Molecular clouds as cosmic ray barometers

Sabrina Casanova

Ruhr Universitaet Bochum & MPIK Heidelberg, Germany

Collaborators: F. Aharonian, S. Gabici, Y. Fukui ...

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Outline

1. Key questions in high energy astrophysics

2. Gamma ray emission from molecular clouds close to cosmic ray sources: probing the origin of cosmic rays

3. Gamma ray emission from clouds far from CR sources: probing the level of the CR background

4. Gamma ray emission from molecular clouds to probe the properties of the CR propagation in the ISM

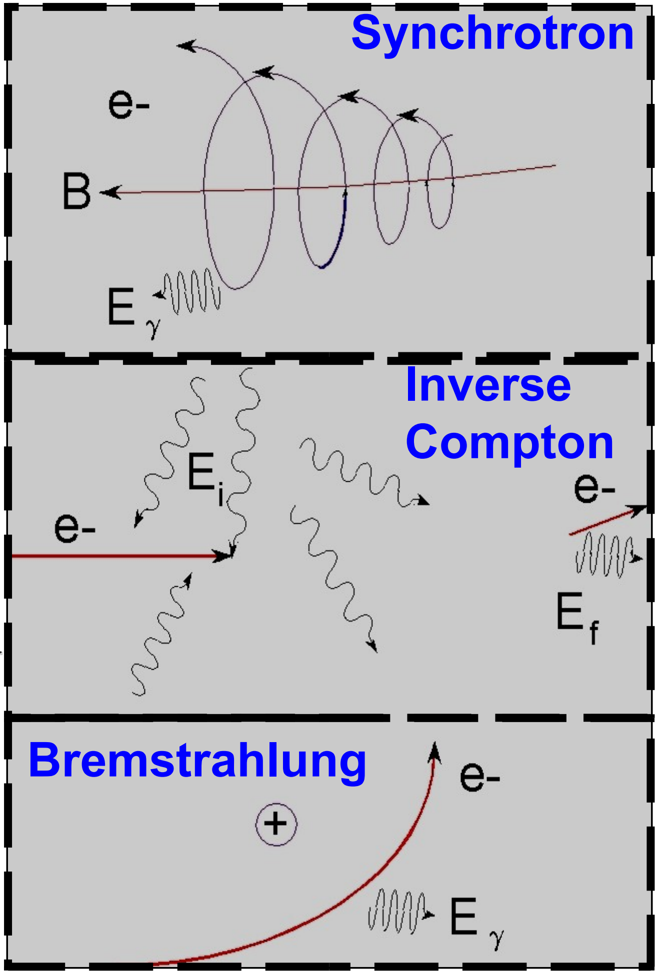
5. Summary

Key Questions in High Energy Astrophysics

- Are SNRs the cosmic ray accelerators ?
- How high in energy can galactic sources produce particles?
- What is the production rate of protons and electrons ?
- How are cosmic ray sources distributed in the Galaxy ? Is there a nearby source of cosmic rays ?
- How do cosmic rays propagate in the Galaxy ?

Gamma-ray Emission :
a probe of CR origin and propagation

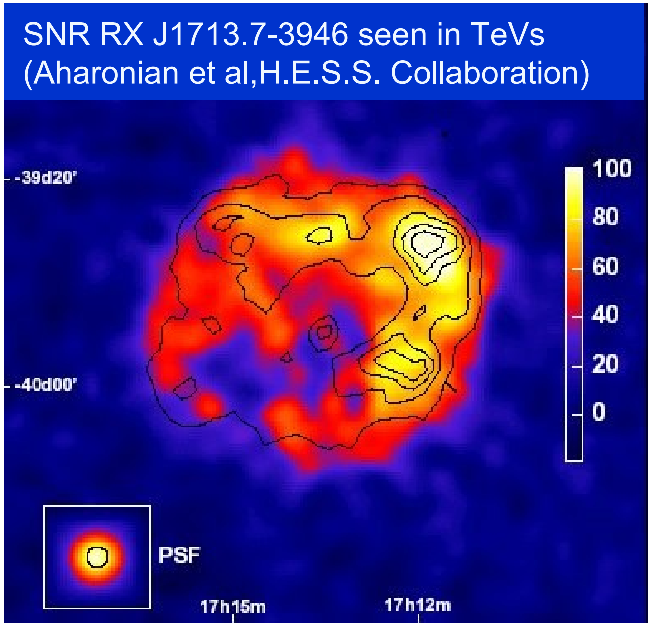
- CRs + gas -> π^o -> 2 γ
  - CRs + gas -> $\pi^+ + \pi^-$ -> ν
- CR signatures for γ-rays
  - Morphology
  - Spectrum
- *But electrons produce gamma-rays, too and very efficiently through IC and bremsstrahlung.*

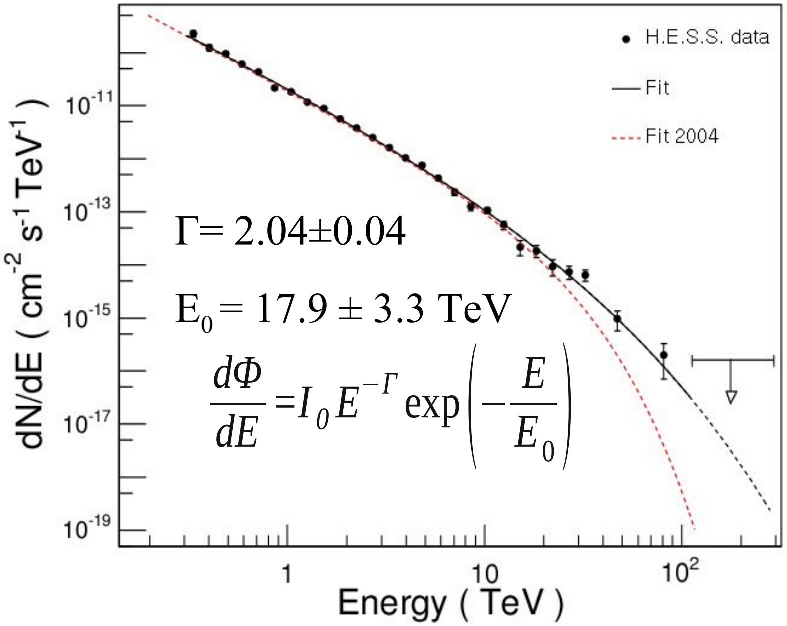


Probing CR origin and escape with gamma-rays from MCs close to sources

Are SNRs the Galactic CR sources ?

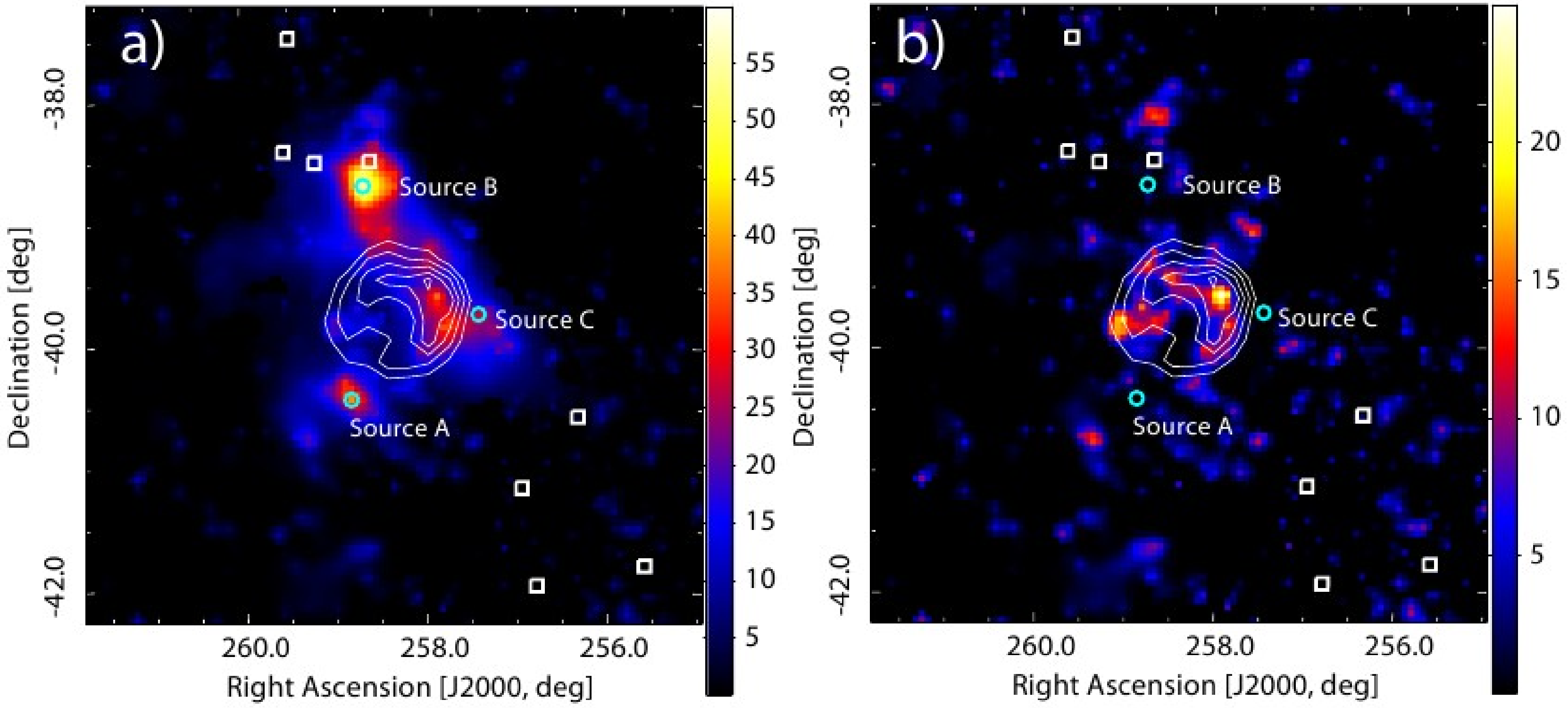
- Best candidates: young SNRs with non-thermal synchrotron X-rays such as RX J1713.7-3946
- TeV γ-rays and shell type morphology : acceleration of e^- and protons (Drury et al, 1994)
- Gammas above 30 TeV -> acceleration of particles up to hundreds TeV
- Correlation TeV/X-ray.
- **IC and hadronic scenarios can both explain the γ-ray emission. We do not have a conclusive proof of CR acceleration.**





FERMI OBSERVATIONS OF RXJ1713-3946

Abdo et al, 2011



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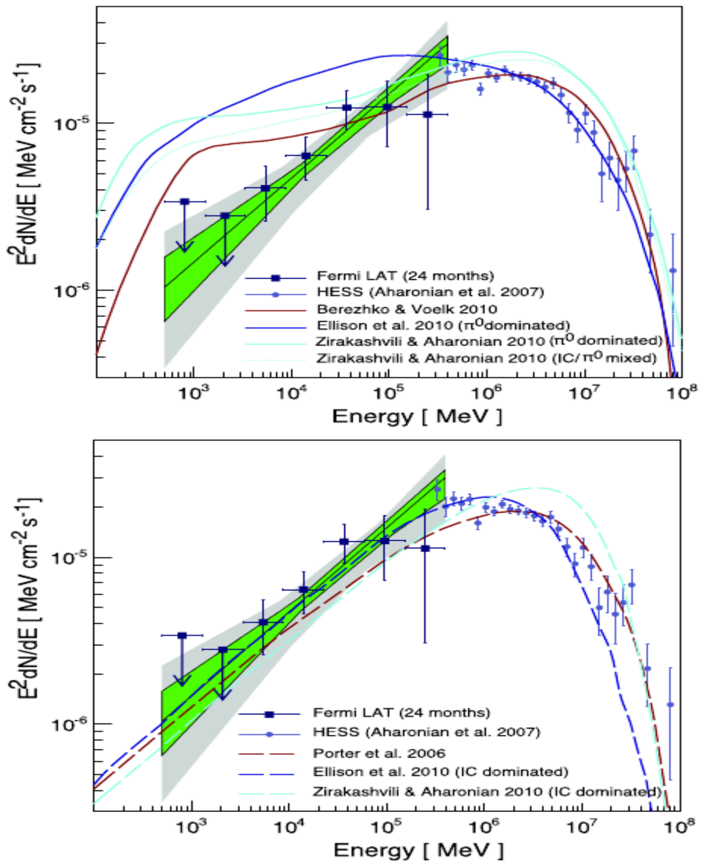
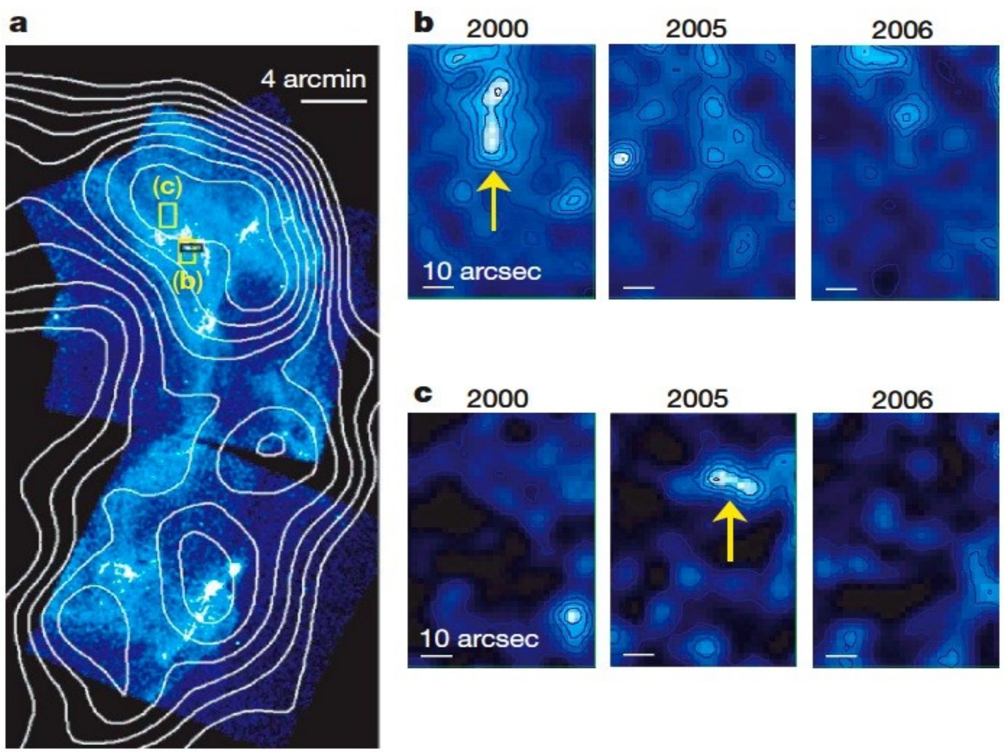


Variability of X-rays on year timescales – witnessing particle acceleration in real time



Uchiyama, Aharonian, Tanaka, Maeda, Takahashi, Nature 2007

•flux increase - particle acceleration

• flux decrease - synchrotron cooling

• it requires B-field of order 1 mG in hot spots and, most likely, 100μG outside. This supports the idea of amplification of B-field by in strong nonlinear shocks through non-resonant streaming instability of charged energetic particles (Bell, 2000 Zirakashvili, Ptuskin Voelk 2007)

Are SNRs the Galactic PeVatron sources?

DSA in SNRs accelerates electrons -> DSA is likely to accelerate protons. However :

- ✓ Quantify the electron vs proton content in SNRs : is VHE emission from SNRs leptonic or hadronic in nature ?
- ✓ What is the max proton energy achieved ? Are CRs accelerated up to PeV energies ?
- ✓ How do CRs escape SNRs and diffuse in the ISM ? There is still no evidence for the existence of escaping CRs.

How do cosmic rays escape their sources ?

$$l_d = \frac{D(p_{max})}{u_{sh}} \lesssim R_{sh}.$$

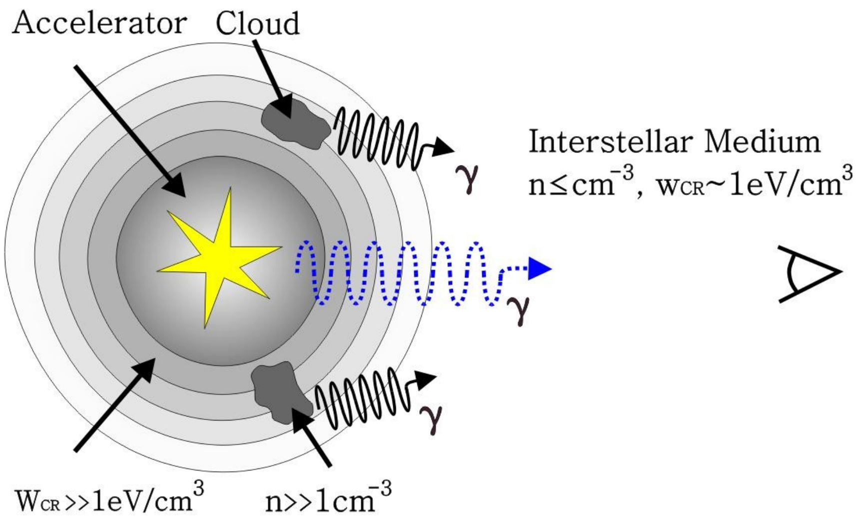
$$D \propto p/B_{sh}$$

$$p_{max}(t) \propto B_{sh} t^{-1/5}$$

Sedov phase : B_{sh} α t $R_{sh} \sim t^{2/5}$

PeV particles are accelerated at the beginning of Sedov phase (~200yrs), when the shock speed is high. PeV particles quickly escape as the shock slows down. Lower energy particles are released later.

Gamma Rays from Molecular Clouds close to CR sources

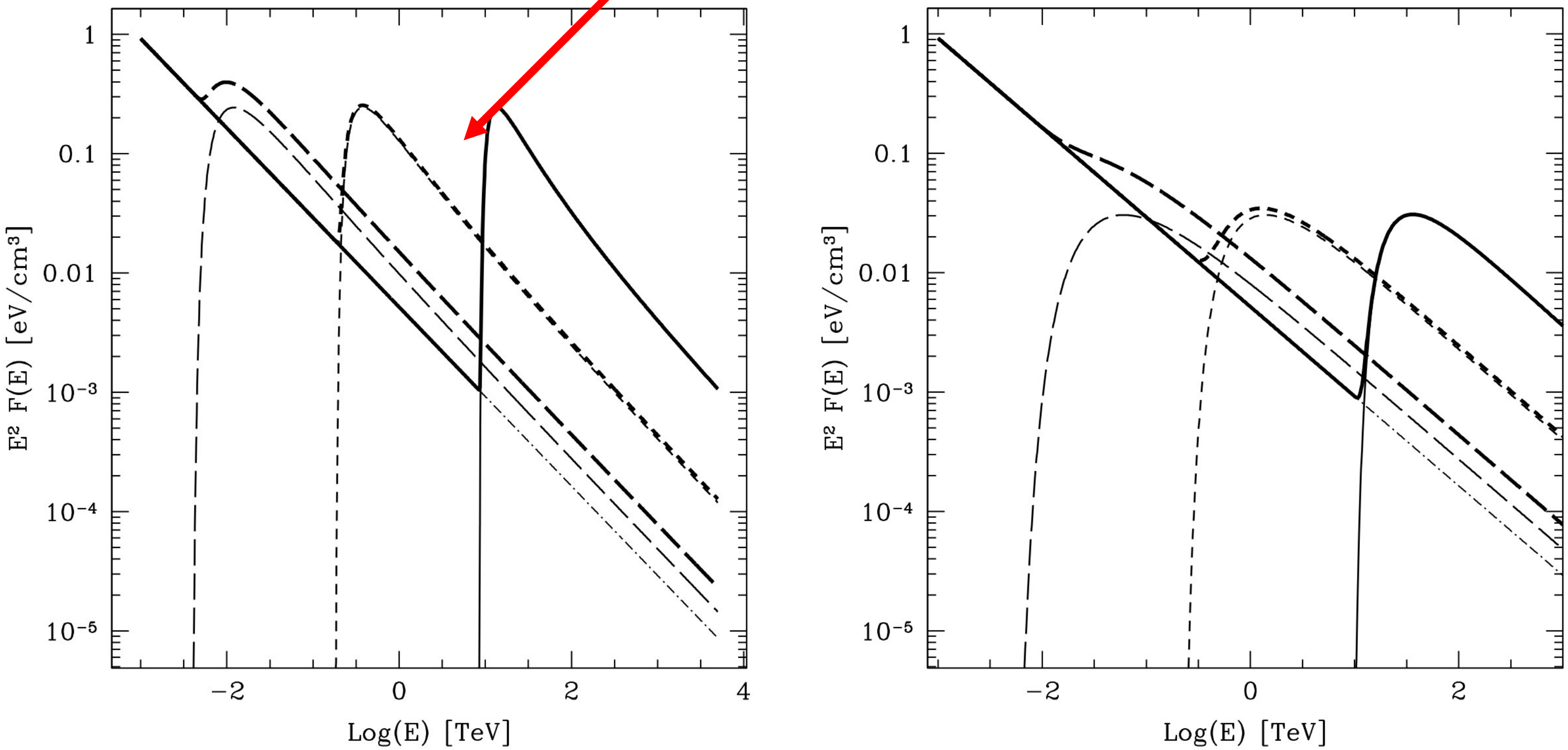


- **Highest energy protons quickly escape the accelerator and therefore do not significantly contribute to gamma-ray production inside the proton accelerator-PeVatron.**
- **MCs are ideal targets to amplify the emission produced by CRs accelerated by nearby sources (**Aharonian & Atoyan, 1996, Aharonian, 2001**)**
- **Gamma rays from nearby MCs are therefore crucial to probe the highest energy protons .**
- **Association CR sources and molecular clouds (**Montmerle 1979, Cassé & Paul 1980**).**

Cosmic ray flux in MCs close to a SNR: dependence on SNR age and location

Runaway CRs

Gabici et al, 2009



1 = 2000 yr
2 = 8000 yr
3 = 32000 yr

Power in CRs: E_{CR} = 3 X 10^{50} erg,

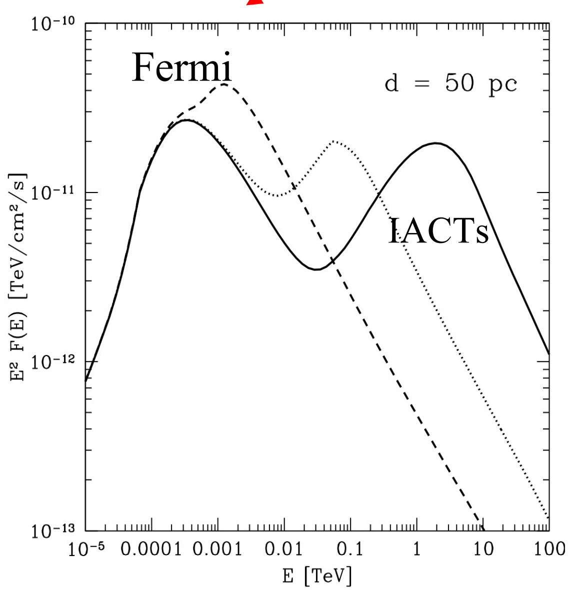
Diffusion coefficient: $D = D_0 E^{0.5}$

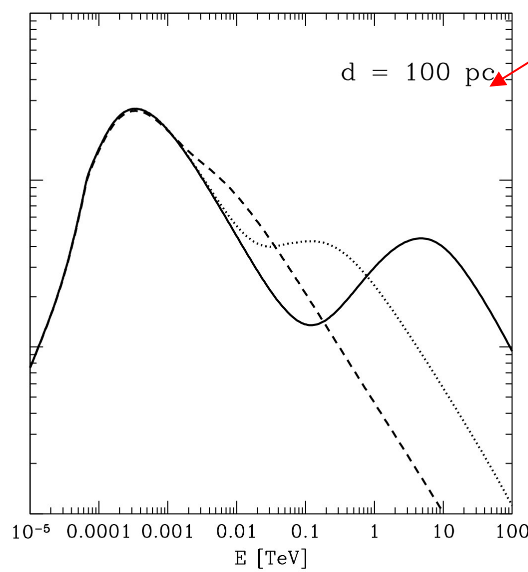
GeV versus TeV emission spectra in MC

1 = 2000 yr
2 = 8000 yr
3 = 32000 yr

GeV ⟷ CR sea
steady

TeV ⟷ SNR CRs
t-dependent





Concave shape
Steep spectrum at GeV energies and hard at TeV

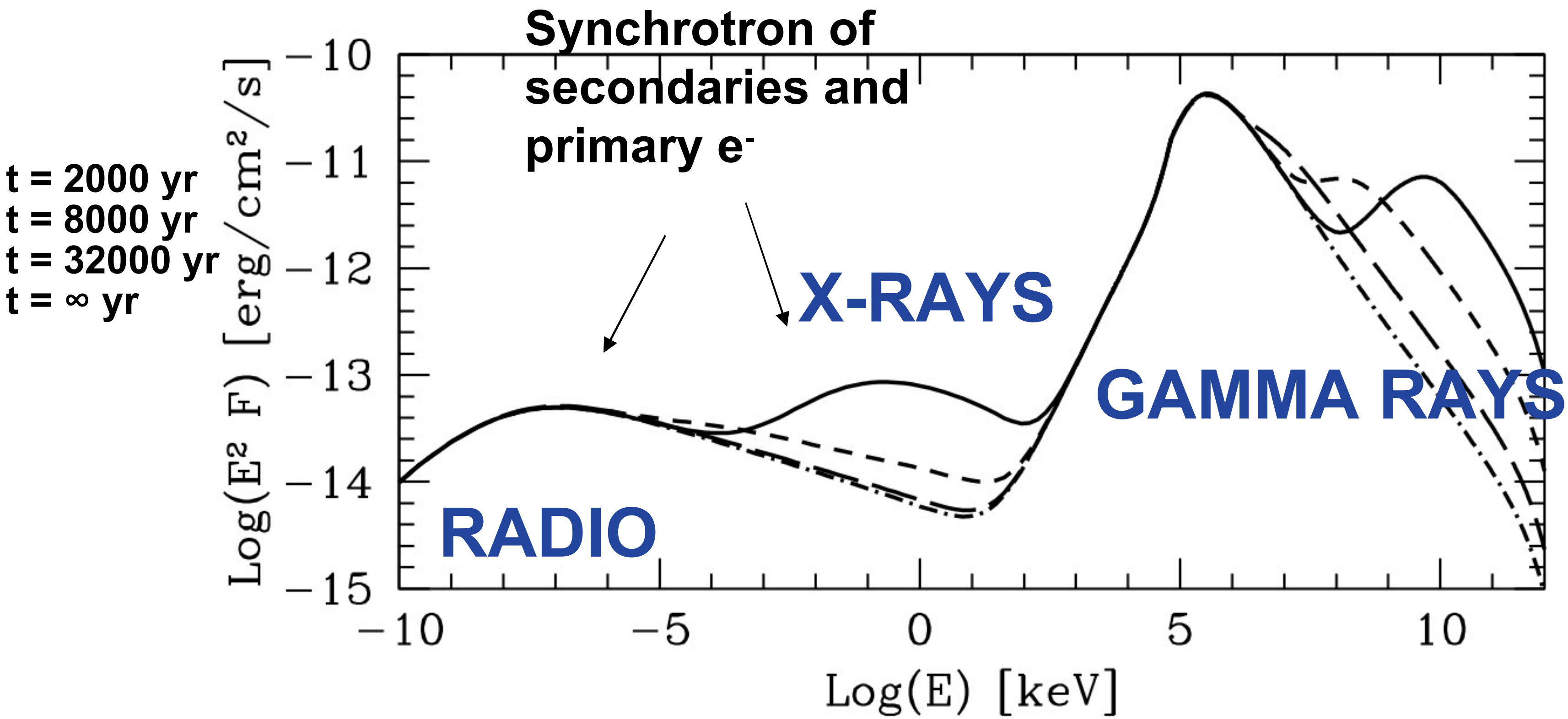
M=10^5 solar masses; R=20pc ;n =120 cm^{-3} ; B=20μG; D=1kpc ;D =10^{28} cm^2 /s

Gabici et al 2009

Multiwavelength emission close to MCs

M=10^5 solar mass; R=20pc ;n=120cm^{-3} ; B=20G ; d (SNR/MC)=100pc ; D=1kpc

Gabici et al, 2009



The gamma-ray emission is an order of magnitude higher than the emission at other wavelengths. So far unidentified TeV sources (dark sources) could be MCs illuminated by CRs from a nearby SNR.

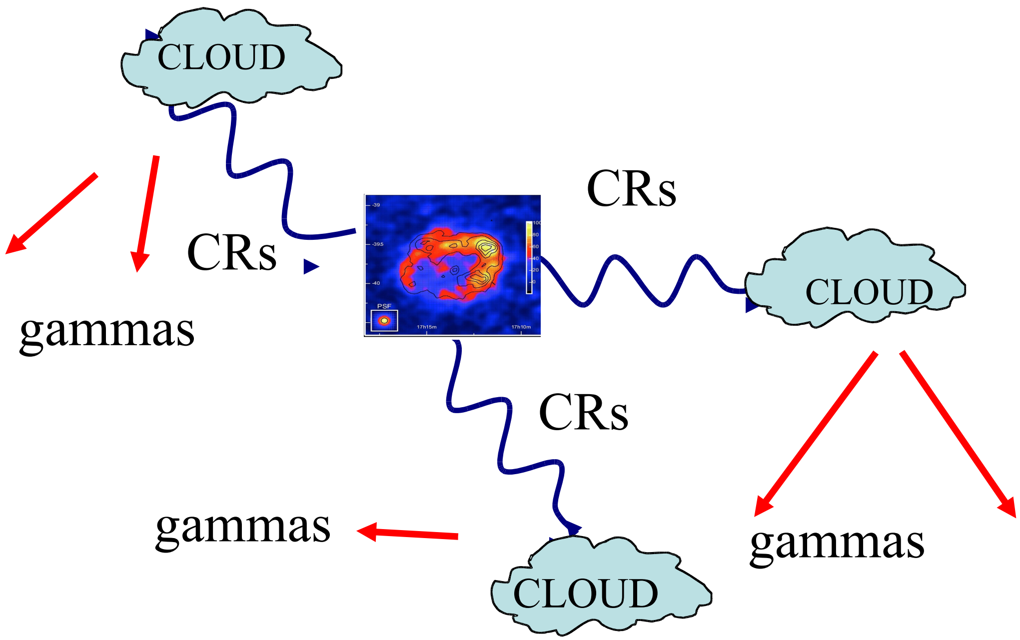
MWL implications

- **GeV-TeV contrast**
- **...and PeV-hard X connection (pp interactions produce secondary electrons)**

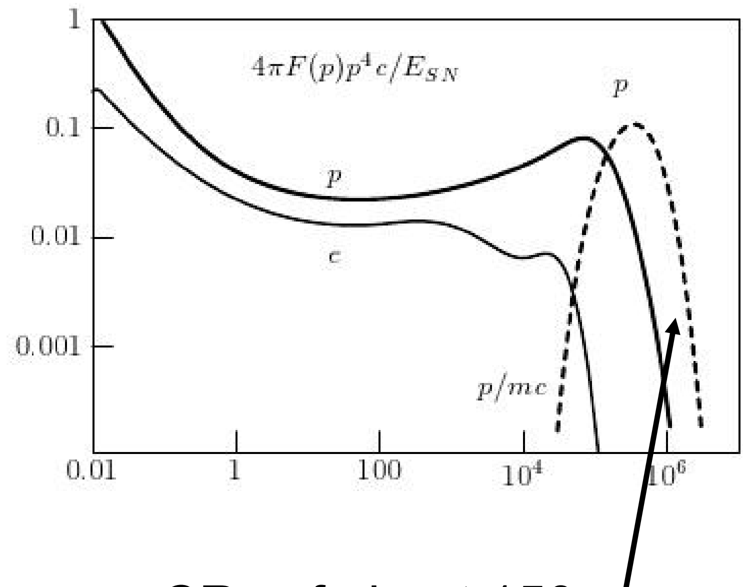
Ee = 100 TeV

$$E_{syn} \approx 20\left(\frac{B}{30\mu G}\right)\left(\frac{Ee}{100TeV}\right)^2 keV$$

Modeling particle escape from young SNRs: RX J1713.7-3946



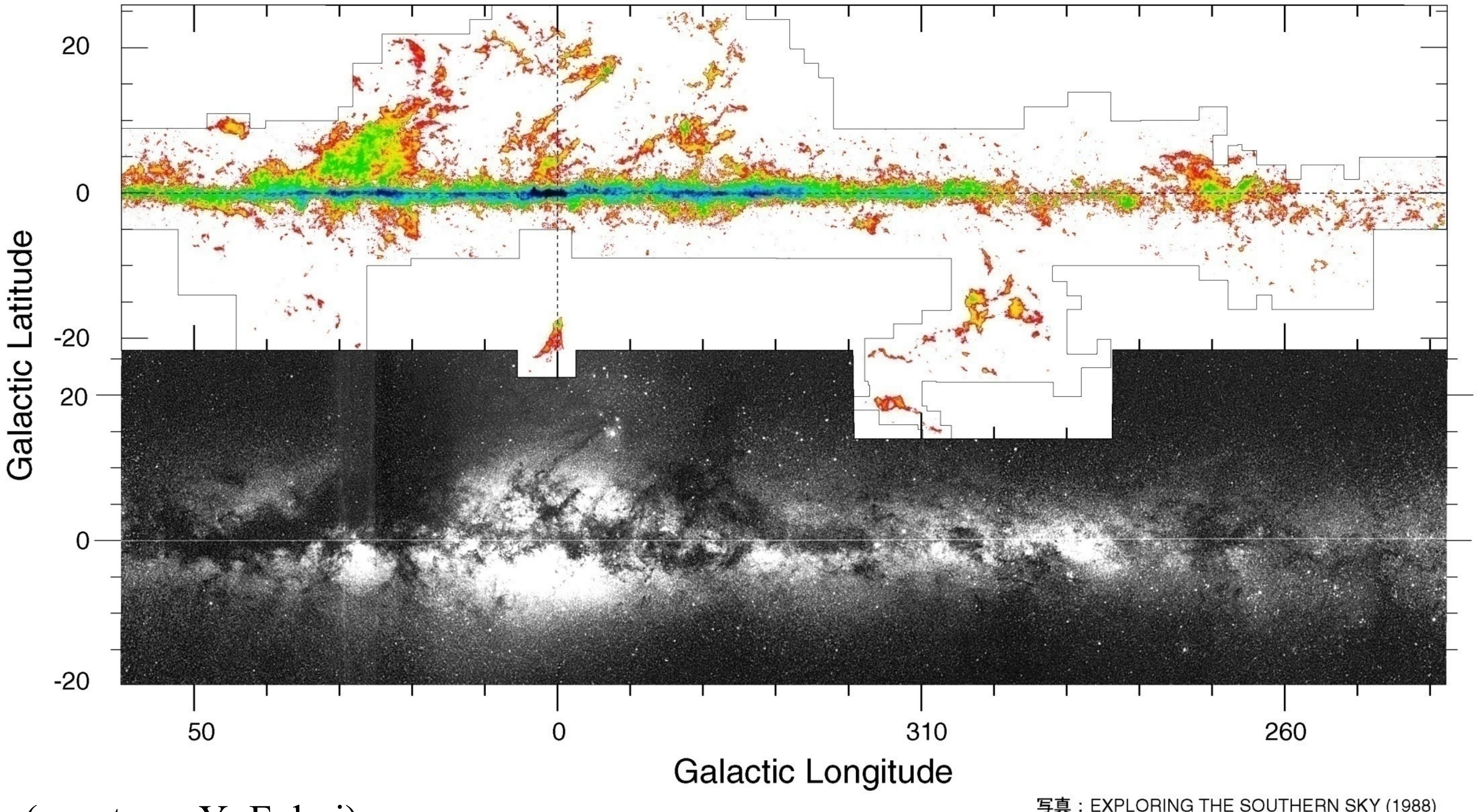
Zirakashvili & Aharonian, 2010



CRs of about 150 TeV are escaping from the shell now

- Energy in CRs: $E_{CR} = 3 \times 10^{50}$ erg
- Source age and location t= 1600 yr, d = 1kpc

The Milky Way in Molecular Clouds (Nanten survey)

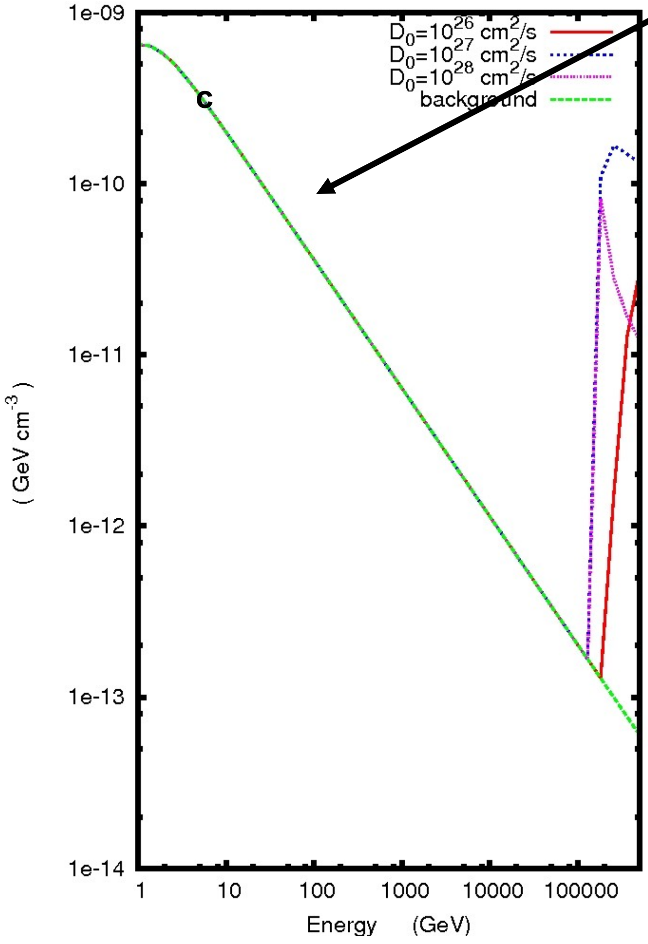


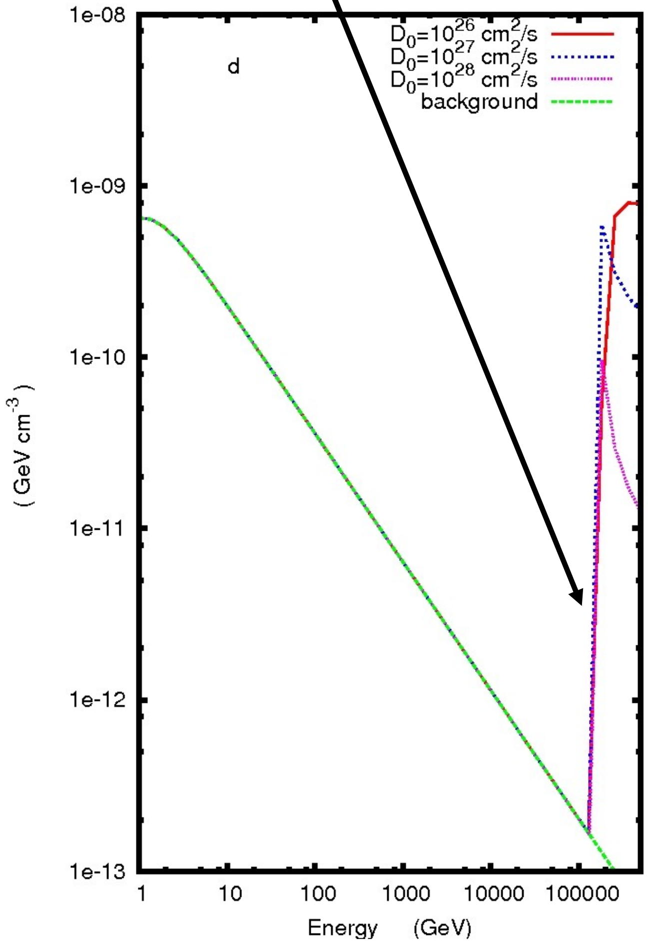
(courtesy: Y. Fukui)

Variety of CR spectra close to RXJ1713

TeV Runaway CRs

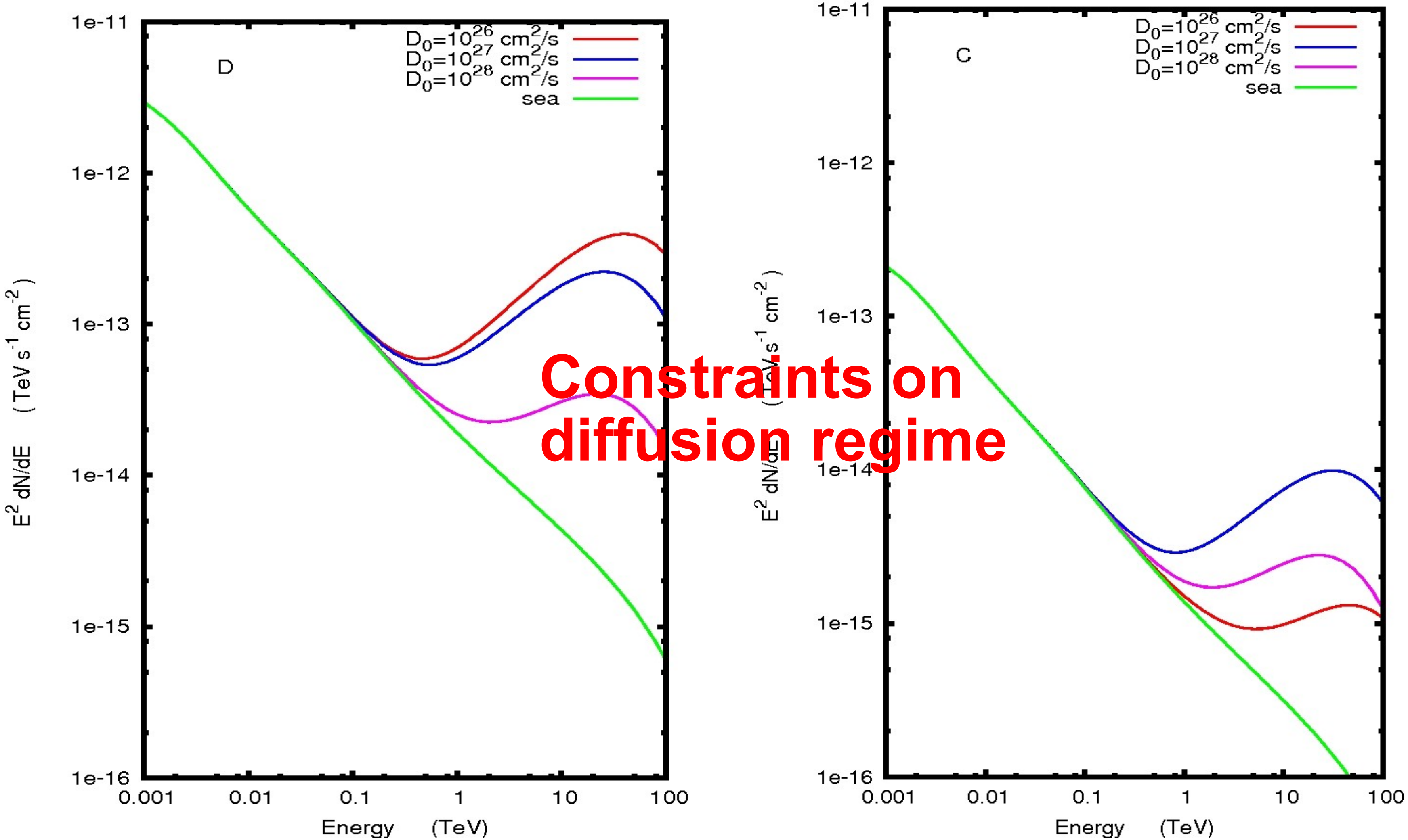
CR background





Casanova et al, 2010

Spectral features of γ-ray spectra close to RXJ1713

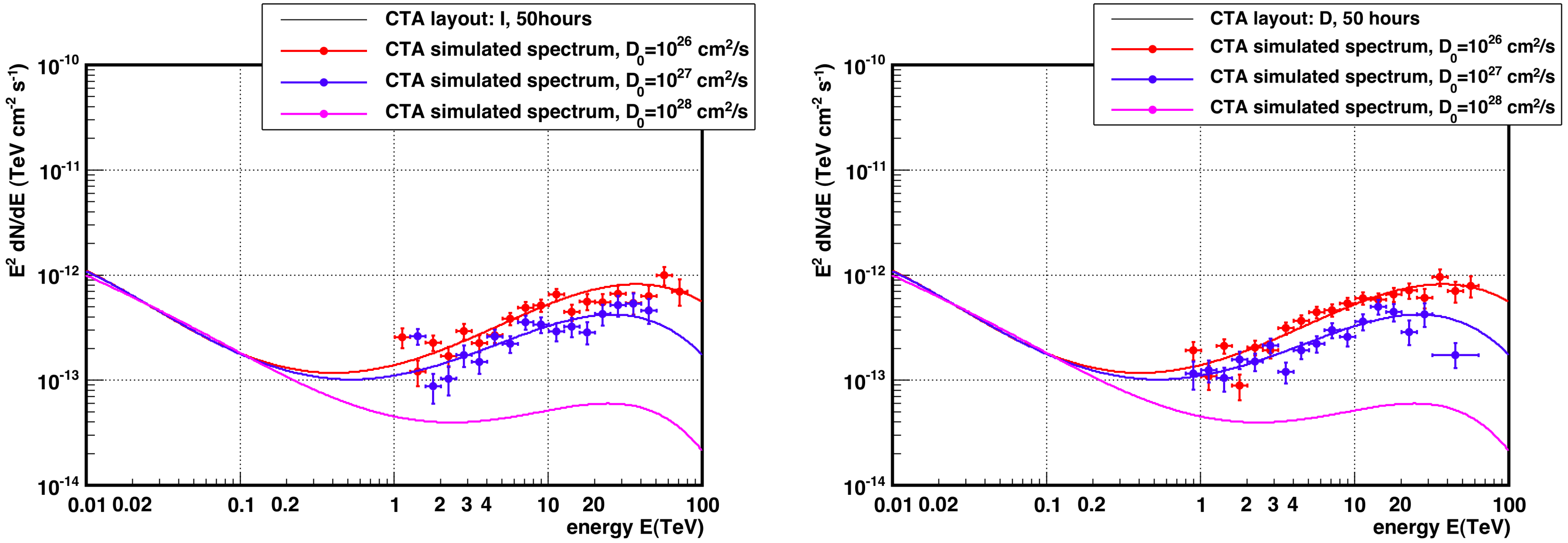


Constraints on diffusion regime

Diffusion coefficient: $D = D_0 E^{0.5}$

Casanova et al, 2010

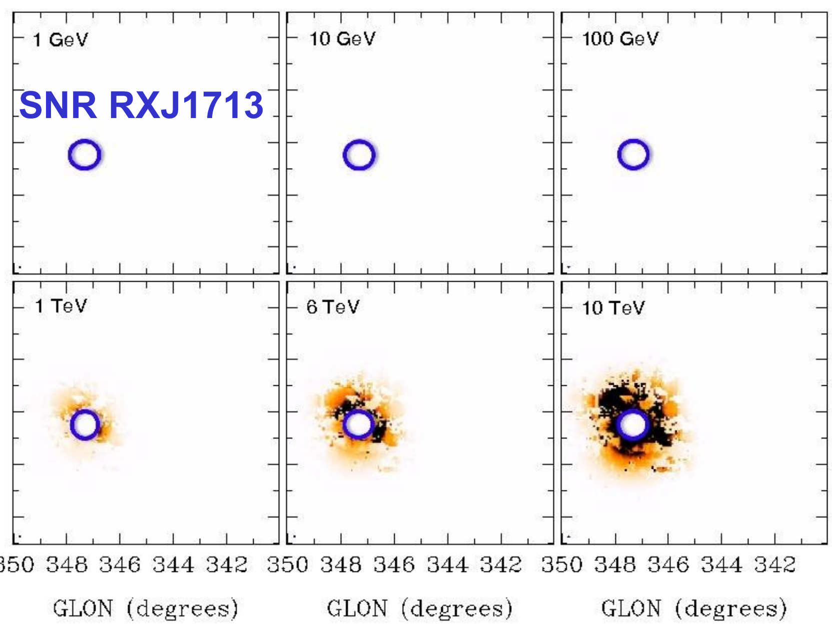
Predictions for the Cherenkov Telescope Array



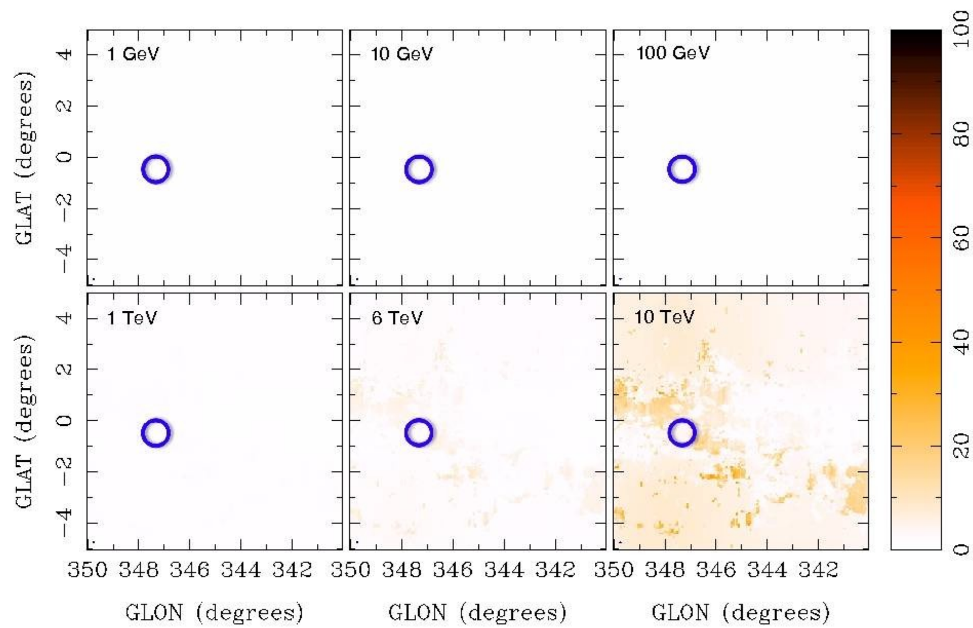
CTA Group on
Diffuse/Extended Sources

Morphology to constrain the CR diffusion regime

$D_o = 10^{26}$ (slow diffusion)



$D_o = 10^{28}$ (fast diffusion)



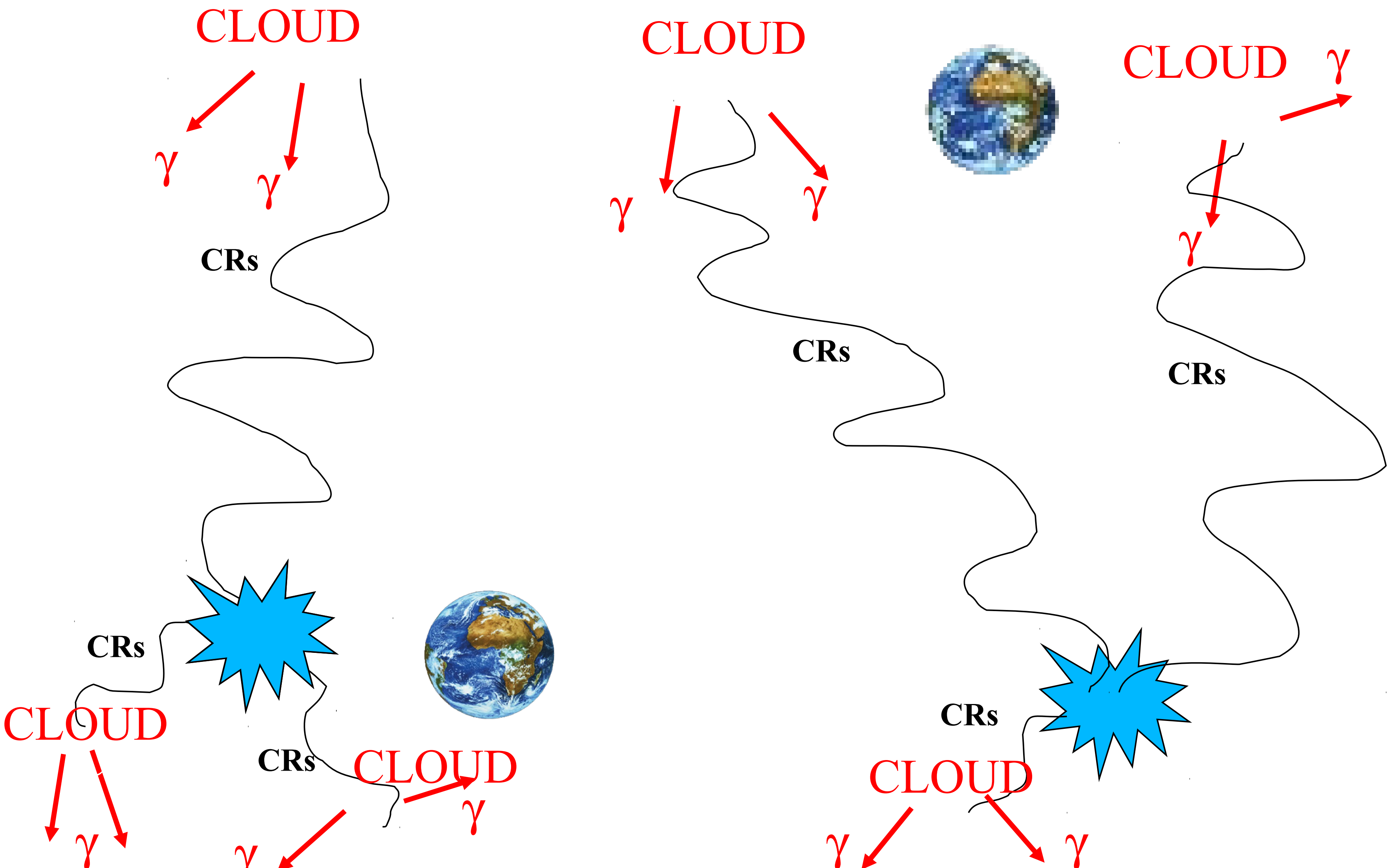
$(\gamma_{\text{Runaway CRs}} + \gamma_{\text{sea CRs}}) / \gamma_{\text{sea CRs}}$

Diffusion coefficient: $D = D_0 E^{0.5}$

Casanova et al, 2010

Molecular Clouds to probe the level of the CR background

Gamma rays from MCs to probe the CR sea



The level of the CR background

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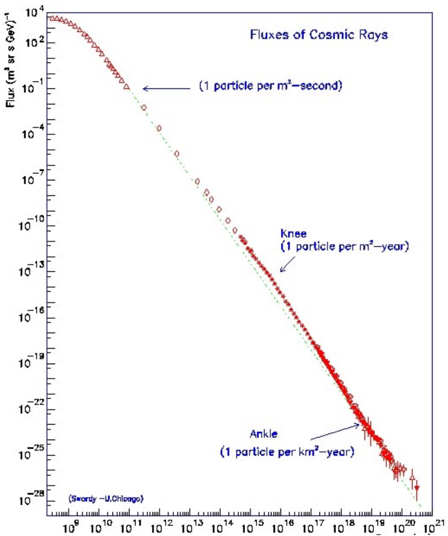
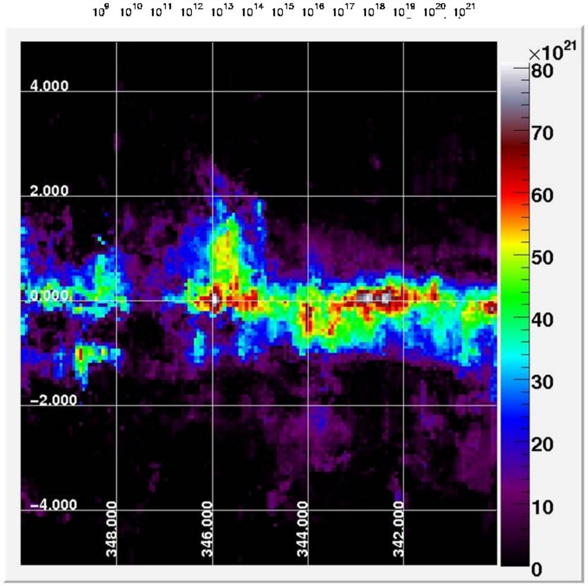
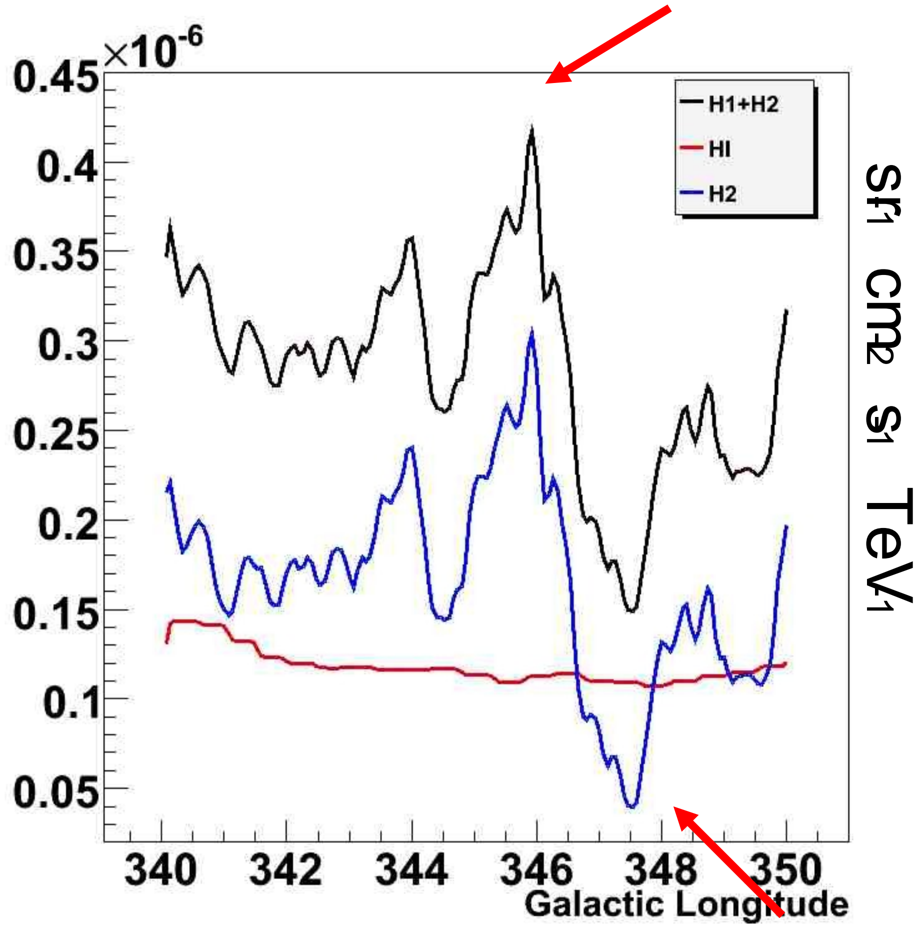
CR flux





Mol Gas Distribution

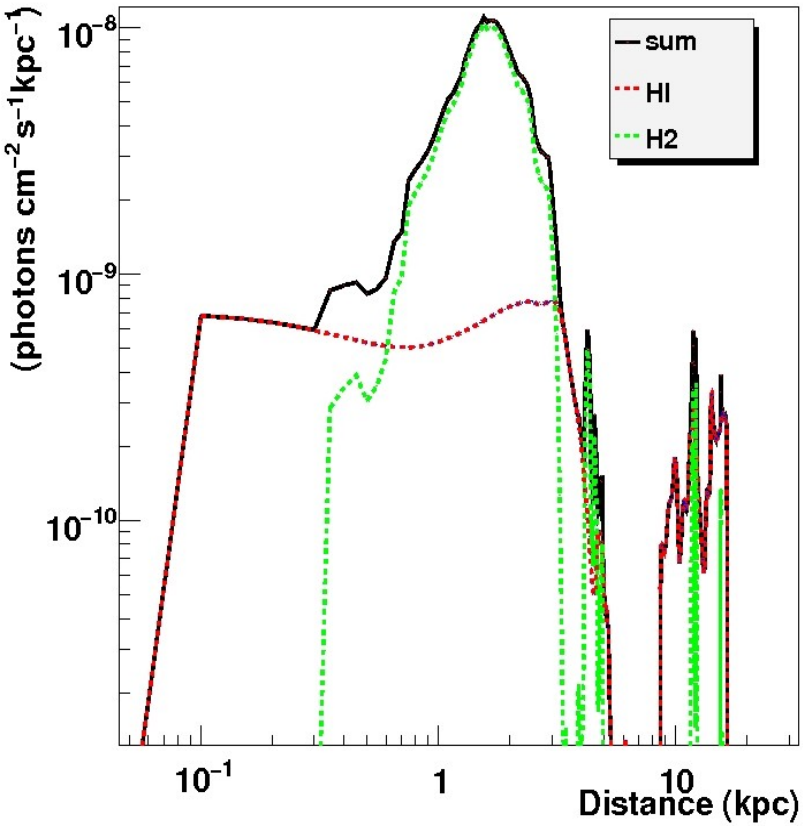
only one or at most few massive MCs



many low mass MCs

Predicted Emission at 100 GeV

Localisation of the peak emission along the line of sight



$$\Phi_{CR} = \Phi_\gamma \; / M_{H2} \, d_{H2}^{\,2}$$

Mass and integral flux as a function of the distance for the region 345.3<l<346 and 1<b<1.7

	Mass $(M_\odot)$ (2)	Mass (H_2) $(M_\odot)$ (3)	Mass (HI) $(M_\odot)$ (4)	$F(E > 1GeV)$ $(cm^{-2}\,s^{-1})$ (5)	$F(E > 100GeV)$ $(cm^{-2}\,s^{-1})$ (6)
$0.5 < d < 30$	20.2	4.2	16.0	1.7×10^{-8}	6.8×10^{-12}
$d < 0.5$	0.0015	0.0005	0.001	2.9×10^{-10}	1.2×10^{-13}
$0.5 < d < 3$	3.2	2.8	0.4	1.4×10^{-8}	5.7×10^{-12}
[illegible]	[illegible]	1.4	15.6	2.3×10^{-9}	9.1×10^{-13}

85% of the emission for the region 345.3<l<346 and 1<b<1.7 is produced between 0.5 and 3 kpc (ok for Fermi detector and CTA at higher energies).

Casanova et al, 2009

Summary

- MCs close to CR sources are ideal targets to amplify the emission produced by runaway CRs penetrating the cloud and to produce very specific observable features in the spectrum and in the morphology of gamma-ray emission.
- MCs can be used as CR barometers to probe the level of the CR background in the Galaxy.
- Gamma rays from Mcs might be used to constrain the diffusion regime.
- Gamma ray detectors start detecting SN-MC associations but still no evidence of runaway CRs from young SNRs such as RX J1713.7-3946 . Next generation of detectors (HAWC & CTA) needed in combination with the knowledge of the gas content in the Milky Way (Herschel, Planck...).