Observational dust properties from mid-IR to far-IR: what we know from local universe to cosmic noon

Alexandra Pope (UMass Amherst)

Dusting the Universe – Tucson, AZ

March 5, 2019

Image credit: NASA/JPL-Caltech

The Evolving Interstellar Medium in Galaxies over the last 11 Gyrs

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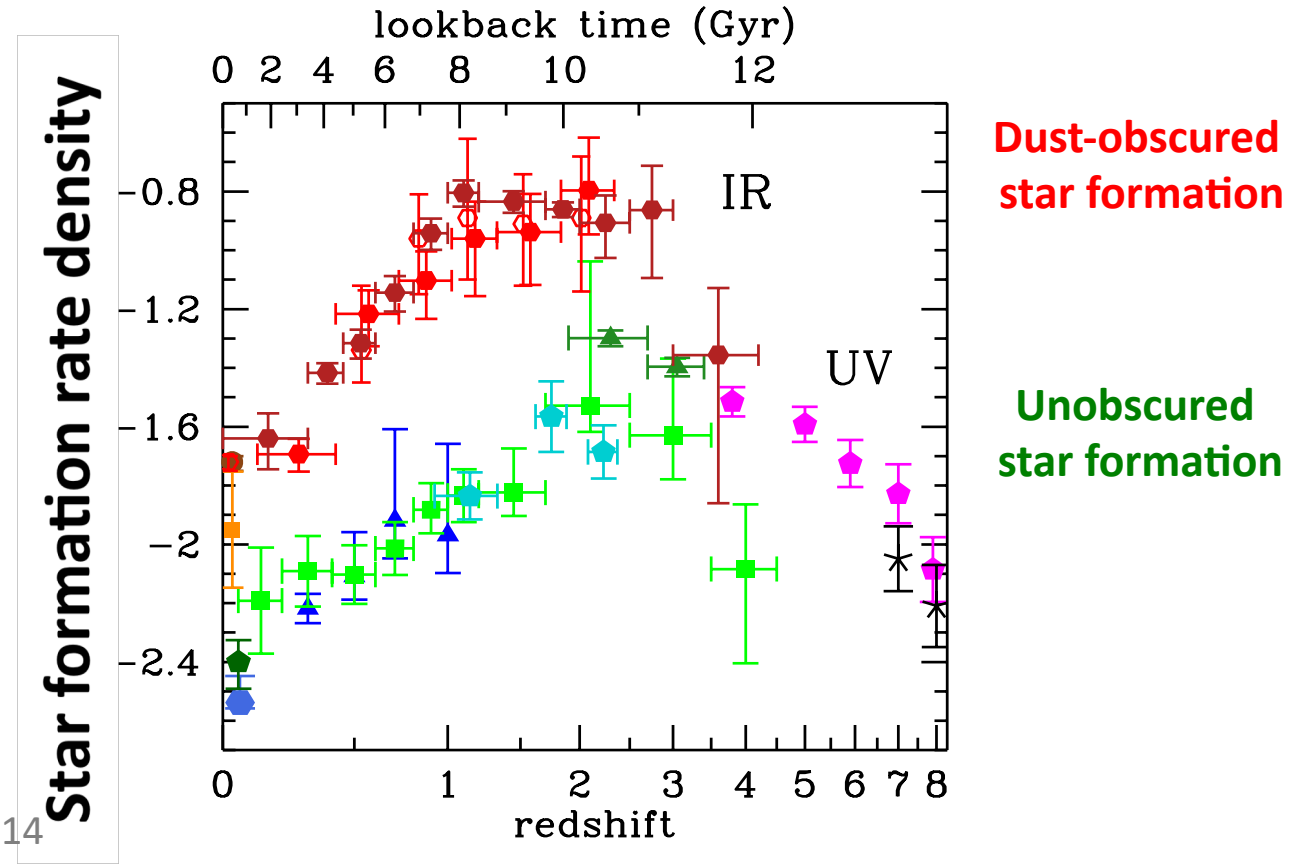
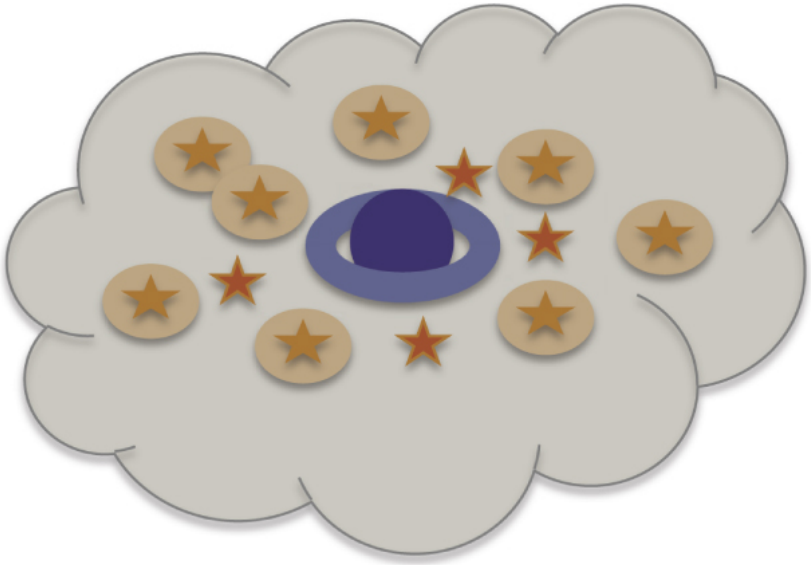
1. Galaxy Evolution was different 11 Gyrs ago
2. The <u>majority</u> of cosmic star formation is hidden behind dust



Madau & Dickinson 2014

The interstellar medium:
Gateway to understanding galaxy evolution



Figures adapted from Roebuck et al. 2016 and Goicoechea et al. 2016

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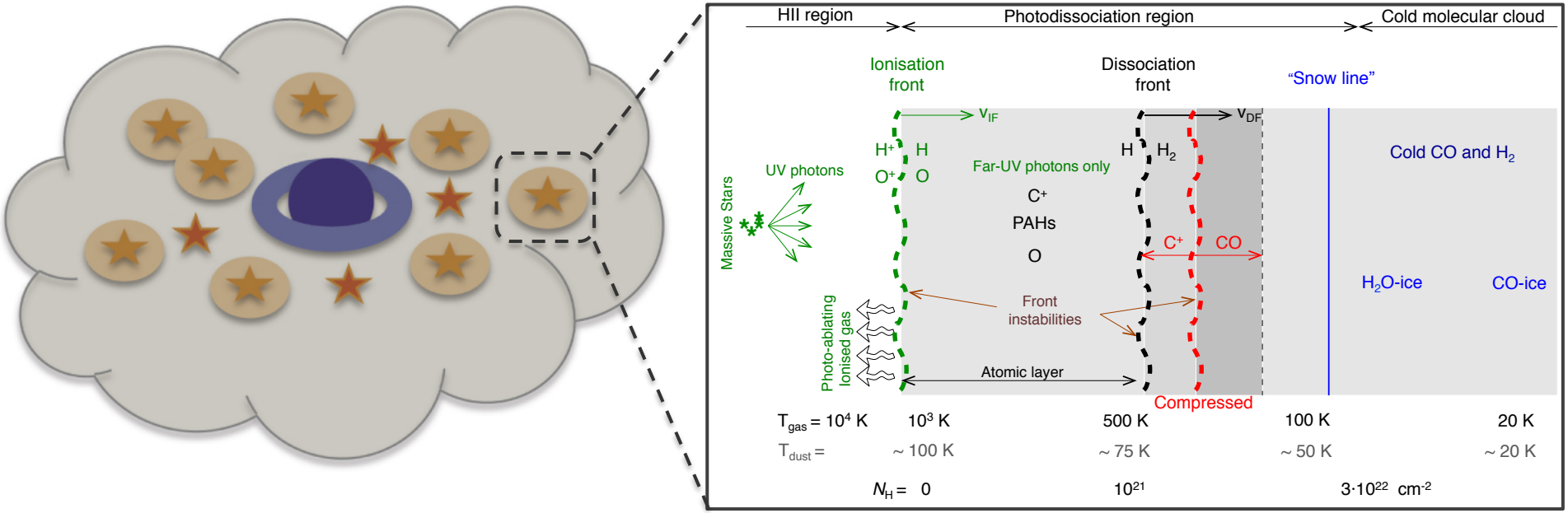

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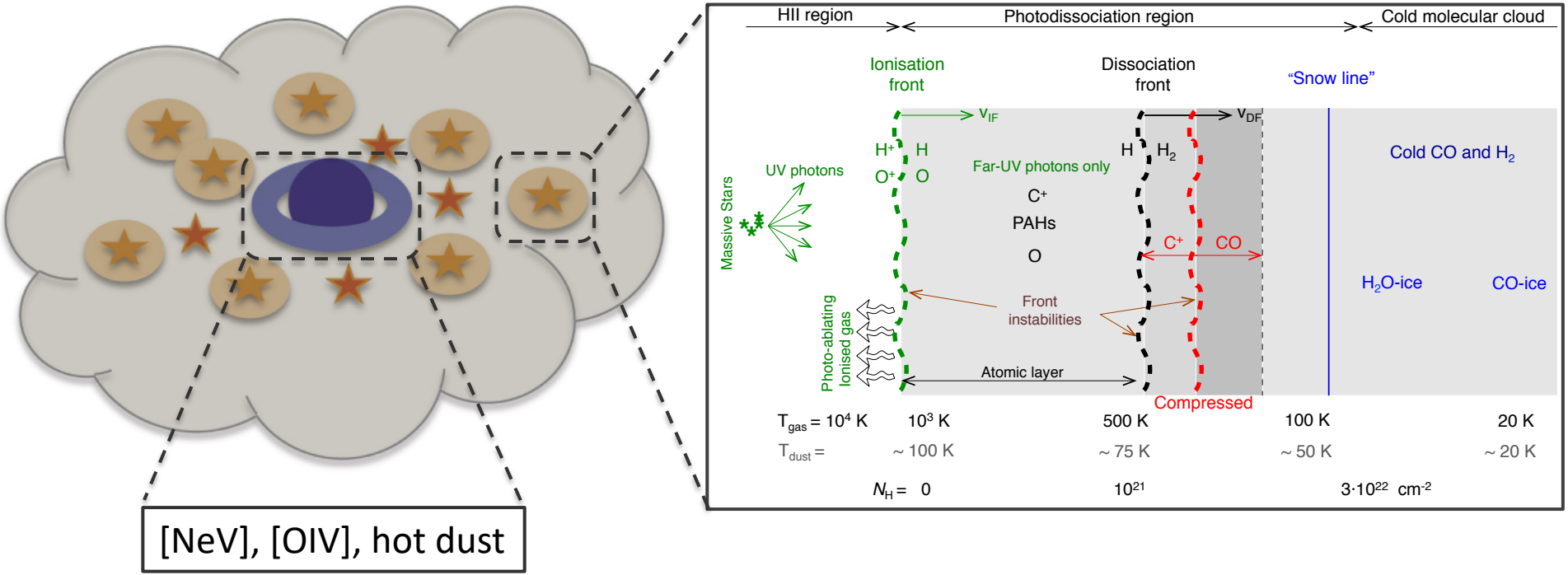
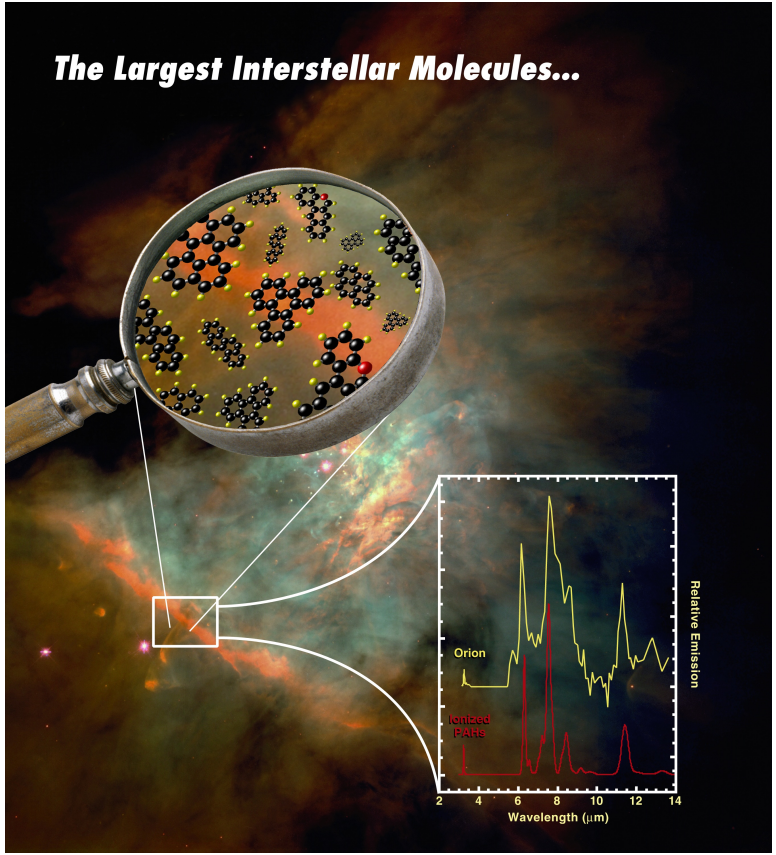
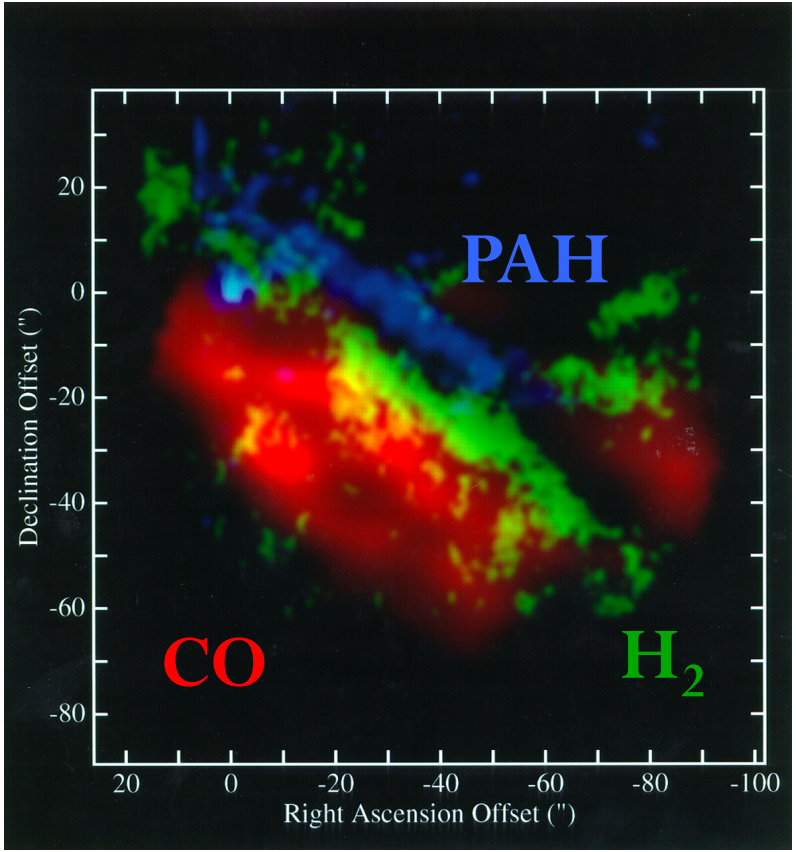


[NeV], [OIV], hot dust

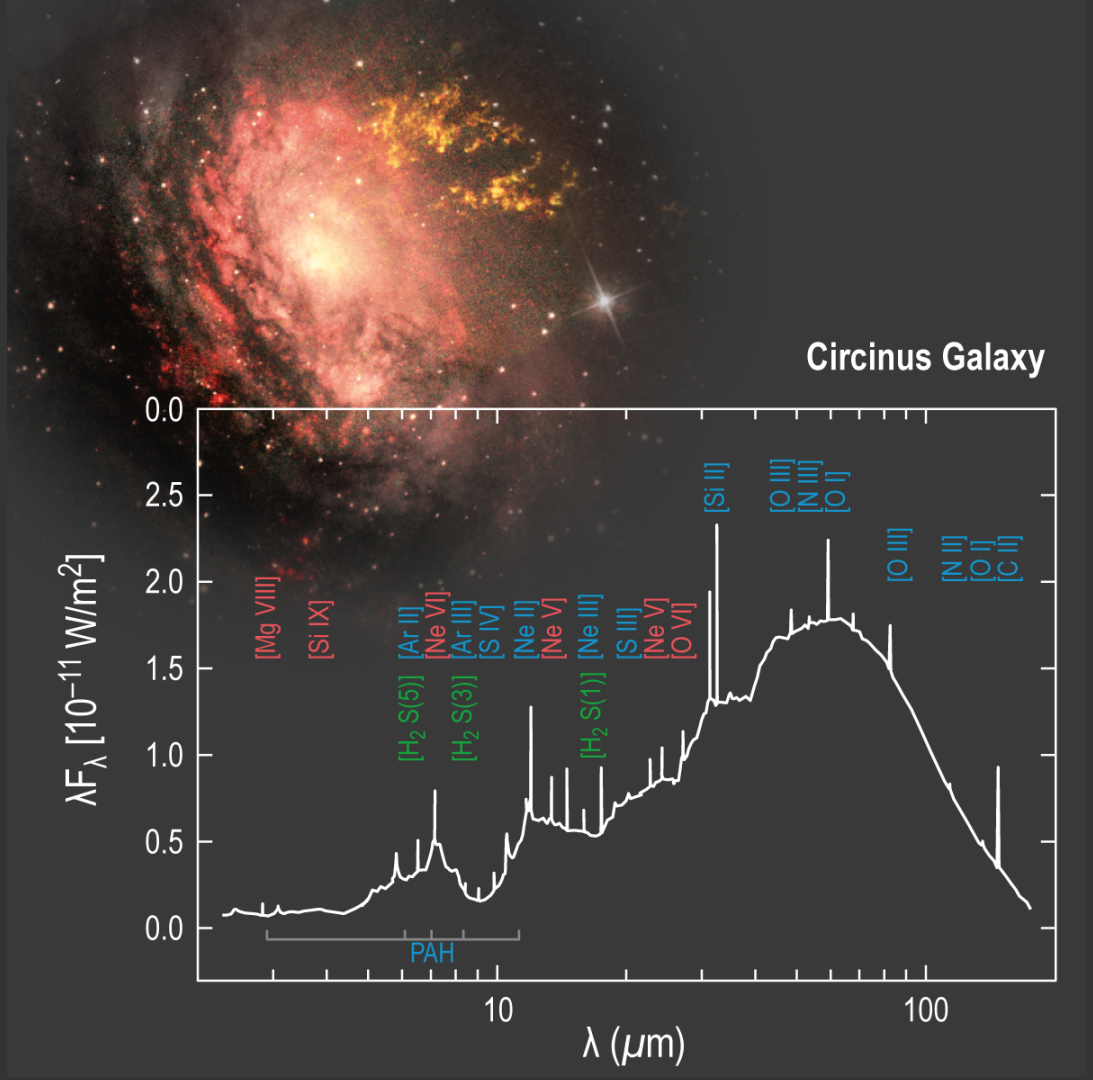
Figures adapted from Roebuck et al. 2016 and Goicoechea et al. 2016

Resolving the interstellar medium in the Milky Way





Hollenbach & Tielens 1997



Star formation

Black hole accretion

Warm molecular gas

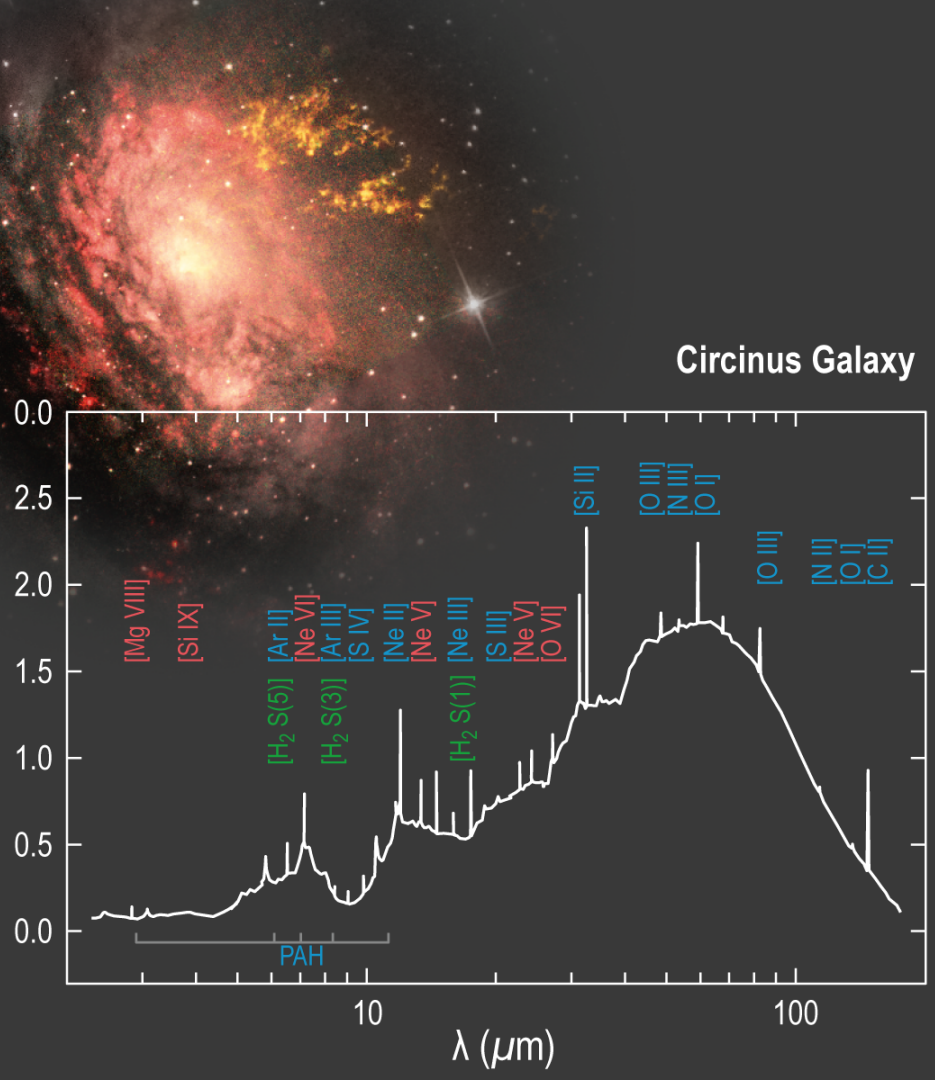
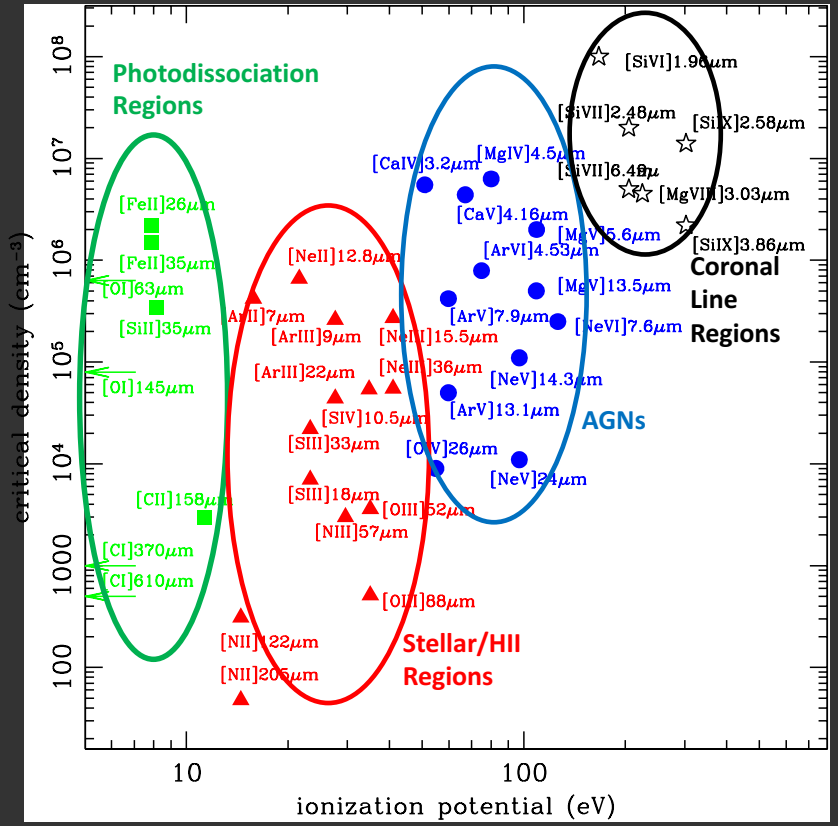


Table 1.1-1 Key infrared diagnostic features

Species	Wavelength	Φ[eV]	Diagnostic Utility
Ionized Atomic Gas			
Ne V	14.3, 24.3	97.1	AGN strength/accretion rate
O IV	25.9	54.9	AGN strength/accretion rate (hot stars)
S IV	10.5	34.8	SB strength/SFR/HII region density,
Ne II	12.3	21.6	ionization
Ne III	15.6, 36.0	41.0	"
S III	18.7, 33.5	23.3	"
Ar III	21.83	27.6	"
O III	51.8, 88.4	35.1	"
N III	57.3	29.6	"
N II	122, 205	14.5	"
			"
Neutral Atomic Gas			
Si II	34.8	8.2	Density and temperature probes of photo-dissociated neutral gas at the interface between HII regions and molecular clouds
O I	63.1, 145		
C II	158	11.3	
C I	370		
Molecular Gas			
H_2	9.66 12.3, 17.0, 28.2		Warm (100-500 K) molecular gas/feedback
HD	37, 56, 112		D/H ratio/gas mass
OH	34.6, 53.3, 79.1, 119		Column density of cold, dense gas, abundance/feedback
OH	98.7, 163		
H_2O	73.5, 90, 101, 107, 180		"
CO	~2600/J		High-J, warm/dense molecular gas/feedback
Dust			
Silicate	9.7, 18		Optical depth. Hot dust emission in QSOs
PAH	6.7, 7.7, 8.5, 11.3, 17		PDR tracer. Star formation rate. Grain properties



Spinoglio et al. 2018

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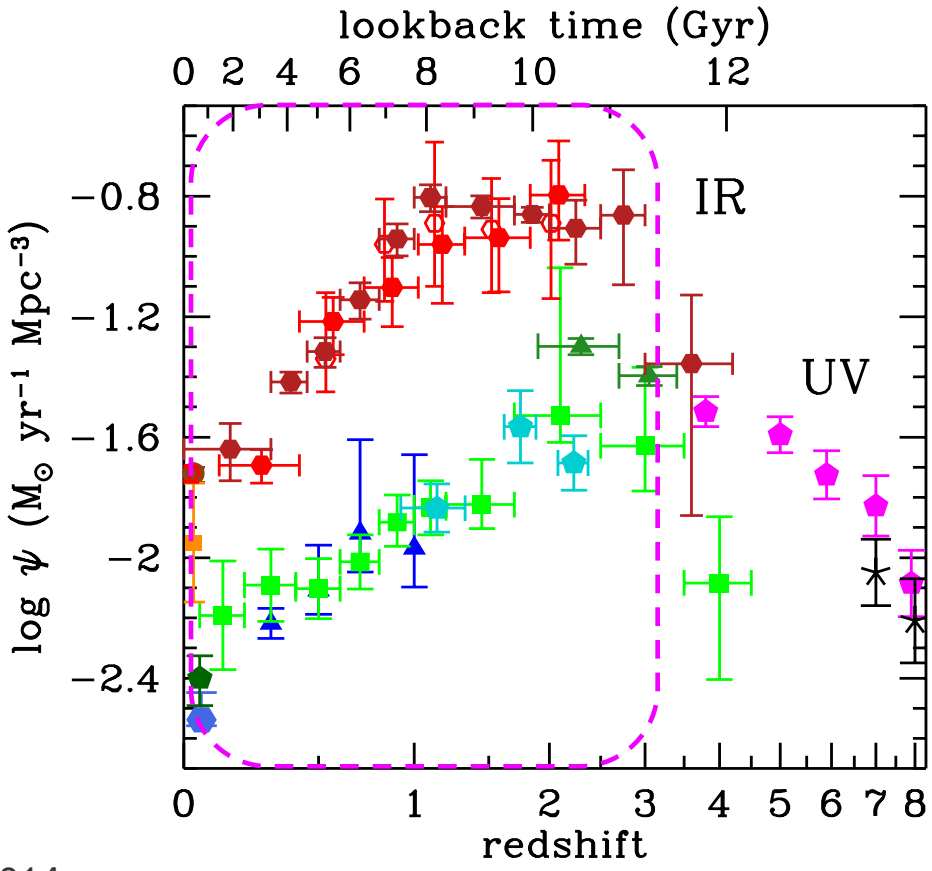
Evolving interstellar medium

1. Molecular gas
2. Dust content and dust obscuration
3. Ionized and neutral gas
4. Polycyclic Aromatic Hydrocarbons
5. AGN heating



Madau & Dickinson 2014

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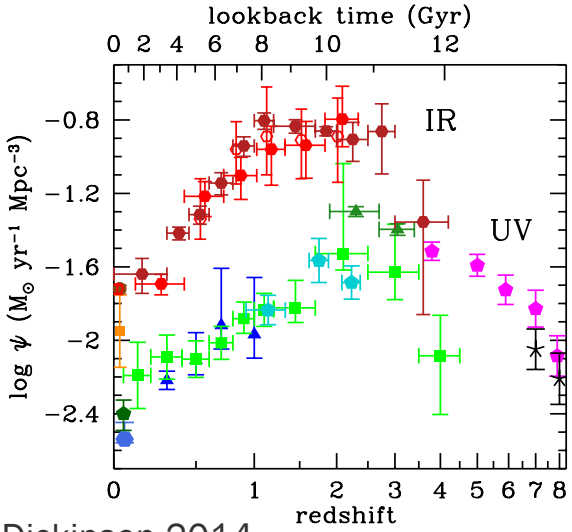

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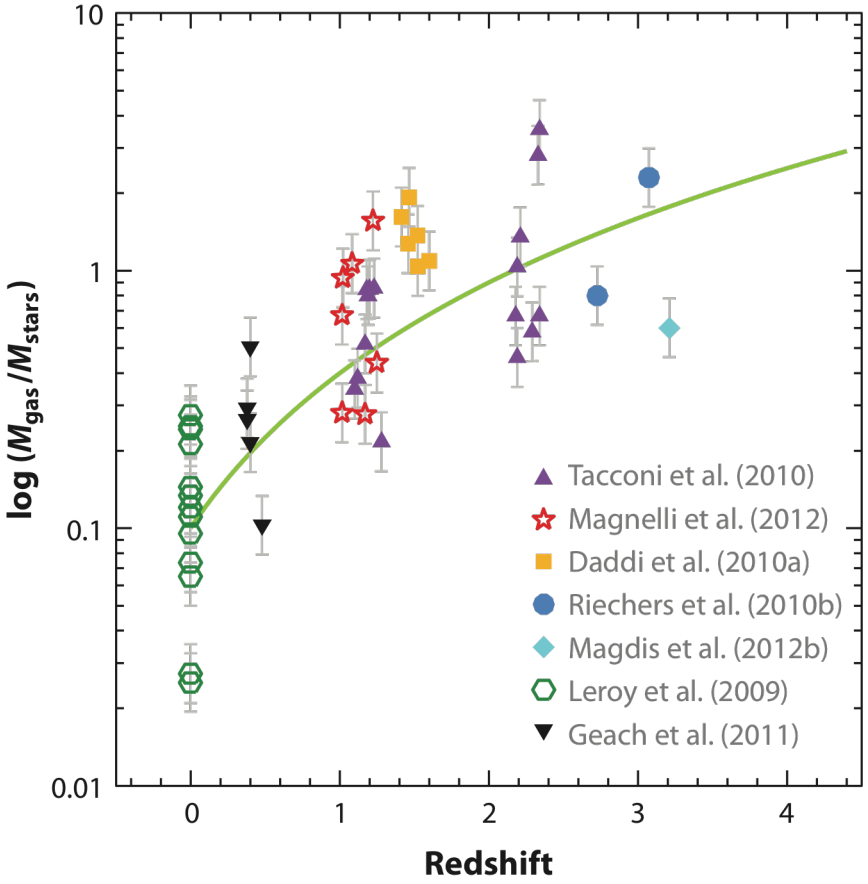

Carilli & Walter 2013

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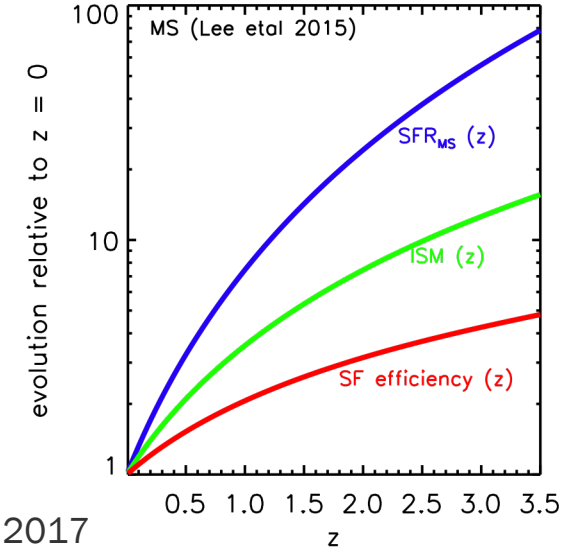
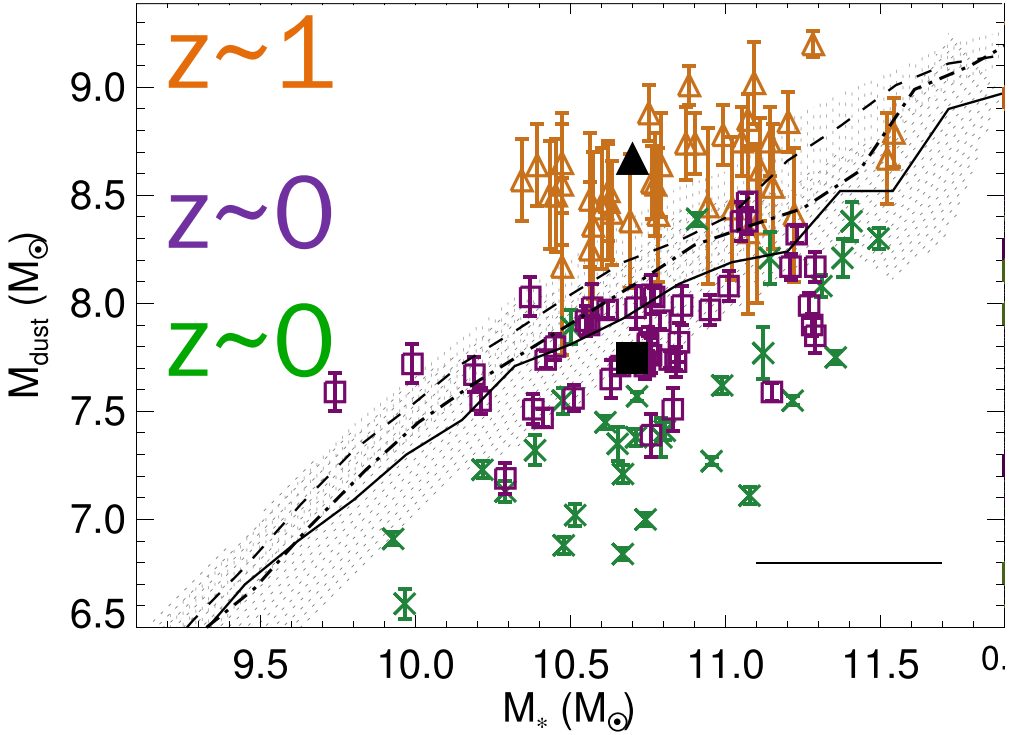


Scoville et al. 2017



Kirkpatrick et al. 2017

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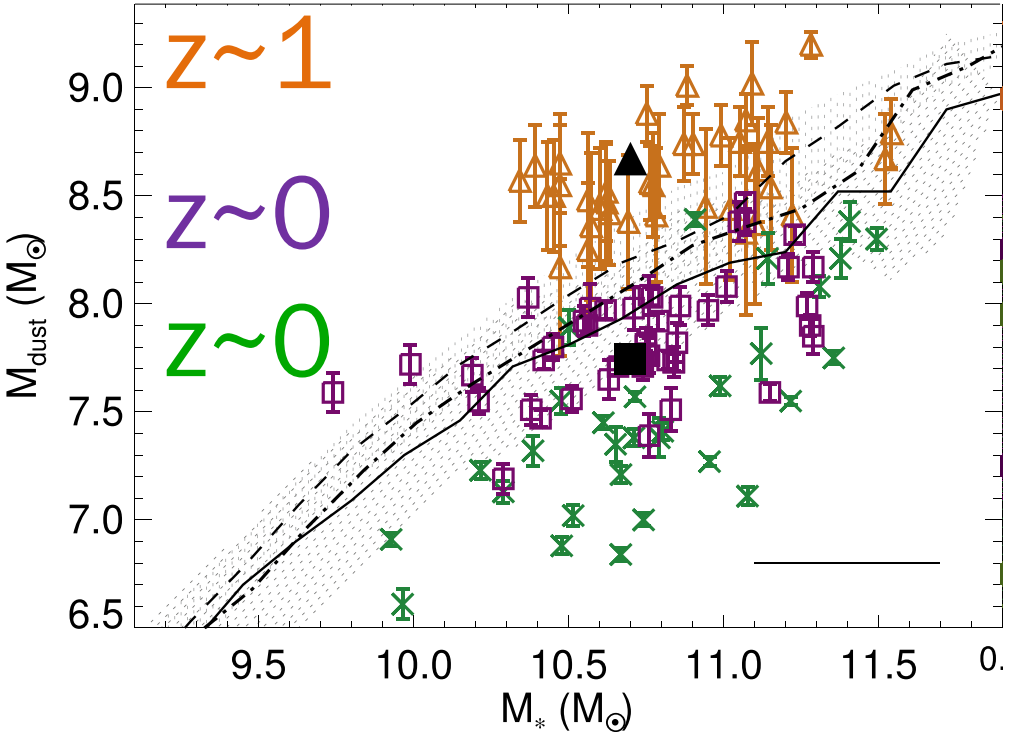

Kirkpatrick et al. 2017

Currently limited to massive galaxies: LMT/TolTEC will measure the dust masses for galaxies 10 x less massive, and from 2020-2022, will do so for tens of thousands of galaxies from z=0-10

toltec.astro.umass.edu

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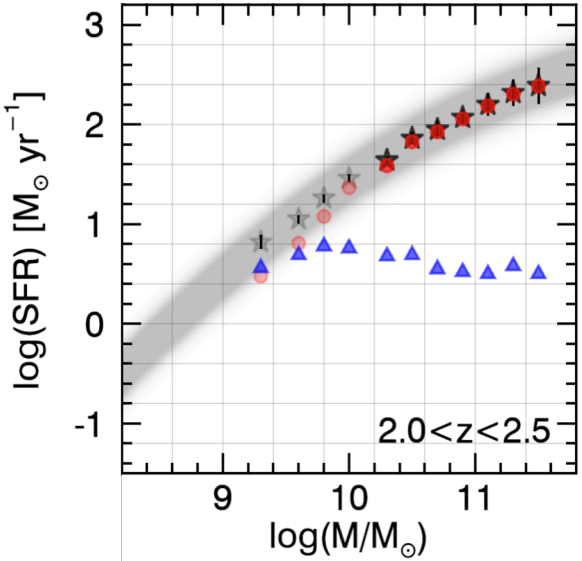
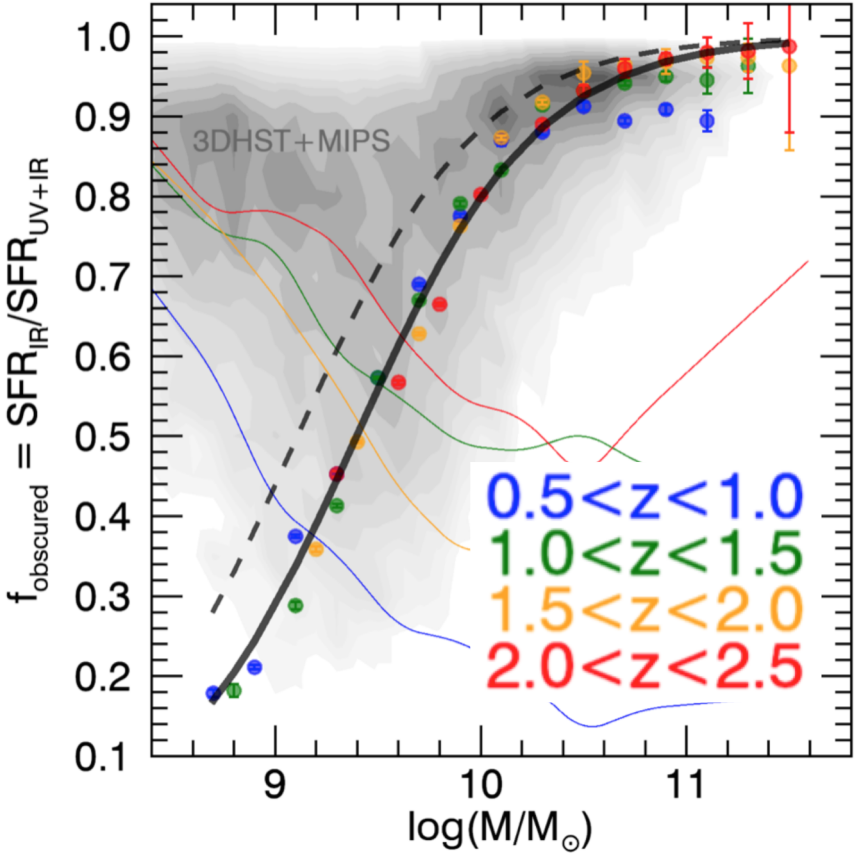


Obscured

Unobscured



Whitaker et al. 2017

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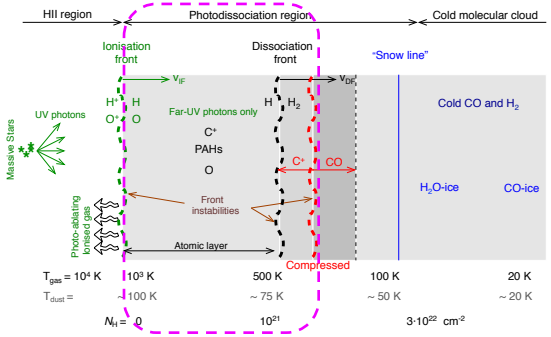
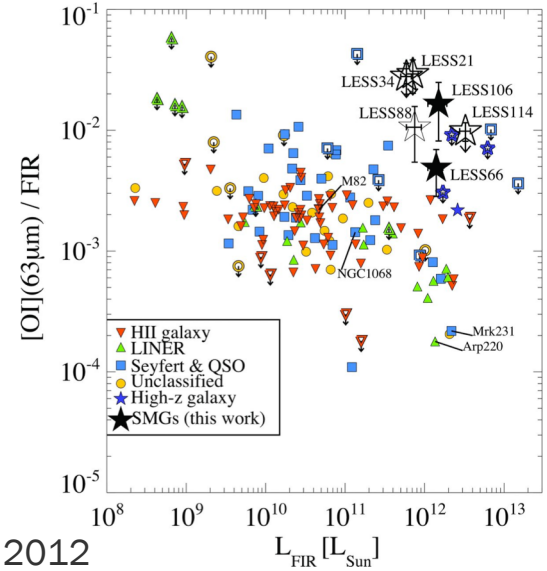
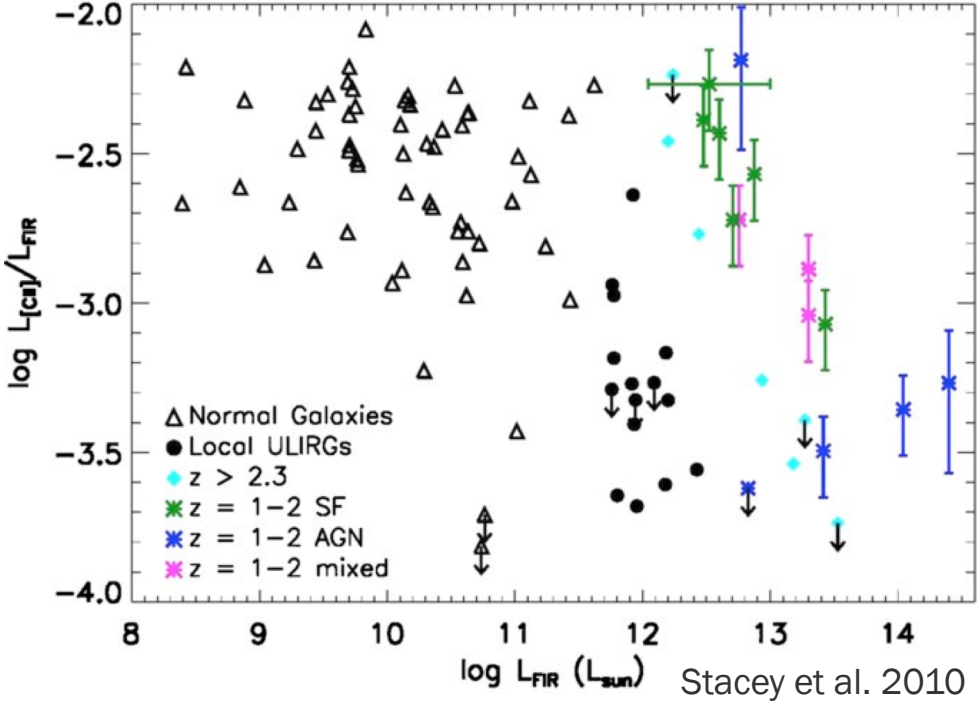




Coppin et al. 2012



Stacey et al. 2010

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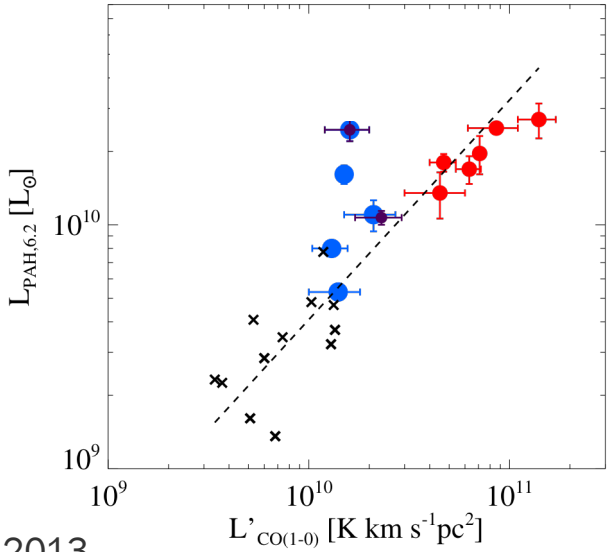
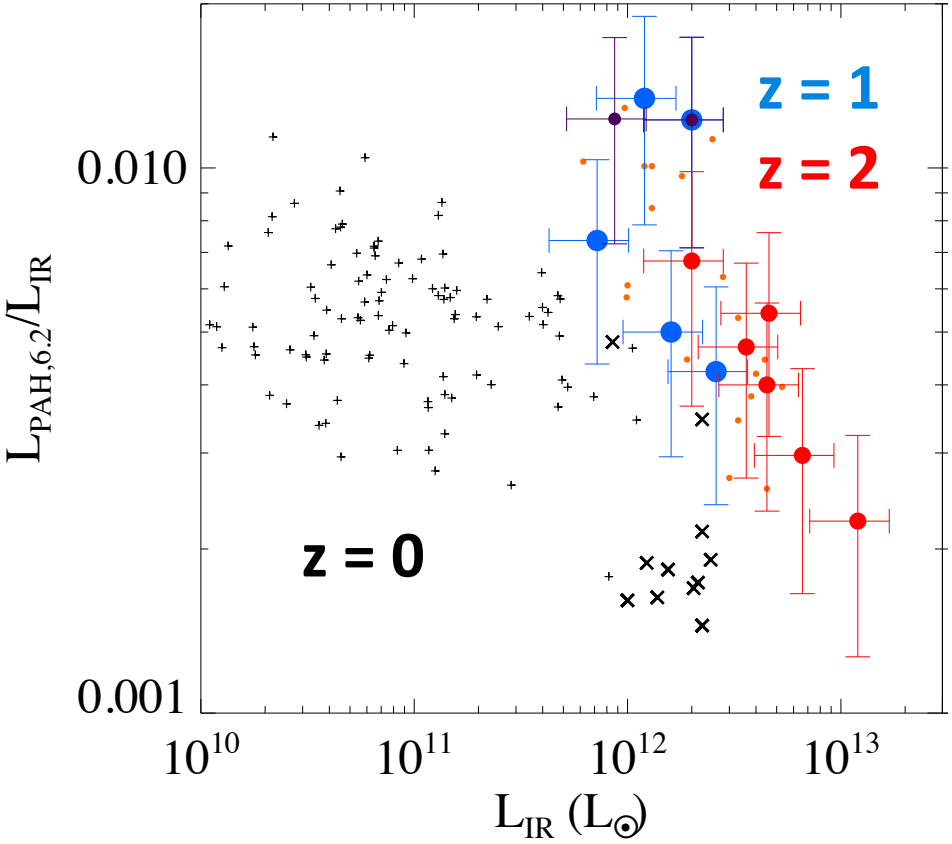


Pope et al. 2013



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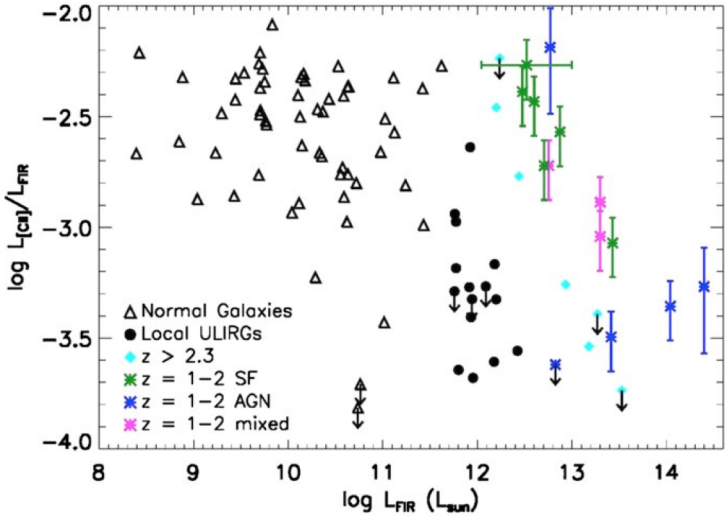
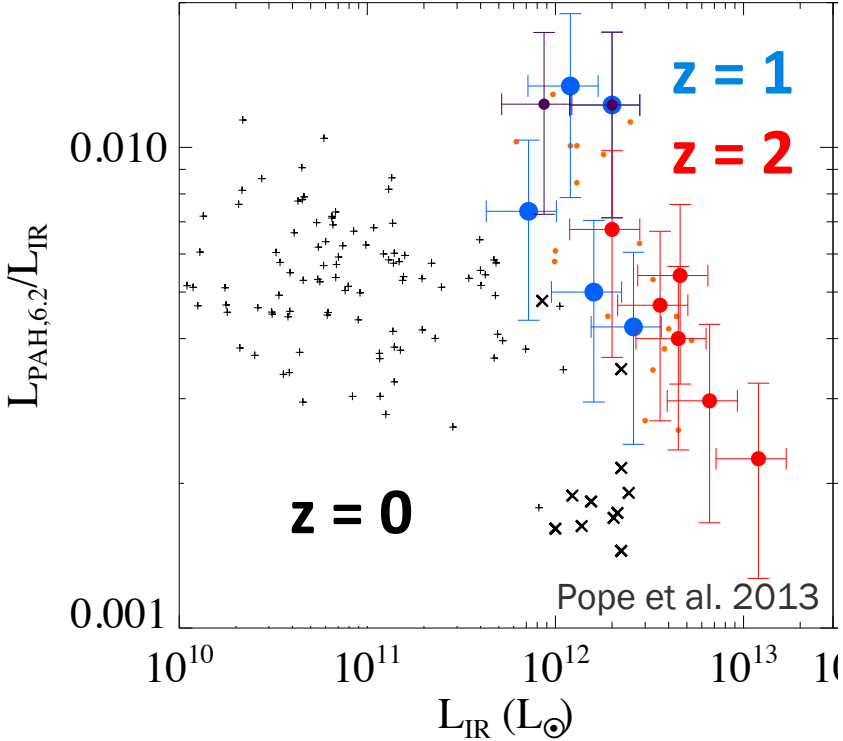


Stacey et al. 2010



Need to look at PAH and [CII] in the **same** galaxies to understand this connection: Jed McKinney (UMass grad student) working on this in z~2 galaxies..... Stay tuned!

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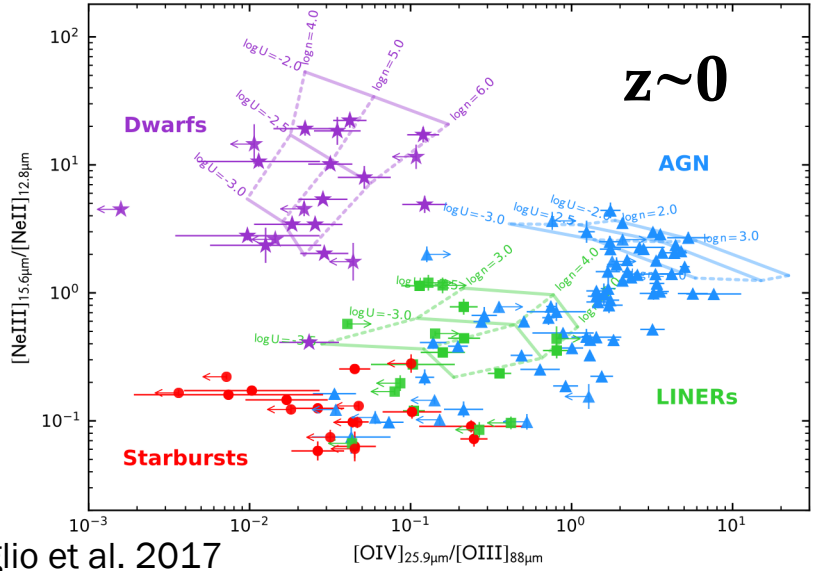
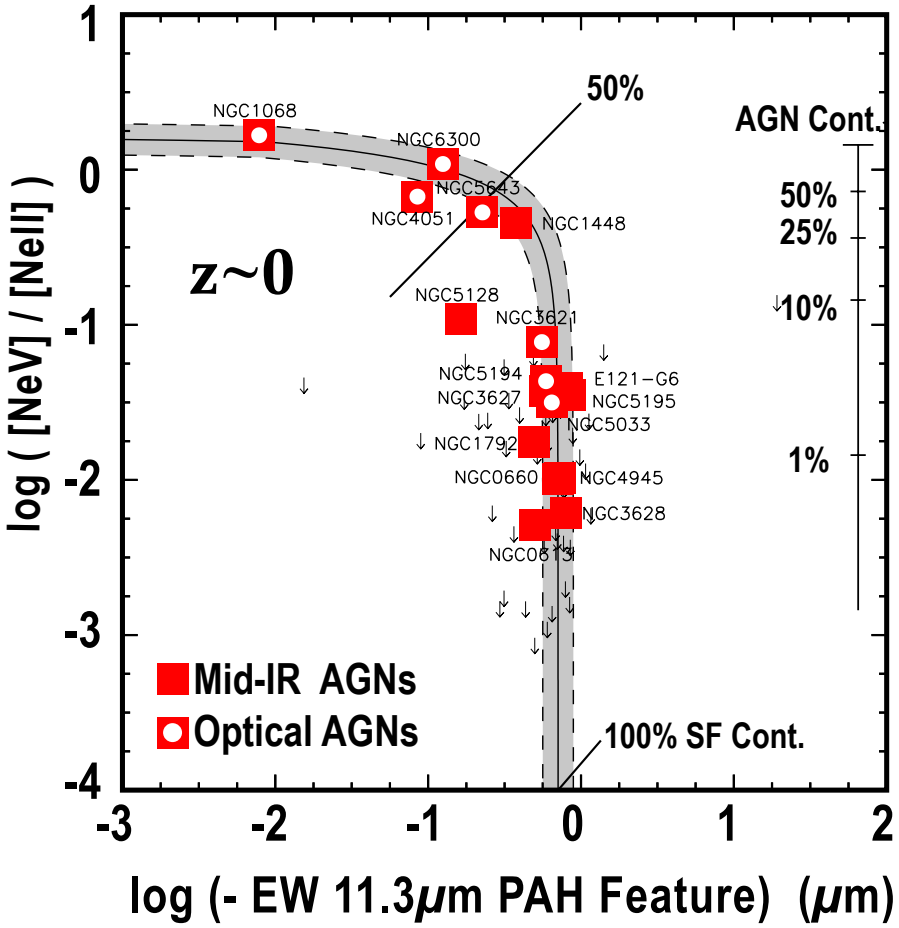


Spinoglio et al. 2017



Goulding & Alexander (2009)

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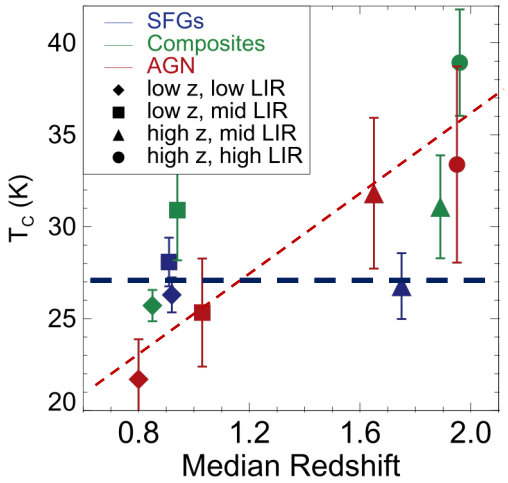

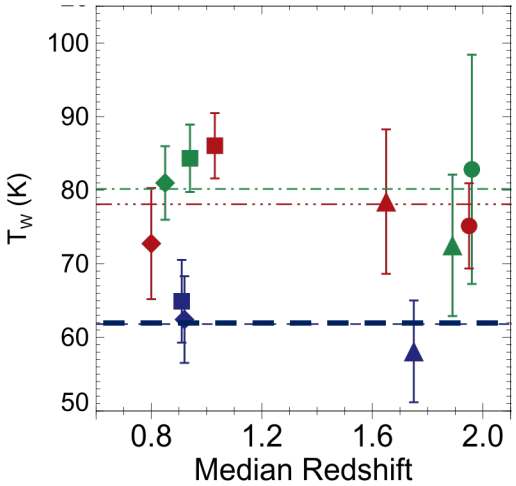

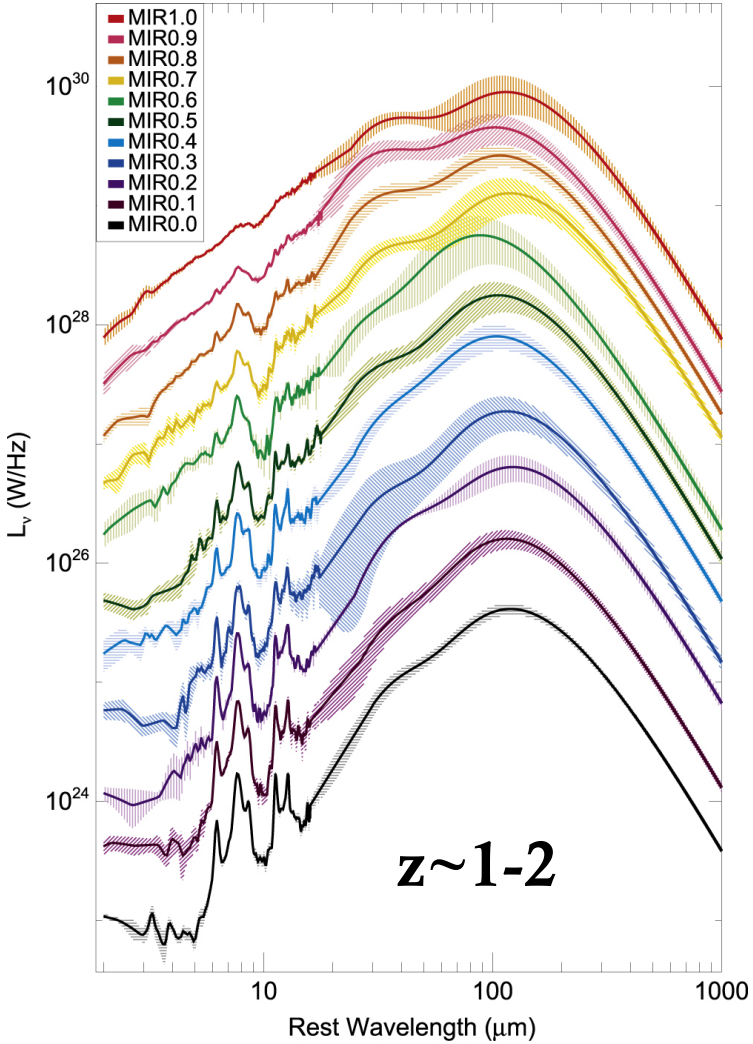

Kirkpatrick et al. 2015

Evolving interstellar medium: What does it all mean?

1. Molecular gas
   - gas fraction ⬆️ ~10 from z=0-1
2. Dust content and dust obscuration
   - dust mass ⬆️ ~10 from z=0-1
   - obscuration (per stellar mass) **does not** evolve from z=0-2.5
3. Ionized and neutral gas
   - Line/L_{IR} ⬇️ w/ L_{IR} but deficit evolves to higher L_{IR} from z=0-3
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   - evolution not well constrained

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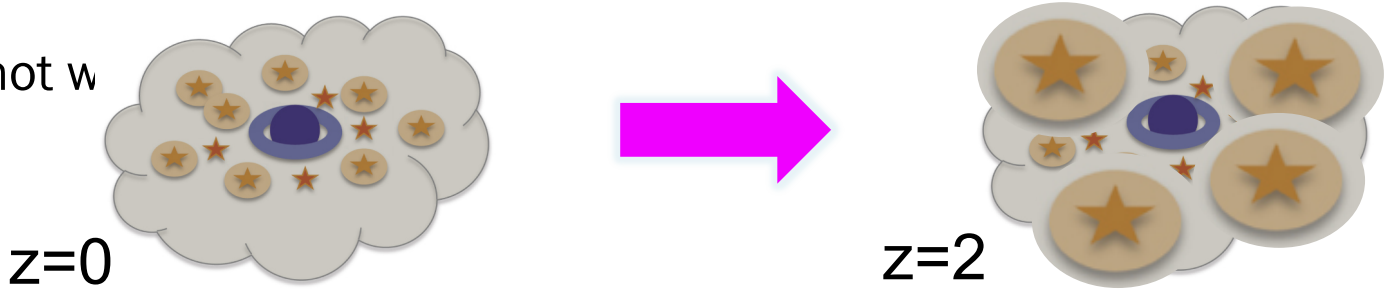
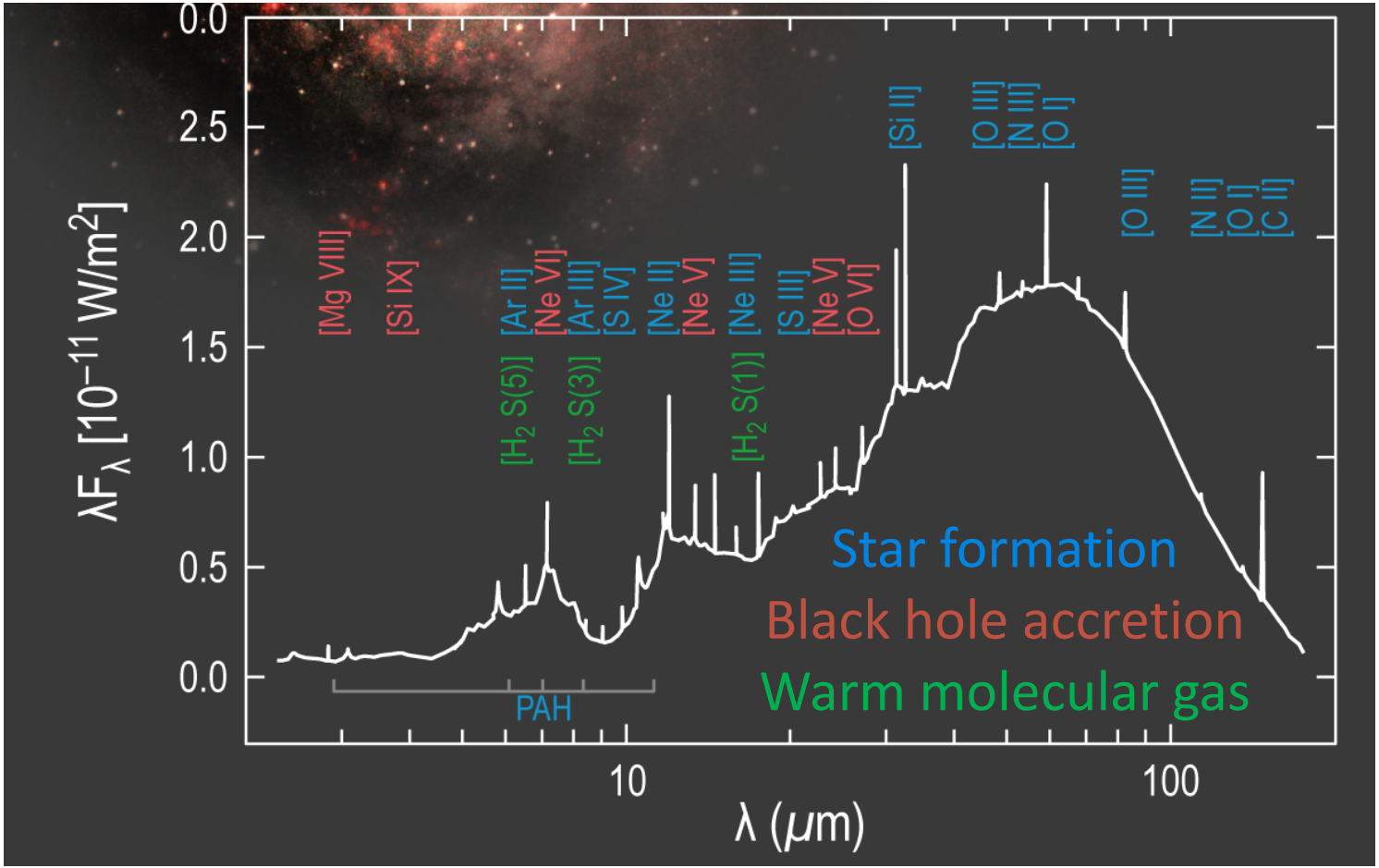
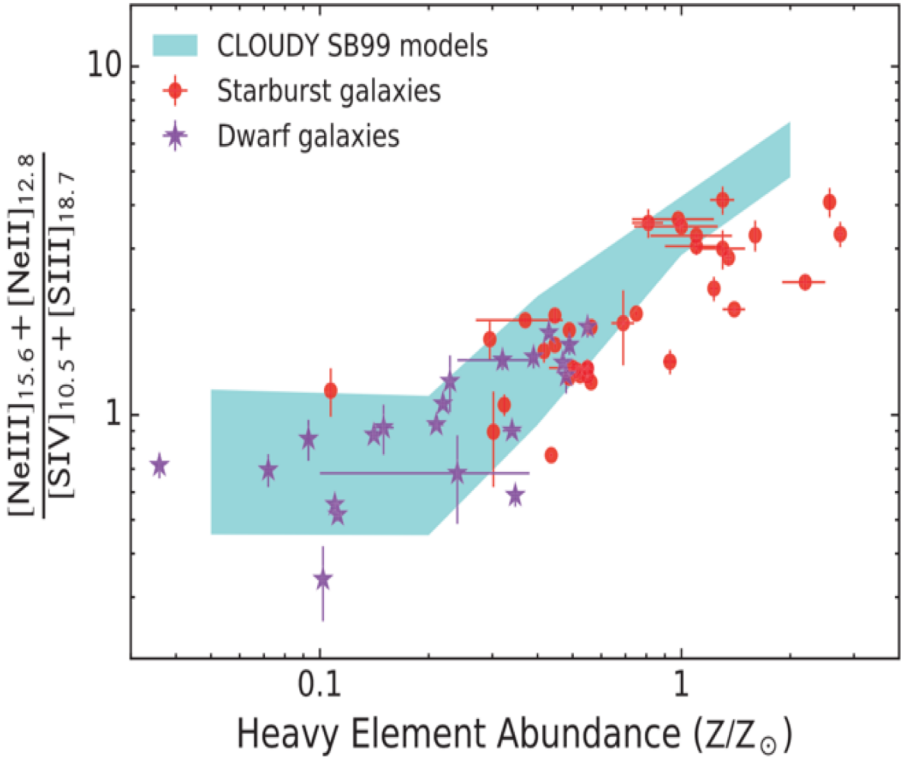


Evolving interstellar medium: Unrealized potential in the infrared



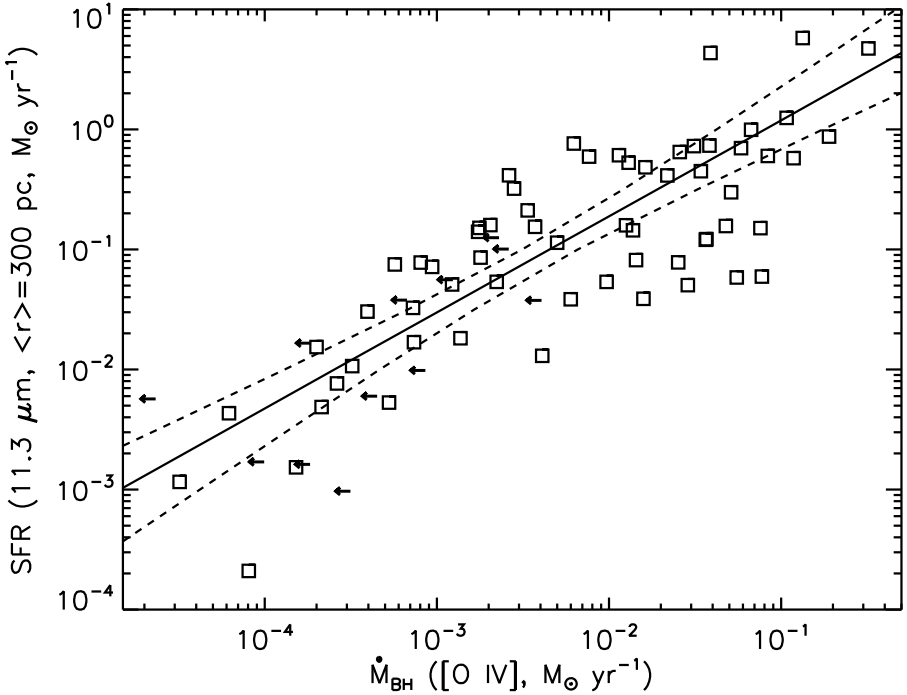
Evolving interstellar medium: Unrealized potential in the infrared

Metallicity

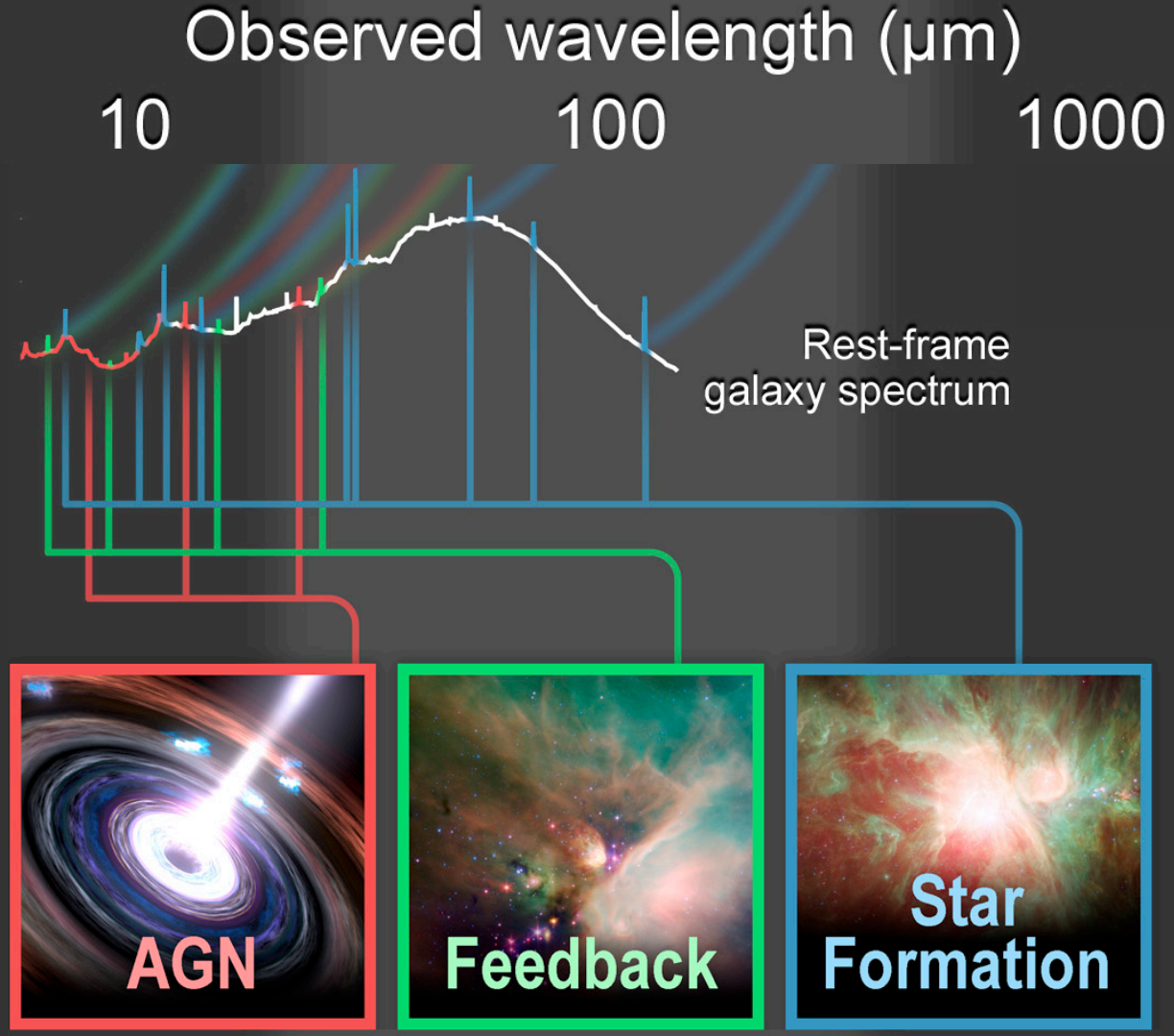


Fernández-Ontiveros et al. 2017

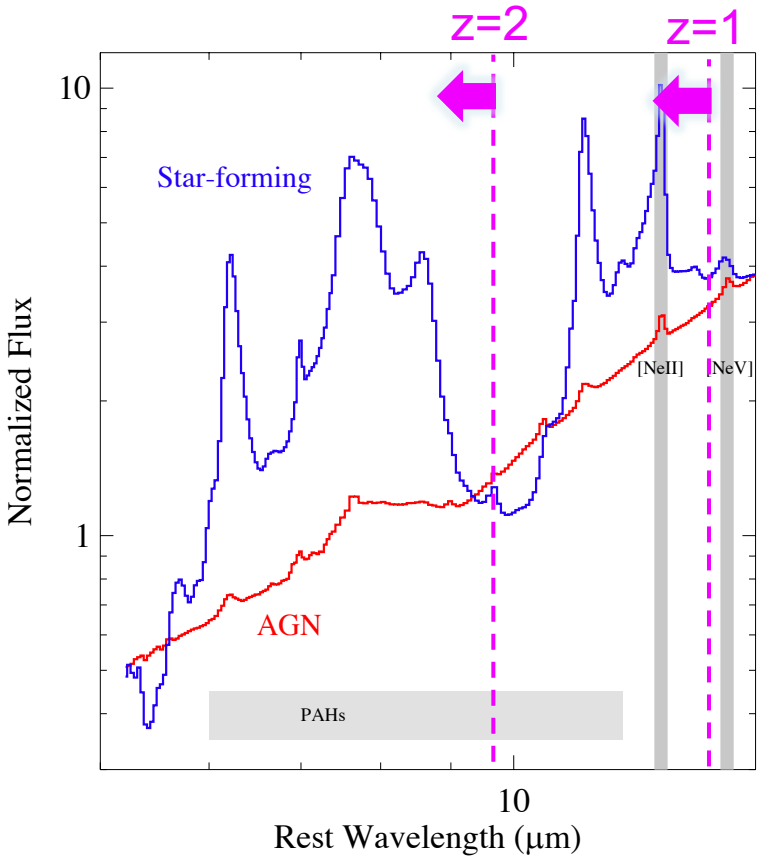
Black hole accretion rates



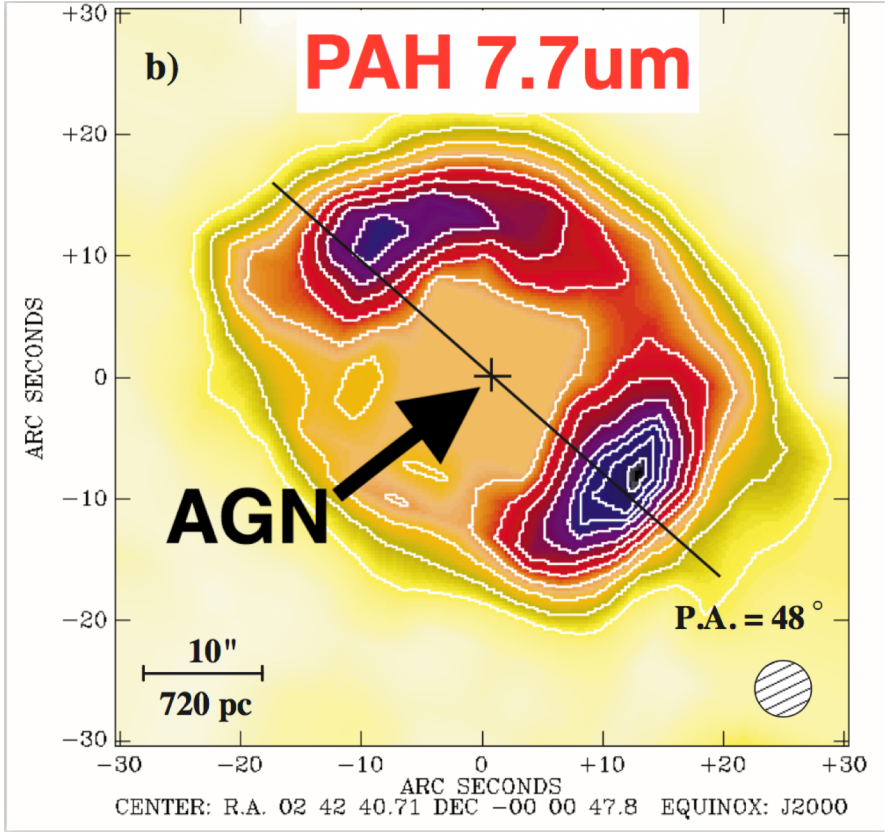
Diamond-Stanic & Rieke 2012


Observed wavelength (μm)
10
100
1000
Rest-frame
galaxy spectrum
AGN
Feedback
Star
Formation

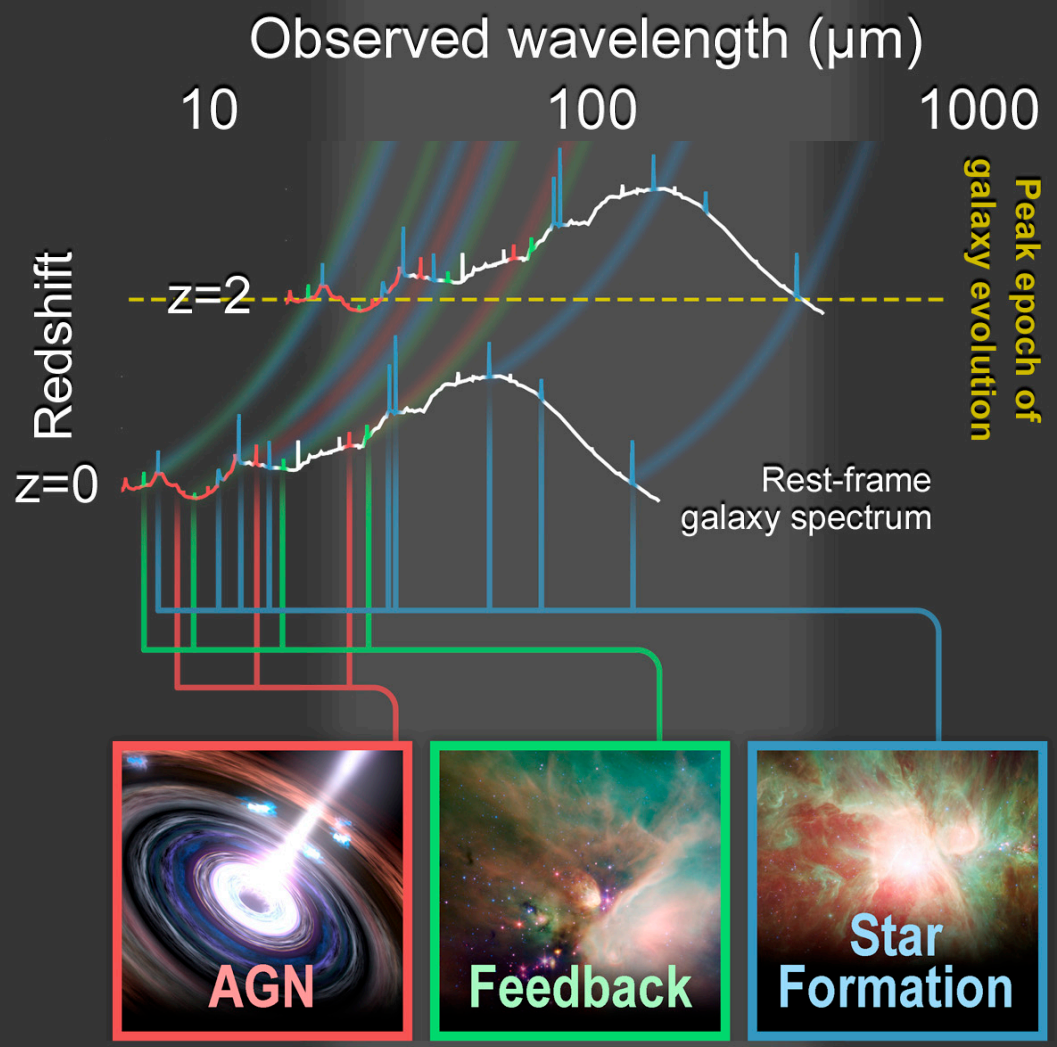
JWST will extend these powerful MIR diagnostics to z~1-2 and begin to spatially resolve

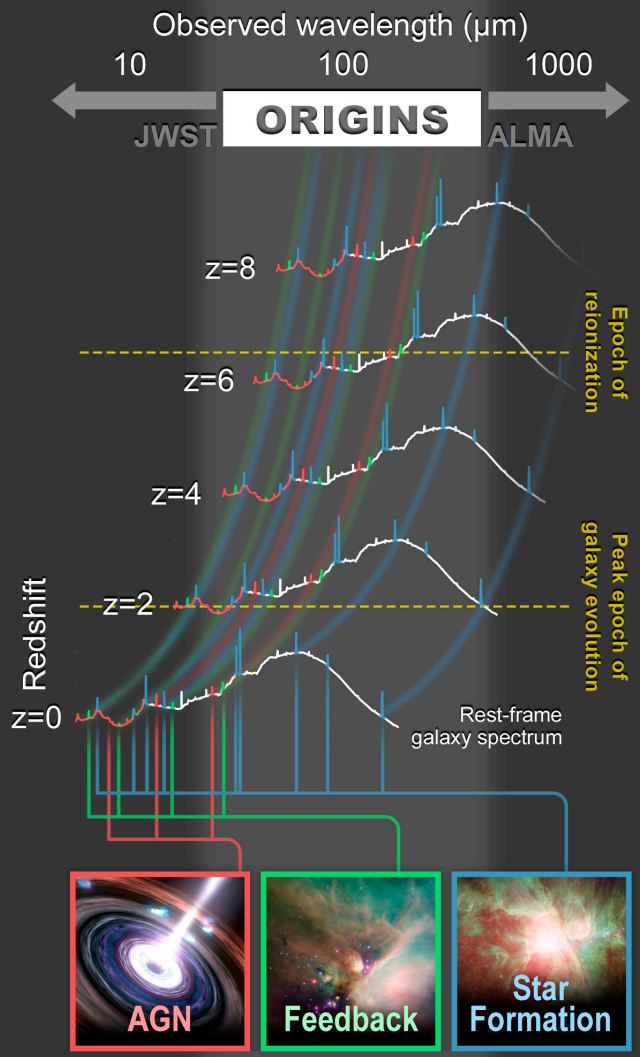


Local ULIRGs: Stierwalt et al. 2013

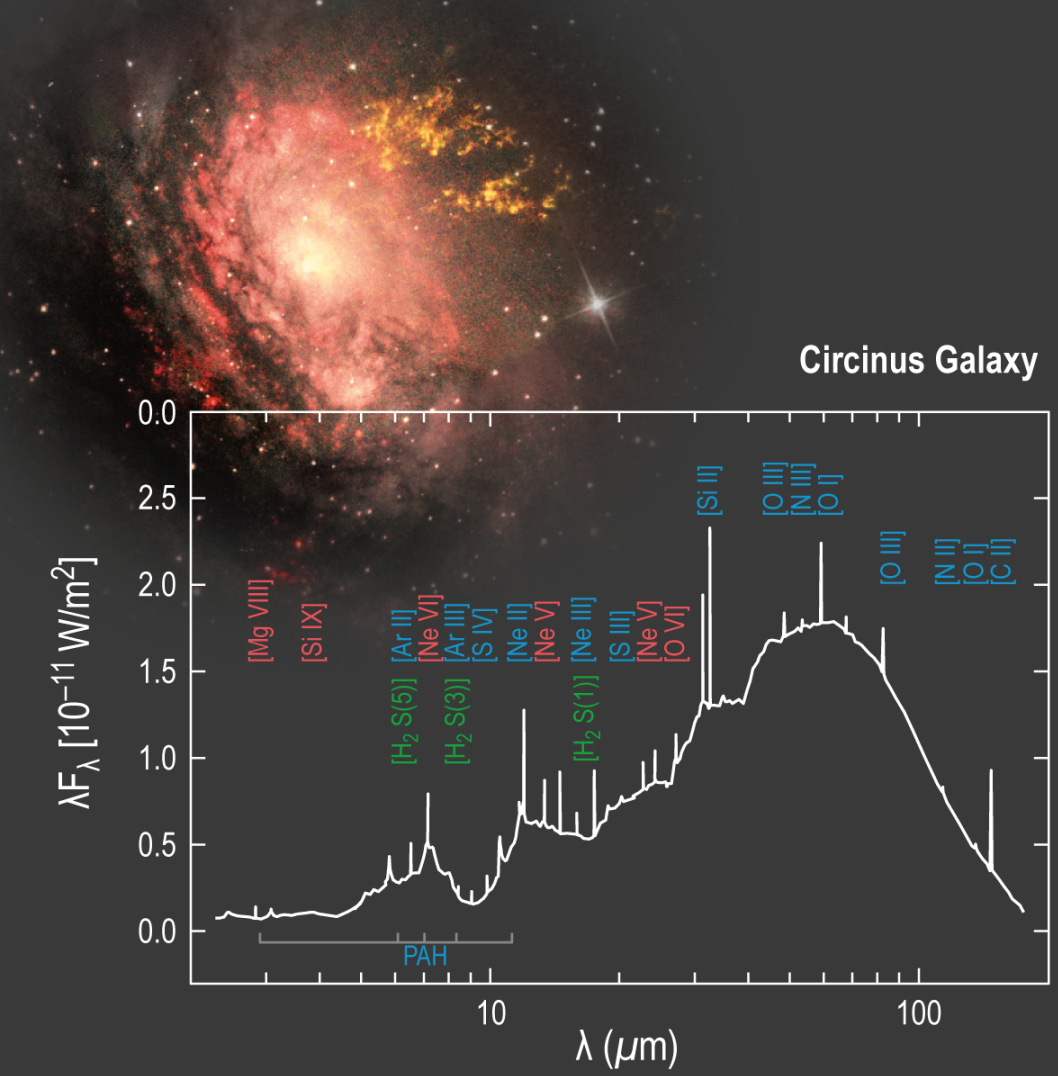


NGC 1068, Le Floc'h et al. 2001


Observed wavelength (μm)
10
100
1000
Redshift
z=2
z=0
Peak epoch of galaxy evolution
Rest-frame galaxy spectrum
AGN
Feedback
Star Formation


Observed wavelength (μm)
10
100
1000
JWST
ORIGINS
ALMA
z=8
z=6
z=4
z=2
z=0
Redshift
Epoch of reionization
Peak epoch of galaxy evolution
Rest-frame galaxy spectrum
AGN
Feedback
Star Formation

Summary



- The conditions in the interstellar medium in galaxies evolve from z=0-3: more gas, more dust, luminous [CII] and PAH emission
- Dust obscuration <u>does not</u> evolve for a given stellar mass galaxy from z=0-2.5
- *Origins Space Telescope* will probe the full suite of ISM tracers in galaxies from z=0-8 (see Friday talk by Lee Armus)