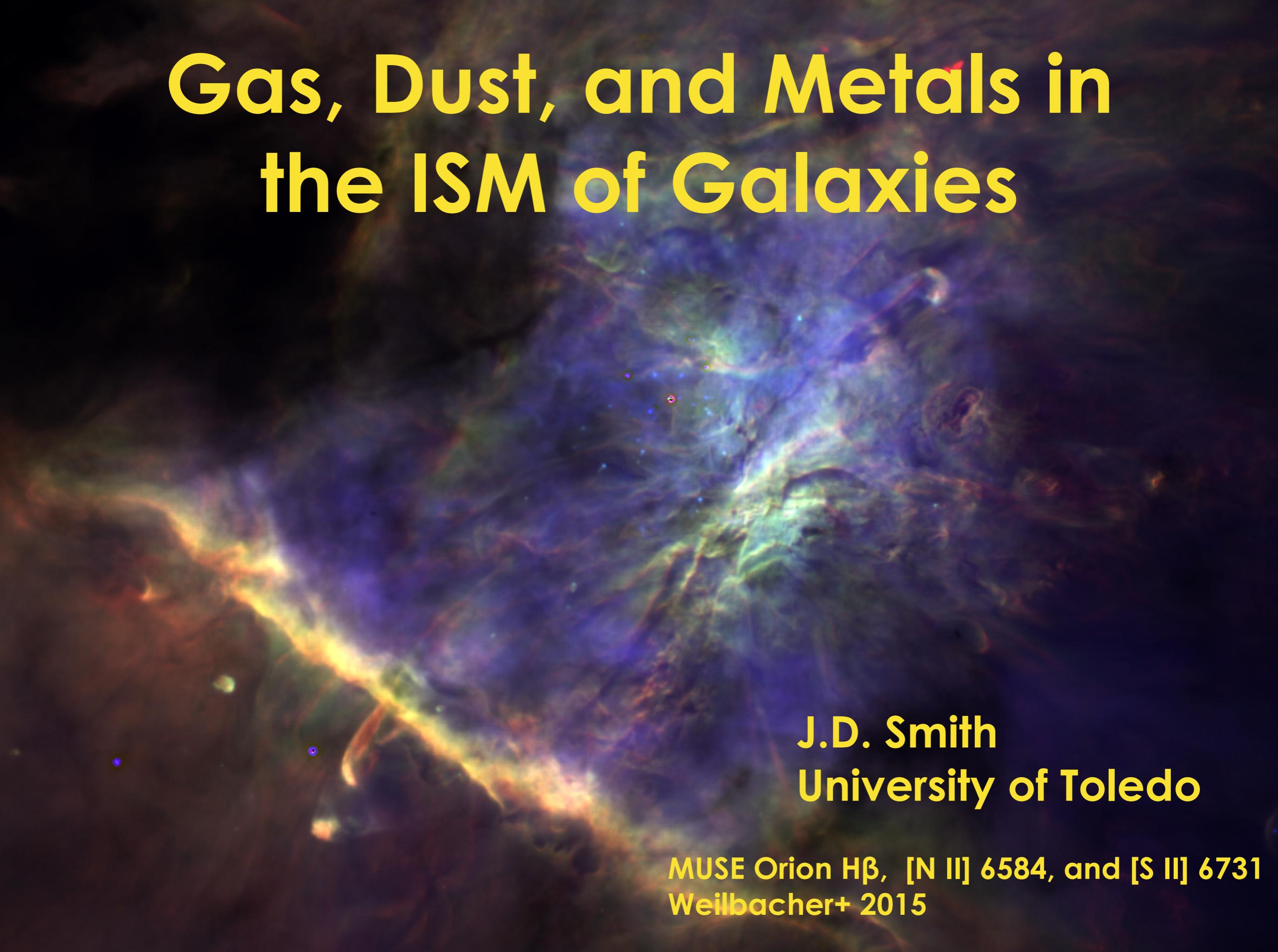


**J.D. Smith**  
**University of Toledo**

**MUSE Orion H $\beta$ , [N II] 6584, and [S II] 6731**  
**Weilbacher+ 2015**

# Gas, Dust, and Metals in the ISM of Galaxies



**J.D. Smith**  
**University of Toledo**

MUSE Orion H $\beta$ , [N II] 6584, and [S II] 6731  
Weilbacher+ 2015

# Gas, Dust, and Metals in the ISM of Galaxies

Impossibly Vague ☞ Delightfully Open-Ended

**J.D. Smith**  
**University of Toledo**

MUSE Orion H $\beta$ , [N II] 6584, and [S II] 6731  
Weilbacher+ 2015

# Gas, Dust, and Metals in the ISM of Galaxies

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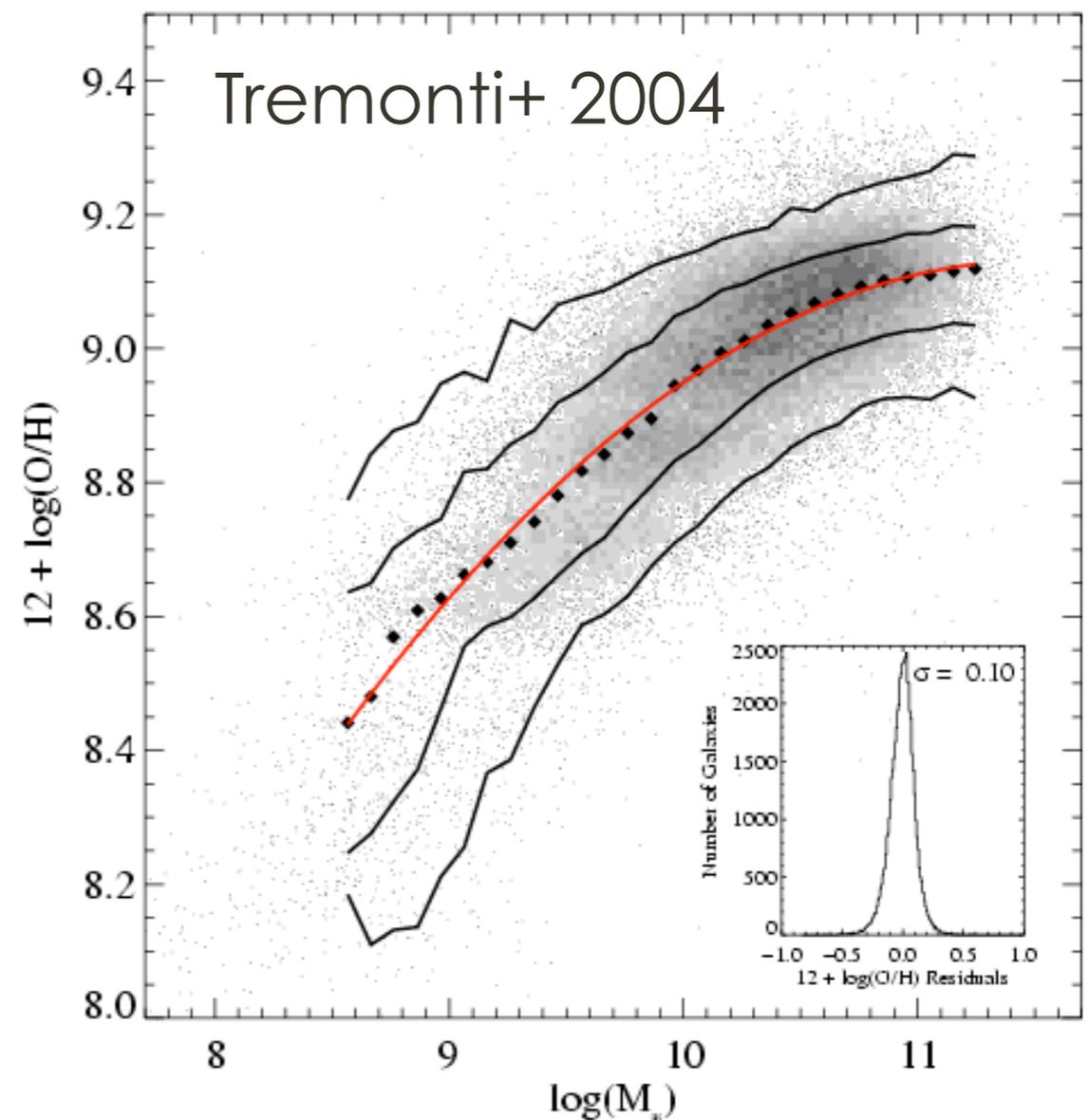
MUSE Orion H $\beta$ , [N II] 6584, and [S II] 6731  
Weilbacher+ 2015

Spitzer, Dust

# 12+log(O/H) — The (Elusive) Oxygen Abundance Scale

*What does 12+log(O/H) mean?*

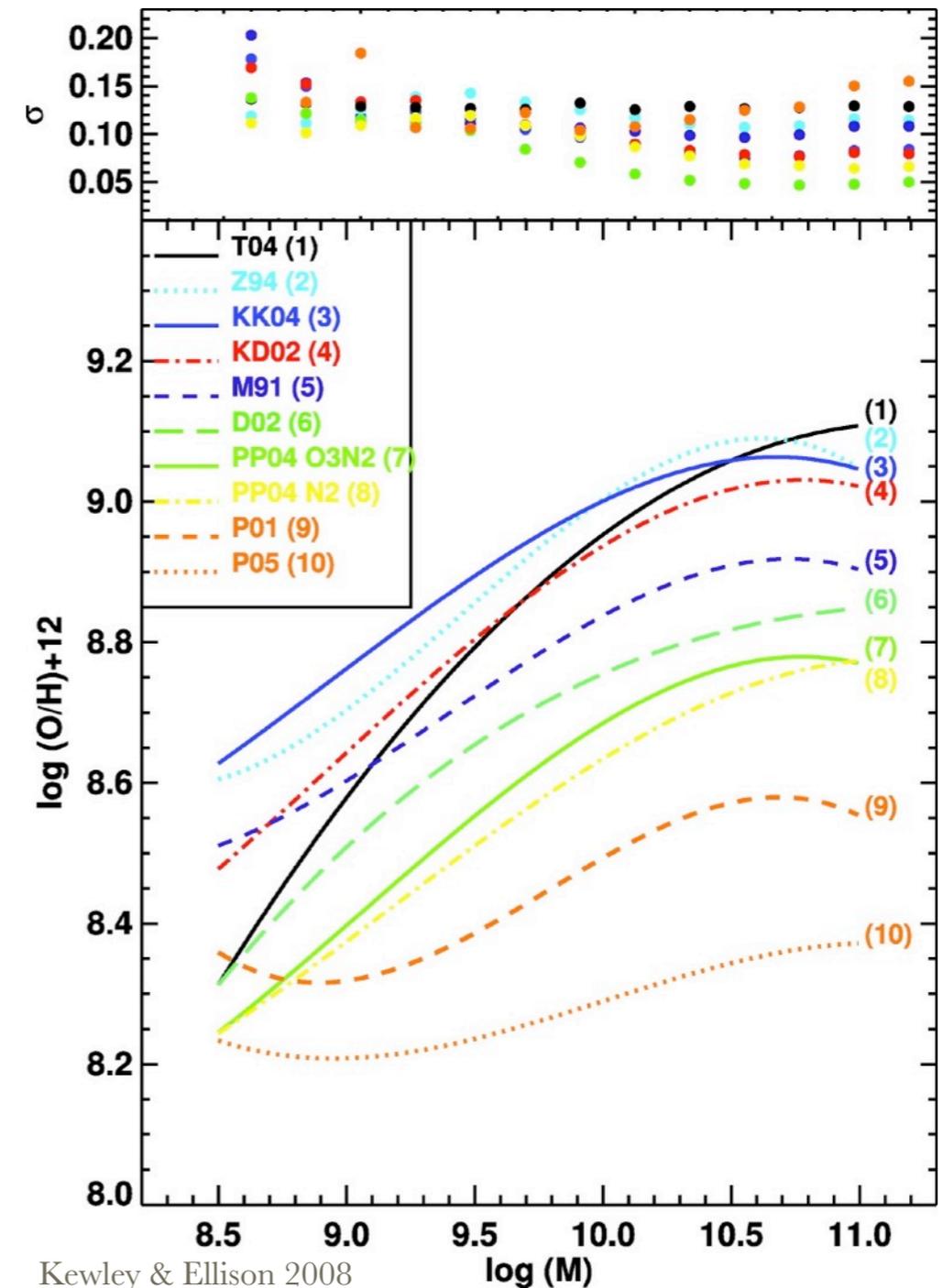
- Using Oxygen is common for metal abundance determinations: convenient bright optical transitions.
- Calibrating:
  - 1) to models of HII regions,
  - 2) to “direct” temperature-sensitive measurements
- disagree by factors of ~3–5!



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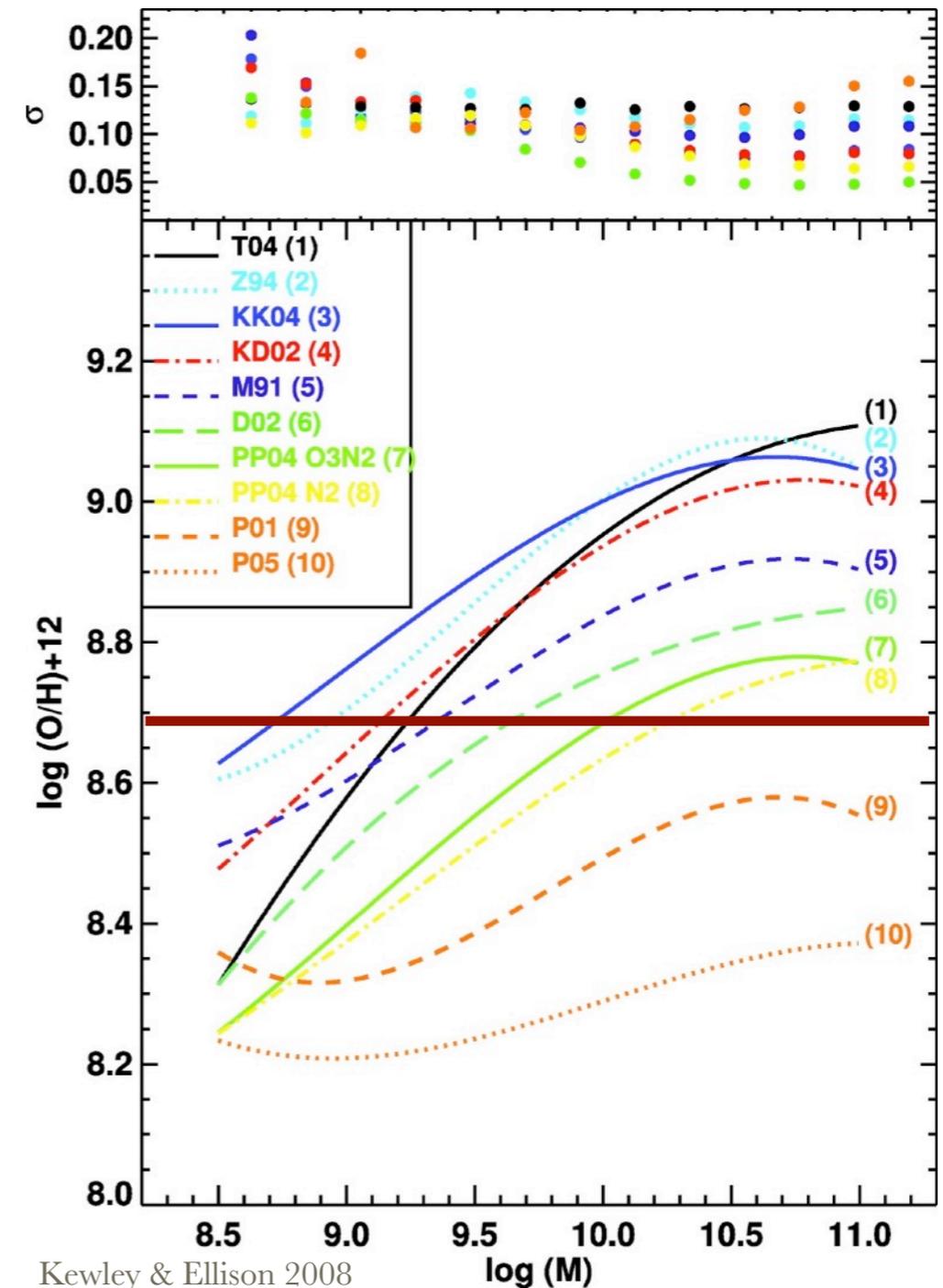
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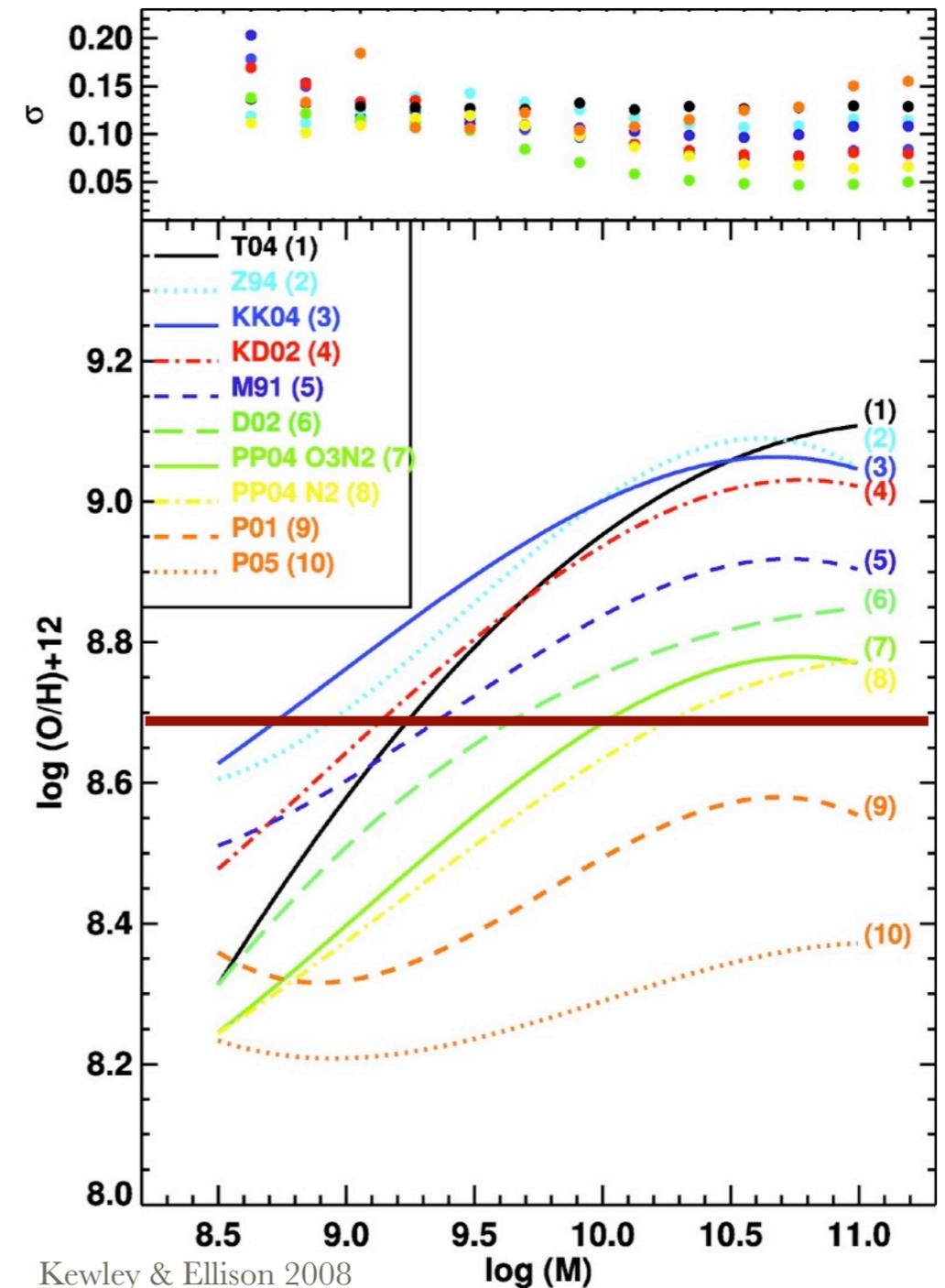
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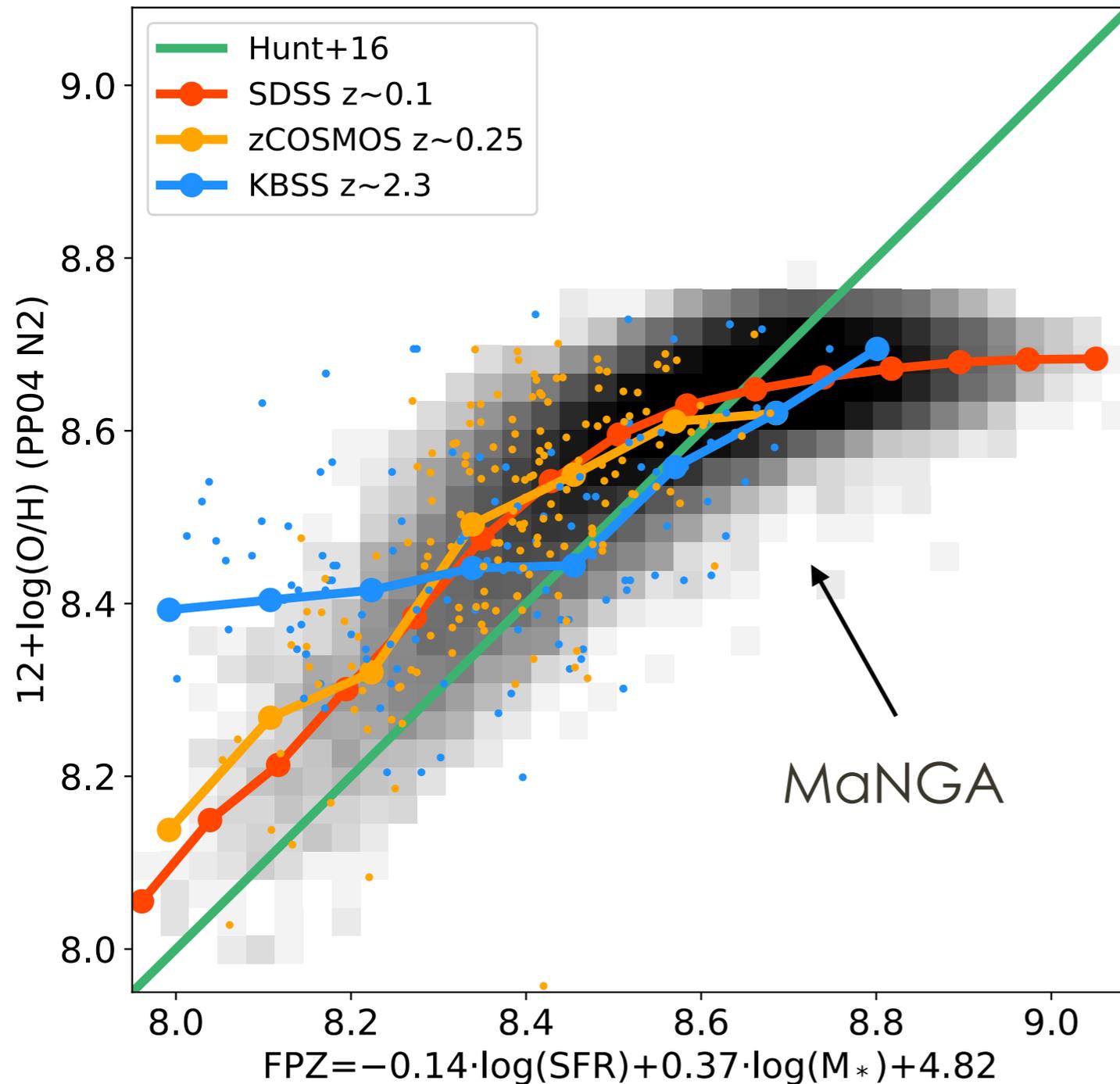
*Is the Universe Super-solar, or Sub-solar?*

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- disagree by factors of ~3–5!



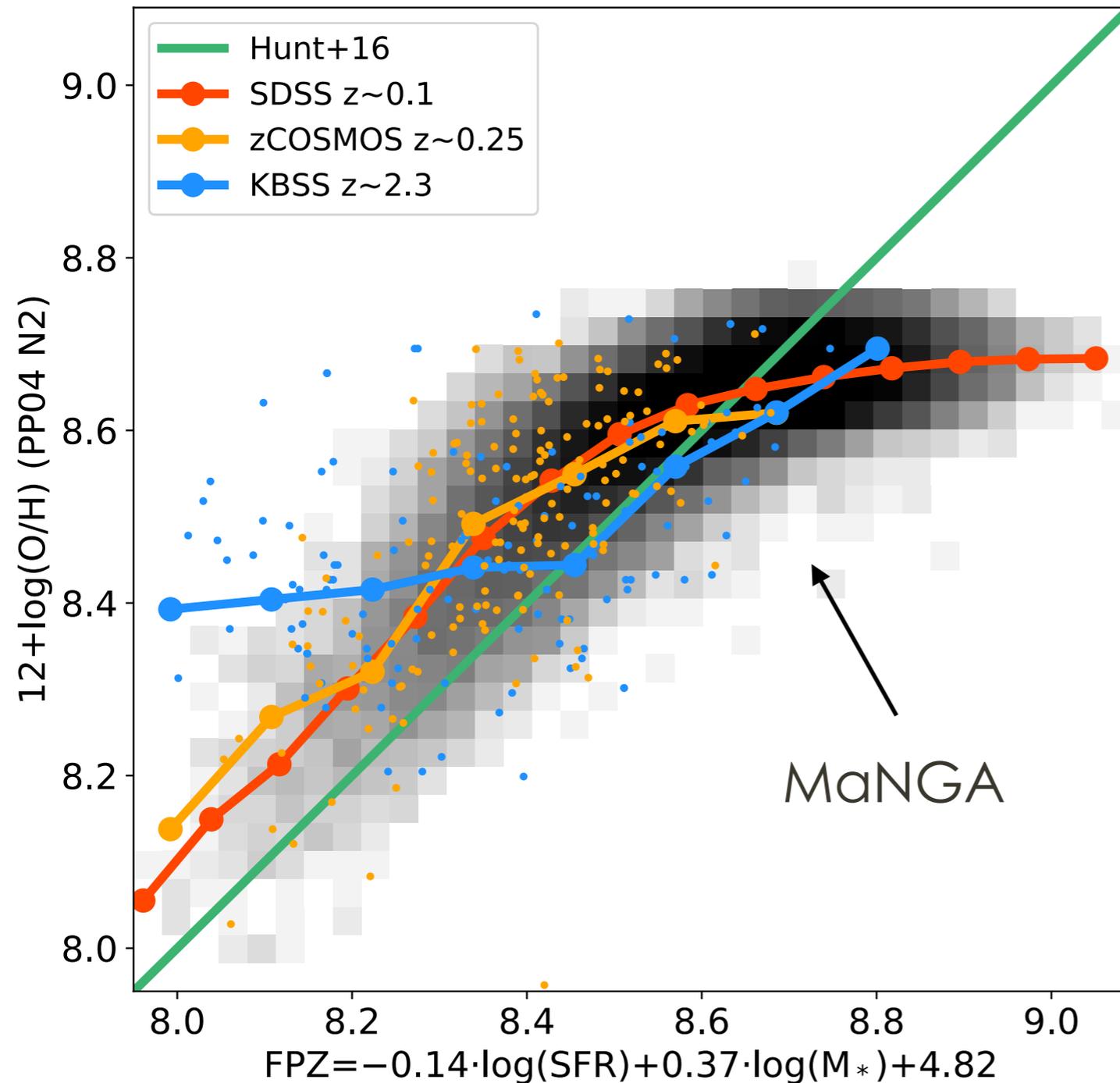
# Metallicity is Fundamental

The  
“**Fundamental  
Metallicity  
Plane**”



Tight relationship  
among **metallicity**,  
**stellar mass**, and  
**star-formation rate**

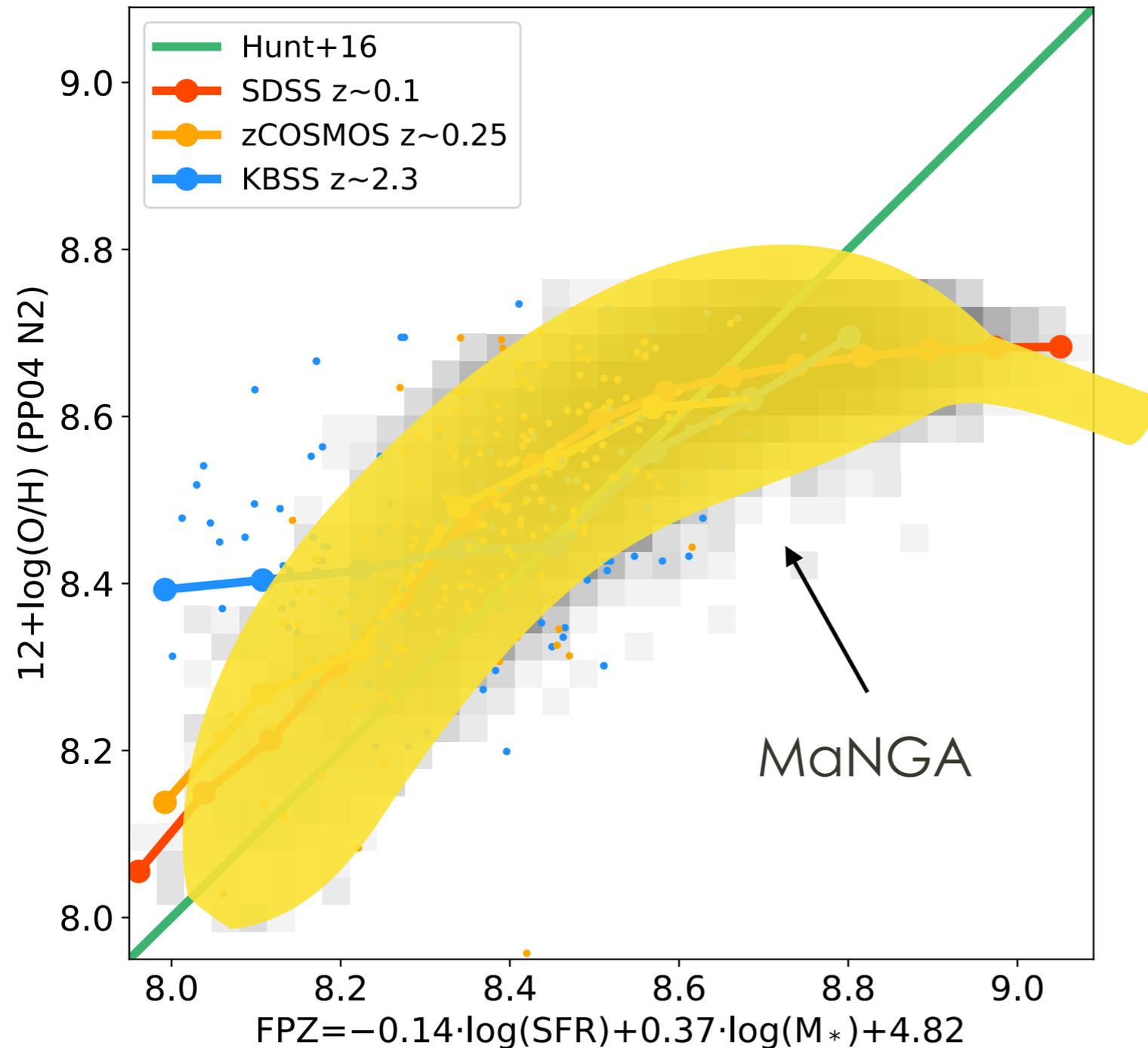
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# Metallicity is Fundamental



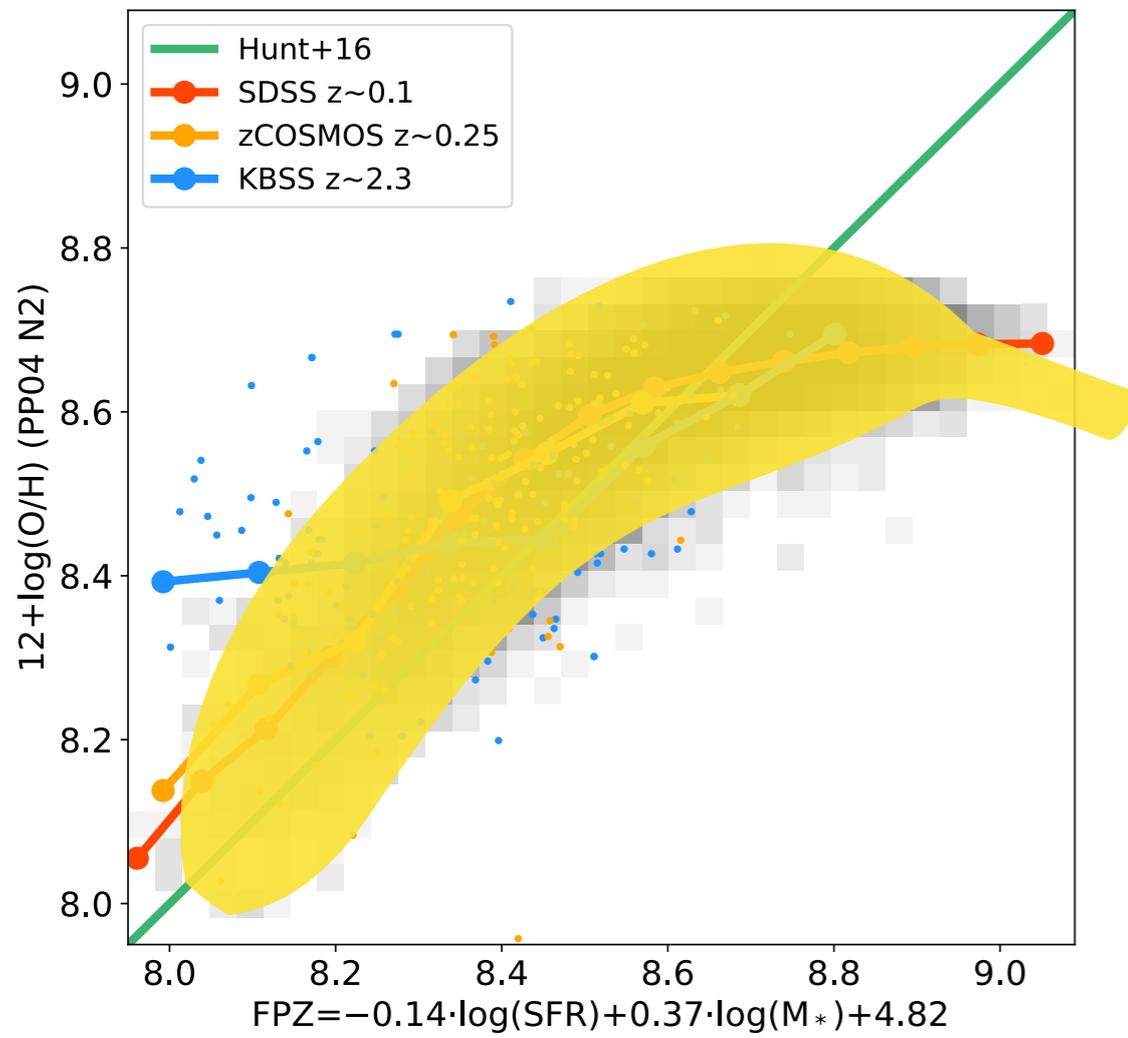
The  
“**Fundamental  
Metallicity**

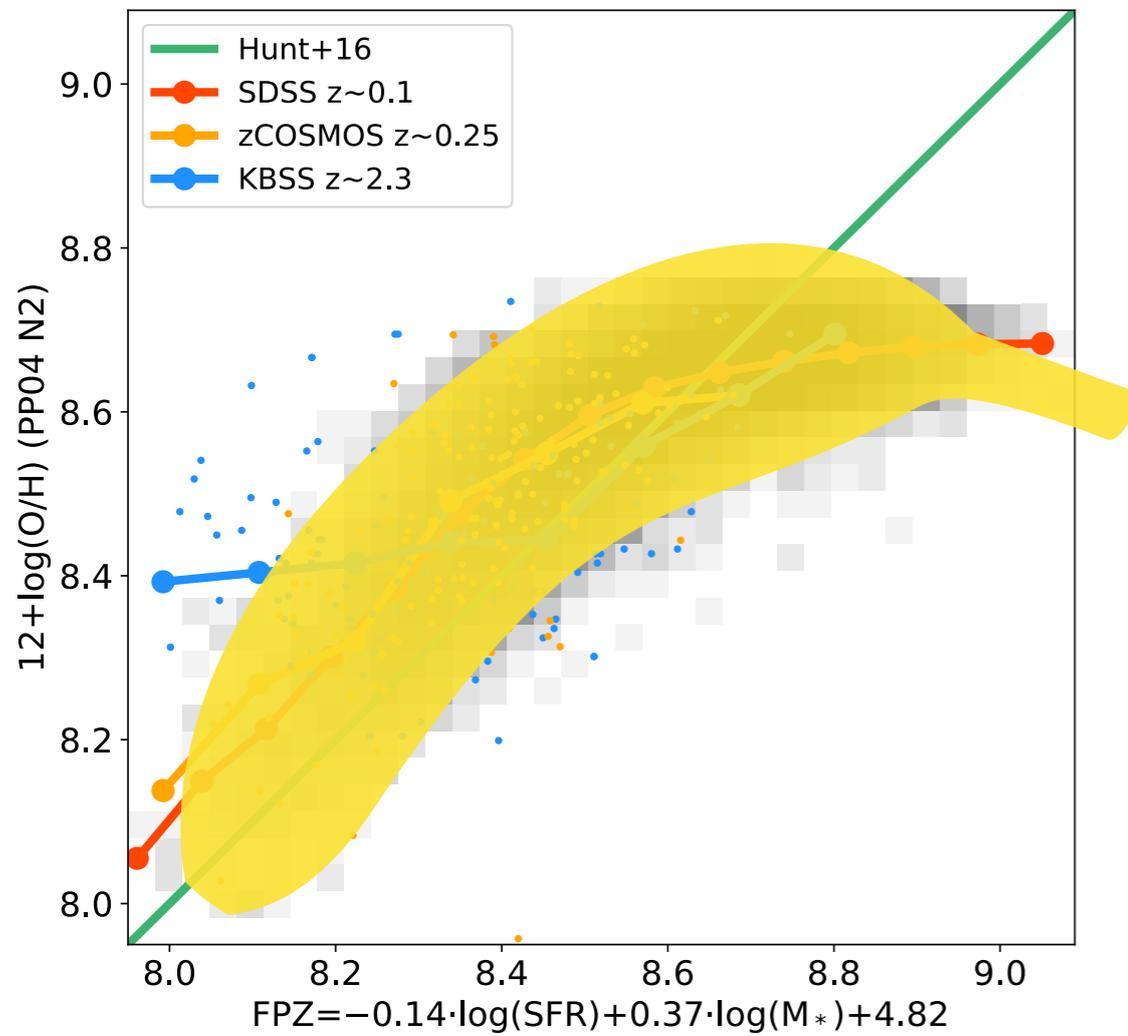
~~Plane~~”

~~Relation~~

**Banana**

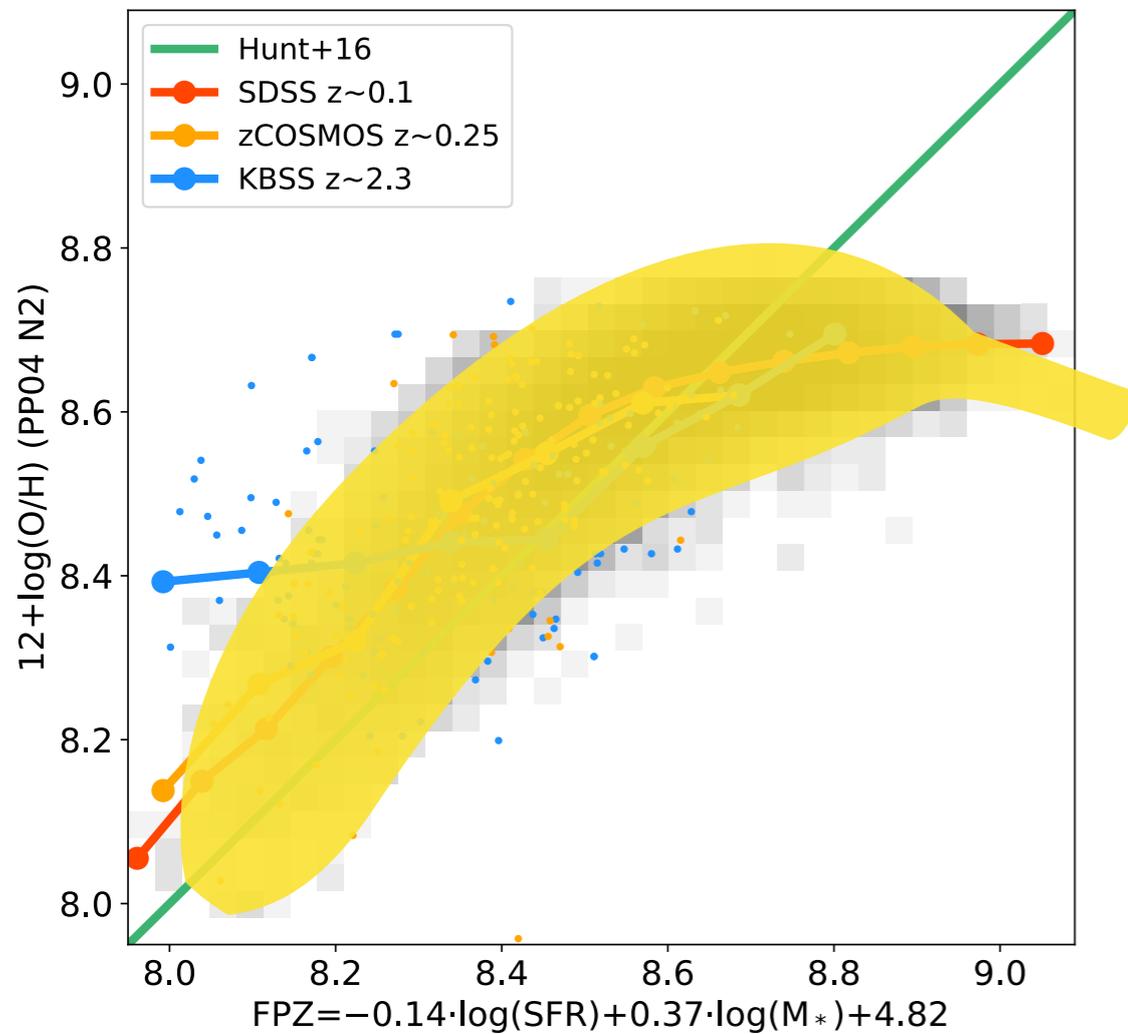
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Dust and metal enrichment result from local physical processes in the ISM — stellar production, depletion & destruction, regrowth dominate here.

**Dust Observer/Modeler**



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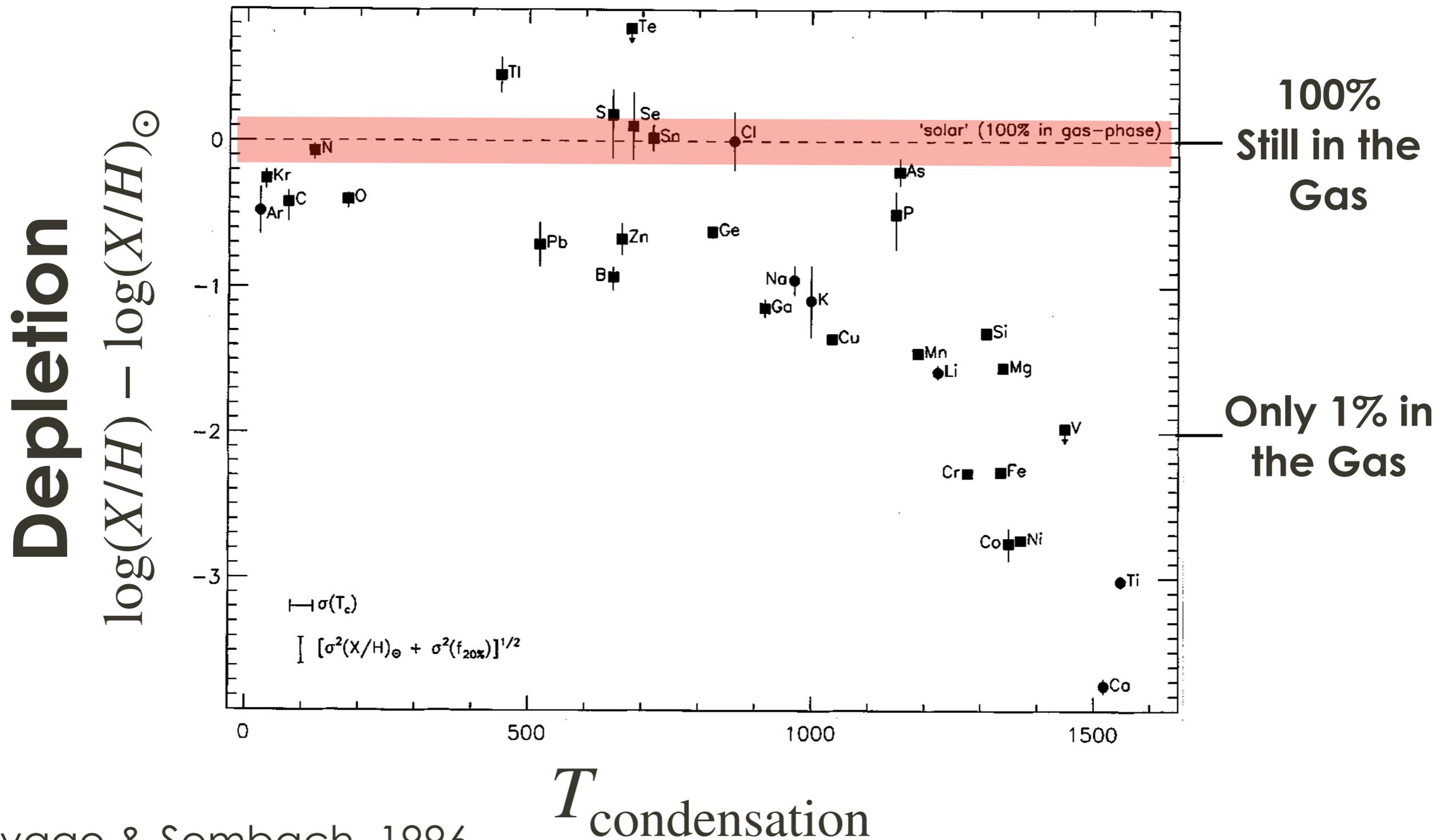
**Dust Observer/Modeler**

Dust & metals are simple tracer particles of the global galactic baryon cycle: gravity, gas kinetics, pristine inflow and enriched outflow set this relationship.

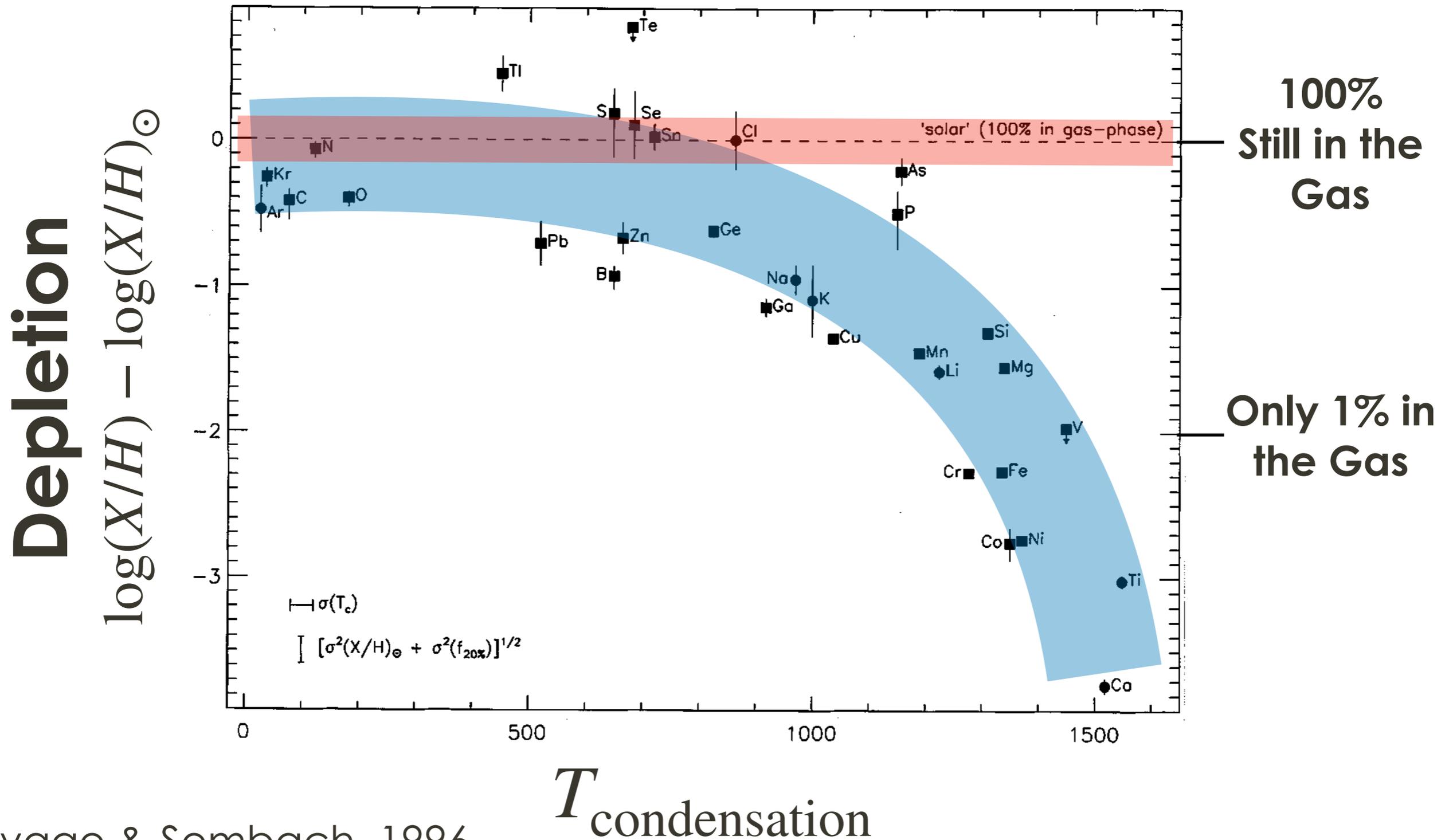


**Galaxy Simulation Theorist**

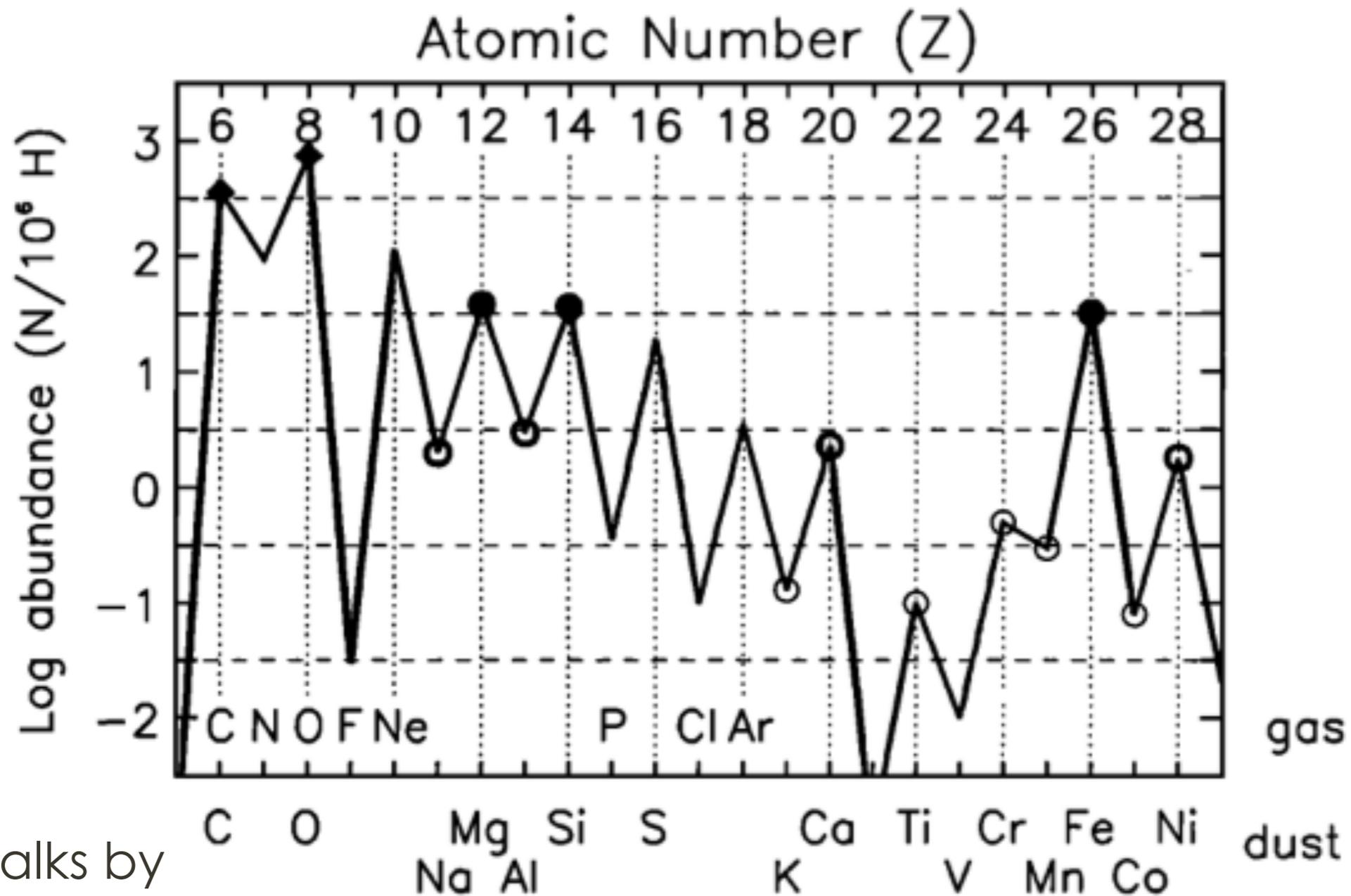
# Metals Condense



# Metals Condense



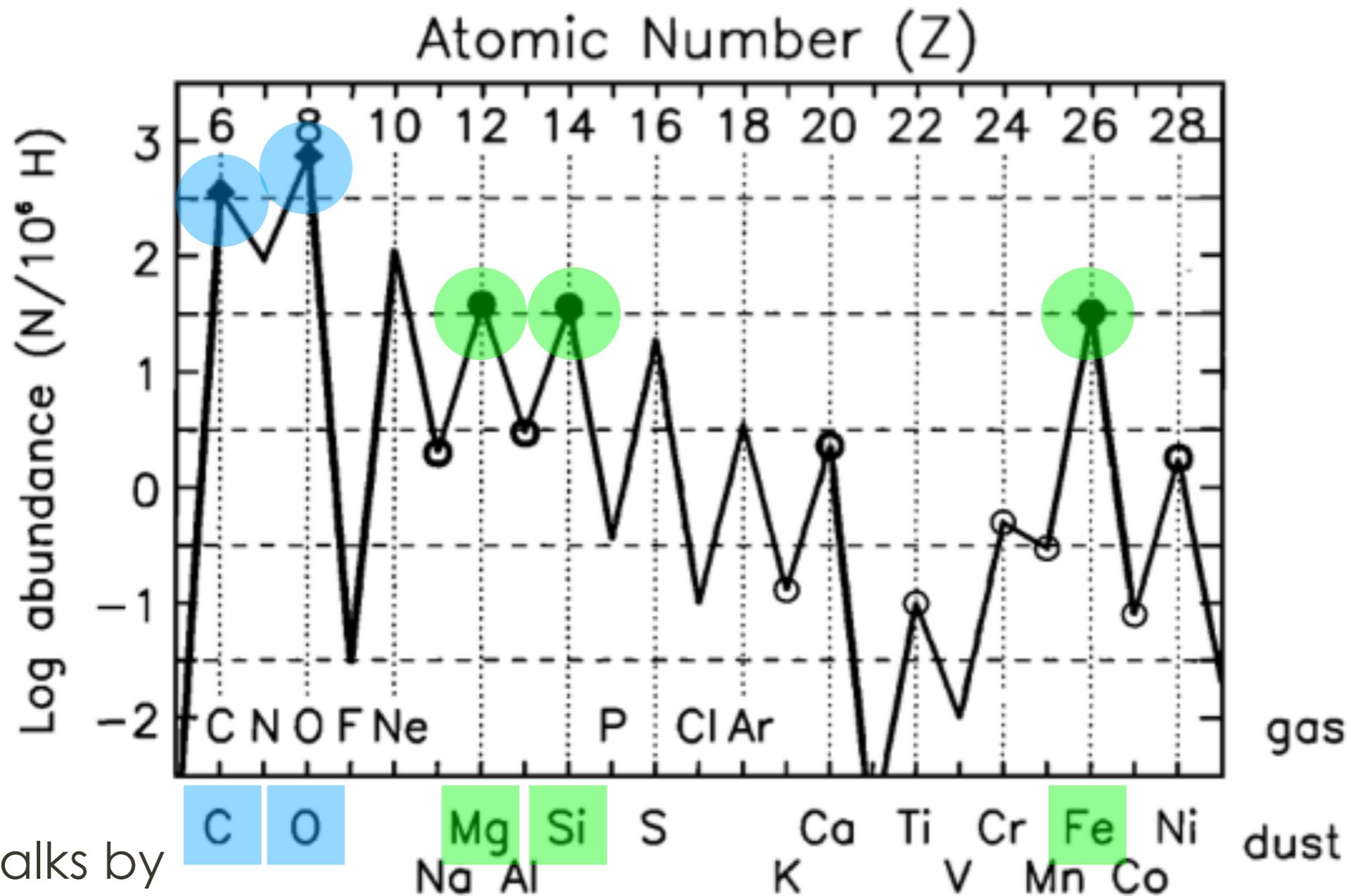
# Dust is Made of Abundant, Condensable Metals



See also talks by  
Jenkins, Roman-  
Duval

Jones, 2000

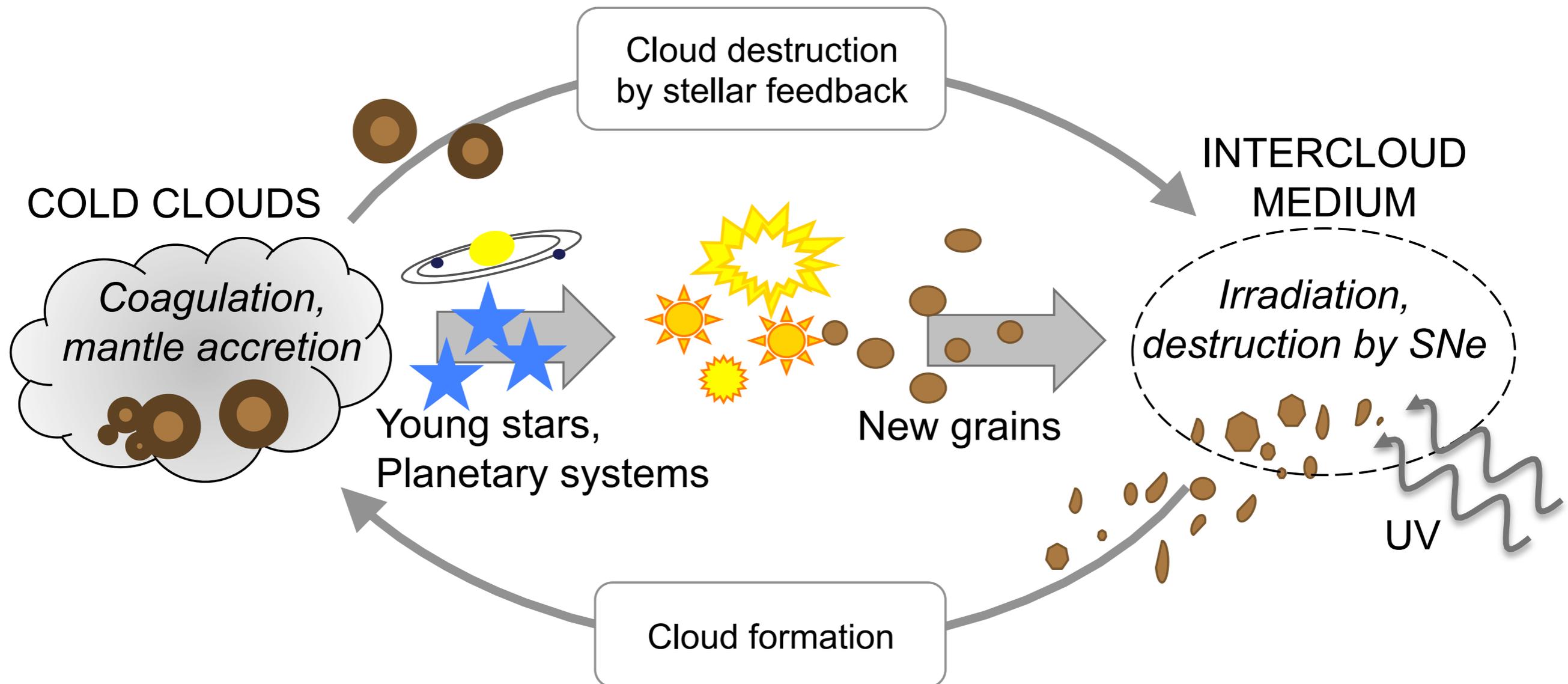
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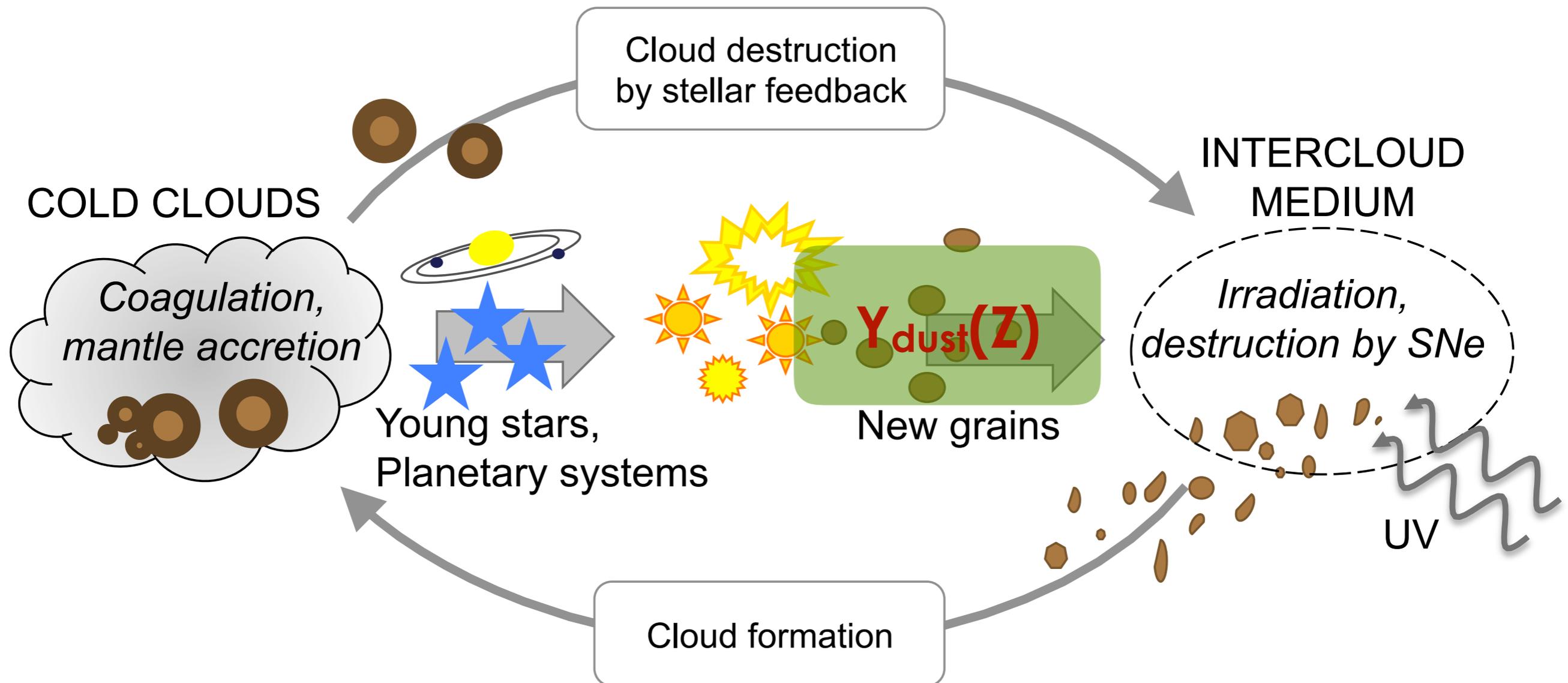
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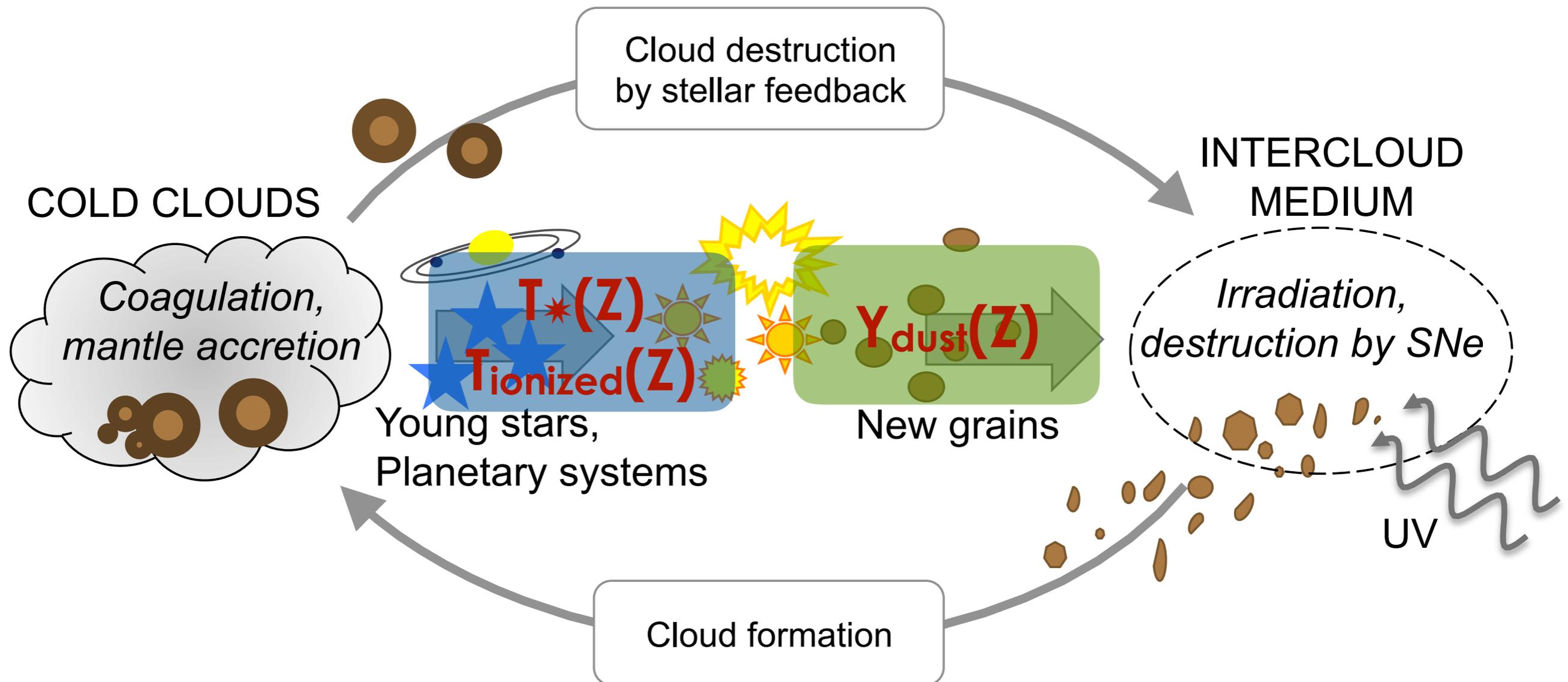
# Metals & Dust (& Gas) — Much Deeper Relationships



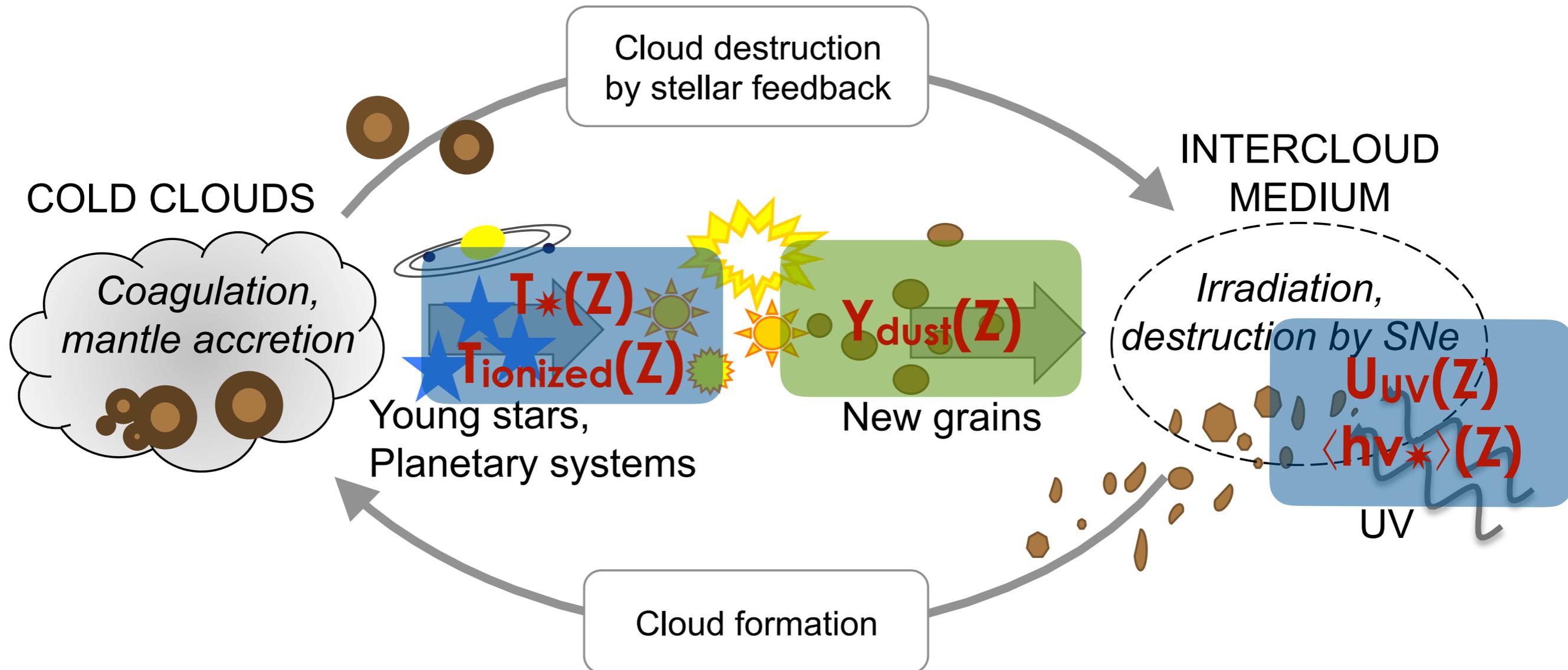
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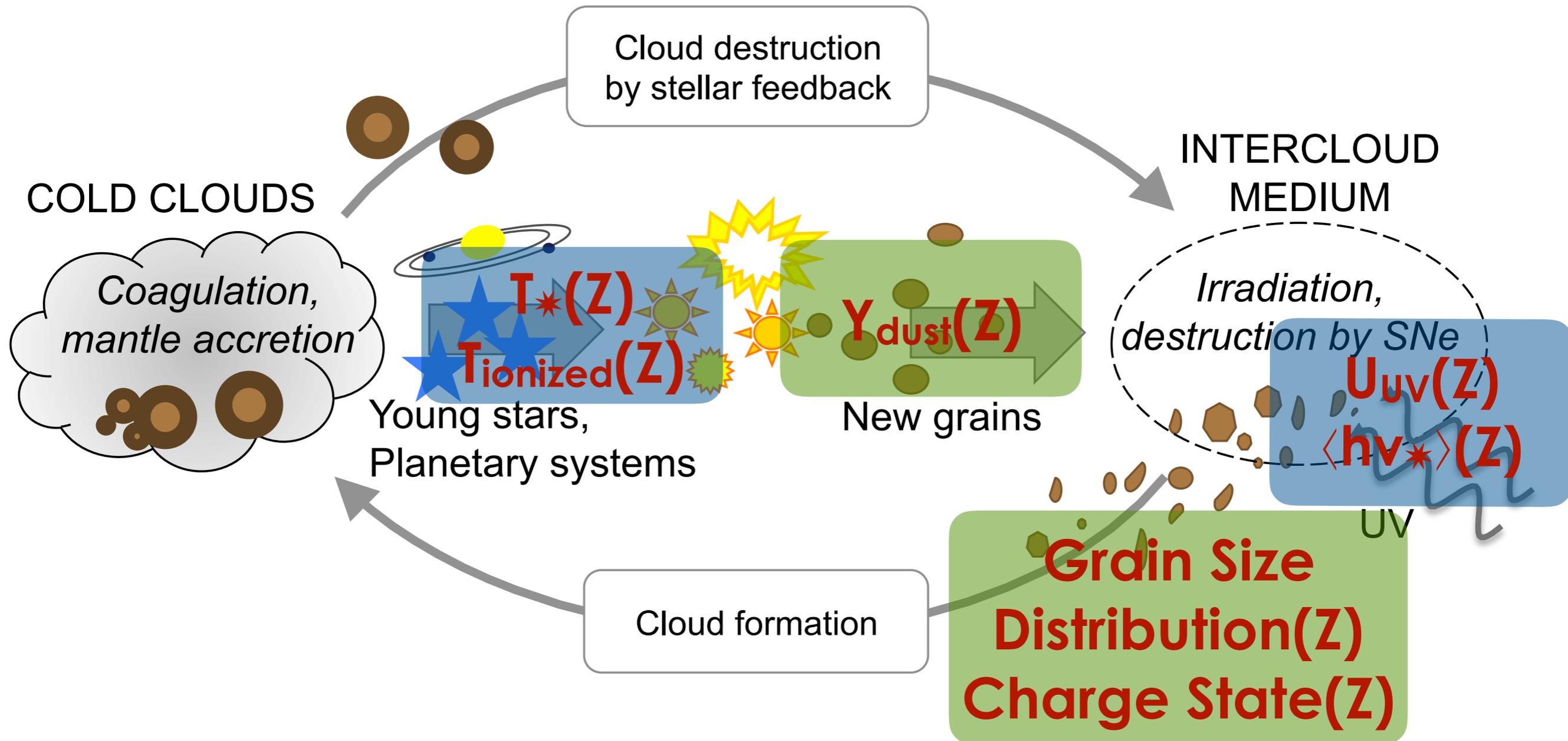
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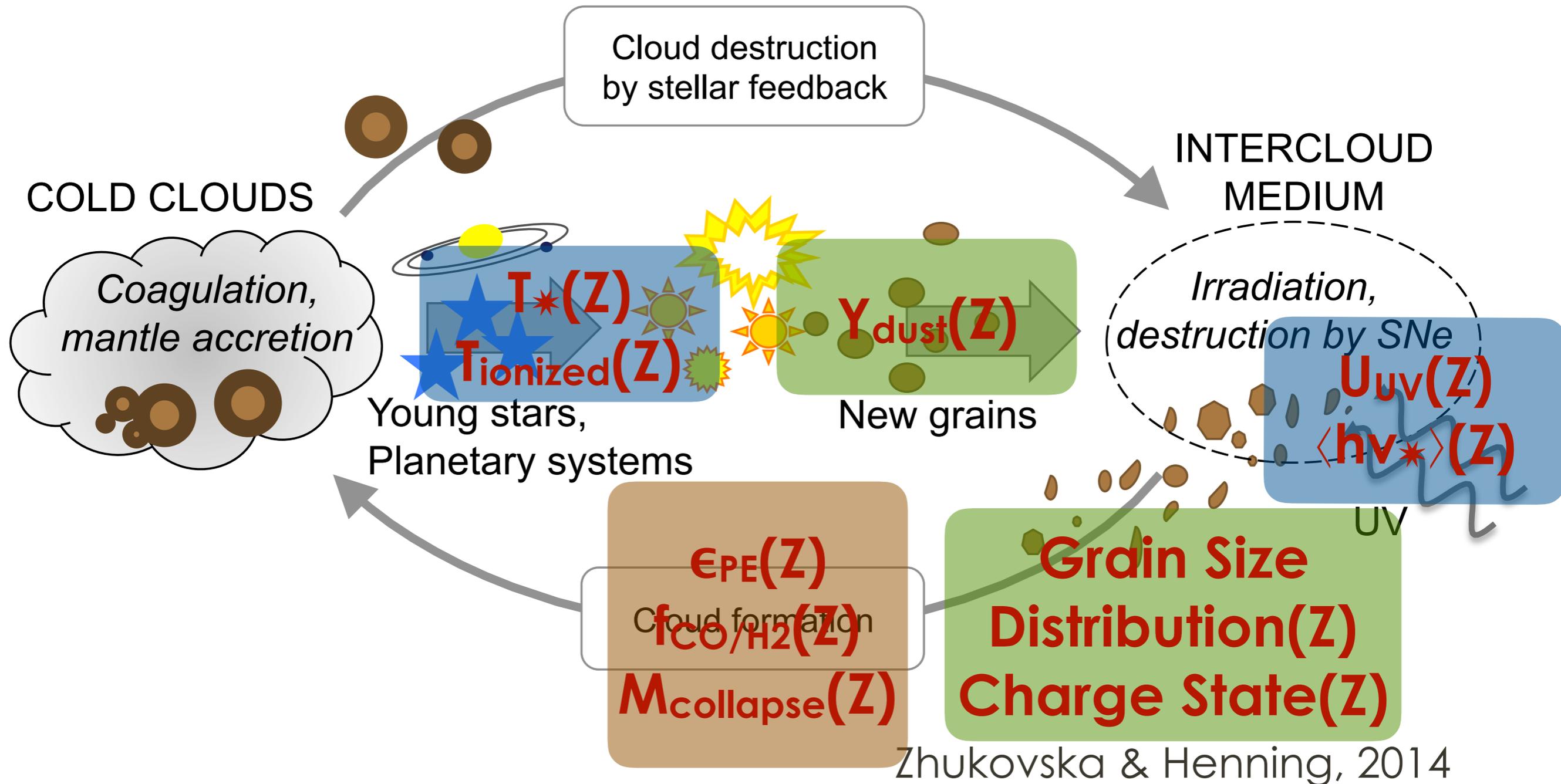
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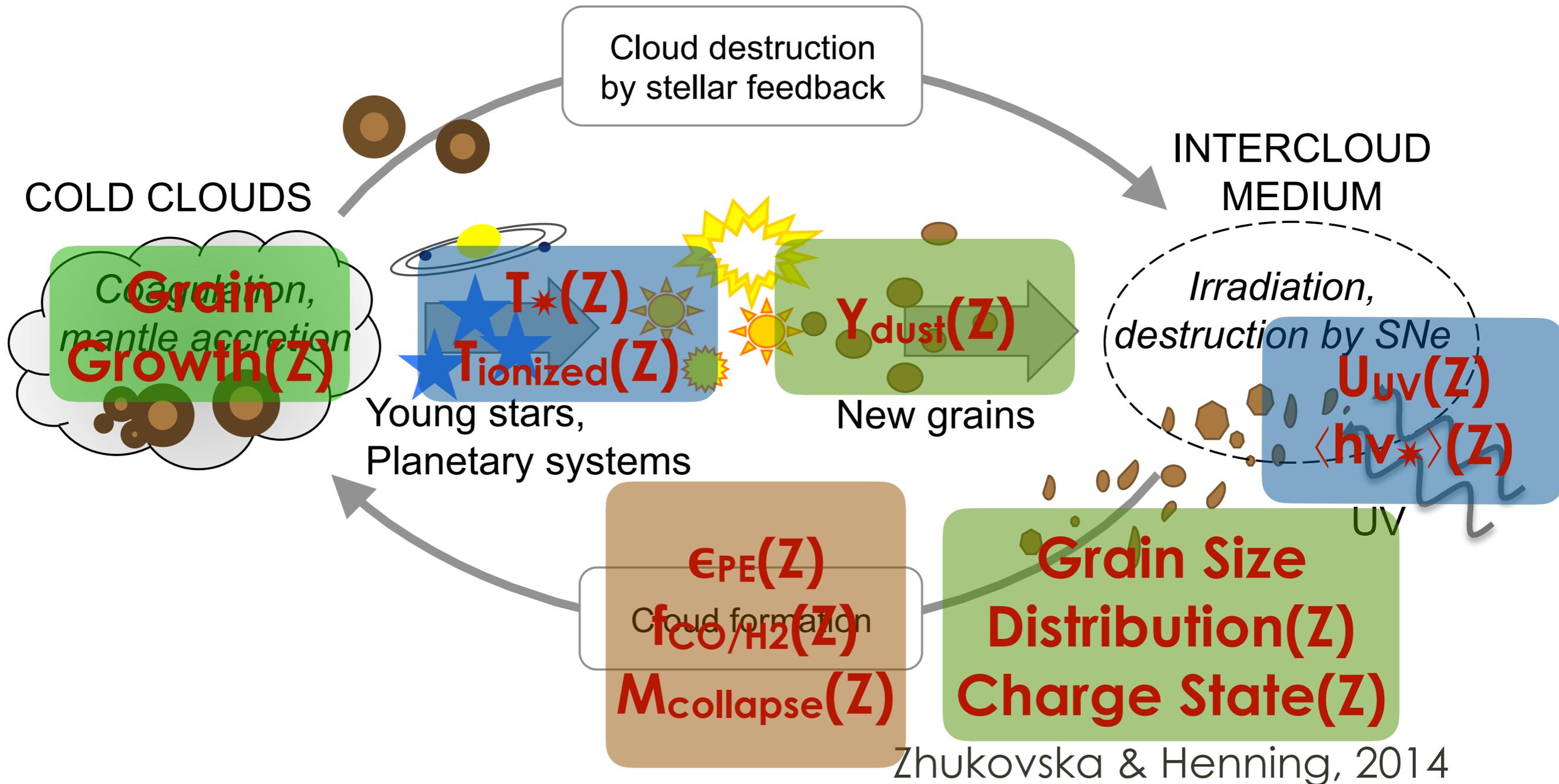
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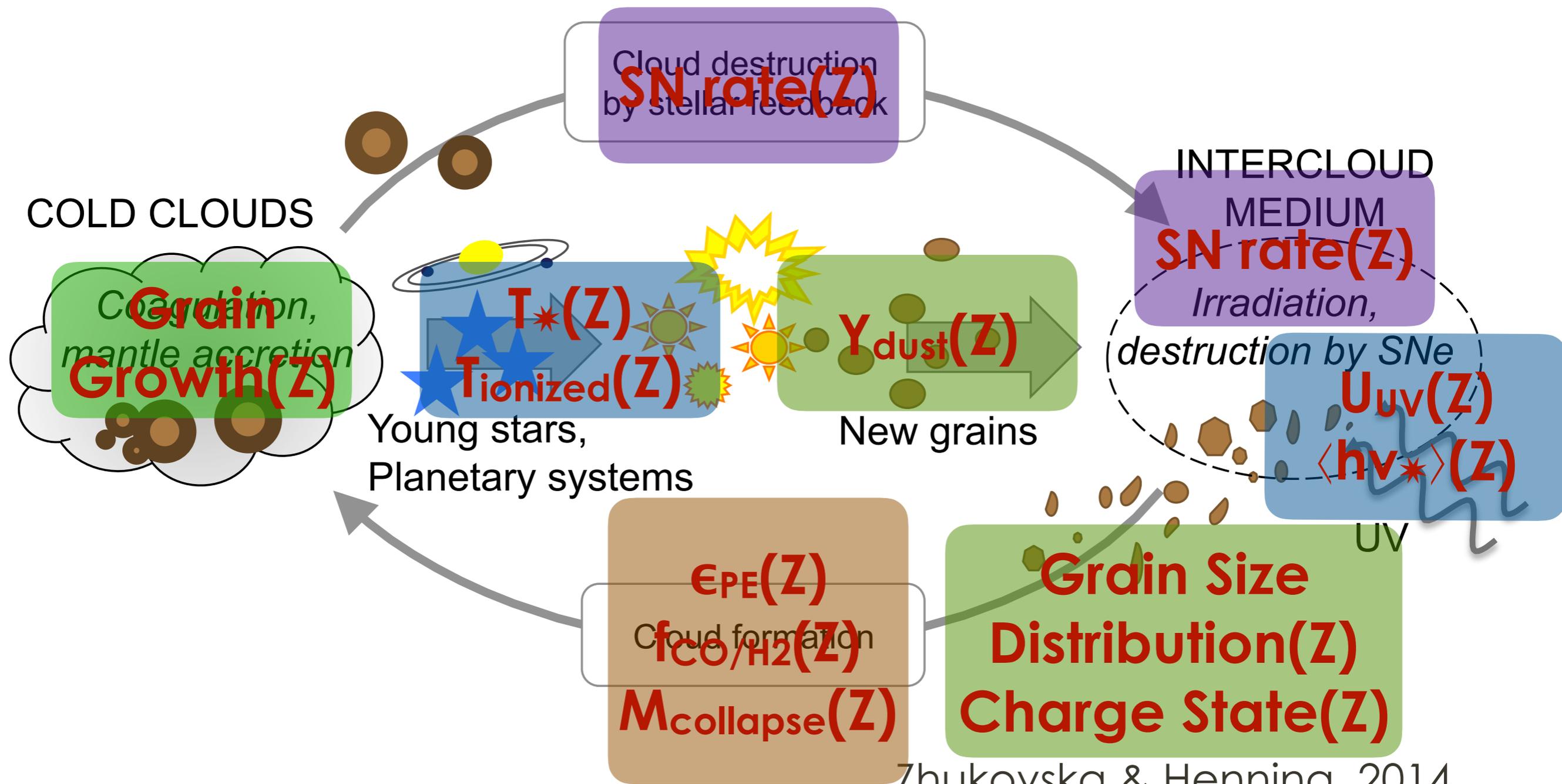


# Metals & Dust (& Gas) — Much Deeper Relationships

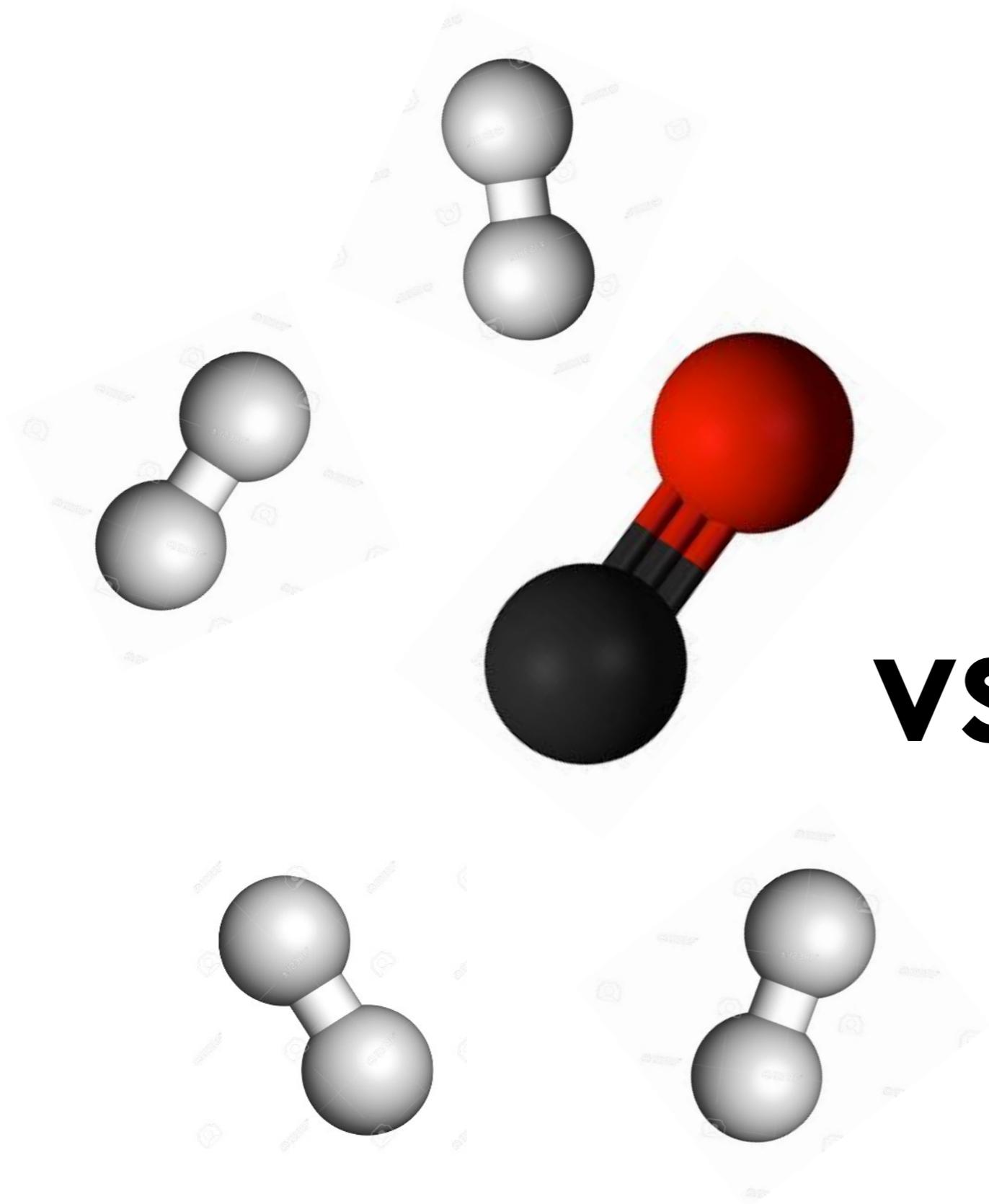


Zhukovska & Henning, 2014

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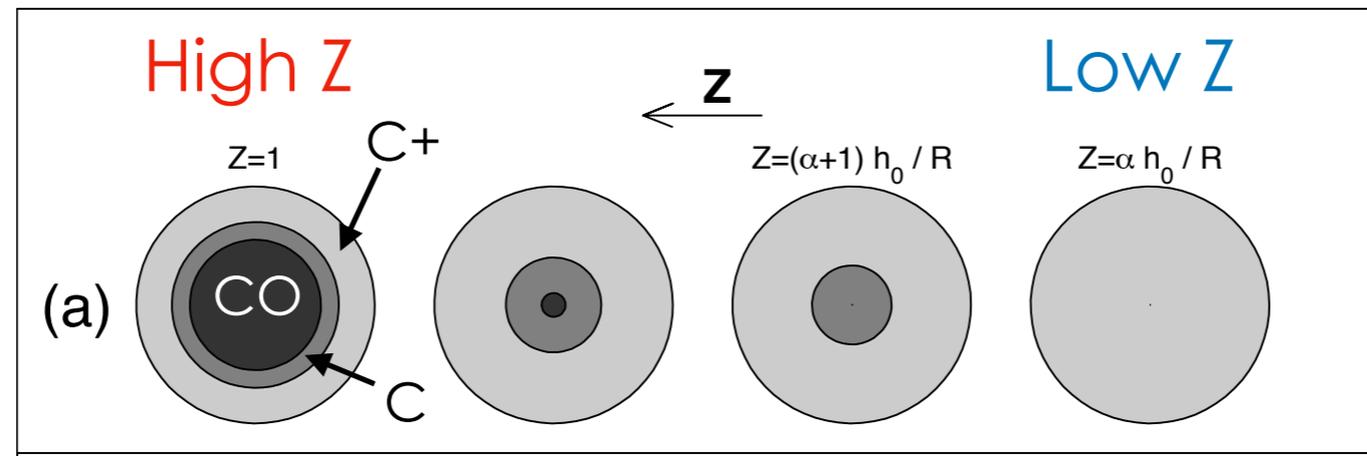
Zhukovska & Henning, 2014



**vs  $Z/Z_{\odot}$**

# Dust, Metals and Star-Forming Gas

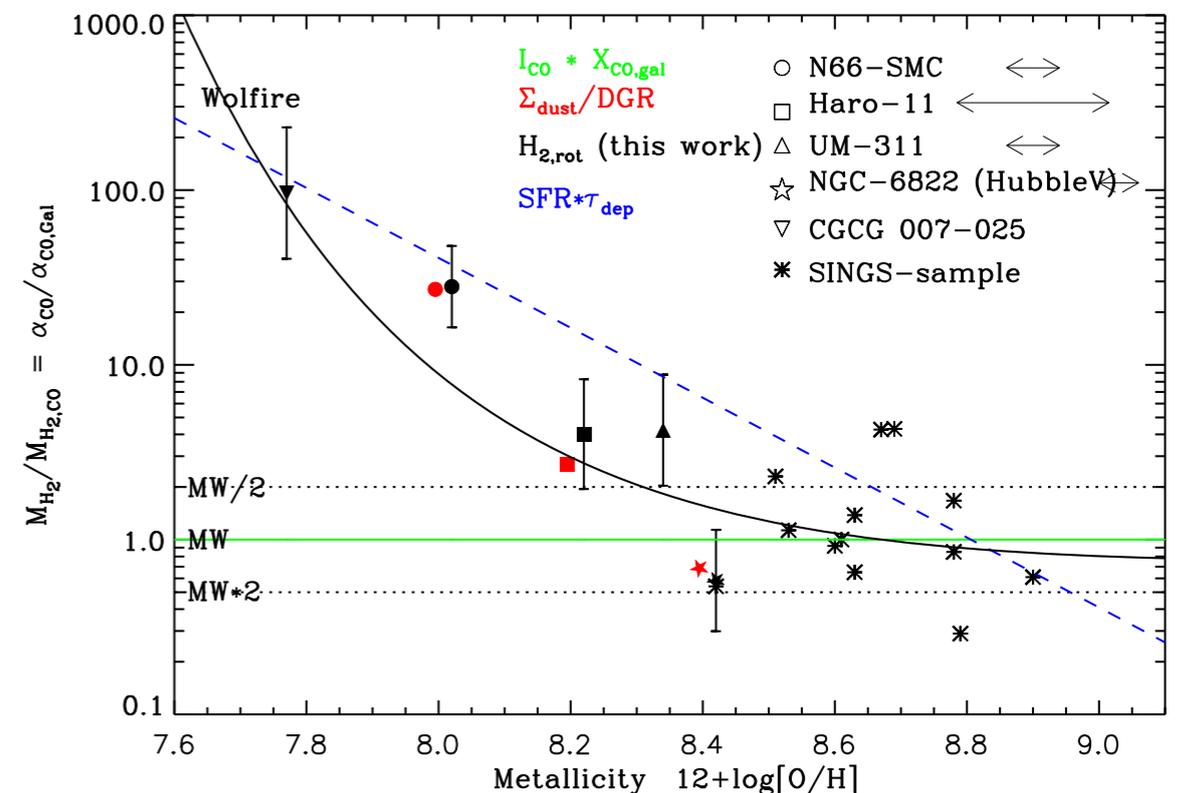
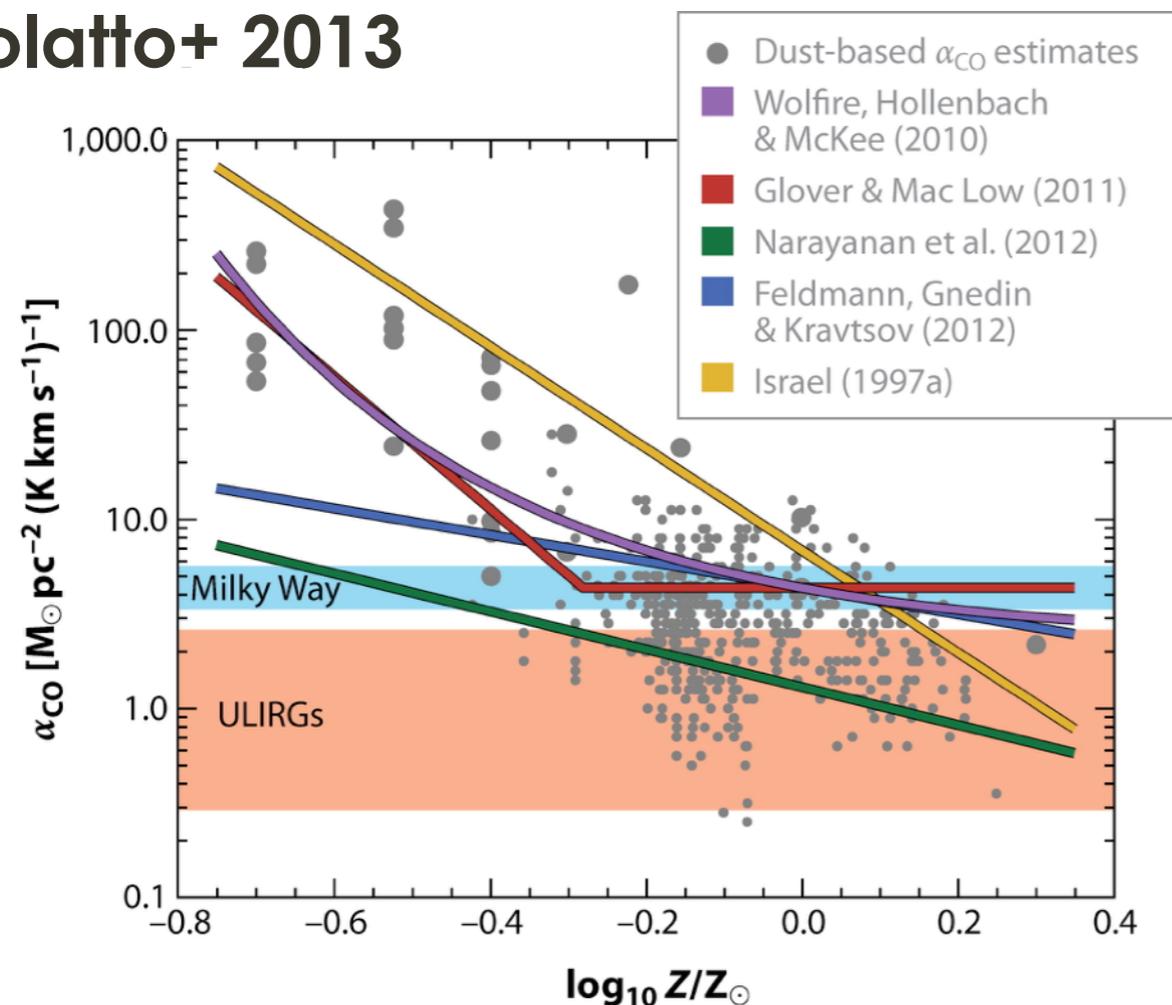
Cloud Structure: *Mediated by Dust/Metals*

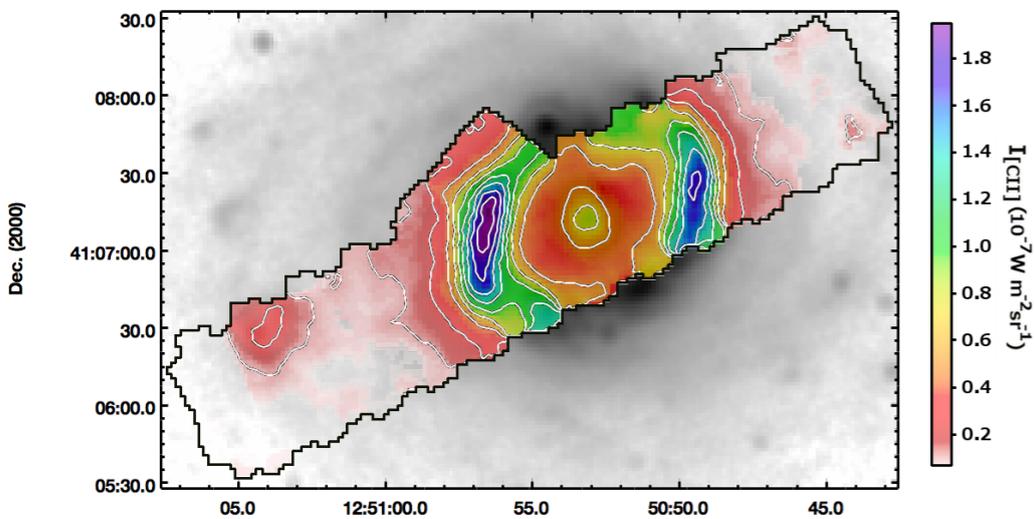


Bolatto+ 1999

$\alpha_{\text{CO}}$  from dust:  
Bolatto+ 2013

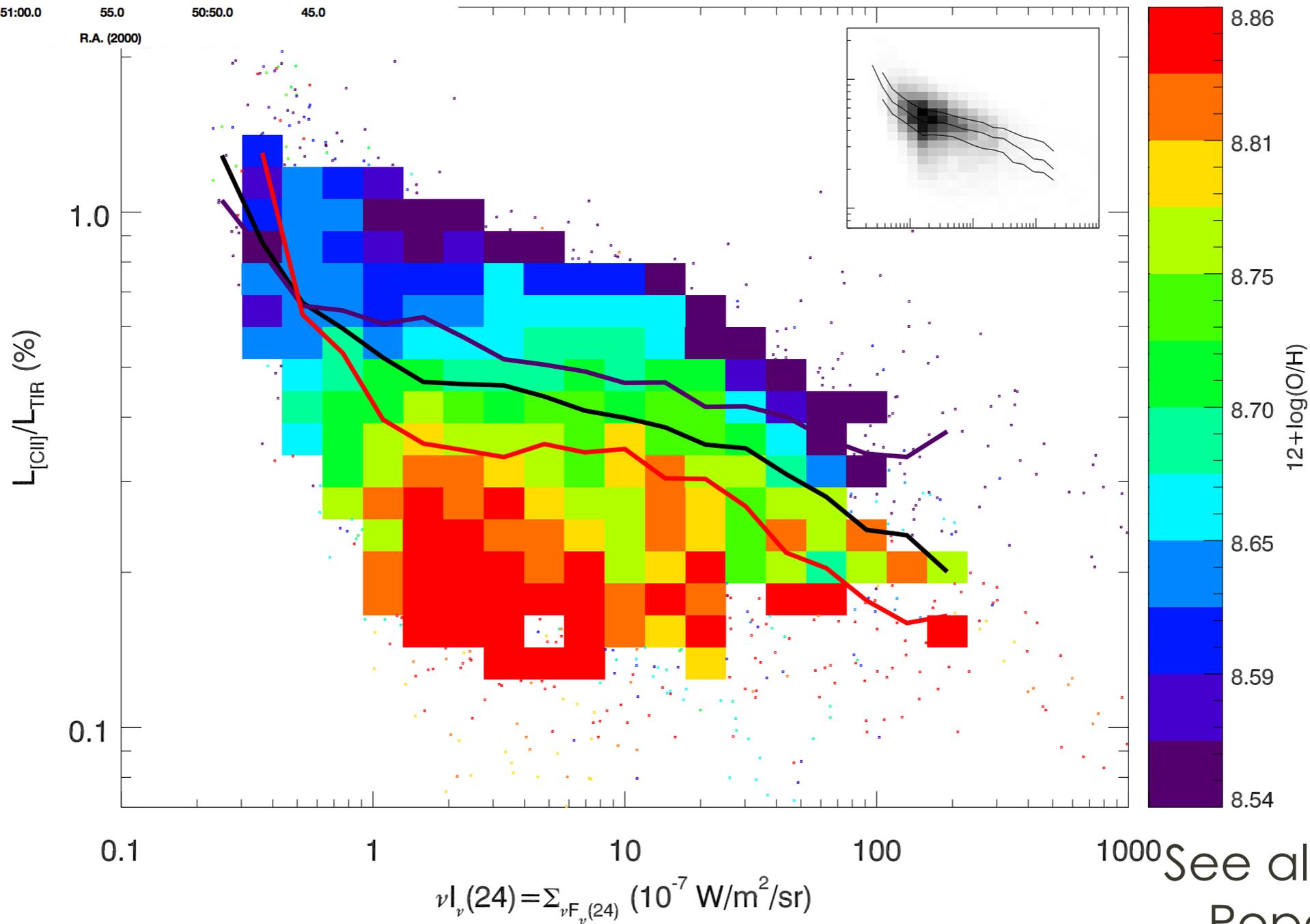
$\alpha_{\text{CO}}$  from  $\text{H}_2$  itself:  
Togi & Smith 2016





# CII deficit — $\epsilon_{PE}$ vs. $Z$

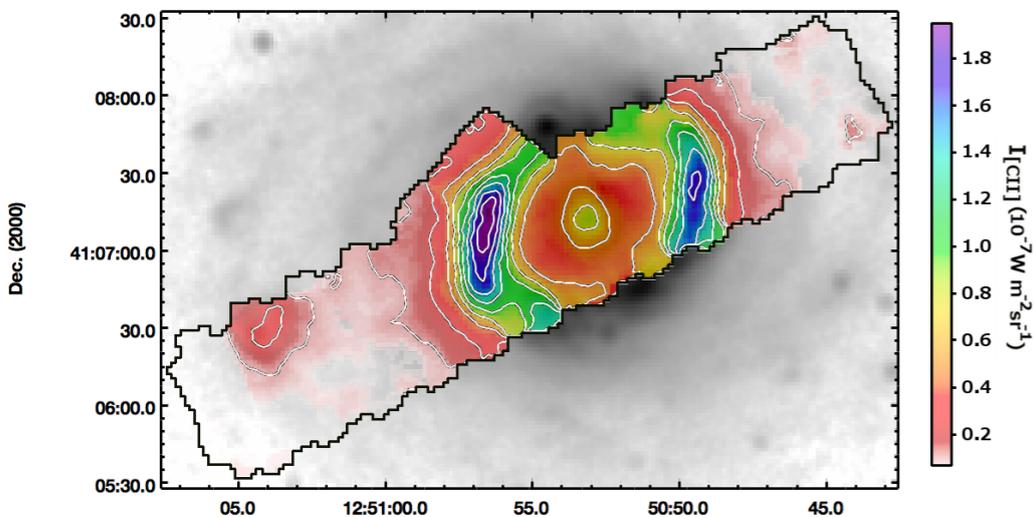
Heating Efficiency



See also talks by  
Pope, Rybak

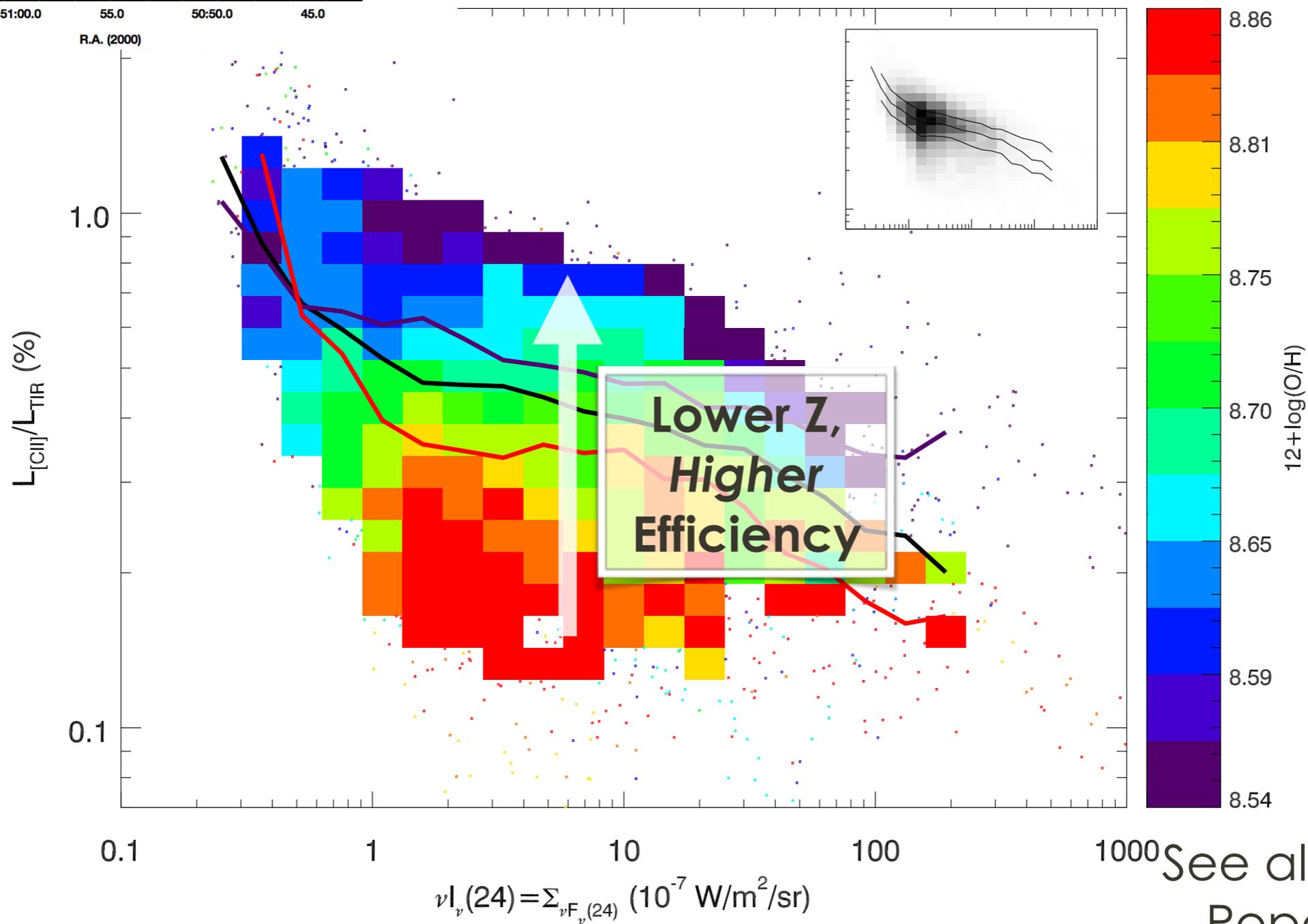
Smith+ 2017

**IR Luminosity Density = ~SFRD**



# CII deficit — $\epsilon_{PE}$ vs. $Z$

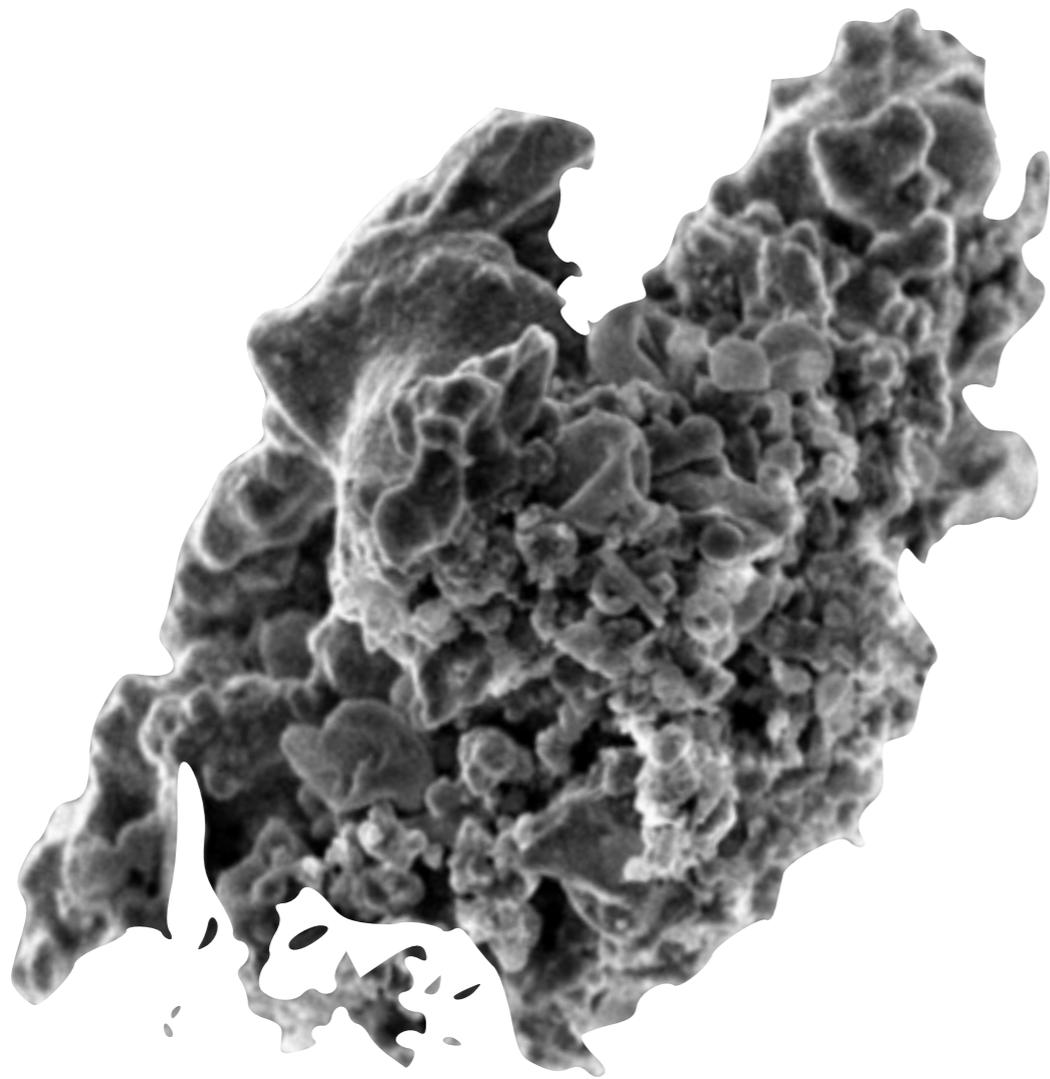
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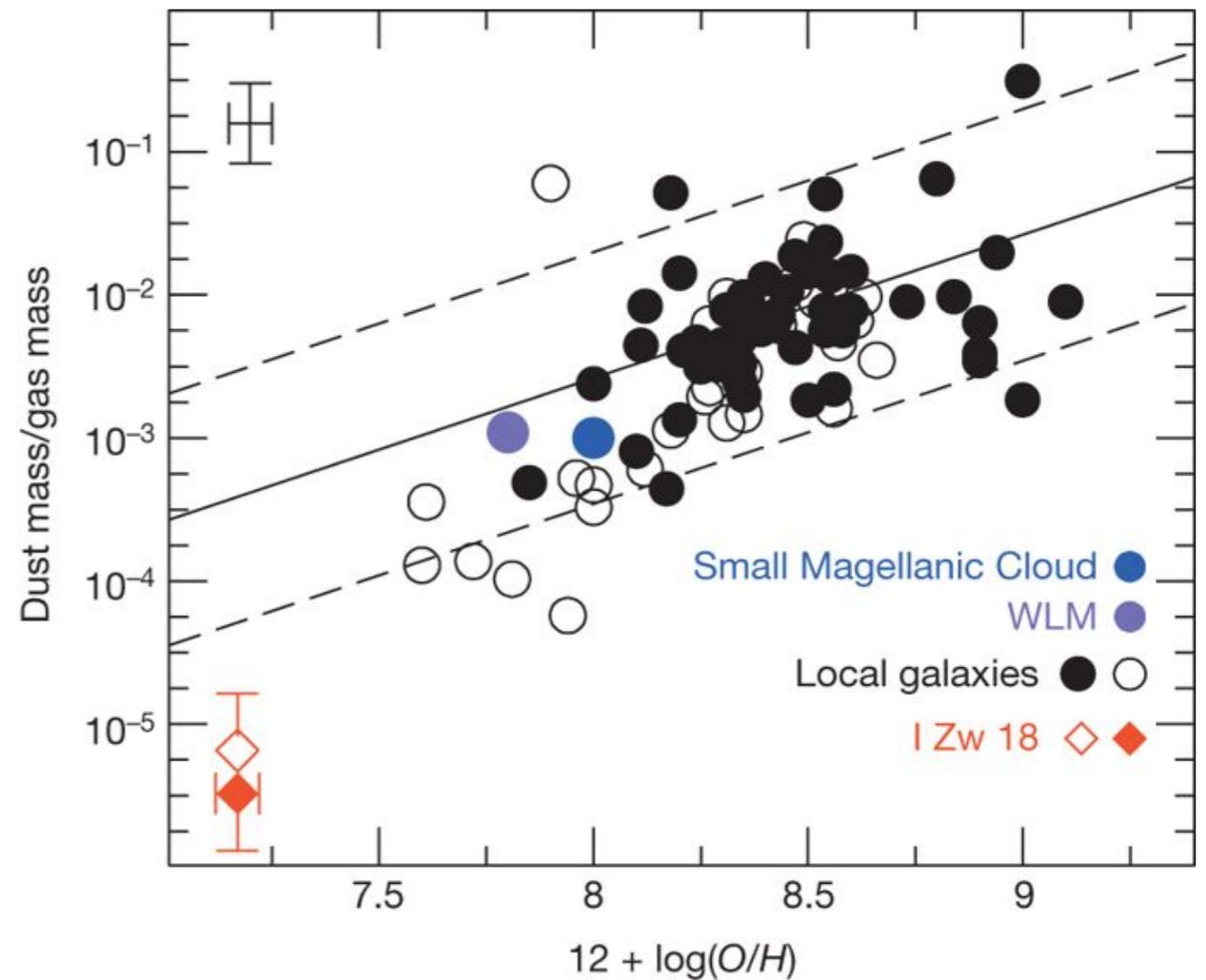
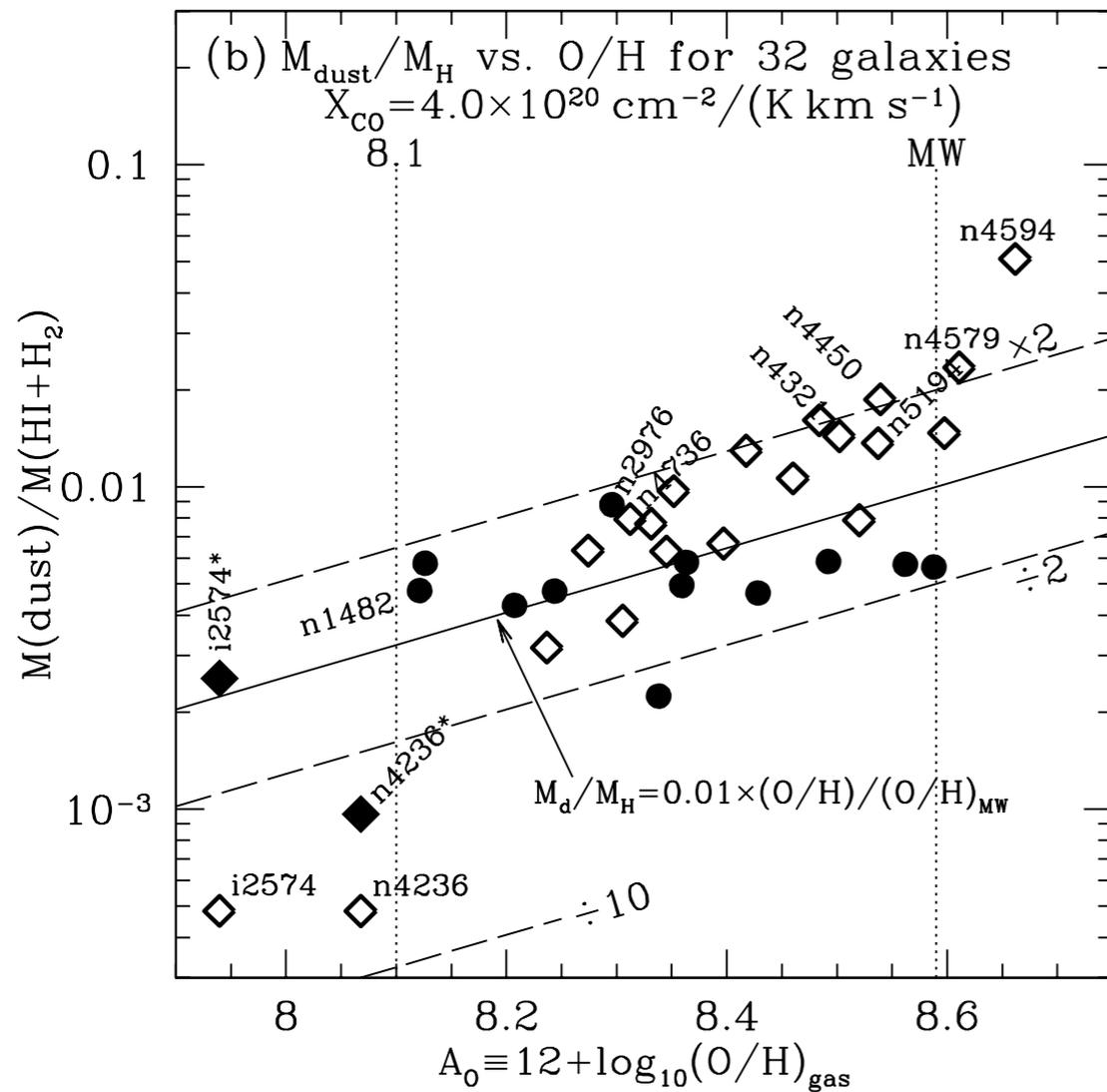
Smith+ 2017

**IR Luminosity Density = ~SFRD**

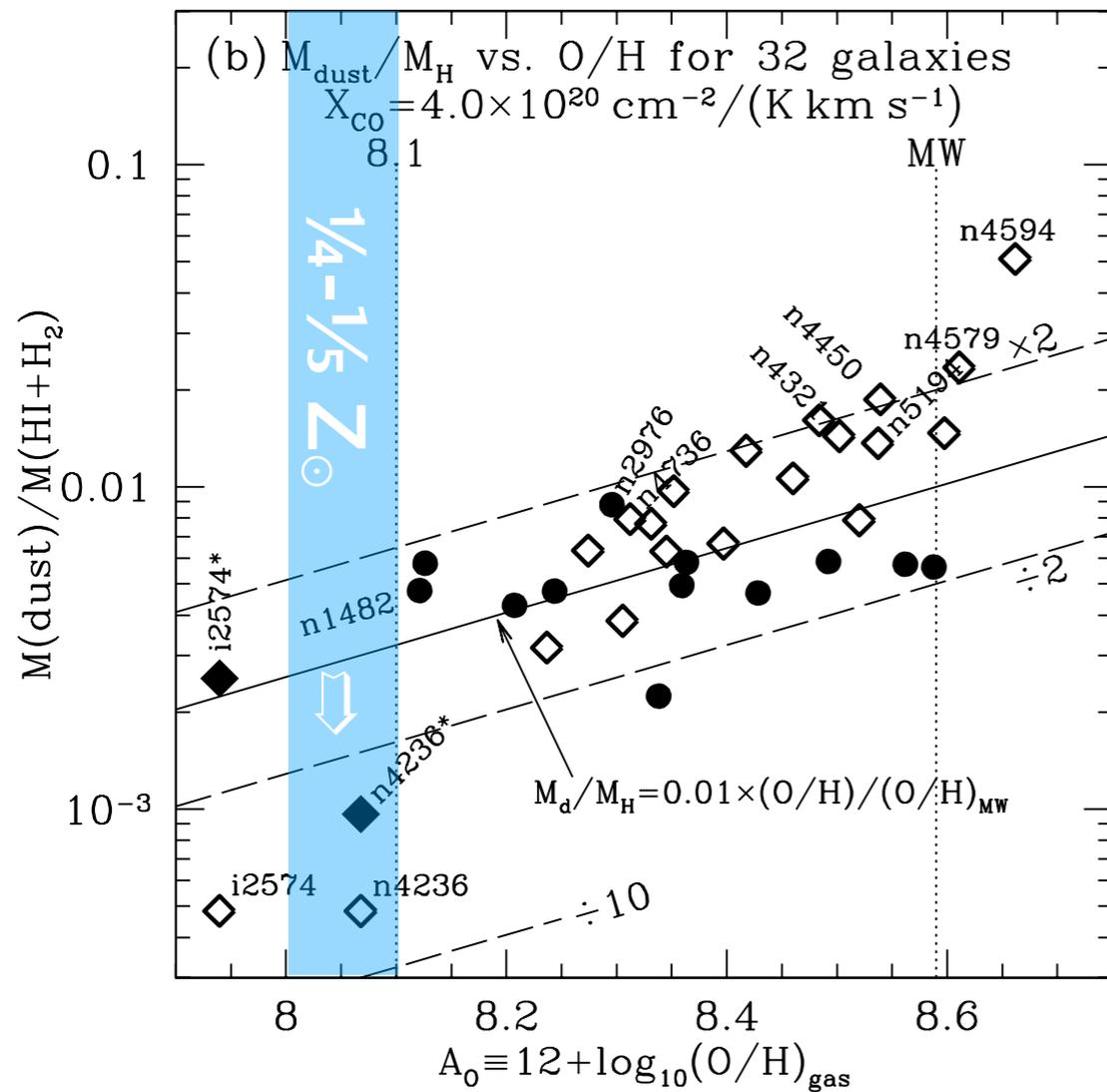


**vs Z/Z<sub>0</sub>**

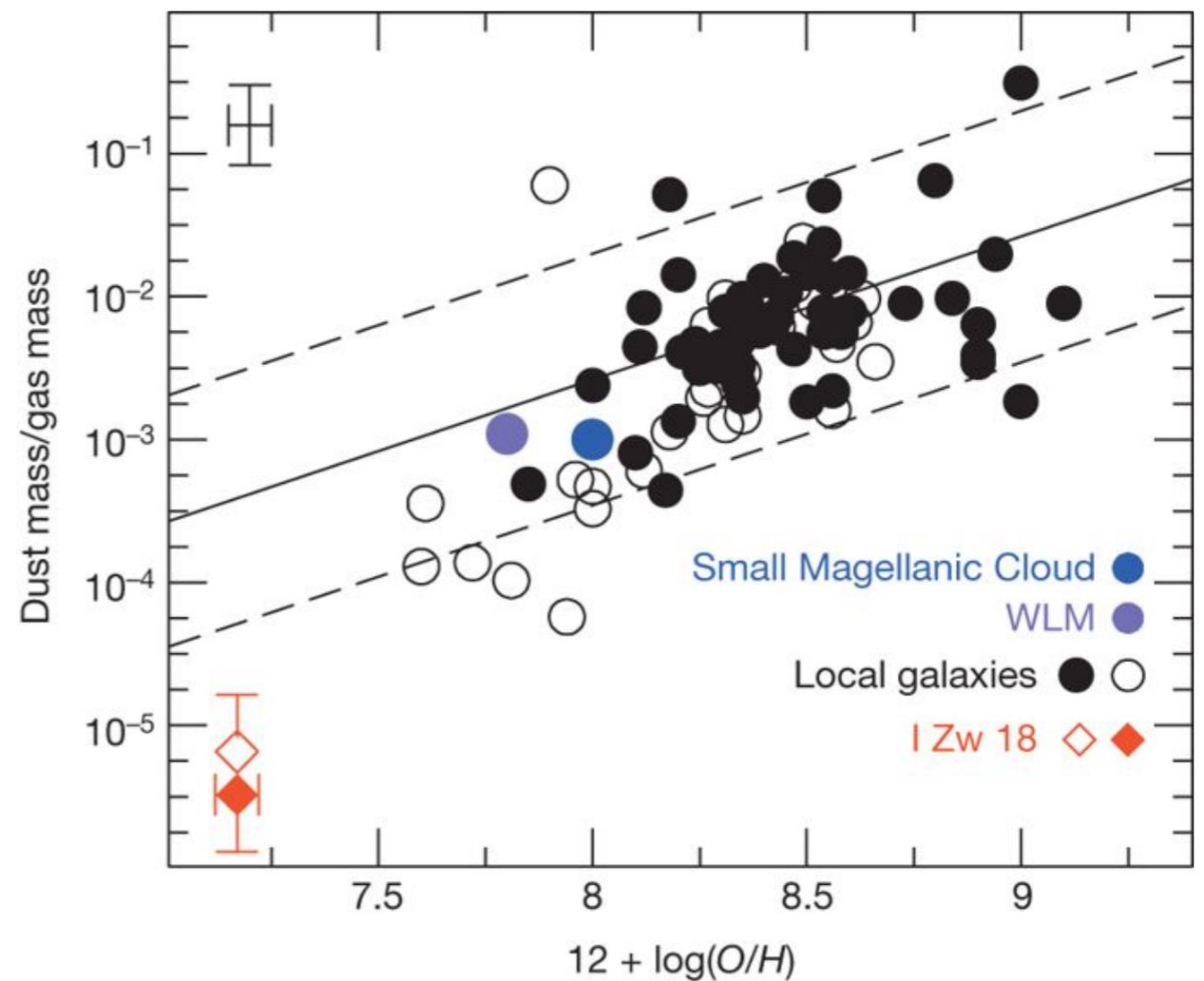
# Fewer Ingredients, Less Dust (obviously)



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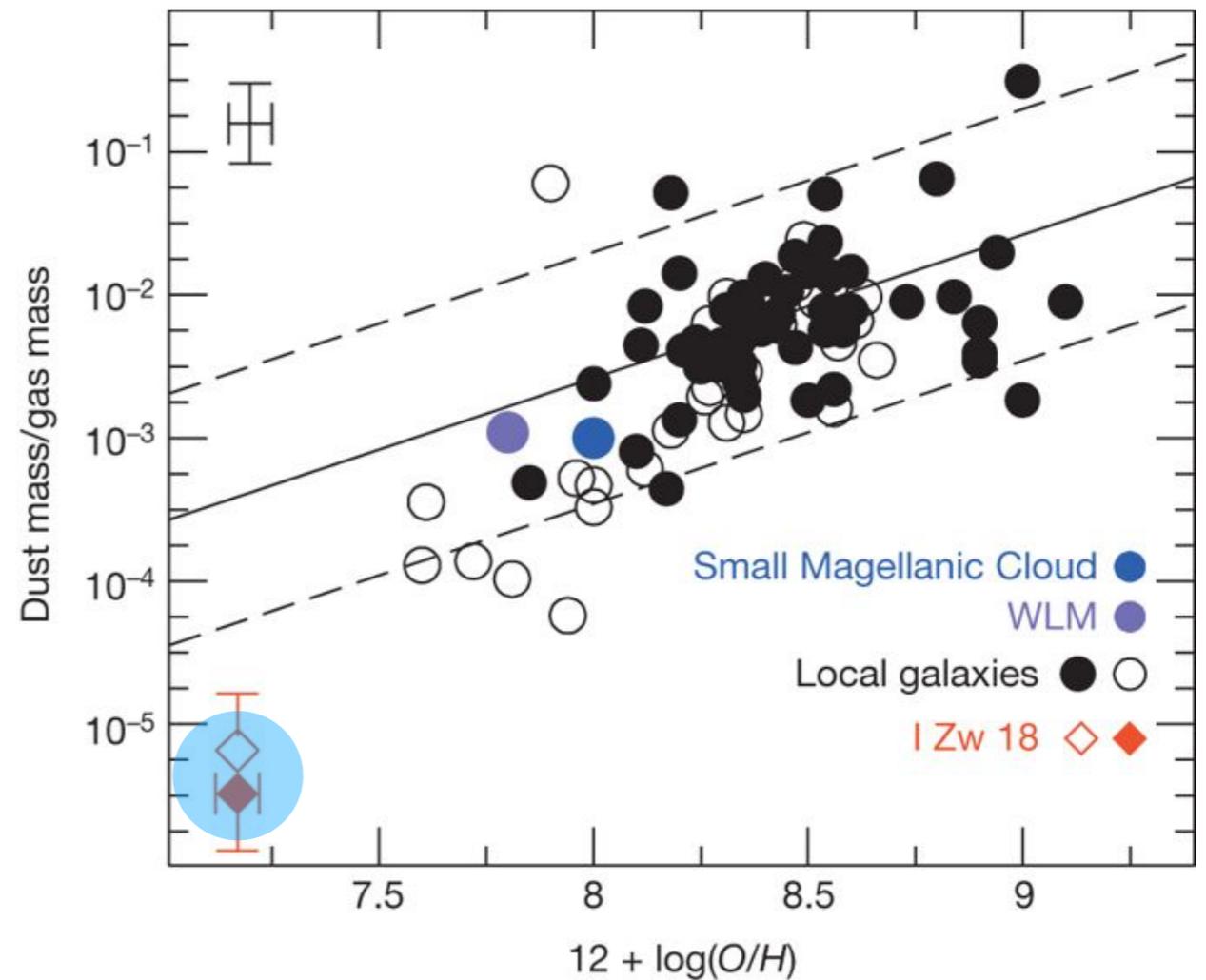
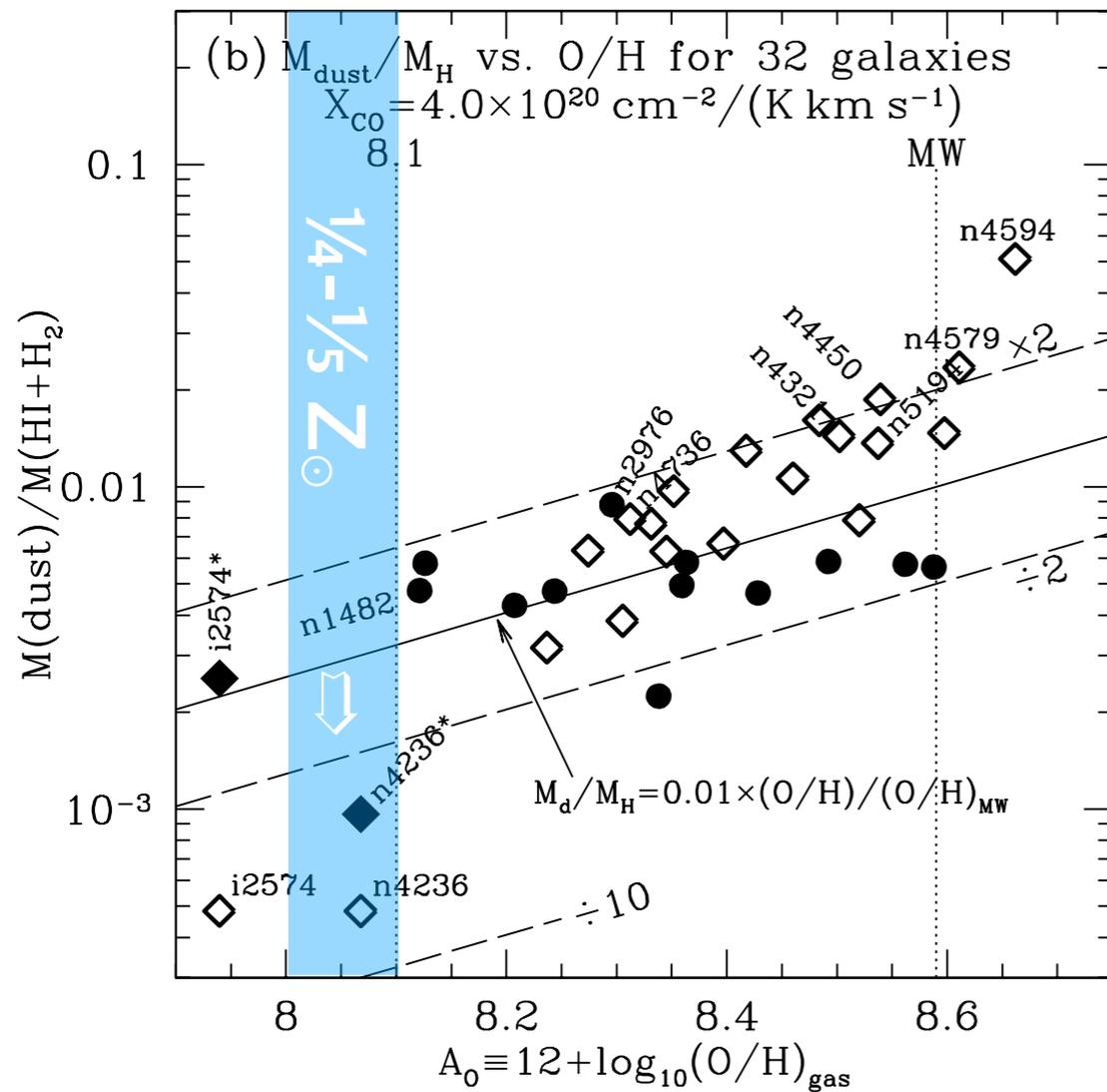


Draine+ 2007

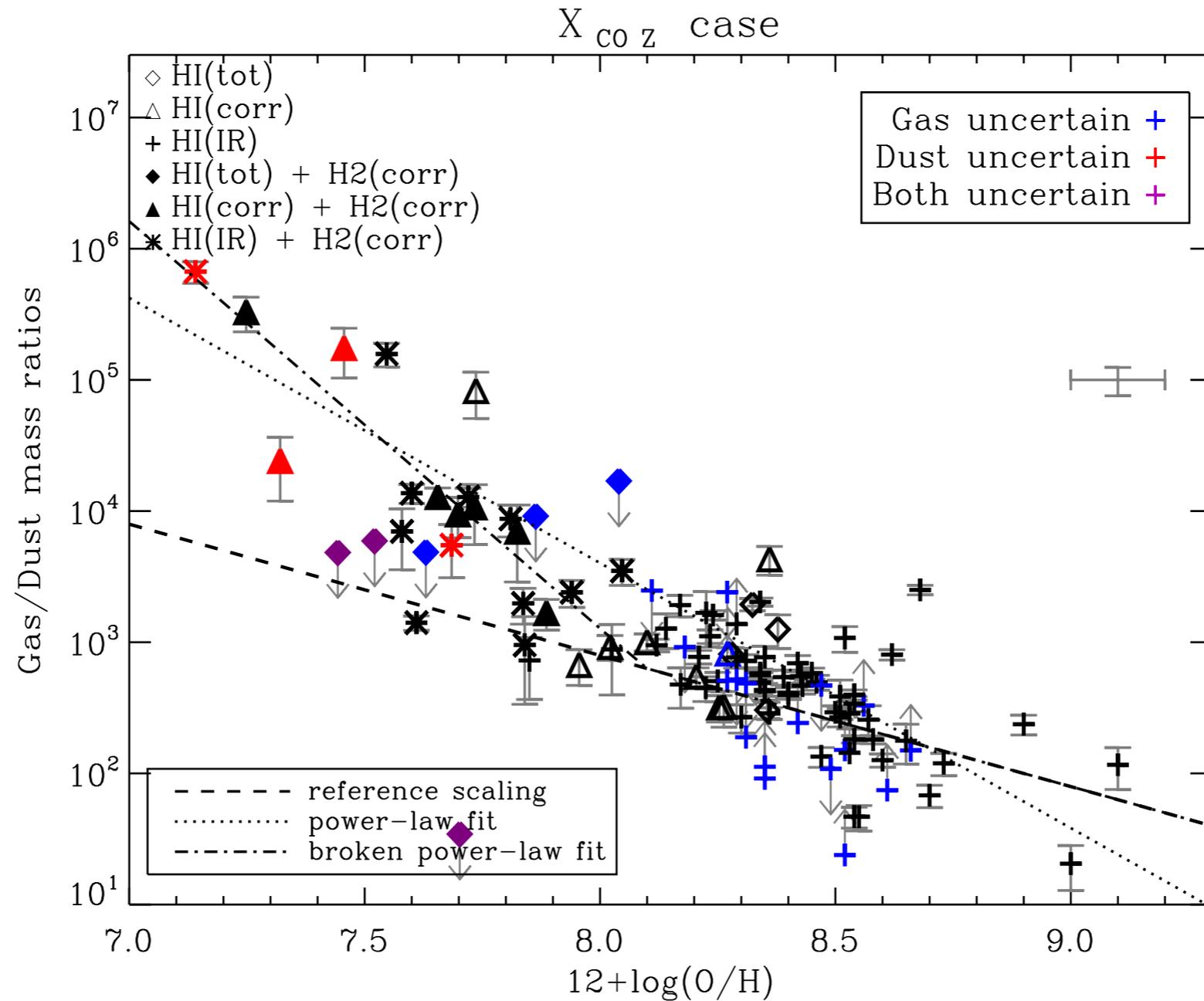


Fischer+ 2014

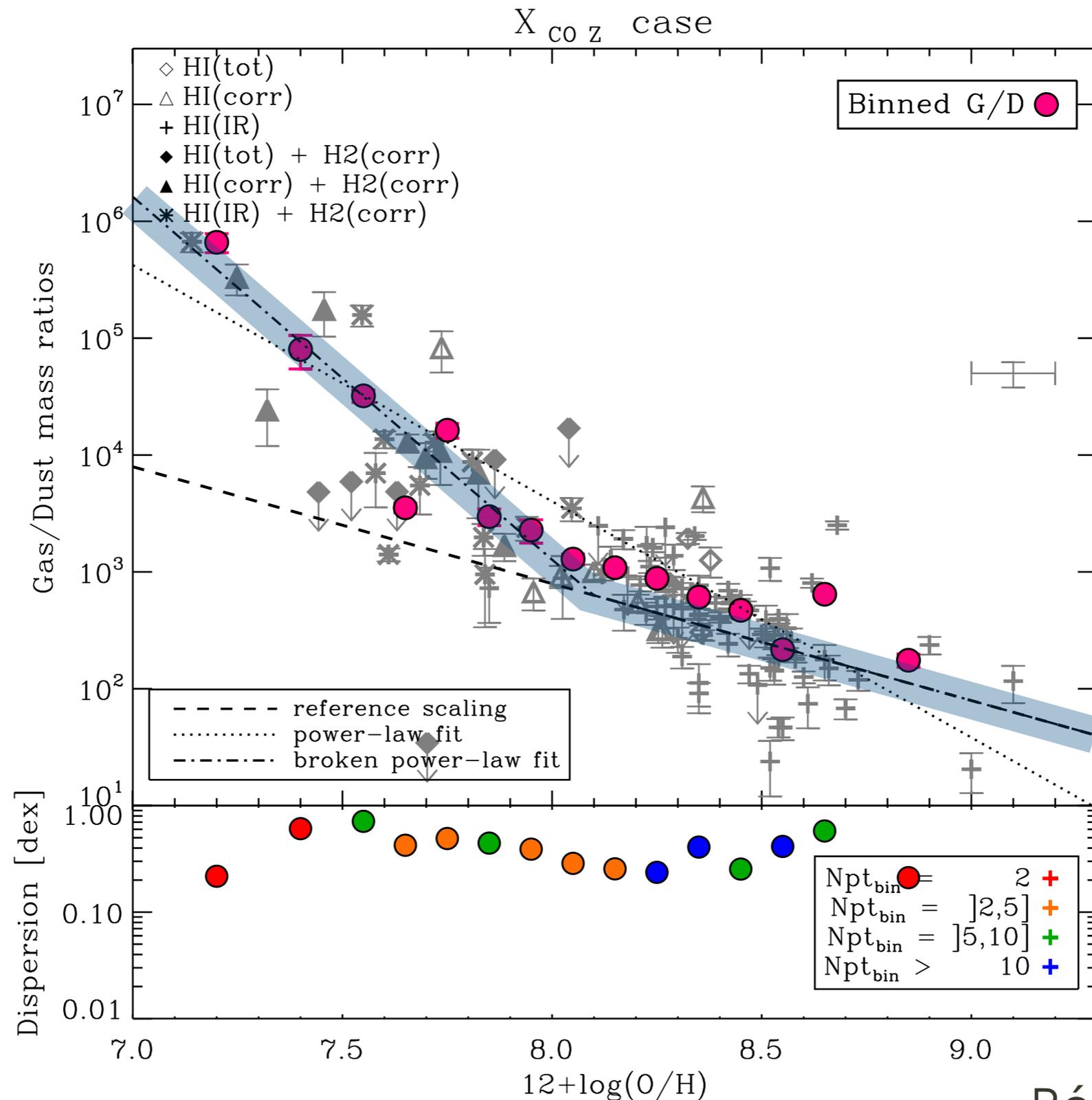
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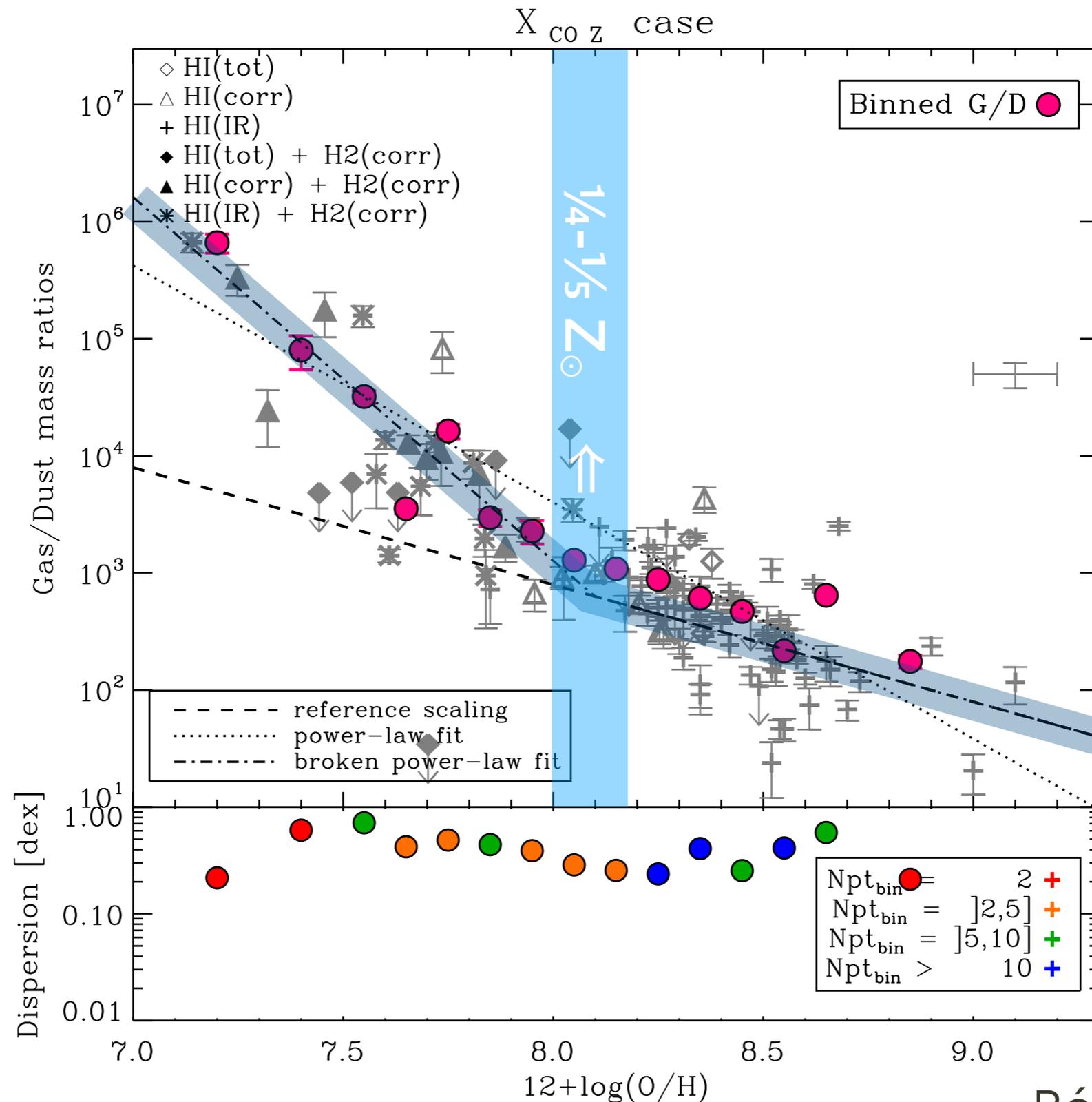
# Low-metallicity Severely Disfavors Dust!



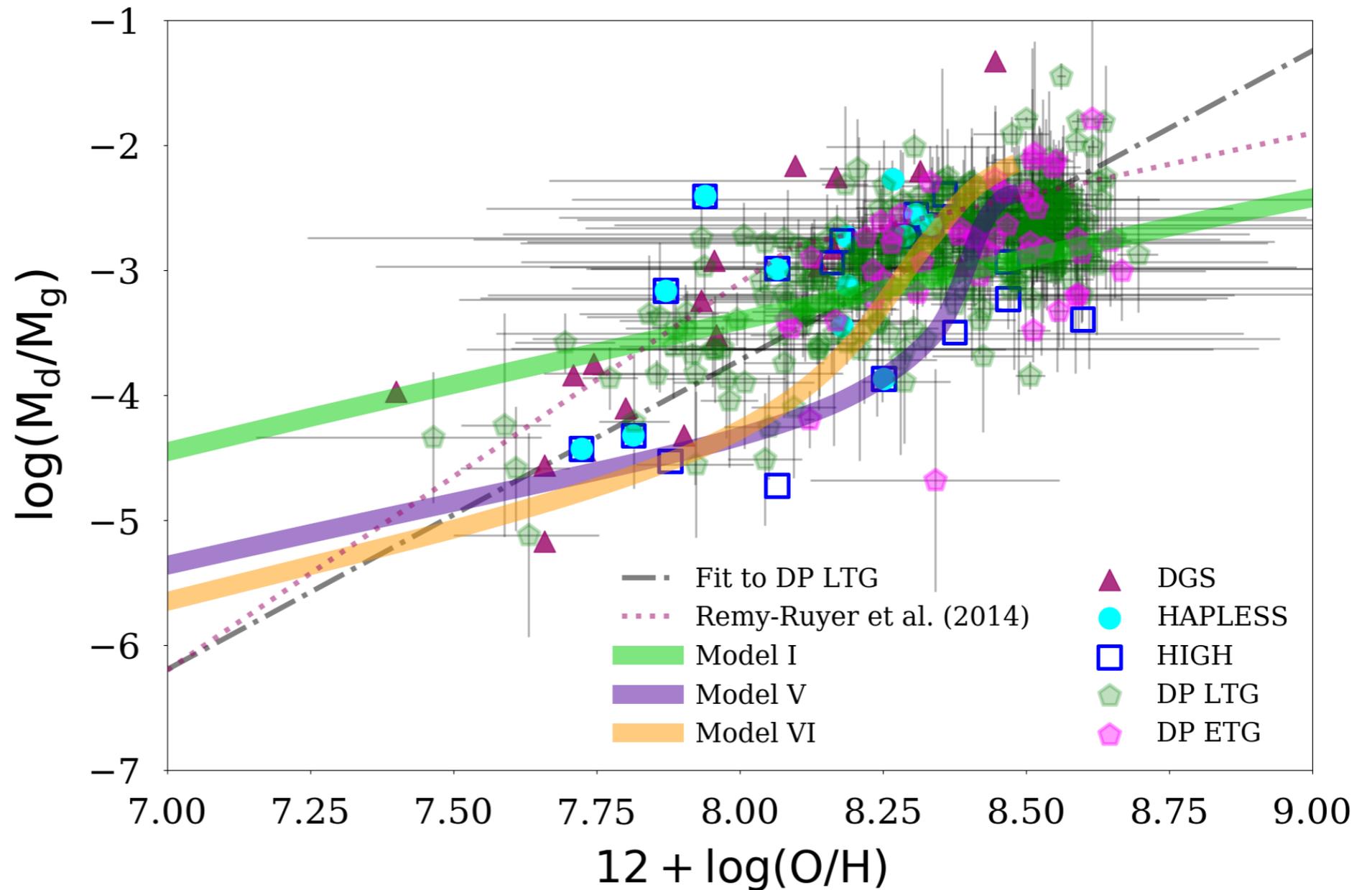
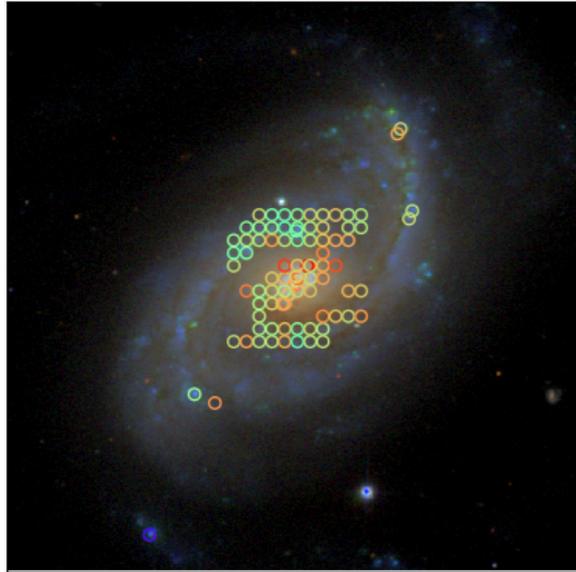
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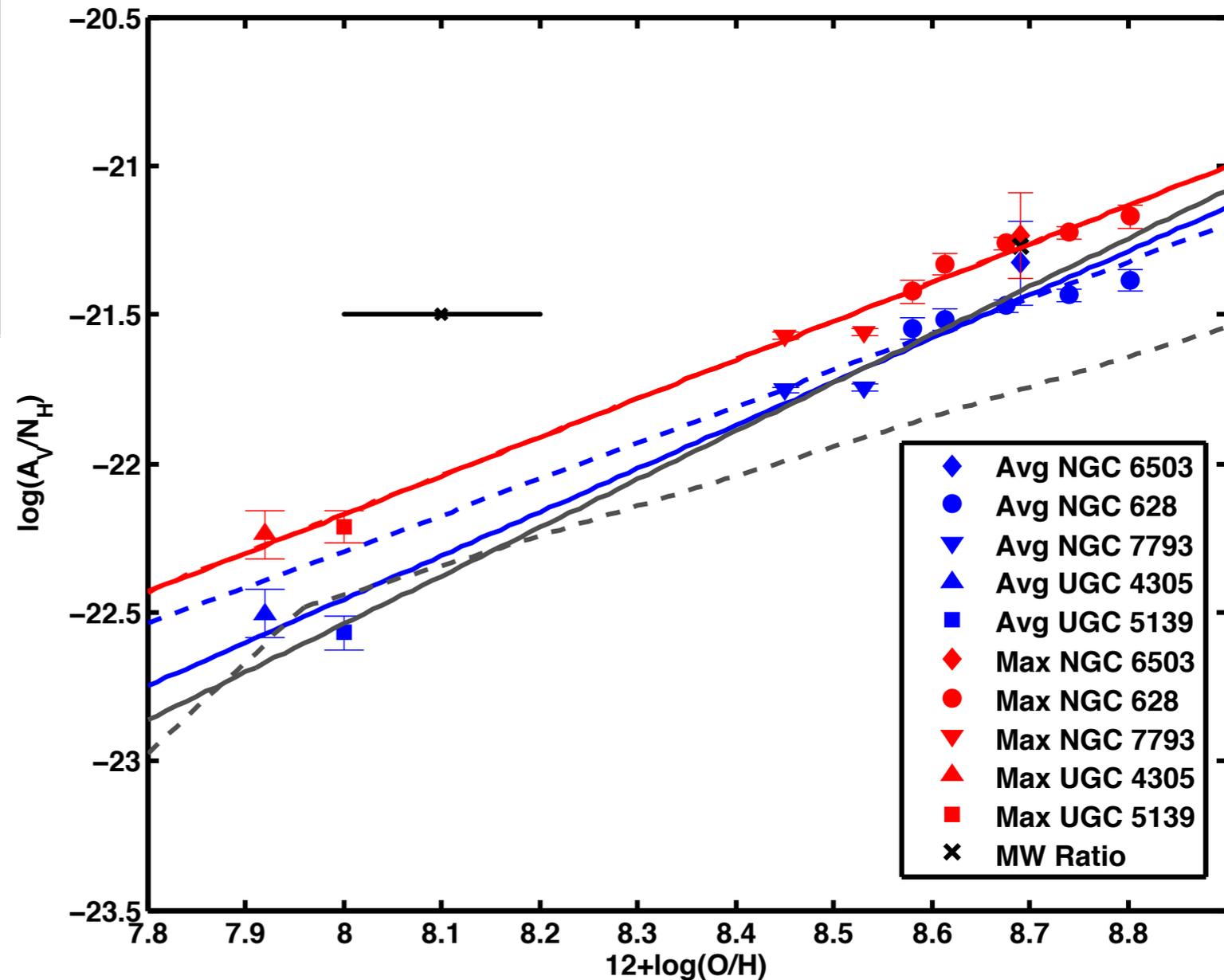
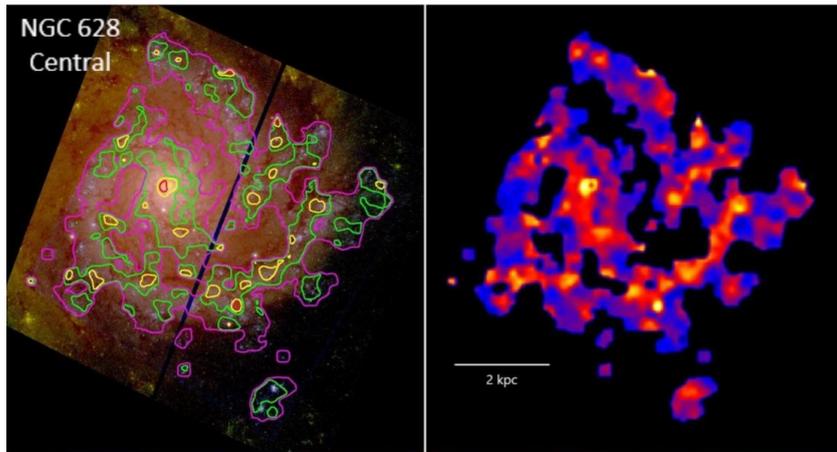


# (Or Does It?)



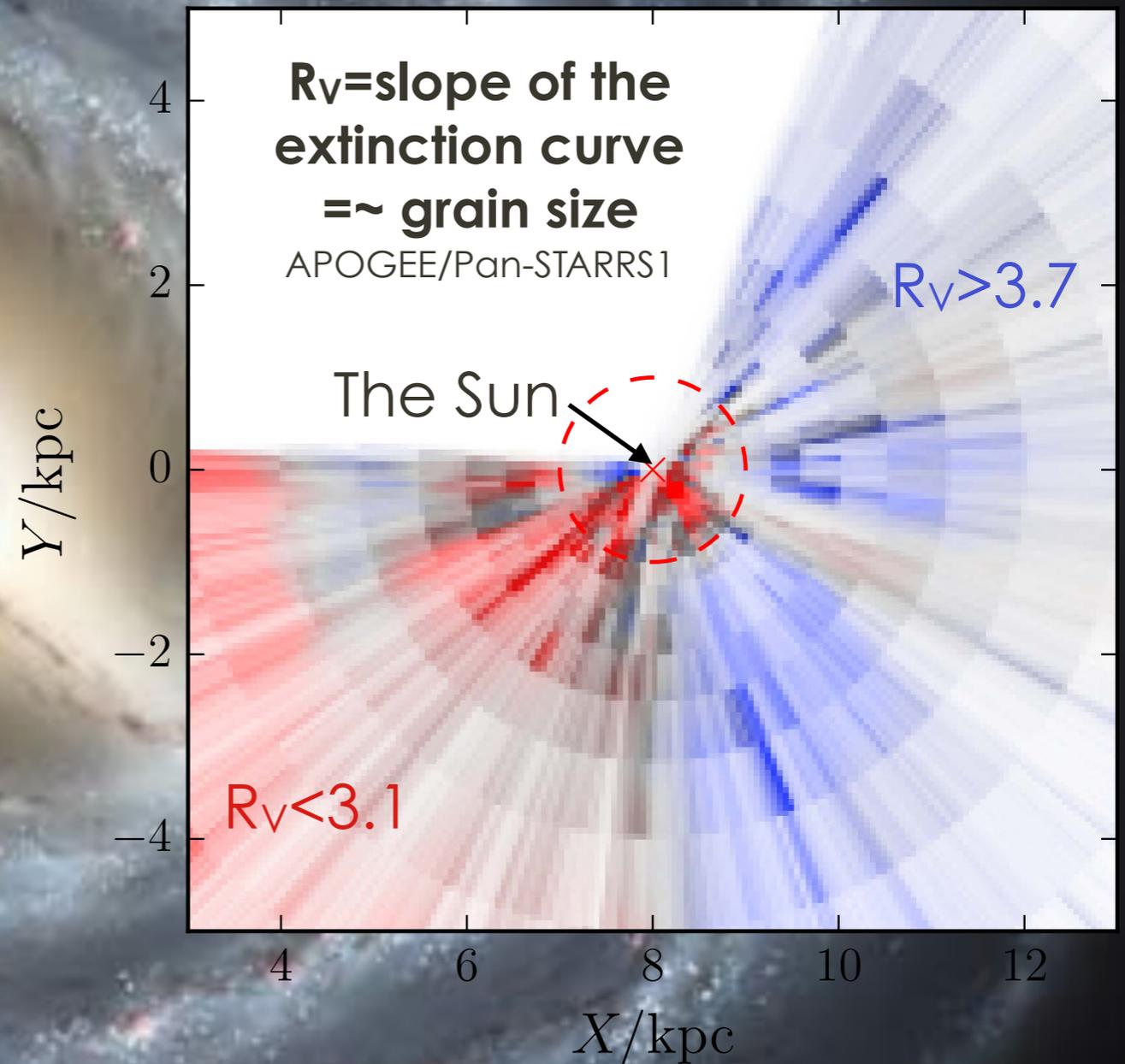
**Consistently  
non-linear**

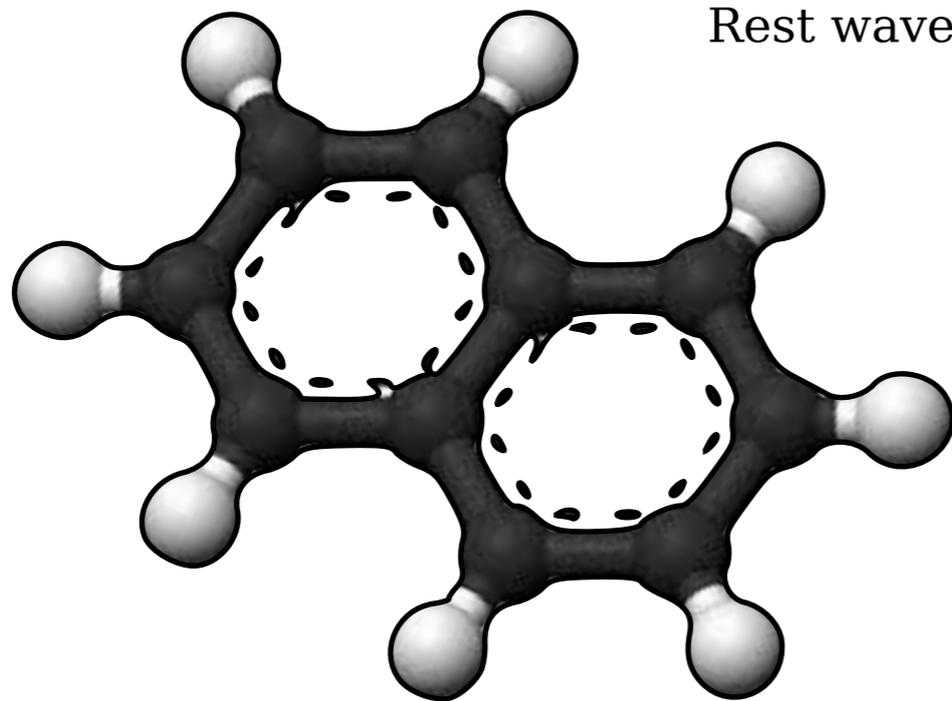
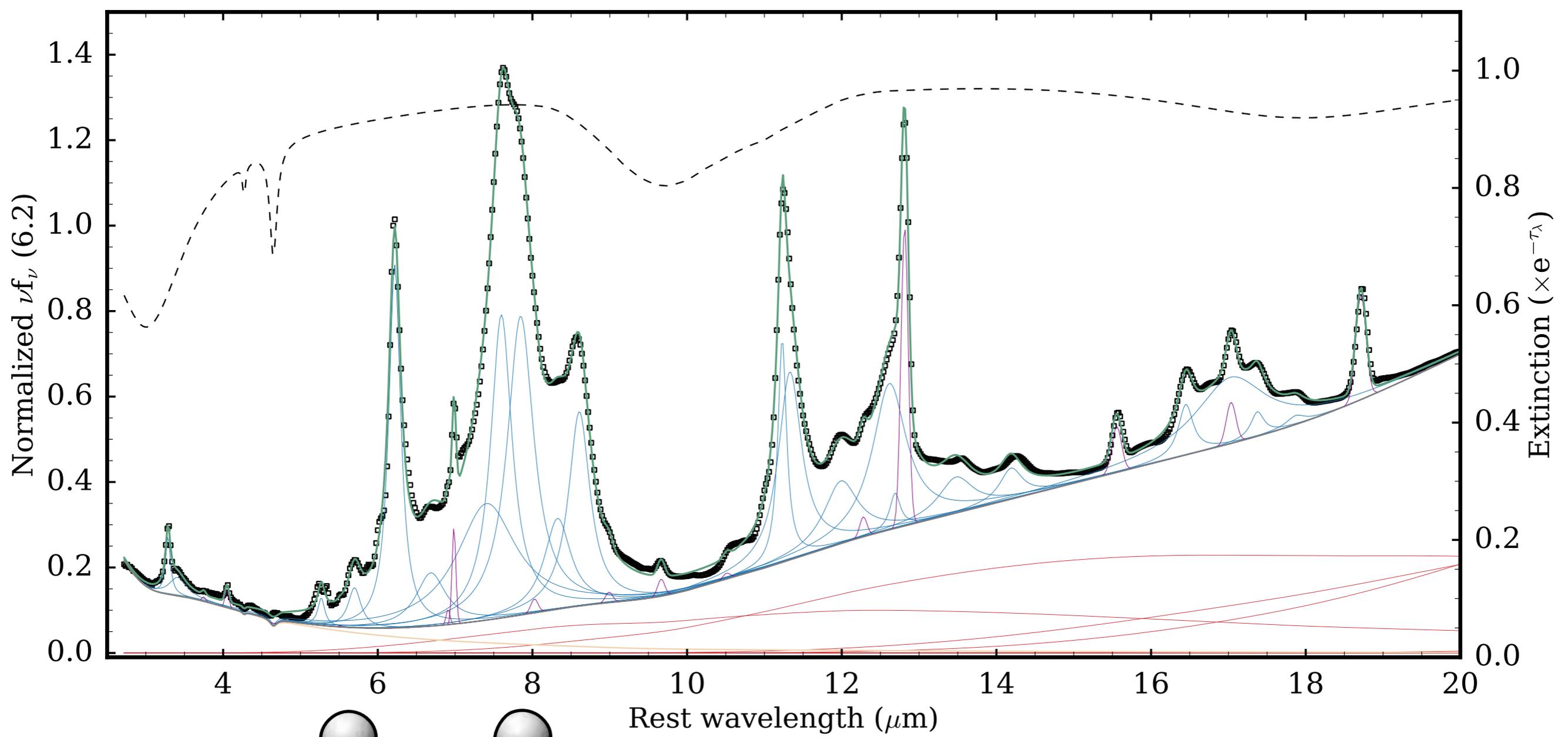
# Lower Z = Less Average Extinction Too



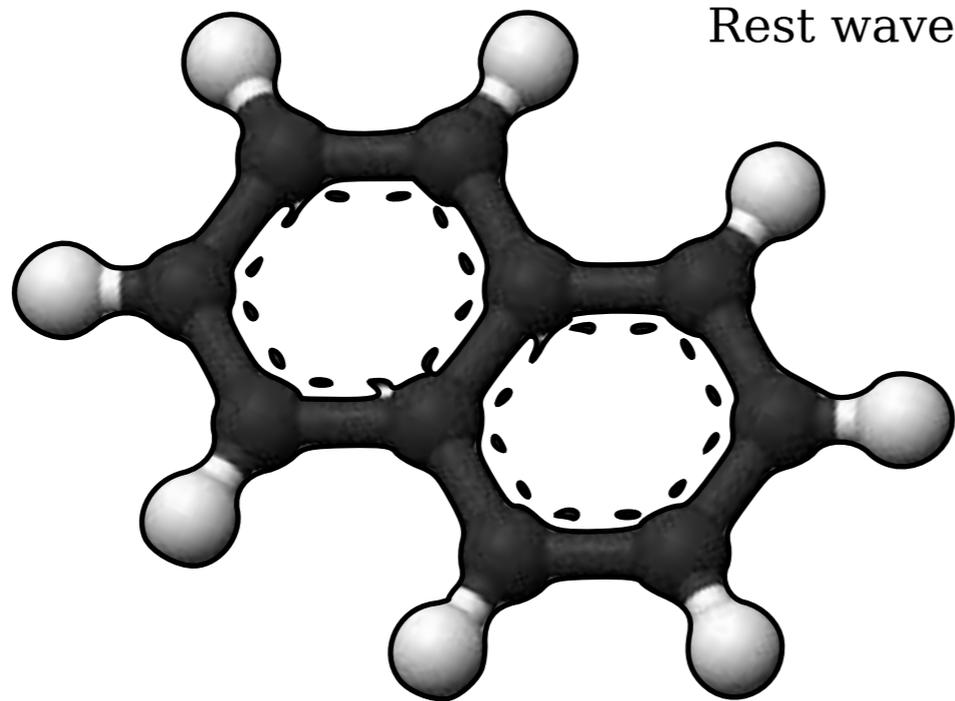
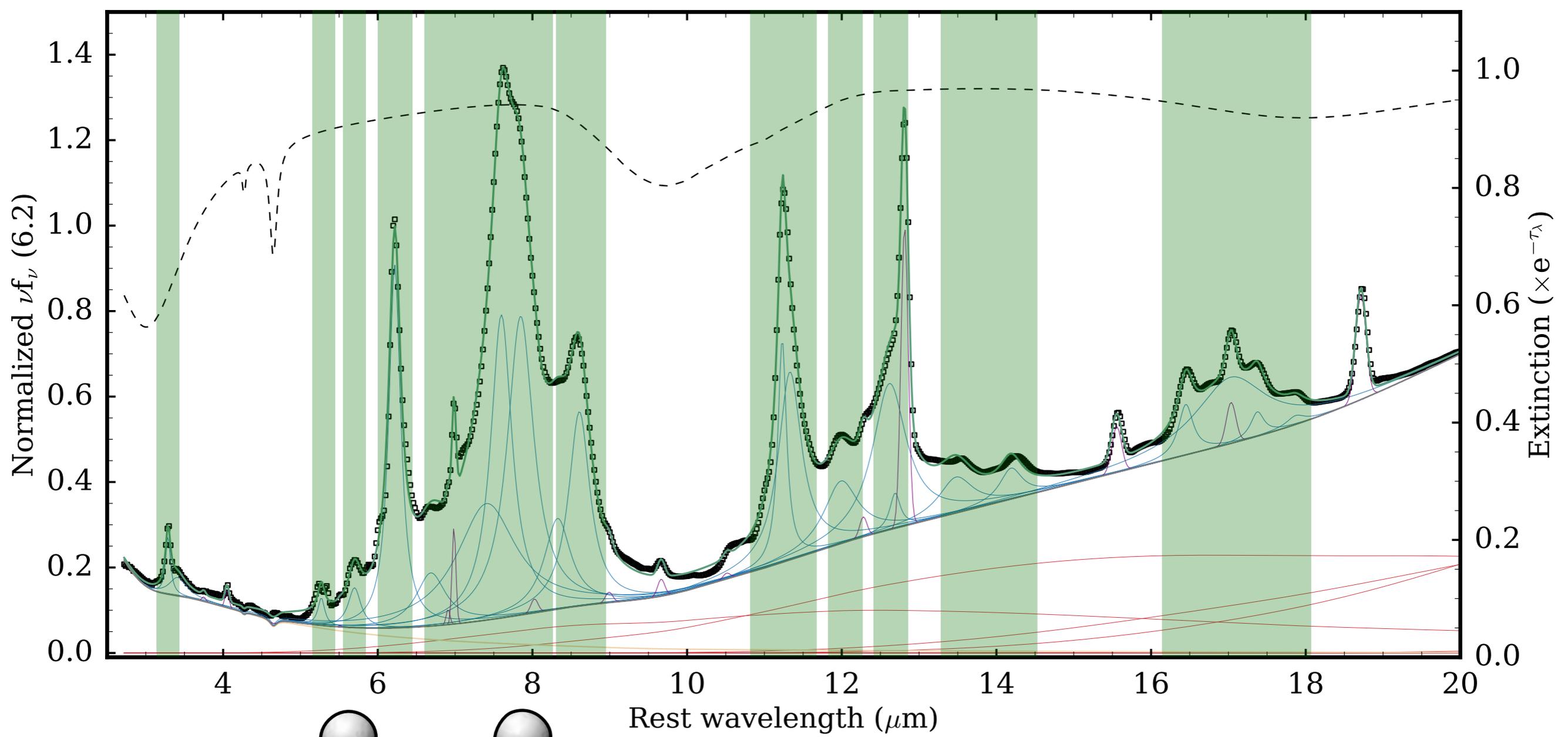
“inconsistent with a  
broken power-law” in  
DGR

# Changes in the Extinction Curve Itself may be driven by Z



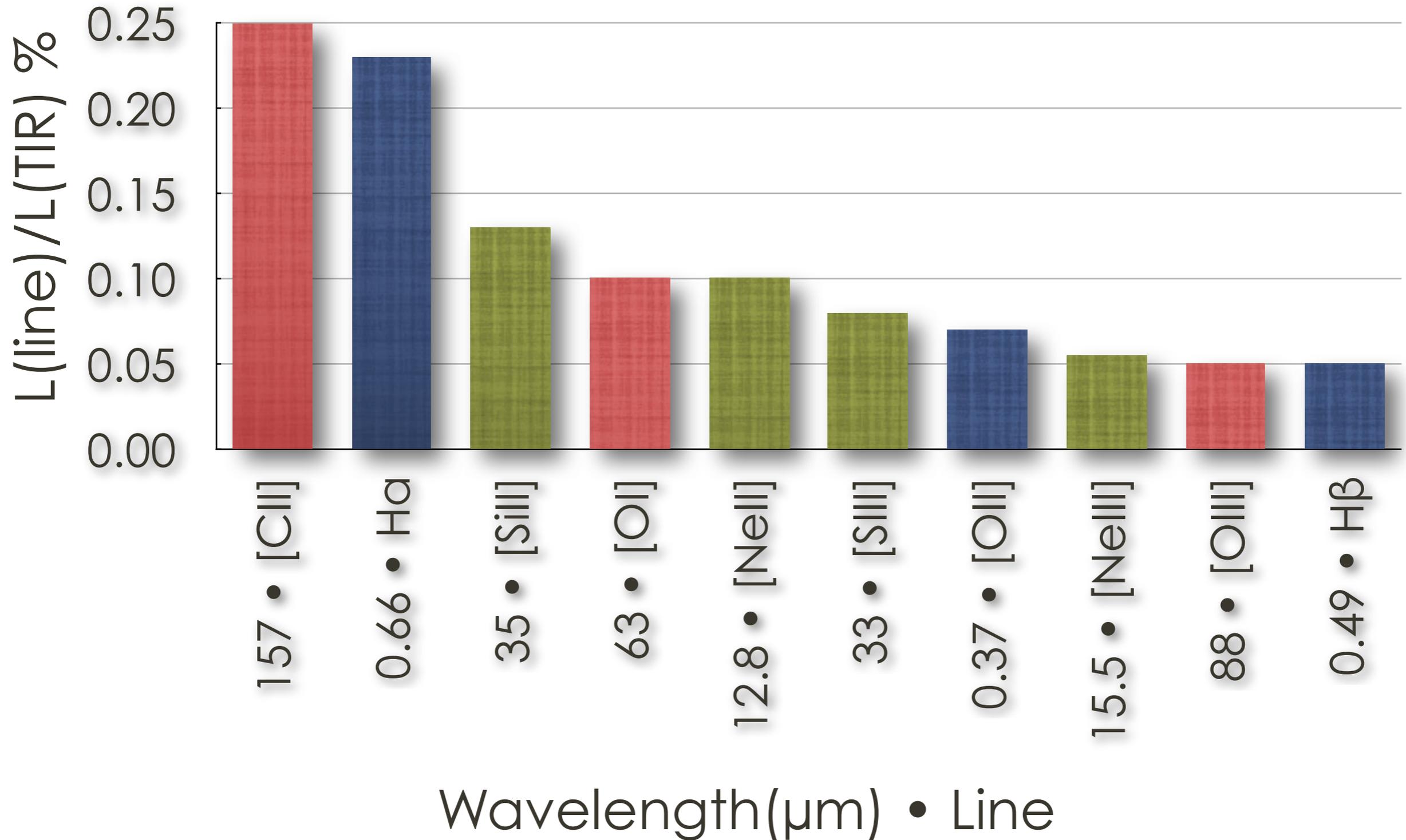


**vs  $Z/Z_\odot$**

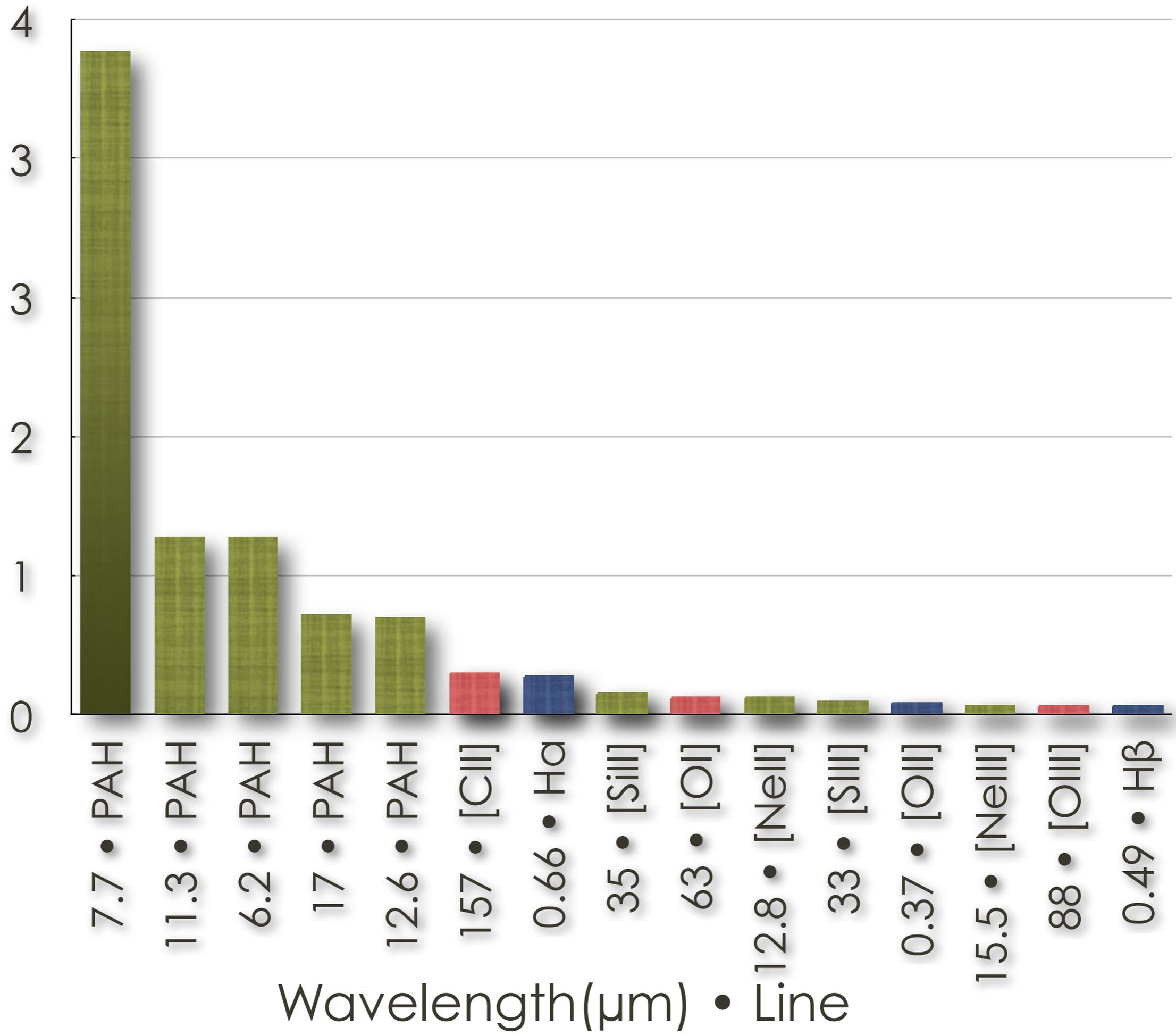


**vs  $Z/Z_\odot$**

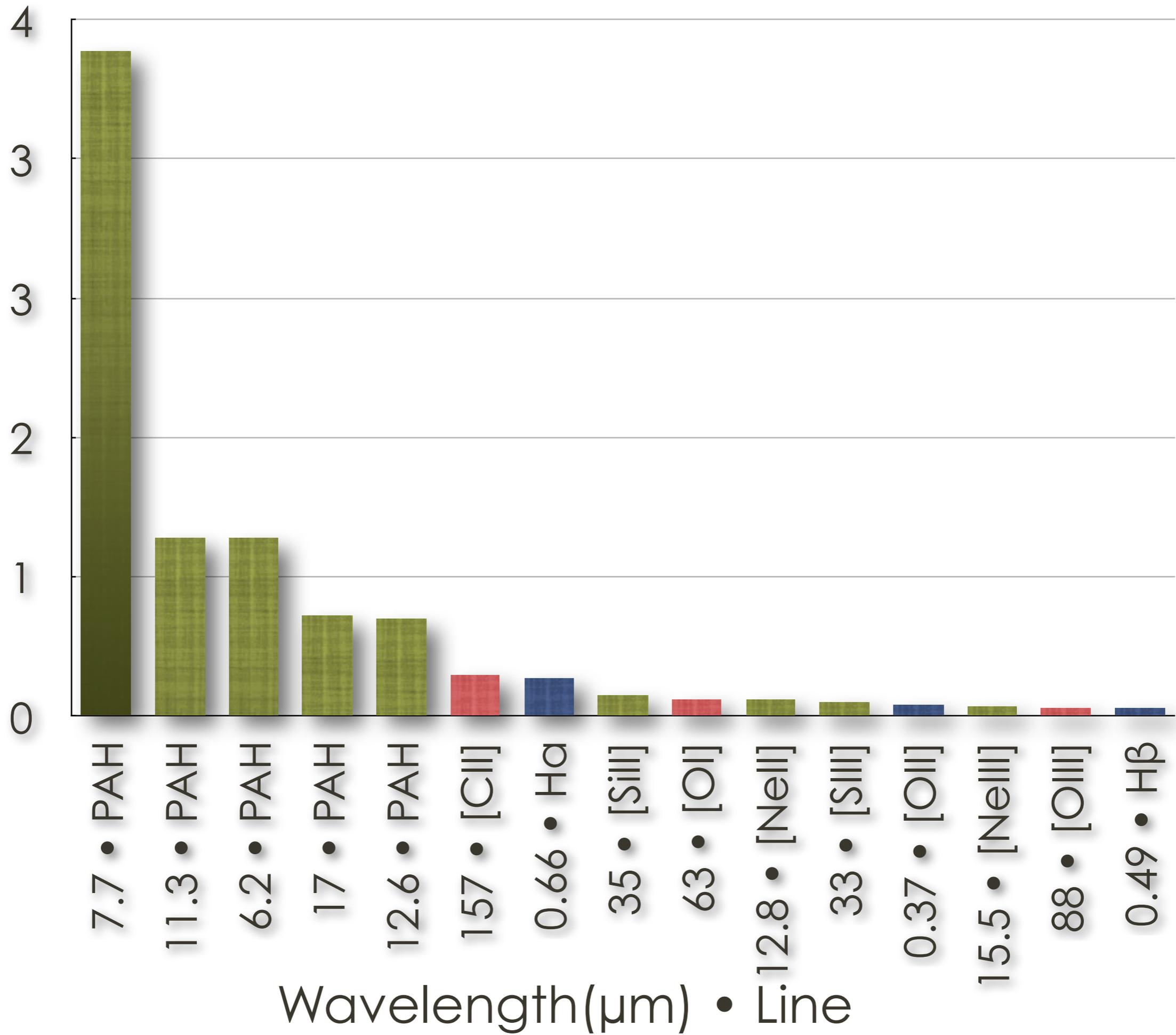
# PAH Bands vs: your favorite line

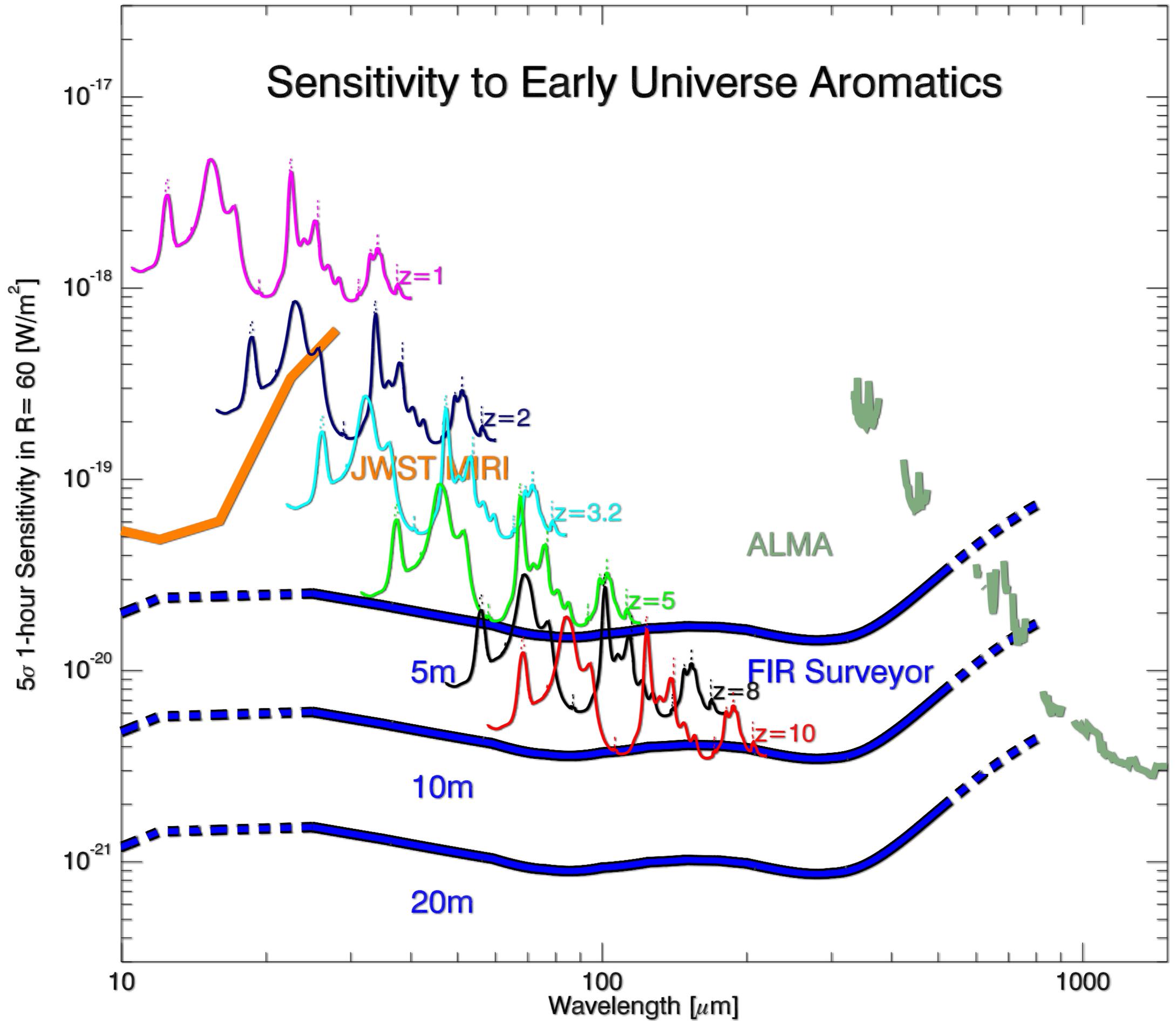


$L(\text{line})/L(\text{TIR}) \%$

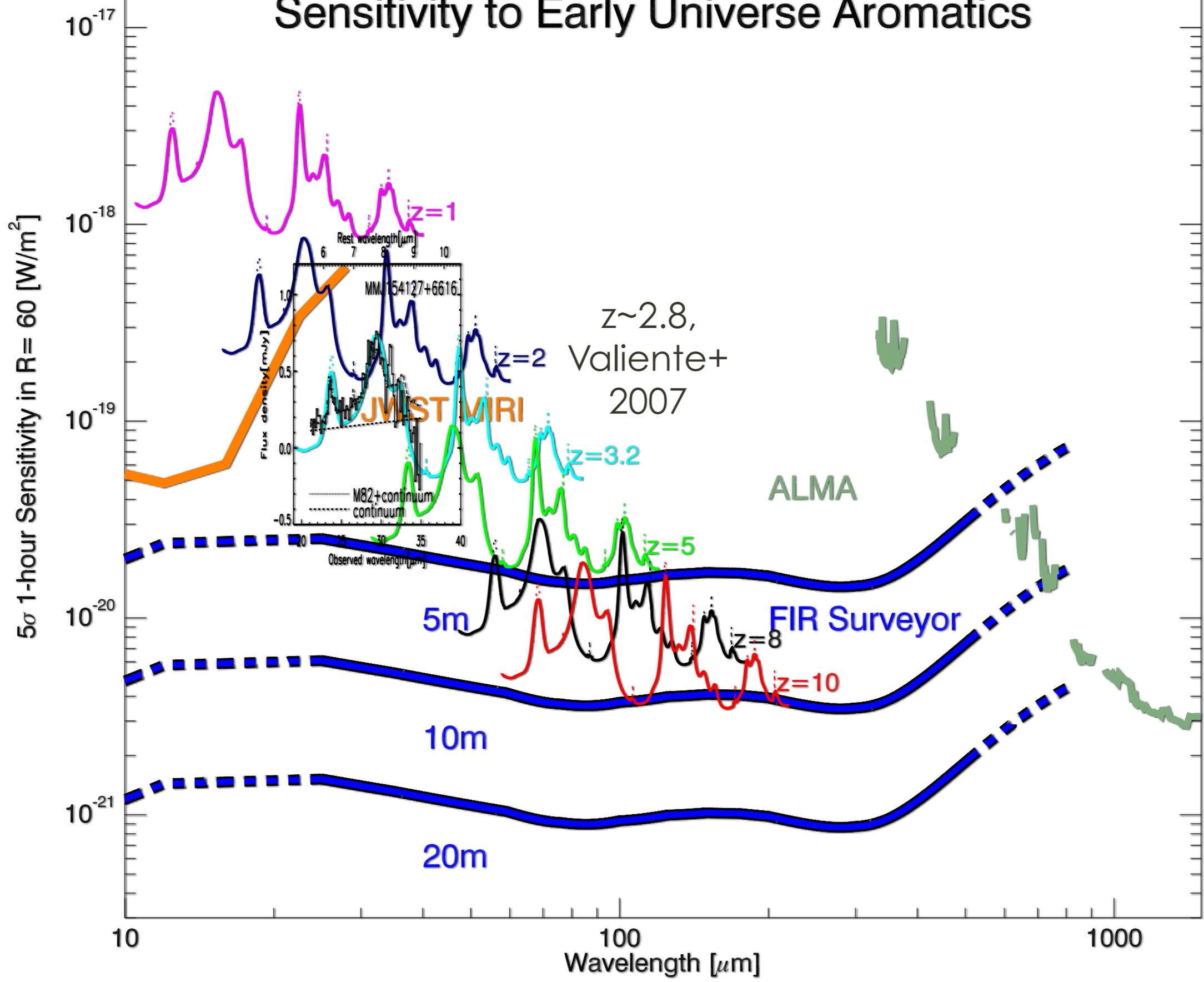


$L(\text{line})/L(\text{TIR}) \%$





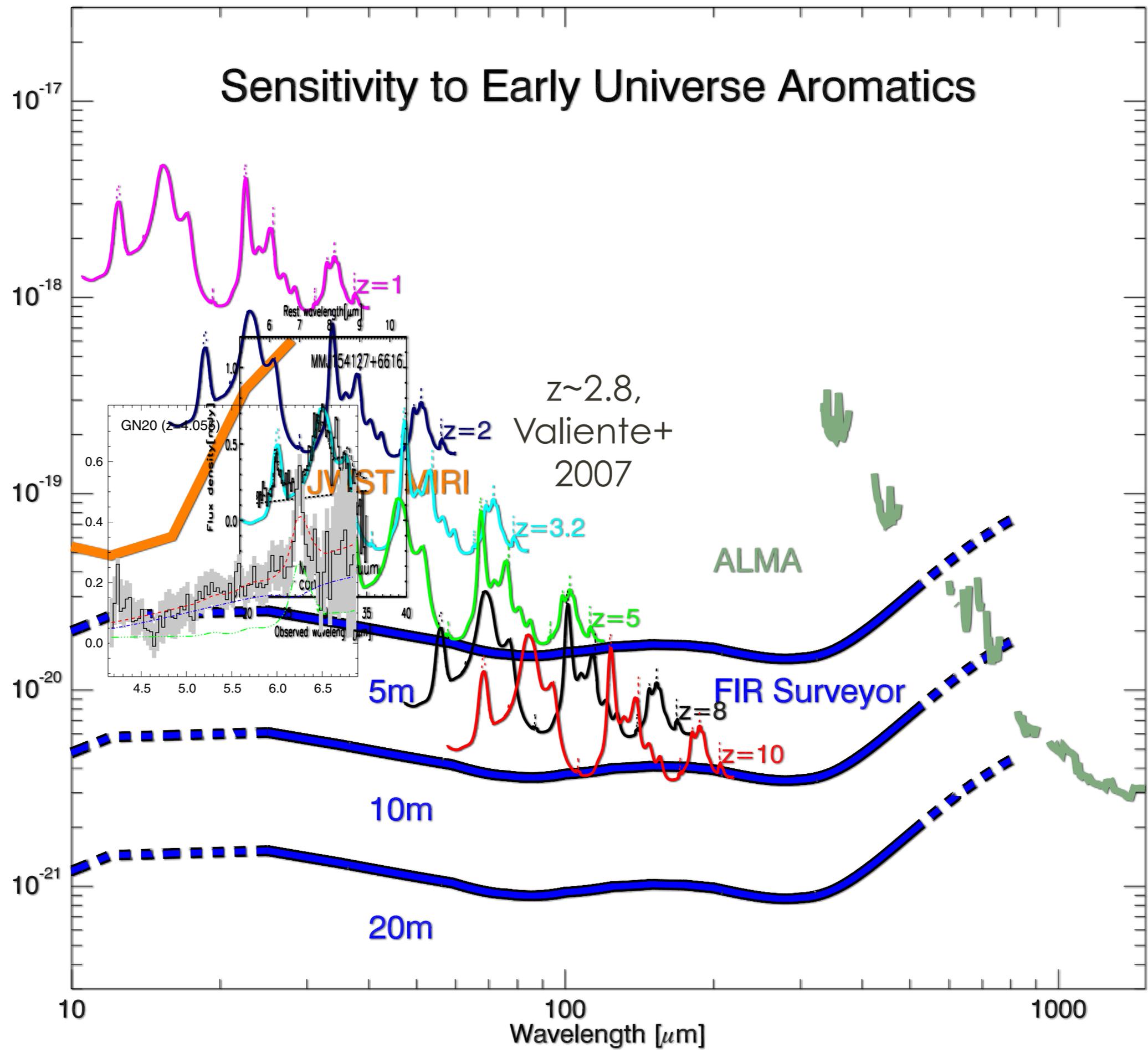
# Sensitivity to Early Universe Aromatics

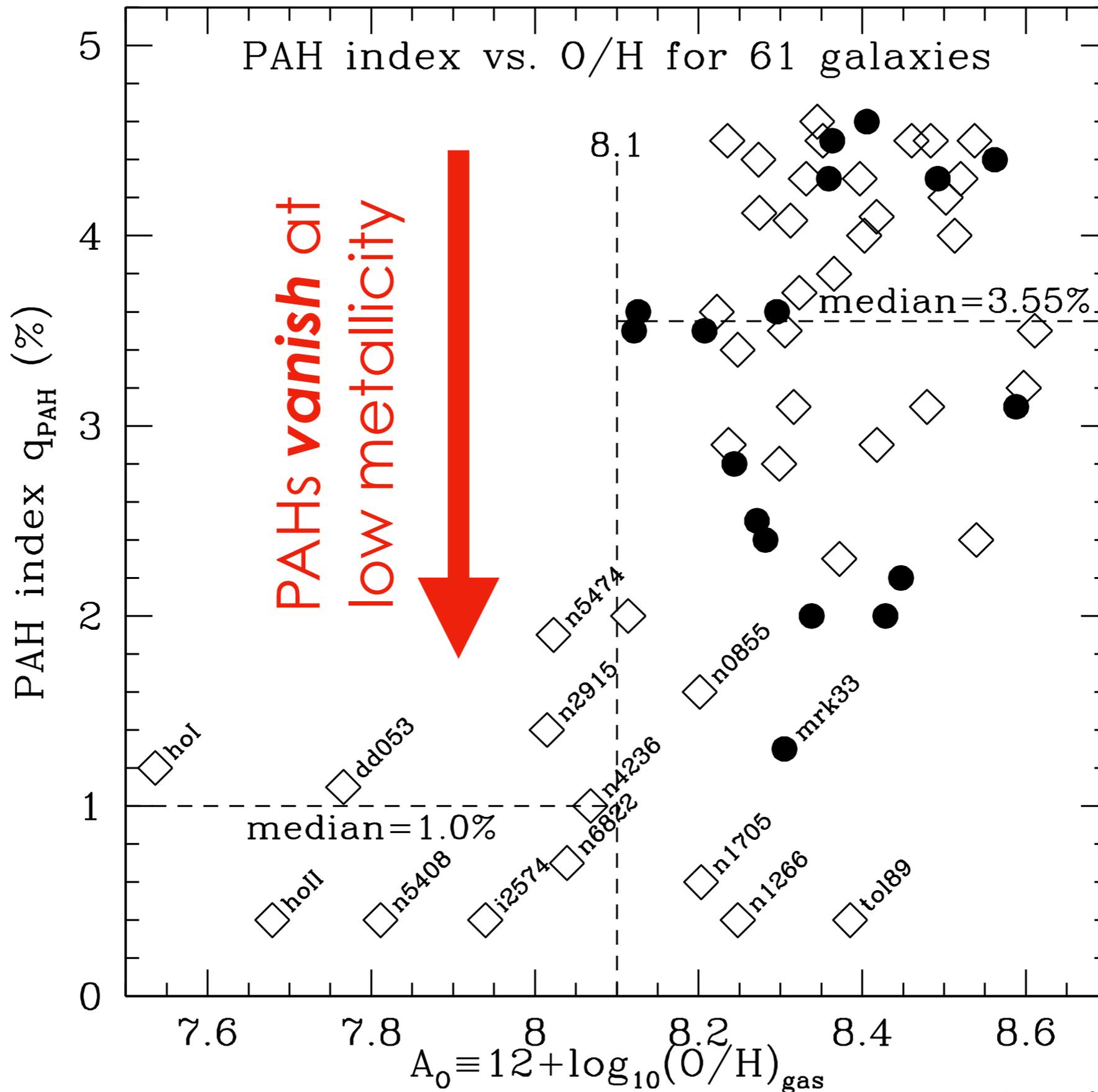


# Sensitivity to Early Universe Aromatics

$z \sim 4$   
Reichers+  
2014

$5\sigma$  1-hour Sensitivity in  $R = 60$  [ $W/m^2$ ]



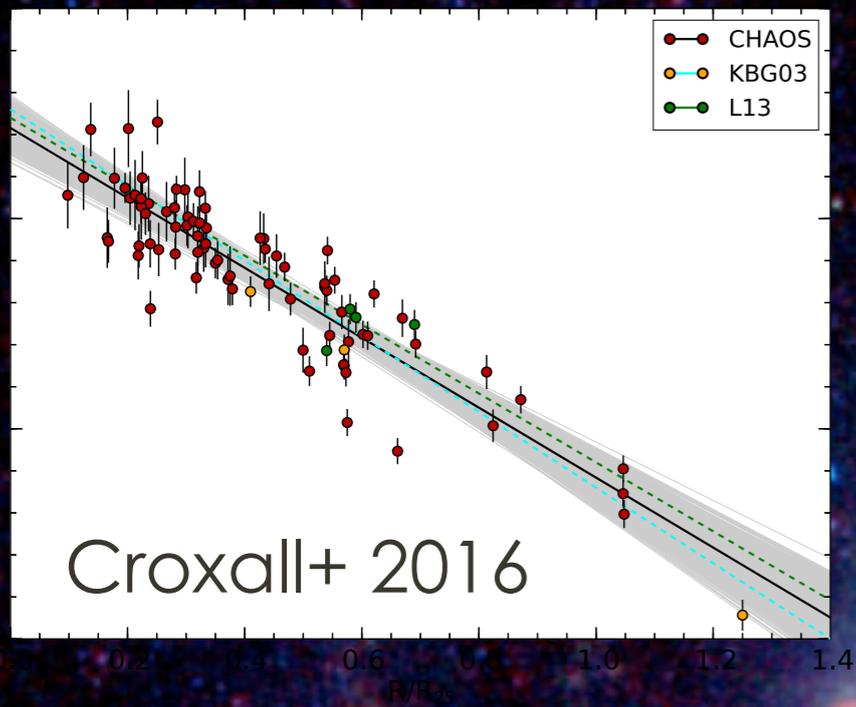


See also: Madden+ 2000, Galliano+ 2005, Engelbracht+ 2005,  
Wu+ 2006, Smith+ 2007, Gordon+ 2008, Sandstrom+ 2012

Draine, 2007



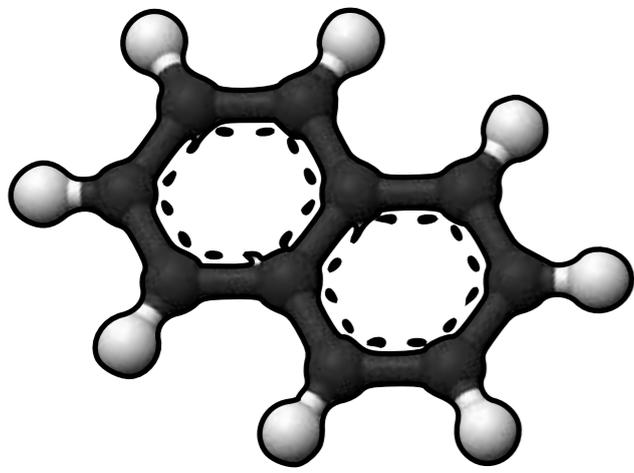
Spitzer's M101, K. Gordon



<Haro11

Super-Solar

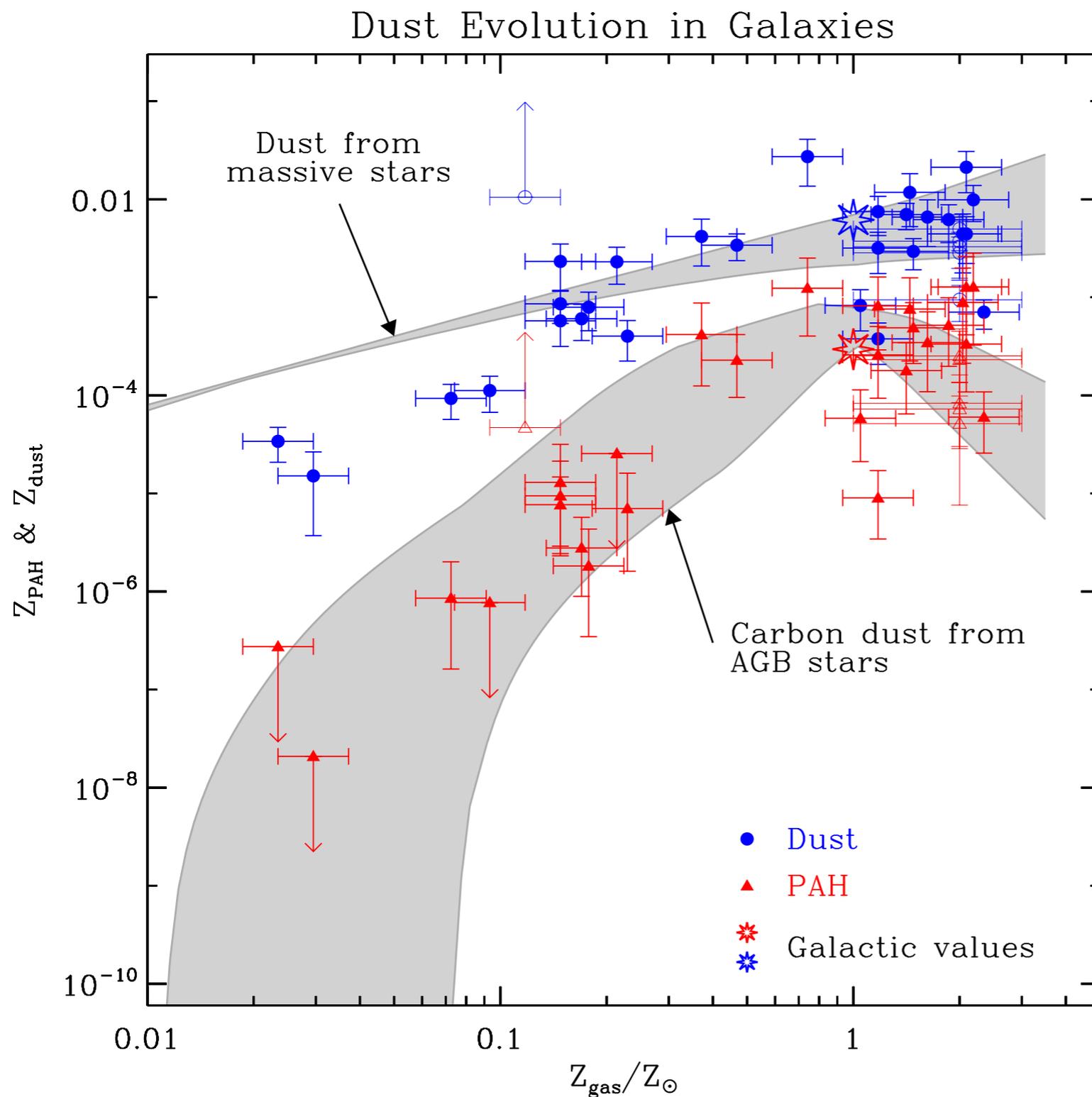
Spitzer's M101, K. Gordon



# *Why* do the PAHs vanish?

- **Carbon Crisis 2.0:** They never get formed by stars (low C to O ratios)
- **You're too impatient:** They didn't yet have time to be formed
- **Low-Z Life is Hard For Small Grains:**
  - **(1):** UV photo-destruction destroys grains
  - **(2):** SN shocks destroy small grains (but also create them??)
  - **(3):** Grain re-growth is inhibited

# Explanations...



**You are  
Impatient:  
Star Formation  
History(Z)**

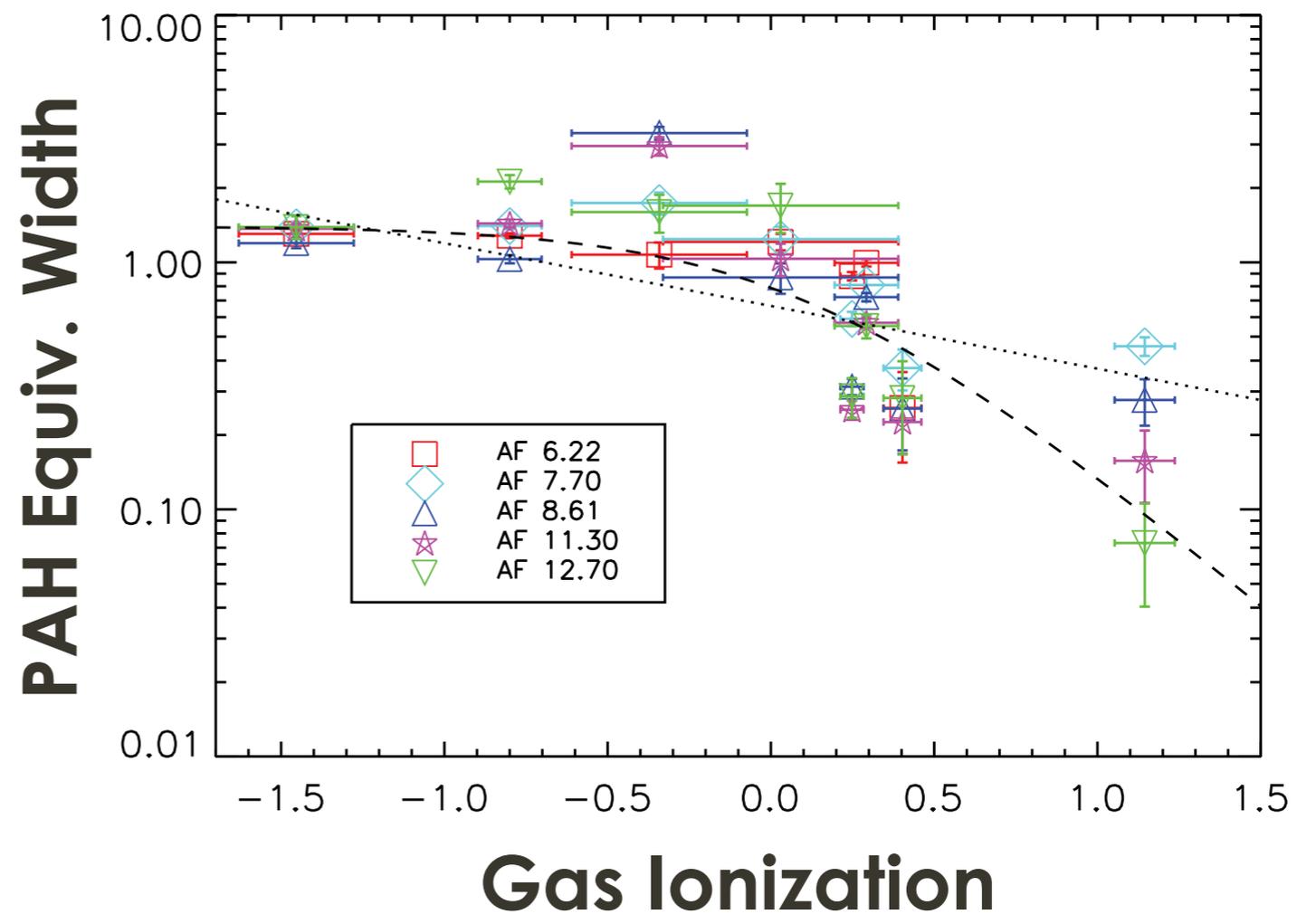
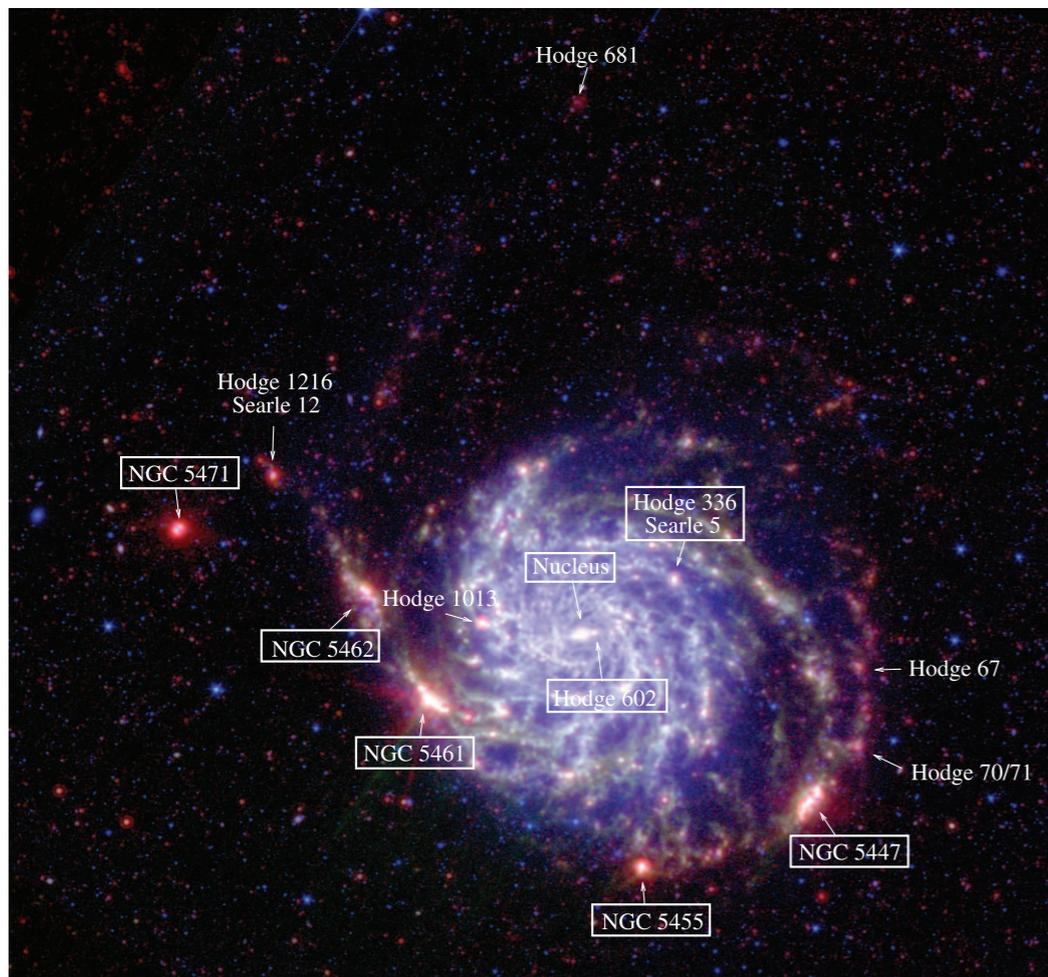
**Delayed onset of  
PAH production**

Galliano+ 2008;  
Dwek+ 2009

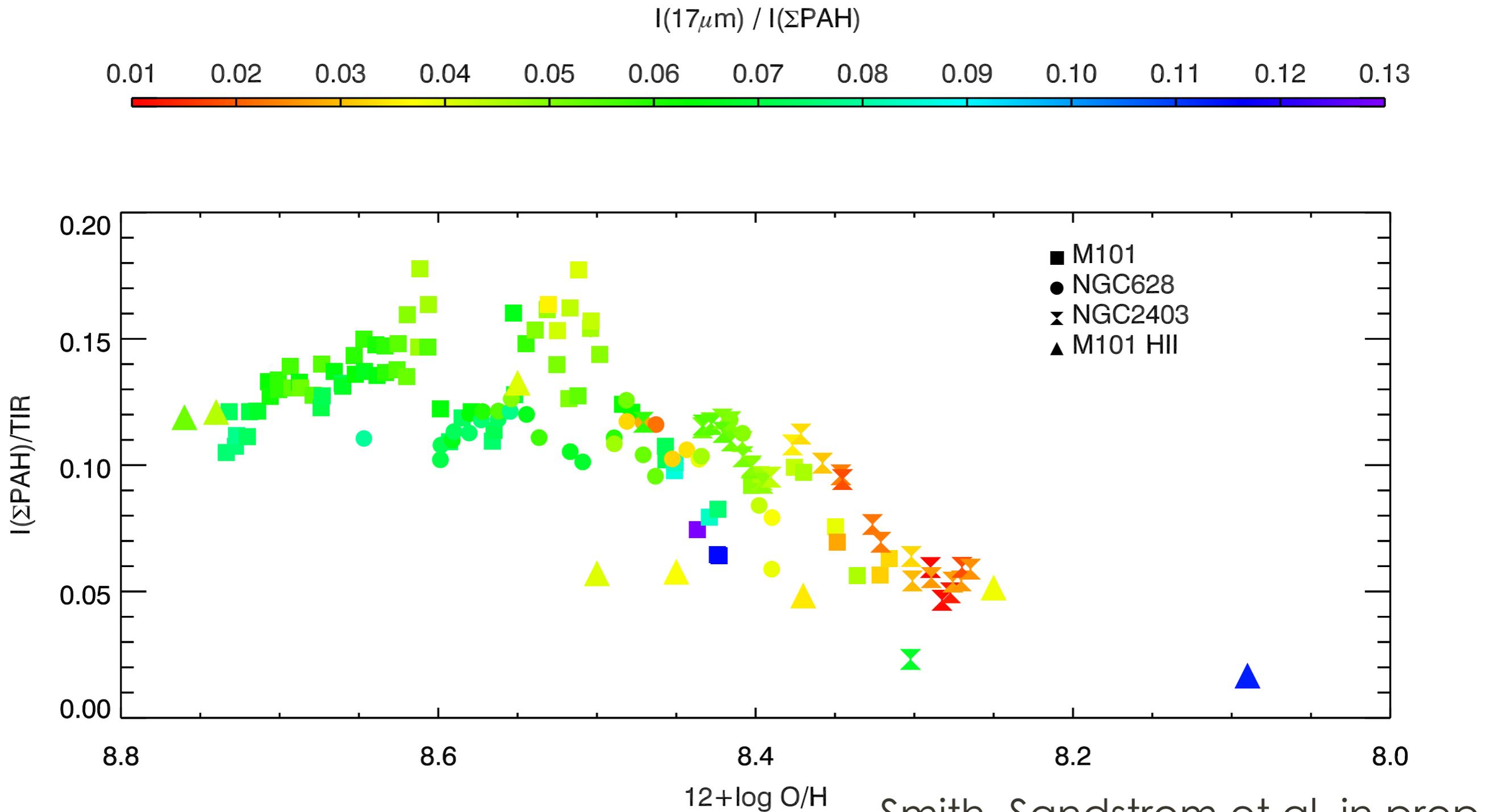
# Explanations...

Life is hard for a  
small grain (1):  
Photons/  
Ionization

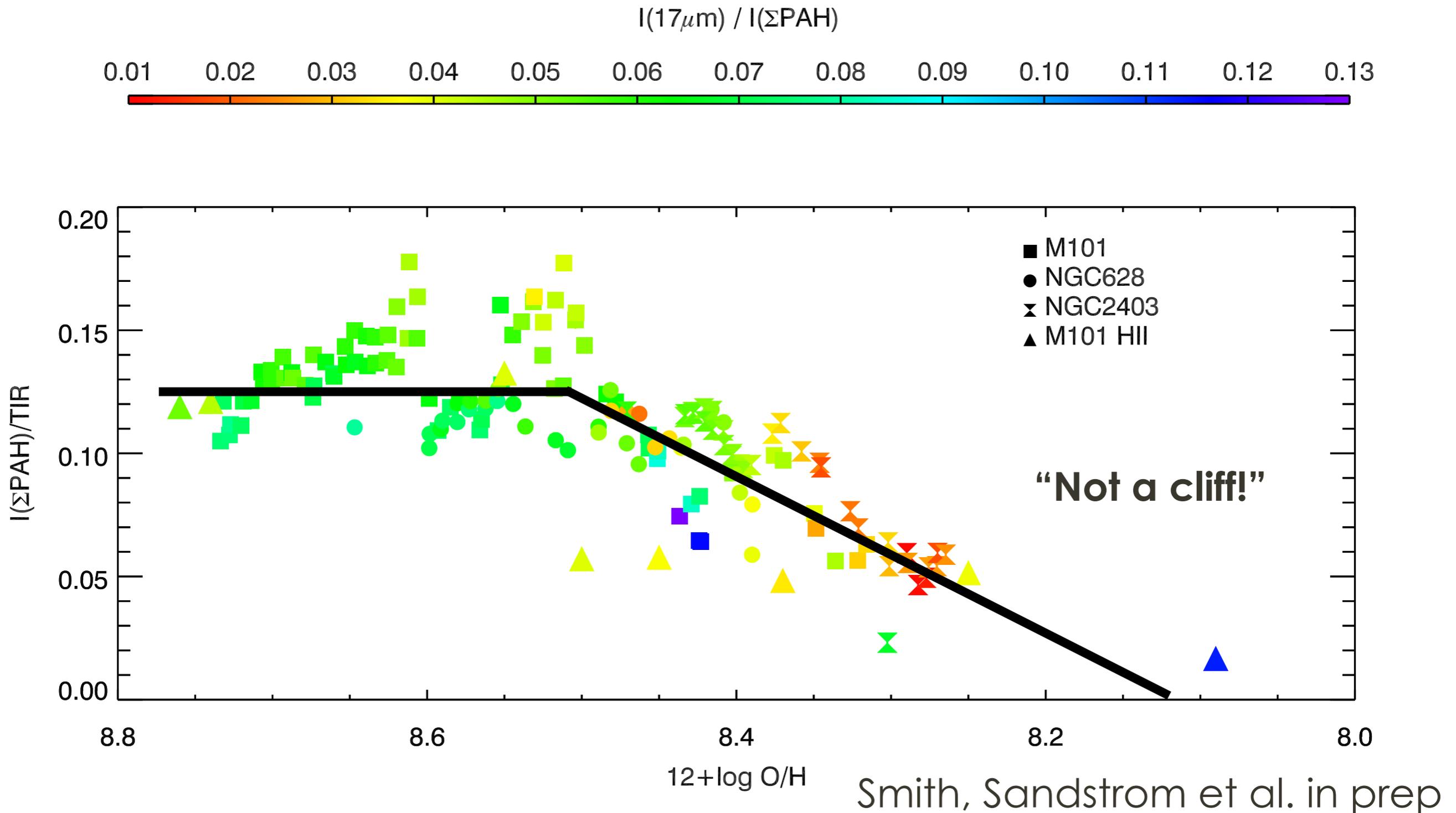
Grain photo-  
destruction at low Z



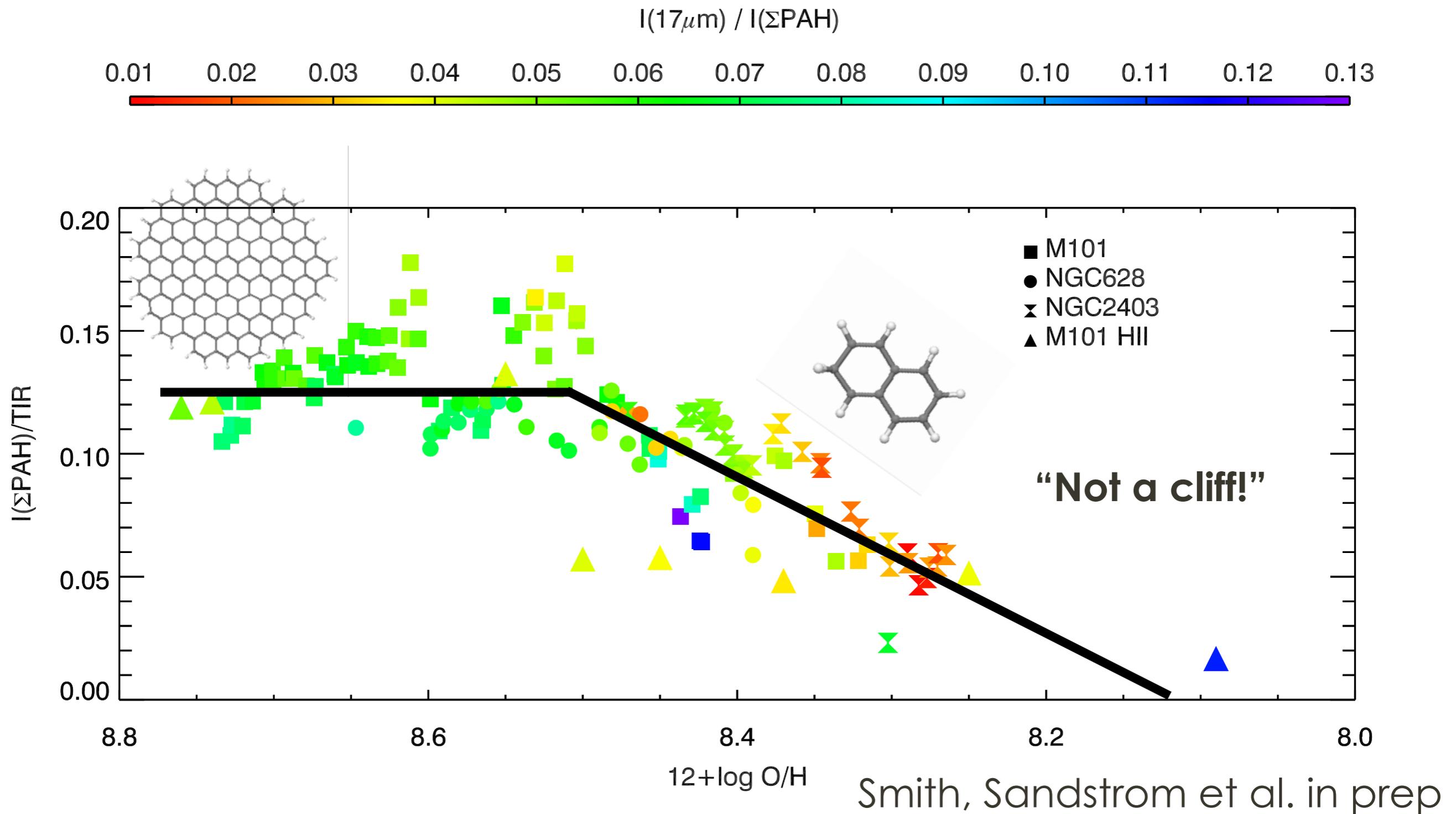
# PAH vs. Z in high dZ/dR Galaxies



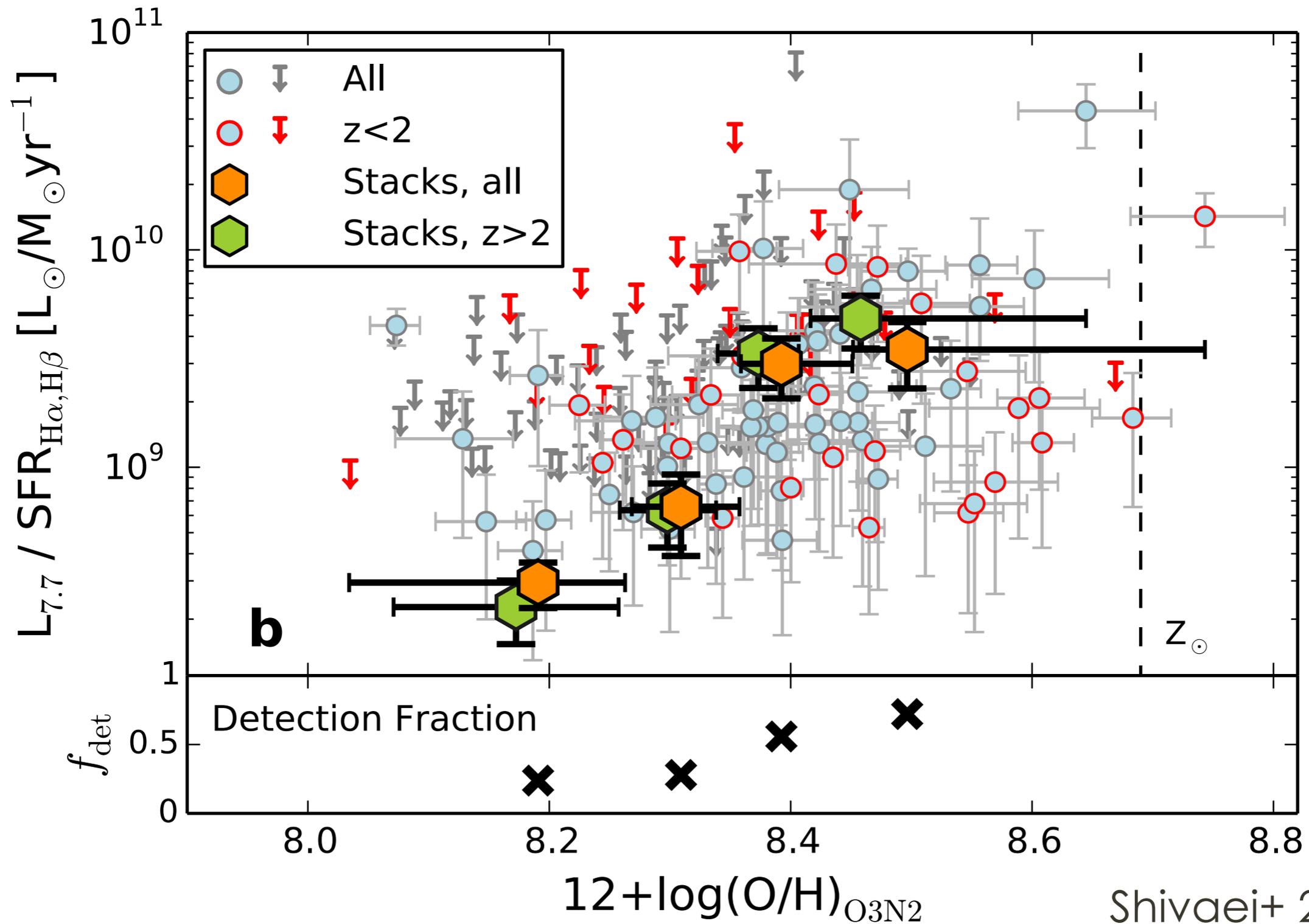
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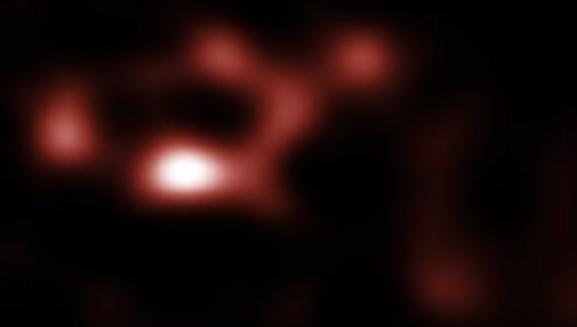


# Strong PAH-metallicity Evolution at $z \sim 2$

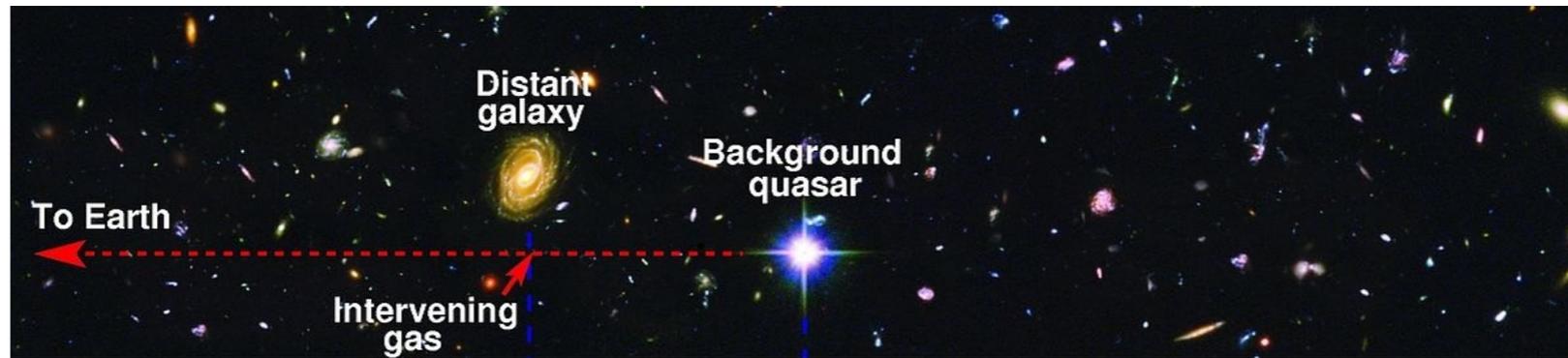


# Dust and Metals in the ISM at High $z$

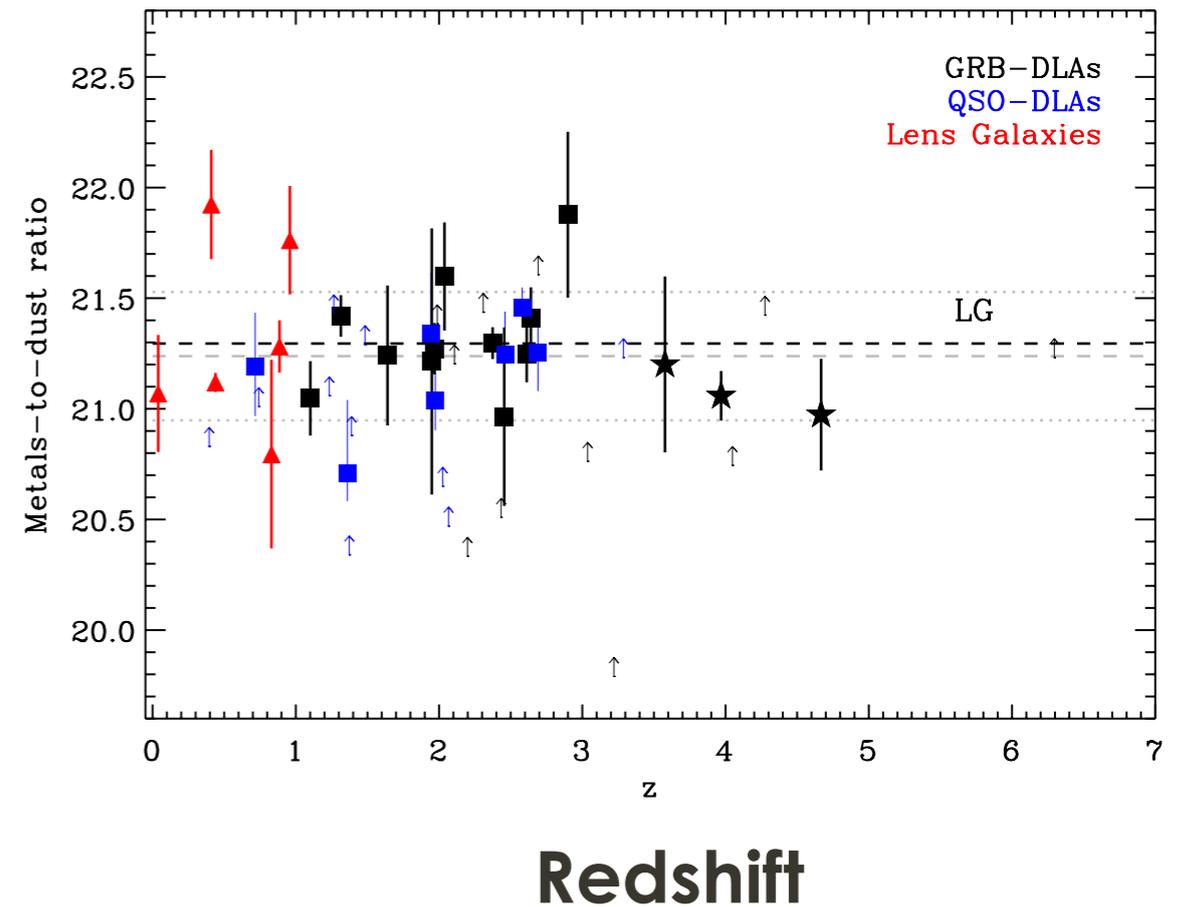
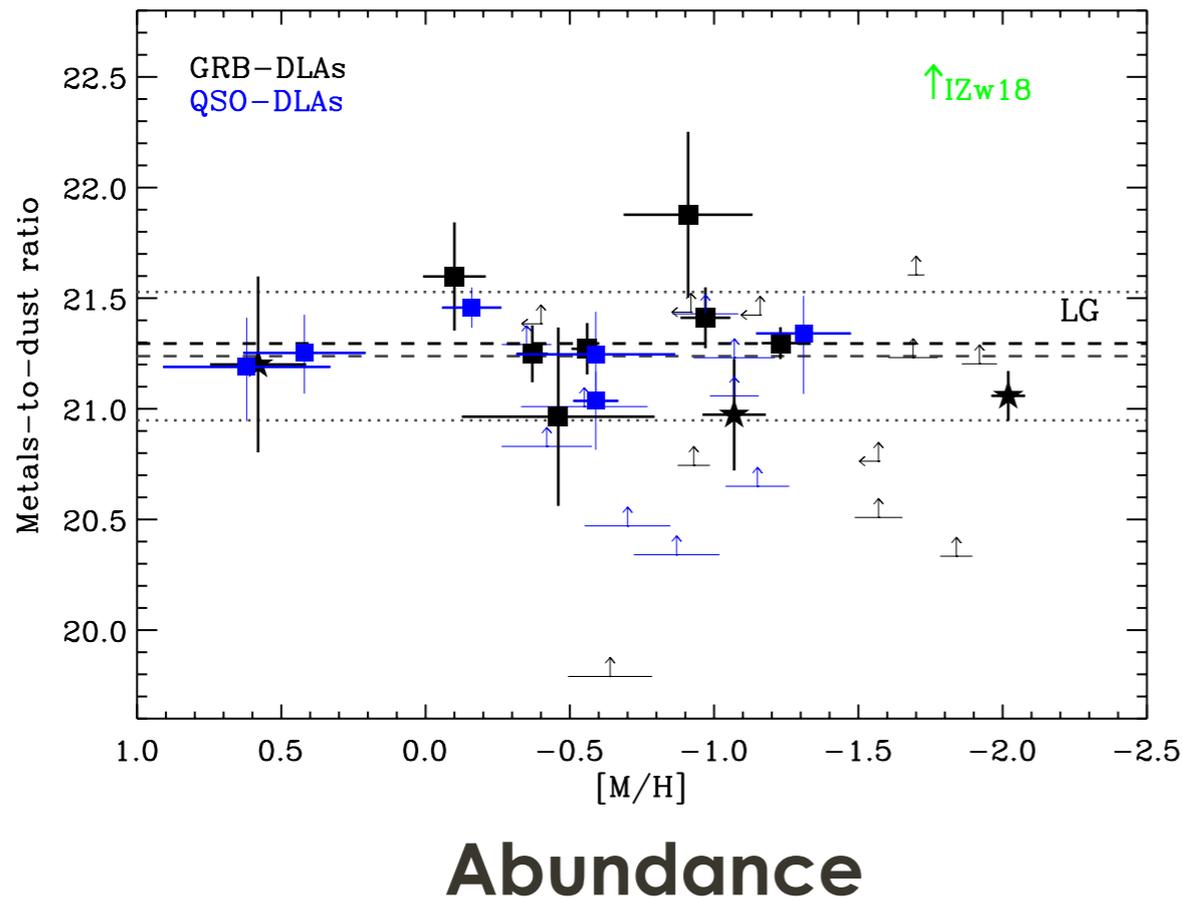
ALMA,  $z=8.4$ ,  
Laporte+ 2017



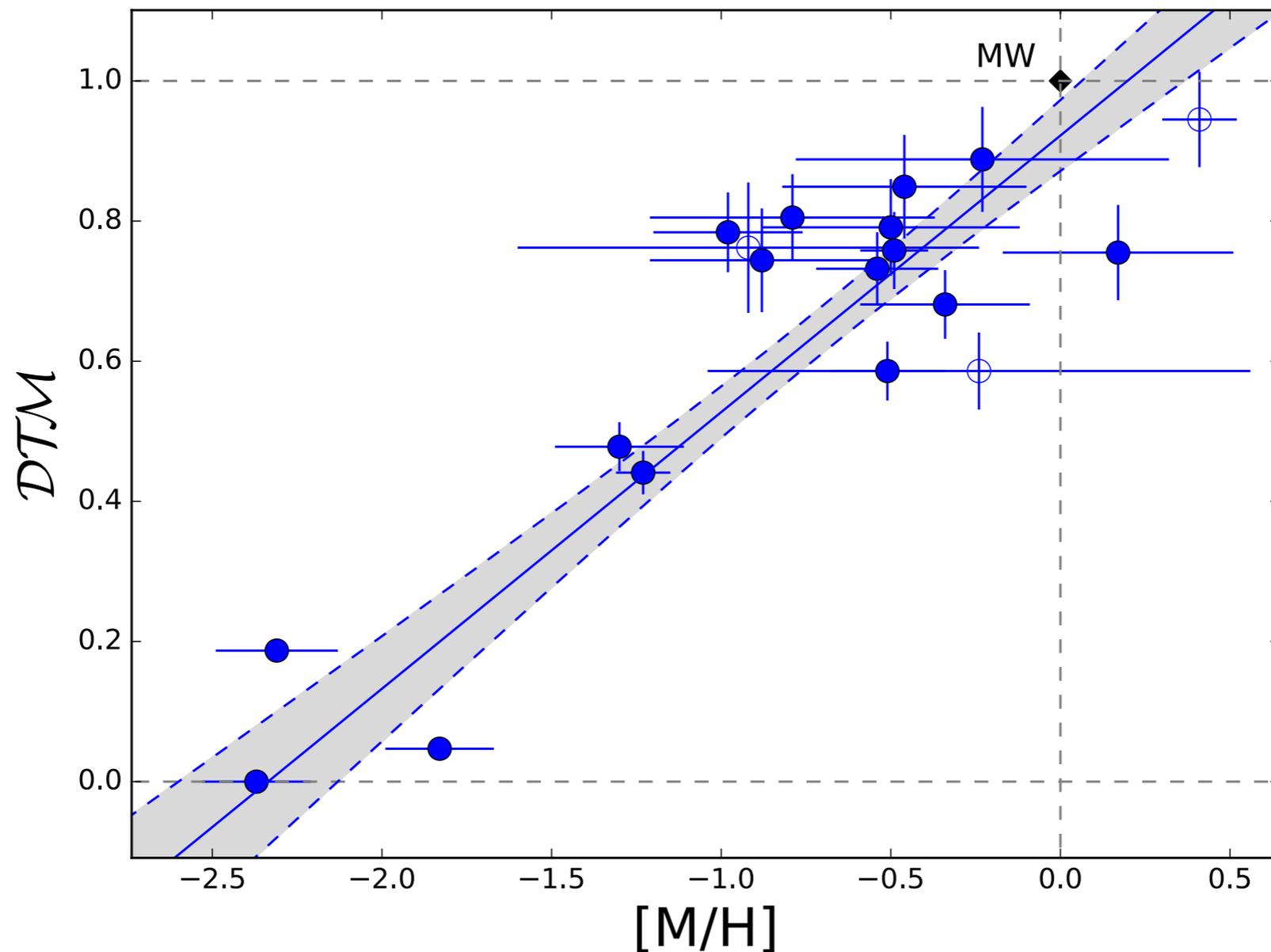
# Dust to Metal Ratio ~Same as MW in DLA's@high-z



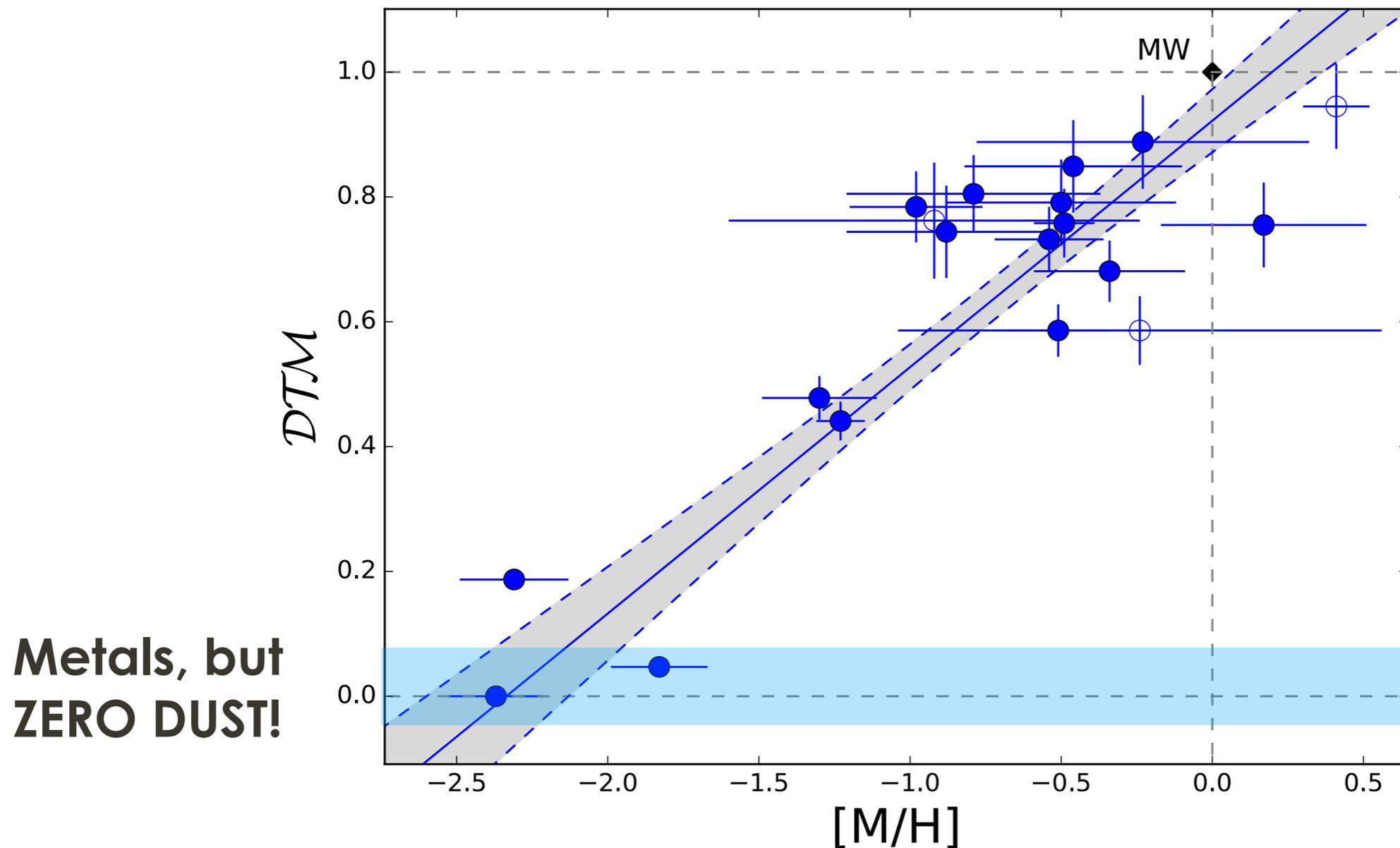
Dust-to-Metals Ratio from extinction/depletion



# OR...Dust-to-Metal Ratio varies *strongly* with metallicity in DLA's@high-z

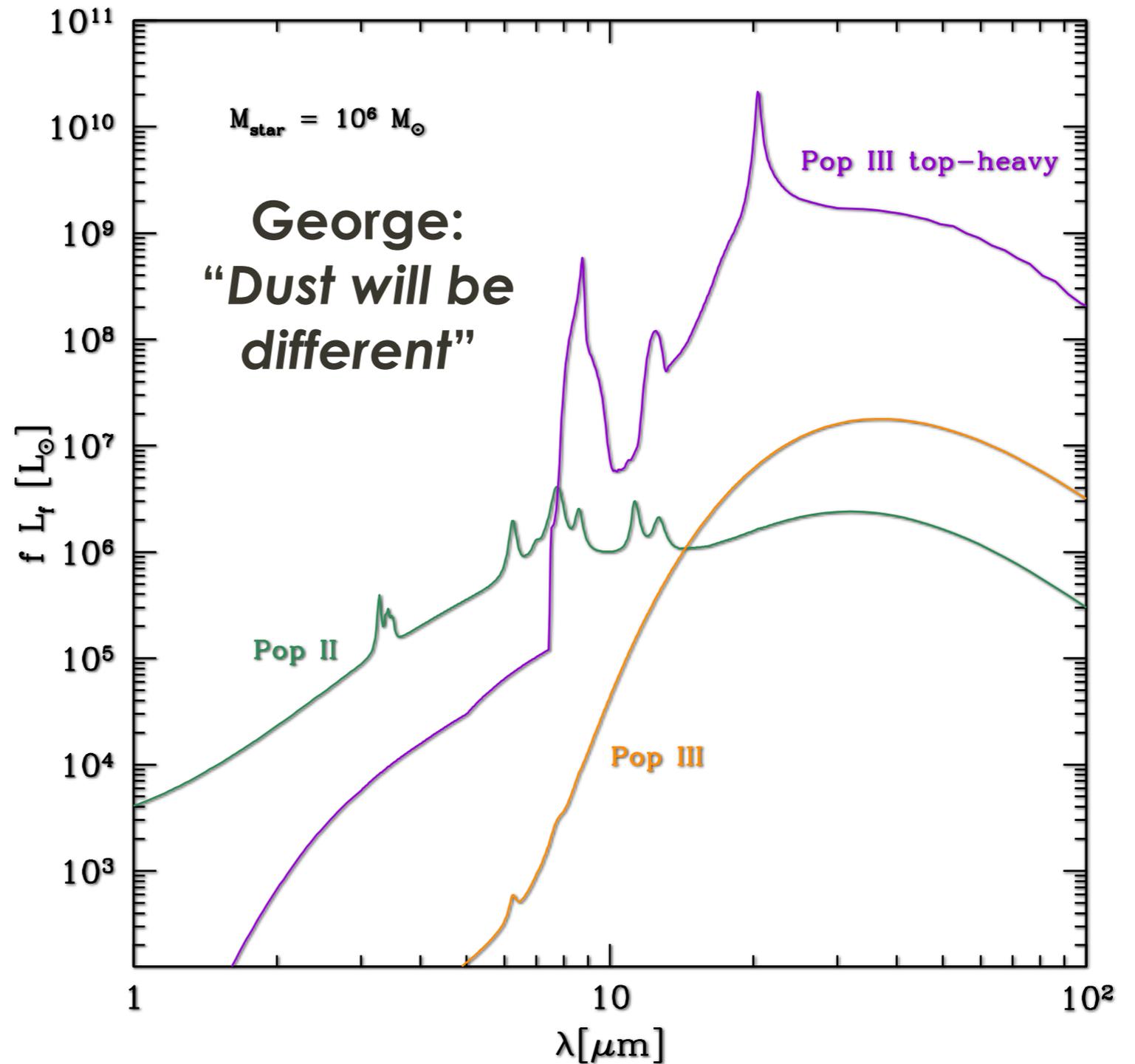
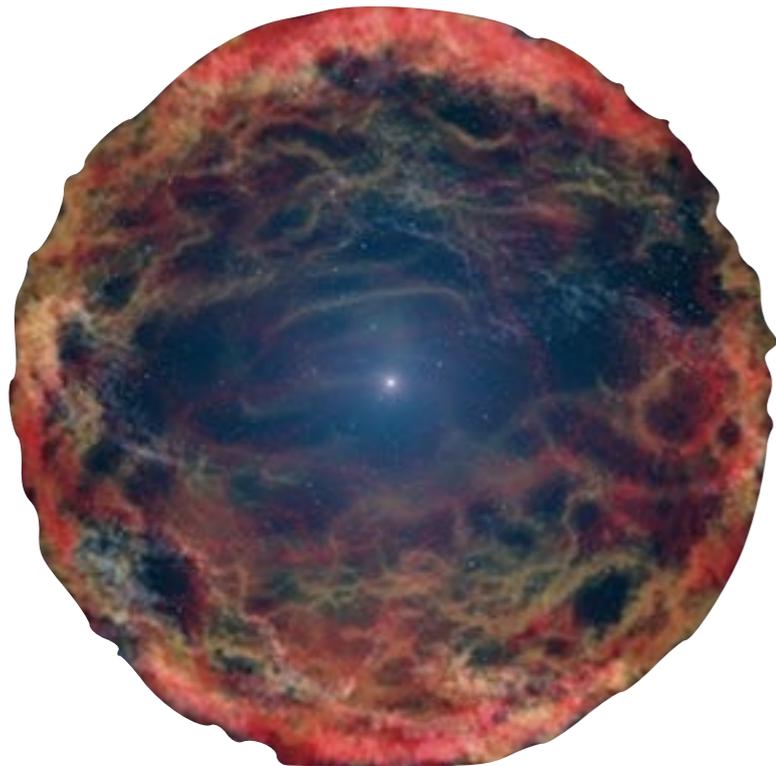


# OR...Dust-to-Metal Ratio varies *strongly* with metallicity in DLA's@high-z

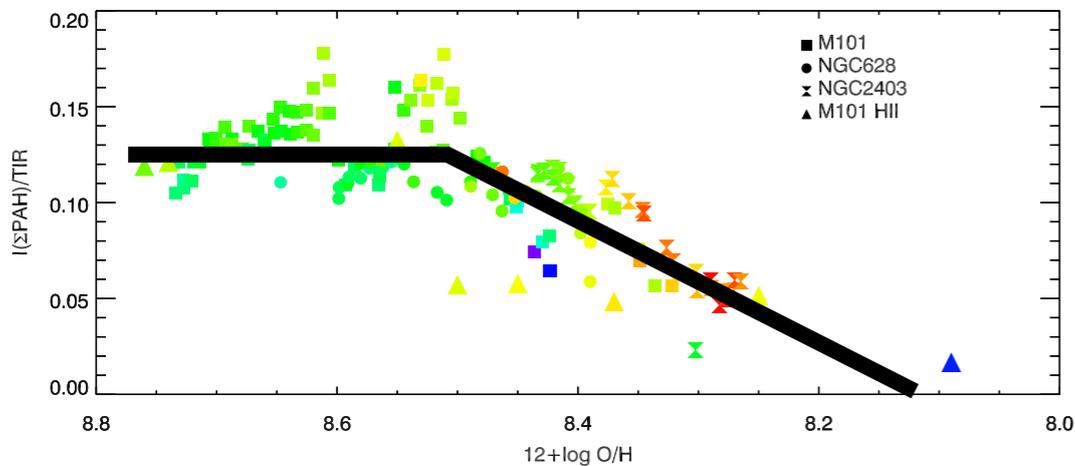


Metals, but  
ZERO DUST!

# Pop III (PI)SNe produce (lots of) Silicate-Rich dust



# Dust vs. Metals in the ISM: Ponderables



- Does dust reliably (if indirectly) trace the metal content of galaxies? When does clouddust overtake stardust?

- What (if anything) is special about  $\sim 1/5-1/4 Z_{\odot}$ ? (CO vanishes, DGR collapses, PAHs evacuate!)

- $Z^2$  vs.  $Z$ : Either dust scales linearly with metallicity, or non-linearly. This distinction is important.

