Linking **ISM cooling emission lines to energetic processes** in high-z metal-poor analogues

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Why study feedback mechanisms in external galaxies

Gain knowledge on the energetic sources' properties themselves

Probe feedback on ISM & SF conditions

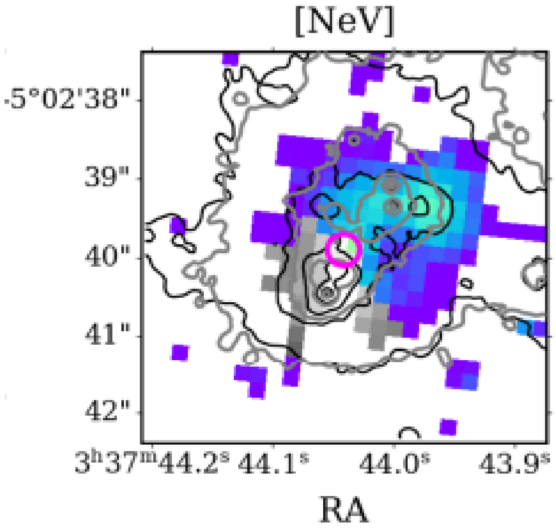
Inform R-MHD simulations for wider cosmological context

- Energetic source properties
  - Stellar population (UV & X-ray photons), X-ray binaries, active galactic nuclei, cosmic rays, shocks
  - → Direct access to *some* sources: UV & X-ray source catalogs, kinematic studies of AGNs…

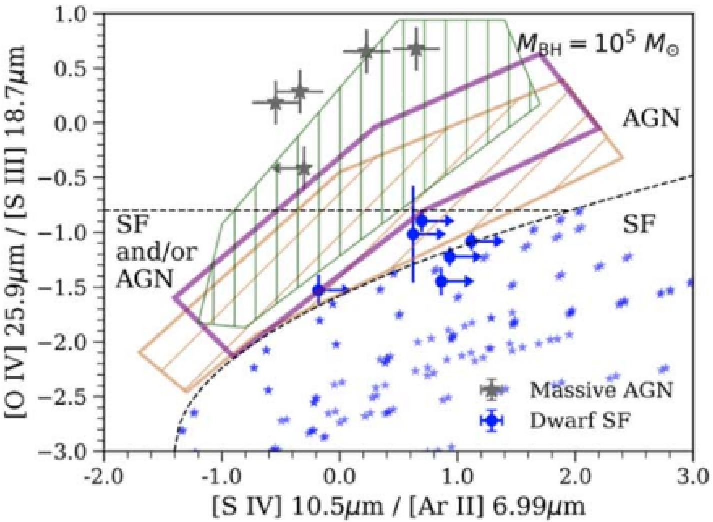
- ISM ionization & heating
  - Indirect constraints on nature/properties of energetic sources **+** telltales of feedback affecting ISM & SF conditions
  - Nature & influence of sources **actually energizing** the ISM?
    - Tracing heating rate **seen by gas** remains difficult → **cooling lines** as tracers
    - *Caveats*: thermal equilibrium, time-dependent cooling, difficult to trace back competing heating processes
  - Robust determinations of some quantities require proper treatment of ionization & **heating** → proper interpretation of **cooling** pathways
    - e.g., Z, SFR, $M(H_2)$, $M(H_2)_{CO\text{-}dark}$…

Ionized gas diagnostics with JWST

- JWST will provide significant progress on the excitation mechanisms in the **ionized gas** of galaxies (including at very low Z)
  - → Probing (collective) signatures of ~100pc regions, ~10Myr "snapshot" of excitation conditions
  - Revealing the major processes between AGN/SF/shocks



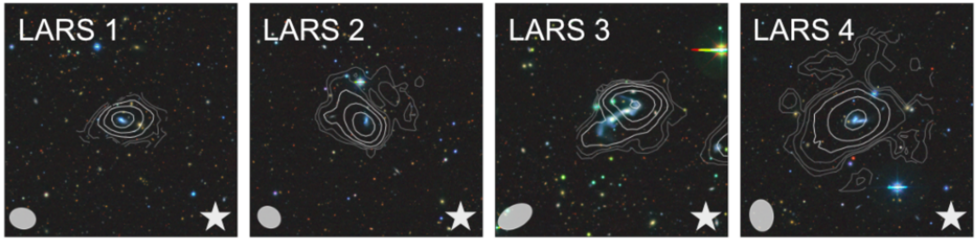
First mid-IR detection [NeV] in a BCD (SBS0335-052; Mingozzi+ 2025)



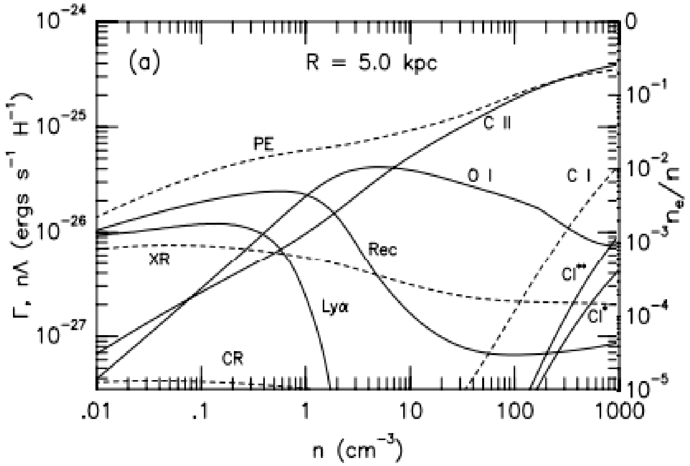
Demarcations separating starbursts and AGN with mid-IR lines (Richardson+ 2022)

HI region properties with PRIMA

- What processes deposit their energy in the **HI region & the SF gas reservoir,** how is the energy dissipated ?
  - → 0.1-1Gyr, ~kpc scales
- Disentangling HI region heating mechanisms is challenging
  - UV ionization of C^0, PE, shocks, soft X-ray PI from compact objects, CRs
  - Coolants: mostly C^+, O^0, H_2, dust (e.g., Dalgarno 1972; Bialy & Sternberg 2019)
  - Lyα at Z≲0.03% solar
- → Dependency on highly-variable HI region properties (depth, density, temperature) as well as general environment (Z, D/G, outflows, galaxy interactions…)



Extended HI gas reservoir in Lyα emitting galaxies ~200Mpc (Le Reste+ 2025)



Heating/cooling in the neutral atomic phase (Wolfire+ 2023)

Potential science case

SF: complex, non-linear, coupling between chemical, thermodynamical, as well as turbulent processes in the ISM

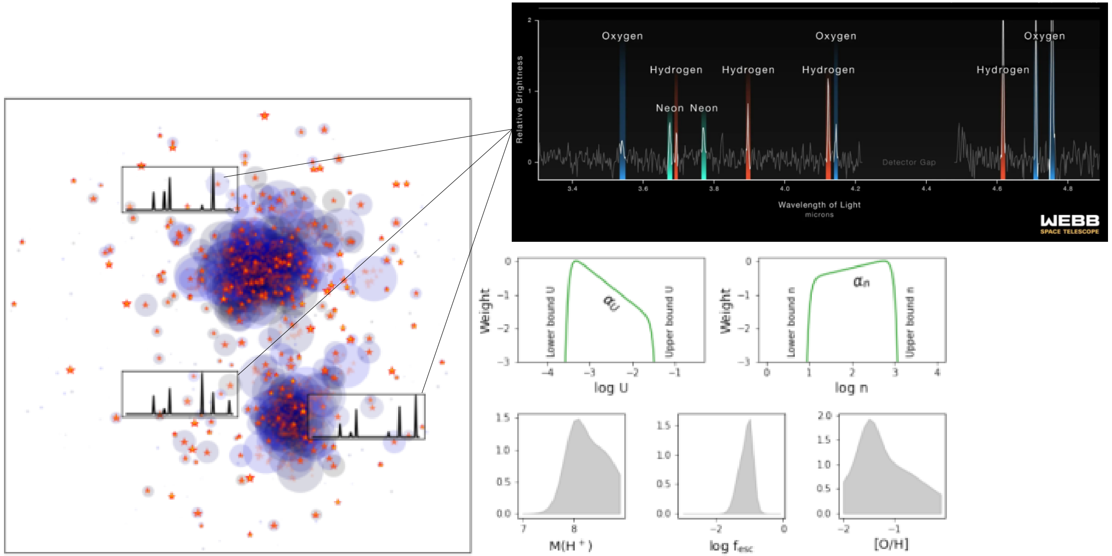
Needs to be examined in various environments, especially in metal-poor galaxies where fundamental differences regarding ISM conditions and the nature and properties of energetic sources are expected

- How do internal processes & feedback drive the evolution of primitive galaxies and their transformation into the present-day galaxy population?
- Goal: Linking spectral emission to energy dissipation and star-formation conditions in primitive galaxies
  - 1) What energetic sources power the low-metallicity ISM, what are their signatures?
    - Can we find tracers applicable to the young Universe?
  - 2) Do/how these heating mechanisms regulate star formation (SFH, available cold H_2 reservoir)?
    - Influence on ISM chemistry and H_2 formation? Role of internal/external processes for quiescence → starburst?
  - 3) How much gas is ejected by feedback mechanisms?
    - Probe outflows for the first time in the nearest extremely metal-poor galaxies?

Why PRIMA is important and timely

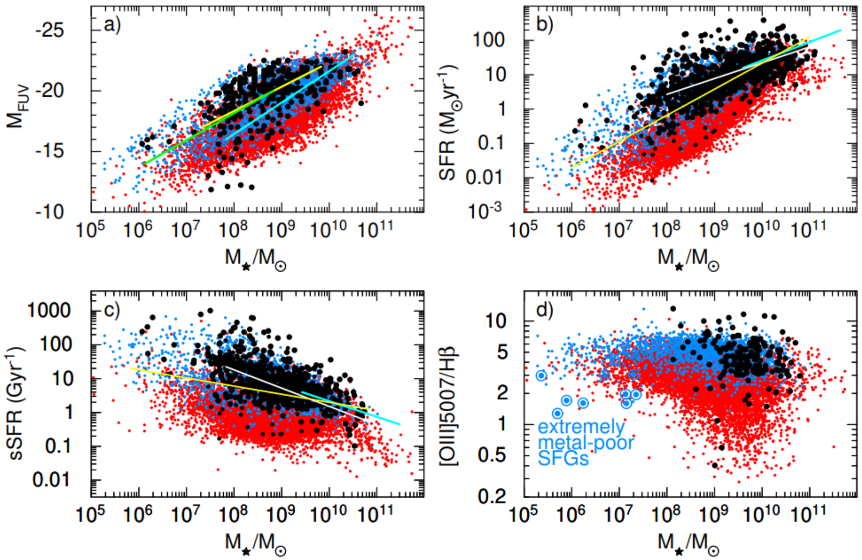
- **State-of-the-art statistical models** to exploit diagnostic power of **full-range spectroscopy**
  - Models are useful only if the origin of all lines is well understood and well constrained
  - PRIMA provides “**phase-resolution**” (instead of velocity/spatial-resolution) to distinguish ISM phases (ionization, density)
    - HI region but also HII region tracers ([OIII]$_{52,88}$, [NII]$_{122,205}$, [NIII]57…) as well as high-ionization species ([OIV]$_{25}$, [NeV]$_{24}$, [ArIV])
  - FIRESS already provides better sensitivity than Spitzer/LH or Herschel/PACS but the sensitivity improvement **per line** (incl. useful upper limits) is tremendous

- Recent **statistical** methods using varying level of information
  - Accounting for distributions of emitting components: MULTIGRIS (Lebouteiller & Ramambason 2022), HOMERUN (Marconi+ 2024), Morisset+ (2025)…
  - Iterative process between **using & updating prescriptions** for the source & ISM properties



Sample

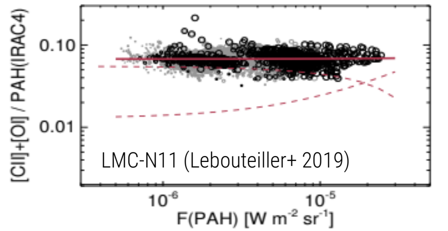
- **Why not high-z directly?**
  - Some HI region lines (e.g., [CII]) now routinely observed in high-z galaxies with ALMA/NOEMA
    - Most metal-poor galaxy detected in [CII]: low-mass galaxy S04590 z=8.496 ~3% solar (and optical lines with JWST; Heintz+ 2023).
    - Also ALPINE survey z~4-6 (most galaxies ~50% solar, Vanderhoof+ 2022)
  - Very small samples of metal-poor galaxies, several far-IR lines in a single source is rare
- Identification of heating mechanisms requires a reference z~0 sample
- Low-Z z~0 galaxies share some properties (compact, metal/dust-poor ISM, SSCs) with high-z galaxies (e.g., Izotov+ 2021; Zou+ 2024)
  - Similarities also with far-IR line ratios (e.g., Inoue+ 2016; Hashimoto+ 2018)
  - → high-z "analogues" (laboratories, really)

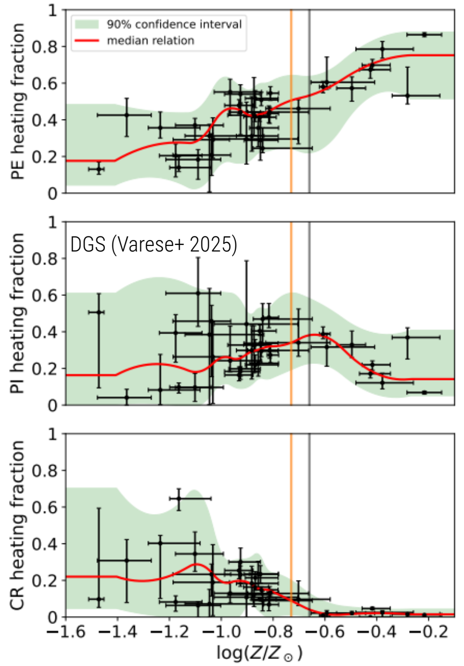


Compact SFGs at z<1 with EW(Hβ)><100Å compared to high-z galaxies in black (Izotov+ 2021)

What we “know”: photoelectric effect heating

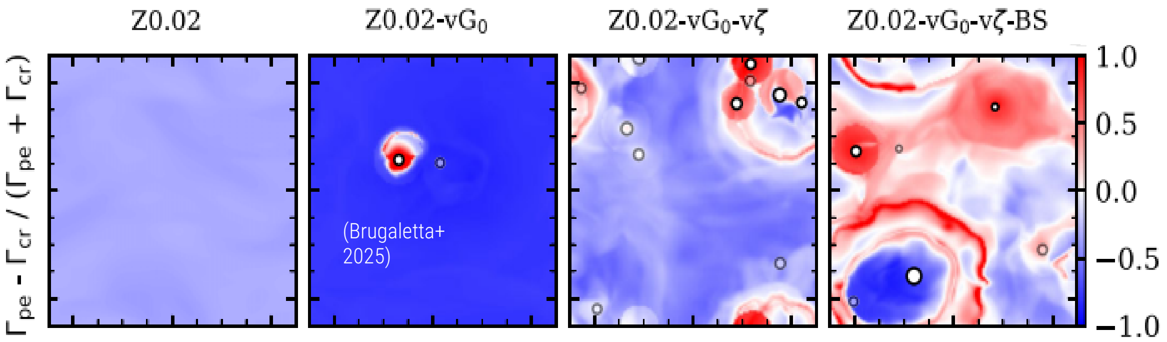
- Dominant neutral atomic ISM heating mechanism in MW and in MW-like ISM (e.g., Bakes & Tielens 1994; Weingartner & Draine 2001)
- Milestone I. Moderately metal-poor ISM (LMC SF regions, 50% solar)
  - PAHs dominate the PE heating, [CII] + [OI] traces the total cooling (Helou+ 2001; Croxall+ 2012; Lebouteiller+ 2012a, 2019; Lambert-Huyghe+ PhD 2021; Belloir+ in prep.)
- Milestone II. XMP (IZw18, 3% solar)
  - PE is negligible, extremely low D/G and low PAH abundance ratio (q_{AF}) (Lebouteiller+ 2017)
- Milestone III. PE vs. Z
  - Fraction of total heating due to PE not dominating anymore for Z<20% solar (Varese+ 2025)
  - Confirmation of theoretical study of Bialy & Sternberg (2019)
- Very few XMPs, crude assumptions on CRIR
- PAHs: JWST XMP catalog to be prepared (dust SEDs as alternative; e.g., SPHEREx?)
- [CII] + [OI]: PRIMA

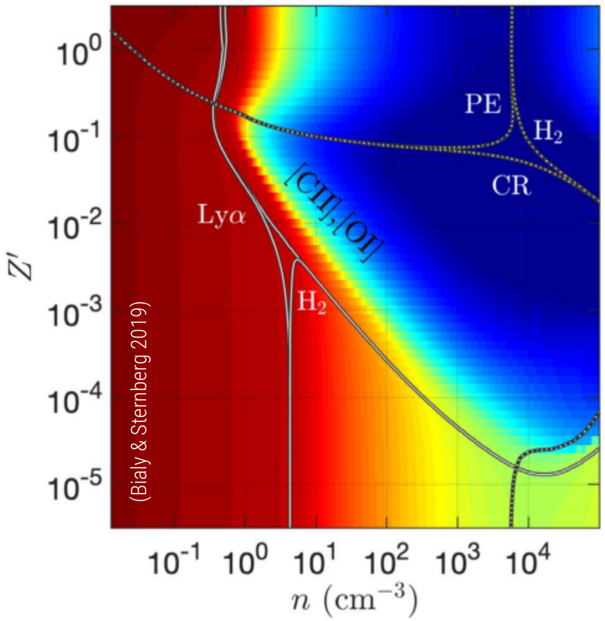




What we (don't) know: cosmic rays

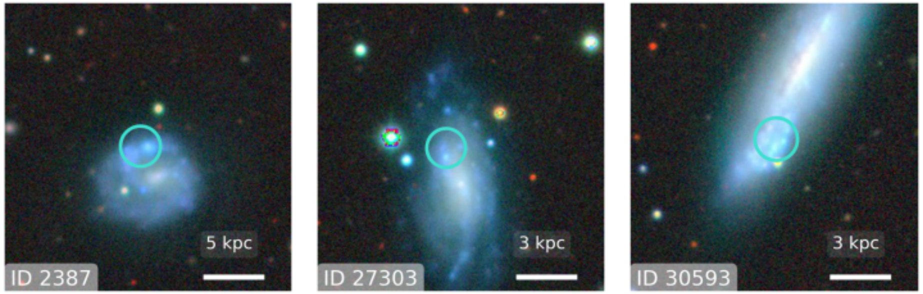
- Some theoretical expectations
  - Bialy & Sternberg (2019): Γ_{CR} heating dominates <10% solar (but XRBs not considered)
  - Brugaletta+ (2025): Γ_{CR} vs. Γ_{PE} highly spatially variable
- **Models:** exploring different CRIR & distributions are needed (Varese+ in prep.)
- **Potential observations:** JWST: H^{3+} in a few objects, ALMA/NOEMA: molecule ionization
- XMPs?
  - Neutral atomic gas tracers at different depths in clouds



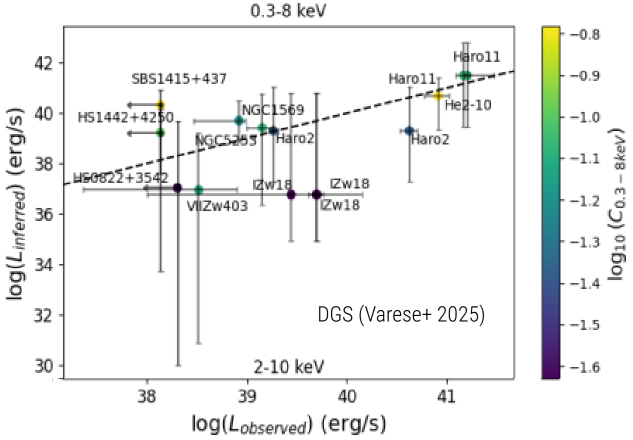


What we “know”: X-ray sources

- X-ray source properties
  - HMXBs: Known theoretical & observational somewhat increased abundance and luminosity of X-ray binaries at low Z (e.g., Cann+ 2024)
  - IMBHs: M_{BH}-M_{*} relationship predicts IMBH-range BHs in dwarf galaxies ($\lesssim 10^{9.5} M_{\odot}$), with a large occupation fraction (e.g., Reines & Volonteri 2015; Cho+ 2024)
- ISM signatures
  - JWST ([OIV], [NeV], [NeVI]…) & optical coronal lines
  - PRIMA: [OIV], [NeV] & neutral gas tracers → may recover direct X-ray flux
  - eROSITA (then NewATHENA) observes and characterizes many X-ray binaries in nearby galaxies and PRIMA is the best mission to reveal their signatures in the neutral ISM



ULX candidates in the outskirts of dwarf galaxies with eROSITA ($<10^{9.5} M_{\odot}$; Bykov+ 2023)

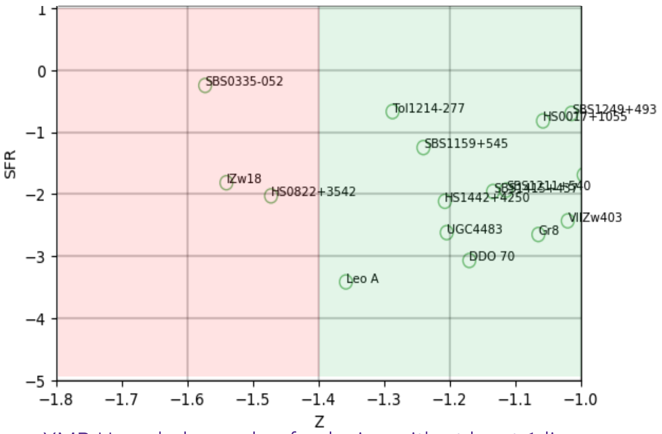


Main limitations so far and why we need PRIMA

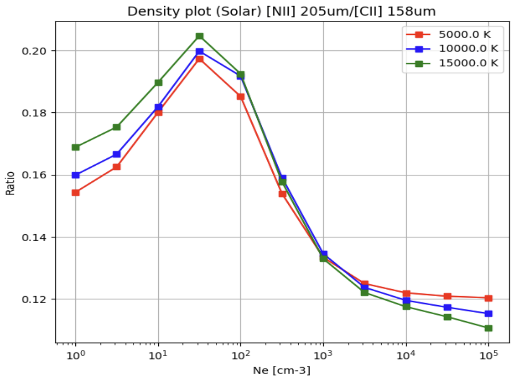
- We have barely started to explore such mechanisms as ionization by **X-rays** and **CRs** in XMPs
  - **Shocks** & **turbulence** pretty much unexplored, especially in neutral gas
  - Difficult to disentangle heating from CRs vs. soft X-ray photoionization → need to be treated **together** in a coherent modeling framework
  - Infer nature of energetic sources from ISM diagnostics **&** feedback of energetic sources on the ISM itself at the same time?
    - Important degeneracies possible → need multiple ISM tracers & phases

- Sample
  - Small XMP sample with far-IR data (even mid-), very few quiescent (pre-starburst)
    - Impossible to draw conclusions on impact of feedback on SF properties

- Tracers
  - Few tracers to work with vs. several complex heating mechanisms that depend heavily on HI region properties
  - Availability of both [OI] lines, potential optical depth of $[OI]_{63}$
  - $[NII]_{205}$ best tracer of [CII] in ionized gas
  - …

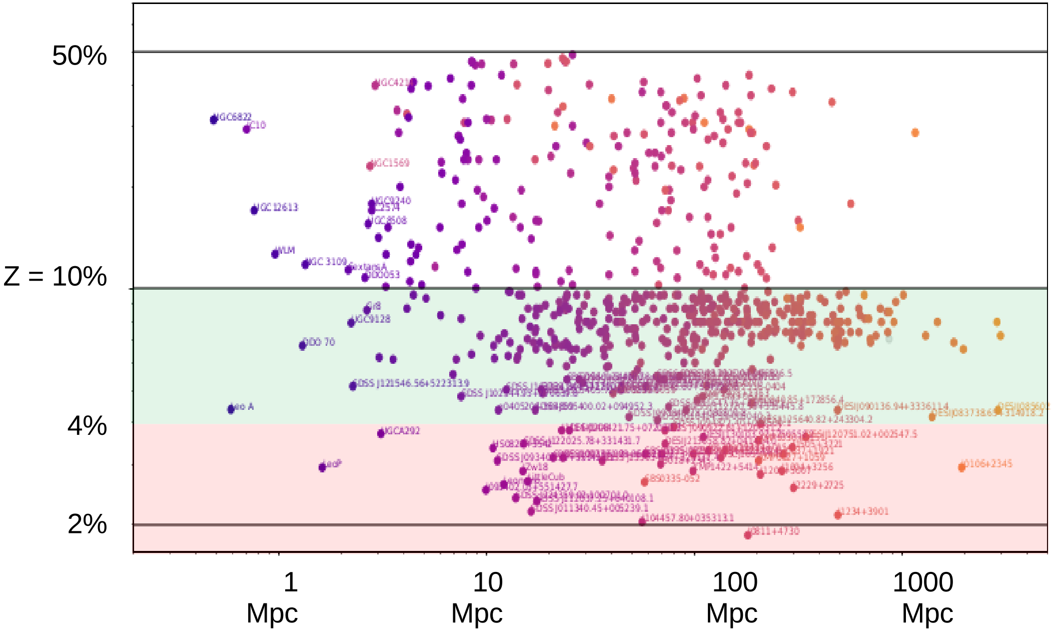


XMP Herschel sample of galaxies with at least 1 line *observed*



XMP sample

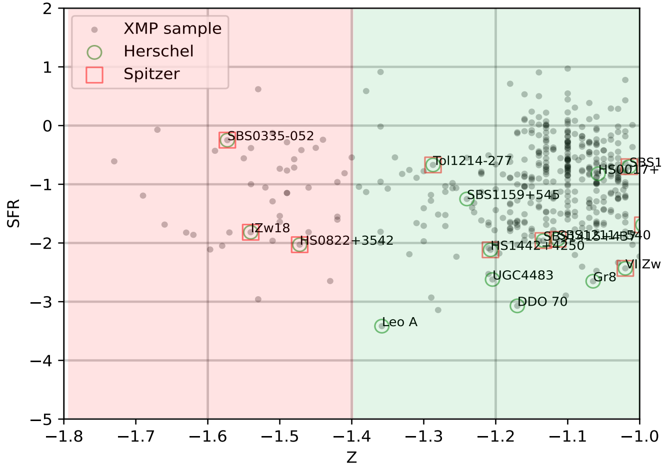
- XMP samples and candidates growing over the years since *Herschel* (DESI, SDSS, VLT, LBT…)



MW/LMC/SMC anchors

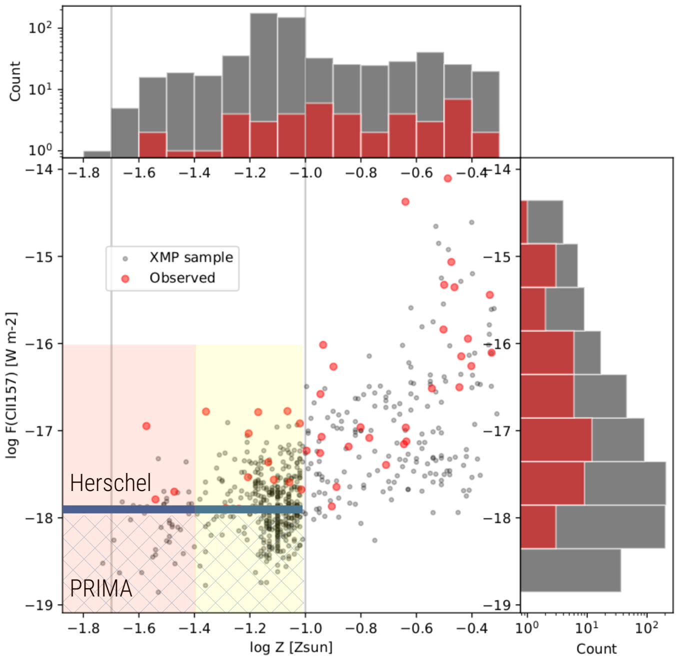
≲10% solar XMP sample for main trends

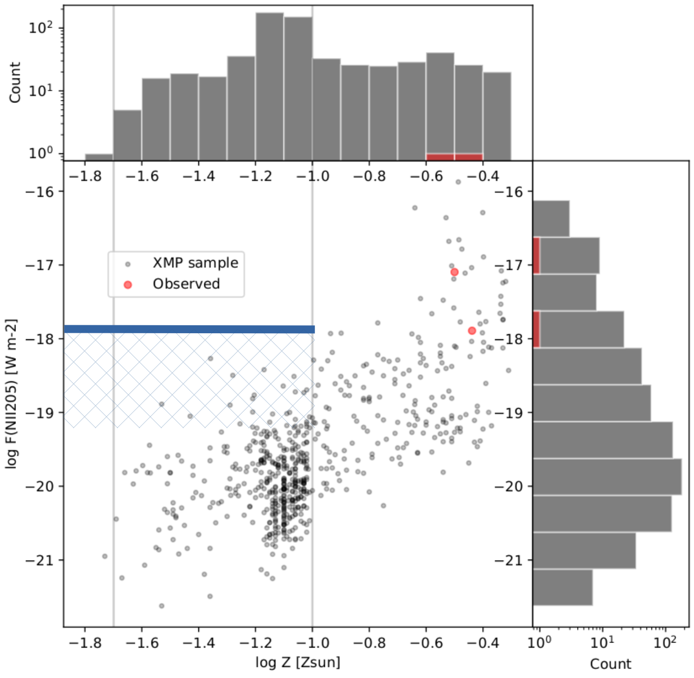
≲4% solar XMP sample for extremes and extrapolations



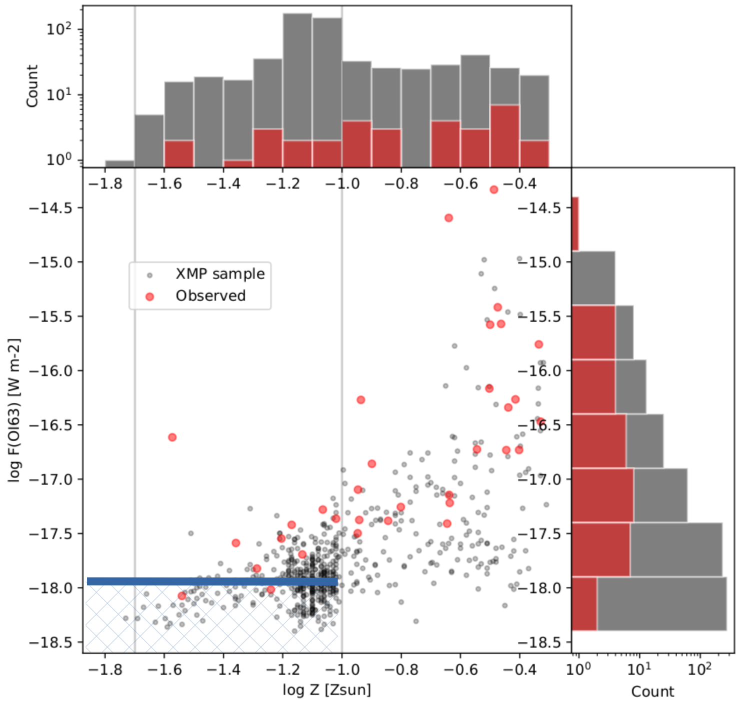
Expected fluxes

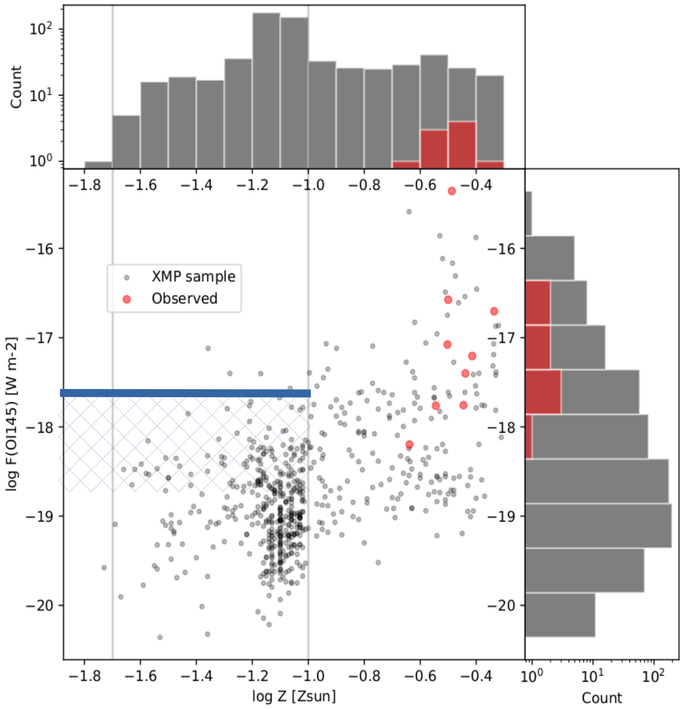
- Observations & predictions from calibrated WISE/W4 → SFR → line flux





Expected fluxes





- Set of many lines at once!

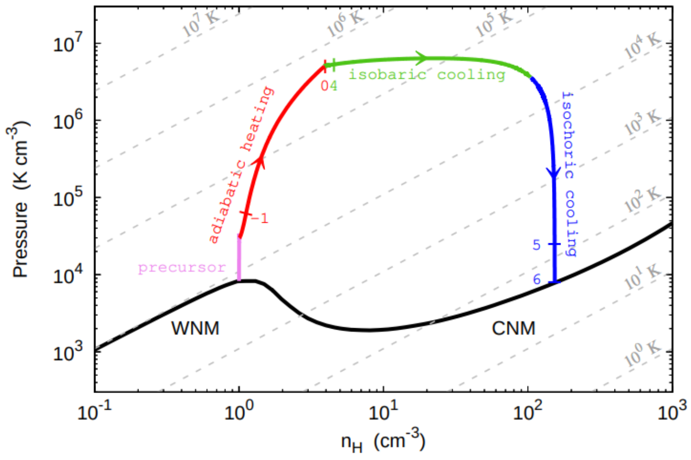
Summary

- PRIMA ideal observatory to probe **nature and influence of energetic sources on star-forming gas reservoir**
  - In particular in extremely metal-poor galaxies → high-z laboratories
- What energetic sources take over PE at low metallicity? What influence on the SF gas reservoir on long time-scales?
  - New PRIMA constraints will feed R-MHD simulations
- **Significant XMP sample** can be observed, principally with FIRESS
- XMP sample also relevant to other objectives
  - Amount of molecular gas (incl. CO-dark H_2) and relationship with SF process → need quiescent XMPs for temporal evolution of H_2 reservoir
  - Moderately metal-poor galaxies important sample for molecular gas inventory ($CO_{14\text{-}13,\ 15\text{-}14}$, OH, also H_2O enhanced at low Z...) and model calibration (HD, [CI] as tracers of the CO-dark H_2 gas)
  - ISM properties favoring escape of ionizing photons

extras

What we (don't) know: mechanical heating

- Dissipation of **turbulence** generated by stellar winds and supernovae
- **Shocks** both dissipate turbulence (at small scales; CNM, dense molecular clouds) and drive it (by injecting energy at large scales)
  - G_0, n can be severely overestimated in PDR models of SF galaxies using CO if shocks not accounted for (e.g., Kazandjian+ 2016)
  - Mechanical heating from low-velocity shocks dominate over X-rays and CRs in CO-bright layers in LMC SF regions, neutral atomic gas layers unaffected (e.g., Lee+ 2016)
- In XMPs? Pretty much unexplored... JWST will likely miss shock signatures in the neutral SF gas reservoir
- **Gas flows and consequences of stellar mechanical feedback**: how much gas is ejected in dwarf galaxies?
  - Probe outflows through ionized gas (e.g., [OIII]) and neutral gas (e.g., [CII]) tracers (easier than molecular tracers, e.g., OH) → FTS?



High-velocty shock: 1 Myr evolution of an ISM fluid particle which is irradiated by the precursor, is heated by the shock front, cools down in isochoric conditions and isobaric as magnetic pressures becomes dominant (Godard+ 2024)

What we (don't) know: cosmic rays

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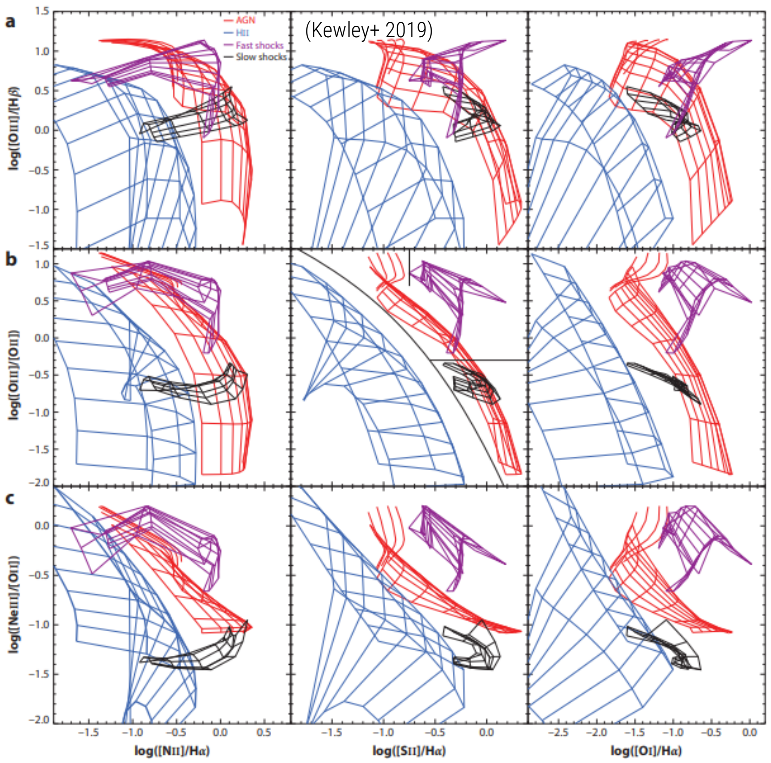
  - Bialy & Sternberg (2019): Γ_{CR} heating dominates <10% solar (but XRBs not considered)
  - Brugaletta+ (2025): Γ_{CR} vs. Γ_{PE} highly spatially variable
- **Models:** exploring different CRIR & distributions are needed (Varese+ in prep.)
- **Potential observations:** JWST: H^{3+} in a few objects, ALMA/NOEMA: molecule ionization
- XMPs?
  - Neutral atomic gas tracers? Difficult to disentangle from soft X-ray photoionization → Need suite of tracers originating at different depths

Model	Description	Conf.[a]	Input parameters: L_X (log erg s^{-1})	CR[b] (× Gal.)	D/G (× Gal.)	Output parameters: n^c_{max} (cm^{-3})	T^d_{stop} (K)	$M(H^0)$ (log $M_\odot$)	M_{dust} (log $M_\odot$)	[C II] (M/O[e])	[O I] (M/O[e])	[Si II] (M/O[e])	$\Gamma_{tot}(HI)$[f] PE	CR
Exploratory models														
M0a	(≈P08's *M2*)	(a)	0	0	0	150	50[g]	3.7	0	0.01	0.01	0.27	0%	0%
......*b*	Dust (Z-scaled D/G)	(a)	0	0	1/50	50	50[g]	4.7	2.6	0.02	0.06	0.35	12%	0%
M1	XR	(a)	40.6	0	0	150	100	7.2	0	1.01	1.10	0.81	0%	0%
M2a	XR + dust (observed D/G)	(a)	40.6	0	1/1000	200	95	7.2	2.2	1.00	1.07	0.77	4%	0%
......*b*	XR + dust (Z-scaled D/G)	(a)	40.3	0	1/50	250	110	7.2	3.4	1.01	1.05	0.62	57%	0%
......*c*	XR + dust (maximum D/G)	(a)	40.6	0	1/300	200	100	7.2	2.6	1.00	1.08	0.77	10%	0%
......*d*	XR + dust (radial D/G)	(a)	40.6	0	1/(150 ↘ 750)	200	105	7.2	3.0	1.02	1.13	0.80	12%	0%
......*e*	XR + dust (extra sector)	(b)	40.6	0	1/(1000, 50)	150	90	7.4	2.3	1.02	1.02	0.75	4%	0%
M3a	XR + cosmic rays	(a)	40.6	1	0	200	110	7.2	0	1.01	1.13	0.81	0%	13%
......*b*	XR + cosmic rays	(a)	40.1	5	0	250	125	7.2	0	1.06	1.00	0.65	0%	65%
......*c*	Cosmic rays only	(a)	0	1	0	25	230	8.1	0	1.04	1.23	0.80	0%	96%
......*d*	Cosmic rays only	(a)	0	5	0	250	150	7.3	0	1.02	1.01	0.66	0%	96%
Full models														
M4a	Best parameter set	(b)	40.6	0.1	1/(1000, 50)	250	100	7.4	2.3	1.05	1.05	0.77	3%	0.7%
......*b*	*M4a* + molecules	(b)	40.6	0.1	1/(1000, 50)	250	80	7.3	2.2	1.03	1.00	0.71	3%	1%
......*c*	*M4b* + clumps	(c)	40.5	0.1	1/1000	150	90	7.3	2.6	1.00	1.12	0.84	3% (23%)	2% (17%)

IZw18 models (Lebouteiller+ 2017)



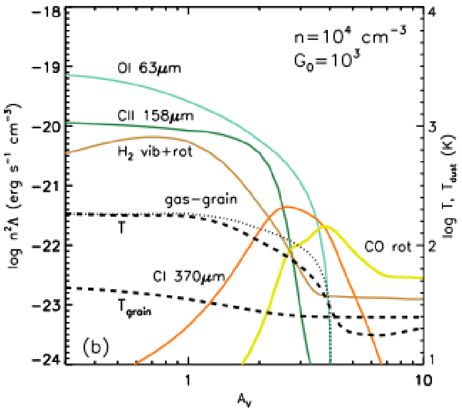
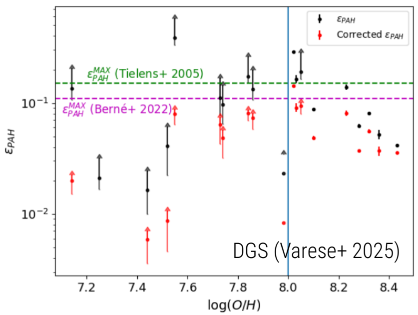
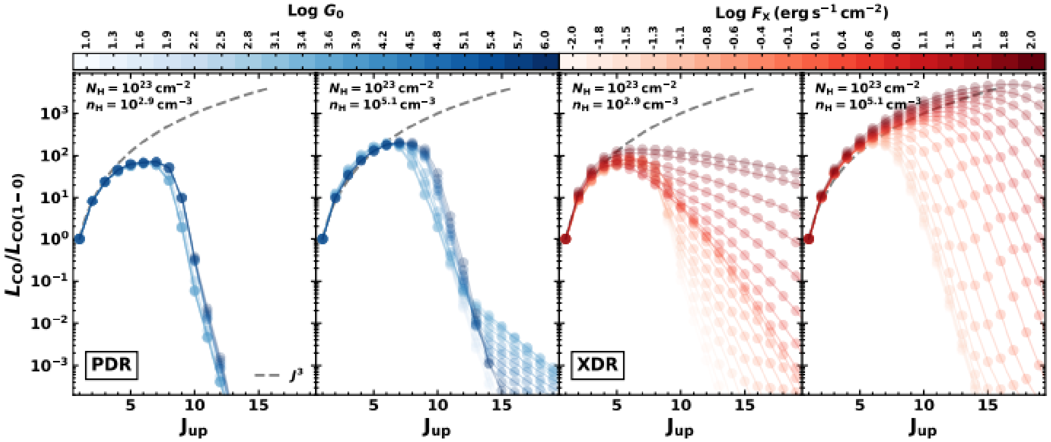


Fig. Cooling vs. A_V (Wolfire+ 2022)

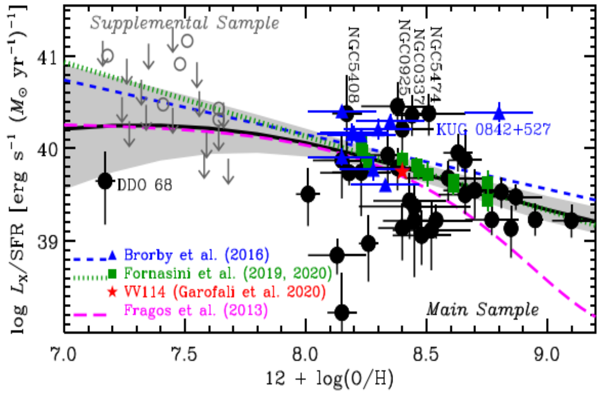




(Wolfire+ 2022)

What we know: X-ray sources

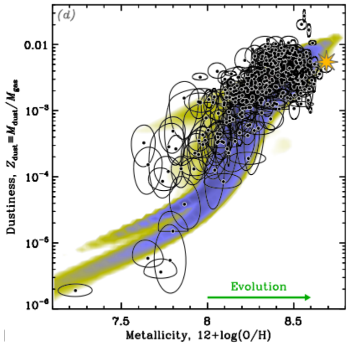
- Agnostic fits compensating current stellar population models, not distinguishing nature of X-ray source (multicolor backbody → accretion disk)
  - Lebouteiller+ (2017): X-ray source required in IZw18 ~ same properties as known ULX. Potential positive feedback due to H_2 formation in gas-phase?
  - Varese+ (2025): predicted X-ray fluxes from mid- and far-IR ISM cooling lines ([OIV], [NeV] especially) in broad agreement with direct X-ray observations
  - Neutral gas tracers useful but requires specific constraints on CRs, shocks or additional tracers to be robust
- Theoretical prescription of X-ray binary population
  - Richardson+, Garofali+, Varese+ (in prep.) → AGN as free additional contribution
  - See also Lecroq+ (2024) for high-energy radiation field from normal stellar population



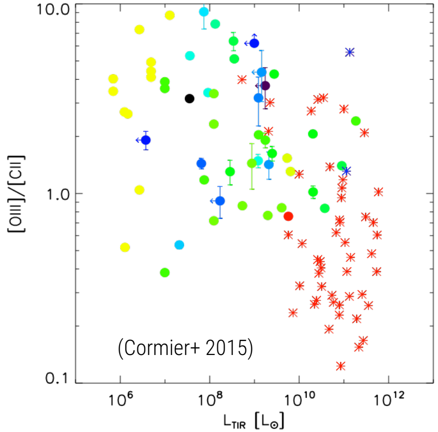
Low-Z galaxies have a relatively higher L_X (Lehmer+ 2021)

The low-Z ISM: the Spitzer and Herschel legacy

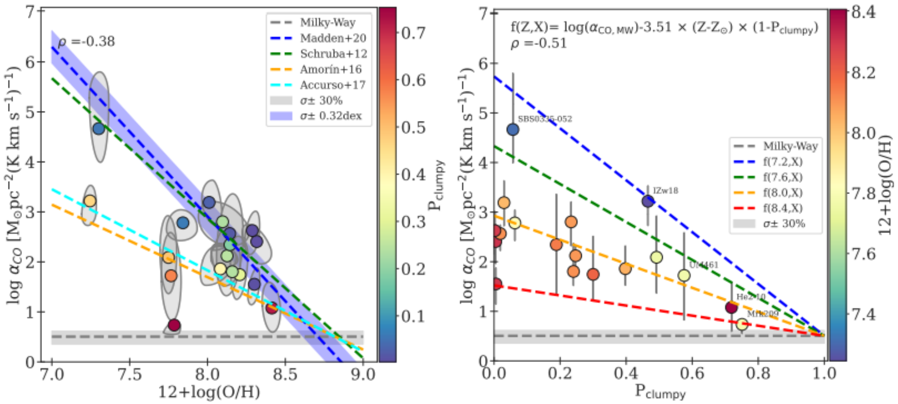
- Low D/G (e.g., Issa+ 1990; Rémy-Ruyer+ 2014; Fisher+ 2014; Galliano+ 2021…)
  - Spatial D/G variations may be important (Hunt+ 2014)
- Low PAH abundance ratio (q_{AF}) (e.g., Madden+ 2000; Engelbracht+ 2005; Wu+ 2006; Draine+ 2007, Hunt+ 2011…)
  - Low formation efficiency driven by low metal abundance (Galliano+ 2021)
  - PE heating expected to become small / negligible at low Z (regardless of the exact PE dust carriers)
- Large volume filling factor of ionized gas (e.g., probed by [OIII]) and small filling factor of dense molecular clouds (e.g., Hunt+ 2017; Ramambason+ 2024)
  - But large, extended, reservoir of CO-dark H_2 gas
  - Sparser, more massive clouds at low Z
- The low-Z ISM is relatively transparent to UV photons in the ionized gas and to X-rays in the ionized + neutral gas



(Galliano+ 2021)



(Cormier+ 2015)



(Ramambason+ 2024)