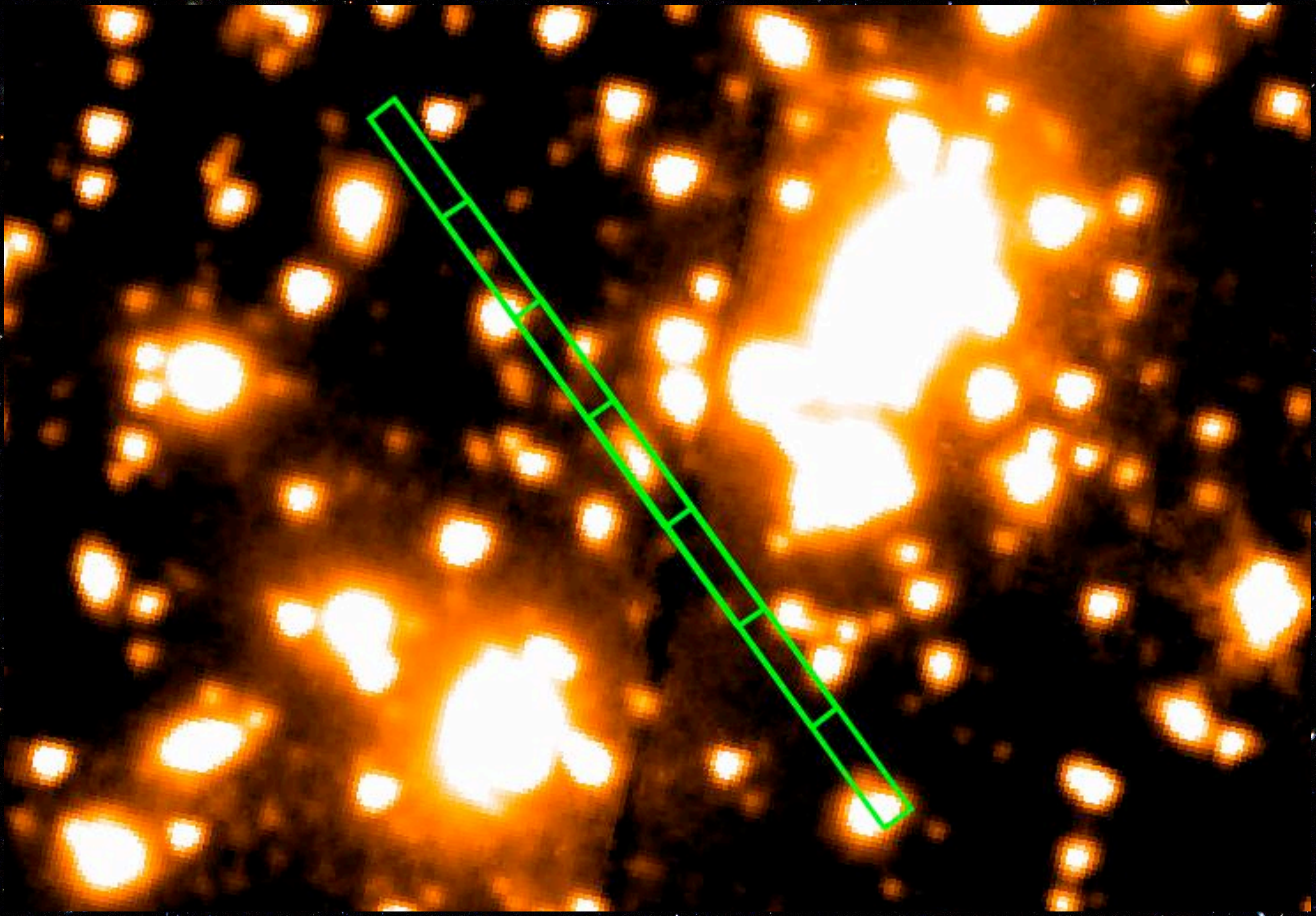

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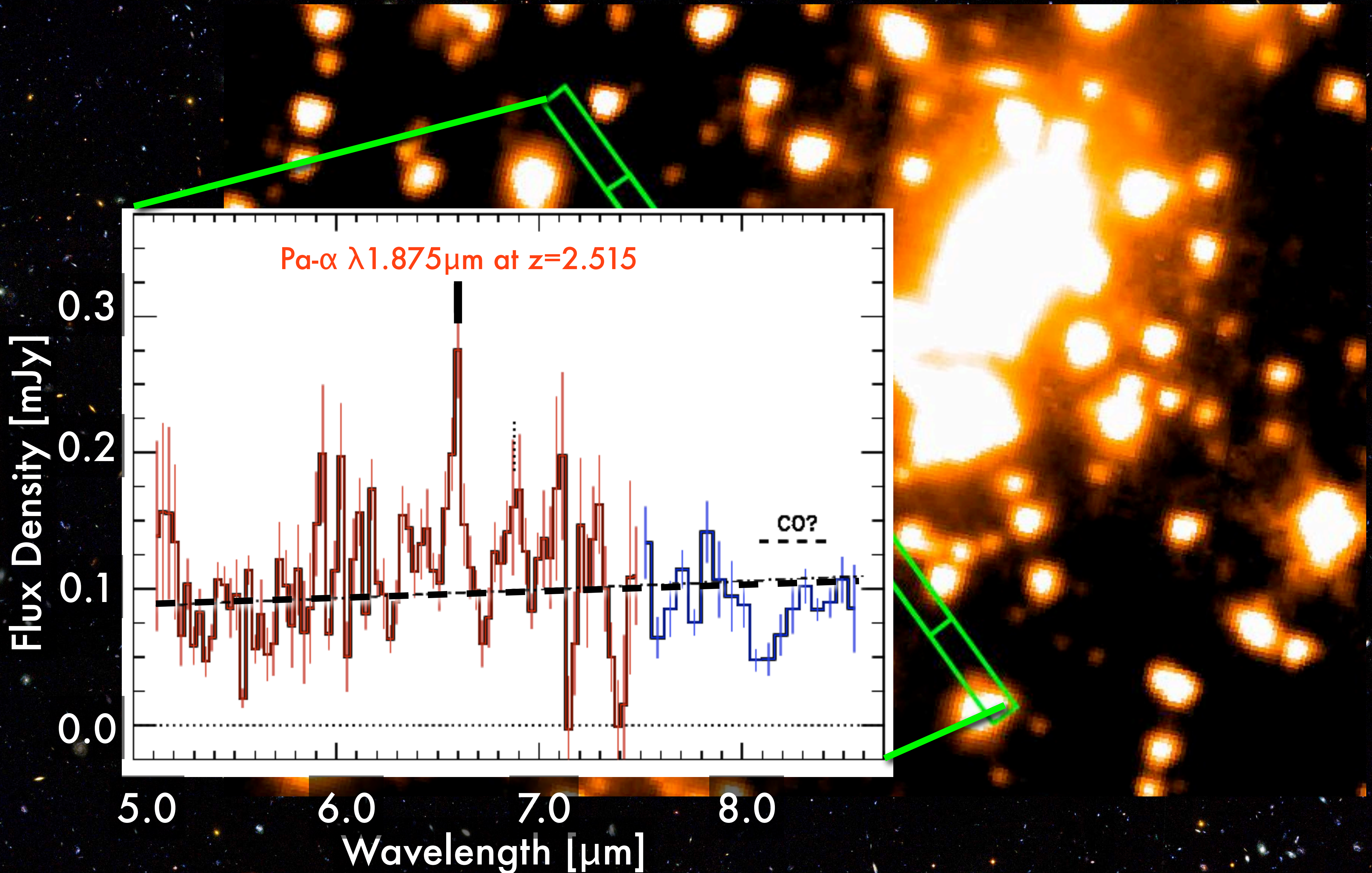
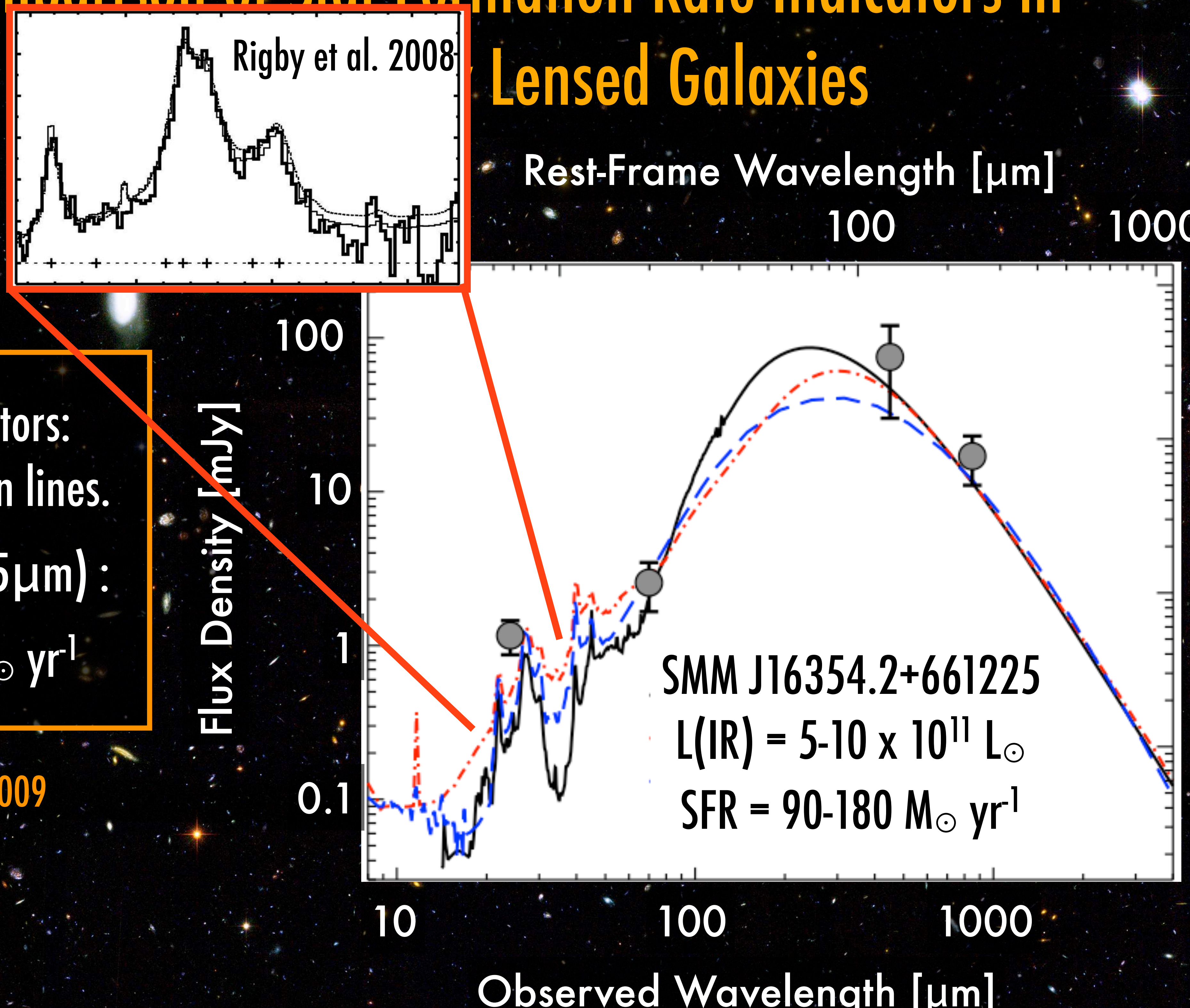


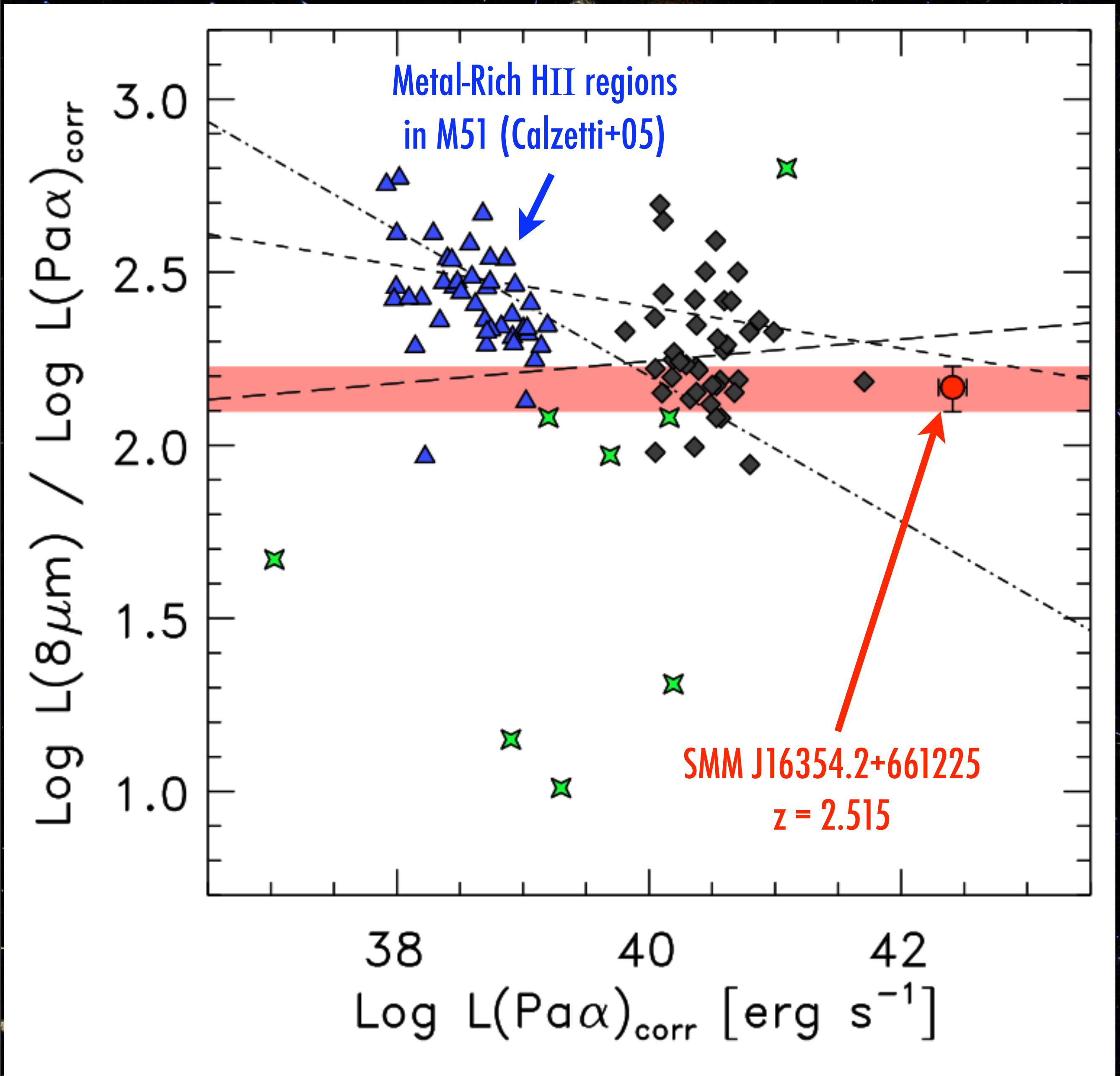
Comparison of Star-Formation Rate Indicators in Lensed Galaxies

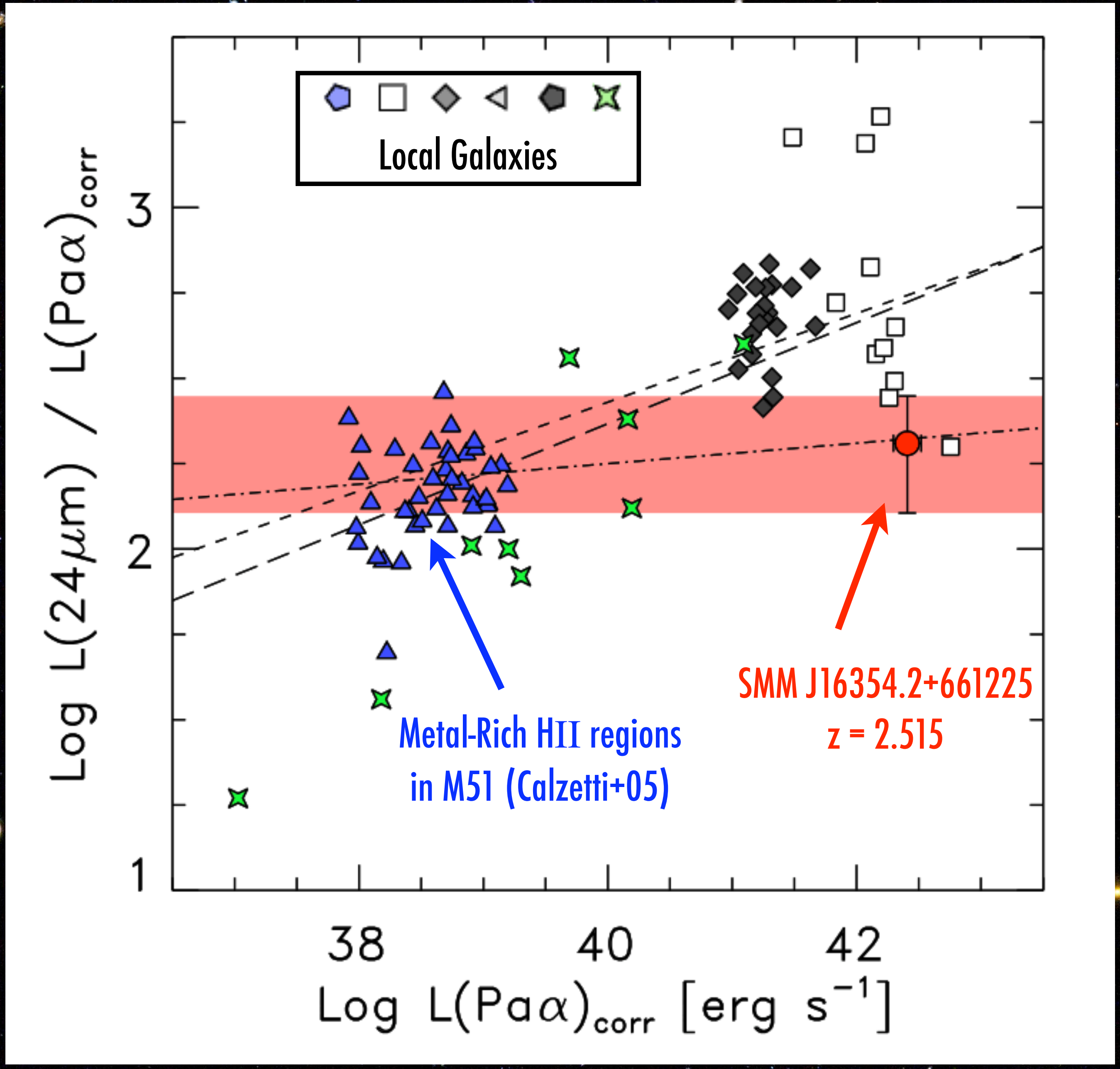


Best SFR indicators:
HI - recombination lines.
Paschen-α (1.875μm) :
SFR=171±28 $M_\odot$ yr^{-1}

Papovich et al. 2009

Comparison of Star-Formation Rate Indicators in Gravitationally Lensed Galaxies





Summary

- Studies of the evolution of massive galaxies using multiwavelength data, in particular with Spitzer, provides an analysis of the bolometric emission from distant galaxies. We are *witnessing* galaxy formation.
- At high redshift, $1.5 < z < 3$, *majority* (>50%) of massive galaxies emit intensively at IR wavelengths. Implies vigorous star-formation and SMBH accretion in massive galaxies.
- At least 25% of massive galaxies at $1.5 < z < 3$ show indications of SMBH accretion. Simultaneous build-up of SMBHs and galaxies. Contribution of AGN and SF to IR emission is unclear and debated.
- However, Spitzer data provide only minimal constraints on full shape of the IR emission from galaxies. Deeper data need at longer wavelengths to measure shape of high redshift galaxies SEDs - achievable with Herschel!
- Ongoing tests of IR emission against Pa-α emission will deepen physical understanding. In a sample of one object, mid-IR to Pa-α ratios consistent with metal-rich HII regions.

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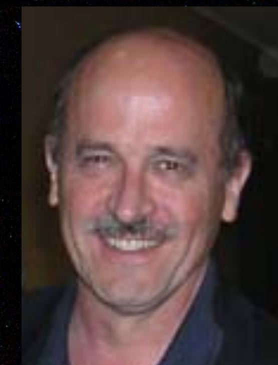

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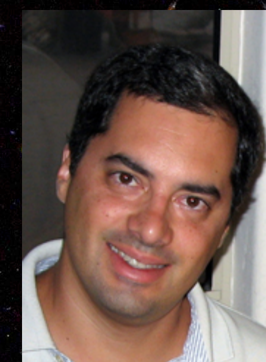

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