Cosmic-ray attenuation in models of Photodissociation Regions

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Cosmic Rays 3 - The salt of the star formation recipe

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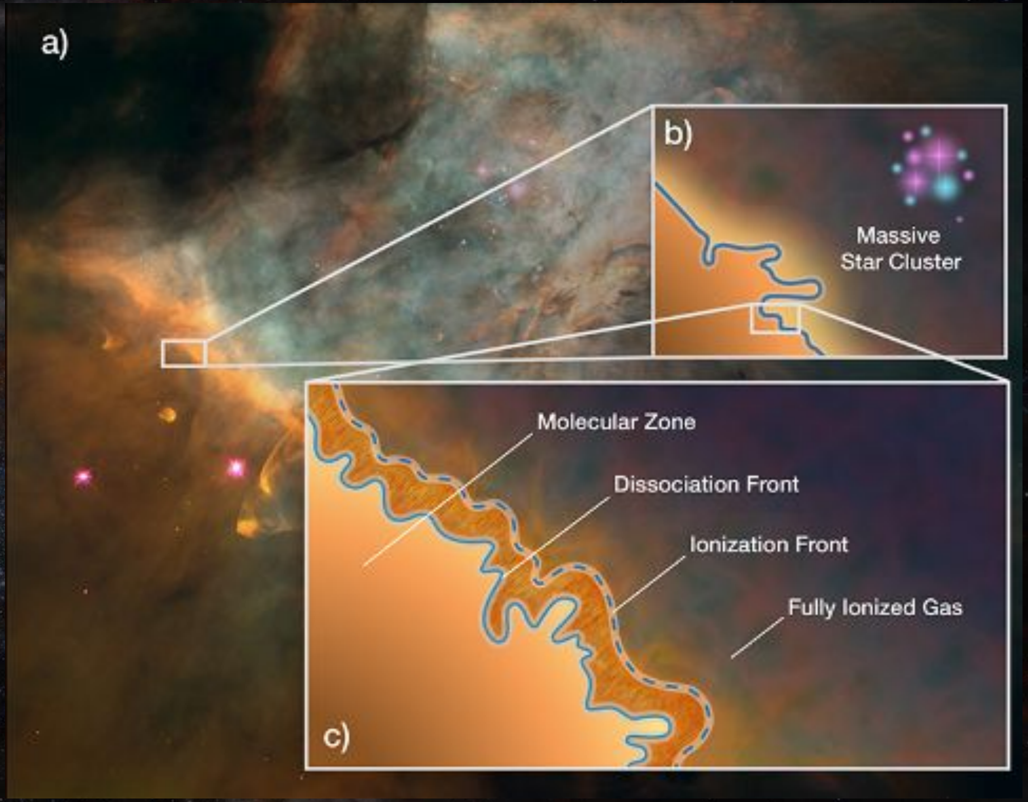
Why Photodissociation Regions (PDRs)?

- ISM regions governed by strong UV radiation (Hollenbach and Tielens 1999)
- Locations with embedded star formation
- Heating/cooling mechanisms influence the chemistry of neutral atomic gas and molecular gas
- PDR lines: [CI], [CII], CO (J=1-J=20), etc.
- Advancements in IR (SOFIA, JWST) and submm lead to deeper understanding of PDRs
- Questions: How cosmic rays influence the PDR chemistry?
- Small changes on the surface but significant deeper in the cloud ($A_V > 10^{-1}$ mag)



NASA, ESA, CSA, Jason Champion (CNRS), Pam Jeffries (STScI), PDRs4ALL ERS Team

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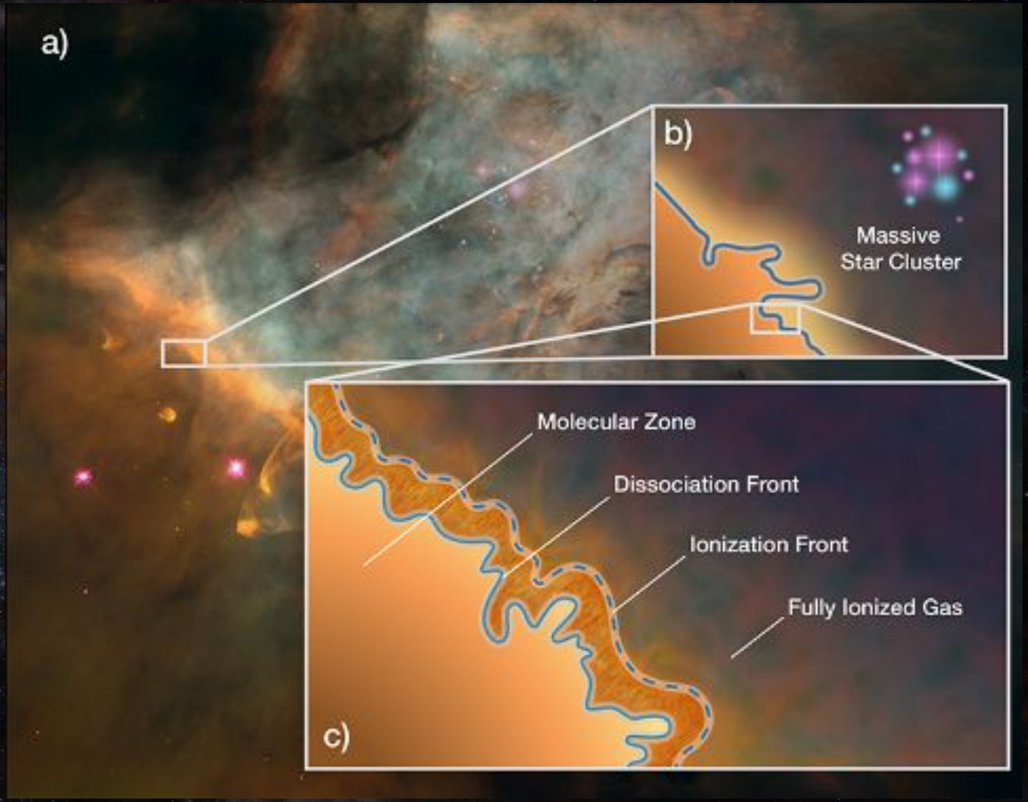

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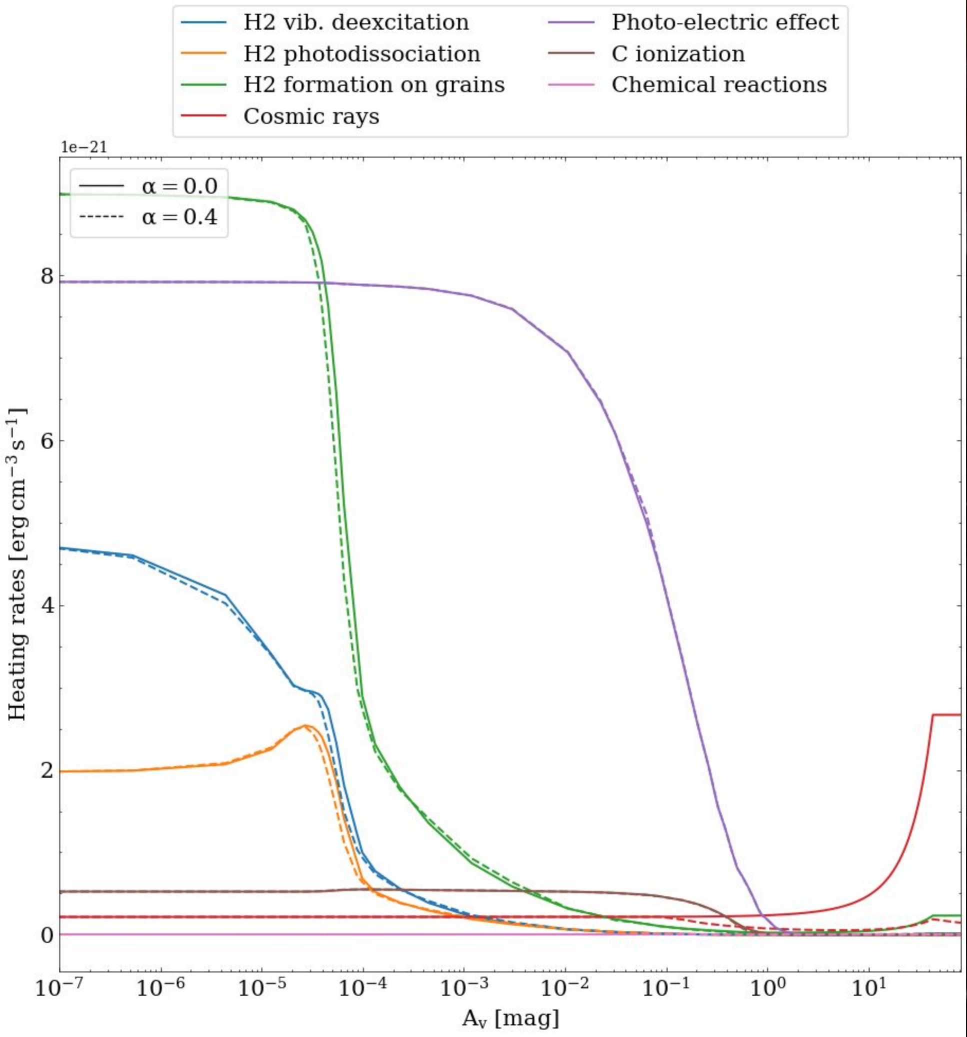

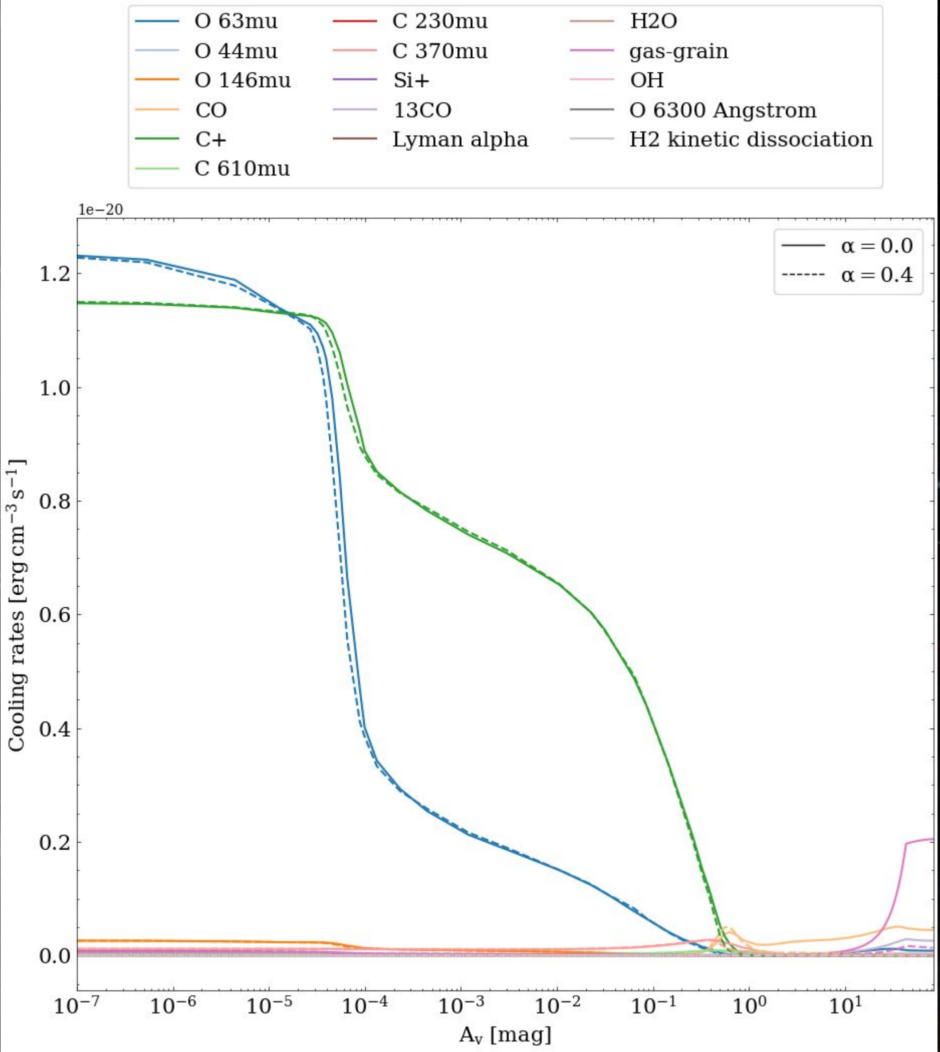

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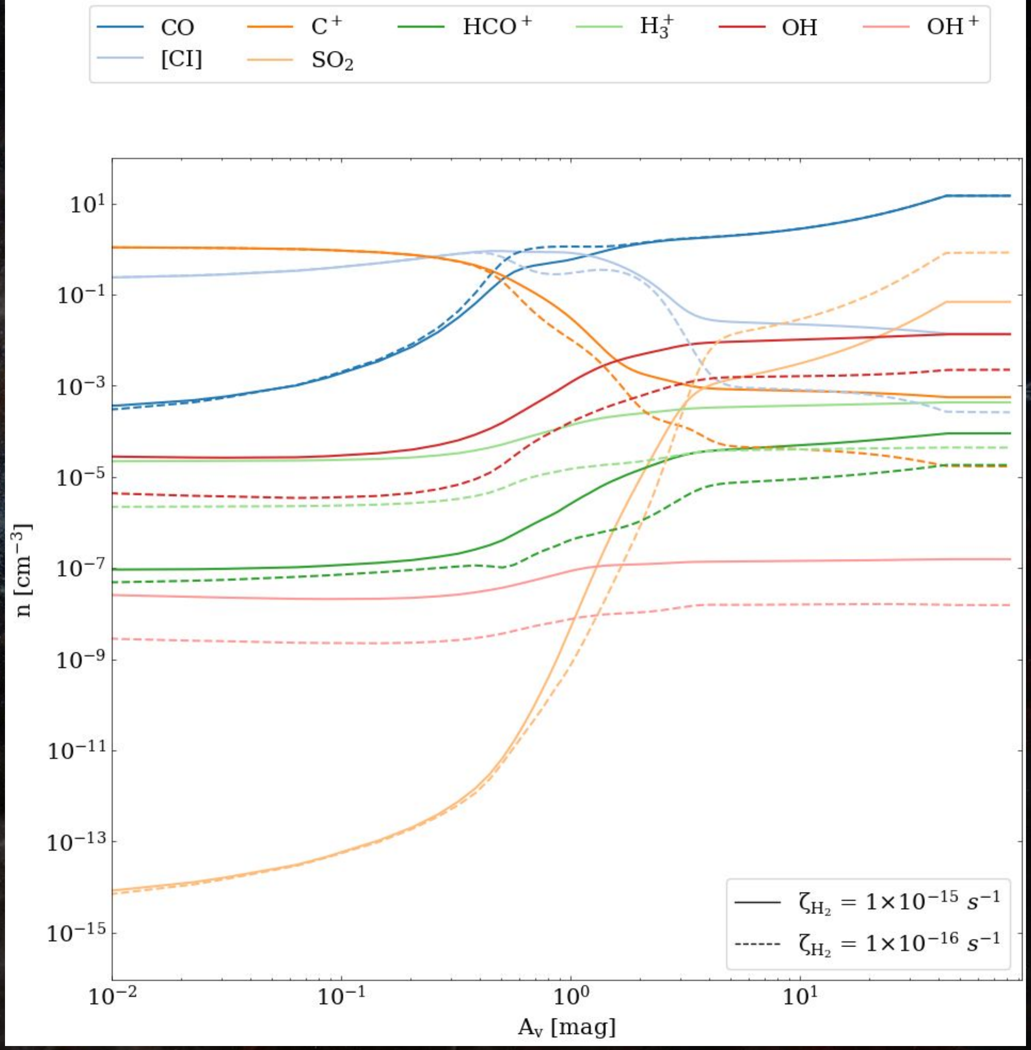
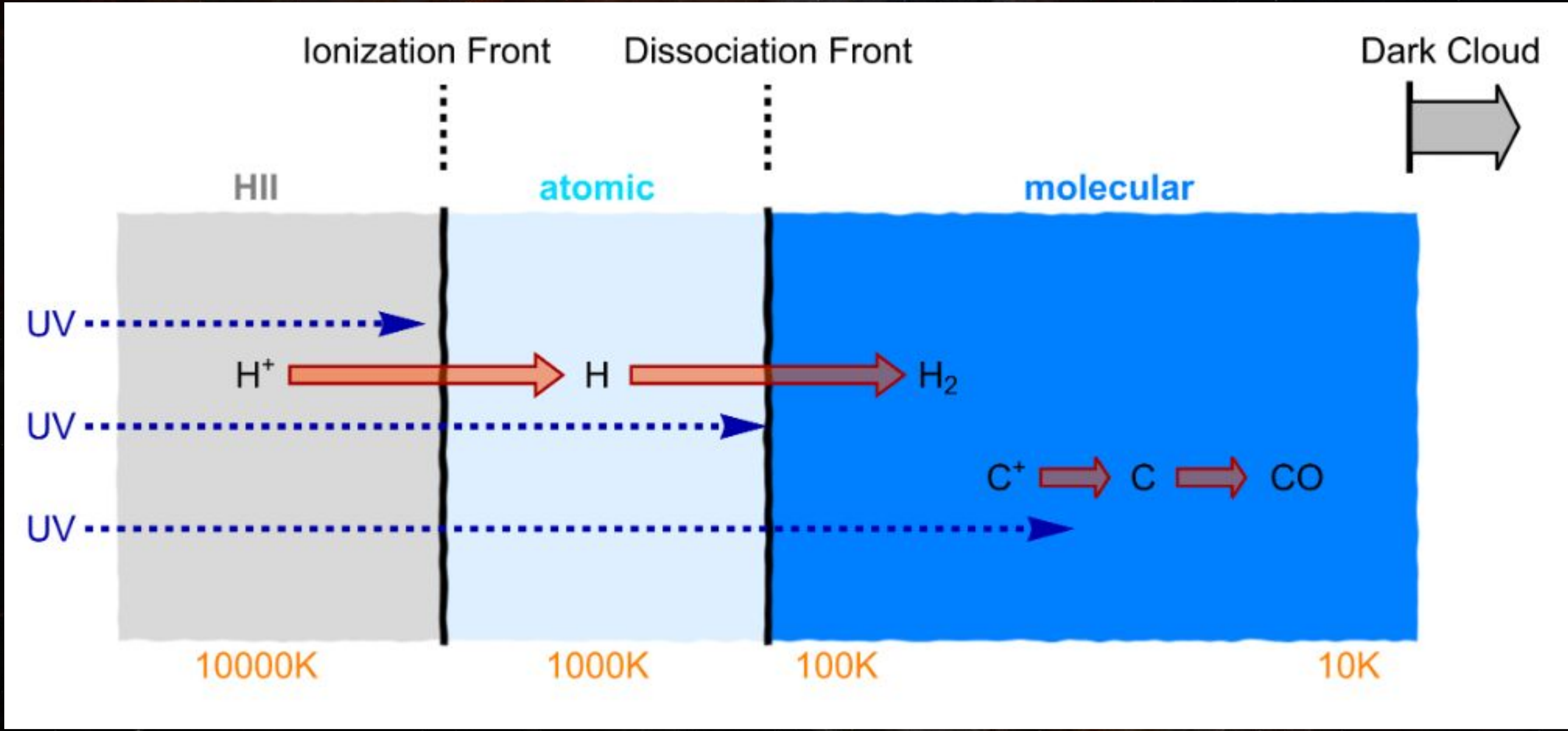


Schematic representation of a PDRs



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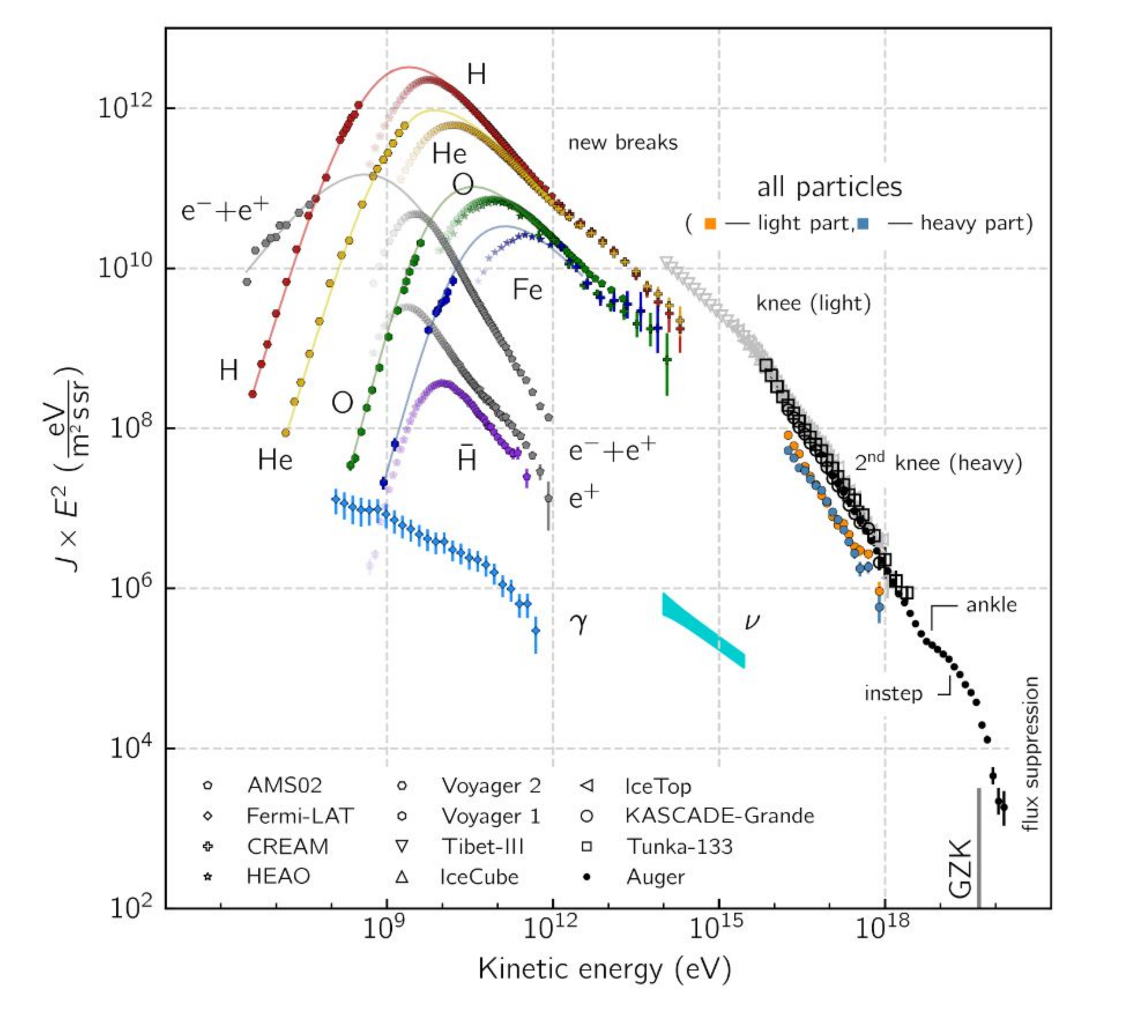
Cosmic Rays information



- ➢ Significant variation of the measured CRIR in different environments (Obolentseva et al.2024, Luo et al. 2024)
- ➢ Single molecule usage for the computation of ζ_{H2} can be biased (Le Petit et al.2004)

Ruszkowski & Pfrommer 2023 (Modified based on the original from Lenok 2022, PhD Thesis)

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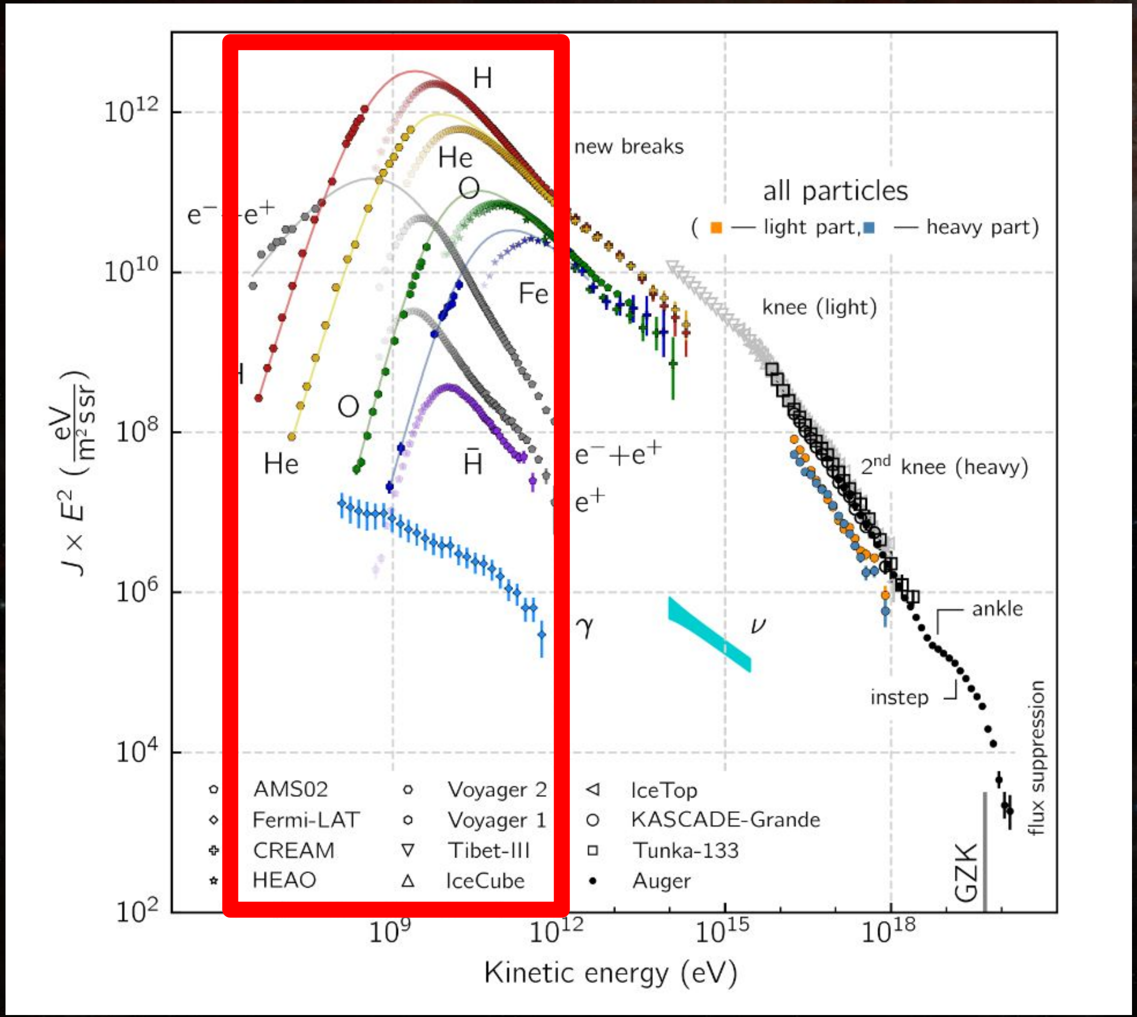

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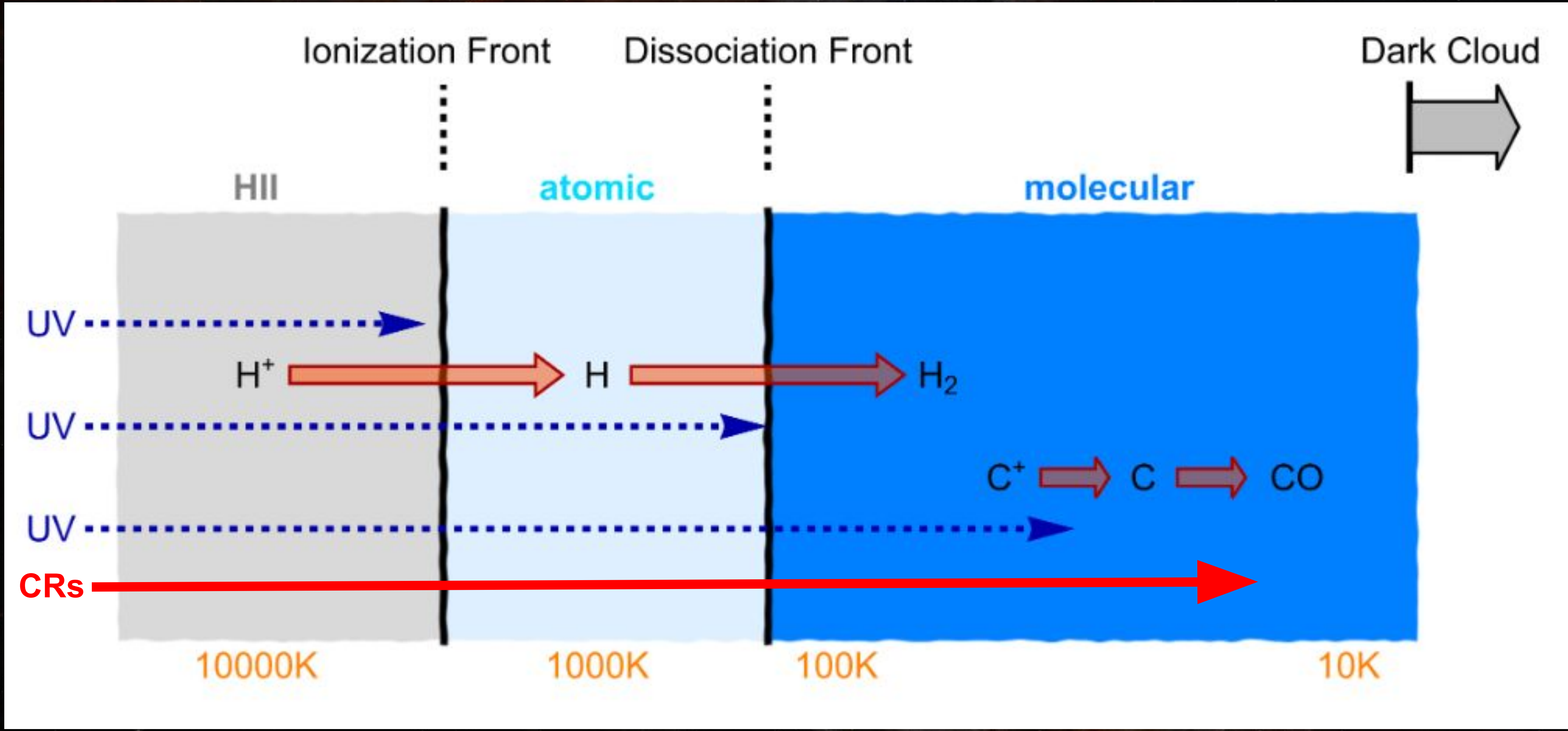
Schematic representation of a PDRs with Cosmic Rays



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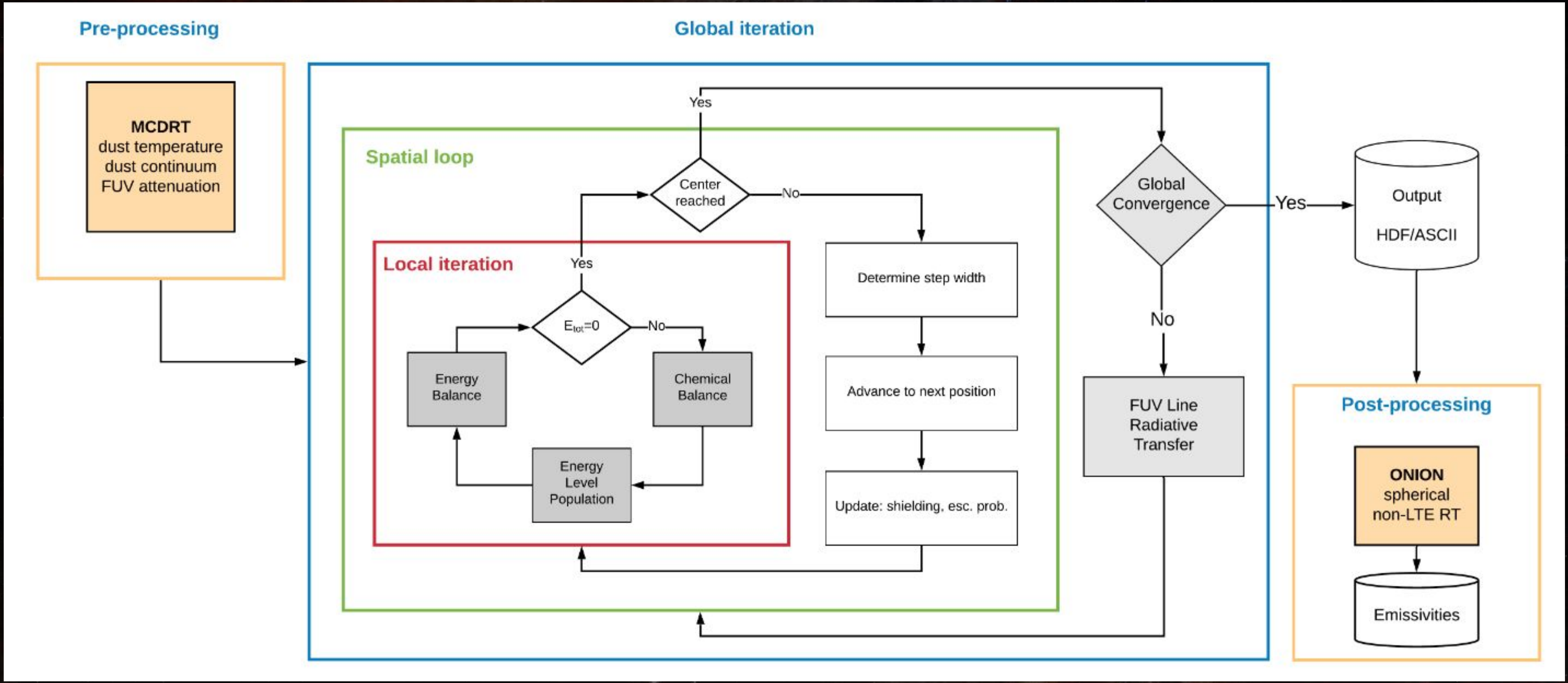
How do we study PDRs

- Combining observations and simulated data
- Modeling of PDRs is essential to better understand them (Hollenbach et al. 1971, Jura 1974, Glassgold & Langer 1975, Black & Dalgarno 1977)
- Numerous PDR codes: KOSMA-τ, KOSMA-τ3D, Meudon, 3D-PDR, UCL_PDR, etc. (Röllig et al.2007)
- Constant cosmic ray treatment is problematic
- KOSMA-τ
    - Only PDR model with spherical geometry (Markus Röllig and Volker Ossenkopf-Okada 2022)
    - Upgraded and adaptive chemistry to include the full surface chemistry (UMIST Database for Astrochemistry; McElroy et al. 2013)
    - Continuum radiative transfer using MCDRT code (Szczerba et al. 1997, Röllig et al. 2013)
    - Bulirsch-Stoer method (Press et al.2007, Sect. 16.4) instead of fixed spatial model grid
    - Update from a shielded CRIR to a unshielded (attenuated)

KOSMA-τ Structure



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Cosmic ray attenuation: The Model

Simple power law attenuation (Padovani et al.2018)

$$\zeta_{CR} = \zeta_0 \, (N_{tot}/R)^{-\alpha}$$

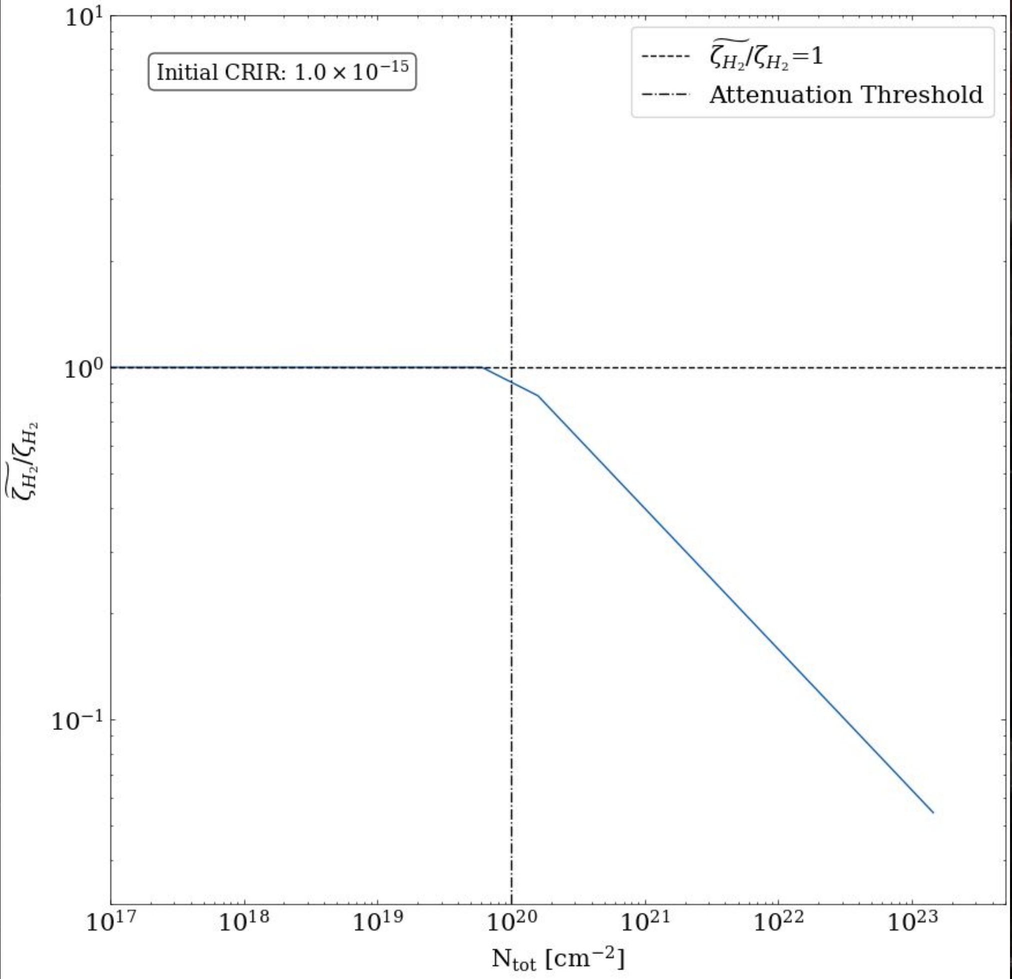
Attenuation Coefficient

Final CRIR

Attenuation Threshold

Original CRIR

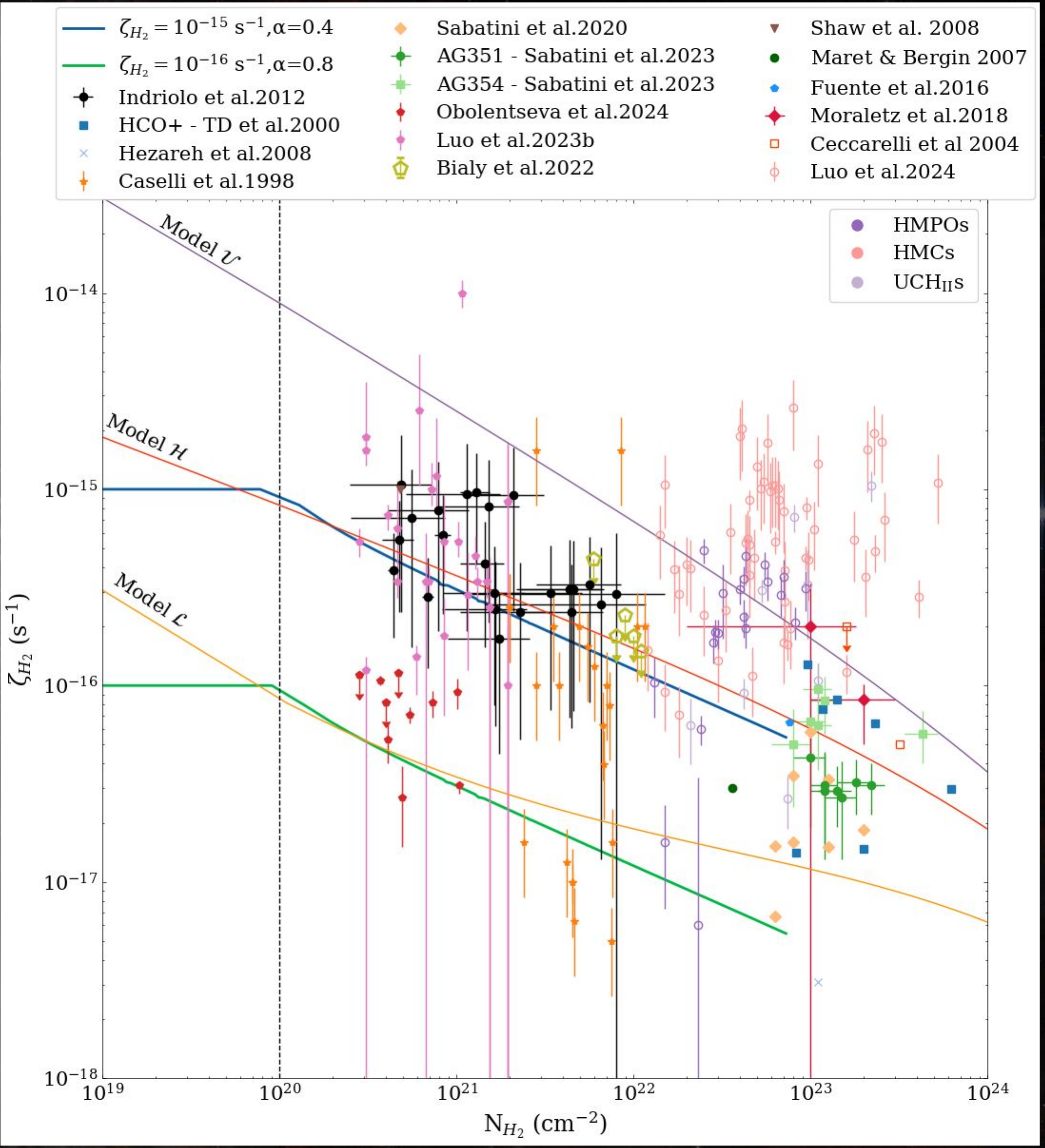
Cosmic ray attenuation: The Model



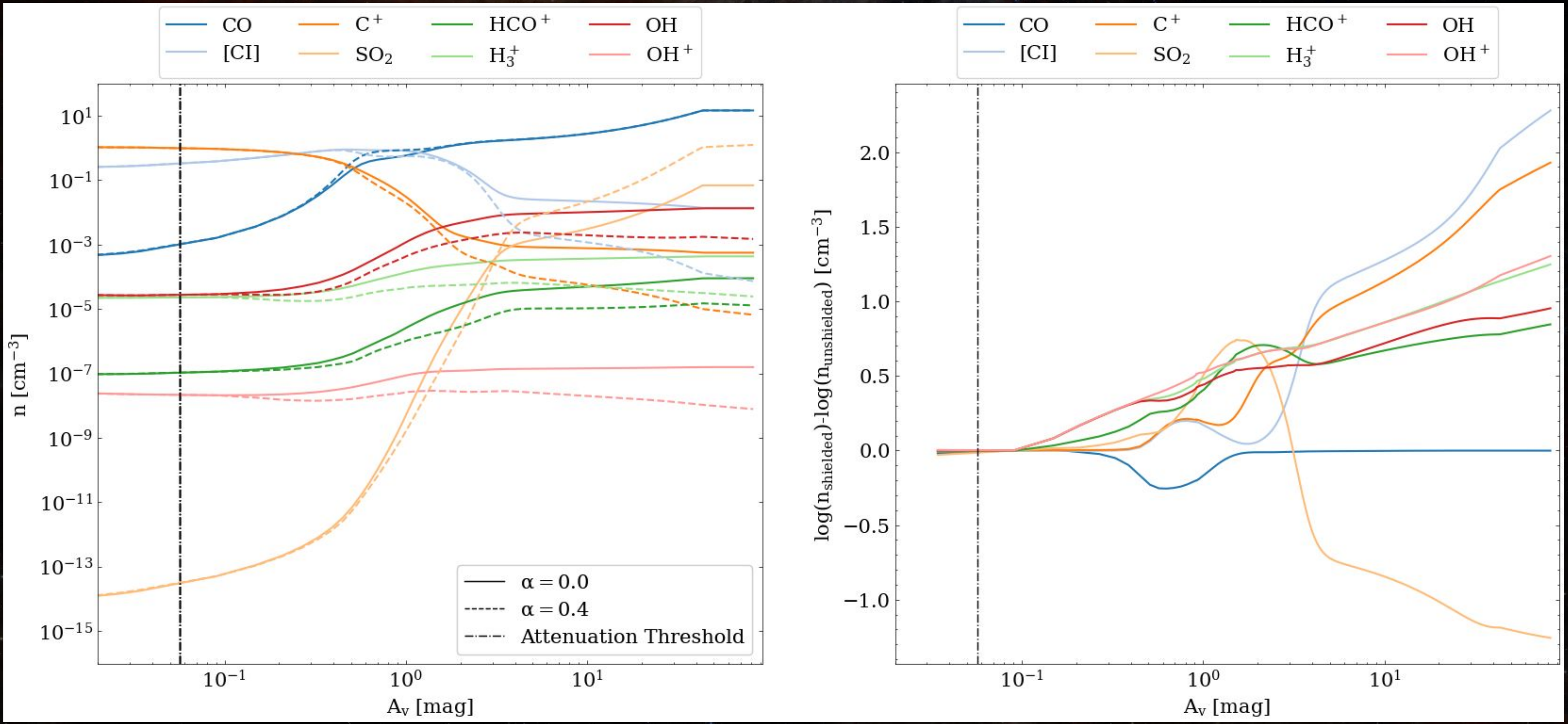
- Initial CRIR, α_{att}=0.4, R=10^{20} cm^{-2} are given
- Initial Conditions: n_{H2}=10^4 cm^{-3}, Z=1.0, R=1pc, ζ_{CR}=1x$10^{-15}$$s^{-1}$, G=10
- Model computes a new CRIR with changing column density based on the adaptive grid
- Structure, chemistry and intensity changes can be visualized using our KOSMA_tau_read tool (*still in development*)

Motivation

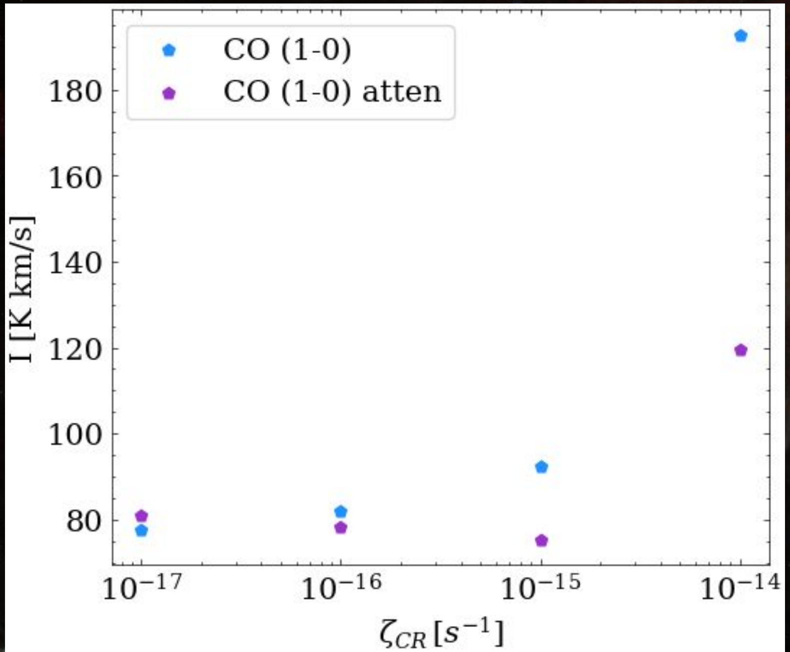
- ➢ Update KOSMA-τ model to include CR attenuation (Padovani et al.2018)
- ➢ Develop the necessary sensitivity tool to detect changes on the PDR structure (*still in development*)
- ➢ Establish the PDR chemistry as a diagnostic tool to study the absolute CR intensity and its attenuation

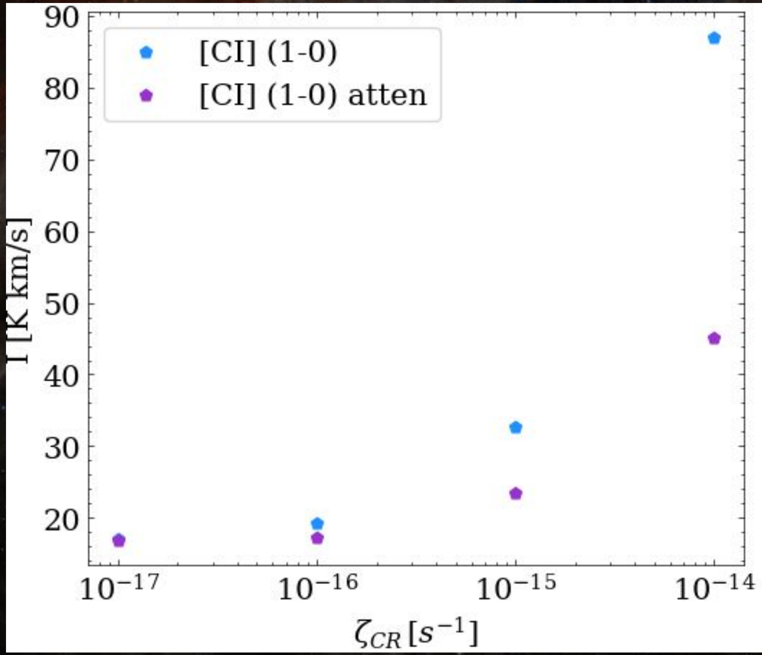


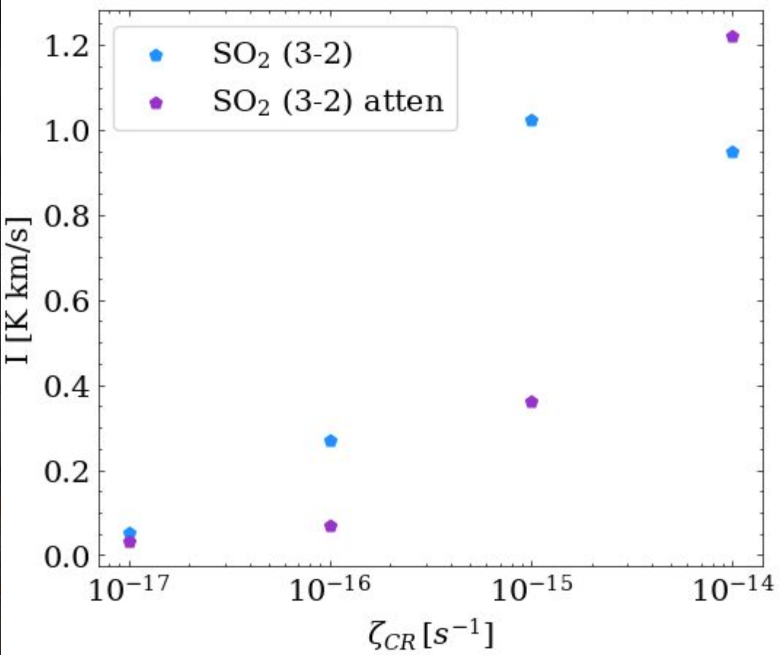
Residuals Result



Intensity Results







- Large absolute intensity difference in high CR environments

Conclusions and Future Plans

- CR attenuation significantly alters the structure of the PDR
- Implemented model highly depends on the initial CRIR
- SO_2 is a promising species for the detection of CR attenuation accessible with mm observations
- Continue with the development of the KOSMA_tau_read sensitivity tool and utilize the new upgrade to run new PDR grids (STAY TUNED!)

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