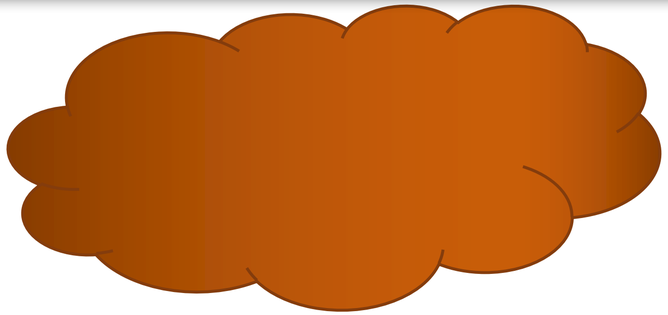
Estimation of the physical conditions in PDRs from IGRINS ro-vibrational H_2 observations

Orion B Workshop

Aurélien PILUSO 06/2025

Context : Star formation

Interstellar medium : Molecular gas reservoir for stellar formation



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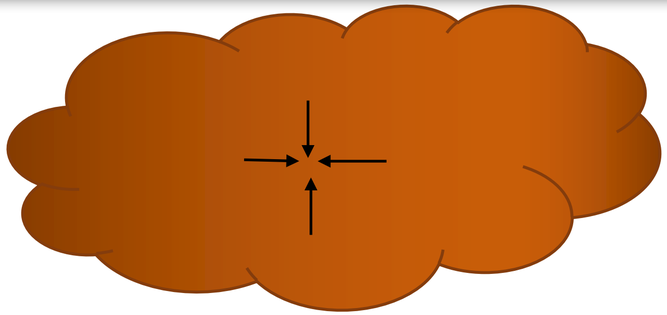

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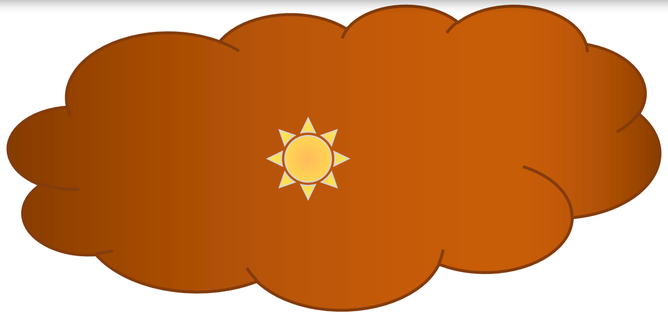

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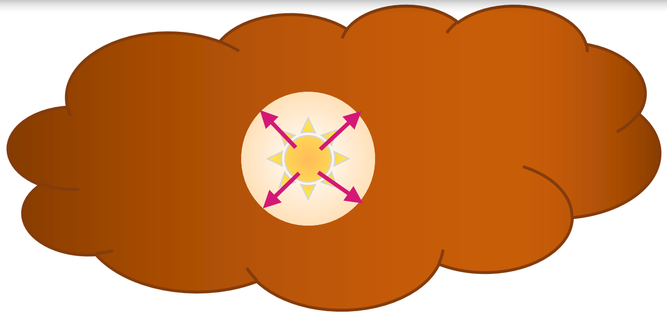

Feedback from forming stars :

✳Mechanical (stellar winds, supernovae)

✳Radiative (UV illumination)

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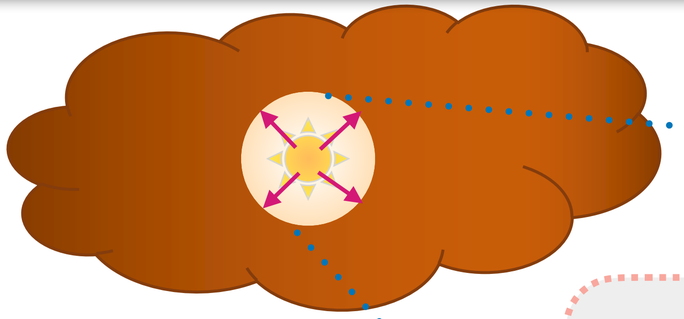

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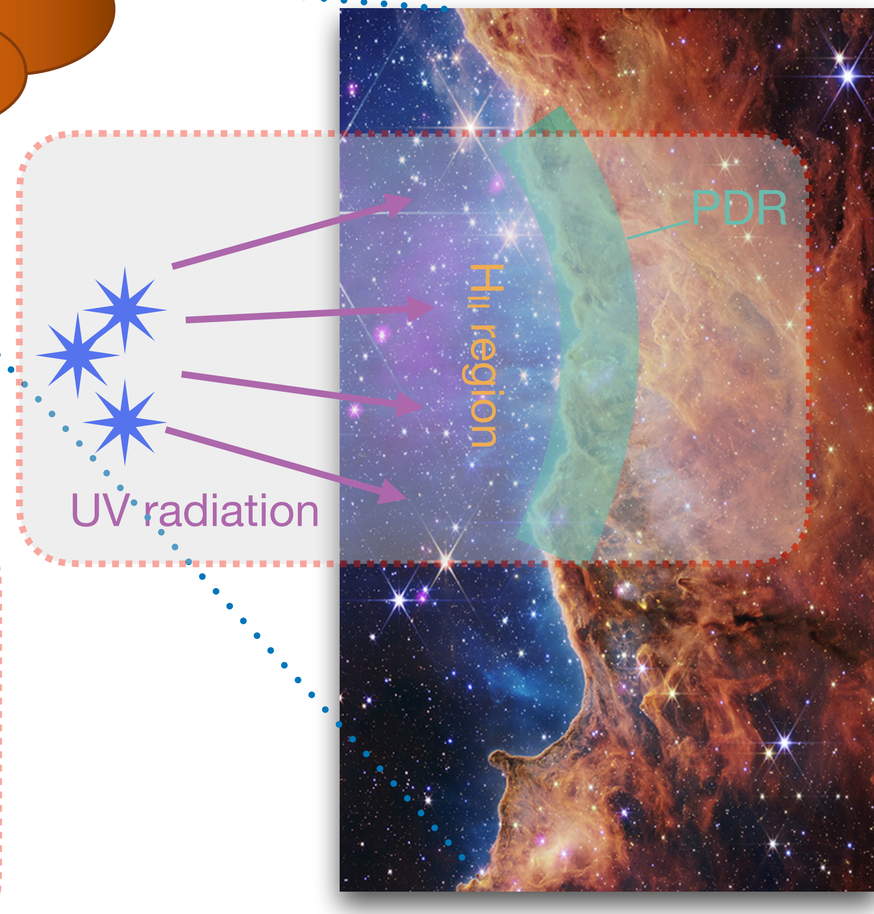
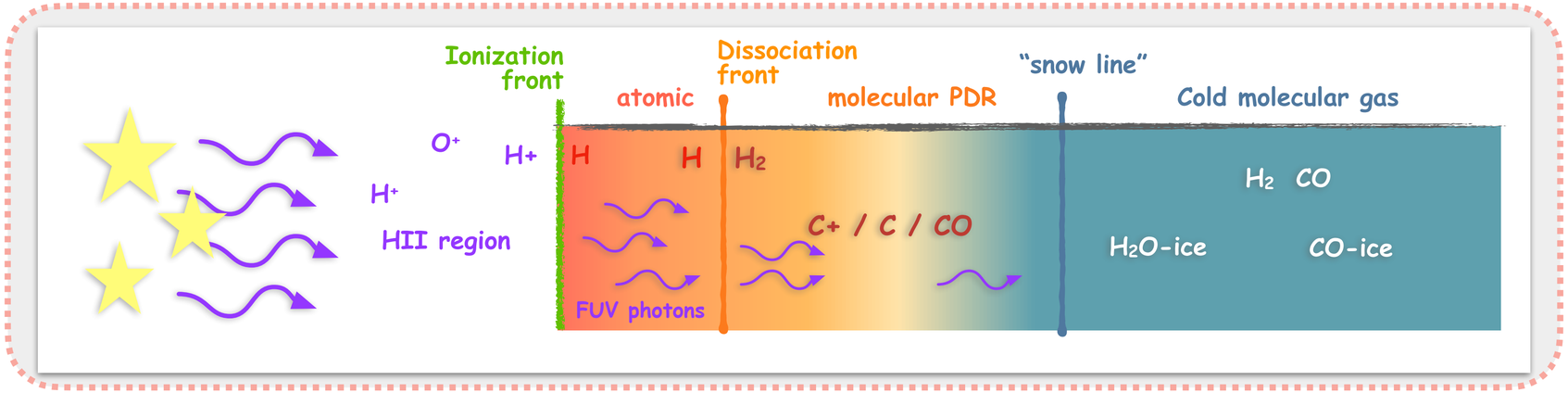


PDR: PhotoDissociation Region

- Radiative feedback of massive stars via UV on the molecular cloud
- UV heats and photodissociates molecules: IR-rich and millimetric emission spectrum
- Excited molecules = Tracker of radiative feedback



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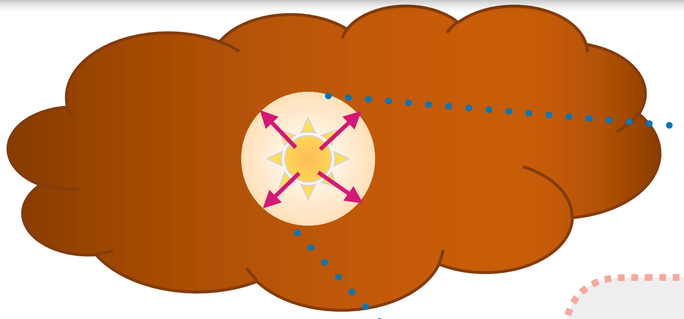

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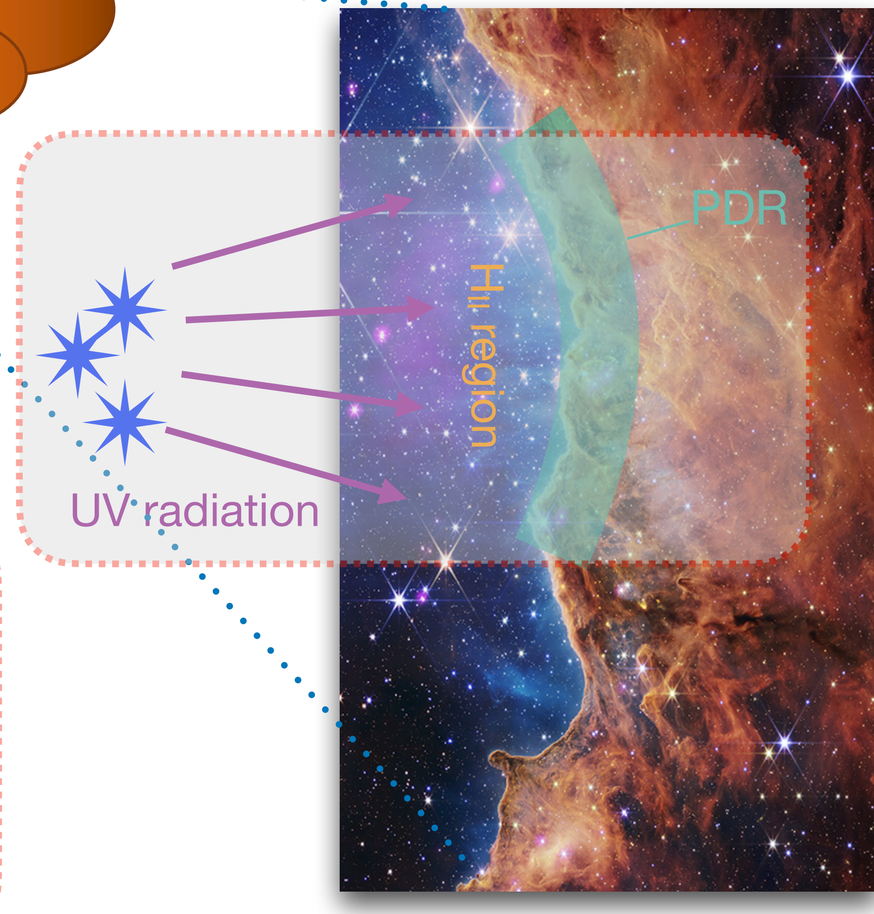

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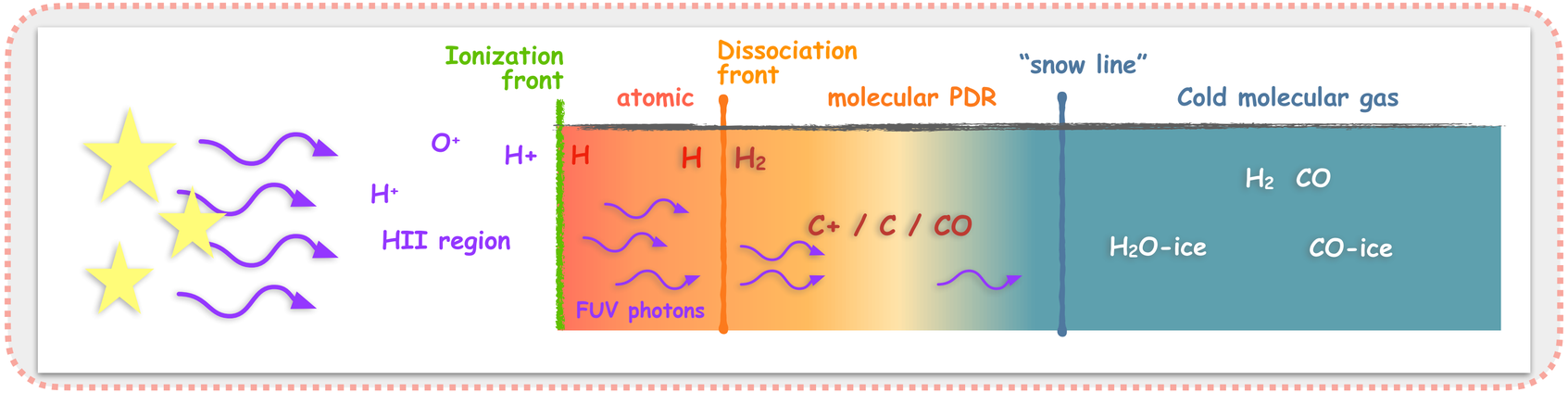
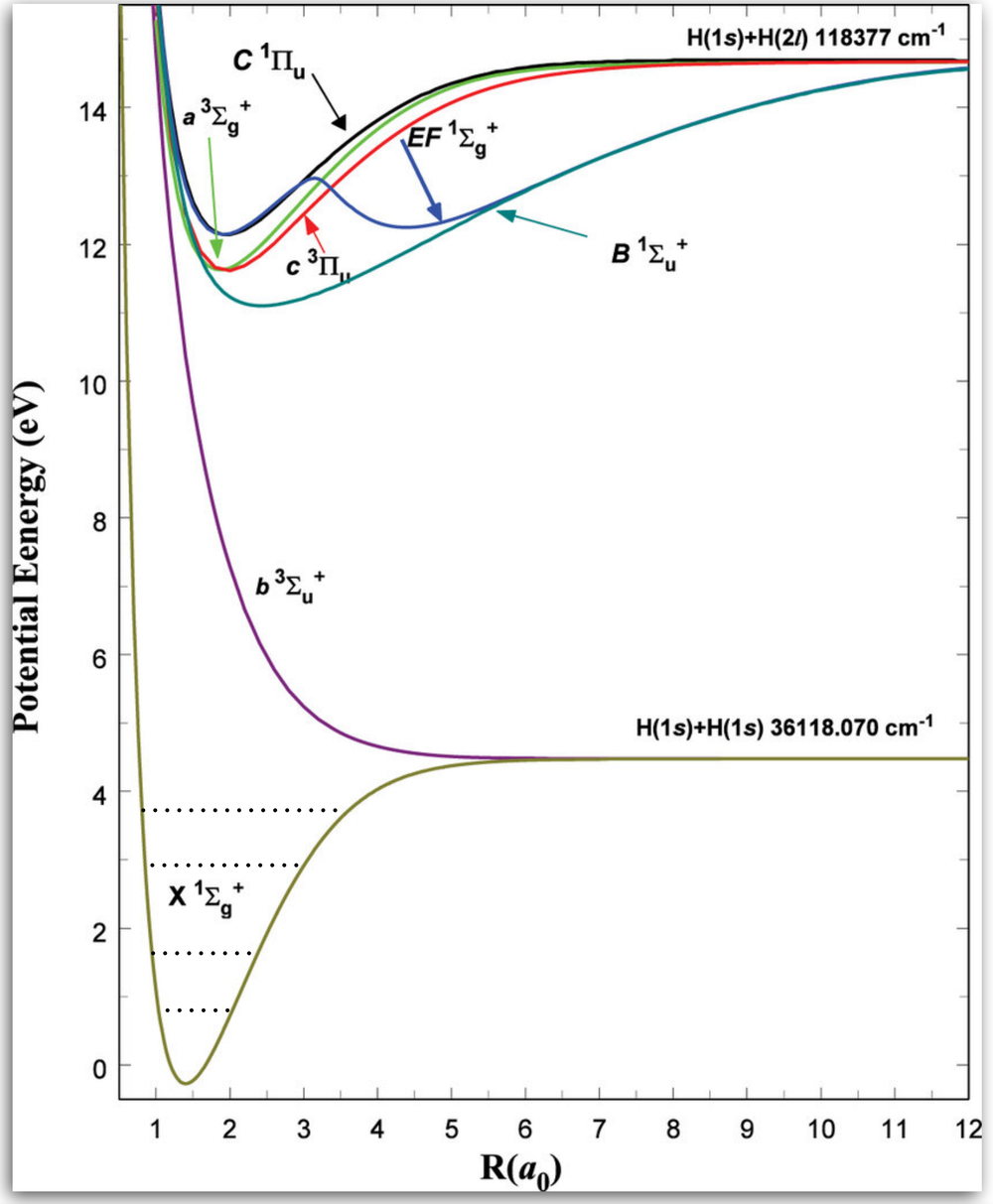


What is the impact of radiative feedback on star formation ?

Observable

H_2 :

- Most abundant molecule in the interstellar medium
- Responsible for a major part of physical and chemical processes occurring in PDRs
- Tracker for UV impact on molecular clouds



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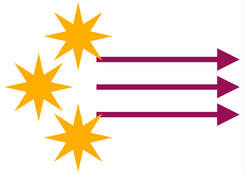

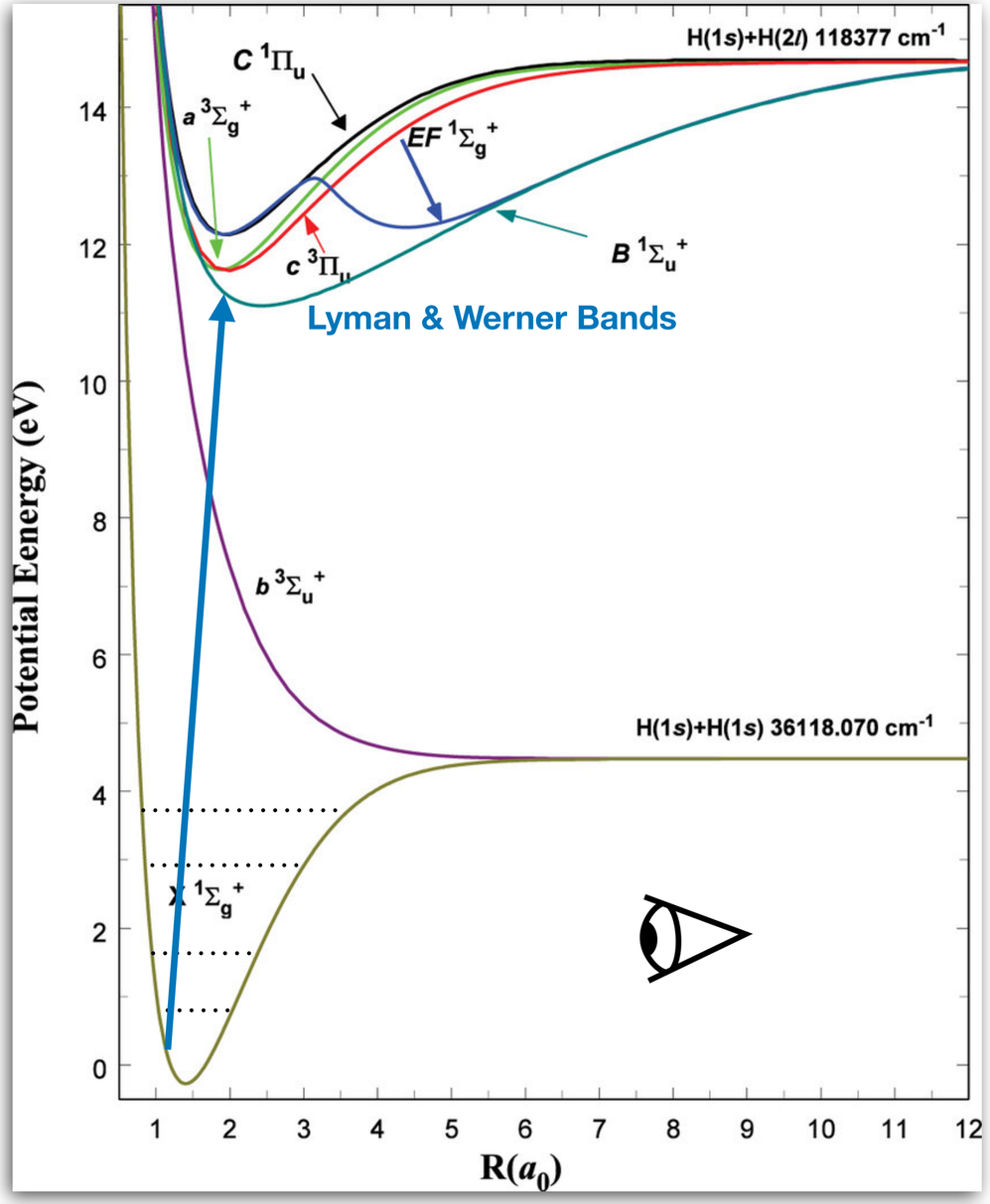

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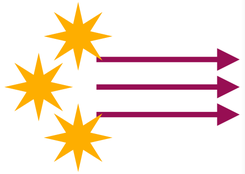

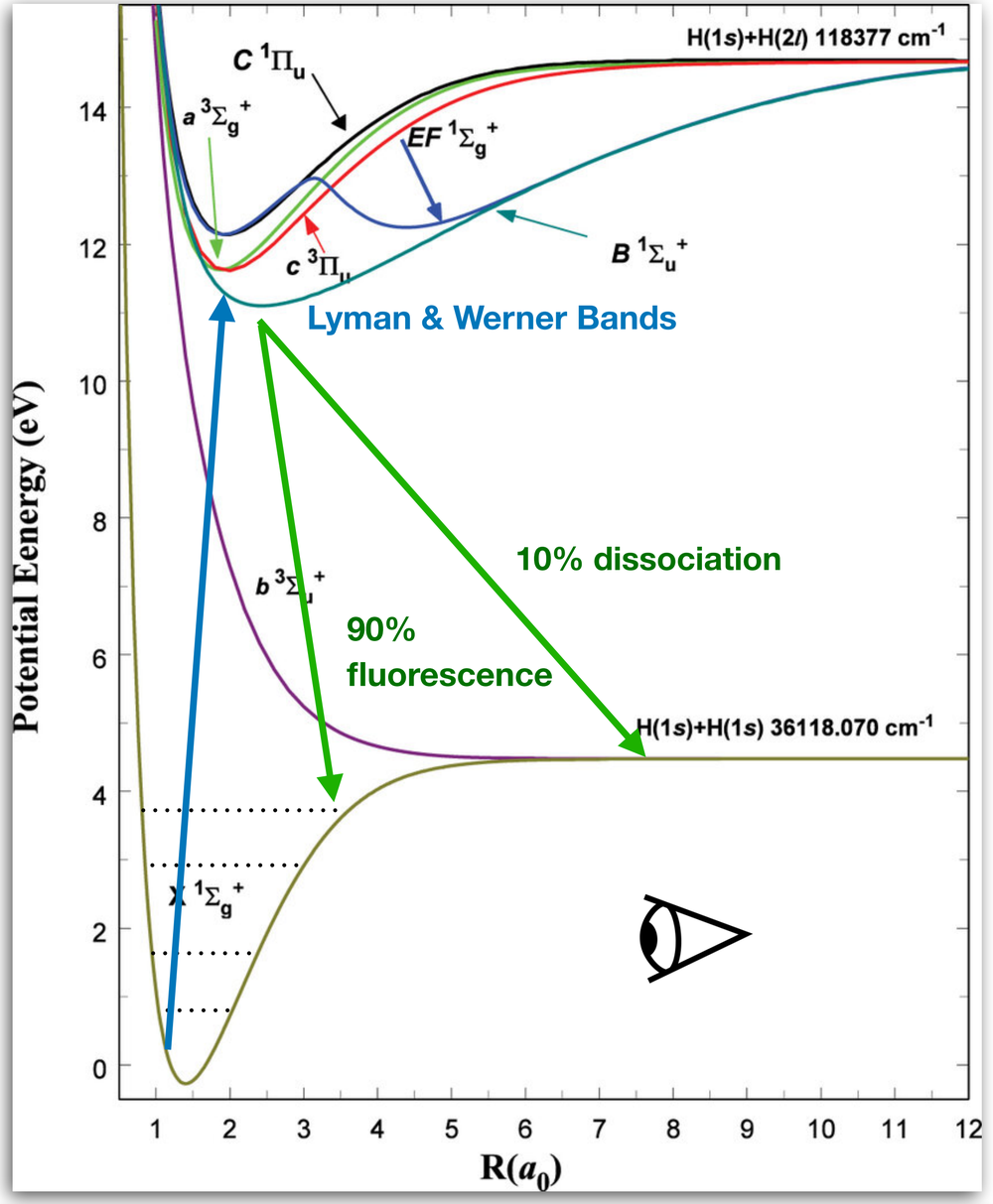

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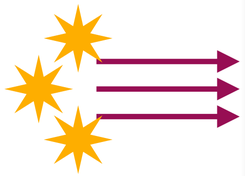
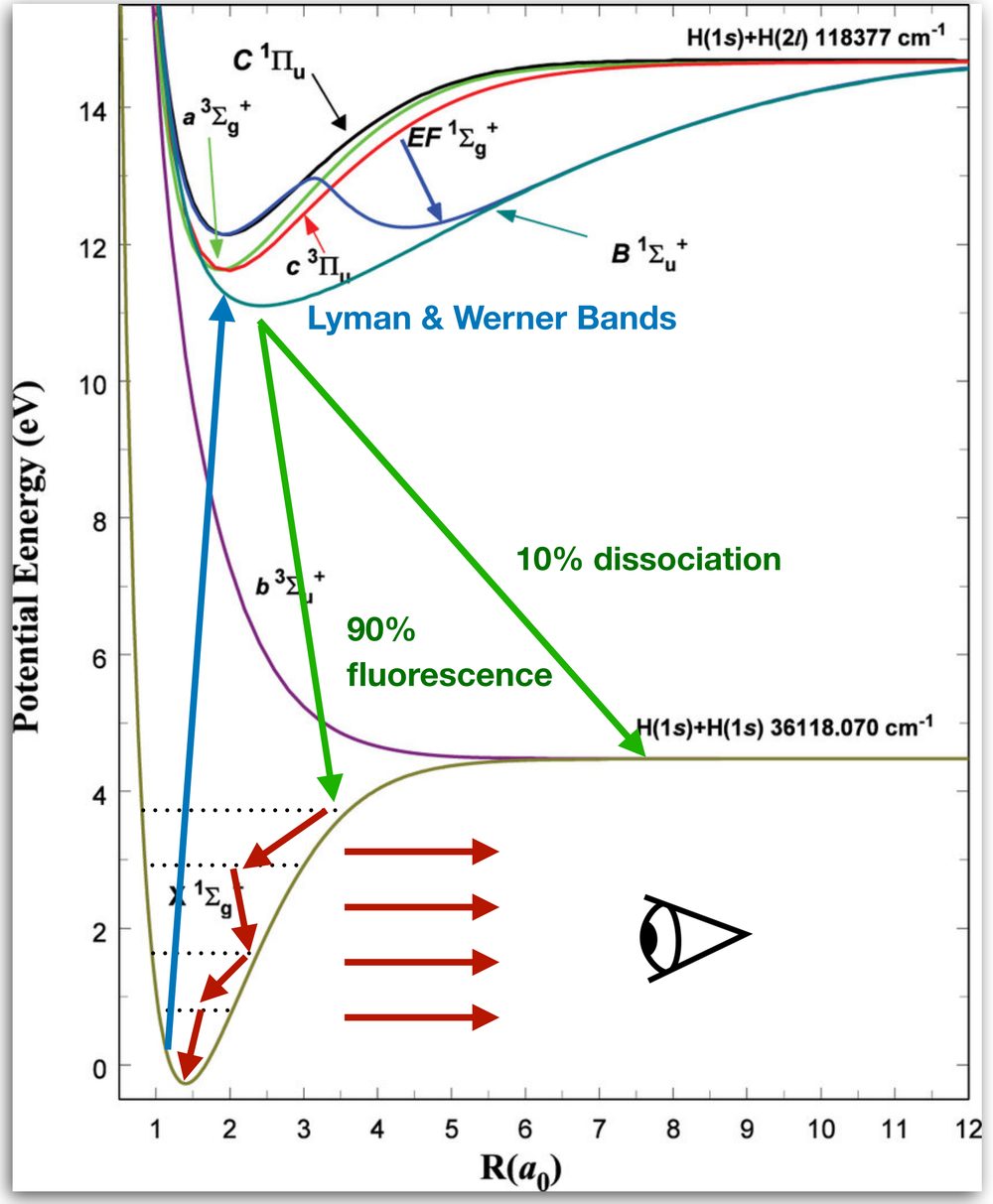
2. ***Fluorescence*** / ***Dissociation***
3. ***Rovibrational cascade (IR emission)***





2. Instrument

Instrument : ***IGRINS*** : **I**mmersion **GR**ating **IN**frared **S**pectrometer

- Covering H and K band (**1.45 and 2.45 μm**)
- Spectral resolution of **45,000**
- **Averaged intensity on a 1” * 15” slit**

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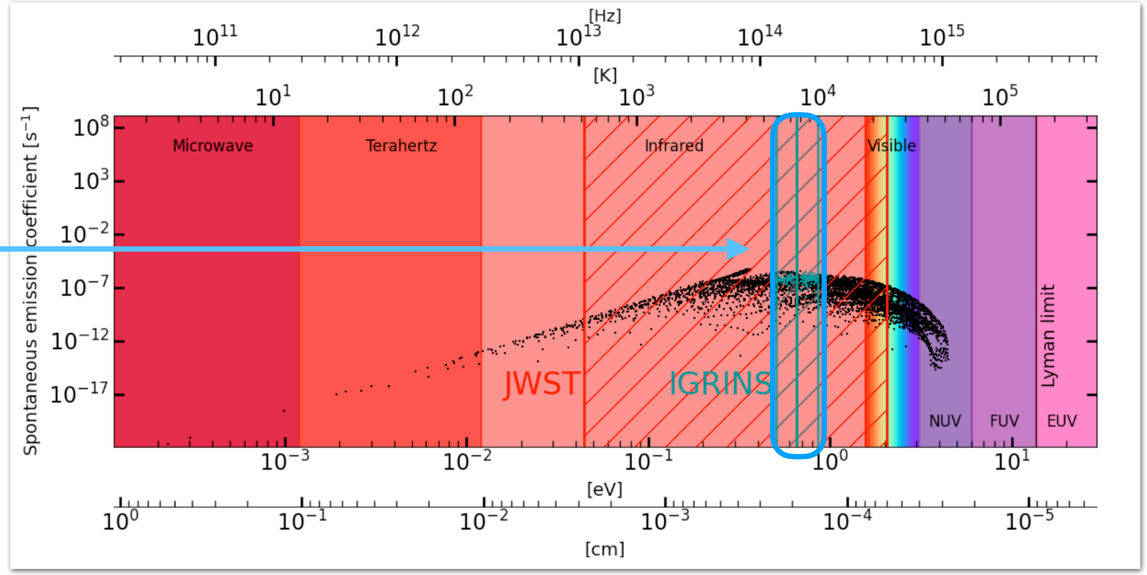

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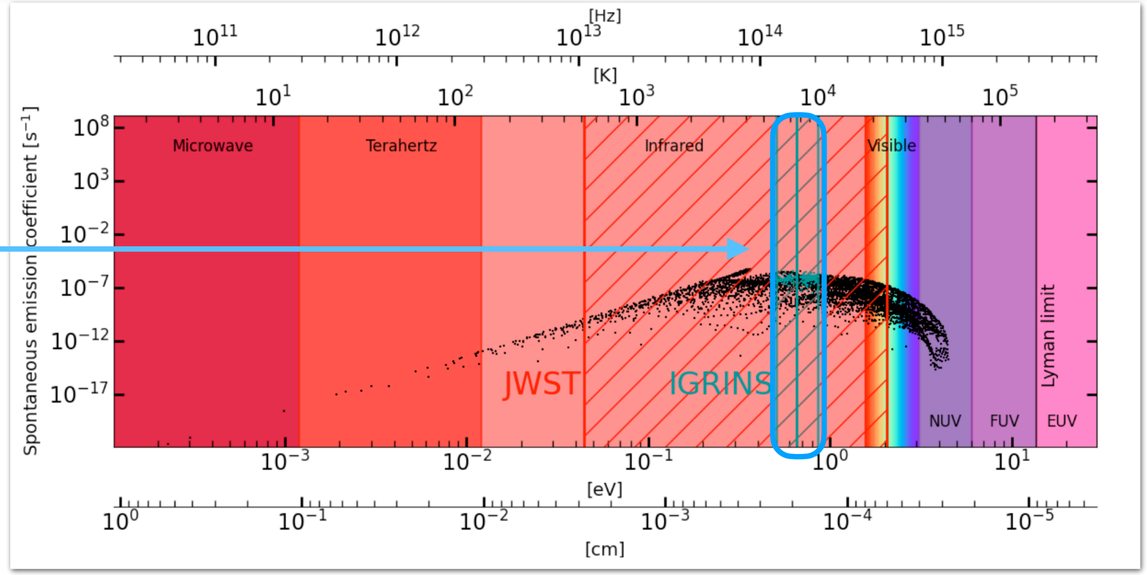

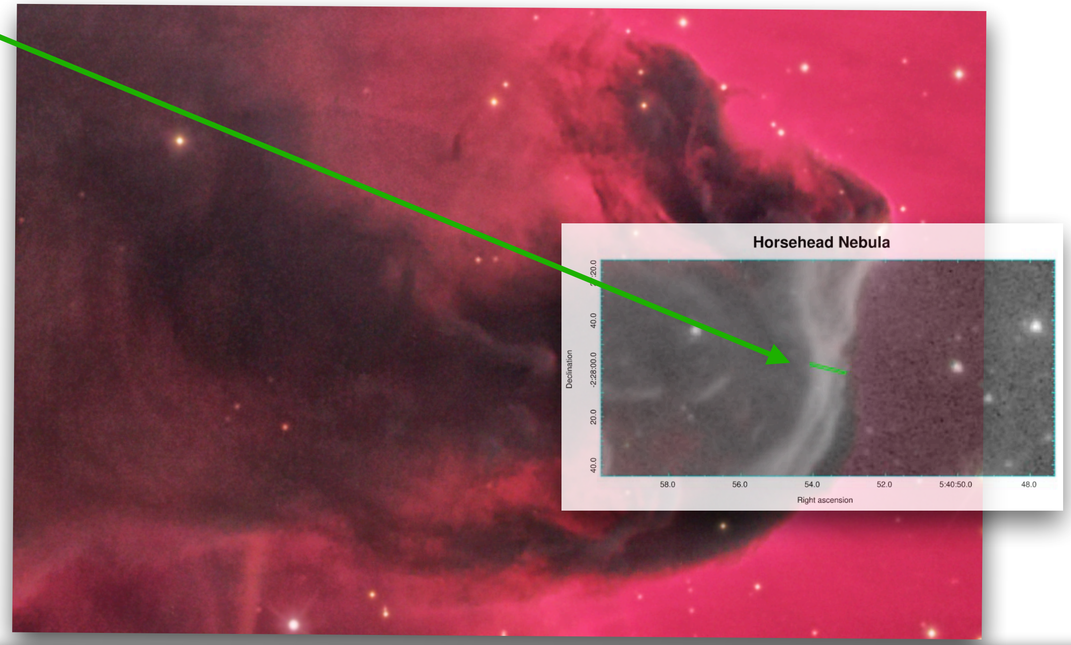

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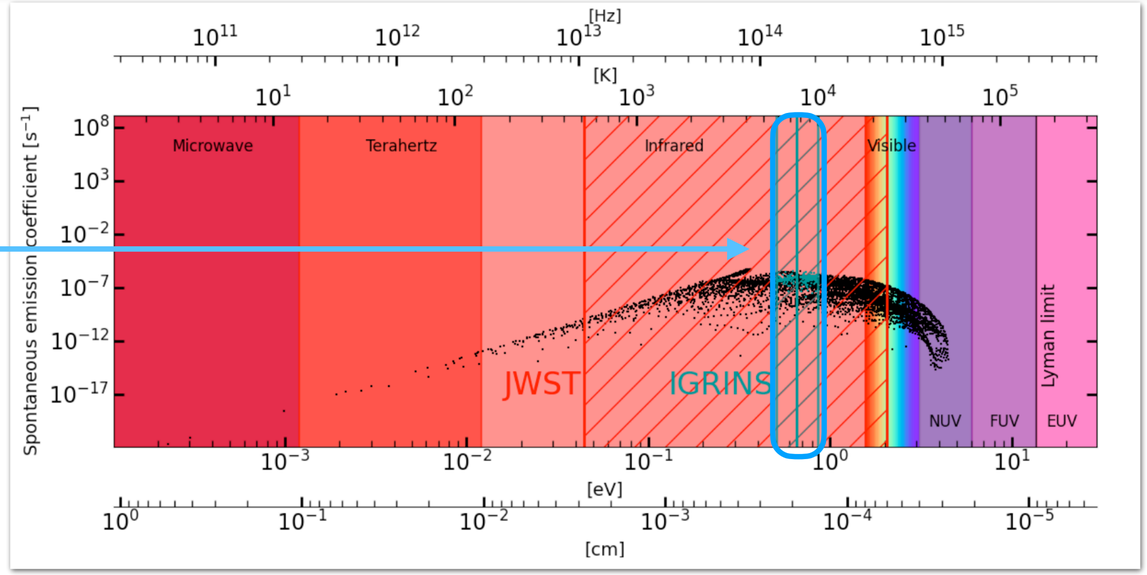
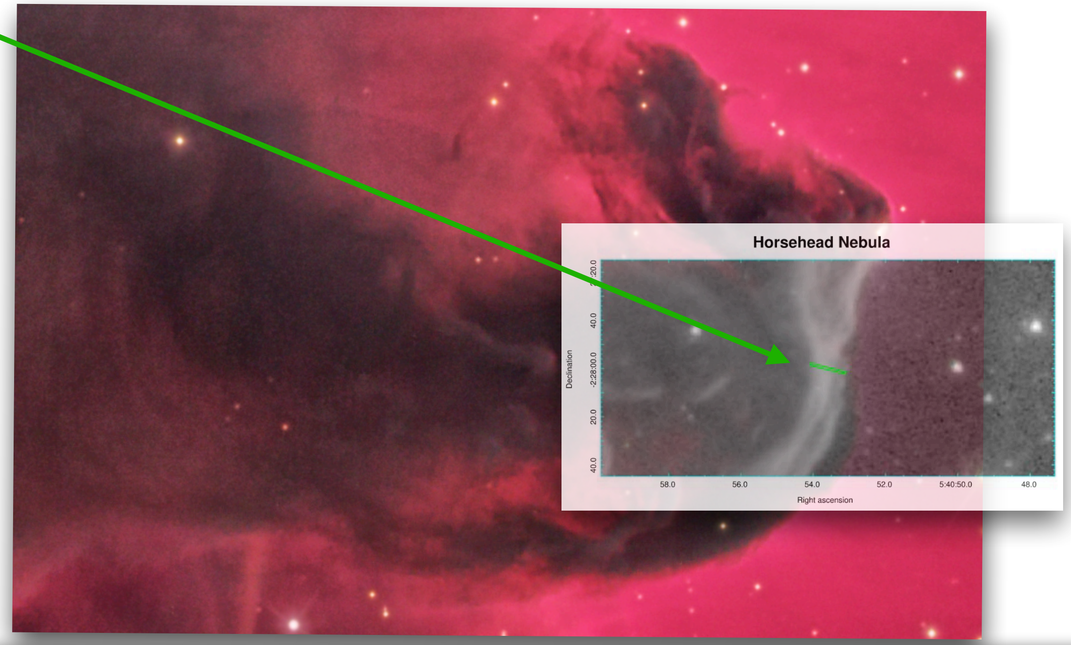


Preliminary study Kaplan et. al. 2021

- **5 PDRs :** *Horsehead Nebula, Orion Bar, NGC2023, S140, IC63*
- **>120 ro-vibrational lines of H_2 per PDR**



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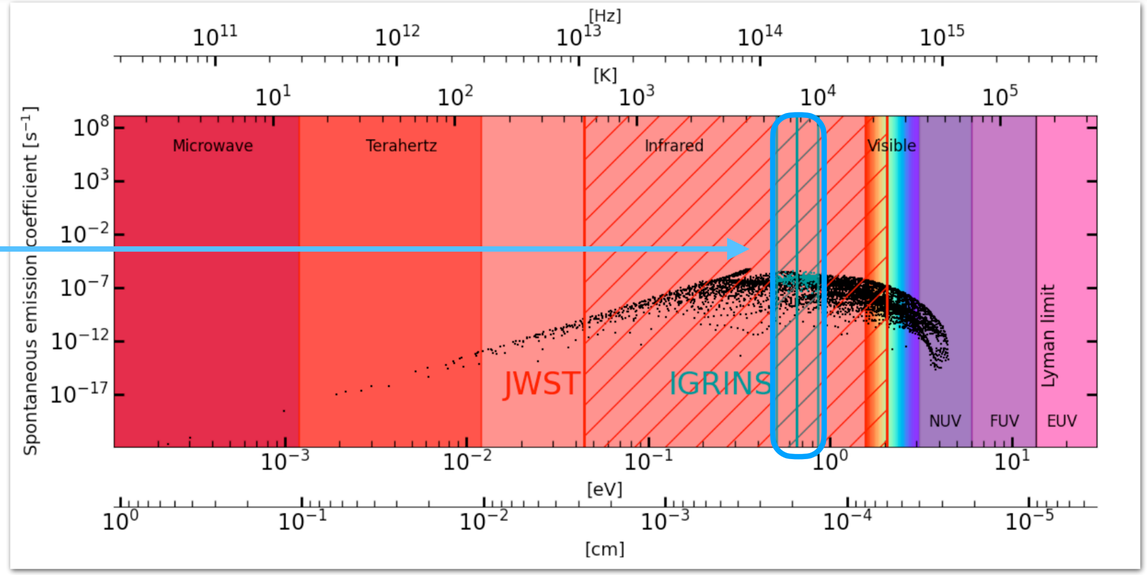

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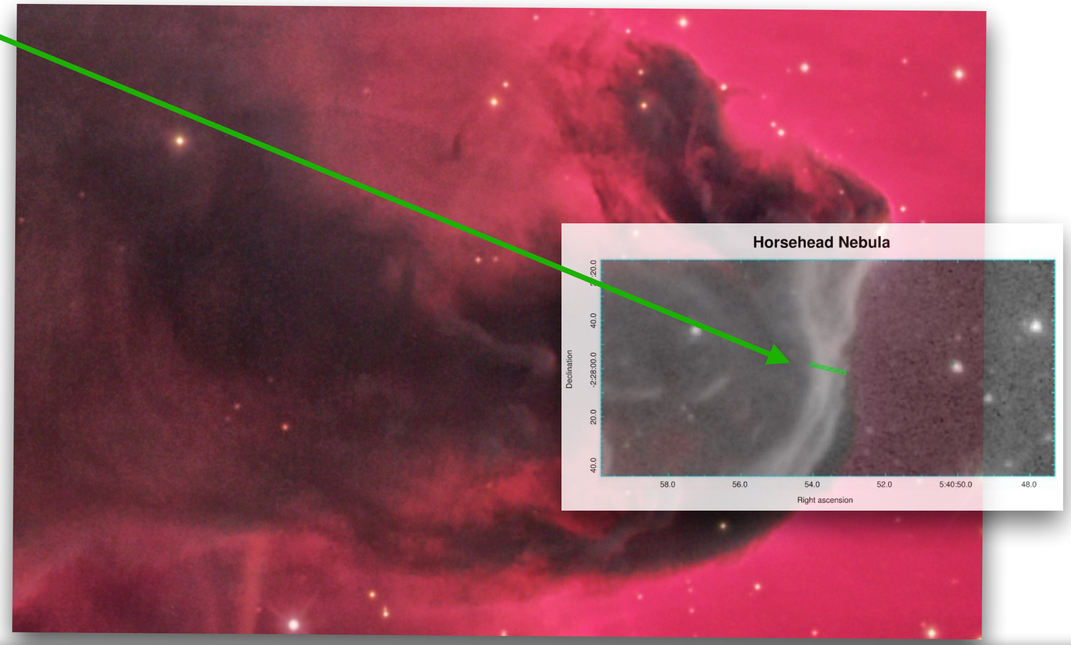
Since :

- Calibrated data: absolute intensity
- Extinction correction of intensities
- Use of a code with detailed physics to model the consequences of observations: the PDR Meudon code



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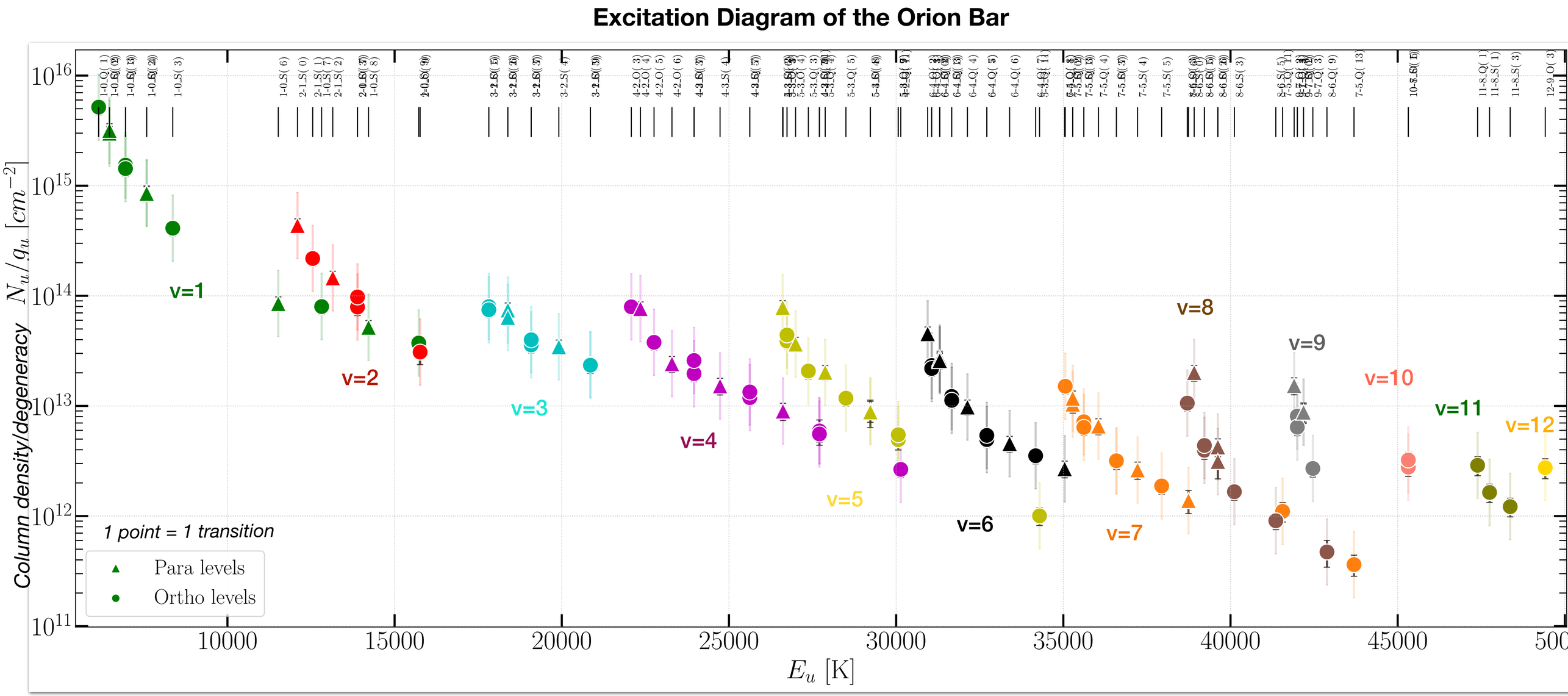

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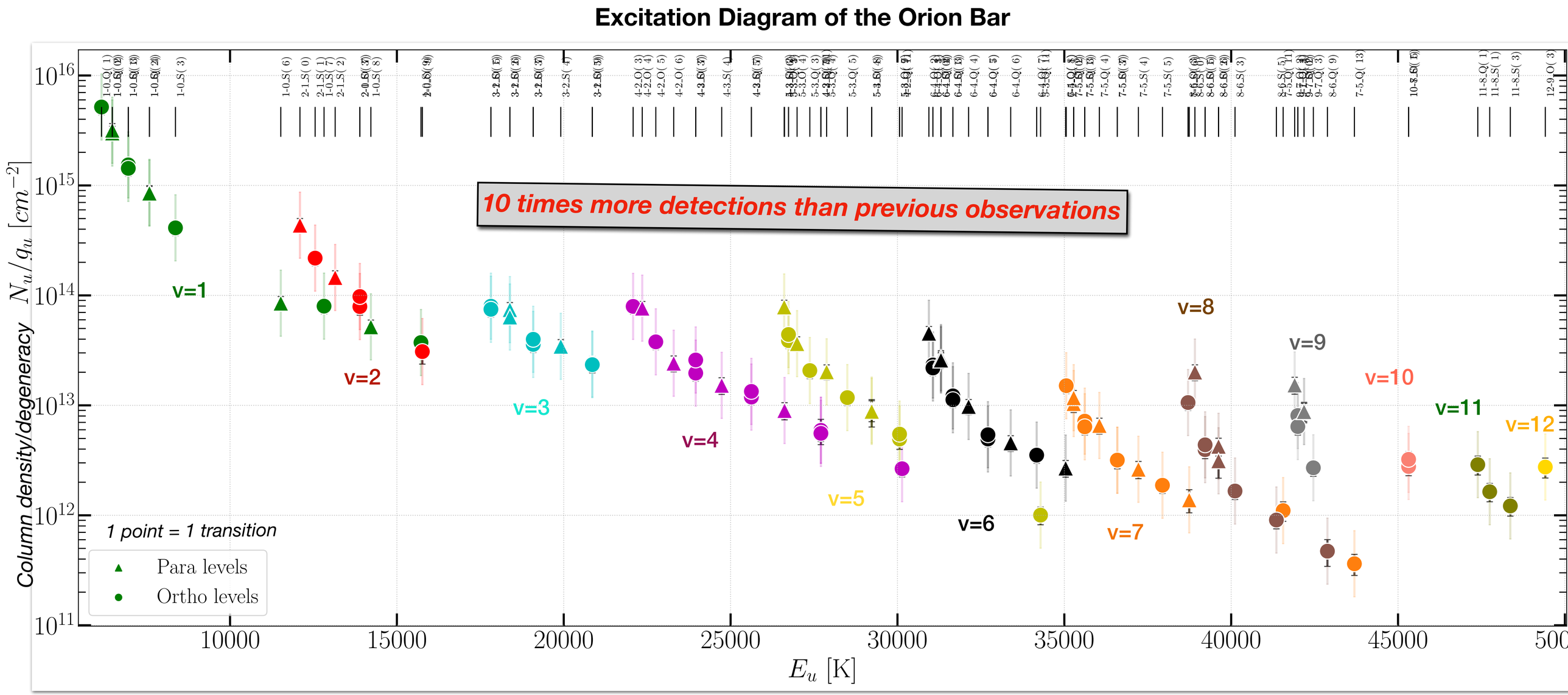
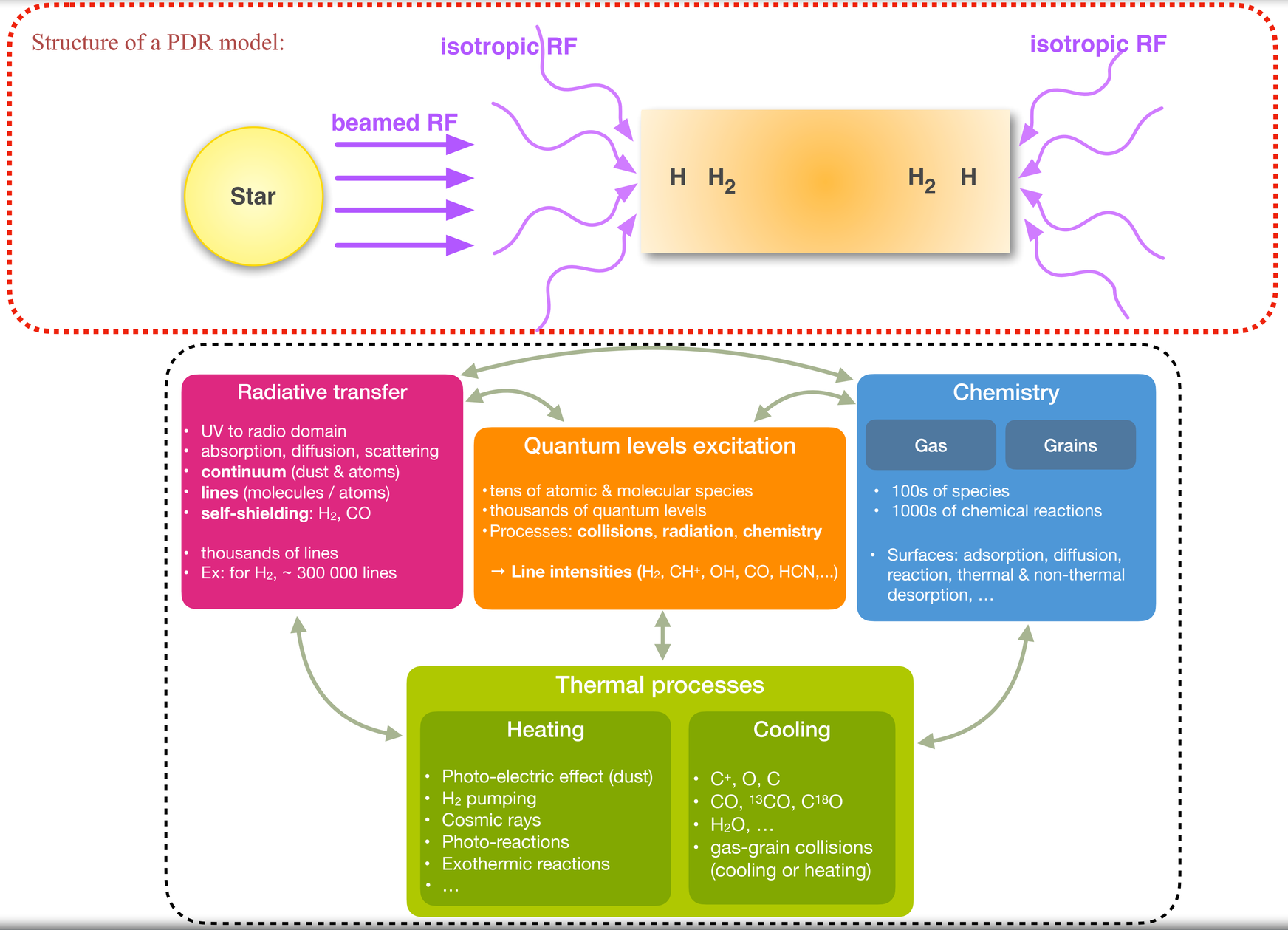


3. Meudon PDR Code

Meudon PDR Code :

- State of the art
- 1D model
- Stationary model
- Isobaric/isocore model



3. Meudon PDR Code

Varying parameters :

- **Thermal pressure** P_{th} between $5 \times 10^5 - 5 \times 10^9\ Kcm^{-3}$
- **UV field intensity** normalized in Habing G_0 between $10 - 10^5$
- **Geometrical Scaling factor** Ω between 0.1 -10

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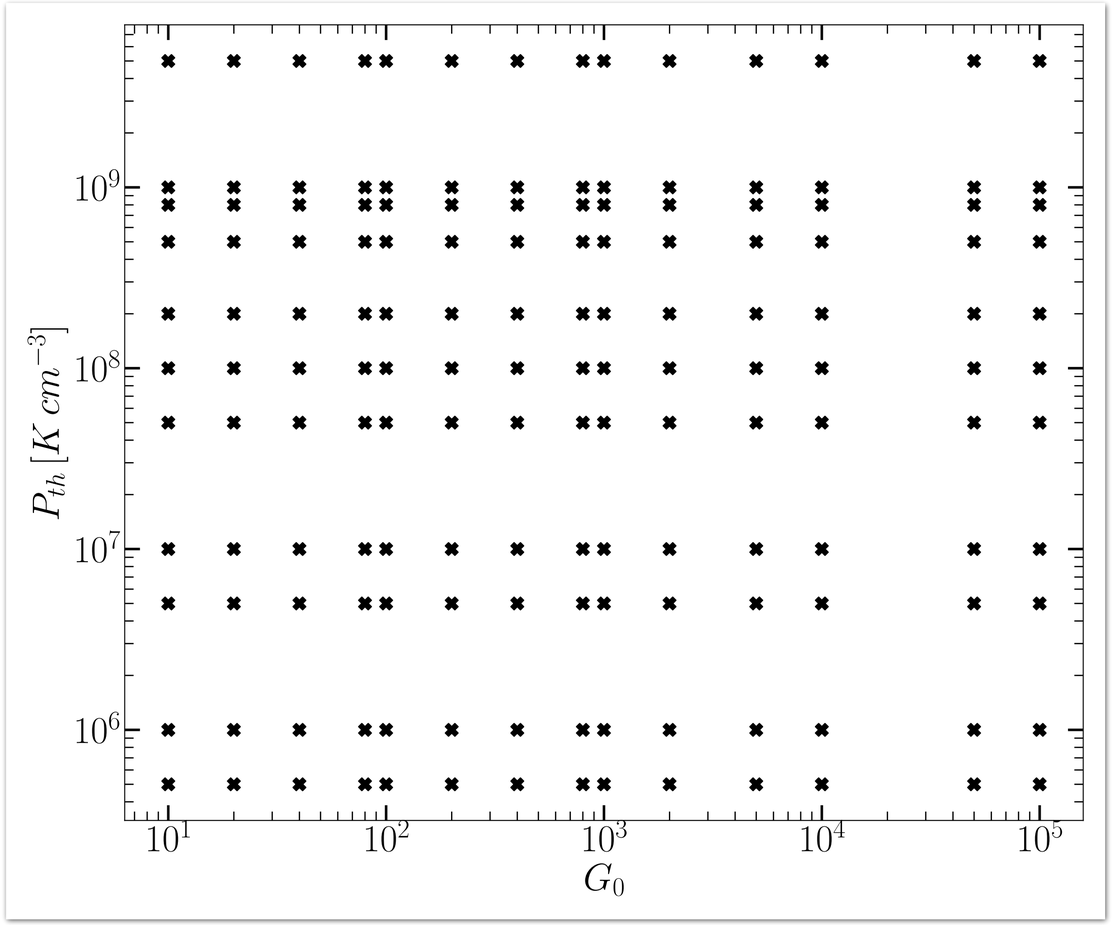
Comparison observations/models :

- Creating a grid on the parameters to be studied

Grid of models for this study



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Approaches to quantify the relevance of the model

- χ^2 minimisation $\chi^2 = \frac{1}{N} \sum \frac{(I_{obs} - \Omega \times I_{mod}(P_{th}, G_0))^2}{\sigma^2}$
- Bayesian inversion and posterior exploration (*beetroots*)

Interpolation within model grid :

- Nonlinear interpolation (*log RBF*)
- Neural Network learning of the grid : *nnbma*

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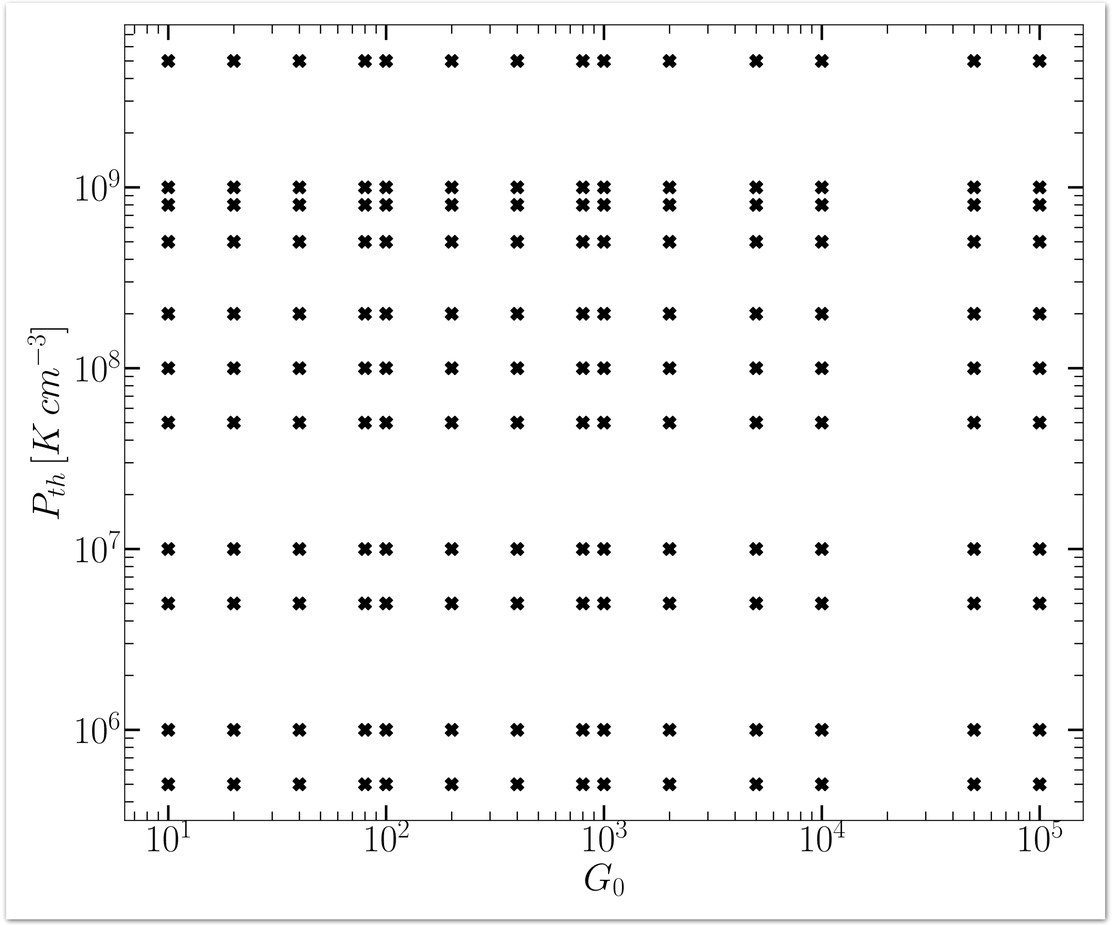
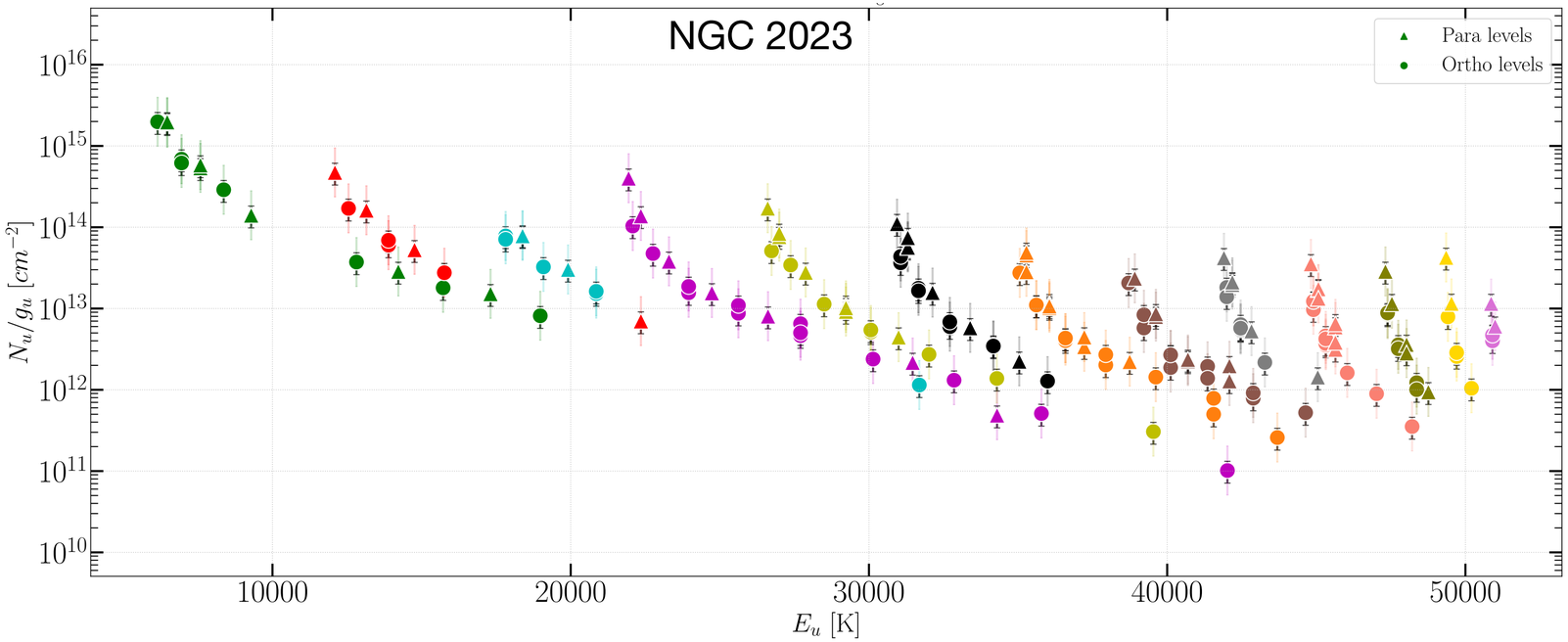


4. Results

Moderate PDRs : NGC 2023 Case

Similar results for Horsehead Nebula, S140, IC63



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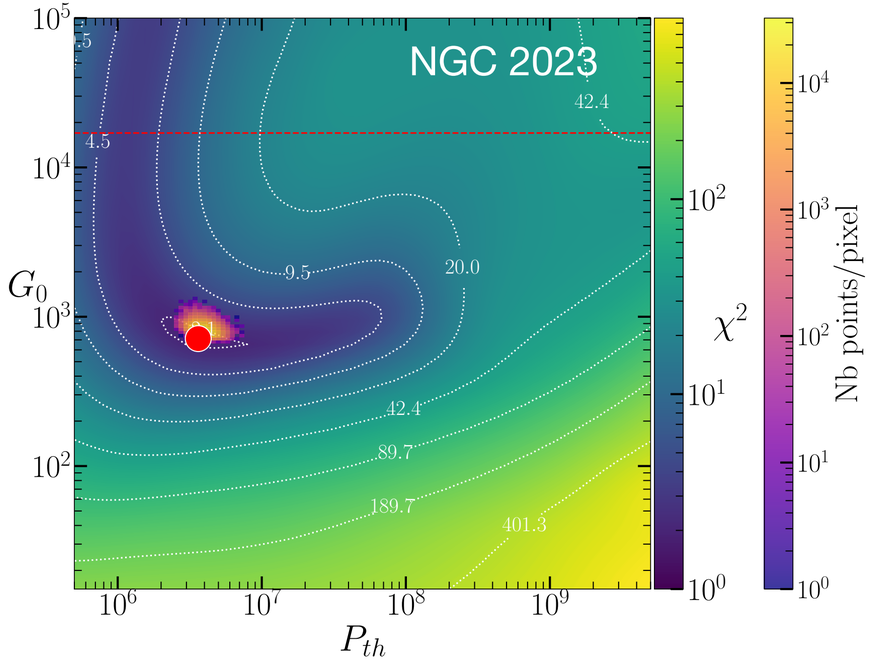

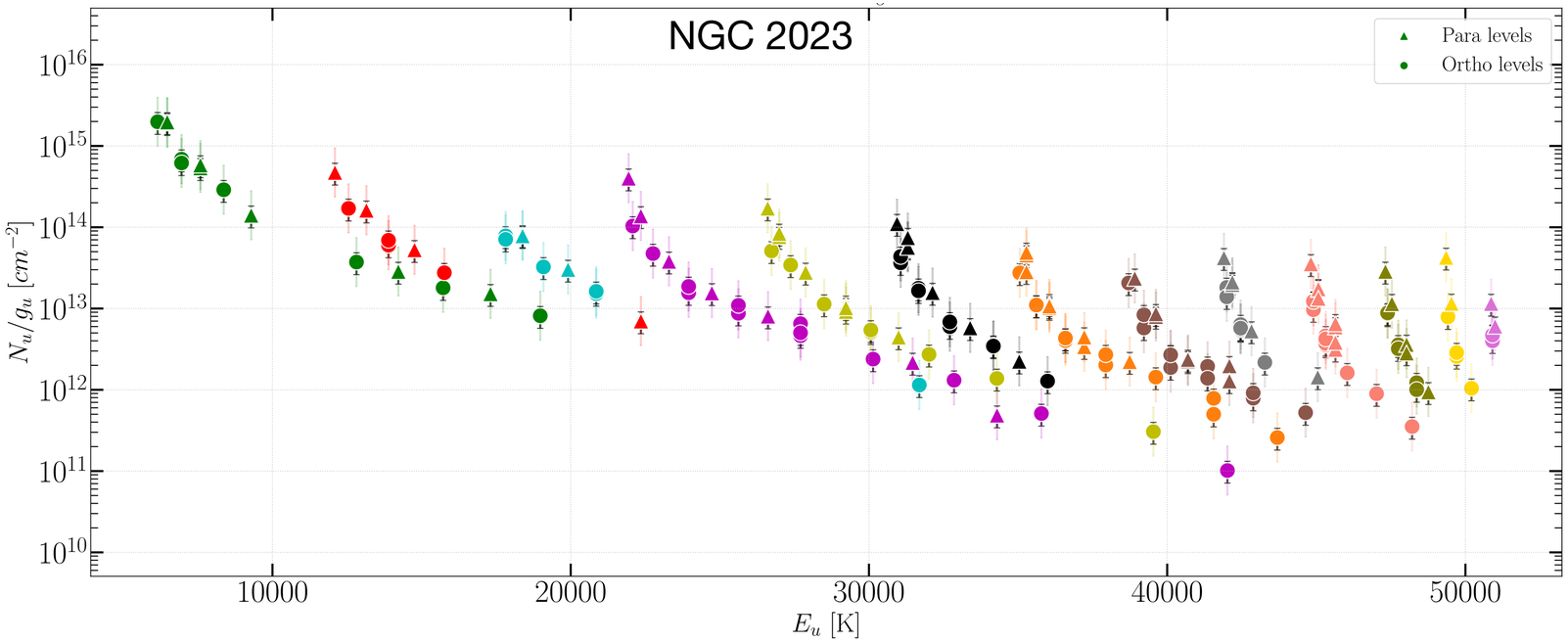

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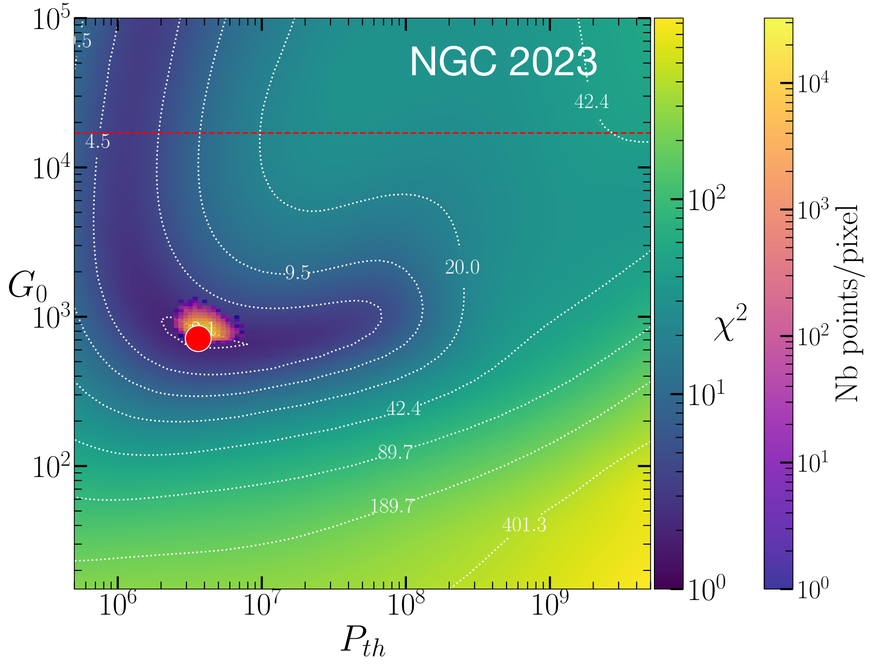

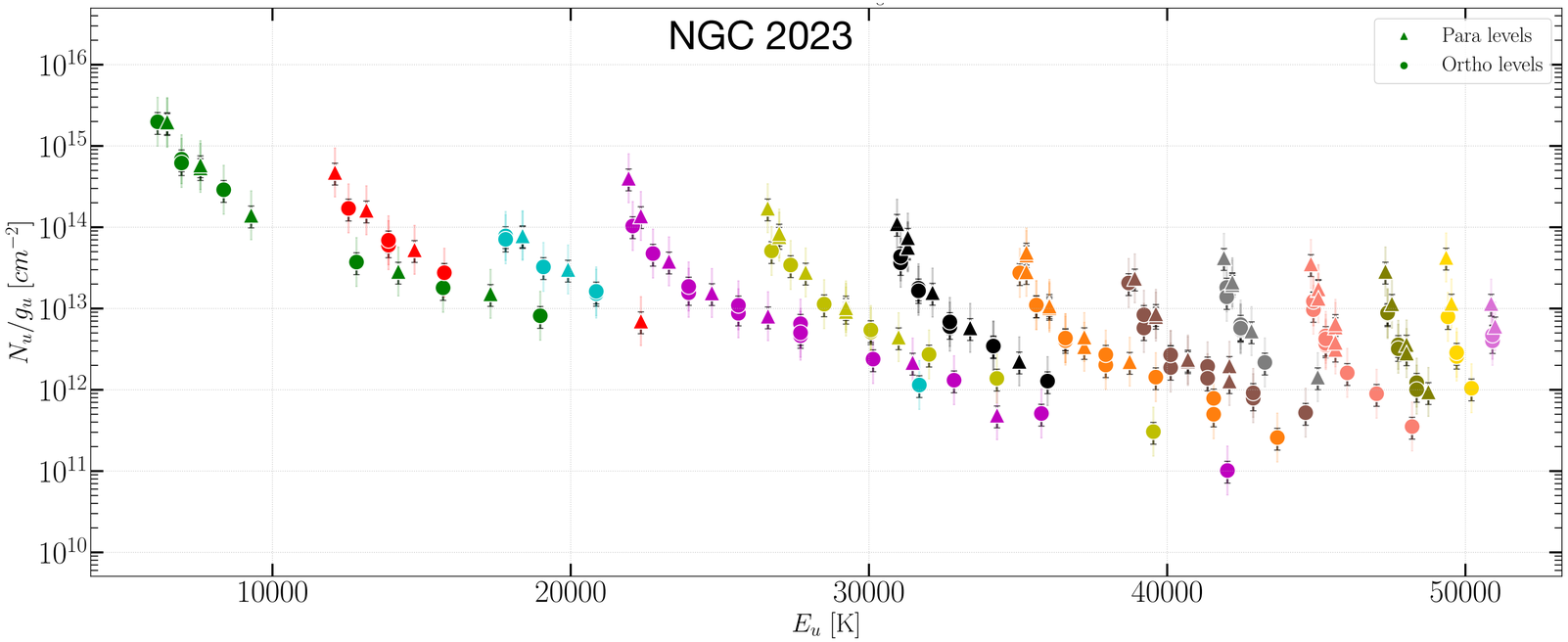

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✓ Sensibility of H_2 lines to physical parameters -> **Great constraint on physical parameters**

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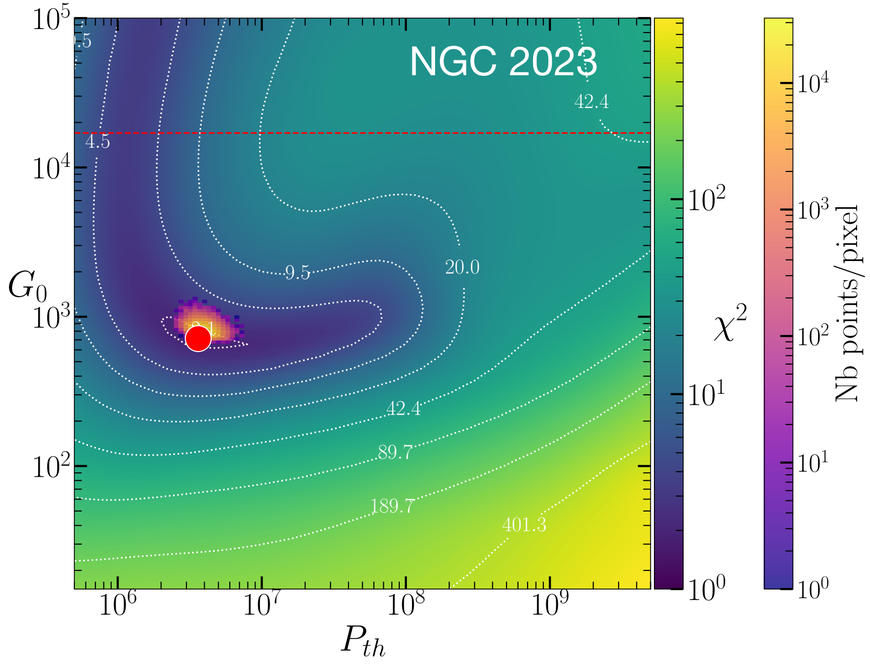

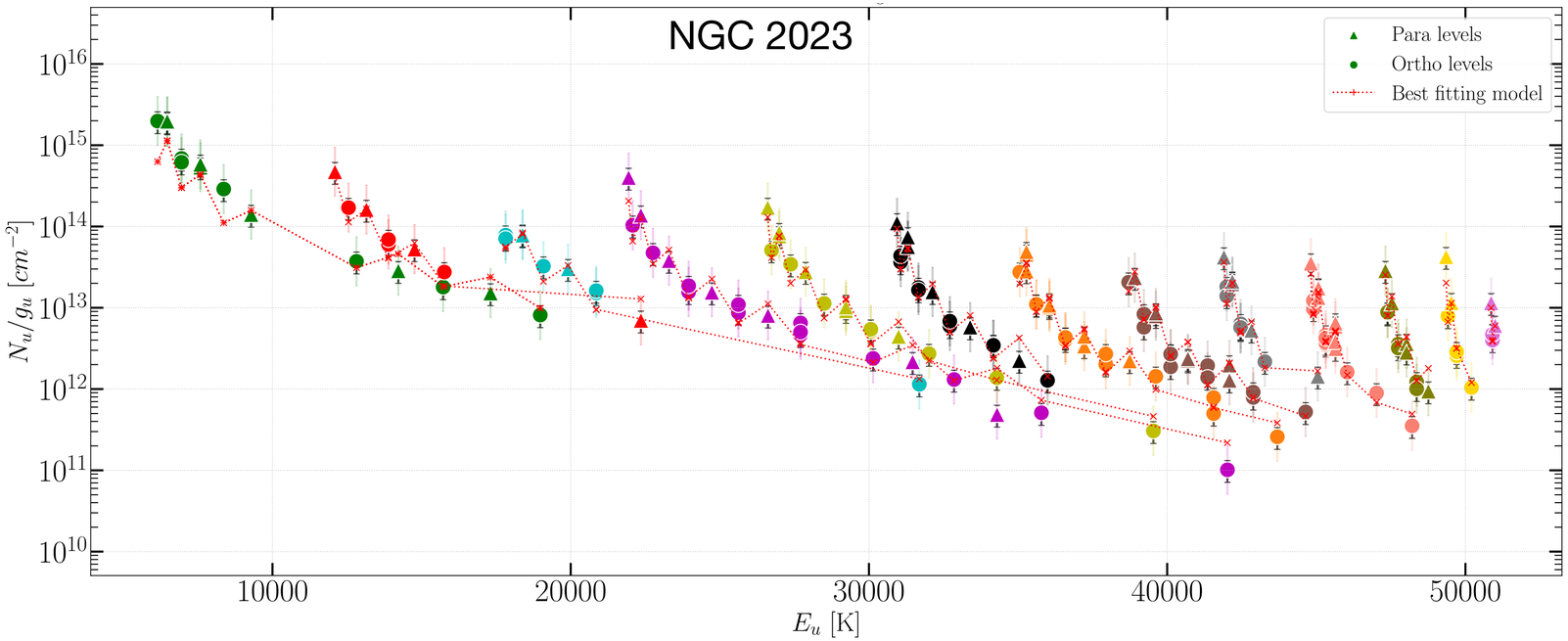

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2. Best Fitting model plot

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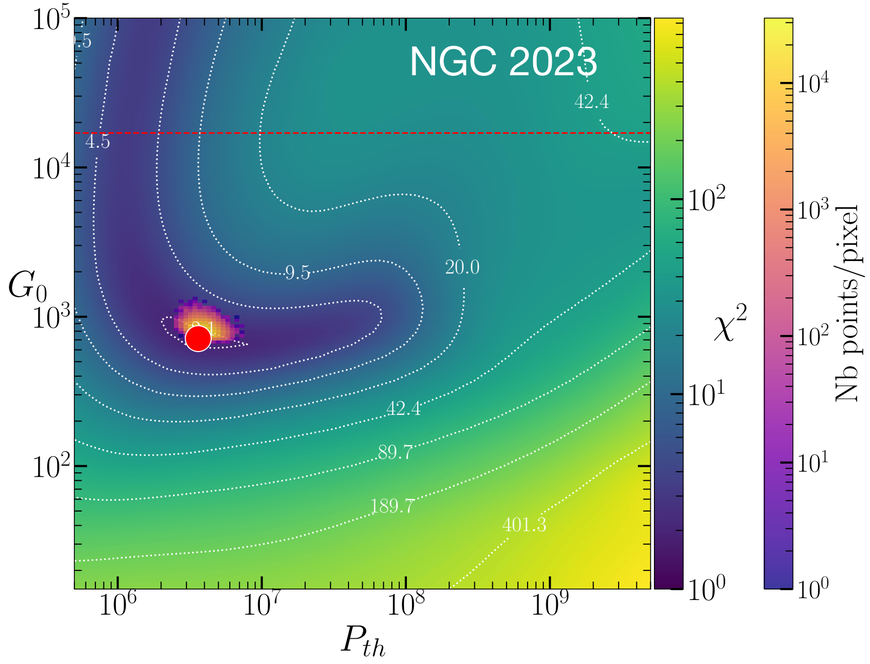

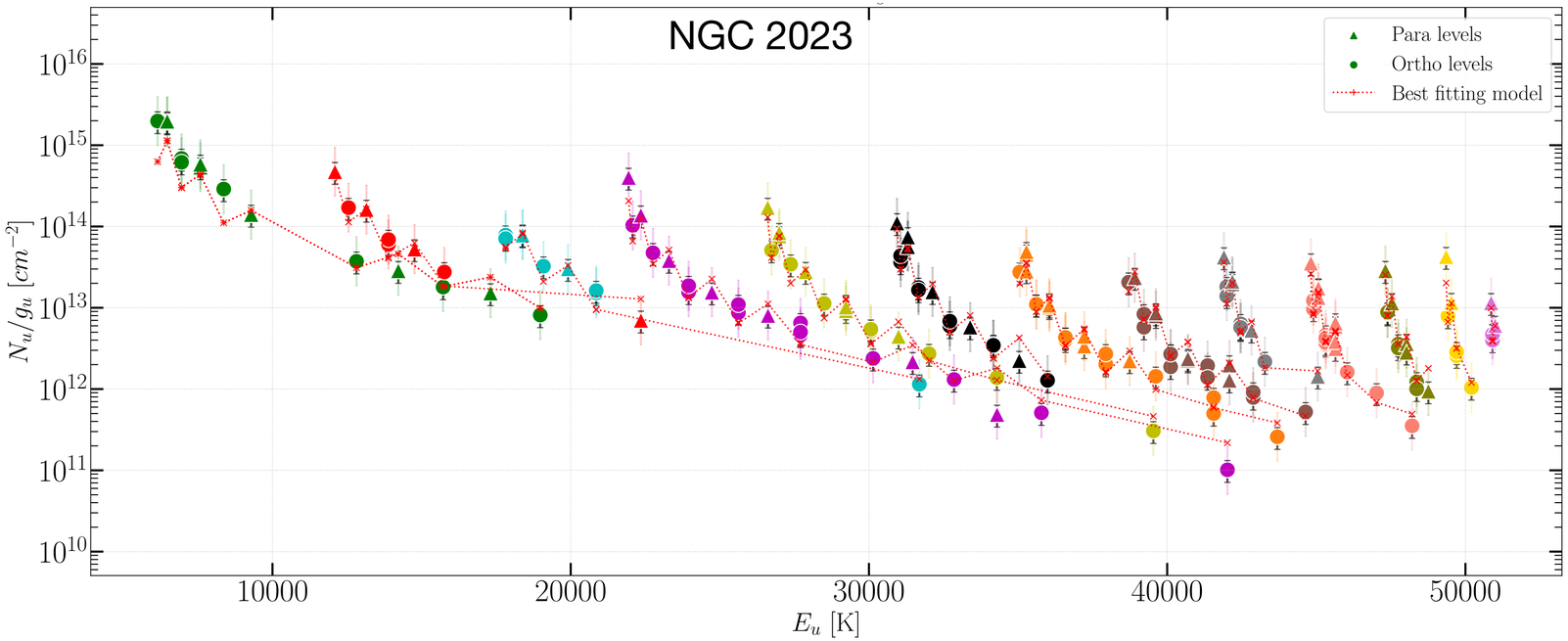

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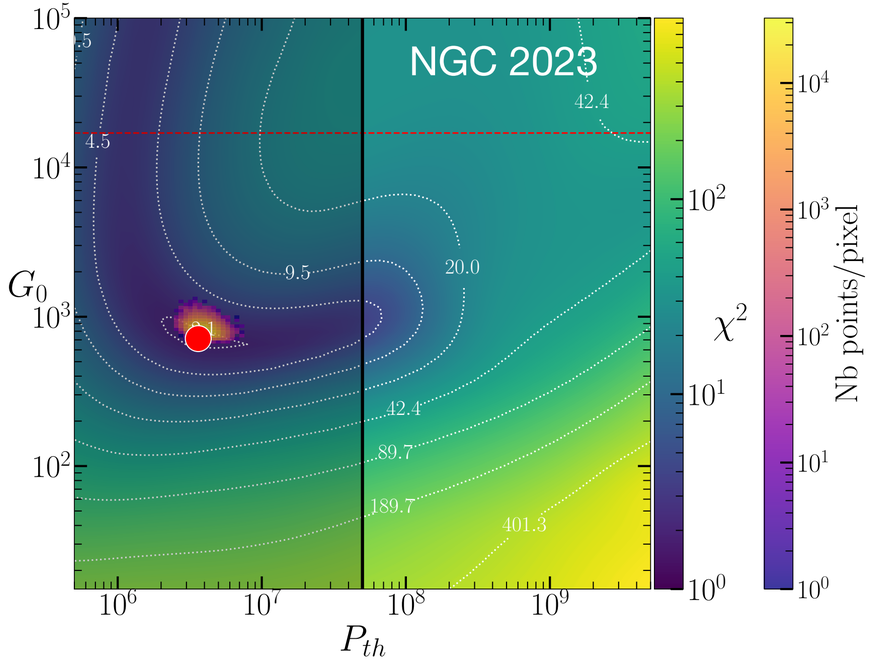

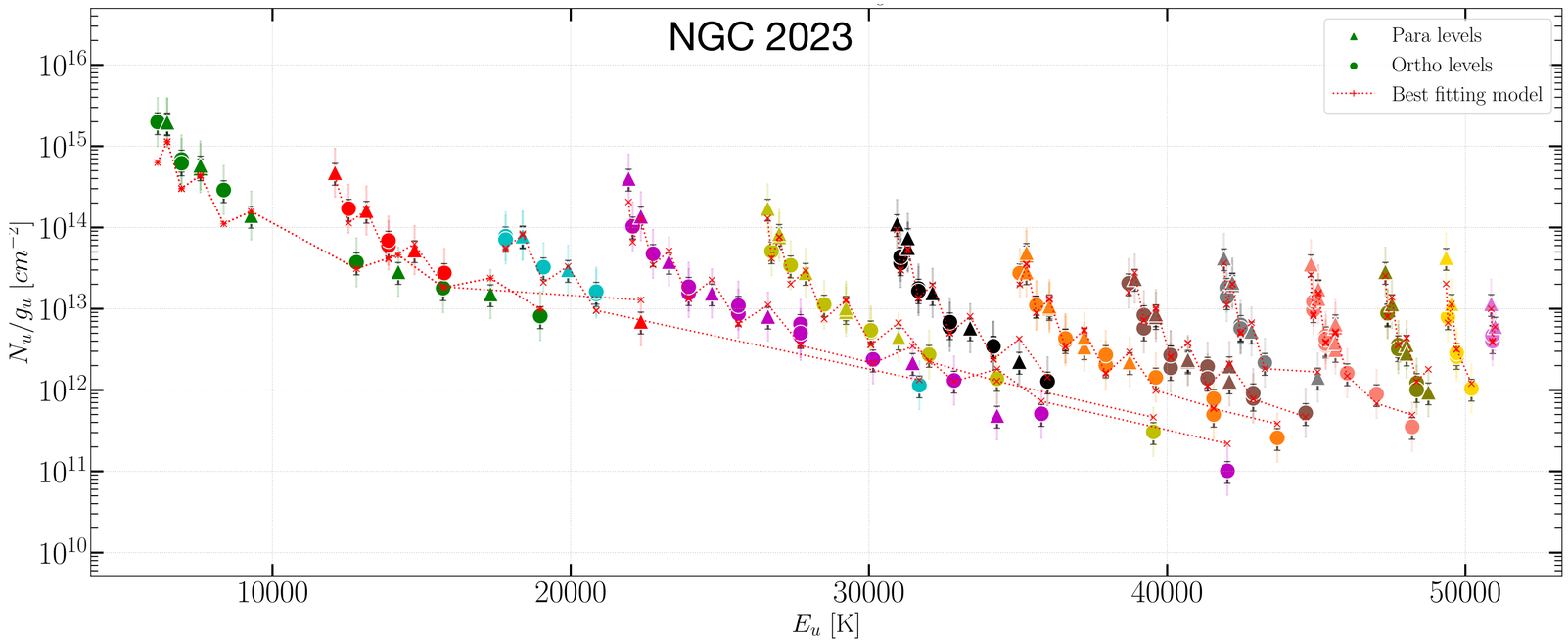

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3. Adding external constraints

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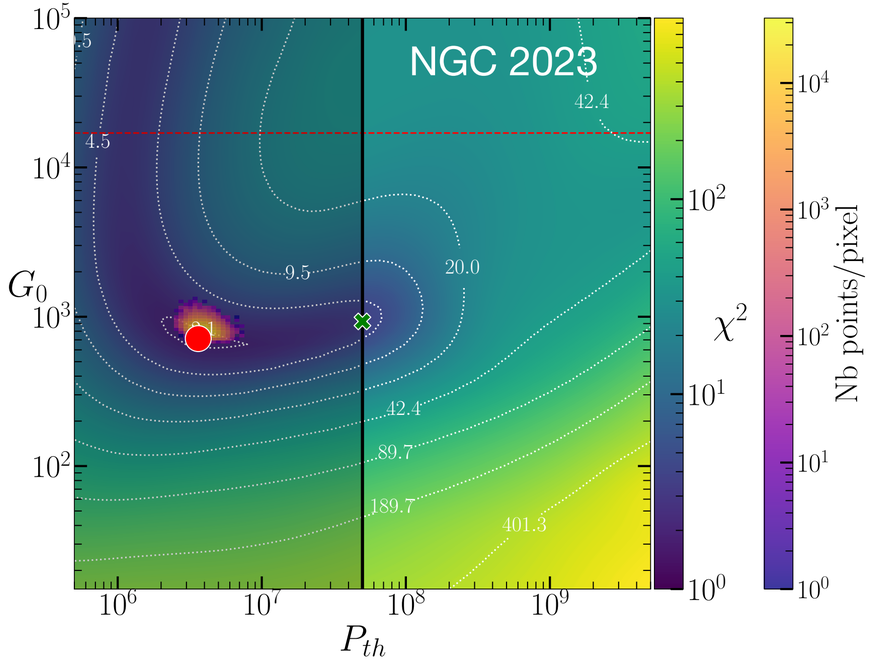

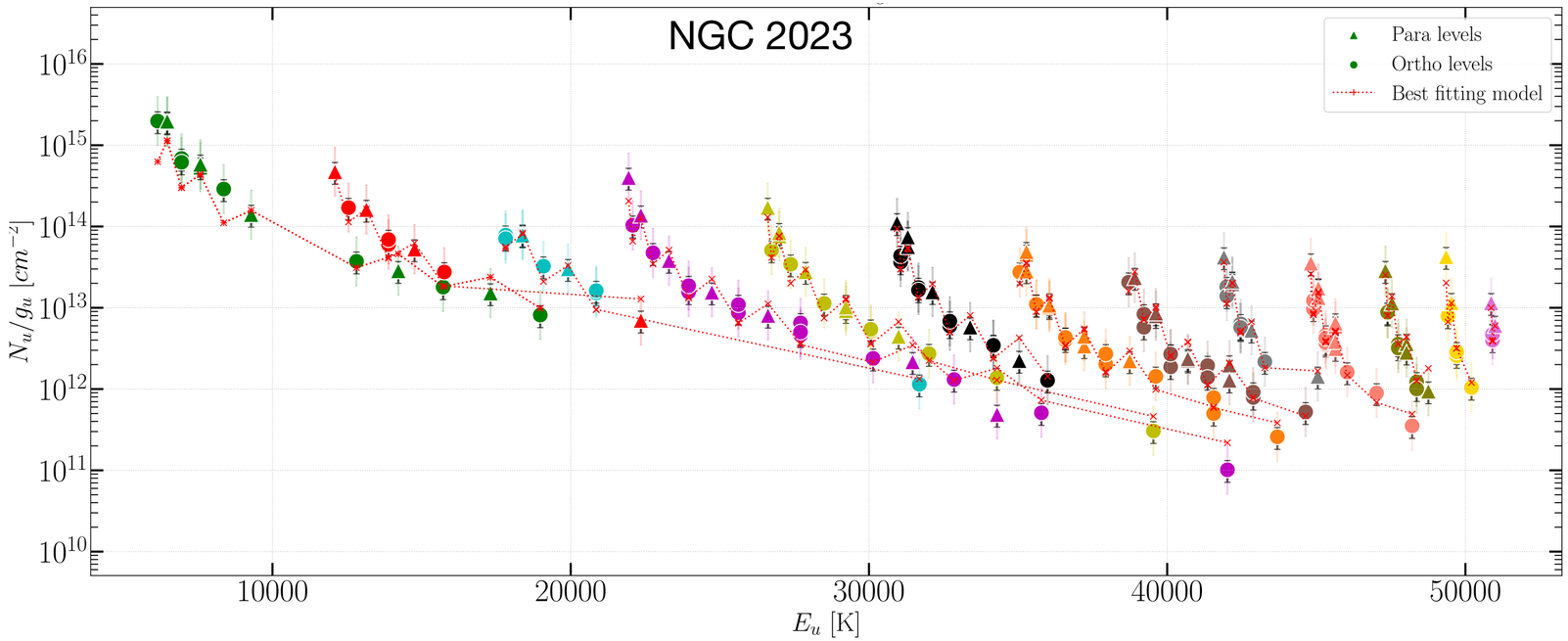

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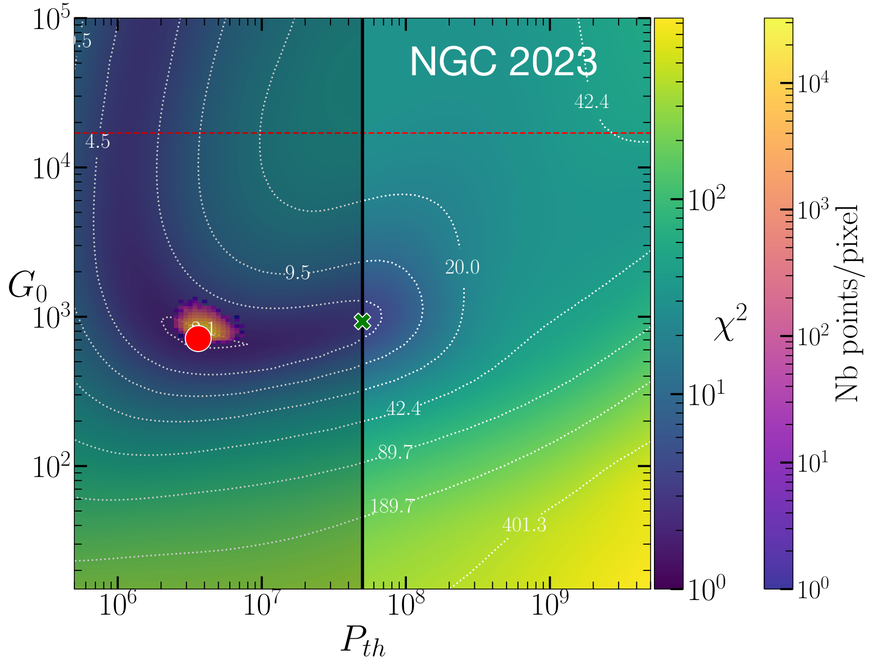

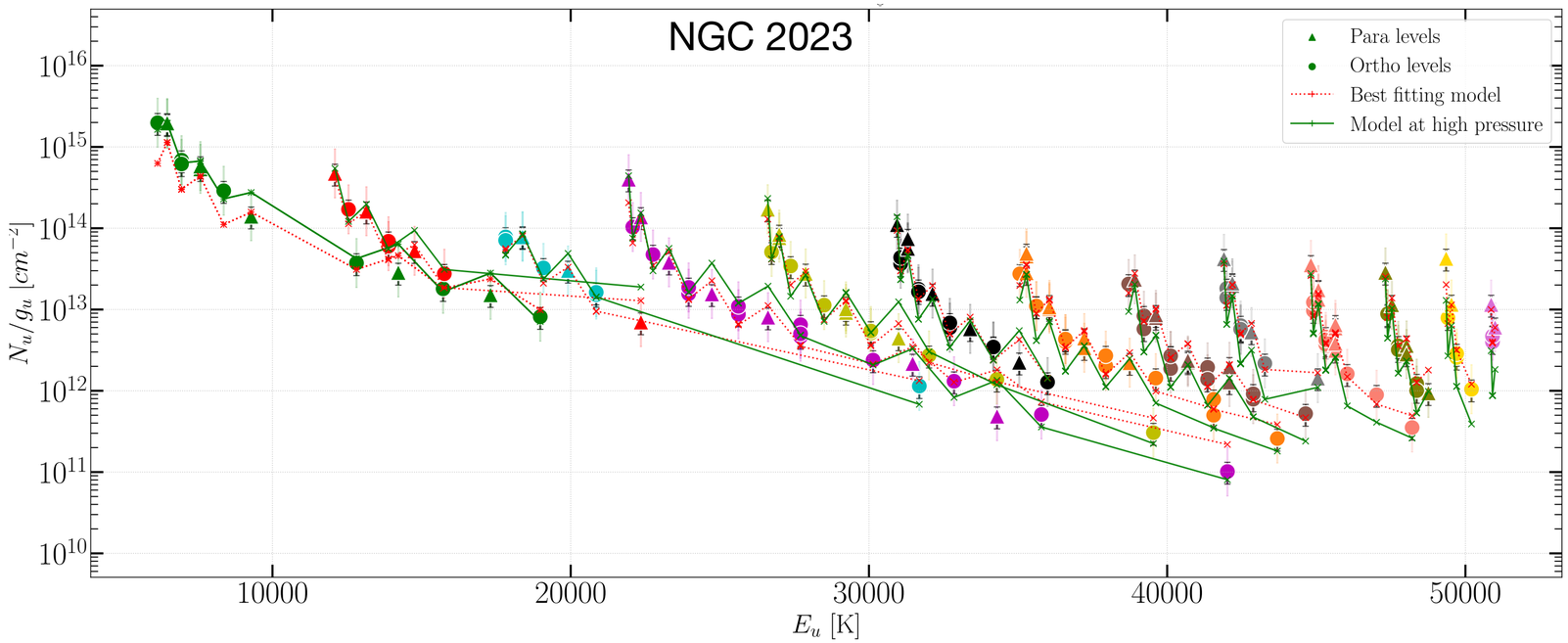

1. Exploration of parameter space
2. Best Fitting model plot
3. Adding external constraints
4. Comparison between most relevant and best fitting model

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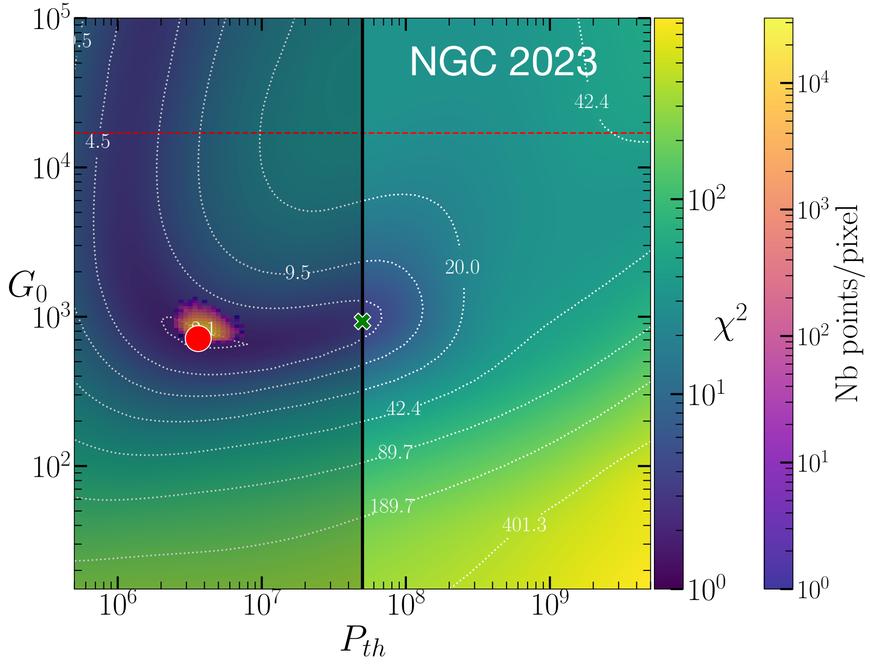
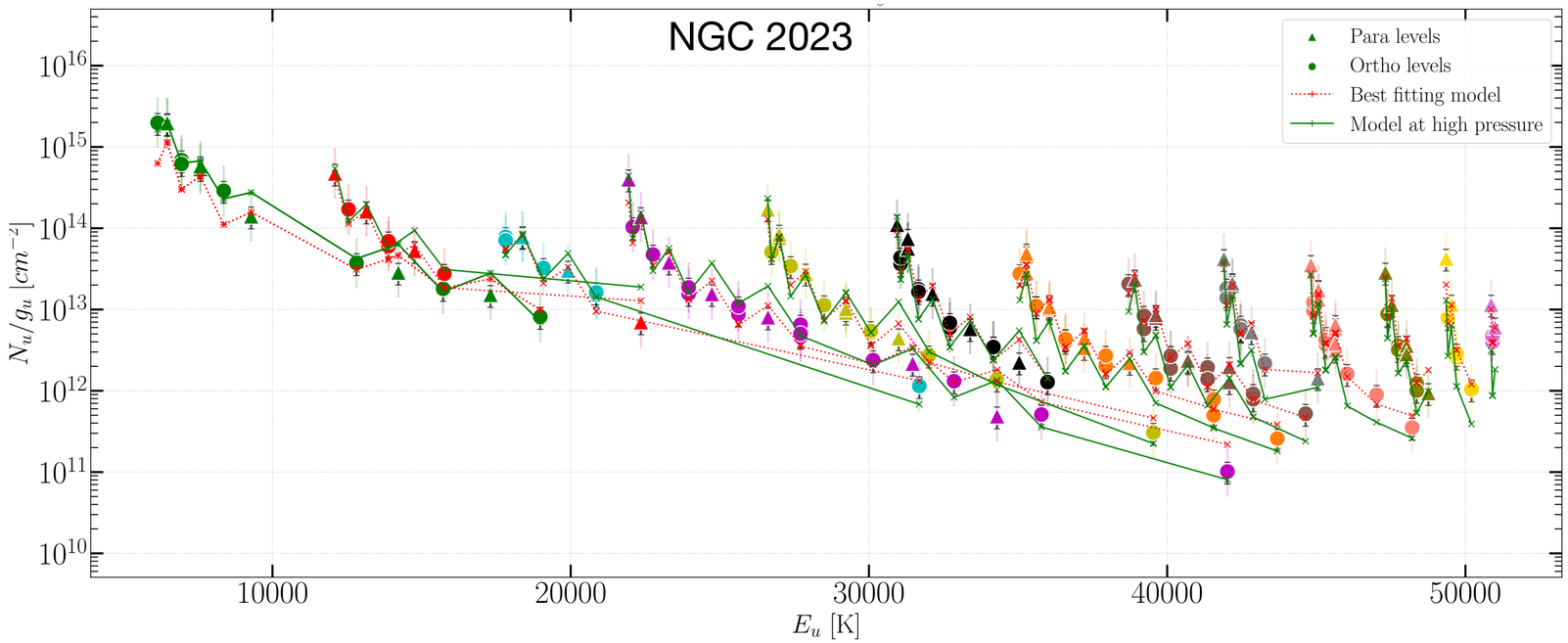
Moderate PDRs : NGC 2023 Case

Similar results for Horsehead Nebula, S140, IC63





1. Exploration of parameter space
2. Best Fitting model plot
3. Adding external constraints
4. Comparison between most relevant and best fitting model

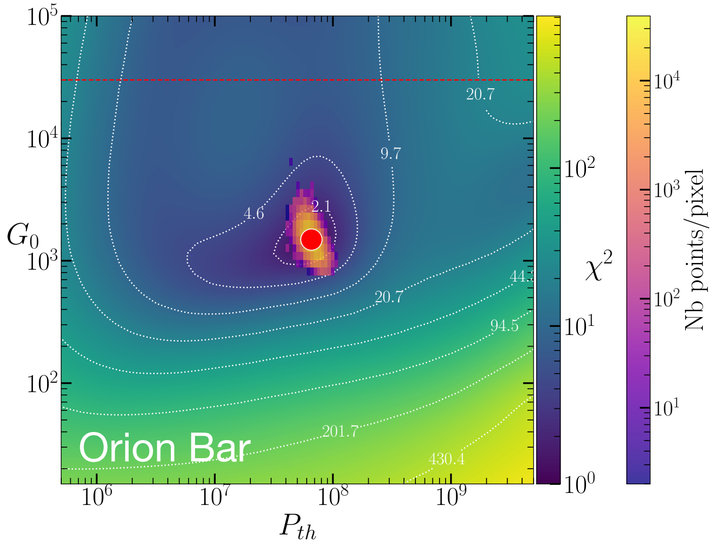
✓ Sensibility of H_2 lines to physical parameters -> **Great constraint on physical parameters**

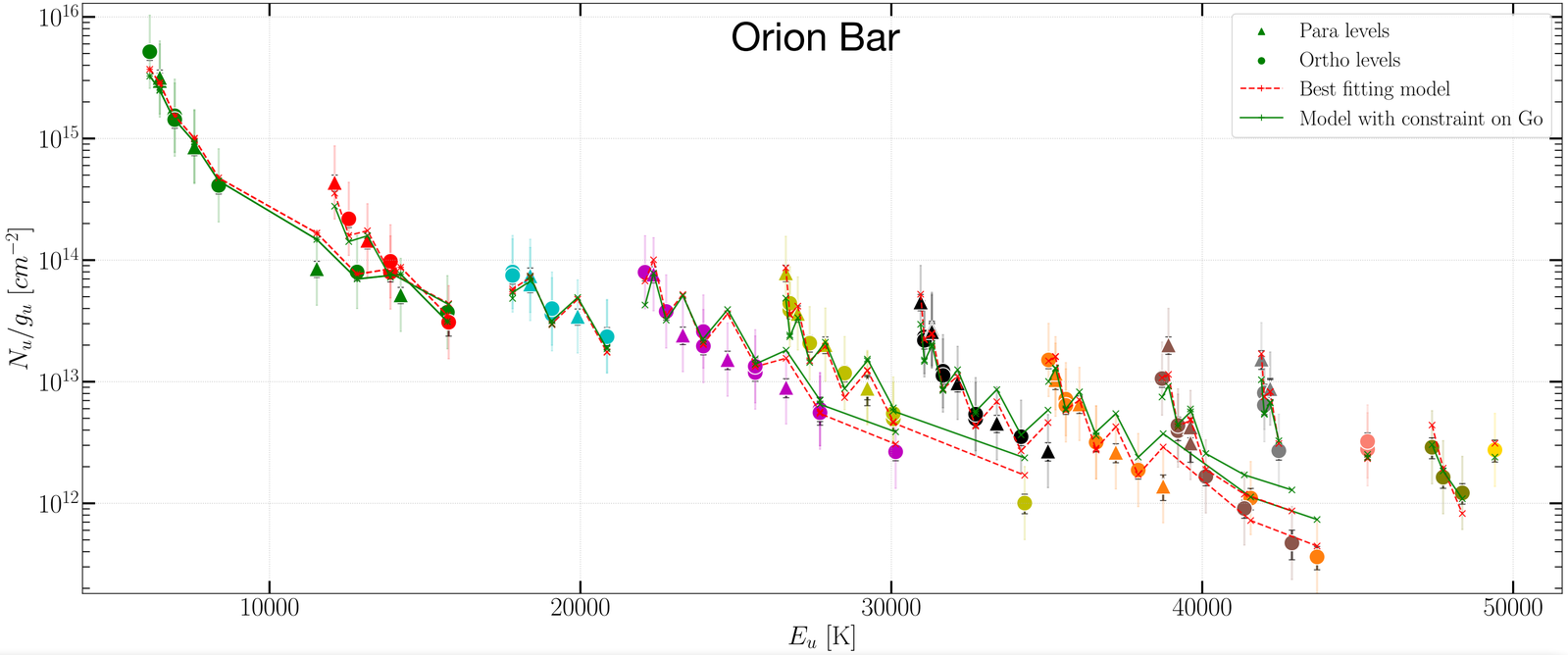
✓ Best model reproduces 90% of the observed lines -> **Accurate physics of PDR modeled**

✓ Parameter space exploration -> **Estimation of uncertainties**

4. Results

Intense PDR : Orion Bar





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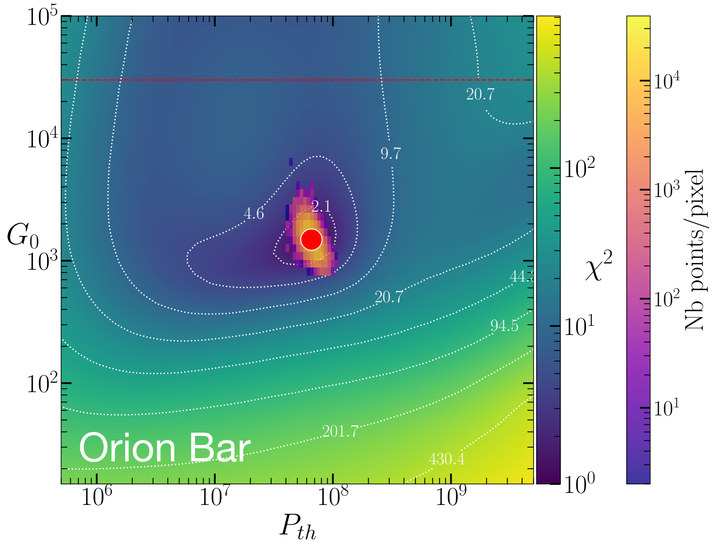

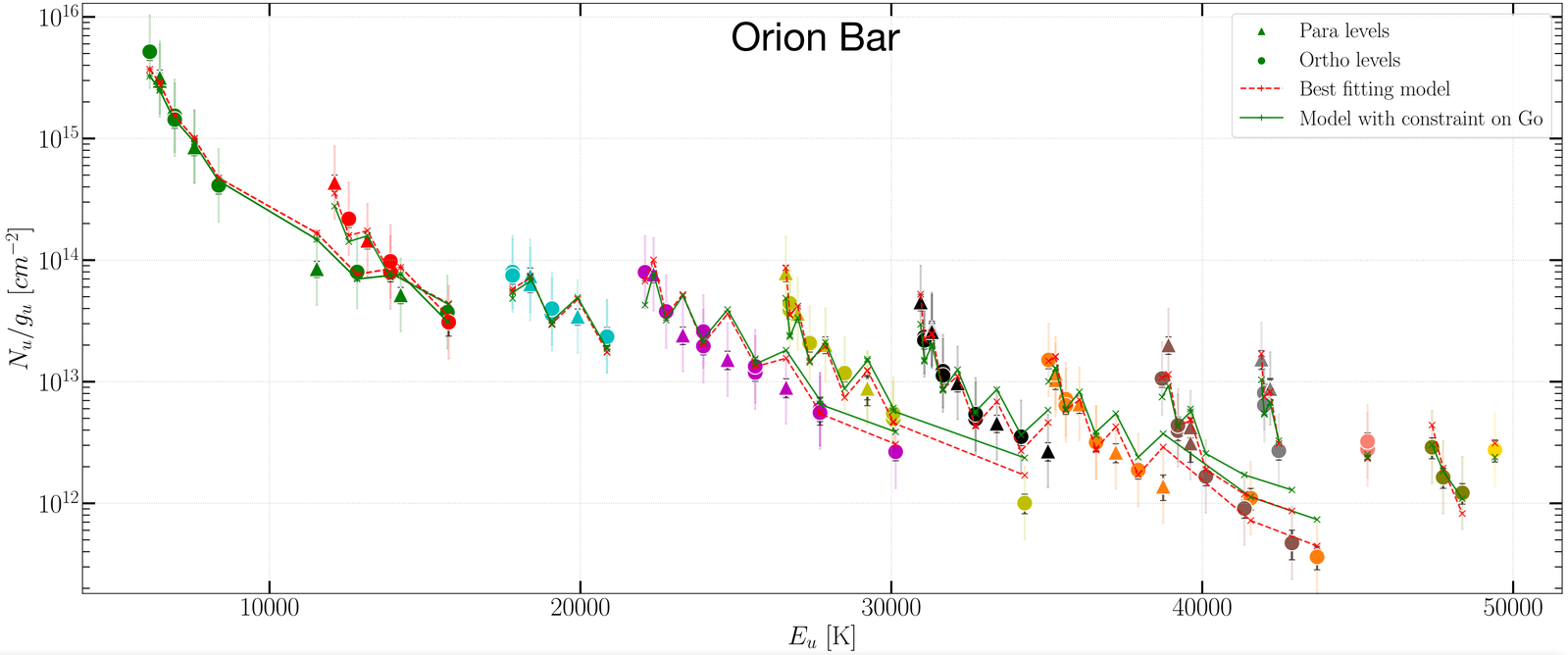

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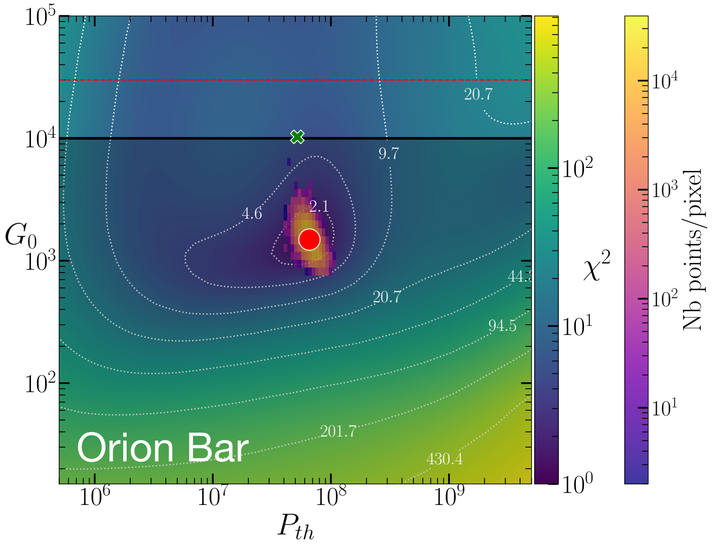
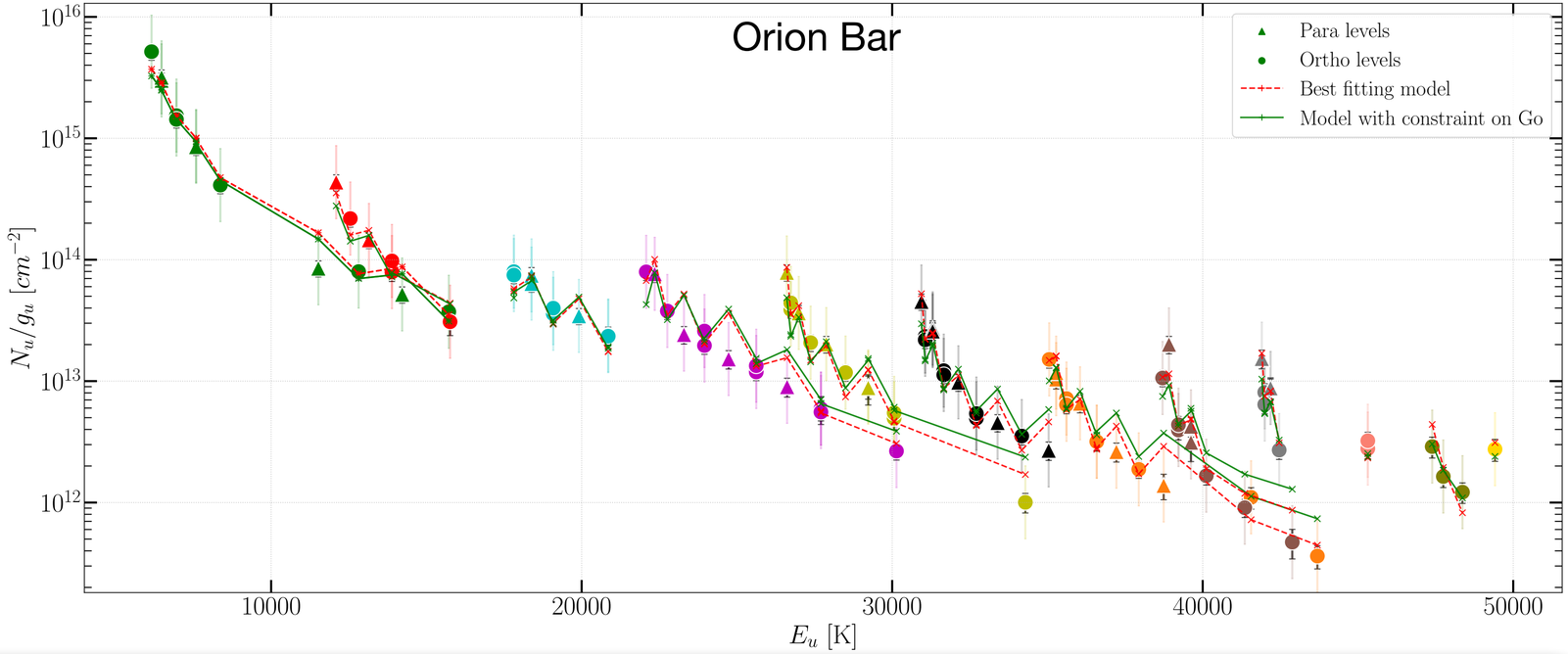
  - Best region needs $G_0 = 10^3$ but we know that the Orion Bar is illuminated at least by $G_0 > 10^4$

➡Addition of prior at high UV intensity

  - Minor changes thanks to the flat region in parameter space





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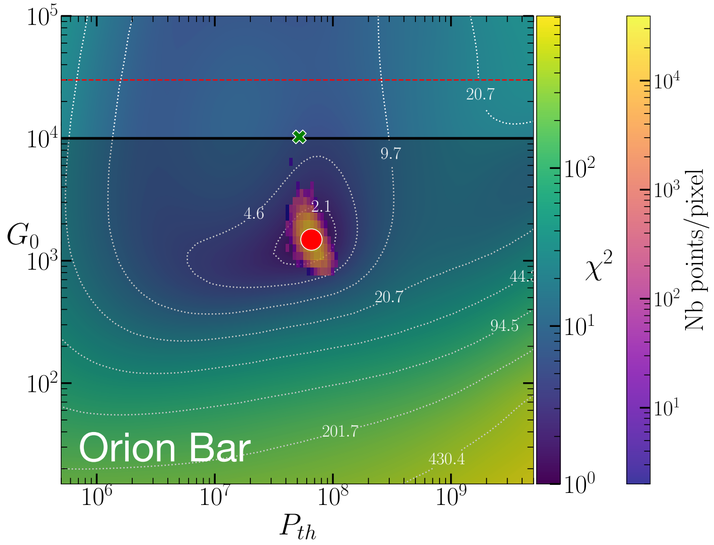
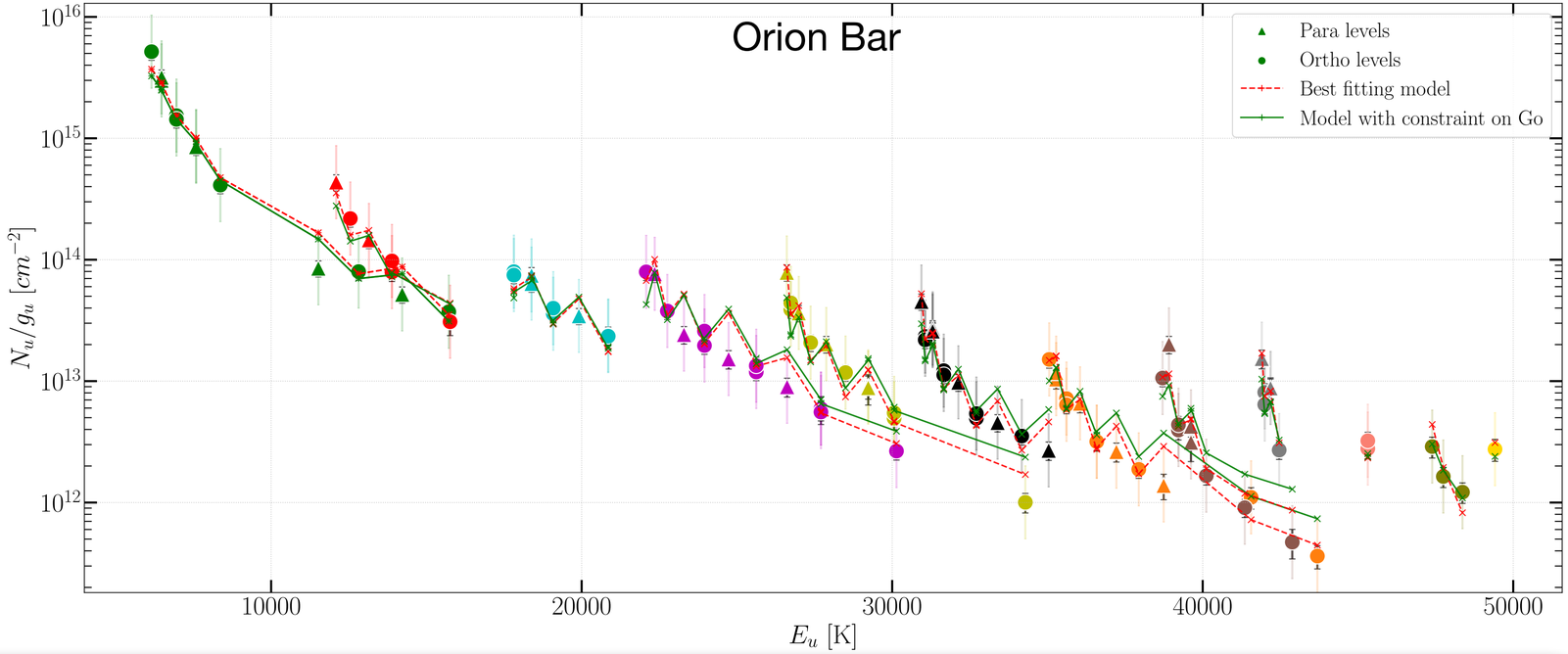


Discussion :

- Overestimation of para levels (*for all v*) linked to a ”zigzag” pattern in models when the observations are linear
  -> Ortho/Para Ratio not well modeled ?



4. Results : most relevant models

Most relevant models according to H_2 rovibrational IGRINS observations (with additional constraints)

PDR	S140	IC63	Horsehead Nebula	NGC 2023	Orion Bar
UV intensity (G_0)	430-580	470-620	220-290	990-1050	10 000- 10 500
Thermal Pressure [K cm-3]	$8*10^5$ - $1*10^6$	2-3 * 10^6	5-7 * 10^6	4.5-5 * 10^7	4.5-5.5 * 10^7
Reduced Chi²	1.7	1.7	3.8	4.4	5
% lines within a factor of 2	95 %	95 %	92 %	85 %	86 %

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Type	H II region edge	Reflection nebula	Dark nebula edge	Reflection Nebula	H II region edge
G_0	4×10^{2ab}	$58^f - 150^g$	$10^{2k\,l}$	$1.7{\times}10^{4o}$	3.1×10^{4s}
$P_{\rm th}(Kcm^{-3})$	$(2 \times 10^6 - 3.2 \times 10^7)^c$	$(8 \times 10^5 - 1.2 \times 10^6)^c$	4×10^{6k}	5×10^{7o}	3×10^{8k}

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4. Results : Pth-Go relation

$P_{th} - G_0$ relationship

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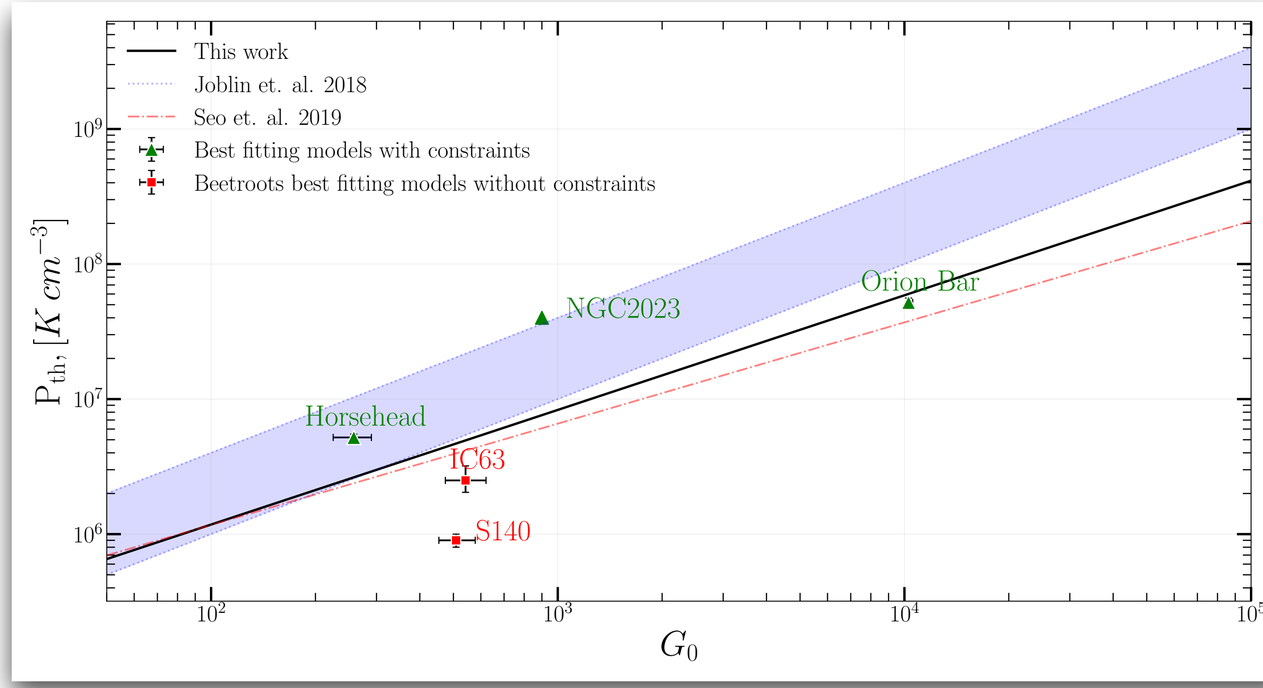
Photoevaporation : PDR compression due to intense FUV illumination making escaping high T gas at same density : correlation between P_{th} and Go



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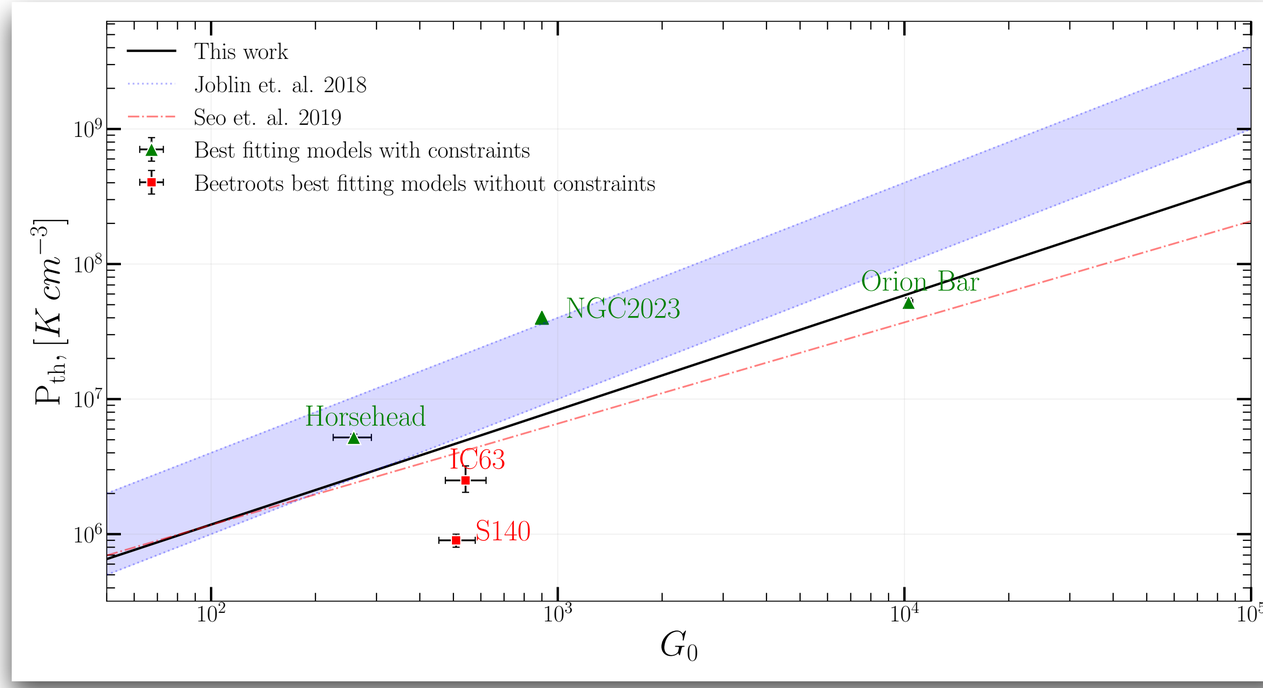

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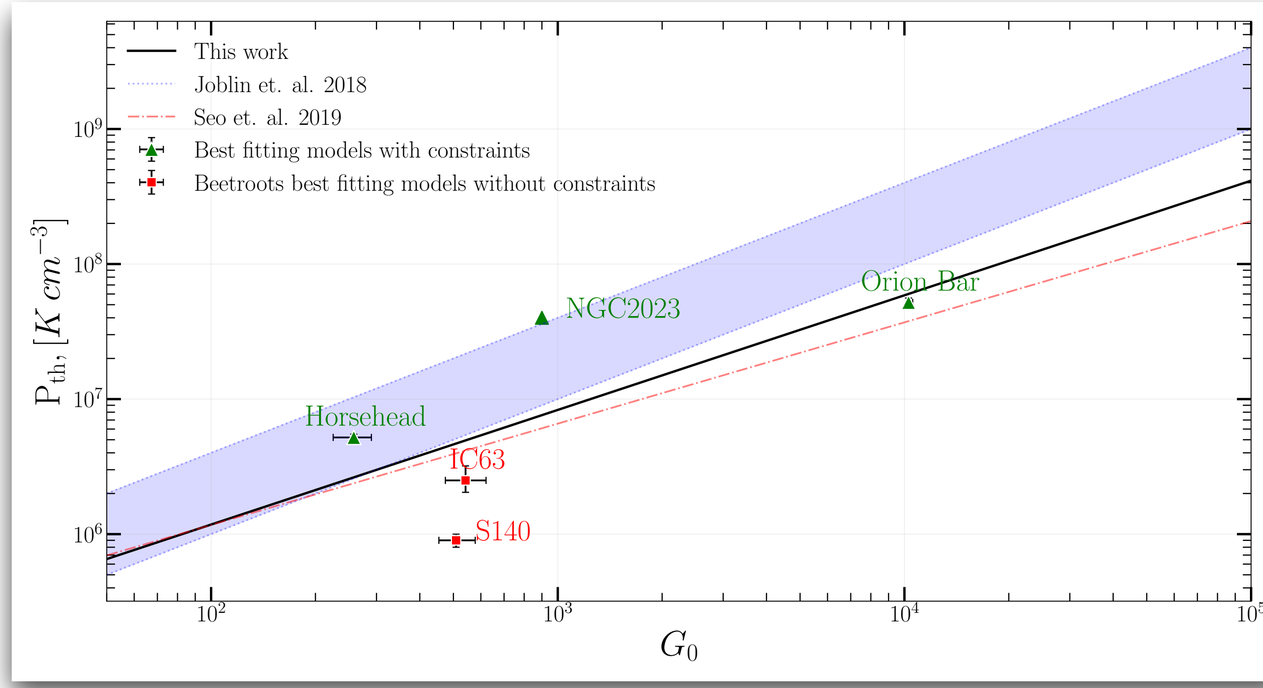

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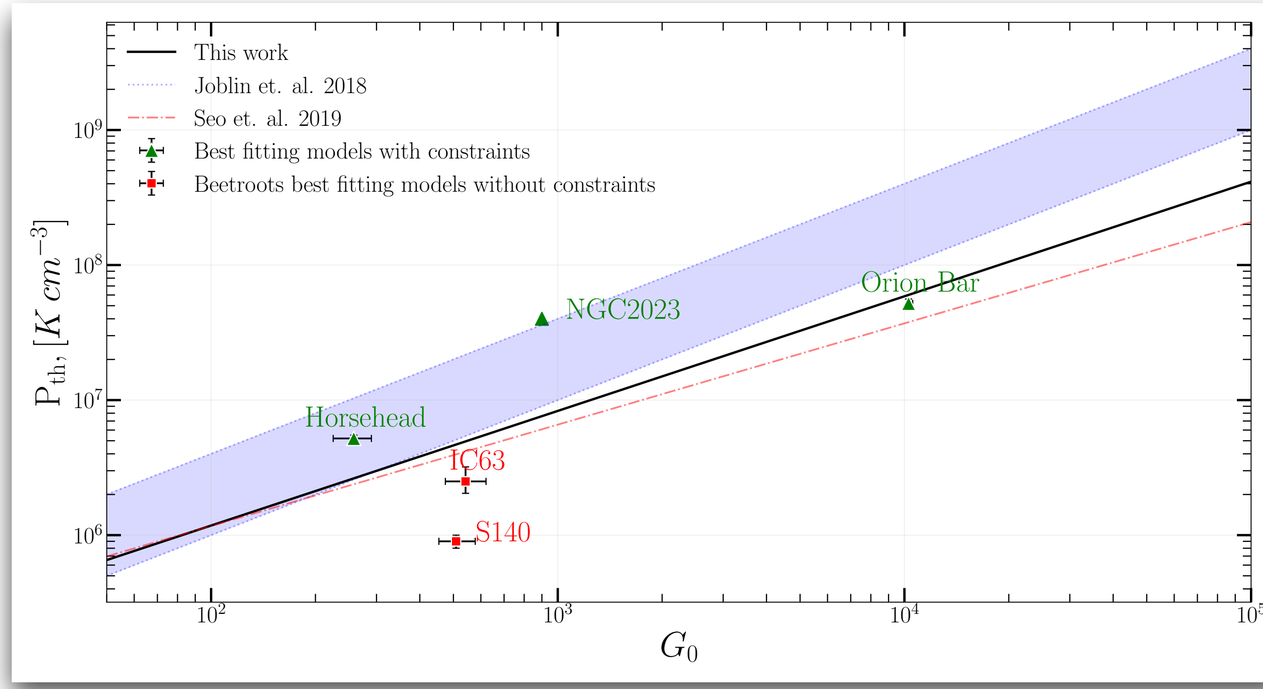

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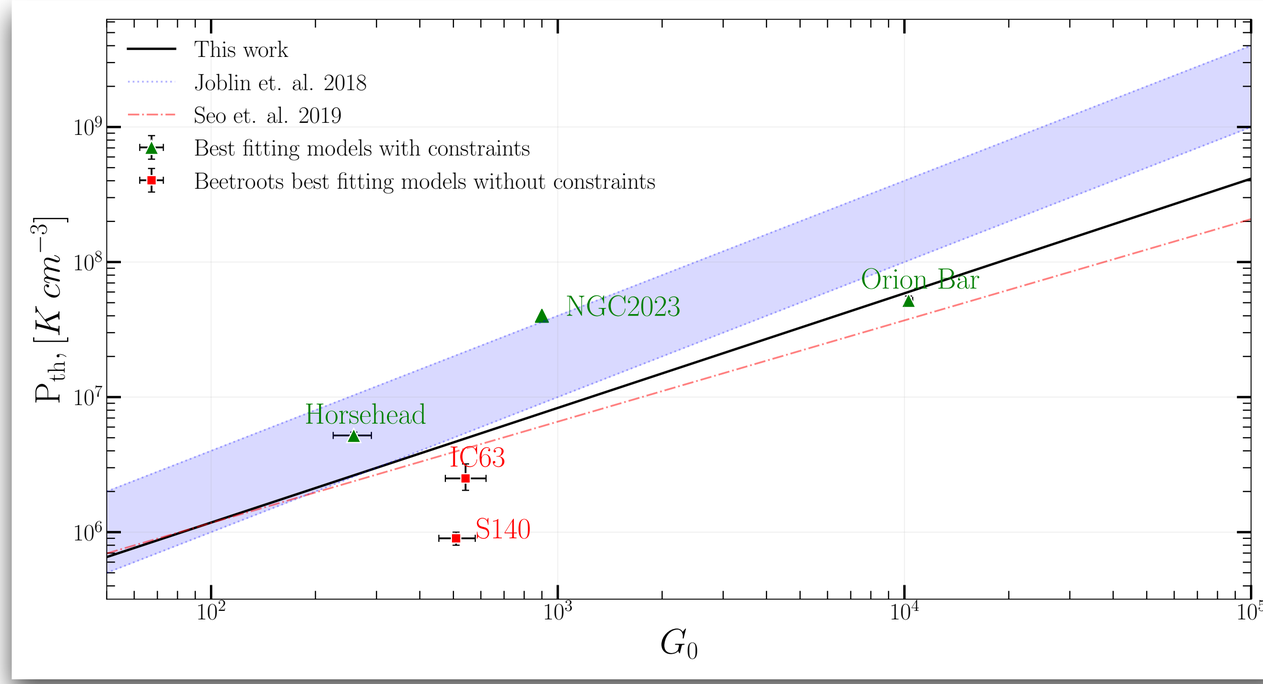


Remark :

- H_2 only pushes toward low pressure
- Adding constraints raises the estimated pressure -> **Flattening of the slope**

4. Results : Microphysical processes

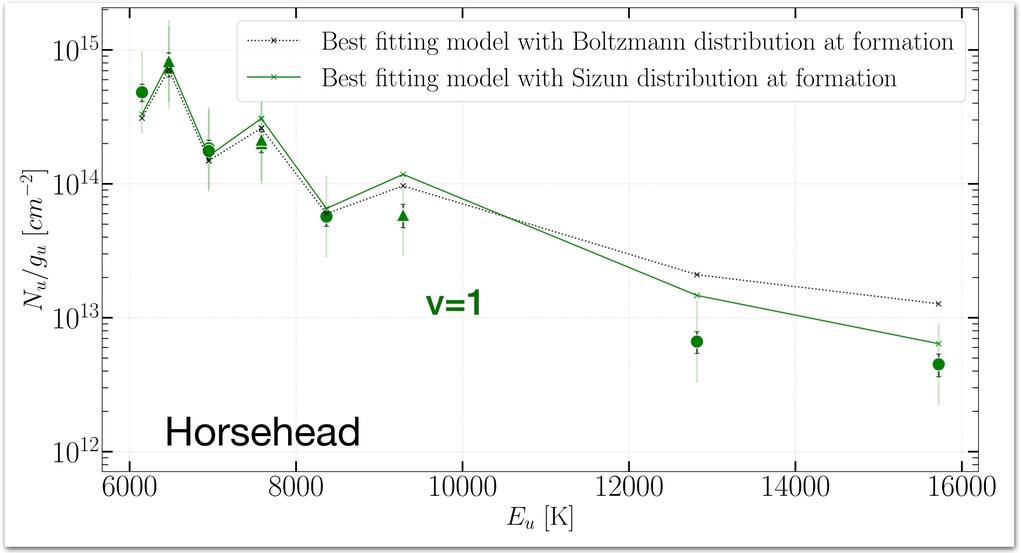
Microphysical process : Distribution at formation for Intermediate PDRs

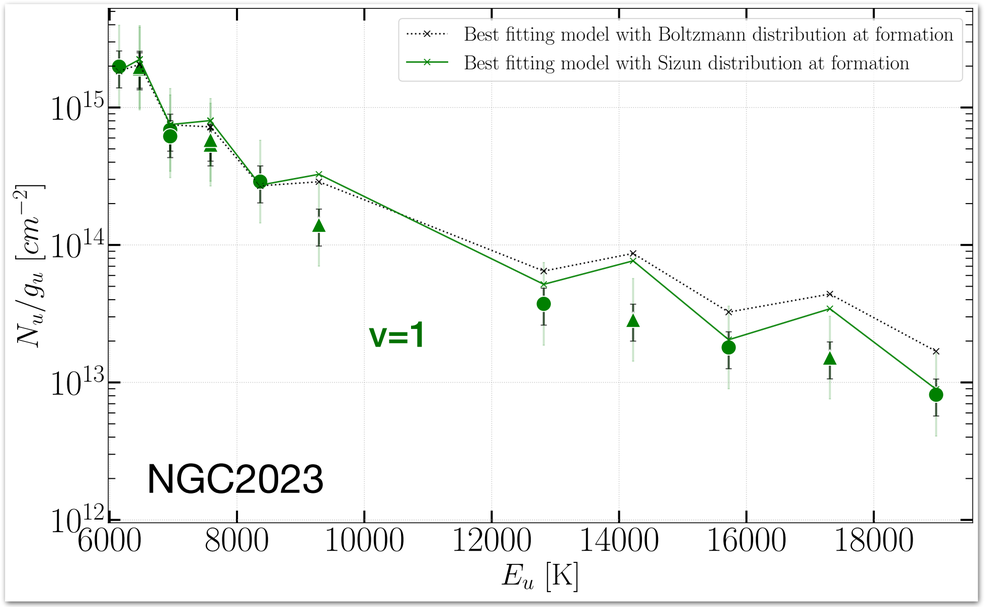
Until now, the observations could not allow to constrain distribution at formation

Comparison between :

A. Boltzmann Distribution

B. Sizun Distribution *(distribution around v=6 and spread in J)*





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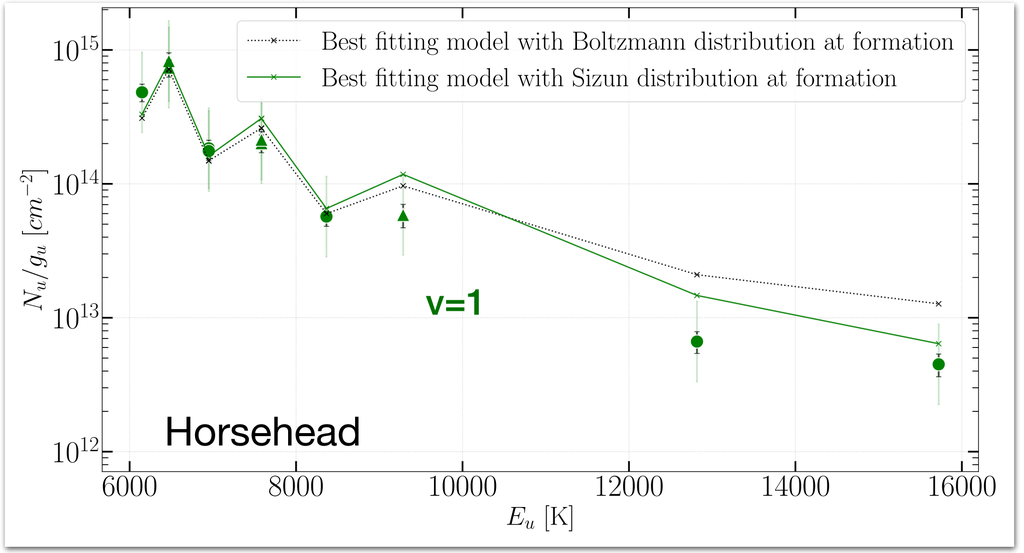

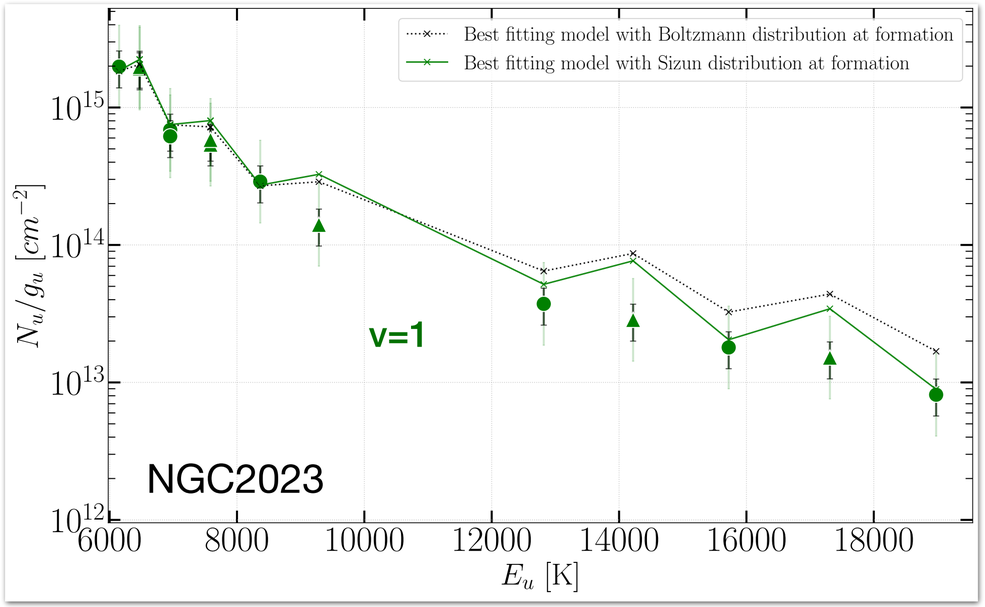

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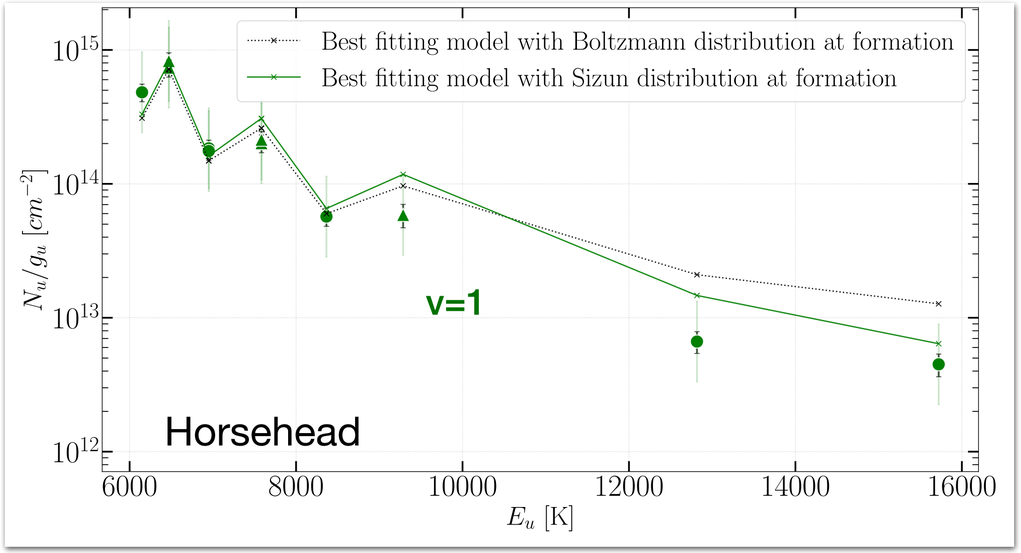

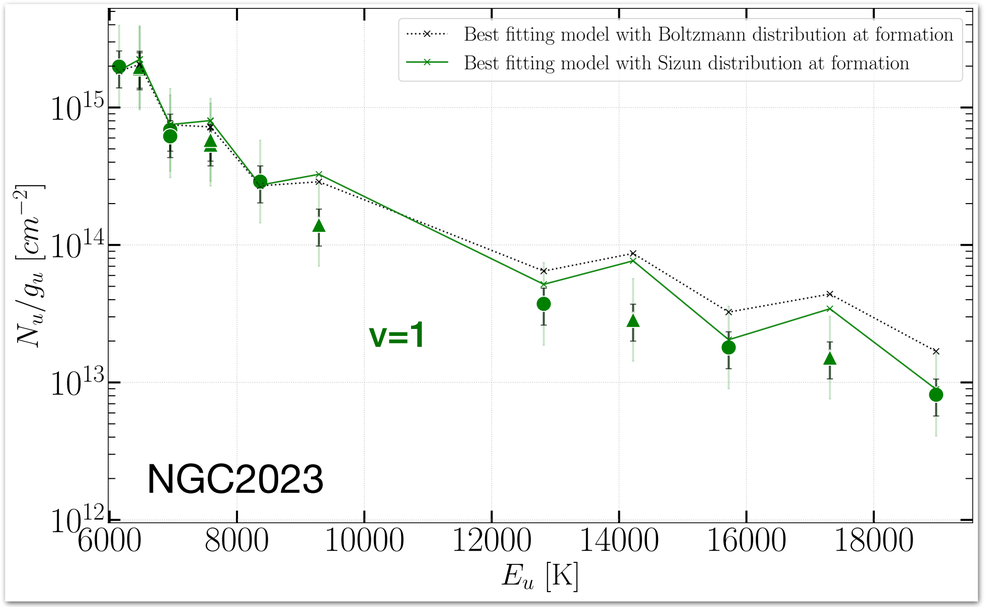

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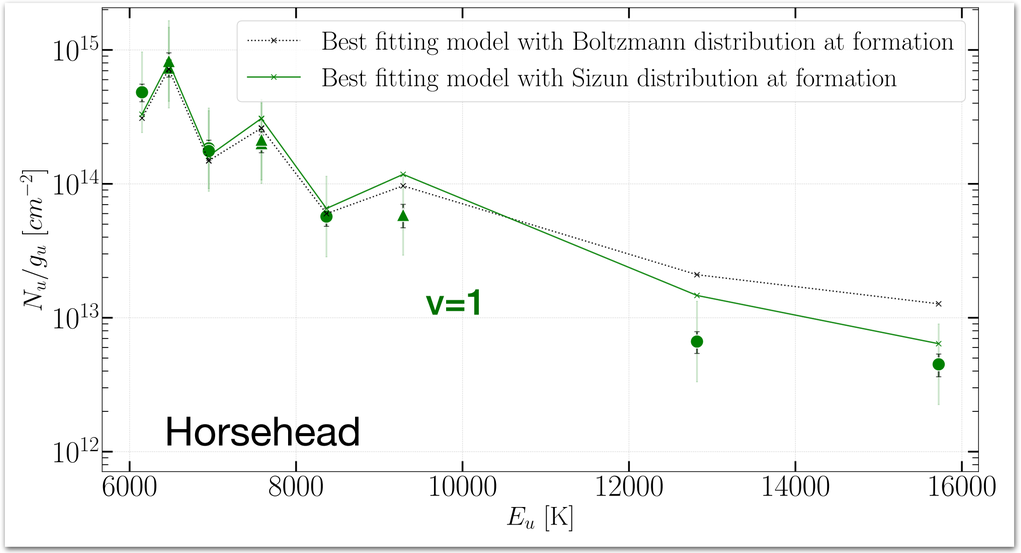
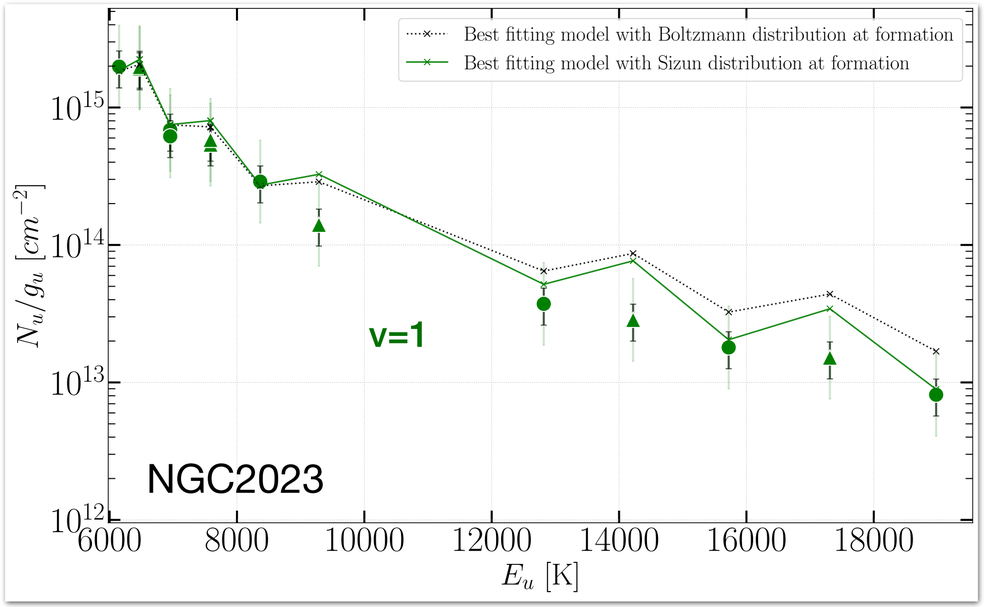
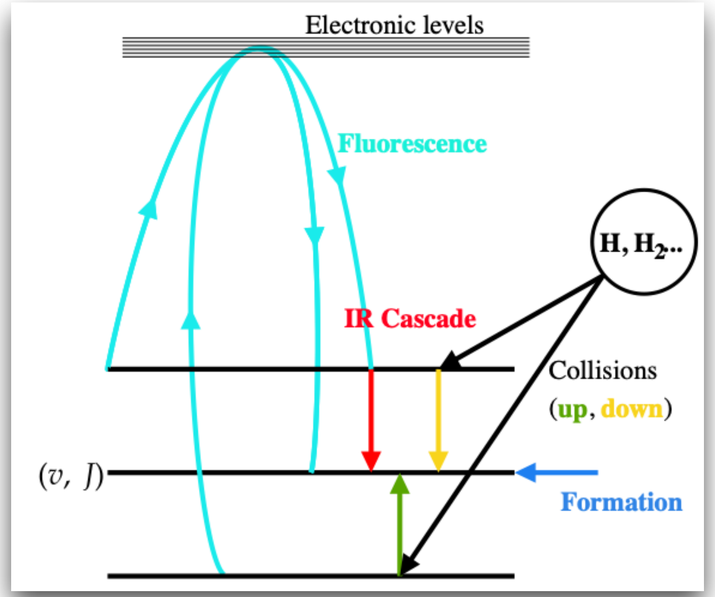
➡ **H_2 forms preferably vibrating than rotating**

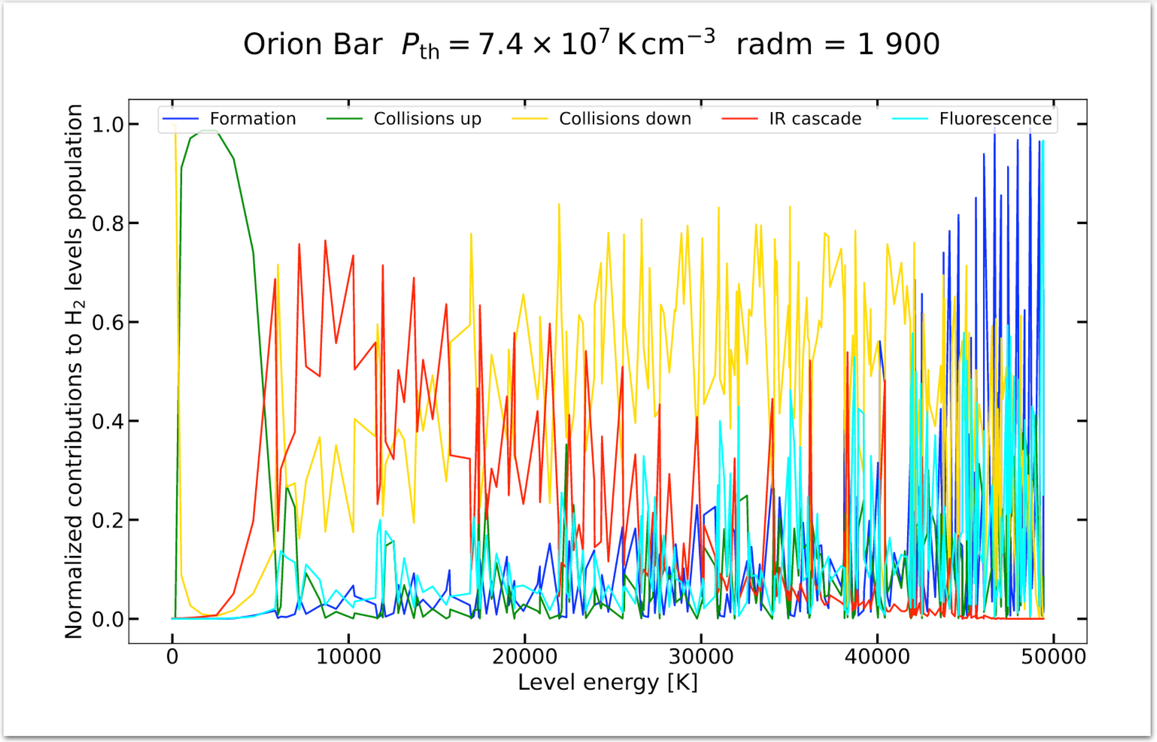




4. Improvement H_2 excitation processes

Microphysical process : Collisional rates for high energy levels





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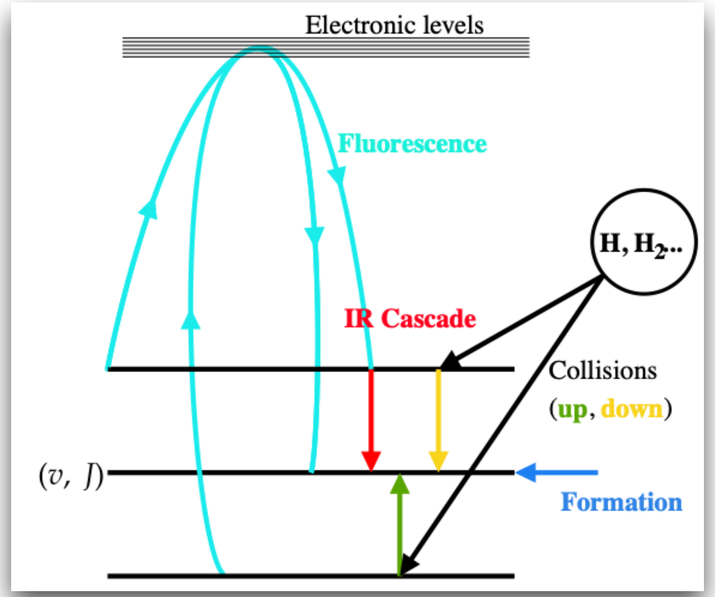

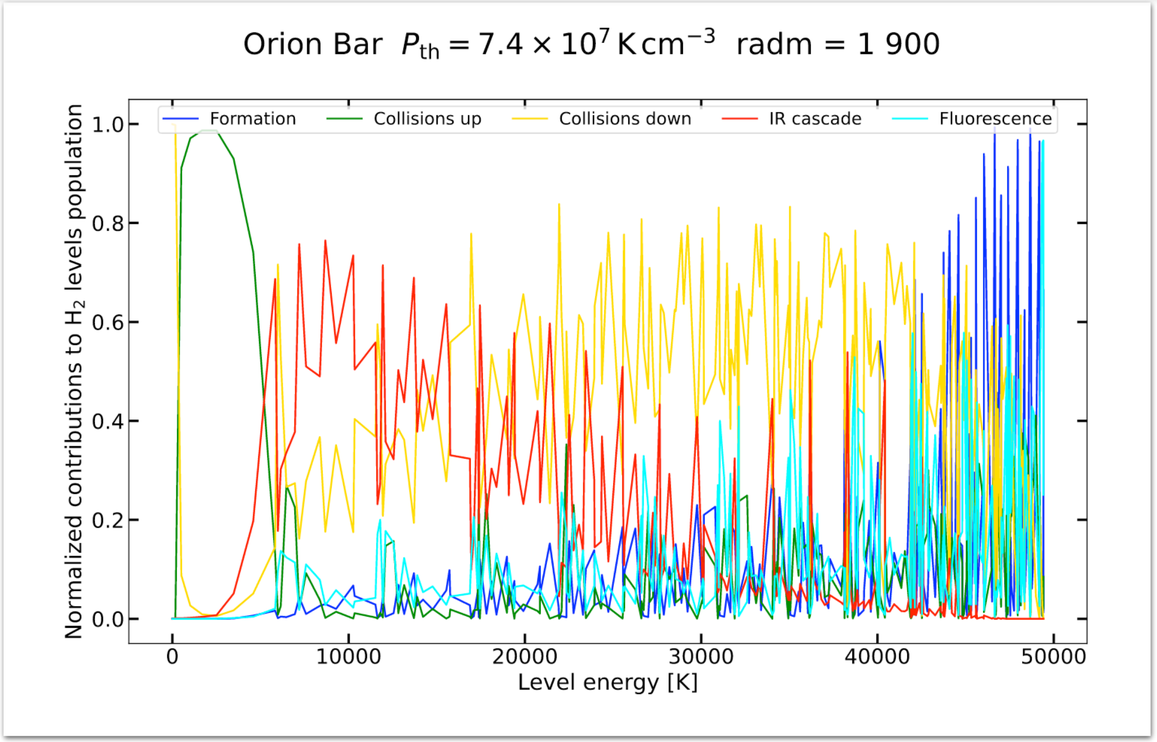

Population repartition of H_2 in its rovibrational levels :

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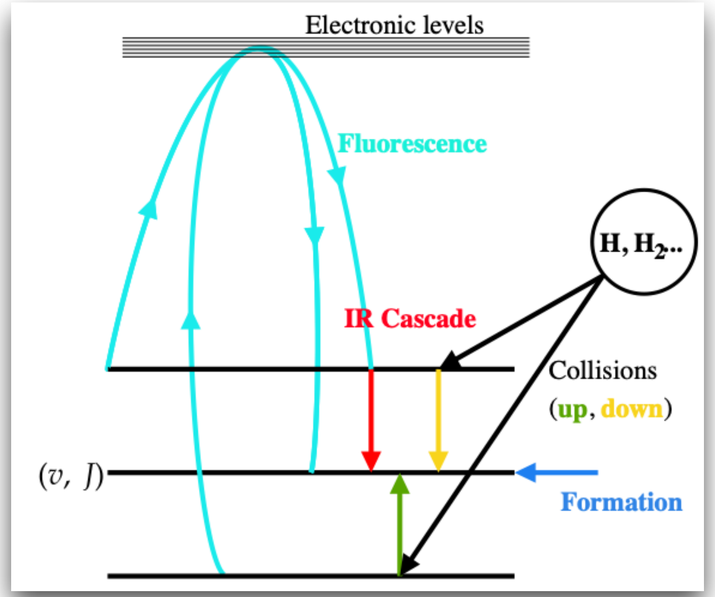

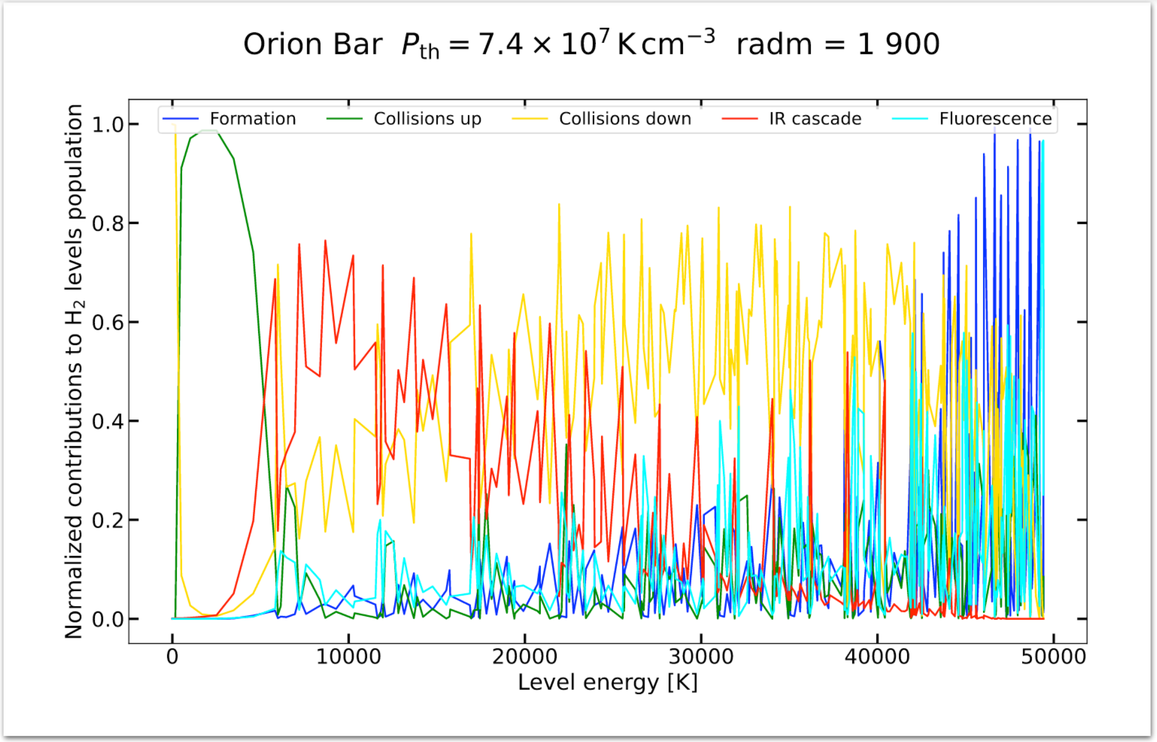

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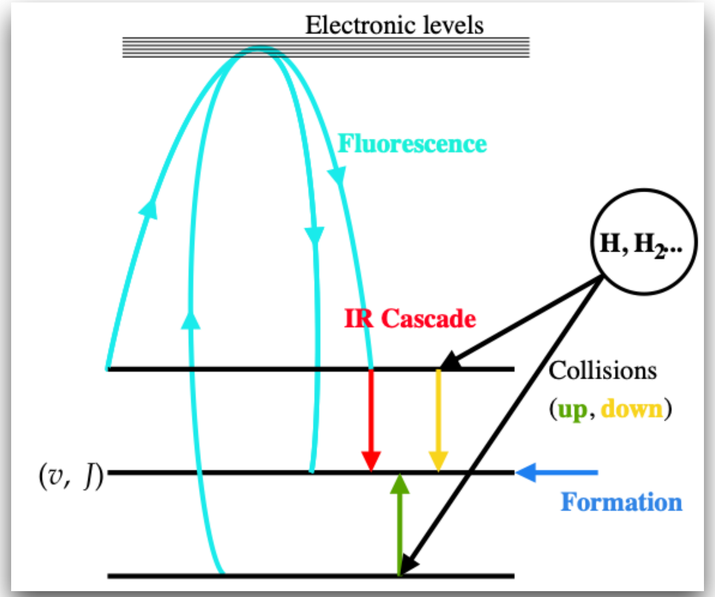

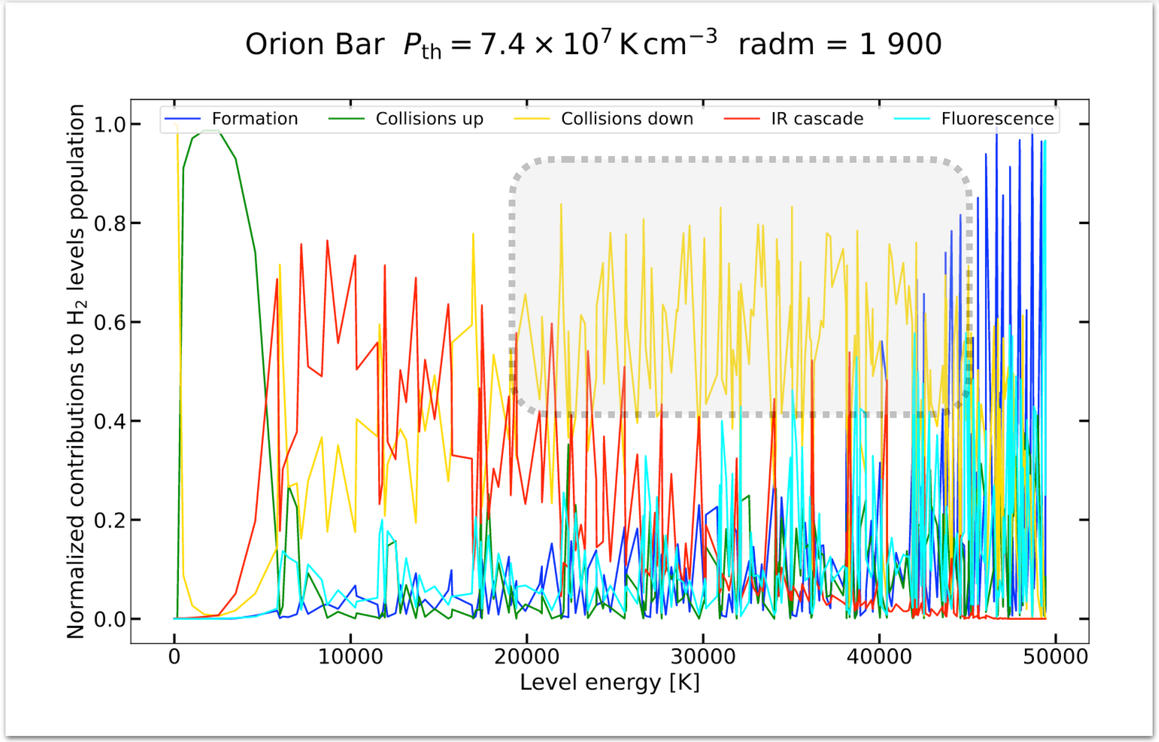

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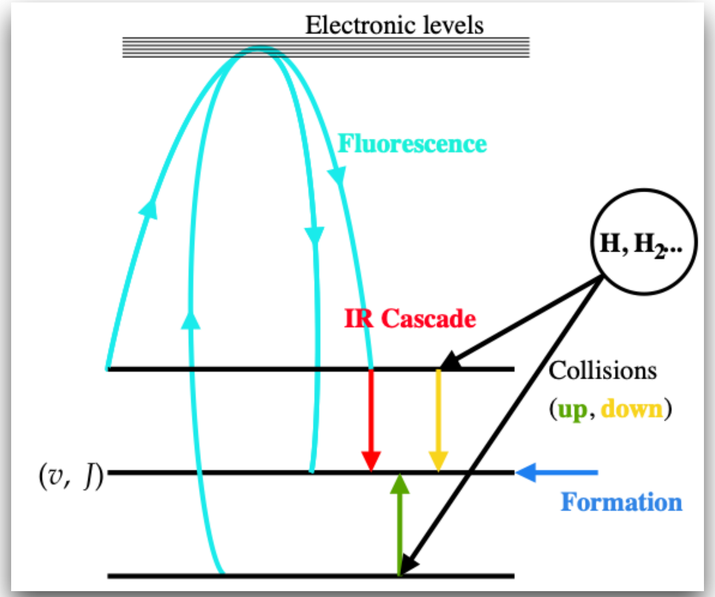

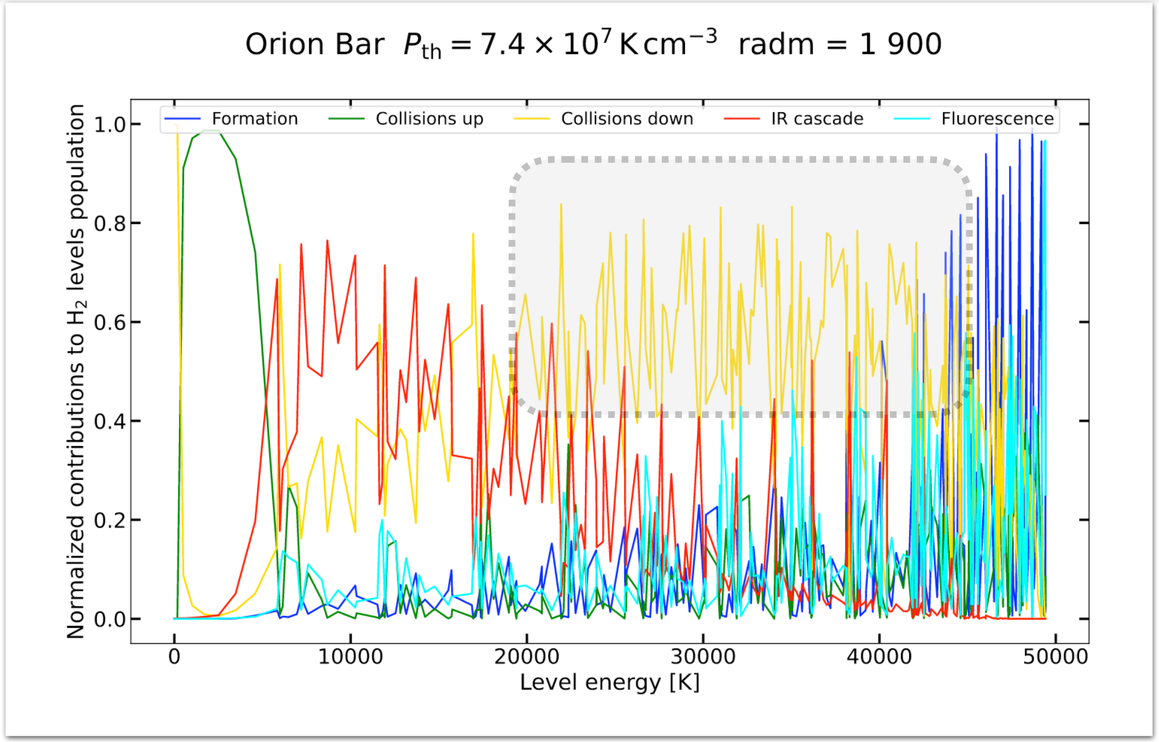

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➡ **Need of consideration of collision rate at high energy levels to accurately model PDRs (intense)**

Maillard PhD 2023

Conclusion

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