High energy radiation from molecular clouds (illuminated by a supernova remnant)

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Outlook

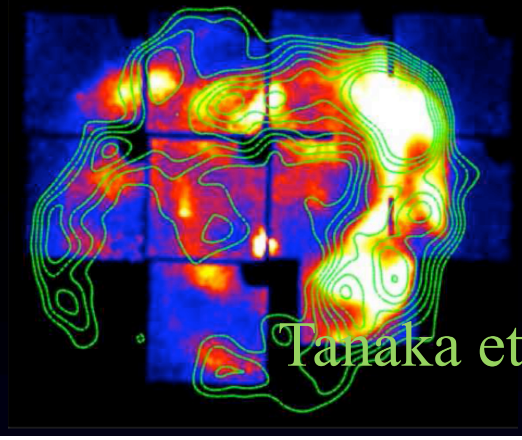
- Introduction: Scientific interests.
- Modelling: Multi-wavelength radiation from irradiated molecular clouds (MCs).
- Discussion: Observability ? further modelling ....
- Conclusions.

Scientific interests

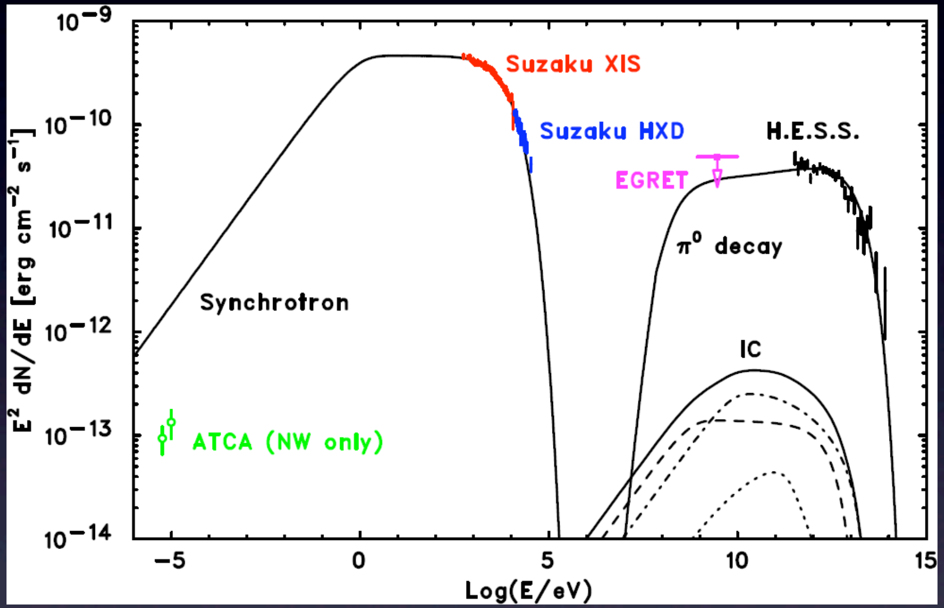
- No definite observationnal proof of CR acceleration at supernova remnant shock fronts.
- <u>High energy observations of Supernova remnants</u>: (see Luke's talk)

  - **X-rays**: filaments, synchrotron radiation by TeV electrons.

  - **gamma-rays**: neutral pion or Inverse Compton ? ... probably both ...
- *Supernova remnants in interaction with molecular clouds* (IC443, W28 .... see Armand's talk)
- <u>A third way</u>: clouds *illuminated* by a «young» SNR (young = a few thousand years).



Tanaka et al'08



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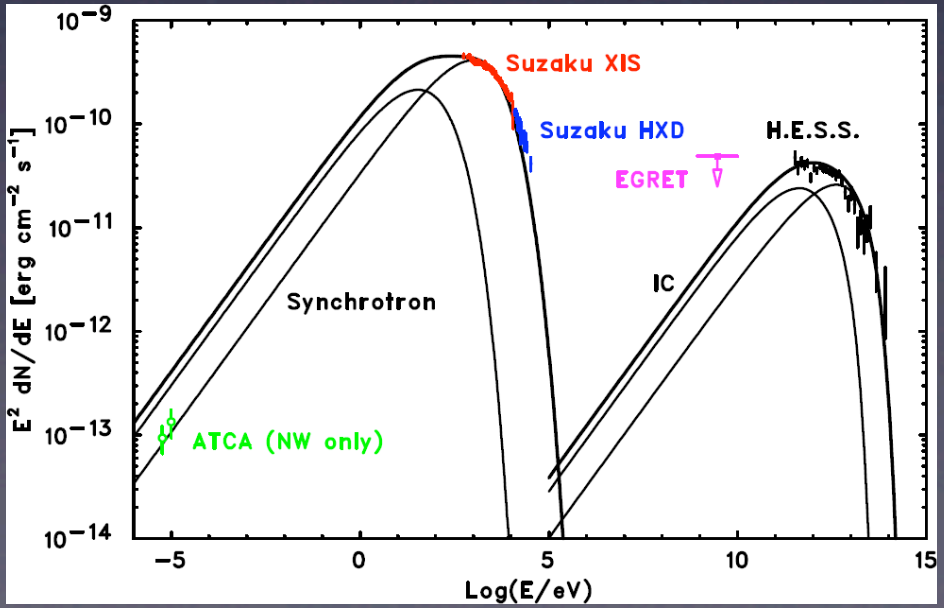


Modelling

See : Gabici et al '09 (and ref. therein)

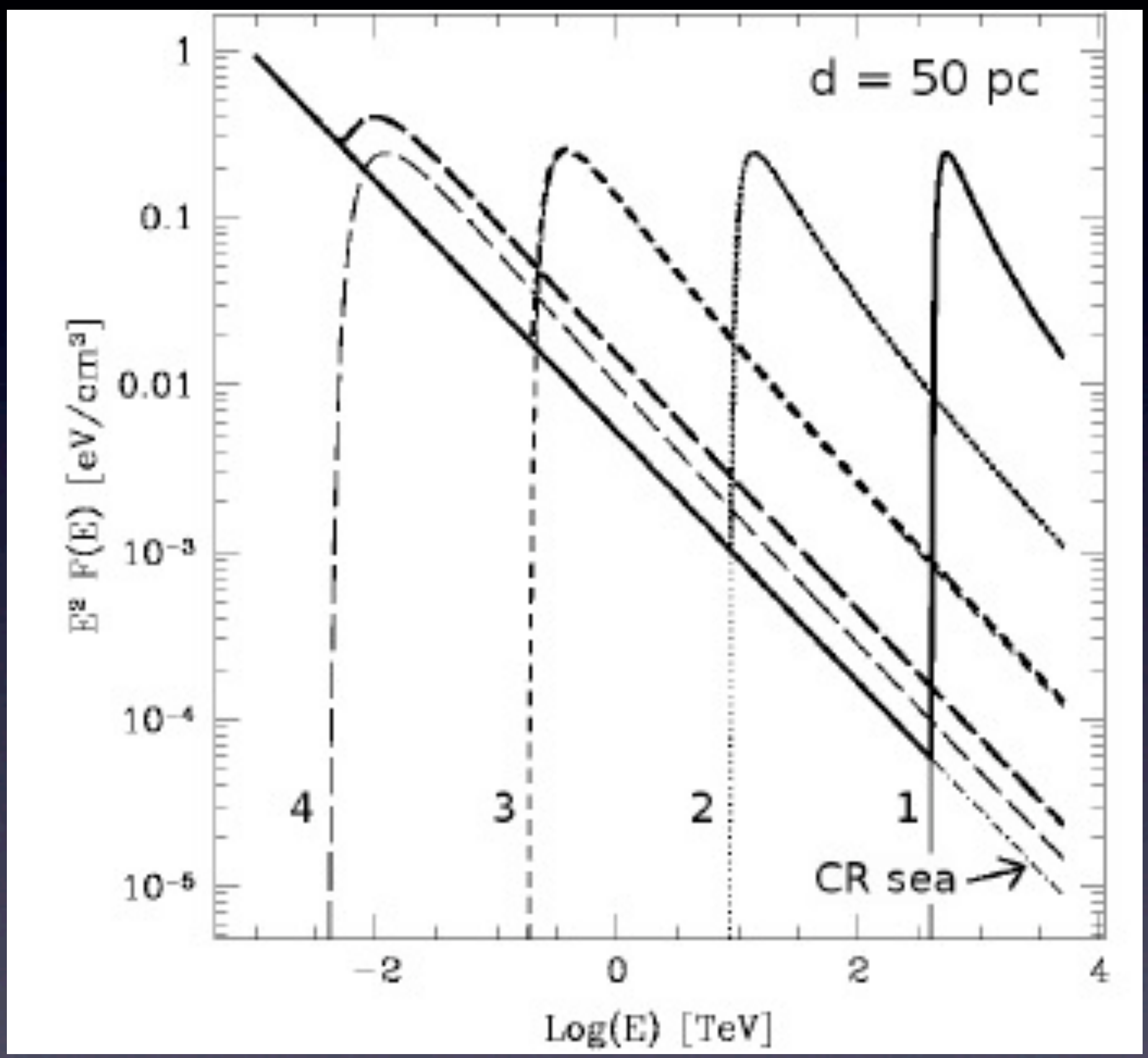
- Assumptions: -parameter of the model-
- *Source:* the CRs are relaxed at the start of the Sedov phase: $R_L \sim R_{sh} (V_{sh}/c)$
  - $E_{max}(t) \propto B(t)\, t^{-1/5} \Rightarrow t^{-\alpha}$
  - Gabici et al $\alpha = 2.4$ => at the end of the Sedov phase E_{max}=1-10 GeV.
- *Transport in the ISM:* Diffusion coefficient: $D(E) = [10^{28}\ cm^2/s]\ (E/4\ GeV)^{0.5}$
  - In the MCs D(E) is x by a parameter $\chi \leq 1$: difference from «standard» diffusion.
- The radius explored (diffusively) by a particle of energy E at a time $t > t_{sedov}$ is:

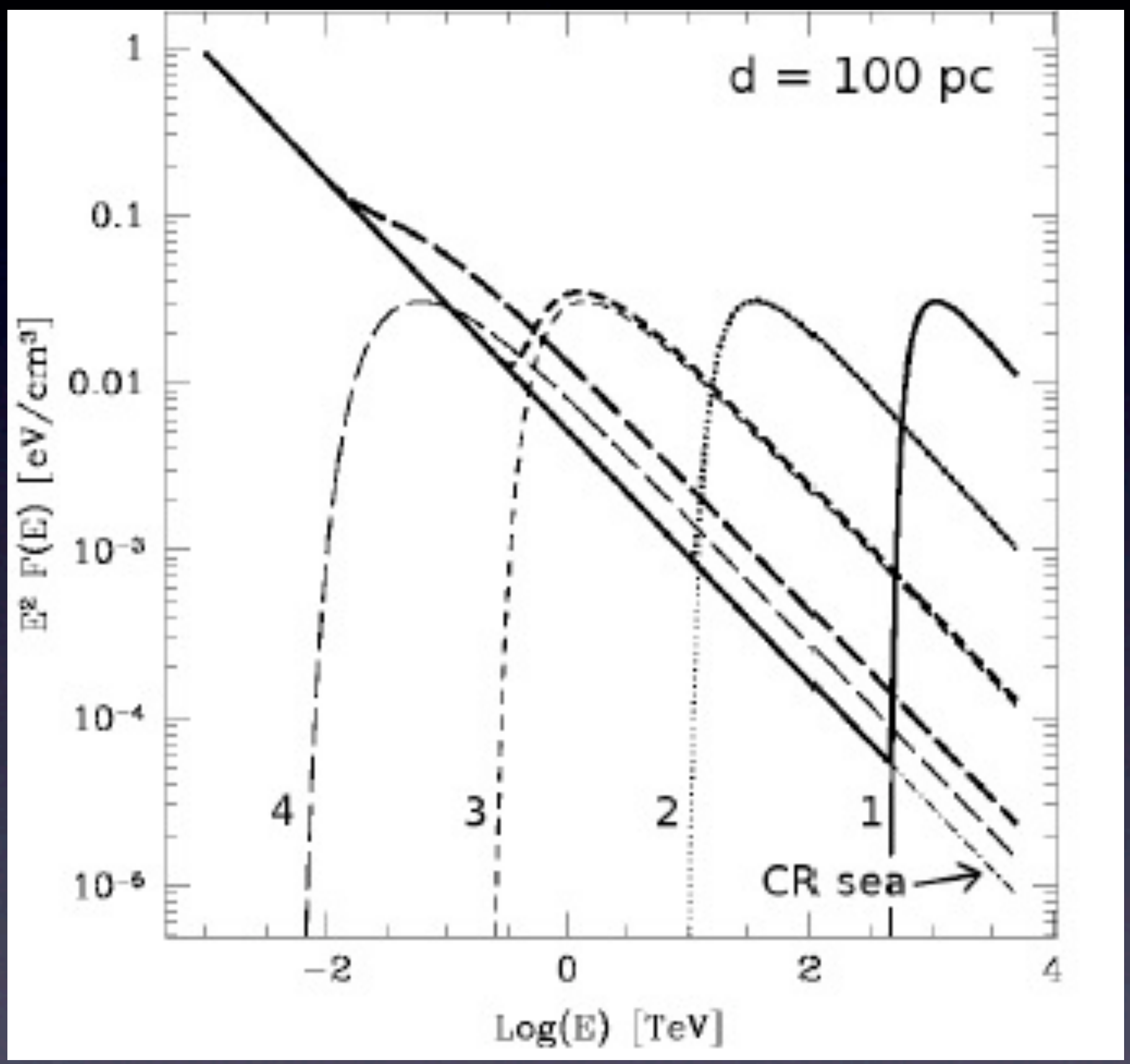
$R(E)=[4D(E)\ (t-t_{esc}(E)]^{1/2}$; $t_{esc}(E) = t_{sedov}\ (E/E_{CRmax})^{1/\alpha}$

Sedov time in a constant density: $t_{sedov} = 209\ yr\ E_{inj}^{-1/2}\ M_{ej}^{5/6} n_{ext}^{-1/3}$

- Solve a diffusion Eq. with a specific source term $Q(E) \equiv \delta(E-E_{max}(t))\ \delta(x)$.

Cosmic-Ray spectrum

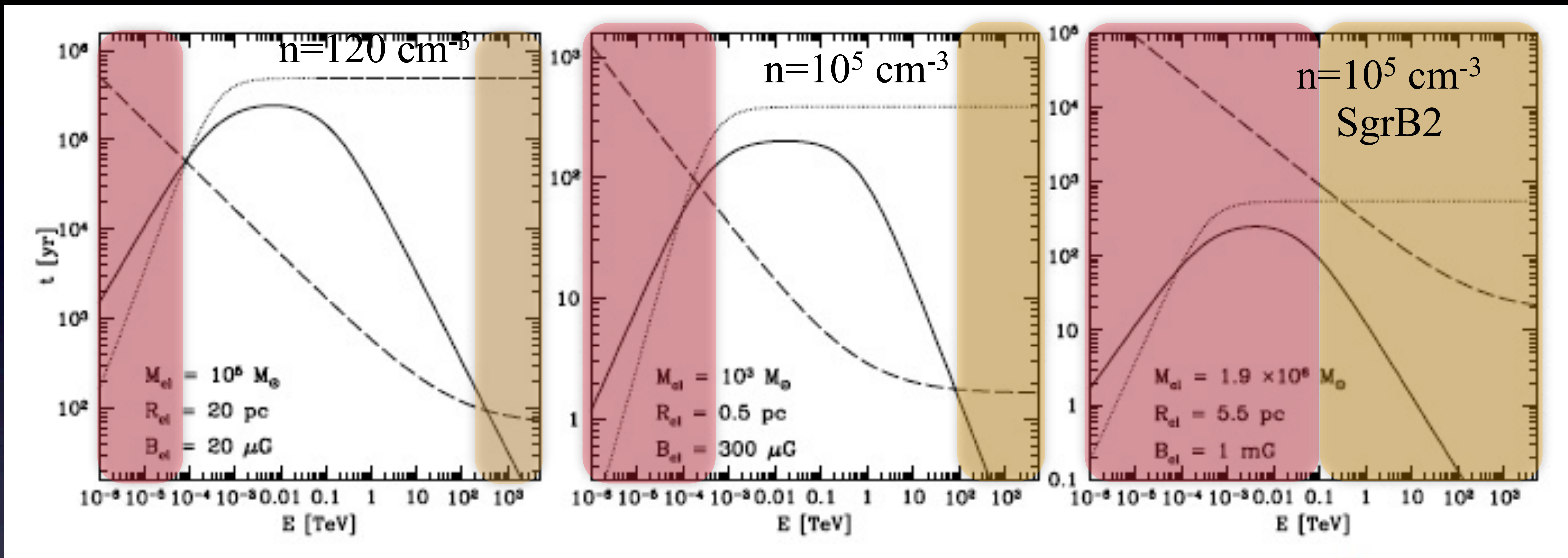




CR spectrum in interaction with a molecular cloud at different timescales at two different distances (Gabici et al ’09)

1: at 500 yrs; 2: 2000 yrs; 3: 8000 yrs and 4: 32000 yrs + CR background (CR sea).

Losses in the MC



- Dominant loss processes inside different type of MCs: *Loss timescale vs energy scale*.

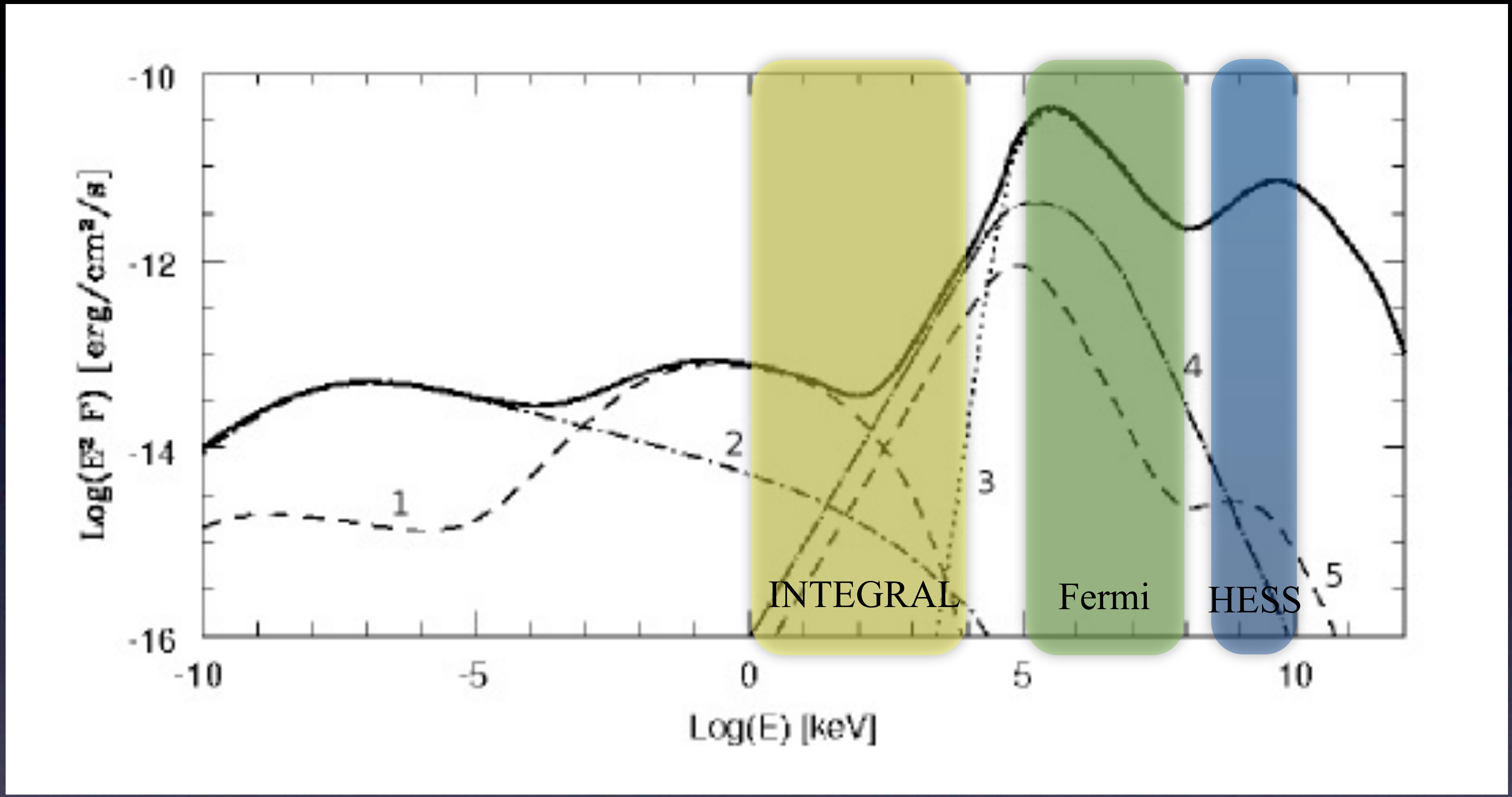
  - Dashed line: CR propagation time over the cloud = $[R_{cl}^2/(6\ D_{in}(E,B))] + [R_{cl}/c]$ = diffusion + crossing.

  - Dotted line: CR losses (ionisation E < 1 GeV, pp interaction E > 1GeV)

  - Solid line: electron/positron losses (ionisation (E < 1 GeV) + Bremsstrahlung + Synchrotron/Inverse Compton losses).

  In the coloured regions particles are confined in the cloud.

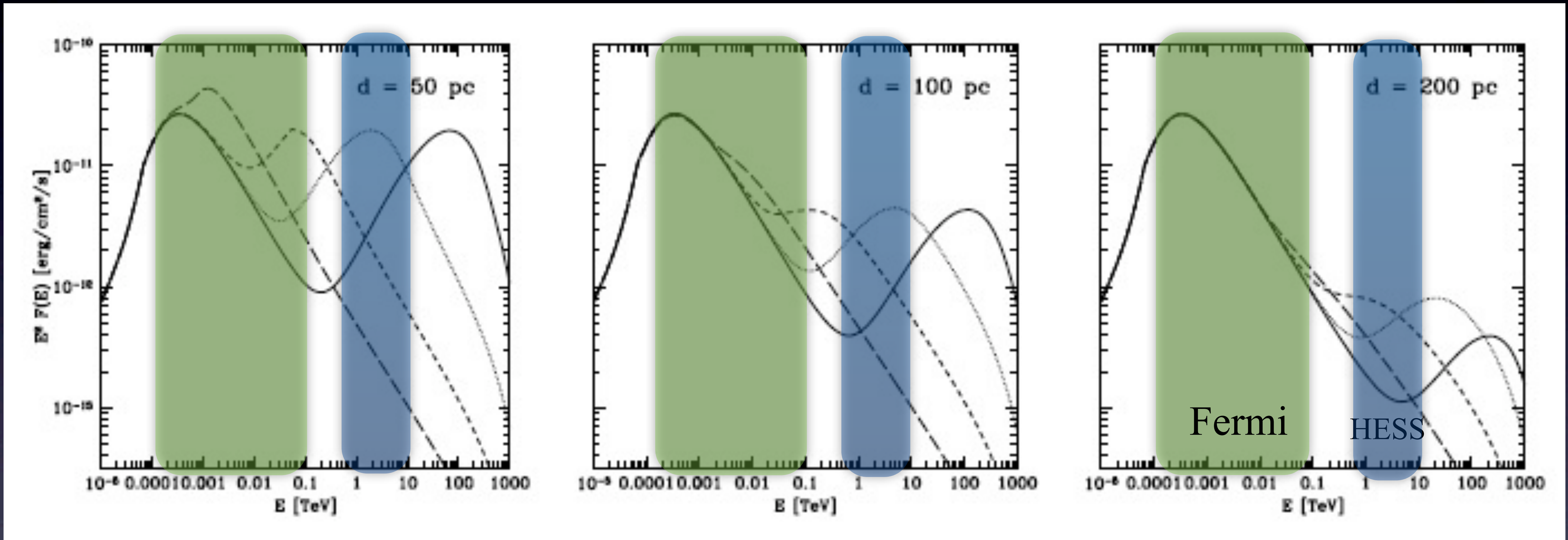
Multiwavelength spectrum



Giant Molecular cloud: d =100 pc, *n = 120 cm^{-3}*, *flat density distribution*, radius = 20pc, B = 20μG, M=10^5 M$_\odot$, at 1 kpc at a time 2000 yrs.

CRs = 3 pion decay
Secondary electrons = 1: synchrotron; 5: Bremstrahlung
Background electrons = 2: synchrotron; 4: Bremstrahlung

Time dependent spectra



Cont: at 500 yrs; thin cont: 2000 yrs; dotted: 8000 yrs and dashed: 32000 yrs + CR background (CR sea).

- Hard spectrum observed at time 8000 yrs > t > 500 years in the HESS waveband.
- Soft spectrum in the Fermi waveband unless very close + a strong impact of the background CRs.

Observations

- What could be a good candidate ?

  - «Dark accelerators» with a hard TeV spectra (several HESS sources are still unidentified).

  - Close to Fermi source (unless the backround flux to be much lower than the local one).

  - Search for good correlation with CO data (difficult to establish a distance).

  - MC cloud close to a SNR (d < 100 pc).

  - Cross it with a radio SNR catalogue; e.g. Green catalogue (> 250 SNR).

  - SNR in the Sedov phase (X-rays) as later no TeV gamma-rays are expected from the MC.

- Gabici et al => consistent framework but some issues are to be discussed.

Supplementary processes - I -

- At the shock front:

  Time dependence of the magnetic field B(t) ? => α ; this depends on the dominant instability.

- Particle escapes during the free expansion phase ? Ptuskin & Zirakashvili ’05 : yes but with a smooth spectrum s ~ 6 (depends on the ejecta density profile => s~4.3)

  ! But non-resonant streaming instability likely dominates the generation of B in the free expansion phase (Bell’04, Pelletier et al’06, Zirakashvili & Ptuskin ’08)

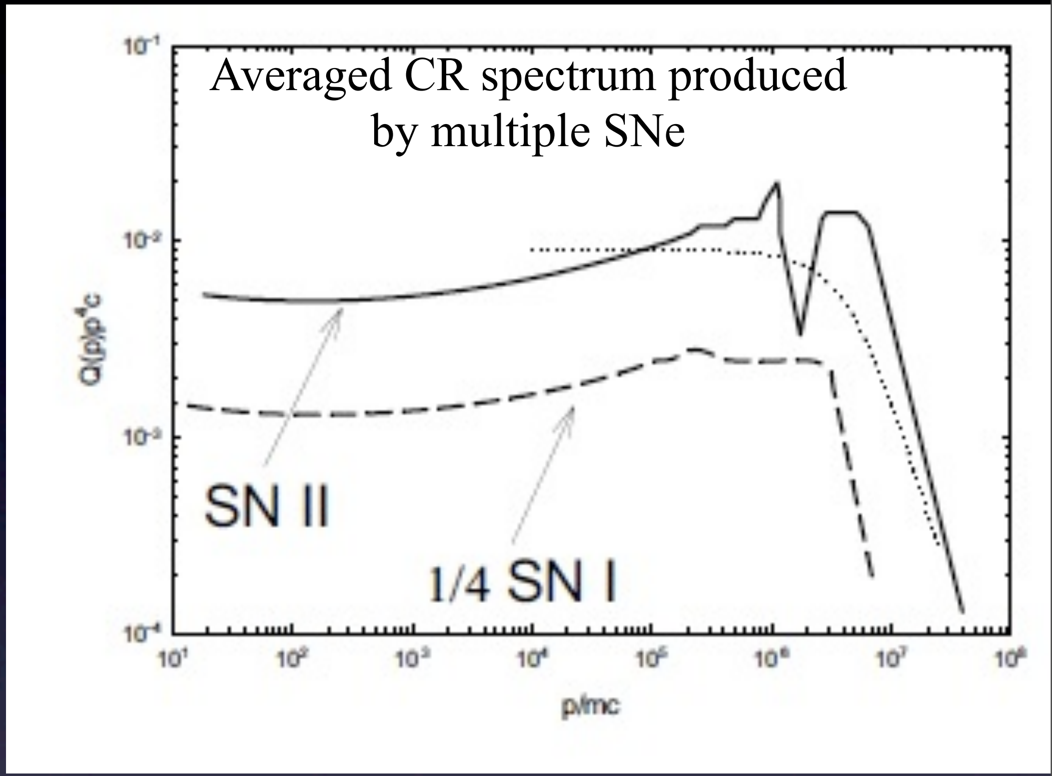
- see Tatischeff ’09 (SN1993J case):

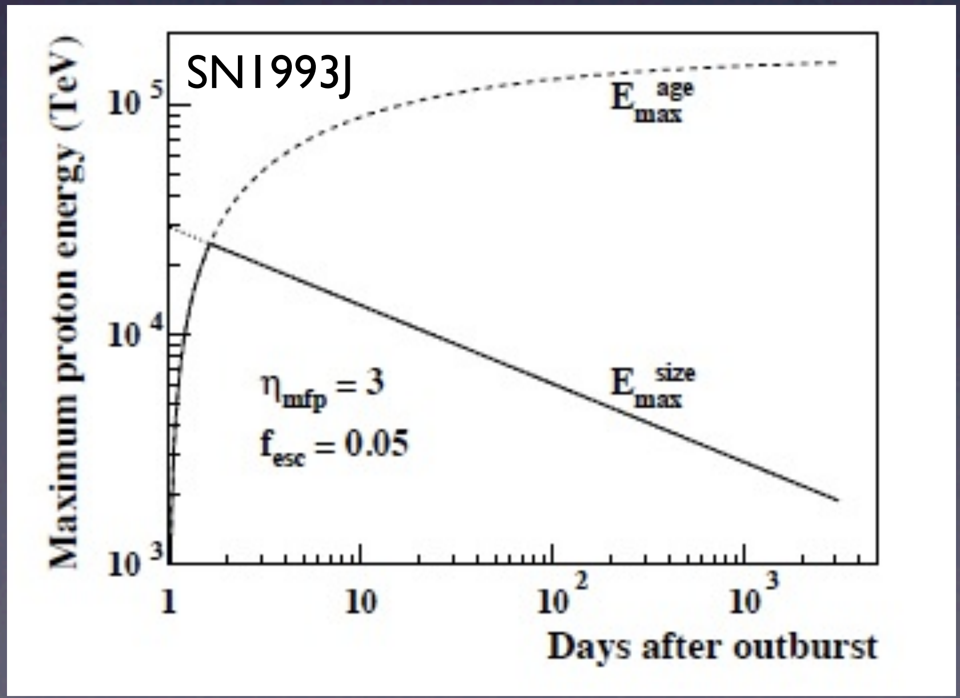
  - Wave growth timescale ~ days at 10^{15} eV (V_{sh}~7x 10^4 km/s, n_{CM}~10^4 cm^{-3})

  - B decreases after the outburst as t^{-1} ; E_{max} ?

  - Targets for CTA or neutrinos telescopes at E > 10-100 TeV

- The analysis of Gabici et al, basically correct E < 10 TeV.





Supplementary processes - II -

- Propagation in the ISM:

  Locally the SN produces an excess of CRs wrt the background flux => pressure gradient => triggers a streaming instability.

  The diffusion coefficient in the diffusion Eq. is likely *non-linear*.

  * Example (Ptuskin et al'08): Level of turbulence fixed by a competition between the wave production and non-linear Kolmogorov damping.

  => $D \propto | \nabla f'x,p,t) |^{-2/3}$

  Self-similar solution => too «efficient» => Strong PeV CRs flux during 10^4 years (checked).

  - The self-similar solution is not the «right» one (Gabici & AM under progress).

  - Kolmogorov damping is not fast enough => high level of turbulence (other cascade modelling, effects of neutrals ....)

  - The wave growth rate is the quasi-linear one.

Supplementary processes - III -

- Propagation inside the molecular clouds (better understanding of diffusion in MHD turbulence)

  * Gabici et al'09 : «standard» diffusion with a parameter χ, but certainly much more complex.

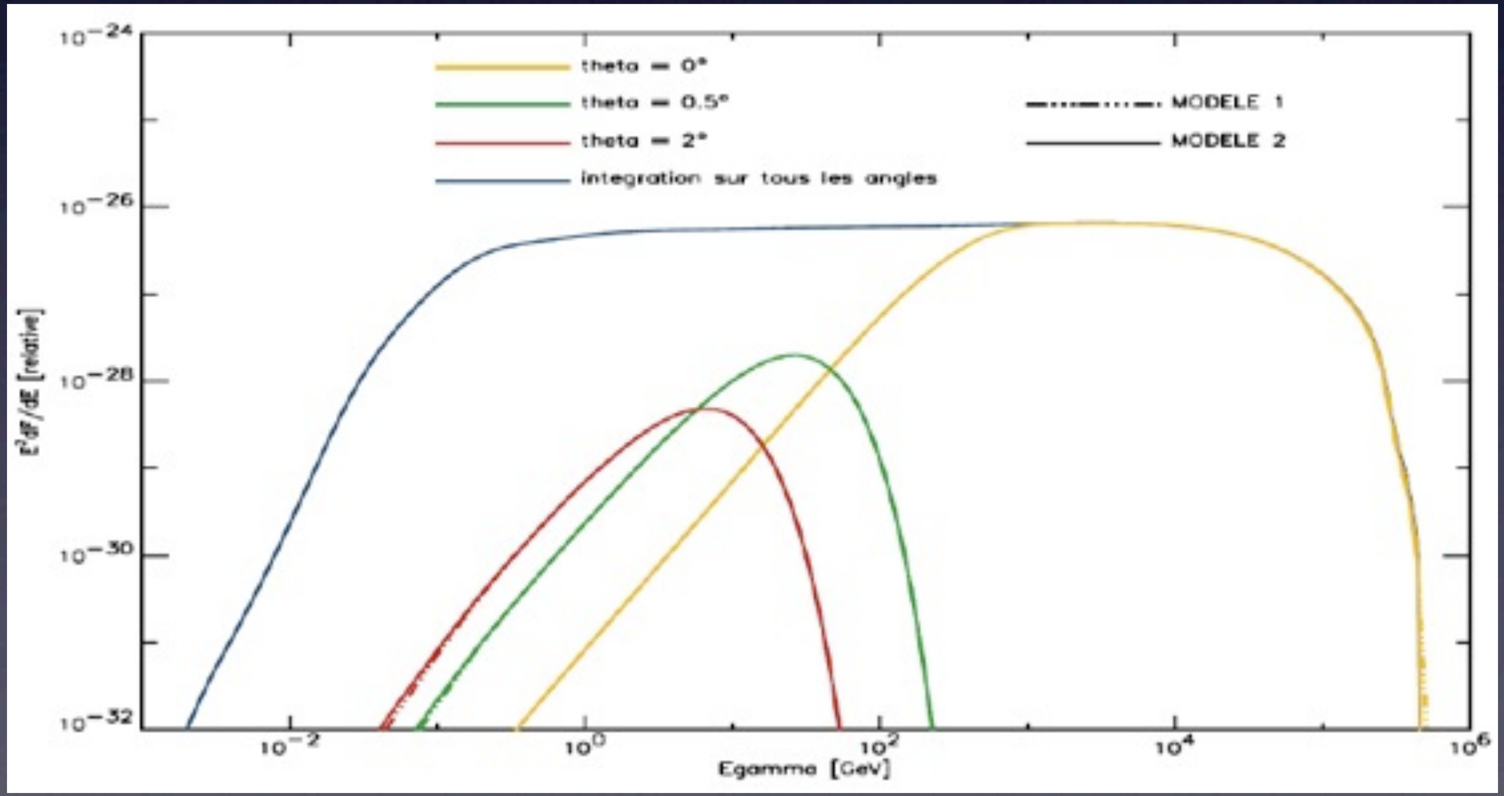
  * Another streaming instability develops there: ionization losses of low energy CRs inside the cloud (Skillin & Strong '76, Shalov et al'90) => may have some impact on the cloud dynamics.

- The pp process is anisotropic:

  * Kinematics => The neutral pion (and gamma-rays) is produced in the hadron direction.

  The clouds (unless very small and close to the SNR) is illuminated anisotropically by the SNR (hemispherical).

  Maximum flux if the cloud is close to the l.o.s. between the SNR and the E.



E^2dN/dE gamma-ray flux for different direction with the incident mono-directional E^{-2} CR flux (100 MeV-1PeV)
Pancrazi '08, Karlsson &Kamae'08

Conclusions

- The MC illumination by a SNR is an important tool to probe the CR distribution close to their sources.

=> probes the physics of diffusive shock acceleration also !

- Simple modelling shows:

- TeV spectrum is hard $(\Gamma < 2)$ for timescales ~ a few hundred/thousand years.

- GeV spectrum depends on the background CR field strongly.

- Important scientific goal for CTA/ neutrinos telescopes.

- However several supplementary processes are to be considered (shock acceleration, CR transport in the ISM and in the MCs, anisotropic irradiation ...)

- Dynamical effects on the cloud itself (to be fully investigated).

- Workshop announcement:

Molecular clouds as probes of cosmic-ray acceleration in supernova remnants

to be held in Carnon- hotel du midi (close to Montpellier) - September 6^{th}-9^{th}

website: http://indico.in2p3.fr/conferenceDisplay.py?confId=1909

passwd: GDRlpta

Registration opened

Maximum number 45.

Topics

- links between astroparticle physics & «low energy» astrophysics
- Observations of molecular clouds in interaction with SNRs: X- and gamma-rays.
- Multiwave-length view of molecular clouds: CO surveys, OH masers ...
- Particle acceleration at SNR shocks
- Cosmic-Ray propagation in the interstellar medium (ISM).
- Molecular clouds irradiation: ionic species (H_3^+ ....) connection with chemistry in the ISM, spallation, dynamical effects on cloud formation ...
- Future of high energy instruments: CTA