DUST ATTENUATION IN DUSTY STAR-FORMING GALAXIES

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In collaboration with

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Szkoła Doktorska - NCBJ

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PRELUDIUM 21

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The "Black Cloud" B68
(VLT ANTU + FORS1)
ESO PR Photo 20a/99 (30 April 1999)
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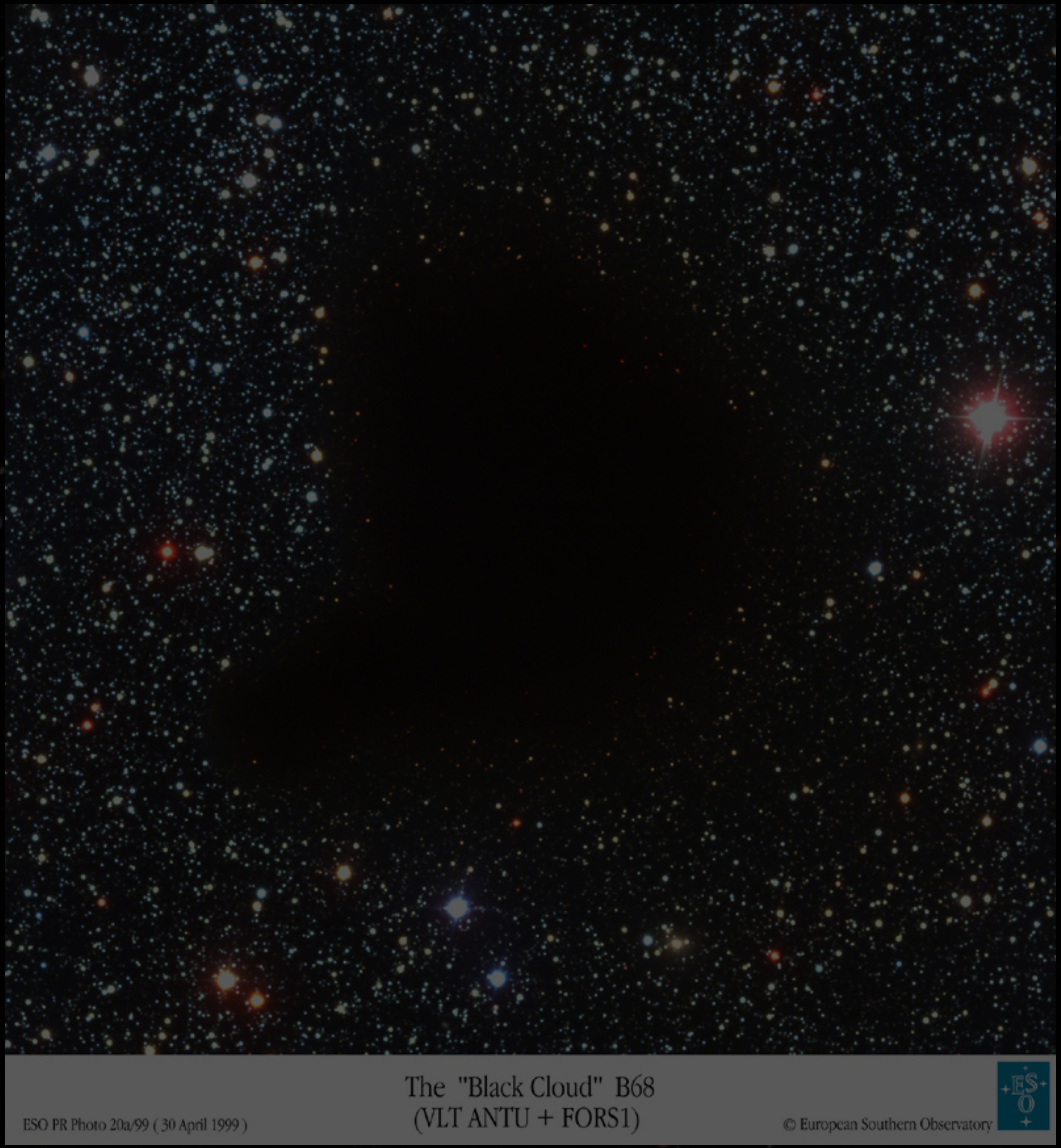
The "Black Cloud" B68
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ESO PR Photo 20a/99 (30 April 1999)
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Outflows
Inflows
Supernovae
Gas cooling
AGN
ISM
Molecular clouds
Star Formation


Outflows
Supernovae
Gas cooling
ISM
Molecular
clouds
Star Formation

DUST ABSORPTION
DUST EMISSION
S_ν (mJy)
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
1
10^0
10^1
10^2
10^3
10^4
10^5
Observed λ (μm)
GALEX
Hubble
JWST
Herschel
ALMA
VLA


MOST OF THE UV PHOTONS ARE LOST
WE CAN RECOVER THEM WITH
ATTENUATION CURVES
UV
STARS
DUST
IR
OBSERVER

THE EXACT SHAPE OF ATTENUATION IS UNKNOWN

$$A_\lambda = m_\lambda - m_{\lambda,0}$$

attenuated unattenuated

A_λ/A_V = The shape of the curve at e.g. λ = 5500 Å

is an attenuation law

UV-optical Slope:
$S \equiv A_{1500}/A_V$

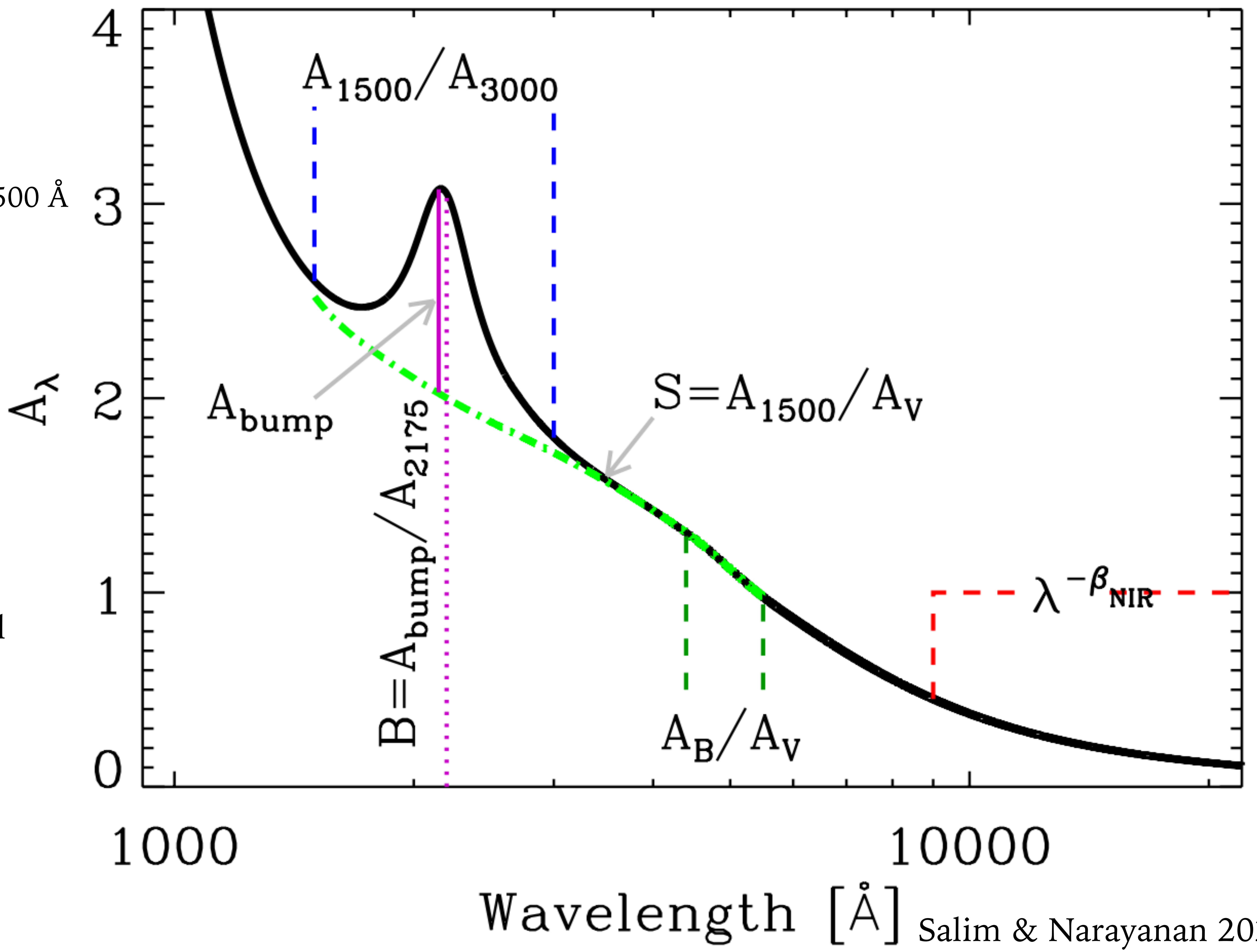
UV (2175 Å) Bump Strength:
$B \equiv A_{\rm bump}/A_{2175}$

UV Slope:
A_{1500}/A_{3000}

Optical Slope:
A_B/A_V

Near-IR Slope: $\beta_{\rm NIR}$
where $A_\lambda/A_V = (\lambda/5500\text{Å})^{\beta_{\rm NIR}}$

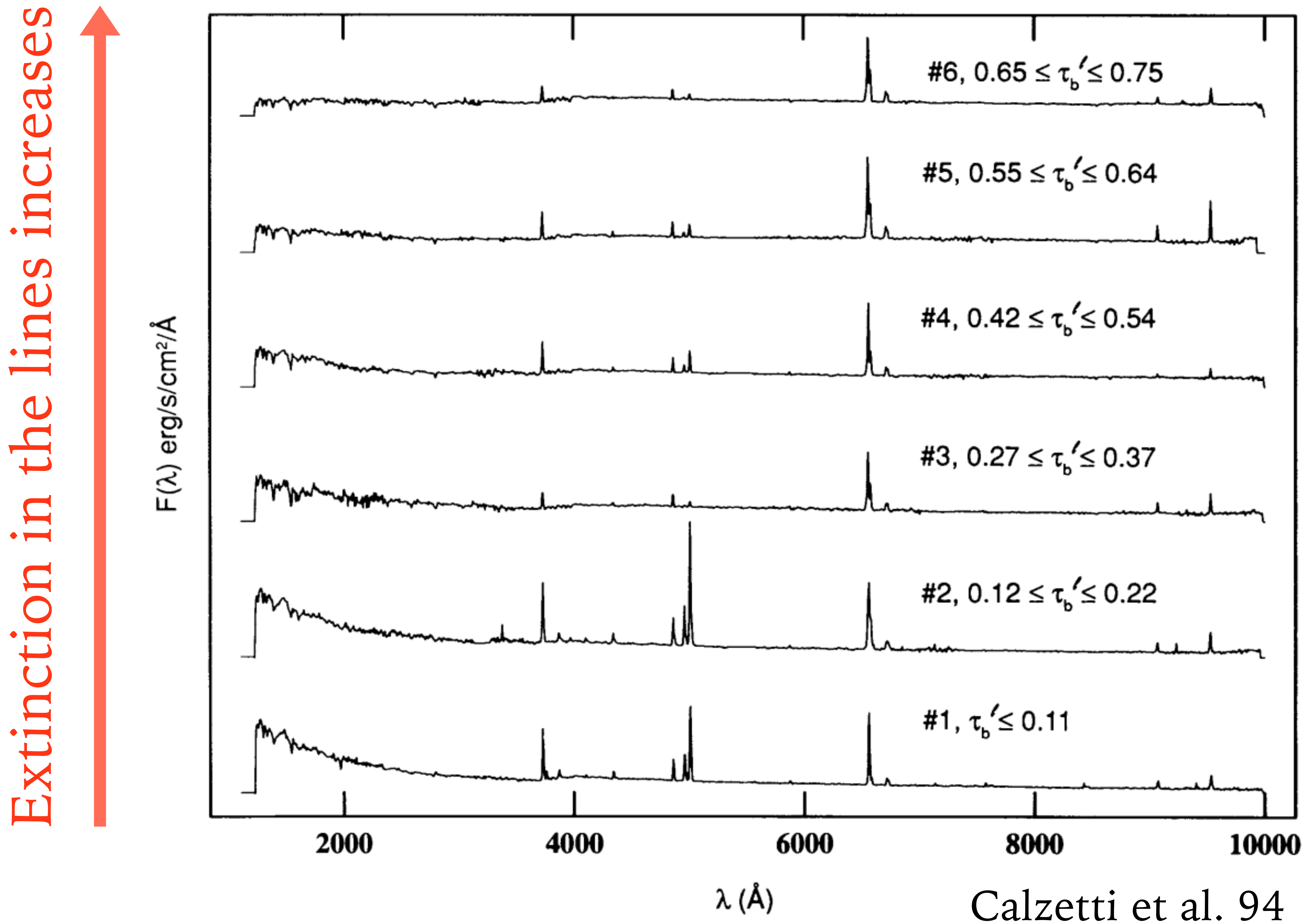
additional features



Salim & Narayanan 2020

The original attenuation law of Calzetti et al., 1994 ⟶ 2000

It is an empirical law measured on a sample of nearby starburst galaxies



Calzetti et al. 94

The UV-visible spectrum, and $H\alpha/H\beta$ vary with dust reddening

Models were developed to understand its shape

Consistent at high redshift (normal star-forming galaxies)

Attenuation law of
Charlot & Fall 2000

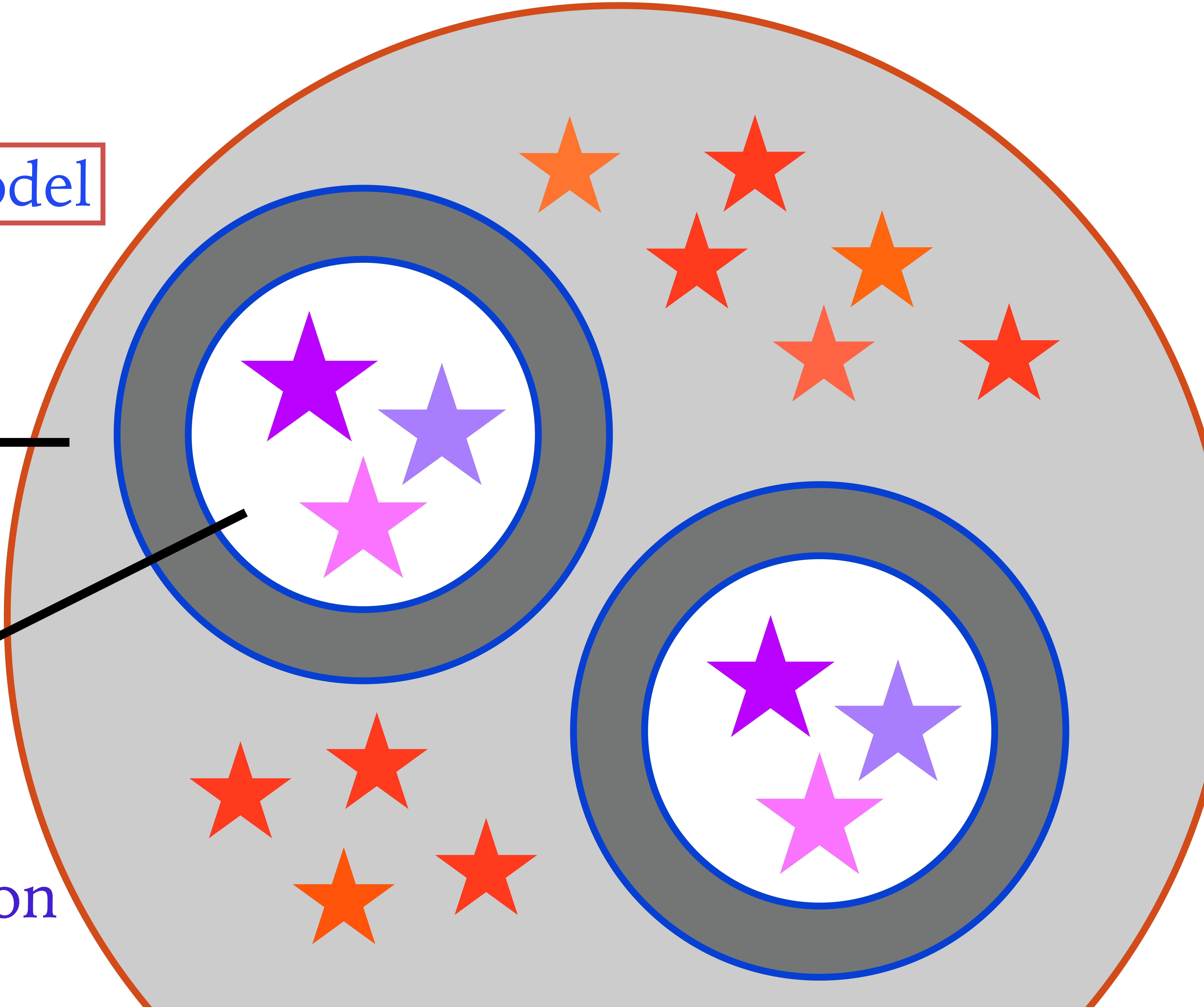
a physically- motivated $\boxed{\text{model}}$

Diffuse ISM

Old stellar population

Stellar nurseries
(birth clouds)

Young stellar population



Calzetti 2000 like laws

Calibrated on 39 nearby UV-bright SBs (Calzetti et al. 1994)
Is the most currently used also at high redshift.

$$A(\lambda) = \frac{A_{\mathrm{V}}}{4.05}\left(k'(\lambda) + D_{\lambda_0,\gamma,E_{\mathrm{b}}}(\lambda)\right)\left(\frac{\lambda}{\lambda_{\mathrm{V}}}\right)^{\delta}$$

Charlot & Fall 2000 law

2 dust components: Birth clouds & ISM

$$A_\lambda = \begin{cases} A_{V,\mathrm{ISM}}\left(\frac{\lambda}{\lambda_V}\right)^{-n_{\mathrm{ISM}}} + A_{V,\mathrm{BC}}\left(\frac{\lambda}{\lambda_V}\right)^{-n_{\mathrm{BC}}} & t \leq t_{\mathrm{threshold}} \\ A_{V,\mathrm{ISM}}\left(\frac{\lambda}{\lambda_V}\right)^{-n_{\mathrm{ISM}}} & t > t_{\mathrm{threshold}} \end{cases}$$

Calzetti 2000 like laws

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slope of the attenuation curve

$$A(\lambda) = \frac{A_V}{4.05}\left(k'(\lambda) + D_{\lambda_0,\gamma,E_b}(\lambda)\right)\left(\frac{\lambda}{\lambda_V}\right)^{\delta}$$

starburst reddening curve   UV bump   5500 Å

Charlot & Fall 2000 law

2 dust components: Birth clouds & ISM

Slopes

$$A_\lambda = \begin{cases} A_{V,\mathrm{ISM}}\left(\frac{\lambda}{\lambda_V}\right)^{-n_{\mathrm{ISM}}} + A_{V,\mathrm{BC}}\left(\frac{\lambda}{\lambda_V}\right)^{-n_{\mathrm{BC}}} & t \leq t_{\mathrm{threshold}} \\ A_{V,\mathrm{ISM}}\left(\frac{\lambda}{\lambda_V}\right)^{-n_{\mathrm{ISM}}} & t > t_{\mathrm{threshold}} \end{cases}$$

Stellar age

CF00 found that $n_{BC} = n_{ISM} = 0.7$ was able to satisfy the dust attenuation in nearby galaxies

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starburst reddening curve   UV bump   5500 Å

a measure

Charlot & Fall 2000 law

2 dust components: Birth clouds & ISM

Slopes

$$A_\lambda = \begin{cases} A_{V,\mathrm{ISM}}\left(\frac{\lambda}{\lambda_V}\right)^{-n_{\mathrm{ISM}}} + A_{V,\mathrm{BC}}\left(\frac{\lambda}{\lambda_V}\right)^{-n_{\mathrm{BC}}} & t \le t_{\mathrm{threshold}} \\ A_{V,\mathrm{ISM}}\left(\frac{\lambda}{\lambda_V}\right)^{-n_{\mathrm{ISM}}} & t > t_{\mathrm{threshold}} \end{cases}$$

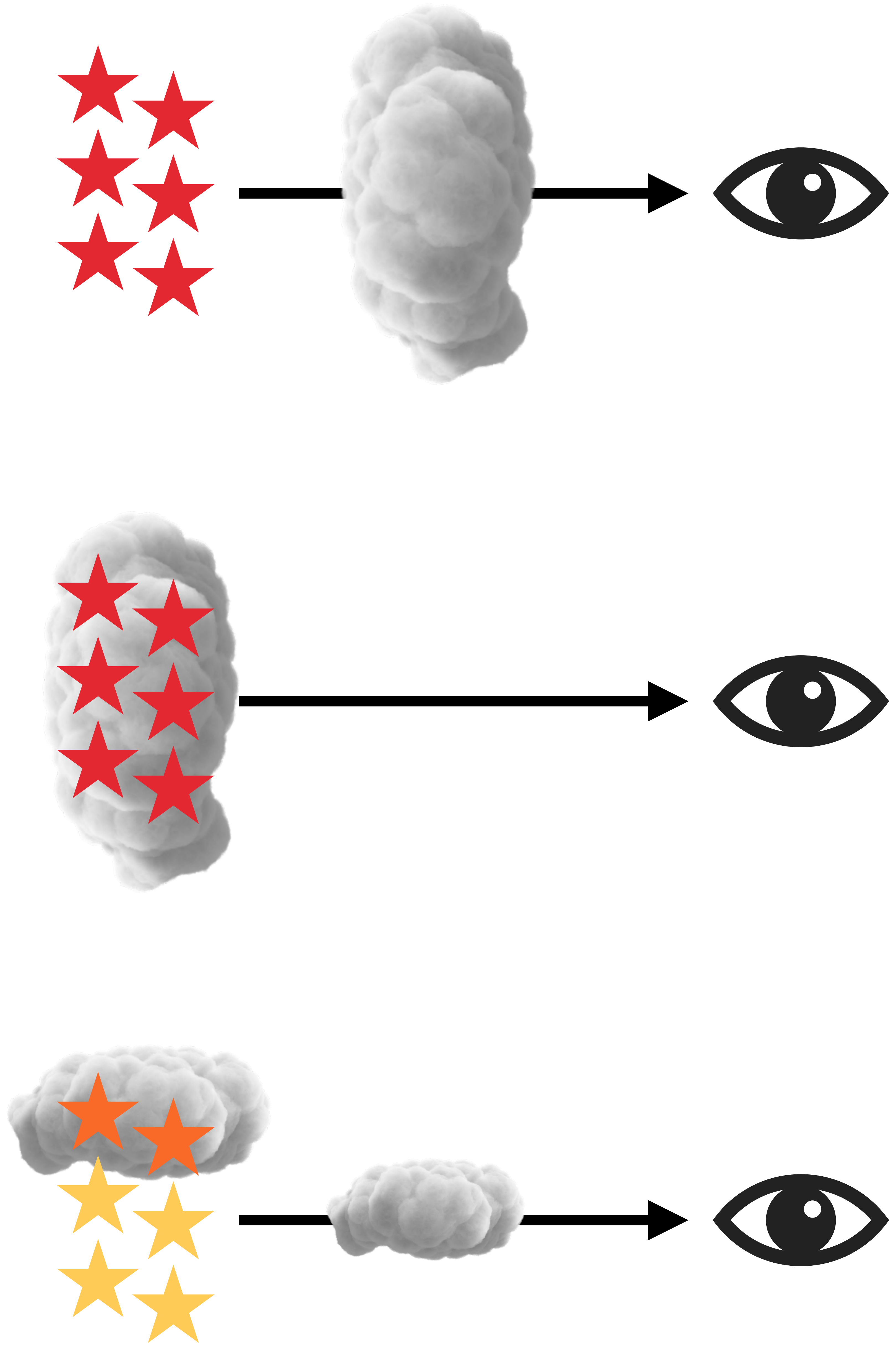
Stellar age

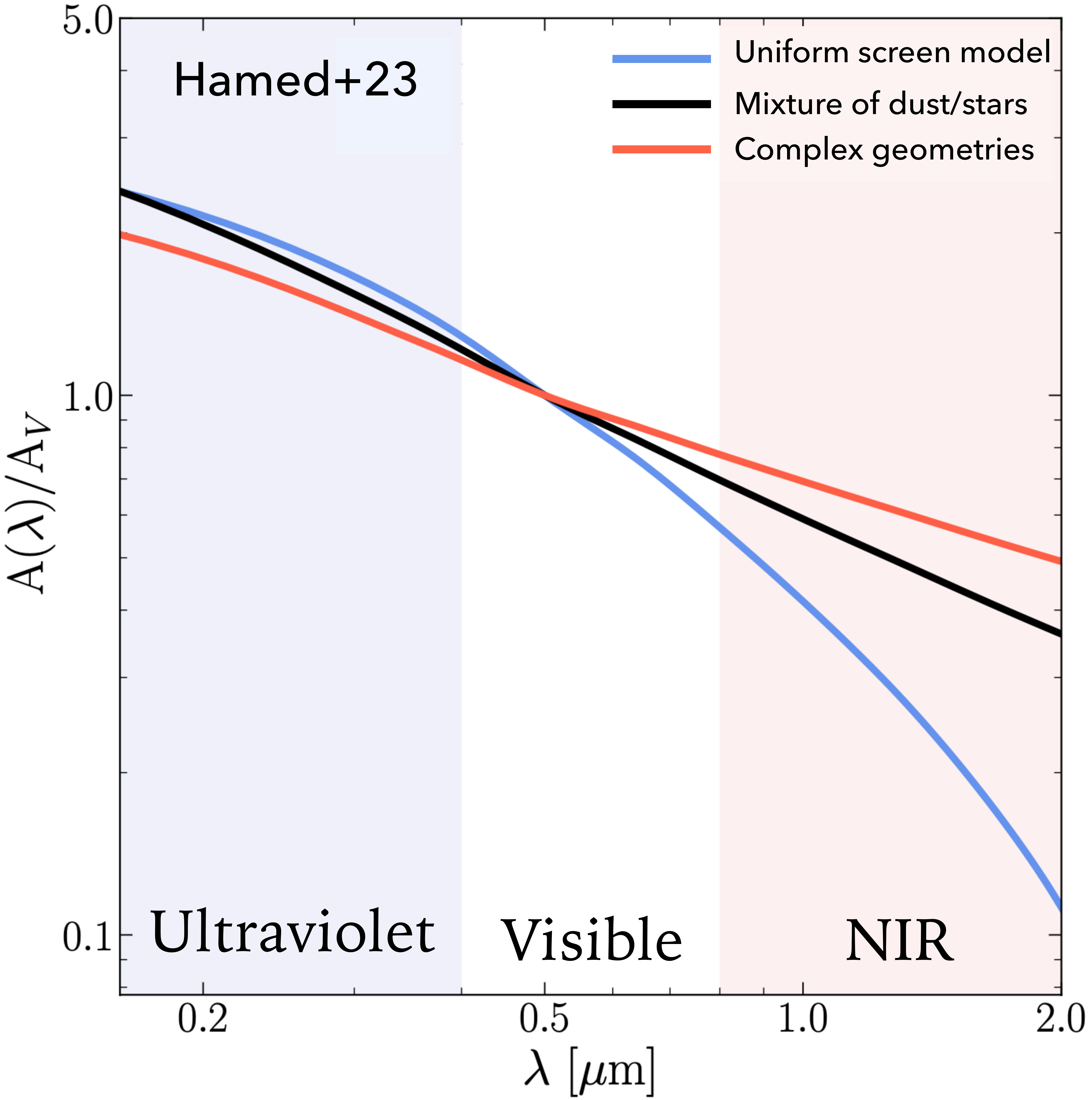
CF00 found that $n_{BC} = n_{ISM} = 0.7$ was able to satisfy the dust attenuation in nearby galaxies

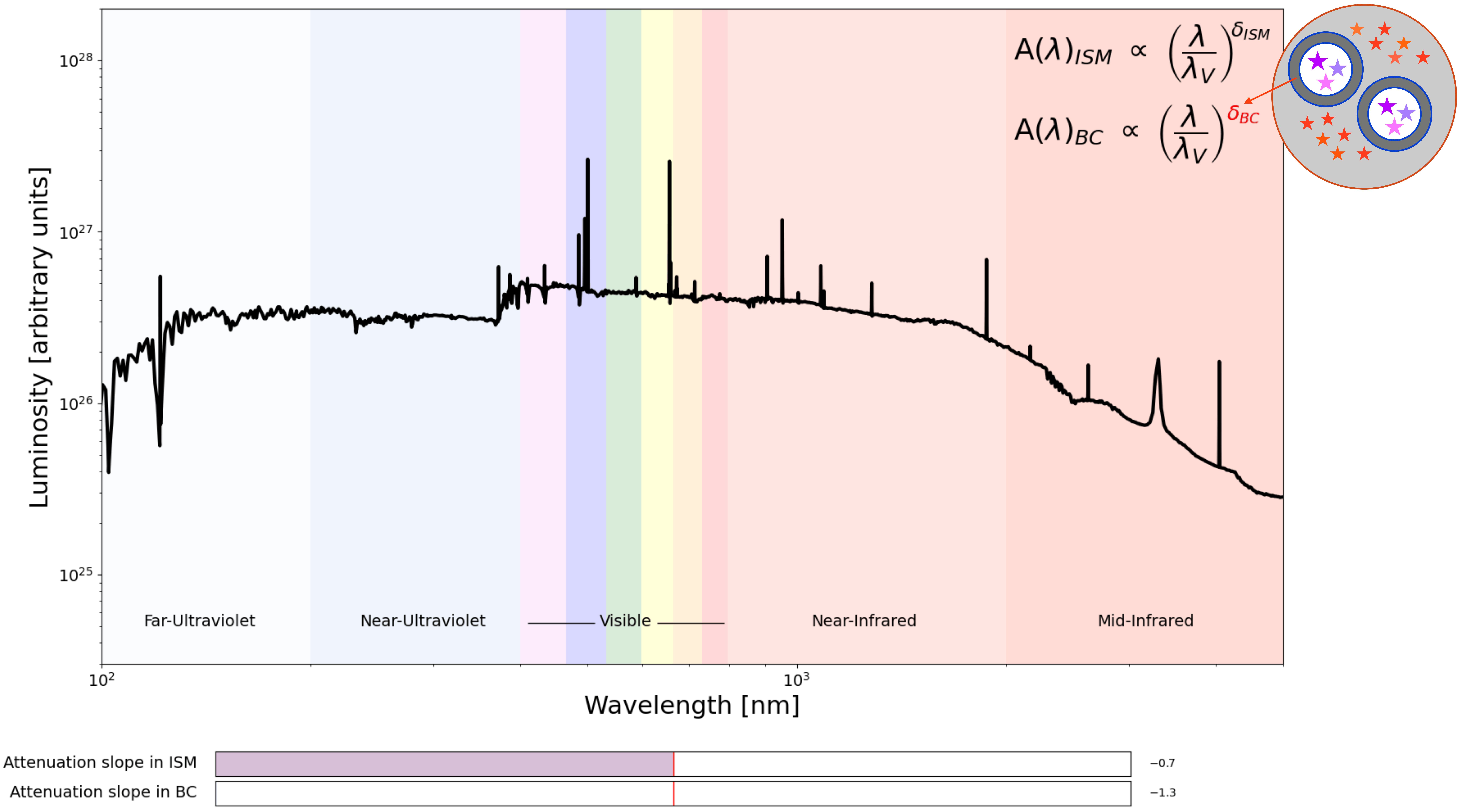
a model

More simplified geometries with obscuration in the ultraviolet result in steeper curves More complex geometries with clumpy dust result in flatter curves

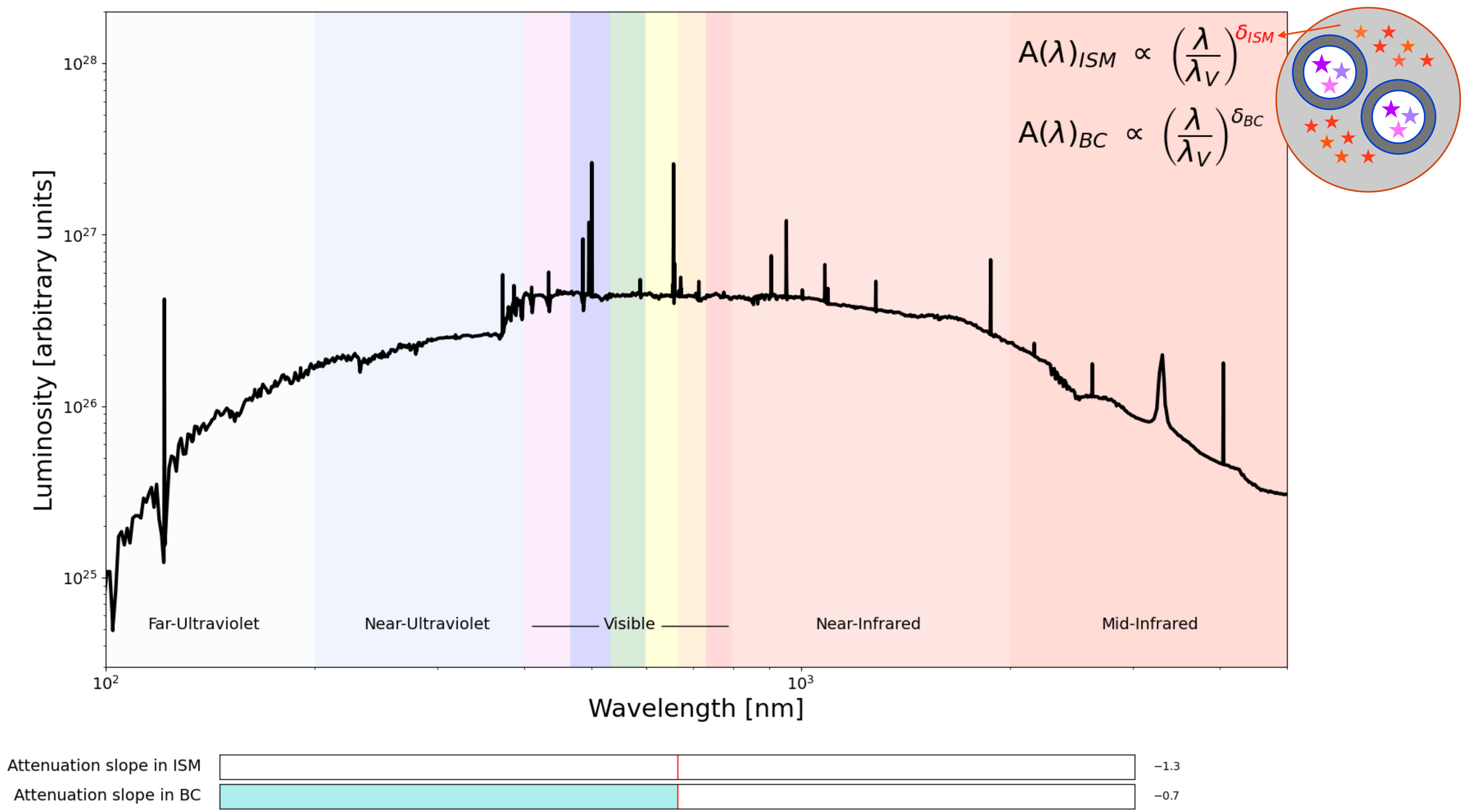
DUST ATTENUATION IS NOT UNIVERSAL!







$A(\lambda)_{ISM} \propto \left(\frac{\lambda}{\lambda_V}\right)^{\delta_{ISM}}$
$A(\lambda)_{BC} \propto \left(\frac{\lambda}{\lambda_V}\right)^{\delta_{BC}}$
δ_{BC}
Luminosity [arbitrary units]
10^{28}
10^{27}
10^{26}
10^{25}
Far-Ultraviolet
Near-Ultraviolet
Visible
Near-Infrared
Mid-Infrared
10^{2}
10^{3}
Wavelength [nm]
Attenuation slope in ISM
−0.7
Attenuation slope in BC
−1.3



$A(\lambda)_{ISM} \propto \left(\frac{\lambda}{\lambda_V}\right)^{\delta_{ISM}}$
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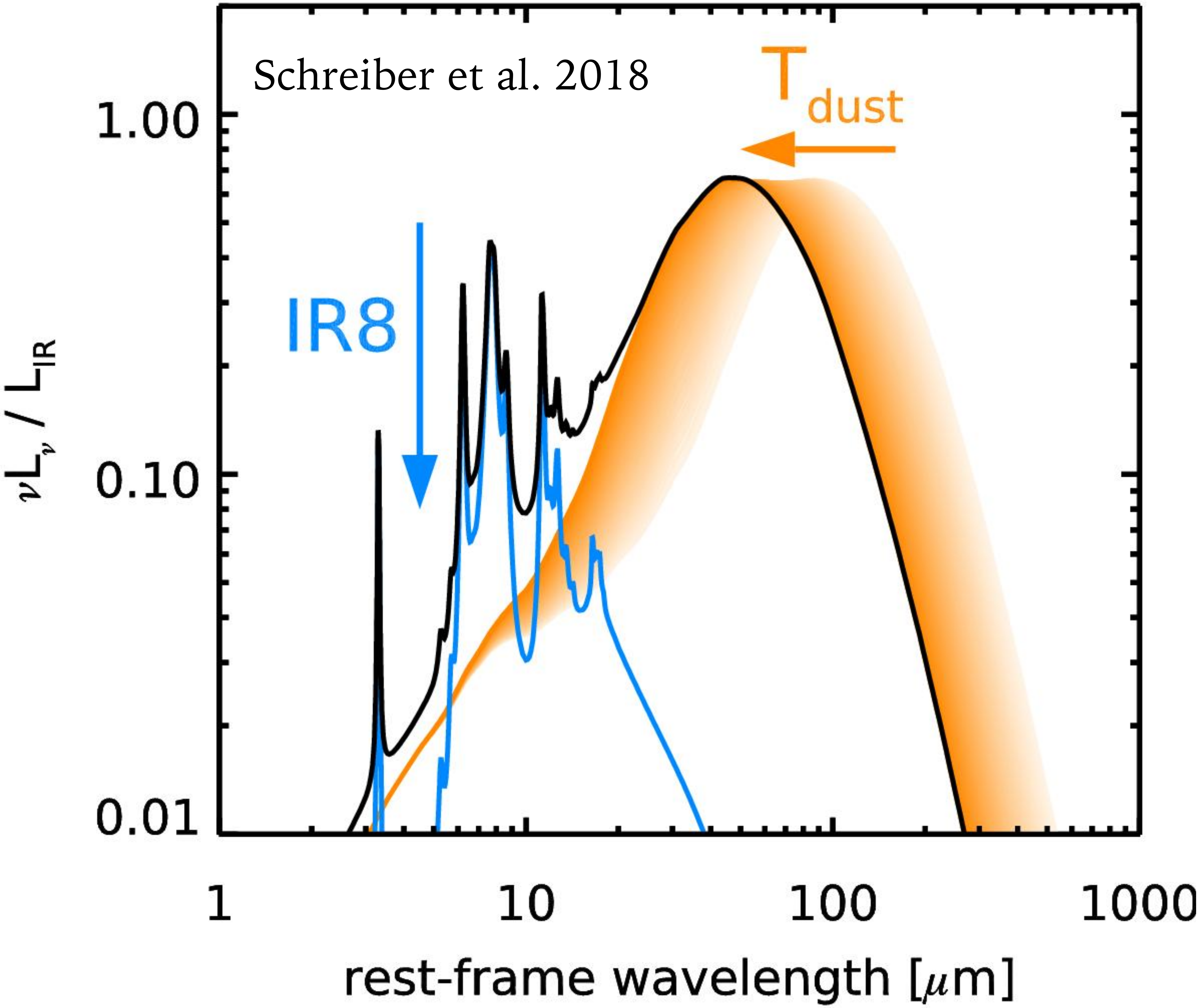
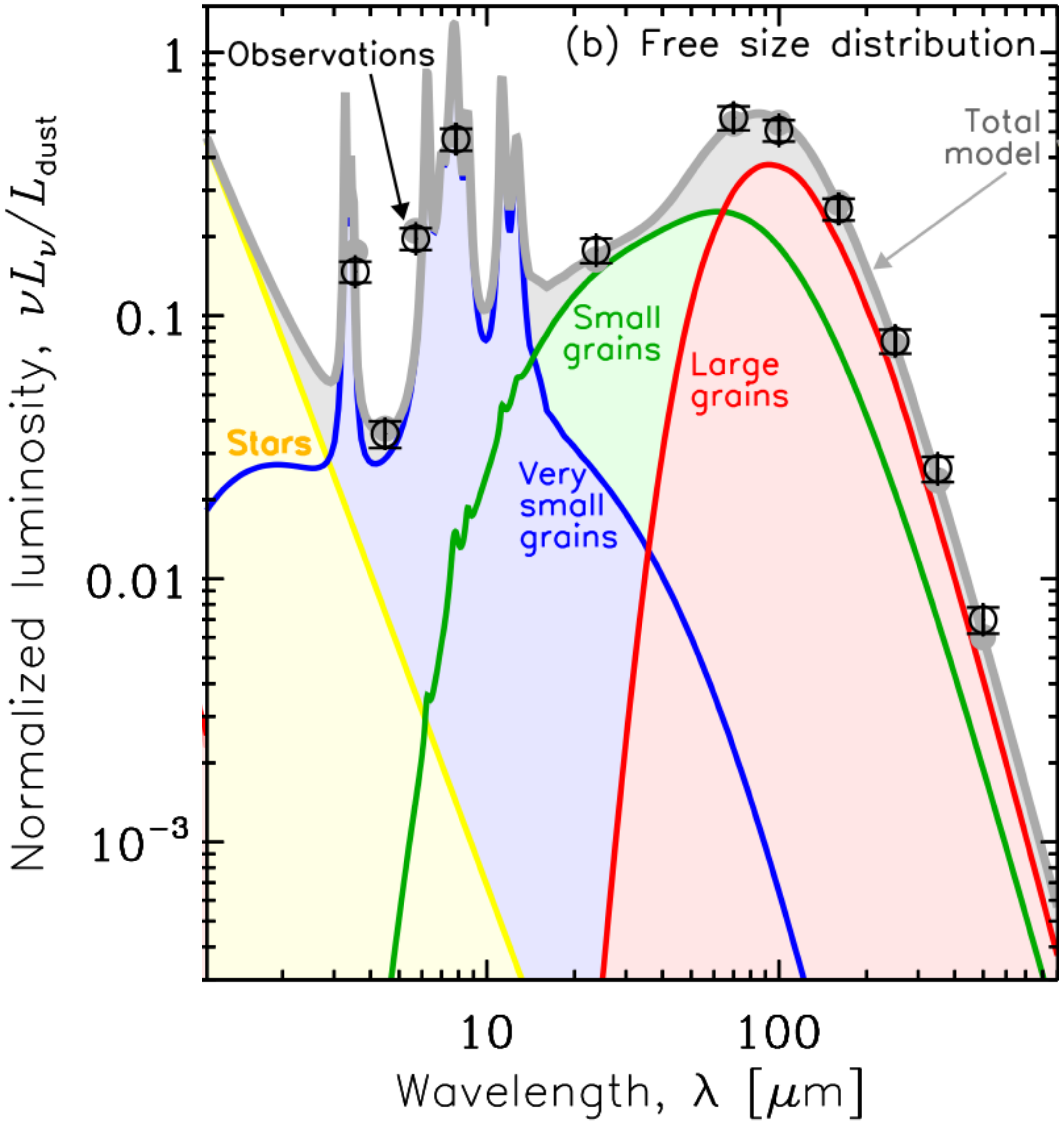
δ_{ISM}
Luminosity [arbitrary units]
10^{28}
10^{27}
10^{26}
10^{25}
Far-Ultraviolet
Near-Ultraviolet
Visible
Near-Infrared
Mid-Infrared
10^2
10^3
Wavelength [nm]
Attenuation slope in ISM
−1.3
Attenuation slope in BC
−0.7

DUST EMISSION





Galliano et al. 2017

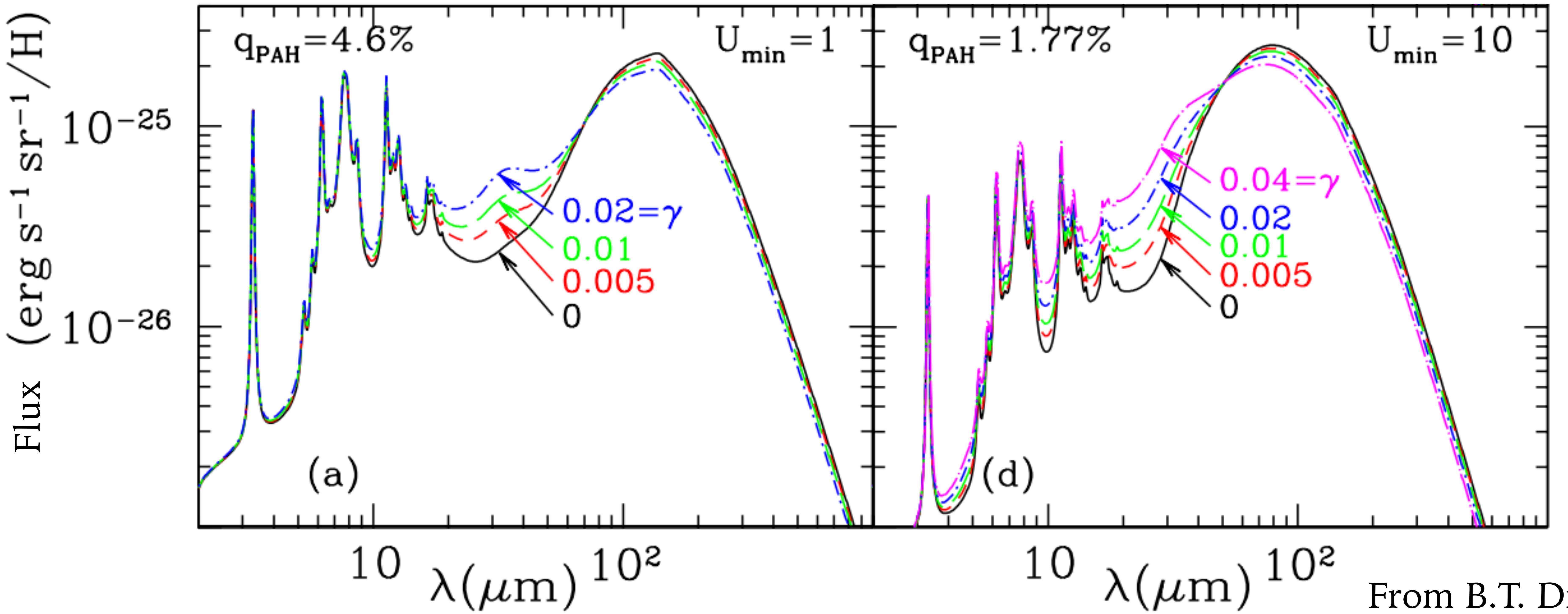
Many models; Dale et al. (2001), Dale & Helou (2002), Schreiber et al. (2018), Draine & Li (2014)

$$\boxed{\frac{dM_{\rm dust}}{dU} = (1-\gamma)M_{\rm dust}\ \ (U - U_{\rm min}) + \gamma M_{\rm dust}\frac{(\alpha-1)}{[U_{\rm min}^{1-\alpha} - U_{\rm max}^{1-\alpha}]}U^{-\alpha}}$$

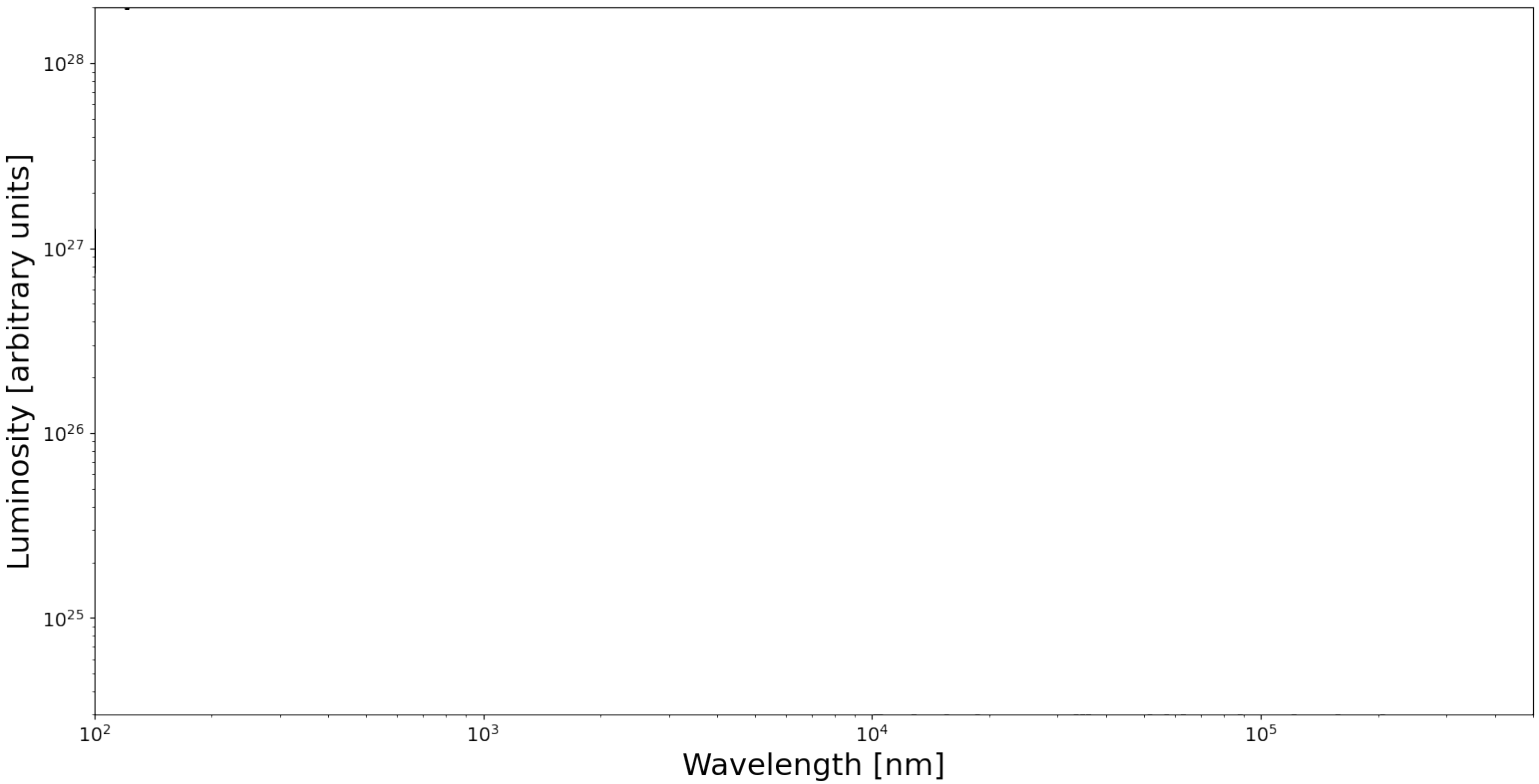
Starlight intensity *U*: $U_{\rm min} < U < U_{\rm max}$

$dM_{\rm dust}$: mass of dust heated by starlight intensities

$(1-\gamma)$ is the fraction of the dust mass that is exposed to starlight

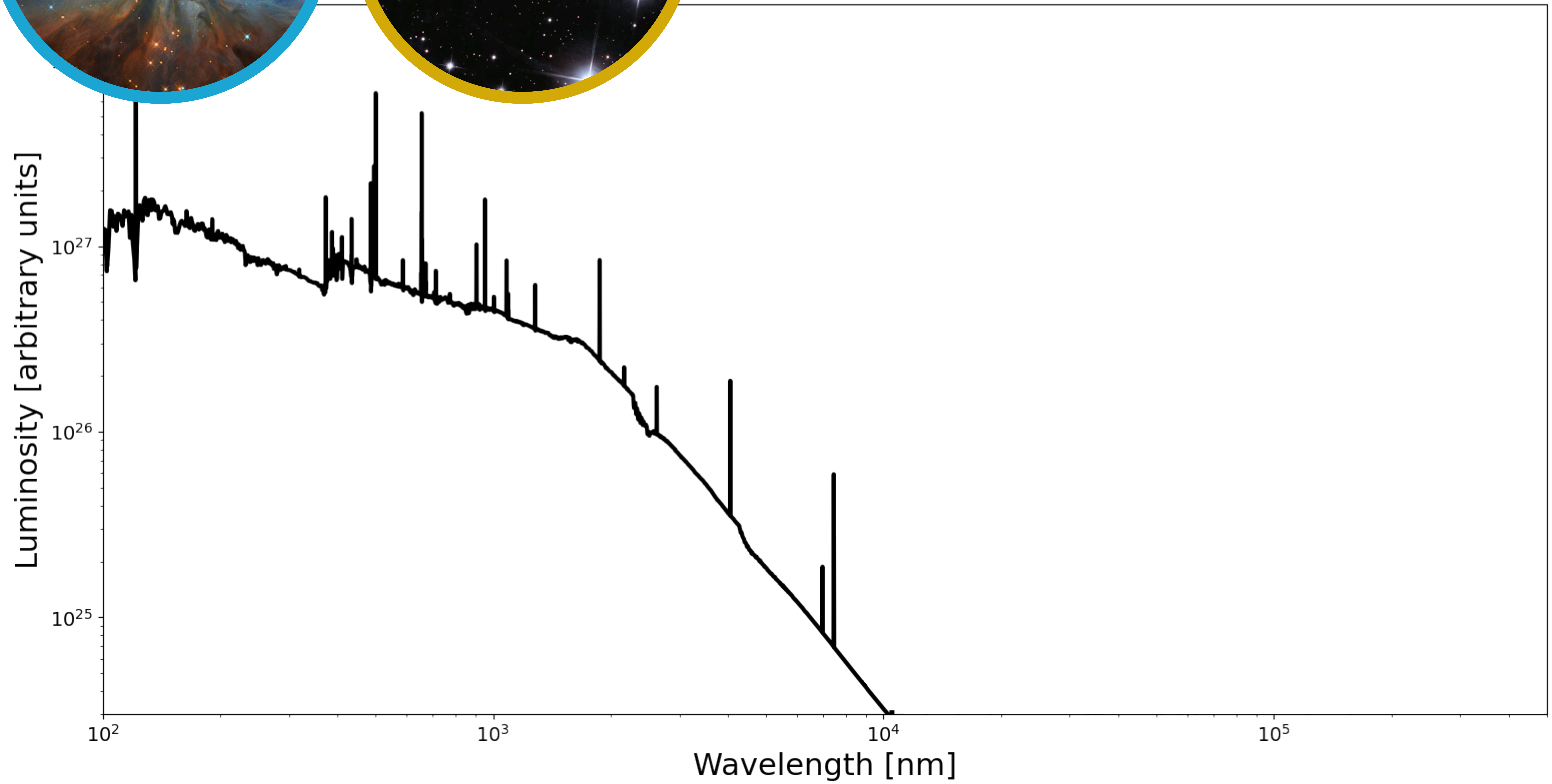


From B.T. Draine 2007

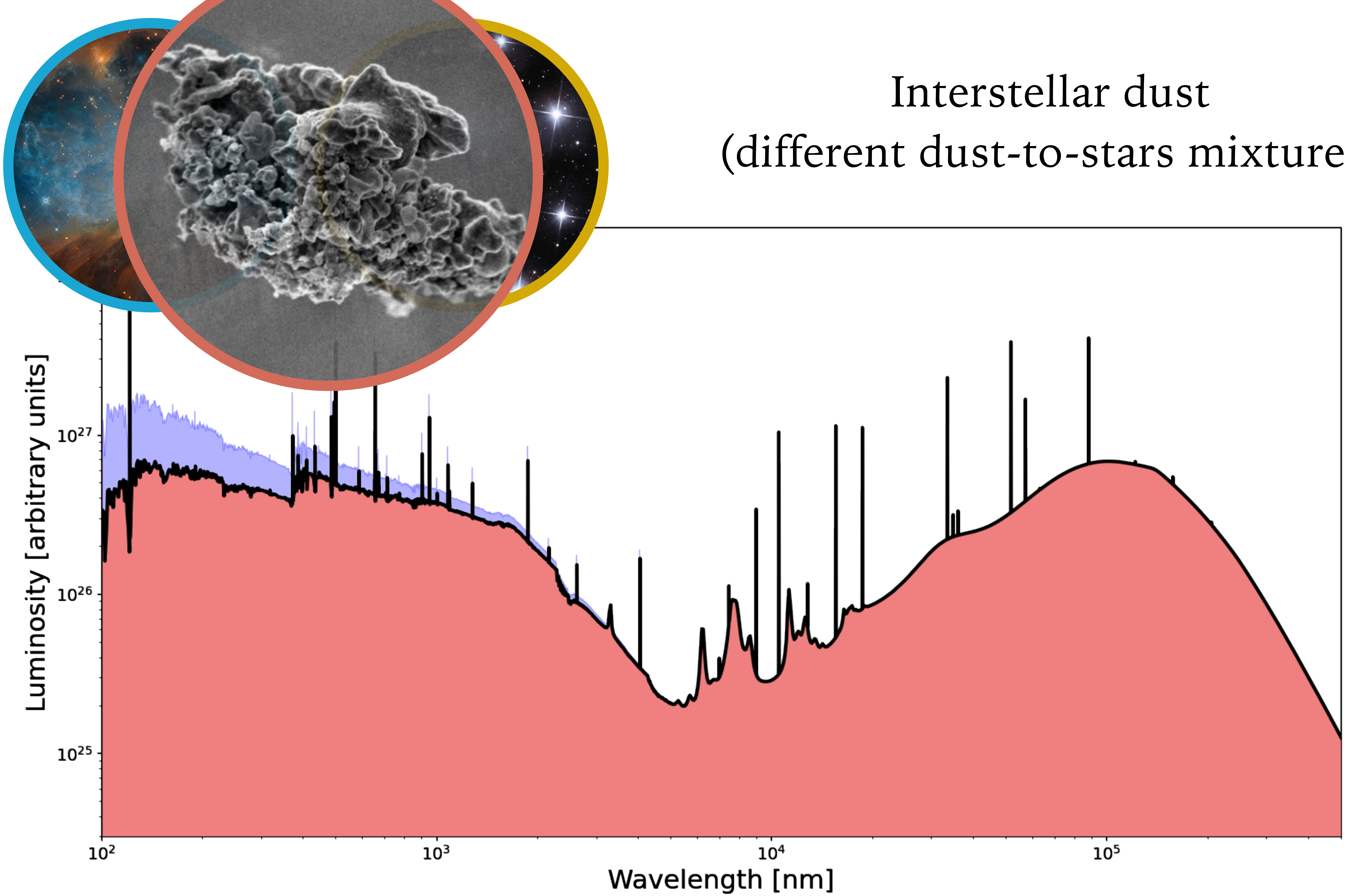


Luminosity [arbitrary units]
10^{28}
10^{27}
10^{26}
10^{25}
10^{2}
10^{3}
10^{4}
10^{5}
Wavelength [nm]

Stellar population: stars at different ages, different metallicities (assuming a SFH)



Interstellar dust
(different dust-to-stars mixtures)



Interstellar dust
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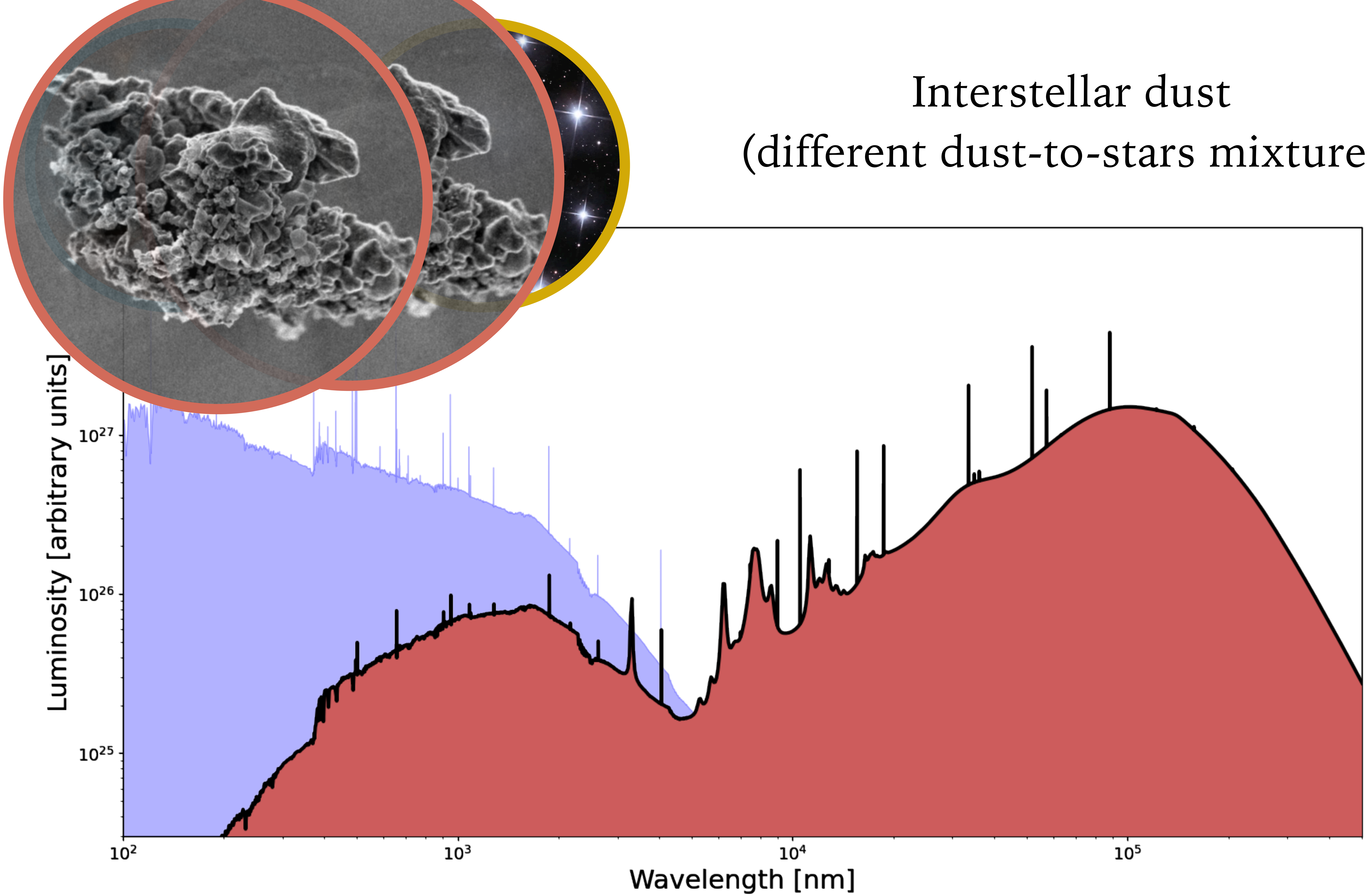
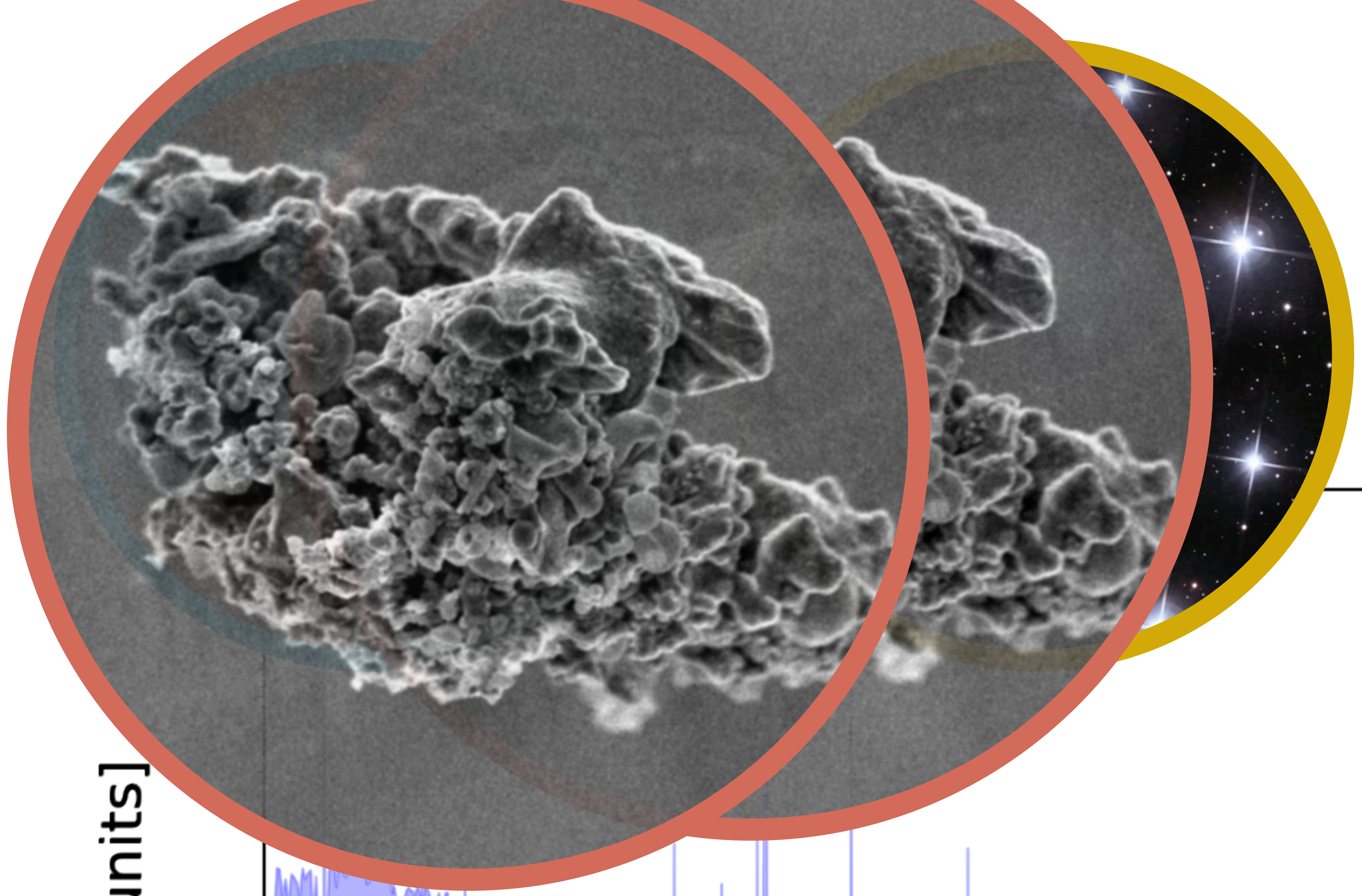
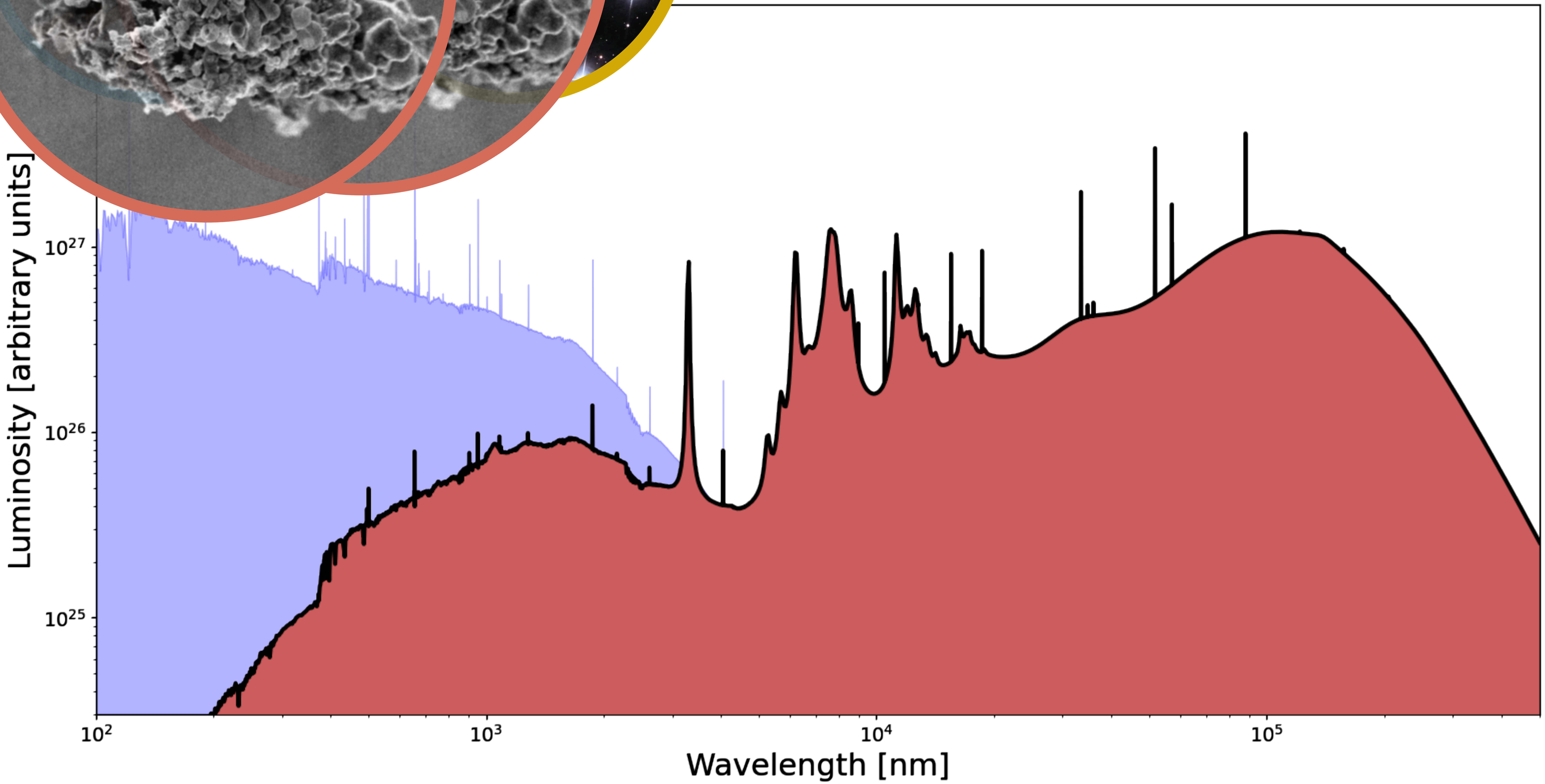
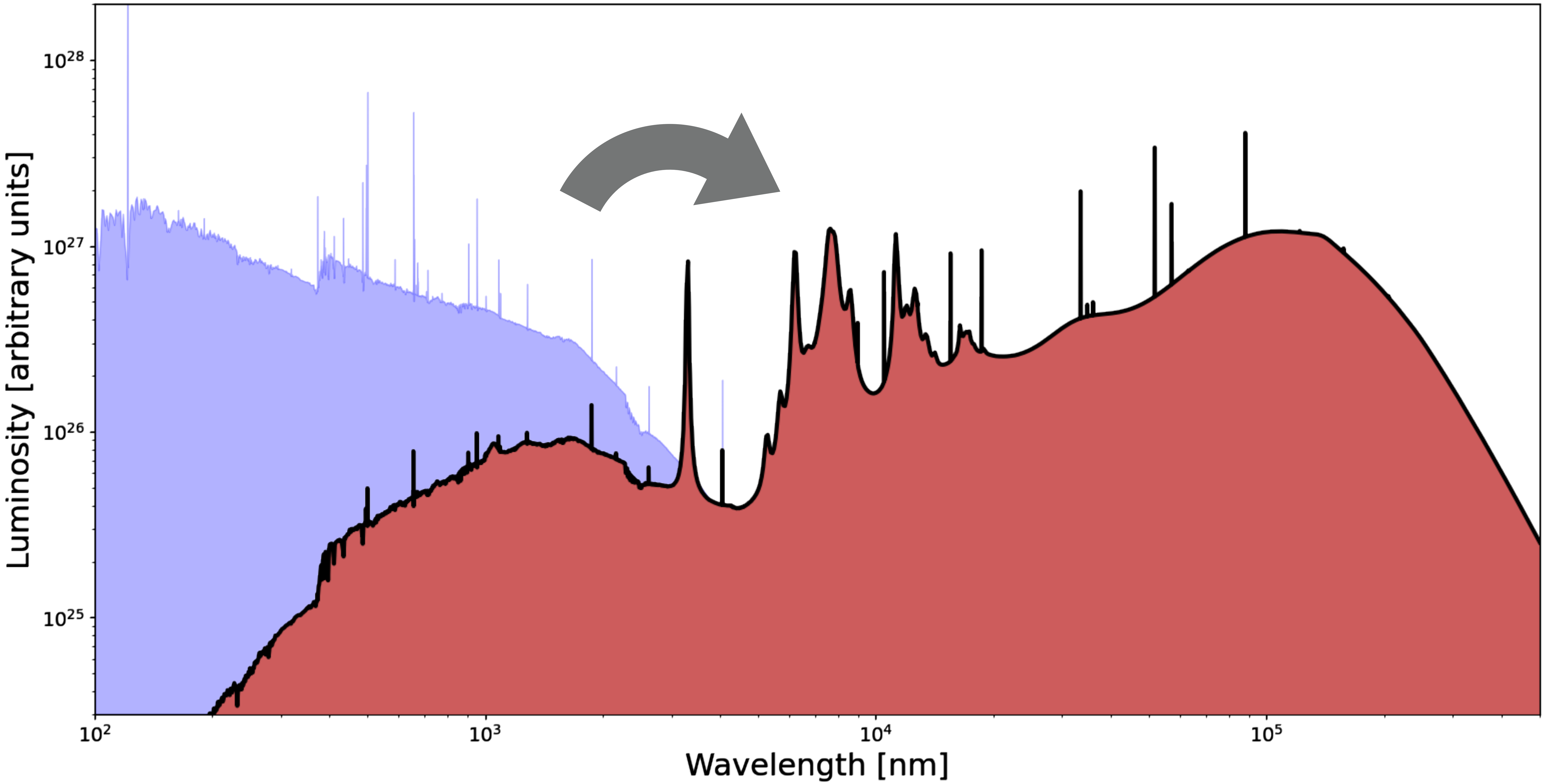


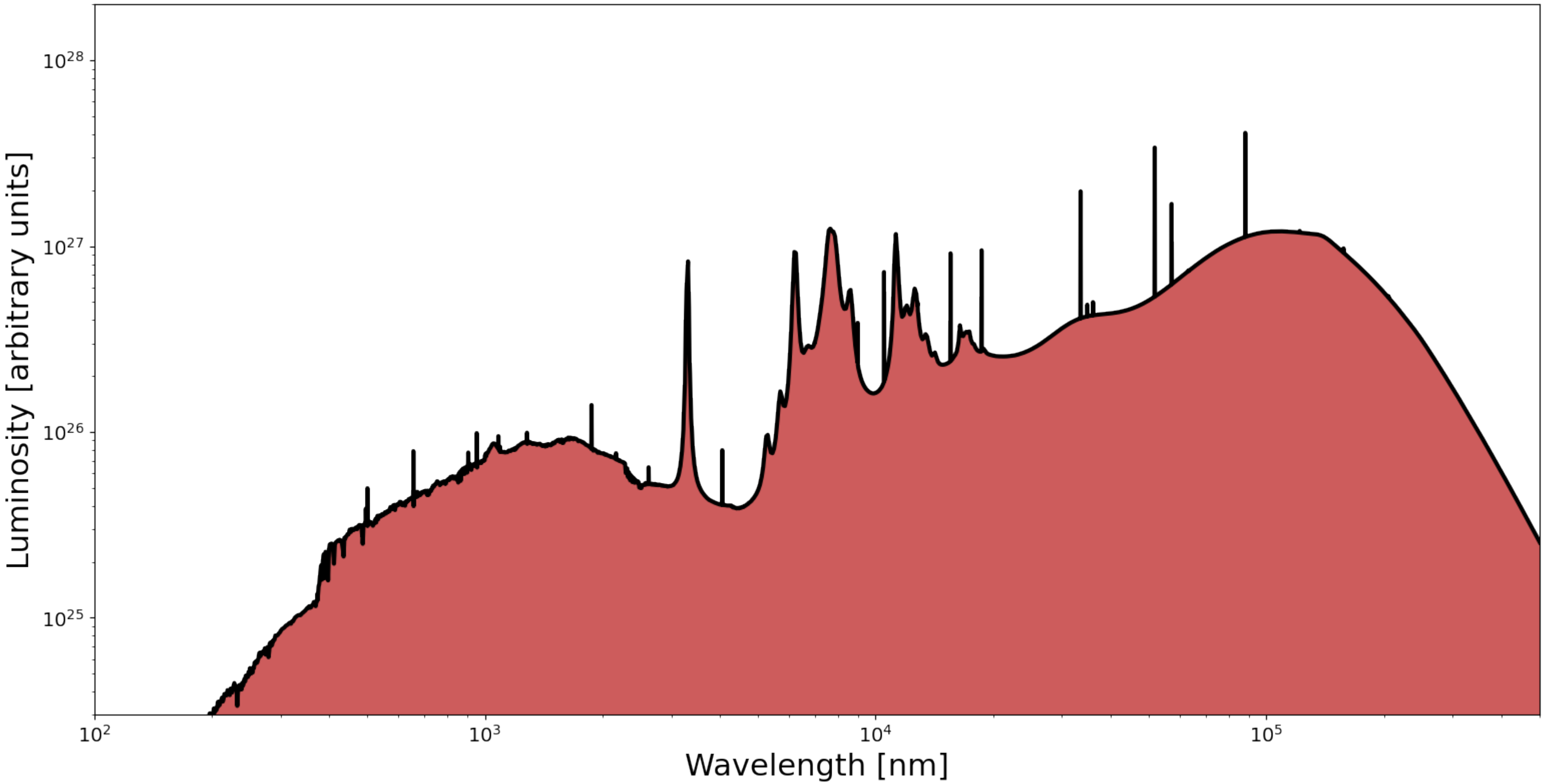
Polycyclic Aromatic Hydrocarbons
(complex molecules of Carbon)
Prominent emission in the MIR





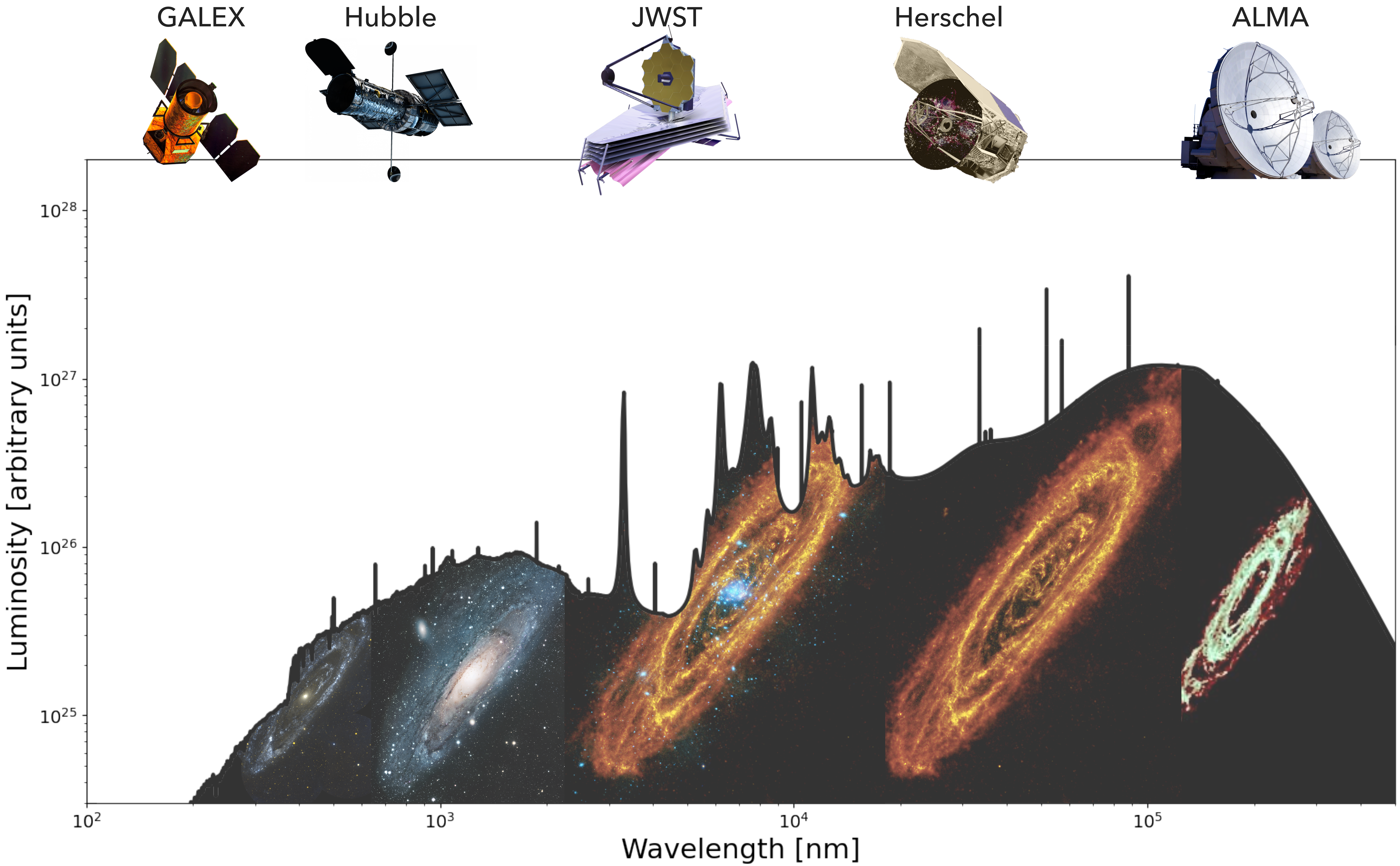


10^{28}
10^{27}
10^{26}
10^{25}
Luminosity [arbitrary units]
10^{2}
10^{3}
10^{4}
10^{5}
Wavelength [nm]

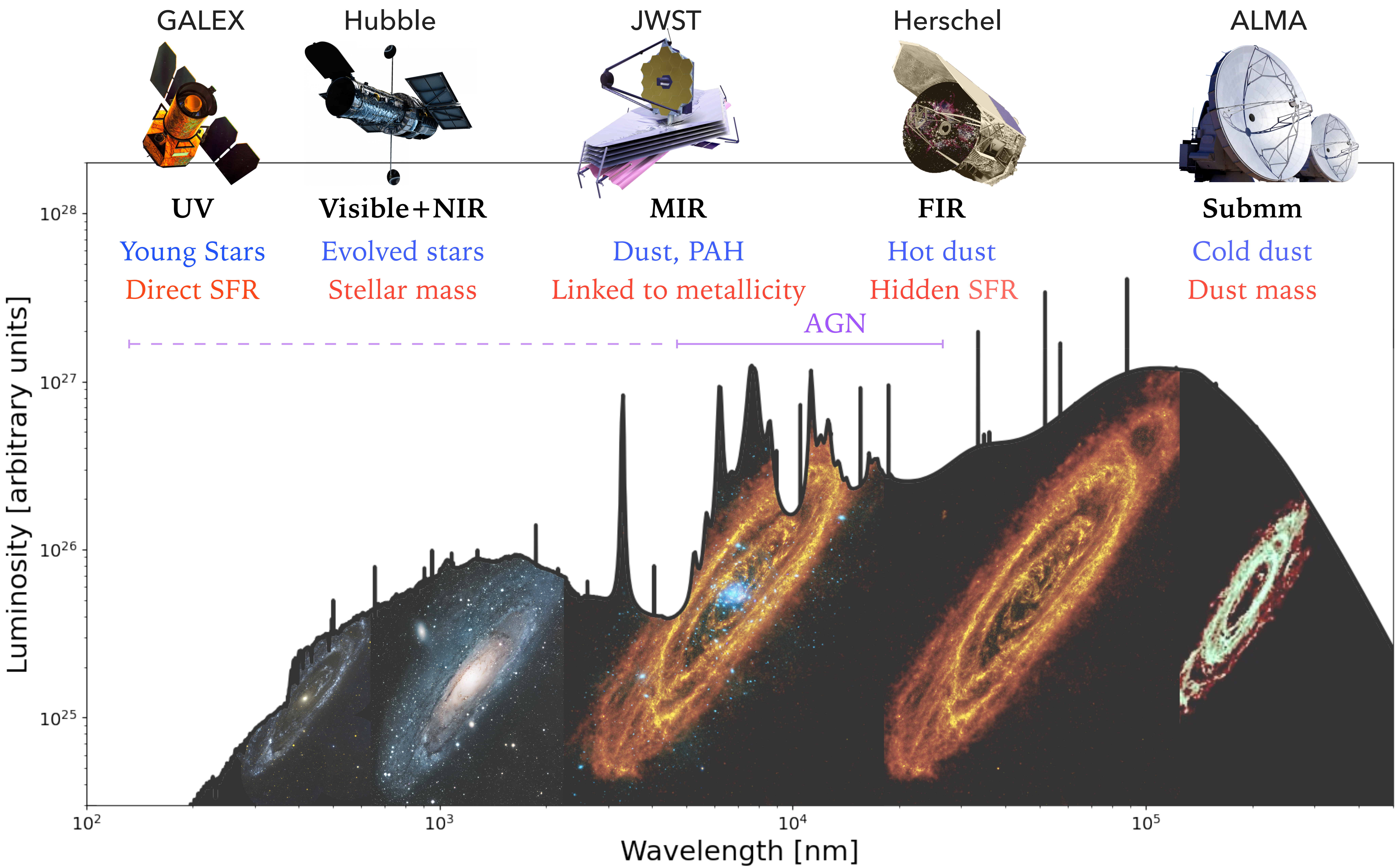


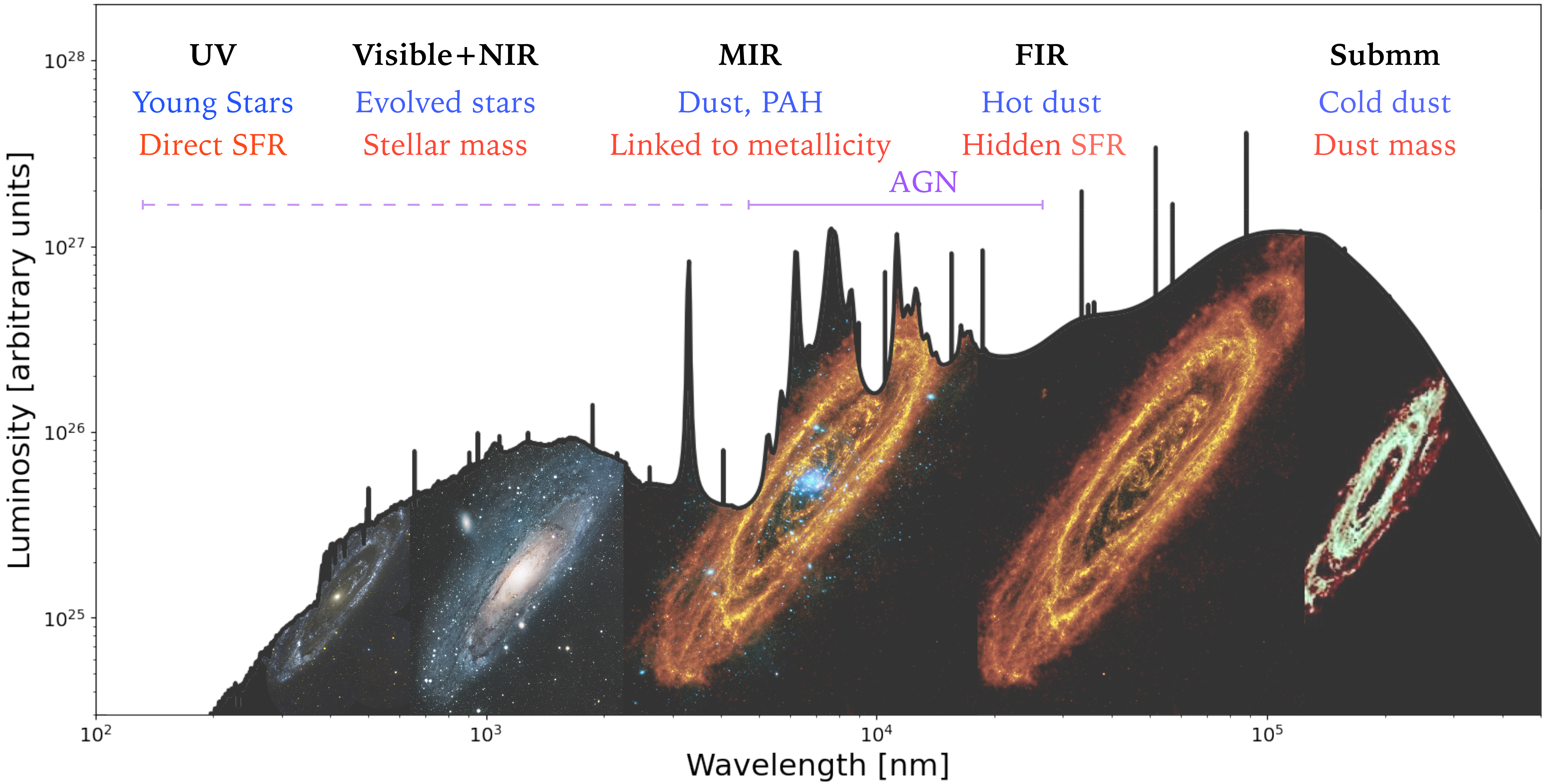
Luminosity [arbitrary units]
10^{28}
10^{27}
10^{26}
10^{25}
10^{2}
10^{3}
10^{4}
10^{5}
Wavelength [nm]

Panchromatic view of a galaxy

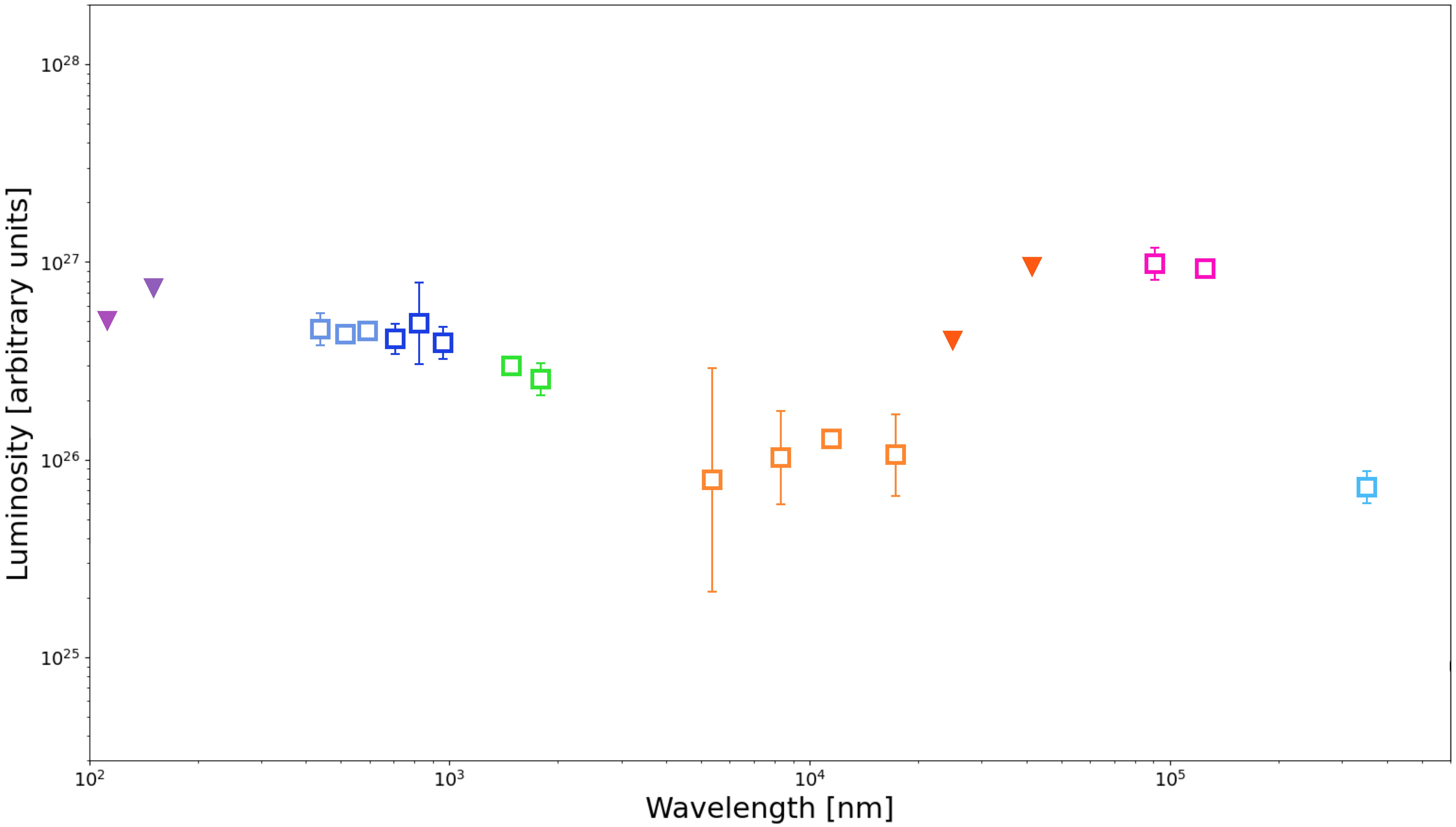


Panchromatic view of a galaxy

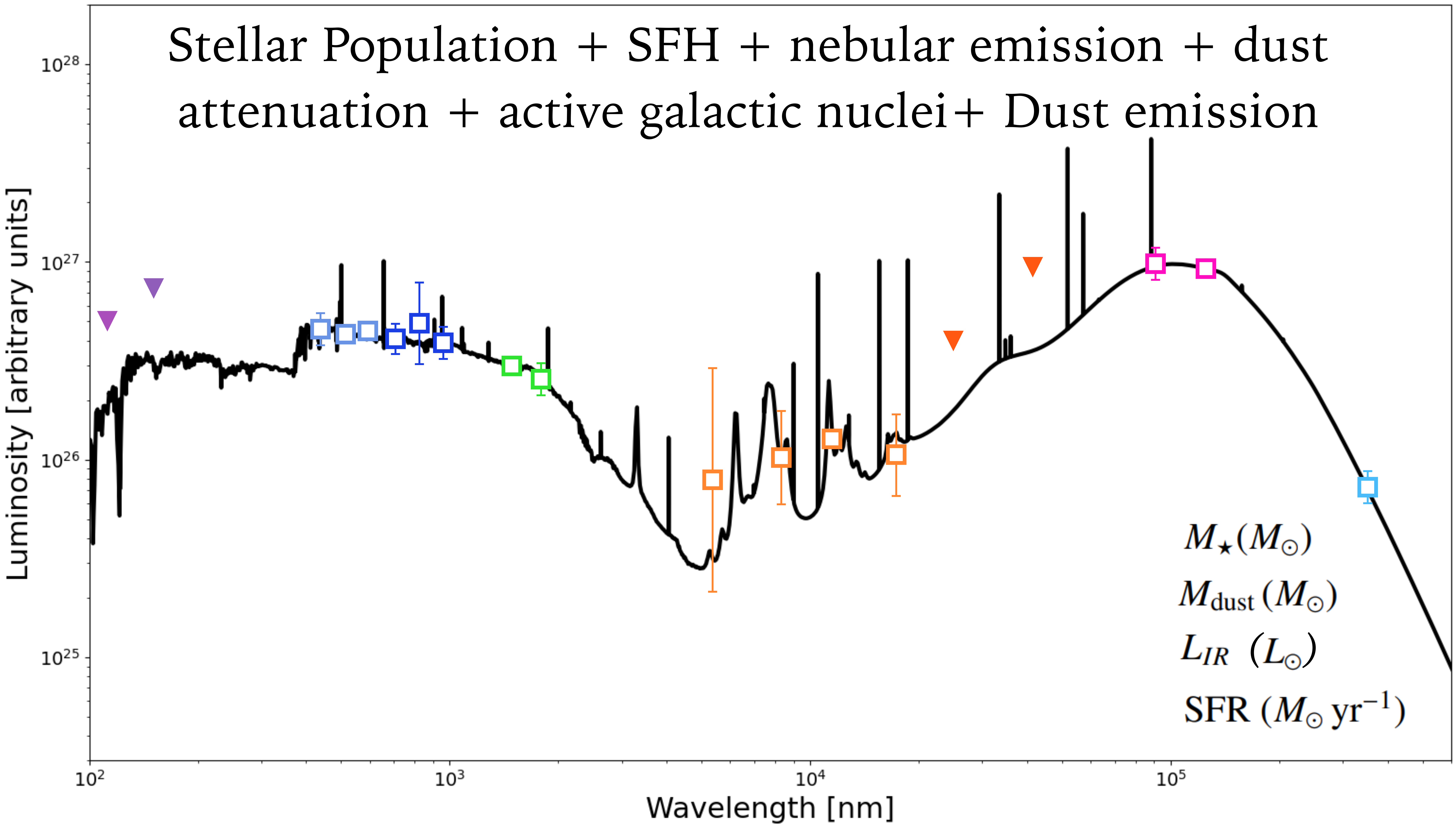



UV
Young Stars
Direct SFR
Visible+NIR
Evolved stars
Stellar mass
MIR
Dust, PAH
Linked to metallicity
FIR
Hot dust
Hidden SFR
Submm
Cold dust
Dust mass
AGN
Luminosity [arbitrary units]
Wavelength [nm]
10^{28}
10^{27}
10^{26}
10^{25}
10^{2}
10^{3}
10^{4}
10^{5}

WHAT WE OBSERVE



WHAT WE MODEL



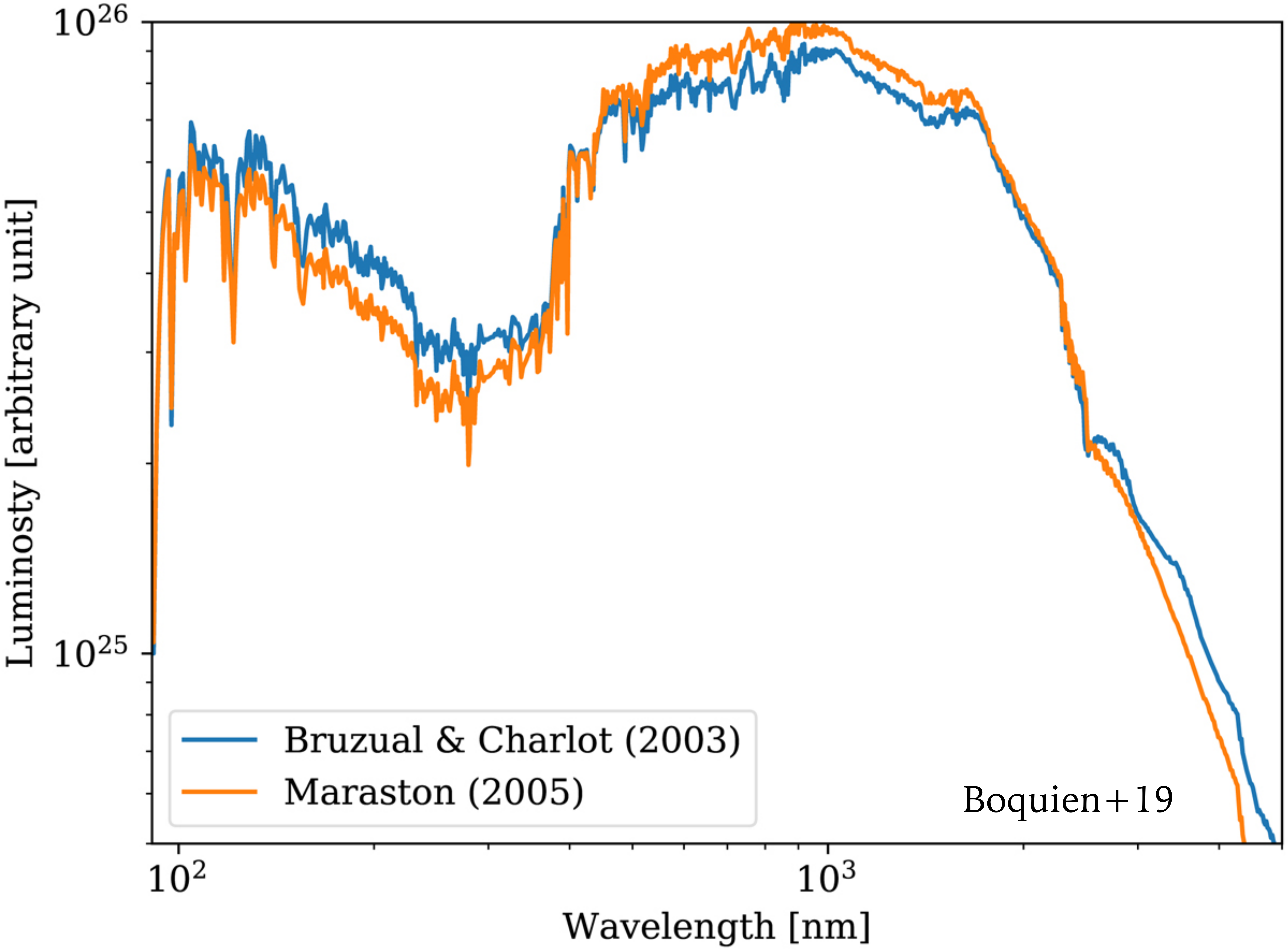
ESTIMATING PHYSICAL PROPERTIES OF GALAXIES

Stellar mass $(M_\star)$ $[M_\odot]$

UV - NIR photometry

Stellar population library

e.g. Bruzual & Charlot (2003)



ESTIMATING PHYSICAL PROPERTIES OF GALAXIES

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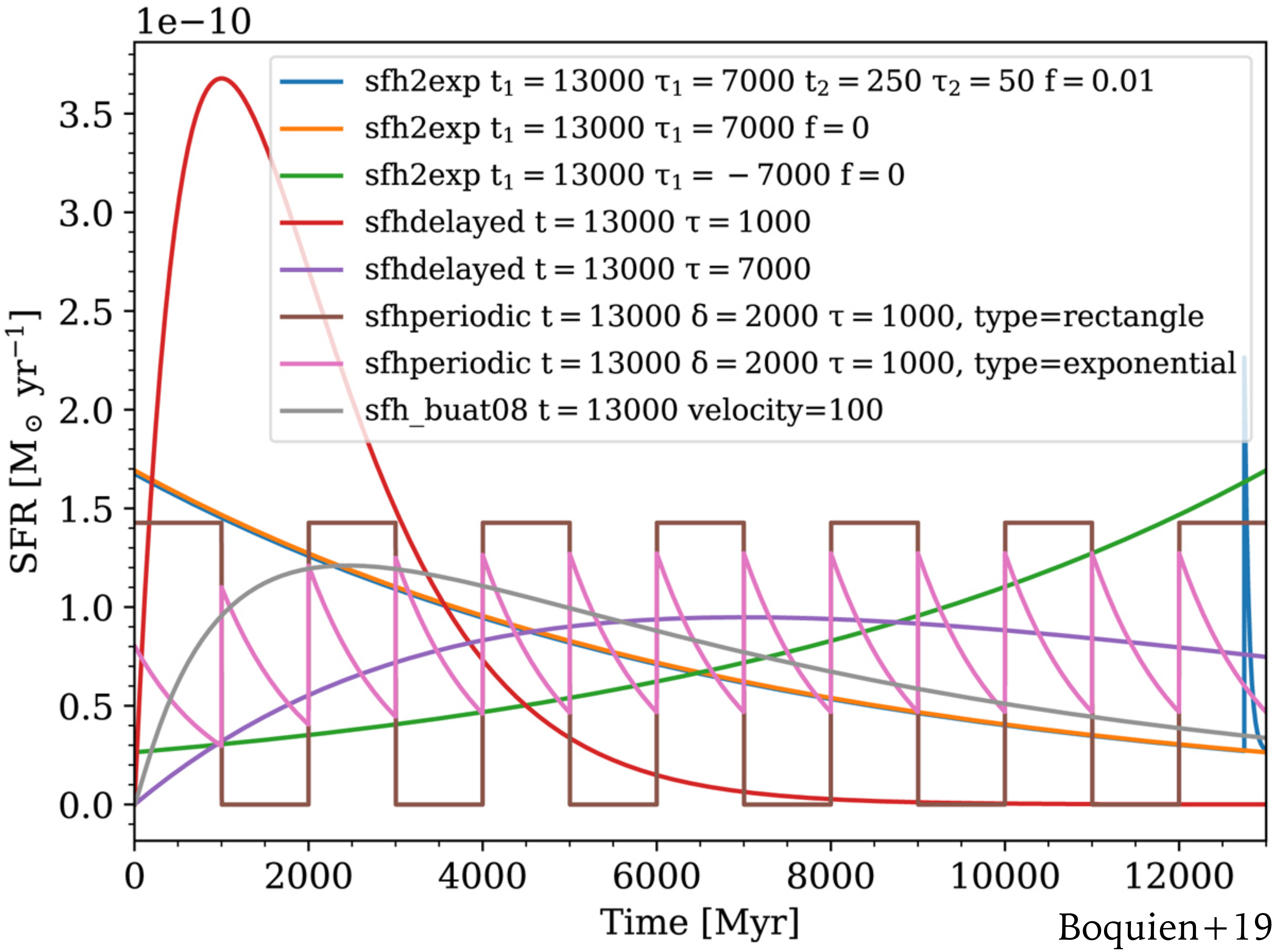
Star formation history



Boquien+19

ESTIMATING PHYSICAL PROPERTIES OF GALAXIES

Stellar mass $(M_\star)$ $[M_\odot]$

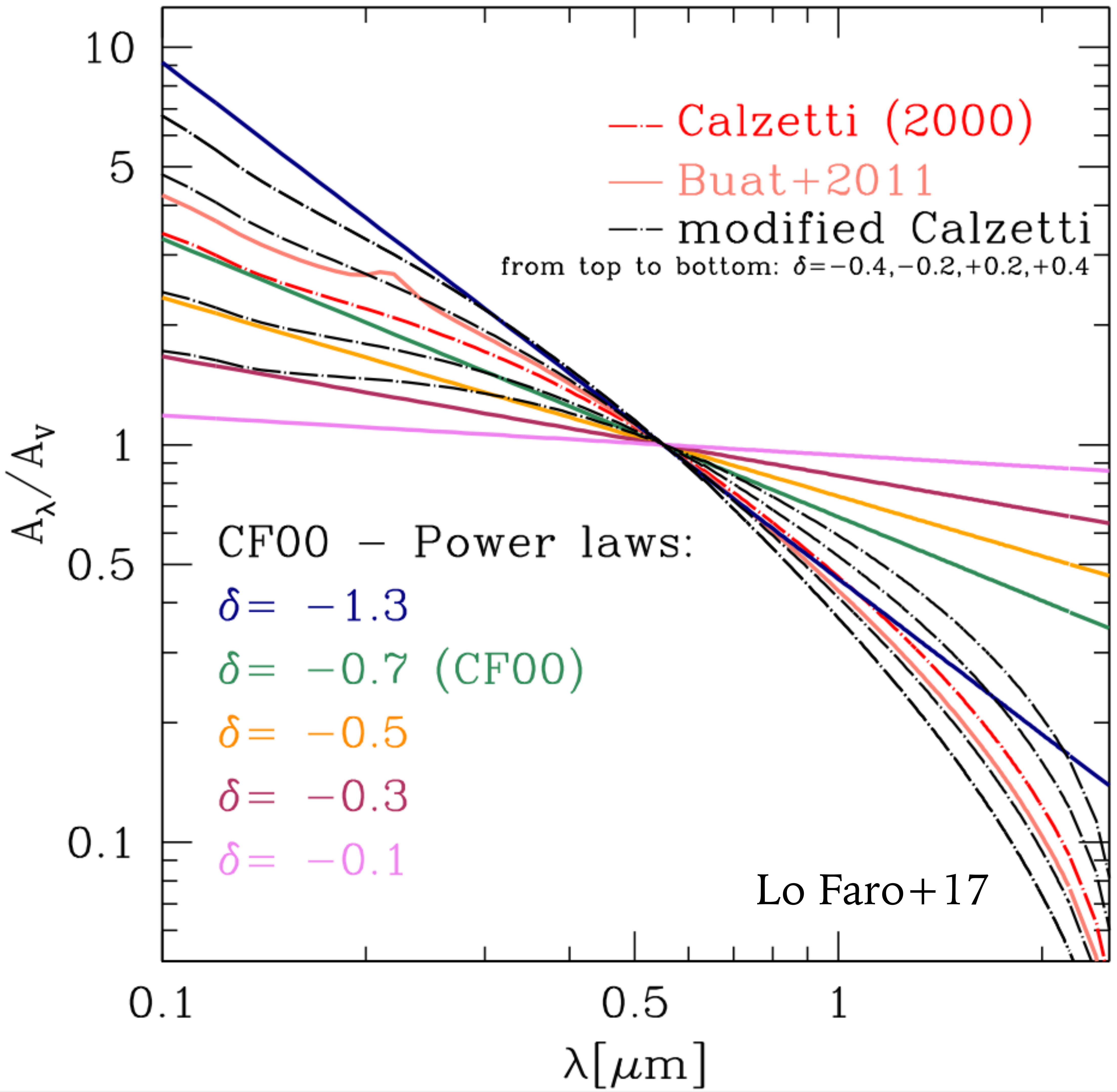
UV - NIR photometry

Stellar population library

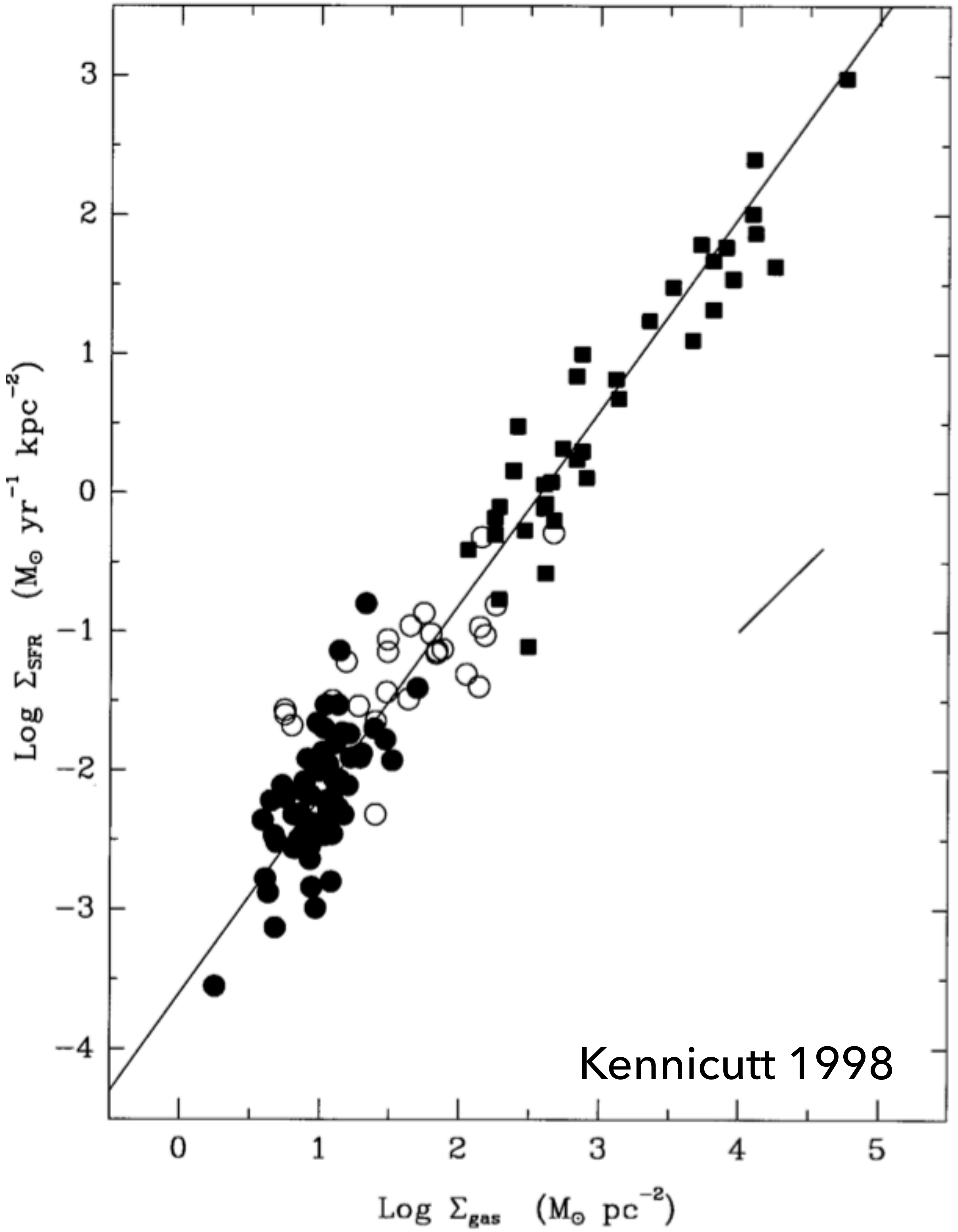
e.g. Bruzual & Charlot (2003)

Star formation history

Dust attenuation



ESTIMATING PHYSICAL PROPERTIES OF GALAXIES



Star formation rate (SFR) $[M_\odot \ year^{-1}]$

Kennicutt - Schmidt law:

SFR surface density correlates with the gas surface density.

H2 is the main ingredient of stellar formation.

BUT

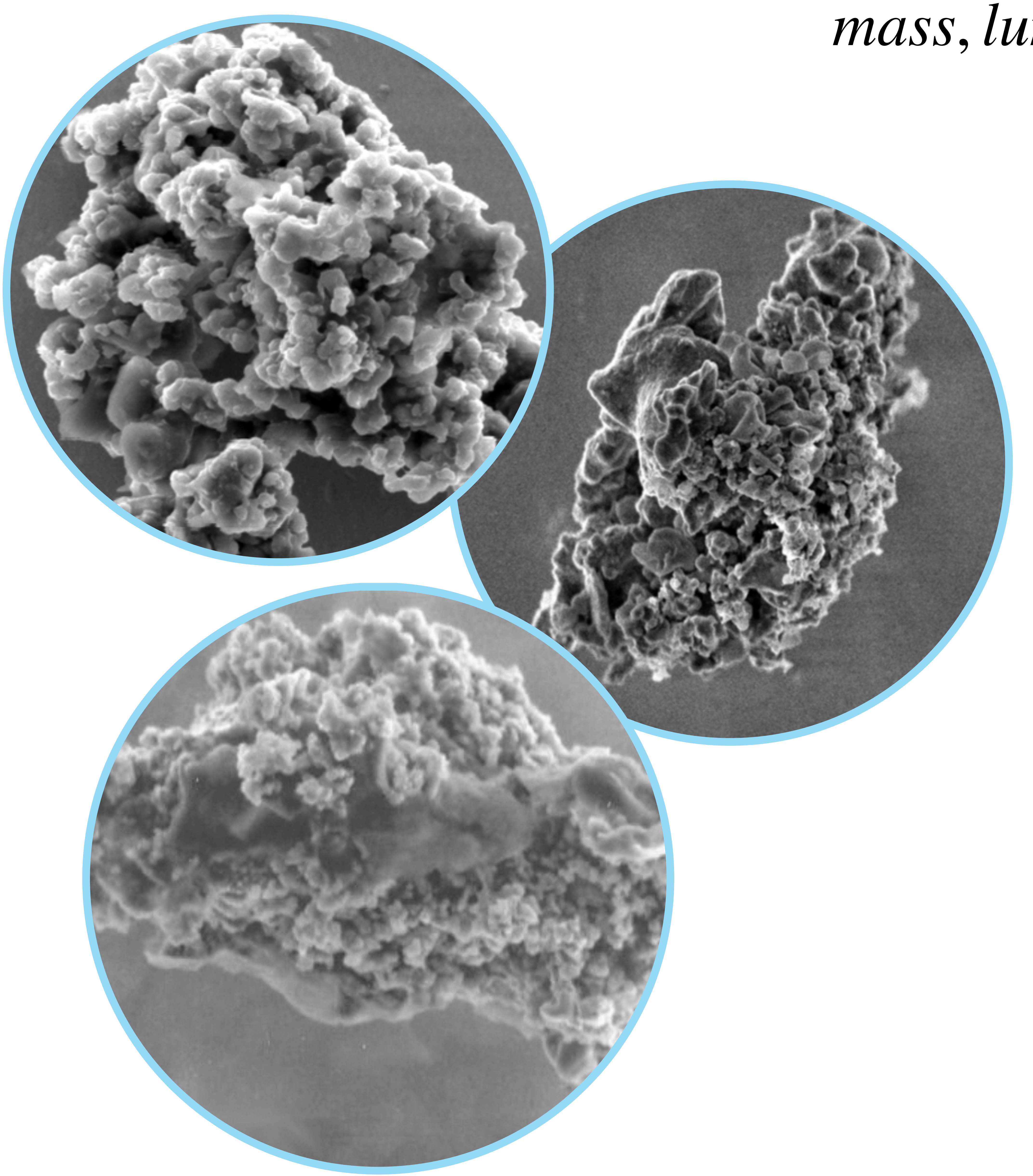
H2 is ~ not detectable

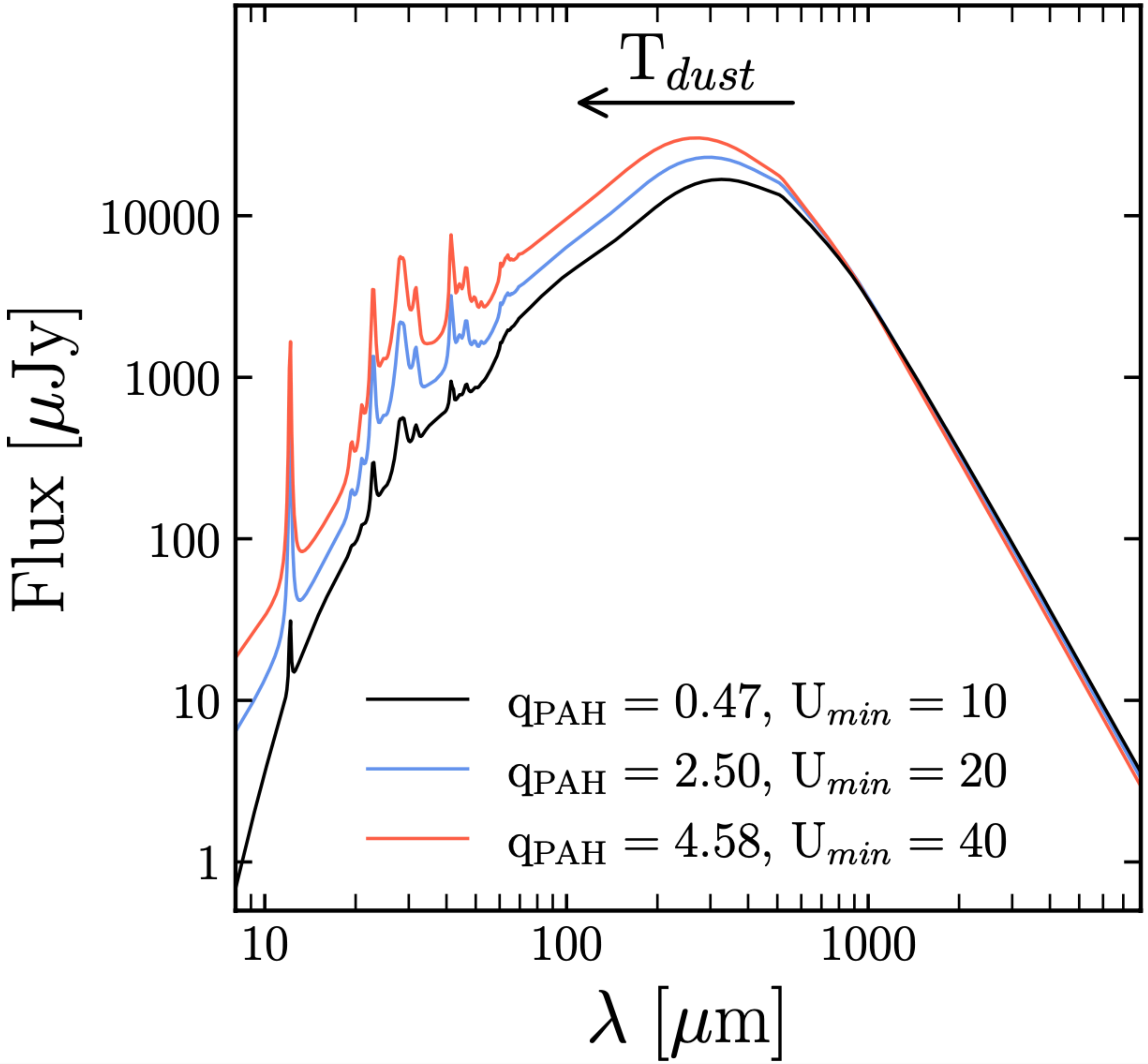
Traced with *e.g.* **CO**

(e.g., Carilli & Walter 2013; Weiß et al. 2013b; Decarli et al. 2019; Riechers et al. 2020).

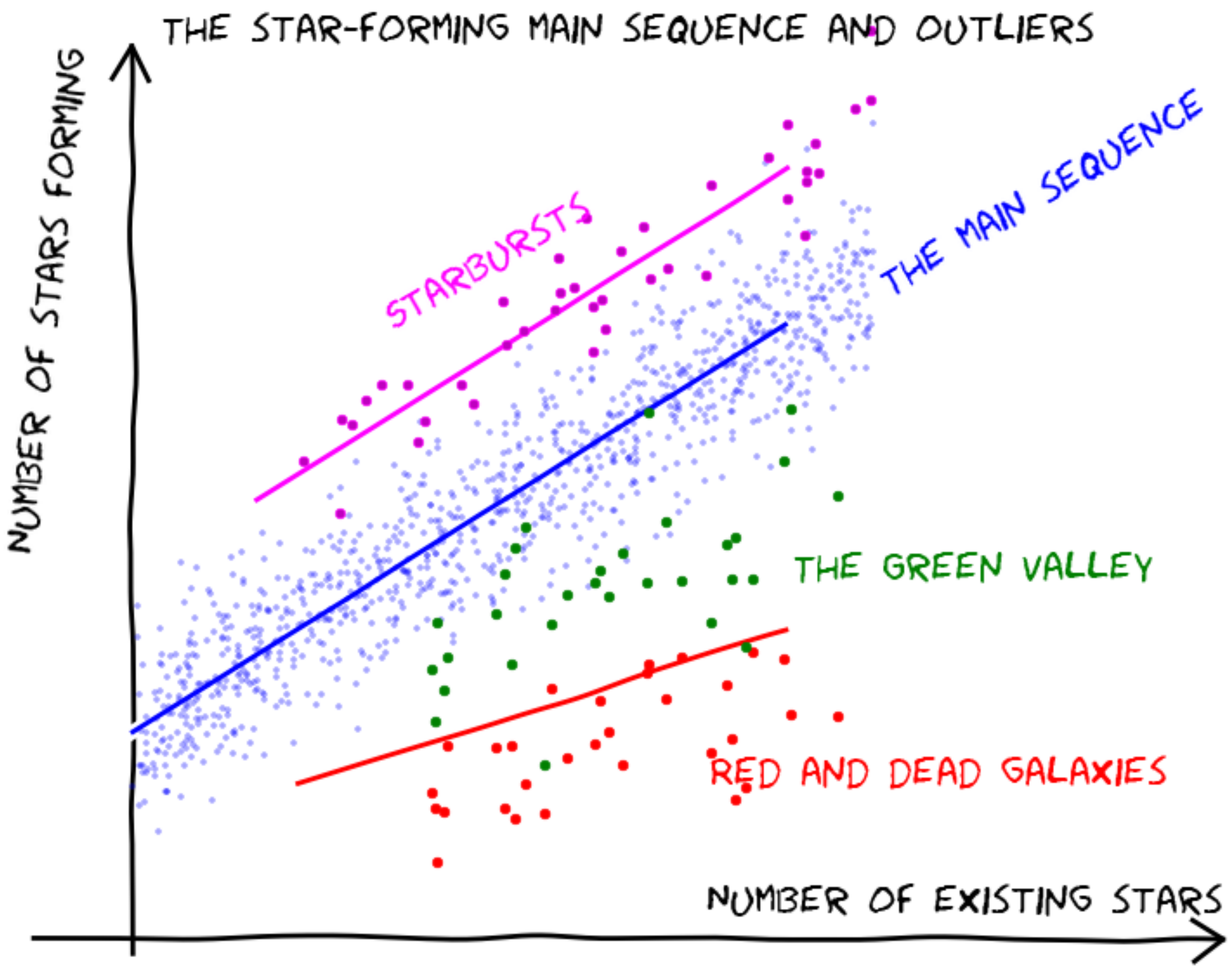
Dust properties

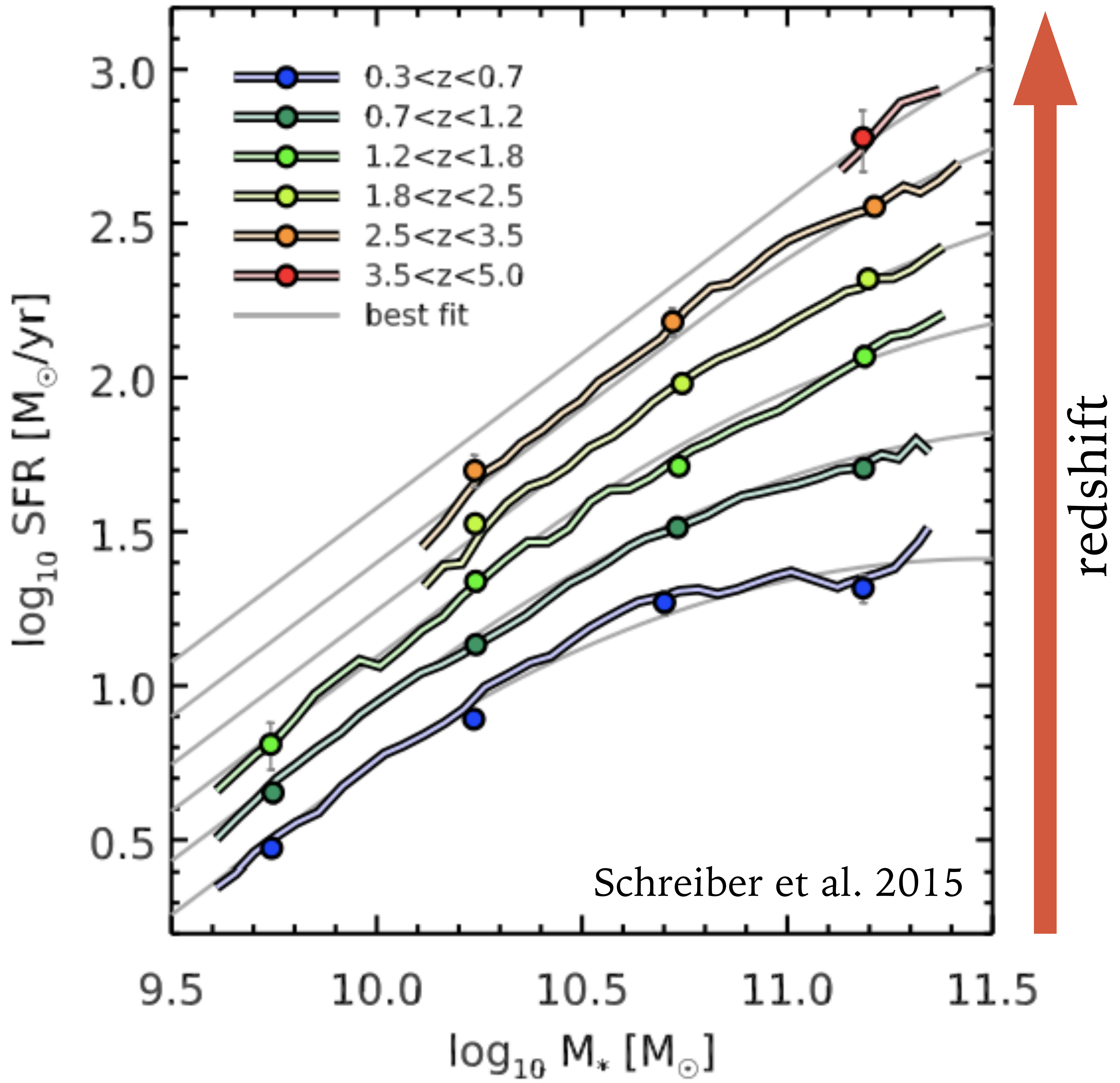
mass, luminosity, temperature





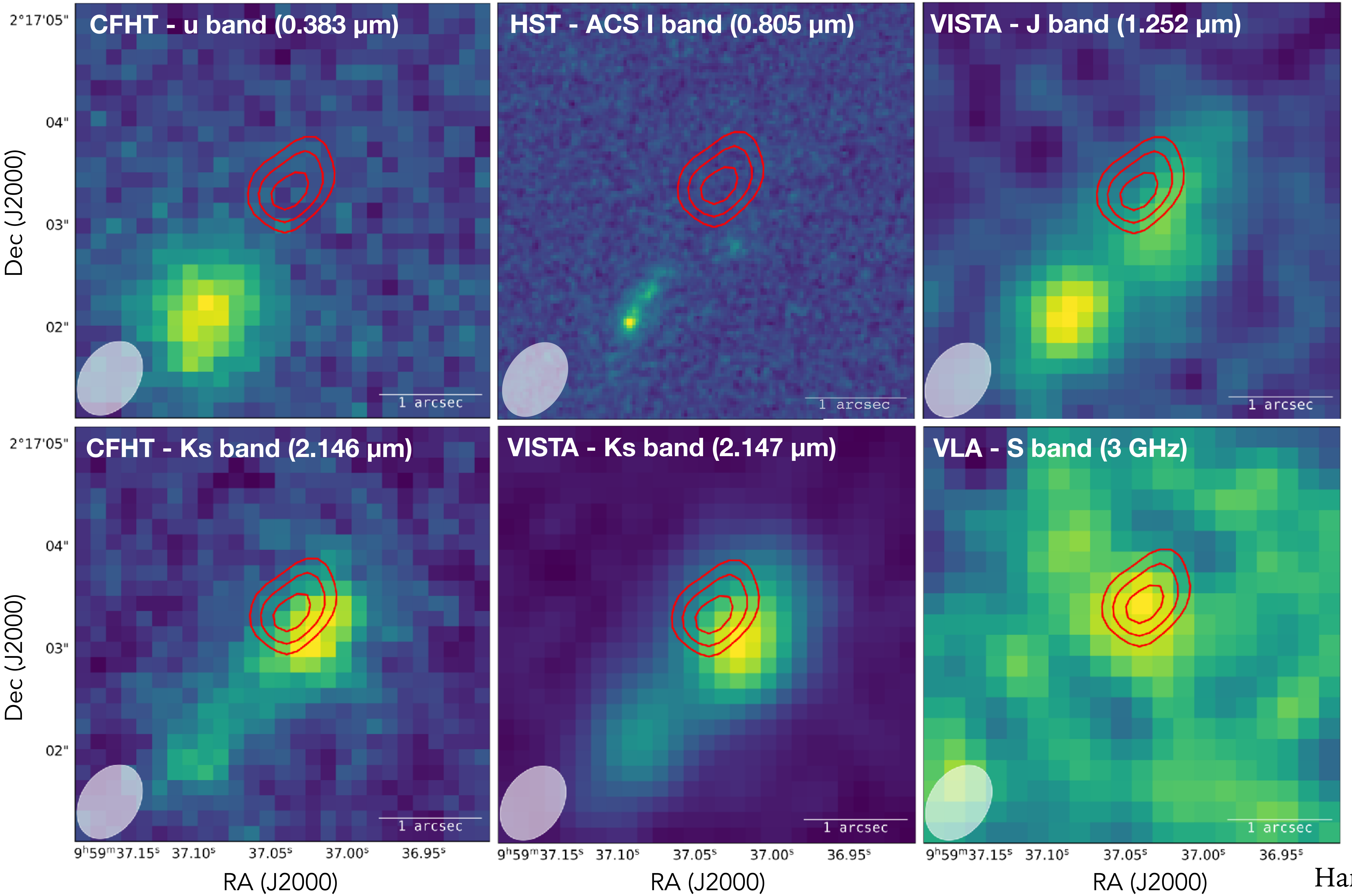
MAIN SEQUENCE OF SFGs



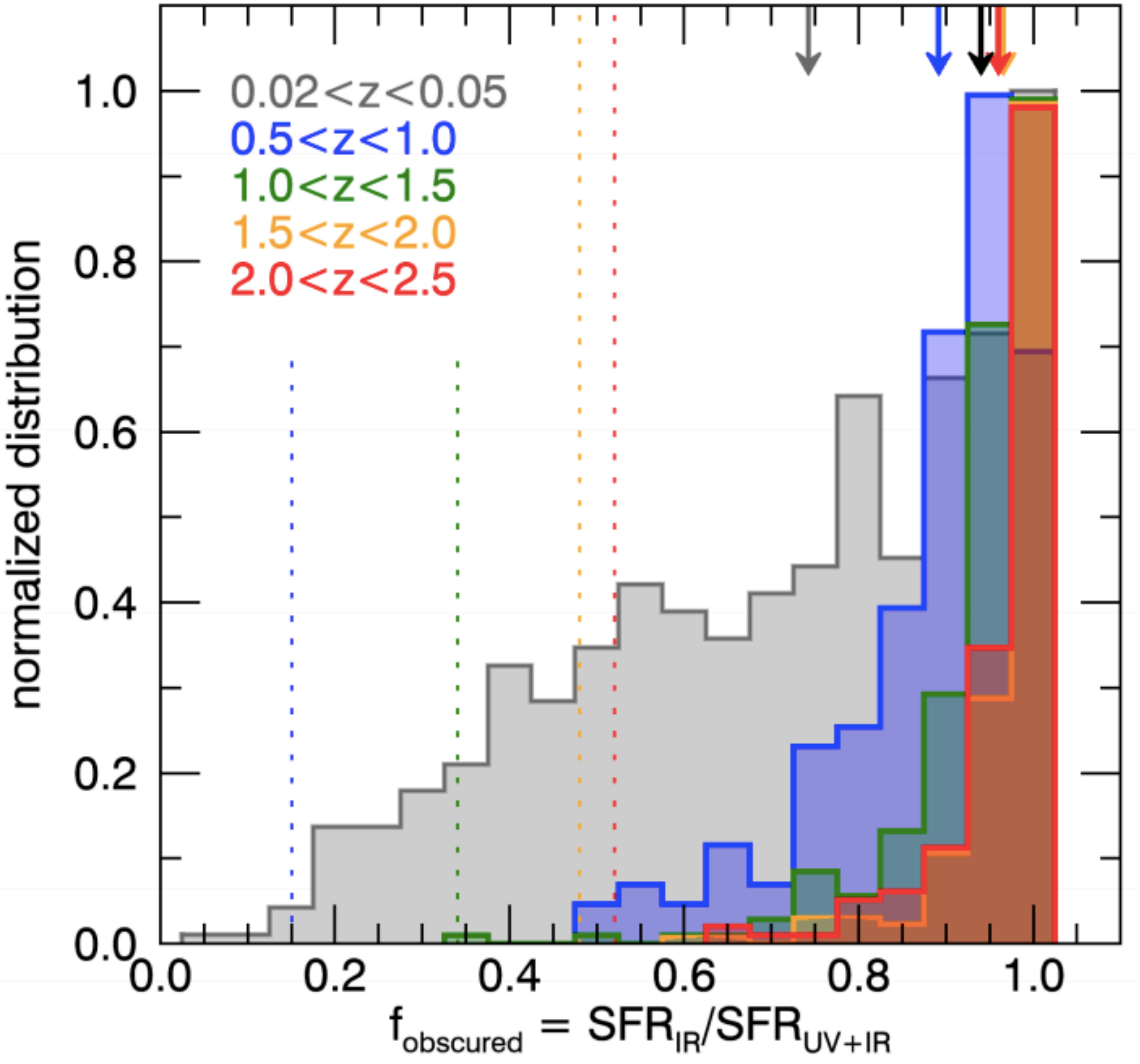


Star formation rate in galaxies is found to correlate with stellar masses

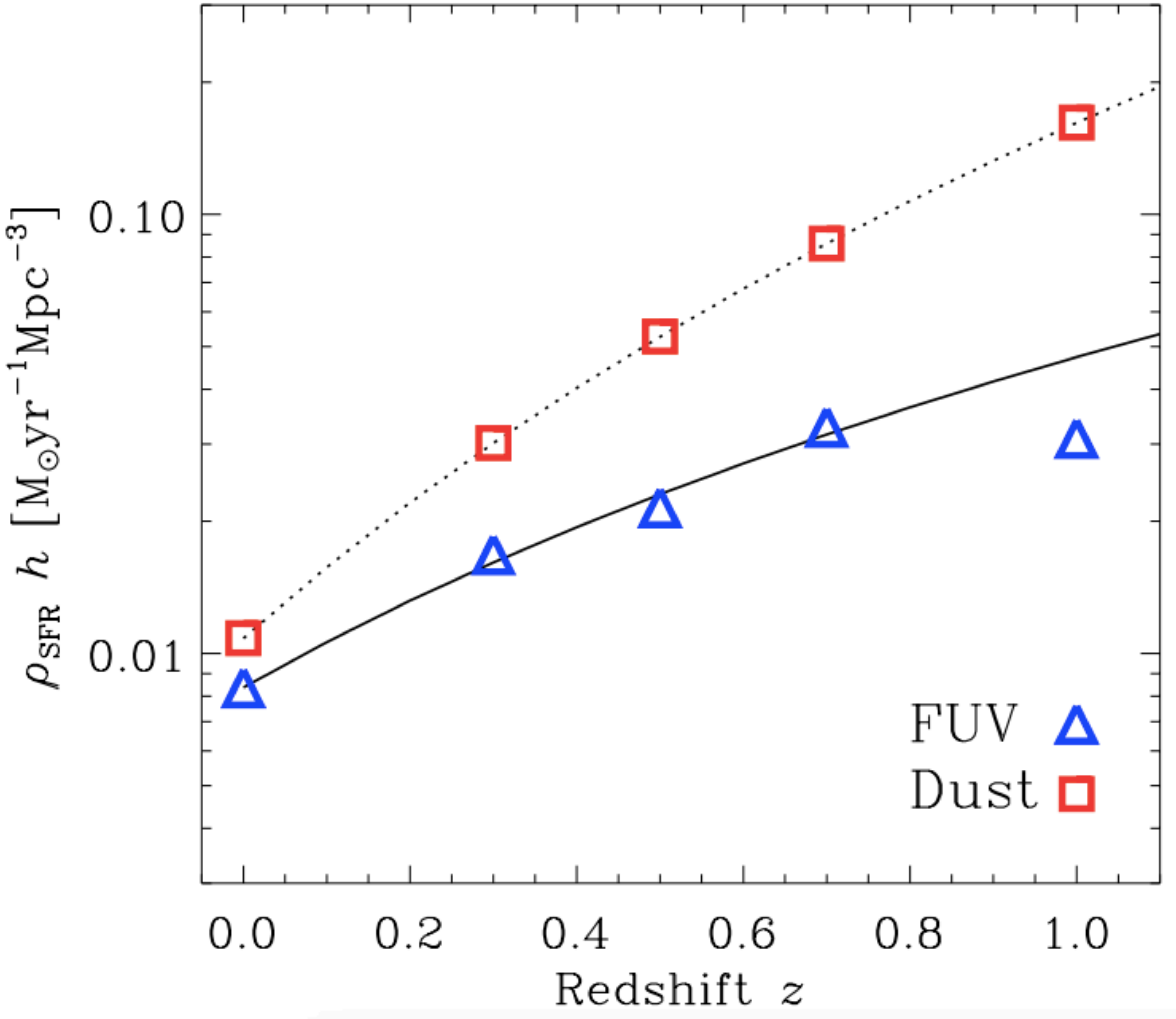
Dust attenuation recipes alter derived stellar masses


CFHT - u band (0.383 μm)
HST - ACS I band (0.805 μm)
VISTA - J band (1.252 μm)
CFHT - Ks band (2.146 μm)
VISTA - Ks band (2.147 μm)
VLA - S band (3 GHz)
1 arcsec
Dec (J2000)
RA (J2000)
2°17'05"
04"
03"
02"
9h59m37.15s
37.10s
37.05s
37.00s
36.95s

Hamed+21



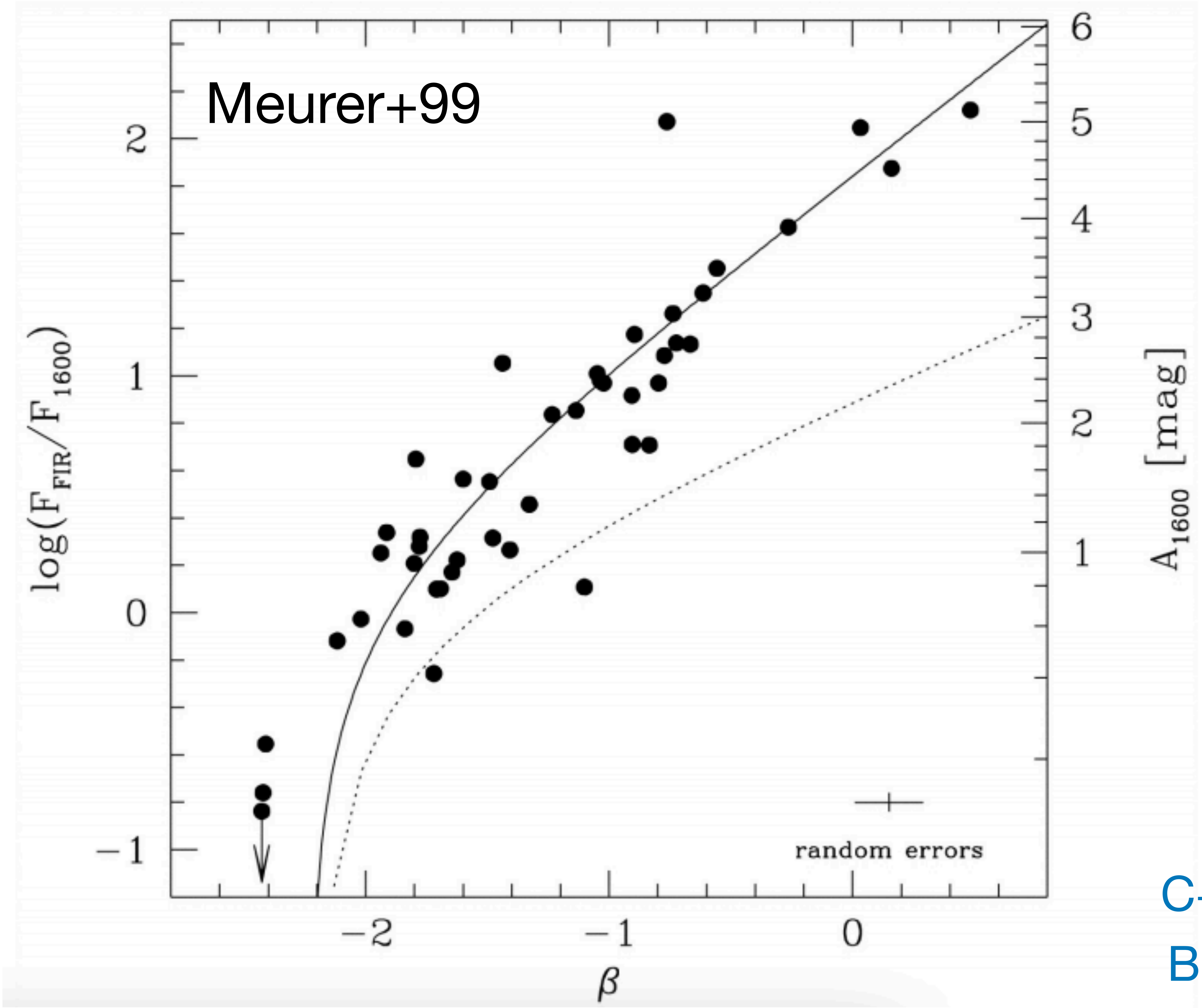
Whitaker et al,. 2017



Takeuchi et al., 2005

At higher redshift, the density of the SFR is mostly obscured.

The original IRX-β relation Meurer et al. 1995, 1999



β: a proxy for dust attenuation in local starburst galaxies

The slope can be measured from GALEX NUV & FUV bands as follows:

$$\beta = \frac{\log(F_{NUV}/F_{FUV})}{\log(\lambda_{FUV}/\lambda_{NUV})} - 2$$

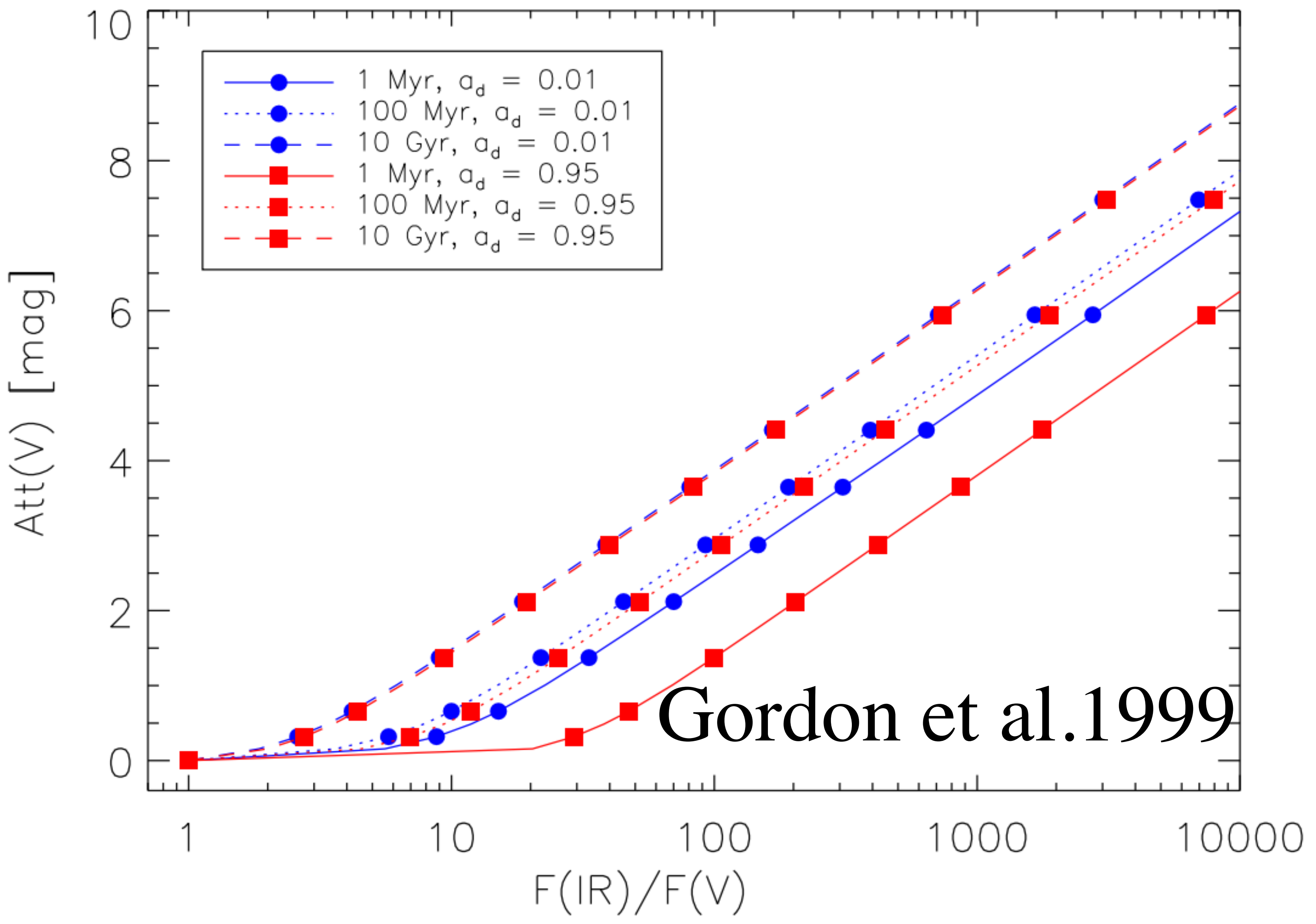
C+94, M+99, C+00, Boquien+12, Burgarella+05
Buat+02,05,06

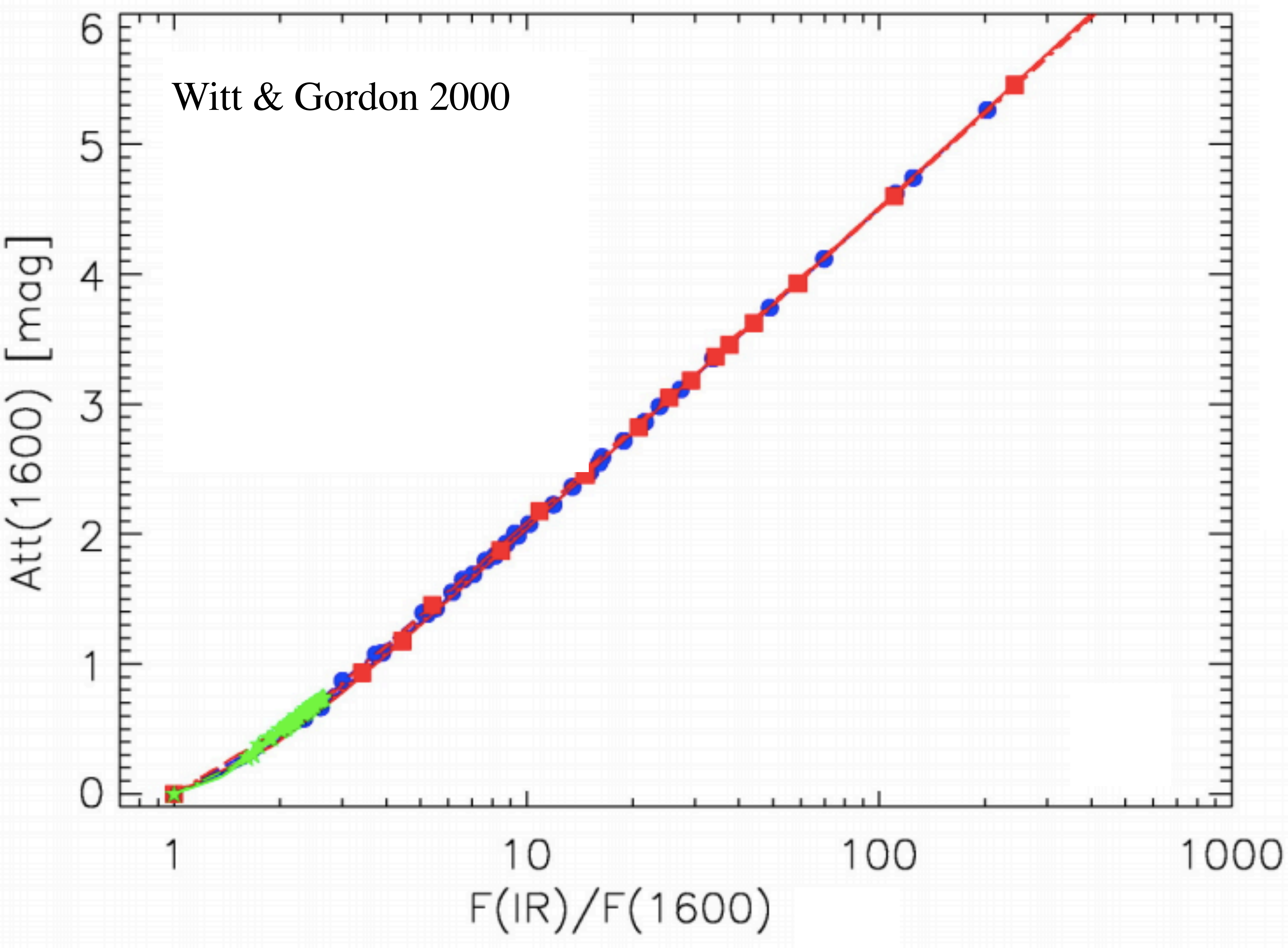
The infrared excess

$$IRX = \frac{L_{IR}}{L_{UV}}$$

$$\propto$$

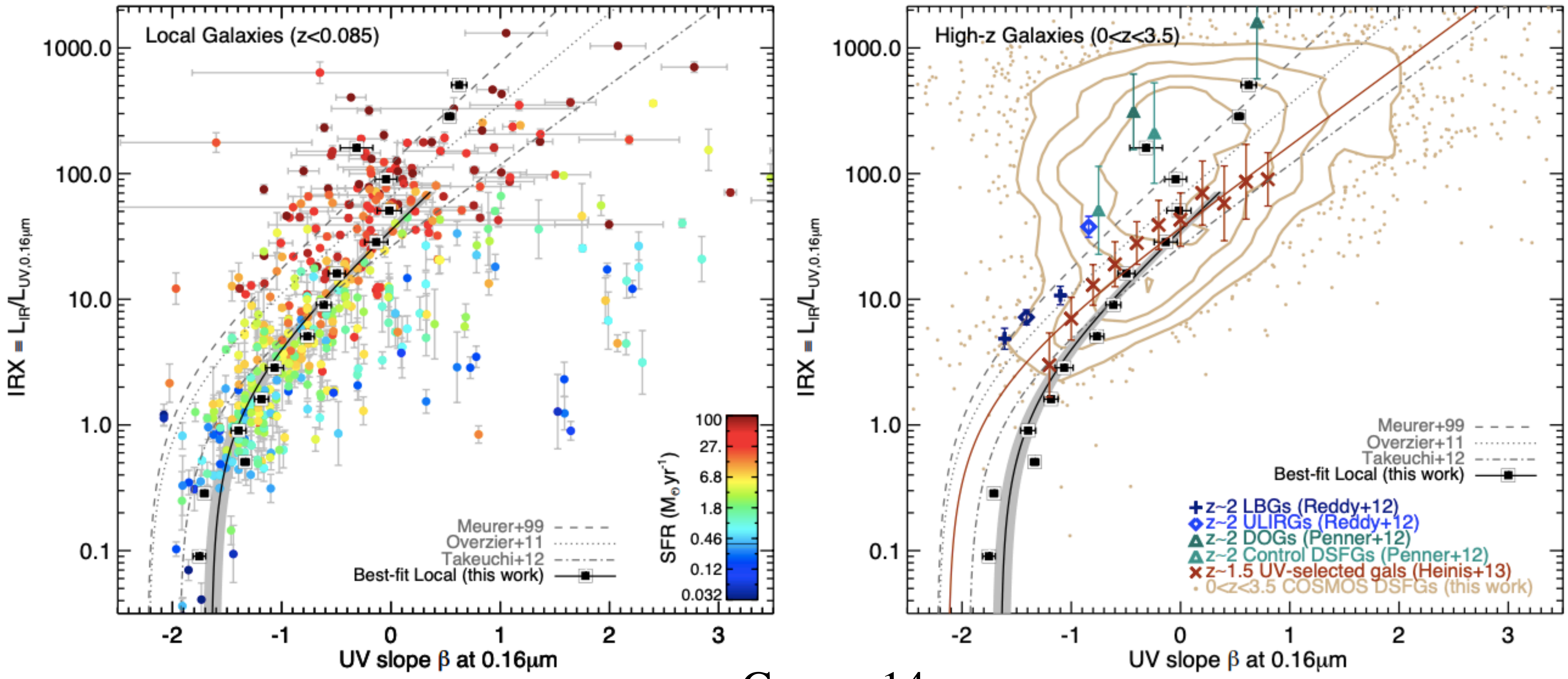
$$A_{FUV}$$





IRX is a proxy for dust attenuation

The IRX-β relation works, most of the time…



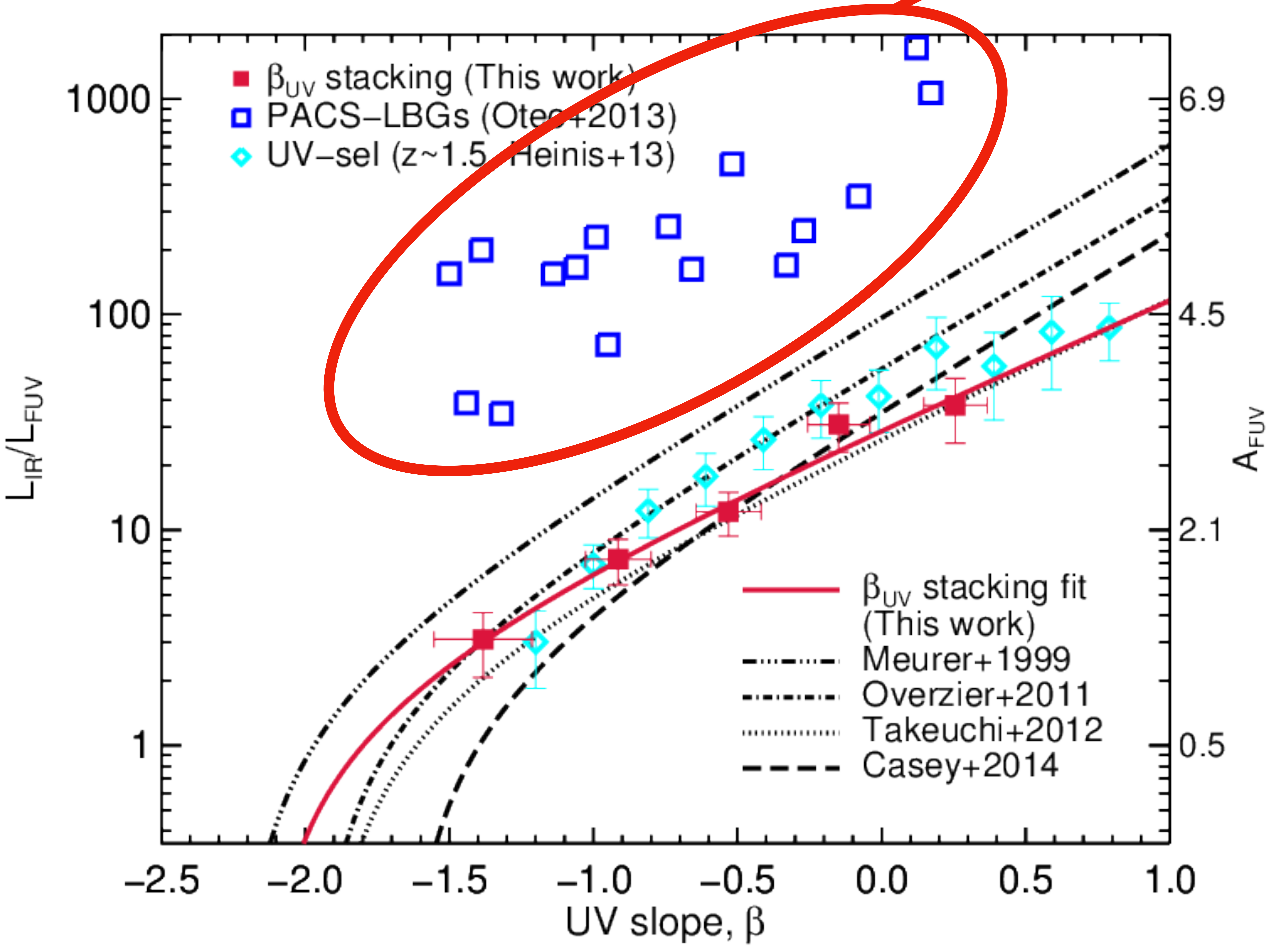
Casey+14

Nearby

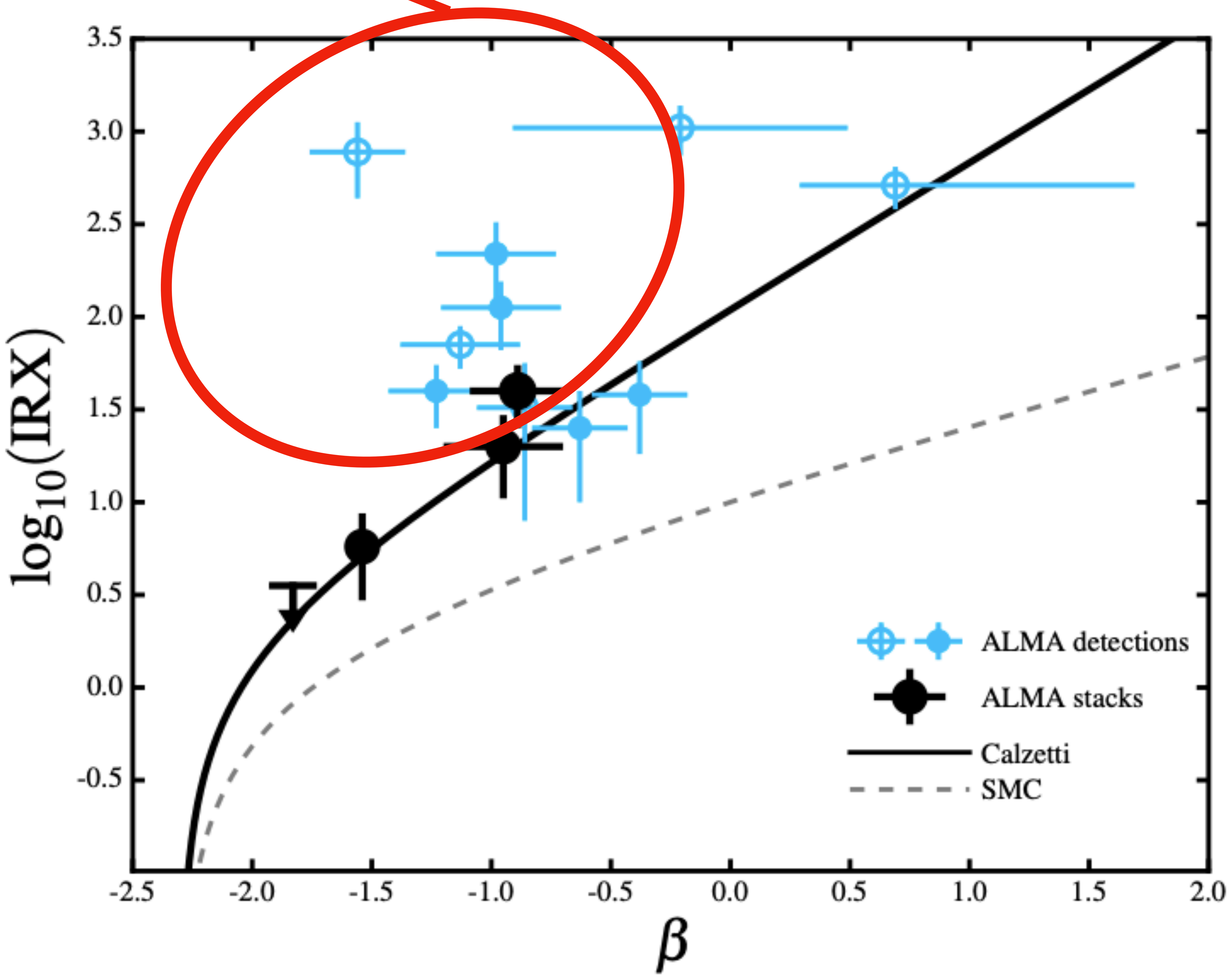
High-z

The IRX-β relation works, most of the time…

?

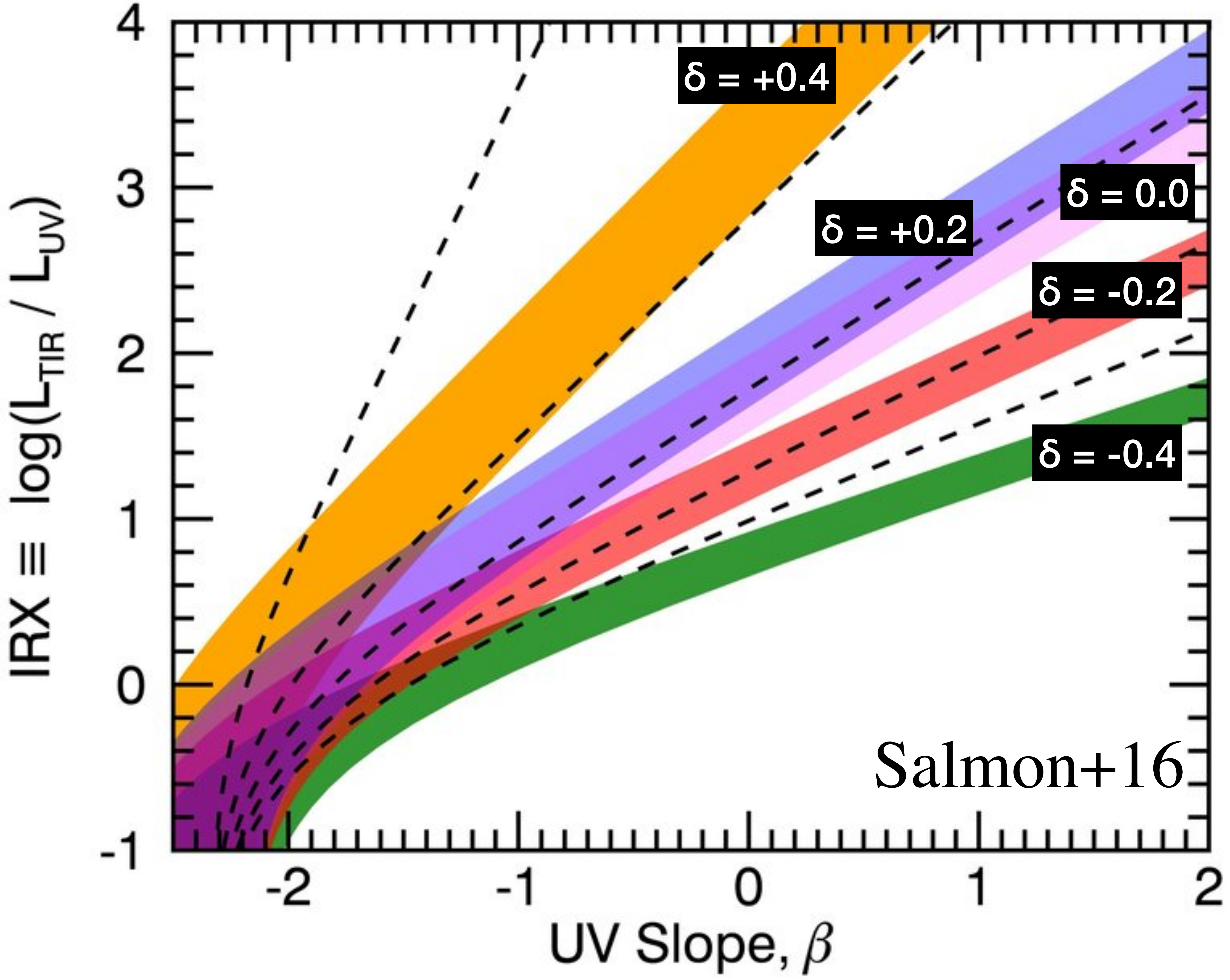


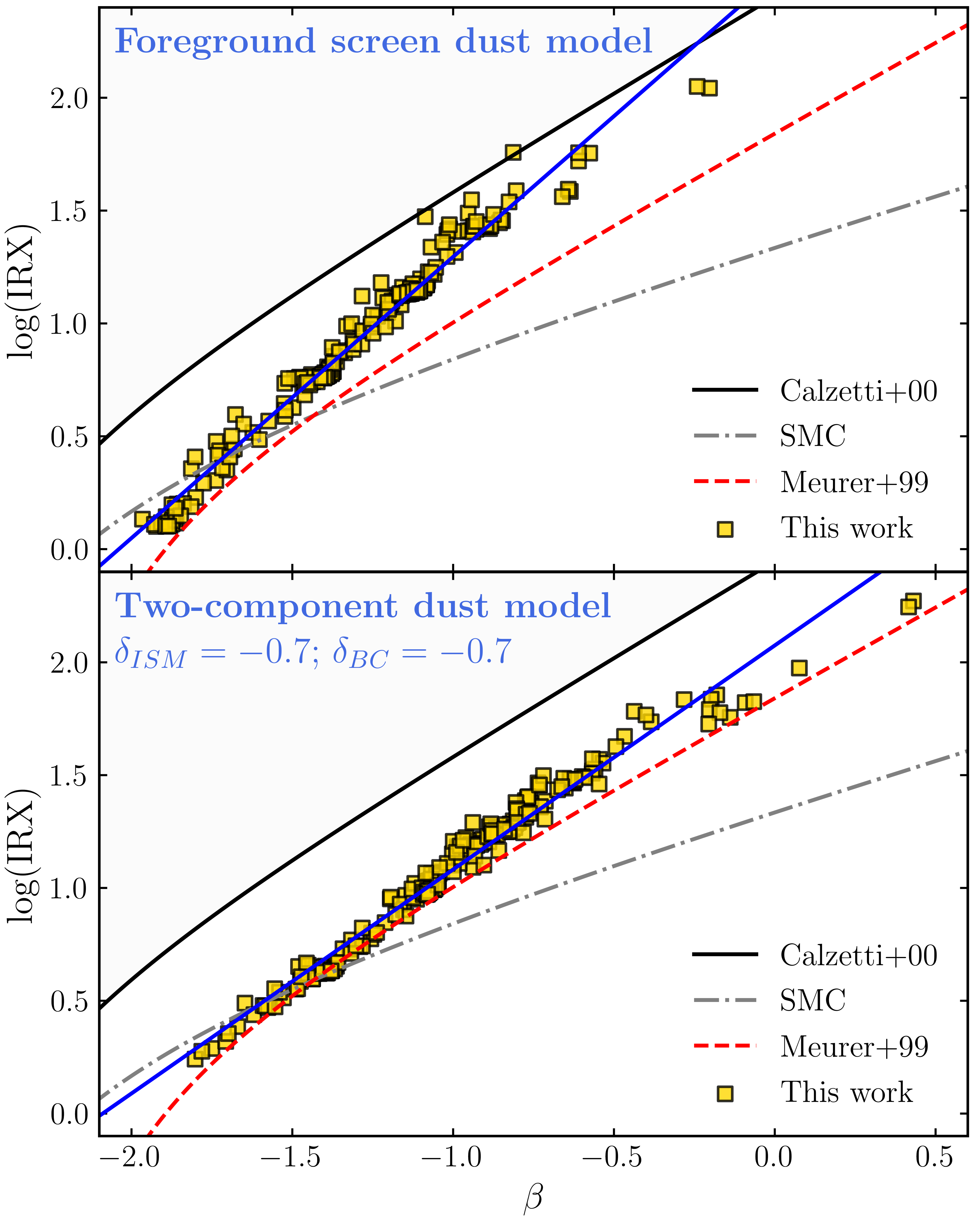
Alvarez Marquez+16



McLure+17

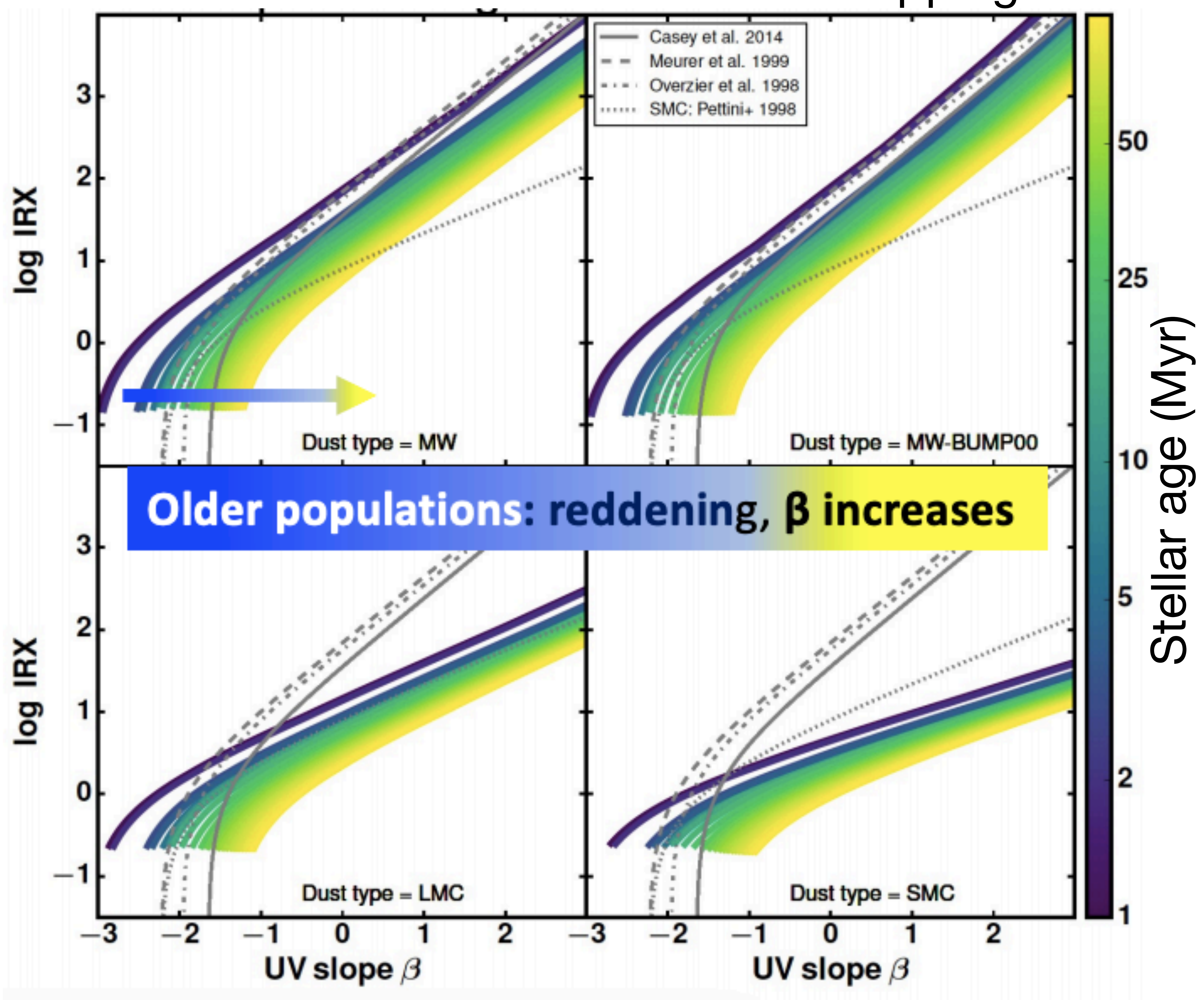
Decoding the IRX-β relation



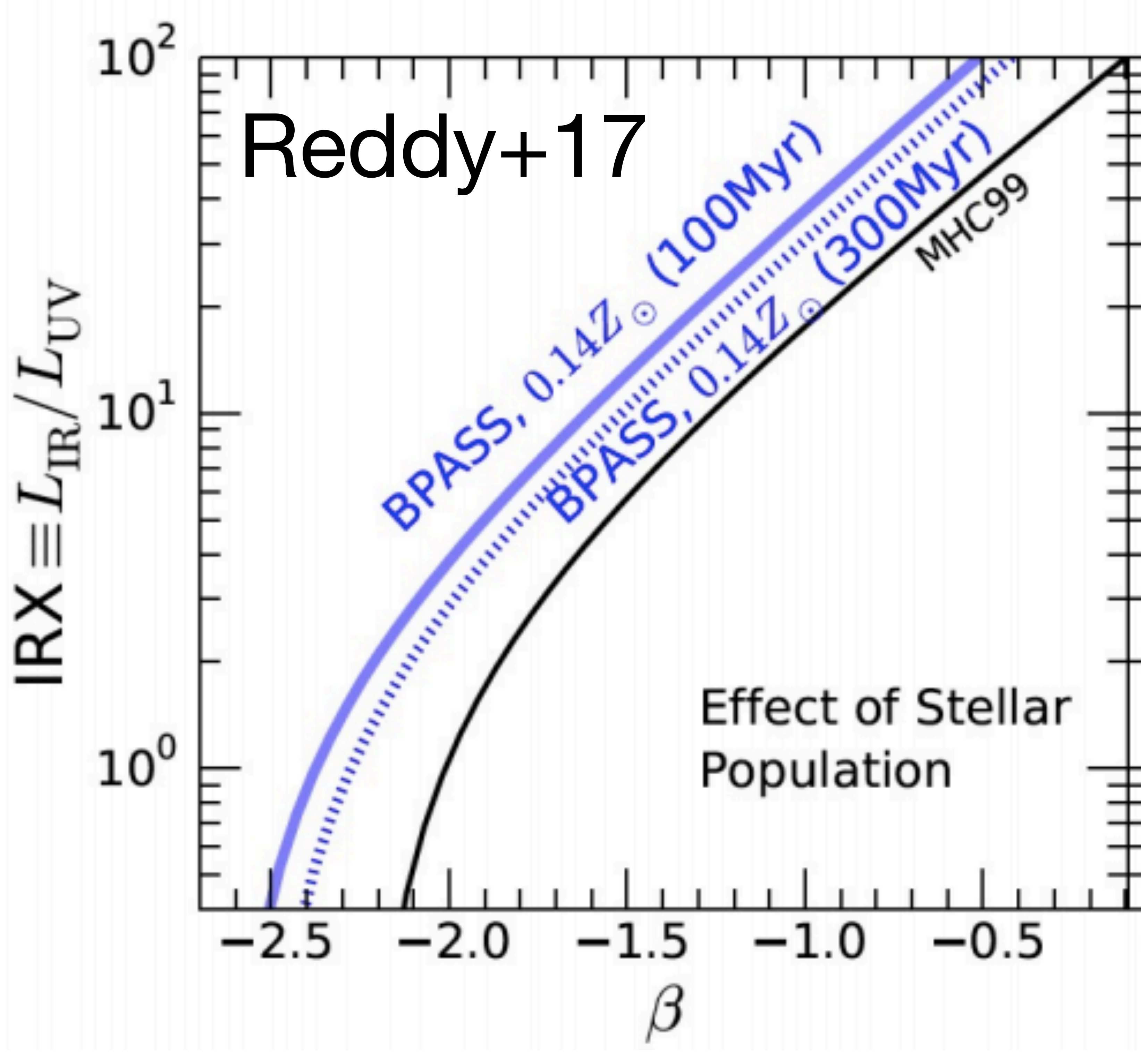


Impact of stellar populations

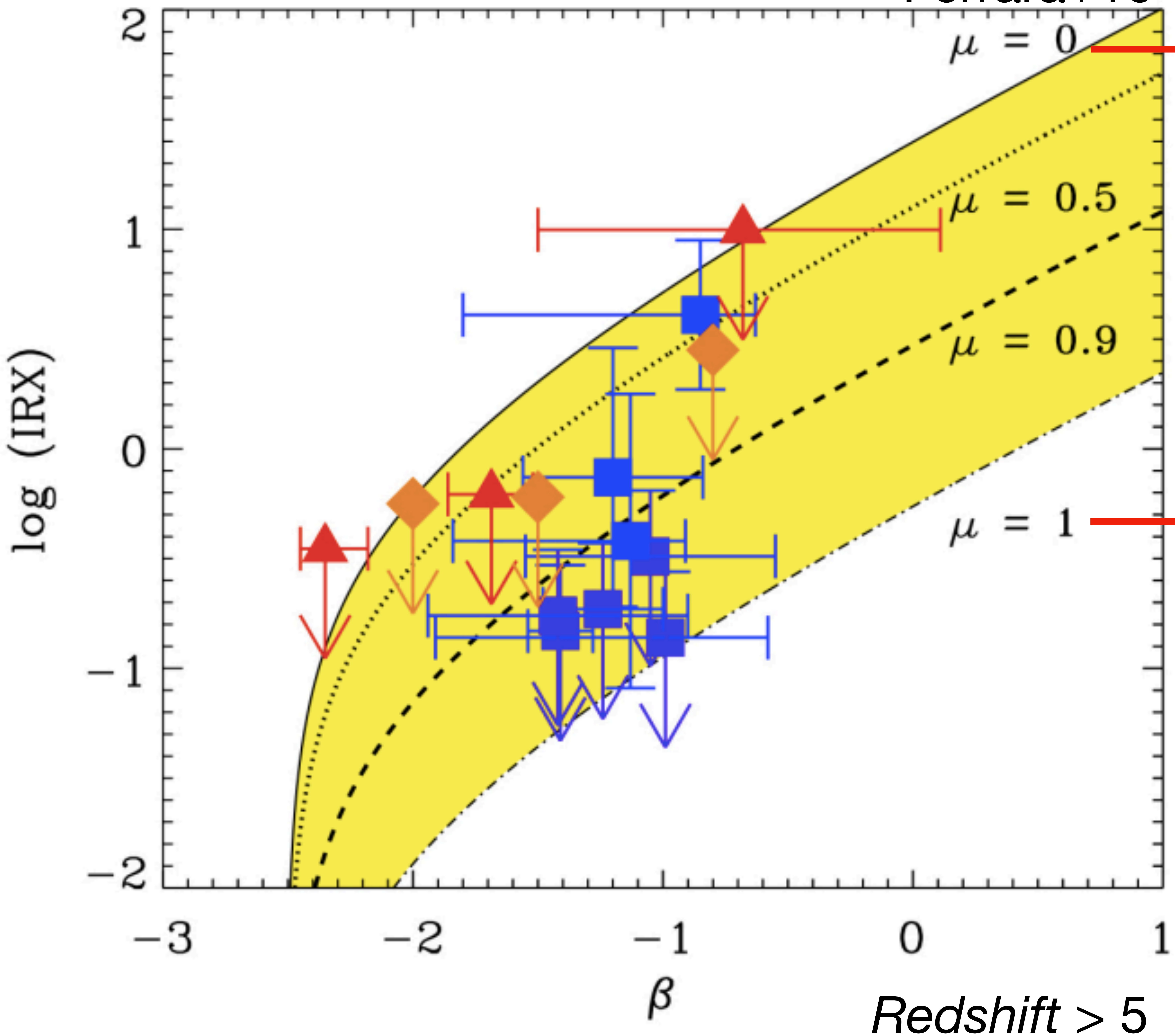
Popping+17



Modifying the stellar population changes β



Ferrara+16



ISM with no molecular component

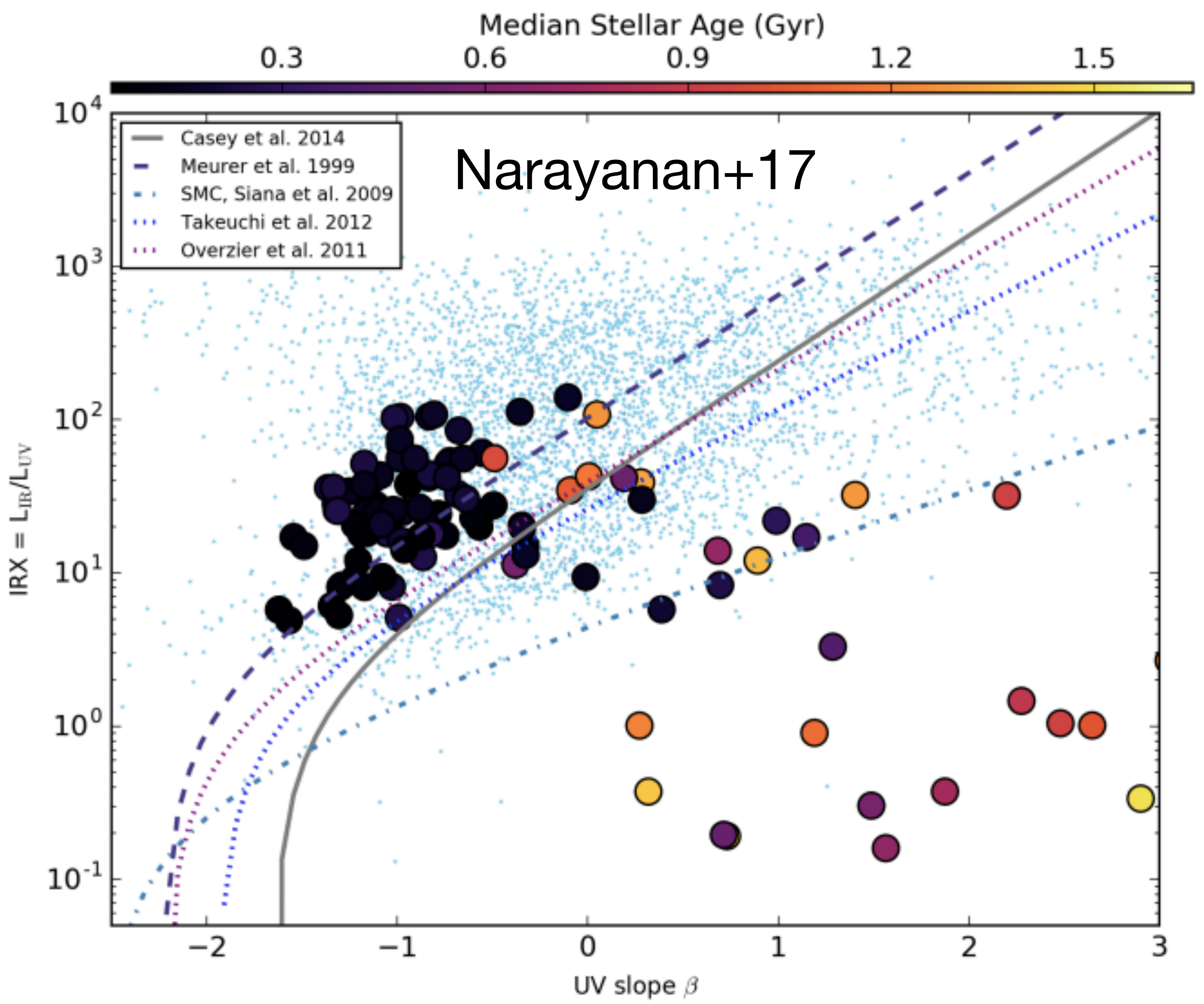
ISM fully rich with molecular gas

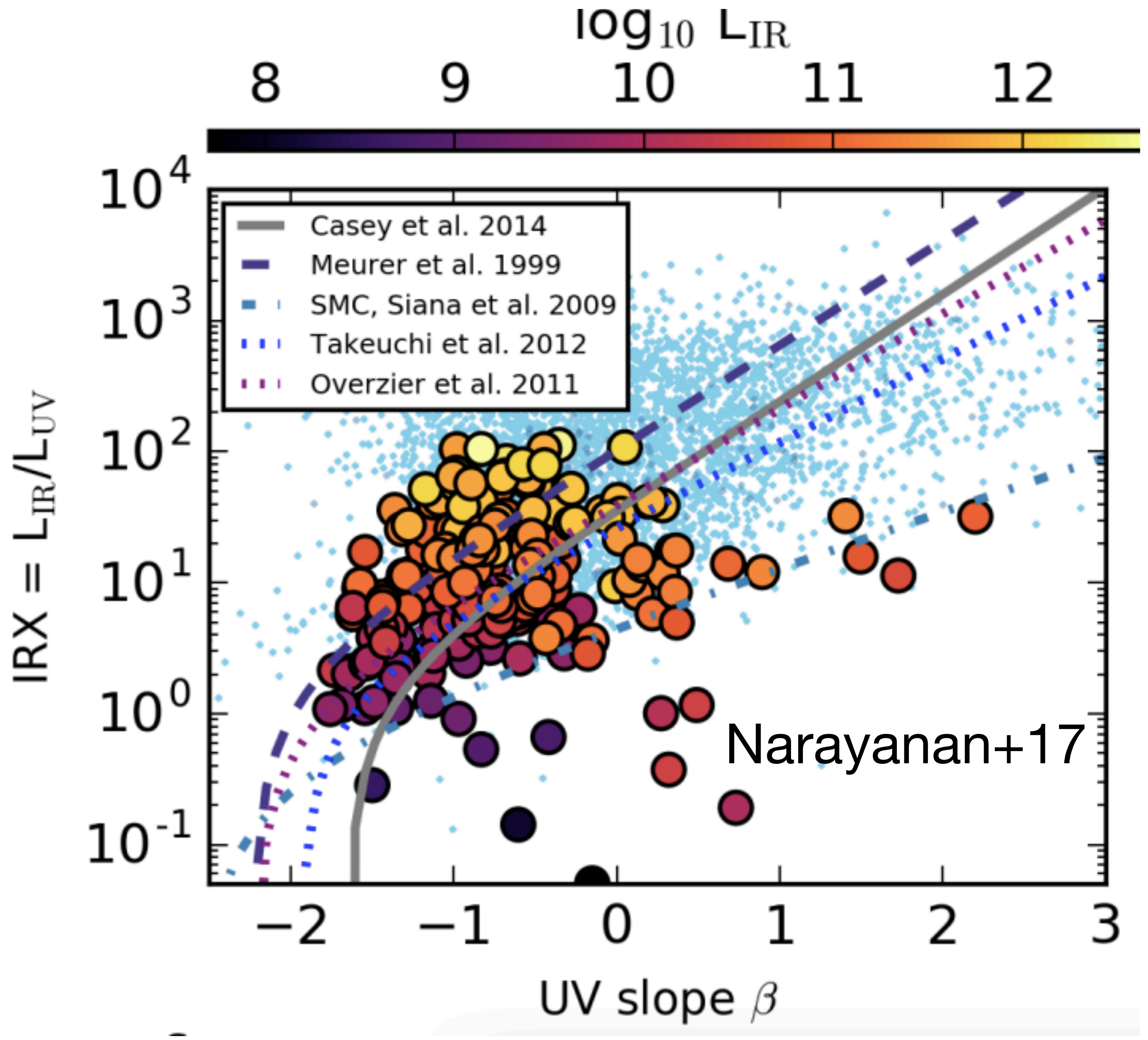
Lower IRX is associated with larger gas reservoirs

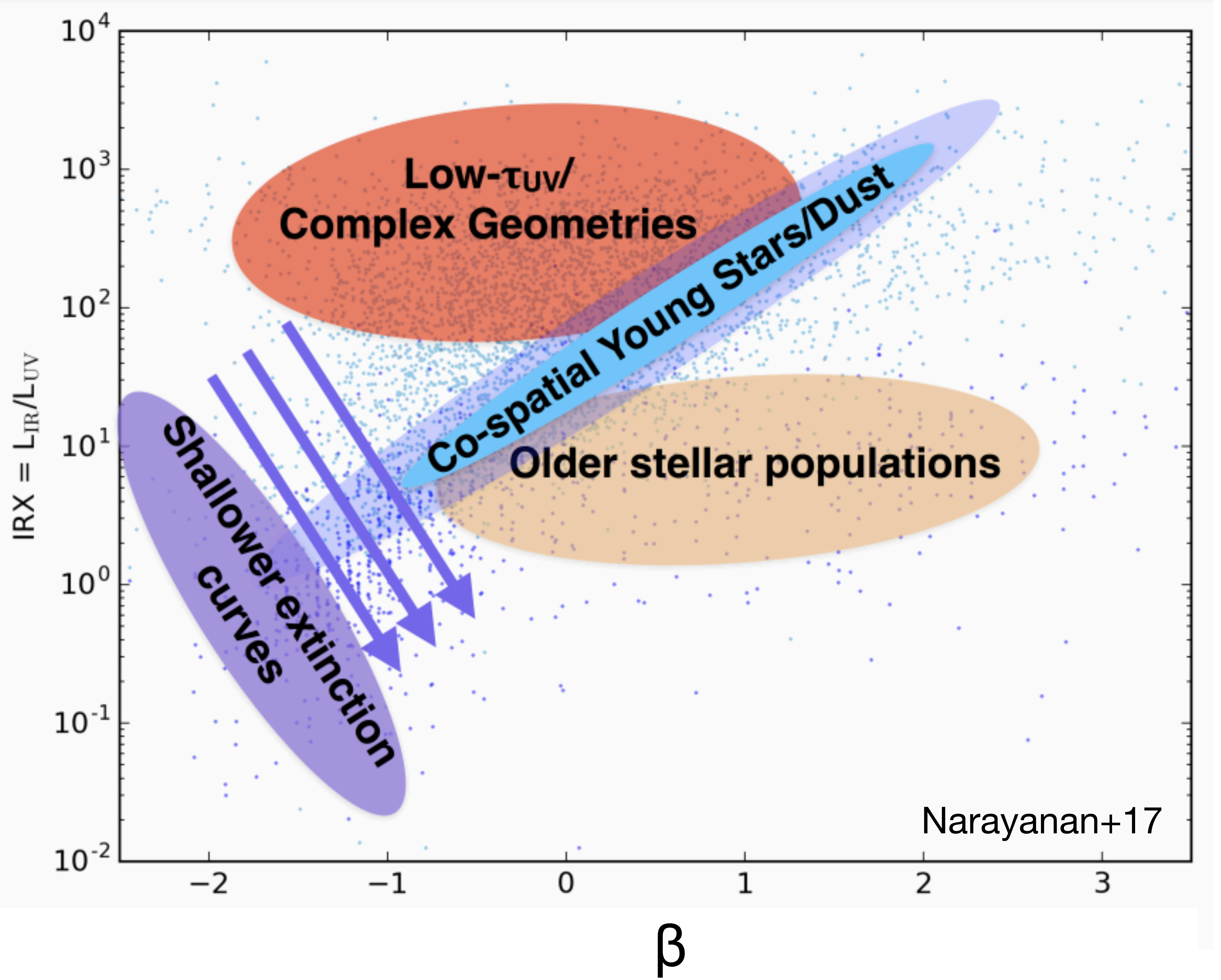
Large gas reservoirs boost star formation

Intense UV radiation field

Redshift > 5


Median Stellar Age (Gyr)
0.3 0.6 0.9 1.2 1.5
Casey et al. 2014
Meurer et al. 1999
SMC, Siana et al. 2009
Takeuchi et al. 2012
Overzier et al. 2011
Narayanan+17
IRX = L_IR/L_UV
UV slope β


log10 L_IR
8 9 10 11 12
Casey et al. 2014
Meurer et al. 1999
SMC, Siana et al. 2009
Takeuchi et al. 2012
Overzier et al. 2011
Narayanan+17
IRX = L_IR/L_UV
UV slope β


Low-τUV/
Complex Geometries
Co-spatial Young Stars/Dust
Older stellar populations
Shallower extinction
curves
Narayanan+17
IRX = L_IR/L_UV
β

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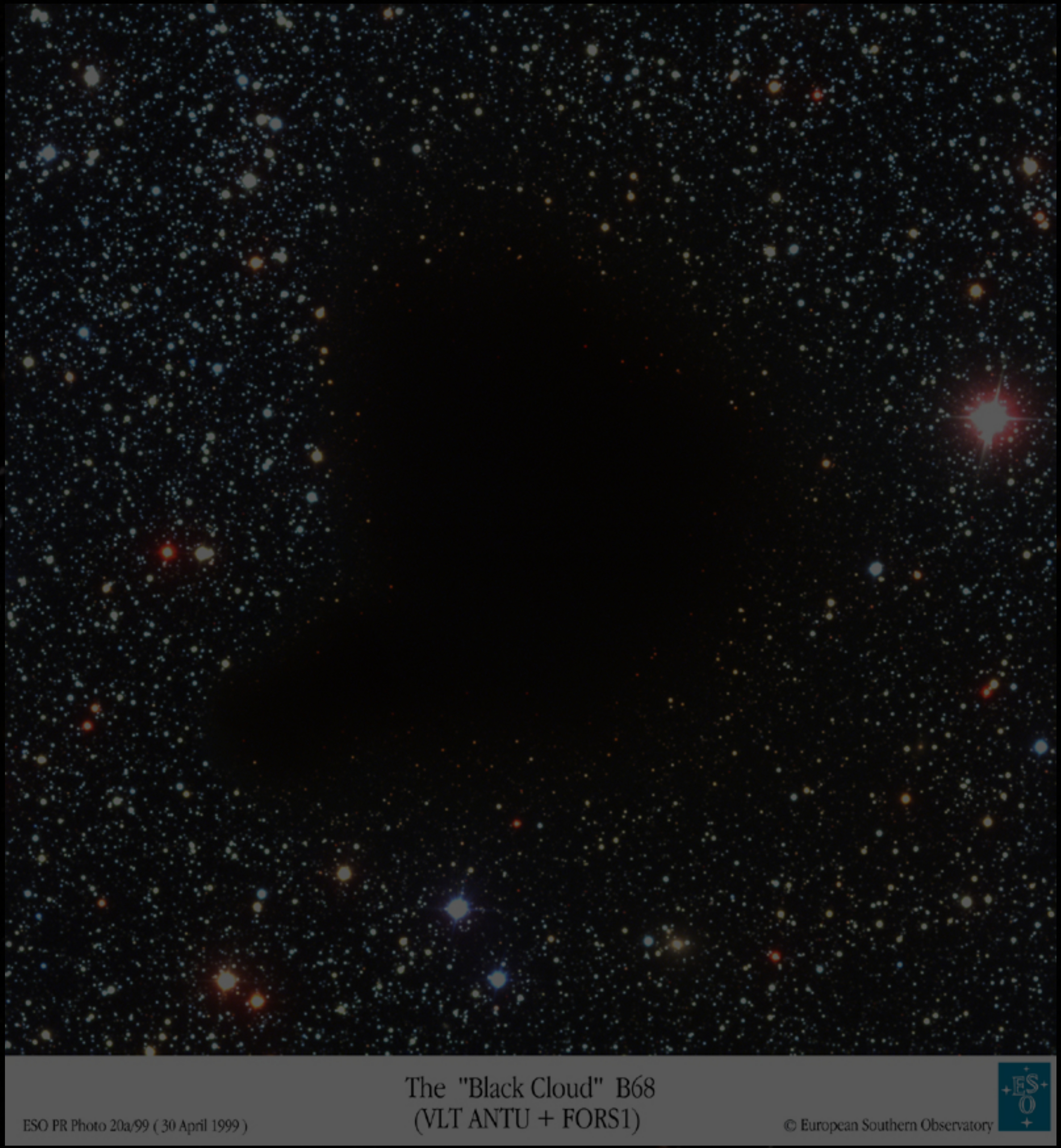
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(VLT ANTU + FORS1)
ESO PR Photo 20a/99 (30 April 1999)
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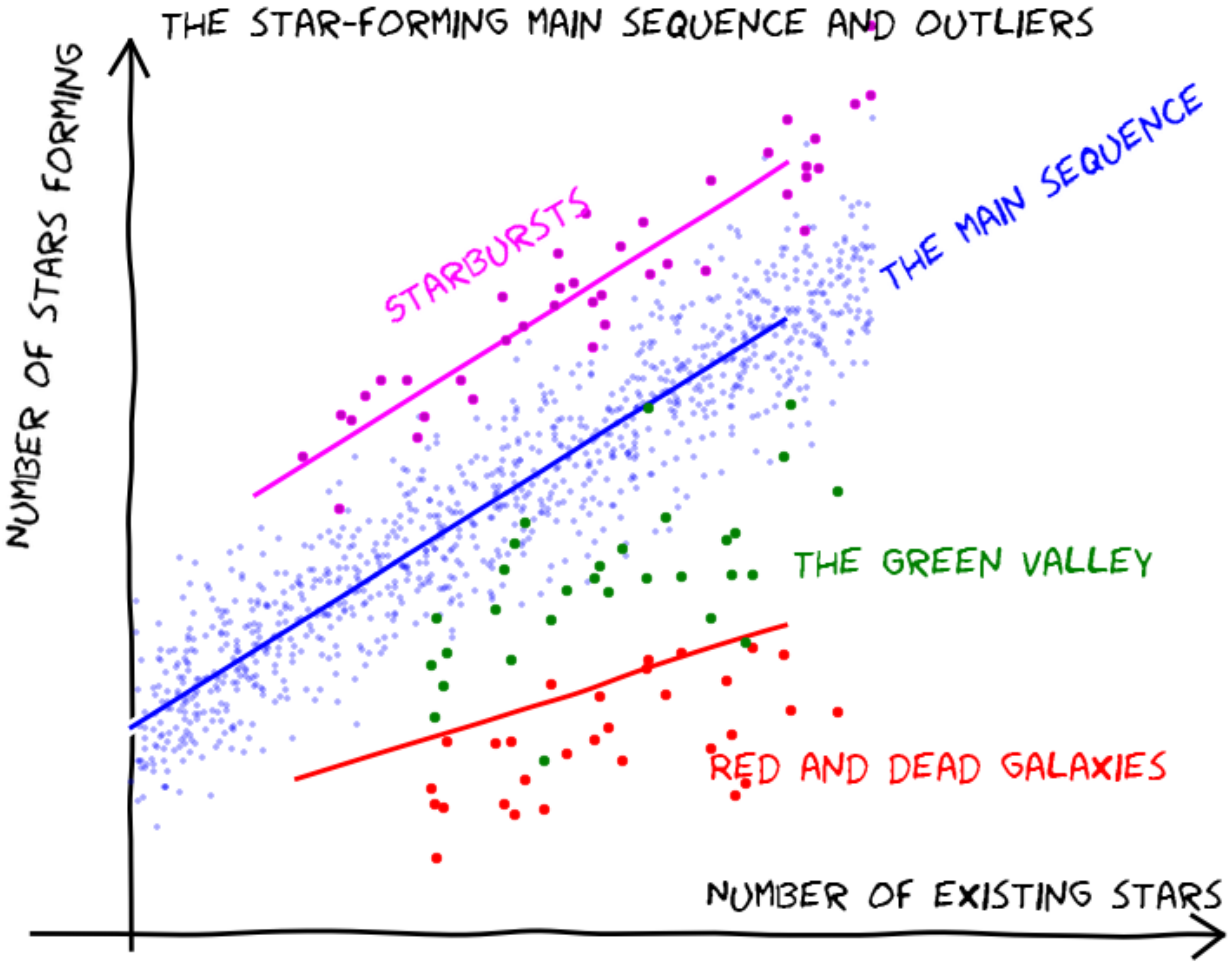
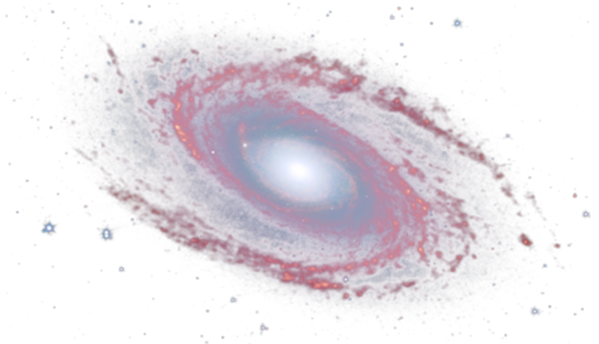
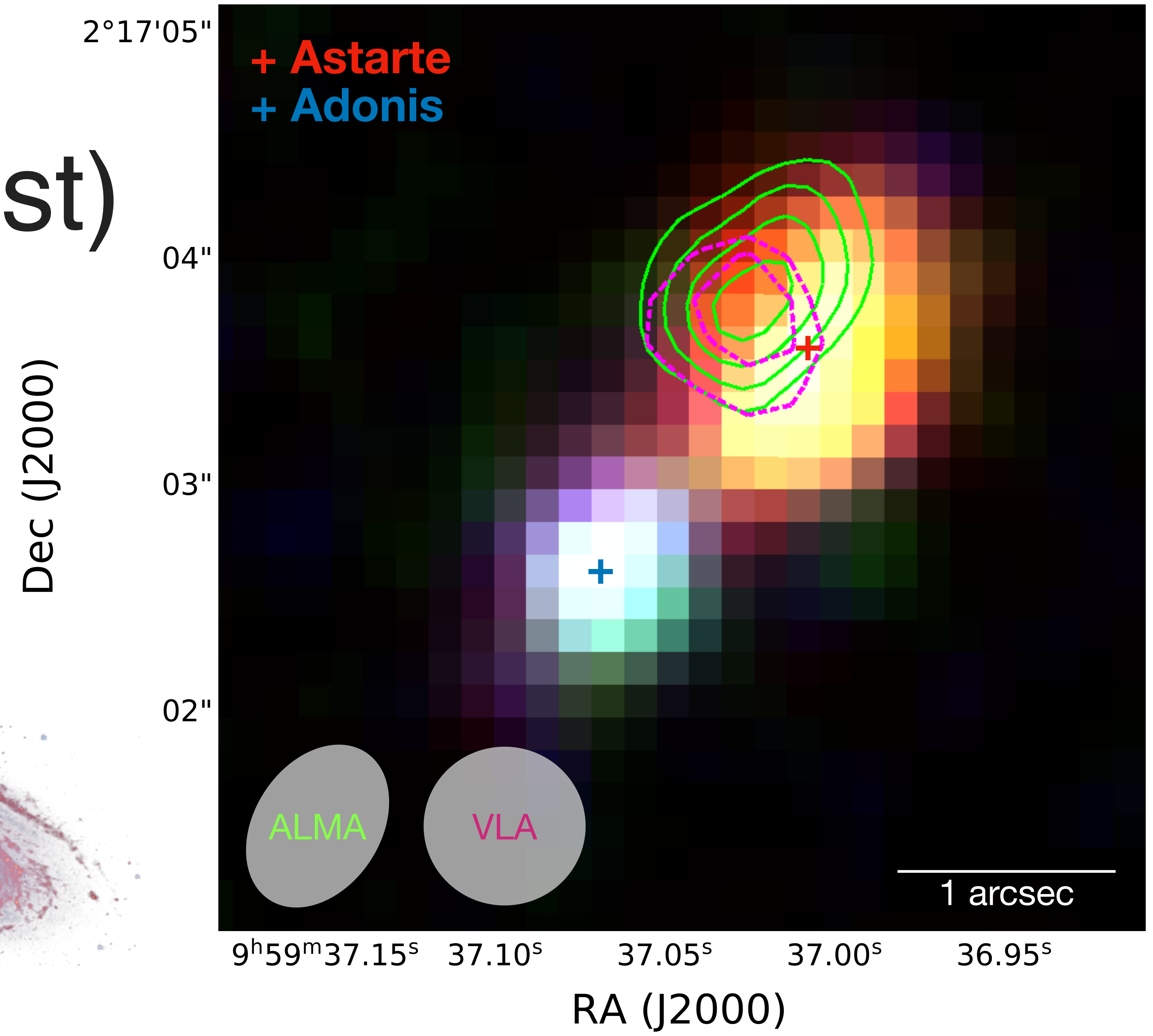
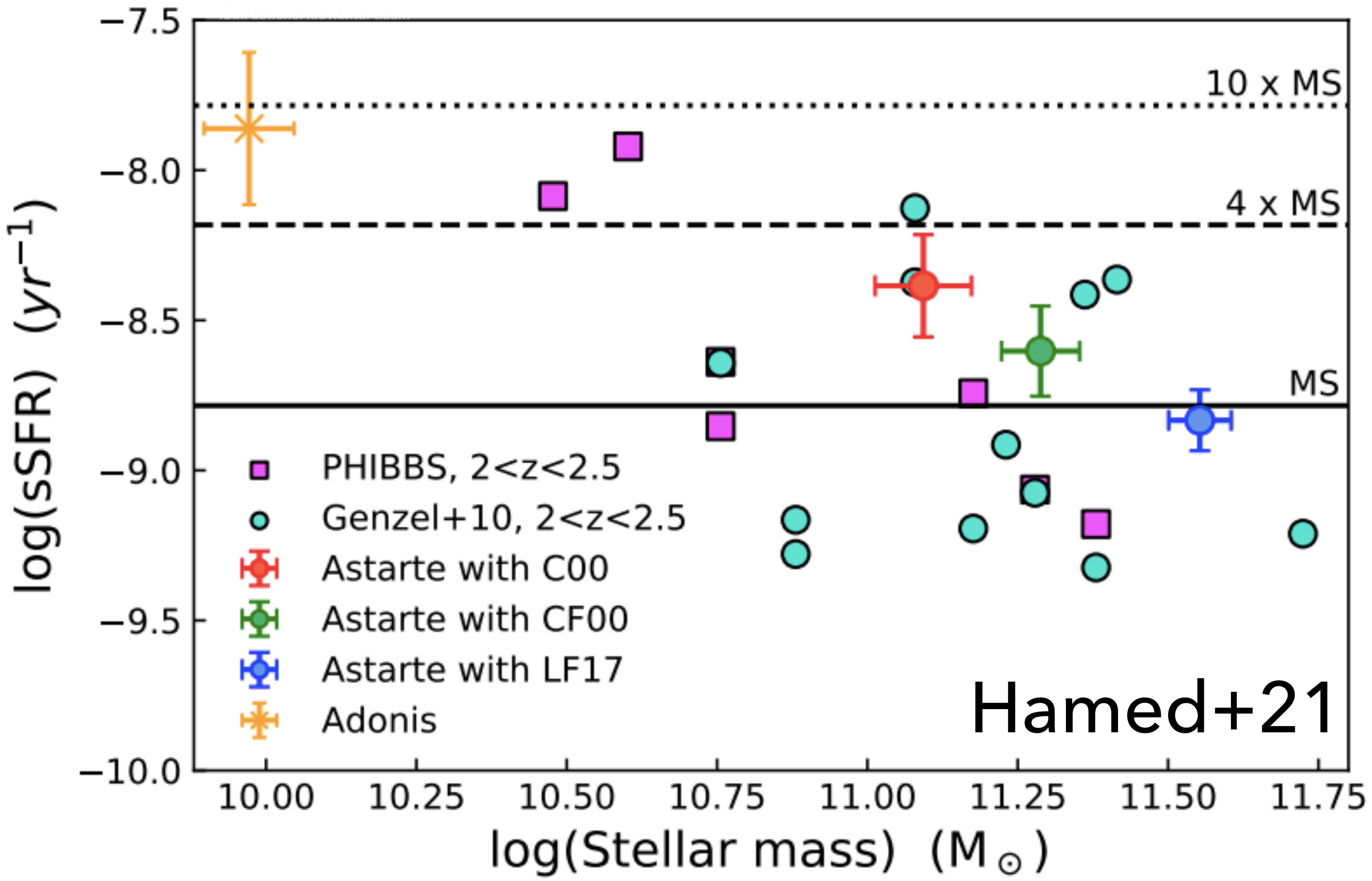
- Dust attenuation can change our views on what is standard and what is not (Main sequence vs Starburst)

- Dust attenuation correlates with dust continuum morphology and compactness of the star forming region and the extent of dust emission.



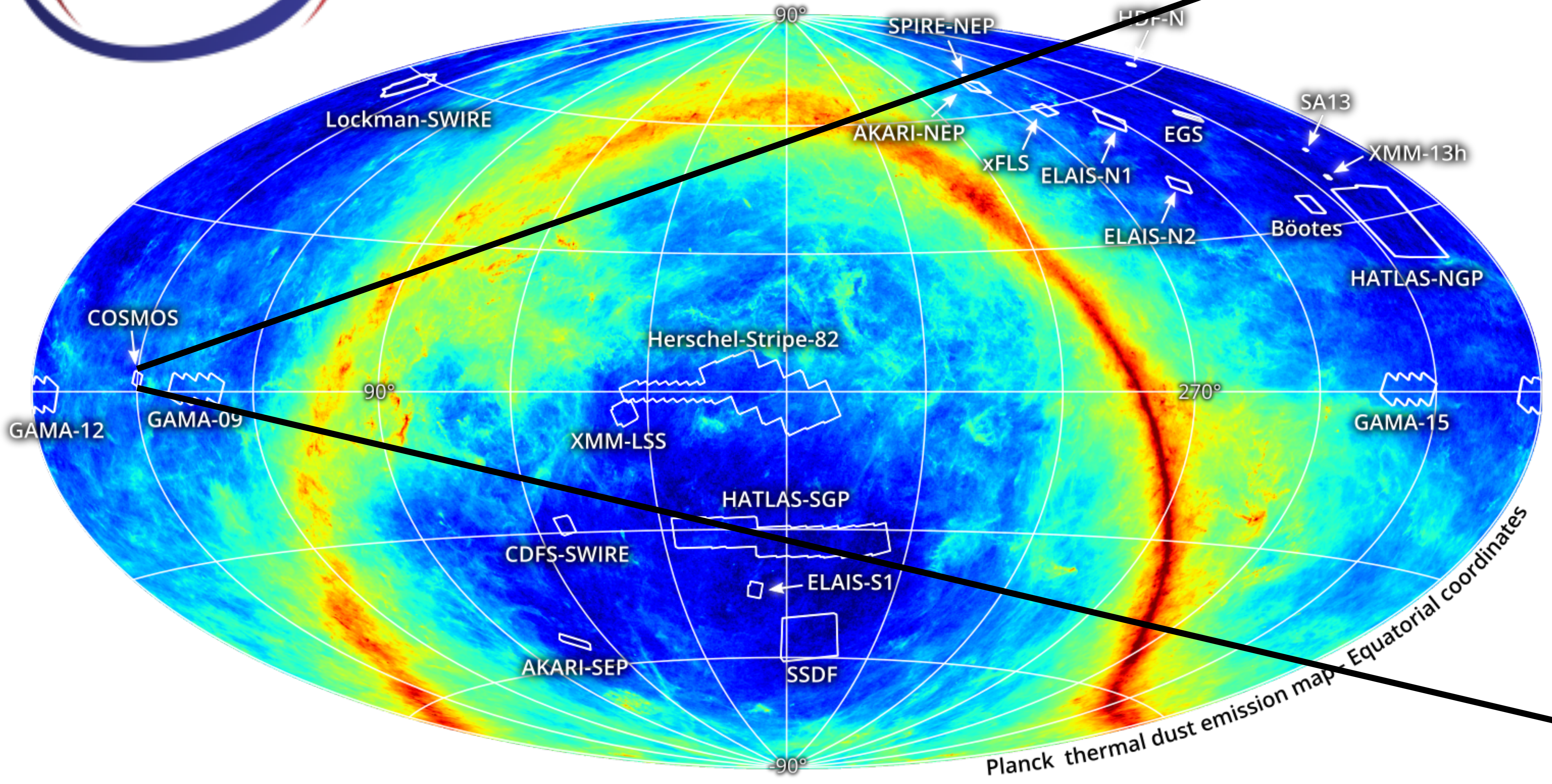


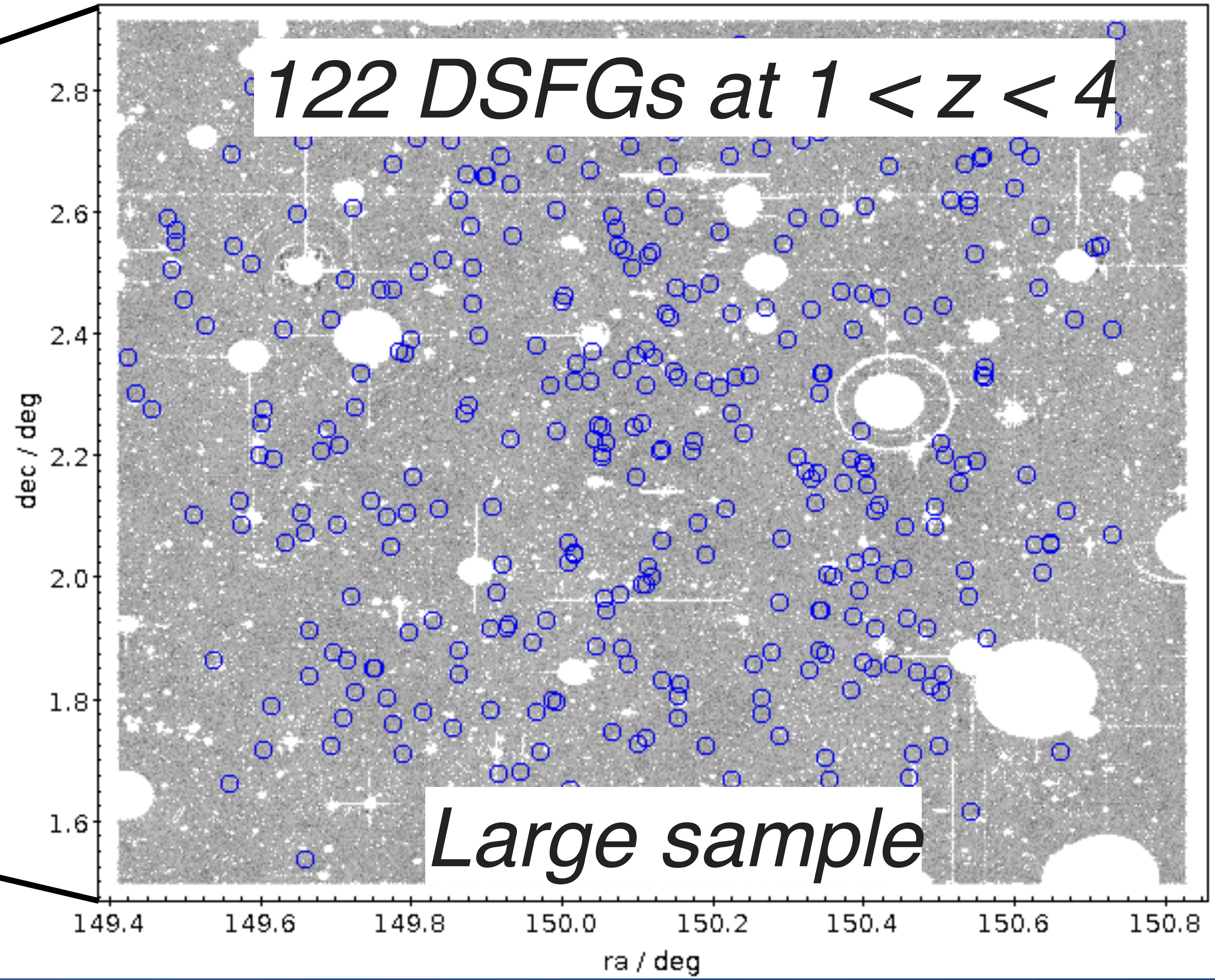




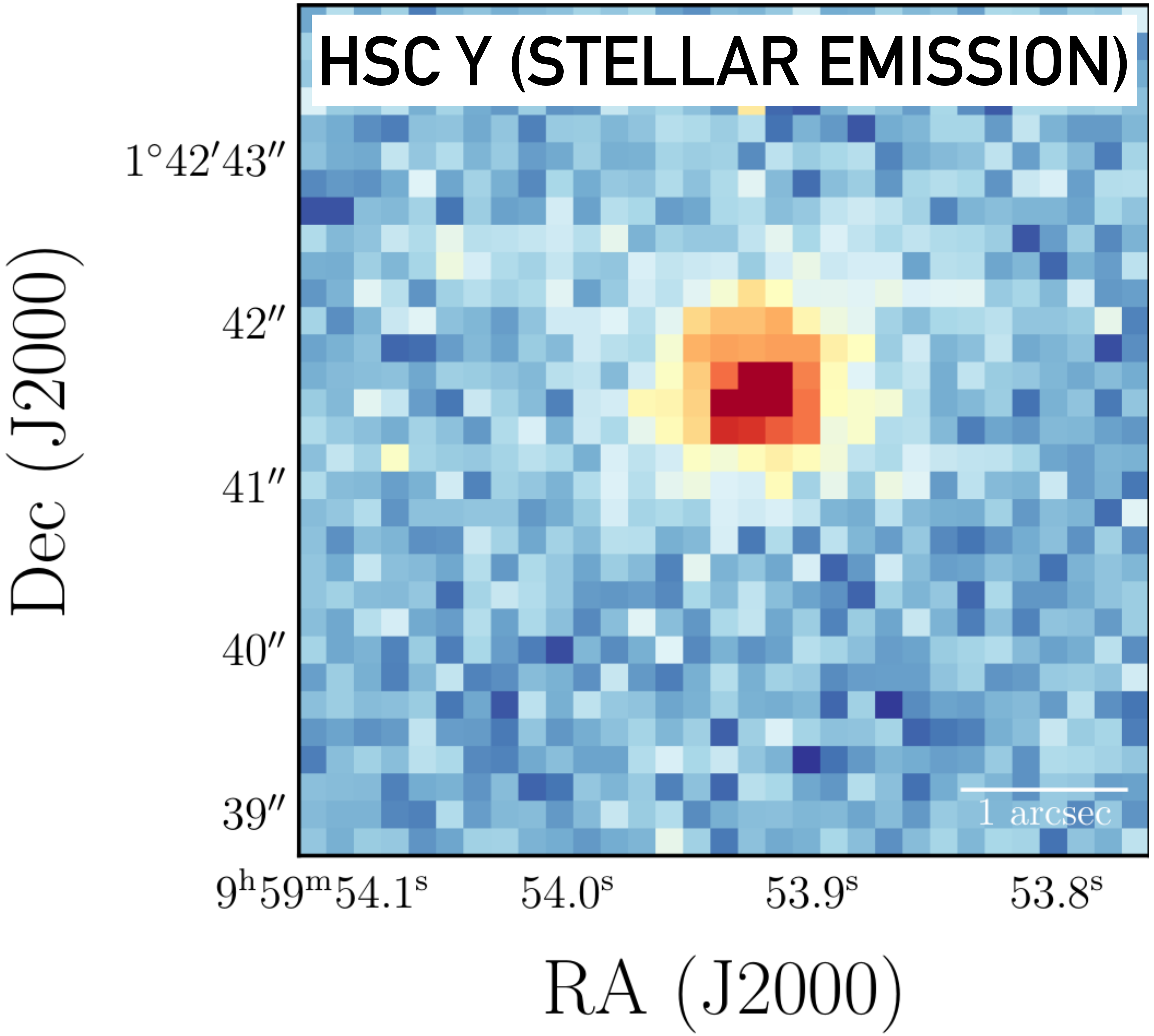
THE EFFECT OF DUST DISTRIBUTION ON ATTENUATION

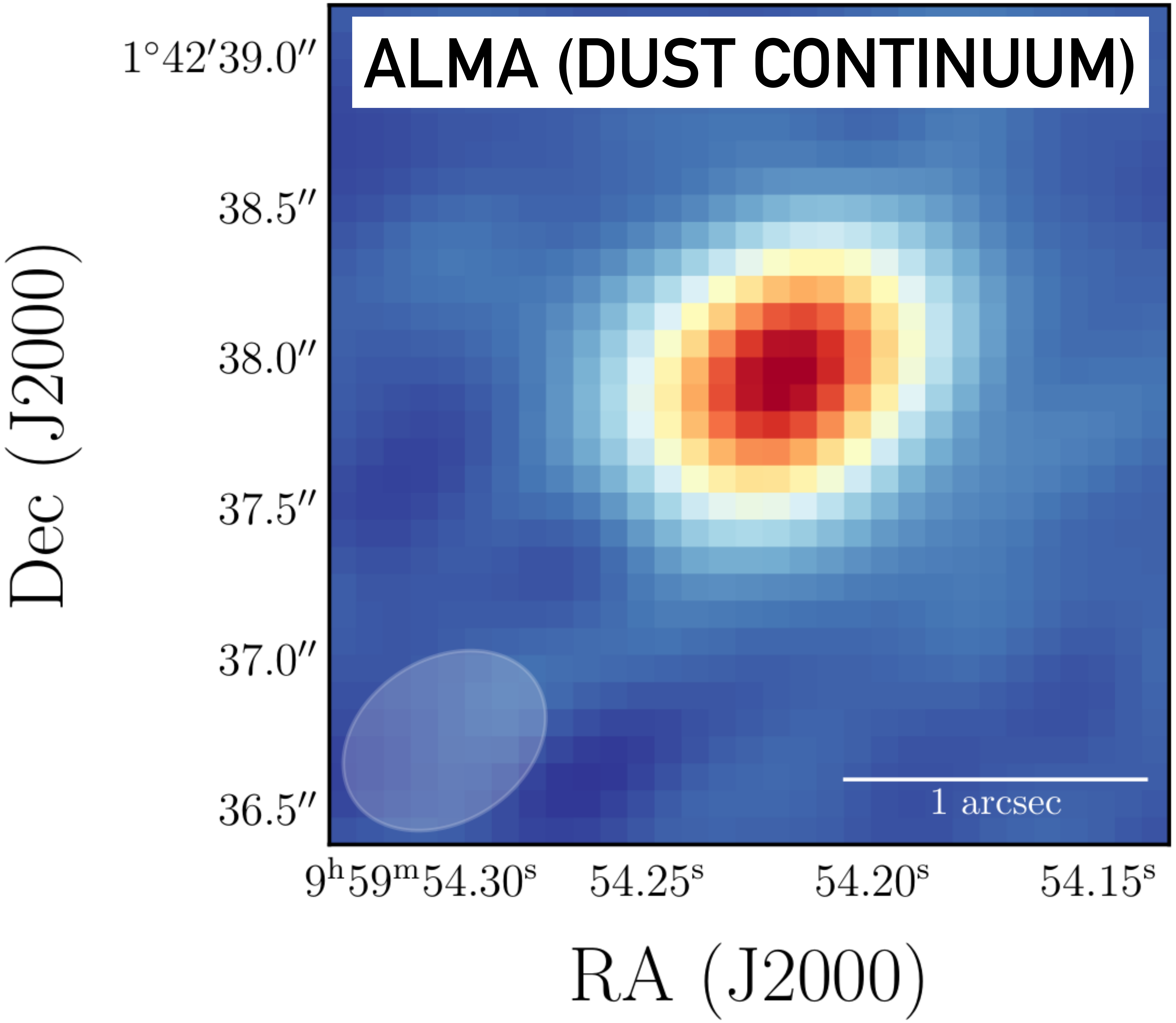
HELP Herschel Extragalactic Legacy Project + A3COSMOS

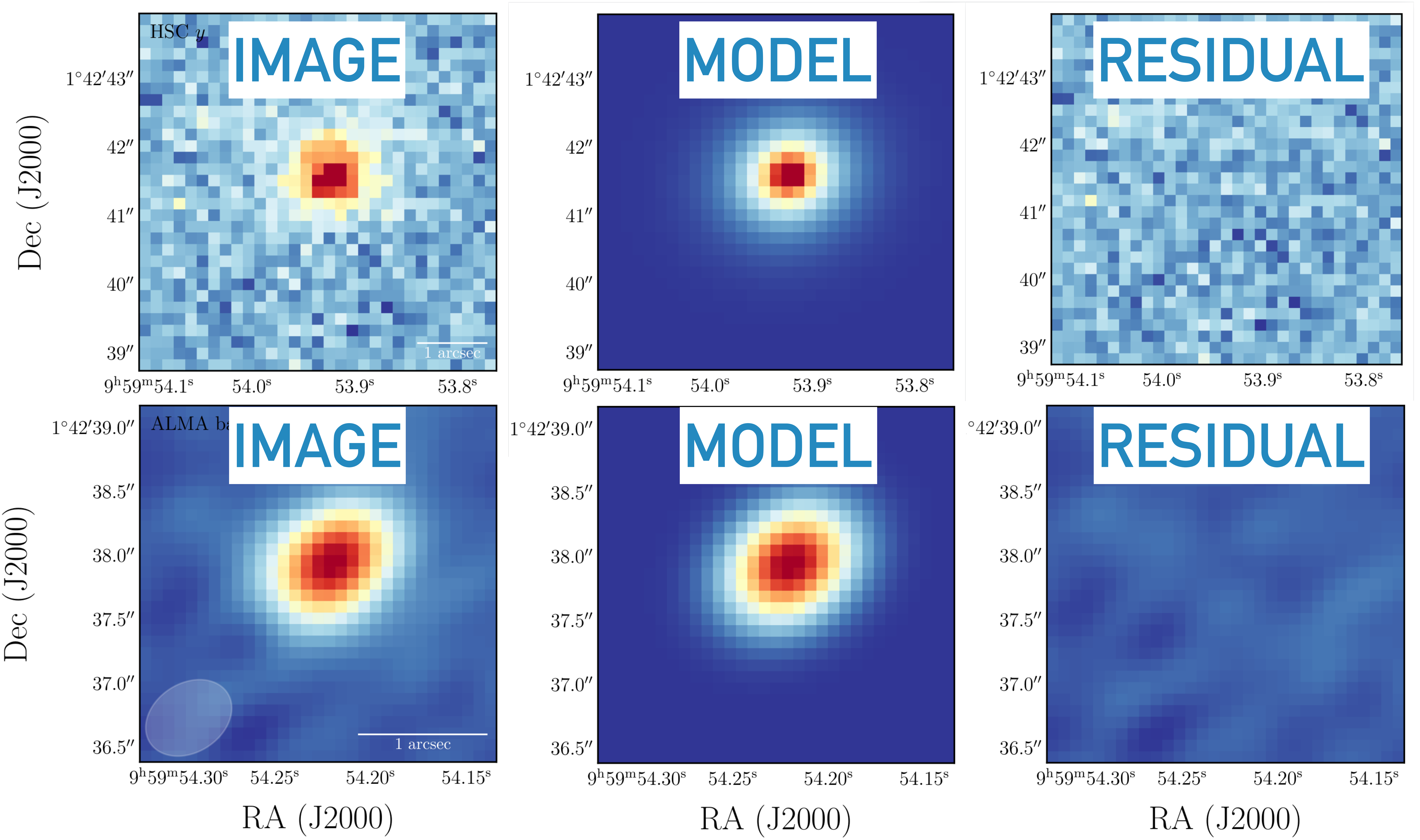




122 GALAXIES DETECTED IN THE Y BAND AND WITH ALMA



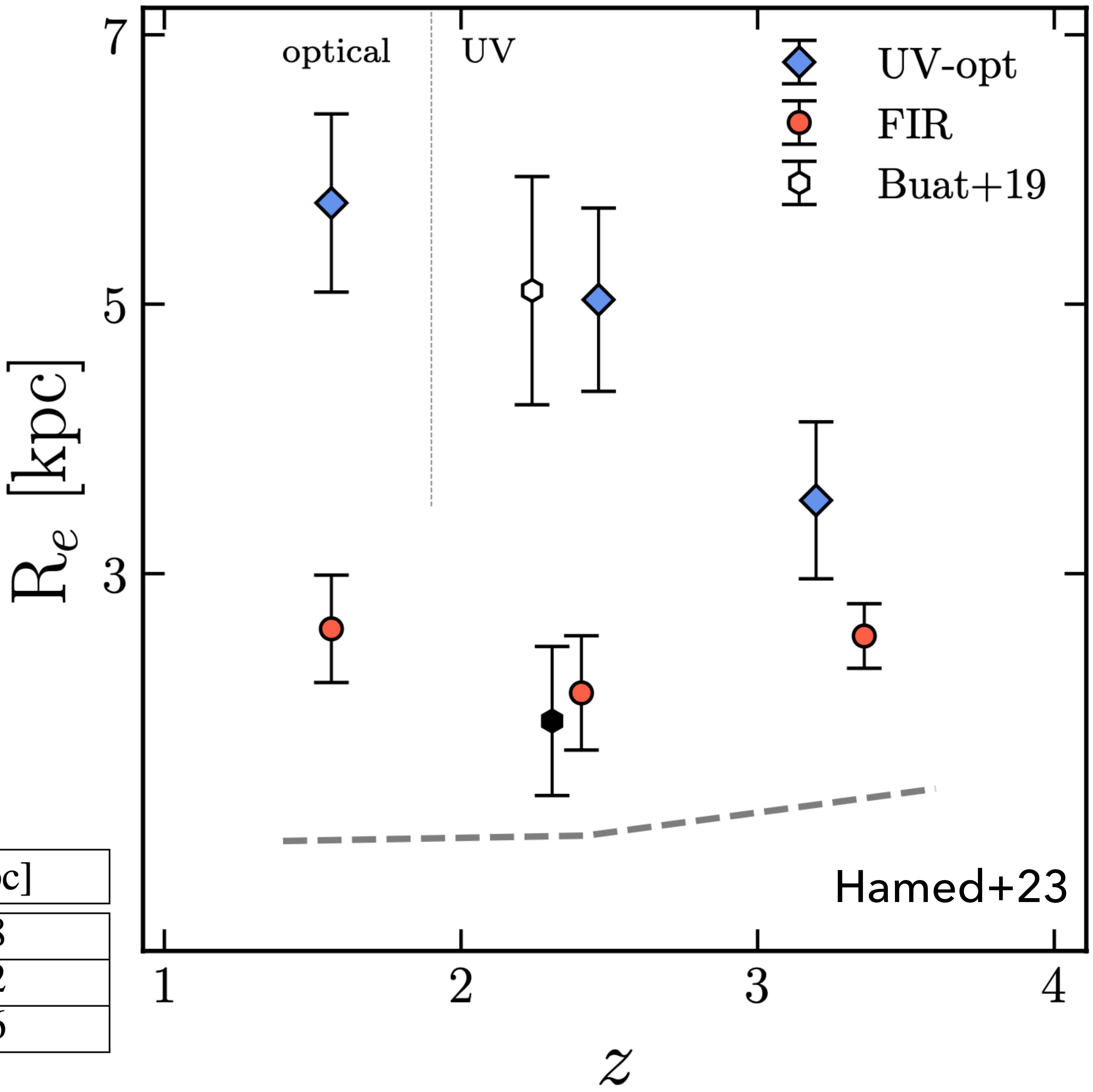




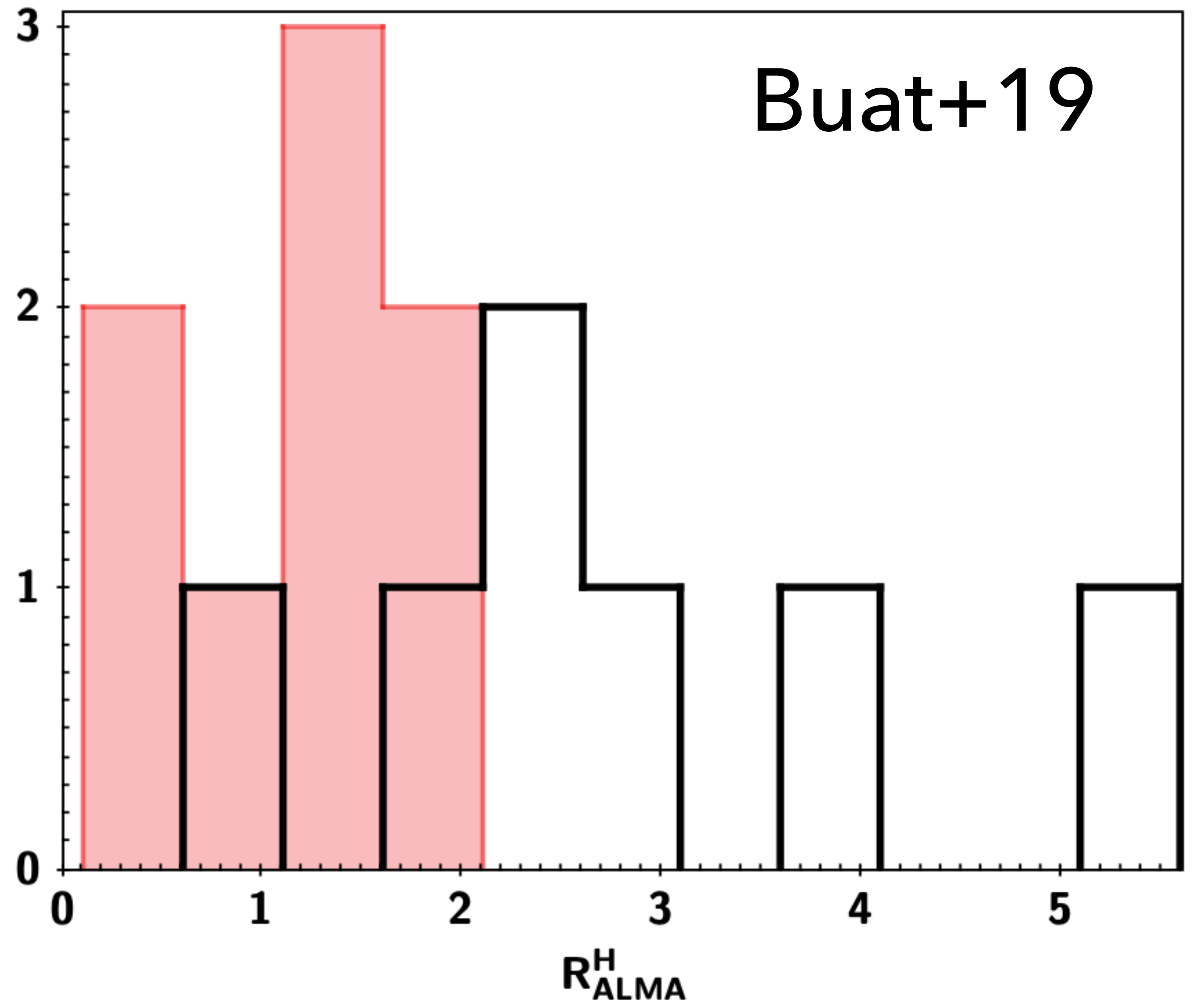
HSC y
IMAGE
MODEL
RESIDUAL
1 arcsec
ALMA ba
IMAGE
MODEL
RESIDUAL
1 arcsec
Dec (J2000)
RA (J2000)
1°42′43″
42″
41″
40″
39″
9h59m54.1s
54.0s
53.9s
53.8s
1°42′39.0″
38.5″
38.0″
37.5″
37.0″
36.5″
9h59m54.30s
54.25s
54.20s
54.15s

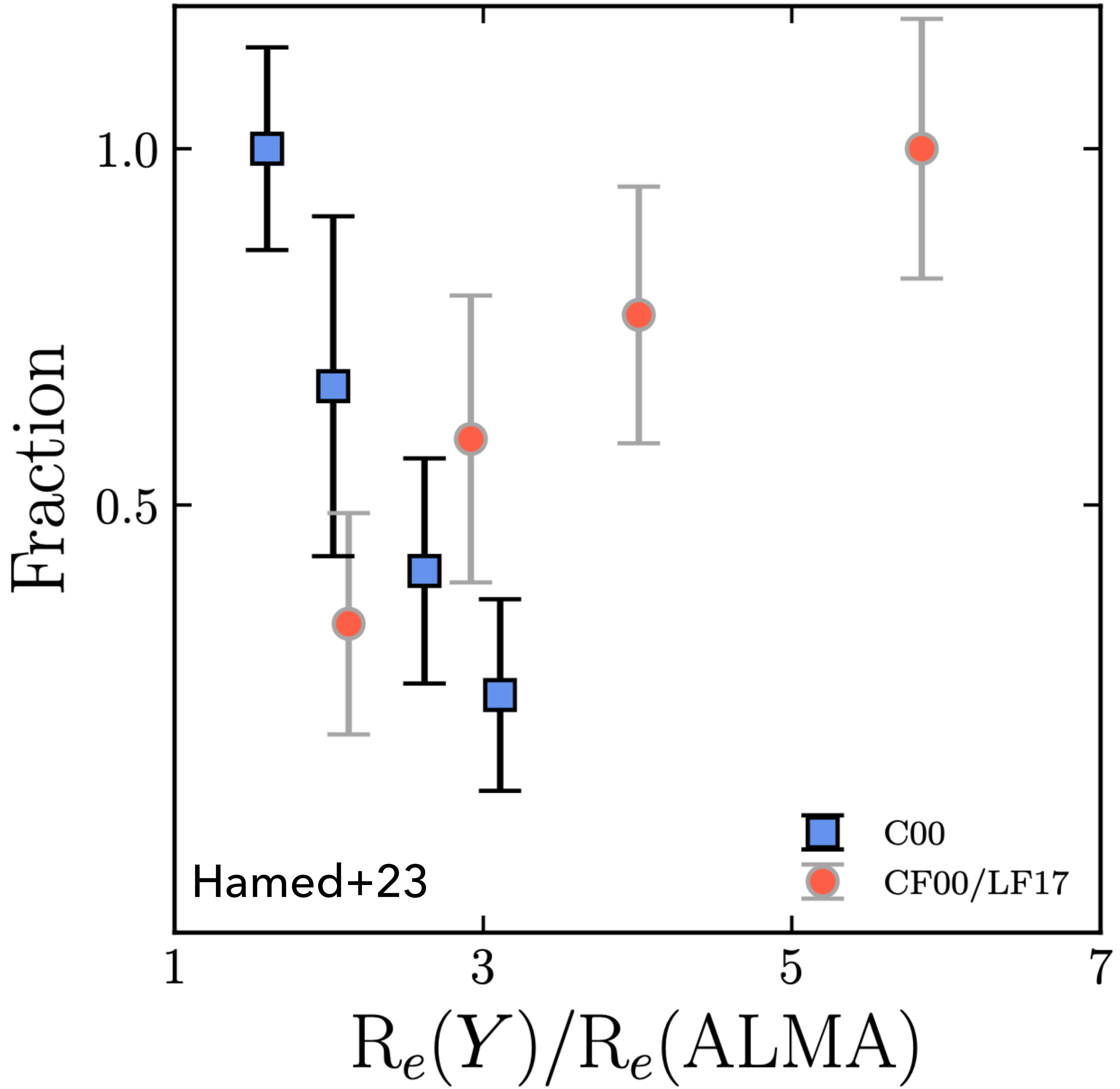
- Largest sample of galaxies to study dust attenuation
- Complete morphological census of DSFGs from $1 < z < 4$ (homogeneously)
- HSC's *Y* band observations sampling optical and UV rest-frame
- Comparable angular resolution
- All size measurements are above detection limit

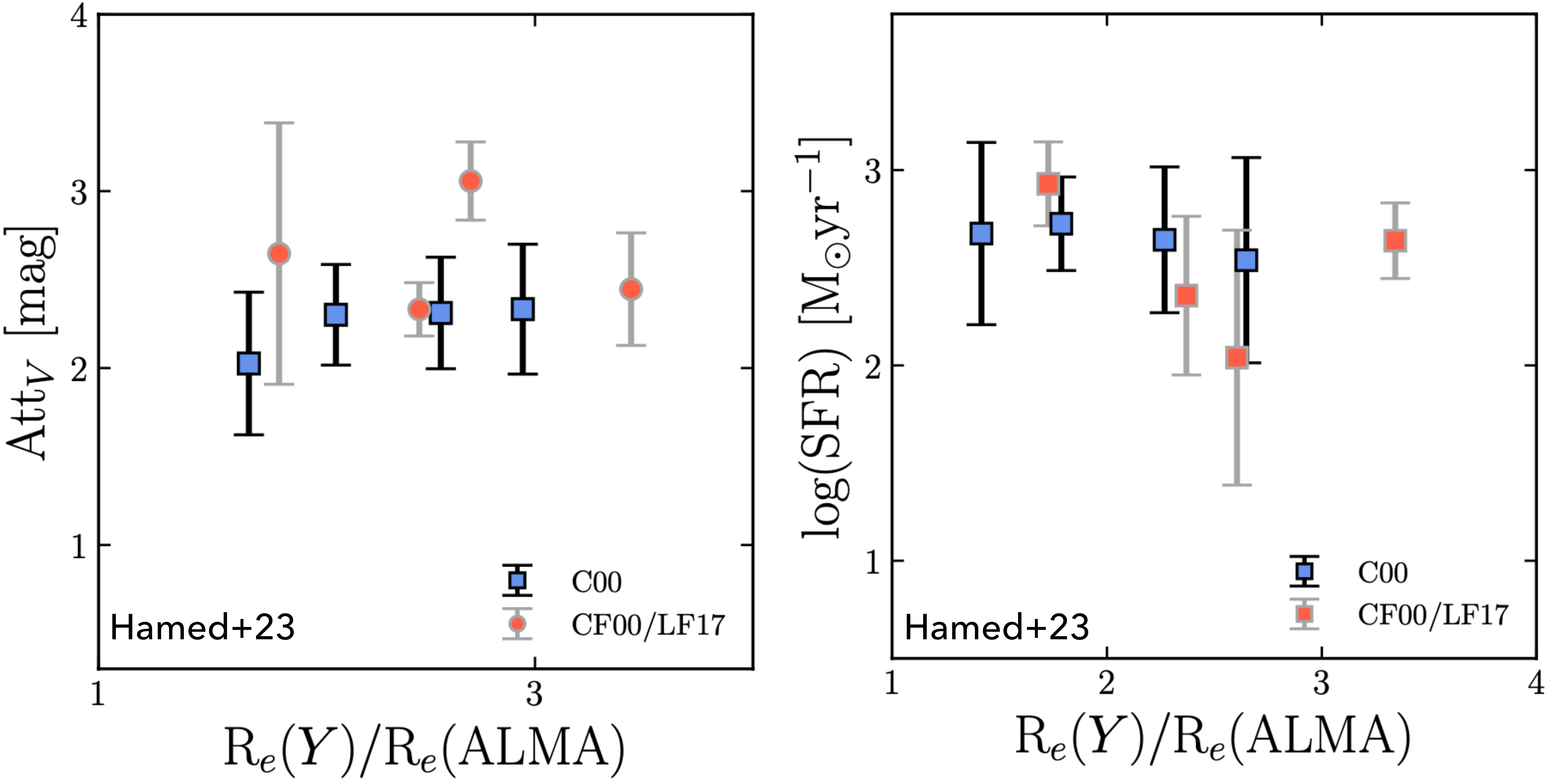
redshift	R_e^{ALMA} [kpc]	R_e^{UV-opt} [kpc]
$1 < z < 2$	2.59±0.25	5.75±0.18
$2 < z < 3$	2.12±0.32	5.03±0.22
$3 < z < 4$	2.54±0.15	3.54±0.26



- Galaxies with smaller opt/UV sizes relative to dust radii largely prefer the Calzetti attenuation law in our sample.
- Larger Re(Y)/Re(ALMA) ratio (>3) preferred Charlot & Fall and its modifications



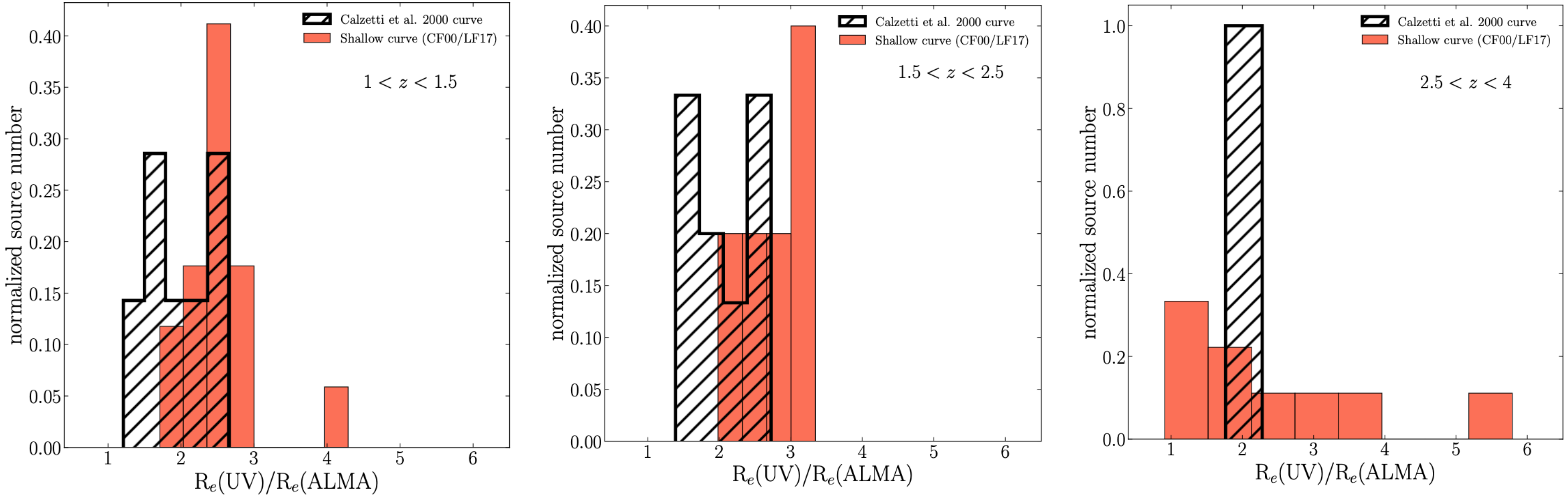




4
3
2
1
Att_V [mag]
1
3
$\mathrm{R}_e(Y)/\mathrm{R}_e(\mathrm{ALMA})$
C00
CF00/LF17
Hamed+23
3
2
1
$\log(\mathrm{SFR})$ [$\mathrm{M}_\odot \mathrm{yr}^{-1}$]
1
2
3
4
$\mathrm{R}_e(Y)/\mathrm{R}_e(\mathrm{ALMA})$
C00
CF00/LF17
Hamed+23

Same trend is observed with redshift. In agreement with Buat+19 for a sample of 7 galaxies at the cosmic noon

Despite its simplicity, the Calzetti law manages to fit half of our sample



Hamed+23

Star-to-Dust compactness
3
2
1
Today
Cosmic noon
6
3
2
1
Universe age [in billion years]
Dust
Stellar emission
Dust
Stellar emission
1 arcsec

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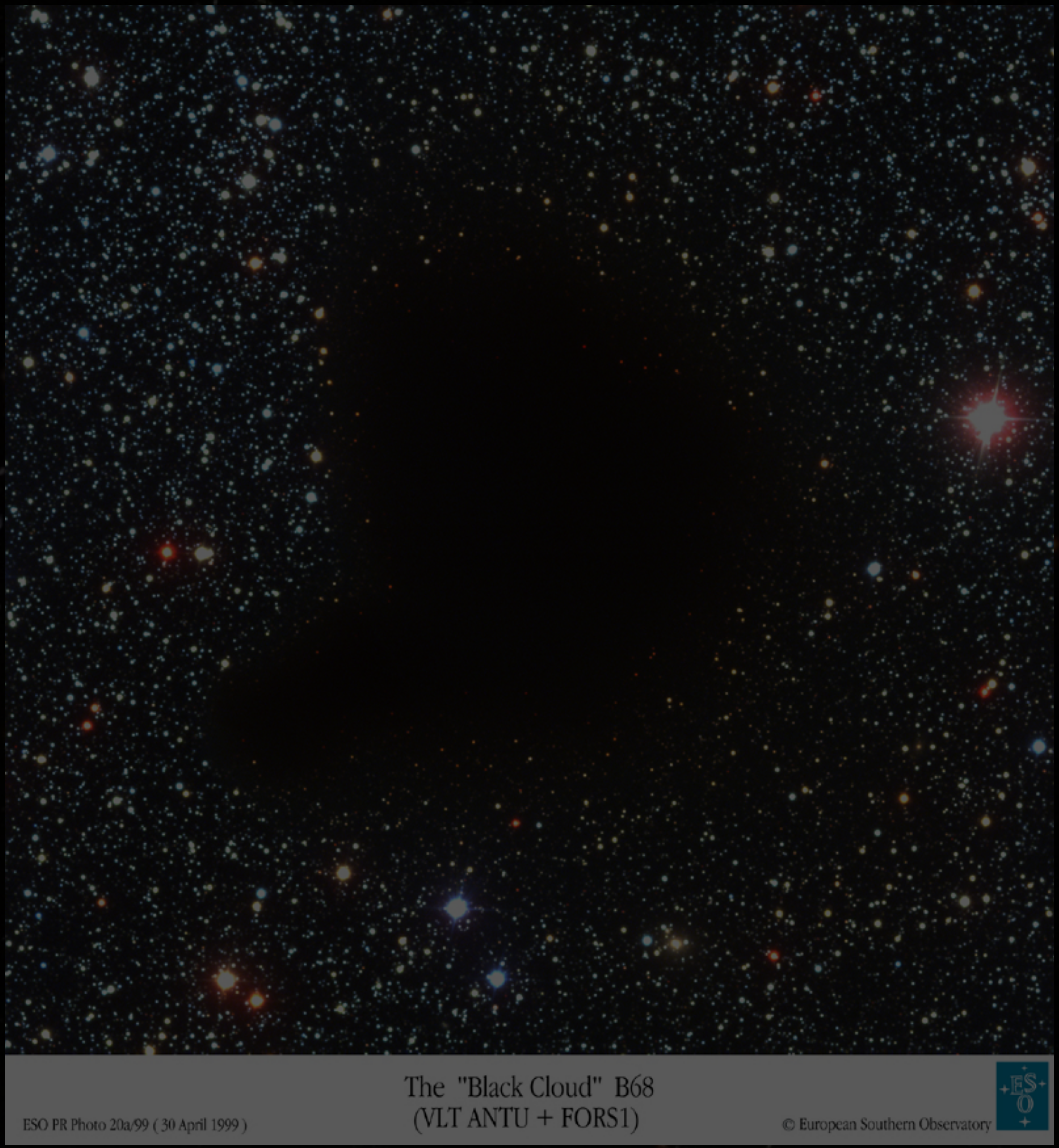
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ESO

RED WINE

infraRED Wavelengths IN Environments

UMO-2022/45/N/ST9/01336

IRX- β DUST ATTENUATION RELATION

Pistis+22,
Figueira+22,
Siudek+18,
Scodeggio+17,
Krywult+17

HELP Herschel Extragalactic Legacy Project + VIPERS VIMOS PUBLIC EXTRAGALACTIC REDSHIFT SURVEY

0.5 < z < 0.8

Hamed+, submitted

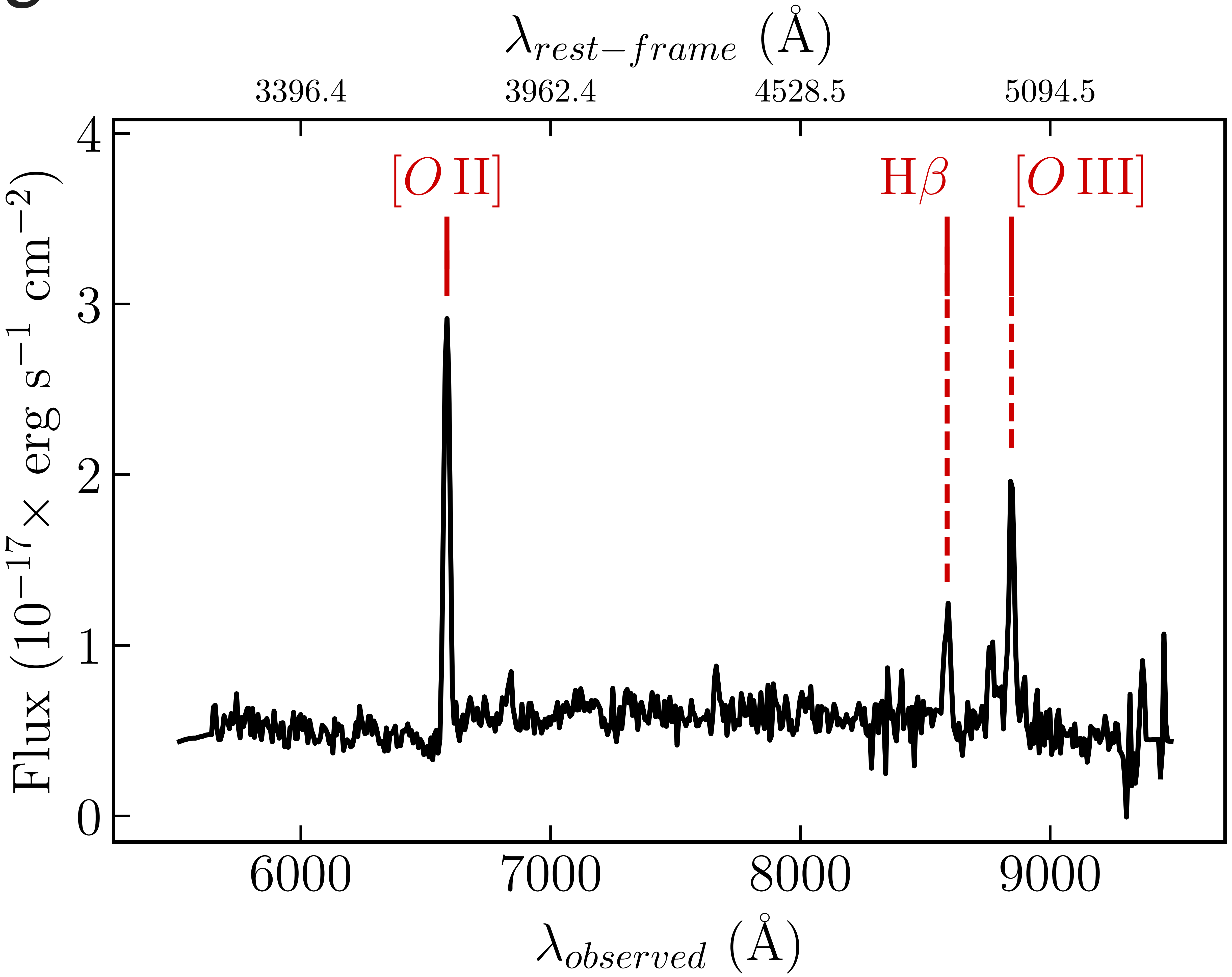
Spectroscopy from VIPERS

+

Photometry from HELP

↓

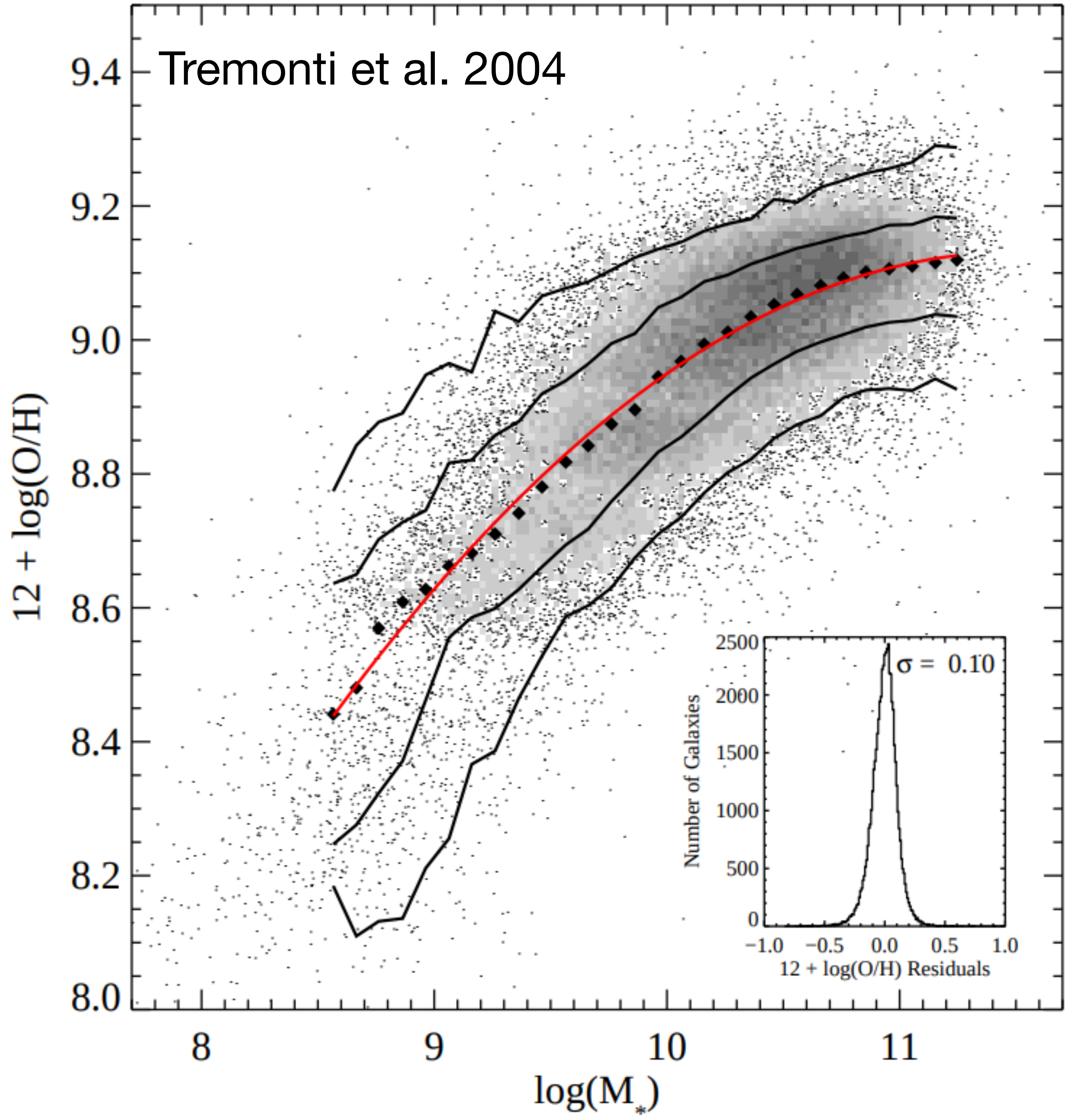
Metallicity estimation
and physical observables



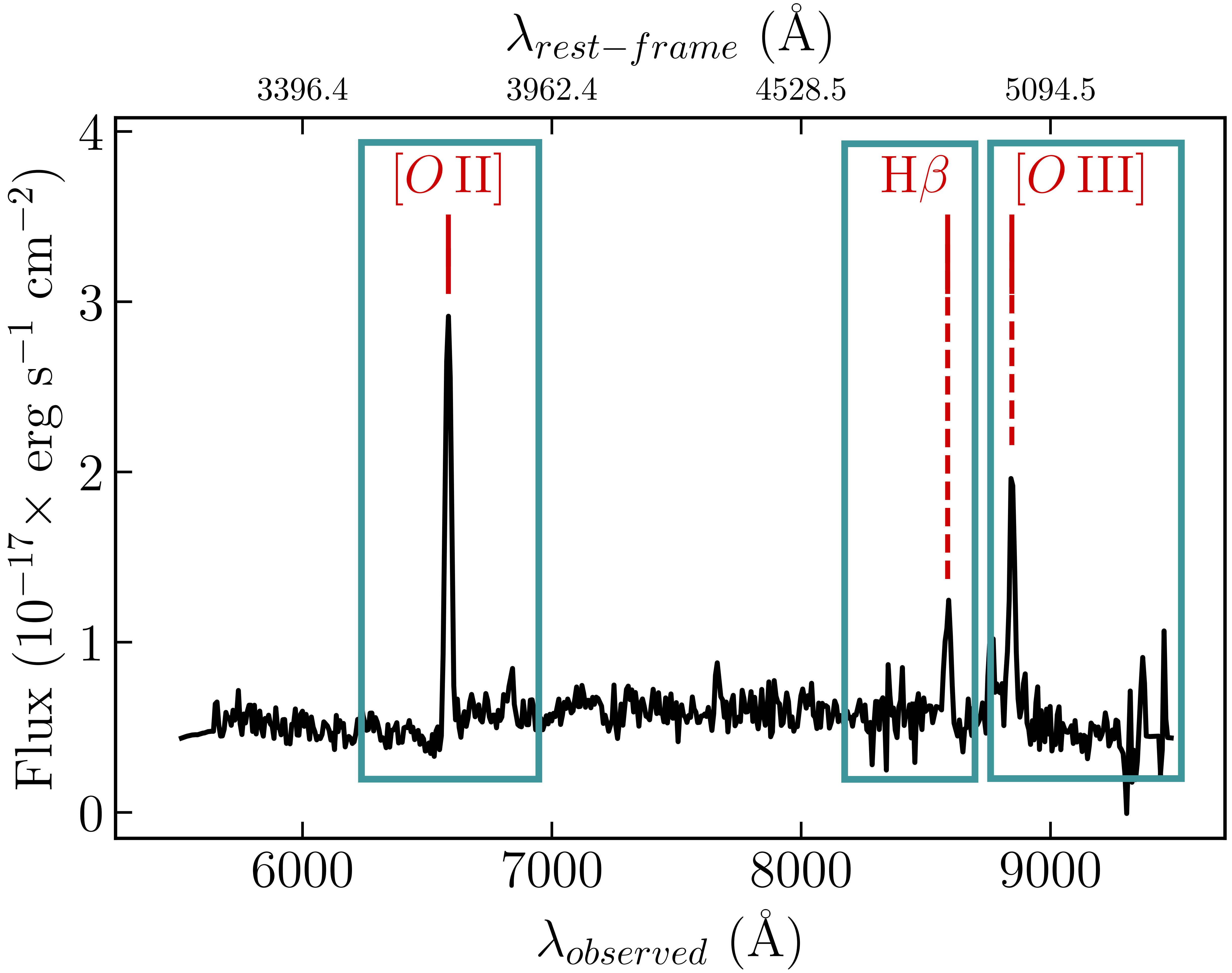
$$R_{23} = \frac{[\mathrm{O\,II}]\,\lambda 3727 + [\mathrm{O\,III}]\,\lambda\lambda 4959, 5007}{\mathrm{H}\beta}$$

(Calibration of Tremonti et al 2004)

$$12 + \log(\mathrm{O/H}) = 9.185 - 0.313x - 0.264x^2 - 0.321x^3 \text{, where } x \equiv \log R_{23}$$

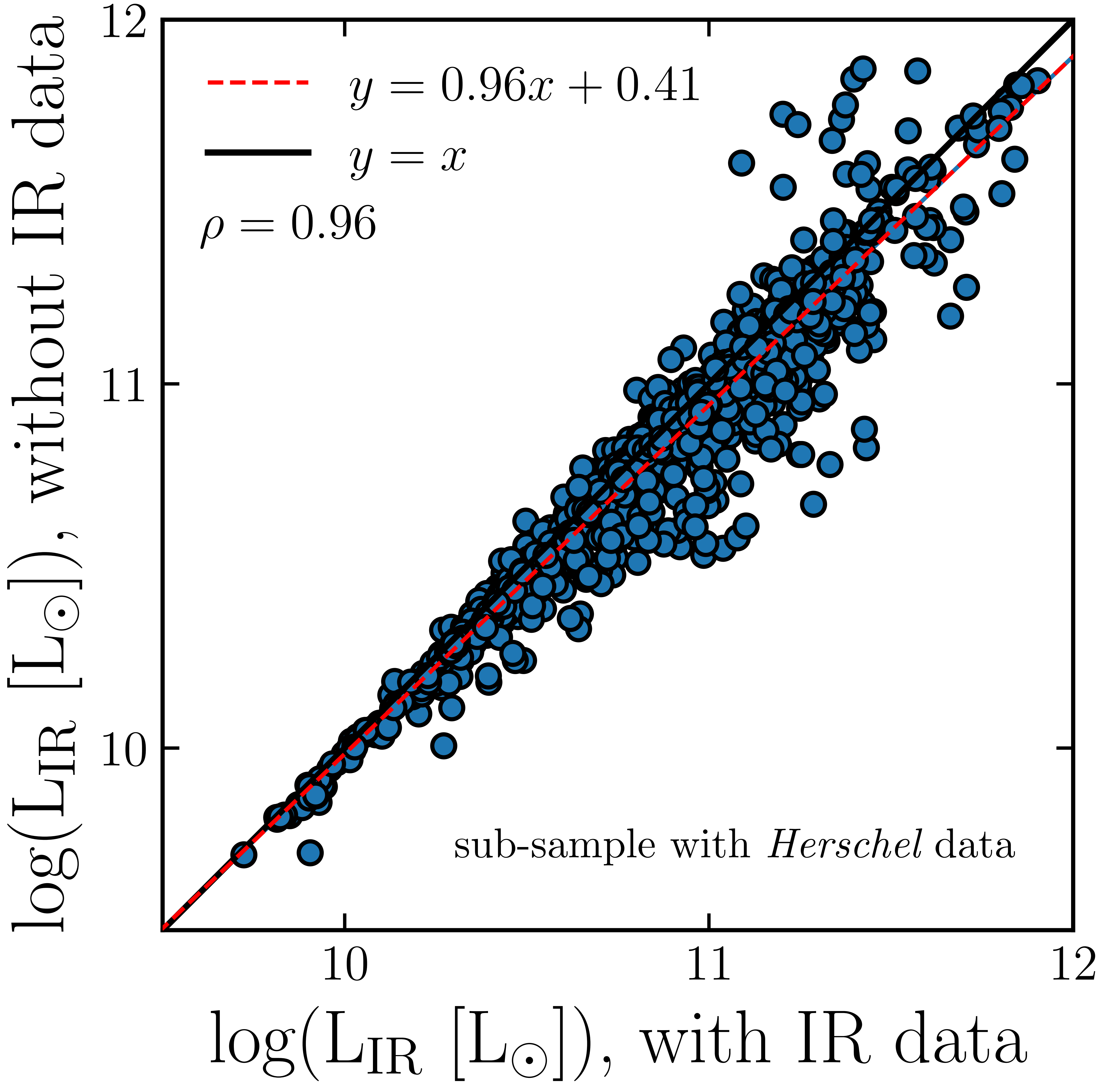


Hamed+, submitted



Panchromatic coverage ➡ Reliable SED

Telescope/ Instrument	Band	λ (μm)	№ of detections
GALEX	FUV	0.15	1049
	NUV	0.23	1049
CFHT/ MegaCam	*u*	0.38	1049
	g	0.49	1049
	r	0.63	1049
	i	0.76	1049
	z	0.89	1049
CFHT/WIRCam	*Ks*	2.14	1049
Spitzer/ IRAC	ch1	3.56	710
	ch2	4.50	471
	ch3	5.74	112
	ch4	7.93	112
Spitzer/MIPS	MIPS1	24	116
	MIPS2	70	18
	MIPS3	160	3
Herschel/ PACS	100 μm	102.62	592
	160 μm	167.14	592
Herschel/ SPIRE	250 μm	251.50	592
	350 μm	352.83	592
	500 μm	511.60	592



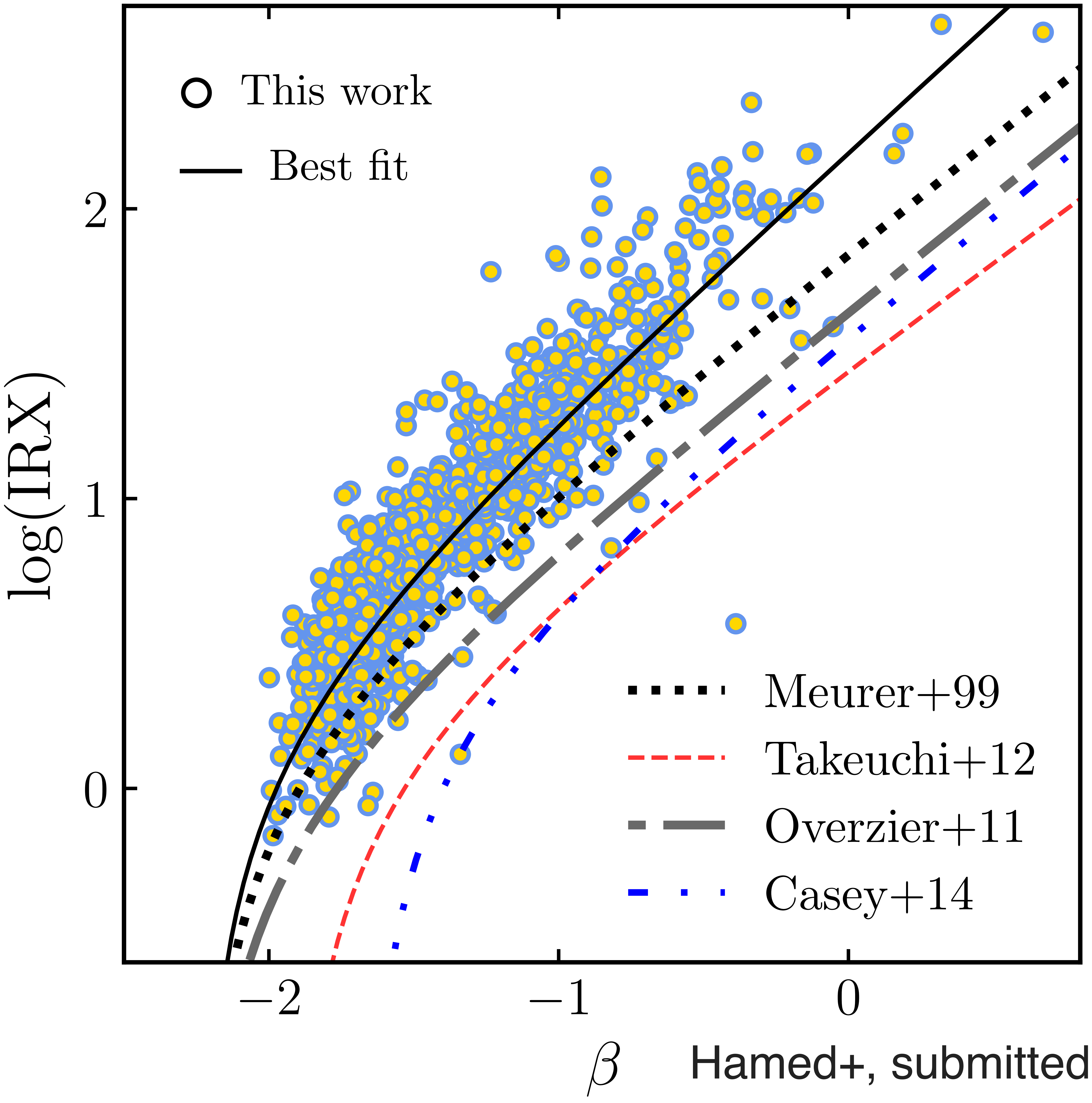
$$A_{\mathrm{FUV}} = (\beta - \beta_0) \times c_\beta,$$

$$A_{\mathrm{FUV}} = 2.5 \times \log(1 + c_{\mathrm{IRX}} 10^{\mathrm{IRX}}),$$

$$\mathrm{IRX} = \log\left(\frac{10^{0.4\times(\beta-\beta_0)c_\beta} - 1}{c_{\mathrm{IRX}}}\right).$$

IRX-β relation
at intermediate redshift

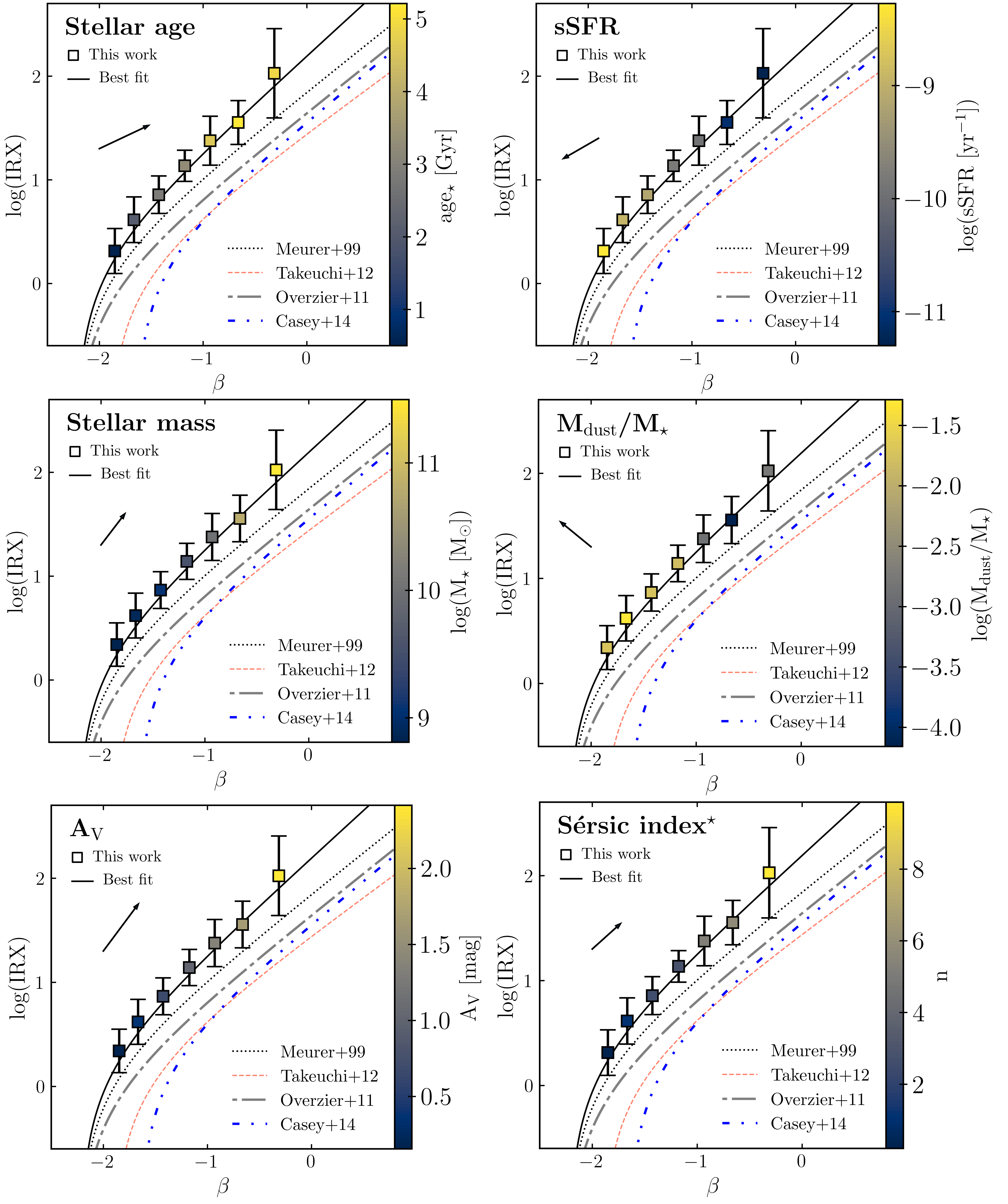
$$\boxed{\mathrm{IRX} = \log[(10^{0.91\beta+2.02} - 1)/0.67].}$$

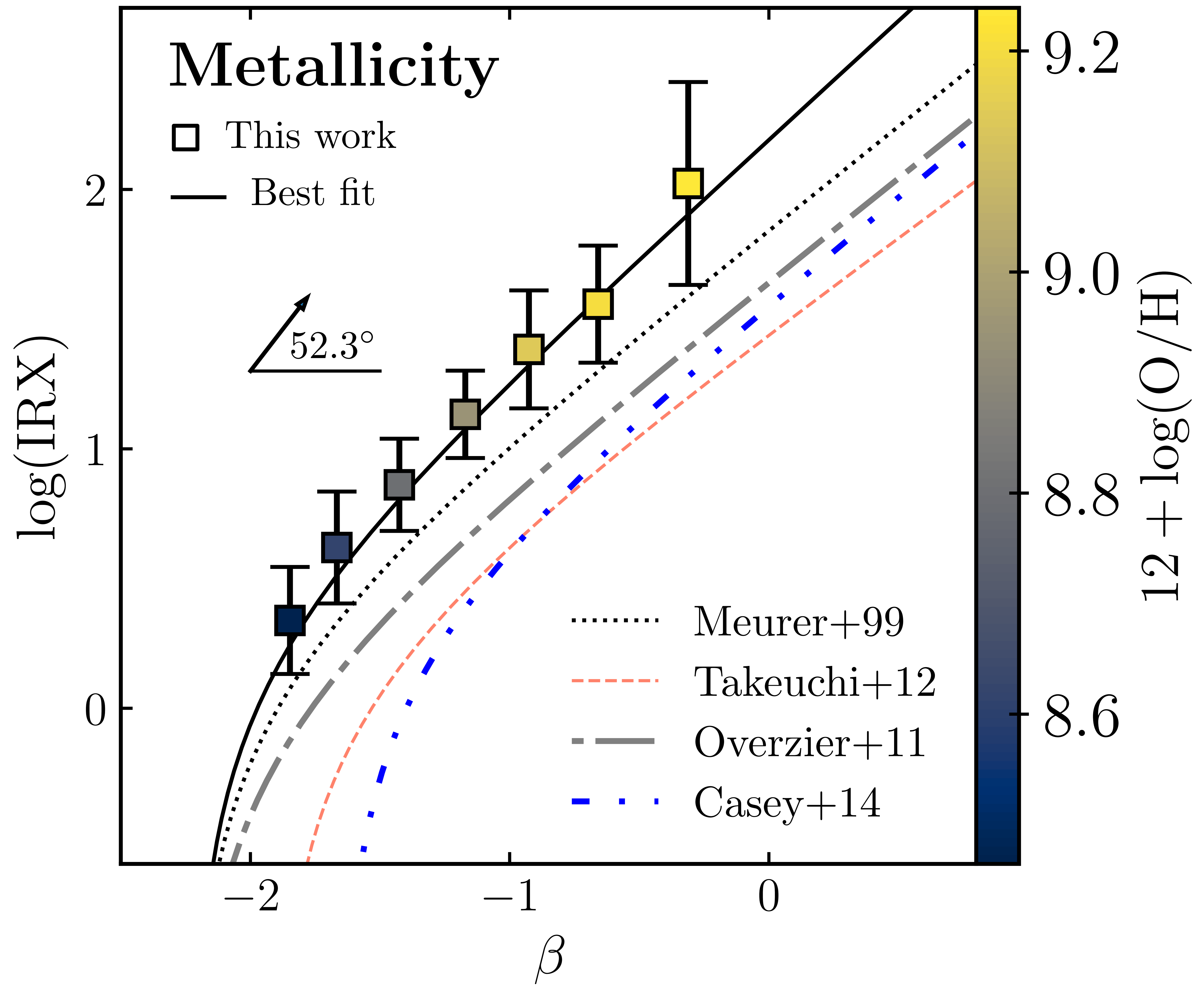


Hamed+, submitted

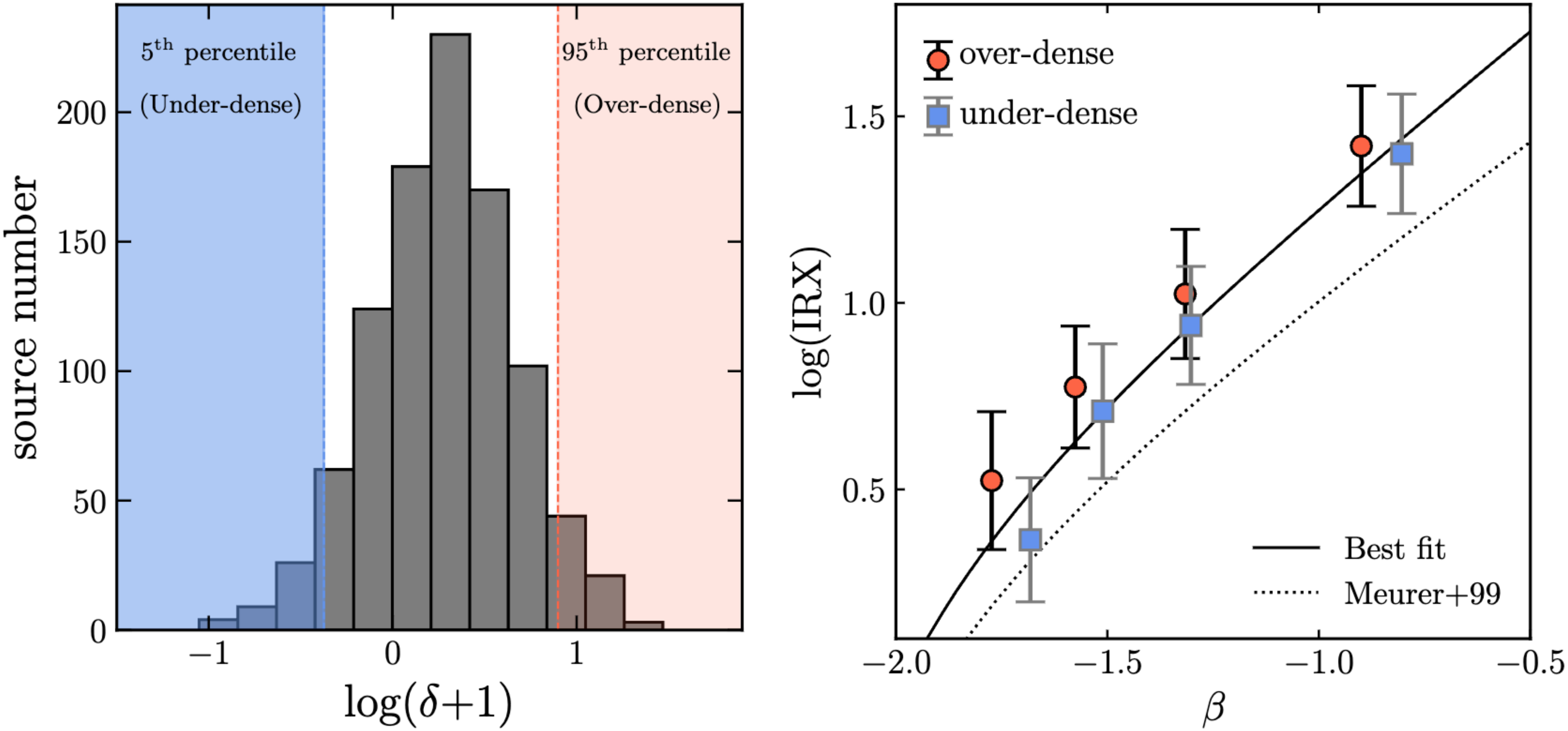
Dust Attenuation correlations with ISM properties

Hamed+, submitted



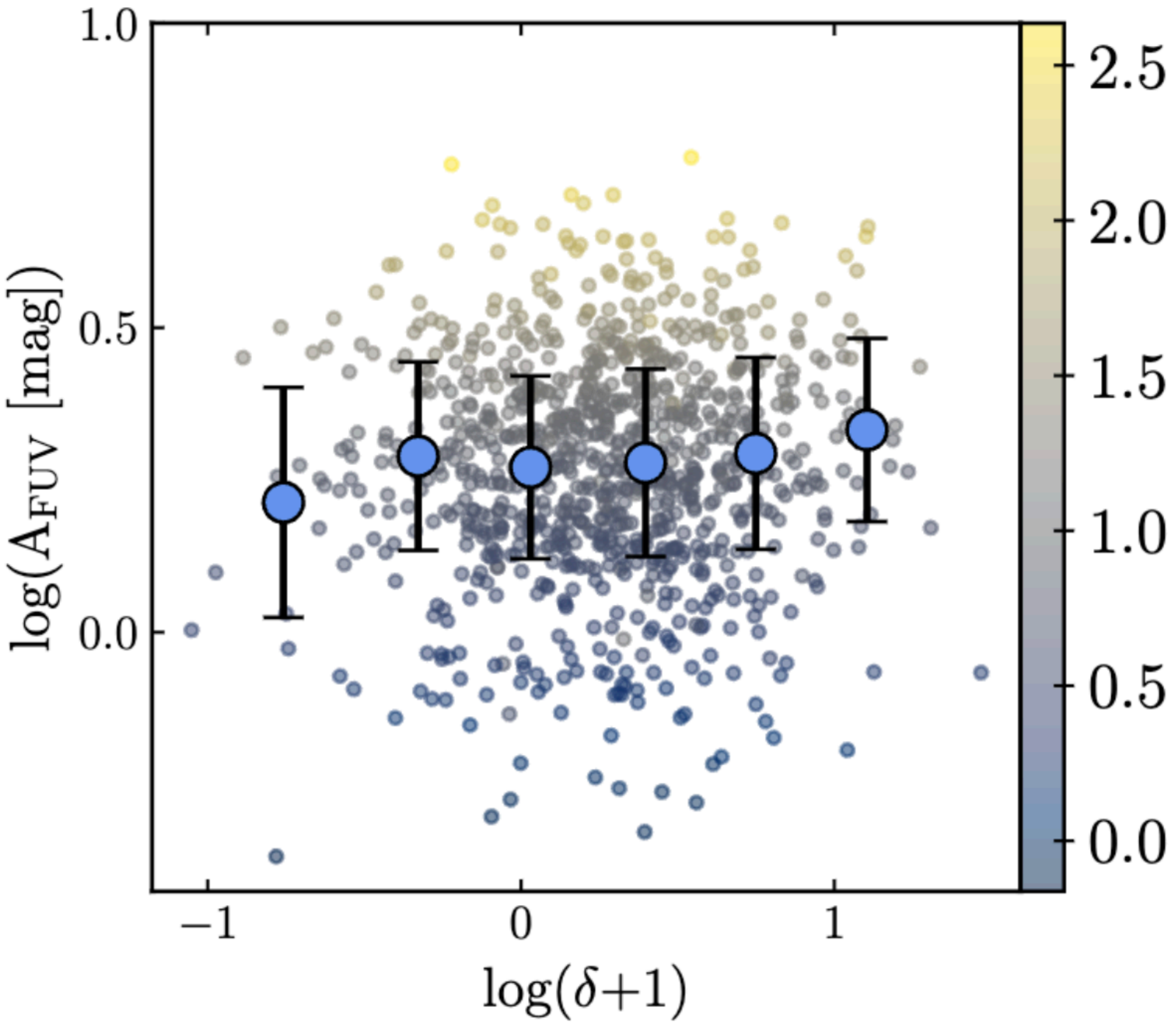


DOES ENVIRONMENT MATTER?



Slight systematic difference?

ENVIRONMENT DOES NOT AFFECT DUST ATTENUATION



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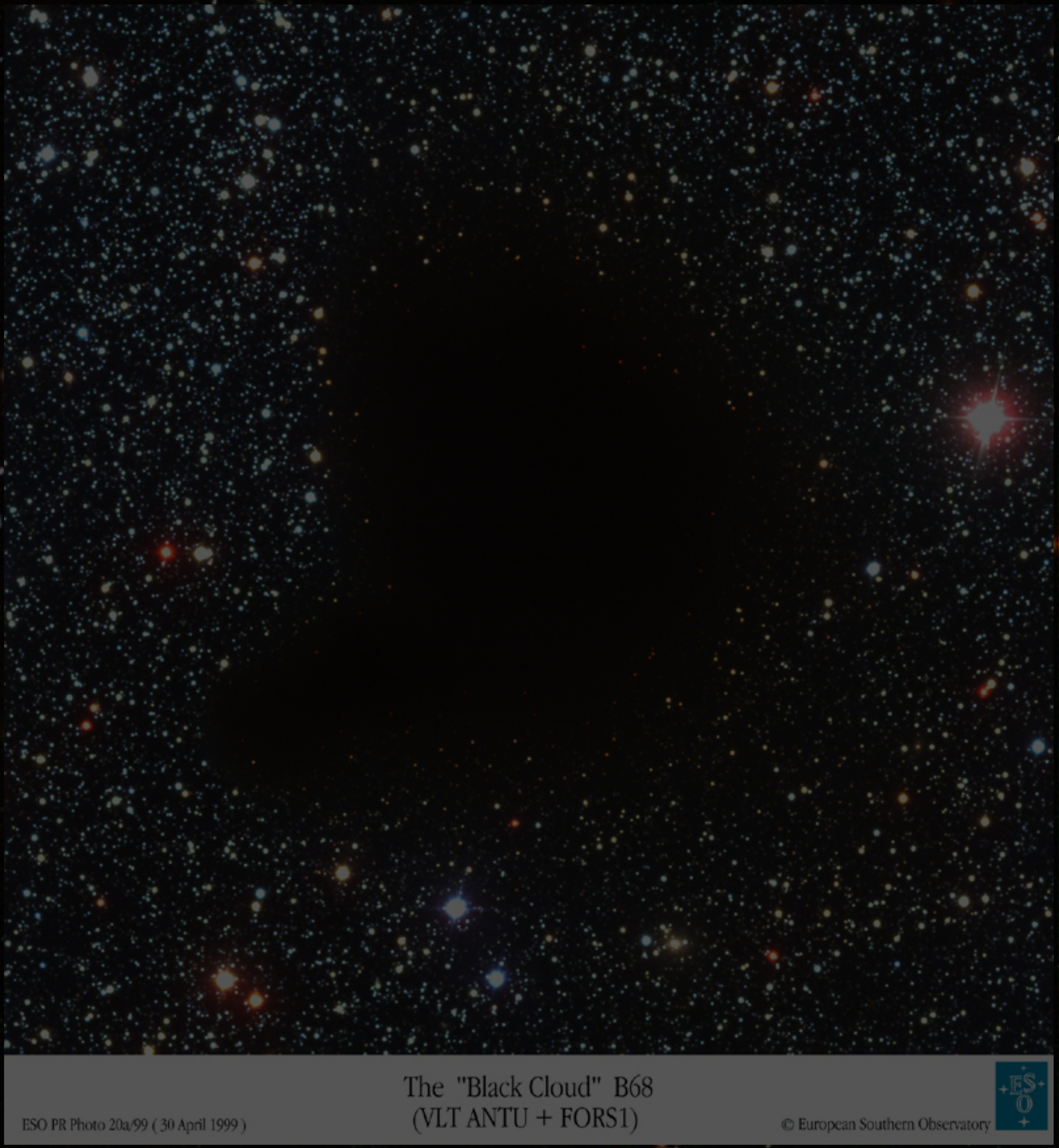

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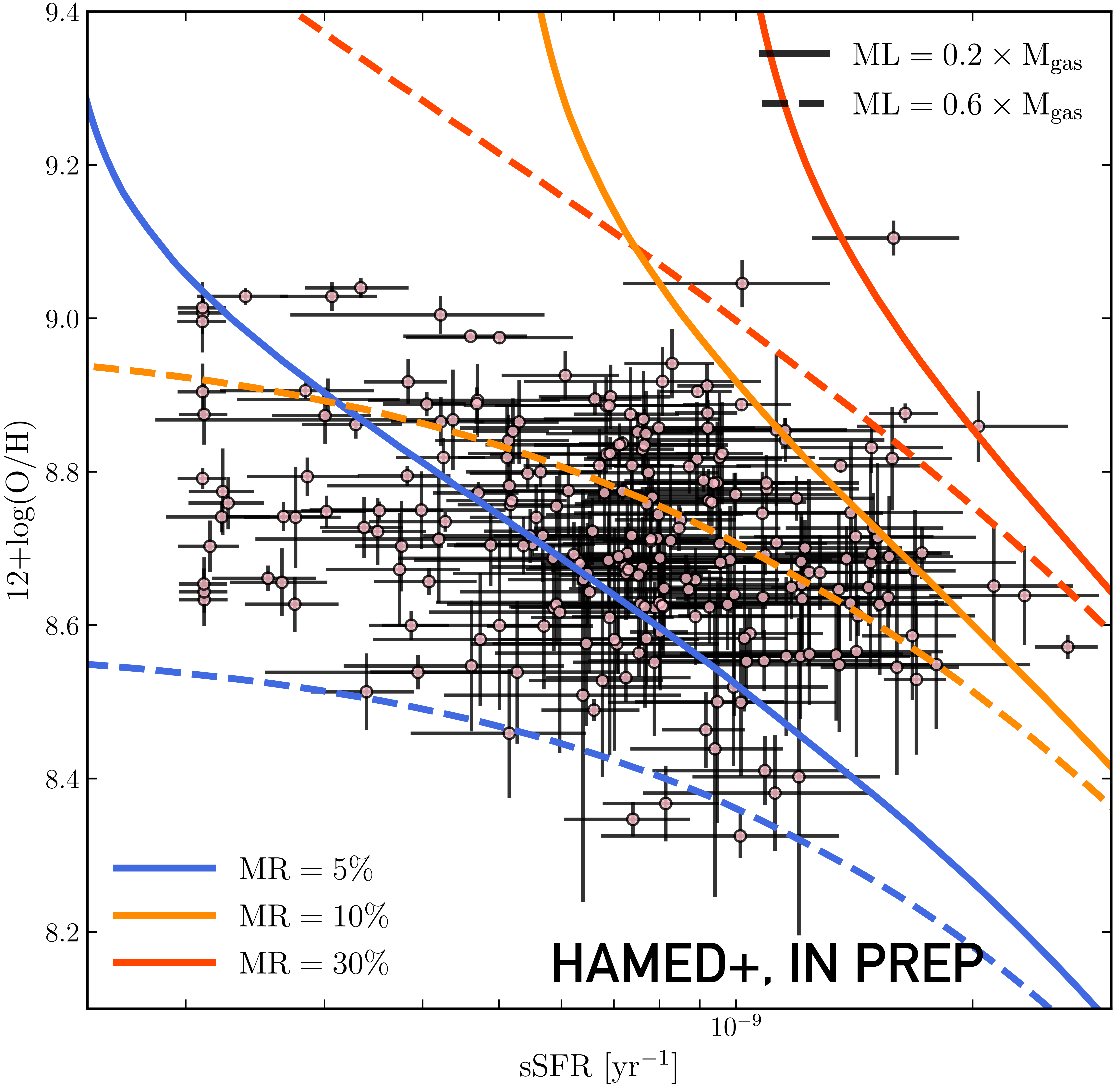
CONCLUSIONS

- Knowing the sizes of dusty star-forming galaxies is important for selecting the appropriate attenuation curve to fit their photometry. More precisely, knowing the relative spatial extent of the emission coming from the stellar population/ star-forming regions, to that of the dust, is crucial in determining the dust attenuation curve.
- Gas-phase metallicity was found to be the strongest correlate with the loci of the galaxies in the IRX-β diagram.
- Strong trends were also found with the galaxies' stellar masses and the age of their main stellar population. Metallicity is one of the drivers of the dust attenuation scatter, which is translated by the older stars and higher masses.
- Environment does not seem to play a role in dust attenuation

PERSPECTIVES

REVERSE ENGINEERING THE STAR FORMATION HISTORY OF GALAXIES FROM MODELLING OF METAL ENRICHMENT IN THE ISM.



THANK YOU