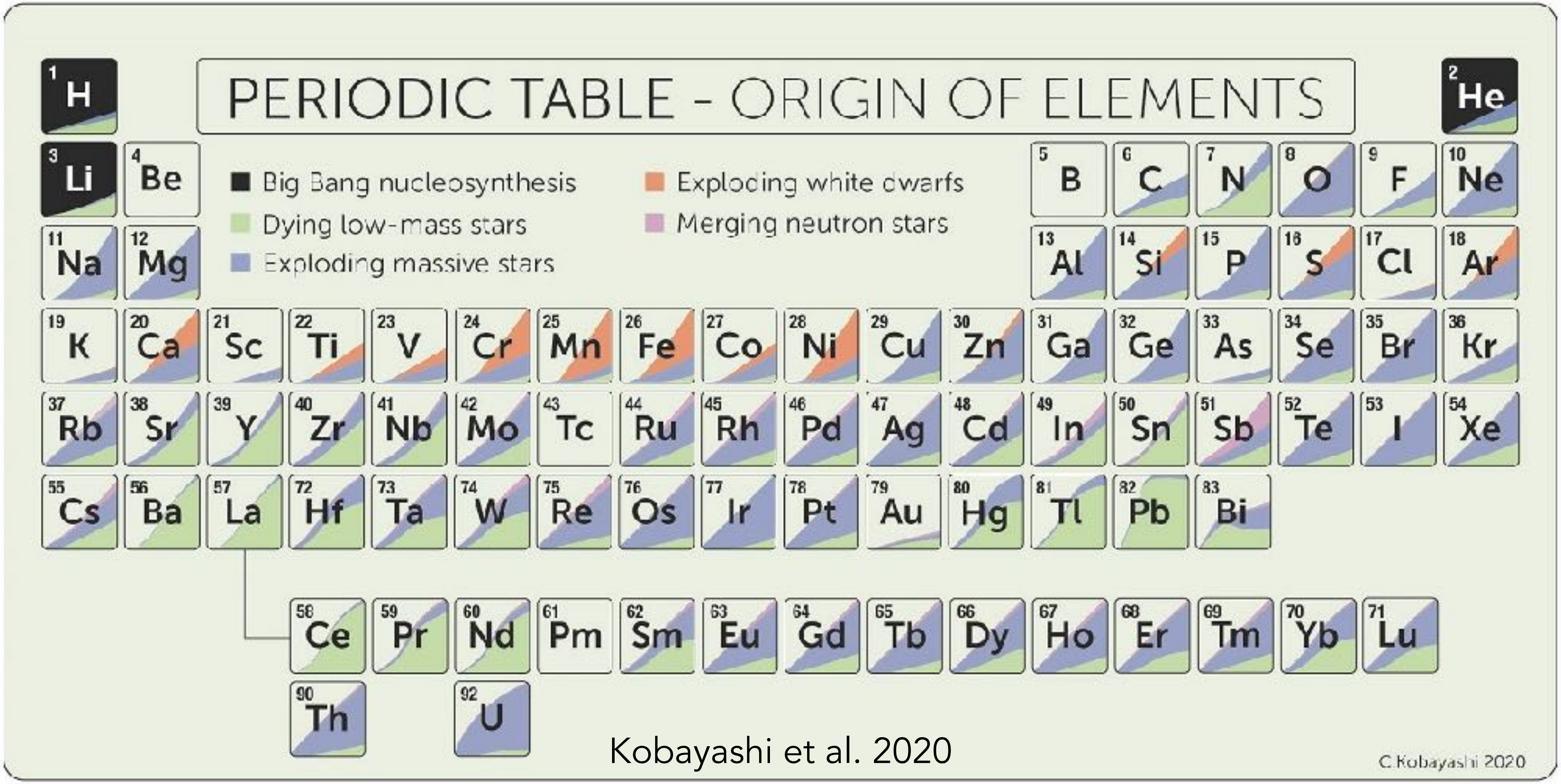
The Low Metallicity Interstellar Medium

Karin Sandstrom - UC San Diego
GISM2 2023

- What is metallicity and when do we consider it low?
- Where do we find low metallicity conditions?
- Dust!
- Effects of low metallicity on the ISM
  - Ionized gas
  - Atomic gas
  - Molecular gas
- Future Prospects

What is metallicity?

Heavy Elements



Kobayashi et al. 2020

Credit: Kobayashi et al / Sahm Keily - https://cosmosmagazine.com/space/astrophysics/origin-of-the-elements-reviewed/

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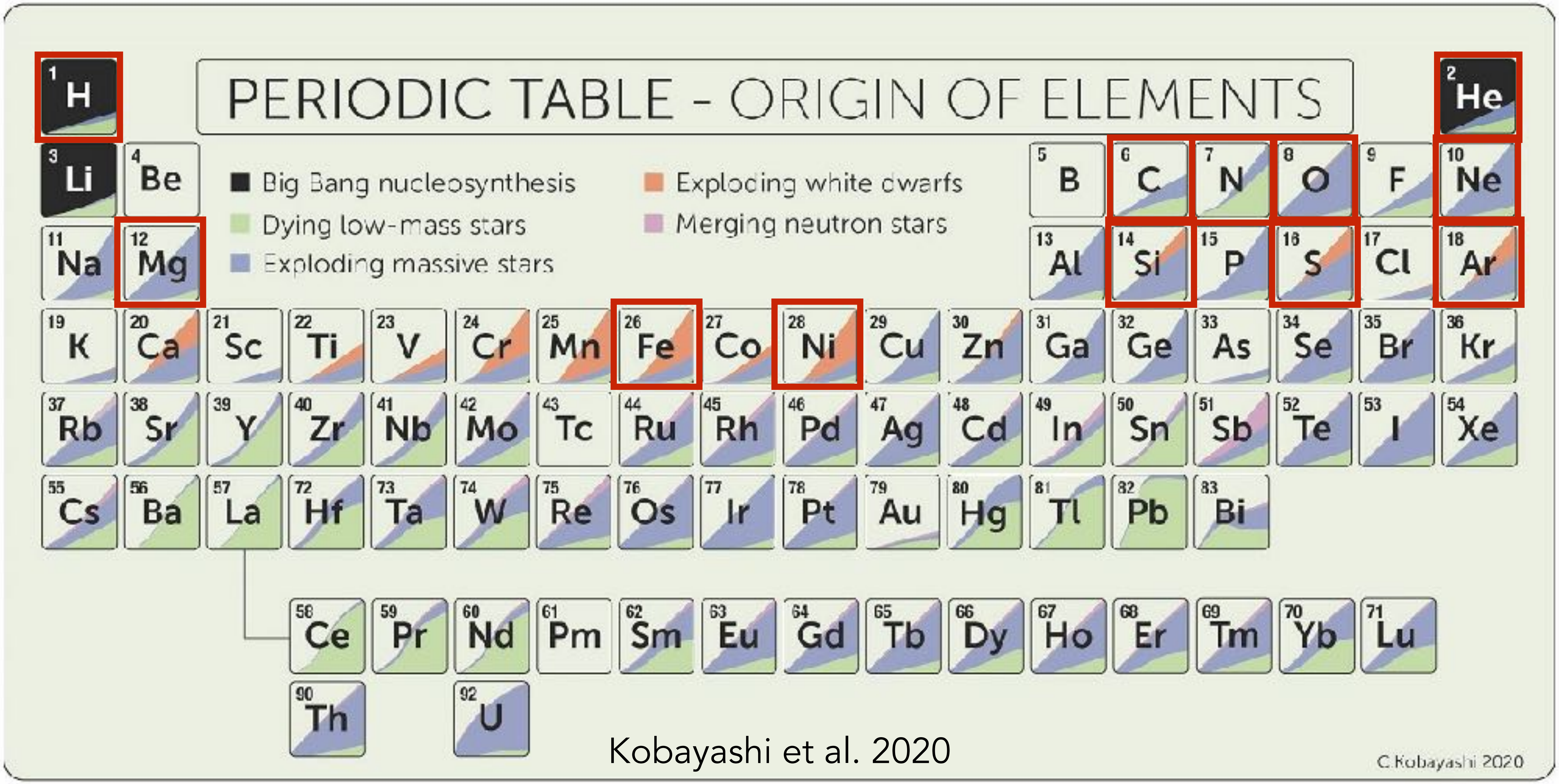

Kobayashi et al. 2020

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Elements with $M_X/M_H > 10^{-4}$

Describing Metallicity: X, Y, Z

Fraction by mass of all elements heavier than H & He:

$$Z \equiv M_{\mathrm{metals}}/M_{\mathrm{baryons}}$$

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$$12 + \log(X/H) \equiv 12 + \log(N_X/N_H)$$

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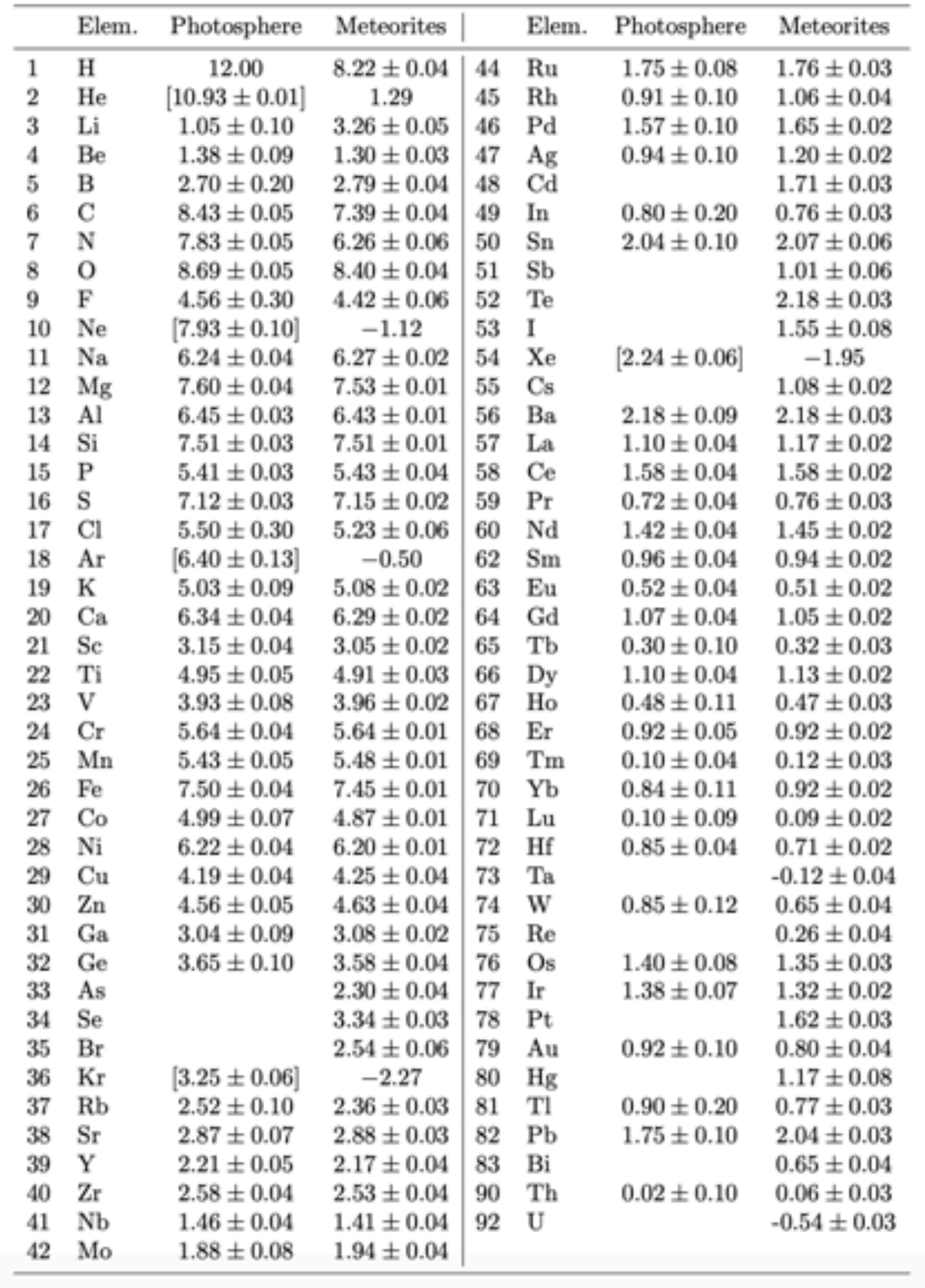
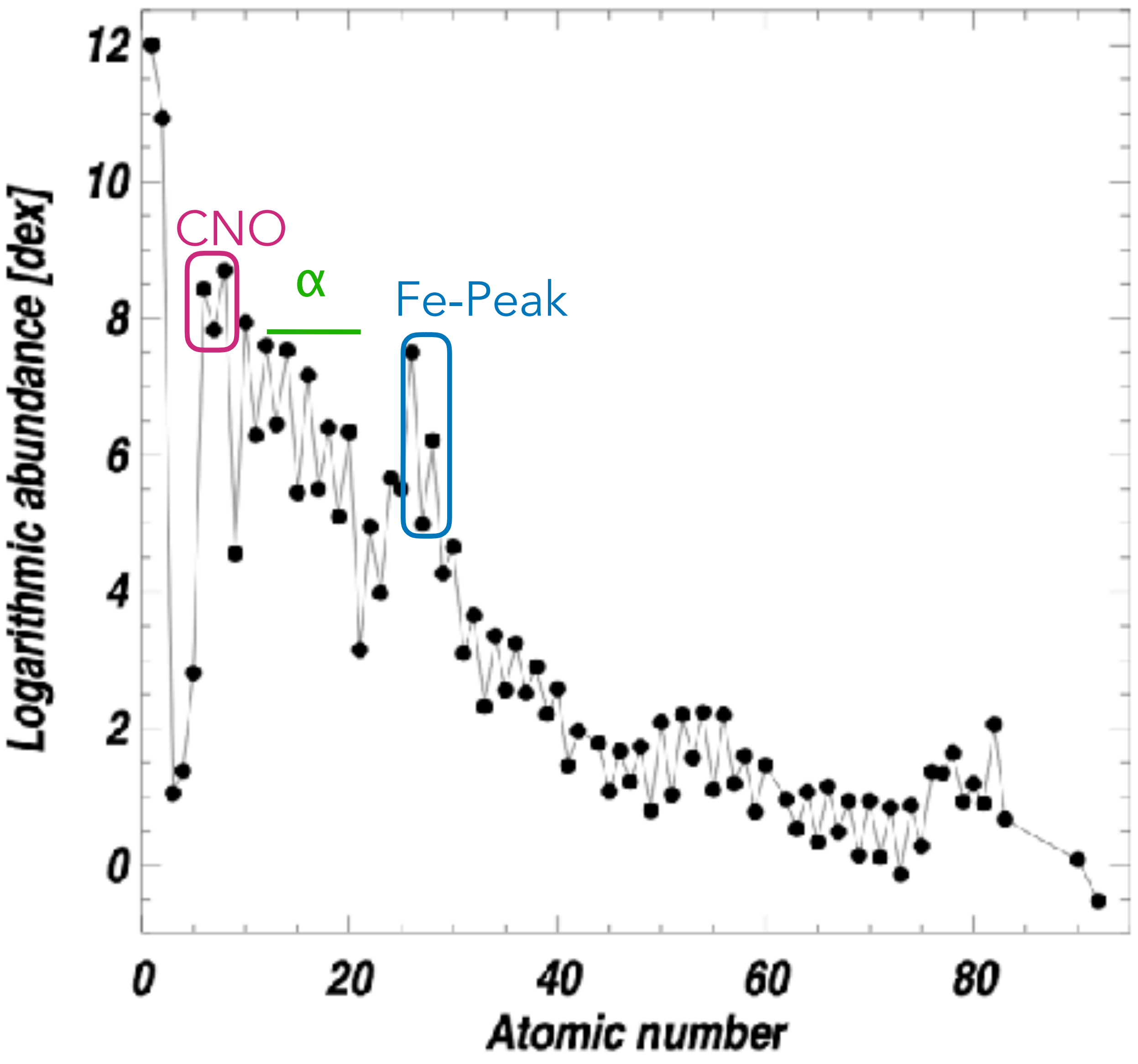
For gas, Oxygen abundance easiest to measure so you'll often see 12+log(O/H). For stars, iron is often easiest, so [Fe/H].

Reference Point: Solar Metallicity



	Elem.	Photosphere	Meteorites		Elem.	Photosphere	Meteorites
1	H	12.00	8.22 ± 0.04	44	Ru	1.75 ± 0.08	1.76 ± 0.03
2	He	[10.93 ± 0.01]	1.29	45	Rh	0.91 ± 0.10	1.06 ± 0.04
3	Li	1.05 ± 0.10	3.26 ± 0.05	46	Pd	1.57 ± 0.10	1.65 ± 0.02
4	Be	1.38 ± 0.09	1.30 ± 0.03	47	Ag	0.94 ± 0.10	1.20 ± 0.02
5	B	2.70 ± 0.20	2.79 ± 0.04	48	Cd		1.71 ± 0.03
6	C	8.43 ± 0.05	7.39 ± 0.04	49	In	0.80 ± 0.20	0.76 ± 0.03
7	N	7.83 ± 0.05	6.26 ± 0.06	50	Sn	2.04 ± 0.10	2.07 ± 0.06
8	O	8.69 ± 0.05	8.40 ± 0.04	51	Sb		1.01 ± 0.06
9	F	4.56 ± 0.30	4.42 ± 0.06	52	Te		2.18 ± 0.03
10	Ne	[7.93 ± 0.10]	−1.12	53	I		1.55 ± 0.08
11	Na	6.24 ± 0.04	6.27 ± 0.02	54	Xe	[2.24 ± 0.06]	−1.95
12	Mg	7.60 ± 0.04	7.53 ± 0.01	55	Cs		1.08 ± 0.02
13	Al	6.45 ± 0.03	6.43 ± 0.01	56	Ba	2.18 ± 0.09	2.18 ± 0.03
14	Si	7.51 ± 0.03	7.51 ± 0.01	57	La	1.10 ± 0.04	1.17 ± 0.02
15	P	5.41 ± 0.03	5.43 ± 0.04	58	Ce	1.58 ± 0.04	1.58 ± 0.02
16	S	7.12 ± 0.03	7.15 ± 0.02	59	Pr	0.72 ± 0.04	0.76 ± 0.03
17	Cl	5.50 ± 0.30	5.23 ± 0.06	60	Nd	1.42 ± 0.04	1.45 ± 0.02
18	Ar	[6.40 ± 0.13]	−0.50	62	Sm	0.96 ± 0.04	0.94 ± 0.02
19	K	5.03 ± 0.09	5.08 ± 0.02	63	Eu	0.52 ± 0.04	0.51 ± 0.02
20	Ca	6.34 ± 0.04	6.29 ± 0.02	64	Gd	1.07 ± 0.04	1.05 ± 0.02
21	Sc	3.15 ± 0.04	3.05 ± 0.02	65	Tb	0.30 ± 0.10	0.32 ± 0.03
22	Ti	4.95 ± 0.05	4.91 ± 0.03	66	Dy	1.10 ± 0.04	1.13 ± 0.02
23	V	3.93 ± 0.08	3.96 ± 0.02	67	Ho	0.48 ± 0.11	0.47 ± 0.03
24	Cr	5.64 ± 0.04	5.64 ± 0.01	68	Er	0.92 ± 0.05	0.92 ± 0.02
25	Mn	5.43 ± 0.05	5.48 ± 0.01	69	Tm	0.10 ± 0.04	0.12 ± 0.03
26	Fe	7.50 ± 0.04	7.45 ± 0.01	70	Yb	0.84 ± 0.11	0.92 ± 0.02
27	Co	4.99 ± 0.07	4.87 ± 0.01	71	Lu	0.10 ± 0.09	0.09 ± 0.02
28	Ni	6.22 ± 0.04	6.20 ± 0.01	72	Hf	0.85 ± 0.04	0.71 ± 0.02
29	Cu	4.19 ± 0.04	4.25 ± 0.04	73	Ta		-0.12 ± 0.04
30	Zn	4.56 ± 0.05	4.63 ± 0.04	74	W	0.85 ± 0.12	0.65 ± 0.04
31	Ga	3.04 ± 0.09	3.08 ± 0.02	75	Re		0.26 ± 0.04
32	Ge	3.65 ± 0.10	3.58 ± 0.04	76	Os	1.40 ± 0.08	1.35 ± 0.03
33	As		2.30 ± 0.04	77	Ir	1.38 ± 0.07	1.32 ± 0.02
34	Se		3.34 ± 0.03	78	Pt		1.62 ± 0.03
35	Br		2.54 ± 0.06	79	Au	0.92 ± 0.10	0.80 ± 0.04
36	Kr	[3.25 ± 0.06]	−2.27	80	Hg		1.17 ± 0.08
37	Rb	2.52 ± 0.10	2.36 ± 0.03	81	Tl	0.90 ± 0.20	0.77 ± 0.03
38	Sr	2.87 ± 0.07	2.88 ± 0.03	82	Pb	1.75 ± 0.10	2.04 ± 0.03
39	Y	2.21 ± 0.05	2.17 ± 0.04	83	Bi		0.65 ± 0.04
40	Zr	2.58 ± 0.04	2.53 ± 0.04	90	Th	0.02 ± 0.10	0.06 ± 0.03
41	Nb	1.46 ± 0.04	1.41 ± 0.04	92	U		-0.54 ± 0.03
42	Mo	1.88 ± 0.08	1.94 ± 0.04				

Present Day Solar Photospheric Abundance is key reference (Asplund et al. 2009)

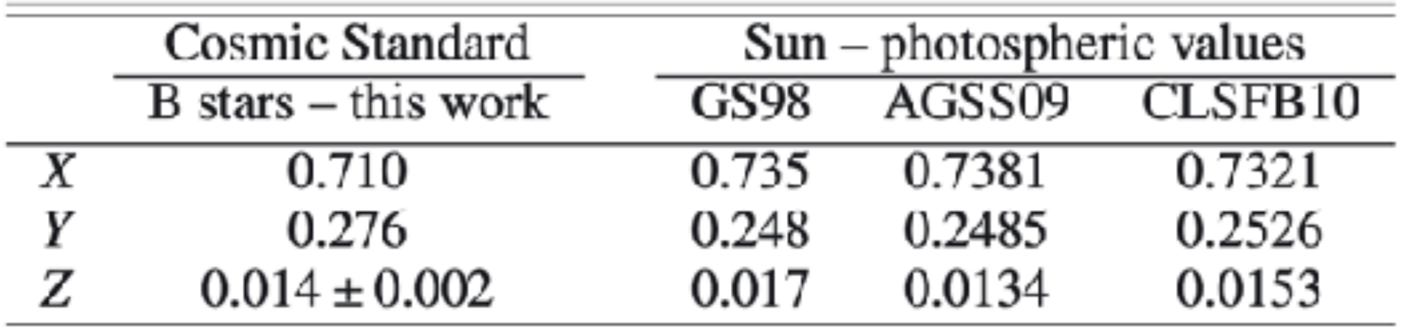


Reference Point: Young Stars

Nieva & Przybilla 2012 - Solar Neighborhood B Star abundances

https://ui.adsabs.harvard.edu/abs/2012A%26A...539A.143N/

The Sun is 4.5 Gyr old, should probably not be representative of current ISM metallicity!

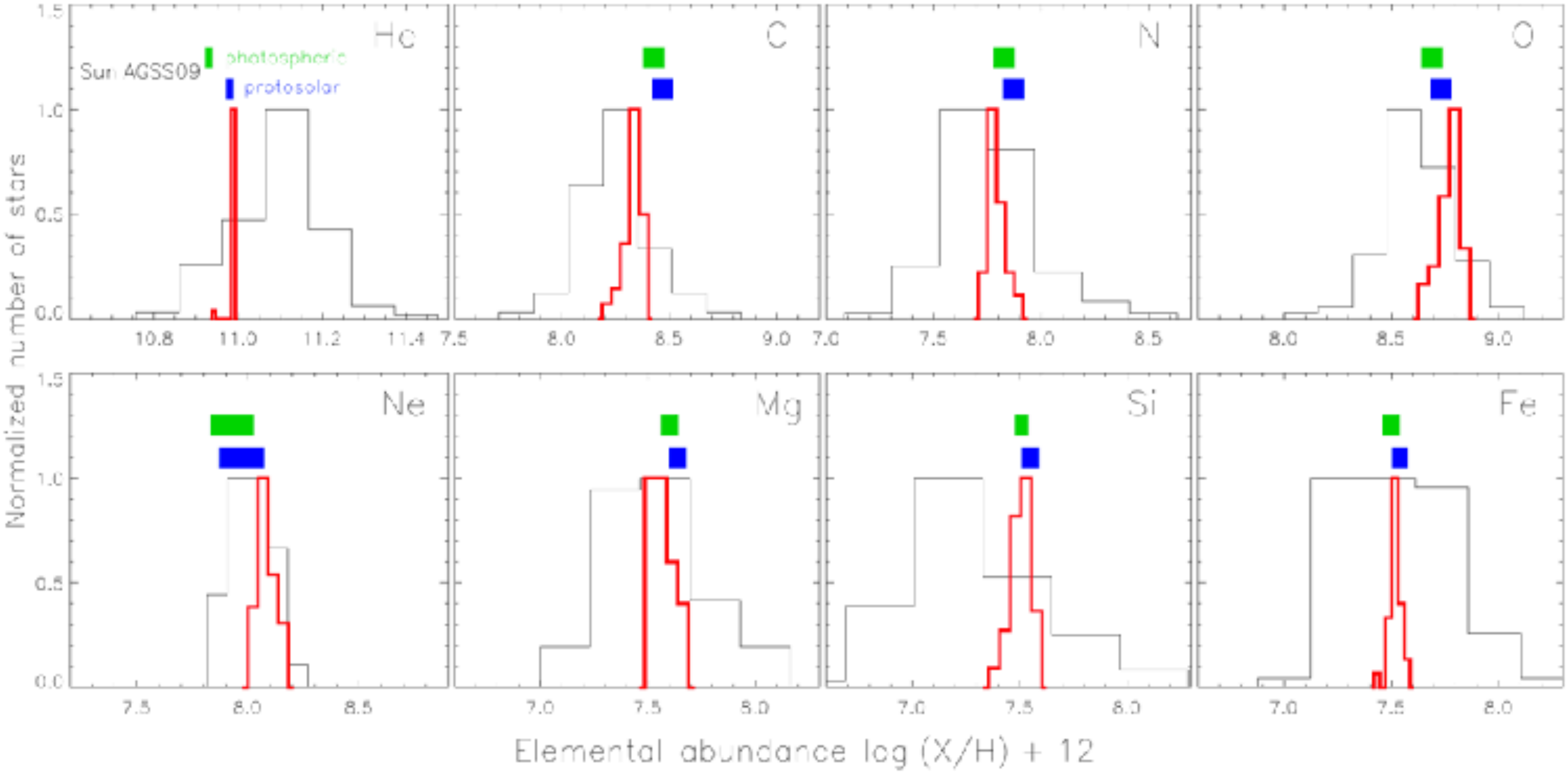


	Cosmic Standard	Sun – photospheric values		
	B stars – this work	GS98	AGSS09	CLSFB10
X	0.710	0.735	0.7381	0.7321
Y	0.276	0.248	0.2485	0.2526
Z	0.014 ± 0.002	0.017	0.0134	0.0153

Solar Photosphere

Protosolar Nebula

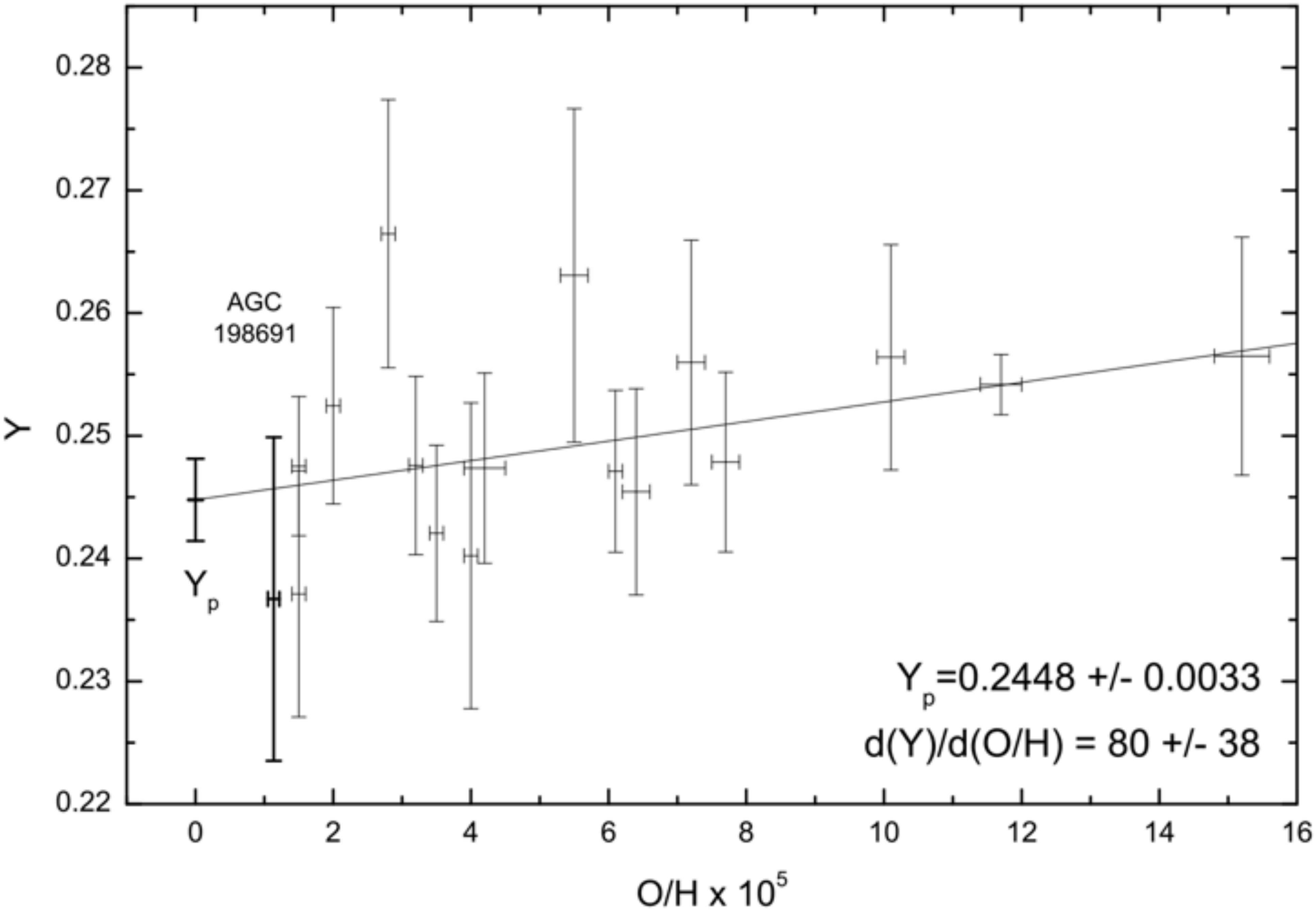
Nearby B stars



Describing Metallicity: Y

Lowest metallicity dwarf galaxies approach the primordial helium abundance (Y_p)

Helium abundance increases as stars return processed material to the ISM.



Aver et al 2022 - https://ui.adsabs.harvard.edu/abs/2022MNRAS.510..373A/

ISM Metallicity Tracers

How can we trace metallicity of the ISM?

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- Detect metals with absorption lines
  - Pro: lets us detect metals in gas that is cool (neutral, molecular)
  - Con: lots of metals will be in dust, getting H for comparison can be tough

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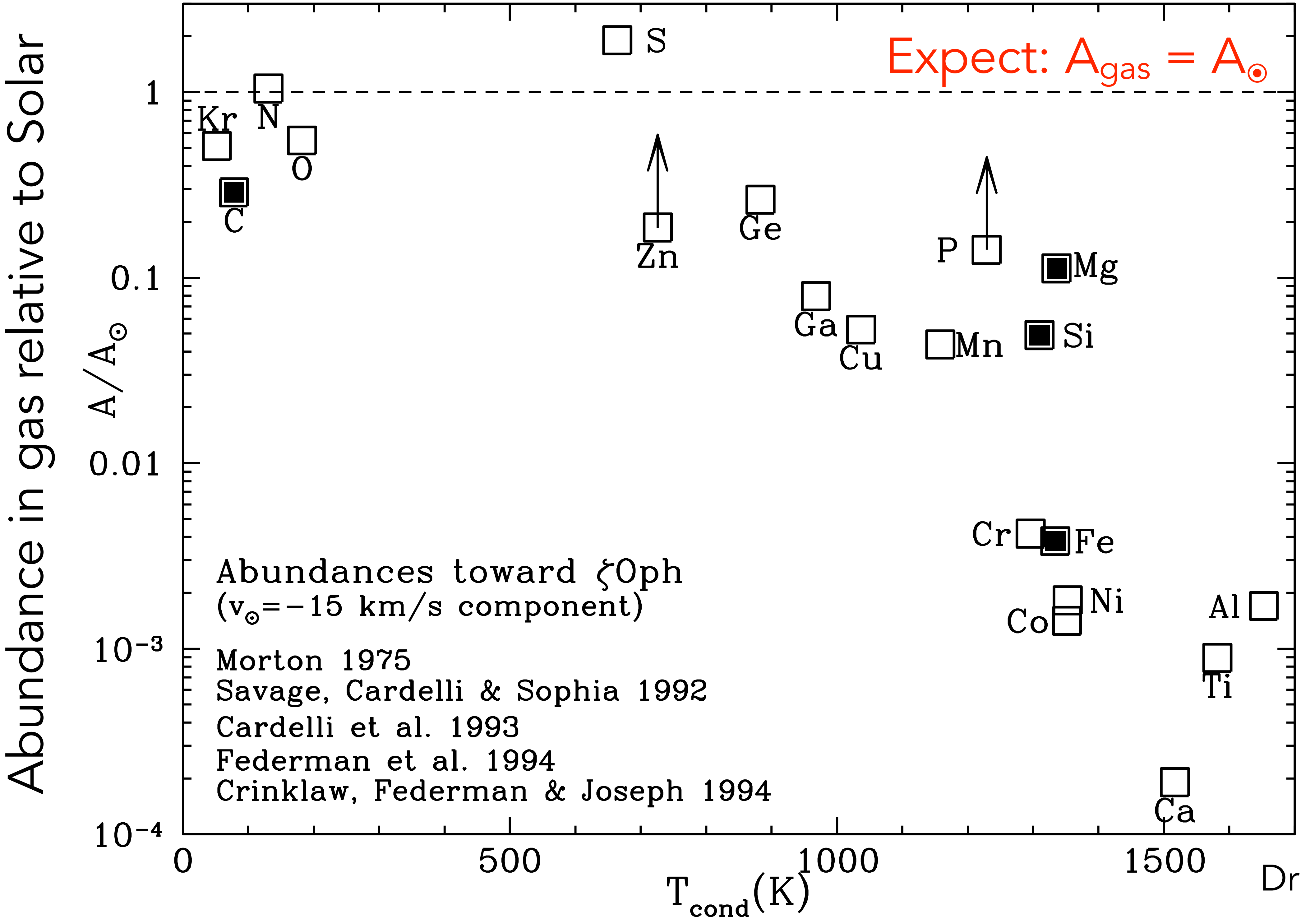
- Detect metals in stellar spectra
  - Pro: young stars should be a good ISM representative, no dust depletion
  - Con: can’t do this in very many other galaxies

ISM Metallicity Tracers

For absorption lines in cool gas, dust **depletion** is very important



Draine 2011

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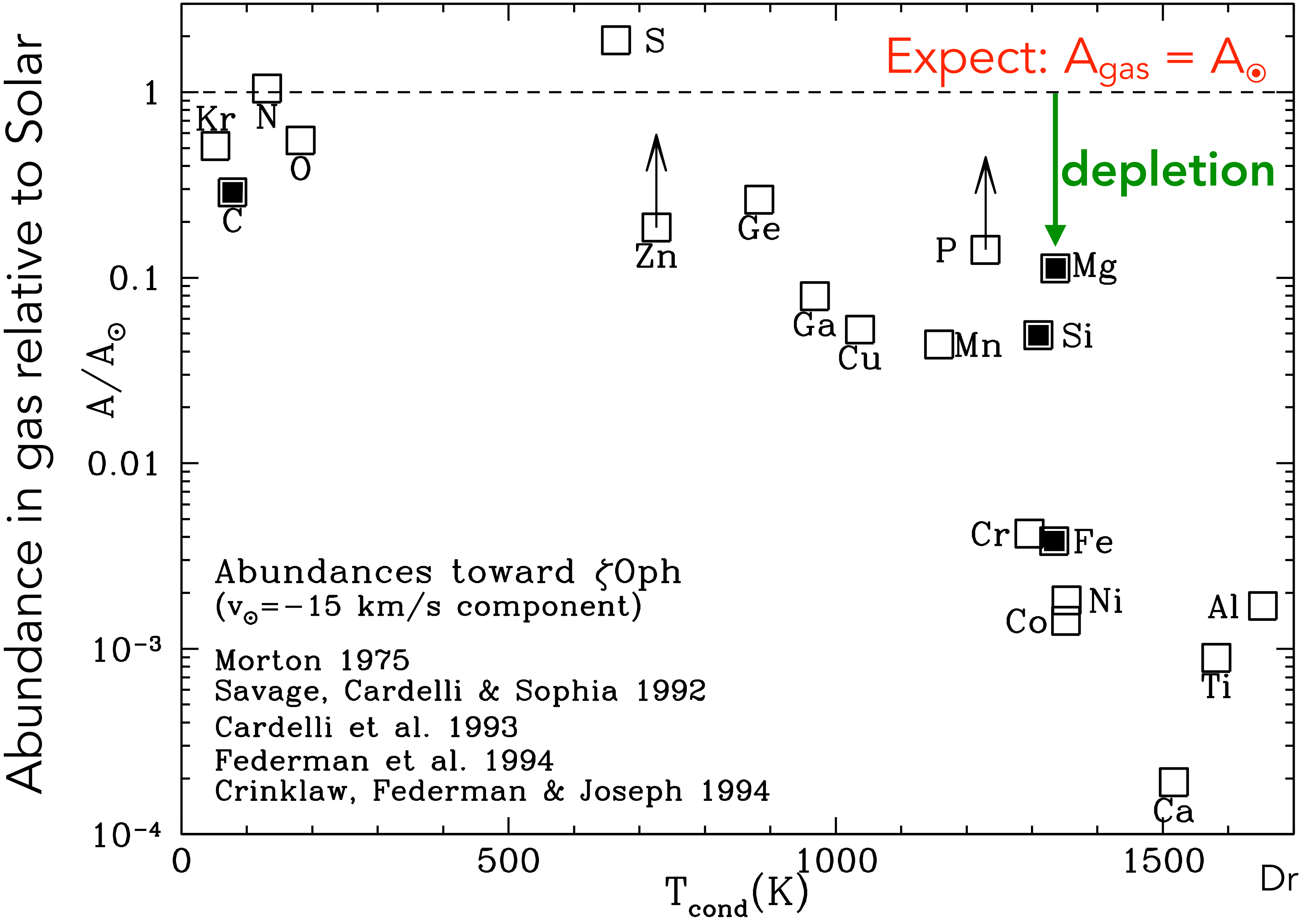
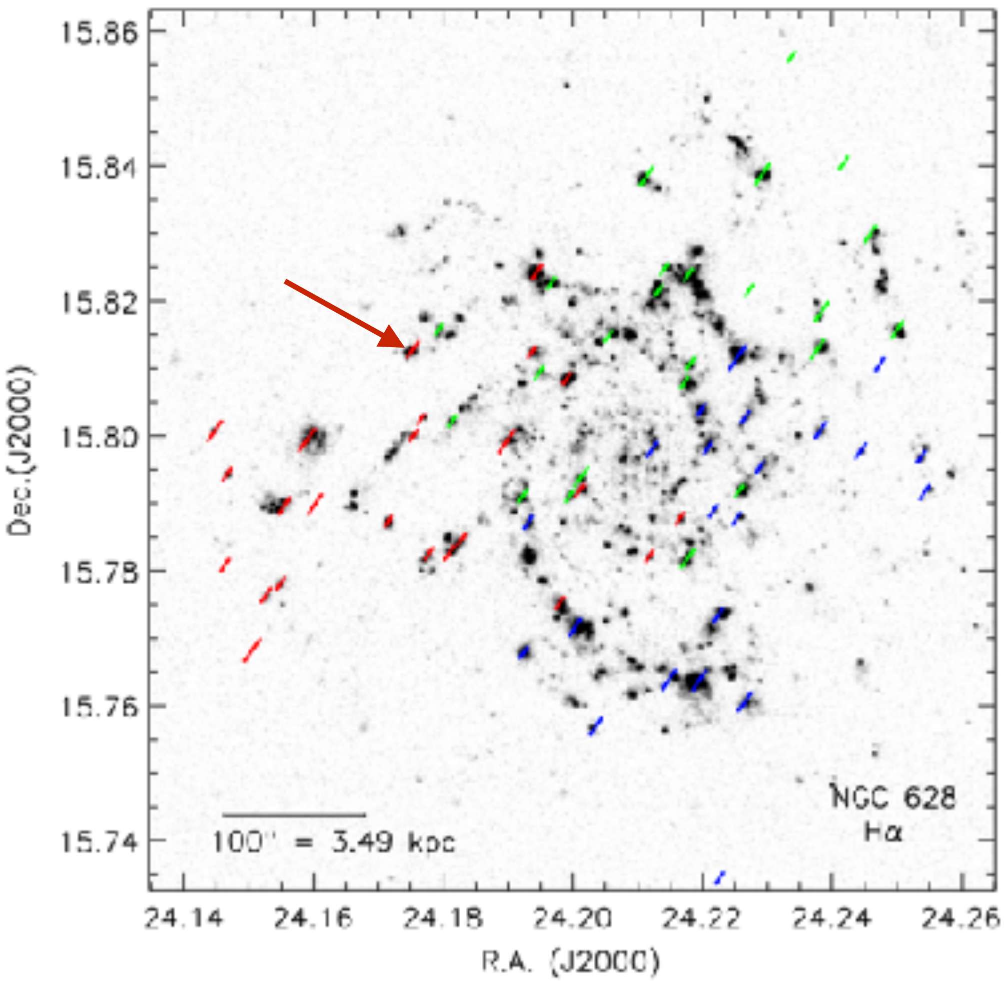


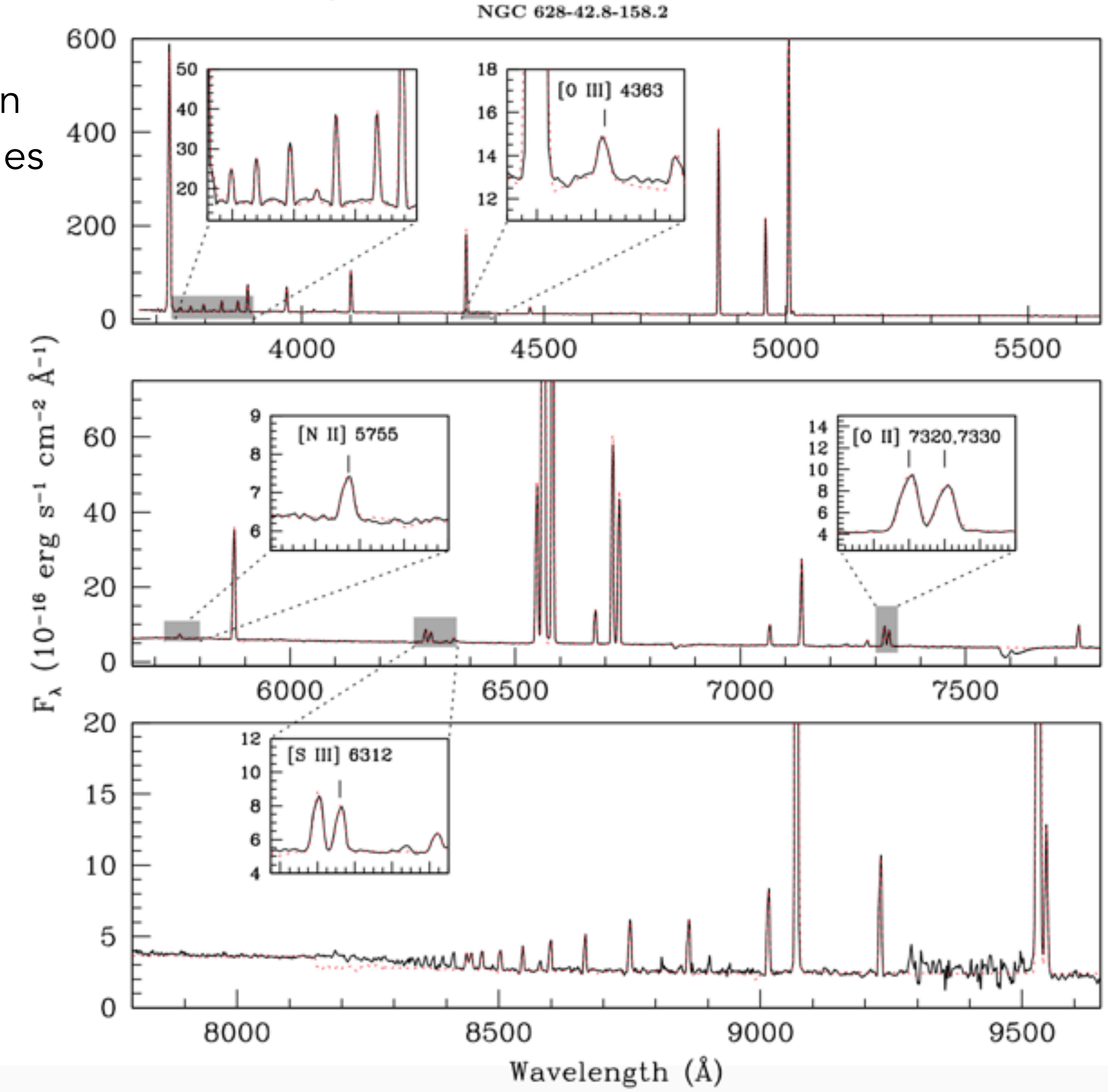
Draine 2011

ISM Metallicity Tracers

Elemental abundance relative to H can be measured using optical emission lines from photoionized gas (HII regions).

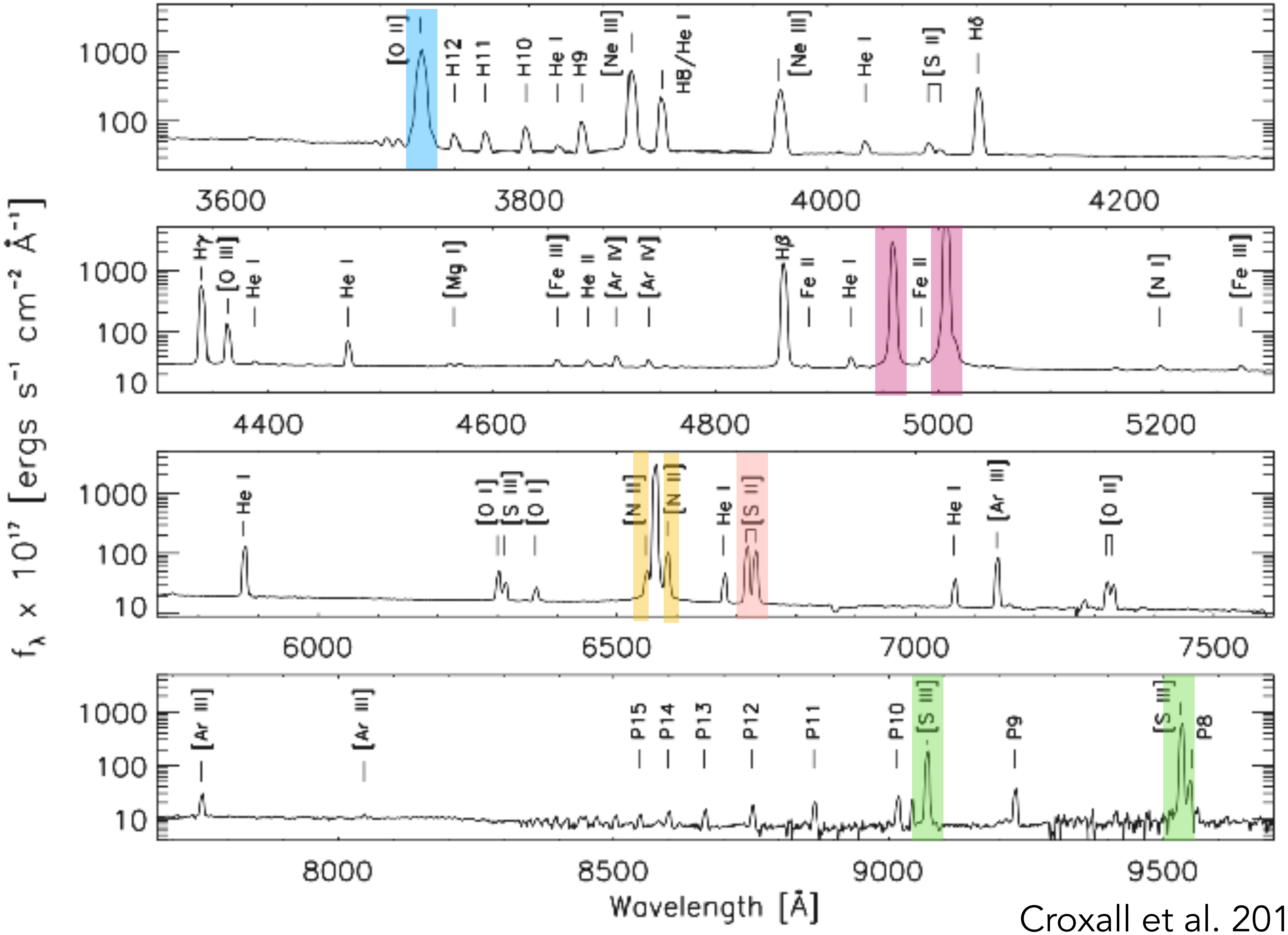
from the CHAOS survey
(Berg et al. 2015)



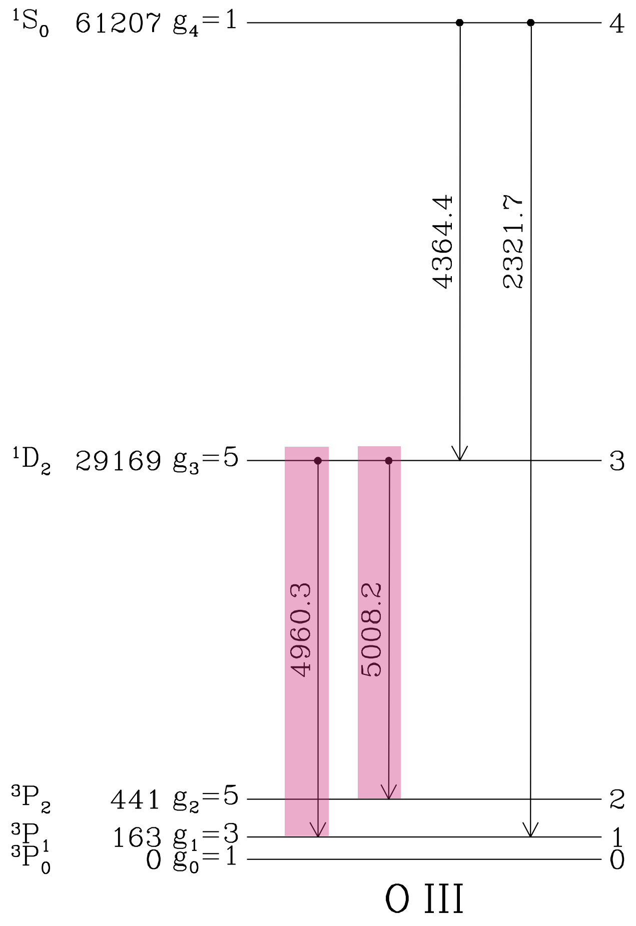


ISM Metallicity Tracers

Emission line metallicities - HII regions have gas warm enough to collisionally excite various lines from metals.

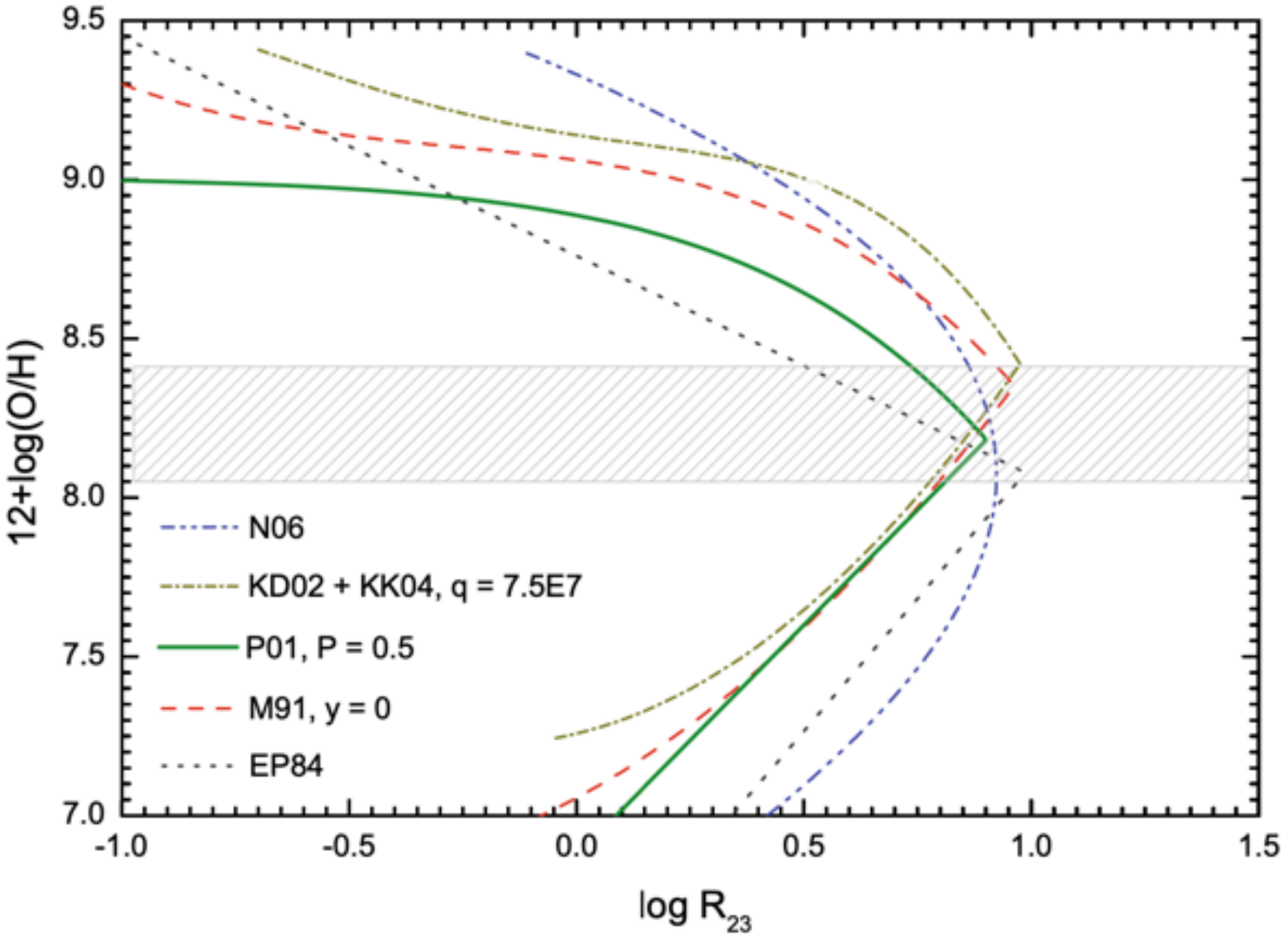


Especially "strong" or "nebular" lines from [OII], [OIII], [NII], [SII], [SIII]



Croxall et al. 2016 - M101 HII region optical spectrum

Strong Line Metallicity Calibrations



$$R_3 = \frac{I([\mathrm{O\,III}])\lambda 4959 + I([\mathrm{O\,III}])\lambda 5007}{\mathrm{H}\beta},$$

$$R_2 = \frac{I([\mathrm{O\,II}])\lambda 3727}{\mathrm{H}\beta},$$

$$R_{23} = R_3 + R_2,$$

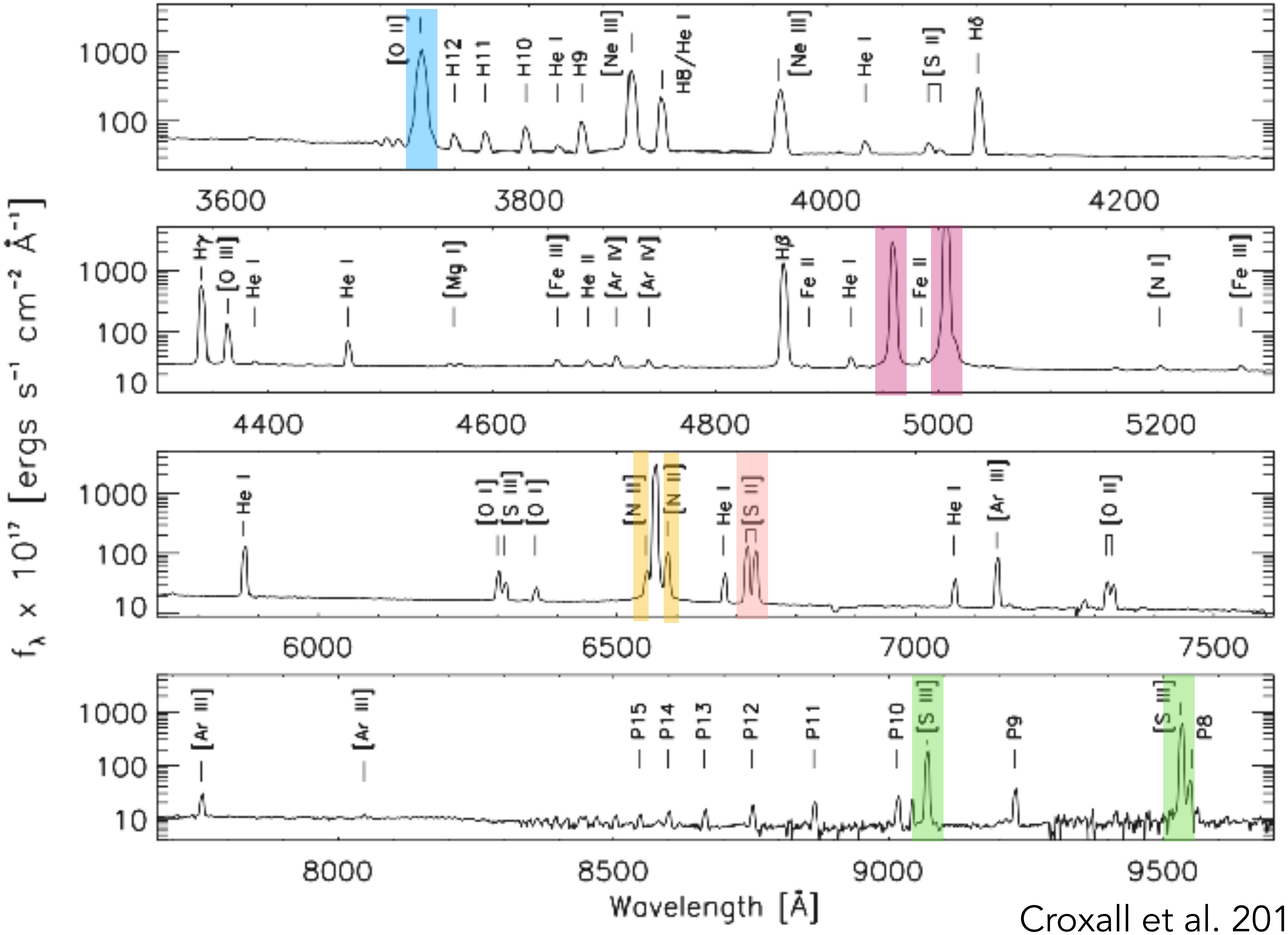
strong line calibrations infer metallicity without knowing electron temperature directly

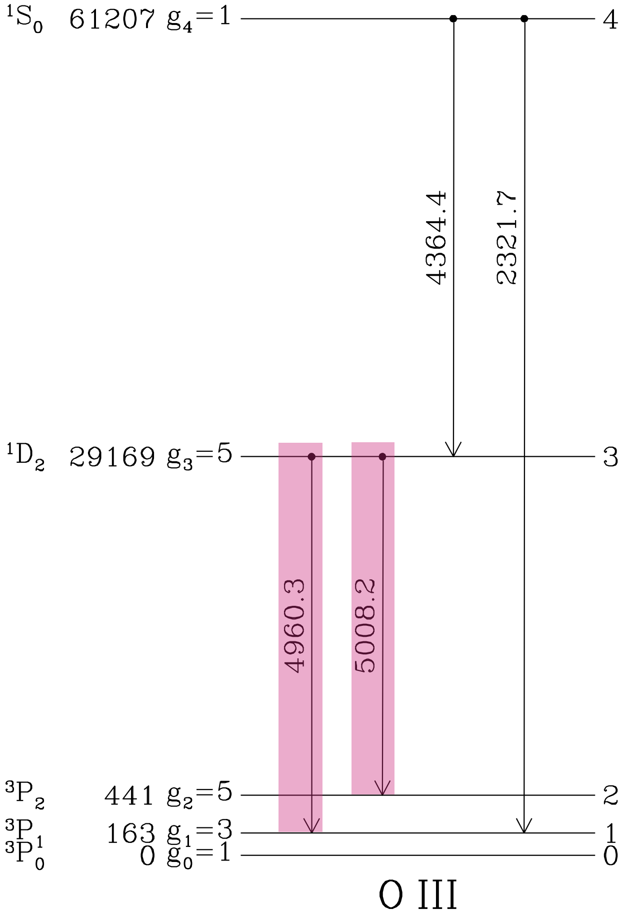
for oxygen, strong-line R23 based calibrations are double valued: 1) total O emission increases with abundance, but 2) HII regions get cooler and lower ionization at high metallicity, so dependence reverses

figure from Lopez-Sanchez & Esteban 2010 -
https://ui.adsabs.harvard.edu/abs/2010A%26A...517A..85L/

Direct Metallicities

Can get electron temperature if you also measure “auroral” line.





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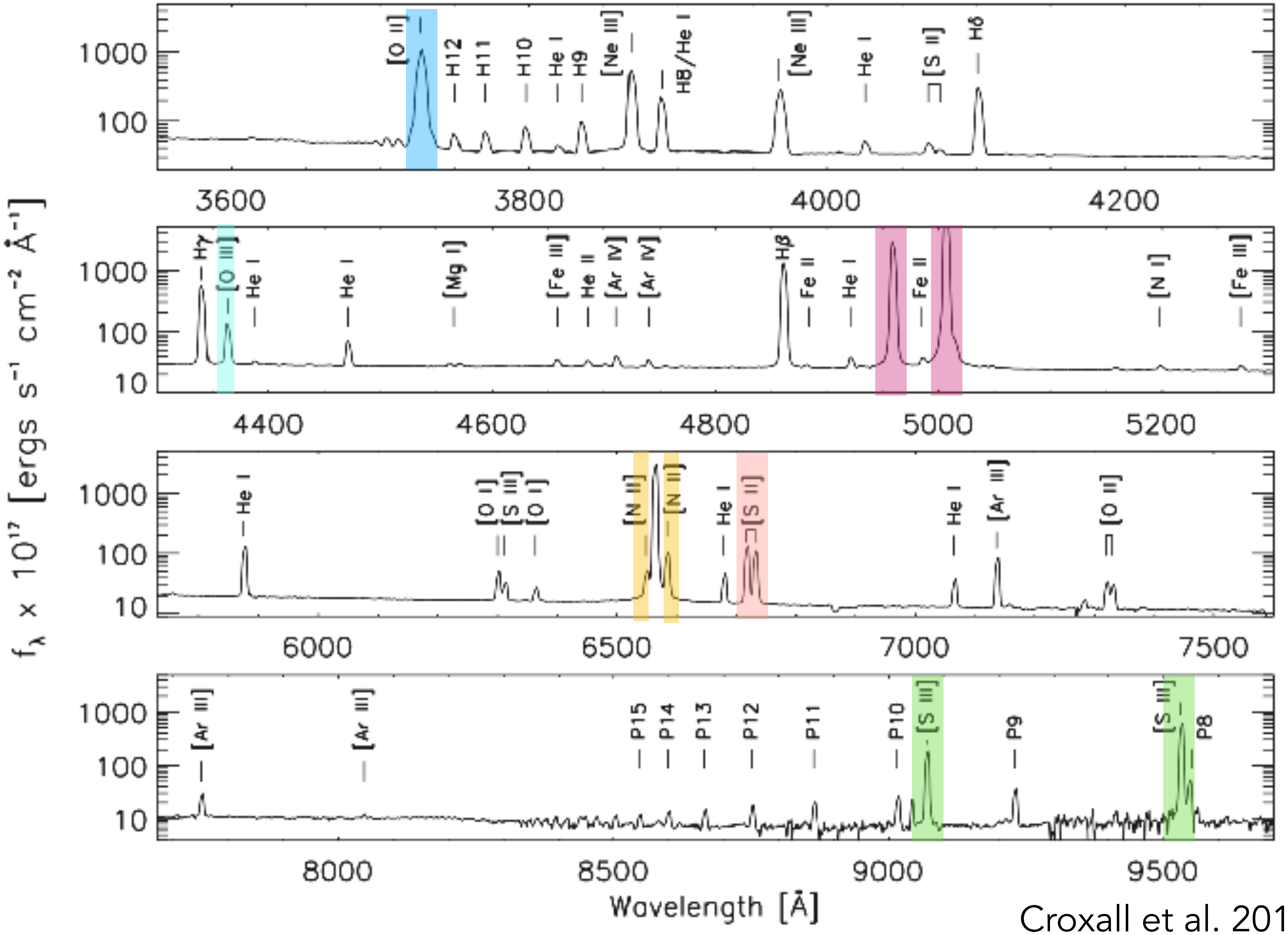

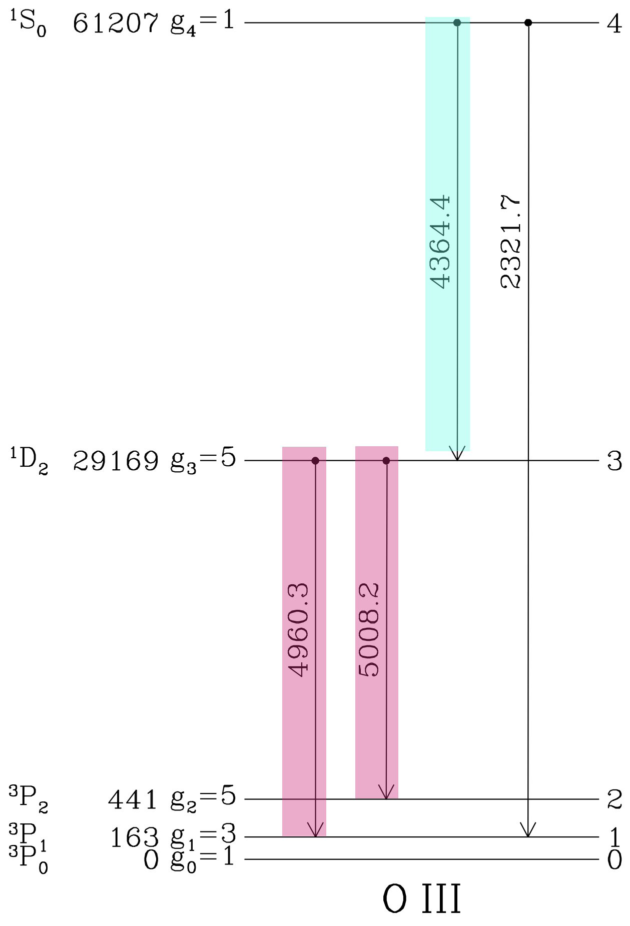

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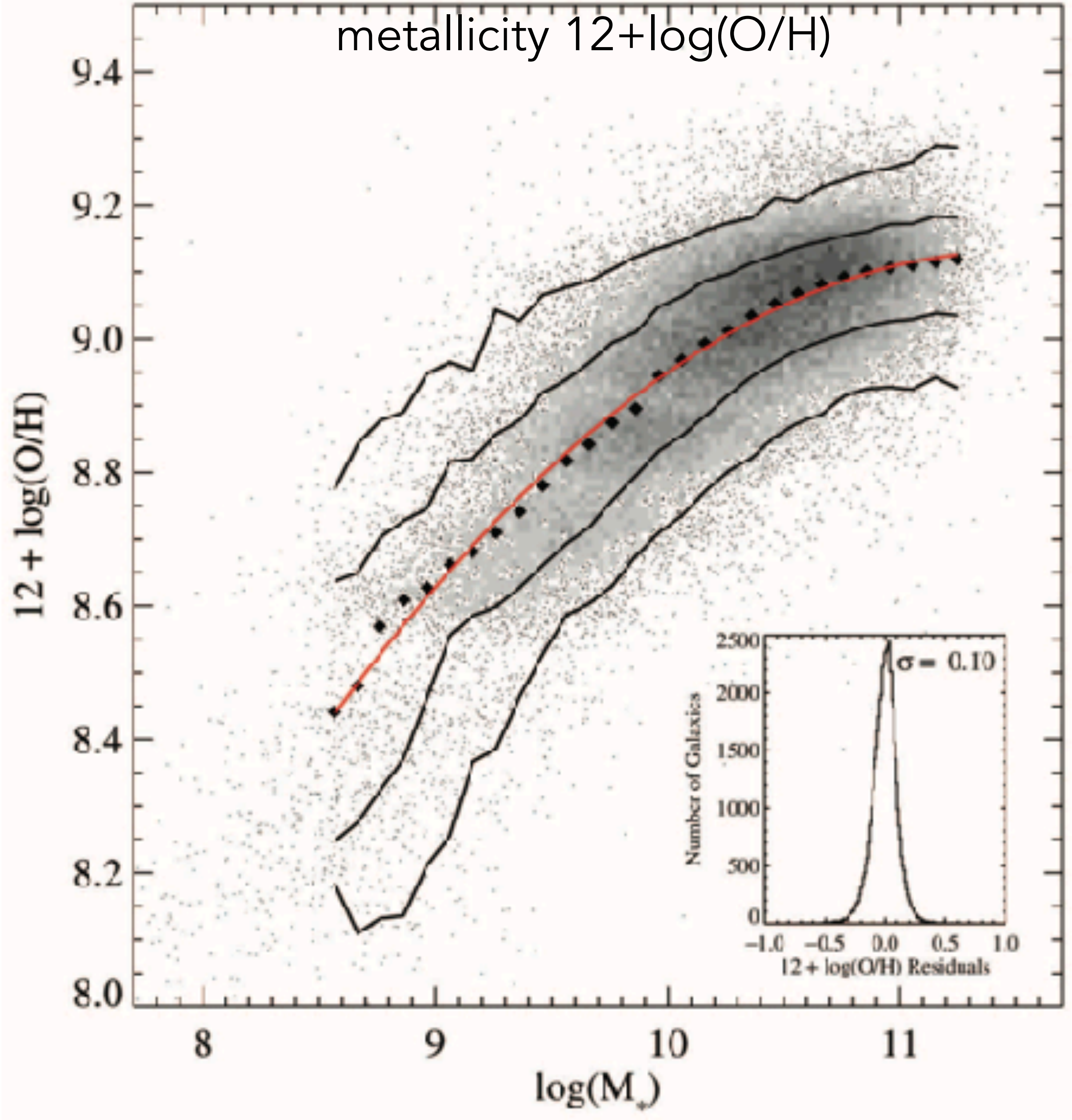
Mass-Metallicity Relationships

Correlation between M_* and gas-phase metallicity 12+log(O/H)



Tremonti et al. 2004 - https://ui.adsabs.harvard.edu/abs/2004ApJ...613..898T/

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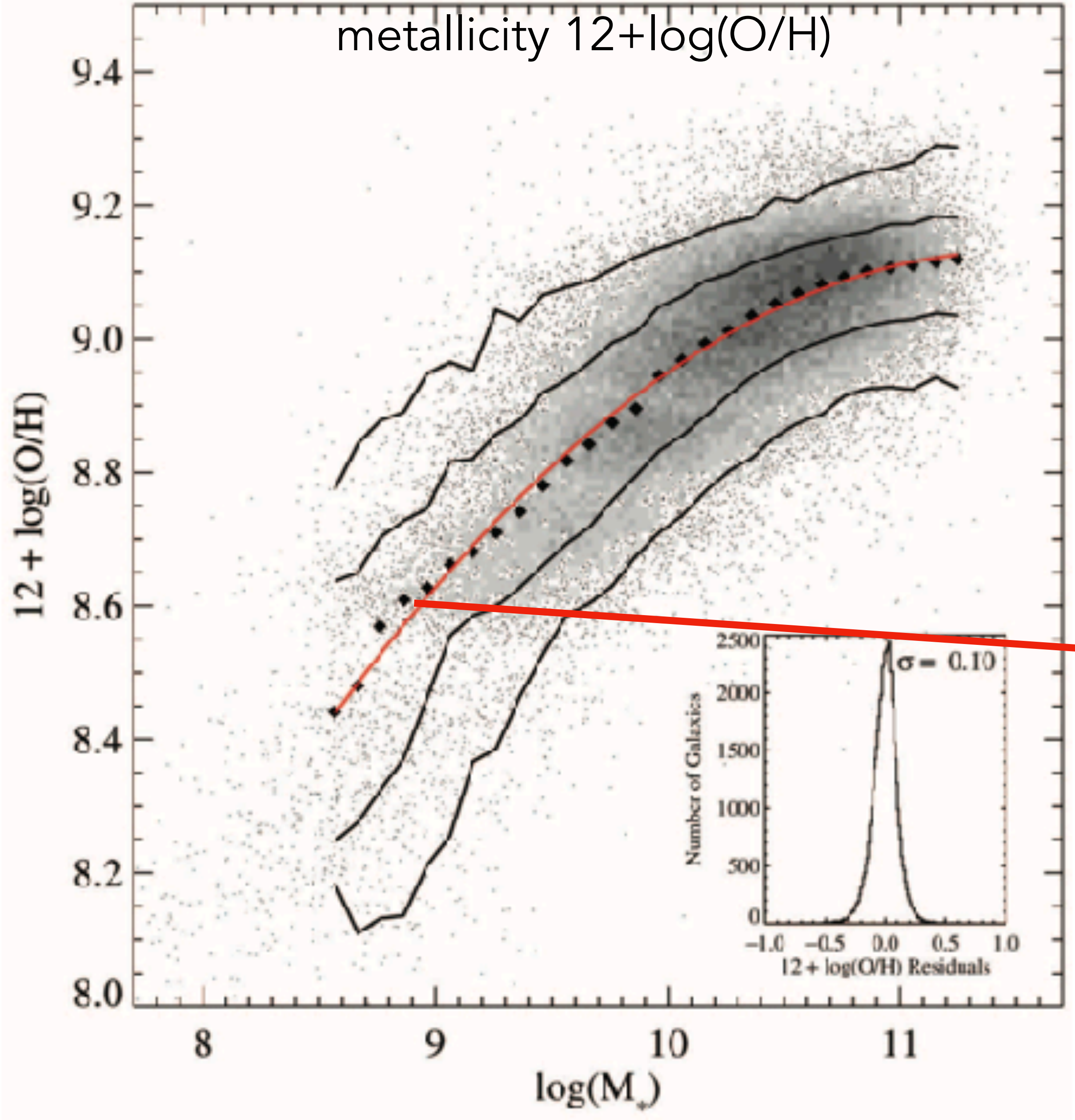

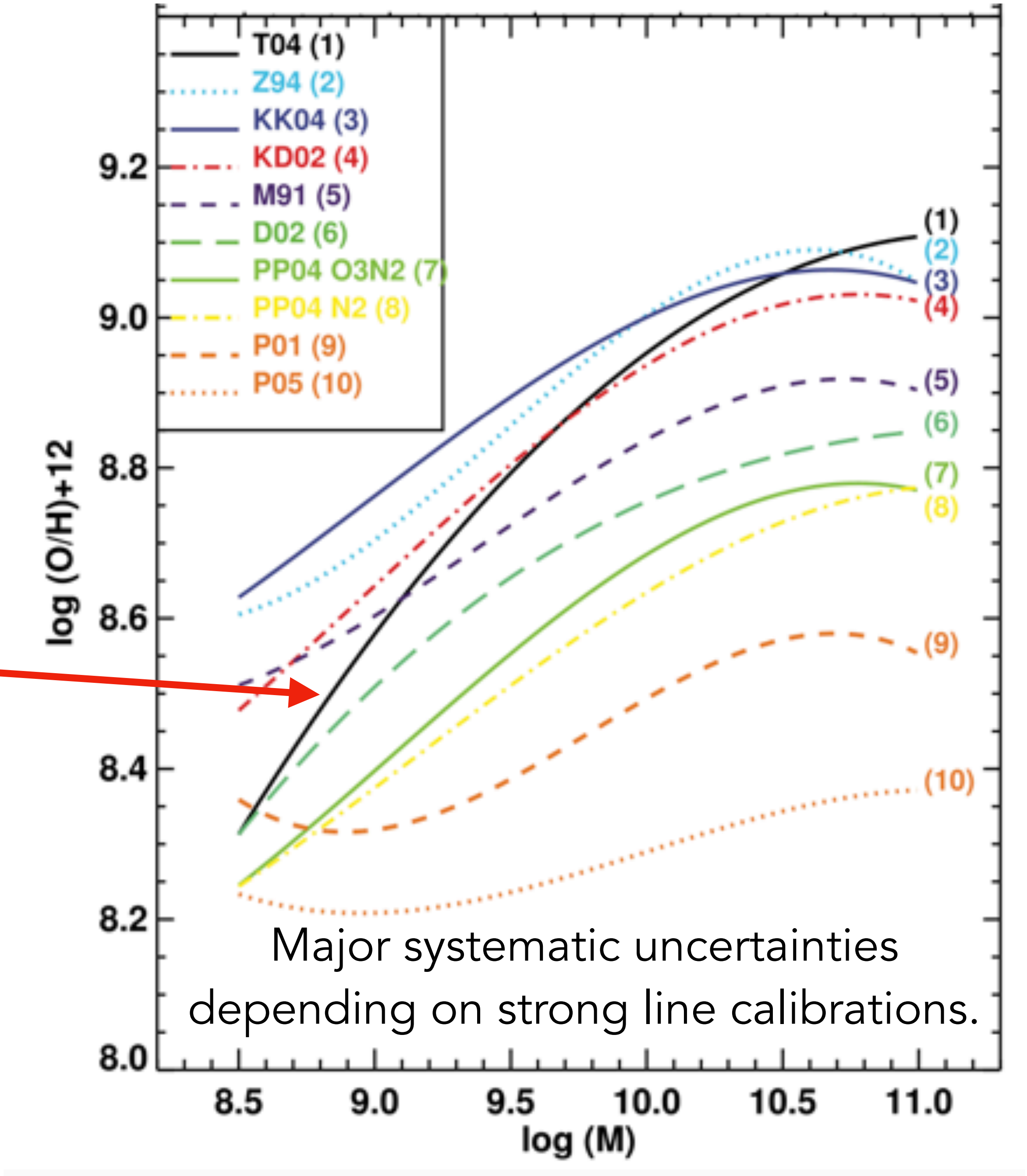

Major systematic uncertainties depending on strong line calibrations.

Tremonti et al. 2004 - https://ui.adsabs.harvard.edu/abs/2004ApJ...613..898T/

Kewley & Ellison 2008 - https://ui.adsabs.harvard.edu/abs/2008ApJ...681.1183K/

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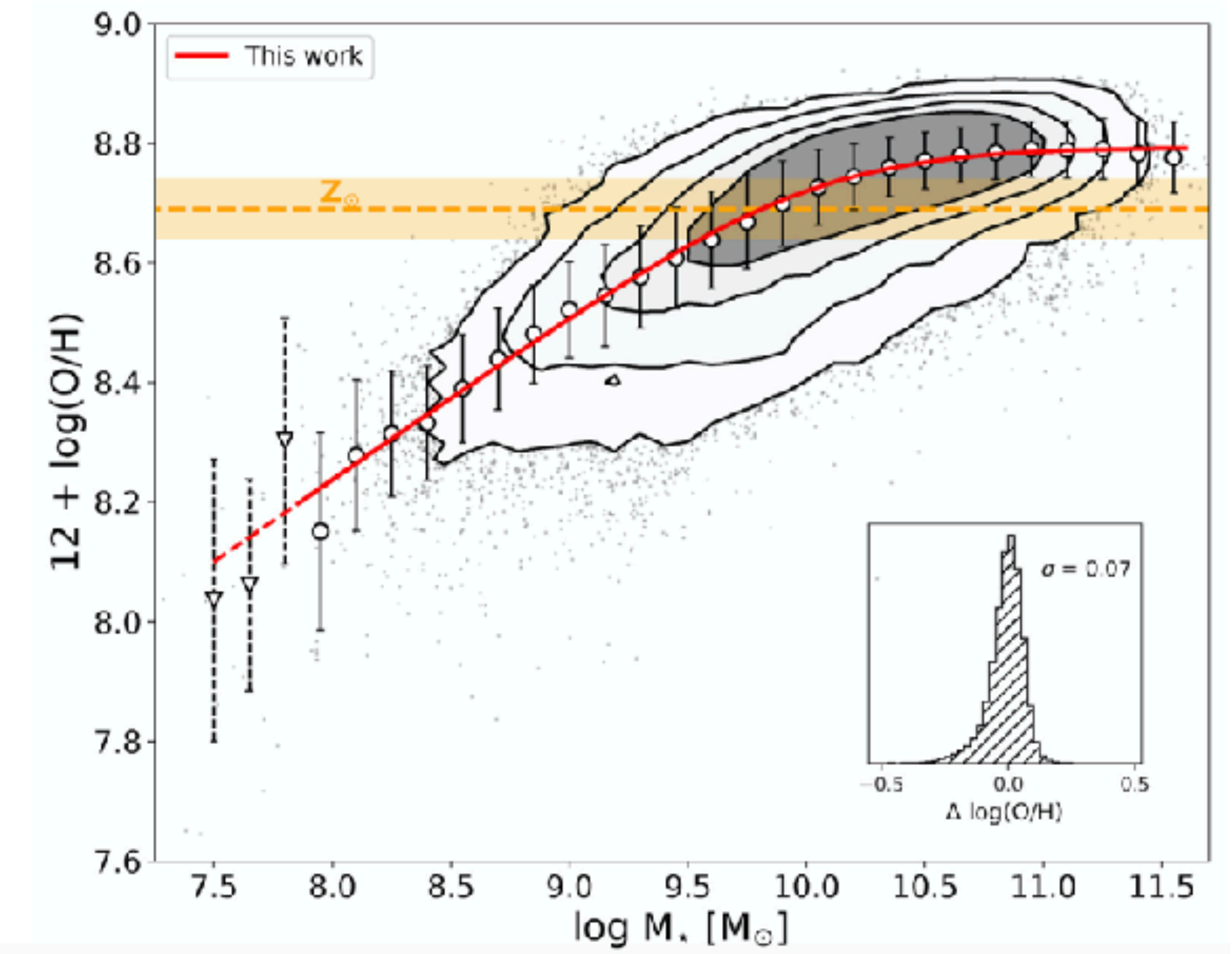


Curti et al. 2020 - https://ui.adsabs.harvard.edu/abs/2020MNRAS.491..944C/

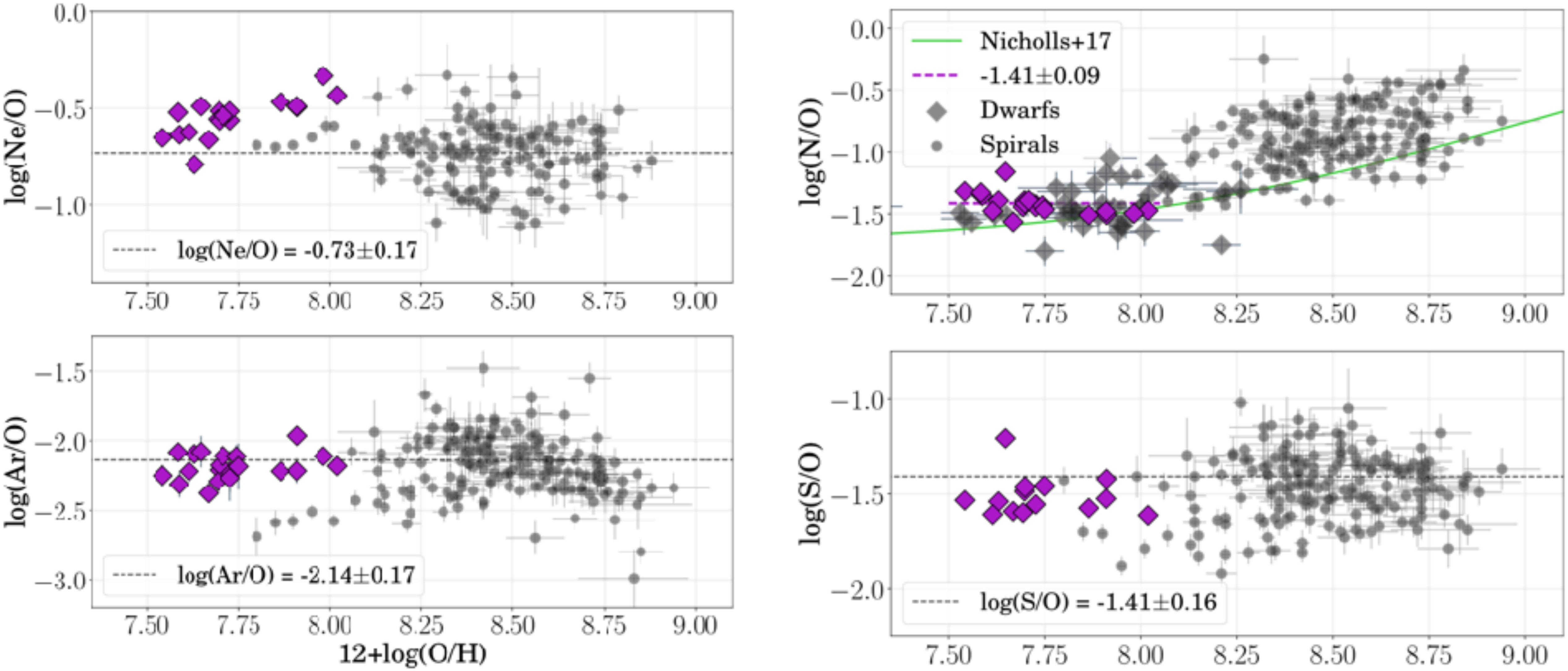
MZ relationship tied to direct Te measured metallicities.

More massive galaxies are more chemically enriched. Steeper slope at low mass, turnover/saturation at high mass.

More generations of chemical enrichment in high mass galaxies, worse ability to hold onto metals in low mass.

Other Elements than O

Not all elements scale linearly with oxygen! Different enrichment mechanisms (AGB vs CCSN, etc). Ne, Ar, S generally have ~constant ratios w/oxygen.



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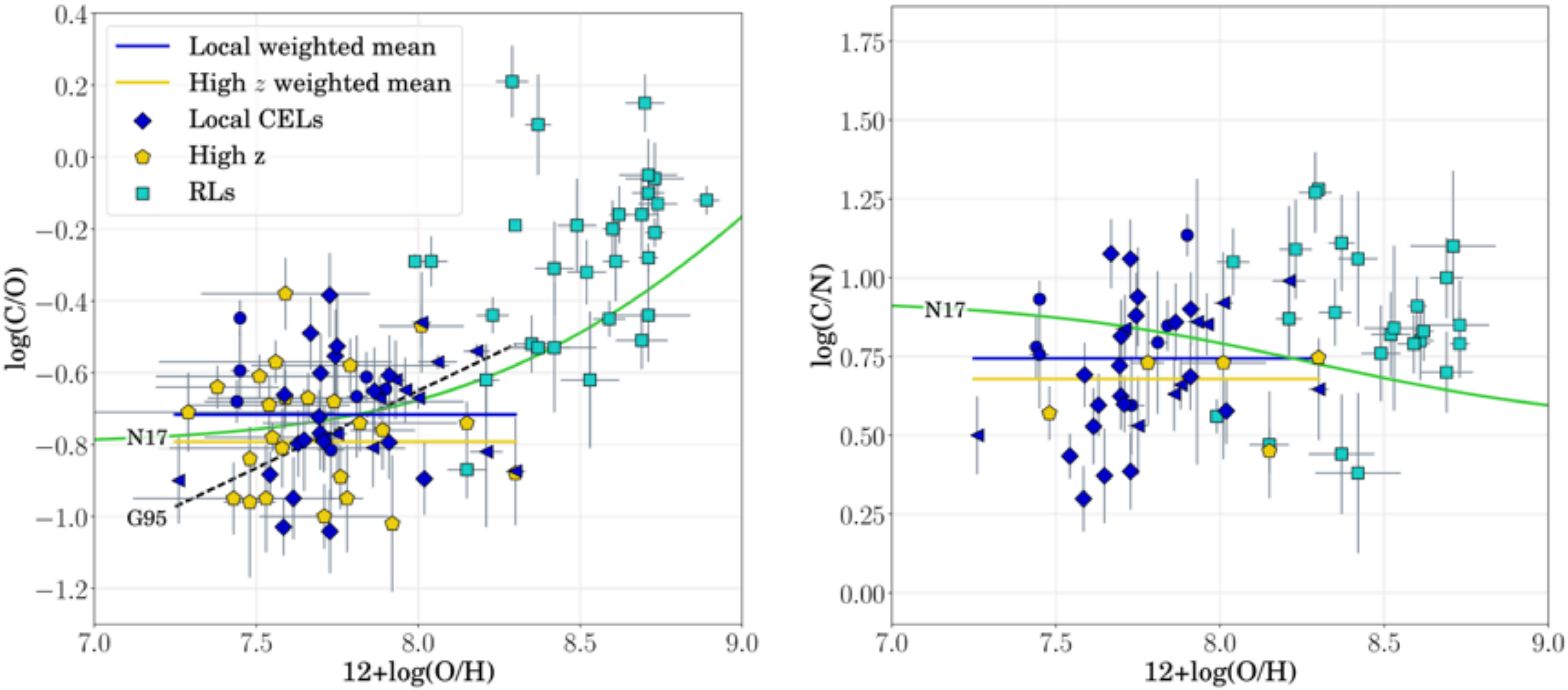


Of particular importance for various ISM processes - C/O abundance may vary a lot!

However, C/N ~constant, suggesting C may have both *primary* (e.g. metallicity independent, from original H & He in star) & *secondary* (from nucleosynthesis that relies on heavier elements) production mechanisms.

Berg et al. 2019 - https://ui.adsabs.harvard.edu/abs/2019ApJ...874...93B/

What is “low” metallicity?

- Some factor lower than MW Solar neighborhood metallicity?
- Some metallicity where things about the ISM begin to notably differ?
- Any thoughts?

Where do we find low metallicity conditions?

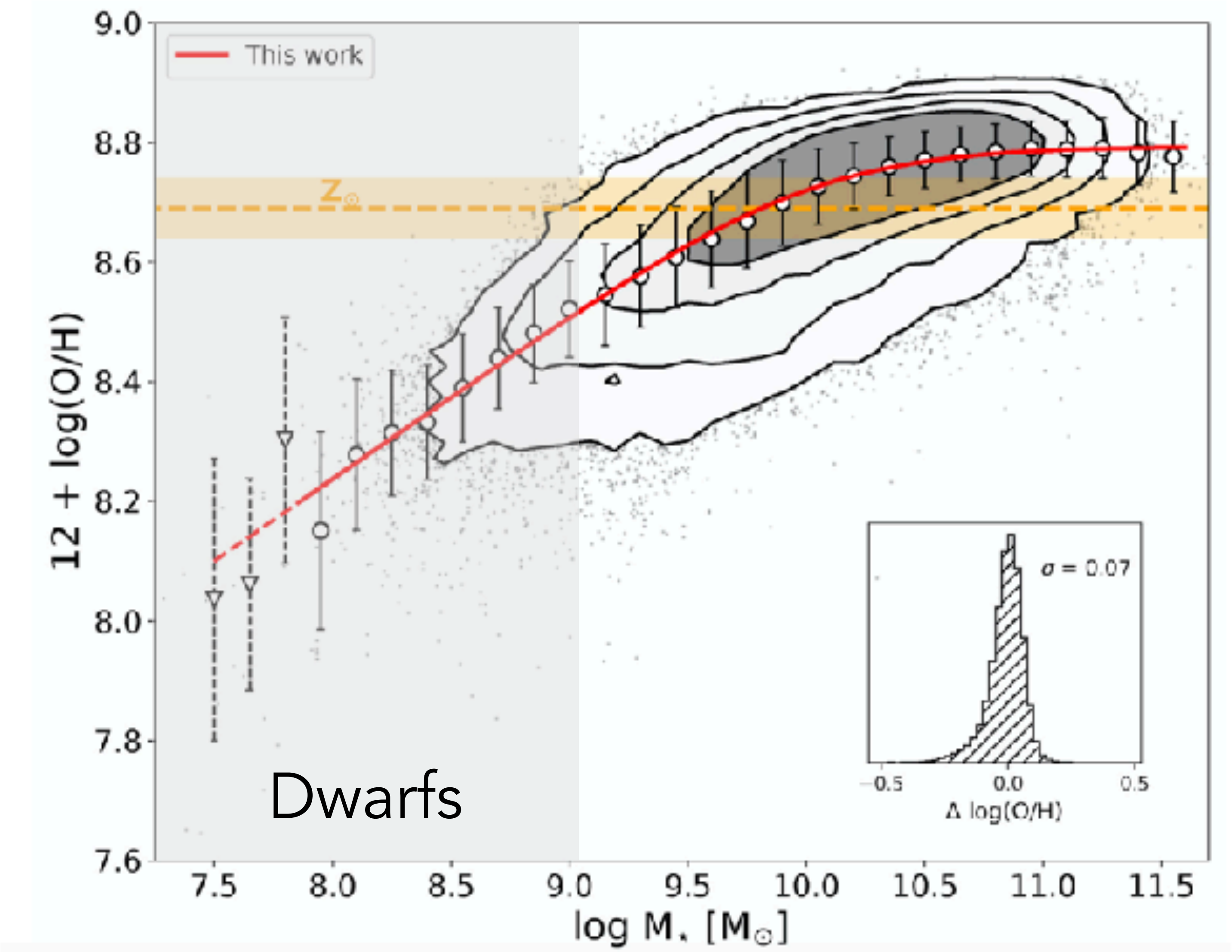
- **Dwarf Galaxies:** galaxies with $M_* < 10^9 M_\odot$, due to the mass-metallicity relationship, tend to have low Z

- **Outskirts of galaxies:** most galaxies have radially declining metallicity gradients, so galaxy outskirts often have low Z

- **High redshift galaxies:** because of galactic chemical evolution, at earlier times galaxies have lower Z on average

Dwarf Galaxies

Below ~10^9 M⊙, average metallicity of galaxies is a factor of ~2 lower than Solar.



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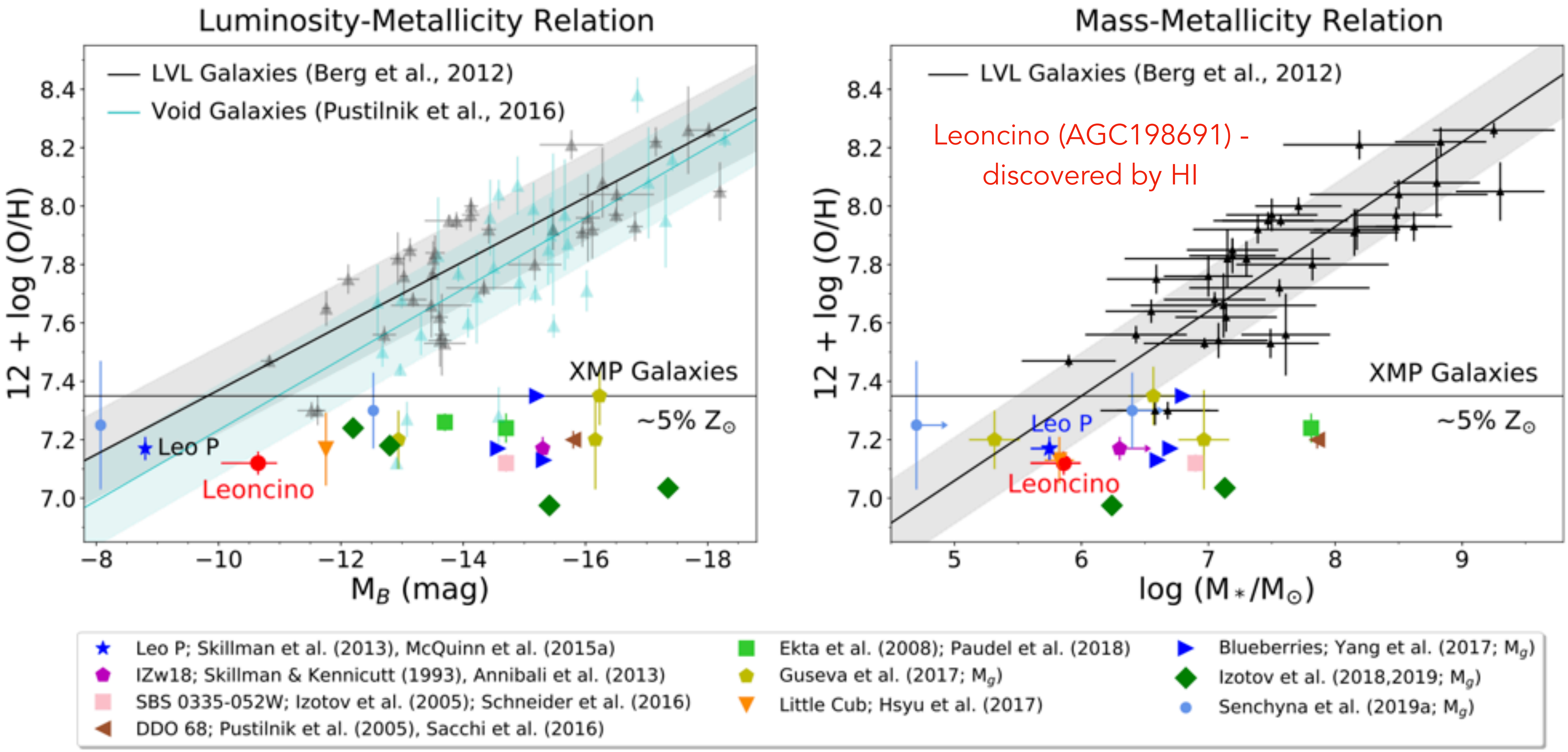
Dwarf galaxies are expected to be relatively homogeneous in metallicity, due to efficient mixing, but comprehensive observational study with IFUs is needed.

Dwarf Galaxies



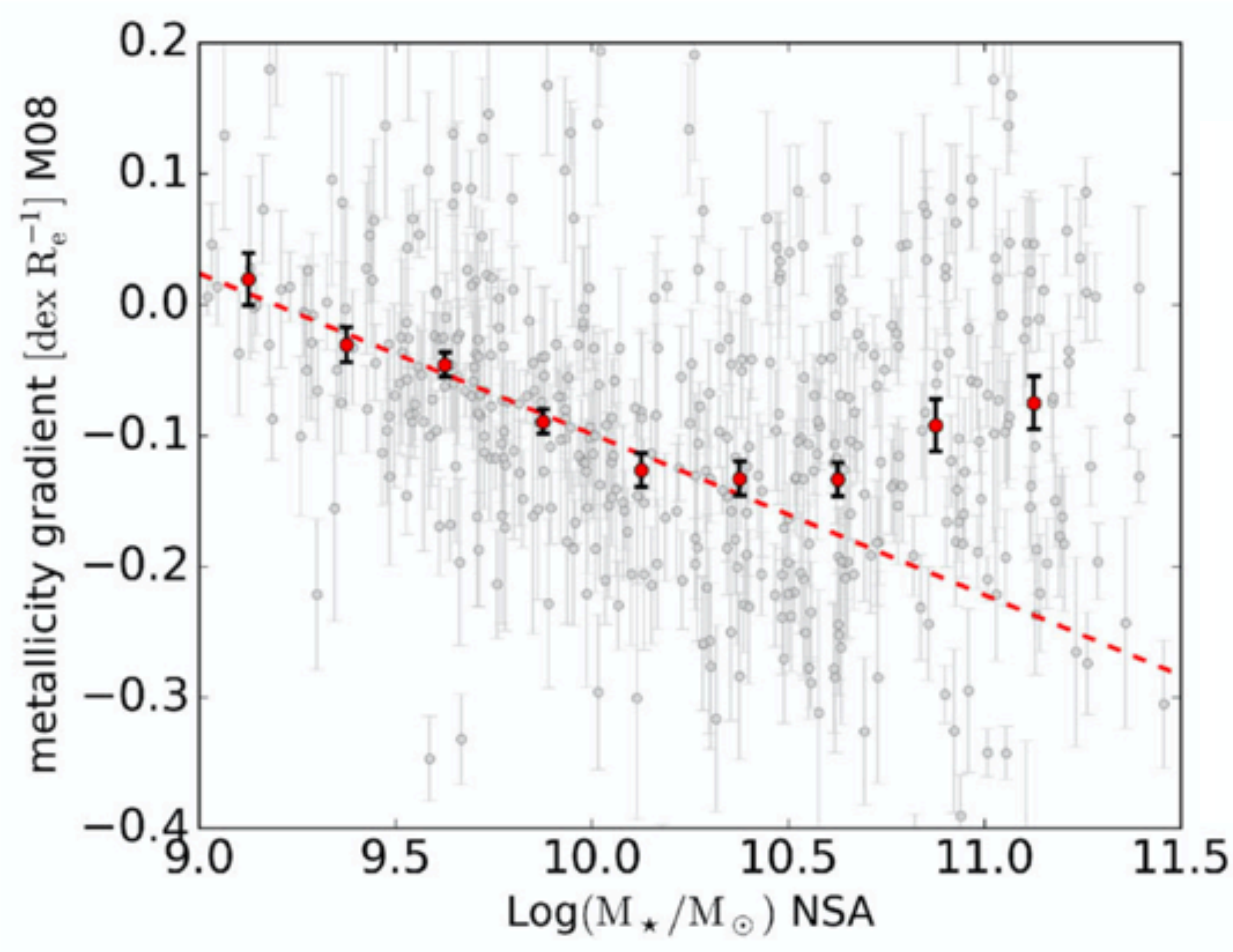
Leoncino (AGC198691) -
discovered by HI

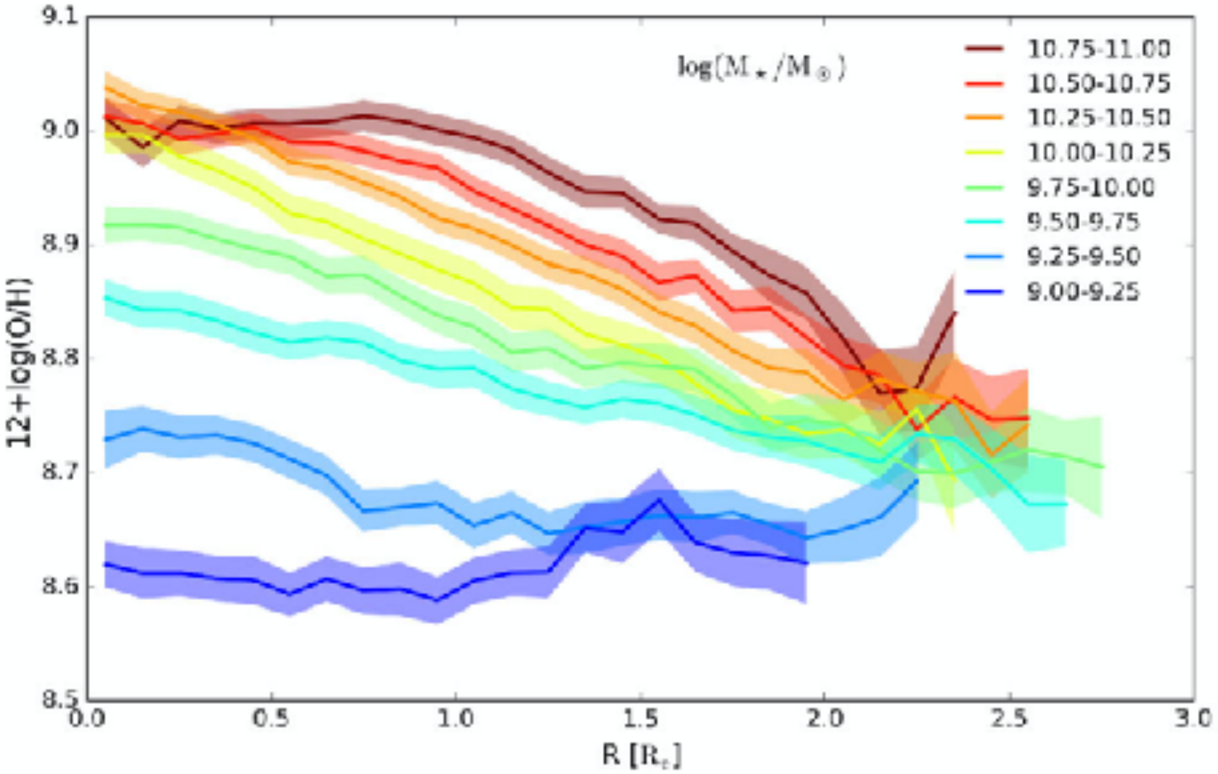
XMPs are compact, have a lot of recent SF, and often evidence for interactions in their HI distribution - suggests they are outliers due to recent accretion of gas from mergers

McQuinn et al. 2020 - https://ui.adsabs.harvard.edu/abs/2020ApJ...891..181M/

Galaxy Outskirts

Galaxies with M>10^9 M⊙, tend to have radially decreasing metallicity gradients in their disks.



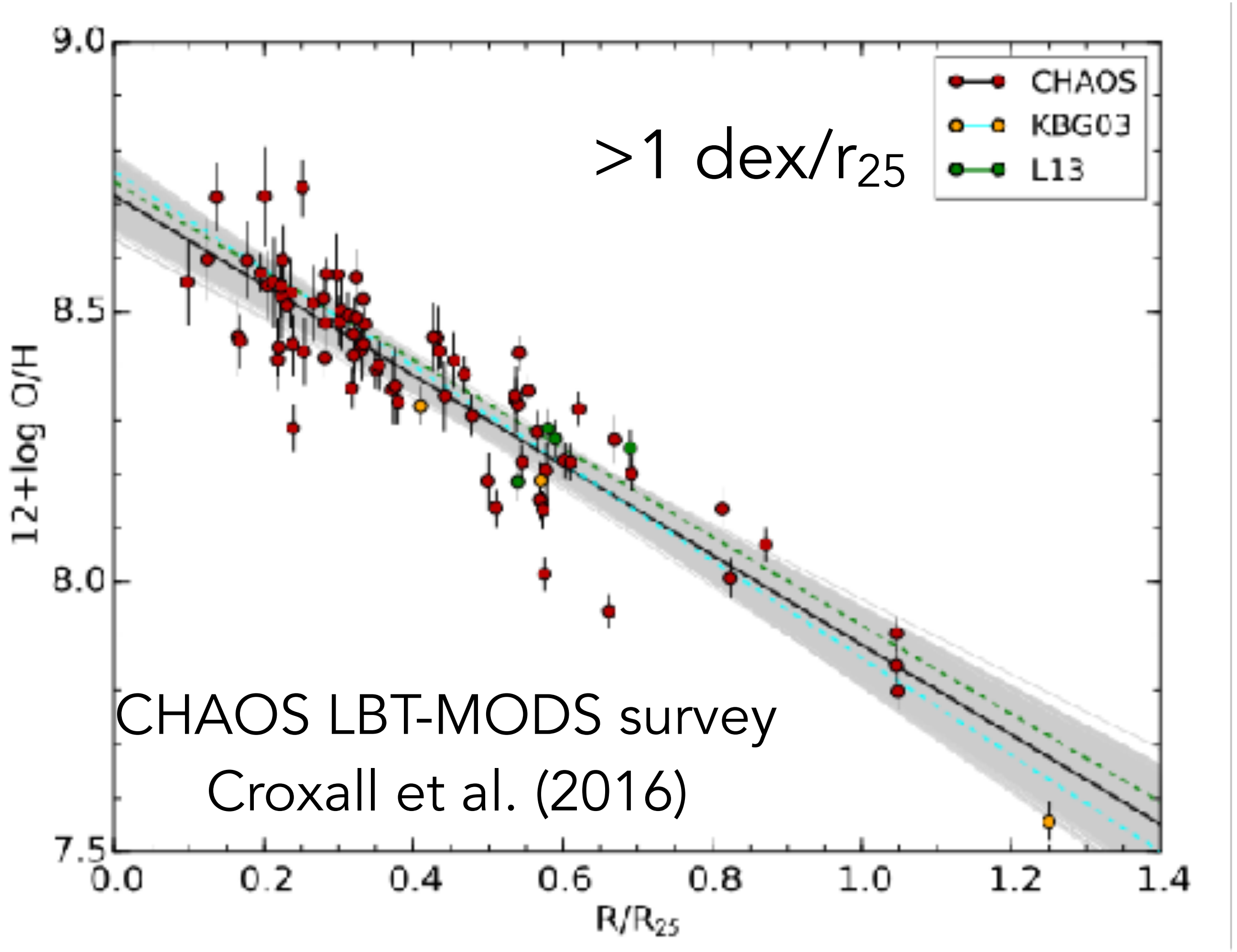


Belfiore et al. 2017 - https://ui.adsabs.harvard.edu/abs/2017MNRAS.469..151B/

Galaxy Outskirts

Spitzer IRAC & MIPS imaging (credit: K Gordon)

M101 has one of the most dramatic radial metallicity gradients,
~MW to sub-SMC metallicity

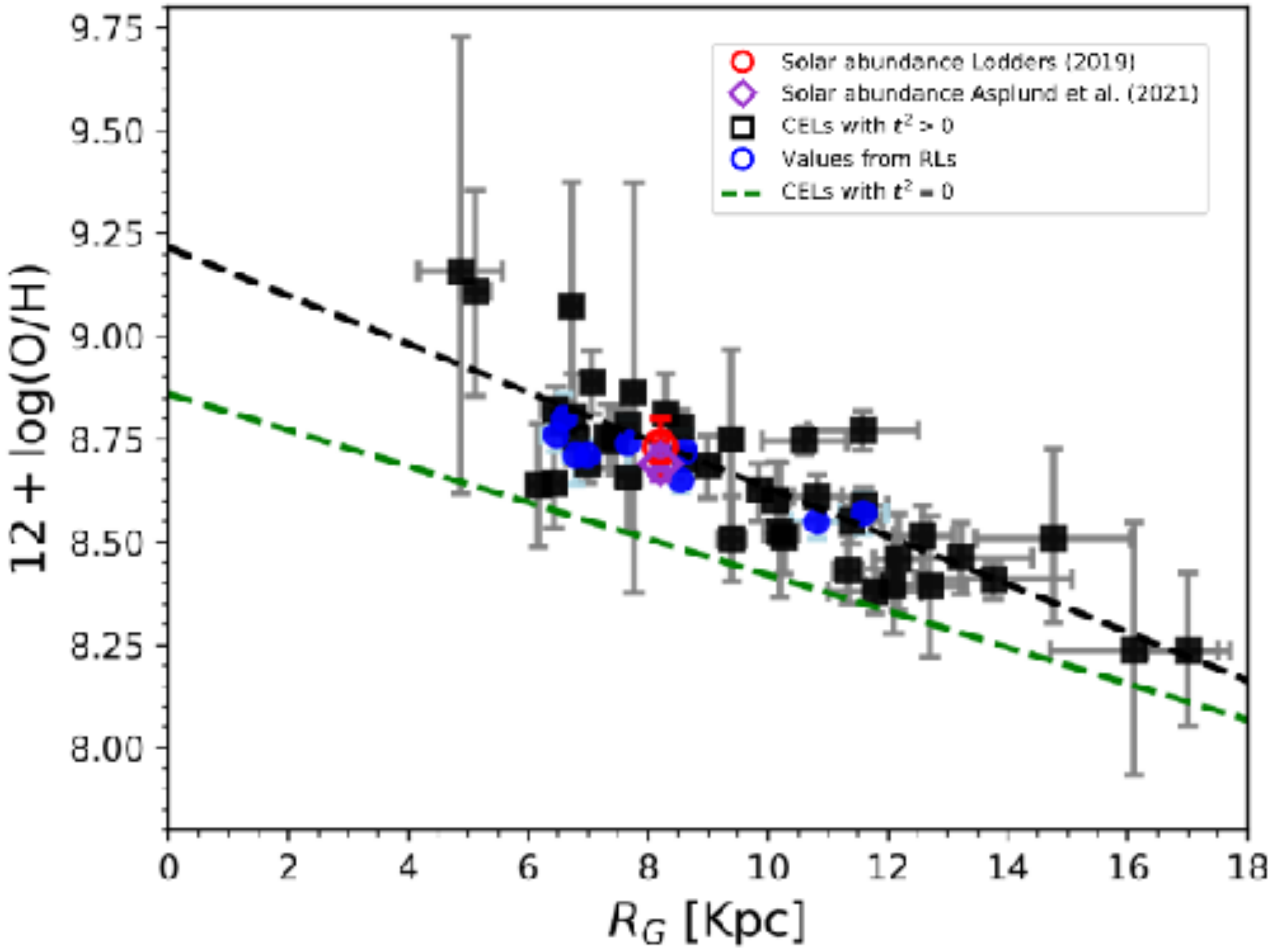


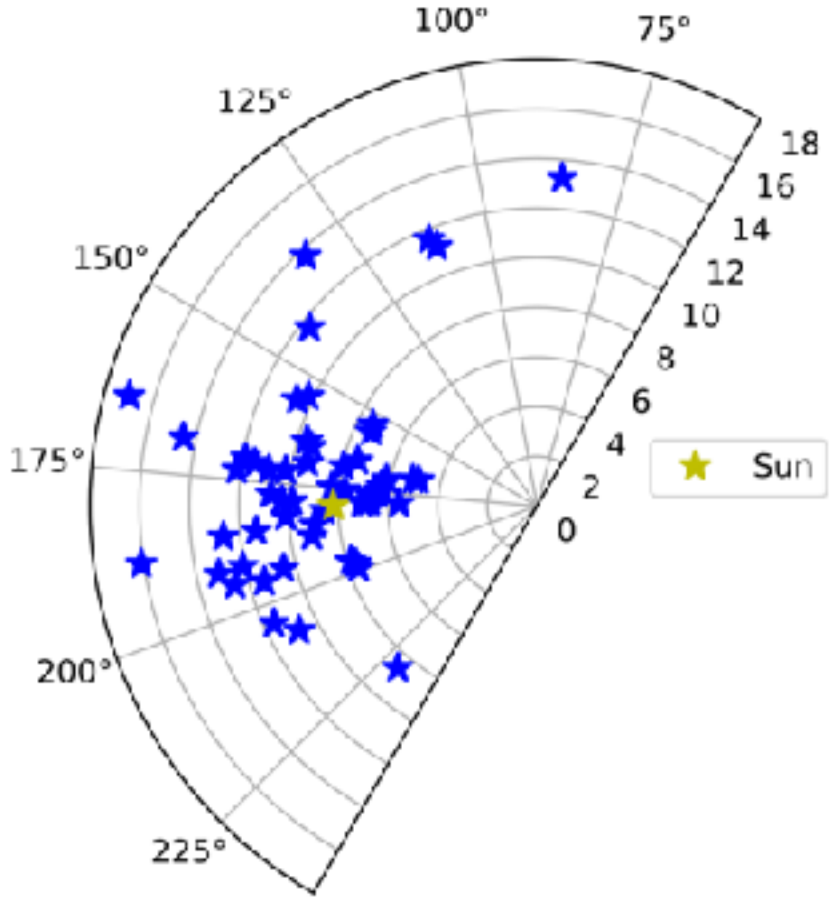
>1 dex/r_{25}

CHAOS LBT-MODS survey
Croxall et al. (2016)

Galaxy Outskirts

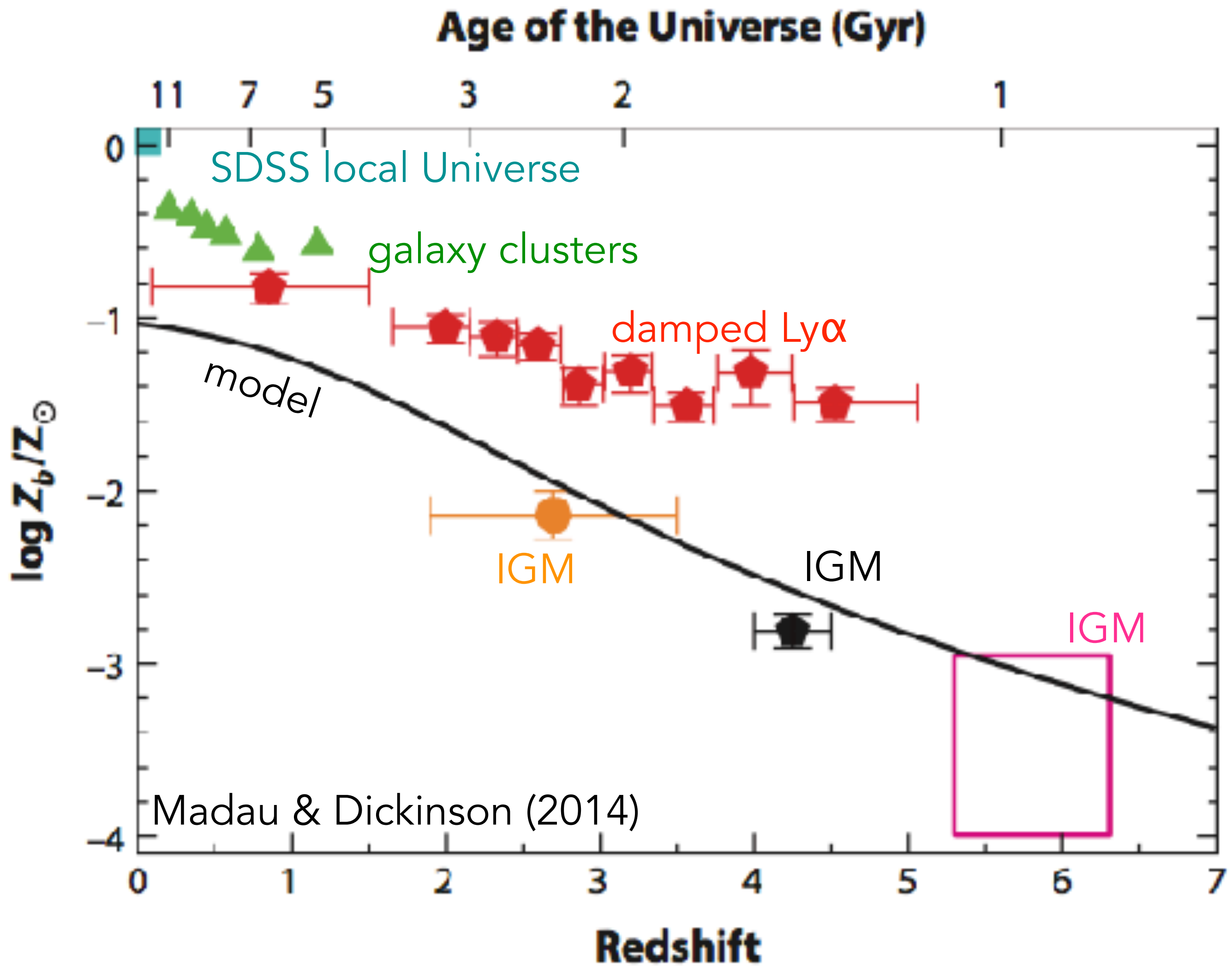
Milky Way also has a radial gradient, so the closest low metallicity environment is actually the outer disk of the MW!





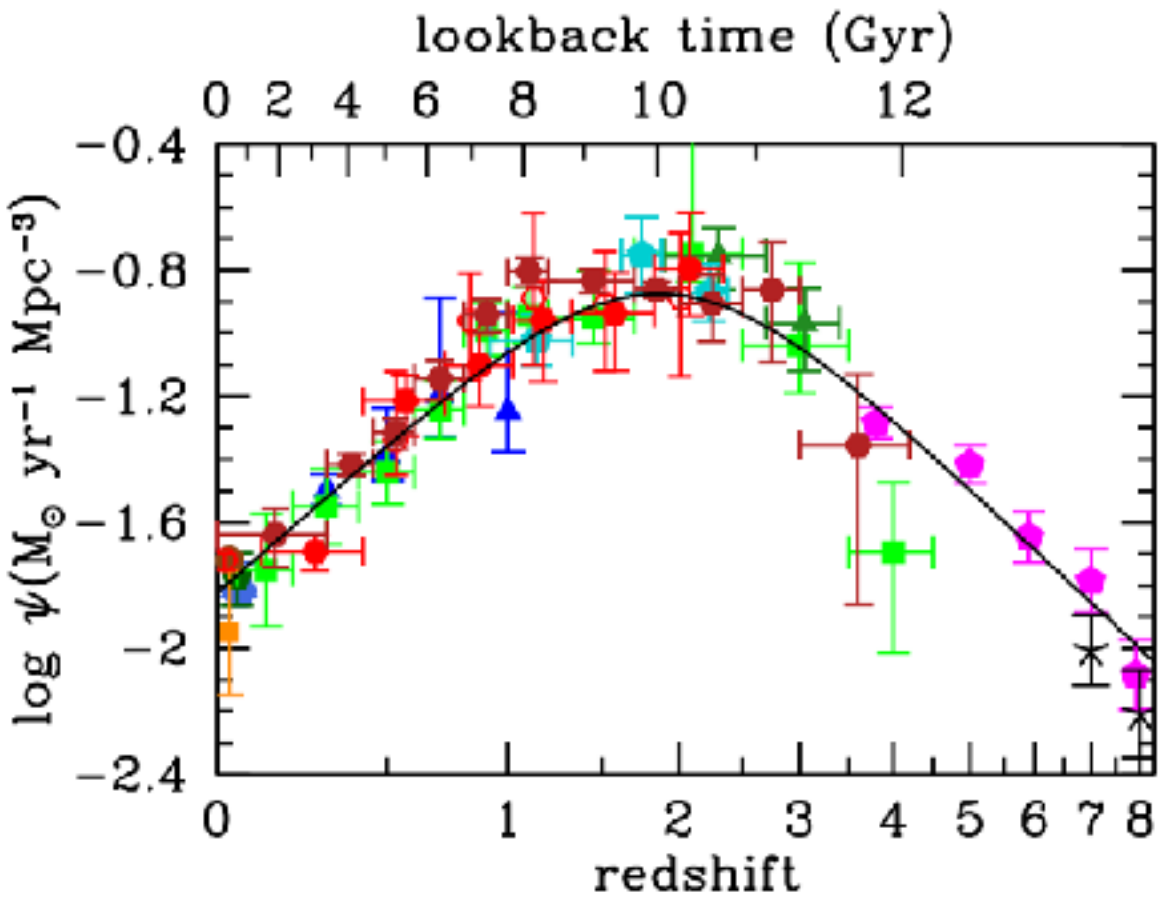
Mendez-Delgado et al. 2022 - https://ui.adsabs.harvard.edu/abs/2022MNRAS.510.4436M/

High Redshift Galaxies

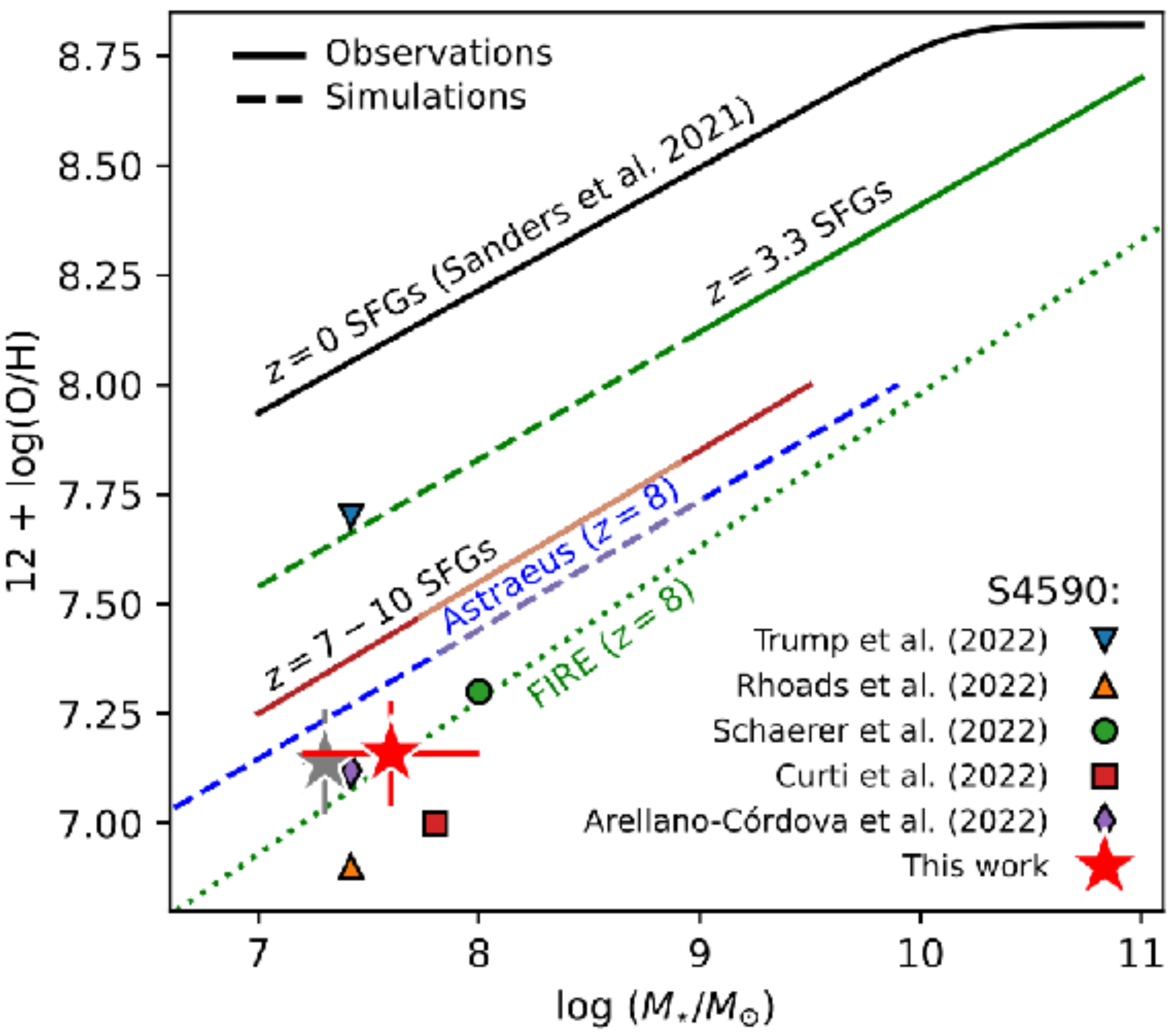


Most of the SF in the Universe happened at lower Z than we currently have in the MW.

Average metallicity for galaxies at peak of SF at z~2 is ~0.1 Z⊙.



High Redshift Galaxies

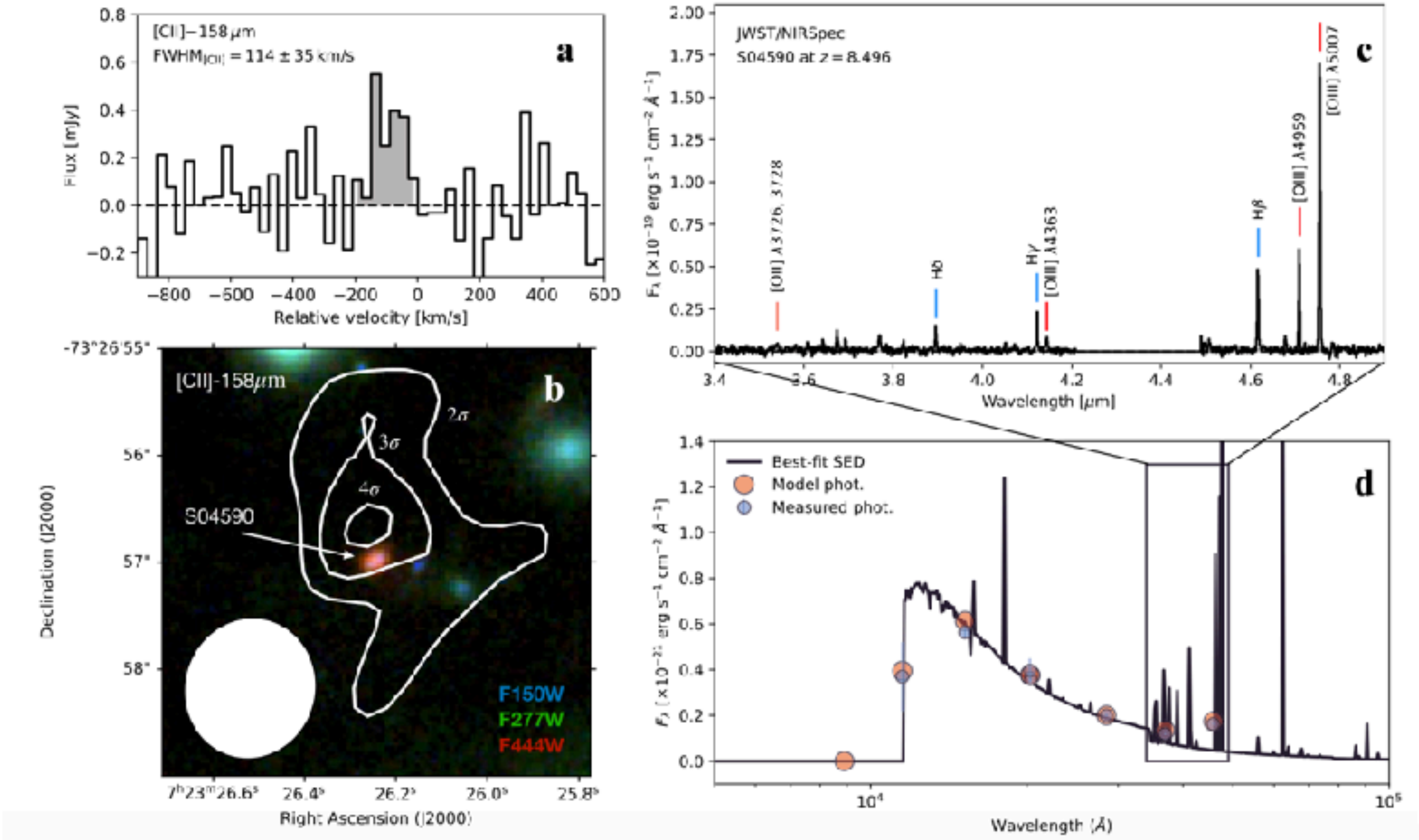


At a fixed stellar mass, higher redshift galaxies are more metal poor than present day galaxies.

Heintz et al. 2023 - https://ui.adsabs.harvard.edu/abs/2023ApJ...944L..30H/

High Redshift Galaxies

With JWST & ALMA can see very high-z galaxies now!



Heintz et al. 2023 - https://ui.adsabs.harvard.edu/abs/2023ApJ...944L..30H/

High Redshift Galaxies

Damped Lyman-alpha Absorbers

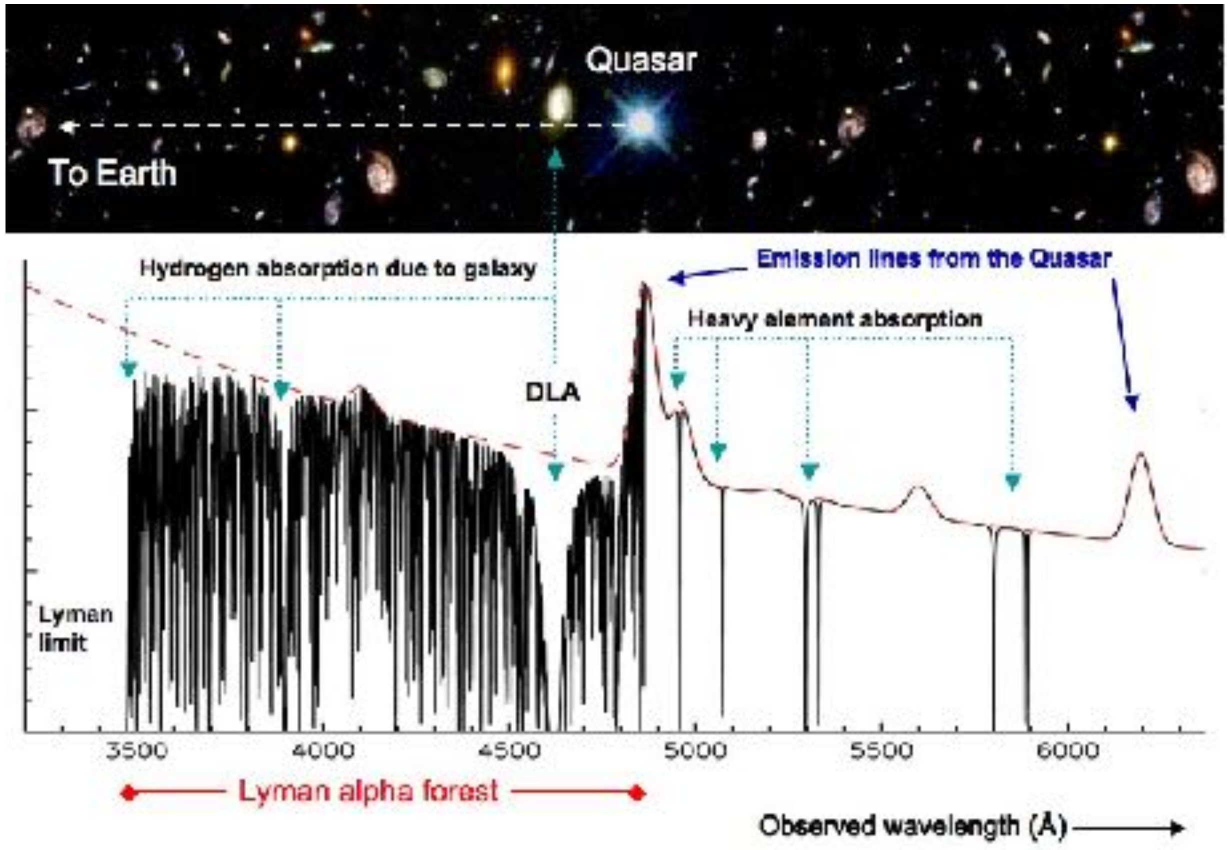
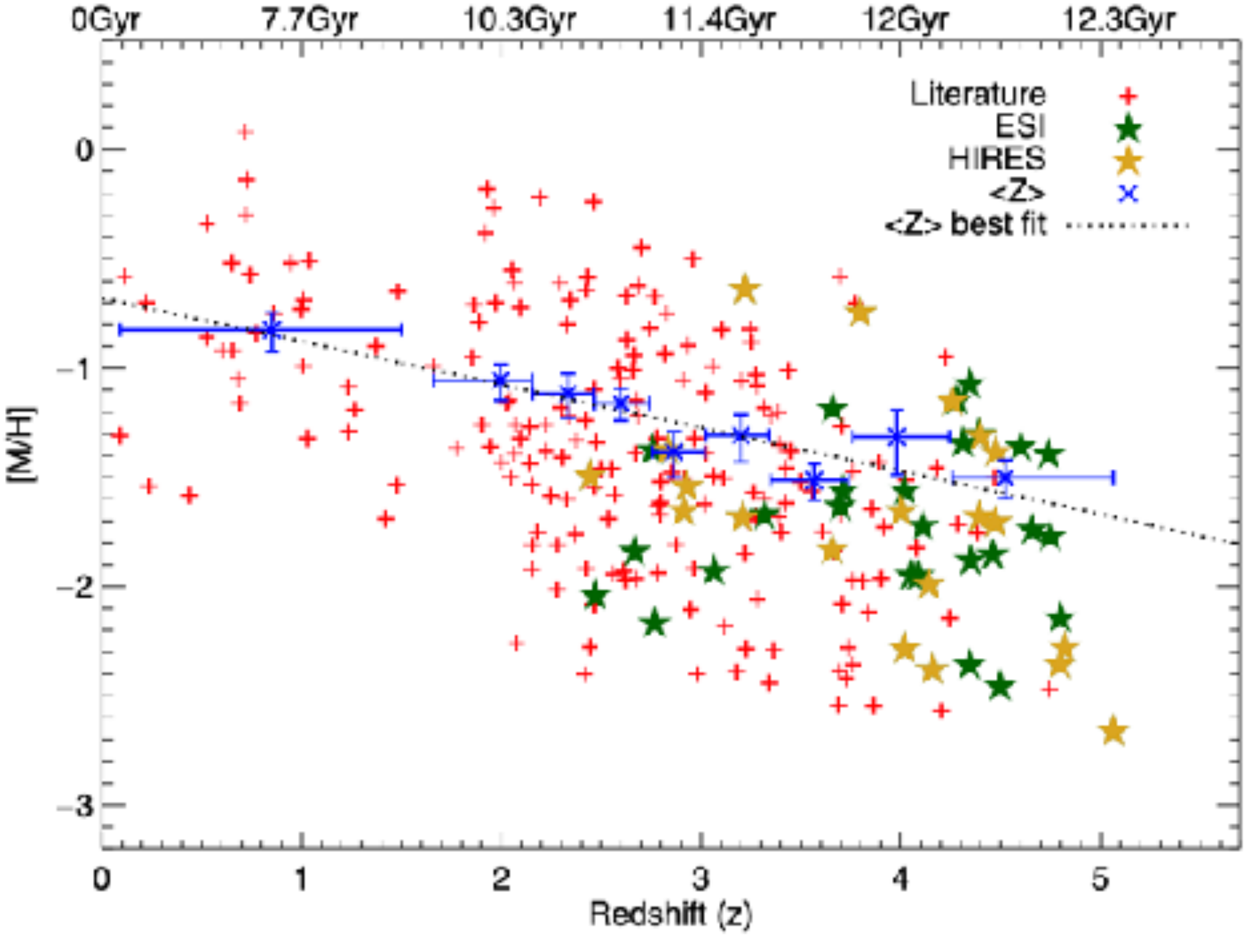


Illustration courtesy of John Webb



Sight-lines to QSOs that randomly intersect galaxies give basically unbiased account of metallicity vs redshift. However, [M/H] measurement involves many different elements, tough to control.

Rafelski et al. 2012 - https://ui.adsabs.harvard.edu/abs/2012ApJ...755...89R/

Dust

Dust

*It’s metals!

Dust Properties

Key properties of dust that vary with metallicty:

- Dust-to-Gas Ratio (or: dust-to-metals, D/M, the fraction of heavy elements in dust)
- Size Distribution
- Composition

How do we measure the dust-to-gas ratio?

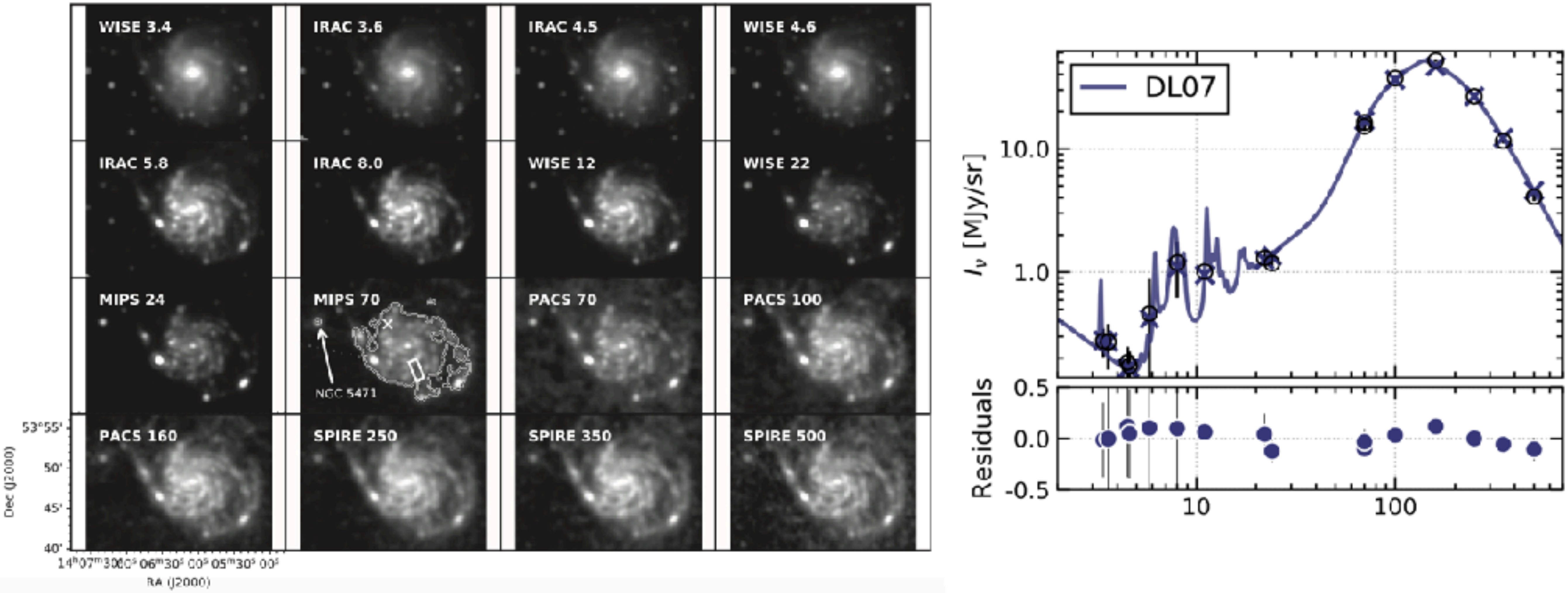
Two Approaches:

- **Multiwavelength observations** - dust from mid- to far-IR, gas from 21 cm and CO. (metallicity from HII region spectra)
- **Depletions** - measure fraction of metals that are in dust. (metallicity from young star reference, or other assumptions)

Dust-to-Gas Ratio vs Metallicity

From Multiwavelength Approach

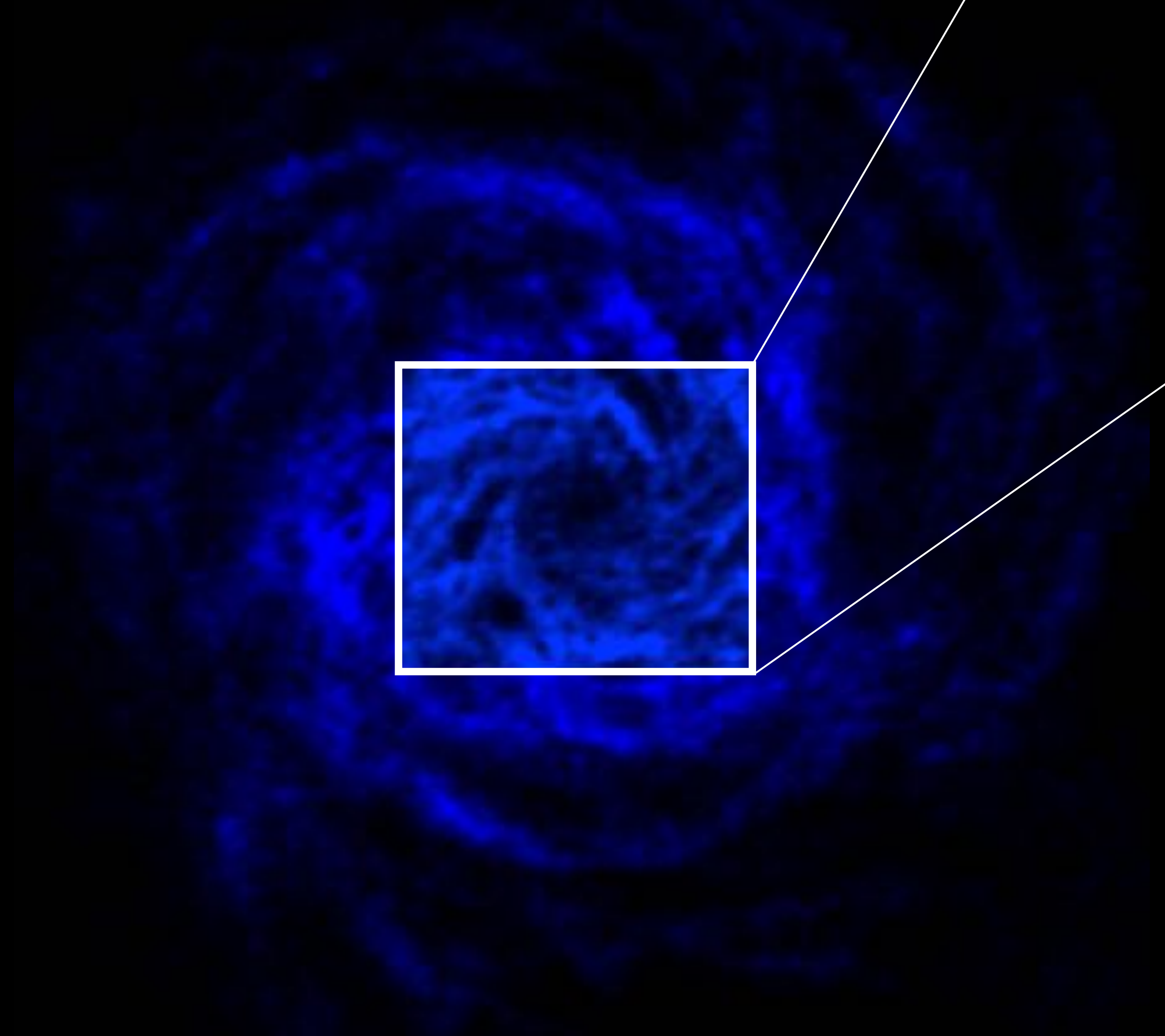
First: measure dust mass surface density with IR SED modeling
(many potential variations on wavelength range, dust model, fitting approach)



Chastenet et al 2021 - https://ui.adsabs.harvard.edu/abs/2021ApJ...912..103C/

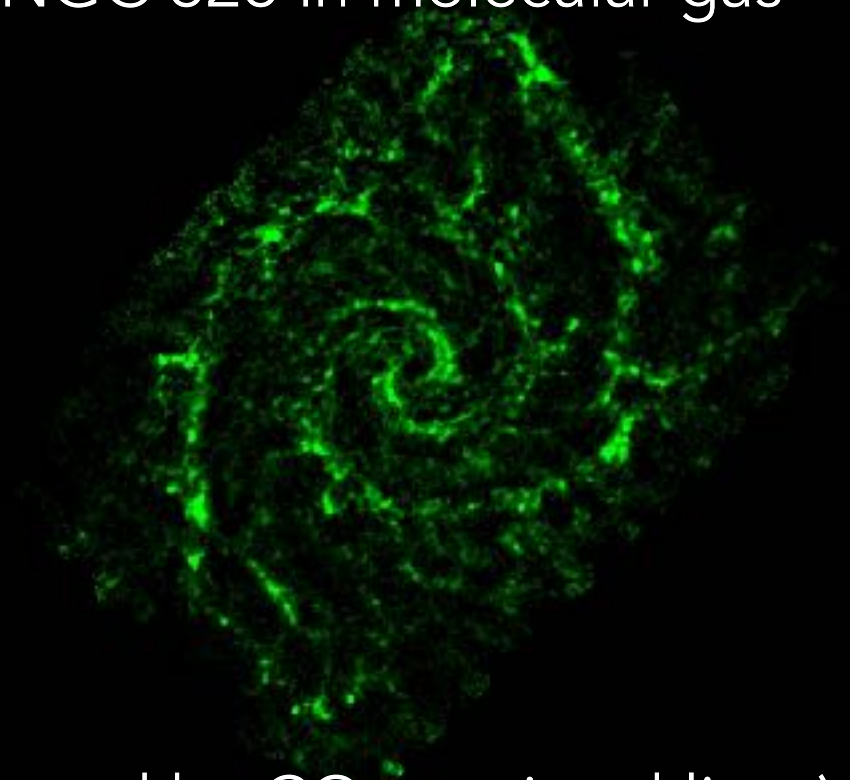
Gas

described by the state of H:
ionized, atomic, molecular
HII HI H_2



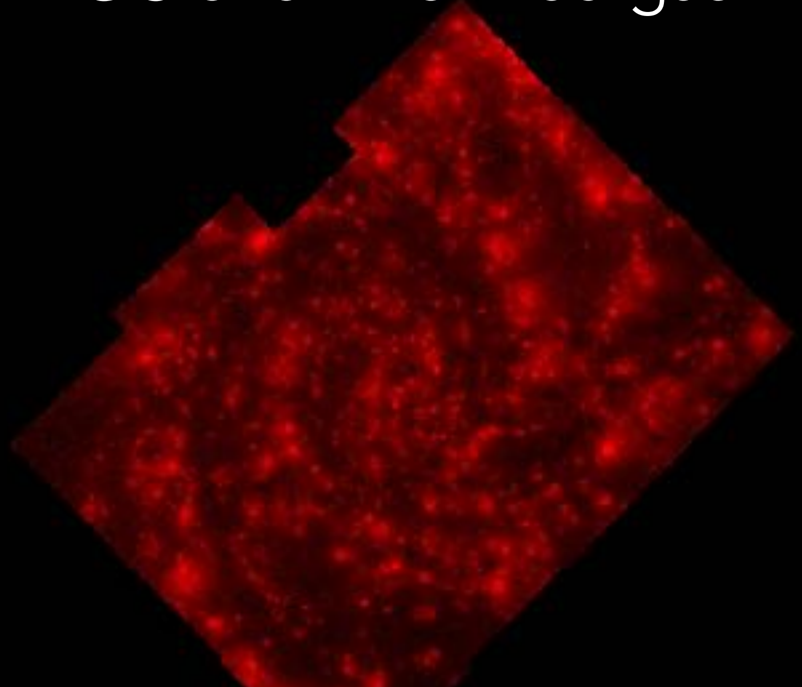
NGC 628 in atomic gas
(traced by the HI 21 cm line)

NGC 628 in molecular gas



(traced by CO rotational lines)

NGC 628 in ionized gas



(traced by H recombination lines,
here Hα 6563 Å)

Gas

described by the state of H: ionized, atomic, molecular

HII HI H_2

Very Large Array

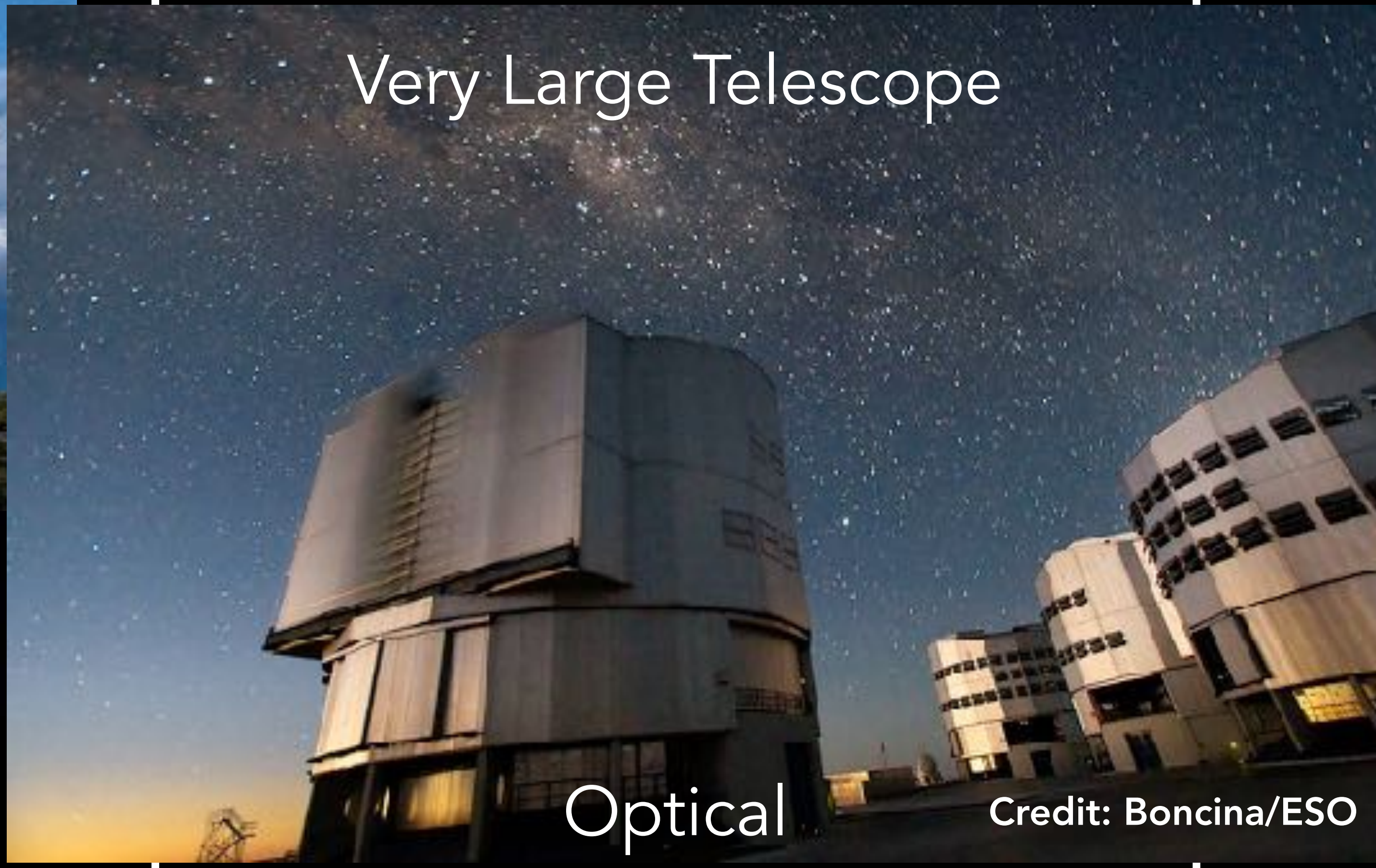
Radio

Credit: NRAO/AUI/NSF

Atacama Large Millimeter Array

Millimeter

Credit: ESO/C. Malin



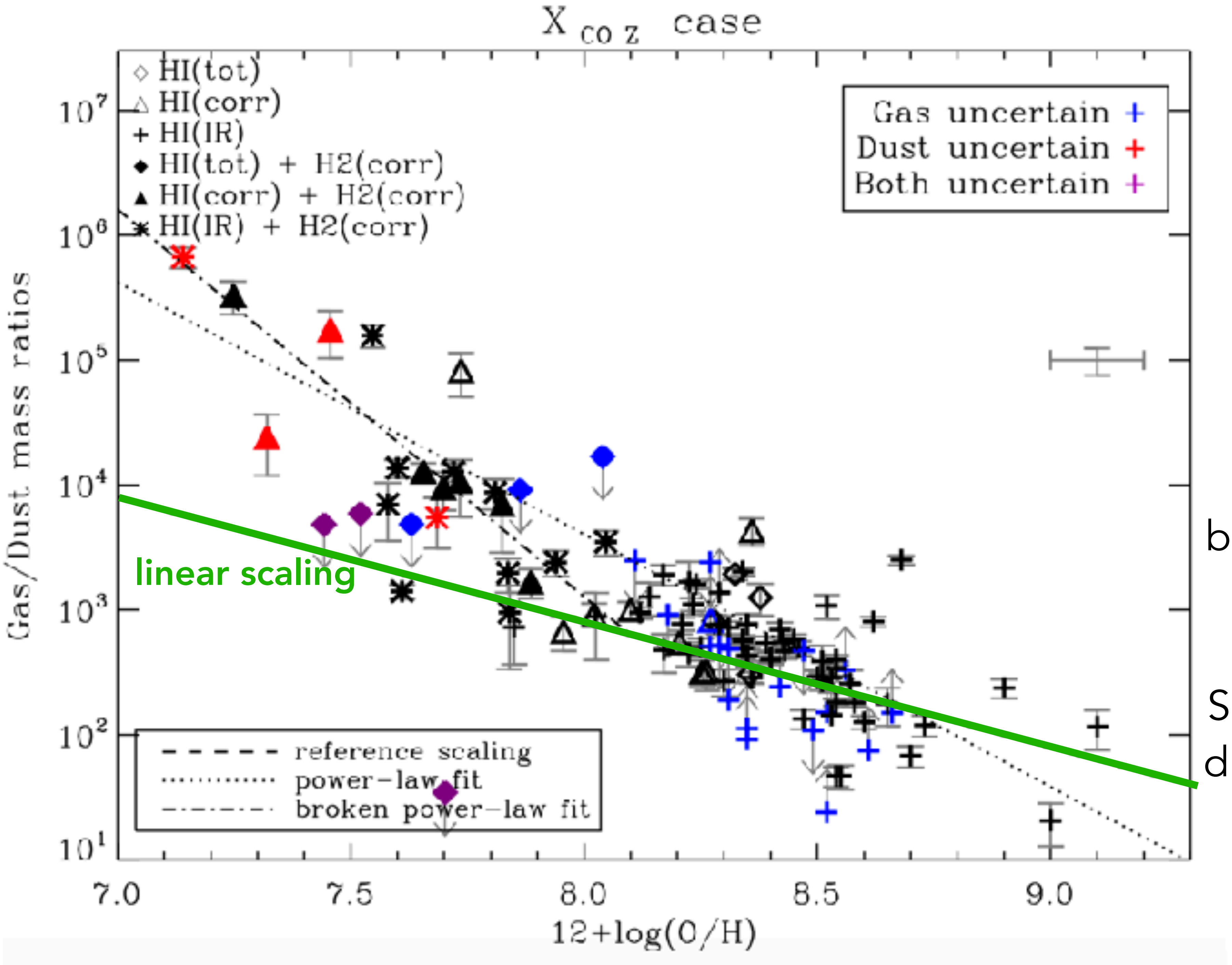
Very Large Telescope

Optical

Credit: Boncina/ESO

Dust-to-Gas Ratio vs Metallicity

Results from Multiwavelength Approach:



Galaxy integrated DGR(Z)

At high metallicity, DGR(Z) agrees reasonably well with linear metallicity scaling.

At low metallicity, deviations become large, even up to orders of magnitude! **DTM changes.**

Scatter at high Z at least partially due to internal metallicity & DGR gradients in galaxies.

Remy-Ruyer et al. 2014 - https://ui.adsabs.harvard.edu/abs/2014A%26A...563A..31R/

Dust-to-Gas Ratio vs Metallicity

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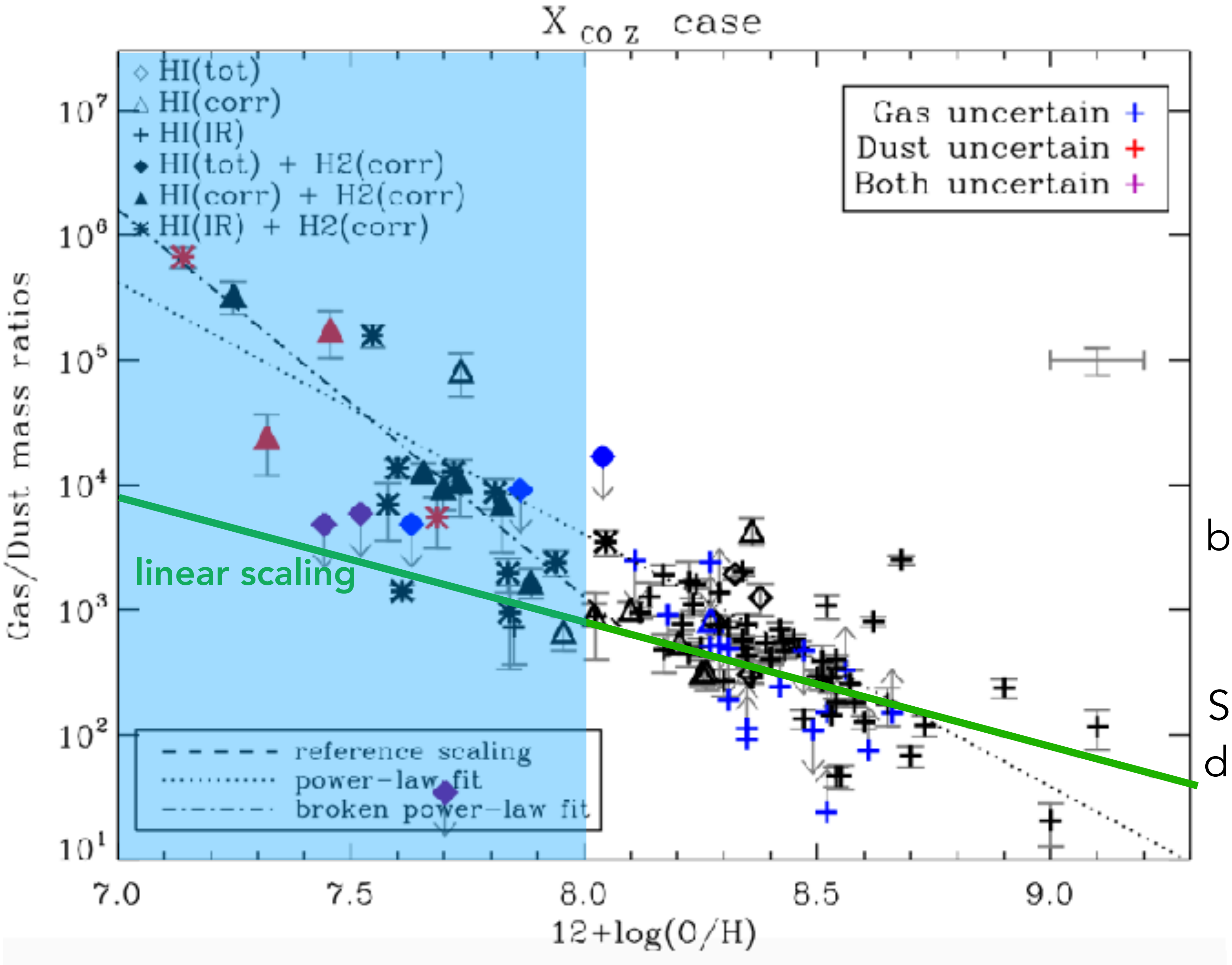

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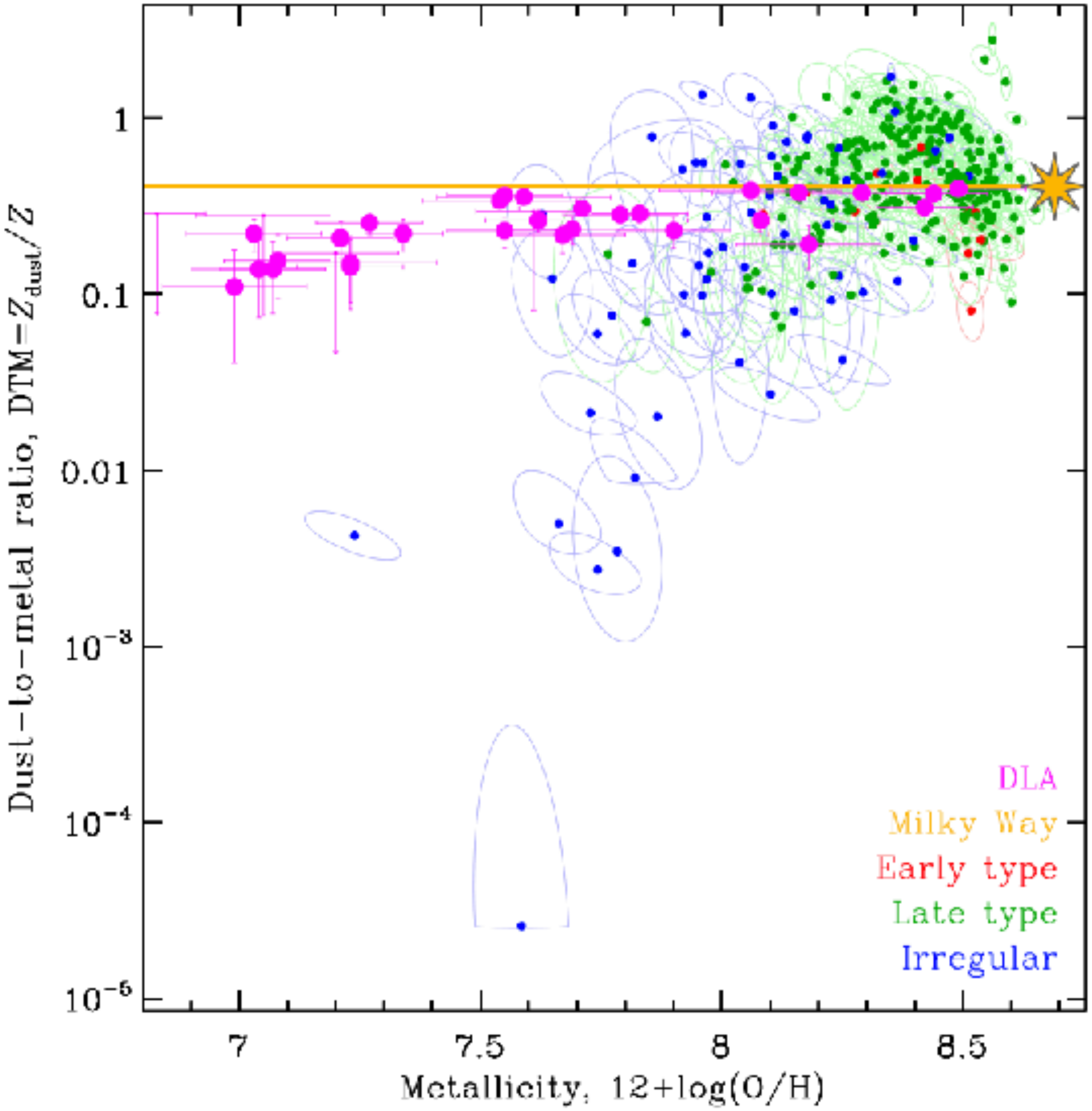
Dust-to-Gas Ratio vs Metallicity



Galaxy integrated DGR(Z)

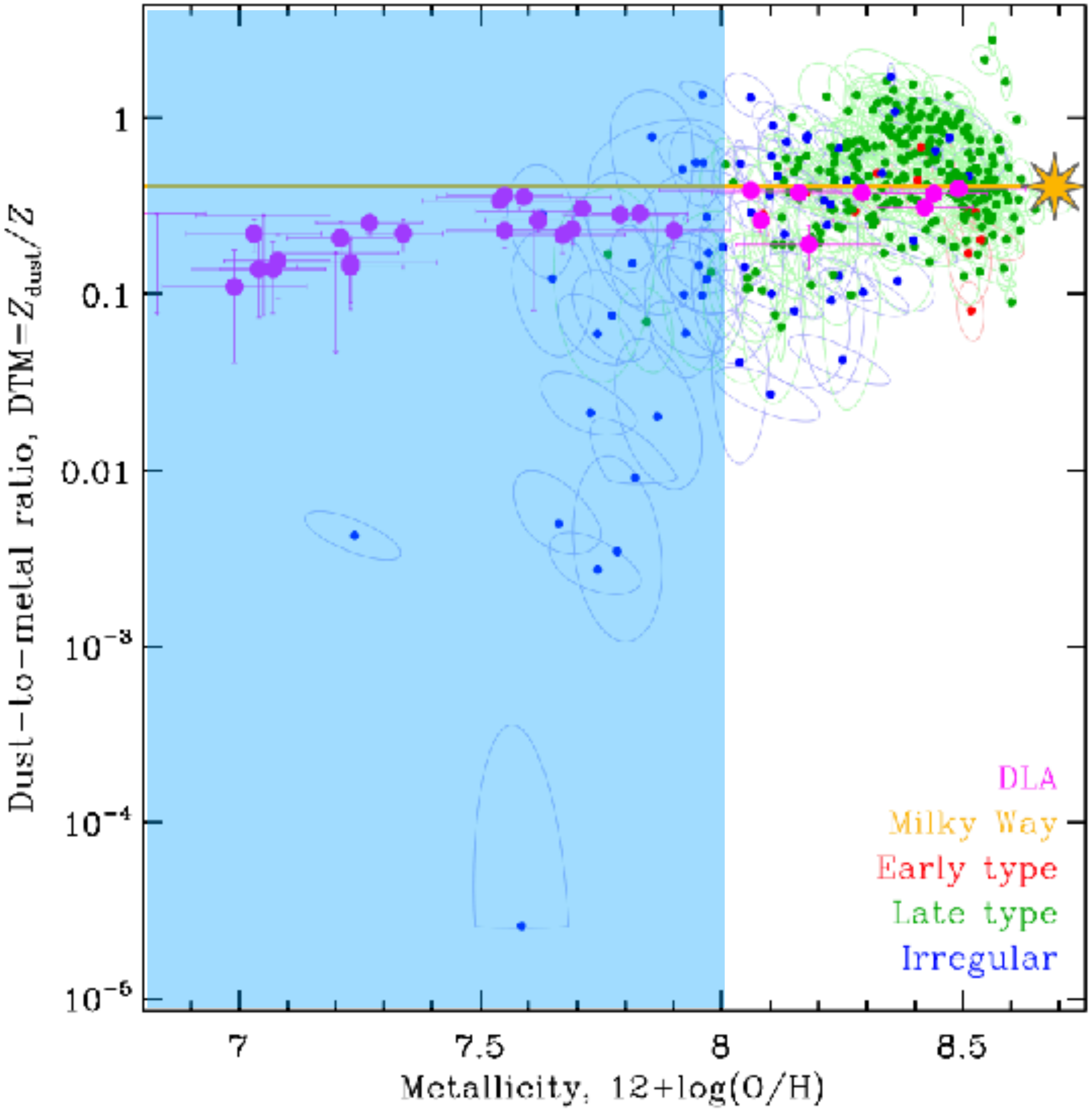
Result of decreasing DTM with metallicity holds up to different modeling approaches.

DTM drops below about 12+log(O/H)~8

DLA points tell a somewhat different story…

Galliano et al. 2021 - https://ui.adsabs.harvard.edu/abs/2021A%26A...649A..18G/

Dust-to-Gas Ratio vs Metallicity



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Dust-to-Gas Ratio vs Metallicity

From Depletion Measurements

observed abundance

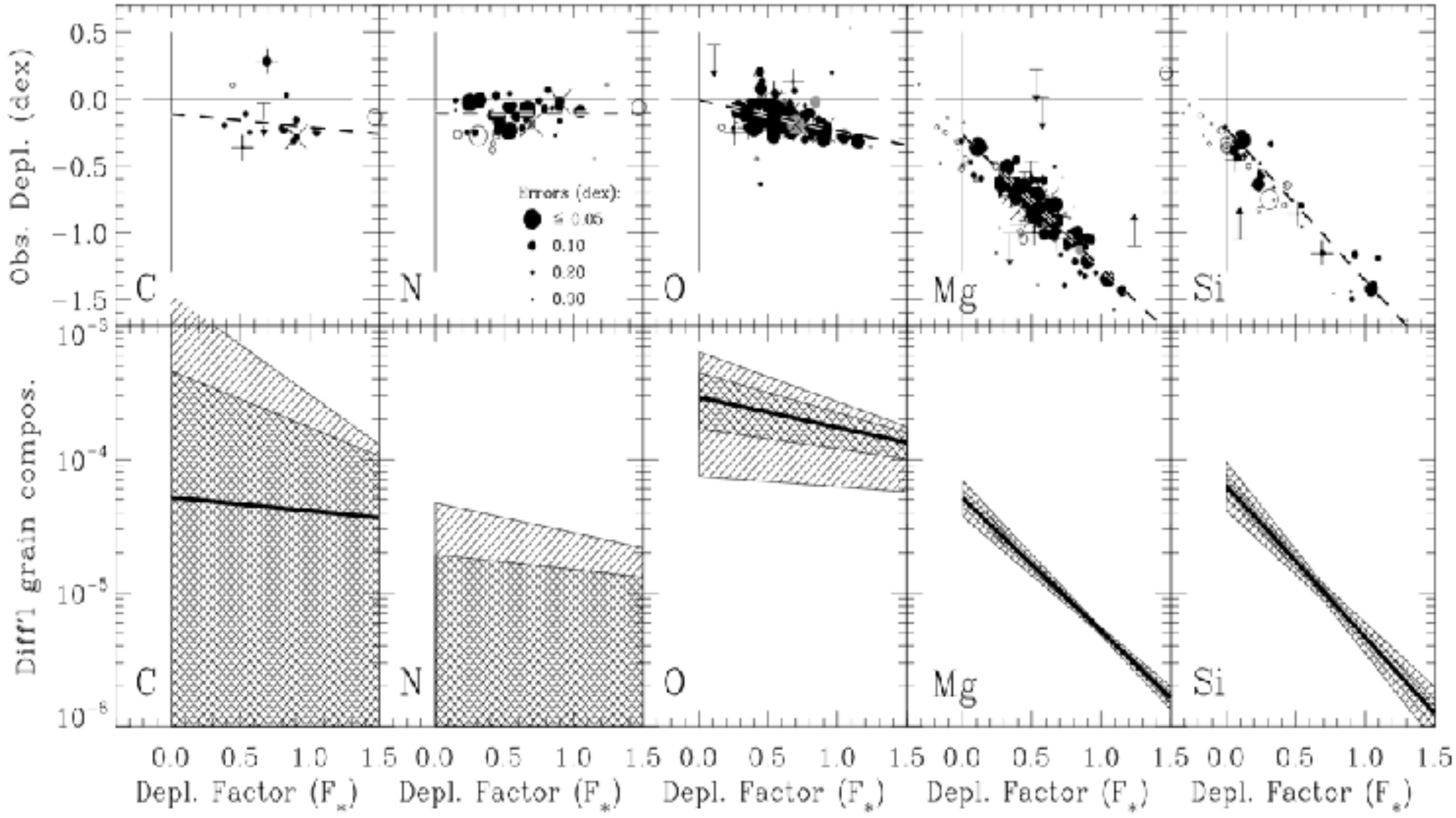
Depletion→ $$\delta(X) = \boxed{\log_{10}\left(\frac{N(\mathrm{X})}{N(\mathrm{H})}\right)} - \boxed{\log_{10}\left(\frac{\mathrm{X}}{\mathrm{H}}\right)_{\mathrm{tot}}}$$ reference abundance

Jenkins 2009 defined F* - factor that describes the overall level of depletion along a given line of sight.

F* varies!

F* increases with average density, f_{H2}, N(H).

Jenkins 2009 - https://ui.adsabs.harvard.edu/abs/2009ApJ...700.1299J/



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To use depletions to estimate DGR or D/M need:

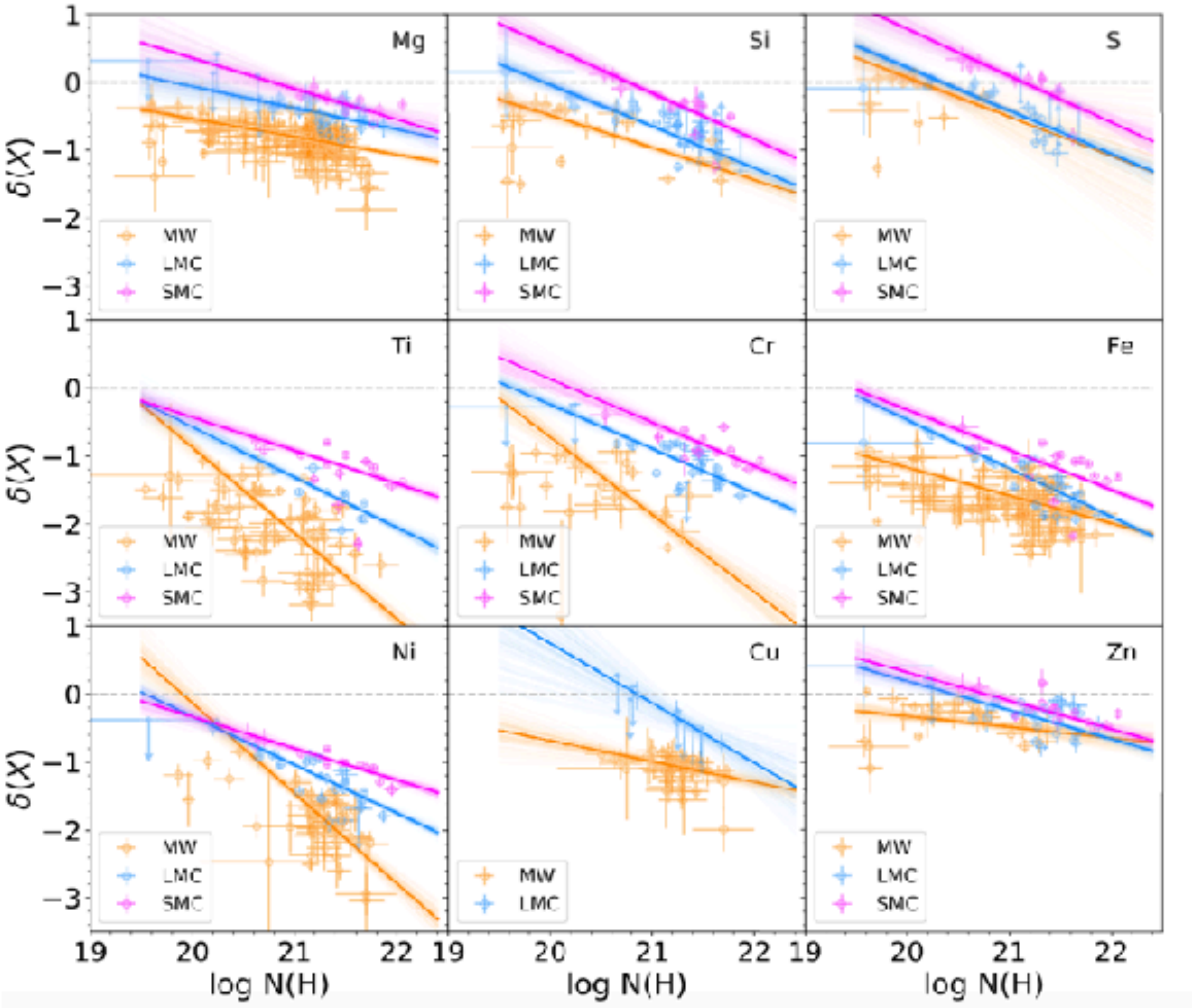
1) reference abundance (get from ratio of very weakly depleted element like Zn to heavily depleted Fe)

2) corrections for unobserved elements (especially C and O which are the largest dust contributors by mass)

3) assumption about abundance patterns vs Z

Dust-to-Gas Ratio vs Metallicity

From Depletion Measurements



Comparison of depletions in MW, LMC, SMC show similar patterns between elements.

Depletion increases with n and N(H), consistent with growth of grains in dense gas. Factor of 3-4 increase in DGR from N(H) = 10^{20} - 10^{22} cm^{-2}.

The D/M 1.2x lower in the LMC compared to the MW, and 2–3 lower in the SMC than the MW.

Comparison to multiwavelength approach shows factors of 2-5 discrepancy, might be far-IR opacities.

Roman-Duval et al. 2022a - https://ui.adsabs.harvard.edu/abs/2022ApJ...928...90R/

Dust-to-Gas Ratio vs Metallicity

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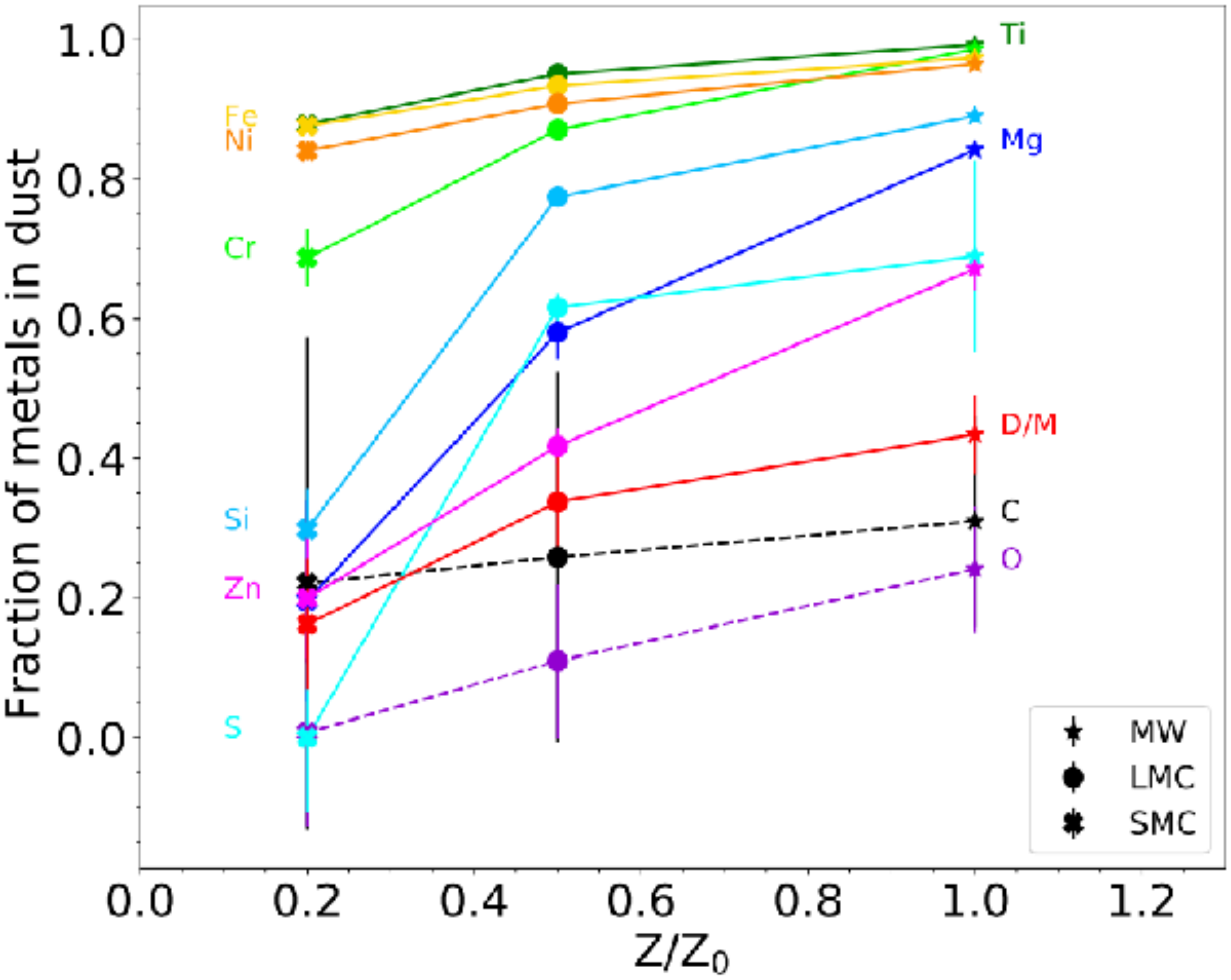

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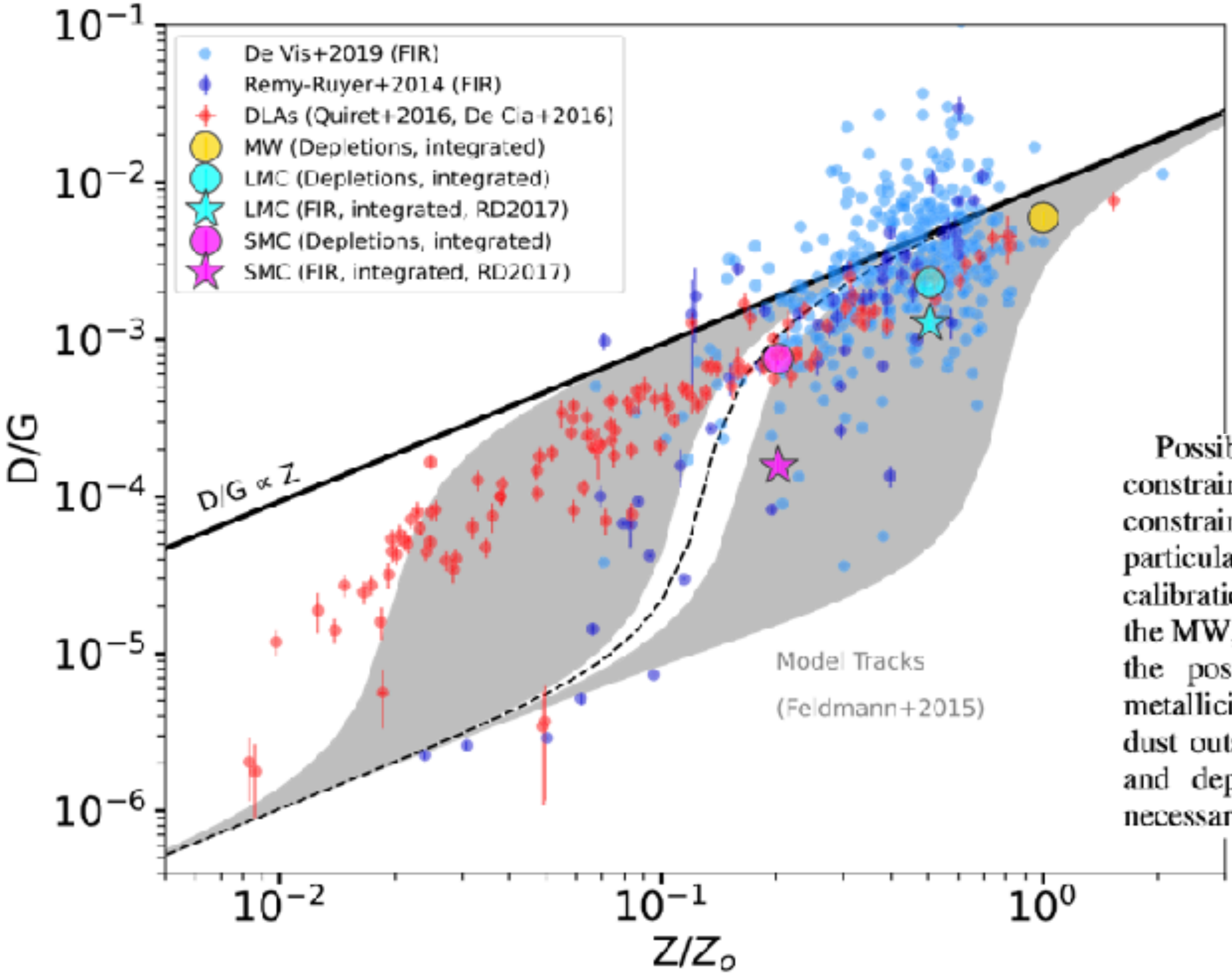
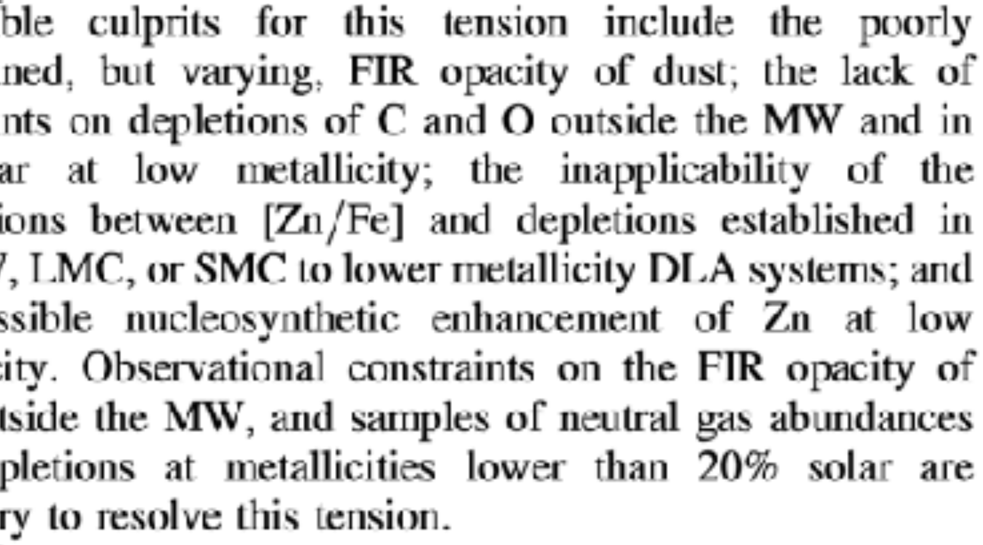
Dust-to-Gas Ratio vs Metallicity

Recall tension between multiwavelength & DLA measurements.



Apply same calibrations to MW, LMC, SMC, DLAs, tension remains.



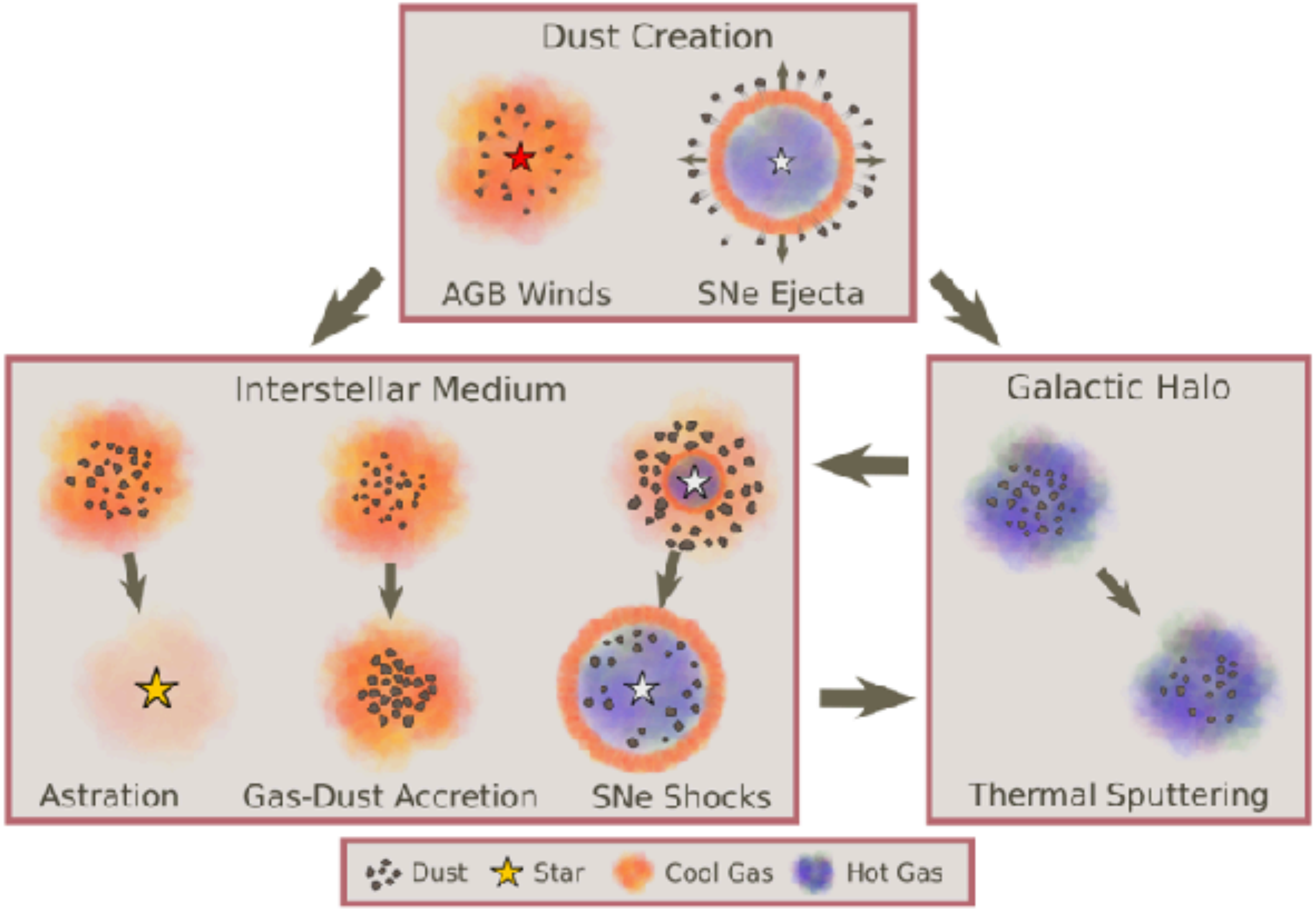
Possible culprits for this tension include the poorly constrained, but varying, FIR opacity of dust; the lack of constraints on depletions of C and O outside the MW and in particular at low metallicity; the inapplicability of the calibrations between [Zn/Fe] and depletions established in the MW, LMC, or SMC to lower metallicity DLA systems; and the possible nucleosynthetic enhancement of Zn at low metallicity. Observational constraints on the FIR opacity of dust outside the MW, and samples of neutral gas abundances and depletions at metallicities lower than 20% solar are necessary to resolve this tension.

Roman-Duval et al. 2022b - https://ui.adsabs.harvard.edu/abs/2022ApJ...935..105R/

Dust-to-Gas Ratio vs Metallicity

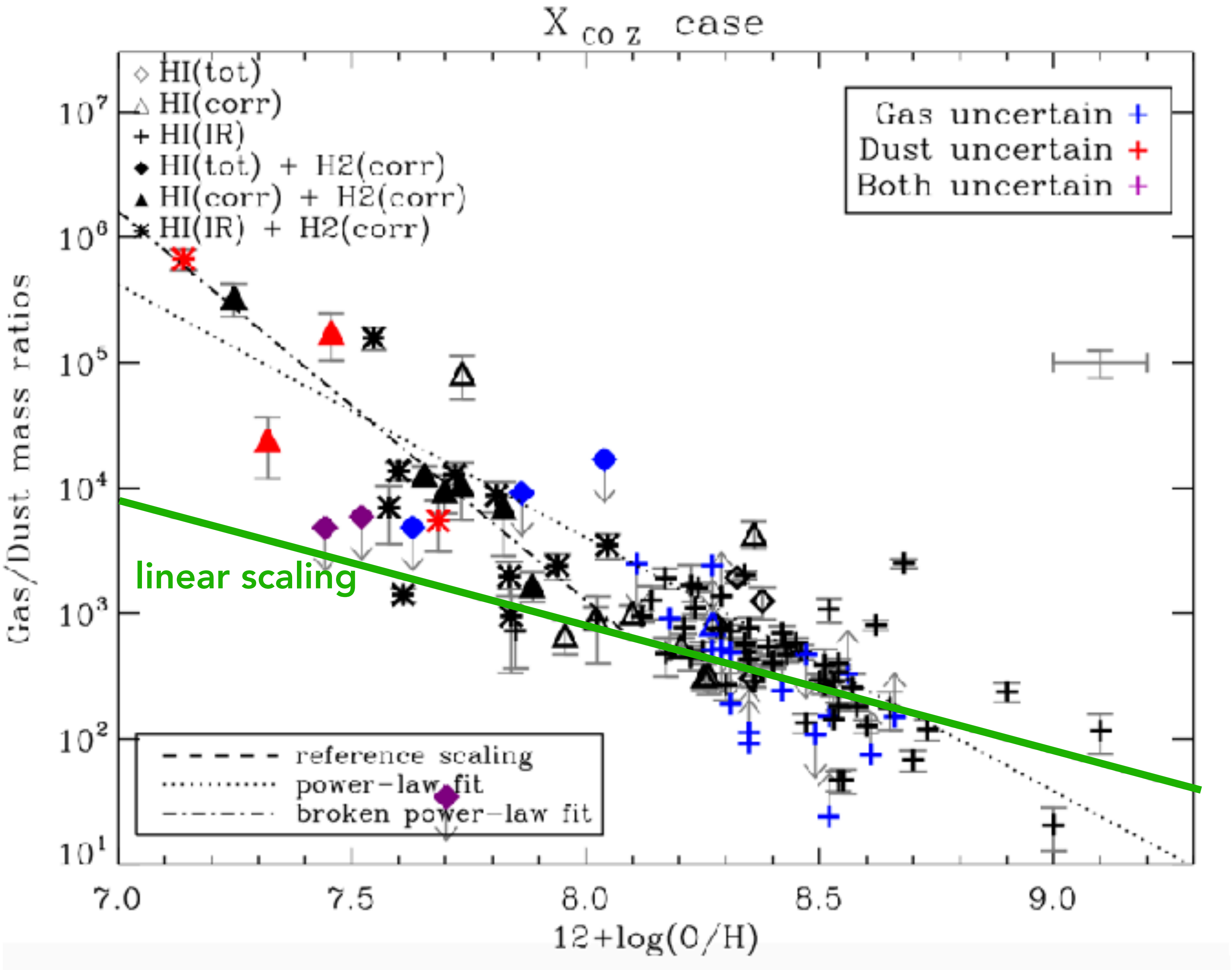
What causes changes in dust-to-metals?

- Formation by evolved stars.
- Formation by core collapse supernovae.
- Destruction by supernova shocks.
- Growth in the ISM by accretion.
- Outflows to CGM
- Shattering, sputtering, coagulation, etc.



Choban et al. 2022 - https://ui.adsabs.harvard.edu/abs/2022MNRAS.514.4506C/

Dust-to-Gas Ratio vs Metallicity



Asano et al. 2013 model

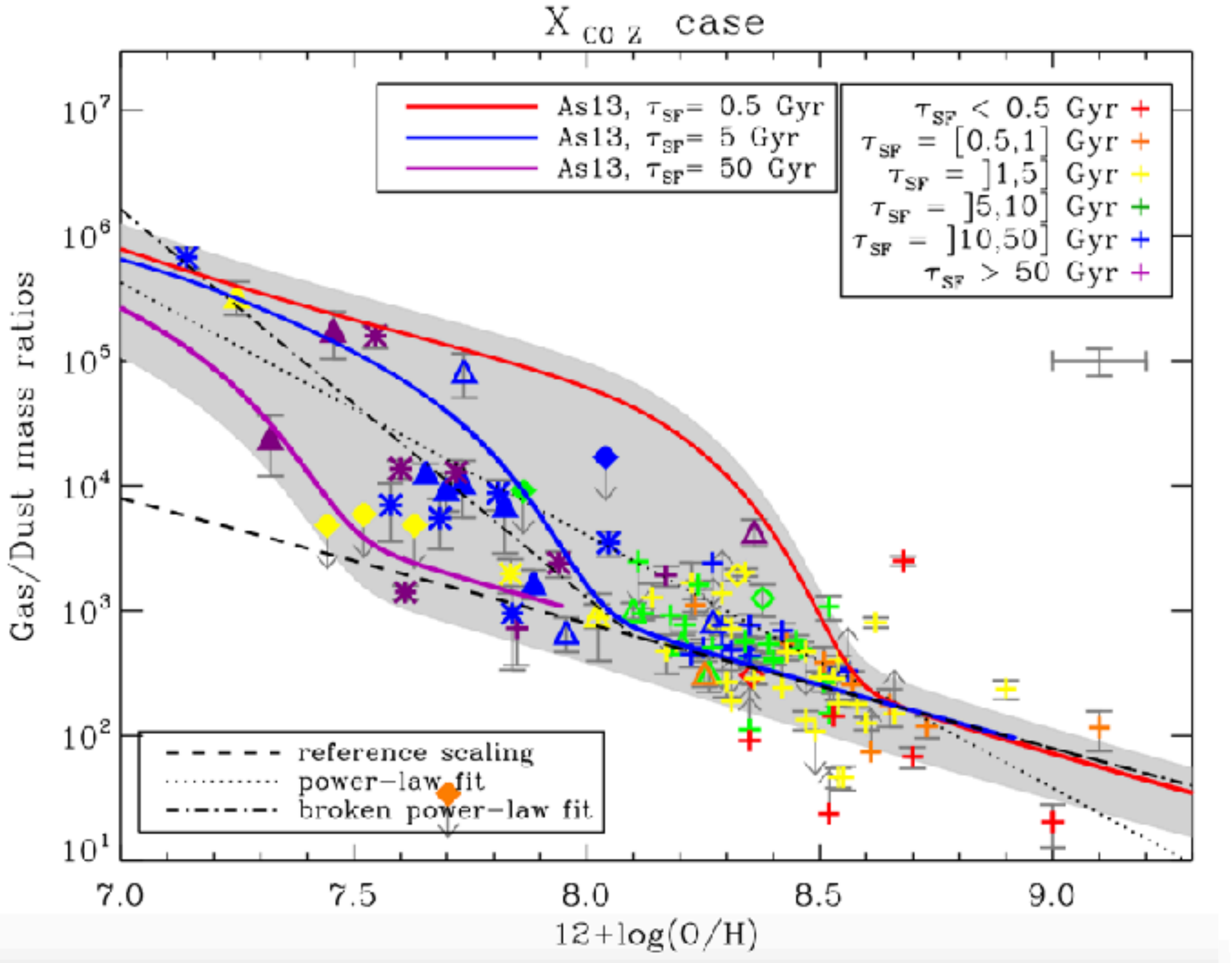
"critical metallicity" at which the rate of dust mass growth exceeds the dust production rate by stars.

Related to relative accretion timescale and star formation timescale.

Critical metallicity traces switch from stardust to ISM grown dust.

Asano et al. 2013 - https://ui.adsabs.harvard.edu/abs/2013EP%26S...65..213A/

Dust-to-Gas Ratio vs Metallicity



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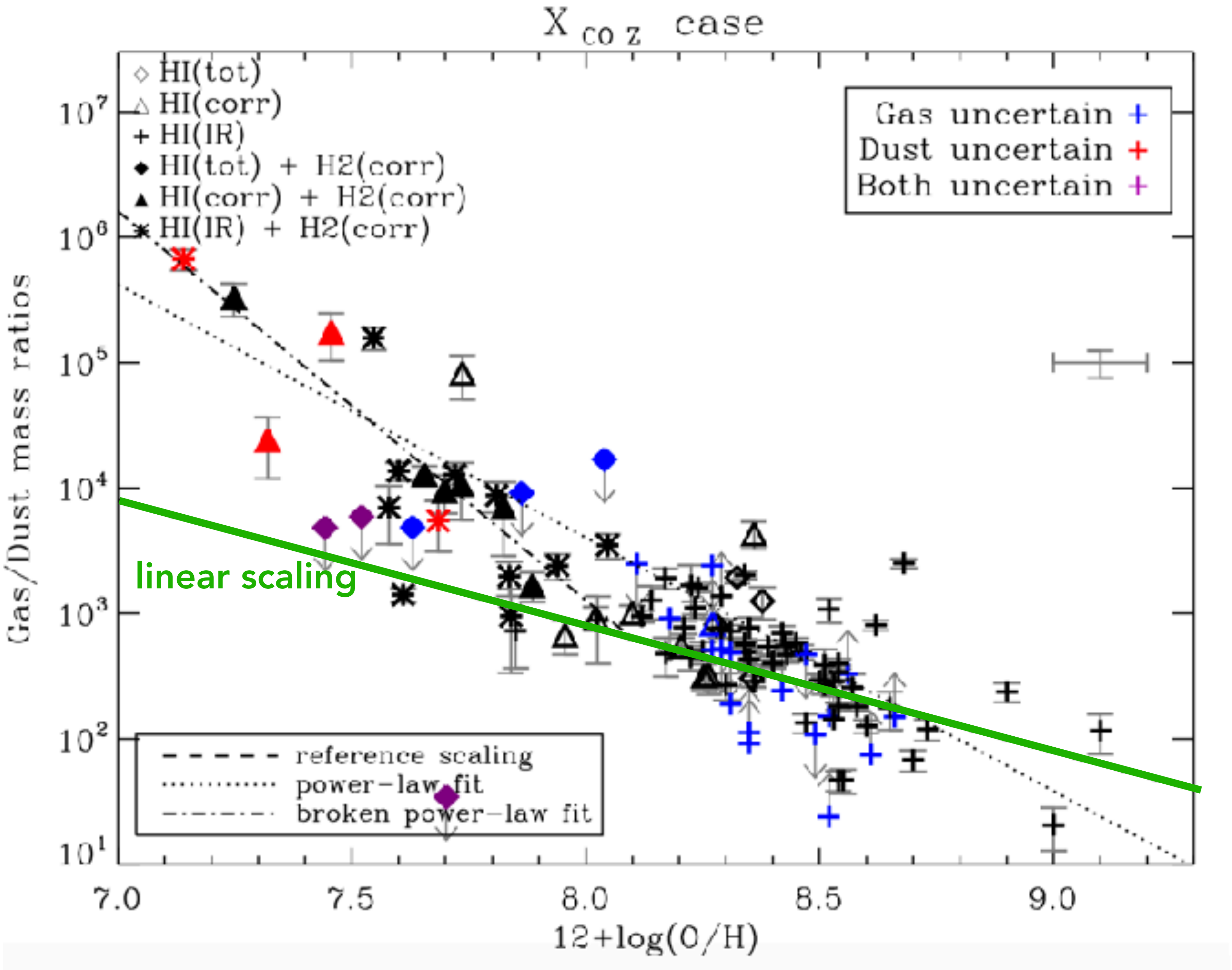


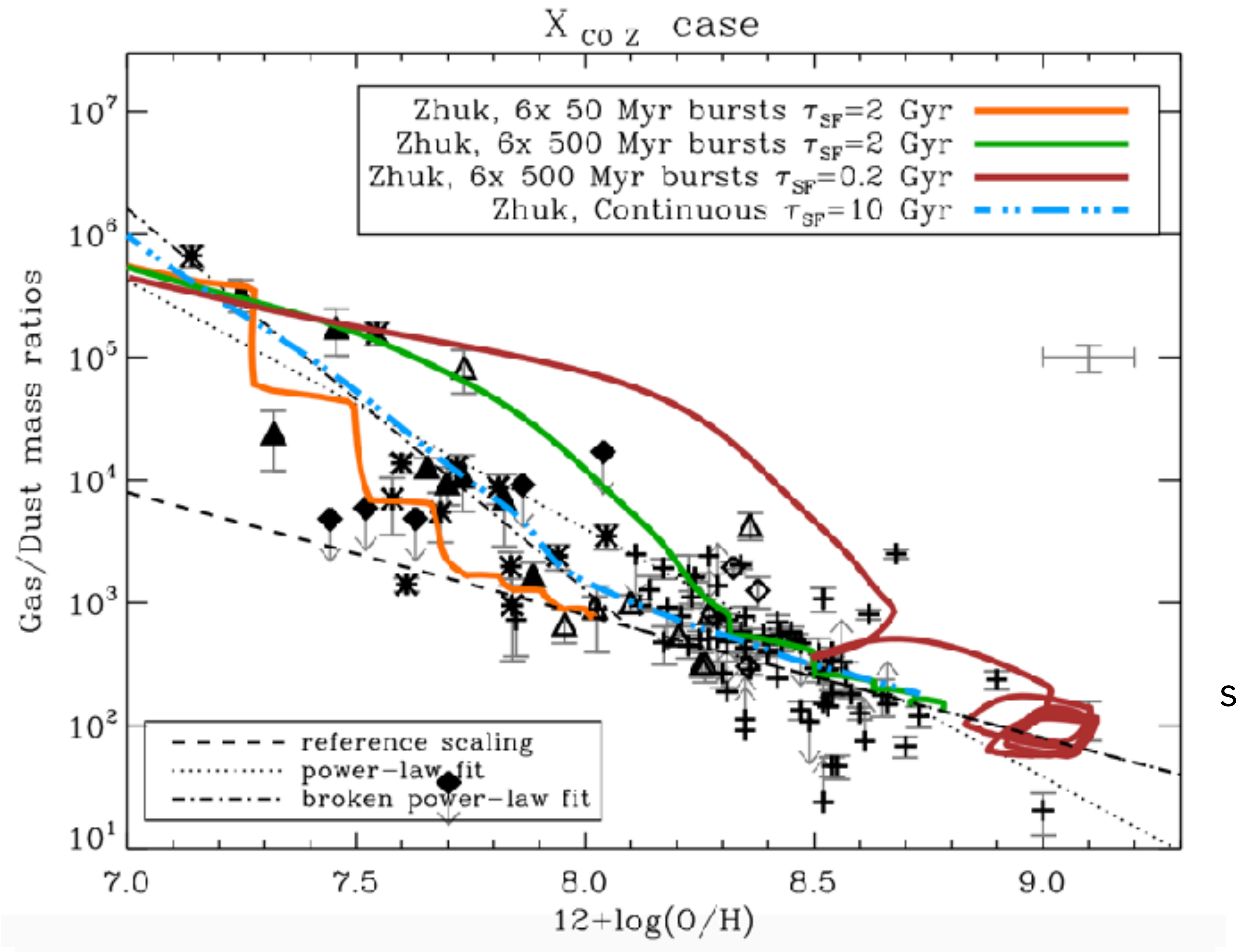
Zhukovska et al. 2014 simulations

Find similar behavior of switch from stardust to ISM growth dominating.

Bursts of SF can introduce grain destruction & subsequent regrowth cycling.

Zhukovska et al. 2014 - https://ui.adsabs.harvard.edu/abs/2014A%26A...562A..76Z/

Dust-to-Gas Ratio vs Metallicity



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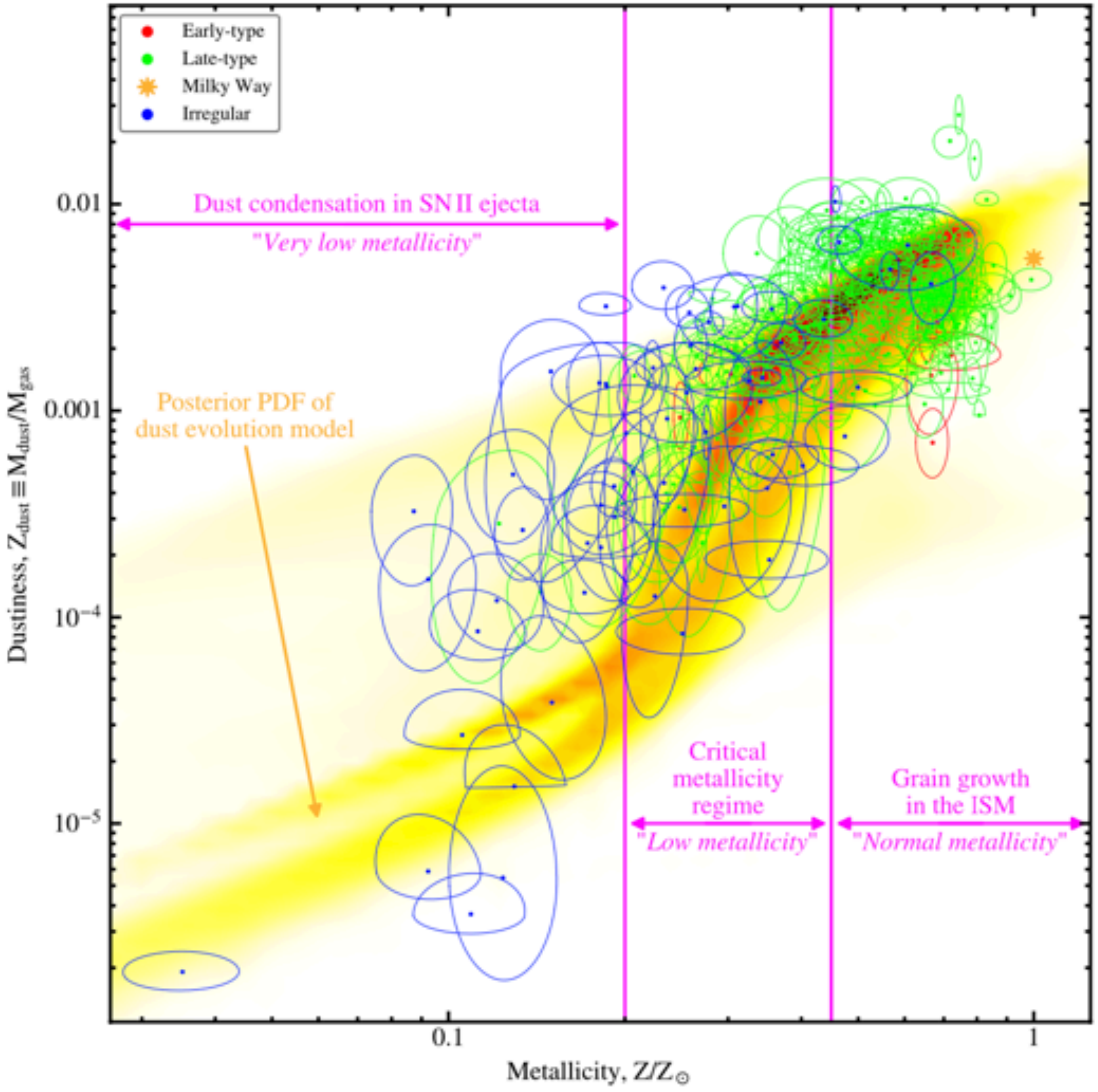
Dust-to-Gas Ratio vs Metallicity

Galliano et al. 2021 - hierarchical Bayesian model of dust evolution built on SED modeling for galaxies



Other models:

- Feldmann 2015 - critical metallicity set by the competition between dust growth and dilution via dust-poor gas inflows
- Priestley et al. 2022 - increasing dust destruction efficiency at low metallicity, grain growth unnecessary.

Galliano 2022 - https://ui.adsabs.harvard.edu/abs/2022HabT.........1G/abstract

Dust-to-Gas & Dust-to-Metals Summary

- At relatively high metallicity, galaxy average DGR scales linearly with metallicity (i.e. D/M ~ constant).

- But! DGR varies at fixed metallicity within galaxies.

- Drop in D/M at low metallicity - general explanation between models and simulations is that at some point ISM grain growth becomes inefficient.

- Much work yet to do to understand grain growth!

Dust Grain Size Distribution

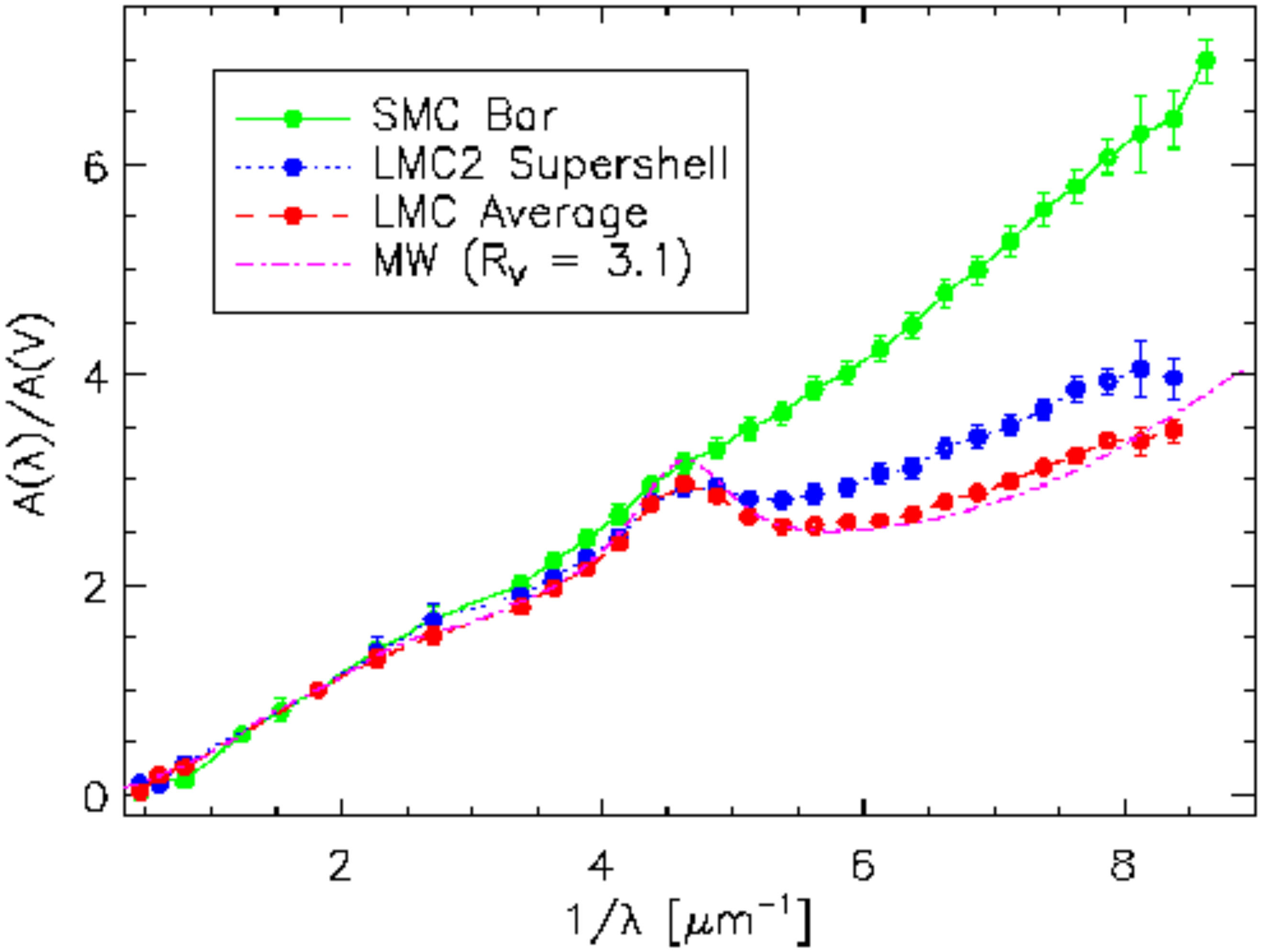
Inferred from UV extinction curve.

Extinction curves can be observed towards UV bright point sources (QSOs, GRBs, individual stars).

Low metallicity extinction curves are generally steeper. **Indicates smaller average grain size.**

But, low metallicity curves also lack the 2175 Å bump.

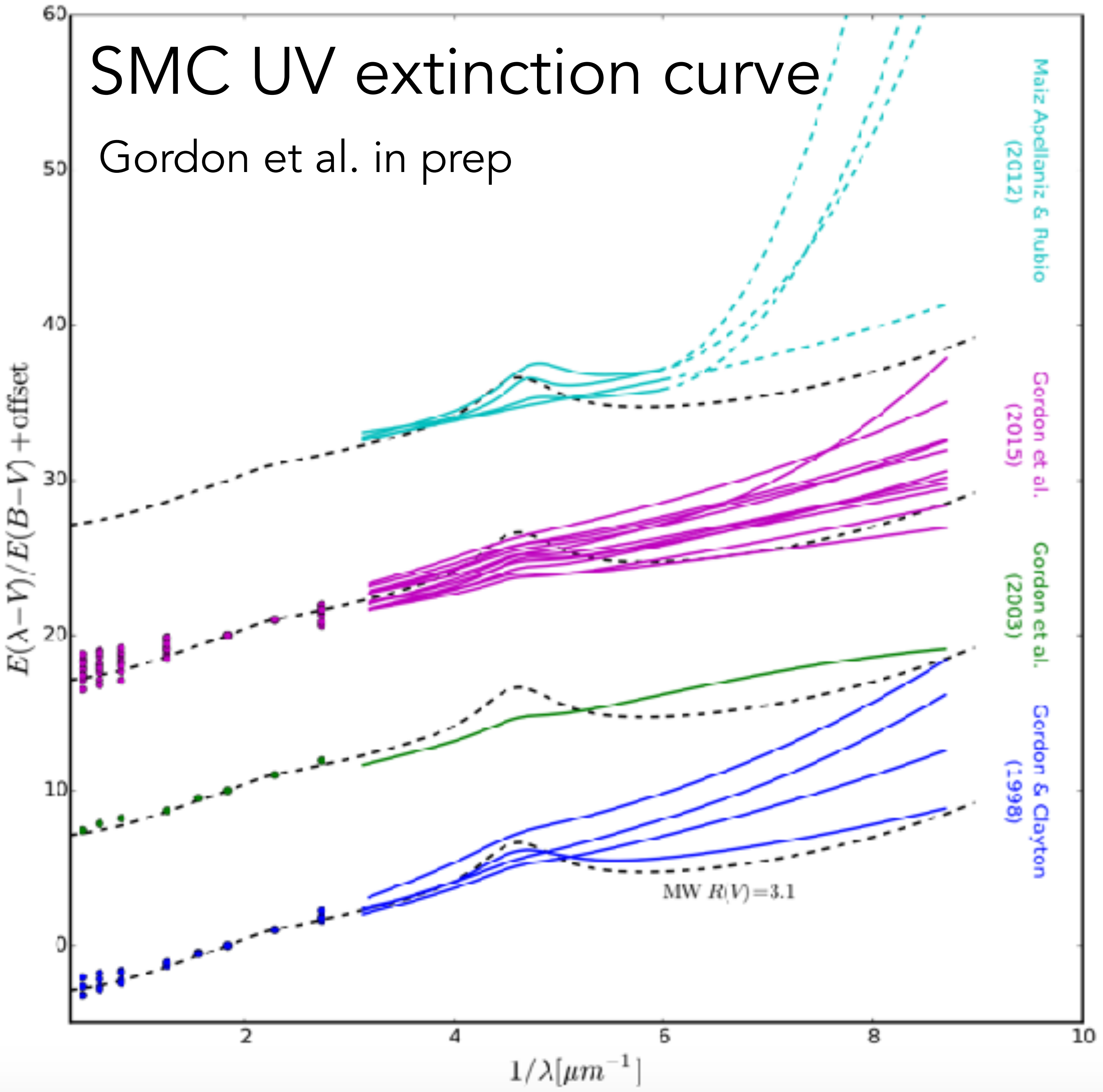
Constraints from IR SED modeling of low metallicity galaxies also suggest enhanced abundance of small grains (e.g. Galliano 2003, 2005).



Gordon et al. 2003 - https://ui.adsabs.harvard.edu/abs/2003ApJ...594..279G/

Dust Composition

2175 Å Bump



SMC UV extinction curve

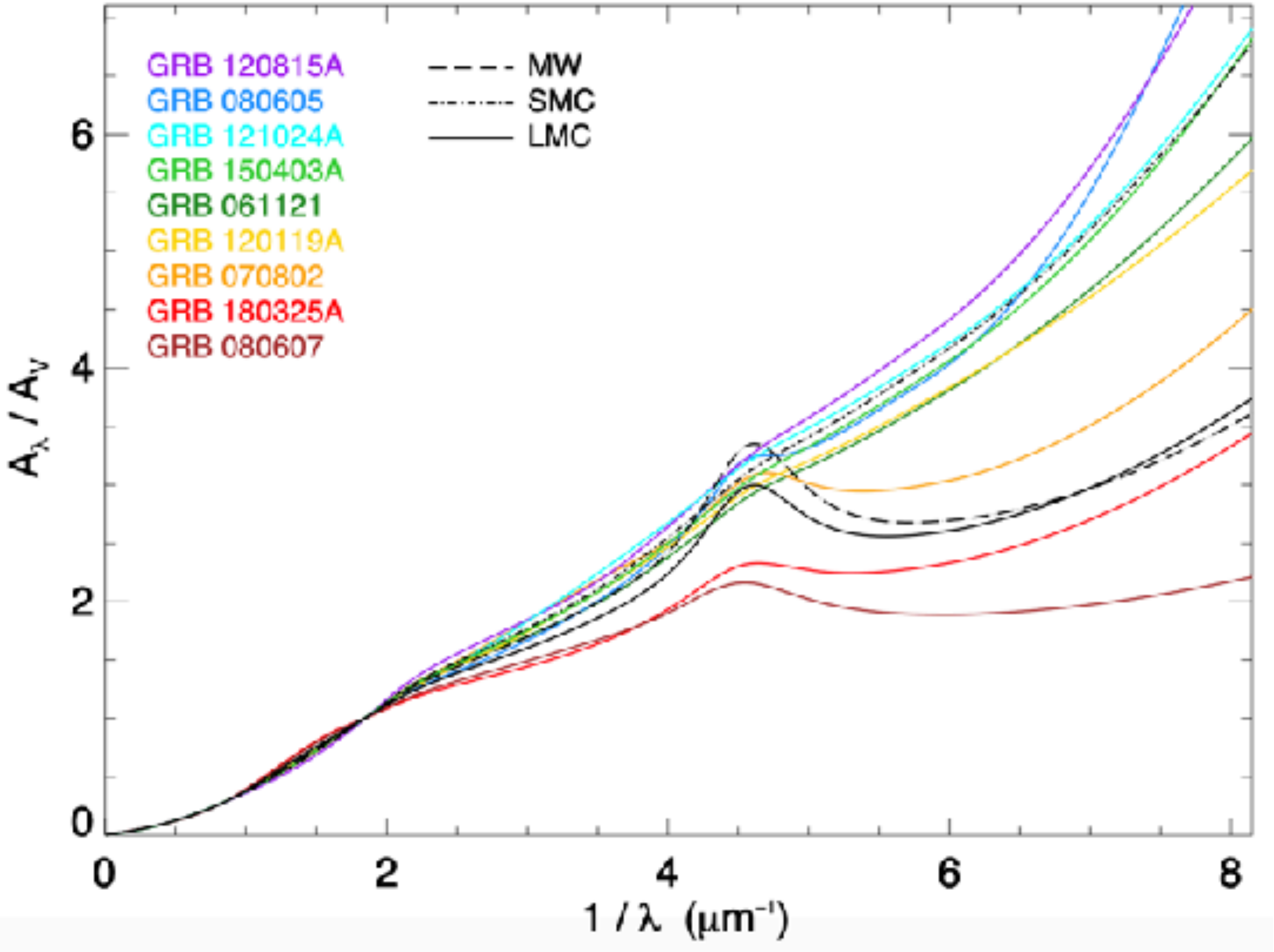
Gordon et al. in prep

SMC UV extinction frequently lacks the 2175 Å bump and shows a steeper slope into the far-UV.

Possible exception:
SMC B1 #1 molecular cloud
(Maiz-Appellaniz et al. 2012)
here 2 stars show the bump.

Dust Composition

2175 Å Bump



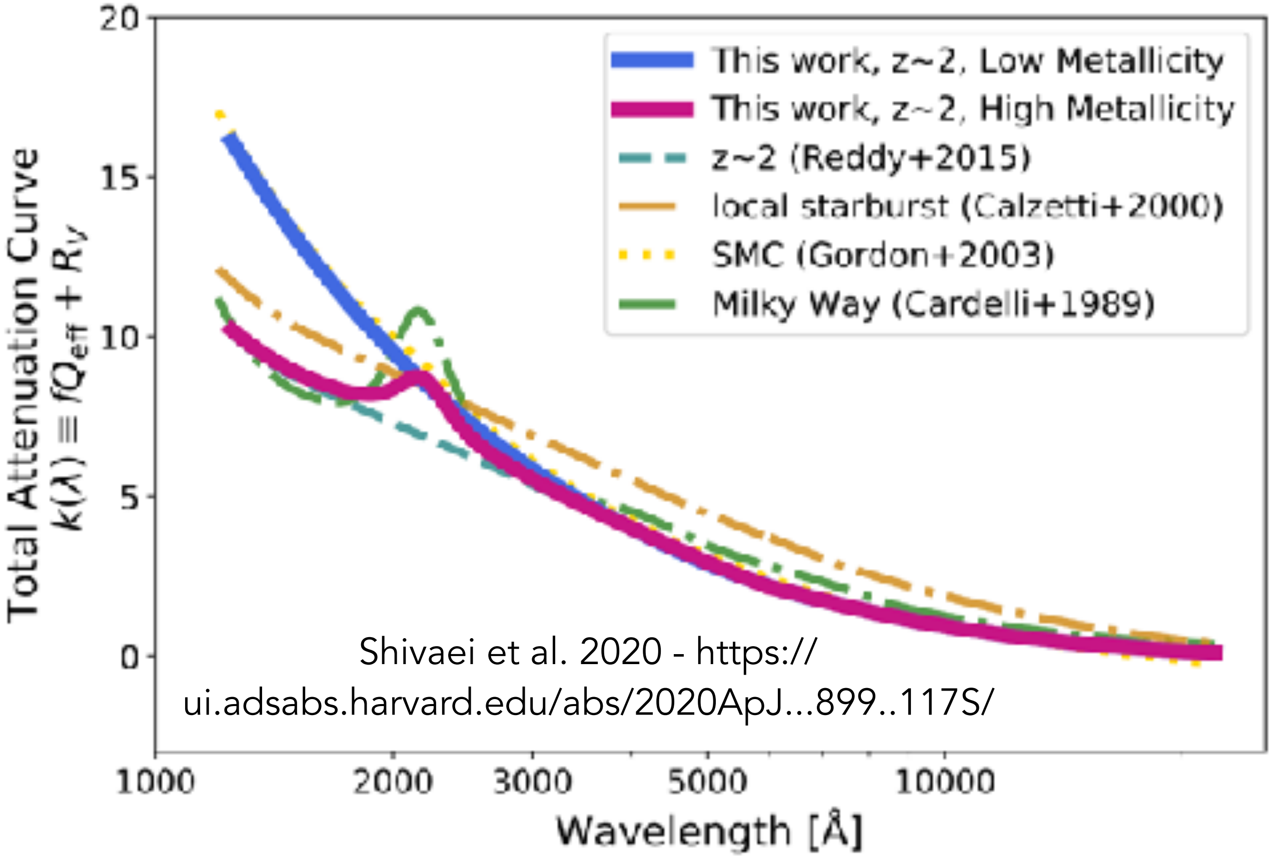
GRB extinction curves show a range of properties, but many lack the bump.

Presence of bump correlated with CI (neutral carbon) detection.

Heintz et al. 2019 - https://ui.adsabs.harvard.edu/abs/2019MNRAS.486.2063H/

Dust Composition

2175 Å Bump



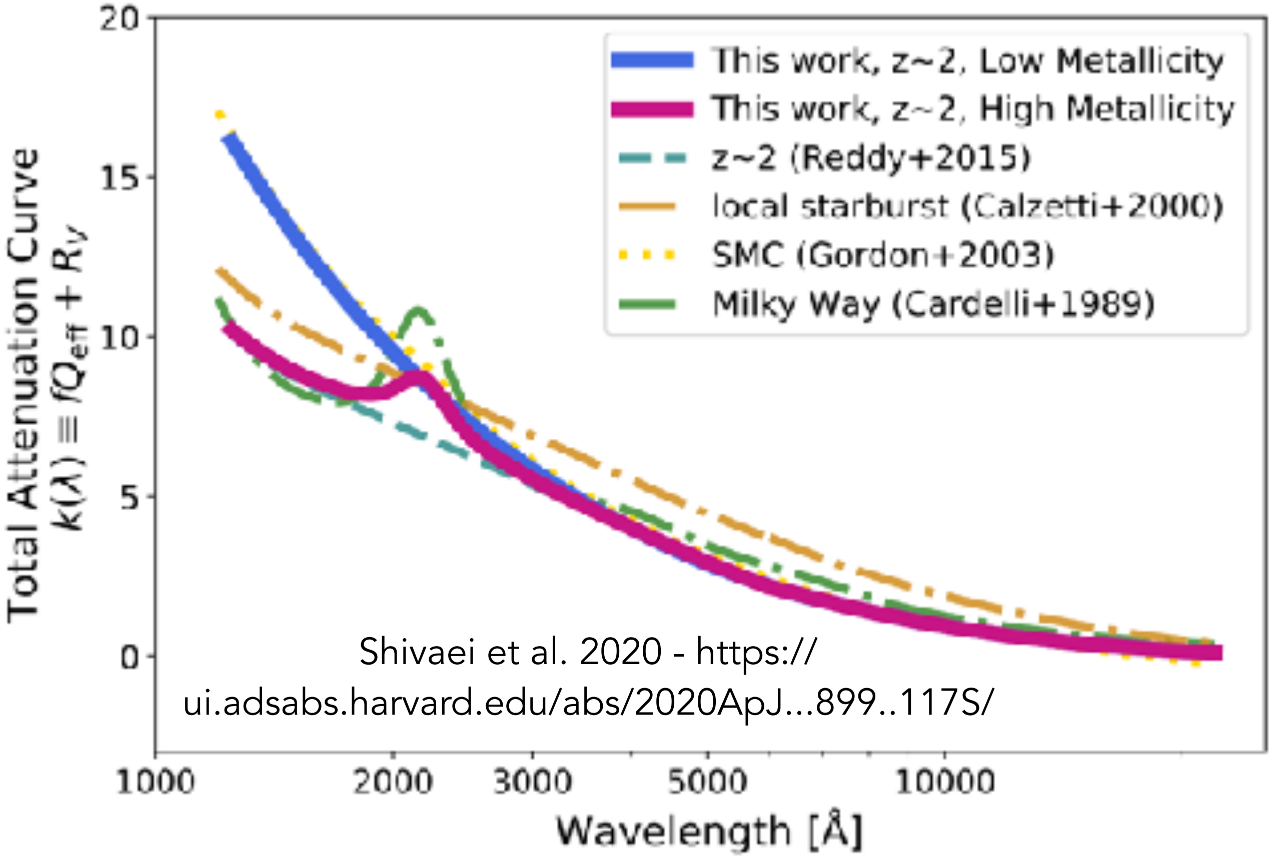
Shivaei et al. 2020 - https://ui.adsabs.harvard.edu/abs/2020ApJ...899..117S/

With SED modeling of resolved regions or entire galaxies, can infer “attenuation” curve, includes extinction, but also geometry, radiative transfer effects.

Low metallicity attenuation curves also suggest steeper FUV rise, lack of 2175 bump.

Dust Composition

2175 Å Bump



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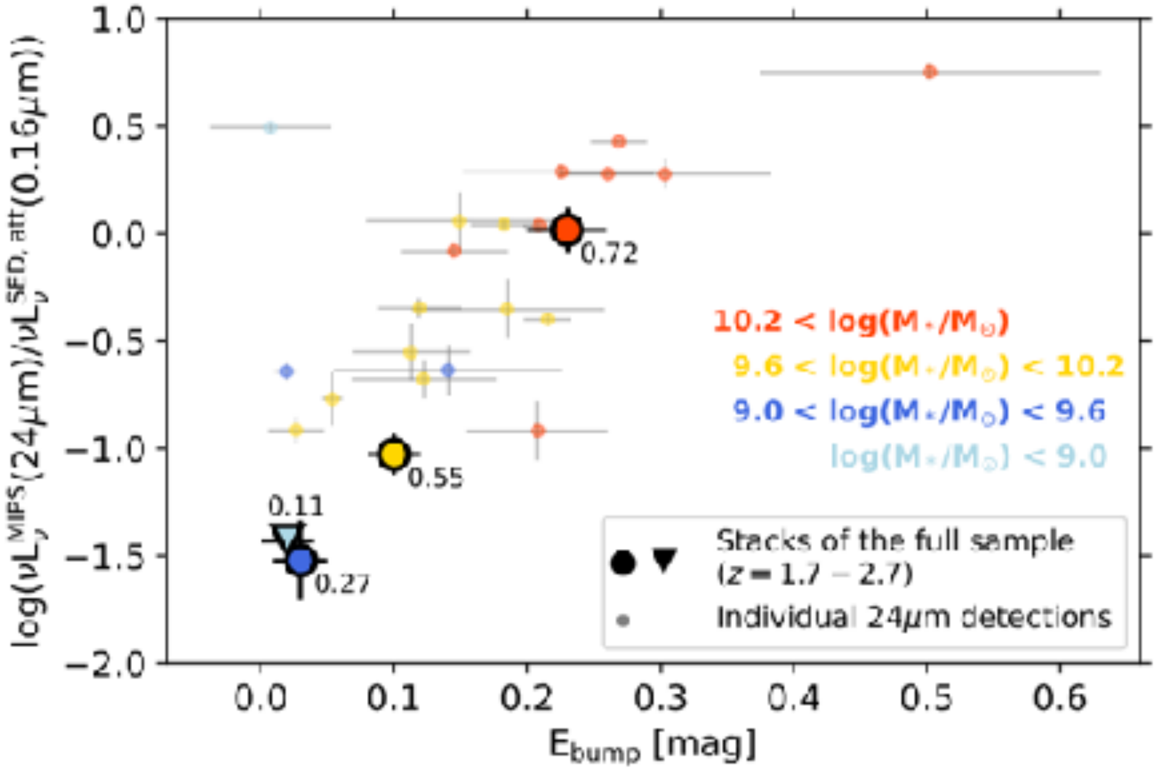
With SED modeling of resolved regions or entire galaxies, can infer "attenuation" curve, includes extinction, but also geometry, radiative transfer effects.

Low metallicity attenuation curves also suggest steeper FUV rise, lack of 2175 bump.

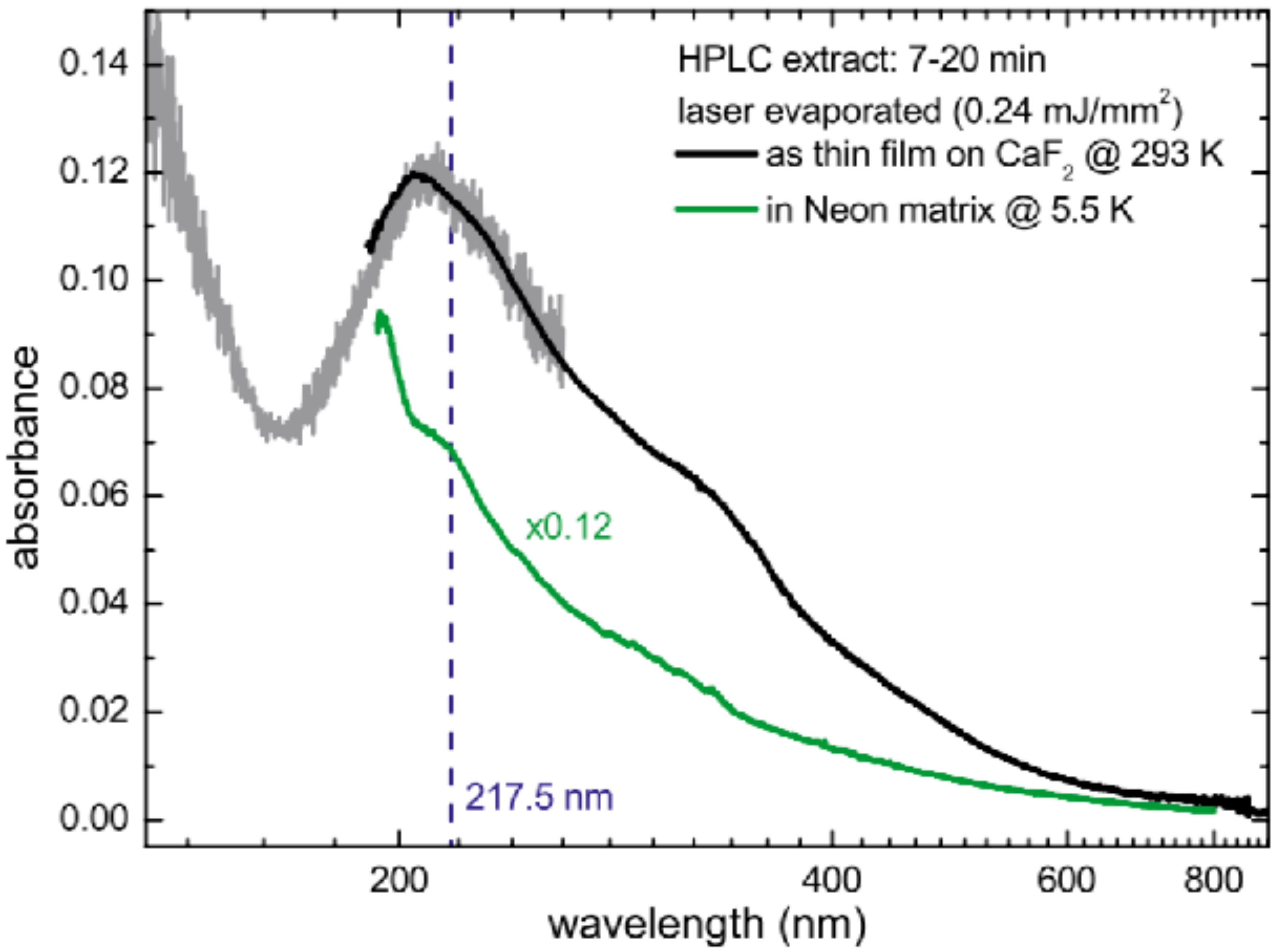
Bump strength in attenuation curves is correlated with redshifted 8 μm PAH emission.

Shivaei et al. 2022 - https://ui.adsabs.harvard.edu/abs/2022MNRAS.514.1886S/



Dust Composition

What is the 2175 Å Bump?



Some kind of carbonaceous dust, probably PAHs.

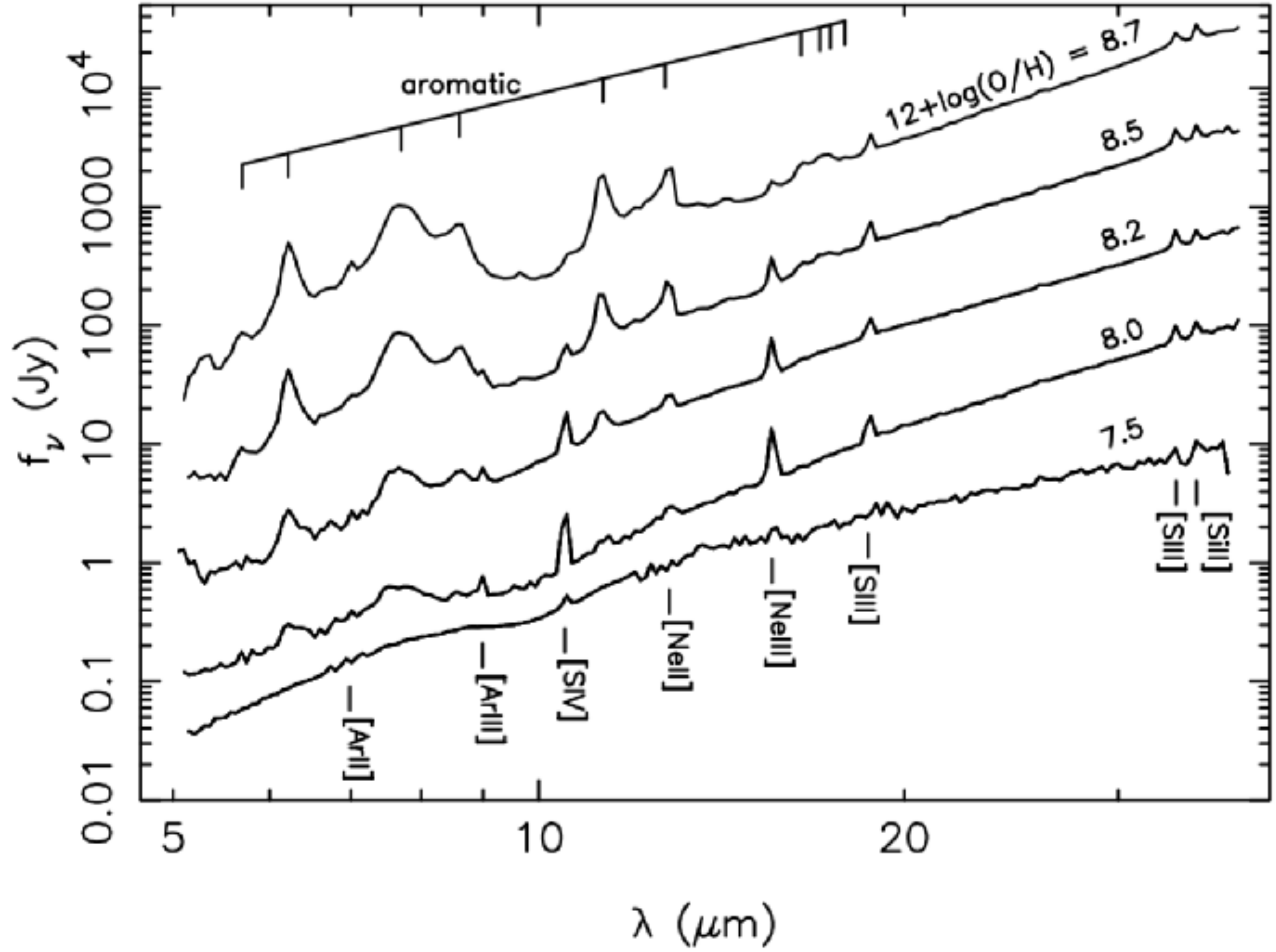
Mixtures of PAHs in the lab can reproduce similar shapes, from a transition in C-C bonds.

Lack of bump at low metallicity matches lack of PAHs…

Steglich et al. 2010 - https://ui.adsabs.harvard.edu/abs/2010ApJ...712L..16S/

PAH Fraction

Engelbracht et al. 2008 - https://ui.adsabs.harvard.edu/abs/2008ApJ...678..804E/



Observations with ISO and Spitzer have shown a deficit of PAH emission from low-metallicity galaxies.

Lots of evidence for this PAH deficiency:
Madden et al. 2000
Hunter et al. 2001
Galliano et al. 2003, 2005
Engelbracht et al. 2005
Madden et al. 2006
O'Halloran et al. 2006
Wu et al. 2006
Jackson et al 2006
Draine et al. 2007
Hunt et al 2011
etc., etc.

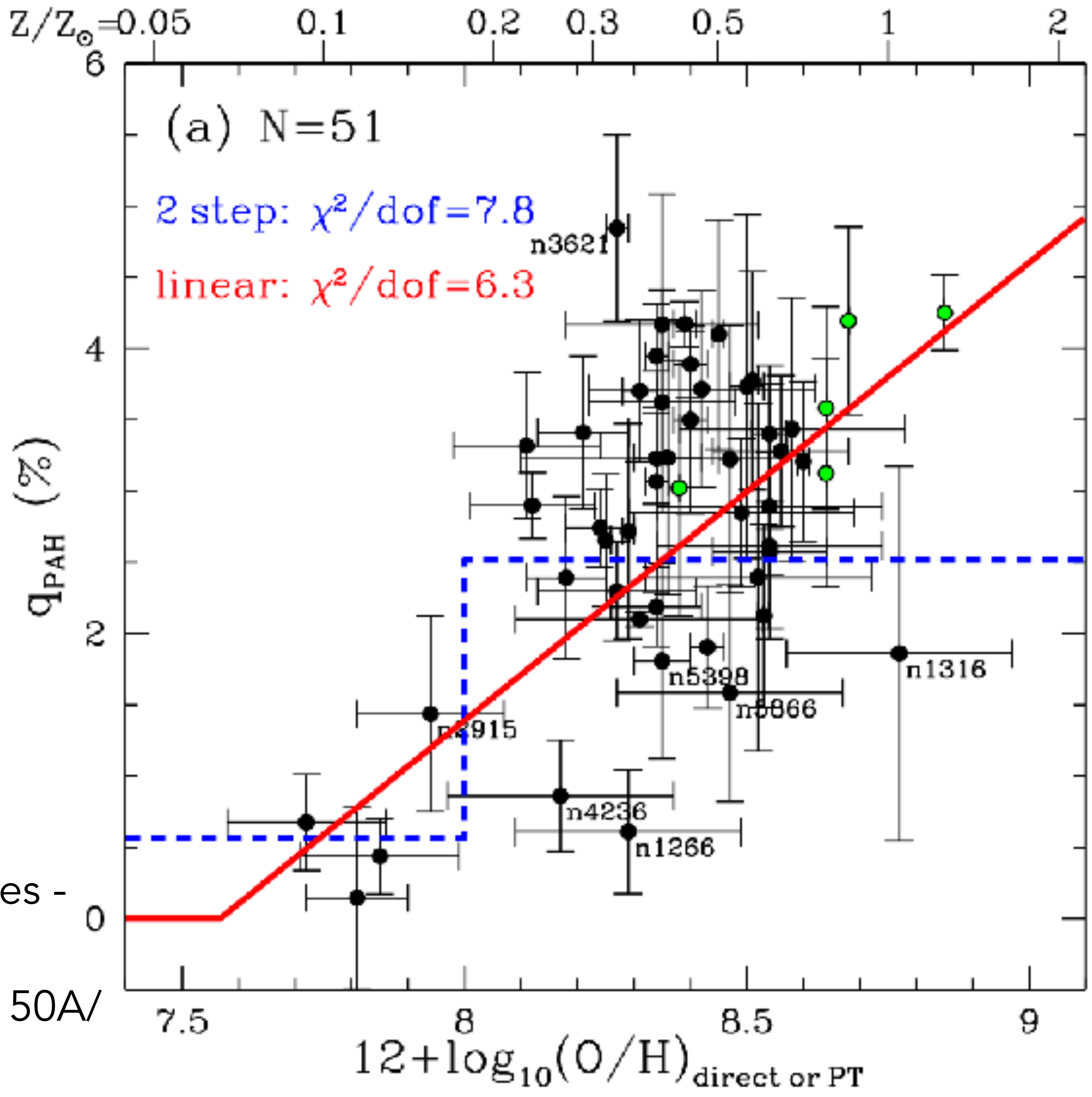
PAH Fraction

From IR SED modeling, can find that this is a deficit in PAHs not a lack of illumination.

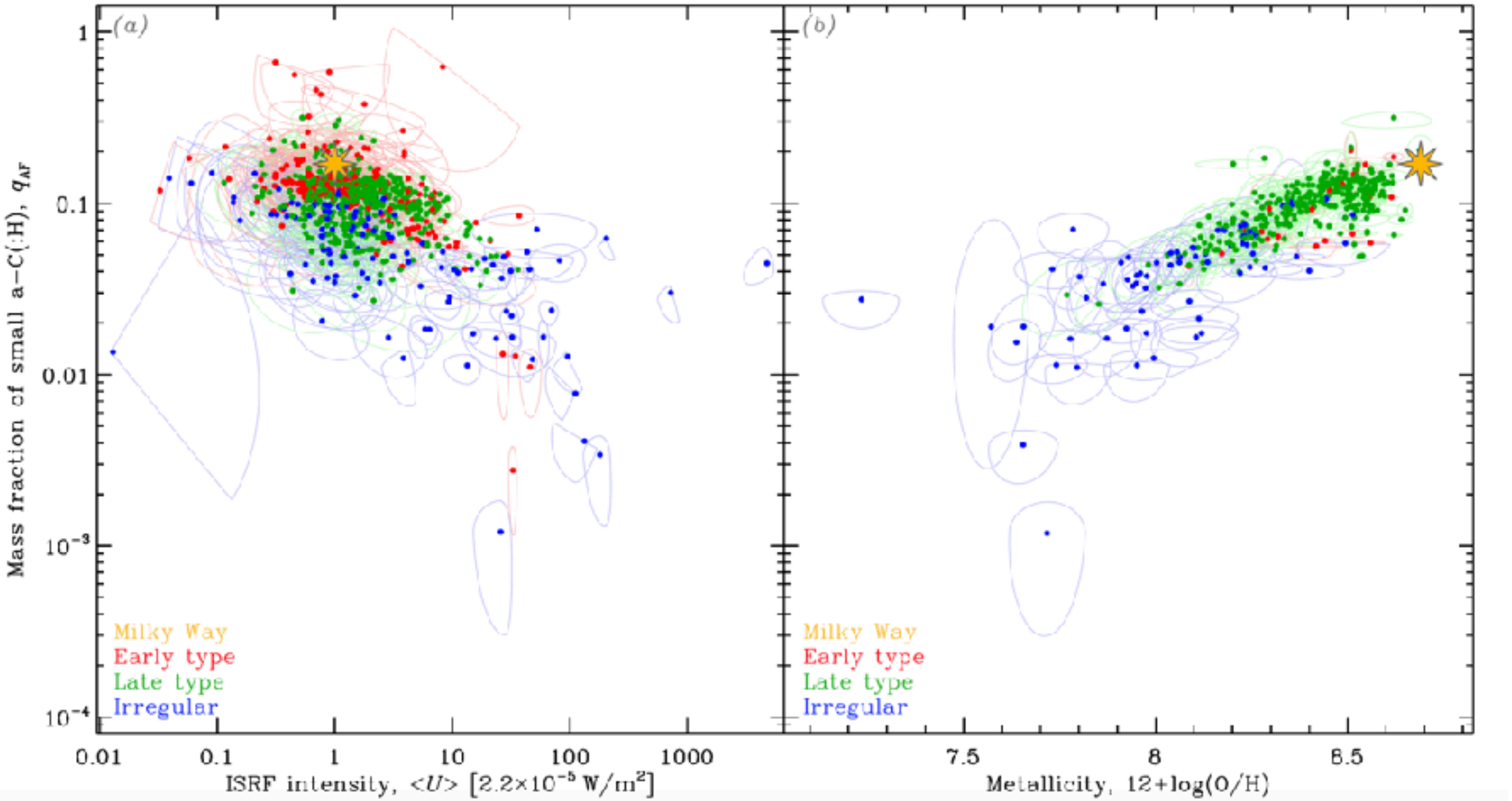
In Draine & Li (2007) model, PAH fraction quantified as:

q_{PAH} = fraction of dust mass in PAHs with $<10^3$ C atoms

Average PAH fraction for 51 nearby galaxies - Aniano et al (2020) - https://ui.adsabs.harvard.edu/abs/2020ApJ...889..150A/



PAH Fraction



Small carbonaceous grain fraction drops with metallicity in other SED modeling approaches as well.

Galliano et al. 2021 - https://ui.adsabs.harvard.edu/abs/2021A%26A...649A..18G/

PAH Fraction

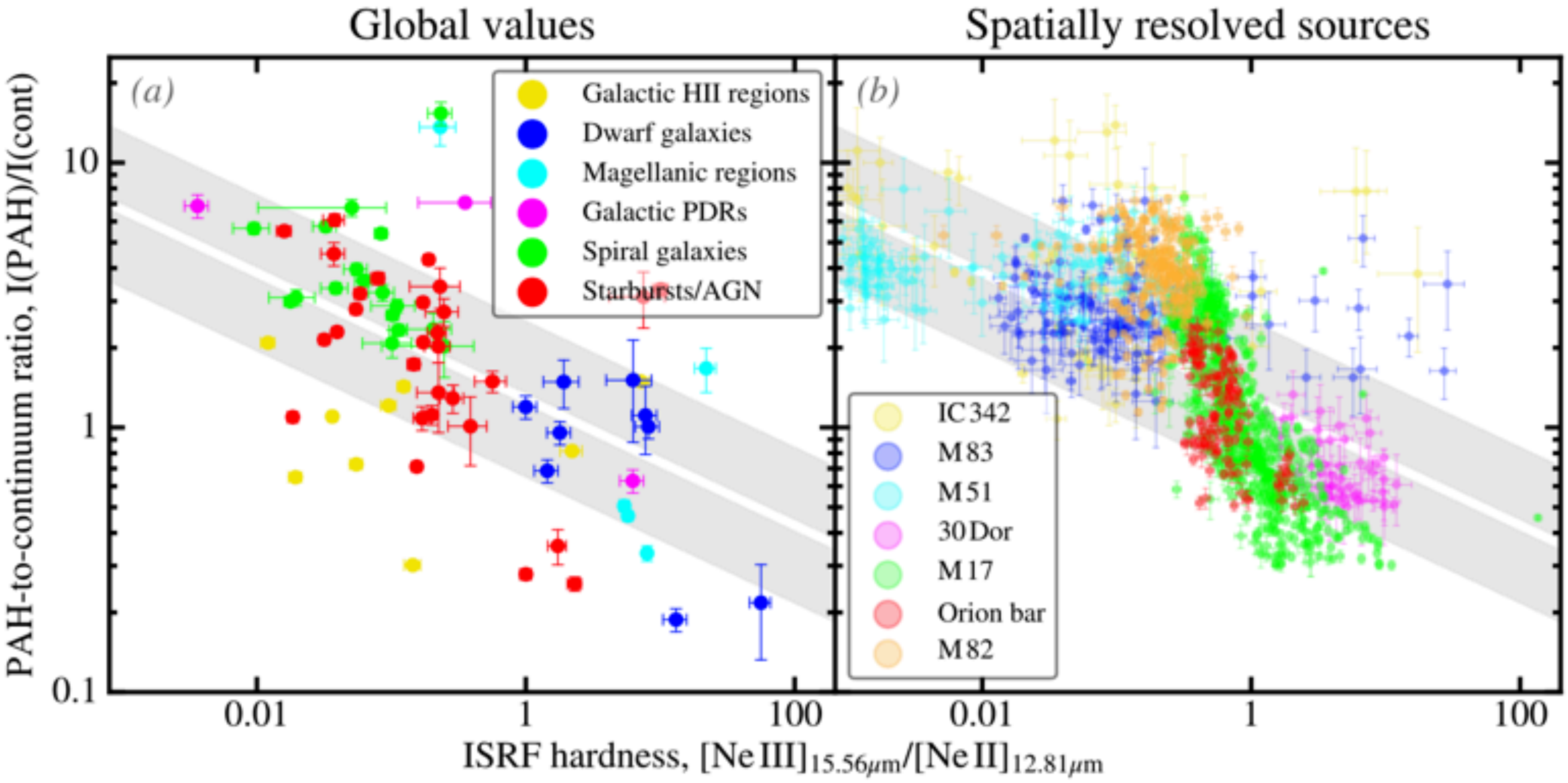
What could drive the PAH deficit at low metallicity?

- Enhanced destruction of PAHs from harder, pervasive radiation fields?
- Impeded formation of PAHs due to decrease in “raw material” - either growth in ISM, or shattering of existing grains?

PAH Fraction

Reasons for the PAH deficit - destruction?

Drop in PAH fraction correlates with radiation field hardness in ionized gas.

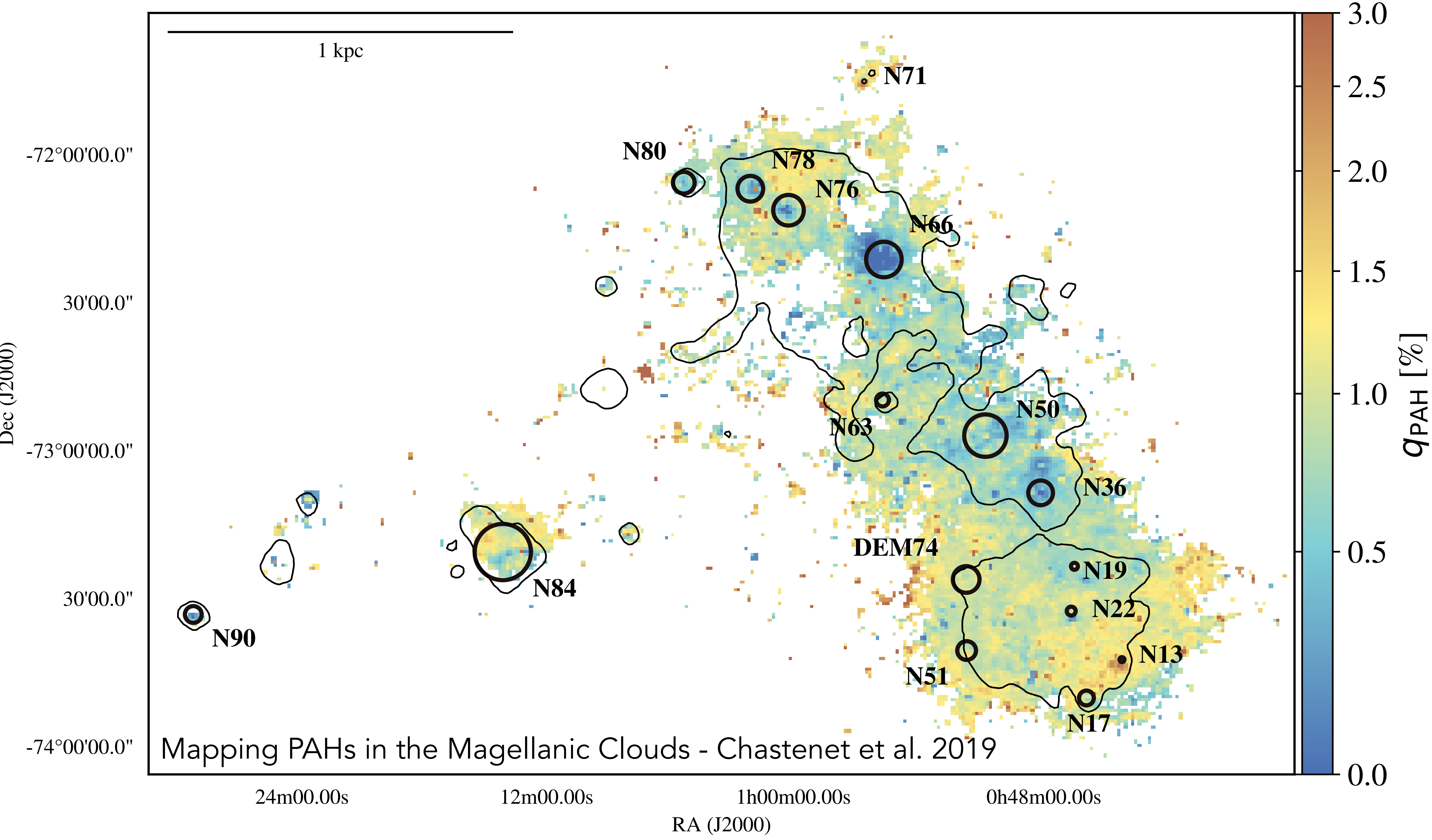


Madden et al. 2006, Galliano et al. 2021

PAH Fraction in the Magellanic Clouds

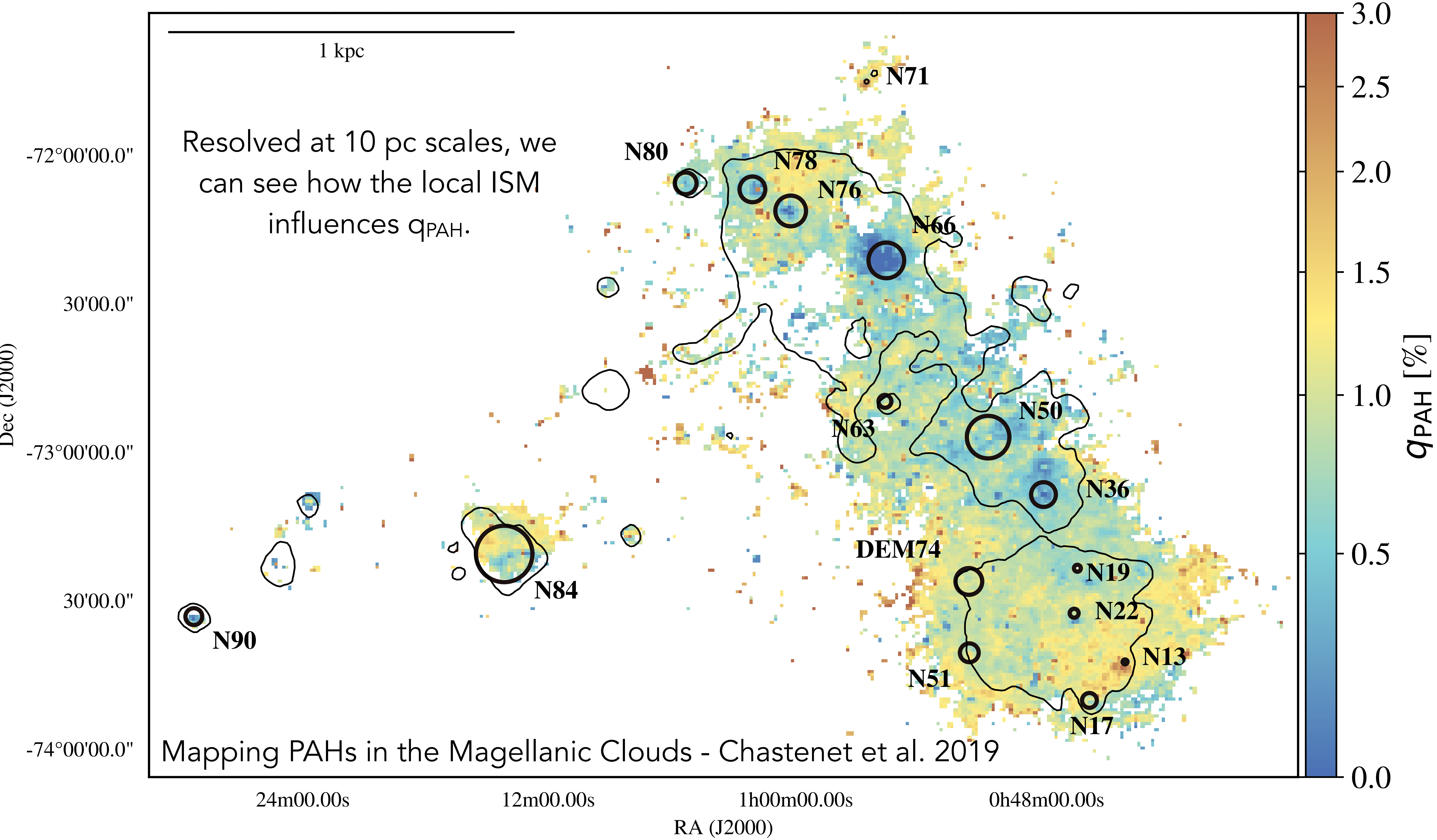
Mapping PAHs in the Magellanic Clouds - Chastenet et al. 2019

PAH Fraction in the Magellanic Clouds



Mapping PAHs in the Magellanic Clouds - Chastenet et al. 2019

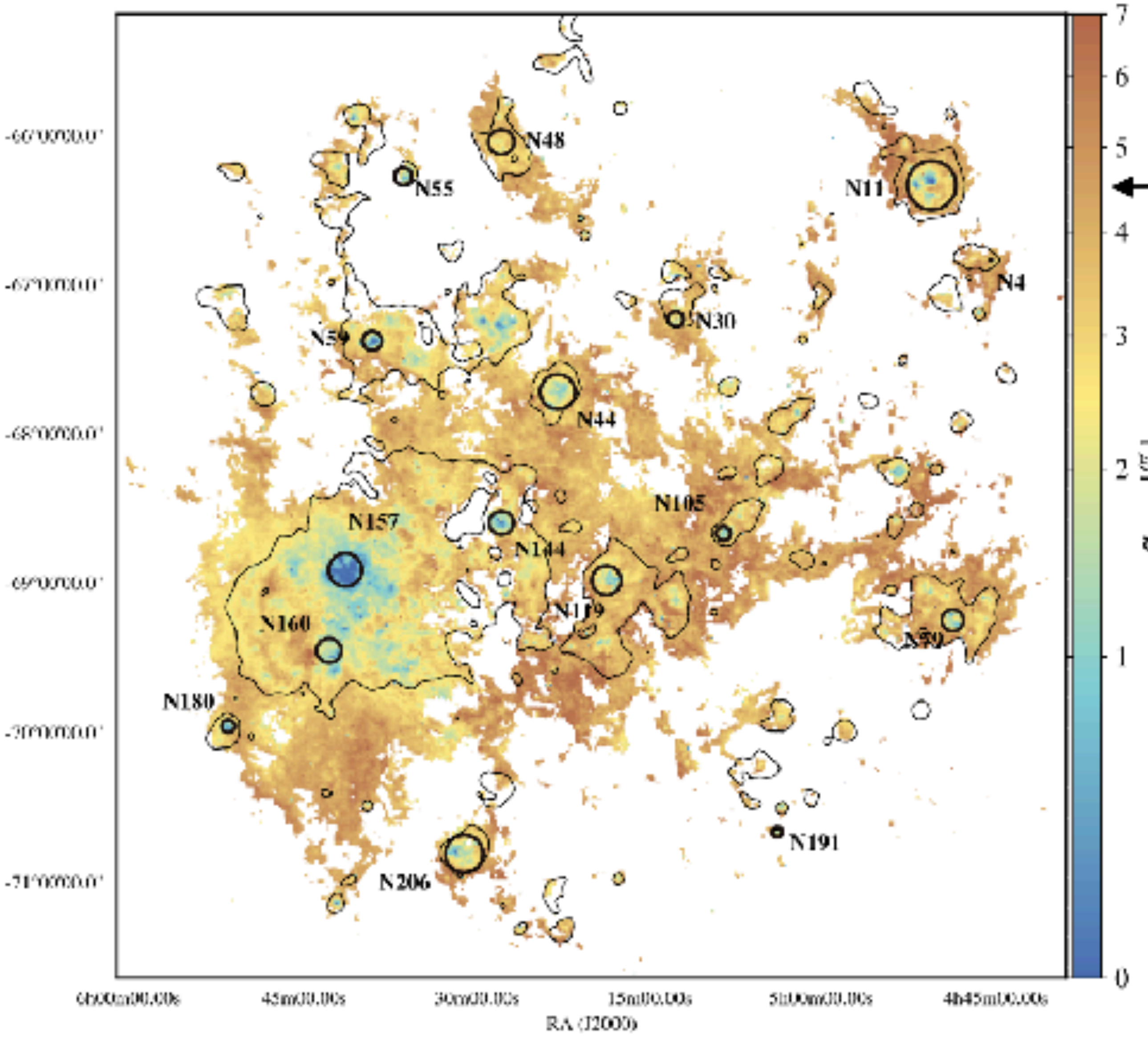
PAH Fraction in the Magellanic Clouds



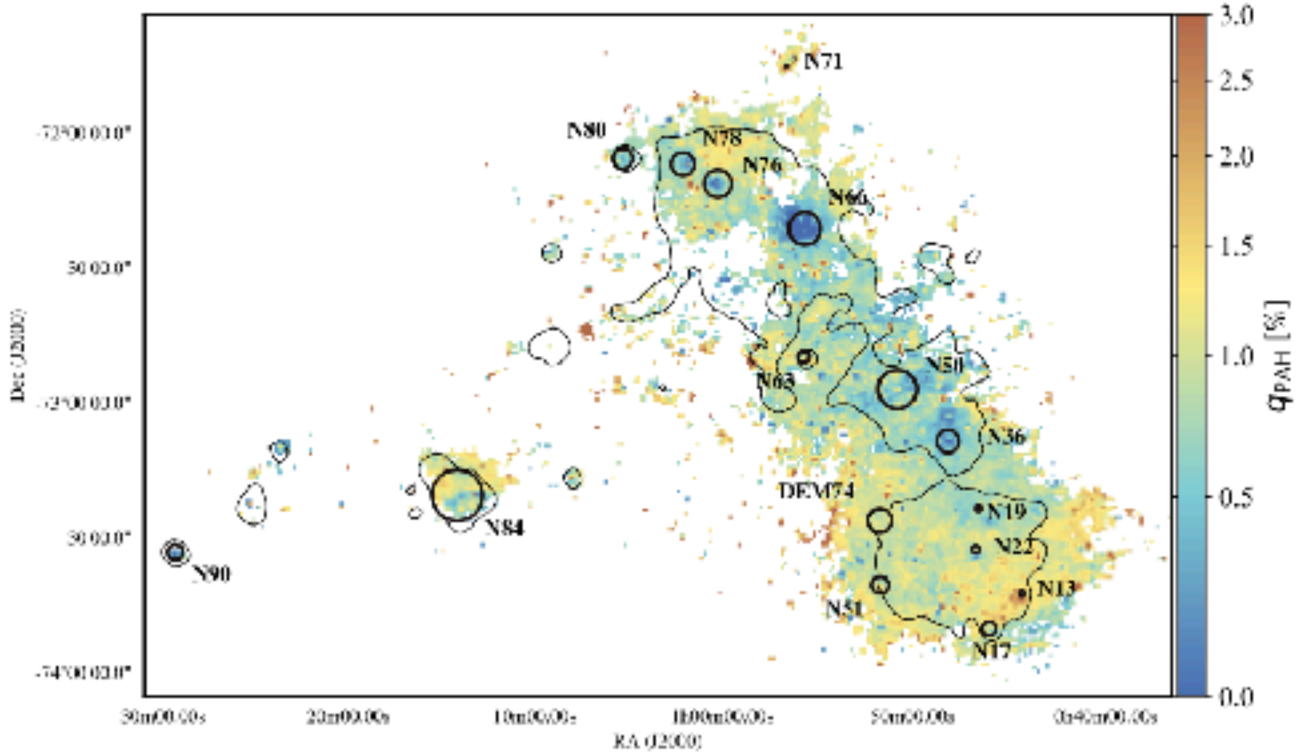
Resolved at 10 pc scales, we can see how the local ISM influences q_{PAH}.

Mapping PAHs in the Magellanic Clouds - Chastenet et al. 2019

PAH Fraction in the Magellanic Clouds



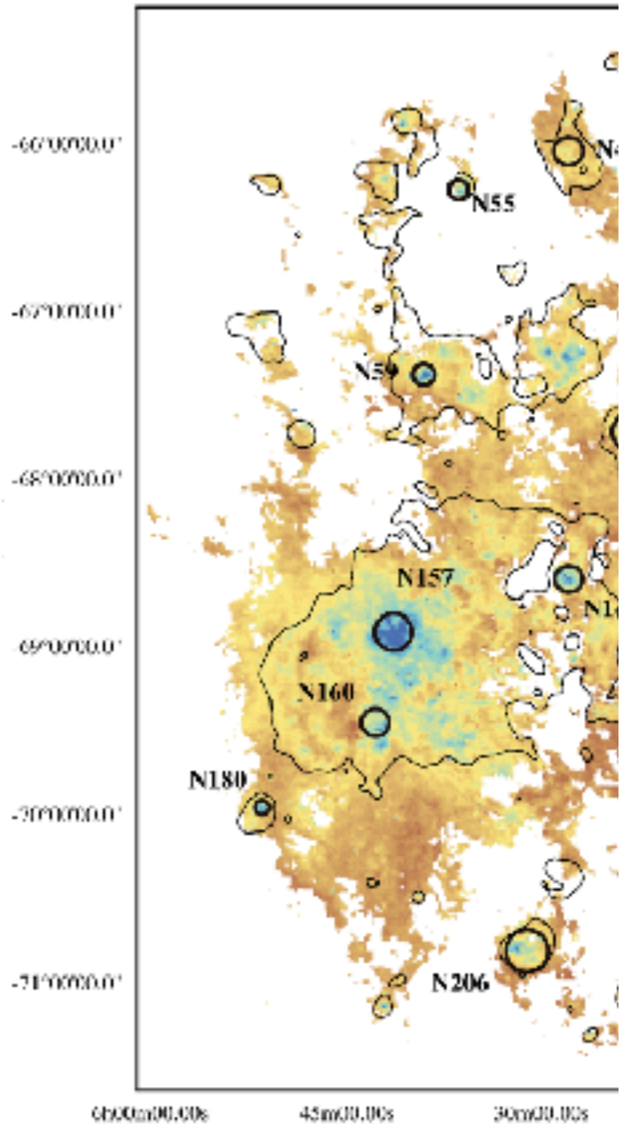
$q_{\rm PAH}^{\rm MW} \sim 4.6~\%$ (diffuse ISM; Li & Draine 2001; Weingartner & Draine 2001)

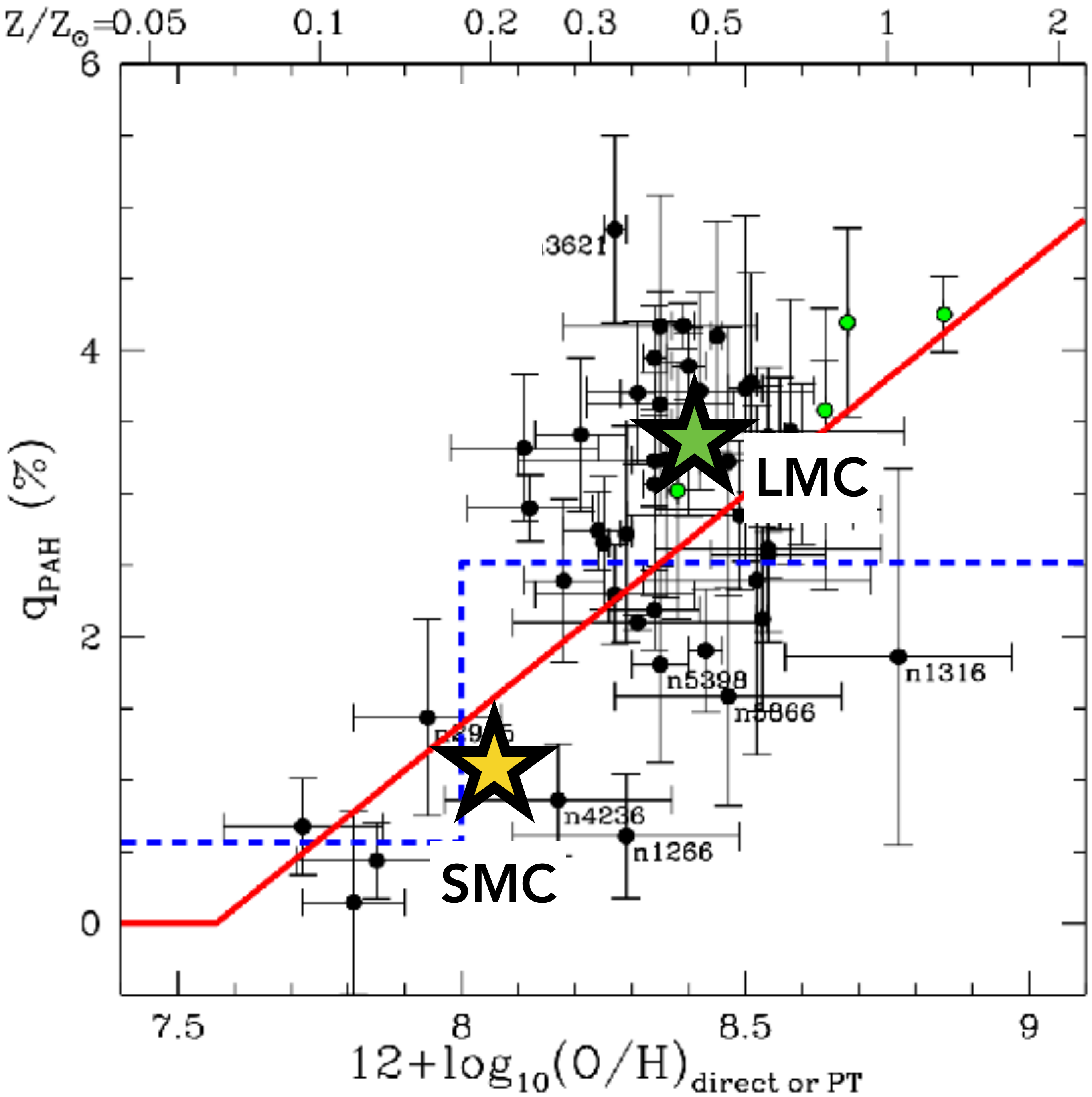


$$\langle q_{\rm PAH}^{\rm LMC} \rangle = 3.3^{+1.4}_{-1.3}~\%$$

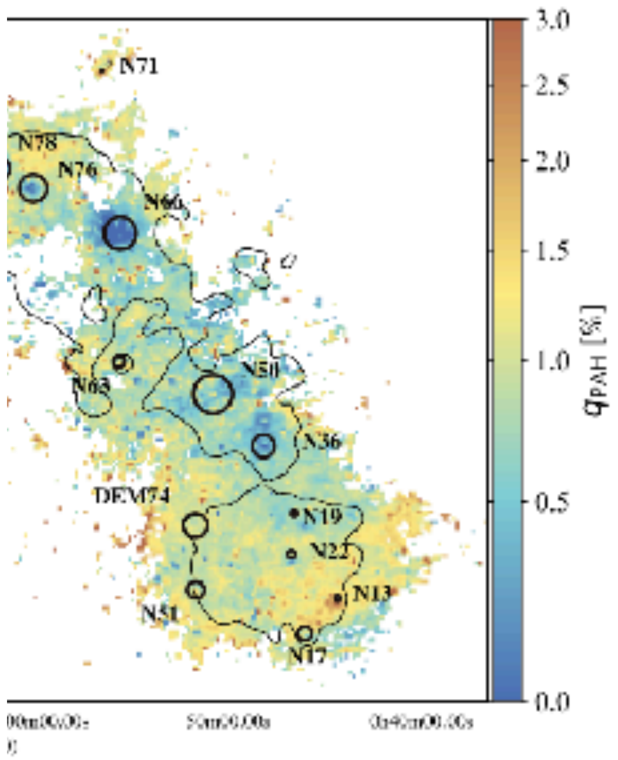
$$\langle q_{\rm PAH}^{\rm SMC} \rangle = 1.0^{+0.3}_{-0.3}~\%$$

PAH Fraction in the Magellanic Clouds



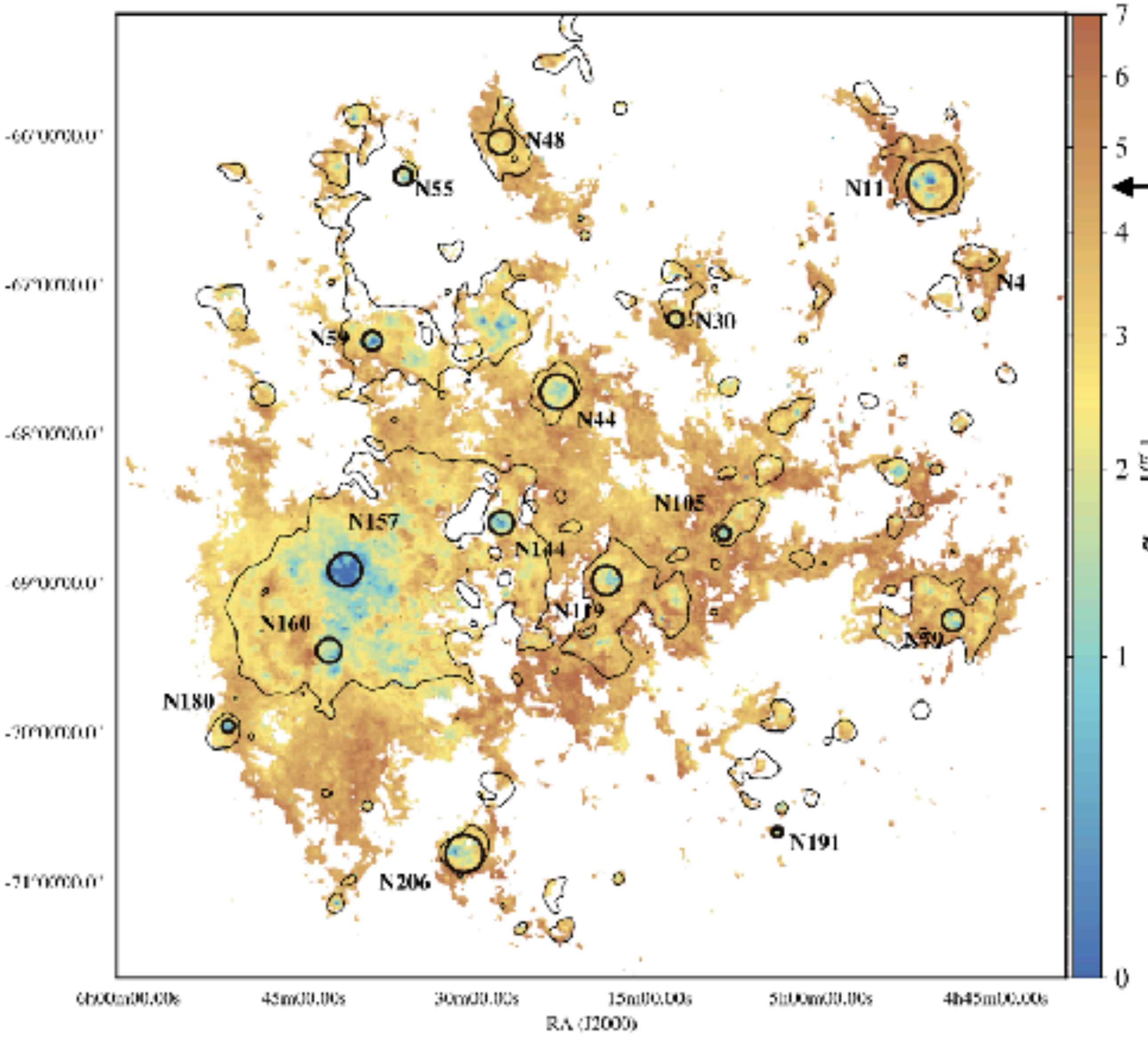


l; Weingartner & Draine 2001)



$\langle q_{\rm PAH}^{\rm LMC}\rangle = 3.3_{-1.3}\ \%$ $\langle q_{\rm PAH}\rangle = 1.0^{+0.3}_{-0.3}\ \%$

PAH Fraction in the Magellanic Clouds



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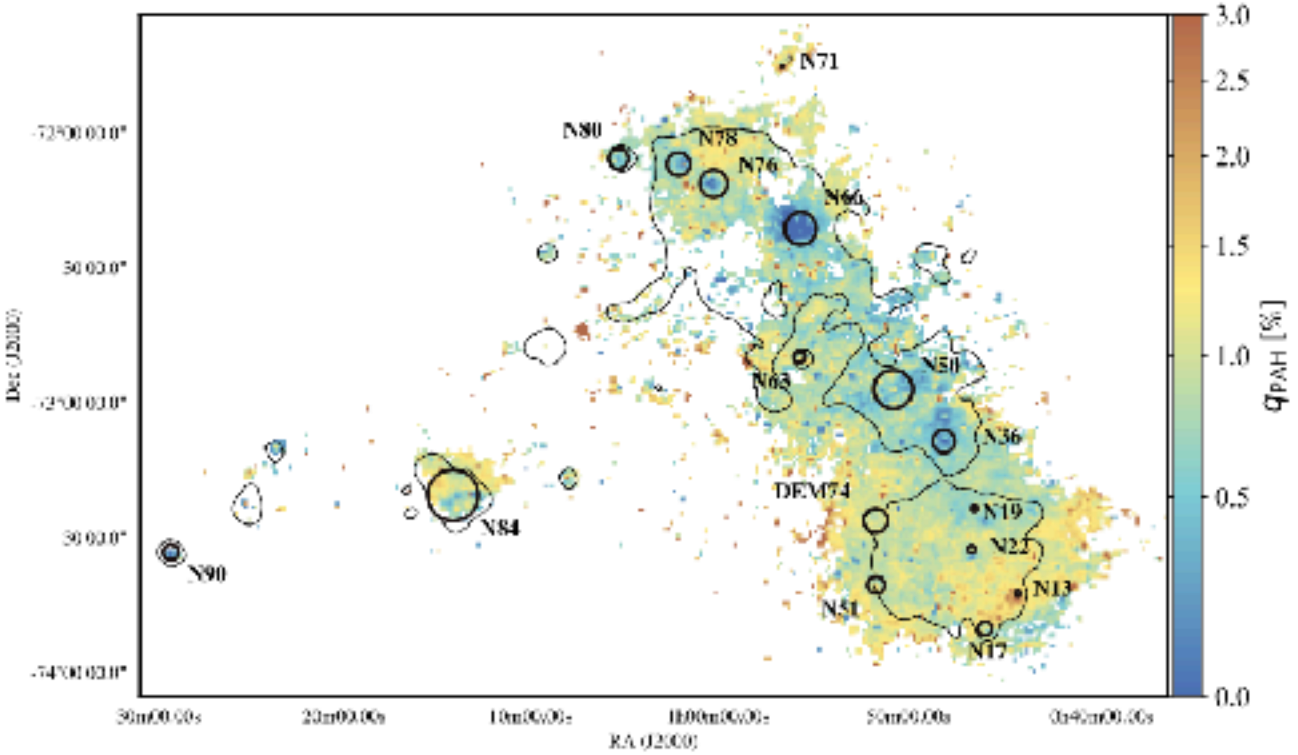
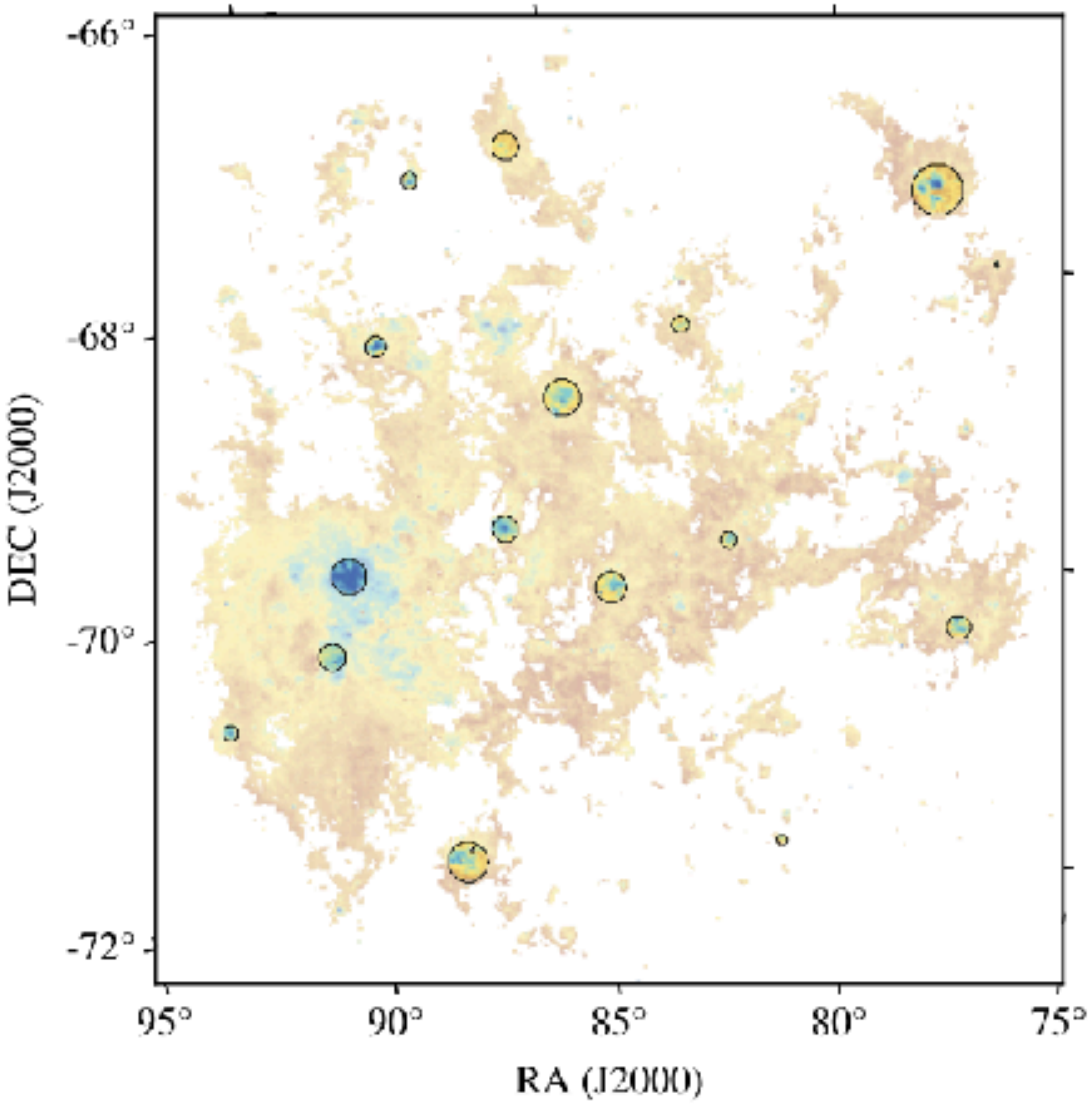


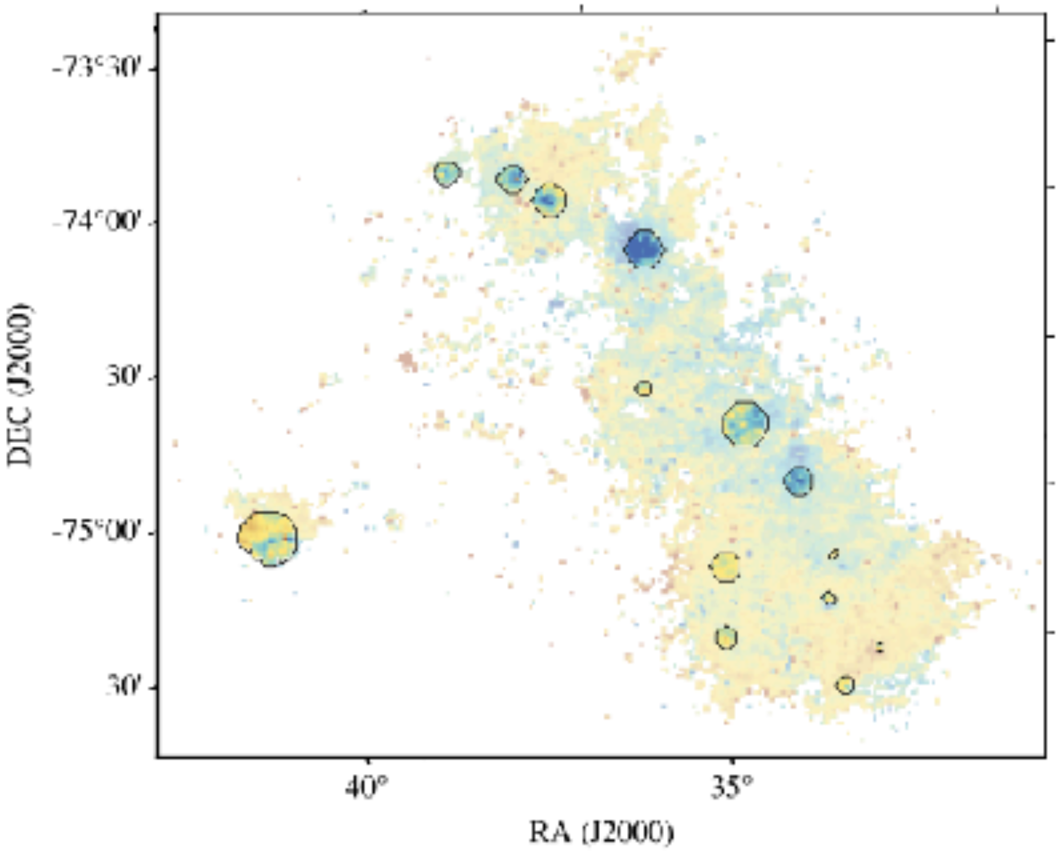
Each galaxy has ~fixed metallicity, but PAH fraction varies substantially within each galaxy.

PAH Fraction in the Magellanic Clouds

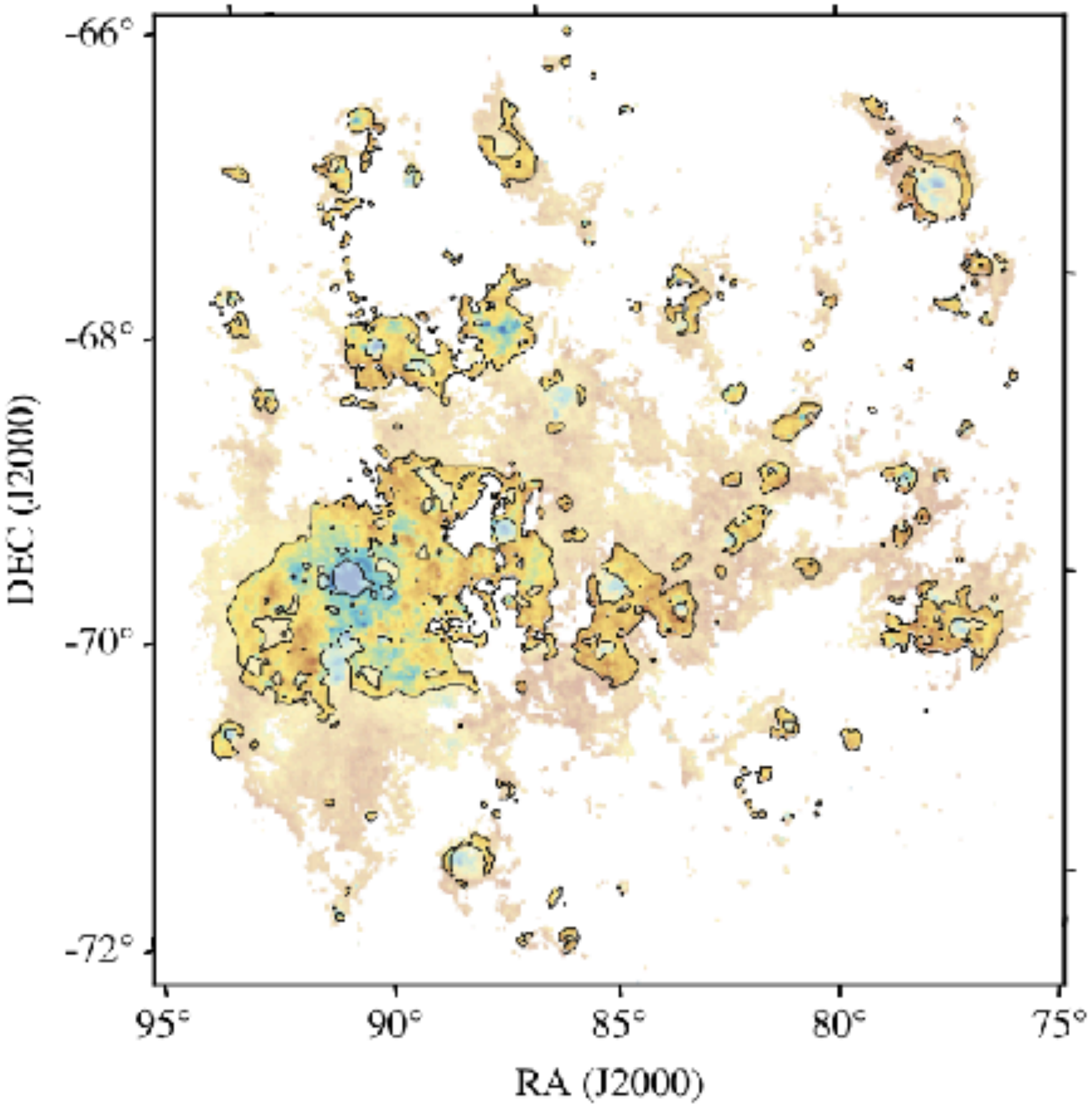


$$\langle q_{\mathrm{PAH}}^{\mathrm{LMC,\ H\ II}} \rangle = 1.8^{+1.1}_{-1.3}\ \%$$

$$\langle q_{\mathrm{PAH}}^{\mathrm{SMC,\ H\ II}} \rangle = 0.8^{+0.3}_{-0.5}\ \%$$

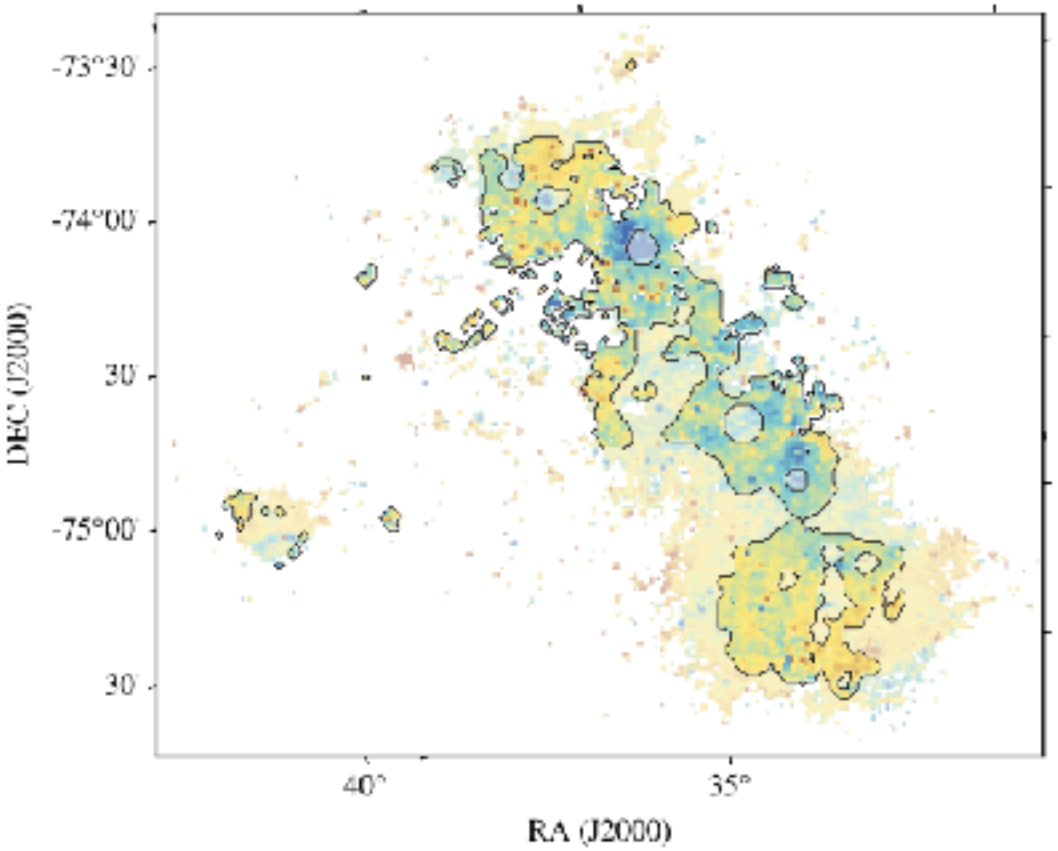


PAH Fraction in the Magellanic Clouds

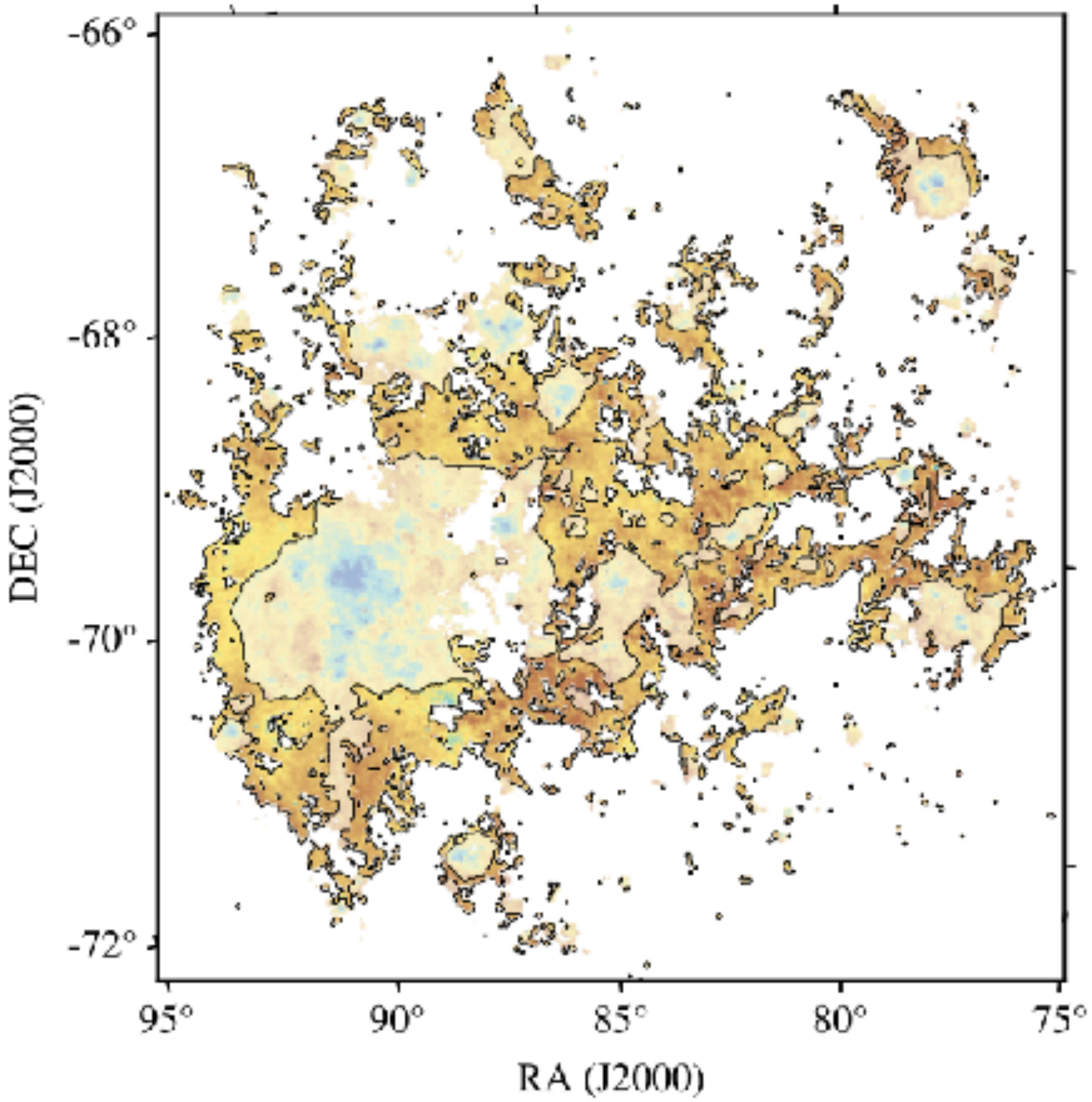


$$\langle q_{\rm PAH}^{\rm LMC,\ ion} \rangle = 2.9^{+1.1}_{-1.2}\ \%$$

$$\langle q_{\rm PAH}^{\rm SMC,\ ion} \rangle = 0.9^{+0.3}_{-0.3}\ \%$$

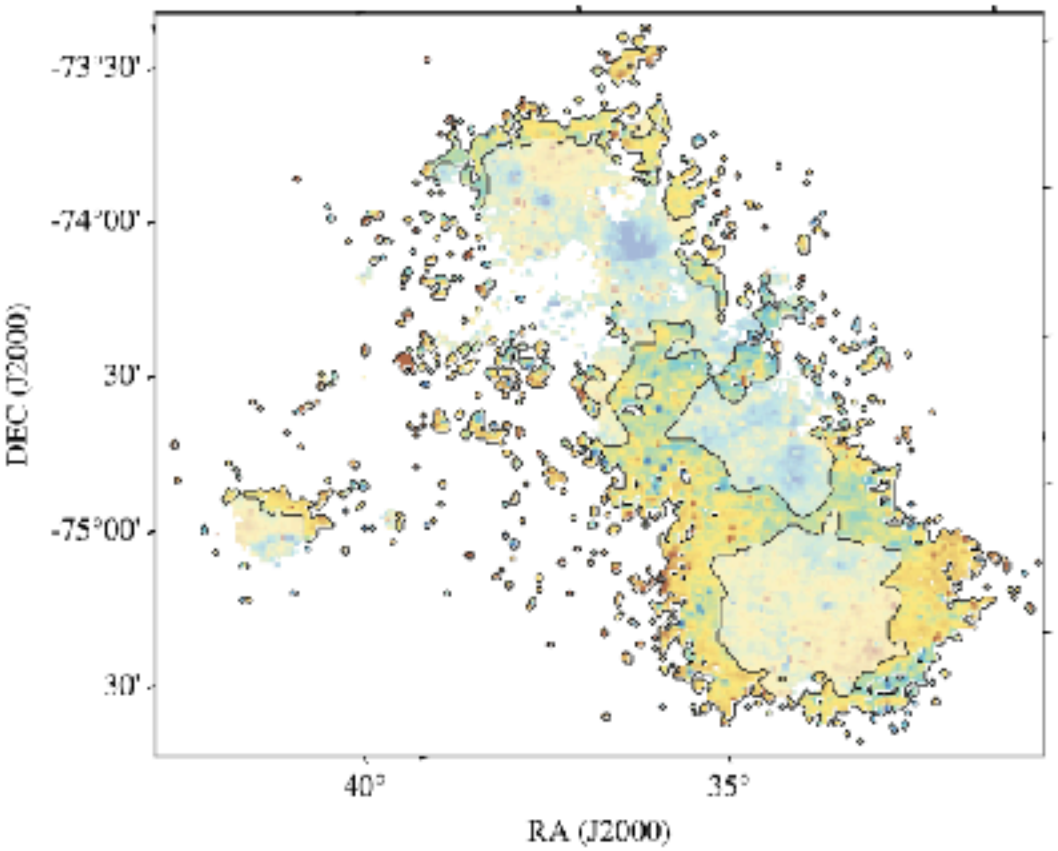


PAH Fraction in the Magellanic Clouds

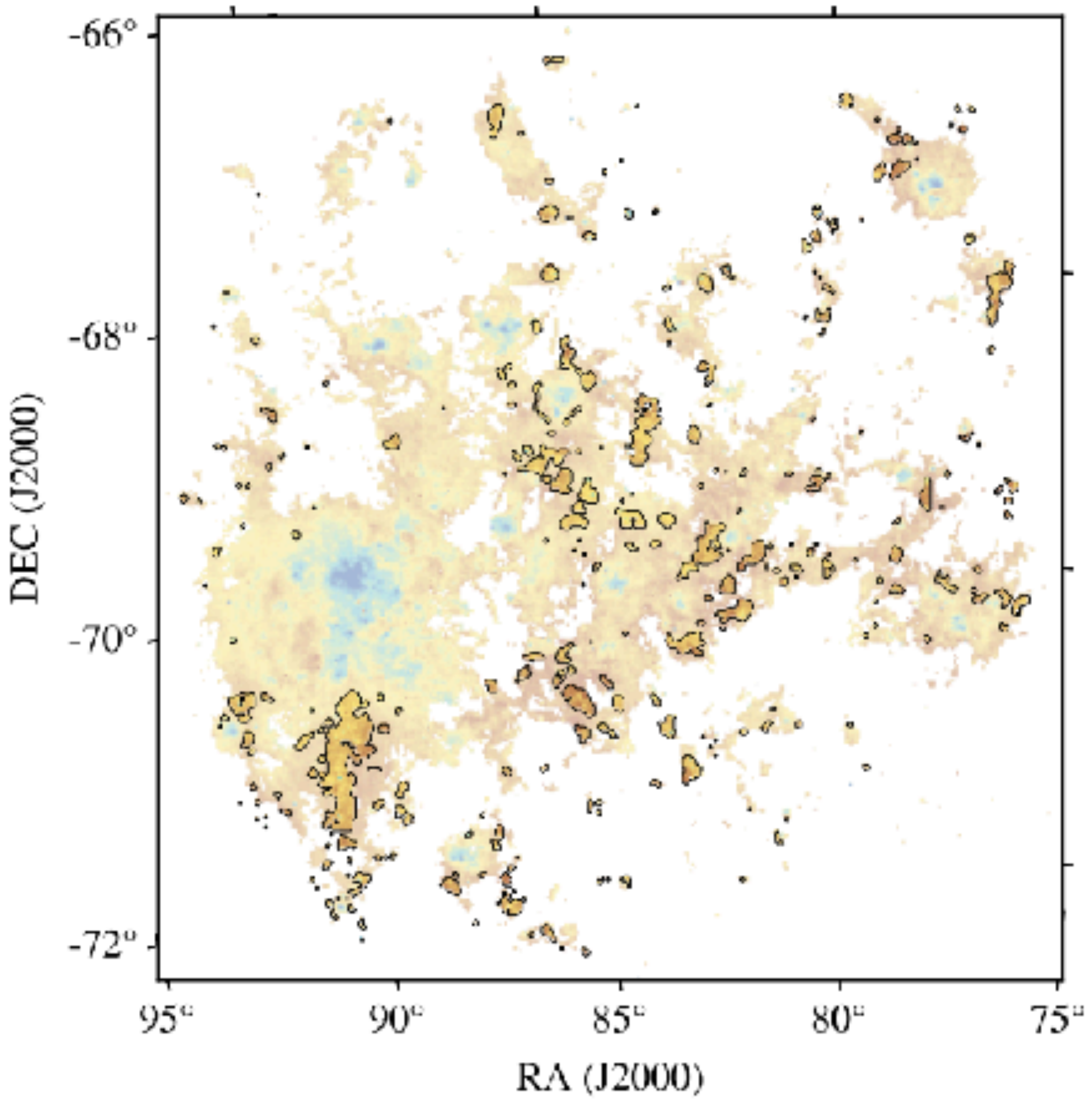


$$\langle q_{\rm PAH}^{\rm LMC,\ dnm} \rangle = 4.1^{+0.6}_{-0.8}\ \%$$

$$\langle q_{\rm PAH}^{\rm SMC,\ dnm} \rangle = 1.1^{+0.2}_{-0.3}\ \%$$

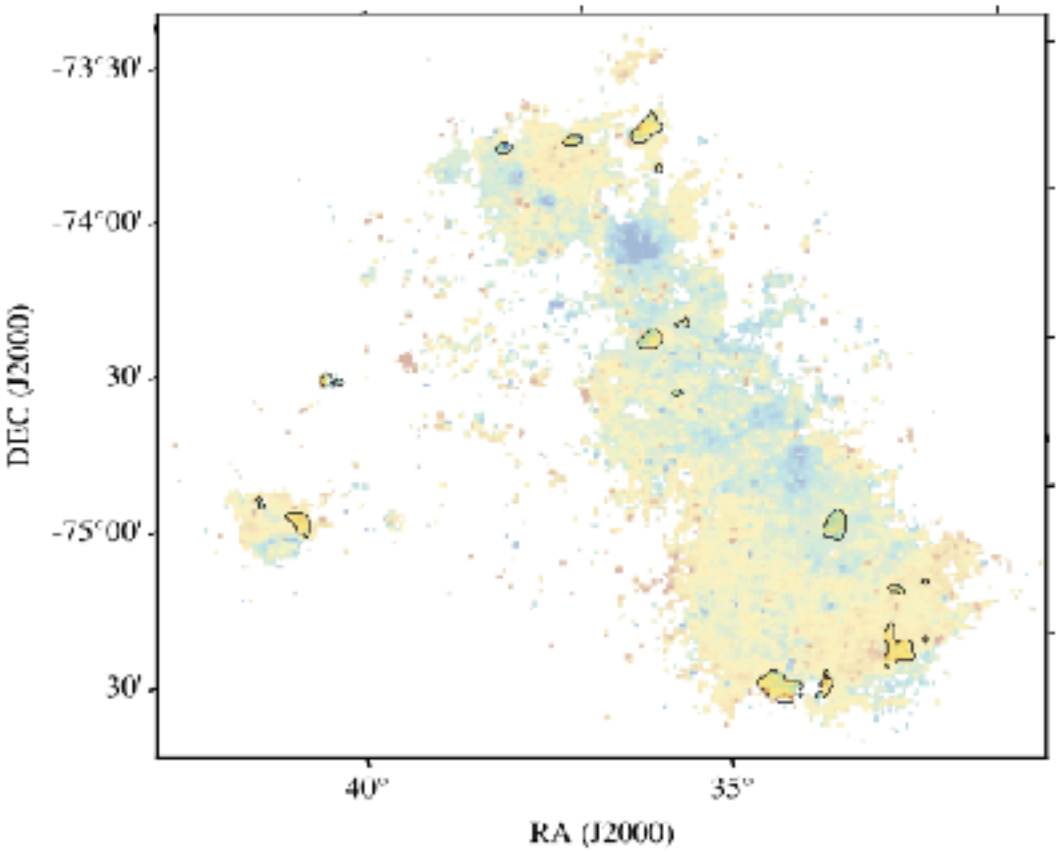


PAH Fraction in the Magellanic Clouds

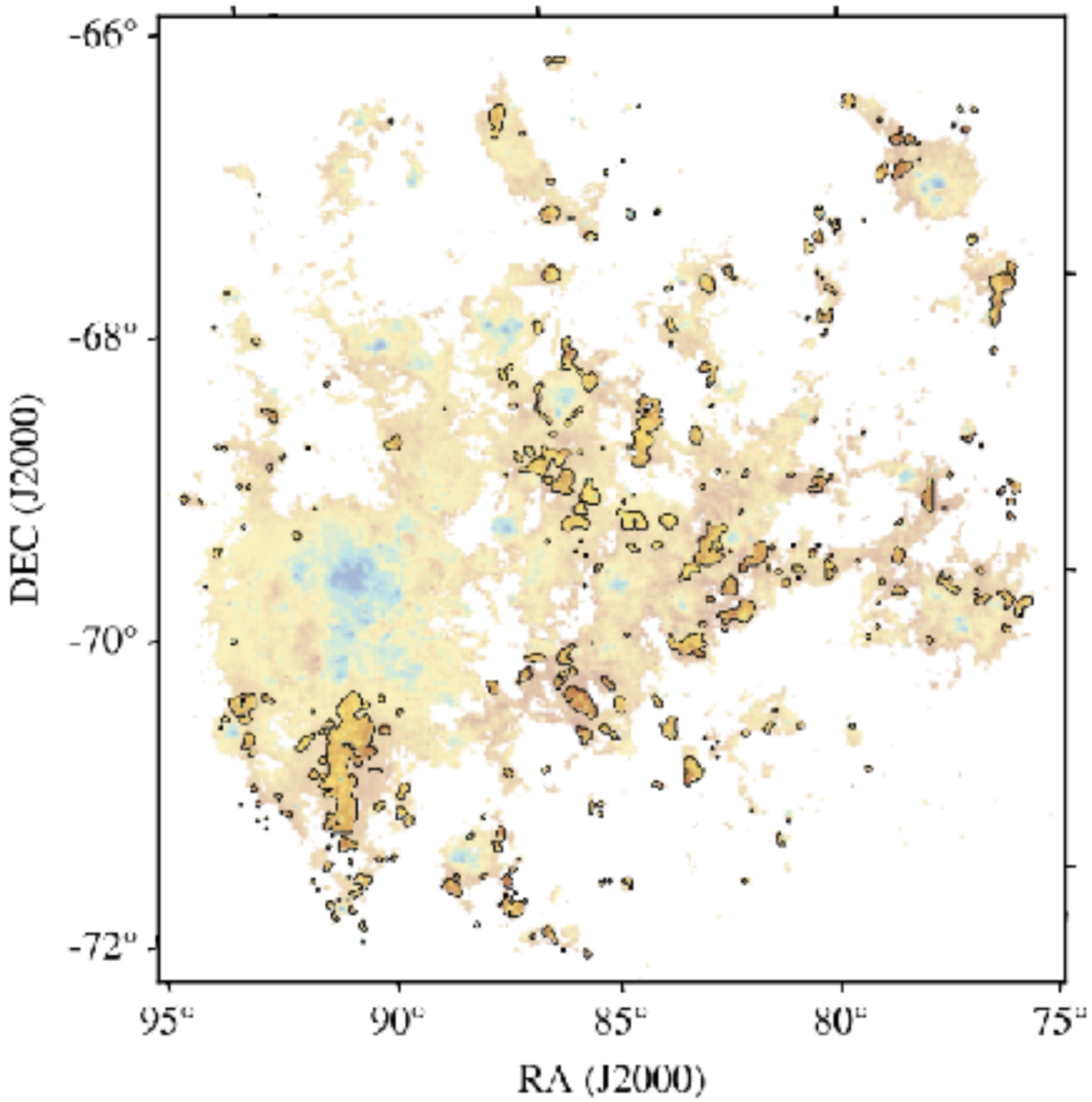


$$\langle q_{\mathrm{PAH}}^{\mathrm{LMC,\ mol}} \rangle = 4.3^{+1.3}_{-0.9}\ \%$$

$$\langle q_{\mathrm{PAH}}^{\mathrm{SMC,\ mol}} \rangle = 1.1^{+0.1}_{-0.2}\ \%$$

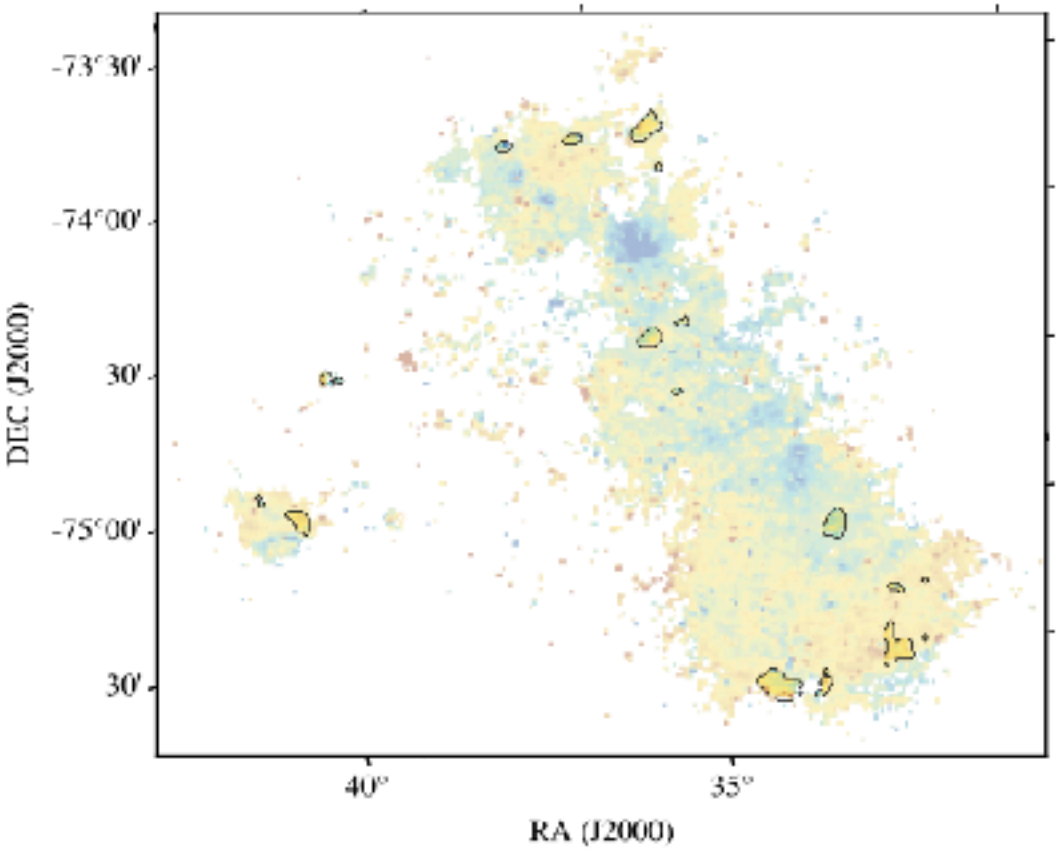


PAH Fraction in the Magellanic Clouds



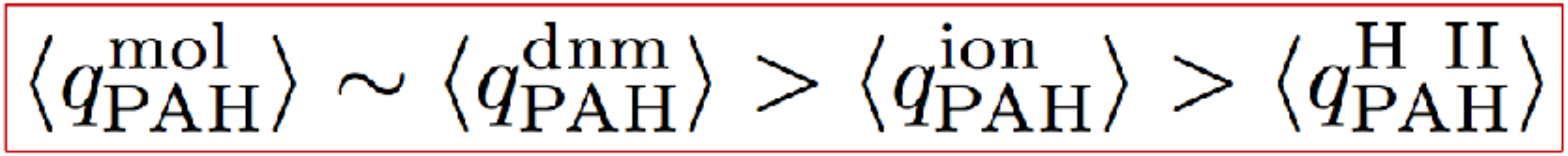
$$\langle q_{\rm PAH}^{\rm LMC,\ mol} \rangle = 4.3^{+1.3}_{-0.9}\ \%$$

$$\langle q_{\rm PAH}^{\rm SMC,\ mol} \rangle = 1.1^{+0.1}_{-0.2}\ \%$$



$$\boxed{\langle q_{\rm PAH}^{\rm mol} \rangle \sim \langle q_{\rm PAH}^{\rm dnm} \rangle > \langle q_{\rm PAH}^{\rm ion} \rangle > \langle q_{\rm PAH}^{\rm H\ II} \rangle}$$

PAH Fraction in the Magellanic Clouds



$$\langle q_{\rm PAH}^{\rm mol} \rangle \sim \langle q_{\rm PAH}^{\rm dnm} \rangle > \langle q_{\rm PAH}^{\rm ion} \rangle > \langle q_{\rm PAH}^{\rm H\ II} \rangle$$

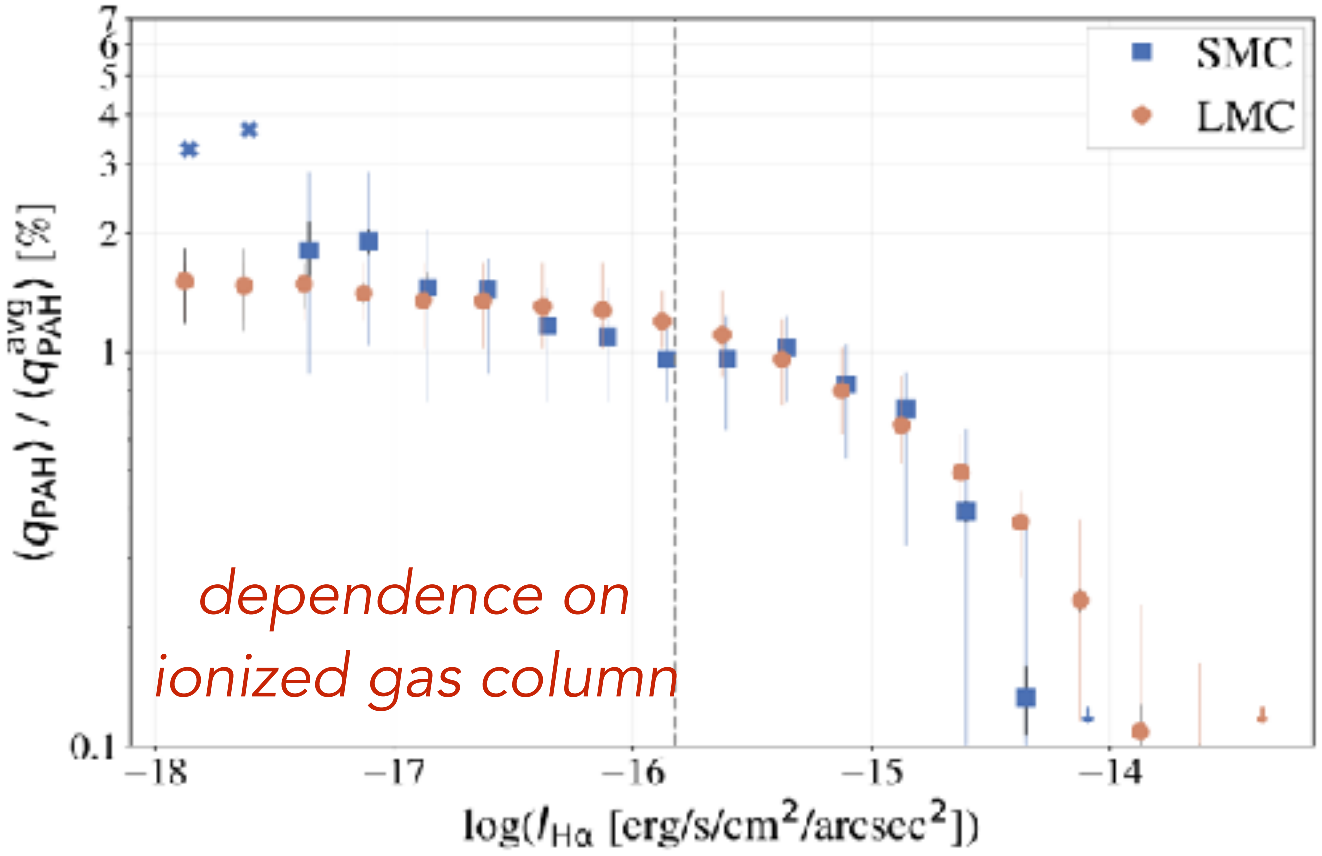
PAH fraction highest in the neutral ISM
(both diffuse HI and H_2)

PAHs are destroyed in regions where ionized gas exists

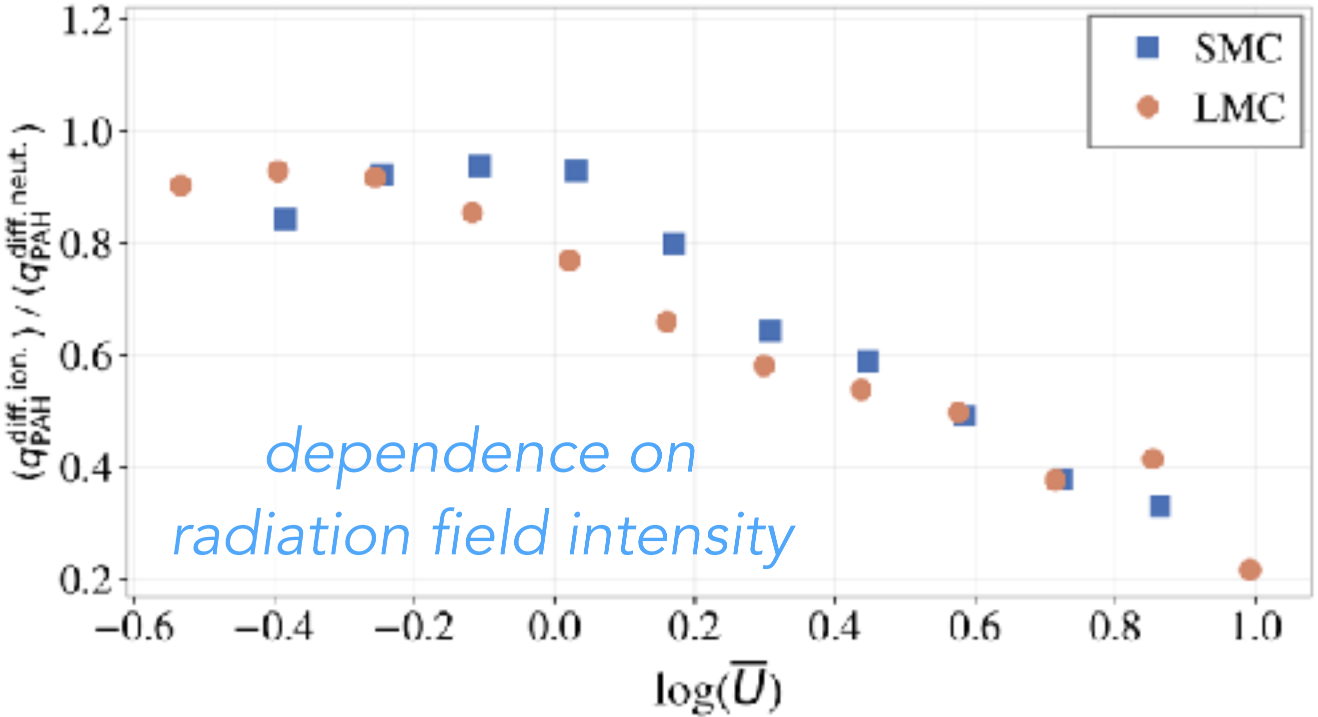
Diffuse neutral medium q_{PAH} gives a baseline
where the least PAH destruction has occurred.

Chastenet et al 2019 - https://ui.adsabs.harvard.edu/abs/2019ApJ...876...62C/

PAH Fraction in the Magellanic Clouds



dependence on ionized gas column



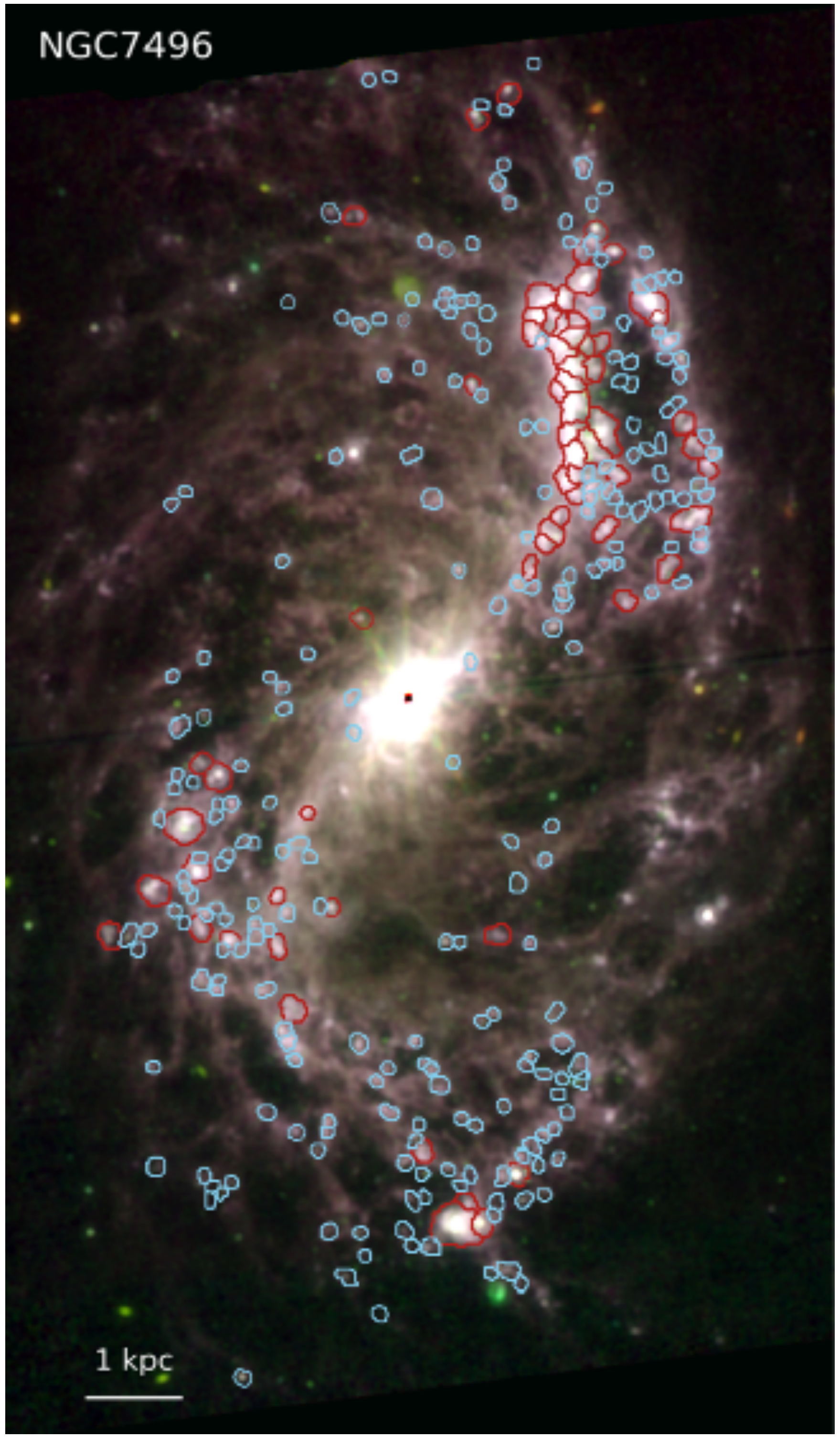
dependence on radiation field intensity

Take neutral gas q_{PAH} as baseline, compare PAH destruction in ionized gas or intense radiation fields.

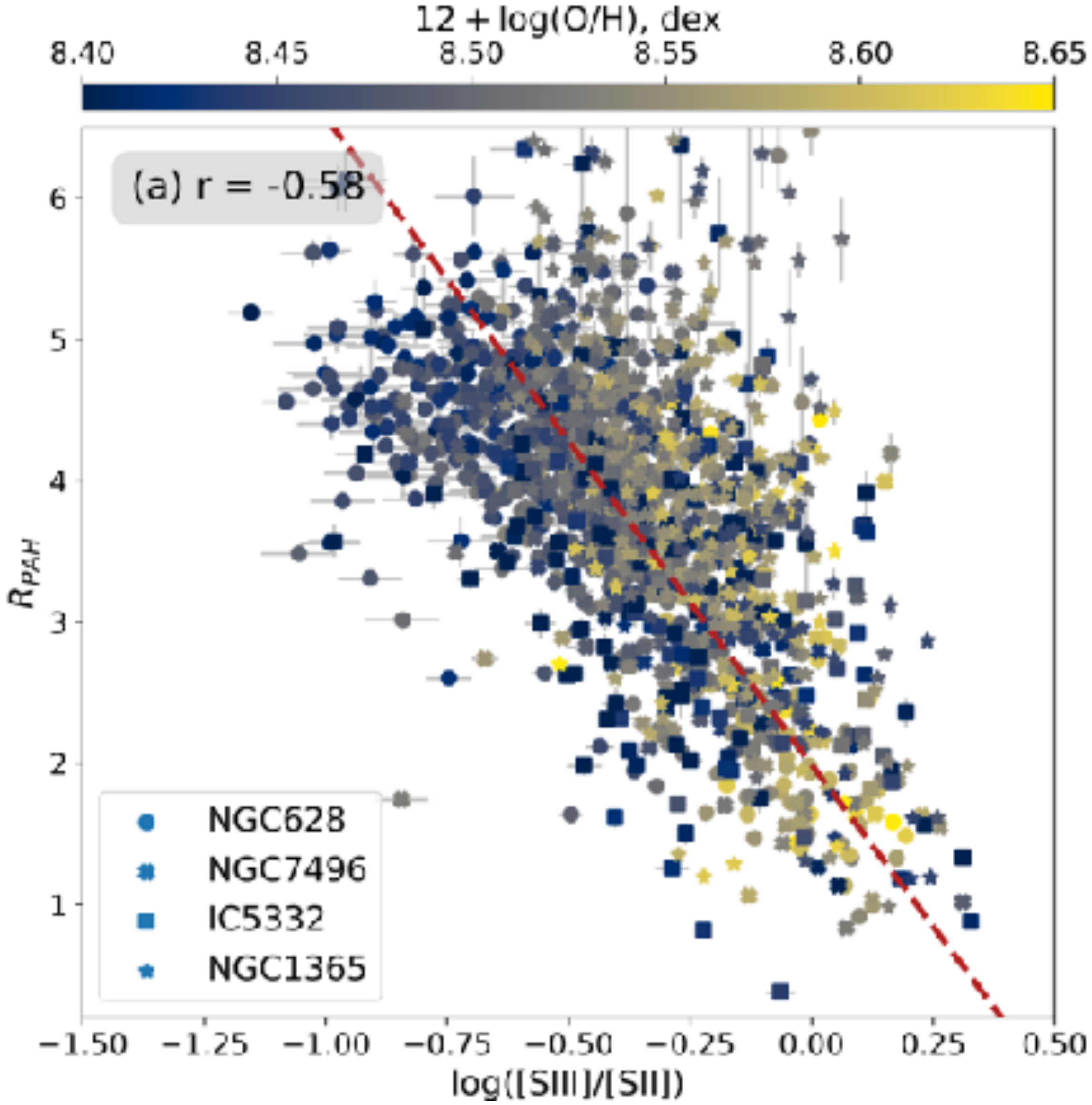
Destruction behaves similarly in SMC & LMC.

Suggests PAH destruction is not highly metallicity dependent.

PAH Destruction from Recent JWST Observations



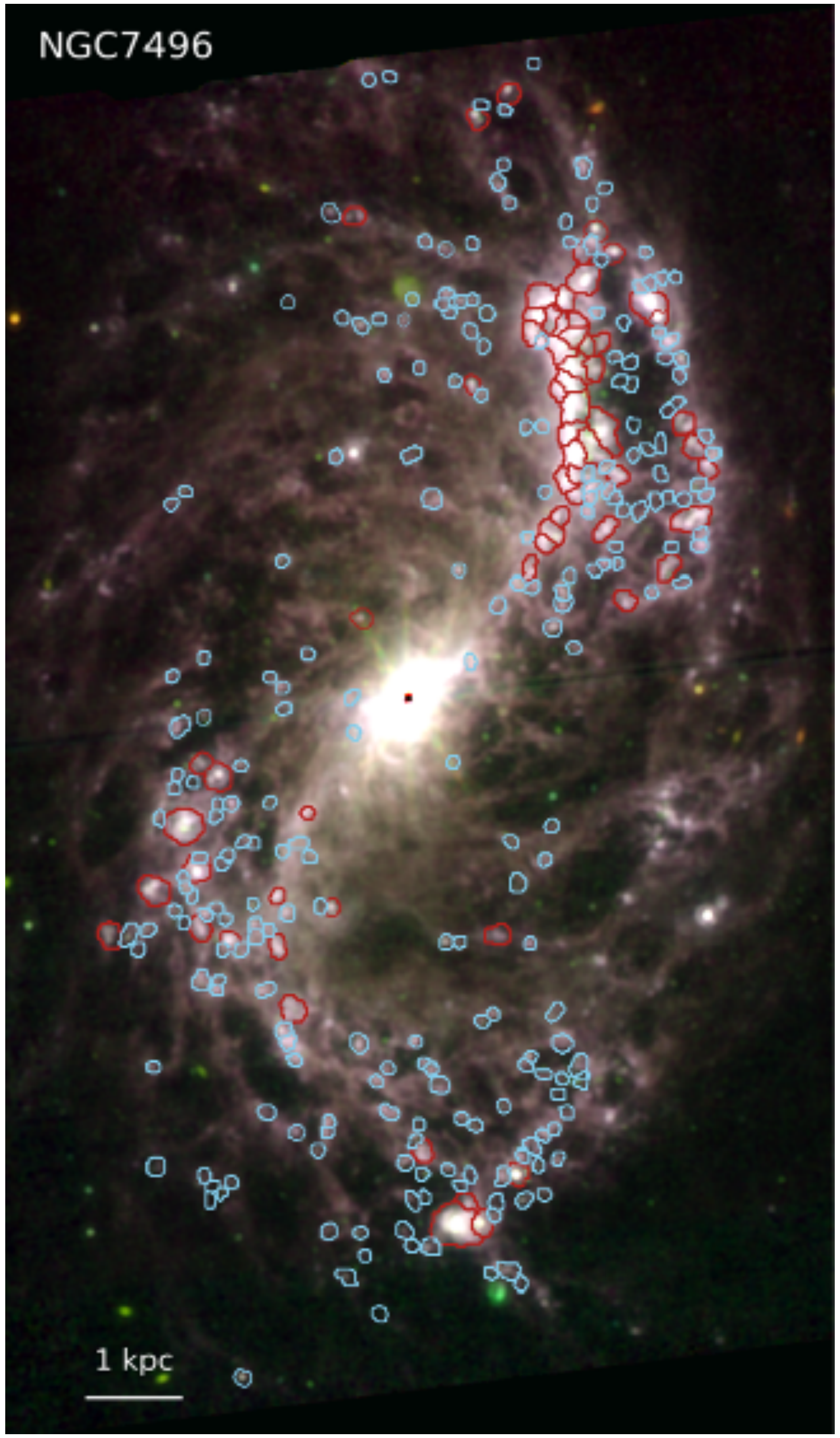
Red = HII regions with $Q_0 > 10^{50}\ \mathrm{s}^{-1}$
Blue = regions with $Q_0 < 10^{50}\ \mathrm{s}^{-1}$



No metallicity trend in HII region PAH destruction in 4 massive spirals.

Egorov et al. 2023 - https://ui.adsabs.harvard.edu/abs/2023ApJ...944L..16E/

PAH Destruction from Recent JWST Observations



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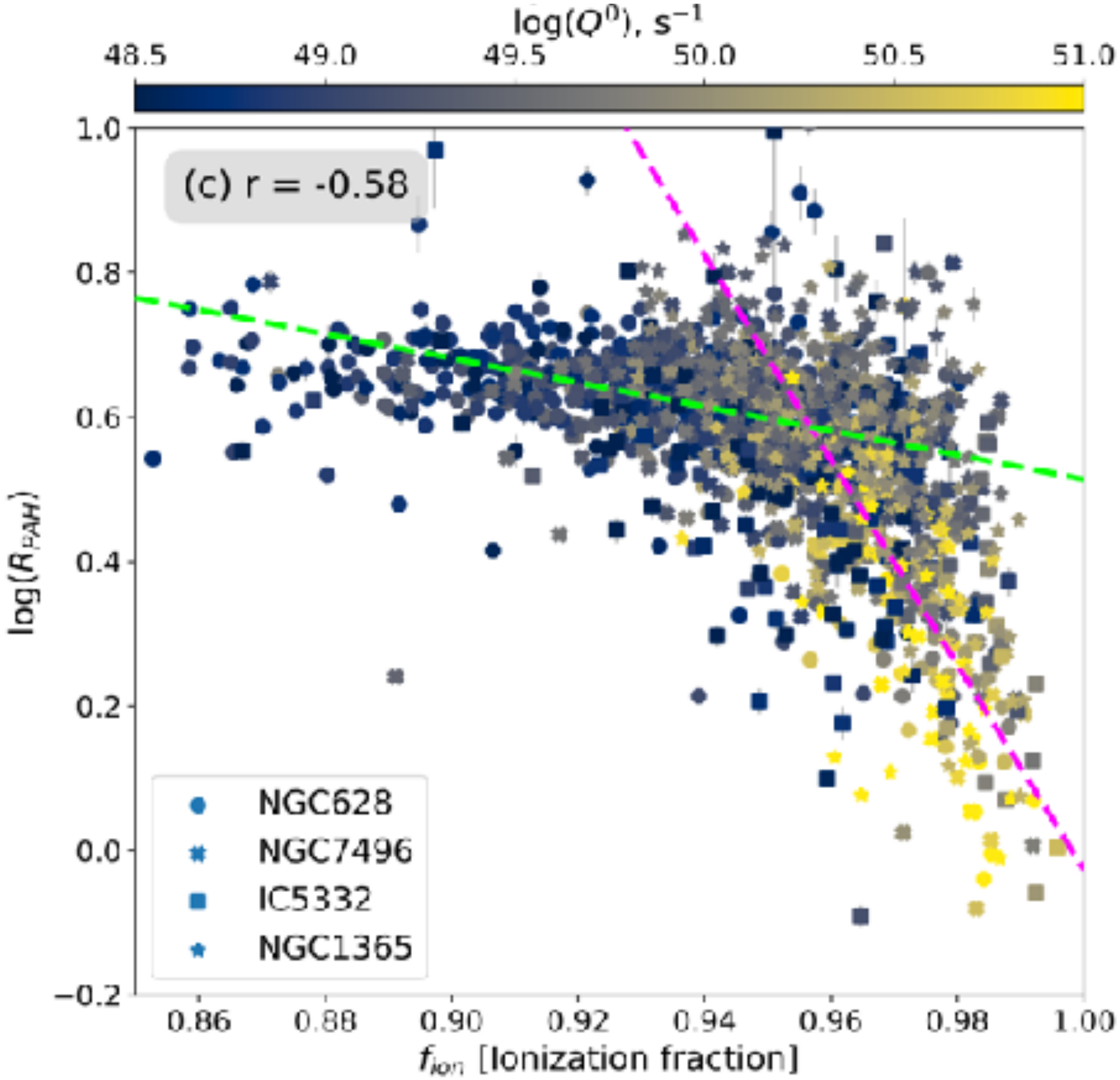

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PAH Fraction in the Magellanic Clouds

What formation mechanism could explain
the highly metallicity dependent neutral ISM q_{PAH}?

Probably not dust input from evolved stars:
AGB carbon-rich dust yields are higher at low Z
(Boyer et al. 2011, 2012)

"ISM-grown" dust should be metallicity dependent:
Shattering of larger grains could produce PAHs.
Growth on existing grain surfaces.
Both are limited by available dust and metals.

Polycyclic Aromatic Hydrocarbons

Mid-IR vibrational features of PAHs let us diagnose their properties including size, charge, and structure.

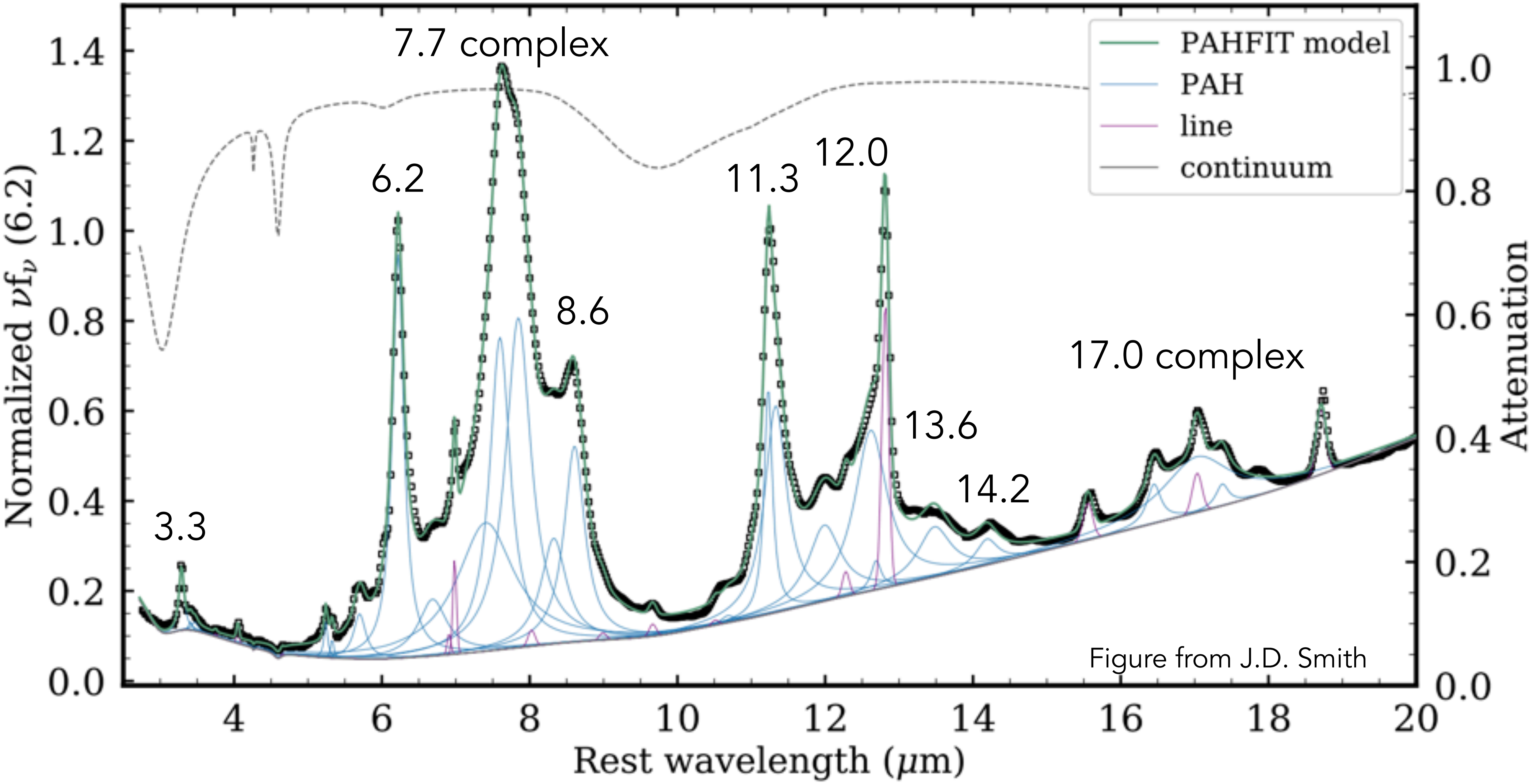

Figure from J.D. Smith

Polycyclic Aromatic Hydrocarbons

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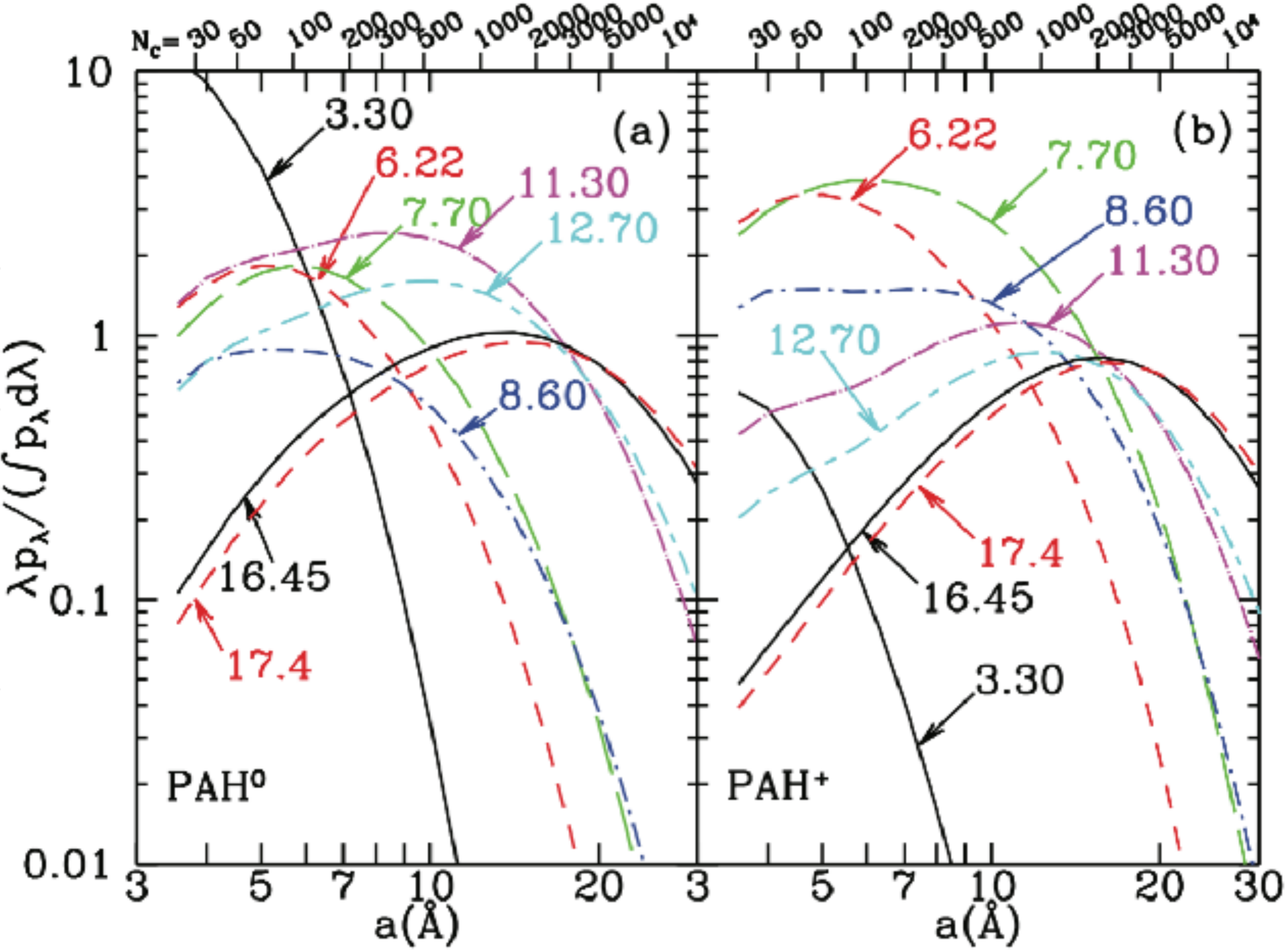


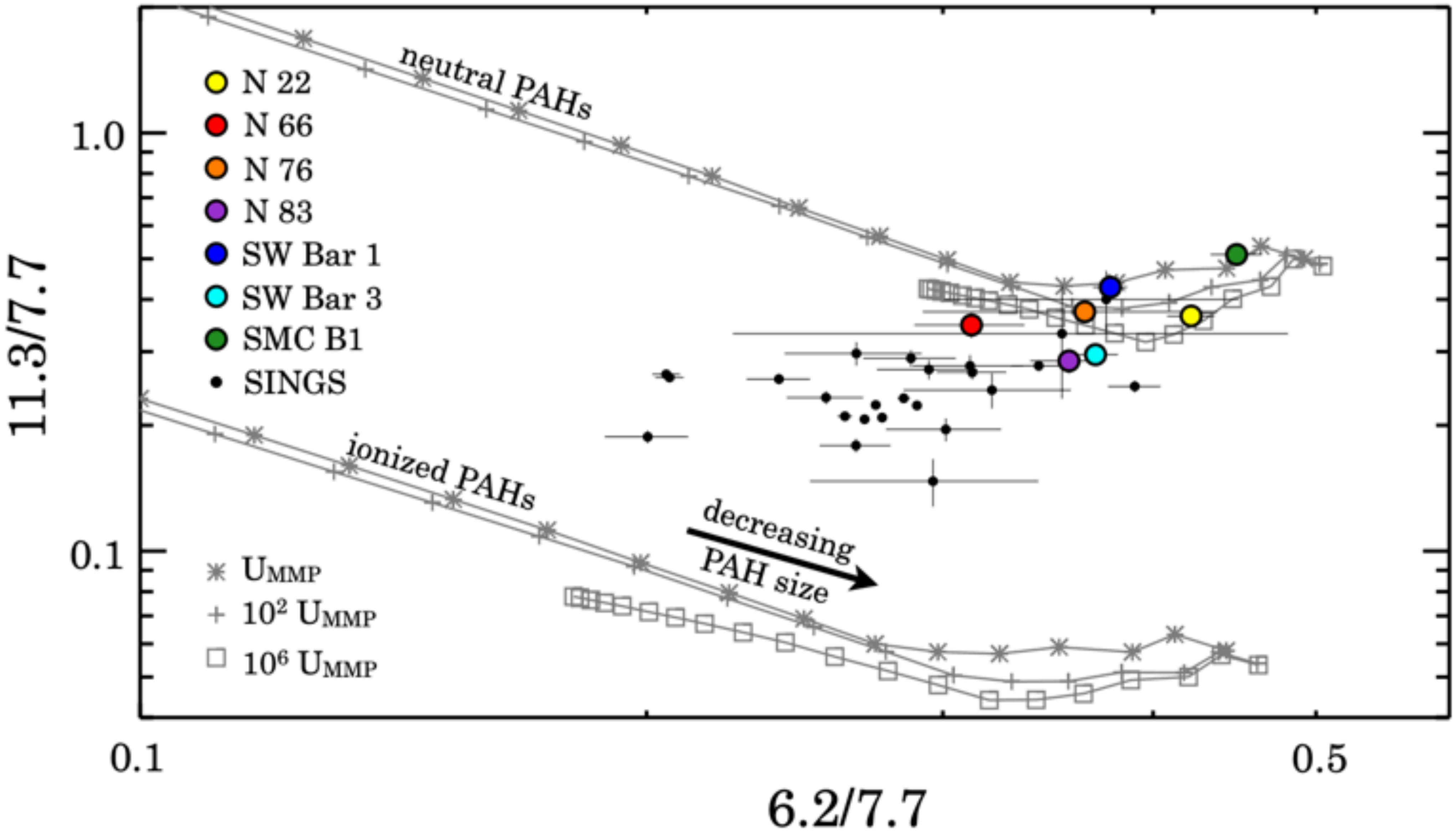
Efficiency of radiating in a given band

PAH size

Draine & Li 2007

PAH Properties in the SMC

SMC PAHs: in the very top corner of the Draine tracks, suggests small, neutral PAHs.



Sandstrom et al. 2012 - https://ui.adsabs.harvard.edu/abs/2012ApJ...744...20S/

Dust Summary

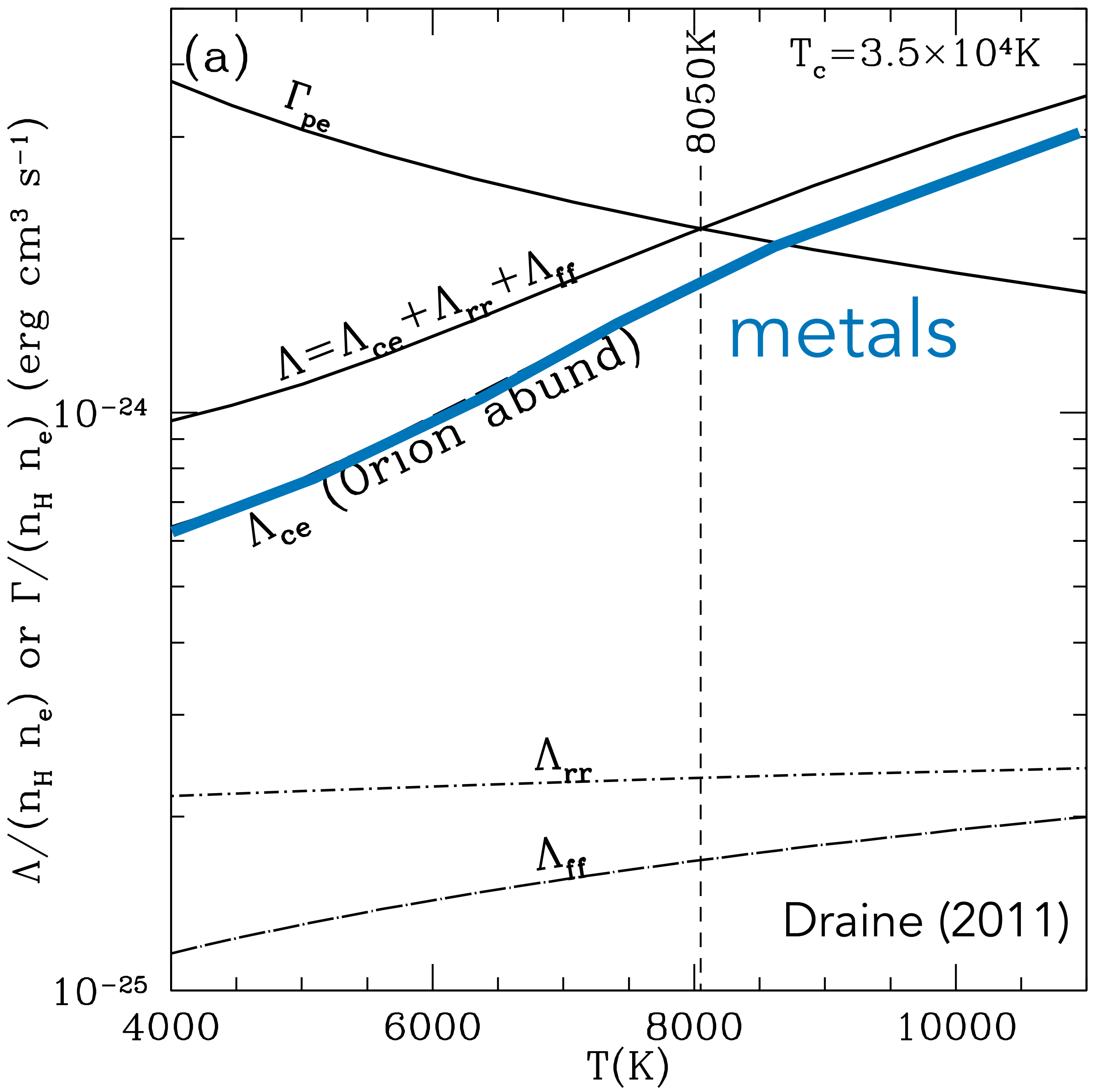
- Grain sizes are smaller.
- 2175 Å bump becomes rare (probably because of decrease in PAH abundance)
- Dust-to-gas drops faster than linearly with Z - changing dust-to-metals ratio, maybe due to inefficient grain growth.
- PAH fraction drops steeply below 12+log(O/H)~8, evidence for PAHs being smaller and more neutral, concentated with CO clumps at low metallicity

The Effects of Low Metallicity on the ISM

Key Point:
Low metallicity changes heating/cooling balance

ISM Phase	Main Heat Source	Main Coolant
Ionized	Photoionization of H	Collisionally excited emission lines from various ions
Atomic	Photoelectric effect from PAHs & small dust grains	[CII] and [OI] fine structure lines
Molecular	Photoelectric Effect at low Av, Cosmic Ray Ionization at higher Av	Molecular rotational line emission, including H2, CO

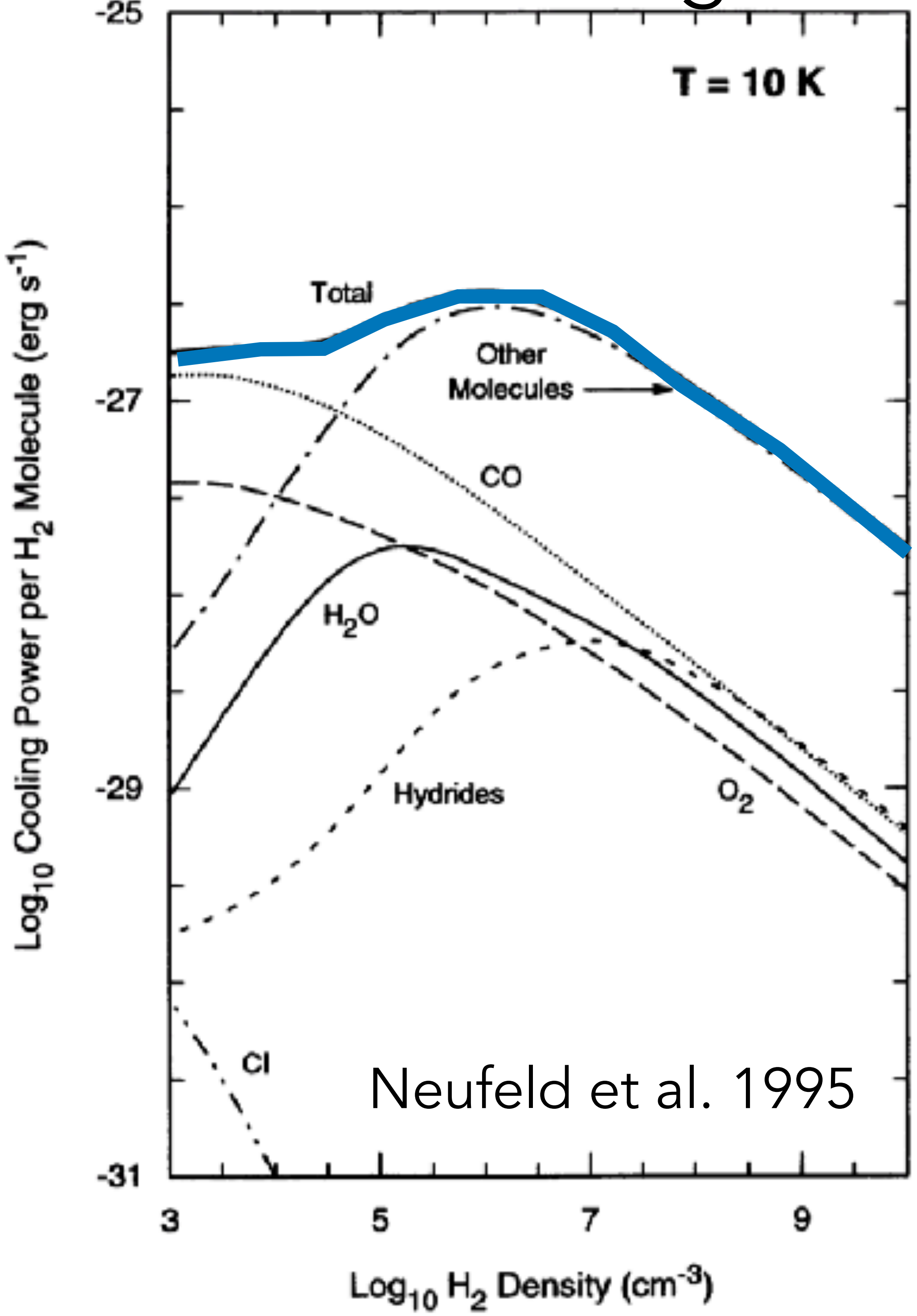
Ionized gas



metals

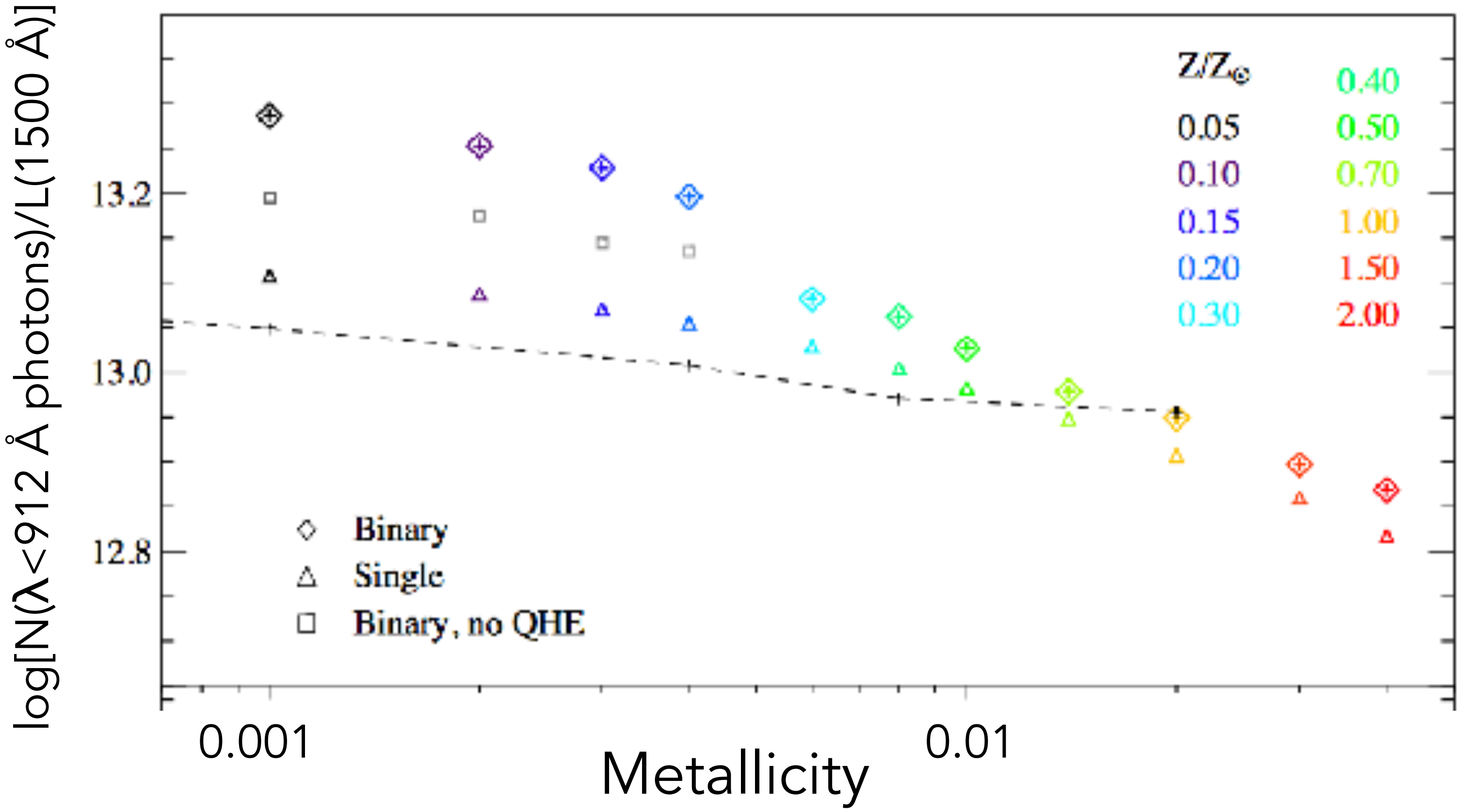
Draine (2011)

Molecular gas



Neufeld et al. 1995

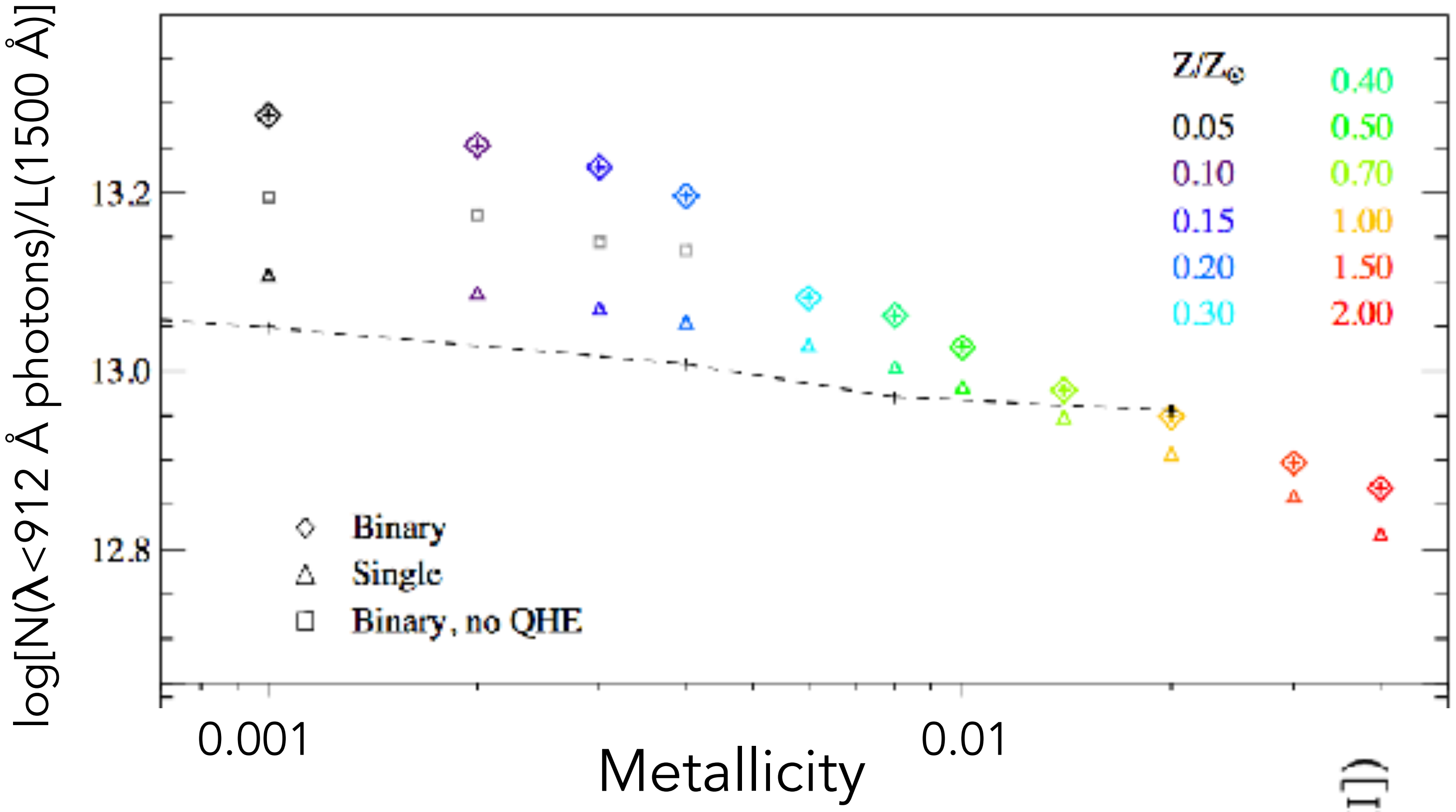
Key Point:
Radiation field produced by stars gets harder due to lower line blanketing.



Radiation field becomes harder for low metallicity stellar populations.

BPASS - Stanway, Eldridge & Becker (2016)

Key Point:
Radiation field produced by stars gets harder due to lower line blanketing.

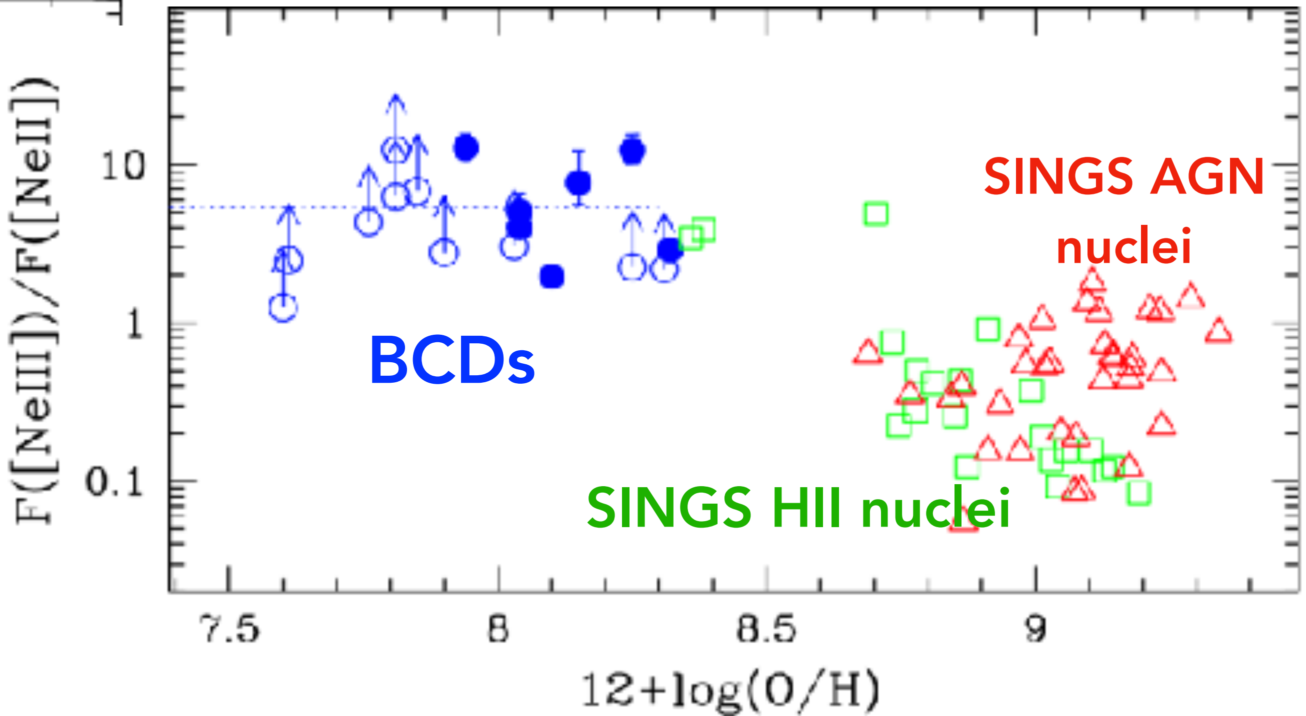


Radiation field becomes harder for low metallicity stellar populations.

BPASS - Stanway, Eldridge & Becker (2016)

This is clearly reflected in line ratio diagnostics of HII regions in dwarf galaxies.

Hunt et al. (2010) - BCDs with Spitzer IRS



Key Point: Drop in DGR (and D/M) leads to overall lower shielding by dust.

Photodissociation Regions = regions where far-UV (<13.6 eV) photons play key role in chemistry, ionization, heating, etc.

Describes ***a lot*** of the ISM.

Structure of PDRs depends heavily on dust since it is responsible for most of the attenuation of UV light.

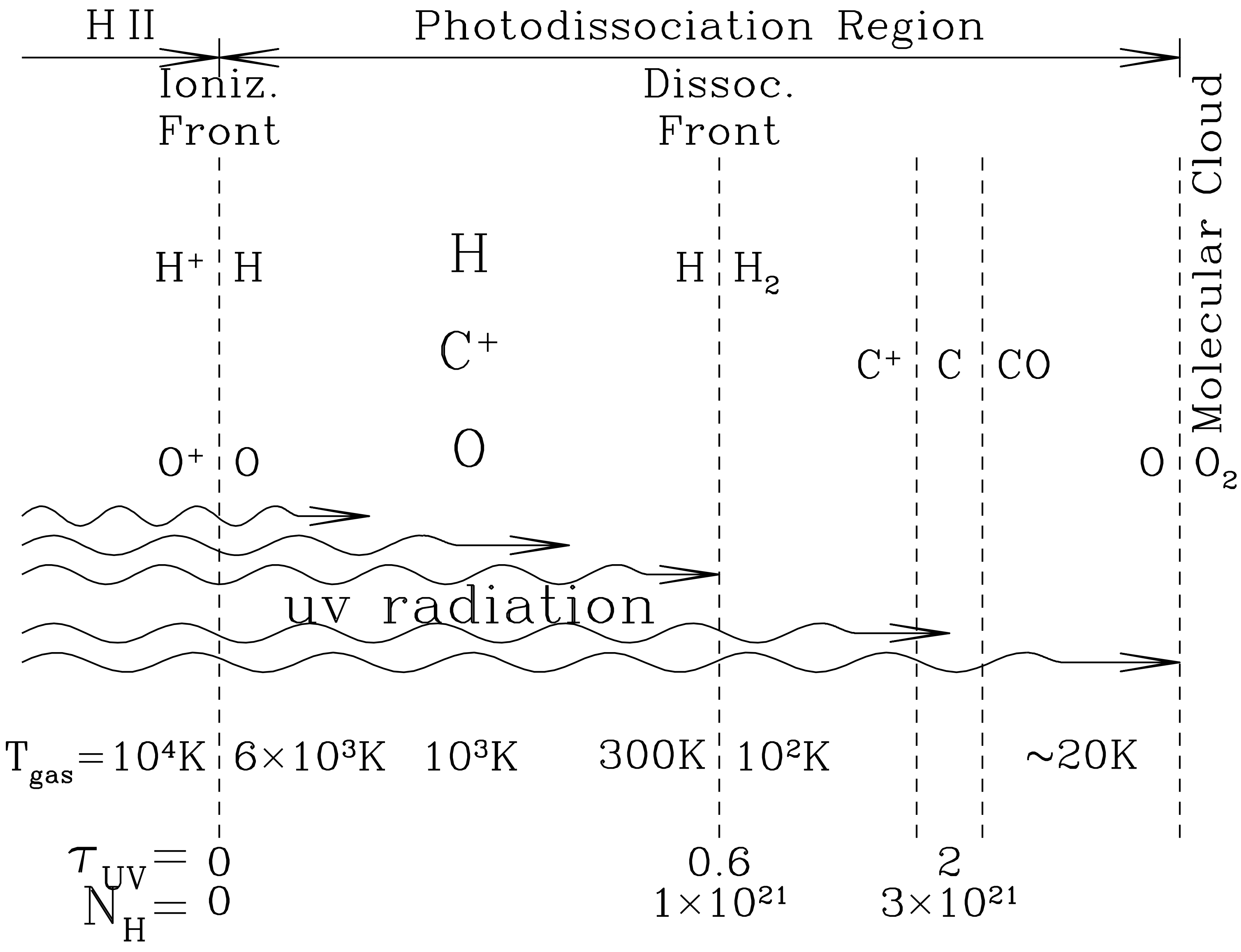


Figure from Draine textbook

Key Point:
Drop in DGR (and D/M) leads to overall lower shielding by dust.

Low metallicity changes all of the critical properties of a PDR:

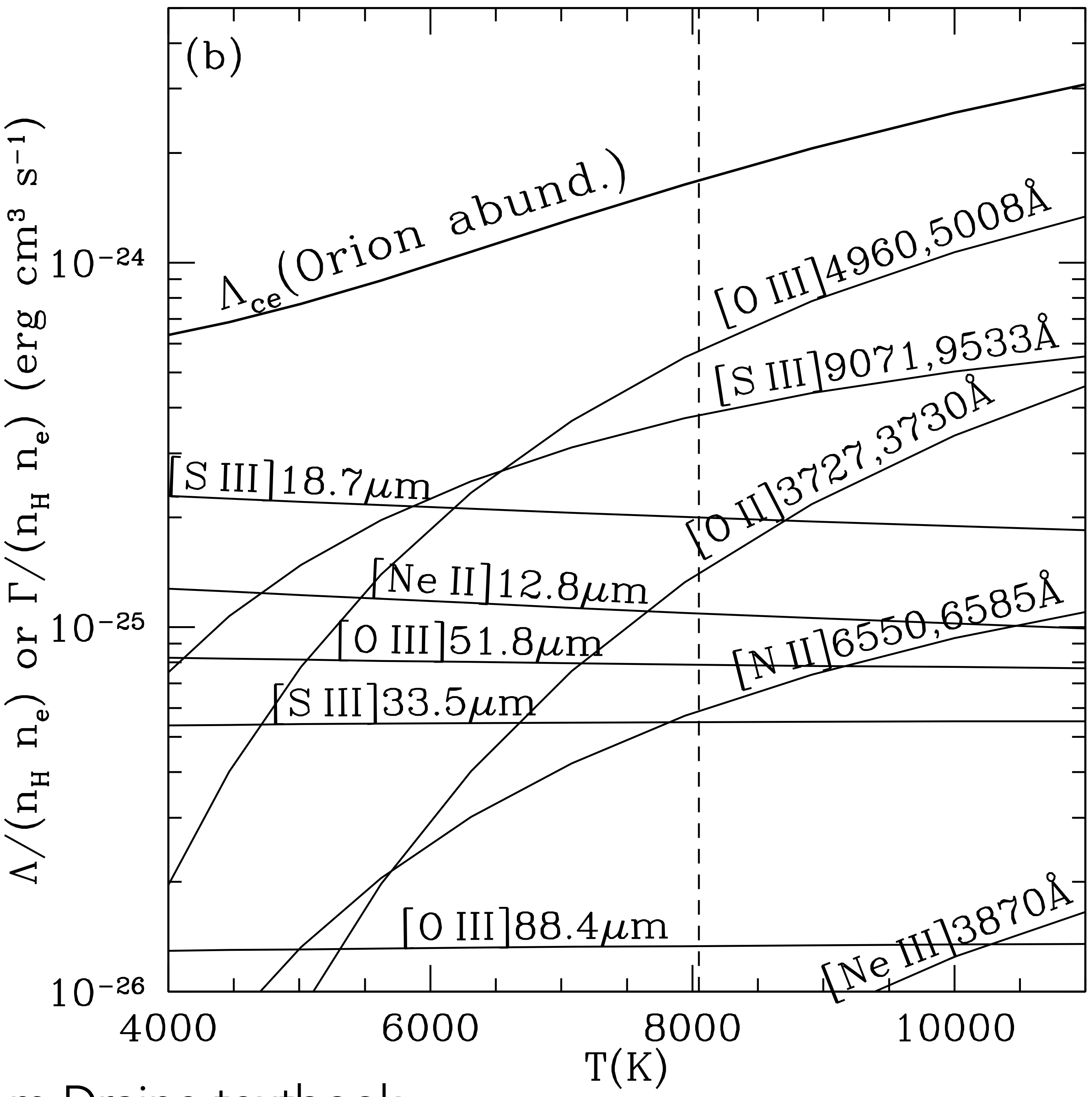
- Radiation fields are harder and less attenuated.
- Dust extinction as a function of wavelength changes.
- Heating rates decrease: efficiency of photoelectric heating drops due to low dust/PAH abundance, lower abundance of heavy elements decreases photoionization heating.
- Cooling rates decrease: lack of metals leads to less cooling via collisionally excited fine structure lines and molecular rotational/vibrational transitions.
- Density structure changes as a consequence of above processes.

Ionized ISM

Ionized gas in low metallicity galaxies has:

- higher electron temperatures
- harder & more pervasive radiation fields
- higher ionization parameter
- larger filling factor of ionized gas

Ionized ISM

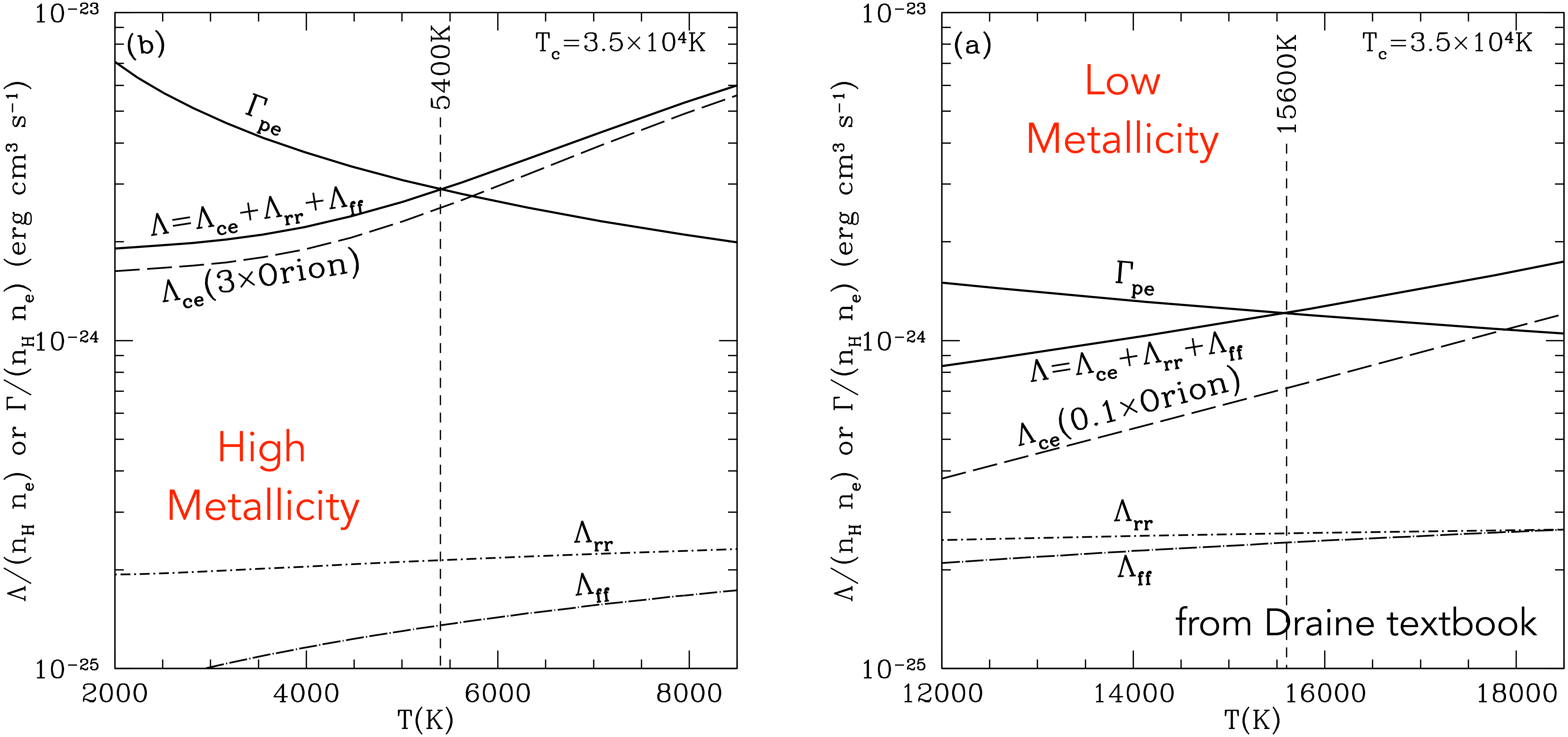


from Draine textbook

Cooling from collisionally excited emission lines is the most important coolant of HII regions.

Ionized ISM

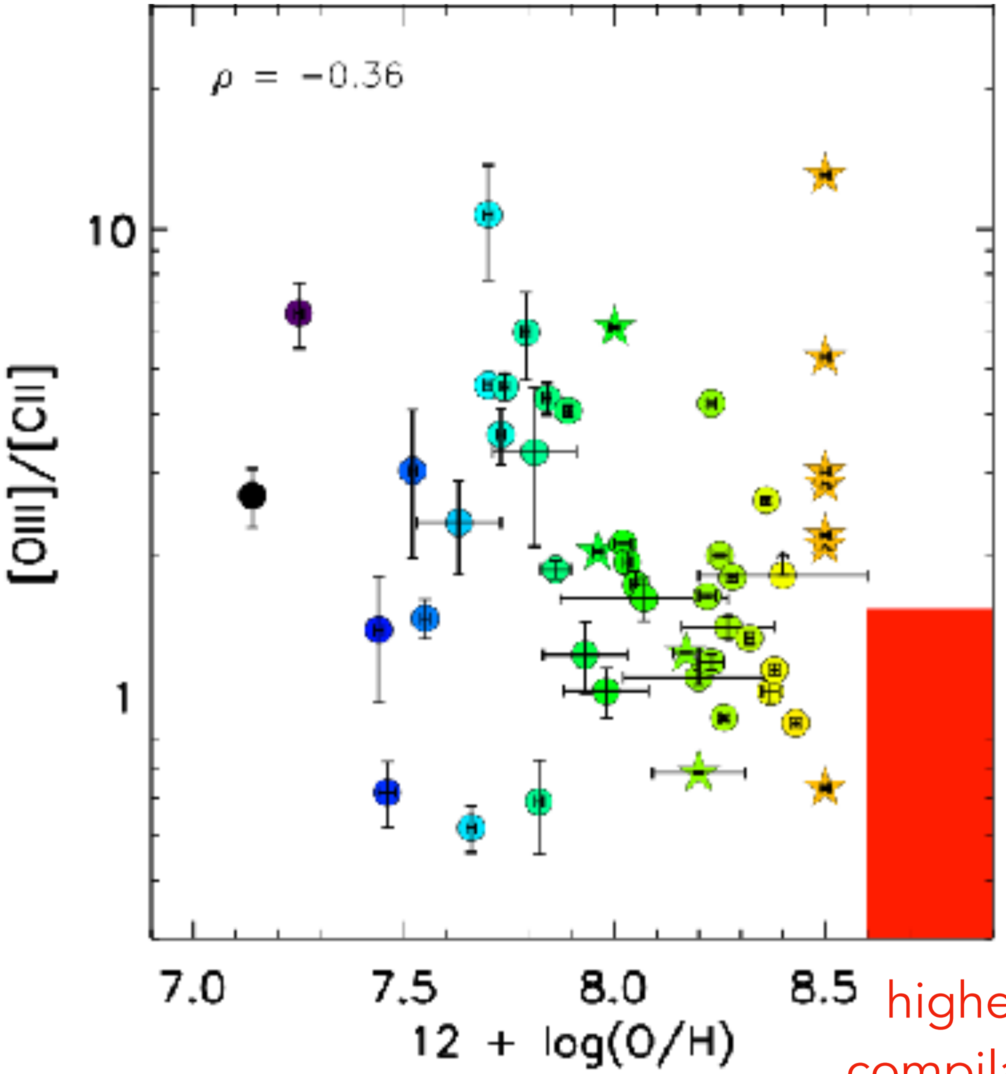
Balance between photoionization heating and collisional excitation cooling sets temperature of HII region.



from Draine textbook

Abundance of heavy elements (e.g. coolants) greatly changes HII region temperature!!

Ionized ISM

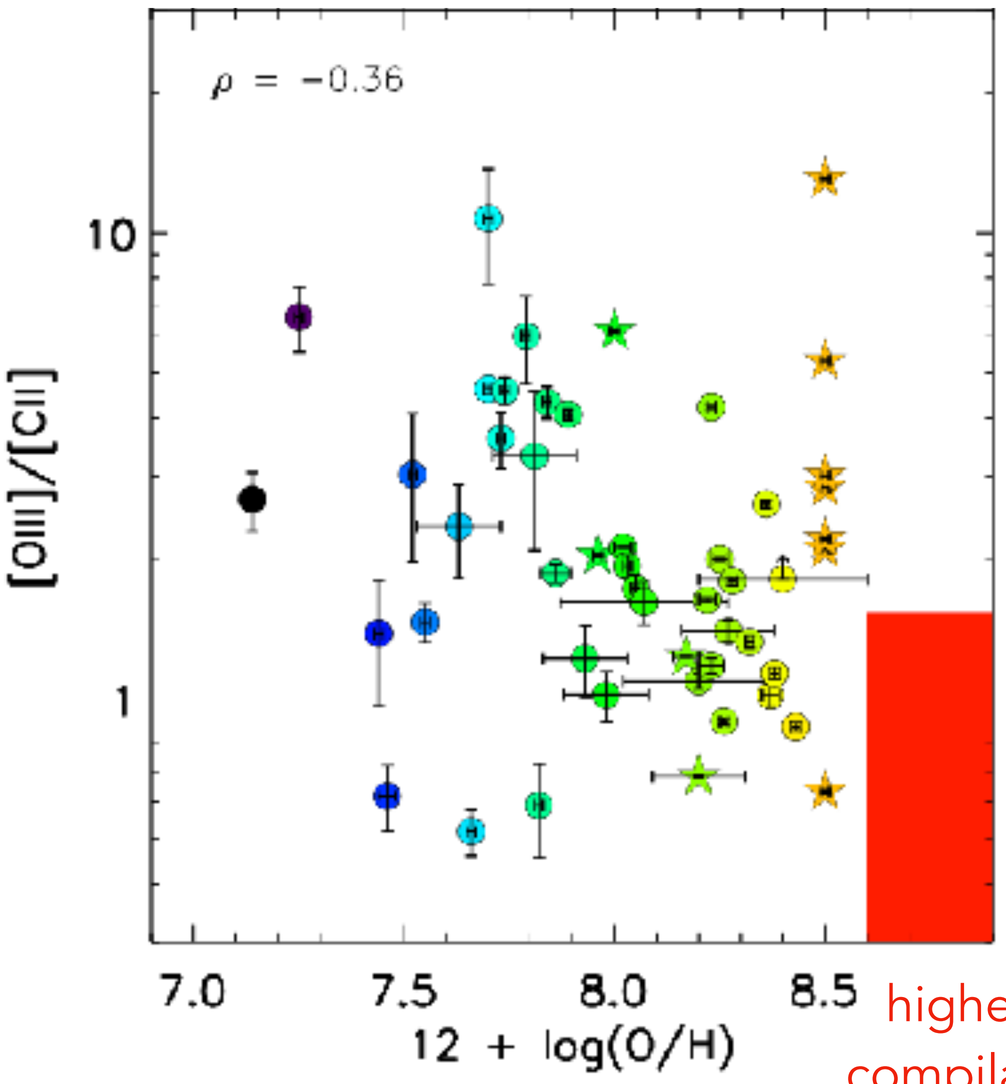


higher Z
compilation

[OIII] 88 μm is the brightest far-IR line observed in dwarf galaxies.

Cormier et al. 2015 - https://ui.adsabs.harvard.edu/abs/2015A%26A...578A..53C/

Ionized ISM

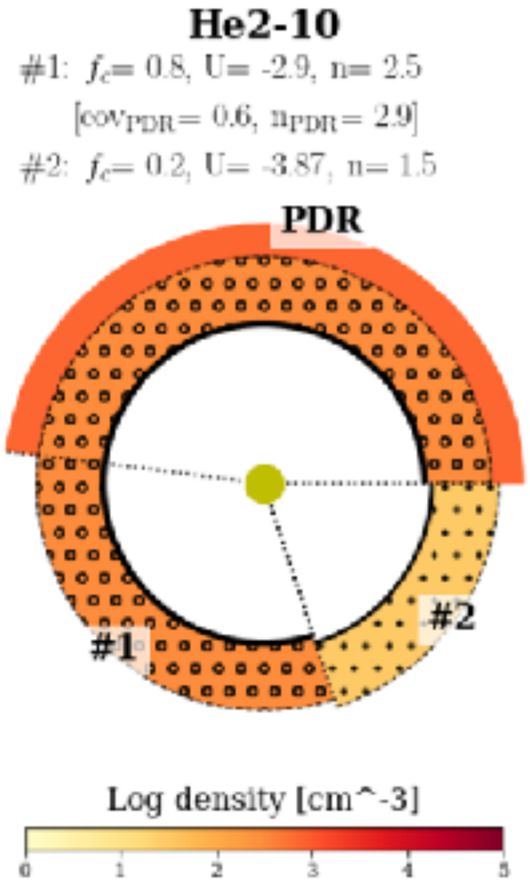


higher Z
compilation

Cormier et al. 2015 - https://ui.adsabs.harvard.edu/abs/2015A%26A...578A..53C/

[OIII] 88 µm is the brightest far-IR line observed in dwarf galaxies.

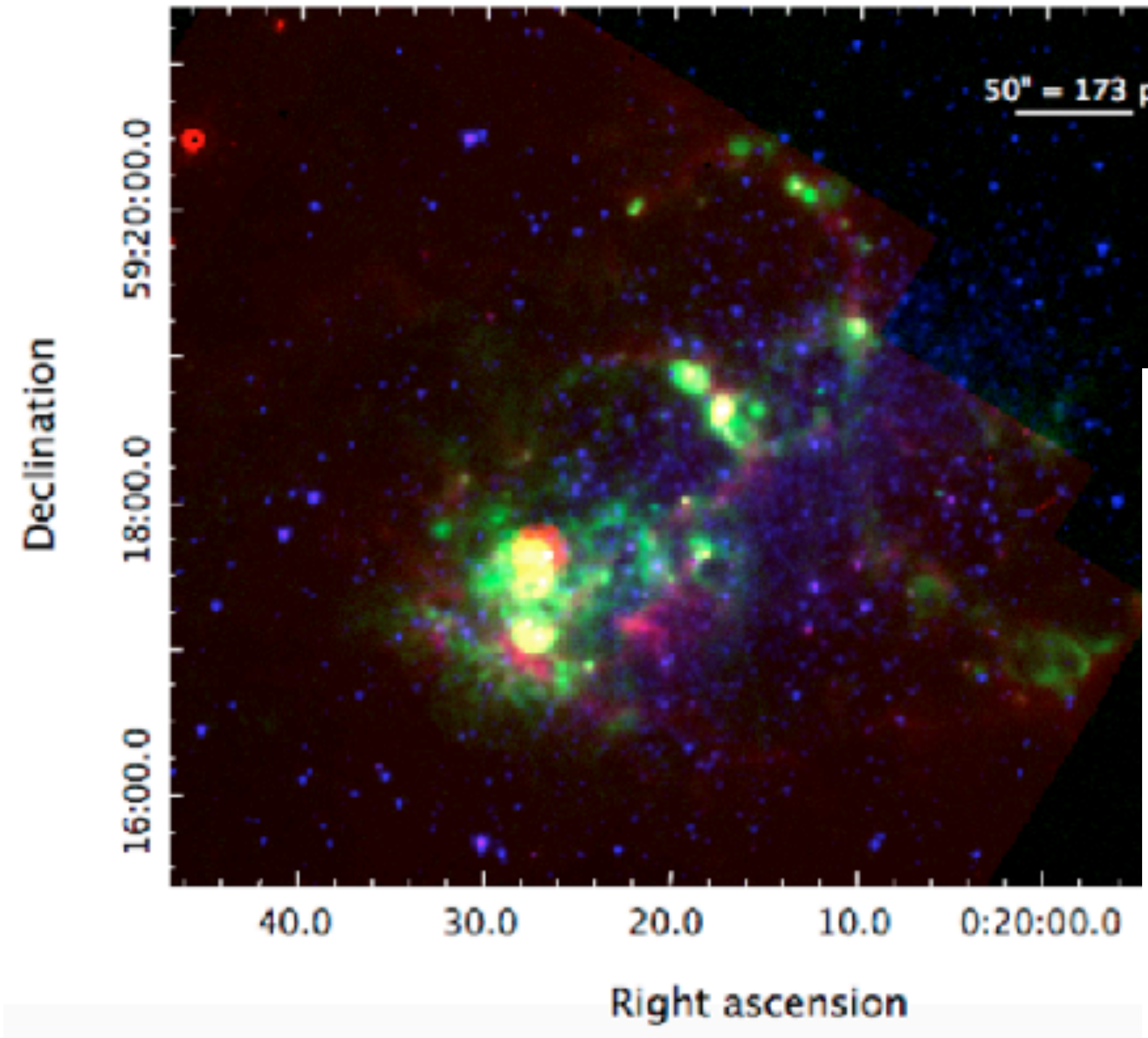
Multi-line modeling of ISM emission in dwarfs shows:
higher ionization parameter
more porous ISM to ionizing photons



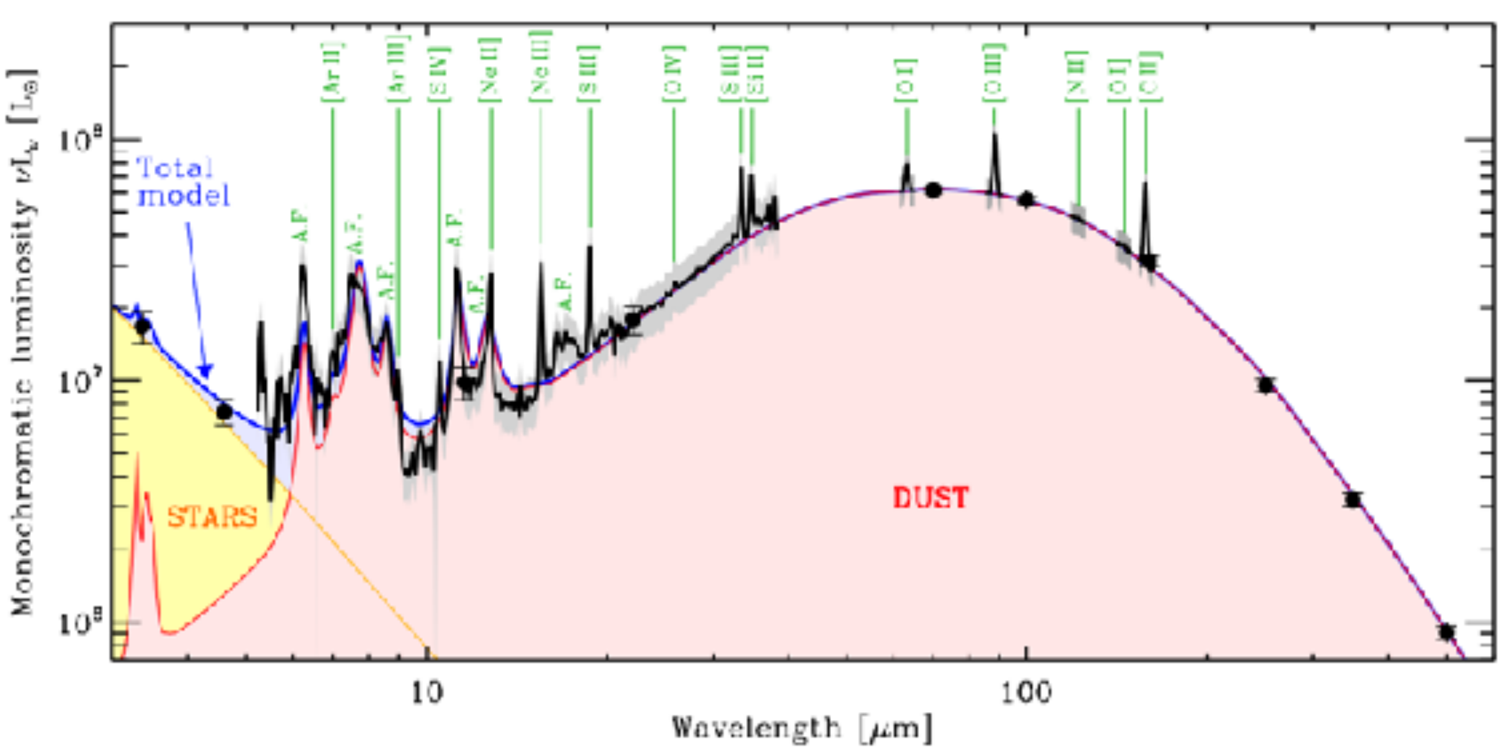
May be related to escape of Lyman continuum photons in high-z galaxies, important for reionization.

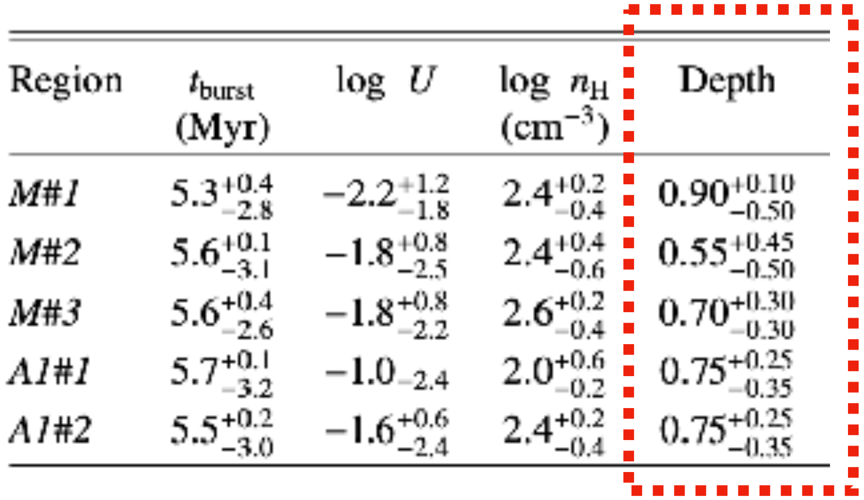
Cormier et al. 2019 - https://ui.adsabs.harvard.edu/abs/2019A%26A...626A..23C/

Ionized ISM



Modeling of mid- and far-IR emission lines from IC 10 show significant portion of ionizing photons can escape SF regions.



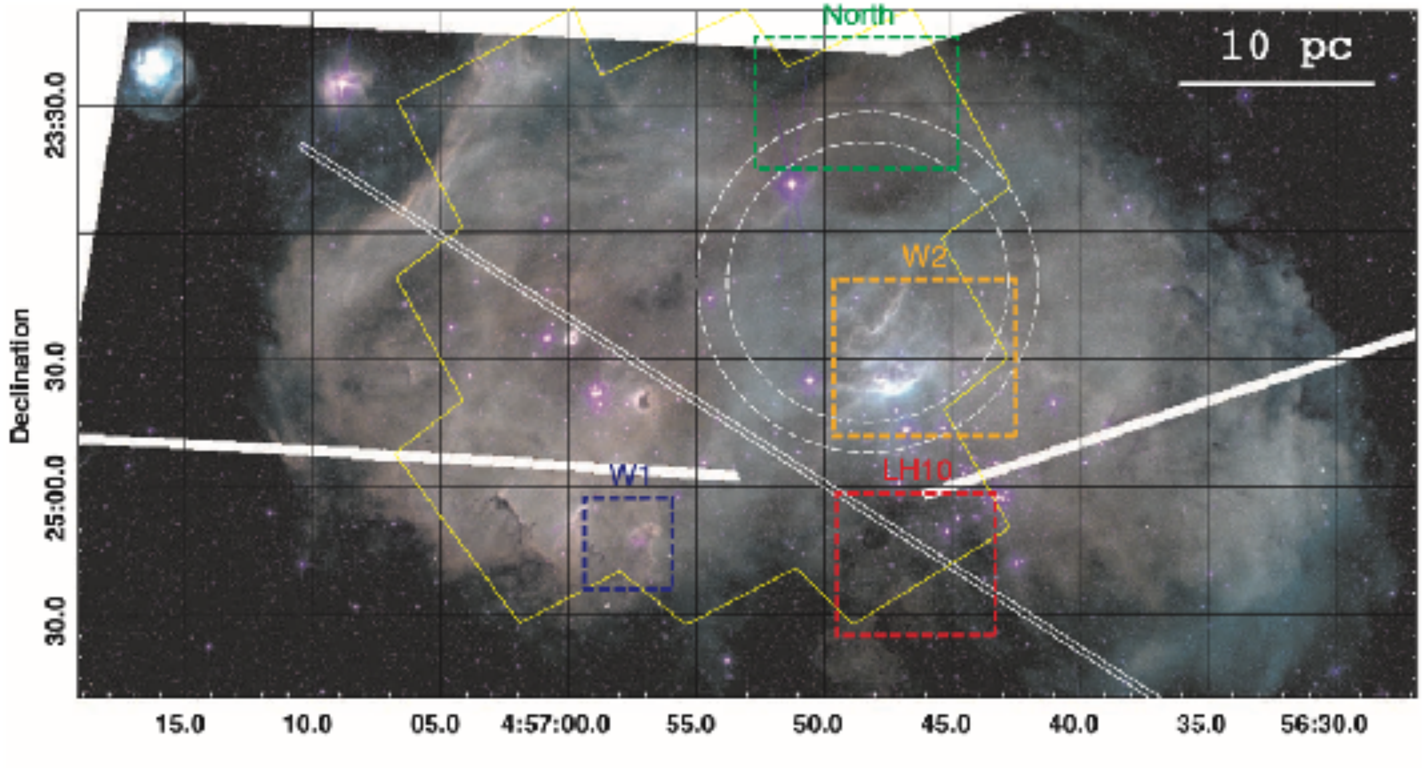


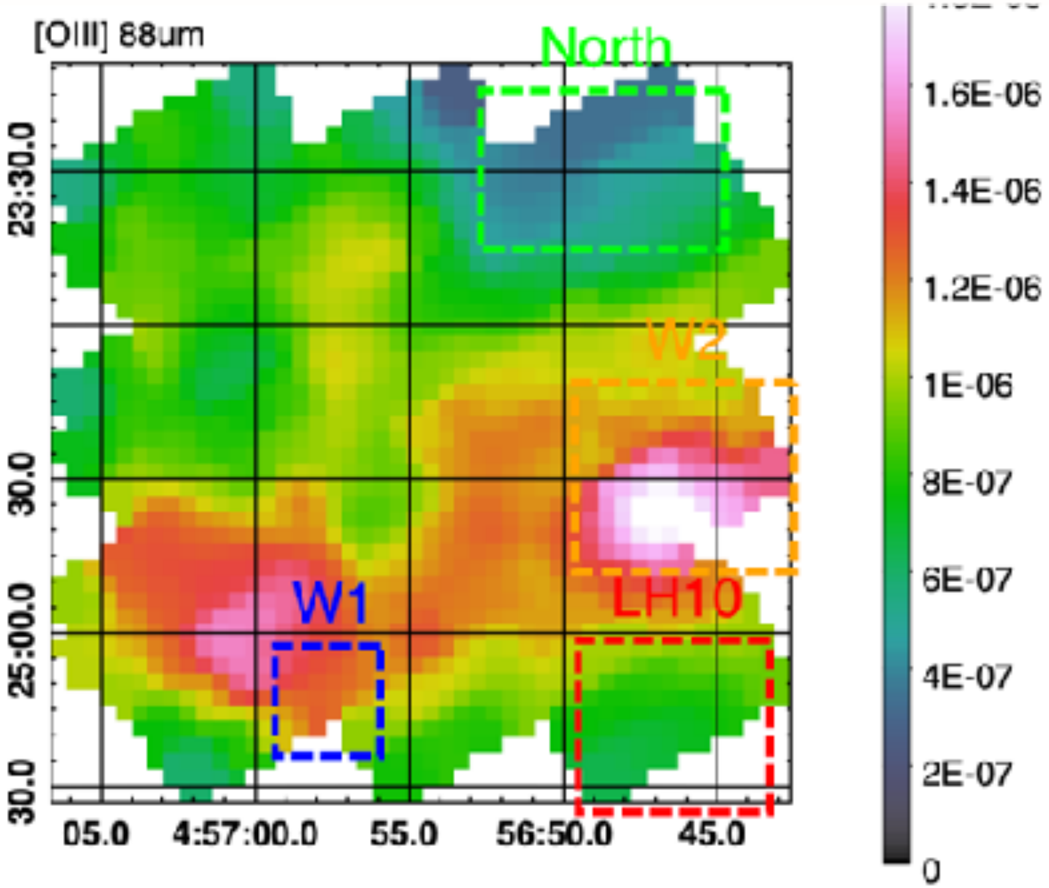
Region	$t_{\rm burst}$ (Myr)	log U	log $n_{\rm H}$ (cm^{-3})	Depth
M#1	$5.3^{+0.4}_{-2.8}$	$-2.2^{+1.2}_{-1.8}$	$2.4^{+0.2}_{-0.4}$	$0.90^{+0.10}_{-0.50}$
M#2	$5.6^{+0.1}_{-3.1}$	$-1.8^{+0.8}_{-2.5}$	$2.4^{+0.4}_{-0.6}$	$0.55^{+0.45}_{-0.50}$
M#3	$5.6^{+0.4}_{-2.6}$	$-1.8^{+0.8}_{-2.2}$	$2.6^{+0.2}_{-0.4}$	$0.70^{+0.30}_{-0.30}$
A1#1	$5.7^{+0.1}_{-3.2}$	$-1.0_{-2.4}$	$2.0^{+0.6}_{-0.2}$	$0.75^{+0.25}_{-0.35}$
A1#2	$5.5^{+0.2}_{-3.0}$	$-1.6^{+0.6}_{-2.4}$	$2.4^{+0.2}_{-0.4}$	$0.75^{+0.25}_{-0.35}$

Depth < 1 suggests “matter-bounded” HII regions where ionizing photons can escape.

Polles et al. 2019 - https://ui.adsabs.harvard.edu/abs/2019A%26A...622A.119P/

Ionized ISM





Extended [OIII] 88 µm emission observed in Magellanic Clouds.

Diffuse ionized gas is pervasive, suggests that ionizing photons can travel significant distances from HII regions.

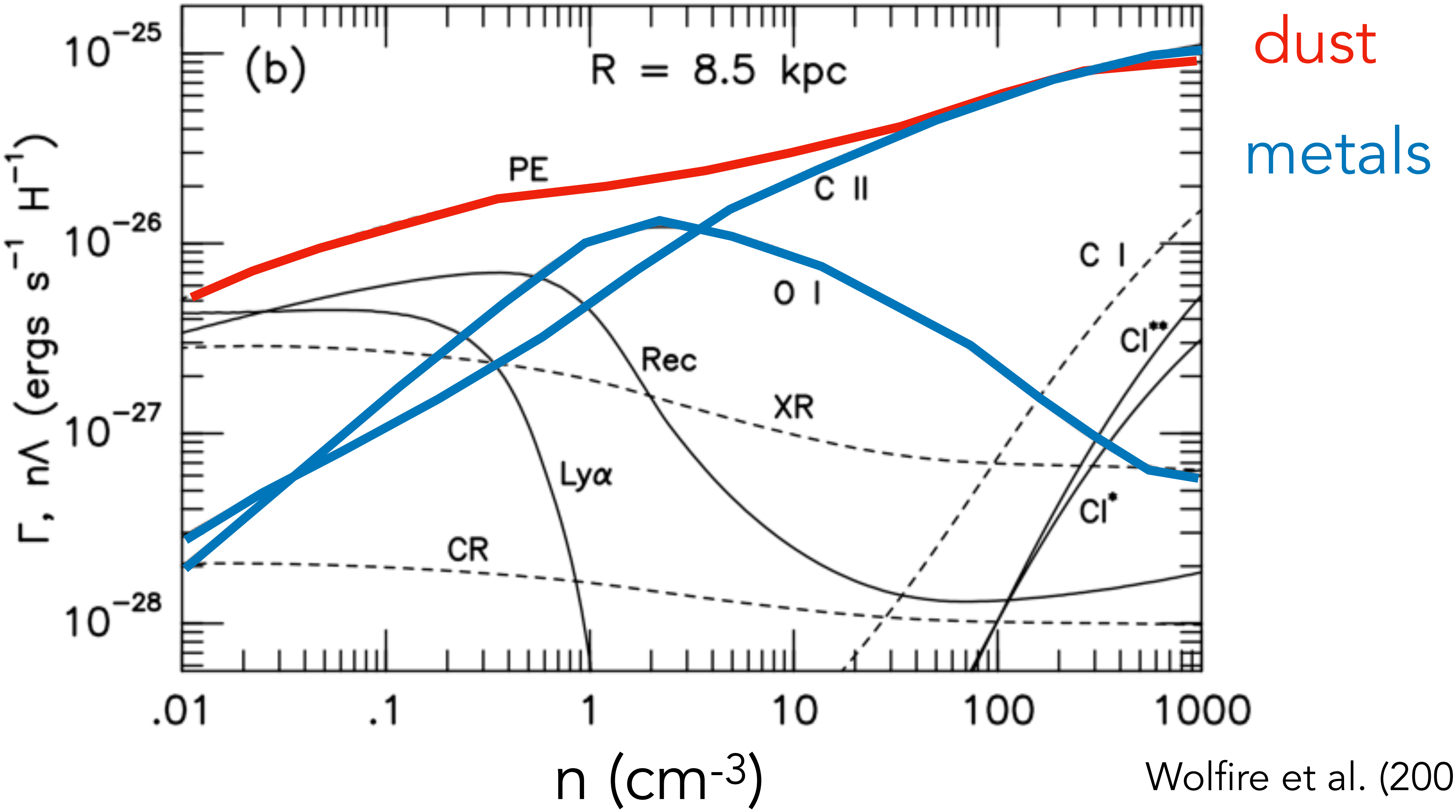
Low density channels, high porosity

Lebouteiller et al. 2012 - https://ui.adsabs.harvard.edu/abs/2012A%26A...548A..91L/

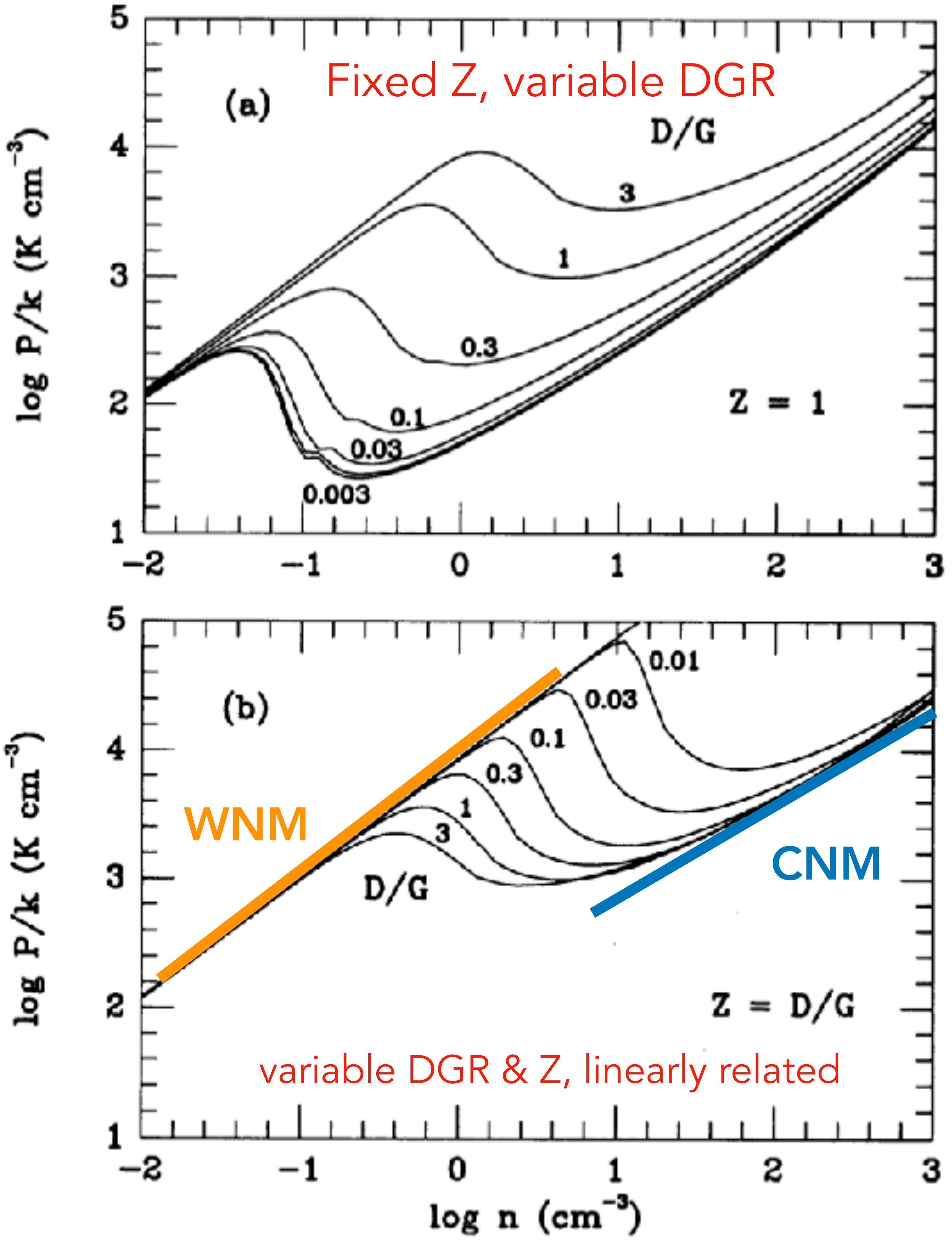
see also Kawada et al. 2011

Atomic ISM

Changes in both heating and cooling in atomic gas



Wolfire et al. (2003)

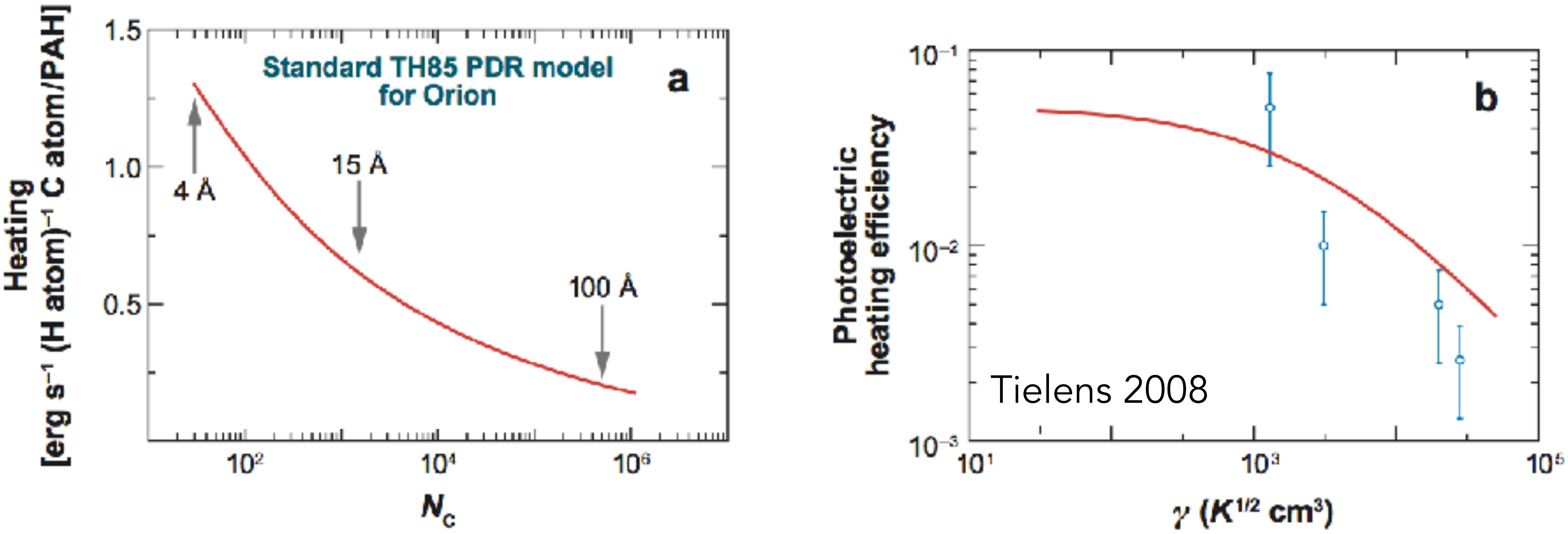


Wolfire et al. (1995)

Changes in metallicity and dust-to-gas ratio have a direct impact on the existence and properties (n, T) of equilibrium phases.

Atomic ISM

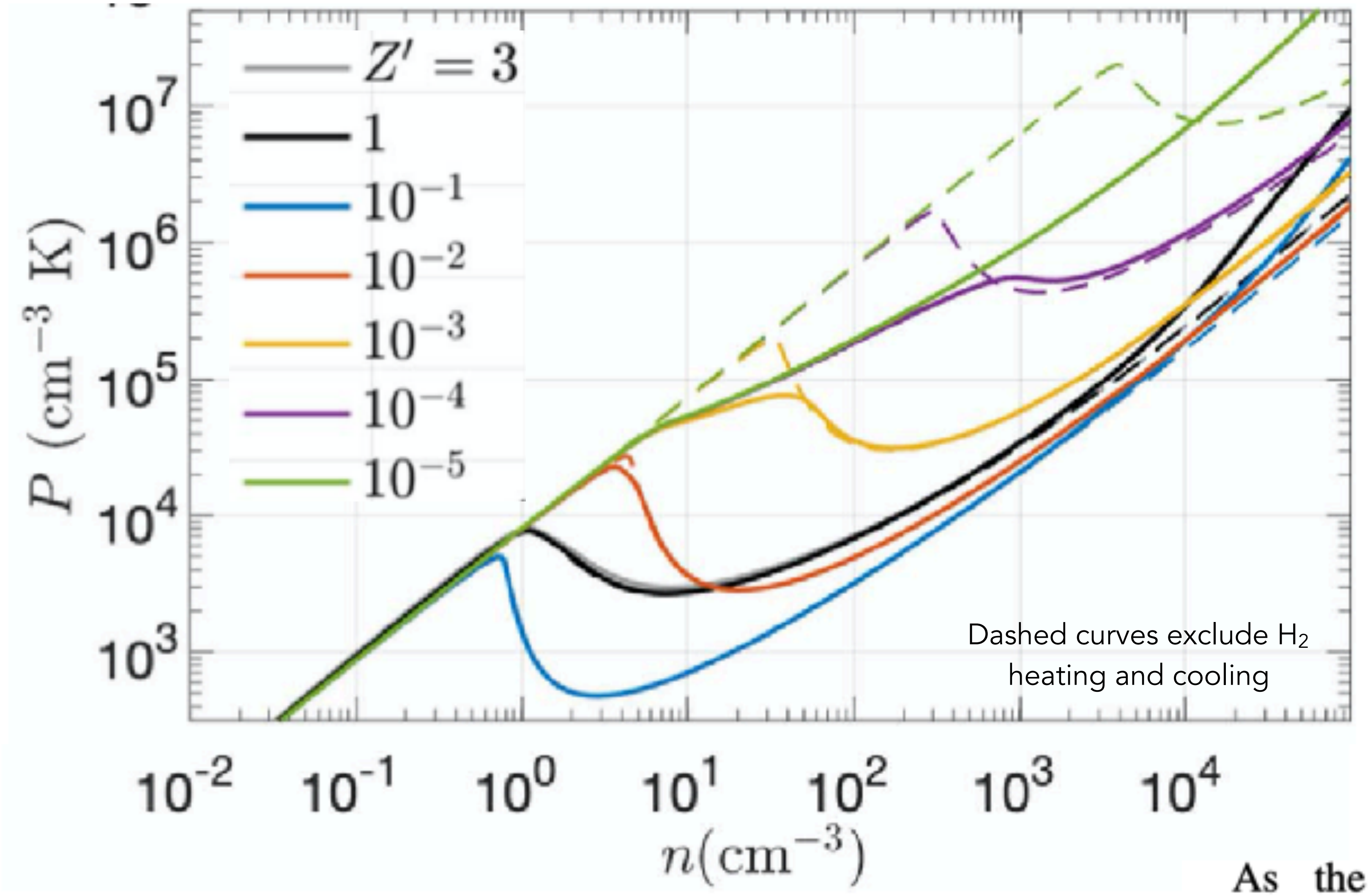
<u>Photoelectric Effect Efficiency</u> depends on PAH abundance, size distribution, and charge of grains!



Tielens 2008

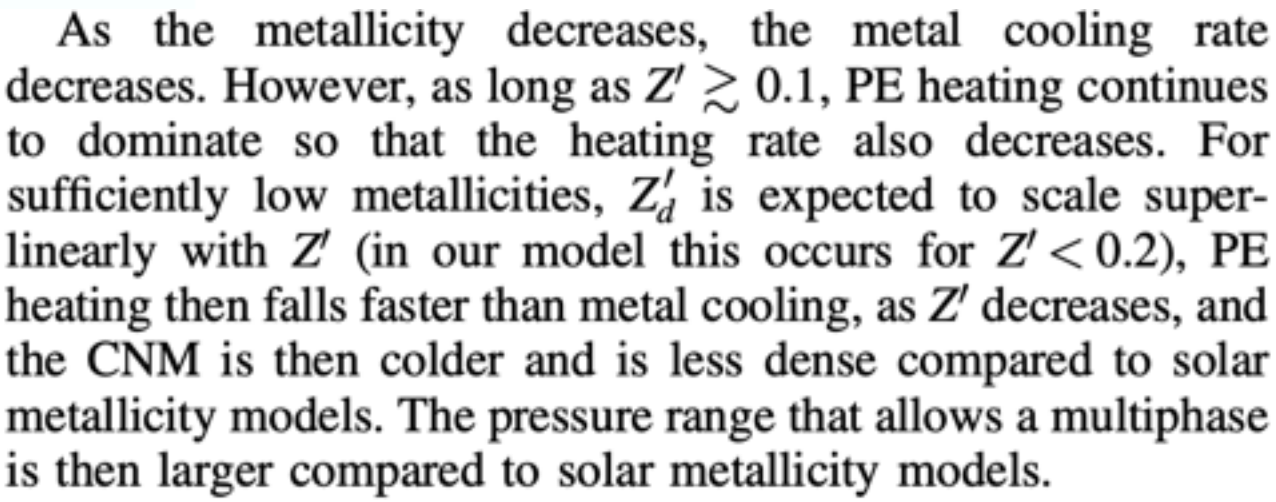
Variation of PAH fraction, size distribution, and charge at low metallicity can matter for setting ISM phase structure.

Atomic ISM



Dashed curves exclude H_2 heating and cooling

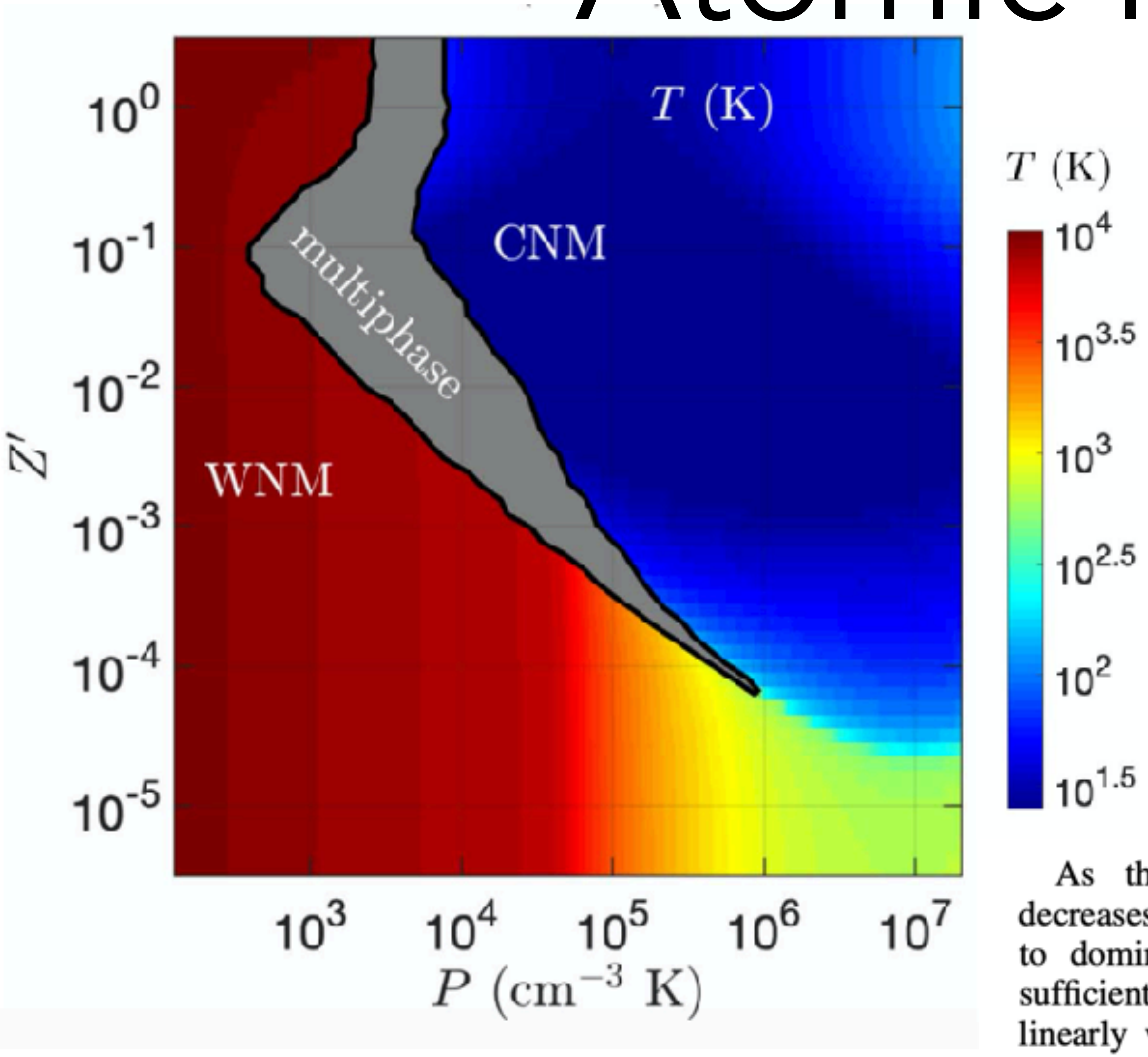
Changing metallicity alters the pressure needed to have multi phase atomic gas, temperature of CNM, fraction of gas in each phase.



As the metallicity decreases, the metal cooling rate decreases. However, as long as $Z' \gtrsim 0.1$, PE heating continues to dominate so that the heating rate also decreases. For sufficiently low metallicities, Z'_d is expected to scale super-linearly with Z' (in our model this occurs for $Z' < 0.2$), PE heating then falls faster than metal cooling, as Z' decreases, and the CNM is then colder and is less dense compared to solar metallicity models. The pressure range that allows a multiphase is then larger compared to solar metallicity models.

Bialy & Sternberg 2019 - https://ui.adsabs.harvard.edu/abs/2019ApJ...881..160B/

Atomic ISM



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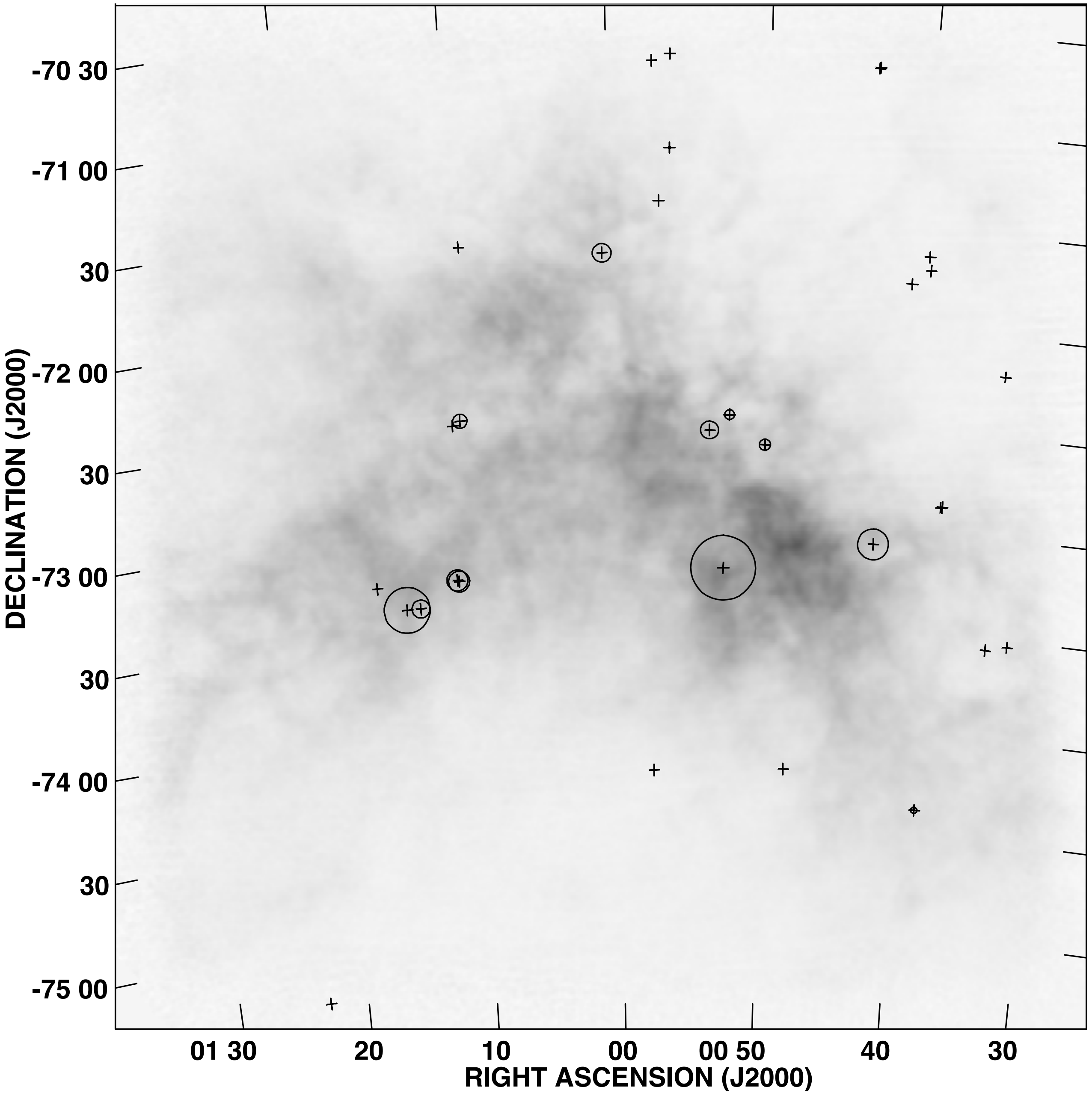
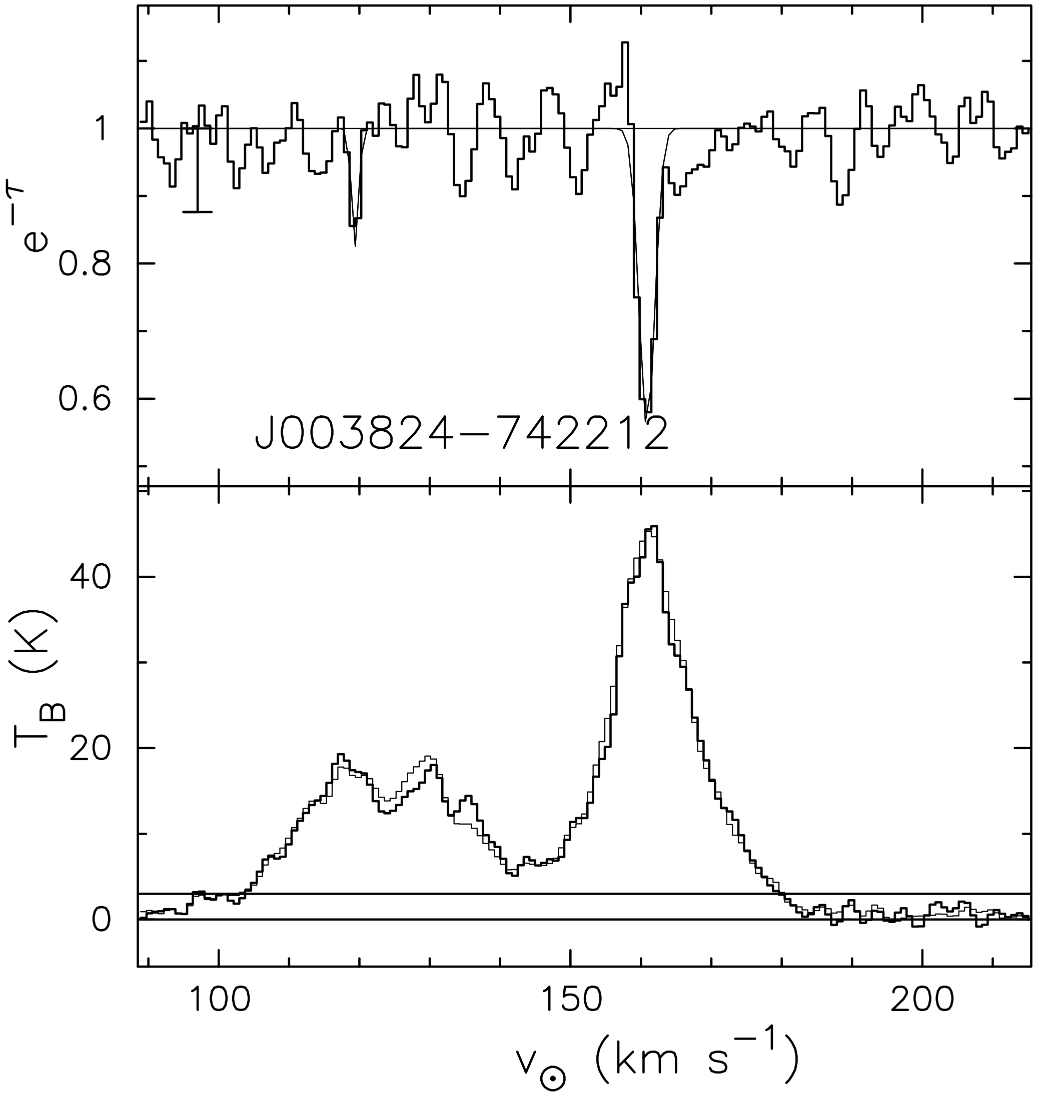
Bialy & Sternberg 2019 - https://ui.adsabs.harvard.edu/abs/2019ApJ...881..160B/

Atomic ISM

SMC HI absorption towards 13 background radio sources

f_{CNM} ~ 15%, T_{CNM} ~ 40 K



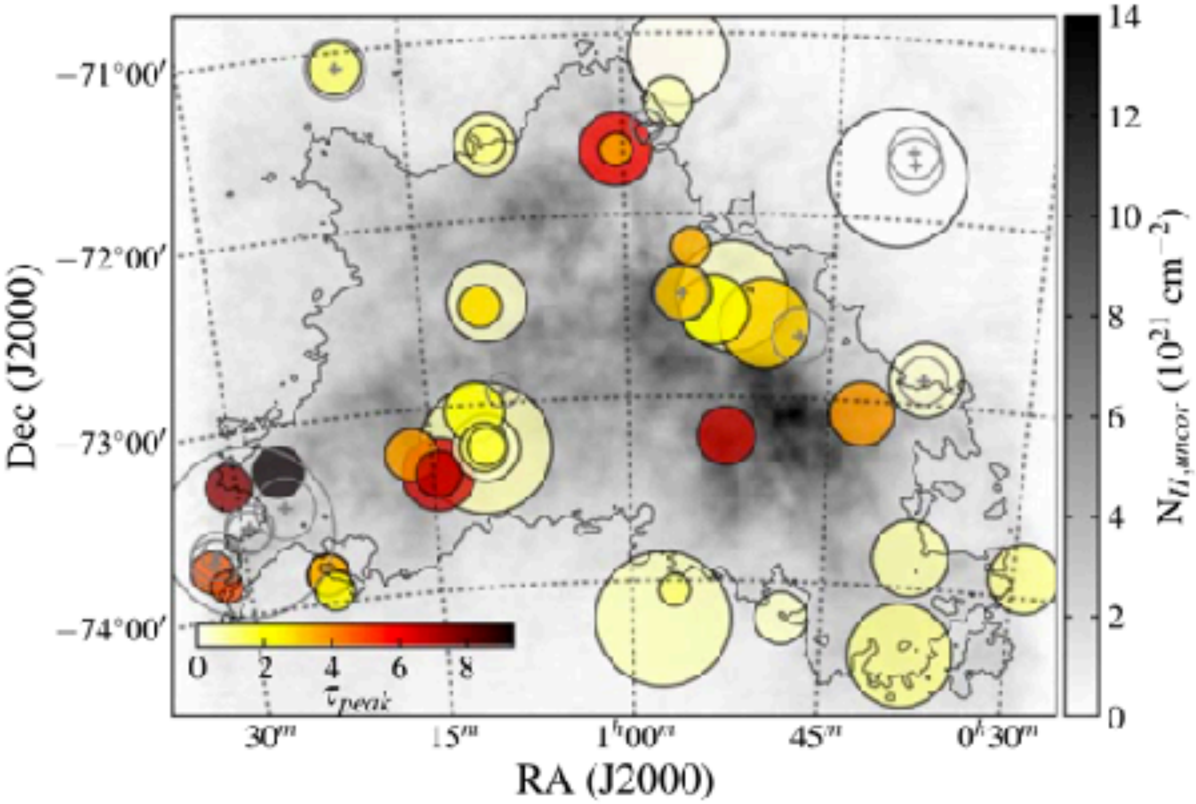


Dickey et al. 2000 - https://ui.adsabs.harvard.edu/abs/2000ApJ...536..756D/

Atomic ISM

SMC HI absorption towards 37 background radio sources

f_{CNM} ~ 20%, T_{CNM} ~ 30 K



Jameson et al. 2019 - https://ui.adsabs.harvard.edu/abs/2019ApJS..244....7J/

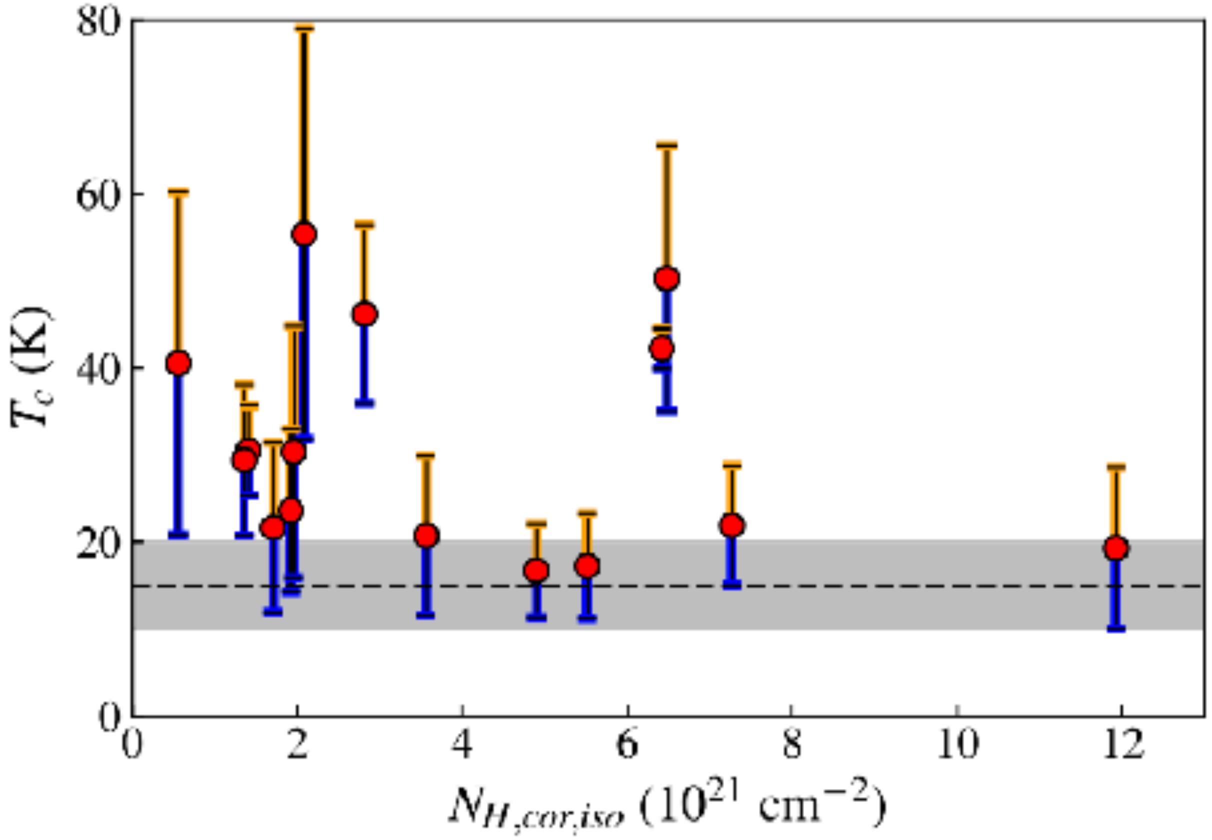
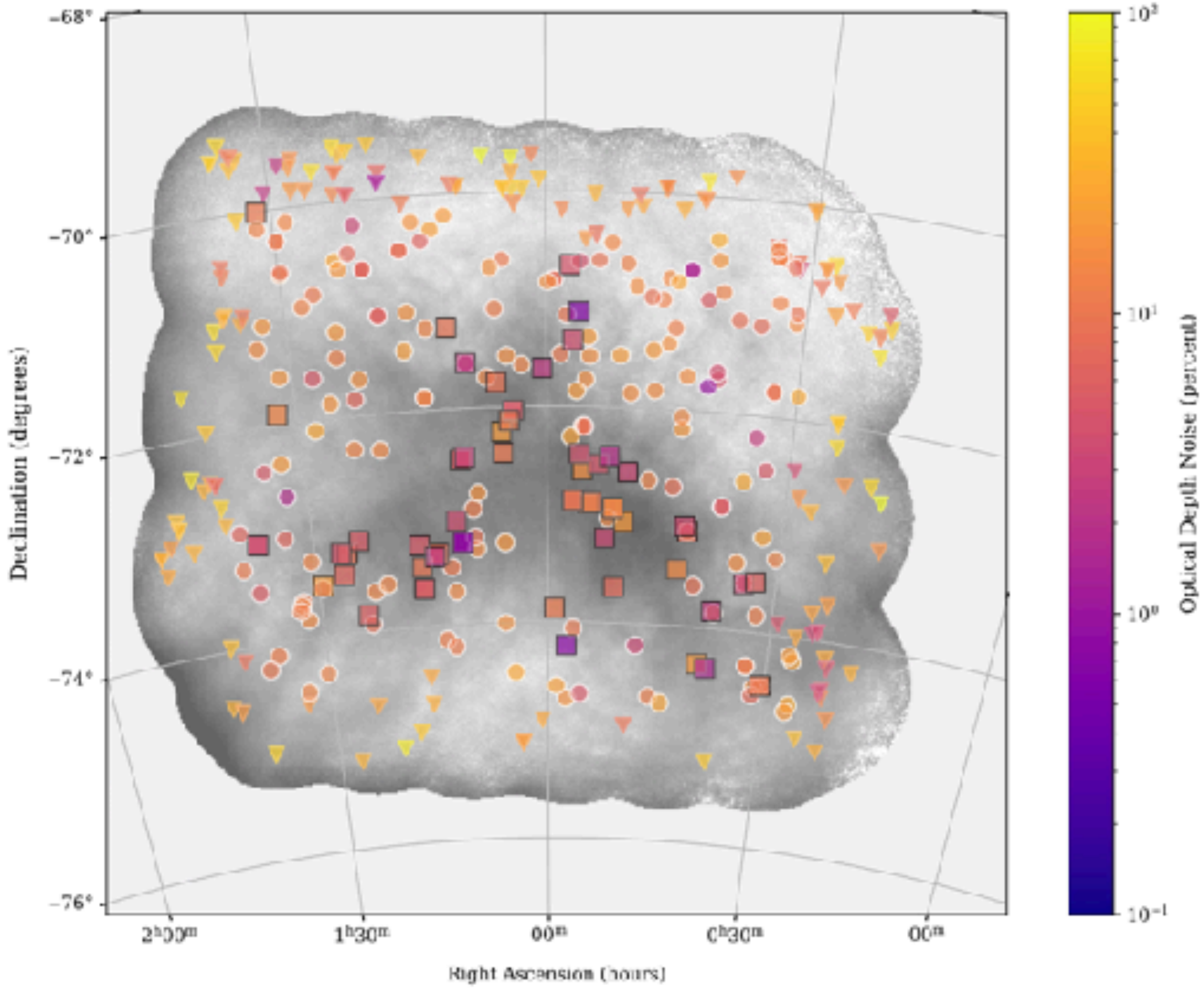


Figure 13. Cold H I gas temperature (T_c) vs. total H I column density. The red points show the T_c estimate for $q = 0.5$, and the error bars show the range of possible T_c from assuming $q = 0.25$ (lower limit in blue) and $q = 0.75$ (upper limit in orange). The dashed line shows $T_c = 15$ K, with the gray shaded area showing ±5 K that accounts for the range of values based on assumed q, which appears to be a floor in the cold gas temperatures.

Atomic ISM



Dempsey et al. 2022 - https://ui.adsabs.harvard.edu/abs/2022PASA...39...34D/

GASKAP pilot survey of SMC absorption - 229 sources

$f_{CNM} = 11\%$

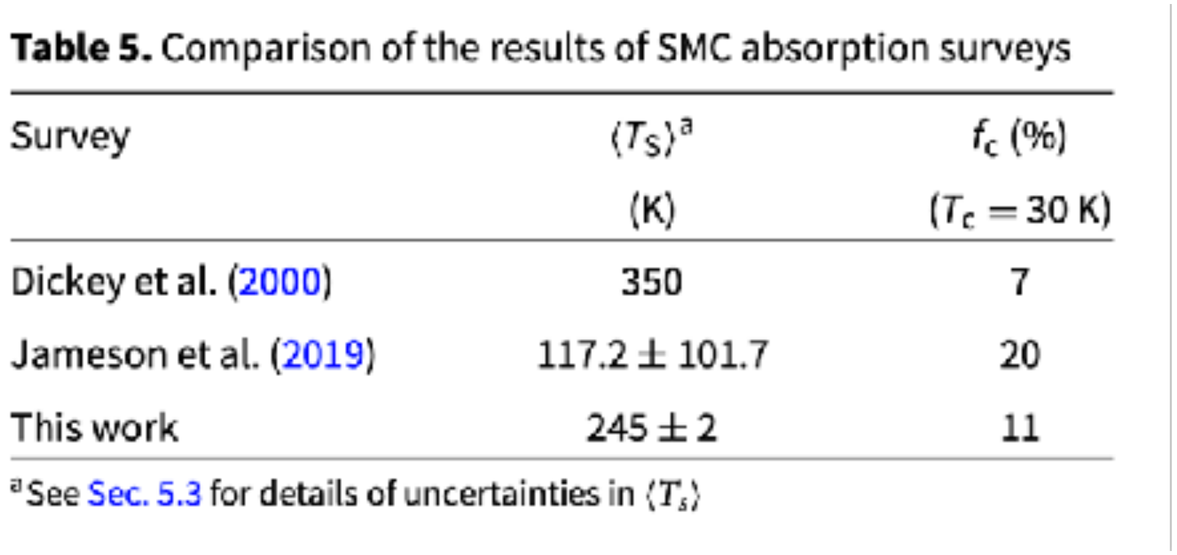


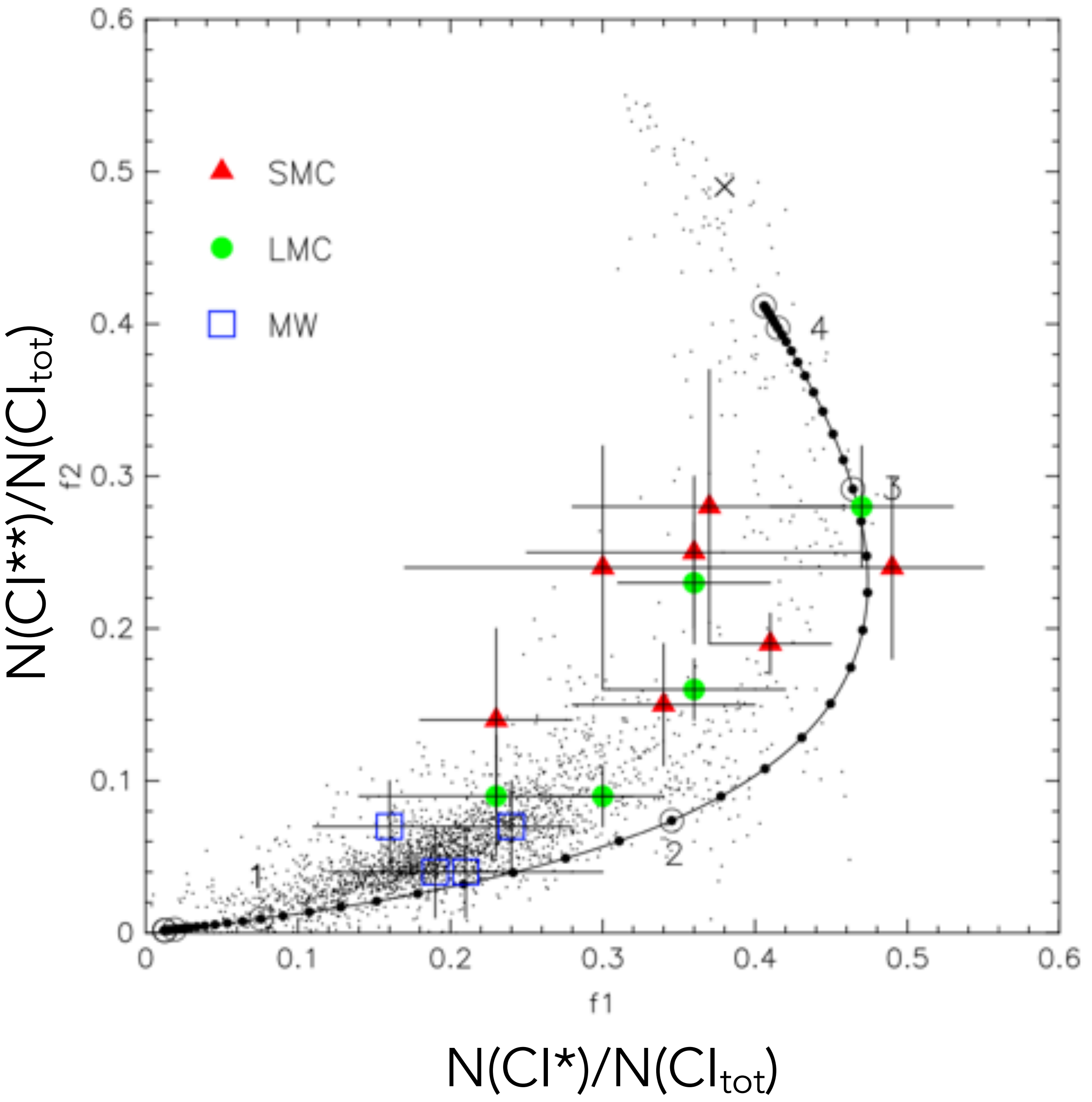
Table 5. Comparison of the results of SMC absorption surveys

Survey	$\langle T_S \rangle^a$ (K)	f_c (%) ($T_c = 30$ K)
Dickey et al. (2000)	350	7
Jameson et al. (2019)	117.2 ± 101.7	20
This work	245 ± 2	11

[a] See Sec. 5.3 for details of uncertainties in $\langle T_s \rangle$

SMC has: Low CNM fraction, probably lower CNM temperature.

Atomic ISM



Welty et al. 2016 - https://ui.adsabs.harvard.edu/abs/2016ApJ...821..118W/

Thermal pressure in CNM from CI, CI*, CI** (in WNM, C is ~fully ionized)

Thermal pressures in LMC & SMC CNM are ~several times higher in MW ISM.

Consistent with predictions from models that higher thermal pressures are needed to obtain stable cold, neutral clouds at low Z.

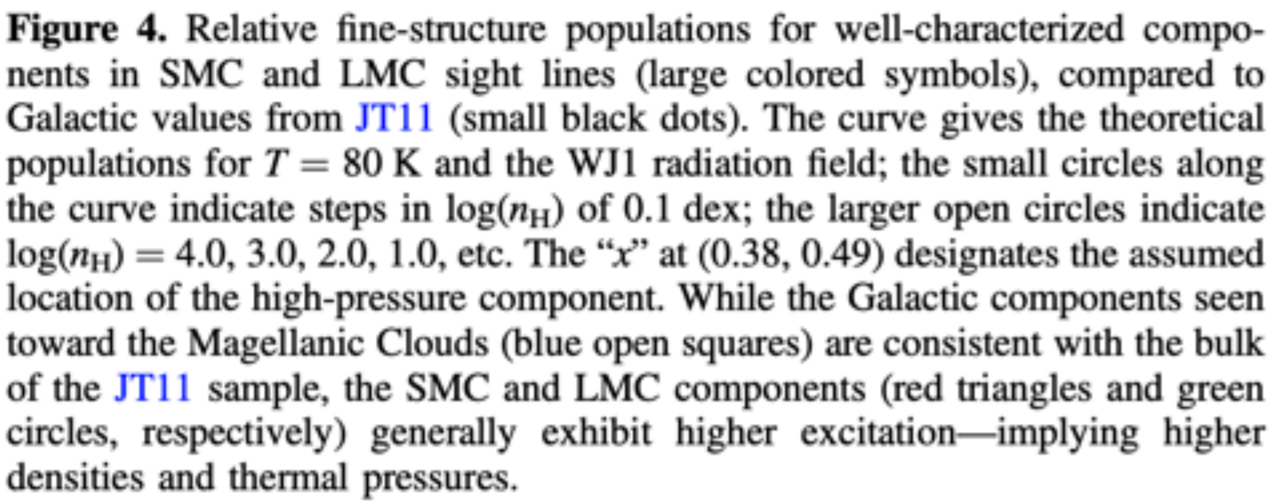
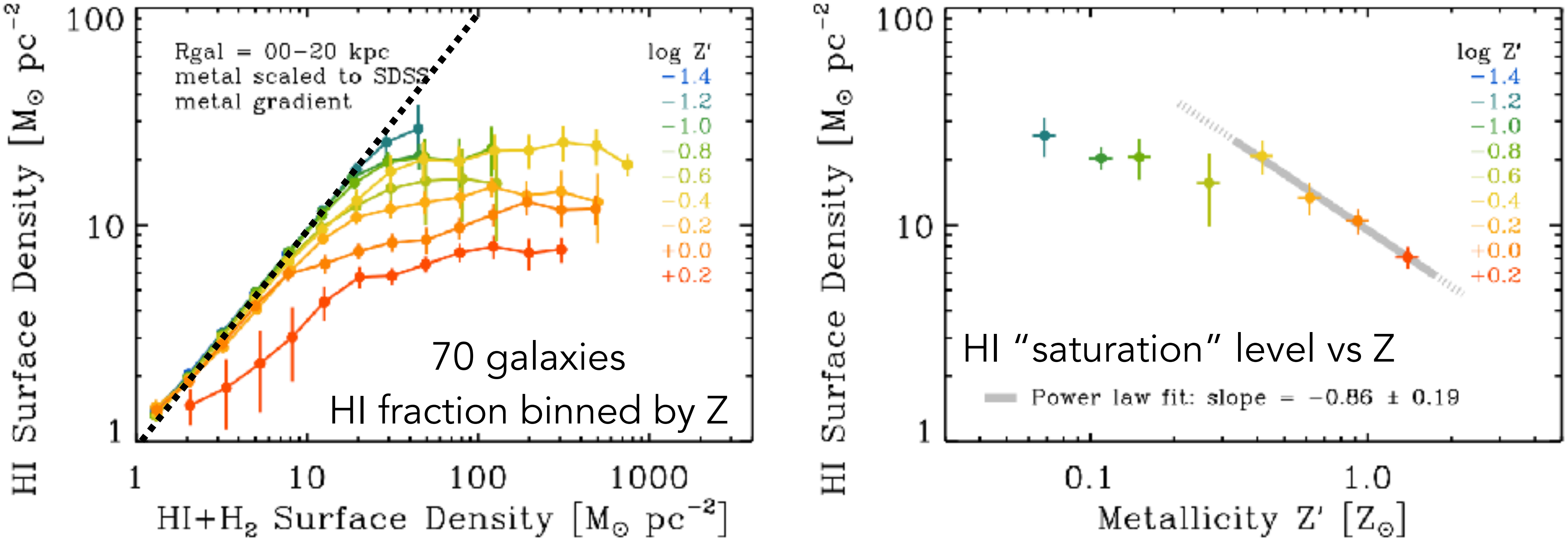


Figure 4. Relative fine-structure populations for well-characterized components in SMC and LMC sight lines (large colored symbols), compared to Galactic values from JT11 (small black dots). The curve gives the theoretical populations for $T = 80$ K and the WJ1 radiation field; the small circles along the curve indicate steps in $\log(n_H)$ of 0.1 dex; the larger open circles indicate $\log(n_H) = 4.0, 3.0, 2.0, 1.0$, etc. The "$x$" at (0.38, 0.49) designates the assumed location of the high-pressure component. While the Galactic components seen toward the Magellanic Clouds (blue open squares) are consistent with the bulk of the JT11 sample, the SMC and LMC components (red triangles and green circles, respectively) generally exhibit higher excitation—implying higher densities and thermal pressures.

Atomic ISM

Forming H_2 out of diffuse neutral ISM

Schruba, Bialy & Sternberg 2018



70 galaxies

HI fraction binned by Z

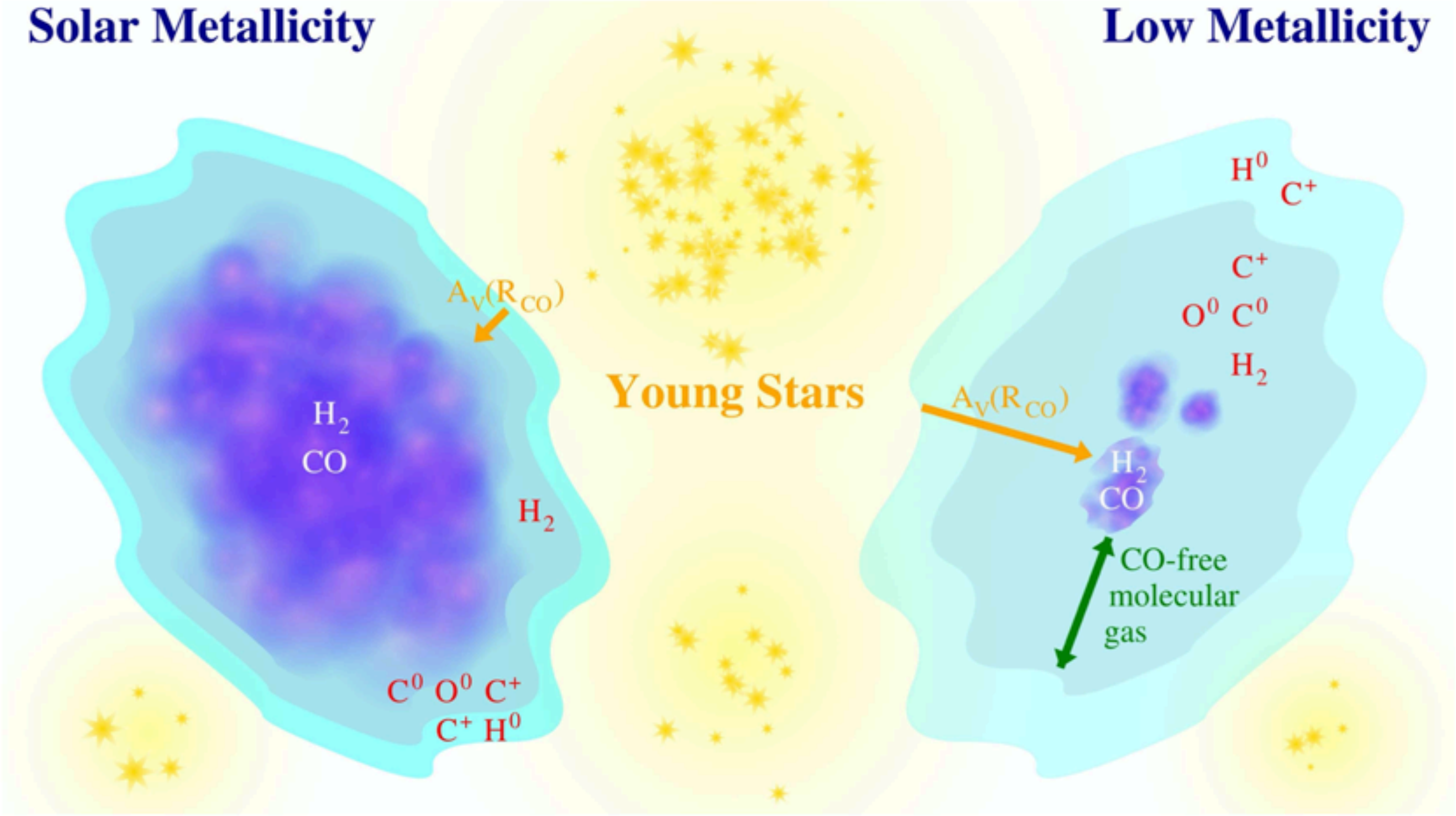
HI “saturation” level vs Z

Max HI surface density decreases with Z,
transition to H_2 occurs at higher Σ consistent with
dust shielding governing HI-to-H_2 transition.

Atomic Gas Summary

- Evidence for lower CNM fractions, colder CNM temperatures in Magellanic Clouds.
- Evidence for higher CNM pressure from UV CI lines.
- This is in good agreement with what thermal instability models predict given changes in heating/cooling.
- Transition from HI to H_2 occurs at higher HI surface density, as expected from shielding models.

Molecular ISM

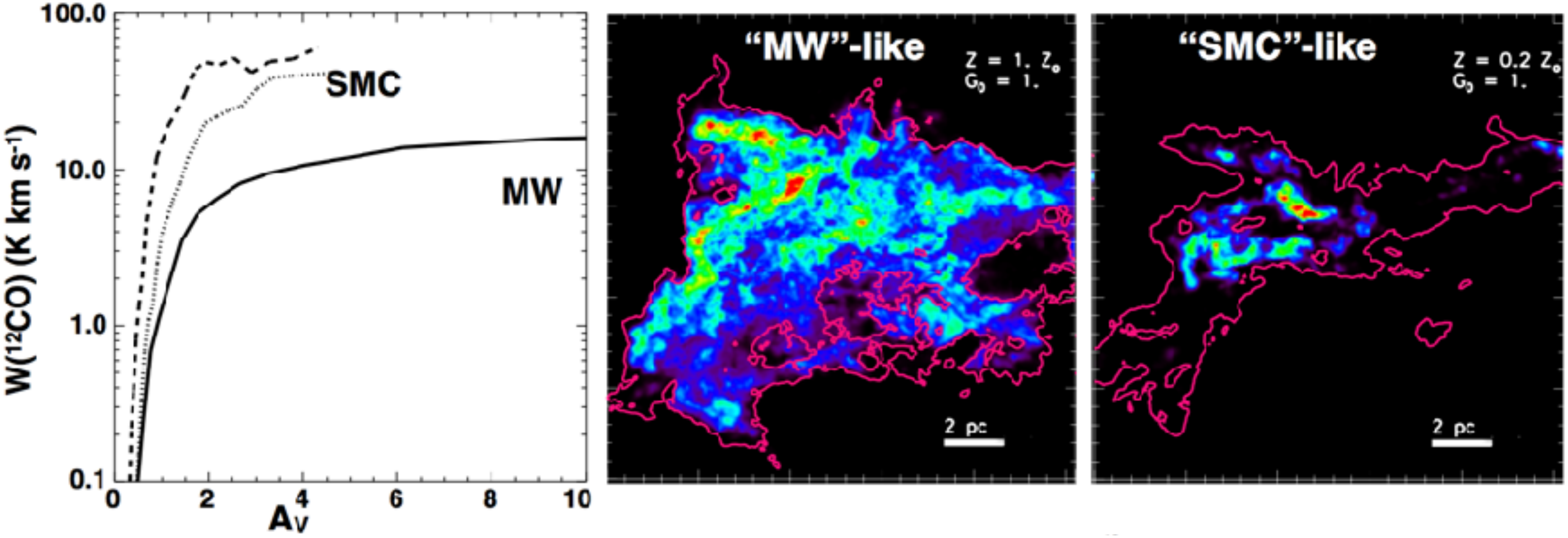


Madden et al. 2020 - https://ui.adsabs.harvard.edu/abs/2020A%26A...643A.141M/

Molecular ISM

The trouble with CO…

Glover & Clark 2012



Molecular cloud simulations by S. Glover, color = CO integrated intensity

Dust grains are the site of H_2 formation and other chemical reactions.
Dust also shields molecules from UV radiation.

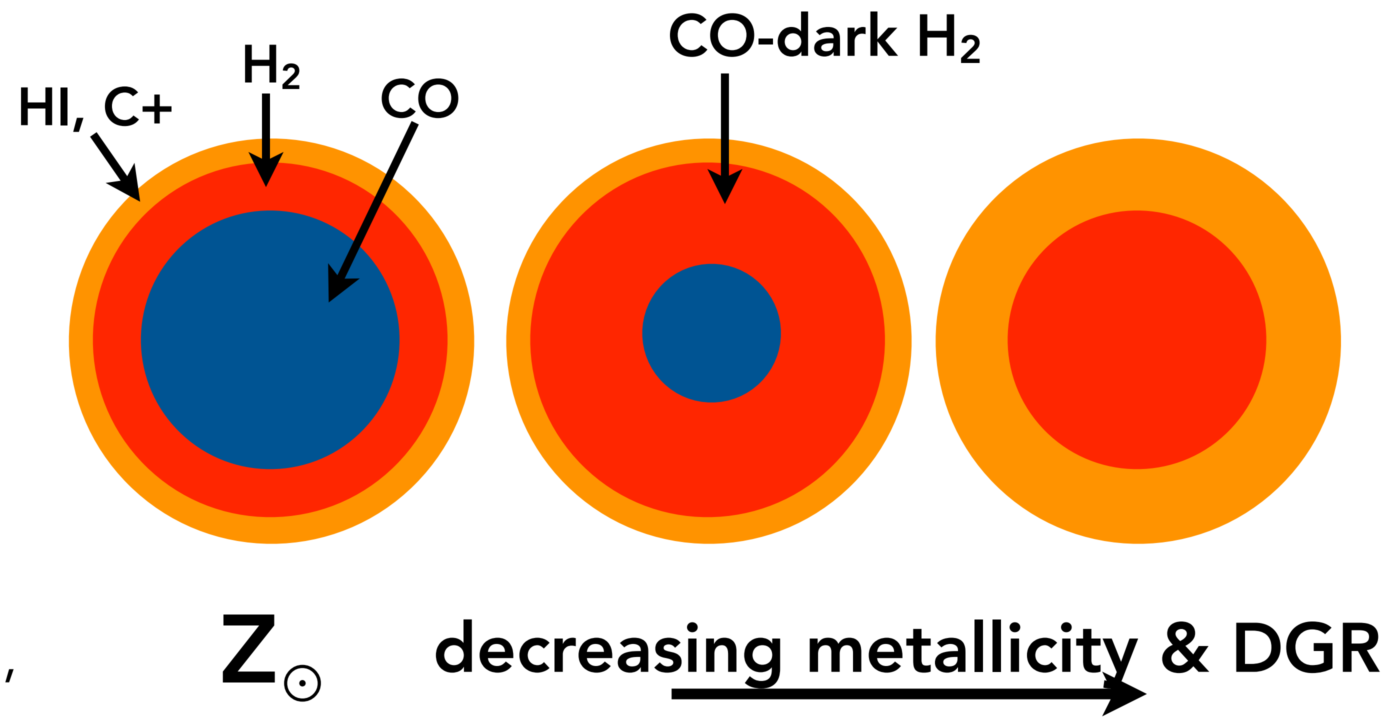
Molecular ISM

The trouble with CO…

At low metallicity, H_2 self-shields, but CO relies on dust.

When there is little dust, CO is photodissociated.

e.g. Maloney & Black 1988, Bolatto et al. 1999, Wolfire et al. 2010, Glover & Mac Low 2011



Molecular ISM

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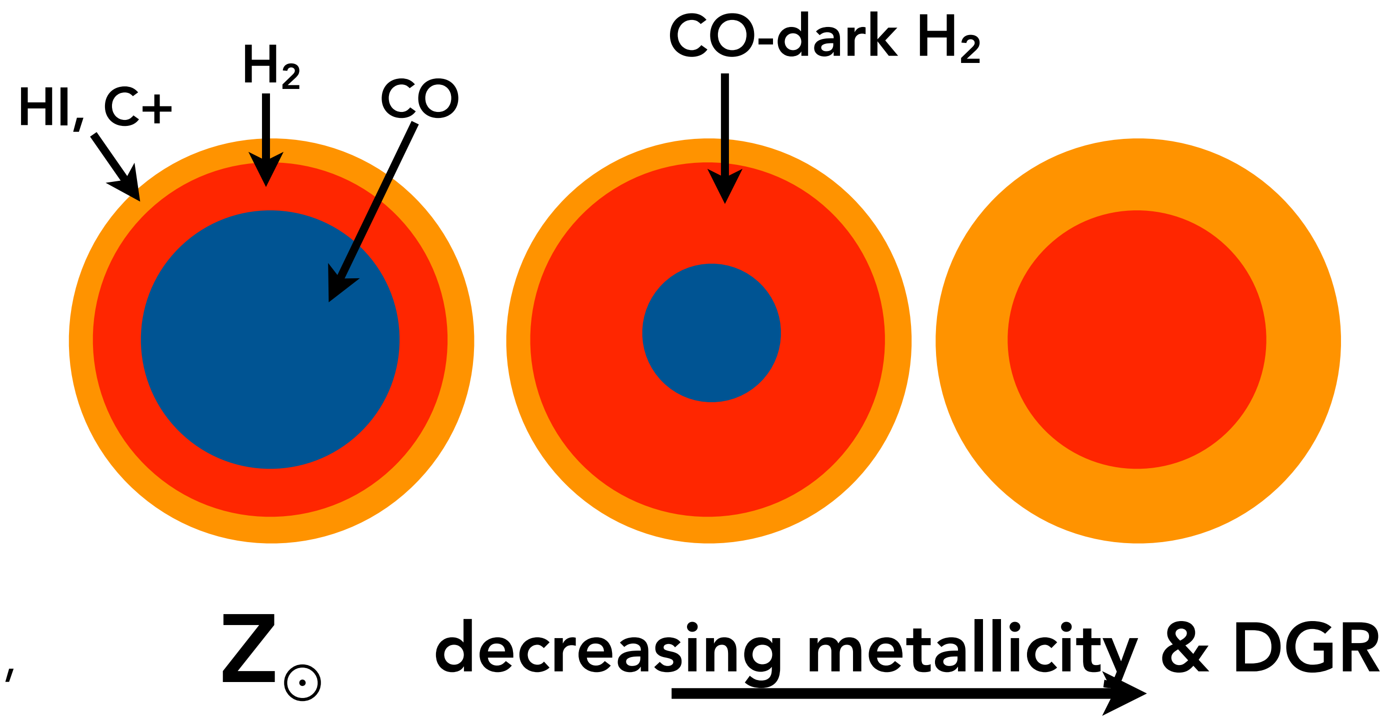


<u>Need to understand as a function of Z:</u>

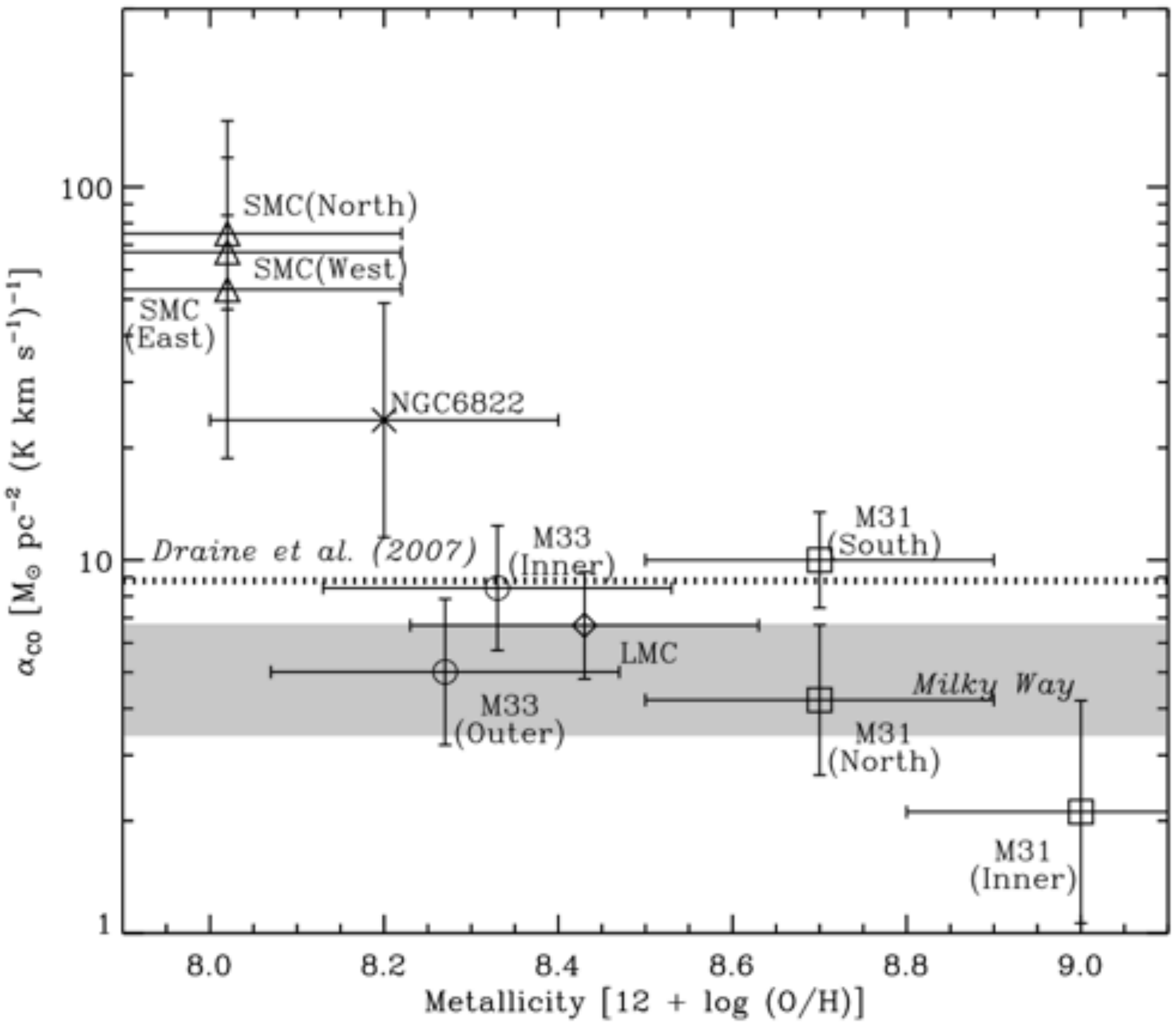
1) fraction of H_2 in "CO-dark" component,
2) CO-to-H_2 conversion factor in the "CO-bright" component,
3) what sets the transition between "CO-dark" and "CO-bright"

Tracing CO-Dark H_2 at Low Metallicity

- With dust
- With [CII]
- With CI
- By inverting the K-S law
- With H_2 rotational lines
- Other things?

Tracing CO-Dark H_2 at Low Metallicity

With dust



Use knowledge of DGR(Z), or by making resolved measurements of Dust/N(HI) and assuming it holds in H_2 as well, can turn dust into gas.

Subtract off HI, remaining is H_2, compare to CO.

* Key Issue: How do we know DGR and do we have to assume it is the same in HI and H_2?

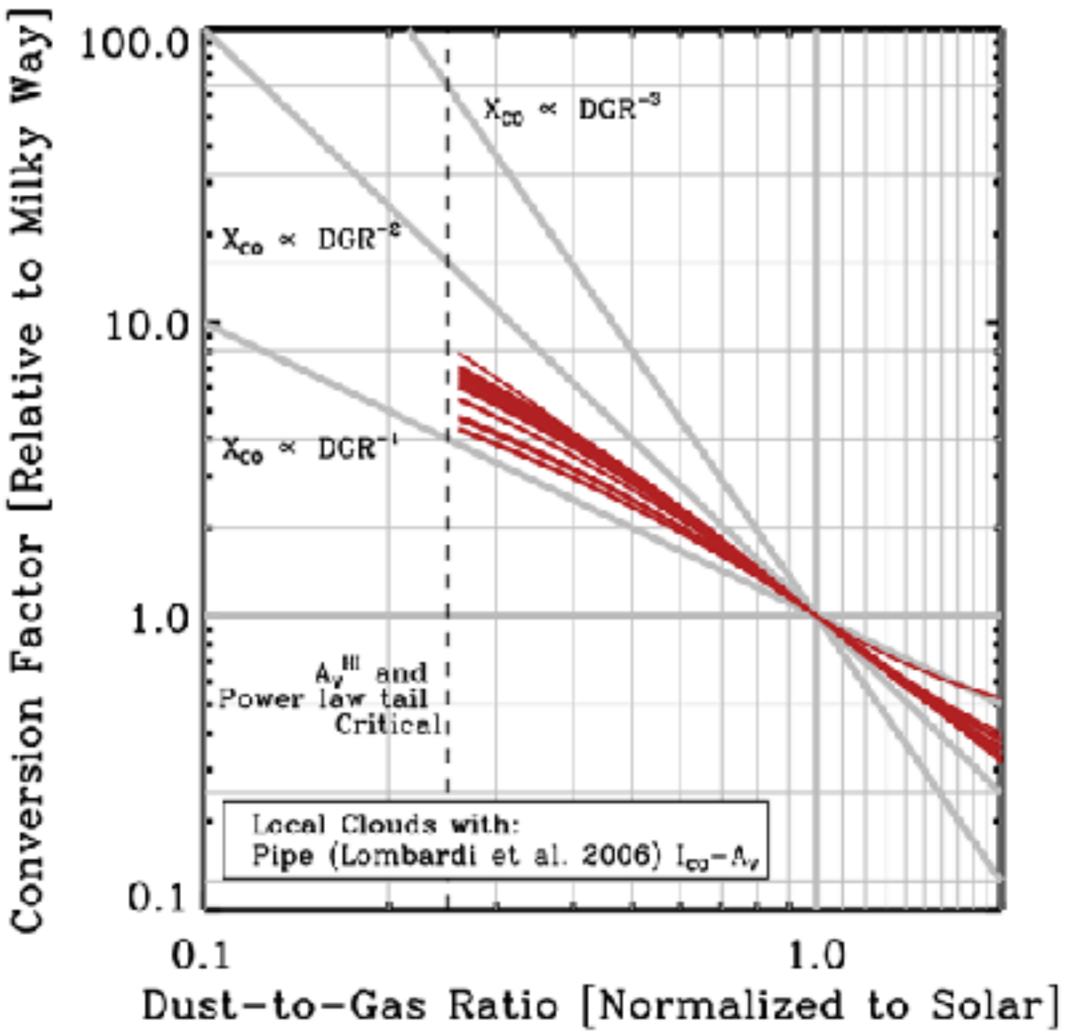
See also Leroy et al. 2009, Lee et al. 2015, 2018, Hunt et al. 2023

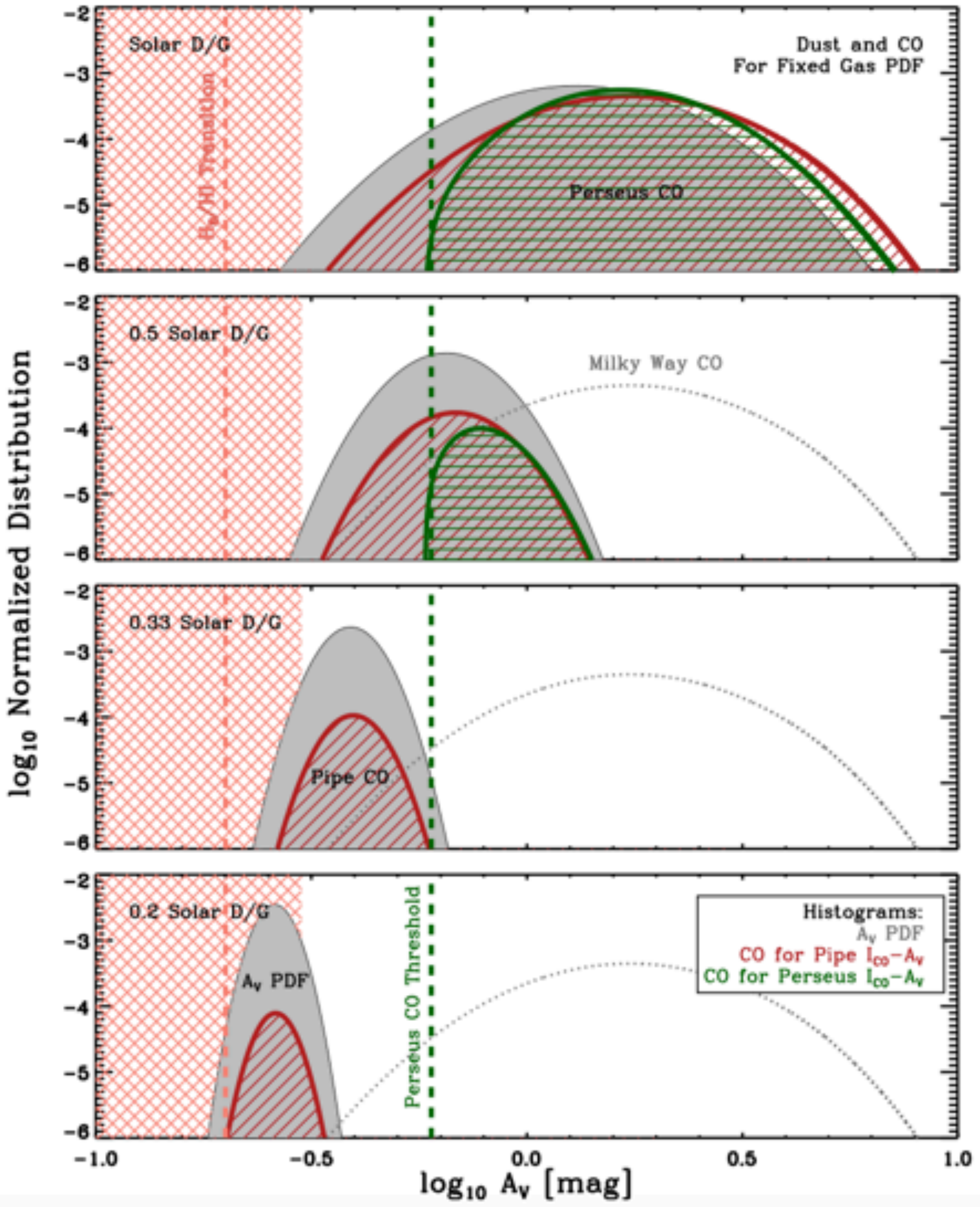
Leroy et al. 2011 - https://ui.adsabs.harvard.edu/abs/2011ApJ...737...12L/

Tracing CO-Dark H_2 at Low Metallicity

With dust

May also be a lot of scatter depending on cloud properties when metallicity gets low



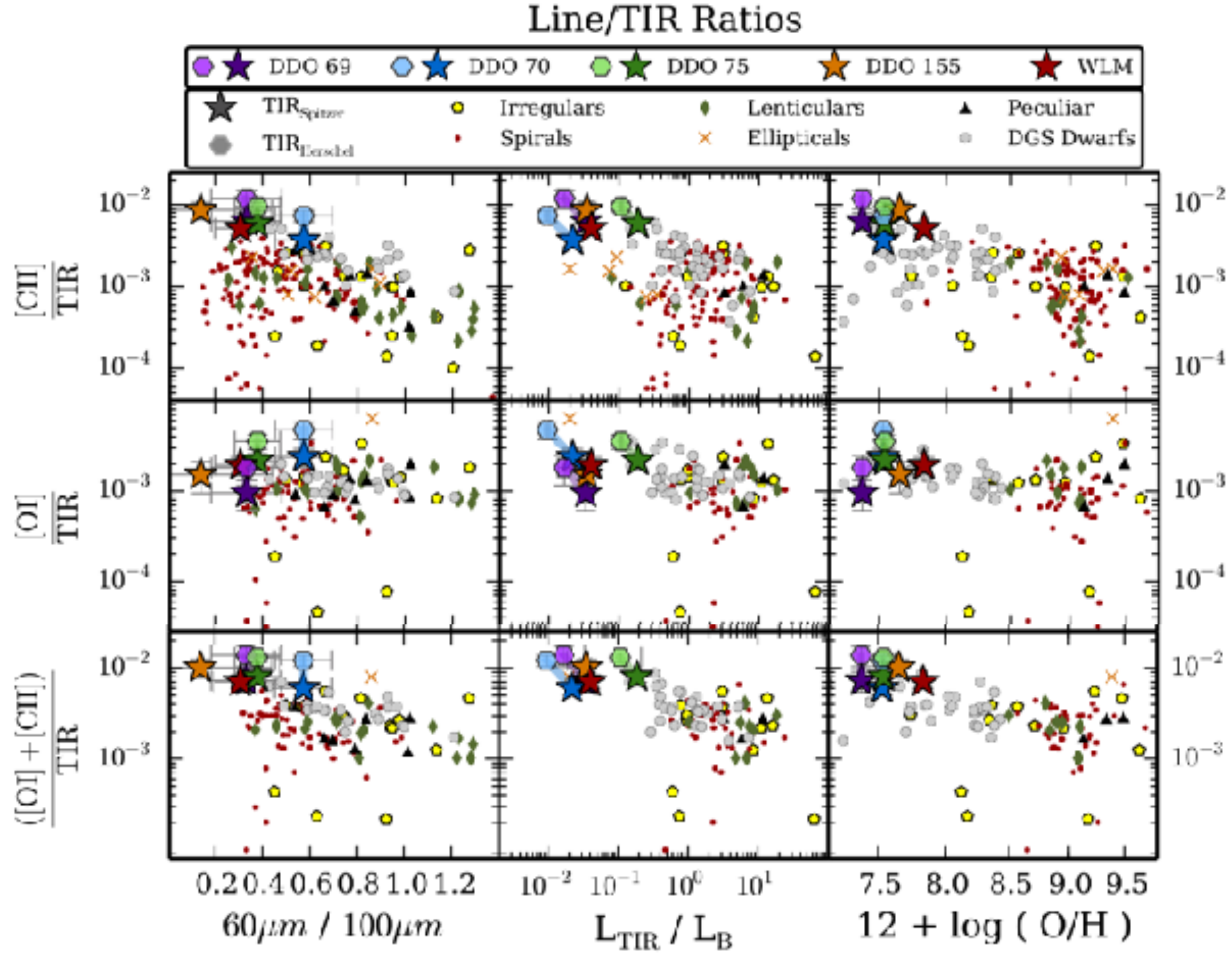


Lee et al. 2015 - https://ui.adsabs.harvard.edu/abs/2015MNRAS.450.2708L/

Tracing CO-Dark H_2 at Low Metallicity

With [CII]

In CO-Dark H_2, most carbon is C+, so [CII] 158 μm is a key tracer.



Low metallicity dwarfs are bright in [CII], show high [CII]/TIR ratios.

Key challenge: decomposing which fraction of the [CII] is coming from various phases (ionized gas, CO-bright H_2, atomic gas, CO-dark H_2).

Low relative [NII] suggesting ionized gas isn't a major contributor, [CII] is coming from PDRs.

Cigan et al. 2016 - https://ui.adsabs.harvard.edu/abs/2016AJ....151...14C/

Tracing CO-Dark H_2 at Low Metallicity

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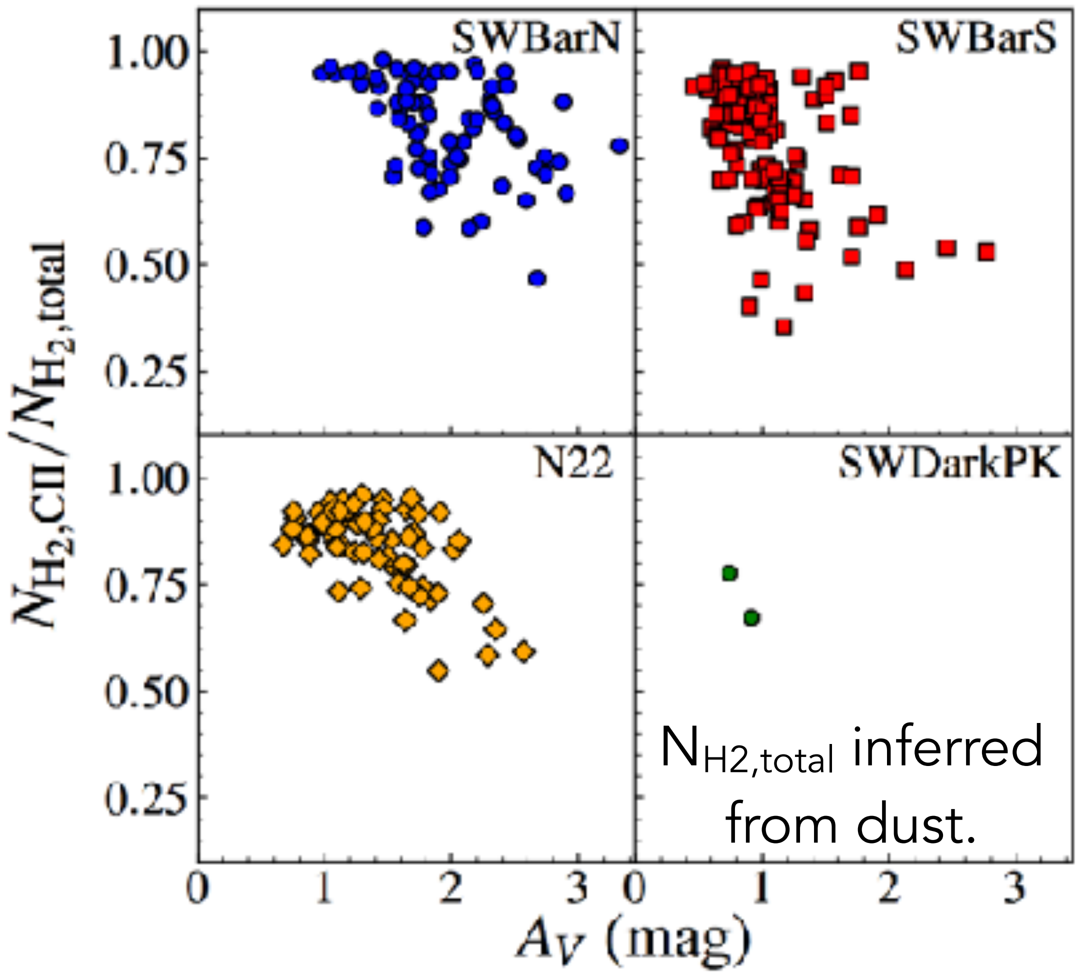
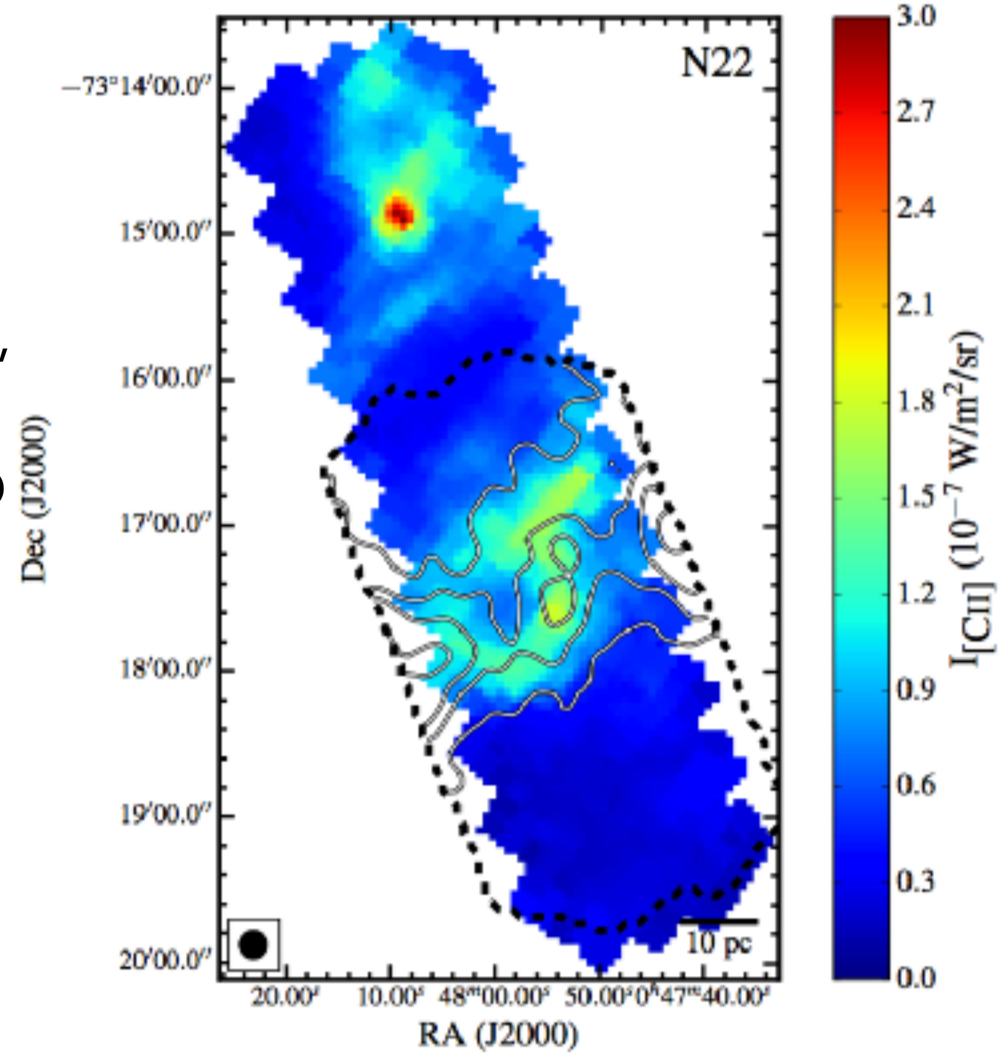


$N_{H2,total}$ inferred from dust.

Jameson et al. 2018 - https://ui.adsabs.harvard.edu/abs/2018ApJ...853..111J/

In Magellanic Clouds and some Local Group dwarfs, can highly resolve the [CII] and HI, CO distributions.



[CII] 158 μm in color, ALMA ^{12}CO 2-1 contours

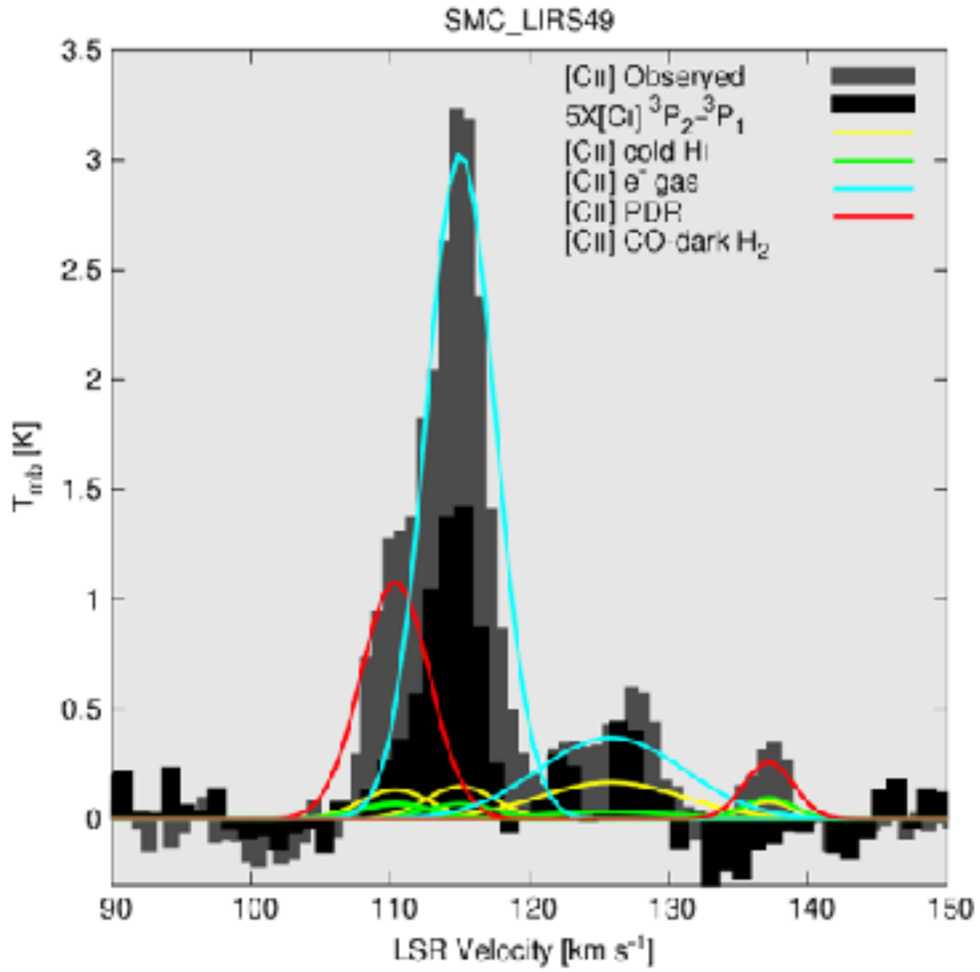
see also: Israel+1996, Pineda+ 2017, Fahrion+ 2017, Chevance+2020

Tracing CO-Dark H_2 at Low Metallicity

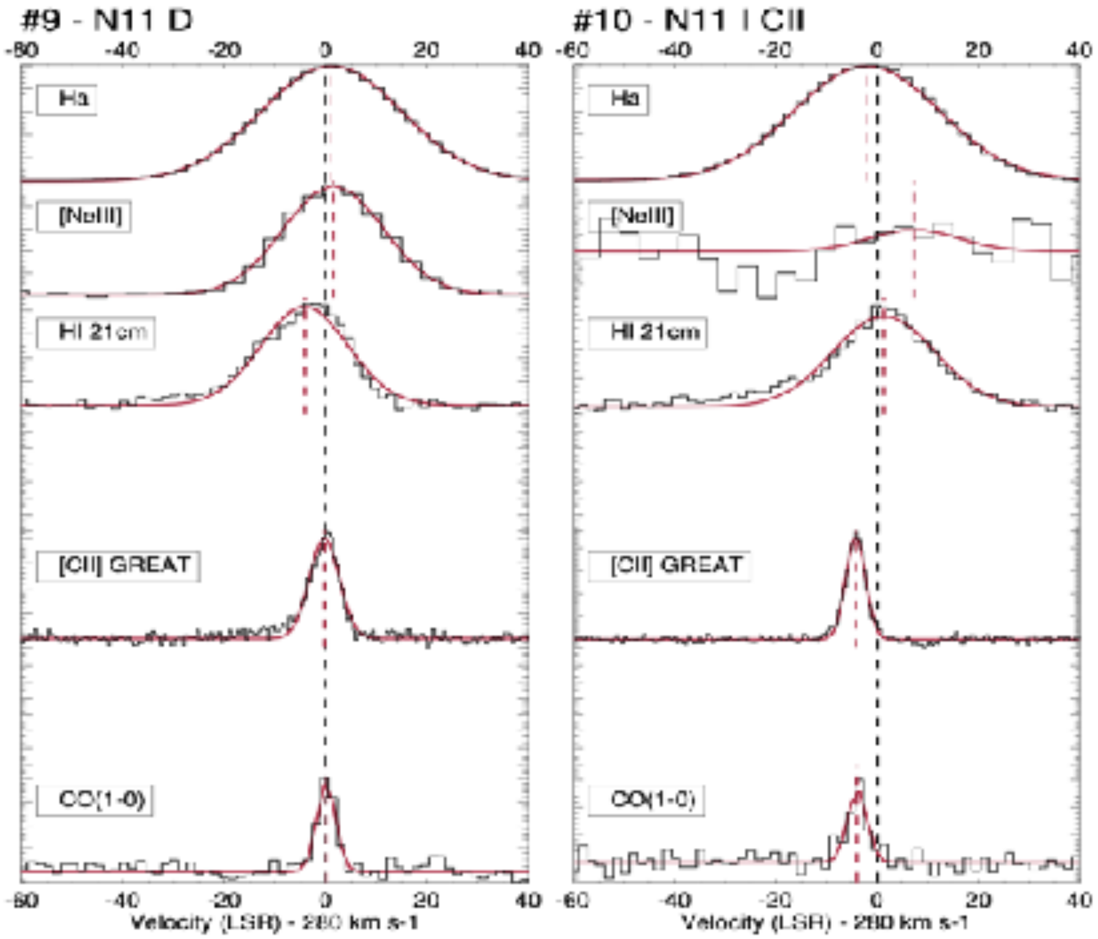
With [CII]

In CO-Dark H_2, most carbon is C+, so [CII] 158 μm is a key tracer.

High velocity resolution allows decomposing HI, CO, CO-dark contributions to [CII].



Pineda et al. 2017 - https://ui.adsabs.harvard.edu/abs/2017ApJ...839..107P/



Lebouteiller et al. 2019 - https://ui.adsabs.harvard.edu/abs/2019A%26A...632A.106L/

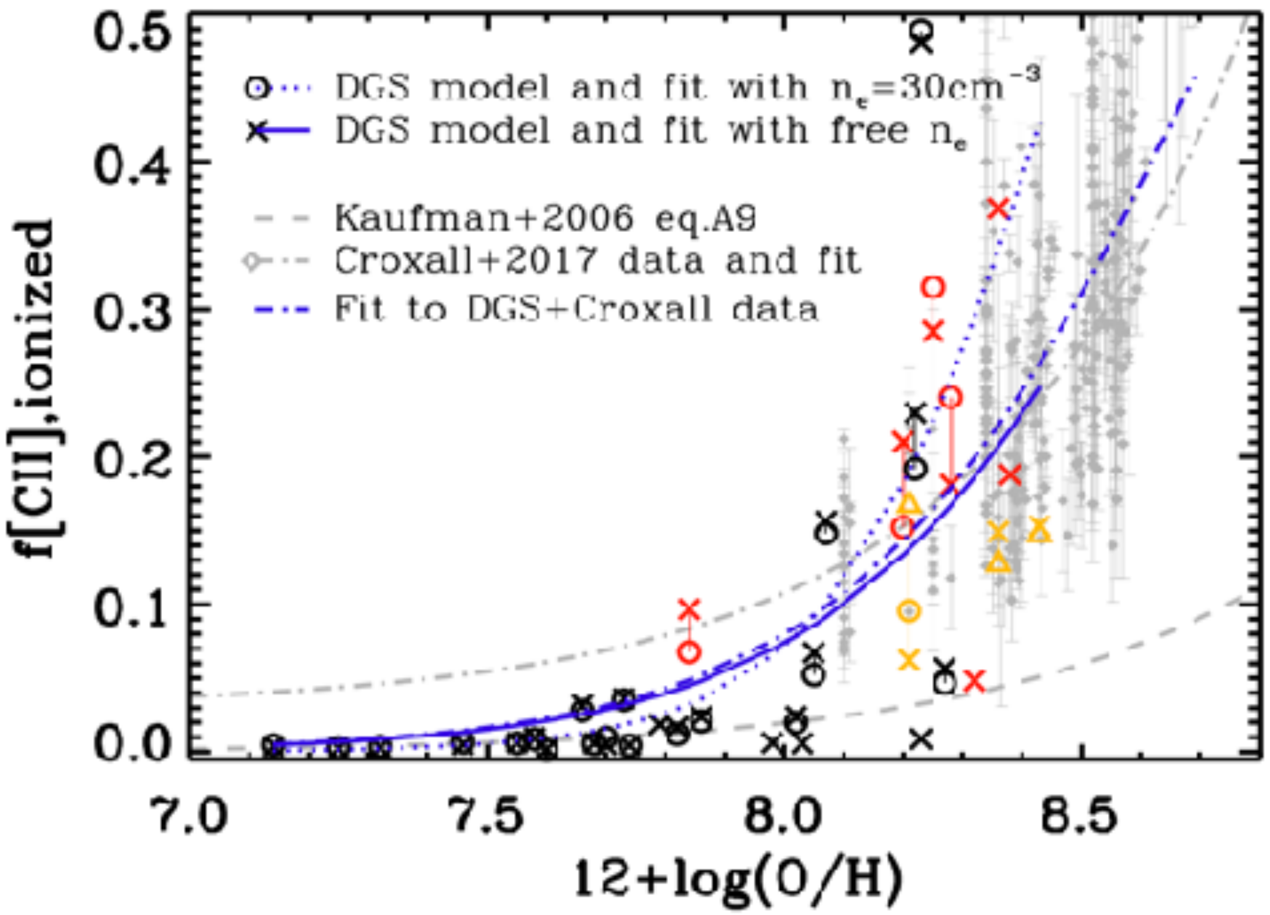
Tracing CO-Dark H_2 at Low Metallicity

With [CII]

In CO-Dark H_2, most carbon is C+, so [CII] 158 μm is a key tracer.

In more distant dwarfs, without velocity resolved data, multi-phase modeling can help dissect [CII] components.

Only a small fraction of the [CII] emission in low metallicity galaxies comes from the ionized gas.



Cormier et al. 2015 - https://ui.adsabs.harvard.edu/abs/2019A%26A...626A..23C/

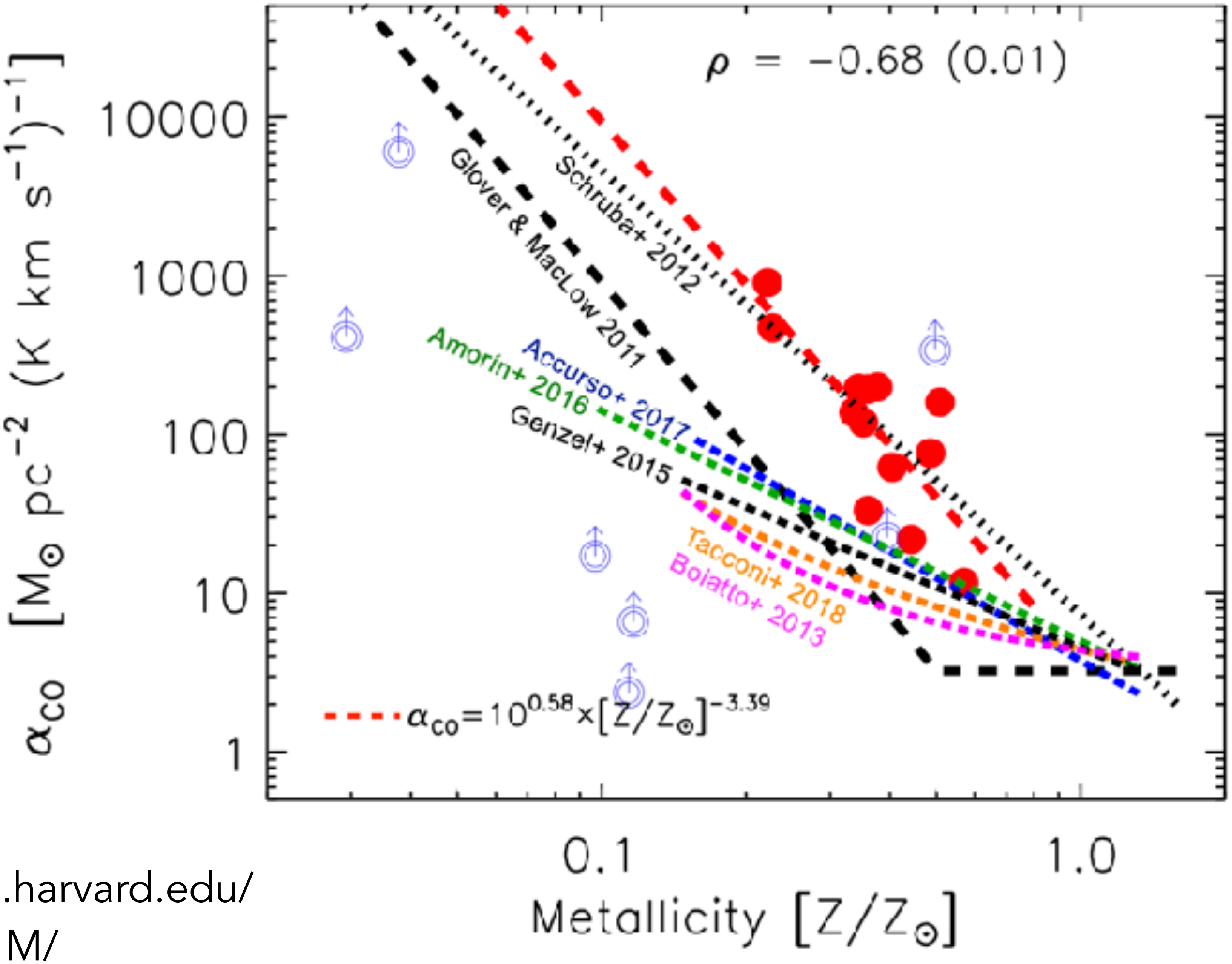
Tracing CO-Dark H_2 at Low Metallicity

With [CII]

In CO-Dark H_2, most carbon is C+, so [CII] 158 μm is a key tracer.

[CII] emission is dominated by PDRs, can be used to trace CO-dark H_2.

About 70-100% of the H_2 not traced by CO, but is traced by [C II].



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Tracing CO-Dark H_2 at Low Metallicity

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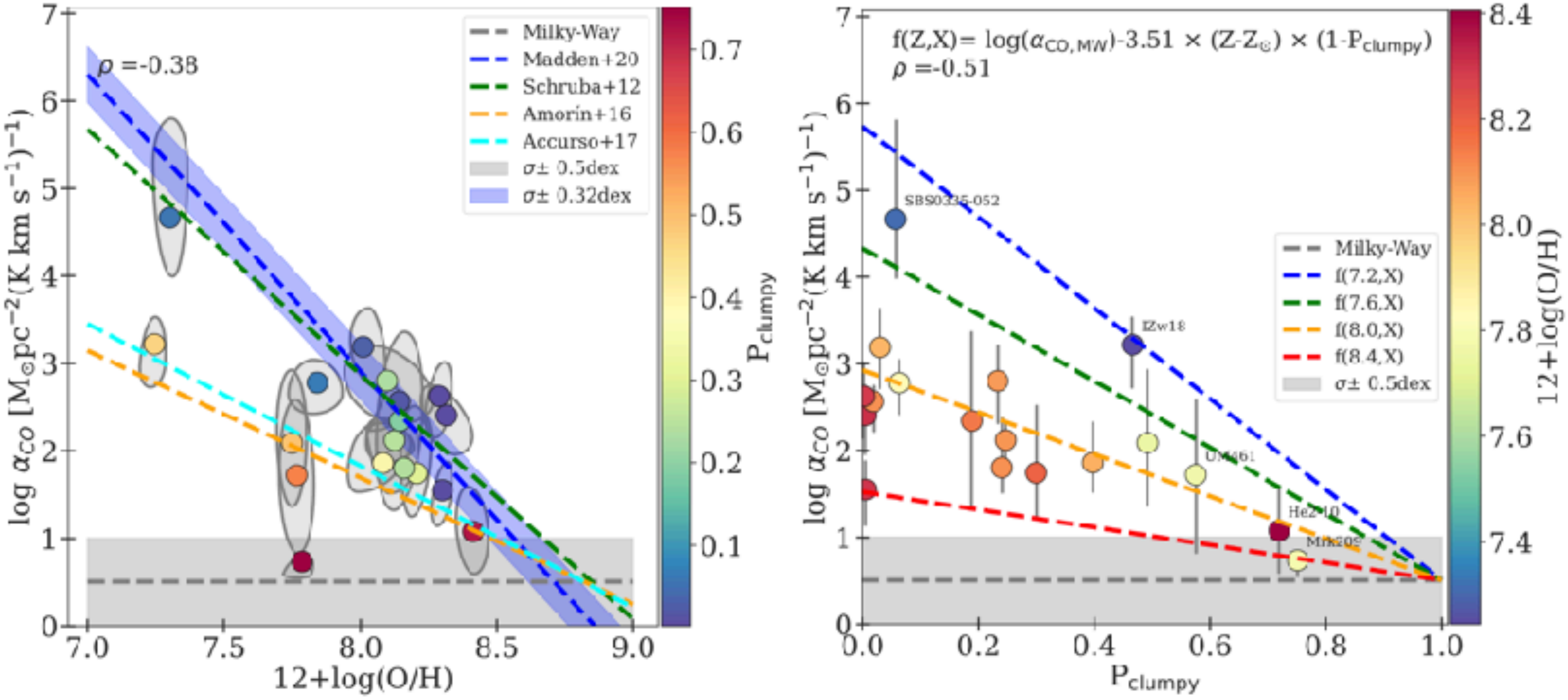
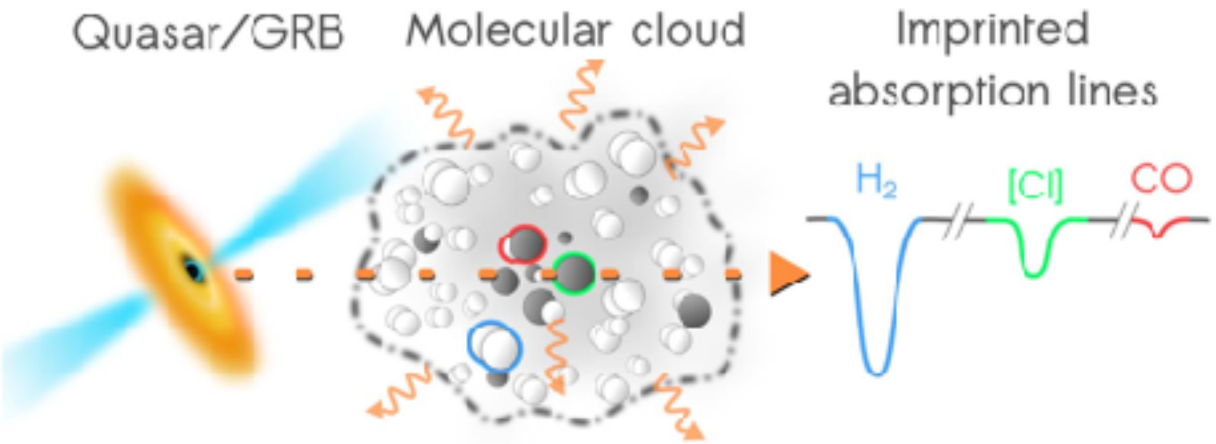


Clumpiness of the H_2 distribution is key to understanding CO-dark H_2 fraction.

Ramambason et al. 2023 - https://ui.adsabs.harvard.edu/abs/2023arXiv230614881R/

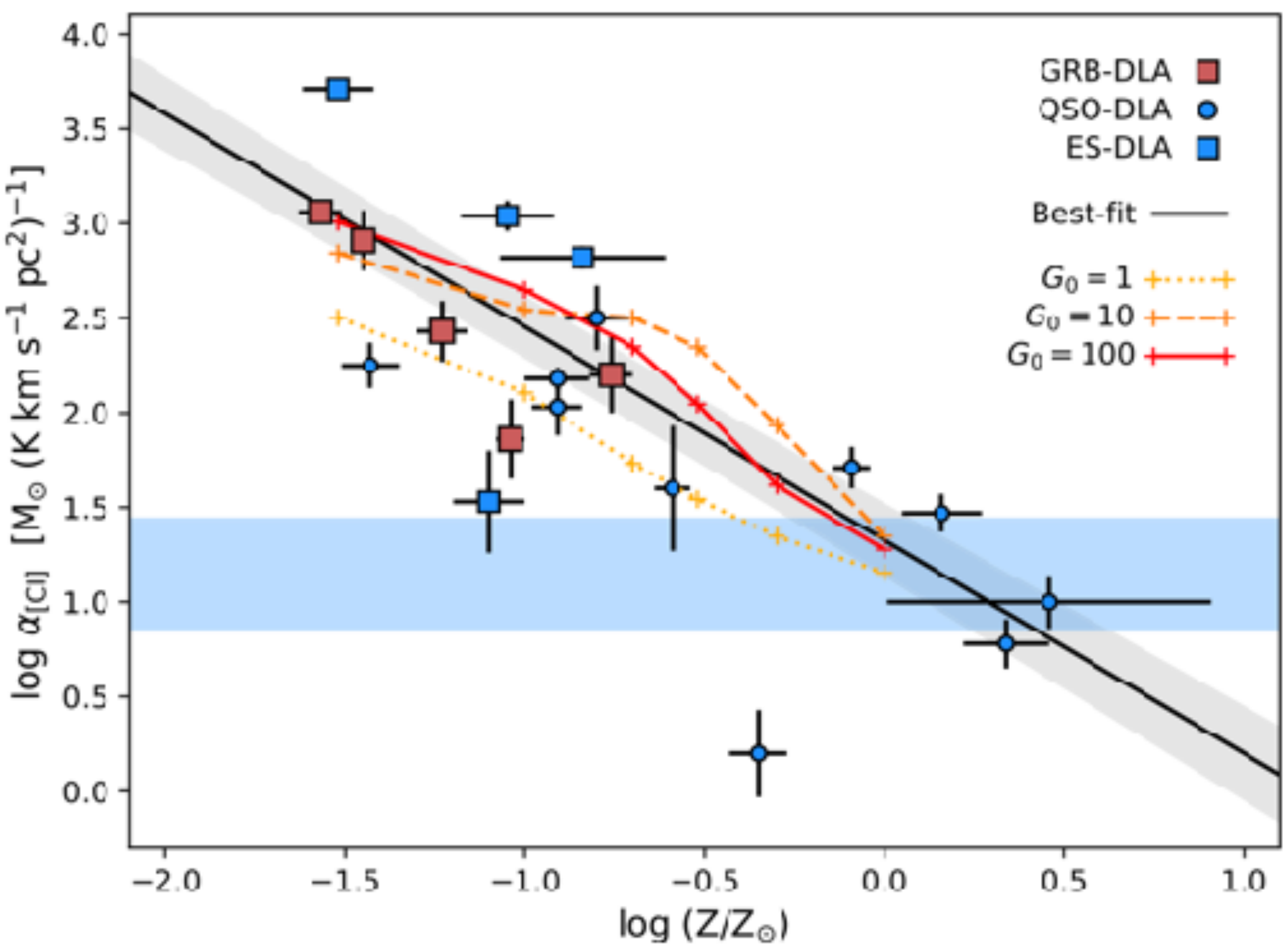
Tracing CO-Dark H_2 at Low Metallicity

With CI



Can observe CI, CI*, H_2, CO in DLA systems and predict CI emission relative to H_2 column.

Result matches well with simulation predictions and matches with measurements in local galaxies in overlapping metallicity range.

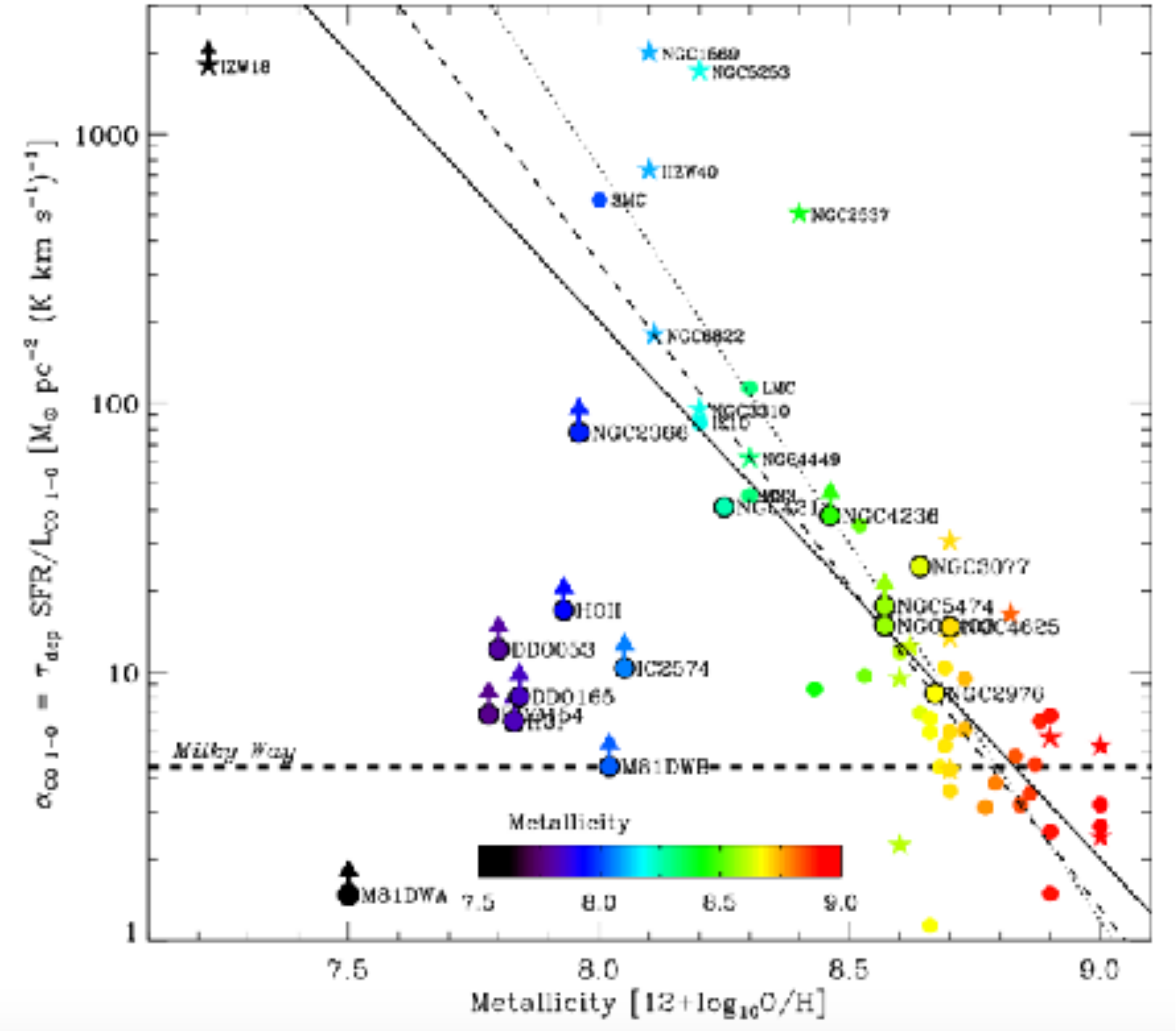


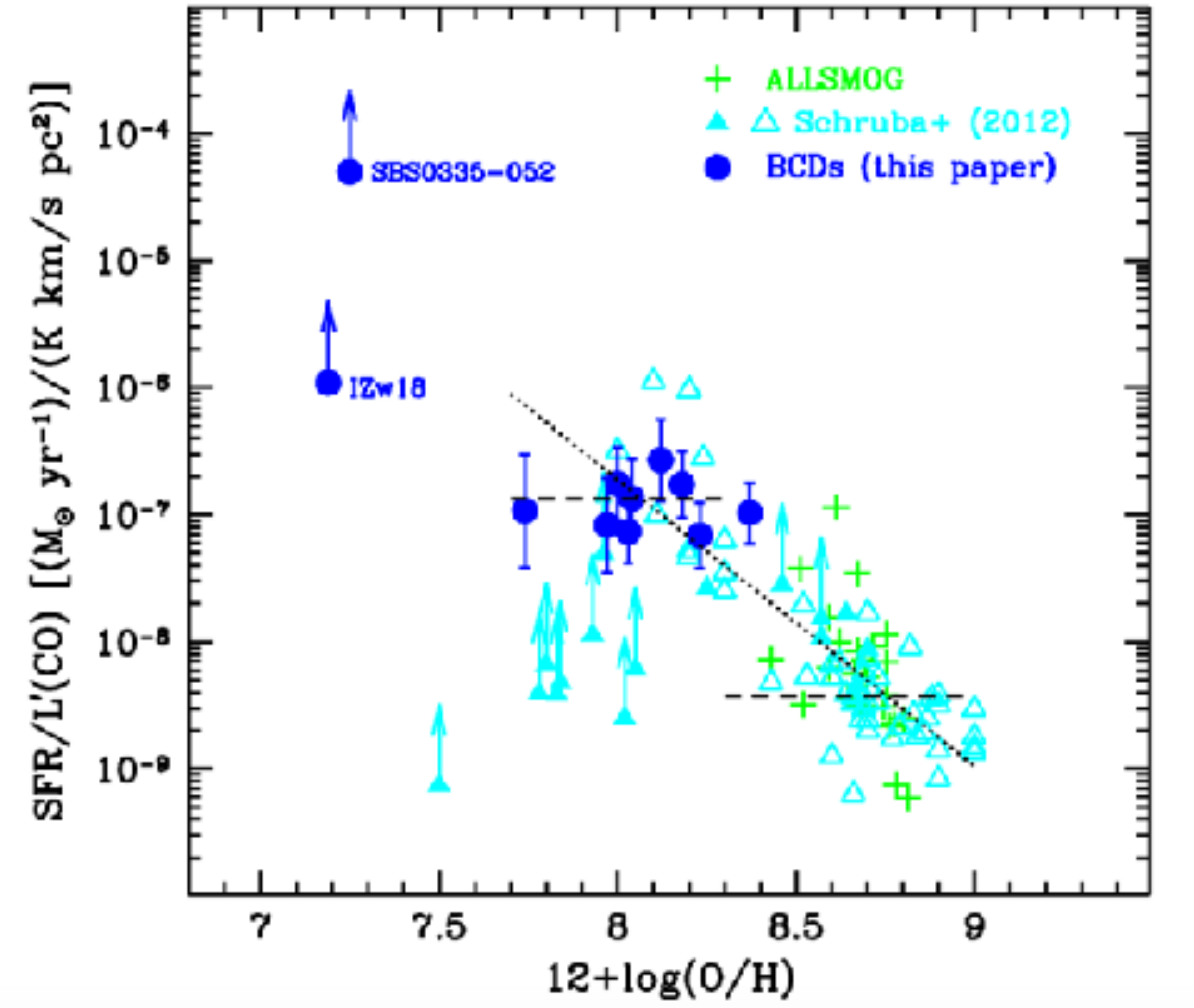
Heintz & Watson 2020 - https://ui.adsabs.harvard.edu/abs/2020ApJ...889L...7H/

Glover & Clark 2016 - https://ui.adsabs.harvard.edu/abs/2016MNRAS.456.3596G/

Tracing CO-Dark H_2 at Low Metallicity

By inverting K-S Law





Use τ_{dep}, measure SFR, infer H_2, compare to CO. Can include other dependences of τ_{dep} on sSFR, etc.

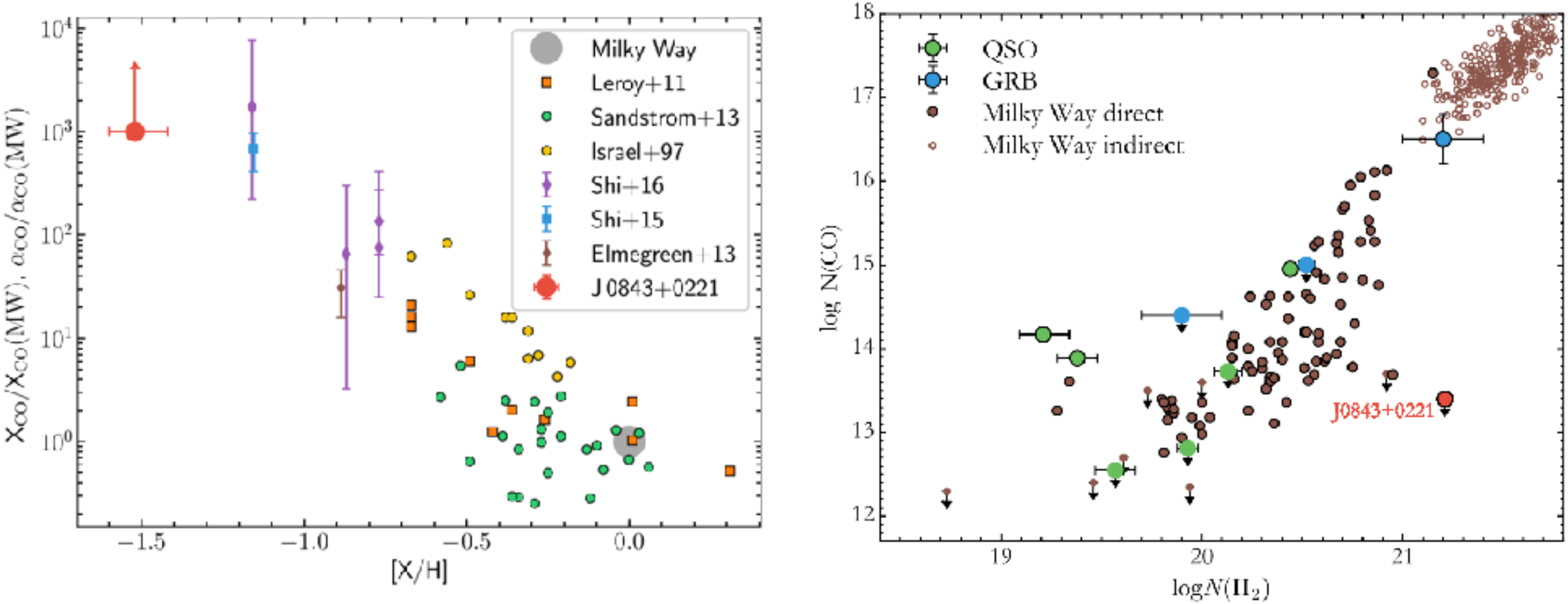
Schruba et al. 2012 - https://ui.adsabs.harvard.edu/abs/2012AJ....143..138S/

Hunt et al. 2015 - https://ui.adsabs.harvard.edu/abs/2015A%26A...583A.114H/

also Genzel et al. 2012, Amorin et al. 2016

Tracing CO-Dark H_2 at Low Metallicity

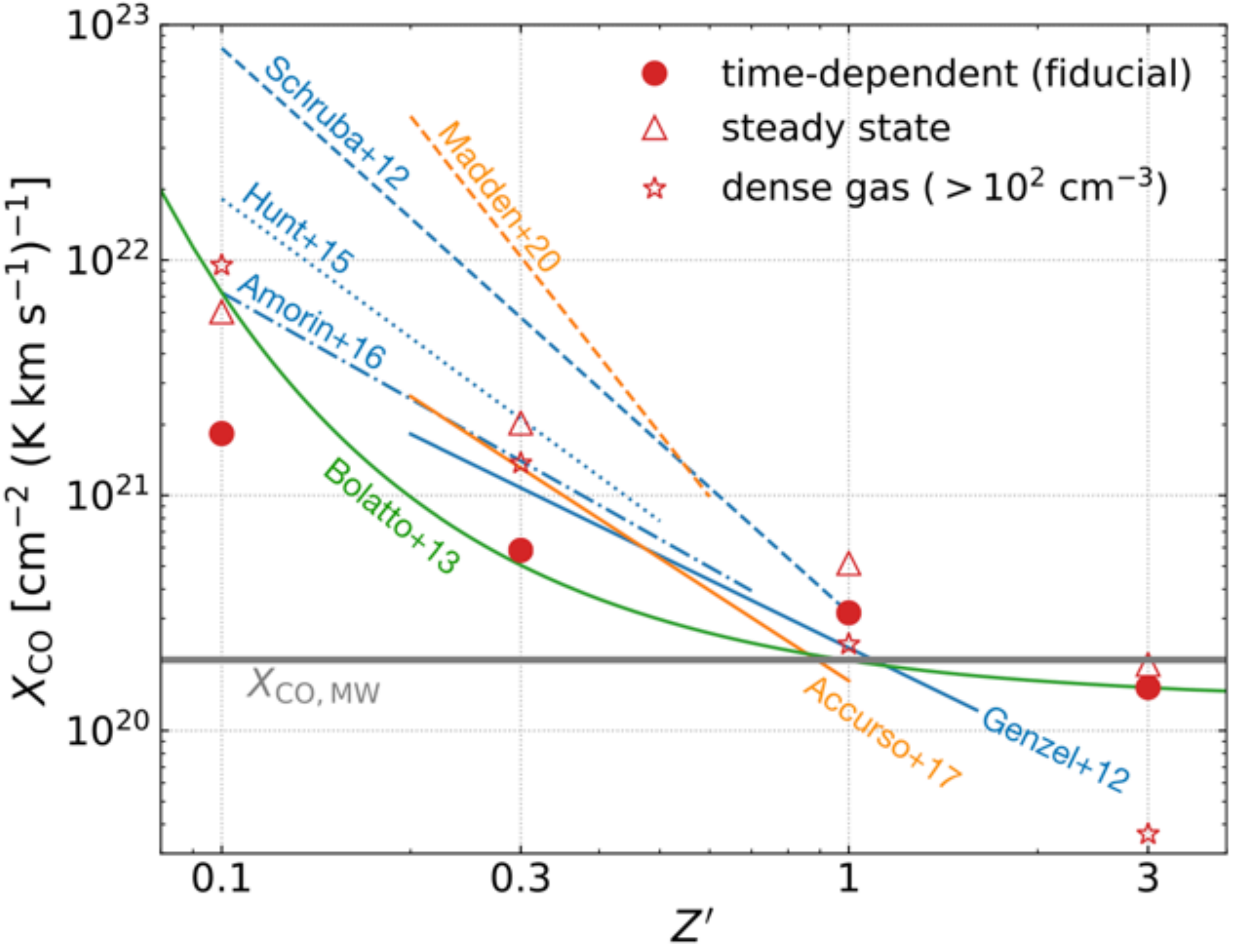
CO and H_2 from absorption in DLAs



H_2 rich DLA system at z=2.78 - H_2 temperature is 120 K, very little dust (A_V<0.1), no CO absorption detected, $X_{CO} > 10^3 X_{CO,MW}$.

Balashev et al. 2017 - https://ui.adsabs.harvard.edu/abs/2017MNRAS.470.2890B/

Tracing CO-Dark H_2 at Low Metallicity



Recent simulations results and compilation of observational prescriptions for CO-dark H_2 correction to CO-to-H_2 conversion factor.

Existence & importance of CO-dark H_2 is very well agreed upon.

Exact amount and appropriate Xco still quite uncertain.

Hu et al. 2022 - https://ui.adsabs.harvard.edu/abs/2022ApJ...931...28H/

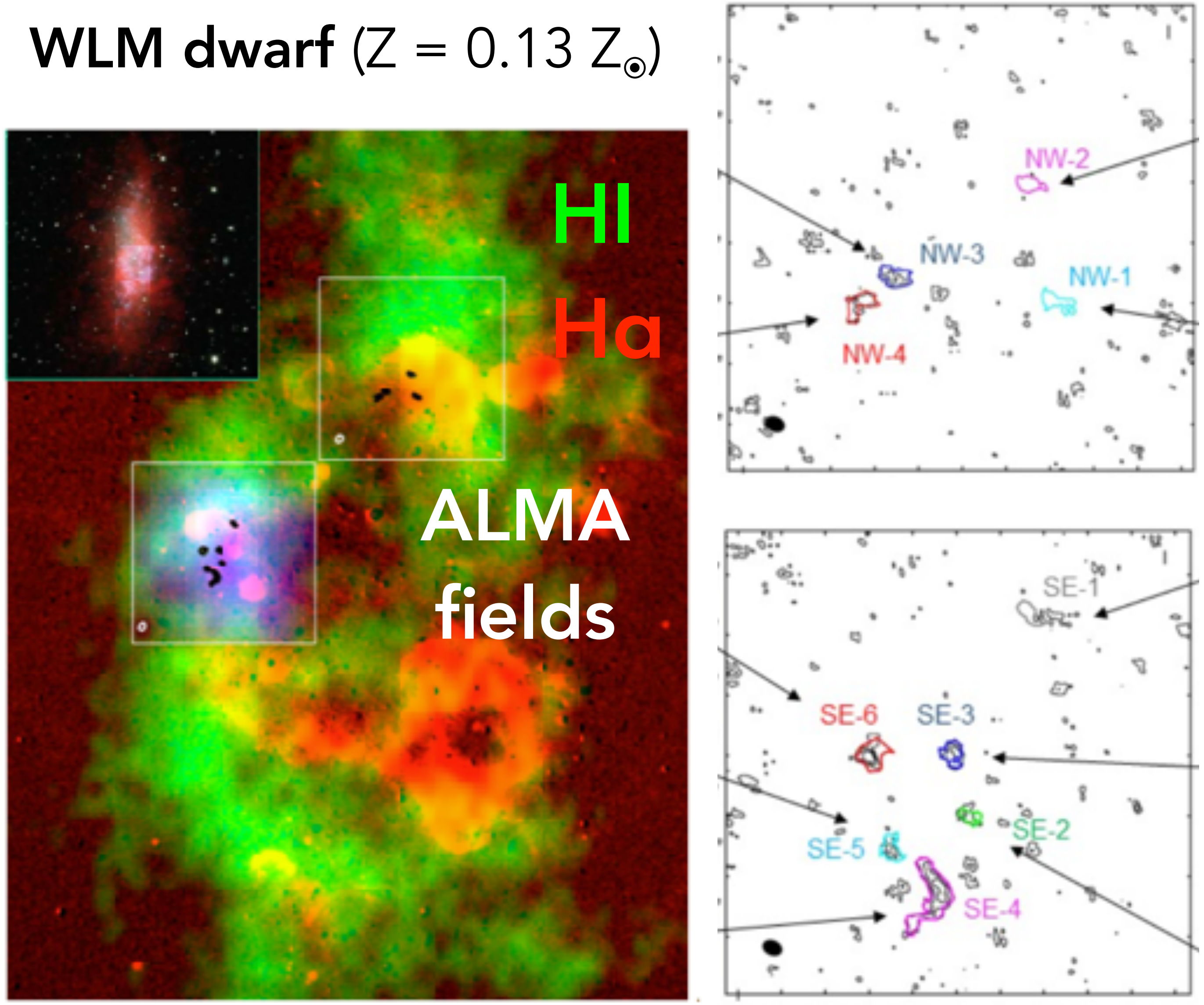
CO-Bright H_2 at Low Metallicity

ALMA reveals compact (~pc) CO-bright clouds at low Z

CO-Bright H_2 at Low Metallicity

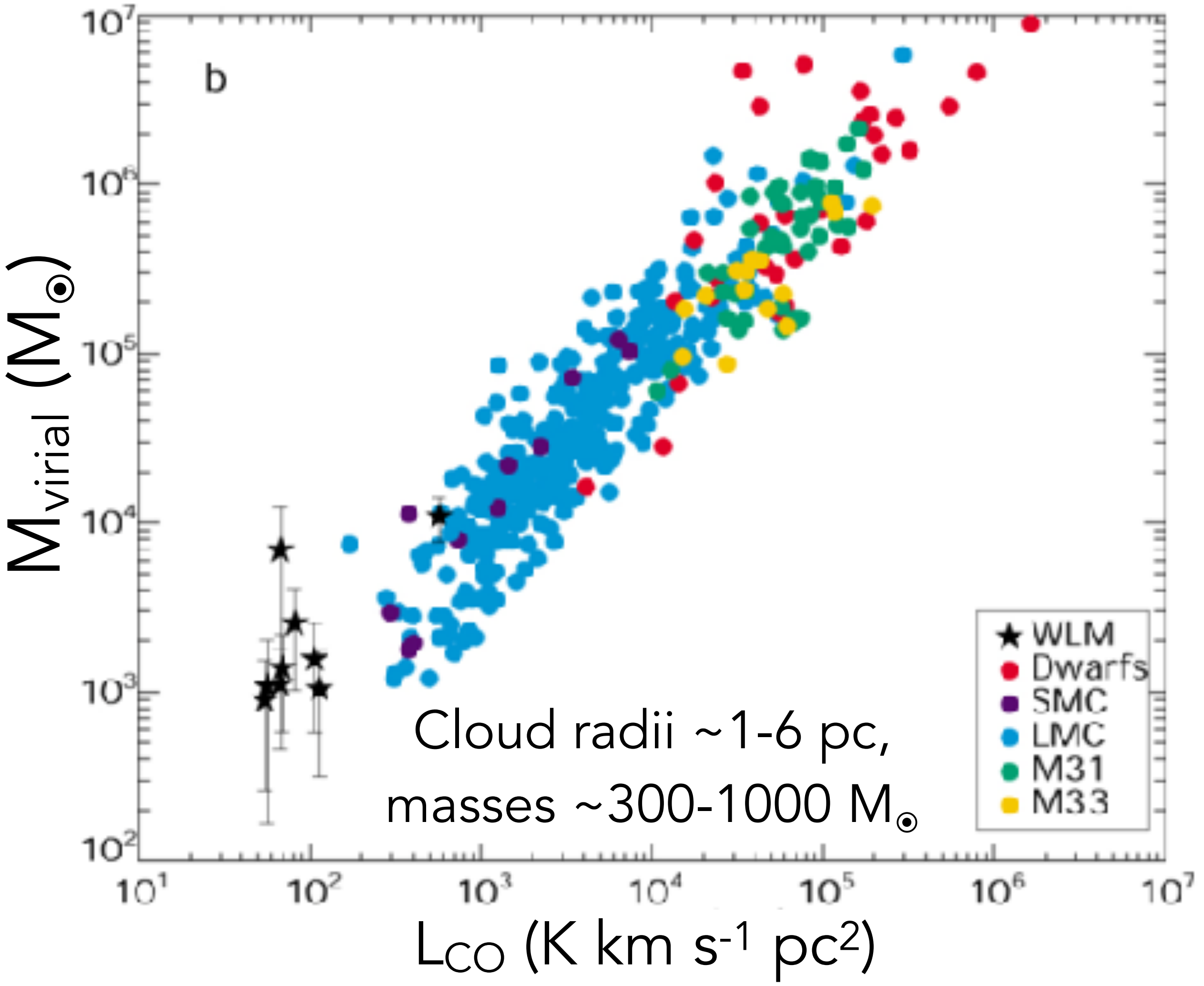
ALMA reveals compact (~pc) CO-bright clouds at low Z

Rubio et al. 2016 - CO in **WLM dwarf** (Z = 0.13 $Z_\odot$)



$\alpha_{CO,bright} \sim 7\times\alpha_{CO,MW}$

$\alpha_{CO,total} \sim 30\times\alpha_{CO,MW}$

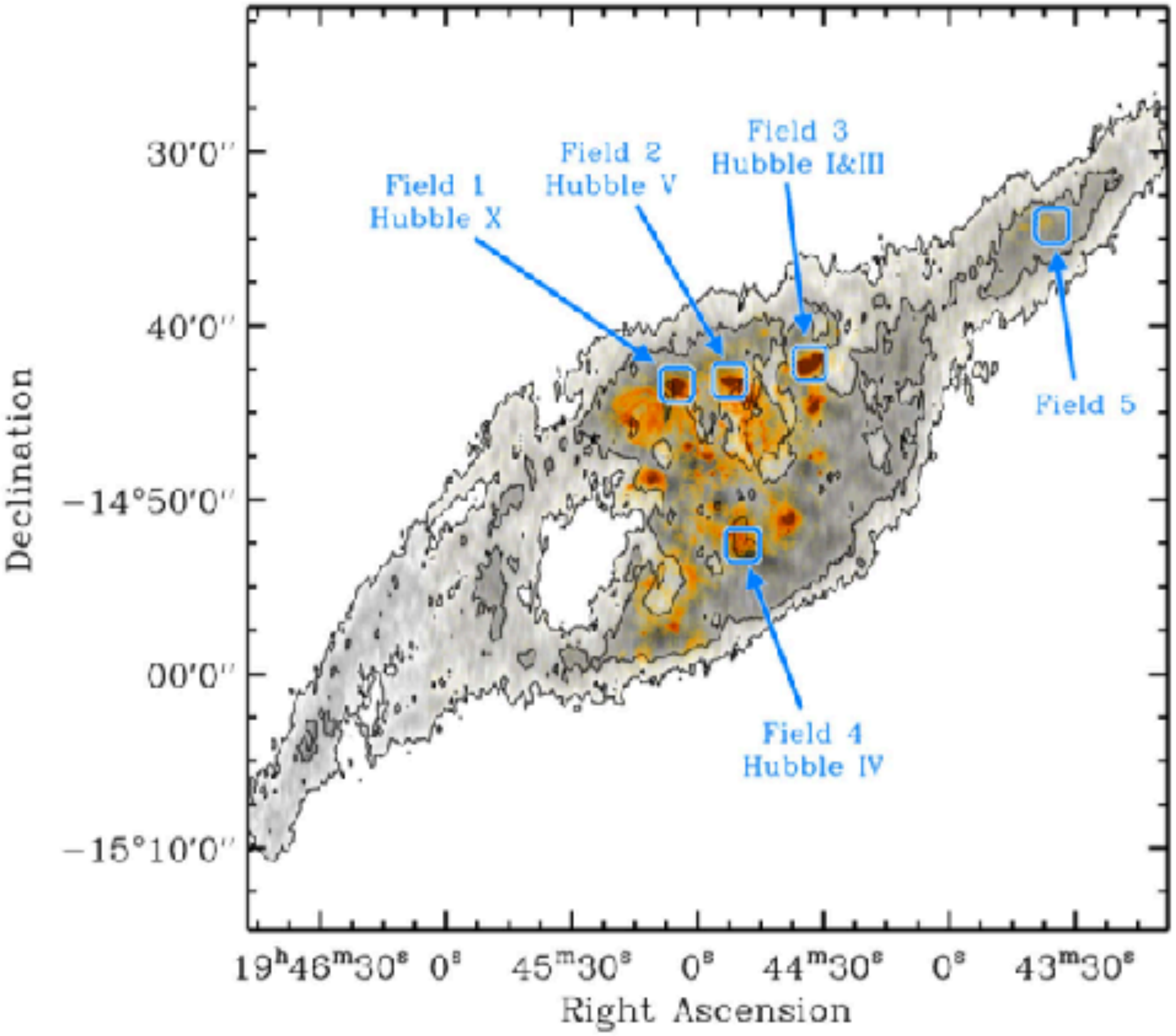


Cloud radii ~1-6 pc, masses ~300-1000 $M_\odot$

CO-Bright H_2 at Low Metallicity

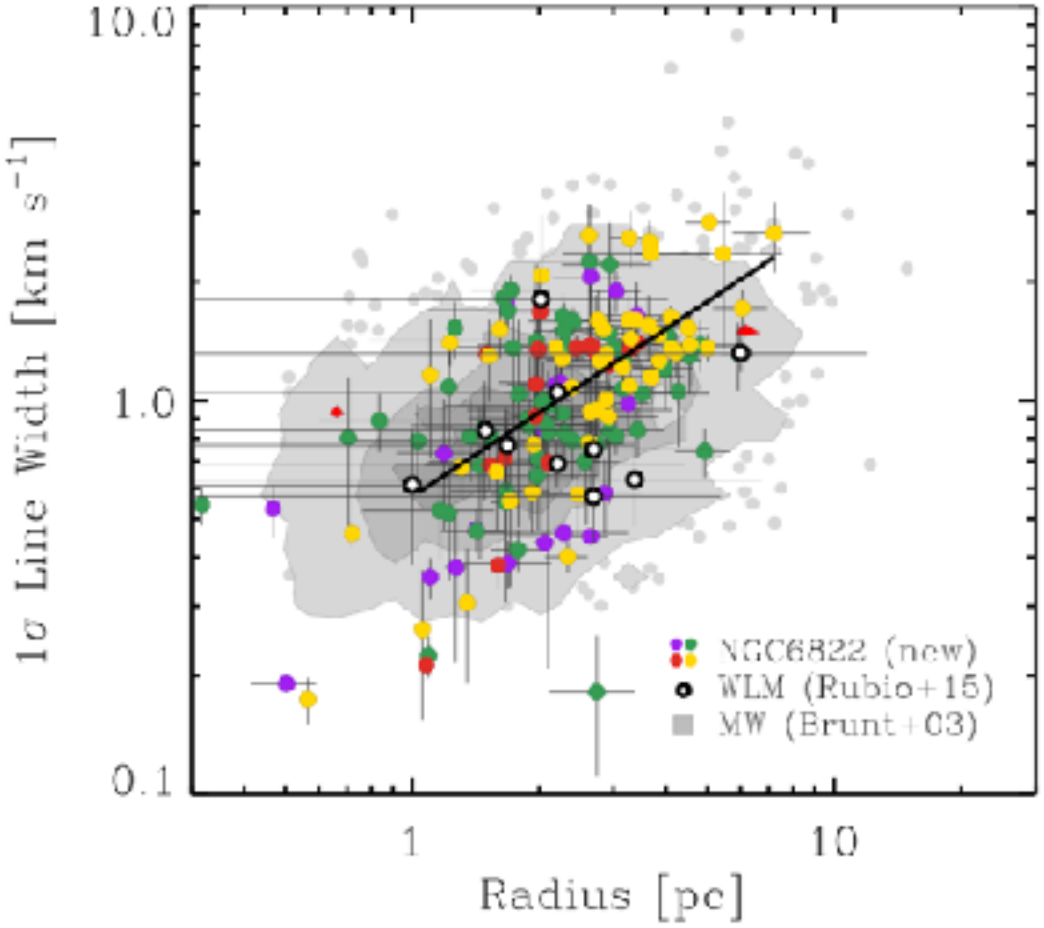
ALMA reveals compact (~pc) CO-bright clouds at low Z

Schruba et al. 2017 -
CO in **NGC 6822** ($Z = 0.2\ Z_\odot$)



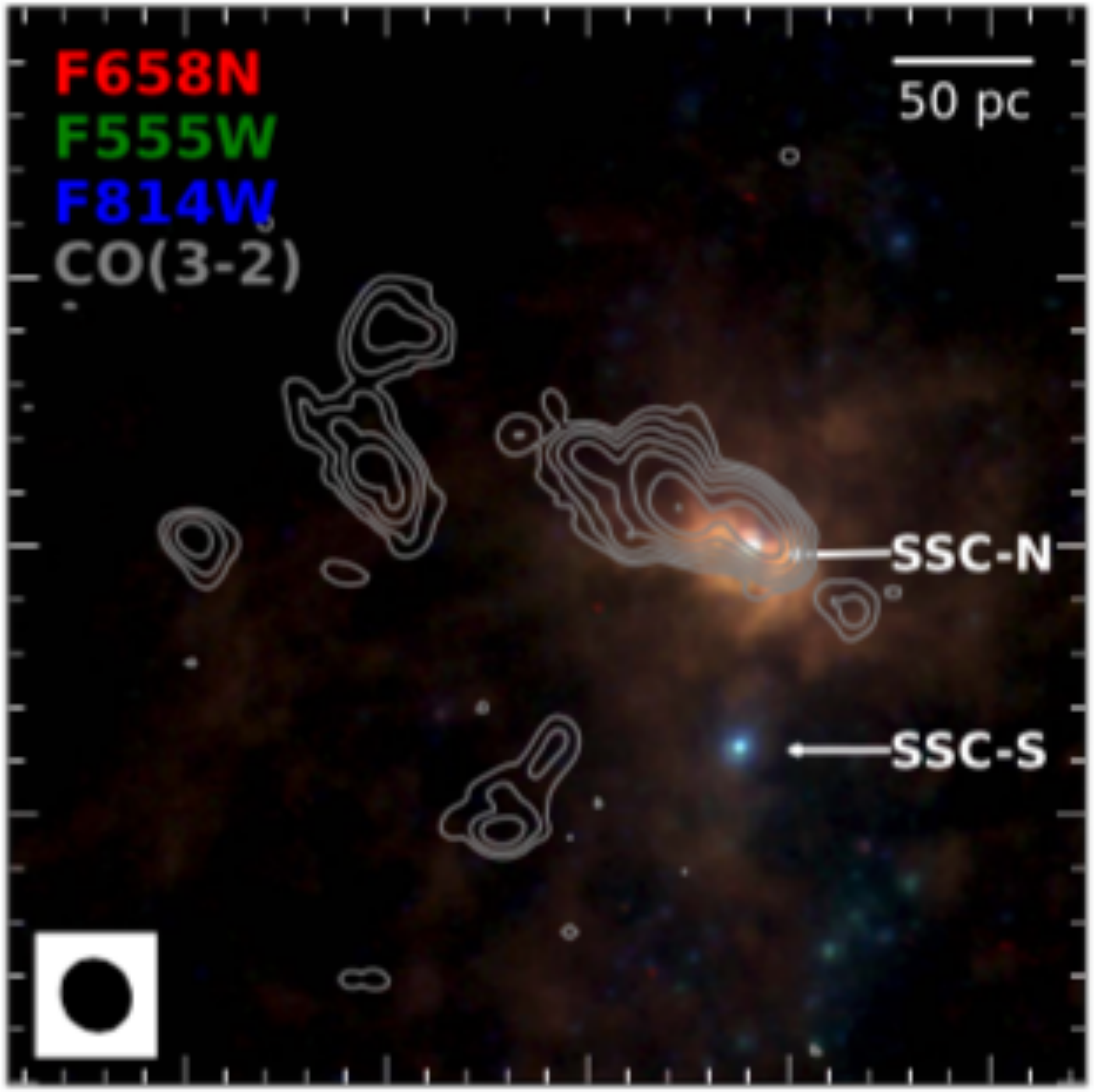
$\alpha_{CO,bright}$ ~ 1-2×$\alpha_{CO,MW}$
$\alpha_{CO,total}$ ~ 20-25×$\alpha_{CO,MW}$

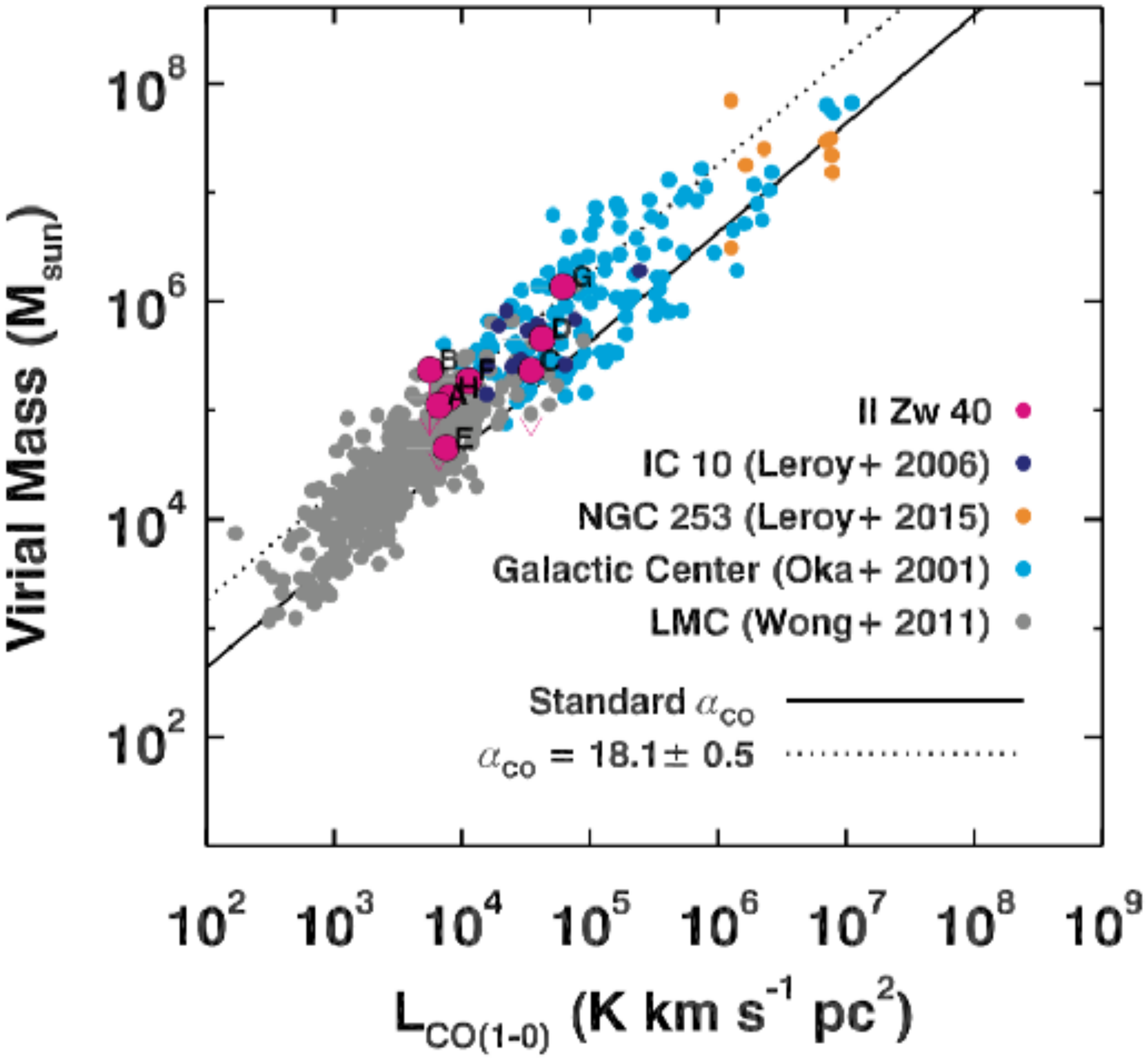
Sizes & masses comparable to WLM.



CO-Bright H_2 at Low Metallicity

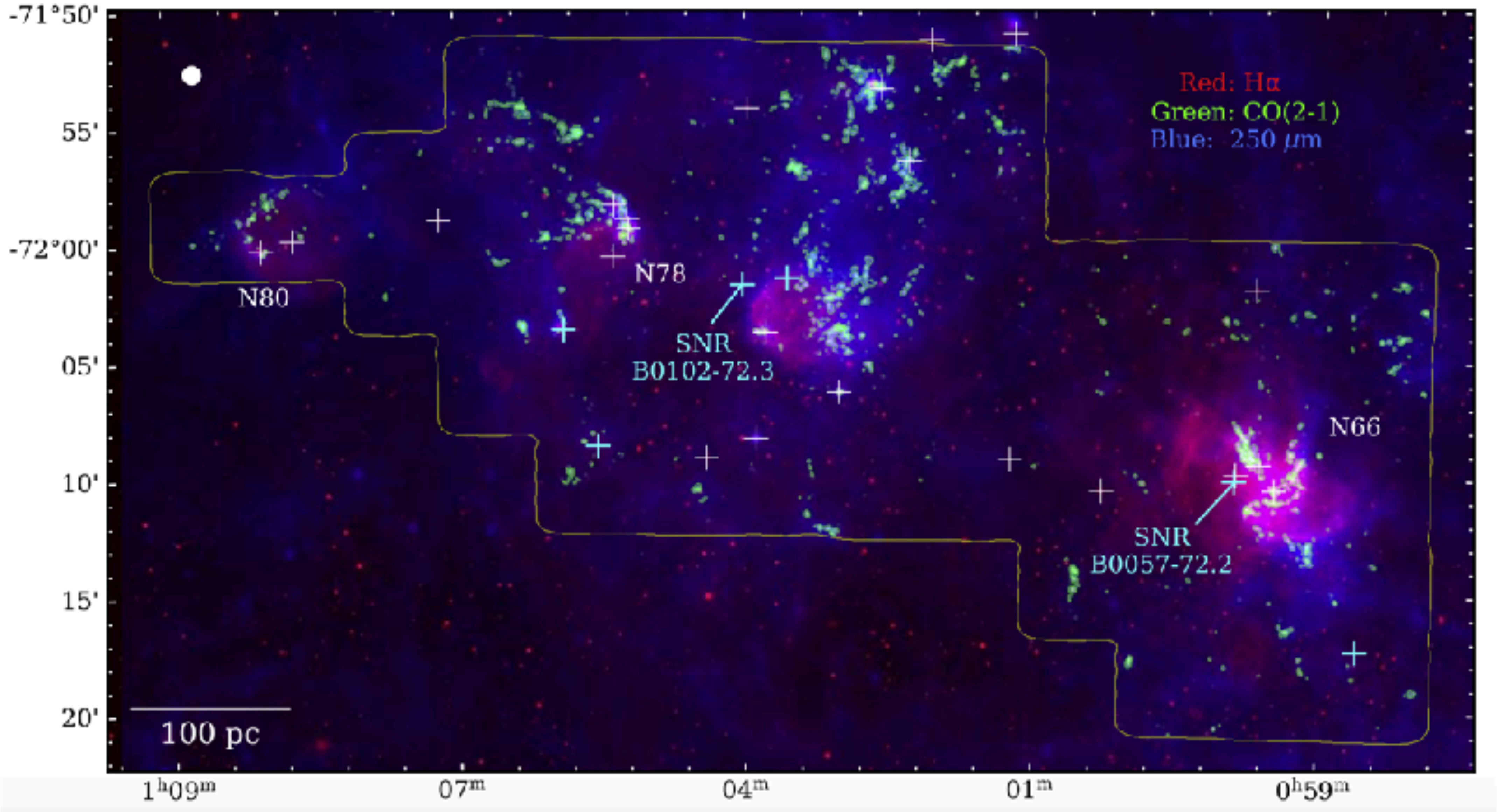
Kepley et al. (2016) finds molecular clouds in low Z starburst
II Zw 40 (1/5 $Z_\odot$) shows $\alpha_{CO,bright} \sim 4\ \alpha_{CO,MW}$





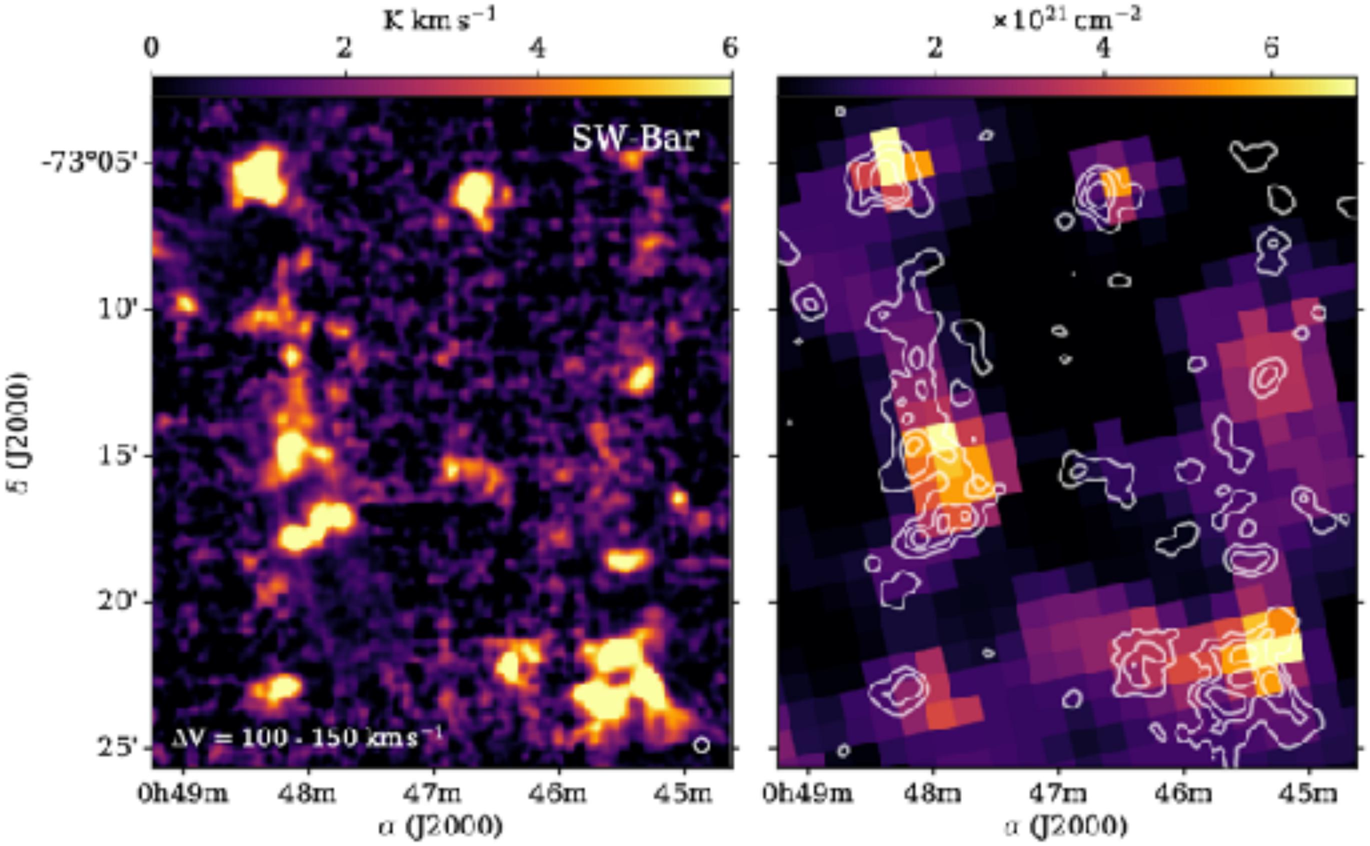
CO-Bright H_2 at Low Metallicity

Recent large area ALMA-ACA surveys of SMC molecular gas, shows compact CO bright clumps throughout, ~90% of H_2 is CO-dark.

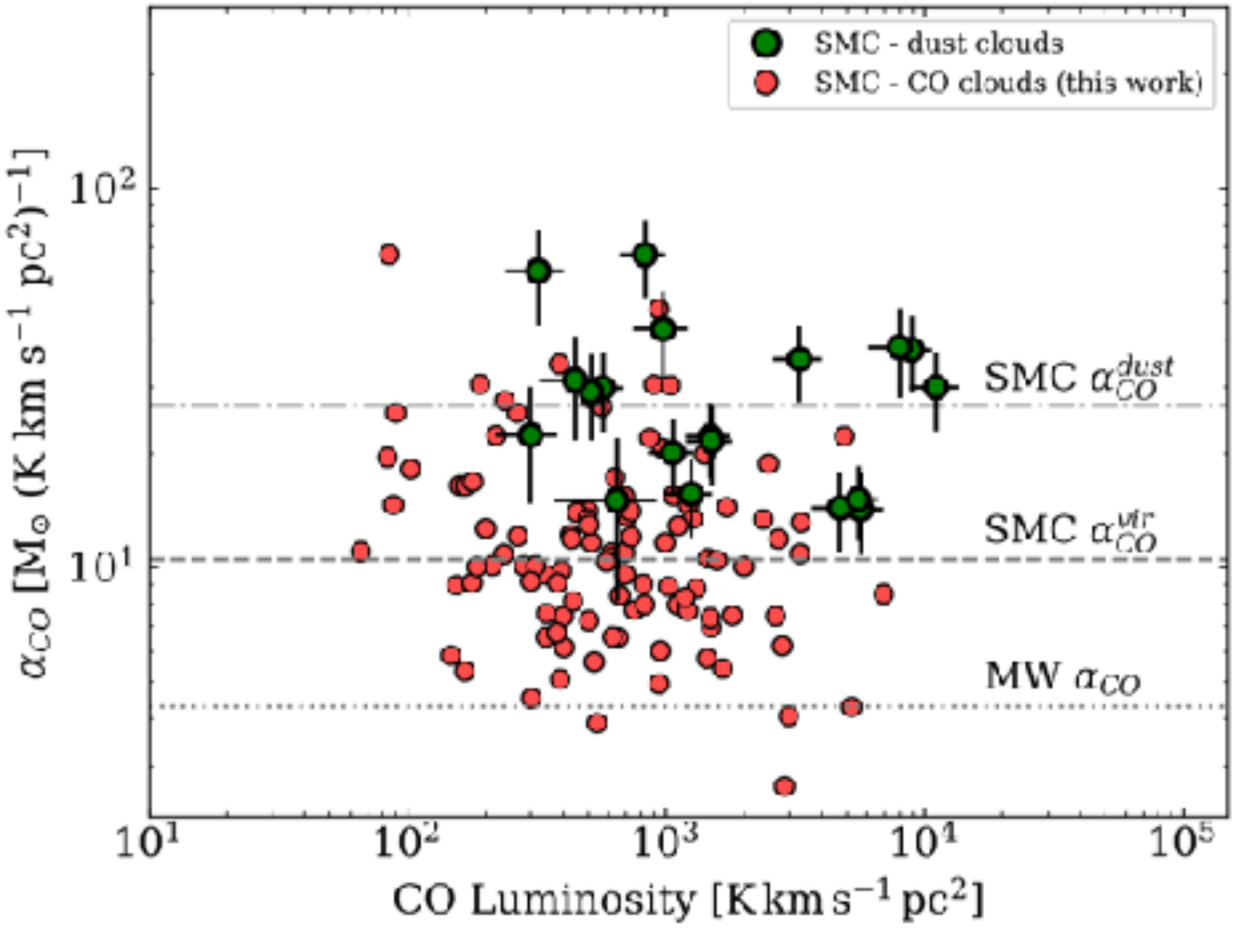


Tokuda et al. 2021 - https://ui.adsabs.harvard.edu/abs/2021ApJ...922..171T/

CO-Bright H_2 at Low Metallicity



APEX CO survey of regions of the SMC, compared to H_2 inferred from dust.



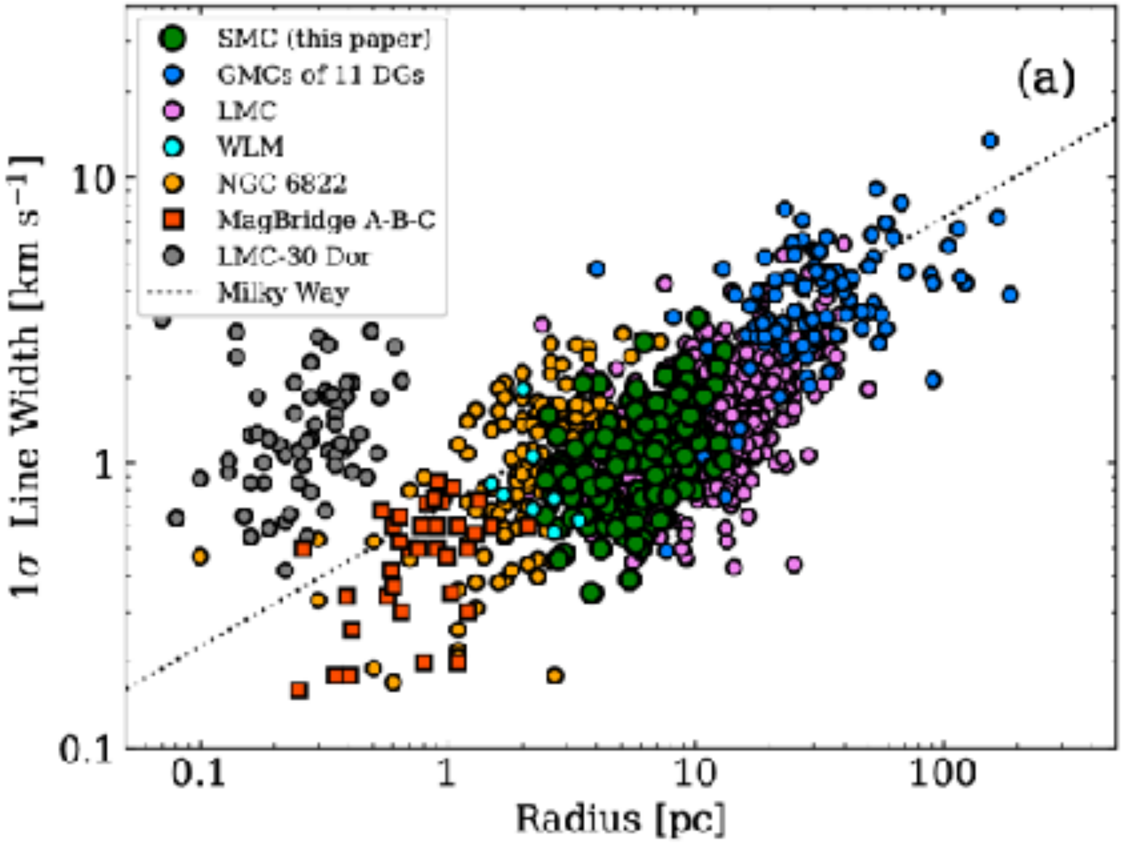
CO-bright Xco from virial mass differs from dust-based Xco

Saldano et al. 2023 - https://ui.adsabs.harvard.edu/abs/2023A%26A...672A.153S/

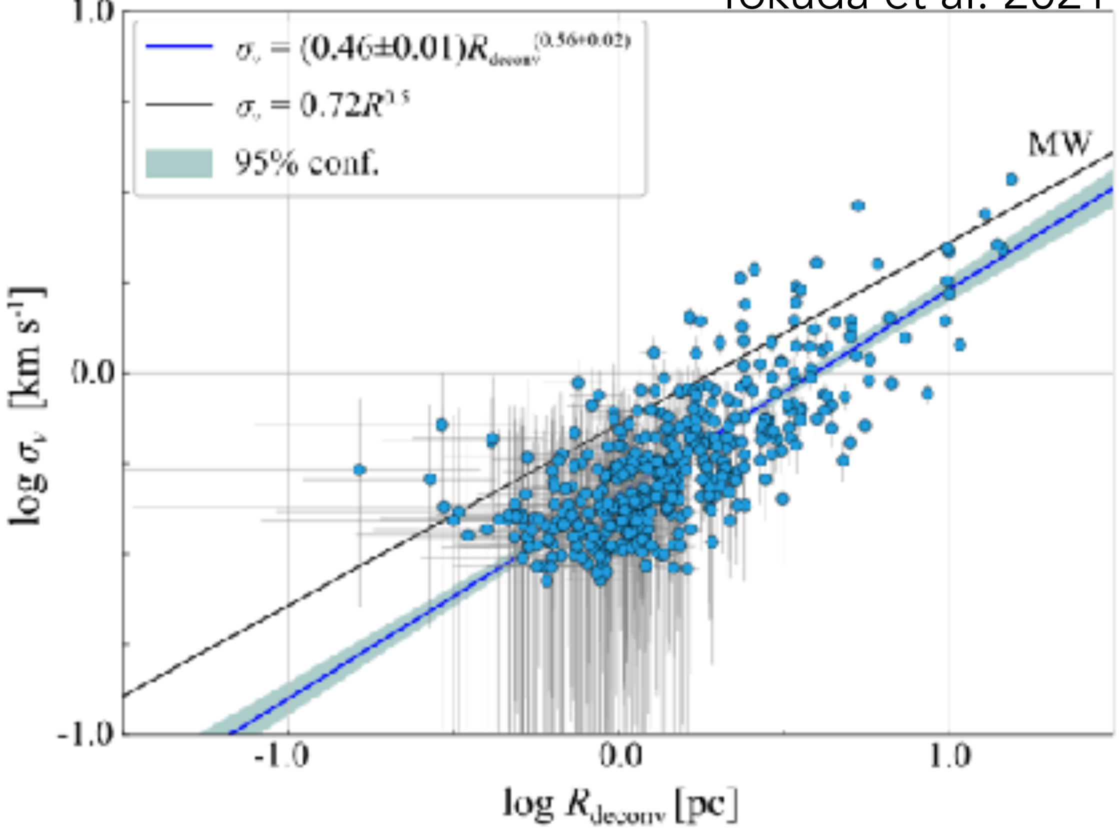
CO-Bright H_2 at Low Metallicity

CO-bright clouds in low Z galaxies tend to fall below MW line width-size relation.

Saldano et al. 2023 compilation



Tokuda et al. 2021



CO-bright region is likely the innermost part of the cloud only, full line width and size are not reflected?
Or maybe the turbulent energy is lower in low metallicity conditions?

CO-dark H2 not likely to be the cause of line width-size offsets in low-metallicity, but virial parameters may be systematically overestimated.
O'Neill et al. 2022 - https://ui.adsabs.harvard.edu/abs/2022ApJ...933..179O/

Molecular Gas Summary

- Most of the H_2 is in a CO-dark component at low metallicity. This can be seen observationally with dust, [CII], CI, inverting the K-S law.

- While agreement is good on the dominance of CO-dark H2, the exact amount is quite uncertain.

- CO-bright H_2 is in small clumps (~pc scale), where Xco is higher than MW, but not dramatically.

NGC 346 in SMC with NIRCam

Credits: NASA, ESA, CSA, O. Jones (UK ATC), G. De Marchi (ESTEC), and M. Meixner (USRA).
Image processing: A. Pagan (STScI), N. Habel (USRA), L. Lenkic (USRA) and L. Chu (NASA/Ames)

The Future!

JWST can now map nearby low metallicity galaxies at incredibly high resolution.

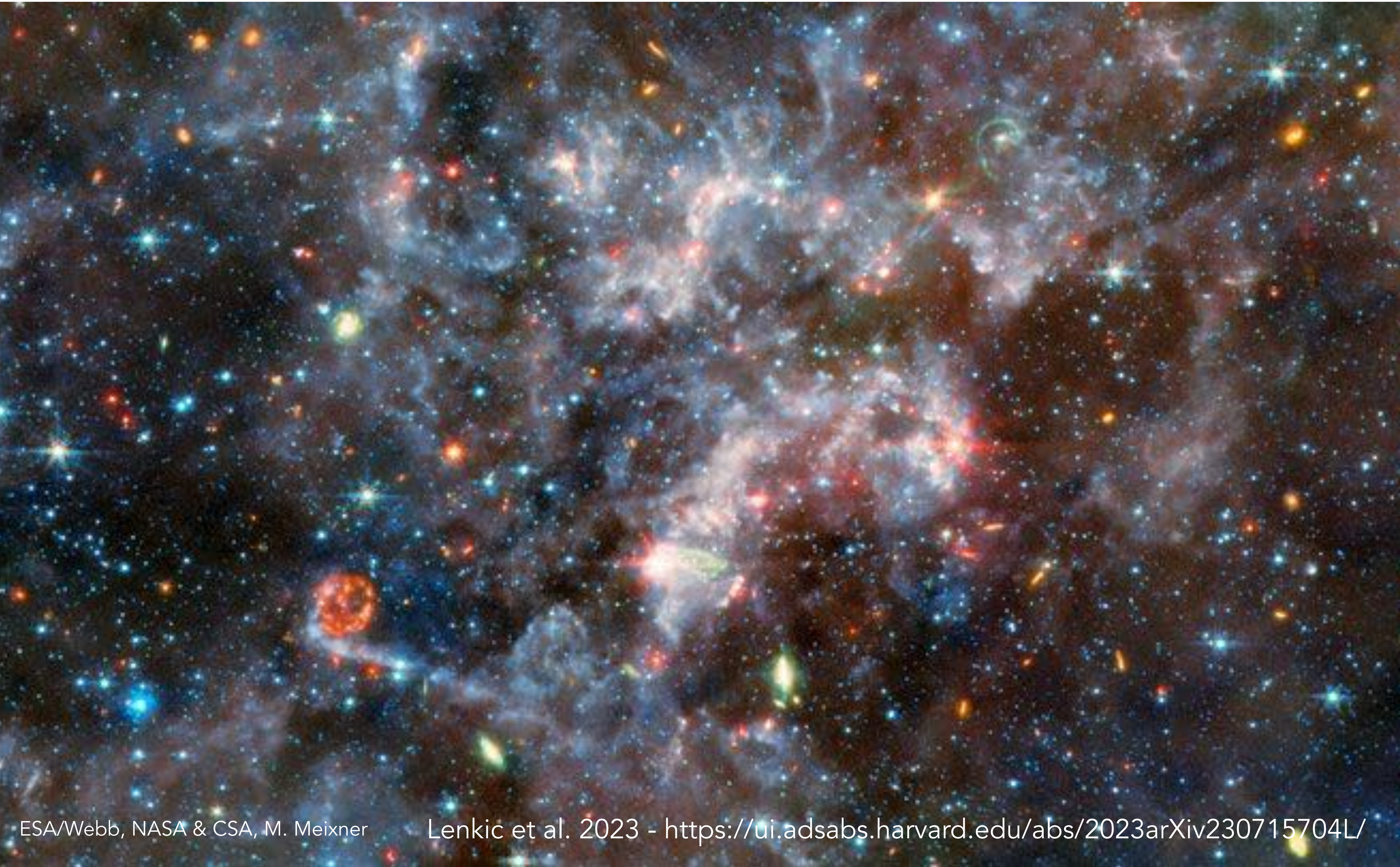
>0.1 pc in the Magellanic Clouds
~pc in Local Group
~10 pc out to 10 Mpc

Photometry & spectroscopy capabilities; tracers of ionized, atomic, molecular; new diagnostics of PAHs (3.3 μm, 3.4 μm features); can find individual YSOs & pre-MS stars

Jones et al. 2023 - https://ui.adsabs.harvard.edu/abs/2023NatAs...7..694J/

The Future!

NGC 6822 with MIRI

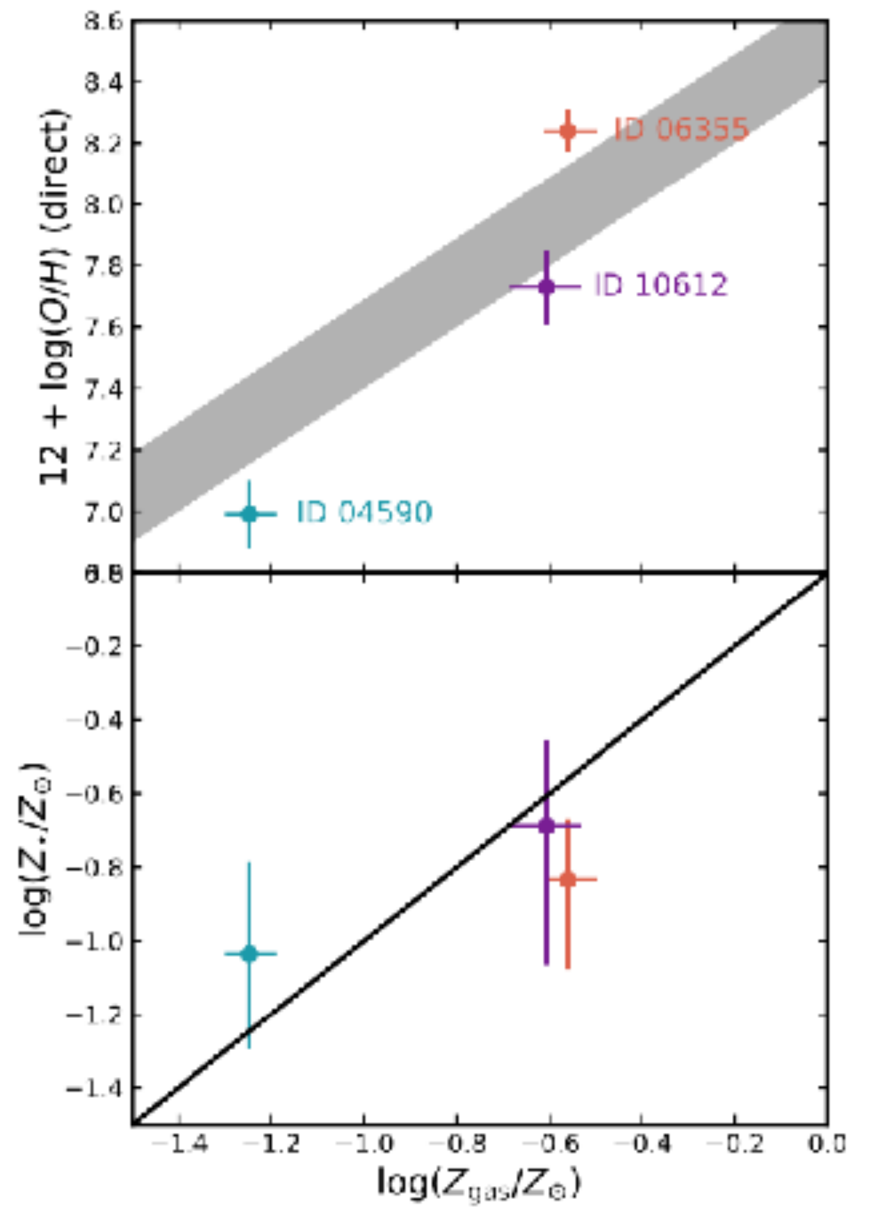


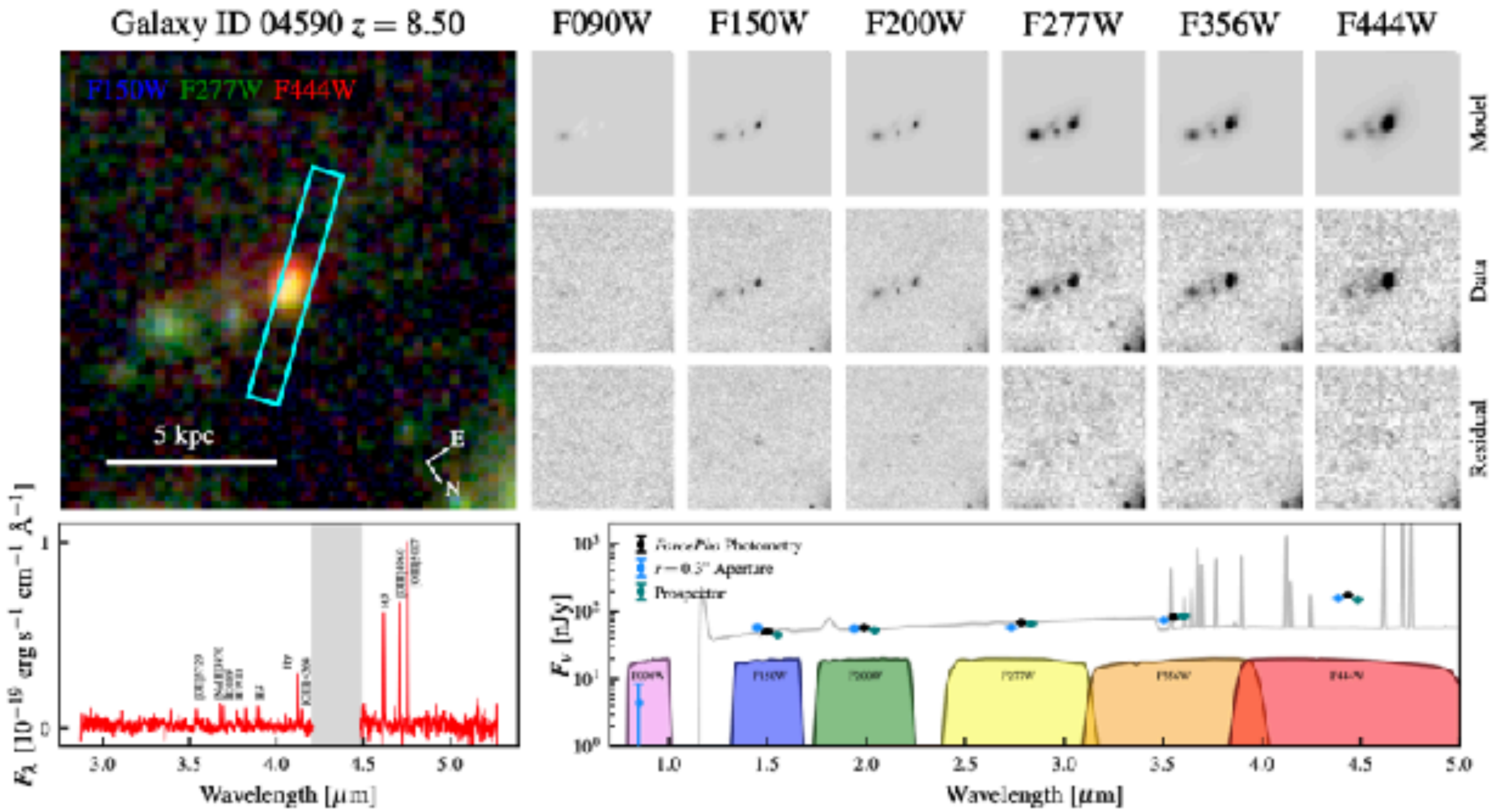
ESA/Webb, NASA & CSA, M. Meixner

Lenkic et al. 2023 - https://ui.adsabs.harvard.edu/abs/2023arXiv230715704L/

The Future!

Many of the same tracers we've studied in nearby dwarfs can now be seen at very high redshift! (optical emission lines with JWST, far-IR lines with ALMA)





Tacchella et al. 2023 - https://ui.adsabs.harvard.edu/abs/2023MNRAS.522.6236T/

Some Thoughts on Future Directions

- Nearby low metallicity targets are often faint, many studies are therefore biased towards the brightest BCD-like, starburst dwarfs. Need to capture more "normal" low metallicity ISM for complete picture.

- Evolution of dust and gas are coupled, D/M varies within galaxies vs N(H) and phase. Complicates use of dust to calibrate CO-dark H_2. Need better constraints on dust evolution!

- Why does the PAH fraction change with metallicity so dramatically? Some combination of formation and destruction? Need to understand actually how PAHs form!

Summary

- Low metallicity has dramatic impacts on the ISM - changes dust, decreased shielding, alters heating/cooling, and more.
- Dust changes: D/M drops, PAH fraction plummets, grain sizes shift smaller, composition changes. A key aspect may be the efficiency of ISM grain growth & where it outpaces stellar dust production.
- Ionized gas is hotter, higher ionization, more porous.
- Atomic gas shows colder but less common CNM and higher CNM pressure, in line with expectations from heating/cooling balance.
- Molecular gas is mostly “CO-dark” with small ~pc scale CO-bright clumps. Lots of agreement on CO-dark dominance, but widely varying measurements of exact proportion.
- JWST + ALMA gives us MW-like resolution in nearby low-Z galaxies and the ability to study the low-Z ISM at high redshift as well. Future is very exciting!