Distant Dusty Universe

Irene Shivaei

Hubble fellow, University of Arizona

JWST MIRI/NIRCam GTO science teams

Image credit: NASA, ESA, and S. Beckwith (STScI) and the HUDF Team

Dust represents only 1% of the ISM mass, but…

Image credit: NASA, ESA, and S. Beckwith (STScI) and the HUDF Team

has important roles in the ISM physics and chemistry,

- Star and planet formation
- Catalysts for formation of certain molecules
- ISM cooling and heating
- ISM gas dynamics
- Coupling the magnetic field to the gas
- …

Image credit: NASA, ESA, and S. Beckwith (STScI) and the HUDF Team

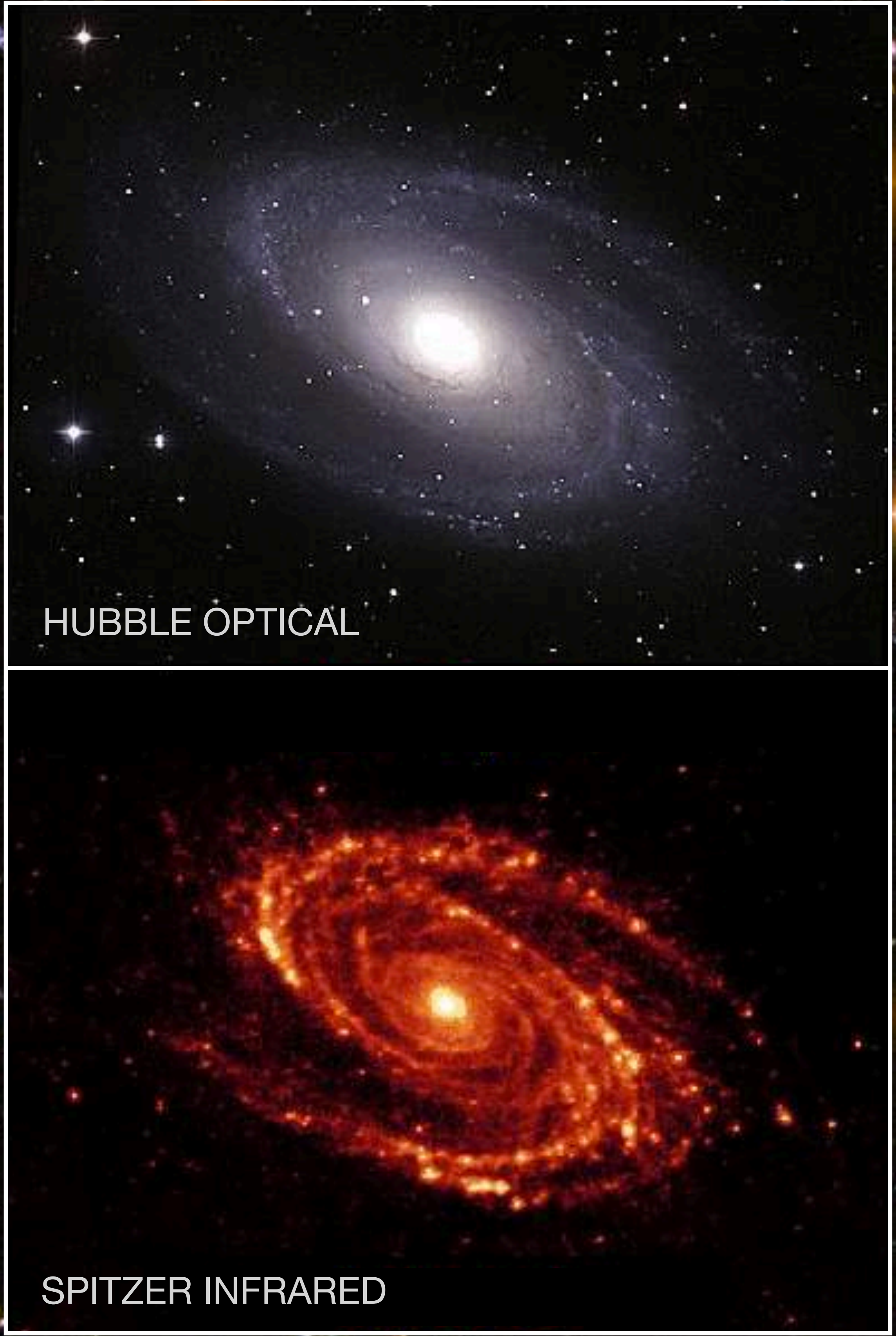
significantly shapes our view of galaxies,

Sombrero Galaxy. Credits: NASA/JPL-Caltech and The Hubble Heritage Team (STScI/AURA)

Image credit: NASA, ESA, and S. Beckwith (STScI) and the HUDF Team

hides a significant fraction of star formation.

M101. Credits: Optical: NASA/ESA/STScI/JHU/K. Kuntz et al; IR: NASA/JPL-Caltech/STScI/K. Gordon



M81. Credits:NASA/JPL/ESA

Andromeda. Credits: Robert Gendler (visible) ; ESA / Herschel / SPIRE / HELGA (far-infrared)

Image credit: NASA, ESA, and S. Beckwith (STScI) and the HUDF Team

Cosmic Infrared Background constitutes half of the Extragalactic Background

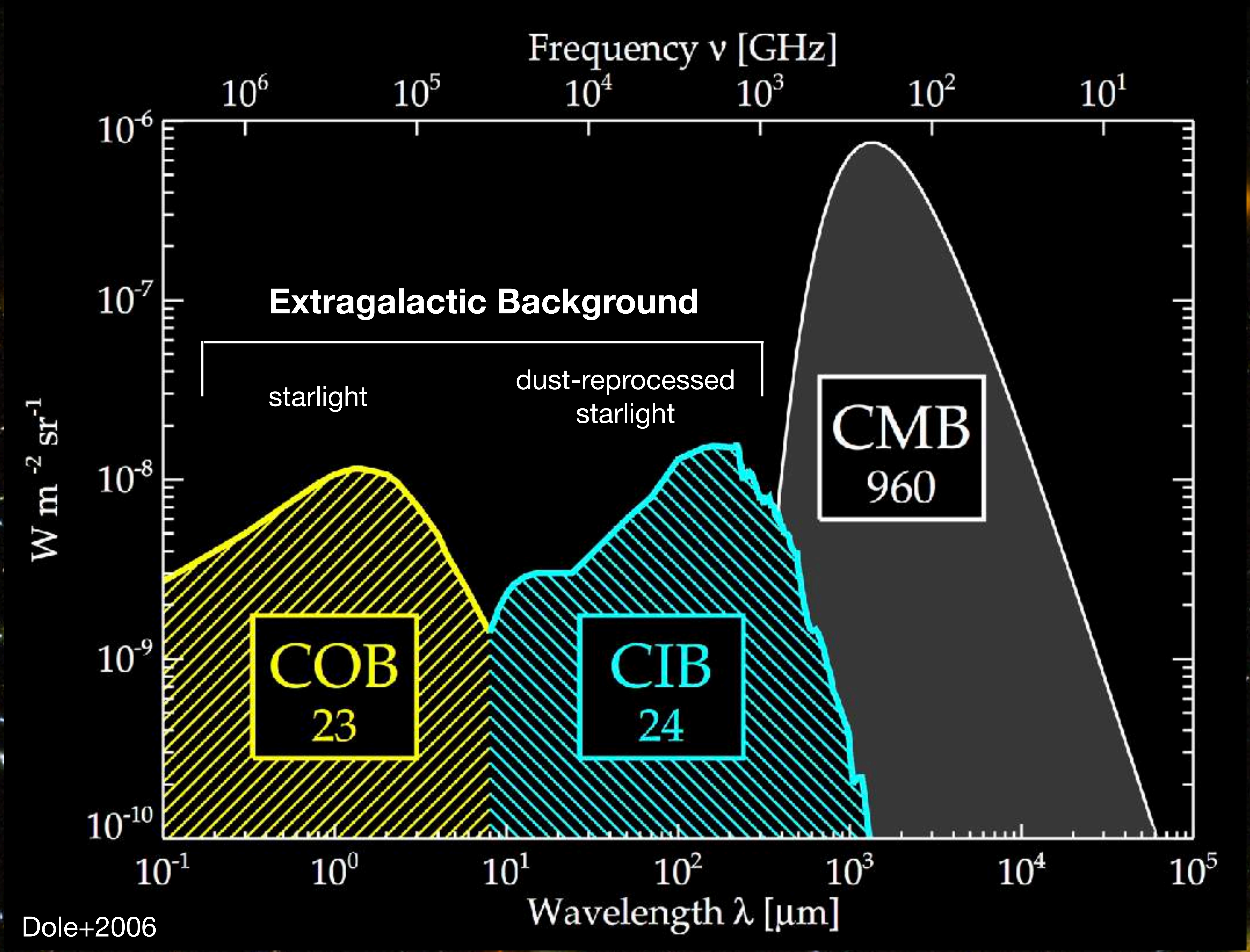
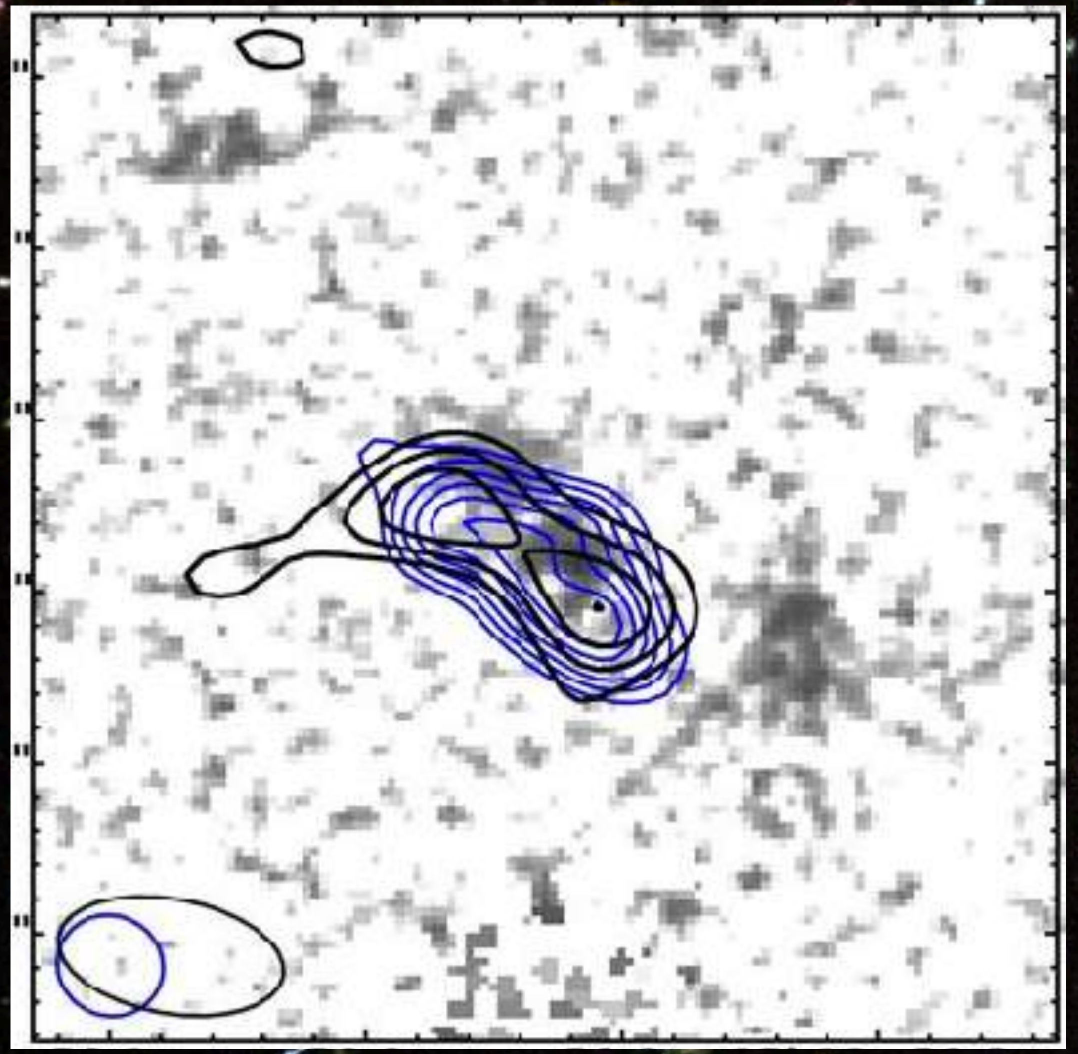
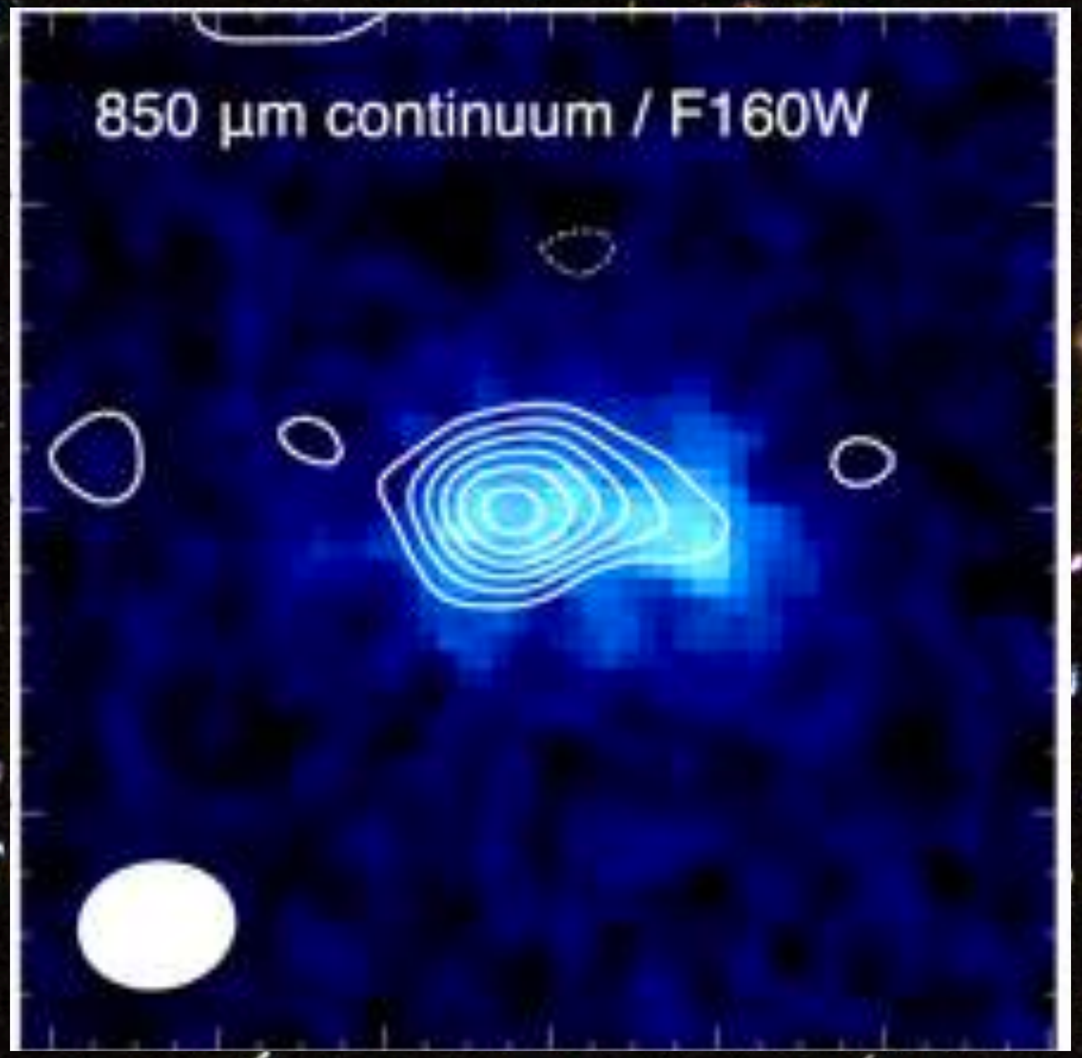


Image credit: NASA, ESA, and S. Beckwith (STScI) and the HUDF Team

and now is observed out to the highest redshifts:

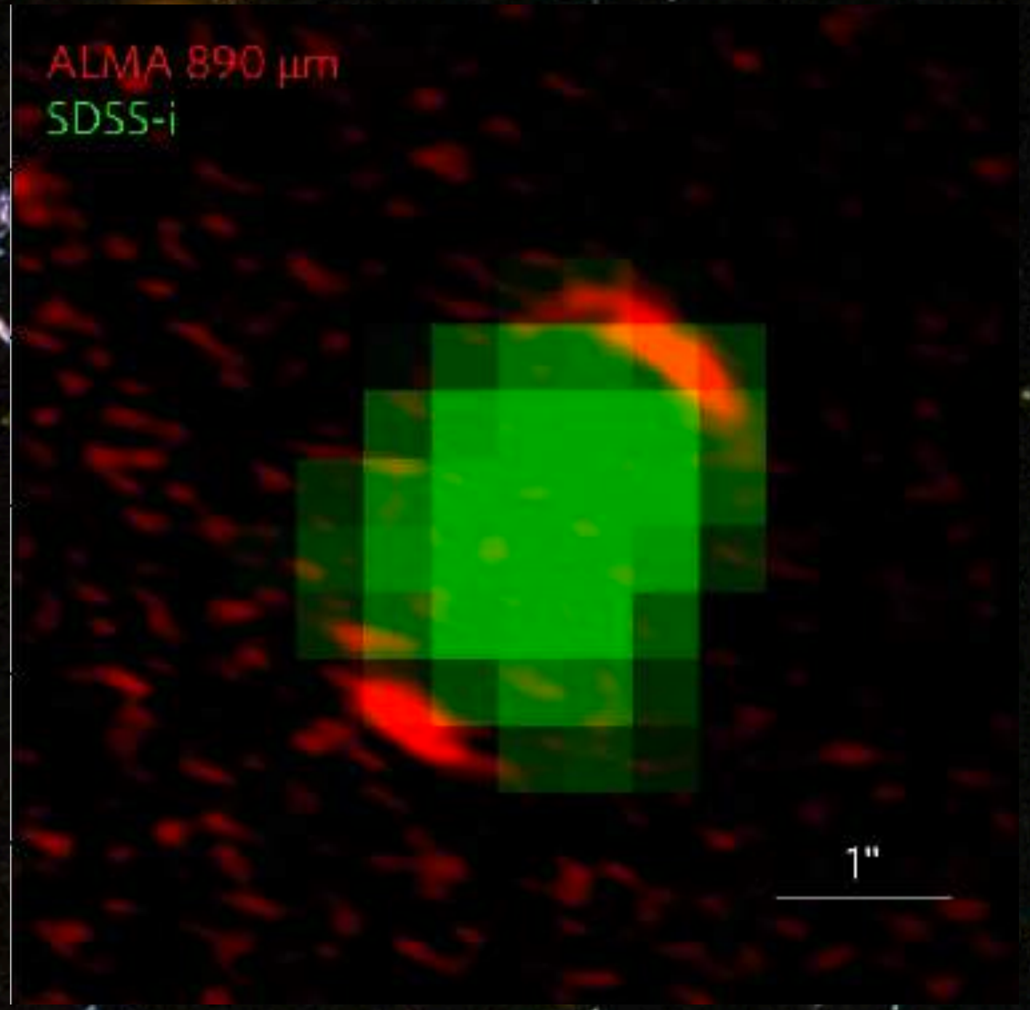


Knudsen+2017
z=7.5



Tamura+2019
z=8.31

Bowler+2018
z=7.17



Zavala+2018
z=6.02

When we observe galaxies, we would like to know…

star formation rate

stellar mass

age

star formation history

stellar population properties: metallicity, binarity

ISM gas properties: abundances, ionizing radiation

dust properties: optical depth, dust mass, dust temperature

We derive the properties from:

star formation rate

stellar mass

age

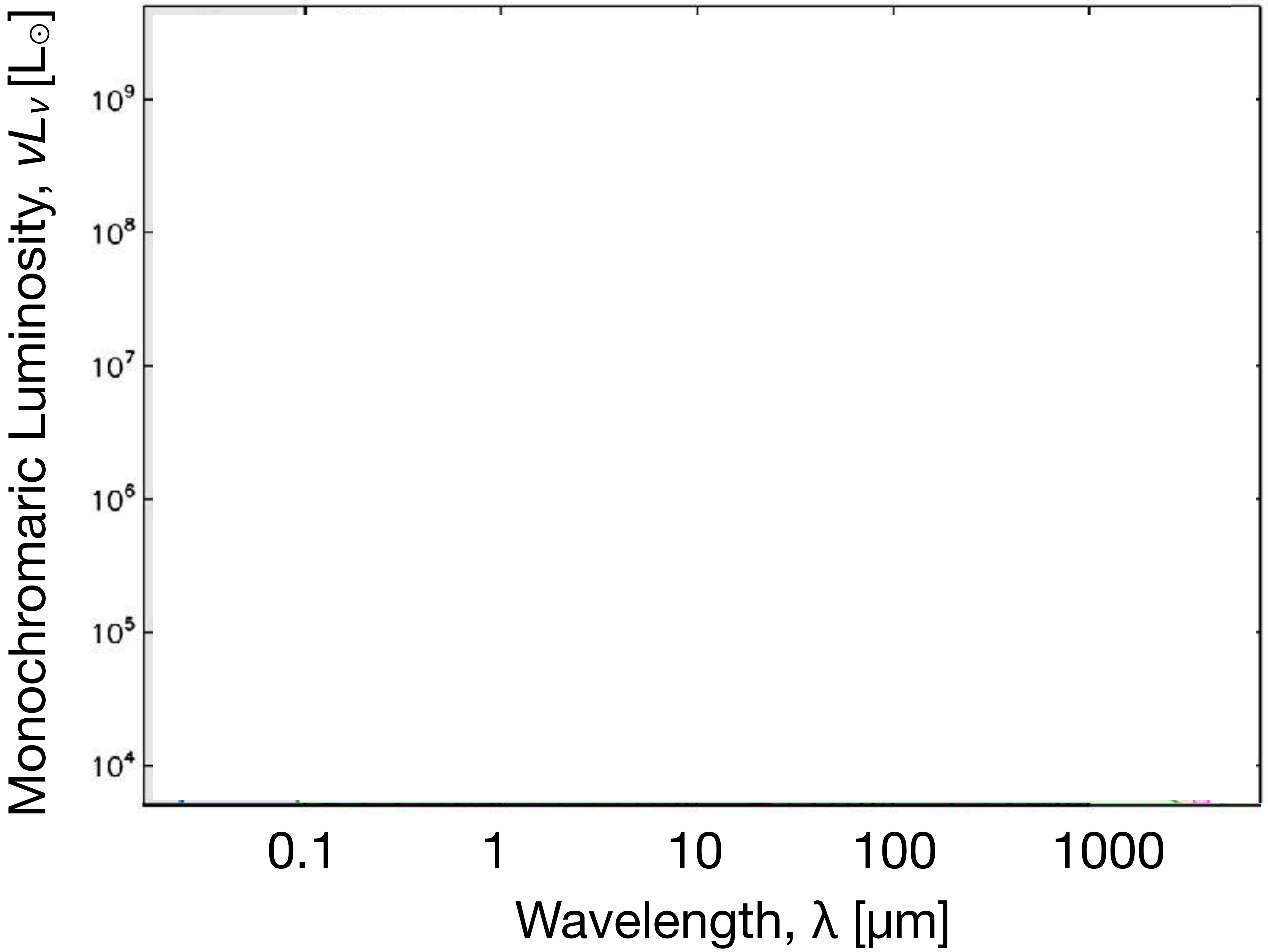
star formation history

stellar population properties: metallicity, binarity

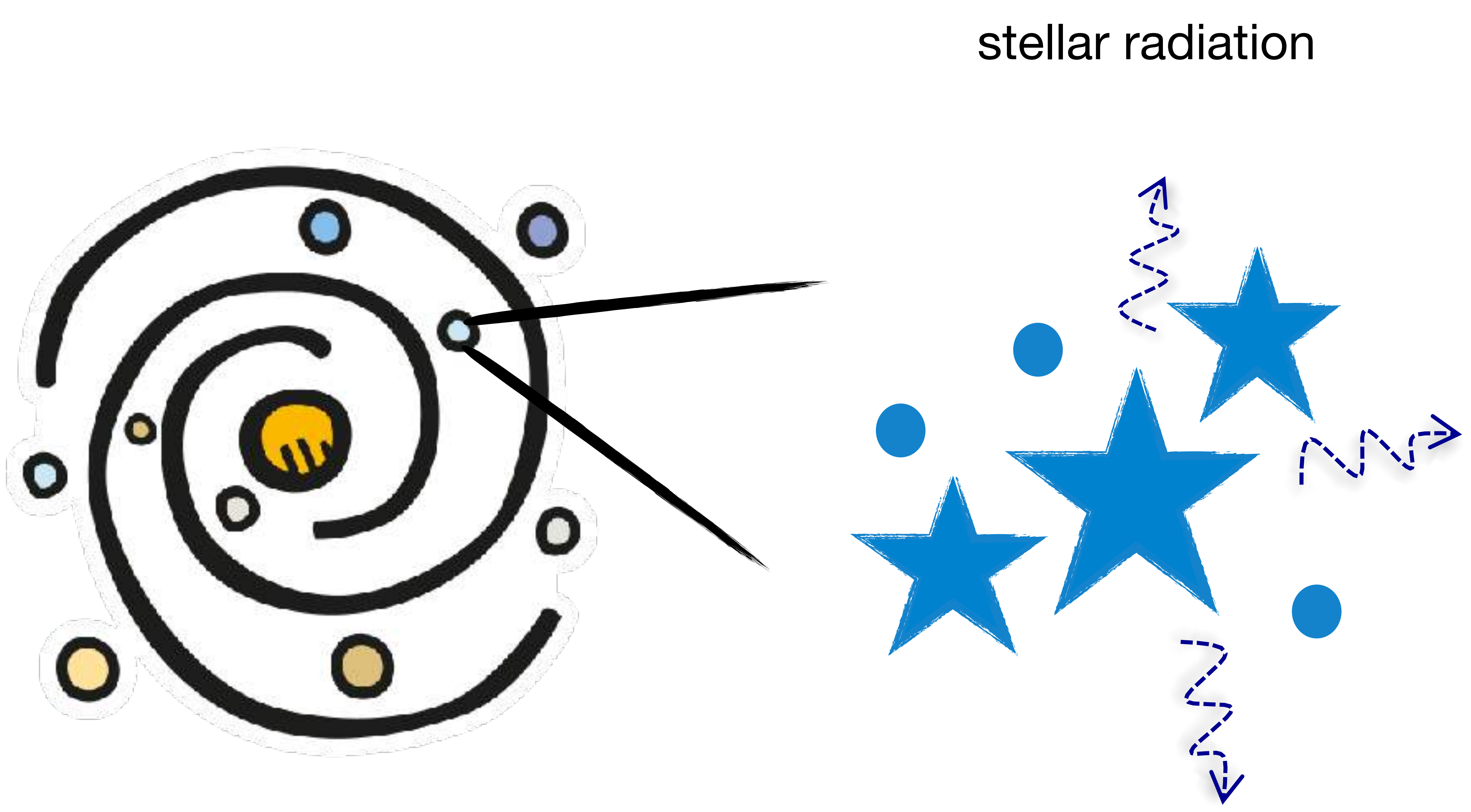
ISM gas properties: abundances, ionizing radiation

dust properties: optical depth, dust mass, dust temperature

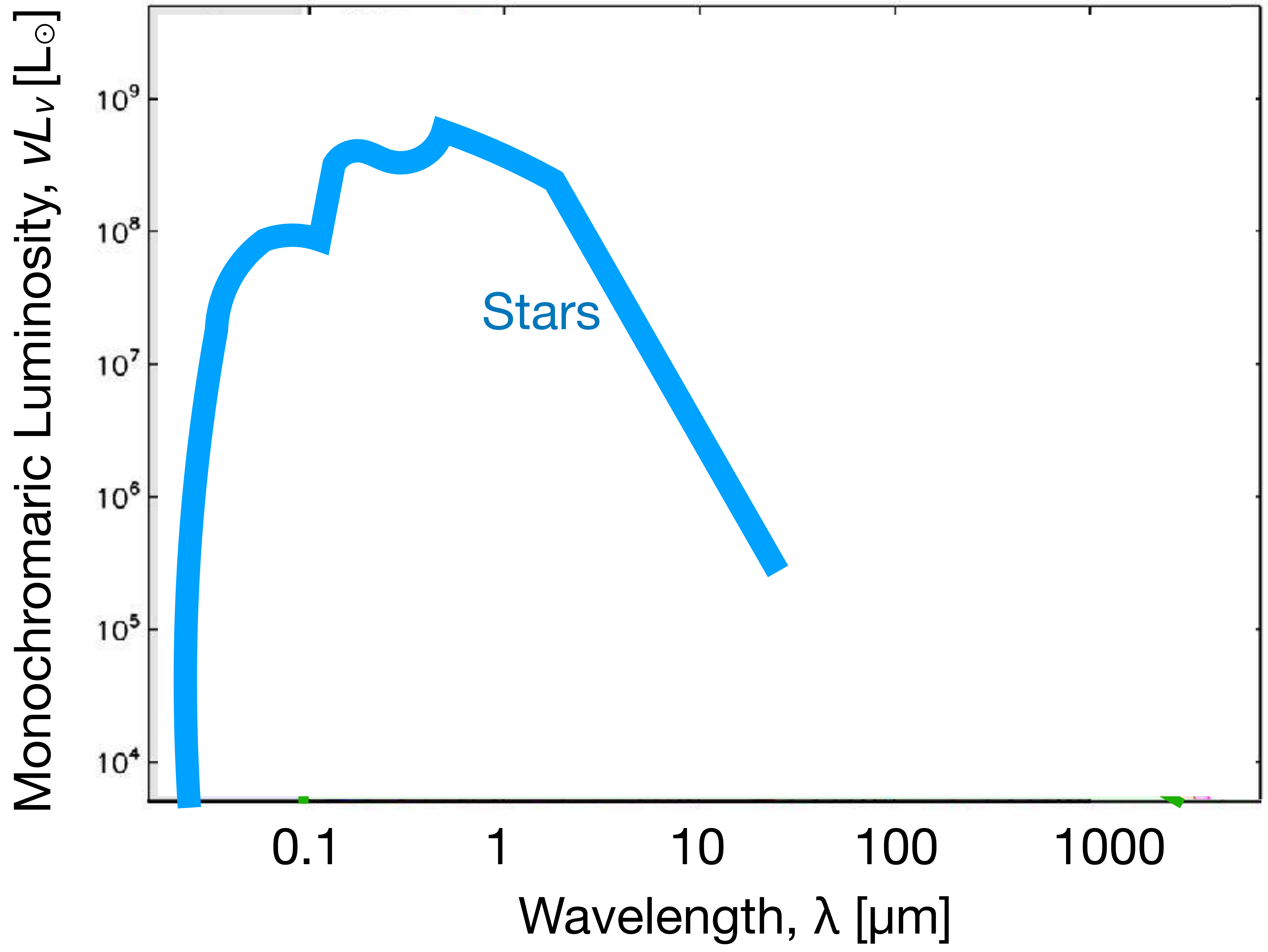
Spectral Energy Distribution (SED) of a galaxy



A SIMPLE MODEL OF GALAXY EMISSION

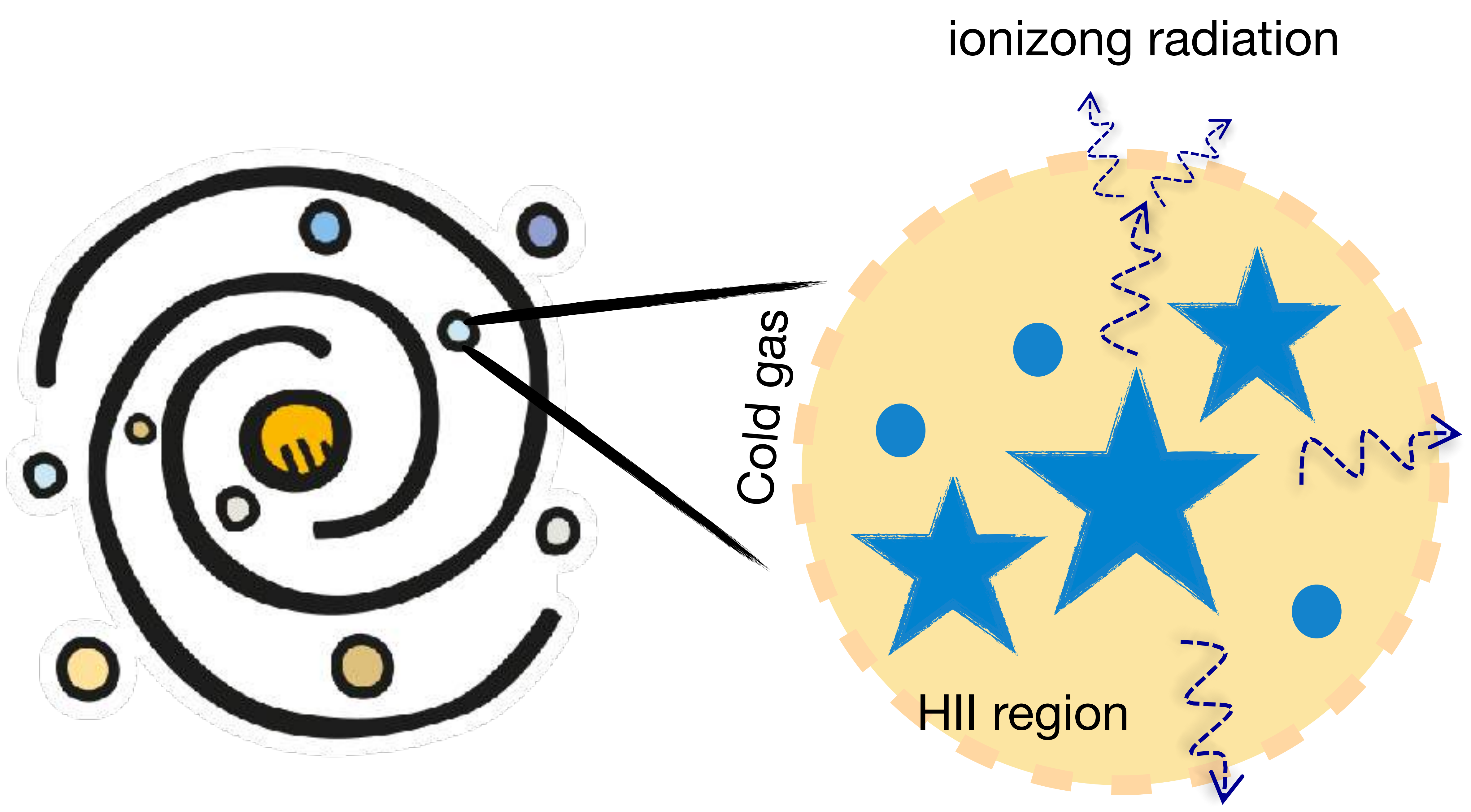


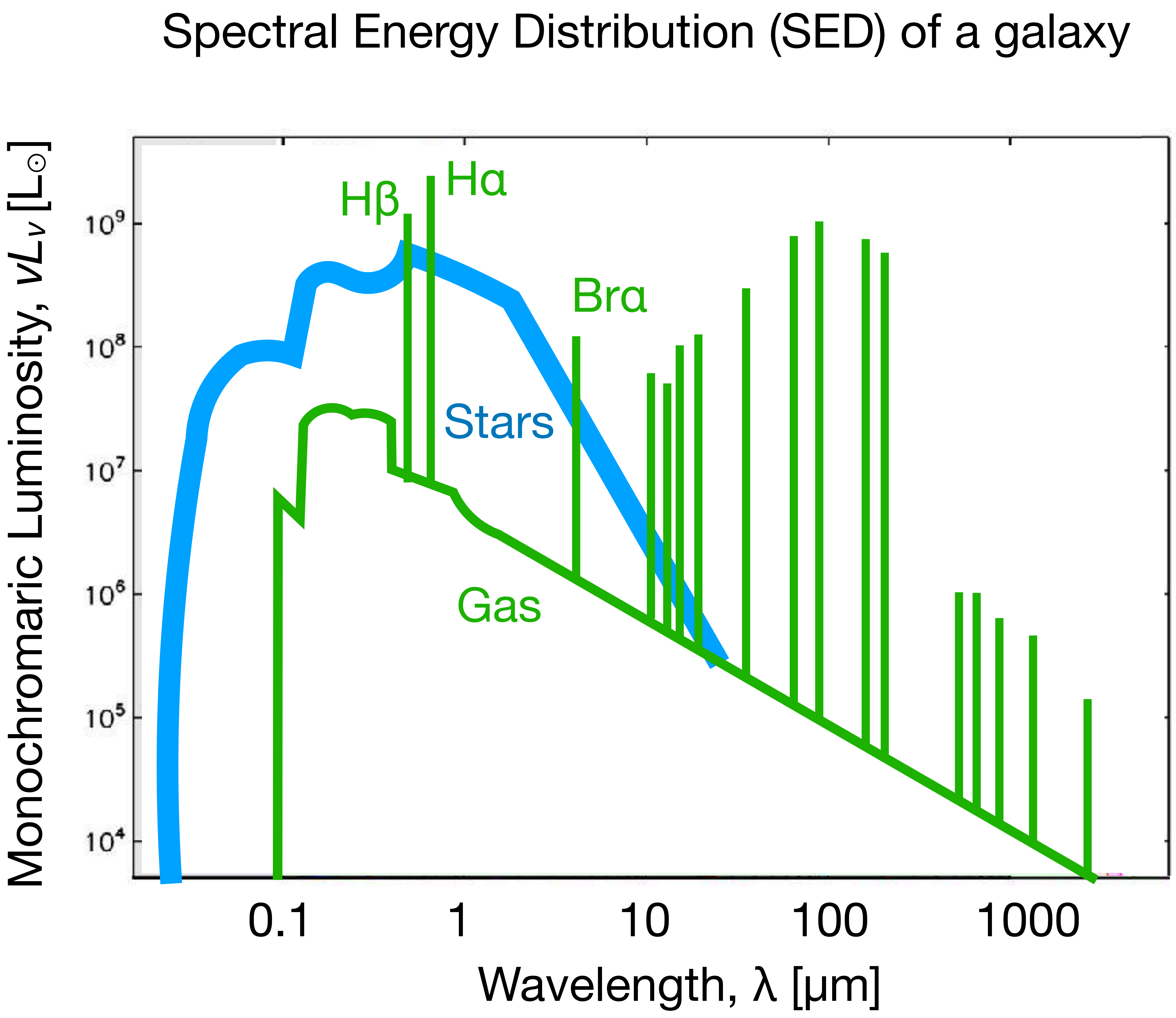
Spectral Energy Distribution (SED) of a galaxy



Data from Galliano, Galametz, and Jones ARAA 2017

A SIMPLE MODEL OF GALAXY EMISSION





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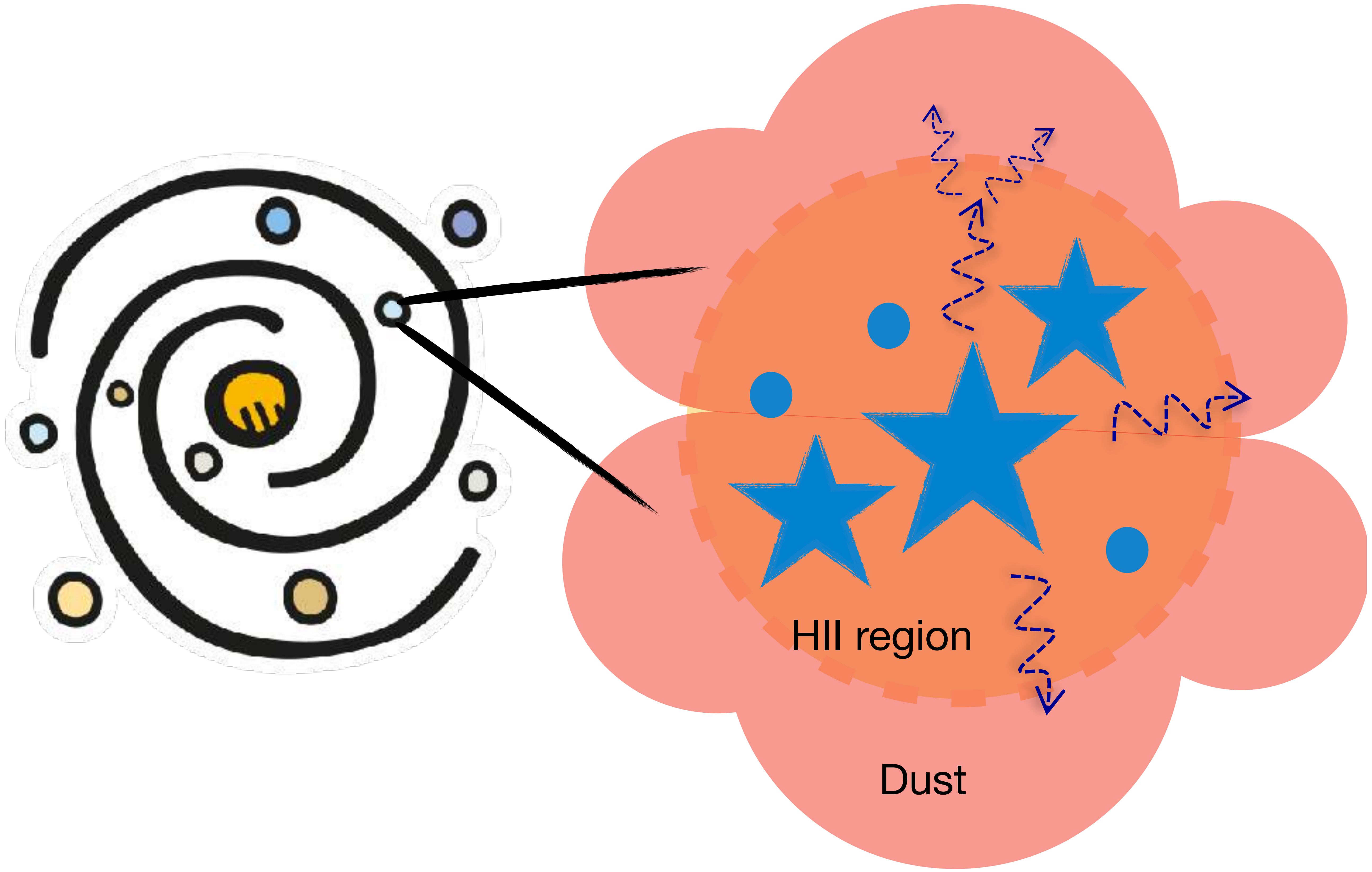

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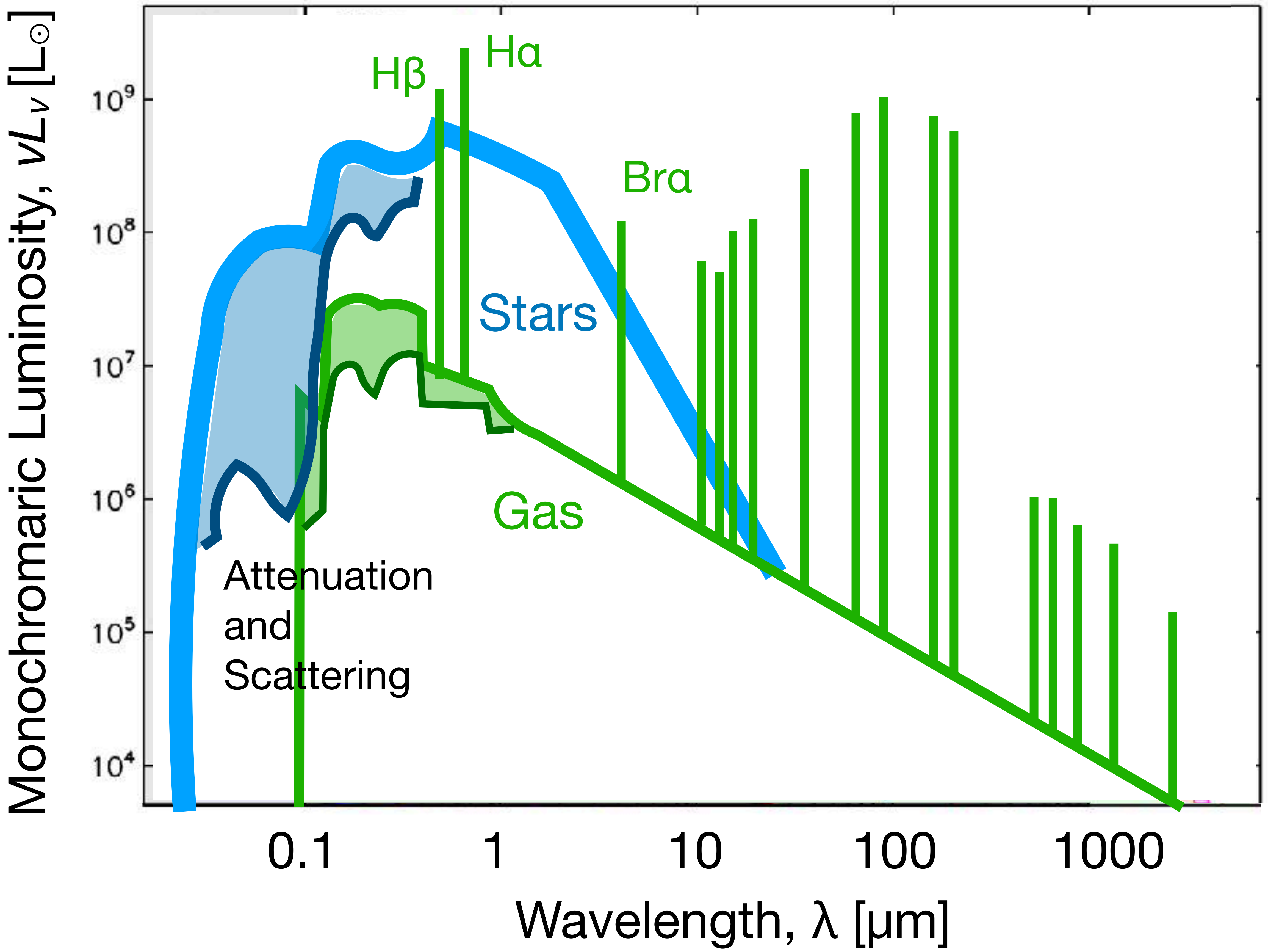

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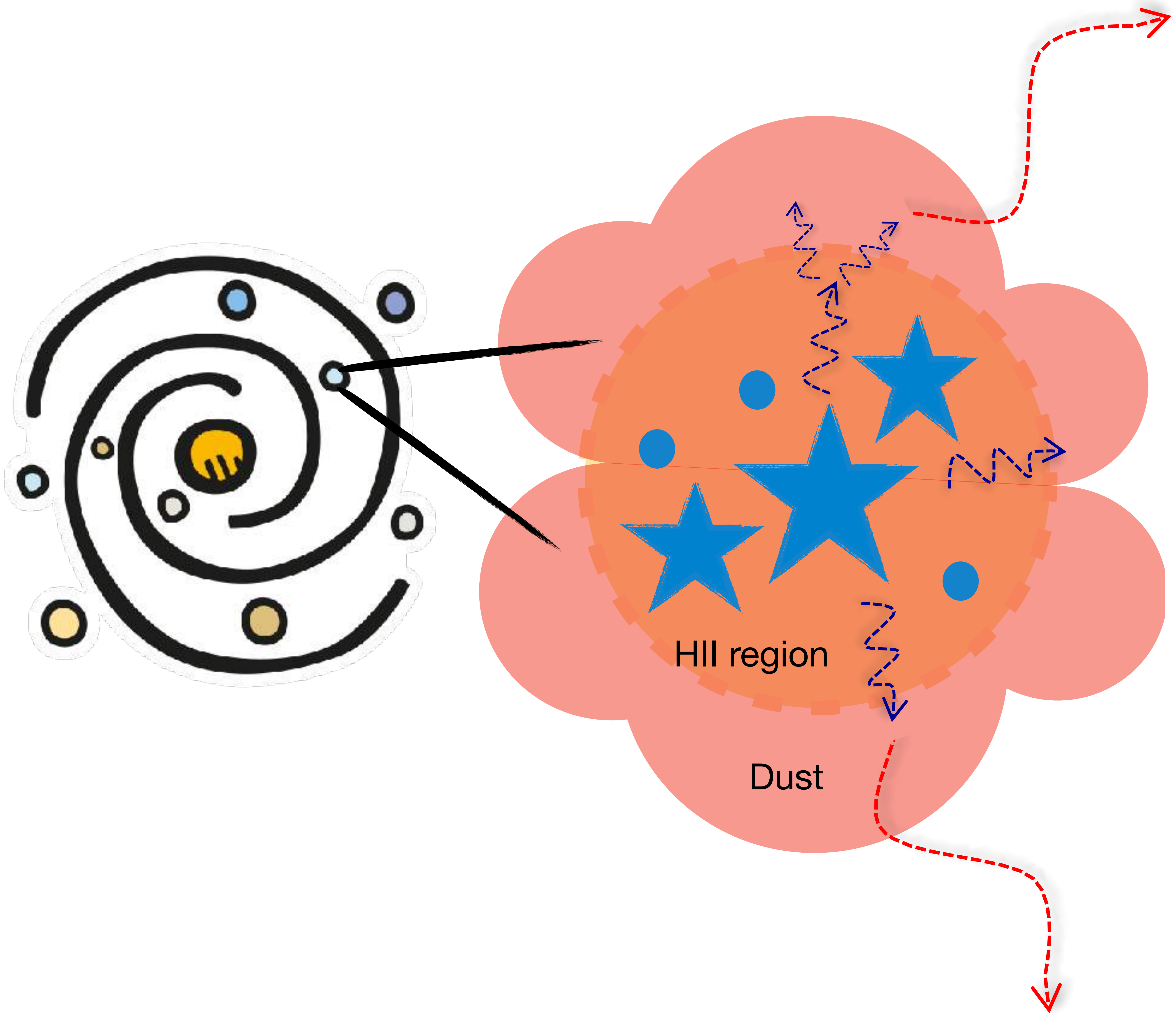
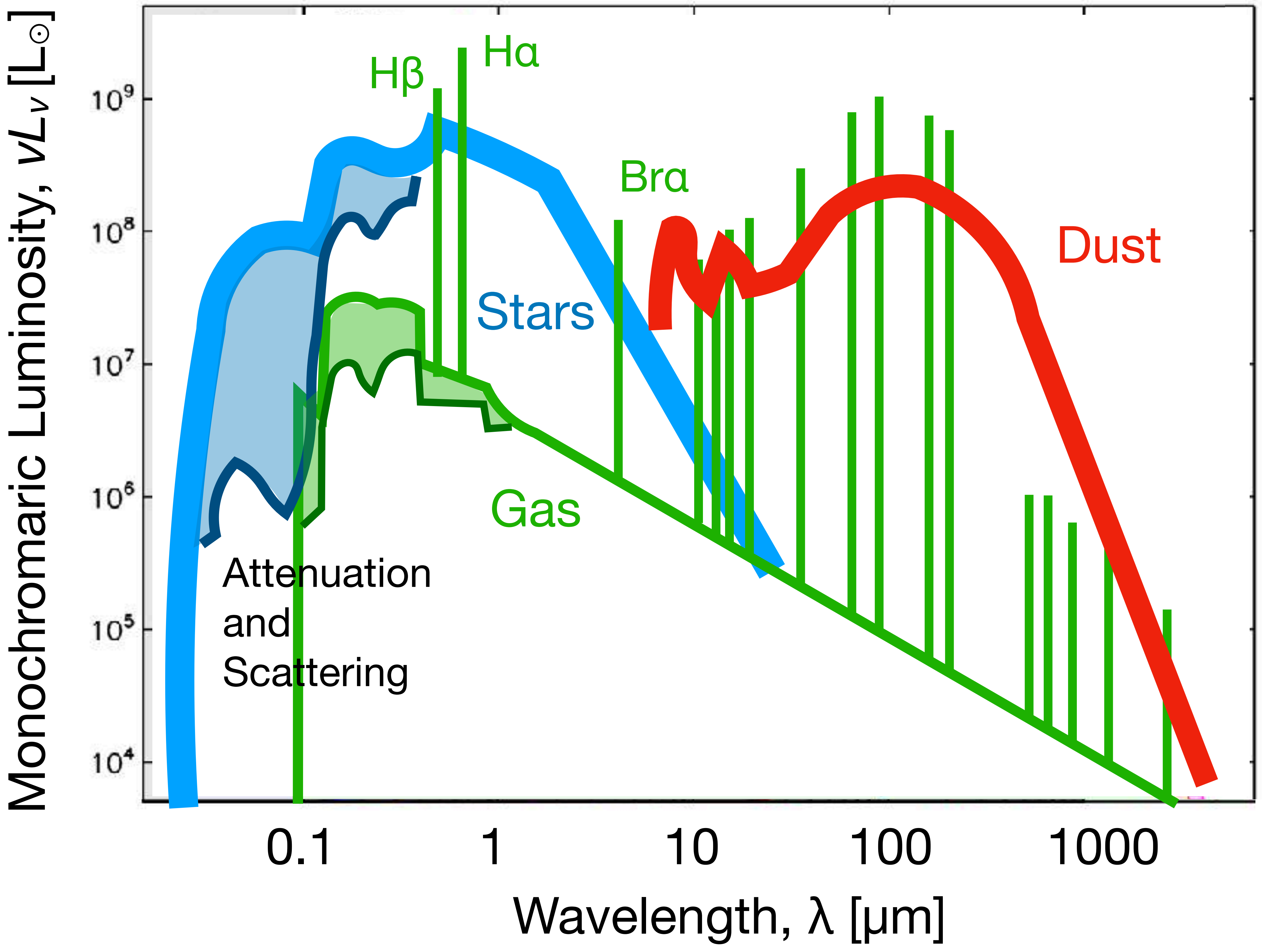


Spectral Energy Distribution (SED) of a galaxy



Data from Galliano, Galametz, and Jones ARAA 2017

Dust attenuation/emission impacts all of these quantities:

star formation rate

stellar mass

age

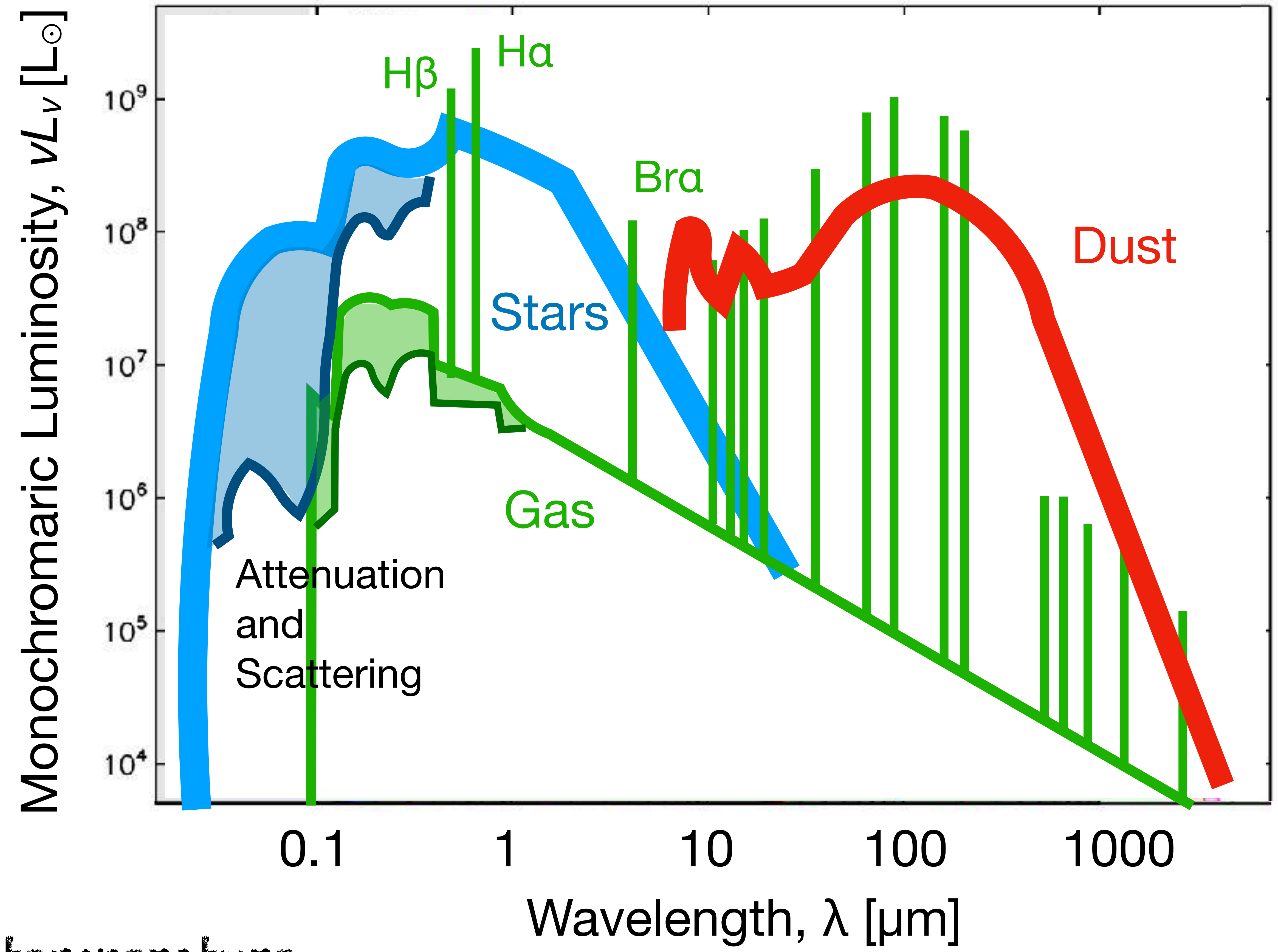
star formation history

stellar population properties: metallicity, binarity

ISM gas properties: abundances, ionizing radiation

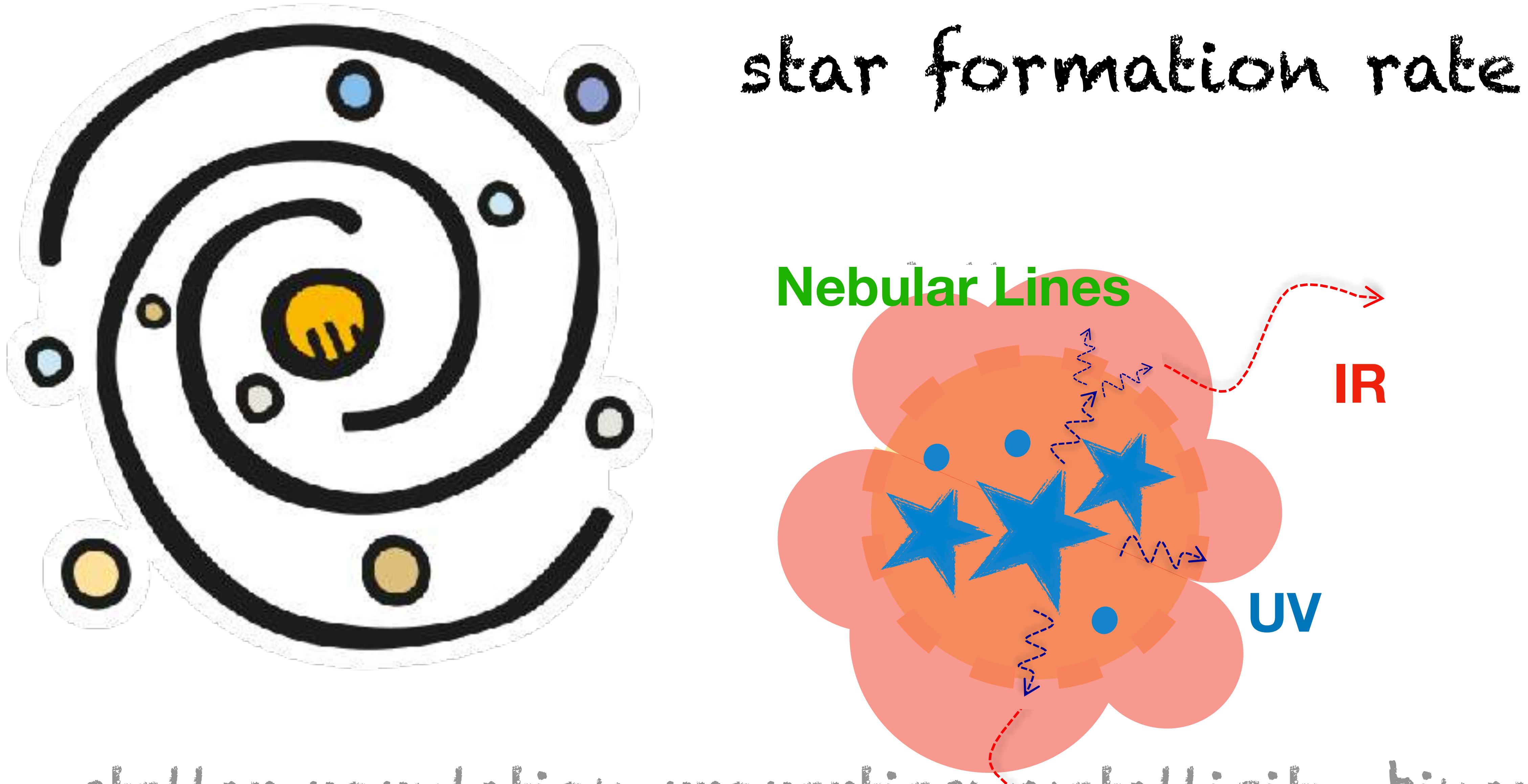
dust properties: optical depth, dust mass, dust temperature

Spectral Energy Distribution (SED) of a galaxy



Data from Galliano, Galametz, and Jones ARAA 2017

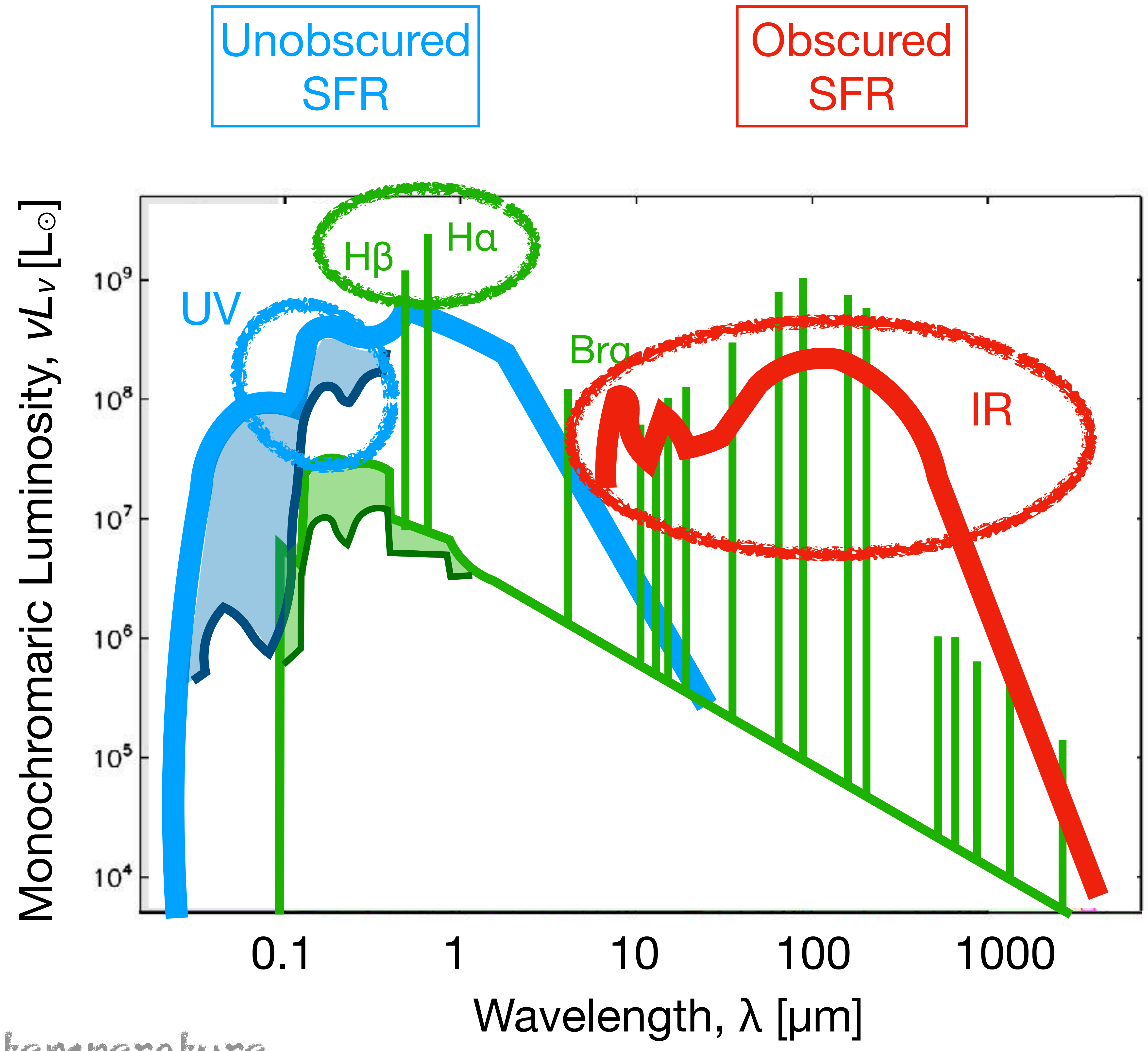
Unobscured and Obscured SFR



stellar population properties: metallicity, binarity

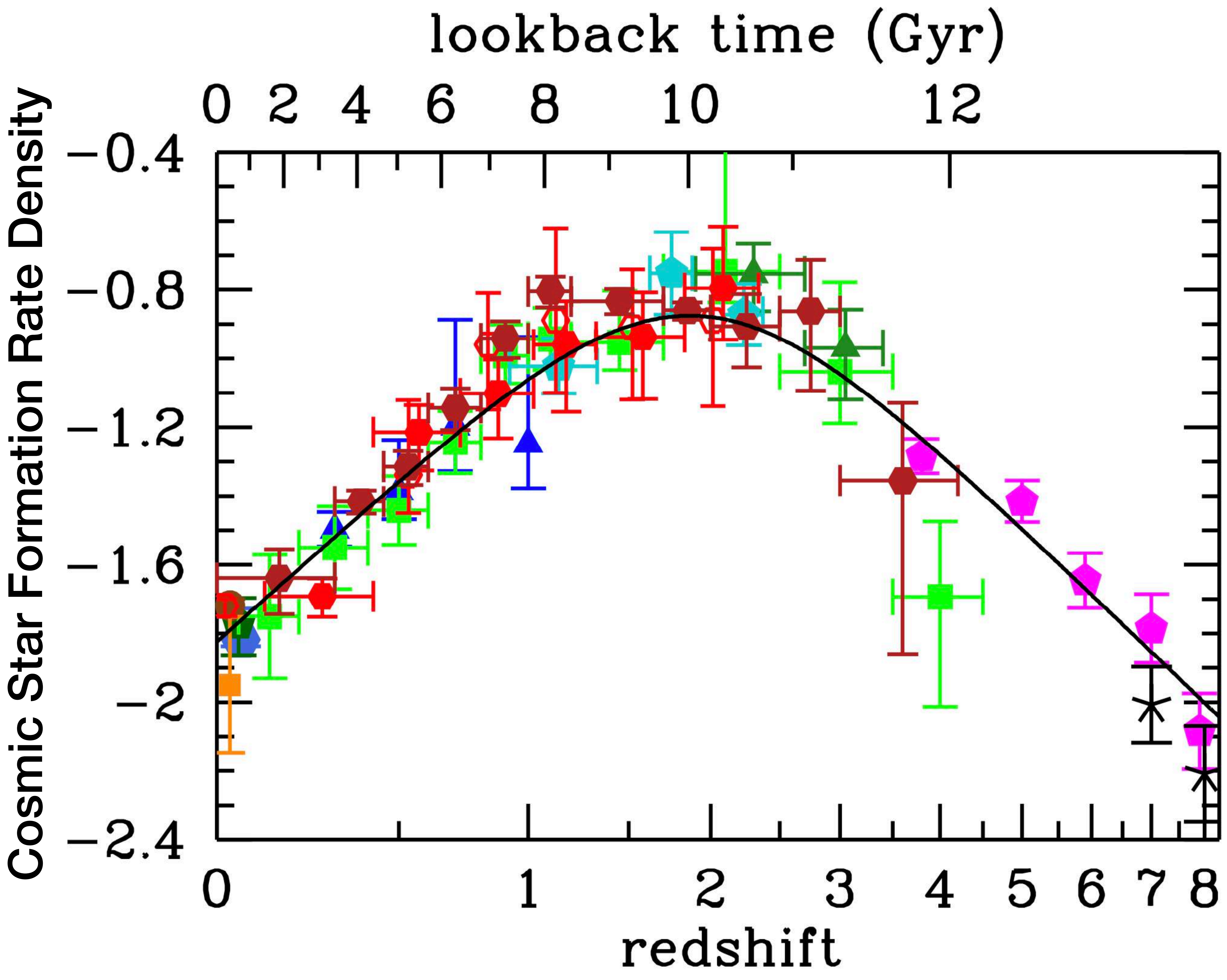
ISM gas properties: metallicity, ionizing radiation

dust properties: optical depth, dust mass, dust temperature



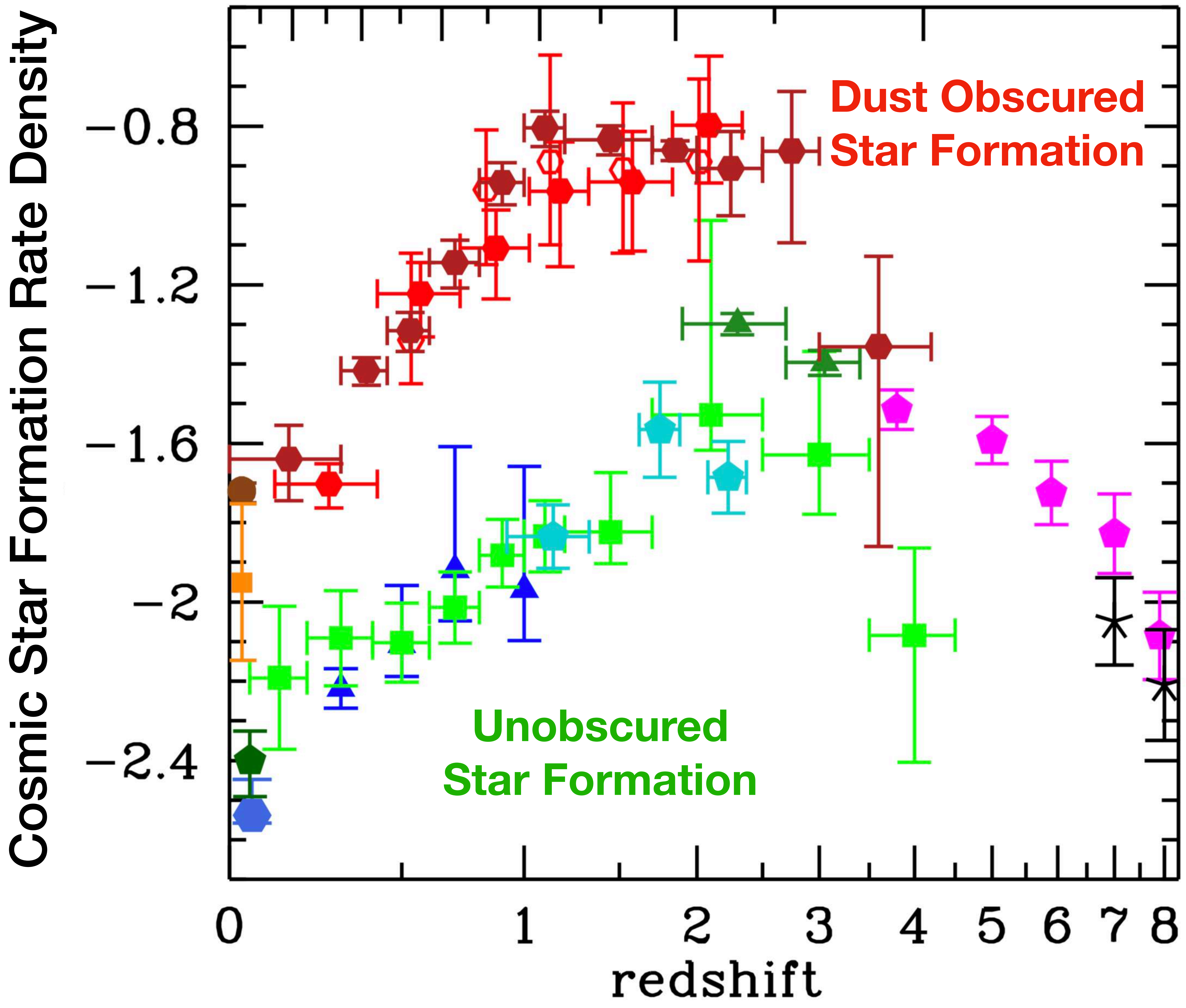
Data from Galliano, Galametz, and Jones ARAA 2017

Cosmic Star Formation Activity



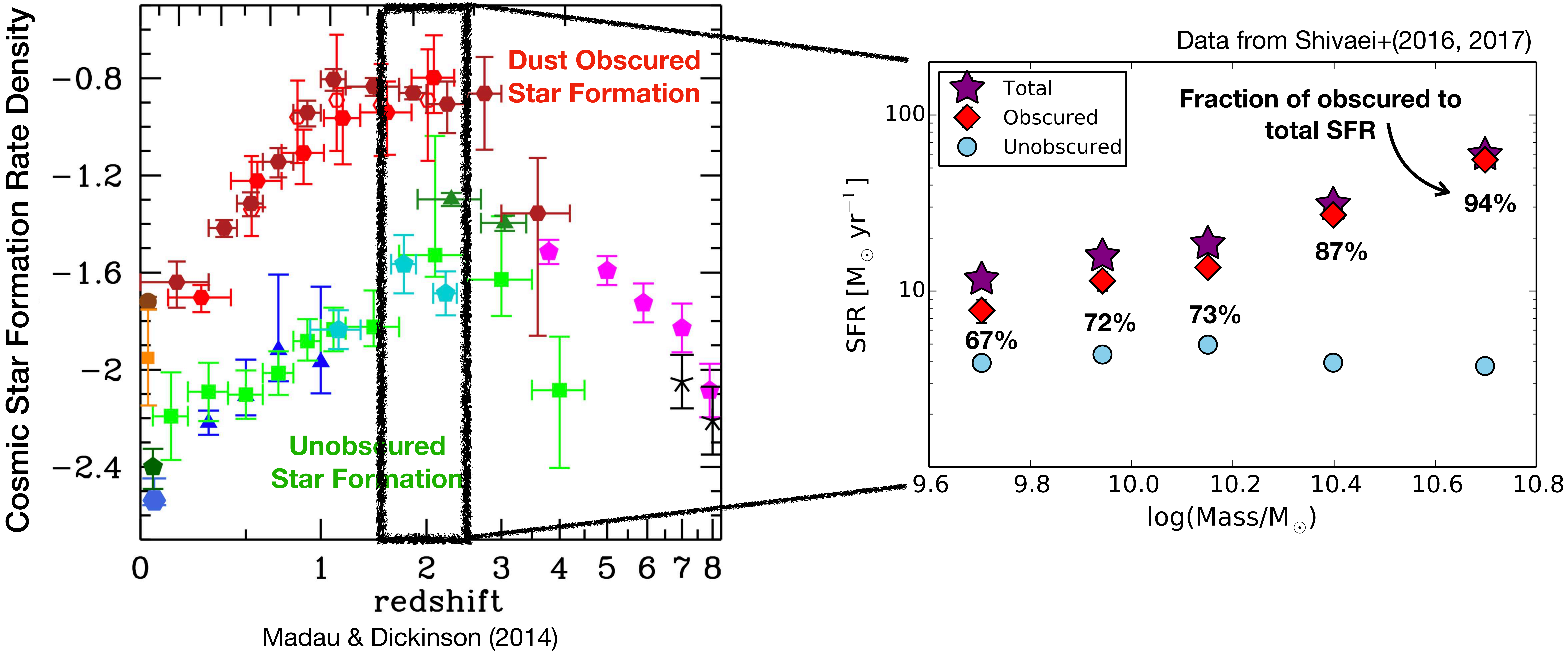
Madau & Dickinson (2014)

SIGNIFICANT FRACTION OF STAR FORMATION IS DUST OBSCURED AT HIGH REDSHIFTS

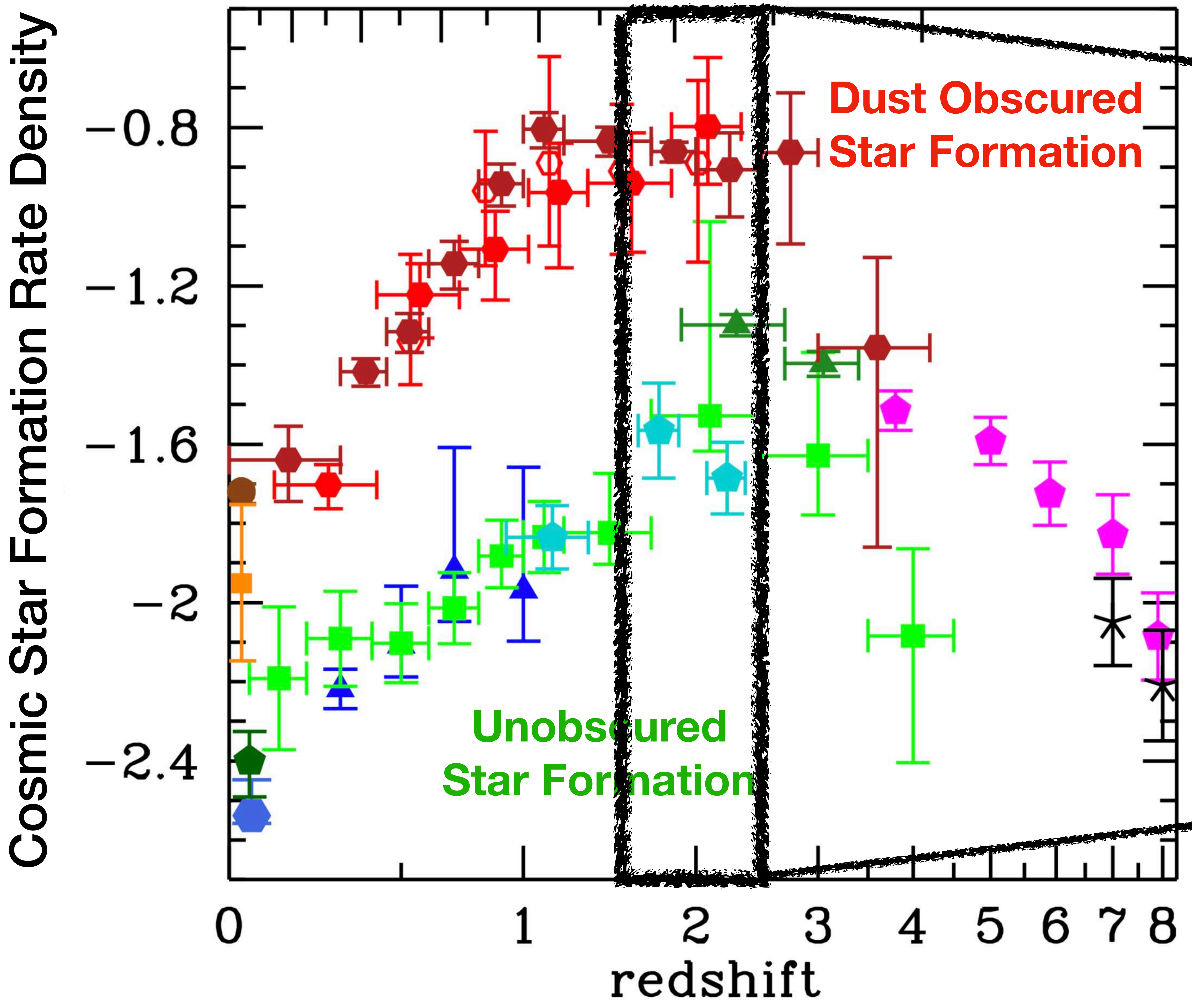


Madau & Dickinson (2014)

Significant fraction of star formation is Dust obscured at High Redshifts



SIGNIFICANT FRACTION OF STAR FORMATION IS DUST OBSCURED AT HIGH REDSHIFTS



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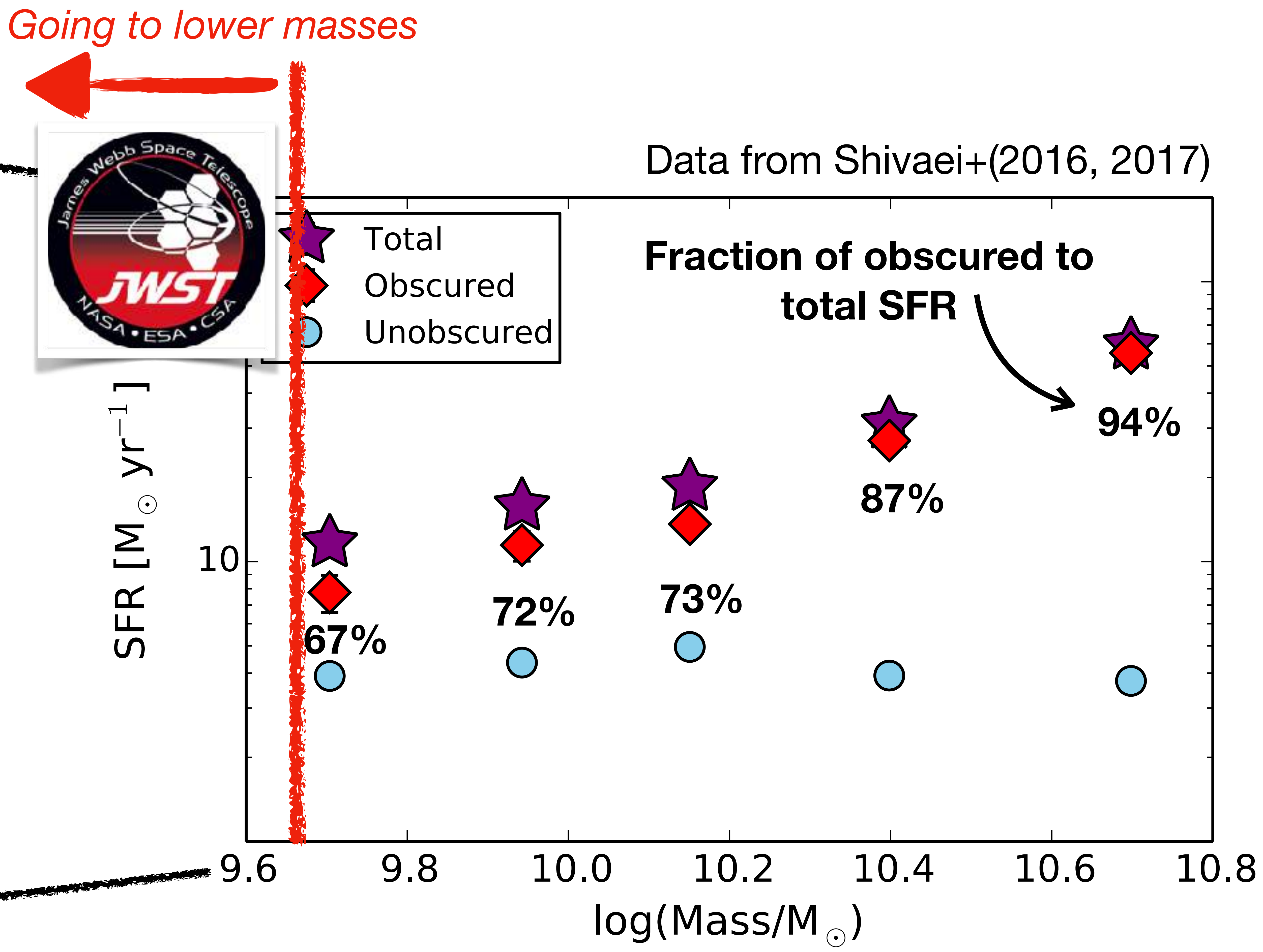
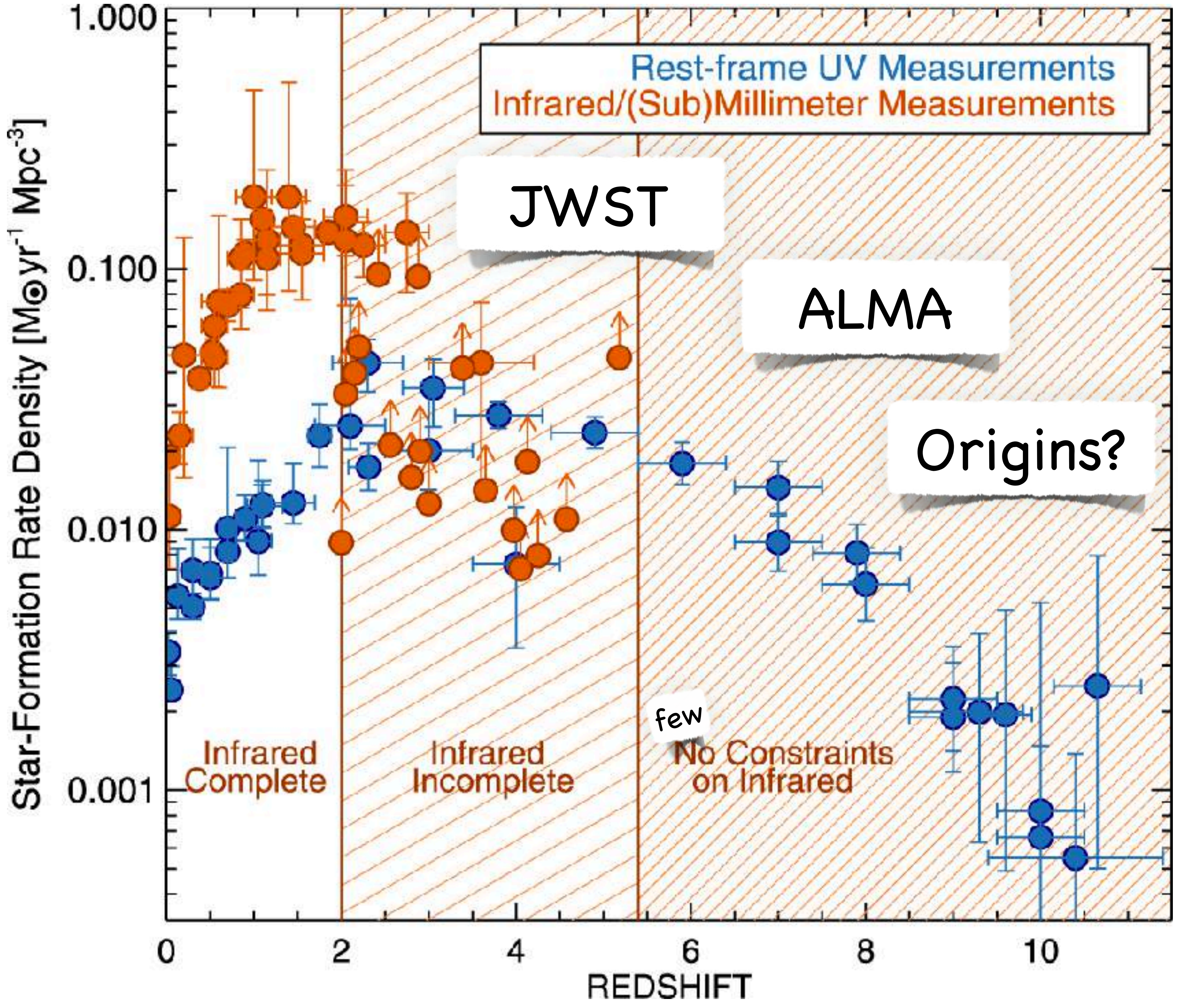
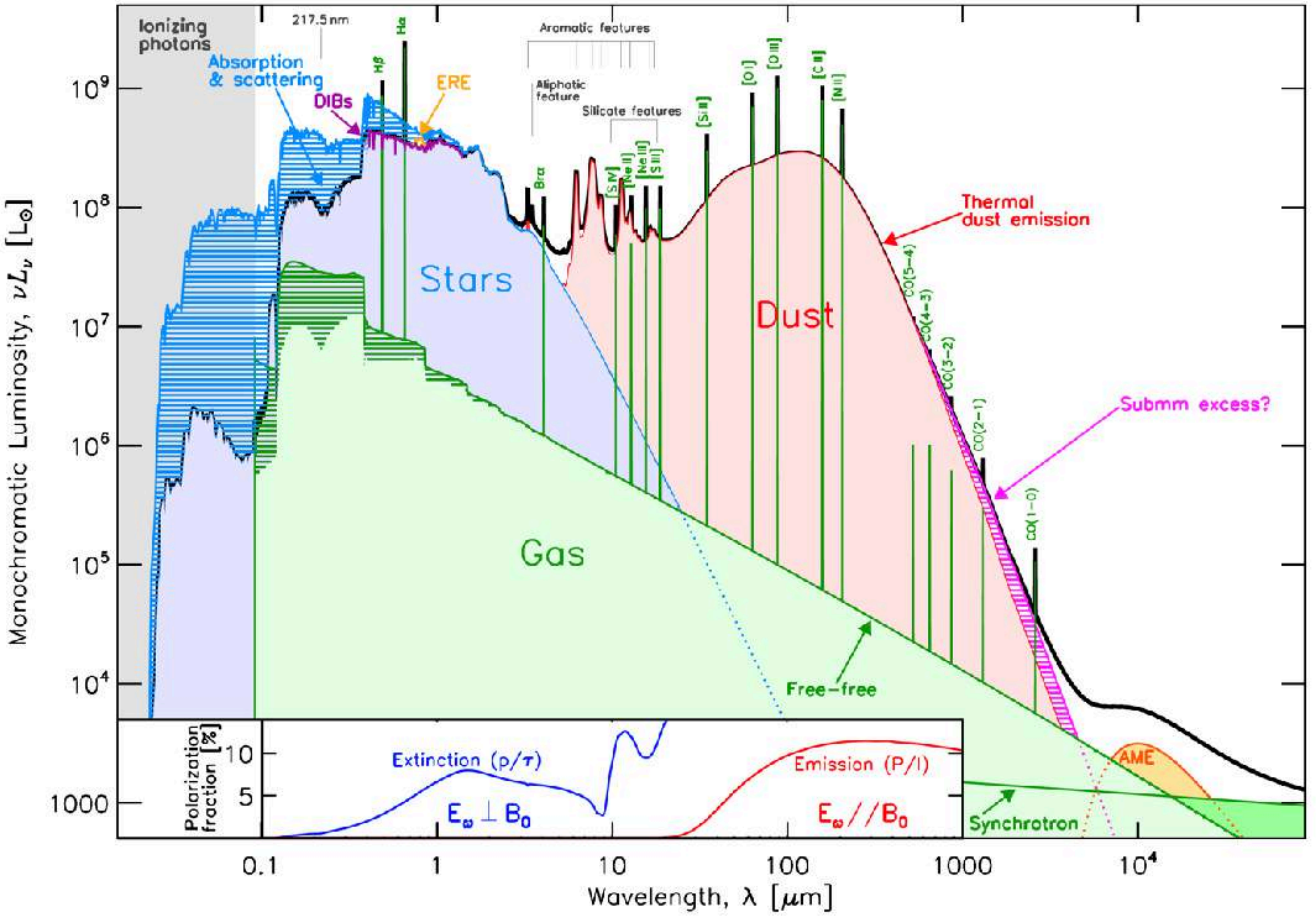


- Step 1: how much dust is there?

Casey+2018



- Step 1: how much dust is there?
- Step 2: evolution of dust and chemical enrichment of the ISM



Galliano, Galametz, and Jones ARAA 2018

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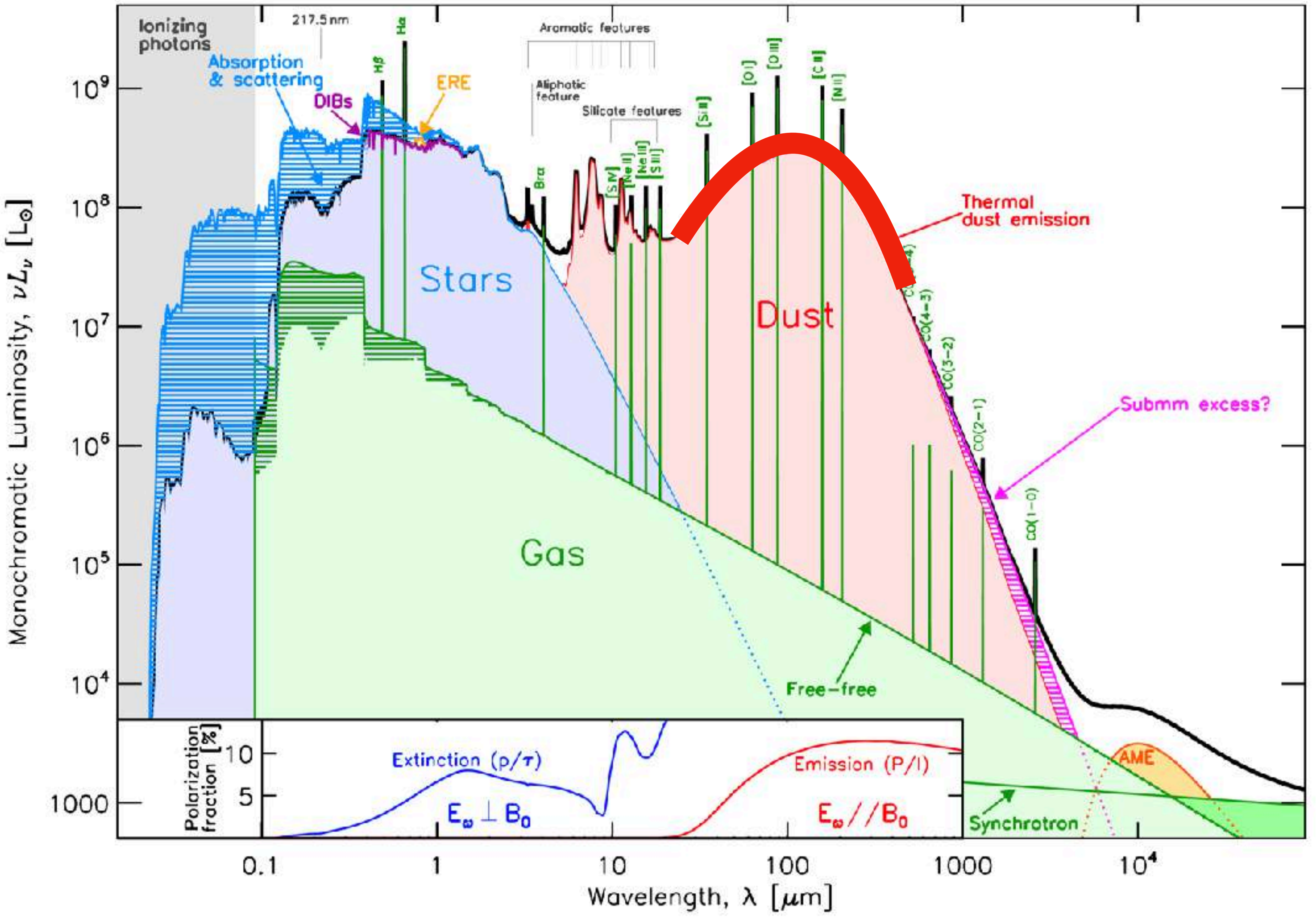

Galliano, Galametz, and Jones ARAA 2018

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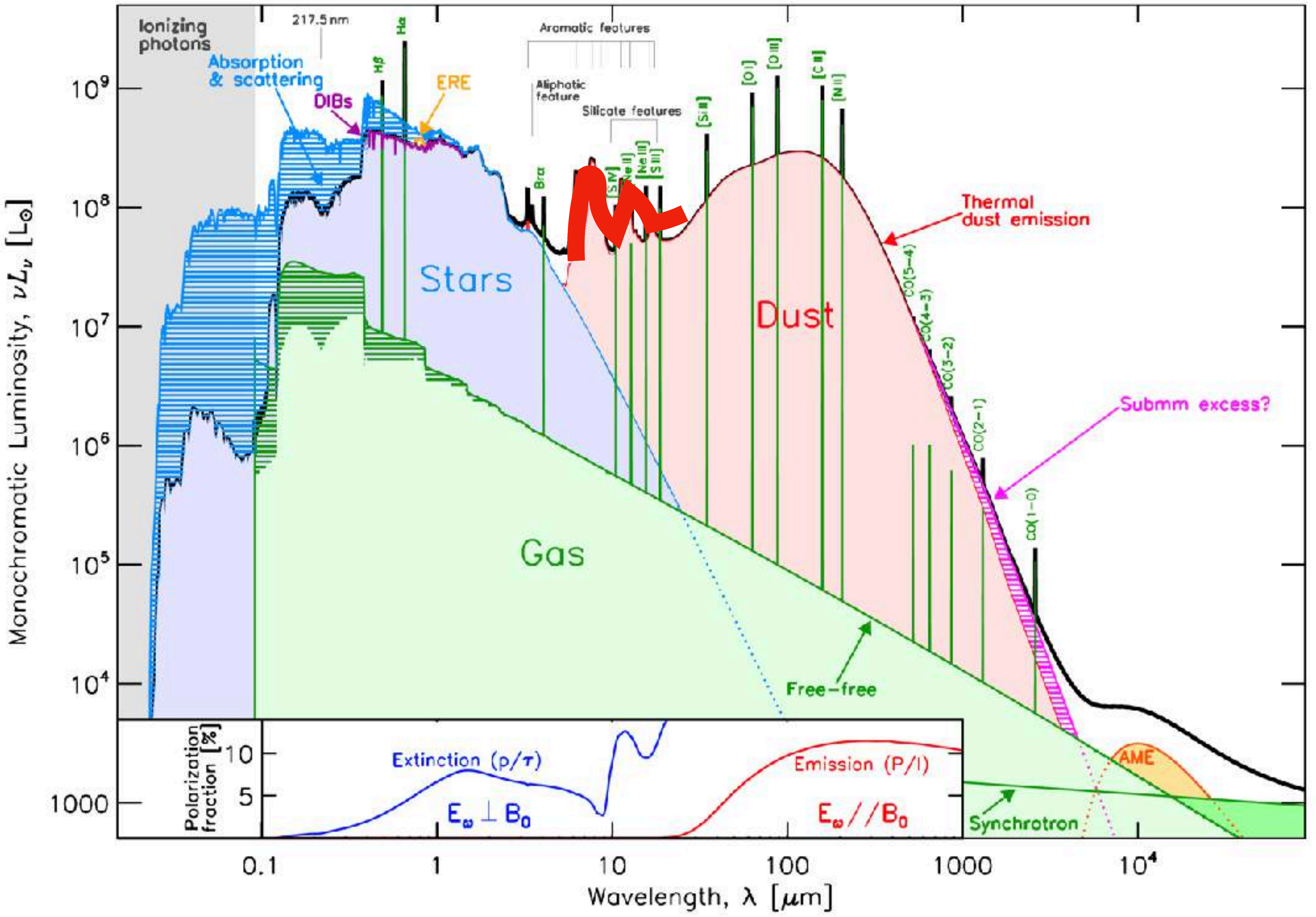

Galliano, Galametz, and Jones ARAA 2018

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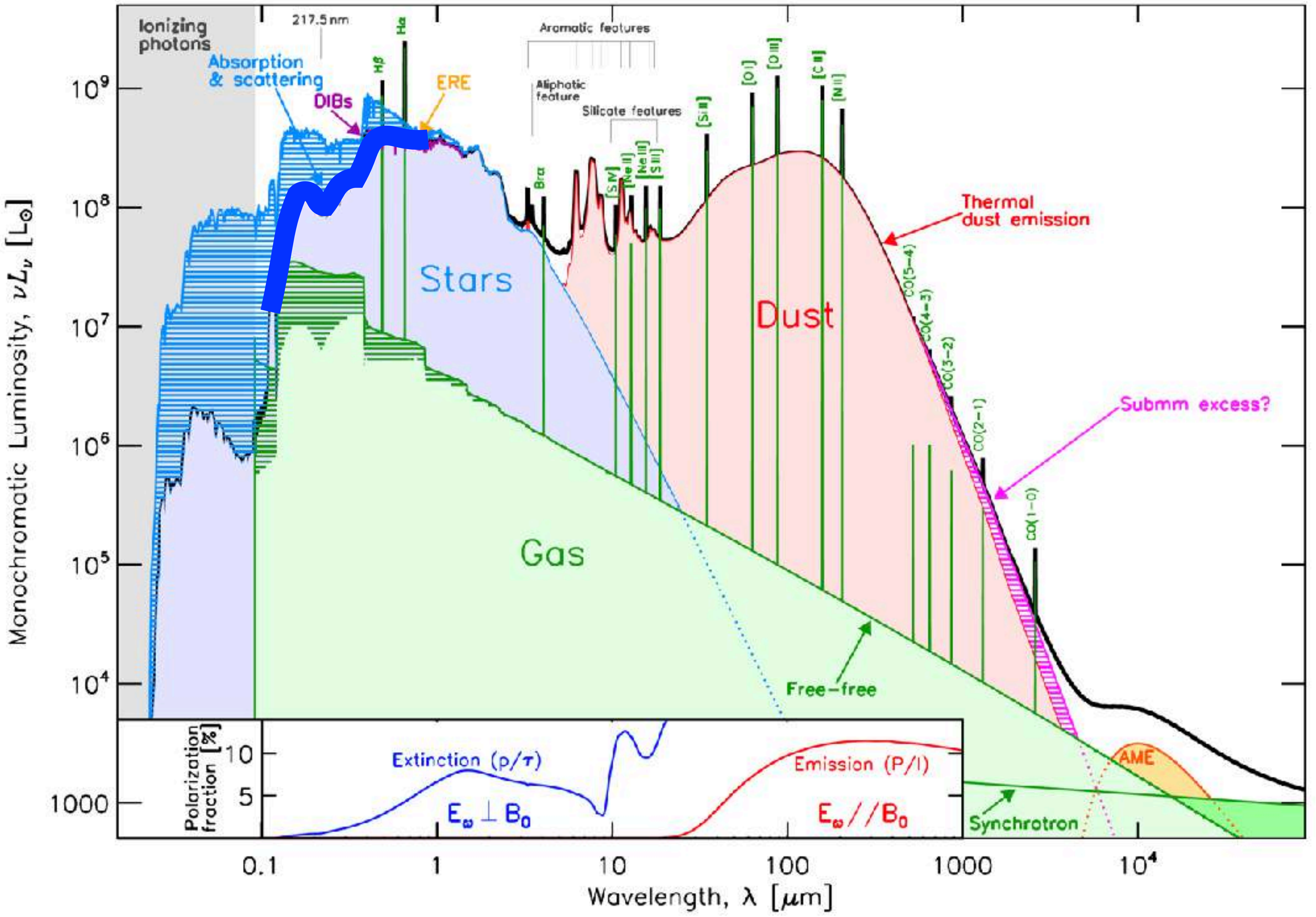
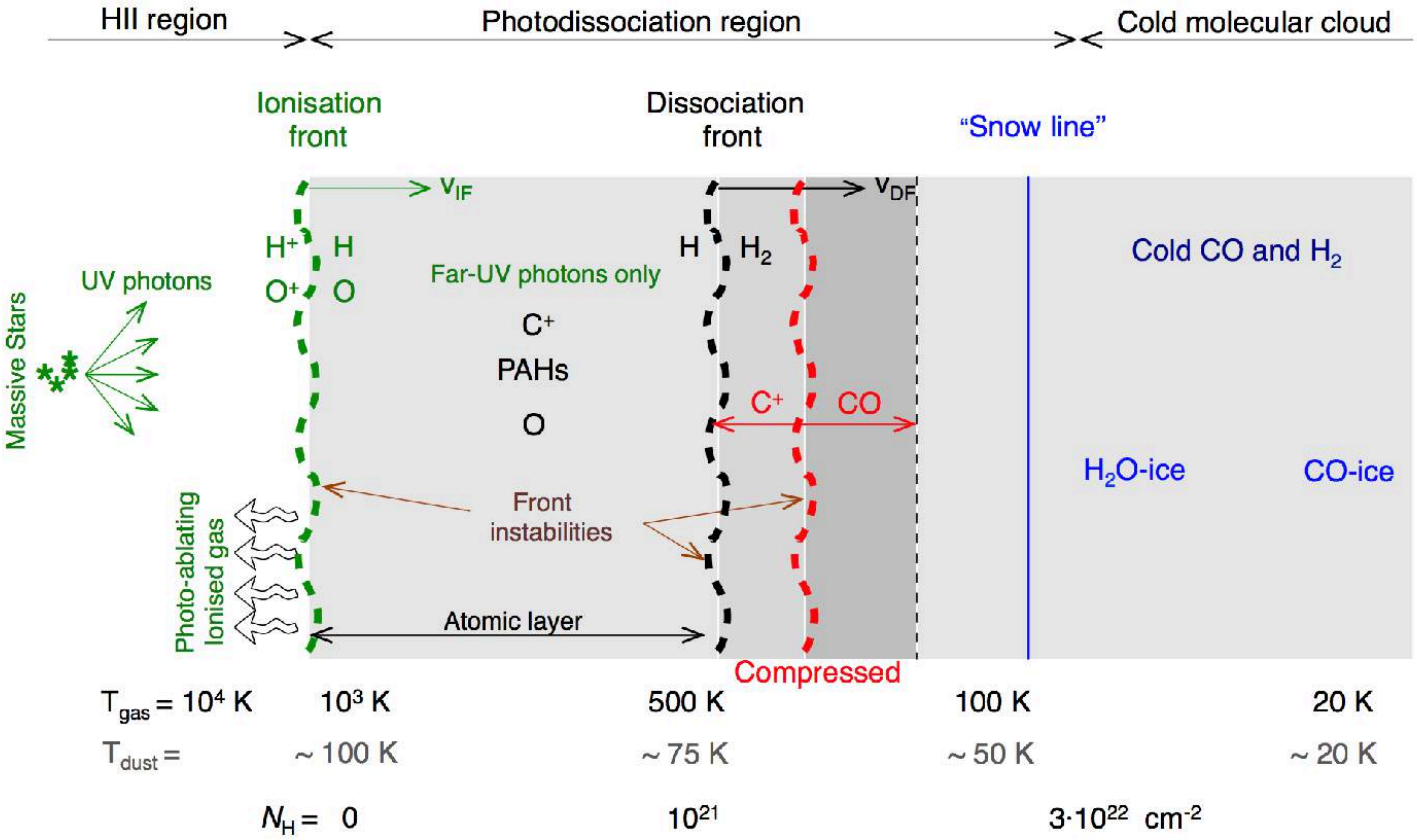


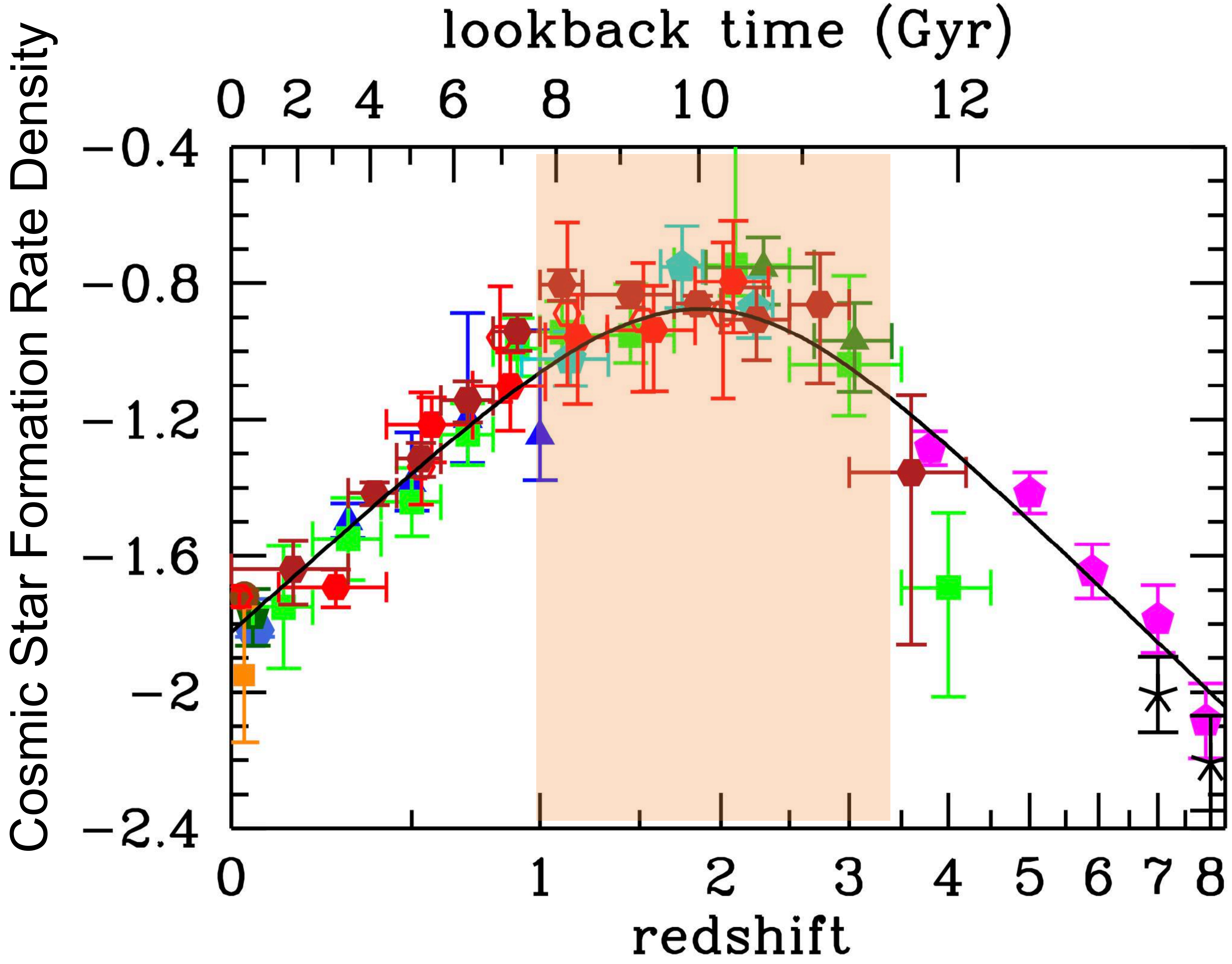
Galliano, Galametz, and Jones ARAA 2018

It's one connected system



Goicoechea et al. (2016)

z ~ 1 – 3: PEAK EPOCH OF COSMIC STAR FORMATION ACTIVITY



Madau & Dickinson (2014)


Far-IR
UV, Optical
Mid-IR
Galaxies at
z ~ 1 – 3
ALMA
Keck
Ground optical/NIR telescopes
Herschel
Hubble
Spitzer
Absorption/ Scattering
Emission Features
Thermal Dust Emission
Stars
Dust
Gas
Absorption/ Scattering
Emission Features
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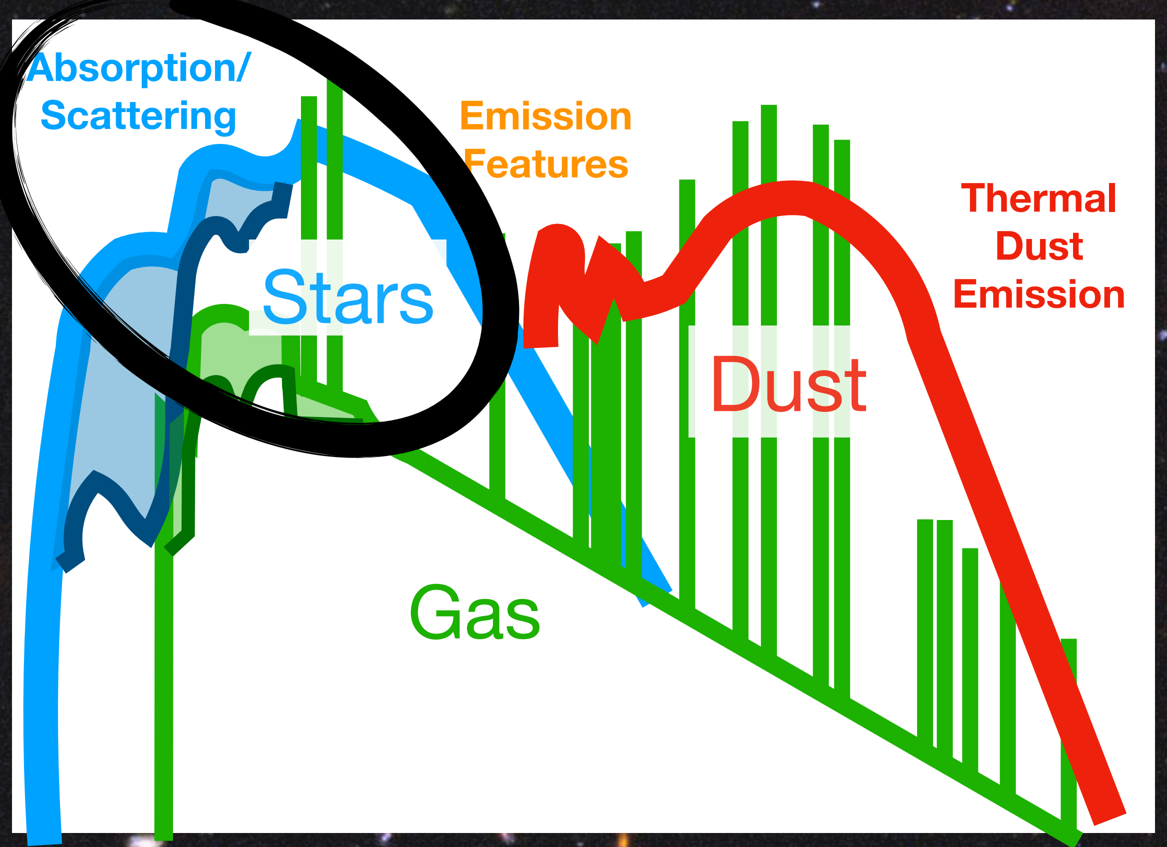
Gas

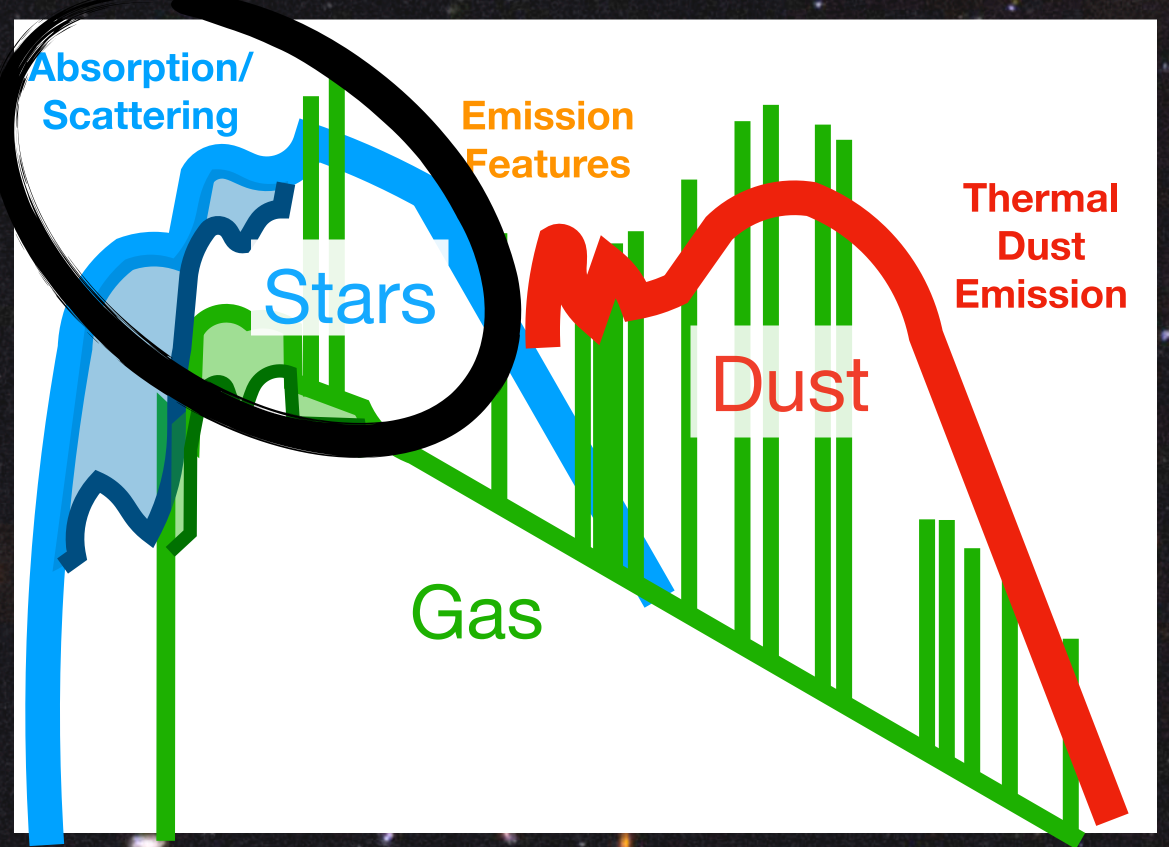
OUTLINE

- Rest-frame optical spectroscopy tracing ionized gas at z~2 (MOSFIRE Deep Evolution Field Survey)

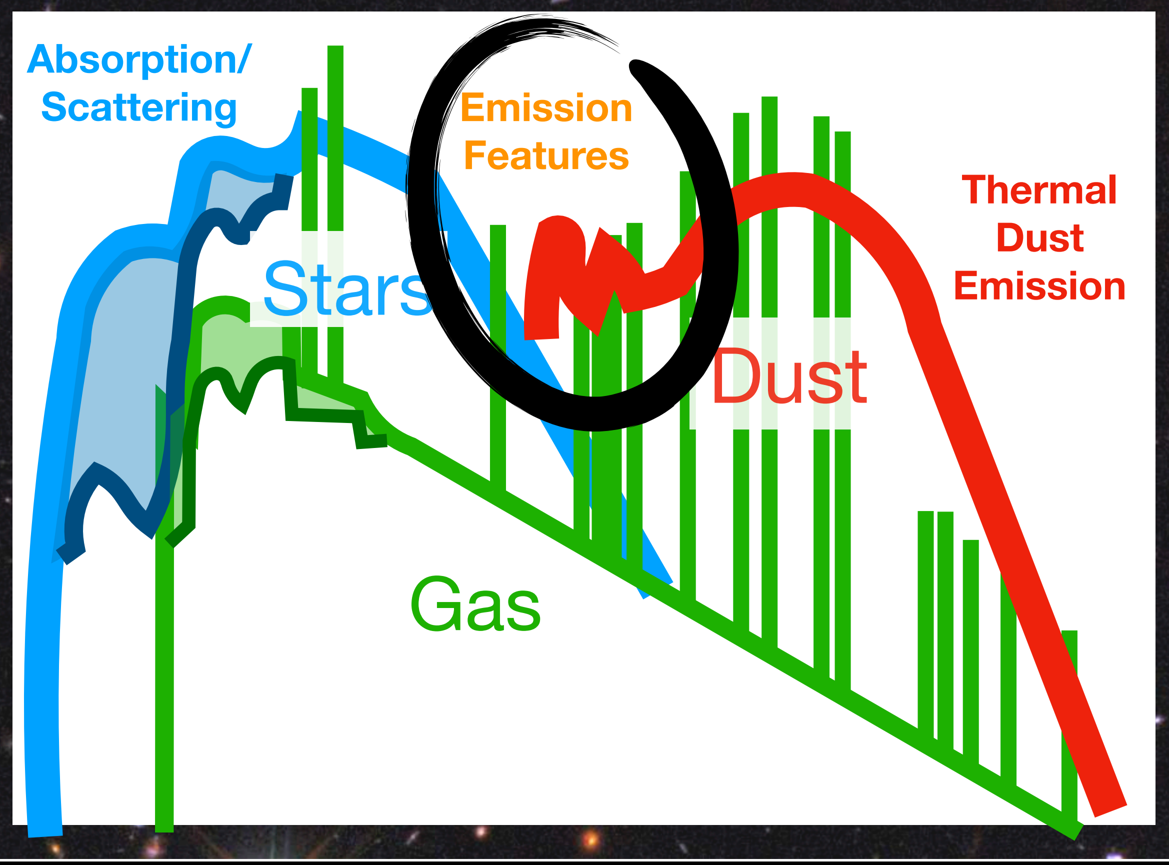


OUTLINE

✳ Rest-frame optical spectroscopy tracing ionized gas at z~2 (MOSFIRE Deep Evolution Field Survey)

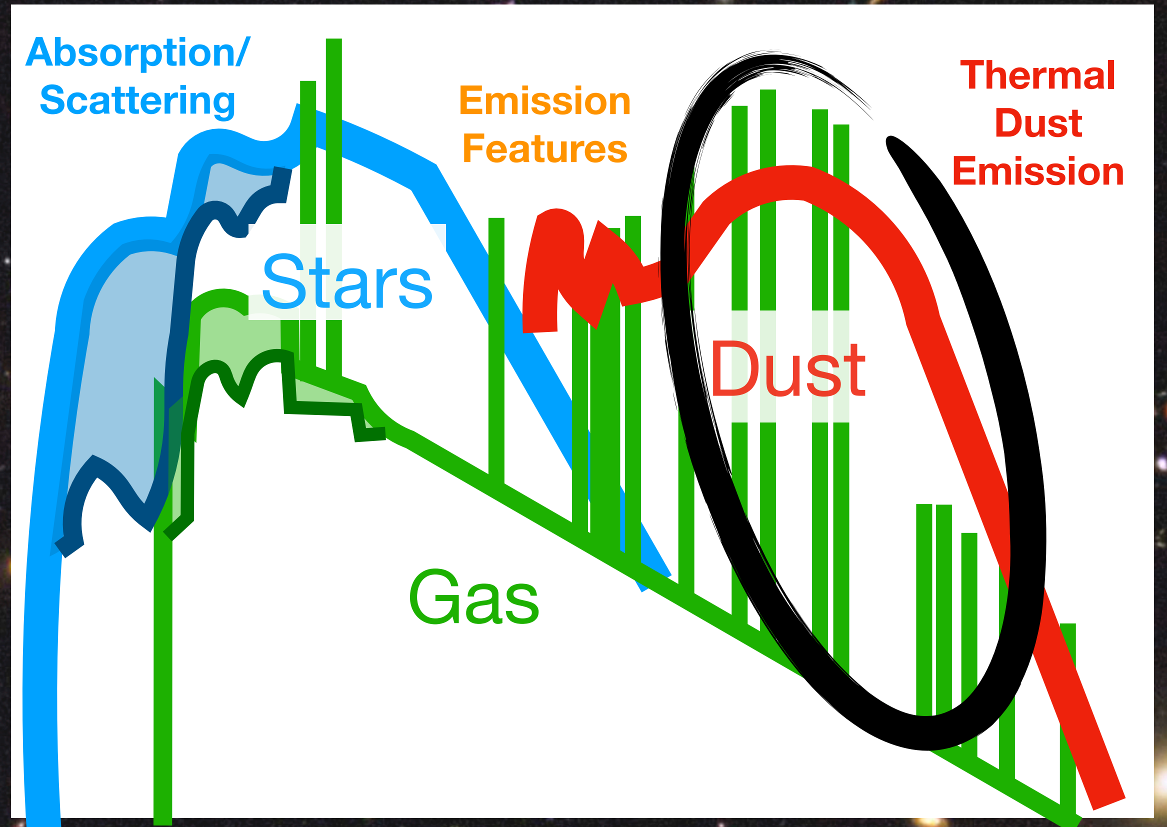


✳ Spitzer MIPS 24um tracing PAH emission at z~2



OUTLINE

✳ ALMA and Herschel tracing far-IR dust emission



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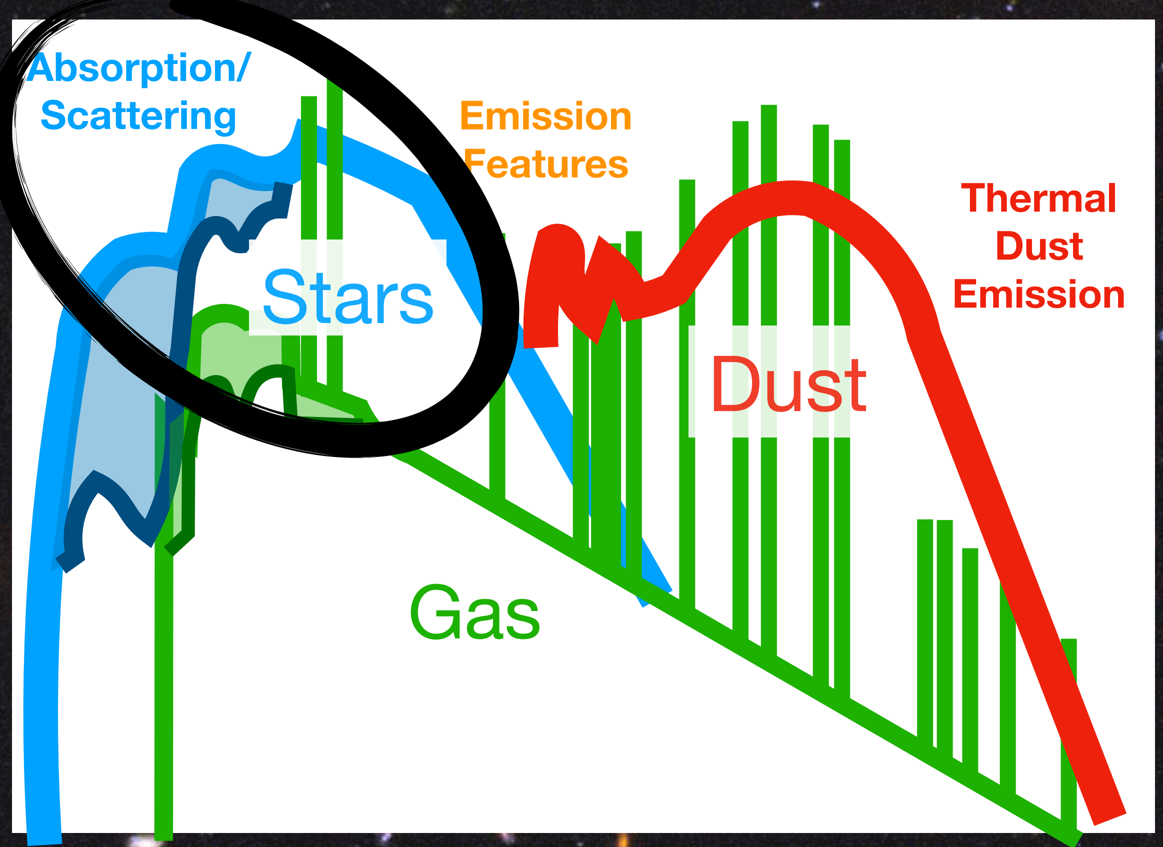

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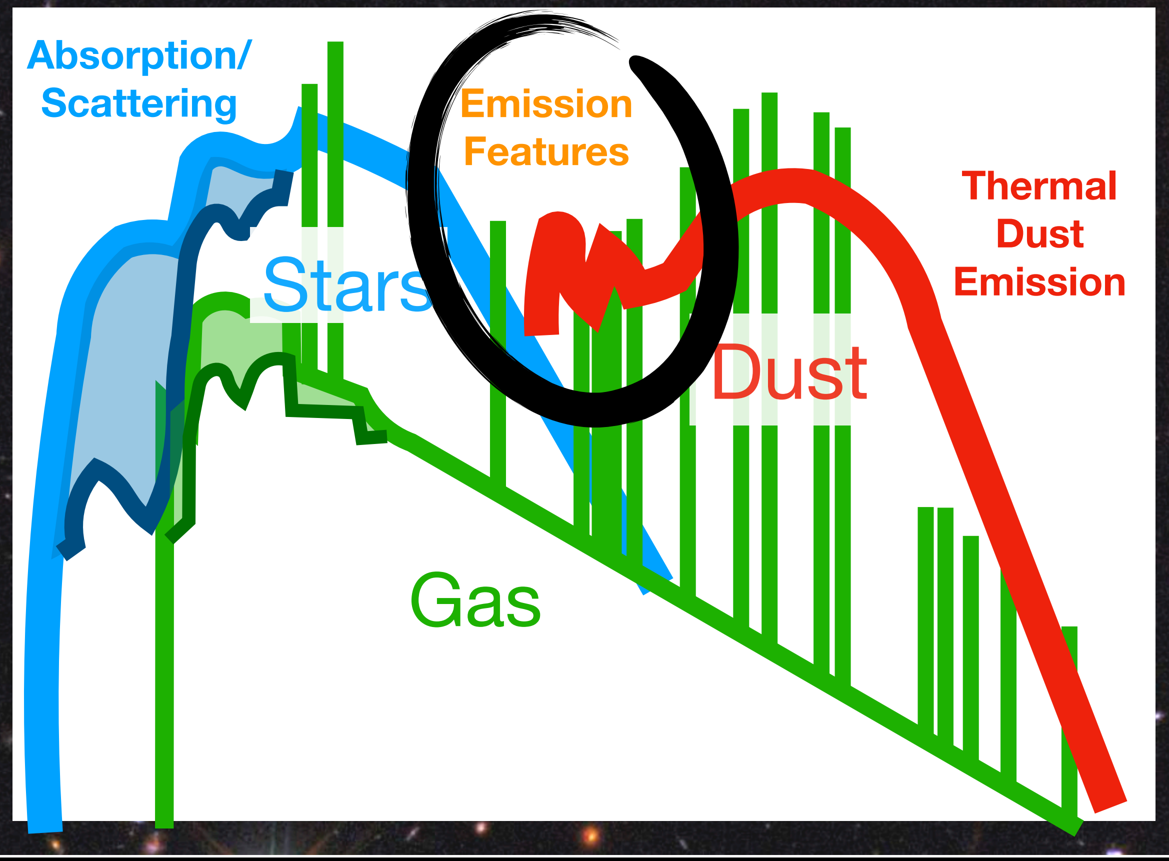
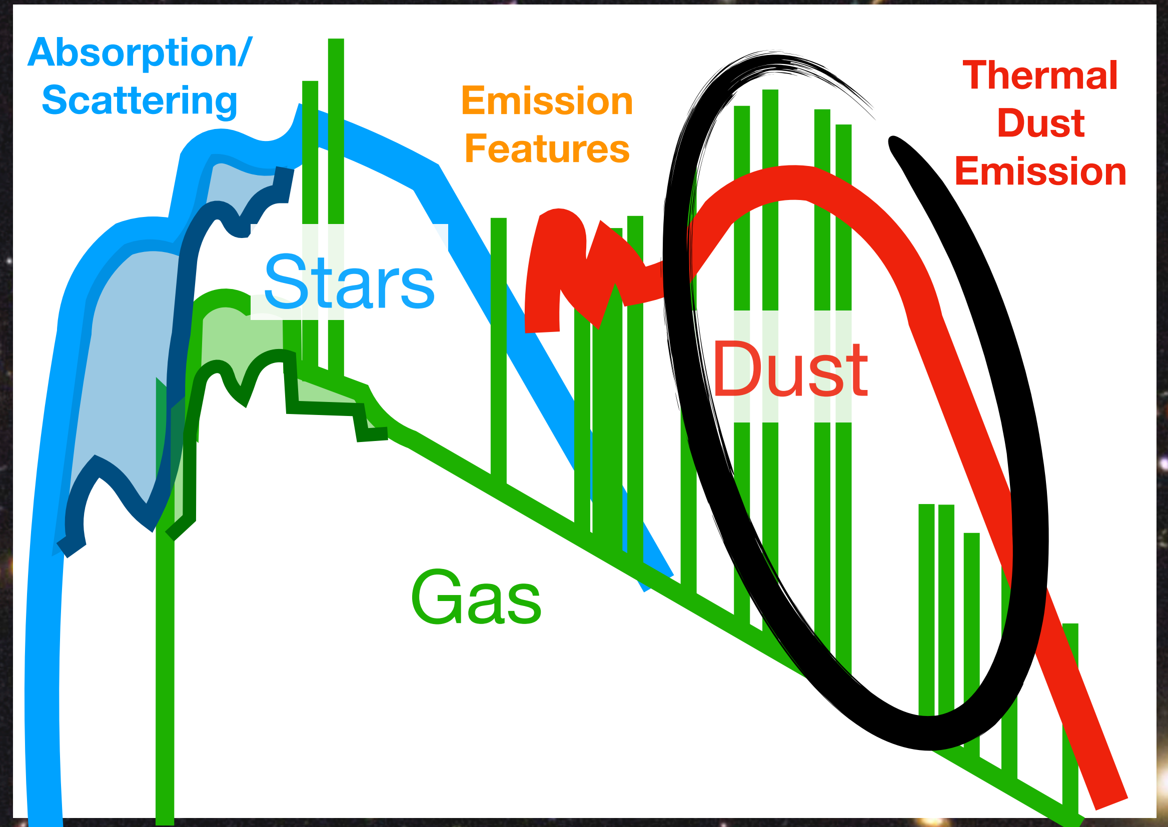


Outline

✳ ALMA and Herschel tracing far-IR dust emission



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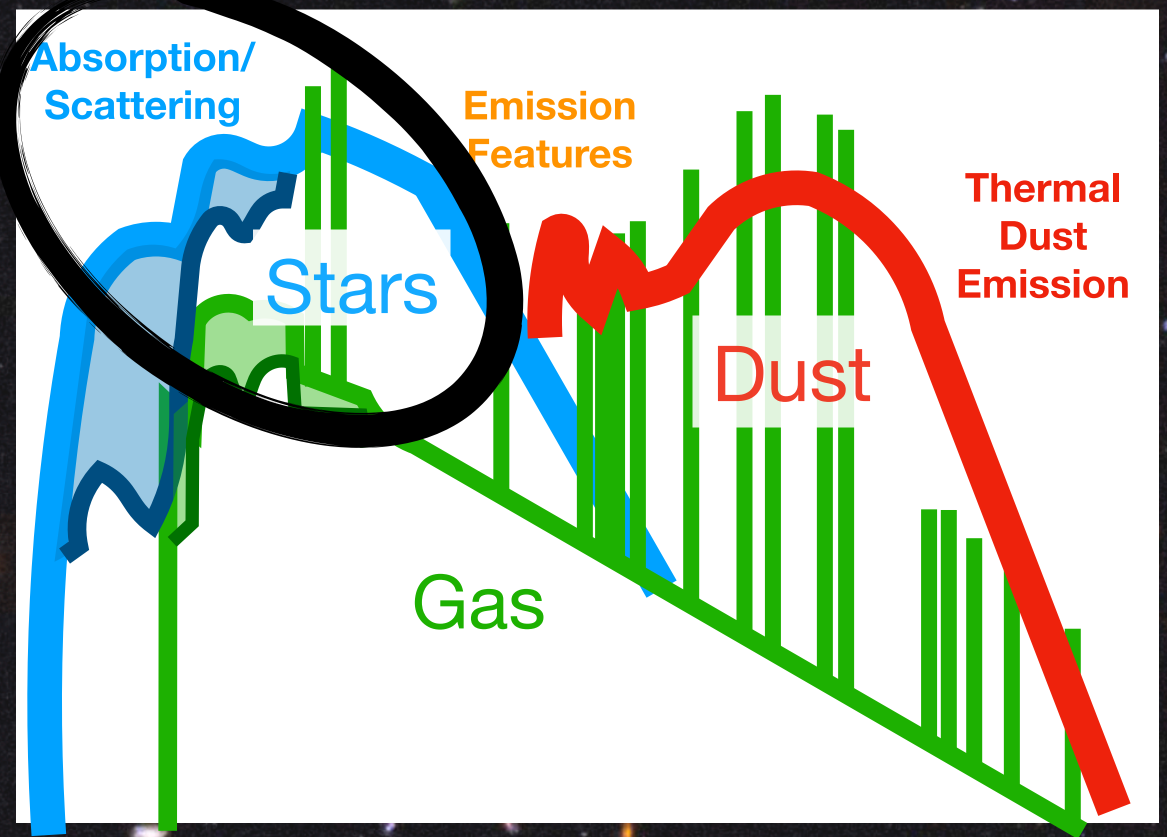
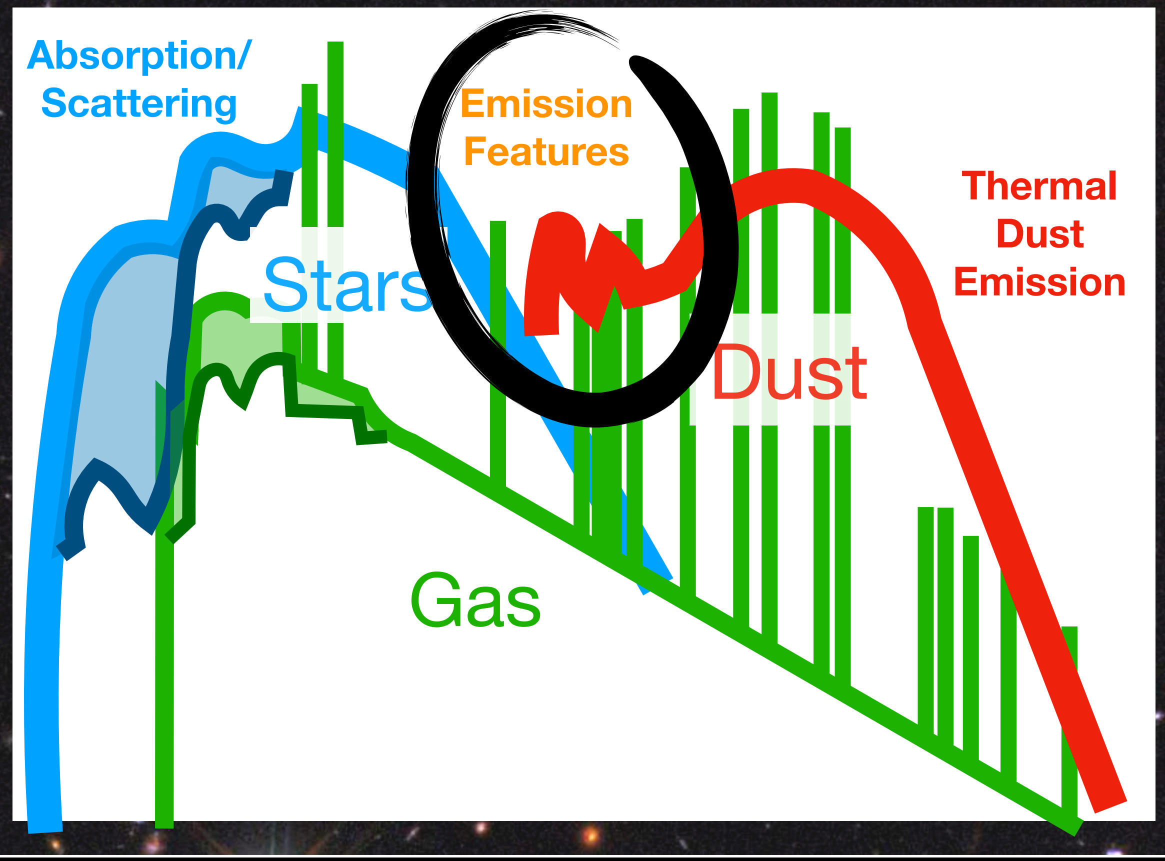
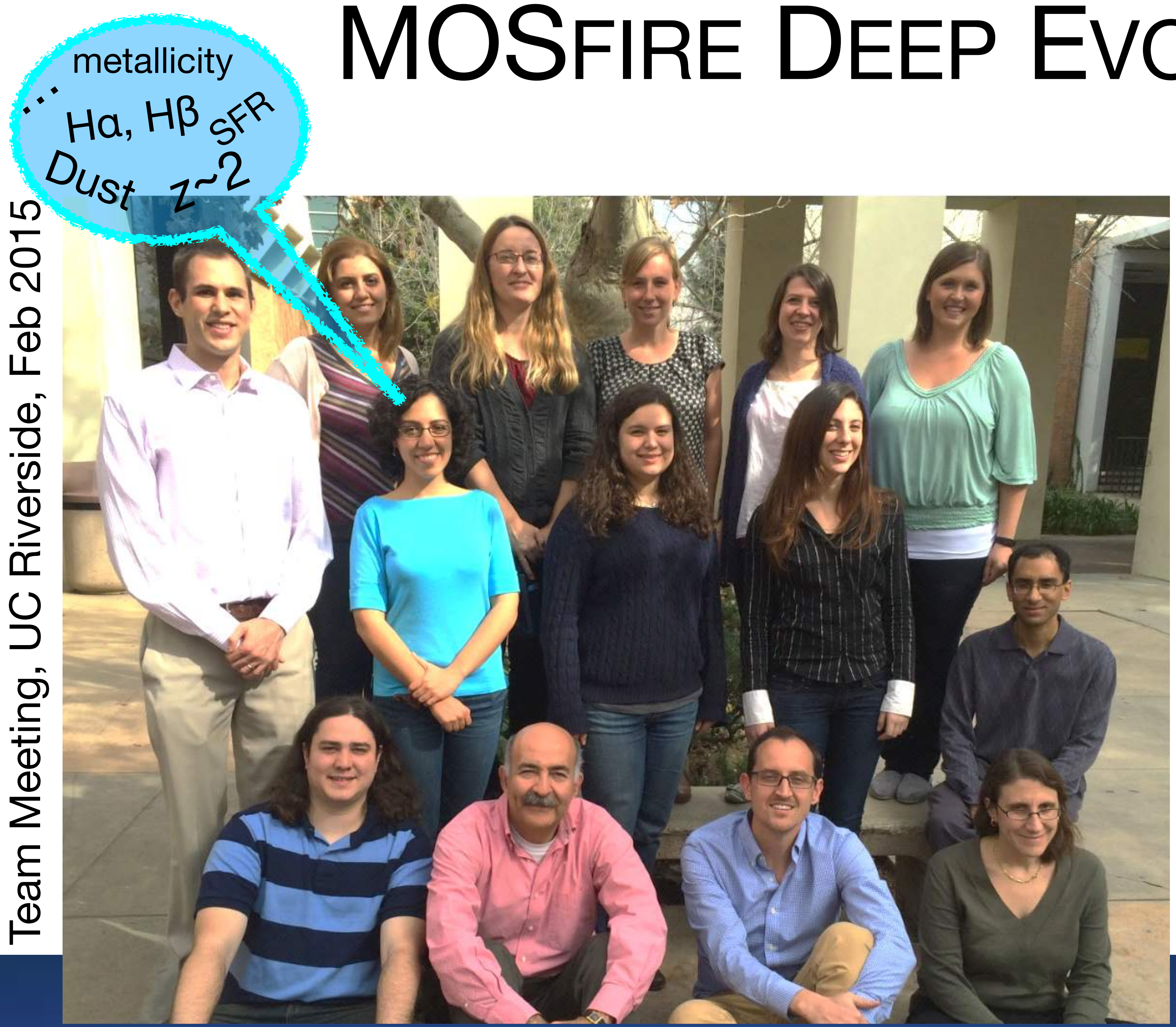


✳ US GTO HUDF survey to trace PAH emission at z~1-2

✳ Spitzer MIPS 24um tracing PAH emission a

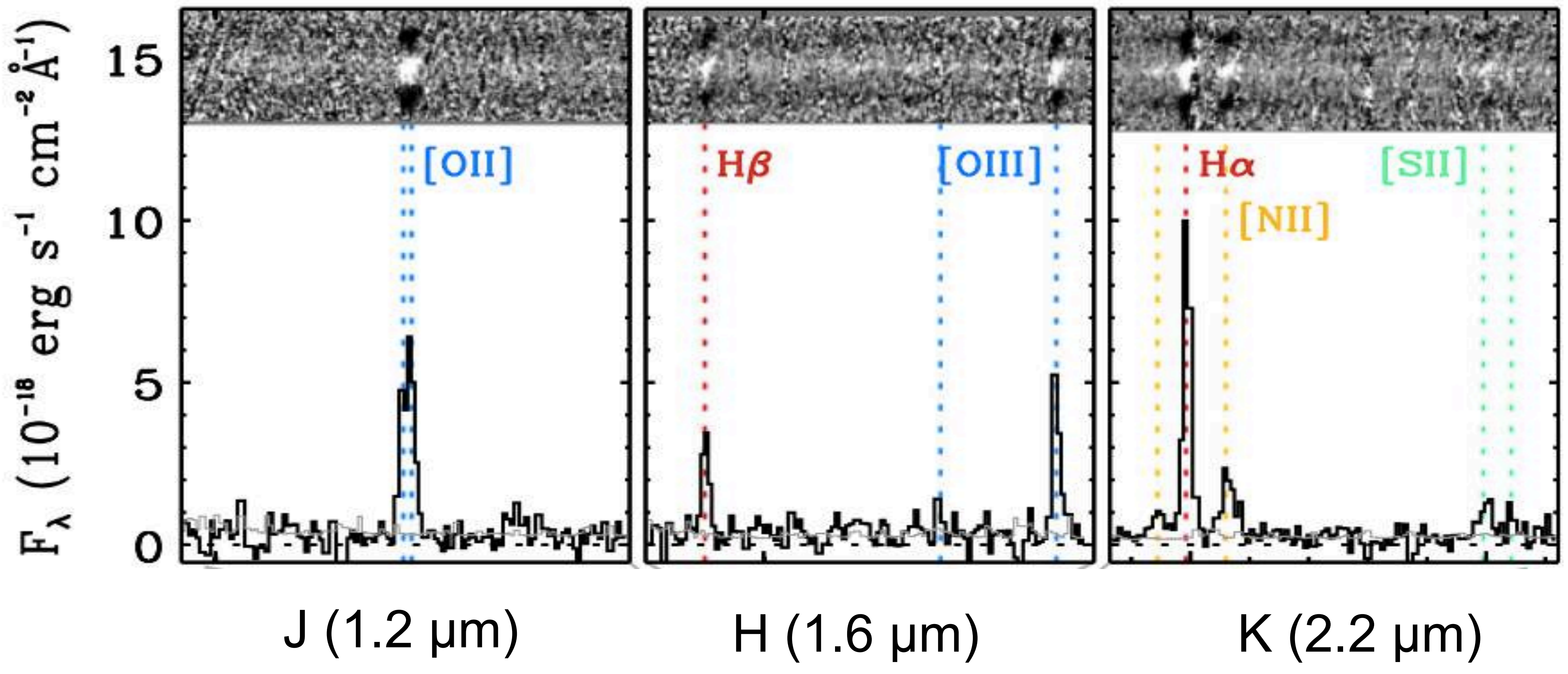


MOSFIRE Deep Evolution Field (MOSDEF) survey



Team Meeting, UC Riverside, Feb 2015

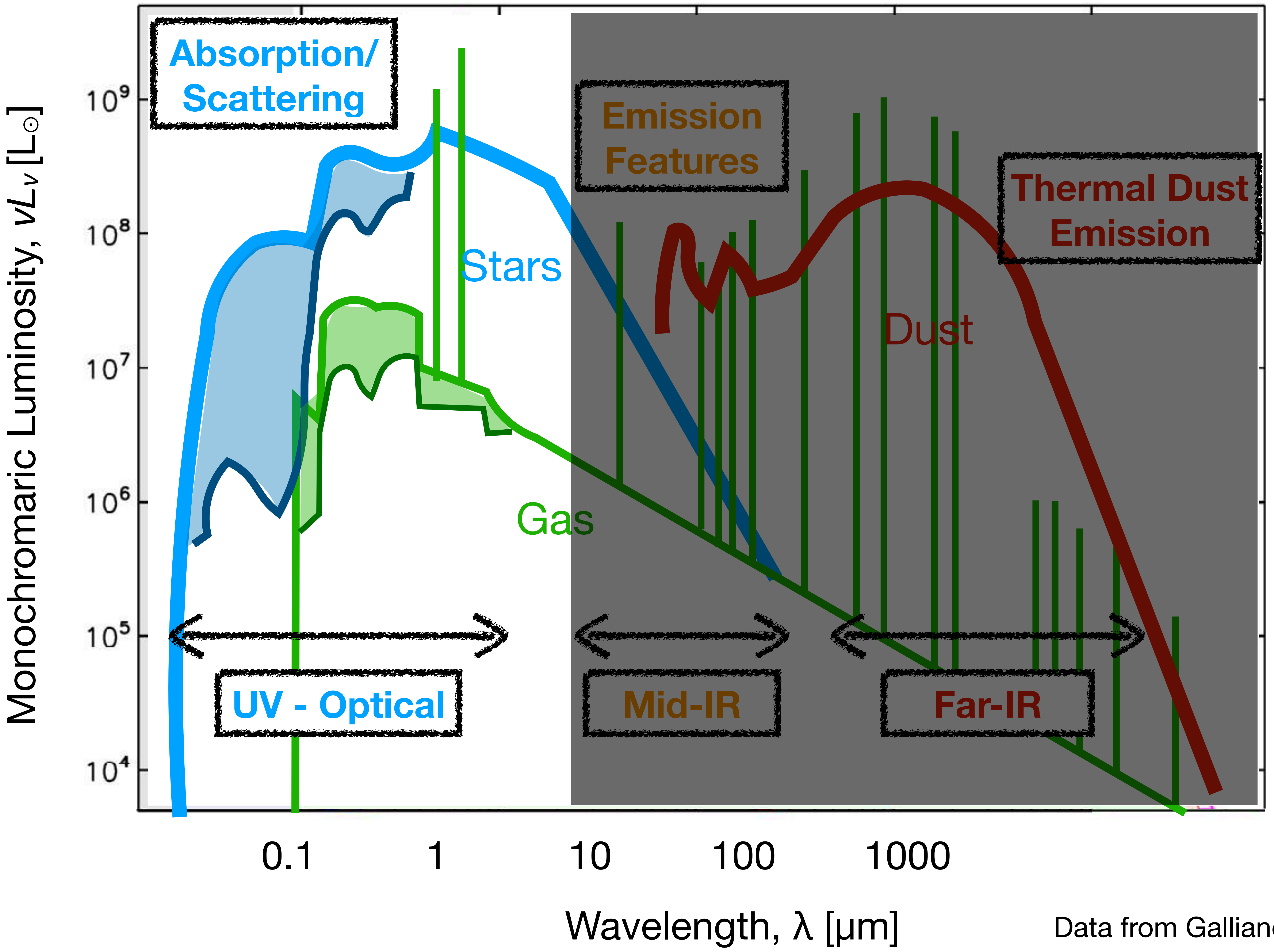
Survey paper: Kriek+2015



Observed spectra at z~2

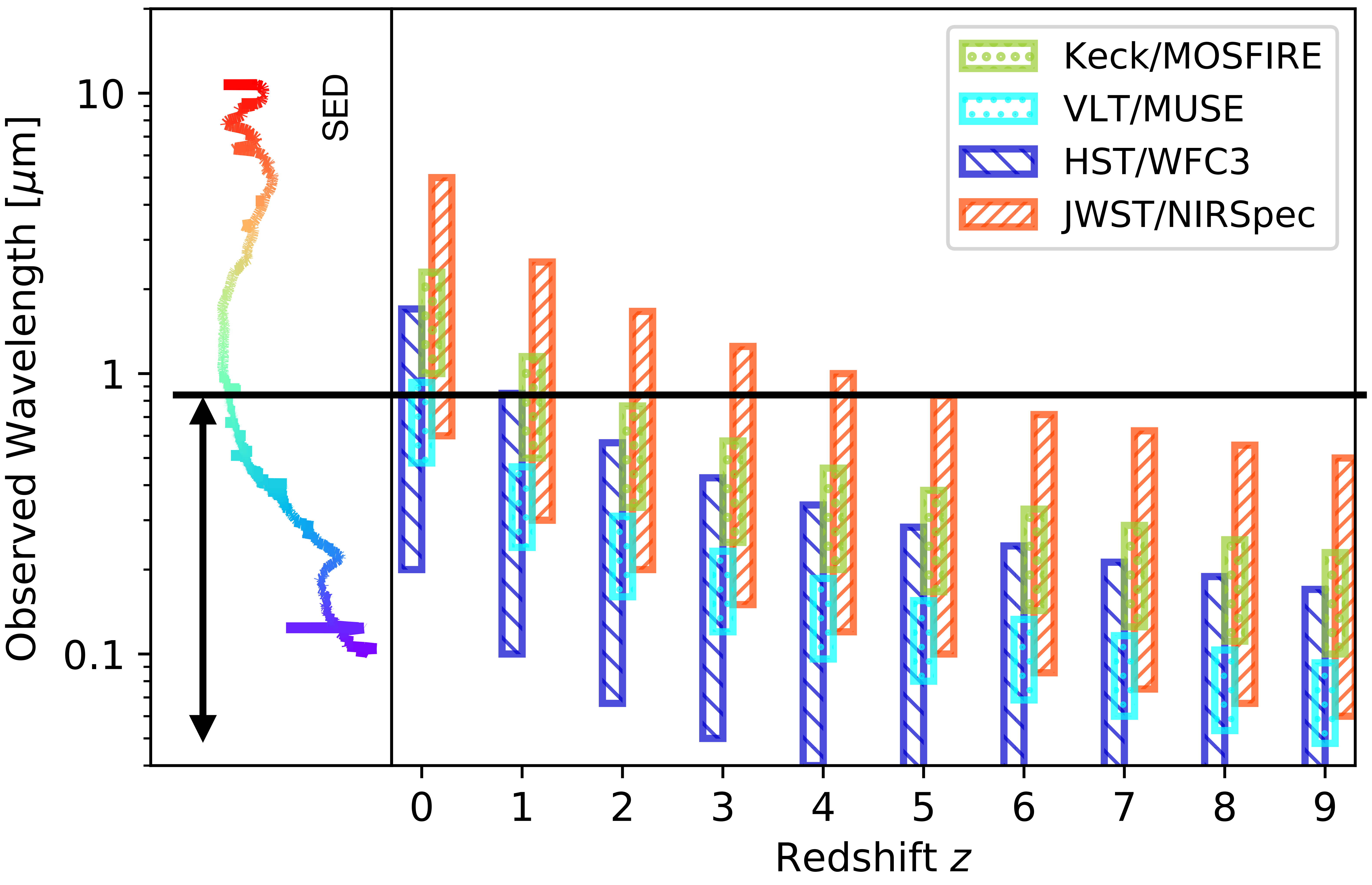
48.5 nights with MOSFIRE on Keck I (2012-2016)
Rest-frame optical spectra of ~ 1500 H-selected galaxies
$1.37 \leq z \leq 3.80$
CANDELS fields
Collaboration between UC Berkeley, UCLA, UC San Diego, UC Riverside

UV-OPTICAL ATTENUATION

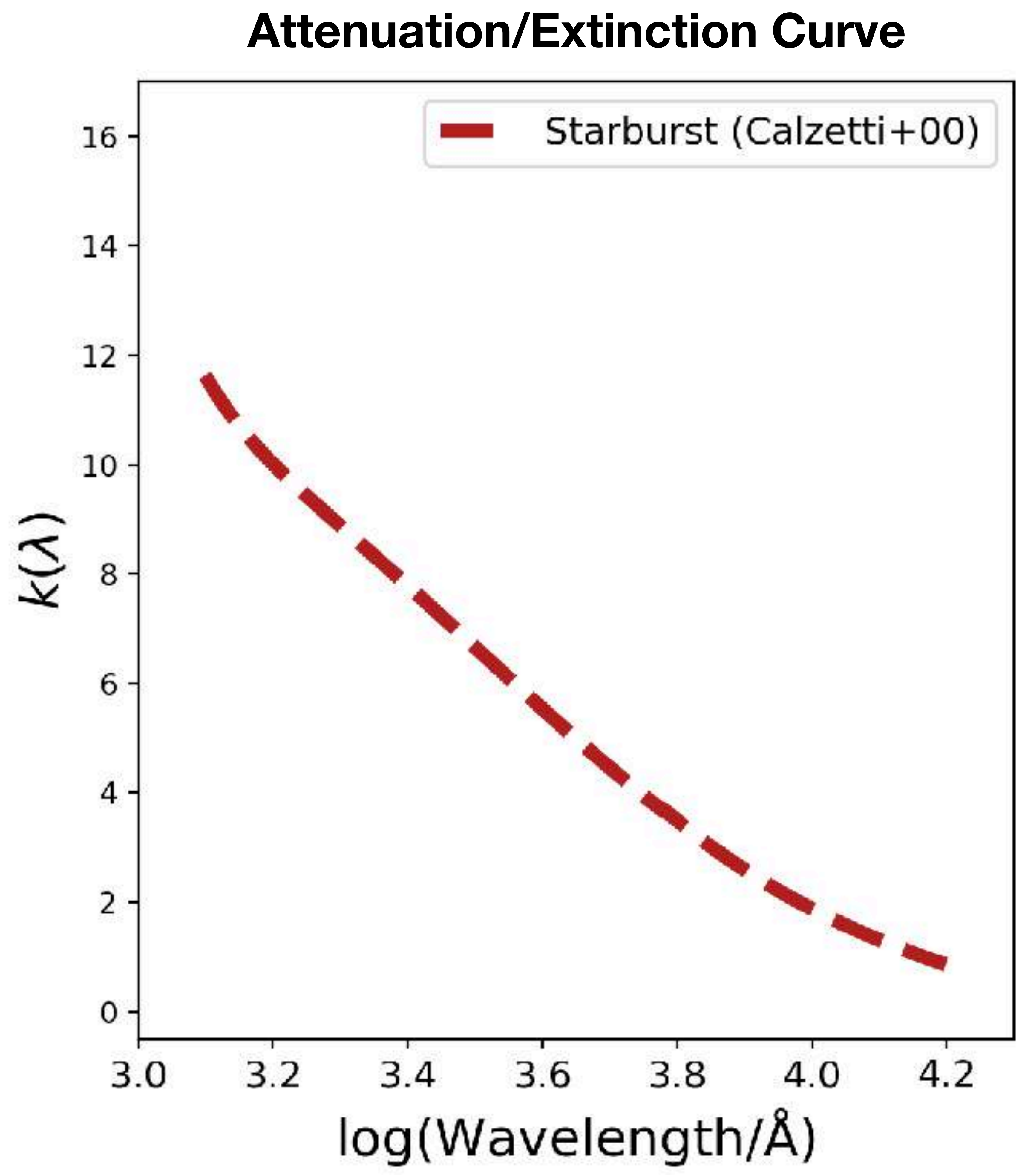


Data from Galliano, Galametz, and Jones ARAA 2018

UV and Optical traced by large ground and space observatories



DUST ATTENUATION/EXTINCTION CURVE



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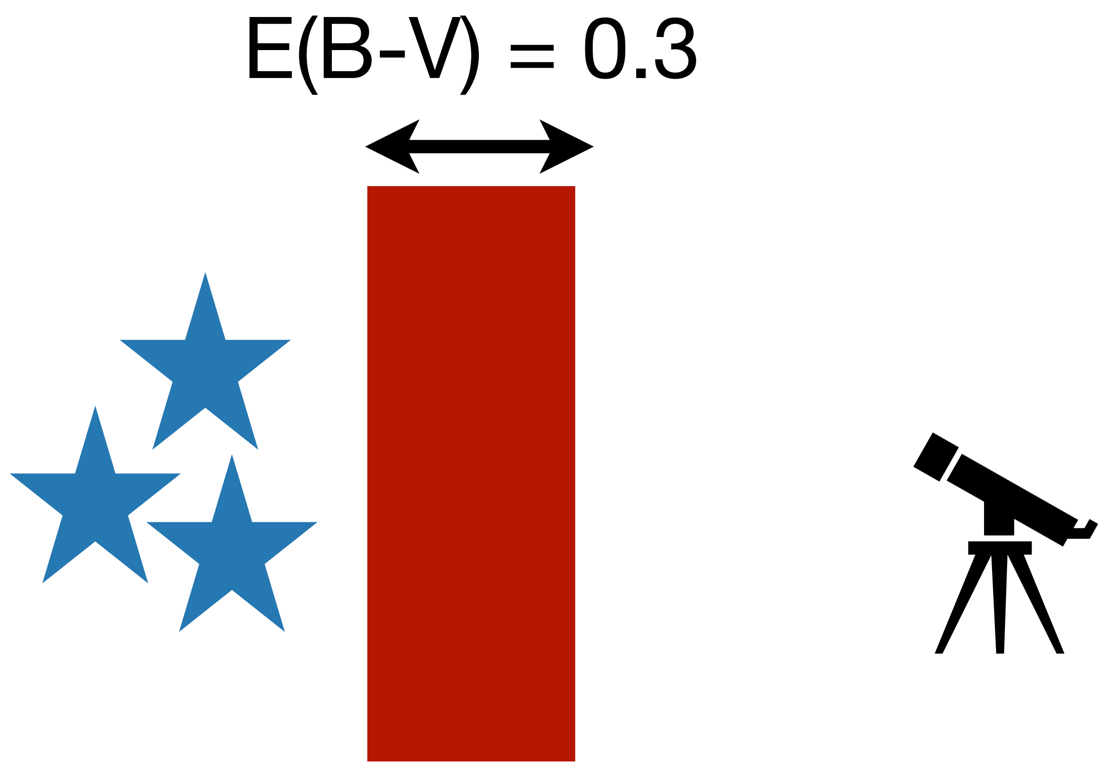
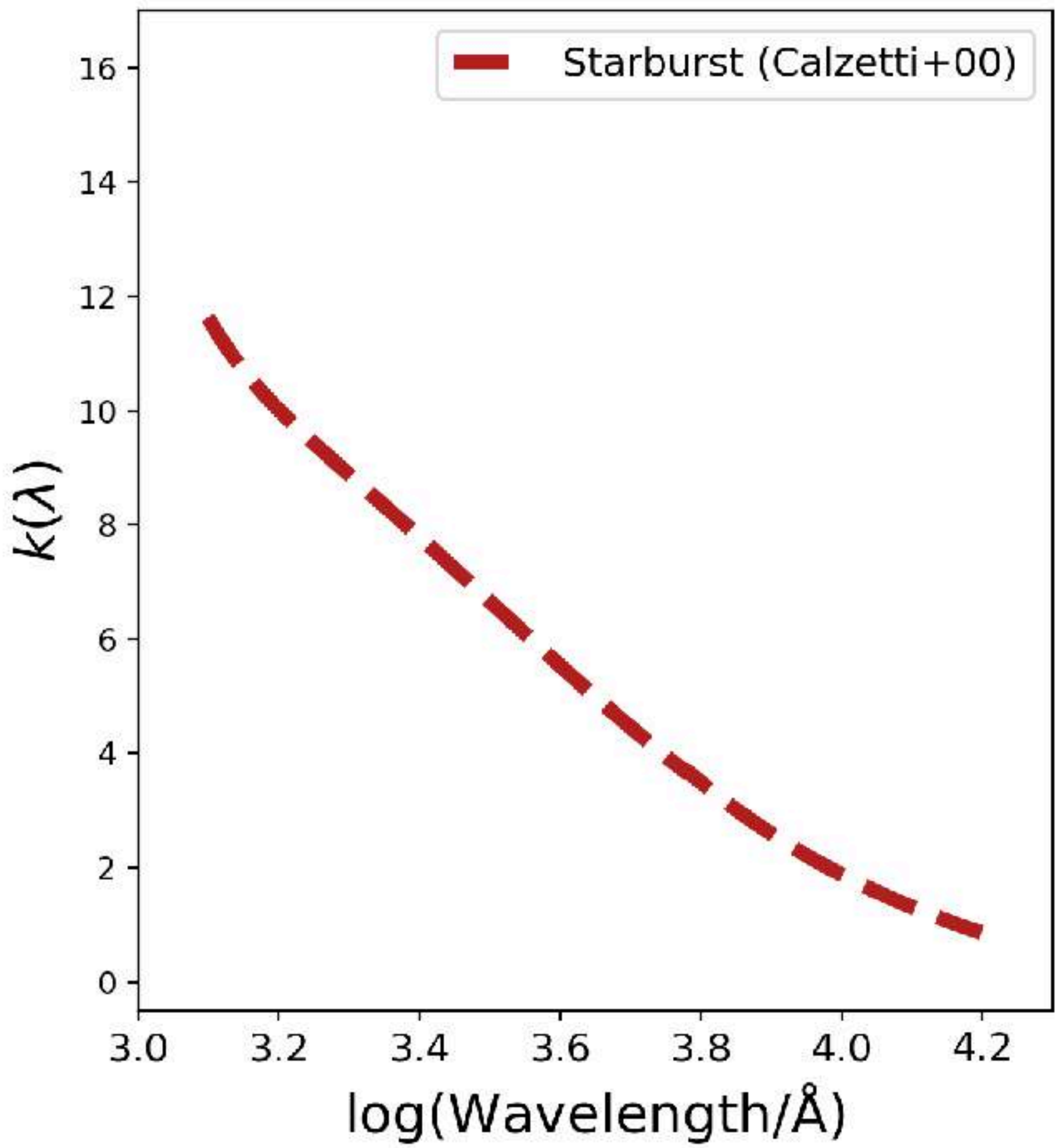
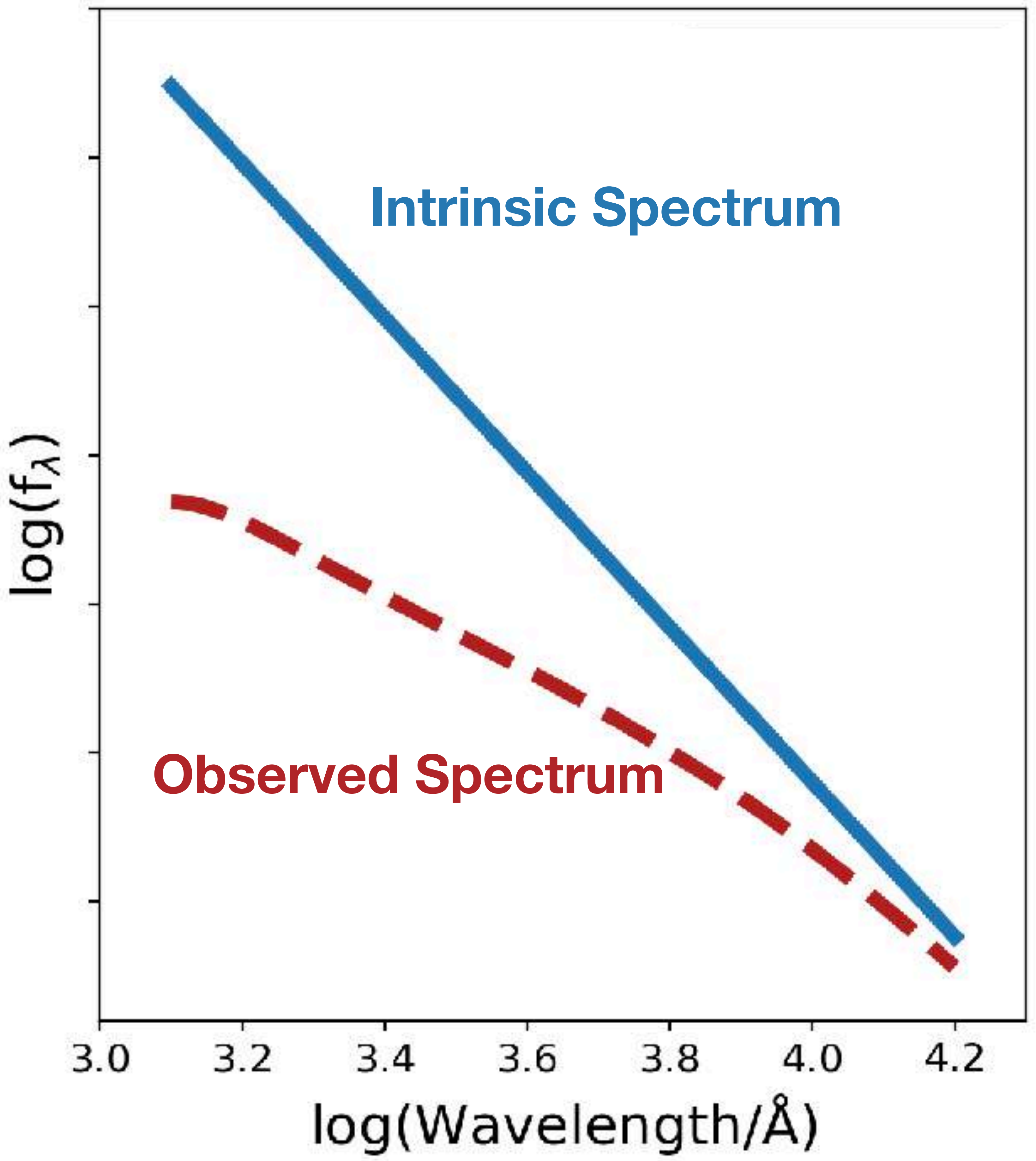


Foreground screen of dust

Attenuation/Extinction Curve

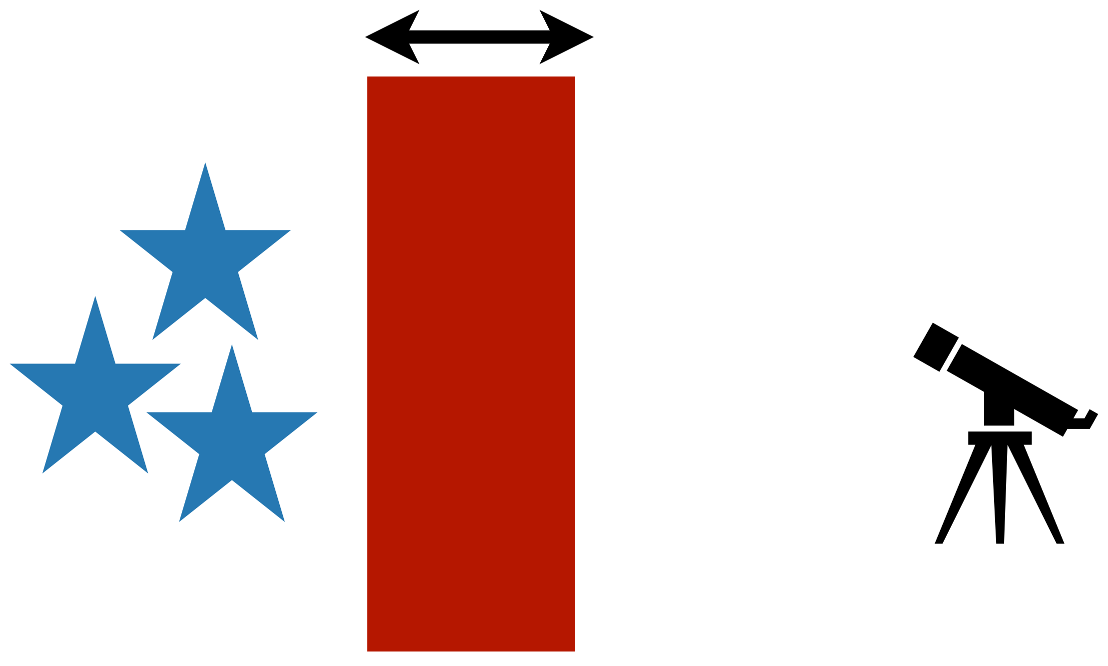


Galaxy Spectrum

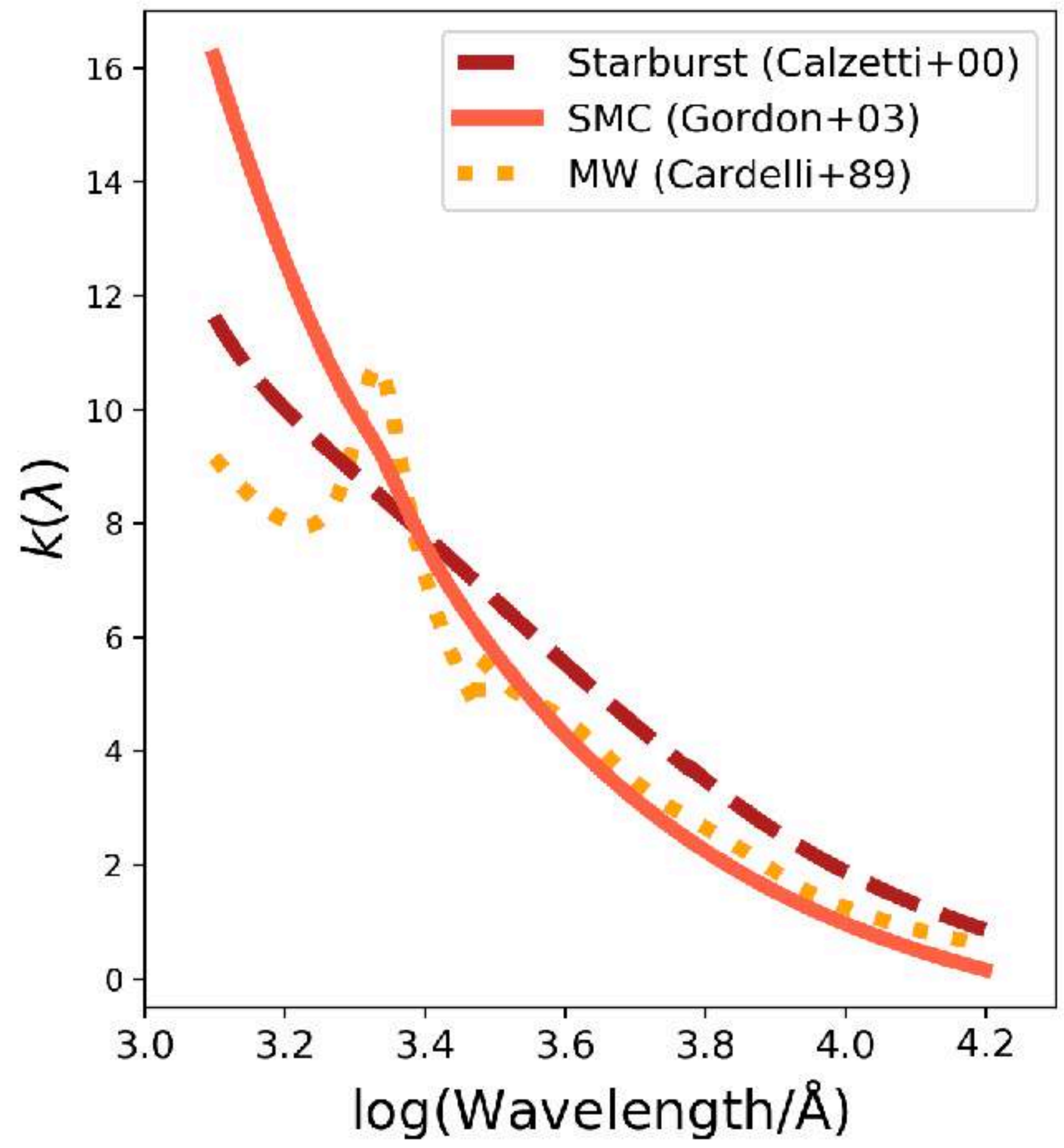


$$f_{\lambda,\,\mathrm{obs}} = f_{\lambda,\,\mathrm{int}} \times 10^{-0.4\,E(B-V)\,k_\lambda}$$

Effect of Dust on two Commonly-used SFR Indicators



Attenuation/Extinction Curve



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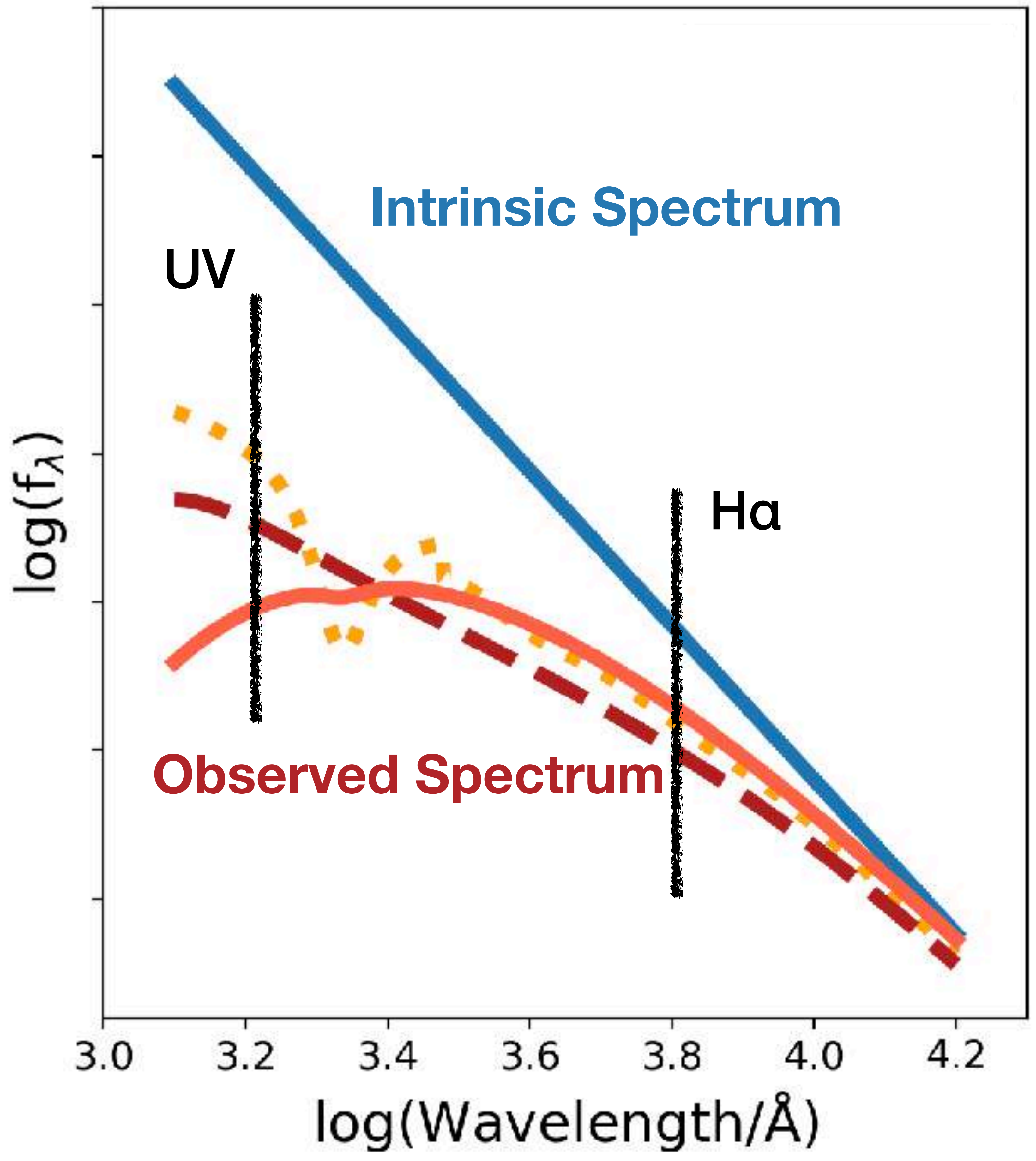
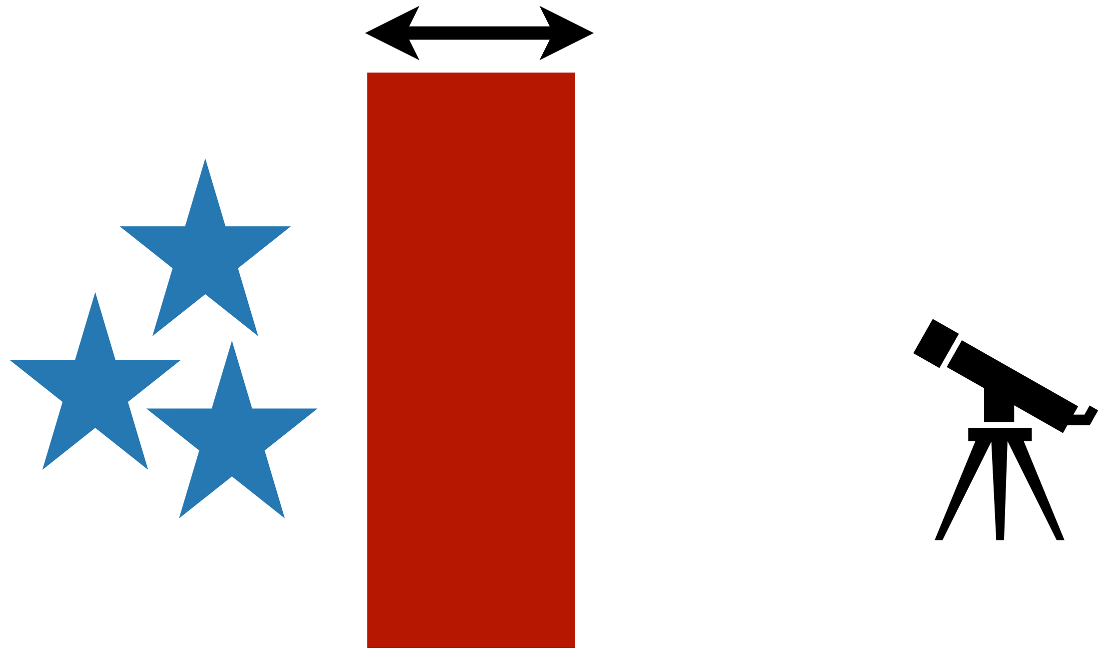


$$f_{\lambda,\,obs} = f_{\lambda,\,int} \times 10^{-0.4\,E(B-V)\,k_\lambda}$$

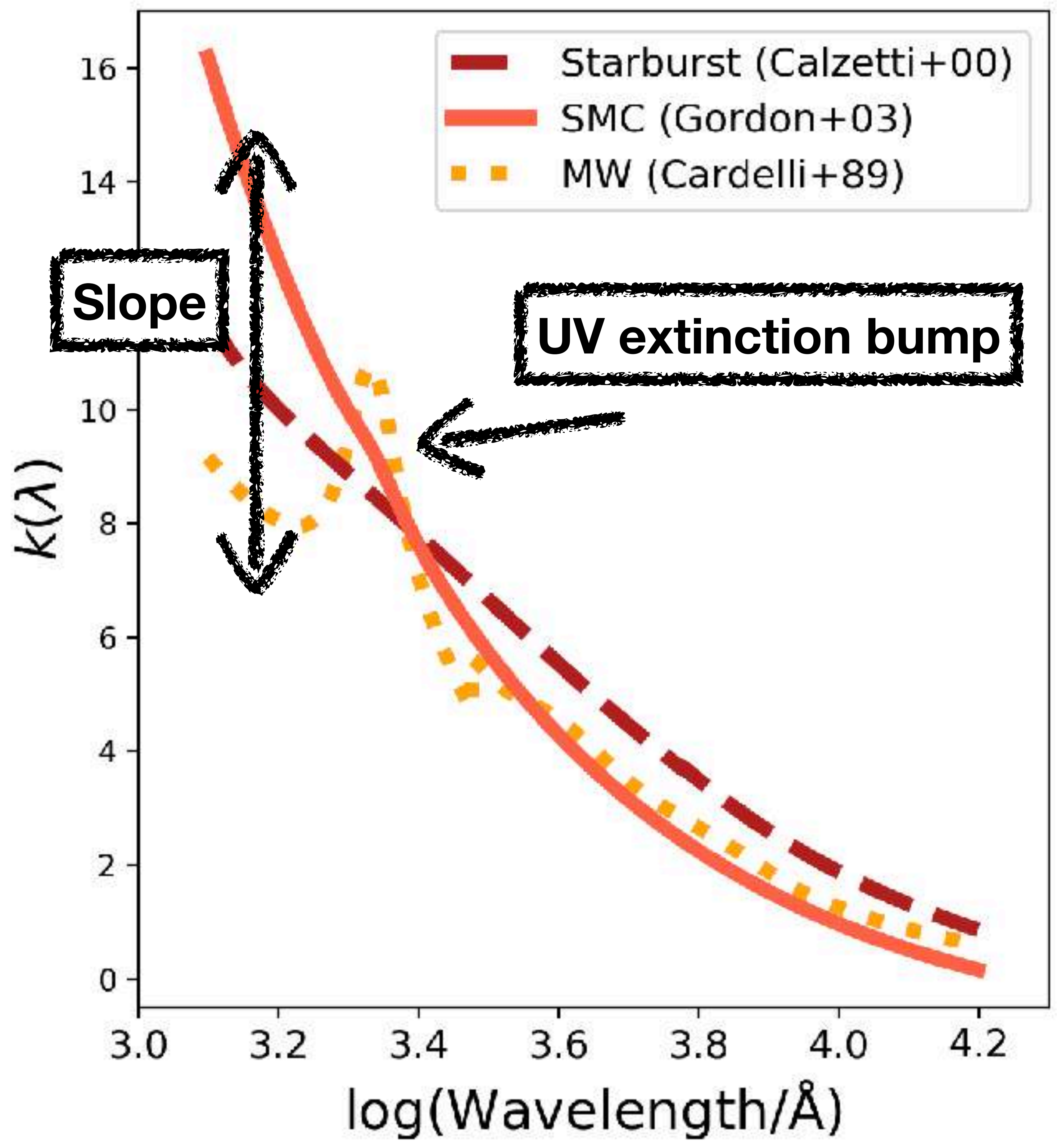
WHICH ATTENUATION CURVE WE SHOULD USE?

E(B-V) = 0.3



Foreground screen of dust

Attenuation/Extinction Curve



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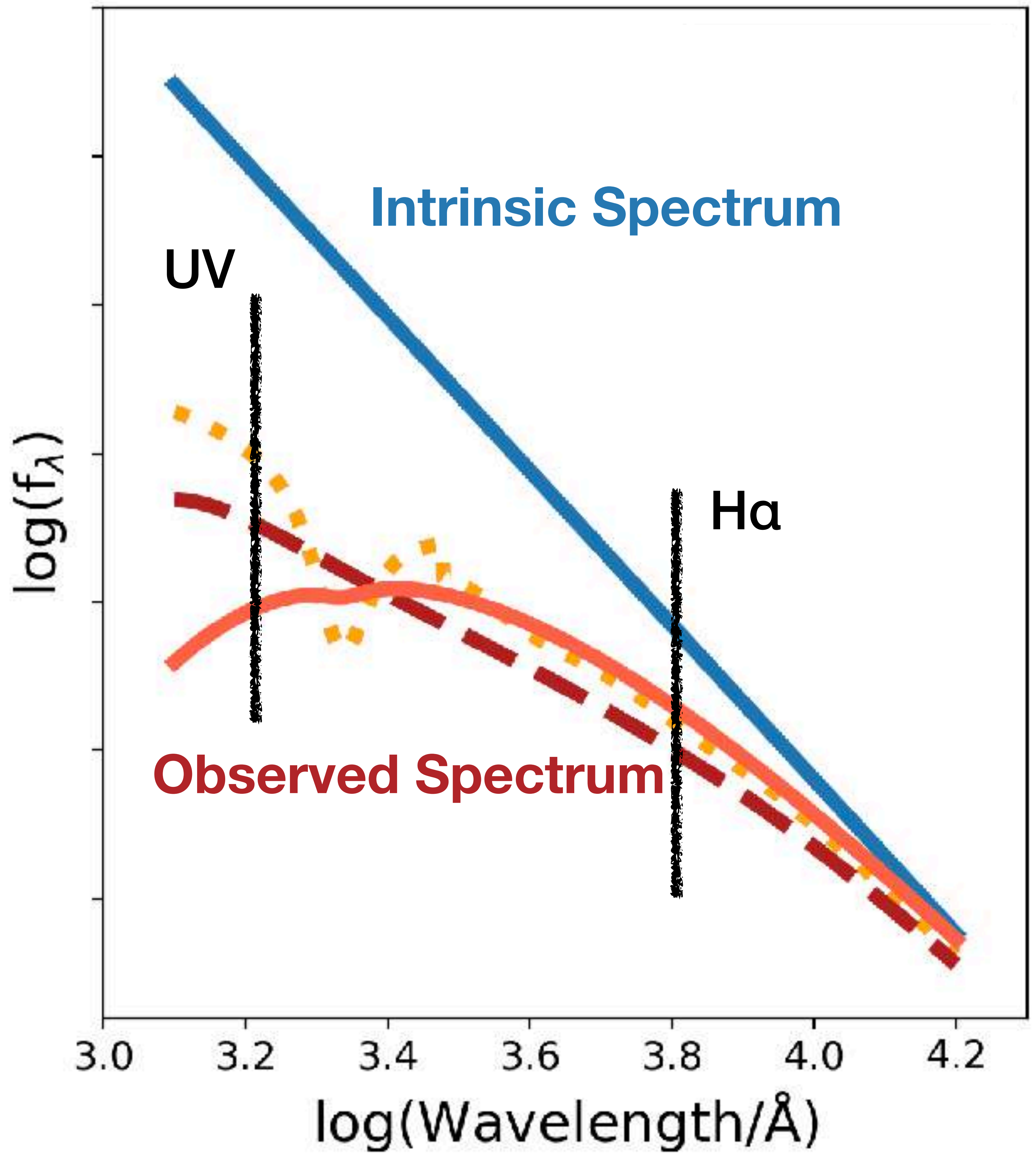
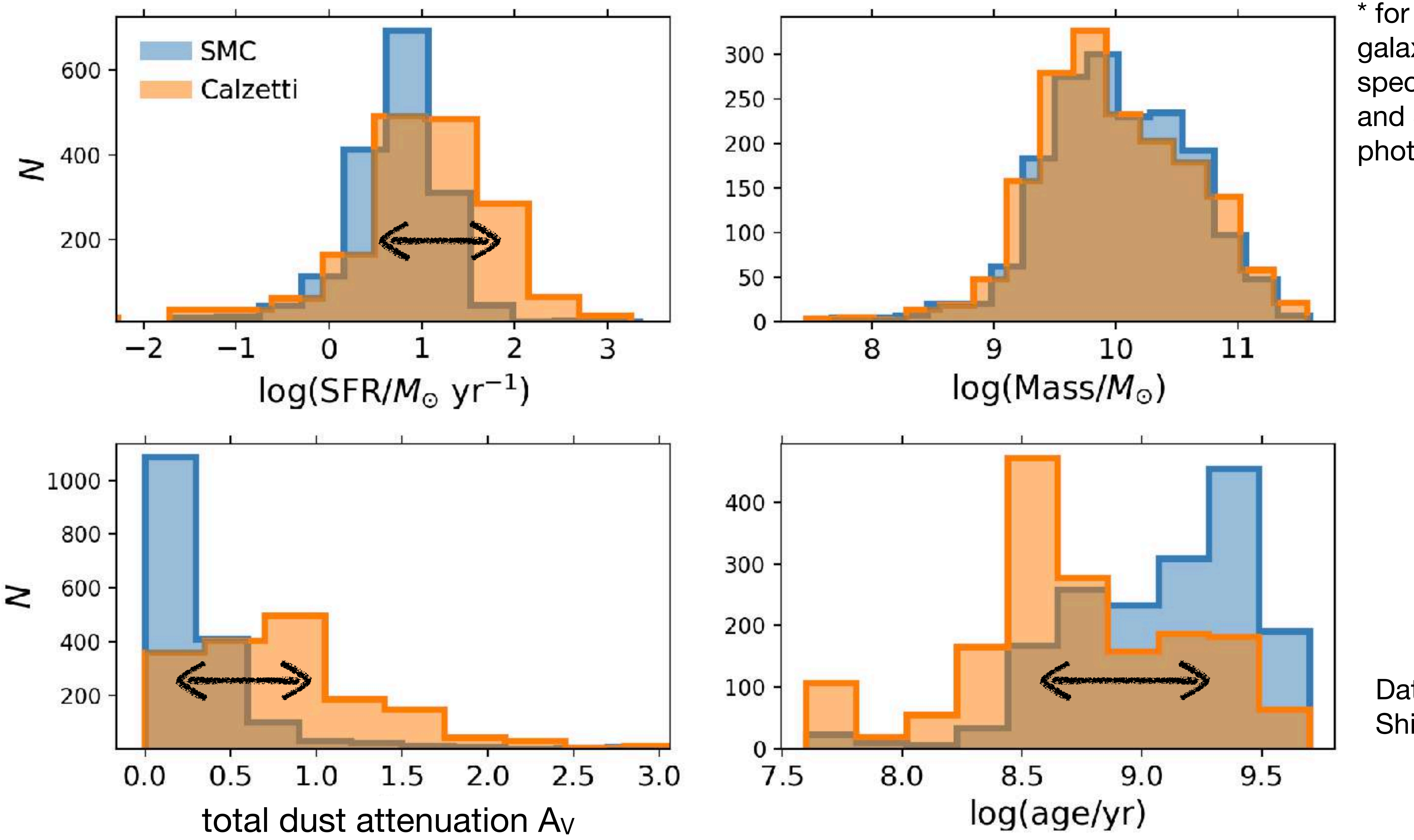


$$f_{\lambda,\,obs} = f_{\lambda,\,int} \times 10^{-0.4\,E(B-V)\,k_\lambda}$$

THE EFFECT OF DUST ATTENUATION CURVE ON SED FITTING*

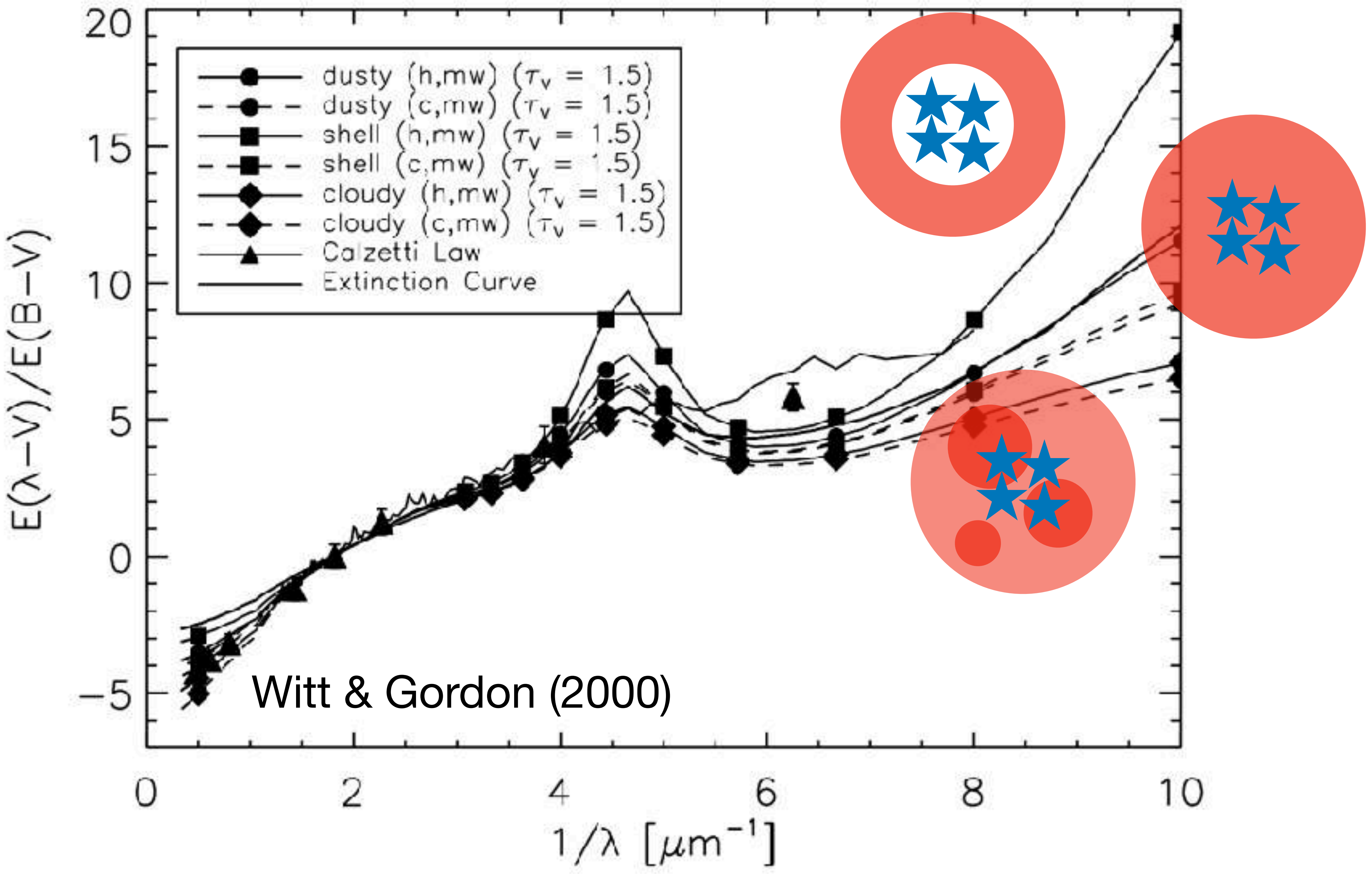


* for a sample of ~1500 galaxies at z~1-3 with spectroscopic redshifts and 3D-*HST* photometry

Data from Shivaei+2020

What makes the Attenuation Curves different?

Geometry of dust with respect to stars



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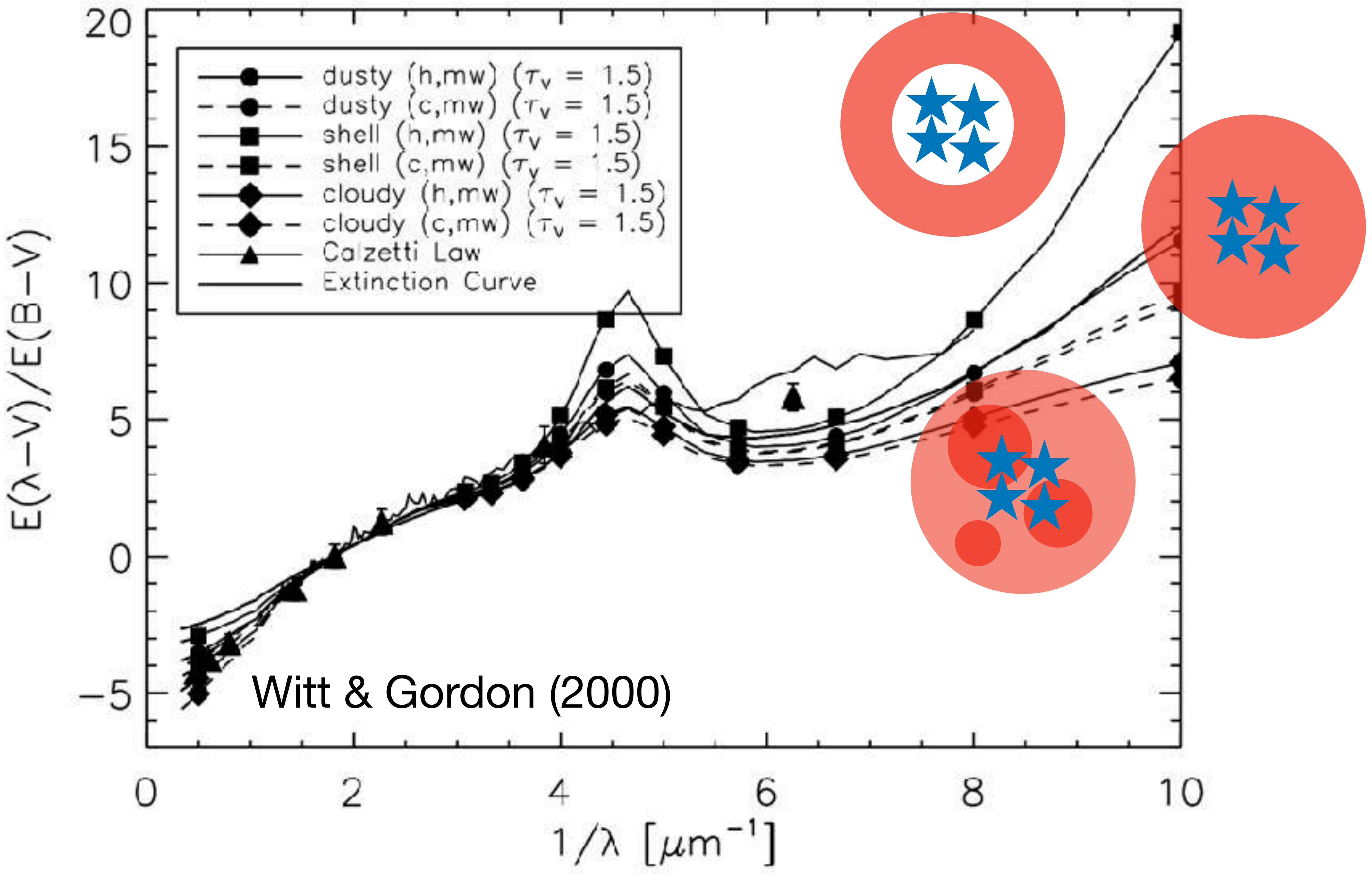
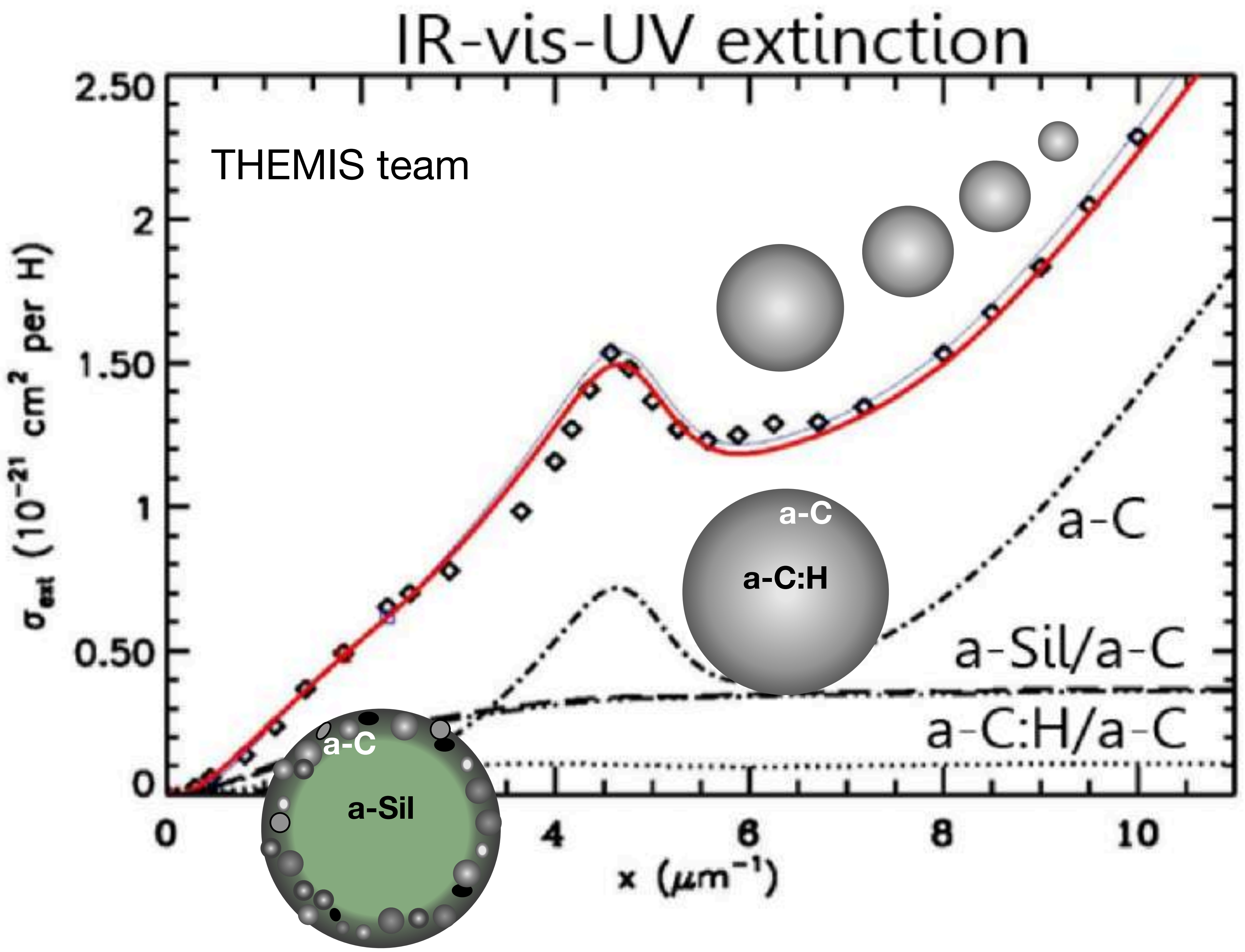


Dust grain composition and size distribution

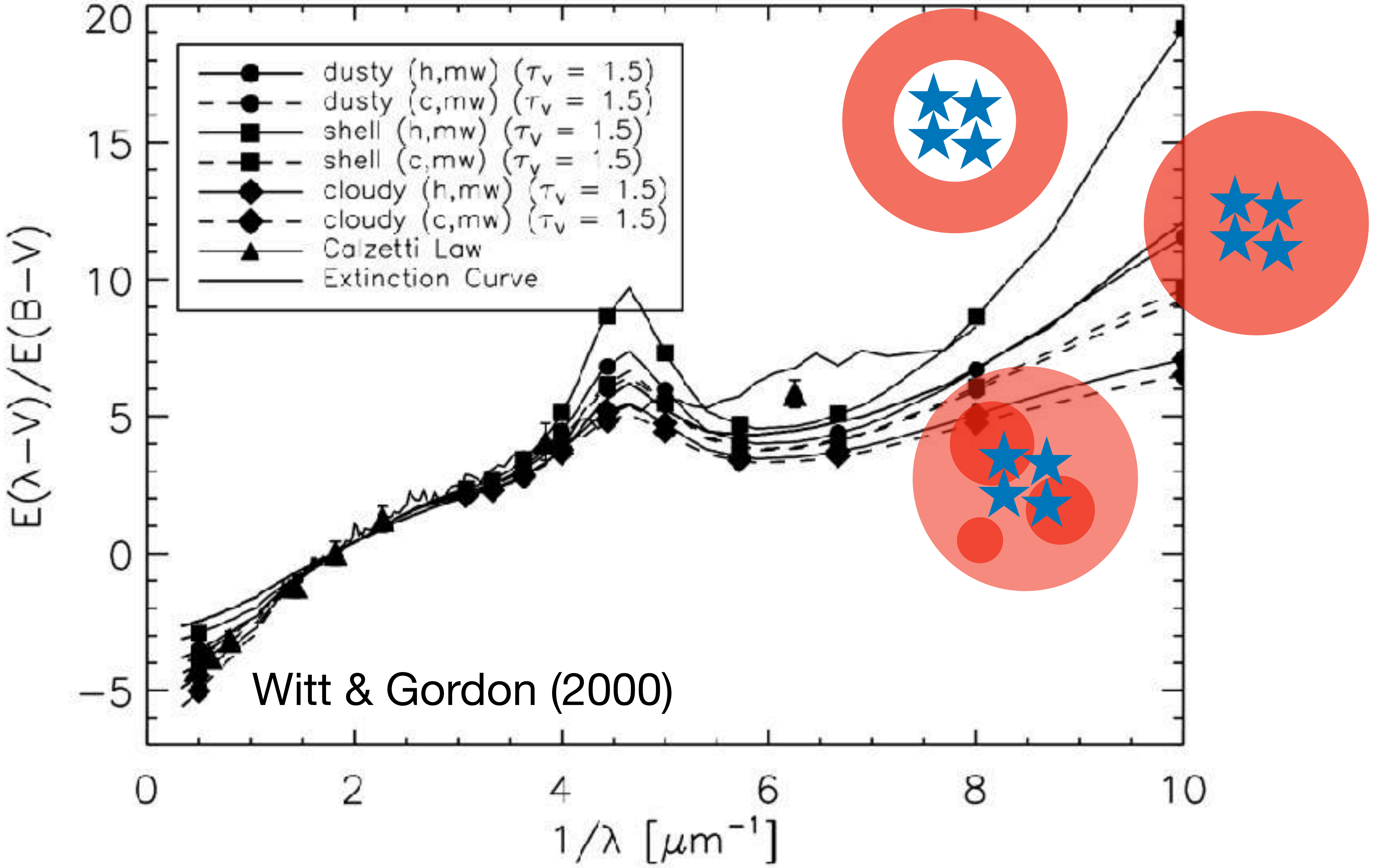


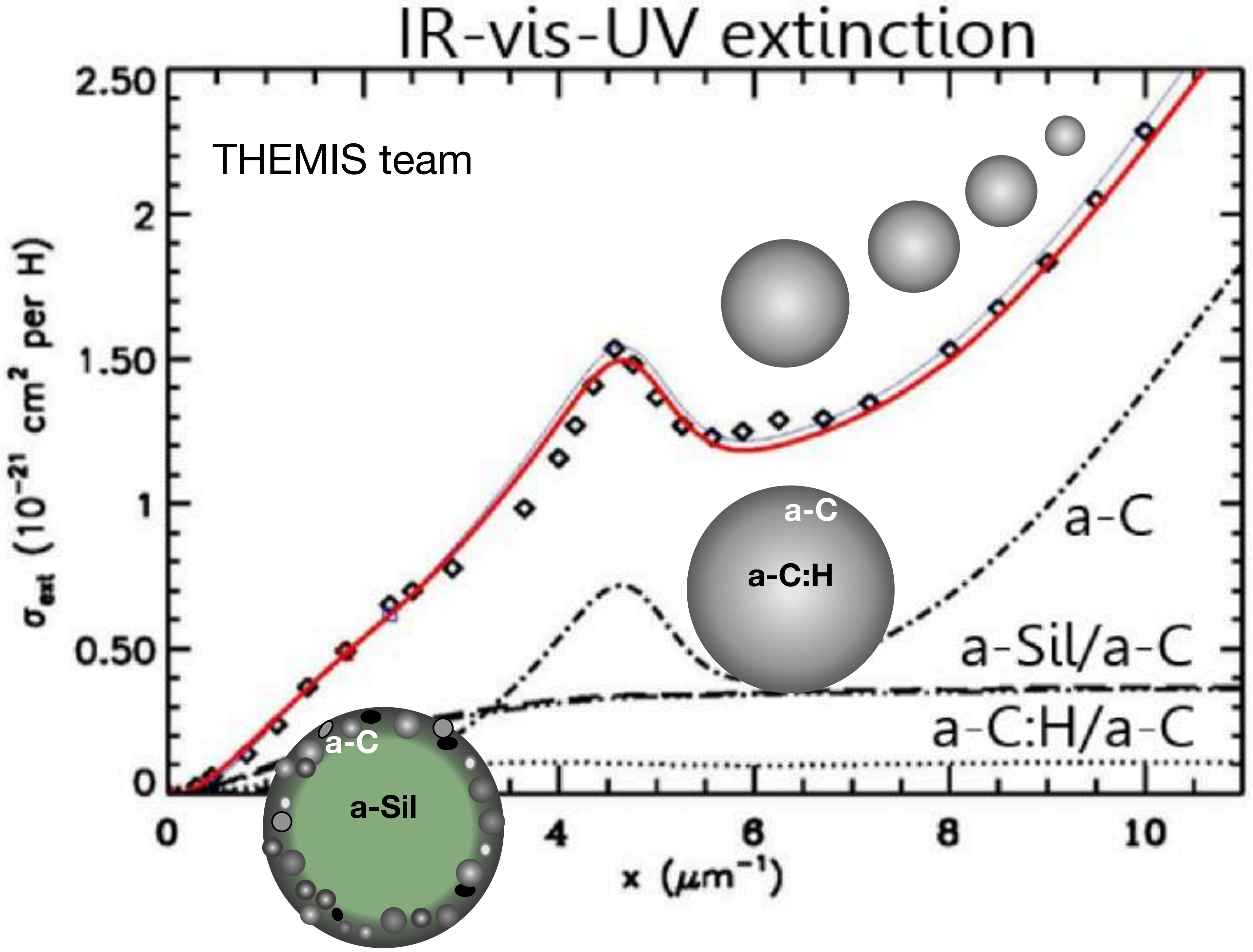
see e.g., Weingartner & Draine (2001)

THE TWO EFFECTS ARE ENTANGLED

Geometry of dust with respect to stars

Dust grain composition and size distribution



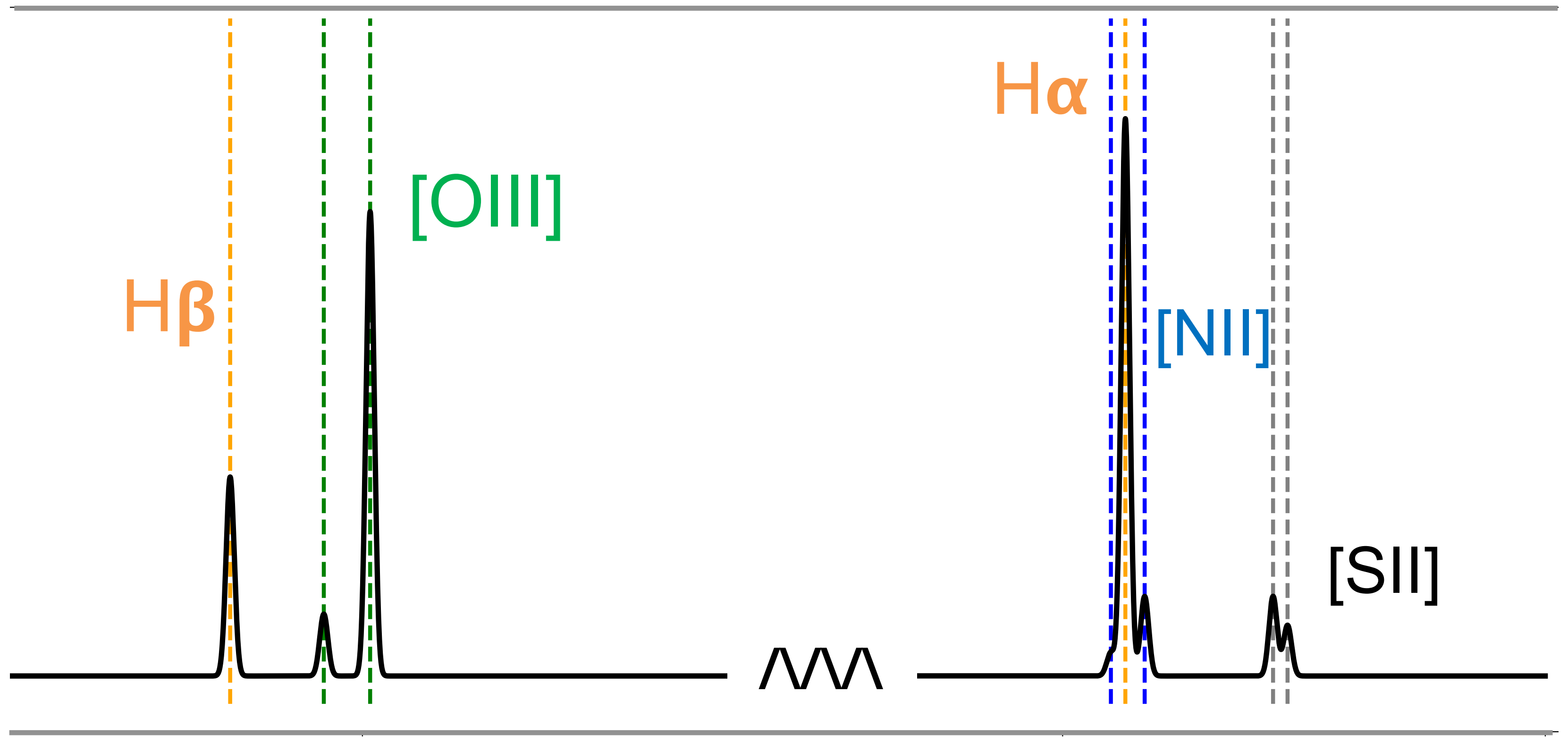


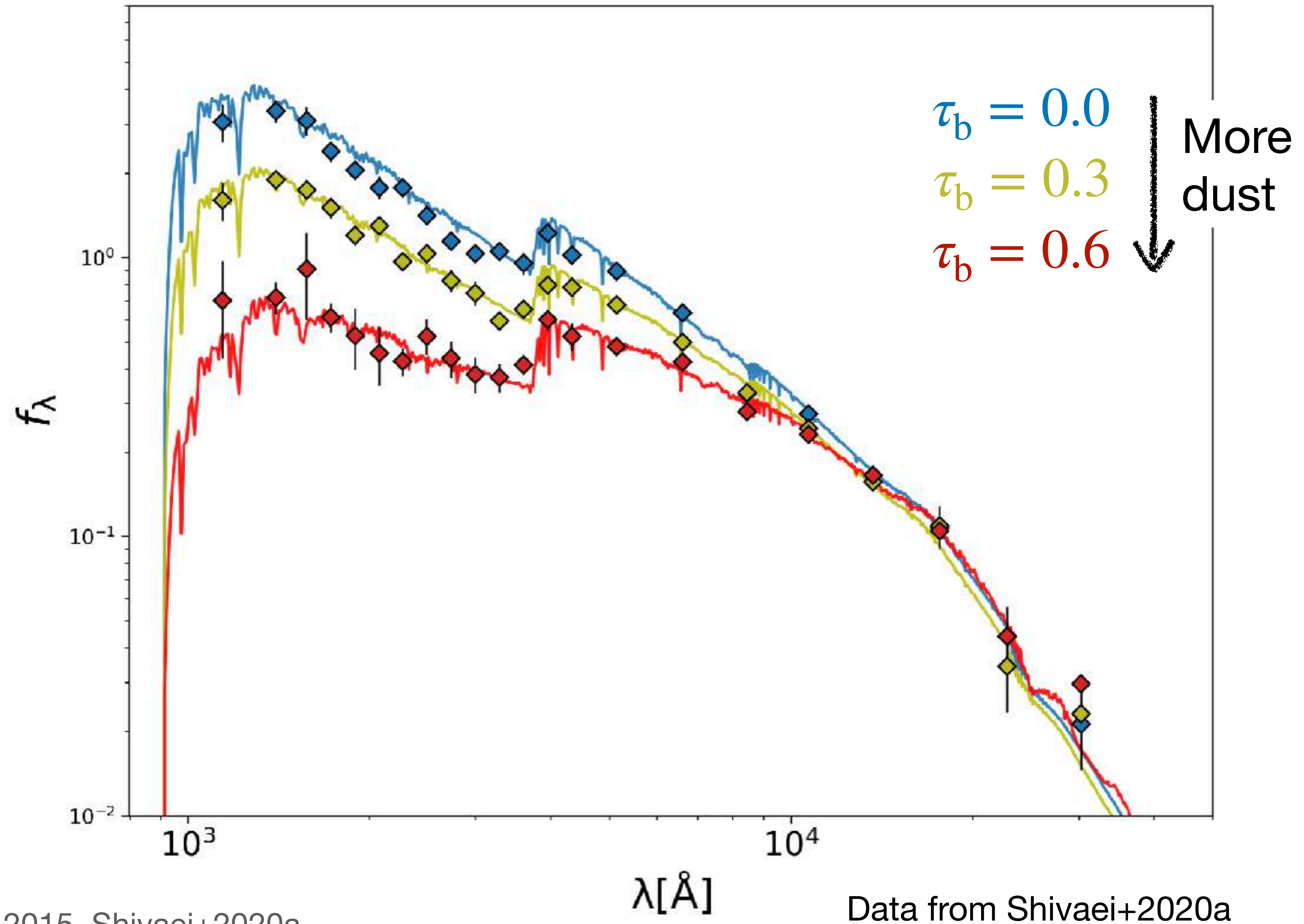
see e.g., Weingartner & Draine (2001)

DERIVING THE ATTENUATION CURVE (METHODOLOGY OF CALZETTI ET AL. 2000)

Young star-forming galaxies have the same intrinsic UV SEDs; sort to less and more heavily obscured bins according to

$$\tau_b \equiv \ln\left(\frac{H\alpha/H\beta}{2.86}\right)$$

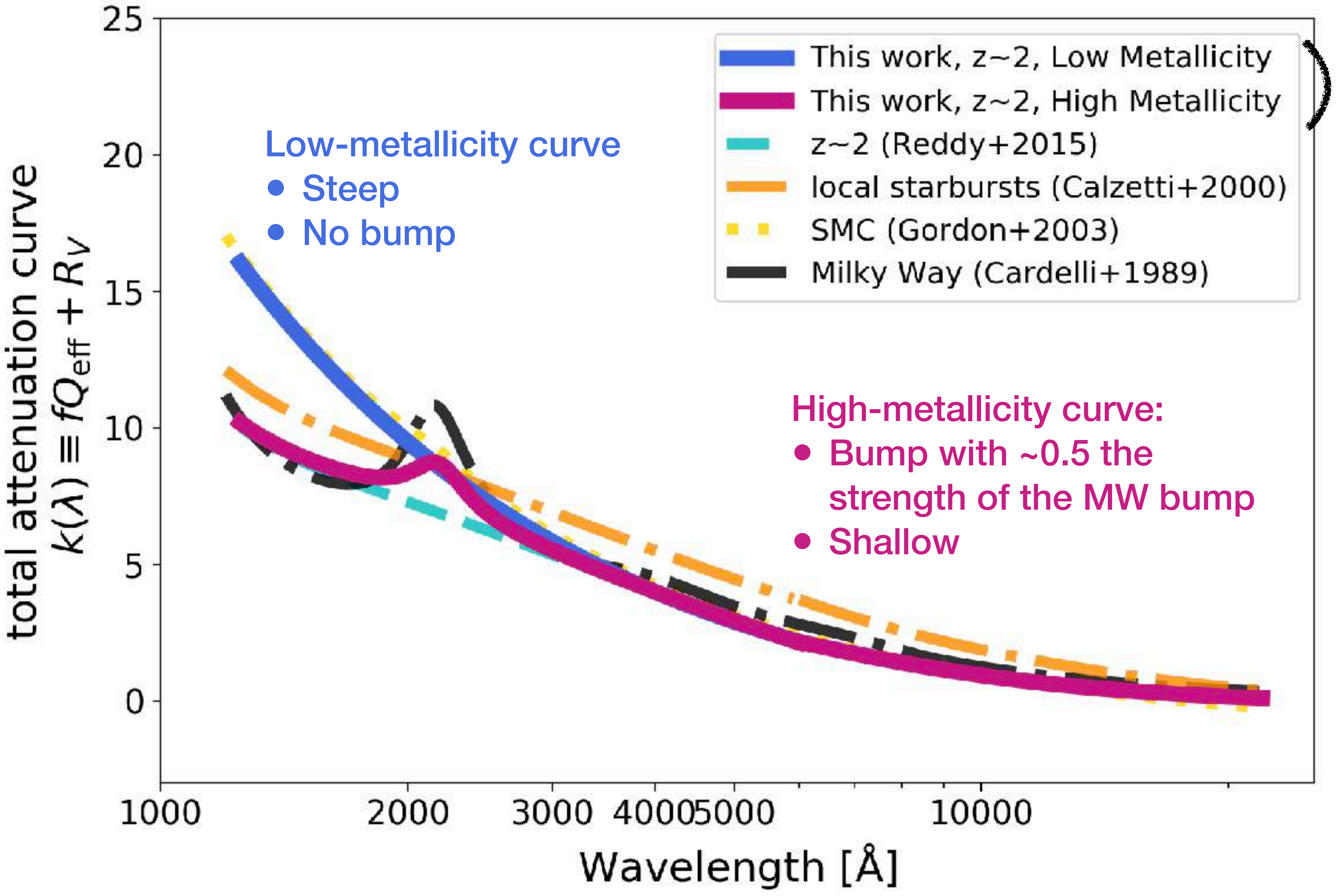




Data from Shivaei+2020a

See also: Calzetti+2000, Battisti+2016, 2017a, 2017b, Reddy+2015, Shivaei+2020a

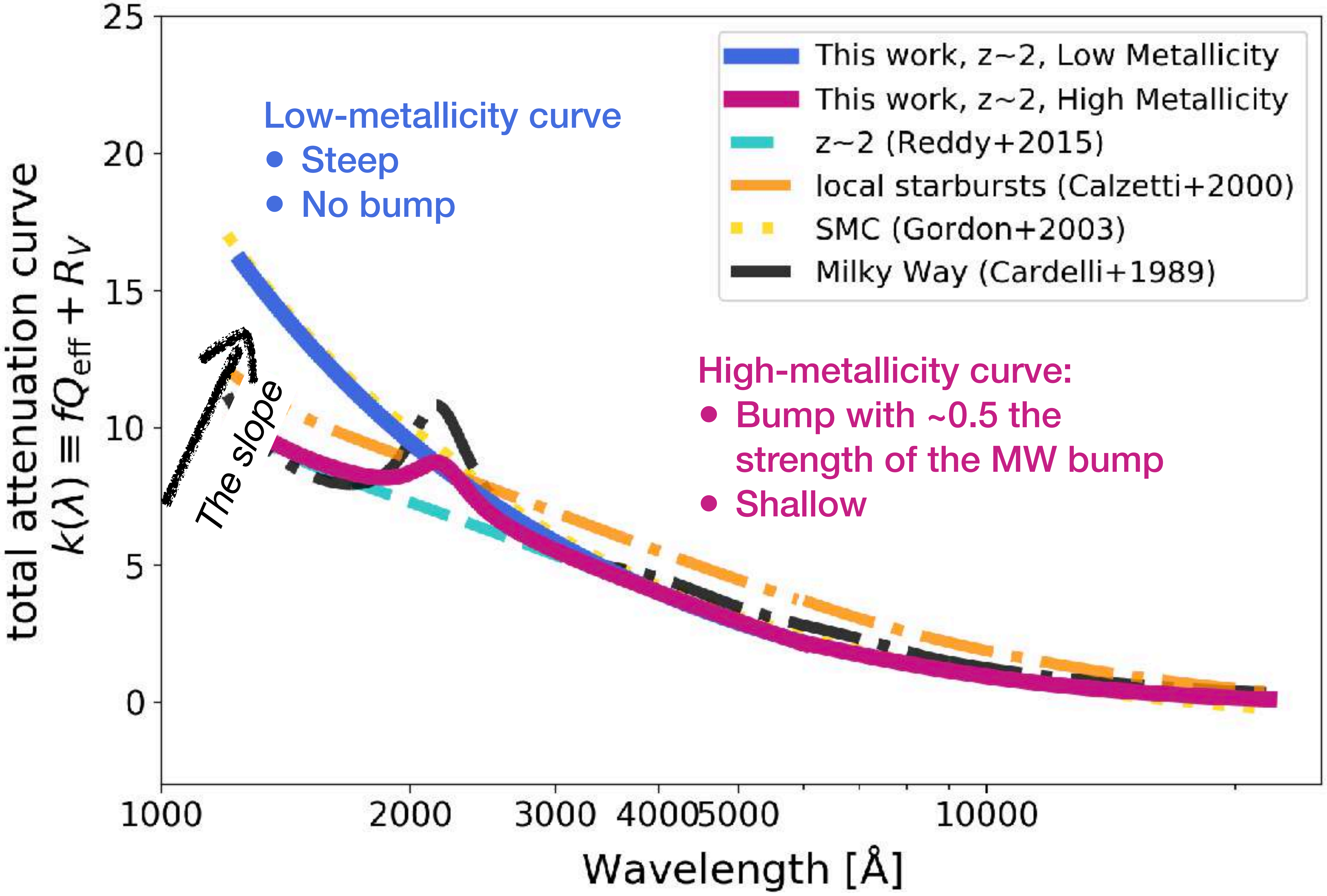
ATTENUATION CURVE AT z~2 AS A FUNCTION OF METALLICITY



Divided at
12+log(O/H)=8.5
$Z \sim 0.6\ Z_\odot$
$\log(M_{\rm stellar}/M_\odot) \sim 10.4$

Shivaei et al. (2020a)

Different dust Grains Properties and/or Age-dependent attenuation

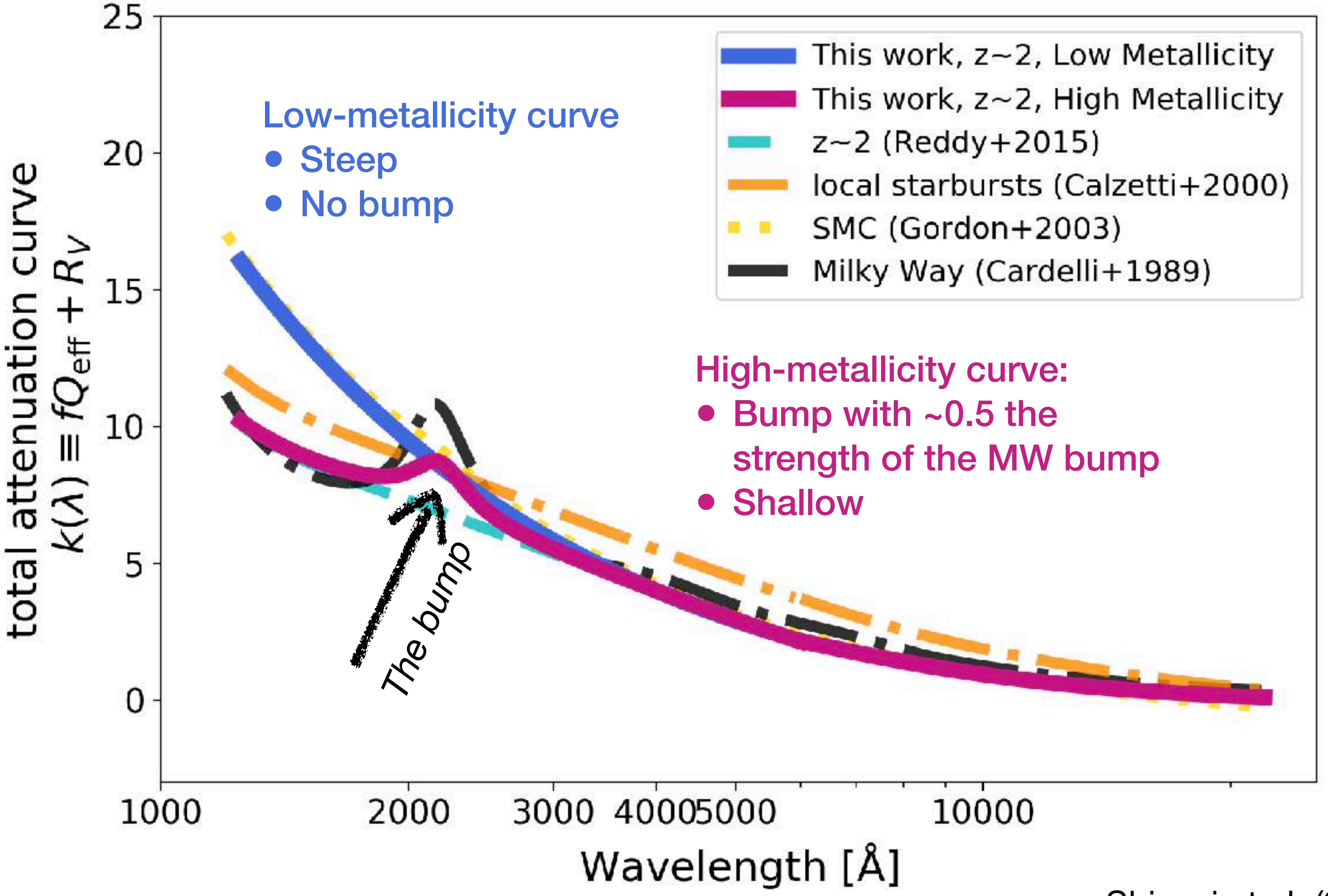


Steep UV rise at low metallicities

- **Grain size**: Small grains (shattering, lower molecular fraction)
- Grain composition: Lower fraction of small carbonaceous to small silicate grains
- Age-dependent attenuation curve

Shivaei et al. (2020a)

Origin of the UV bump feature

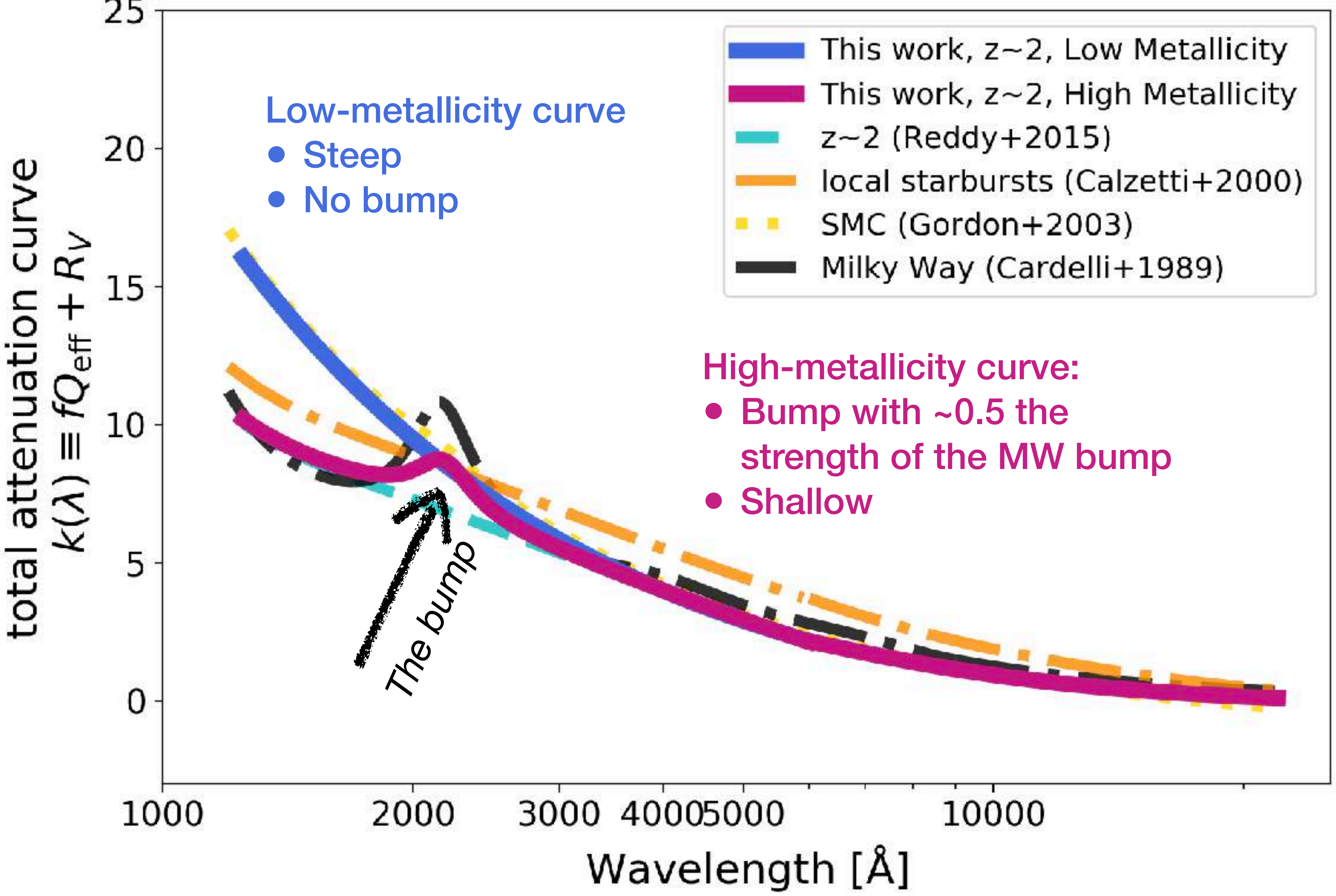


Shivaei et al. (2020a)

- Grains that produce the bump are not present in low-metallicity environment (destroyed by hard radiation? Not produced?)

Origin of the UV bump feature

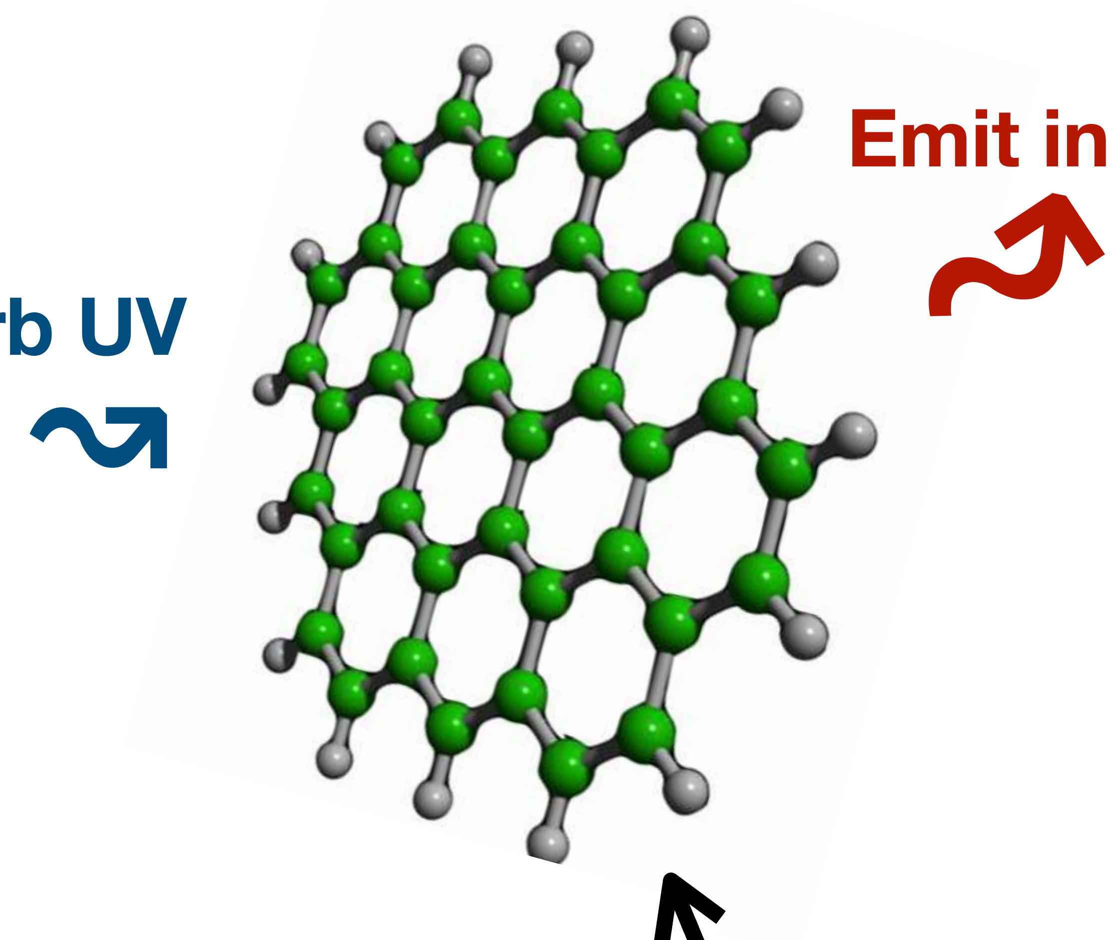
Shivaei et al. (2020a)

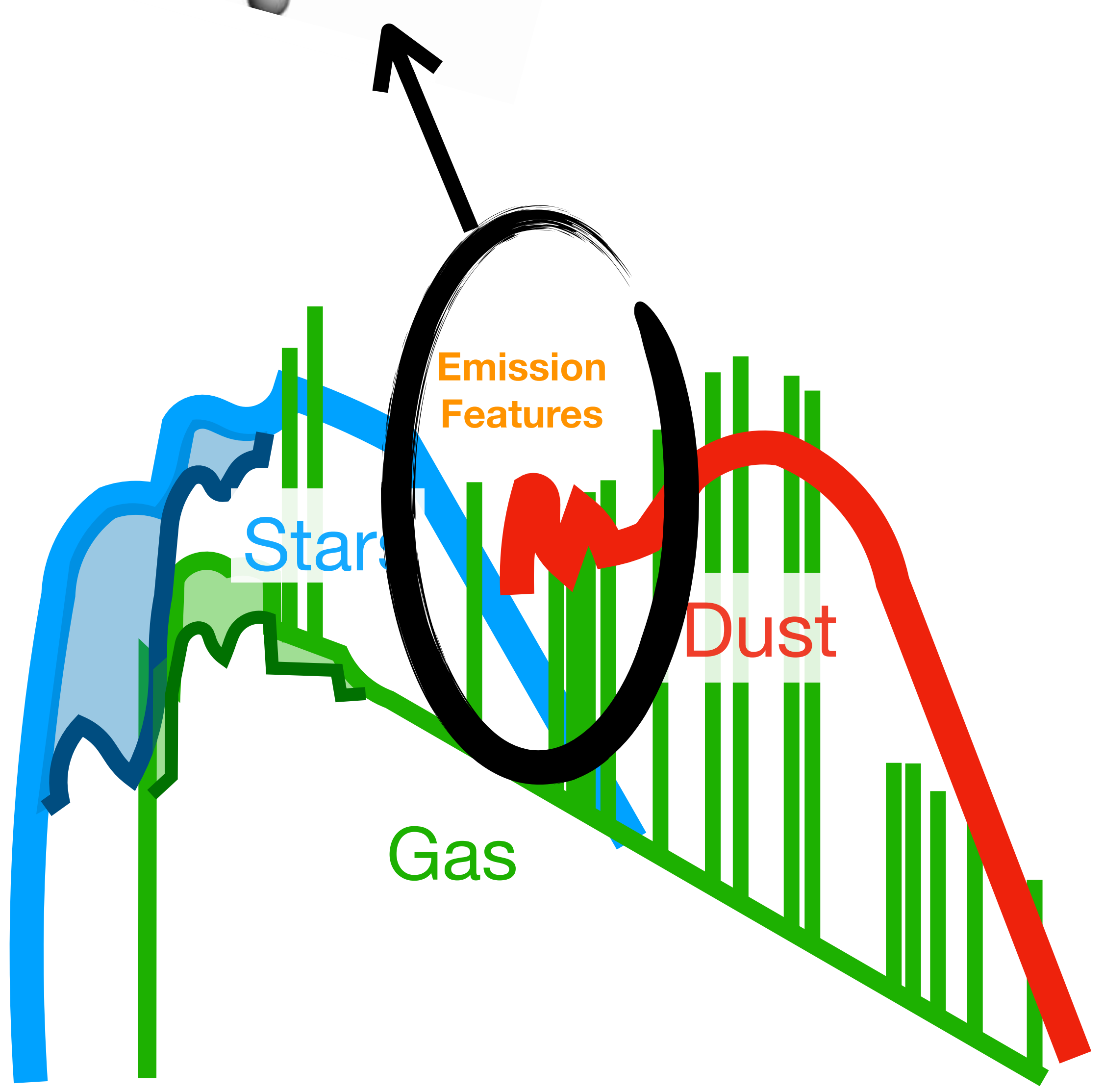


Low-metallicity curve
- Steep
- No bump

High-metallicity curve:
- Bump with ~0.5 the strength of the MW bump
- Shallow

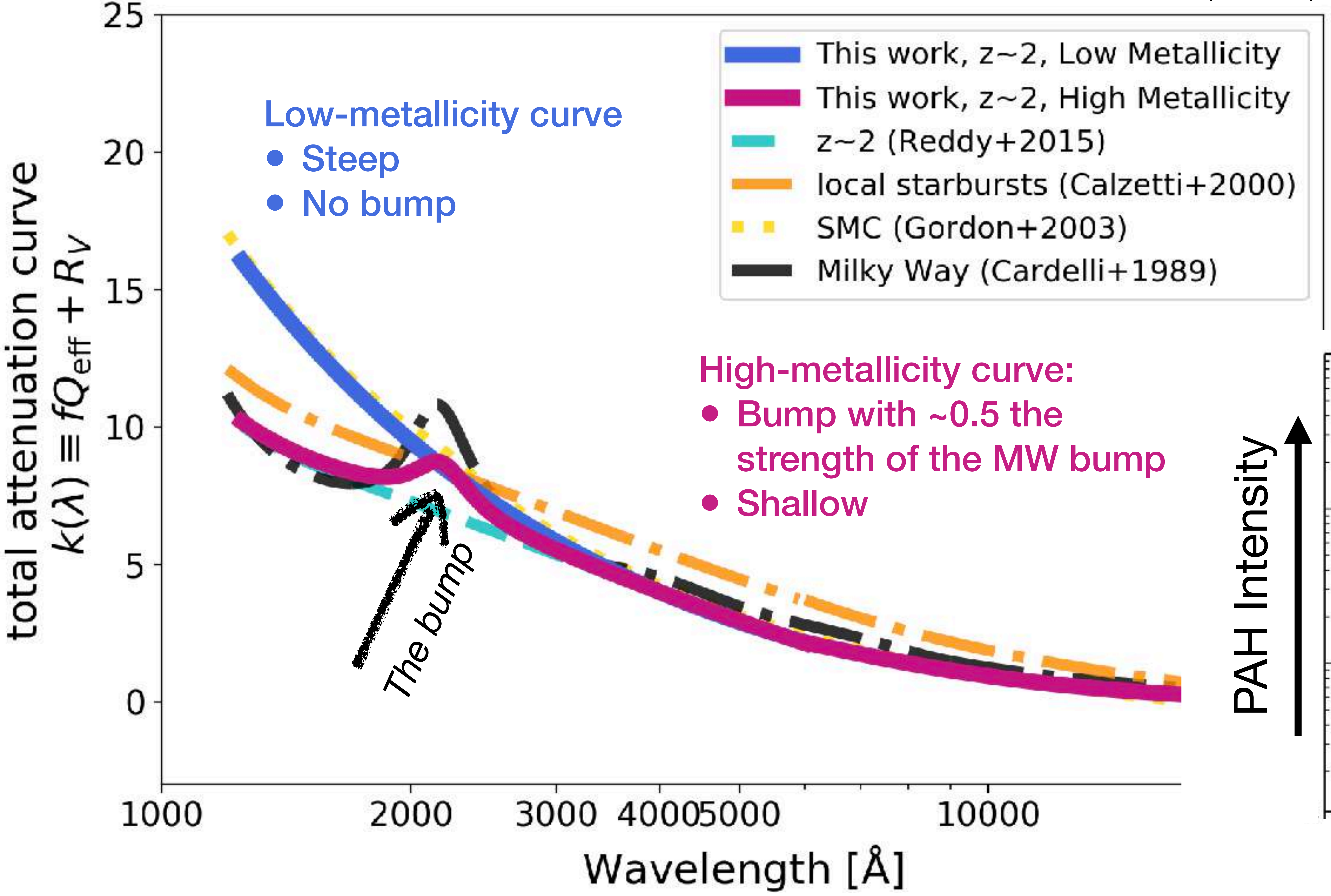
PAH: Polycyclic Aromatic Hydrocarbon



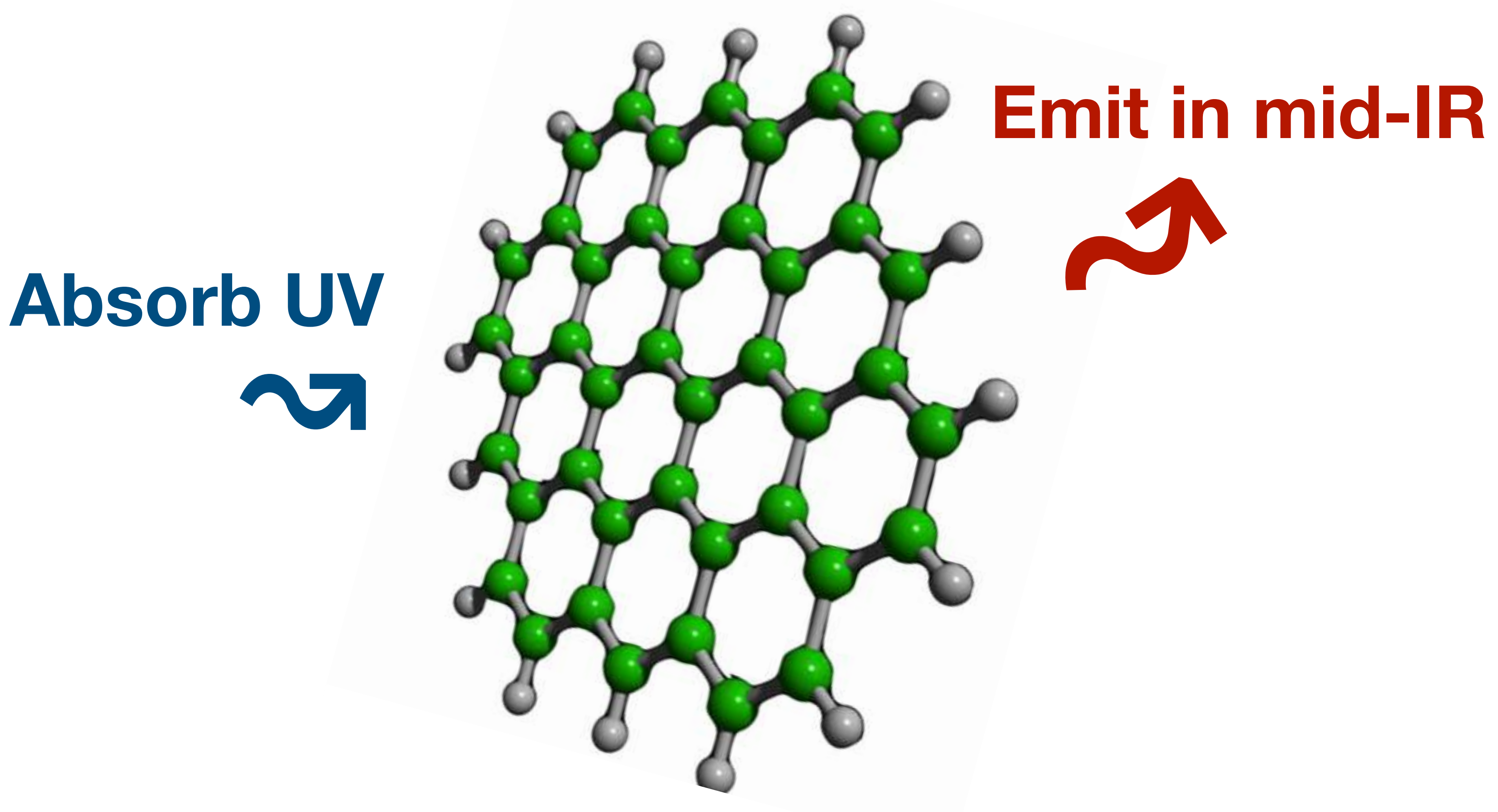


PAHs as the origin of the Bump?

Shivaei et al. (2020a)

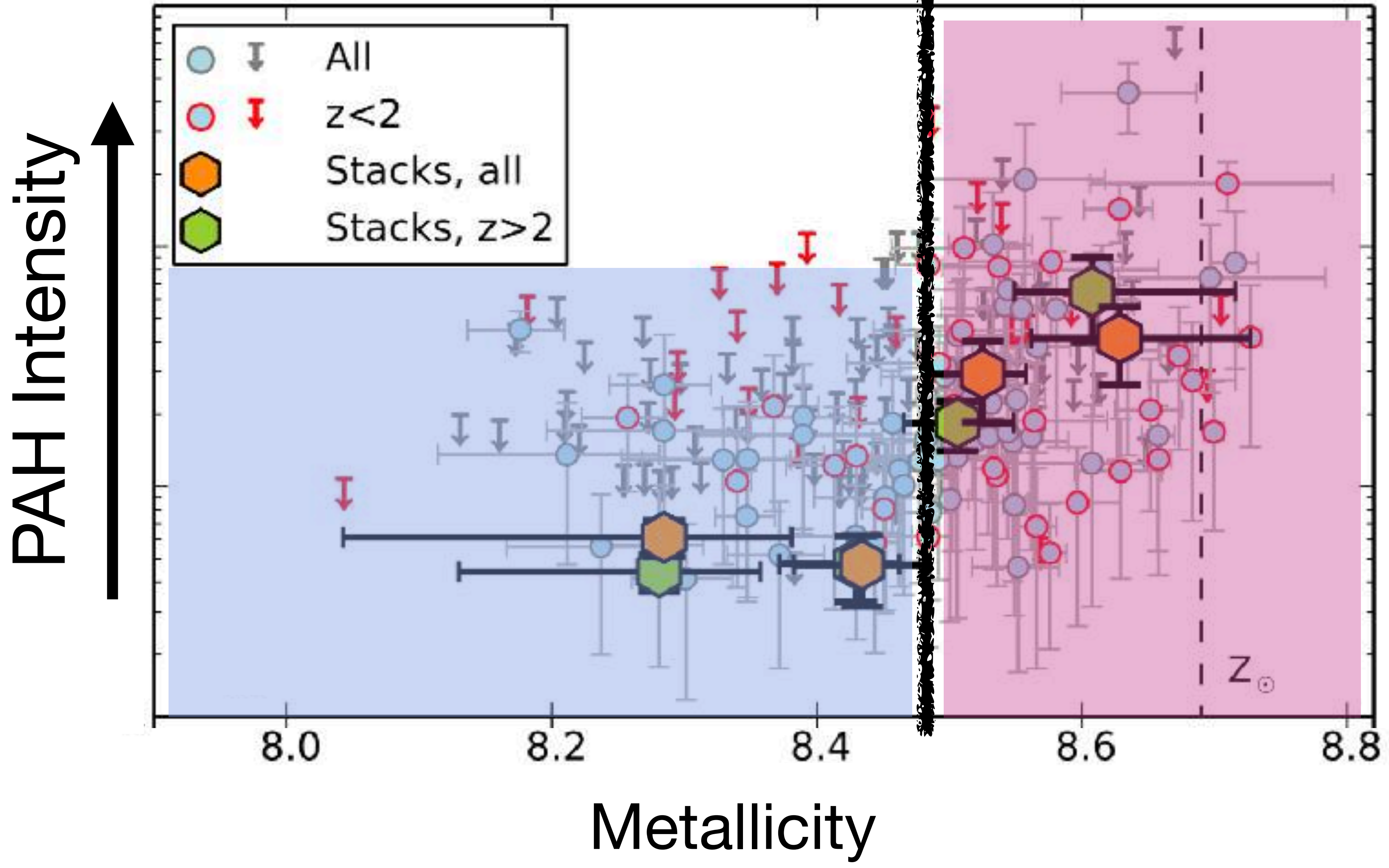


PAH: Polycyclic Aromatic Hydrocarbon



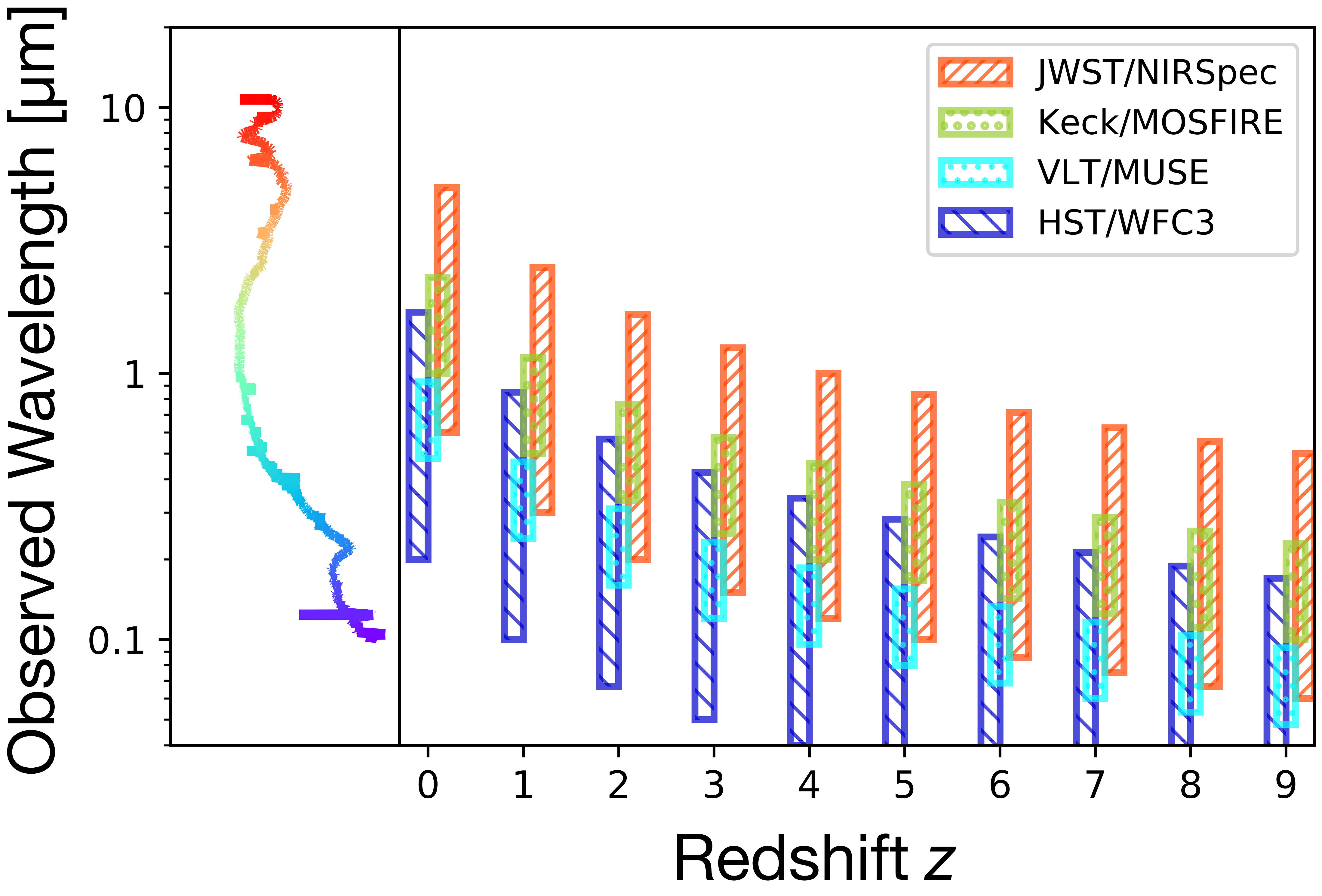
Shivaei et al. (2017)

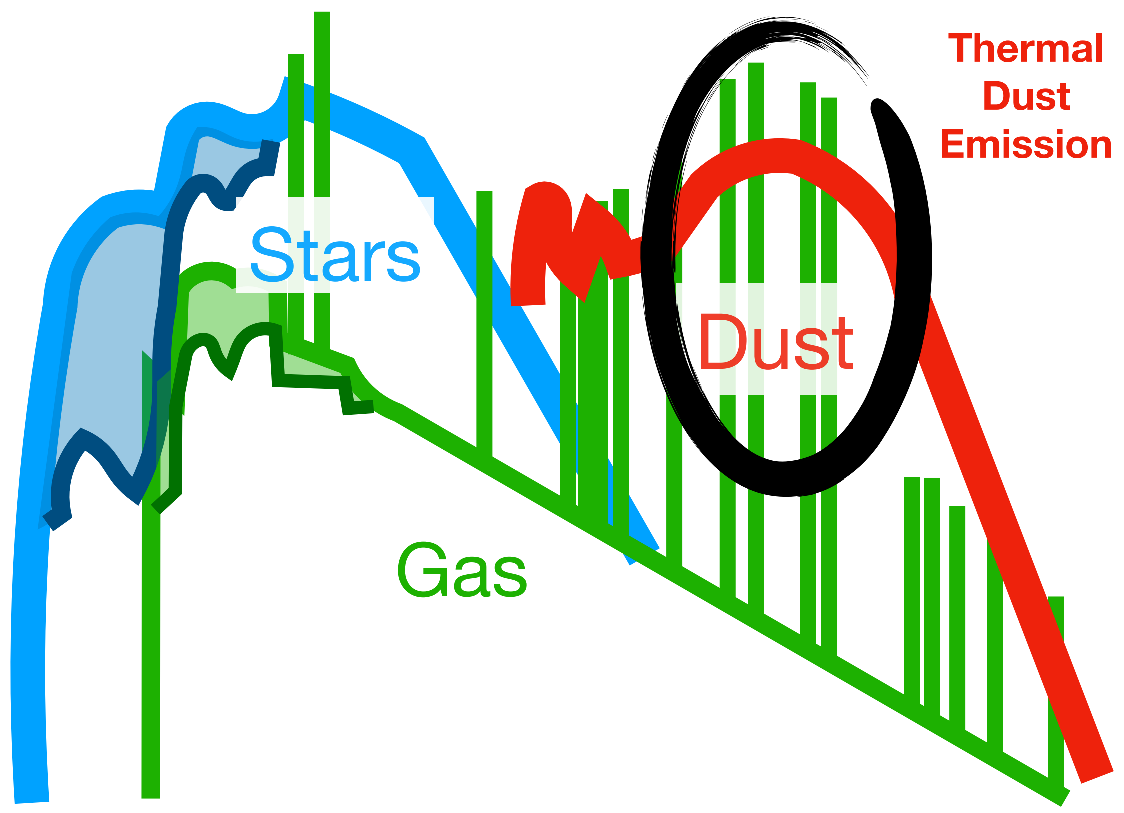
12+log(O/H)~8.5

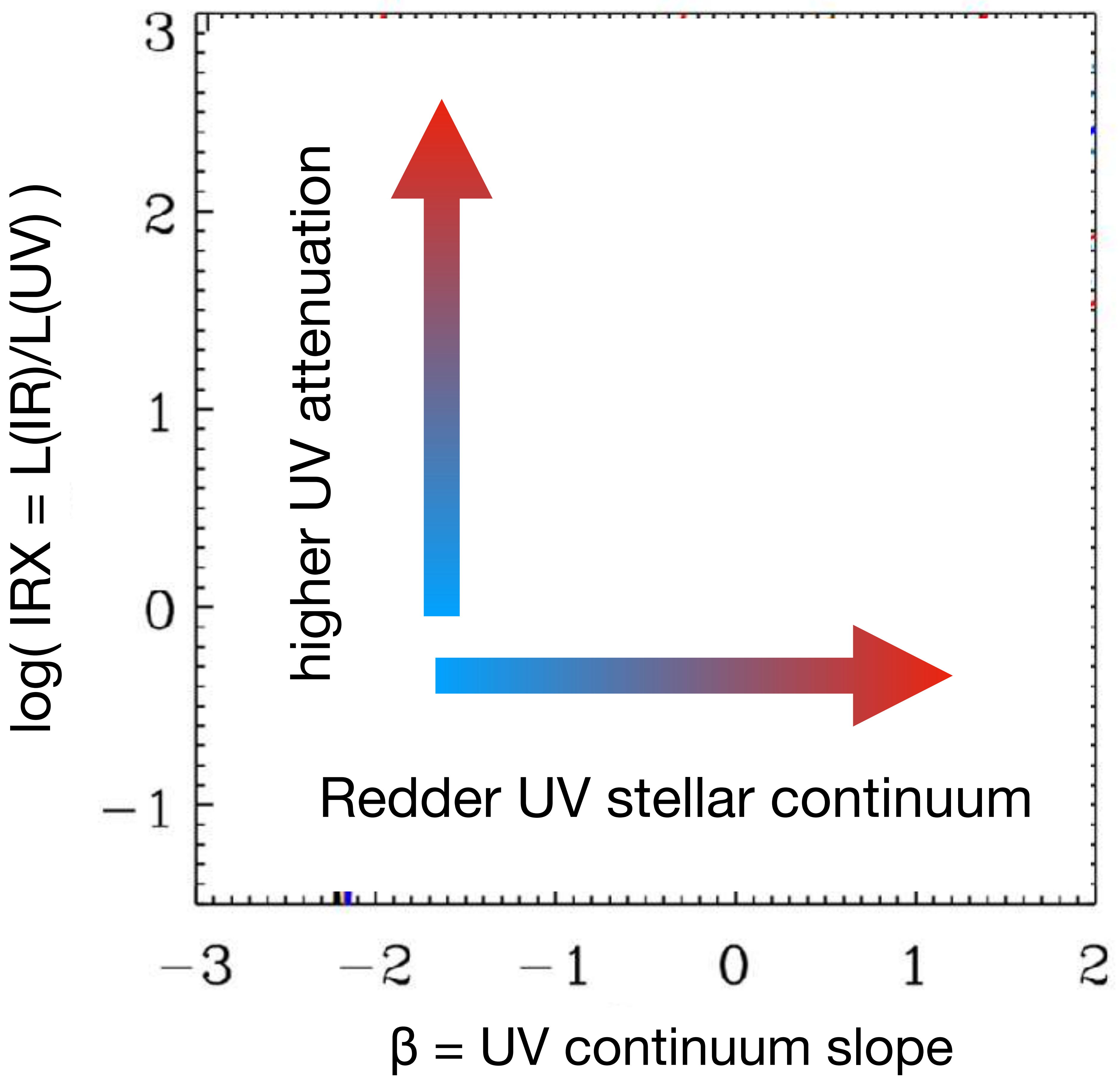


IRX-β DUST ATTENUATION RELATION

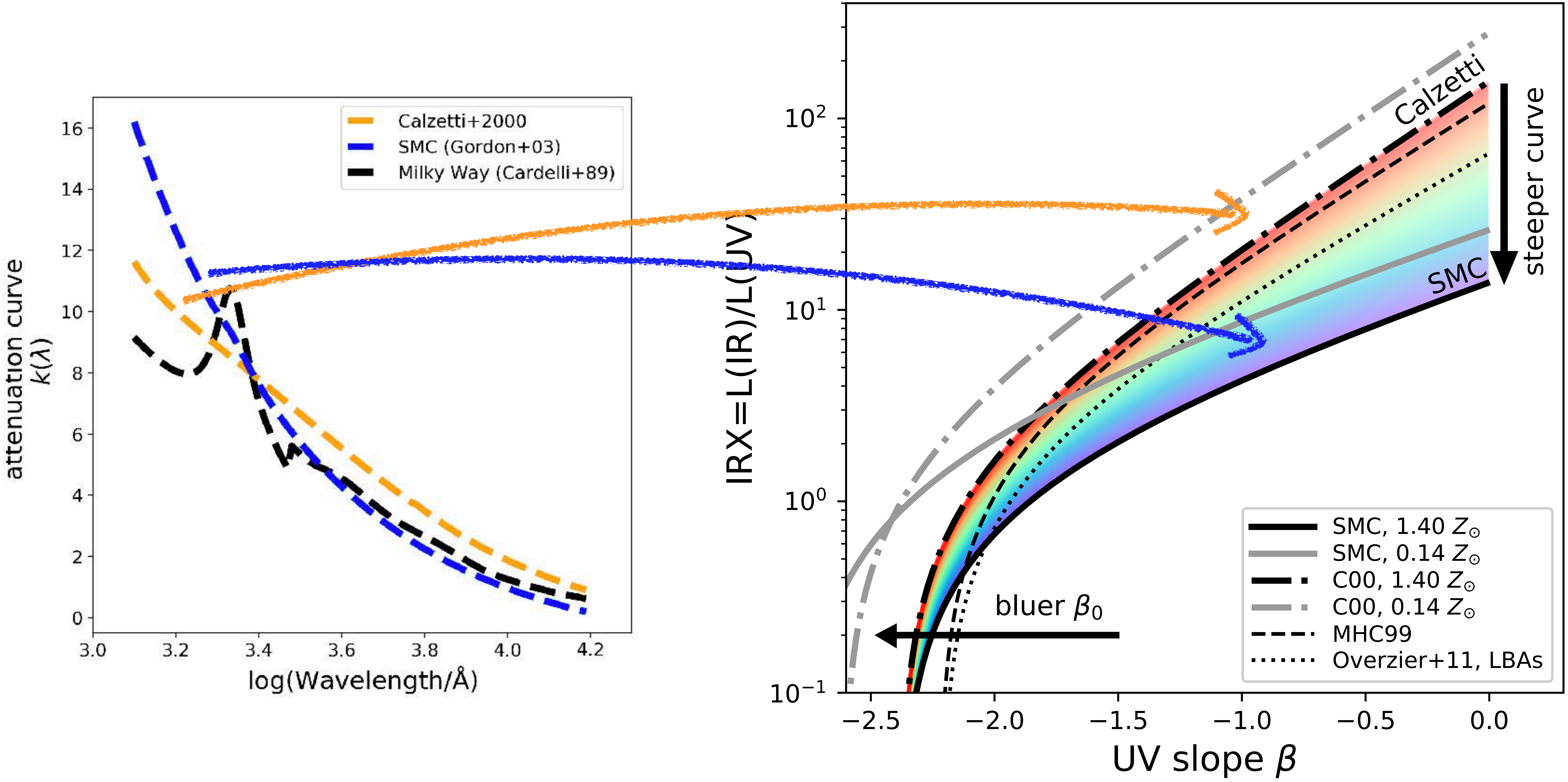
At high redshifts, only UV is accessible for large samples of typical galaxies







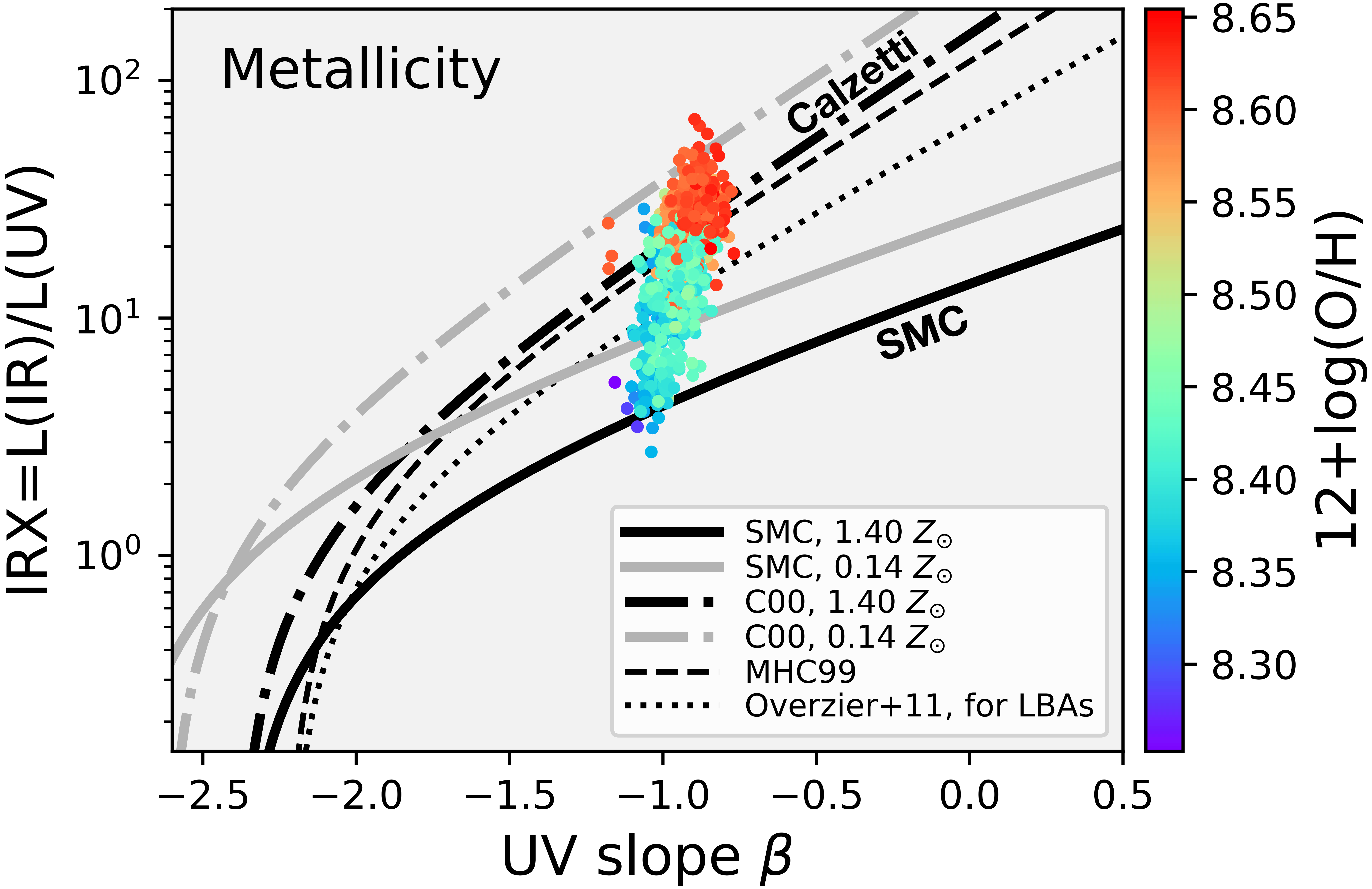
WHAT DETERMINES THE LOCUS OF GALAXIES IN IRX-β?



At a given β, IRX strongly correlations with metallicity

Metallicity is an important factor in the scatter of IRX-β
(the correlation with mass is much weaker)

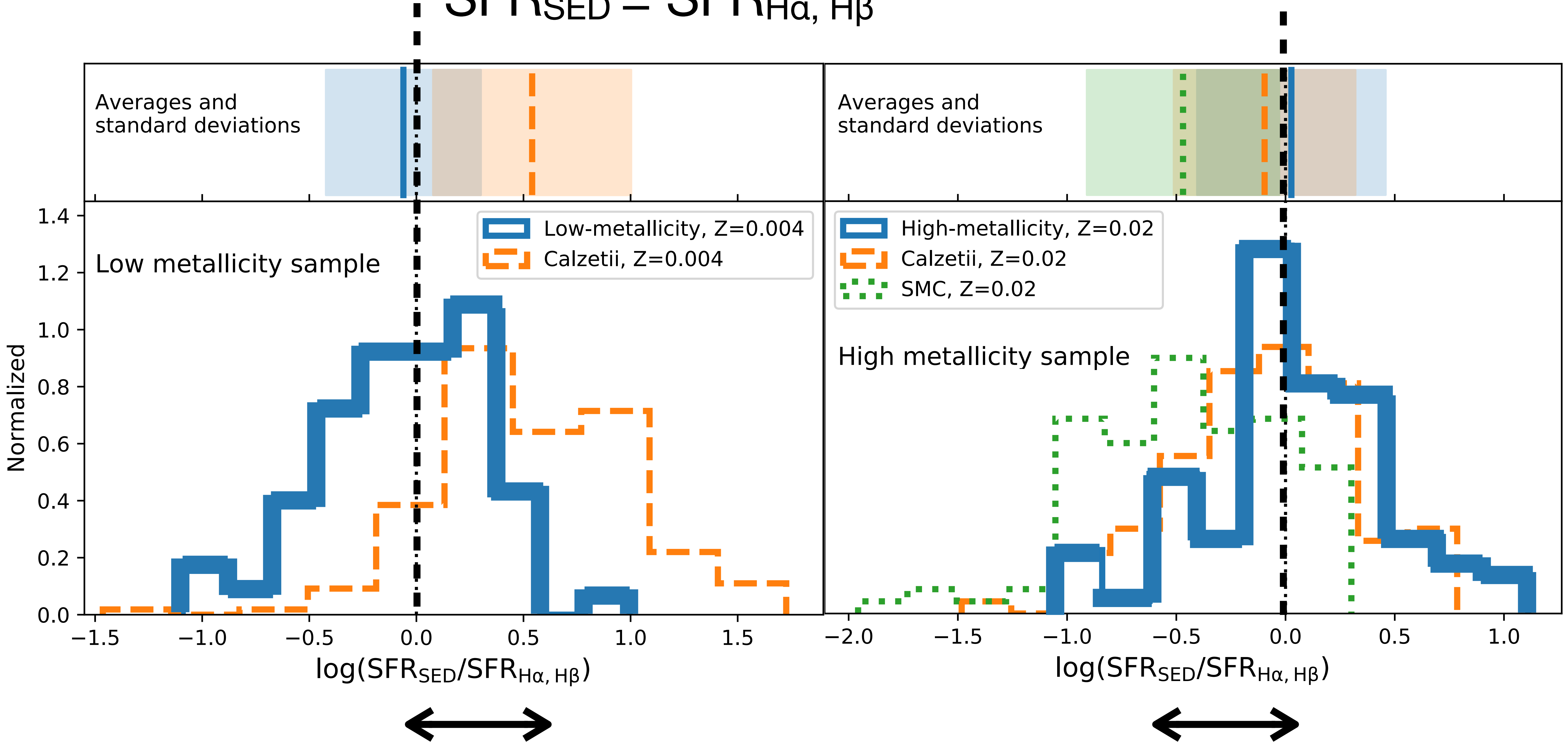
Shivaei et al. (2020b)



UV SFRs corrected using metallicity-dependent dust curves are accurate

Tested against Hα, Hβ star-formation rates:

$SFR_{SED} = SFR_{H\alpha, H\beta}$



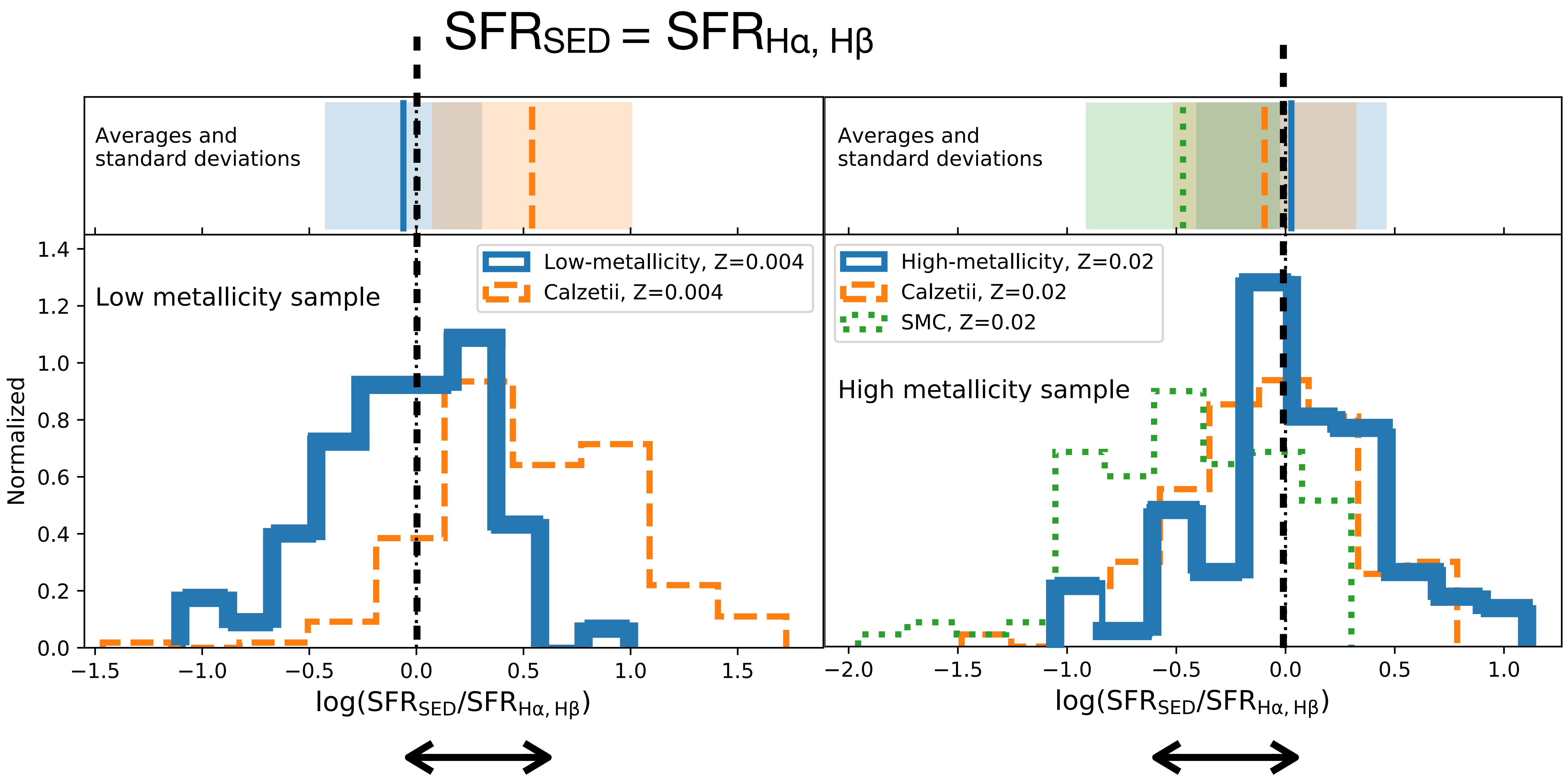
Using a shallow curve for low-metallicity or a steep curve for high-metallicity

affects SFR estimates by x3

Shivaei et al. (2020a)

UV SFRs corrected using metallicity-dependent dust curves are accurate

Tested against Hα, Hβ star-formation rates:

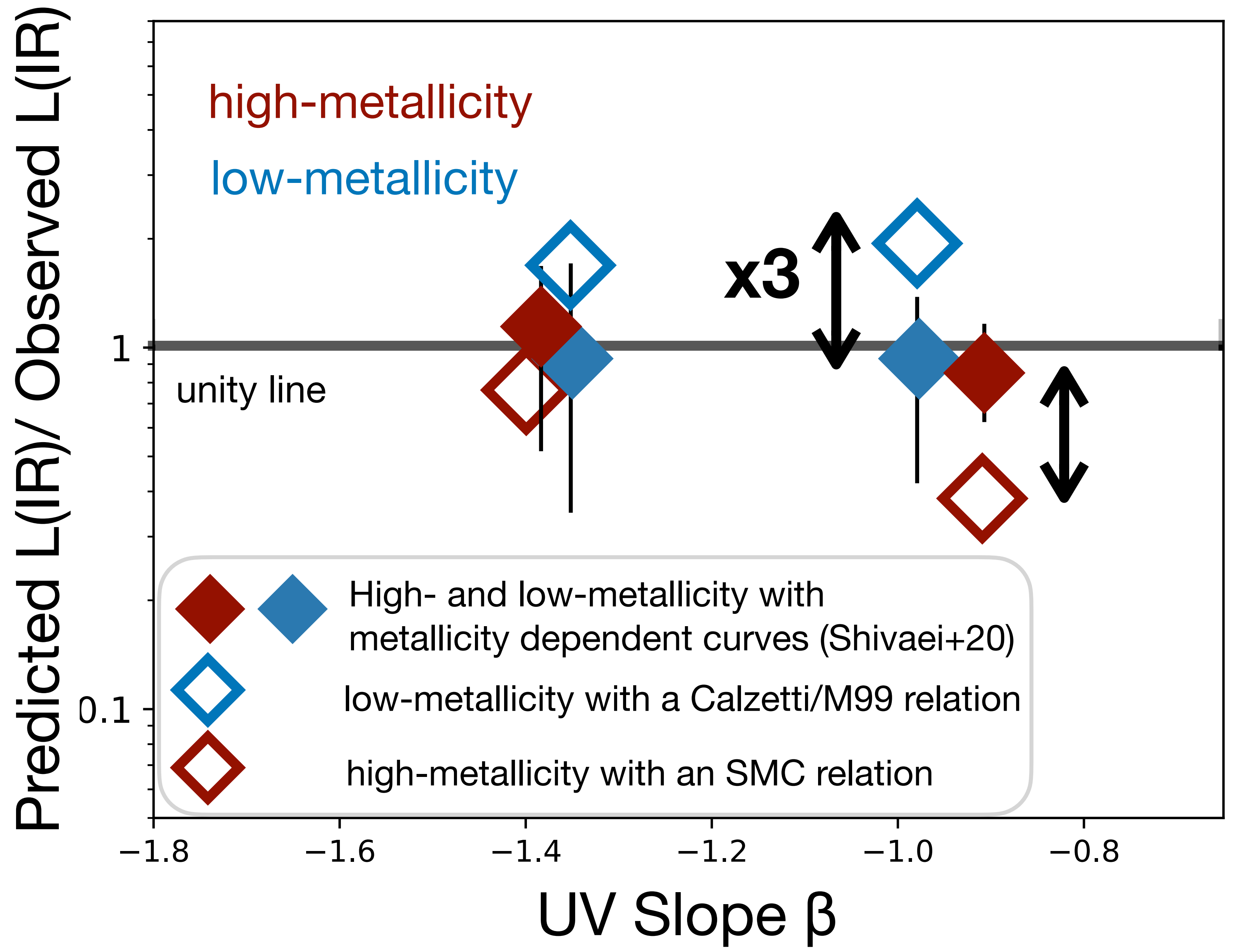


Using a shallow curve for low-metallicity or a steep curve for high-metallicity

affects SFR estimates by x3

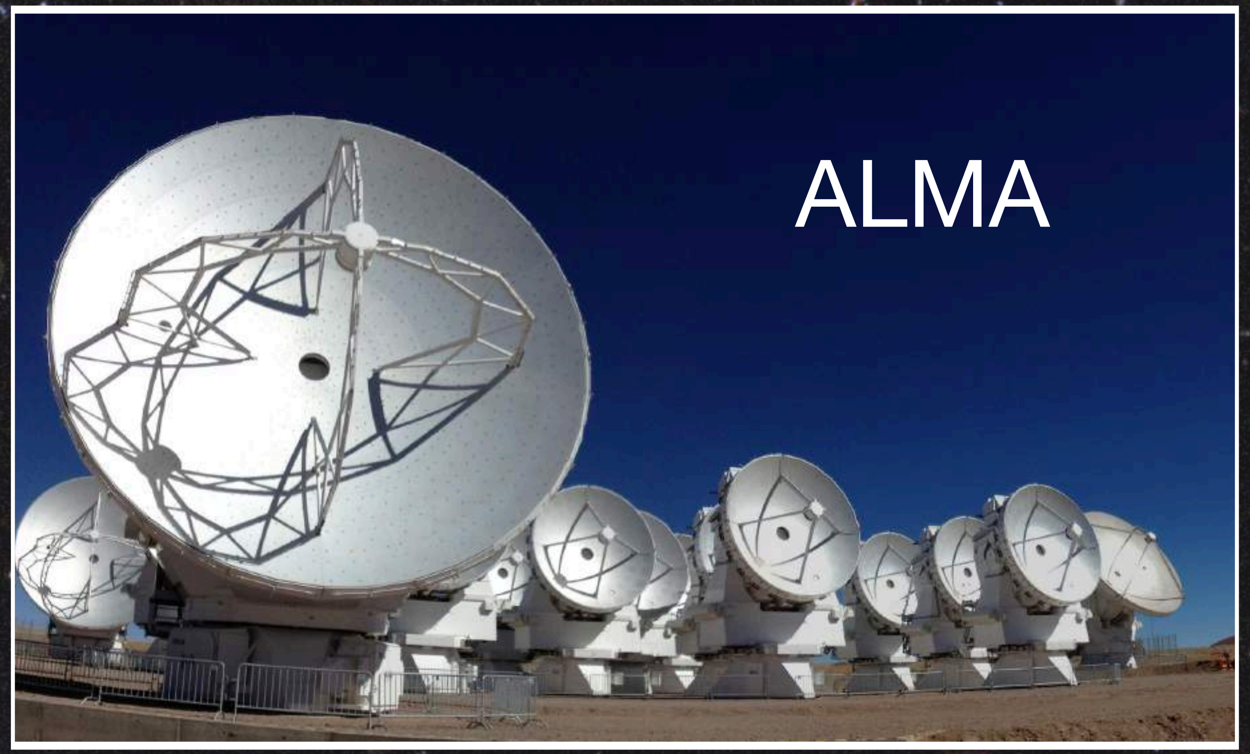
Shivaei et al. (2020a)

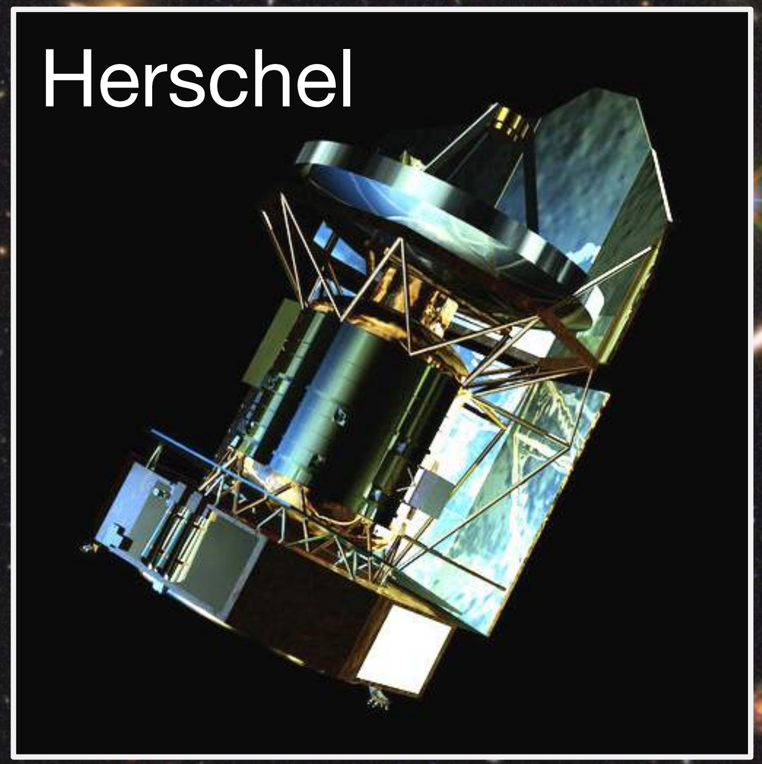
and IR measurements:

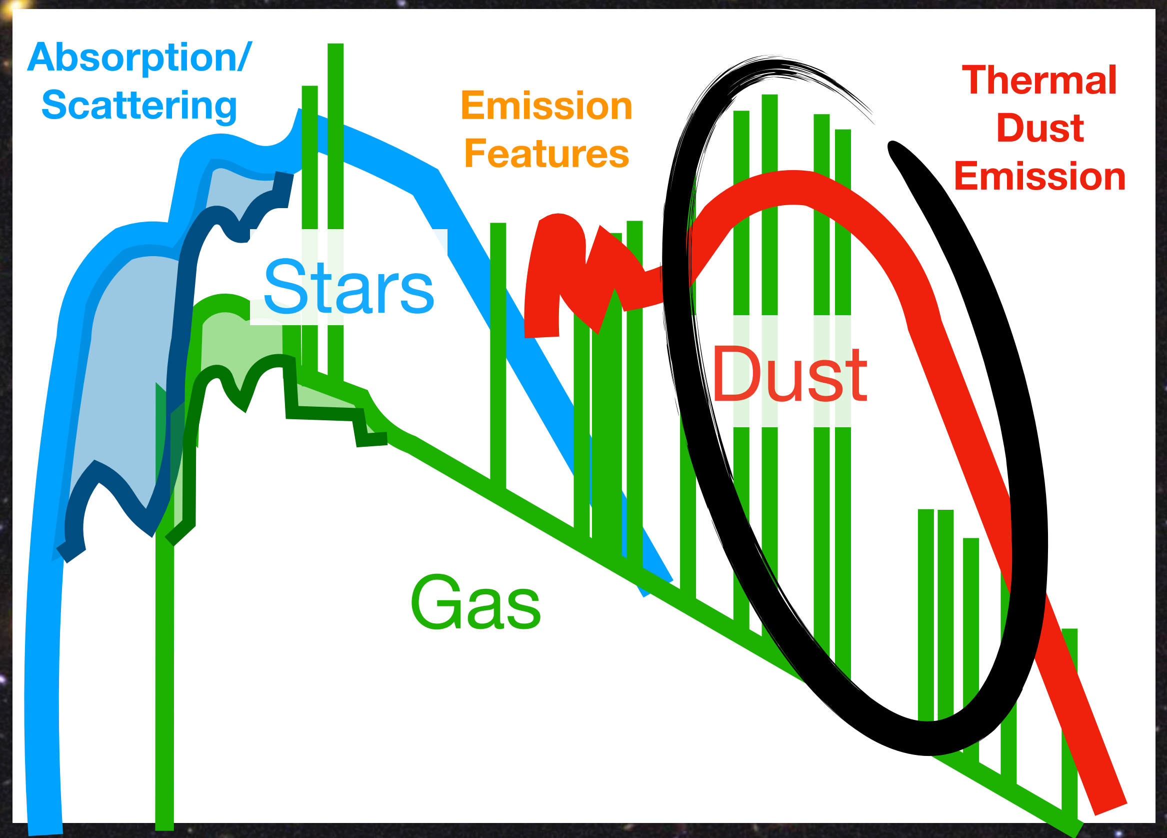


Shivaei et al. (2020b)

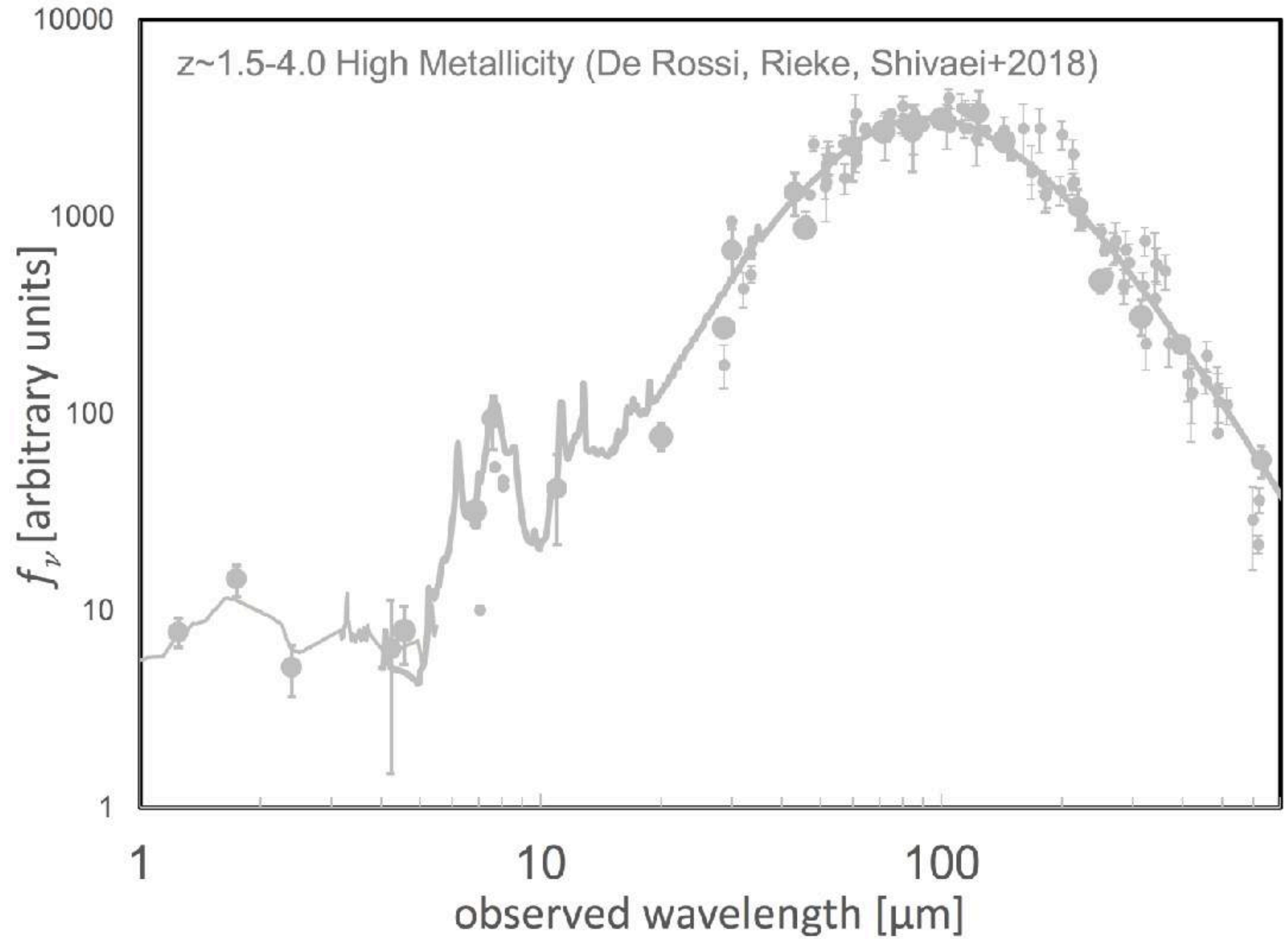
* ALMA and Herschel tracing far-IR dust emission





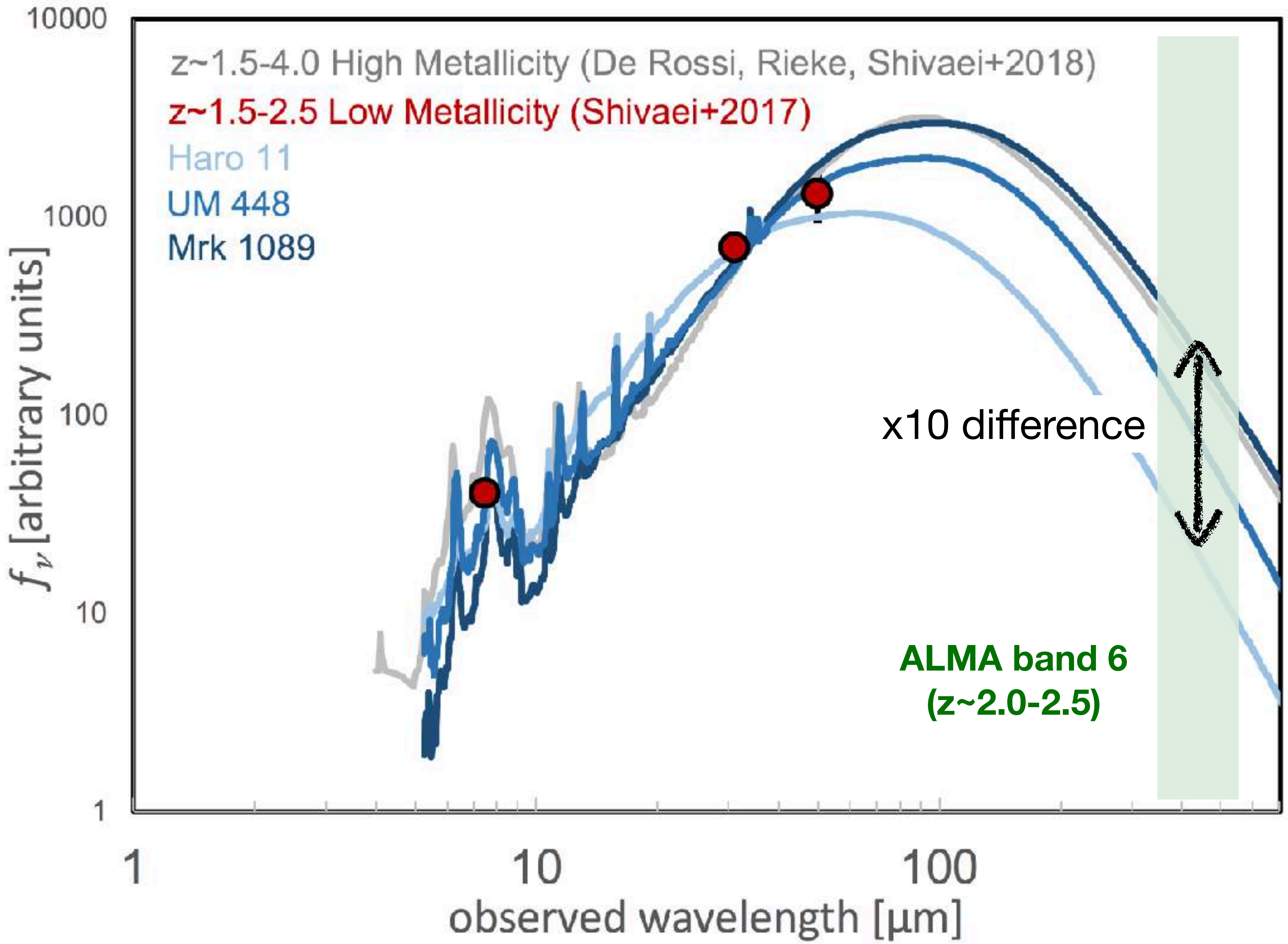


We have a good understanding of the behavior of cold dust emission in IR-bright star-forming galaxies at *z*>1



Observations: **$\langle L_{IR} \rangle = 6 \times 10^{12}\ L_\odot$**
Model: Rieke+2009 template of $\log(L_{IR})$=11.25

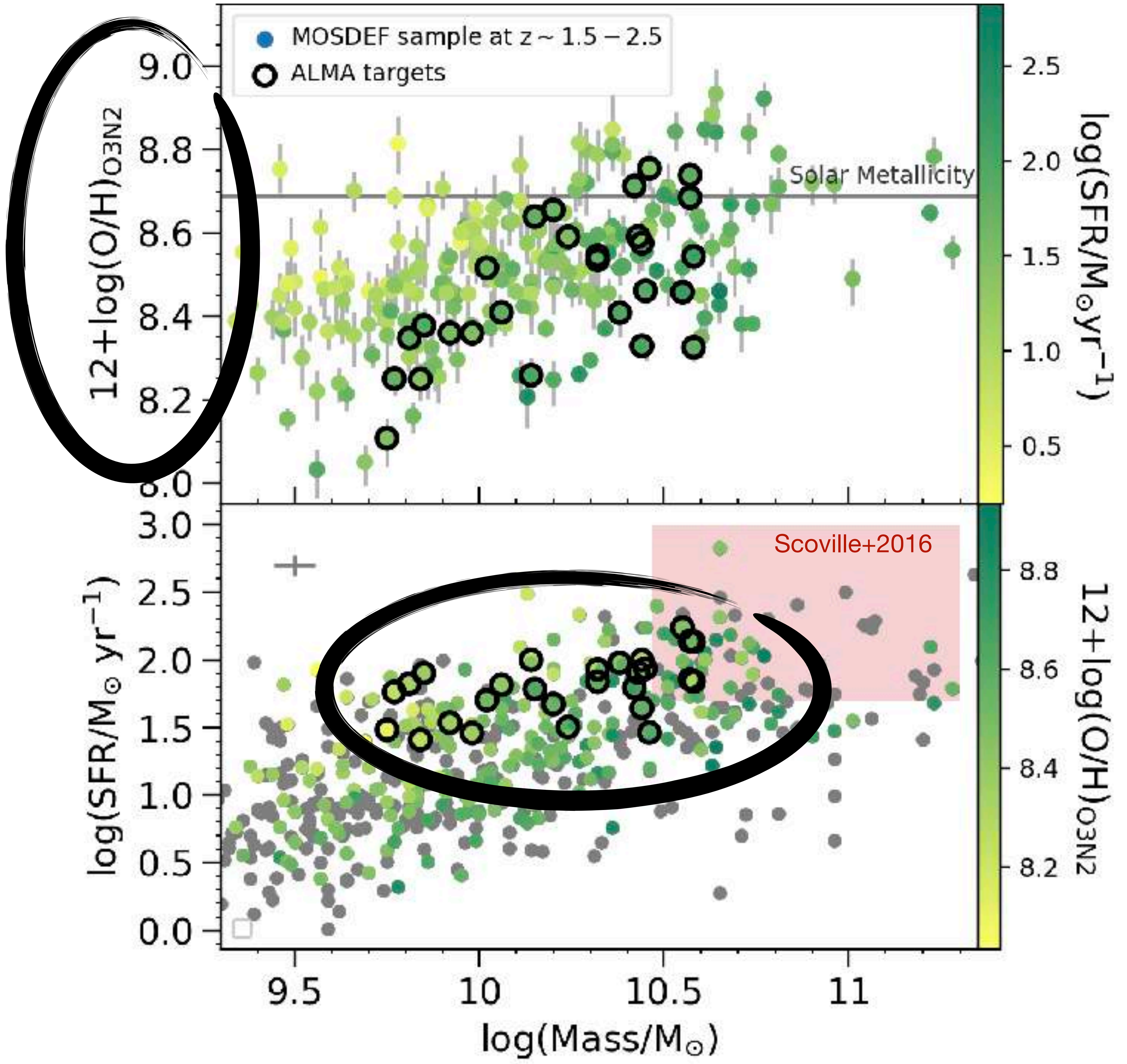
FIR dust continuum emission in *typical* z~2 galaxies



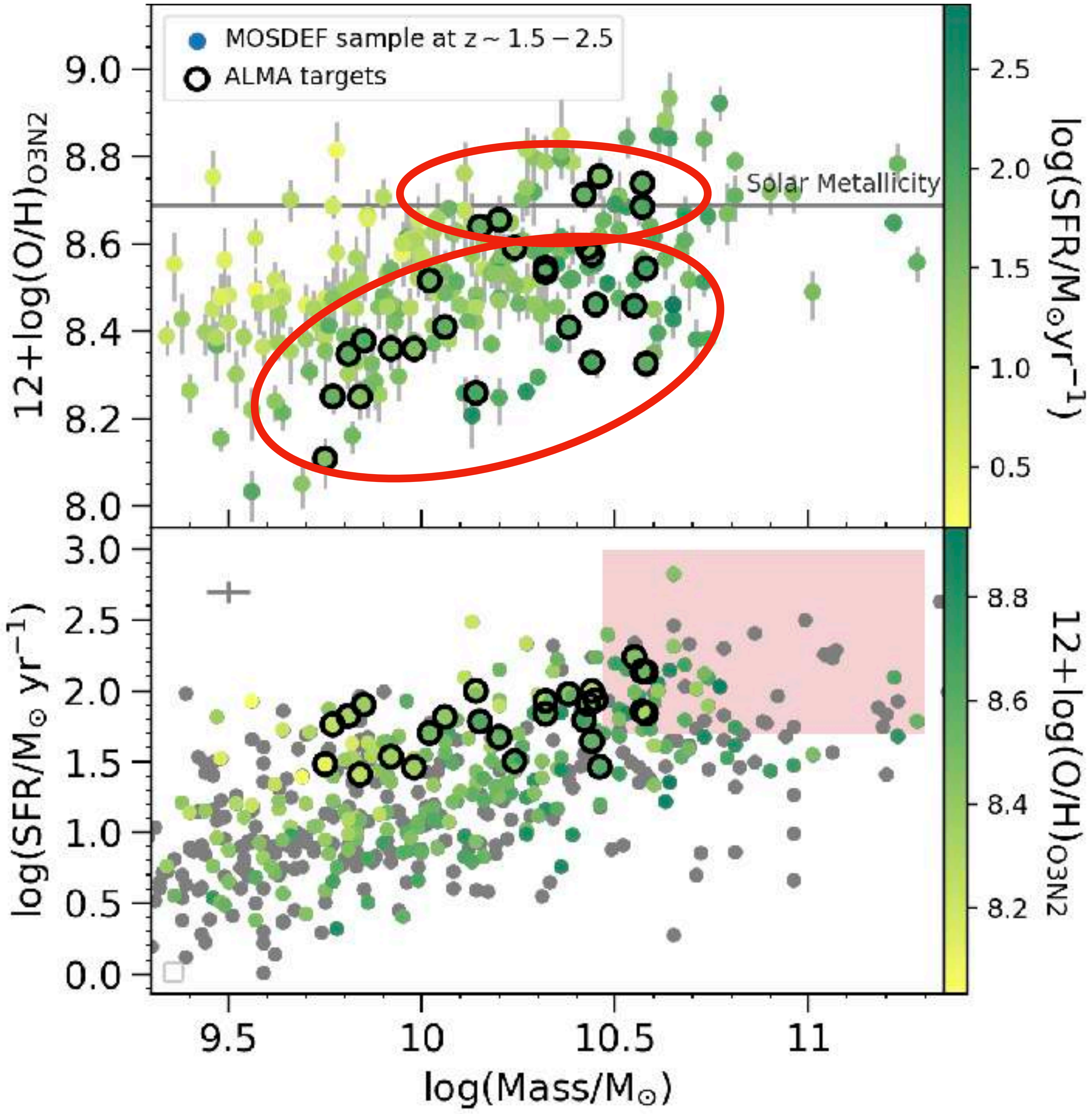
Deep 38-hour ALMA Cycle-7 program to trace dust continuum emission in *typical* z~2 galaxies (PI: I. Shivaei)

Metallicity measurements (MOSDEF survey)

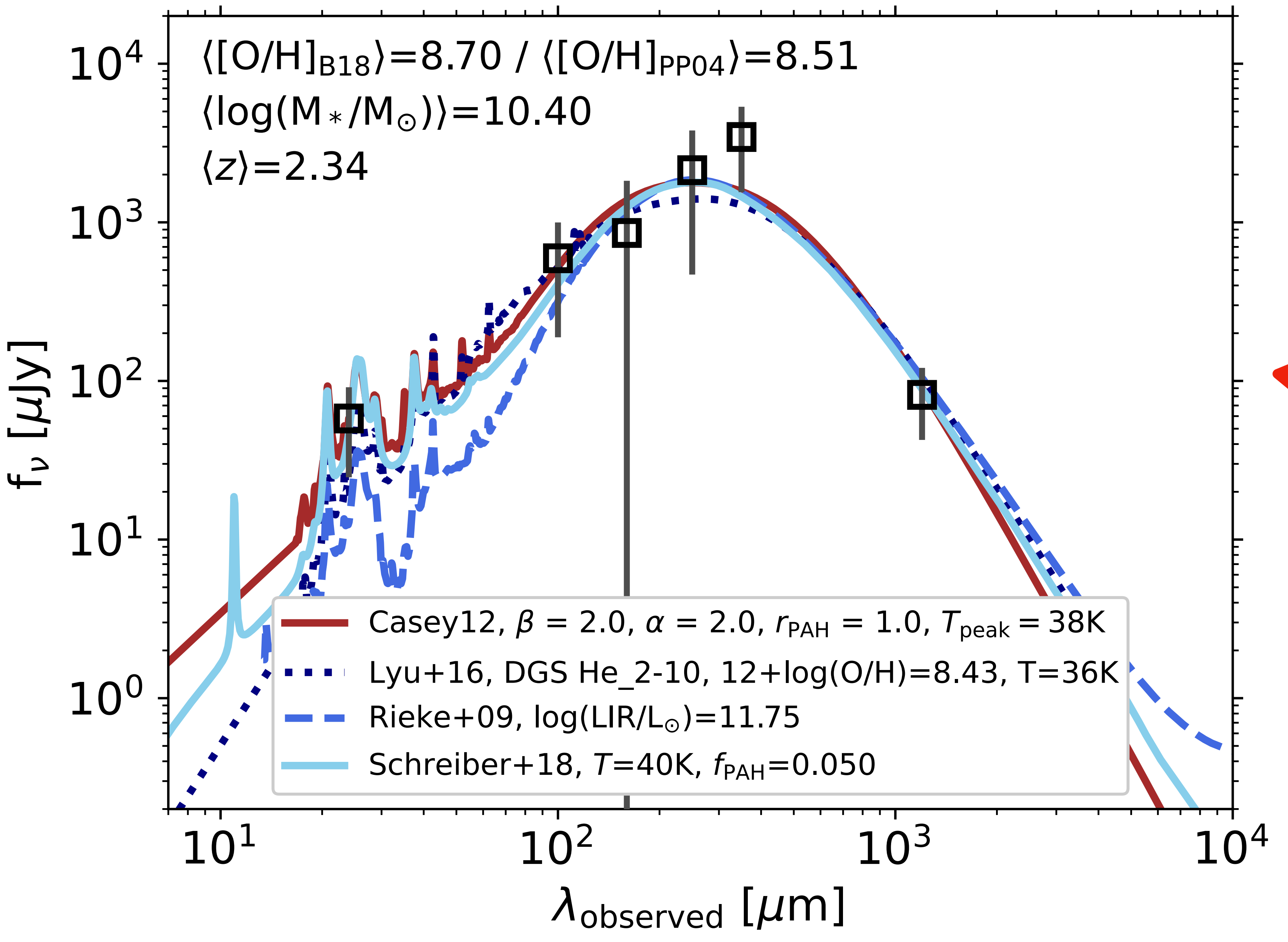
Tracing a new unexplored parameter space

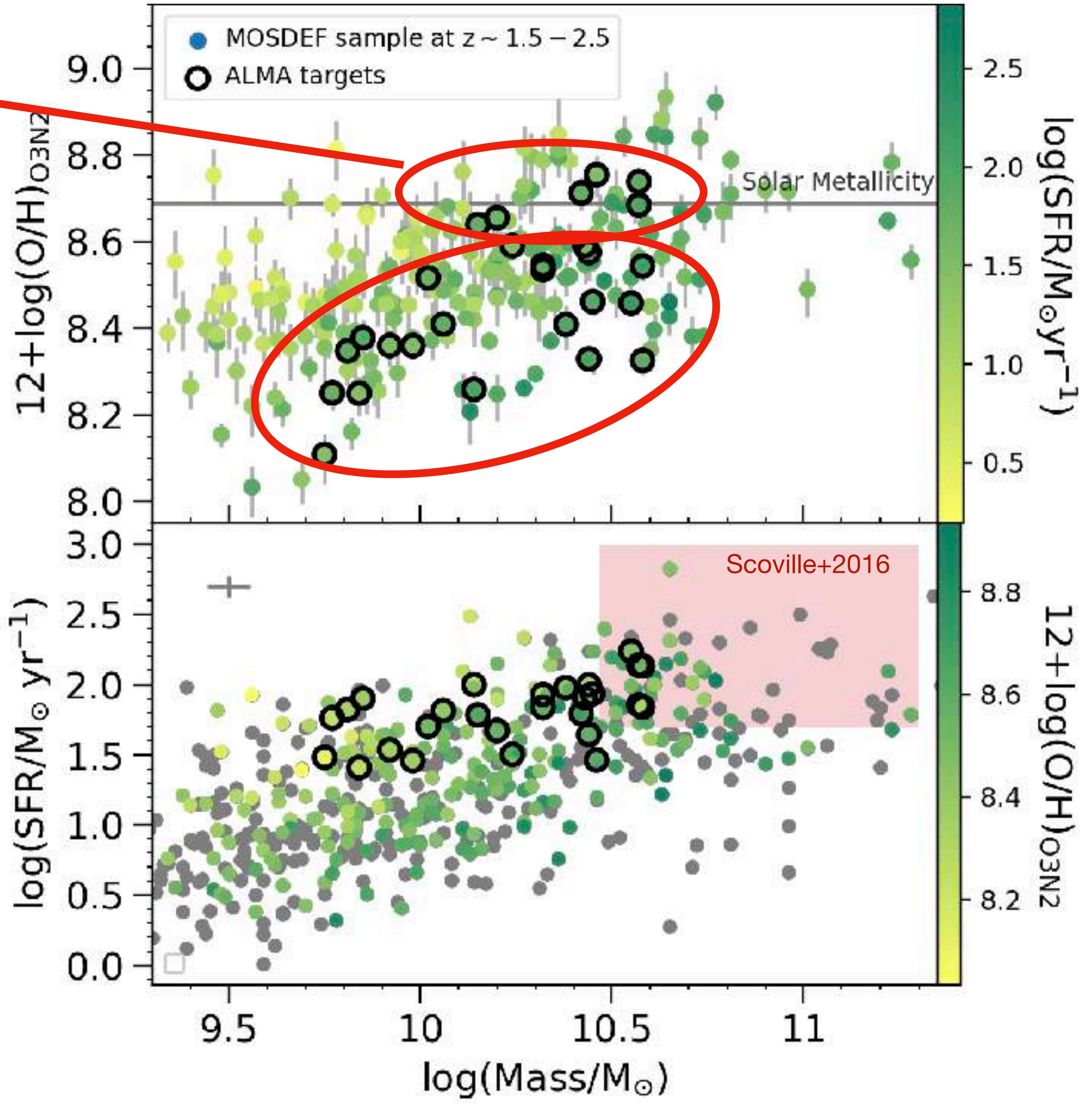


Shivaei et al. (in prep)



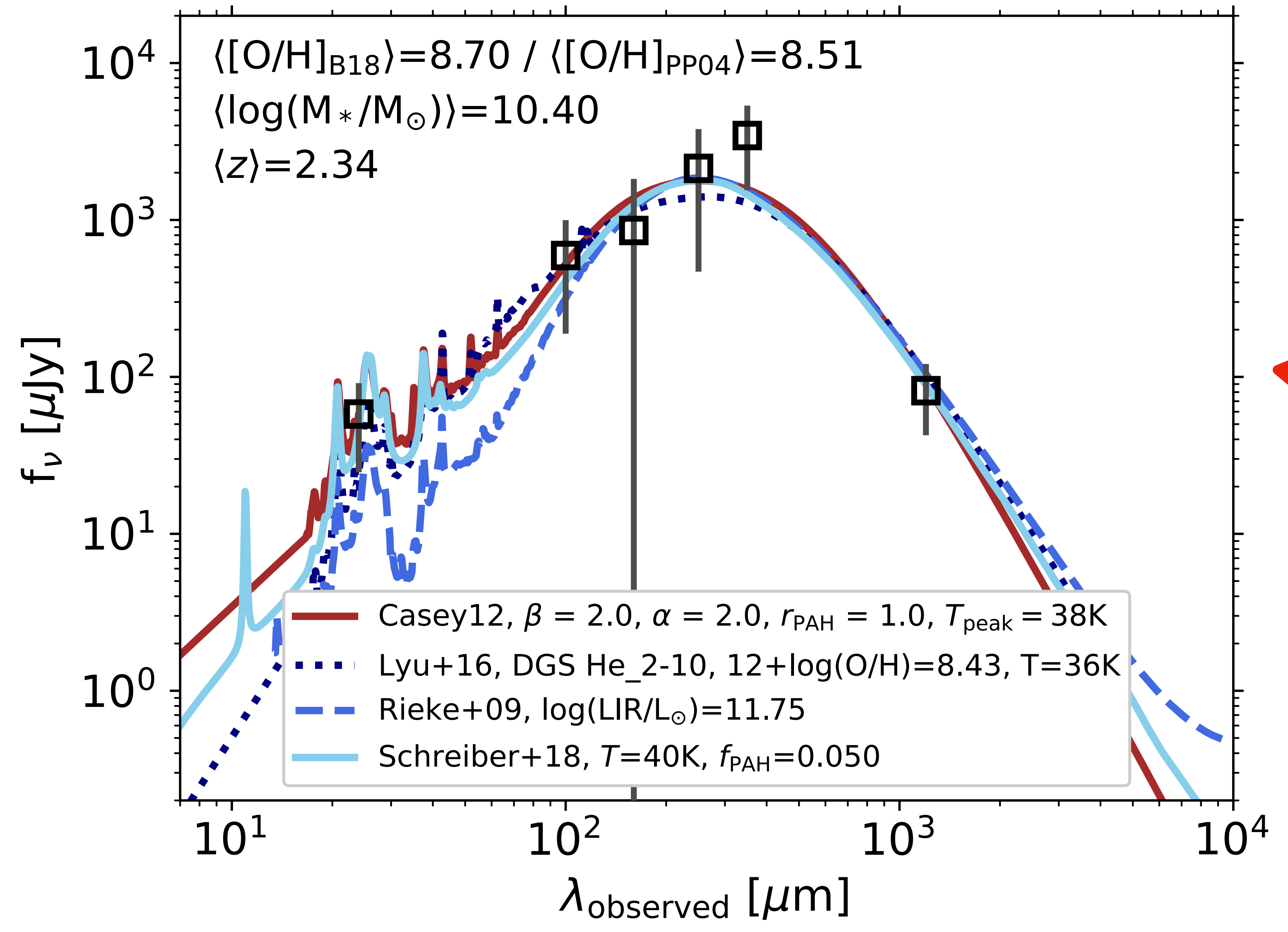
Shivaei et al. (in prep)

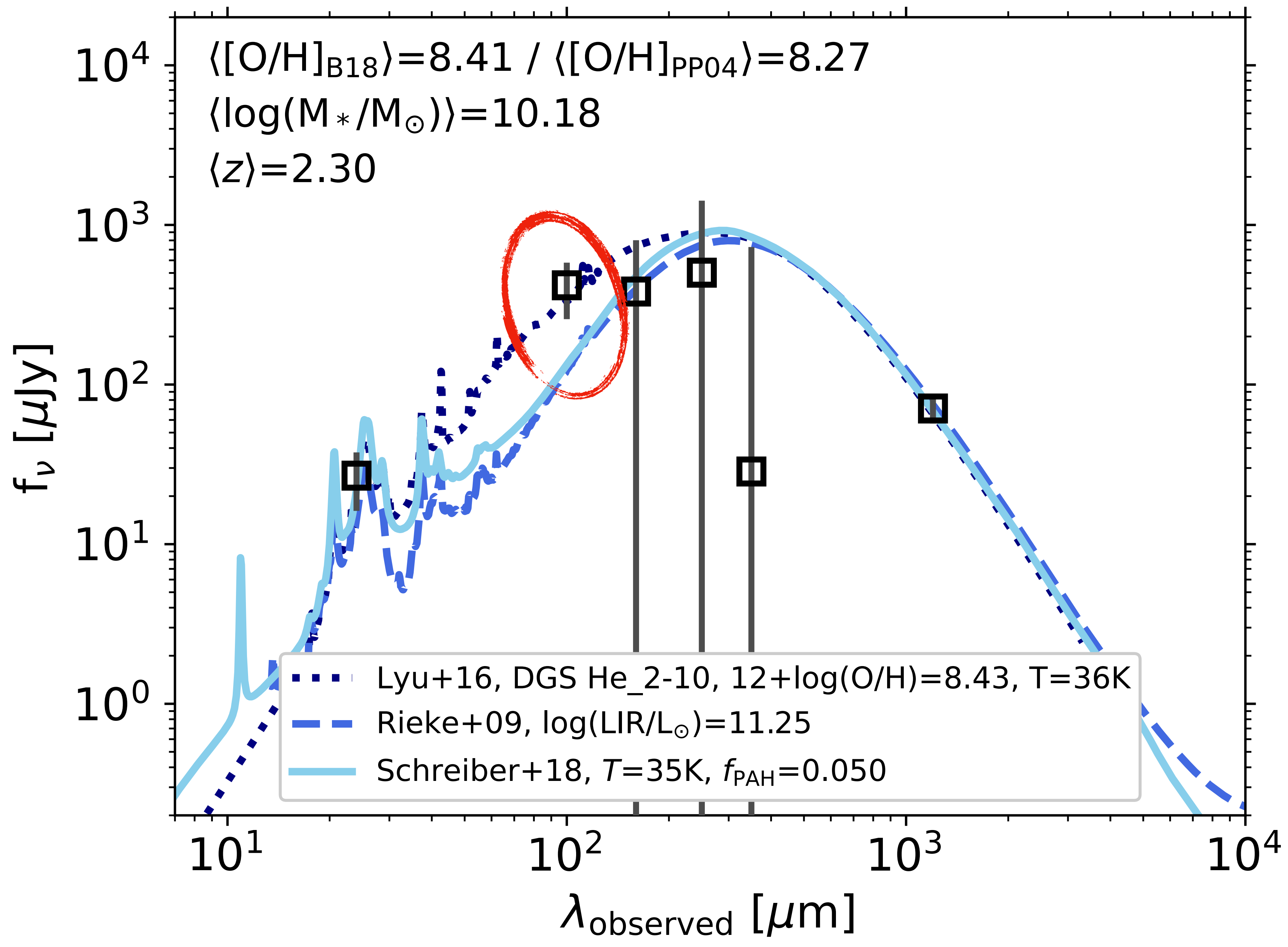


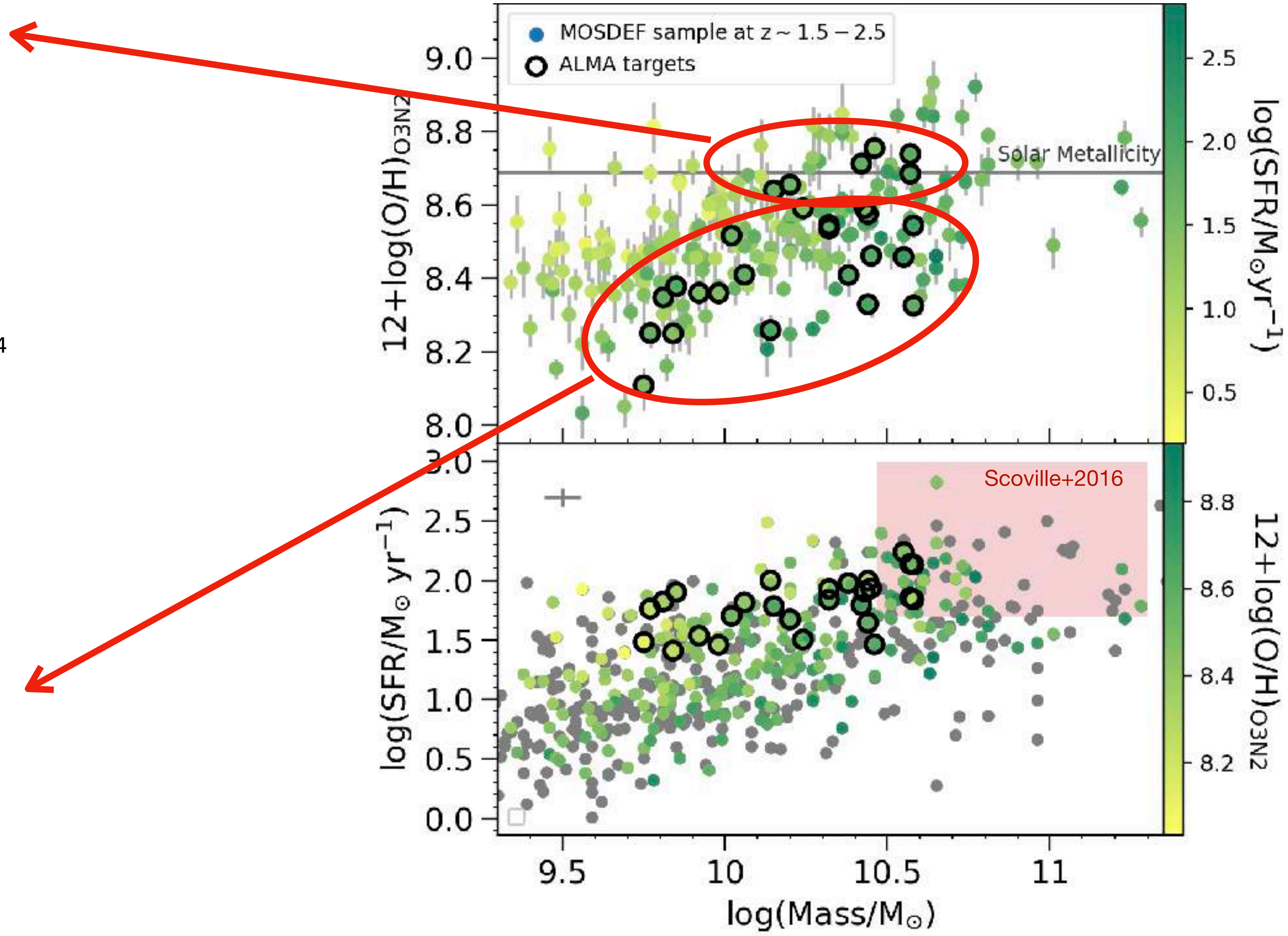


Shivaei et al. (in prep)

The IR SED gets hotter and wider at low metallicities

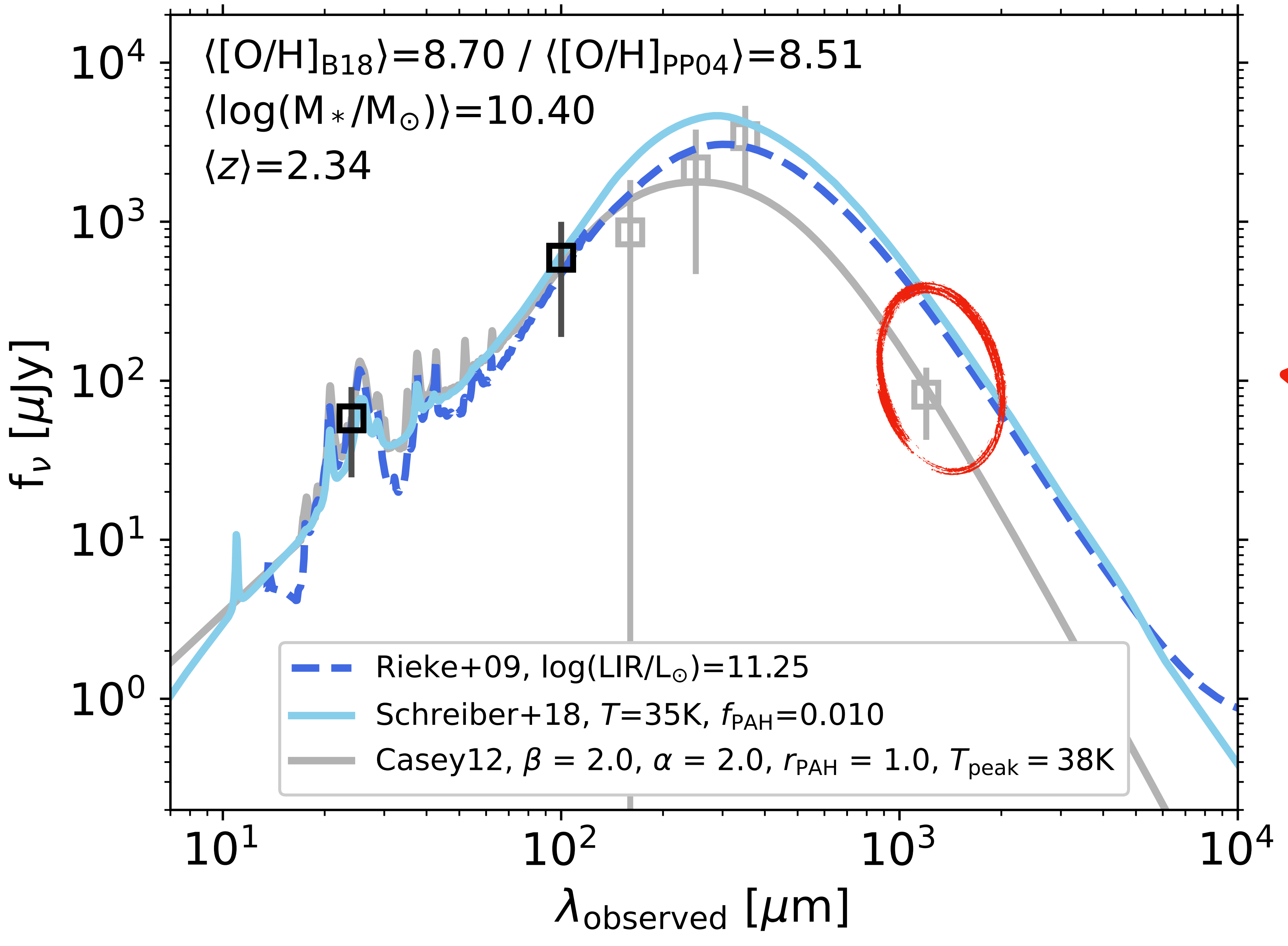


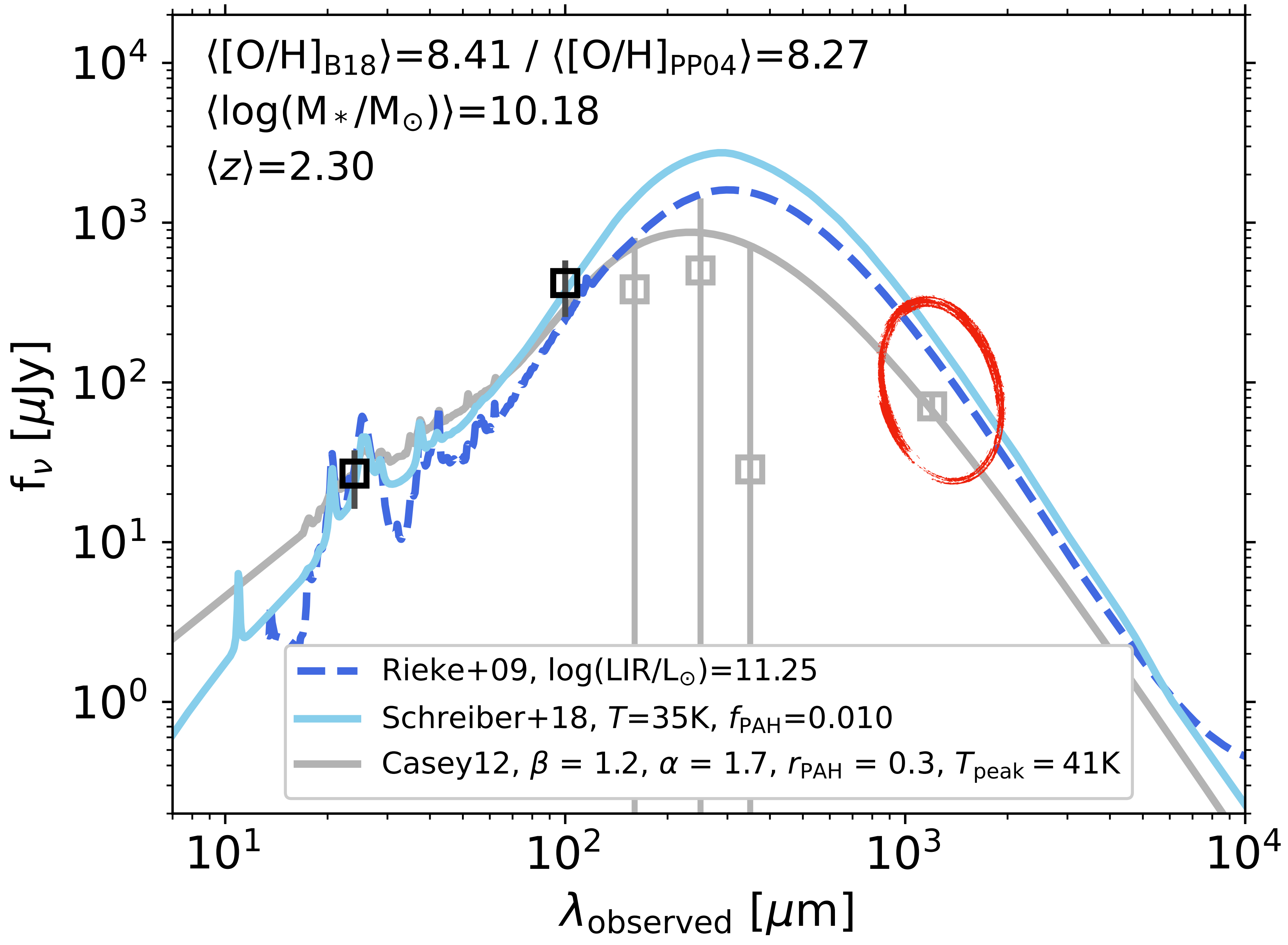


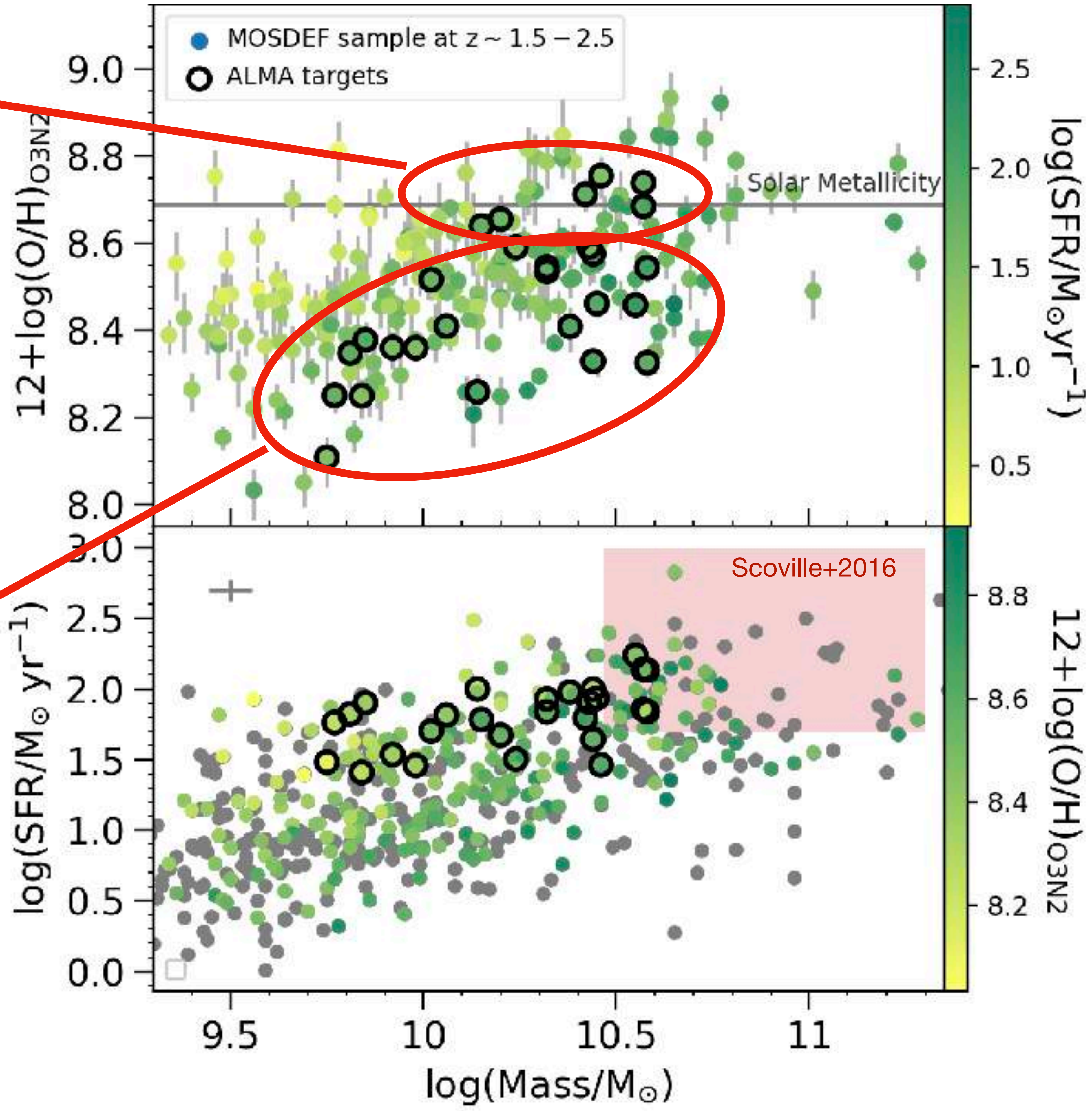


Shivaei et al. (in prep)

If only fit to IR data shoreward of the peak: ALMA flux will be over-estimated



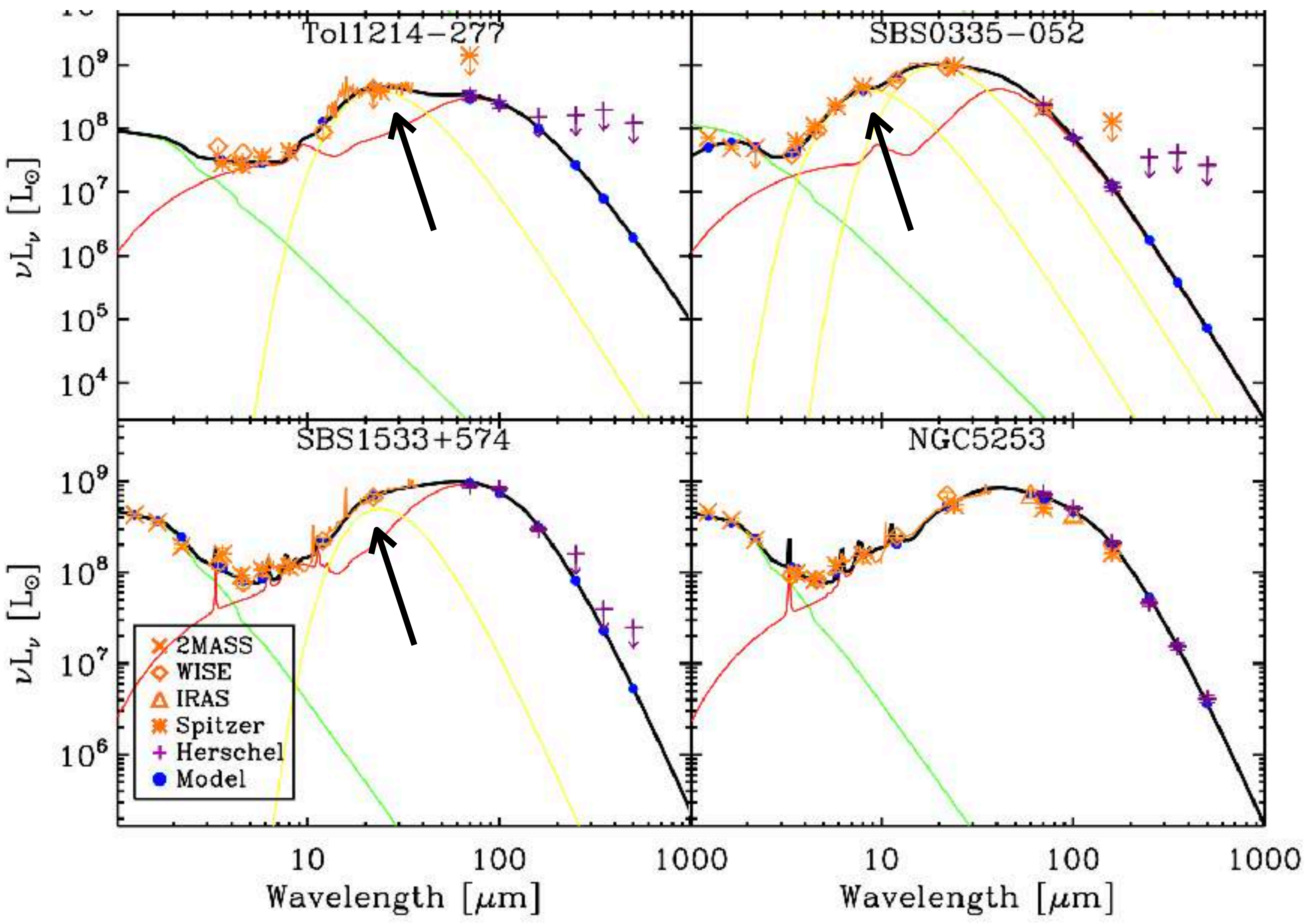




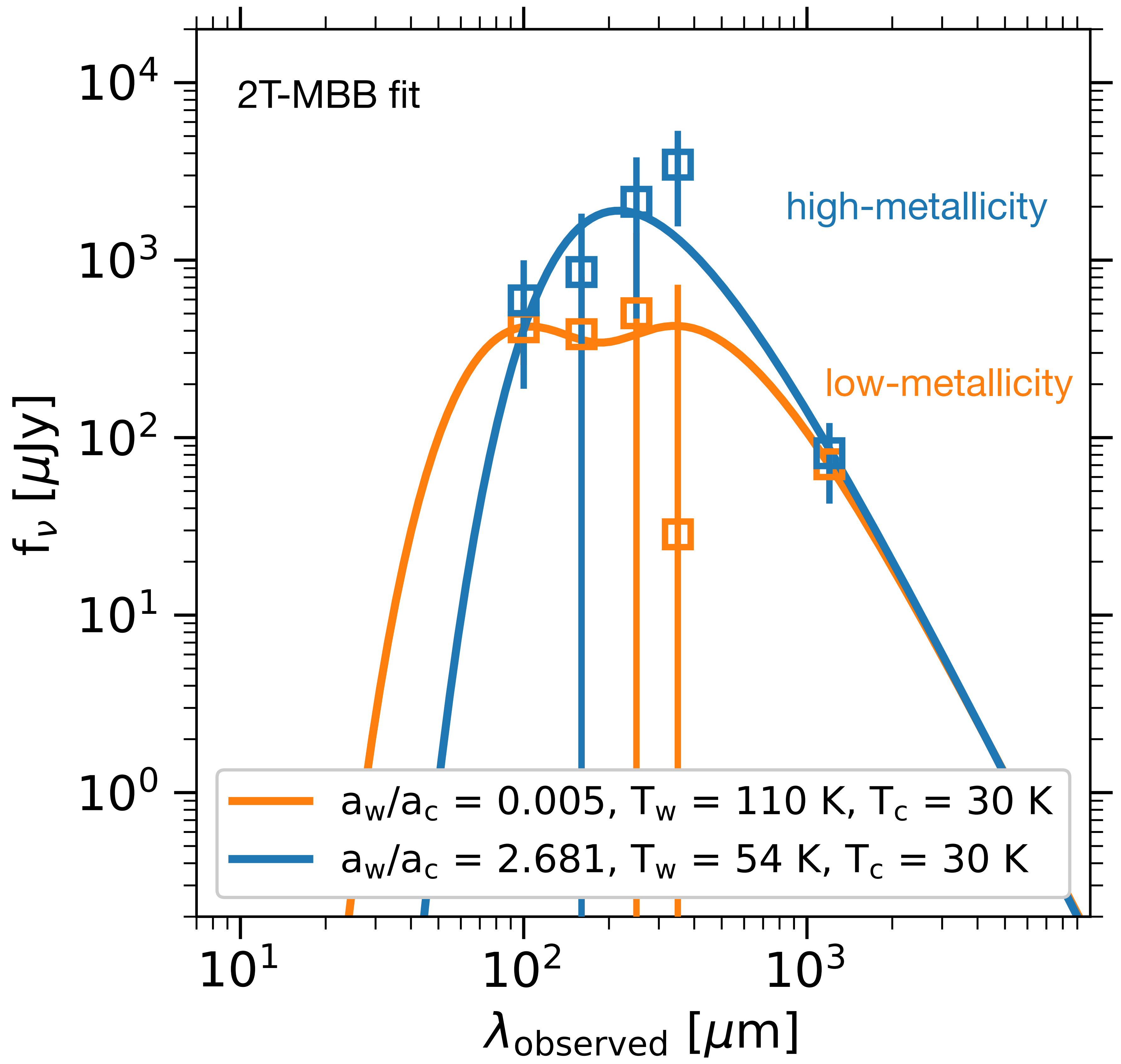
Shivaei et al. (in prep)

Similar intense warm component has been observed in local dwarf galaxies (DGS survey):

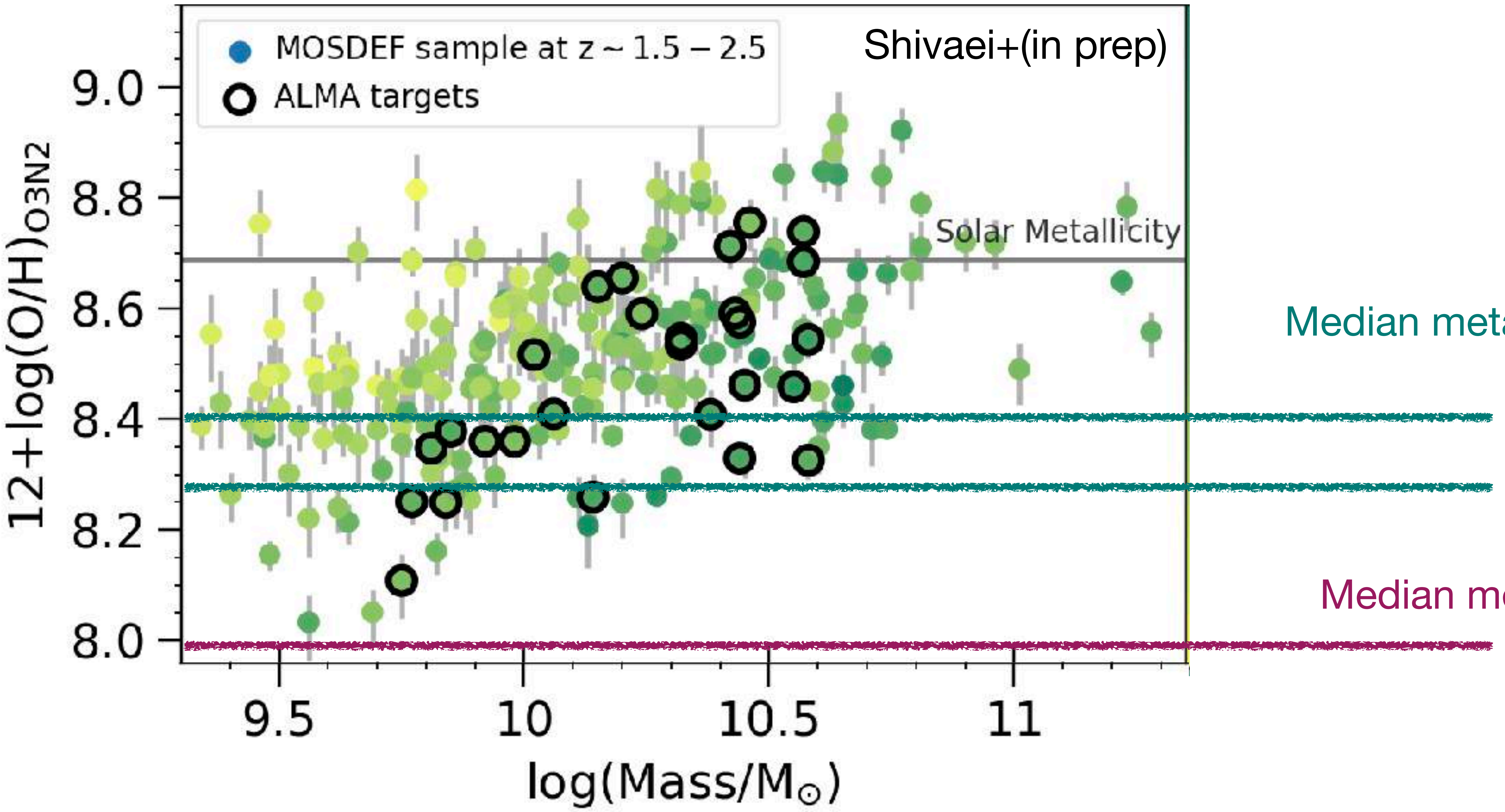
Remy_Ruyer+2015



Shivaei+(in prep)



Same effect at z~0 and z~2 but at different O/H:



Median metallicity of z~2 “low-metallicity” sample (Shivaei+):

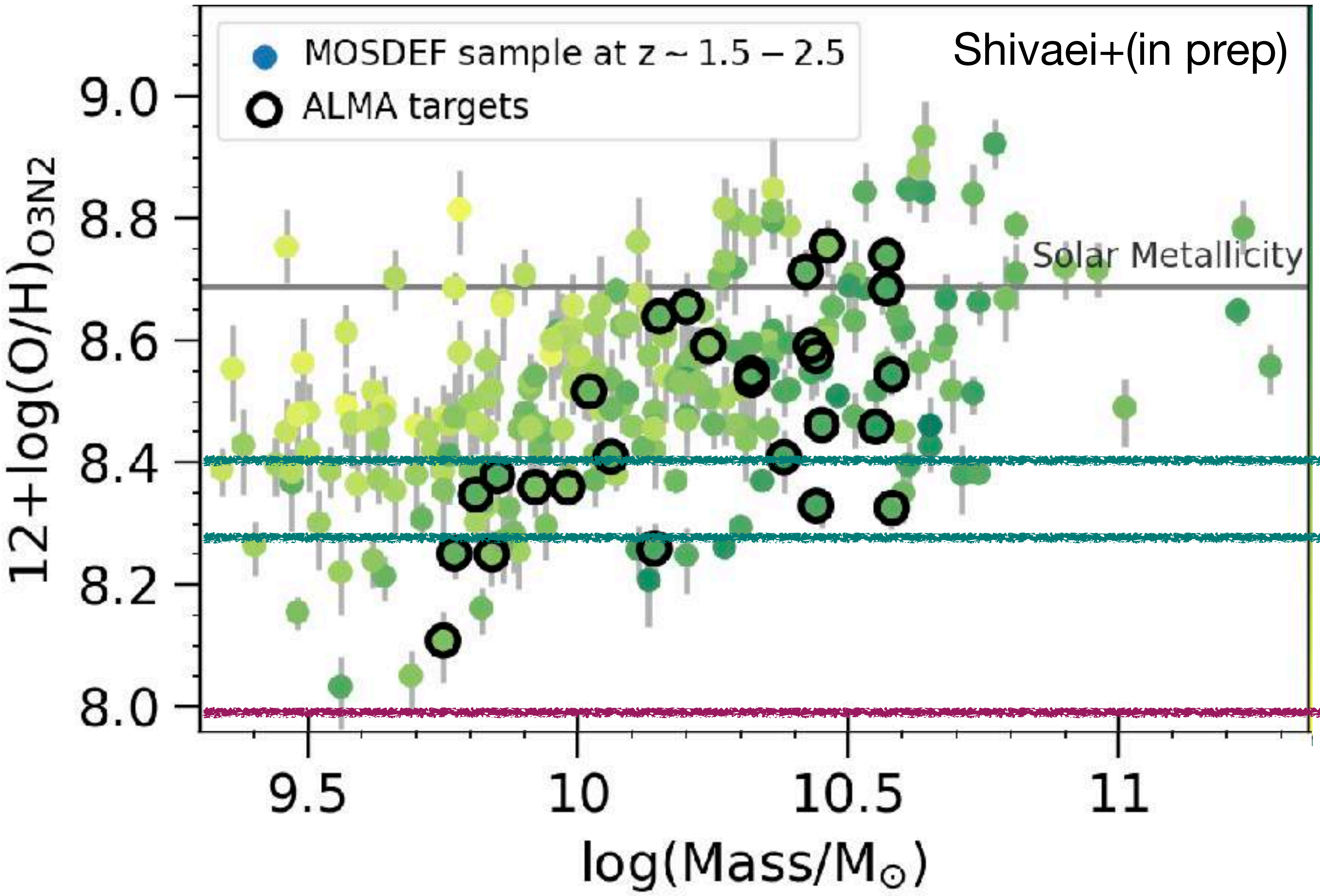
$12+\log(O/H)_{B18} = 8.4$ or

$12+\log(O/H)_{PP04} = 8.3$

Median metallicity of z~0 DGS sample (Remy-Ruyer+2015):

12+log(O/H) = 7.9

The IR emission properties of dwarf galaxies at z~0 are observed in more luminous galaxies at z~2:



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$12+\log(O/H)_{B18} = 8.4$ or

$12+\log(O/H)_{PP04} = 8.3$

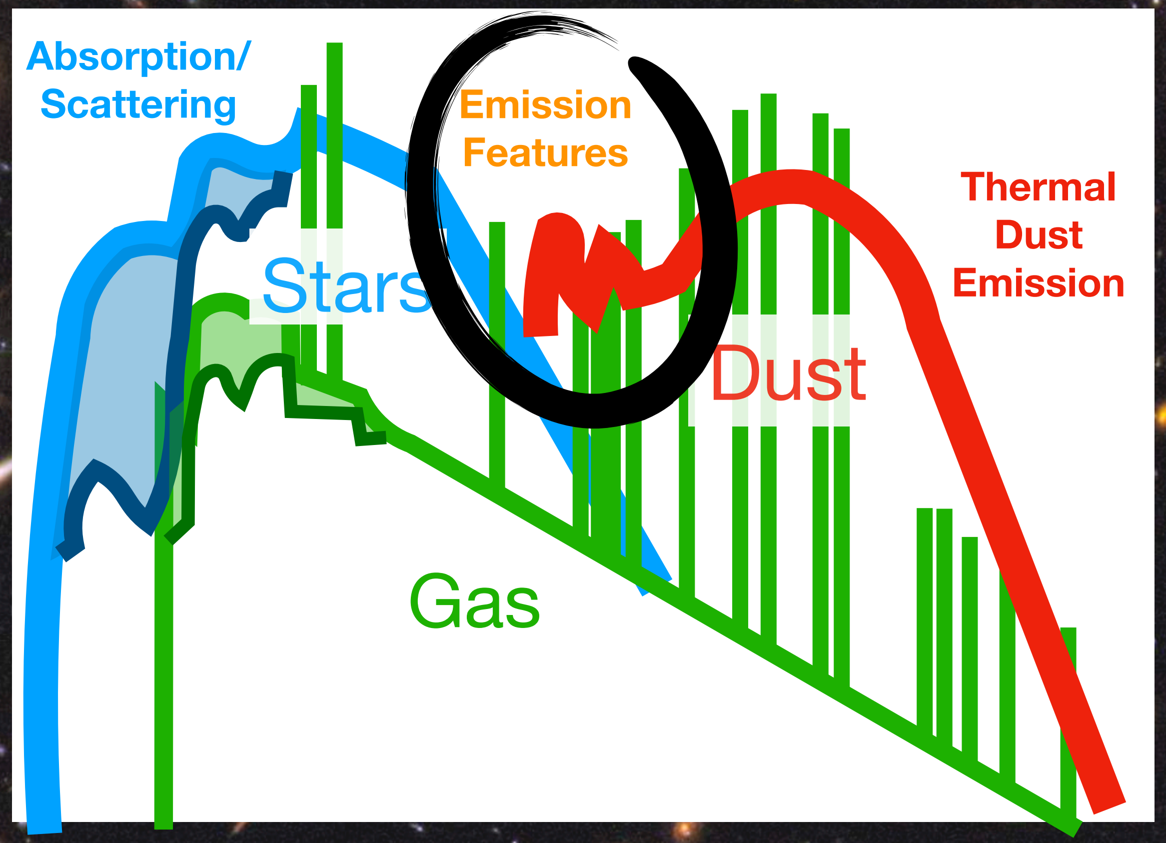
Median metallicity of z~0 DGS sample (Remy-Ruyer+2015):

$12+\log(O/H) = 7.9$

- Calibrations at z~2 are incorrect by ~0.3 dex [unlikely ❌]
- More intense interstellar radiation field at a given O/H at z~2 [likely; super-solar O/Fe abundances at z~2 ✅]
- Lower dust/gas at a given O/H at z~2 [not known ❓]

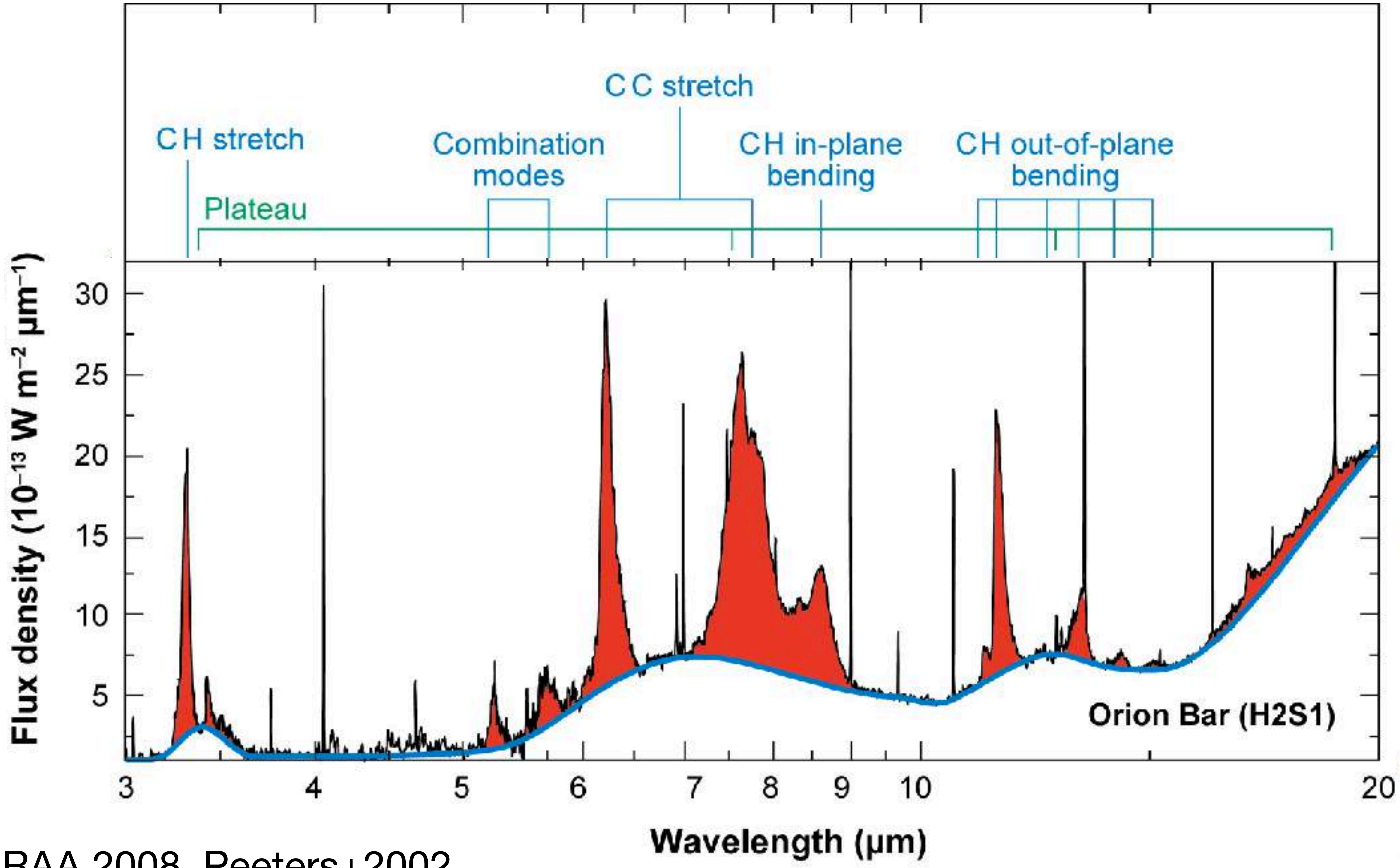
Future with JWST

* US MIRI GTO HUDF survey to trace PAH emission at z~1-2

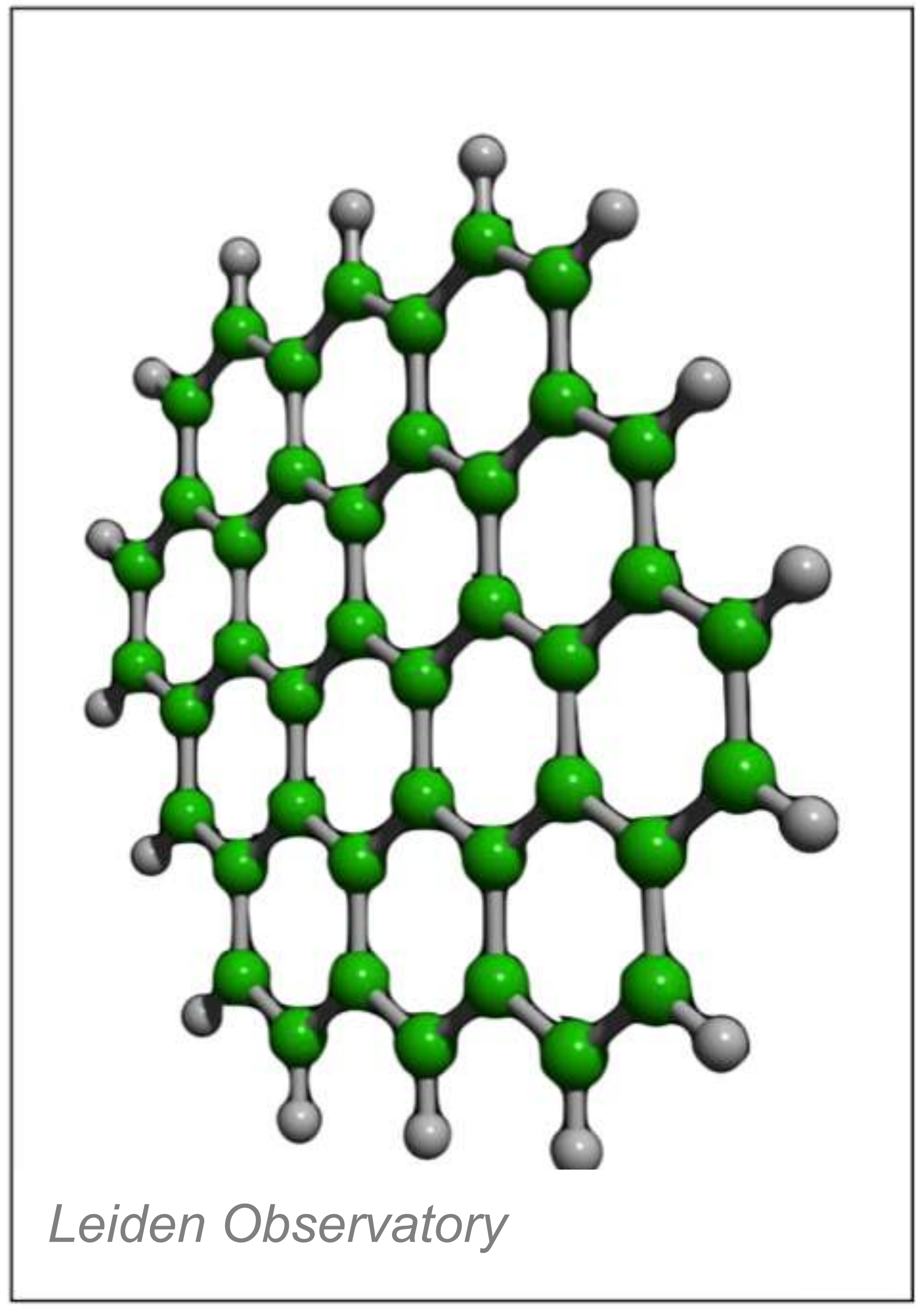


THE MID-IR SPECTRA OF GALAXIES

- The mid-IR emission features are commonly attributed to PAH emission
- PAHs are the most abundant organic molecules in space and account for up to ~ 20% of the IR emission of galaxies

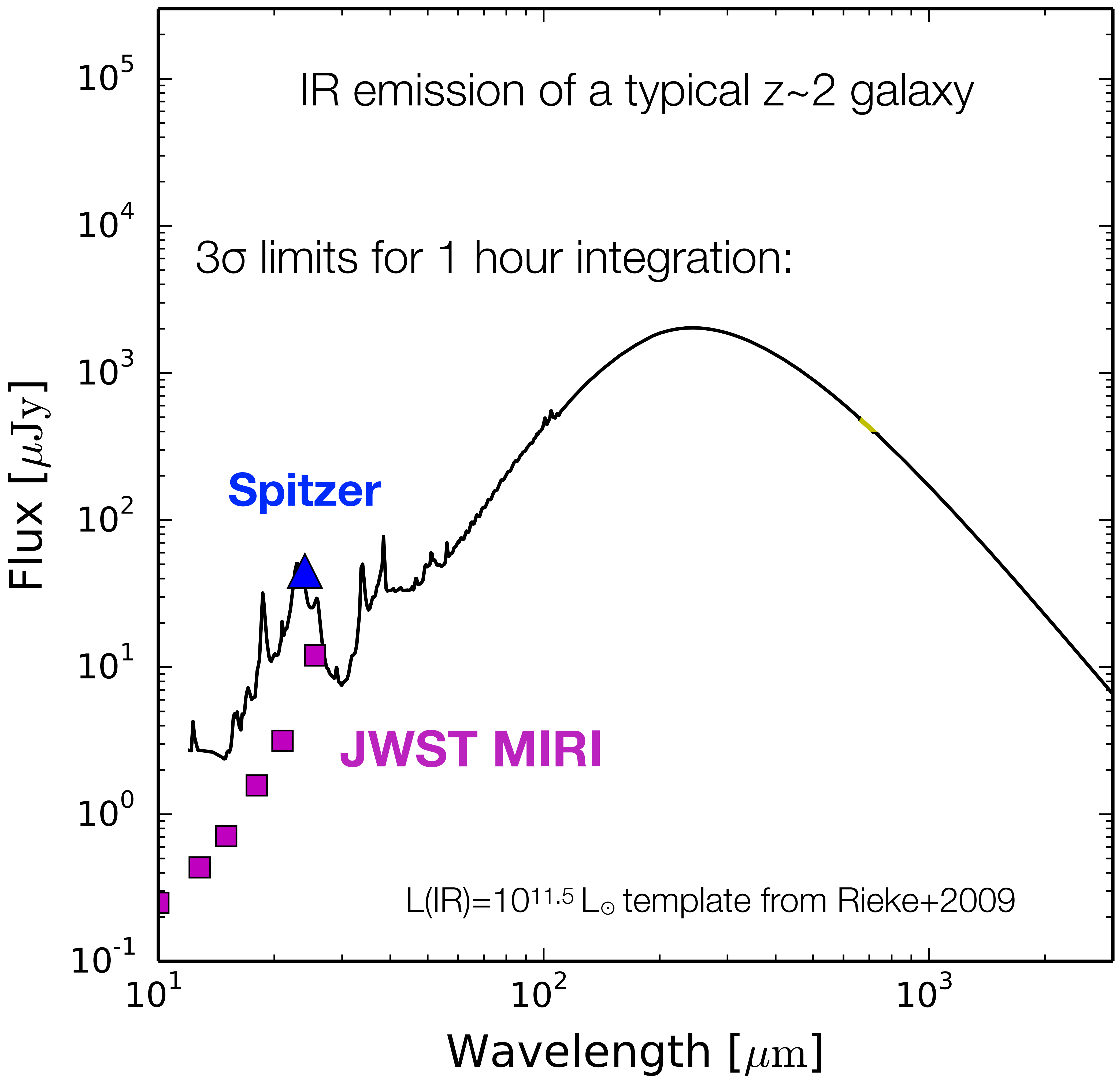


Tielens ARAA 2008, Peeters+2002

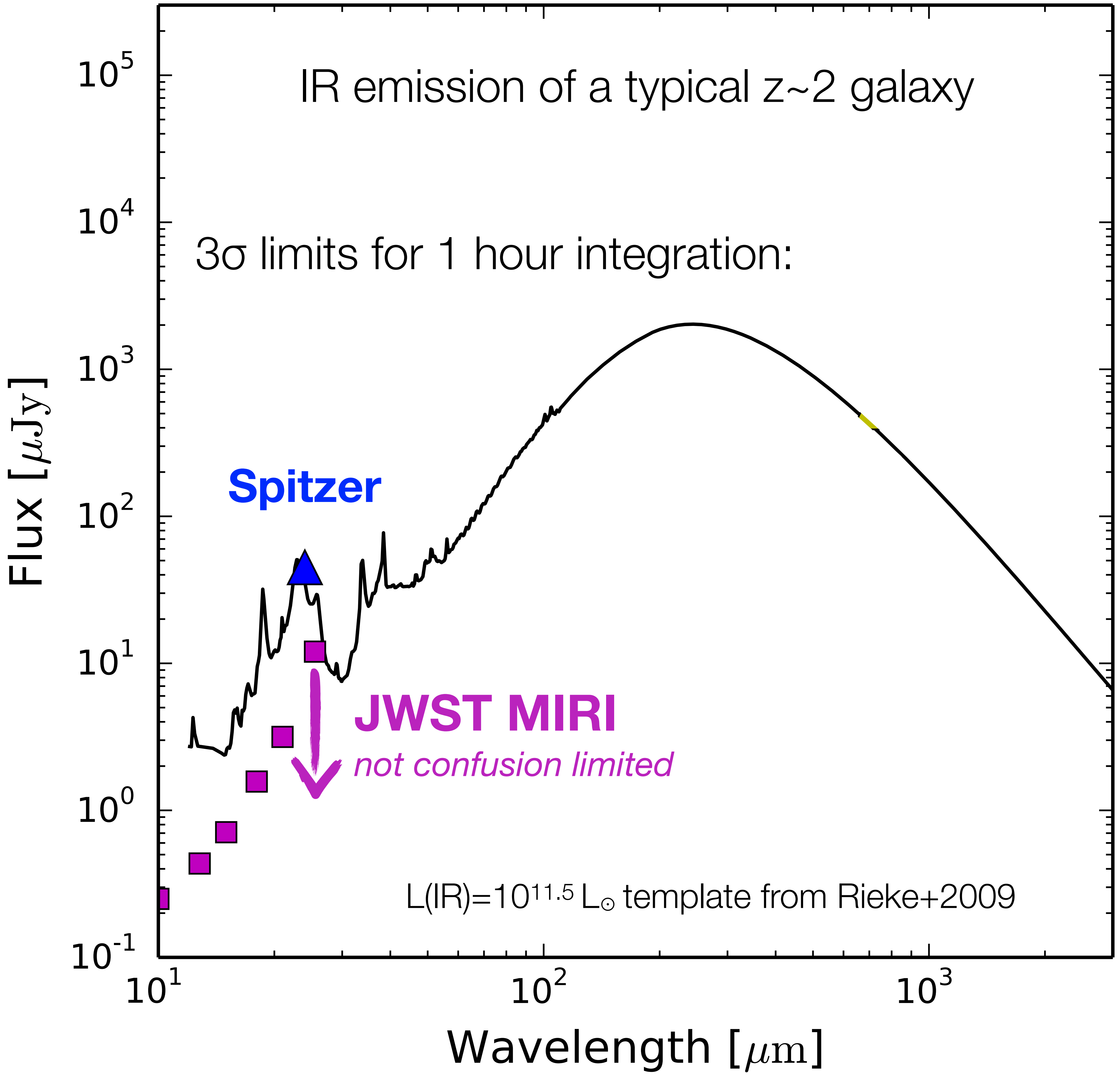


Polycyclic Aromatic Hydrocarbon (PAH) molecule

HIGHER SENSITIVITY



HIGHER SENSITIVITY, HIGHER RESOLUTION



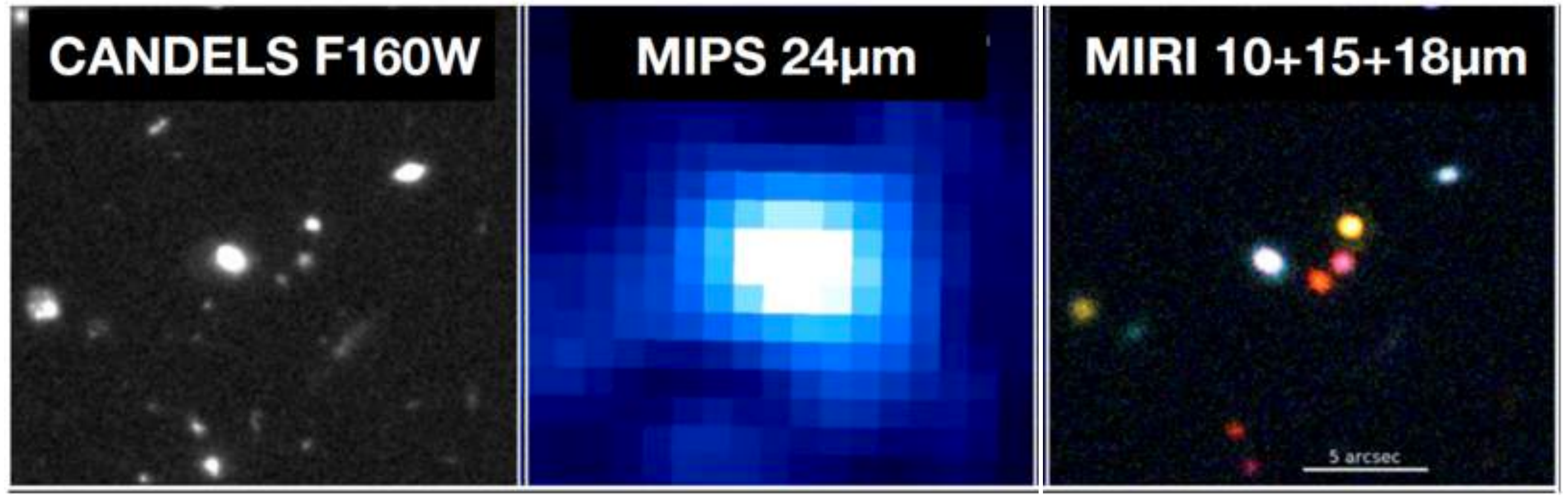
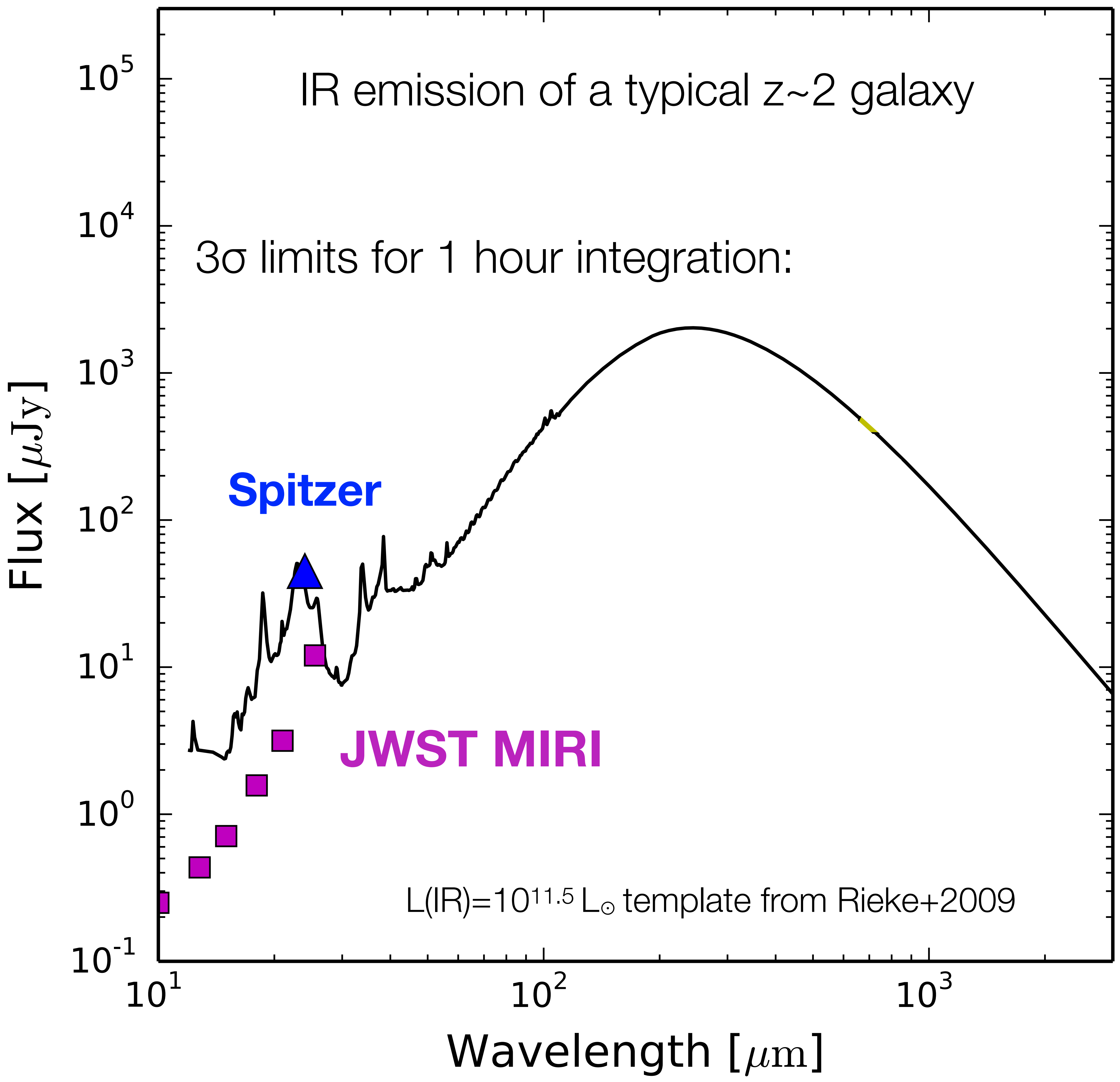
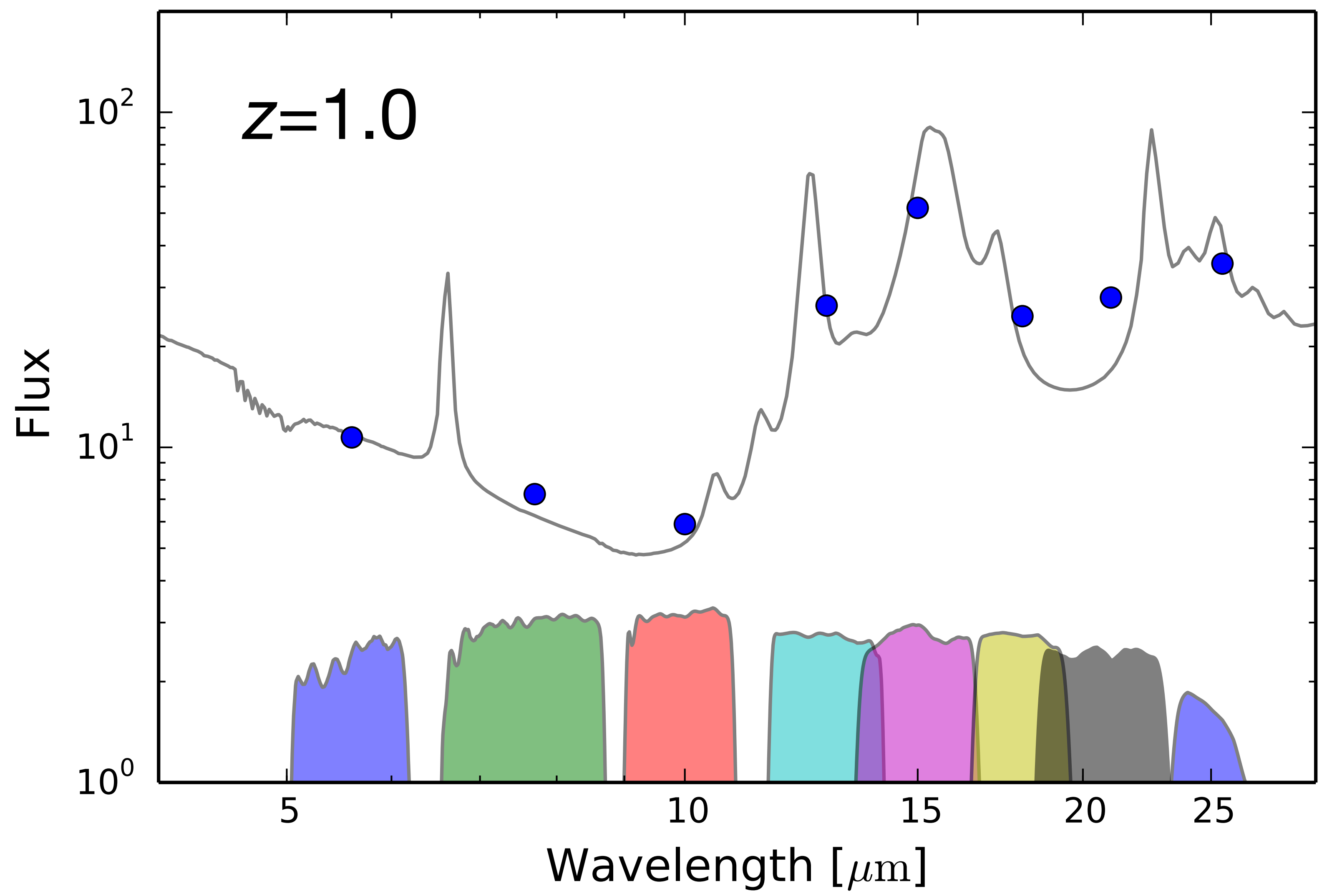


Image credit: Casey Papovich

HIGHER SENSITIVITY, HIGHER RESOLUTION, MULTIPLE BANDS





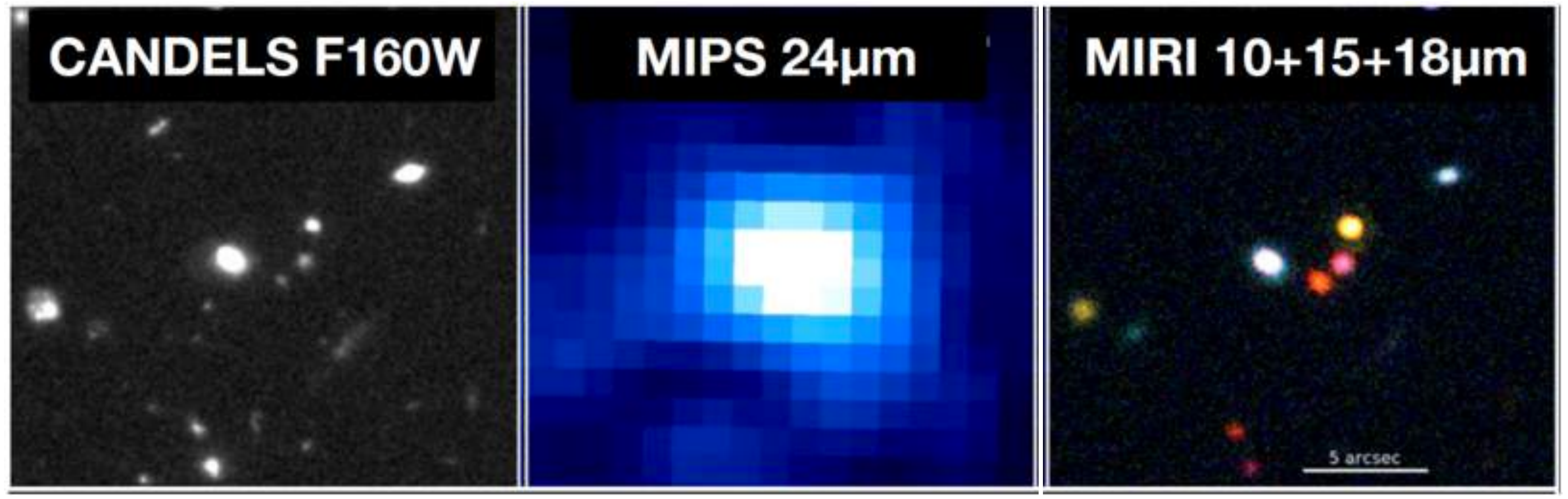


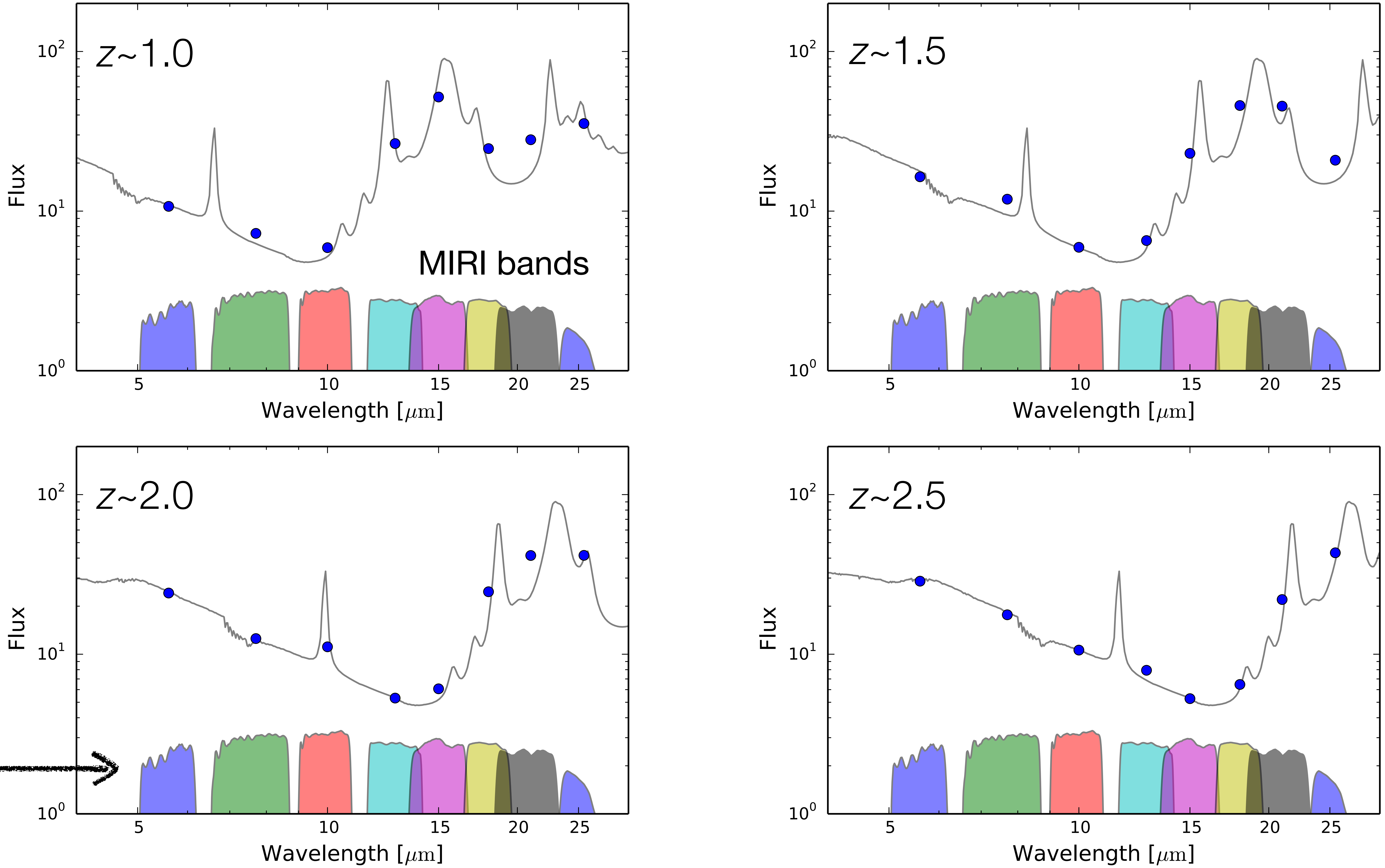
Image credit: Casey Papovich

TRACING MID-IR EMISSION AT Z~1-2 WITH JWST MIRI

JWST/MIRI GTO EXTRAGALACTIC PROGRAM IN GOODS-SOUTH (PI: GEORGE RIEKE, UNIVERSITY OF ARIZONA)

Survey Parameters:

- 5 – 25μm
- 30 arcmin²
- ~8μJy at 21μm (10σ)
- ~30 hours (exposure time)
- NIRSpec follow-up



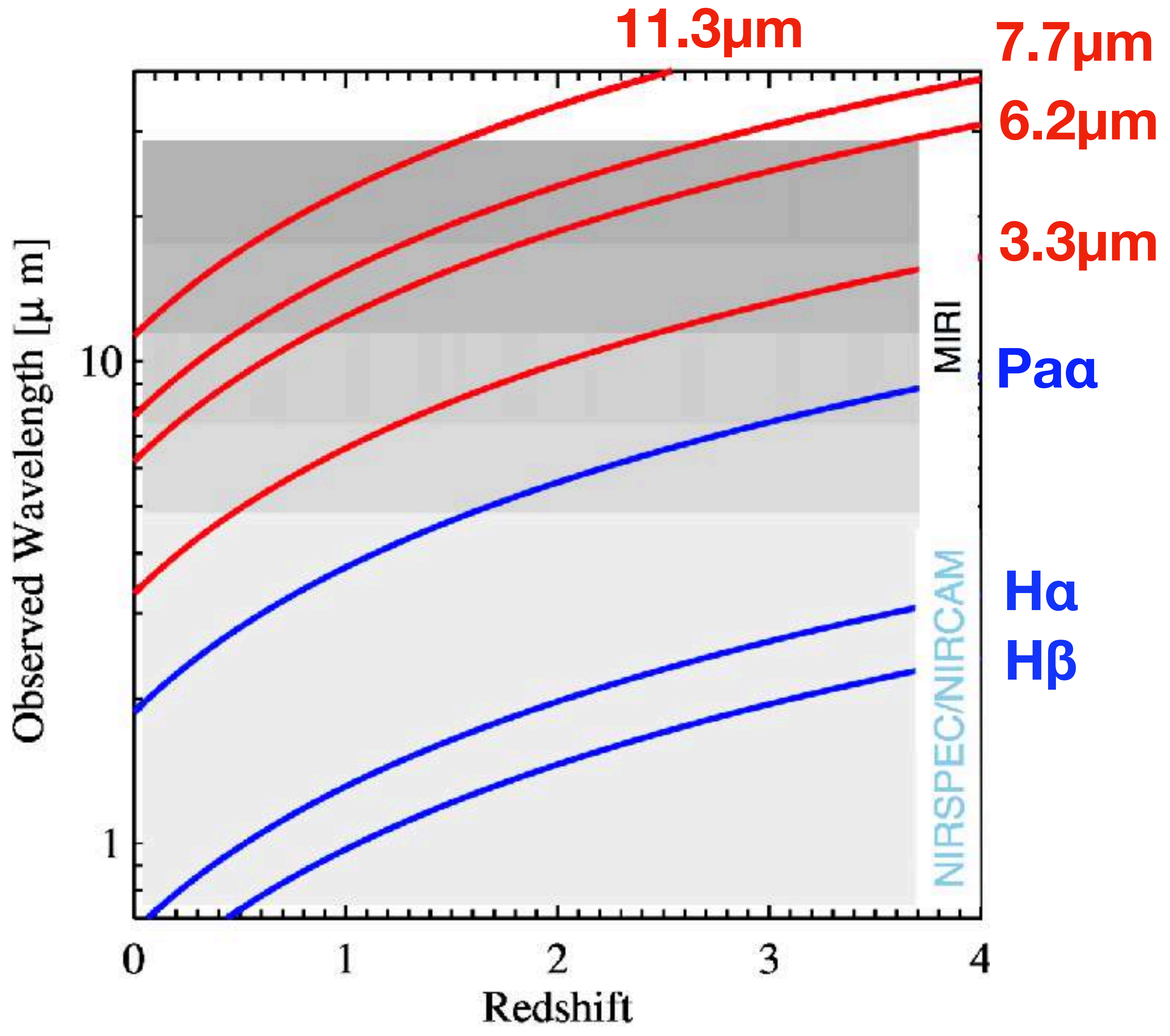
MIRI bands (5-28μm) will provide a very low-res spectra (R~5)

see: Rieke, Alberts, Shivaei+2019, *JWST/MIRI Surveys in GOODS-S*

COMPLETE PICTURE OF STAR FORMATION AT z~2

JWST/MIRI GTO EXTRAGALACTIC PROGRAM IN GOODS-SOUTH

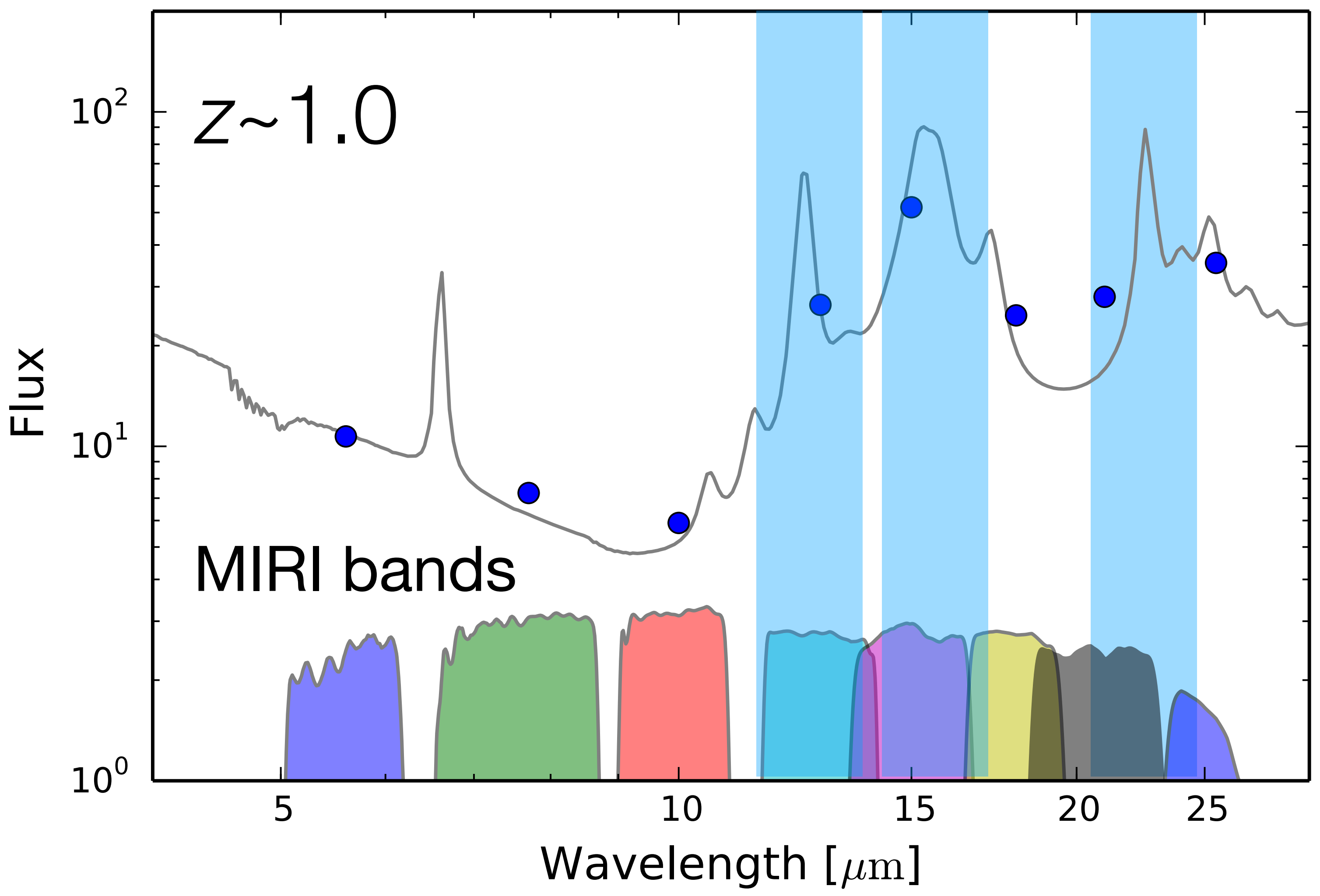
- > 800 galaxies with SFR >10 $M_\odot$/yr at z~1-2
- S/N~10 at 21μm
  - at z~2 corresponds to obscured SFR of ~10 $M_\odot$/yr and L(IR) ~ 10^{11} $L_\odot$
  - An order of magnitude deeper than Spitzer/MIPS

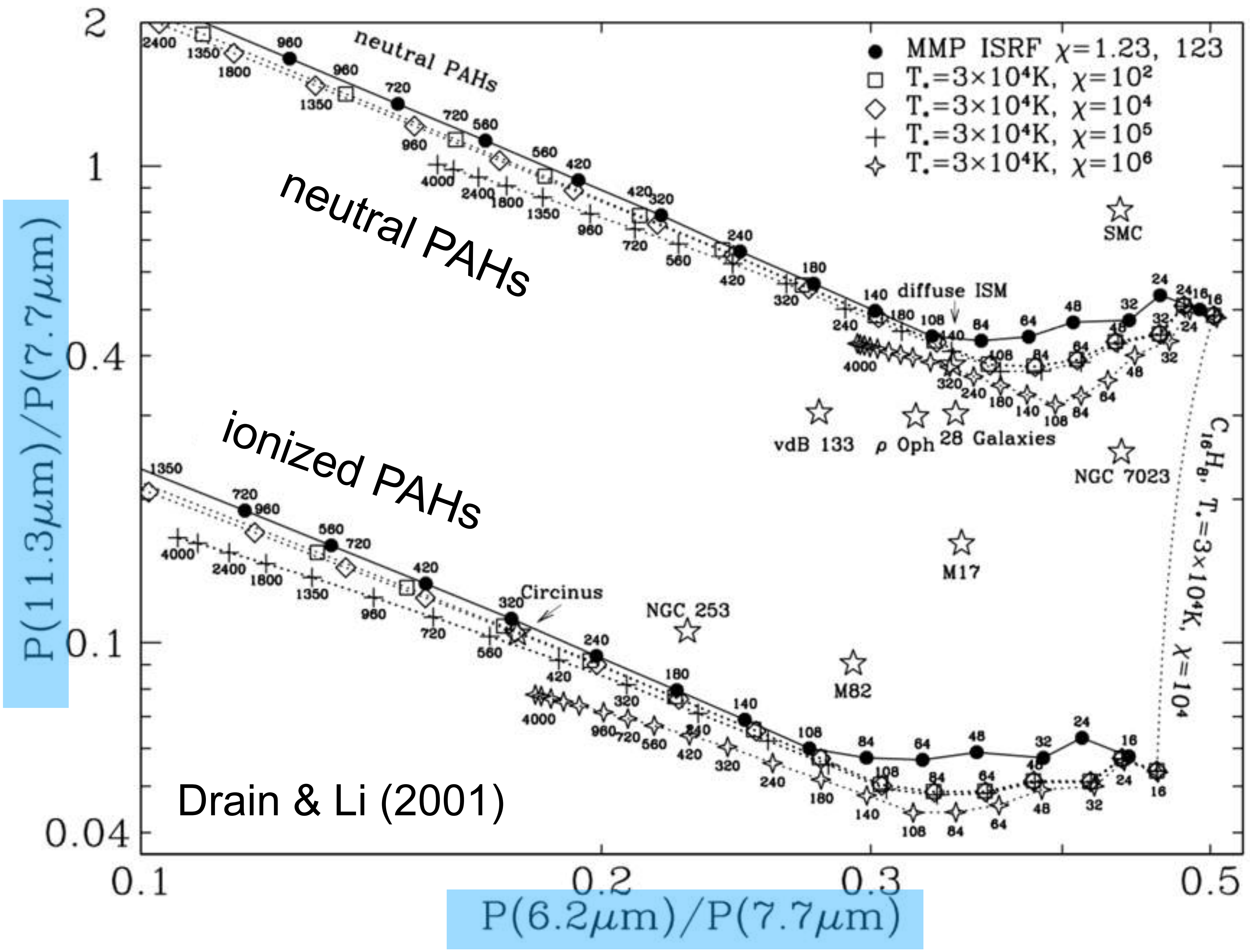


MID-IR AROMATIC BANDS RELATIVE INTENSITIES

JWST/MIRI GTO EXTRAGALACTIC PROGRAM IN GOODS-SOUTH

- Properties of PAH molecules in high-z galaxies
  - size and charge state



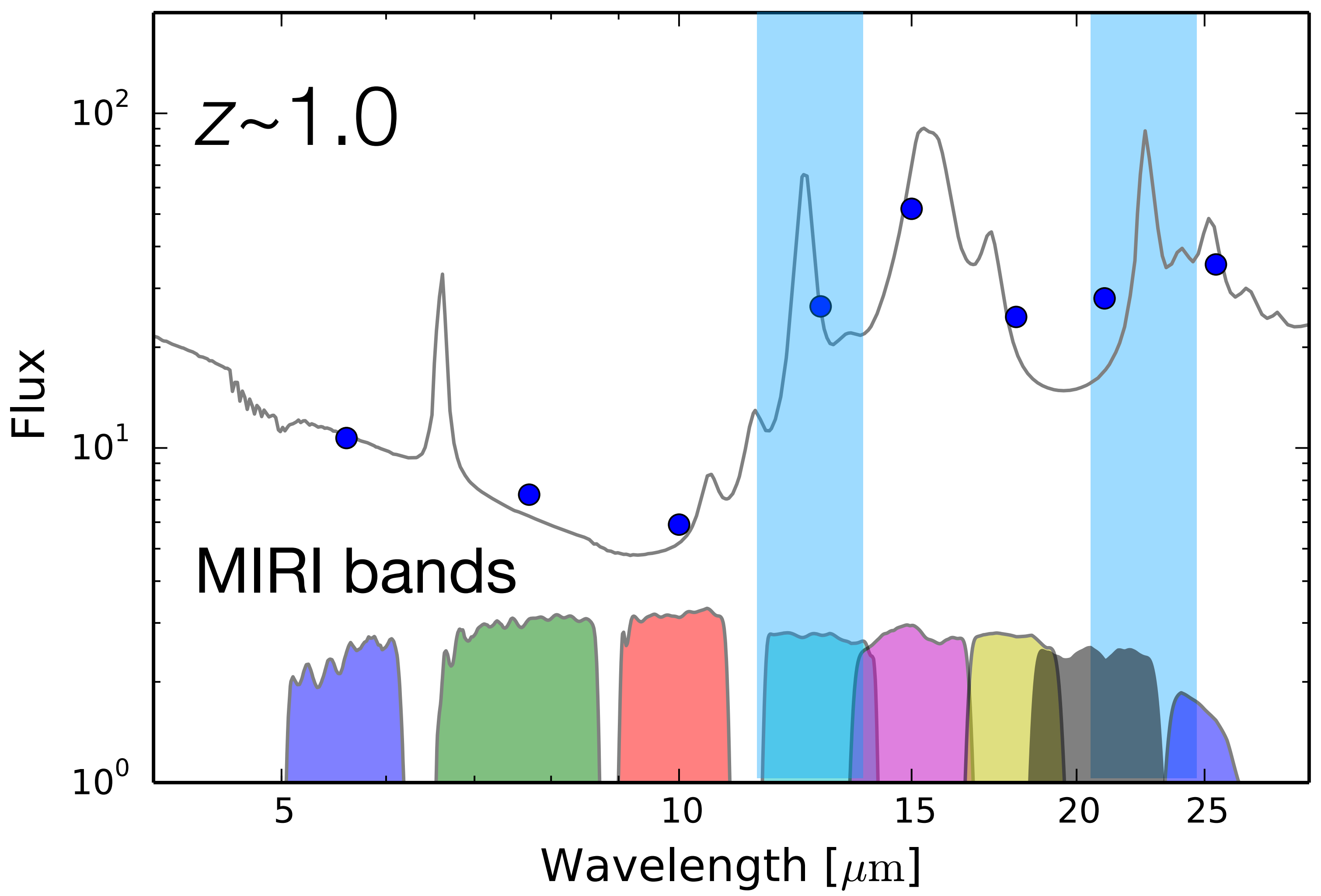


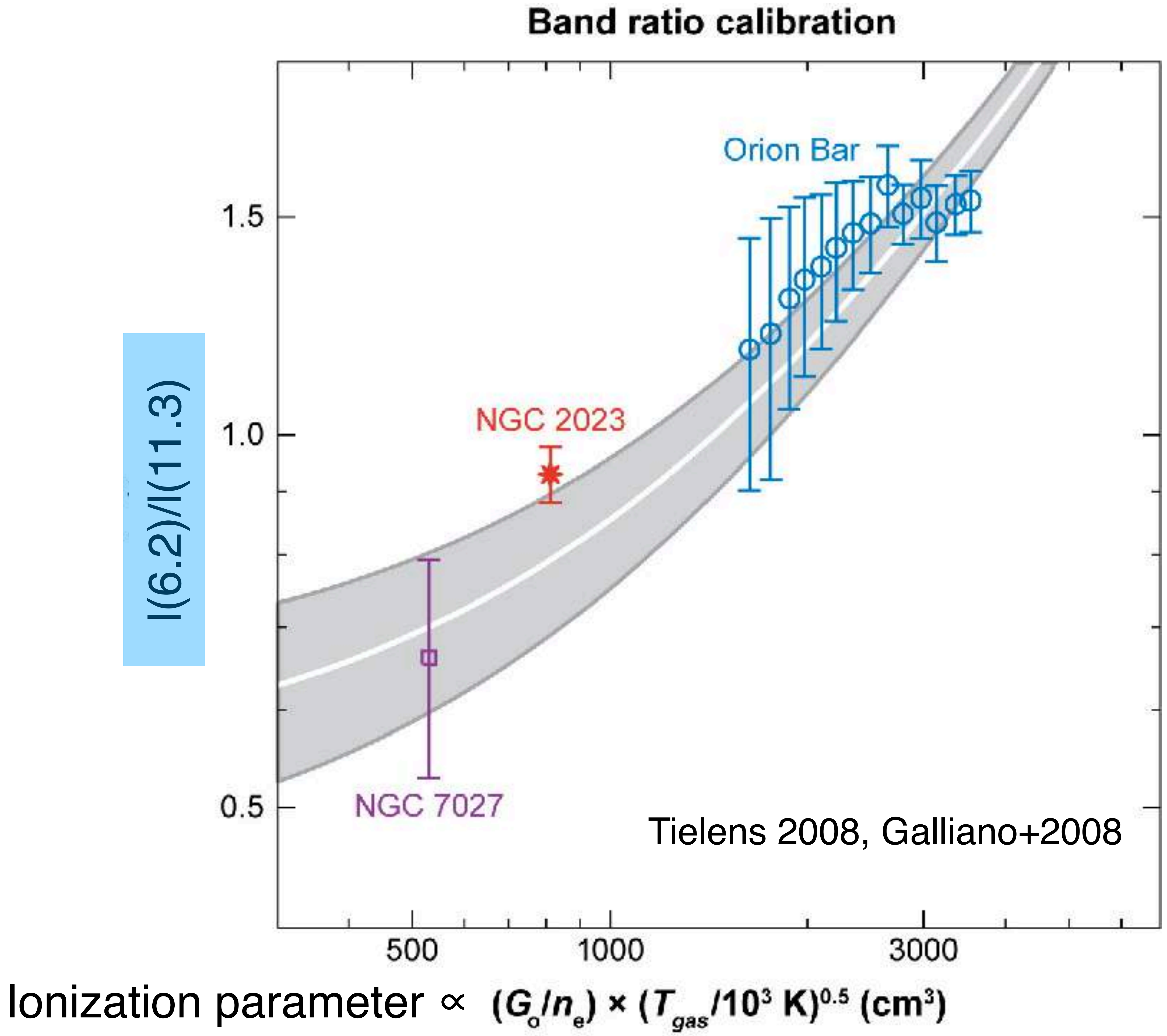
See also: Tielens 2008, Smith et al. 2007, Draine & Li 2007, Peeters et al. 2002, Hony et al. 2001, Galliano et al. 2008, Maragkoudakis et al. 2020

MID-IR AROMATIC BANDS RELATIVE INTENSITIES

JWST/MIRI GTO EXTRAGALACTIC PROGRAM IN GOODS-SOUTH

- Properties of PAH molecules in high-z galaxies
  - size and charge state
- Physical conditions of ISM and emitting sources
  - the radiation field to which PAHs are exposed to



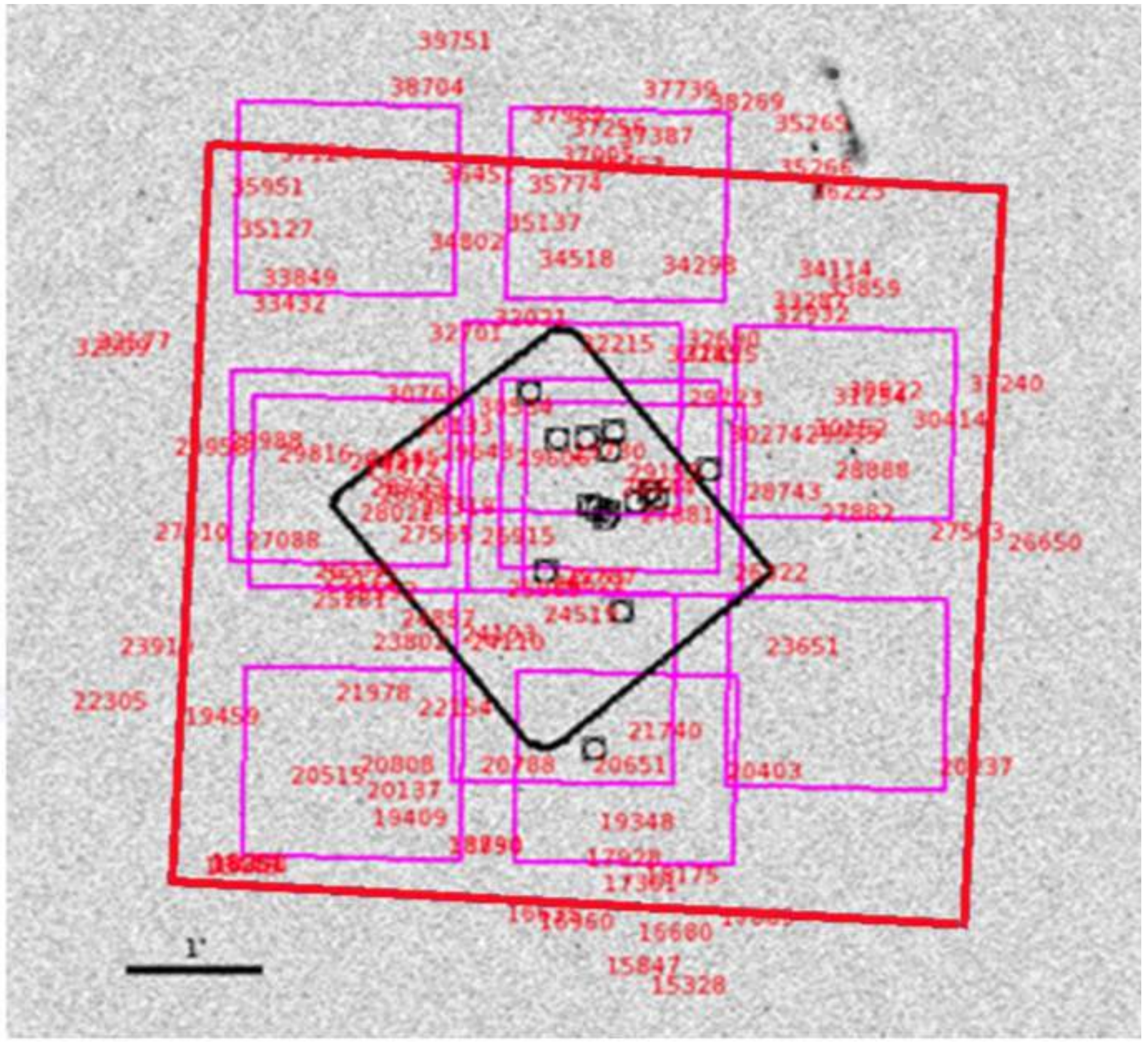


See also: Tielens 2008, Smith et al. 2007, Draine & Li 2007, Peeters et al. 2002, Hony et al. 2001, Galliano et al. 2008, Maragkoudakis et al. 2020

NIRSPEC SPECTROSCOPIC FOLLOWUP

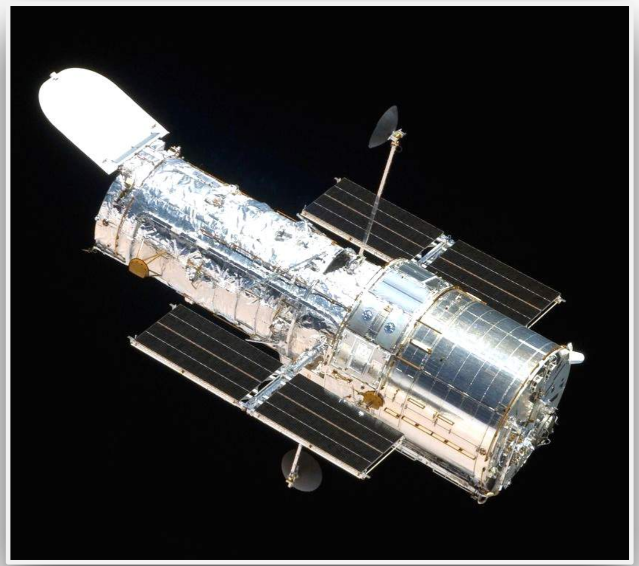
JWST/MIRI GTO EXTRAGALACTIC PROGRAM IN GOODS-SOUTH

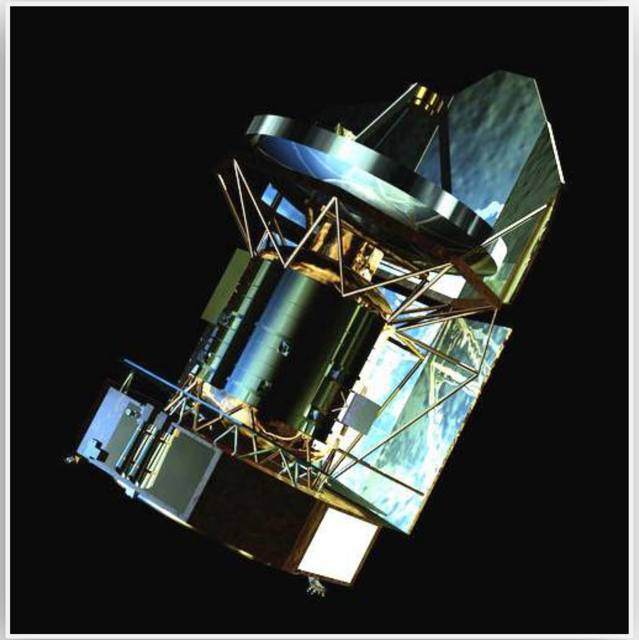
- NIRSpec MSA, 1-5μm, R=1000
  - G140M/F100LP: 7ksec
  - G235M/F170LP: 7ksec
  - G395M/F290LP: 3.5ksec
- 3 pointings
- [OII], Hβ, [OIII], Hα, [NII], Paα
- Hα SFRs ~ 1$M_\odot$/yr at z~2
  - $F_{H\alpha}$ ~ 10^{-18} erg/s/cm^2



SUMMARY


- The first studies that connect the ionized gas properties to dust attenuation and emission features in typical L* galaxies at Cosmic Noon:
  - A steep attenuation curve at low gas metallicities (steeper than the Calzetti starburst curve)
  - Hotter and a wider range of dust temperatures at sub-solar metallicities
  - Understand the physics of ISM and its evolution compared to z~0





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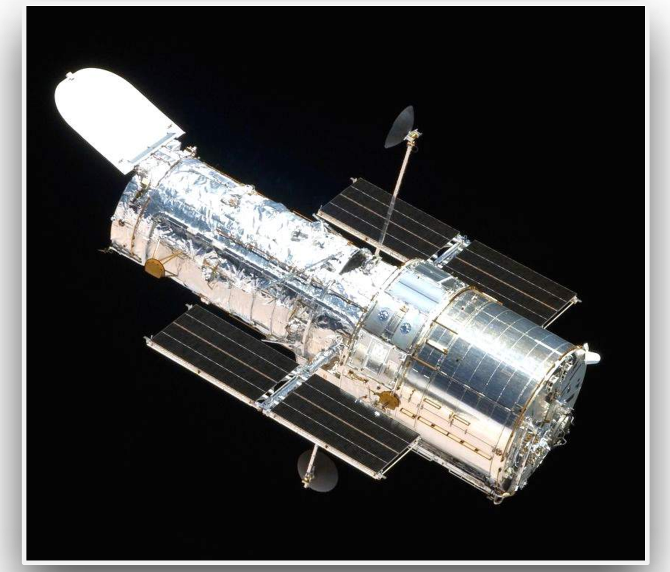

- Multi-wavelength spectroscopic and photometric surveys of galaxies and AGN at z~1-3 are the next frontier: