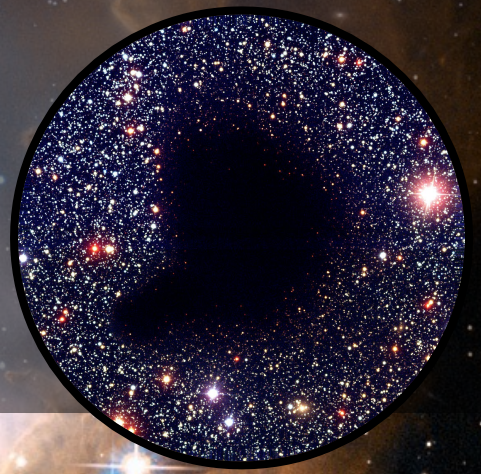
# Cold clouds as Cosmic-Ray Detectors


## Shmuel Bialy

*CTC Postdoctoral Prize Fellow*
*University of Maryland*

*Soon… Technion, Israel*


Marco Padovani, Daniella Galli (INAF)
S. Belli (U Bologna); A. Ivlev, T. Grassi (MPE),
L. Scarlett, U Rehill D. Fursa, I Bray (Curtin U),
M Zammit (LANL)


NGC 602 – HST/NASA/ESA.

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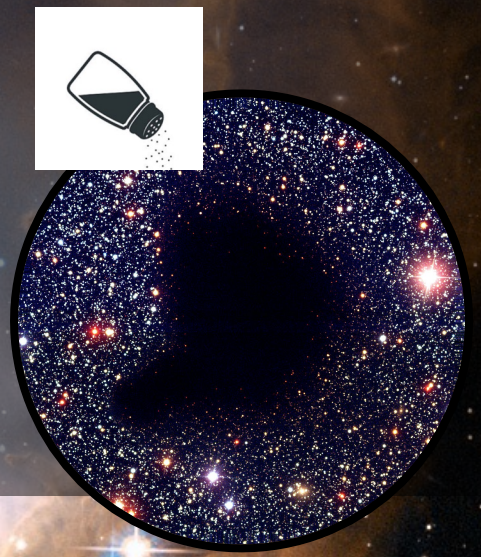


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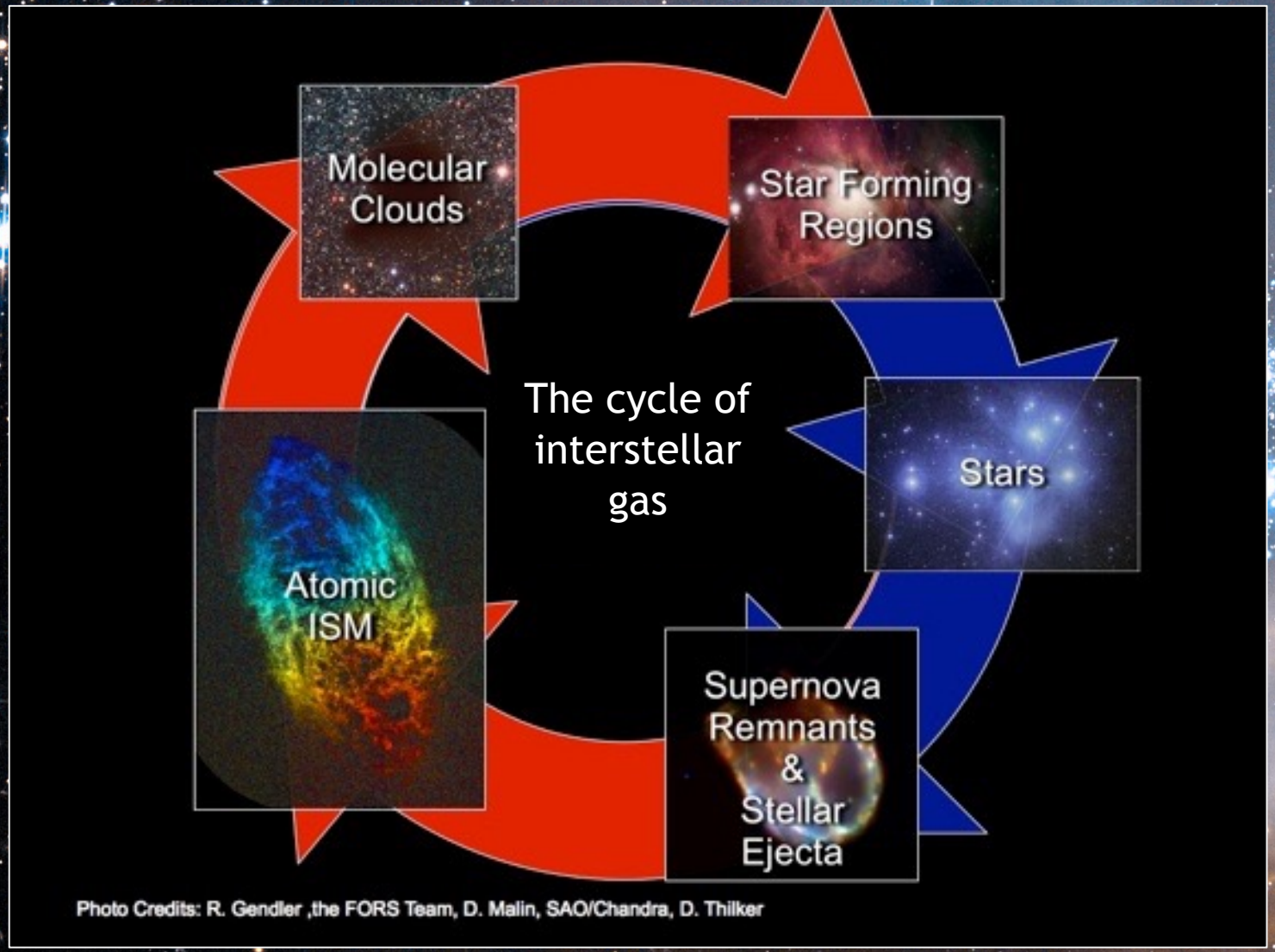
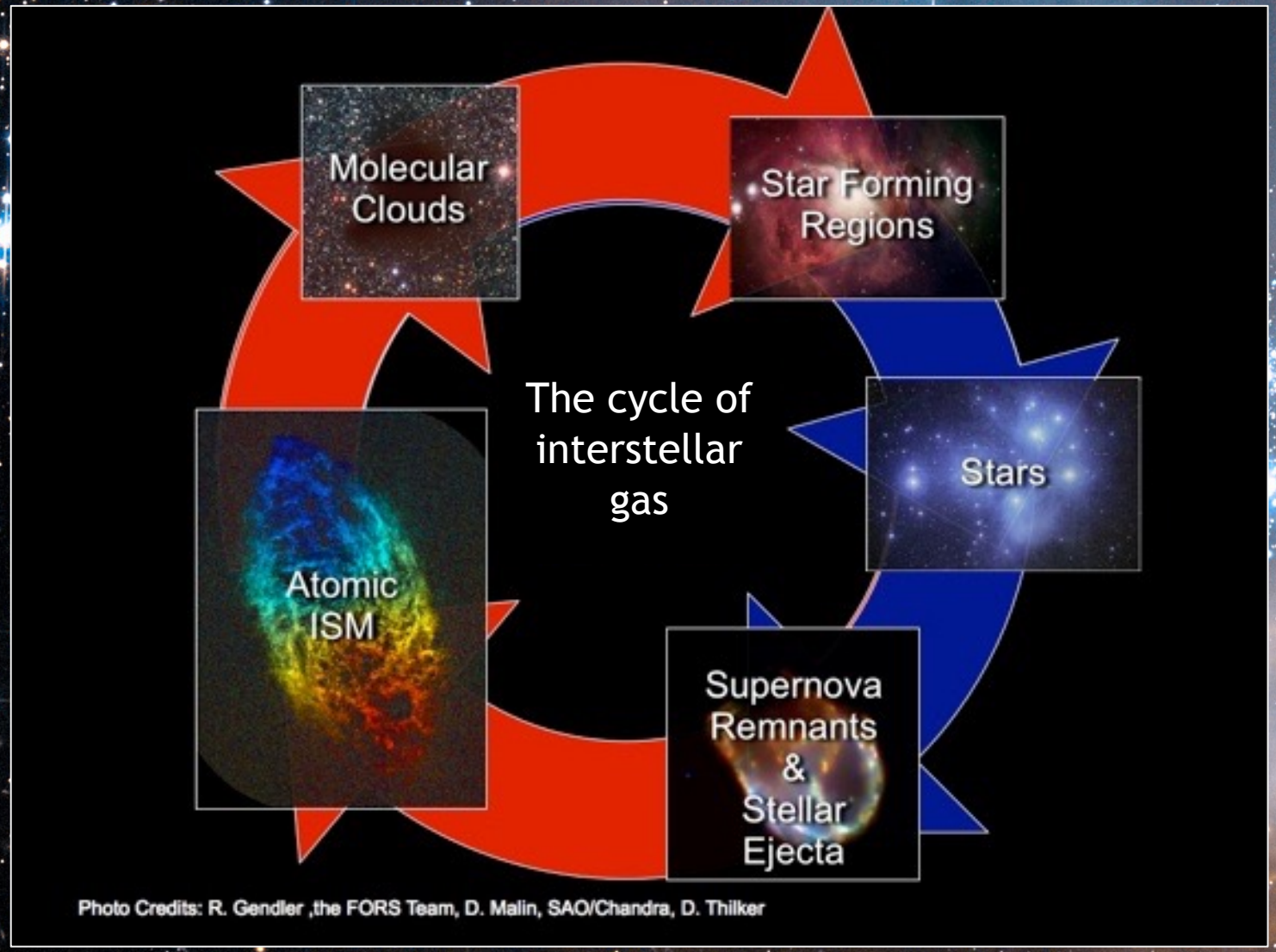
# The cycle




NGC 602 - HST/NASA/ESA.

# The cycle



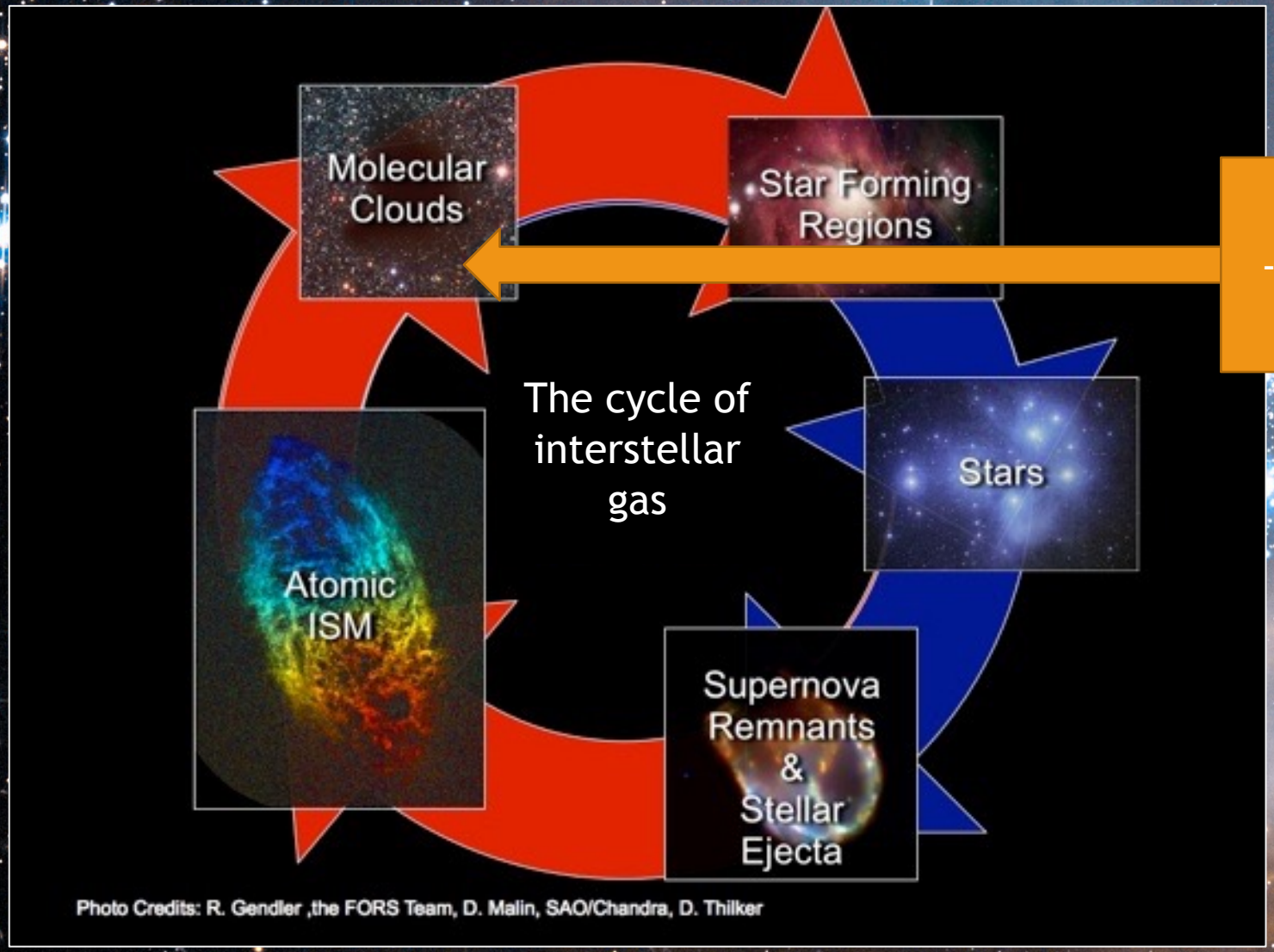

Stellar "Feedback"

- UV radiation
- Winds and outflows
- Supernova
- Cosmic-rays

- ❑ Shapes interstellar clouds: T, $\rho$, chemistry, B
- ❑ Regulates star-formation

NGC 602 - HST/NASA/ESA.

# The cycle



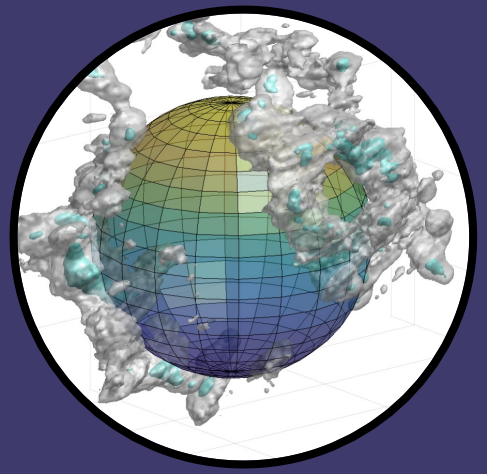

- Shielded from UV radiation
- Dominated by low-energy cosmic-rays (E ~< 1 GeV - TeV)

NGC 602 - HST/NASA/ESA.

# How do stars shape interstellar gas?

my interests

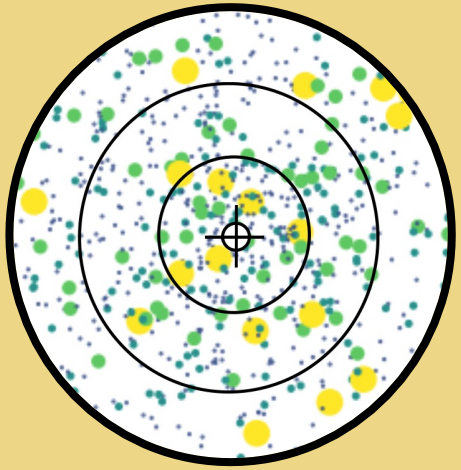
*Supernovae*



## The “Per-Tau Shell”
Supernova and Cloud Formation

- *3D mapping*
- *Cloud formation process*
- *3D visualization*

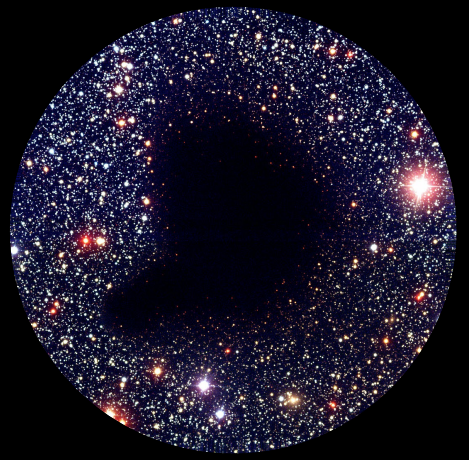
*UV radiation*



## The UV Interstellar Radiation Field

- *Analytic model*
- *ISM thermal phases*
- *Star-formation*

*Cosmic Rays*



## Cold Clouds as Cosmic-Ray Detectors

- *$H_2$ excitation*
- *Cosmic-ray propagation*
- *Sources and spectrum of low E CRs*

# Introduction

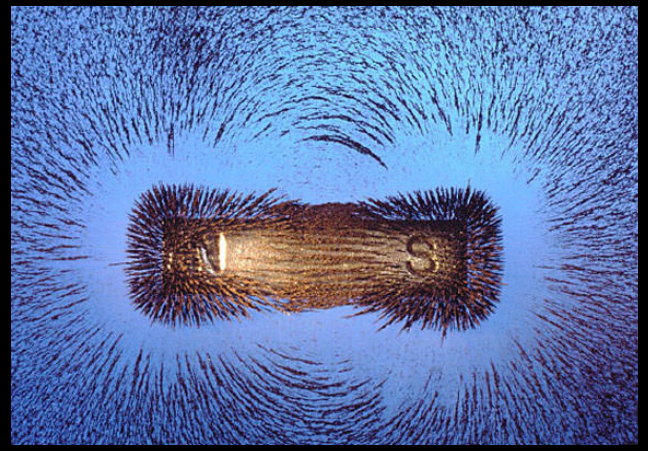
Why should we care?

*Cosmic Rays*

Low energy (E<1 GeV) CRs
$\Longrightarrow$ Ionization (primary + secondary)

chemistry

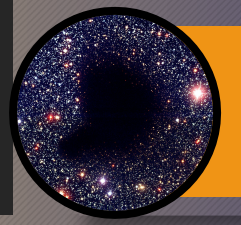
heating



Coupling to B fields

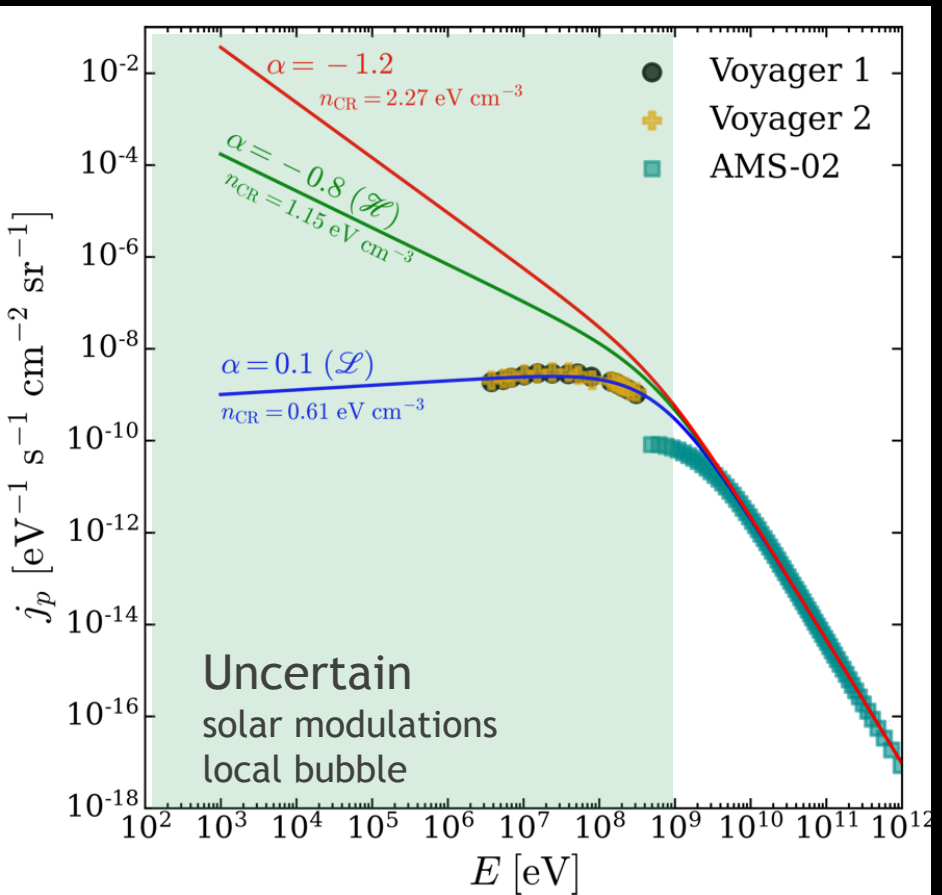
# Introduction

What is the spectrum of low-energy CRs?

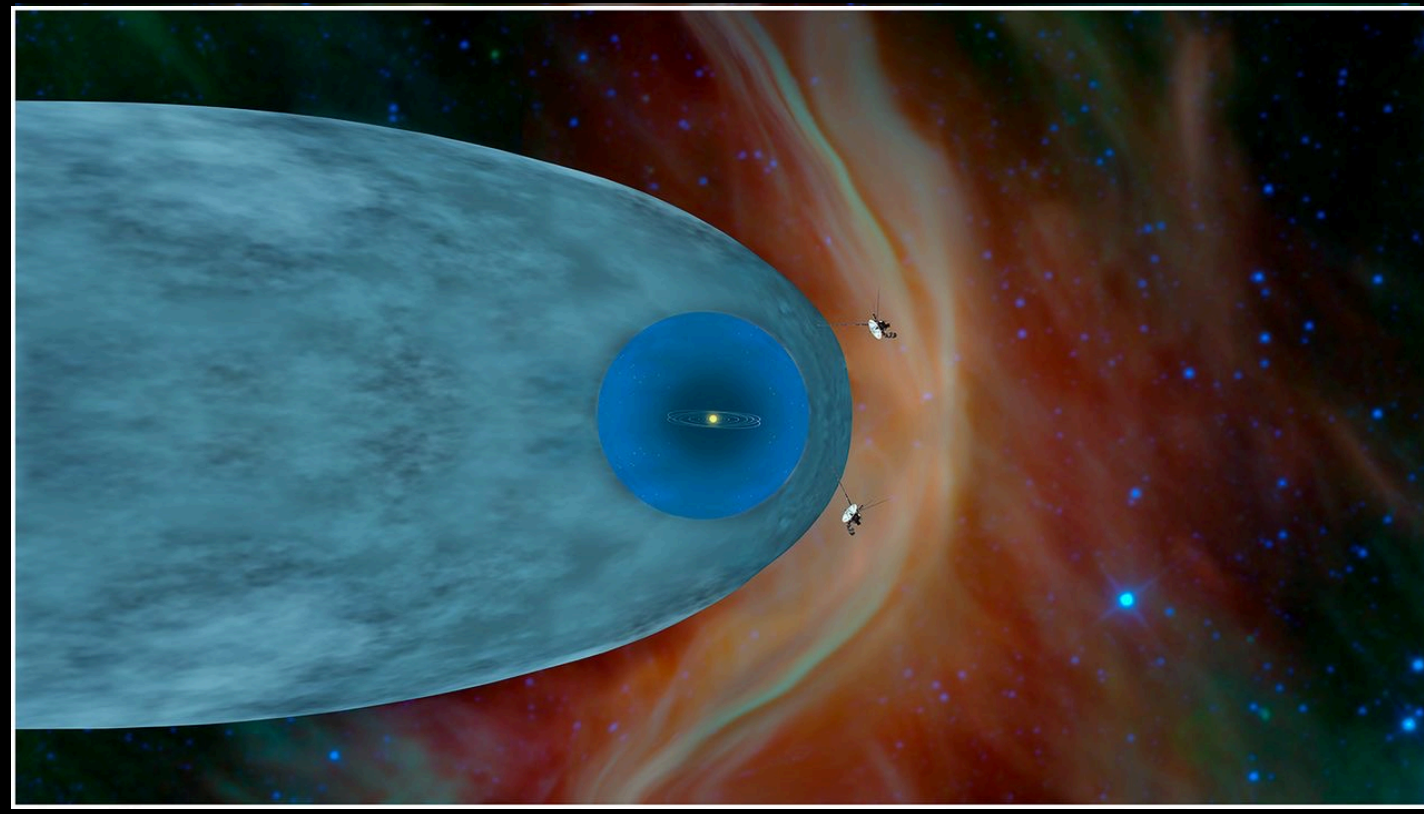


*Cosmic Rays*

Direct observations: Earth and space



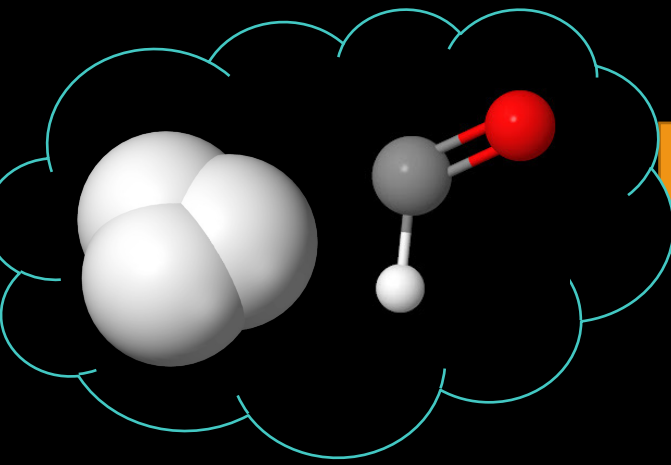

Measured CR proton spectrum



credit: NASA/JPL-Caltech

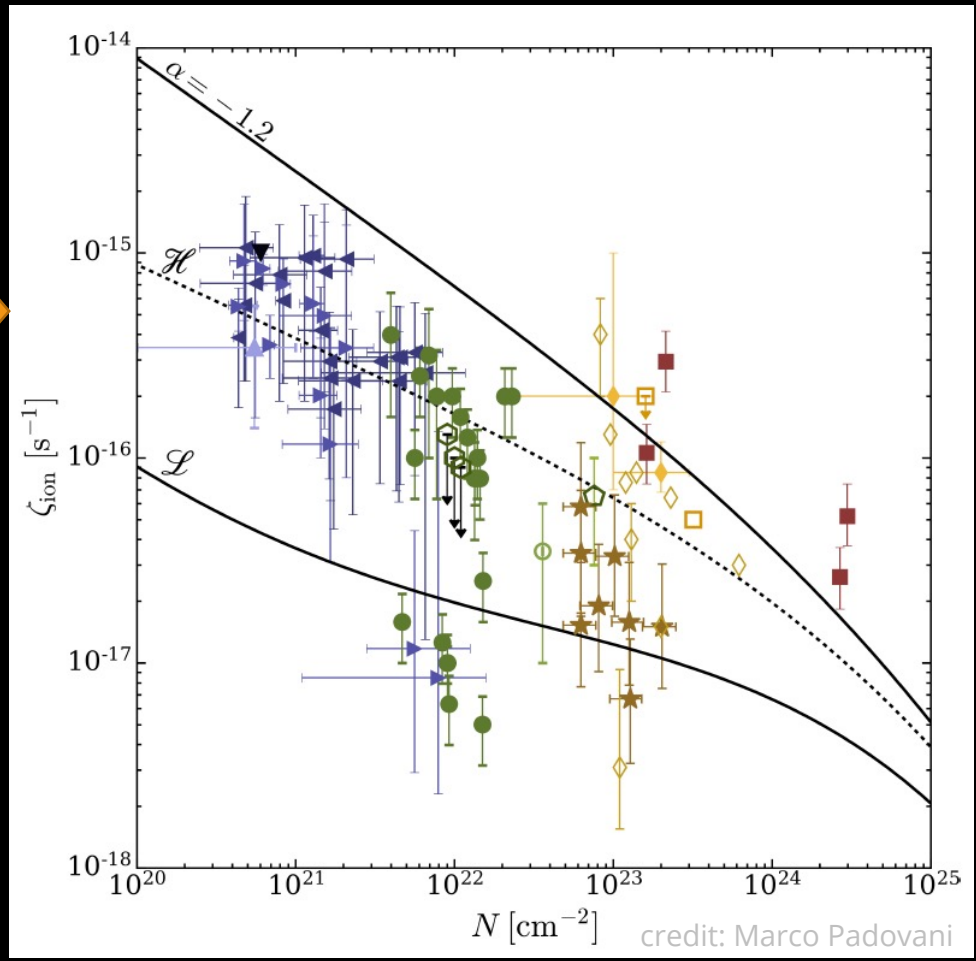
# What is the flux of low-energy cosmic-rays?

**Indirect observations:**
astrochemistry in interstellar clouds



Uncertainty:
observational
chemical models
assumptions: n, $x_e$

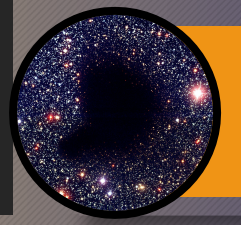
credit: Marco Padovani




credit: Marco Padovani

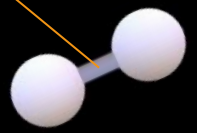
# The idea

Use H2 excitation to probe cosmic-rays

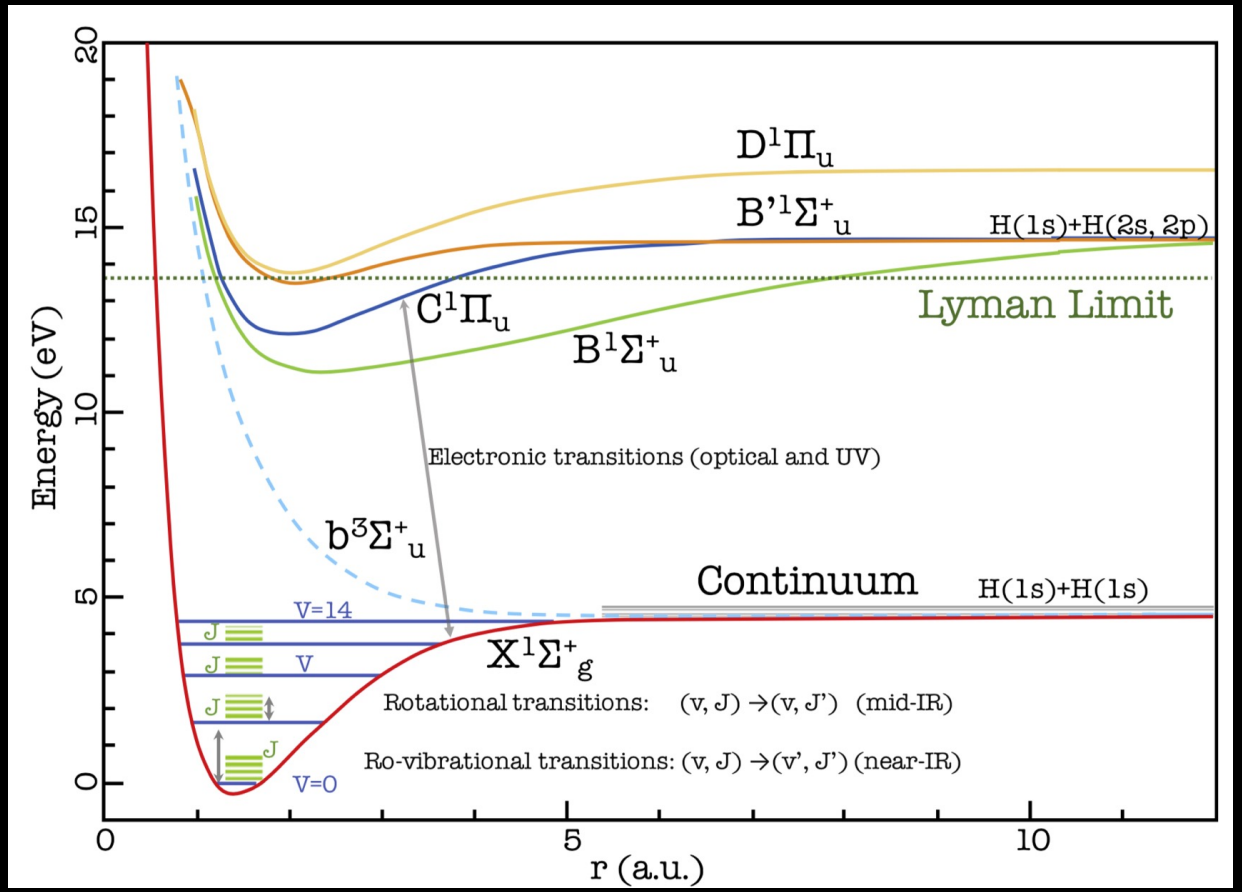


Cosmic Rays

Cosmic ray (secondary e-)



## H2 energy level diagram

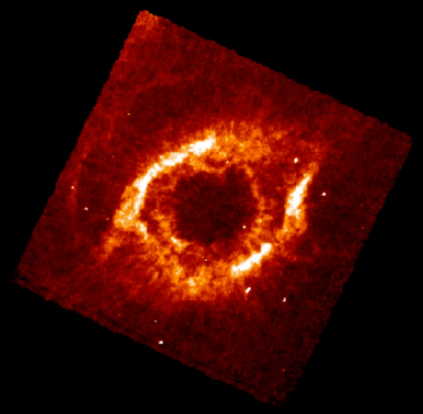


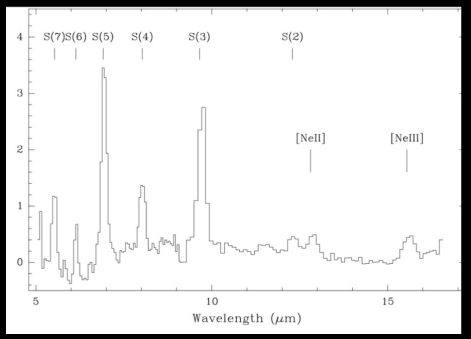
# The idea

Use H2 excitation to probe cosmic-rays

*Cosmic Rays*

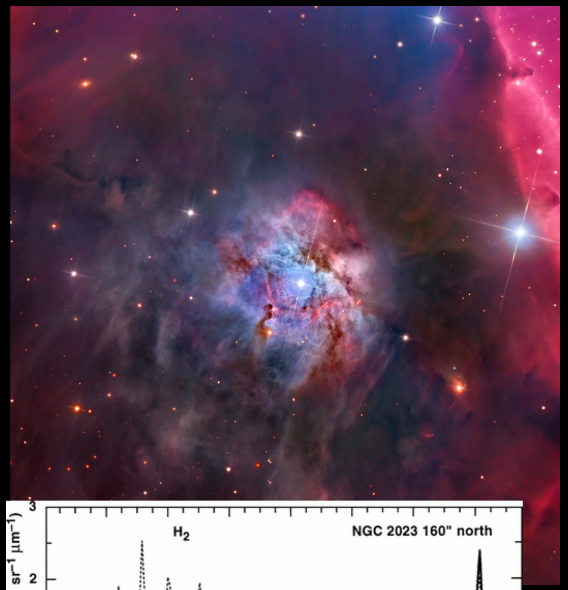
## Planetary nebula






Collisional (high T)

## Photo-dissociation region



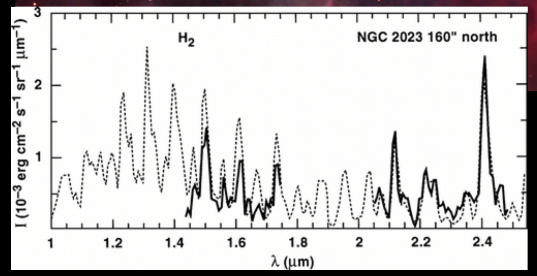
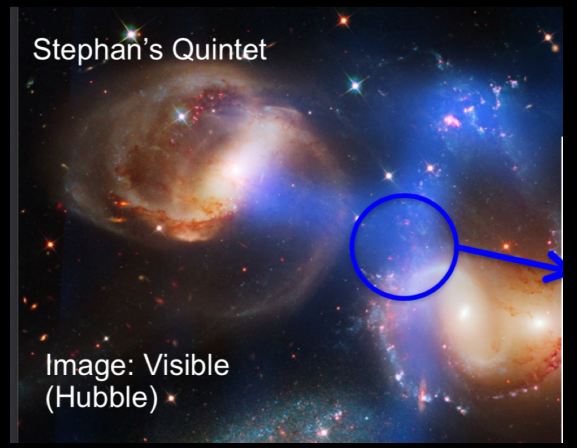
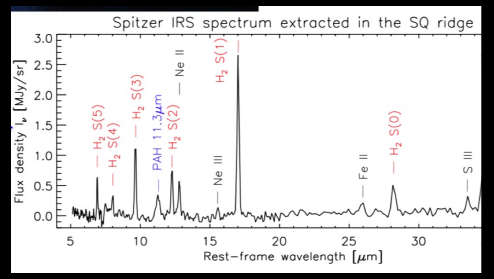



Photo excitation

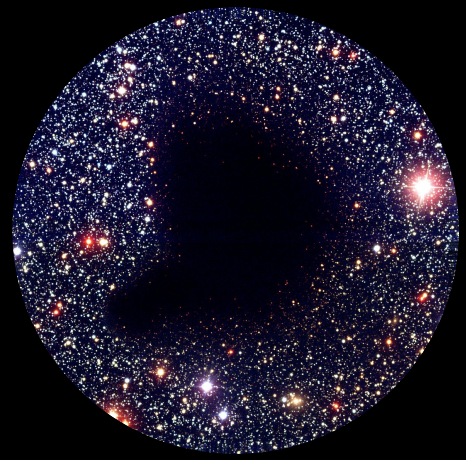
## Shocked gas




Collisional (high T)

## Cosmic-rays?



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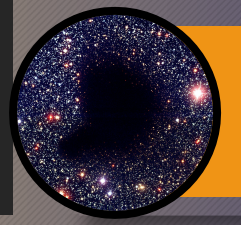
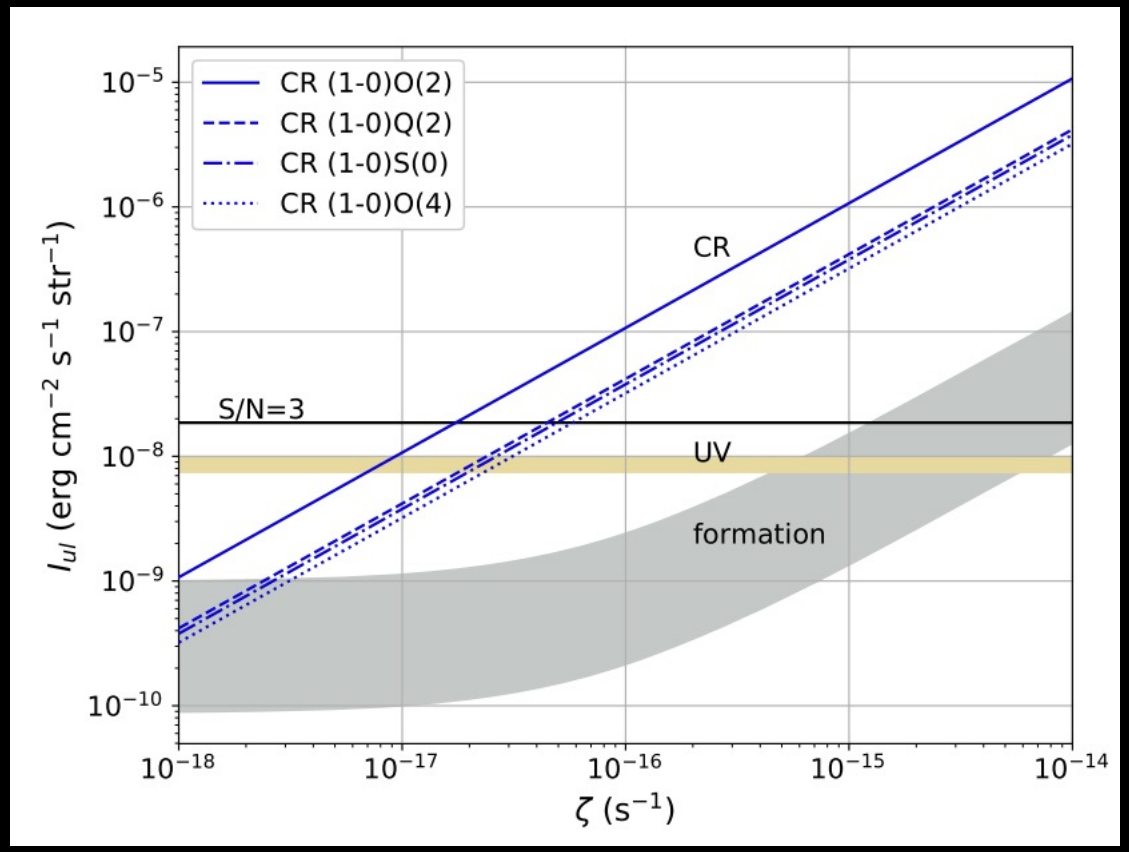
Use H2 excitation to probe cosmic-rays



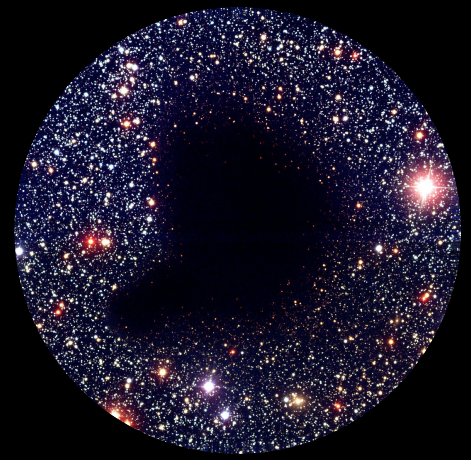
*Cosmic Rays*




The four lines that are preferentially excited by cosmic-rays

v=1
J=0 or 2

Cosmic-rays

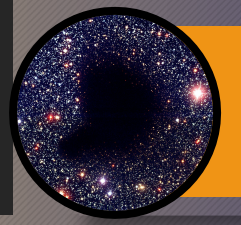


$$I_{ul,(\mathrm{cr})} = \frac{1}{4\pi} g N_{\mathrm{H_2}} \zeta_{\mathrm{ex}} p_{u,(\mathrm{cr})} \alpha_{(u)l} E_{ul},$$

Bialy (2020, Nature Com. Phys. 3 32)

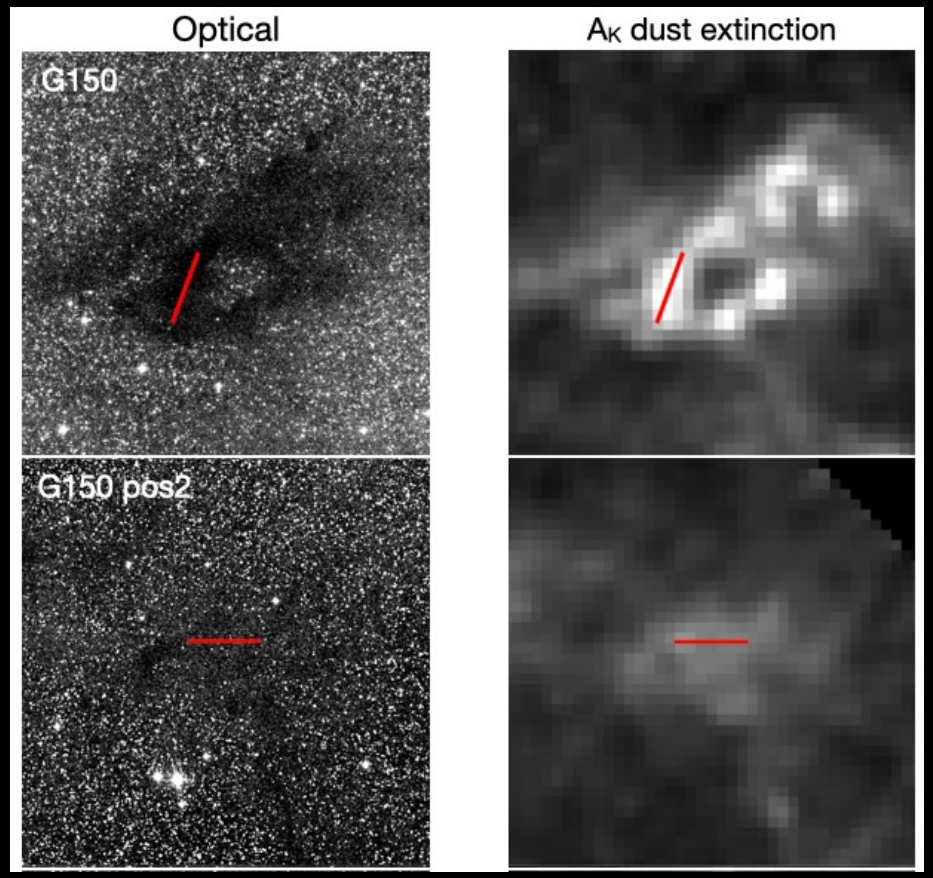
# Observations

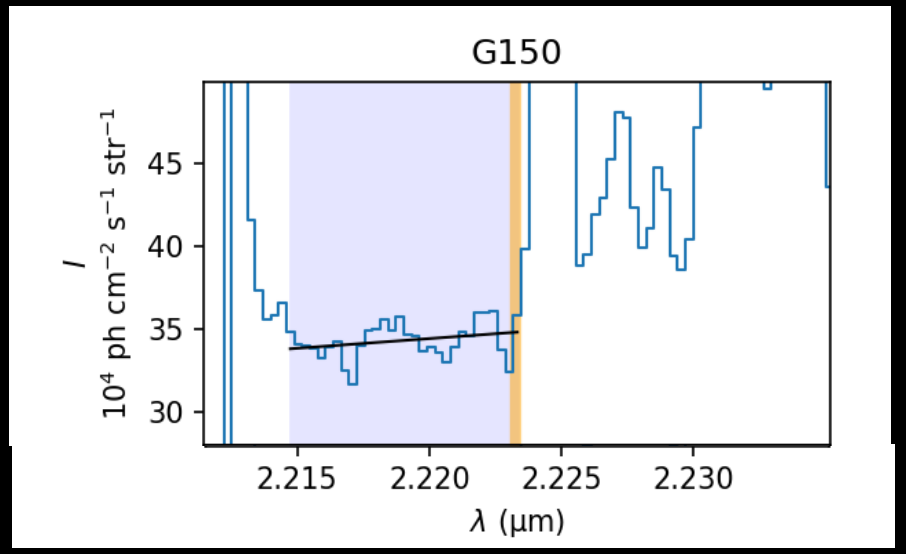
Constrain the CR spectrum and ionization rate



*Cosmic Rays*

NIR spectroscopy of molecular nearby clouds

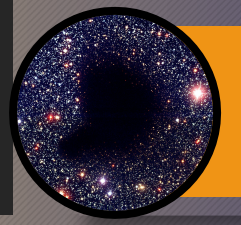


MMT 6.5m Arizona

Bialy et al. 2022 (AA letters, 658, L13)

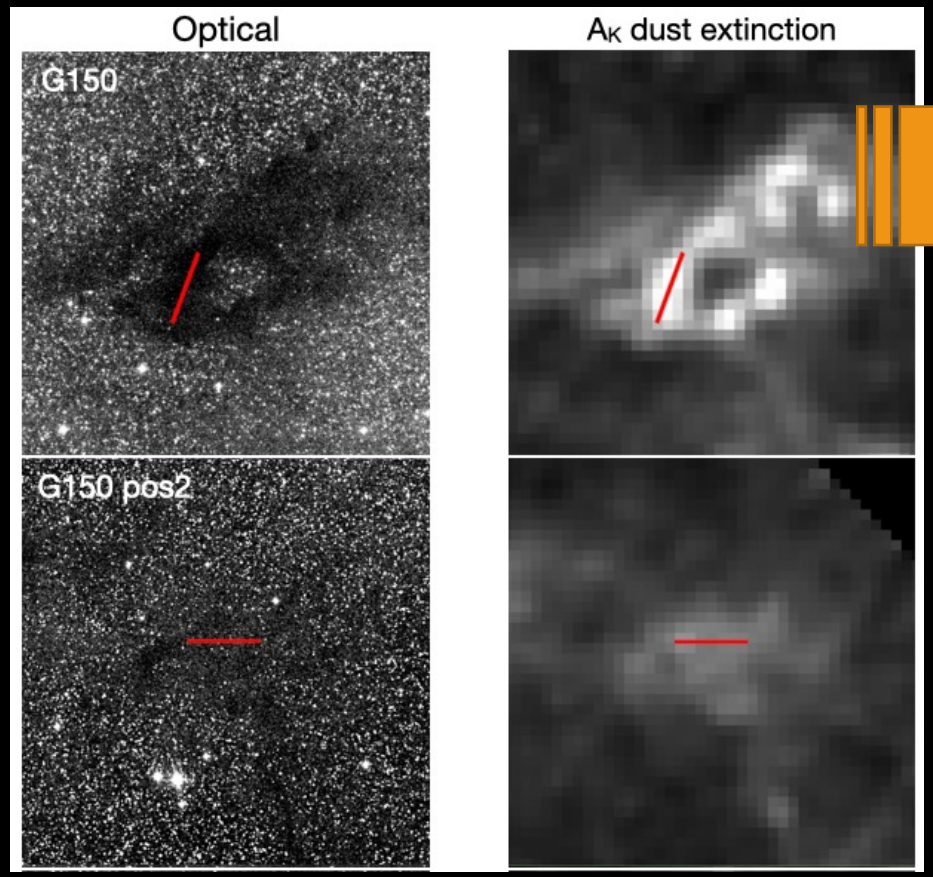
# Observations + Model



Cosmic Rays

Constrain the CR spectrum and ionization rate

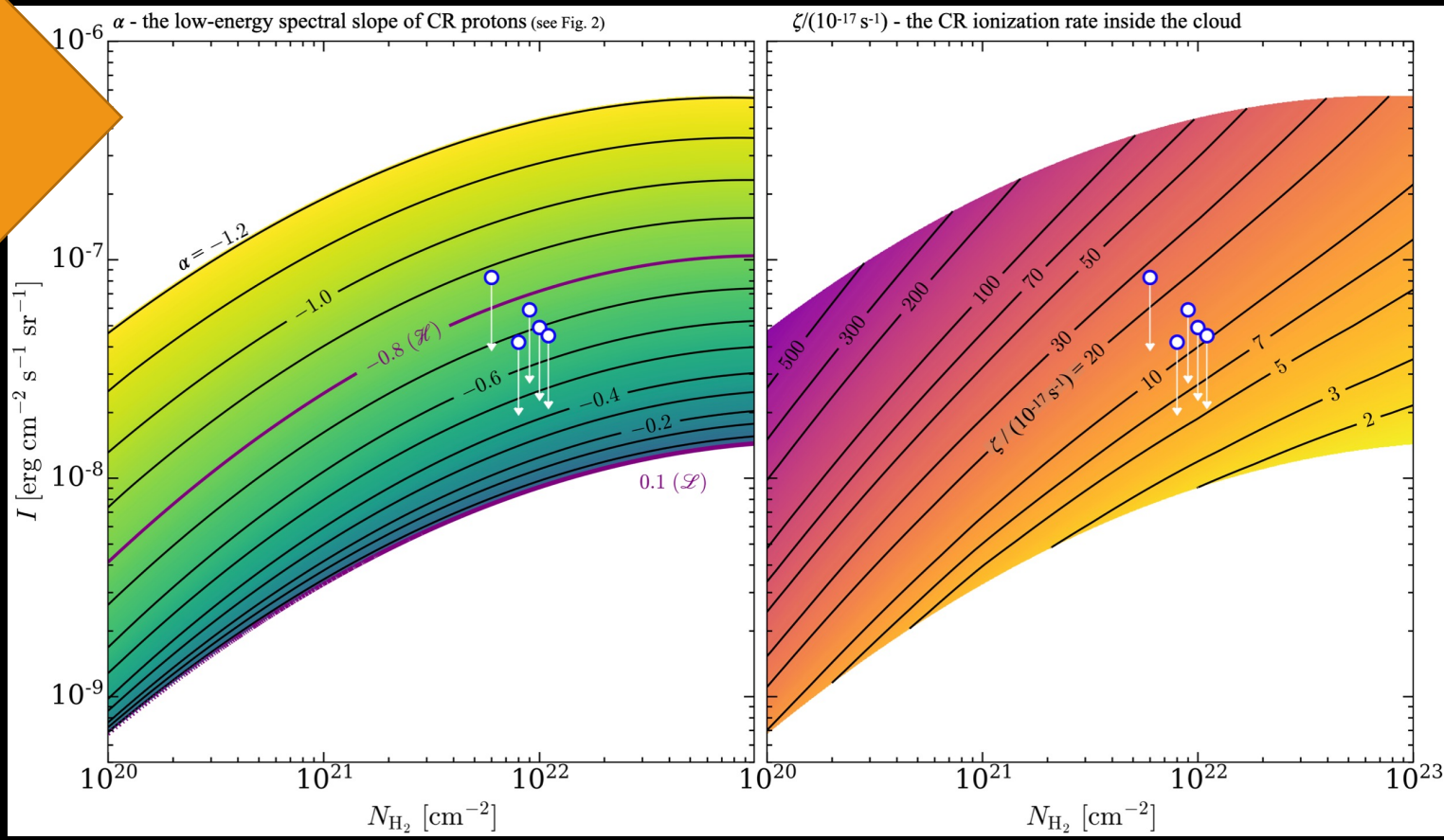
NIR spectroscopy of molecular nearby clouds




Bialy et al. 2022 (AA letters, 658, L13)

Slope of CR proton spectrum (interstellar)

Ionization rate inside the clouds



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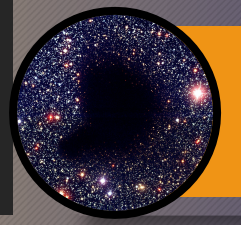

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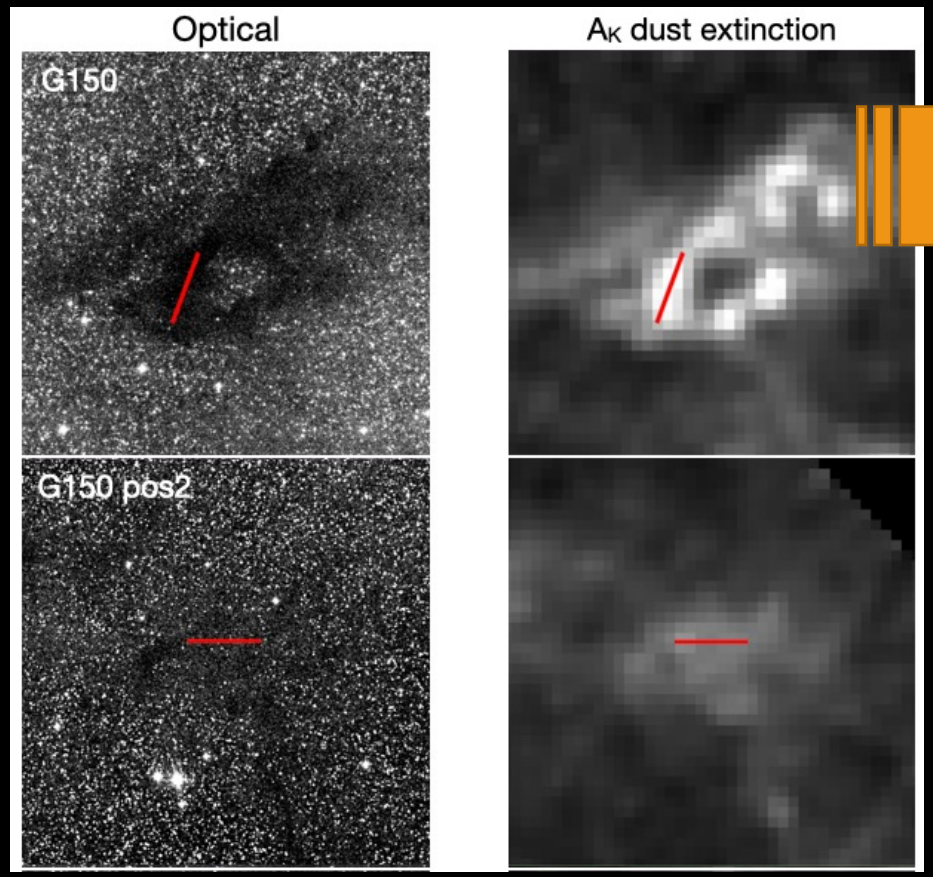


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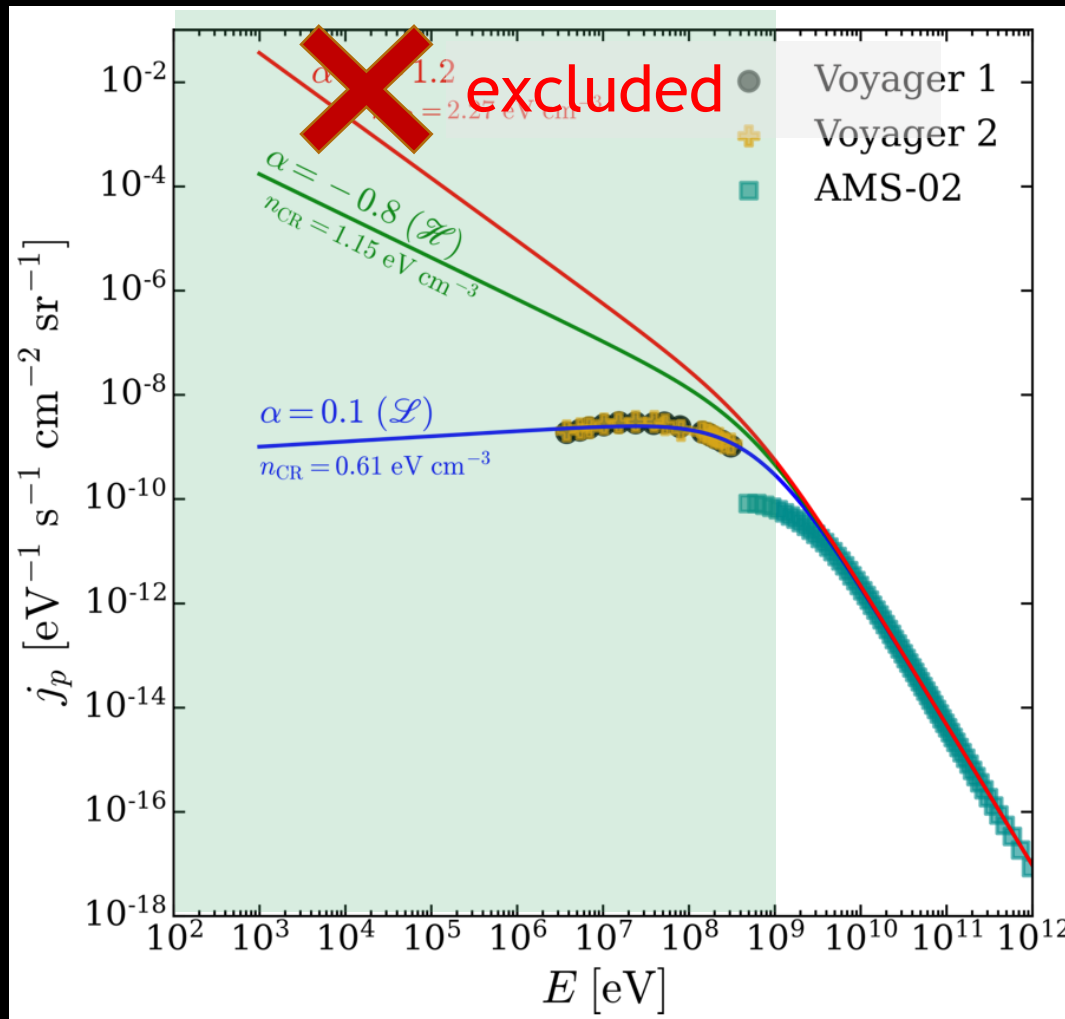
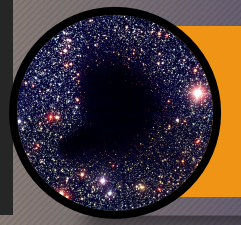


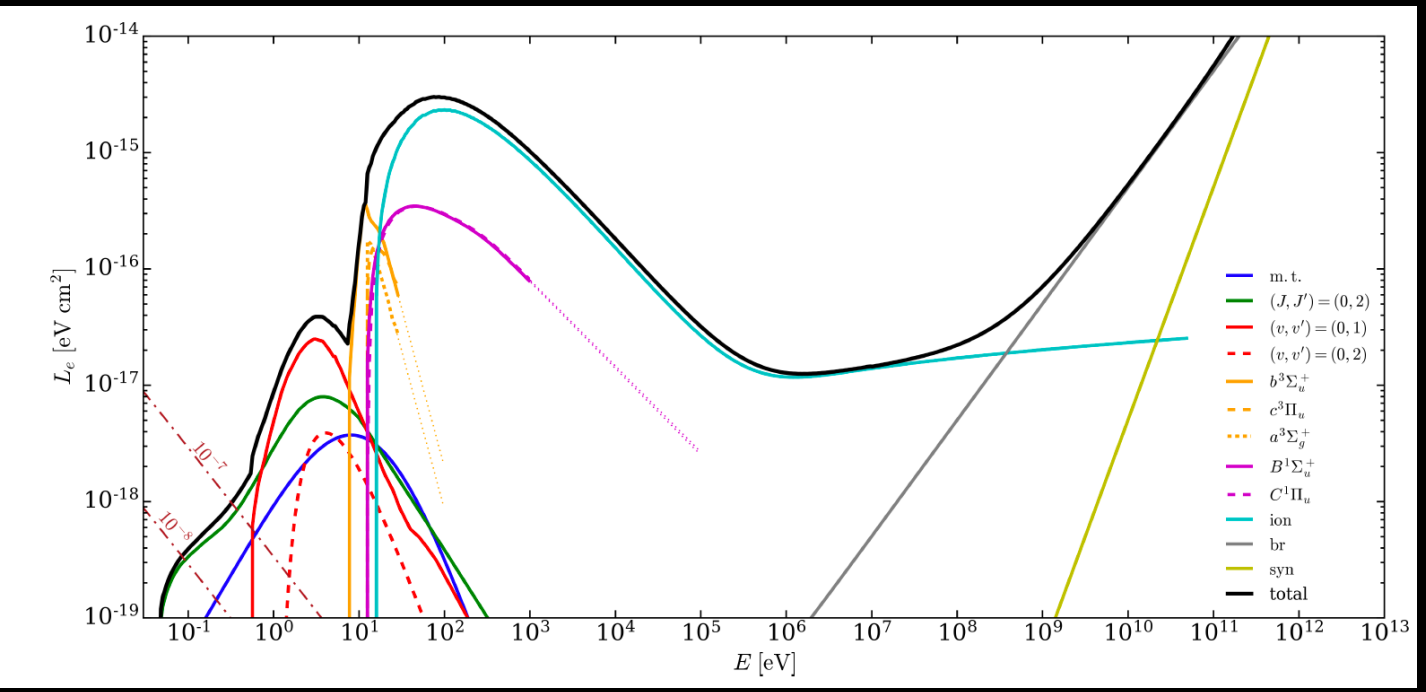
# CR propagation model

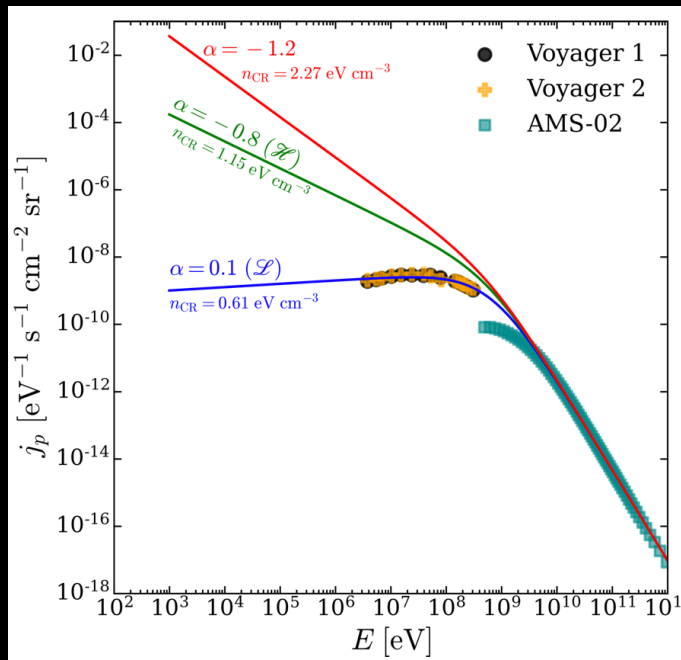




## Constrain the CR spectrum and ionization rate

Energy loss per $cm^{-2}$ of cosmic-ray electrons propagating into a molecular cloud (similarly, Lp for protons)




Padovani, Bialy et al. 2022 (A&A 658 189)

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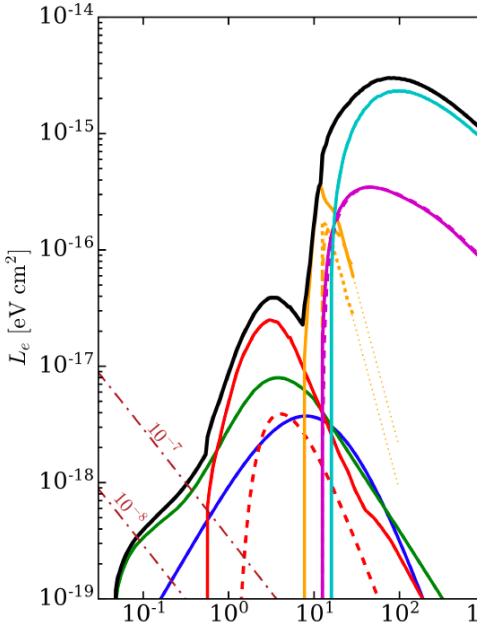
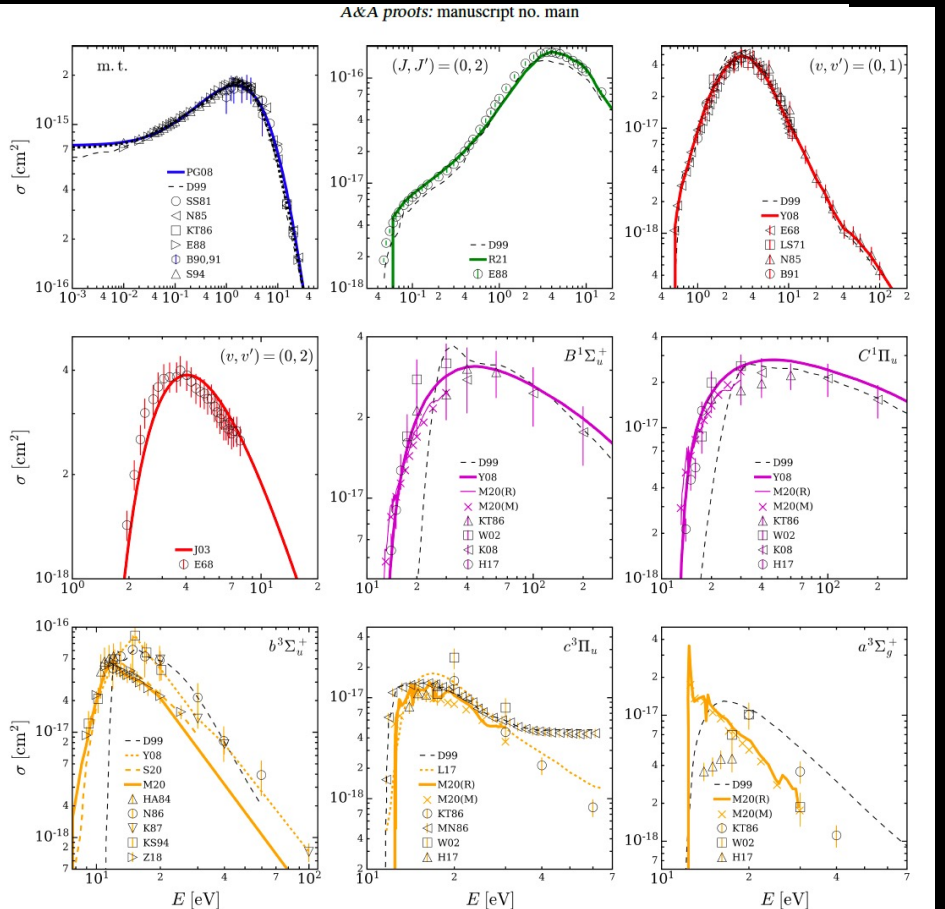
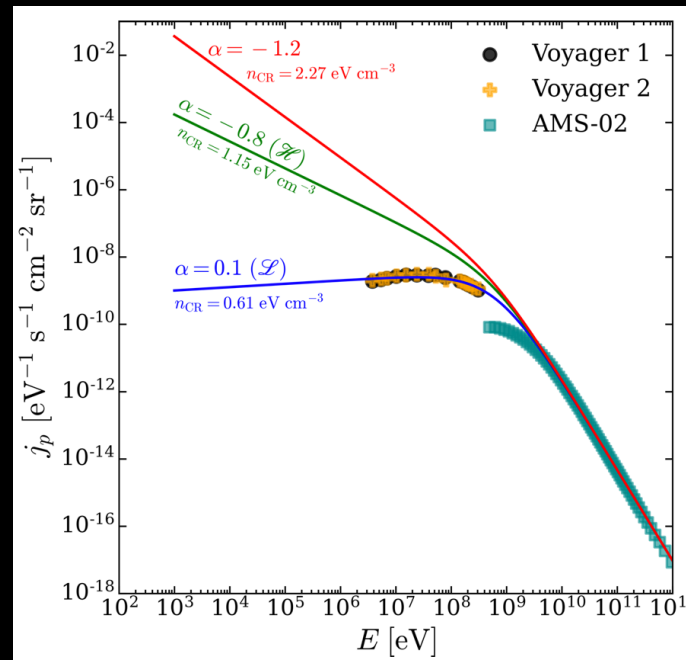



Padovani, Bialy et al. 2022 (A&A 658 189)

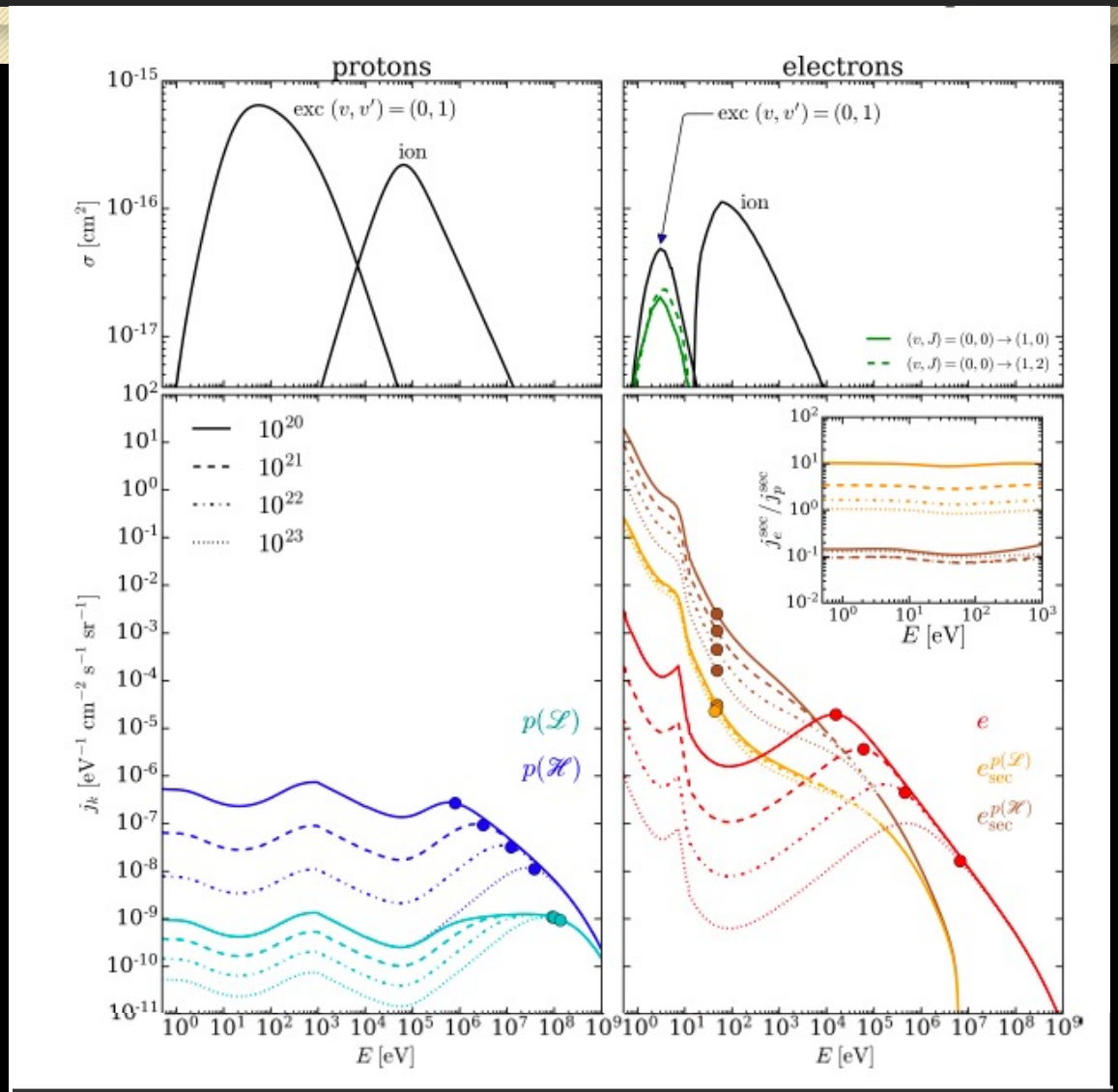
# CR propagation model

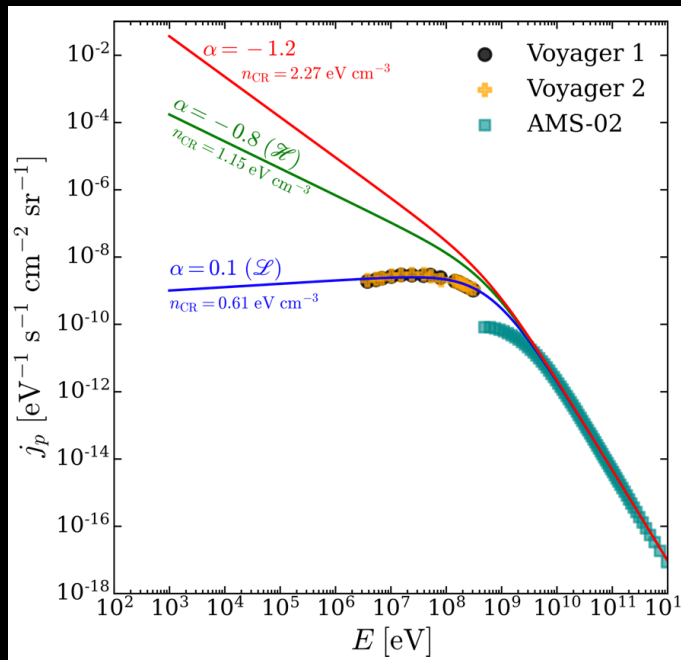


Spectra at different cloud depth

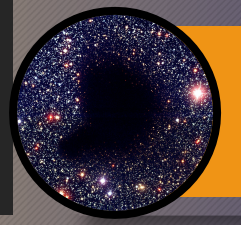
(for the different incident spectra powerlaws)

Padovani, Bialy et al. 2022 (A&A 658 189)



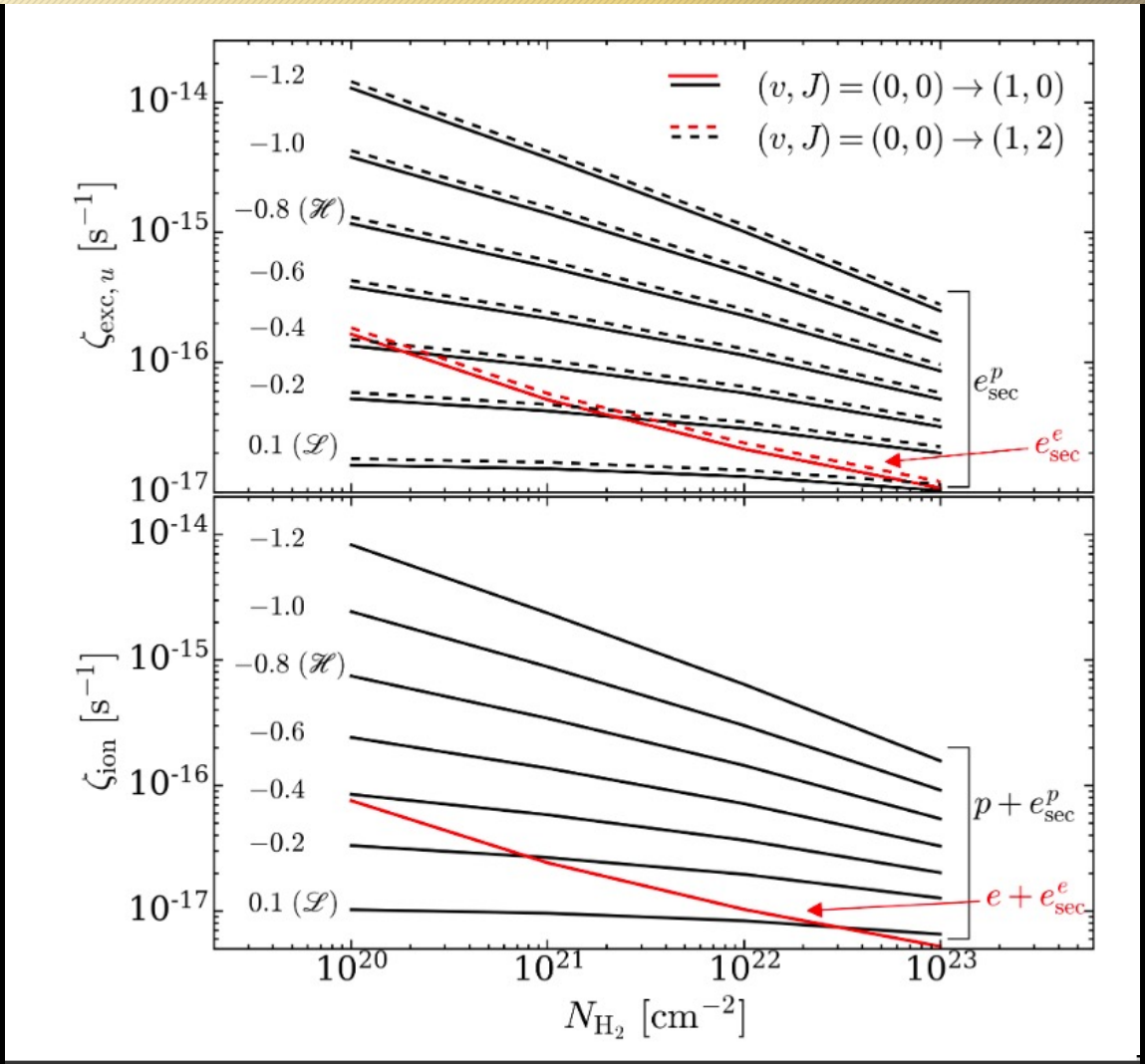



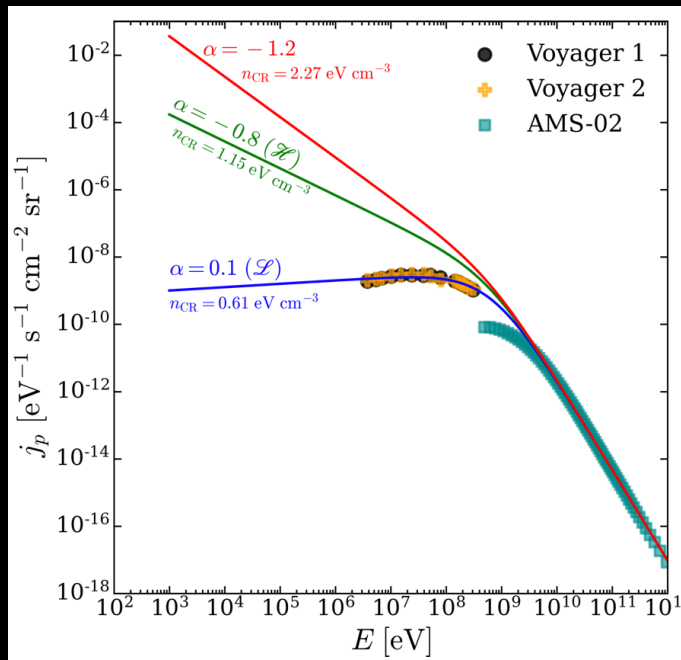
# CR propagation model



Cosmic Rays

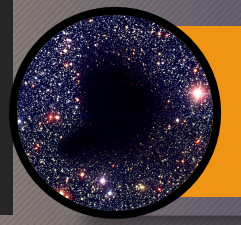
CR excitation and ionization rates at different cloud depth




Padovani, Bialy et al. 2022 (A&A 658 189)

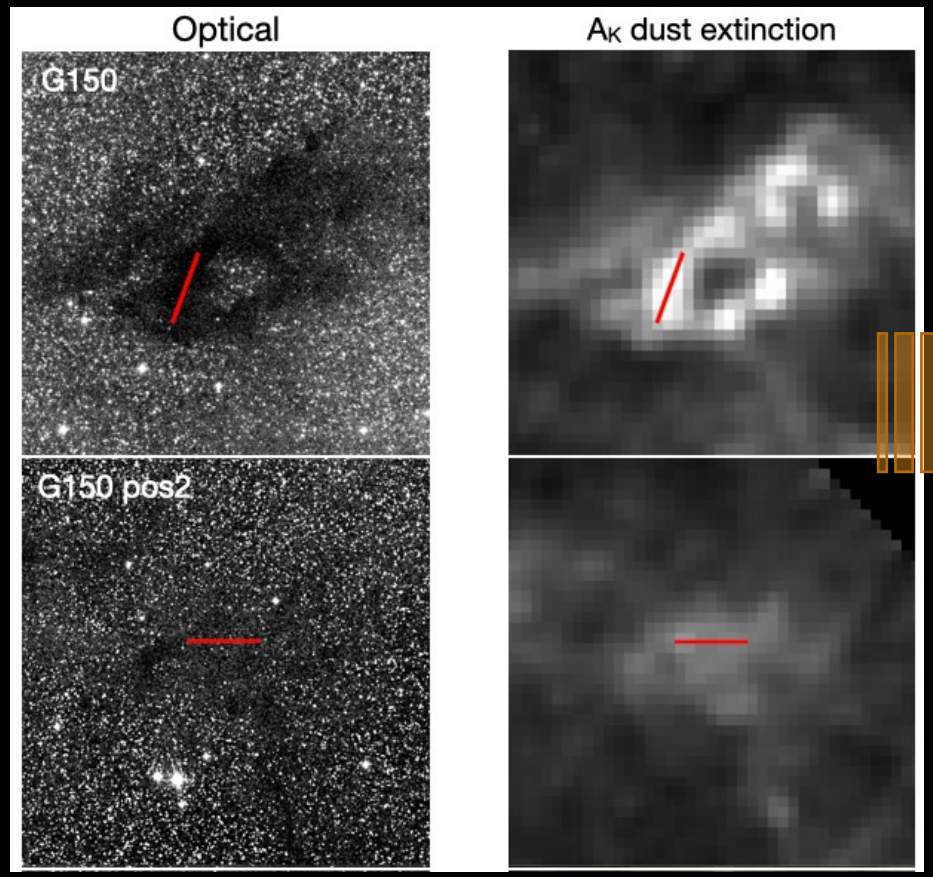
# Observations + Model



Cosmic Rays

Constrain the CR spectrum and ionization rate

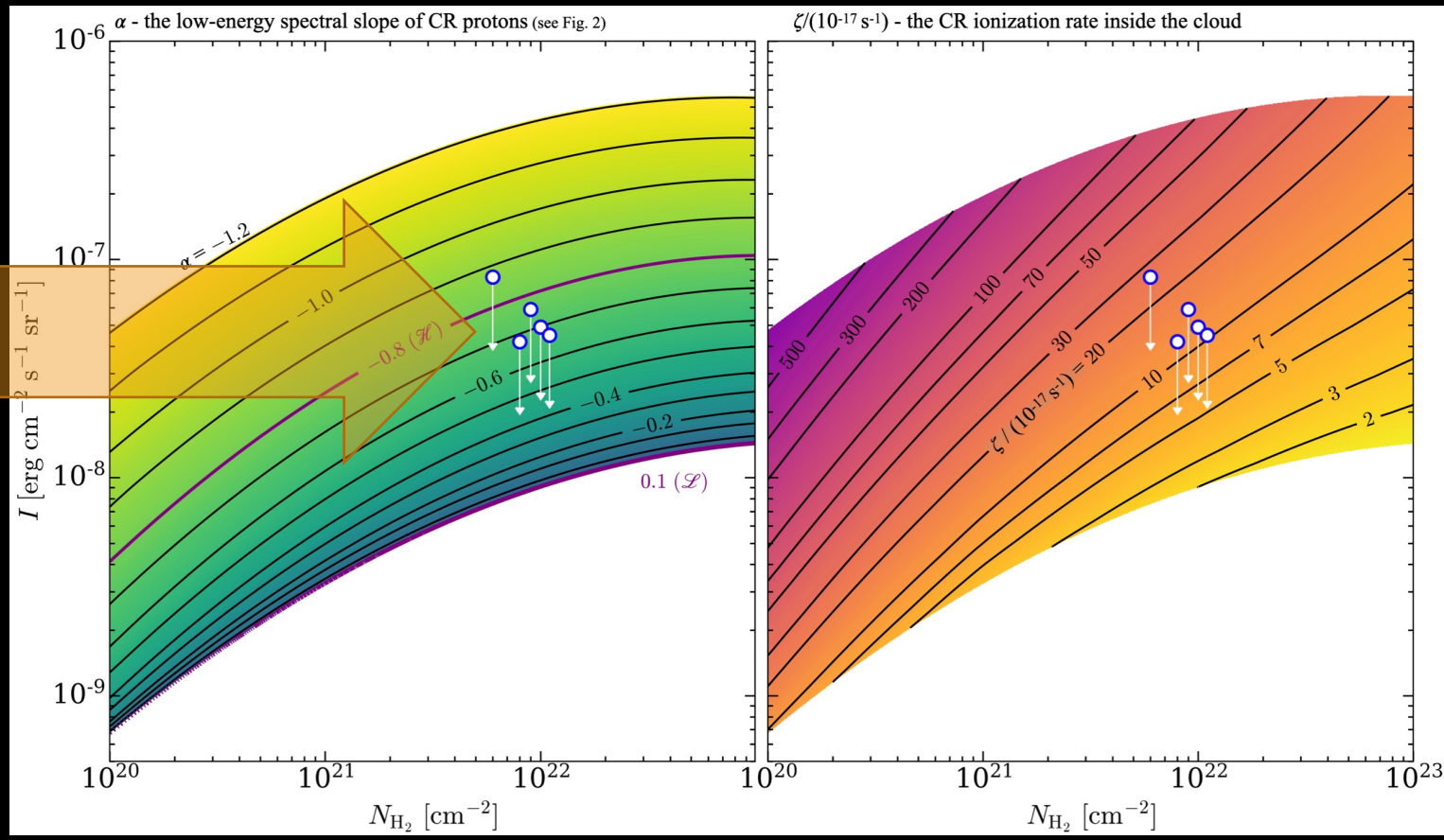
NIR spectroscopy of molecular nearby clouds




Bialy et al. 2022 (AA letters, 658, L13)

Slope of CR proton spectrum (interstellar)

Ionization rate inside the clouds



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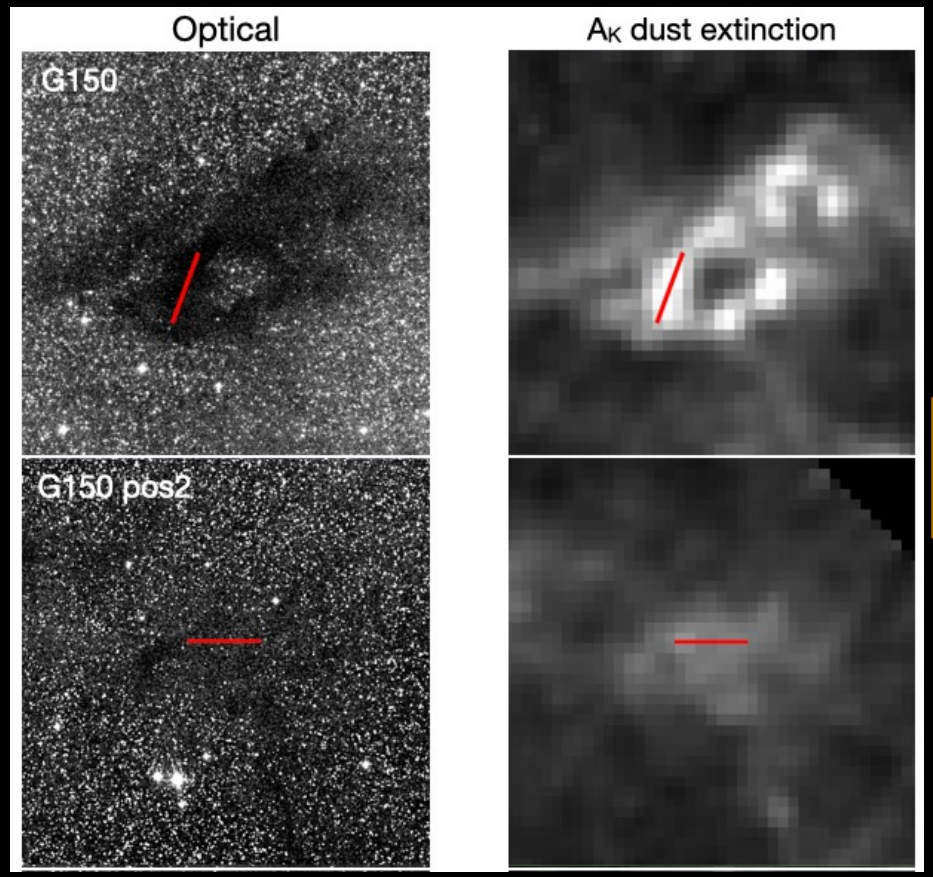


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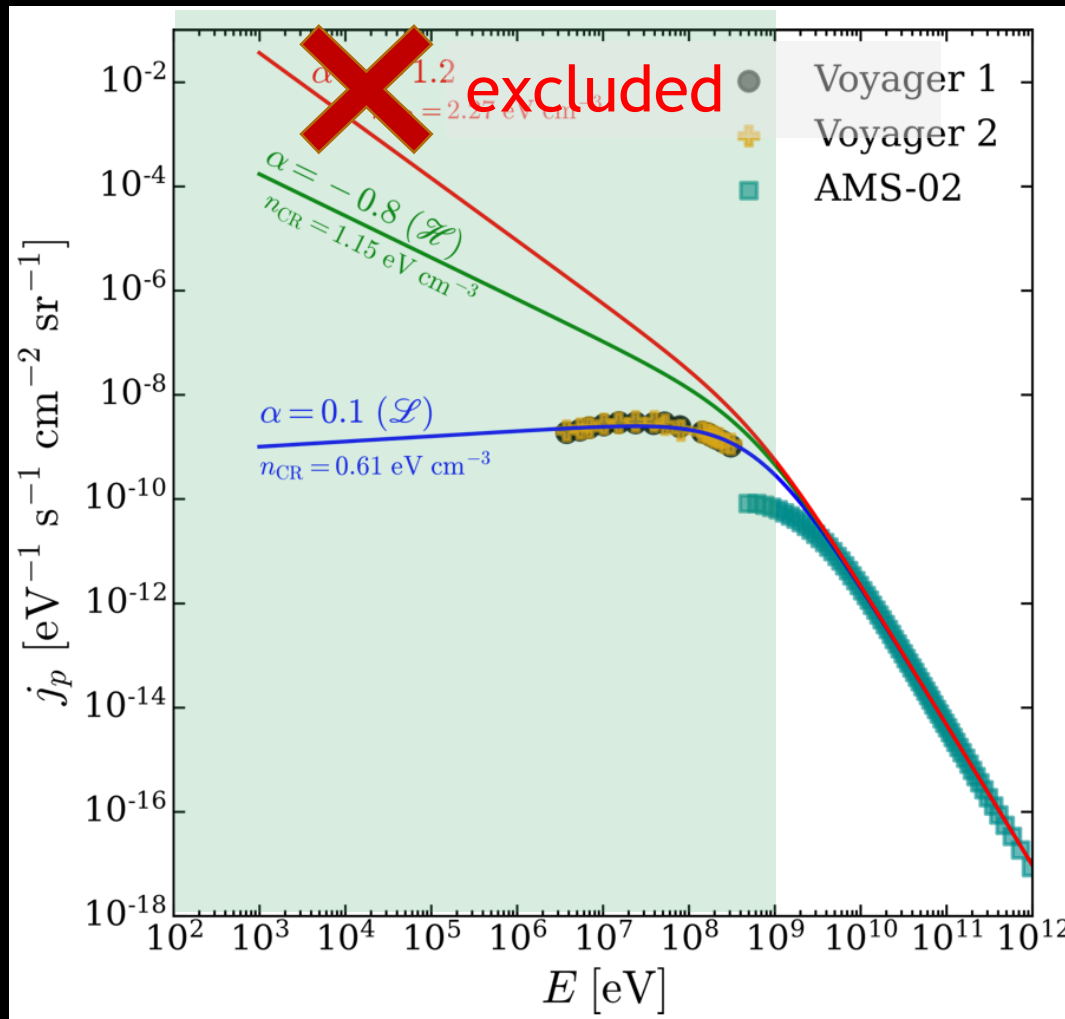

# The Future is Now

*Cosmic Rays*

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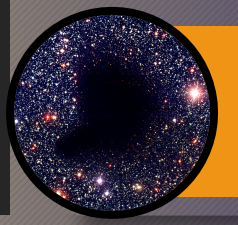

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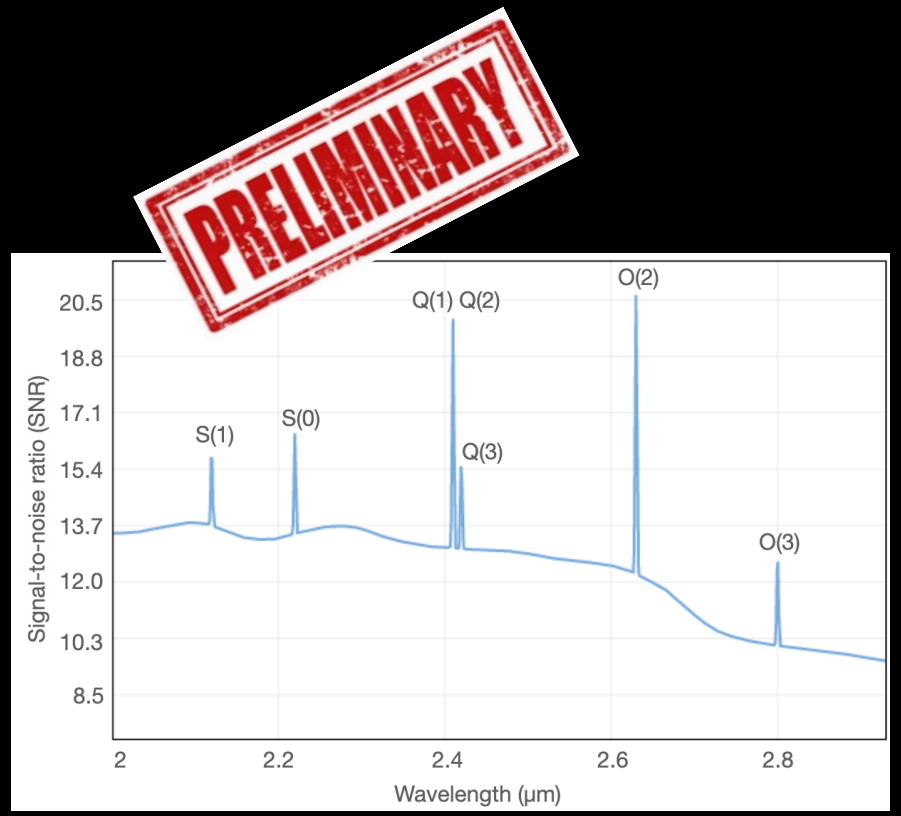
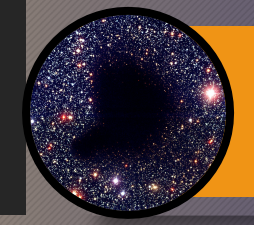



Integration over 10 shutters with JWST's NIRSpec instrument, 1.3 hrs

# The Future is Now



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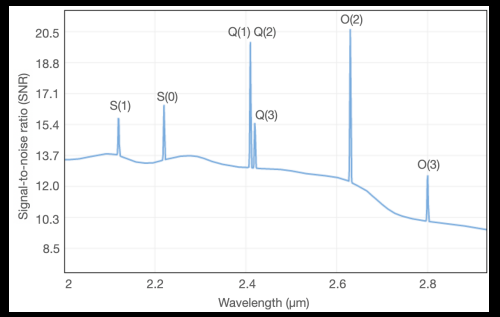
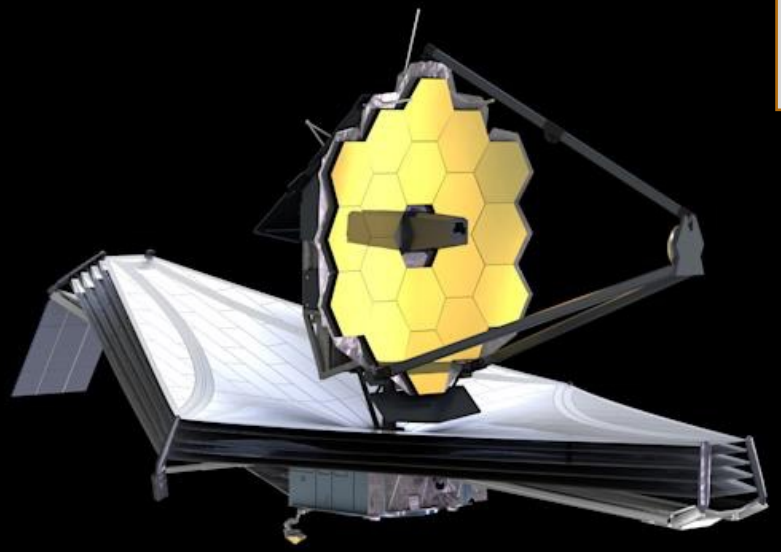
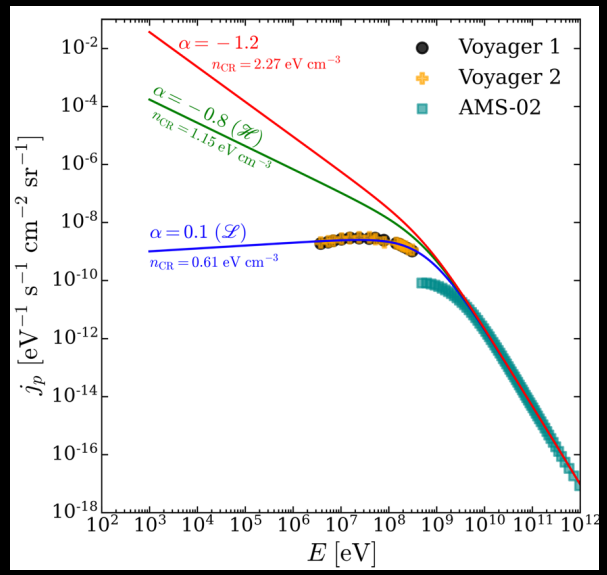
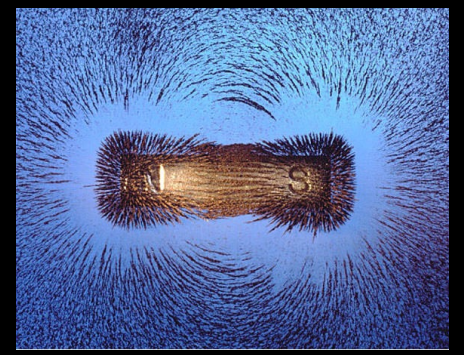


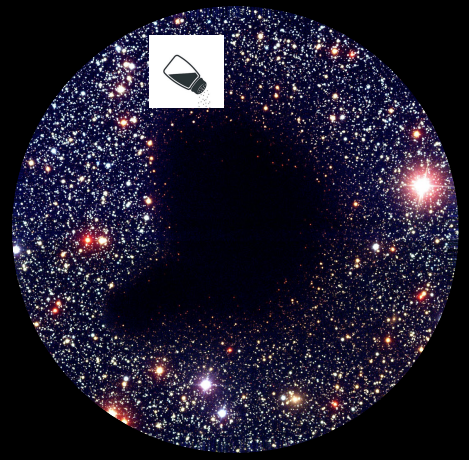




# Looking Forward

Shmuel Bialy

Cold Clouds as
Cosmic-Ray Detectors



***Observational constraints***

- *Constrain $\zeta$ in dense clouds using $H_2$*
- *Constrain the CR spectrum at low energies*

***By observing a population of clouds:***

- *Homogeneity level and Diffusion coefficient*
- *Sources of CRs*

# Looking Forward

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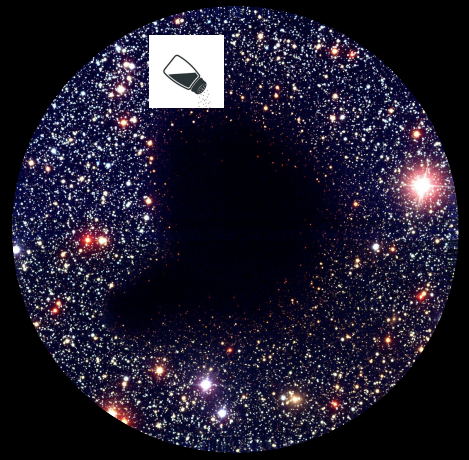

*Theoretical improvements*

- *3D cloud model (w B.Gaches)*
- *Additional excitation processes (UV, formation)*
  - *PDR+CRDR model (w B. Godard)*
- *A complete vJ excitation cross section catalog*
- *Magnetic fields*

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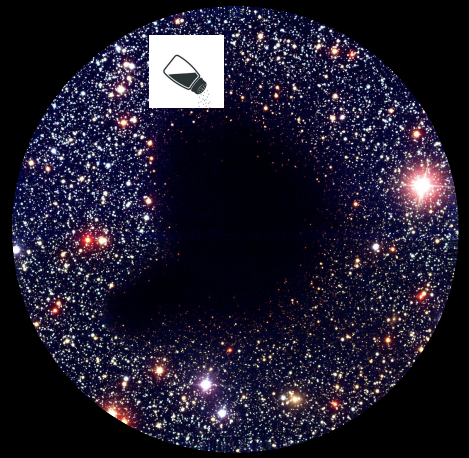

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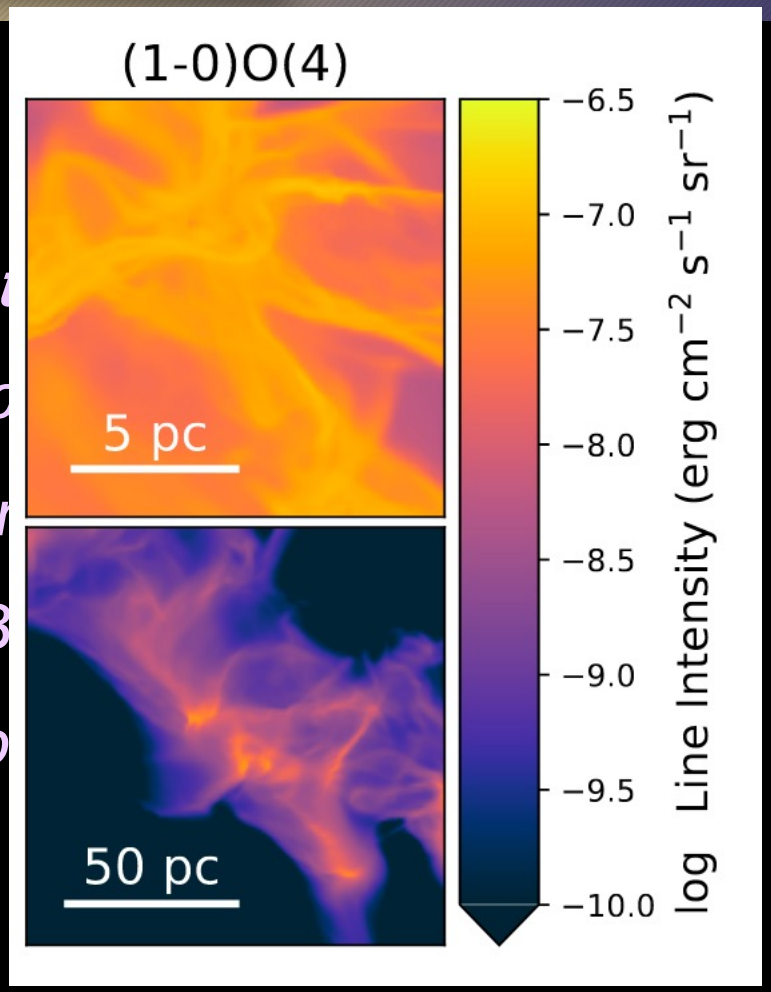
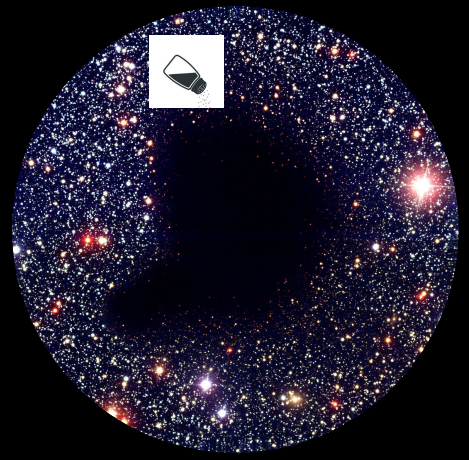



Gaches et al. (2022, A&A 664 A150)

# Looking Forward

Shmuel Bialy

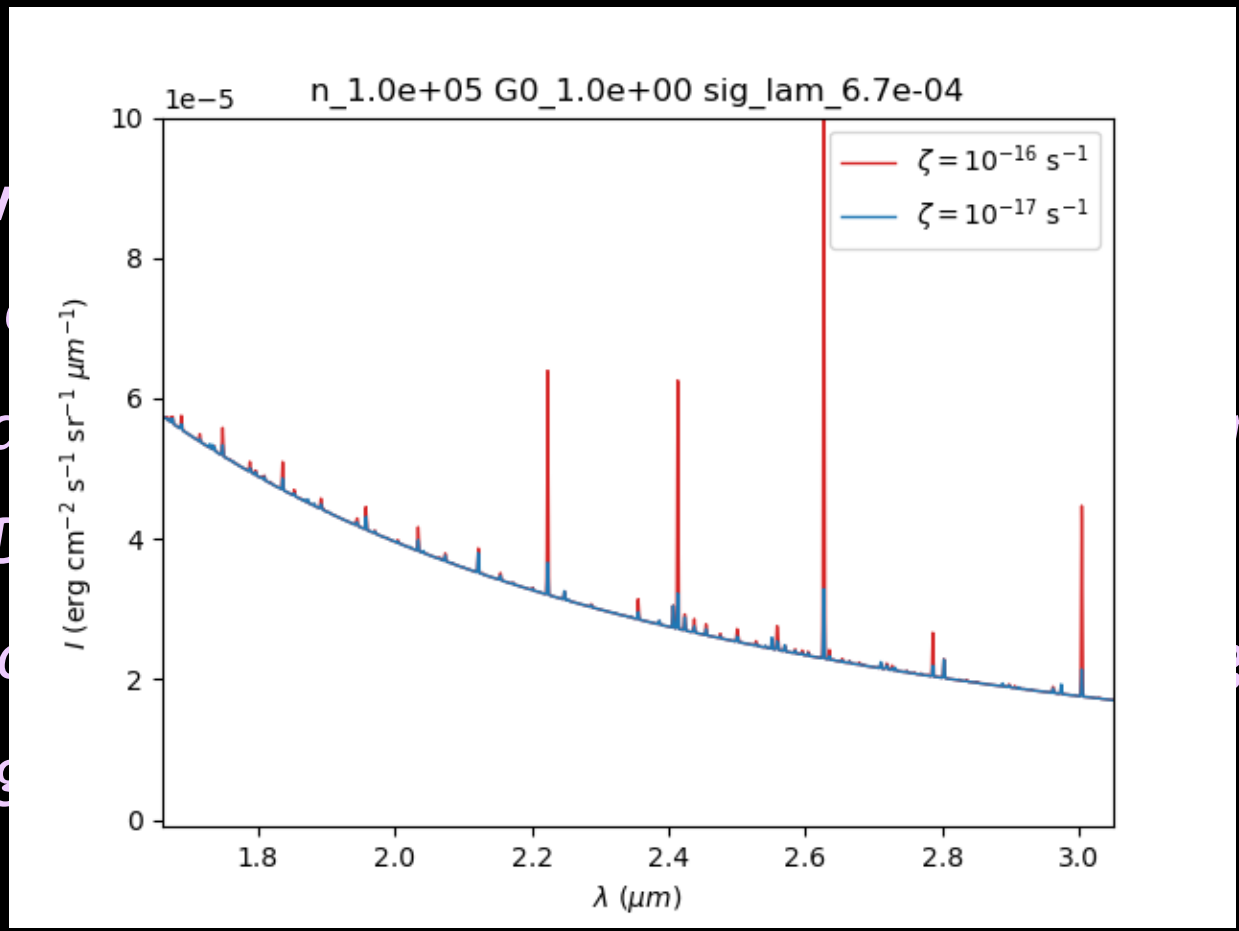
## Cold Clouds as Cosmic-Ray Detectors



*Theor*

- *3D (*
- *Ado*
- *- PD*
- *A co*
- *Mag*

*n)*




Bialy & Godard in prep

# Looking Forward

Shmuel Bialy

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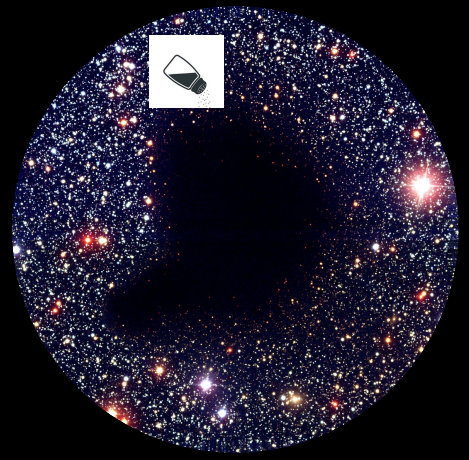

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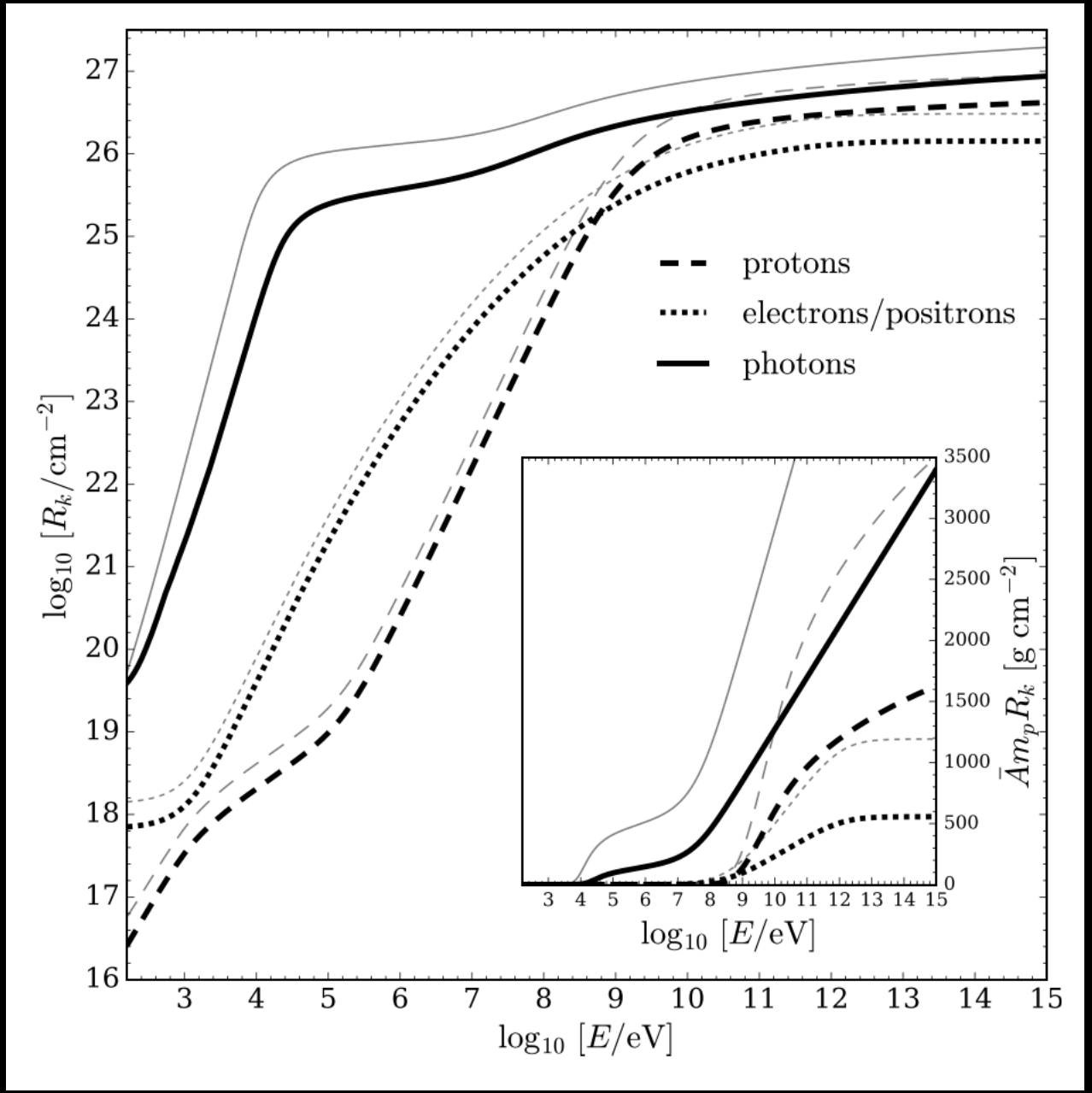
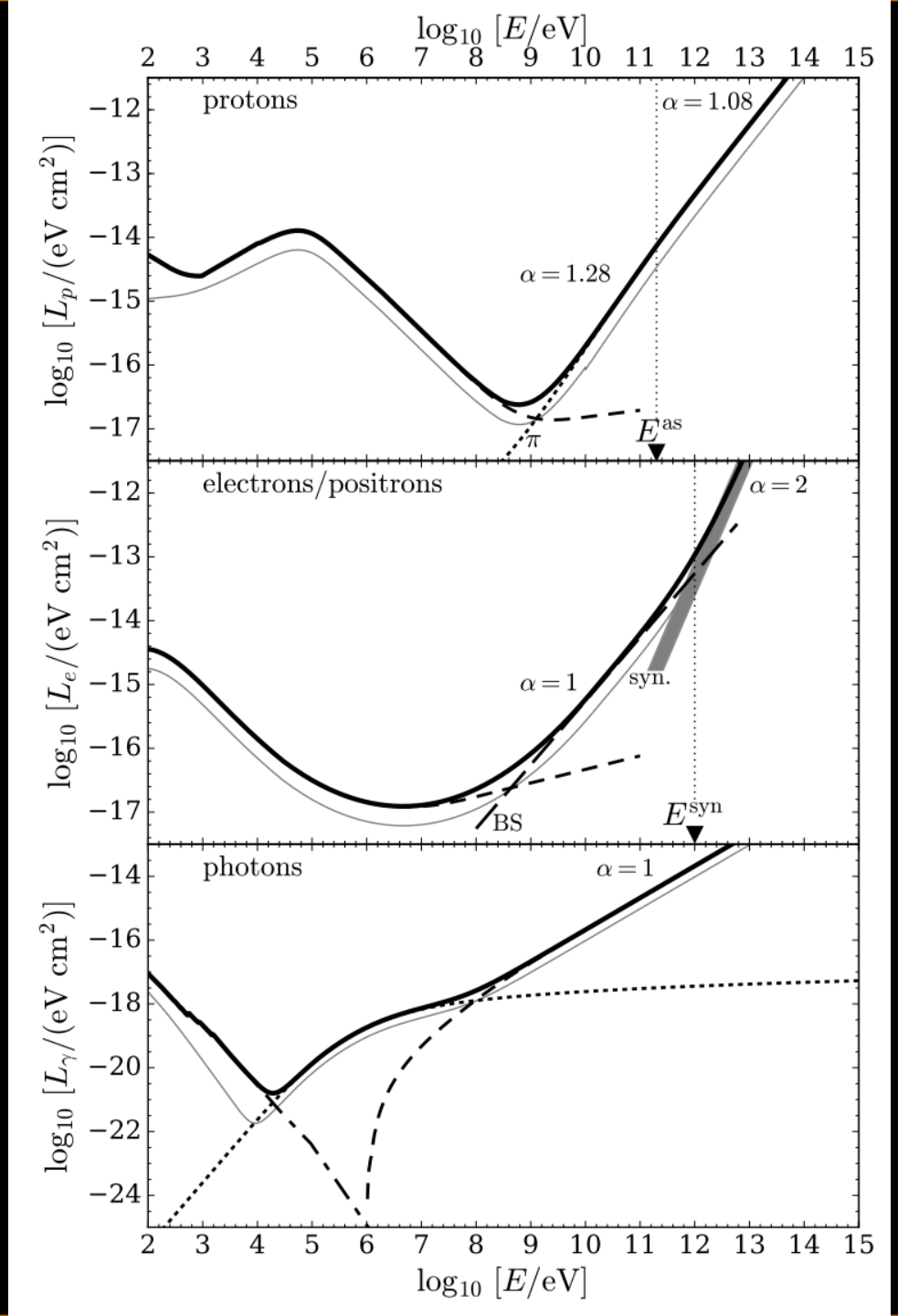



Padovani, Bialy et al. 2022 (A&A 658 189)




Padovani, Bialy et al. 2022
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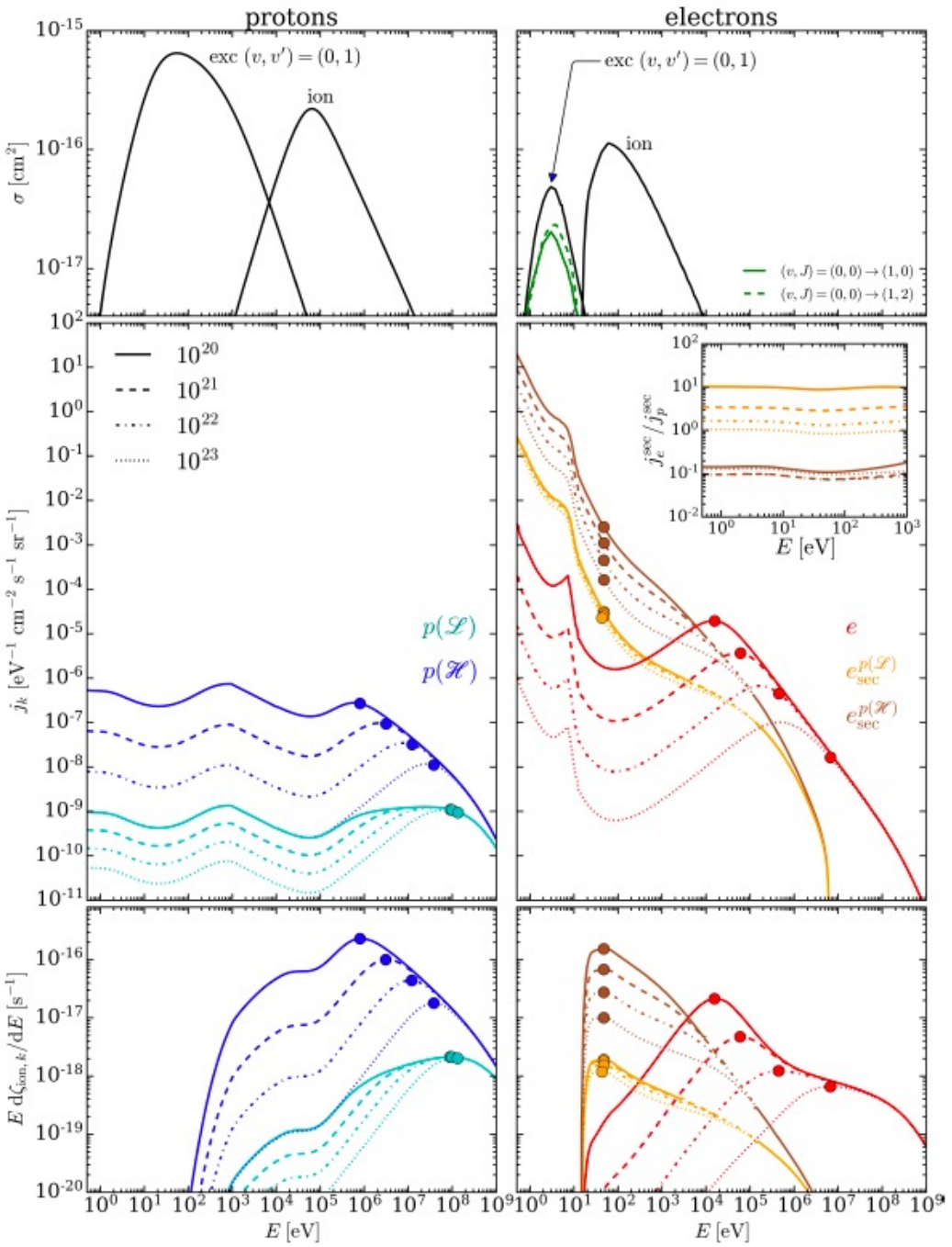


Padovani, Bialy et al. 2022
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