

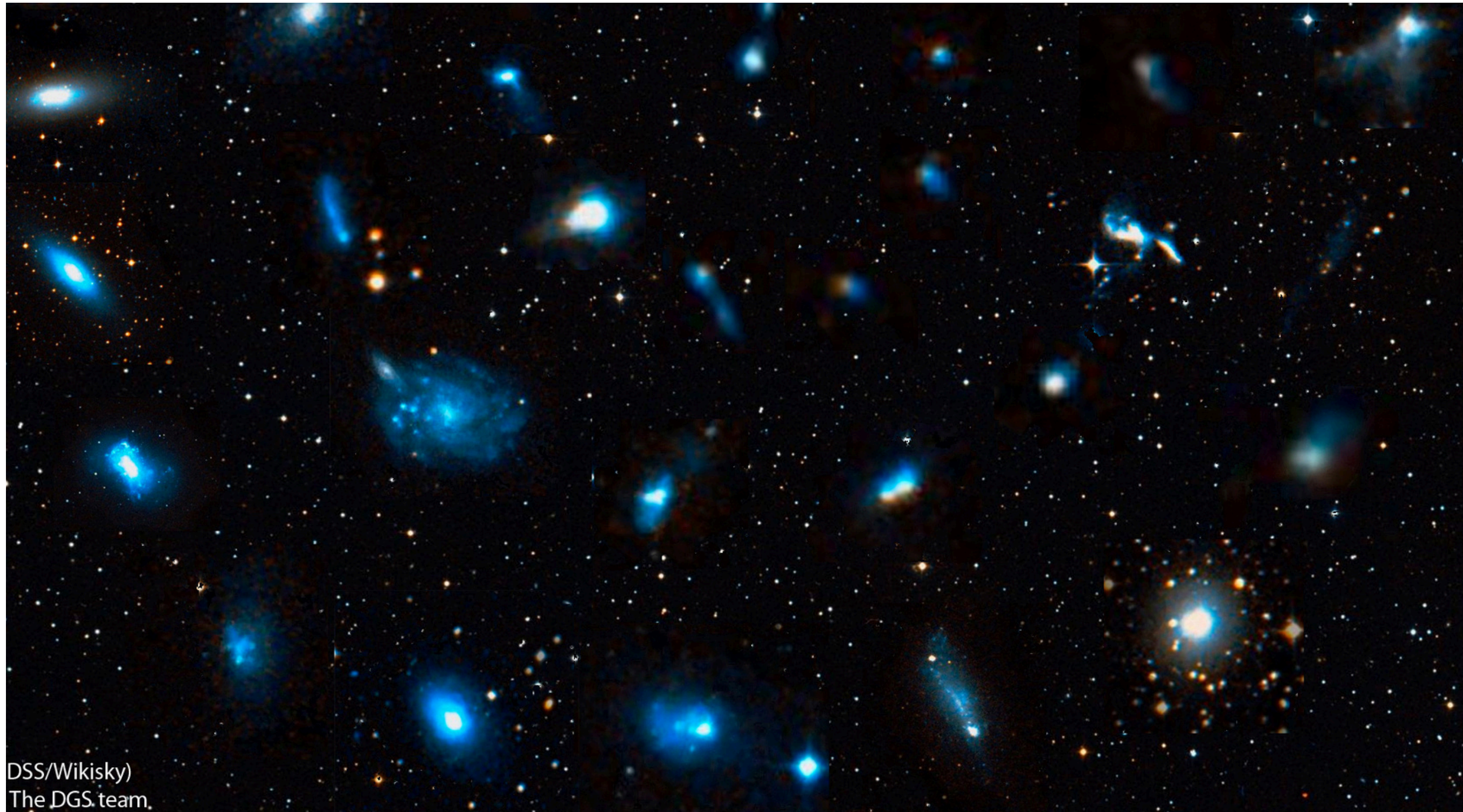
# Modeling the neutral gas heating in low metallicity galaxies

M.Varese<sup>(1)</sup>, V.Lebouteiller<sup>(1)</sup>, L.Ramambason<sup>(2)</sup>, F.Galliano<sup>(1)</sup>, C.T.Richarson<sup>(3)</sup>, S.C.Madden<sup>(1)</sup>

<sup>(1)</sup> Université Paris-Cité, Université Paris-Saclay, CEA, CNRS, AIM, 91191 Gif-sur-Yvette, France

<sup>(2)</sup> Institut für Theoretische Astrophysik, Zentrum für Astronomie, Universität Heidelberg, Albert-Ueberle-Str. 2, D-69120 Heidelberg

<sup>(3)</sup> Physics Department, Elon University, 100 Campus Drive, Elon, NC 27244, USA



DSS/Wikisky)  
The DGS team.

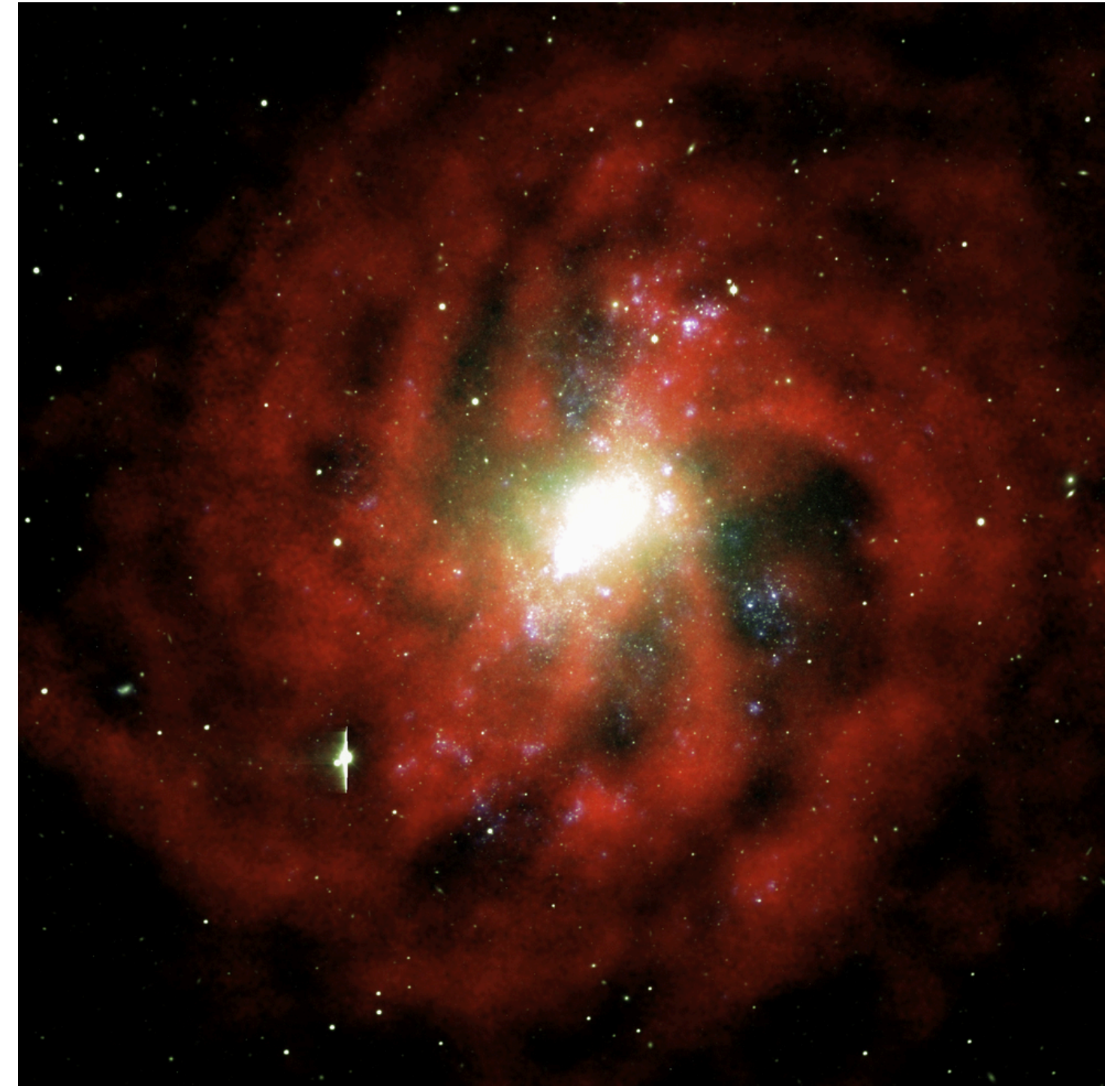


maxime.varese@cea.fr

## Why to study the neutral atomic gas heating ?

- Star formation occurs from cold, **molecular gas clouds**
- Neutral atomic gas  $\longrightarrow$  Molecular gas
- Heating as a **regulator of star formation** (e.g, Chevance et al. 2022)
- Heating of the atomic gas:
  - Hydrogen ionization
  - Photoelectric effect
  - Shocks
  - Turbulence
- SFR and heating efficiency diagnostics: based on IR cooling lines

**Here, we study only the radiative feedback, i.e. photoelectric effect and hydrogen ionization heating**



*NGC4214 HI map - LITTLE THINGS survey - Hunter et al. (2012)*

# Neutral atomic gas heating mechanisms

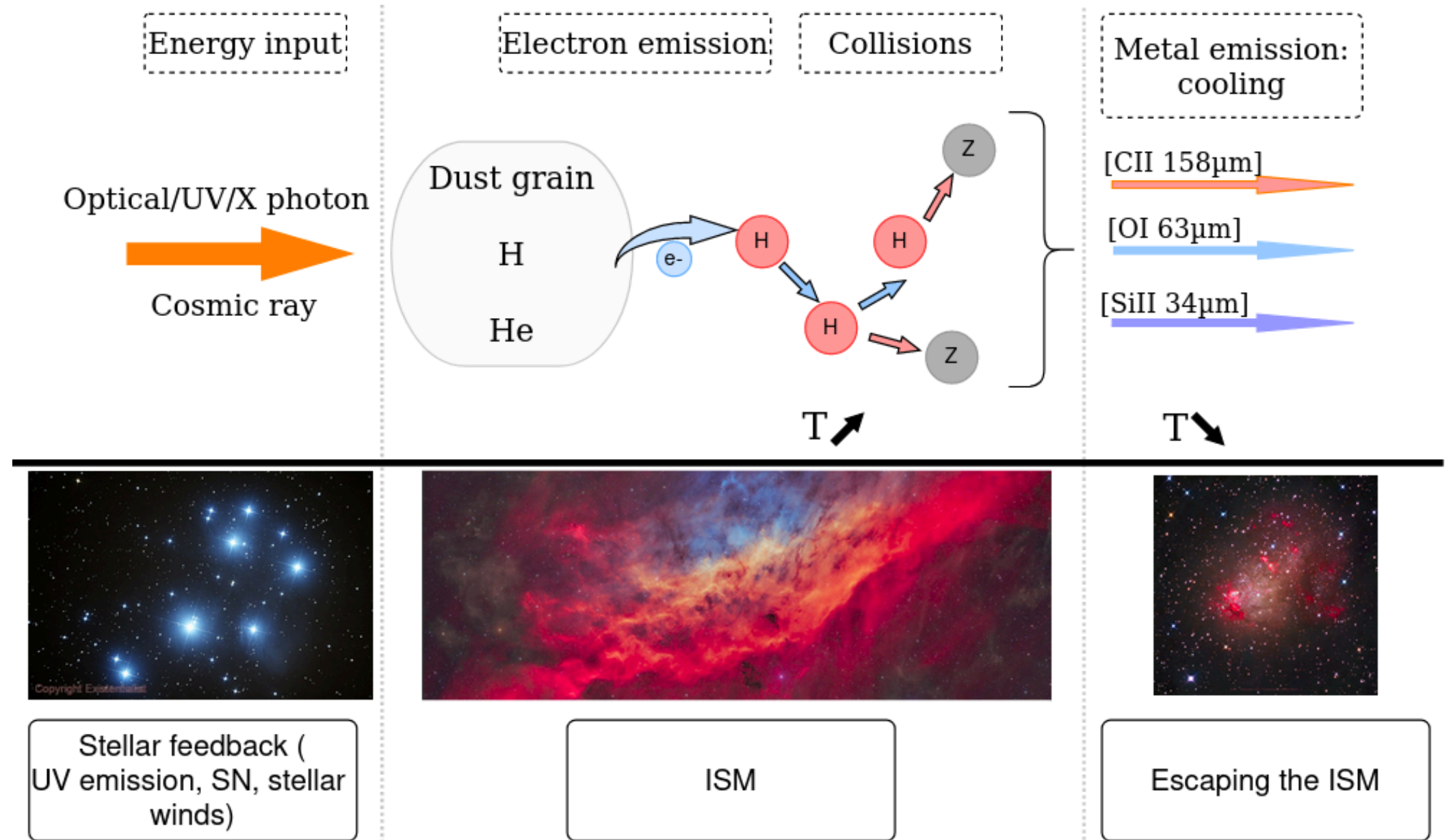
Electron released by:

- **photoelectric effect** on a dust grain
- **photoionization** by a photon (**UV or X-ray**)
- ionization by a **cosmic ray**

Collisions → energy transferred to the gas

**Metal cooling lines** → energy escapes the ISM

- $[CII] 158\mu m$
- $[OI] 63\mu m$
- $[SiII] 34.8\mu m$



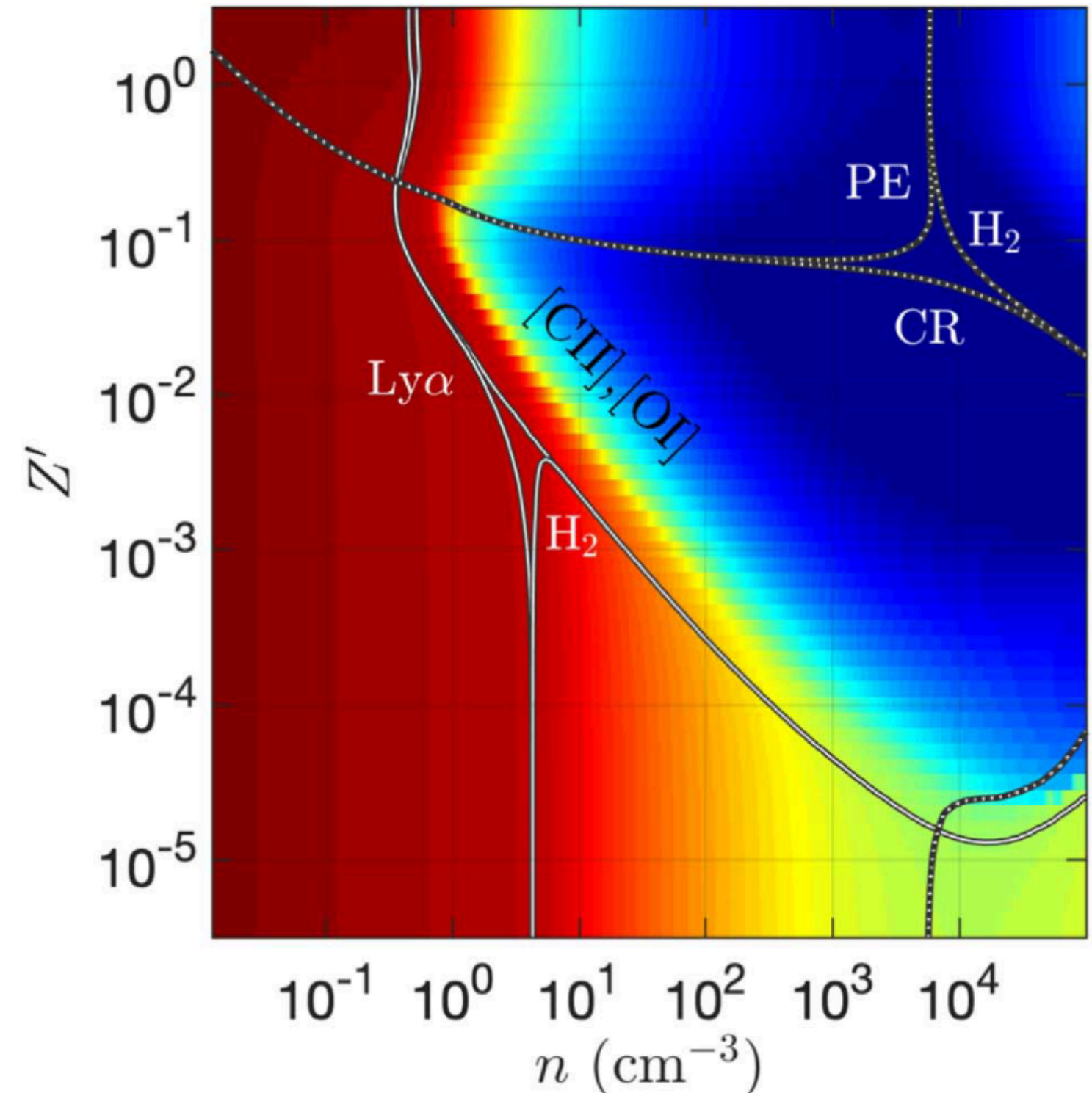
**SHOCKS NOT CONSIDERED**

## Neutral atomic gas heating mechanisms

In the Milky Way, the photoelectric effect dominates the heating of the atomic gas (Wolfire et al. 2003)

- Low Z environment: dust-to-gas mass ratio decreases (e.g, Galliano et al. 2021)

How do the photoelectric effect, X-ray photoionization and cosmic rays contribute to the heating of the neutral atomic gas at various metallicities?



*Dominant heating mechanism depending on density and metallicity, Bialy & Sternberg (2019)*

# Neutral atomic gas heating mechanisms

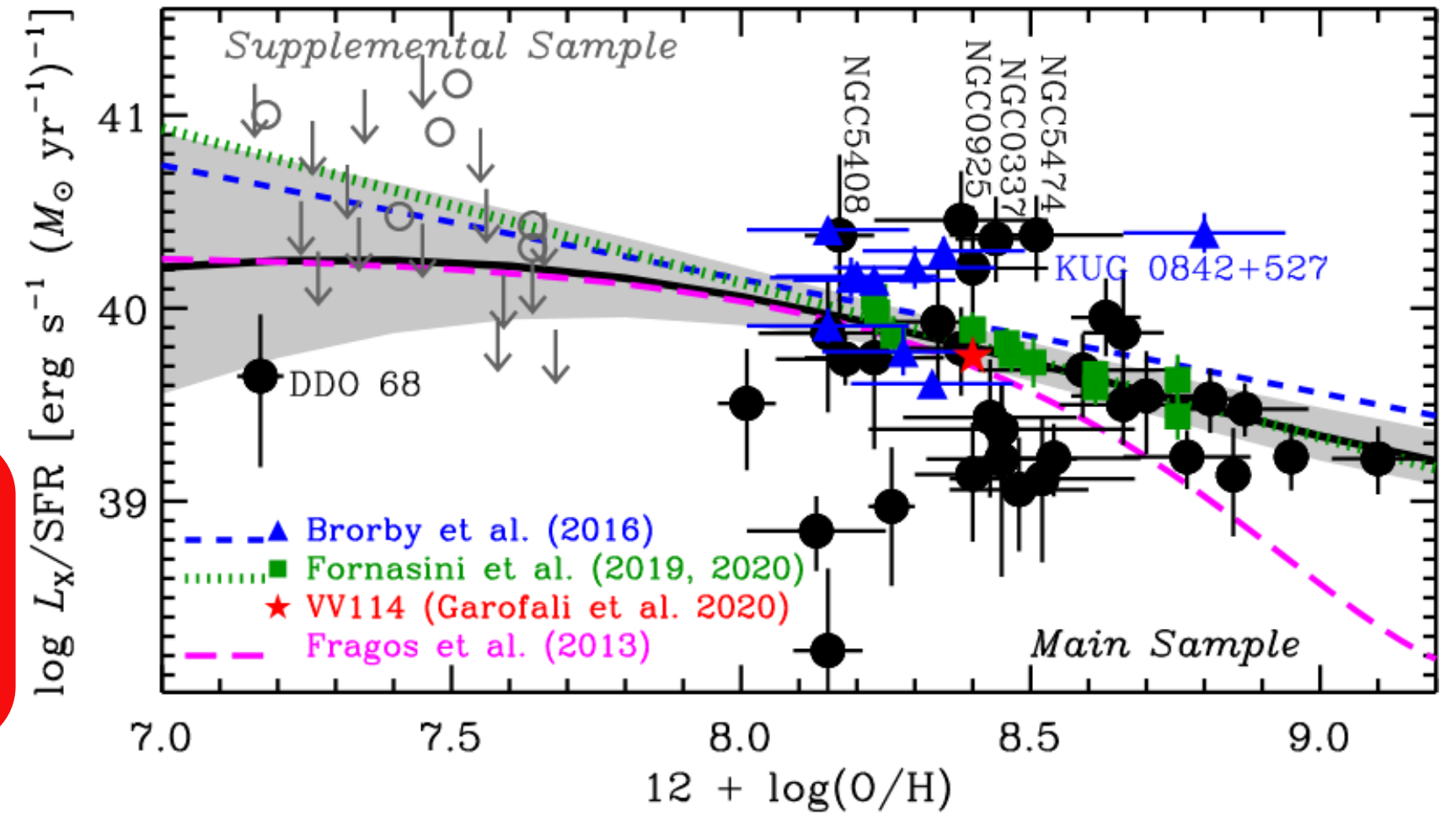
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How do the photoelectric effect, X-ray photoionization and cosmic rays contribute to the heating of the neutral atomic gas at various metallicities ?

- Low Z environment: X-ray luminosity increases (e.g, Brorby et al. 2016, Lehmer et al. 2021)

Can the X-ray becomes the dominant source of heating in low metallicity galaxies ?

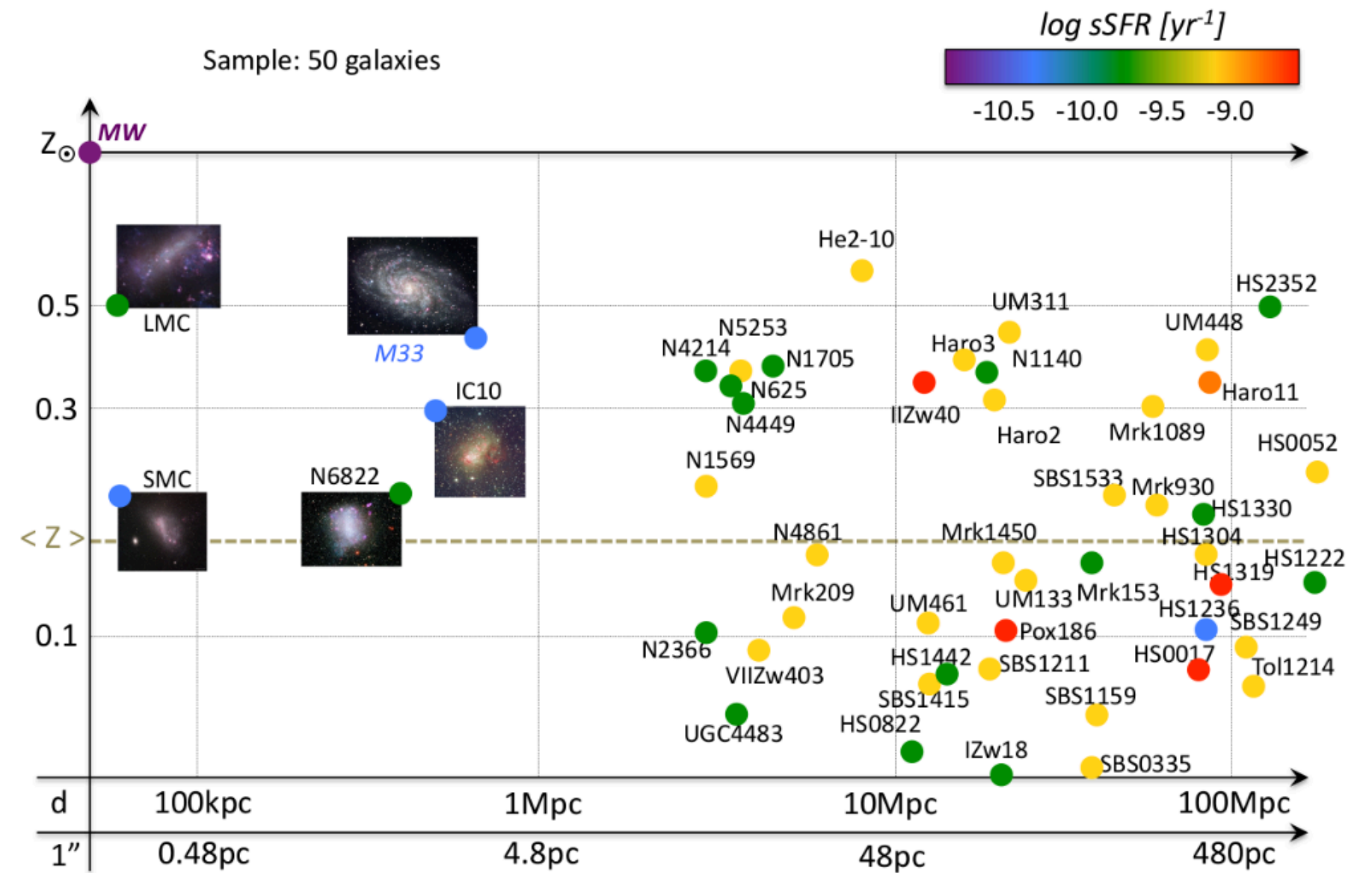


$L_X/SFR$  vs.  $Z$ , Lehmer et al. (2021)

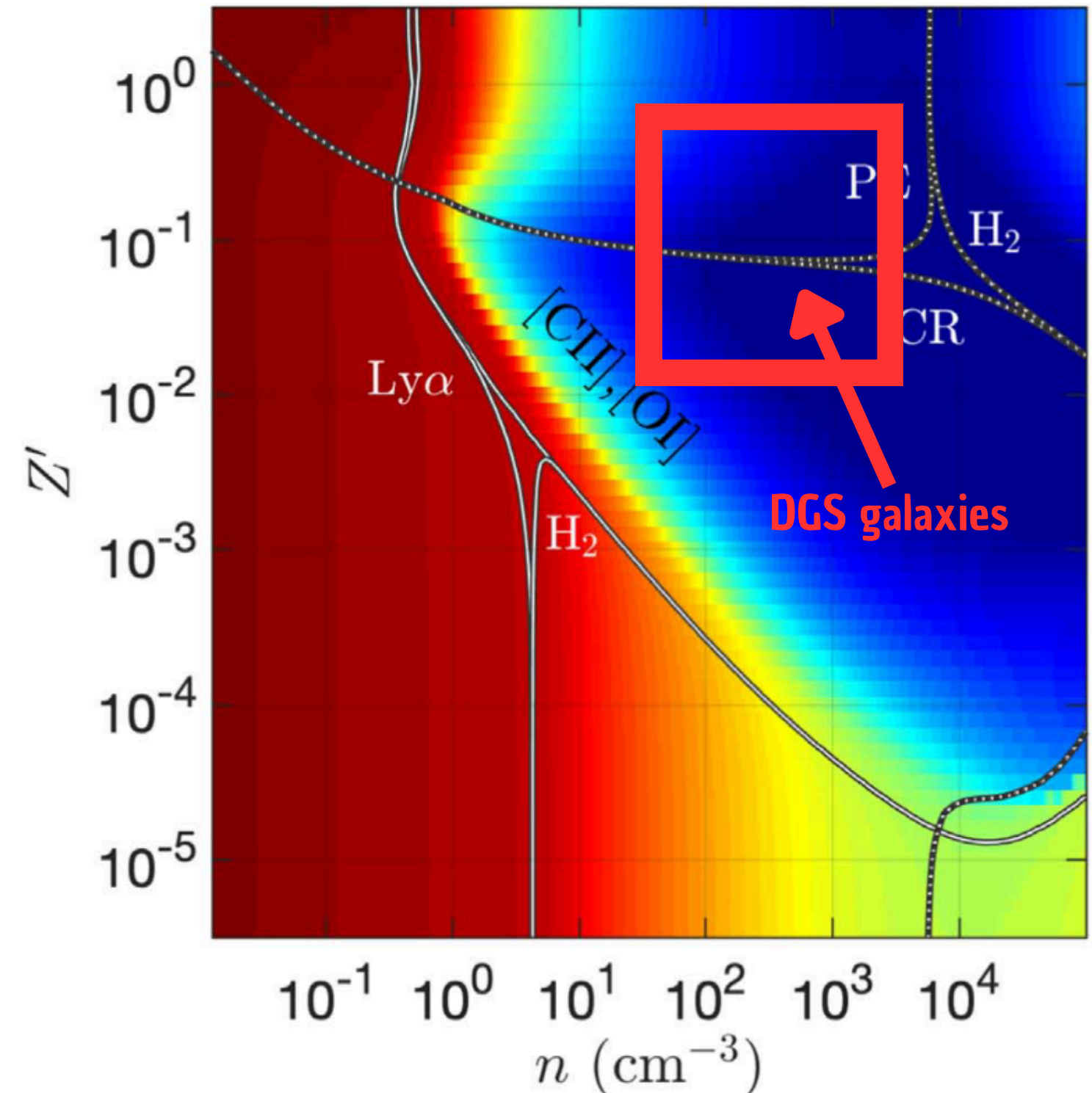
X-ray emission from stellar compact objects: HMXB, ULXs.  
No AGNs !

# The Dwarf Galaxy Survey (DGS, Madden et al. 2013)

- 37 local dwarf galaxies, **spatially unresolved**
- Metallicity spans from  $1/35 Z_{\odot}$  to  $1/2 Z_{\odot}$
- **Spectroscopic IR** observations with Spitzer and Herschel
- **Ultraluminous X-ray sources (ULXs)** detected in **11 galaxies** in X-rays (e.g, Ott et al. 2005; Karett and Feng. 2016)
- Measured X-ray luminosity not used as constraint.

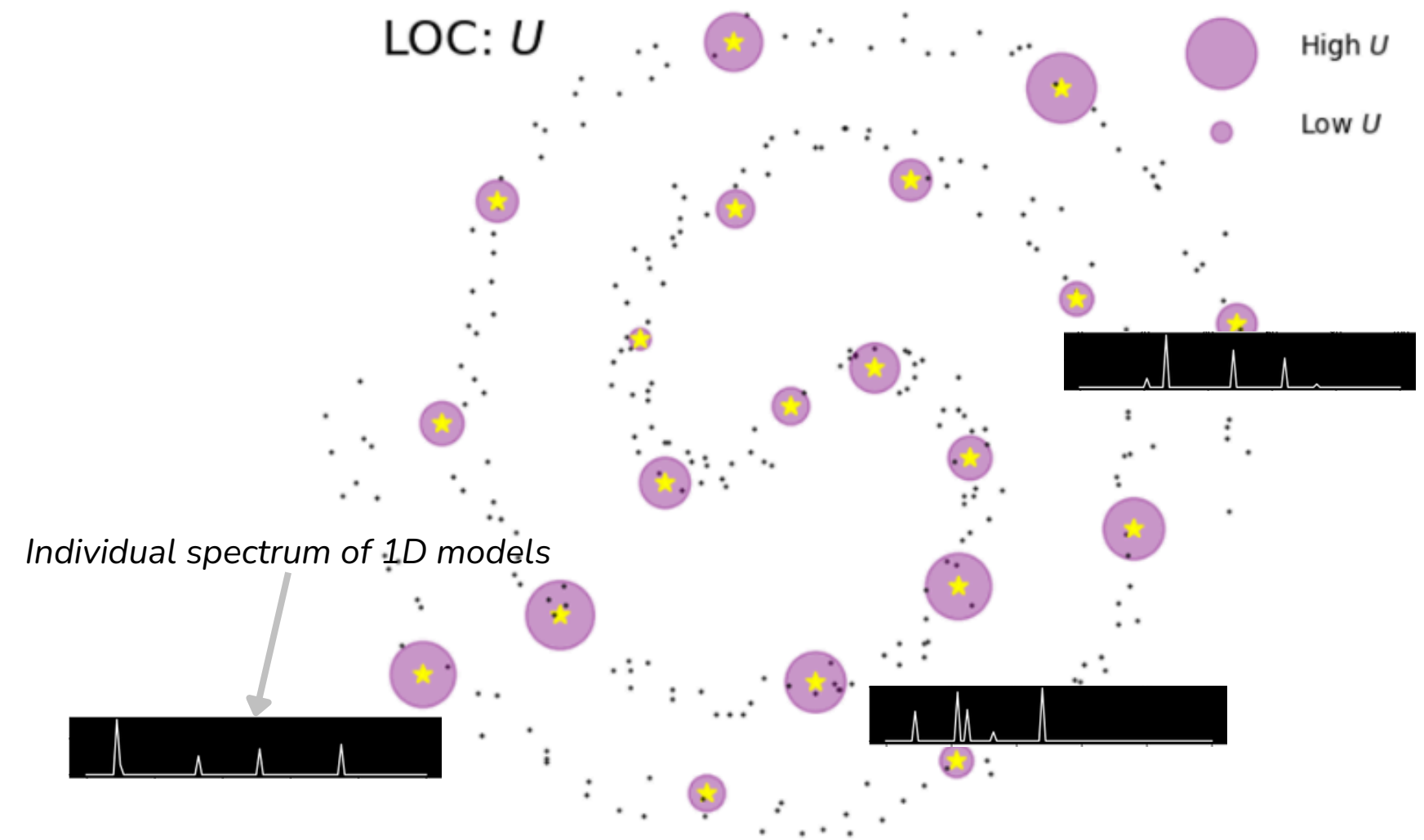


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- Corresponds to the **PE-CR transition** from Bialy & Sternberg. (2019)



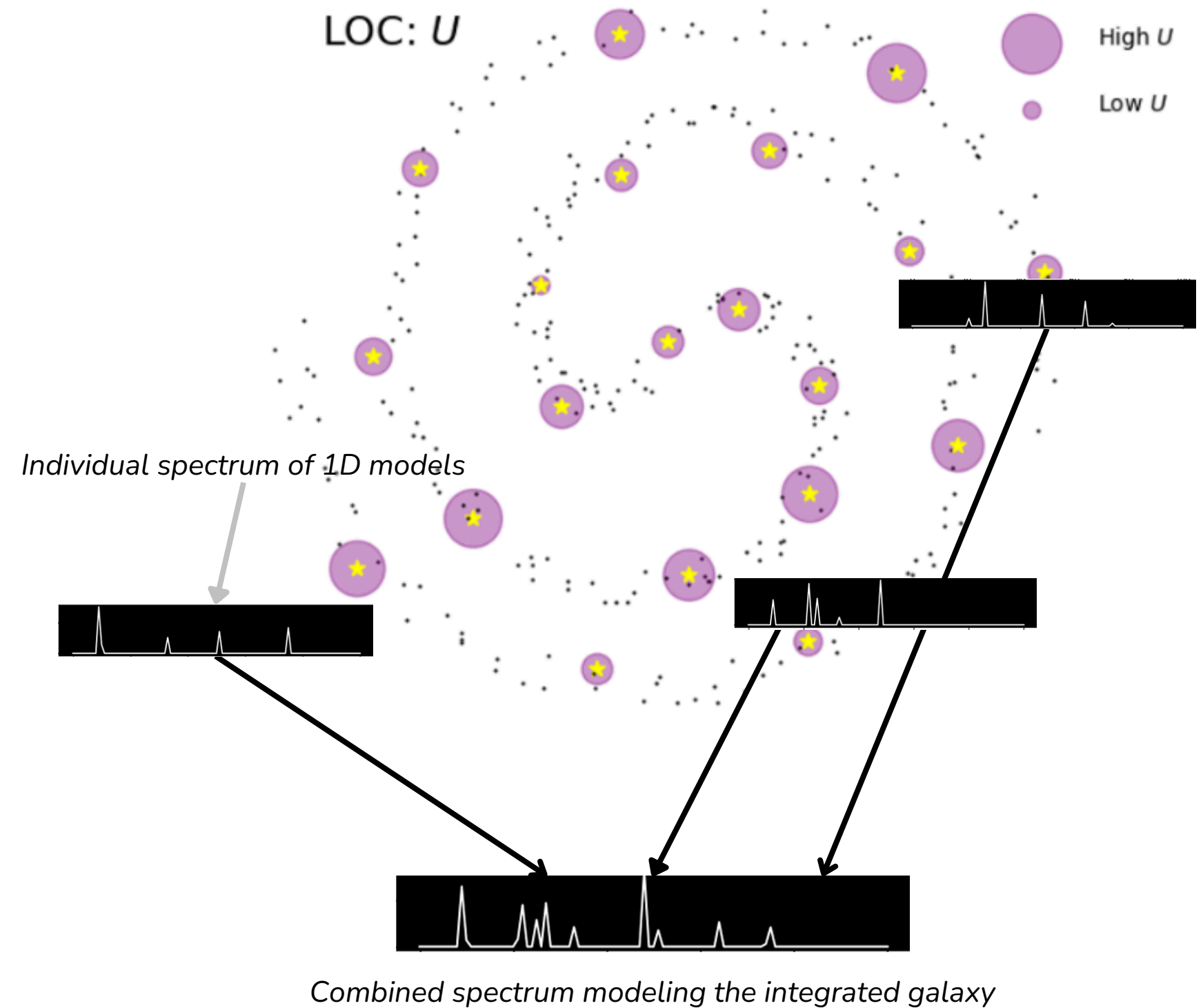
*Dominant heating mechanism depending on density and metallicity, Bialy & Sternberg (2019)*

- **1D photoionization models:** central source (stellar cluster + X-ray source) + ISM ( $n, Z, \text{depth}$ )
- **Complex ISM structure:** collection of 1D model
- Models combined through **statistical distributions**
- Complex modelling with a **few parameters**
- SFGX (Star Forming Galaxy with X-ray sources, Ramambason et al. 2022) database of Cloudy models (Ferland et al. 2017)



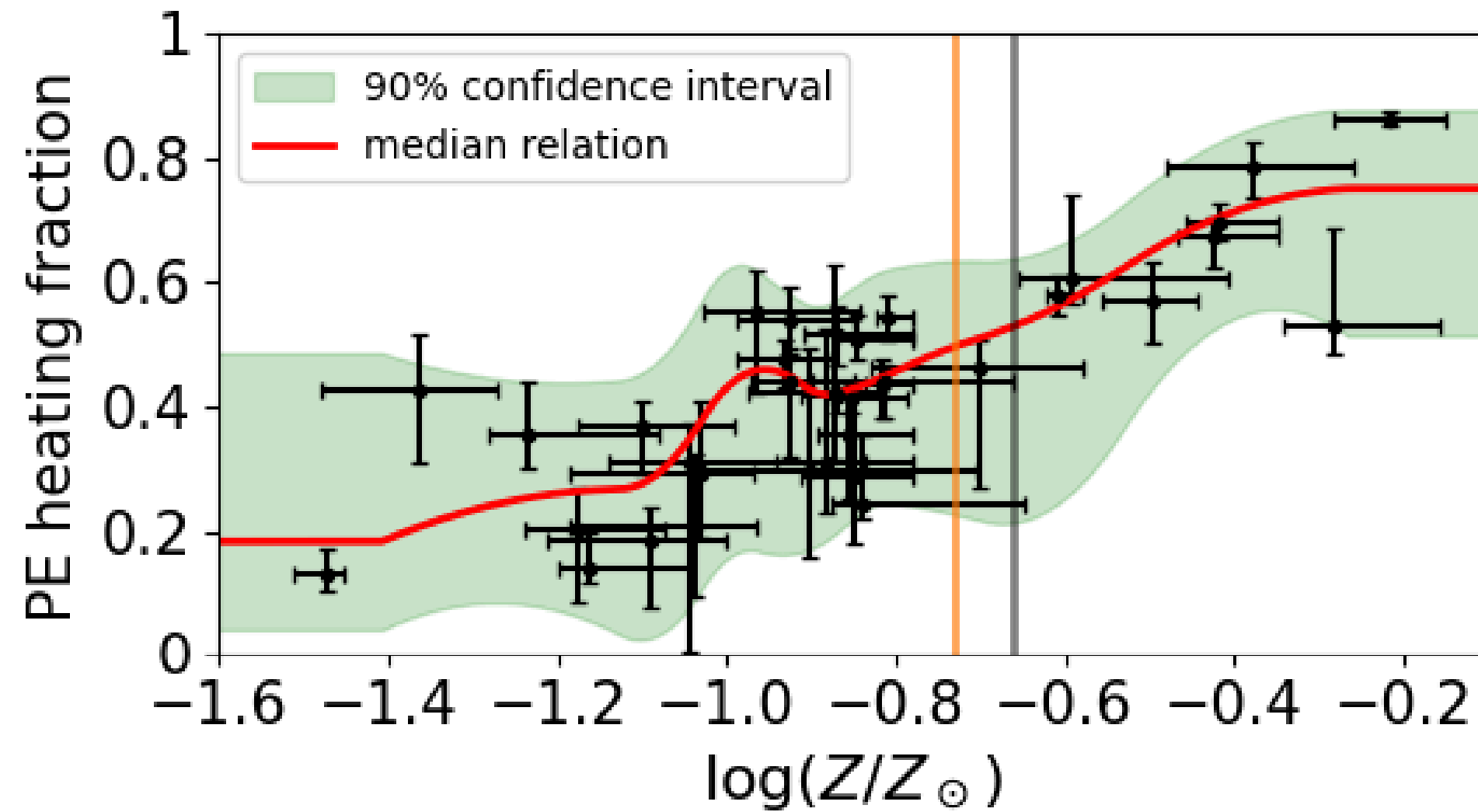
From Lebouteiller et al. (Submitted)

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- SFGX (Star Forming Galaxy with X-ray sources, Ramambason et al. 2022) database of Cloudy models (Ferland et al. 2017)
  
- Best combination of models found using the MULTIGRIS code (Lebouteiller & Ramambason. 2022).



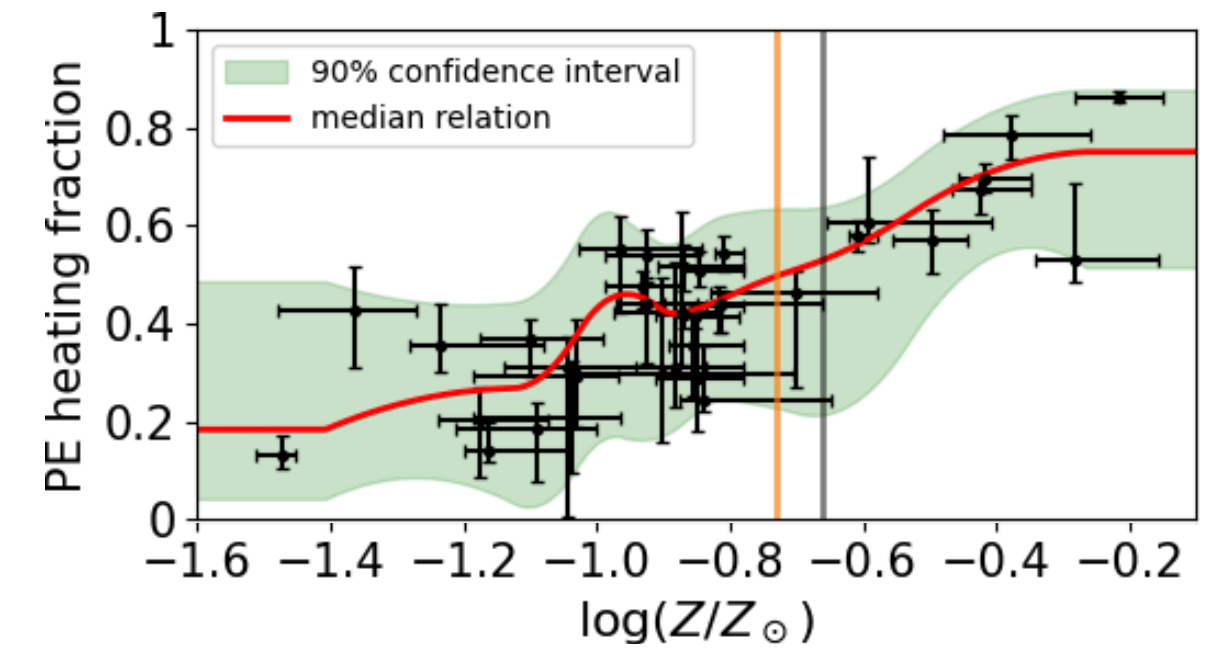
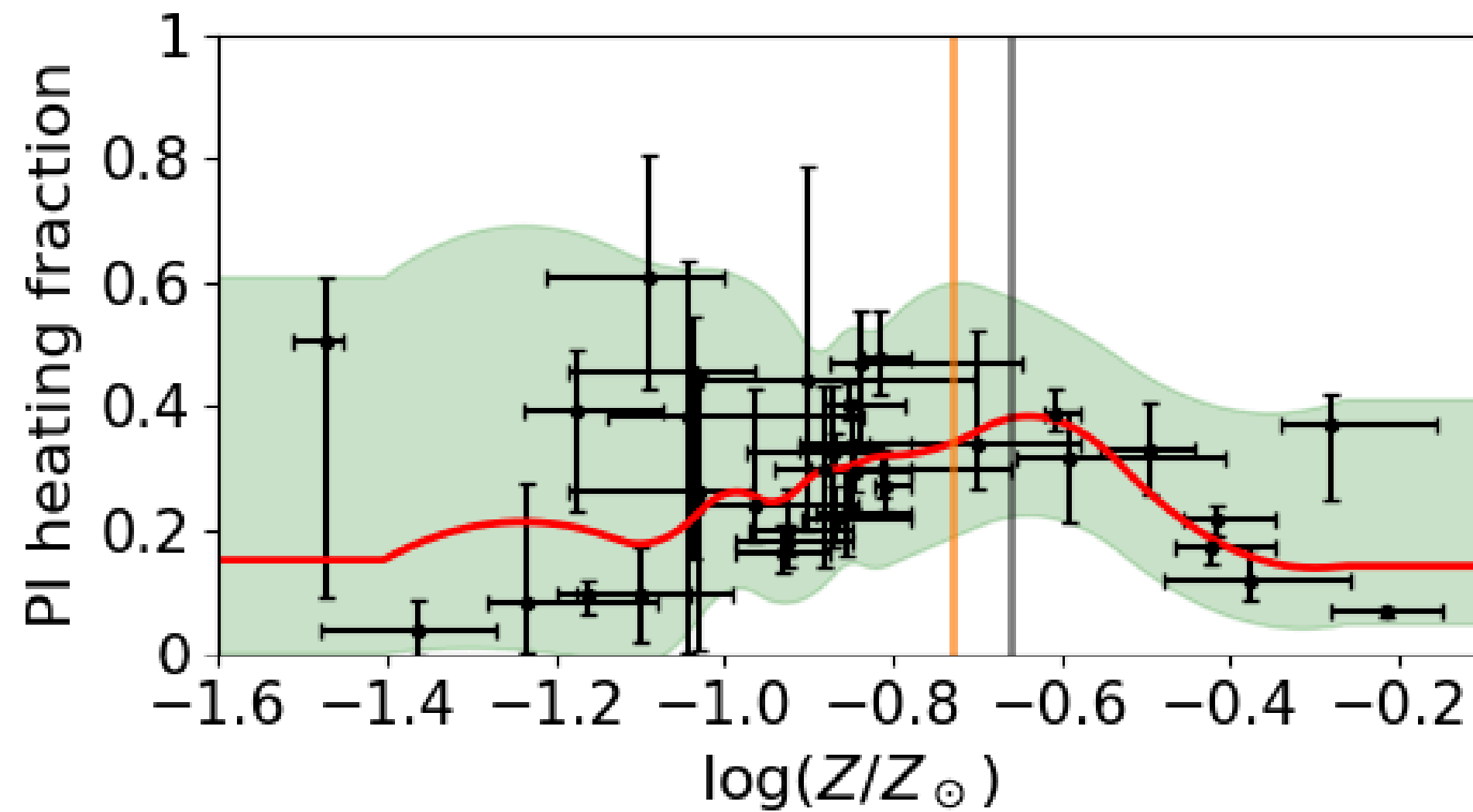
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## Photoelectric effect heating



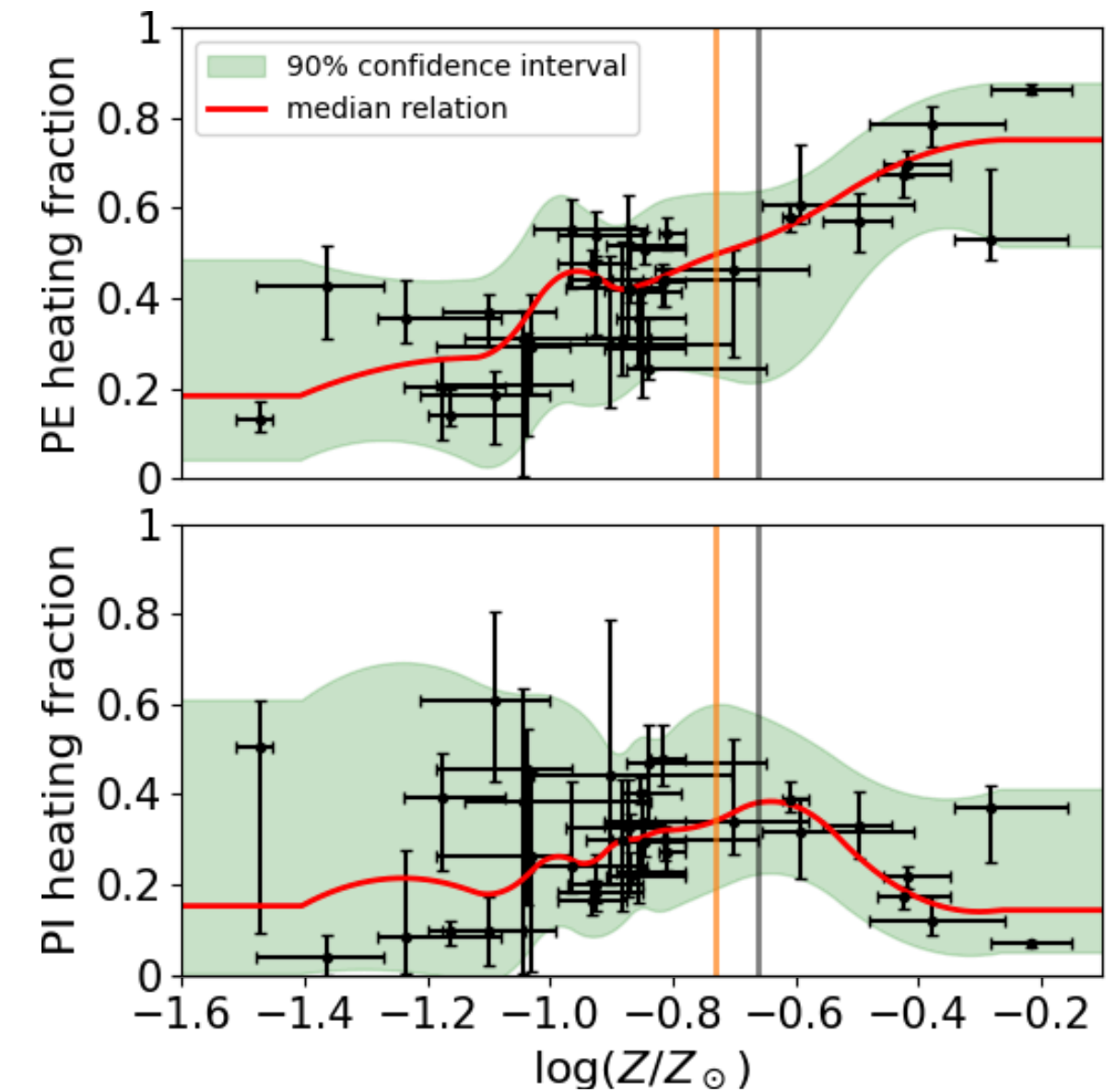
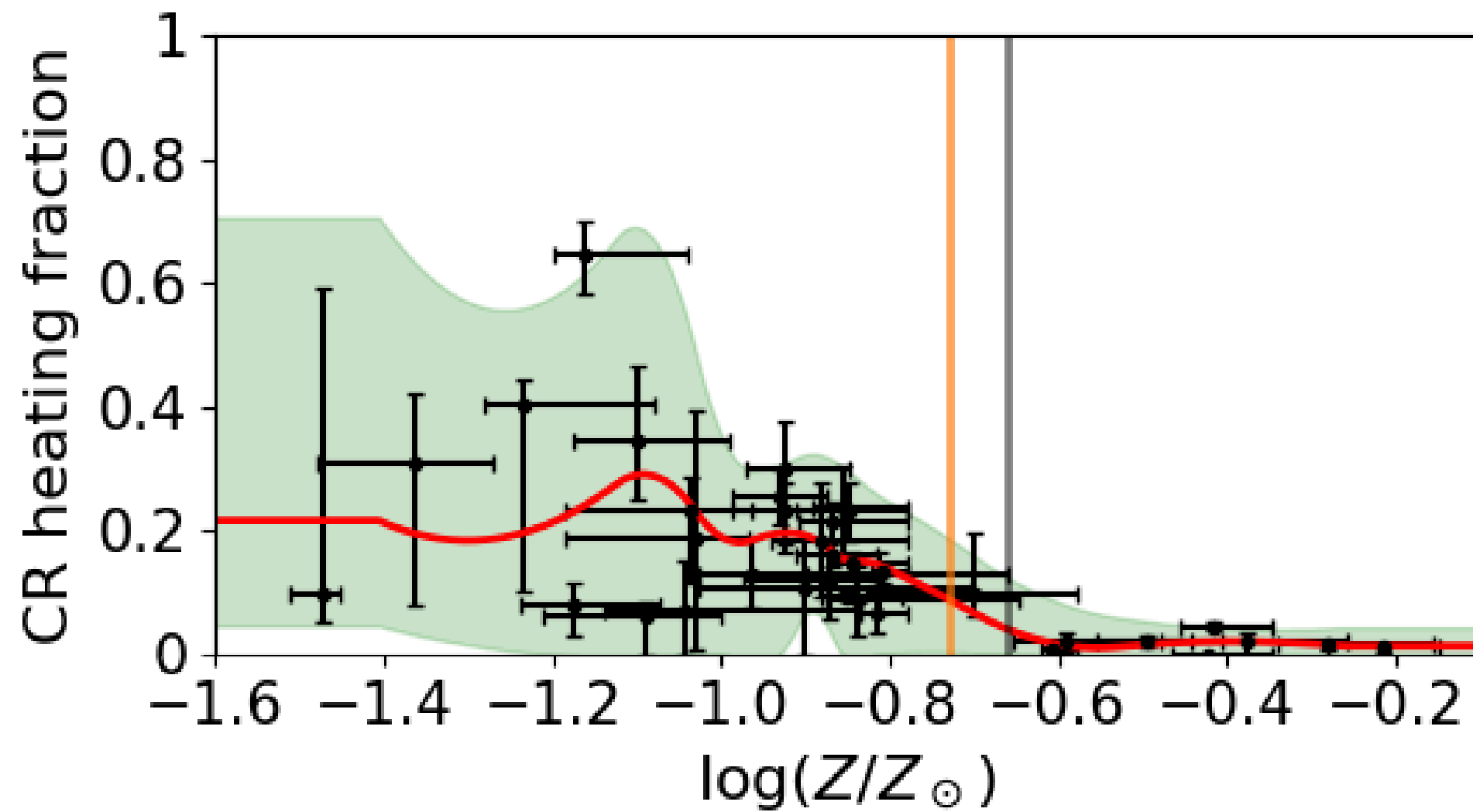
- Photoelectric effect heating dominates at high metallicity.
- At lower metallicity, it drops down to 20% of the total heating.

# Photoionization heating



- Photoionization (UV+X-ray photons) contributes significantly to the heating at every metallicity
- In a couple of galaxies, it is the dominant source of heating

## Cosmic rays heating

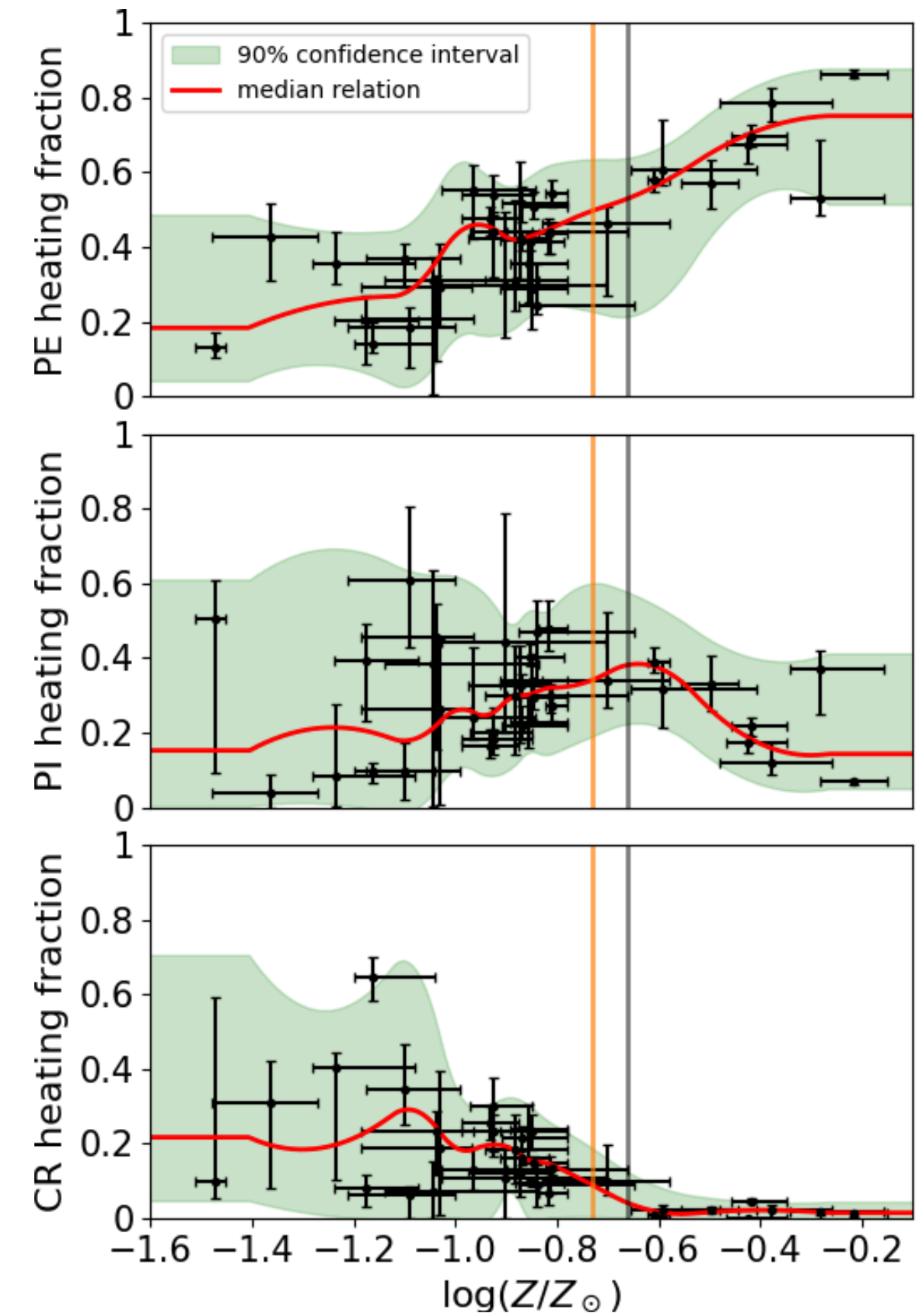


- CR heating is negligible in high metallicity galaxies.
- The CR heating fraction increases with decreasing metallicity, up to 60% in one galaxy.
- **Caveat:** one unique CRIR considered, probably overestimated

# Heating of the neutral gas - general picture

- Photoelectric effect heating decreases with  $Z$
- Photoionization (UV+X-ray photons) contributes significantly to the heating at every metallicity
- CR heat only at low metallicity

**Stellar compact objects X-ray might provide a significant X-ray feedback in low metallicity environments, effectively regulating star formation in low metallicity star forming galaxies.**

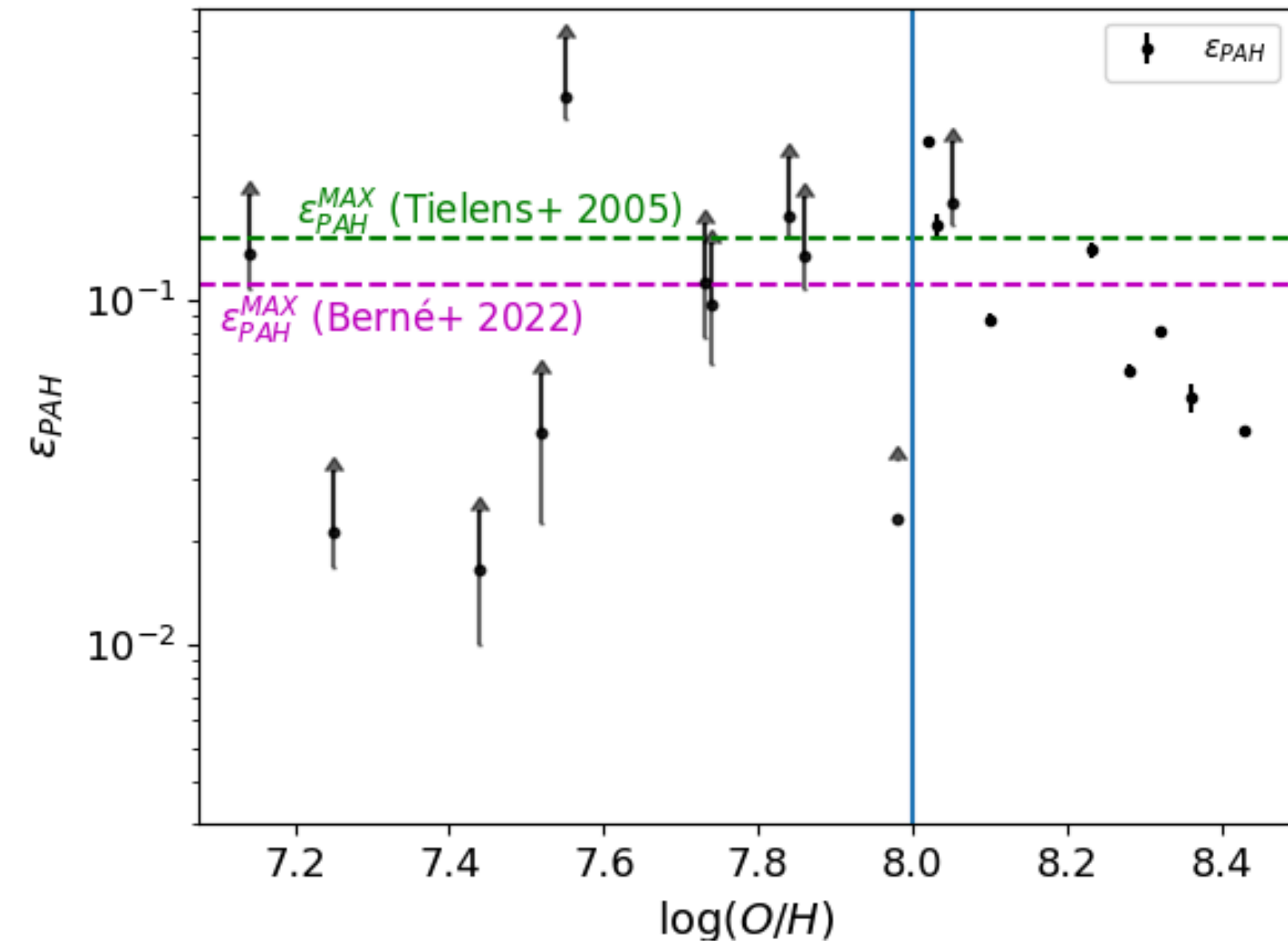


# PAH heating efficiency

- Observational proxy for **PAH heating efficiency** if PAH heating dominates (ok in MW, Berné et al. 2022):

$$\epsilon_{\text{PAH}} = \frac{[\text{CII}] 158 \mu\text{m} + [\text{OI}] 63 \mu\text{m}}{L_{\text{PAH}} + [\text{CII}] 158 \mu\text{m} + [\text{OI}] 63 \mu\text{m}}$$

- Problem:** galaxies above the maximum theoretical value



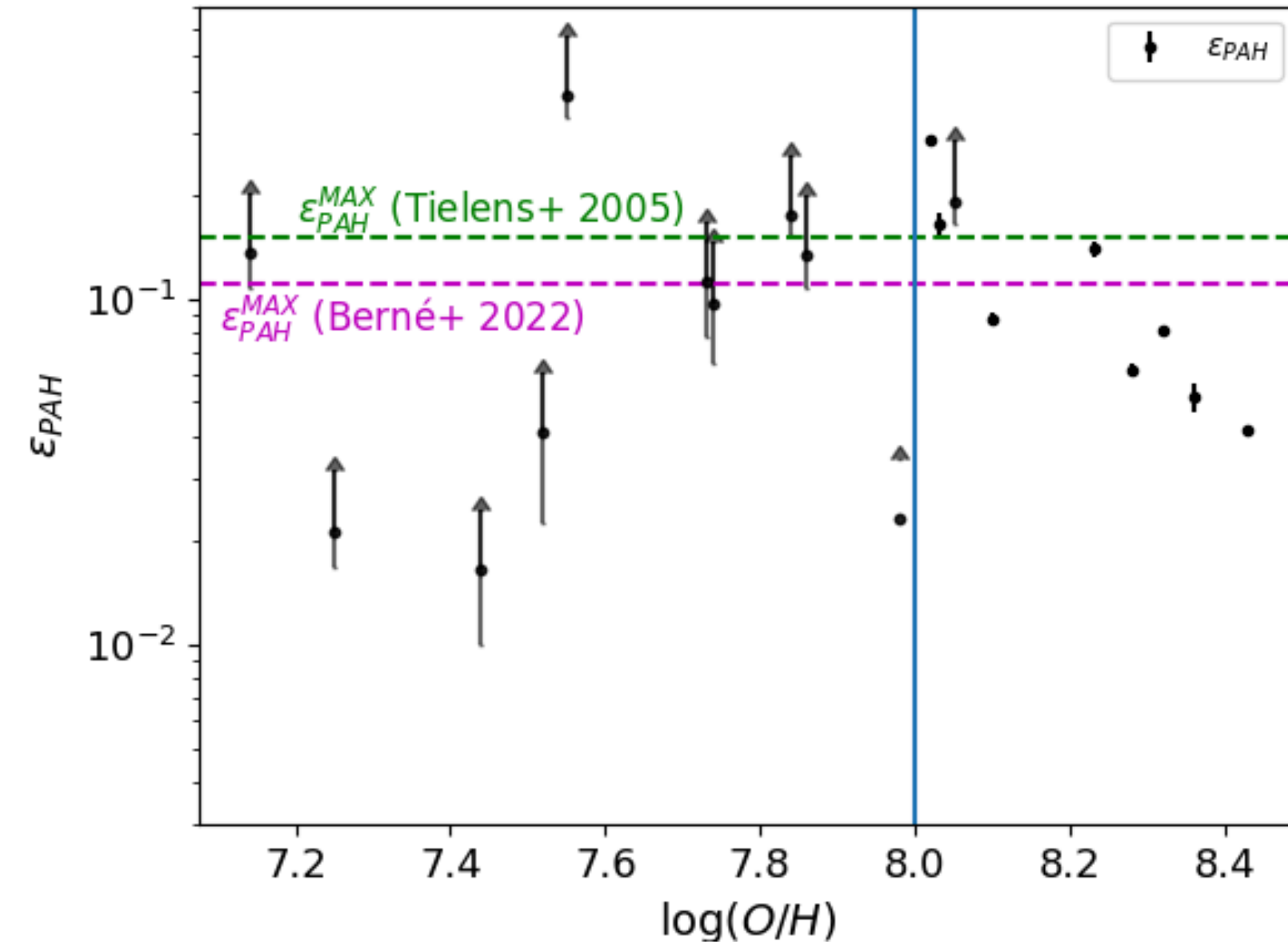
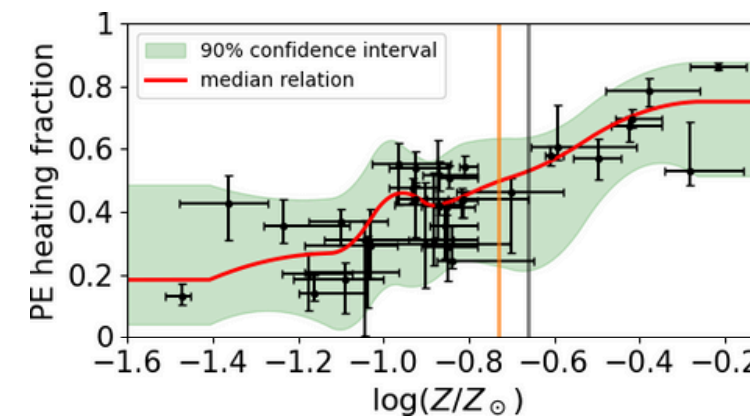
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- **Problem:** galaxies above the maximum theoretical value
- Correction for the fraction of photoelectric effect heating:

$$\epsilon_{\text{PAH}} = \frac{\alpha([\text{CII}] 158 \mu\text{m} + [\text{OI}] 63 \mu\text{m})}{L_{\text{PAH}} + \alpha([\text{CII}] 158 \mu\text{m} + [\text{OI}] 63 \mu\text{m})}$$



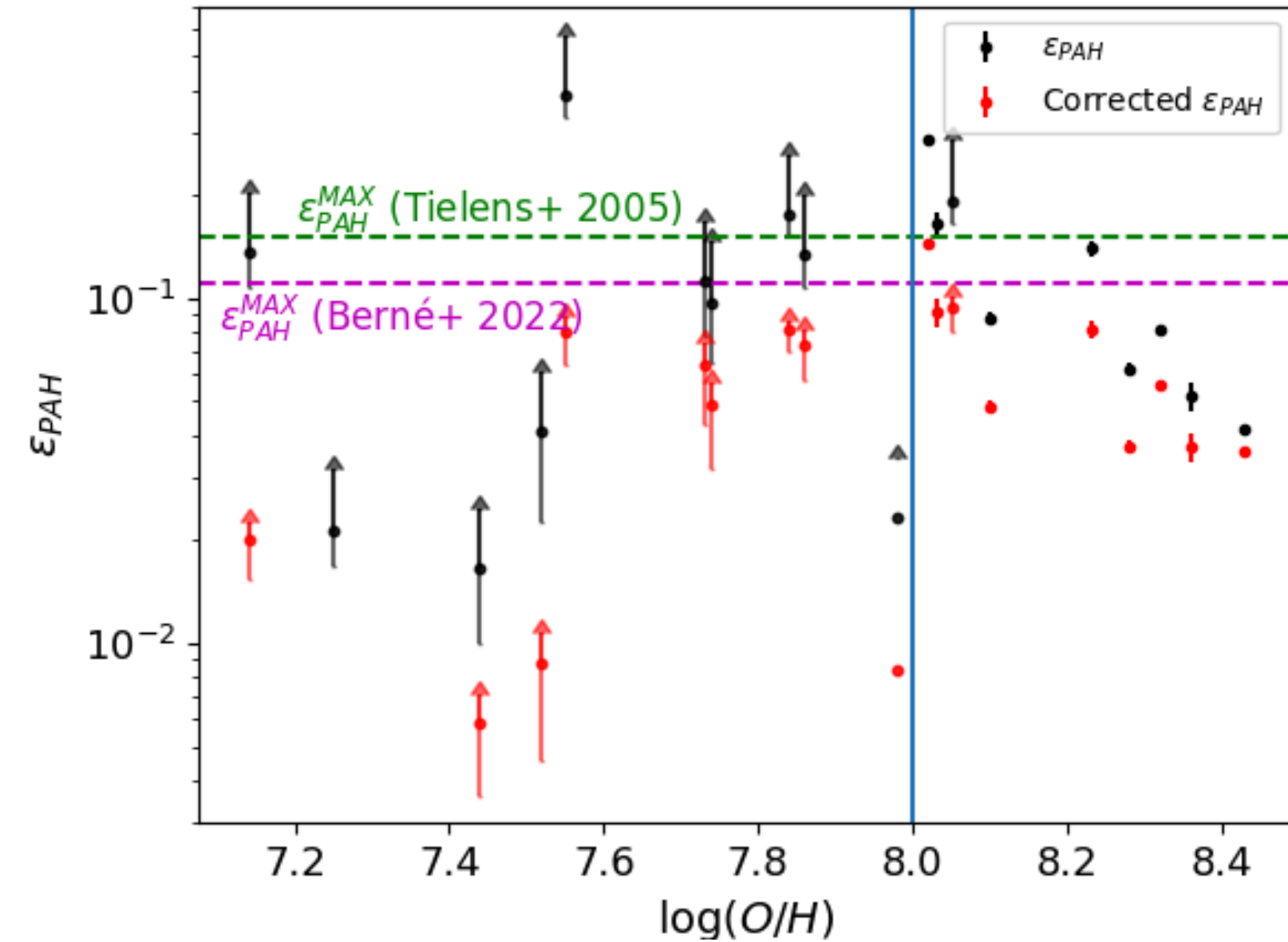
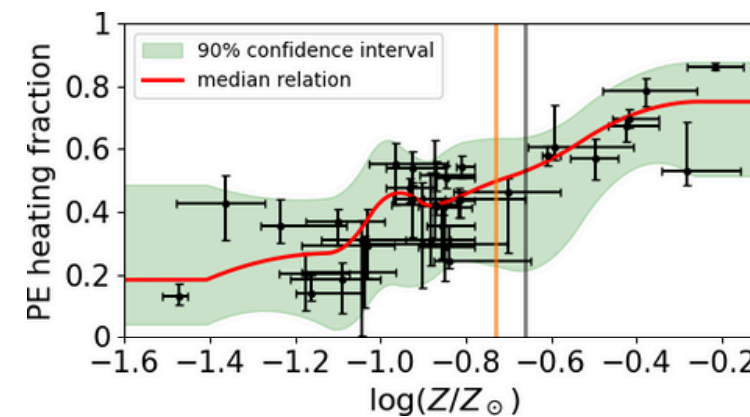
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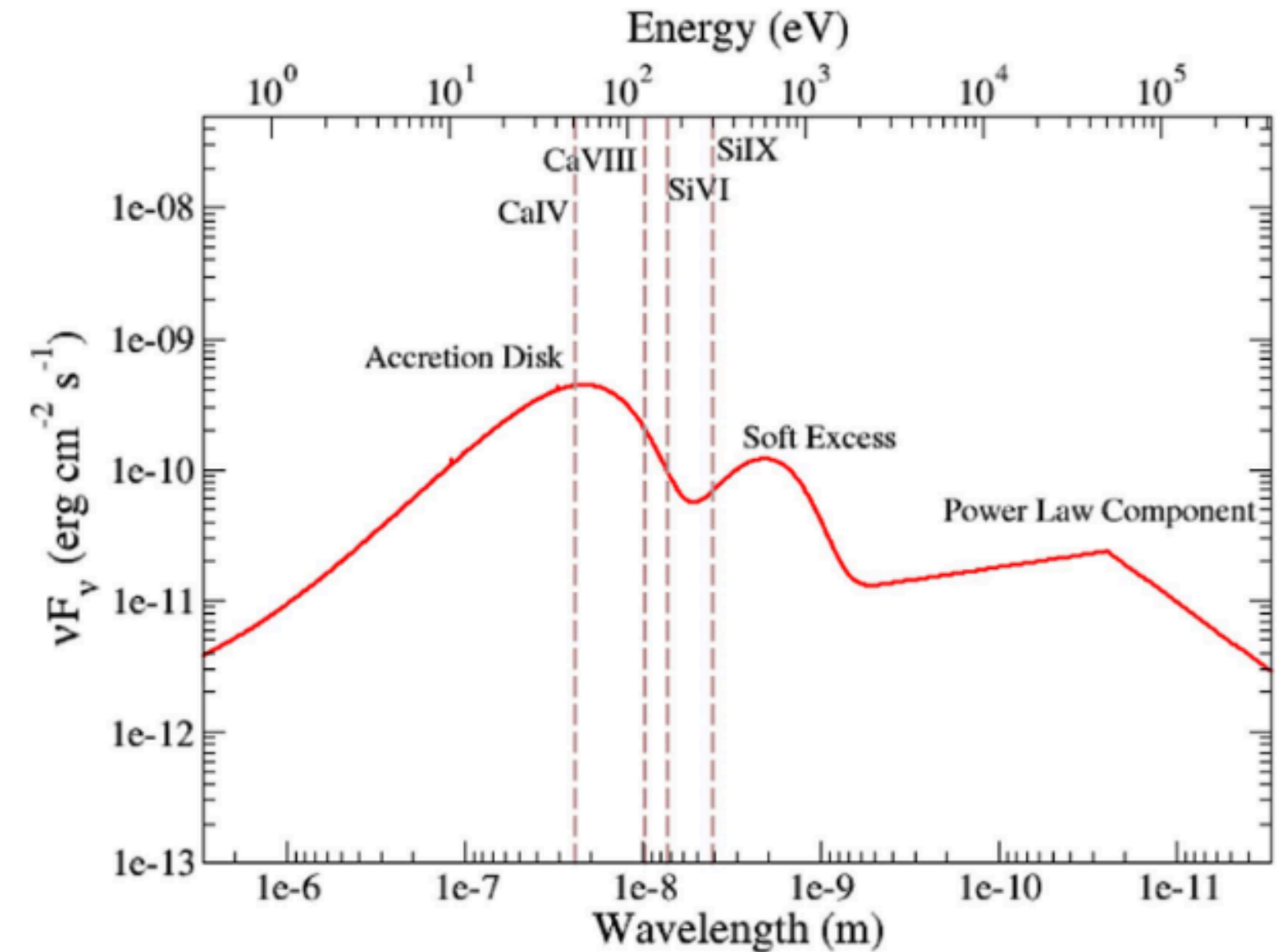


- Now compatible with theoretical expectation !**

FOR MORE INFOS ON PHOTOELECTRIC EFFECT HEATING EFFICIENCY:  
SEE LEO BELLOIR'S POSTER

Auxiliary question: can we use our model to predict the X-ray fluxes of galaxies ?

- High ionization potential lines as tracers of X-ray properties of AGNs (Cann et al. 2018). Can we use them to constrain ULXs as well ?

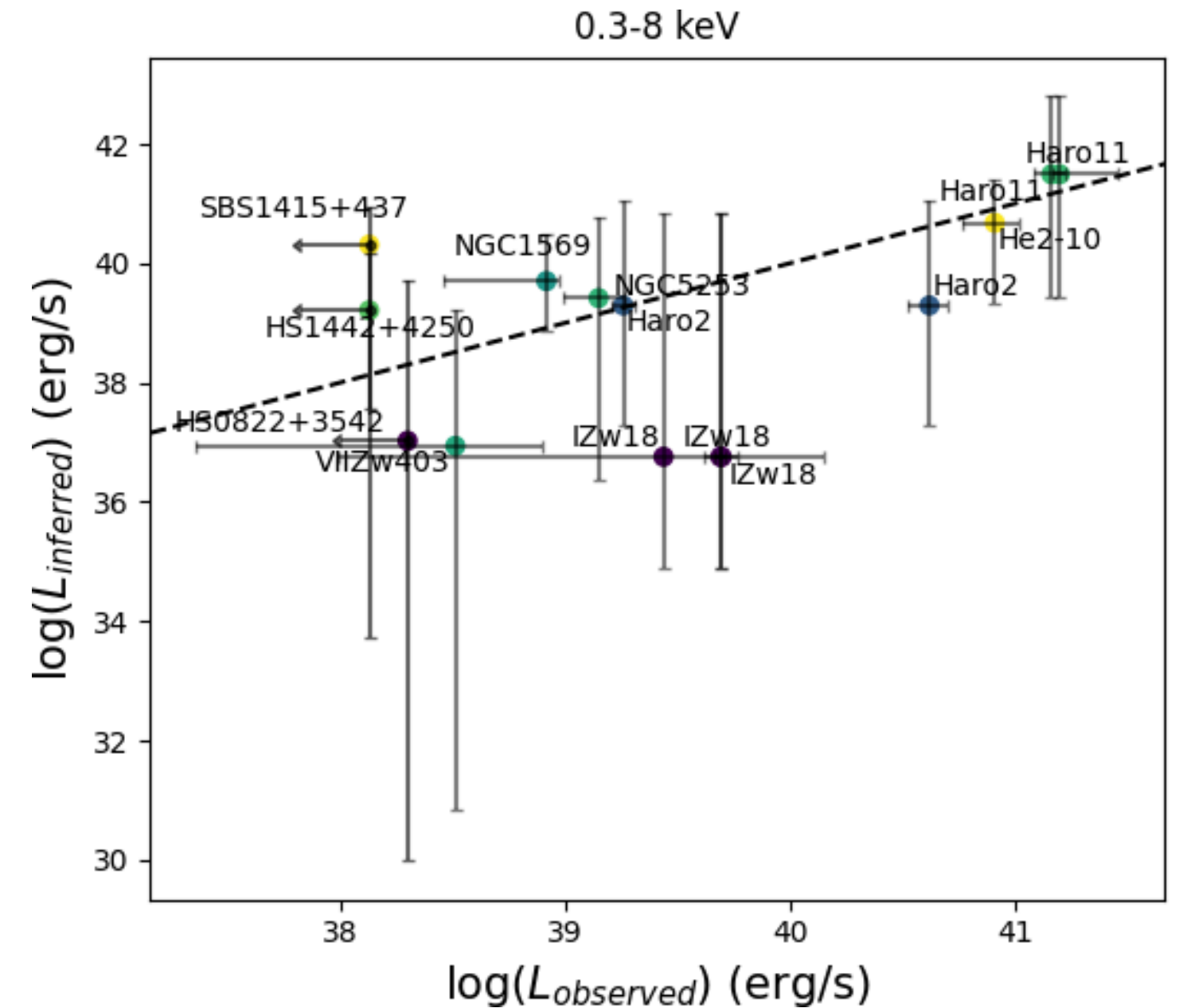


AGN X-ray SED, Cann et al. (2019)

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- 0.3-8 keV luminosity predicted fairly well
- X-ray sources needed to reproduce  $[OIV]26\mu m$

Only IR lines are used to predict the X-ray luminosity !



1:1 correlation not expected



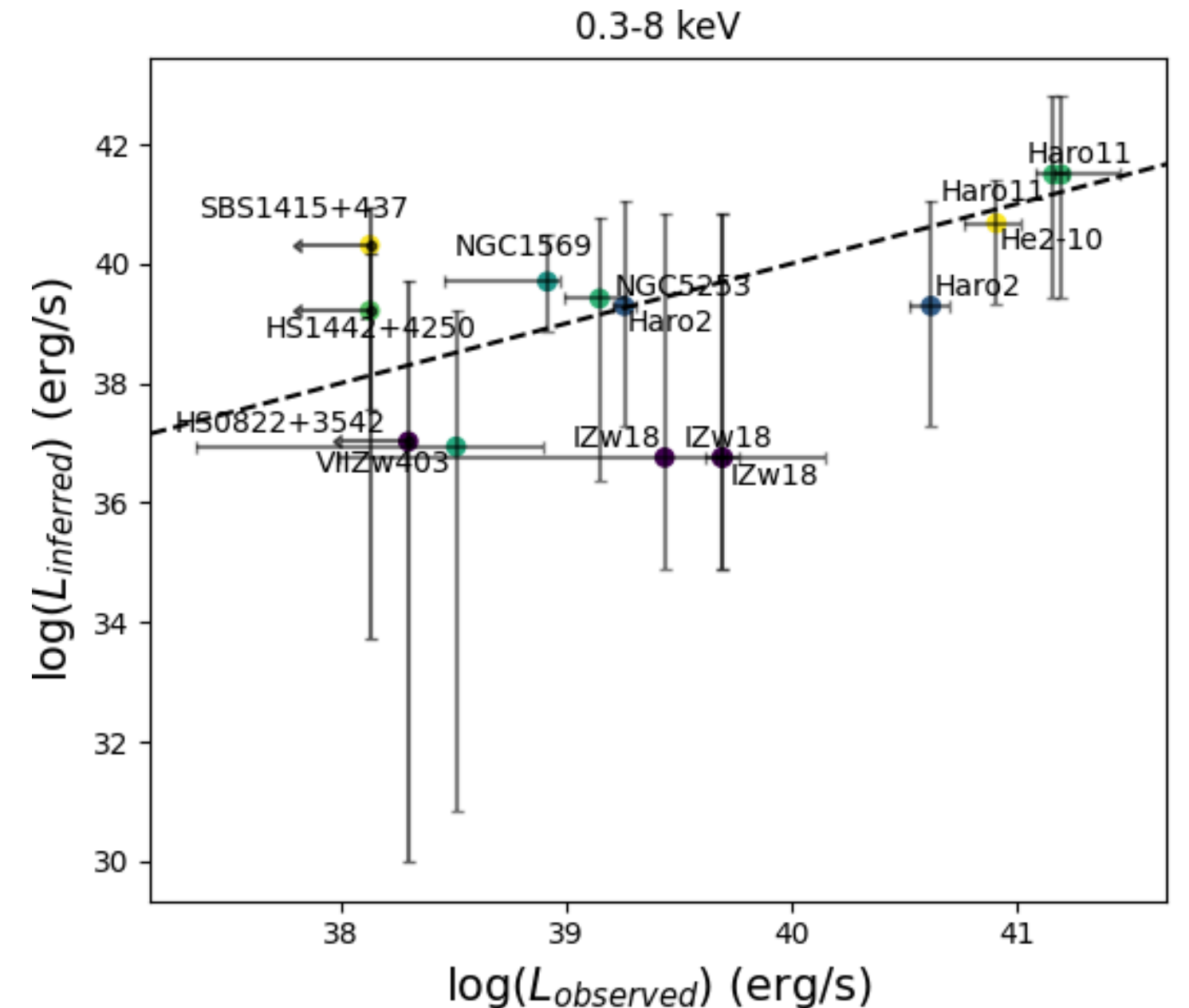
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**Only IR lines are used to predict the X-ray luminosity !**

- High ionization potential lines  $\rightarrow$  better constraint ?
  - $[NeV]14\mu m$  (91 eV)
  - $[SiXI]1.93\mu m$  (523 eV)

**Observable with JWST !**



**1:1 correlation not expected**



## Conclusion and perspective

- High Z environments: Photoelectric effect dominates the heating of HI
- Stellar compact objects are a significant source of HI heating in low Z environments
- High ionization IR lines can be used as a probe for X-ray emission

### What next ?

- Better models for **X-ray emission** and **cosmic rays**
- New constraint in optical (and UV ?)
- Extending the sample toward **very low metallicity galaxies**

- Mid & Far IR spectroscopy: better constraint for heating and X-ray emission → JWST + **PRIMA**
- A potential probe for **IMBH in dwarf galaxies** or **X-ray faint AGNs** ?

