MAX-PLANCK-GESELLSCHAFT

Penetration of low-energy cosmic rays into clouds and disks

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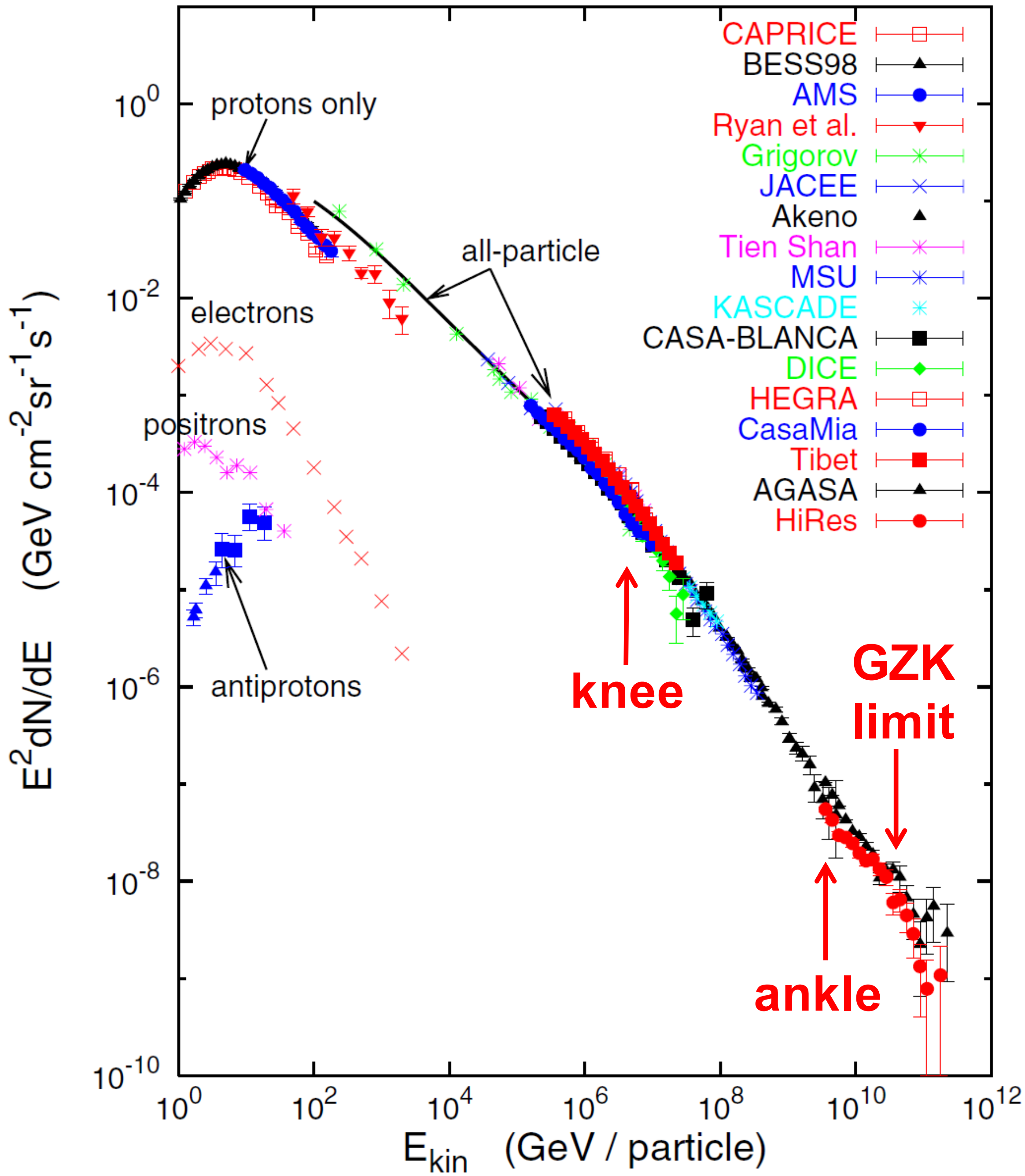
Outline

- Introduction
- Magnetic mirroring and focusing
- CRs in (very) dense regions
- Self-modulation of penetrating CRs
- Summary

Energy spectra of CRs



Energy densities in the ISM:

$$W_{\rm CR} \approx 1.4\ \mathrm{eV/cm^3}$$

$$W_B \approx 0.9\ \mathrm{eV/cm^3}$$

$$W_T \approx 0.5\ \mathrm{eV/cm^3}$$

$$W_{\rm turb} \approx 0.2\ \mathrm{eV/cm^3}$$

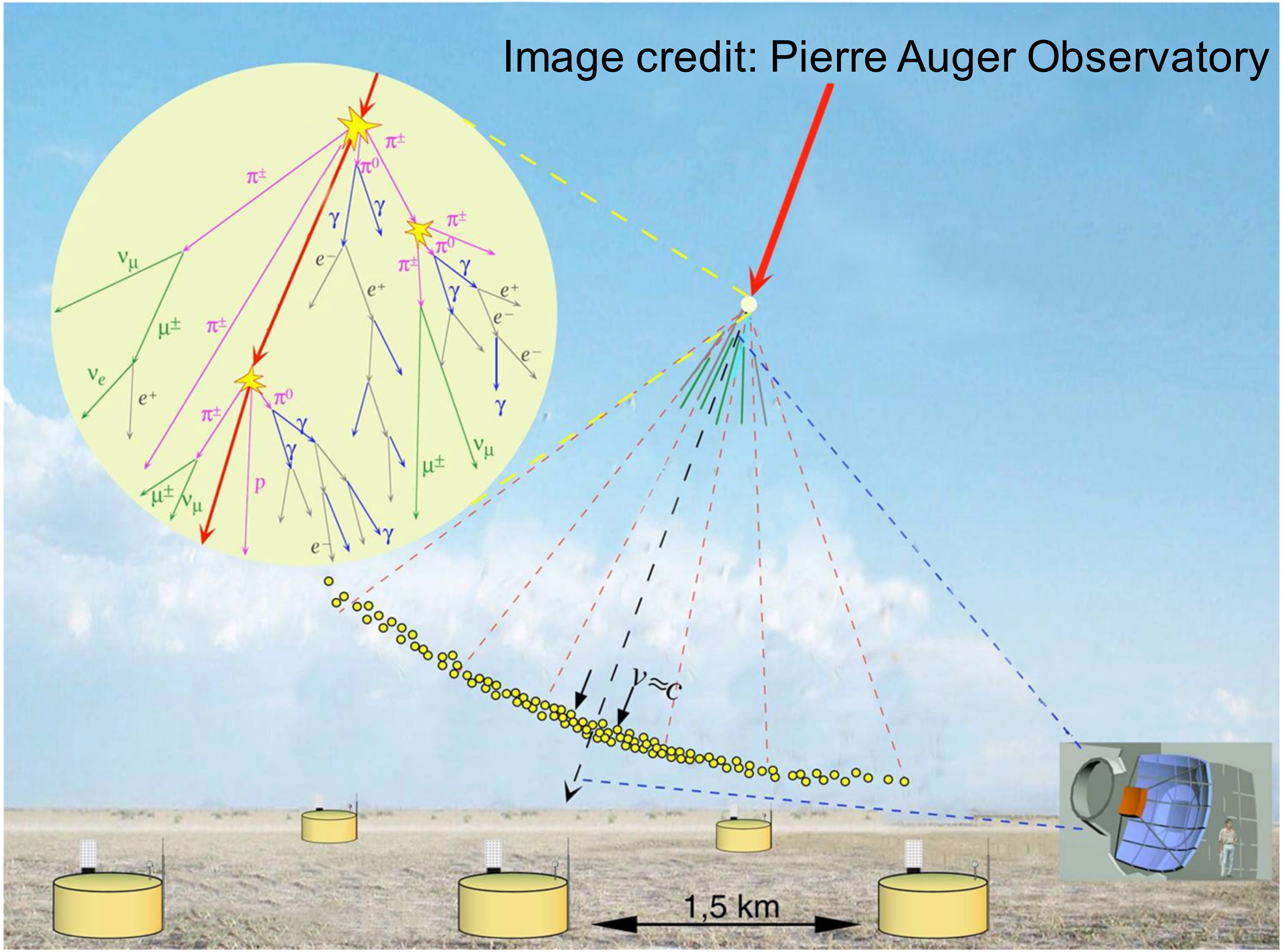
Cosmic Rays are

extremely dilute, non-thermal, relativistic gas

Gaisser et al., 2006

Air sowers

A natural laboratory for elementary particle physics



Giant molecular clouds

Eagle Nebula

Image credit: NASA

Protoplanetary disks

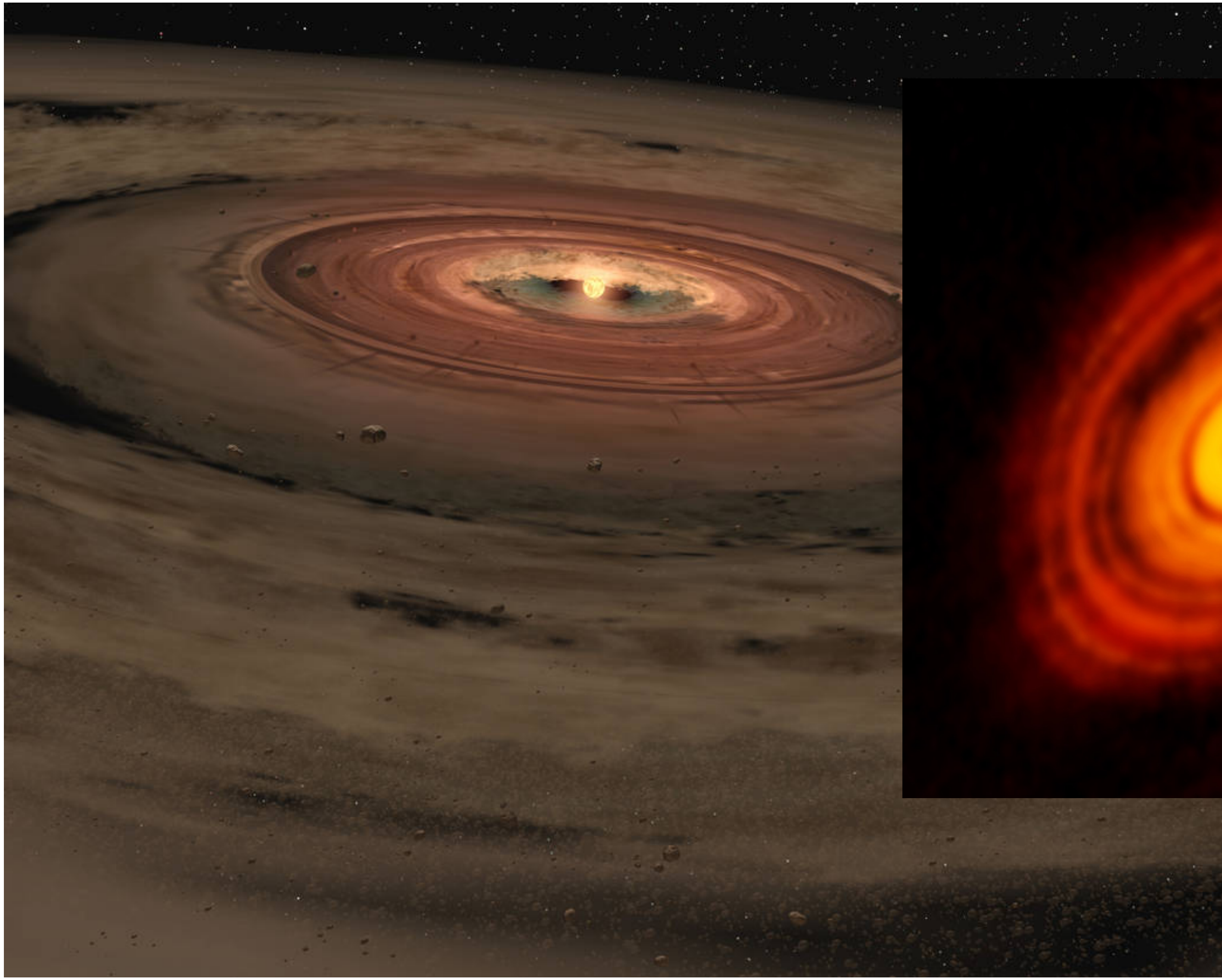


Image credit: NASA/JPL

HL Tau disk

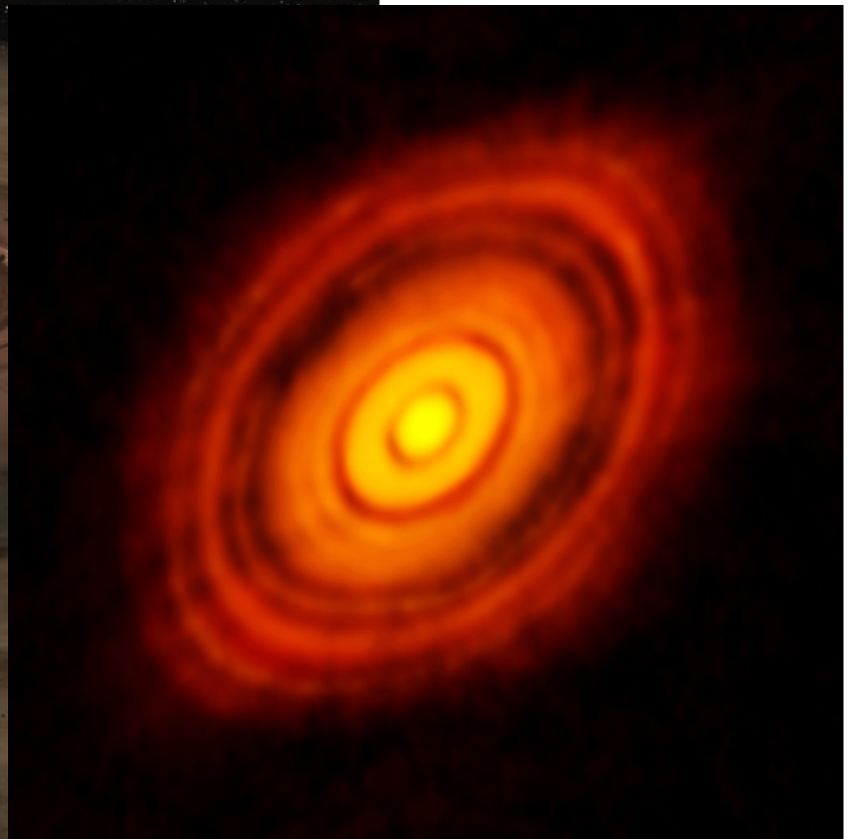


Image credit:
ALMA telescope

Stages of star formation

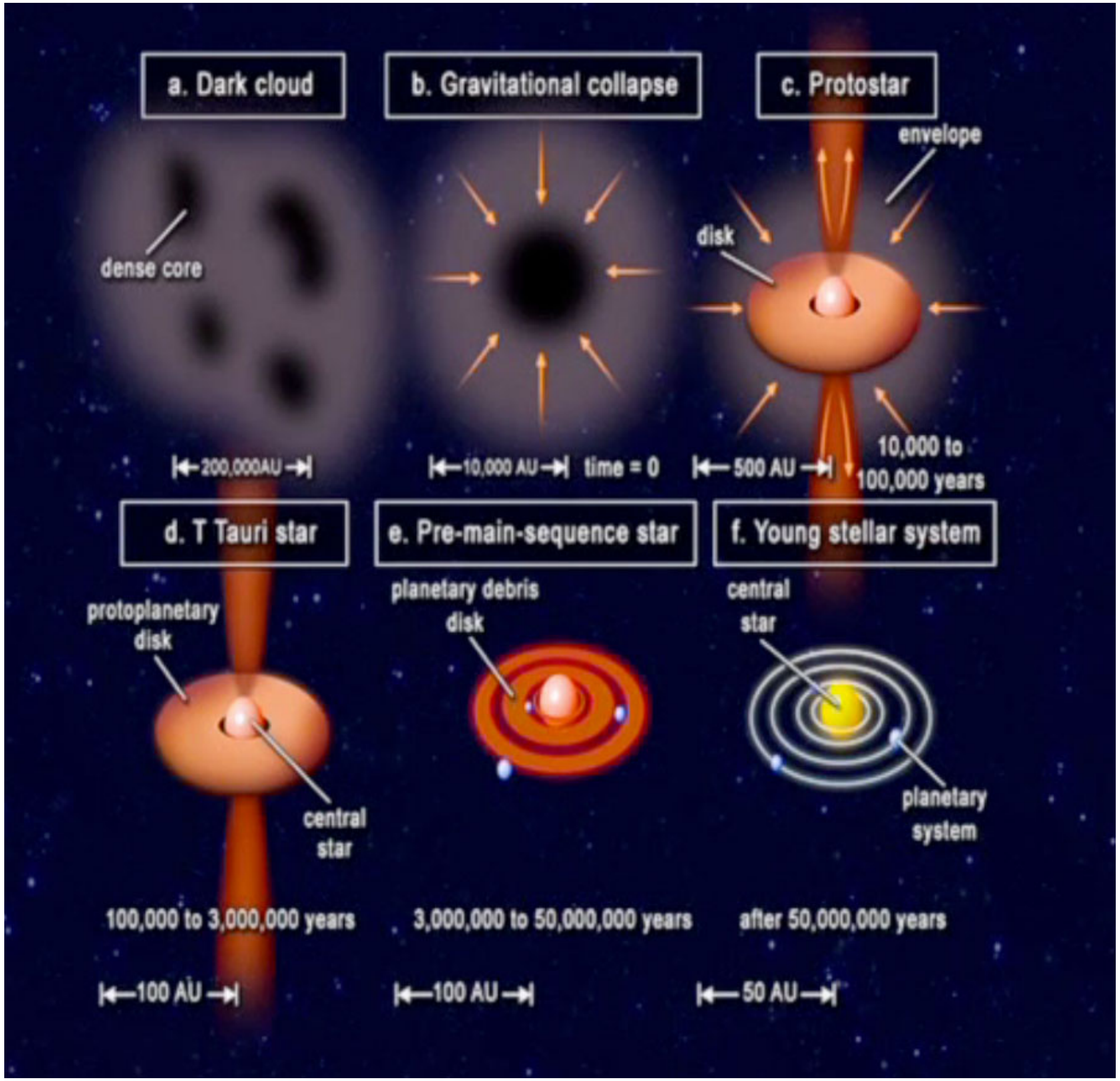


Image credit: Google Images

Processes driven by *low-energy* CRs in clouds and disks

- **Ionization in UV- and X-ray-shielded regions:**

  coupling of gas to magnetic field

  ⇒ magnetic braking, onset of rotational instabilities, …

  gas heating

  ⇒ cloud dynamics, chemistry, …

  desorption of ice

  ⇒ gas density, abundances of complex molecules, …

  dust charging

  ⇒ dust coagulation, chemical processes on grains, …

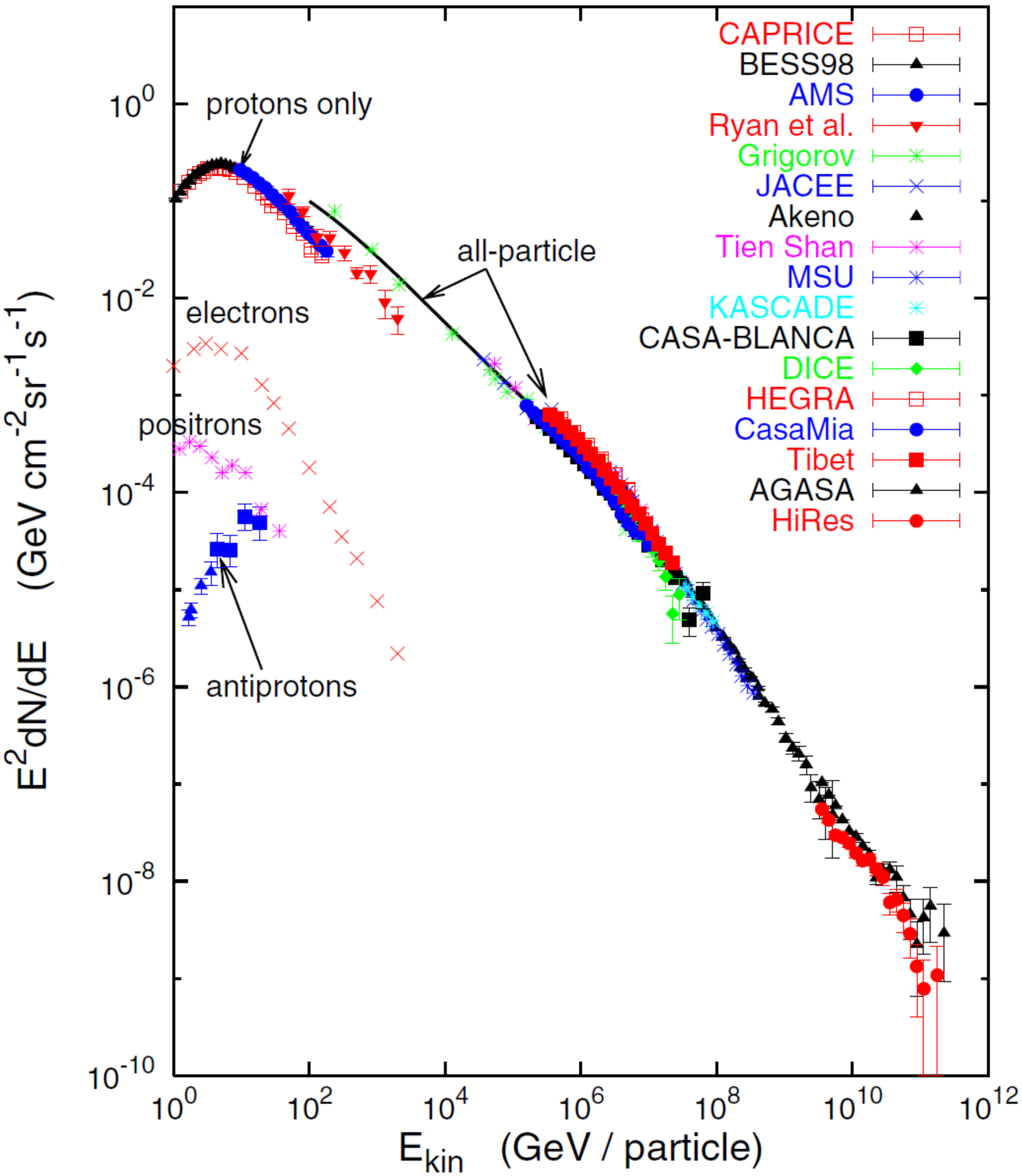
- **Formation of polyatomic molecules:**

  $p_{CR} + H_2 \rightarrow H_2^+$ ⇒ $H_2^+ + H_2 \rightarrow H_3^+$ ⇒

  $H_3^+ + [O, CO, N] \rightarrow [OH^+, HCO^+, N_2H^+]$ ⇒ …

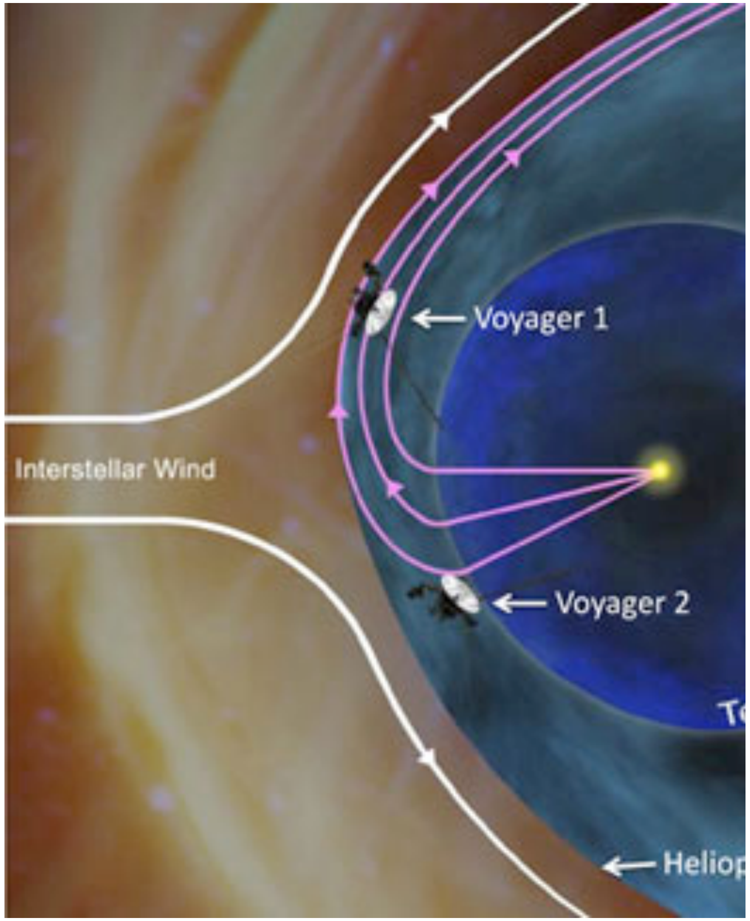
- …

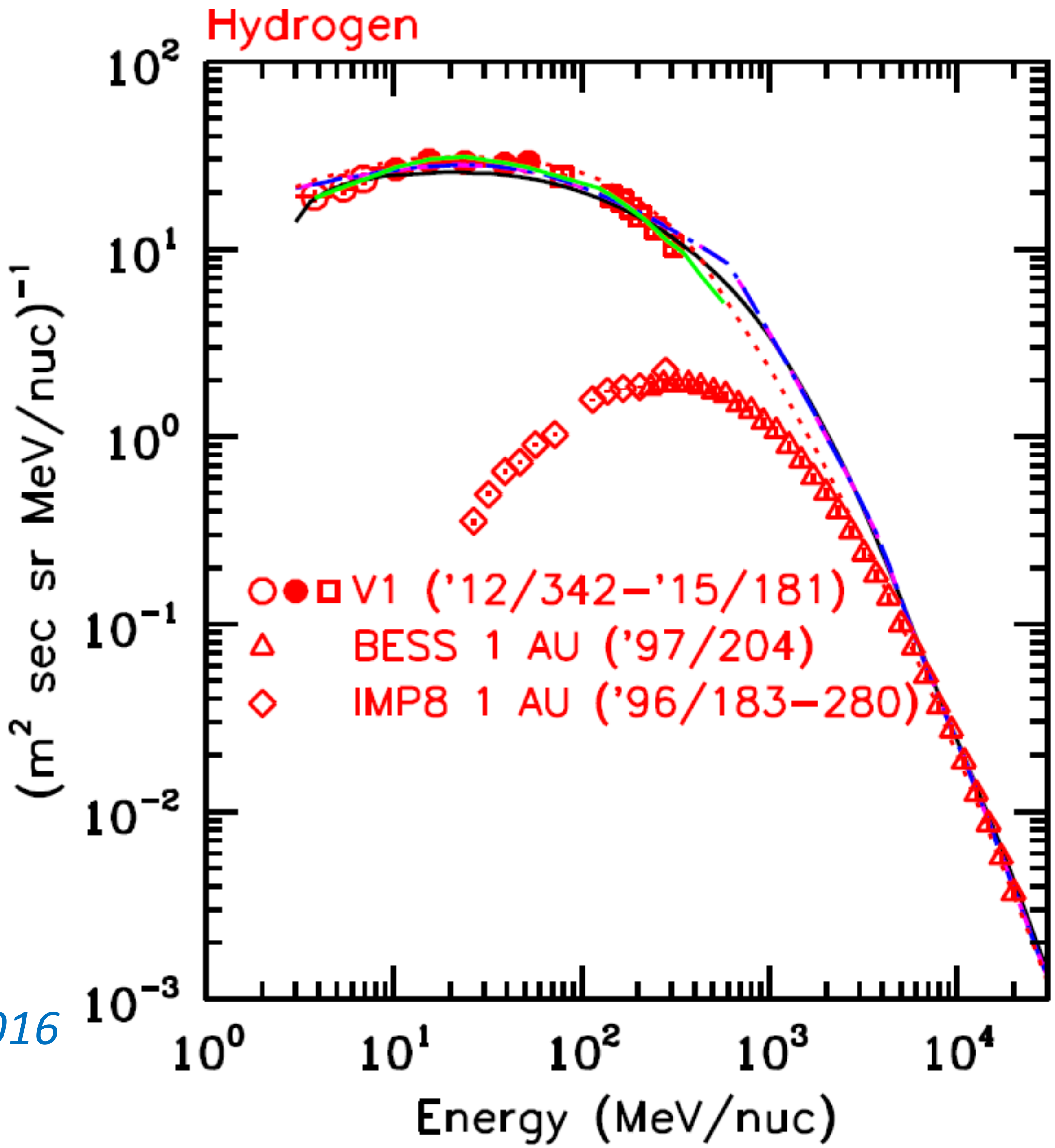
What about low-energy CRs?



Gaisser et al., 2006

Solar modulation: Voyager 1 data





Cummings et al., 2016

Importance of sub-relativistic protons for ionization

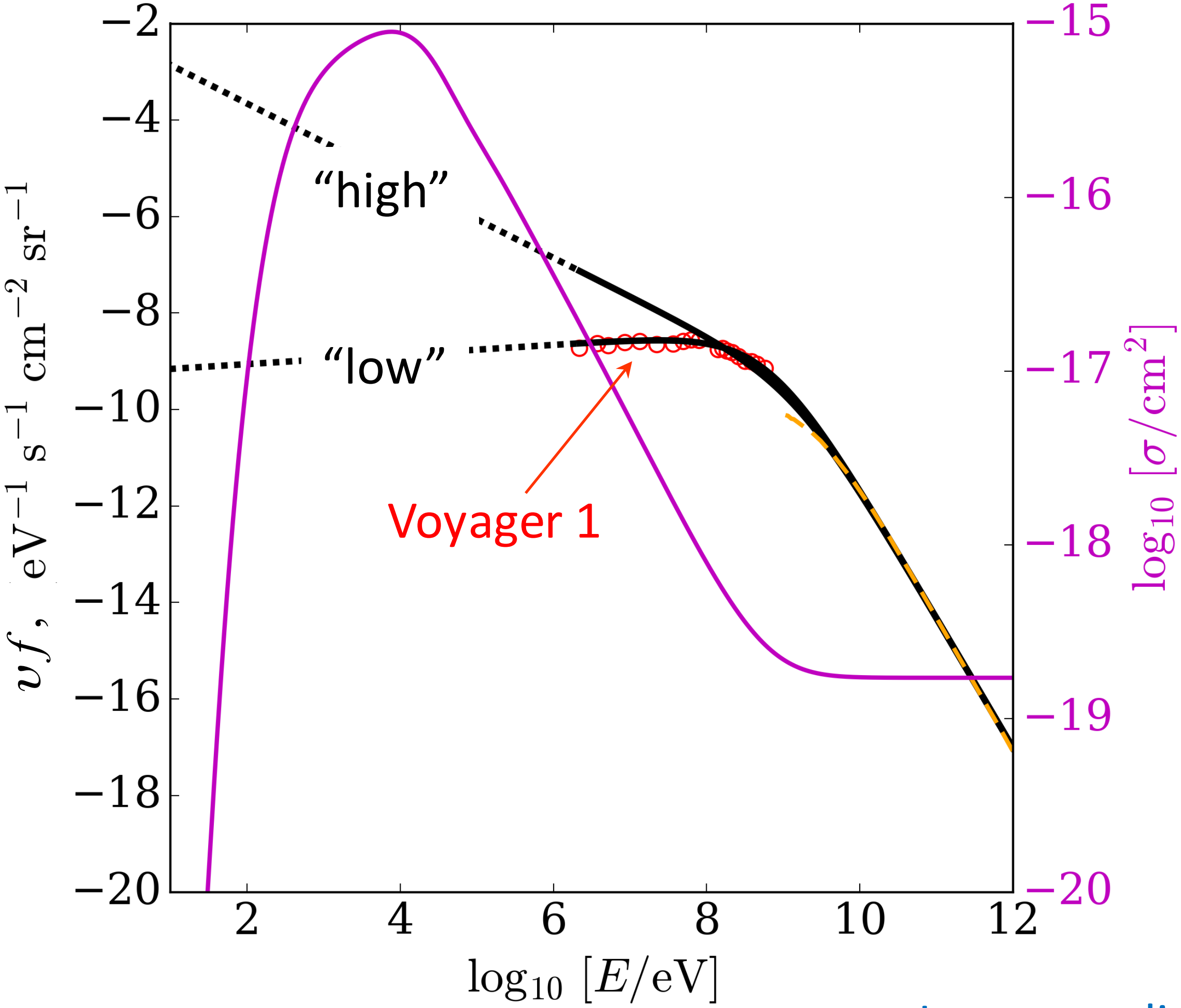


Image credit: Daniele Galli

Comparison with observations

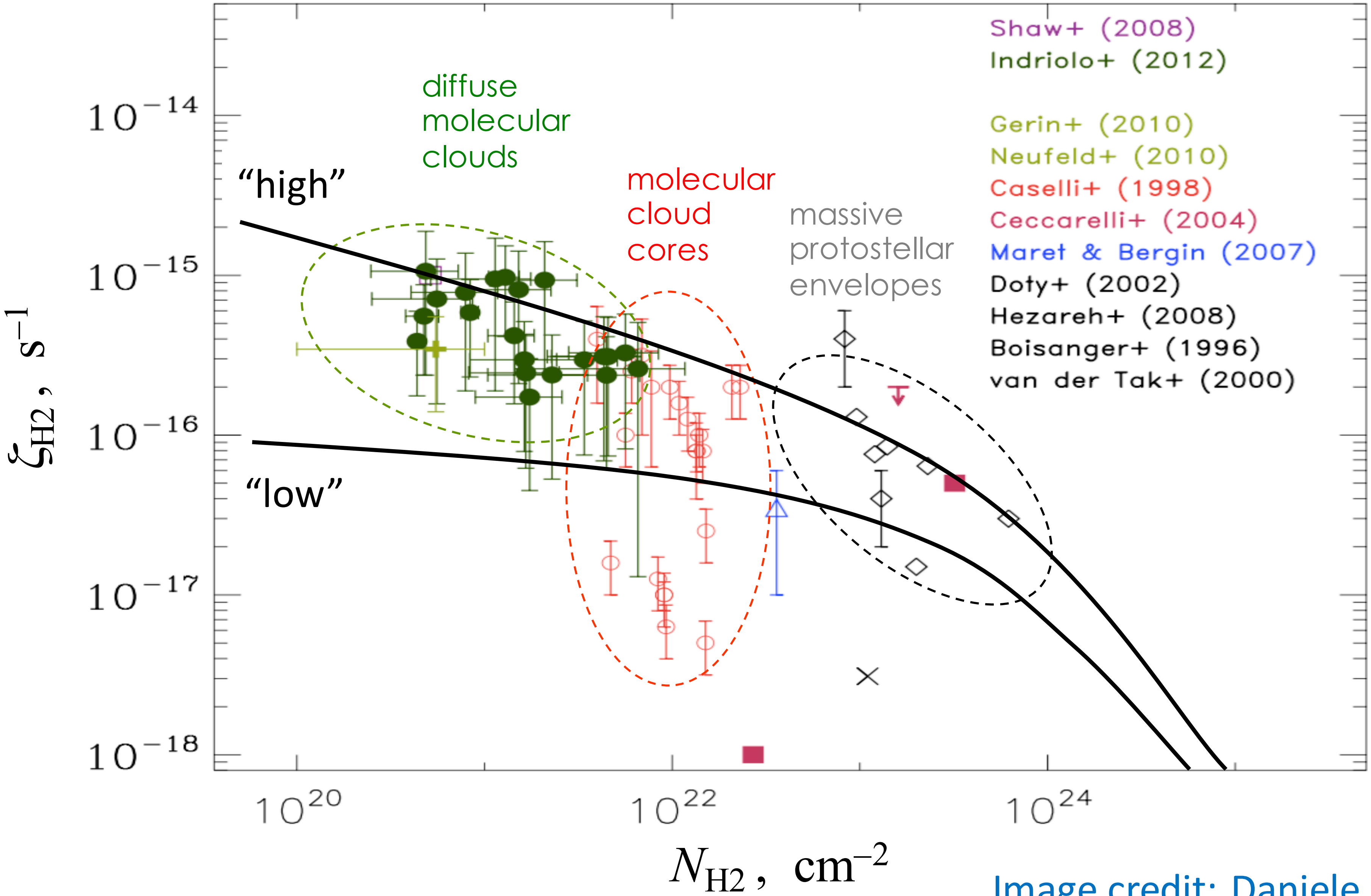


Image credit: Daniele Galli

Critical uncertainties

- Knowledge of low-energy ($\lesssim$ 1 GeV) CR spectra in interstellar medium (“boundary conditions” for clouds and disks).
- Choice of proper transport regimes for CRs penetrating into clouds and disks.

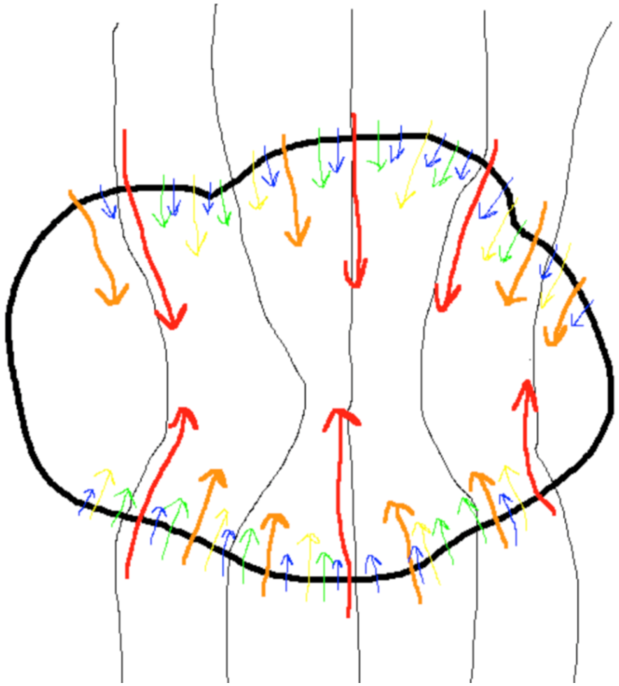
$\Downarrow$

Self-consistent treatment of fundamental processes driven by CRs: ionization/heating, formation of disks, dust evolution …

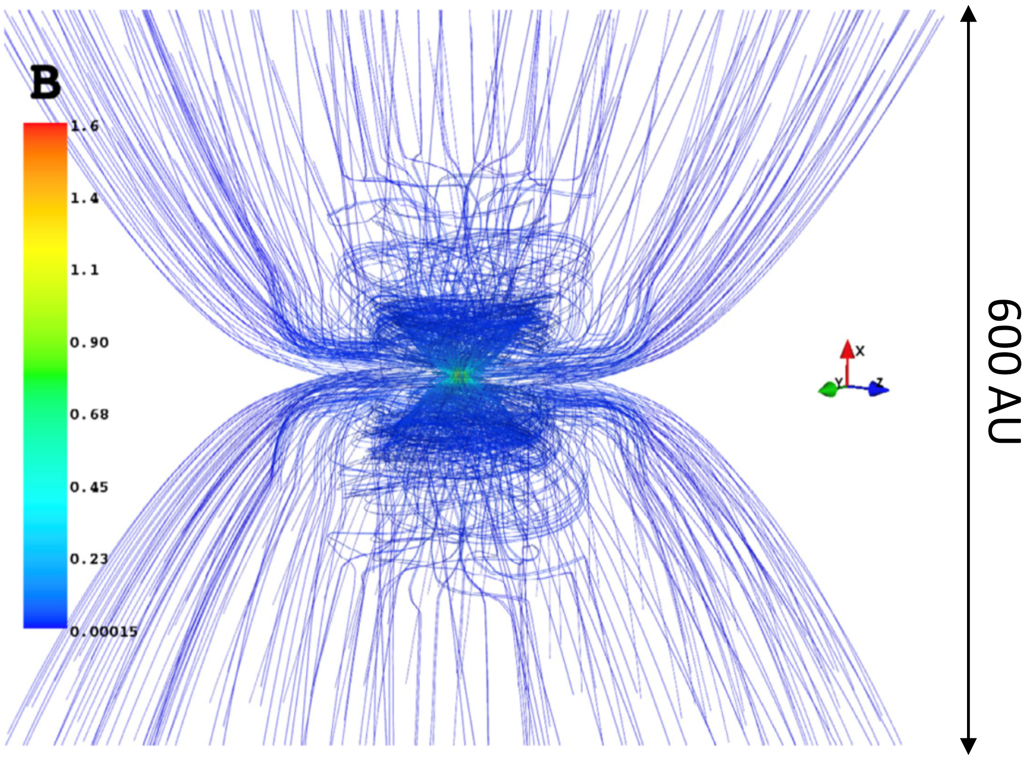
Magnetic mirroring and focusing

Silsbee et al., ApJ (2018)

Magnetic field in dense clouds



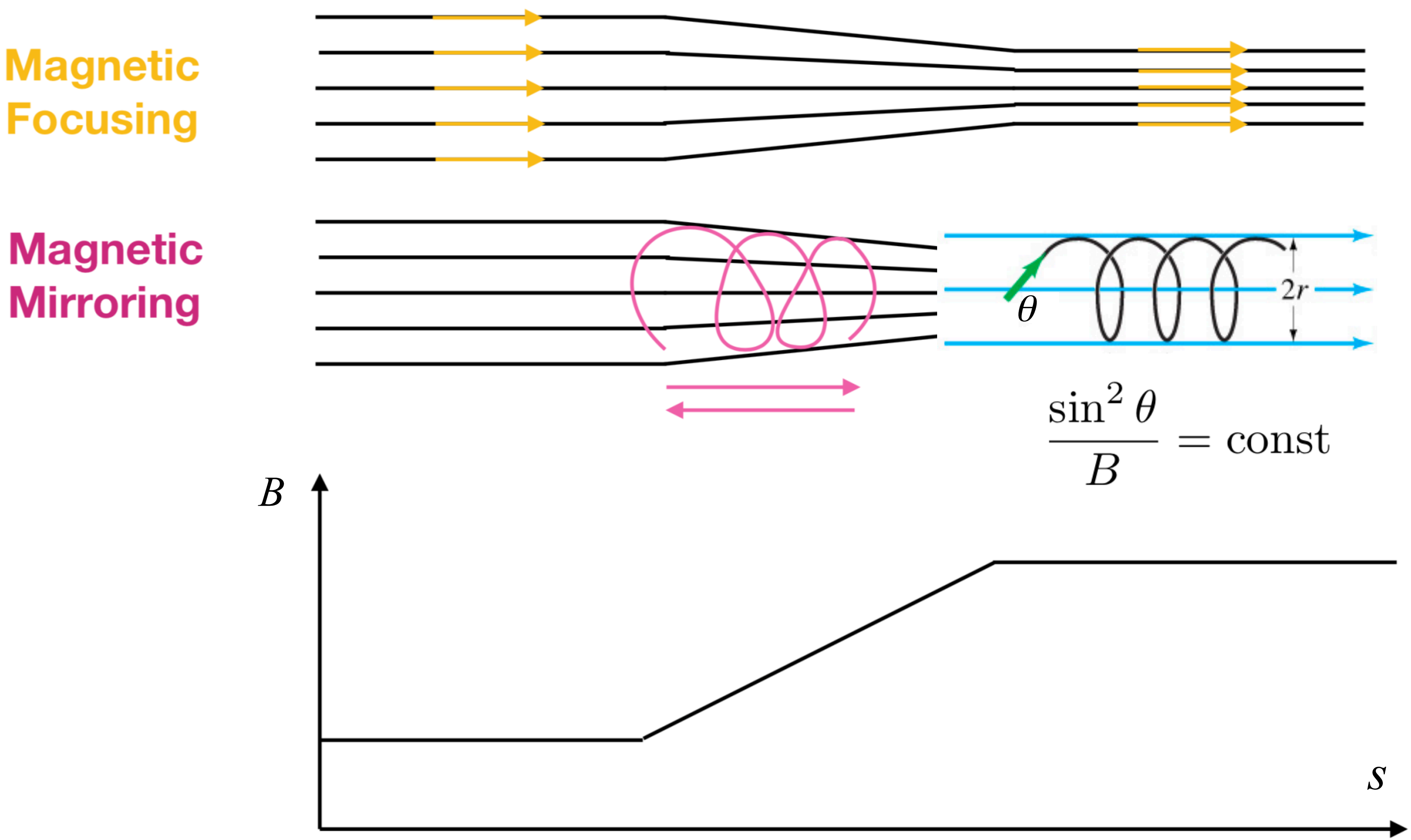
Kedron Silsbee (artistic view)



Padovani et al., 2013

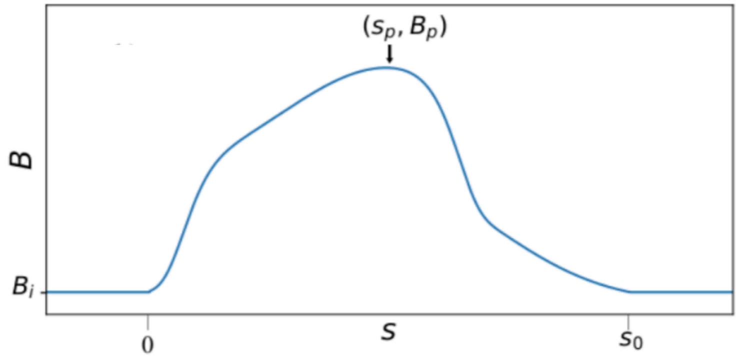
Magnetic field in dense cores is enhanced by orders of magnitude

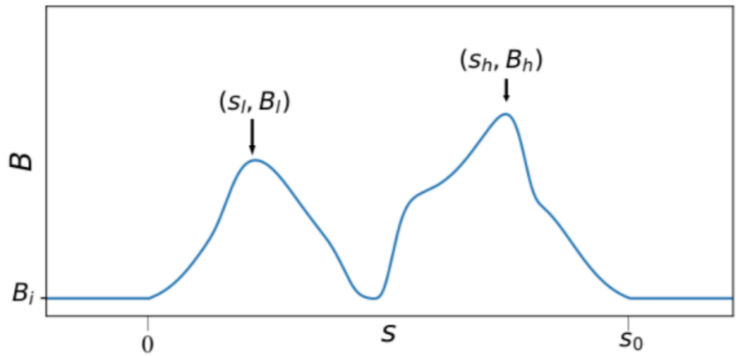
Mirroring and focusing



Field strength along the line

Field line can have arbitrary behavior within the cloud.





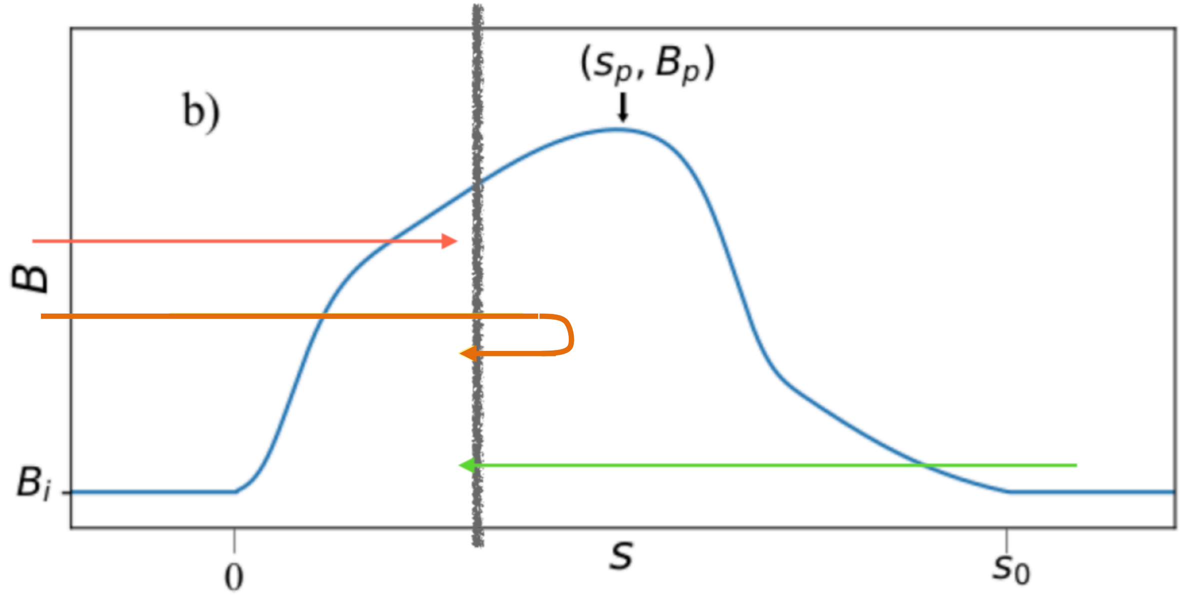
Relevant quantity is the strength of the field along the line.

Liouville theorem: $f(\mu, s) = f_i(\mu_i)$

$$\mu \equiv \cos\theta$$

$$\frac{1-\mu^2}{B} = \text{const}$$

Single-peak case



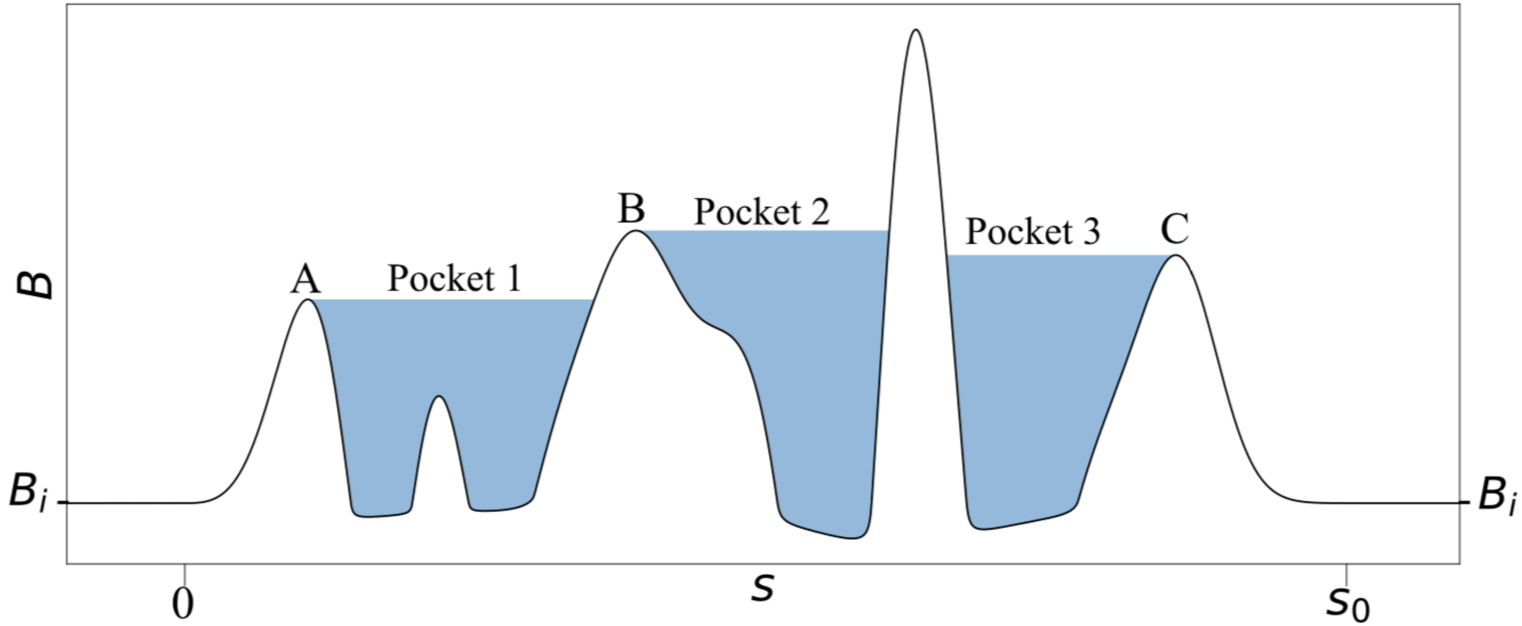
Particles belong to three groups:

- forward-moving: $0 \leq \mu \leq 1$
- mirrored: $-\mu_p(s) \leq \mu \leq 0$
- passed from the other side: $-1 \leq \mu \leq -\mu_p(s)$

$$\mu_p = \sqrt{1 - \frac{B(s)}{B_p}}$$

The entire sphere of 4π is filled ⇒ CR density is conserved

Magnetic pockets



Density in pocket A: $$\frac{n(s)}{n_\mathrm{i}} = \sqrt{1 - \frac{B(s)}{B_\mathrm{A}}}$$

CR density can be decreased drastically!

CRs in (very) dense regions

Padovani et al., A&A (2018)

Transport of CRs

CR protons up to ~10^{15} eV are well magnetized at the scale of a problem, so their propagation is along the local magnetic field (coordinate s).

The CR distribution function $f(E, s, \mu)$ is governed by the transport equation:

$$\frac{\partial S}{\partial s} + \frac{\partial}{\partial E}\left(\dot{E} f\right) + \nu_{\rm cat} f = 0$$

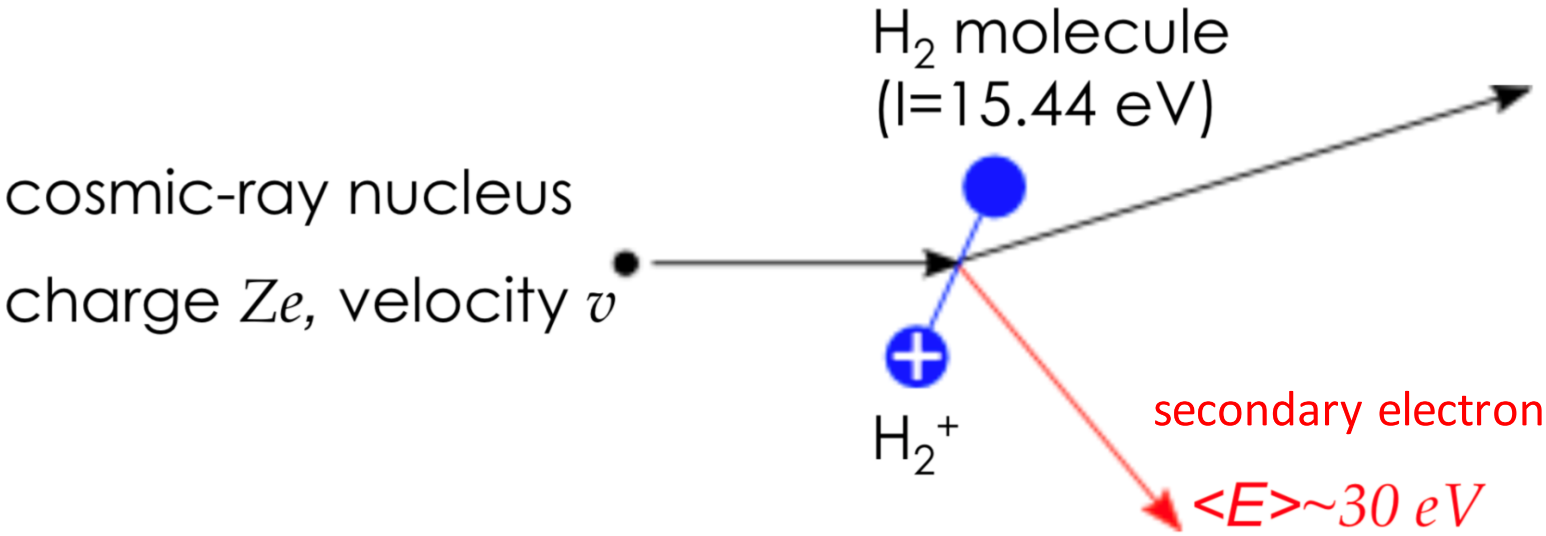
continuous losses   catastrophic losses

Weak scattering: $S \approx \mu v f$ (e.g., Coulomb collisions)

Strong scattering: $S \approx -D \frac{\partial f}{\partial s} + u f$ (e.g., MHD turbulence)

The solution critically depends on the scattering regime and the dominant mechanism of energy loss

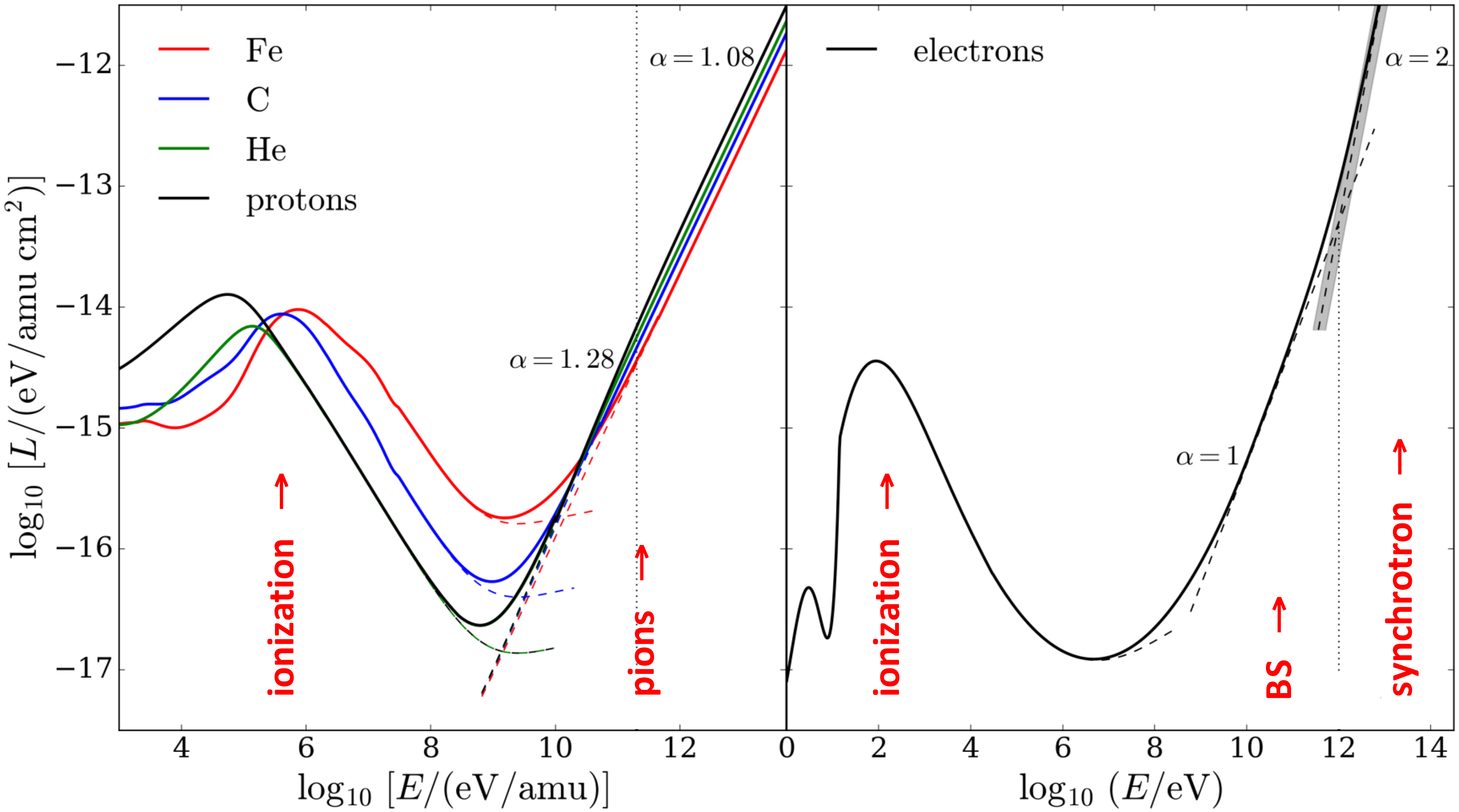
CR ionization (weak scattering)



CR particles lose only a small fraction of their energy in each ionization collision ⇒ continuous losses.

Energy loss functions

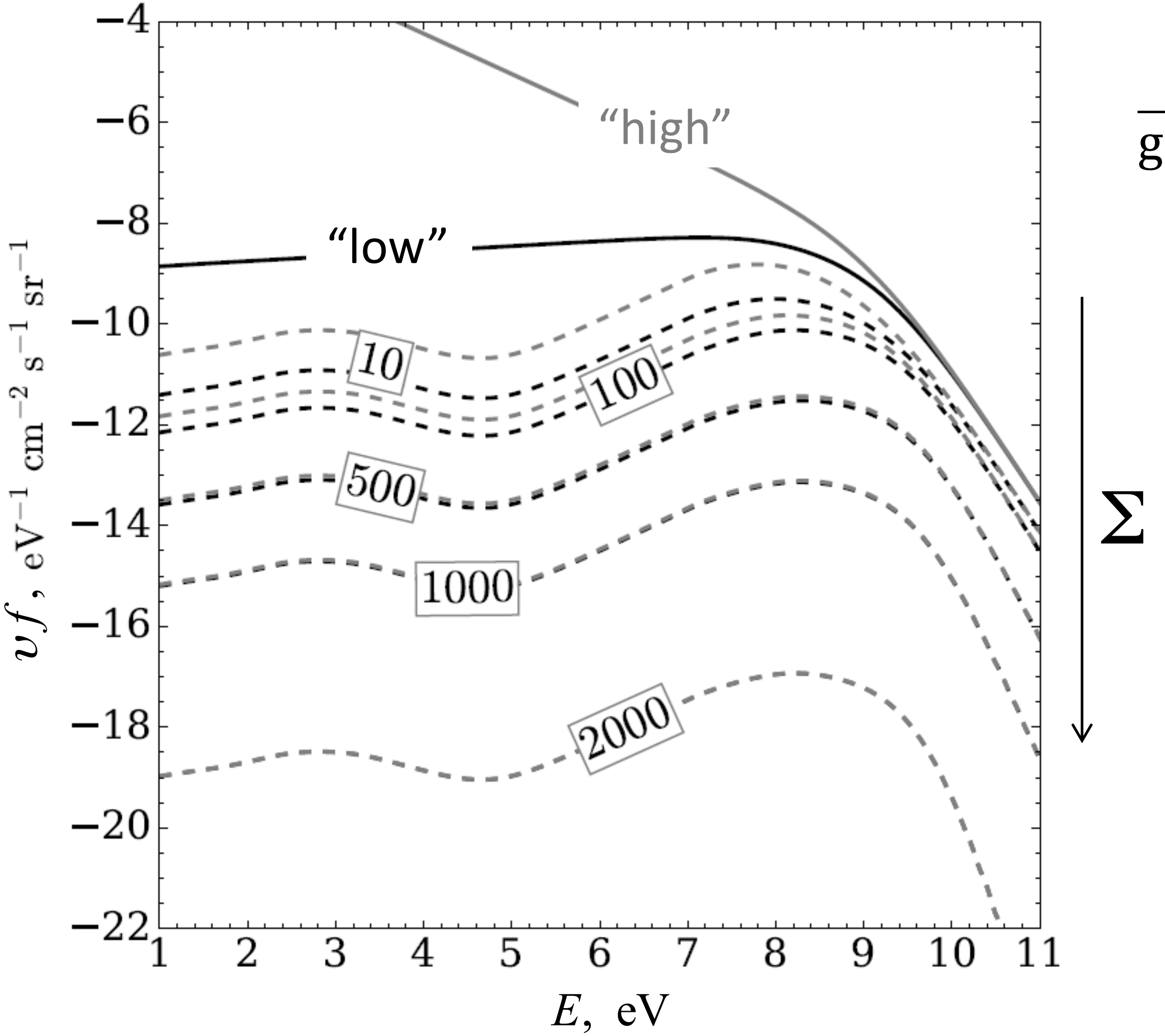
For continuous losses it is convenient to introduce $L(E) = \dot{E}/\upsilon\, n_{H2}$, describing deceleration along the CR path with the effective column density $N = \int n_{H2}\, ds$.



Loss function $L(E)$ determines the stopping range for a given CR species:

$$N(E) = \int_0^E dE/L(E)$$

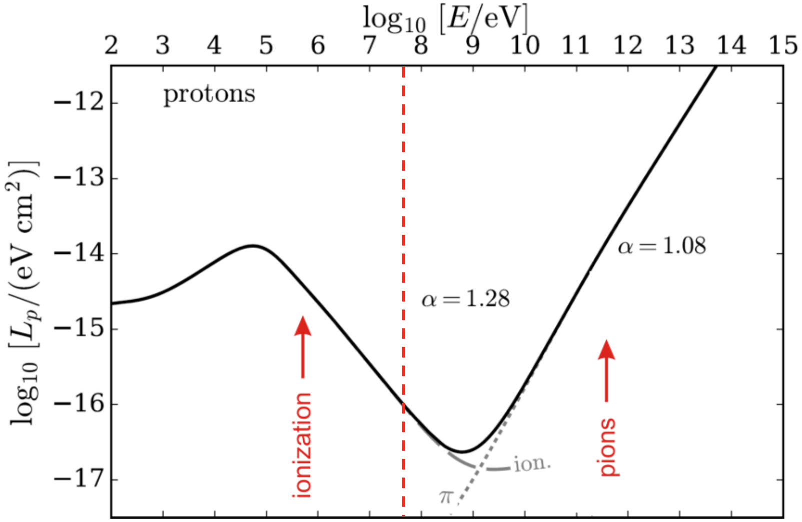
Attenuation of CR protons (free streaming)



$$\frac{\Sigma}{\text{g cm}^{-2}} \approx 4\times10^{-24}\frac{N}{\text{cm}^{-2}}$$

Uncertainty of the initial spectrum is unimportant at $\Sigma \gtrsim 200$ g cm^{-2} ($N \gtrsim 5\times10^{25}$ cm^{-2}).

Stopping range of CRs

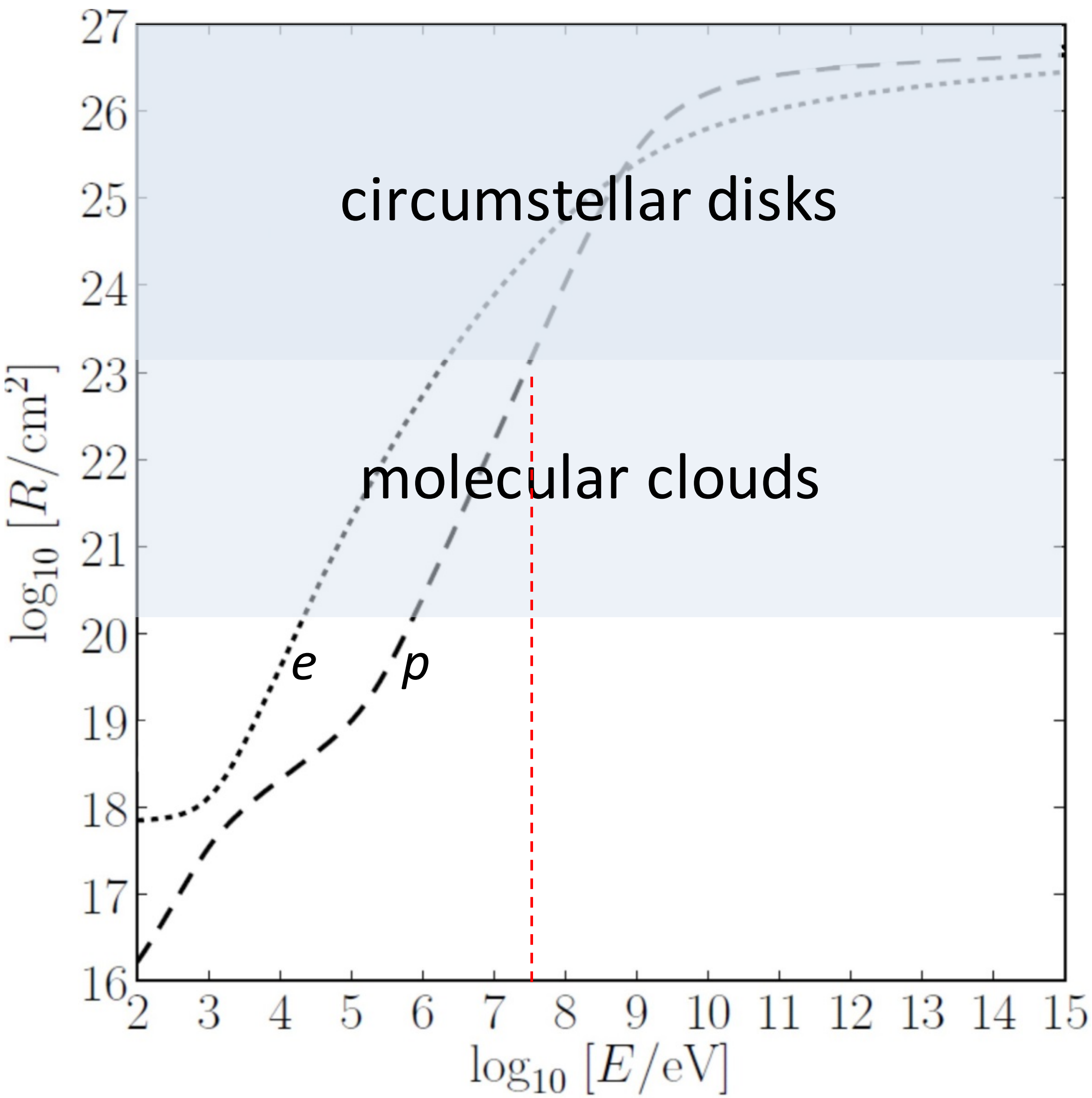


The stopping range of CRs,

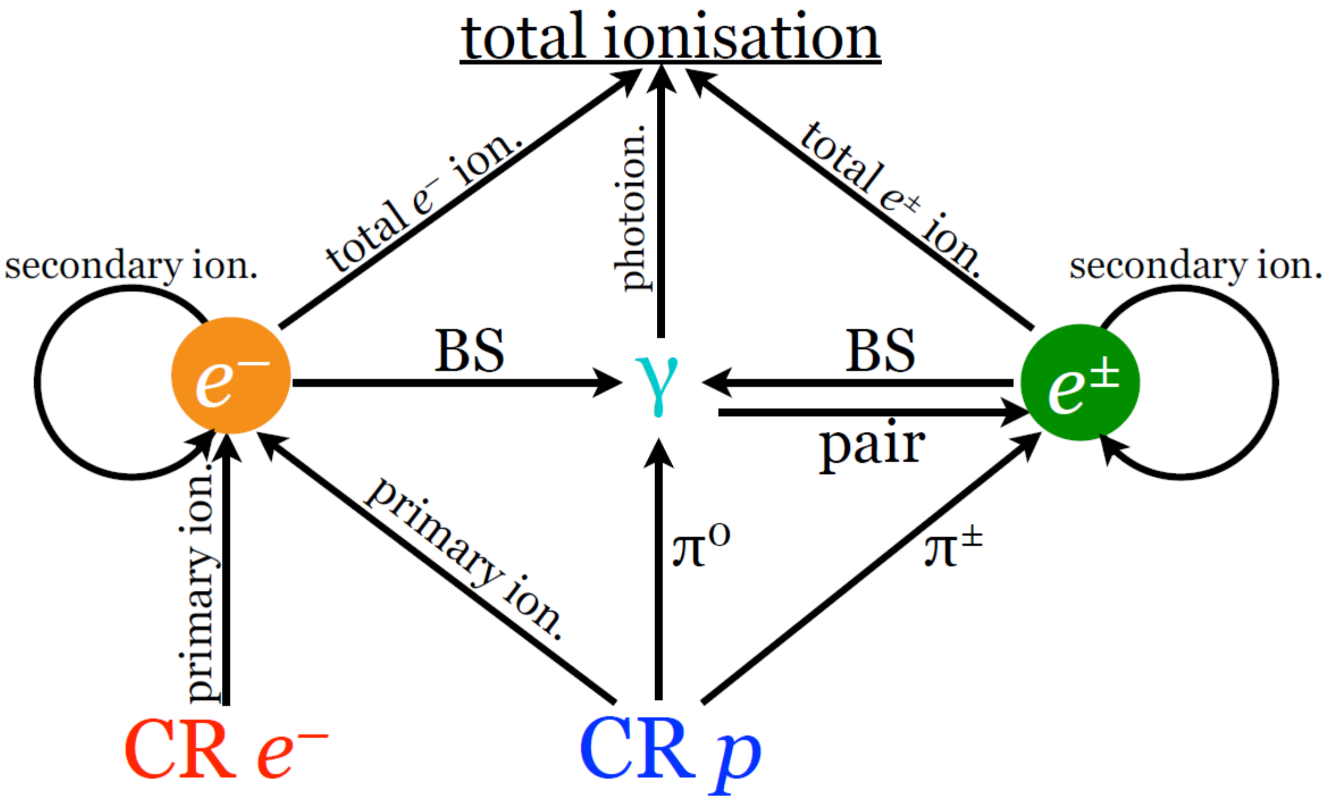
$$R(E) = \int_0^E dE/L(E),$$

is finite for CR species.

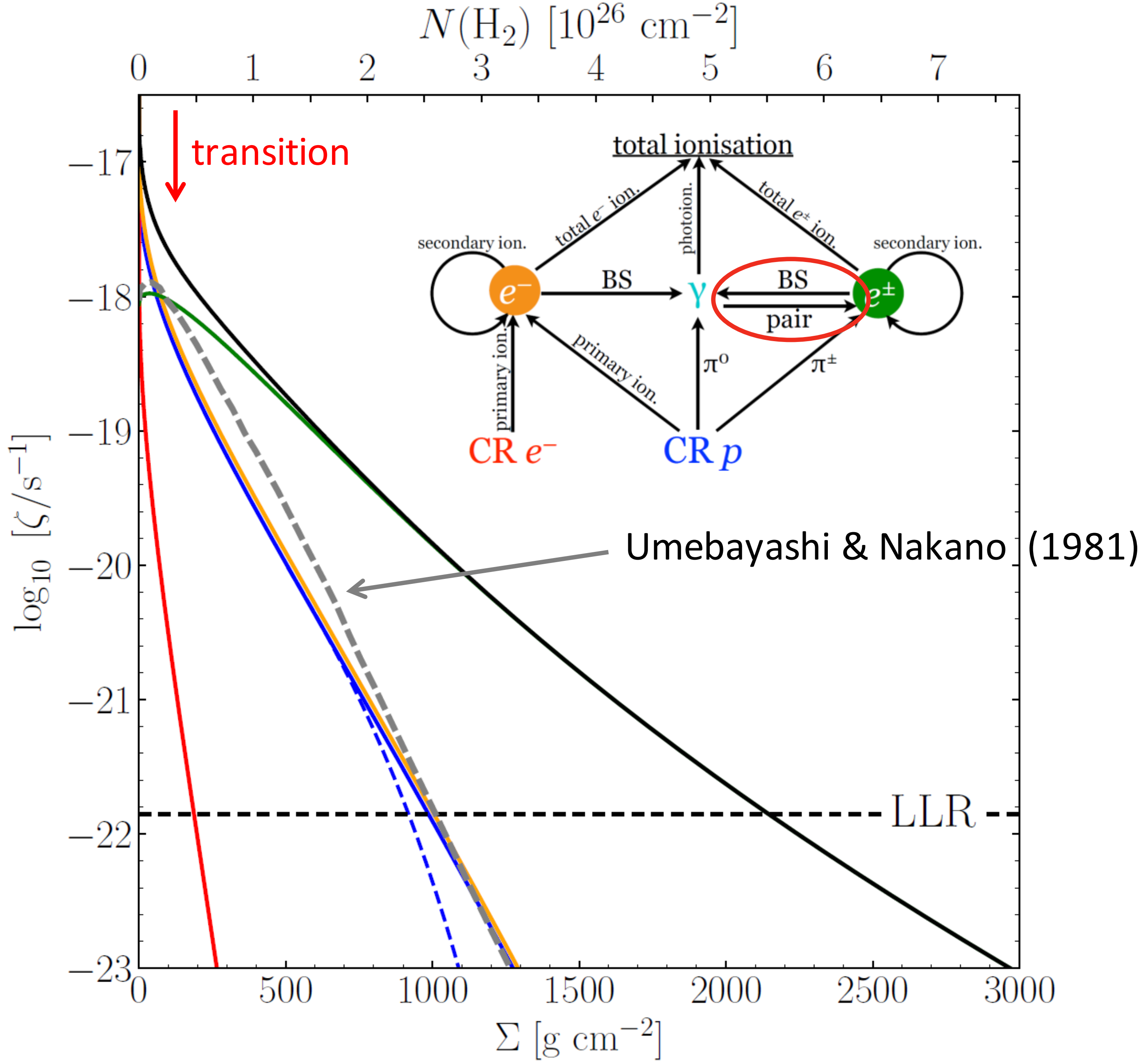
Ionization in disks is due to secondary CRs.



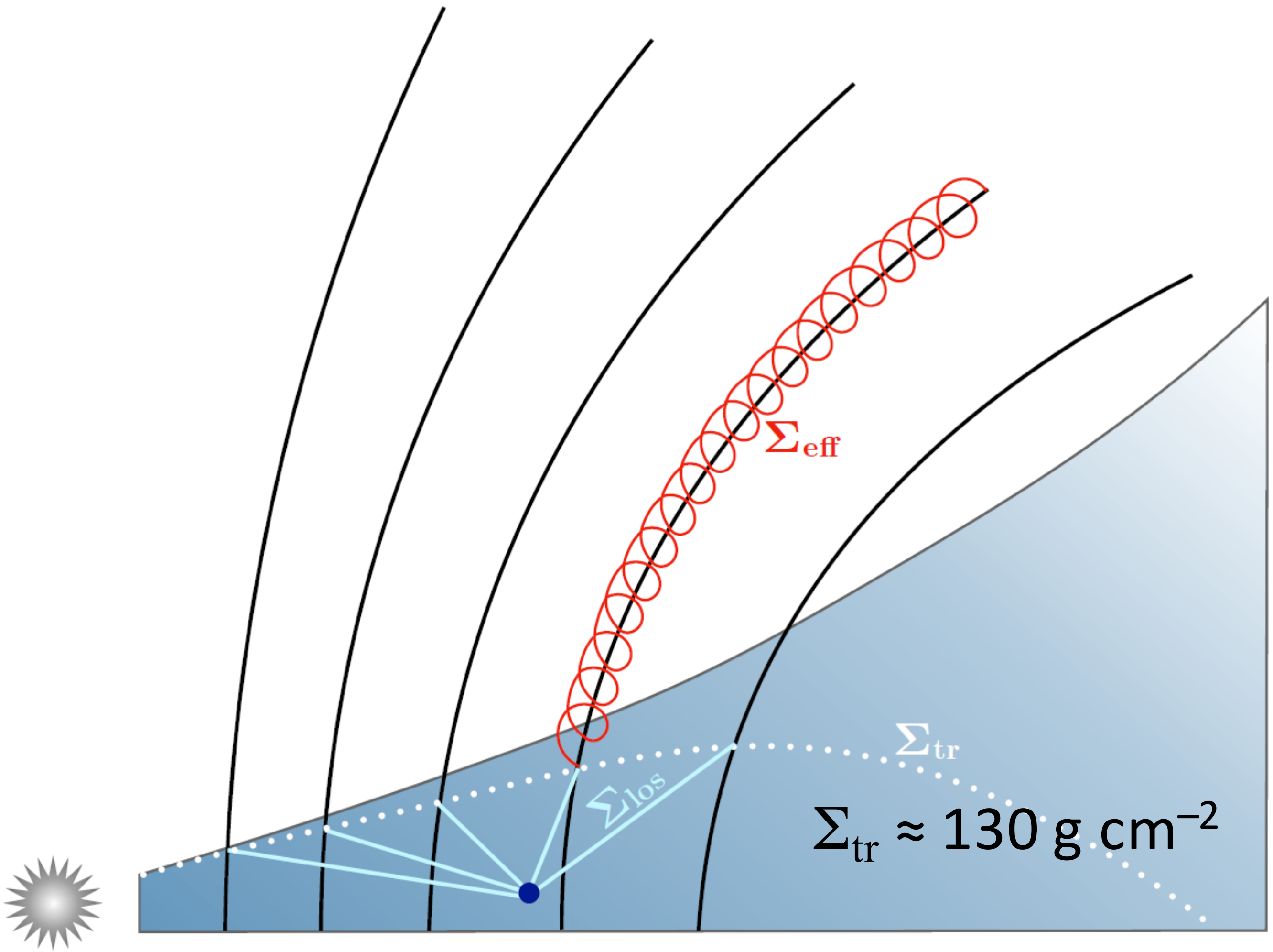
Ionization mechanisms



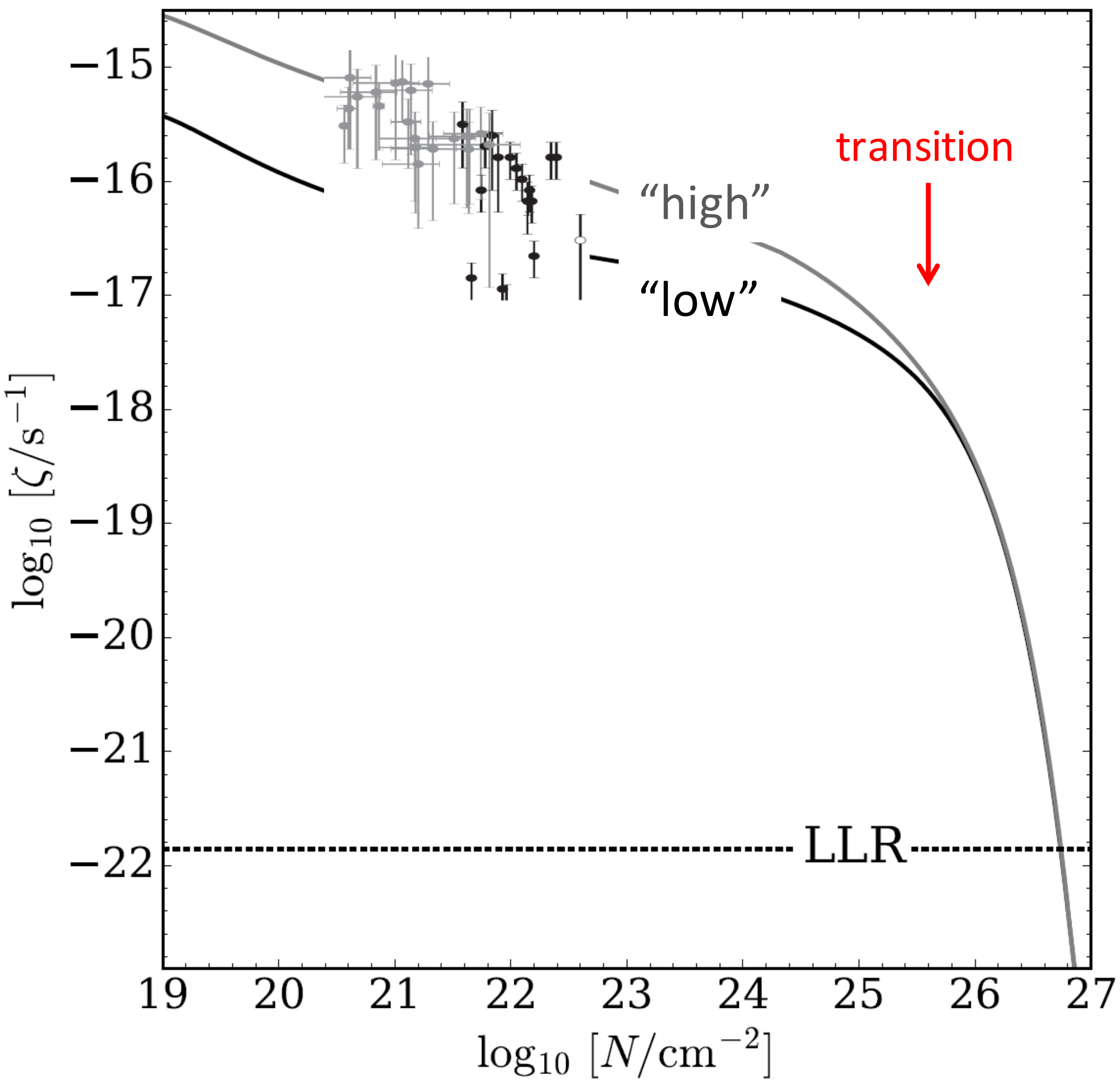
Total ionization rate (model "high")



Transition from the effective to line-of-sight column density



Zoom to lower *N*



Self-modulation of CRs

Ivlev et al., ApJ (2018)

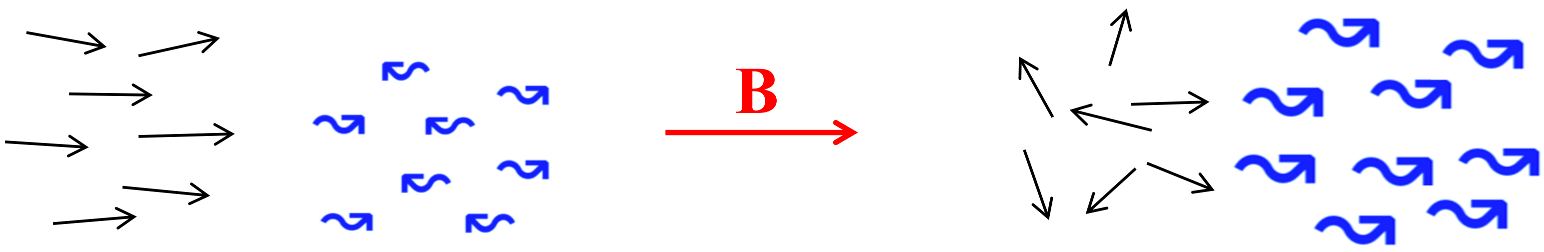
Dogiel et al., ApJ (2018)

Streaming instability

(*Lerche 1967; Kulsrud & Pearce 1969*)

CR stream enters **quiescent plasma**

Isotropic CRs *diffuse* and *drift* with the **excited MHD waves**



$$S_{\rm free} = uf$$

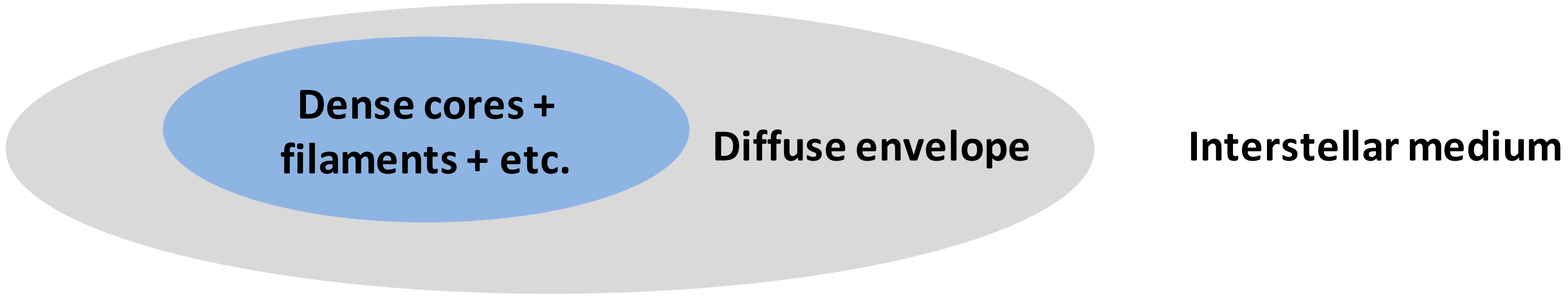
$$S_{\rm diff} = -D\frac{\partial f}{\partial s} + v_{\rm A} f$$

- Streaming CRs (with the flux velocity $u >> v_{\rm A}$) resonantly excite MHD waves.
- The total momentum (CRs + waves) is conserved $\Rightarrow$ CRs are isotropized.
- The wave excitation rate $\gamma_{\rm CR} \propto pv(S - v_{\rm A} f)$.

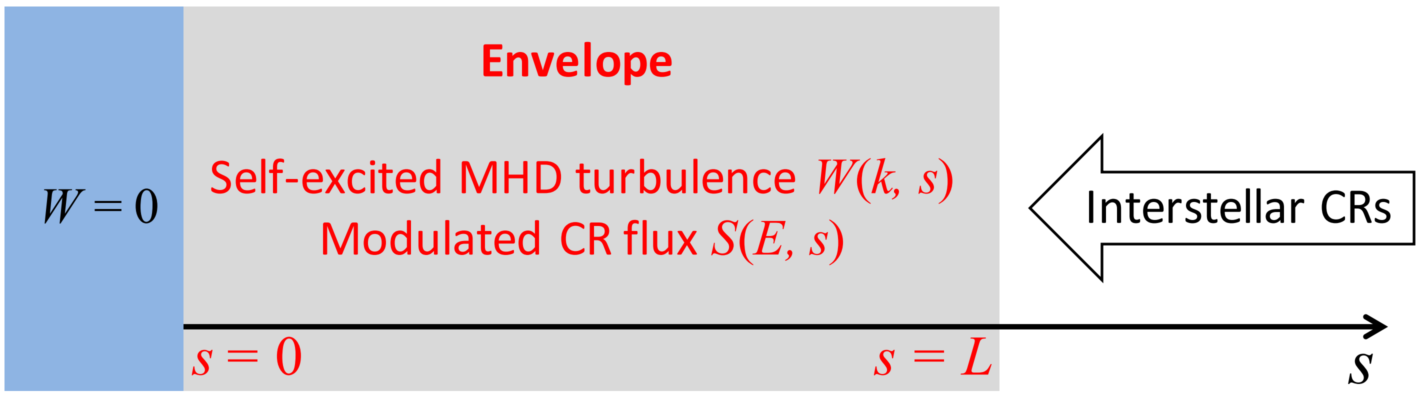
Self-excited turbulence

- CRs in dense MCs experience strong attenuation.
- Hence, a steady flux of CRs is formed from diffuse interstellar medium into dense cores.
- This triggers streaming instability (*Lerche 1967; Kulsrud & Pearce 1969*), and thus generates self-excited MHD turbulence (*Skilling & Strong 1976; Cesarsky & Volk 1978, … , Morlino & Gabici 2015*).
- Self-excited MHD turbulence is important for variety of processes at larger scales, e.g., CR escape from SN remnants *(Aloisio & Blasi 2016)*, Galactic winds *(Recchia et al. 2016)*, Galactic halo *(Evoli et al. 2018)*, …

Model setup: geometry



- We identify 3 characteristic regions, and focus on processes in the diffuse envelope.
- CRs propagate along the magnetic field $\Rightarrow$ 1D equations.



Universal flux of self-modulated CRs

- According to *Kulsrud & Pearce (1969)*, the excitation rate of MHD waves is $\gamma_{CR} \propto pv(S - v_A f)$.
- In a free-streaming regime, $S(E) \sim v f_{IS}(E)$. Then the balance of the wave excitation and damping yields the threshold energy E_{ex}:

$$pv^2 f_{IS}\big|_{E_{ex}} = const$$

below which the turbulence is excited.

- For $E < E_{ex}$, we obtain a universal flux as long as $S/f_{IS} >> v_A$:

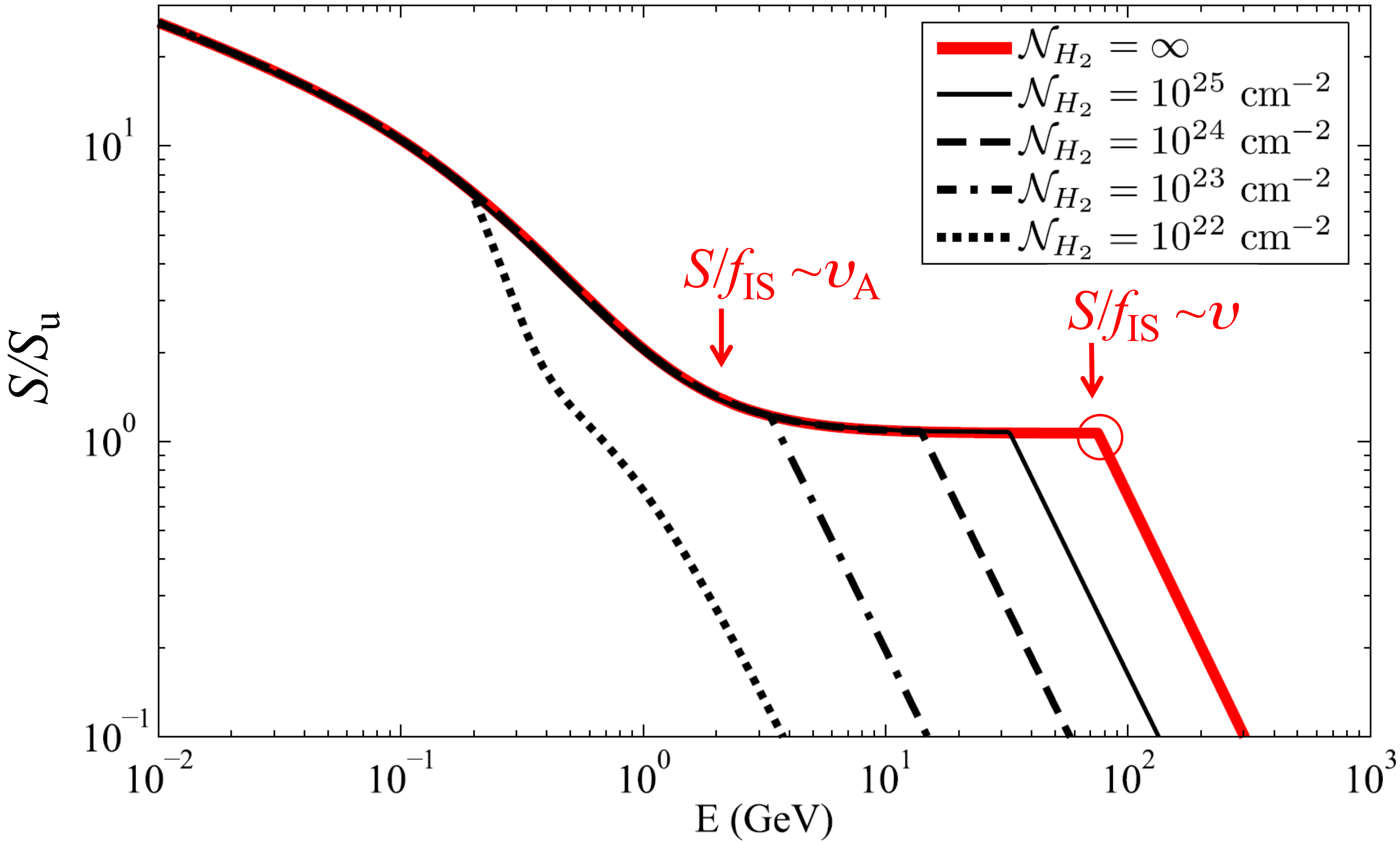
$$\boxed{S(E) \approx const/(pv) \equiv S_u(E)}$$

which does not depend on f_{IS}.

- At lower E, the flux approaches the advection asymptote $v_A f_{IS}$.

$S(E)$ curve for different $\mathcal{N}_{\mathrm{H2}}$

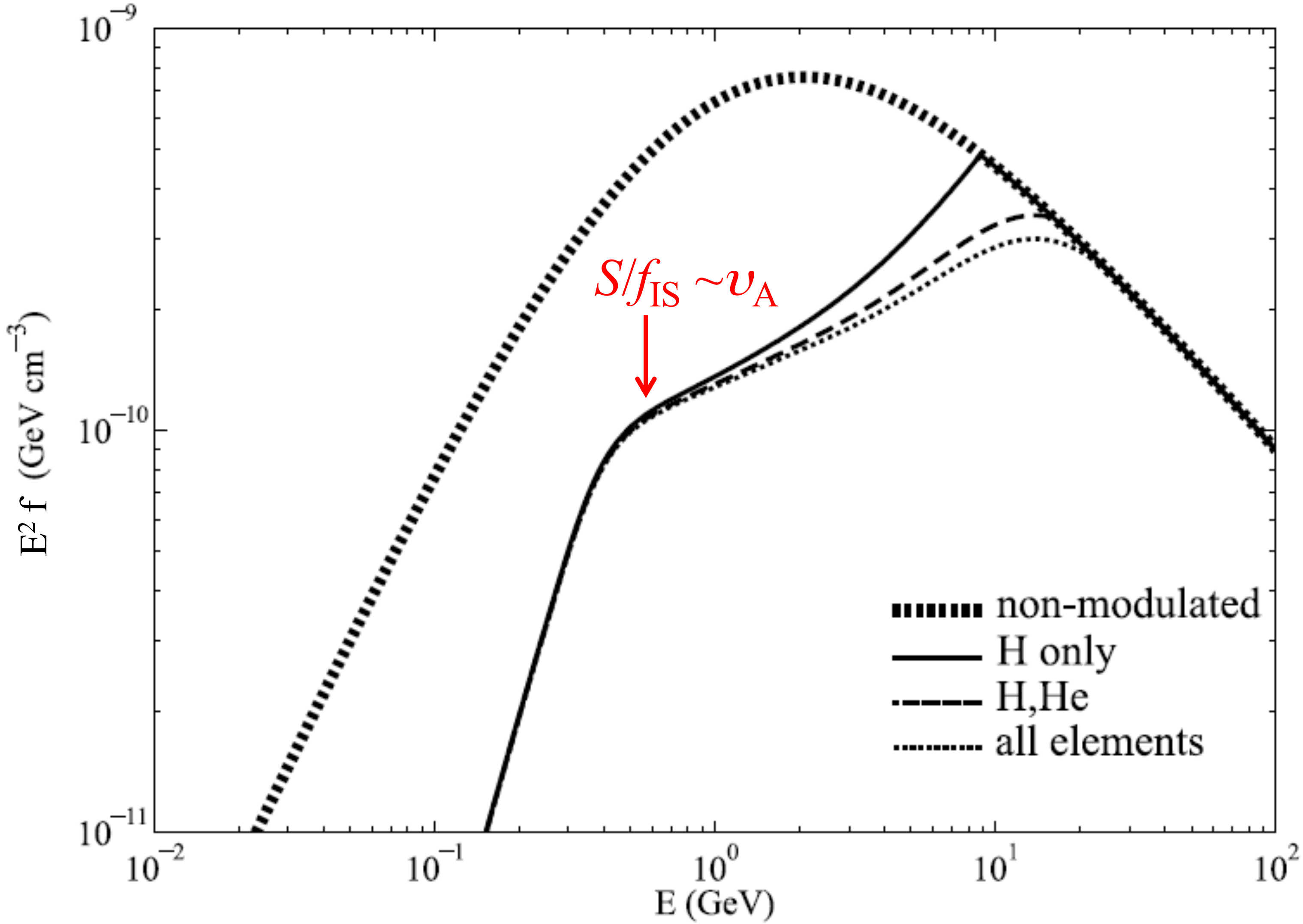
$S_{\mathrm{u}} = const/(p\upsilon)$



Decreasing N_{H2} leads to lower E_{ex},

but the modulated flux at $E < E_{\mathrm{ex}}$ remains unchanged.

Modulation of CR protons in CMZ



5 × local IS spectrum; $N_{\rm H2} = 10^{23}$ cm^{-2}; $n_{\rm H2}$ (envelope) $= 10$ cm^{-3}

Summary

- A careful choice of the transport regime for interstellar CRs penetrating molecular clouds and disks is crucial for accurate calculation of the processes occurring in these dense objects.

- Interstellar CR spectra at energies below ~ 1 GeV remain highly uncertain.

- The CR spectra can be constrained by combined analysis of available observations:

  H_3^+ ions in cloud envelopes;
  gas-phase chemistry in low-density clouds;
  gas/dust temperature in dense cores.