Galactic Cosmic Rays: from sources to Earth

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Introduction

Sources: Supernova remnants

Transport in the interstellar medium

Perspectives for AMS-02

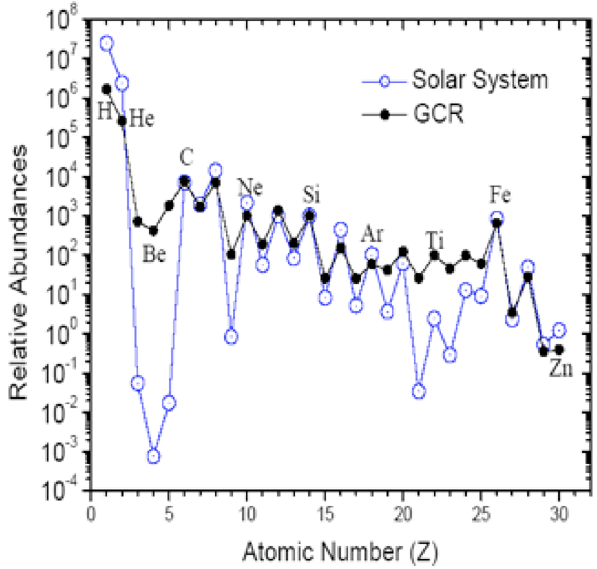
Conclusions

Introduction

- Galactic cosmic rays: observables

Les observables du rayonnement cosmique

spectre de masse



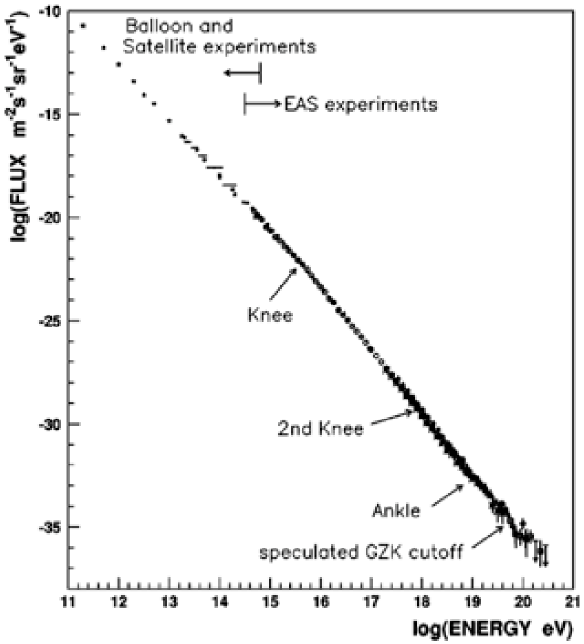
[Israel 2004]

99% de nucléons + 1% e-

abondance quasi-solaire

= source ⊗propagation

spectre en énergie

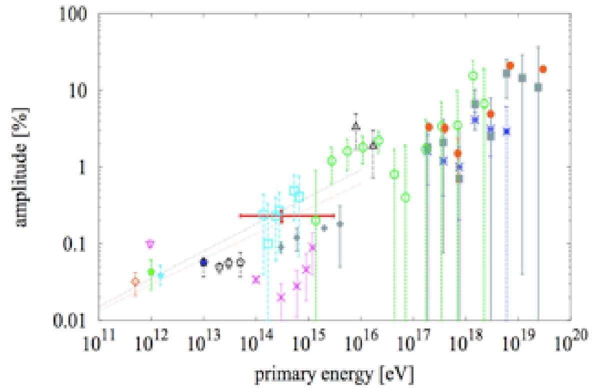


[Nagano & Watson 2000]

loi de puissance avec cassures

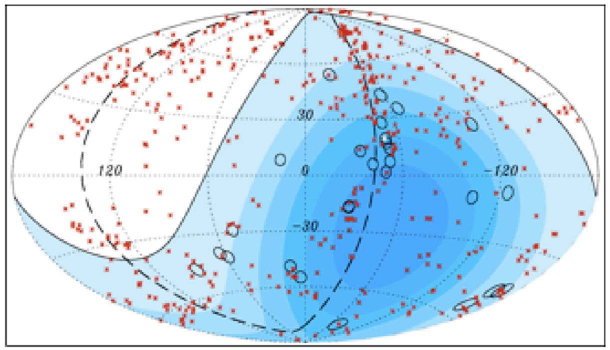
> 10 ordres de grandeur en énergie !

spectre angulaire



[Iyono et al 2005]

rayonnement isotrope (marche au hasard dans le champ B galactique)

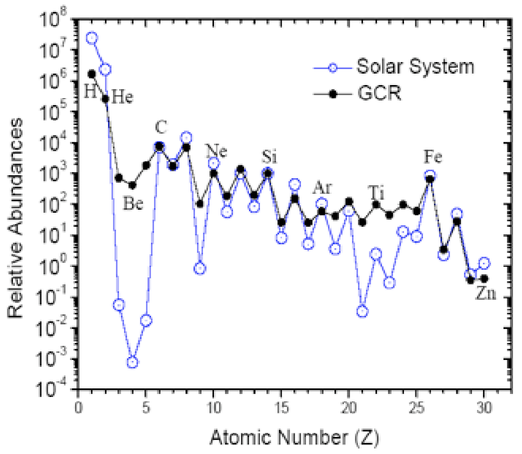


[Pierre Auger Coll. 2007]

sauf à ultra hautes énergies

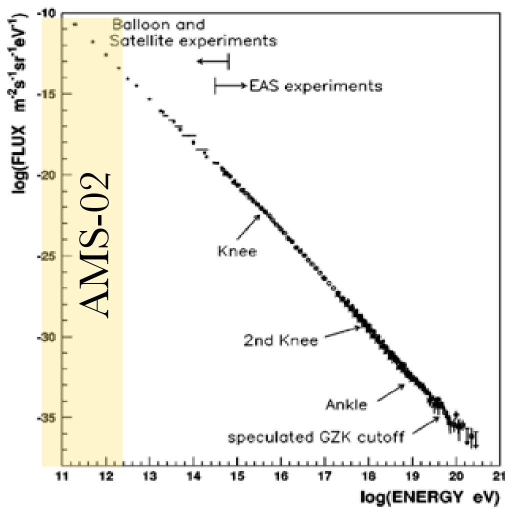
Scientific goals of AMS-02

spectre de masse



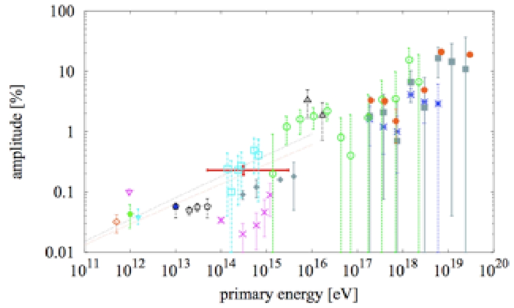
[Israel 2004]

spectre en énergie



[Nagano & Watson 2000]

spectre angulaire



[Iyono et al 2005]

S/P (up to 1TeV)
Positrons (up to 300 GeV)
Electrons (up to 1TeV)
Anti H, D (up to 300 GeV)
Radioactive isotopes

$E_{max\text{-}H}$ = a few TeV/n

Any estimate/upper limits on electron/positron flux anisotropy is important (Pohl 09)

- Aim of the talk: discuss links between AMS-02 and microphysics in astrophysical sources and transport in the ISM … not restricted to phenomenology.

Sources of GCR

- Supernova remnants (SNR):
  - Positive arguments
  - Recent observations
  - Recent developments in the theory of particle acceleration
- Other sources: Pulsars (see Timur's talk), micro-Quasars

Arguments: Standard GCR model

- Energetic : Around 20% of the explosion of a SN to be injected into energetic particles to explain the local CR energy density (1.5 ev/cm^3).
- Composition : Acceleration of standard interstellar matter + spallation along the CR path in the Galaxy.
- Spectrum : Source spectrum close a power-law with an energy index of 2-2.1

All fit rather well in the supernova remnant diffusive shock acceleration model (Drury+01)

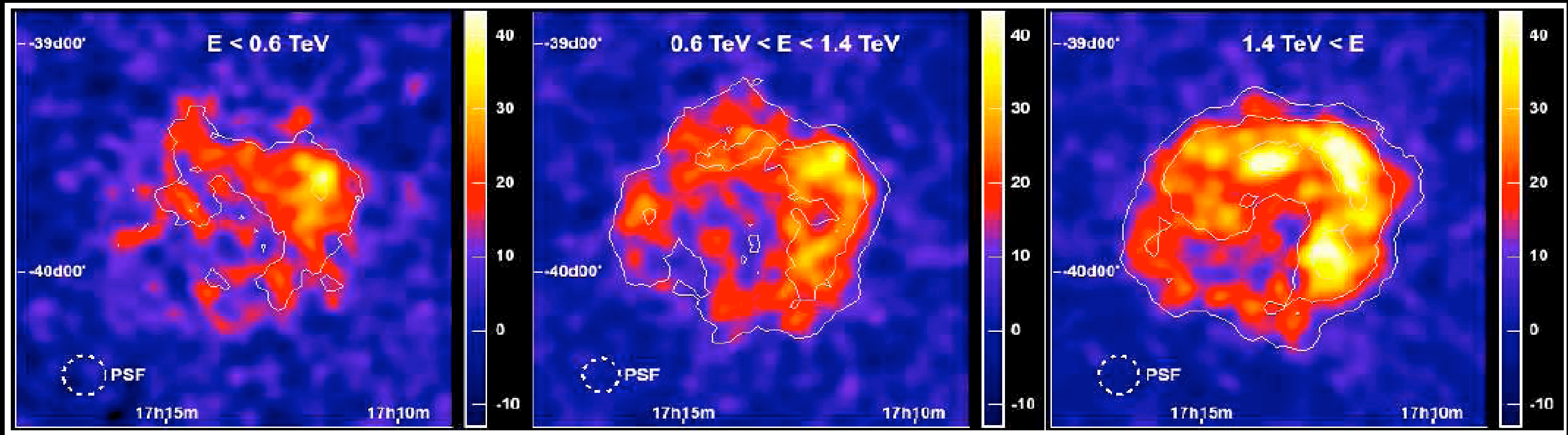
Particle acceleration in (young) SNR: observations

- Multiwavelength spectrum + gamma-ray emission
- X-ray Filaments

High energy particles in SNR

Breakthrough by Tcherenkov telescopes: HESS, MAGIC, VERITAS

SNR RXJ1713-3946.5



Aharonian+06

- Source spectrum: power-law ($\Gamma = 2.1$)

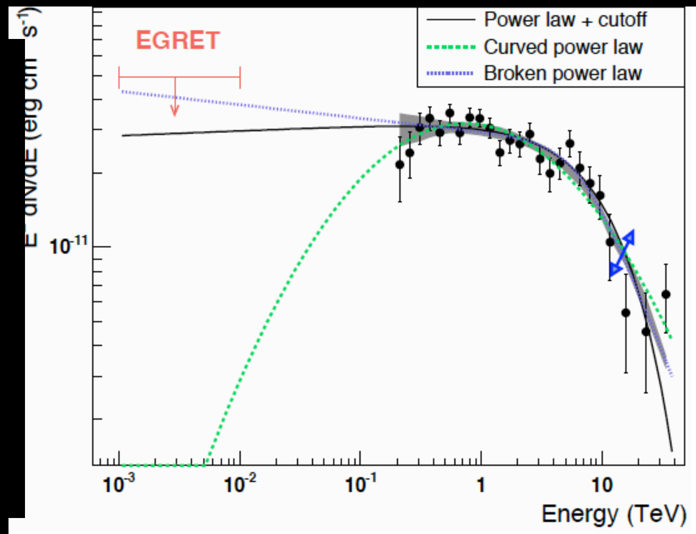
+cut-off E_c~10 TeV (at least softening)

- 5 other SNRs:

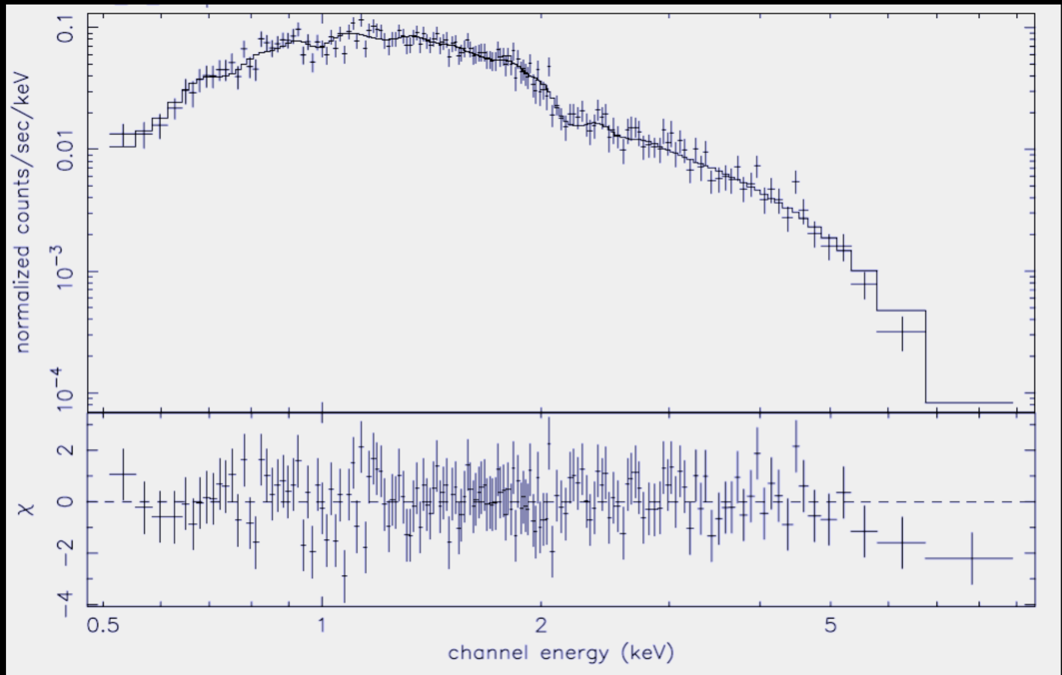
Cassioppeia A, IC 443

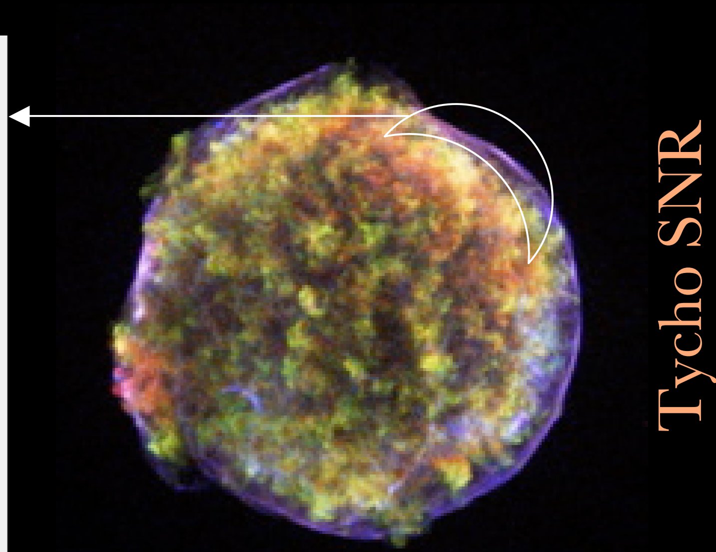
(Fermi+Veritas,Magic)

RCW86, SN1006, W51 (Fermi+HESS)



X-ray filaments





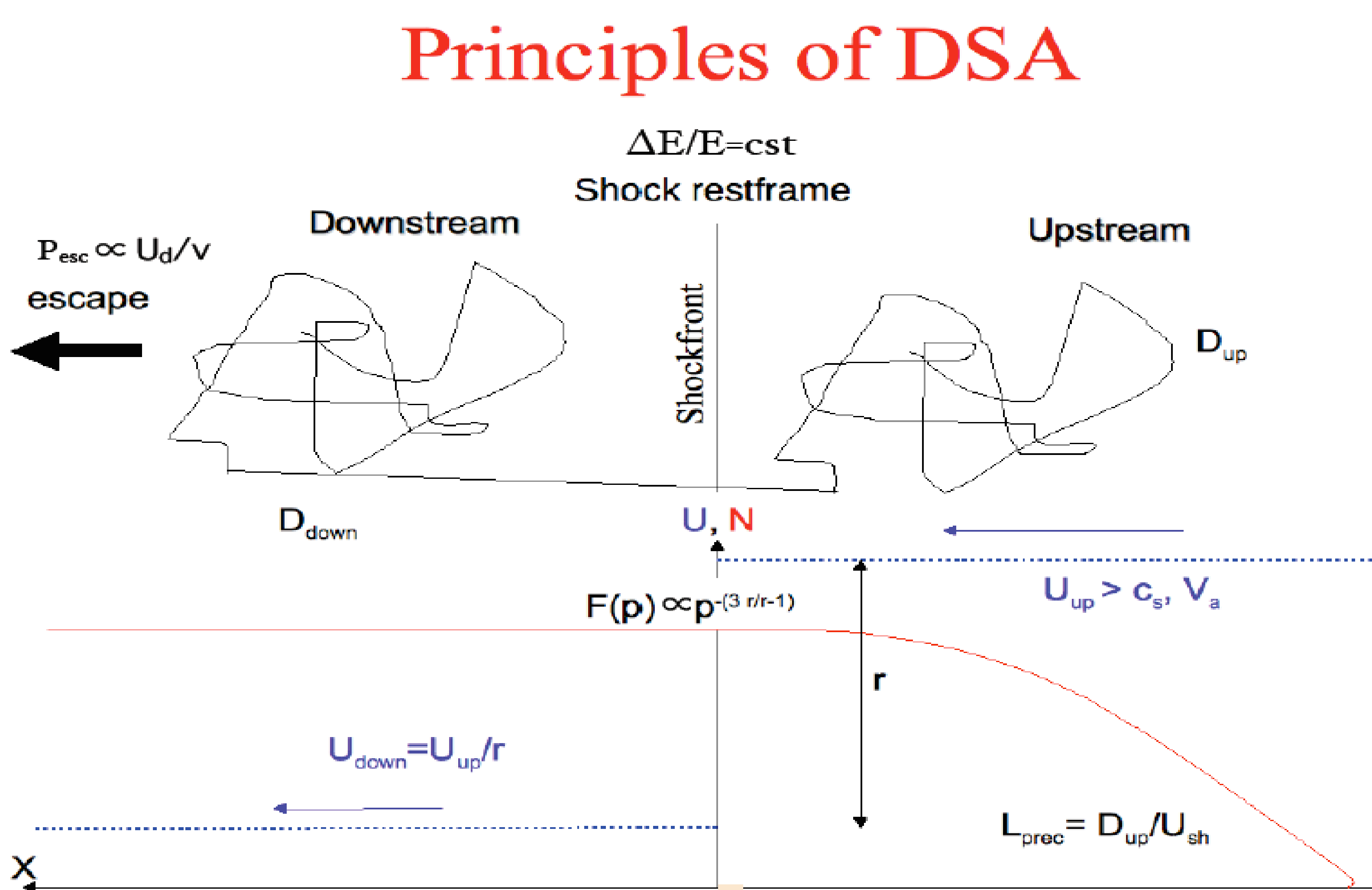
Hwang+02

Non-thermal spectrum= synchroton radiation of multi-TeV electrons in strong magnetic fields

MF ~ 100-500 μGauss about 100 x ISM MF

Particle acceleration in SNR: theory

- Diffusive shock acceleration = acceleration of particles through successive cycles of shock crossing (Bell78)



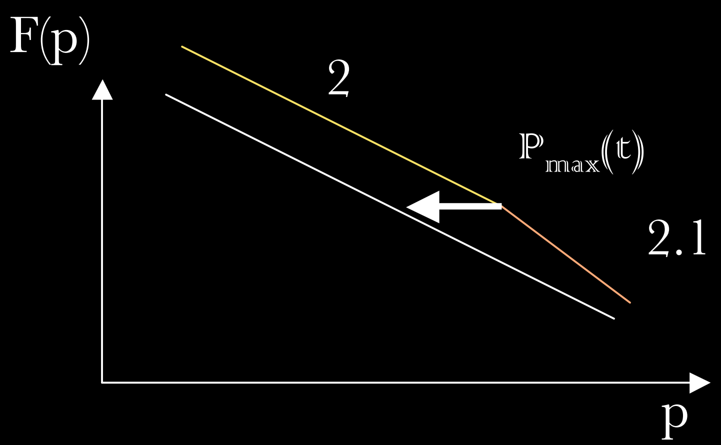
Wave-particle resonant interaction (see next)

* *Wave = EM fluctuations*

<u>In shocks</u>: Wave can be self-generated by the particle population.

Particle acceleration in SNR: theory

- Diffusive shock acceleration = acceleration of particles through successive cycles of shock crossing (Bell78)
  - Fermi acceleration: constant relative energy gain.
  - Diffusive: shock crossing provoked by scattering off magnetic fluctuations.
- Production of a power-law (energy spectrum):
  - Test particle s = 2 (r=4 strong non-relativistic shock)
  - Including adiabatic losses downstream and time dependent maximum energy s = 2.1 (Bogdan & Völk83) or effect on compression ratio r<4…



Sources: caveats & issues

- Caveats: Non-liear effects (Drury & Malkov 01)

1) Backreaction: Energetic particle pressure 10-50% ram pressure => shock modification through higher compression.
2) Magnetic field amplification: Energetic particles produces MF fluctuations (Bell 04, Pelletier+06, Marcowith+06, Marcowith & Casse 10)
   - Increase the confinement and E_{max}
   - Pump energy to the EP population and soften the spectrum
   - Reduce the compression of the plasma; hence the backreaction

- Issues
  - The whole process ?
  - The fate of accelerated particles $E_{max}(t)$?
  - Injection process <=> shock formation
  - Relative injection electrons/positrons-ions $K_{ep} \sim 10^{-2}$

Sources: interests for AMS-02

- Constrains on K_{ep} : Primary electrons.
- Secondaries positrons produced at source (pp collision) as it seems to be required from PAMELA's results.

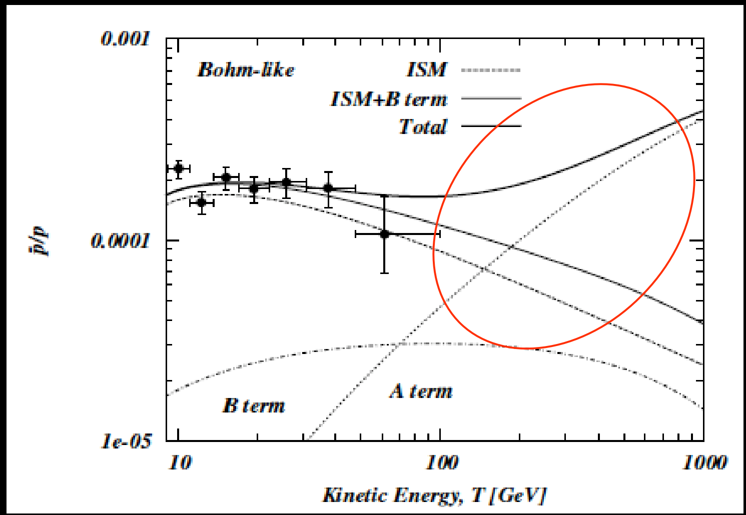
Example: <u>The old SNR model:</u> 2 components in addition to the spallation component (also multiple acceleration in close bubbles)

- e^+/e^-: Two populations at sources (injected from the interaction of primaries and then advected downstream, further accelerated at shock) Blasi'09 => flat distribution of reaccelerated pairs (diffusion effects)
- Anti-protons prediction consistent with PAMELA measurements (same components as in the $e^{+/-}$ case) Blasi & Serpico'09
- Constraints from S/P ratios ? Gamma-rays?:

flat secondary component …

Antip-p spectrum: old SNR model vs PAMELA

Slope of the A (accelerated) term sensitive to the diffusion regime IN the source



Cosmic ray propagation

- Cosmic ray release and propagation
- More complex effects:
  - Close to the sources
  - In the interstellar medium
  - Solar wind modulation (see dedicated talk)

CR release in the interstellar medium

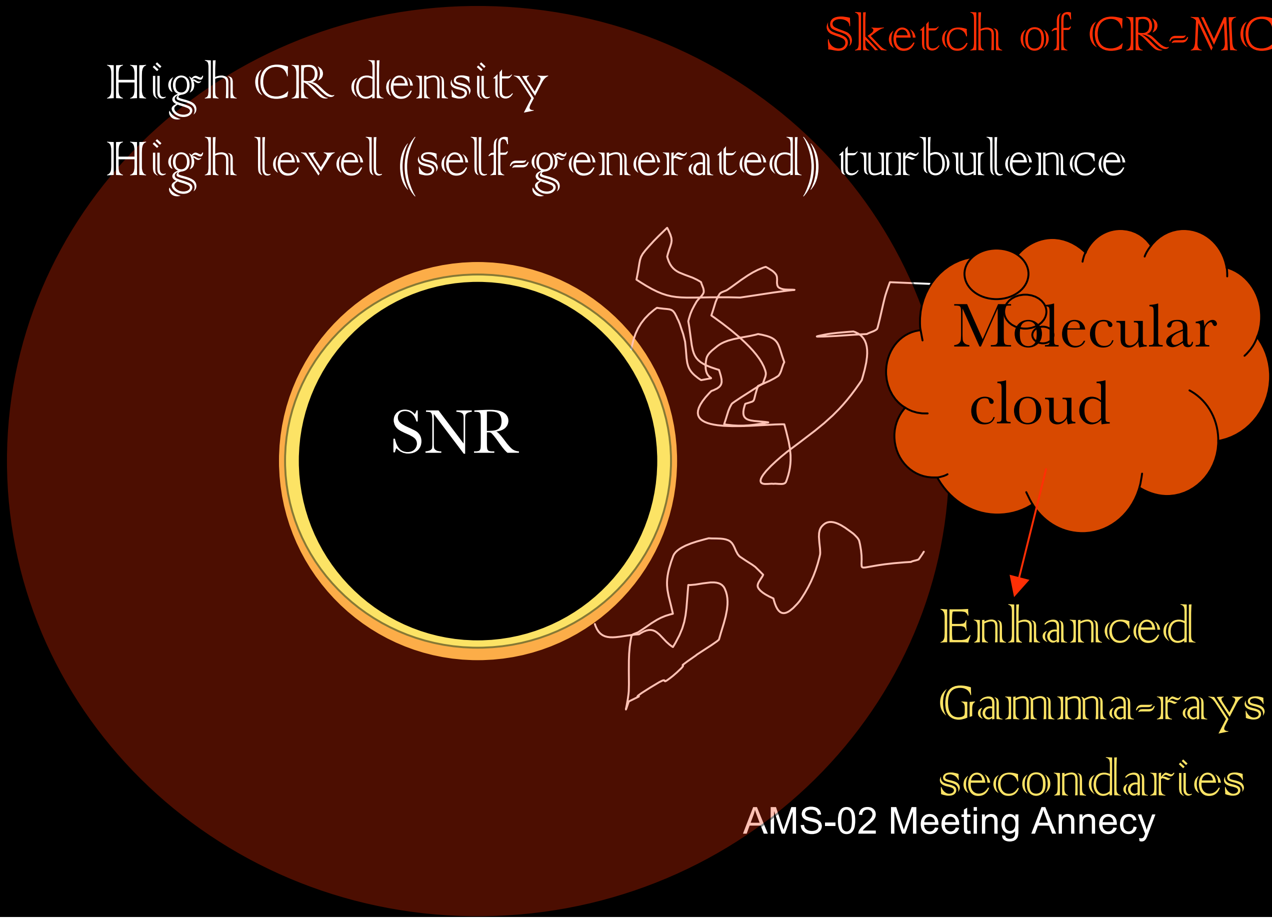
- Depends on:
  - Shock dynamical properties (that may be modified by CRs & waves)
    - $R_{sh}(t)\ V_{sh}(t) \equiv D(E_{CR-Max}) \propto t^{-1/5}$ (in Sedov phase)
  - Magnetic field time evolution <=> microphysics
    - $D(E_{CR-max}) \equiv c\ r_L(E_{max})^a \propto B(t)^{-a}$ $(B(t) \propto t^{-a'/a})$
    - a: depends on the turbulence properties
  - A SNR releases its CRs as a delta function at $E_{max} \propto t^{-(a'+1/5)}$
  - Role of external turbulence (local injection of fluctuations).

CR-Molecular clouds interaction

- Local CR gradient: CR confinement around sources (external turbulence and self-generated turbulence) Ptuskin+08 : likely different than mean ISM.

Fujita+10: CR confine close to the SNR shock until the sonic regime is reached.

Sketch of CR-MC interaction



CR sea
Low level turbulence (injection at large scales)

Enhanced Gamma-rays & secondaries

Gabici+07

Particle transport microphysics

- DSA and transport in the ISM based on wave-particle interaction (wave with a wave number $k = 1/\lambda$) => velocity pitch-angle scattering
  - Wave-particle resonance
  - Non resonant: advection, large scale chaotic motions …
- Complete description exists only in *quasilinear-theory (QLT)* Schlickeiser 02
  - Particle motion is unperturbed !

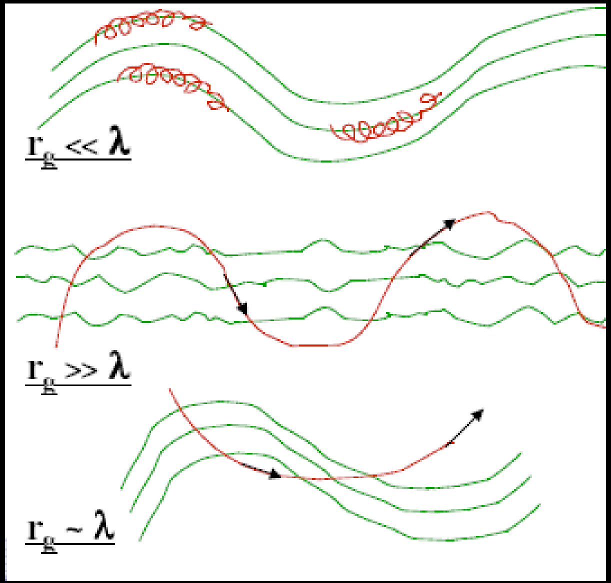
  $\Rightarrow$ Limited to small turbulence level $\delta B << B$.
- 3D turbulence usually approximated by a composite 2D-Slab model => analytical calculations: adapted to solar wind

Synchrotron resonance:

Energetic particle-MHD wave

$\omega << \Omega$

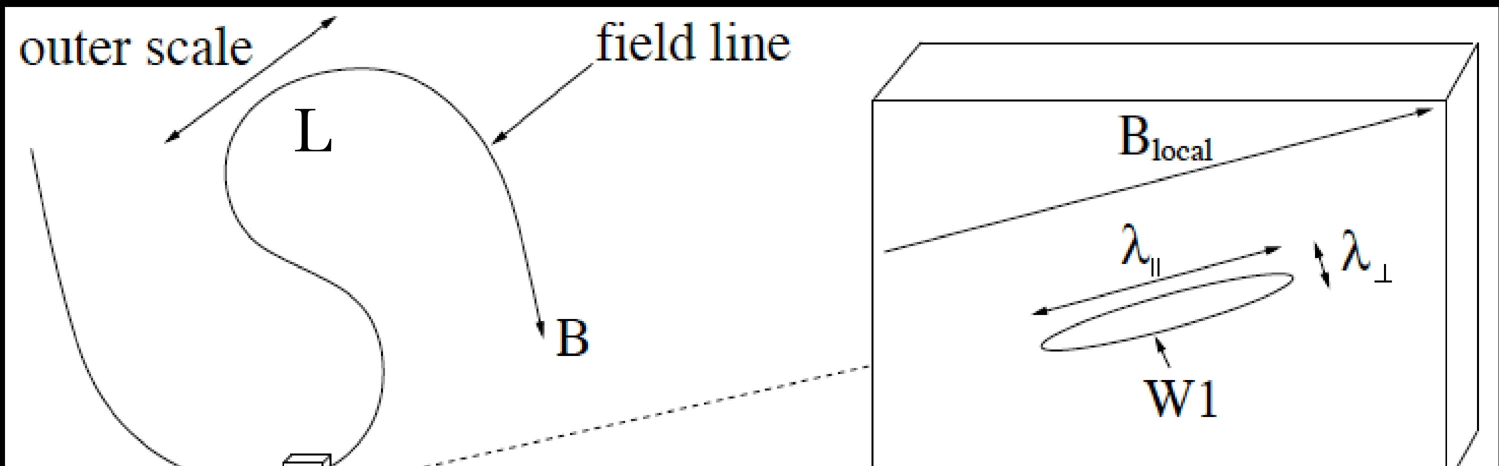
$R_g = v/\Omega \sim \lambda$



See meeting in Montpellier

More complex effects

- But simulations (see e.g. Biskamp 03) show (incompressible turbulence):
  - MHD turbulence is made of Alfvénic (Alfvén, slow magnetosonic like) modes ≠ Slab + 2D
  - MHD turbulence is anisotropic (Higdon 84, Goldreich & Sridhar 95)
- QLT has some caveats:
  - Anisotropic turbulence is highly unefficient in scattering CRs.
  - 90° problem - Perpendicular transport (infinite mfp)
- Several solutions proposed:
  - Resonance boadening in different non-linear models …. Yan & Lazarian 08, Shalchi 09



MHD turbulence anisotropy

$$\lambda_{//} = L^{1/3}\,\lambda_{\perp}^{2/3}$$

Chandran 04

Transport: Current issues

1. The turbulence in the ISM is *compressible* : Fast magnetosonic waves (non resonant interaction)
   – Account from the different ISM phases & damping properly.
2. Two basic approaches:
   – Start from a model of turbulence and calculate the diffusion coefficients = model dependent (e.g. Casse+02)
   – Start from MHD simulations and re-construct the diffusion coefficients = limited in scale resolution (e.g. Beresnyak+10)
3. Derive D_{pp} : stochastic Fermi acceleration (only available in QLT)
4. Include the possibility of non diffusive transport.
5. Combine the different sources of turbulence (large scale, self-generated close to the sources)
6. Include the retroaction of CRs on flows and hence turbulence.

Transport: interests for AMS-02

- Escape from the Galaxy controlled by the interaction with turbulence injected at large scales <=> S/P ratios.
  - Transport index δ = 0.3 (Kolmogorov), 0.5 (Kraichnan), 1 (shock turbulence)
  - Still pending issue; e.g. Kraichnan/Kolmogorov => Fast/Alfvén waves dominated dynamics.
- Escape from the sources controlled by the interaction with turbulence injected by the cosmic rays themselves <=> local CRs
  - Electrons/positrons measurements (especially beyond few tens GeV) can probe this physics + Radioactive elements + Gamma-ray emission can probe the physics of escape.

    ⇒ Source census (see Timur's talk)

    ⇒ Molecular cloud census

    ⇒ Radiation fields census (see Timur's talk)

    ⇒ Test different source magnetic field relaxation models & time dependence of escape.