Charged Cosmic Rays up to the knee region and beyond (I)

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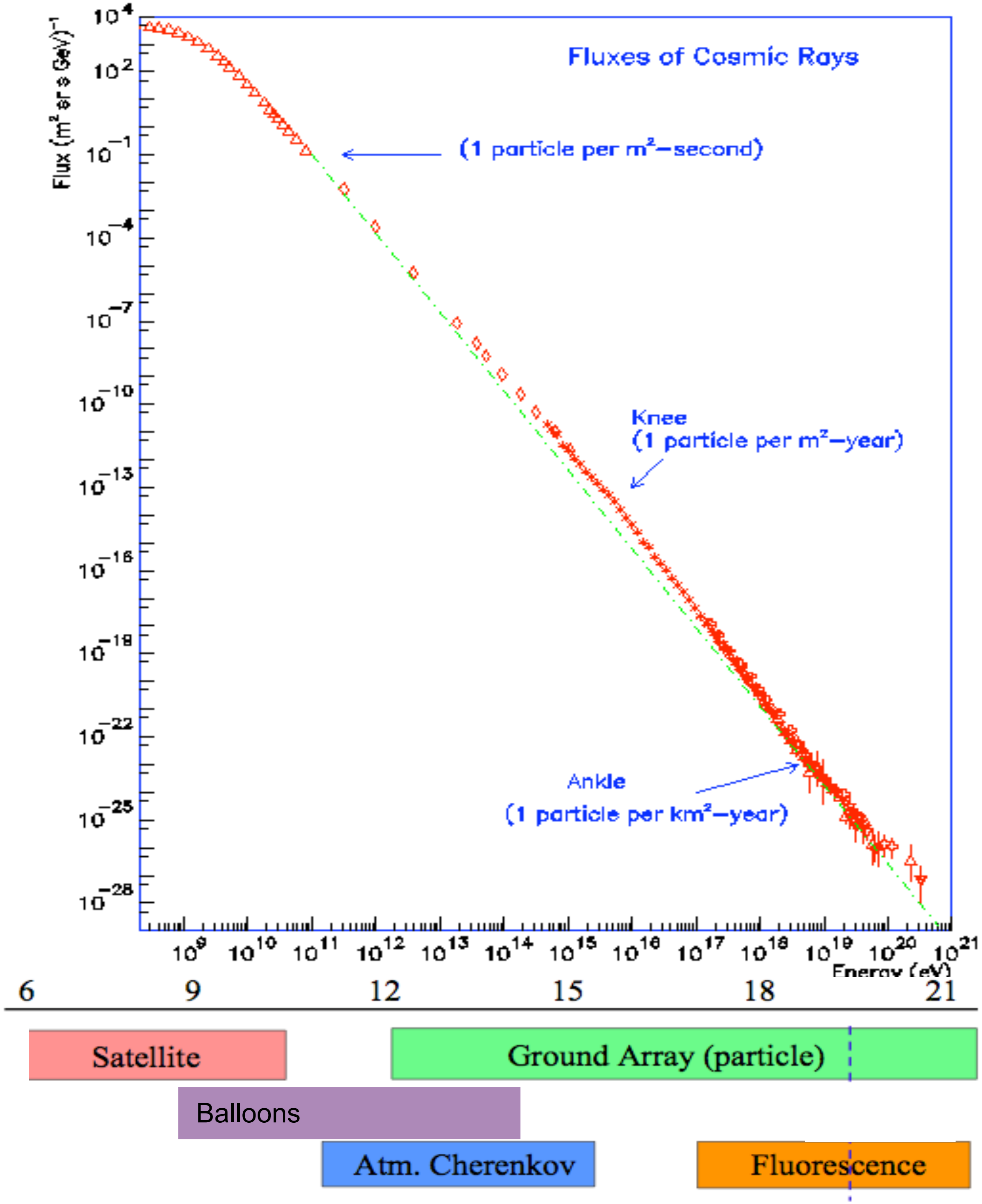
Outline of the lecture

Introduction
Origin, acceleration and propagation of cosmic rays
Models of the knee
Extensive Air Showers
Energy spectrum and composition: measurements and results
The measurement of the p-Air cross section
Anisotropy studies with EAS arrays
The Galactic to Extragalactic transition
Future projects



Cosmic rays consist of

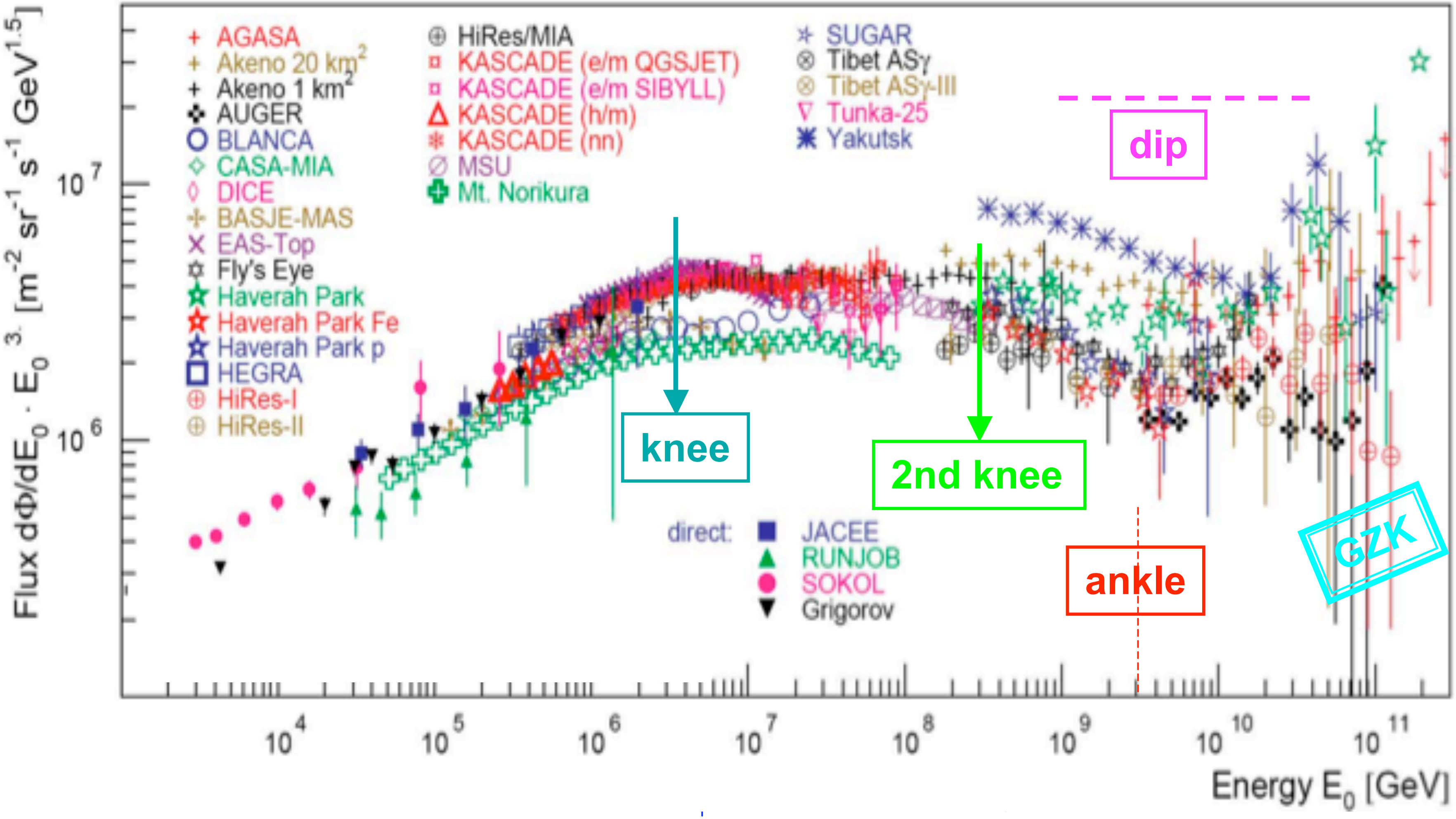
- stellar nucleosynthesis products accelerated in the ISM
- fragments products from interactions during propagation

At Earth:

- Charged particles: >80% protons, ~10% He, plus heavy nuclei, electrons
- Neutral particles: γ,ν,antiν

Particle fluxes fall steeply with increasing energy

- direct measuments only below the knee
- above 10^{14} eV, ground-based air shower experiments



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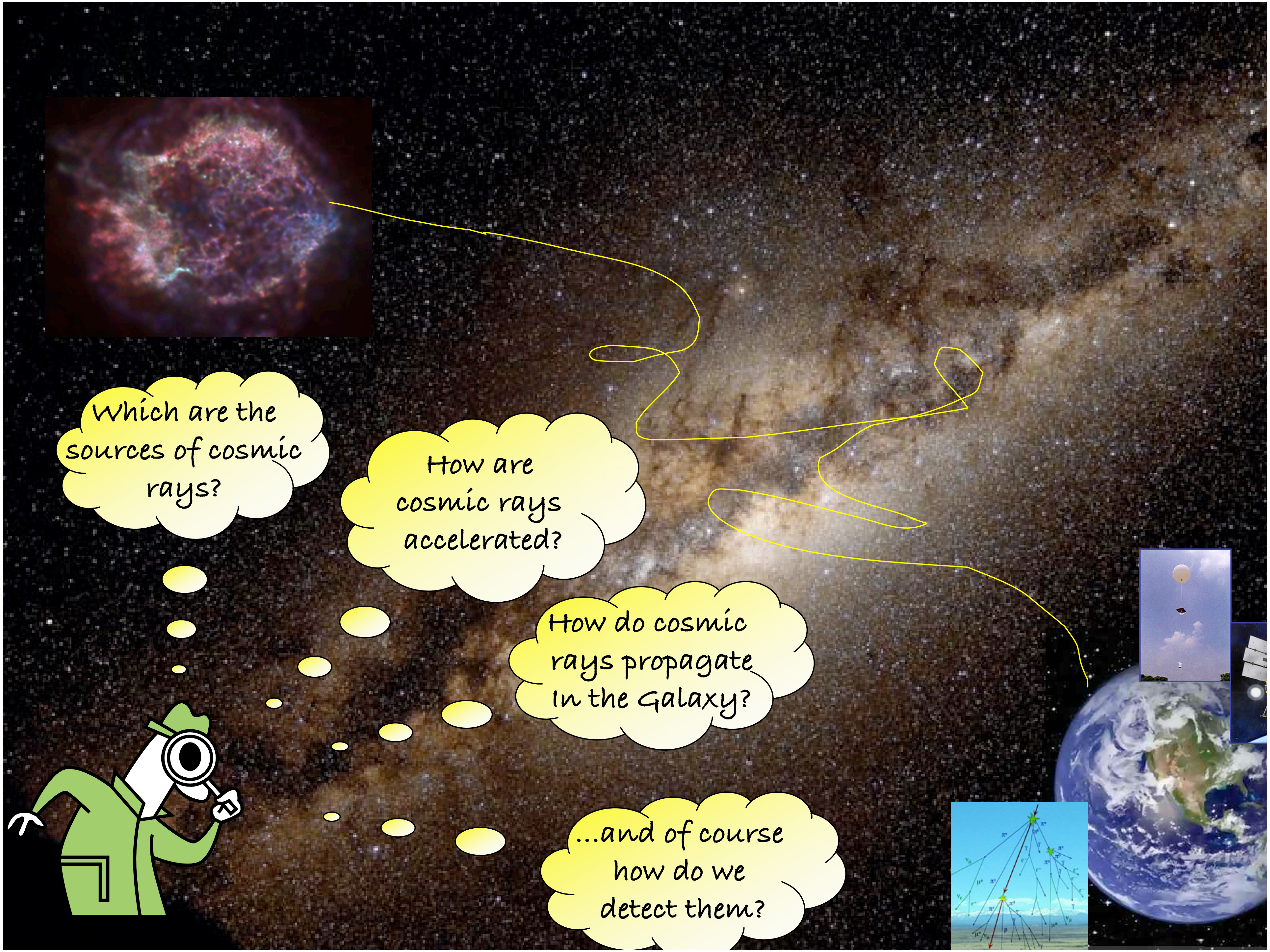


Which are the sources of cosmic rays?

How are cosmic rays accelerated?

How do cosmic rays propagate in the Galaxy?

...and of course how do we detect them?

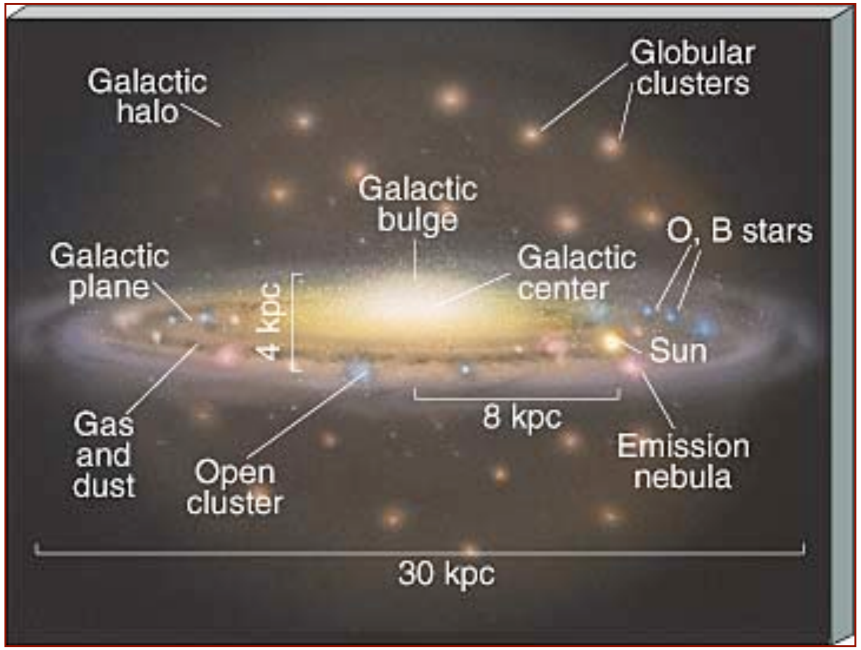
Our Galaxy

Disk: concentration of interstellar dust and gas

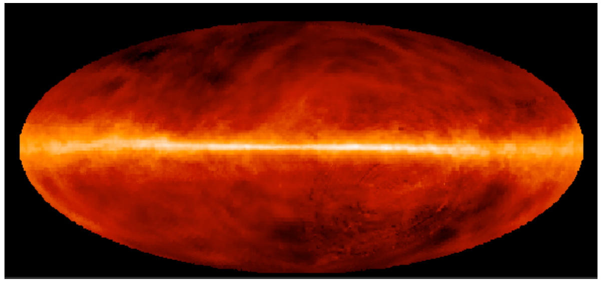
Galactic bulge: large distribution of stars surrounding the Galactic center. In the Galactic center, the Sag A* radio source with black hole

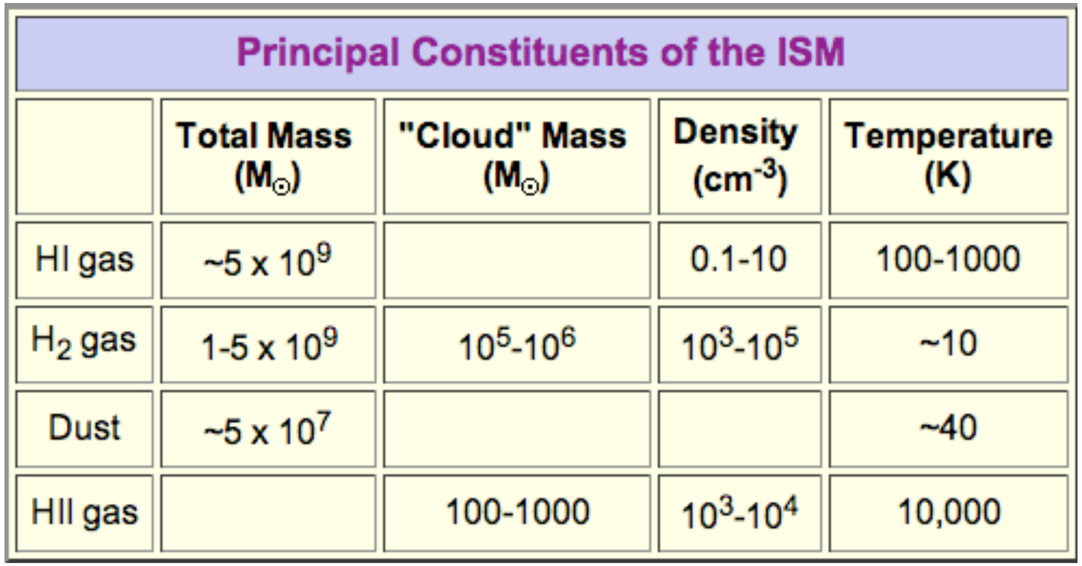
Halo: spherical distribution of globular clusters and old stars

Arms: four major spiral arms; the Sun is located on the smaller Orion arm, within the Galactic disk, about 8 kpc from the center



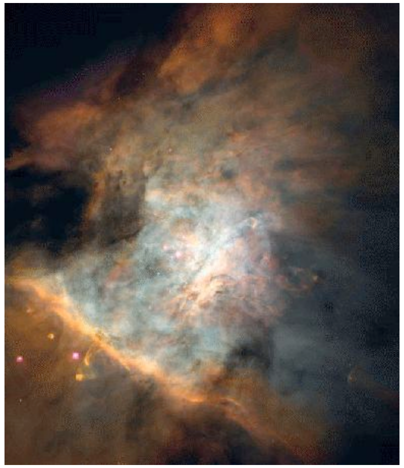
The Interstellar Medium





Principal Constituents of the ISM

	Total Mass ($M_\odot$)	"Cloud" Mass ($M_\odot$)	Density (cm^{-3})	Temperature (K)
HI gas	~5 x 10^9		0.1-10	100-1000
H_2 gas	1-5 x 10^9	10^5-10^6	10^3-10^5	~10
Dust	~5 x 10^7			~40
HII gas		100-1000	10^3-10^4	10,000



$\rho \sim 1$ atom/cm^3 (90% gas, 10% dust)

$\rho_E(gas) \sim \rho_E(cr) \sim \rho_E(B) \sim 1$ eV/cm^3

$B \sim 3\ \mu G$

Visible light is efficiently absorbed or scattered by ISM, so masking most of the Milky Way

Radio & infrared light does pass through the ISM.

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Introduction

**Origin, acceleration
and propagation
of cosmic rays**

Sources of cosmic rays
- kind of sources
- Energetics
- Composition at source

Acceleration mechanism
- Fermi model
- Diffusive Shock Acceleration Model: pro's and con's

Trasport
- The trasport equation
- information from elemental composition
- ...and from primary nuclei
- secondary/primary ratio

Models of the knee

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Anisotropy studies with EAS arrays

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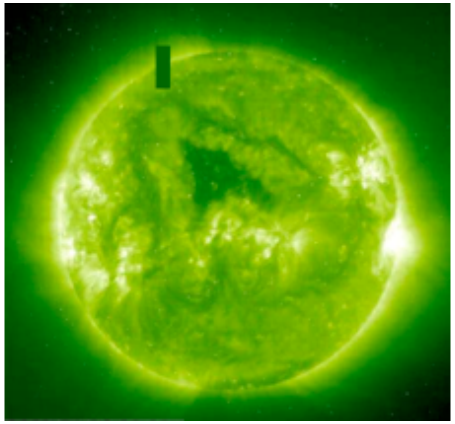
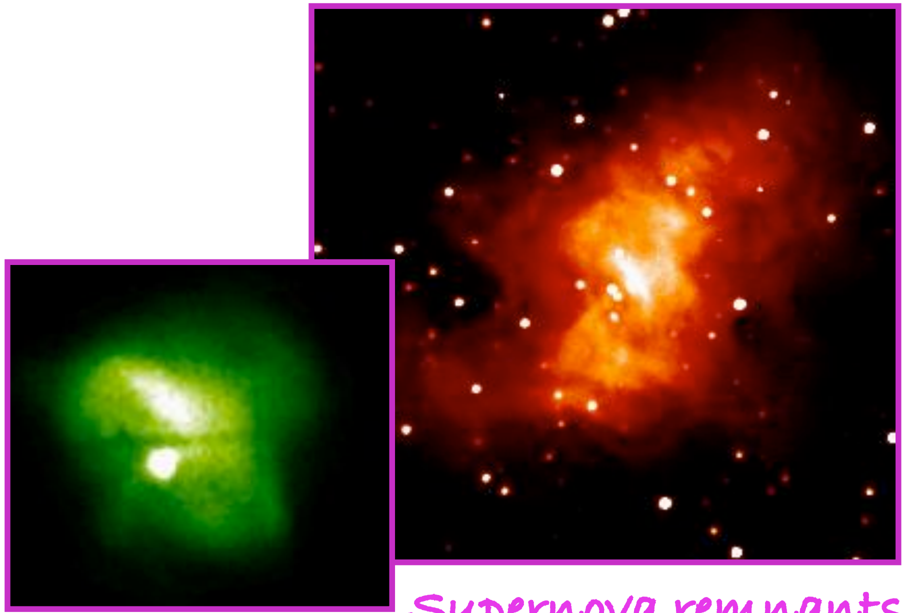
Sources of Cosmic Rays

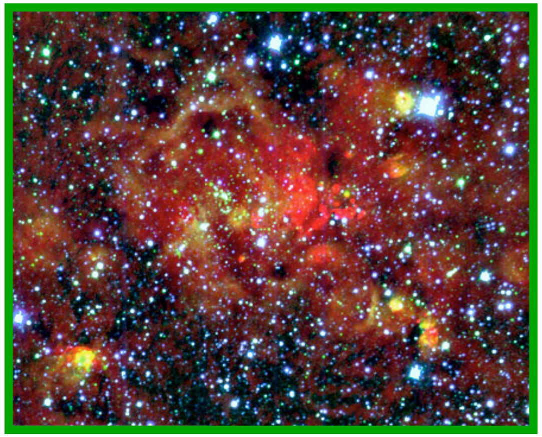


Solar system

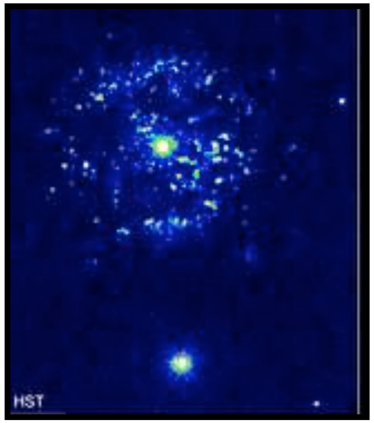


Supernova remnants

Pulsar, pulsar wind nebulae

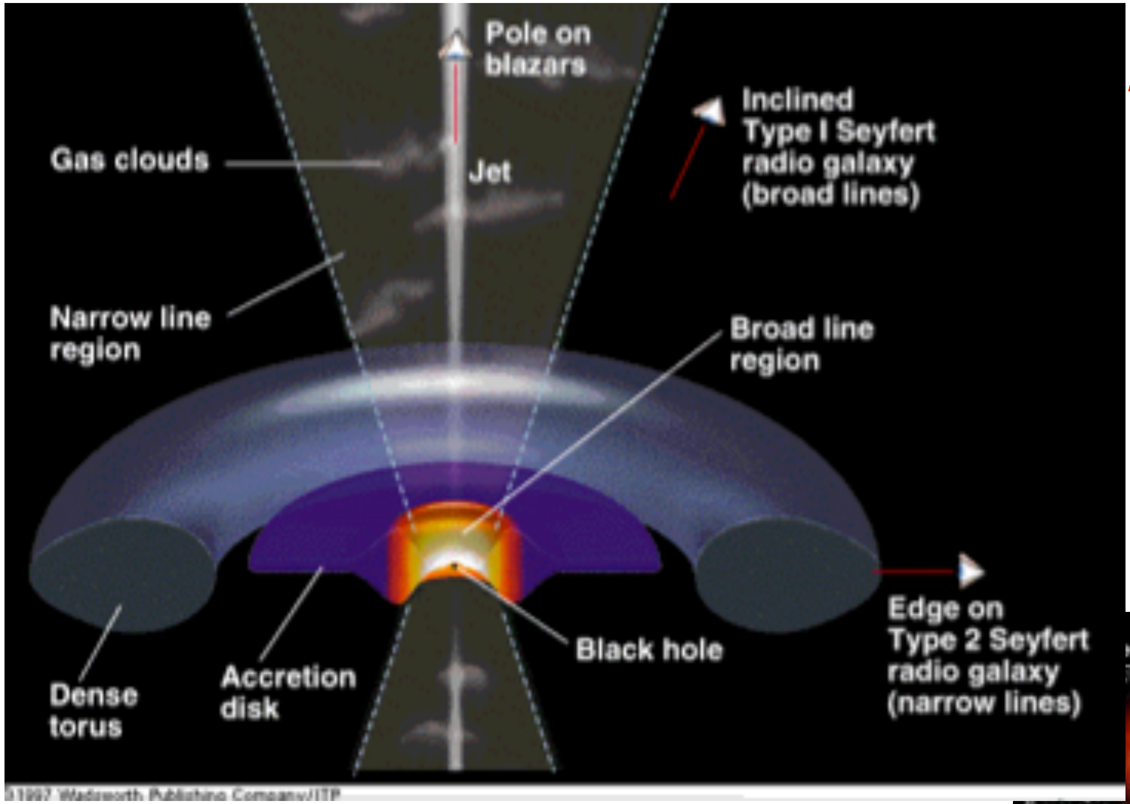


Star forming regions



Nova remnants

Sources of Extragalactic Cosmic Rays



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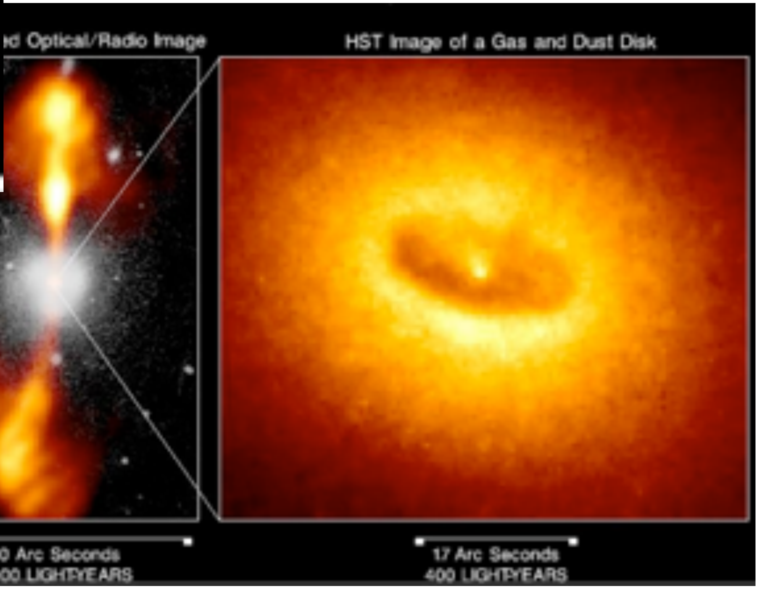
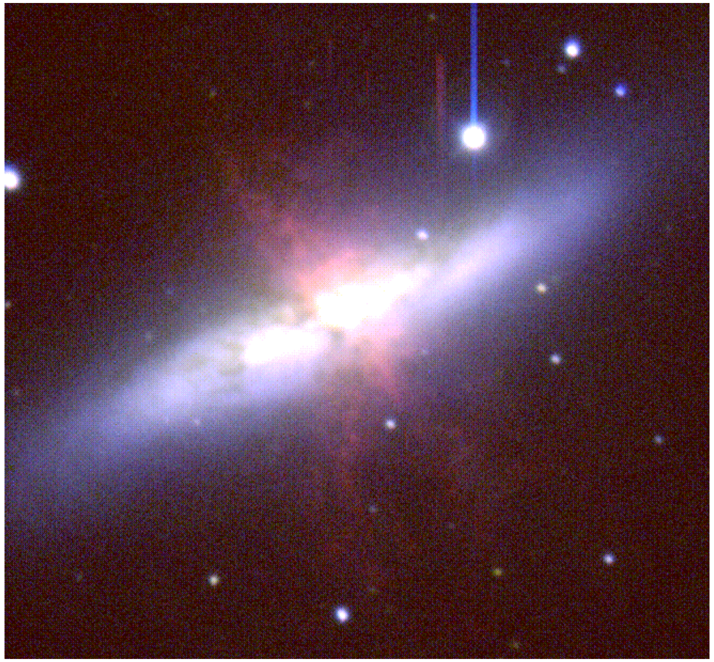
AGN unified model

Differecies depend on our view orientation respect to the Disk : Quasars, blazars, Seyfert...

NGC 4261





Starburst galaxies

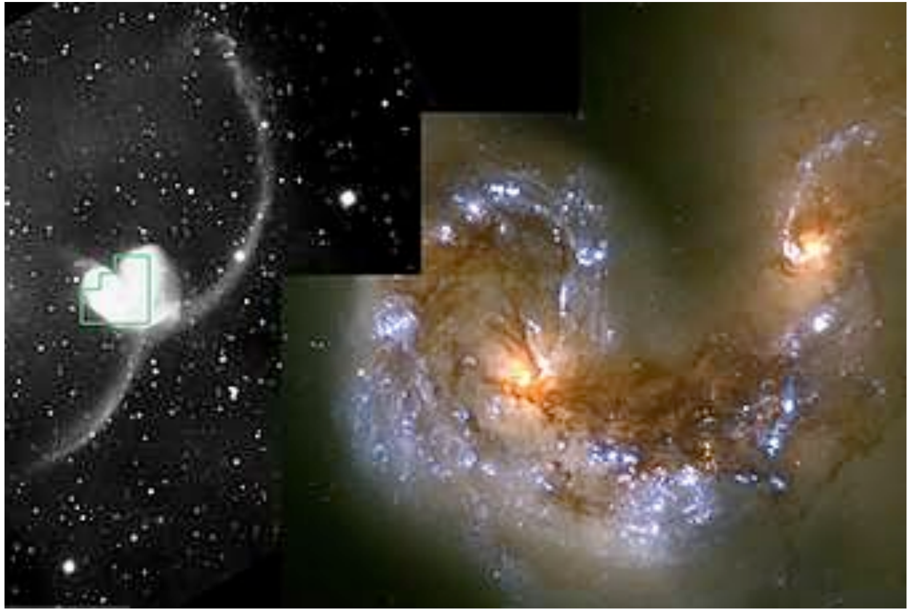
BCG, LIRG, ULIRG

M82,
IRAS19297-046

Galaxies collisions

Cesarsky & Ptuskin,
23rd ICRC, Calgary, 2 (1993) 341.

Antennae
system (NGC
4038+4039)



Sources of Cosmic Rays: SNRs

Cosmic ray intensity $d\phi(E)/dE \sim 1.8\ E^{-\gamma}\ cm^{-2}\ s^{-1}\ sr^{-1}\ GeV^{-1}$

Differential number density of c.r. $n(E)=4\pi/c\ \phi(E)$

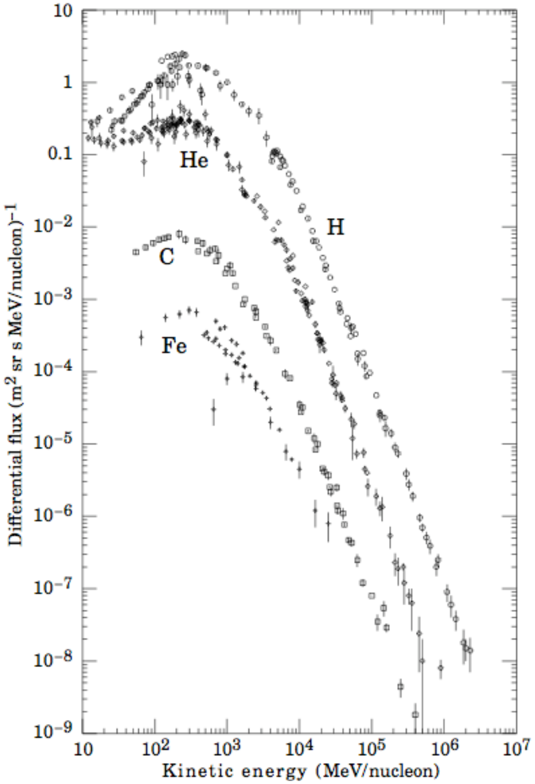
Cosmic ray density in the ISM $$\boxed{\rho_E = \frac{4\pi}{c}\int E\frac{d\varphi}{dE}dE \approx 1\ \mathrm{eV\ cm^{-3}}}$$

Power required:

$V_{Disk}=\pi R^2 h \sim 4.2\ 10^{66}\ cm^3$

$\tau_{esc} \sim 6\ 10^6\ y$

$P = \rho_{cr}\ V_{disk} / \tau_{esc} \approx 4\ 10^{40}\ erg/s$



SN and SNRs:

SN rate in Galaxy $\nu=1$ SN/ 30 y

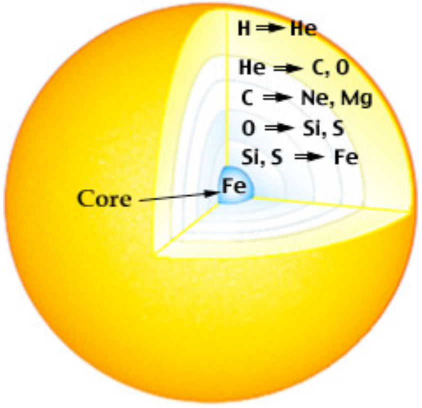
SN mass 10 $M_{Sun} \sim 10 \times 2\ 10^{33}$ g, $E_{kin} \sim 10^{51}$ erg

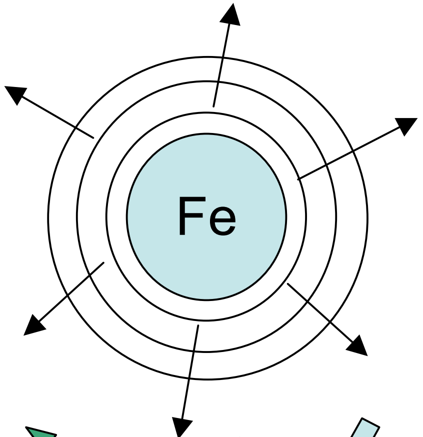
If acceleration efficiency $\varepsilon \sim 10\%$

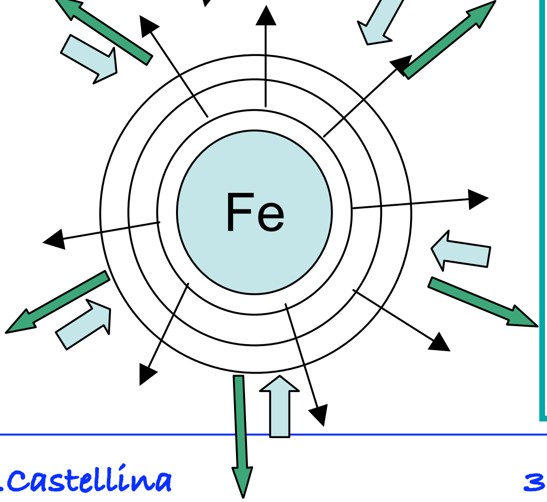
Power required:

$W= \varepsilon\ E_{kin} / \nu \sim 10^{41}\ erg/s$

Supernovae and SNRs







Stars with $M > 8\, M_\odot$: the collapse can be catastrophic and rapid.

When the whole core is converted to Iron, it contracts very rapidly and collapses, because the gravitational force is not balanced by the outward force of the pressure .

In the dense iron core : $e^- + p \rightarrow n + \nu$

Neutrinos escape; cooling and further contraction of core up to nuclear density 4×10^{17} kg/m^3

Powerful wave of pressure sent outward into the outer core.

The material surrounding the core, falling down onto the core, encounters this wave of pressure.

In a fraction of a second the material begins to reverse its motion and move towards the star surface.

The wave of pressure accelerates as it encounters less and less resistence and soon reaches a velocity greater than the speed of the sound becoming a **SHOCK WAVE**, like the sonic boom of a supersonic airplane.

The shock wave ejects the material at speed of thousand of Km/s

SN1987A in the Large Magellanic Clouds (170000 light-years)

After a few hours, the shock wave reaches the surface of the star, heating the surface layers; energy released very large

A portion of this energy escapes in a form of light and in one or two days the exploding star becomes brighter than a billion of Suns: a SUPERNOVA.

At the end of this process a compact stellar remnant and an expanding gaseous shell are created

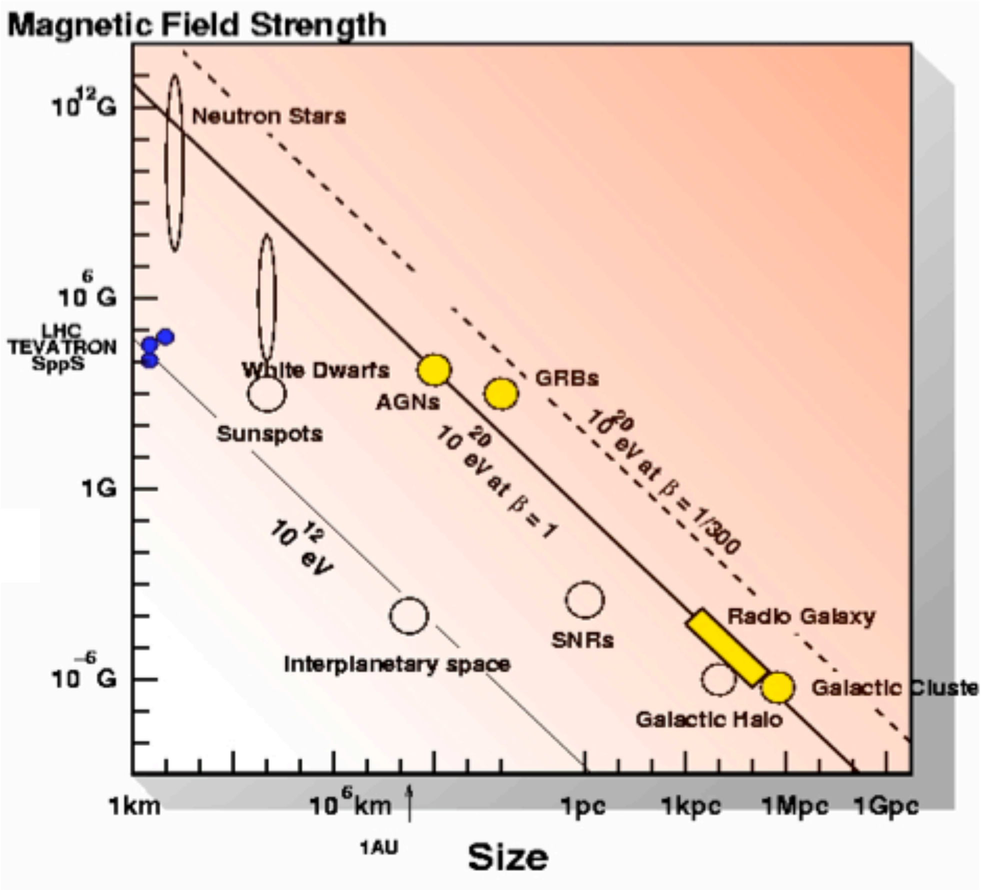
The stellar remnant is a neutron star or black hole

The expanding gaseous shell interacts with the interstellar medium

This region of the interstellar medium is called Supernova Remnant

Diffusive Shock Acceleration Model

- Particles are scattered across the shock fronts of a SNR, gaining energy at each crossing - based on the Fermi mechanism (1° order)
- This model gives a power energy spectrum E^{-q} with $q > 2$ typically.
- When the gyroradius r_L becomes comparable to the shock size L, the spectrum cuts off.



$mv^2/r = ZeBv \qquad pv/r = ZeBv$

$r_L\,[\mathrm{pc}] \sim E_{PeV}/B_{\mu G}Z$

In accel. site

$L_{pc} >> r_L$

ρ_{rad} and ρ_{mat} small

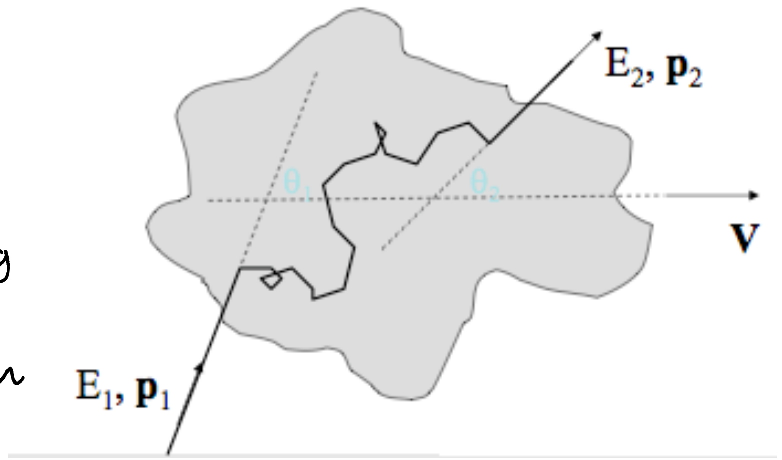
$B_{\mu G} \longrightarrow$ fast t_{acc}

small energy losses

$B_{\mu G}L_{pc} > E_{PeV}/Z\beta$

$E_{max} \propto Z$

Fermi Acceleration



2nd order stochastic acceleration:

Particle encounters magnetic irregularities moving with velocity v in the ISM

towards it (head-on collision) → energy gain

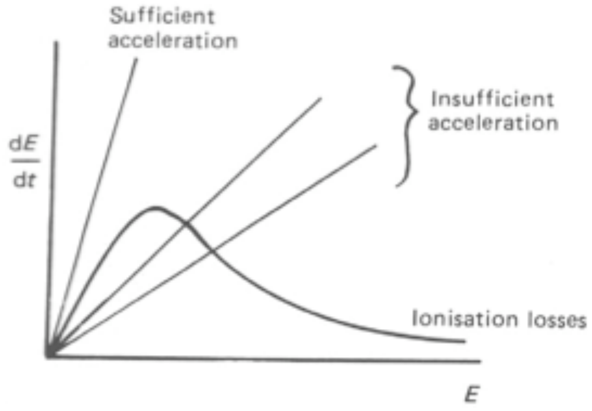
away from it → energy loss

Head-on collisions more frequent: net gain $\xi = \Delta E/E \sim 4/3\, \beta^2$

Power law spectrum

$N(E) \sim N_0\, E^{-x}$ with $x = 1 + (k\, \tau_{esc})^{-1}$

but

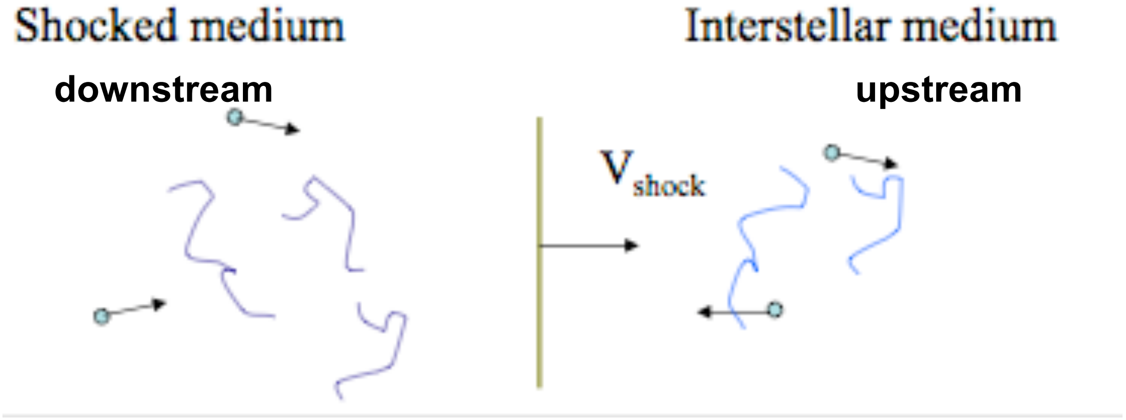


- Clouds random velocities $\beta \sim 10^{-4}$ and $L \sim 1$ pc
  $\tau_{coll} \sim$ few years : collisions are not frequent enough
  too inefficient energy gain

- τ_{acc} **must be rapid enough** to overcome the ionization energy losses
  (or particle injected with energy >> maximum energy loss rate)

- It does not explain **the observed slope** $x \sim 2.1$

First order Fermi Acceleration



Particles crossing strong shock waves in both directions
Collisions are always head-on: energy gain $\xi = \Delta E/E = 4/3\, \beta$ (1st order)
The velocities of particles are randomized on each side of the shock

- There is one slope for a power law energy spectrum: $N(E) \sim N_0\, E^{-2}$
- The Fermi mechanism has an efficiency ~ few %
- The maximum energy a particle can reach in this way is Emax ~ 300 Z TeV
  subsequent cutoffs of the spectra are expected as Z rises

Diffusive Shock Acceleration Model

The source spectrum is a power law with ~ expected slope

The accelerators are efficient enough

The maximum acceleration energy $E_{max} \sim 3\ 10^{15}\ Z$ eV

TeV γ rays from hadroproduction in SNRs

Residence time in Galaxy is not $\propto E^{-0.6}$

Source spectrum slope vs release spectrum slope ?

Very few SNR sources of TeV γ rays

Time integrated luminosity of certain SNRs not enough to feed L_{CR}

Electrons can't diffuse far enough from SNR to explain radio

[see e.g. A.Dar, astro-ph/0601329]

Diffusive Shock Acceleration Model

From the diffusion equation for a primary nucleus [assuming no feed-down from heavier, no energy losses in ISM]

$$Q(E) \sim N(E)/\tau_{esc} \sim N(E)\ E^{\delta}$$

Since the observed flux

$$\Phi(E) \sim E^{-\gamma}\ cm^{-2}s^{-1}sr^{-1}GeV^{-1}$$

is related to the local energy density spectrum of cr :

$$N(E) = 4\pi/c\ \Phi(E)$$

If $\gamma \sim 2.7$ and $\delta \sim 0.6$

$$Q(E) \propto E^{-\gamma+\delta} \sim E^{-2.1}$$

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Hadronic or electronic nature of parent CRs in a SNR source

SNR γ-ray spectra >10 TeV

strong radiative losses

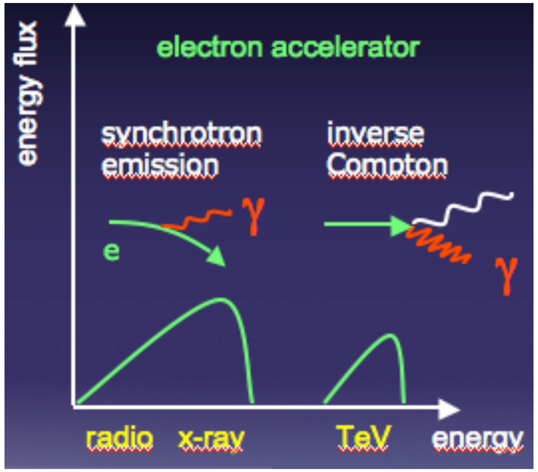
cutoff in IC spectrum

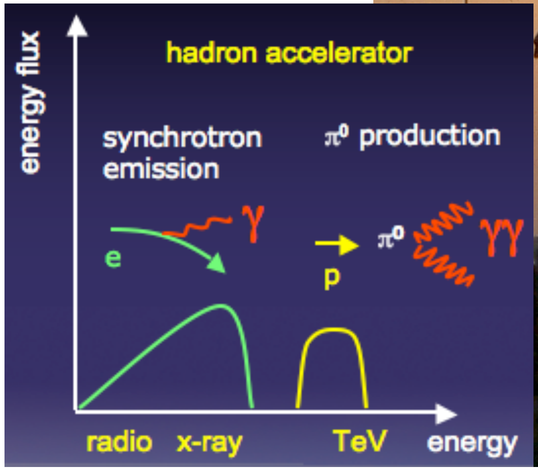
Older SNRs

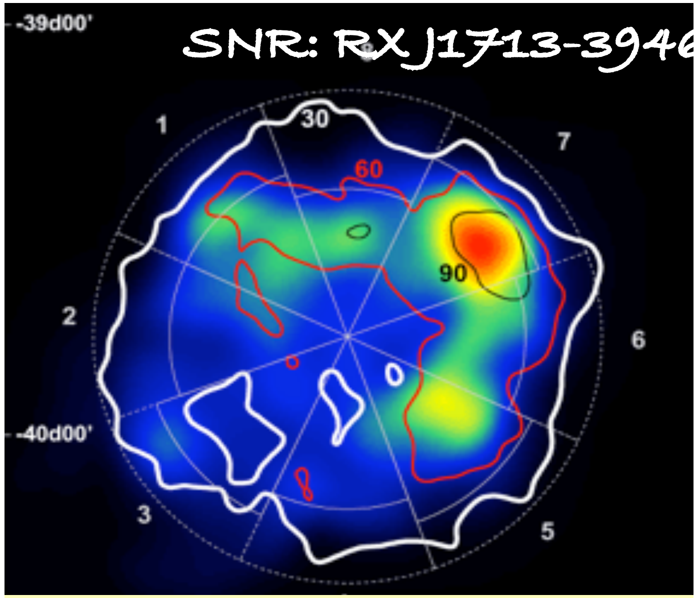
electron radiative cooling

SNRs interacting with molecular clouds

$n>10^3$ cm^{-3}

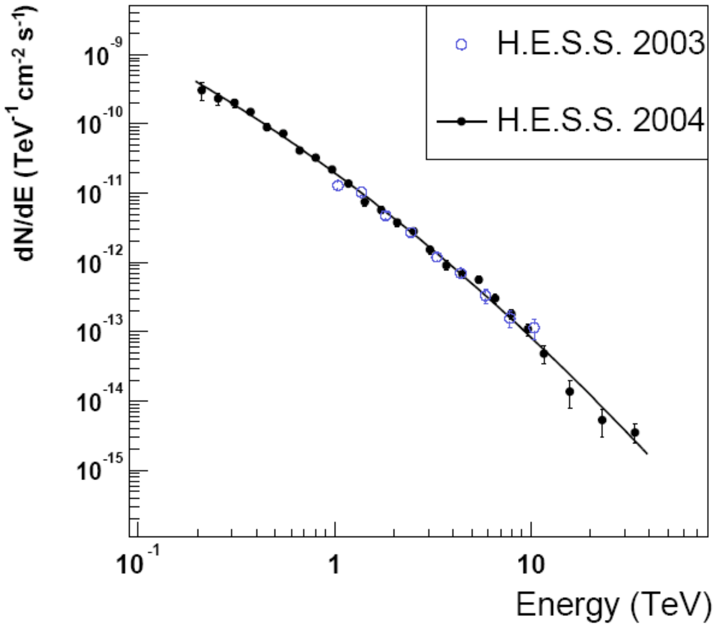


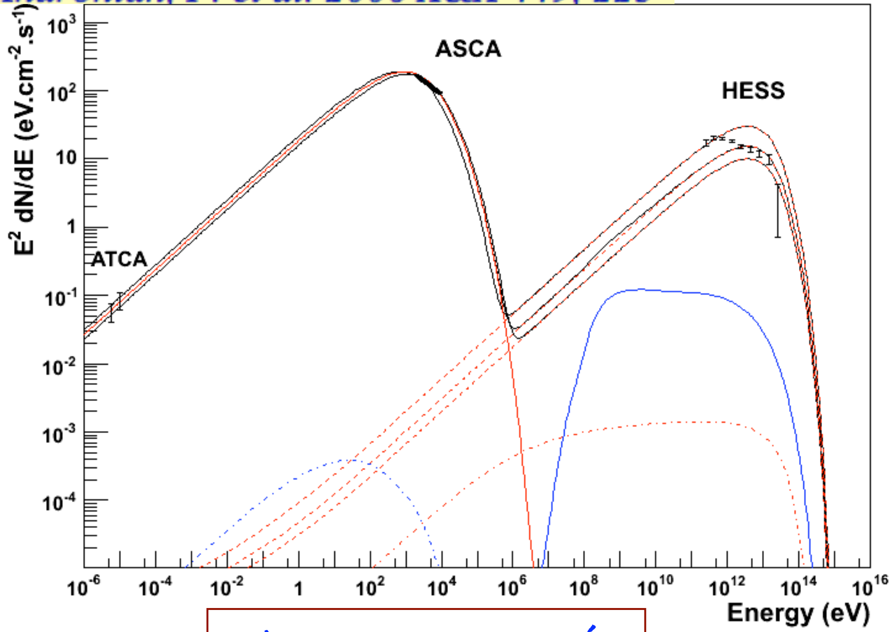




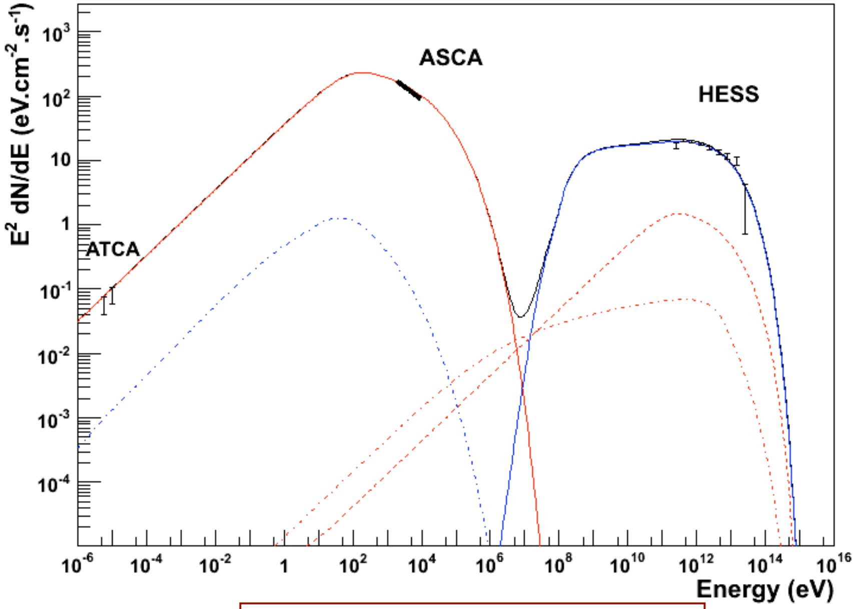
Aharonian, F. et al. 2004, Nature 432, 75

Aharonian, F. et al. 2006 A&A 449, 223

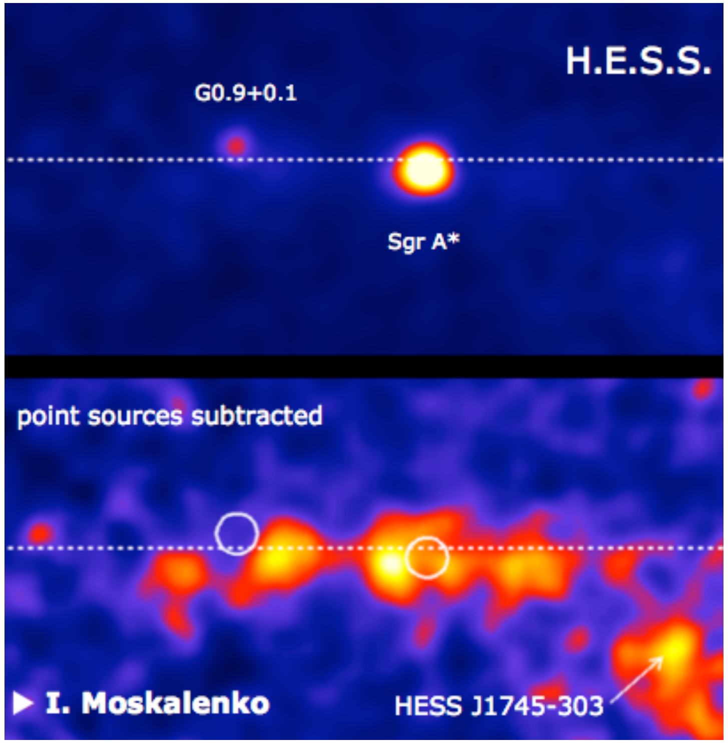




Electron scenario



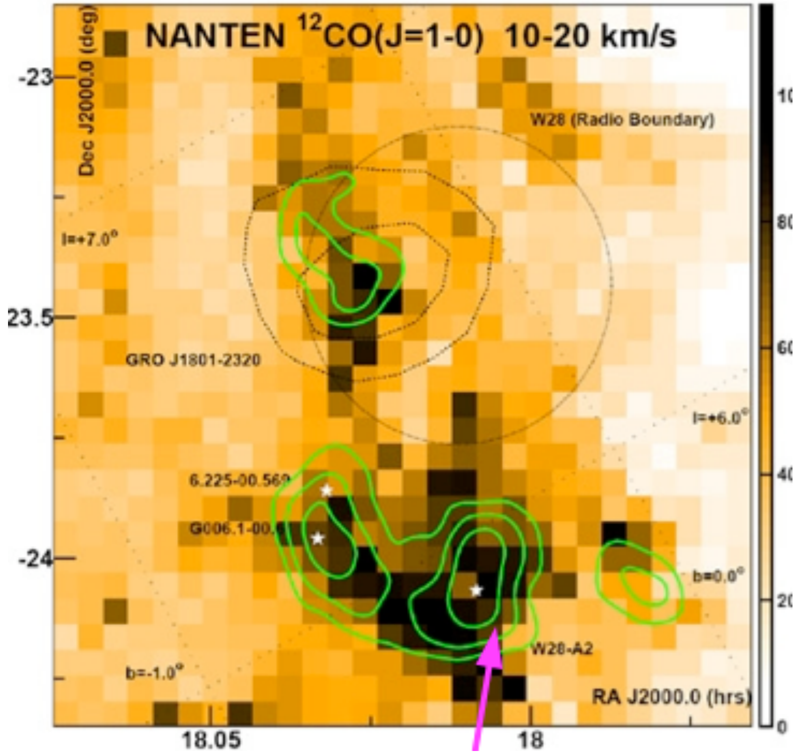
Hadronic scenario



γ_{VHE}>100 GeV emission from the central 200 pc of Galaxy

$dN/dE = 1.73\ 10^{-8}\ E_{\gamma}^{-2.29}$
$TeV^{-1}\ cm^{-2}\ s^{-1}\ sr^{-1}$

Strong correlation between γ emission and target material (CS emission: 3-8 $10^{7}\ M_{sol}$ of interstellar matter in clouds)



γ_{VHE} emission coincident with molecular cloud in W28

Spatial correlation is strong
p/nuclei interact with ambient matter of density $n>10^{3}\ cm^{-3}$
...hint for HADRONIC ORIGIN

W28 is in a region of rich star formation ...other accelerators?

Diffusive Shock Acceleration Model

The source spectrum is a power law with ~ expected slope

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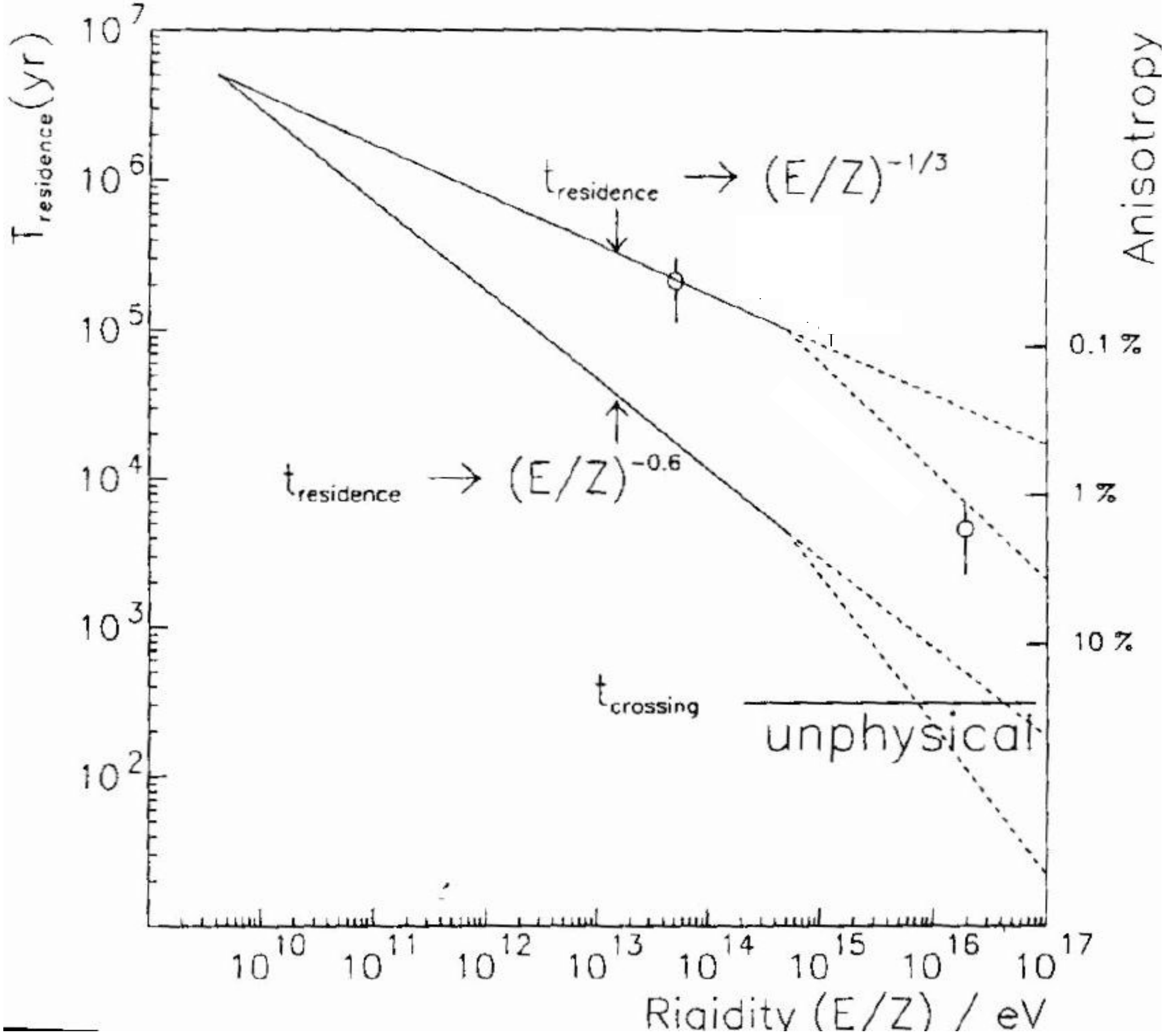
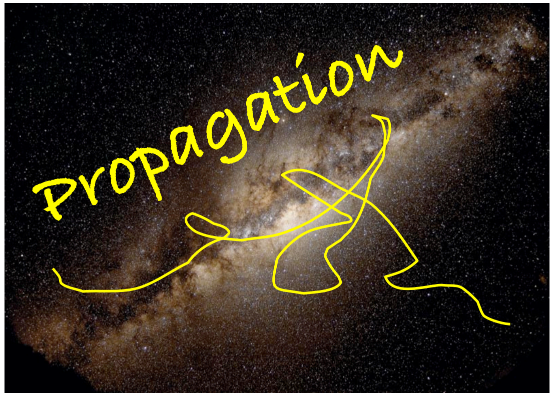
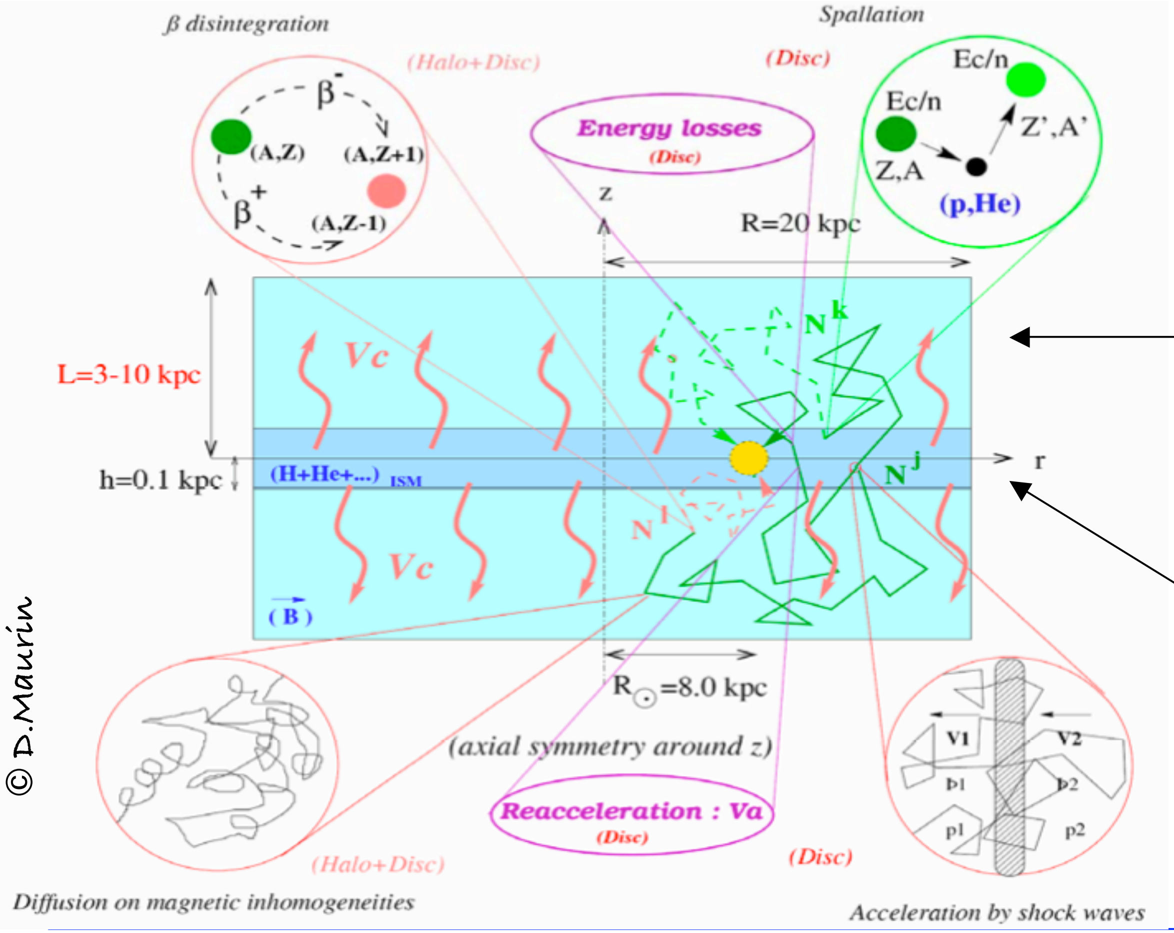


$T_{residence}$(yr)
10^7
10^6
10^5
10^4
10^3
10^2
Anisotropy
0.1 %
1 %
10 %
$t_{residence} \rightarrow (E/Z)^{-1/3}$
$t_{residence} \rightarrow (E/Z)^{-0.6}$
$t_{crossing}$
unphysical
10^{10}
10^{11}
10^{12}
10^{13}
10^{14}
10^{15}
10^{16}
10^{17}
Rigidity (E/Z) / eV



Diffusion models should

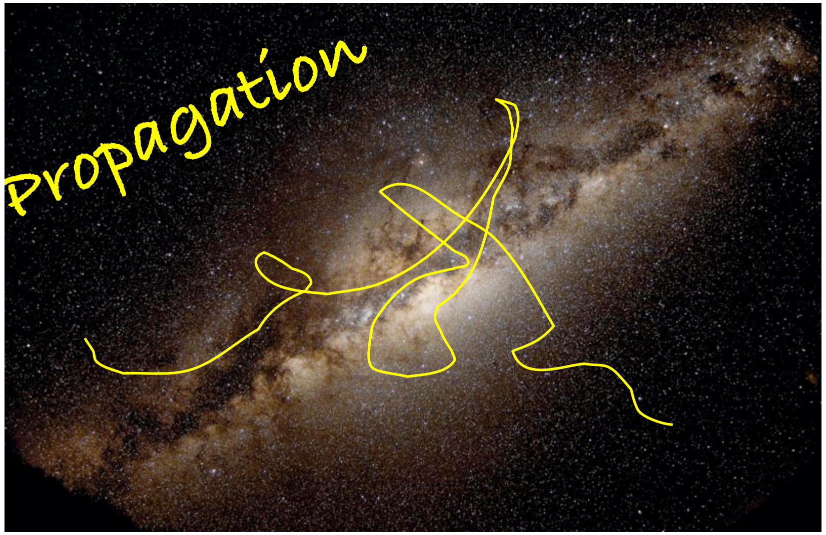
Explain the cosmic ray composition
Describe the cosmic ray spatial distribution
Give a consistent model for all species



Diffusive halo with convection and nuclear Reaction

$\langle \rho \rangle = 1\ \mathrm{cm}^{-3}$

Disk, where sources and ISM are located



The trasport equation

$\lambda_{esc} \approx 10$ g/cm^2

$n_{ISM} \approx 1$ cm^{-3} $\rho_{ISM} \approx 10^{-24}$ g/cm^3

$L = X/\rho \approx 10^{25}$ cm ⇨ 3 Mpc >> h_{Galaxy}

$$\frac{\partial N}{\partial t} = \overbrace{\boxed{\nabla\cdot\left(D_i \nabla N_i\right)}}^{\text{Diffusion}} - \overbrace{\boxed{\frac{\partial}{\partial E}\left[b_i(E) N_i(E)\right]}}^{\text{Energy losses and acceleration}} - \overbrace{\boxed{\nabla\cdot\vec{u} N_i(E)}}^{\text{Convection}} + \overbrace{\boxed{Q_i(E,t)}}^{\text{Source}}$$

$$- \underbrace{\boxed{p_i N_i}}_{\text{Nuclei losses by collision and decay}} + \underbrace{\boxed{\frac{vp}{m}\sum_{k\geq i}\int \frac{d\sigma_{i,k}(E,E')}{dE} N_k(E') dE'}}_{\text{Nuclei gain from higher energy (e.g. nuclear fragmentation)}}$$

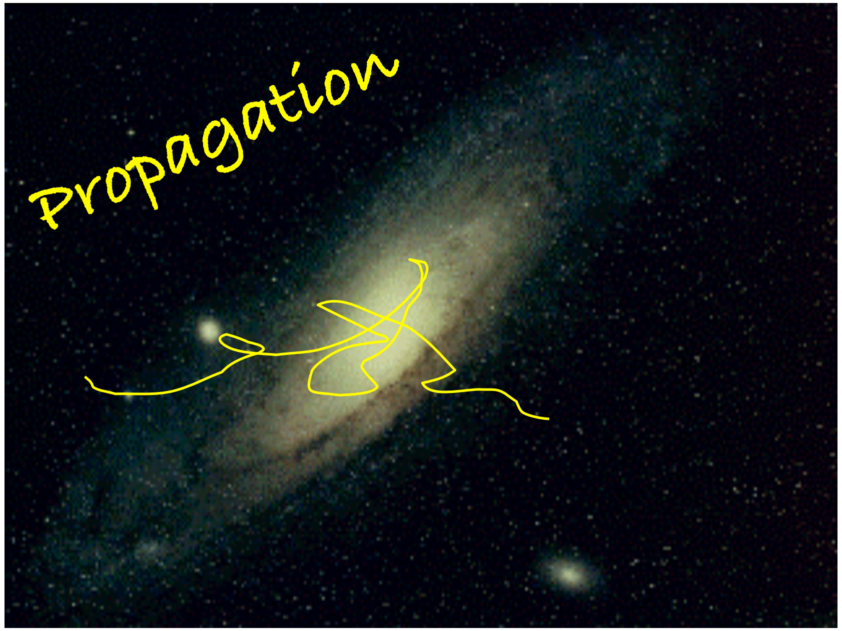
$$p_i = \frac{v\rho\sigma_i}{m} + \frac{1}{\gamma\tau_i}$$

High energy:

✓Source injection spectrum $Q_i(E) \propto E^{-\alpha}$

✓Diffusion coefficient

$K(E) \propto E^{\delta}$



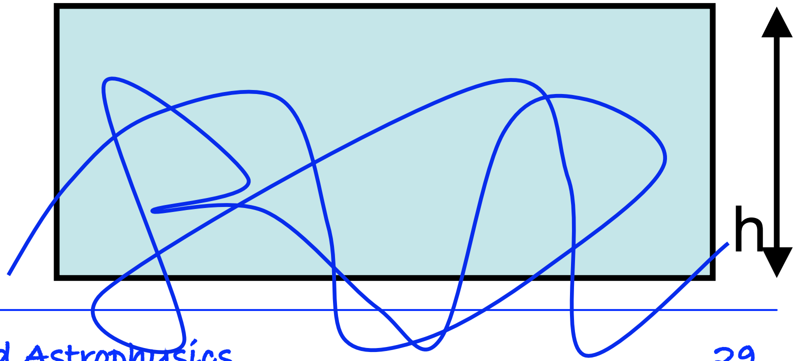
The Leaky Box Model:

The Galaxy is modelled as a box where CR propagate freely and Where there is a constant probability of escape $\tau_{esc}^{-1} << c/h$

- No diffusion: $\nabla(D_i \nabla N_i) \Longrightarrow - N/\tau_{esc}$
- Homogeneity: $V_c = 0$, no collisions or energy losses.
- All quantities are averaged

$$-N_i(E)/\tau_{esc} + \overline{n}\, v\, \sigma_i N_i = Q_i(E) + \Sigma_{j>i} \overline{n v} \sigma_{ji} N^j$$

$$<\lambda_{esc}> = <\rho> \beta c \tau_{esc}$$



The primary/secondary ratio in the Leaky Box Model:

For primaries: source spectrum $Q_i(E) \propto E^{-\alpha}$

diffusion in the ISM with $K(E) \propto E^{\delta}$

$$N_P/\tau_{esc} + \bar{n}\, v\, \sigma_p N_P = Q_P + \cancel{\Sigma_{j>i} n v \sigma_{ji} N^j}$$

$$\mathbf{N_P} = Q_P/(1+\bar{n} v \sigma_P \tau_{esc}) \;\; \mathbf{= Q_P/(1+\sigma_P\, \lambda_{esc})}$$

For pure secondaries:

$$N_S/\tau_{esc} + \bar{n}\, v\, \sigma_S N_S = \cancel{Q_P(E)} + \Sigma_{P>S} n v \sigma_{PSi} N_P = \bar{n} v \sigma_{PS} N_P$$ (for 1 primary only!)

$$N_S + \lambda_{esc}\, \sigma_S N_S = \lambda_{esc}\, \sigma_{PS} N_P$$ (...and λ_{esc} the same for primary or secondary!)

$$\mathbf{N_S = (\lambda_{esc}\, \sigma_{PS} Q_P)/(1+ \lambda_{esc}\sigma_S)\,(1+ \lambda_{esc}\sigma_P)}$$

$$\boxed{\frac{N_S}{N_P} = \frac{\lambda_{esc}\, \sigma_{PS}}{(1+ \lambda_{esc}\sigma_S)}}$$

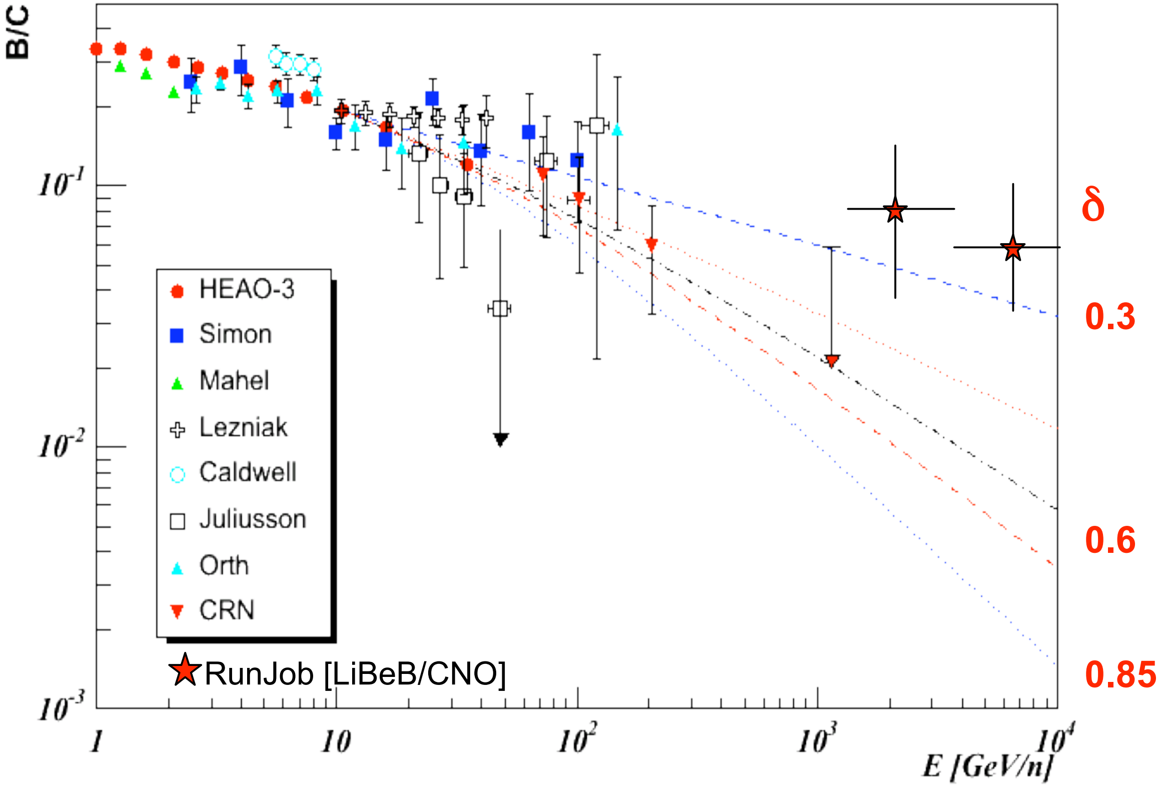
$S/P \longrightarrow \lambda_{esc}$

if cross sections are known

$\lambda_{esc} \longrightarrow \tau_{esc}$

if n is known

…Secondary/Primary ratio



B/C shaped mainly by the diffusion coefficient slope δ

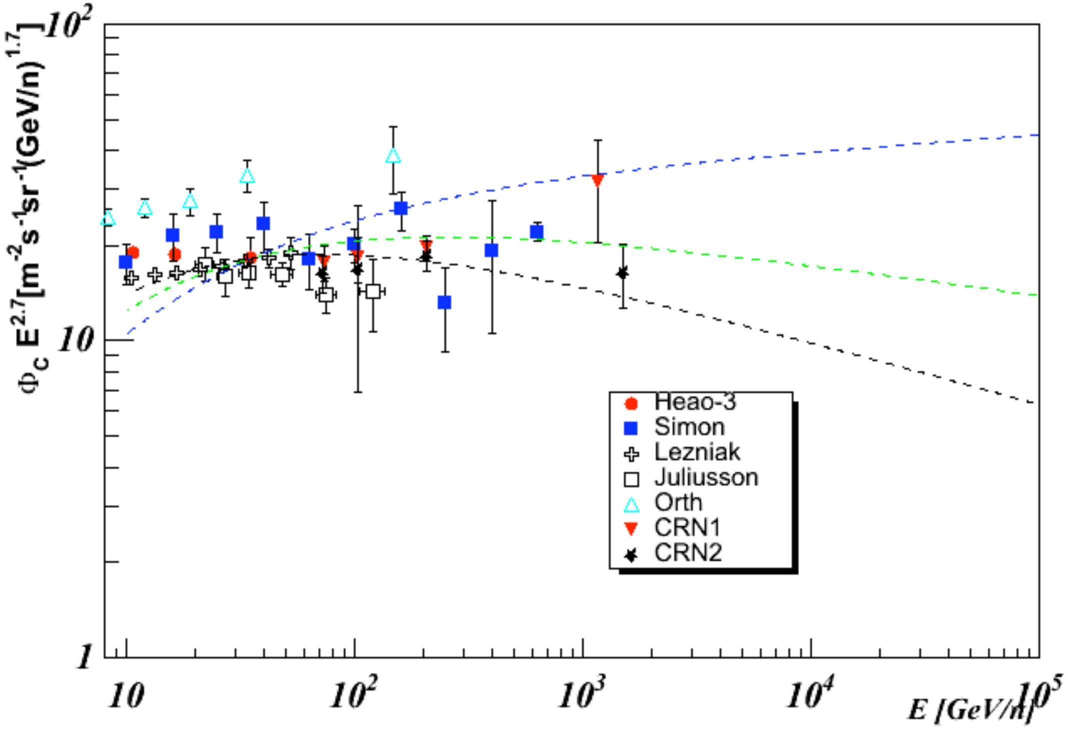
K_0, L, V_c, V_A not important for E≥ 100 GeV/n

No relevance of injection spectrum: checked for **a**=[1.8-2.5] equal for each nucleus or for different **a**i (Wiebel-Sooth)

- Region of interest ≥ 100 GeV/n
- Very few experimental data above this energy, but current and future detectors will have the ability of exploring the high energy range up to the knee region

Measurement of B/C ratio to get a measure of δ (diffusion coefficient slope)

[© A.Castellina & F.Donato, Astrop.Phys. 24(2005) 146.]



1.9

2.05

2.2

α

Measurement of light primary nuclei flux to get a measure of α (acceleration coefficient slope)

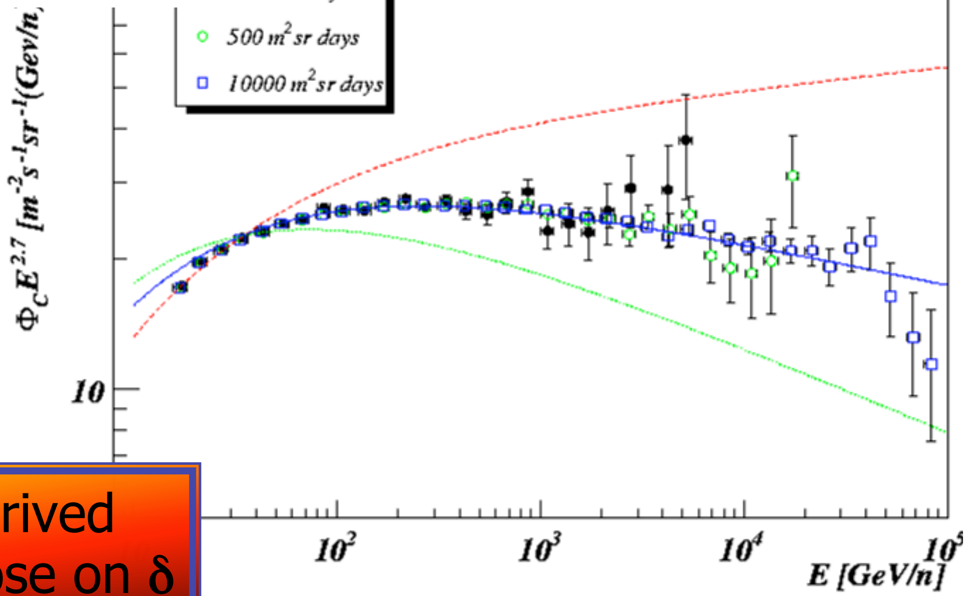
Flux of Carbon

predictions for

$\delta = 0.6$, $\alpha = 1.9, 2.05, 2.2$

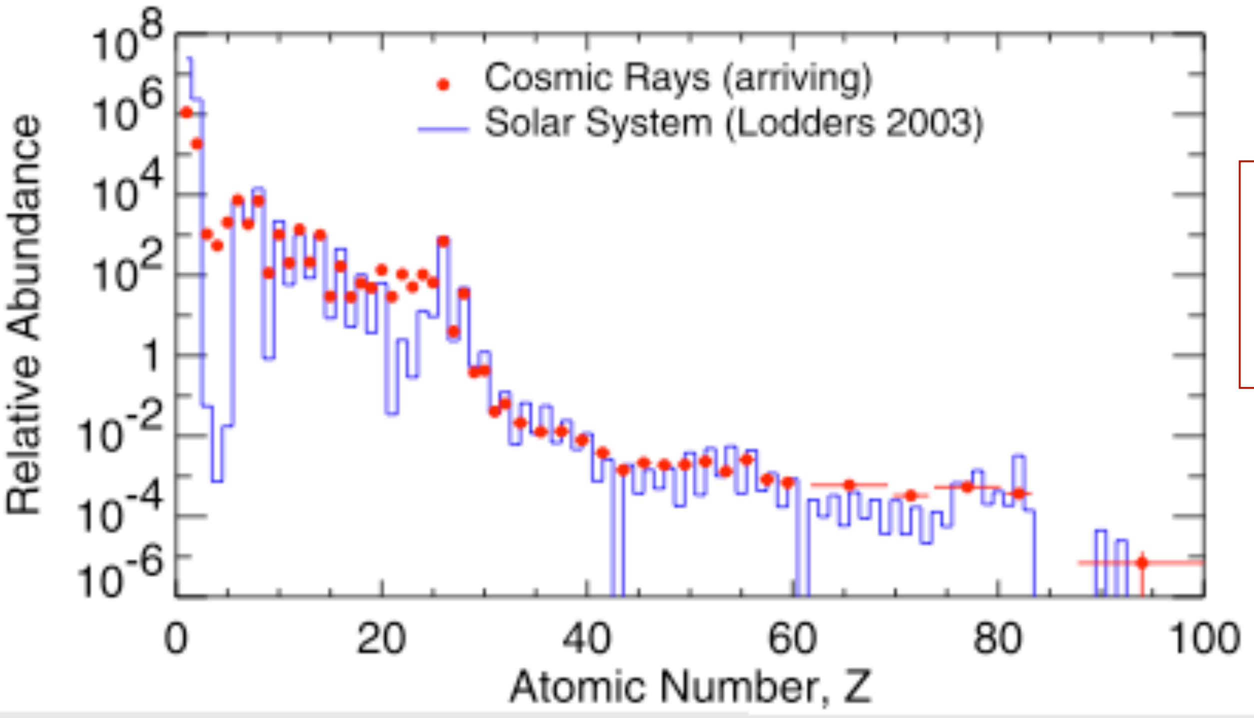
normalization at 35 GeV/n

(error 15 %)



The acceleration slope can be derived without uncertainties other that those on δ

Composition at Earth



Results from:
Z=1-2 BESS
Z=3-30 CRIS
Z>30 HEAO-3, Ariel-VI

General similarity of the two samples

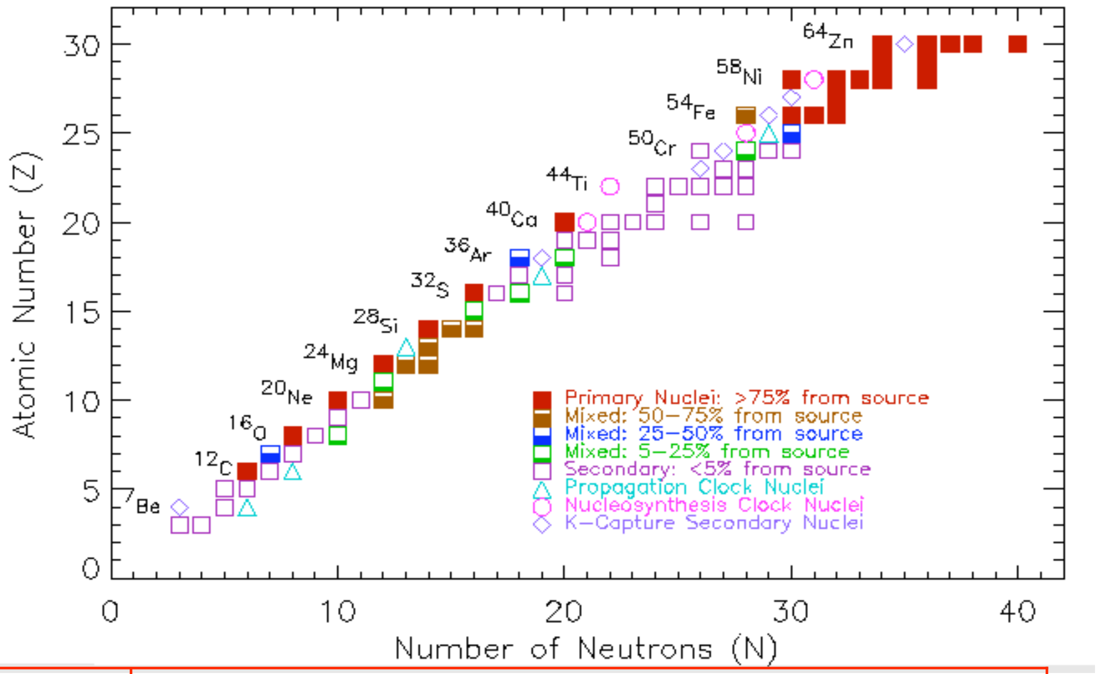
H, He are less abundant in CR than in SS

difficulty in ionizing and accelerate them to high energy

Li,Be,B and sub-Fe are more abundant in CR than in SS

these are spallation products

Information from elemental and Isotopic composition



Primary nuclei	Conditions of nucleosynthesis in sources. Models of propagation
Primary isotopes decaying by electron capture	Time elapsed between nucleosynthesis and acceleration
Secondary isotopes decaying by $\beta^{\pm}$ emission	Average time elapsed between production and escape
Secondary isotopes decaying only by electron capture	Reacceleration

Clocks

Acceleration Delay Clocks: Δt (nucleosynthesis-acceleration)

- ✓ time in low T environment is short delay if seeds are grains formed in SN ejecta, longer for material injected in flare stars coronas
- ✓ ^{59}Ni, ^{57}Co decay by electron capture only in low T environment, otherwise after acceleration they are stable

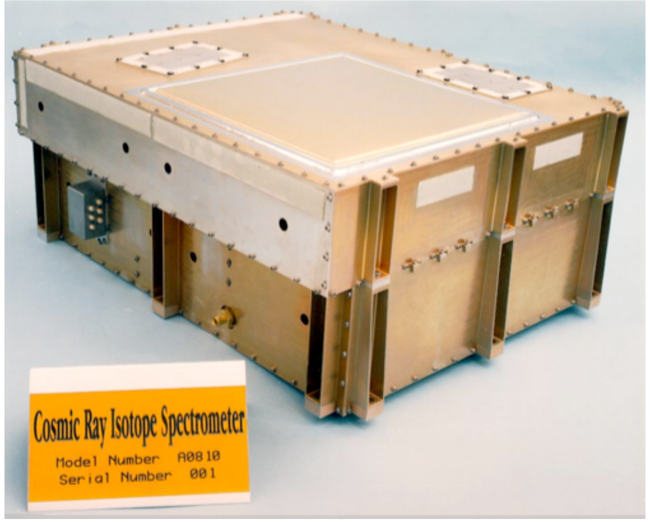
$>10^5$ y [Connell et al. 24th ICRC, Rome, 2 (1995) 602]

Propagation Clocks: Δt (production-escape)

- ✓ measure the surviving fraction, ratio of observed abundance to expected one if the nuclei did not have time to decay
- ✓ ^{10}Be decaying by β^- emission ($\tau_{1/2}=1.5\ 10^6$ y)

$\approx 1\text{-}2\ 10^7$ y [Wiedenbeck et al. Astrop.J.Lett. 239 (1980) L139]

CRIS [Cosmic Ray Isotope Spectrometer]

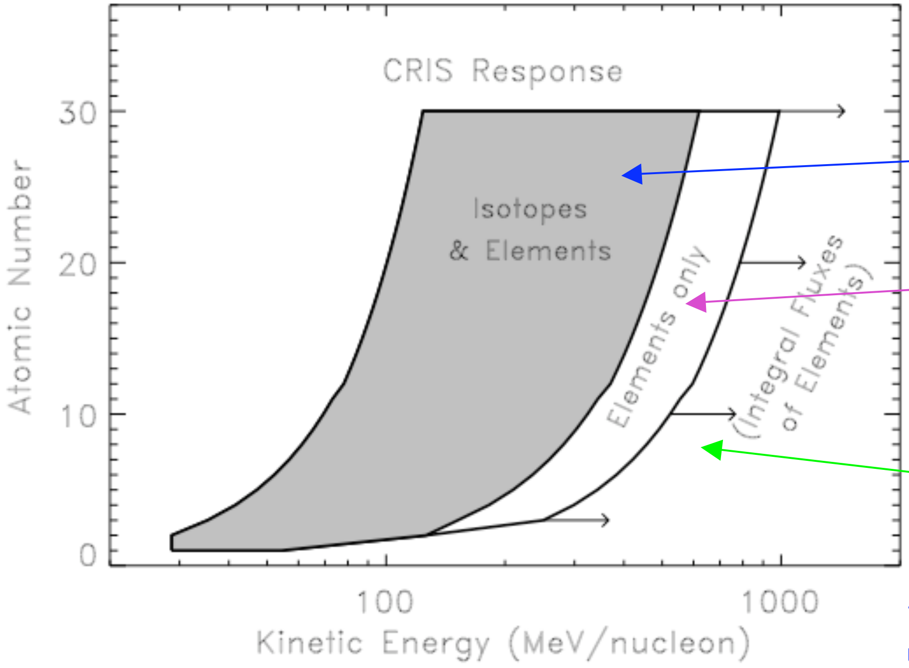


4 silicon detector layers
Scintillating fiber hodoscope

Mass resolution
O ≤ 0.15 amu
Fe ≤ 0.25 amu

$1 \leq Z \leq 30$

50 - 500 MeV/n



Best measured isotopes and elements

"Elements only": patterns of dE/dx, no measure of total energy

Lower limit on energy

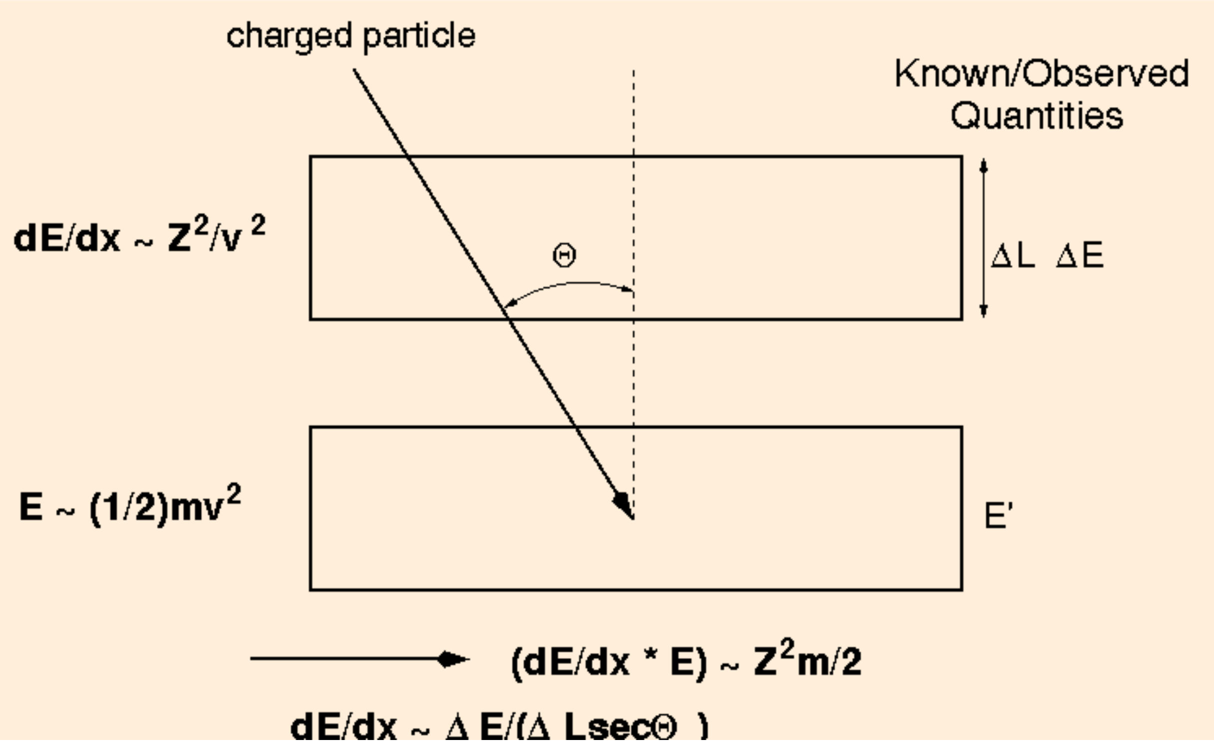
CRIS charged particle identification

Incident direction from hodoscopes (scintillating fibers in alternate direction)

Energy from silicon detectors (4 one above the other)

ΔE=energy deposit in 1 layer

$E_{tot} \approx E'$

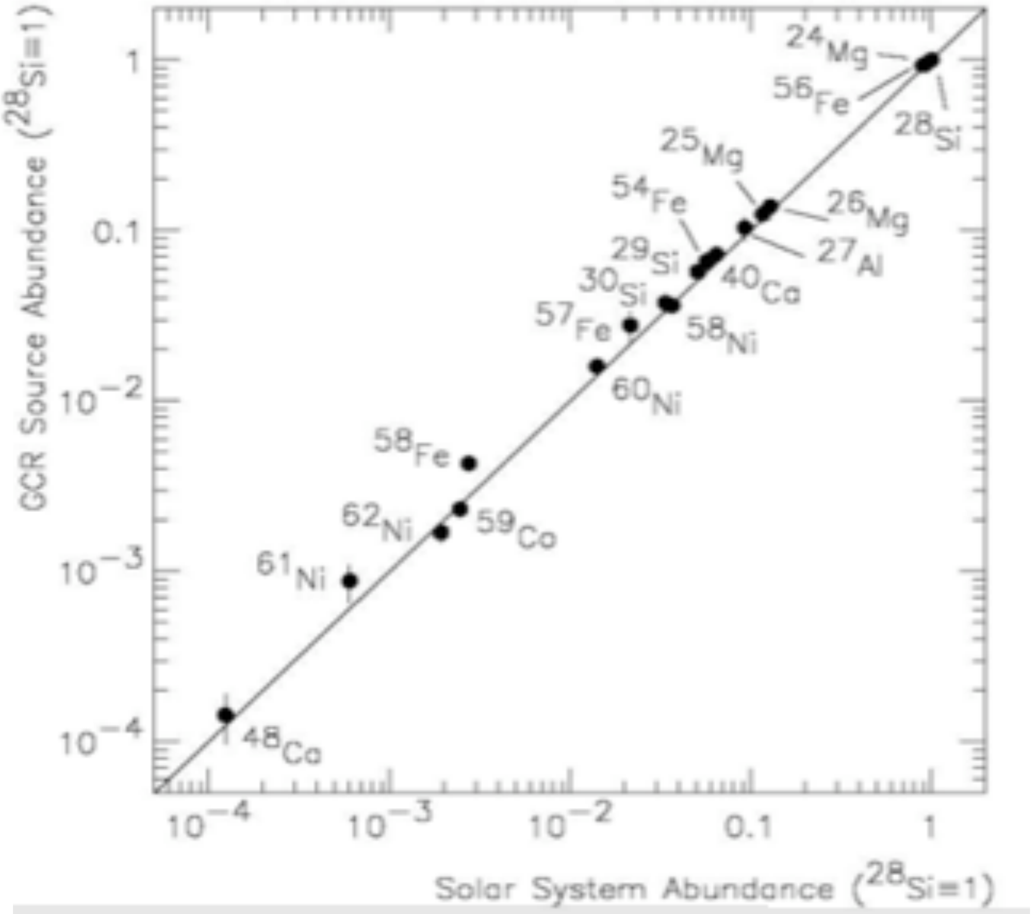


$$\boxed{\Delta E \times E_{tot} \approx Z^2 m}$$

Systematics minimized by use of multiple layers (redundant determination of Z,m)

Composition at source

Abundances at source are similar to those of the solar system



- Cosmic rays are accelerated out of a well mixed Interstellar matter in both samples

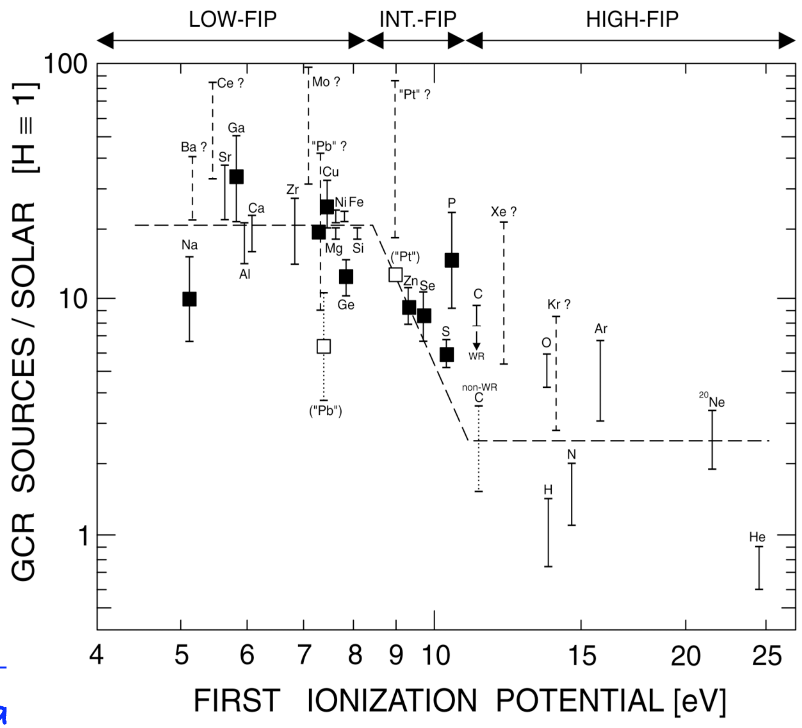
- $^{22}Ne/^{20}Ne = (0.387 \pm 0.007^{sys} \pm 0.022^{stat})$
  ~ 5.3 times more than in solar system!

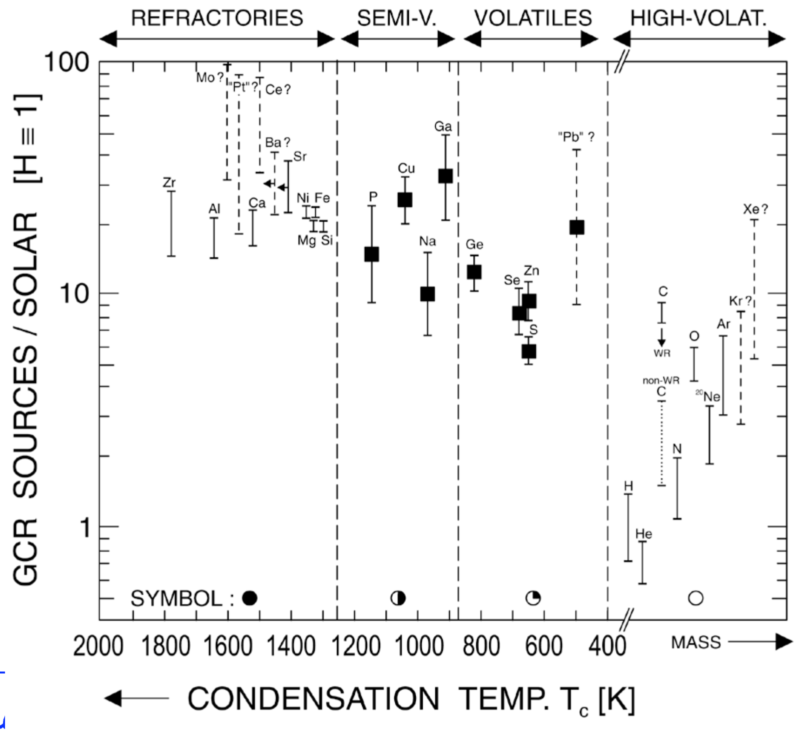
[Wiedenbeck M. et al., Proc. 28th ICRC Tsukuba, Japan, 4, 1899 (2003)]

GCR source abundances of elements (relative to solar-system abundances) well organized by FIP: the higher the FIP the lower the ratio, suggesting stellar atmosphere injection

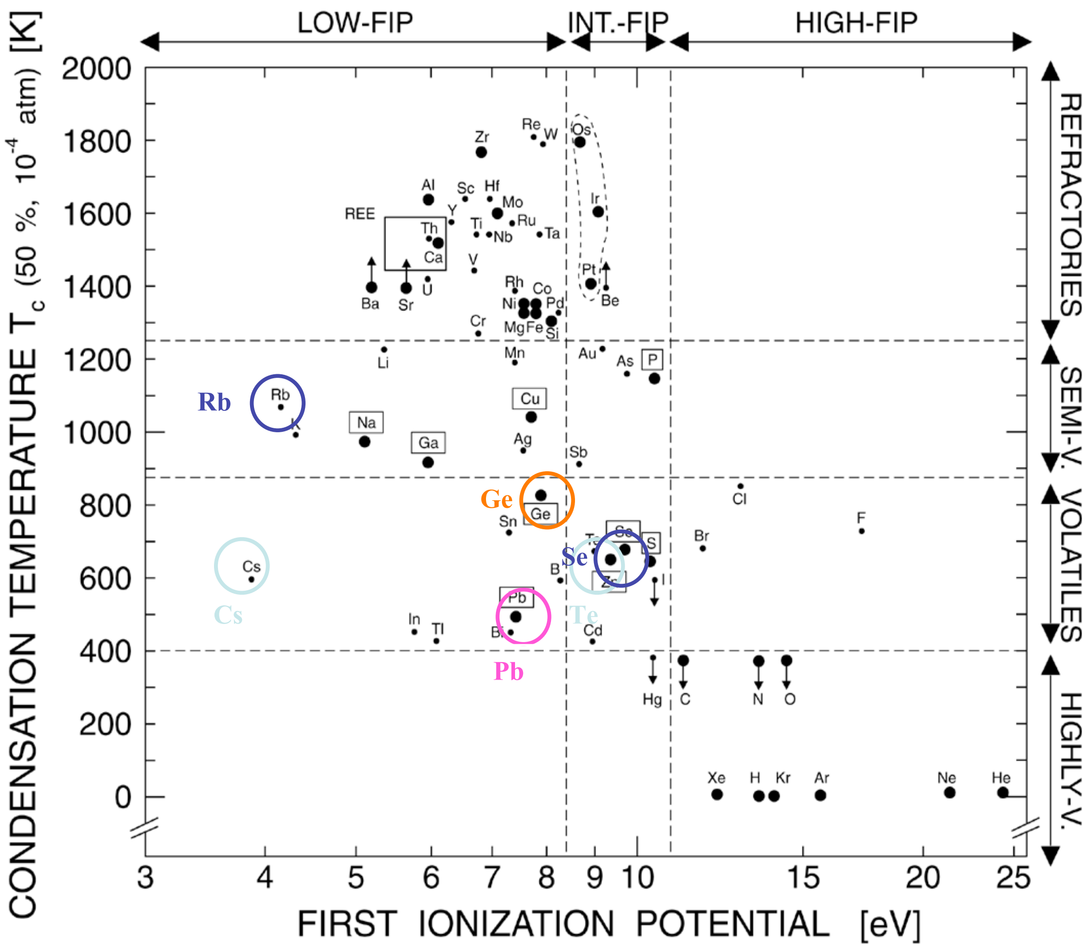
GCR source abundances also well organized by volatility: lower ratio for higher volatility suggesting origin in dust grains

It is difficult to distinguish FIP from volatility because most low-FIP elements are refractory.





Several UH elements break the FIP/volatility degeneracy



- ^{32}Ge, ^{37}Rb, ^{50}Sn, ^{55}Cs etc. can break the correlation since they are low FIP and volatile or semivolatile.

- ^{22}Na has to be measured at high energy to be primary

What is the source of the accelerated nuclei?

Superbubbles

blown by stellar winds and SN in OB associations

Size about 100-1000 pc

90% core collapses in our Galaxy occur in superbubbles

SN shocks accelerate superbubble material

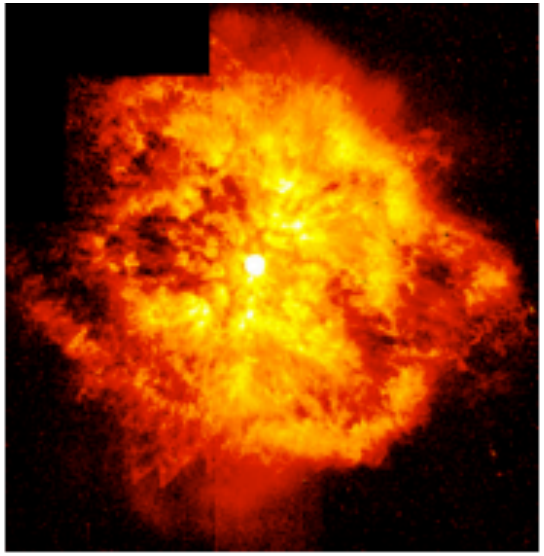
- Higdon et al. ApJ To be pub., Aug. 2005; ApJ 590 (2003) 822; ApJ 509 (1998) L33; Lingenfelter et al. ApJL 500 (1998) L153.
- Streitmatter et al. A&A 143 (1985) 249.

Superbubble (N 70) in the Large Magellanic Cloud (ESO-VLT image)

The N44 superbubble [© Gemini telescope, Chile]

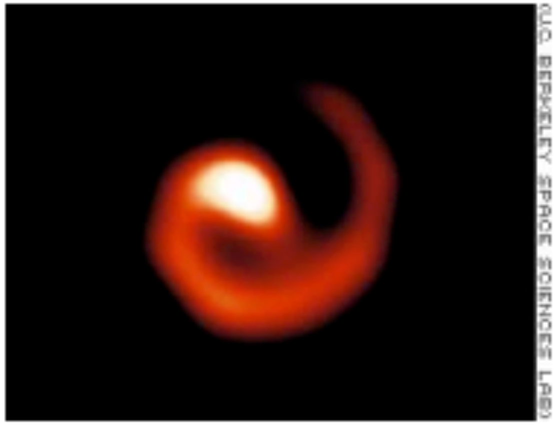
Wolf-Rayet stars

- Evolutionary phase of massive O & B type stars➔ exist primarily in OB associations
- WR Mass—15-45 $M_\odot$
- High velocity surface winds (~1,000-4,000 km/s) eject material into the ISM
- Often are dusty and ~>60% are binaries—puzzle how dust can exist in such a hot environment
- Two phases—WN and WC
  - WN--CNO processed material is ejected with production of high $^{13}C/^{12}C$ and $^{14}N/^{16}O$ ratios
  - WC--Wind enrichment of He-burning products: esp. C, O, and ^{22}Ne through reaction $^{14}N(\alpha,\gamma)^{18}F(e^{+}\nu)^{18}O(\alpha,\gamma)^{22}Ne$



Diam~0.2pc

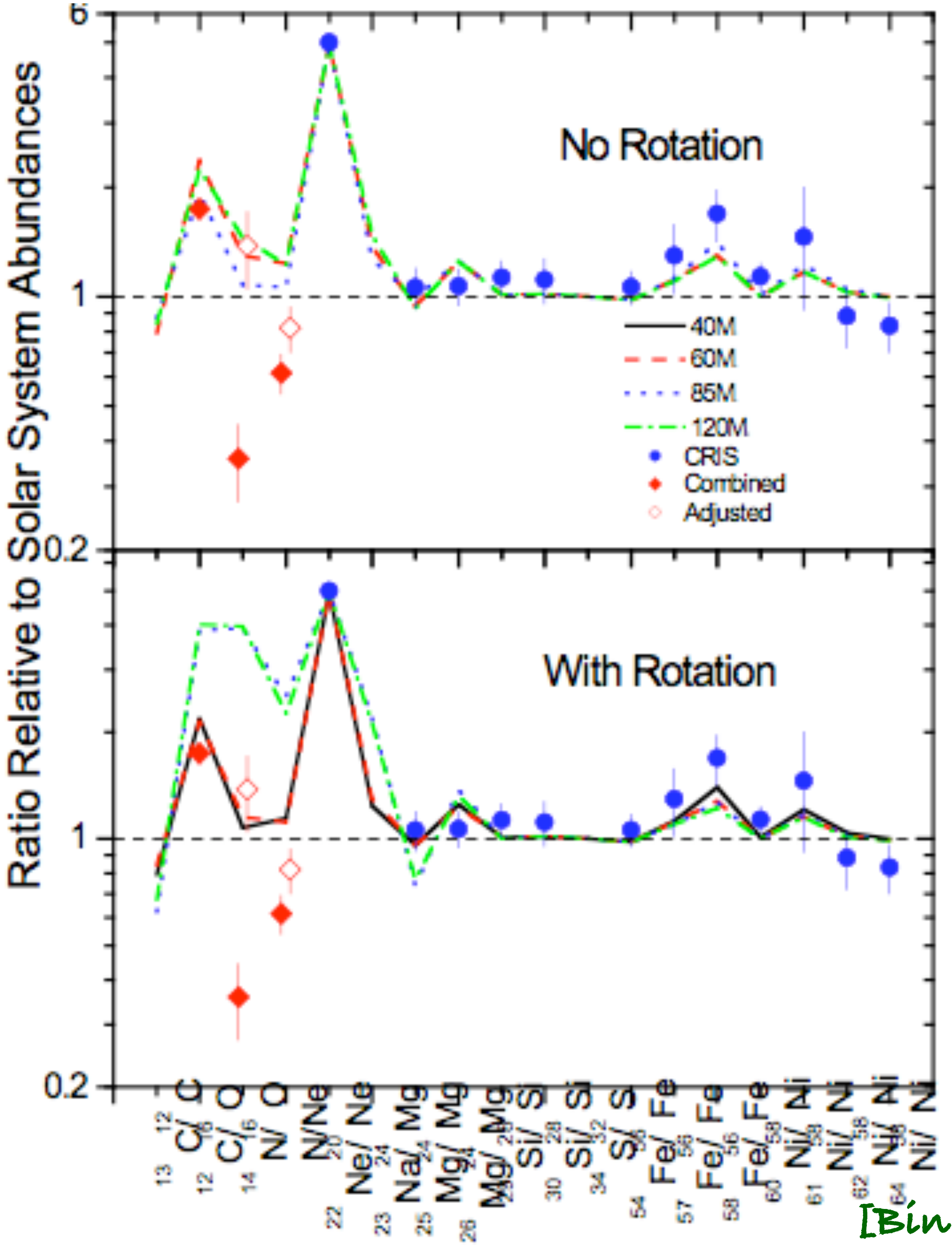
WR-124 in Sagittarius—Hubble Image



Diam~200au

WR-104 in Sagittarius—Keck Telescope Image

[© Binns, Aspen 2005]



[Binns W.R. et al., New Astron.Rev. 2008]

Model for Wolf-Rayet stars with various initial masses, with and without rotation.

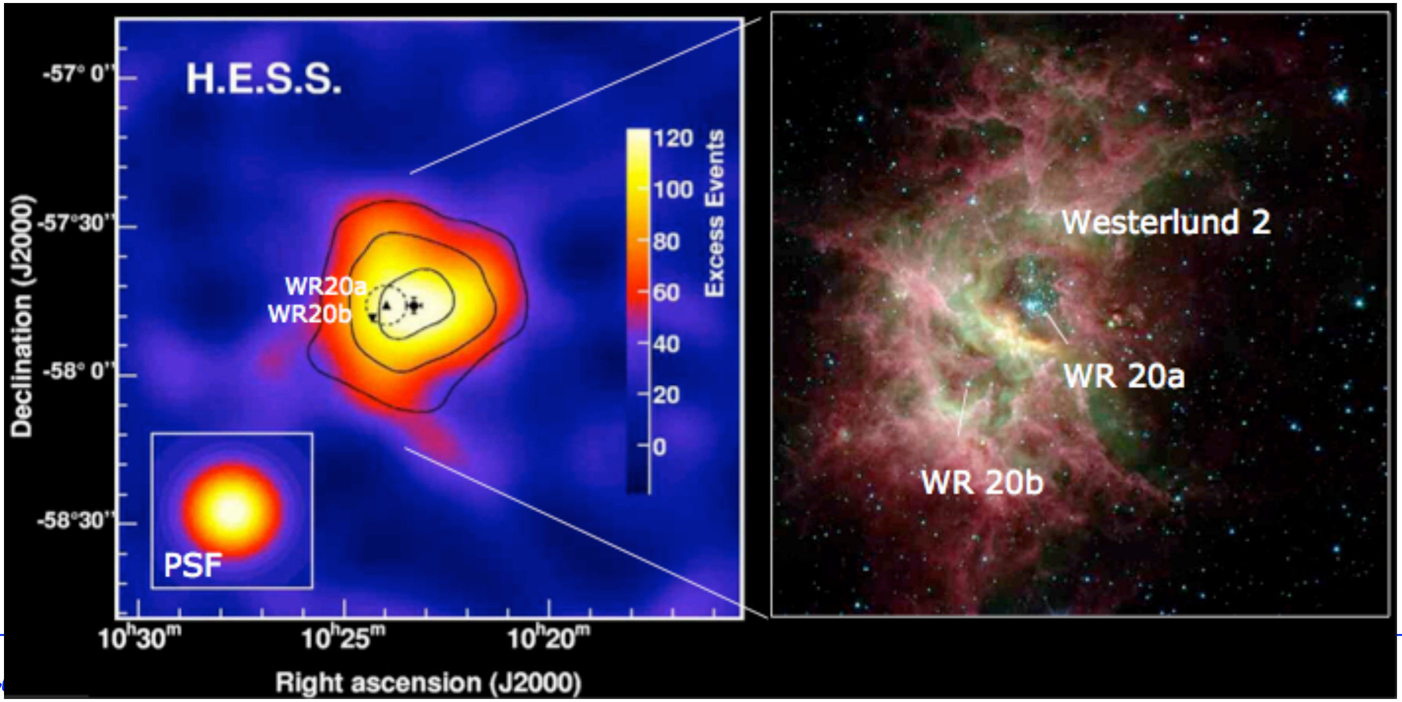
- CRIS indeed observes enhanced ratios for $^{12}C/^{16}O$, $^{22}Ne/^{20}Ne$ and $^{58}Fe/^{56}Fe$, as predicted in WR models if about 20% WR contribution
- CRIS observes consistency with Solar System abundances for the ratios which are not enhanced in WR models

WR star ejects are an important component of cosmic ray source material

Superbubbles, where most WR stars and core-collapse SN reside must be main sites of injection of material as GCR seeds and sites of origin and acceleration of a big fraction of GCRs.

This conclusion is strengthened by discovery of TeV γ-ray sources from star forming regions … “The answer is blowing in the wind” [Butt Y.M., Nature 446 (2007) 986]

J2032+4130 and Cygnus OB2 [Aharonian et al., Science 3007 (2005) 1938]
J1023-575 in the RCW49 [Aharonian et al., A&A 467 (2007) 1073,



Outline of the lecture

Introduction

Origin, acceleration and

Models of the knee

Extensive Air Showers

Experimental techniques.

Energy spectrum and composition: measurements and results

Models of the knee : comparison with data

Anisotropy studies with EAS arrays

Models describing the Galactic to Extragalactic transition

Present results in the transition region

Future projects

From Acceleration processes
From propagation and leakage
…or new physics

The origin of the knee

Acceleration in SNRs:

finite lifetime of shock Emax $\propto$ Z 10^{15} eV

[SNRs - oblique shocks / single sources...]

- $E_{knee} \propto Z$
- Composition heavier above knee
- No anisotropy change

Diffusion process:

probability of escape from Galaxy = f(Z)

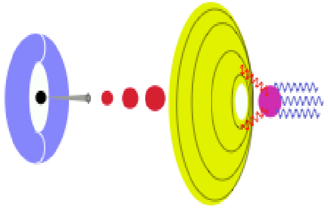
[Minimum pathlegth - Hall diffusion - Turbulent diffusion etc.]

- $E_{knee} \propto Z$
- Composition heavier above knee
- Anisotropy $\propto E^{\delta}$

Cannonball Model:

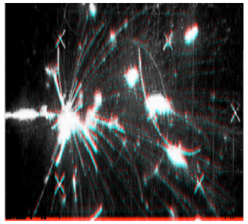
probability of escape from Galaxy = f(Z)

[Minimum pathlegth - Hall diffusion - Turbulent diffusion etc.]



Interaction with bckg particles:

[Photo-disintegration - interaction with ν in galactic halo etc.]



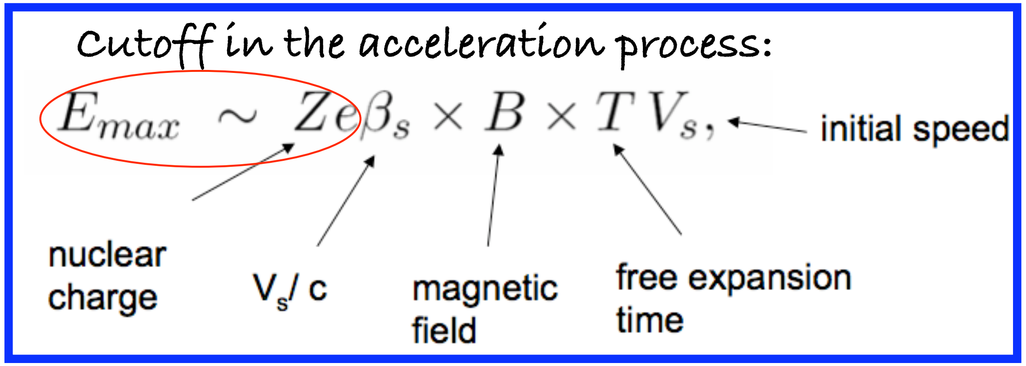
Change in particle interaction:

[Gravitons,SUSY etc.]

$E_{knee} \propto A$

[J.R.Hoerandel, Astrop.Phys.21 (2004) 241 updated]

ACCELERATION IN SNRs



Cutoff in the acceleration process:

$$E_{max} \sim Ze\beta_s \times B \times T V_s,$$

initial speed

nuclear charge

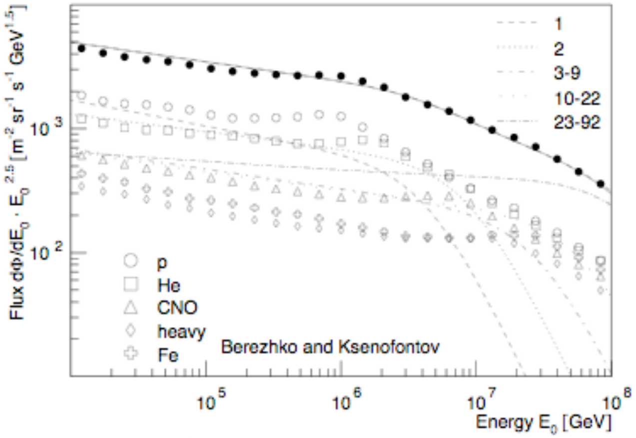
V_s/c

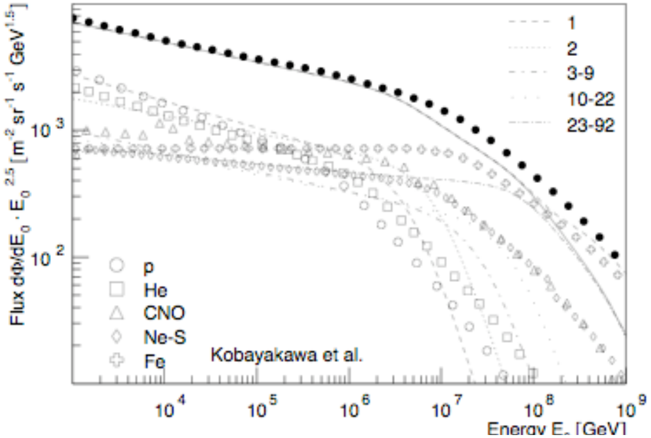
magnetic field

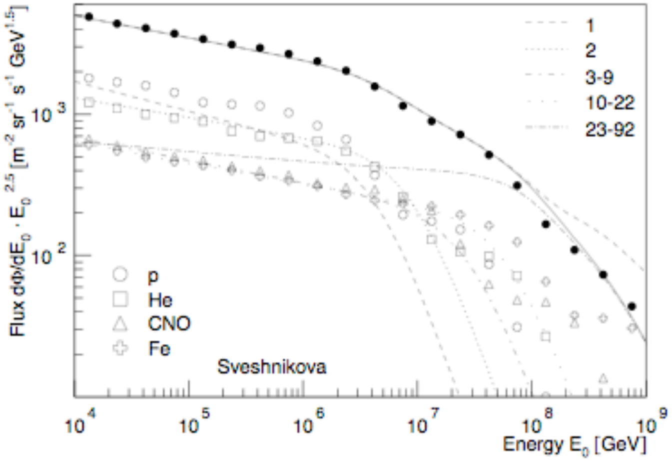
free expansion time

Differencies due to variations of the diffusive shock acceleration

... in SNR	Berezhko & Ksenofontov
... in SNR + radio galaxies	Stanev
... in oblique shocks	Kobayakawa
... in variety of SNR	Sveshnikova
Single source model	Erlykin & Wolfendale
Reacc. in galactic wind	Völk & Zirakashvili







LEAKAGE FROM GALAXY

Knee caused by the leakage of particles from the Galaxy

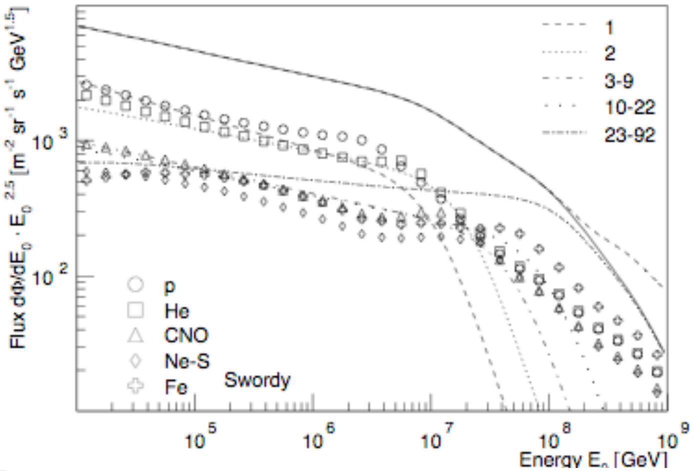
$E_{Knee} \propto Z$

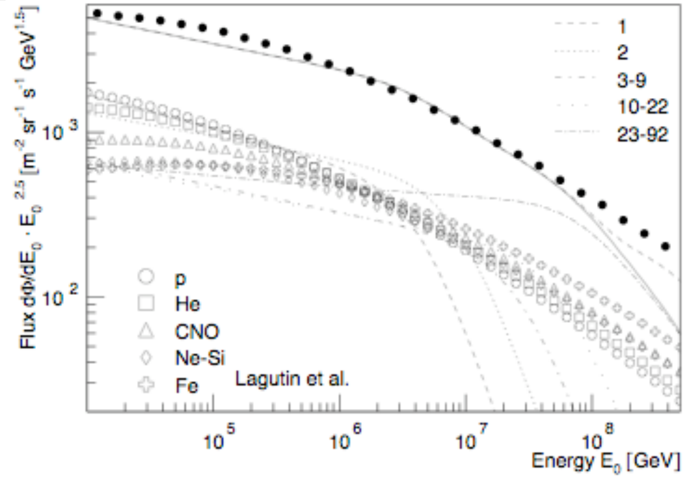
Minimum pathlength model Swordy

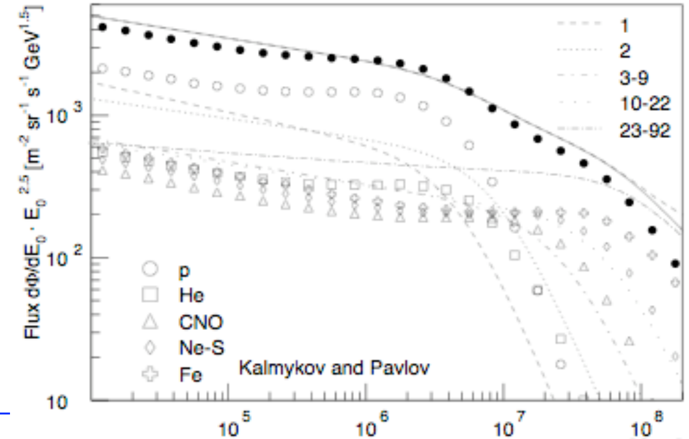
Anomalous diffusion model Lagutin ..

Differencies due to drift in the magnetic field of Galaxy

...Hall diffusion model	Ptuskin
...Diffusion in turbulent m.f.	Ogio & Kakimoto
...Diffusion and drift	Roulet







CANNONBALL MODEL

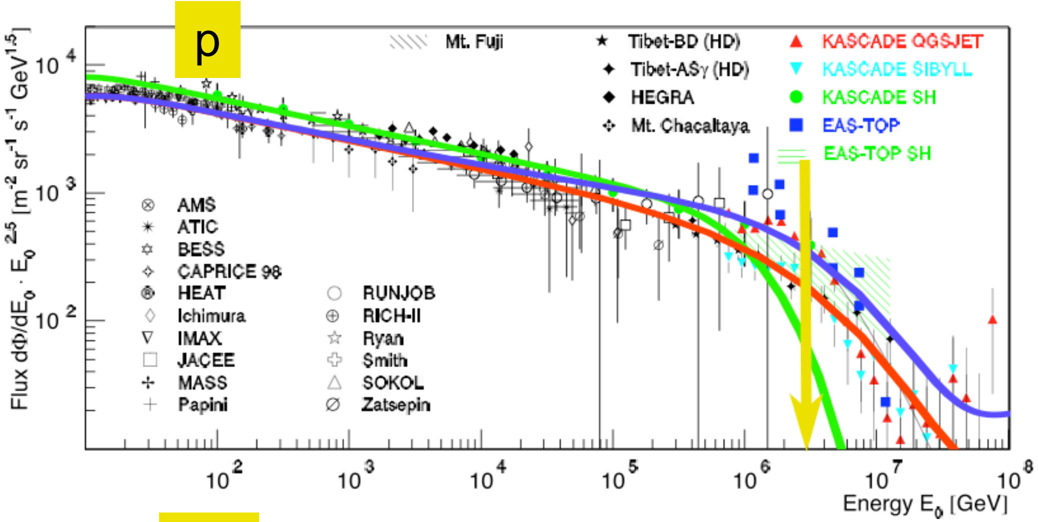
A moving CB scatters particles to (e.g. for $\gamma > 1000$)

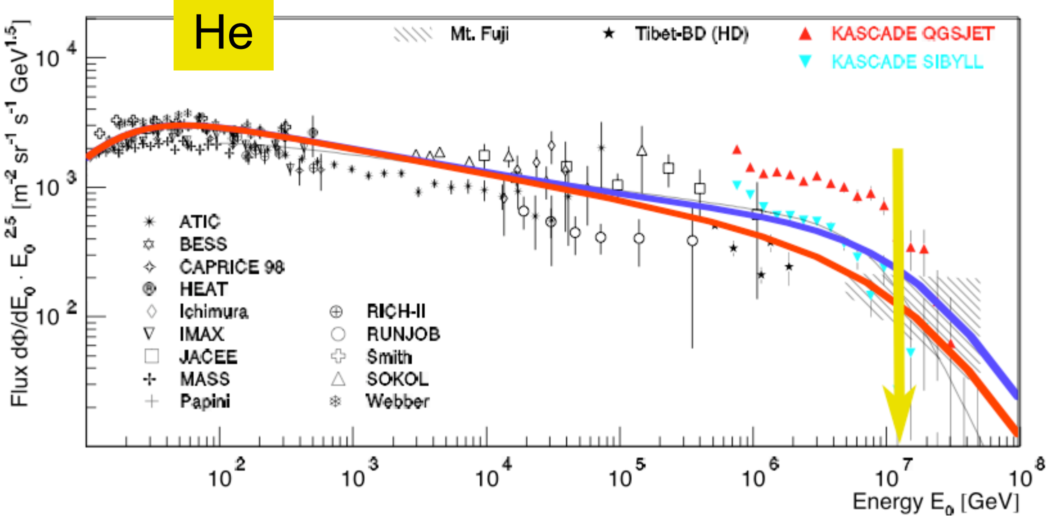
$$E_{Knee} \propto A\ (2\text{-}4)10^{15}\ \mathrm{eV}$$

Two relativistic ejecta of plasma matter, the cannonballs, are emitted in SN and generate GRBs and CRs [De Rujula, Dar]

They account for CRs at all energies

The knee is due to elastic magnetic scattering



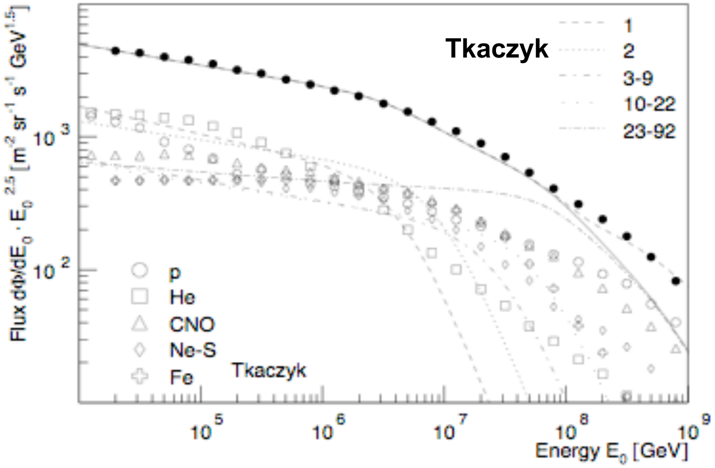


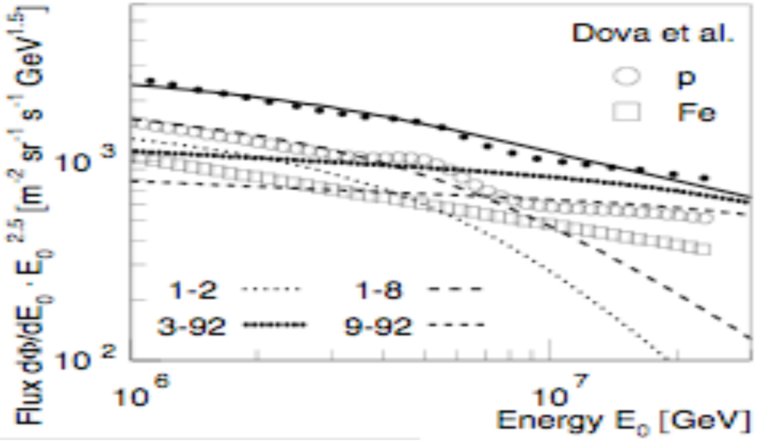
INTERACTION - I

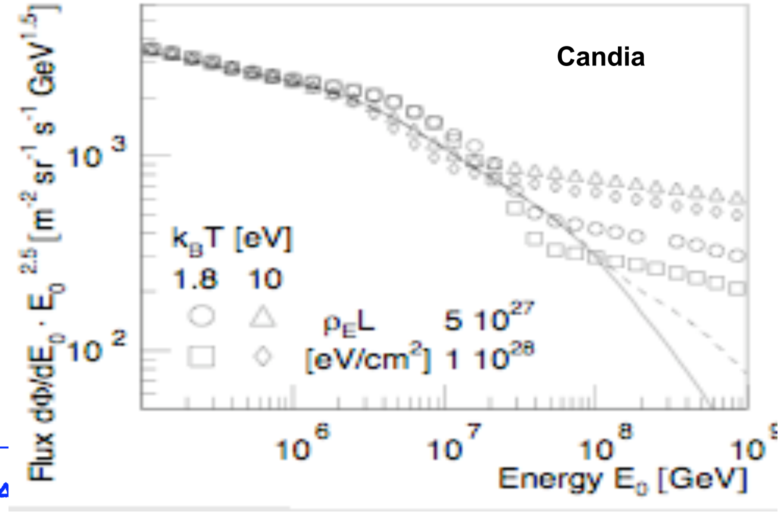
Knee caused by the interaction of cosmic rays with background particles

$$E_{Knee} \propto A$$

Diffusion model + photo-disintegration (on field of soft γ around sources)	Tkaczyk
Interaction with neutrinos in galactic halo	Dova
Photo-disintegration (on optical and UV photons)	Candia





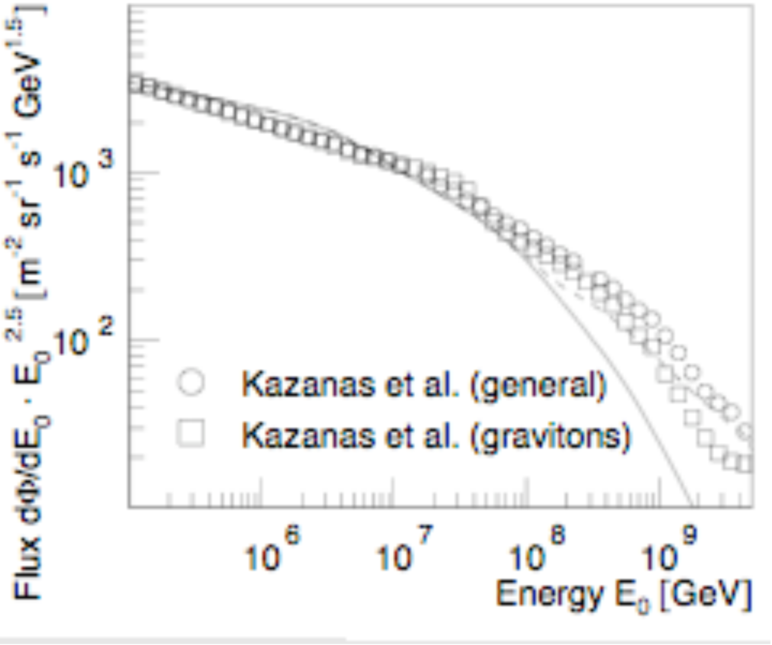


INTERACTION - II

the primary CR energy is underestimated

Knee is a threshold effect

$E_{Knee} \propto A$



New physics in atmosphere Kazanas, Nicolaidis
(supersymmetry)

Starting from initial galactic and extragalactic components, gravitons are produced.
Free parameters are
the fundamental scale of gravity Mg~8 TeV
the dimensions $(4+\delta)$, $\delta \sim 4$

The "Standard Model" of Galactic Cosmic Rays

- The source population of GCRs is very similar to solar system composition
  + 20% addition from Wolf-Rayet stars (in superbubbles)

- These particles were accelerated recently (~10-20 My) from a source population of ISM and dust [SN feed the ISM with products of nucleosynthesis]

- Refractory elements are clustered in grains and accelerated more efficiently

- DSA at SN driven shocks produces power law energy spectra $\propto E^{-\alpha}$, **with** $\alpha>2$ up to some maximum energy $\propto 3\ 10^{15}$ Z eV

  Taking into account propagation with a diffusion coeff. $\propto E^{1/3}$ the observed spectra can be reproduced $\propto E^{-2.7}$

- The knee feature of the GCR spectrum is modeled either relating it to acceleration and/or propagation processes or invoking new physics