Theory of cosmic ray acceleration and transport

status and perspectives

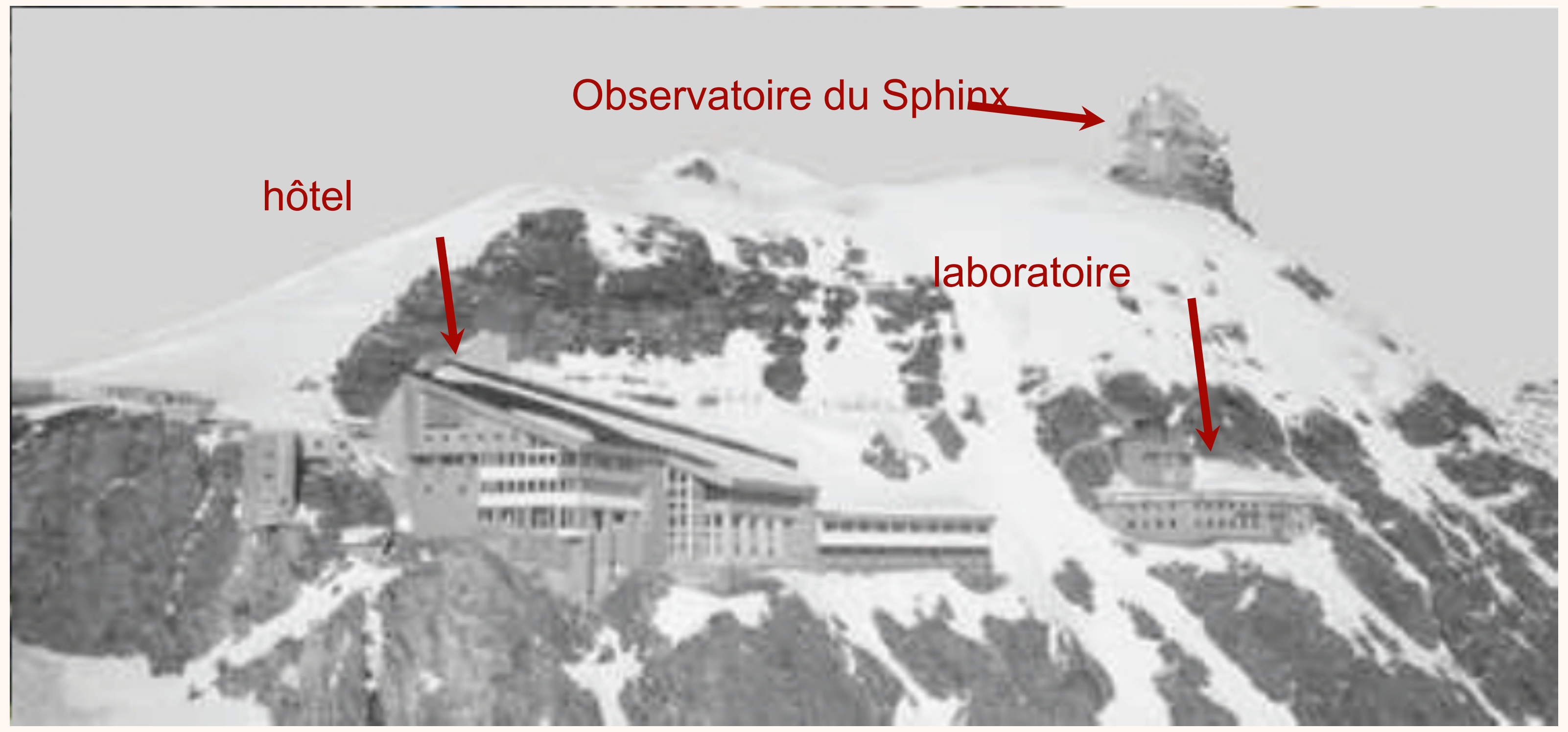
Alexandre Marcowith LUPM LABORATOIRE MONTPELLIER UNIVERS & PARTICULES — Journée Théorie IN2P3 2021 —

Scientific context

More than 100 years after the discovery the origin is still not known

V. HESS and next contributors : CR come from space, not only of solar origin (H. Alfvèn's guess)

Particle physics started with Cosmic Ray studies until 50's (discovery of air showers, P. Auger 1938), > discovery of positrons, muons …



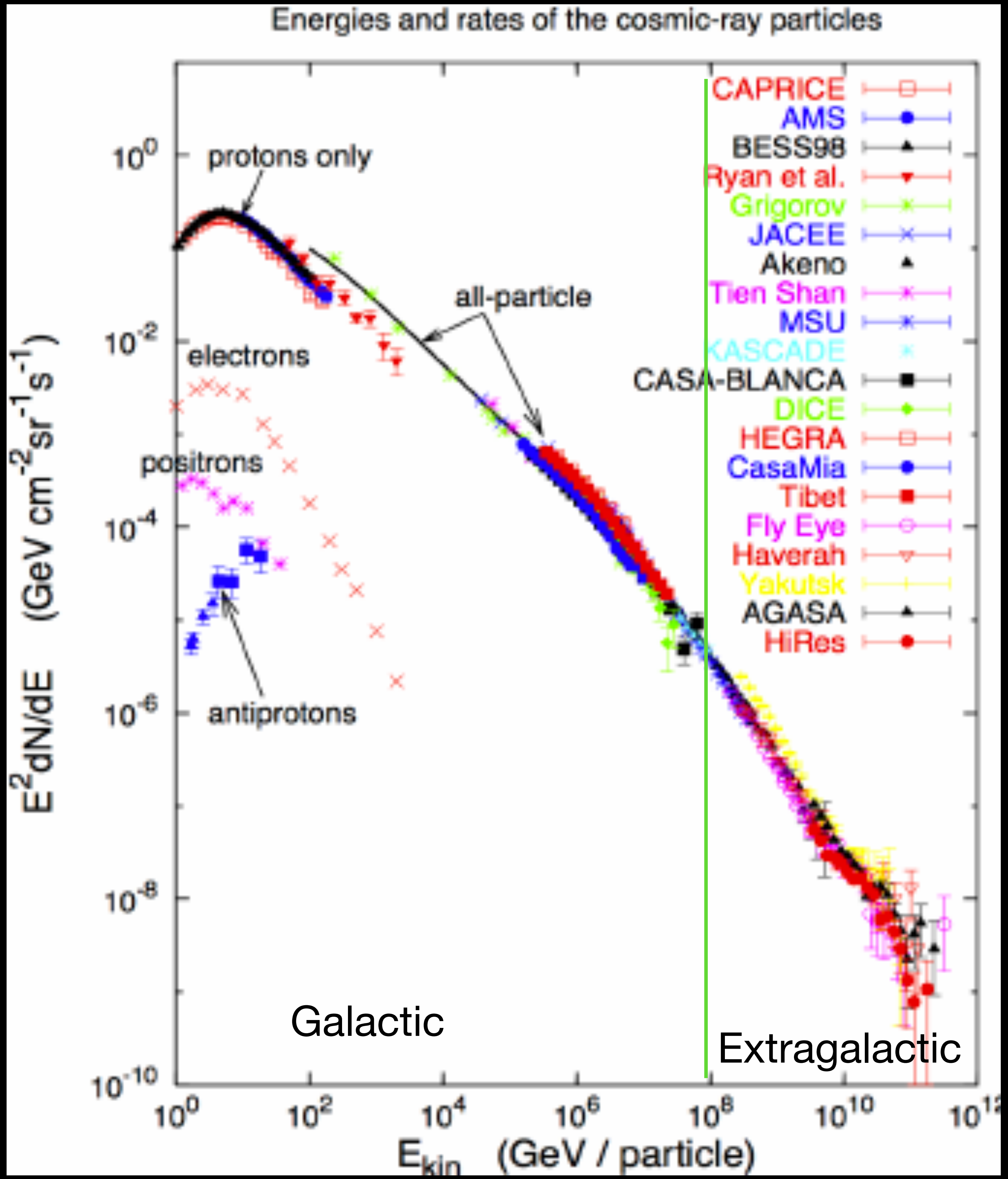
laboratoire de la JungFraujoch (3 500 m)

References:

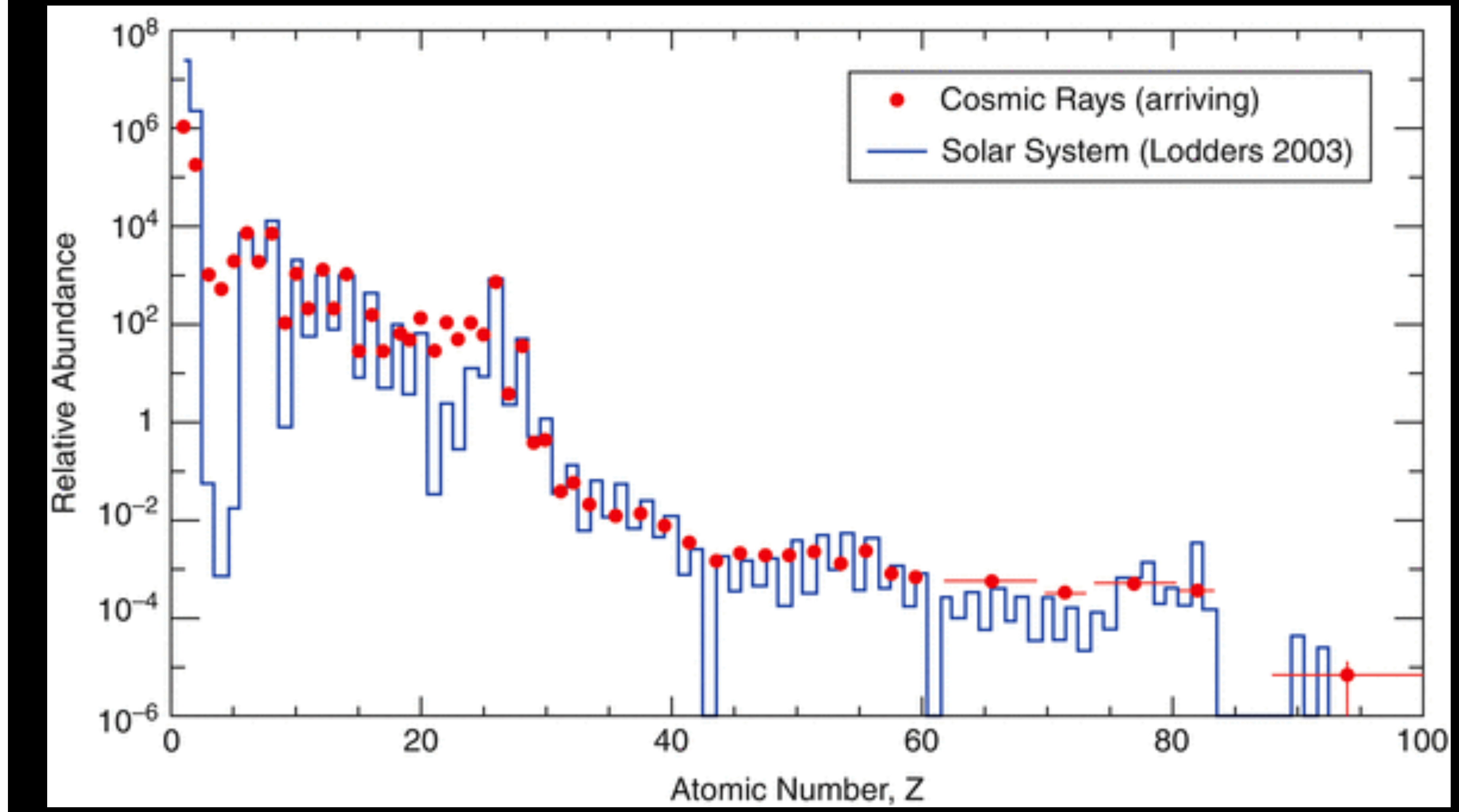
https://www.refletsdelaphysique.fr/articles/refdp/pdf/2013/01/refdp201332p8.pdf

The three Cosmic Ray spectra

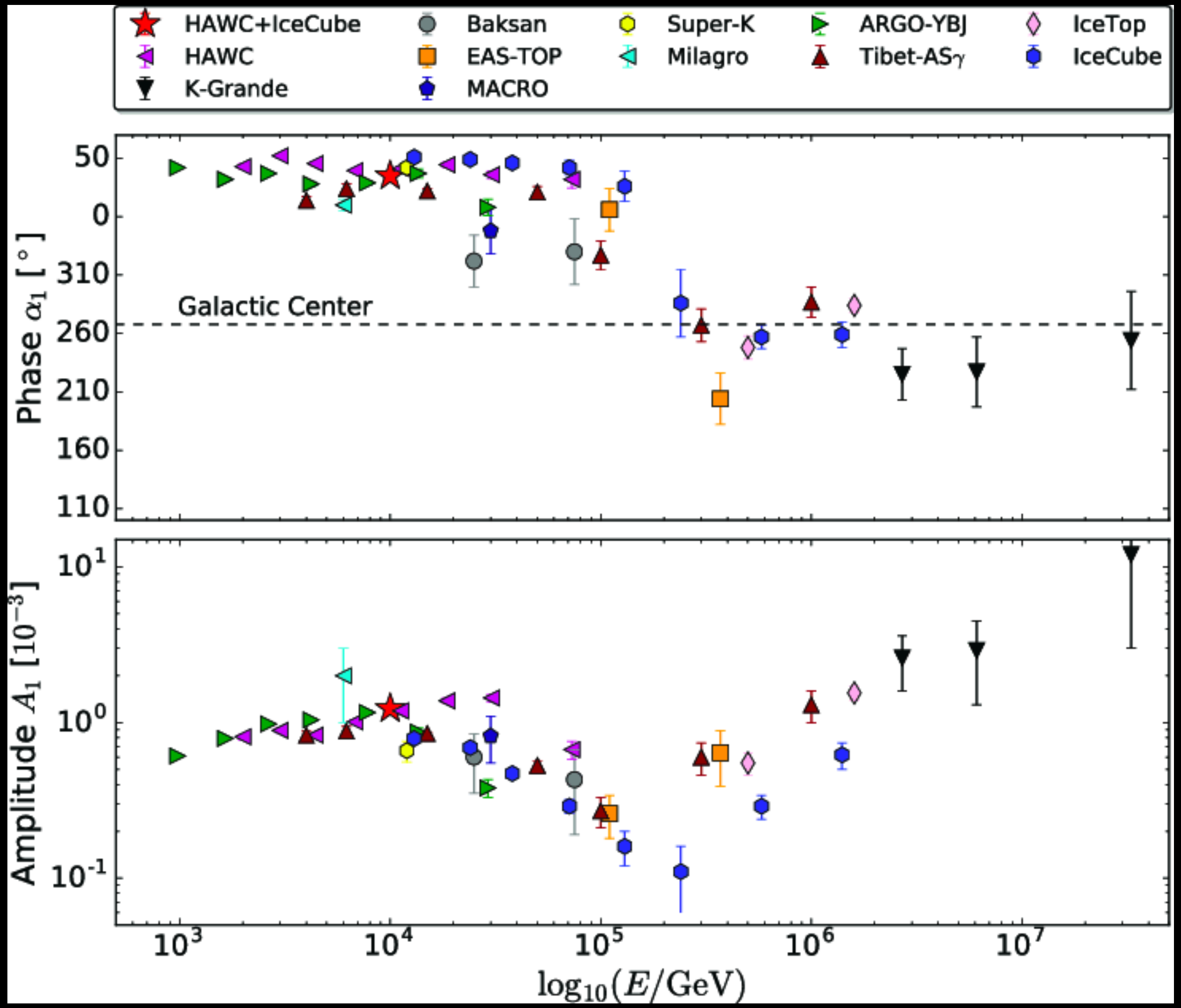
Energy spectrum / Composition spectrum / Angular spectrum



From MeV to almost ZeV or 10^{21} eV



Light element production by spallation
(here composition @ a few GeV/N)



High level of isotropy
(anisotropy increases at the highest energies)

Cosmic Ray sources

Galactic sources : energies : MeV-100 PeV

- <u>Most favorite</u> : Remnants of Supernova but other could contribute : massive star clusters, pulsars (for leptons), the central galactic black hole (Sagittarus A*)…

- <u>Main energetic argument</u> : Pressure into CRs : $P_{\rm CR} = \frac{e_{\rm CR} V_{\rm G}}{T_{\rm res}} \sim 10^{41} {\rm erg/s}$ ~ 10% power injected by Supernovae in the Galaxy (for 3 SNe/century)

— Energetically feasible —

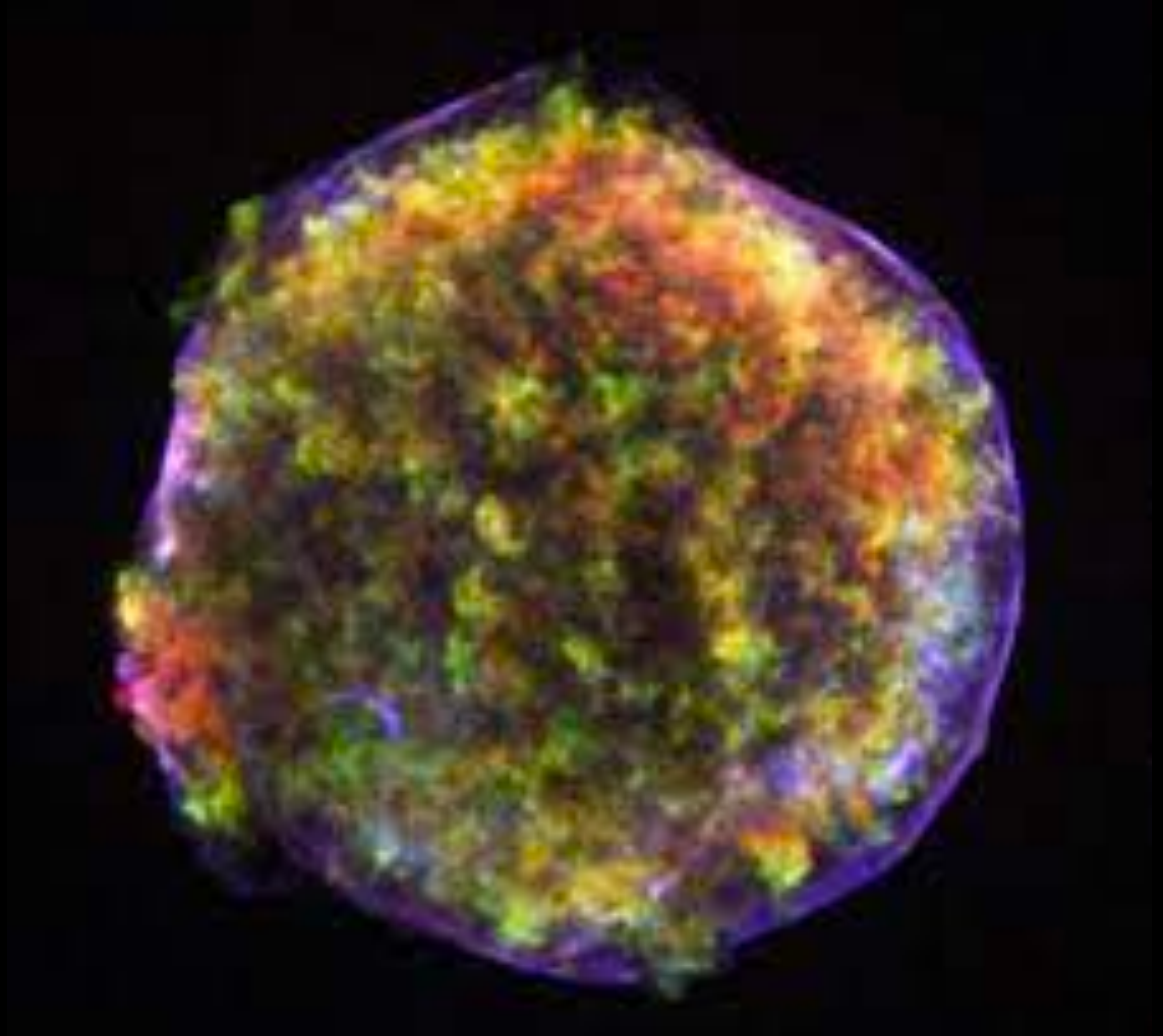
[V_G galactic disk volume, T_{res} CR galaxy residence time, e_{CR} CR energy density]

- Observations do show particle acceleration is on-going.

Evidences of acceleration phenomenon

Supernova remnants : non-thermal spectrum from radio to gamma-rays + X-ray filaments

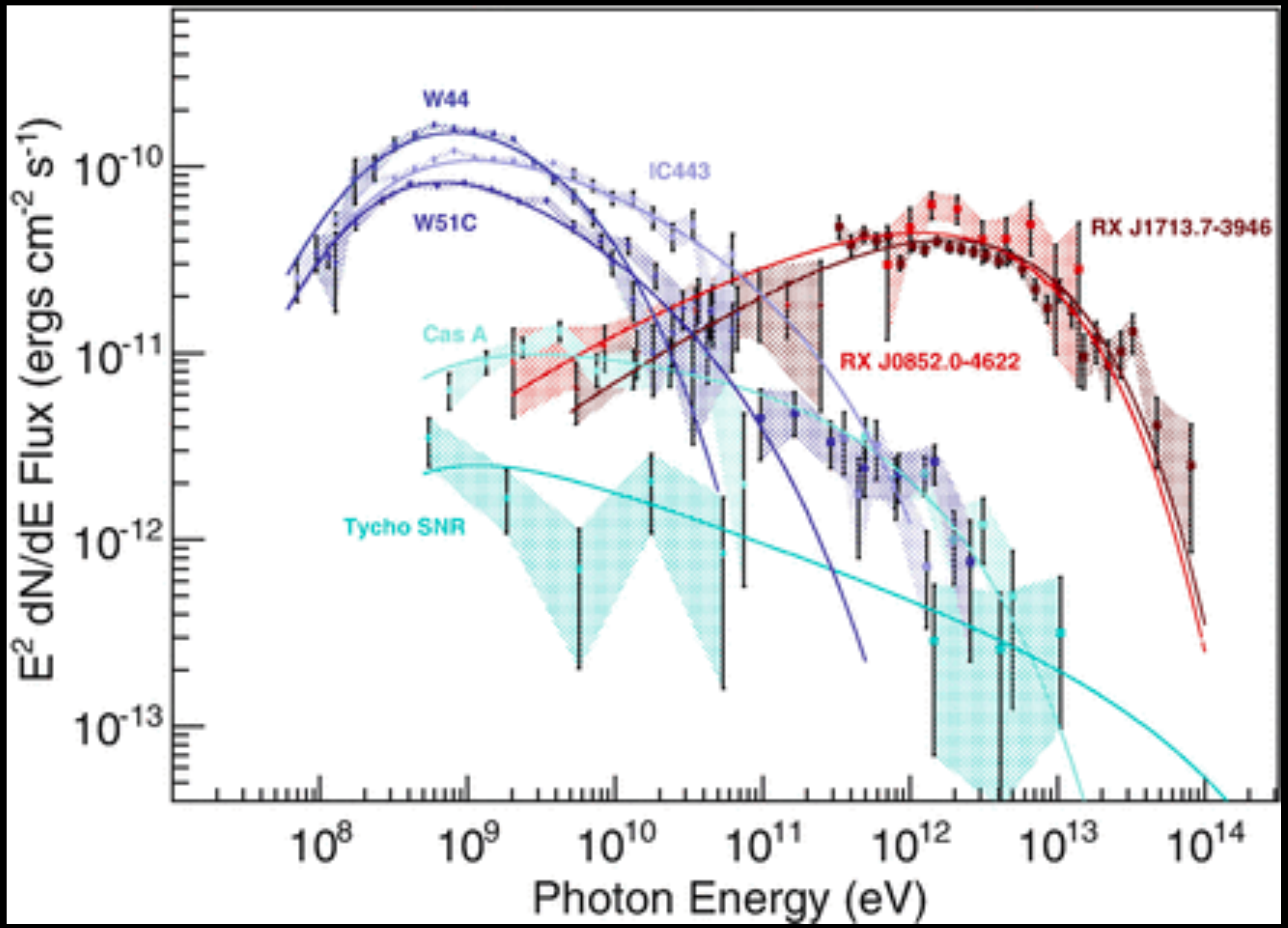
Tycho SNR image at X-rays by the Chandra satellite



Blue: thin rims associated with the forward shock : non-thermal synchrotron radiation by TeV electrons in up to milli Gauss level magnetic fields.

Evidence of strong magnetic field amplification by on-going plasma processes (eg Parizot et al 2006 A&A)

Gamma-ray spectra of several historical supernovae



Non-thermal (power-law) photon distribution + require relativistic particles (kinetic energies above GeV to TeV)

Cosmic Ray sources

Galactic sources : energies : MeV-100 PeV

- Most favorite : Remnants of Supernova but other could contribute : massive star clusters, pulsars (for leptons), central galactic black hole …
- Main energetic argument : $P_{\rm CR} = \frac{\epsilon_{\rm CR} V_{\rm G}}{T_{\rm res}} \sim 10^{41} {\rm erg/s}$ ~ 10% power injected by Supernovae in the Galaxy (for 3 SNe/century) — Energetically feasible —
- Observations do show particle acceleration is on-going.

Several big issues :

1) Fine … but one major difficulty is to link what we observe at sources and what we measure on Earth (see the transport problem)

2) We do not know yet how exactly CR escape from their sources.

3) Calculating CR distribution at sources is a very complex task because of high degrees of non-linearity.

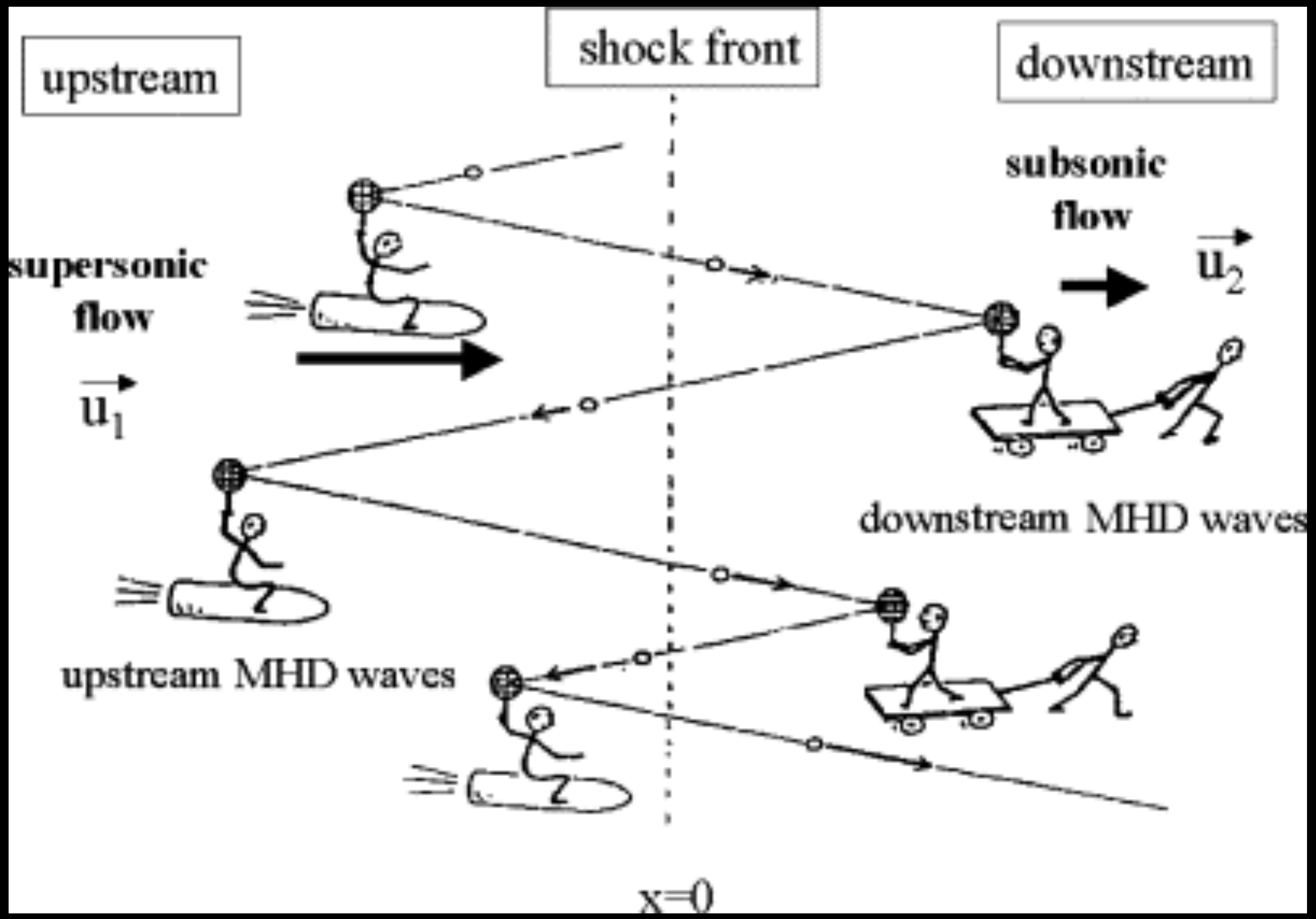
(3) Non-linear plasma physics at sources

Particle acceleration at fast, strong shocks

- Main mechanism: diffusive shock acceleration but in fact challenging : multi-scale physics of a complex system

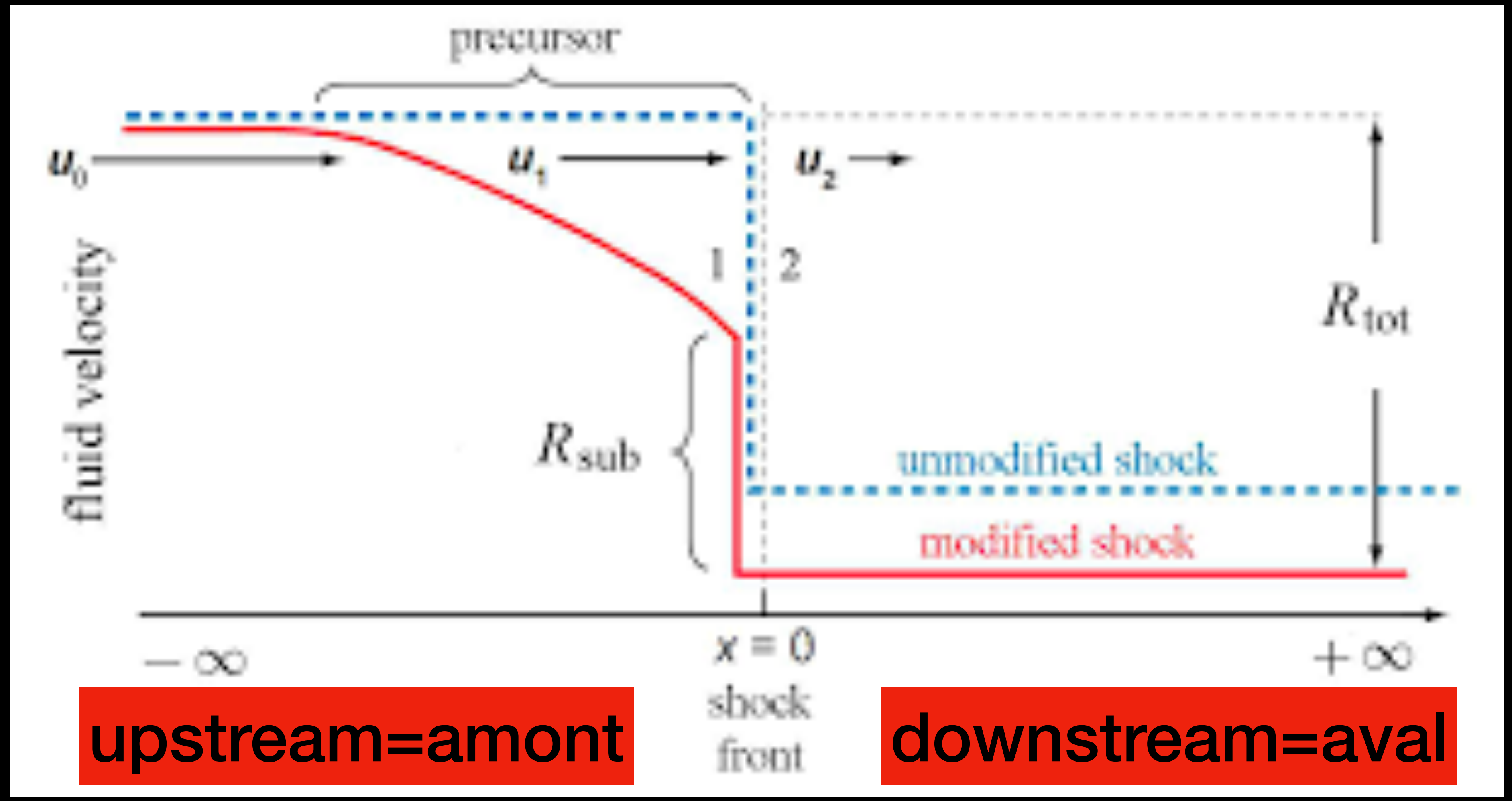
> CR back-reaction and self-generated turbulence : up to 8-9 orders of magnitude in scales to cover : indeed Particles are injected from the shocked plasma downstream (MeV) and have to be accelerated up to PeV energies

Principle of diffusive shock acceleration (DSA, eg Bell 1978 MNRAS)



CR scattering back and forth the shock front with a compression ratio r by magnetic perturbations naturally produces power-law distributions N(E) scaling as $E^{-(r+2/r-1)}$

Shock profile including CRs back-reaction in fluid Eqs (eg Drury et al 1981)



The compression ratio depends on the particle energy, non universal power-law anymore

Non-linear plasma physics

Strong developments of numerical studies

- Challenging : multi-scale physics of a complex system

> CR back-reaction and self-generated turbulence : up to 8-9 orders of magnitude in scales to cover.

> Different tools : Particle-in-cell (small scales, injection), hybrid methods and kinetic-magnetohydrodynamics (largest scales), semi-analytical solutions of 1D Fokker-Planck equation

Technique	Particle-in-cell	hybrid	Magneto-hydrodynamic	Vlasov / Fokker-Planck
scales	$c/w_{pe} \sim L$	$c/w_{pe} << L$	L =system scale Time > $1/w_{ci}$	all (in principle)
based on …	Maxwell + Lorentz force	Maxwell + Lorentz force, electrons as fluid	MHD + Lorentz force	kinetic Eqs for the non-thermal component
geometry	usually 1D, 2D	1-2D rarely 3D	2D rarely 3D	usually 1D

Distribution function = sum of individual (macro) particles — Fluid description

Described in Marcowith et al 2020 LRCA

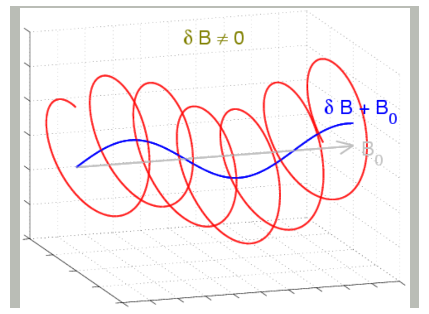
(2) Escape from sources

Still the effect of CR self-generated turbulence

When relaxed from the accelerator still CR have some over density/pressure and carry some current => trigger a series of plasma instabilities (still widely unexplored). Actually very complex : intrinsically 3D, time-dependent, non-linear.

> <u>One (popular) case</u> : CR resonant streaming instability (Nava et al 2016 MNRAS): Solve non-linear kinetic Eqs (Fokker-Planck like as for Markov processes) CR Pressure P_{CR} + Alfvén waves intensity I(k).

N.B. : The resonant character is $k = 1/r_g$, r_g is the CR gyro radius $r_g = (E/ZeB)$, E= kinetic energy, Ze charge, B total magnetic field strength



Non-linear coupled Eqs

$$\frac{\partial P_{\rm CR}}{\partial t} + V_{\rm A}\frac{\partial P_{\rm CR}}{\partial z} = \frac{\partial}{\partial z}\left(\frac{D_{\rm B}}{I}\frac{\partial P_{\rm CR}}{\partial z}\right),$$

$$\frac{\partial I}{\partial t} + V_{\rm A}\frac{\partial I}{\partial z} = -V_{\rm A}\frac{\partial P_{\rm CR}}{\partial z} - 2\Gamma_{\rm d} I + Q,$$

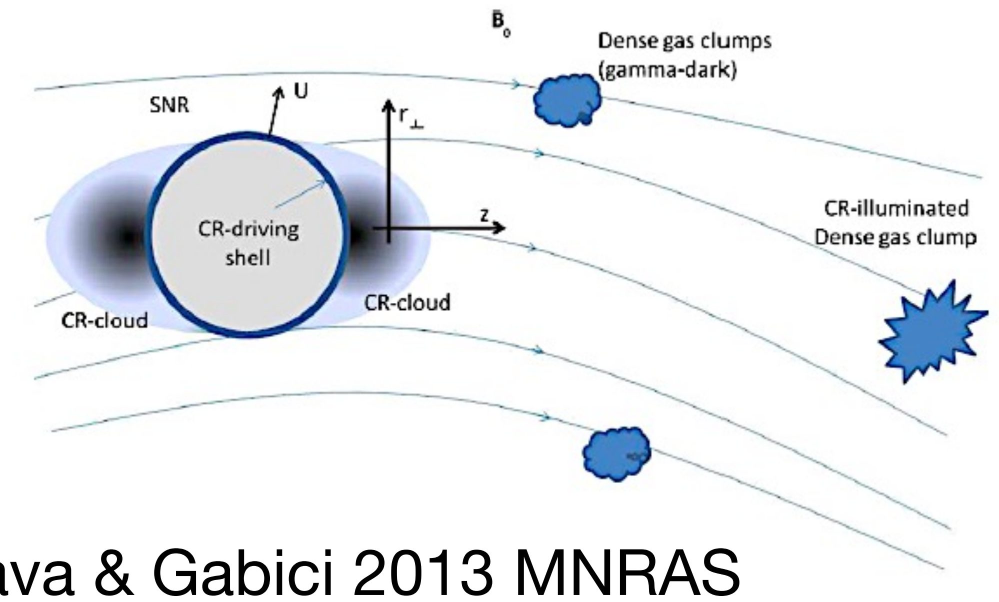
Non-linearity $D = \frac{D_{\rm B}}{I(k)} \propto \frac{r_g c}{I(k = 1/r_g)}$

Wave damping $\Gamma_{\rm d}$ It depends on the interstellar (galactic) medium properties (temperature, fraction of neutrals …)

CR diffusion D

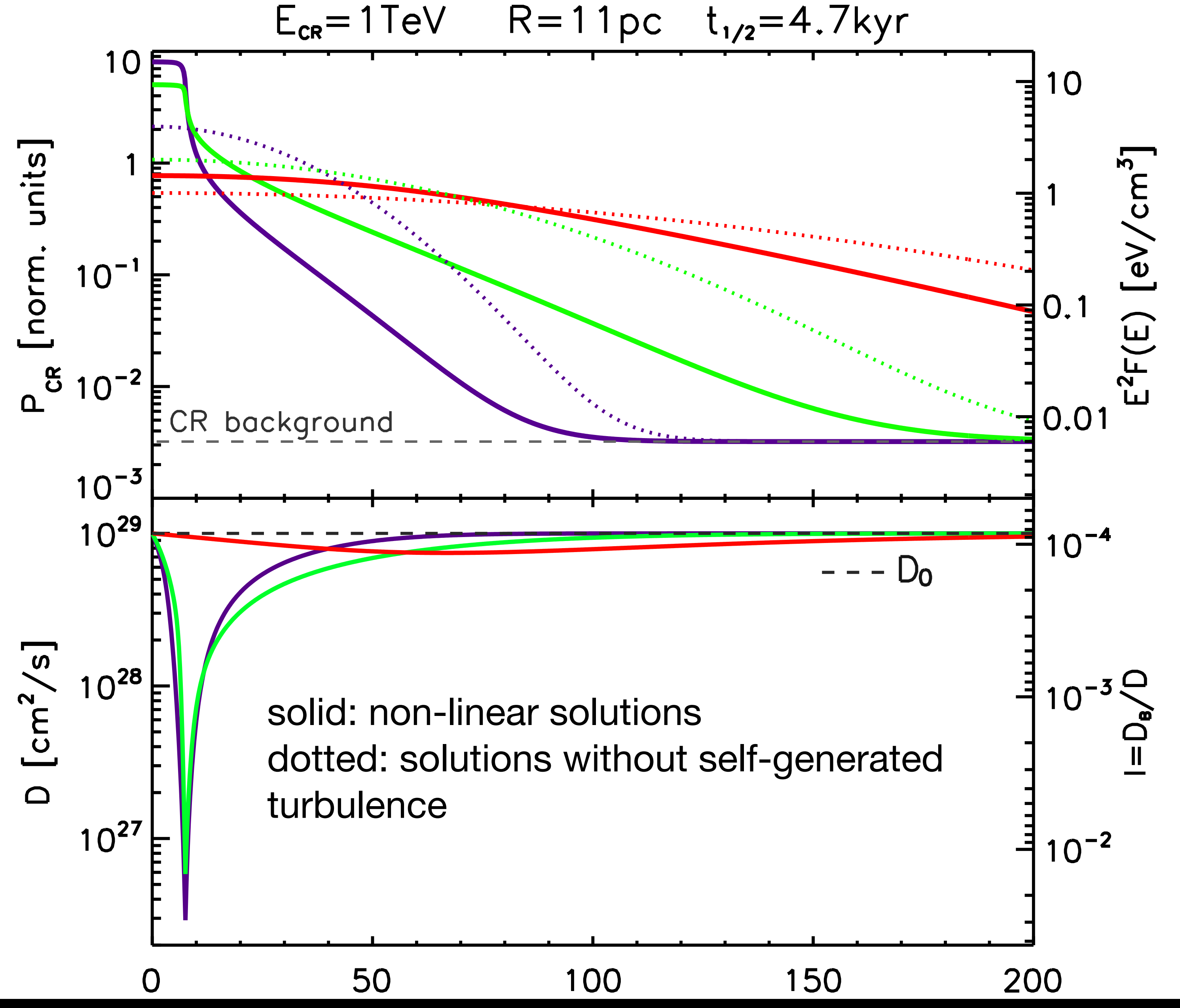
Advection at the Alfvén speed V_a

1D propagation



Nava & Gabici 2013 MNRAS

time dependent evolution of CR pressure & diffusion coefficient



(1) Cosmic Ray transport: microphysics

From sources to Earth : the journey through interstellar medium

- Most standard way : the quasi-linear theory (first order (Born) approximation) : solve transport (Fokker-Planck like) Eqs. (see back-up slide 1)

   A. The particle trajectory is the unperturbed one (Larmor motion)

   B. The amplitude of the fluctuations is low

   C. Perturbations exist at all scales (fully-developed turbulence)

> But QLT again is not valid *at* sources and *around* sources (to which spatial and time extend ?) : requires numerical simulations (PIC - MHD …).

Not even sure it is valid in the mean interstellar medium: the turbulence properties are strongly space and time-dependent (intermittency phenomenon, its effect barely addressed: Shukurov et al 2017).

(1) Cosmic Ray transport: phenomenology

Based on Quasi-linear theory

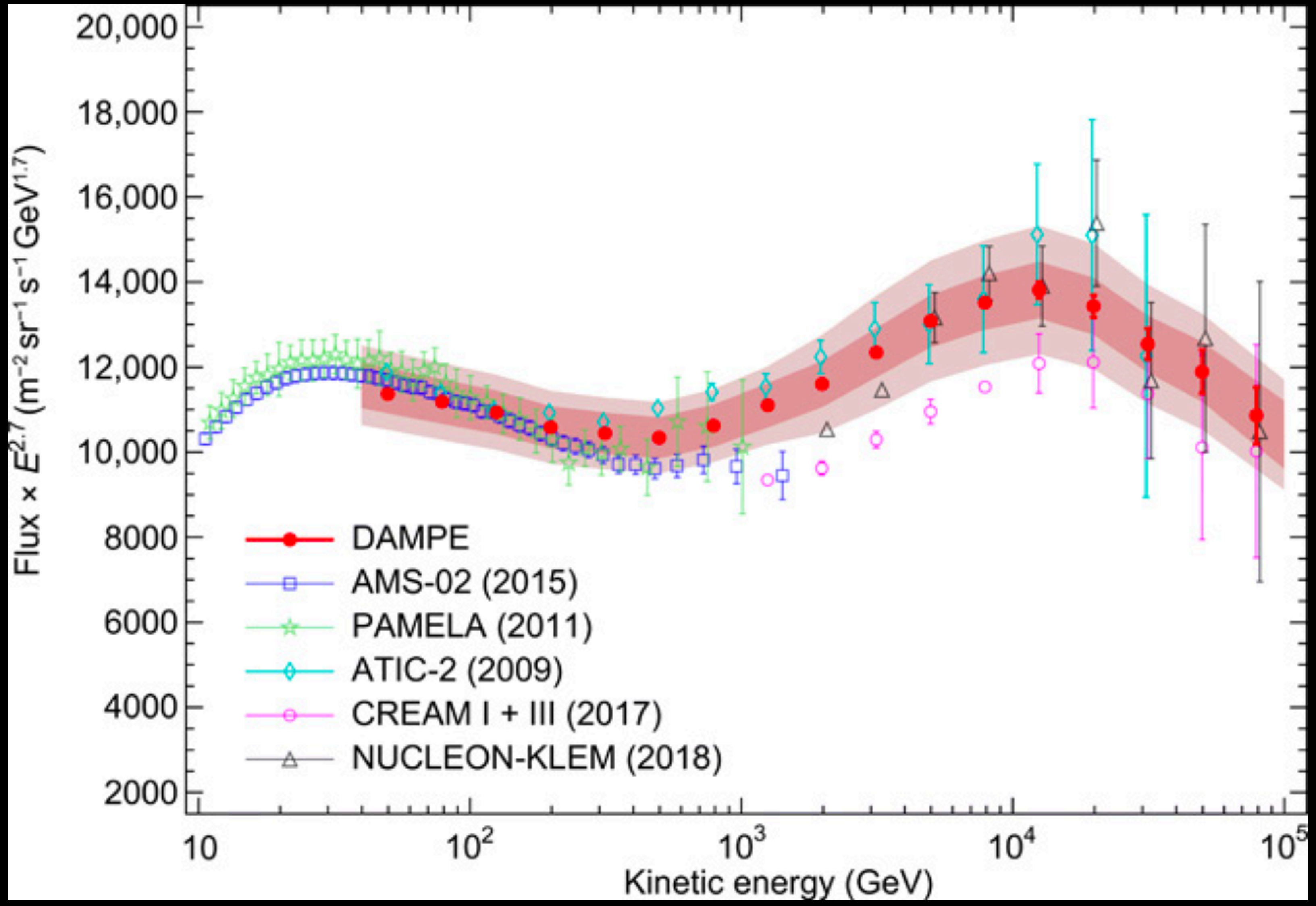
- Diffusion is almost parallel to the mean magnetic field

Diffusion coefficient $D(E) = D_0 \left(\frac{E}{E_0} \right)^a$, D_0, E_0, a adjusted by observations (spectra, anisotropy).

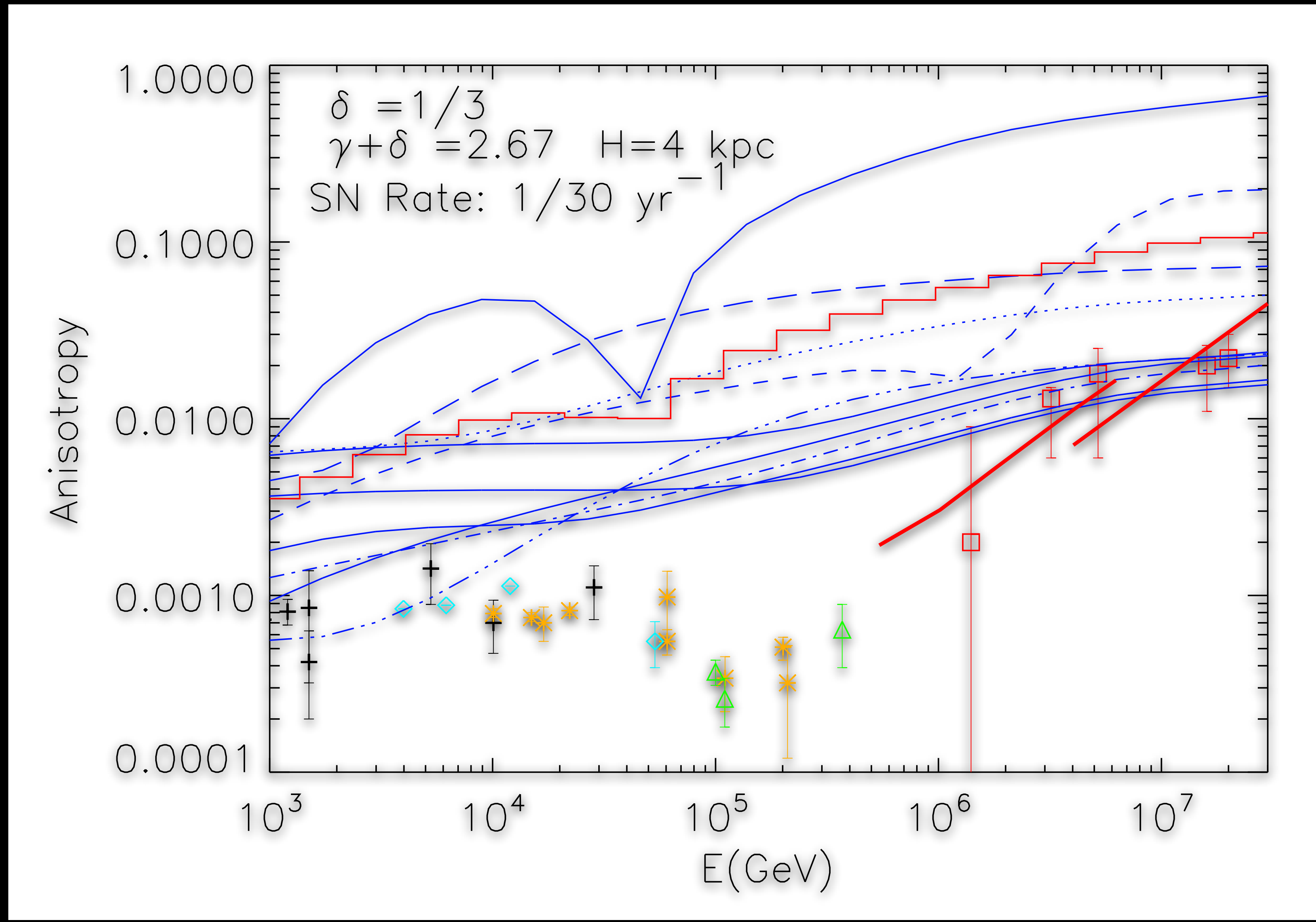
Typically $D_0 = 10^{28} \mathrm{cm}^2/\mathrm{s}$, $\mathrm{E}_0 = 4\mathrm{GeV}$, $\mathrm{a} = 1/3$

> But difficult to explain the full spectral properties: hardening around 200 GeV, too large anisotropy, gamma-ray gradient problem, low energy fit … need for more refined theory, interstellar medium models …

An et al 2019



Blasi & Amato 2012 JCAP



French theory teams

IN2P3	INSU	CEA
APC (low energy, acceleration, transport, multi-messengers, Galactic + Extragalactic)	CRAL (star formation dynamics, transport)	IAM Saclay (low energy, acceleration, dynamics, Galactic)
IJClab (low energy, transport, Galactic + Extragalactic)	IAP (low energy, acceleration, transport, Extragalactic)	CELIA (acceleration, Laser)
LAPTH (transport, Galactic)	IPAG (acceleration, Extragalactic, Galactic)	LULI (acceleration, Laser)
LPSC (transport, Galactic)	IRAP (acceleration, transport, Galactic)	
LUPM (acceleration, transport, dynamics, Galactic, multi-messengers)	LUTH (acceleration, Extragalactic)	

+ Important support by INP
+ Teams involved in cosmo-chemistry like IMPMC @ MHNN, CEREGE …(see back up slide 2)
+ Teams in space plasma physics like LATMOS …

Cosmic Ray physics

Prospects + organisation

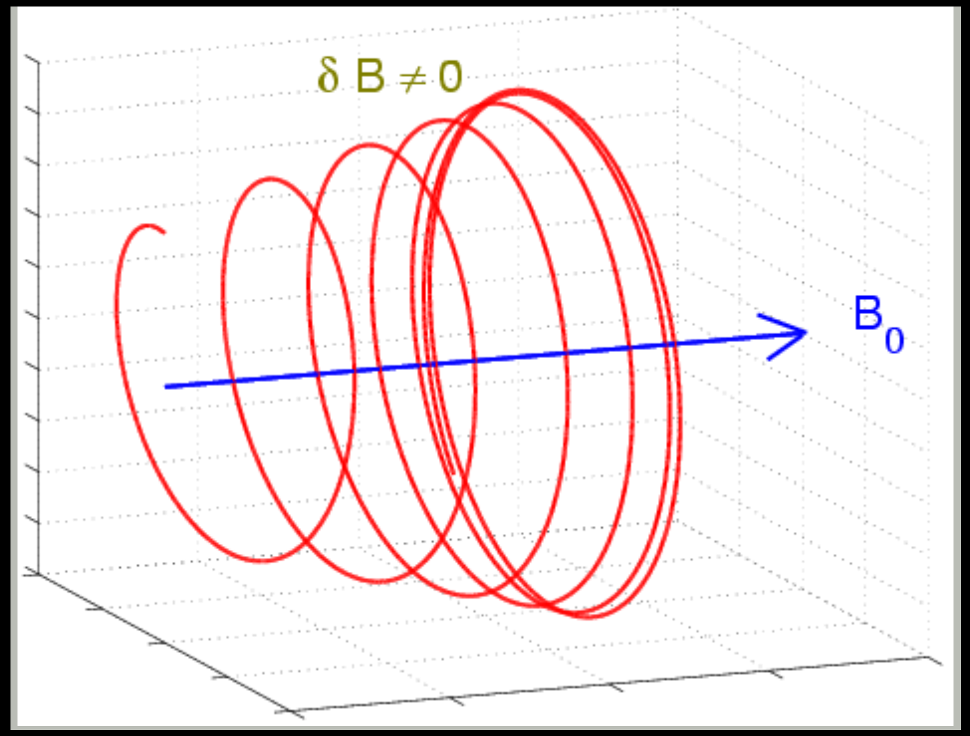
- What do we need:
  - Effort on a better understanding of the microphysics (analytical/numerical)
- Better organisation of the french community
  - INTERCOS project : IN2P3 funded project 2021-2023.
  - Links with laboratory experiments — laser physics, irradiation experiments …

Back-up

(1) Cosmic Ray transport: microphysics (ba1)

From sources to Earth : the journey through interstellar medium

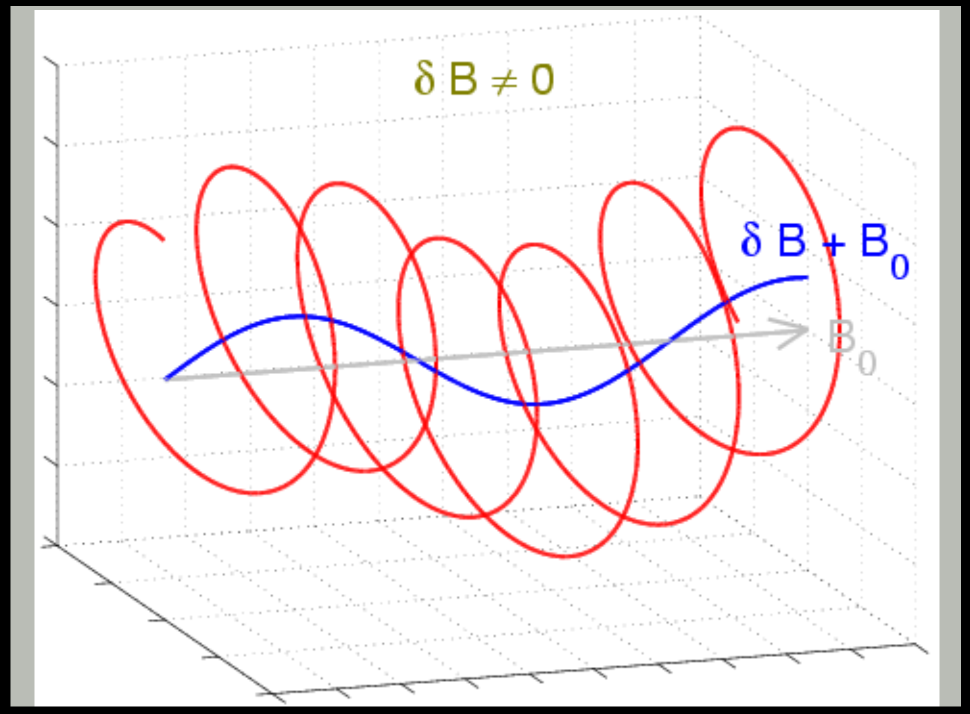
- Two main effects (in sources diffusion is more isotropic) (see A. Shalchi 2009 ASSL)
  - Diffusion parallel to the mean magnetic field: pitch-angle random walk (parallel Lorentz force component, B mean along z here, v particle speed)



$$\frac{v_{\|}}{v} = \dot{\cos(\alpha)} = \frac{\Omega}{v}\left(v_x \frac{\delta B_y}{B} - v_y \frac{\delta B_x}{B}\right), \Omega = v/r_g$$

  - Diffusion perpendicular to the mean magnetic field: magnetic field line wandering.

$$v_x = v_{\|}\frac{\delta B_x}{B}$$



Example for the perpendicular diffusion coefficient: $D_{\perp}(t) = \frac{\langle \Delta x^2 \rangle}{2t} = \int_0^{\infty} dt \langle v_x(t) v_x(0) \rangle$ involves

terms like $\langle v_{\|}(t)\delta B_x(t) v_{\|}(0)\delta B_x(0)\rangle$, time correlations of order 4.

  - The problem is that: in order to reach a particular x at a time t, the pathway depends on the turbulence crossed along it, so the above integro-differential equation can not be straightforwardly solved.

Cosmic Rays and star formation dynamics (ba2)

A new emerging theme

- Low energy Cosmic Rays: keV-MeV leptons + MeV-GeV hadrons (protons).

> Matter ionization where photons can not penetrate (matter-magnetic fields coupling)

> Source of heat.

> Spallation, radioactive elements production, impact over dust.

> Initiate complex prebiotic chemistry in proto-planetary medium.

> GeV CR proton pressure gradients drive winds at galactic scales.

> CR pressure effects contribute to galactic (and circum-galactic ?) magnetic dynamo.