ESCAPING OF COSMIC RAYS AND INTERACTION WITH ISM

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LECTURE IV

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SUMMARY

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

- **The journey to the Earth**
  - ***The Galactic magnetic halo and the leaky-box model***
  - ***Beyond the leaky-box model***

- **The gradient problem in the Galactic CR spectrum**

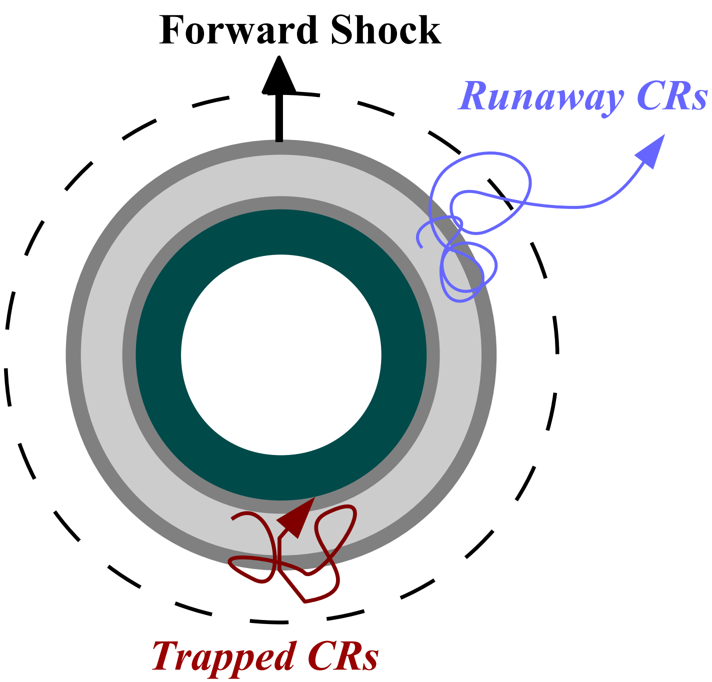
- **The positron excess**

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 $\longrightarrow$ 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 $\xi_{esc}(t)$ of the incoming kinetic energy is converted into escaping flux:

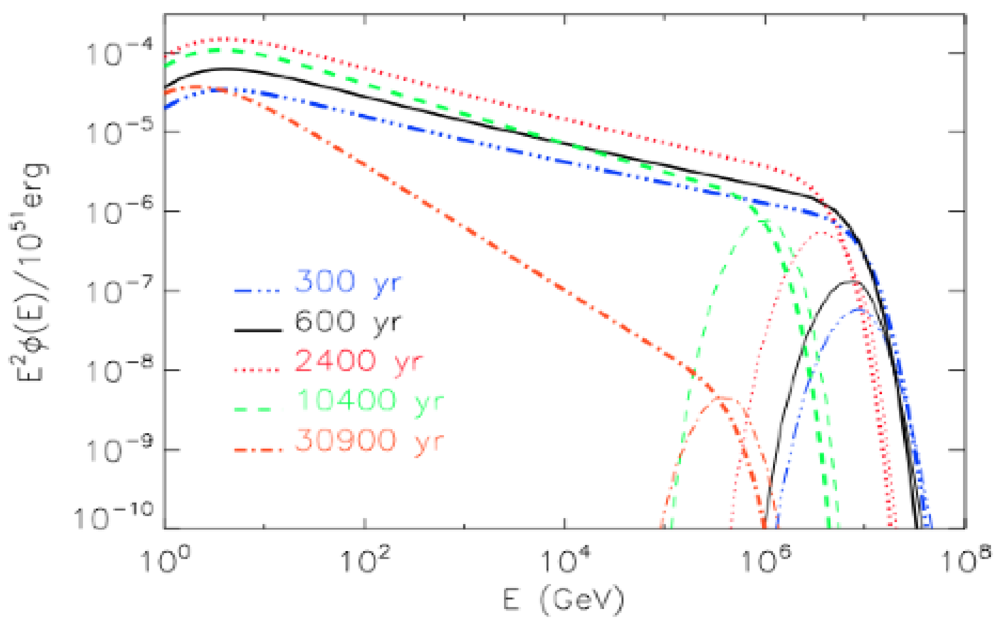
$$4\pi p^2 dp\, f_{esc}(p)\, pc = \xi_{esc}(t)\, \frac{1}{2}\rho u_{sh}^3\, 4\pi R_{sh}^2\, dt$$

Evolution during the Sedov-Taylor phase:

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

$$f_{esc}(p) \propto \xi_{esc}(t)\, p^{-4}$$

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



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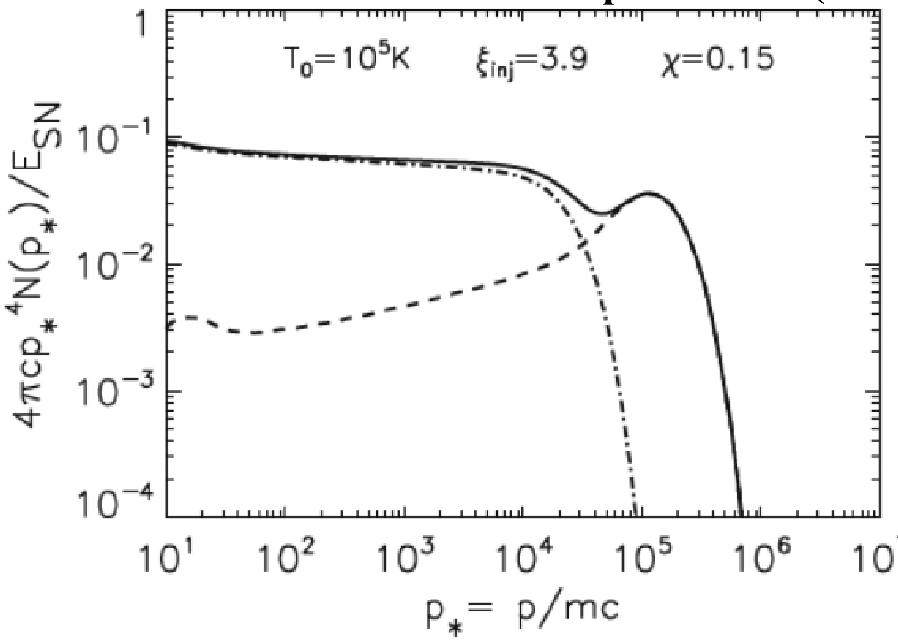
When non-linear effects are included $f_{esc}(p)$ tends to be harder than p^{-4}.

The final spectrum is the sum of particle escaping plus particles trapped and released when the shock disappears

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



IS THERE A WAY TO TEST THE ESCAPING PROCESS?

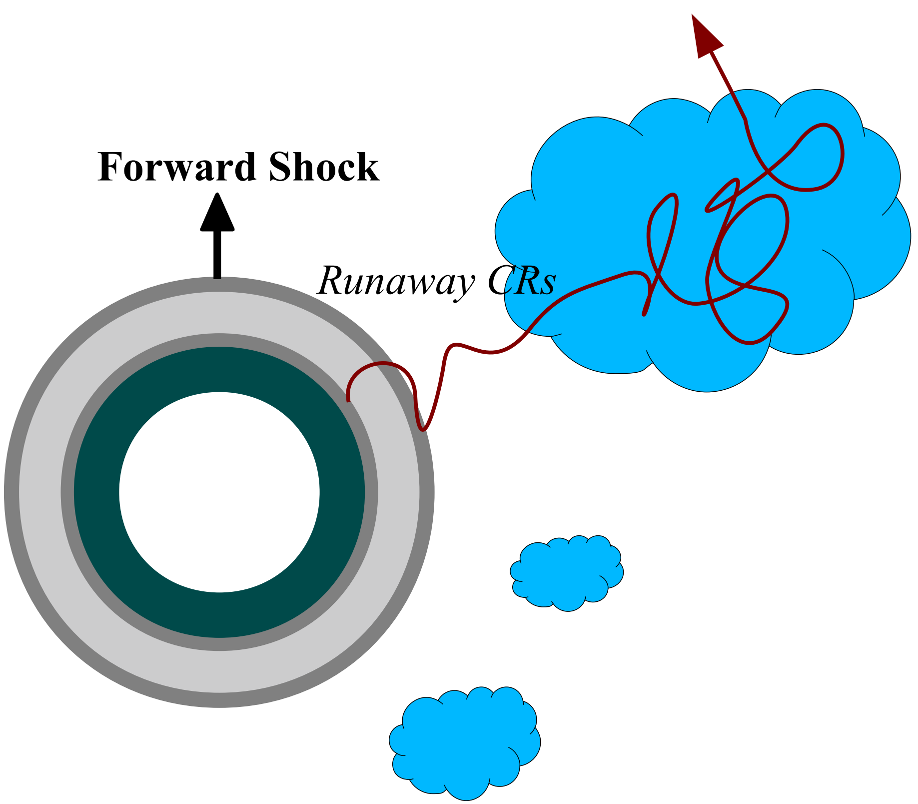
SNR-MOLECULAR CLOUDS ASSOCIATIONS

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

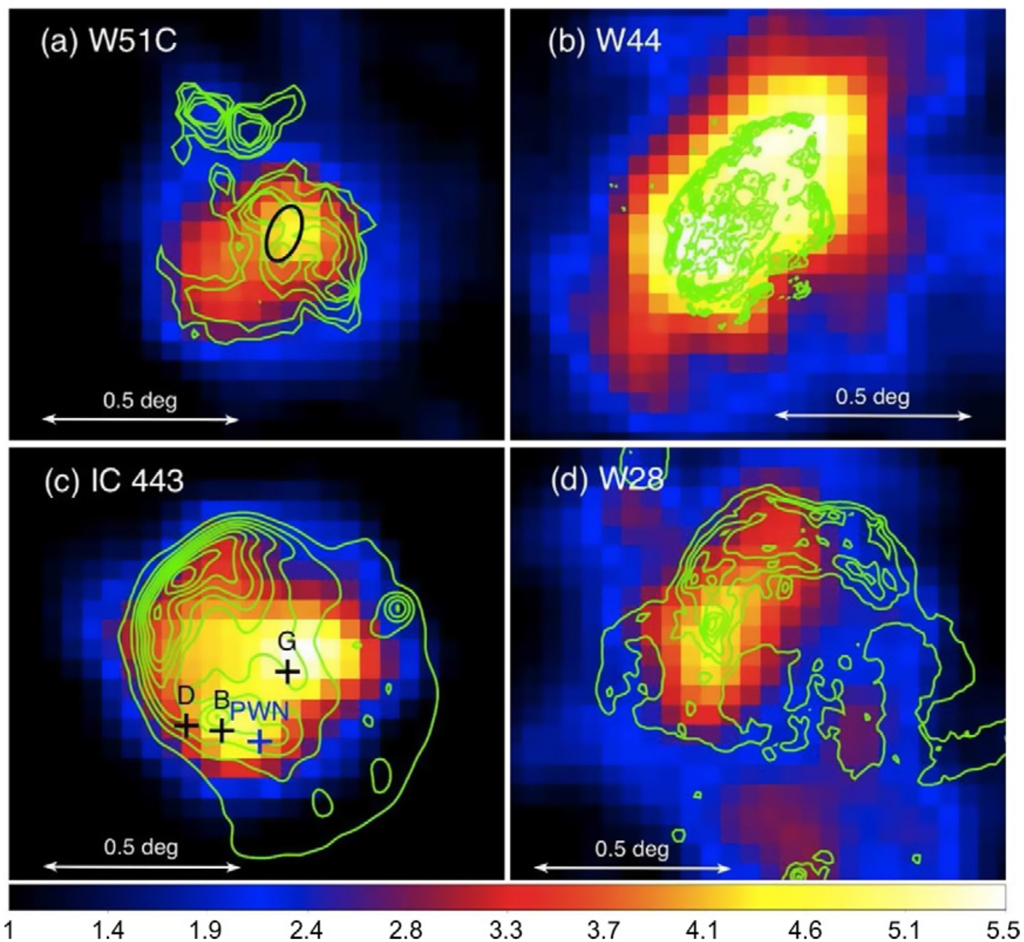
- The ionization rate of several molecules depends on the CR flux (H_2, H_3^+, CH, OH, C_2, DCO^+, HCO^+,......)

- 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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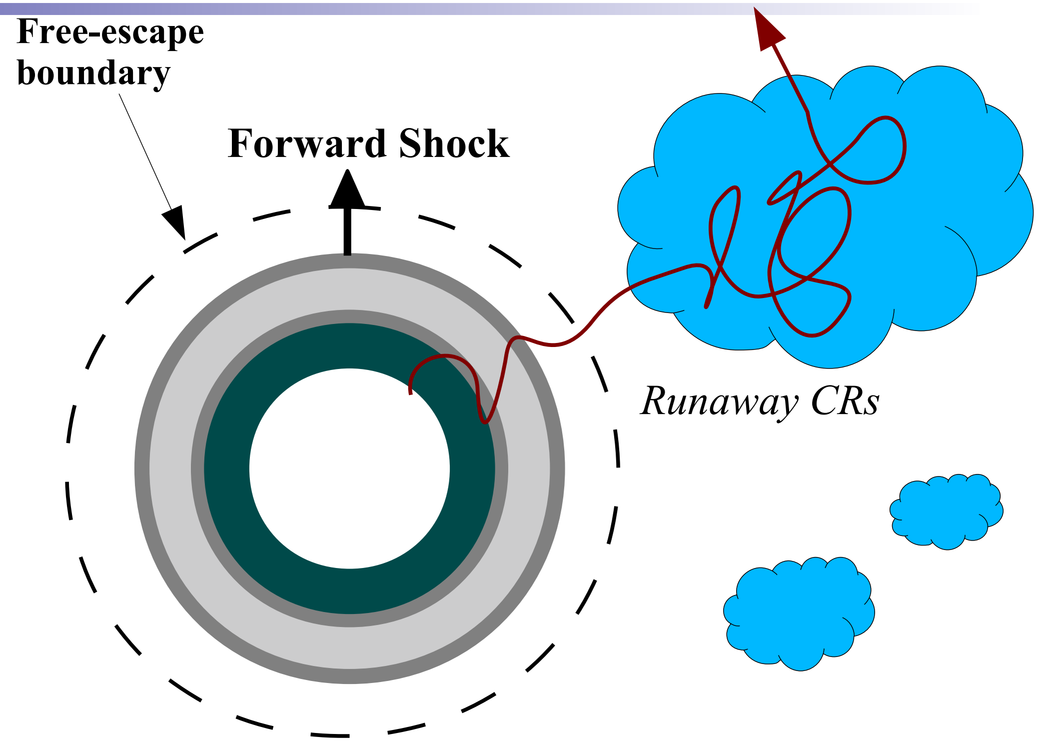
Gamma-rays from Molecular clouds

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

→ detectable level of TeV emission if

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

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



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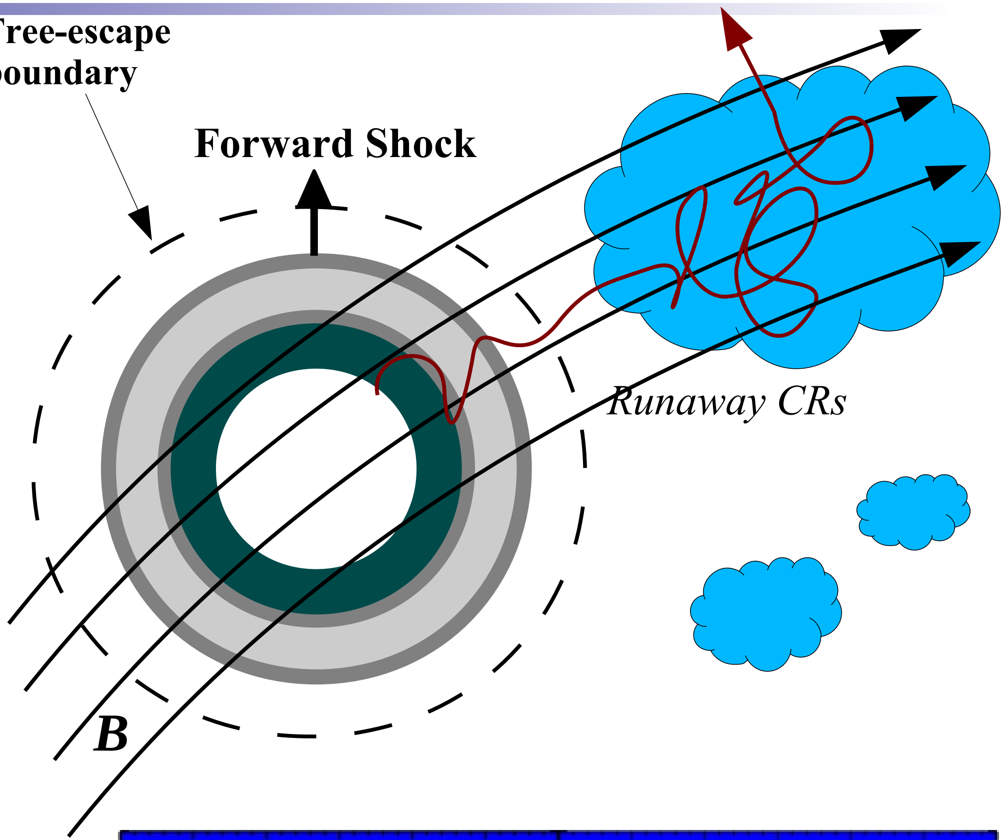
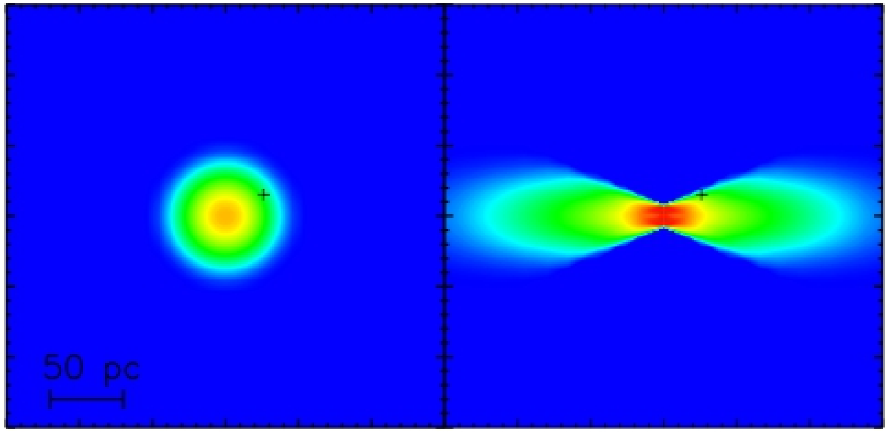
→ this happen when the cloud is located at d <~ 100 pc from the SNR (for 3D diffusion model)

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

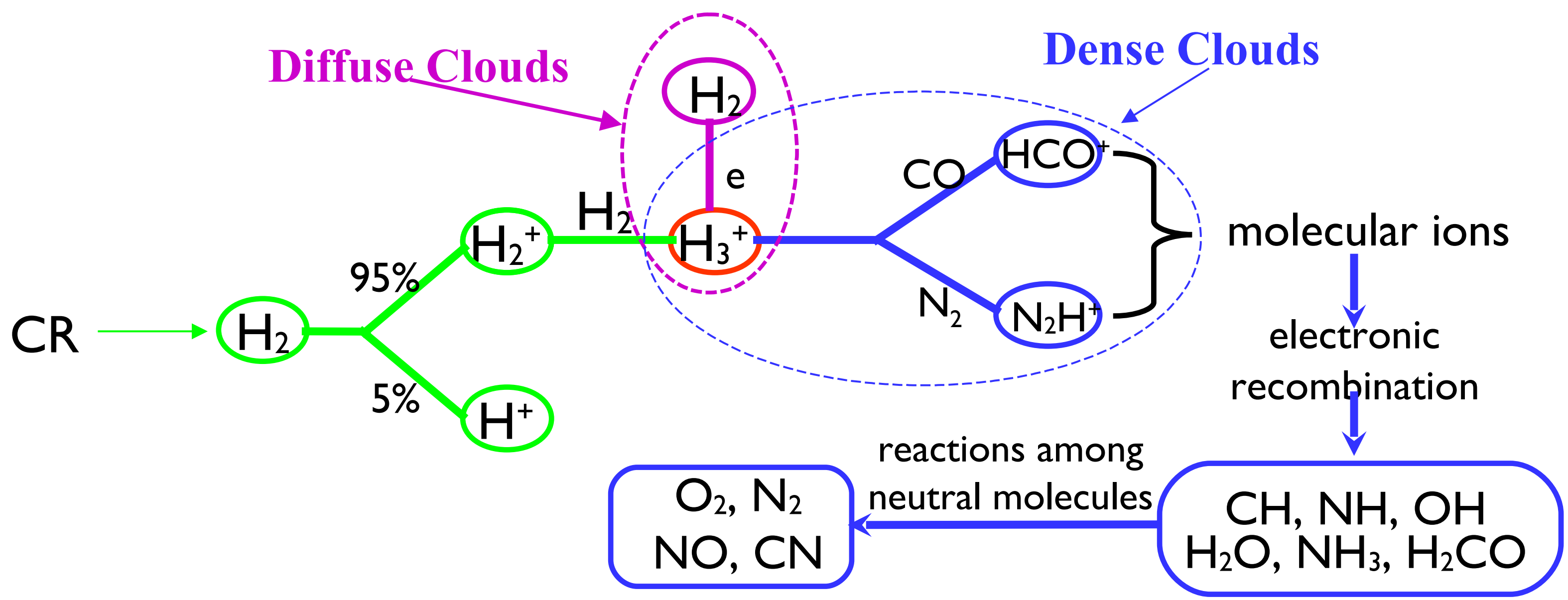




Simulation from Nava & Gabici (2012)

Understanding the cloud chemistry and dynamics

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) $\xi_{CR} \simeq 10^{-17} s^{-1}$

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

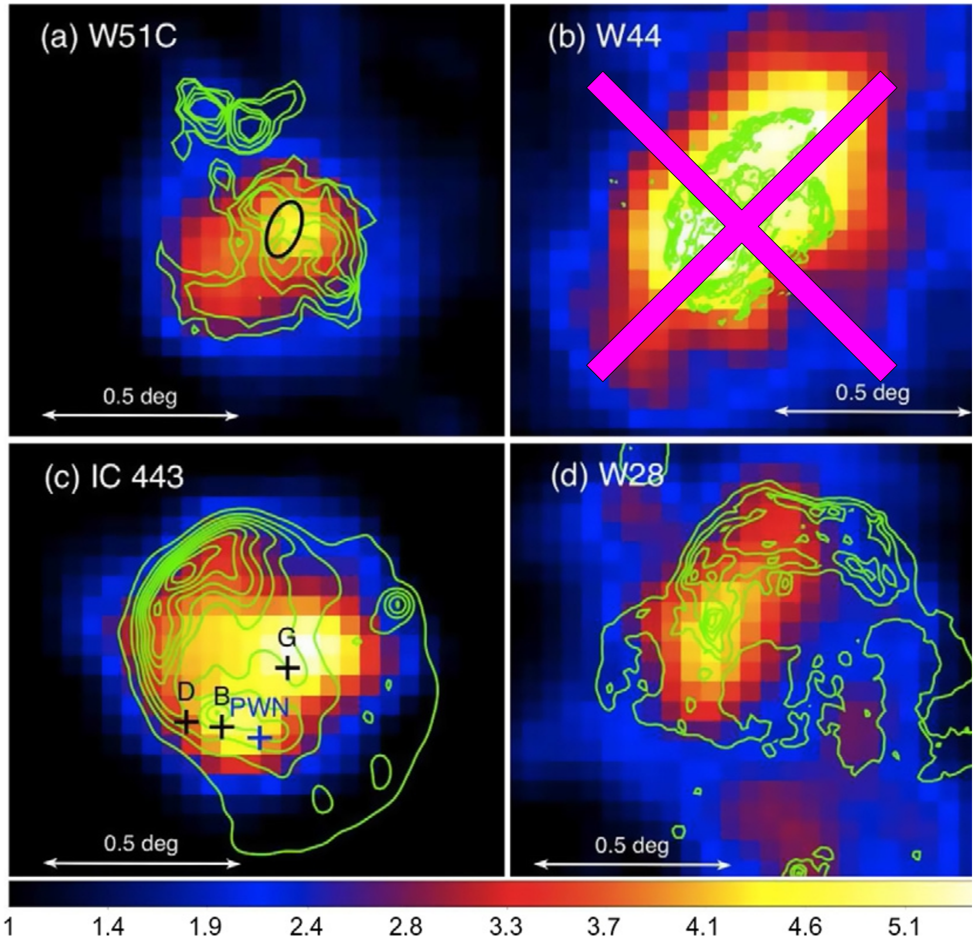
2) CR interactions affect the cloud temperature

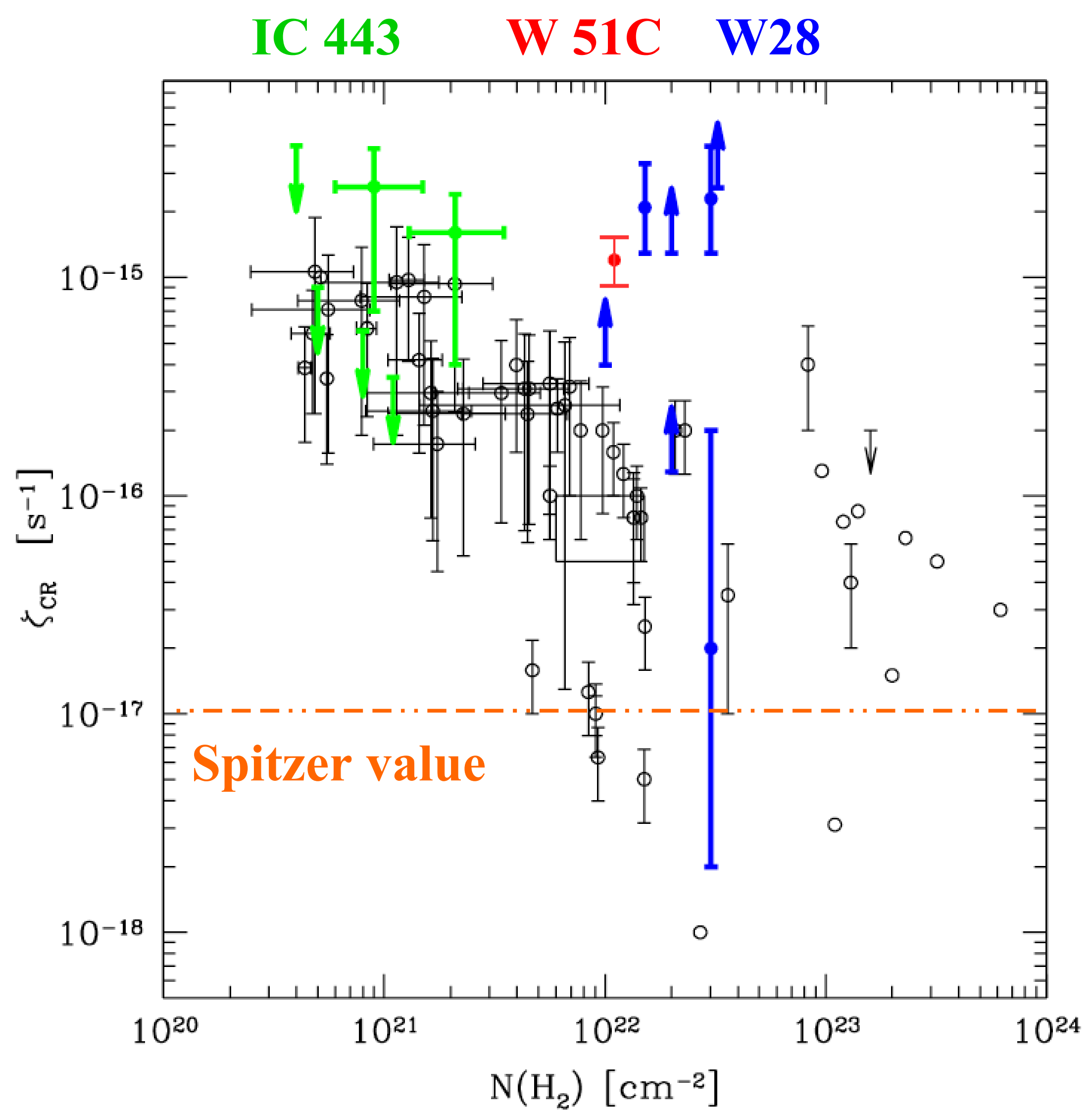
3) Ionization controls the coupling between gas and magnetic filed

- The gravitational collapse occurs in the very deep core when the gas and the magnetic filed decouple form eachother

Enhanced ionization rate in MC-SNR systems

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

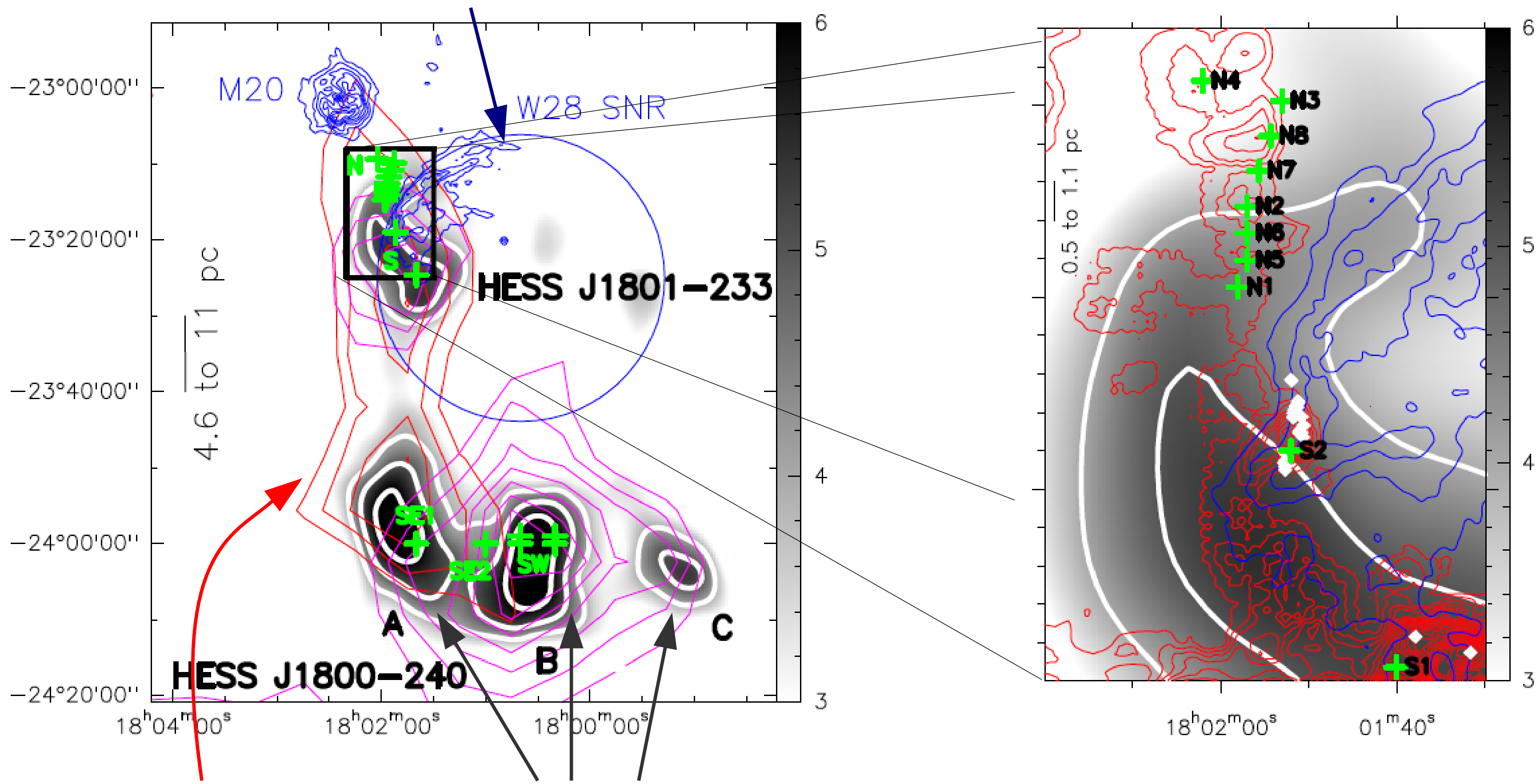




CR induced ionization of molecular clouds interacting with SNR W28

[Vaupr³, 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

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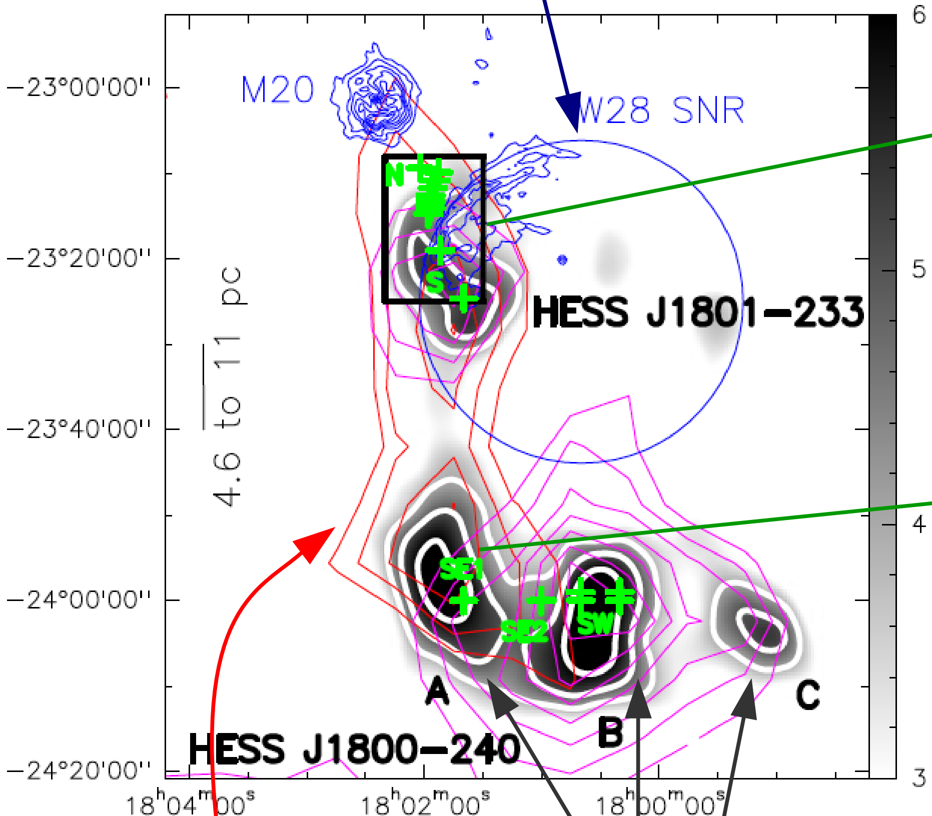
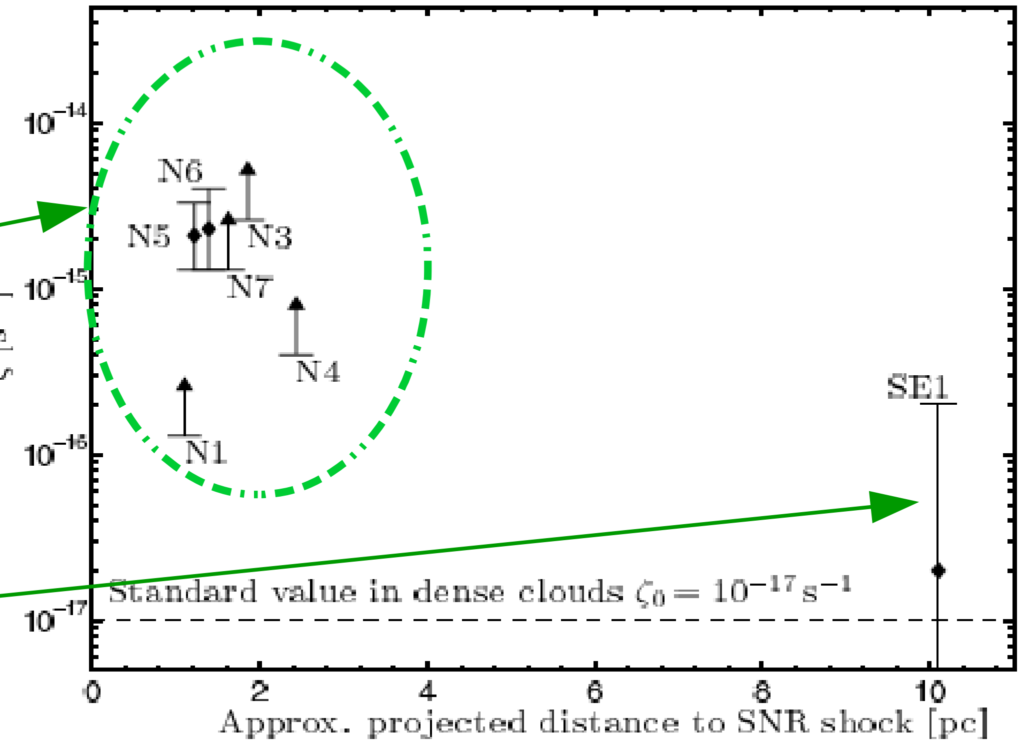




CO emission

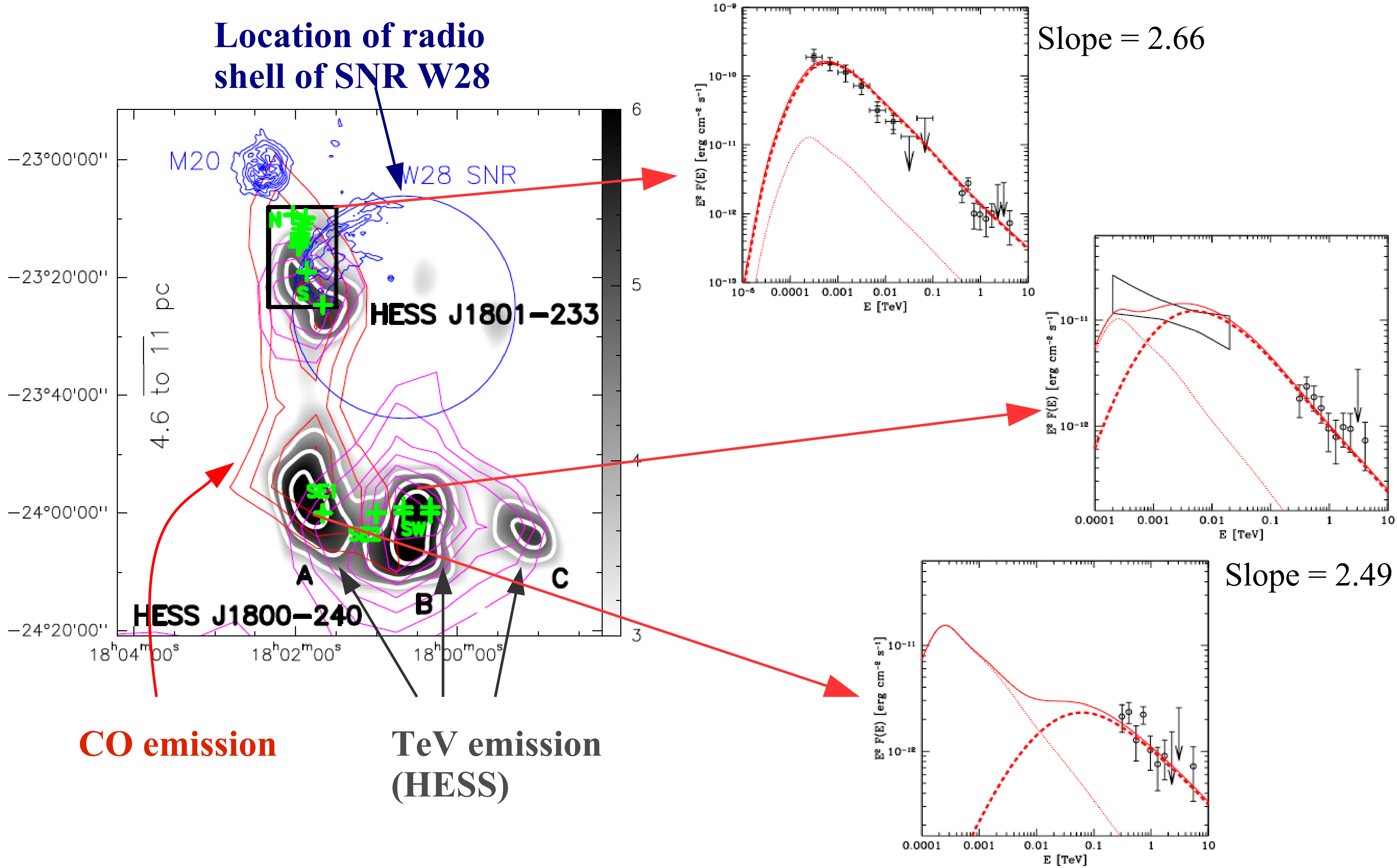
TeV emission (HESS)

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]



CR induced ionization of molecular clouds interacting with SNR W28

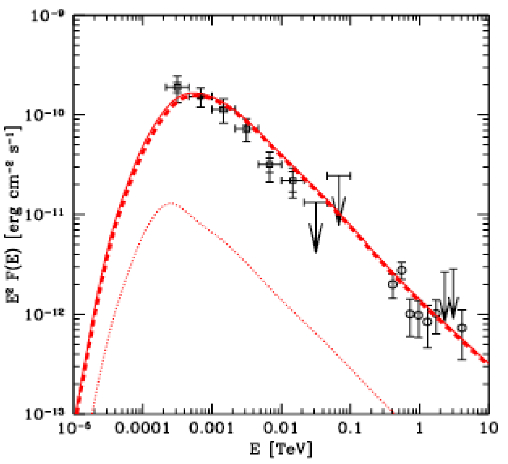
[Gabici &. Montmerle, ICRC 2015]

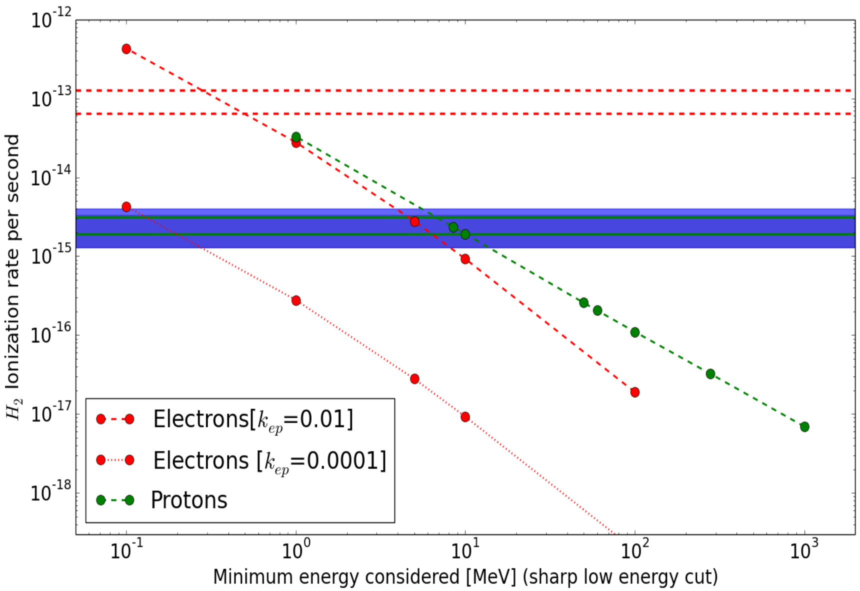
For the region where the shock is impacting the cloud we calculate the ionization rate using the same proton spectrum that produces the gamma-ray emission

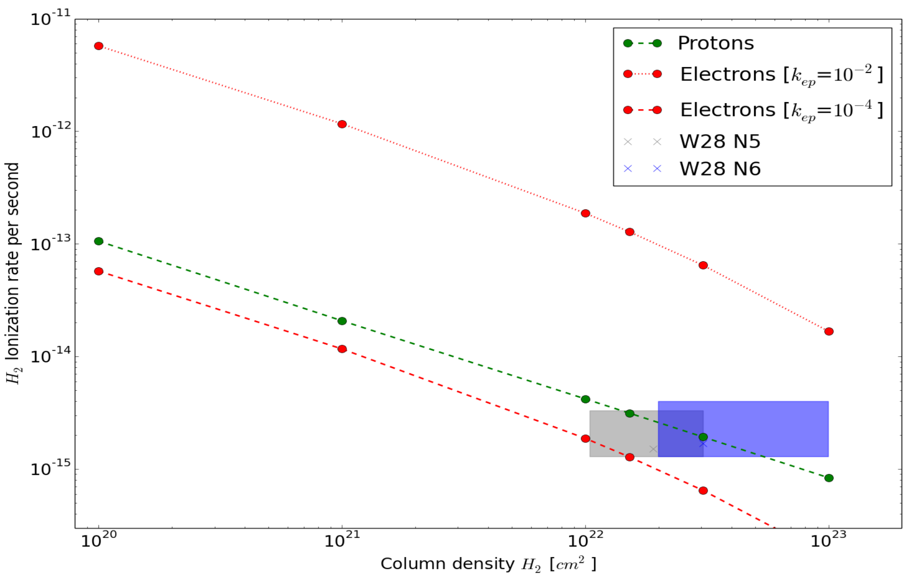
→ Protons alone can be responsible for the observed ionization rate with a low energy cut-off ~ 10 MeV

→ The observed ionisation does constrain the CR electron spectrum implying either a very low kep of ~1e-4 @ 1 GeV of a spectral turnover below ~ 10MeV

Gamma-ray spectrum







Effect of self amplfication of waves in the vicinity of a SNR

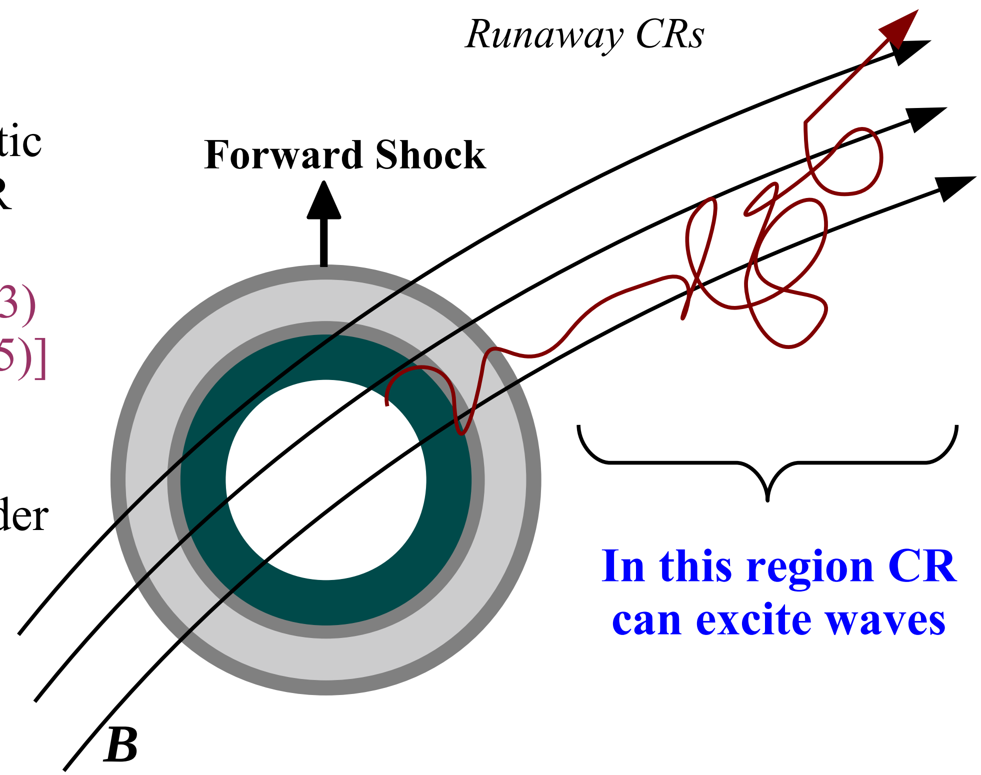
During the process of escaping, CR can excite magnetic turbulence (via streaming instability) that keep the CR close to the SNR for a long time, up to 10^5 yr

[Malkom et al. (2013)
Nava et al. (2015)]

The region where this can happen is at most of the order of the coherence-length of the magnetic field (after this distance the diffusion becomes 3D and the CR dendity drops rapidly below the average Galactic value)

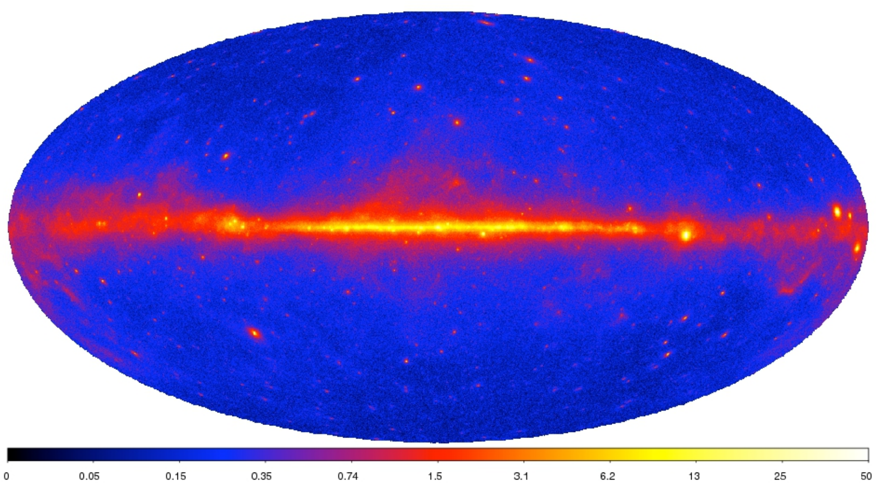
During the time CR spend in the vicinity of sources they can produce diffuse emission via
$\pi^0 \rightarrow \gamma\ \gamma$

CAVEAT: the presence of neutral can damp the amplification because of the ion-neutral friction



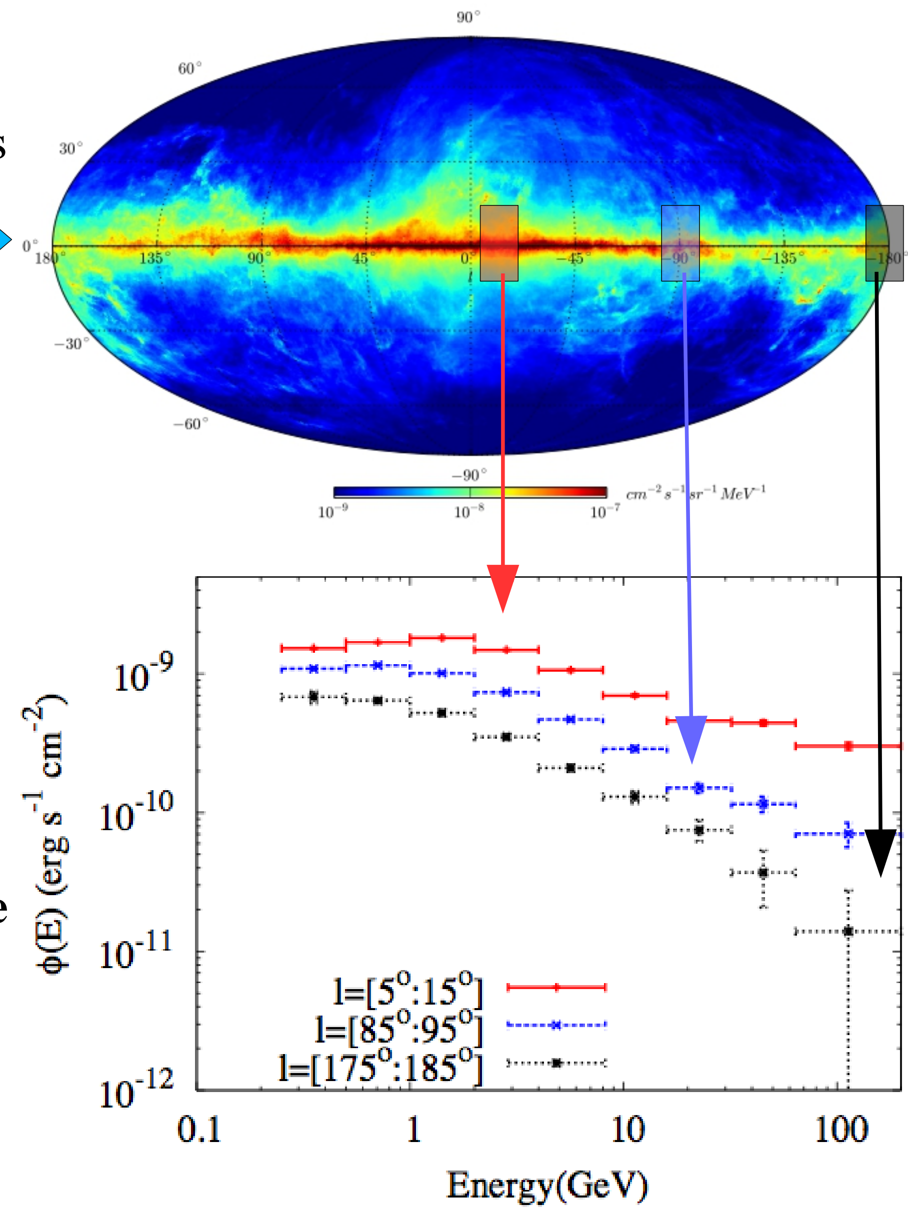
Diffusive Galactic emission

FermiLAT all sky map



Subtracting
known sources

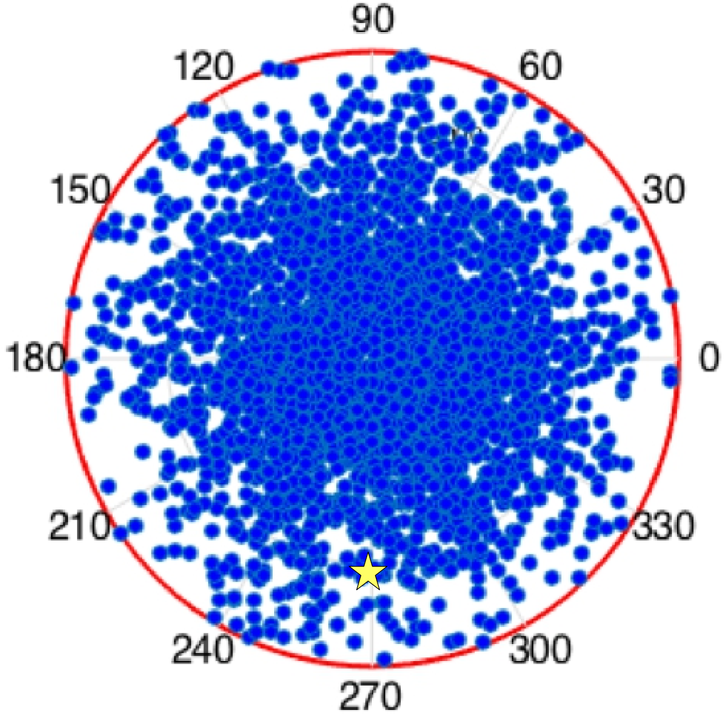
FermiLAT diffuse emission



Diffuse Galactic γ-ray flux for three different andular sectors extracted from the Fermi-LAT data
[Yang-Aharonian-Evoli(2016)]

Contribution of escaping CRs to the diffuse Galactic γ-ray emission

Distribution of SNRs in the galactic plane during the last ~10^5 yrs using a rate of 1 SN/(30 yr)



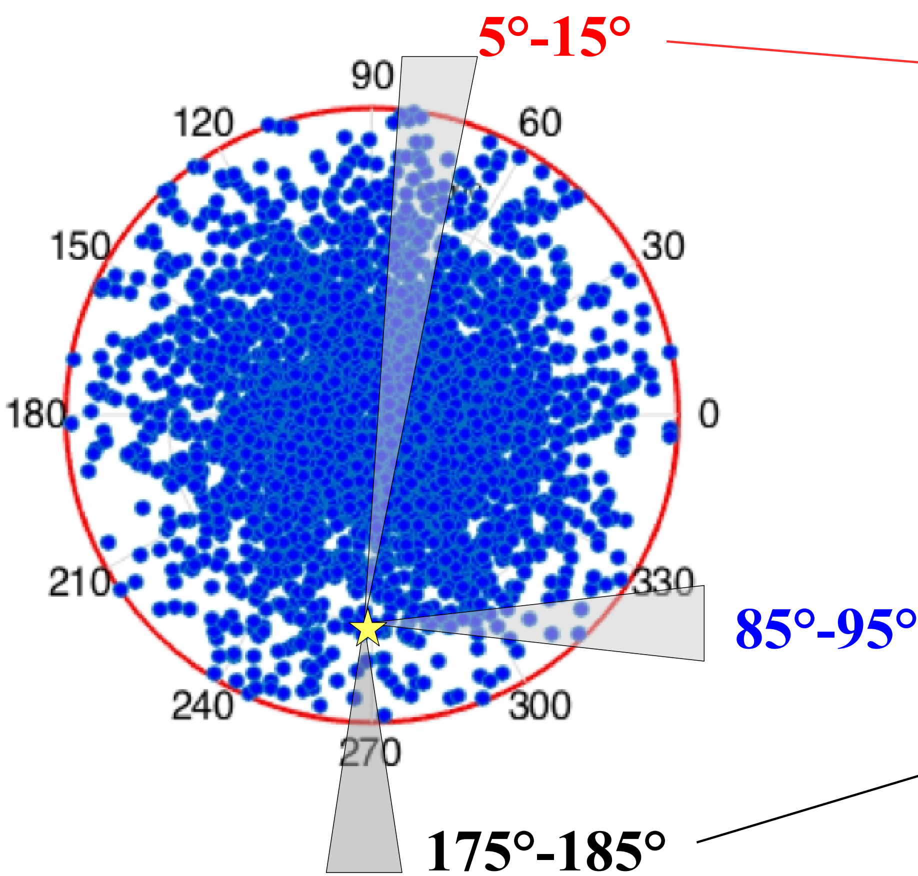
Contribution of escaping CRs to the diffuse Galactic γ-ray emission

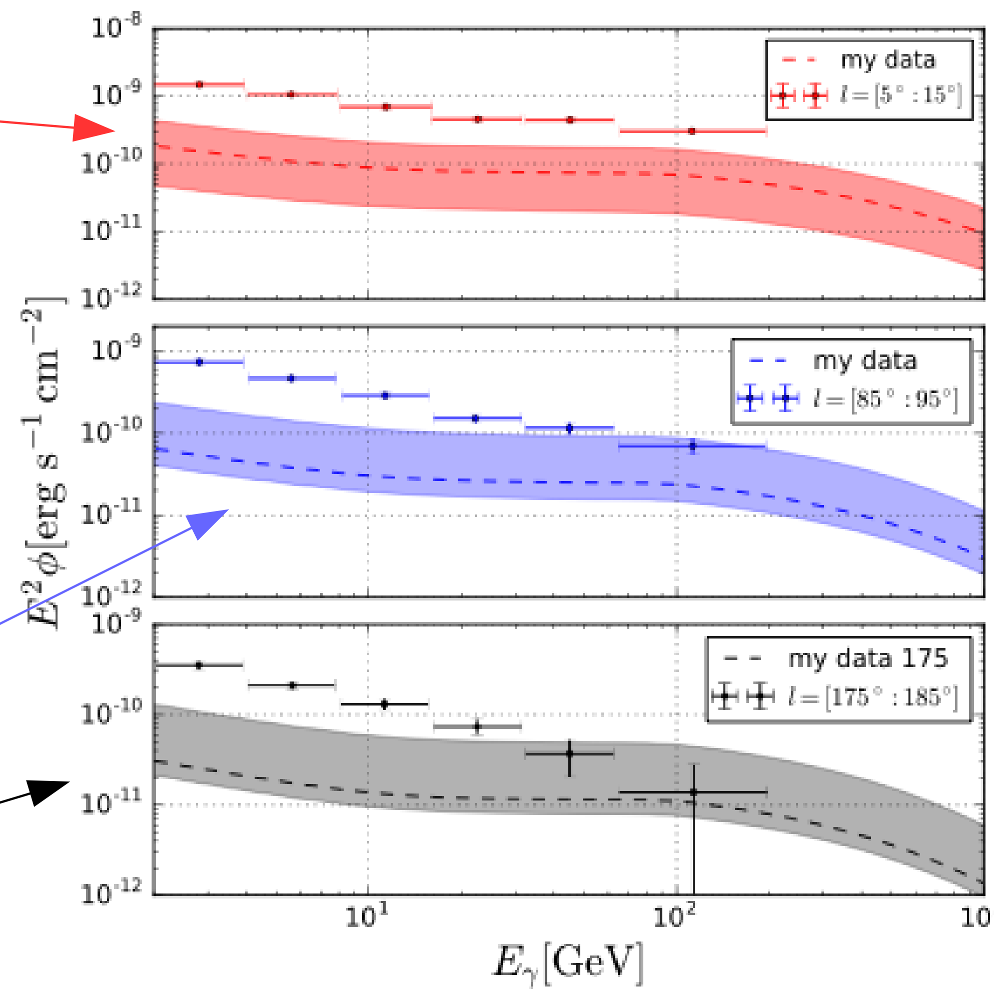
Comparison between Fermi-LAT data and theoretical prediction

[D'Angelo, GM, P. Blasi (2016)]

Distribution of SNRs in the galactic plane during the last ~10^5 yrs using a rate of 1 SN/(30 yr)

$$n_i = 1.0\, cm^{-3}; \qquad n_H = 0.05\, cm^{-3}$$



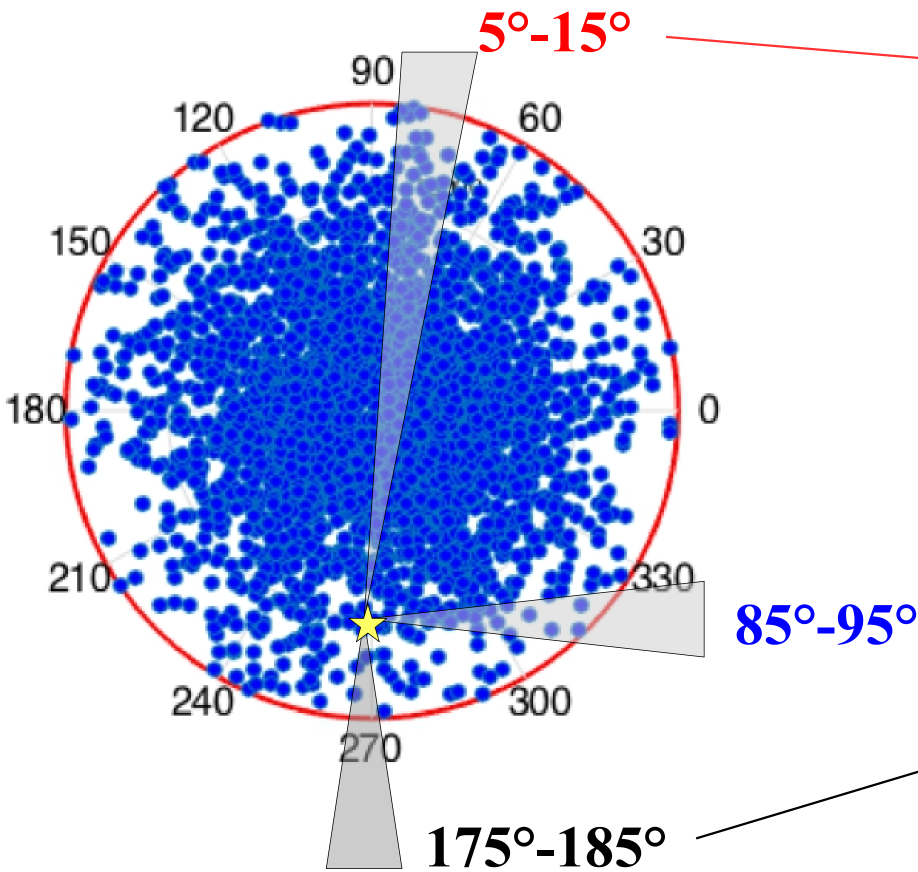


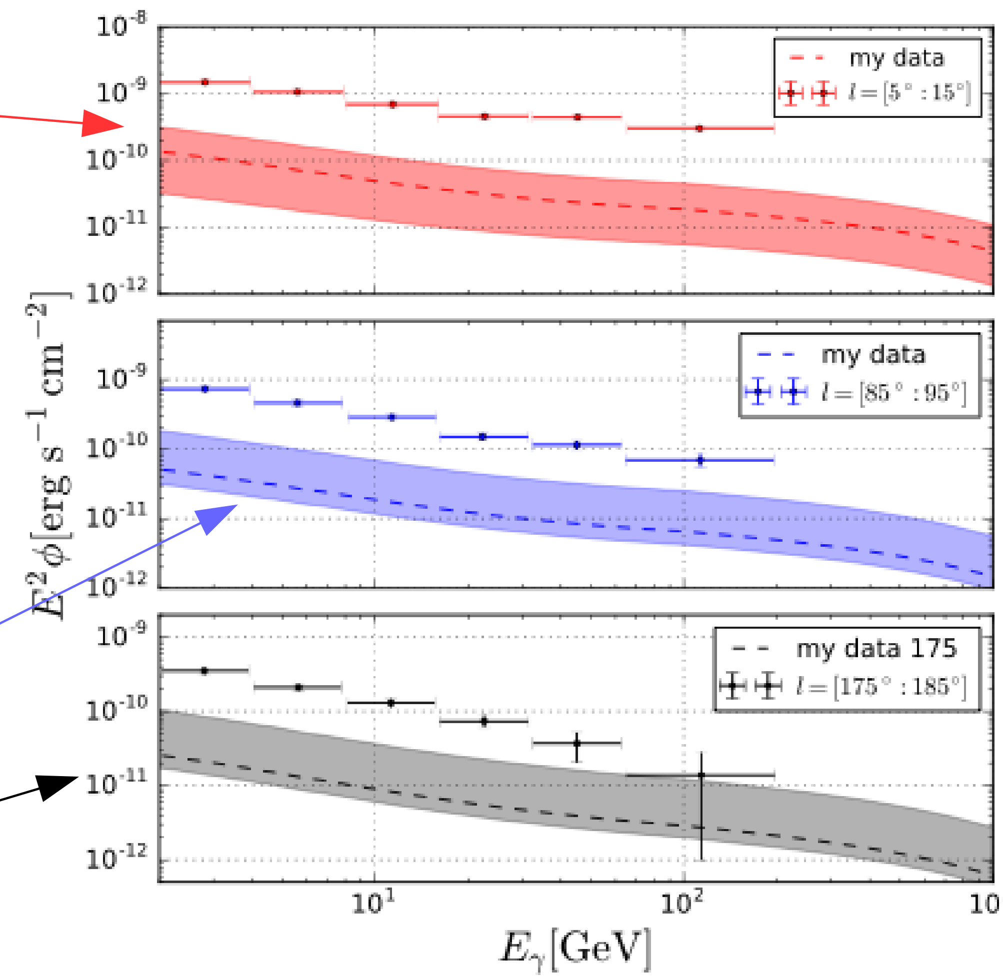
Contribution of escaping CRs to the diffuse Galactic γ-ray emission

Comparison between Fermi-LAT data and theoretical prediction
[D'Angelo, GM, P. Blasi (2016)]

Distribution of SNRs in the galactic plane during the last ~10^5 yrs using a rate of 1 SN/(30 yr)

$$n_i = 0.45\, cm^{-3}\ ; \qquad n_H = 0.05\, cm^{-3}$$





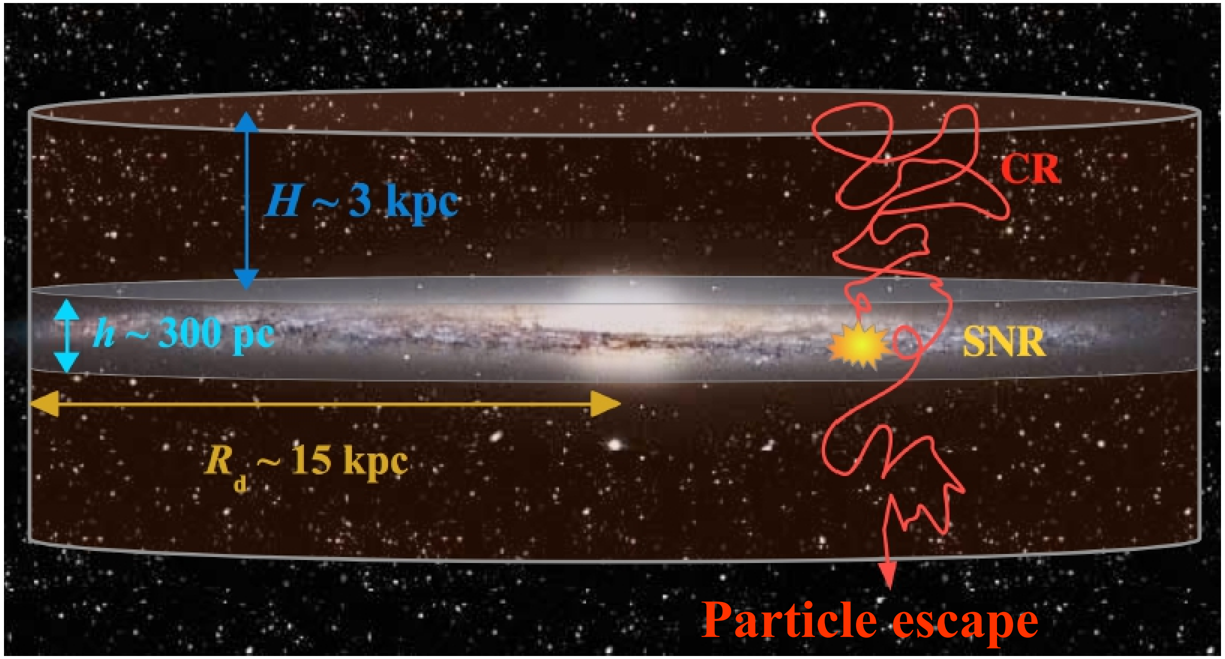
THE JURNEY TO THE EARTH

Diffusion in the Galactic halo

To infer the spectrum injected by sources we need to understand the CR diffusion in the Galactic halo.

The most widely used model is the leaky-box with the following properties

- All surces are located in the Galactic disc and explode with rate R_{SN}
- The diffusion coefficient $D(E)$ is assumed constant everywhere in the halo
- The CR distribution vanish at $z = H$
- H~3-4 kpc inferred from diffuse synchrotron emission



Secondary/primary ratio

In the leaky-box model the **spectrum of primary CR** in the Galaxy is:

$$N_{pri}(E) = N_{SNR}(E) R_{SN} \frac{1}{\pi R_d^2 2H} \tau_{esc}$$

Spectrum injected by sources; SN rate; Halo's volume; Escaping time

Assuming diffusion, $D(E) = D_0 E^{\delta}$, the escaping time is: $\tau_{esc} \simeq \frac{H^2}{D}$

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

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

$$\frac{N_{sec}(E)}{N_{pri}(E)} \propto E^{-2\delta}$$

Only a function of the escaping time

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

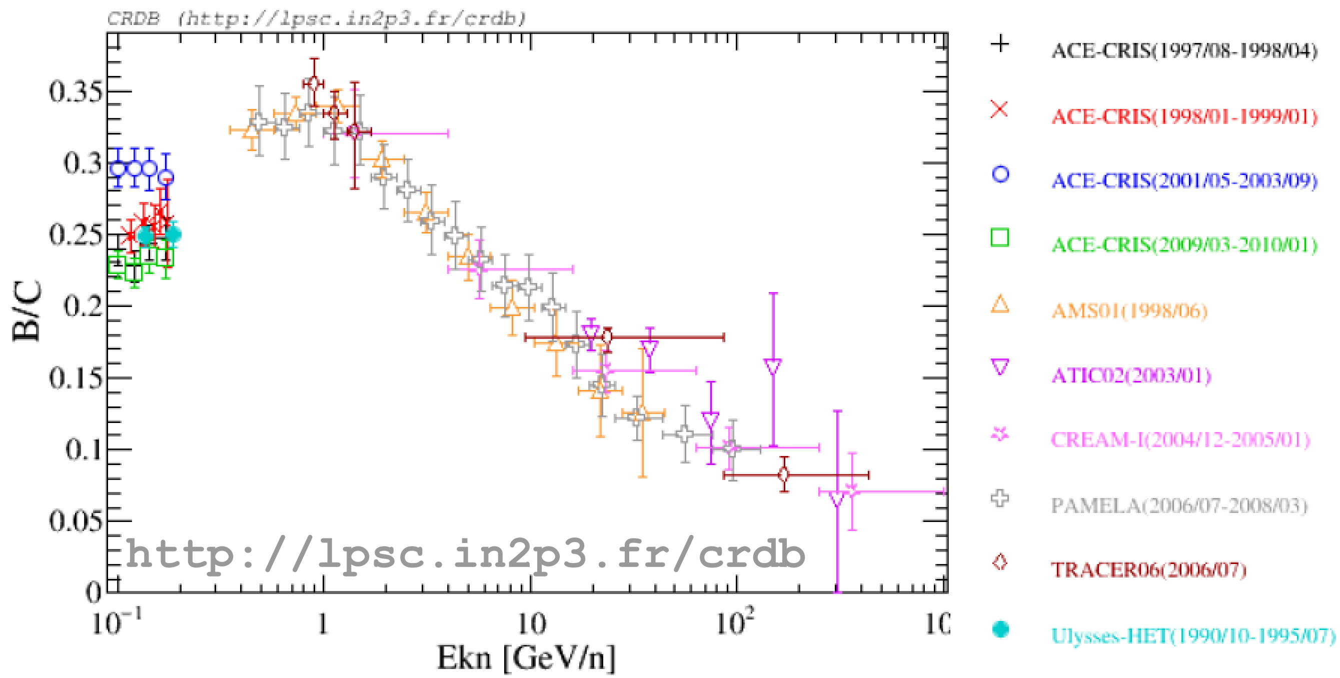
Boron over Carbon ratio taken from several experiments. Data are compatible with anything in the interval

$$0.3 < \delta < 0.6$$

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

$\rightarrow 2.1 < \gamma_{inj} < 2.4$

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



Based on present data of B/C it is still difficult to discriminate between different values of the slope od D(E) **Waiting for AMS data**

Beyond the leaky-box model

The picture provided by the leaky-box 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)

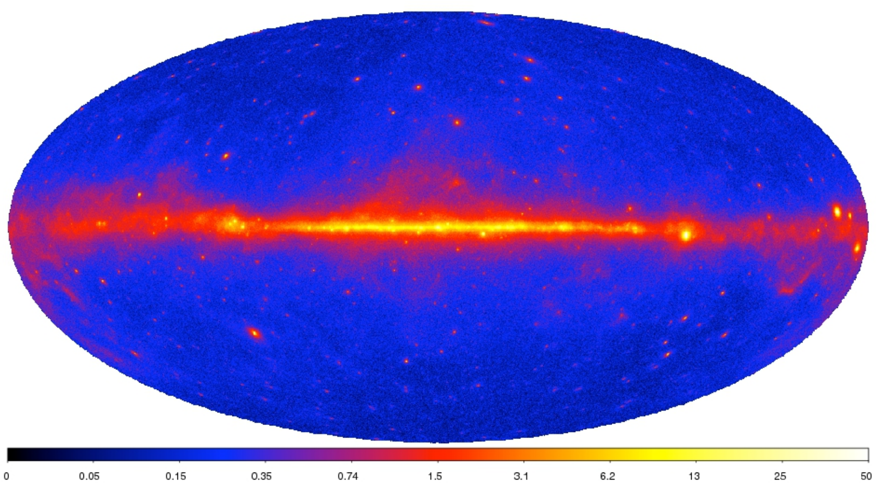
A more realistic model should account for important physical ingredients:

- **Generation of turbulence by SN explotions**
  → 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:

Diffusive Galactic emission

FermiLAT all sky map



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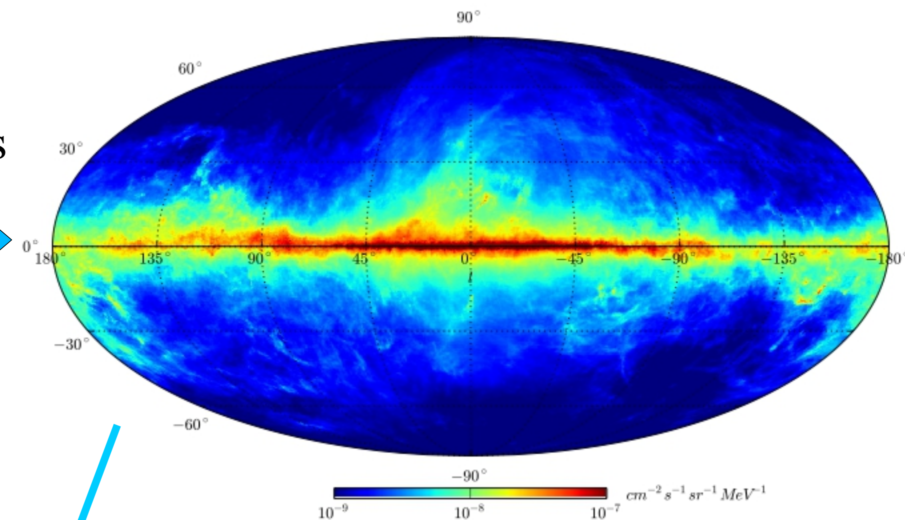
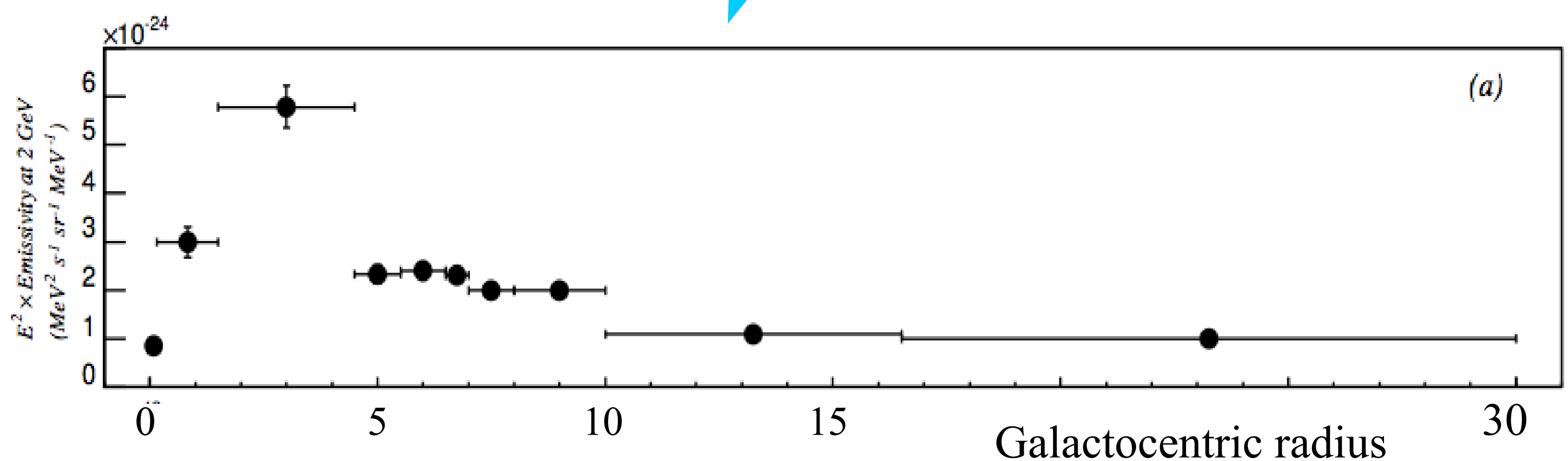
FermiLAT diffuse emission



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

E^2 × emissivity
at 2 GeV

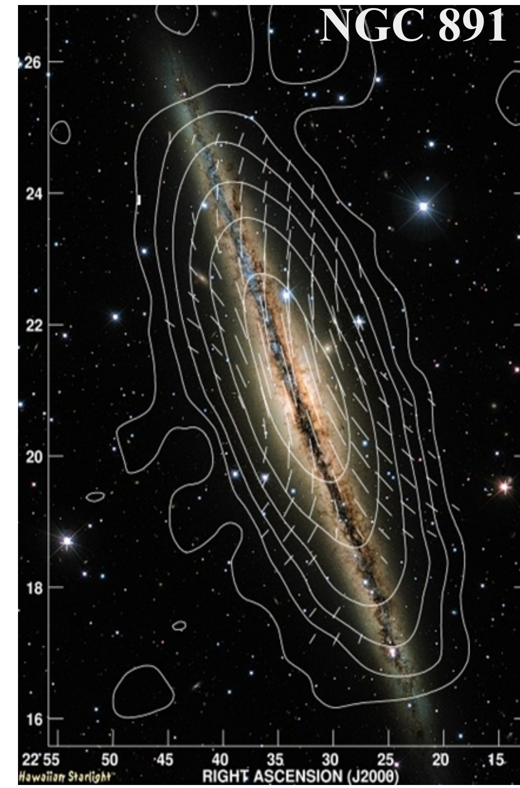


Why a Galactic halo?

Evidences for the Galactic magnetic halo:

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

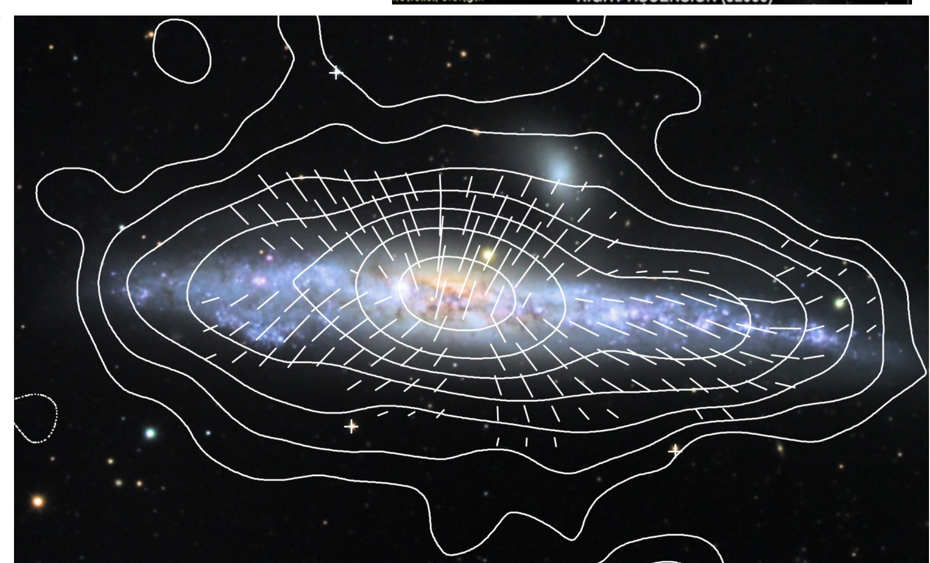
What is the origin of the magnetic Halo?



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.

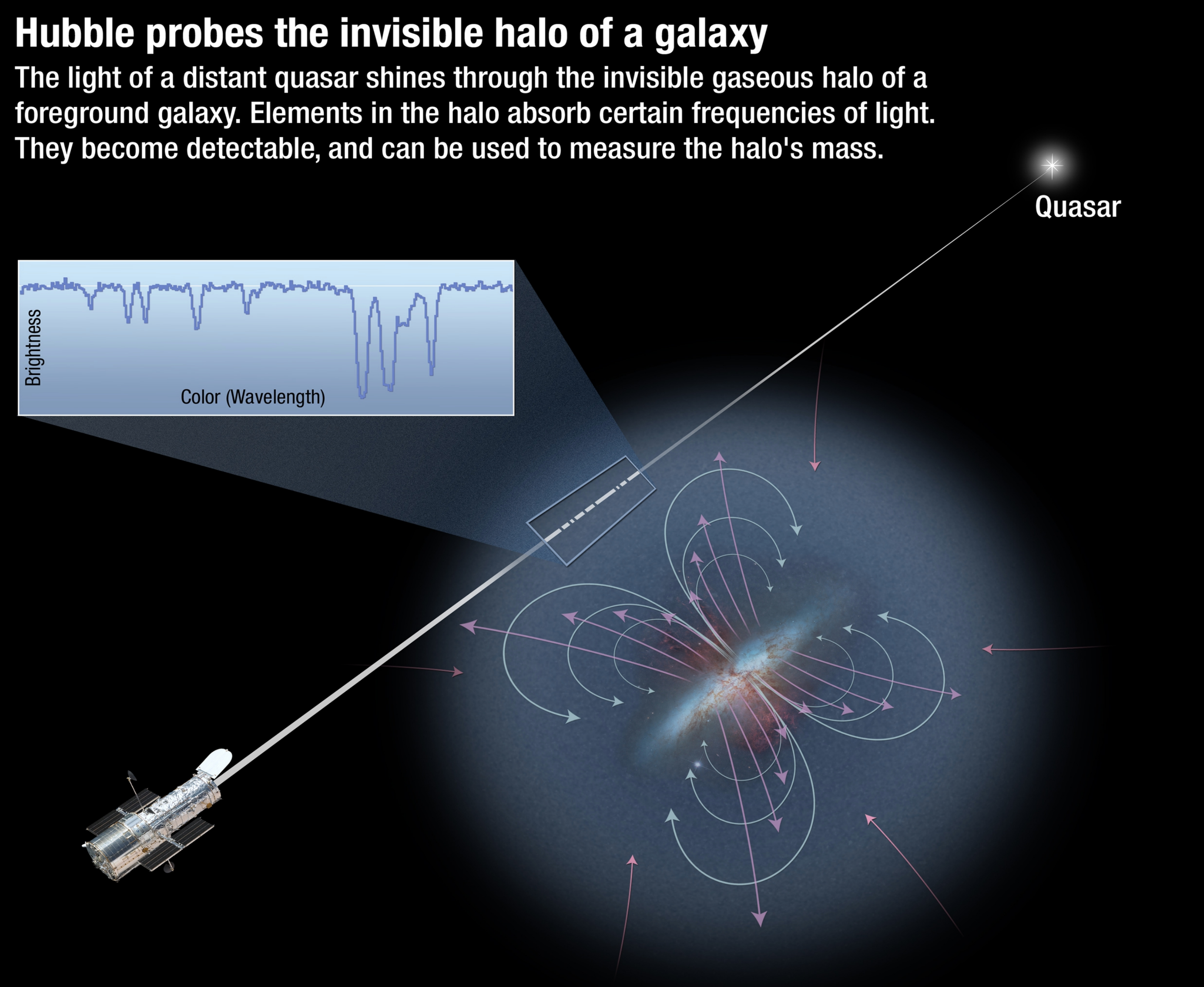
These observations support the idea of a "**galaxy wind**" which is driven by the energy of star formation processes in the disk and transports gas, magnetic fields and cosmic-ray particles into the halo.

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 sturbust 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!!)

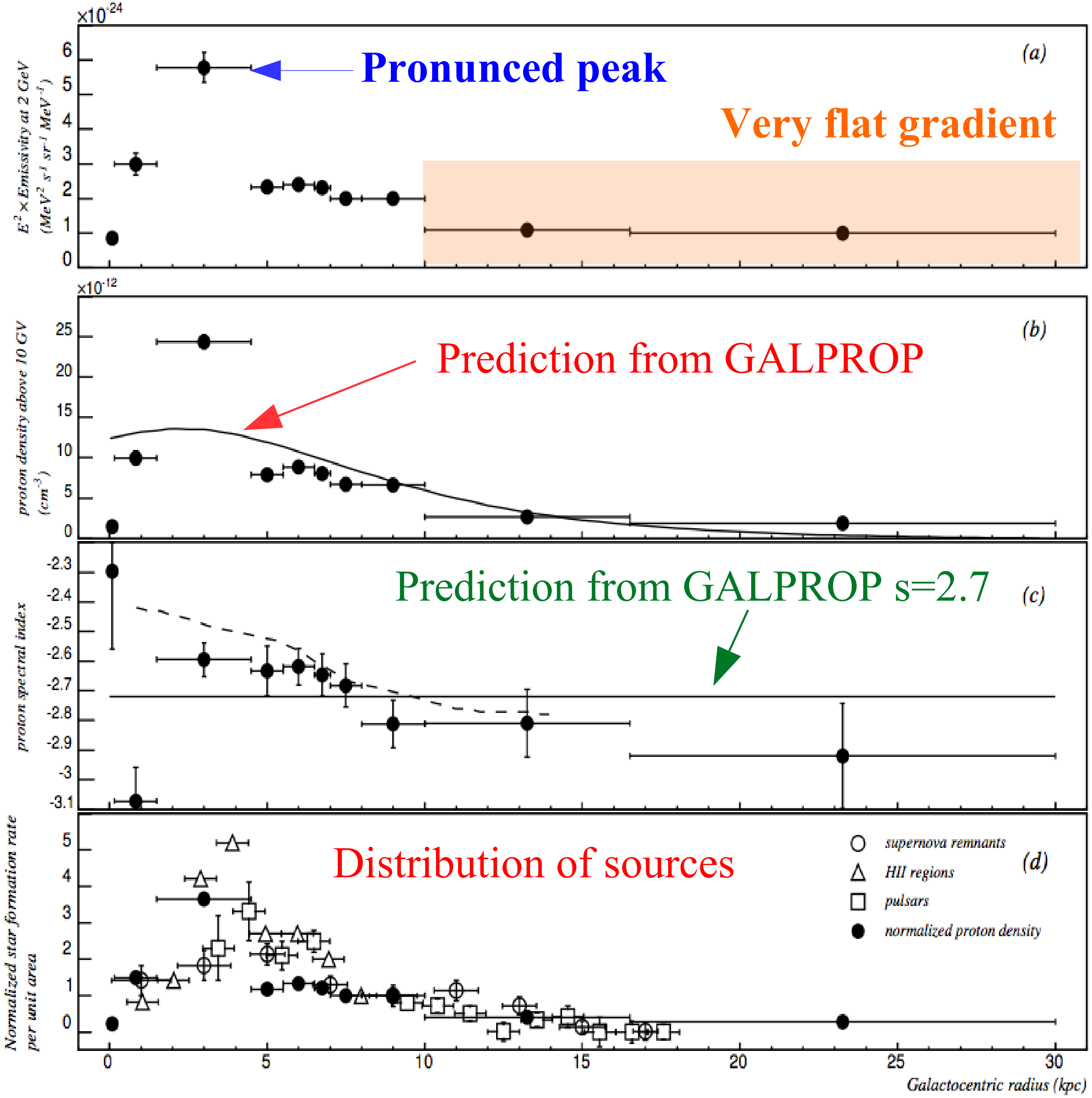
- And also the matallicity: $Z \sim 0.2\text{-}0.3$

→ The halo has been probably polluted by a Galactic wind

Galactic wind observed in X-rays from starburst galaxy M82

THE GRADIENT PROBLEM IN THE GALACTIC CR SPECTRUM

The problem of CR gradient 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

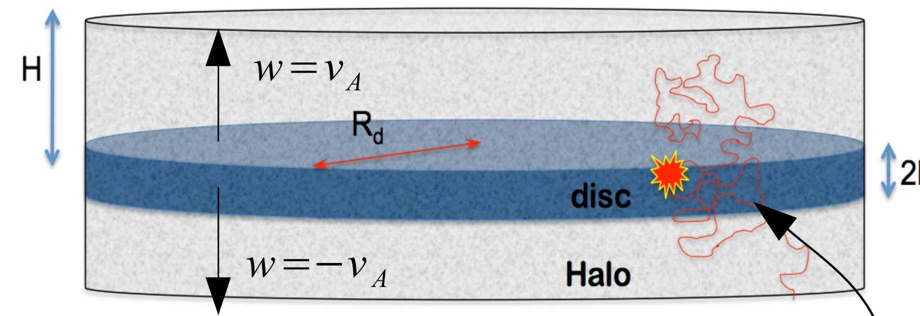
- The slope @ 20 GeV is not constant

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

A 1-D slab model with self-generated turbulence

CR transport equation with diffusion and advection due to Alfvén speed in the z direction only

$$-\frac{\partial}{\partial z}\left[D(z,p)\frac{\partial f}{\partial z}\right] + w\frac{\partial f}{\partial z} - \frac{p}{3}\frac{\partial w}{\partial z}\frac{\partial f}{\partial p} = Q_0(p)\delta(z),$$



Diffusion coefficient in the turbulence with power spectrum $W(k) = k\,\mathcal{F}(k)$

$$D(z,p) = \frac{r_L(p)v(p)}{3}\left[\frac{1}{\mathcal{F}(k)}\right]_{k=1/r_L}$$

Spectrum injected at the disk

$$Q_0(p) = \frac{\xi_{\rm inj} E_{\rm SN} \mathcal{R}_{\rm SN}(R)}{4\pi\Lambda c (m_p c)^4}\left(\frac{p}{m_p c}\right)^{-\gamma}$$

CR amplification due to streaming instability

$$\Gamma_{\rm cr} = \frac{16\pi^2}{3}\frac{v_A}{\mathcal{F}(k)B_0^2}\left[p^4 v(p)\frac{\partial f}{\partial z}\right]_{p=eB_0/kc}$$

Non-linear Landau damping

$$\Gamma_{\rm nlld} = (2c_k)^{-3/2} k v_A \mathcal{F}(k)^{1/2}$$

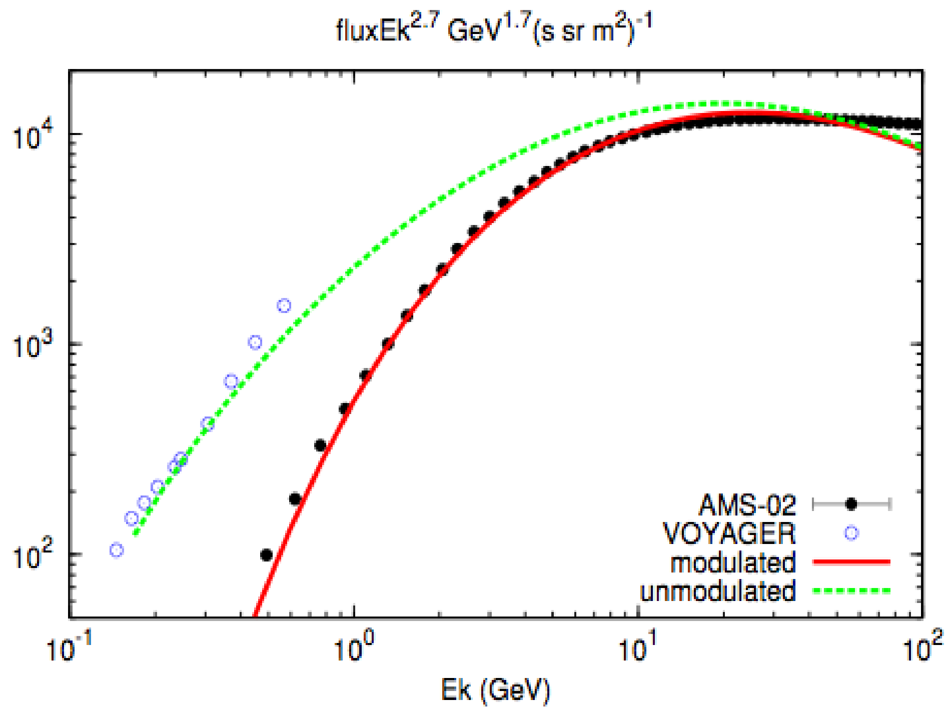
Assuming $\Gamma_{cr} = \Gamma_{nlld}$

In the diffusion dominated case ($D >> v_A H$) the solution is analytical:

$$f_0(p) = \frac{3c_k^3}{r_L v}\left(\frac{16\pi^2 p^4}{B_0^2}\right)^2 H Q_0(p)^3 \propto \frac{Q_0^3}{B_0^3}$$

A 1-D slab model with self-generated turbulence

Local CR spectrum



Fitting the local CR spectrum provides

$$\frac{\xi_{inj}}{0.1} \times \frac{R_{SN}}{1/30\ yr} = 0.3$$

$$\gamma = 4.2$$

$$B_{sun} = 1\,\mu G$$

Injection efficiency and slope are assumed the same for the whole Galaxy

A 1-D slab model with self-generated turbulence

CR spectrum in the Galaxy

We take the source distribution in the Galaxy from Green (2015)

$$f_{\mathrm{SNR}} \propto \left(\frac{R}{R_\odot}\right)^{\alpha} \exp\left(-\beta \frac{R - R_\odot}{R_\odot}\right) \qquad \alpha = 1.09 \quad \beta = 2.87$$

Large scale magentic field in the Galaxy:

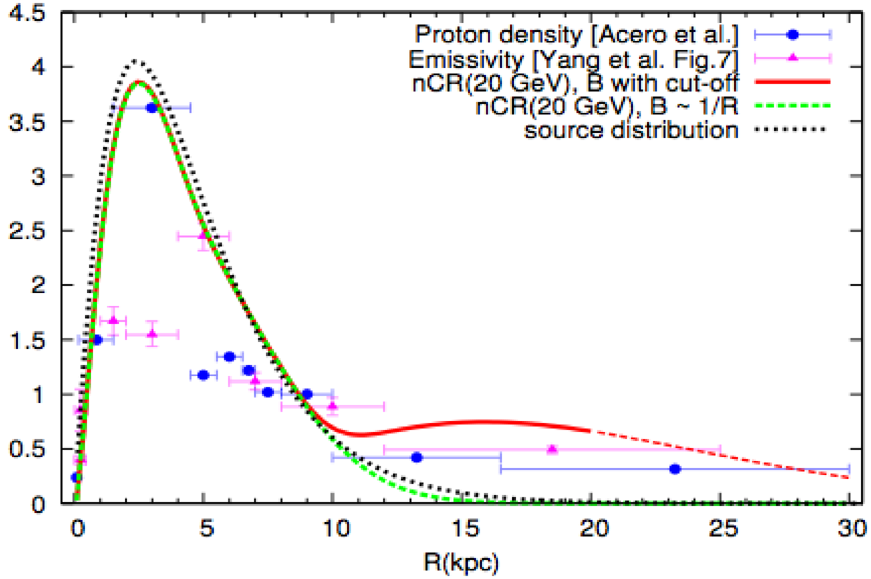
$$B_0(R < 5\,\mathrm{kpc}) = B_\odot R_\odot / 5\,\mathrm{kpc}$$
$$B_0(R > 5\,\mathrm{kpc}) = B_\odot R_\odot / R\,,$$

$$B_0(R > 10\,\mathrm{kpc}) = \frac{B_\odot R_\odot}{R} \exp\left[-\frac{R - 10\,\mathrm{kpc}}{d}\right]$$

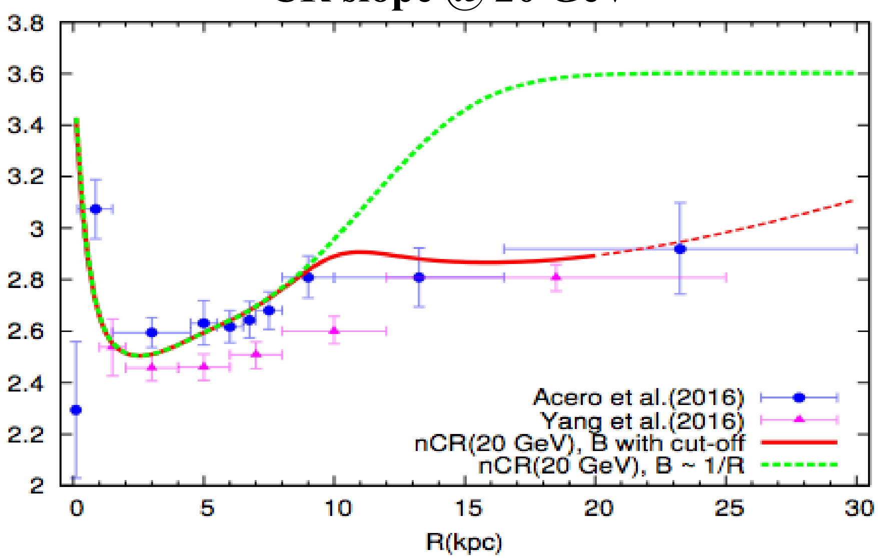
The flatness of CR spectrum occurs because:

$$f_{CR} \propto \left(\frac{Q_0(R)}{B_0(R)}\right)^{s} \qquad with \quad s = 1-3$$

CR spectrum density @ 20 GeV

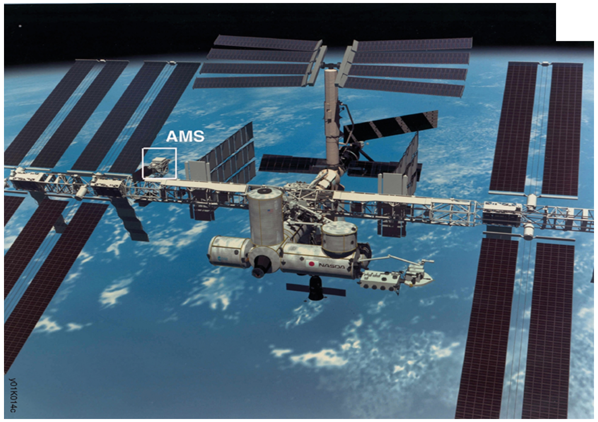


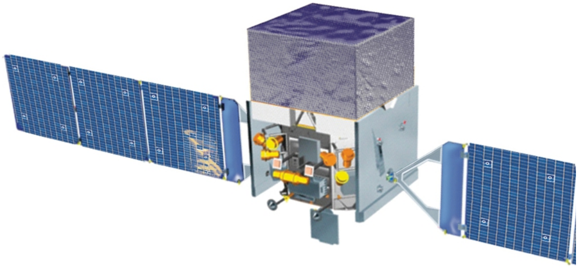
CR slope @ 20 GeV

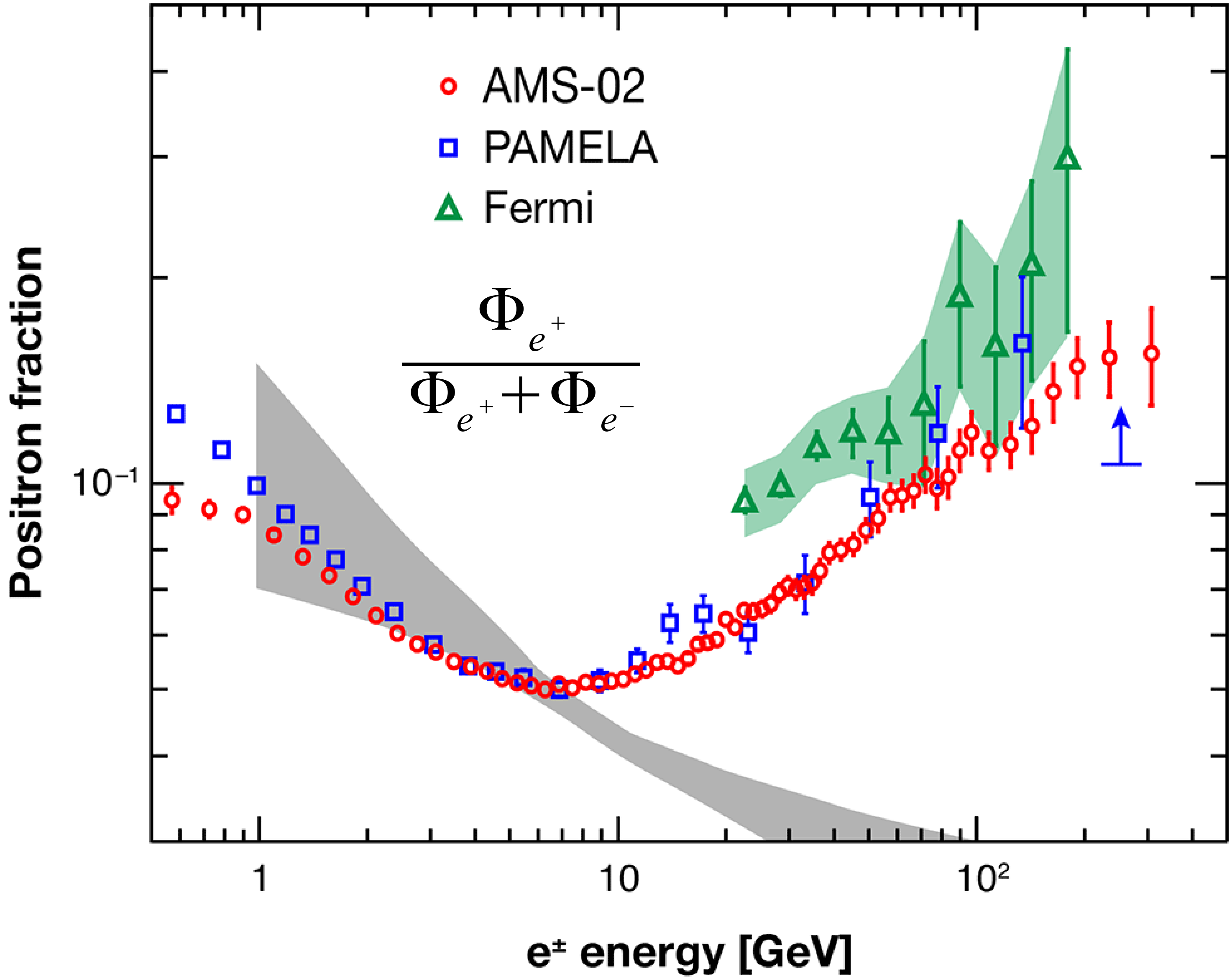


SECONDARY POSITRONS

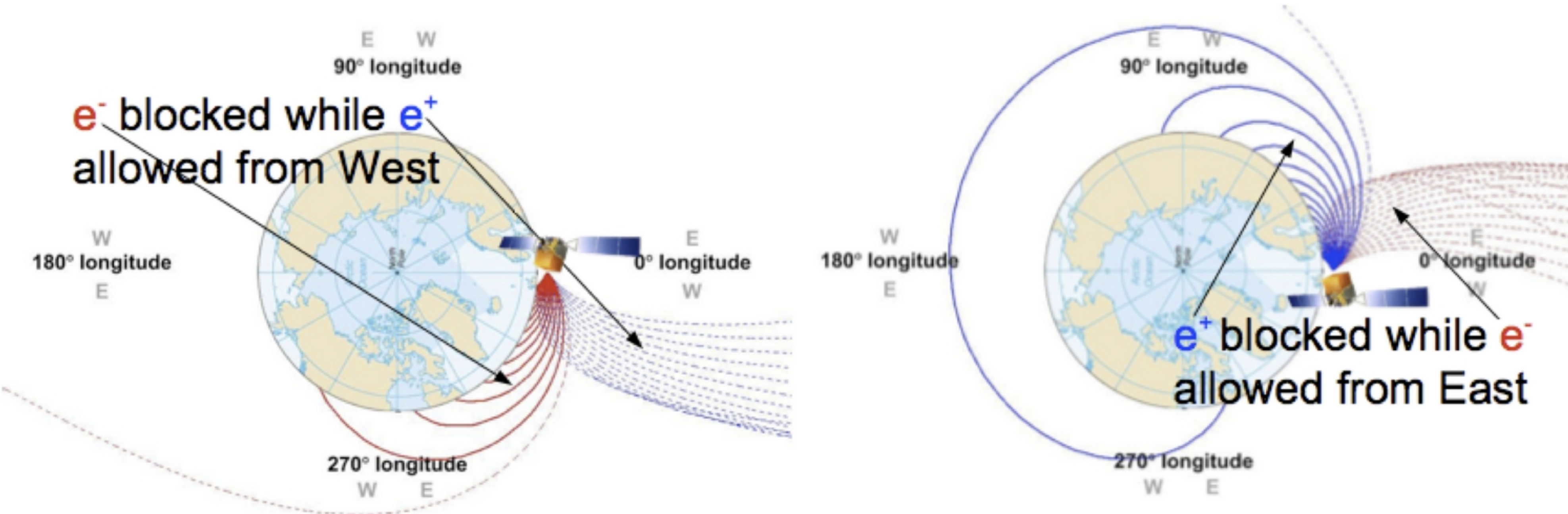
POSITRON FRACTION







POSITRON FRACTION WITH FERMI-LAT



SOURCES OF ASTROPHYSICAL POSITRONS

Radioactive Decays (e.g. in SNRs)

Secondary products of hadronic interactions

Electron-positron pair creation ($\gamma + \gamma \rightarrow e^+ + e^-$)

Pulsar magnetospheres (cascade multiplication in Intense magnetic fields)

Dark Matter Annihilation?

SPECTRUM OF PRIMARY CRs

Spectrum of primary protons in the leaky-box model

$$N_p(E) = N_{SNR}(E)\, R_{SN}\, \frac{1}{\pi R_d^2\, 2H}\, \tau_{esc} \propto E^{-\gamma-\delta}$$

Spectrum injected by sources

SN rate

Halo's height

Escaping time

Spectrum of primary electrons. If energy losses are dominant upon diffusion (typicallly for $E > 10$ GeV) than the escape time is replaced by the time for energy losses:

Loss time

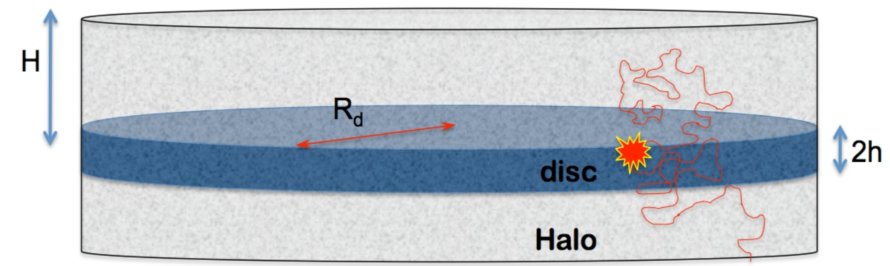
$$N_{e^+}(E) = N_{SNR}(E)\, R_{SN}\, \frac{\tau_{loss}}{\pi R_d^2 \sqrt{D(E)\,\tau_{loss}}} \propto E^{-\gamma-1/2-\delta/2}$$

Spectrum injected by sources

SN rate

Loss length-scale

SPECTRUM OF SECONDARY POSITRONS



Injection rate of positrons from protons interactions:

$$Q_{e^+}(E')\,dE' = N_p(E)\,dE\, n_{gas}\,\sigma_{pp}\,c \propto E^{-\gamma-\delta}$$

Equilibrium spectrum for secondary positrons (end electrons) at Earth:

$$N_{e^+}(E) \approx Q_{e^+}(E)\,\frac{\tau_{loss}}{\pi R_d^2 \sqrt{D(E)\,\tau_{loss}}} \propto E^{-\gamma-1/2-3\delta/2}$$

POSITRON FRACTION

$$\frac{\Phi_{e^+}}{\Phi_{e^+}+\Phi_{e^-}} \approx \frac{\Phi_{e^+}}{\Phi_{e^-}} \propto E^{-\delta}$$

Monotonically decreasing function of energy

Dark Matter as source of positrons

Dark Matter annihilation may lead to production of electron-positron pairs due to hadronization of $p-\bar{p}$ pairs with production and decay of charged pions.

In order to explain the observed positron fraction, the Dark Matter candidate must satisfy some rather artificial conditions:

1) the boosting factor associates with the DM annihilation must largely exceed the one obtained in numerical simulations of large scale structure formation
2) The cross section needs to be much larger than for normal WIMPS
3) In order to avoid overproduction of anti-protons one has to require that DM particles is leptophilic

All these conditions appear to be too much *ad hoc* to address one single issue

WHICH ARE THE POSSIBLE ASTROPHYSICAL EXPLANATIONS?
STAY TUNED...