# ISM structure and the star formation rate

## The Role of Cosmic Rays

Shmuel Bialy

*Technion – Israel Institute of Technology*

*2 years ago…*

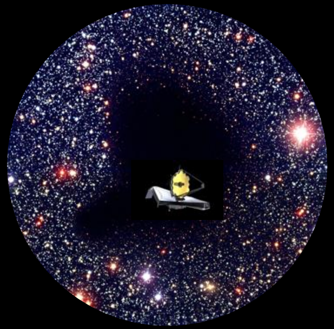
*Dense Molecular Cloud Cores*

*“Cold Clouds as CR detectors”*

*Bialy (2020)*
*Padovani et al. (2022)*
*Gaches et al. (2022)*

*2 years ago…*

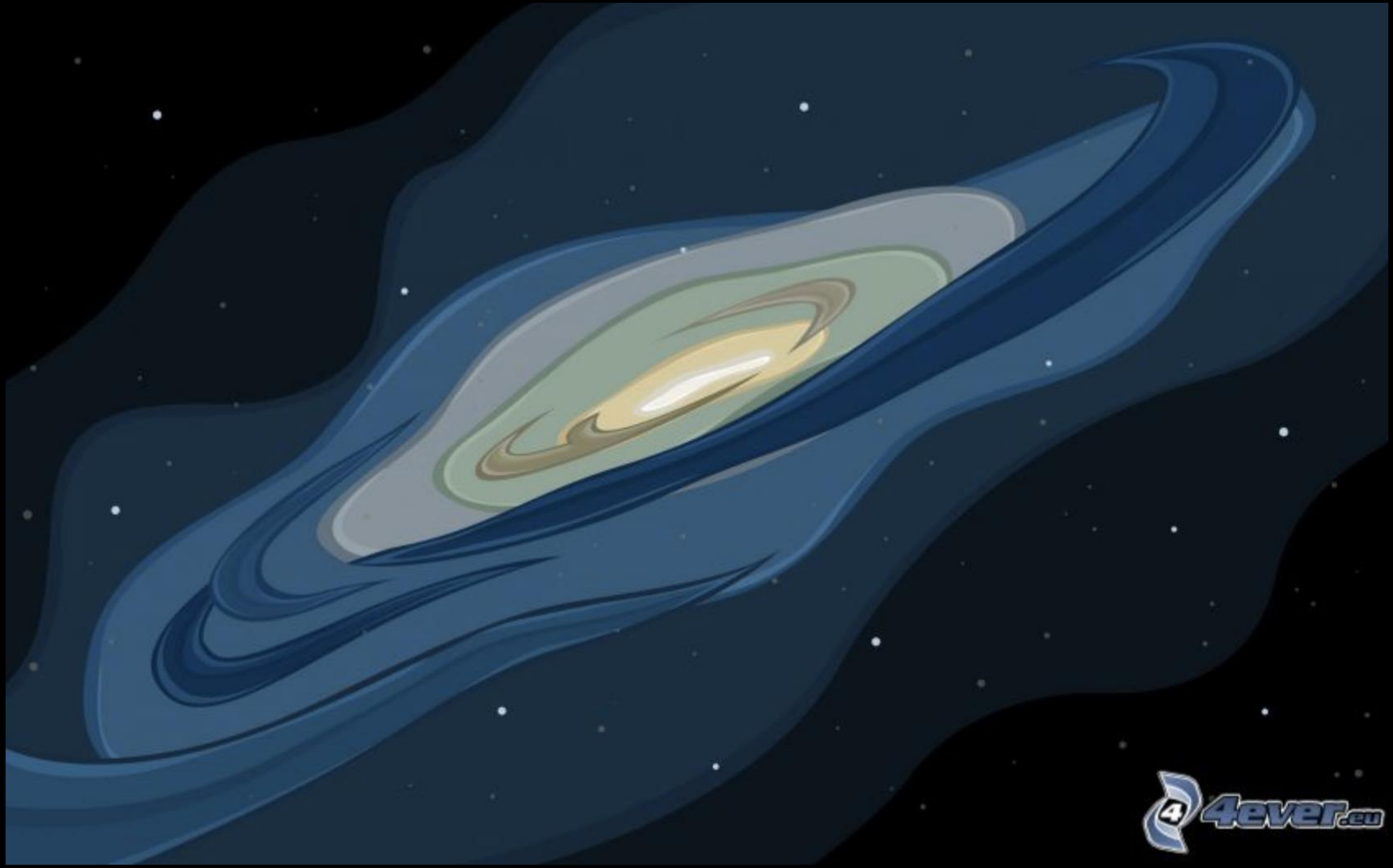
## *Molecular Cloud Cores*



*“Cold Clouds as CR detectors”*

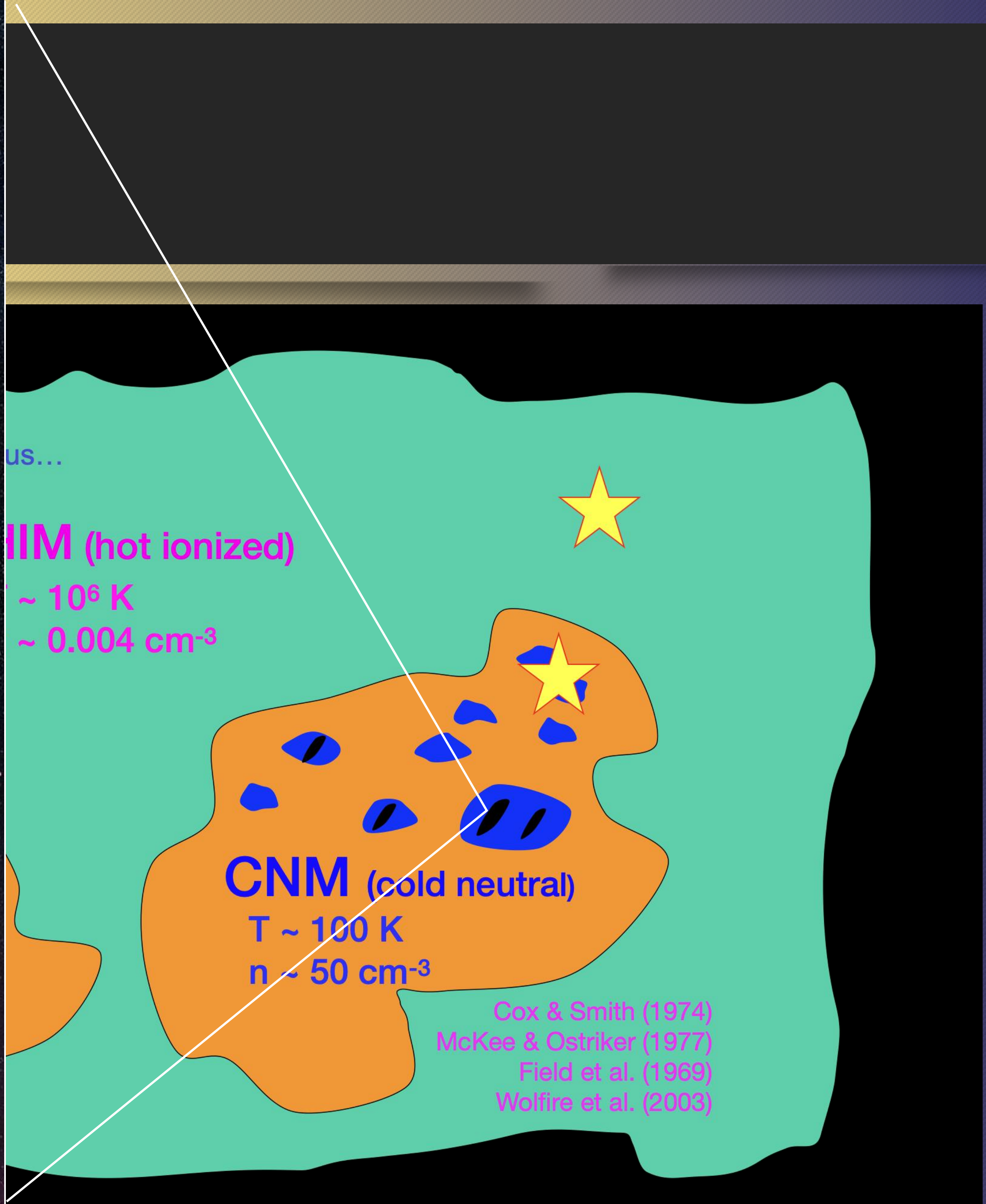
*Today…*

# *The ambient ISM - galactic scales*



## *How do CRs control the ISM structure and the SFR?*


Star-formation
Human-formation
Dense dark molecular clouds


us…
HIM (hot ionized)
~ 10^6 K
~ 0.004 cm^-3
CNM (cold neutral)
T ~ 100 K
n ~ 50 cm^-3
Cox & Smith (1974)
McKee & Ostriker (1977)
Field et al. (1969)
Wolfire et al. (2003)

# Goals

A) Theory of ISM's phase structure

- Predict ISM's propoerties: n, T, P
  as functions of conditions
  (Z' - metallicity, $I_{UV}$ - radiation intensity, $\zeta$ - CR ionization rate)

# Take home

## Low Metallicity (Z’) galaxies

- First galaxies (z~10,  JWST)
- Dwarf galaxies


1. CRs dominate ISM heating
2. ISM become denser and pressuraized
3. Thermal pressure 💪 $\gg$ Turbulent pressure 🥴
4. SFR efficiency $\Sigma_{SFR}/\Sigma_{gas}$ ⤵ and $t_{dep}$ ⤴

# Our Model

**ISM physics**

**Heating:**

- FUV: photoelectric heating – $\boldsymbol{I_{UV}}$ *and* $\boldsymbol{Z'_{\mathrm{dust}}}$
- CR (or X-ray) ionization - $\boldsymbol{\zeta}$

**Cooling:** line emission

- Lyman $\alpha$ (n=1 transition of H)
- $C^+$ and O fine-structure transitions ***Z'***

  (+$H_2$ chemistry and cooling/heating)

***Thermal Balance***

**[cooling=heating]**

# Results I:

# ISM's multiphase at low Z'

# The multiphase ISM – solar metallicity (Z'=1)

Small P  - only WNM
Large P - only CNM

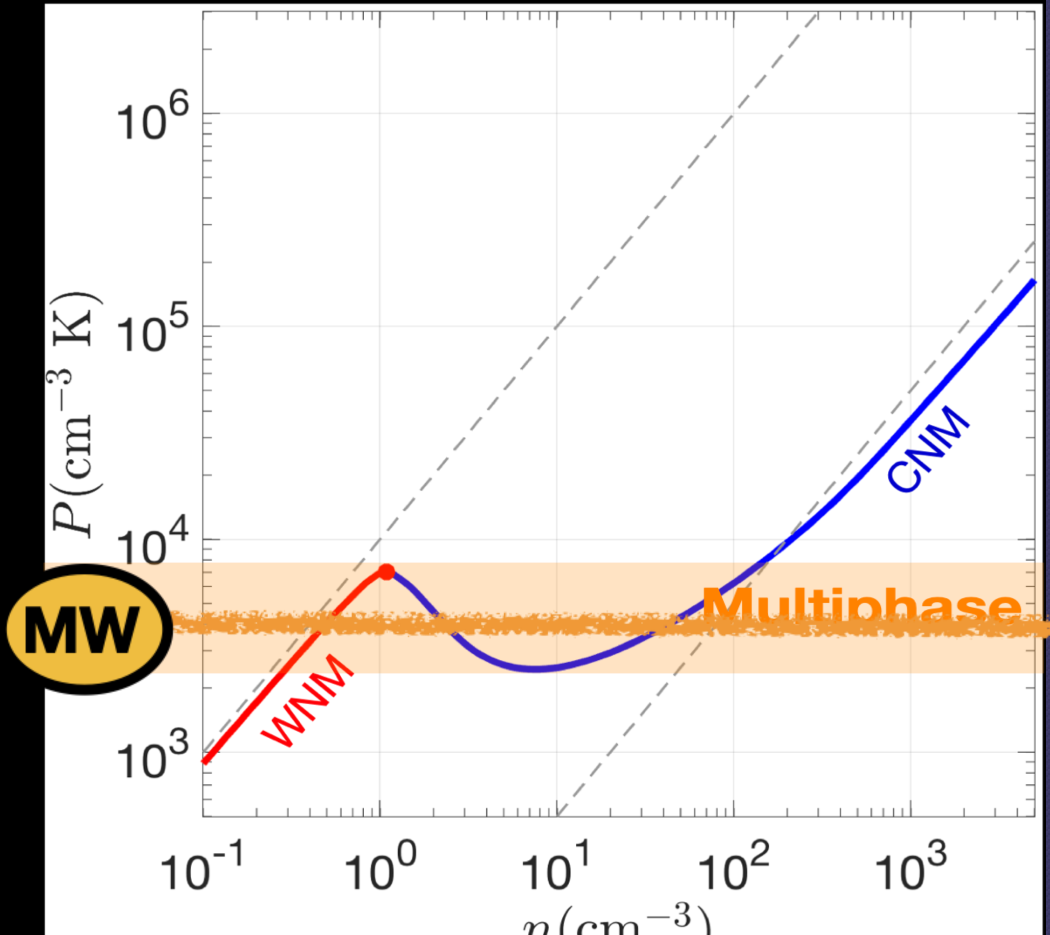
Within a narrow pressure range ($P_{min}$ - $P_{max}$) a multiphase WNM-CNM exists

In agreement with Wolfire et al (95, 23)

**The observed ISM pressure $P \sim 3000$ K cm$^{-3}$, is inside the multiphase zone!**

Jenkins & Tripp (2001)
Wolfire et al. (2003)

Phase diagram - Solar metallicity (Z'=1)




Bialy & Sternberg (2019)

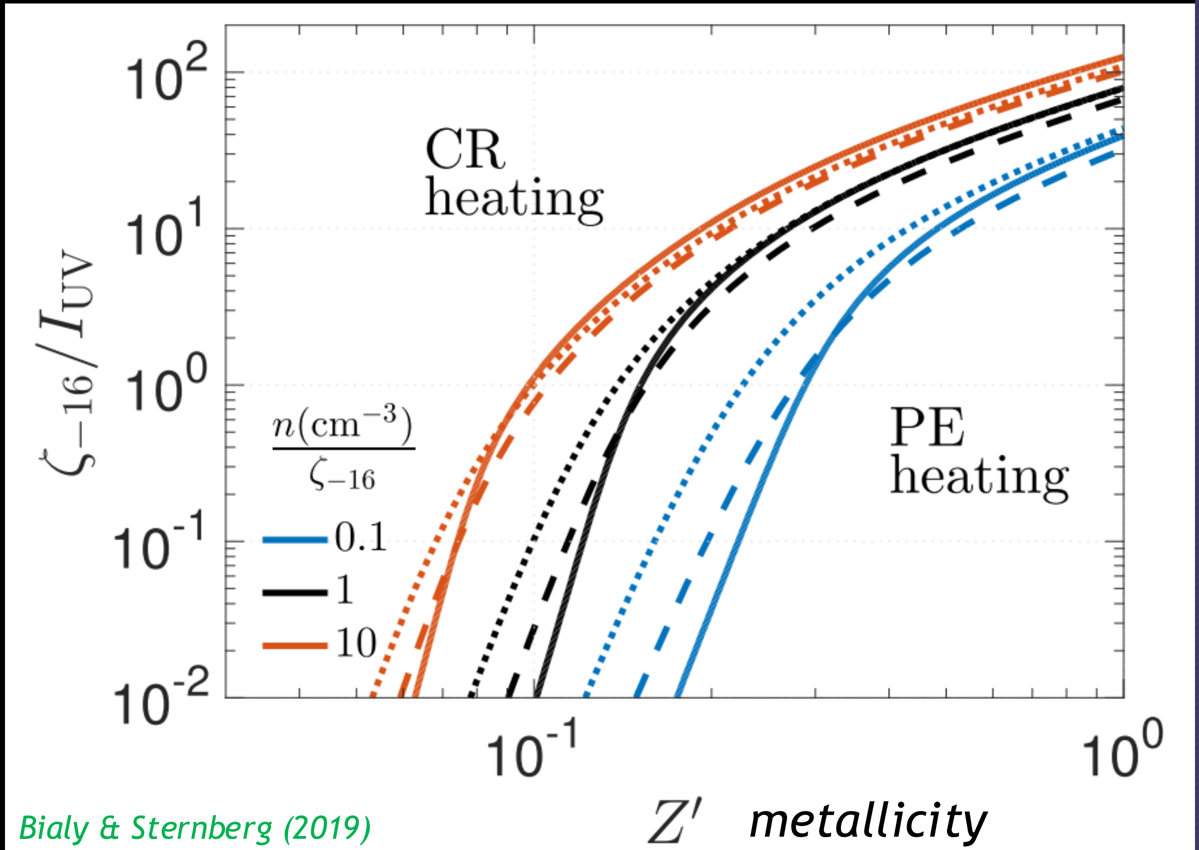
# Low Z' – CRs kick in!

## *UV photoelectric heating vs- Cosmic ray ionization heating*

***At Z' ~ 1 (solar metallicity)***
*Photoelectric (PE) heating dominates*

***For Z' < 0.1***
*cosmic ray ionization dominates heating*

*Why?*
*PE heating is mediated through dust*
*CRs heat the gas directly via H ionization*




Bialy & Sternberg (2019)

# Low Z’ – High pressure and density ISM due to CR heating

***At low Z’:***

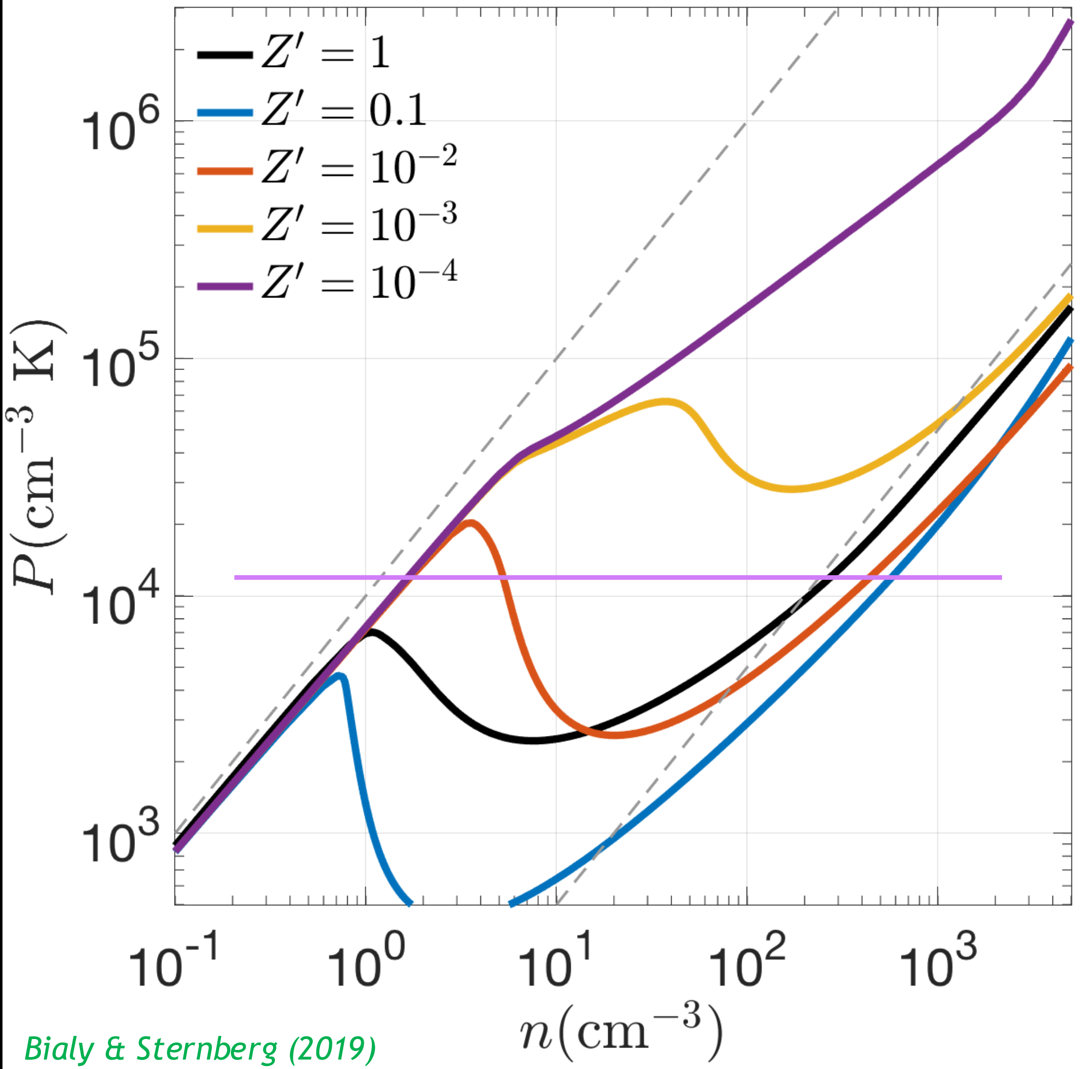
*Heating rate per volume* $\propto \zeta_{CR}$

*Cooling rate per particle* $\propto n Z'$

As Z’ decreases,
The Multiphase density and pressure increase ⤴

Thermal pressure becomes dominant ($P_{th} > P_{turb}$)

Wouldn’t be the case if not for the CRs



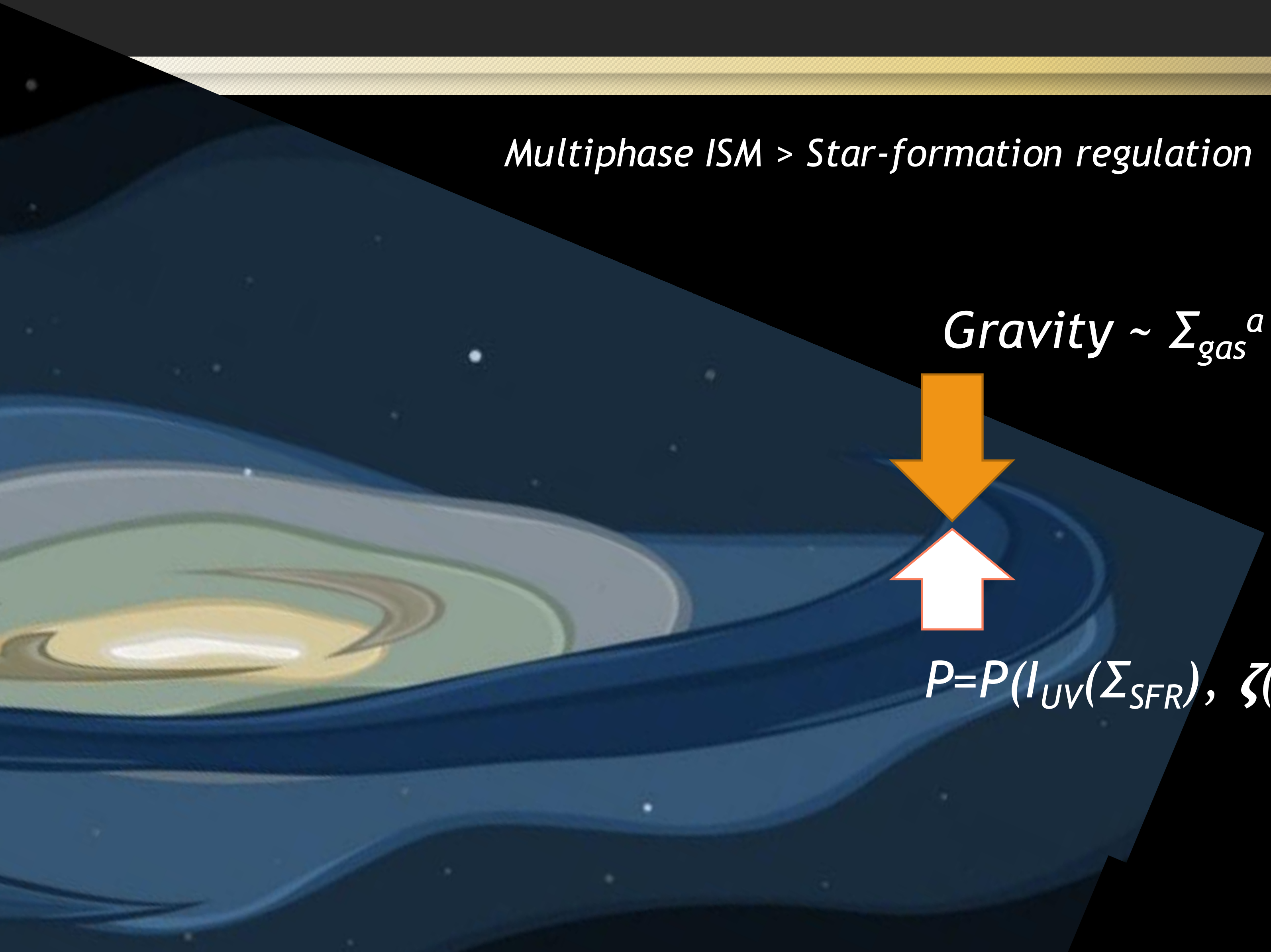

*Bialy & Sternberg (2019)*

# Results II:

# The SFR law at low Z’

# Star Formation Law

*Multiphase ISM > Star-formation regulation*



$Gravity \sim \Sigma_{gas}^{a}$

$P = P(I_{UV}(\Sigma_{SFR}),\ \zeta(\Sigma_{SFR}),\ Z')$

# Star Formation Law

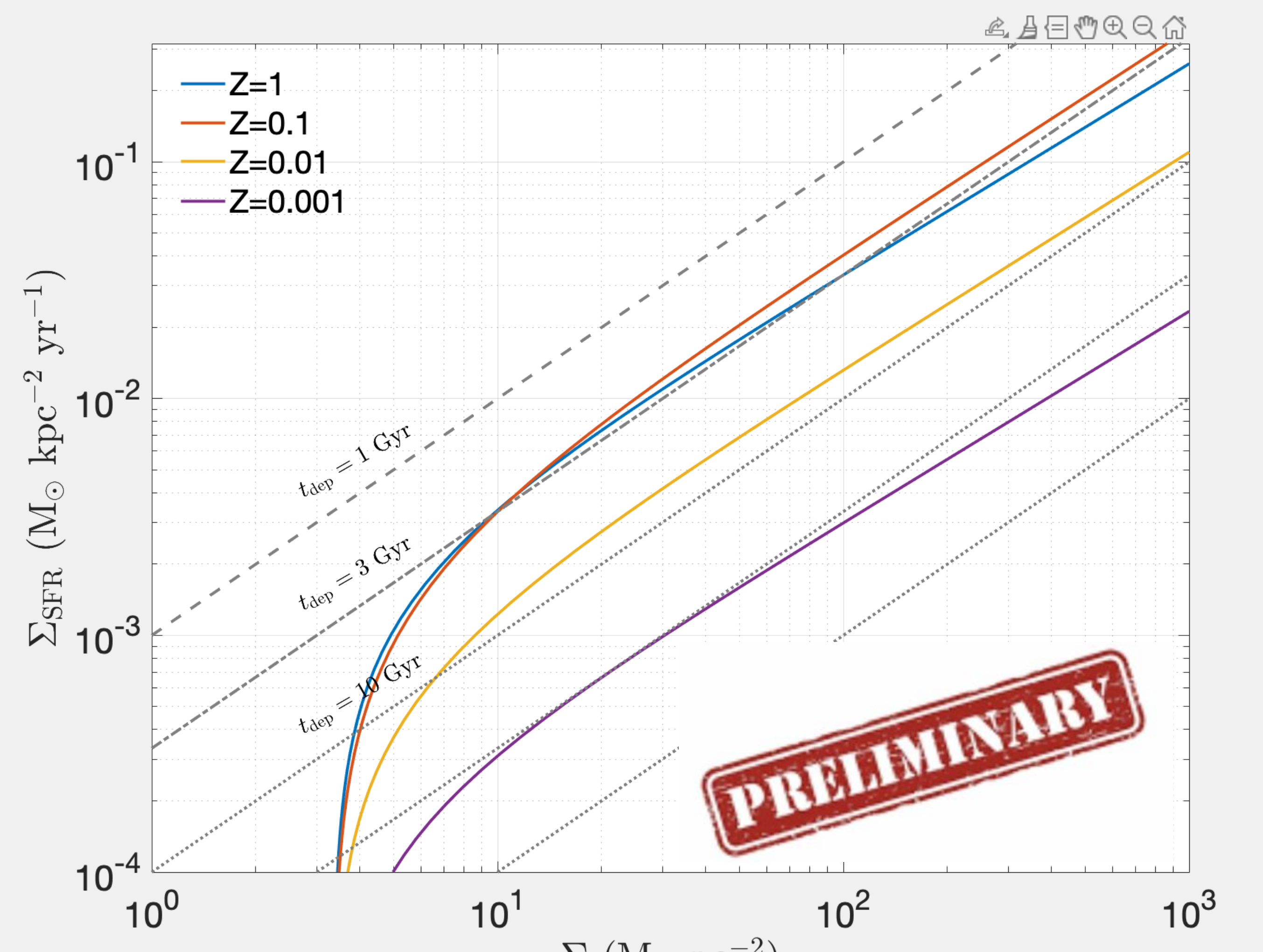
*Multiphase ISM*

*> Star-formation regulation*

A metallicity- dependent star formation law

Low metallicity galaxies form stars less efficiently due to CR heating

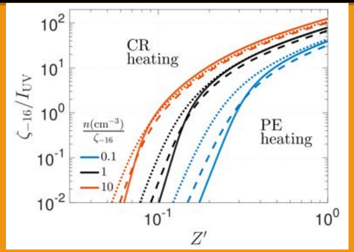
Wouldn't be the case if not for the CRs



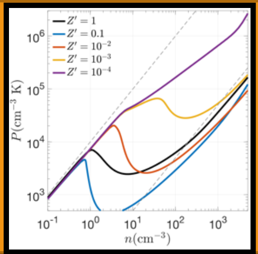

*Klein & Bialy (in prep)*

# Summary

(1)

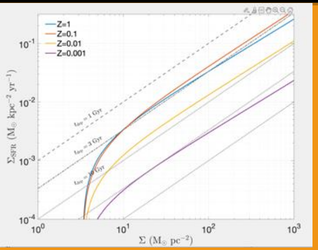



(2+3)




*Bialy & Sternberg (2019)*

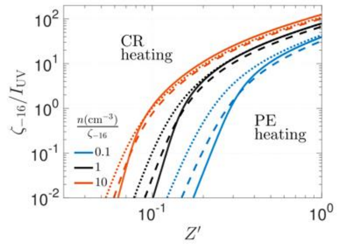
(4)




*Klein & Bialy (in prep)*


# Summary

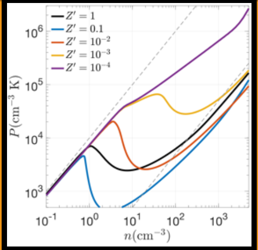
(1) At low Z’ CRs dominate ISM heating



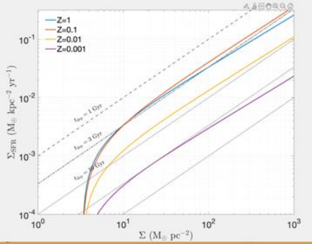

*Bialy & Sternberg (2019)*

(2) ISM become denser and pressuraized

(3) Thermal pressure💪 ≫ Turbulent pressure🥴




(4) SFR efficiency $\Sigma_{SFR} / \Sigma_{gas}$ ⤵ and $t_{dep}$ ⤴

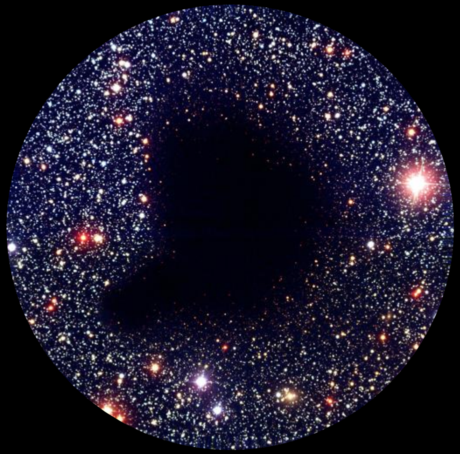



*Klein & Bialy (in prep)*

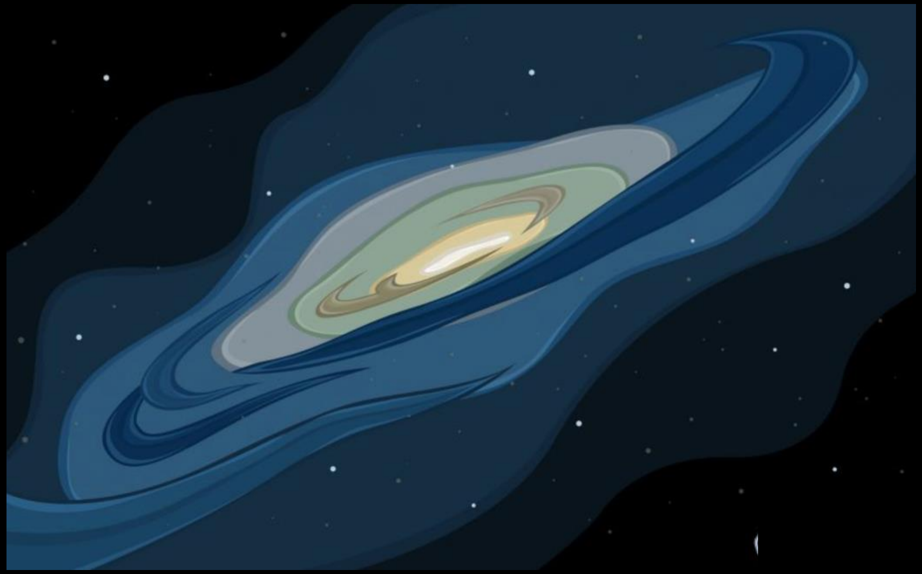
# EXTRA SLIDES

# Cosmic Rays

*Dense Molecular Cloud Cores*



*Neutral atomic ISM*



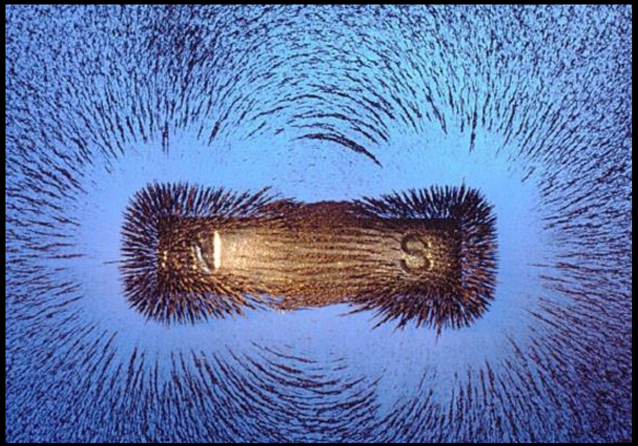
# Cosmic-Rays - *Dense Molecular Cloud Cores*

Low energy cosmic-rays

Ionization (primary + secondary)

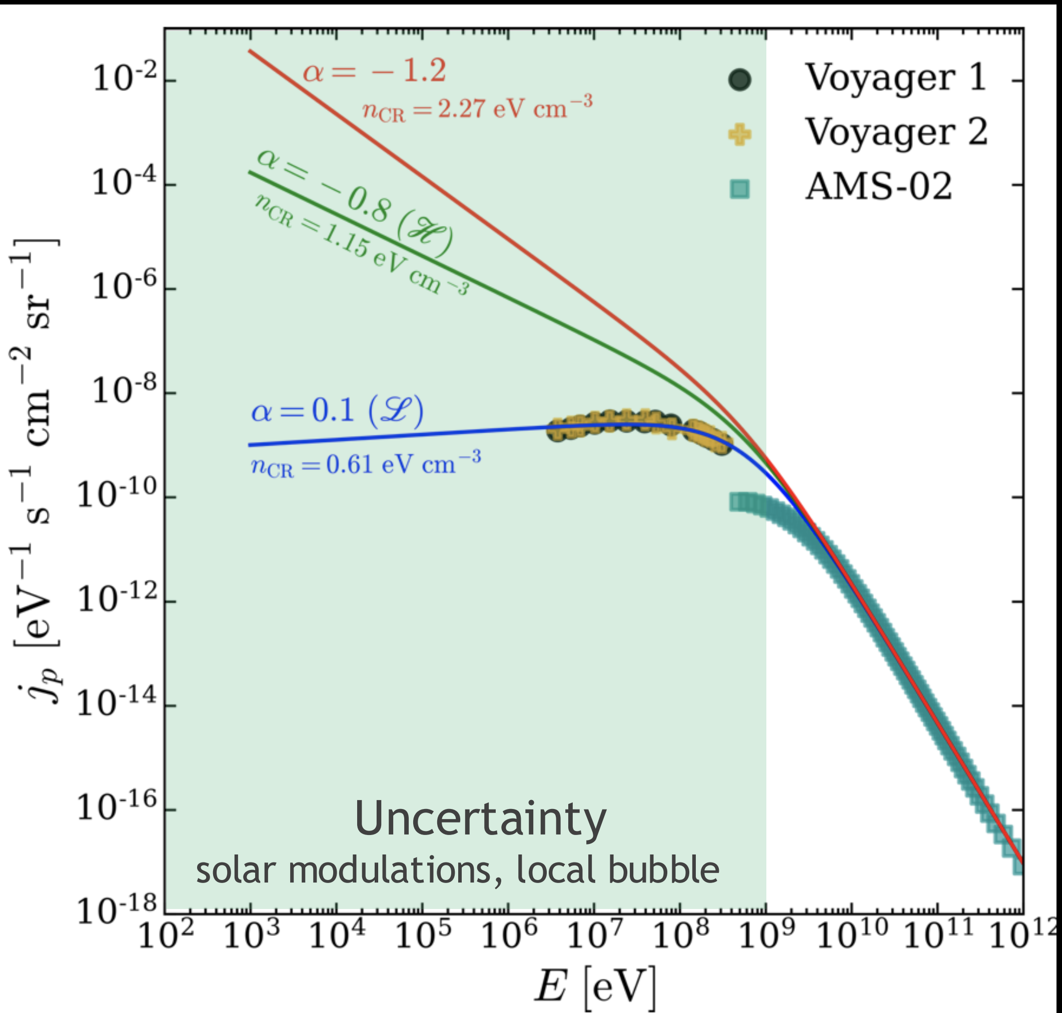
chemistry

heating

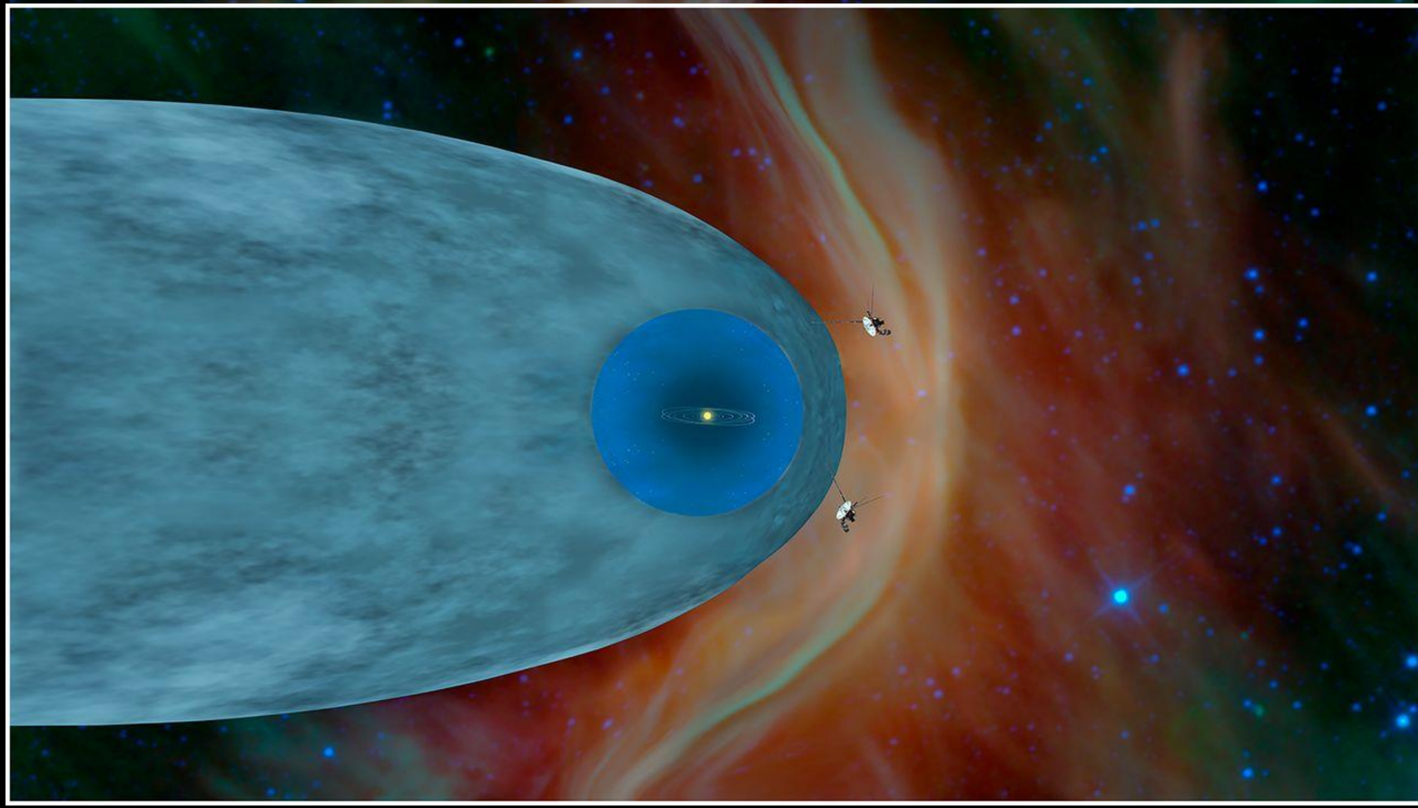


Coupling to B fields

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



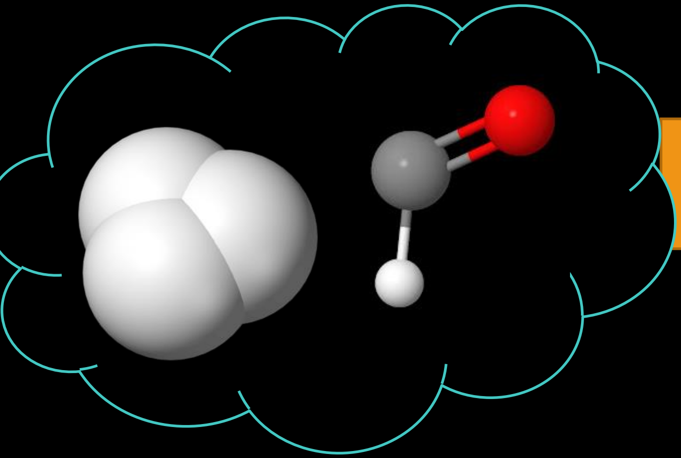

Direct observations: Earth and space



credit: NASA/JPL-Caltech

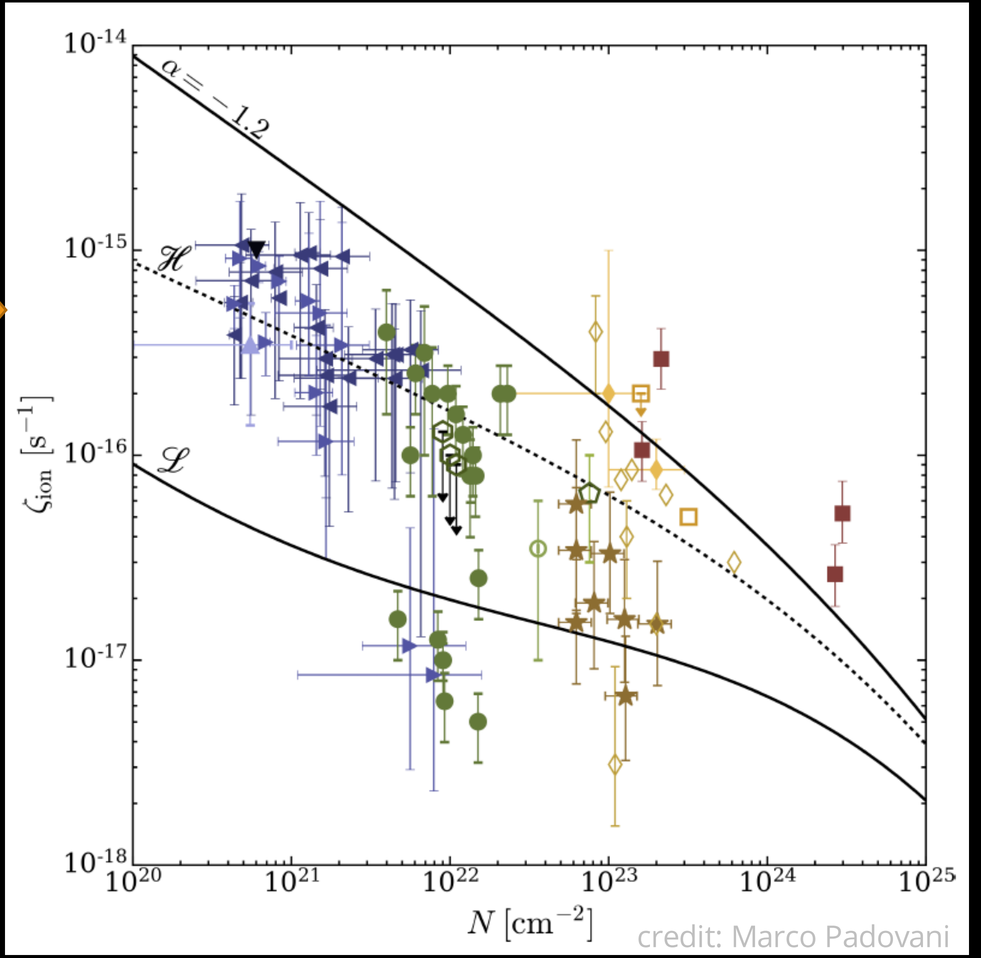
# What is the flux of low-energy cosmic-rays?

**Indirect observations:**
astrochemistry in interstellar clouds



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

credit: Marco Padovani



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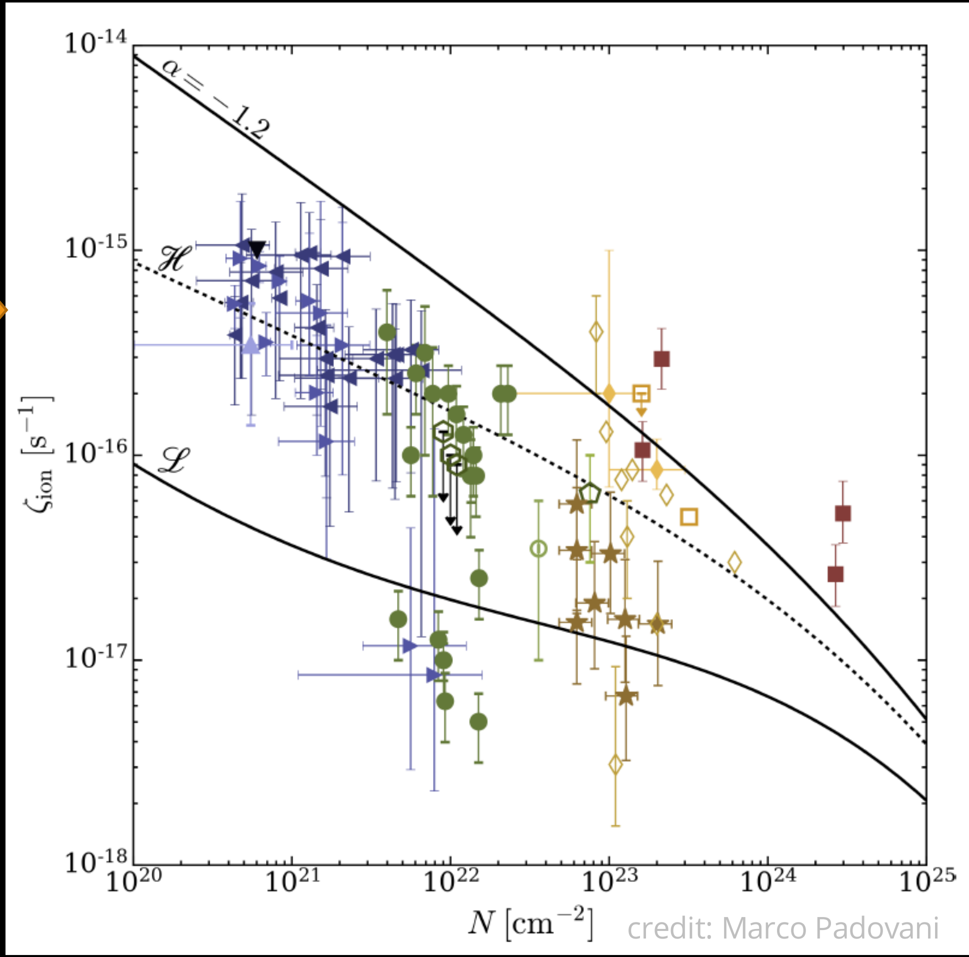
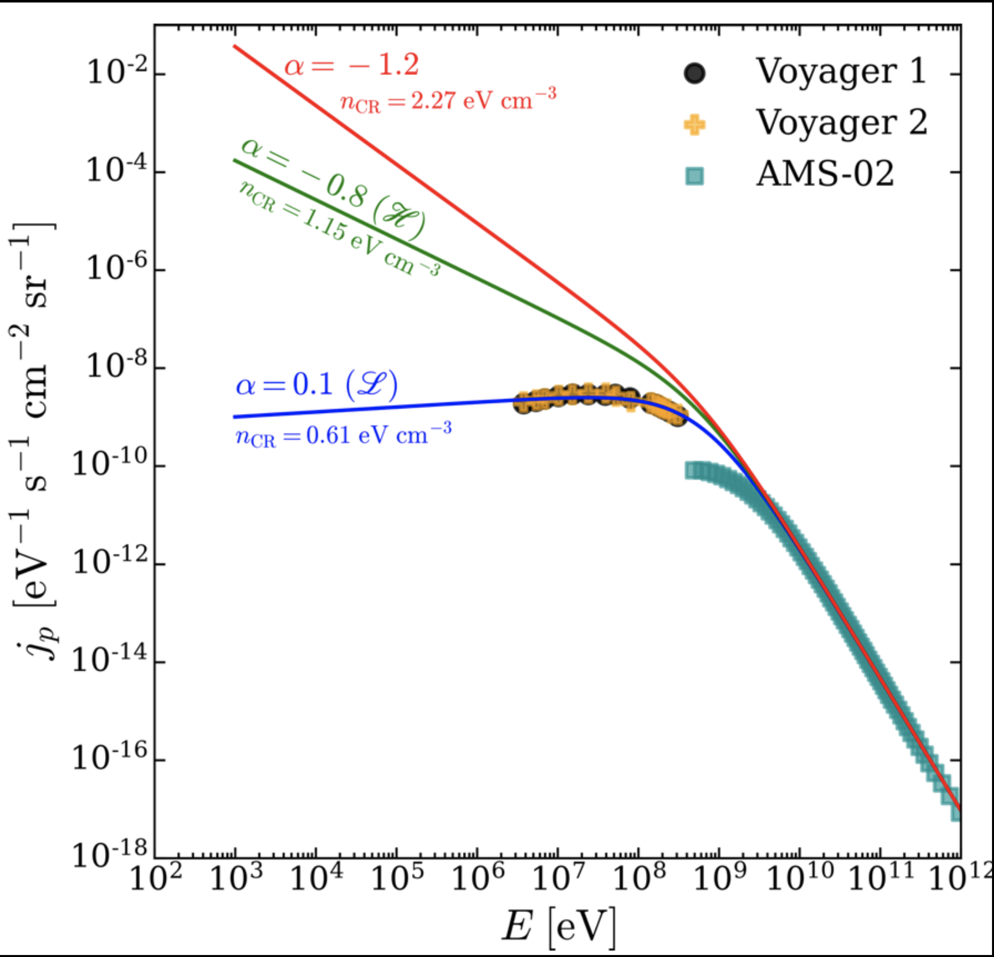
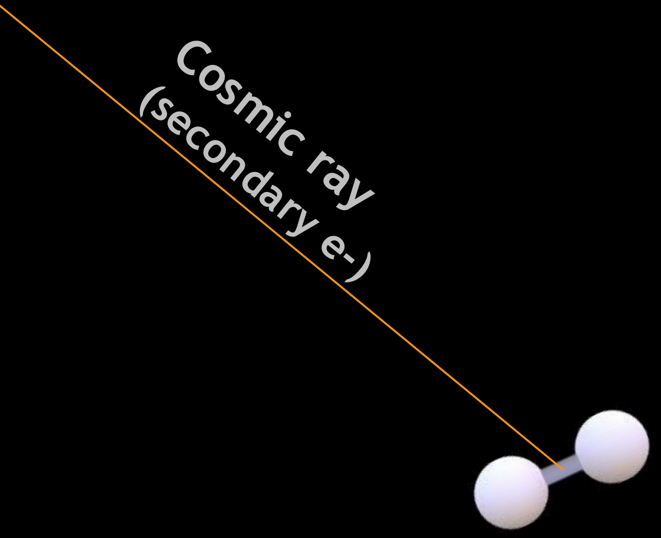
els
n, $x_e$



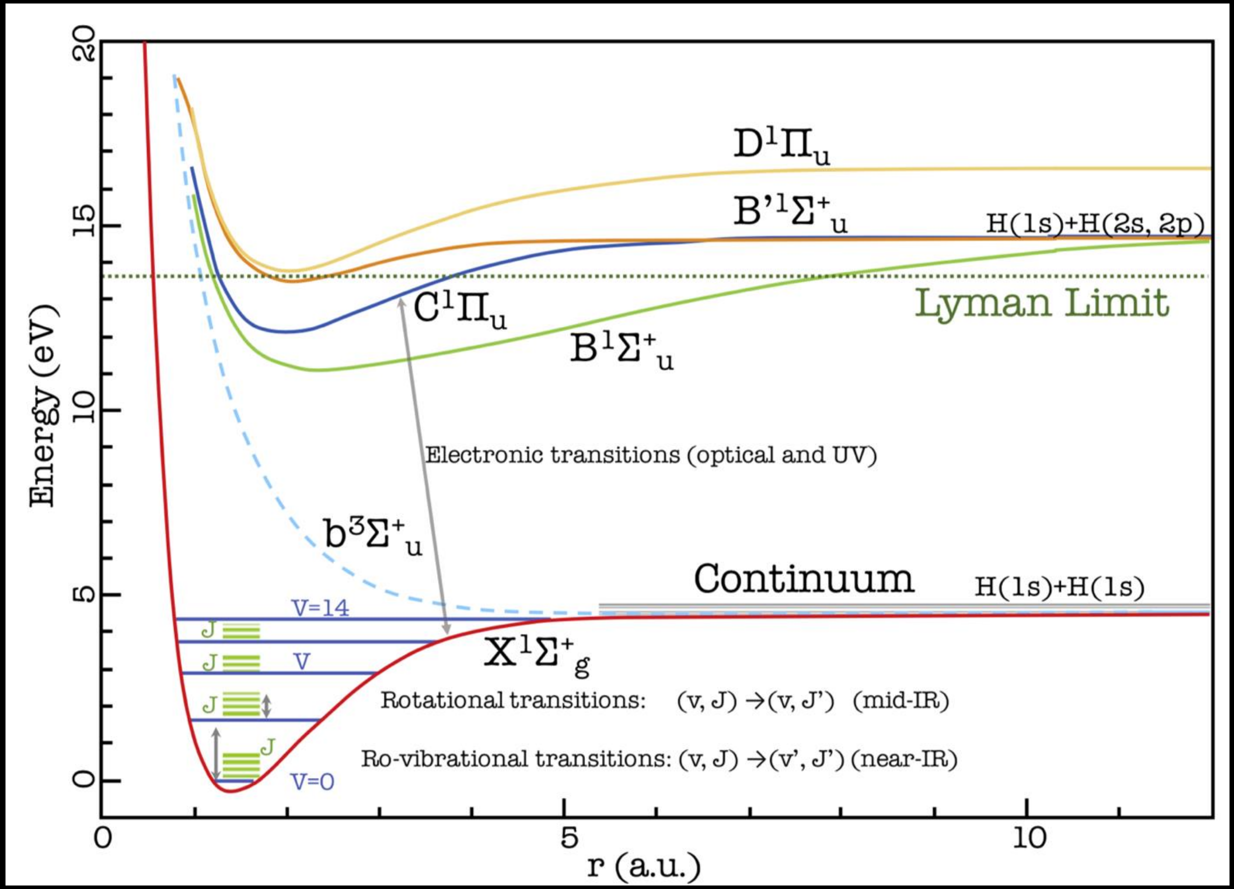



# The idea

Use H2 excitation to probe cosmic-rays



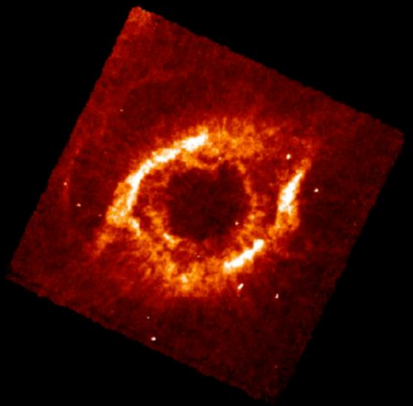

H2 energy level diagram

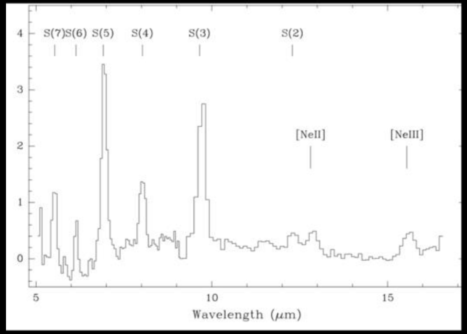


# The idea

## Use H2 excitation to probe cosmic-rays

### Planetary nebula






Collisional (high T)

### Photo-dissociation region

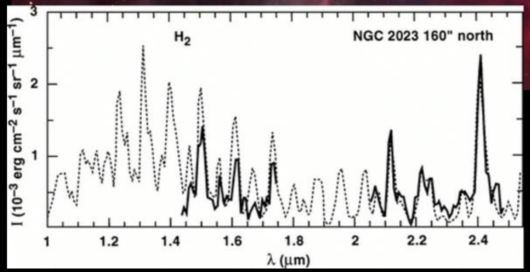
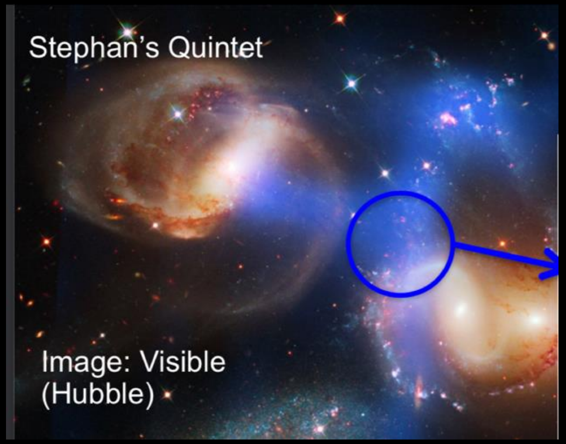
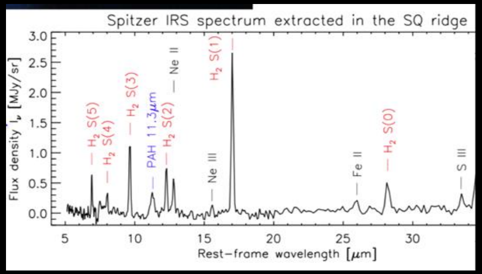



Photo excitation

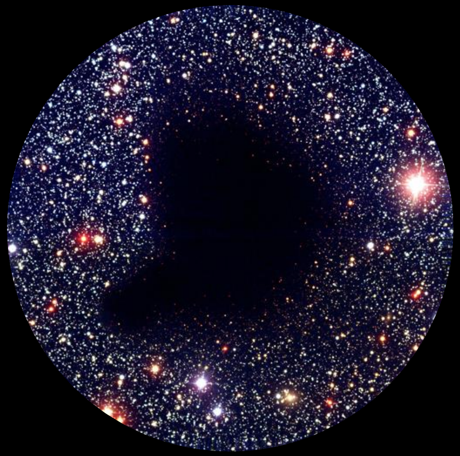
### Shocked gas



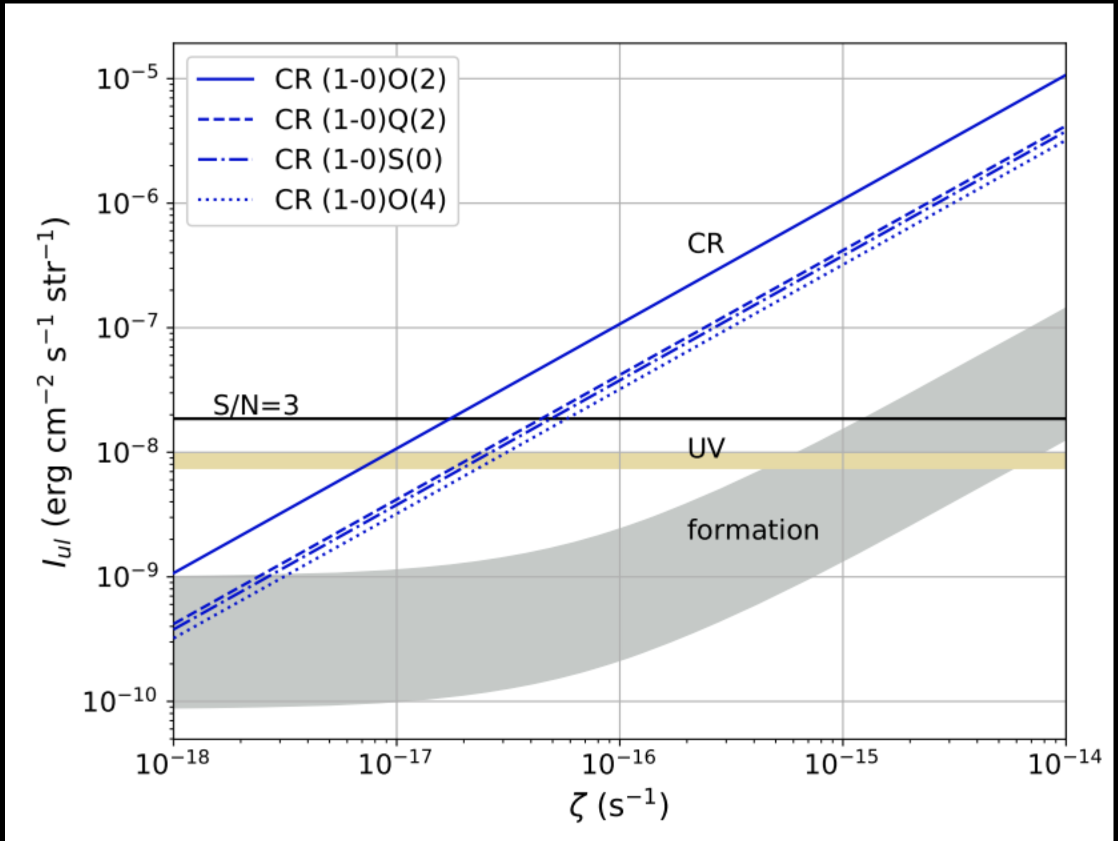

Collisional (high T)

### Cosmic-rays?



# The idea

Use H2 excitation to probe cosmic-rays



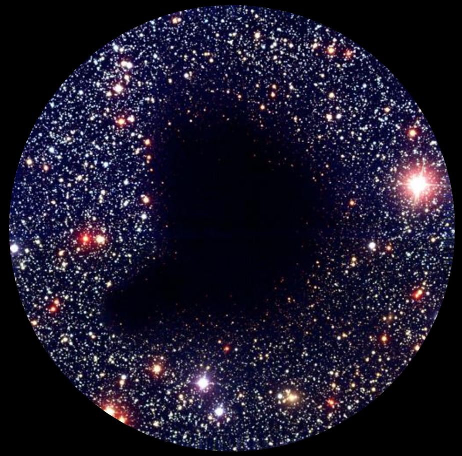

Bialy (2020, Nature Com. Phys. 3 32)

The four lines that are preferentially excited by cosmic-rays

v=1
J=0 or 2

$$I_{ul,(\mathrm{cr})} = \frac{1}{4\pi} g N_{\mathrm{H}_2} \zeta_{\mathrm{ex}} p_{u,(\mathrm{cr})} \alpha_{(u)l} E_{ul},$$

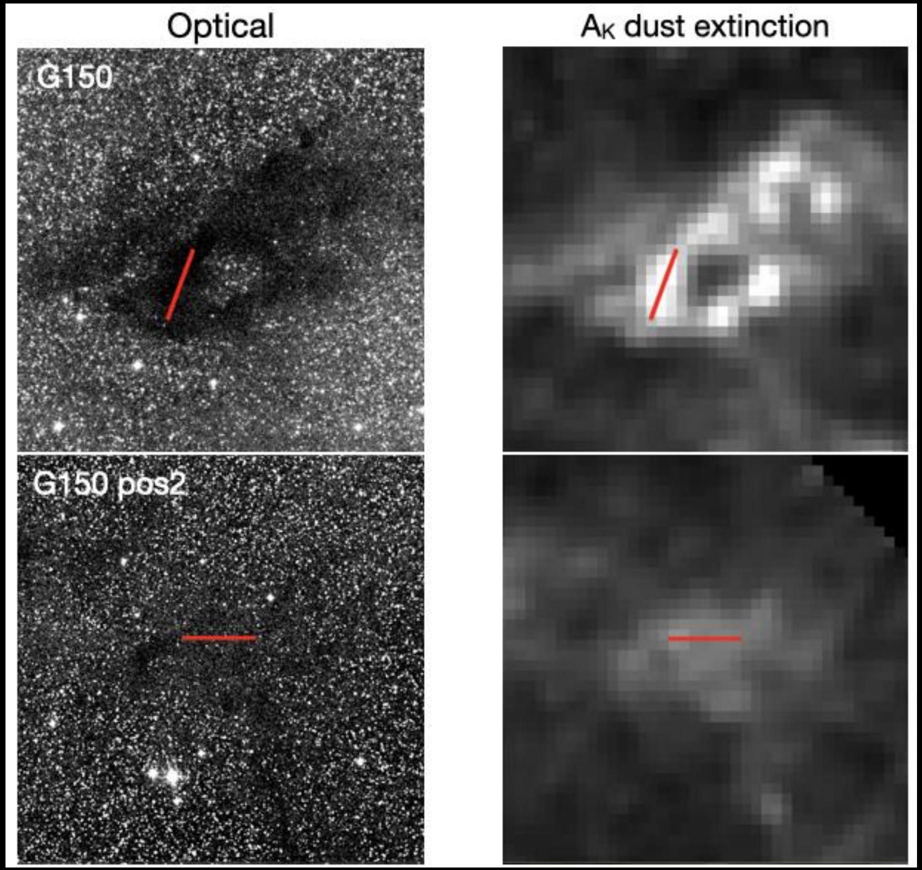
Cosmic-rays

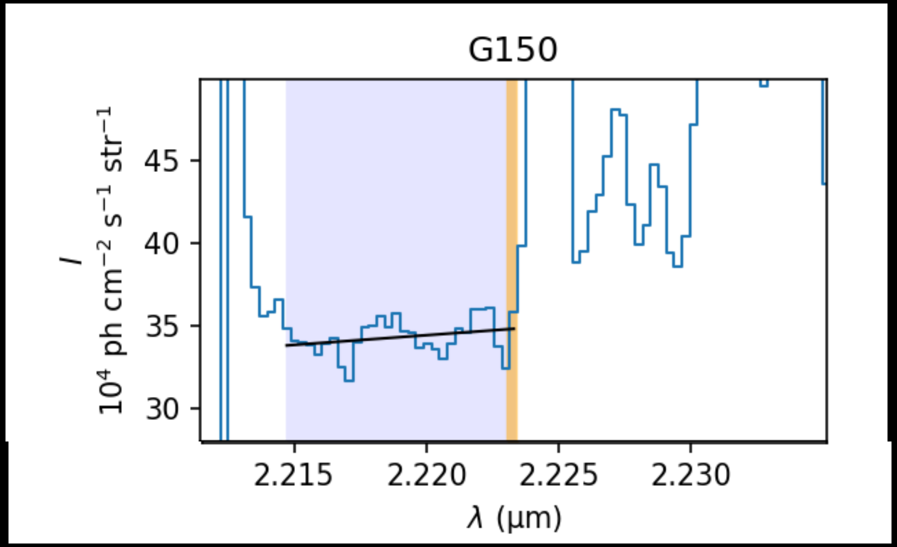


# Observations

## Constrain the CR spectrum and ionization rate

NIR spectroscopy of molecular nearby clouds



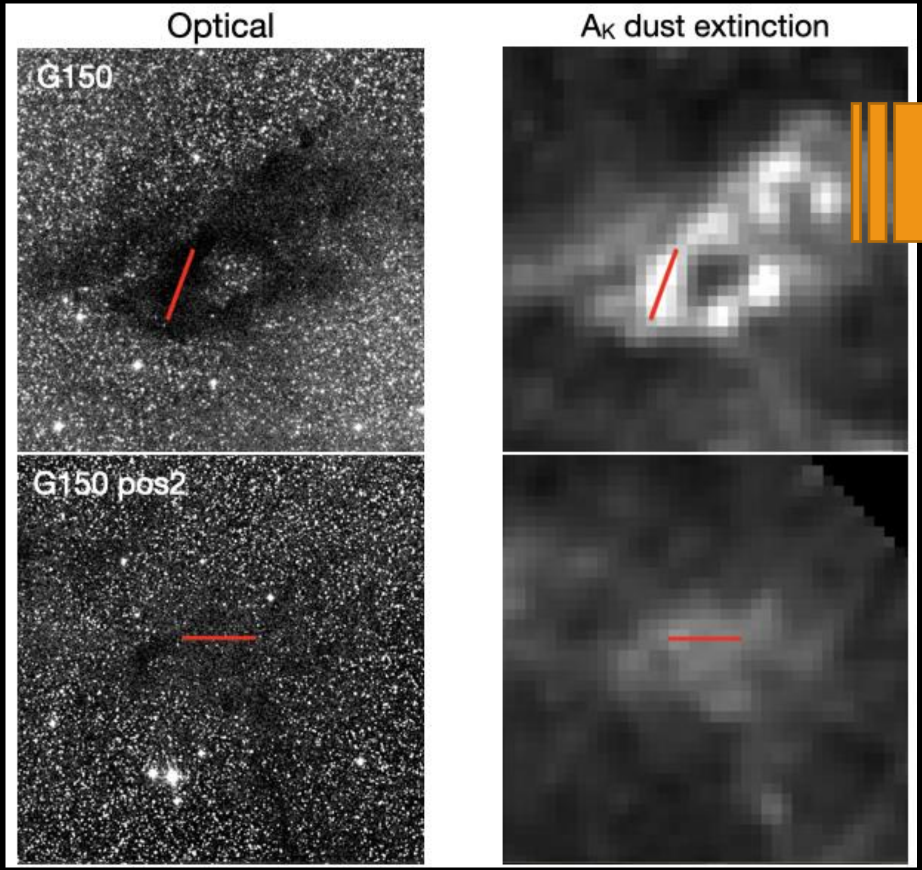

MMT 6.5m Arizona

Bialy et al. (2022)

# Observations + Model

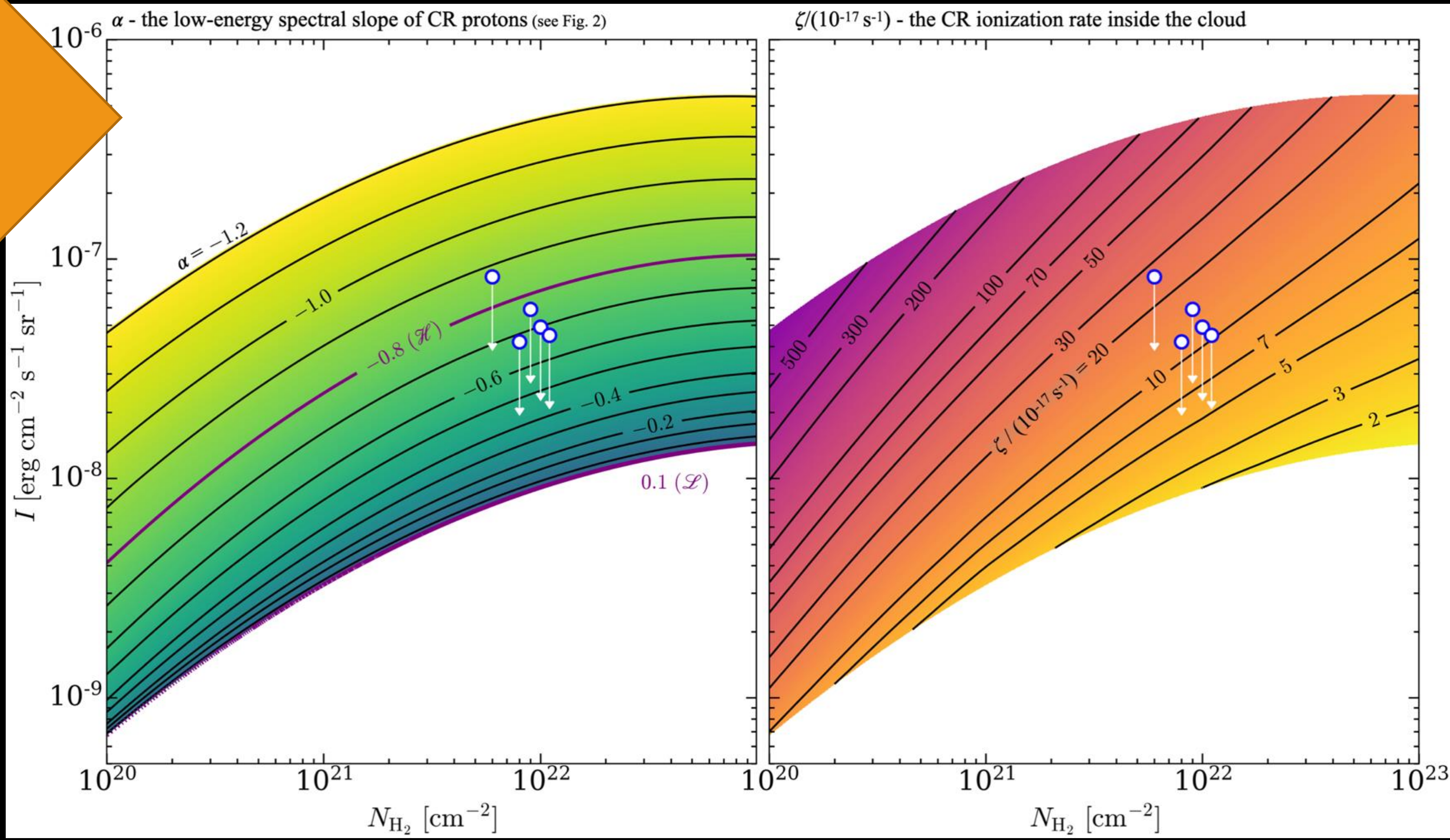
Constrain the CR spectrum and ionization rate

NIR spectroscopy of molecular nearby clouds




Slope of CR proton spectrum (interstellar)

Ionization rate inside the clouds

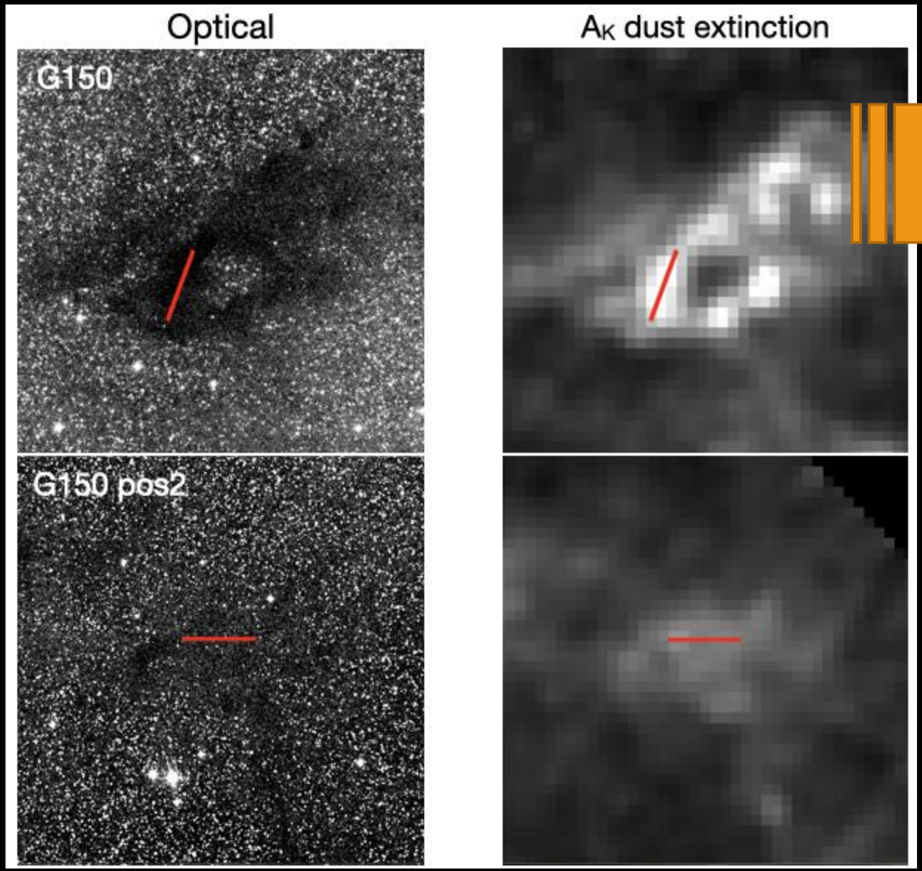



Bialy et al. (2022)

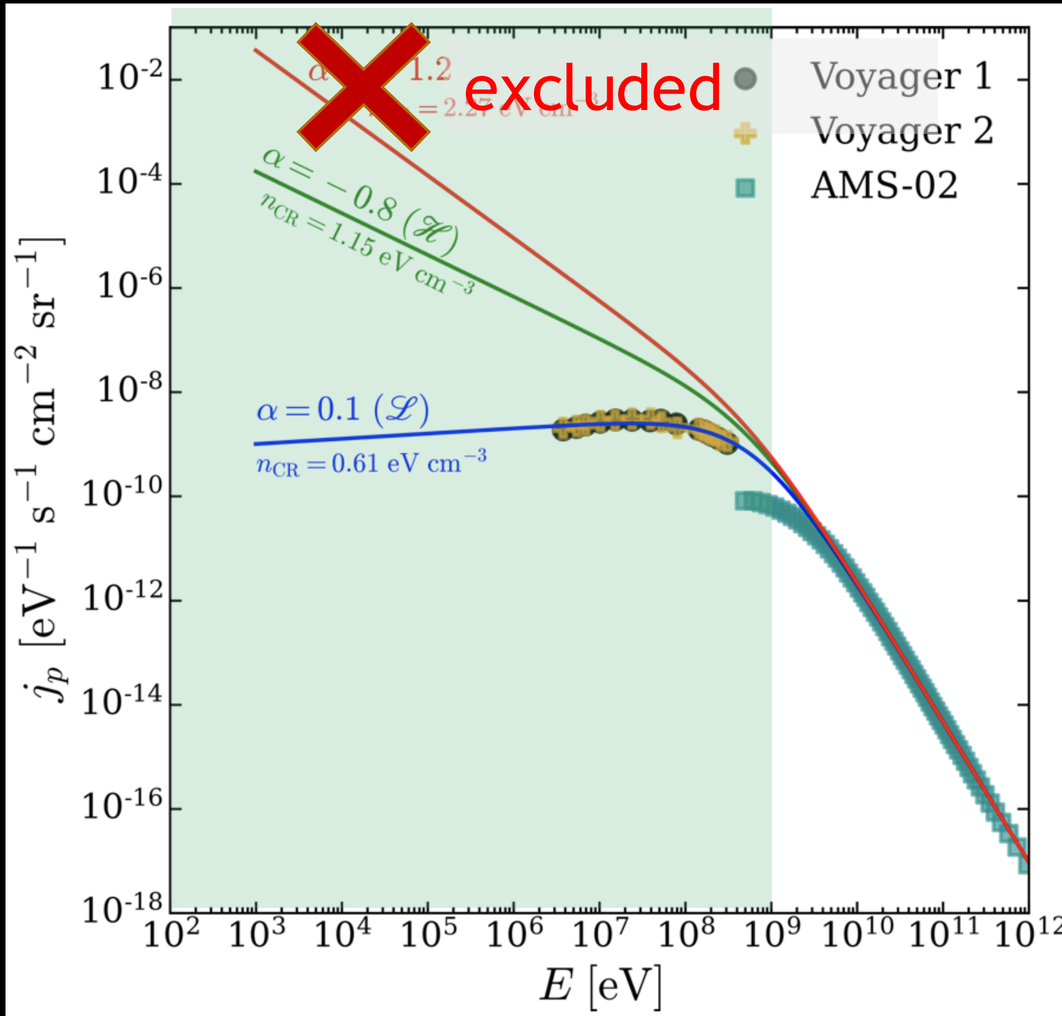
# Observations + Model

**Constrain the CR spectrum and ionization rate**

NIR spectroscopy of molecular nearby clouds



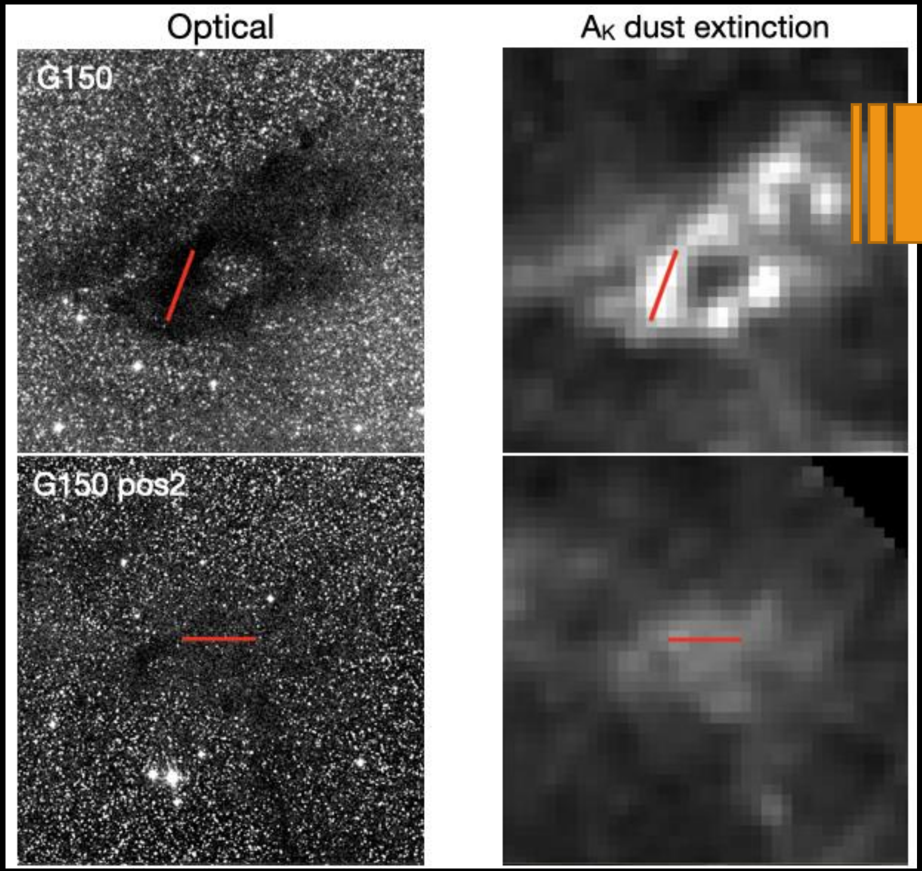

Bialy et al. (2022)



# Observations + Model

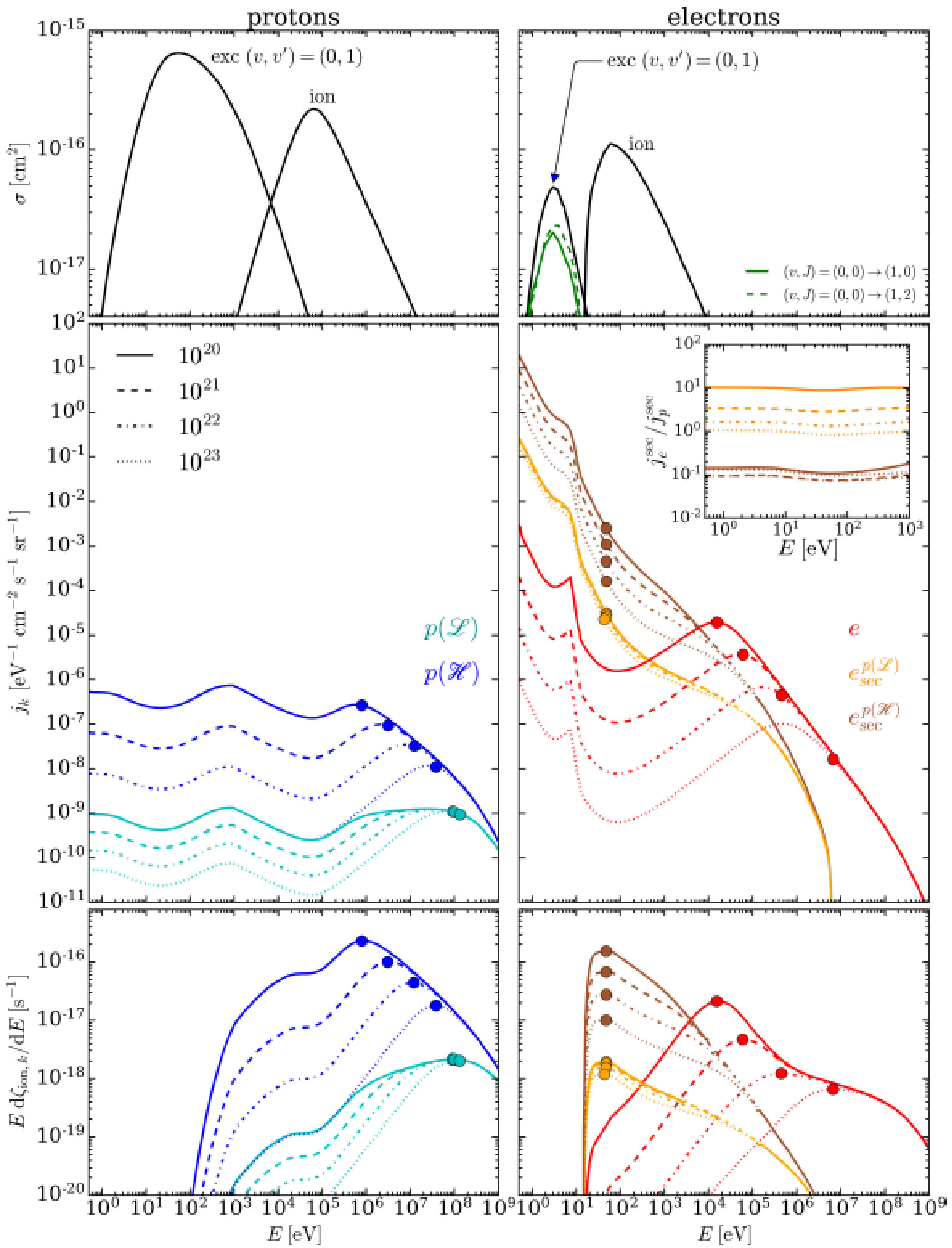
Constrain the CR spectrum and ionization rate

NIR spectroscopy of molecular nearby clouds

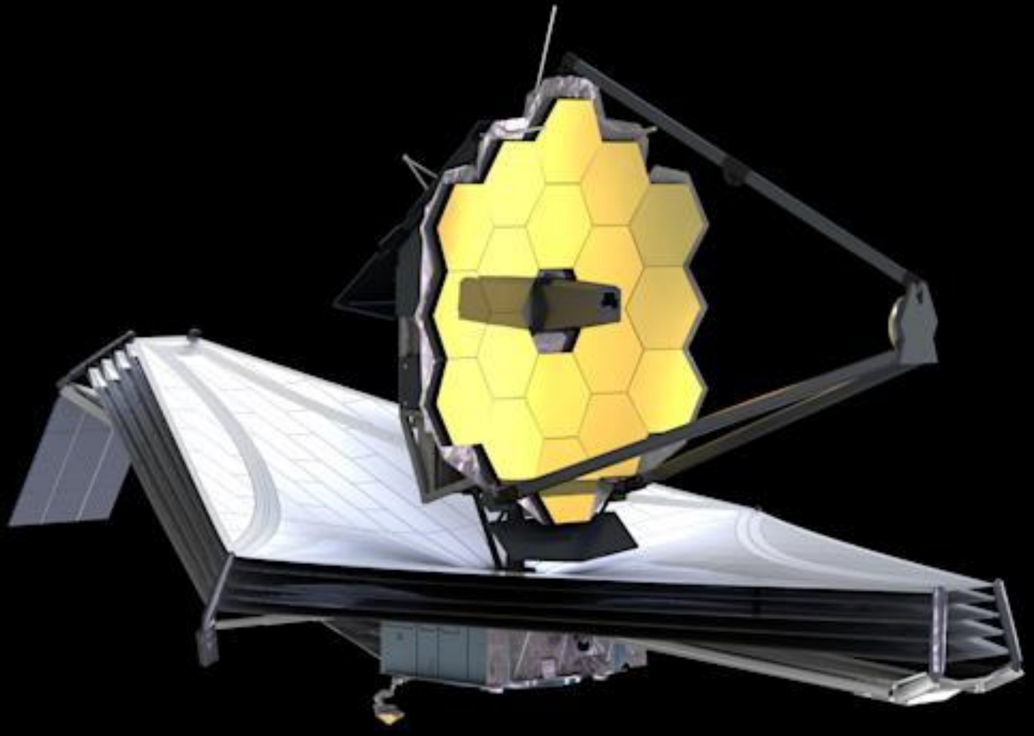



Bialy et al. (2022)

Modeling CR propagation Padovani, Bialy et al. (2022)



# The Future is Now



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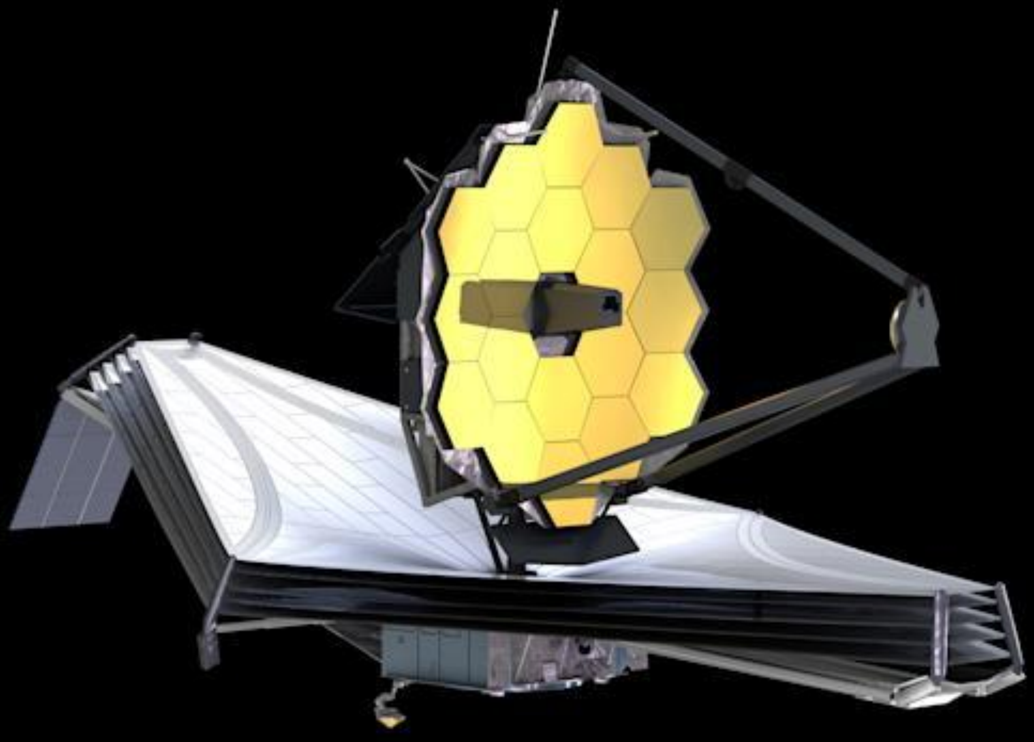
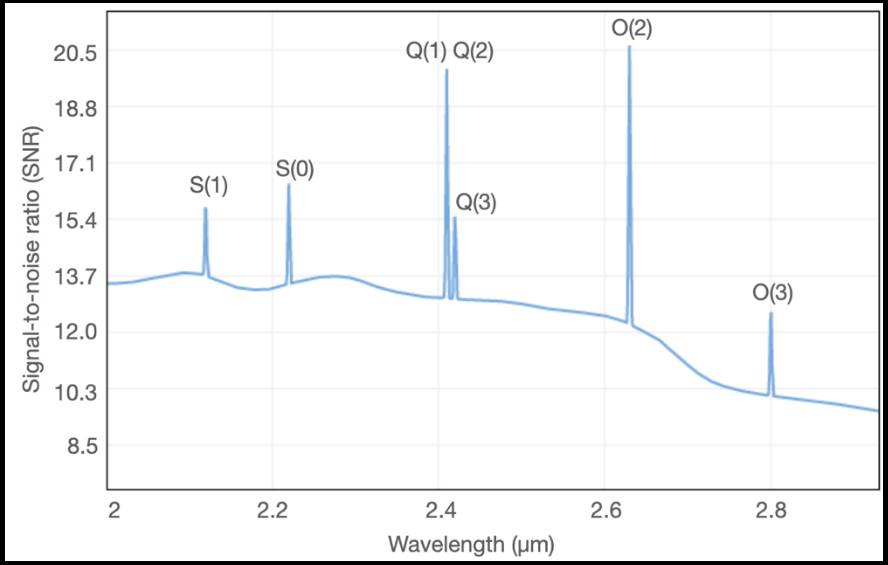
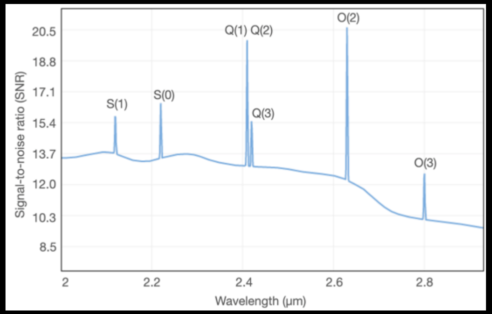
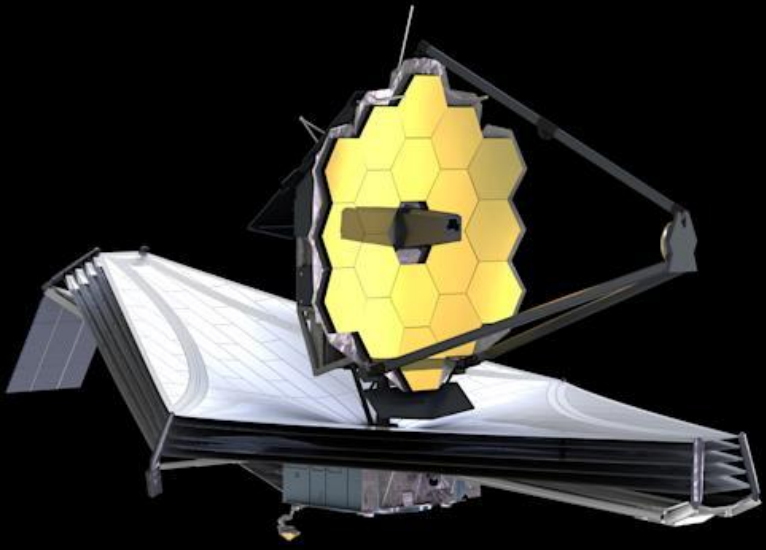


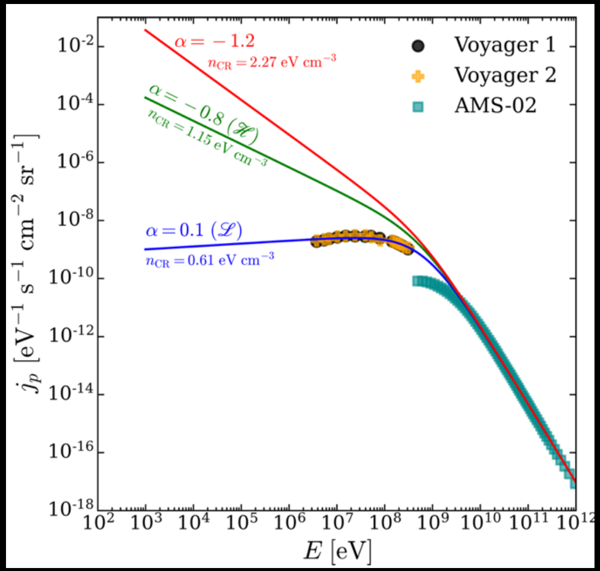


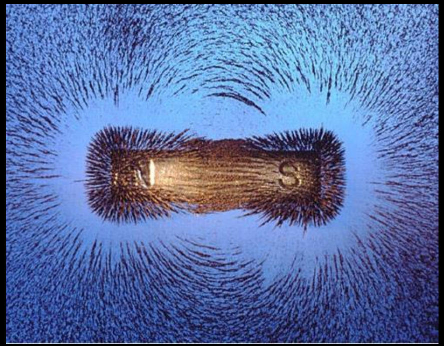

Integration over 10 shutters with JWST's NIRSpec instrument, 1.3 hrs

# The Future is Now



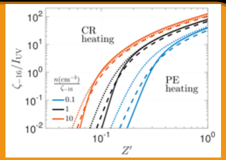





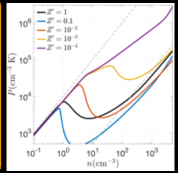



# Summary

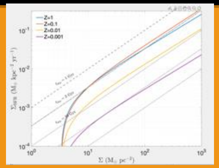
(1)



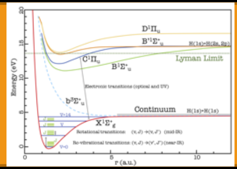

(2)



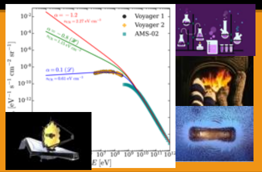
(3)

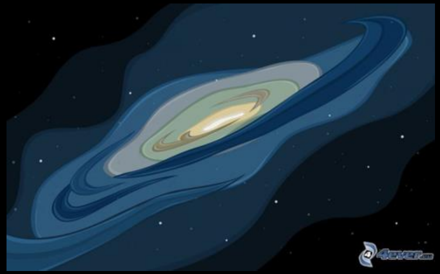


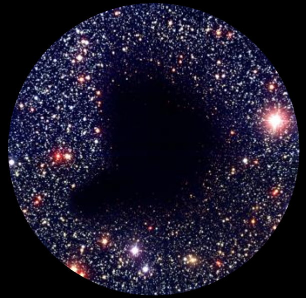
(4)




(5)

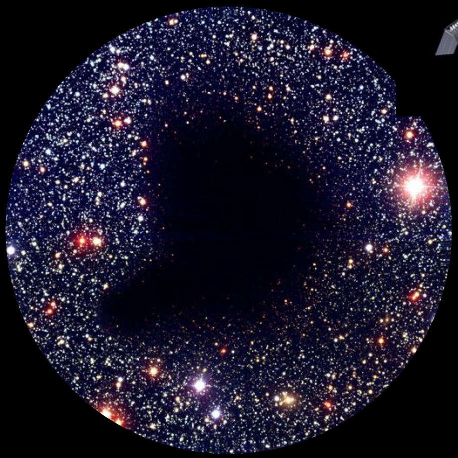




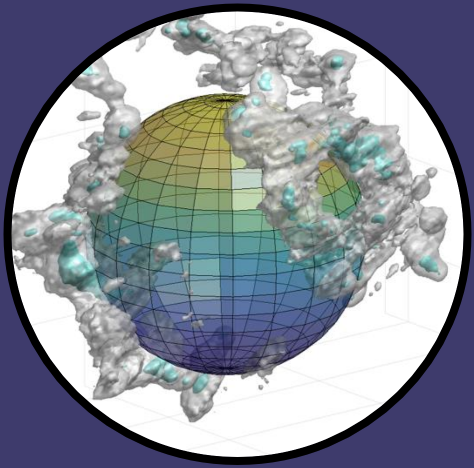
# Looking Forward

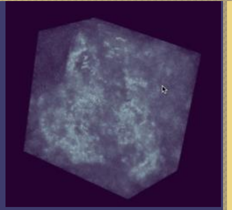
Shmuel Bialy
*CTC postdoc*



## Cold Clouds as Cosmic-Ray Detectors

- *Constrain the spectrum of low energy CRs*
- *Sources of CRs, and CR propagation*

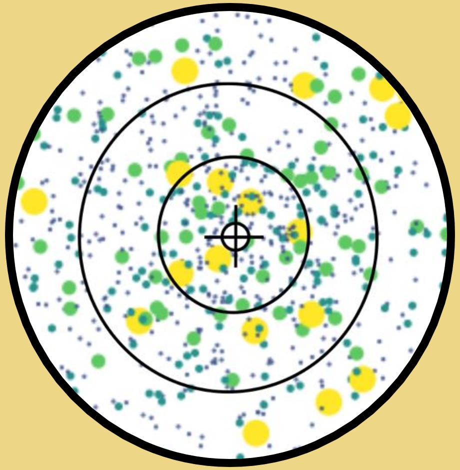


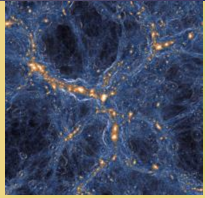


## Supernova feedback & mapping interstellar gas

- *The role of SN in star formation, and shaping interstellar gas*
- *The structure of our "galactic atmosphere"*

sbialy.wixsite.com/pertau



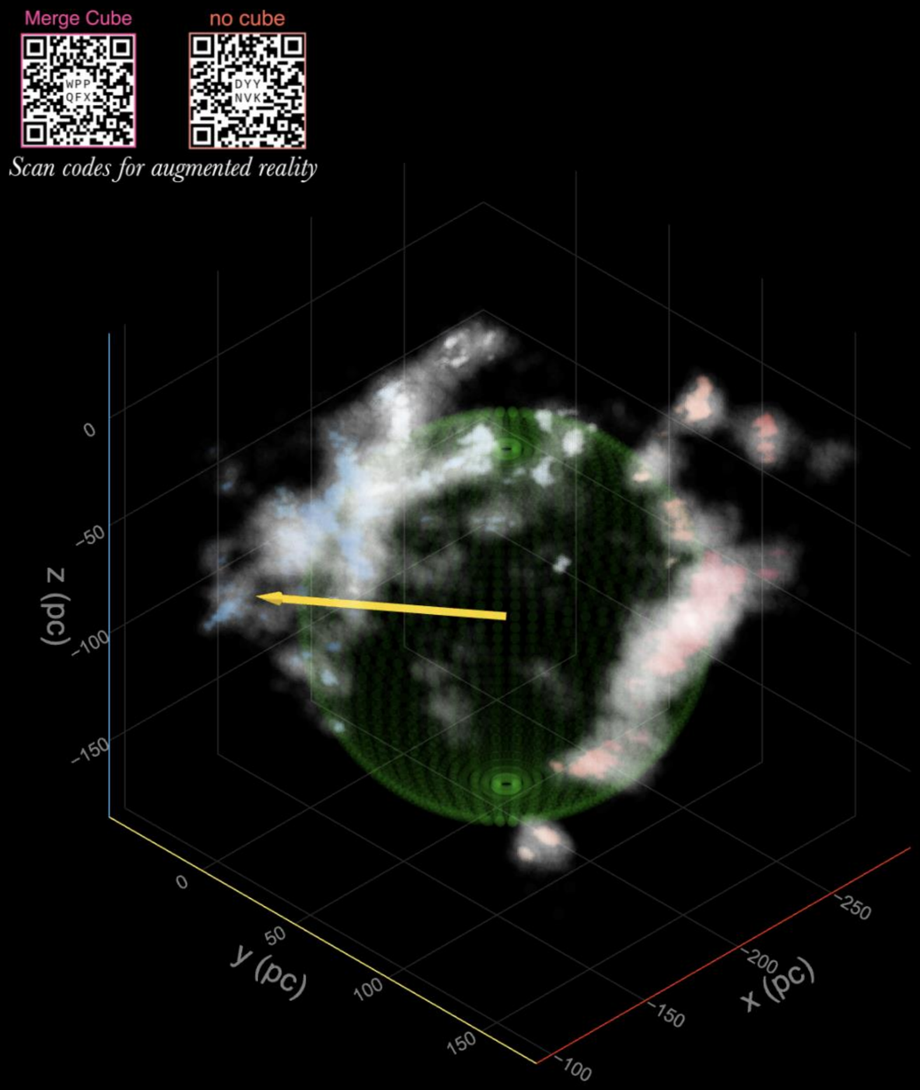


## The FUV Interstellar Radiation Field

- *Observing molecular gas at high z*
- *Sub-grid model for ISM and star formation in cosmological sims*

Per Tau

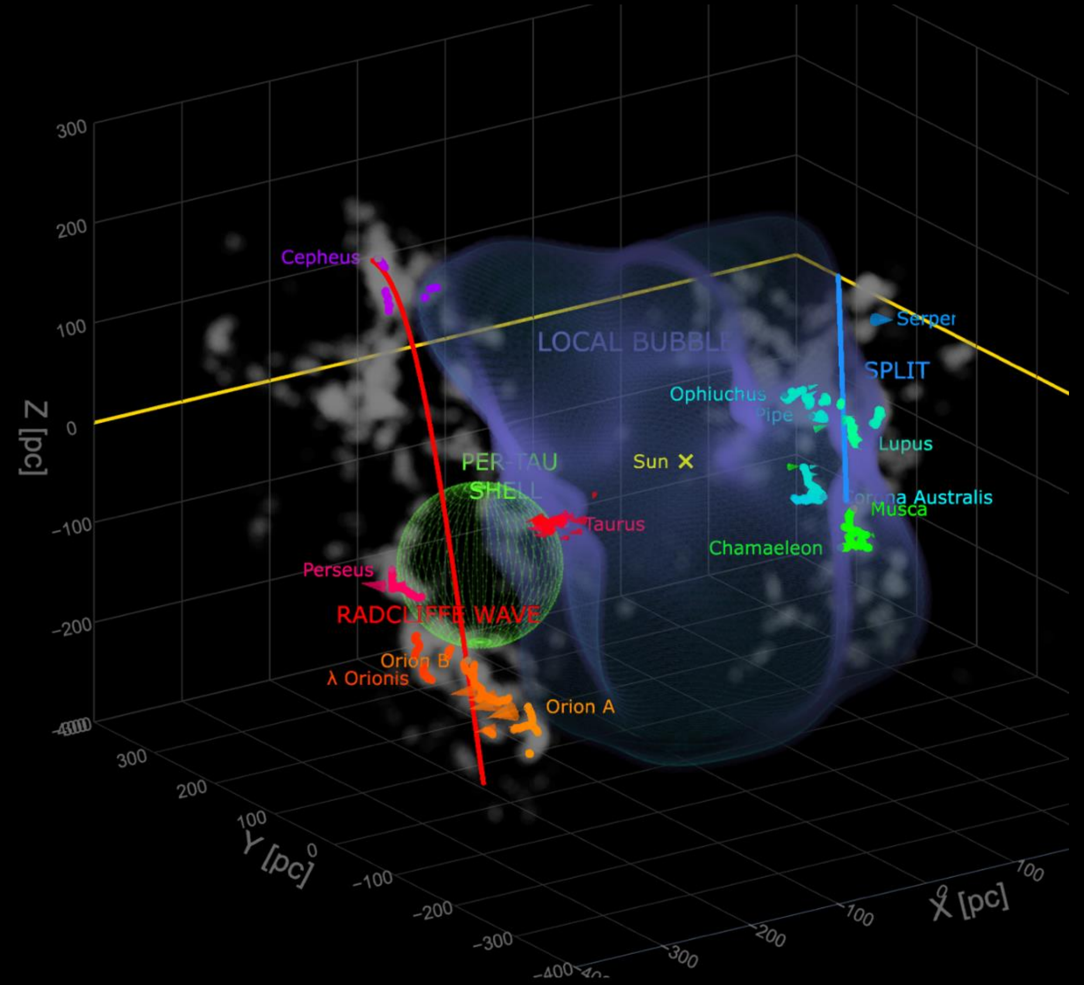
Interactive Figure




Bialy et al. 2021 (ApJ Letters 919 L5)

The expanding local bubble

Interactive Figure




Zucker, Goodman, Joao, **Bialy** et al. Nature 2022 scan this…



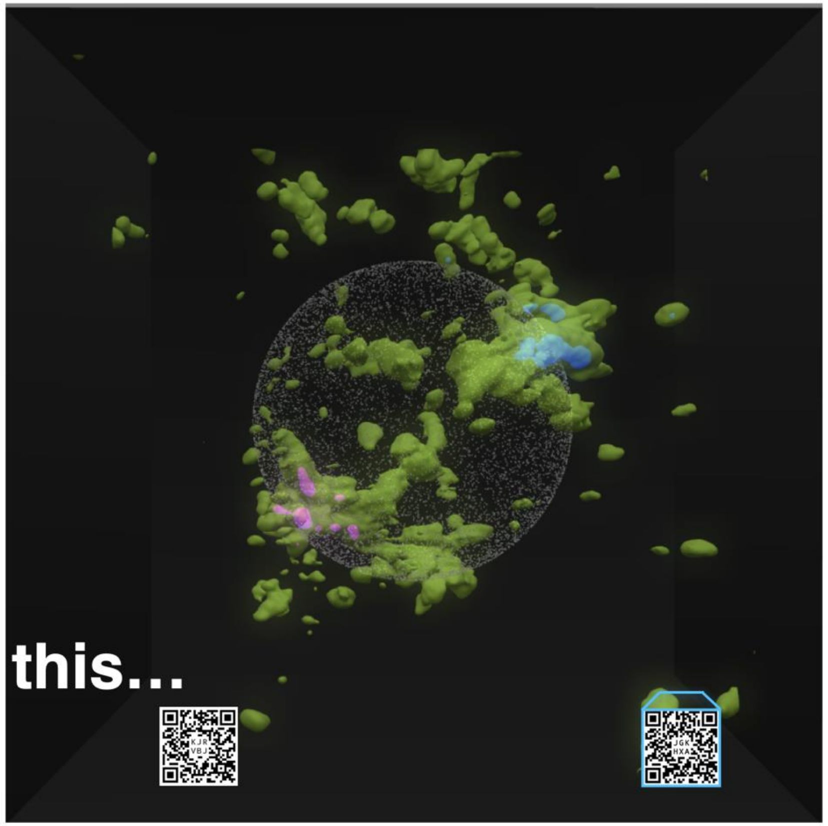


FIG. 1.— Density $n = 5$ cm$^{-3}$ iso-surfaces in the Perseus-Taurus region as derived from 3D-dust extinction observations. The coordinates are the 3D galactic $x-y-z$ coordinates (see footnote 1). Overlaid is our spherical shell model (Eq. 5). The positions of Perseus and Taurus and the sun are indicated.

It is useful to express the results in terms of gas density. We first derive a conversion factor which we use to convert the reported dust opacity density $s$, into gas Hydrogen nuclei particle density $n$ (units: cm$^{-3}$). The gas column density and dust extinction are related through the wavelength-dependent extinction curve, $A_\lambda/N_\mathrm{H}$, where $A_\lambda$ is the dust extinction at wavelength $\lambda$ and $N_\mathrm{H}$ is the H nuclei column density. For the Gaia G-band, $\lambda = 673$ nm (central wavelength), $A_\mathrm{G}/N_\mathrm{H} = 4\times 10^{22}$ mag cm$^2$ (reference XXX). In terms of the dust opacity $\tau_\mathrm{G}/N_H = 3.7\times 10^{-22}$ cm$^2$. Following the definition of $s_x$ we get

$$\Delta N_\mathrm{H} = s_x \left(\frac{\tau_\mathrm{G}}{N_\mathrm{H}}\right)^{-1} \frac{\Delta L}{\mathrm{pc}} . \quad (2)$$

Dividing by $\Delta L$ we obtain the gas density (averaged over the 1 pc$^3$ resolution element):

$$n = \frac{\Delta N_\mathrm{H}}{\Delta L} = 880\, s_x \,\mathrm{cm}^{-3} . \quad (3)$$

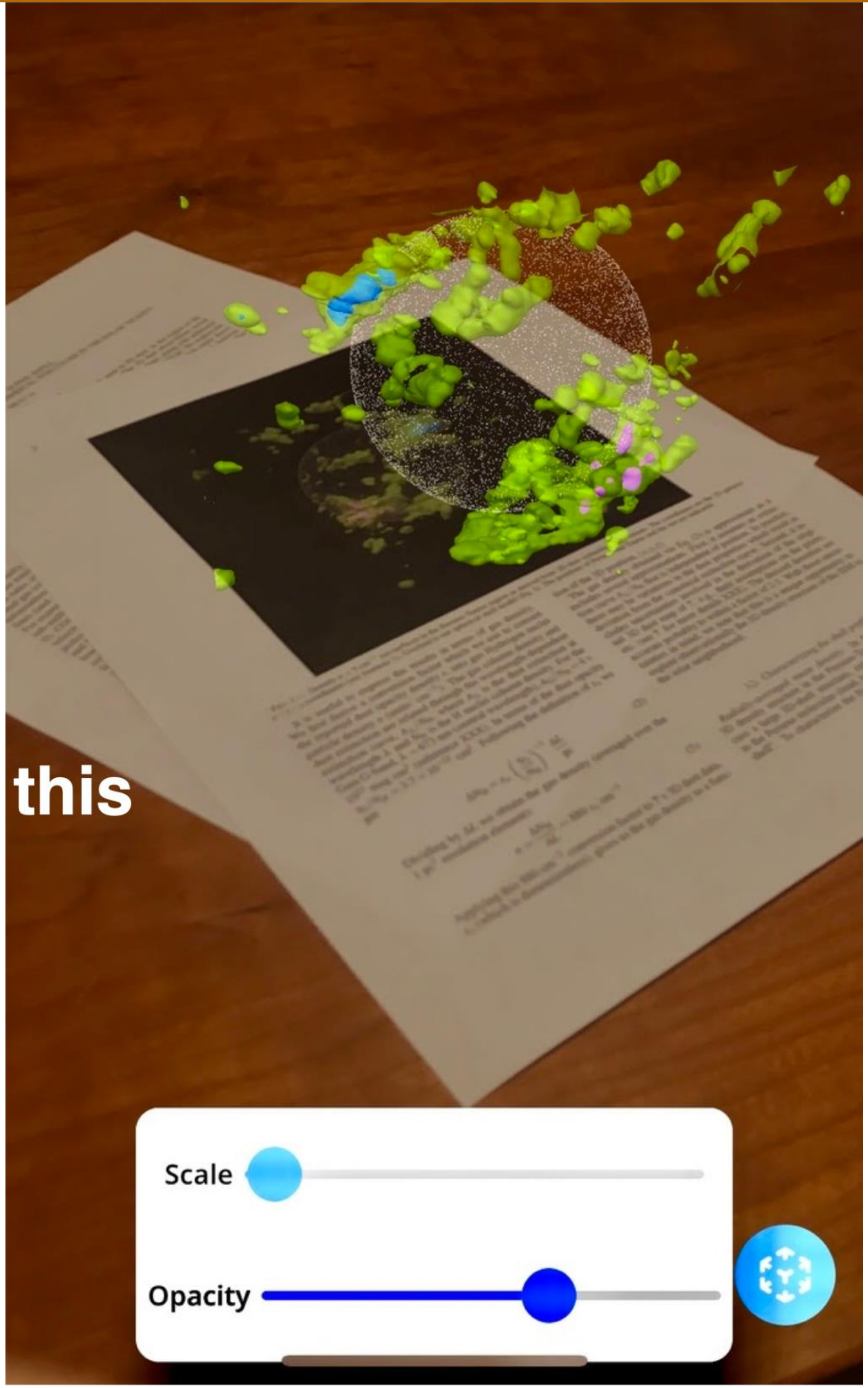
tion of the 3D position, $(x, y, z)$.

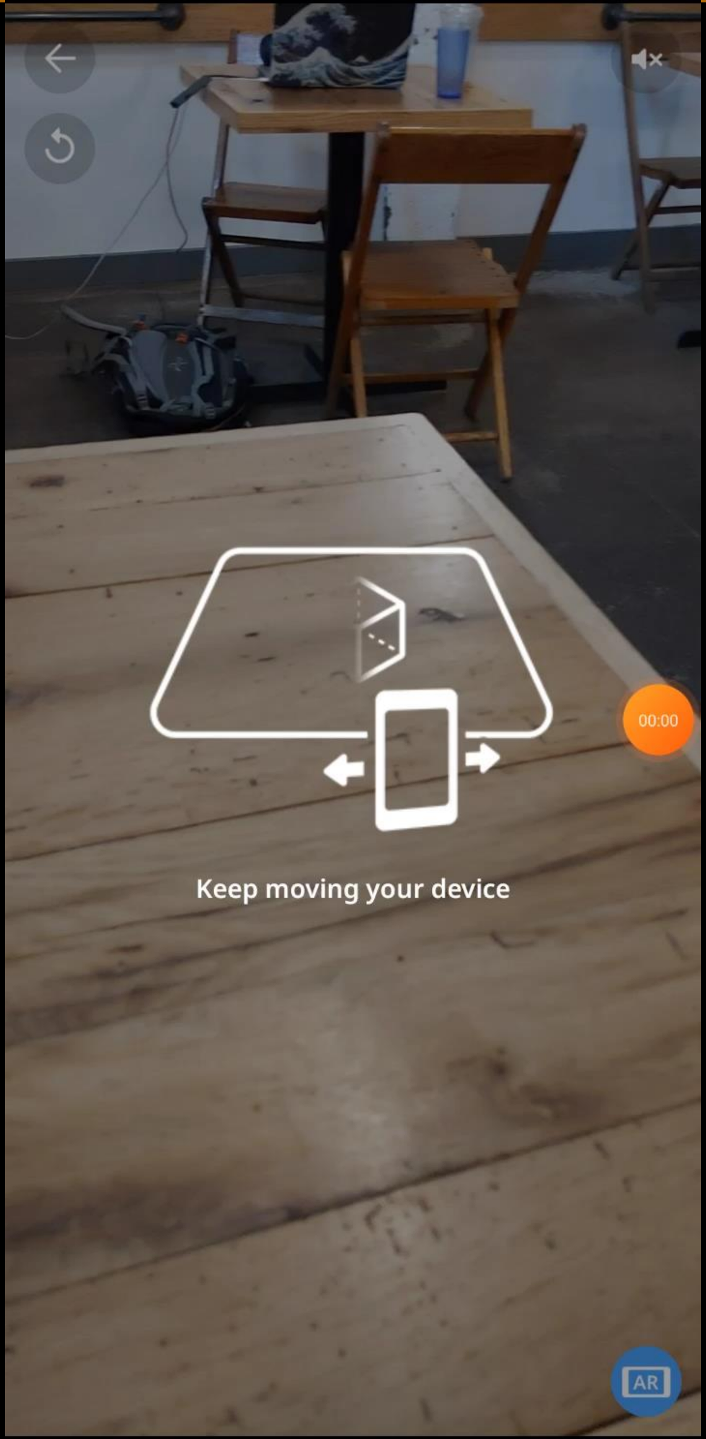
The gas density obtained via Eq. (3) is approximate as it includes several approximations. First, it assumes an extinction curve $A_\lambda/N_\mathrm{H}$ that is independent of position. In practice, there may be variations in the dust properties which result in deviation from the canonical extinction curve. Second, it includes uncertainties involved in the derivation of the original 3D dust map of ?, e.g., their assumptions on the priors, etc. (see ? for more details XXX). The derived densities are accurate probably to within a factor of 2-3. With these uncertainties in mind, we note that this is a unique opportunity to explore observationally the 3D density structure of the ISM in the solar neighborhood.

### 3.2. *Characterizing the shell profile*

*Radially-averaged mean density:* In §4 we explore the 3D density structure in the Perseus-Taurus region, and discuss a large 3D-shell structure, extending from the Taurus

…see this

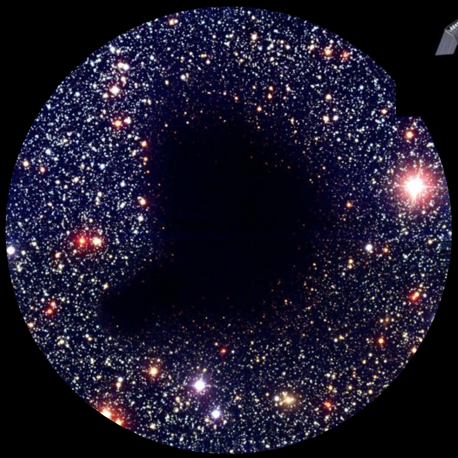





Bialy et al. 2021 (ApJ Letters 919 L5)

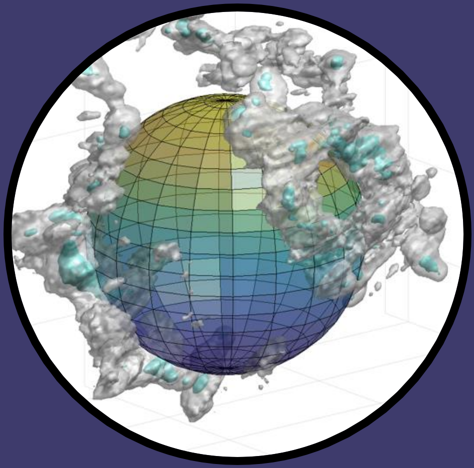
# Looking Forward

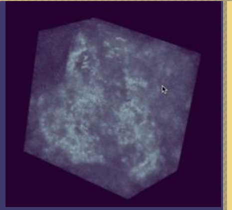
Shmuel Bialy
*CTC postdoc*



## Cold Clouds as Cosmic-Ray Detectors

- *Constrain the spectrum of low energy CRs*
- *Sources of CRs, and CR propagation*

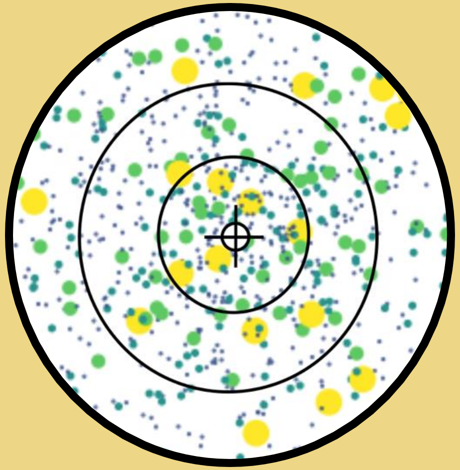


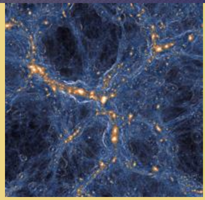


## Supernova feedback & mapping interstellar gas

- *The role of SN in star formation, and shaping interstellar gas*
- *The structure of our "galactic atmosphere"*

sbialy.wixsite.com/pertau



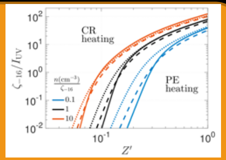


## The FUV Interstellar Radiation Field

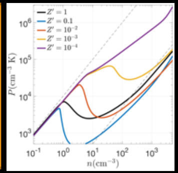
- *Observing molecular gas at high z*
- *Sub-grid model for ISM and star formation in cosmological sims*

# Summary

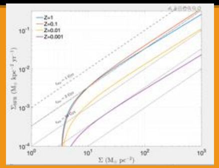
(1)



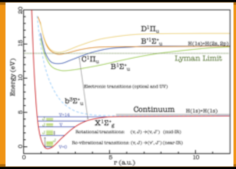

(2)



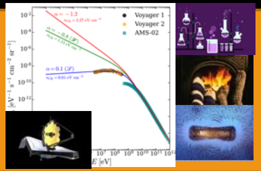
(3)

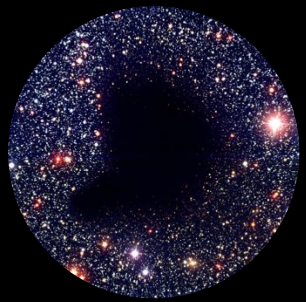


(4)



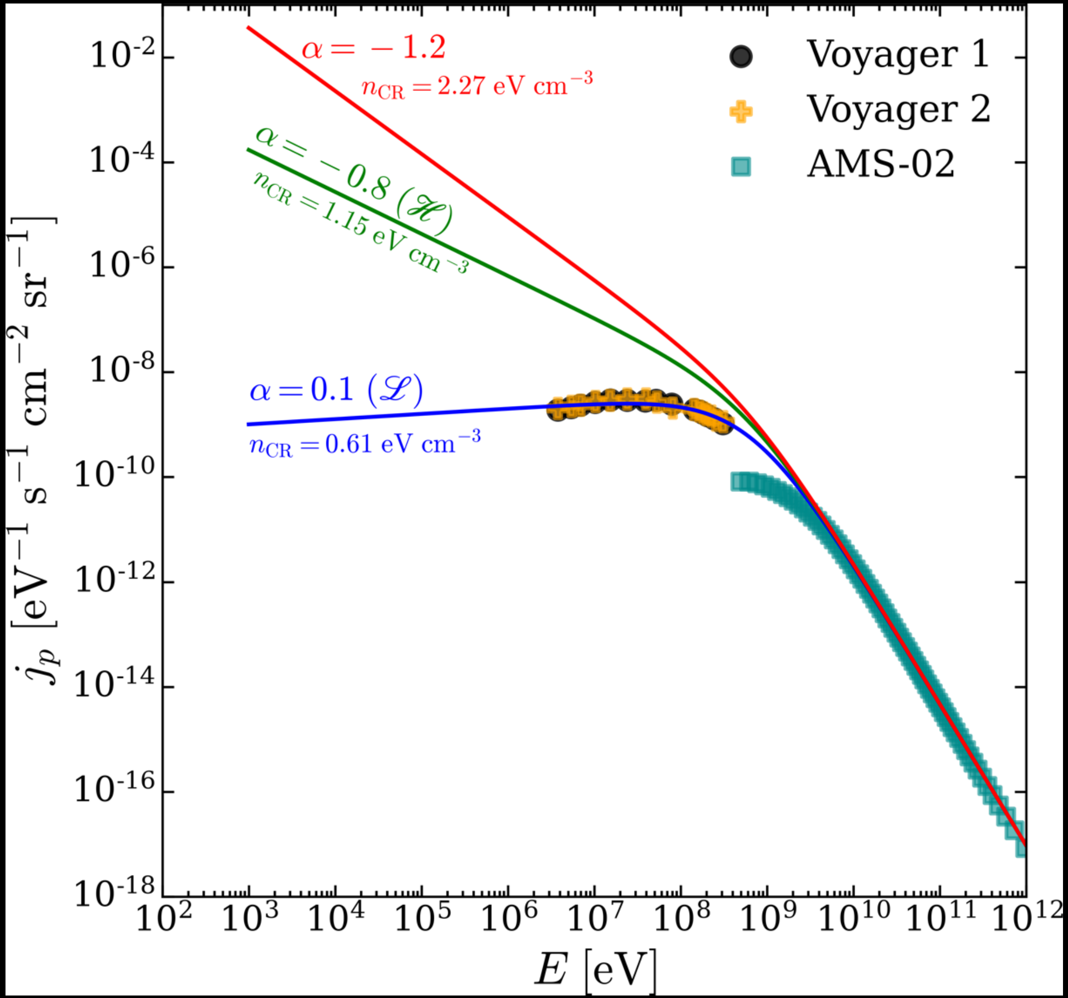
(5)



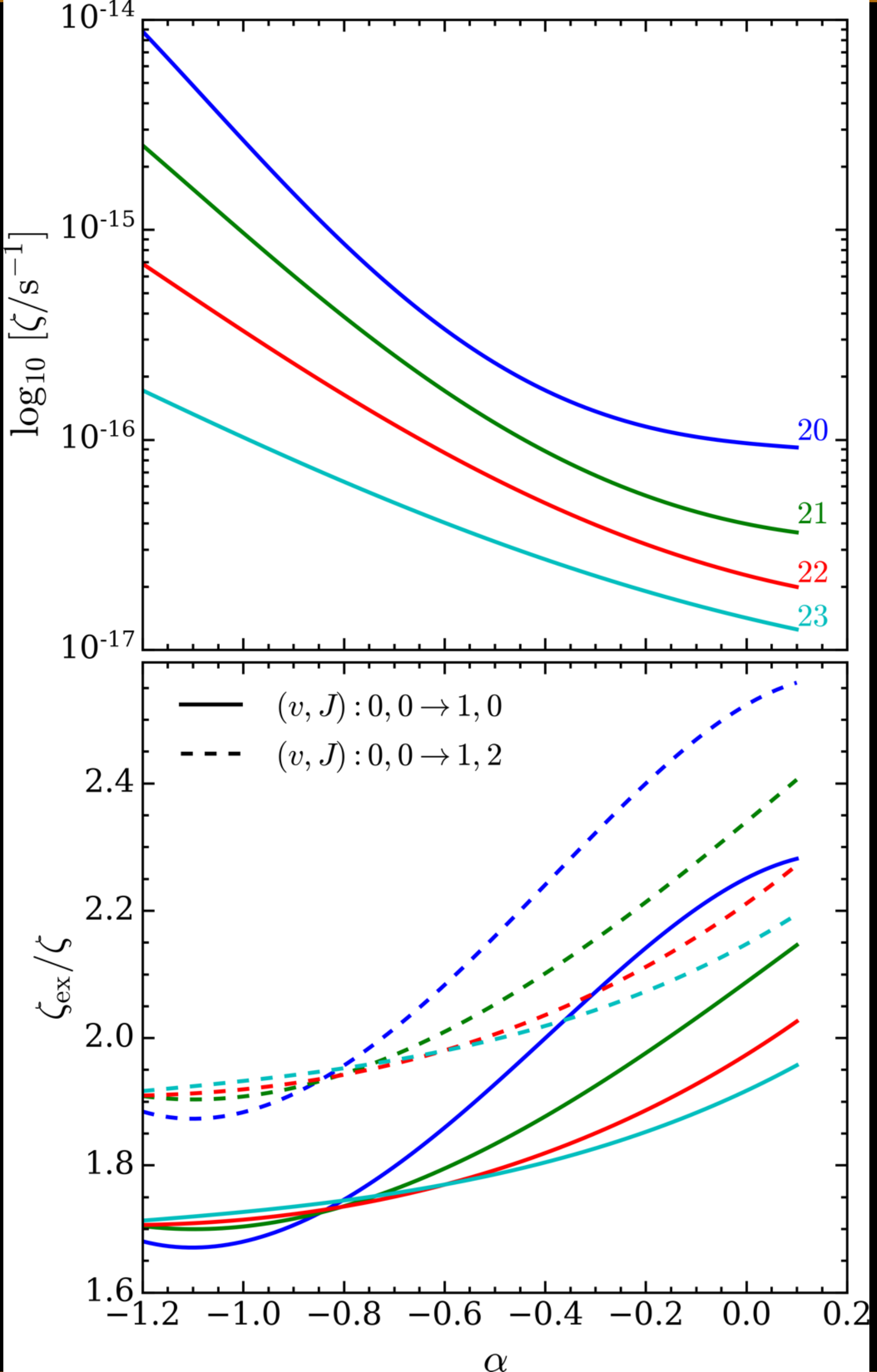



Bialy et al. 2021 (Harvard-Smithsonian press-release)

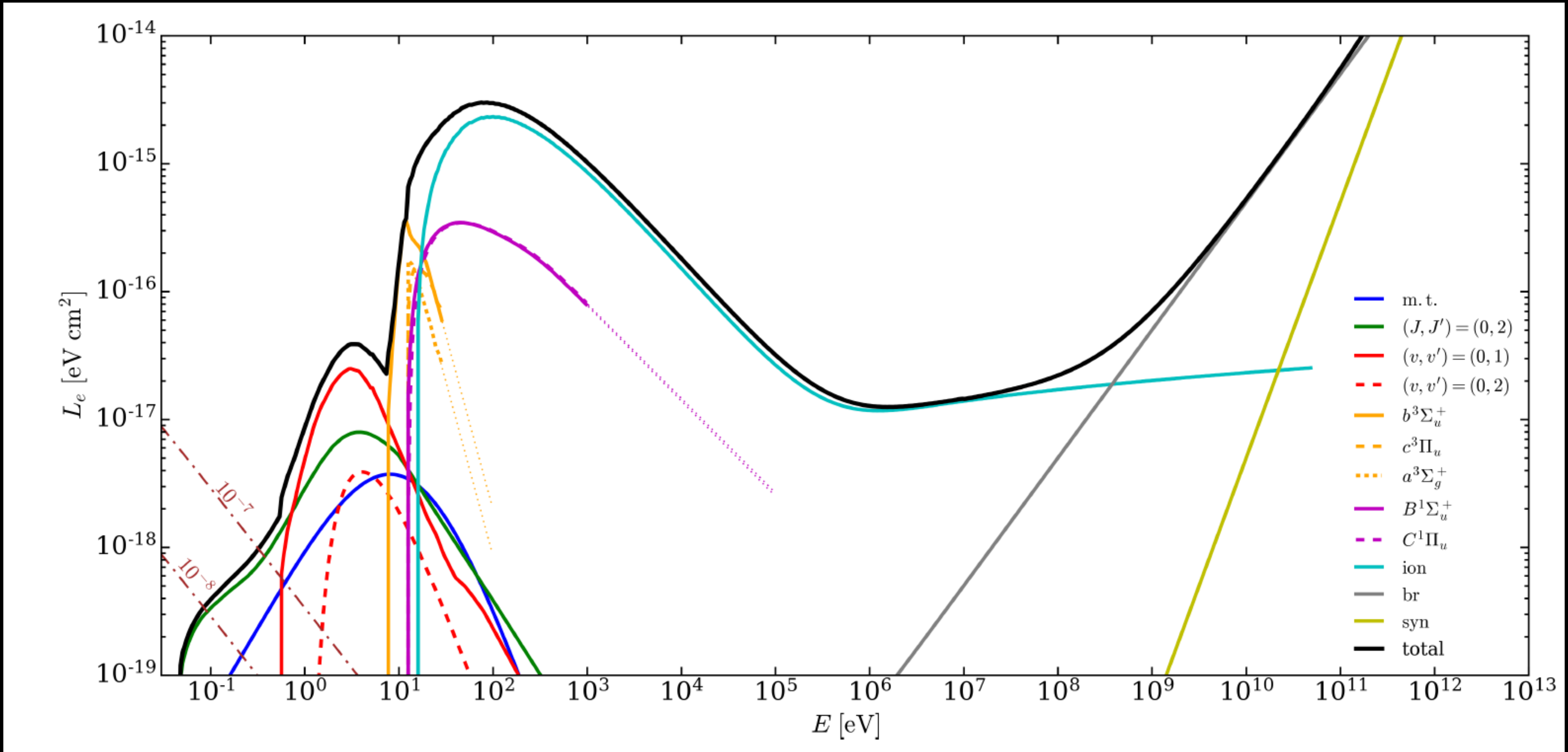
Video credit: Jasen Chambers



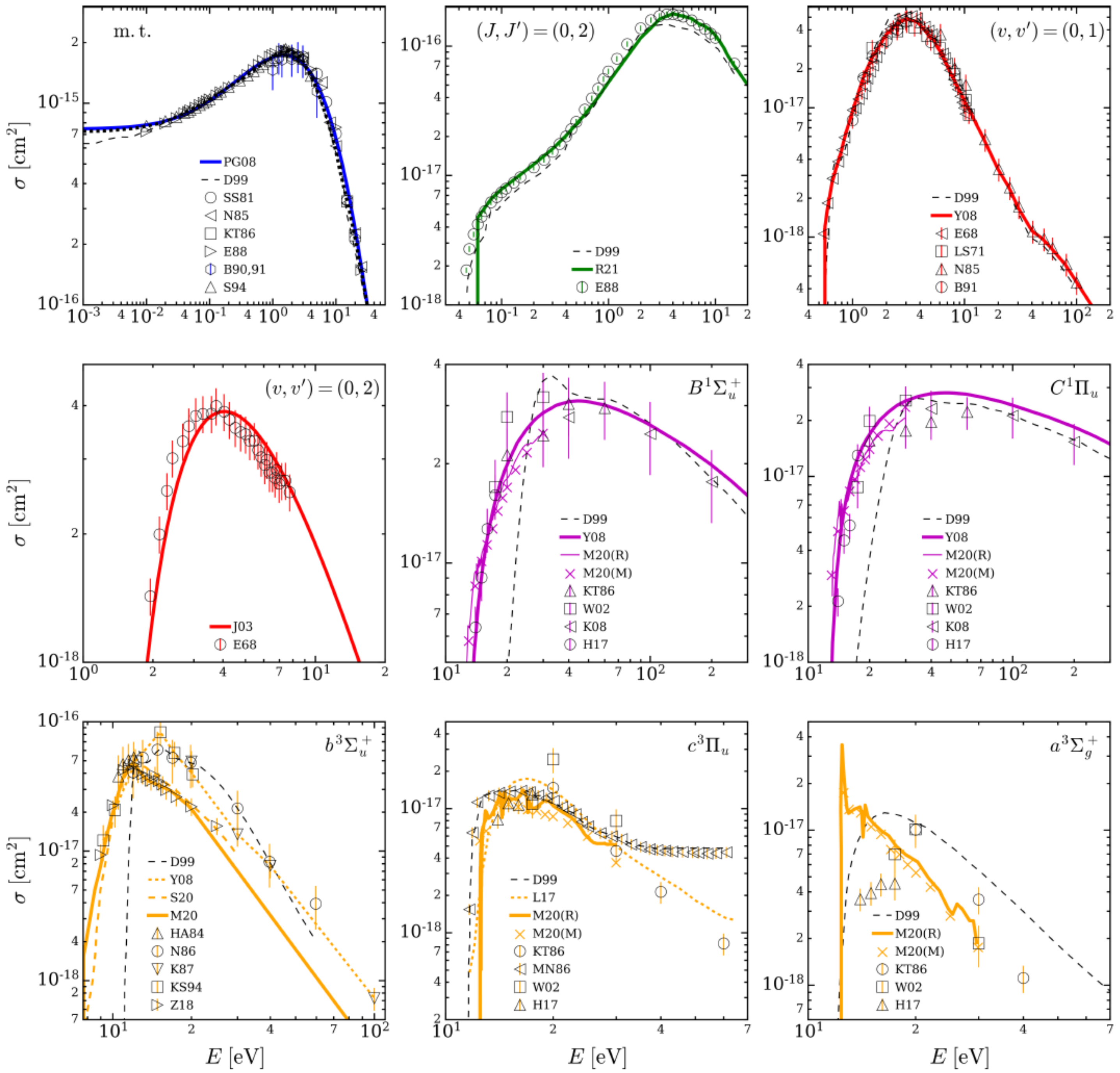
$\alpha = -1.2$
$n_{\rm CR} = 2.27$ eV cm$^{-3}$
$\alpha = -0.8$ ($\mathscr{H}$)
$n_{\rm CR} = 1.15$ eV cm$^{-3}$
$\alpha = 0.1$ ($\mathscr{L}$)
$n_{\rm CR} = 0.61$ eV cm$^{-3}$
Voyager 1
Voyager 2
AMS-02
$j_p$ [eV$^{-1}$ s$^{-1}$ cm$^{-2}$ sr$^{-1}$]
$E$ [eV]

$\log_{10}$ [$\zeta$/s$^{-1}$]
20
21
22
23
$(v, J): 0, 0 \rightarrow 1, 0$
$(v, J): 0, 0 \rightarrow 1, 2$
$\zeta_{\rm ex}/\zeta$
$\alpha$



$L_e$ [eV cm$^2$]
$E$ [eV]
$10^{-7}$
$10^{-8}$
m. t.
$(J, J') = (0, 2)$
$(v, v') = (0, 1)$
$(v, v') = (0, 2)$
$b^3\Sigma_u^+$
$c^3\Pi_u$
$a^3\Sigma_g^+$
$B^1\Sigma_u^+$
$C^1\Pi_u$
ion
br
syn
total

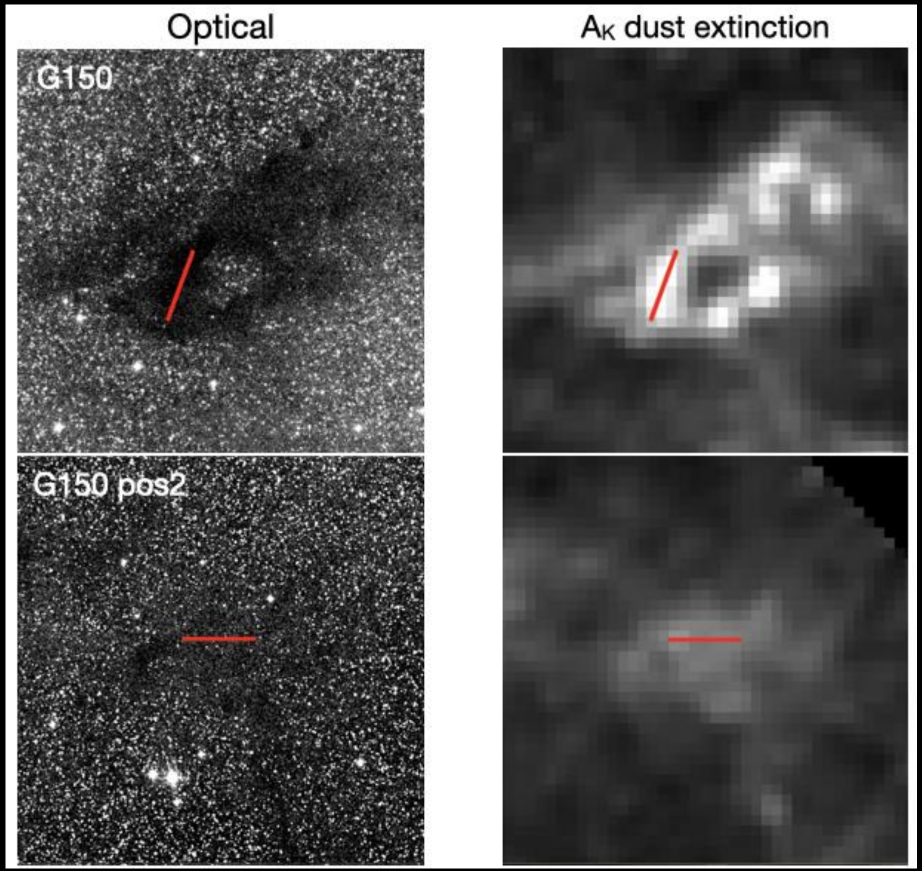

m. t.
PG08
D99
SS81
N85
KT86
E88
B90,91
S94
$(J, J') = (0, 2)$
D99
R21
E88
$(v, v') = (0, 1)$
D99
Y08
E68
LS71
N85
B91
$(v, v') = (0, 2)$
J03
E68
$B^1\Sigma_u^+$
D99
Y08
M20(R)
M20(M)
KT86
W02
K08
H17
$C^1\Pi_u$
D99
Y08
M20(R)
M20(M)
KT86
W02
K08
H17
$b^3\Sigma_u^+$
D99
Y08
S20
M20
HA84
N86
K87
KS94
Z18
$c^3\Pi_u$
D99
L17
M20(R)
M20(M)
KT86
MN86
W02
H17
$a^3\Sigma_g^+$
D99
M20(R)
M20(M)
KT86
W02
H17
$\sigma$ [cm$^2$]
$E$ [eV]

# Observations + Model

*Cosmic Rays*

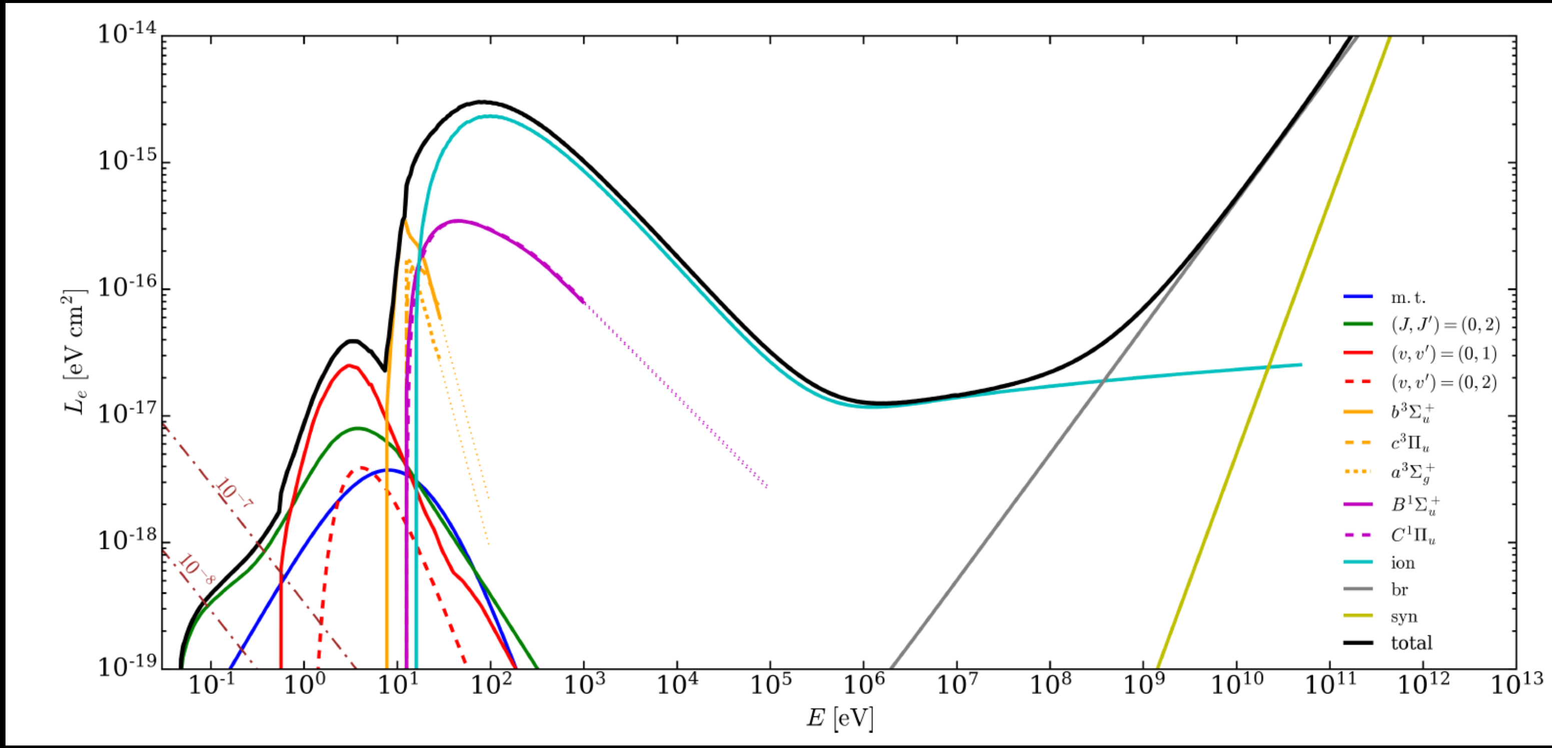
Constrain the CR spectrum and ionization rate

NIR spectroscopy of molecular nearby clouds

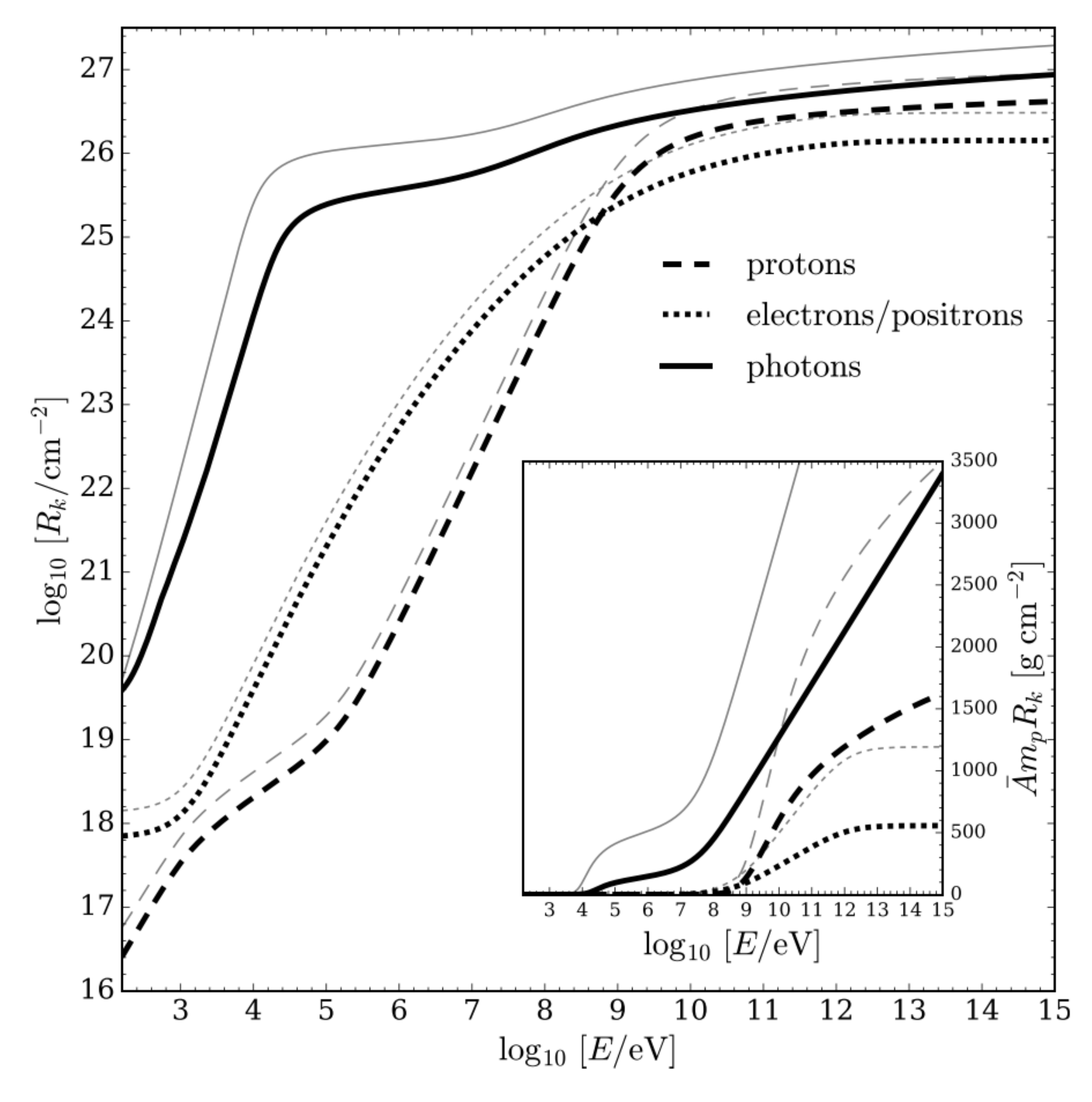



Bialy et al. (2021, submitted)

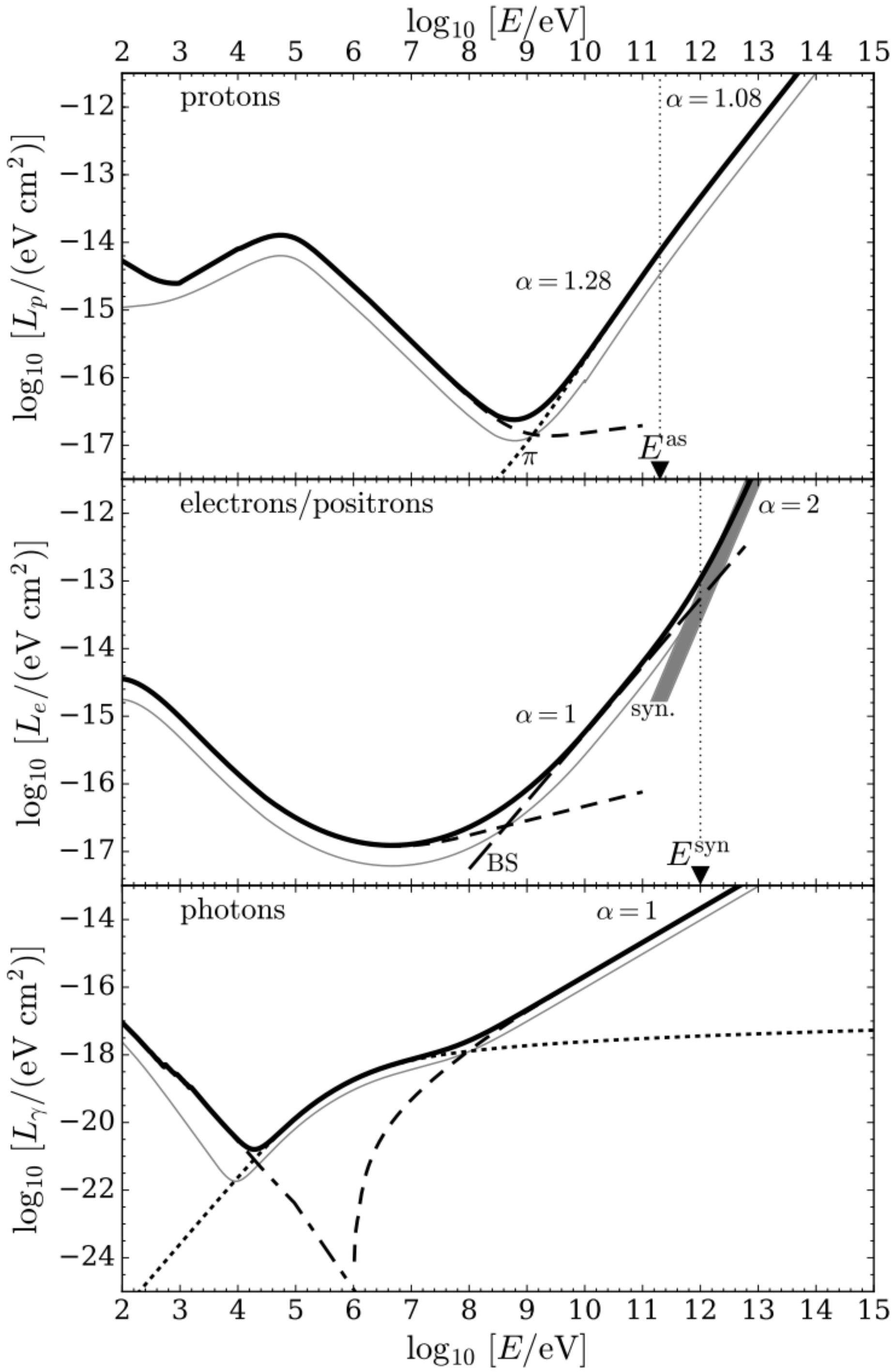
Energy loss per cm$^{-2}$ of cosmic-ray electrons propagating into a molecular cloud



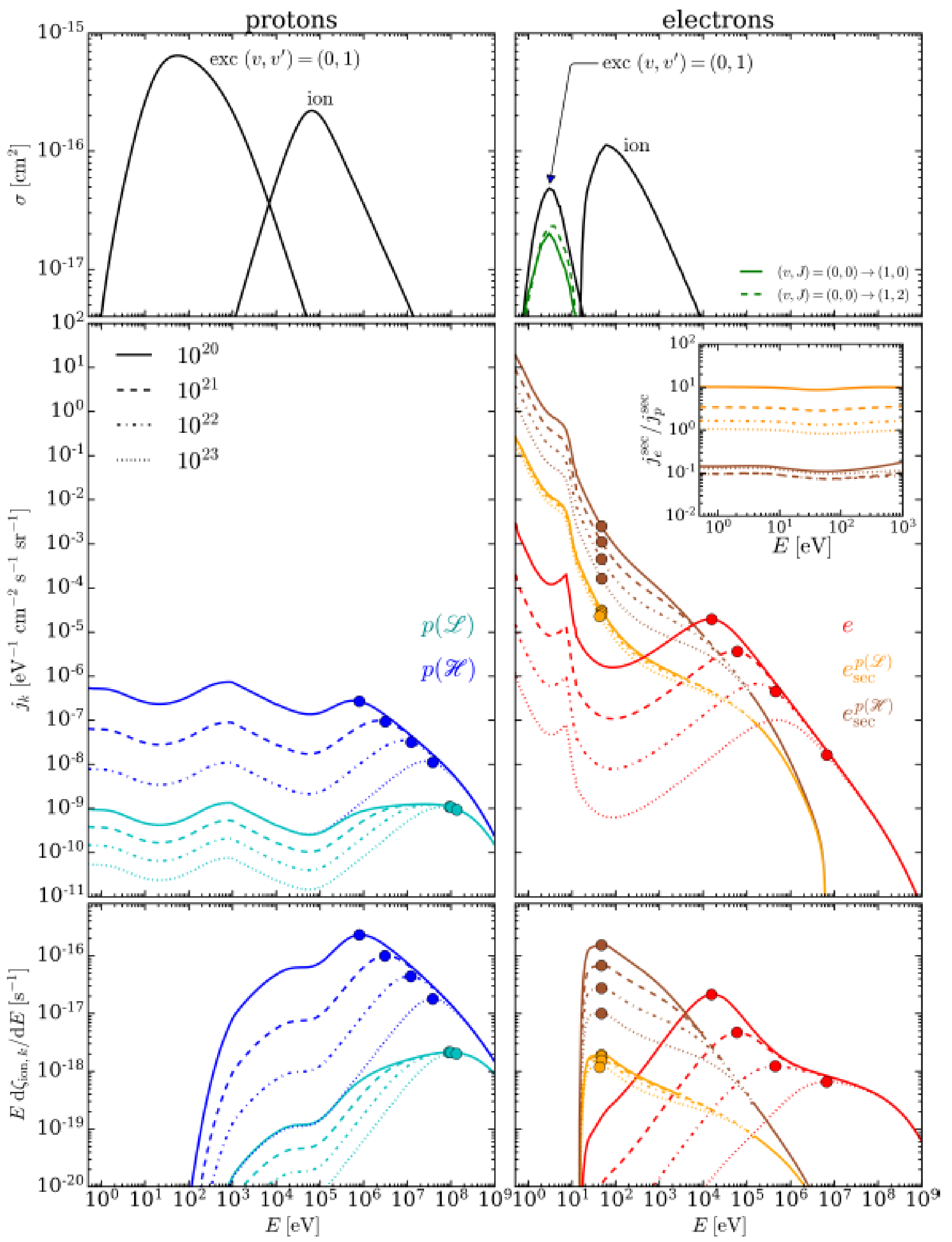

Padovani & Bialy, et al. (2021, submitted)



protons
electrons/positrons
photons
$\log_{10}\,[R_k/\mathrm{cm}^{-2}]$
$\log_{10}\,[E/\mathrm{eV}]$
$\bar{A}m_pR_k\,[\mathrm{g\ cm}^{-2}]$
$\log_{10}\,[E/\mathrm{eV}]$



$\log_{10}[E/\mathrm{eV}]$
protons
$\alpha = 1.08$
$\alpha = 1.28$
$\pi$
$E^{\mathrm{as}}$
$\log_{10}[L_p/(\mathrm{eV\ cm^2})]$
electrons/positrons
$\alpha = 2$
syn.
$\alpha = 1$
BS
$E^{\mathrm{syn}}$
$\log_{10}[L_e/(\mathrm{eV\ cm^2})]$
photons
$\alpha = 1$
$\log_{10}[L_\gamma/(\mathrm{eV\ cm^2})]$
$\log_{10}[E/\mathrm{eV}]$



protons
electrons
exc $(v, v') = (0, 1)$
ion
$\sigma$ [cm$^2$]
$(v, J) = (0, 0) \rightarrow (1, 0)$
$(v, J) = (0, 0) \rightarrow (1, 2)$
$10^{20}$
$10^{21}$
$10^{22}$
$10^{23}$
$j_k$ [eV$^{-1}$ cm$^{-2}$ s$^{-1}$ sr$^{-1}$]
$p(\mathscr{L})$
$p(\mathscr{H})$
$e$
$e_{\rm sec}^{p(\mathscr{L})}$
$e_{\rm sec}^{p(\mathscr{H})}$
$j_e^{\rm sec}/j_p^{\rm sec}$
$E$ d$\zeta_{{\rm ion},k}$/d$E$ [s$^{-1}$]
$E$ [eV]