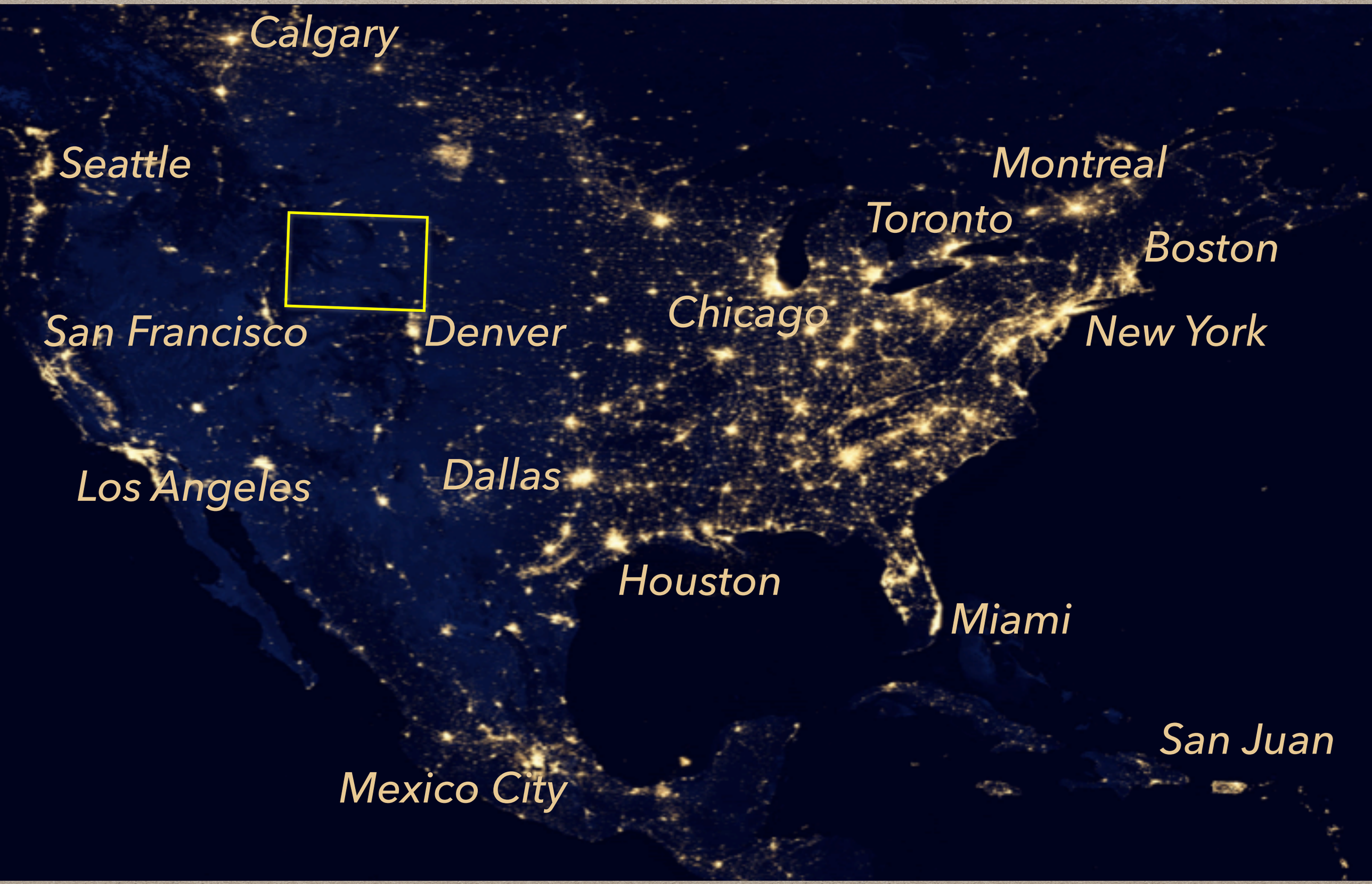
Le Milieu Interstellaire des Galaxies Normales

The Interstellar Medium of Normal Galaxies

Daniel Dale

University of Wyoming

NGC628 – PHANGS



Où est Wyoming?

Où est Laramie?

University of Wyoming

12,000 students

State's sole 4-year institution

Laramie elevation: 2200m

OUTLINE

- *'Normal' galaxies*
- *Spectra: stars & dust*
- *Scaling Relations*
- *Star formation & the ISM*
- *Open questions & future directions*

Vianney

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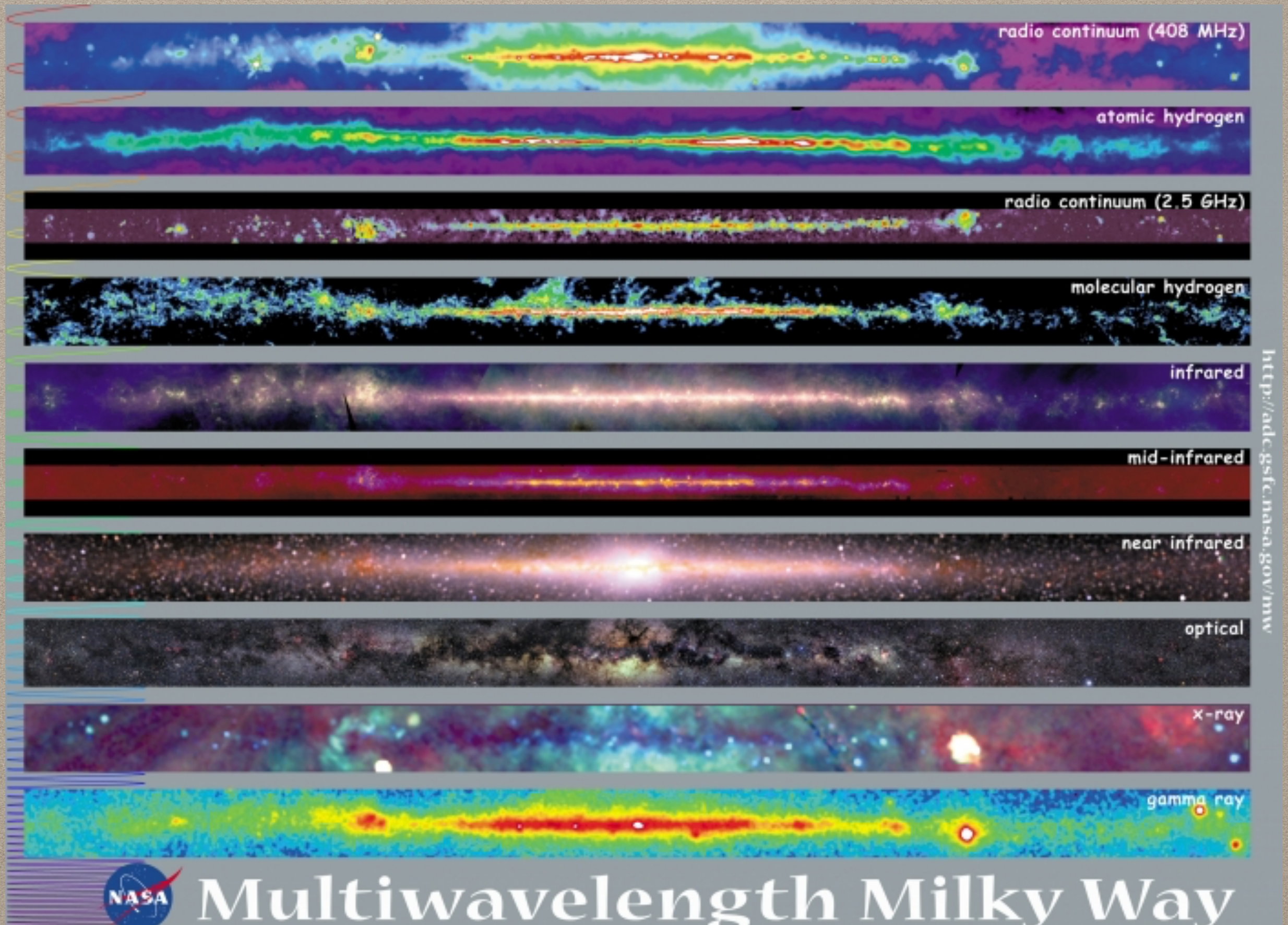
Vianney

How do astronomers think of a galaxy?



How does the media think of a galaxy?

‘Truly spectacular’: NASA’s James Webb telescope captures purple spiral galaxy

How do astronomers think of a galaxy?

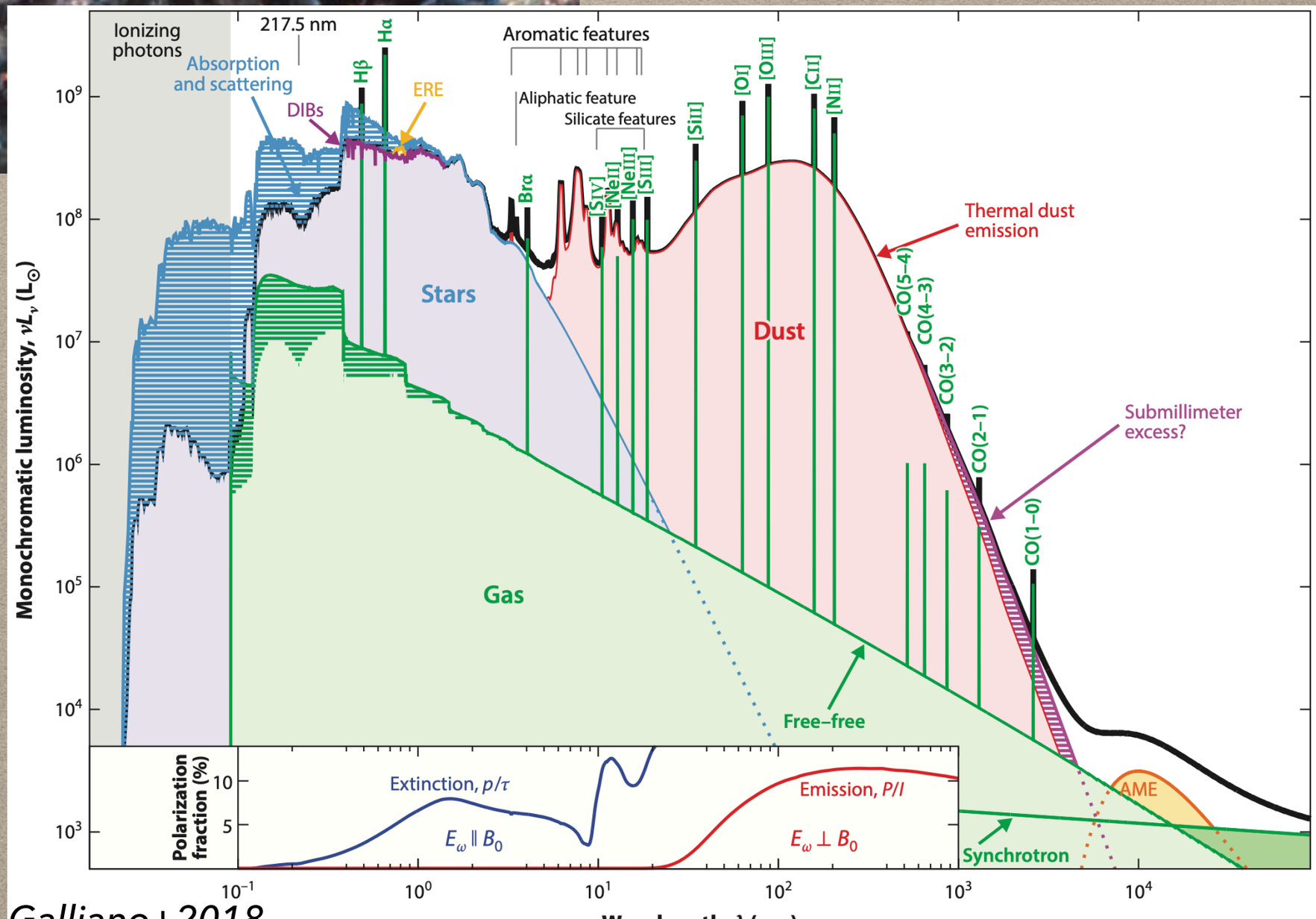
The PHANGS team & Judy Schmidt

NGC 628

How do astronomers think of a galaxy?

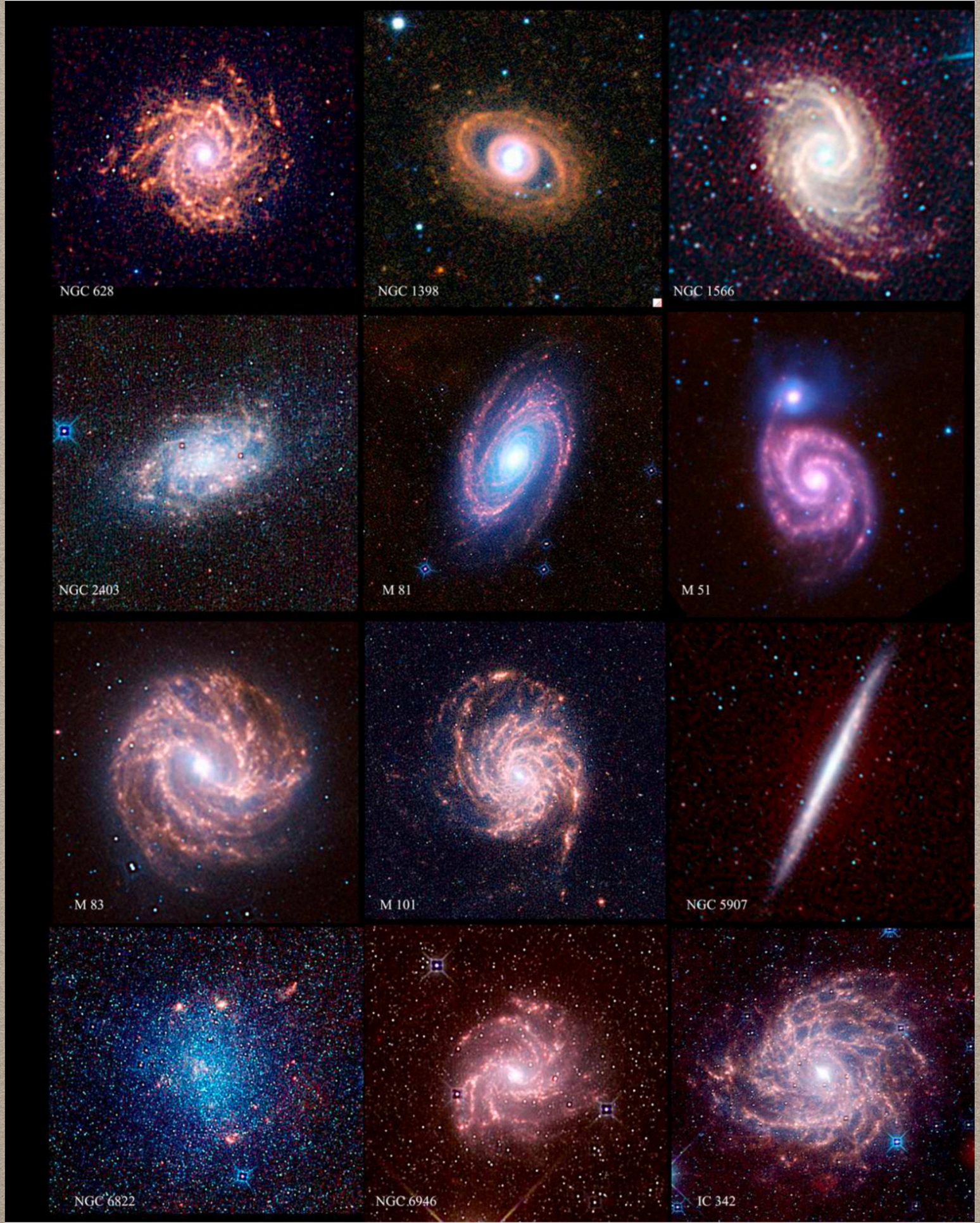
The PHANGS team & Judy Schmidt

Golf: *'Drive for show, putt for dough'*
Astronomy?



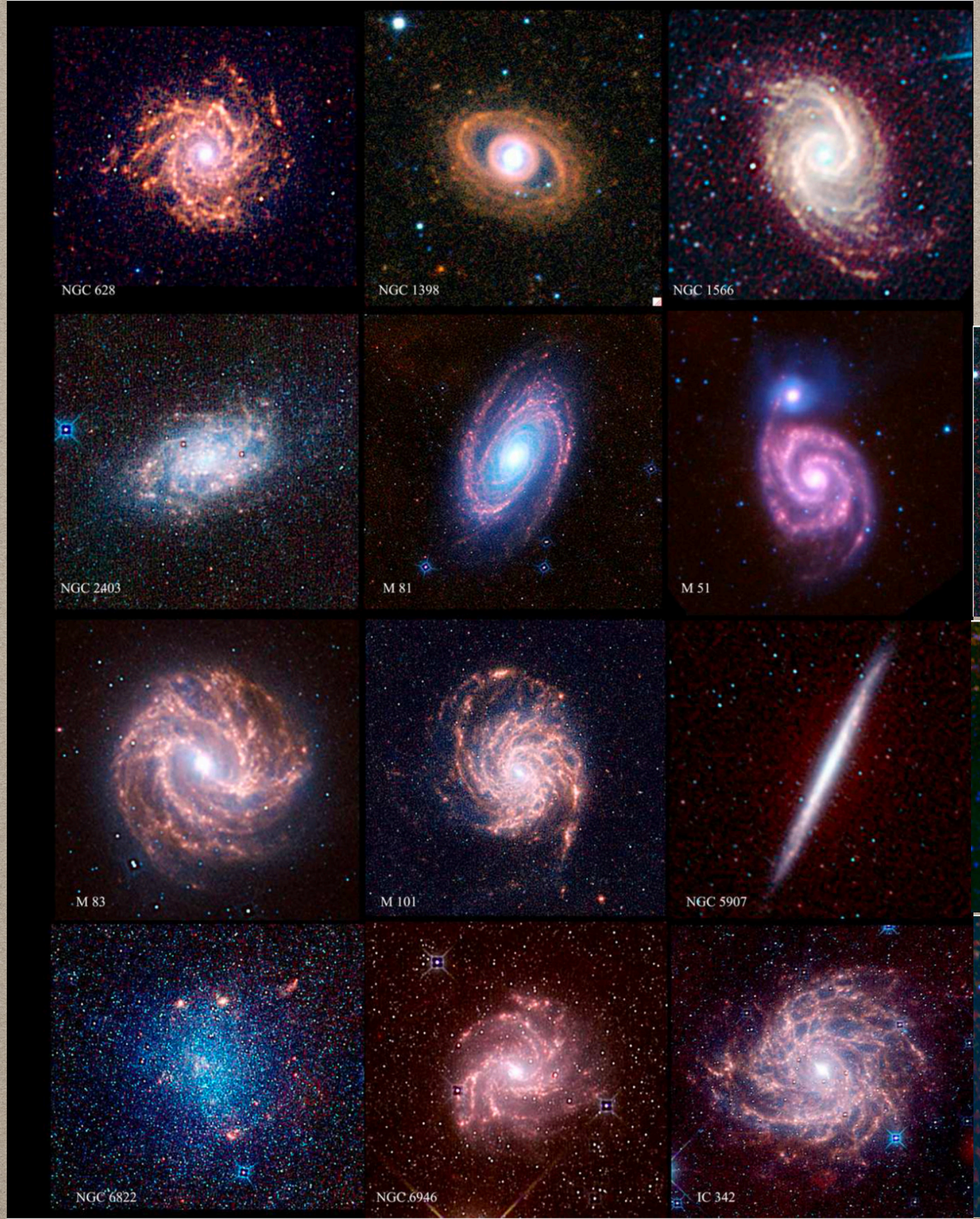
Galliano+2018

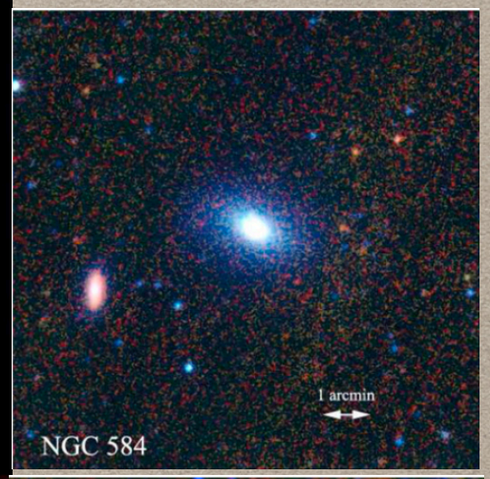
WISE infrared view of nearby galaxies

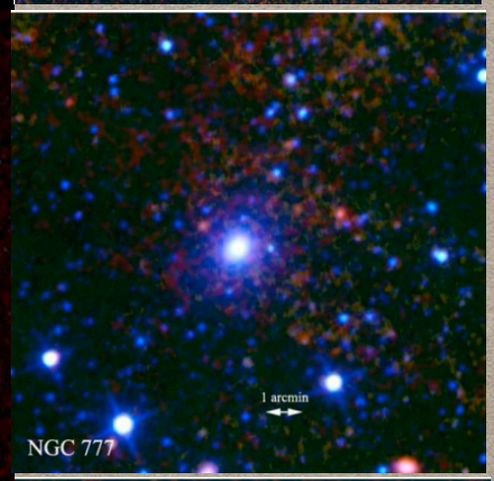


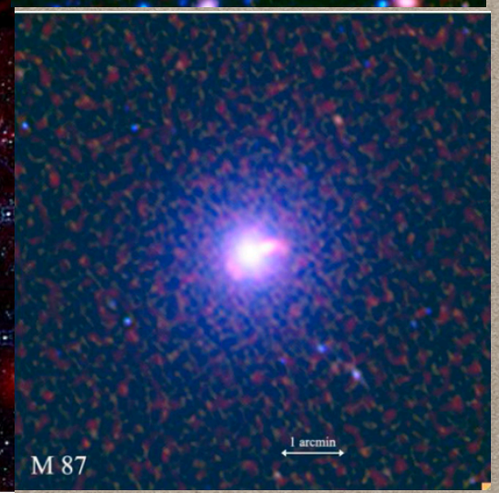
Jarrett+2013

WISE infrared view of nearby galaxies





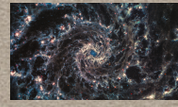




AGN

Jarrett+2013

*'Normal' for a galaxy can mean:**



*Red indicates student challenge

'Normal' for a galaxy can mean:

- ***Lacks a dominant AGN*** ***!***
- ***Solar metallicity*** ***within 2x***
- ***Moderate, constant SF*** ***~10^0 $M_\odot$/yr***
- ***Average stellar mass*** ***10^9-10^{11} $M_\odot$***
- ***Moderate infrared luminosity*** ***<10^{11} $L_\odot$; sub-LIRG***
- ***Spiral vs elliptical vs irregular***
- ***Field vs cluster***

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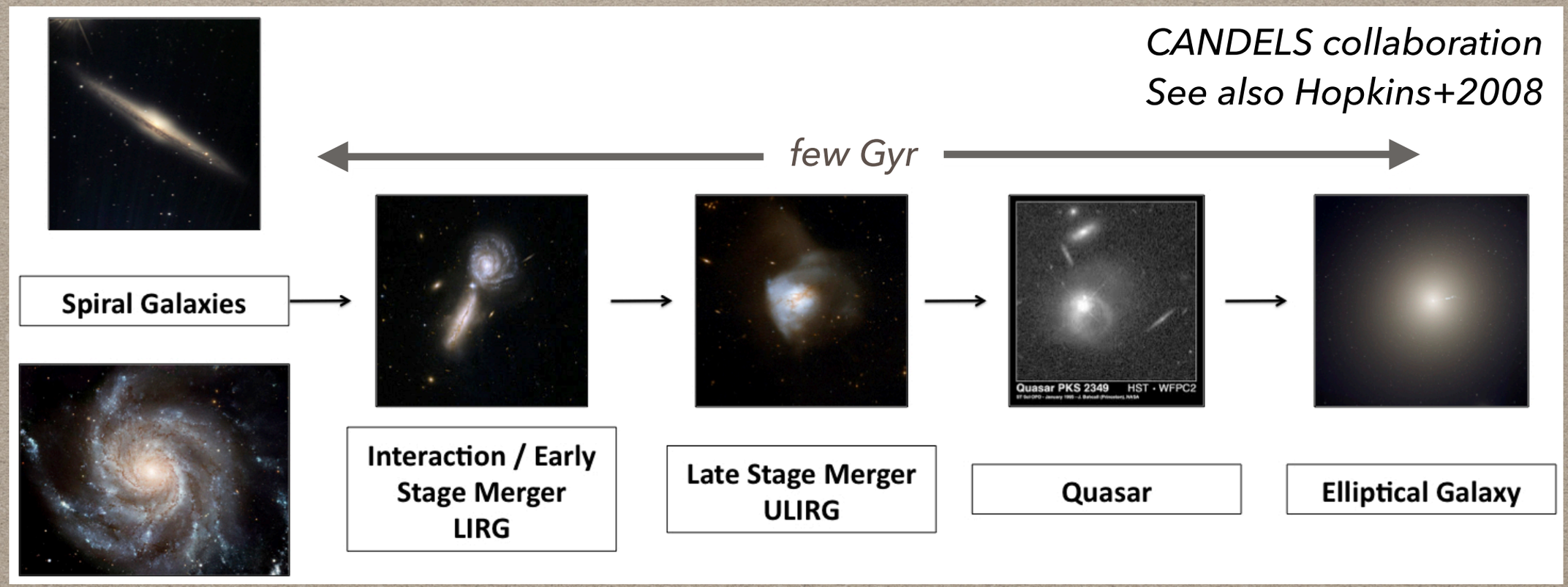

Superlatives in Astronomy

Ultraluminous infrared galaxy
Hyperluminous infrared galaxy
Extremely low metallicity galaxy
Ultra diffuse galaxy
Ultra compact HII region
Supernova
Kilonova
Microquasar
Ultra-high redshift galaxy
Super star cluster
Mega constellation

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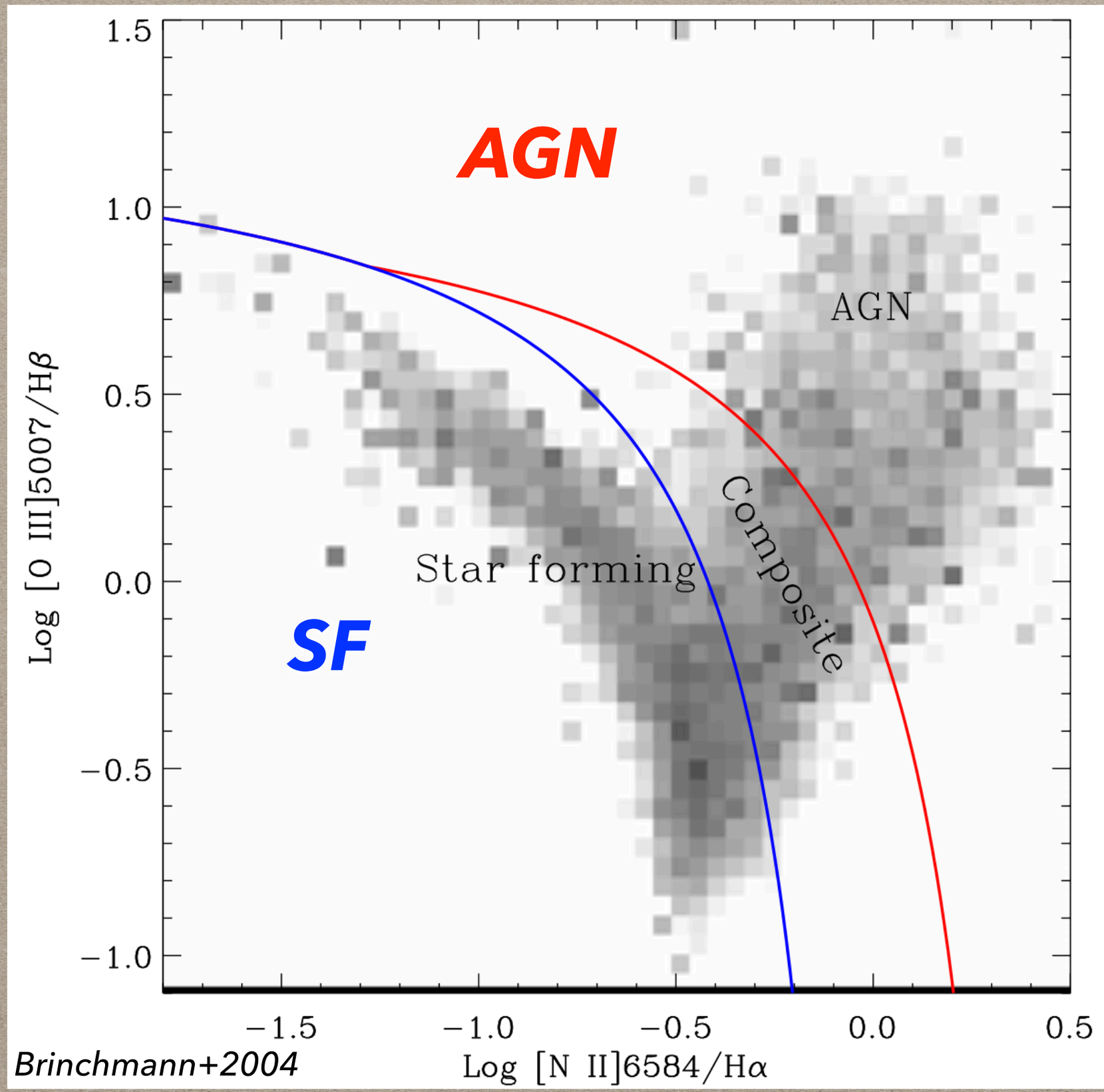
—-> INCREDIBLY NORMAL GALAXY!

Assessing 'normality'

See Lebouteiller and Groves slides



Brinchmann+2004

***'BPT diagram'* to distinguish between AGN and SF**

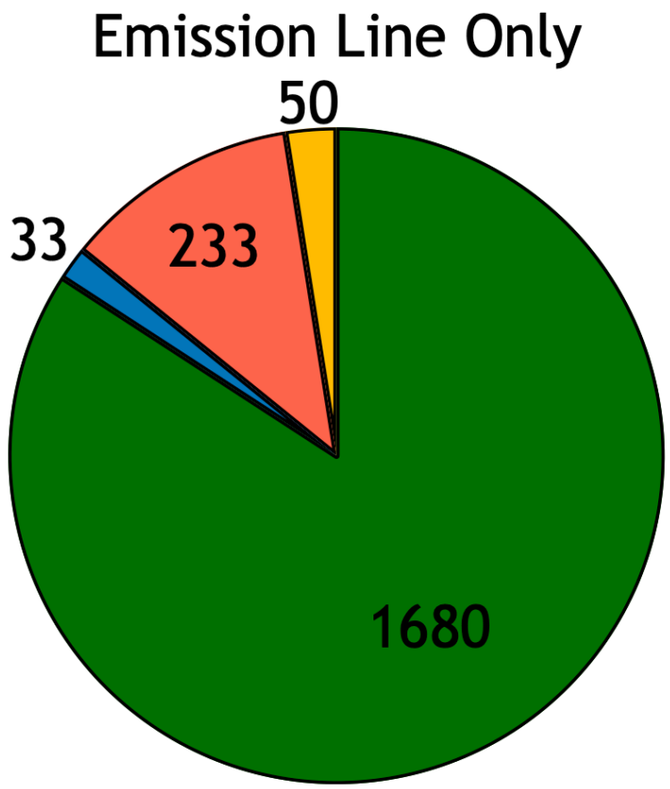
Early SDSS result on 10^5 galaxies

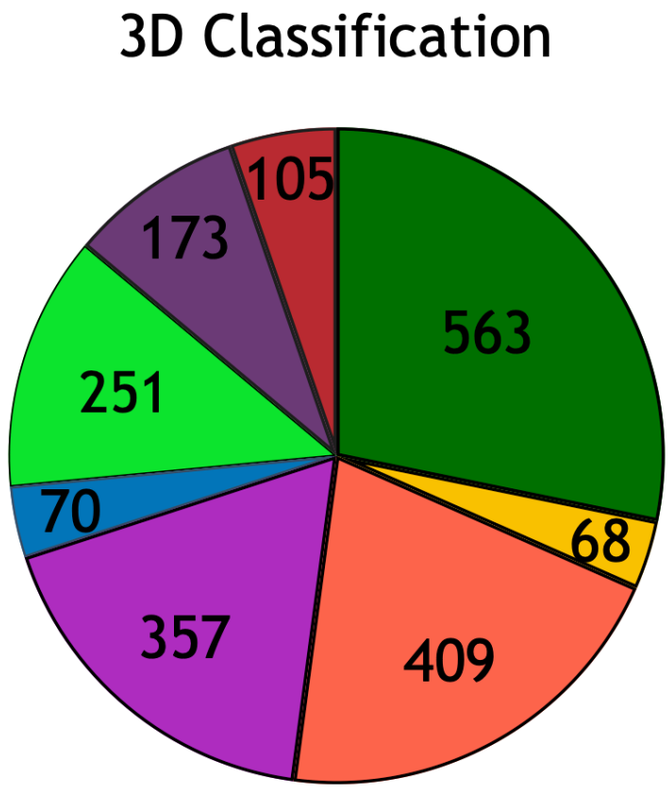
**** Why is a short 'wavelength baseline' important?***

Assessing 'normality'

See Lebouteiller and Groves slides

New approaches include using IFU datacubes to leverage spatial information + velocity dispersion





Non-SFing % for 2000 SAMI galaxies?

16% vs 72%

Johnston+2023

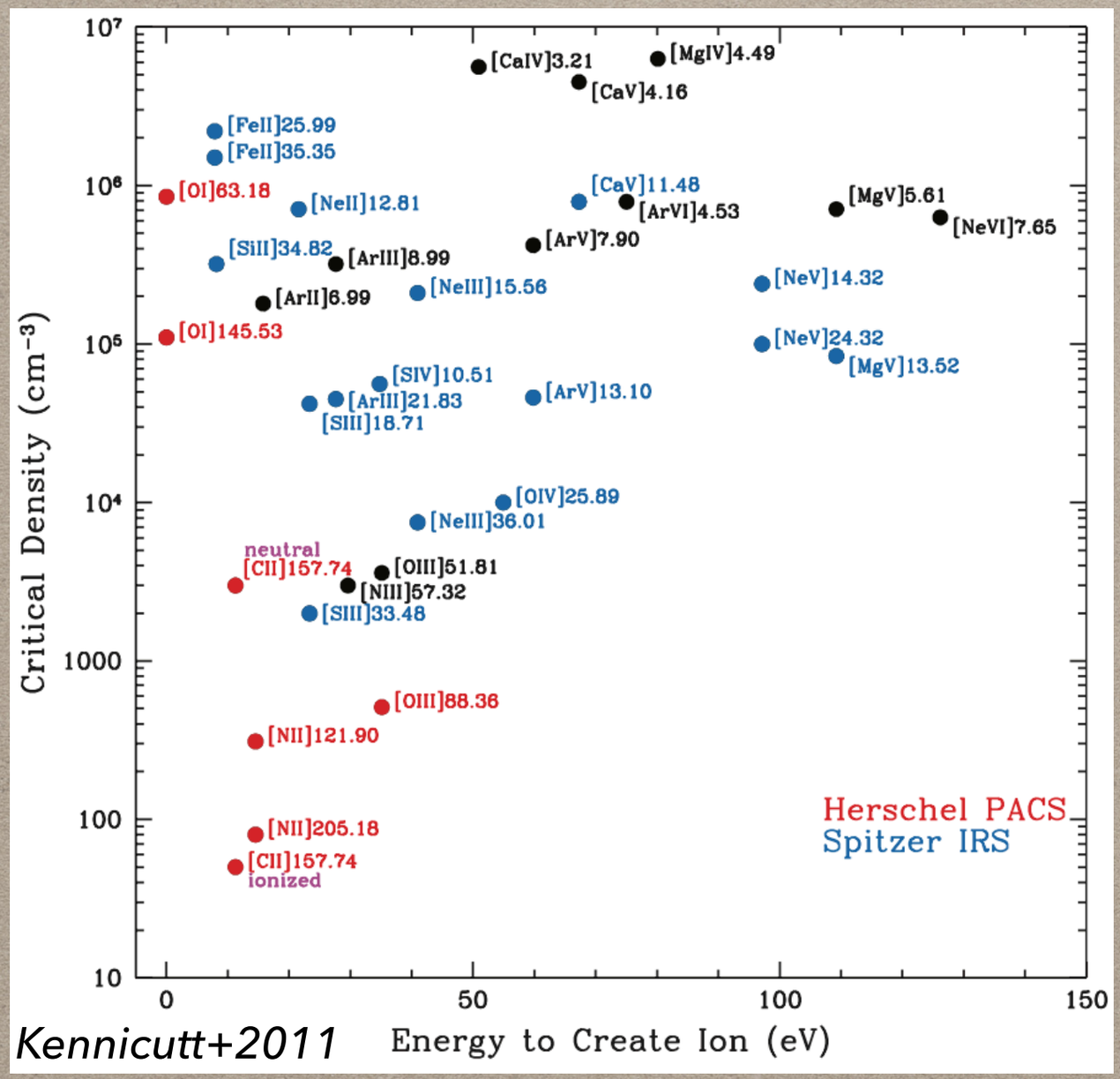
Assessing 'normality'

*Or other line/feature ratio combinations **

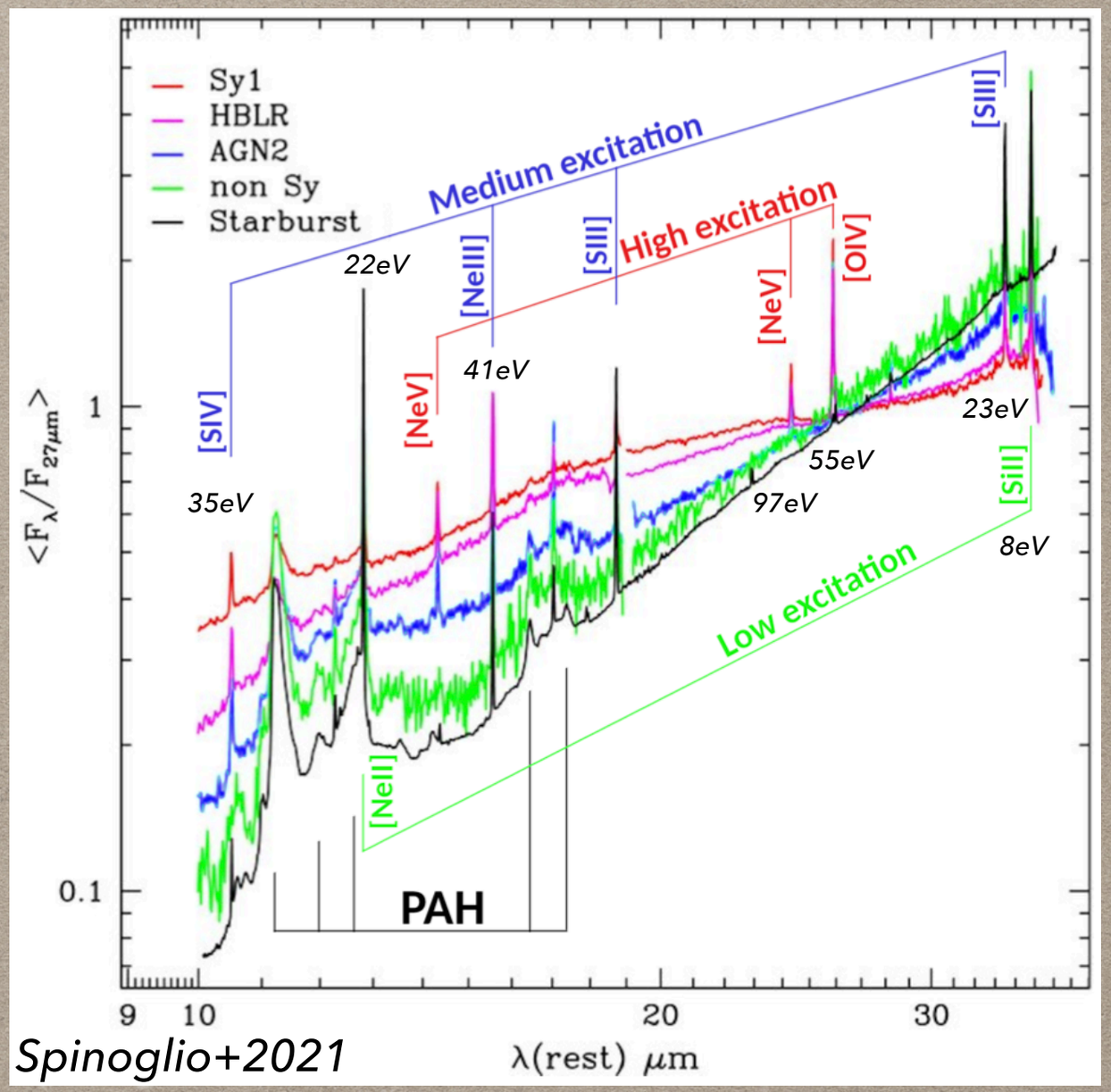
What kinds of line ratios would be ideal for distinguishing between AGN-powered and SF-powered sources?

Assessing 'normality'

Or other line/feature ratio combinations that leverage differing ionization potentials



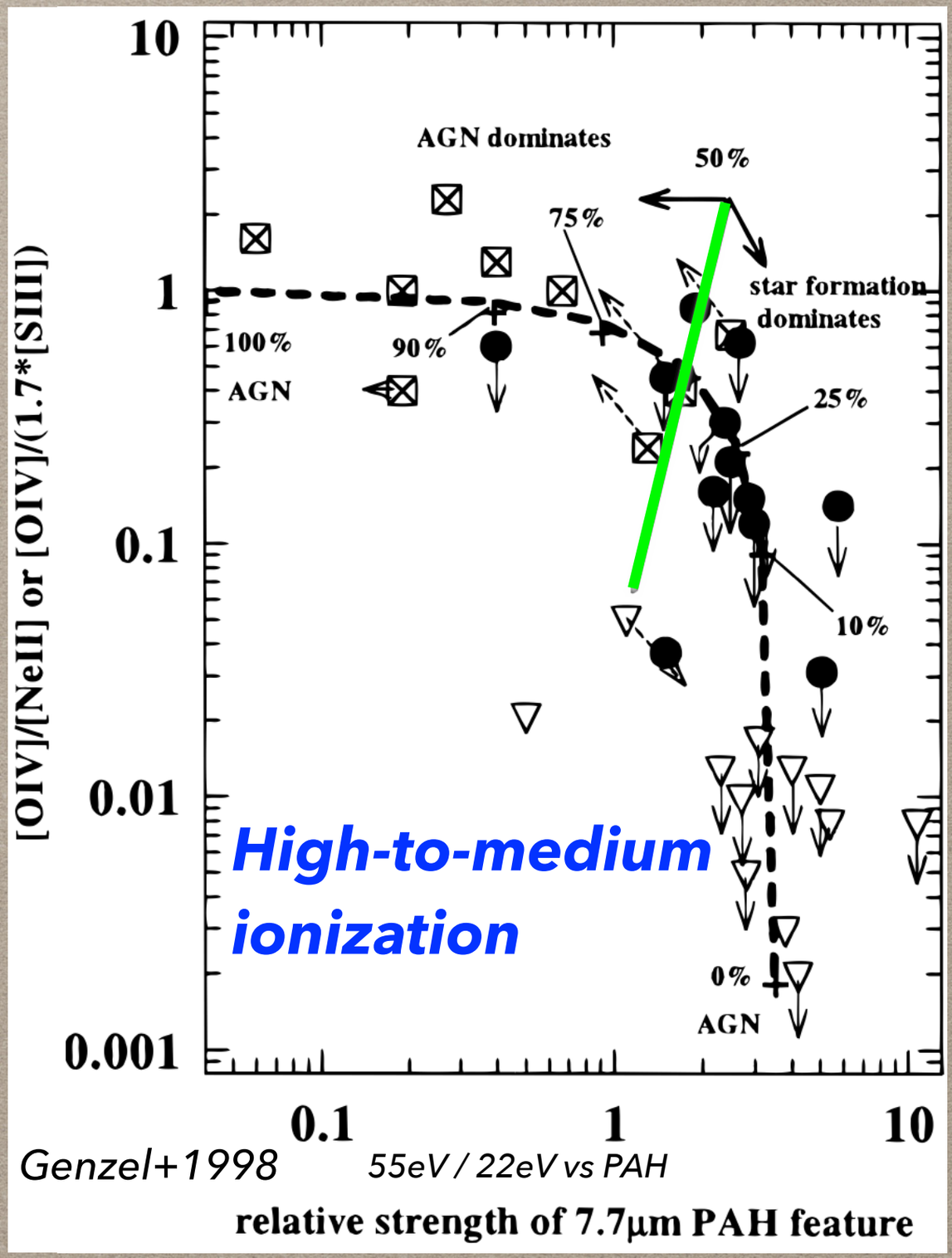
Kennicutt+2011



Spinoglio+2021

Assessing 'normality'

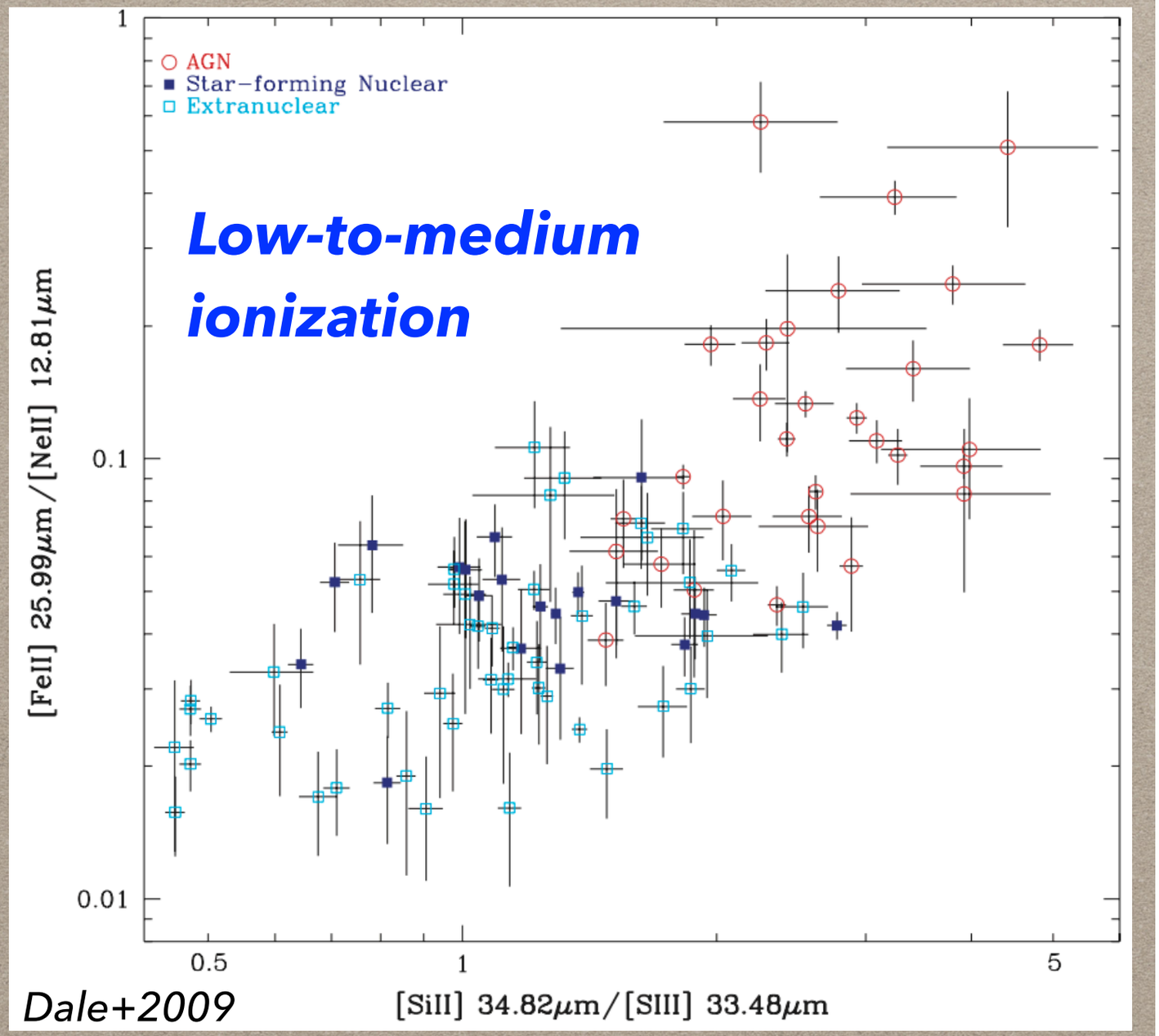
Or other line/feature ratio combinations that leverage differing ionization potentials



Genzel+1998 *55eV / 22eV vs PAH*

Assessing 'normality'

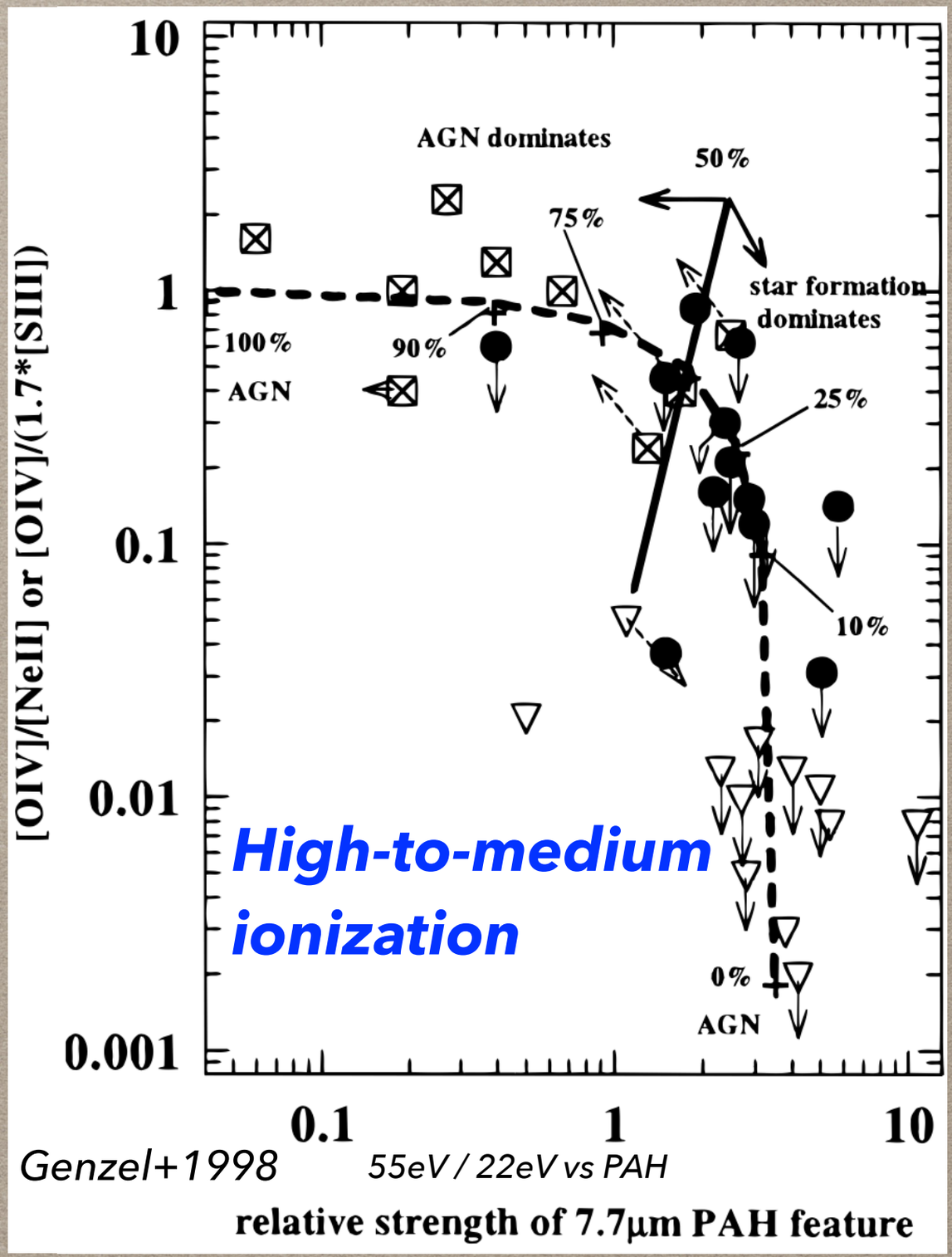
Or other line/feature ratio combinations that leverage differing ionization potentials



Dale+2009

SINGS sample

8eV / 22eV vs 8eV / 23eV



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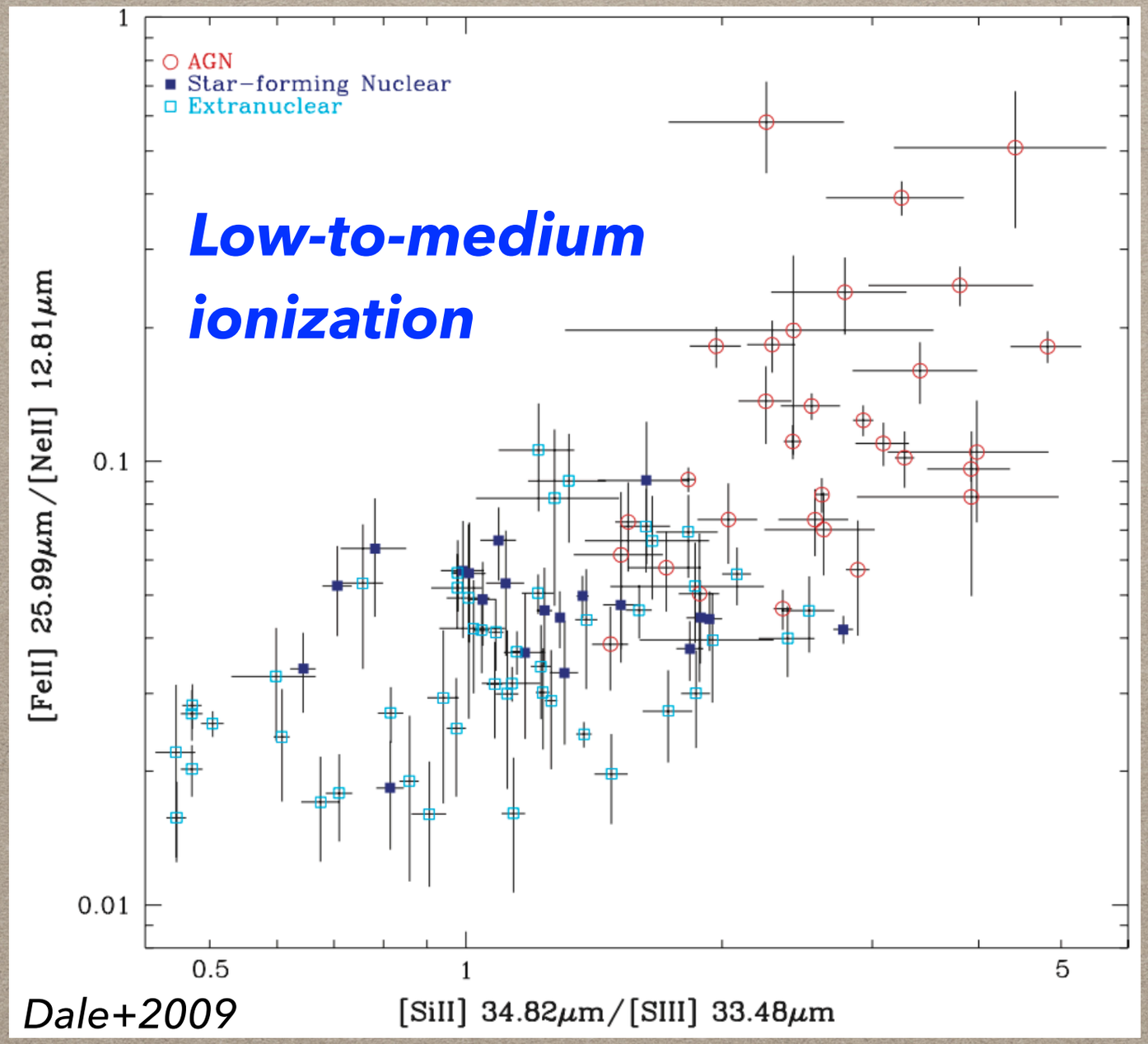


Dale+2009

Refractory elements returned to gas phase near AGN

Nebular lines drive ratios down

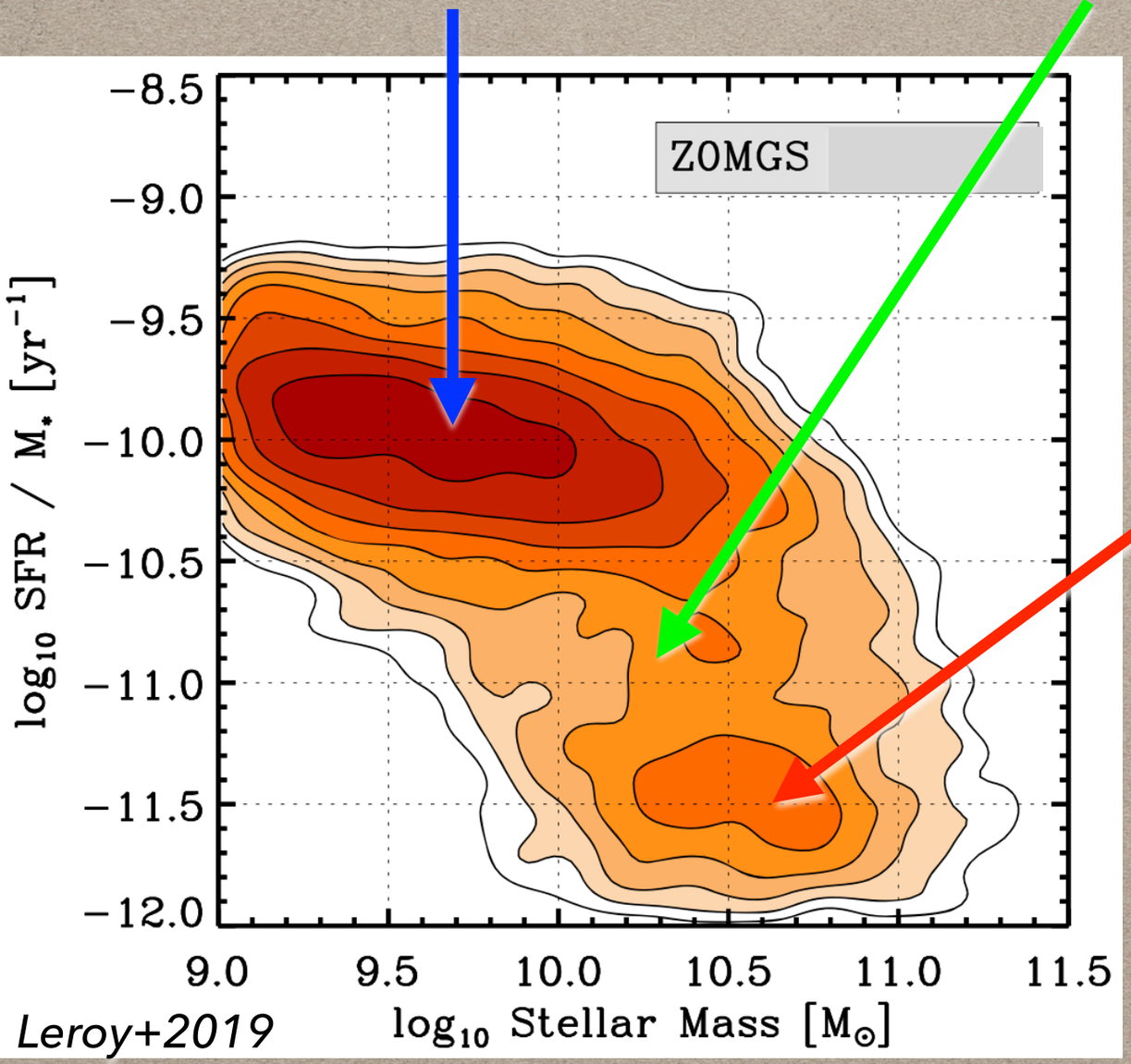
X-rays with low absorption x-sections induce strong secondary low-ionization lines ~1-2 kpc from AGN in XDRs

[SiII],[FeII] predicted to be enhanced for dense PDRs and XDRs

8eV / 22 eV vs 8 eV / 23 eV

'Normal' galaxies

Blue Cloud *Green Valley* *Red Sequence*

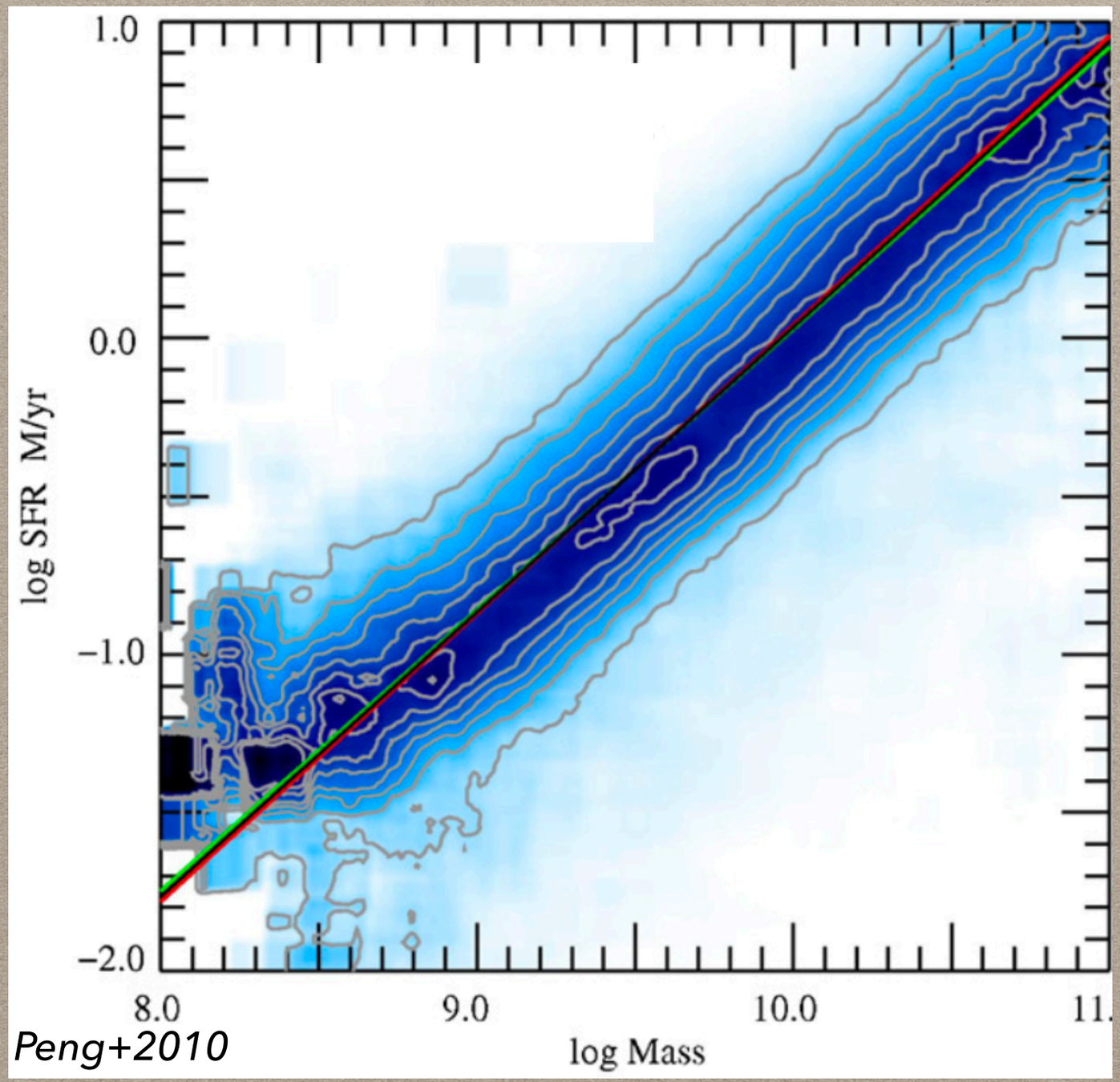


Leroy+2019

Salim+2019 z=0 Multiwavelength Galaxy Synthesis

'SF Galaxy Main Sequence'

Blue star-forming galaxies define a well-defined sequence



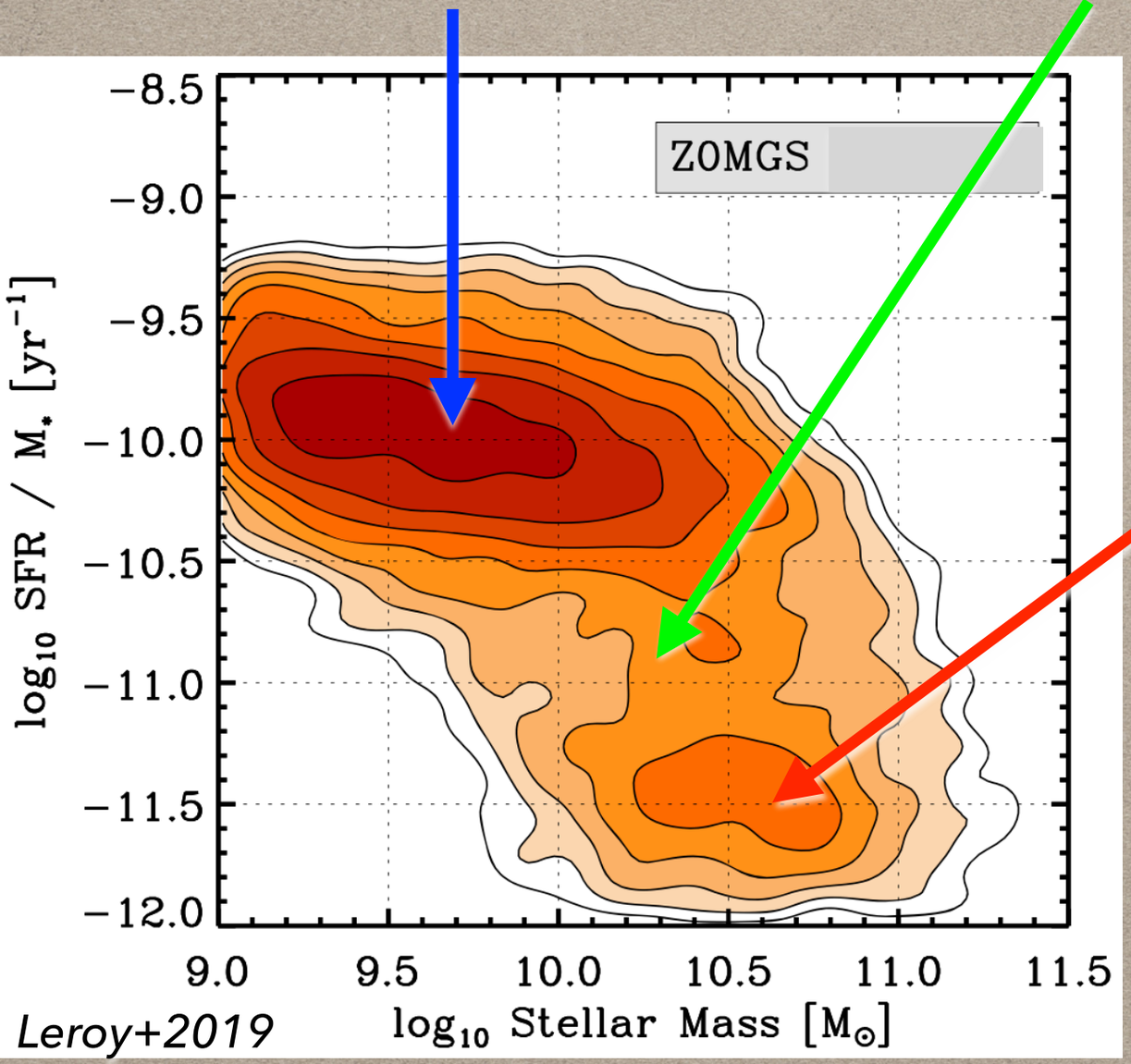
Peng+2010

10^4 SDSS galaxies

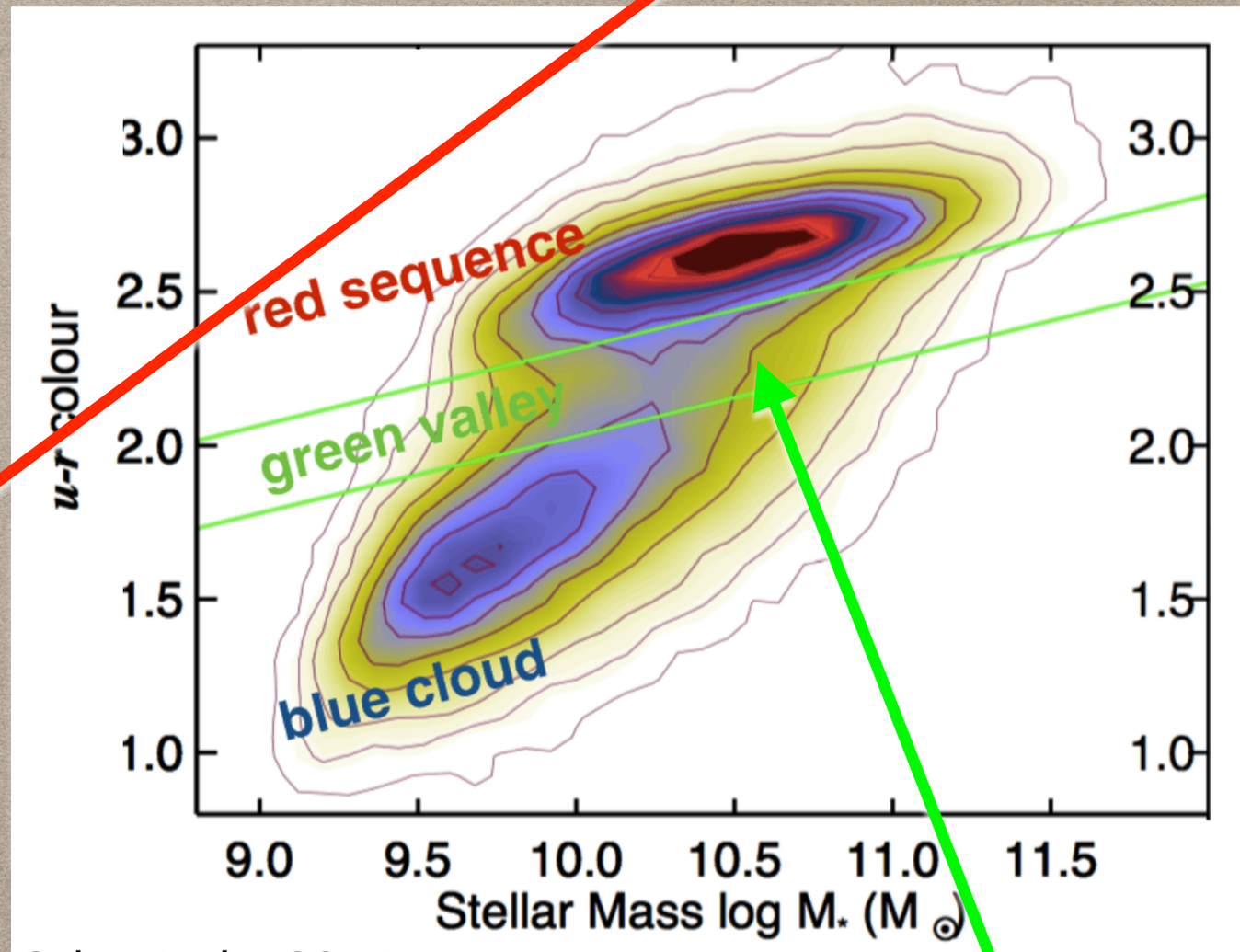
SFR ~ 0.01-10 $M_\odot$/yr

'Normal' galaxies

Blue Cloud *Green Valley* *Red Sequence*



Leroy+2019



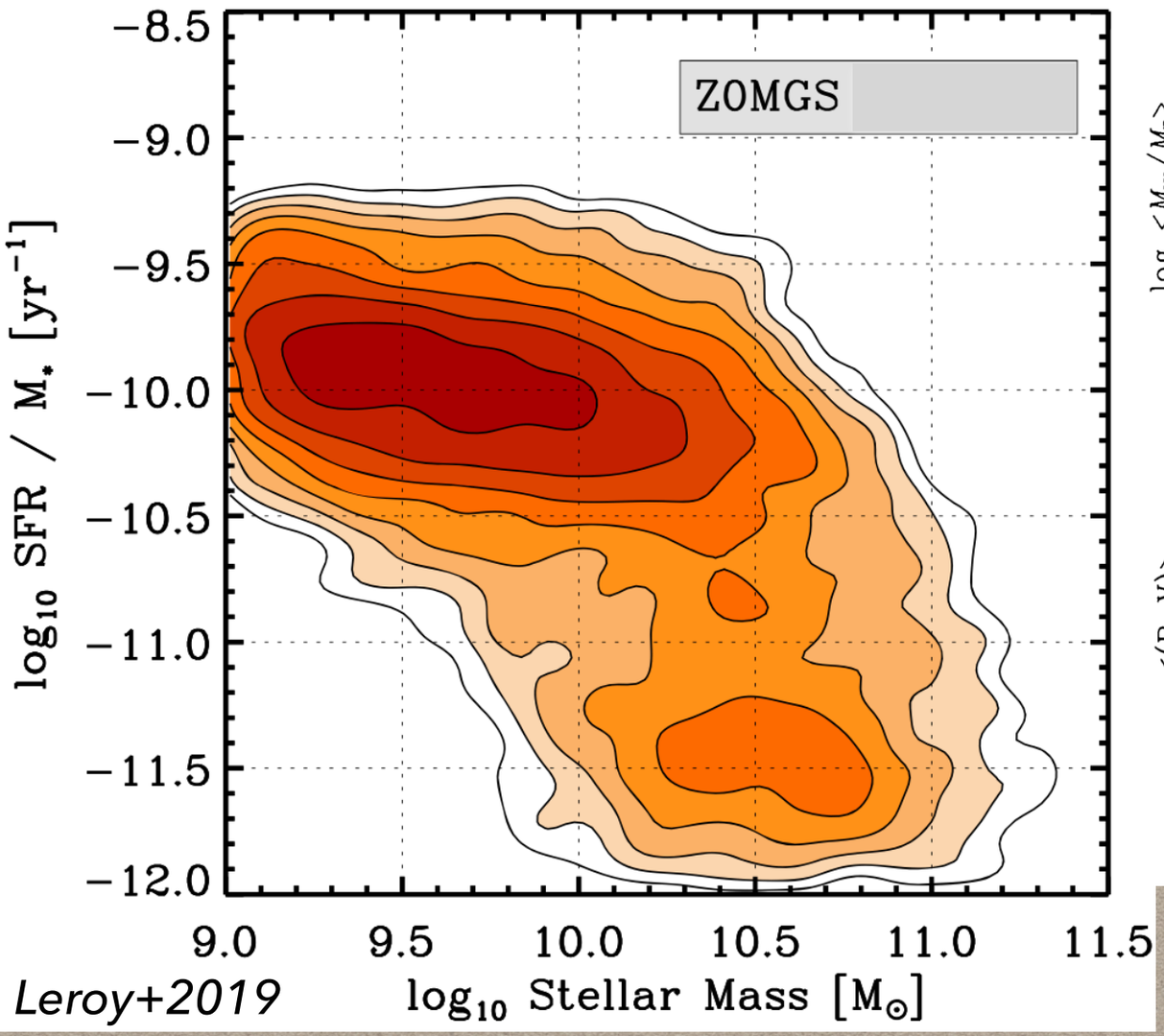
Schawinski+2014

Salim+2019 z=0 Multiwavelength Galaxy Synthesis

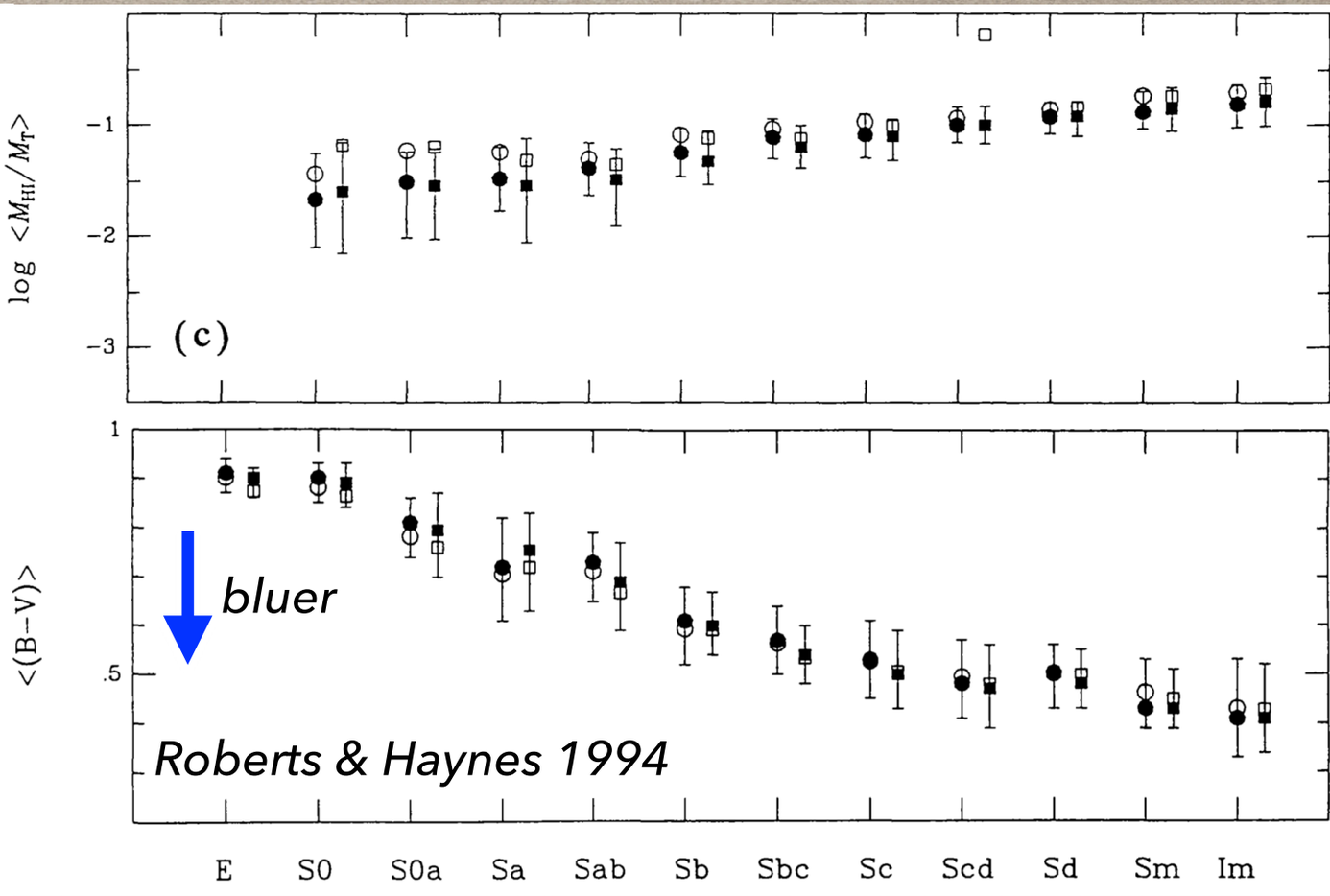
'Quick' transition due to gas consumption and SN/AGN feedback halting SF?

'Normal' galaxies

New school

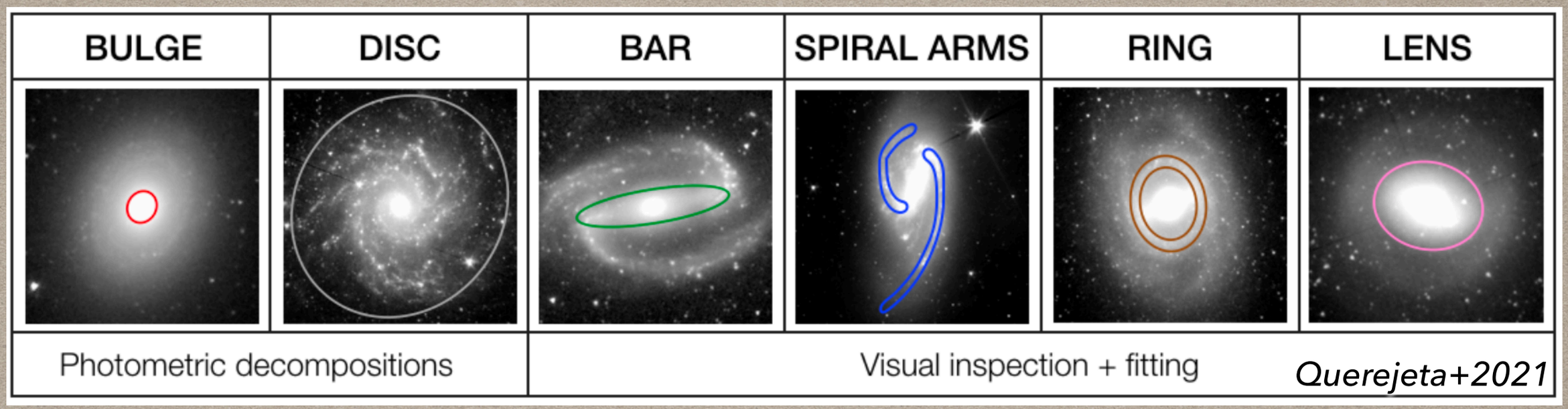


Old school



Bluer and more gas-rich for later-types

Morphological structure of star-forming spirals



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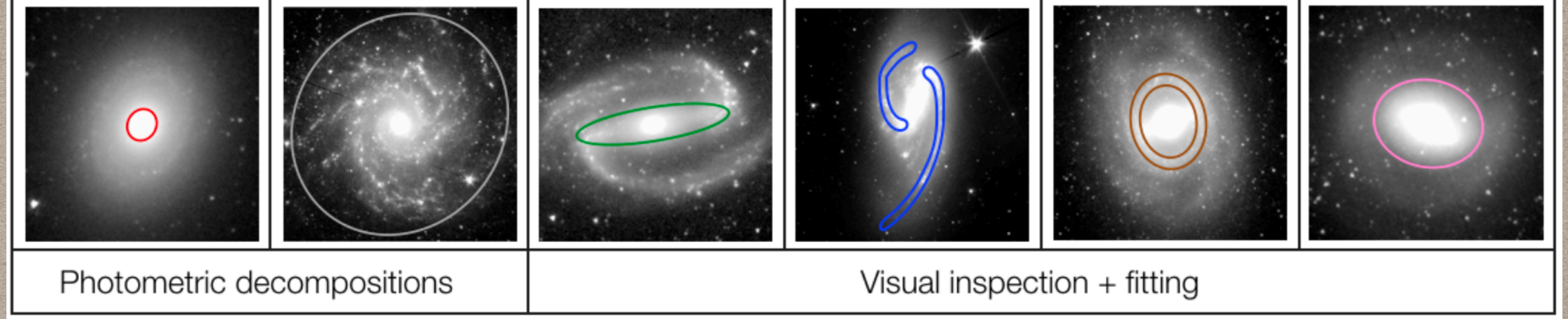
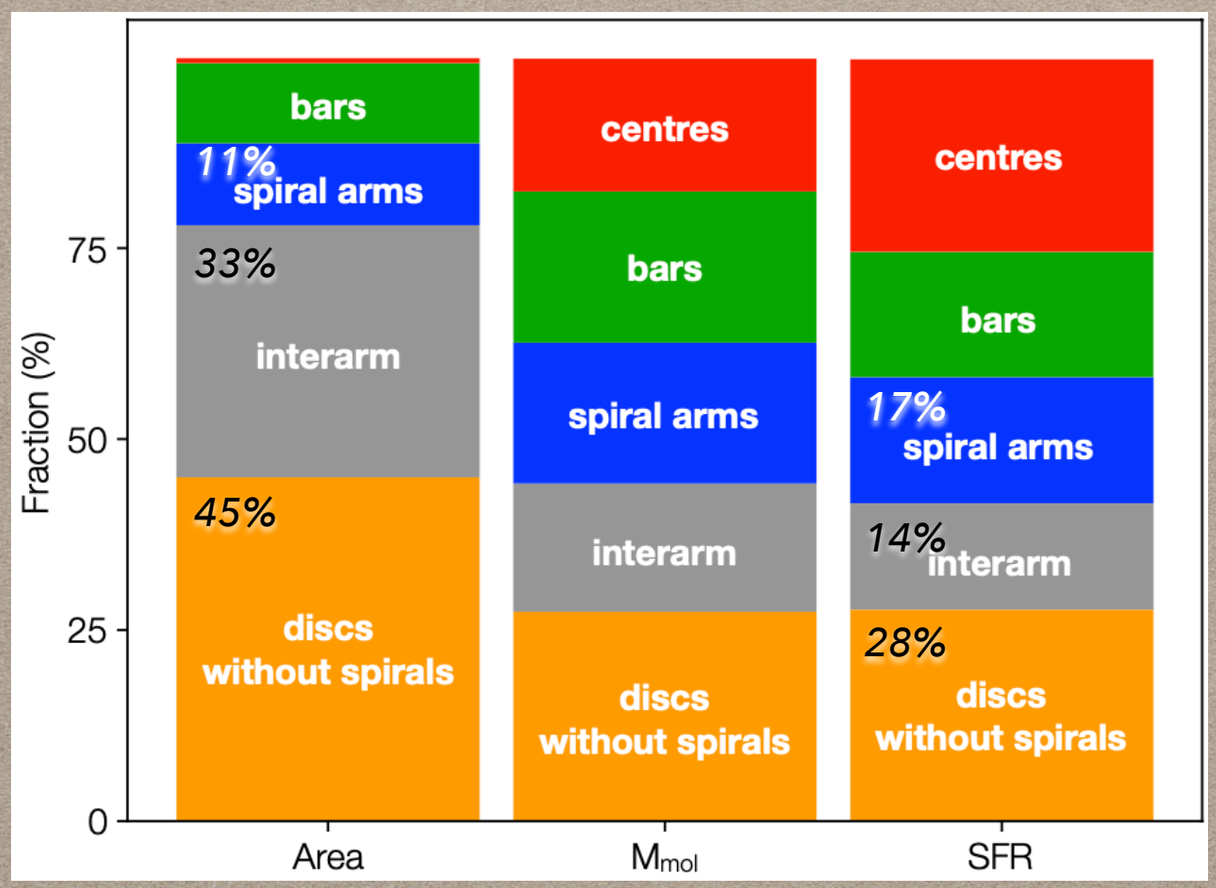




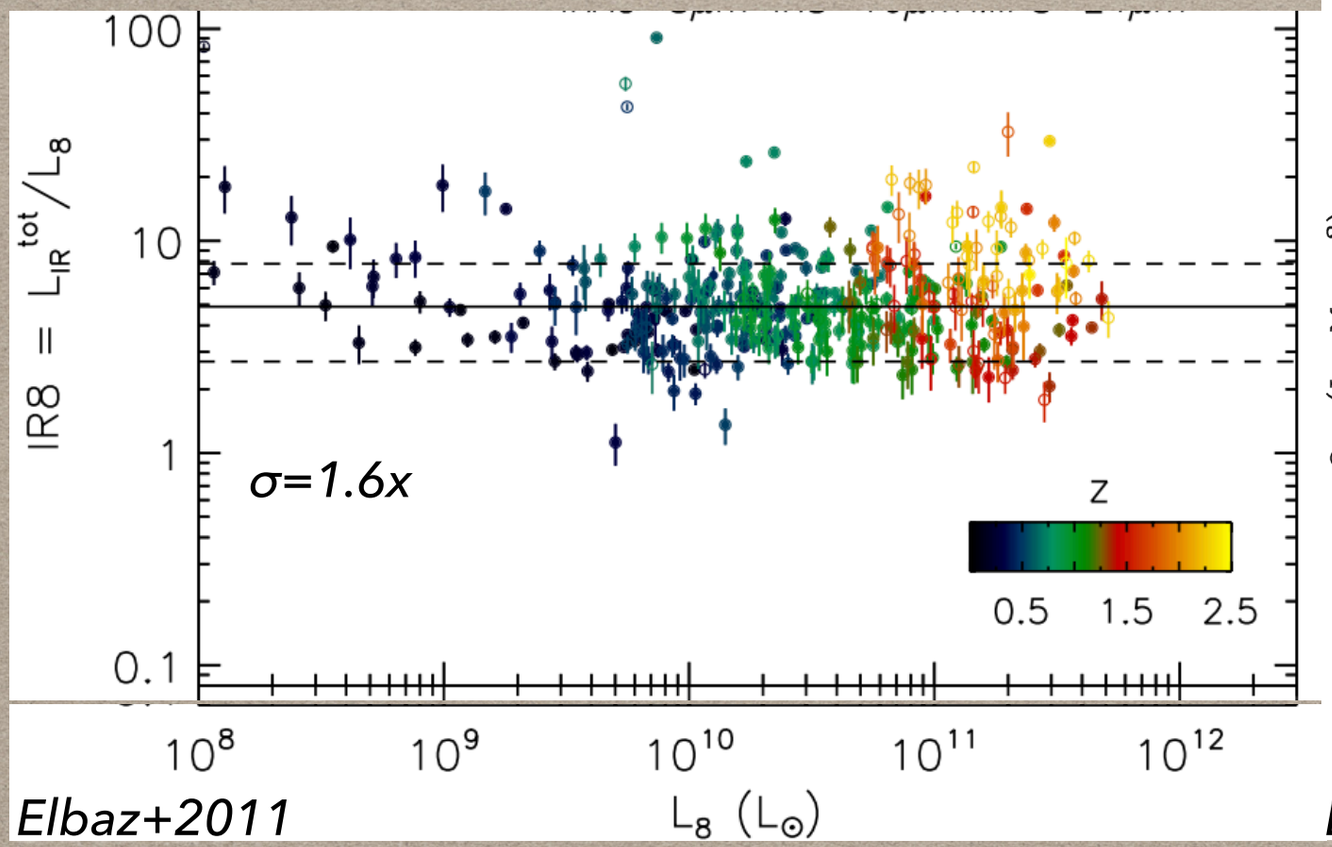
Querejeta+2021

Arms can shock/compress gas and thus enhance SF

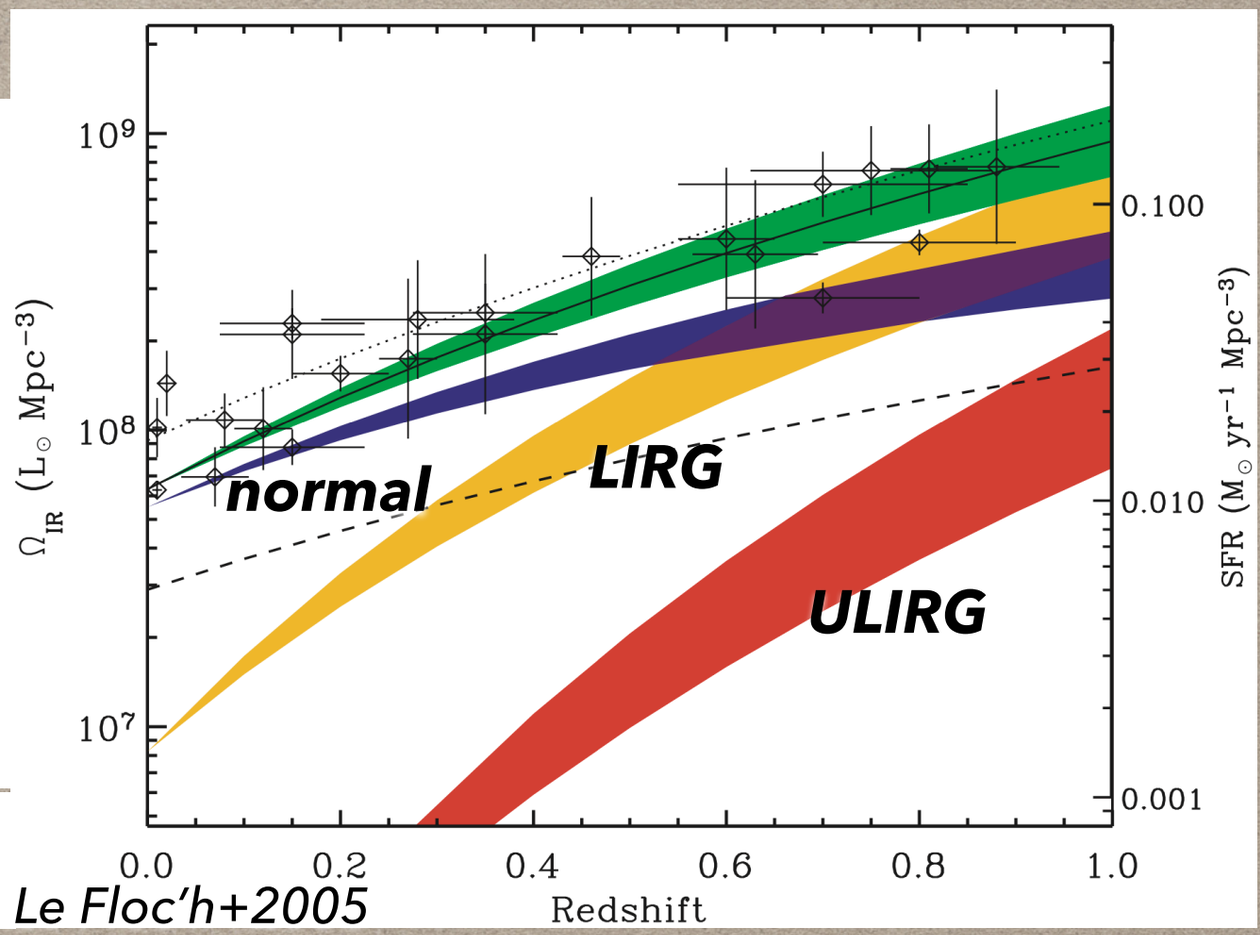
Arms ~2x higher CO and SFR surface densities

But do not dominate (integrated) gas and SF

'Normal' galaxies in a cosmological context



Elbaz+2011



Le Floc'h+2005

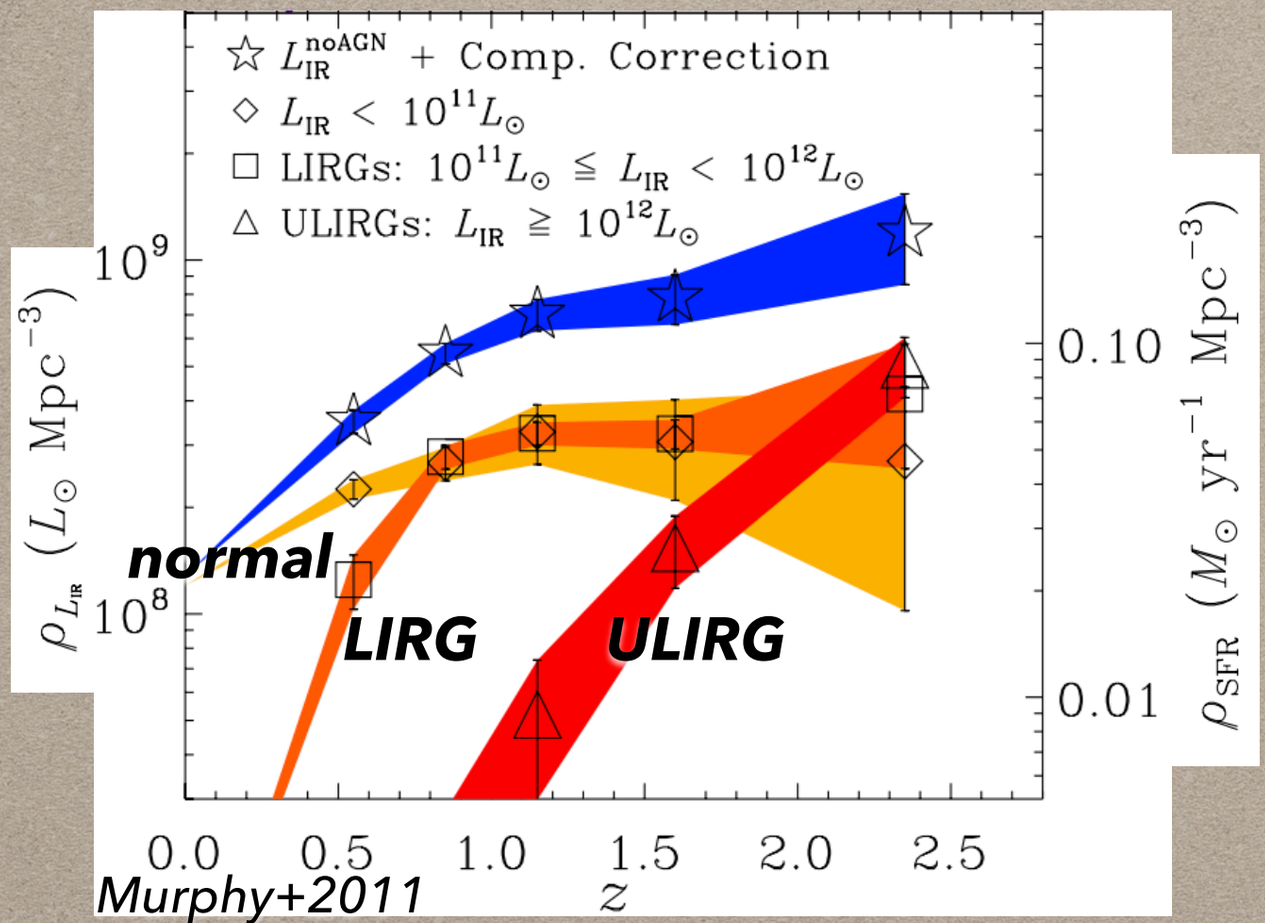
'Infrared Main Sequence' *Normal vs LIRG vs ULIRG*

Enhanced IR8 = compact starbursts

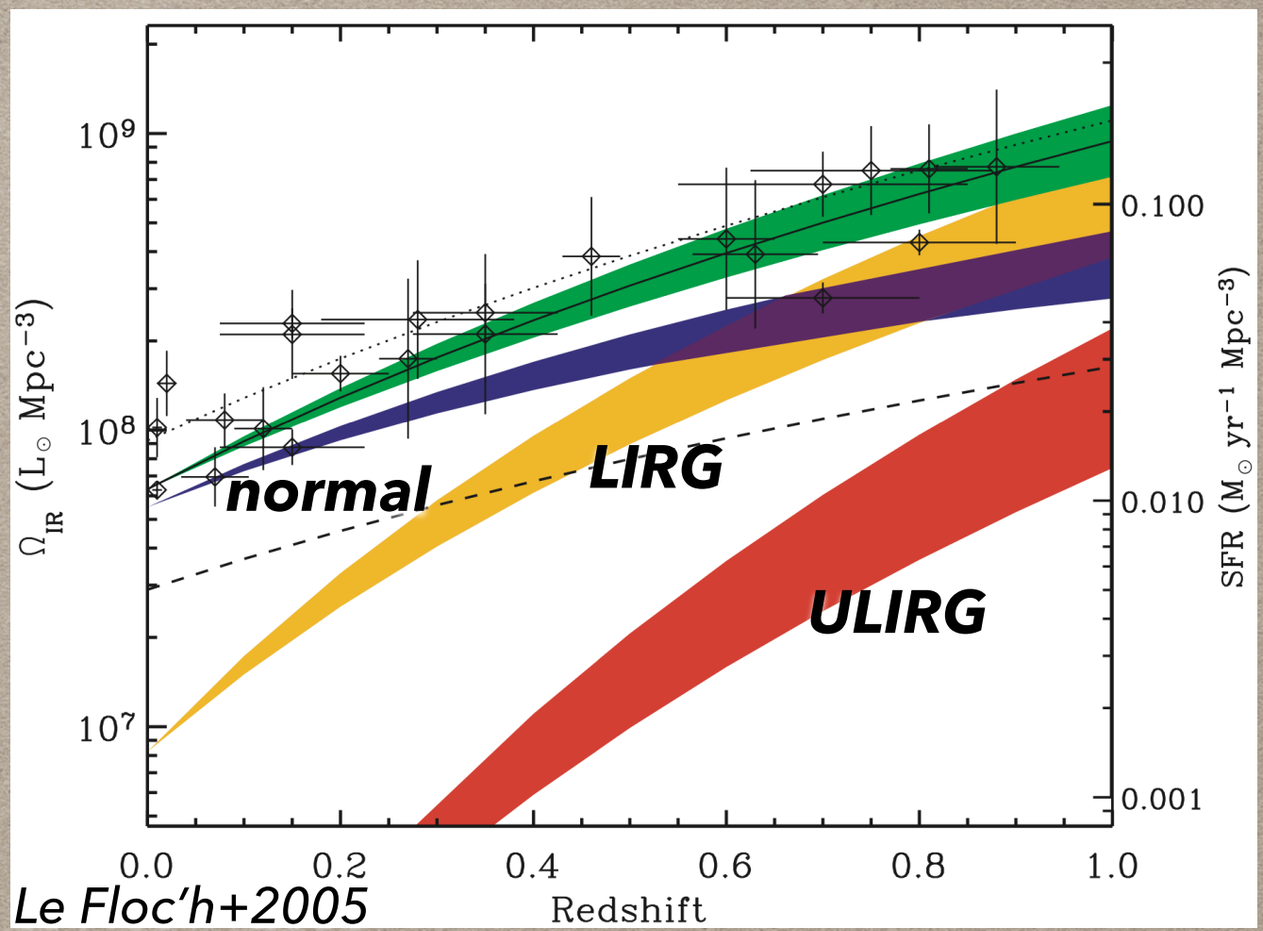
Local (U)LIRGs in starburst mode w/SF occurring over short durations in compact regions

Distant (U)LIRGs have SF occurring 'normally' over extended periods

'Normal' galaxies in a cosmological context



Murphy+2011



Le Floc'h+2005

Normal vs LIRG vs ULIRG

OUTLINE

Joanne

- *'Normal' galaxies*
- ***Spectra: stars & dust***
- *Scaling Relations*
- *Star formation & the ISM*
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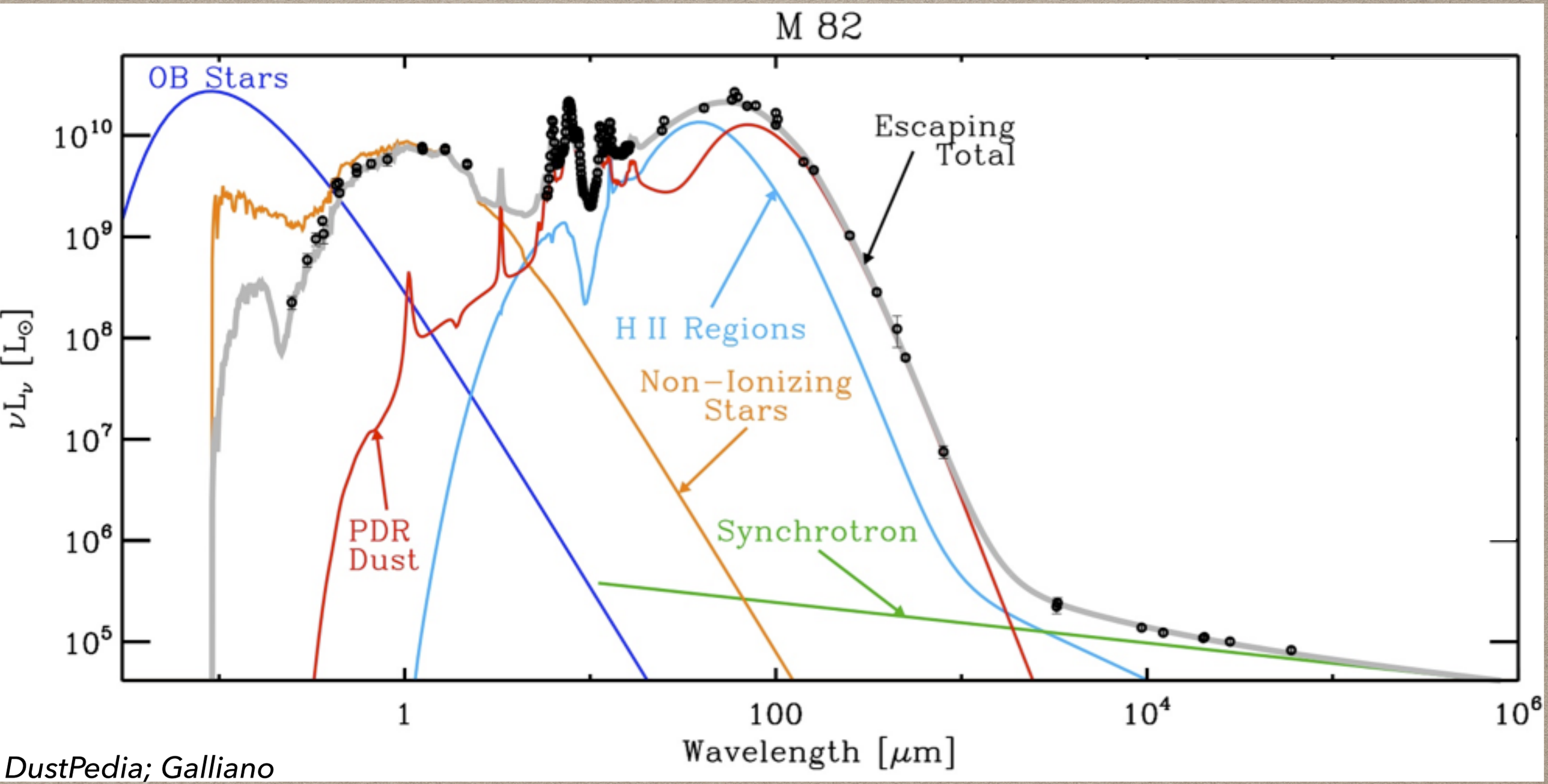
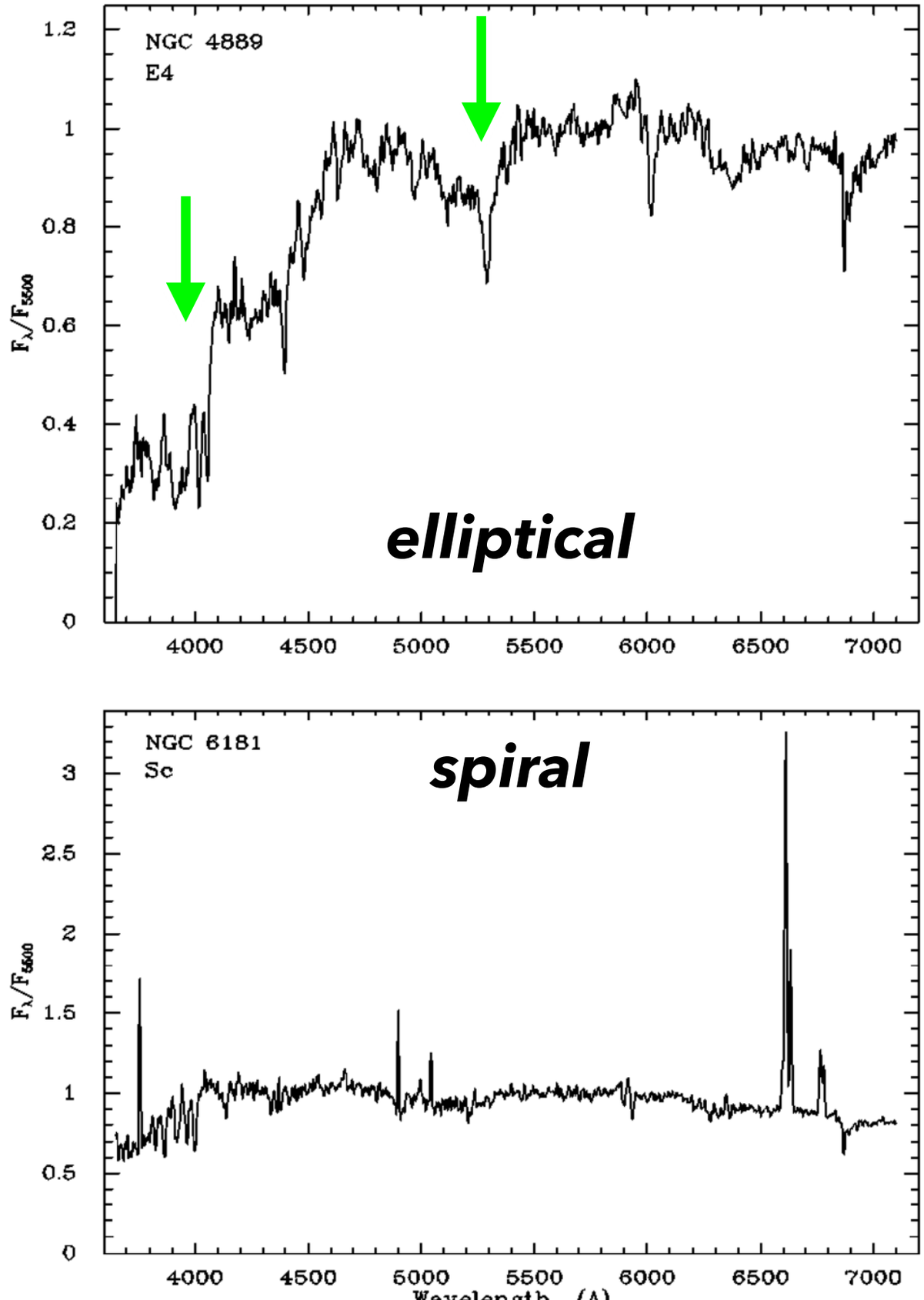
Normal Galaxy Spectra



DustPedia; Galliano

Optical spectra: Z, n_{e^-}, T_{e^-}, SFR, A_V, BPT, age, M_*, …

Kennicutt 1998 "Star Formation in Galaxies Along the Hubble Sequence"



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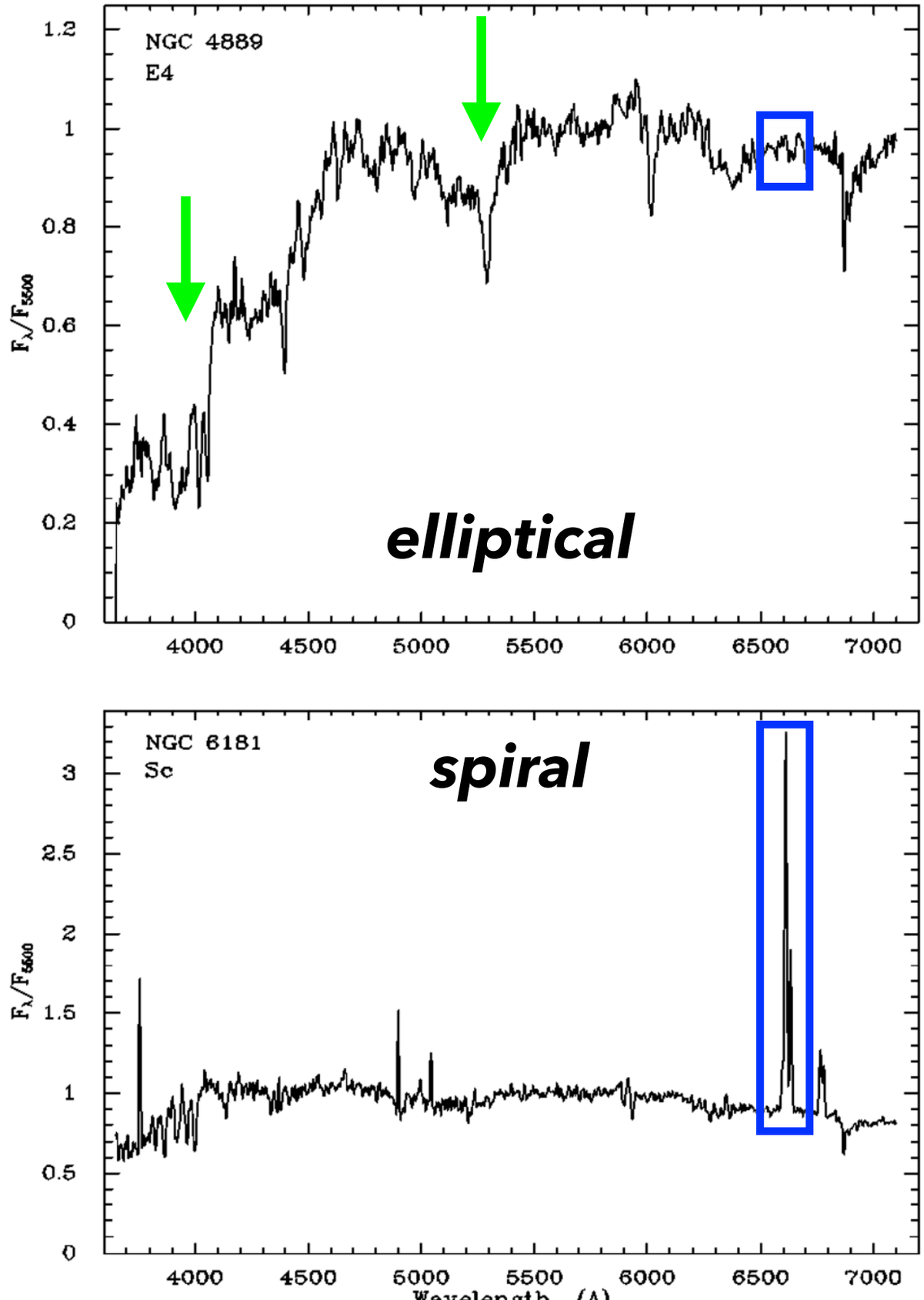

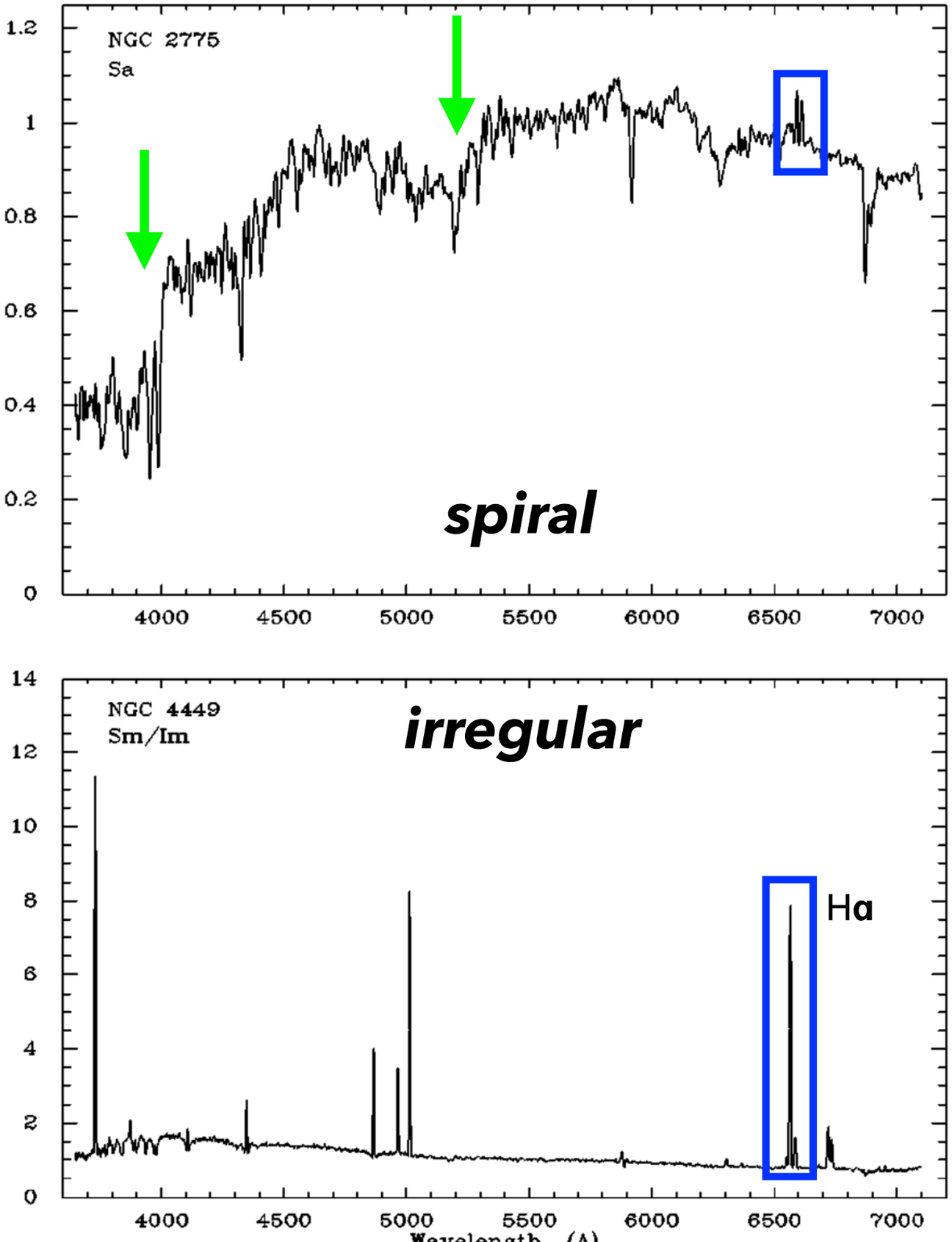

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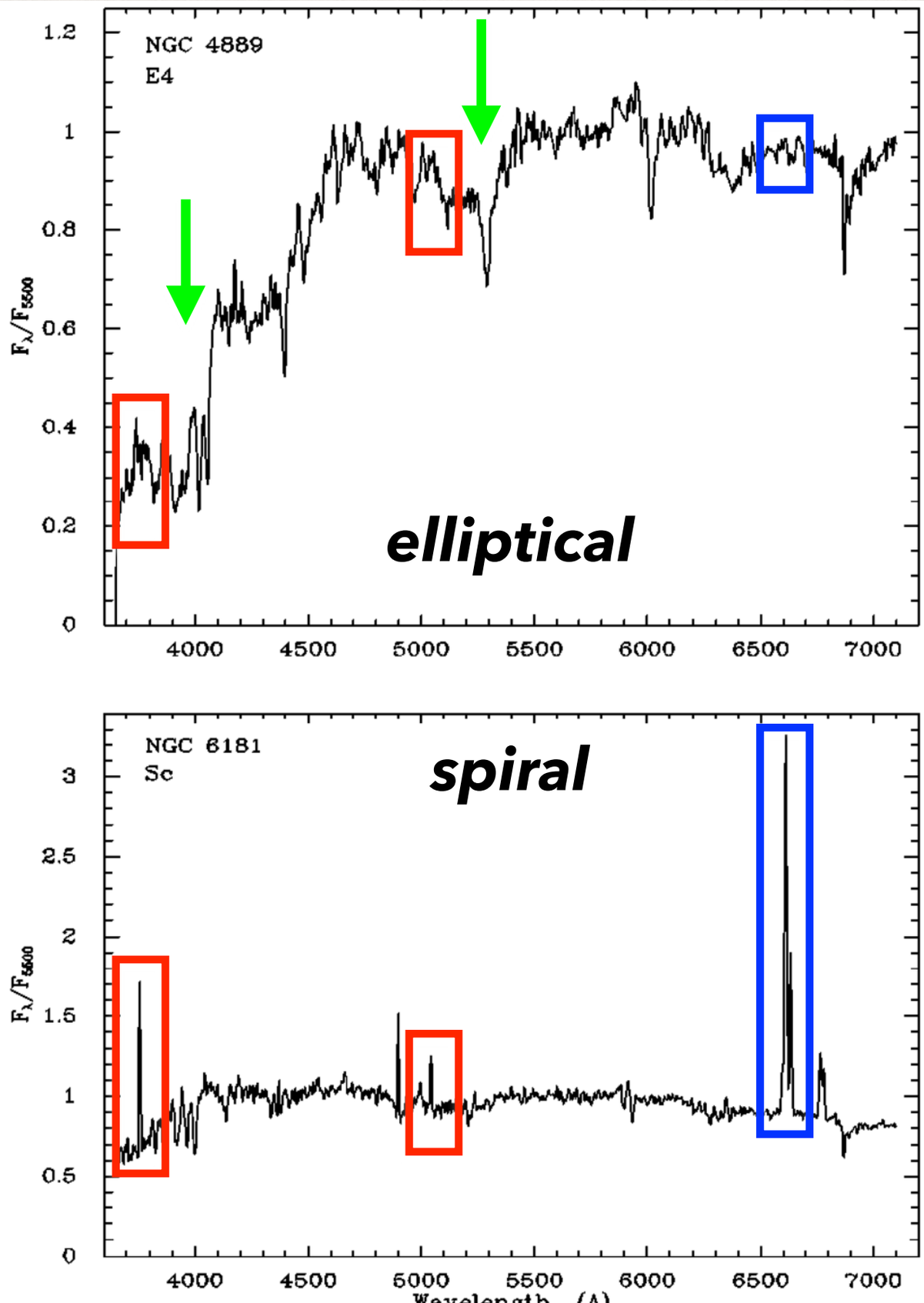
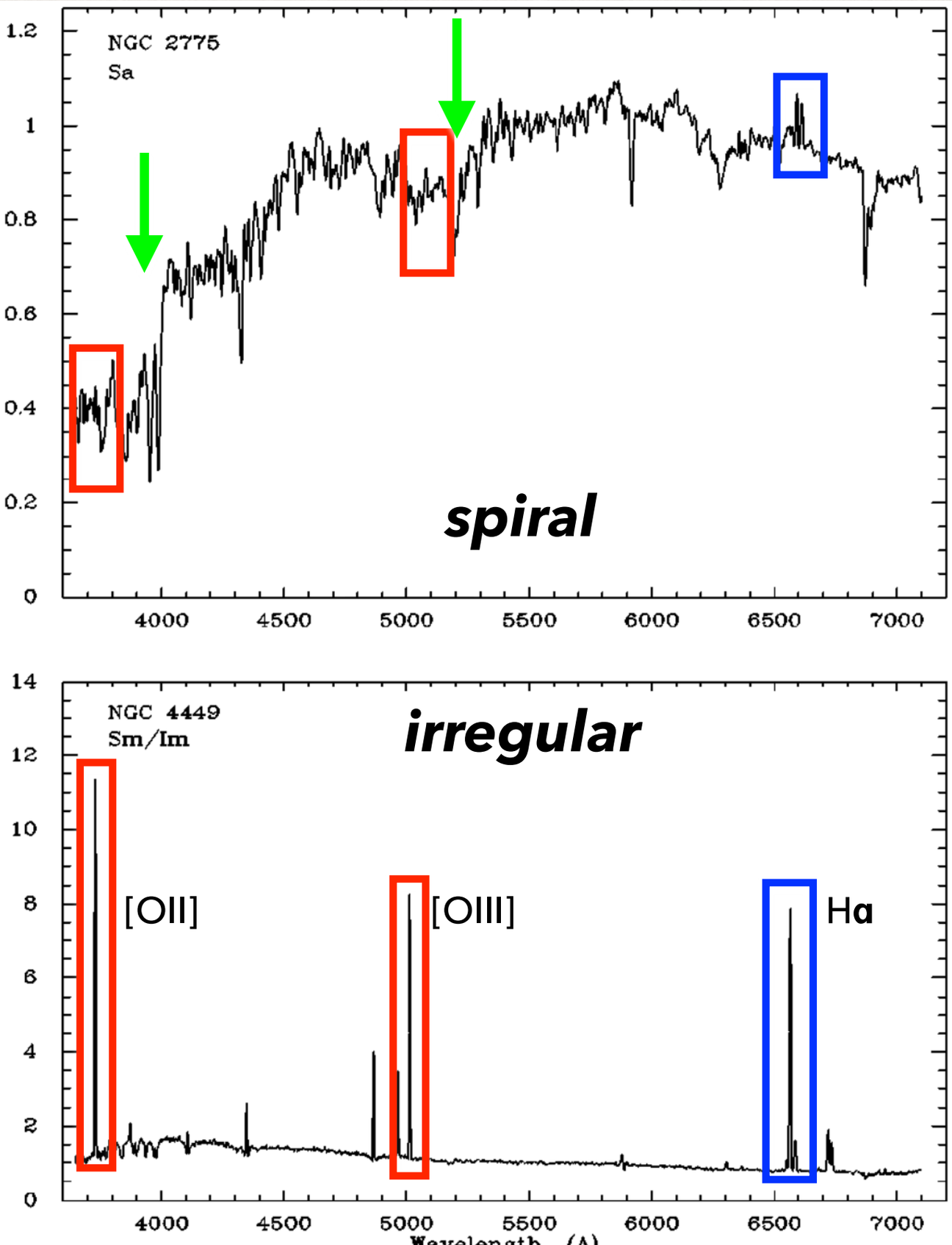
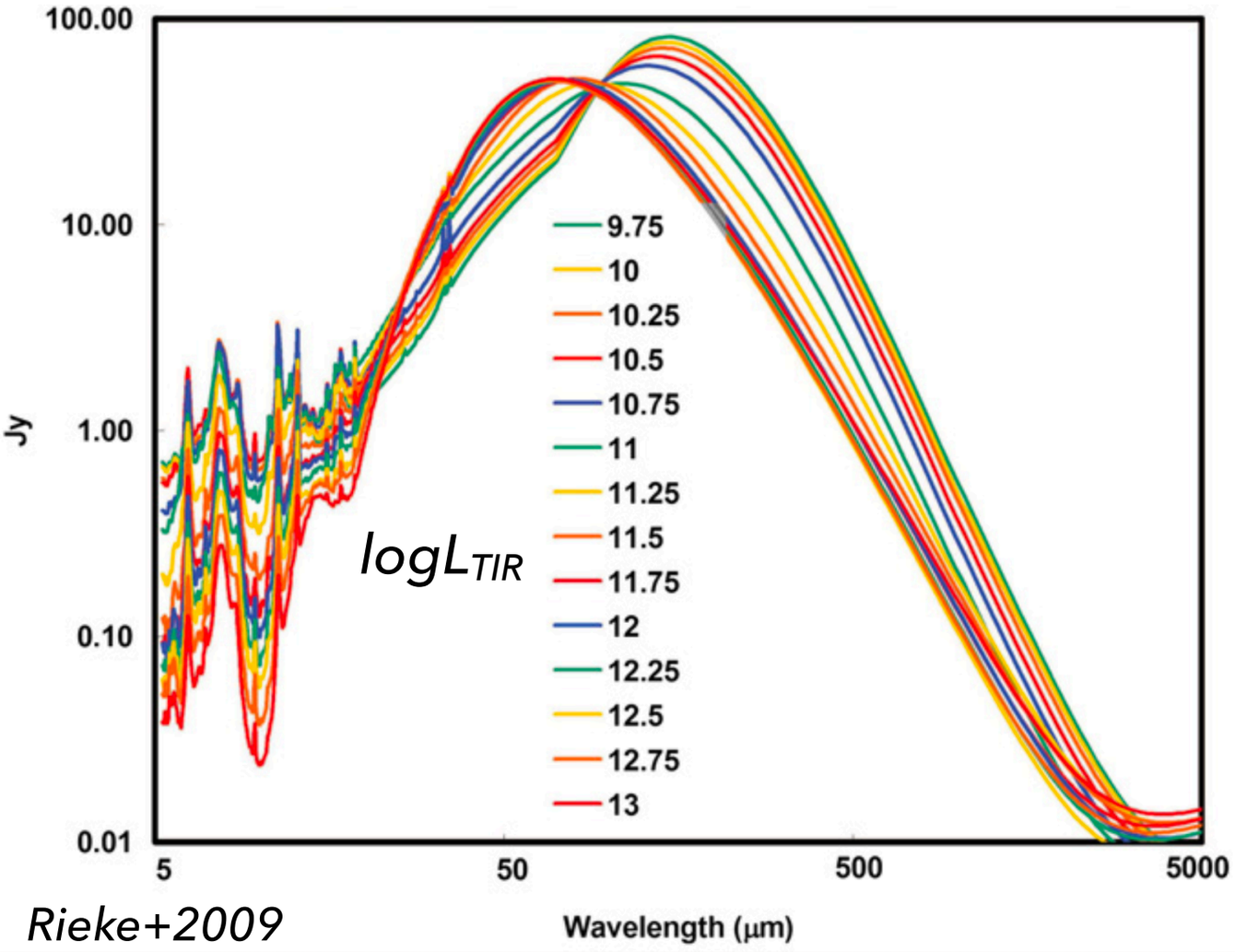
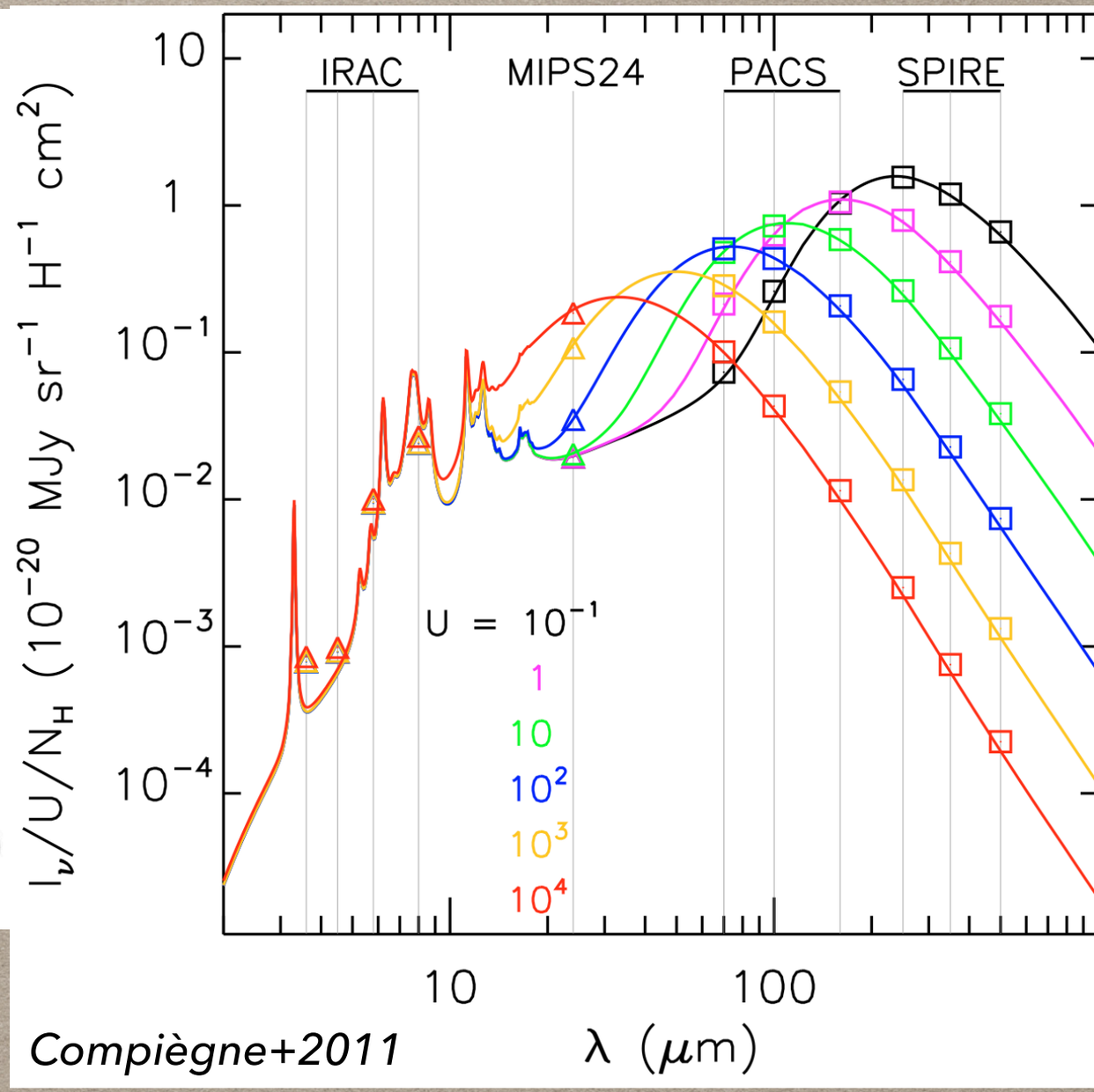




Infrared spectra: M_d, T_d, q_{PAH}, U, Z, n_{e^-}, T_{PDR}, CO excitation, …



Rieke+2009

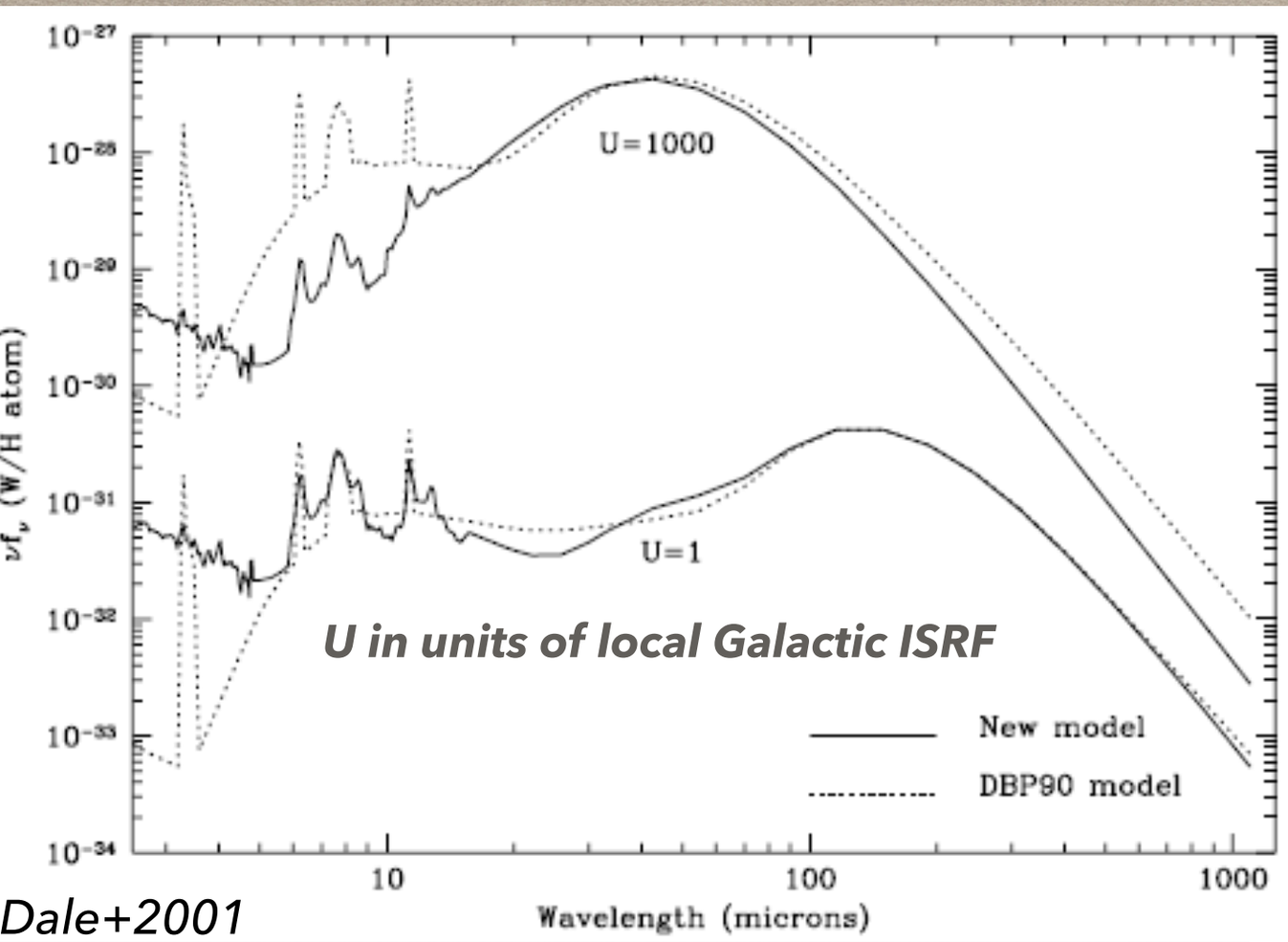


Compiègne+2011

DustEM

Empirical, semi-empirical, theoretical, …

Dust SED Models



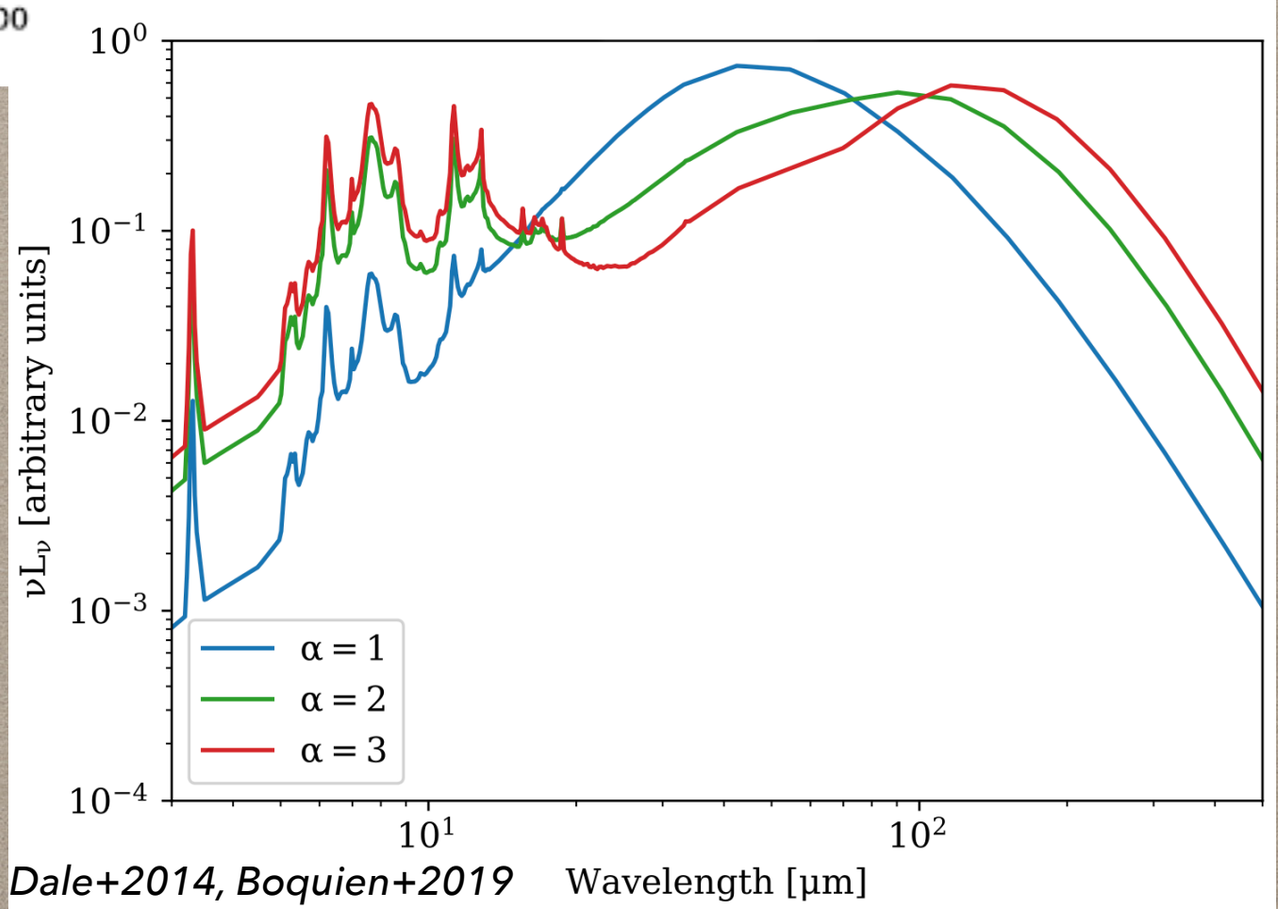
Dale+2001

Power-law distribution for the intensity of the dust heating

$$dM_{\rm d} \propto U^{-\alpha}\ \ dU$$

A "1-parameter" family of SEDs

Helpful for understanding CIGALE parameters!

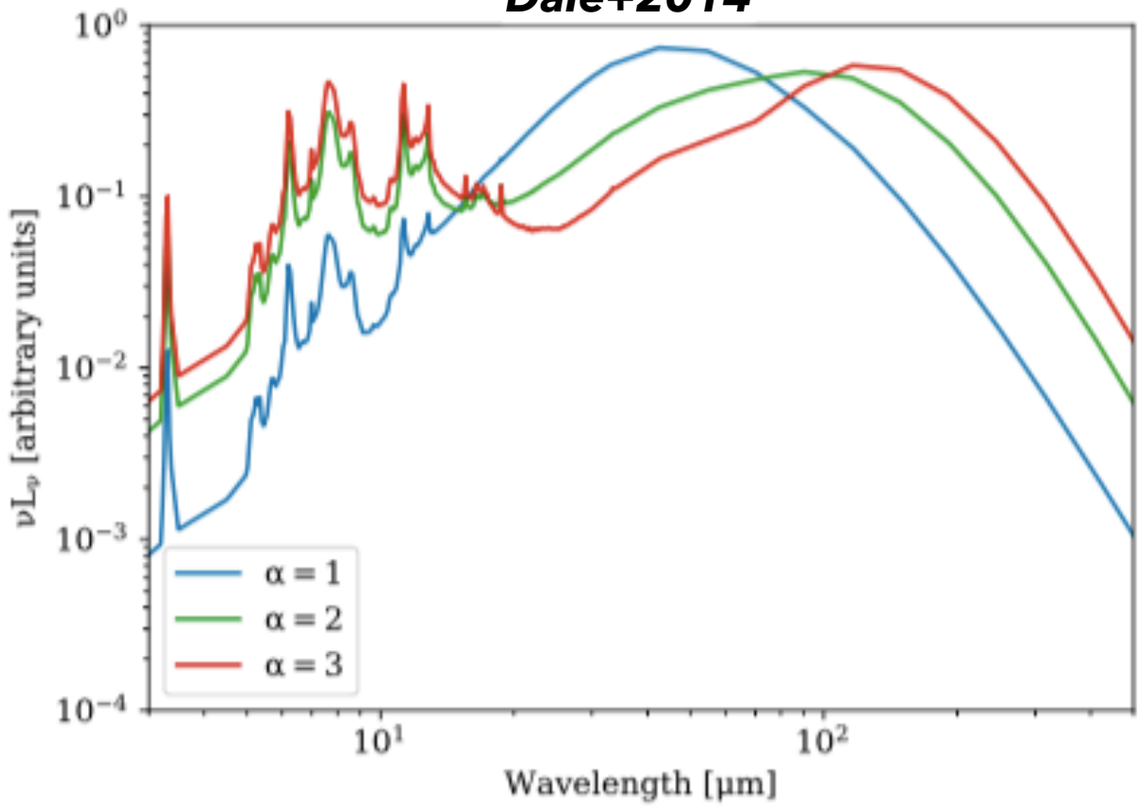


Dale+2014, Boquien+2019

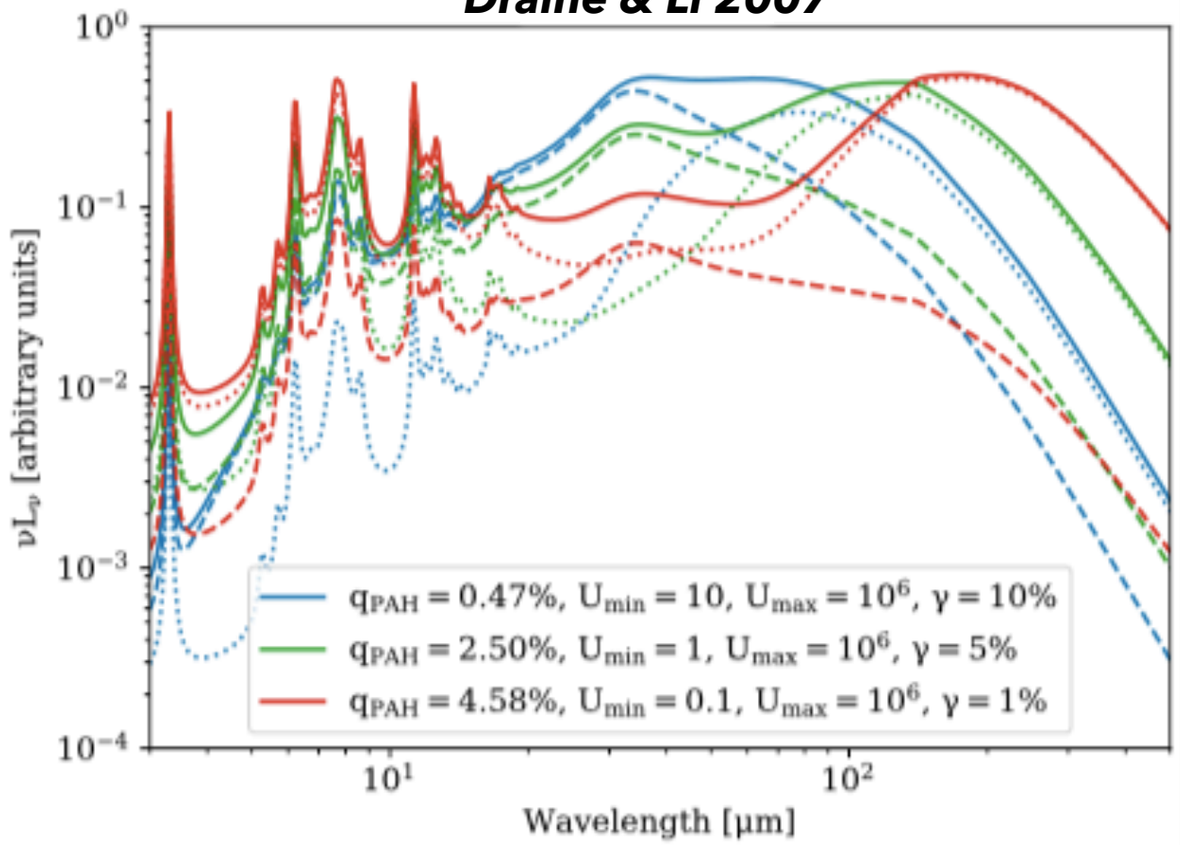
Dust SED Models

CIGALE (Boquien+2019)

Dale+2014



Draine & Li 2007



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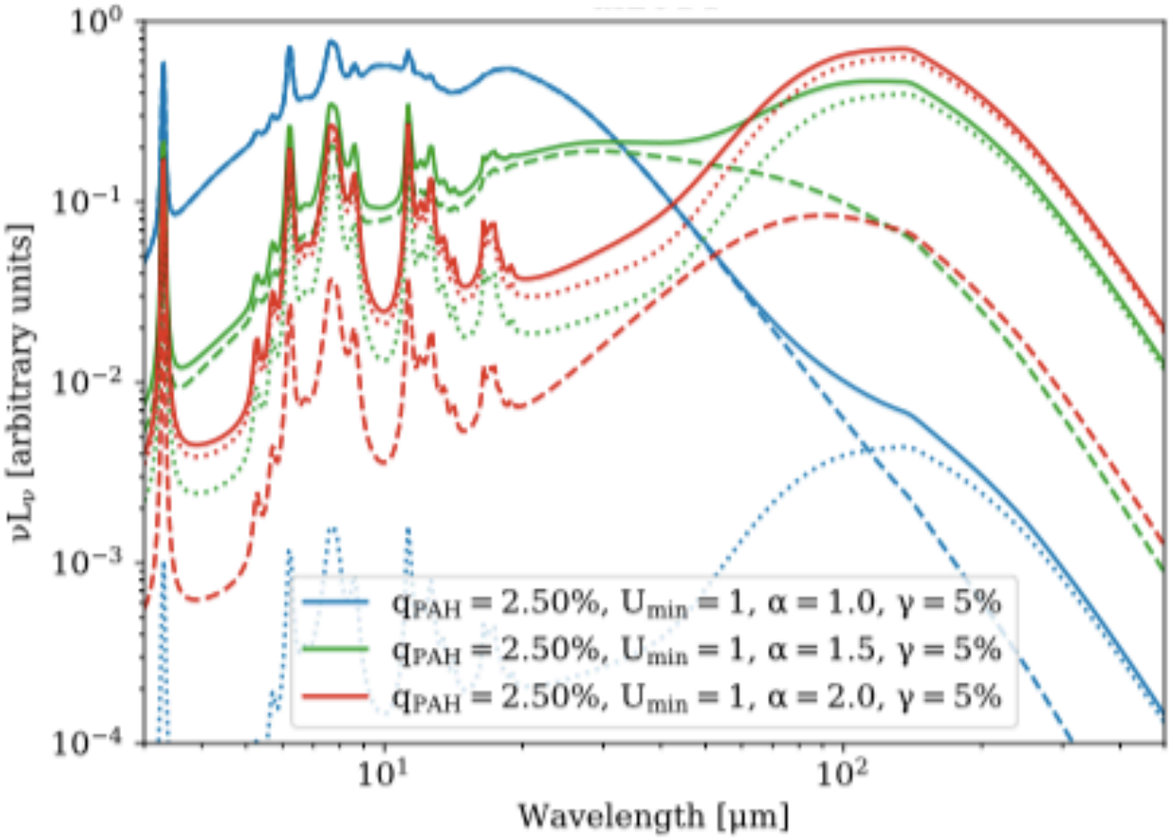
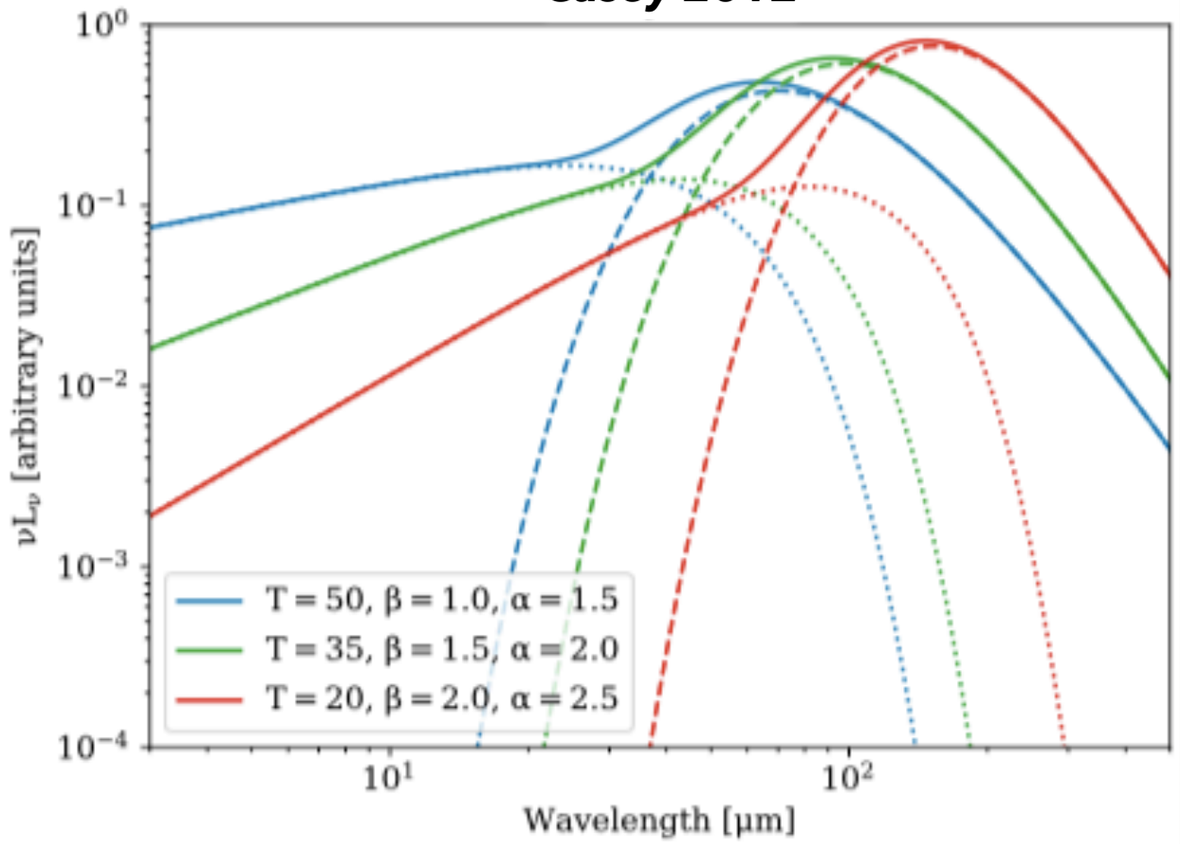


Casey 2012



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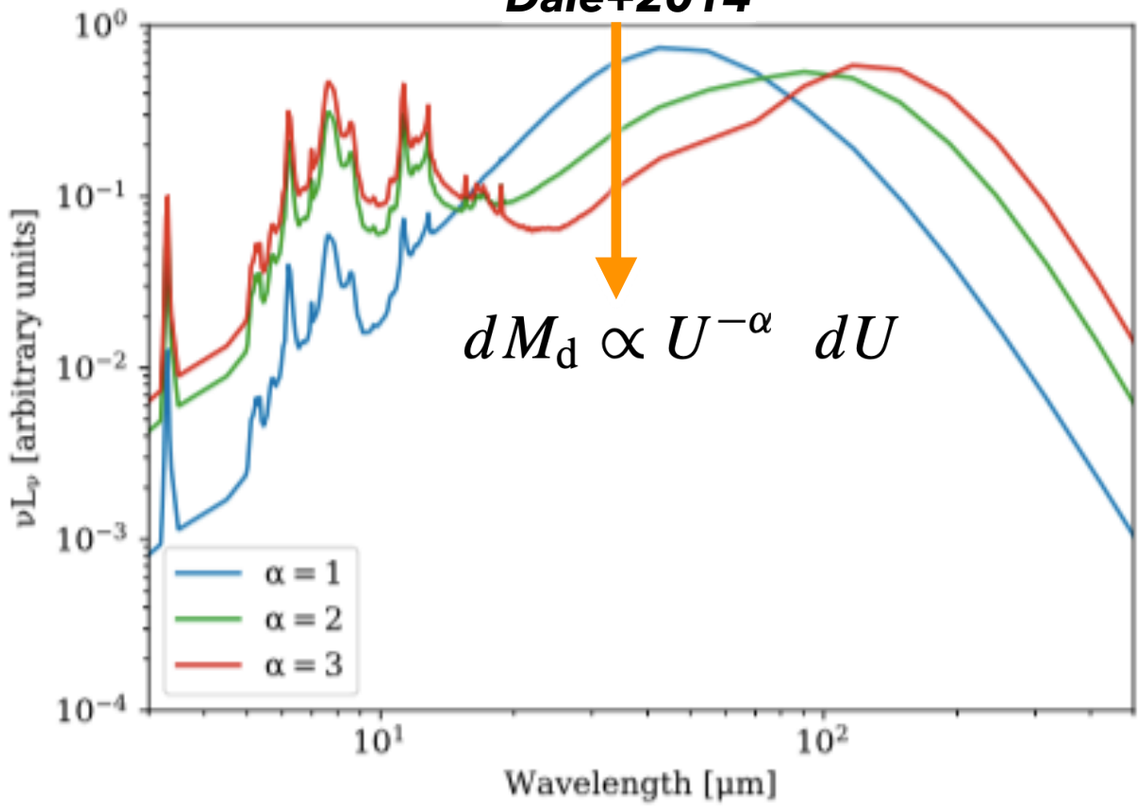
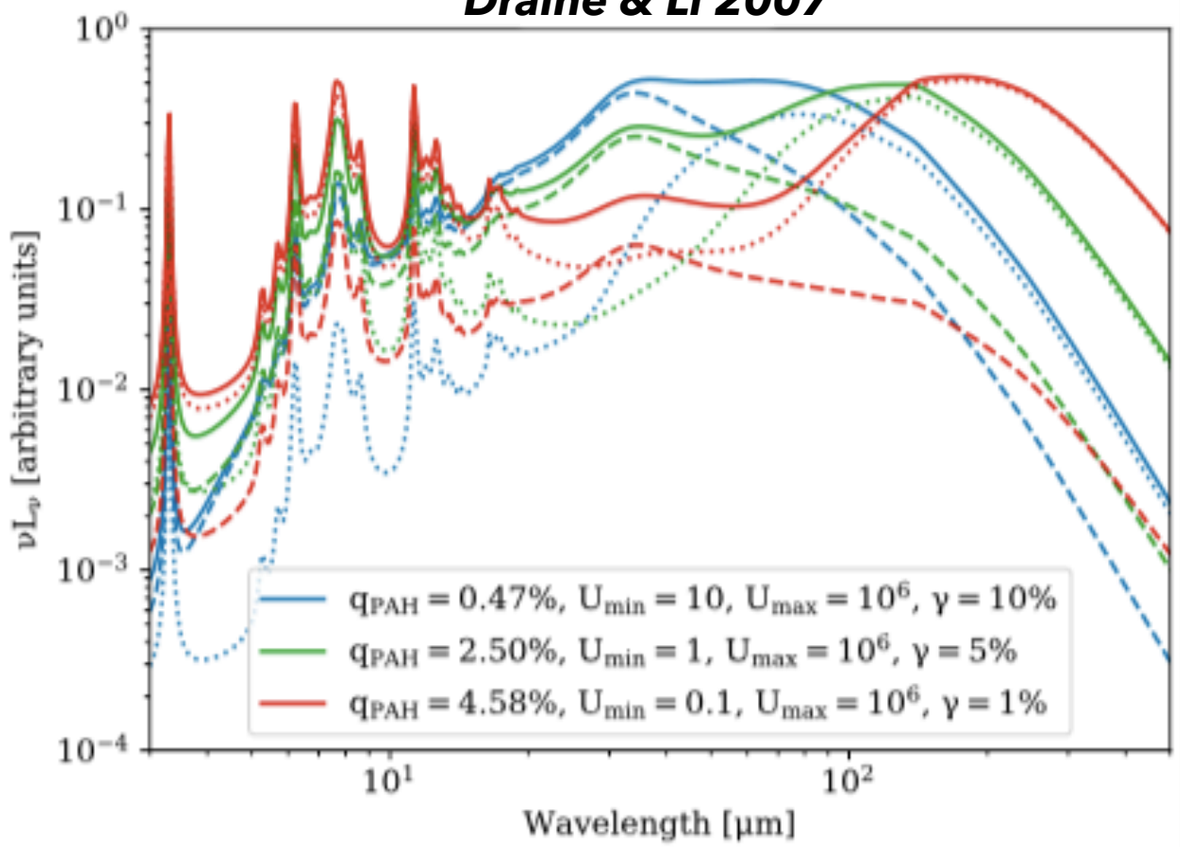
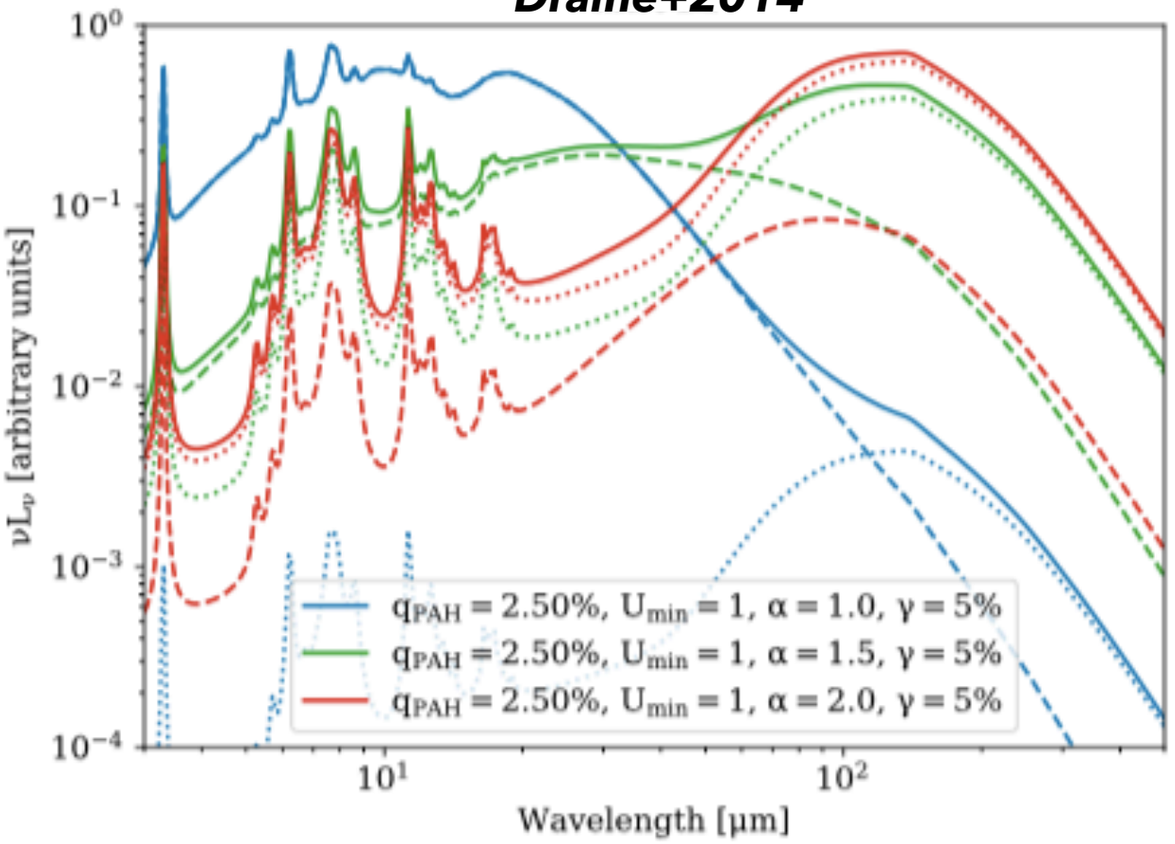


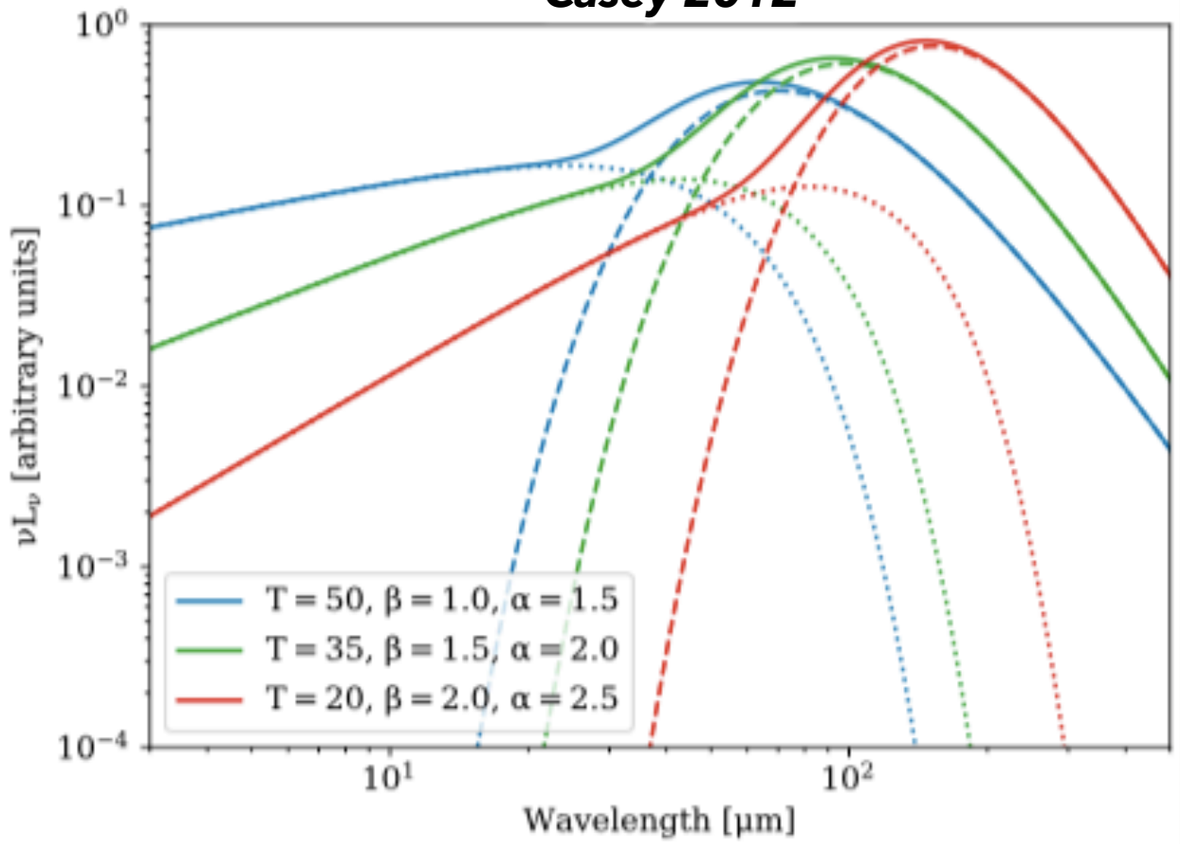
Draine & Li 2007



Draine+2014



Casey 2012



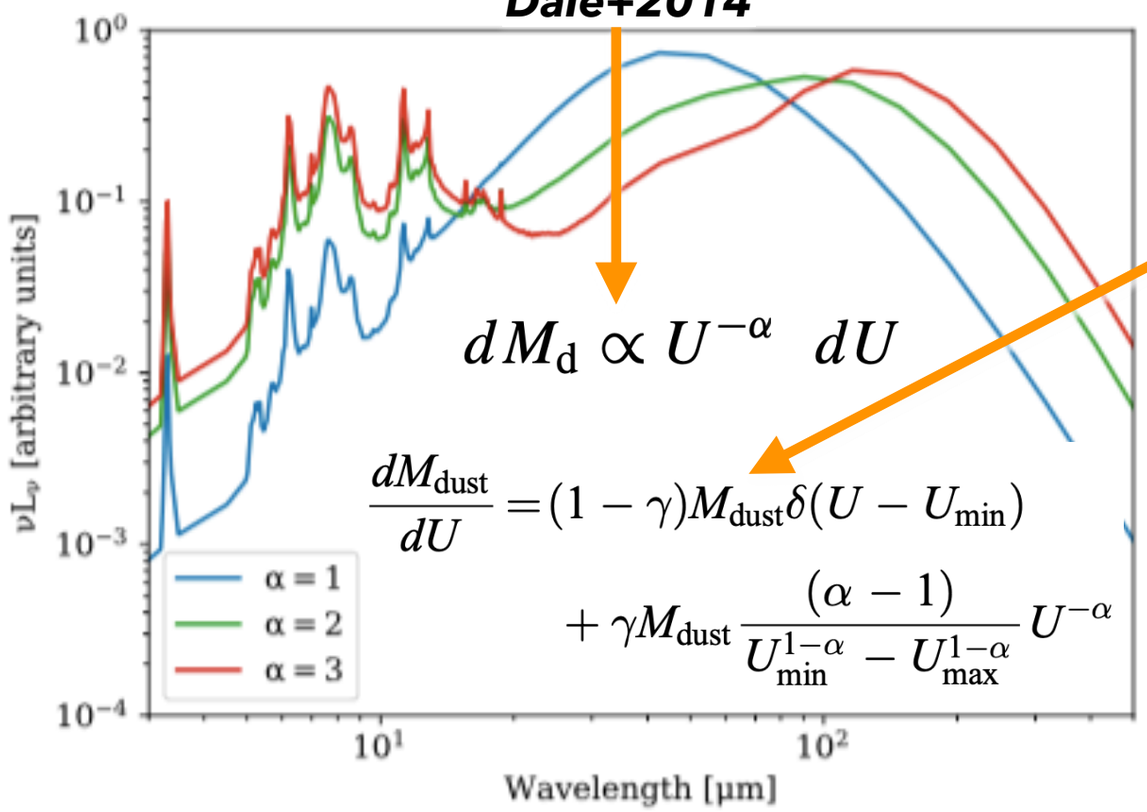
Dust SED Models

CIGALE (Boquien+2019)

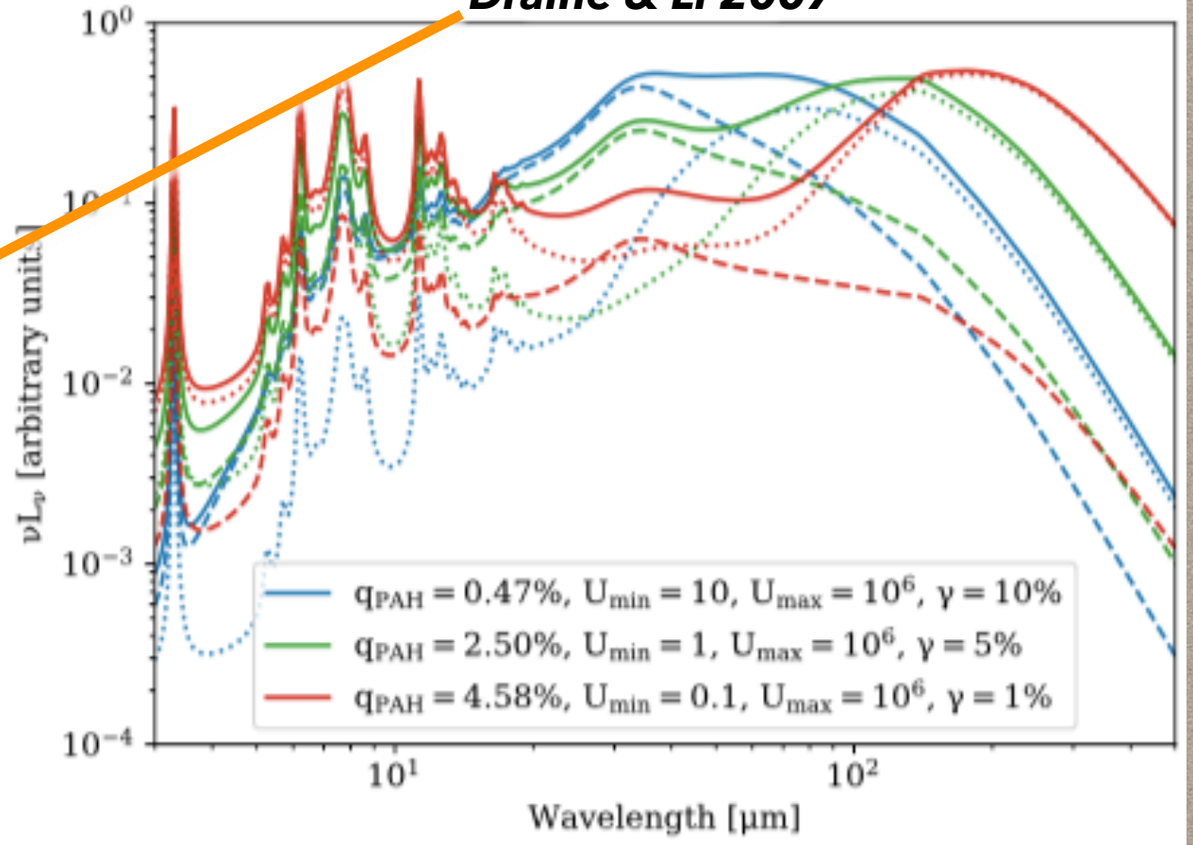
Dale+2014

$$dM_{\rm d} \propto U^{-\alpha}\ dU$$

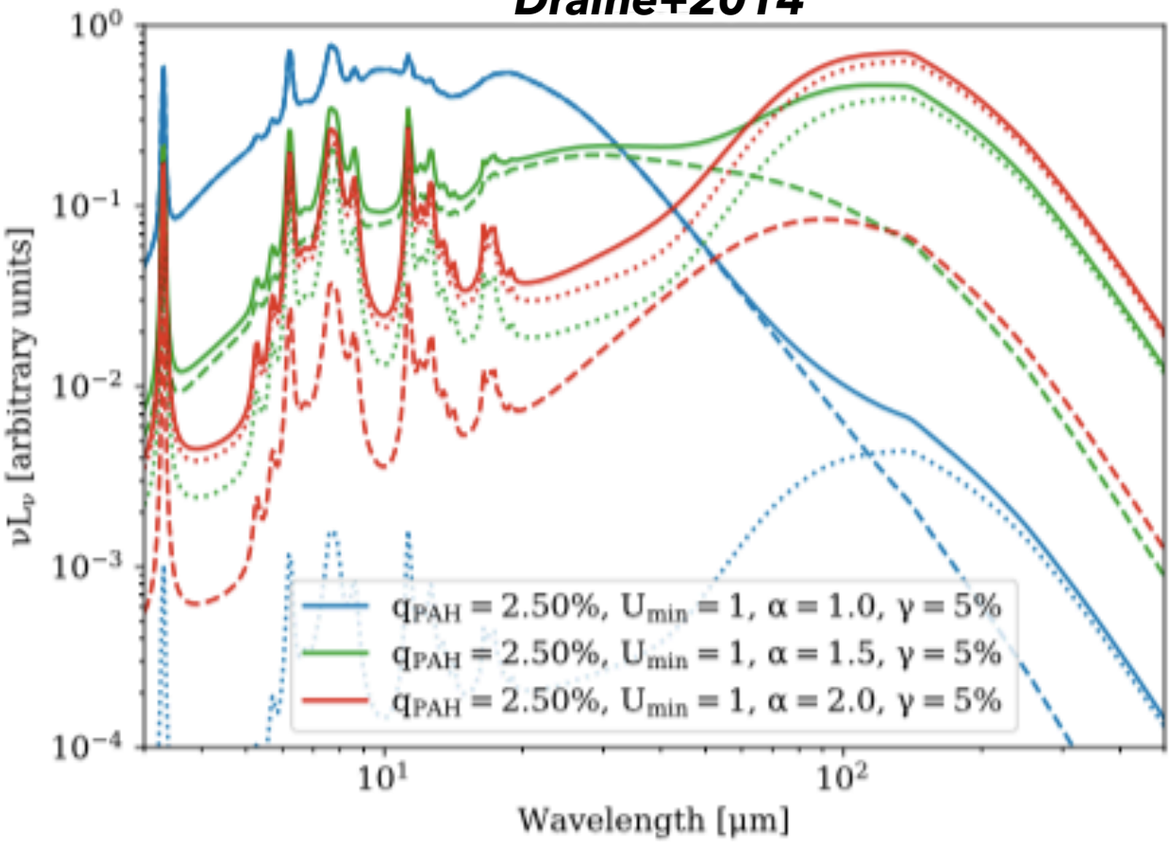
$$\frac{dM_{\rm dust}}{dU} = (1-\gamma) M_{\rm dust} \delta(U - U_{\rm min}) + \gamma M_{\rm dust} \frac{(\alpha-1)}{U_{\rm min}^{1-\alpha} - U_{\rm max}^{1-\alpha}} U^{-\alpha}$$



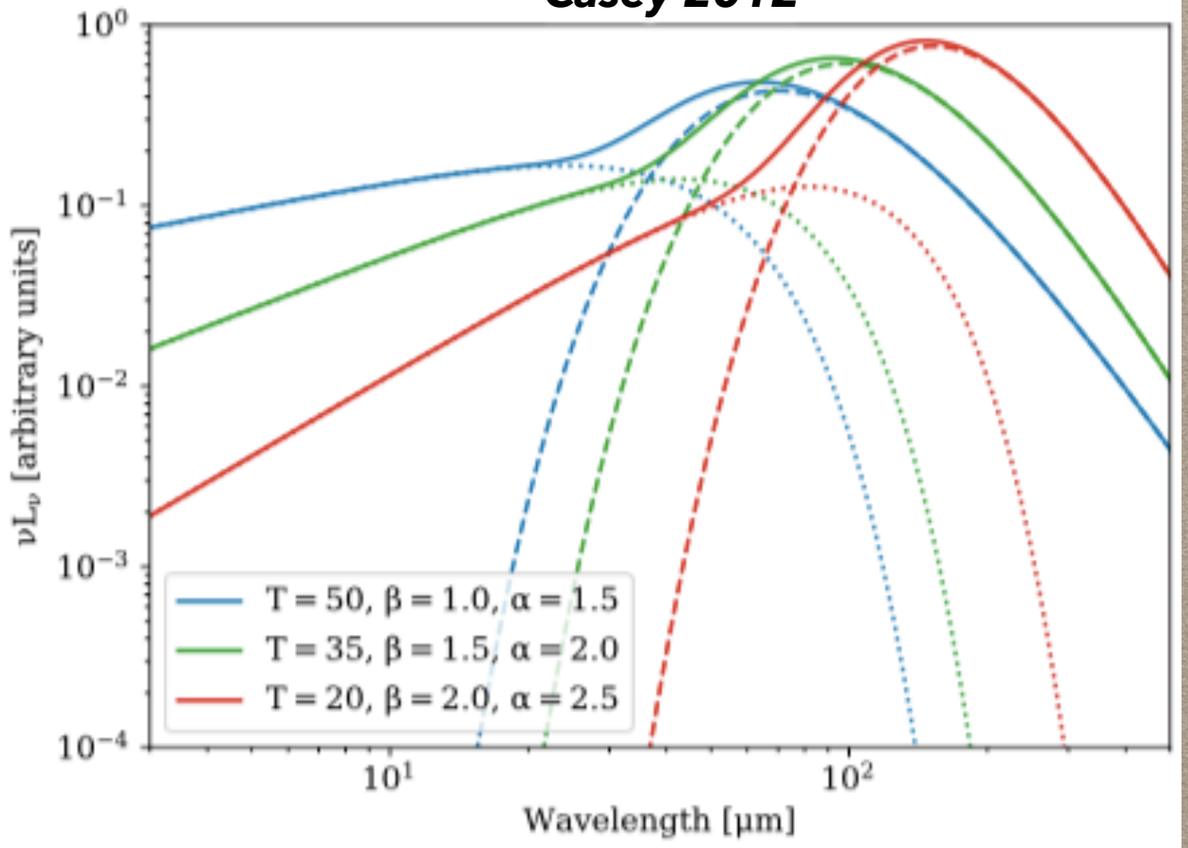
Draine & Li 2007



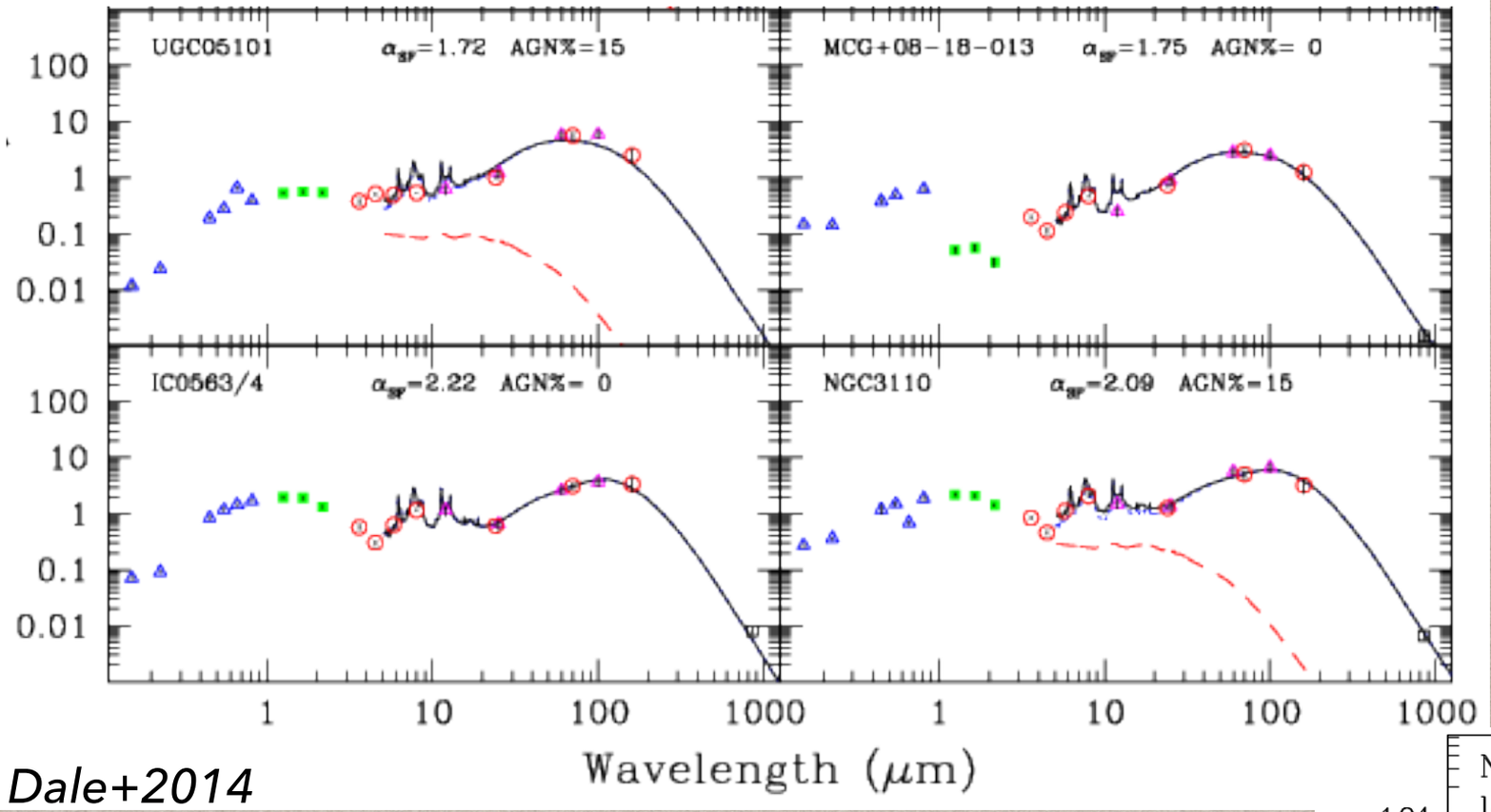
Draine+2014



Casey 2012



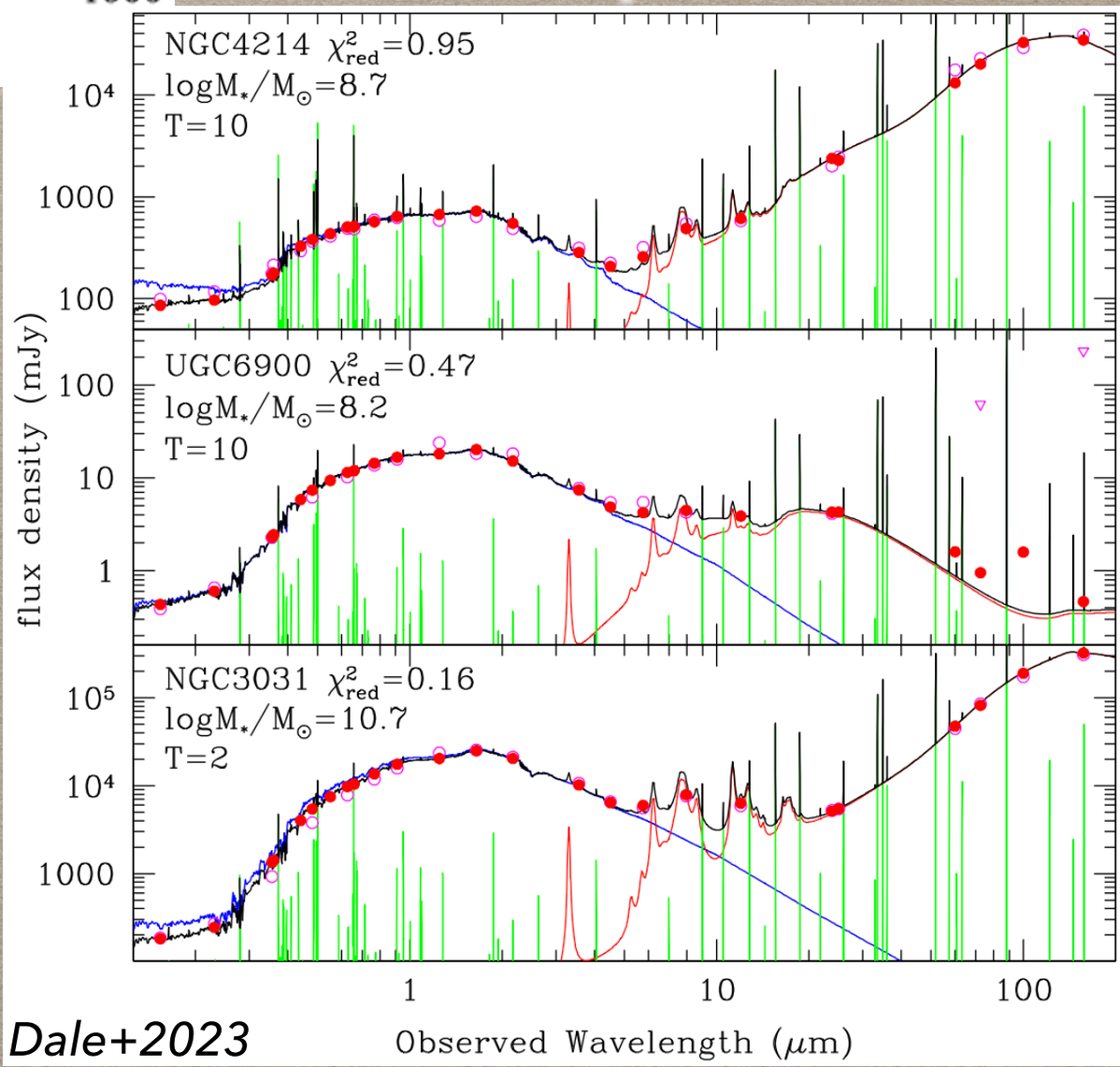
Dust SED Models



Dale+2014

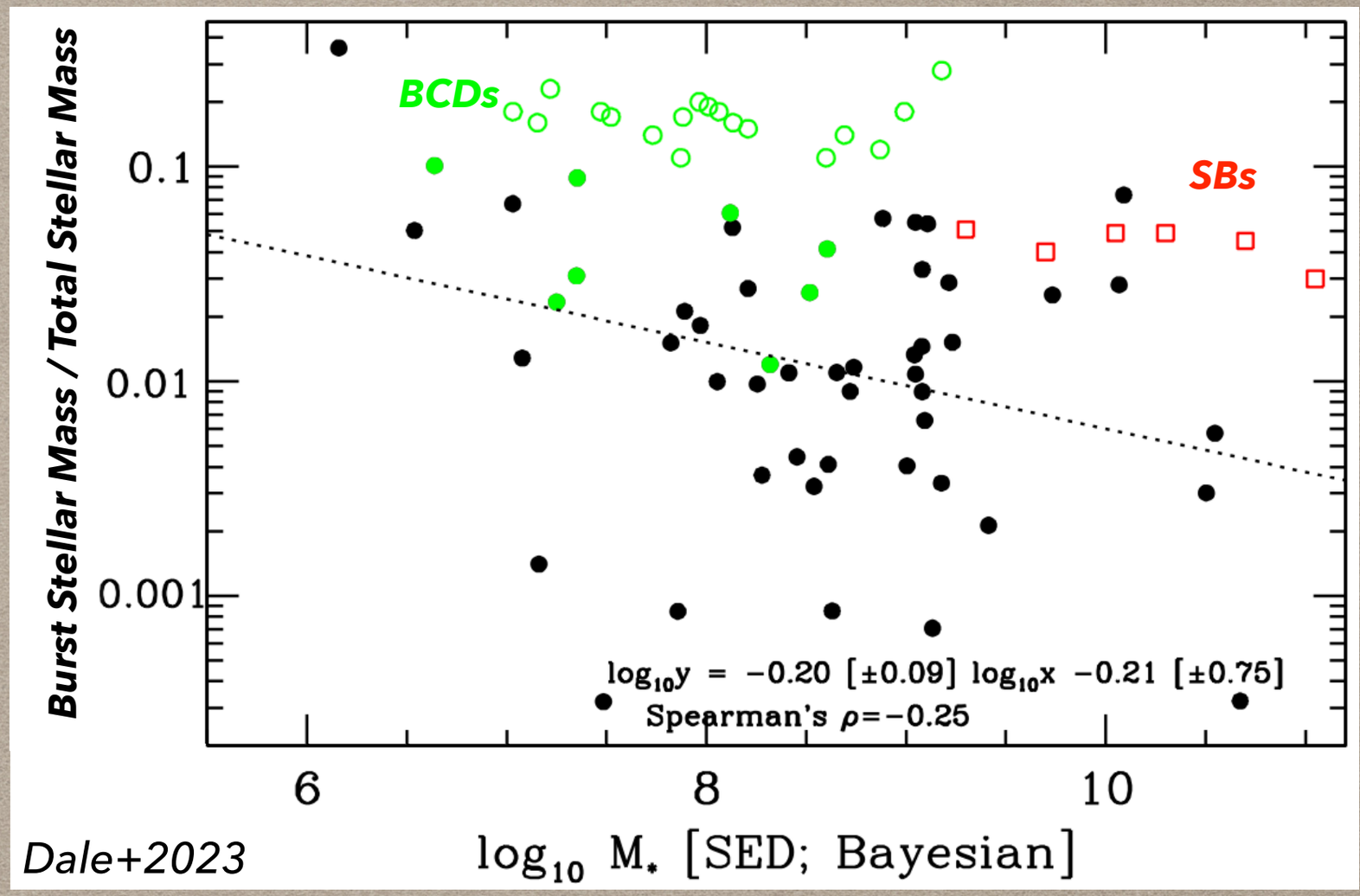
"1parameter"

multi-parameter



Dale+2023

Local Volume Legacy
258 galaxies
75% dwarfs ($M_* < 10^9 M_\odot$)

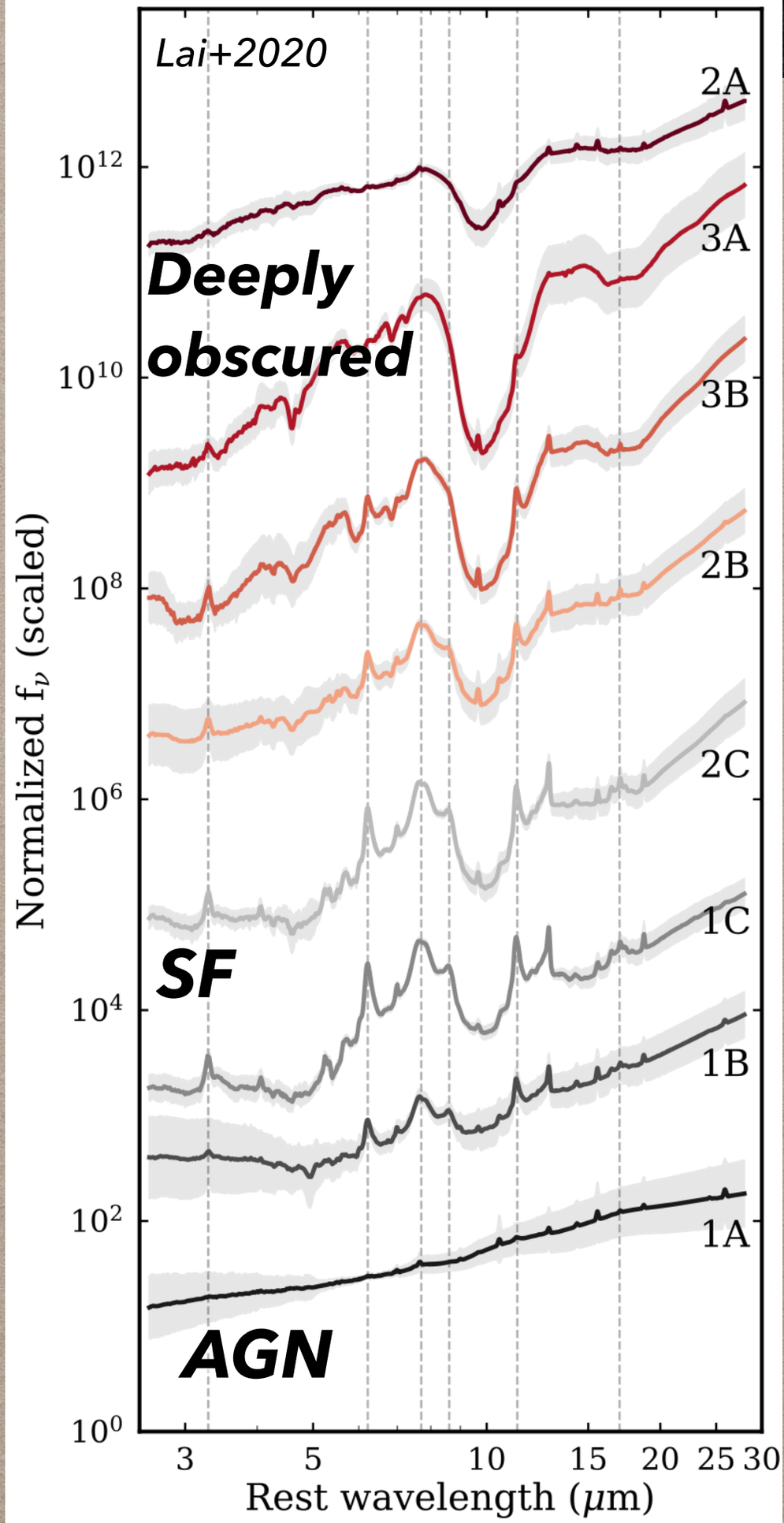


Stellar mass from a recent burst proportionally more important for dwarf galaxies

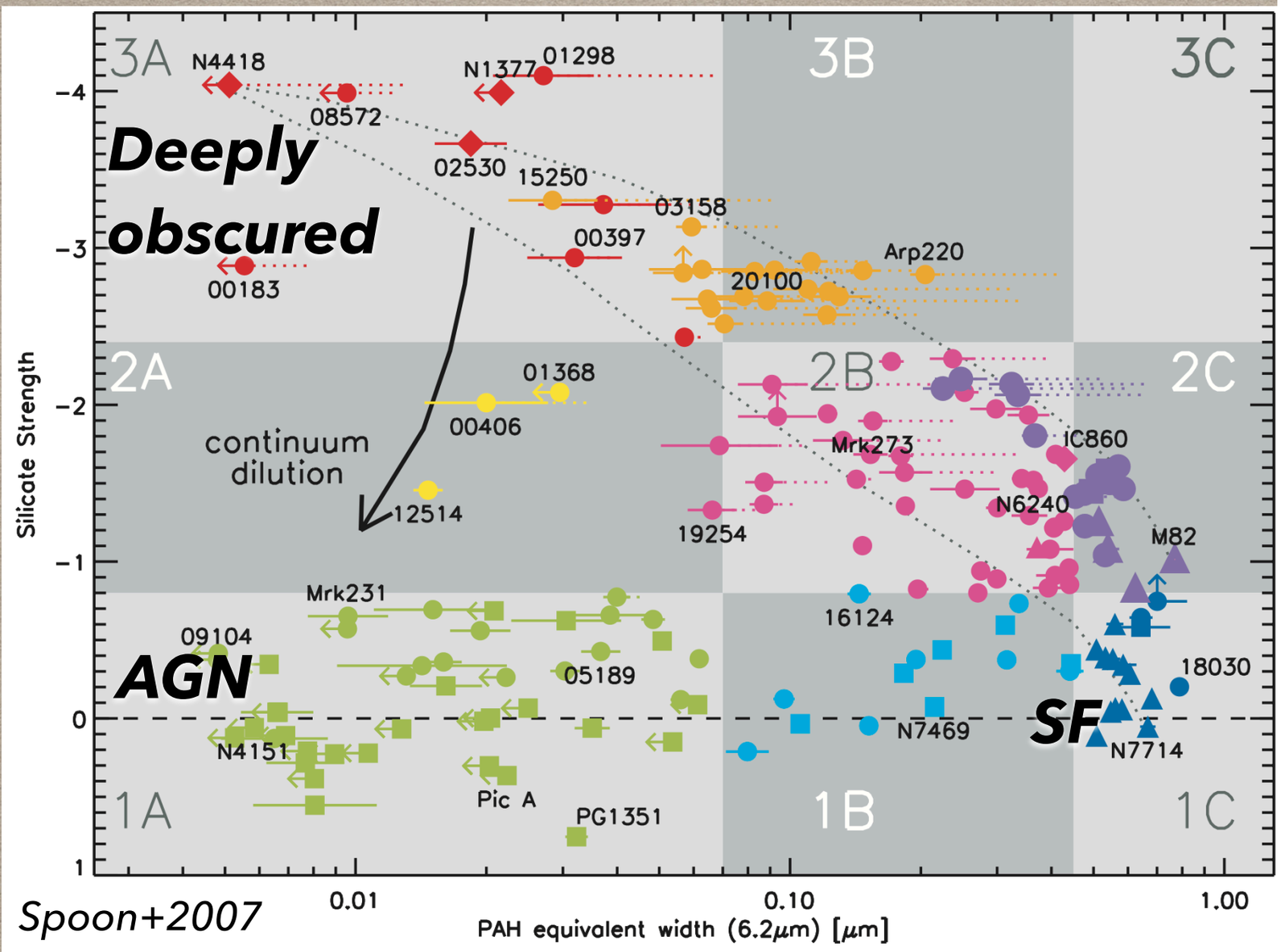
(but not at the same levels as for starbursts and BCDs)

PAHs (or lack thereof) used to trace/probe:

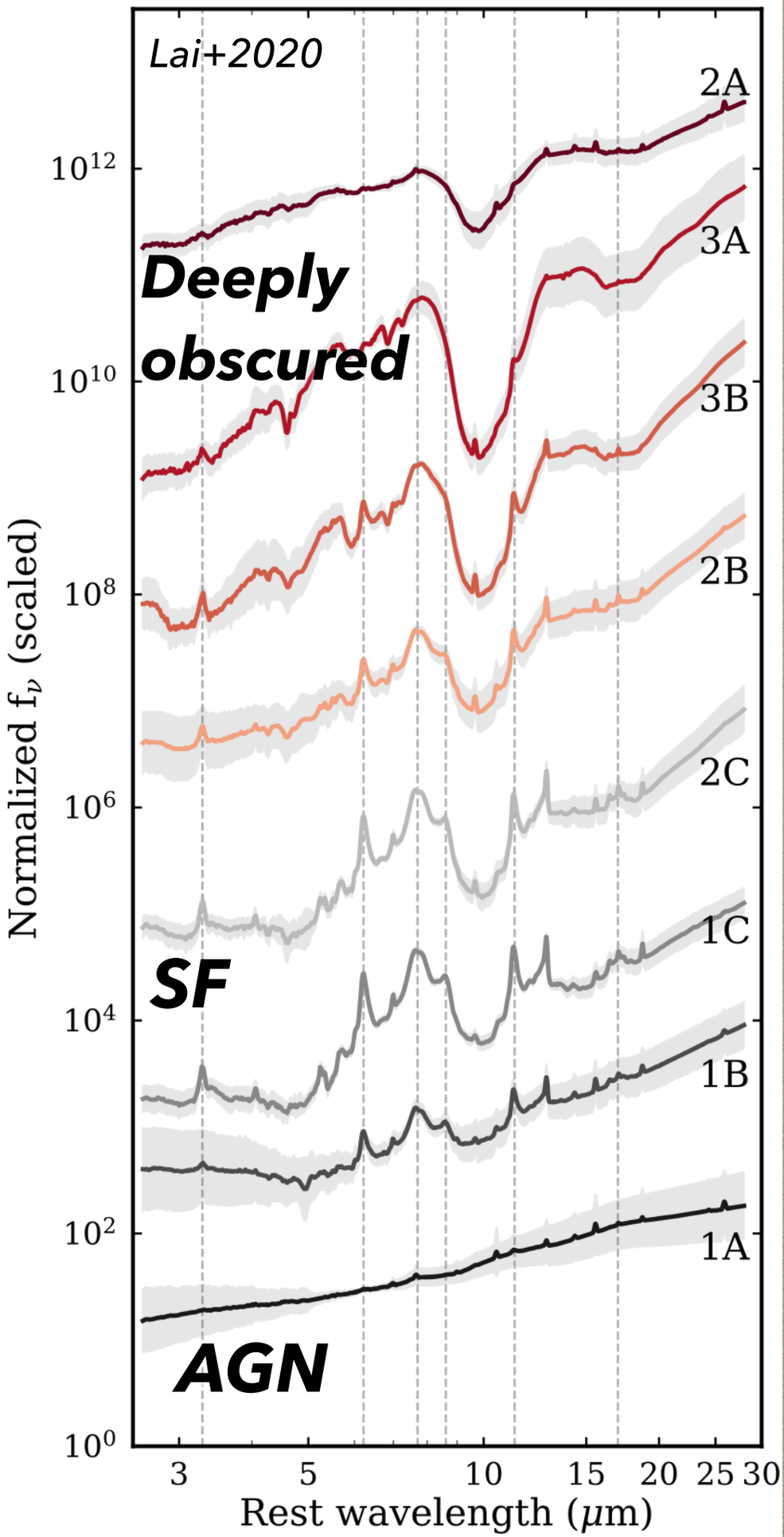
SF
SFR
PDRs
MCs
CO-dark gas
ISRF
SF vs AGN
redshift
…



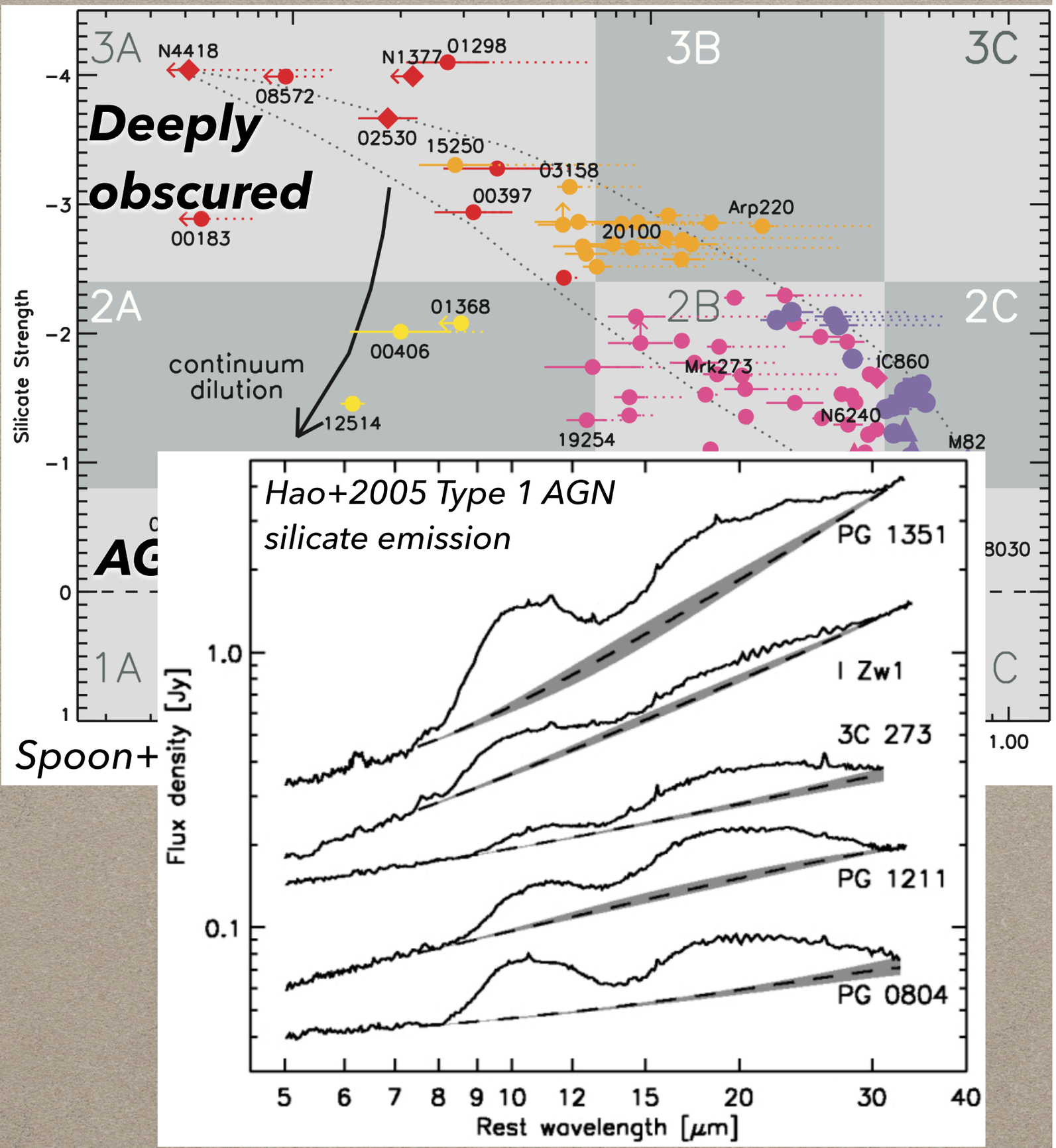
Mid-Infrared Spectra

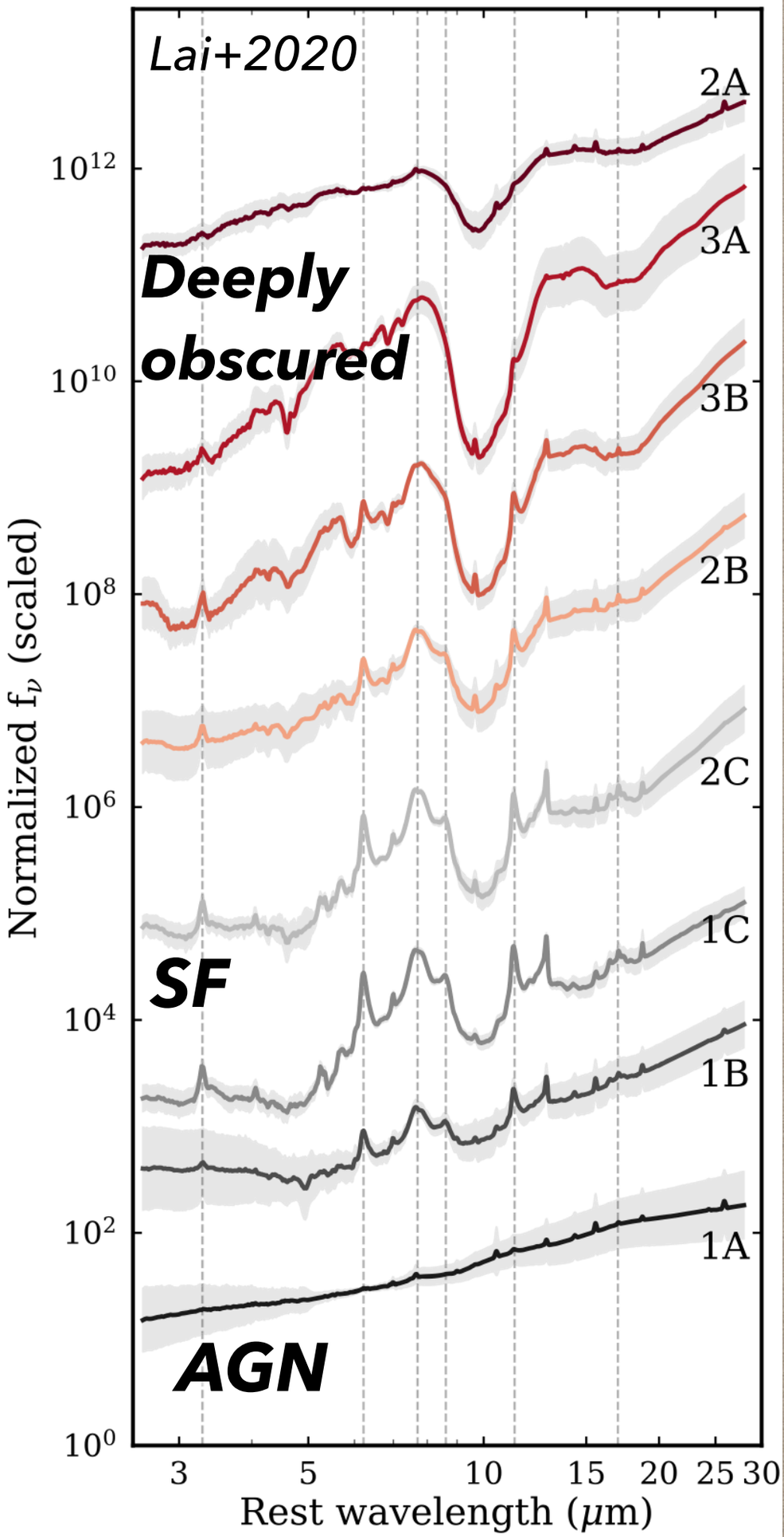


The two branches likely reflect clumpy vs non-clumpy dust geometries



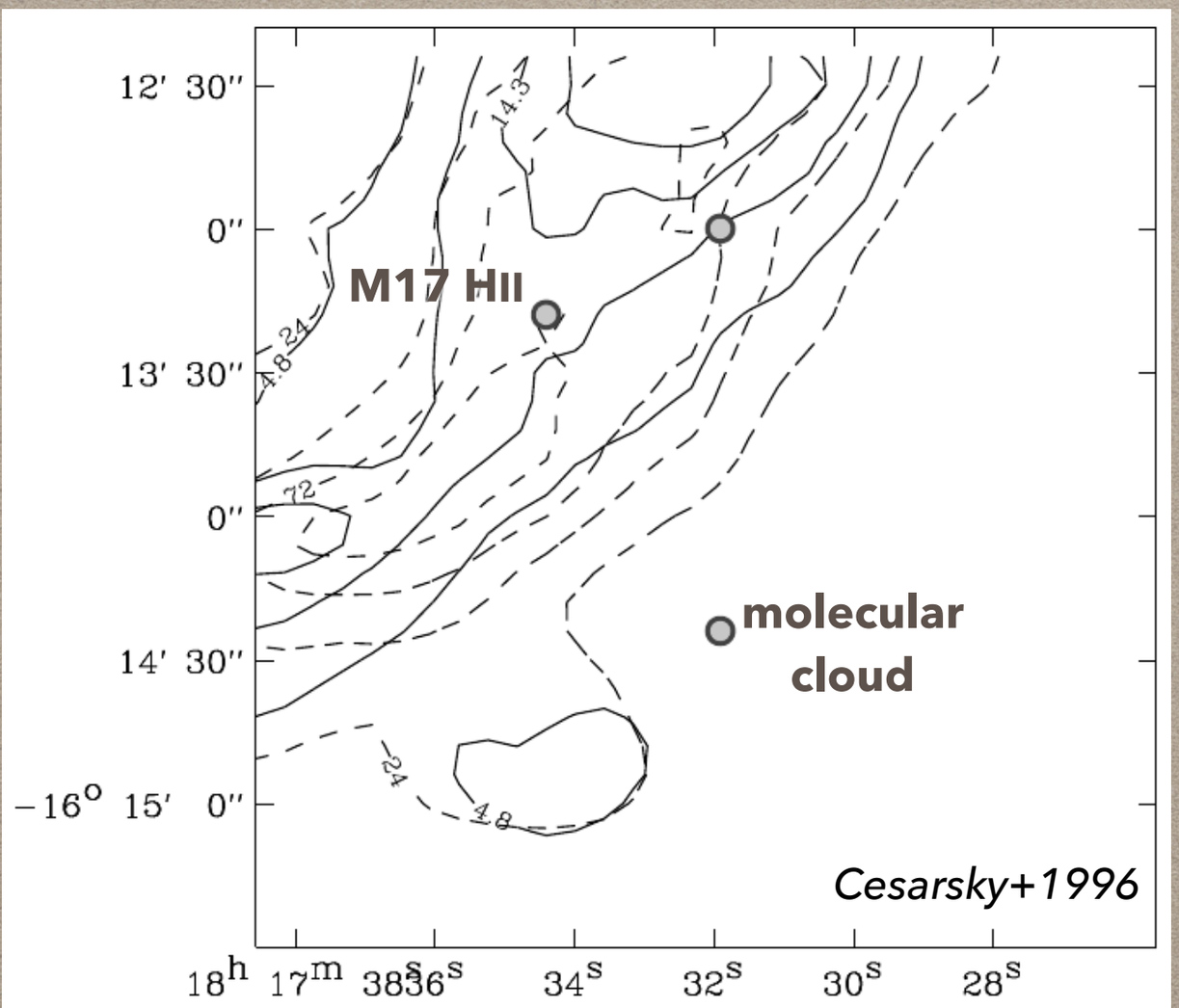
Mid-Infrared Spectra

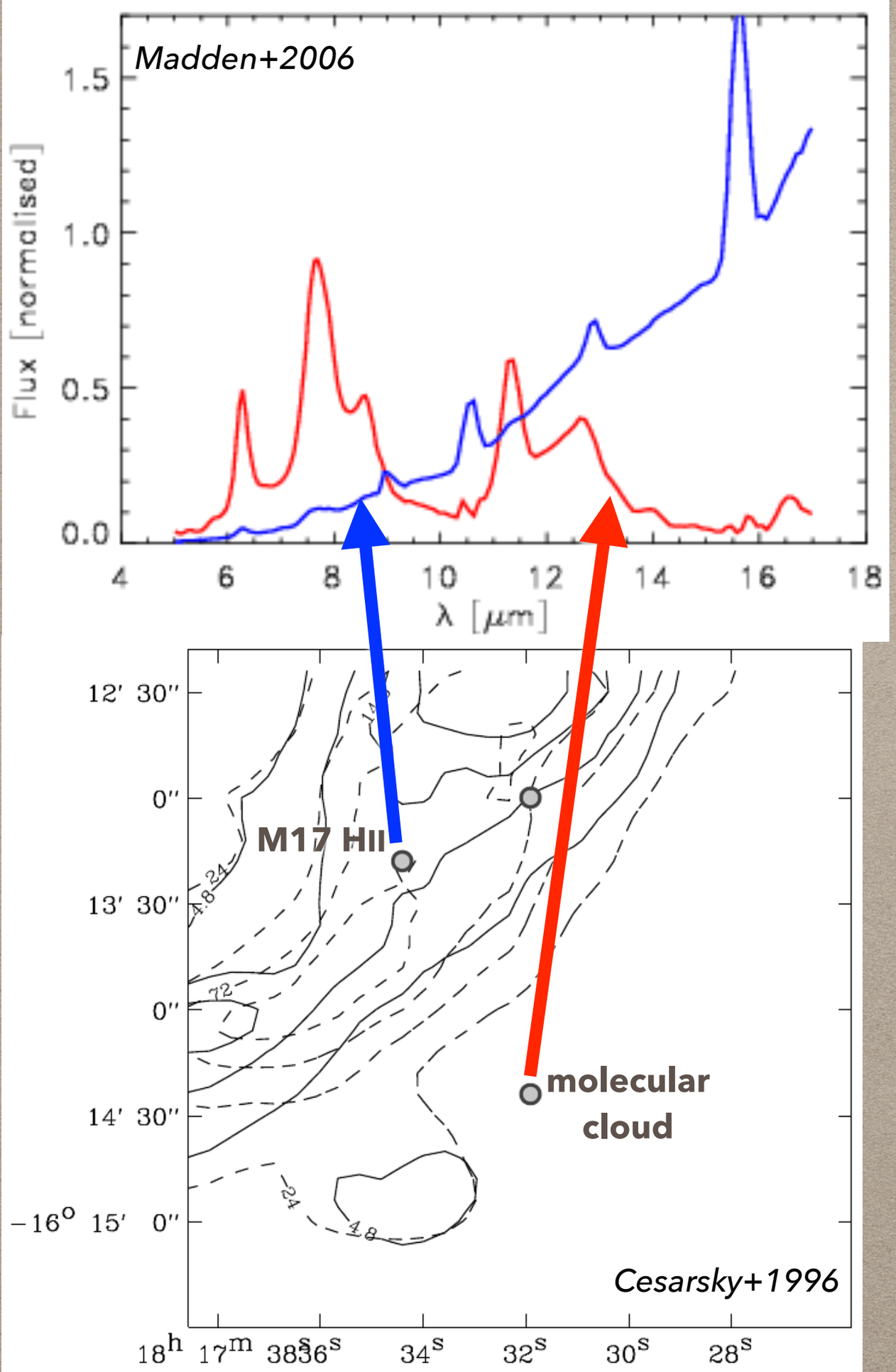




ISO view of M17

-HII region devoid of PAH emission
-molecular cloud rich in PAH





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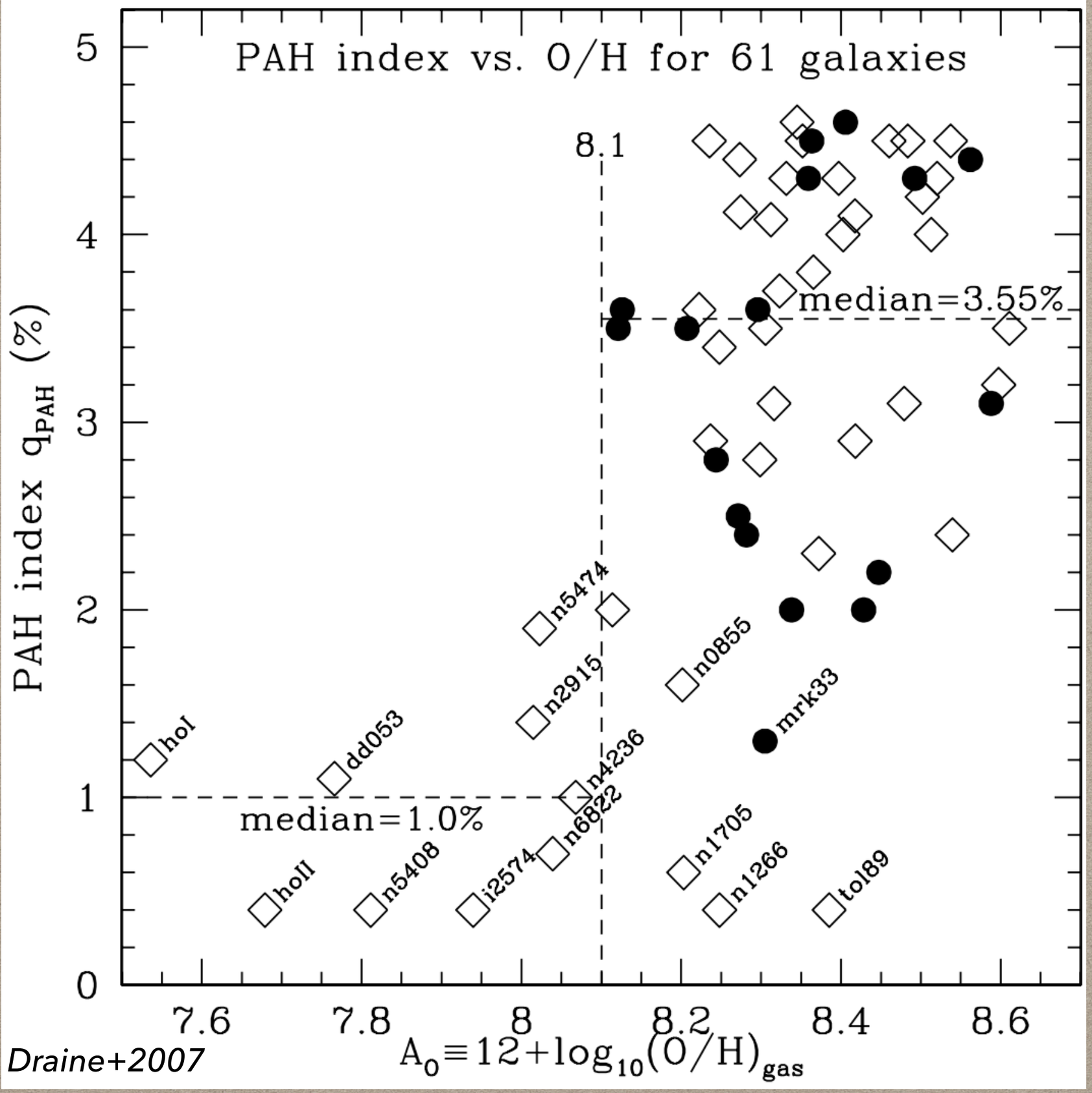
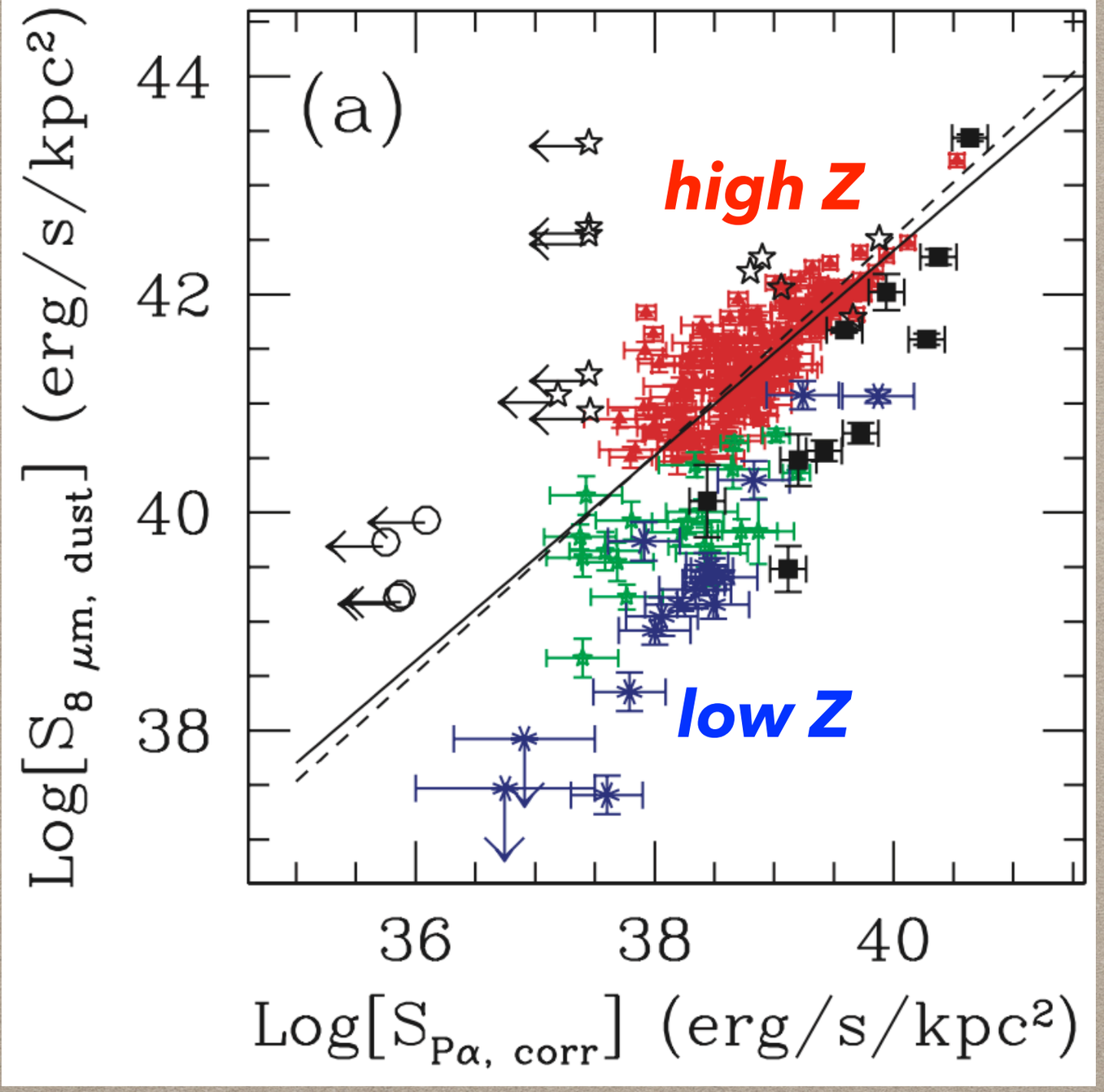


Draine+2007

Kennicutt+2003

Using PAHs as an all-purpose tool has its challenges

PAH dust mass fraction is low for low Z



Calzetti+2007

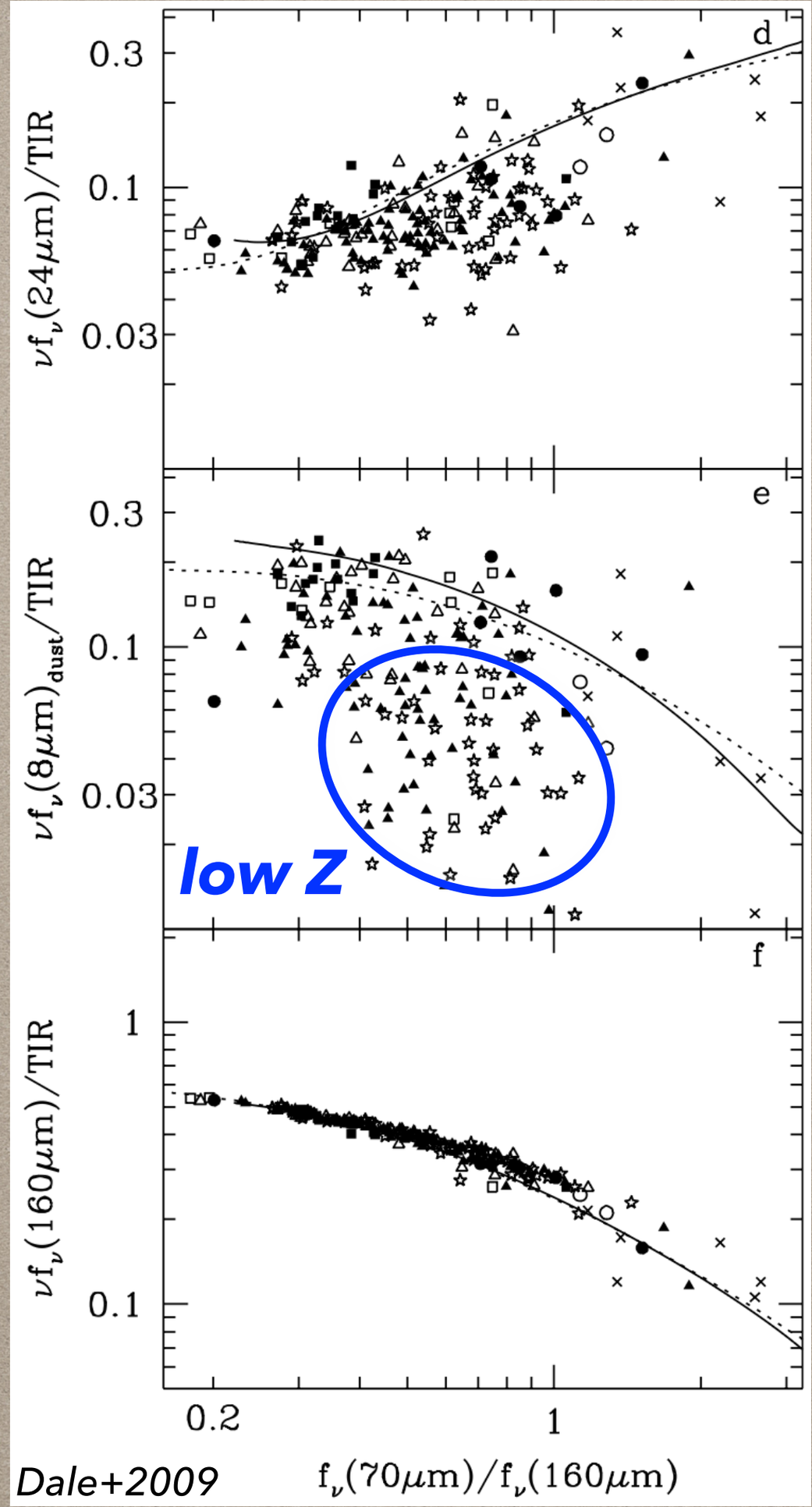
Kennicutt+2003

Using PAHs as an all-purpose tool has its challenges

PAHs weak at low Z and in hard radiation fields

Local Volume Legacy

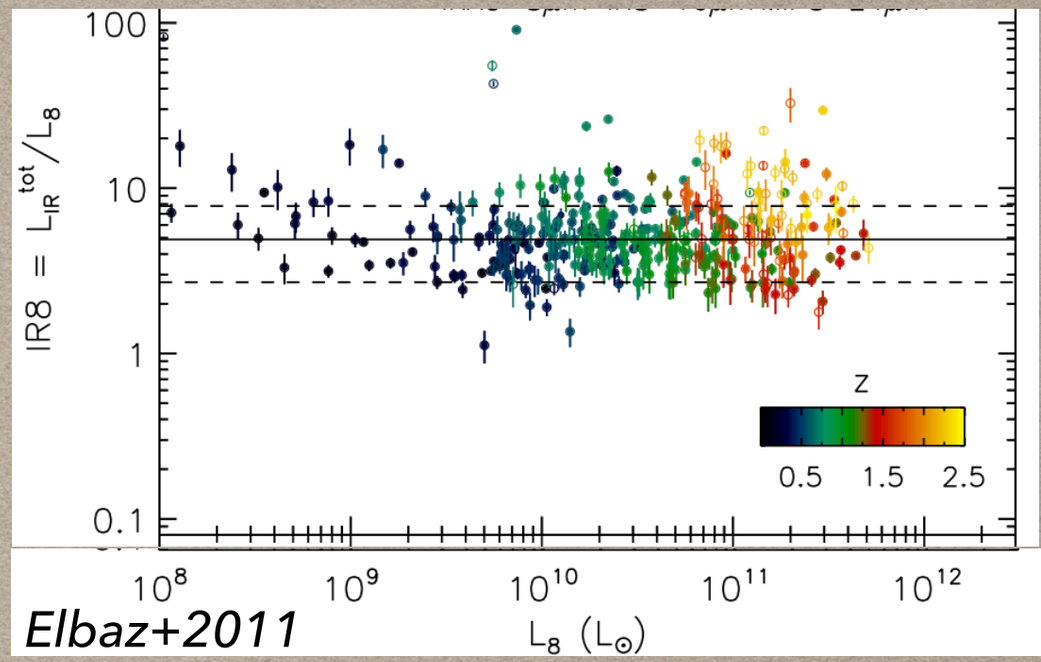
258 galaxies, 75% dwarfs ($M_* < 10^9$)



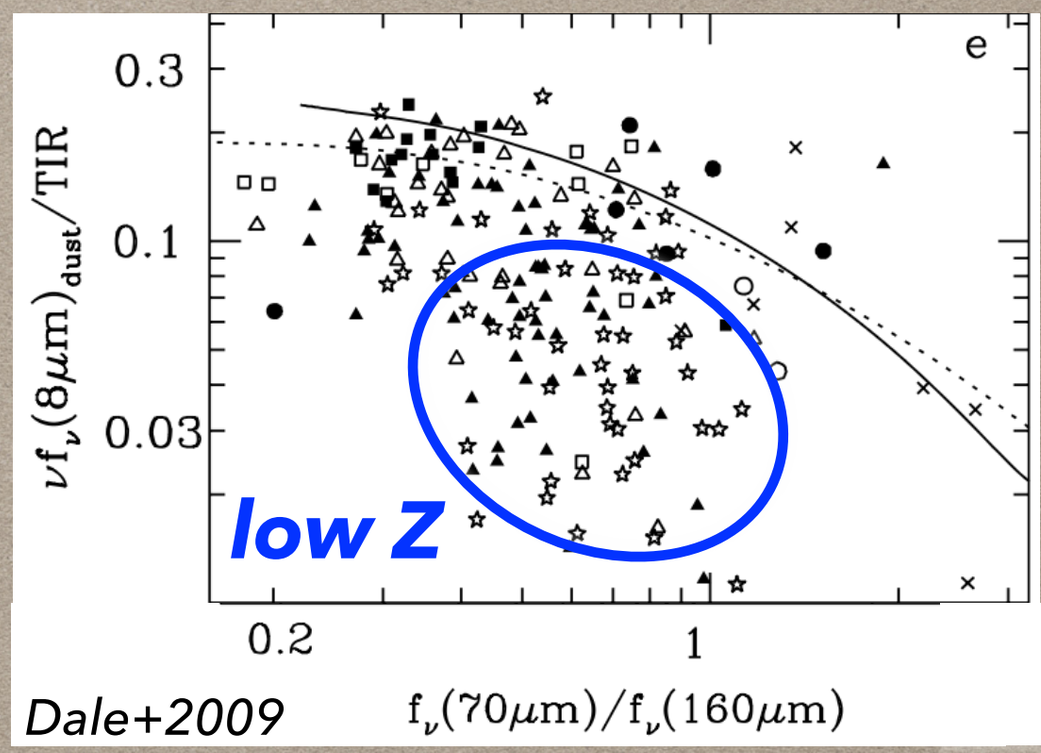
Dale+2009

Local Volume Legacy
258 galaxies, 75% dwarfs ($M_* < 10^9$)

IR Main Sequence applicable to 'normal' SFing disk galaxies, e.g., Elbaz+2011



Elbaz+2011



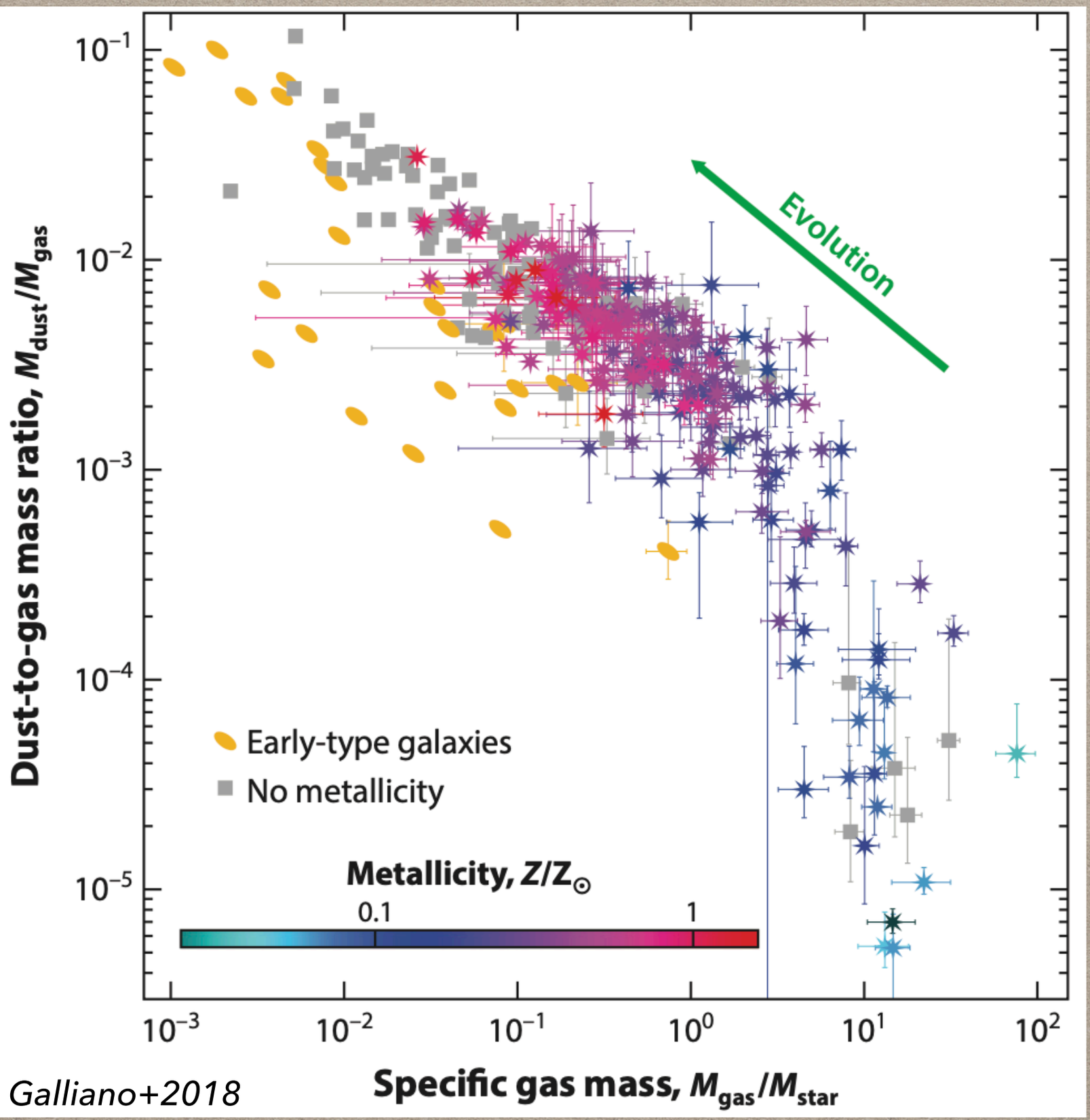
Dale+2009

OUTLINE

- *'Normal' galaxies*
- *Spectra: stars & dust*
- ***Scaling Relations***
- *Star formation & the ISM*
- *Open questions & future directions*

Hsiao-Wen

Normal Galaxy Scaling Relations

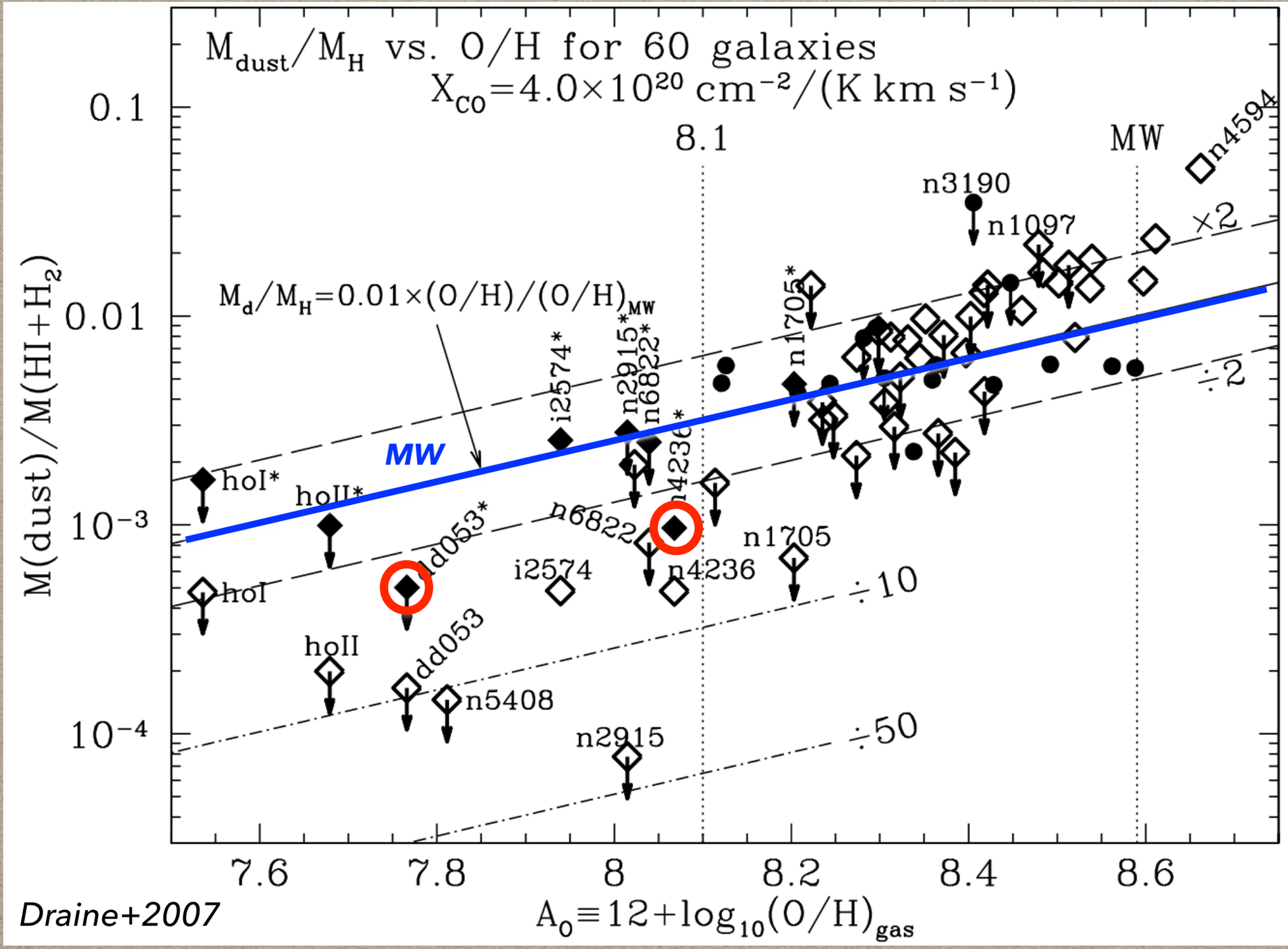


Galliano+2018

Stars form and deplete the gas while enriching the ISM with dust

Early types below late types

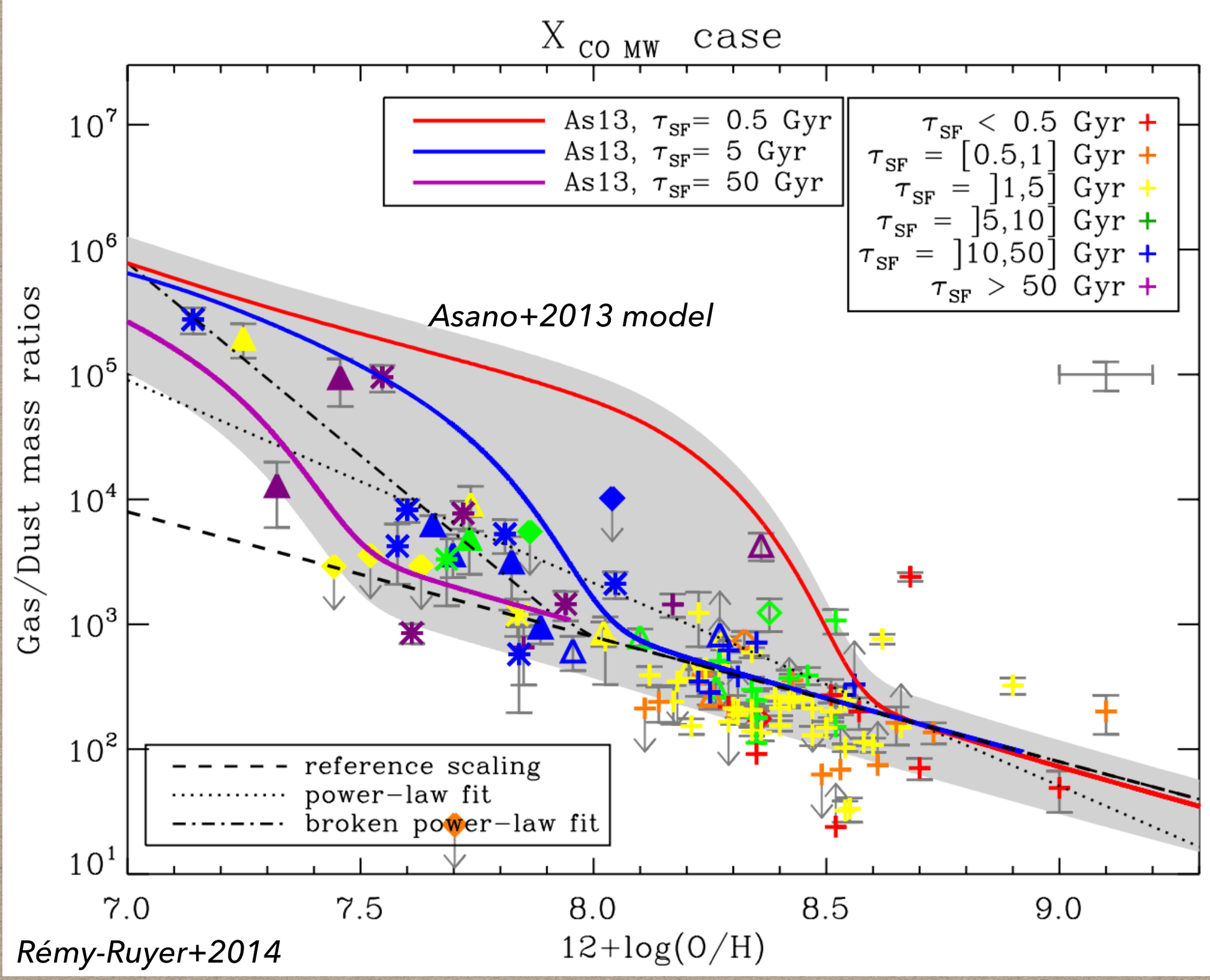
Dust/gas vs Z



Draine+2007

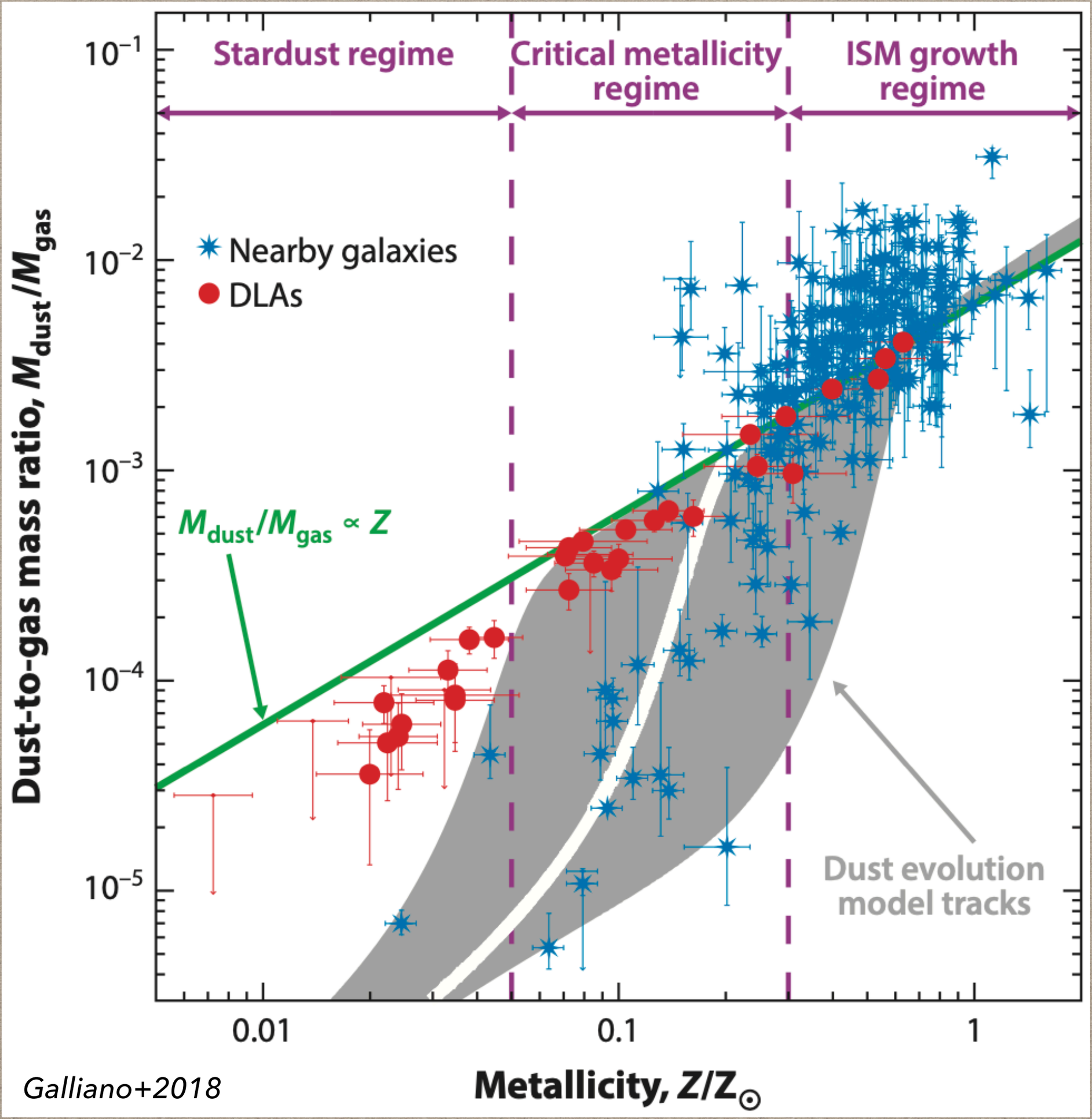
- ***Follow MW extrapolation***
- ***Reasonable when gas and dust spatially overlap***
- ***>50% Fe,Mg,Si in solid grains***

Dust/gas vs Z



- ***Harder ISRF for low Z more easily processes dust***
- ***Smaller dwarf galaxy volume –> SNe larger impact***

Dust/gas vs Z



Galliano+2018

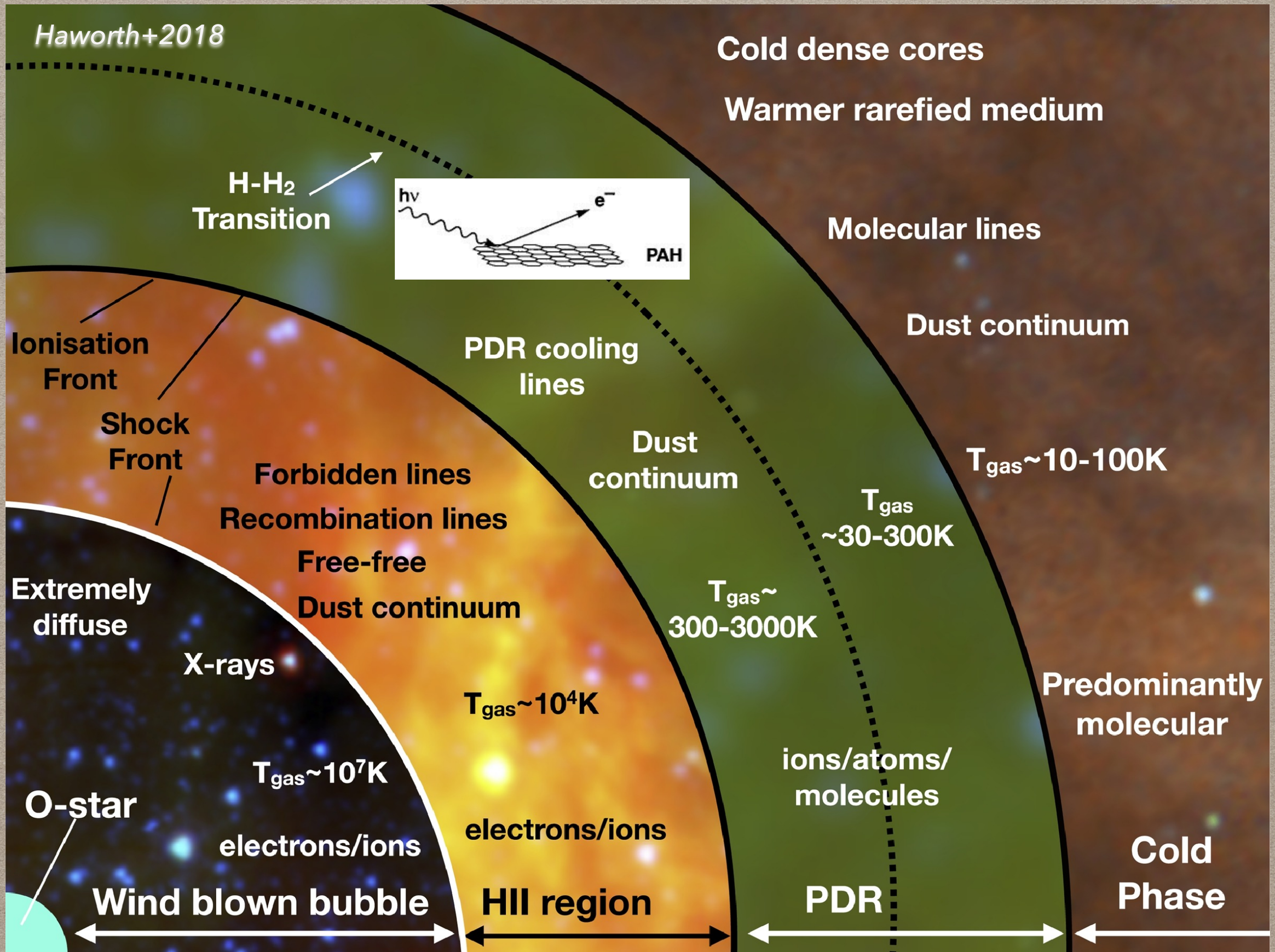
Models balance production and destruction by SNe plus ISM grain growth

DLAs more closely follow extrapolation of metal-rich galaxies (and not the model)

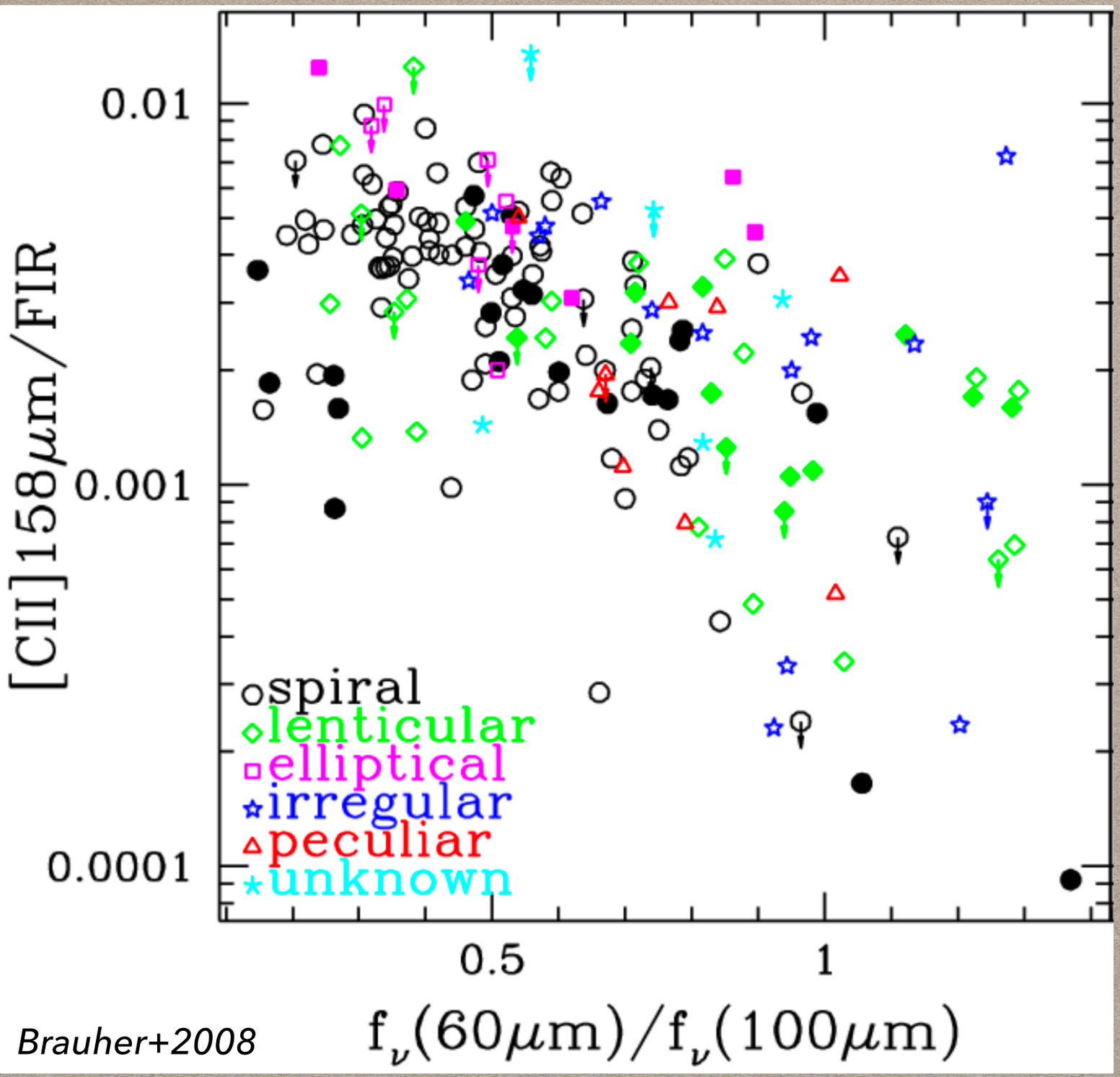
High SN dust condensation efficiency coupled with weak ISM grain growth rate

ISM / PDR structure

See Benjamin Godard's slides

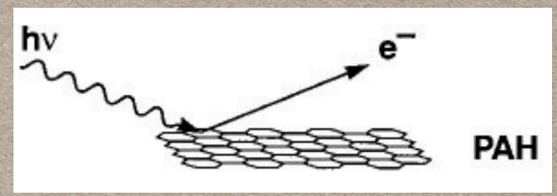


The '[CII] Deficit' as a probe of the ISM



Brauher+2008

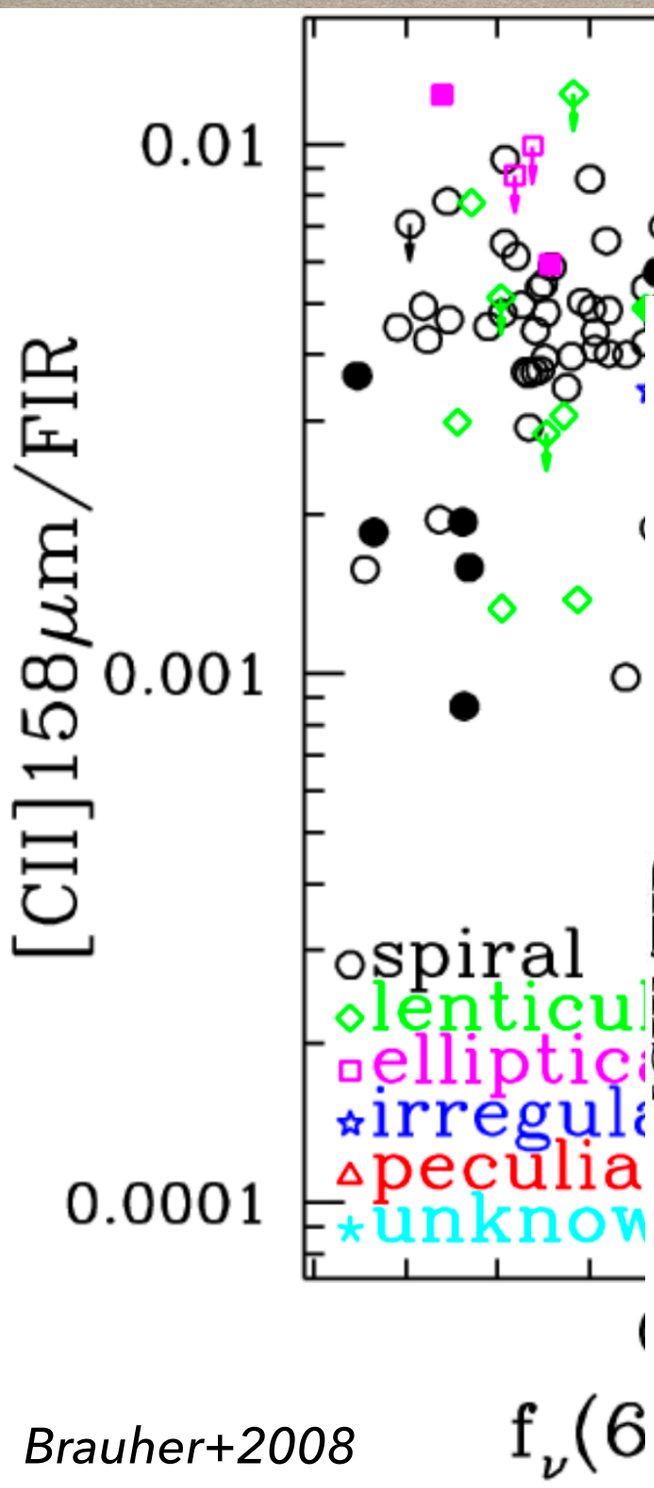
Heating of neutral ISM critically reliant on photo-ejected e-s from PAHs



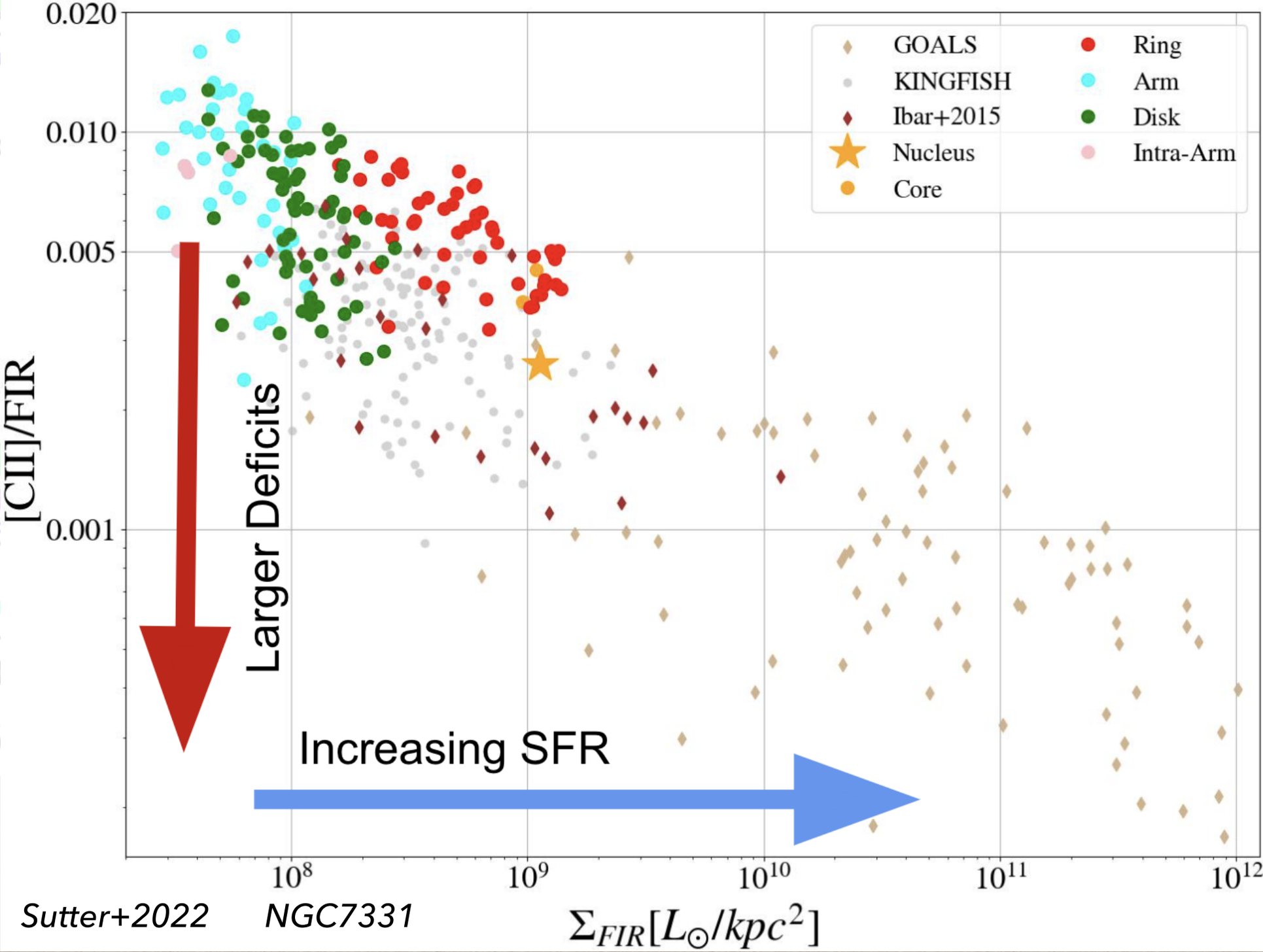
Initial results encompassed entire galaxies (ISO)

The '[CII] Deficit' as a probe of the ISM

Resolved studies SOFIA+Herschel

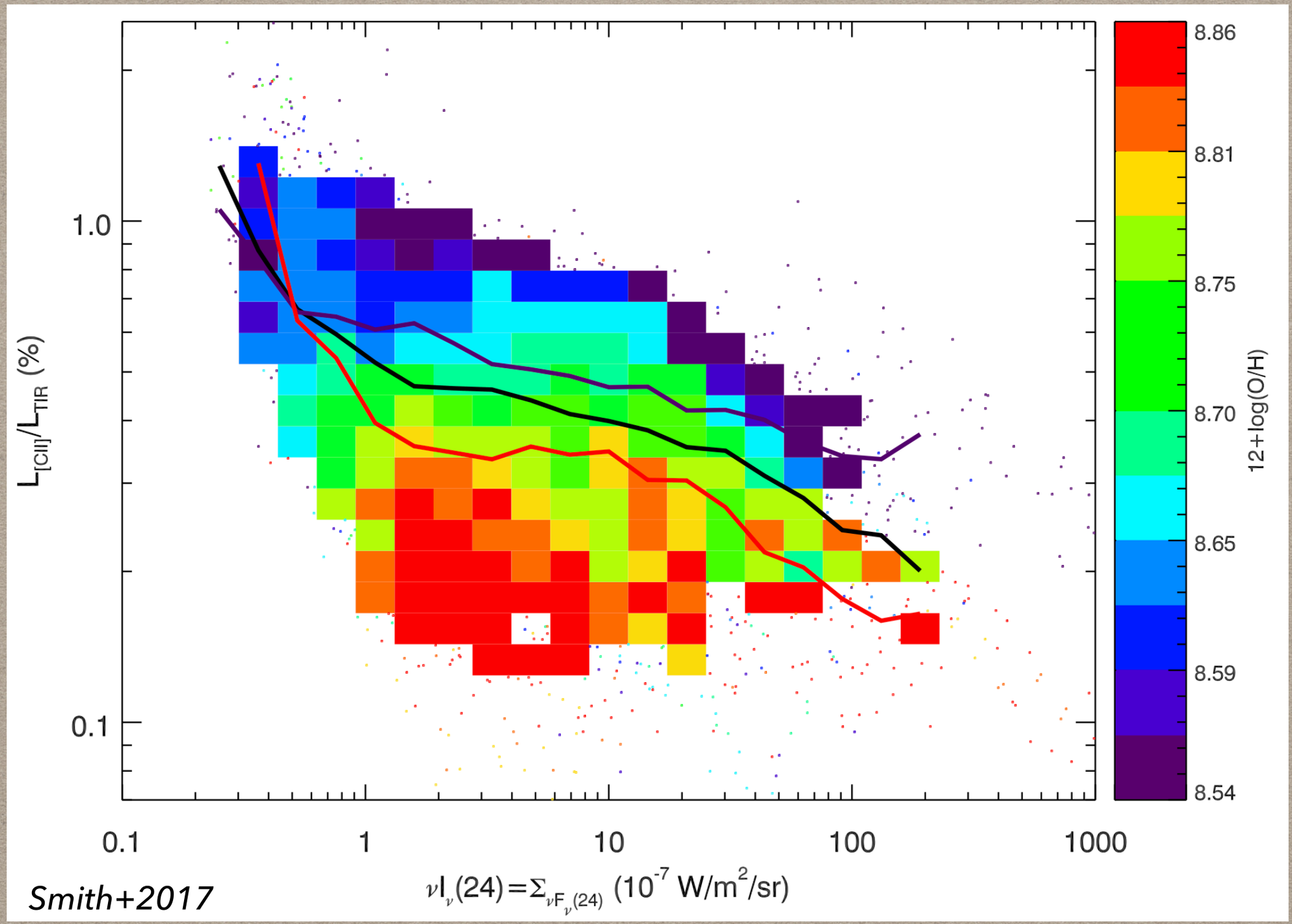


Brauher+2008



Sutter+2022 NGC7331

The '[CII] Deficit' as a probe of the ISM



Herschel / KINGFISH

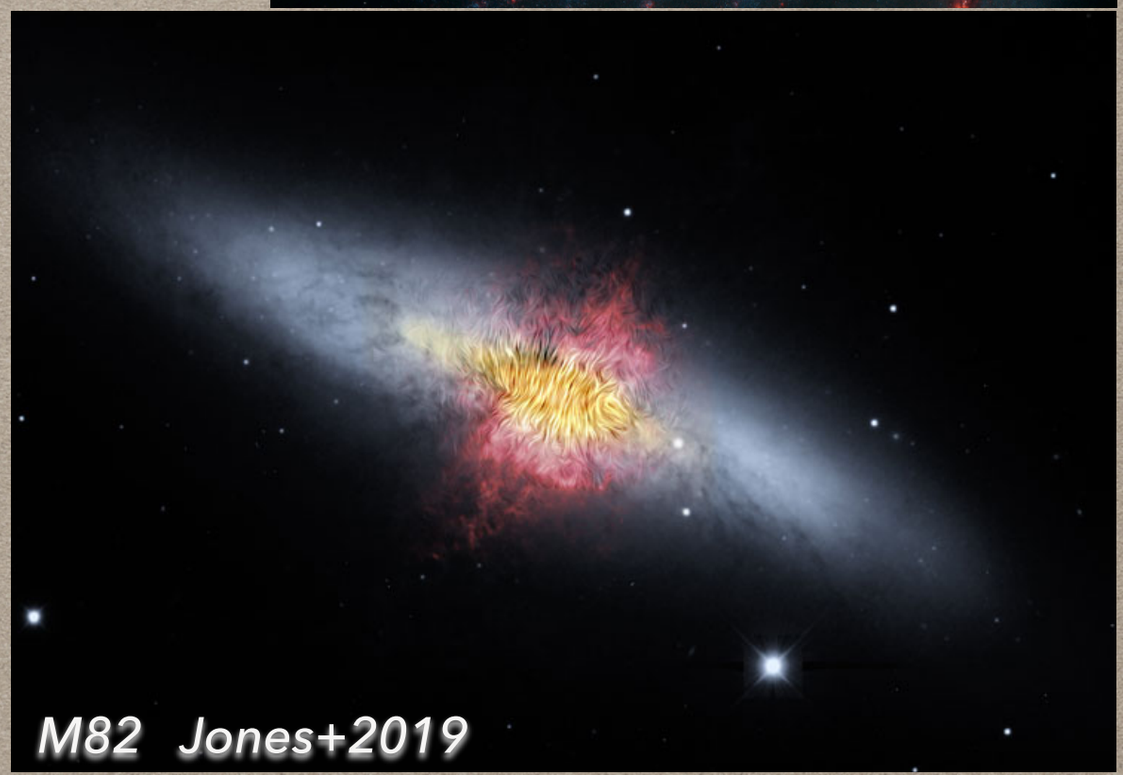
Larger C+/TIR for lower metallicity Z

–> harder radiation increases fraction of energy going into photo-ejected electrons, thereby increasing C+/TIR?

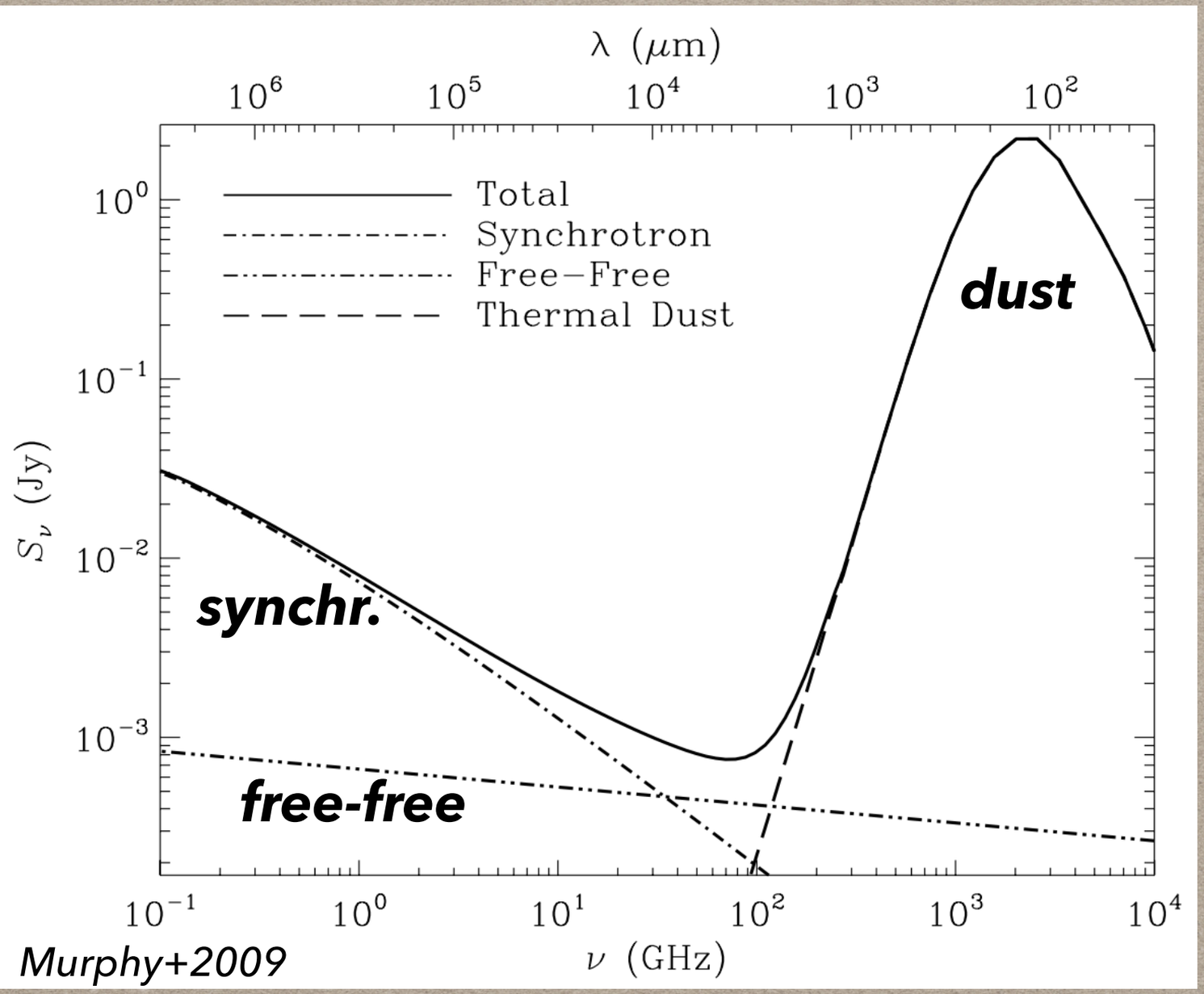
B fields critical to SF & CR physics, but maps are scarce for nearby normal galaxies

SALSA

Survey of Extragalactic Magnetism with SOFIA

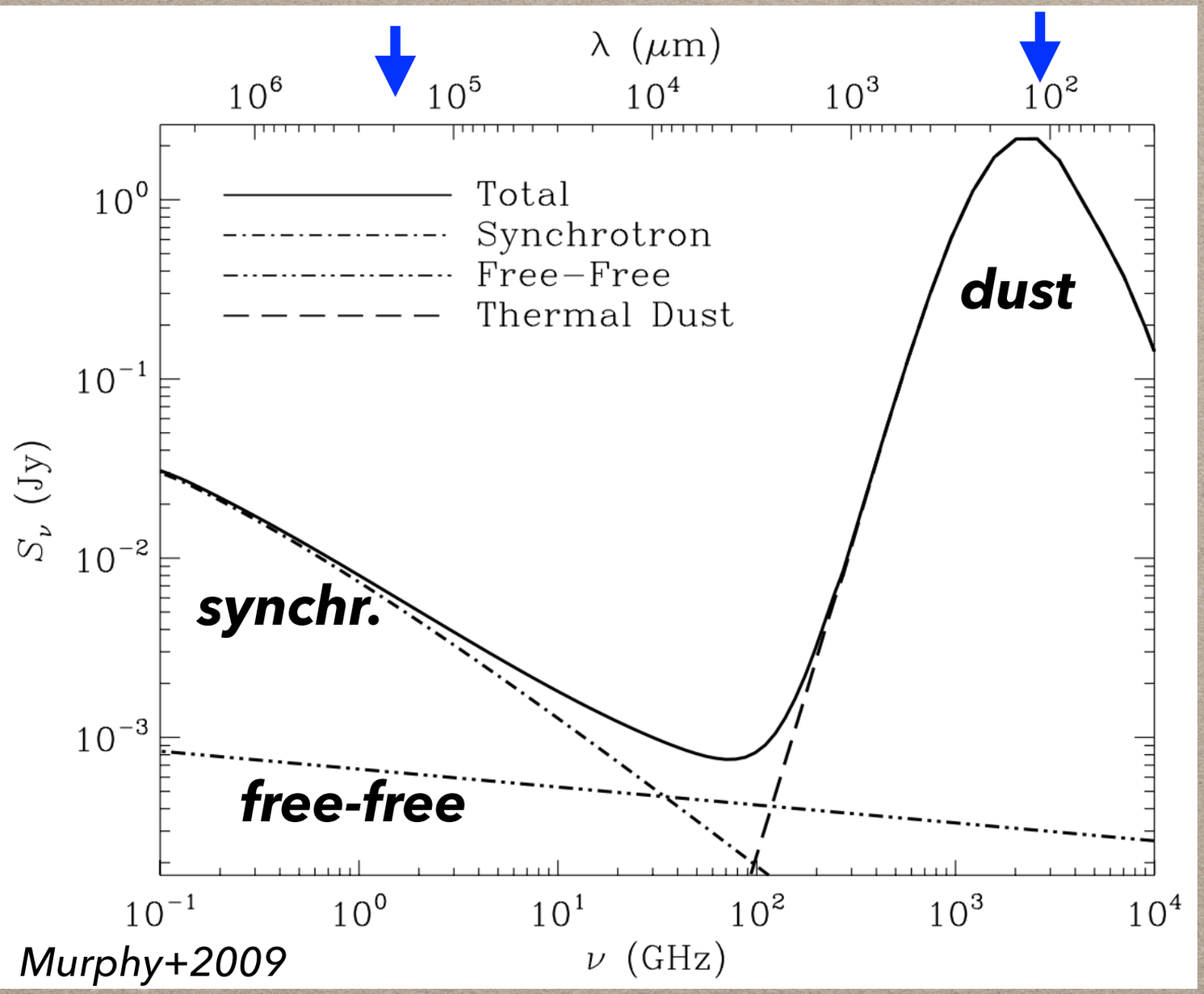


Normal Galaxy Scaling Relations



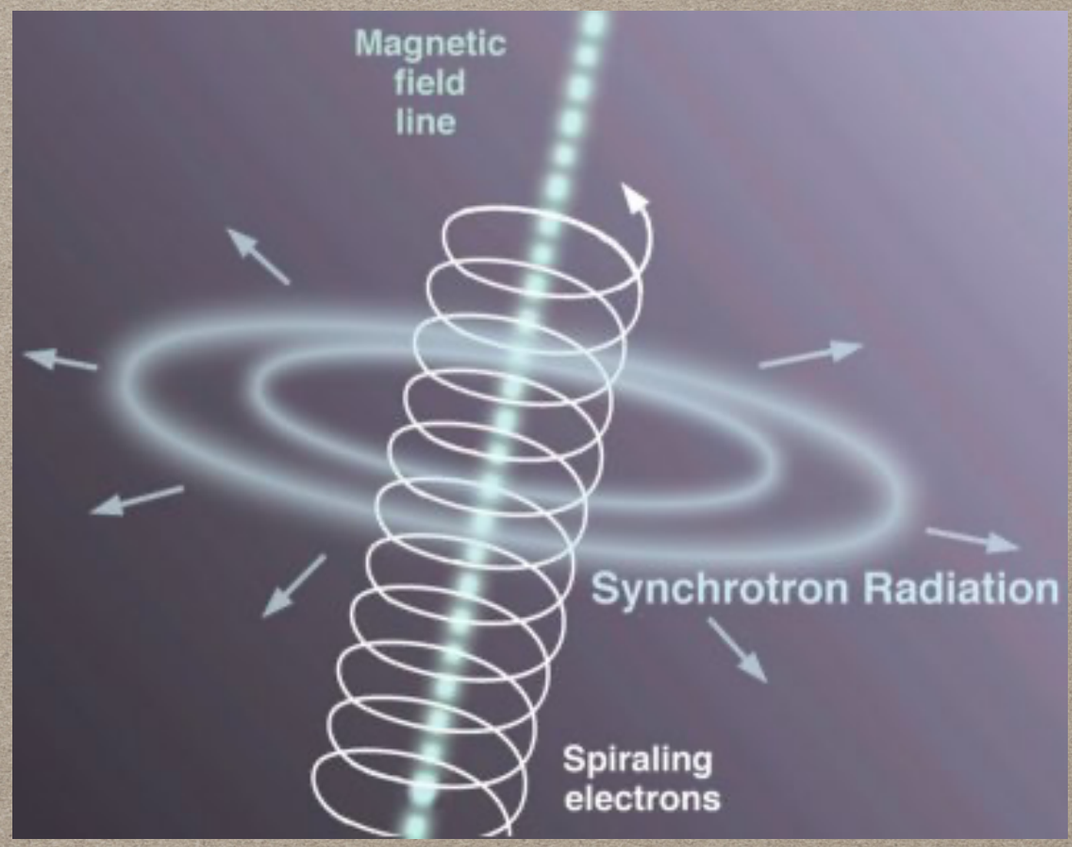
Murphy+2009

Normal Galaxy Scaling Relations



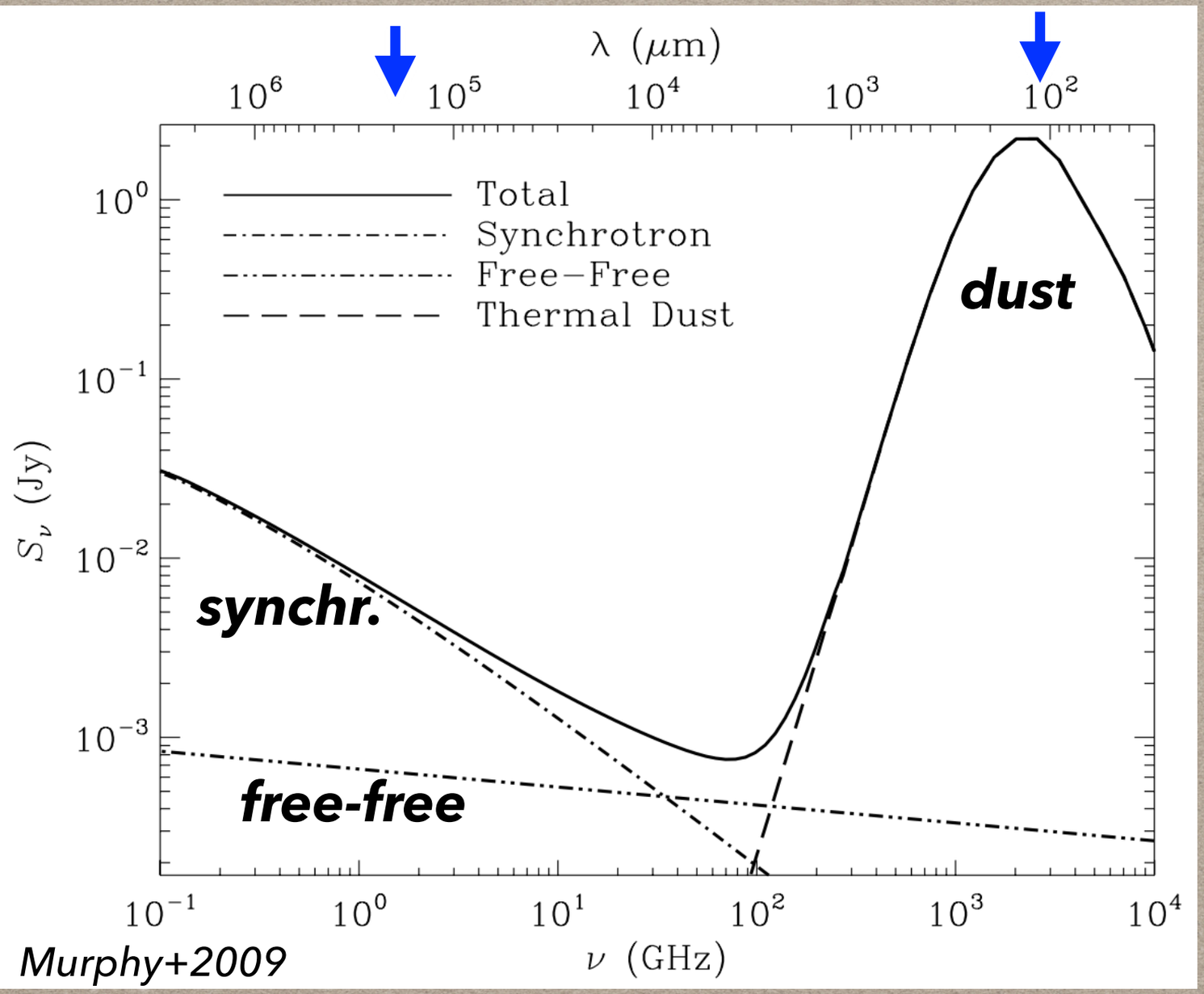
Murphy+2009

The far-infrared traces SF; radio continuum traces synchrotron radiation from SN-ejected e⁻s spiraling around B fields ('non-thermal')



Jon Lomberg / Gemini Observatory

Normal Galaxy Scaling Relations



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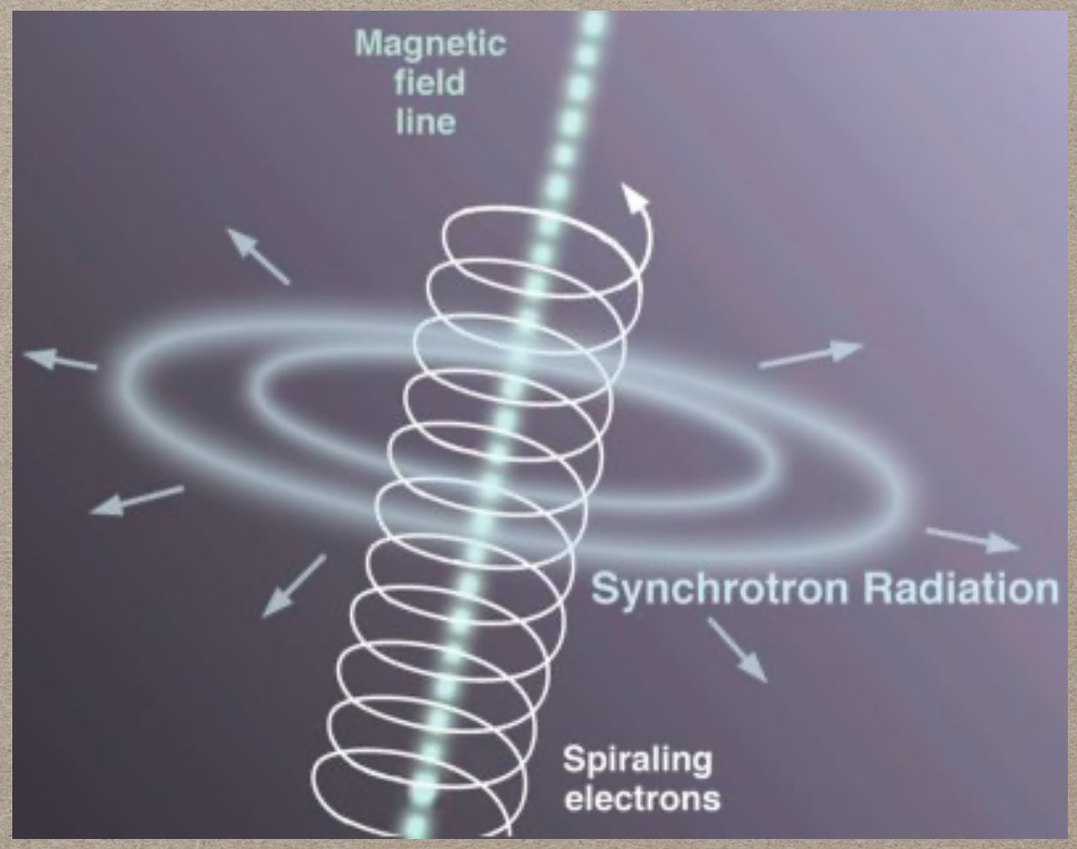
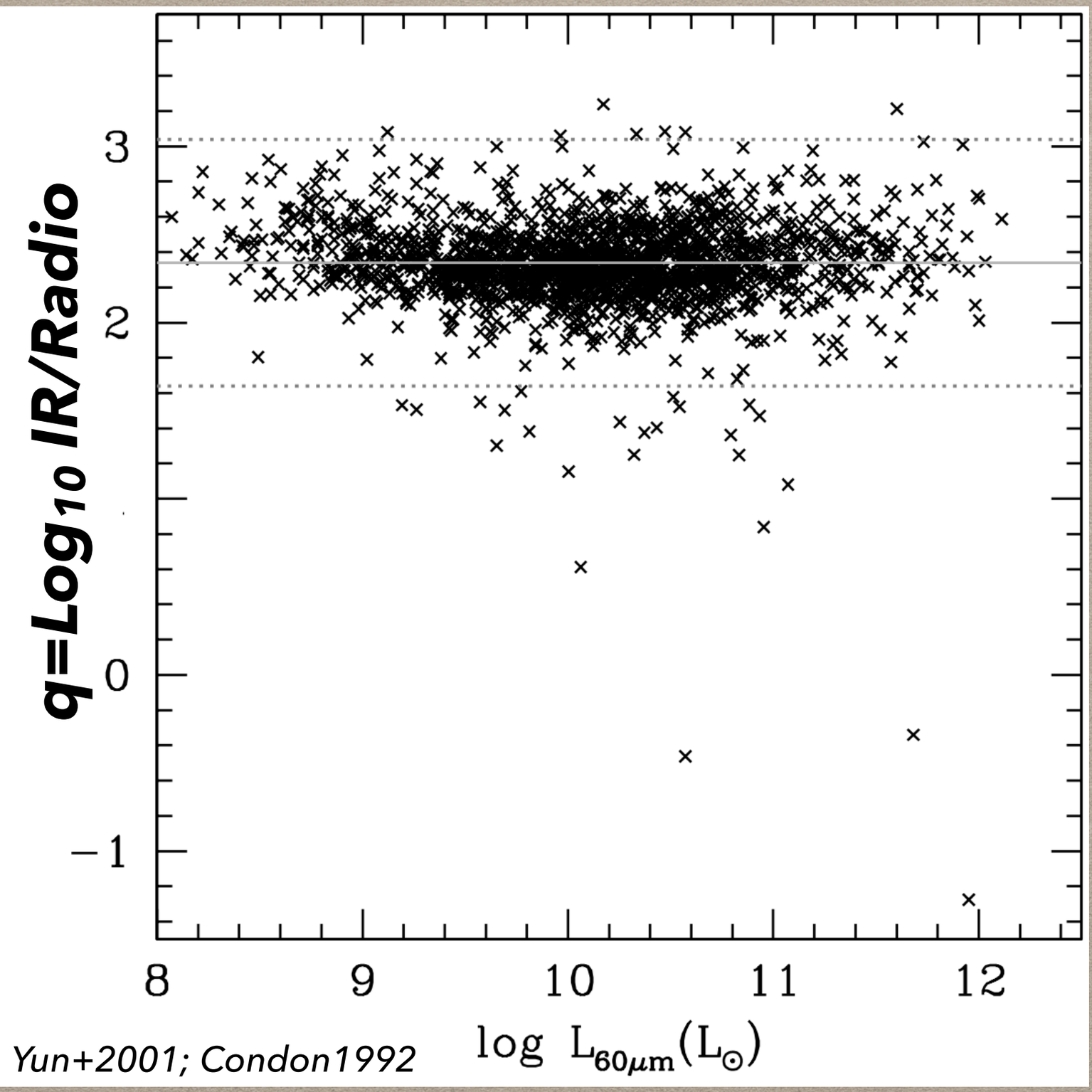


Jon Lomberg / Gemini Observatory

Mean free ISM path for UV photons is ~100pc vs 1-2 kpc for cosmic ray e⁻ diffusion length

Normal Galaxy Scaling Relations



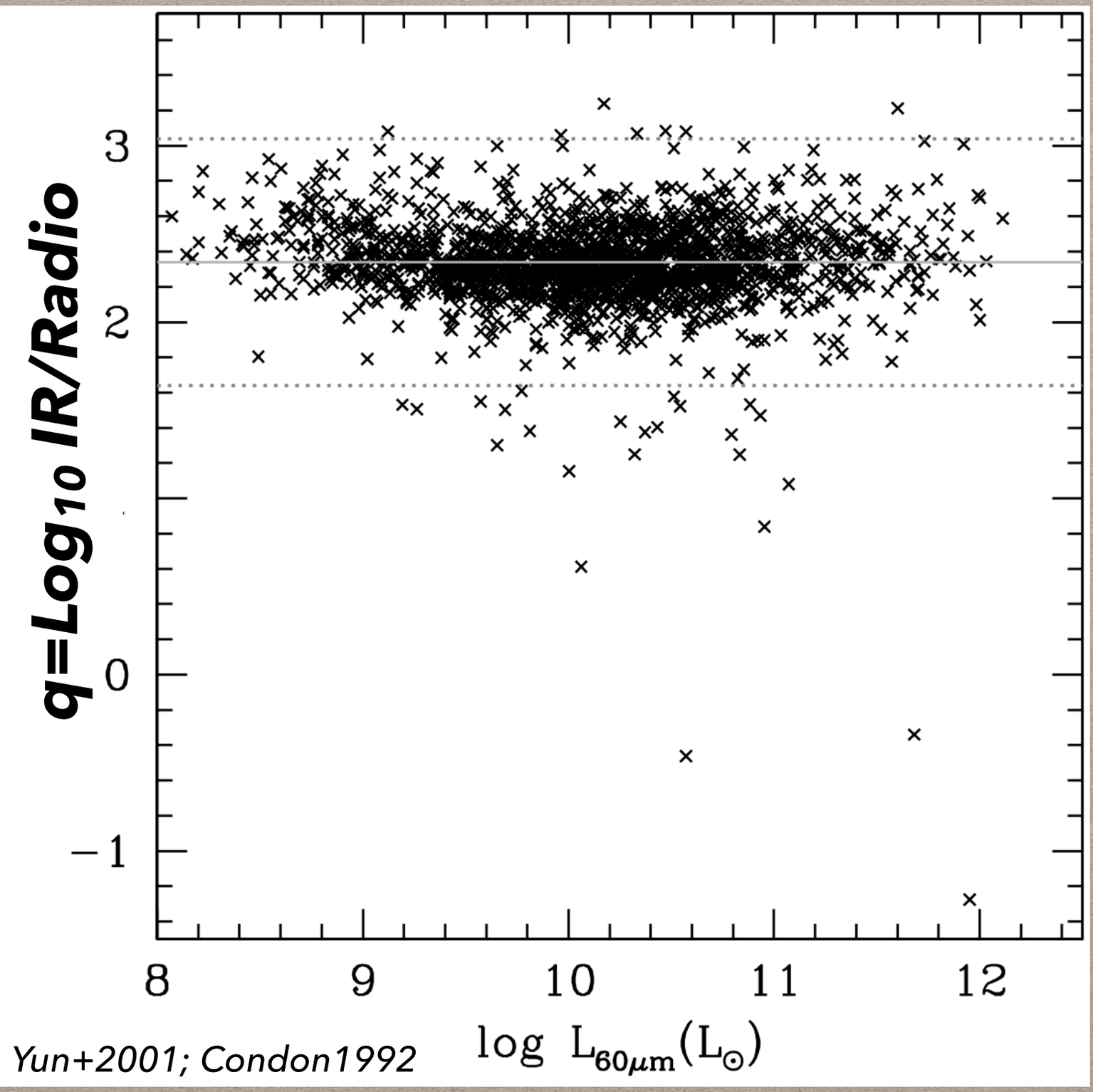
Yun+2001; Condon1992

$q = \log_{10}$ IR/Radio

The infrared-to-radio correlation is one of the tightest * known for normal galaxies

*** How tight is it?**

Normal Galaxy Scaling Relations



Yun+2001; Condon1992

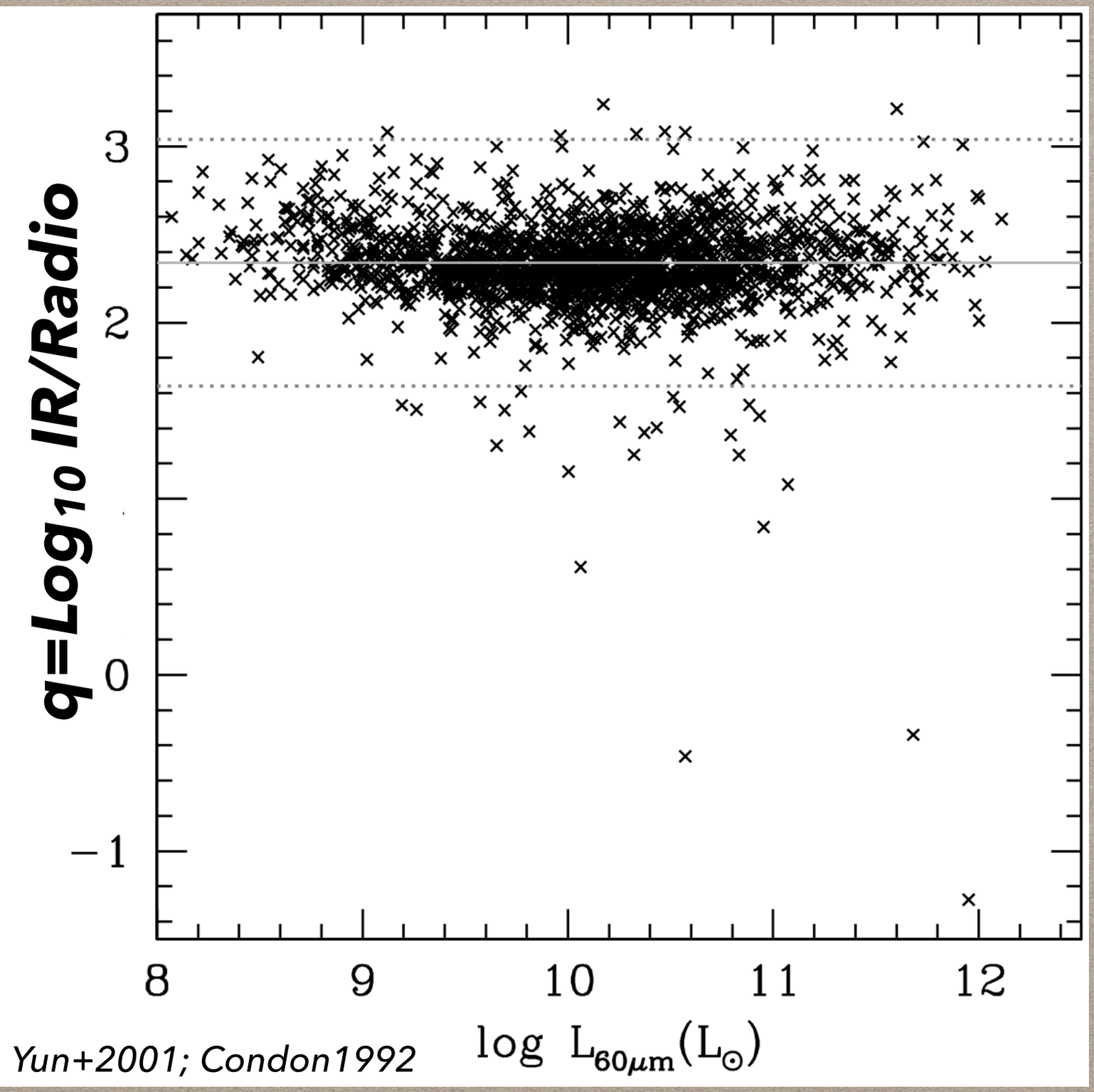
$q = \log_{10}$ IR/Radio

The infrared-to-radio correlation is one of the tightest * known for normal galaxies

* **How tight is it?**

σ~0.3dex or in linear terms a factor of ~2x

Normal Galaxy Scaling Relations



Yun+2001; Condon1992

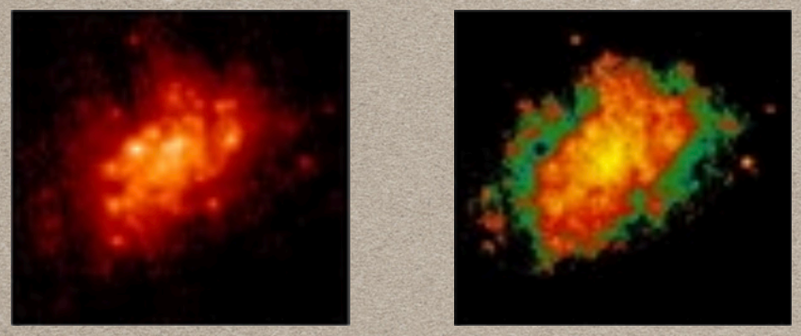
$q = \log_{10}$ IR/Radio

The infrared-to-radio correlation is one of the tightest known for normal galaxies

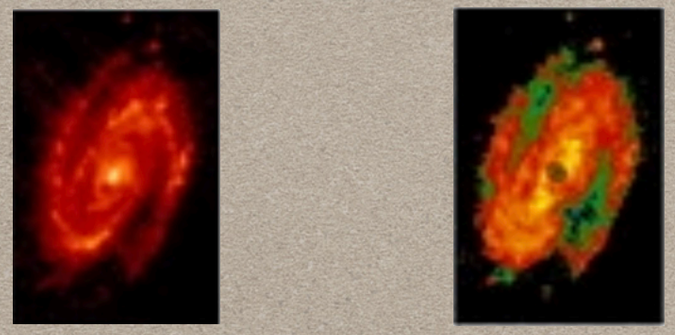
* **Predict where q should be larger in normal star-forming galaxies**

Normal Galaxy Scaling Relations

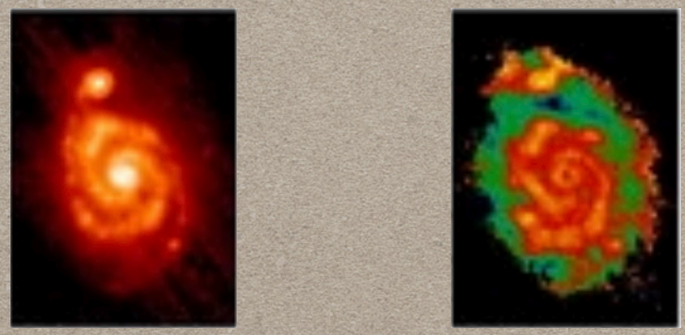
$I_{70\mu m}$ $q_{70\mu m}$



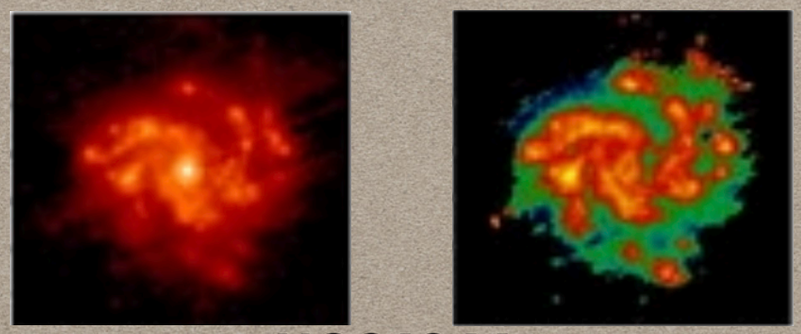
NGC2403



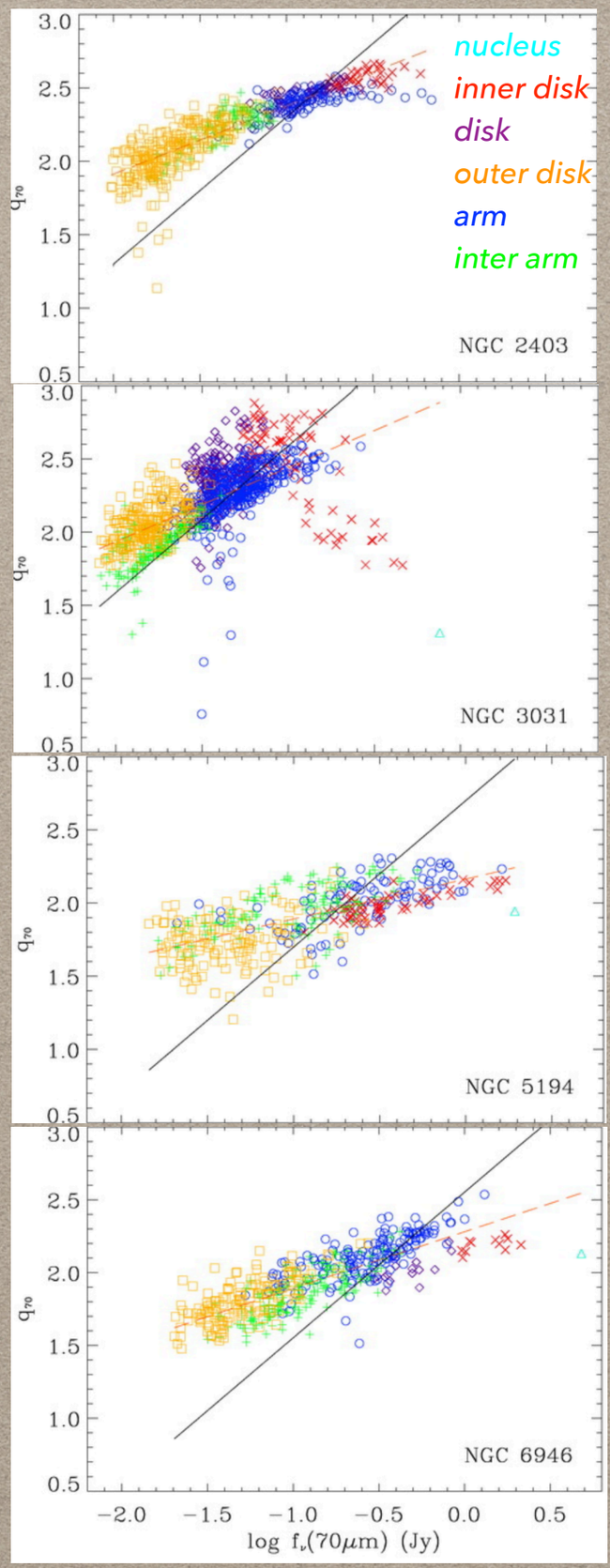
NGC3031



NGC5194



NGC6946



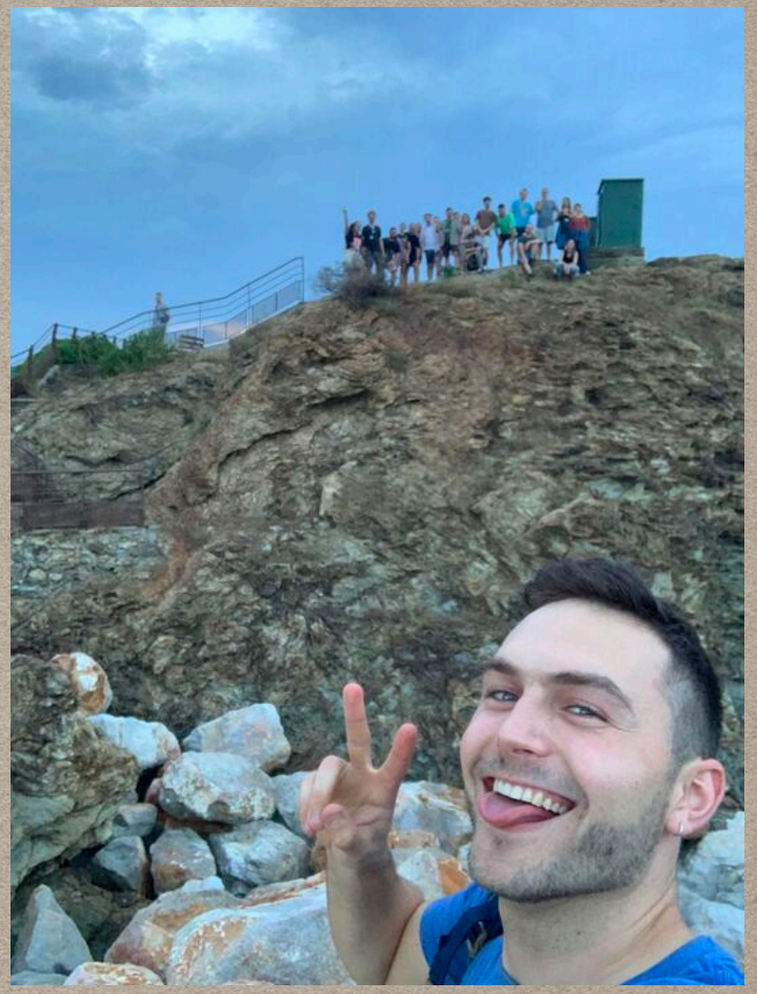
Predict where q should be larger in normal star-forming galaxies

–> In the spiral arms and other SFing regions

Murphy+2006

OUTLINE

- *'Normal' galaxies*
- *Spectra: stars & dust*
- *Scaling Relations*
- ***Star formation & the ISM***
- *Open questions & future directions*



Elias

Star Formation History – common parameterizations

Constant	$SFR(t) = SFR(t_0)$
Exponential ('tau model')	$SFR(t) = SFR(t_0)\ \ e^{-t/\tau}$
Delayed exponential	$SFR(t) = SFR(t_0)\ t\ e^{-t/\tau}$
Late burst or quenching	
Periodic	
Non-parametric	

** Student challenge: In units of the assumed τ value, at what time for a **delayed exponential** does the SFR peak?*

Dale+2016

Star Formation History – common parameterizations

Constant	$SFR(t) = SFR(t_0)$
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Late burst or quenching	
Periodic	
Non-parametric	

* ***Student challenge: In units of the assumed τ value, at what time for a delayed exponential does the SFR peak?***

$d/dt\ (SFR(t)) = 0 \rightarrow t=\tau$

Dale+2016

Star Formation History – common parameterizations

Constant $SFR(t) = SFR(t_0)$

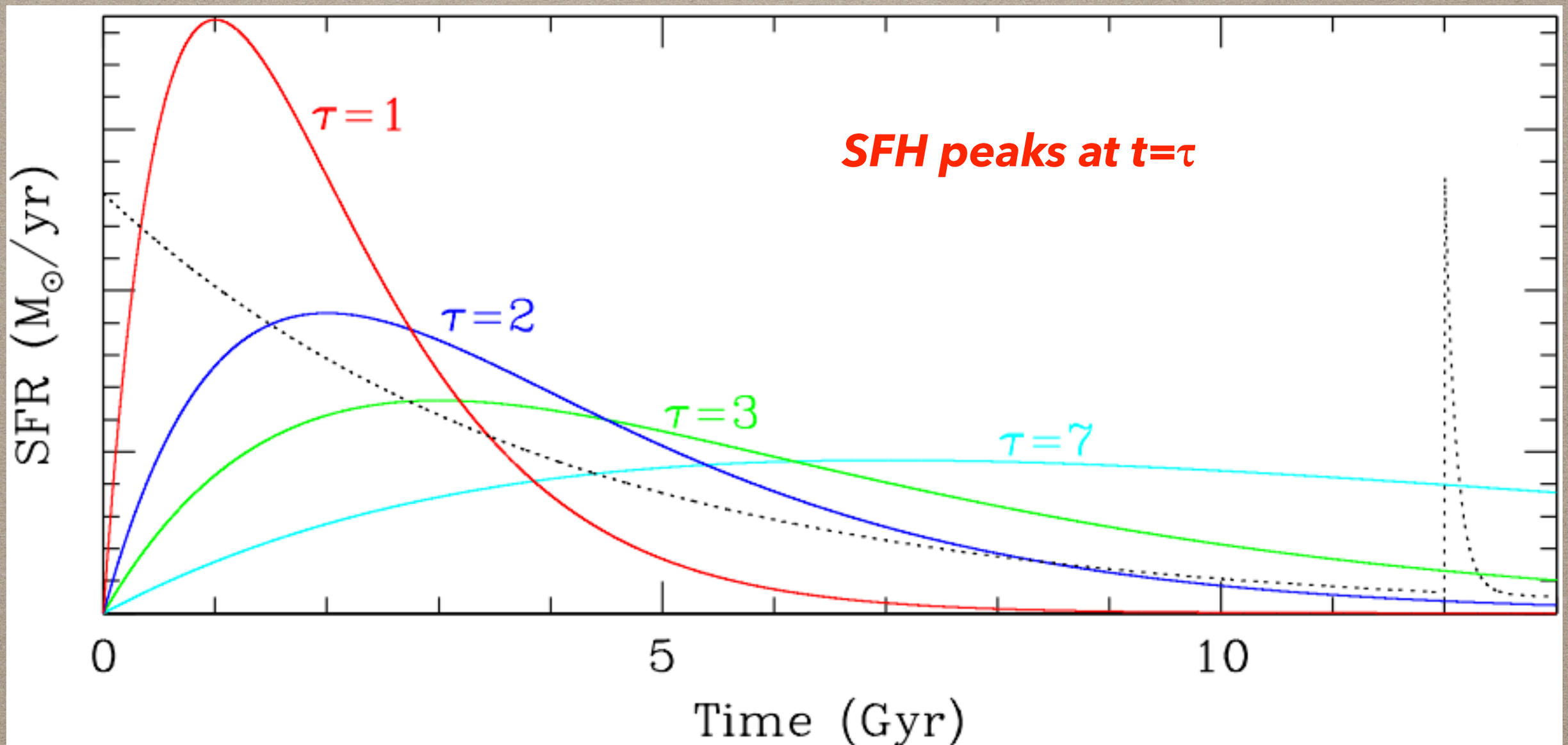
Exponential ('tau model') $SFR(t) = SFR(t_0)\ e^{-t/\tau}$

Delayed exponential $SFR(t) = SFR(t_0)\ t\ e^{-t/\tau}$

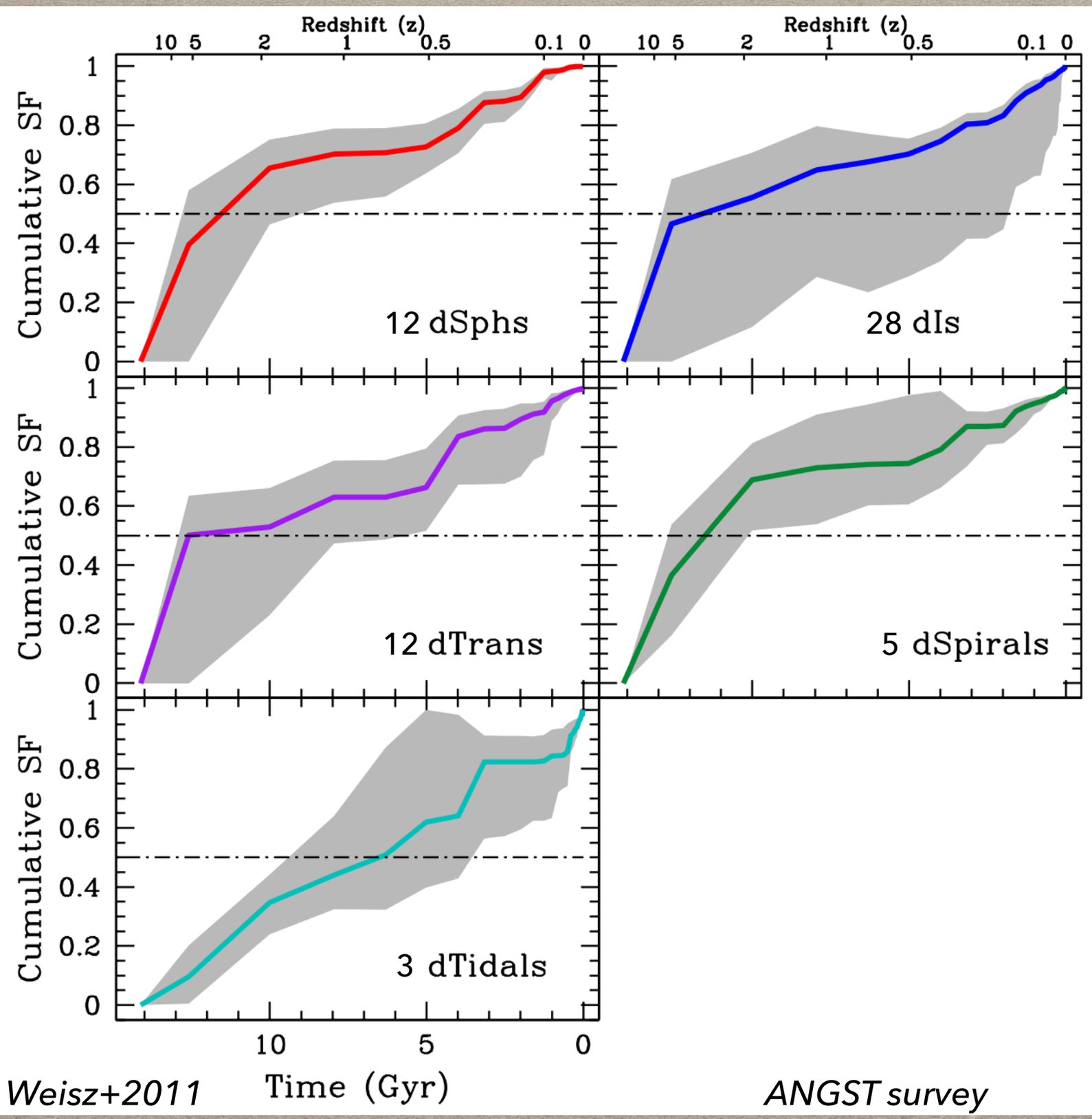
Late burst or quenching

Periodic

Non-parametric



Star Formation Histories – Application #1

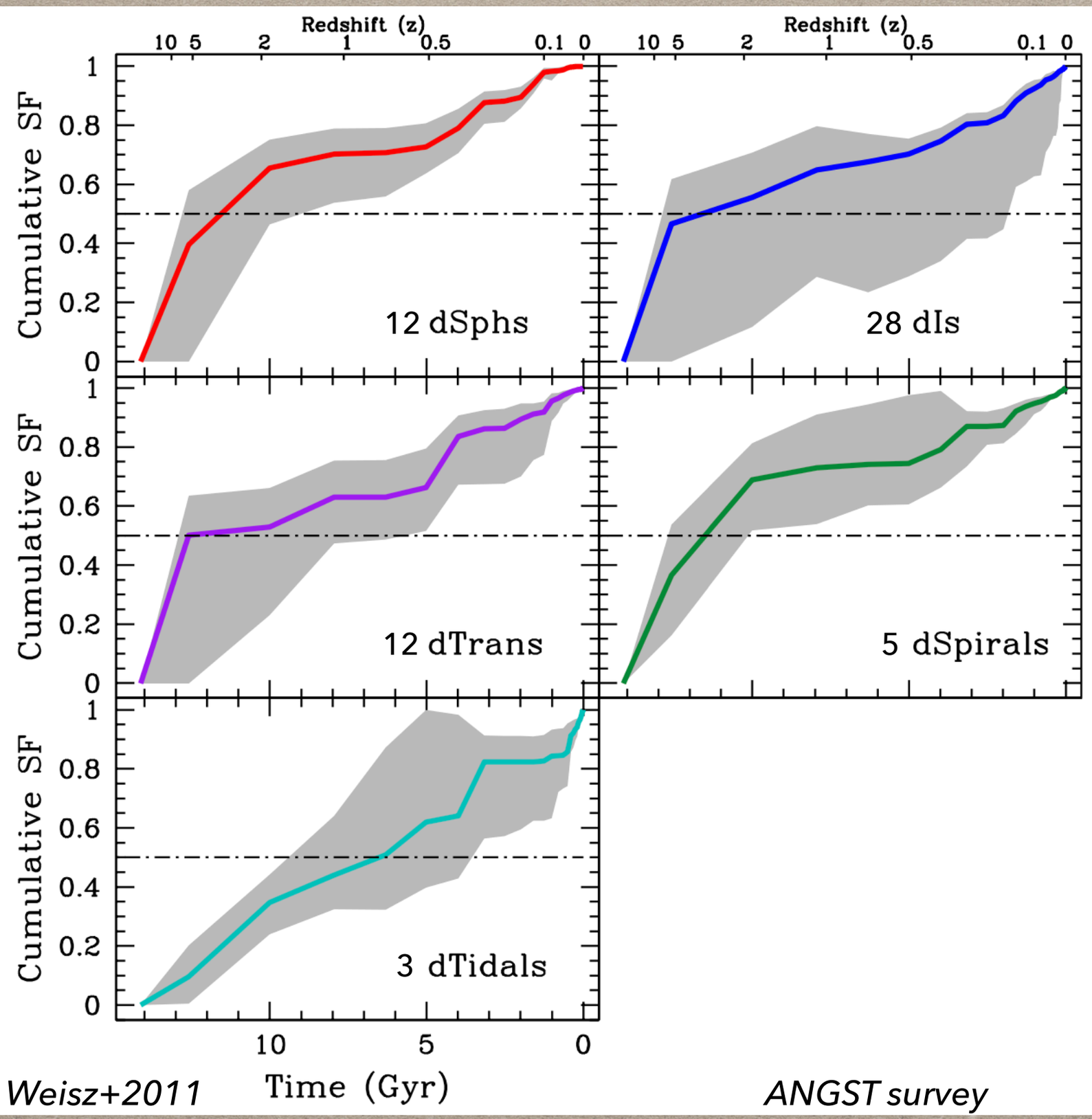


60 ANGST dwarfs

Typical local dwarf galaxy formed >50% of its M⋆ prior to z~1

* ***Which dwarf type has the largest % of its stars formed in the most recent Gyr?***

Star Formation Histories – Application #1



60 ANGST dwarfs

Typical local dwarf galaxy formed >50% of its M⋆ prior to z~1

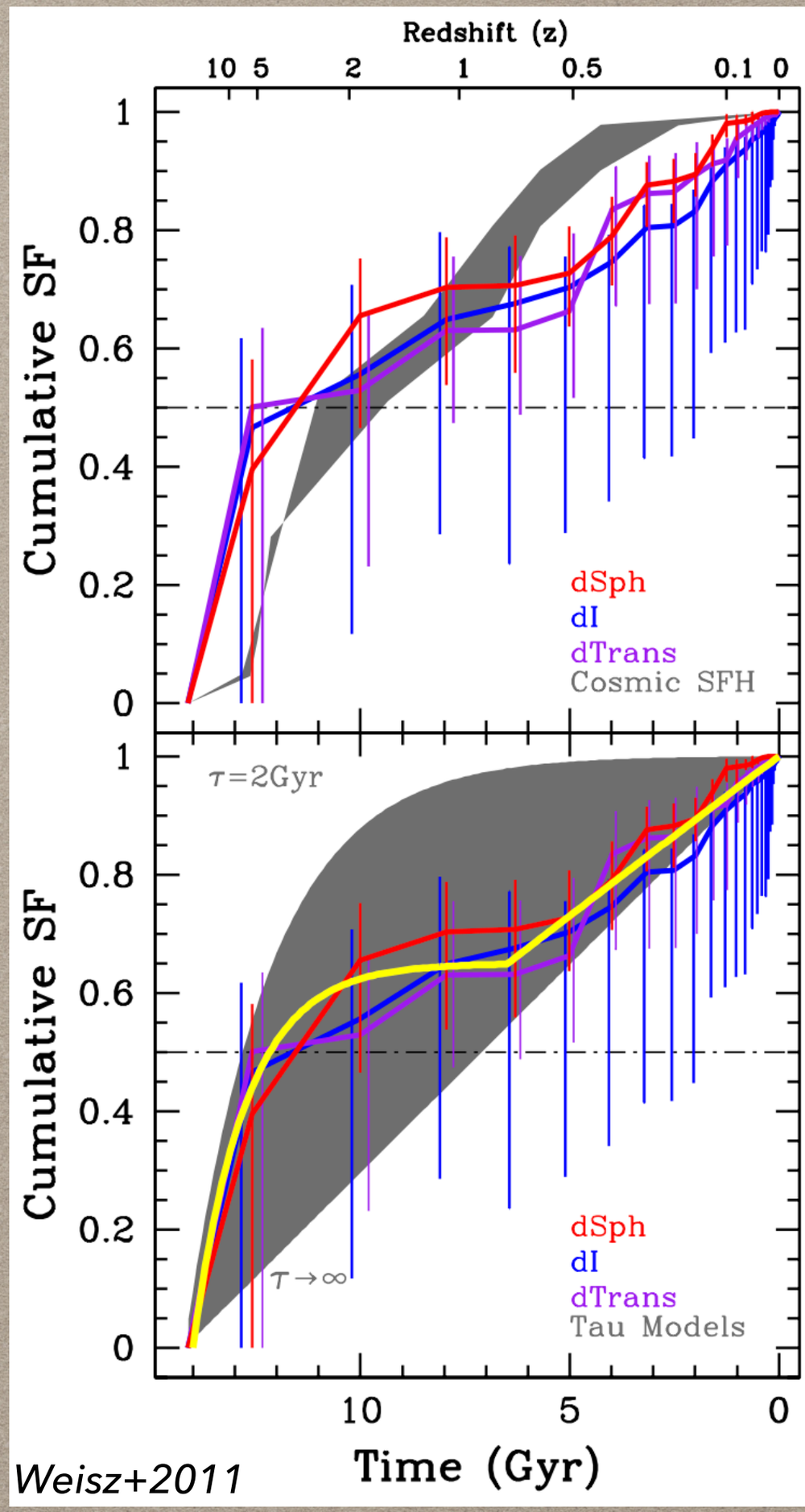
Most recent Gyr:

dSph	*dI*	*dTran*	*dSpir*	*dTidal*
2%	*8%*	*4%*	*5%*	*15%*

Star Formation Histories – Application #1

By z~0.5, dwarf galaxies deviate from cosmic SFH
–> cosmic downsizing

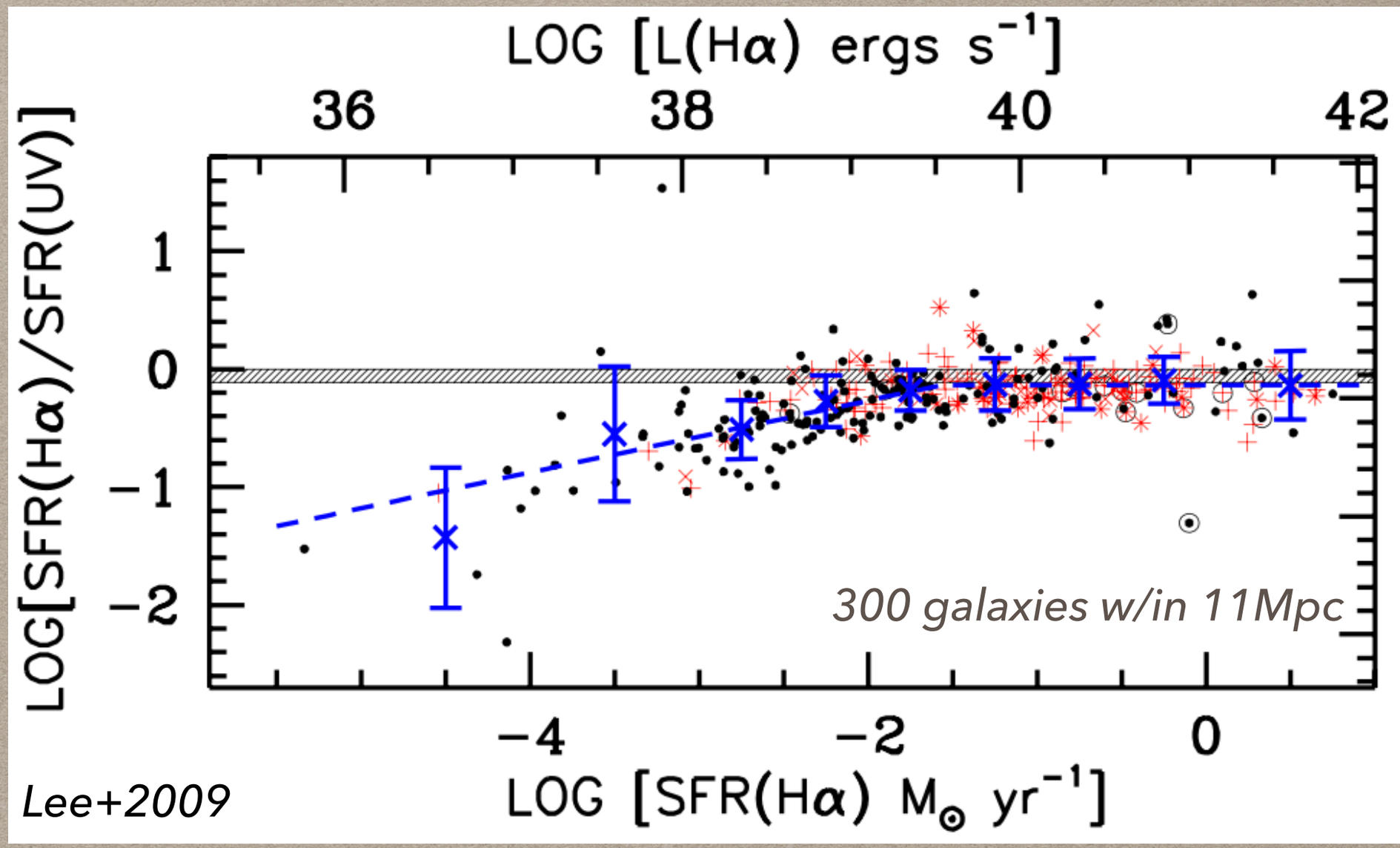
Exponential SFH followed by a constant SFH



Weisz+2011

Star Formation Histories – Application #2

SFR(Hα) < SFR(UV) for lower L dwarf galaxies



Lee+2009

Investigated:

A_V

stellar models

metallicity

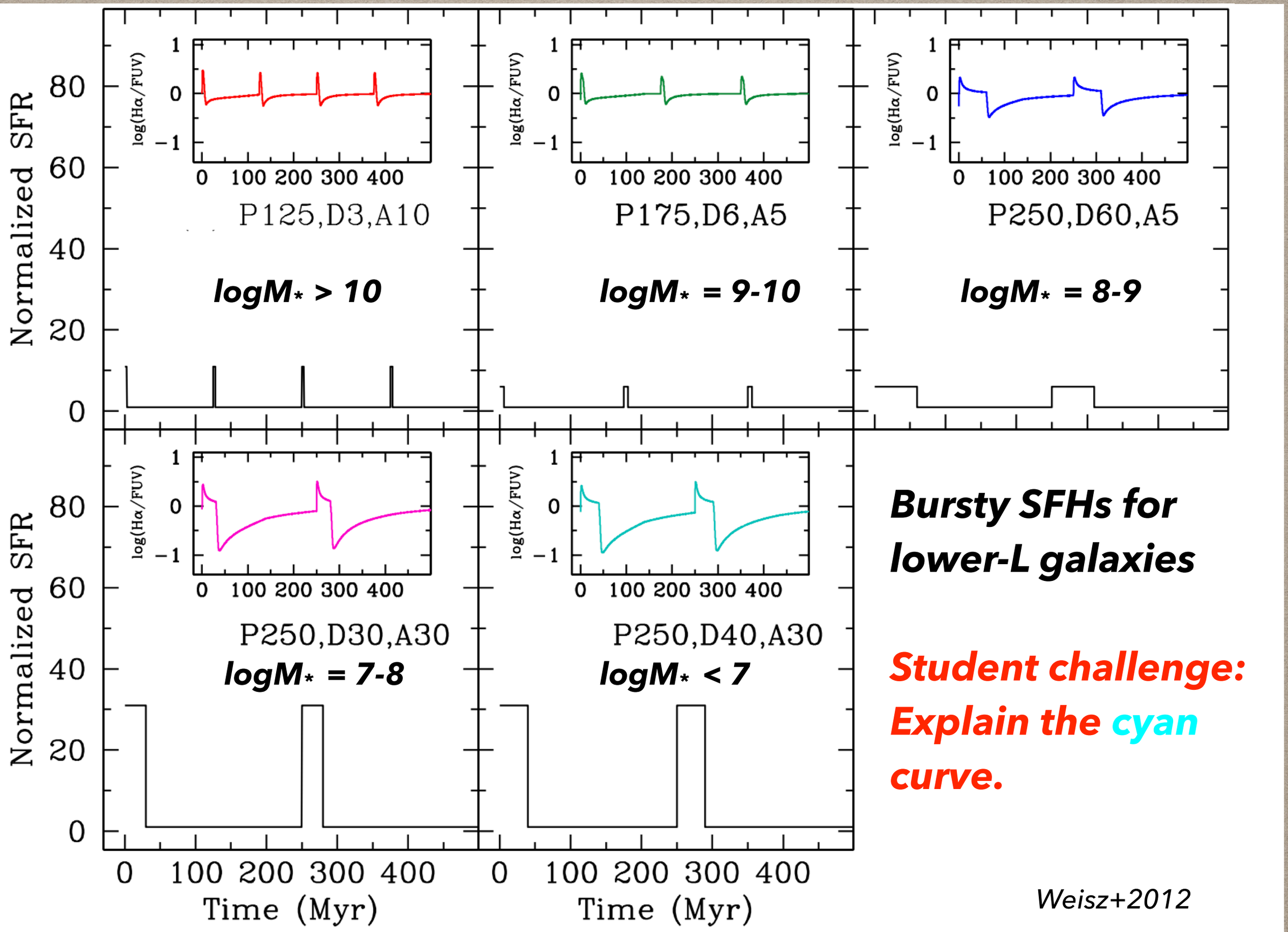
ionizing photon loss

IMF deficient in high-mass stars

stochasticity in high mass SF at low SFR …

None fully explain the discrepancy

Star Formation Histories – Application #2

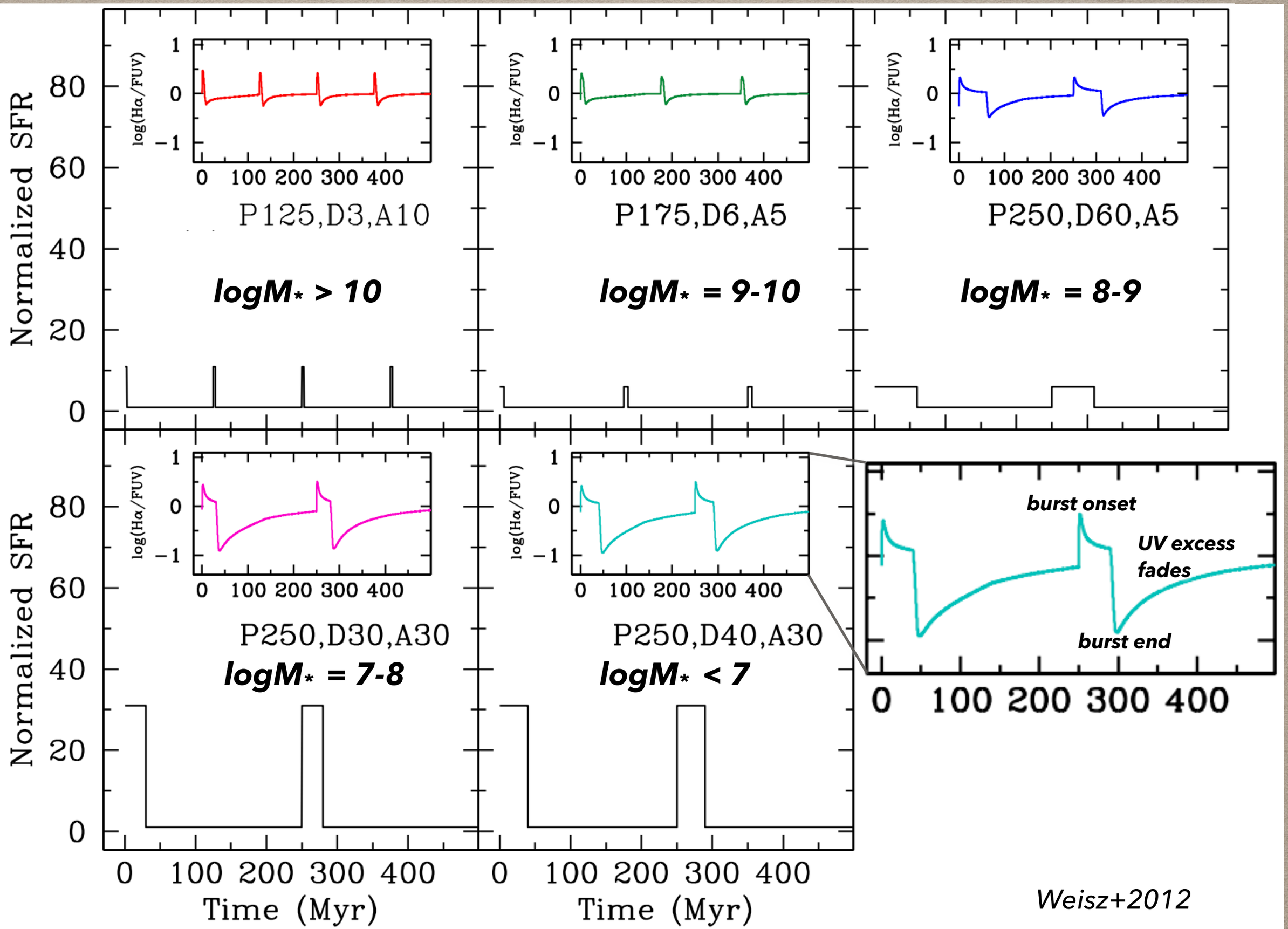


Bursty SFHs for lower-L galaxies

Student challenge: Explain the cyan curve.

Weisz+2012

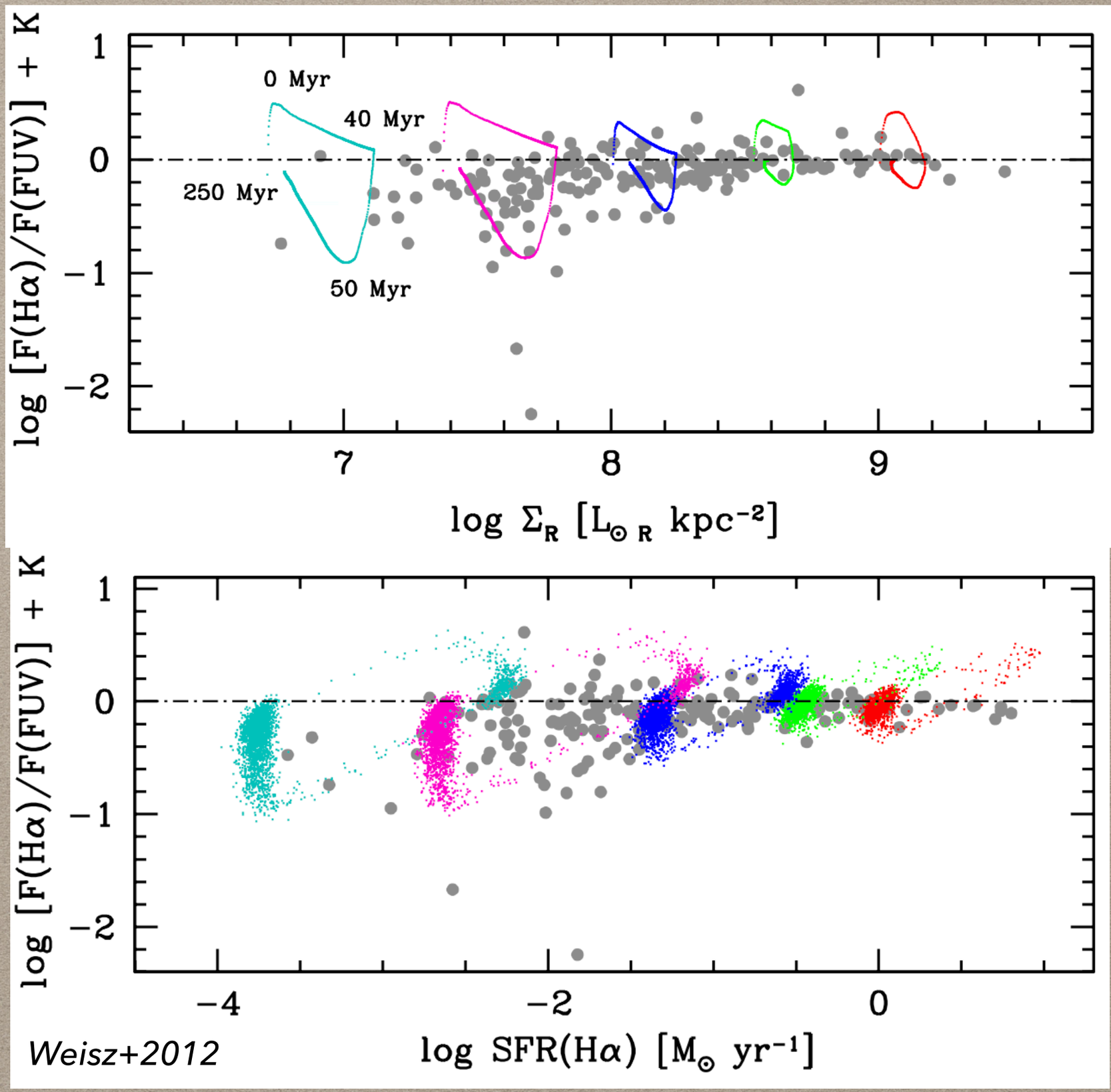
Star Formation Histories – Application #2



Weisz+2012

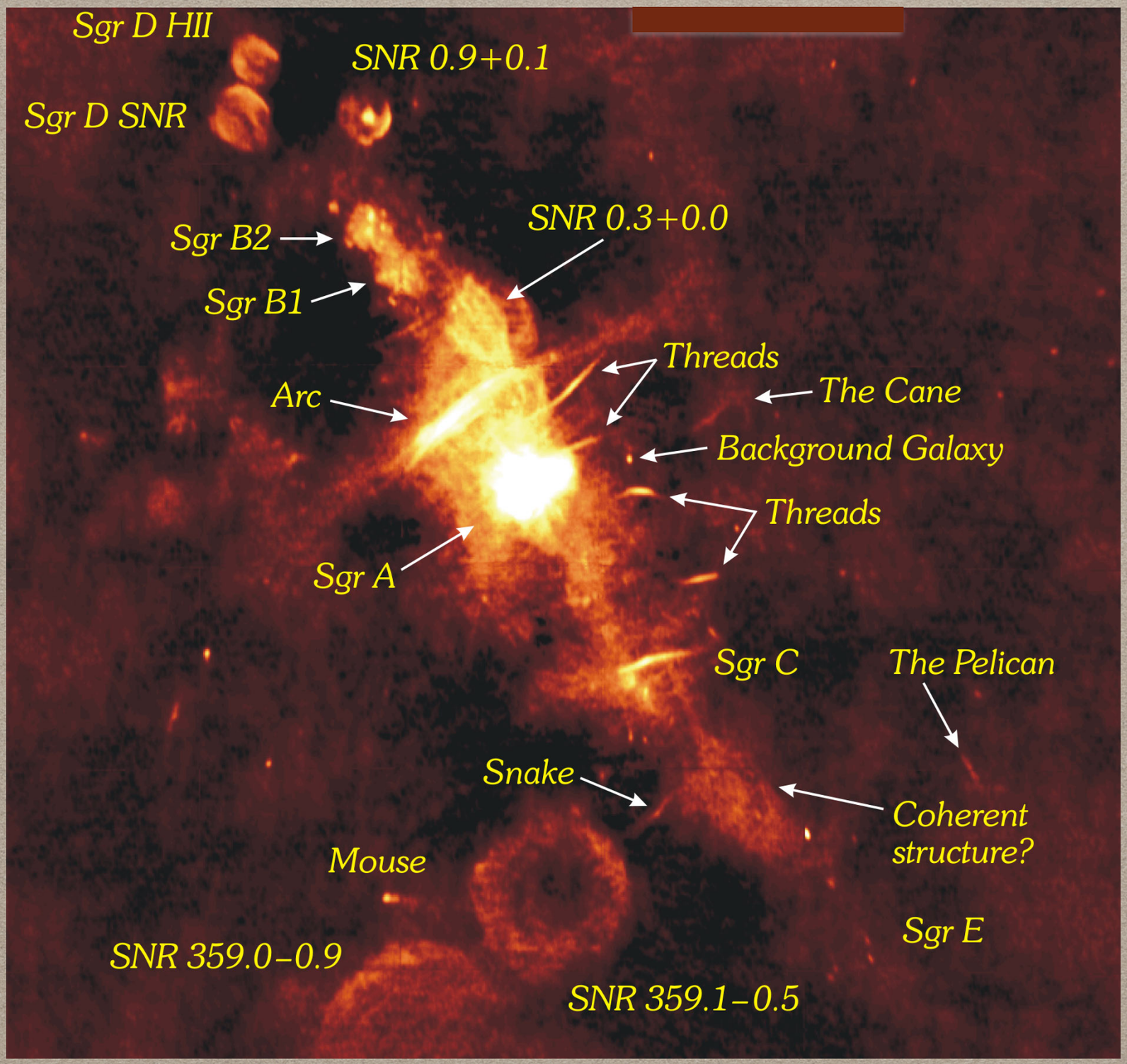
Star Formation Histories – Application #2

The resulting predicted SFR ratios are broadly consistent with the data



Weisz+2012

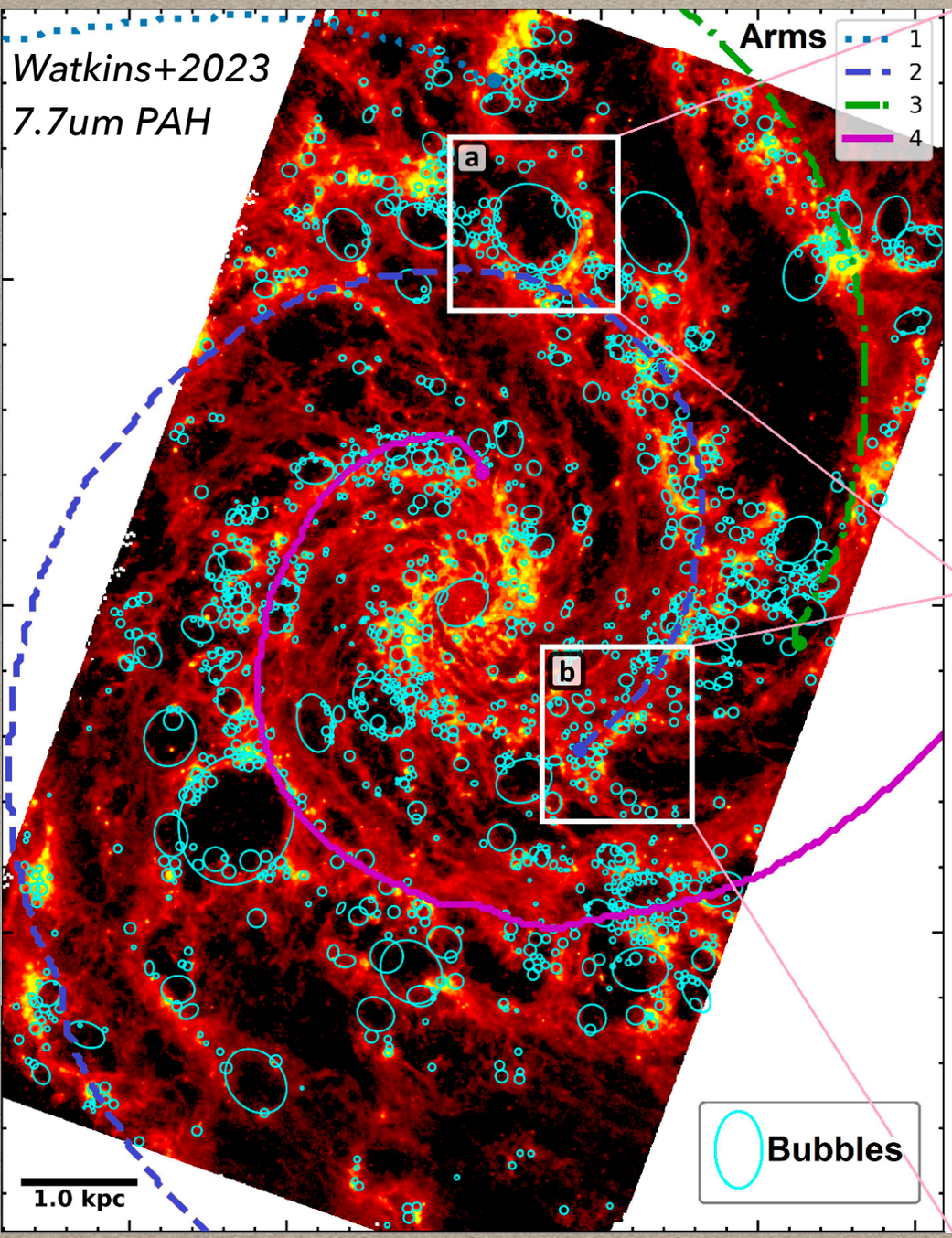
Bubbles in Nearby Galaxies

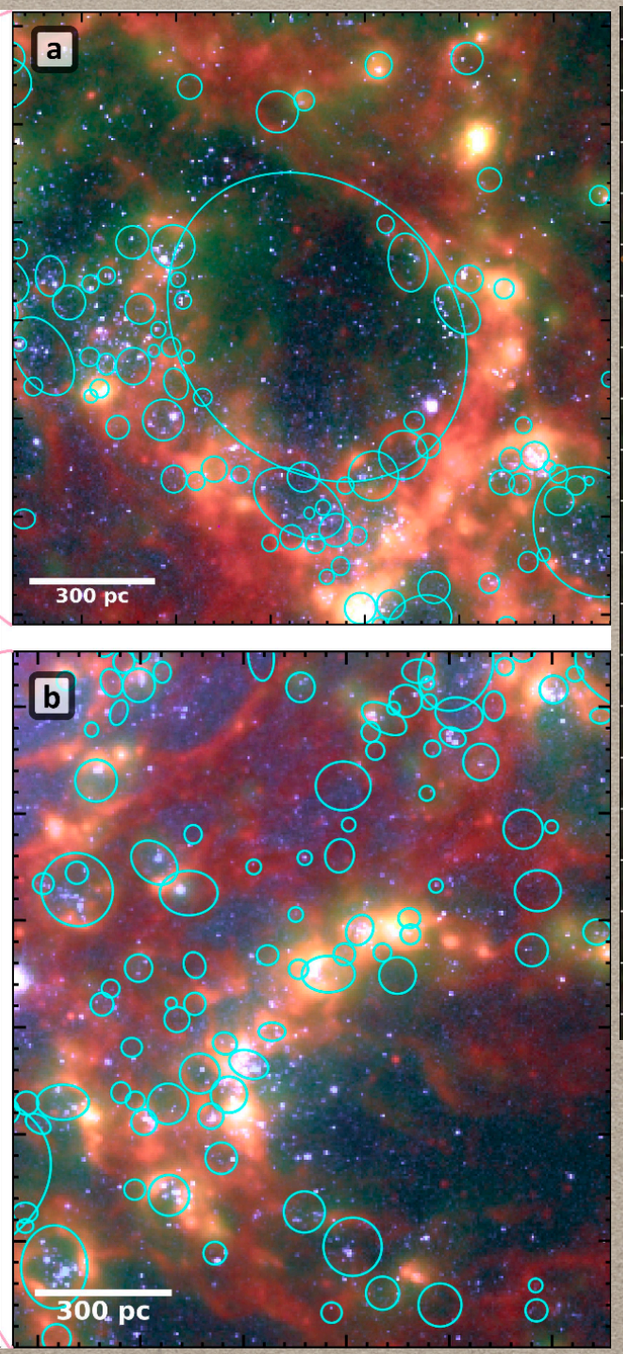


Sites of active SF generate 'bubbles' in the ISM

Image credit: NRAO

Bubbles in Nearby Galaxies – PHANGS pilot projects on N628





Most bubbles lie near a spiral arm, with radii increasing downstream

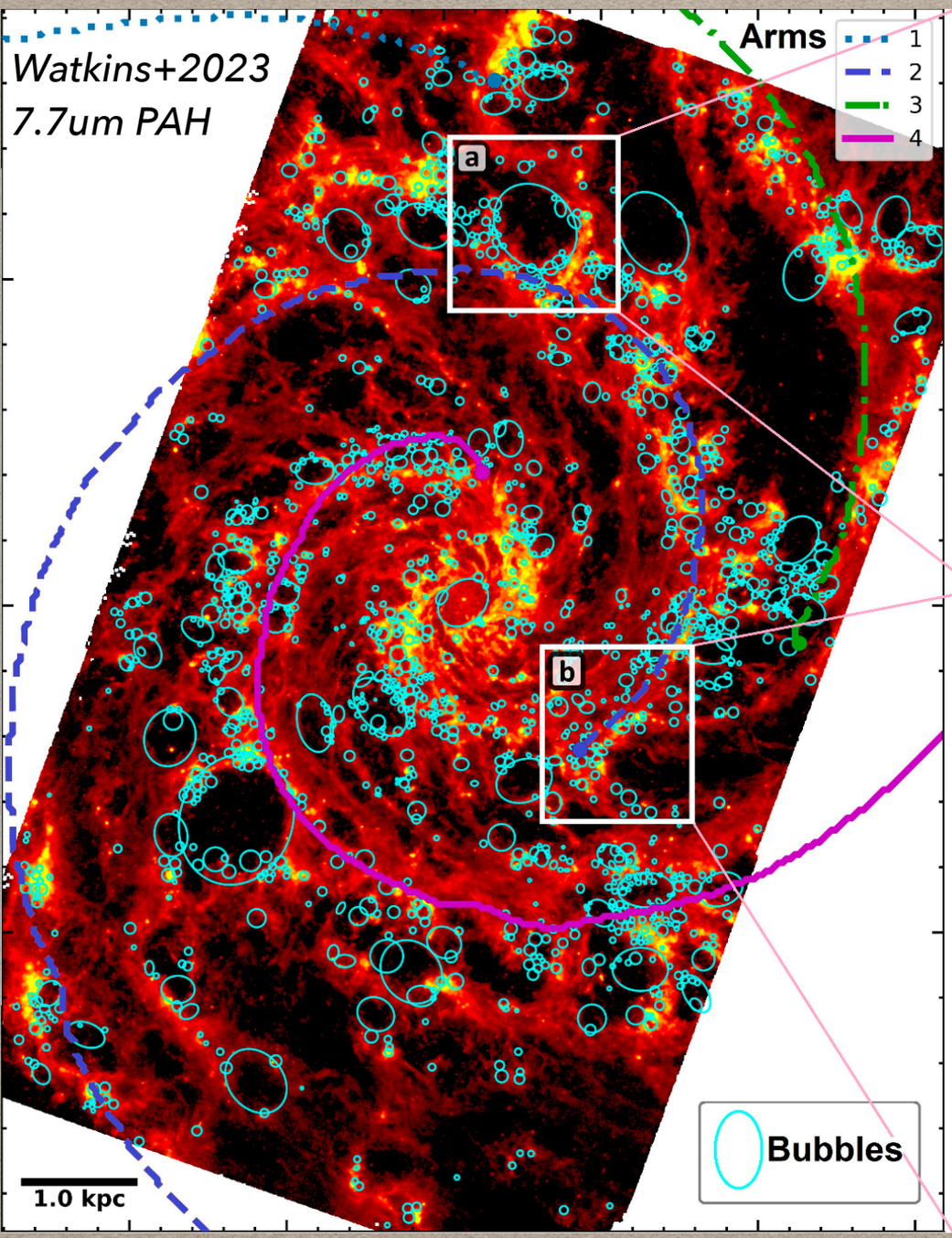
Bubble elongation ~aligned with spiral arm

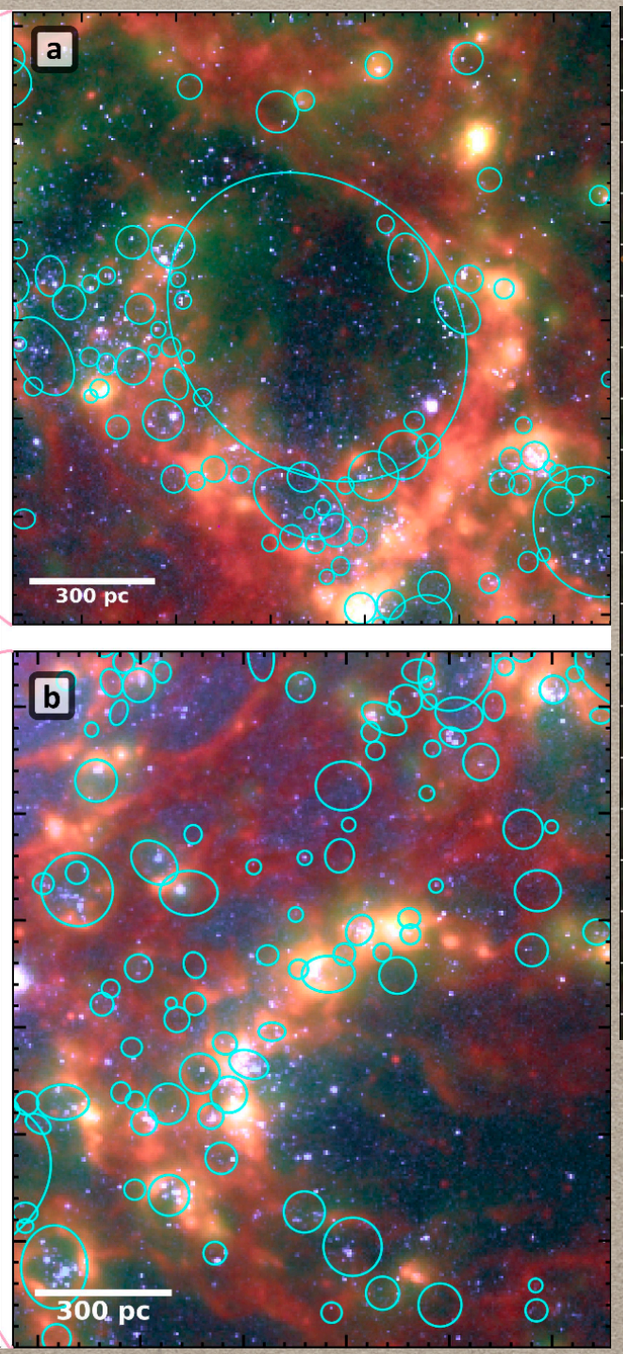
Bubbles are expanding, and merging is likely common

Hα brightest in the shells, and coincident with young & massive star associations

–> bubbles shaped and driven by stellar and SN feedback processes

Bubbles in Nearby Galaxies – PHANGS pilot projects on N628

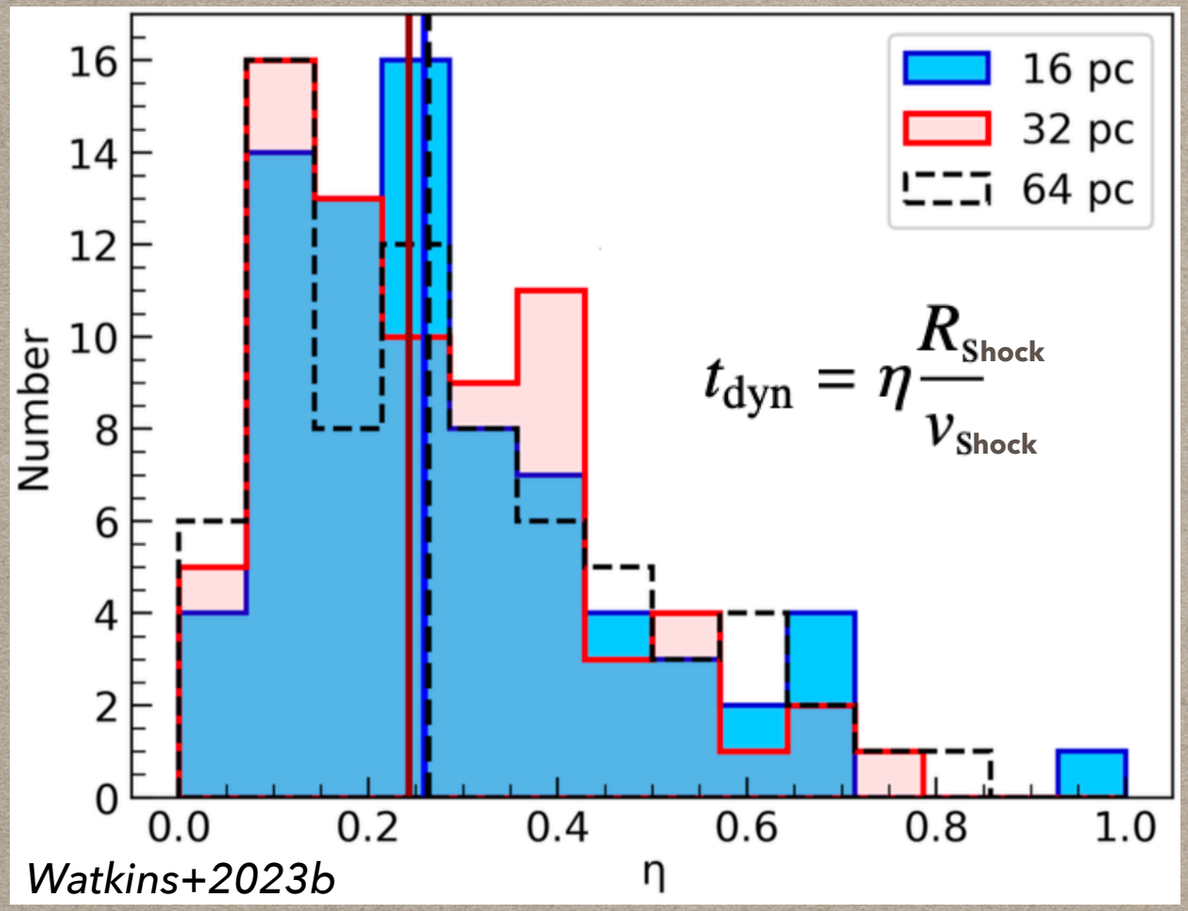


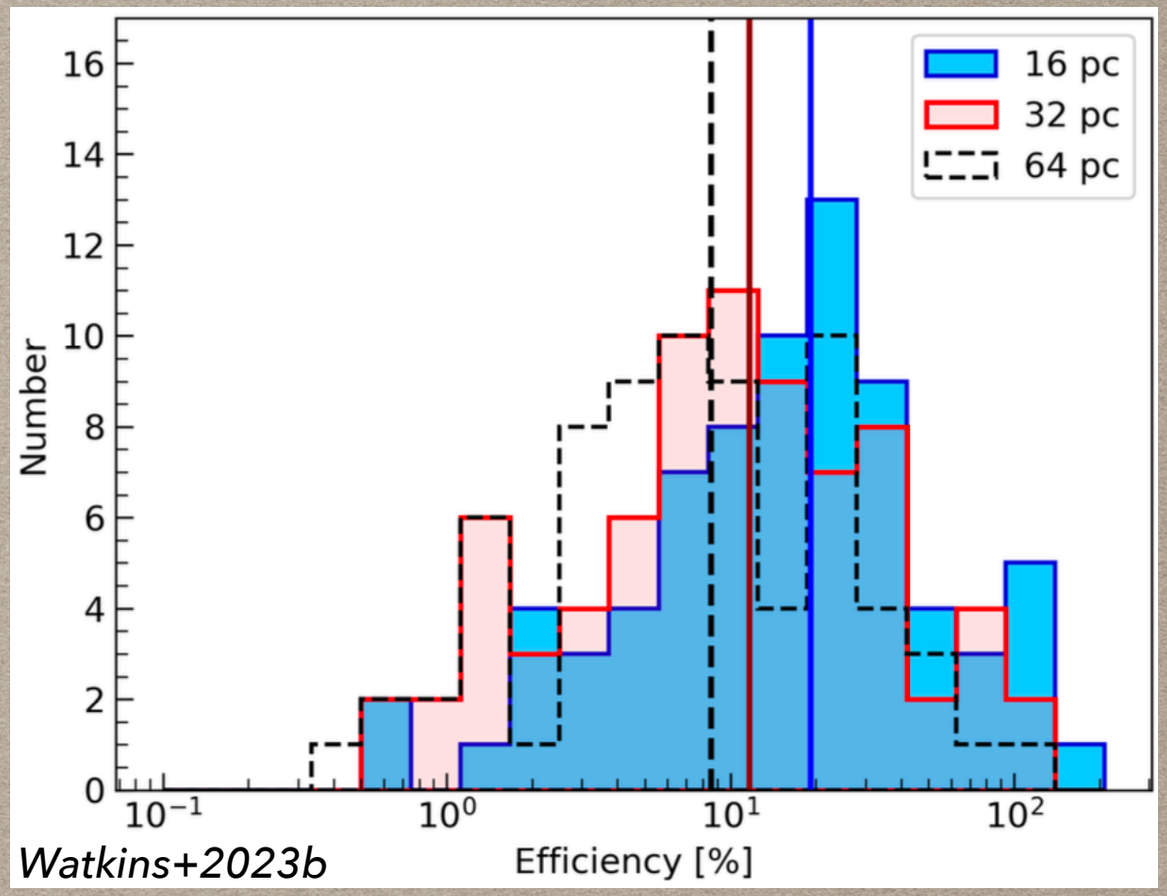


Bubble Zoo!

A citizen science project to be run by Galaxy Zoo

CO superbubbles in 18 PHANGS galaxies





325 cavities, 88 superbubbles

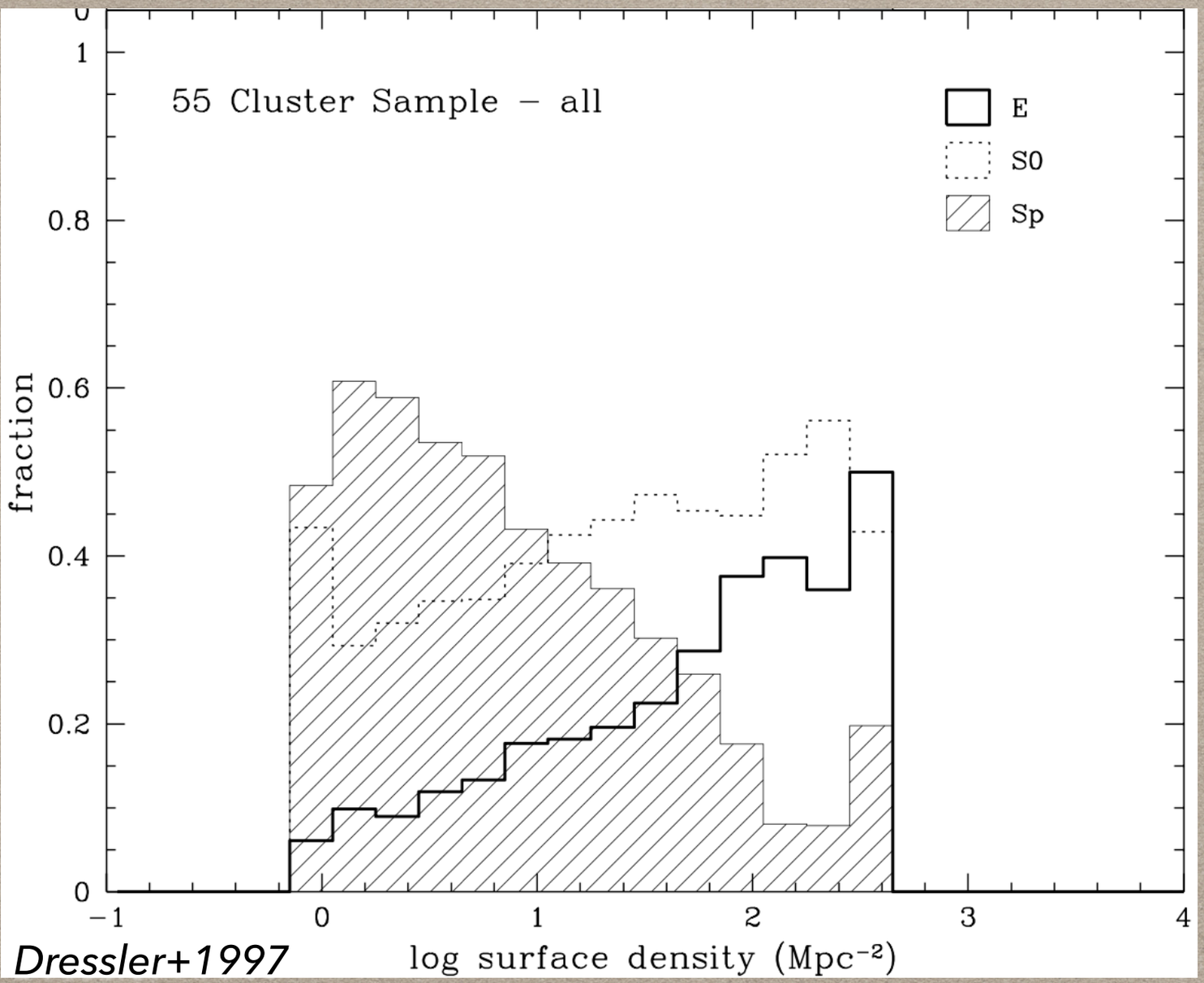
Radii + expansion speeds to derive ages and necessary mechanical power

Scaling coefficient η closer to SN blast wave-driven shocks (than stellar wind-driven)

Predicted & catalog stellar ages & masses agree,

assuming a model where SNe inject energy into the ISM with 10% coupling efficiency

Classic Morphology-Density Relation

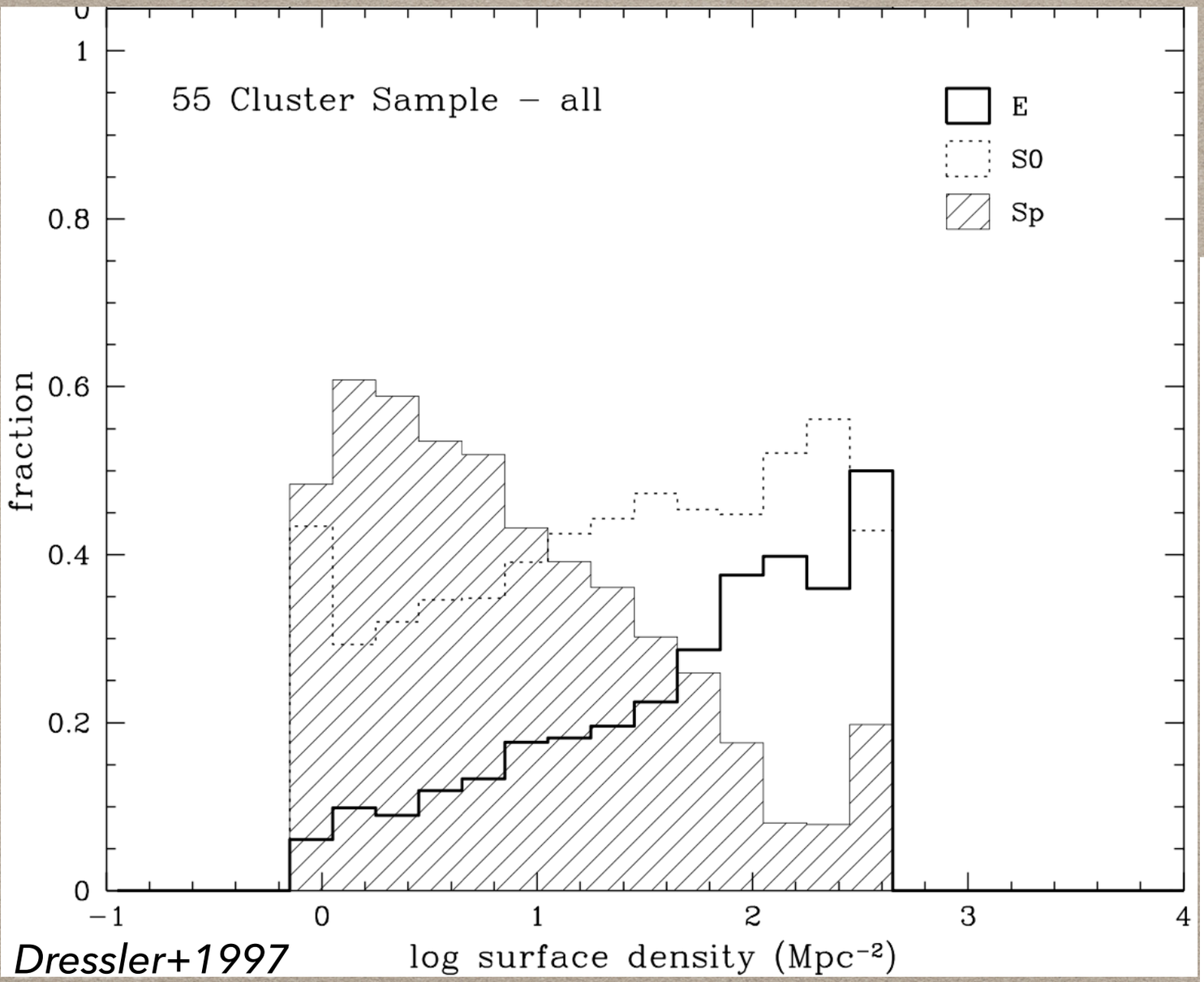


Dressler+1997

Ellipticals more common in denser environments, e.g., the cores of galaxy clusters

Dressler 1980

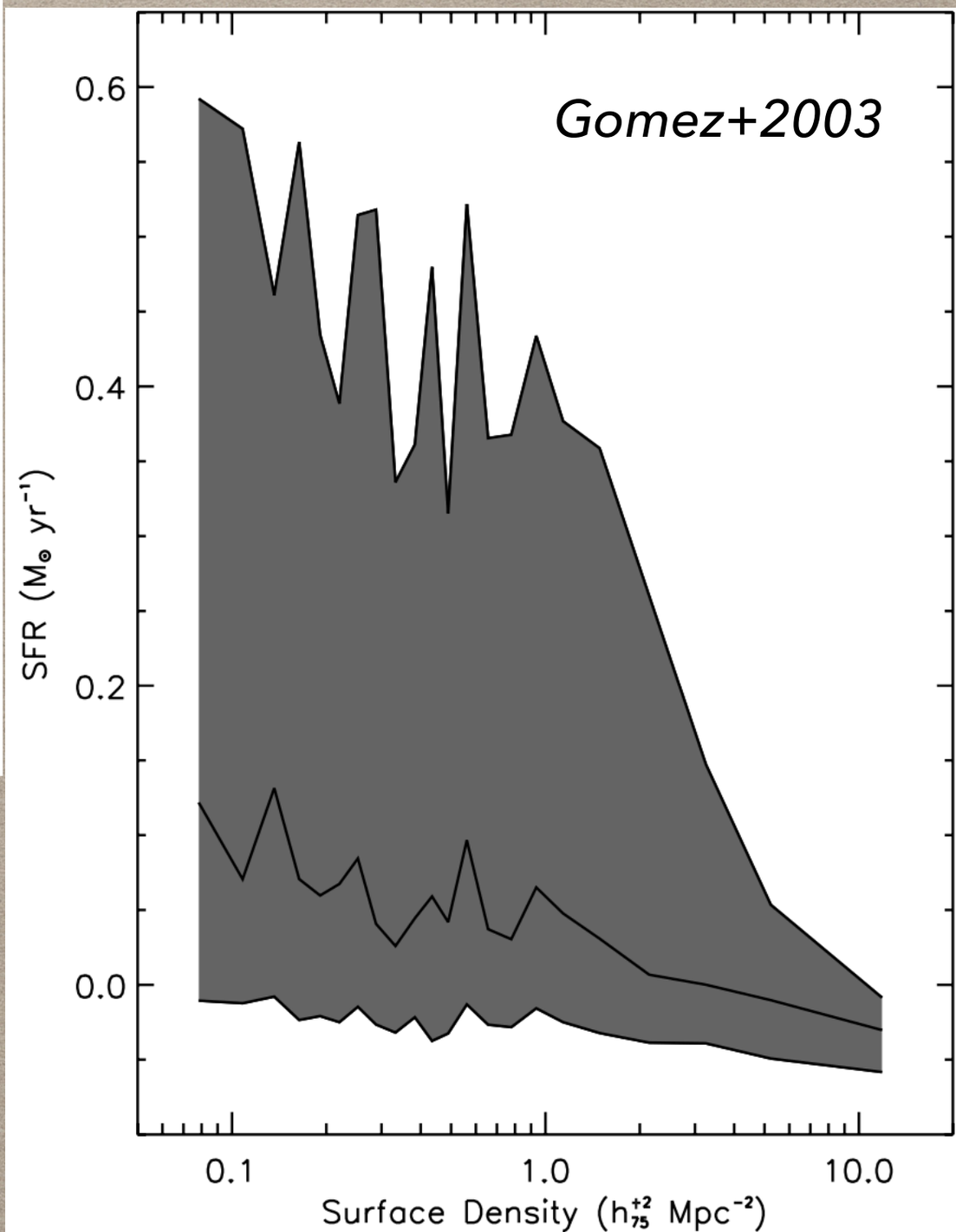
Classic Morphology-Density Relation



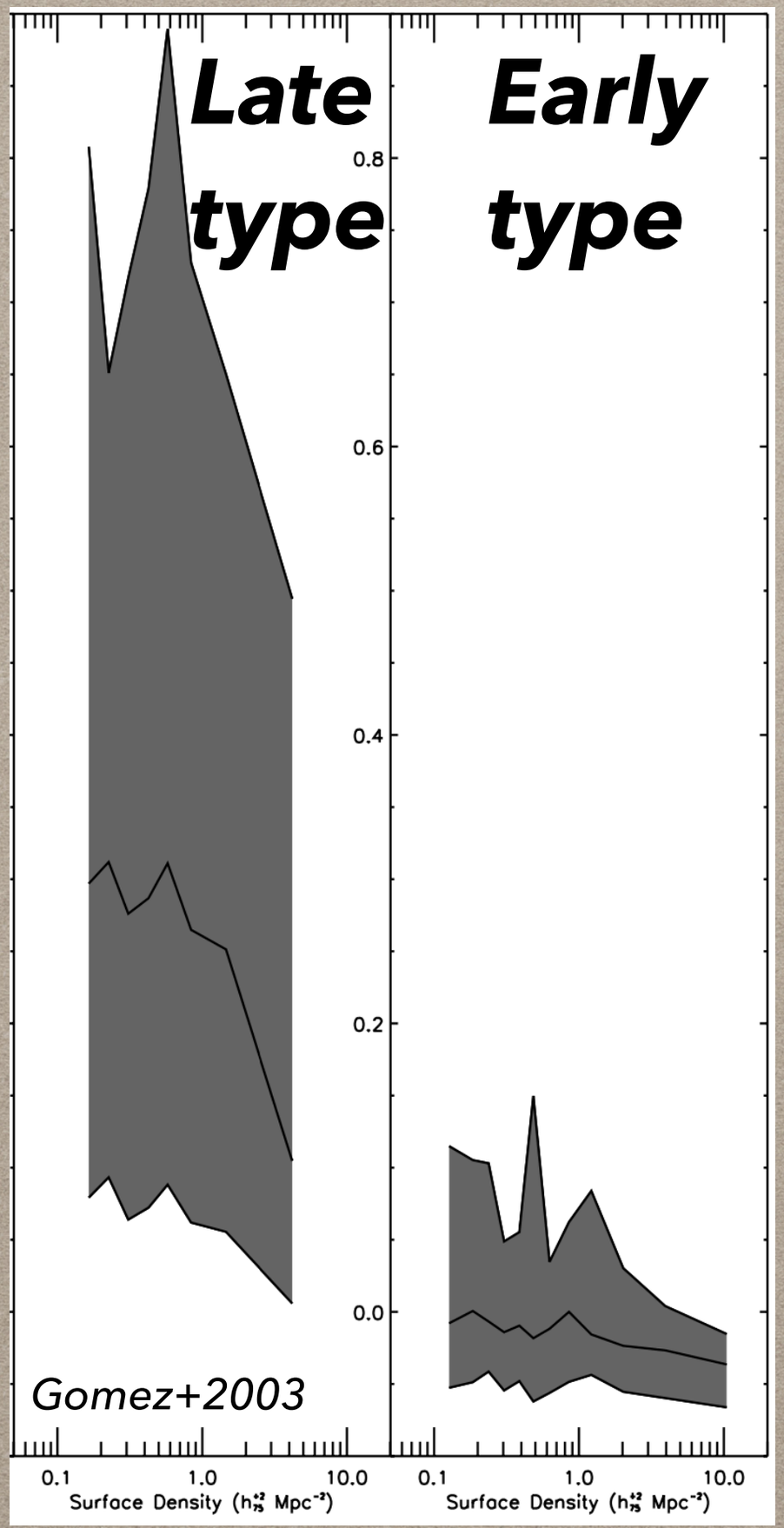
Dressler+1997

- *10^4 SDSS cluster galaxies*
- *SFR drops for increasing galaxy number density*

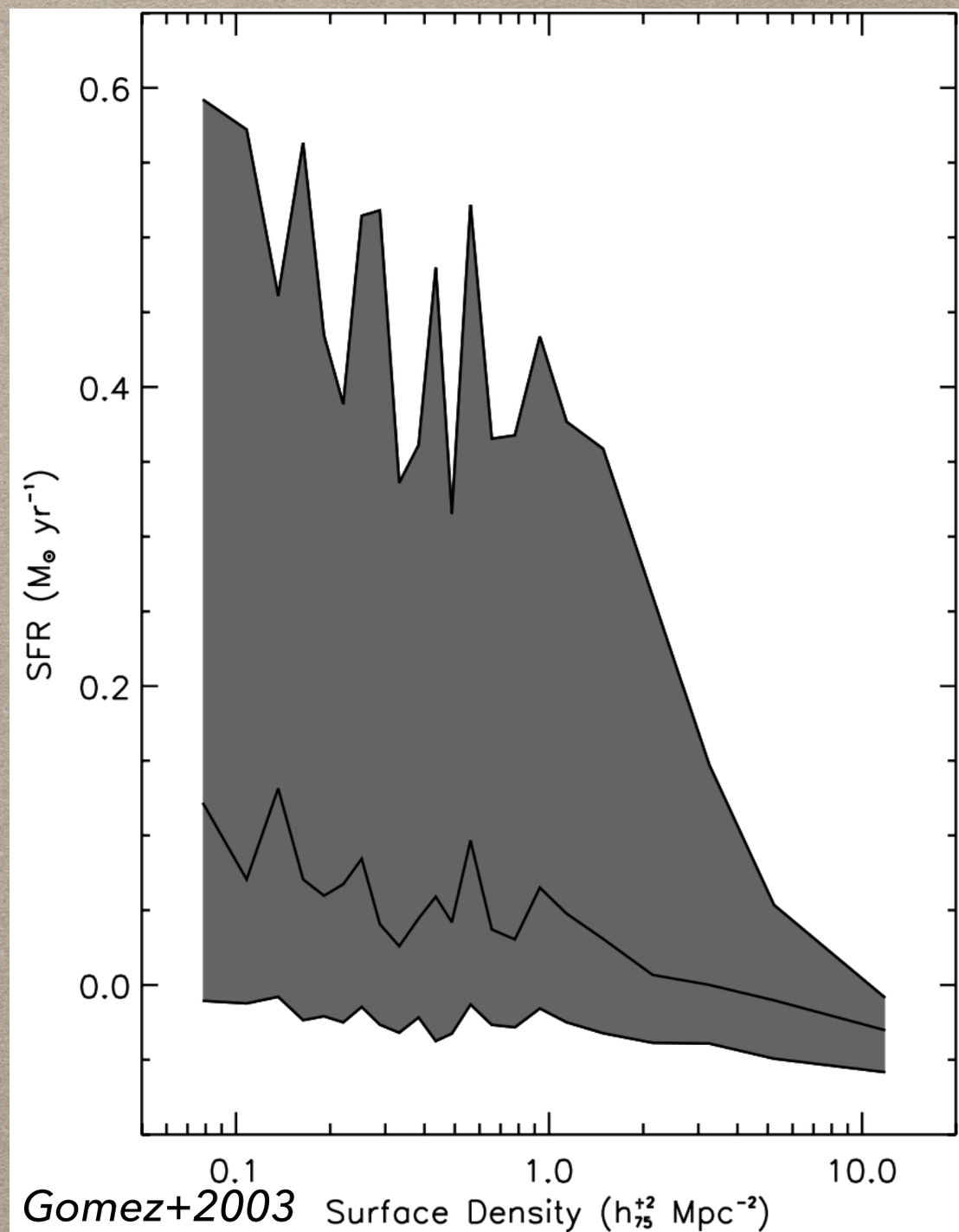
SFR-Density Relation



Interestingly, also holds true separately for spirals and ellipticals



SFR-Density Relation



OUTLINE

JC Milhet

- *'Normal' galaxies*
- *Spectra: stars & dust*
- *Scaling Relations*
- *Star formation & the ISM*
- ***Open questions & future directions***

Open questions & future directions

Star Formation

How do stars form? What is the balance of positive and negative feedback? What is the rate of multiplicity in SF? Sims need to avoid building overly massive galaxies, and doing it too quickly.

Magnetic Fields

What is the origin of magnetic fields? Why are they (sometimes) spiral? What was the B in galaxies at z~15, and how did it impact SF?

Dark Matter Haloes and Envelopes in General

What are the properties of DM haloes of normal galaxies when the haloes contain more than one galaxy? How often do normal galaxies co-habitate DM haloes with 'abnormal' galaxies? Are extended HI and radio emission envelopes common or rare?

'Normal'

Should we revisit the definition of 'normal'? How do SBs get defined and ruled out? Should the definition be modulated by intensity or covariance on some spatial scale? How to account for SMBHs alternating between dormant and active? –> What fraction of its lifetime does a galaxy spend in the normal phase?

Thank you