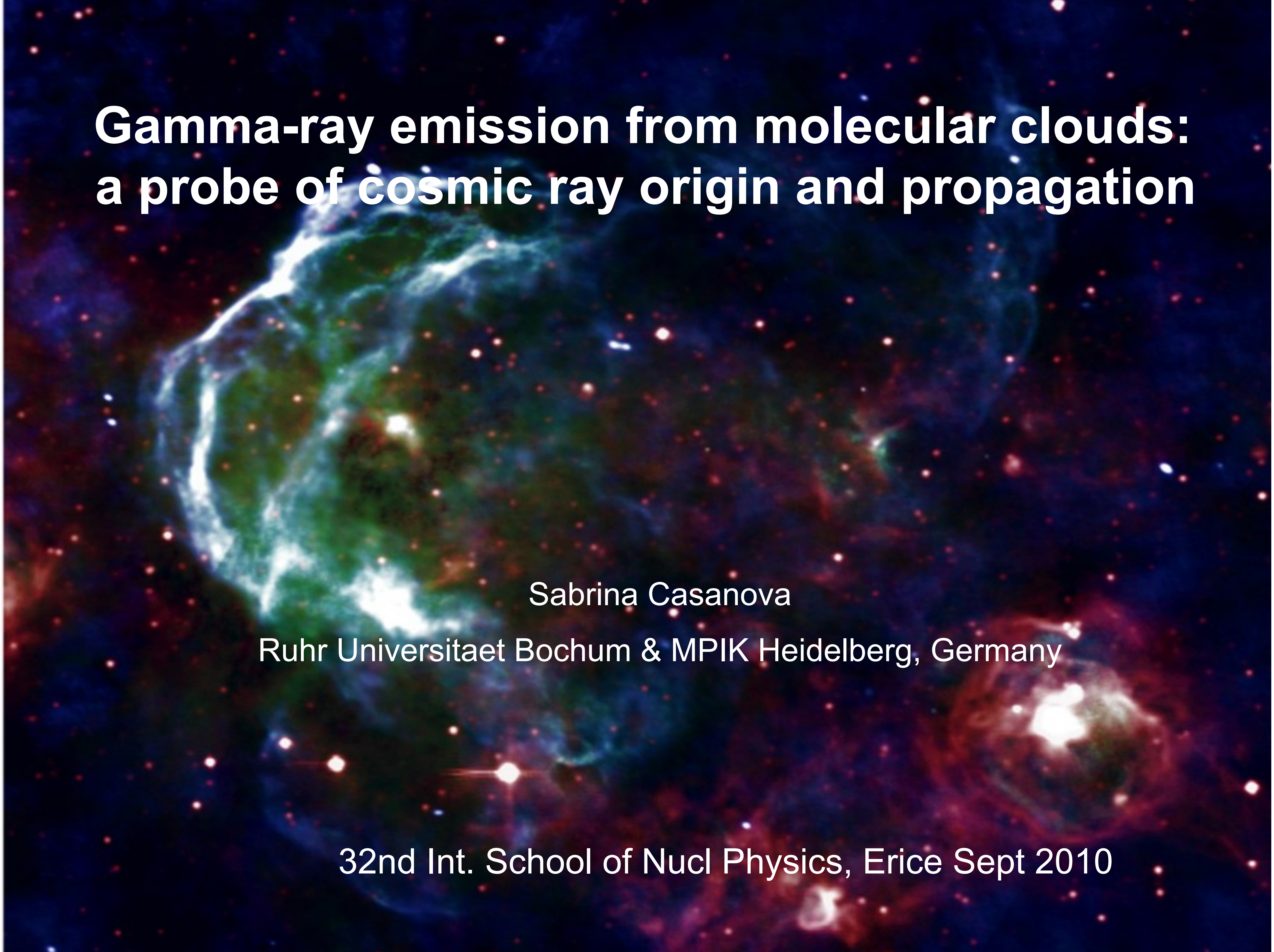

Gamma-ray emission from molecular clouds: a probe of cosmic ray origin and propagation

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Outline

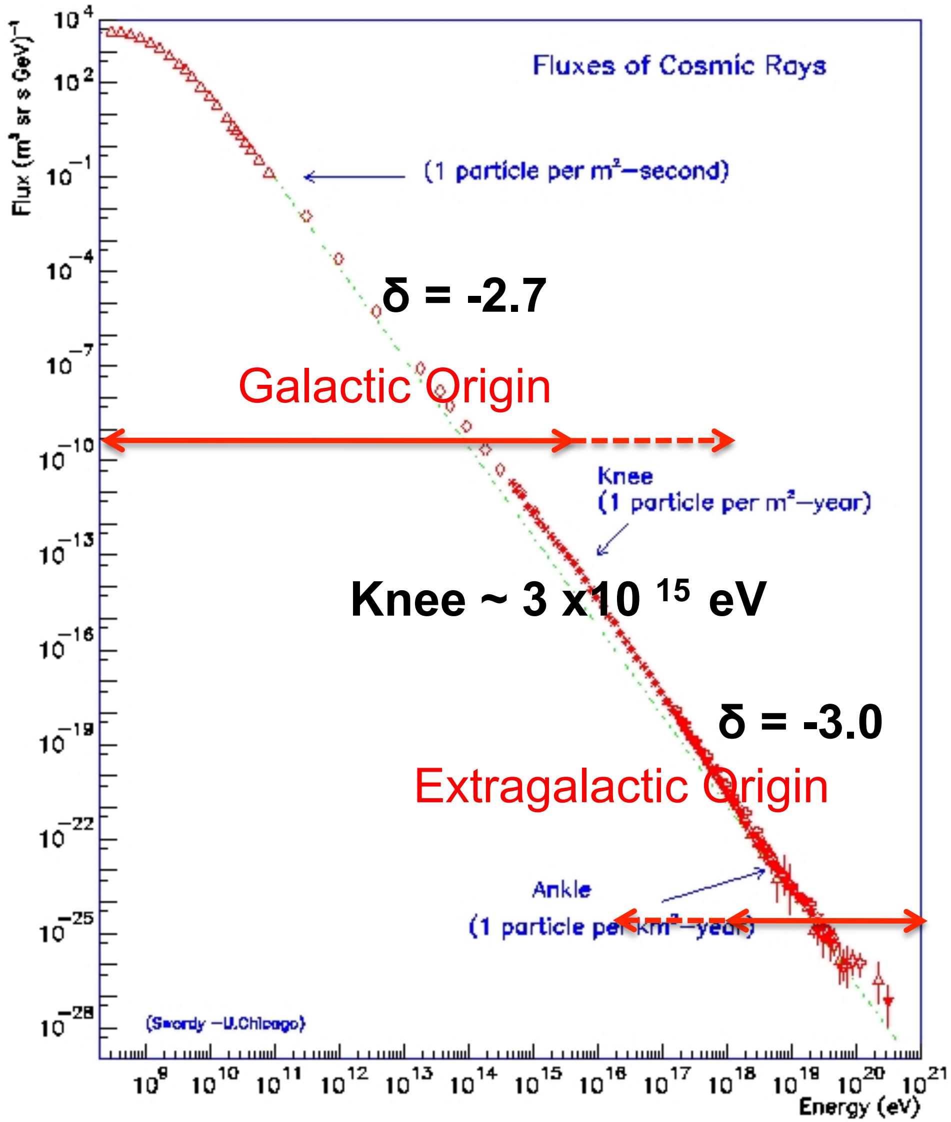
1. The Standard Model of Cosmic Rays
2. Open Questions in High Energy Astrophysics
3. Gamma Ray Emission from Molecular Clouds as a tool to probe CR origin and propagation
    1. Molecular Clouds as CR Barometers
    2. Searching for evidence of CR Pevatrons
4. Observations of SNR-MC associations
5. Summary

The Cosmic Ray Spectrum at Earth

- Almost featureless spectrum

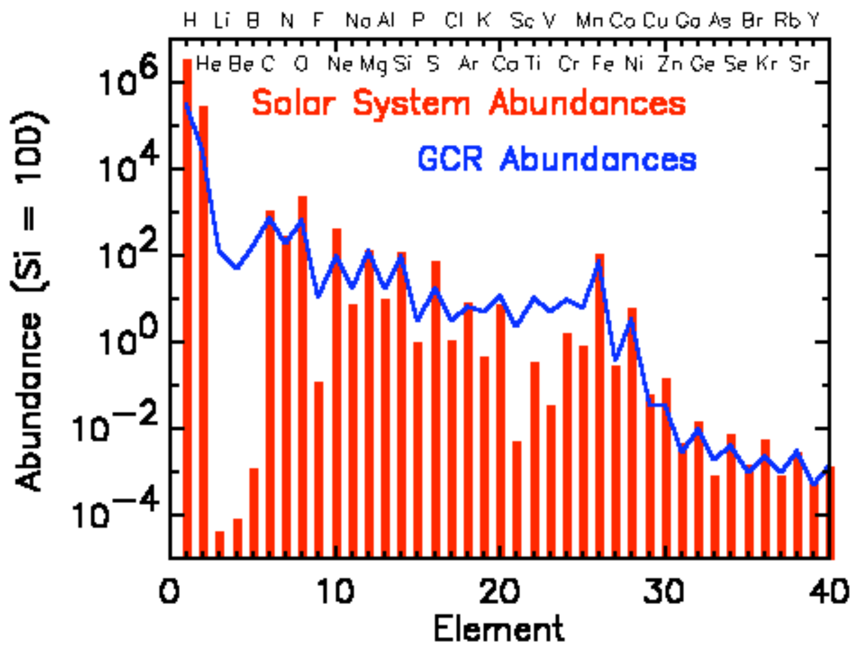
- Galactic accelerators have to inject particles up to at least to the knee at PeV energies

- Isotropy up to very high energy: 1 TeV proton in B=1uG, Gyro-Radius = 200AU= 0.001pc



Cosmic Ray Abundances < 100 GeV

- **Secondary particle production (B/C ratio) implies CR pass through 5-10 g/cm^2 in lifetime**
  - Average Galactic plane density of 1 H atom/cm^3 implies CR traverse 1000 kpc for a lifetime of 3 x 10^6 yr
  - Ratio decreases with energy implies higher energy CR escape Galaxy more quickly
- **Long lived radioactive isotope (e.g. Be^{10}) implies even longer lifetime so CR spend considerable time in Galactic halo**



Standard Model of Cosmic Rays

- Galaxy is Leaky Box
  - Energy Dependent Escape of CRs from the Galaxy $E^{-0.3 \text{ to } -0.6}$
  - CR source spectra must be $dN/dE = E^{-2.1 \text{ to } -2.4}$ to match $E^{-2.7}$ CR spectrum measured at Earth

- Supernova Remnants accelerate cosmic rays
  - With a rate of 1/30 years and energy available of 10^{51} erg SNs produce the necessary power to sustain the Galactic CR population
  - Diffusive Shock Acceleration (DSA) predicts
    10% efficiency for the acceleration process
    E^{-2} type spectrum to very high energies

- Model Explains Most Observations, but is not proven

Open Questions in High Energy Astrophysics

Concerning the origin of cosmic rays

- Are SNRs the Galactic cosmic ray accelerators ?
- If yes, how high in energy can SNRs accelerate particles?
- What is the production rate of CRs and electrons ?
- How are cosmic ray sources distributed in the Galaxy ? Is there a nearby (<100 parsecs) source of cosmic rays ?

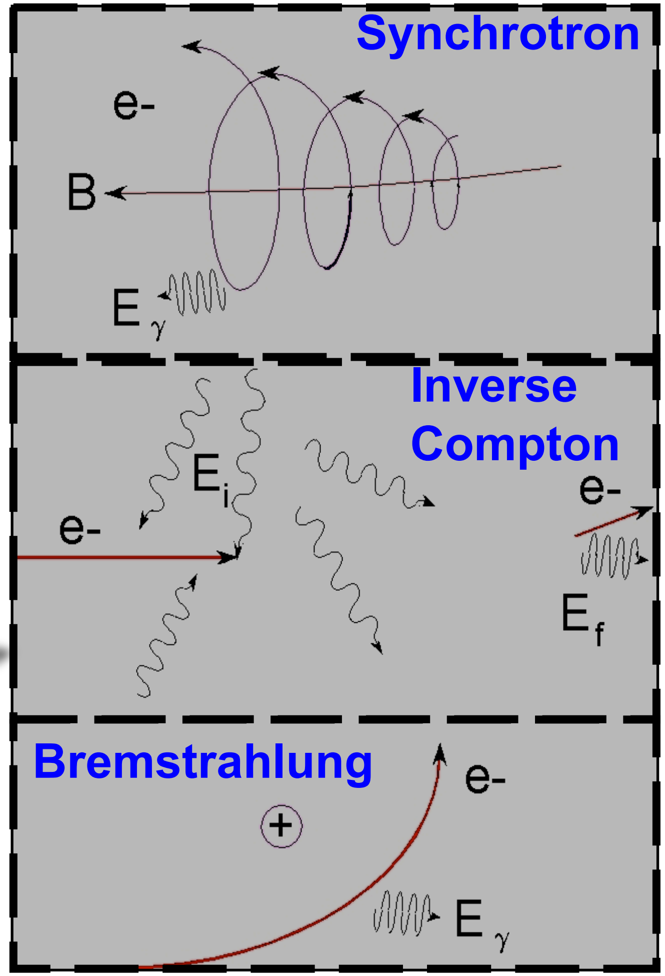
Concerning the character of propagation of CRs

- What is the diffusion regime ?
- What is the level of the cosmic ray background, which is the average CR flux produced by the long propagation of CRs in the Galaxy?

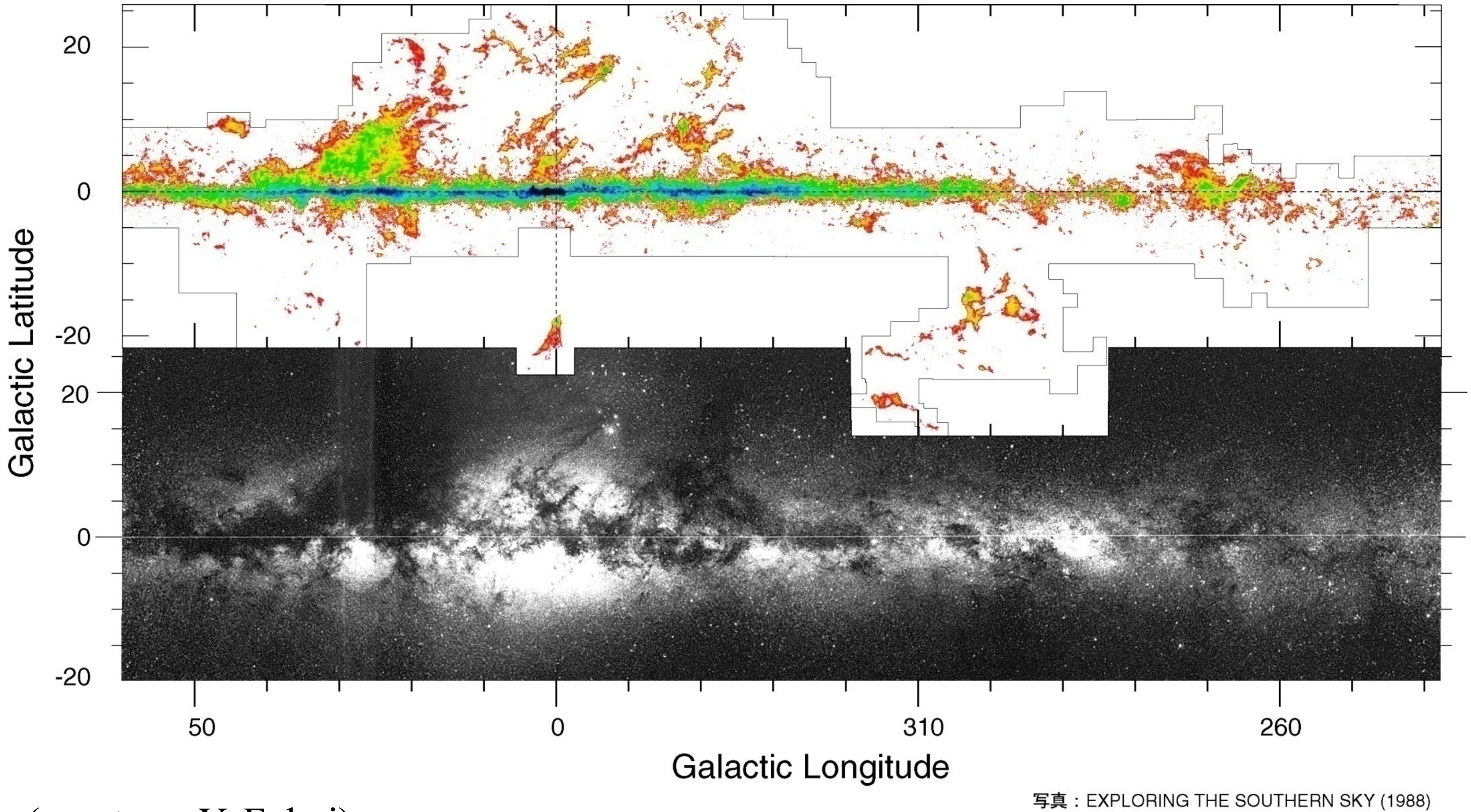
Gamma-ray Emission :
a probe of CR origin and propagation

- 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.*

Relativistic Electrons Produce Gamma-Rays

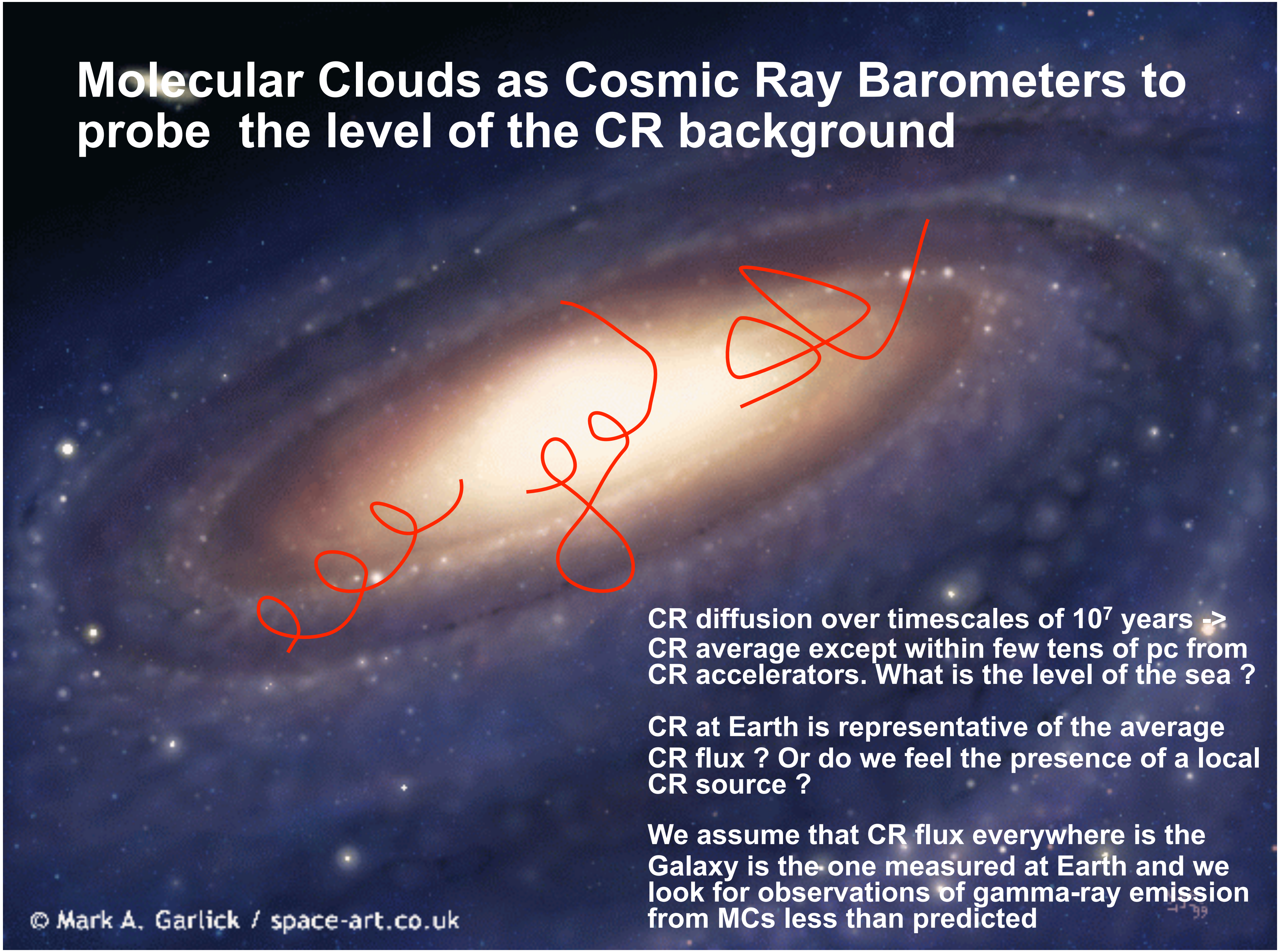


The Milky Way in Molecular Clouds (Nanten survey)



(courtesy: Y. Fukui)

Molecular Clouds as Cosmic Ray Barometers to probe the level of the CR background



CR diffusion over timescales of 10^7 years -> CR average except within few tens of pc from CR accelerators. What is the level of the sea ?

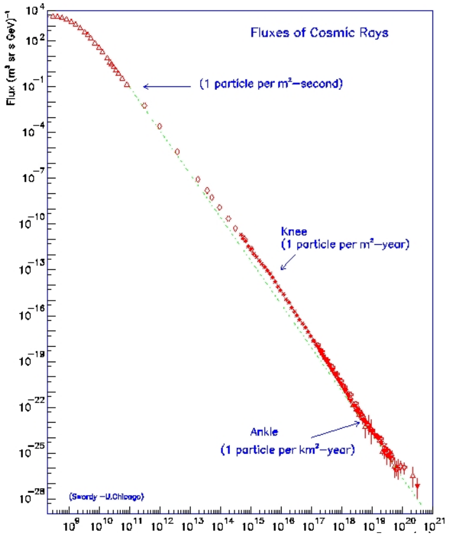
CR at Earth is representative of the average CR flux ? Or do we feel the presence of a local CR source ?

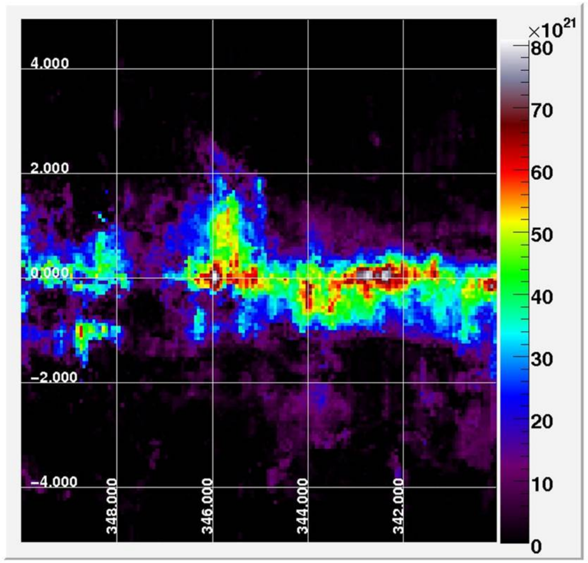
We assume that CR flux everywhere is the Galaxy is the one measured at Earth and we look for observations of gamma-ray emission from MCs less than predicted

The level of the CR background

Casanova et al, 2009

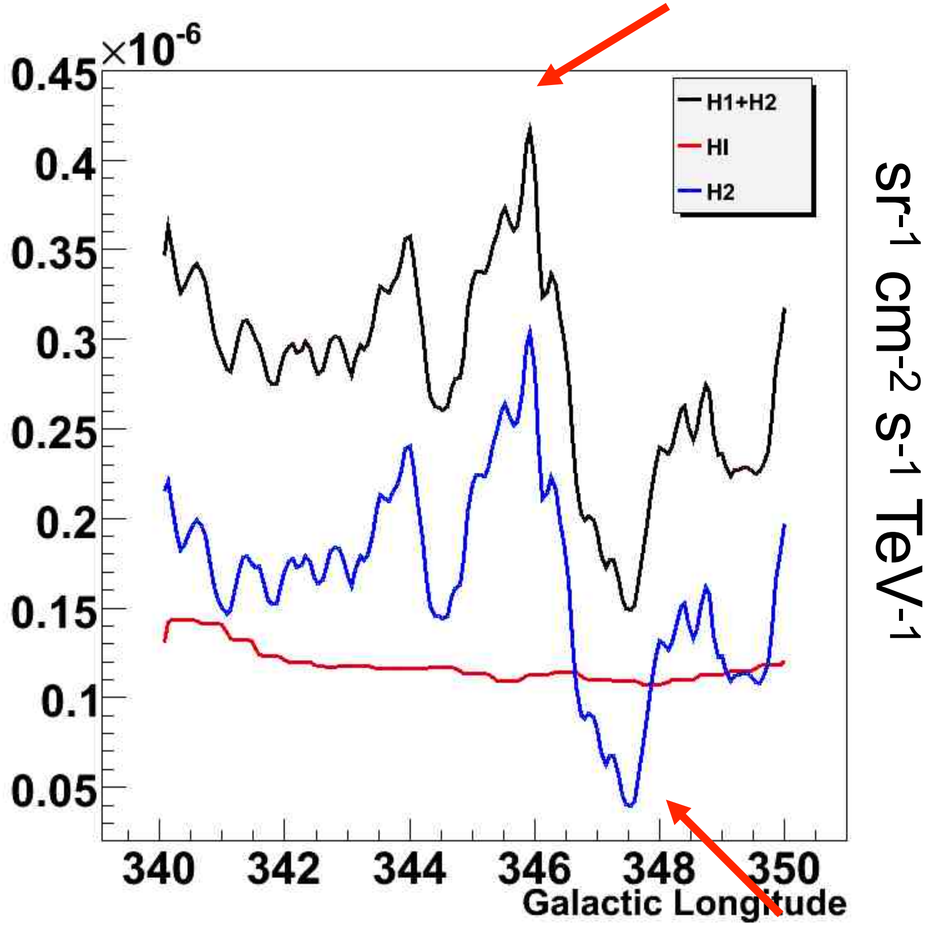
CR flux





Mol Gas Distribution

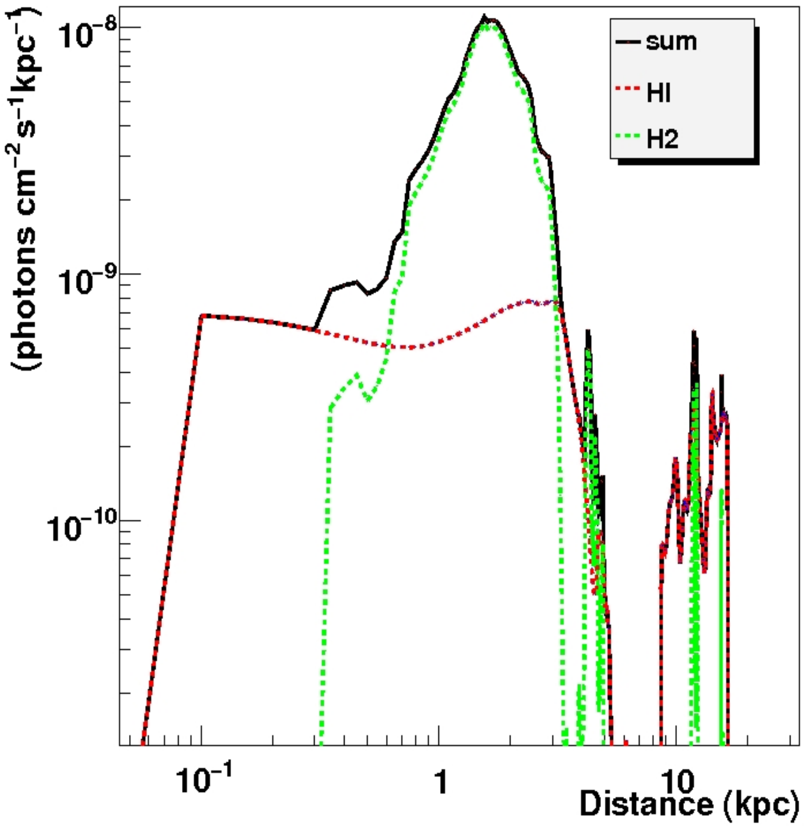
only one or at most few massive MCs



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

(1)	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}
d > 3	17.0	1.4	15.6	2.3×10^{-9}	9.1×10^{-13}

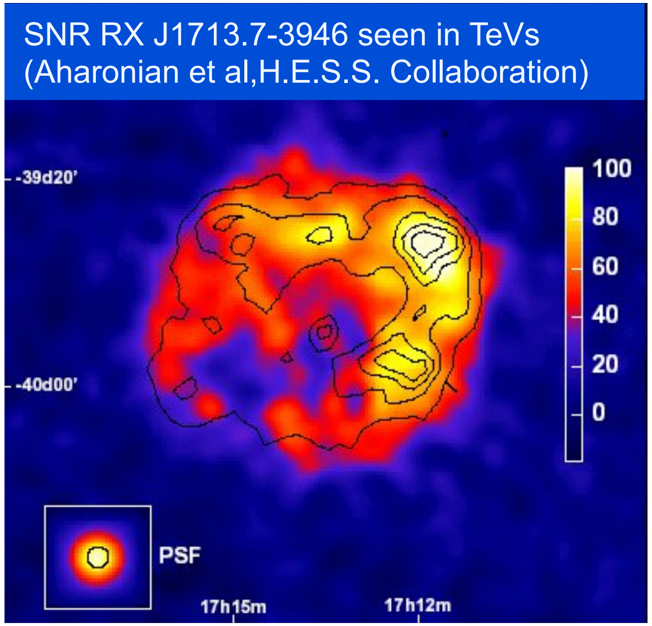
85% of the emission for the region 345.3<l<346 and 1<b<1.7 is produced between 0.5 and 3 kpc (ok for Fermi detector).

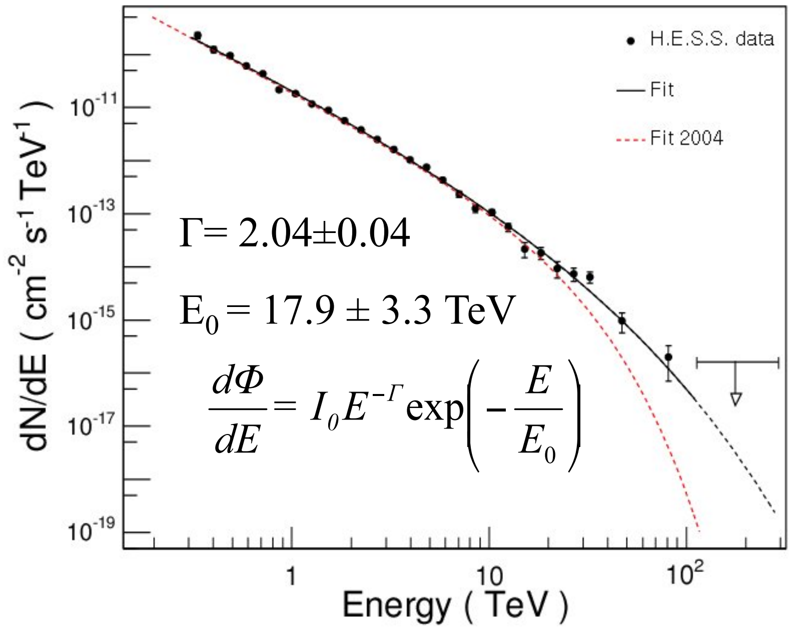
Casanova et al, 2009

Searching for the CR Pevatrons

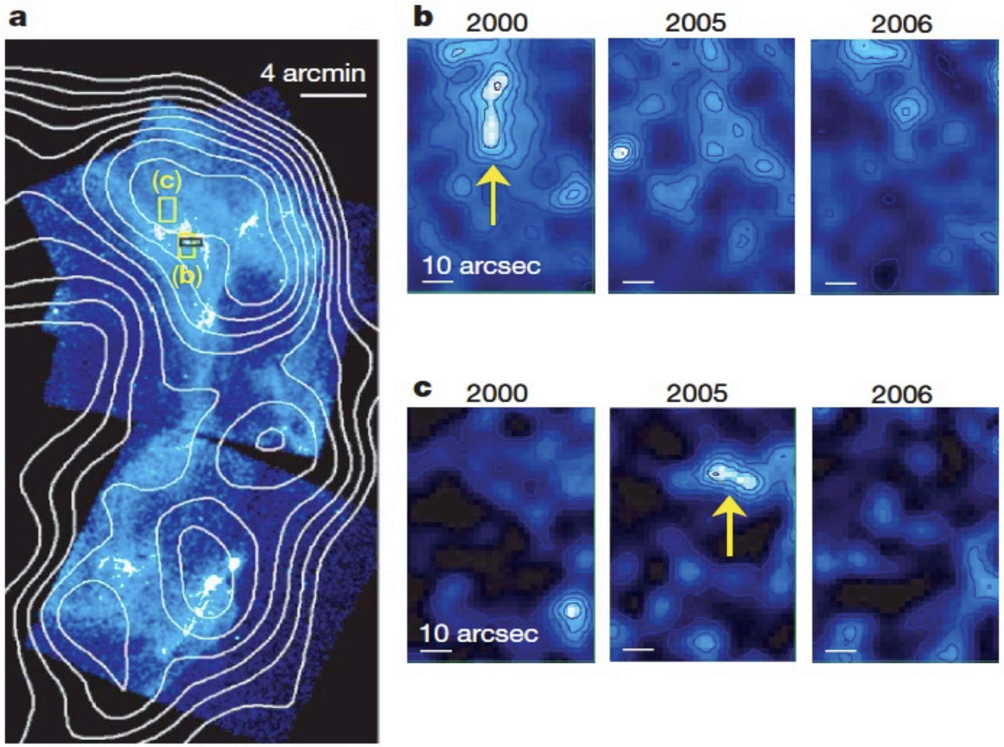
Are SNRs the Galactic PeVatron sources ?

- 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 particle 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.





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)

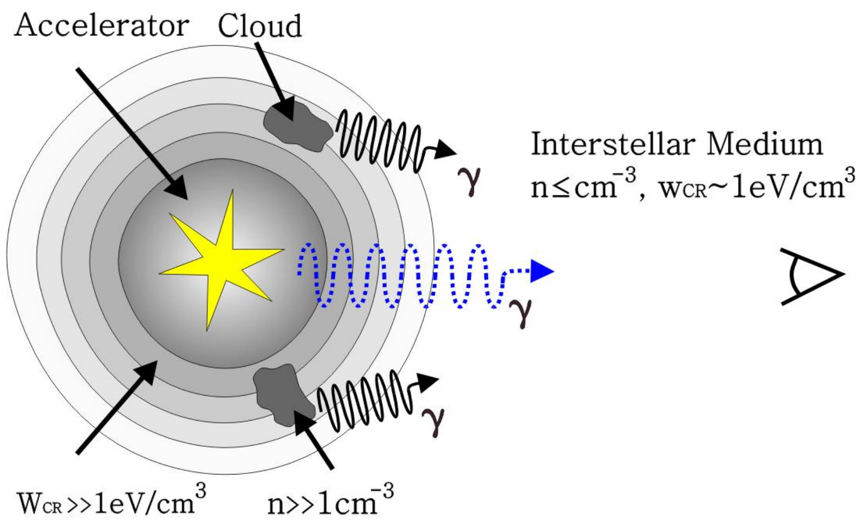
Are SNRs the Galactic PeVatron sources?

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.

- 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.
- Even if a SNR accelerates particles up to PeV energies, a SNR is a PeVatron for a very short time

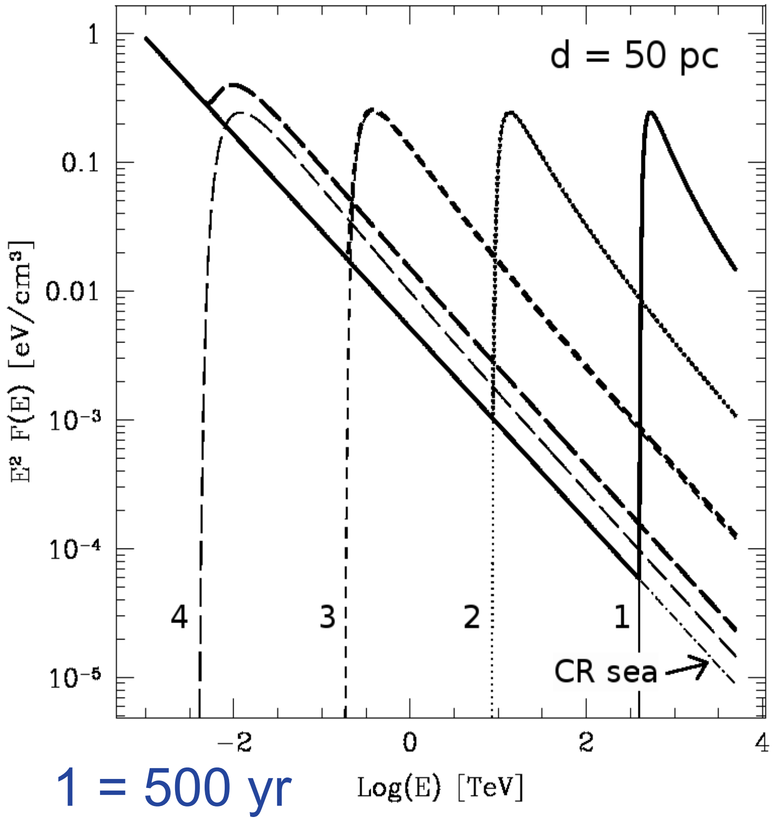
Gamma Rays from Molecular Clouds close to CR sources

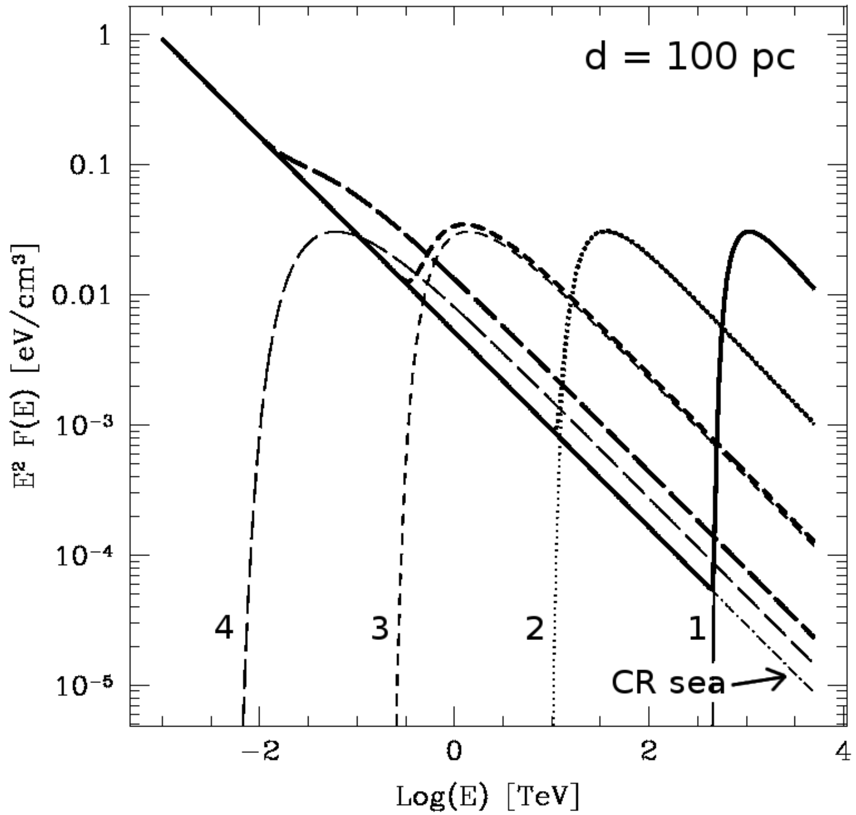


- MCs are ideal targets to **amplify the emission** produced by CRs accelerated by nearby sources (Aharonian & Atoyan, 1996, Aharonian, 2001)
- **Highest energy protons quickly escape** the accelerator and therefore do not significantly contribute to gamma-ray production inside the proton accelerator-PeVatron. **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

Gabici et al, 2009





1 = 500 yr
2 = 2000 yr
3 = 8000 yr
4 = 32000 yr

Power in CRs: $E_{CR} = 3 \times 10^{50}$ erg,

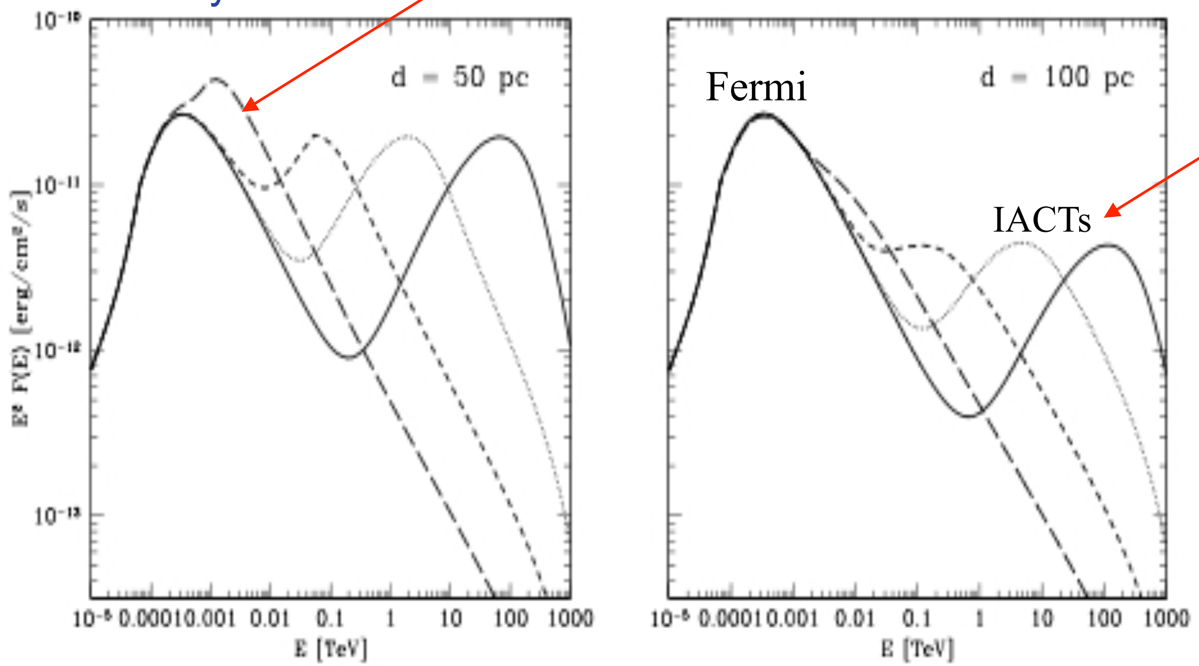
Diffusion coefficient: $D = D_0 E^{0.5}$

GeV versus TeV emission spectra in MC

1 = 500 yr
2 = 2000 yr
3 = 8000 yr
4 = 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

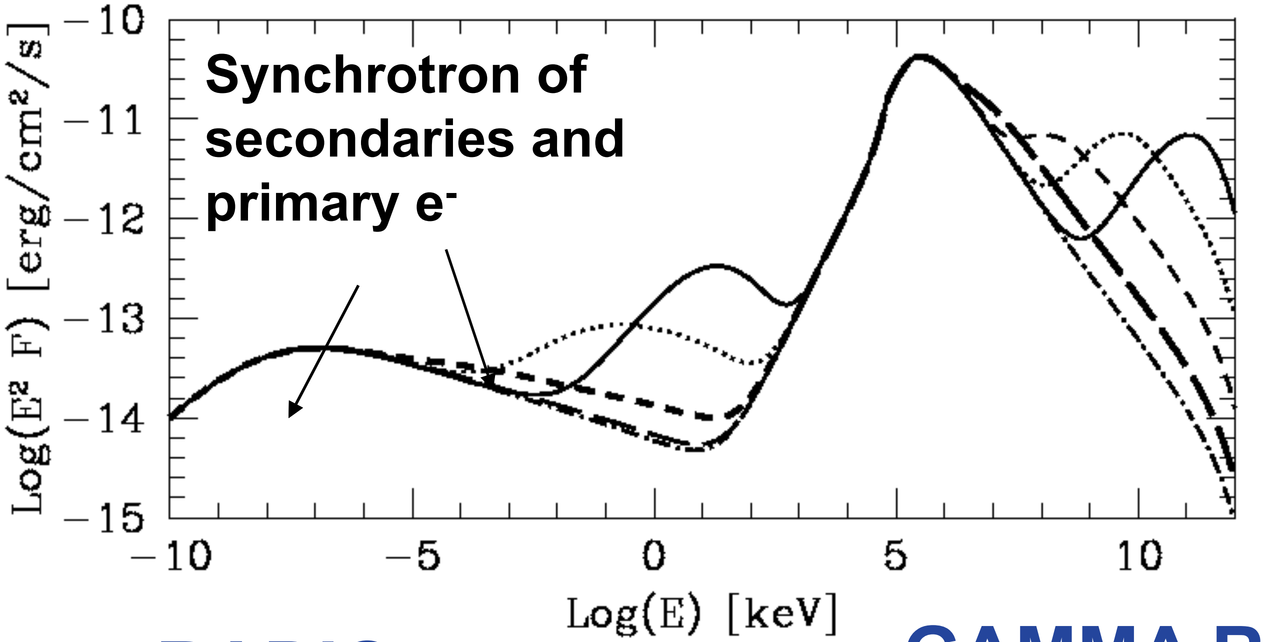
Gabici et al 2009

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

t = 500 yr
t = 2000 yr
t = 8000 yr
t = 32000 yr
t = ∞ yr



RADIO **X-RAYS** **GAMMA RAYS**

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.

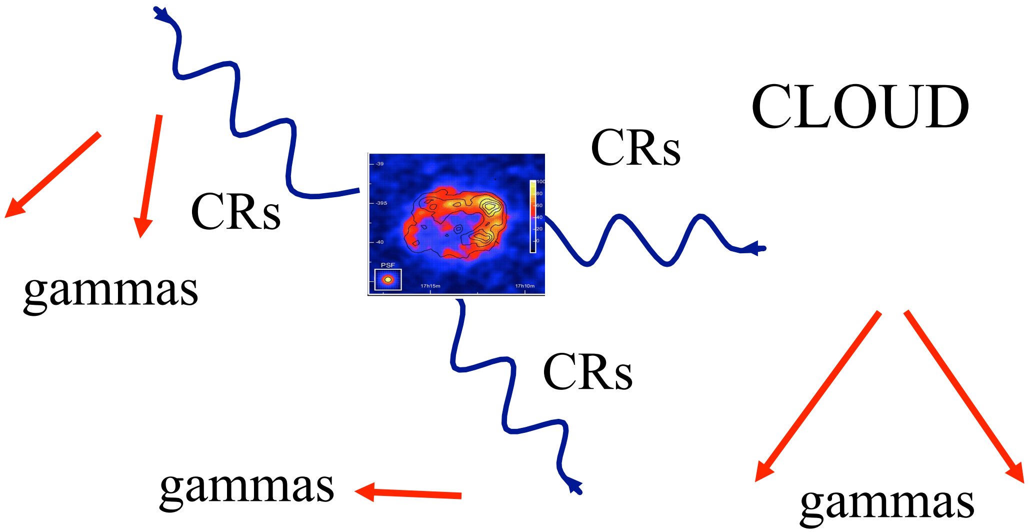
MWL implications

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

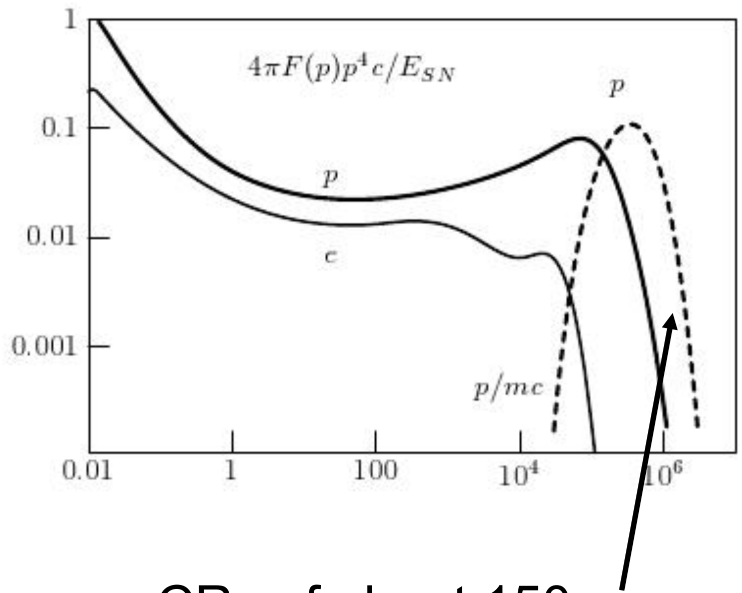
Ee = 100 TeV

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

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



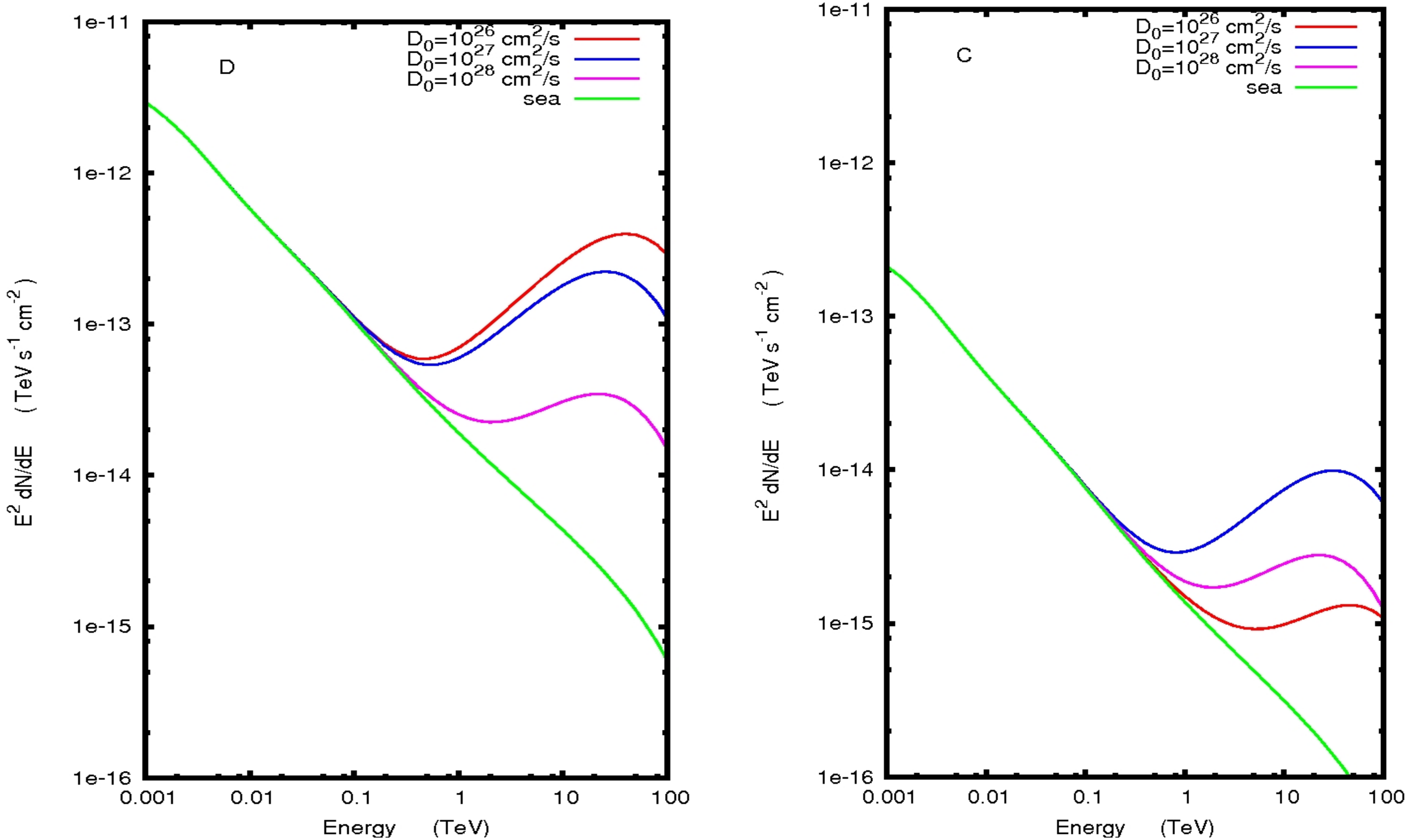
Zirakashvili & Aharonian, 2010



CRs of about 150 TeV are escaping from the shell now

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

Spectral features in the emission to look for in the molecular clouds around RX J1713.7-3946

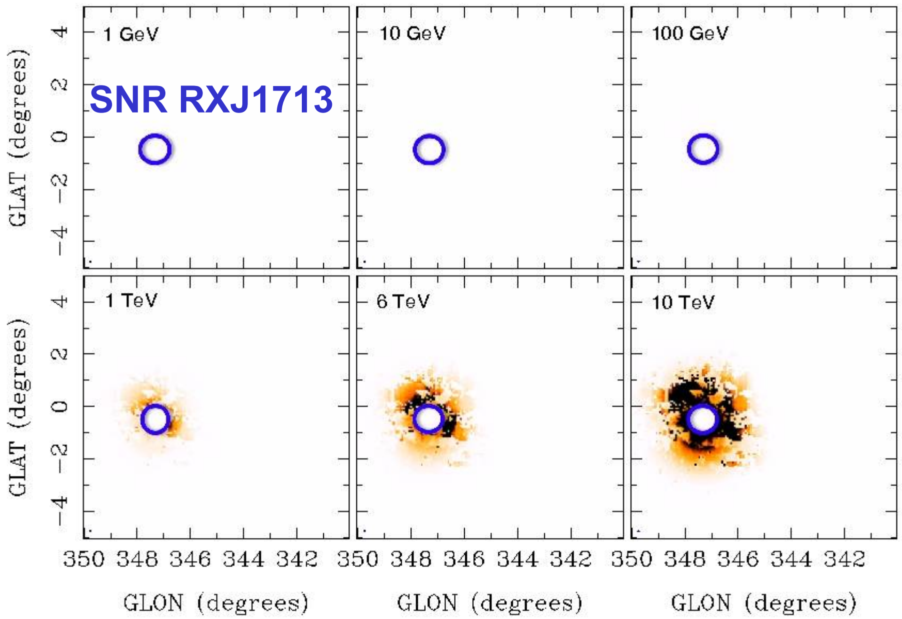


Diffusion coefficient: $D = D_0 E^{0.5}$

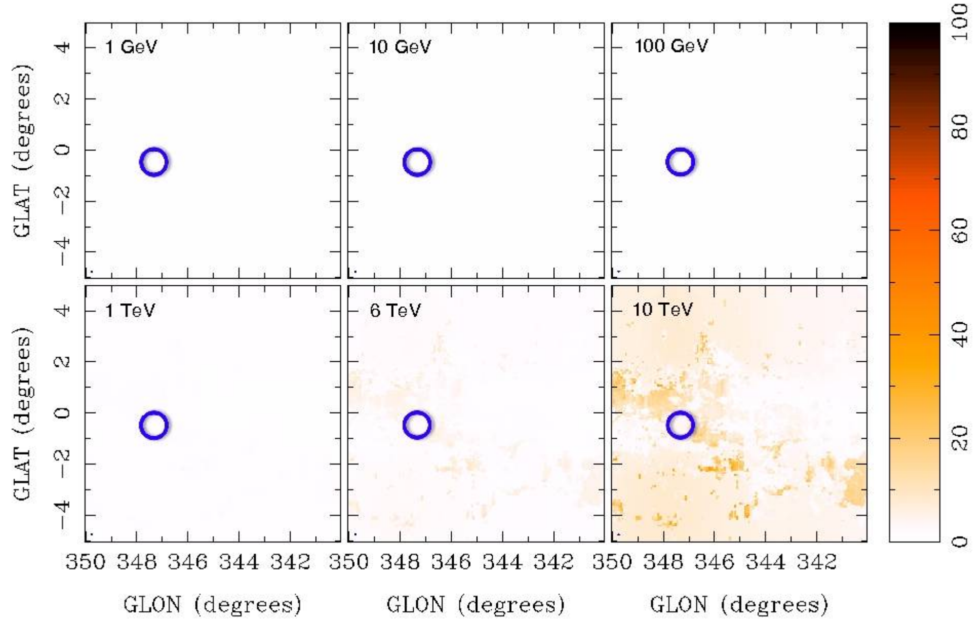
Casanova et al, 2010

Morphology to constrain the CR diffusion regime

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



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



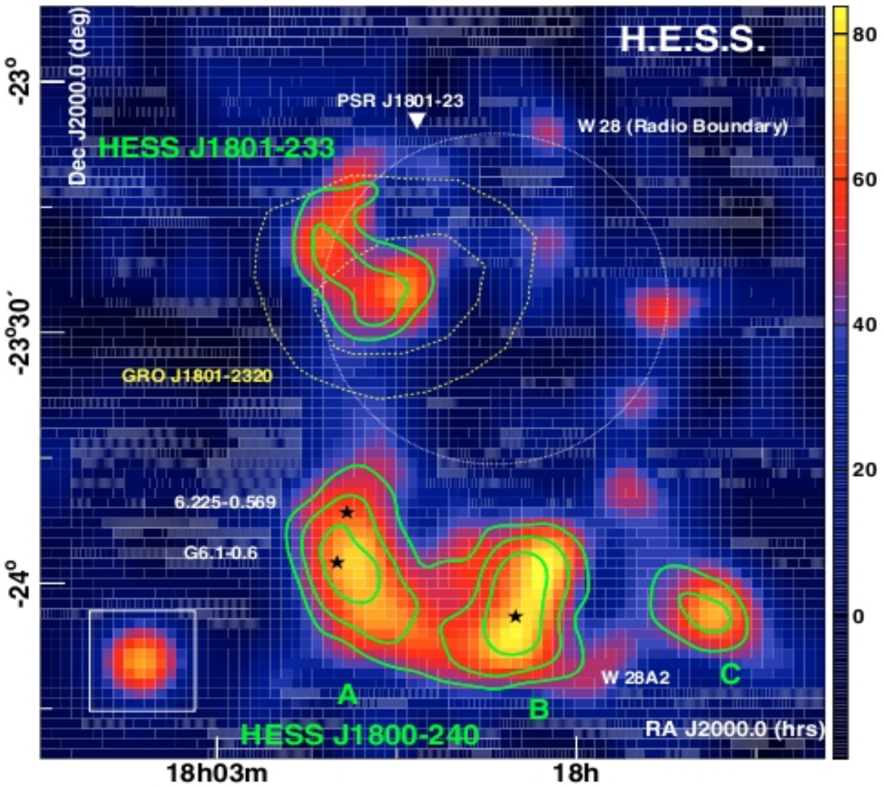
$(\gamma_{\text{Runaway CRs}} + \gamma_{\text{sea CRs}}) / \gamma_{\text{sea CRs}}$

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

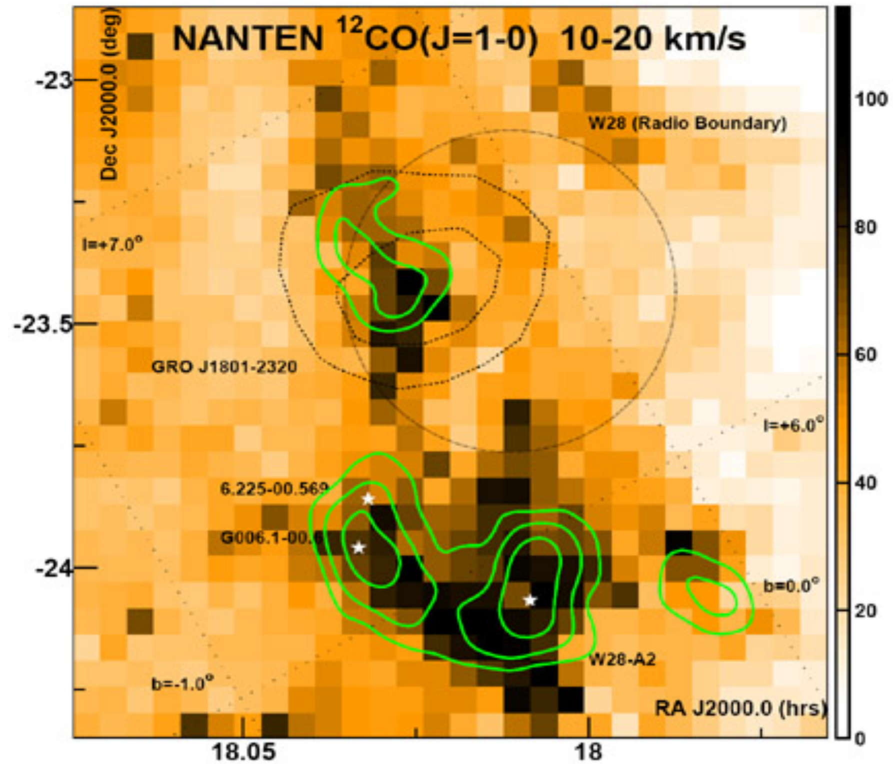
Casanova et al, 2010

Observations of SNR-MC associations

Molecular Clouds close to the old SNR W 28



H.E.S.S. collaboration, F. Aharonian et al., and Y. Moriguchi, Y. Fukui, NANTEN, 2008



W28 : an old SNR (30000 yrs) and nearby molecular clouds.The VHE/ molecular cloud association could indicate a hadronic origin for HESS J1801-233 and HESS J1800-240

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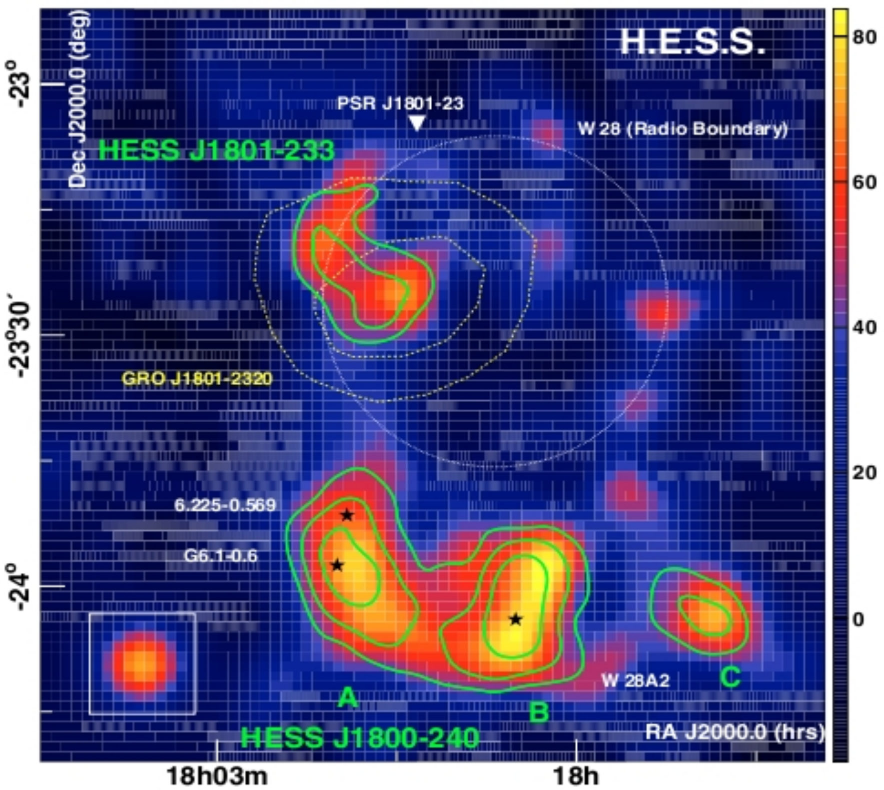
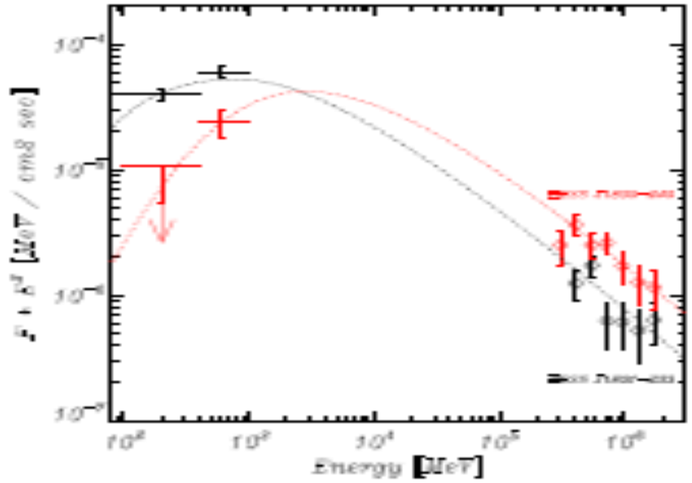
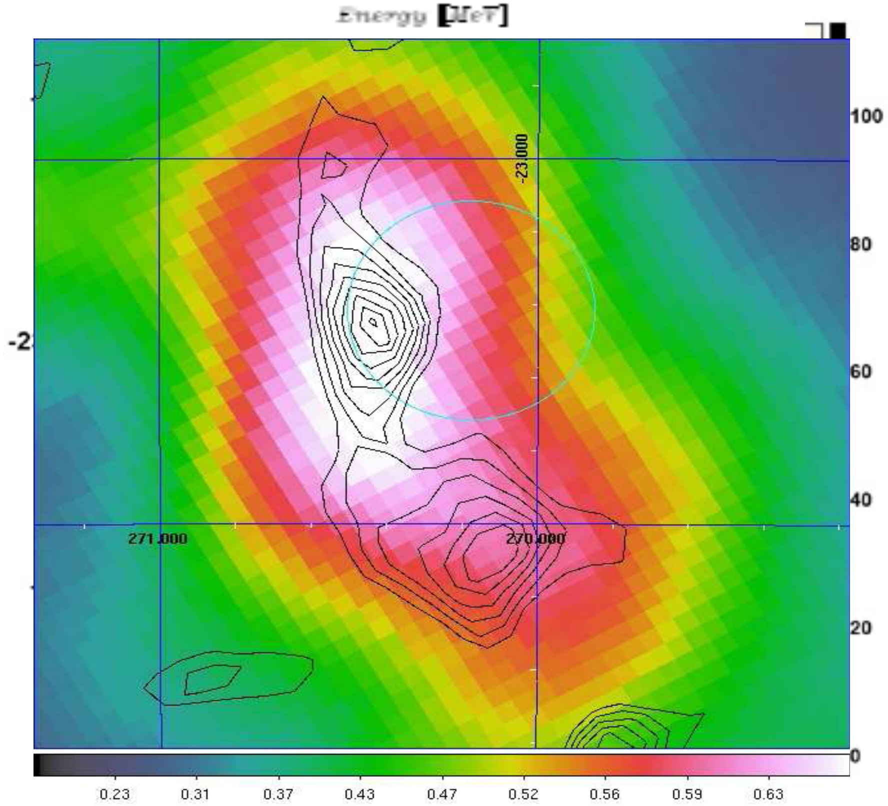


AGILE,Giuliani et al, 2010





W28 : an old SNR and nearby molecular clouds.The VHE/molecular cloud association could indicate a hadronic origin for HESS J1801-233 and HESS J1800-240

Summary

- Still many open questions in high energy astrophysics
- MCs can be used as CR barometers to probe the level of the CR background in the Galaxy. Detection of gamma rays from CR sea possible to Fermi.
- 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.
- 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.


Thank you
for your attention!