ESCAPING OF COSMIC RAYS AND PROPAGATION THROUGH THE GALAXY

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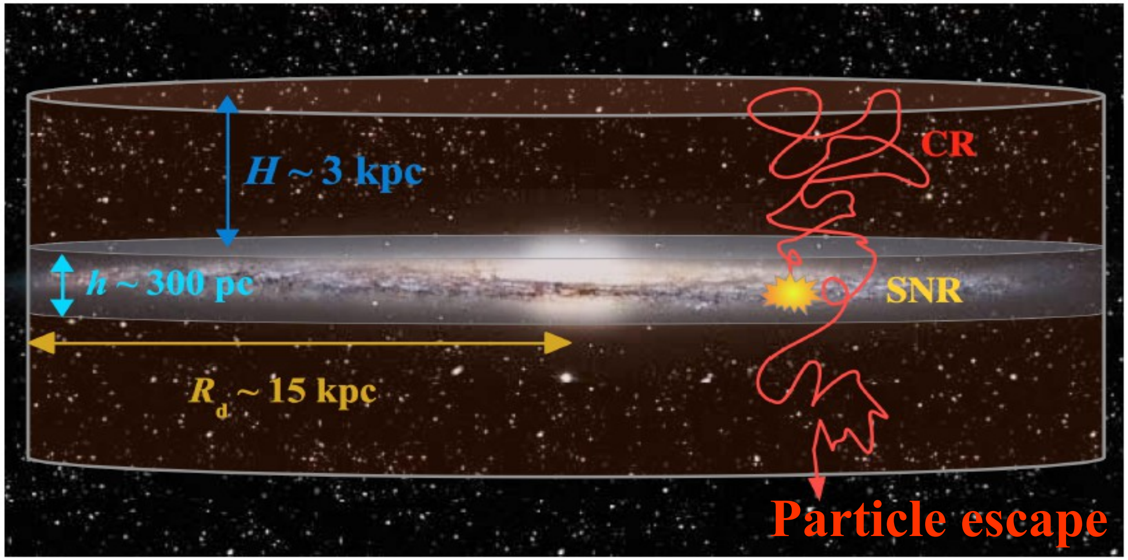
SUMMARY

- **The journey to the Earth**
  - ***The Galactic disk/halo diffusion model***
  - ***Beyond the standard diffusion model***
  - ***The gradient problem in the Galactic CR spectrum***

- **How particles escape from the source**
  - ***Interaction between escaping particles and Molecular Clouds***
  - ***Combining ionization and gamma-ray emission***

THE JURNEY OF CRs TO THE EARTH

Basic Halo model



In the basic picture of CR propagation model:

- CRs diffuse in a magnetic halo larger than the Galactic disc
- The CR distribution vanish at $z = H$ (H~3-4 kpc from diffuse synchrotron emission)
- The diffusion coefficient $D(E)$ is assumed constant everywhere in the halo

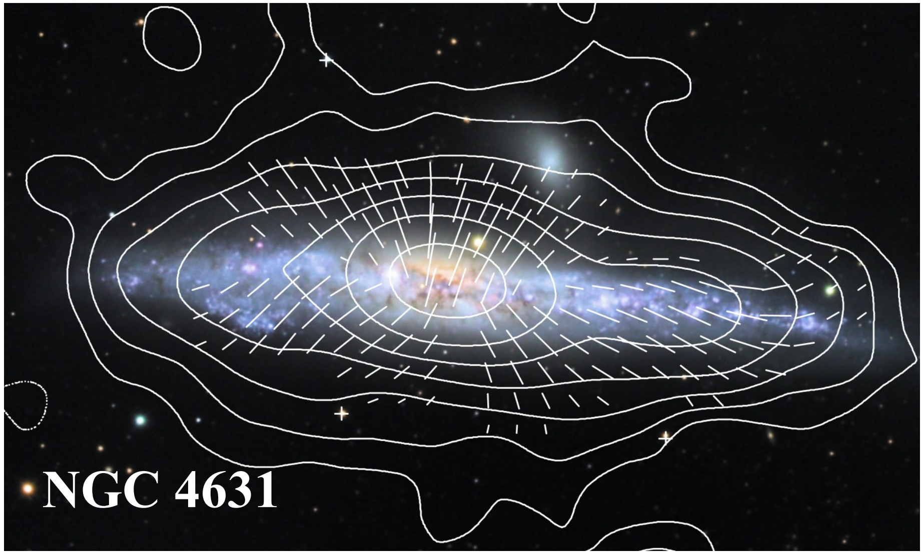
These requirements are needed because:

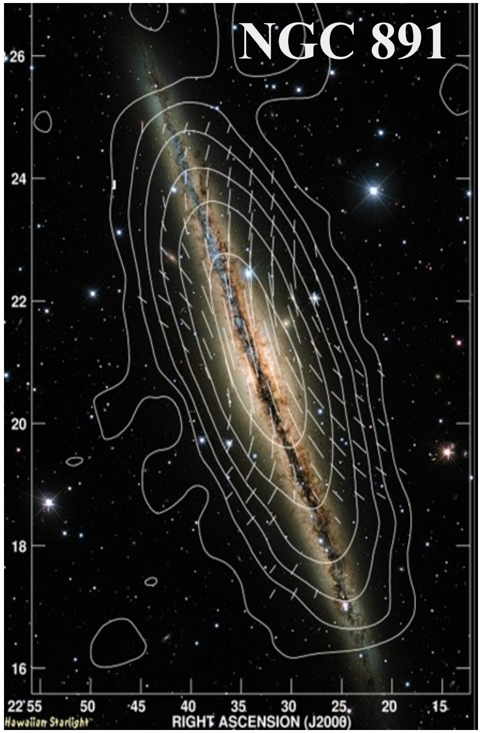
- Long residence time of CRs in the Galaxy
- Isotropy in the CR incoming direction

Radio halos in external galaxies

Evidences for the Galactic magnetic halo:

1) Detection of magnetic field around other galaxies
2) Detection of synchrotron emission around the Milky Way
3) Evidence of hot plasma from X-ray emission and absorption lines





Radio halos in external galaxies

Evidences for the Galactic magnetic halo:

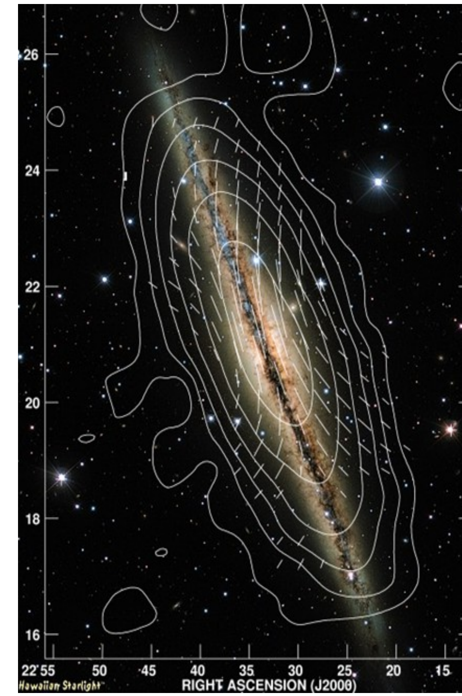
1) Detection of magnetic field around other galaxies
2) Detection of synchrotron emission around the Milky Way

What is the origin of the magnetic Halo?

Sometimes the X-shaped magnetic field structure in the halo is accompanied by strong vertical fields above and below the central region of the disk.

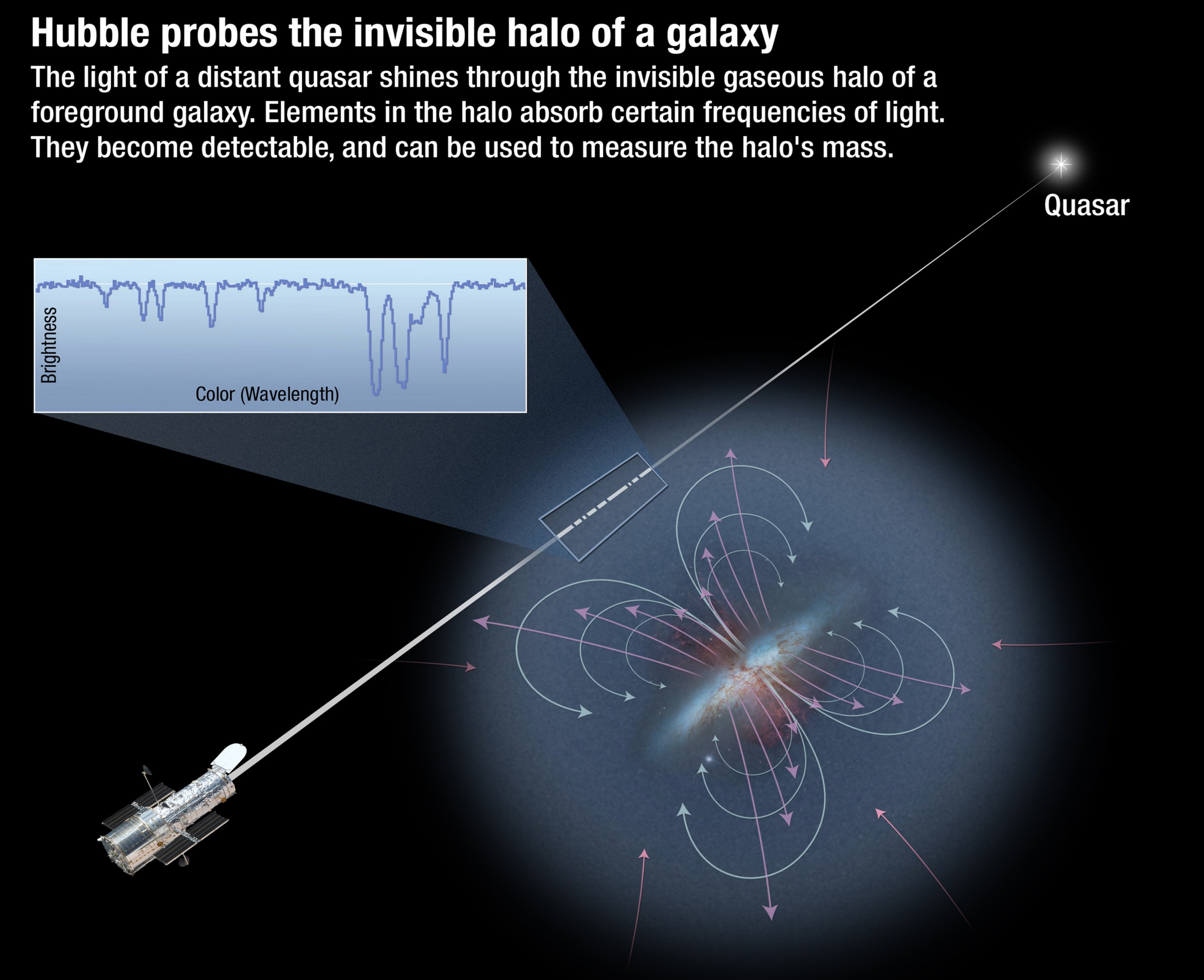
These observations support the idea of a "**galaxy wind**" which is driven by the energy of star formation processes in the disk and transports gas, magnetic fields and cosmic-ray particles into the halo.

The speed of the outflow can be measured from radio observations and is of the order of 300 km/s.



Magnetic halo around galaxy NGC 4631

Evidence of galactic halos from absorption of optical lines



Evidence of galactic halos from X-ray emission and absorption lines

Thermal X-ray emission has been observed from the region around starburst galaxies.

➢In some “normal” galaxies the presence of a hot temperature gax ($T \sim 10^6$ K) has been inferred from absorption lines in X-rays (especially lines OVI , OVII and OVIII)

➢ Also the Milky Way presents the same absorption lines [e.g. Kalberla & Dedes (2008), Miller & Bregman (2013)]

➢ From those lines the total mass of the halo can be estimated

$$M_{halo} \sim 10^{10}\, M_{sol}$$

(comparable with the total barionic mass in the disk!!)

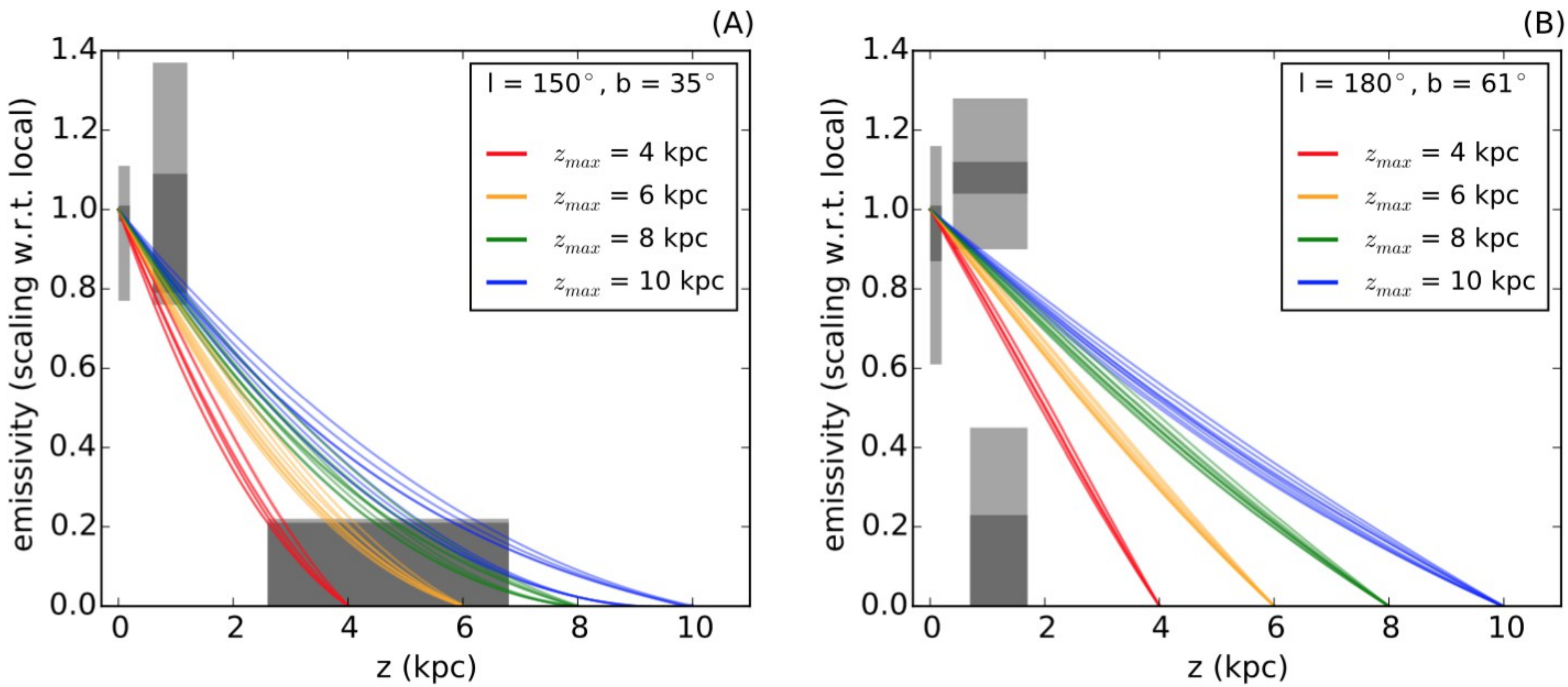
➢ And also the metallicity: $Z \sim 0.2\text{-}0.3$

→ The halo has been probably polluted by a Galactic wind

Galactic wind observed in X-rays from starburst galaxy M82

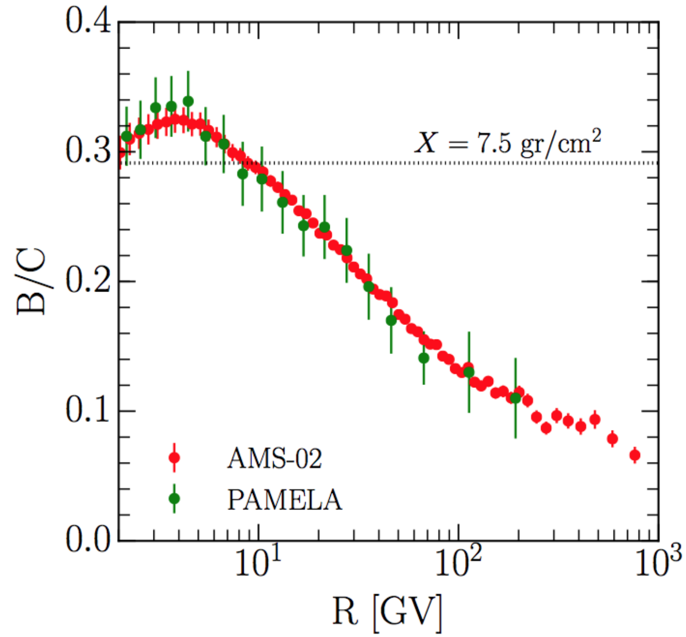
The gamma-ray halo in the Milky Way

(Tibaldo et al., 2015, ApJ]



- Using high-velocity clouds to measure the emissivity per atom as a function of z (proportional to CR density)
- Indication of a halo with *H* >~ few kpc

The diffusive paradigm of Galactic CRs



- The ratio of Boron and Carbon fluxes provides us with the best estimates of the time spent by CRs in the Galaxy before escaping.

$$N_B = N_c R_{spal} \tau_{esc} \rightarrow N_B / N_c = X m_p / \sigma$$

- The grammage traversed by CRs is related to the escape time:

$$X(E) = \bar{n} \mu v \tau_{esc}(E)$$

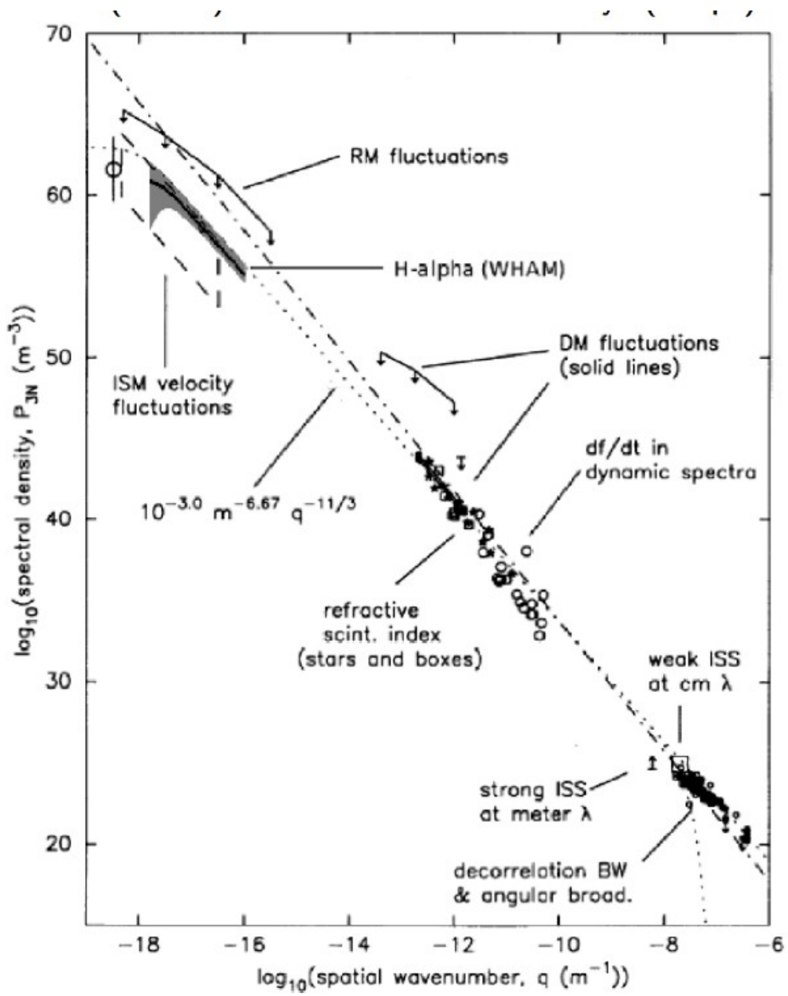
From measurements: $X(E \simeq GeV) = 10\, gr\, cm^{-2}$

- If we assume that the gas is concentrated in a thin disc, *h*, and the diffusive halo extends to a height *H*, the mean density

$$\bar{n} = n_{disc}\ h/H \sim 0.1 \left(\frac{h}{200\ pc}\right) \left(\frac{H}{2\ kpc}\right)^{-1} cm^{-3}$$

- the typical escape time at *E* ~ 1-10 GeV is: $\boxed{\tau_{esc} = 50 (H/2\, kpc)\, Myr}$

The interstellar turbulence



Electron density flucuation in the ISM [Armstrong et al. 1995, ApJ 443, 209]

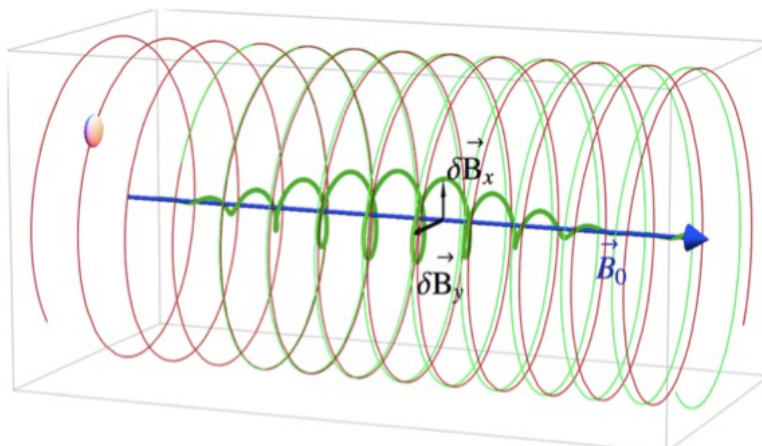
- Turbulence is stirred by SNe at a typical scale L~ 10-100 pc
- Fluctation of velocity and magnetic field are Alfvénic
- They have a Kolmogorov spectrum $k^{-5/3}$ (density is a passive tracer so it has the same spectrum: $\delta n \propto \delta B^2$):

$$W(k)\,dk = \frac{\langle \delta B(k) \rangle^2}{B_0^2} = \frac{2}{3}\frac{\eta_B}{k_0}\left(\frac{k}{k_0}\right)^{-5/3}$$

- Where $k_0 = L^{-1}$ and the level of turbulence is

$$\eta_B = \int_{k_0}^{\infty} W(k)\,dk \sim 0.01 - 0.1$$

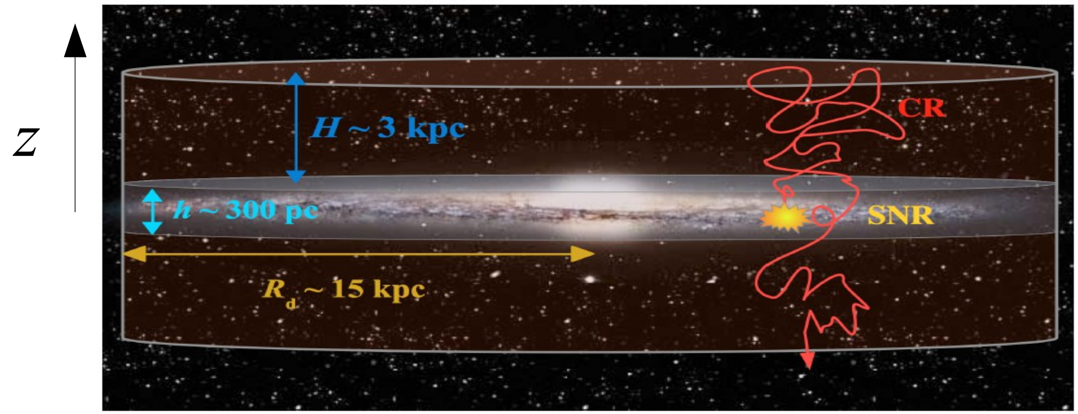
Charged particles in a turbulent field: quasi-linear theory



- The turbulent field is a small perturbation with respect to the regular component
- Particles interact with waves resonantly: $k_{\mathrm{res}} = 1/r_{\mathrm{L}}(\mathrm{p})$
- A diffusion behaviour follows with typical diffusion coefficient

$$D_{zz}(p) = \frac{v\, r_L}{3} \frac{1}{k_{res} W(k_{res})} \sim 3\times10^{28} \left(\frac{p}{GeV/c}\right)^{1/3} cm^2\, s^{-1}$$

The cosmic ray transport equation in the halo



$$-\frac{\partial}{\partial z}\left[D_{zz}\frac{\partial f}{\partial z}\right] + u\frac{\partial f}{\partial z} - \frac{du}{dz}\frac{p}{3}\frac{\partial f}{\partial p} = Q_{SN} - \frac{1}{p^2}\frac{\partial}{\partial p}\left[p^2\,\dot{p}\,f\right] + Q_{frag/decay}$$

- 1-D spatial diffusion along z
- Advection by Galactic wind/outflow: $u = u_{\mathrm{W}} + v_{\mathrm{A}} \sim v_{\mathrm{A}}$
- Adiabatic expansion/compression
- Source term proportional to SNR profile
- Energy losses: ionization, IC, bremsstrahlung, synchrotron...
- Production/destruction of nuclei due to inelastic scattering of decay

Basic prediction of the halo model

- For primary CR species (e.g. H, C, O,...) at energies where we can ignore energy losses and advection, the transport equation simplifies as

$$-\frac{\partial}{\partial z}\left[D_{zz}\frac{\partial f}{\partial z}\right] = Q_{SN}(p)\delta(z)$$

Injection rate per unit surface

Injection only occurs in the Galactic plane

- Using the boundary condition $f(z=\pm H)=0$, for $z\neq 0$ one has:

$$f(z,p) = f_0(p)\left(1-\frac{z}{H}\right)$$

- While the solution in the Galactic plane is

$$f_0(E) = f_{SNR}(E)R_{SN}\frac{1}{\pi R_d^2 2H}\frac{H^2}{D}$$

Spectrum injected by sources

SN rate

Halo's volume

Escaping time

$$\tau_{esc} \simeq \frac{H^2}{D}$$

Secondary/primary ratio

The energy dependence of the **spectrum of primary CR** in the Galaxy is:

$$\left.\begin{array}{l} Q_{SN} = R_{SN}\, f_{SNR} \propto p^{-\gamma} \\ D = D_0\, p^{\delta} \end{array}\right\} \quad f_{pri}(p) = \frac{f_{SNR}(p)\, R_{SN}}{\pi R_d^2\, 2H} \frac{H^2}{D(p)} \propto p^{-\gamma-\delta}$$

The **spectrum of secondary particles** produced by spallation in the Galaxy is:

$$f_{sec}(p) \simeq f_{pri}(p)\, R_{spal}\, \tau_{esc} \propto p^{-\gamma_{inj}-2\delta}$$

$$\boxed{\frac{f_{sec}(p)}{f_{pri}(p)} \propto p^{-\delta} \propto E^{-\delta}}$$

Only a function of the escaping time: secondary/ primary gives us the energy dependence of diffusion

Note: H and D_0 cannot be measured independently

Secondary/primary ratio

The ratio $N_{sec}(E)$ / $N(E)$ provides a direct probe on the energy dependence of the Galactic diffusion coefficient and hence allow us to infer the spectrum injected by the sources

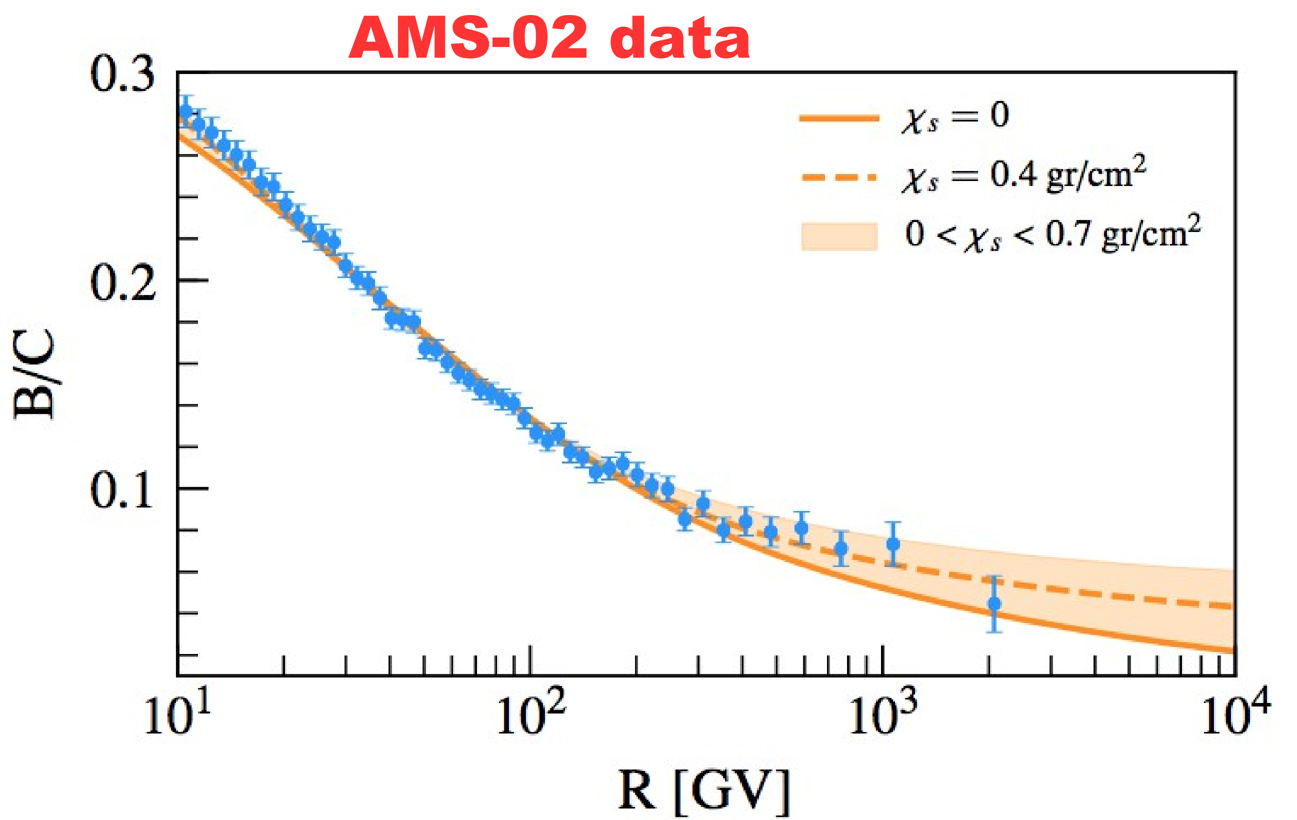
Boron over Carbon ratio taken from several experiments. Data are compatible with anything in the interval

$$0.3 < \delta < 0.5$$

we know that $\delta + \gamma_{inj} = 2.7$

$\rightarrow 2.2 < \gamma_{inj} < 2.4$

$\rightarrow \tau_{esc}\ (E› 1\ \mathrm{GeV}) \sim 5\times10^6$ yr



Beyond the simple disk/halo model

The picture provided by the disk/halo model is physically unsatisfactory:

- **What is the physical meaning of *H* ?**
- **Where the diffusion coefficient originates?**

Notice that this model is widely used in the literature (e.g. GALPROP)

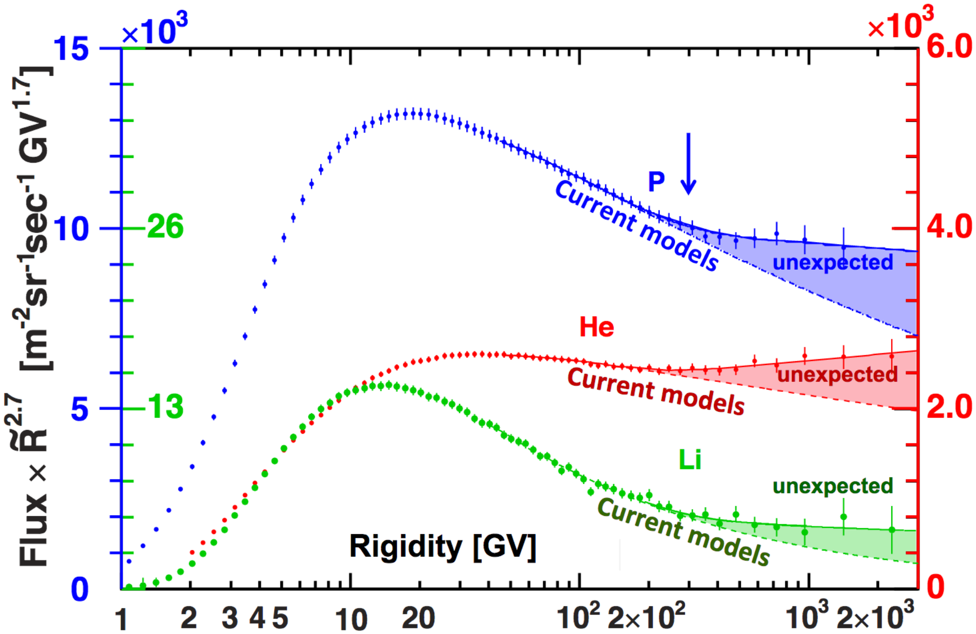
A more realistic model should account for important physical ingredients:

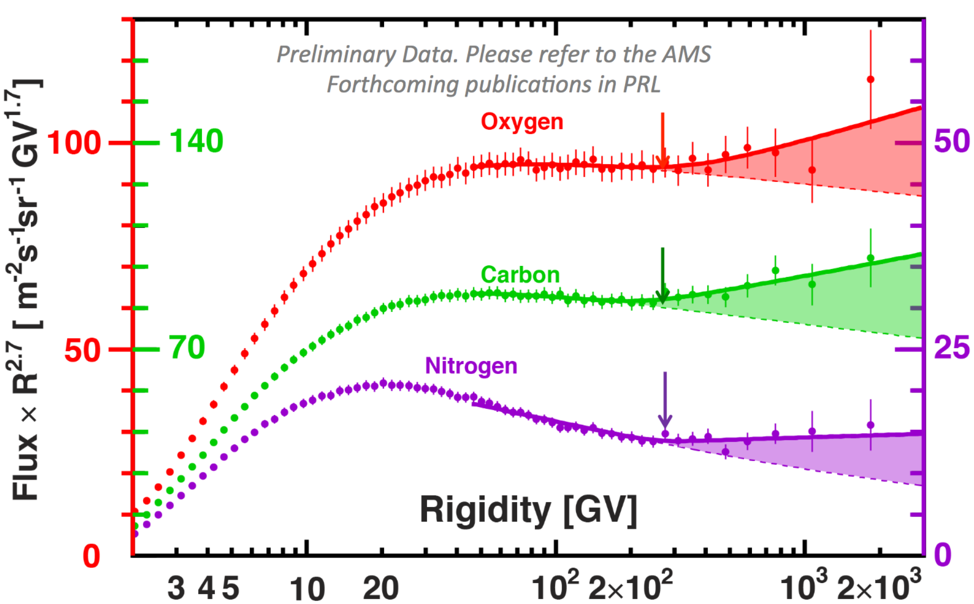
- **Generation of turbulence by SN explosions**
  → dependence of $D(E)$ on galactocentric radius
- **Cascade of the turbulence**
  → dependence of $D(E)$ on galactocentric radius and altitude
- **Galactic wind generated by CRs**
  → advection of particles

BUT THERE IS ALSO AN OBSERVATIONAL REASON:

Anomaly 1: spectral hardening

Aguilar+ AMS-02 collaboration., PRL (2015, 2016, 2019)





Recent measurements by PAMELA and AMS-02 revealed the existence of a fine structure:

At rigidity of ~300 GV all spectra show a spectral hardening

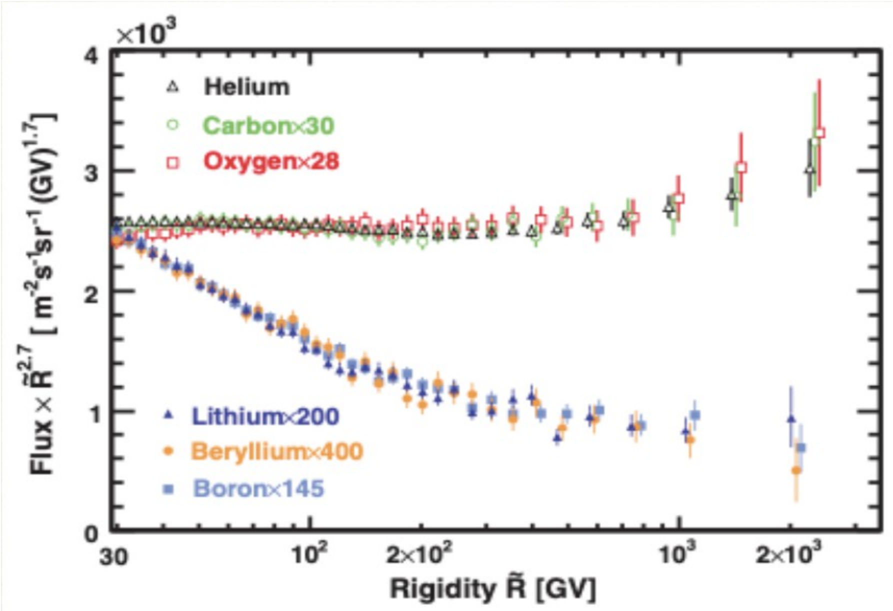
$$f_0(p) = \frac{Q_{SN}(p)}{2\pi R_{disc}^2} \frac{H}{D(p)}$$

Either the injected spectrum or the diffusion present a break at ~300 GV

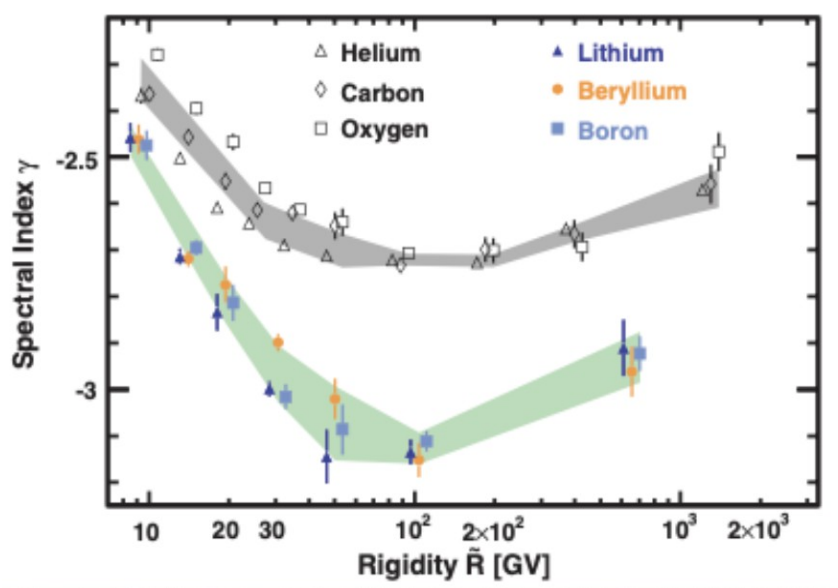
Spectral hardening for secondary CRs

Aguilar+ AMS-02 collaboration., PRL 120 021101 (2018)

Spectrum of primaries vs. secondaries



Spectral index

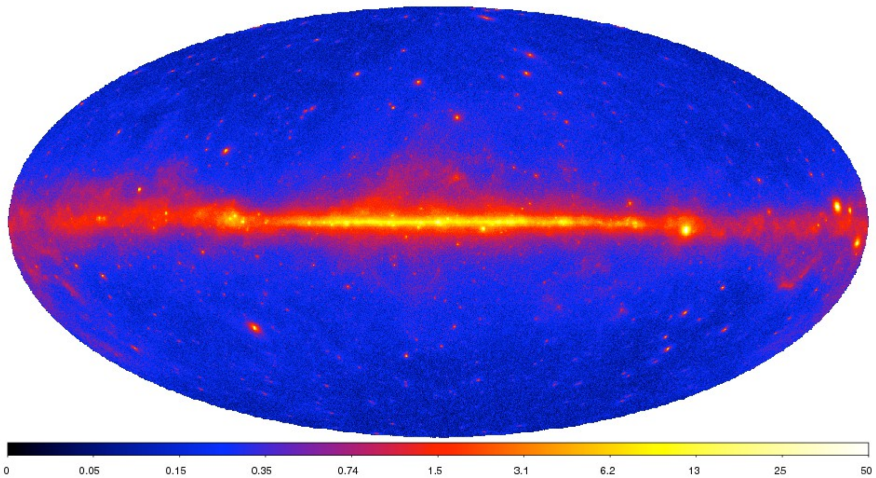


$$f_{SEC}(E) \propto f(E)_{pri} \tau_{esc} \propto E^{(-\gamma - 2\delta)}$$

- Spectral hardening for secondary species is larger than primaries
- This supports the origin of break due to propagation rather than primary acceleration inside sources

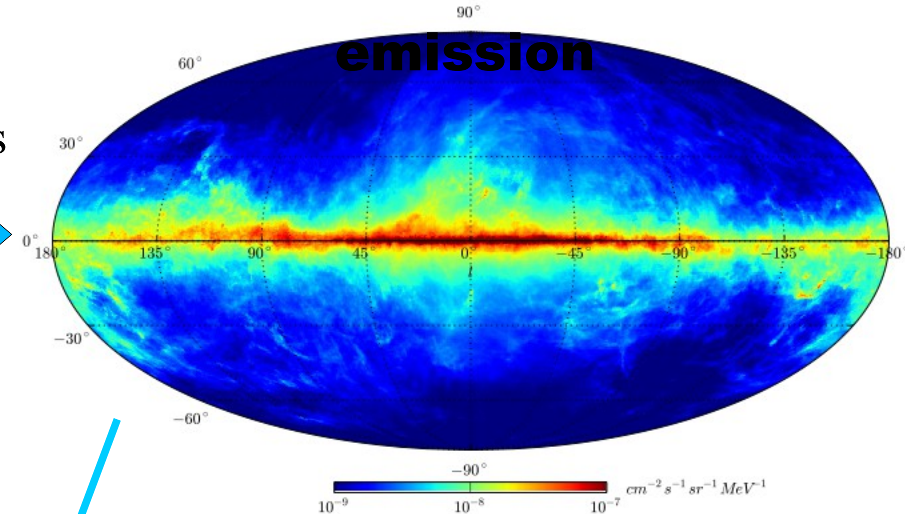
Diffusive Galactic emission

FermiLAT all sky map



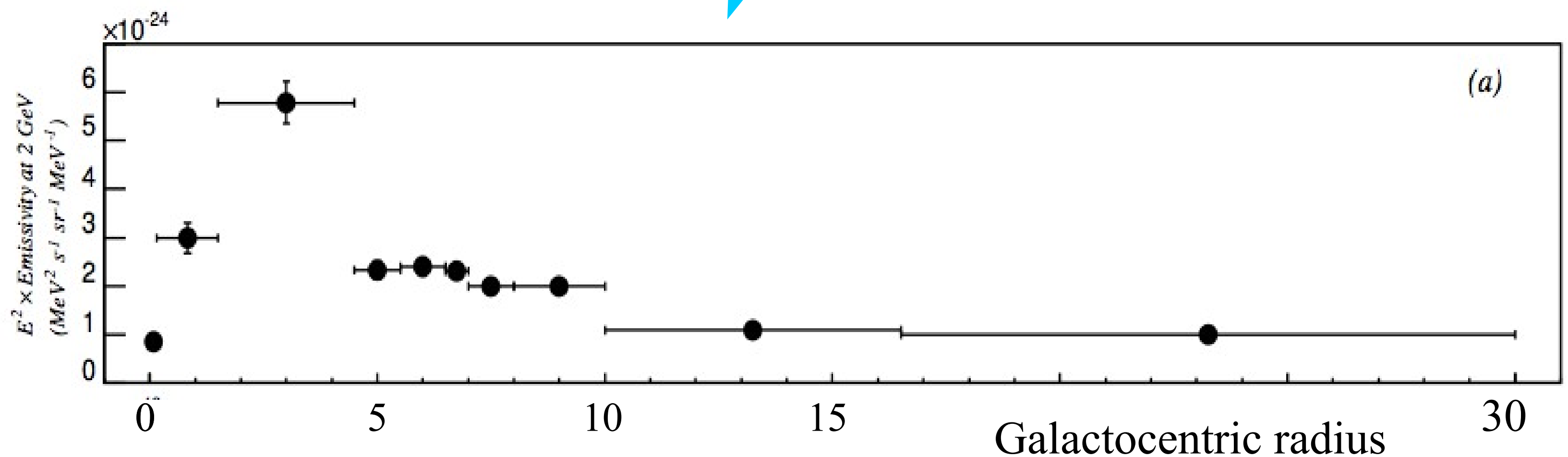
Subtracting known sources

FermiLAT diffuse emission

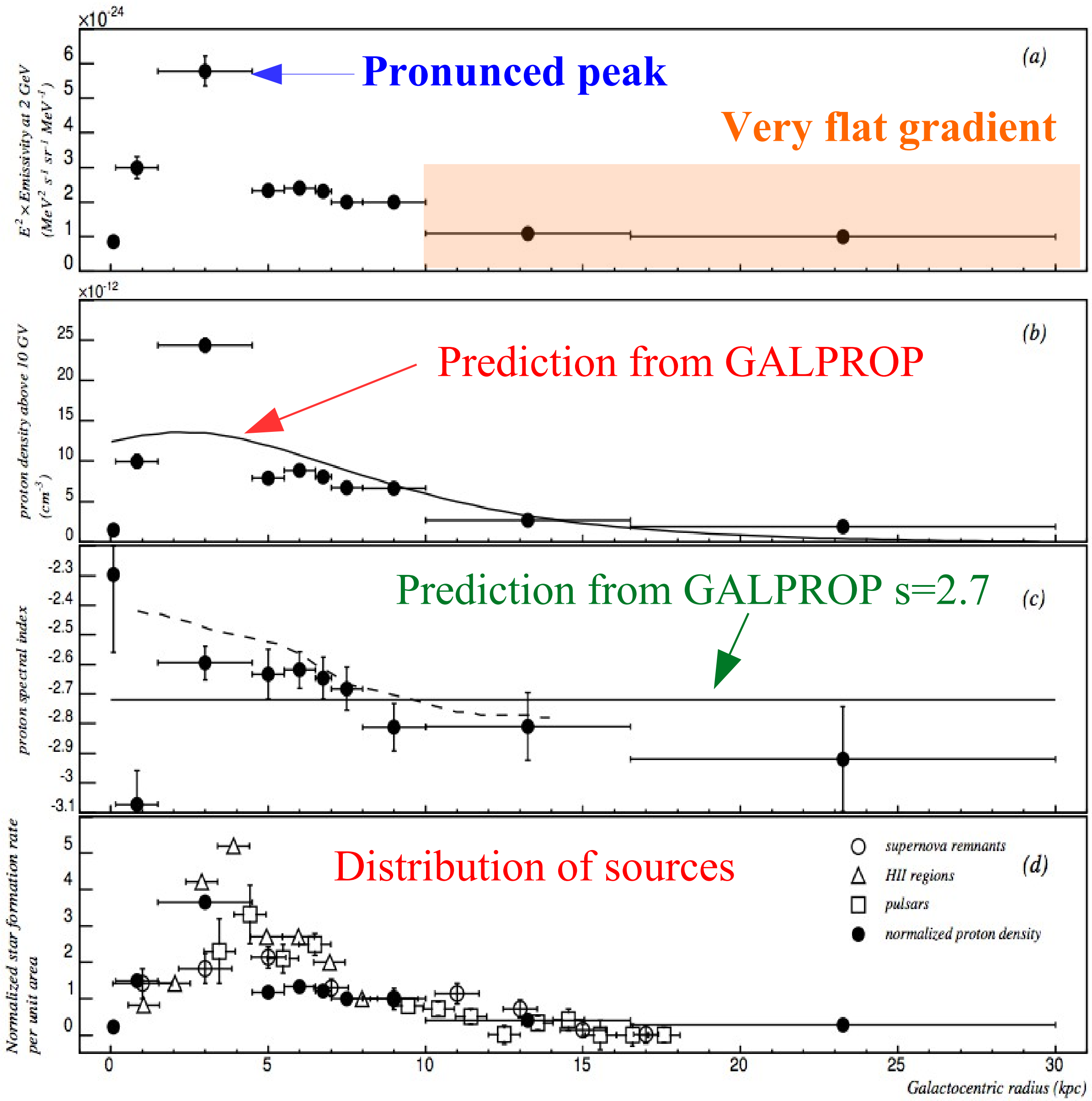


From Acero et al. (2016) ApJS, 223, 26

$E^2 \times$ emissivity at 2 GeV



Anomaly 2: the cosmic ray distribution in the Galactic plane



Recent results from FermiLAT collaboration on the CR distribution in the Galactic plane
[Acero et al. arXiv:1602.07246]

- In the outer region ($R > 8$kpc) the CR density at ~20 GeV is flat
(i.e. decreases much slower than the source distribution)

- In the inner region the CR density has a peak at ~ 3 kpc

- The slope @ 20 GeV is not constant

This scenario is difficult to accommodate in a standard leaky-box model

Equation for the turbulence evolution

(Jones 1993, ApJ 413, 619]

$$\frac{\partial W}{\partial t} = \frac{\partial}{\partial k}\left[D_{kk}\frac{\partial W}{\partial k}\right] + \frac{\partial}{\partial z}\left(v_A W\right) + \Gamma_{CR} W + Q_k$$

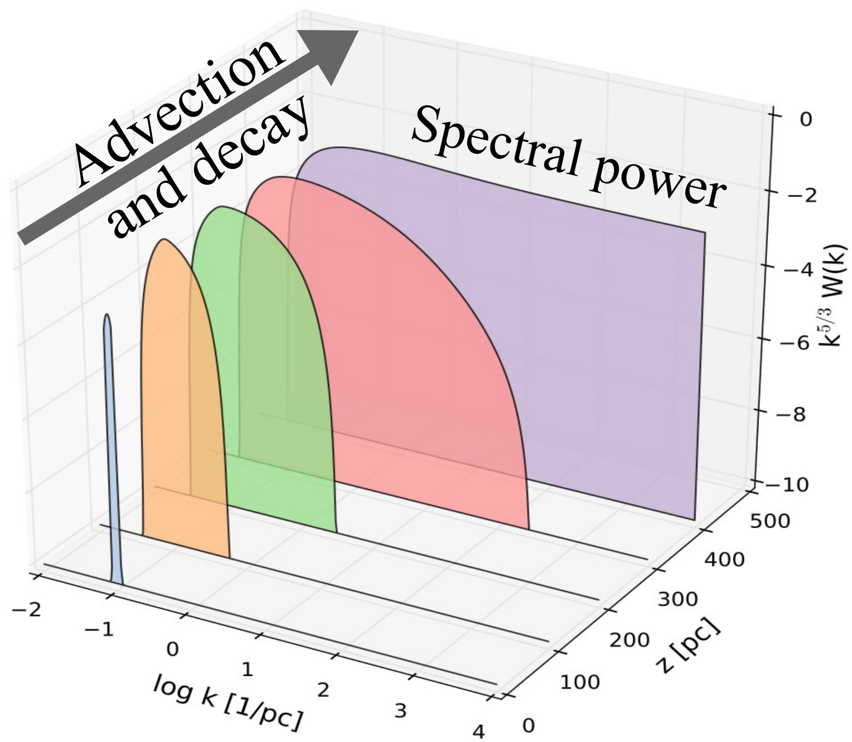
- Diffusion in k-space (non-linear): $D_{kk} = c_k \,|\, v_A \,|\, k^{7/2}\, W^{1/2}$
- Advection of waves at the Alfvén speed
- Waves growth due to CR streaming: $\Gamma_{CR} \propto \partial f / \partial z$

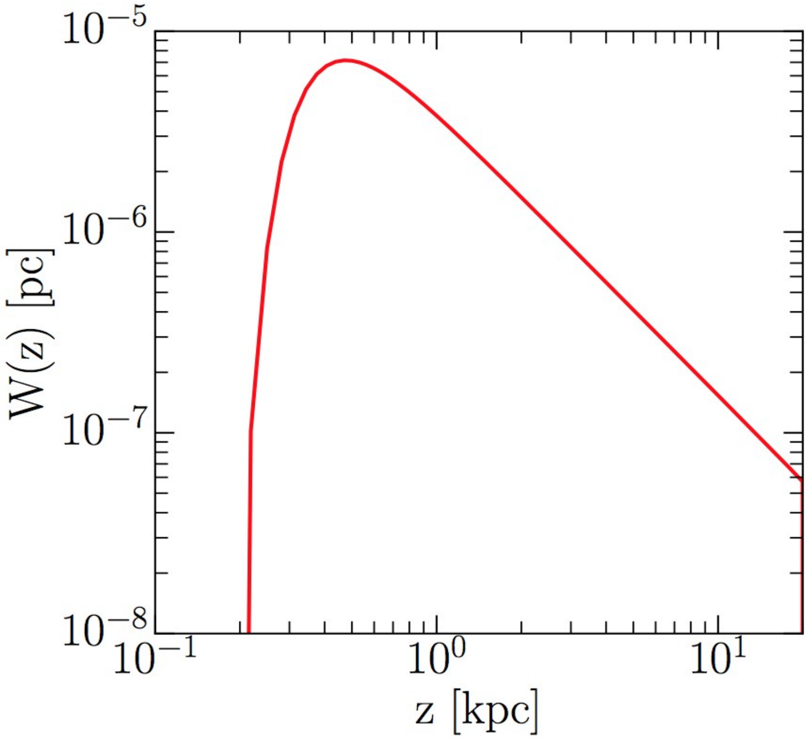
$$\Gamma_{CR} = \frac{16\pi}{3}\frac{v_A}{k\, W(k)\, B_0^2}\left[v\, p^4 \frac{\partial f}{\partial z}\right]$$

- External (e.g. SNe) source term in the disc: $Q \sim \delta(z)\, \delta(k - k_0)$
- In the absence of CR it returns the Kolmogorov spectrum: $W(k) \sim k^{-5/3}$

Developing the turbulent halo

Large scale turbulence generated inside the Galactic disc by SN explosion advected and decaying through Kolmogorov cascade.



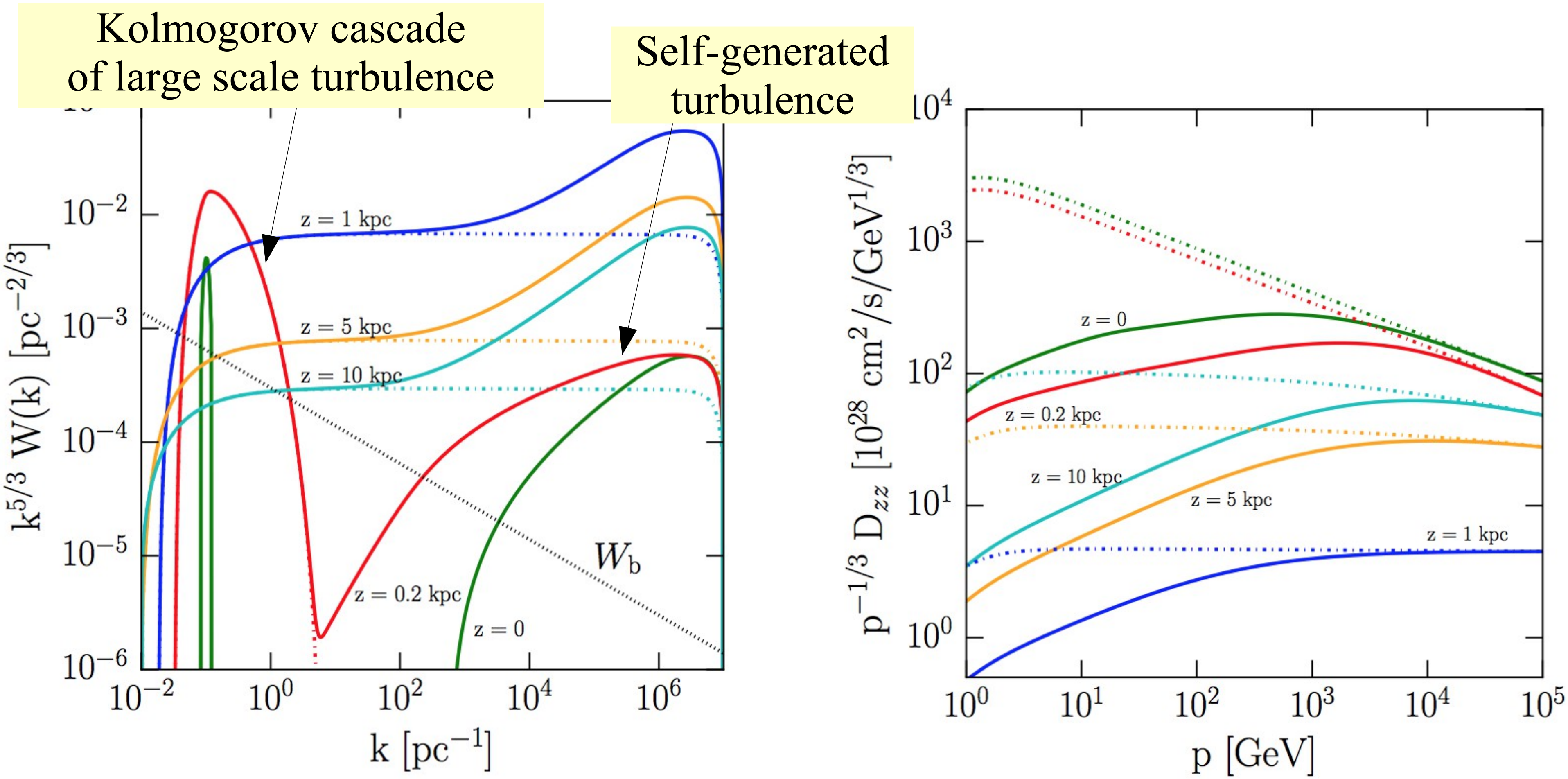


$$\tau_{cascade} = \tau_{adv} \rightarrow \frac{k_0^2}{D_{kk}} = \frac{z_c}{v_A} \rightarrow \boxed{z_c \sim kpc}$$

- z_c sets the scale where the turbulent cascade develops
- The boundary H does not have any physical meaning

Non-linear cosmic ray transport: a global picture

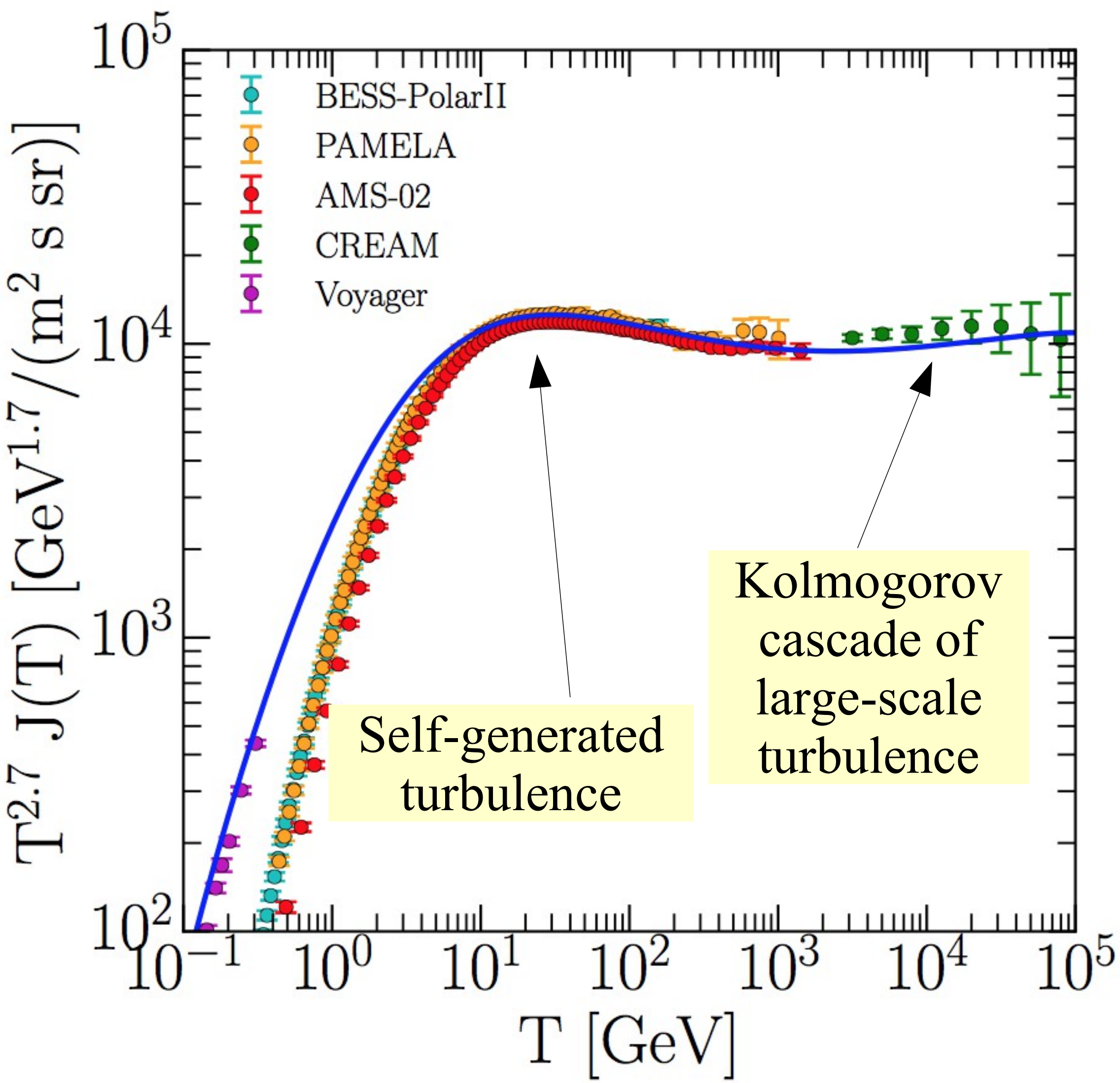
(Evoli, Blasi, GM, Aloisio, 2018, PRL]



Turbulence spectrum without (dotted) and with (solid) CR self-generated waves at different distance from the galactic plane.

Non-linear cosmic ray transport: a global picture

(Evoli, Blasi, GM, Aloisio, 2018, PRL]



- Pre-existing waves (Kolmogorov) dominates above the break
- Self-generated turbulence dominates below ~100 GeV
- Voyager data are reproduced with no additional breaks, but due to advection with self-generated waves
- The boundary ($H = 100$ kpc) has no impact on the result
- Low energy spectrum is well accounted by advection without introducing *ad hoc* breaks in the primary spectra.

Summary

- The disk/halo diffusion model describes pretty well the CR propagation and experimental results

- However, this same model in hits basic version fails in some respects:
  - Observationally:
    - Does not explain the slope hardening at ~ 300 GeV/nucleon
    - Does not explain the gradient observed along the galactic plane
  - Theoretically:
    - It relies on a too simple model for diffusion
    - There is no reason for a sudden of the magnetic halo

- Those problems can be solved or at least mitigated accounting for the generated turbulence and its time/spatial evolution

ESCAPING FROM THE SOURCES

SPECTRUM OF RELEASED PARTICLES

WHAT IS THE FATE OF ACCELERATED PARTICLES?

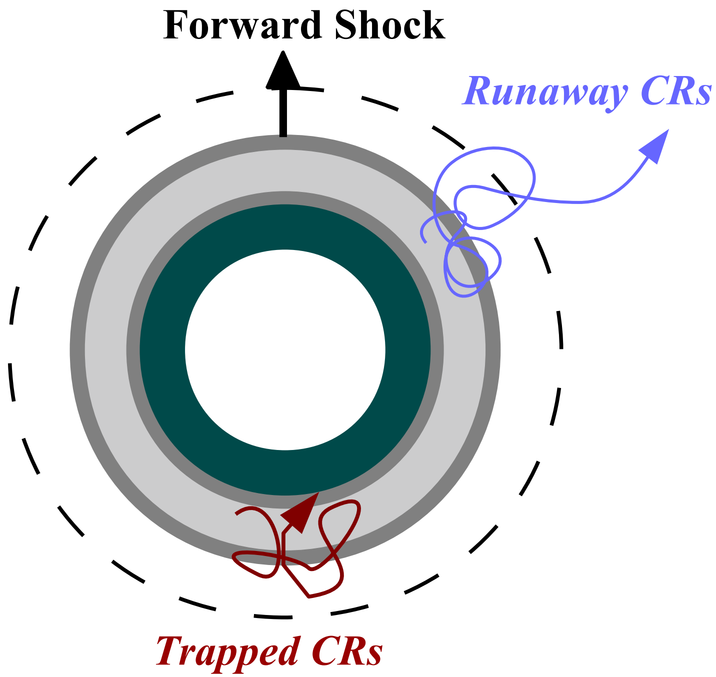
- Particles trapped downstream will be released when the shock disappear and merges into the ISM

- Because of adiabatic losses particles lose energy $\rightarrow$ reaching the knee would be even more difficult

- We need particles release during the acceleration process

- Escaping particles are also required to amplify the magnetic field in the *non-resonant Bell instability*

- The process of escaping is tightly connected with the problem of maximum energy and it is not completely understood.



SPECTRUM OF RELEASED PARTICLES

Let assume that a fraction ξ_{esc}(t) of the incoming kinetic energy is converted into escaping flux:

$$4\pi p^2 dp\, f_{esc}(p)\, pc = \xi_{esc}(t)\, \frac{1}{2}\rho u_{sh}^3\, 4\pi R_{sh}^2\, dt$$

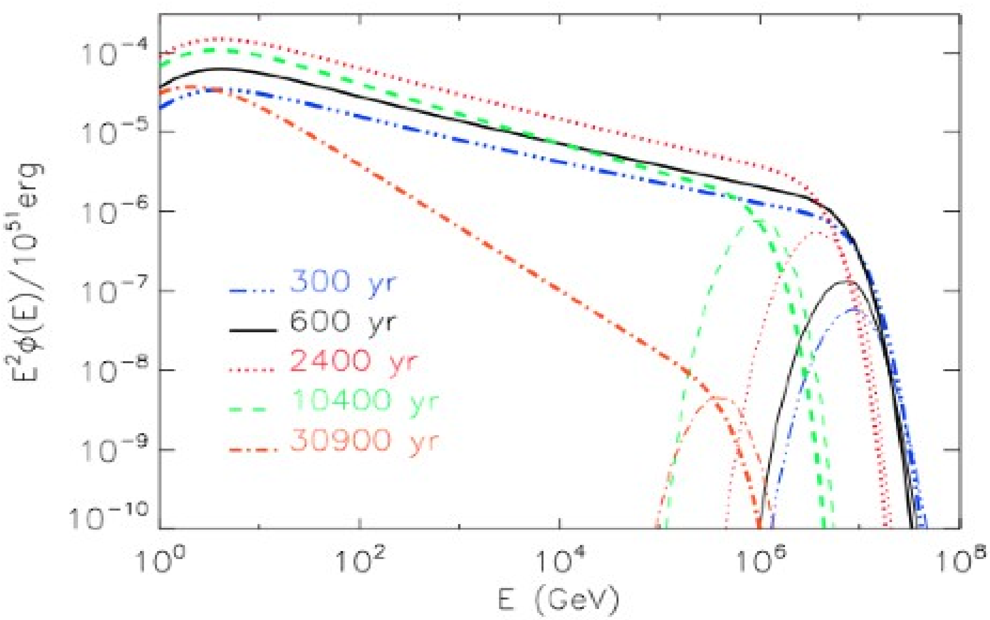
Evolution during the Sedov-Taylor phase:

$$\begin{cases} R_{sh} \propto t^{2/5} \\ u_{sh} = \dfrac{dR_{sh}}{dt} \propto t^{-3/5} \end{cases} \Rightarrow u_{sh}^3 R_{sh}^2 = const$$

$$p \propto t^{-\alpha} \rightarrow \frac{dt}{dp} \propto p^{-1-1/\alpha}$$

$$\Rightarrow \boxed{f_{esc}(p) \propto \xi_{esc}(t)\, p^{-4-1/\alpha}}$$

Prediction of non linear theory from Caprioli et al. (2010)



IS THERE A WAY TO TEST THE ESCAPING PROCESS?

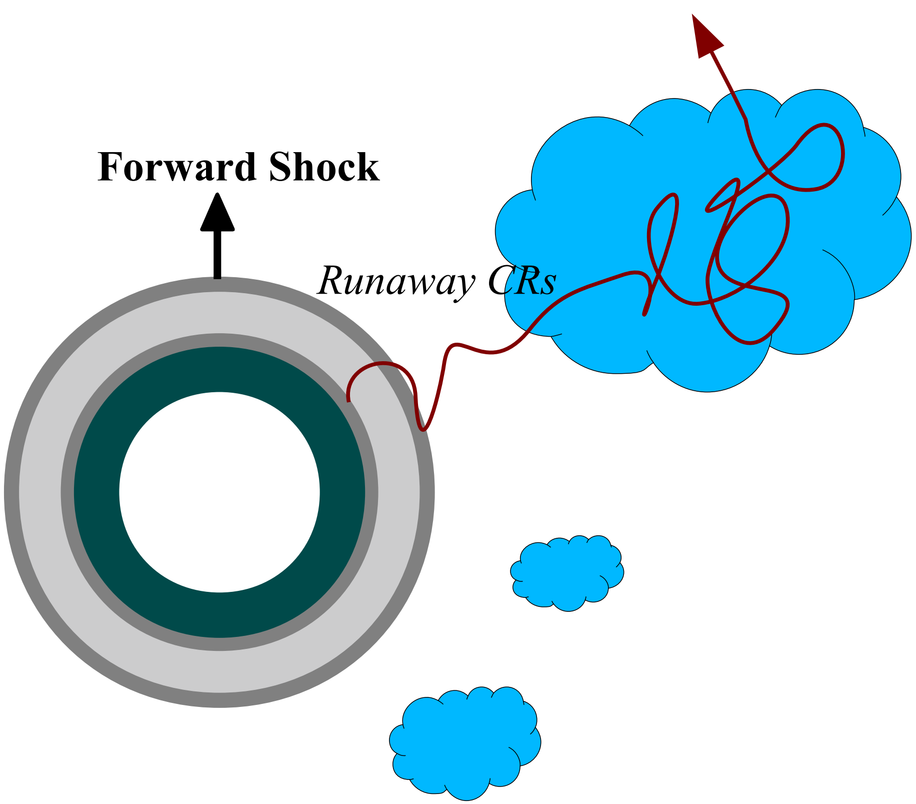
SNR-MOLECULAR CLOUDS ASSOCIATIONS

MCs as CR barometers

Interactions inside the clouds:

1) $p_{CR}\, p_{gas} \rightarrow \pi^0 \rightarrow \gamma\gamma$

2) Ionization $p_{CR} H_2 \rightarrow p_{CR} e^- H_2^+$



OBSERVATIONS of MCs in γ-RAYS:

- CRs interact inside MCs
  $$pp \rightarrow \pi^0 \rightarrow \gamma\gamma$$
- strong emission in GeV range
- γ-emission sensible to CR energy $E > 280$ MeV

- MCs can be used to test different CR spectra:
  1) average Galactic spectrum (isolated clouds)
  2) injected spectrum (MC close to SNR)

DETECTION OF IONIZATION

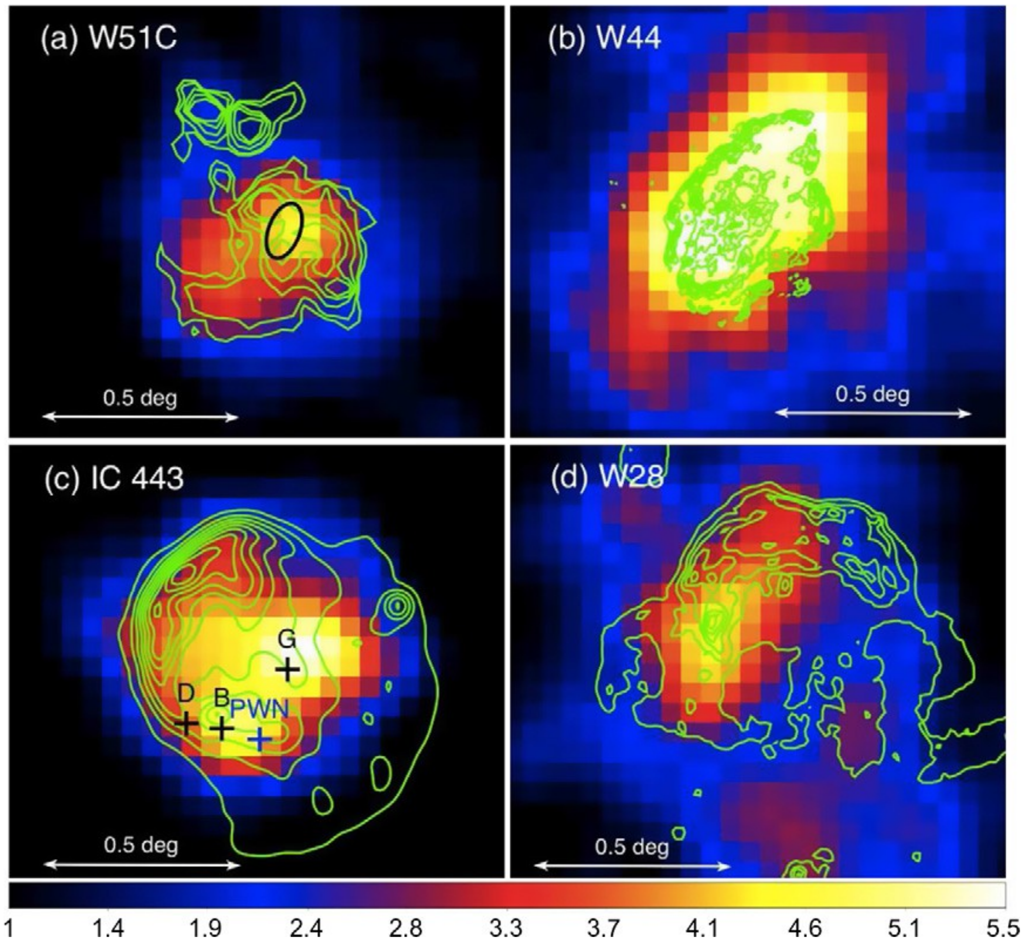
- The ionization rate of several molecules depends on the CR flux (H_2, H_3^+, CH, OH, C_2, DCO^+, HCO^+,……)

- Ionization sensible to CR energy $E > 0.1$ MeV

Is it possible to use combined information from ionization and γ-ray emission to infer the CR spectrum from ~MeV up to ~TeV and beyond?

MCs as CR barometers

Examples of γ-ray emission from clouds close or interacting with SNRs - [*Fermi*-LAT]



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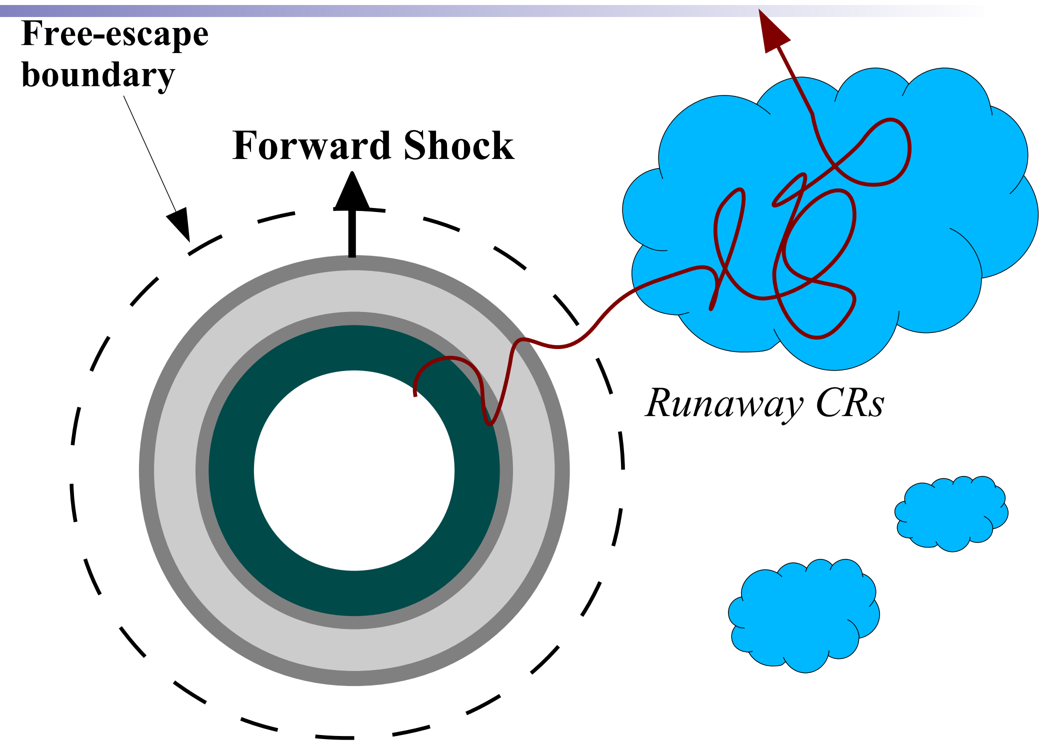
Gamma-rays from Molecular clouds

For a typical SNR at 1 kpc distance and a MC mass of $10^4\ M_\odot$

→ detectable level of TeV emission if

$$n_{\mathrm{source,CR}} > n_{\mathrm{gal,CR}}$$

→ this happen when the cloud is located at d <~ 100 pc from the SNR (for 3D diffusion model)



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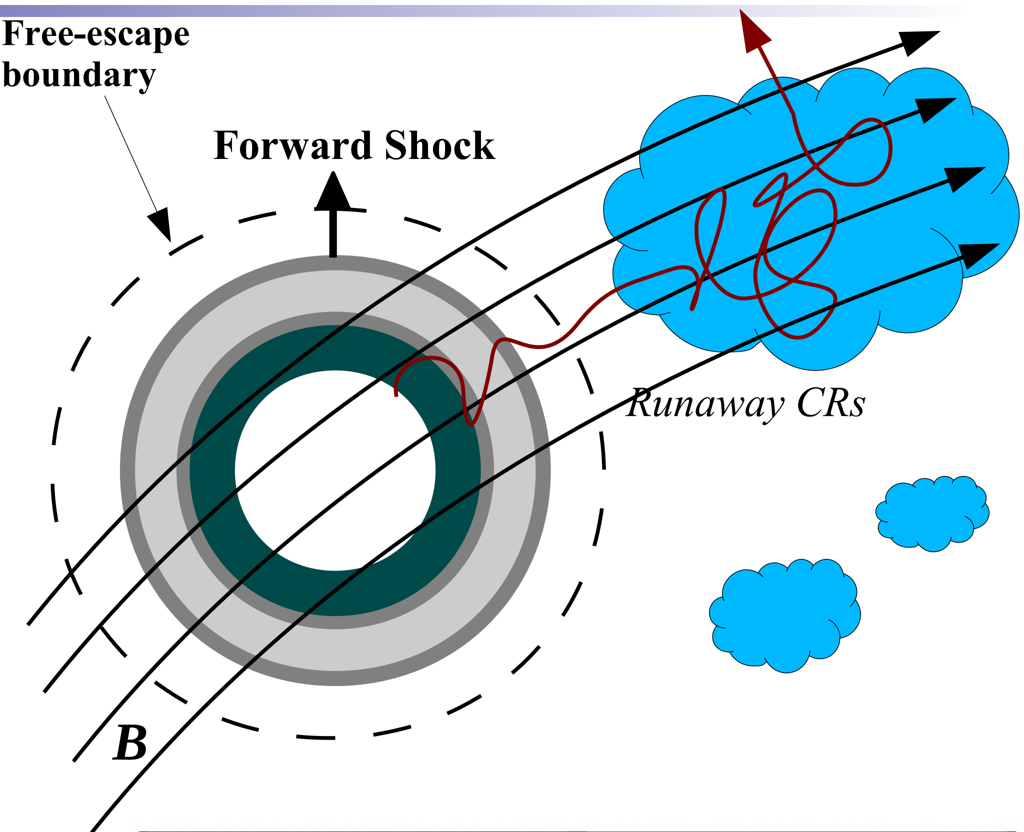
$$n_{\mathrm{source,CR}} > n_{\mathrm{gal,CR}}$$

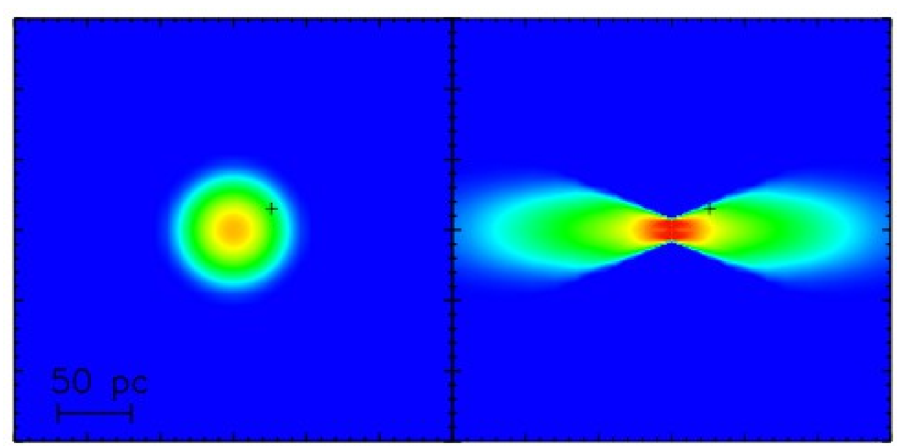
→ this happen when the cloud is located at d <~ 100 pc from the SNR (for 3D diffusion model)

The distance can be enhanced to d <~500 pc if we consider the 1-D propagation along magnetic field line

→ the source can be observable for ~ 10^4 yr

CTA will probably discover tens of SNR-MC associations



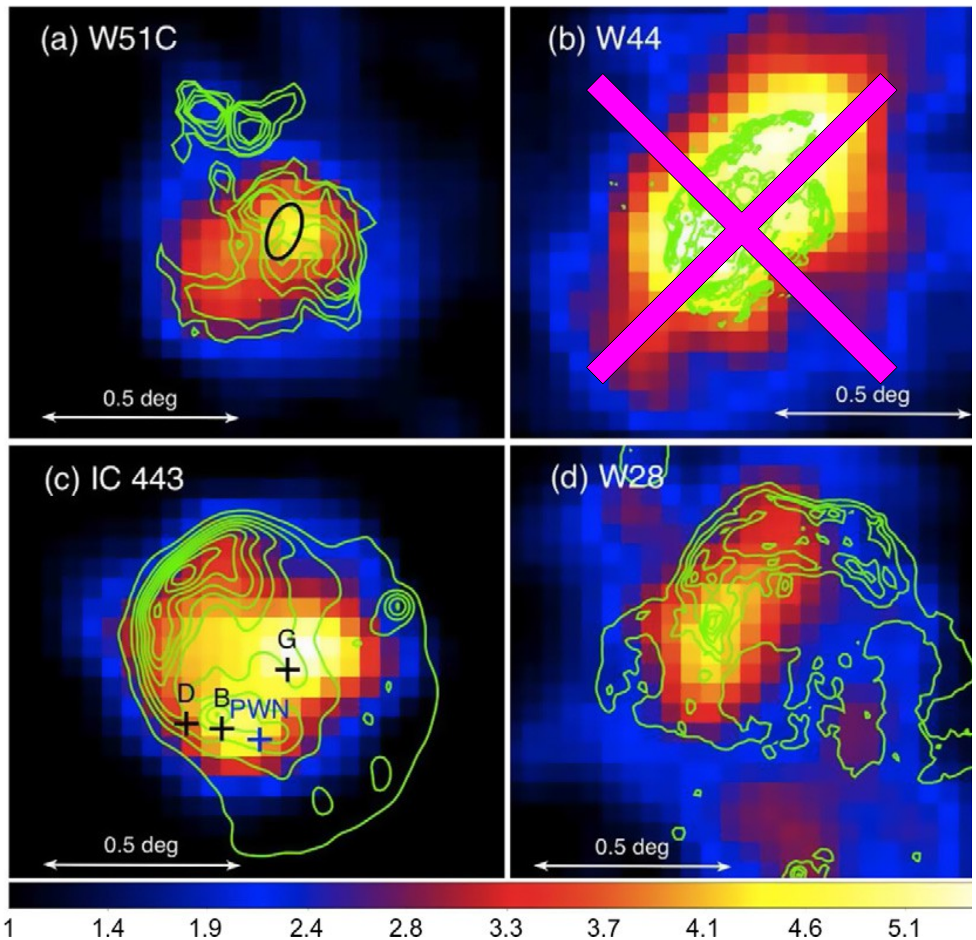


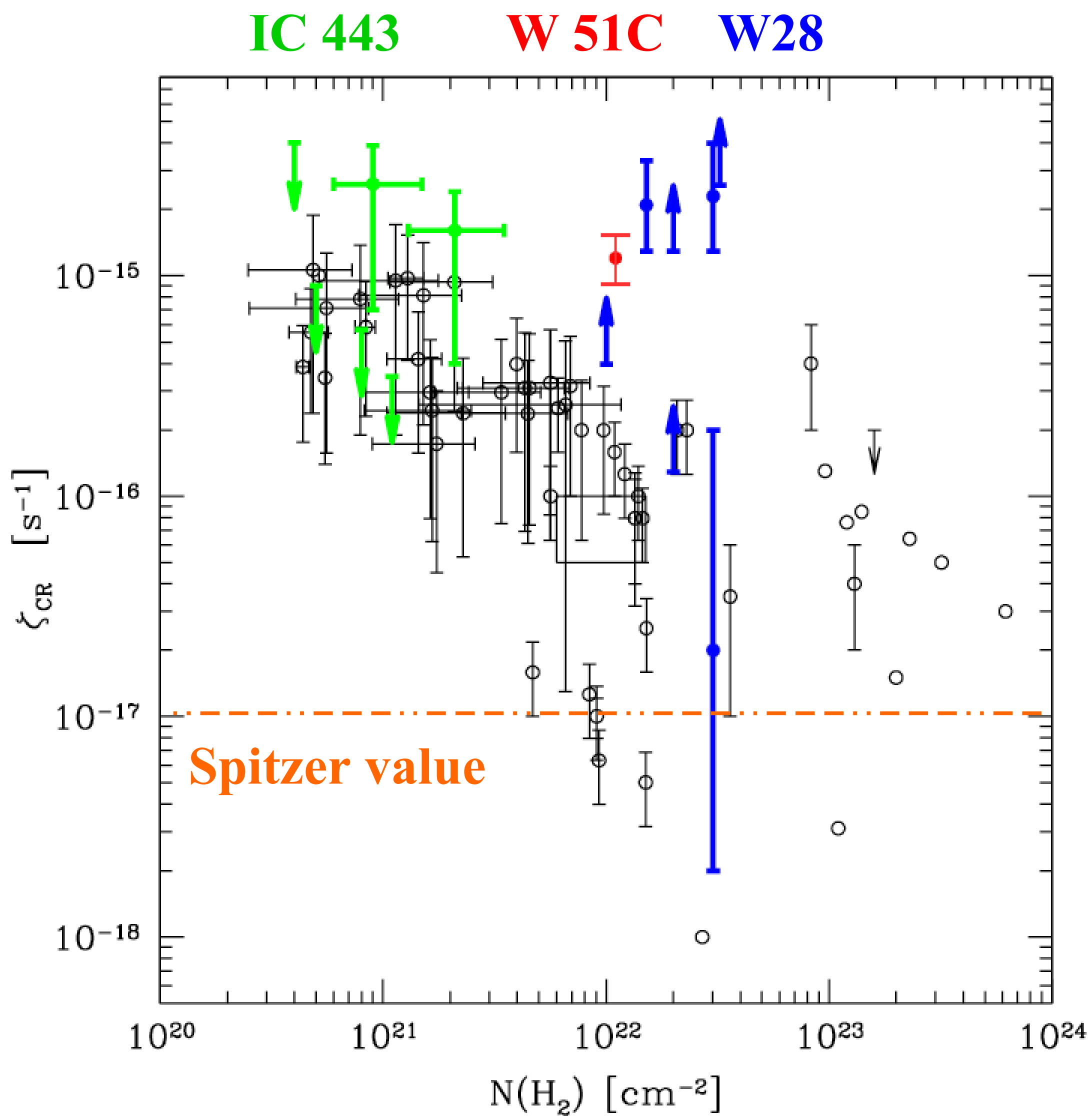
Simulation from Nava & Gabici (2012)

Enhanced ionization rate in MC-SNR systems

[See Gabici & Montmerle (2015) ICRC proceeding]

Examples of γ-ray emission from clouds close or interacting with SNRs - [*Fermi*-LAT]

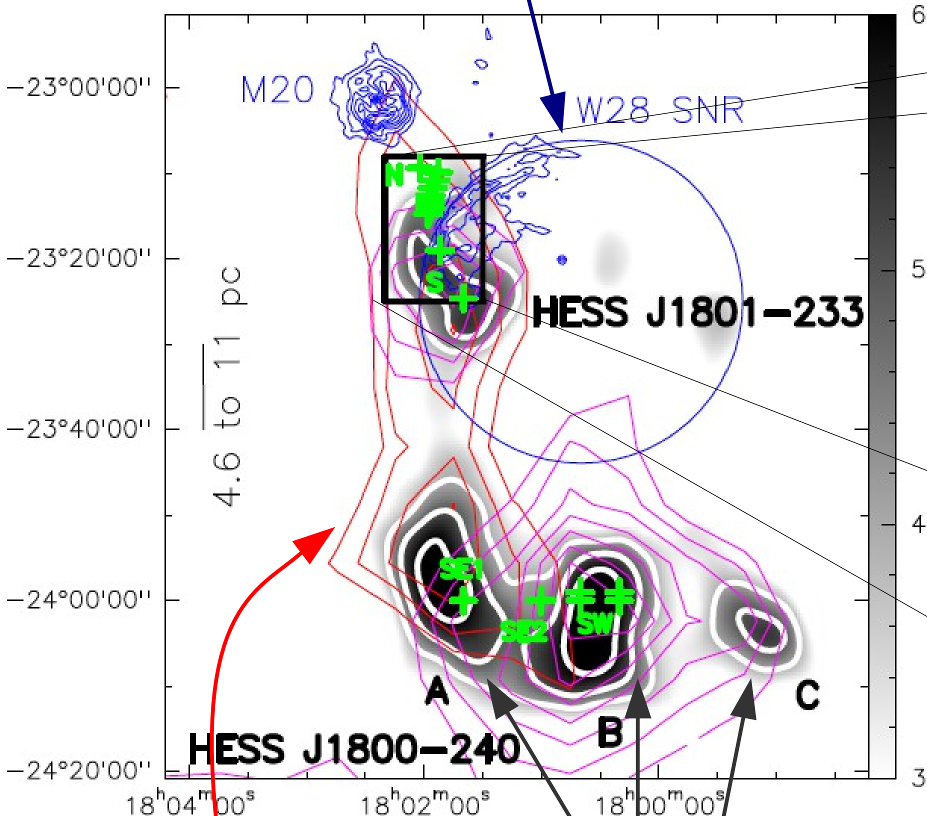


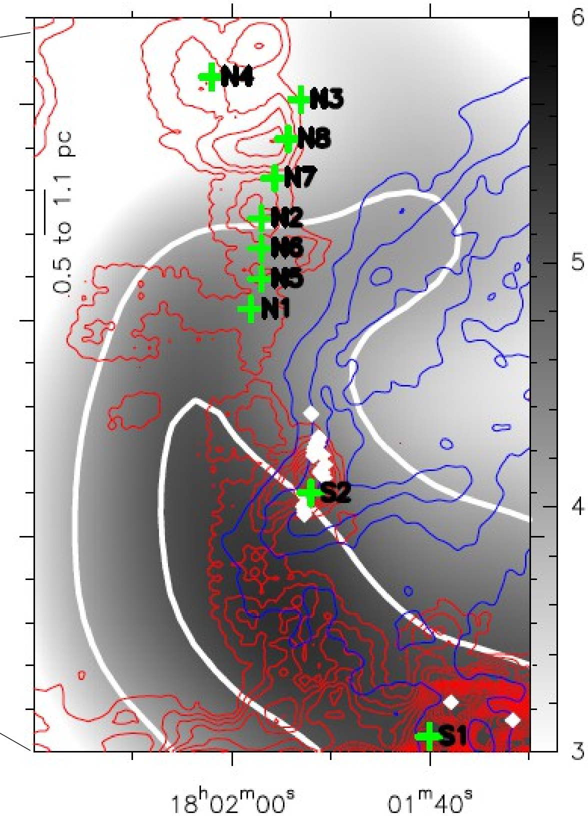


CR induced ionization of molecular clouds interacting with SNR W28

[Vaupr[3], Hily-Blant, Ceccarelli, Dubus, Gabici &. Montmerle 2014, A&A]

Location of radio shell of SNR W28





CO emission

TeV emission (HESS)

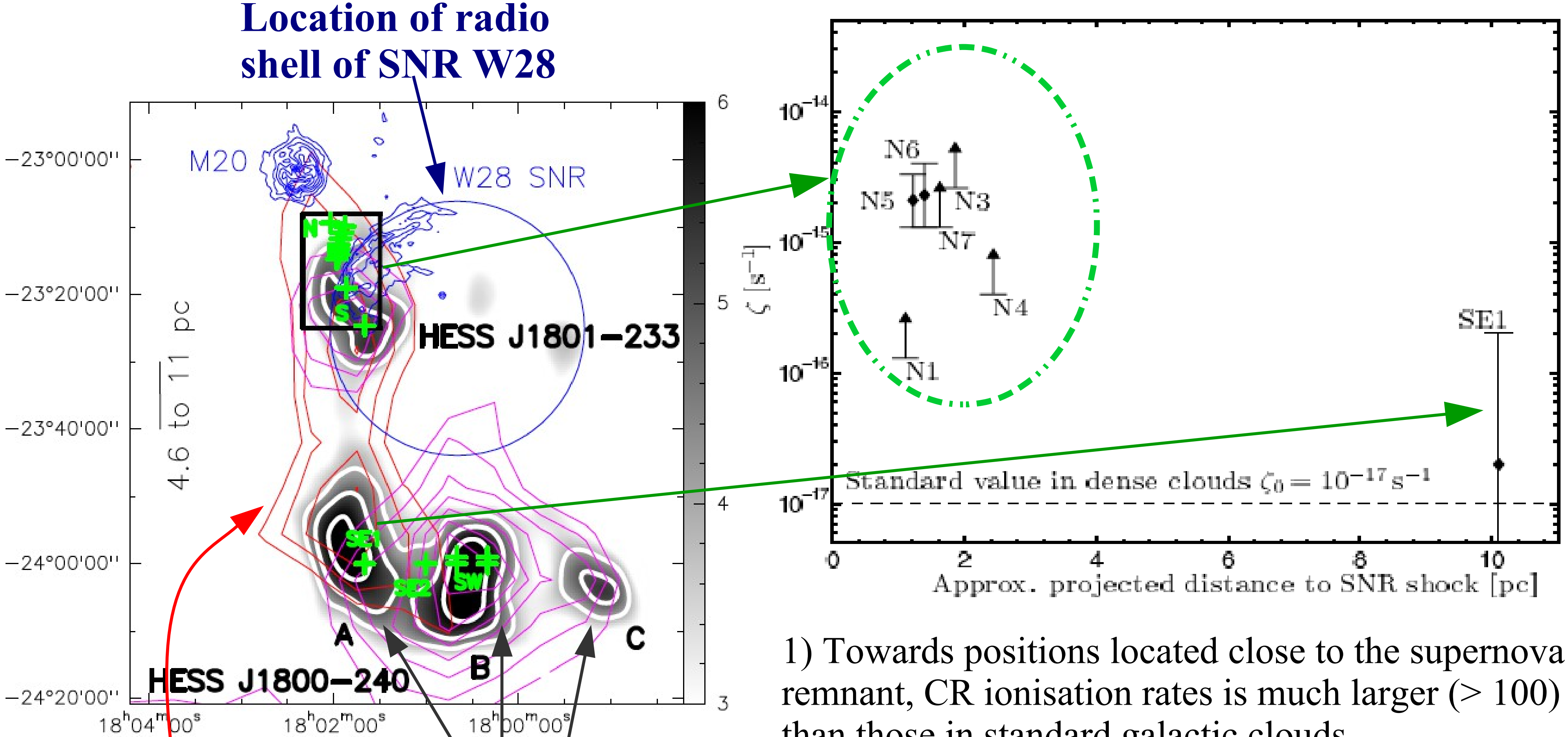
✚ HCO^+, DCO^+ , etc.

◆ HO maser

CR induced ionization of molecular clouds interacting with SNR W28

[Vaupr[3], Hily−Blant, Ceccarelli, Dubus, Gabici &. Montmerle 2014, *A&A*]

Location of radio shell of SNR W28



CO emission

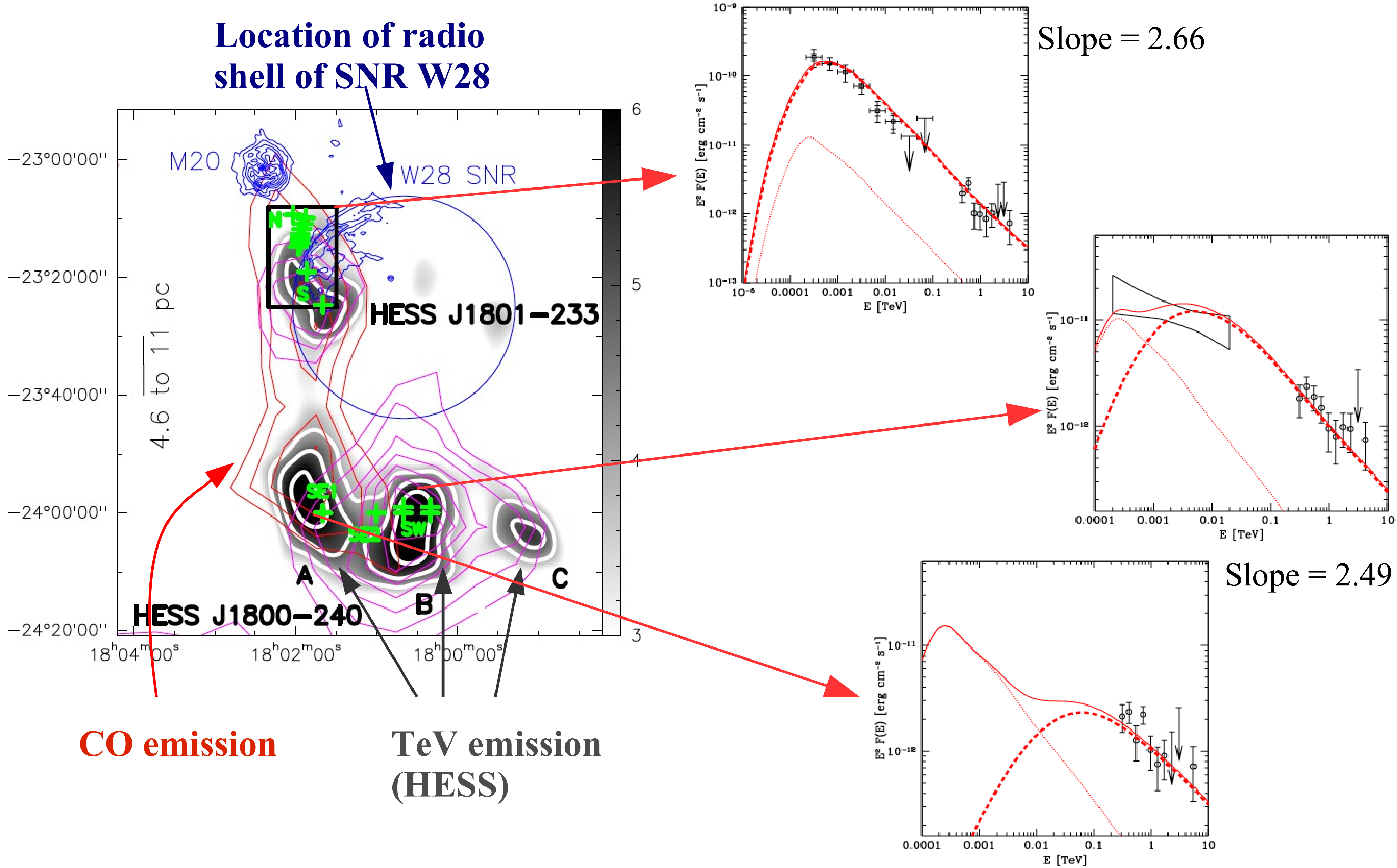
TeV emission (HESS)

1) Towards positions located close to the supernova remnant, CR ionisation rates is much larger (> 100) than those in standard galactic clouds.

2) Towards one position situated at a larger distance, the CR ionisation rate is close to the standard value in Galactic dense clouds

CR induced ionization of molecular clouds interacting with SNR W28

[Gabici &. Montmerle, ICRC 2015]



Understanding the cloud chemistry and dynamics

1) CR are a primary source of ionization inside a cloud

- For column densities $N_H > 10^{20}$ cm^2 CRs are the only agent able to penetrate inside the cloud (photons are easily shielded)
- The ionization fraction drives the chemistry of molecular clouds

2) CR interactions affect the cloud temperature

3) Ionization controls the coupling between gas and magnetic field

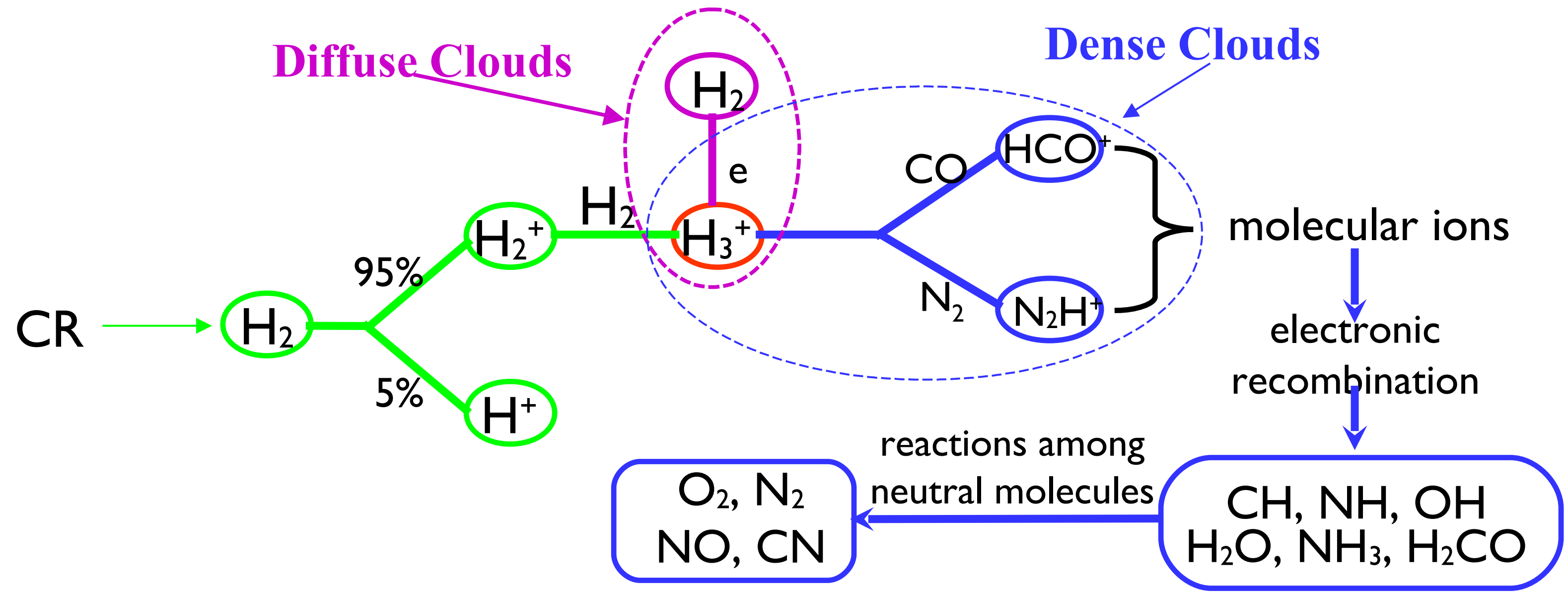
- The gravitational collapse occurs in the very deep core when the gas and the magnetic field decouple form each other

Large CR density → suppression of star formation

Understanding the cloud chemistry and dynamics

[see Gabici & Montmerle, 2017]

CR are a primary source of ionization inside a cloud



Ionization rate: $$\xi_{CR} = \int_{I}^{E_{max}} j_{CR}(E)\,\sigma^{ion}(E)\,dE$$

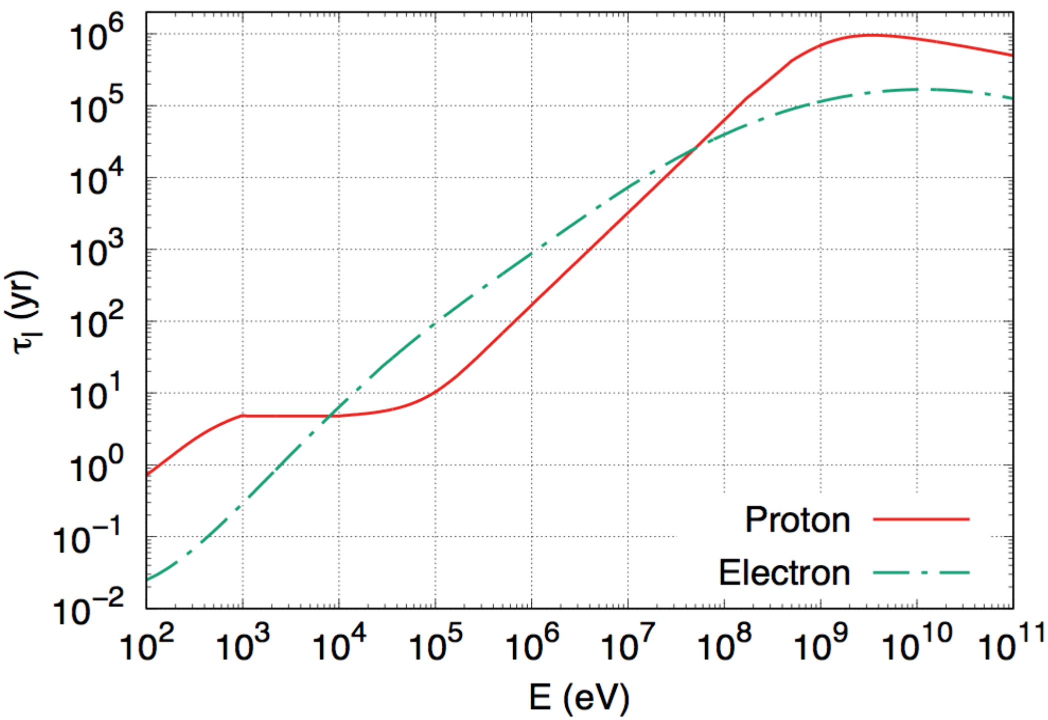
Spitzer value
(typical of high density clouds) $$\xi_{CR} \simeq 10^{-17}\,s^{-1}$$

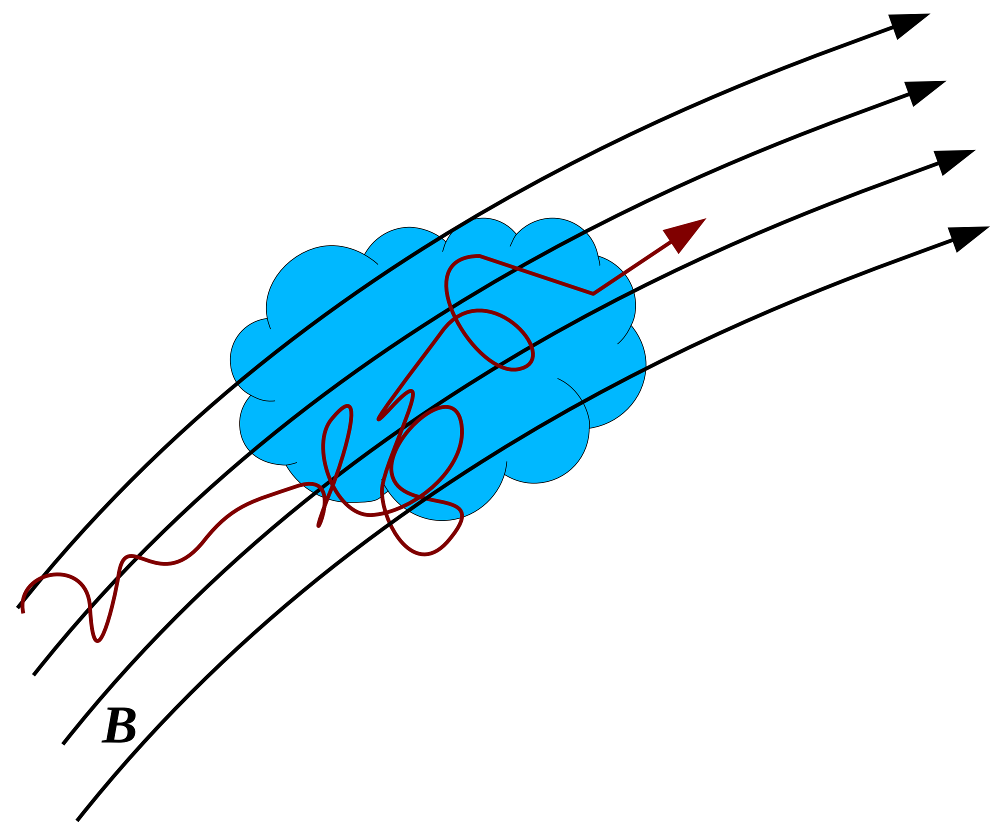
CR induced ionization of molecular clouds accounting for losses

Electrons and protons lose energy while penetrating inside a molecular cloud due to ionization losses

Total energy loss time for protons and electrons

$$\tau_{loss} = \frac{E}{dE/dt}$$



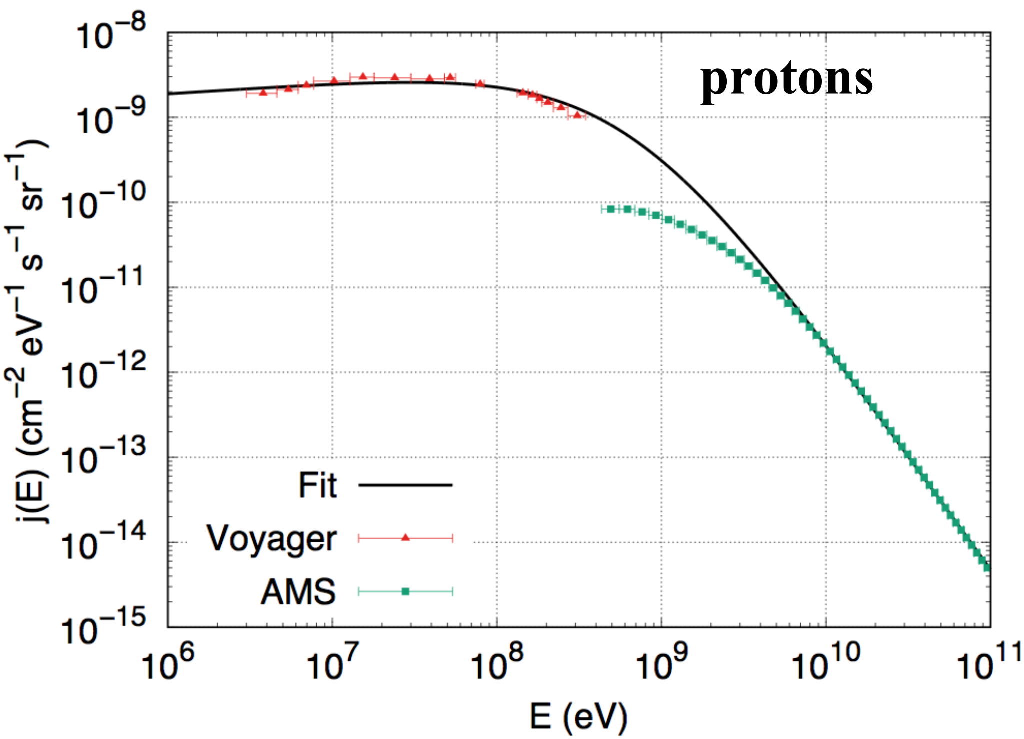


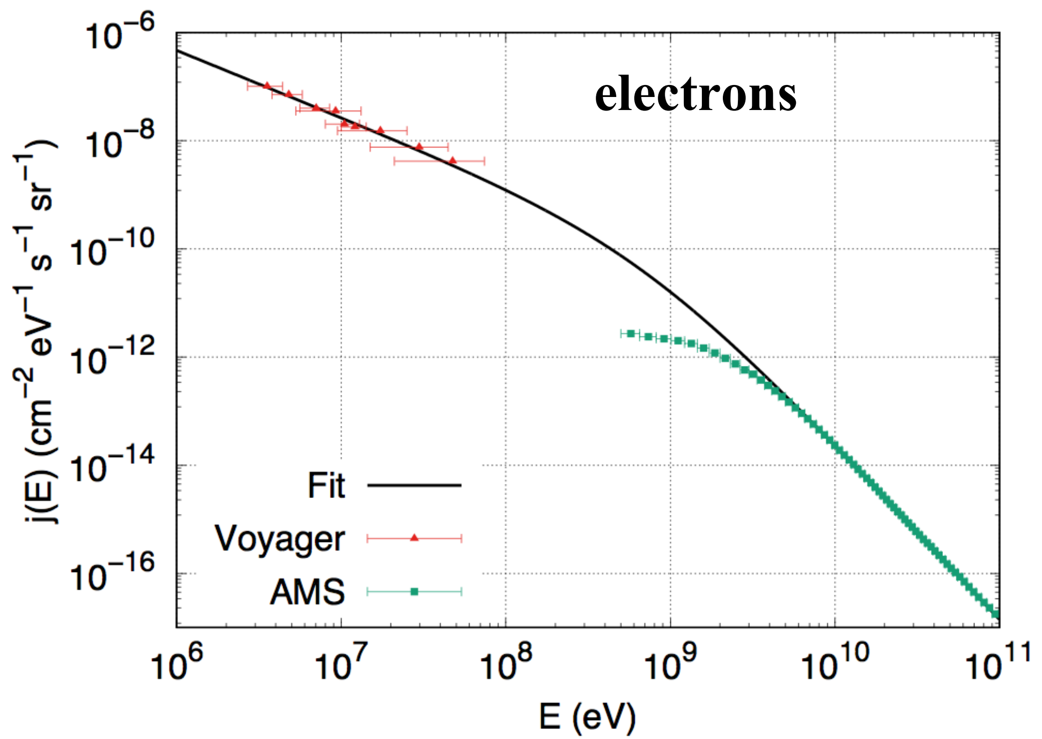
CR induced ionization of molecular clouds accounting for losses

[V. Phan, GM &. S Gabici, 2015]

We assume that the spectra of electrons and protons everywhere in the Galaxy is equal to the one measured at the Earth

Local CR spectra from AMS-02 plus Voyager





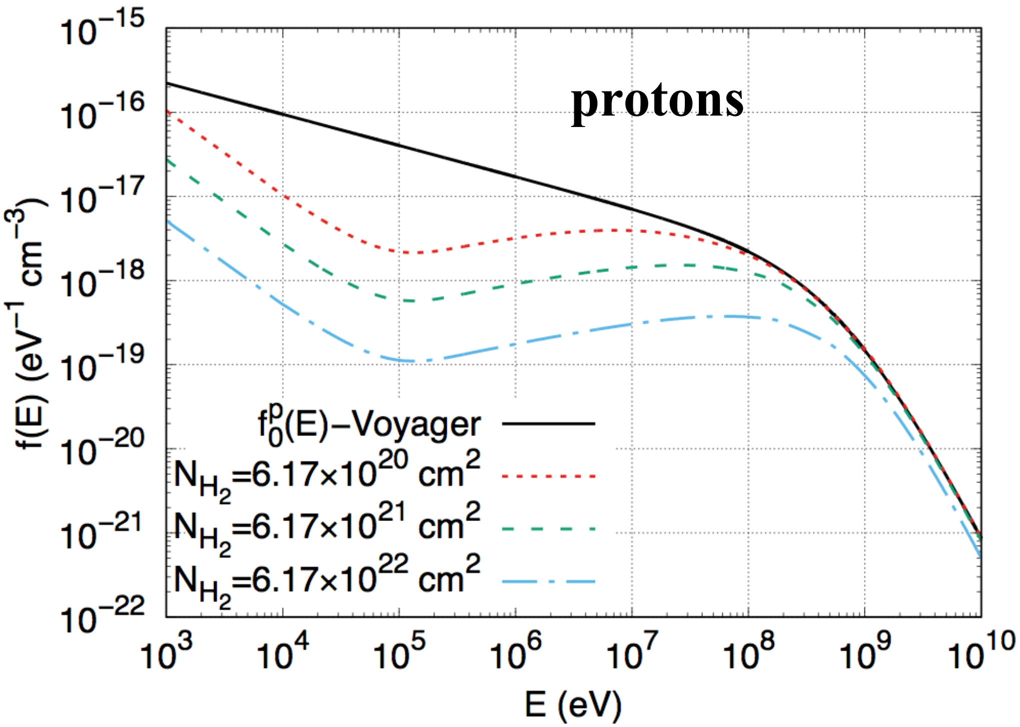
CR induced ionization of molecular clouds accounting for losses

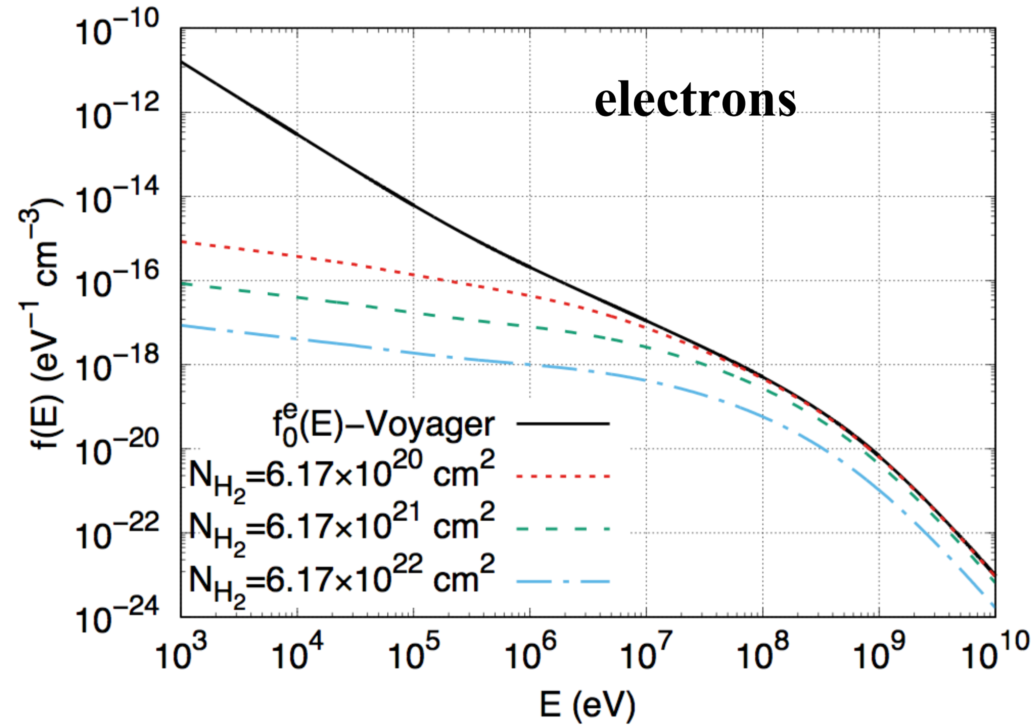
[V. Phan, GM &. S Gabici, 2015]

The calculation of spectra inside a cloud require solving the transport equation including ionization losses and Alfvén advection:

$$\frac{\partial f}{\partial t} = \frac{\partial}{\partial x}\left[D\frac{\partial f}{\partial x}\right] - v_A\frac{\partial f}{\partial x} - \frac{1}{p^2}\frac{\partial}{\partial p}\left[\dot{p}p^2 f\right]$$

Solution: Electron and proton spectra inside a cloud as a function of column density

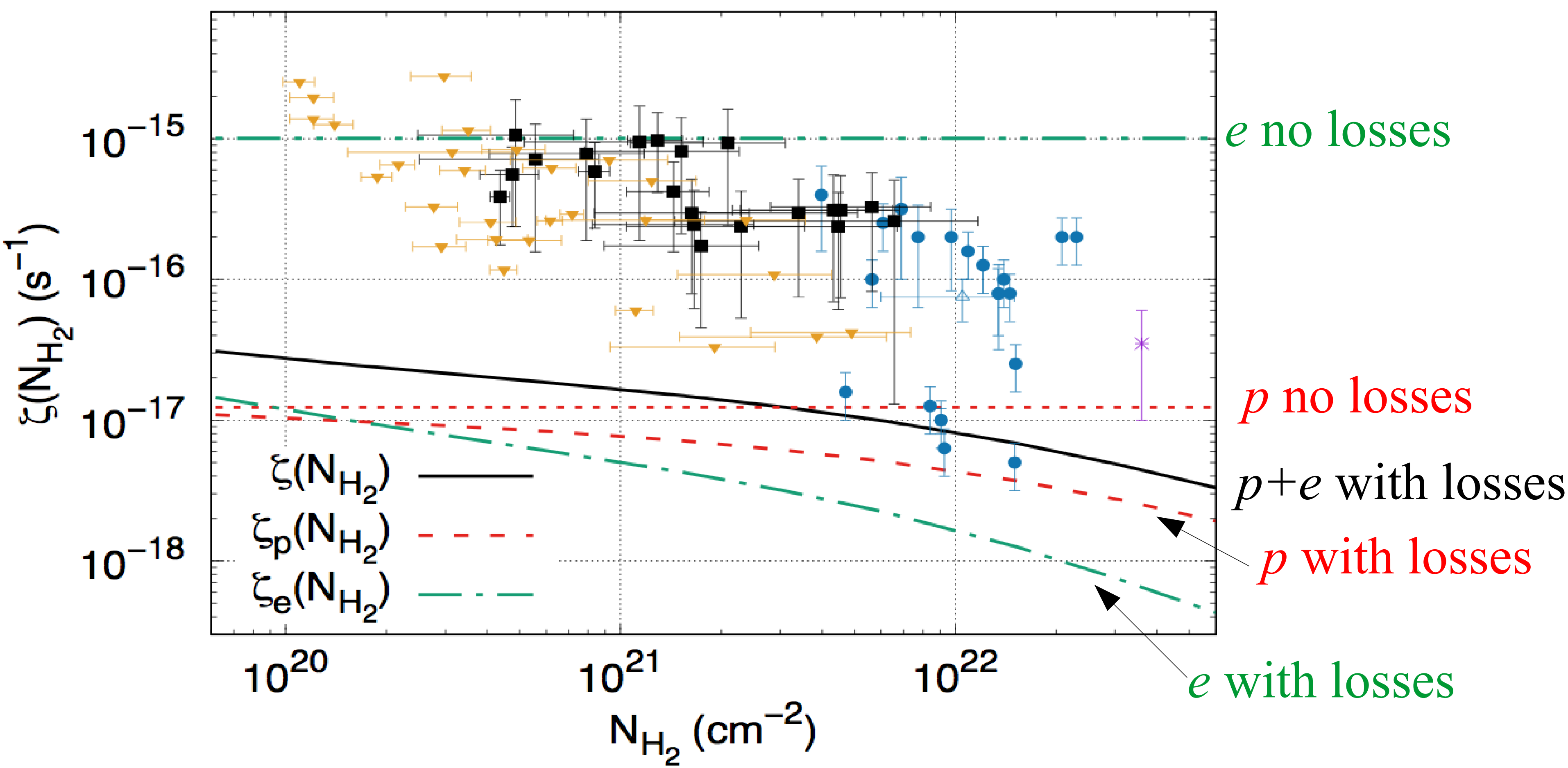




CR induced ionization of molecular clouds accounting for losses

[V. Phan, GM &. S Gabici, 2015]

Ionization rate as a function of column density



The ionization rate is not enough to account for observed data!

→ other source(s) of low-energy CRs is requires