Lectures & objectives

ISAPP 2014
(Belgirate)
21-30 July 2014

Transport of cosmic rays in the Galaxy and in the heliosphere (~ 4h30)

- What is GCR (Galactic Cosmic Ray) physics and transport
- Relevant time scales: ≠ species have ≠ phenomenology
- Main modelling ingredients: key parameters and uncertainties
- Tools to solve the transport equation

Charged signals: electrons/positrons, antibaryons (~1h30)

- What is astroparticle physics and DM (Dark Matter) indirect detection
- What are the astrophysical backgrounds + uncertainties [nuclear]
- Phenomenology of DM signals + uncertainties [transport and dark matter]
- Pros and Cons of DM indirect detection with charged GCRs

→small part of multi-messenger and multi-wavelength analyses

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Important: these lectures are not about...

Plasma physics:

- Diffusive shock wave acceleration
- Microscopic approach of diffusion and transport

CRs at all energies:

- Low E CRs (e.g., 511 keV line from positron annihilation)
- VHE and UHE CRs (knee and ankle)

DM candidates:

- Particle physics models relevant for DM indirect detection
- Review of the best DM candidates in the context of GCRs

Useful references

Textbooks on CRs and CR propagation

Perfect for beginners

High Energy Astrophysics (1981+1992, 2004): Longair

... undisputed classic

The Origin of Cosmic Rays (1964): Ginzburg and Syrovatskii

... c*omprehensive but uneven and higher level*

Astrophysics of Cosmic Rays (1990): Berezinskii, Bulanov, Dogiel, Ginzburg, and Ptuskin

Bias towards diffusion coefficient

Cosmic Ray Astrophysics (2002): Schlickeiser

... stronger bias

Nonlinear Cosmic Ray Diffusion Theories (2009): Shalchi

Bias towards High Energy CRs (cosmic-ray showers)

Cosmic Rays and Particle Physics (1990): Gaisser

High Energy Cosmic Rays (2004, 2010): Stanev

Strong bias towards surface detectors (neutron and muon detectors)

Cosmic Rays: Variations and Space Explorations (1974): Dorman

Cosmic Rays in the Earth's Atmosphere and Underground (2004): Dorman

Cosmic Rays in the Magnetosphere of the Earth and Other Planets (2006): Dorman

Let's get started!

Transport of cosmic rays (CR) in the Galaxy

I. Introduction; Galactic Cosmic Rays
1. Early history of CRs: discovery and disputes
2. GCR journey (from source to detector)
3. Timeline
4. Observables and questions

II. Processes, ingredients, characteristic times
1. Definitions
2. Diffusion (space and momentum)
3. Convection and adiabatic losses
4. Energy losses
5. Catastrophic losses
6. All together

III. Solving the equations: GCR phenomenology
1. The full transport equation
2. Source terms: primary and secondary contributions
3. A matrix of transport equations
4 (Semi-)Analytical, numerical, & MC solutions
5. Stable species: degeneracy K_0 /L
6. Radioactive species and local ISM
7. Leptons and local sources

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GCRs-I.pdf

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Historical perspective

How cosmic rays were discovered and why they received this misnomer
Adv. in Space Res. 53 (2014) 1388–1404
Dorman & Dorman

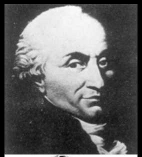
As many great discoveries, **the phenomenon of cosmic rays was discovered mainly accidentally, during investigations that sought to answer another question**: what are sources of air ionization? This problem became interesting for science about 230 years ago in the end of the 18th century, when physics met with a problem of leakage of electrical charge from very good isolated bodies. [...] These discoveries were recognized among greatest in the 20th Century and were awarded by Nobel Prize.

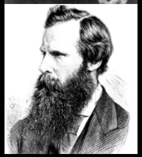
Historical perspective: ionic conductivity of gas

Study of atmospheric electricity

1785 – Charles Coulomb
Charge loss ("electricity dispersion") occurs mainly through air

1879 – William Crookes
Speed of discharge decreases with P: ionization of air is the direct cause





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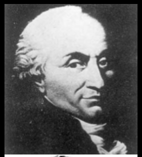

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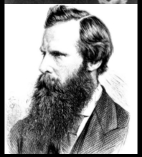

Natural radioactivity

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Discovery of X-rays (or Röntgen rays)

1896 – Henri Becquerel, Marie & Pierre Curie (Nobel 1903)
Discovery of spontaneous radioactivity



1897 – Joseph John Thomson (Nobel 1906)
Discovery of electron

1900 – Henri Becquerel
β *radioactivity = electrons*
1903,1914 – Ernest Rutherford (Nobel 1908)
α *radioactivity = helium*
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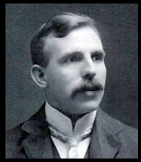

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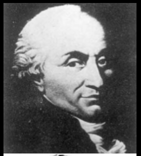

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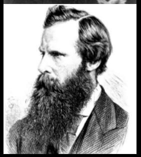

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End of 19th century – J.J. Thomson
Electric conductivity of gasses strongly increases under the influence of X-rays and radiation from radioactive elements
→ Theory of ionic conductivity of gasses

Historical perspective: nature of the source of ions?

Start of 20th century

- Radiation constantly ionizing the air
- Discharge of an electroscope explained by an insignificant number of ions in air

→ **What is the nature of the unknown source of ions?**

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1900 – J. Elster and H. Geitel

Data: conductivity of air strongly fluctuates depending on atmospheric conditions, over land or sea, and height of the place of observations
→ Main source of ionization of air are radioactive emanations accumulating in atmosphere + radioactive substances in the Earth's crust

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1901 – C.T.R. Wilson (invented later the cloud chamber, Nobel 1927)

Data: speed of leakage for + and - charge is identical, proportional to P
→ "*future [...] will show that formation of ions in air [...] is caused by radiation which arises out of our atmosphere to similarly X-ray or cathodic rays, but possesses considerably bigger penetrating ability*"

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But Wilson changed his mind:

Data: speed of ionization in a tunnel, no reduction w.r.t. usual conditions
→ "*It is improbable therefore that ionization is caused by radiation passing through our atmosphere. Most likely, as has concluded Geitel, this is property of air*"

Historical perspective: proof of an extraterrestrial radiation?

- **A decade of unrewarded efforts...**

  1902-1909 – Improvements of apparatus, data at ground, sea, mountain level... w/o shielding

  Review of Kurtz (1909)

  - γ-radiation from the earth's crust;
  - radiation coming from the atmosphere;
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  } Resolutely rejected as improbable!

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- **Ionisation constant with altitude (whereas decrease expected)**

  1909-11 – A. Gockel: 3 balloon flights @ 4500 m (unpressurised detector)
  1909-10 – T. Wulf: electroscope + measurements at Eiffel tower
  1909-12 – D. Pacini: underwater (require non-terrestrial radiation)

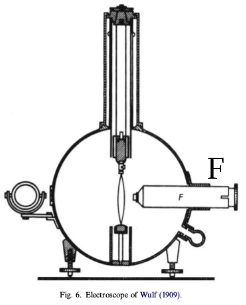

Fig. 6. Electroscope of Wulf (1909).

Electroscope: speed of discharge related to distance change between the wires (microscope F)

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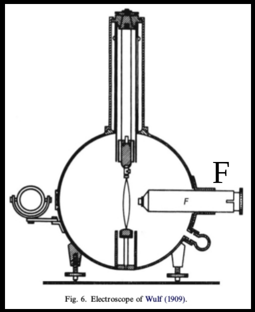

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- **Proof of existence: V. Hess (1911-1912)** → "*ultra-gamma radiation*"

1911: First measure of γ-ray attenuation in air, predict absorption for d≥500 m
→ "*there should be other source of a penetrating radiation in addition to γ-radiation from radioactive substances in earth crust*"

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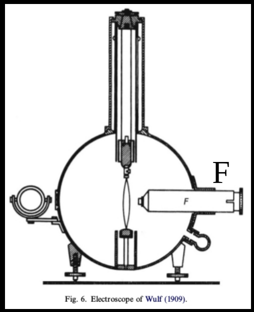

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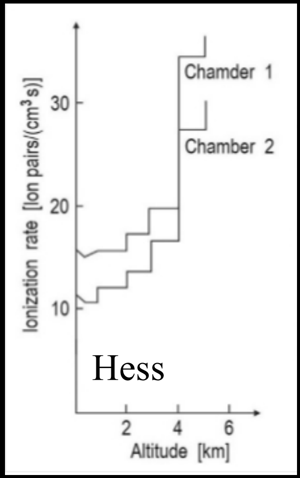

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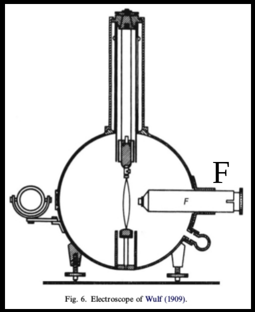

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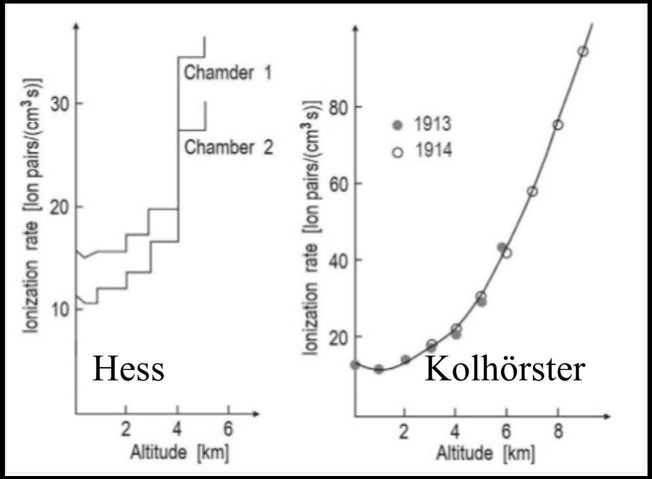

… and confirmation by Kolhörster (1913-1914)

Historical perspective: debates on science or human nature?

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Alternative explanation
- High altitude radioactive pollution
- Particle acceleration up to high energies during thunderstorms

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- **Cosmic rays are extra-terrestrial particles... (Hess: Nobel 1936)**

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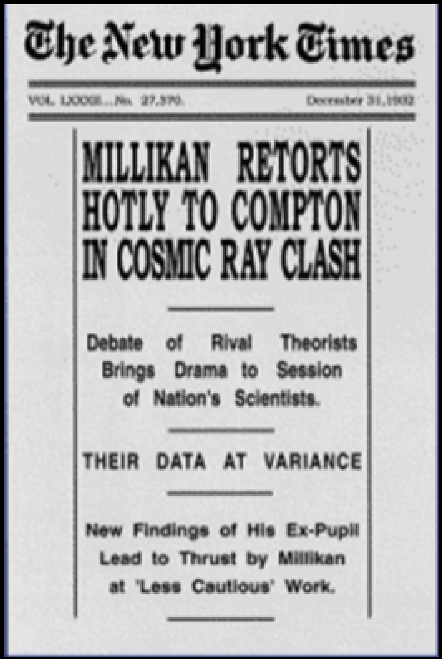
The New York Times

MILLIKAN RETORTS HOTLY TO COMPTON IN COSMIC RAY CLASH

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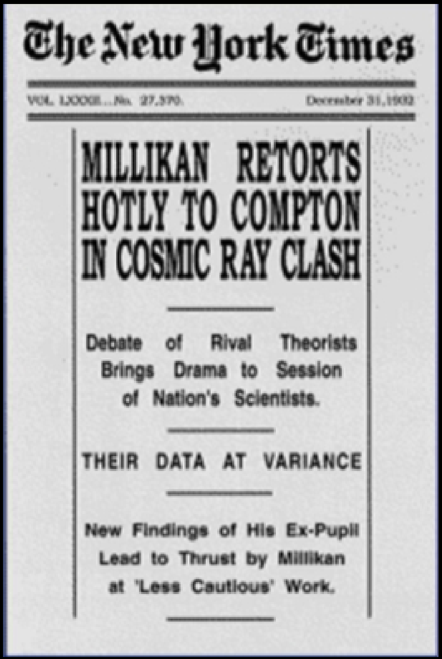
  1930s
  - Latitude surveys (Clay, Compton, Rossi...) + Störmer's theory (1910-1911)
    → cosmic rays are charged particles
  - West–East CR asymmetry (Johnson, Seidl, Burbury, Fenton)
    → the largest part of primary CR are positively charged particles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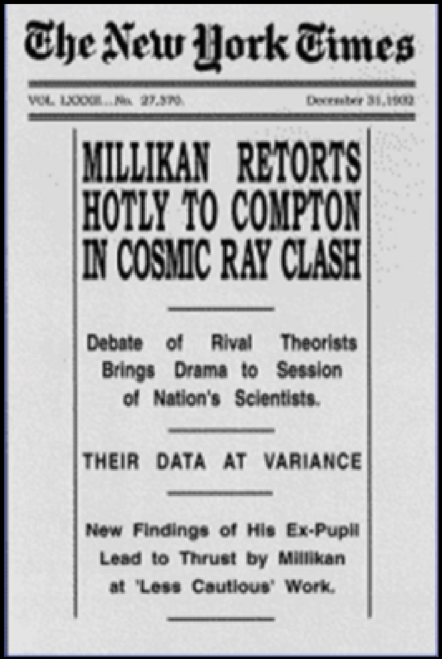
  →Interesting sociological aspects of science...

  Clay (discoverer of latitude effect in 1927): "*Mr Millikan [...] is violating the truth, as he does, for his own profit, without any scruples*"
  Alvarez (Nobel 1968, PhD student of Compton) on Millikan: *"First of all, I do not believe latitude effect, but if you really have this effect, then I first discovered it"*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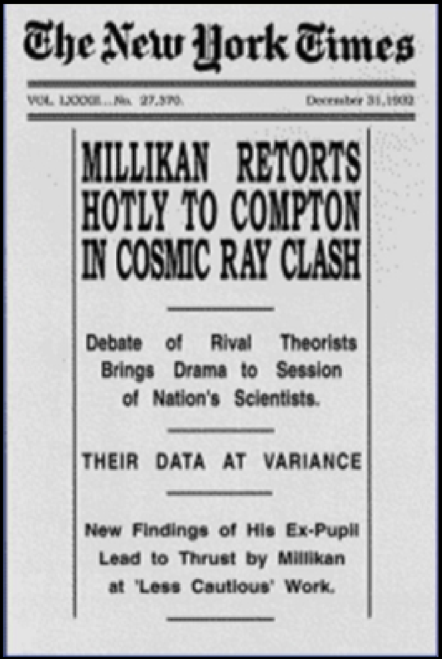
CR Romancing: The Discovery of the Latitude Effect and the Compton-Millikan Controversy
Historical Studies in the Physical and Biological Sciences 19, No. 2 (1989) 211-266
M. De Maria and A. Russo

The Discovery of CRs: Rivalries and Controversies between Europe and the US
Historical Studies in the Physical and Biological Sciences 22 (1991) 165-192
M. De Maria, M. G. Ianniello and A. Russo


The New York Times

MILLIKAN RETORTS HOTLY TO COMPTON IN COSMIC RAY CLASH

Debate of Rival Theorists Brings Drama to Session of Nation's Scientists.

THEIR DATA AT VARIANCE

New Findings of His Ex-Pupil Lead to Thrust by Millikan at 'Less Cautious' Work.

Historical perspective: opening the space age...

- **First World War... delayed interest until 1921 (USA), 1923 (Germany)**

- **Another period of doubt... [Millikan = Nobel 1923]**

  1922 – Millikan & Bowen: unmanned balloons (15 500 m reached)
  → High altitude radiation (10 km), but 4x smaller than expected

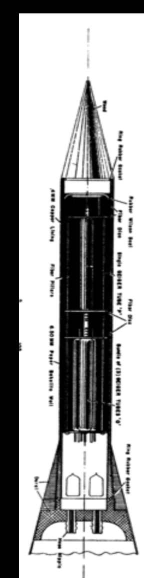
  1923 – Millikan: absorption factor of high-altitude radiation in lead
  → "*The radiation for the most part nevertheless has a local origin*"

  Alternative explanation
  - High altitude radioactive pollution
  - Particle acceleration up to high energies during thunderstorms

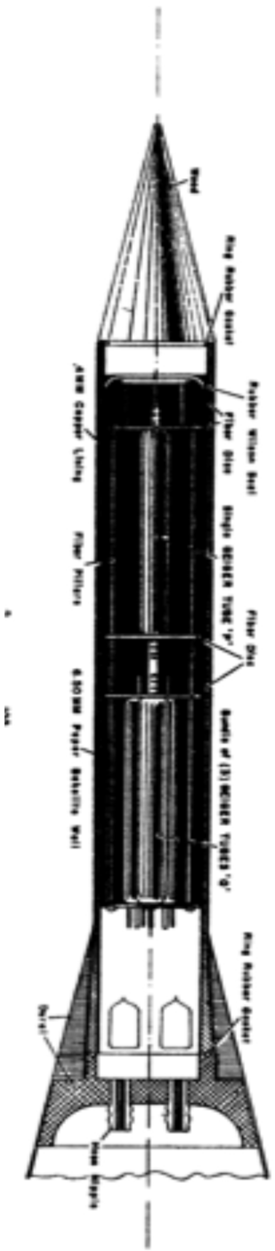
  1926 – Millikan & Cameron
  → *"These rays do not occur from our atmosphere and consequently can be rightfully named by **'cosmic rays'**"*

- **Cosmic rays are extra-terrestrial particles... (Hess: Nobel 1936)**

  1947: First measurement out of the atmosphere with a rocket!



Historical perspective: opening the space age...

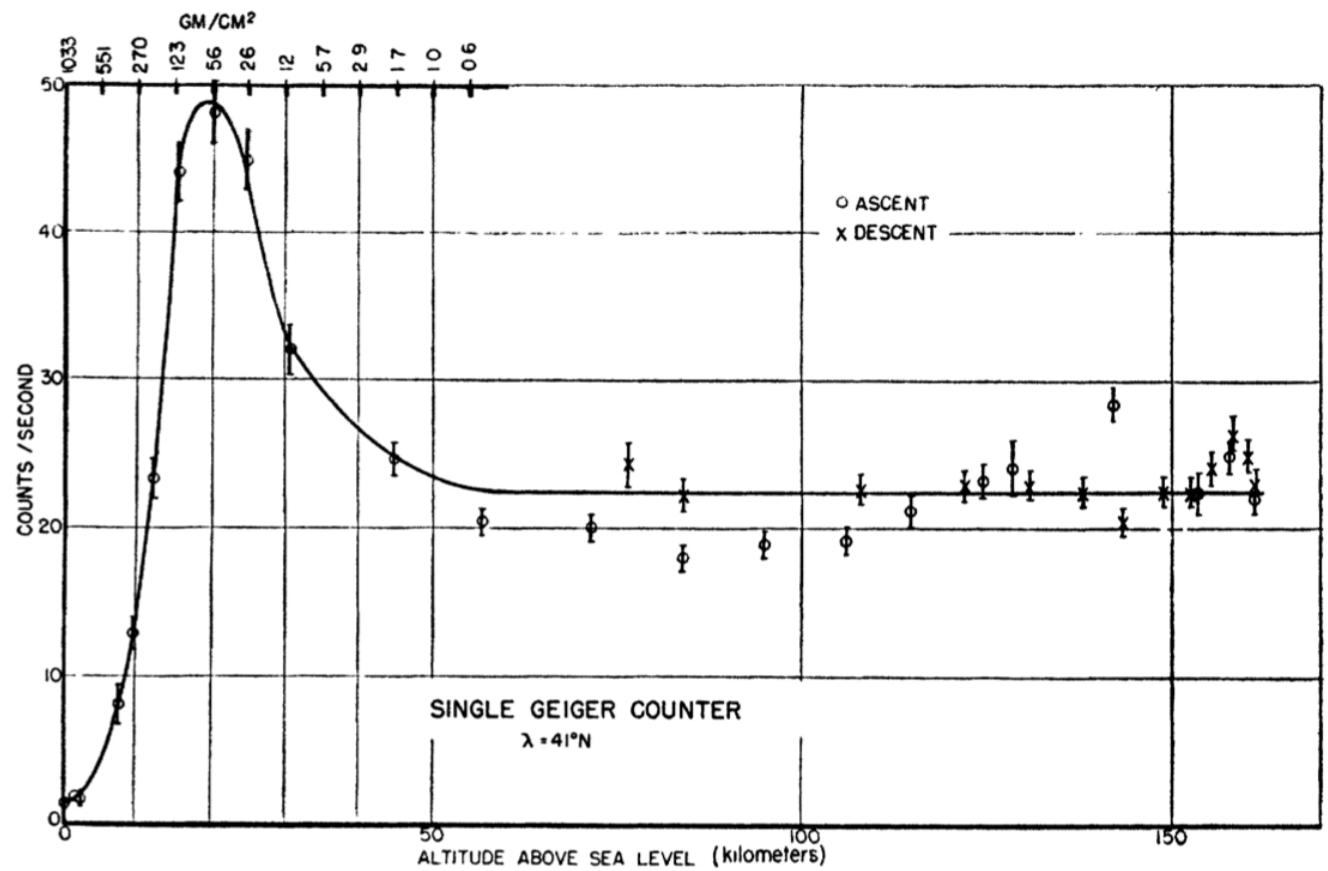


PHYSICAL REVIEW VOLUME 73, NUMBER 3 FEBRUARY 1, 1948

The Cosmic-Ray Counting Rate of a Single Geiger Counter from Ground Level to 161 Kilometers Altitude

J. A. VAN ALLEN AND H. E. TATEL*
Applied Physics Laboratory, Johns Hopkins University, Silver Spring, Maryland

(Received October 16, 1947)

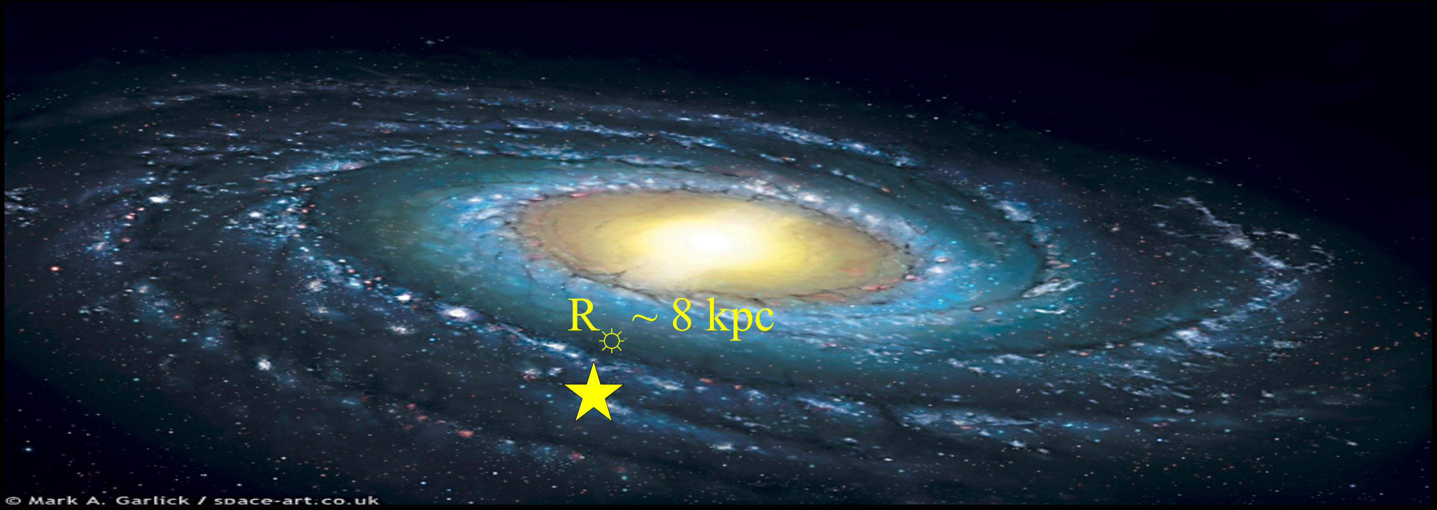


Transport of cosmic rays (CR) in the Galaxy

I. Introduction: Galactic Cosmic Rays (GCR)

1. Early history of CRs: discovery and disputes
2. GCR journey (from source to detector)
3. Timeline
4. Observables and questions

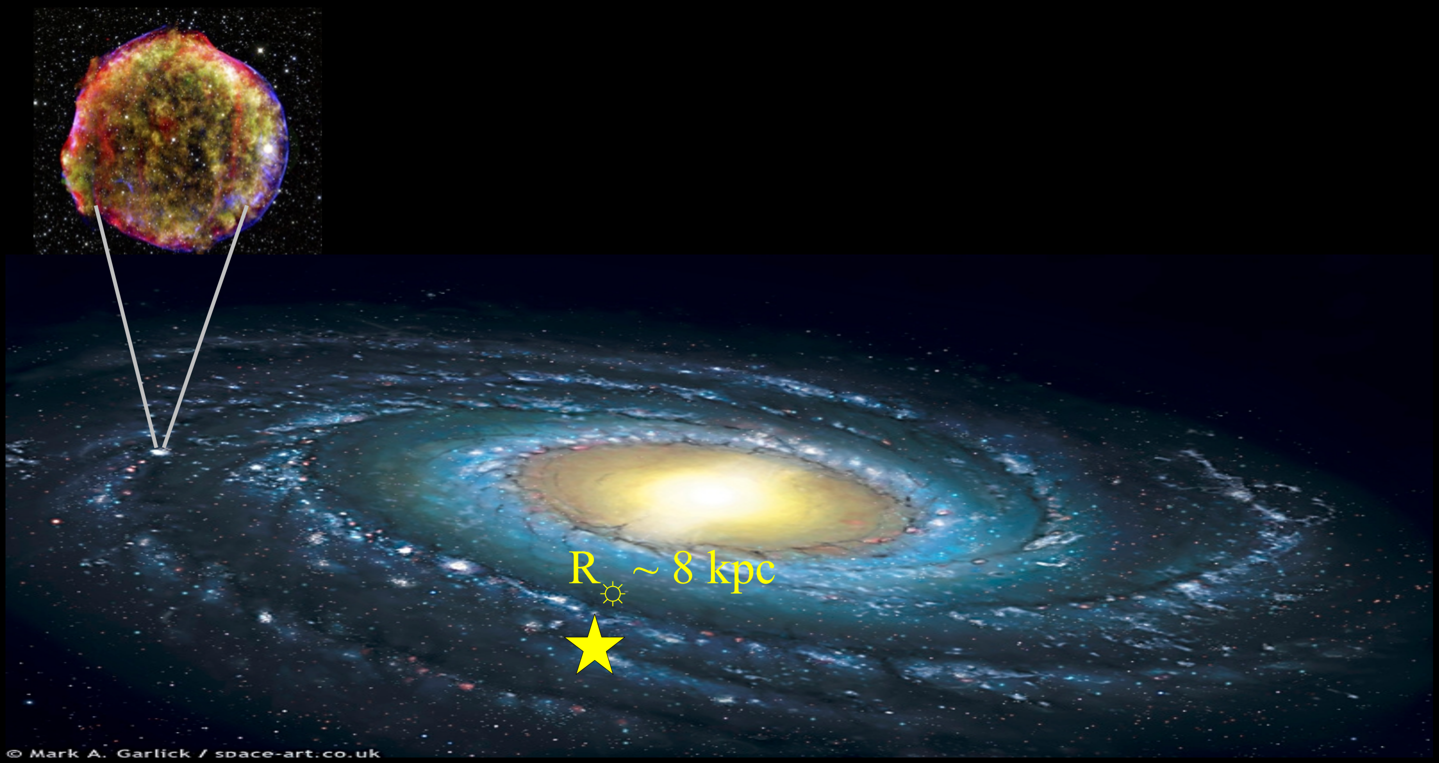
Charged cosmic rays in the Galaxy



Charged cosmic rays in the Galaxy: sources

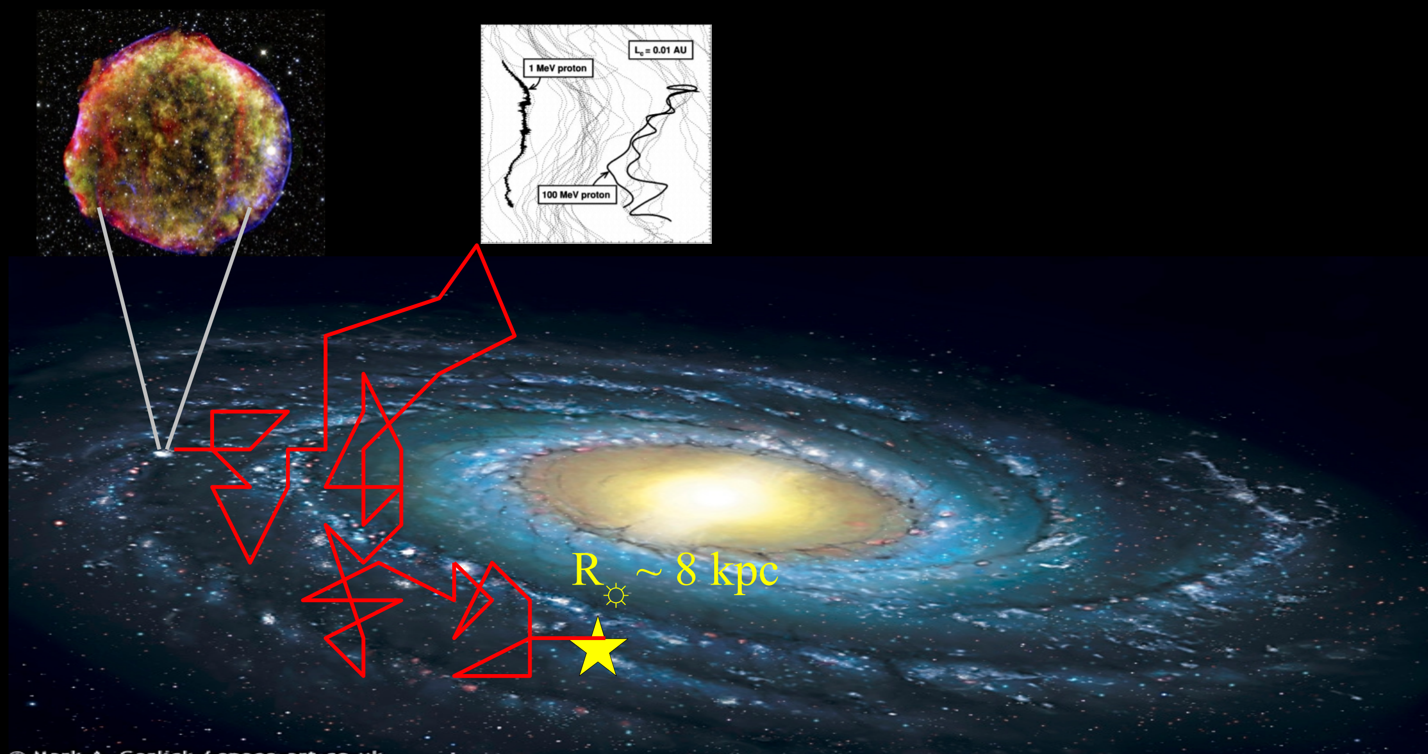
1. Source injection

- spectrum ~ R^{-2}
- abundances



Charged cosmic rays in the Galaxy: diffusion

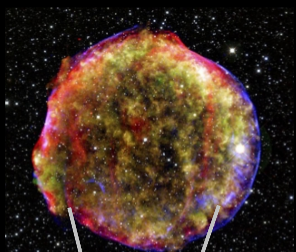
1. Source injection
- spectrum ~ R^{-2}
- abundances

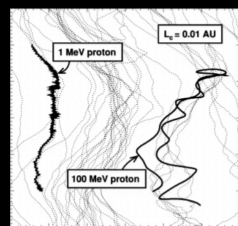


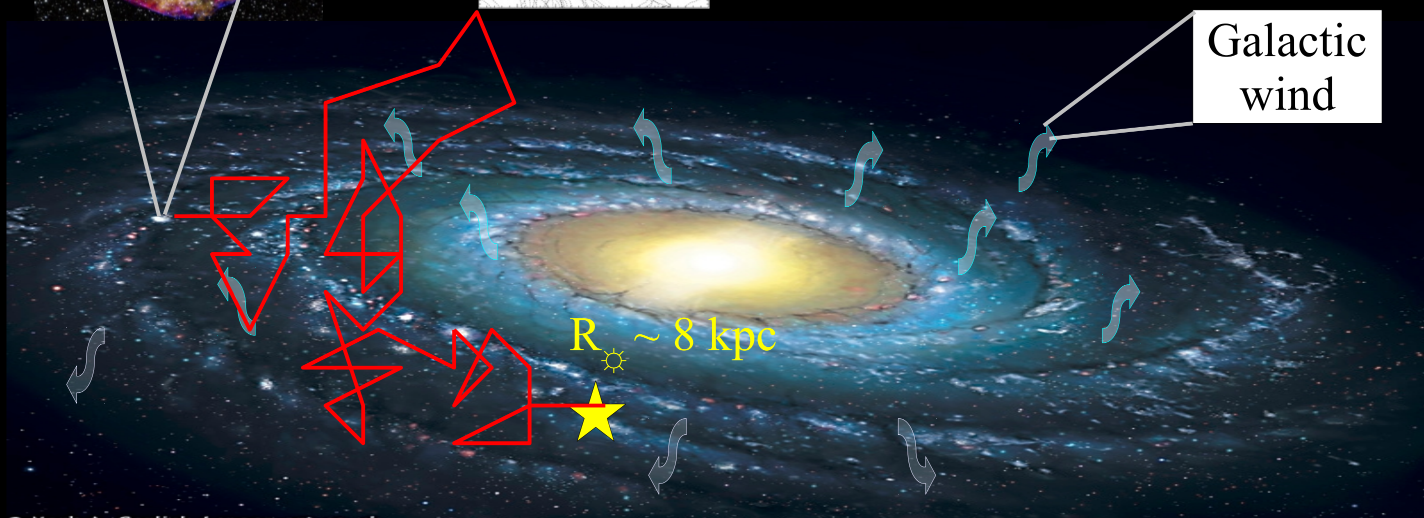
Charged cosmic rays in the Galaxy: convection

1. Source injection

- spectrum ~ R^{-2}
- abundances

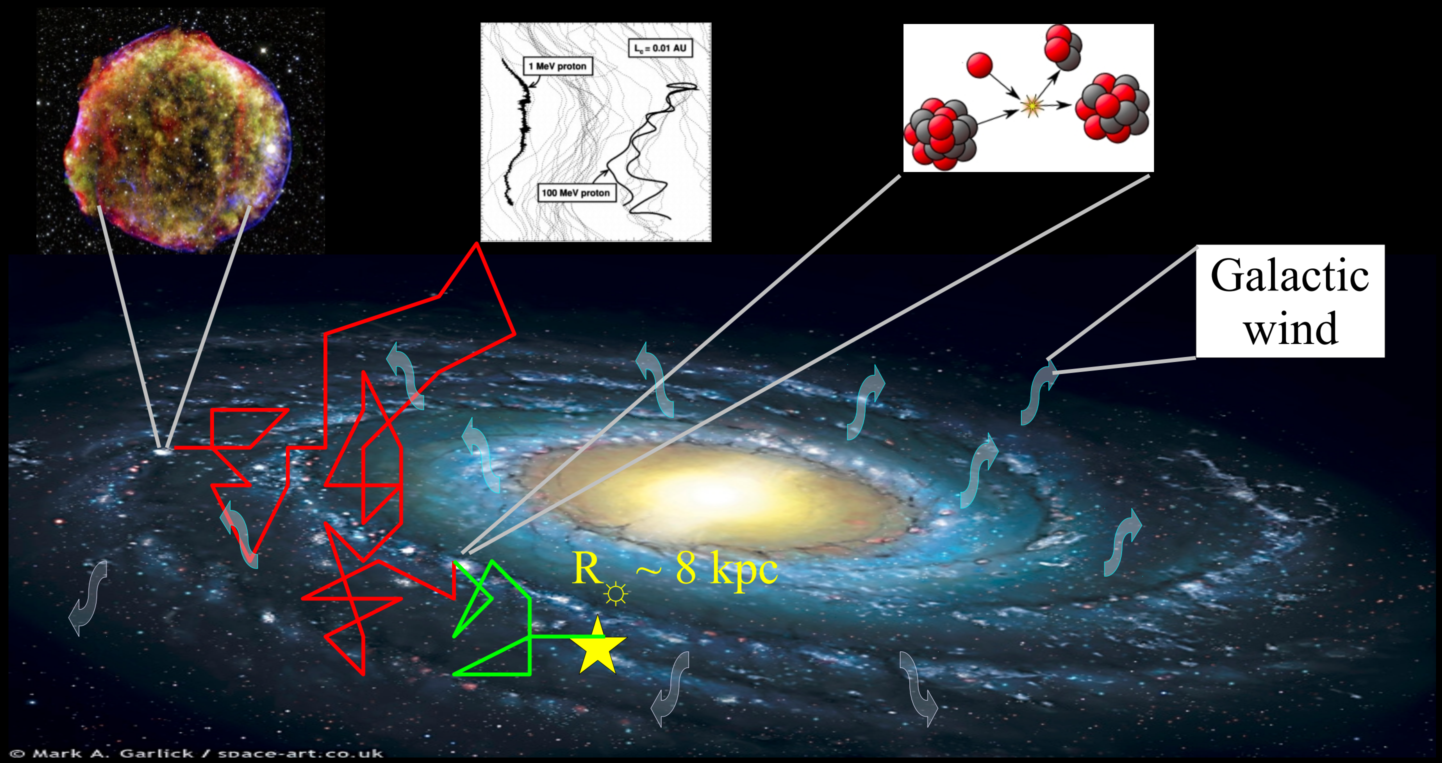






Charged cosmic rays in the Galaxy: interactions

1. Source injection
- spectrum ~ R^{-2}
- abundances



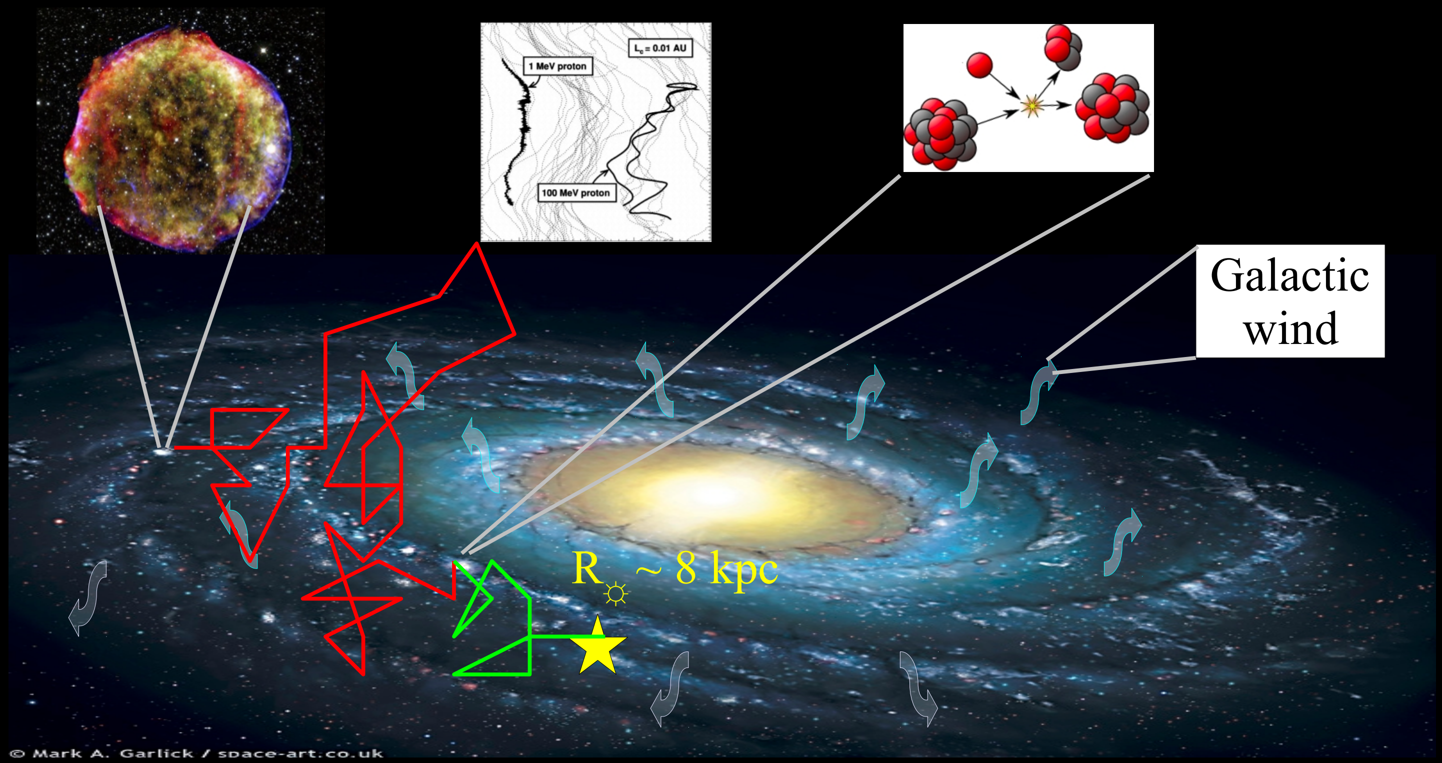
Charged cosmic rays in the Galaxy: all together

1. Source injection

- spectrum ~ R^{-2}
- abundances

2. Transport in the Galaxy

- diffusion: $R^{-\delta}$
- convection
- energy gains/losses
- fragmentation/decay



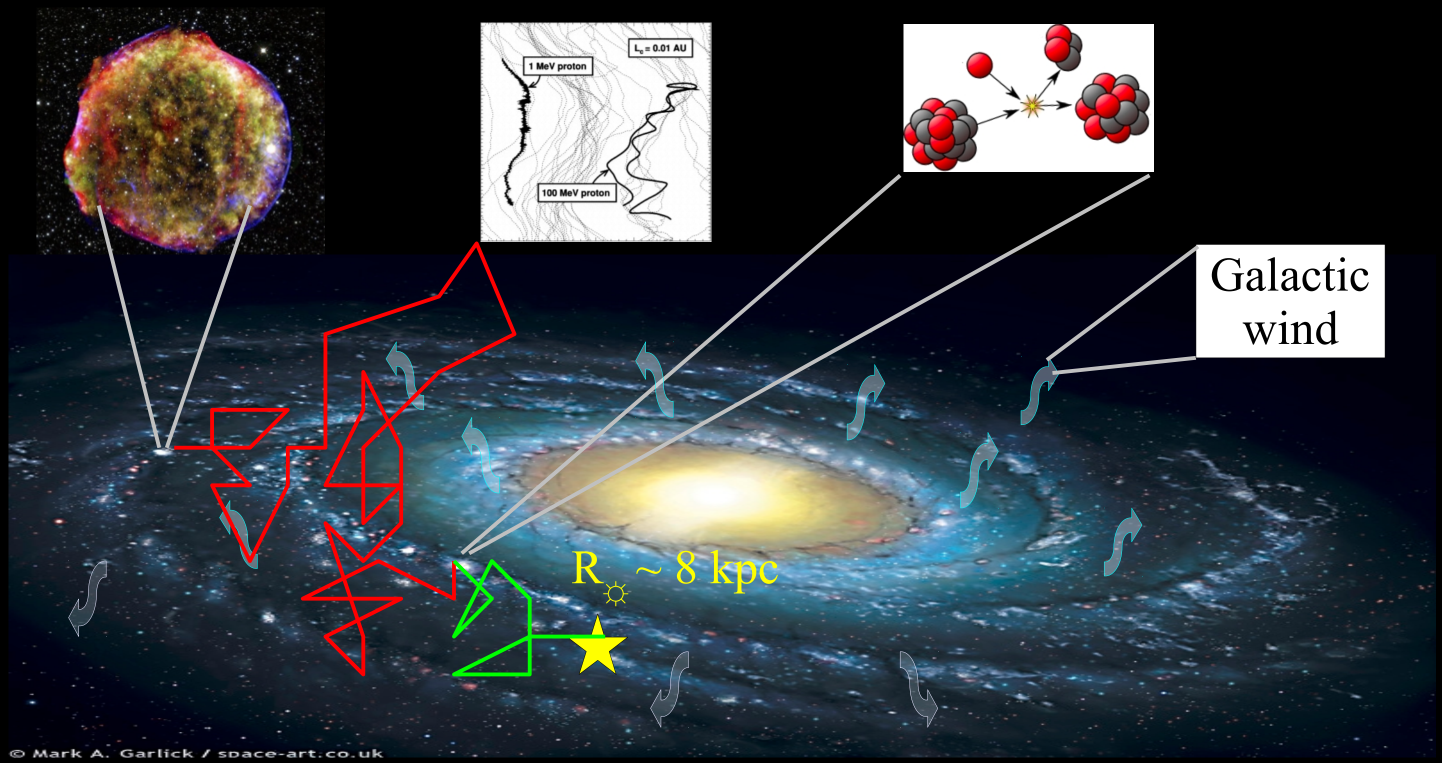
Charged cosmic rays in the Galaxy: phenomenology

1. Source injection

- spectrum ~ R^{-2}
- abundances

2. Transport in the Galaxy

- diffusion: $R^{-\delta}$
- convection
- energy gains/losses
- fragmentation/decay



Particles reaching Earth come from:

- whole diffusive volume for stable species
- small volume (~ 100 pc) for radioactive nuclei and high energy electrons

→ different species sample different regions of the Galaxy

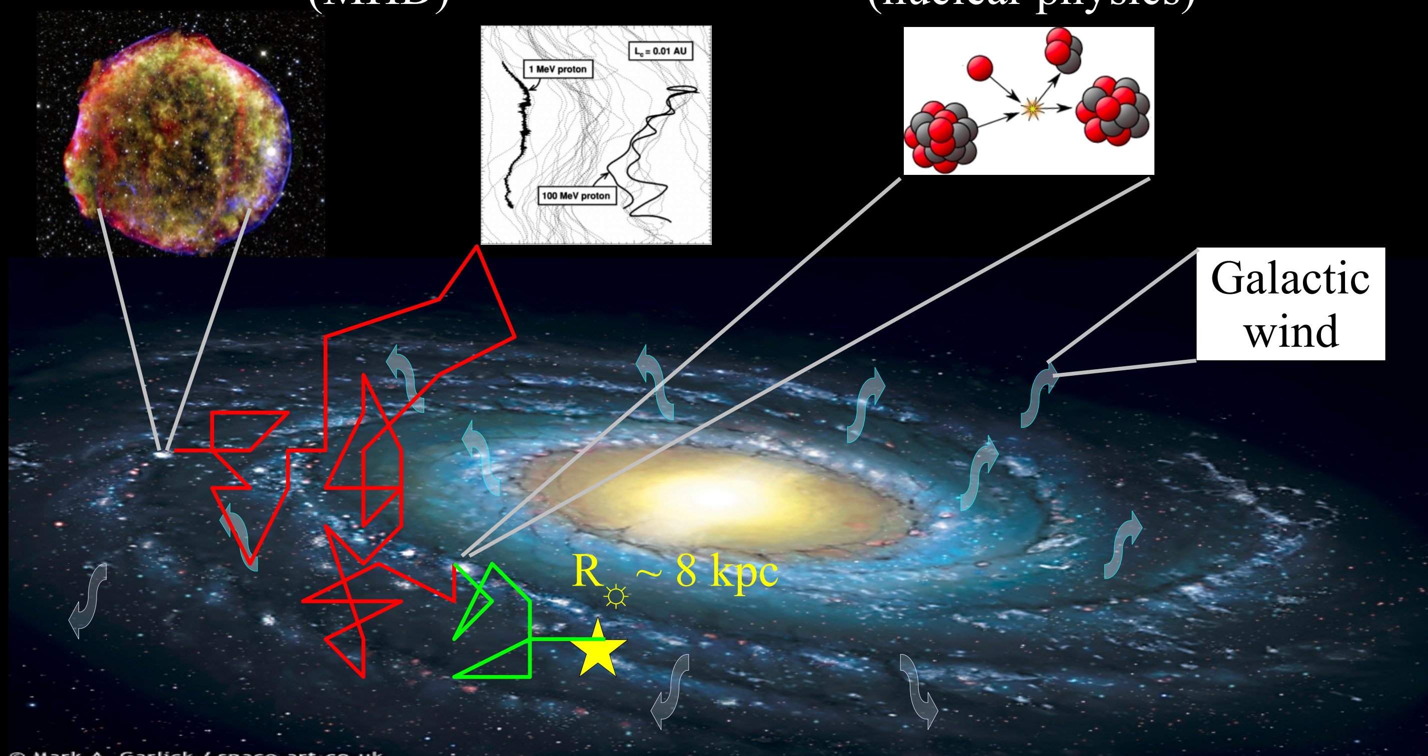
Charged cosmic rays in the Galaxy: physics involved

1. Source injection
- spectrum ~ R^{-2}
- abundances

2. Transport in the Galaxy
- diffusion: $R^{-\delta}$
- convection
- energy gains/losses
- fragmentation/decay

(MHD)

(nuclear physics)



(astrophysics + particle physics)

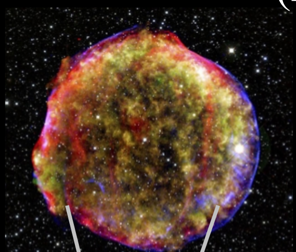
Charged cosmic rays in the Galaxy: dark matter

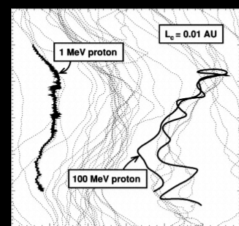
1. Source injection
- spectrum ~ R^{-2}
- abundances

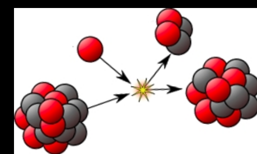
2. Transport in the Galaxy
- diffusion: $R^{-\delta}$
- convection
- energy gains/losses
- fragmentation/decay

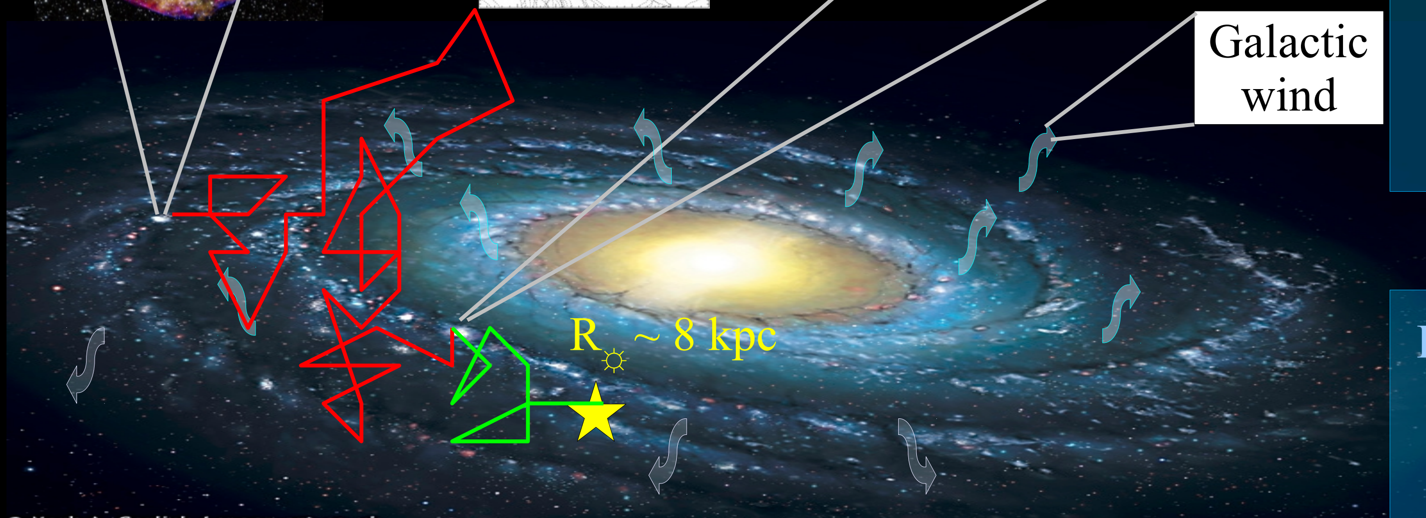
(MHD)

(nuclear physics)









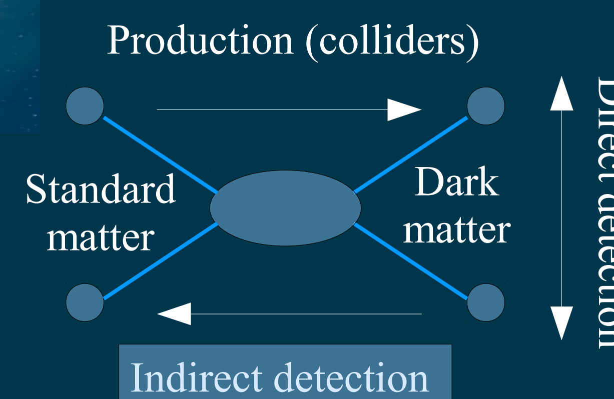
(astrophysics + particle physics)

What about dark matter?

Universe (after Planck)
- 68.3 % dark energy
- 26.8 % dark matter
- 4.9 % ordinary matter

MW dark matter halo
- ~ spherical halo
- radius ~300 kpc

How to detect dark matter?



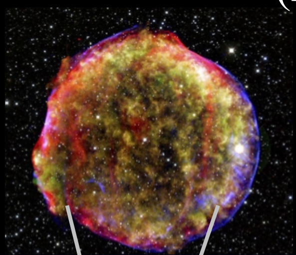
Charged cosmic rays in the Galaxy: DM indirect detection

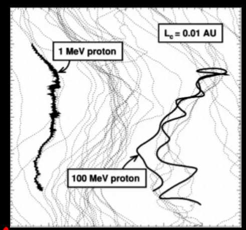
1. Source injection
- spectrum ~ R^{-2}
- abundances

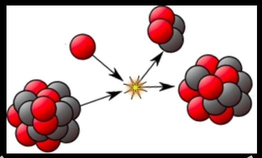
2. Transport in the Galaxy
- diffusion: $R^{-\delta}$
- convection
- energy gains/losses
- fragmentation/decay

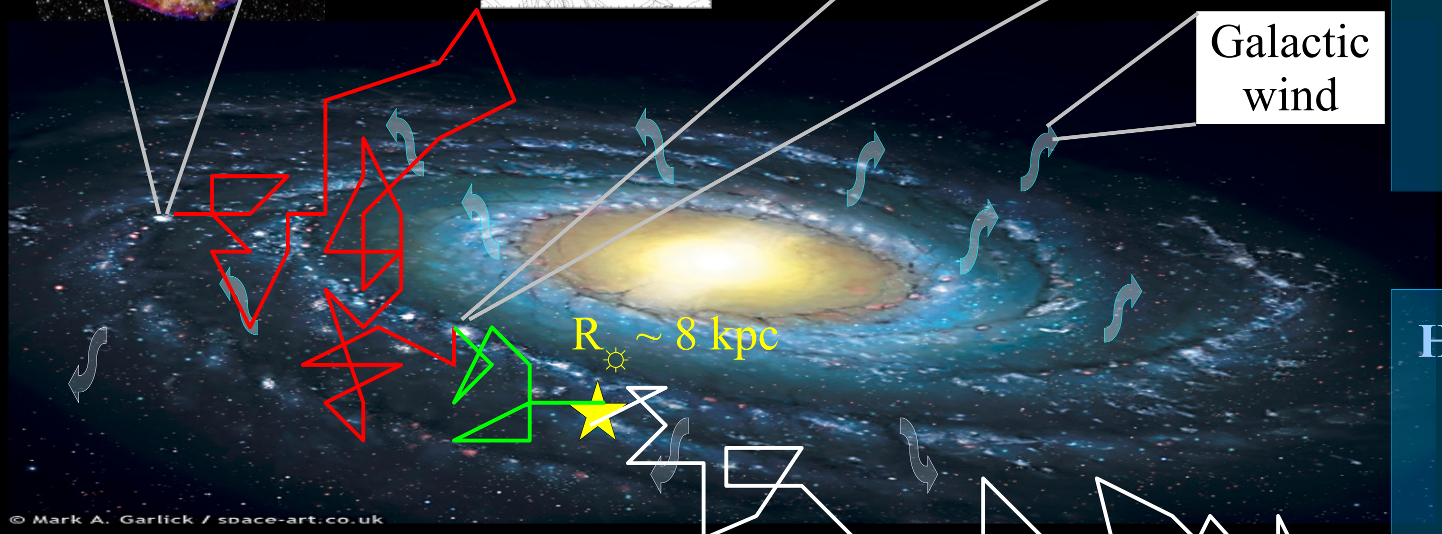
(MHD)

(nuclear physics)









(astrophysics + particle physics)

→ Sources for DM-induced cosmic rays from DM halo (not only disc)

What about dark matter?

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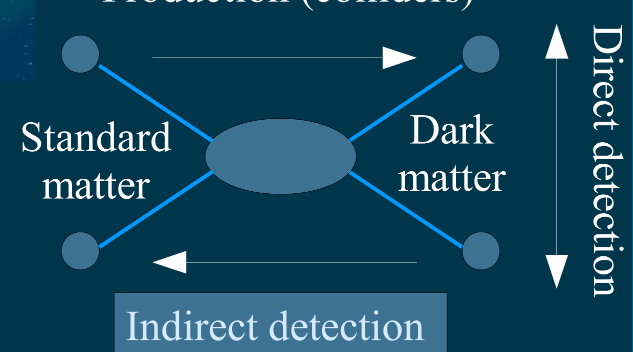
- 26.8 % dark matter
- 4.9 % ordinary matter

MW dark matter halo
- ~ spherical halo
- radius ~300 kpc

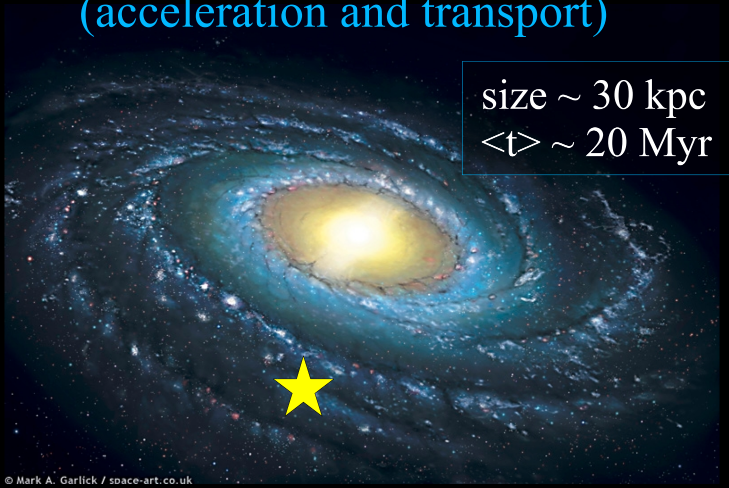
How to detect dark matter?



An unexpected journey: processes and typical scales

1. Cosmic rays in the Galaxy

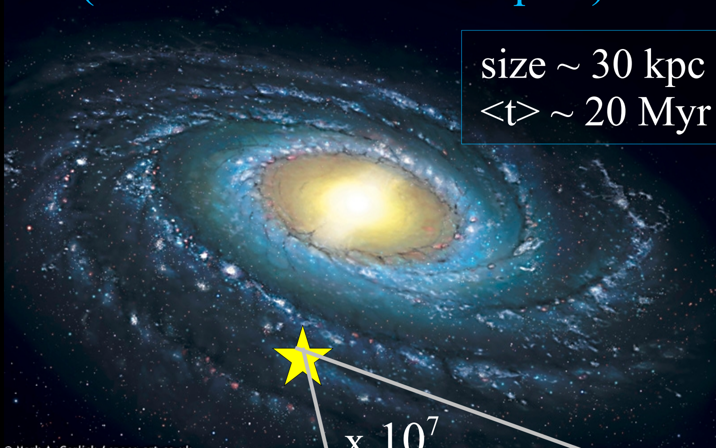
→ Spectra and abundances (acceleration and transport)



An unexpected journey: across the Solar cavity

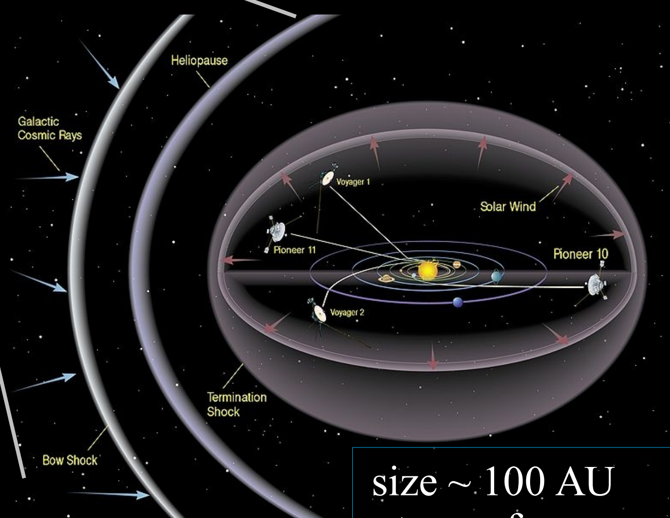
1. Cosmic rays in the Galaxy

→ Spectra and abundances
(acceleration and transport)



size ~ 30 kpc
<t> ~ 20 Myr

x 10^7



size ~ 100 AU
<t> ~ a few years

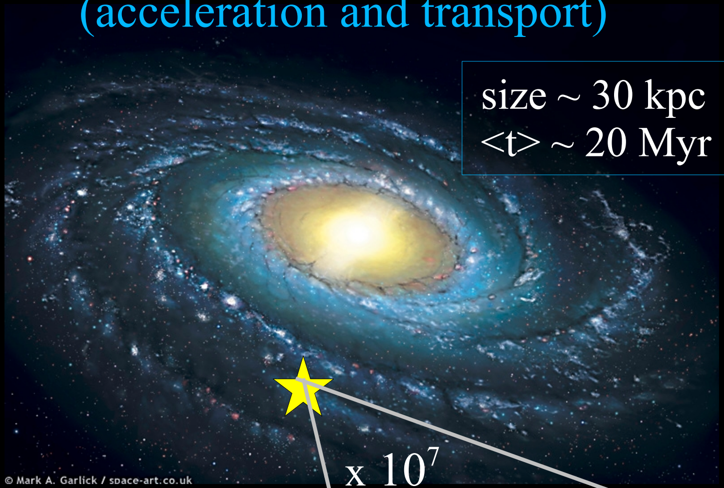
2. Transport in the Solar cavity

→ flux modulation < 10 GeV/n
→ time dependence

An unexpected journey: across the Earth magnetosphere

1. Cosmic rays in the Galaxy

→ Spectra and abundances (acceleration and transport)

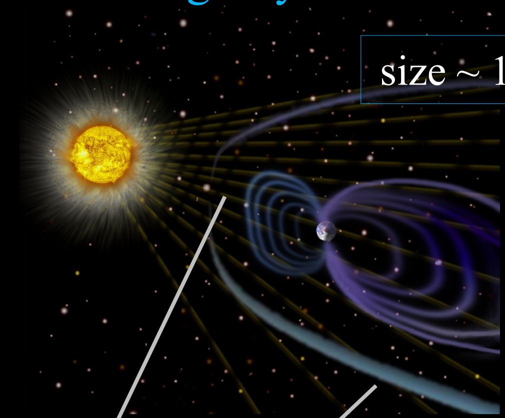


size ~ 30 kpc
<t> ~ 20 Myr

x 10^7

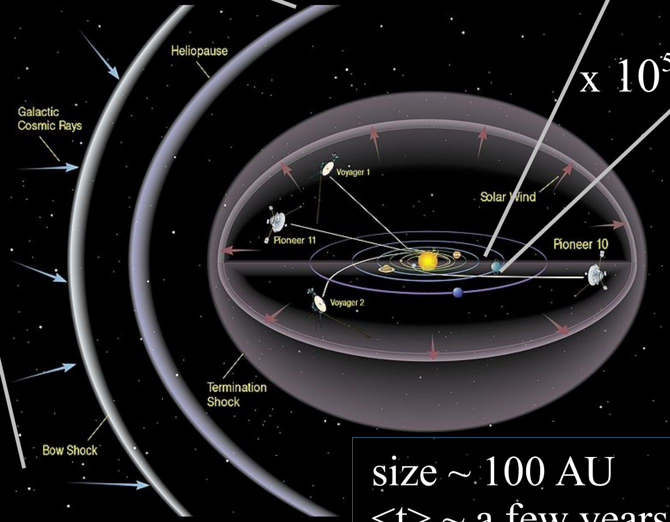
3. Earth magnetic shield

→ Cut-off rigidity for detectors



size ~ 10^4 km

x 10^5



size ~ 100 AU
<t> ~ a few years

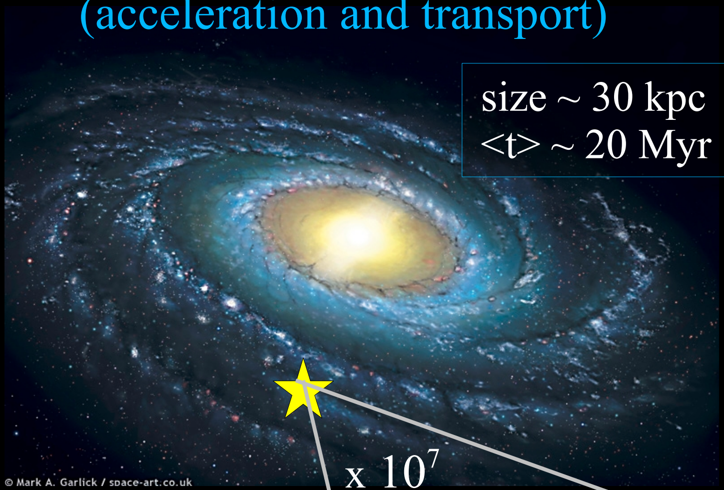
2. Transport in the Solar cavity

→ flux modulation < 10 GeV/n
→ time dependence

An unexpected journey: across the Earth atmosphere

1. Cosmic rays in the Galaxy

→ Spectra and abundances (acceleration and transport)

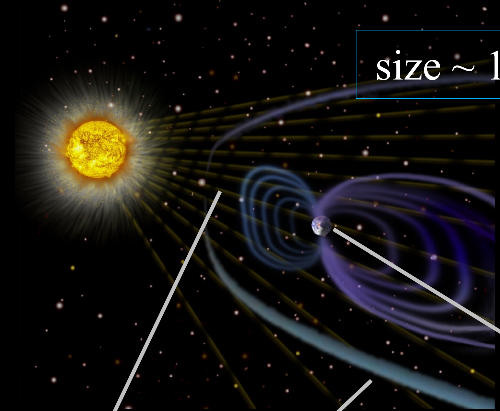


size ~ 30 kpc
<t> ~ 20 Myr

x 10^7

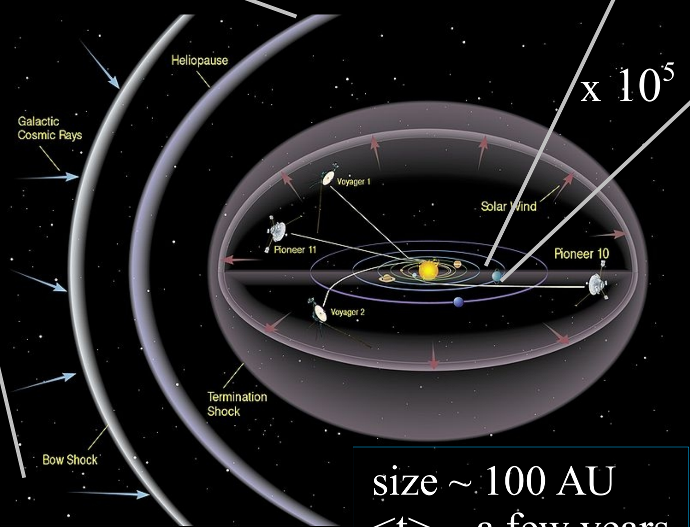
3. Earth magnetic shield

→ Cut-off rigidity for detectors



size ~ 10^4 km

x 10^2



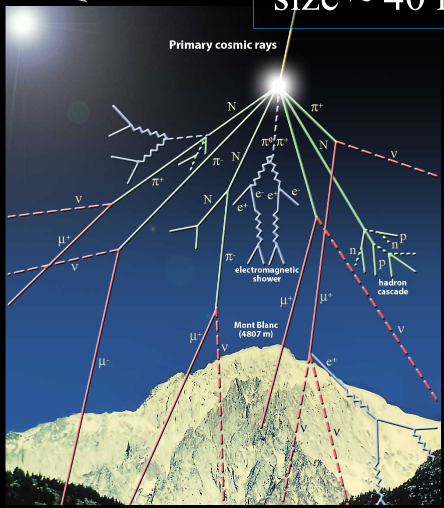
x 10^5

size ~ 100 AU
<t> ~ a few years

2. Transport in the Solar cavity

→ flux modulation < 10 GeV/n
→ time dependence

size ~ 40 km



4. Atmospheric showers

→ Ground-based detection
→ Solar activity monitoring
[N.B.: Čerenkov flash ~ 10^{-8} s]

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I. Introduction: Galactic Cosmic Rays (GCR)

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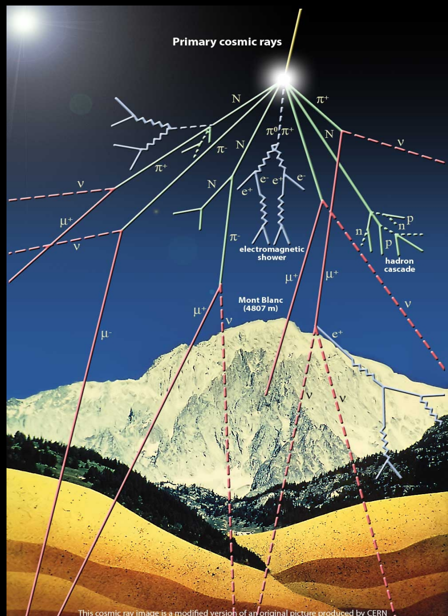
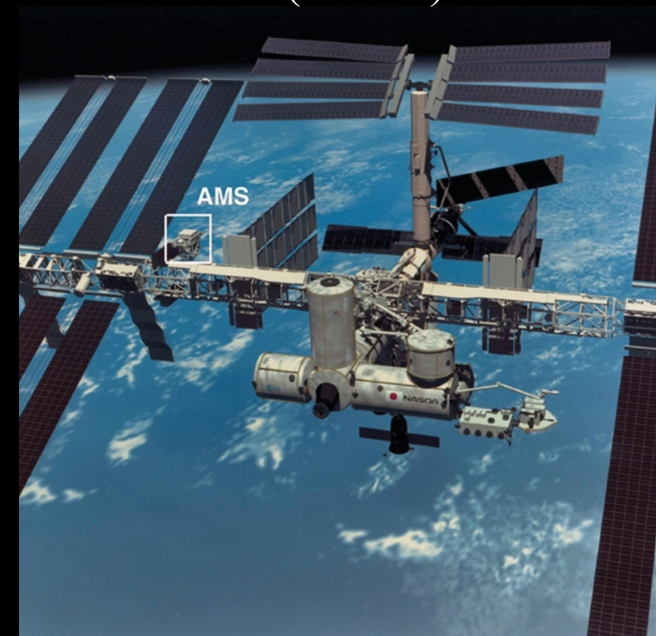
Timeline: CR identification

Mountain altitude < 5 km



CREAM balloon ~ 40 km

AMS-02 (on ISS) ~ 300 km



CR discovery — 1910

e^-, e^+

Diffuse γ

$\bar{p}$

TeV astronomy

ν

$\bar{d}$?

1910 — 1930 — 1950 — 1980 — 2000

e^+, μ, π , K, Λ

Elements up to U

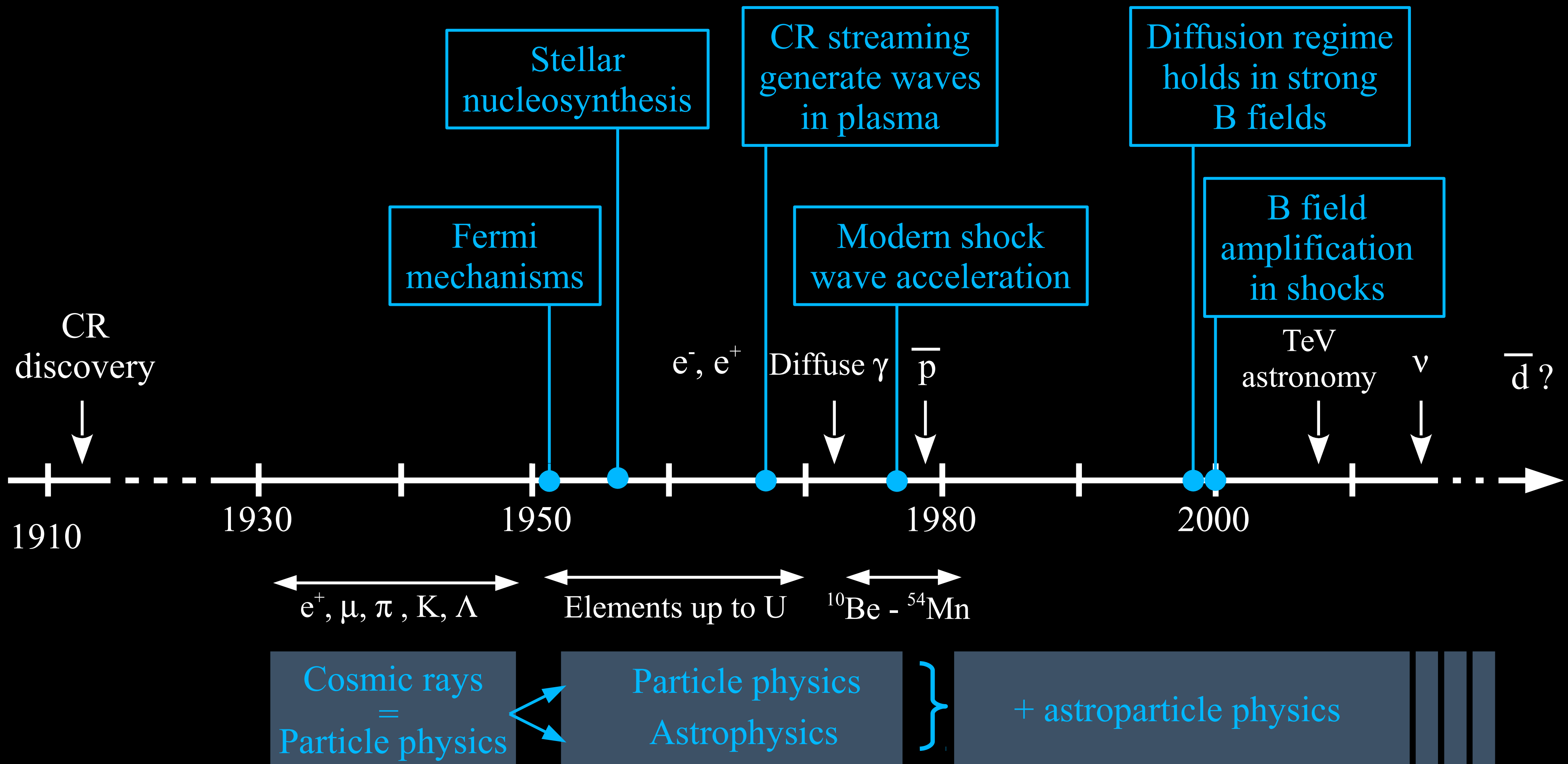
^{10}Be - ^{54}Mn

Cosmic rays = Particle physics

Particle physics
Astrophysics

+ astroparticle physics

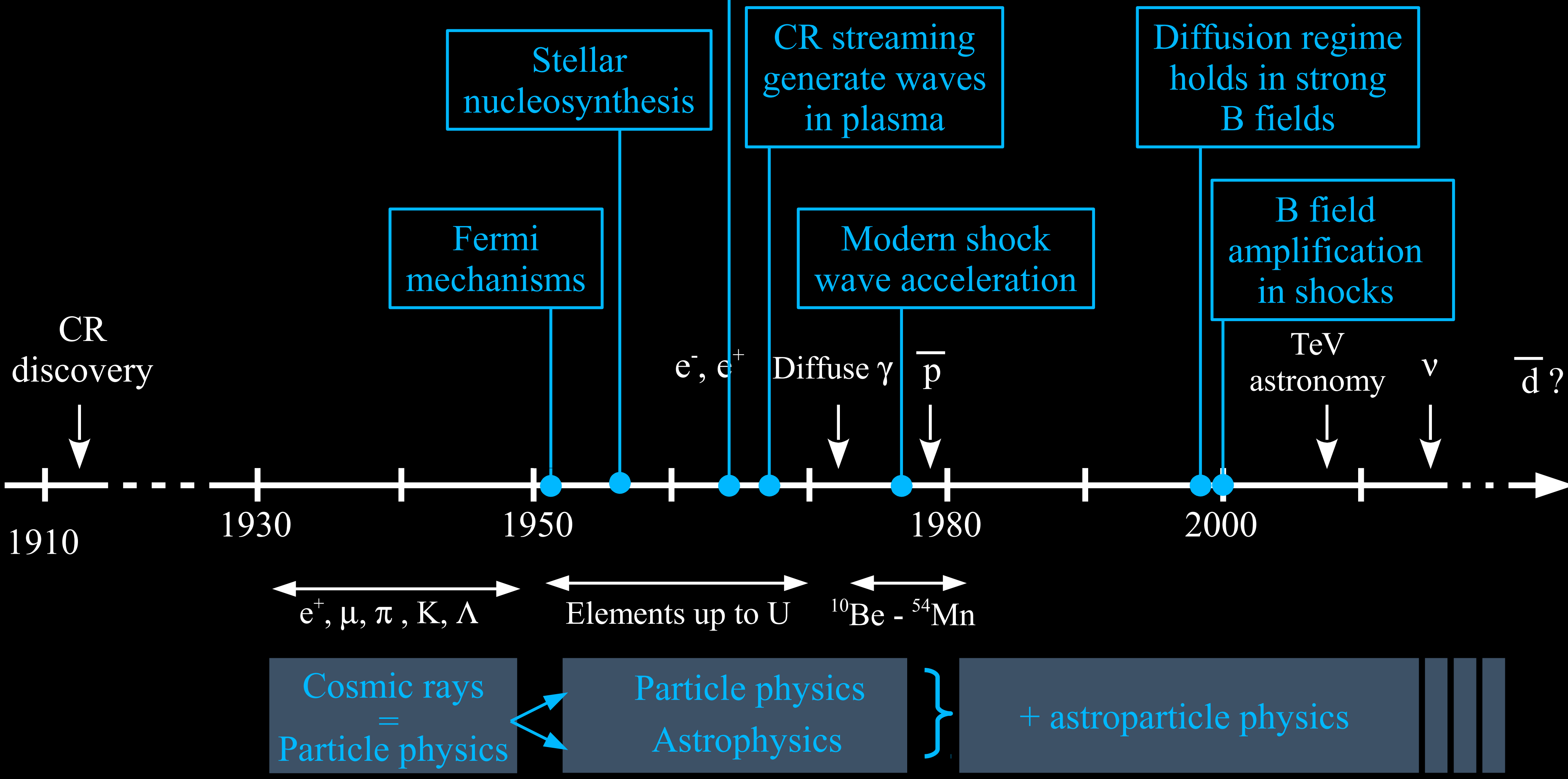
Timeline: CR theory



The transport equation

Transport parameters: K_0 and δ (diffusion normalisation and slope), L (diffusive halo size), V_c (convection)

$$\overbrace{\frac{\partial N^j}{\partial t}}^{\text{Variation}} + \overbrace{\left(-\vec{\nabla}\cdot\left(K(E,\vec{r})\vec{\nabla}\right) + \vec{\nabla}\cdot\vec{V}(\vec{r})\right)}^{\text{Transport (diff+conv)}} N^j + \overbrace{\left(\Gamma_{\rm rad} + \Gamma_{\rm inel}\right)}^{\text{catastrophic losses}} N^j + \overbrace{\frac{\partial}{\partial E}\left(b^j N^j - c^j \frac{\partial N^j}{\partial E}\right)}^{\text{E gain/losses}} = \overbrace{Q^j(E,\vec{r}) + \sum_{m_i>m_j} \Gamma^{i\to j} N^i}^{\text{Sources (prim+sec)}}$$



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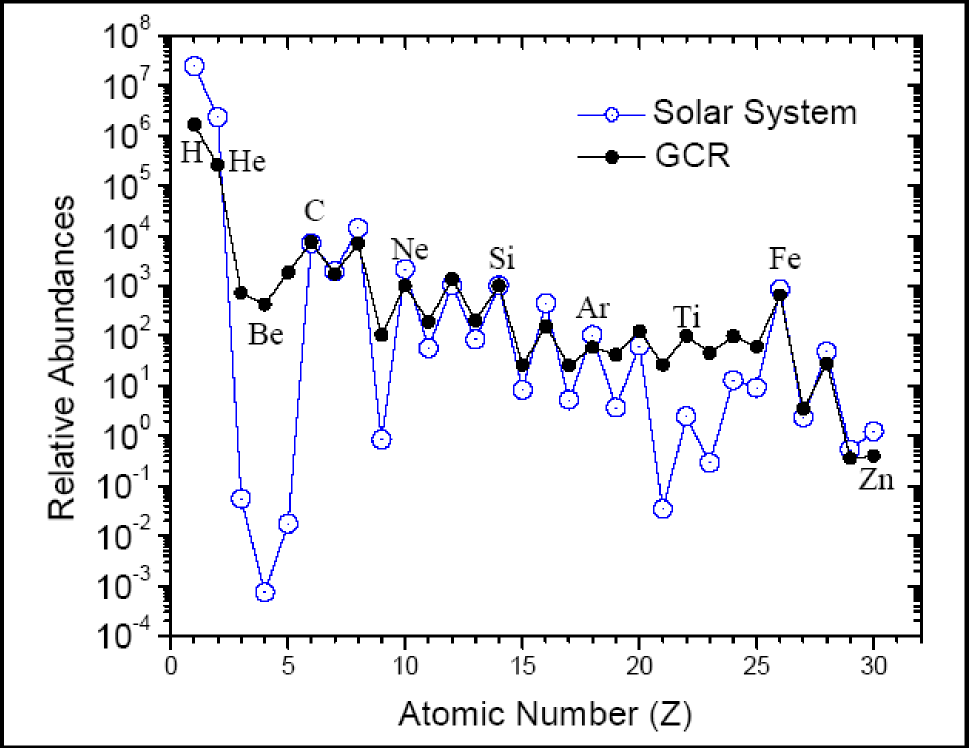
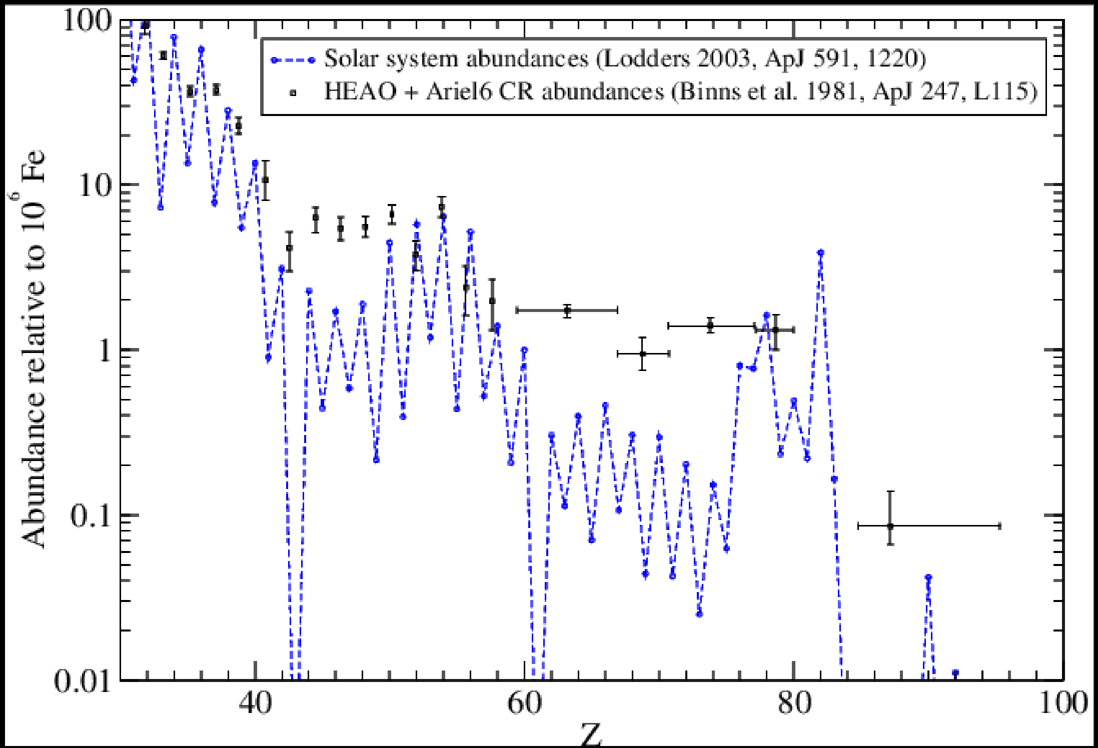
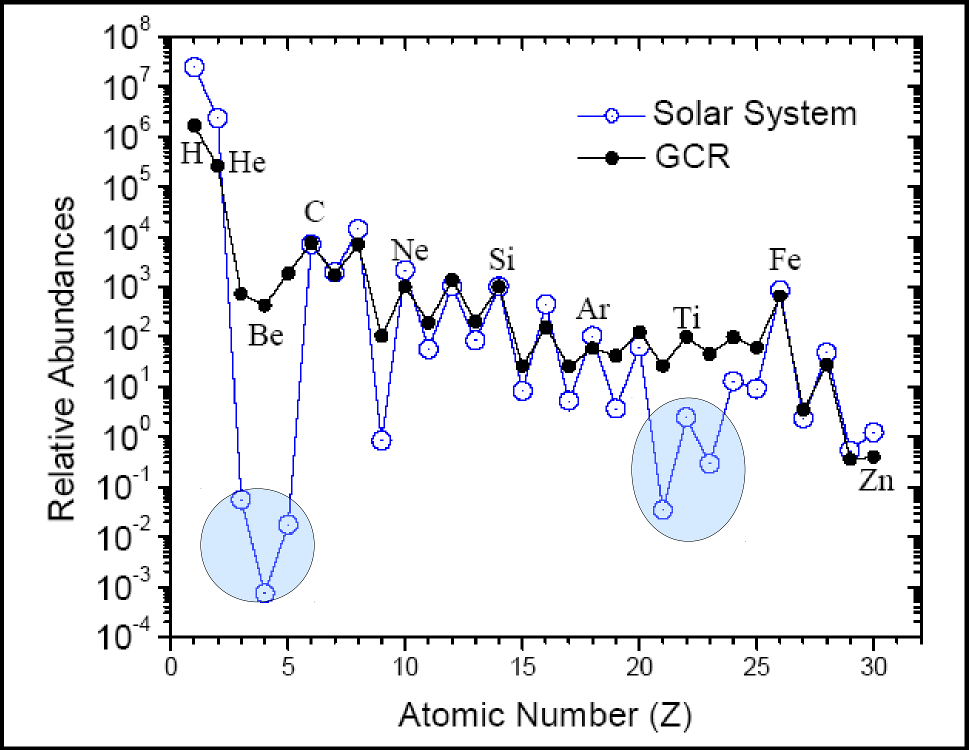
CR composition: elemental abundances

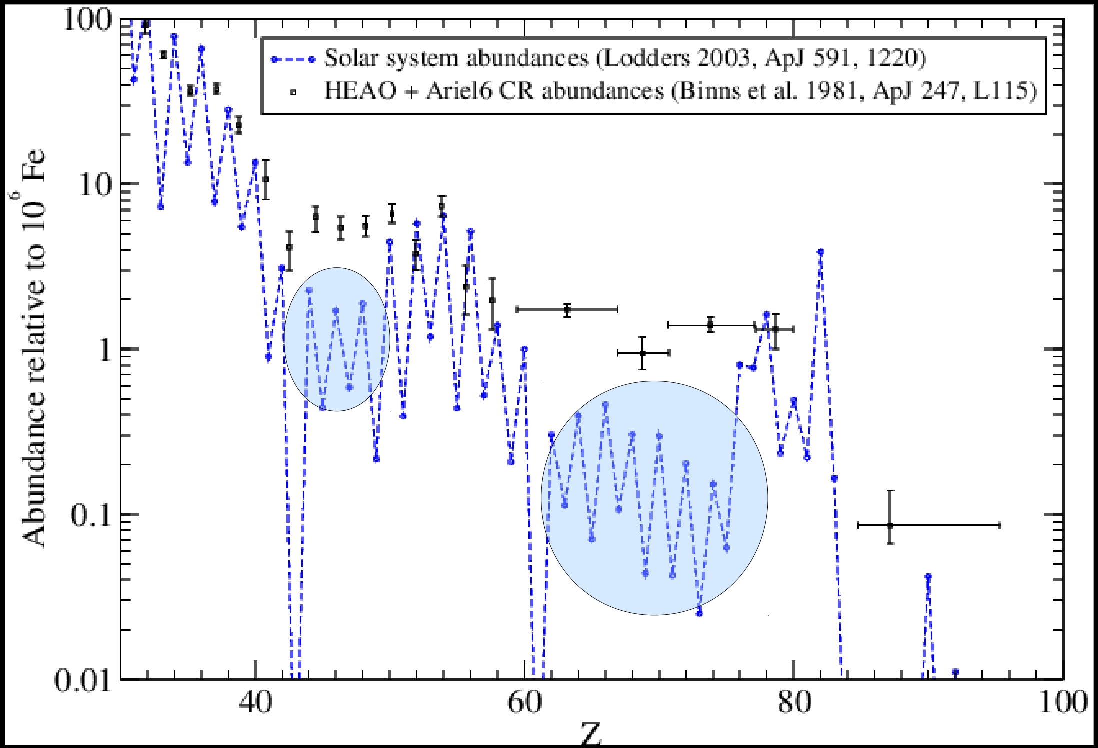




http://www.srl.caltech.edu/ACE/ACENews/ACENews83.html

CR composition: elemental abundances





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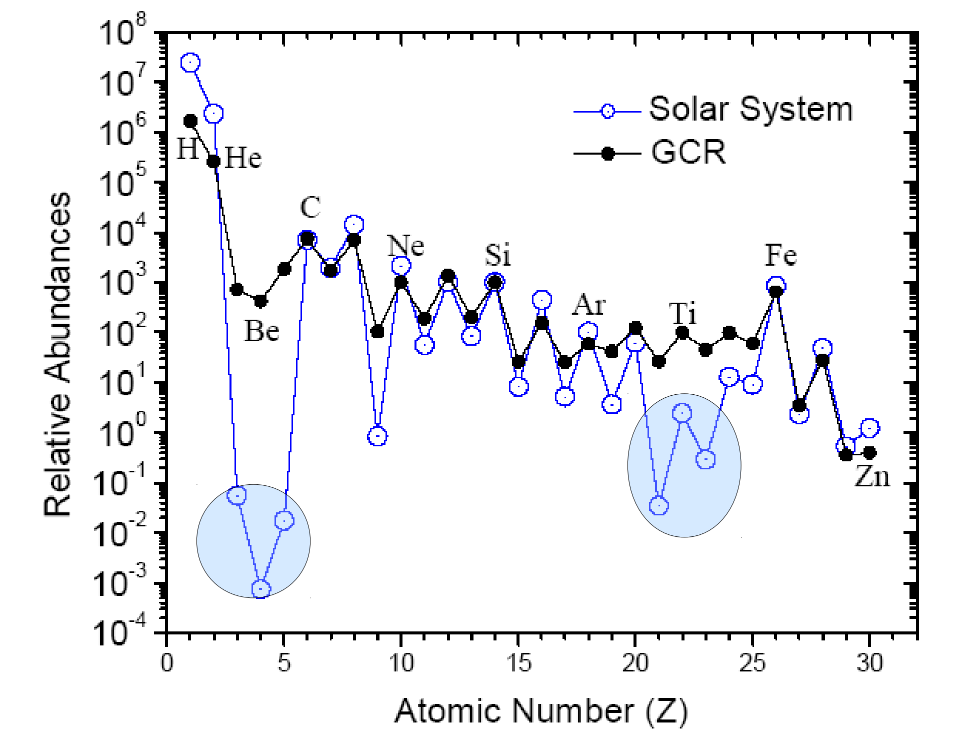
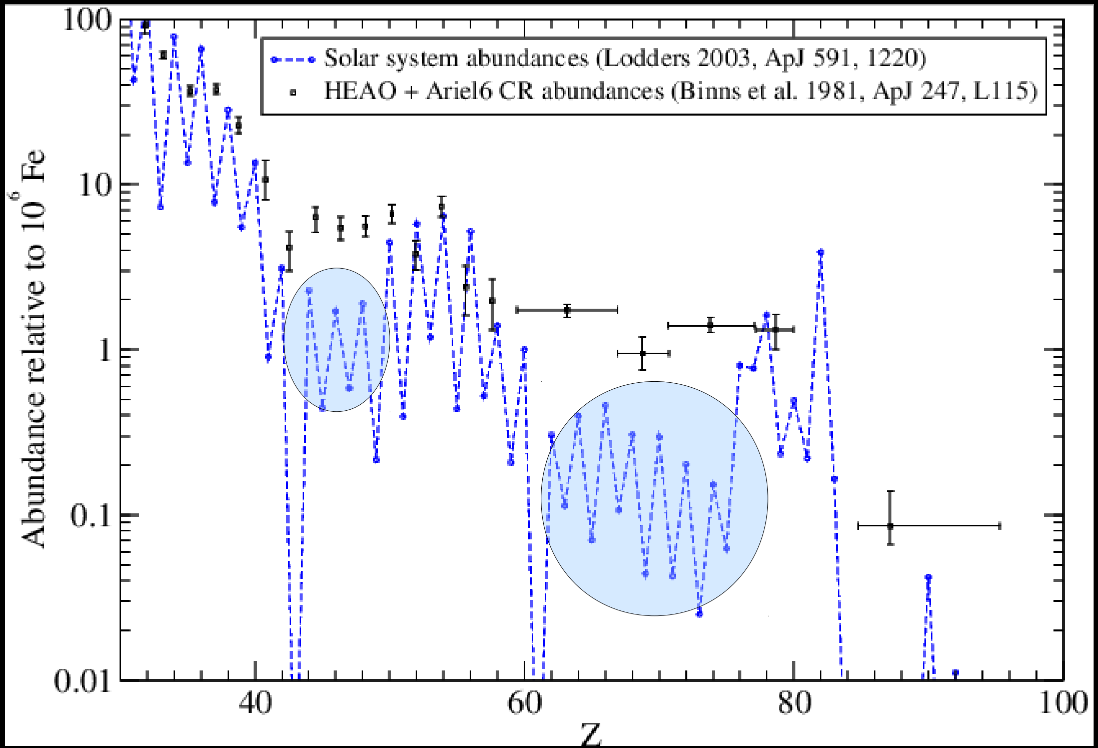
Definitions:

- Primary species: accelerated at the source (e.g., H, C)
- Secondary species: absent of source → fragmentation of heavier primary nuclei (e.g., C→B)
- Mixed species (e.g., N): both contributions

CR composition: elemental abundances





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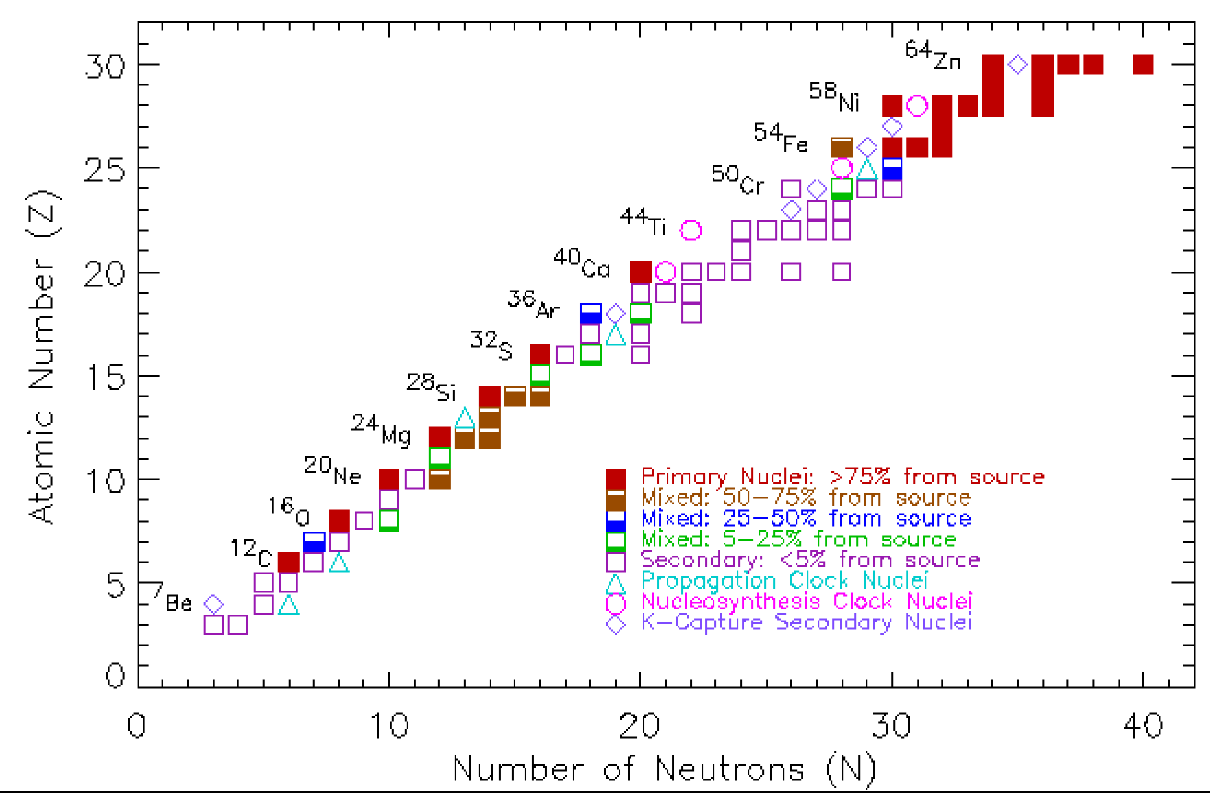
- Mixed species (e.g., N): both contributions

Questions:

- Source: nucleosynthesis (r- and s- process for UHCR) + acceleration (injection/efficiency)
- Transport: parameters required to provide the right abundances

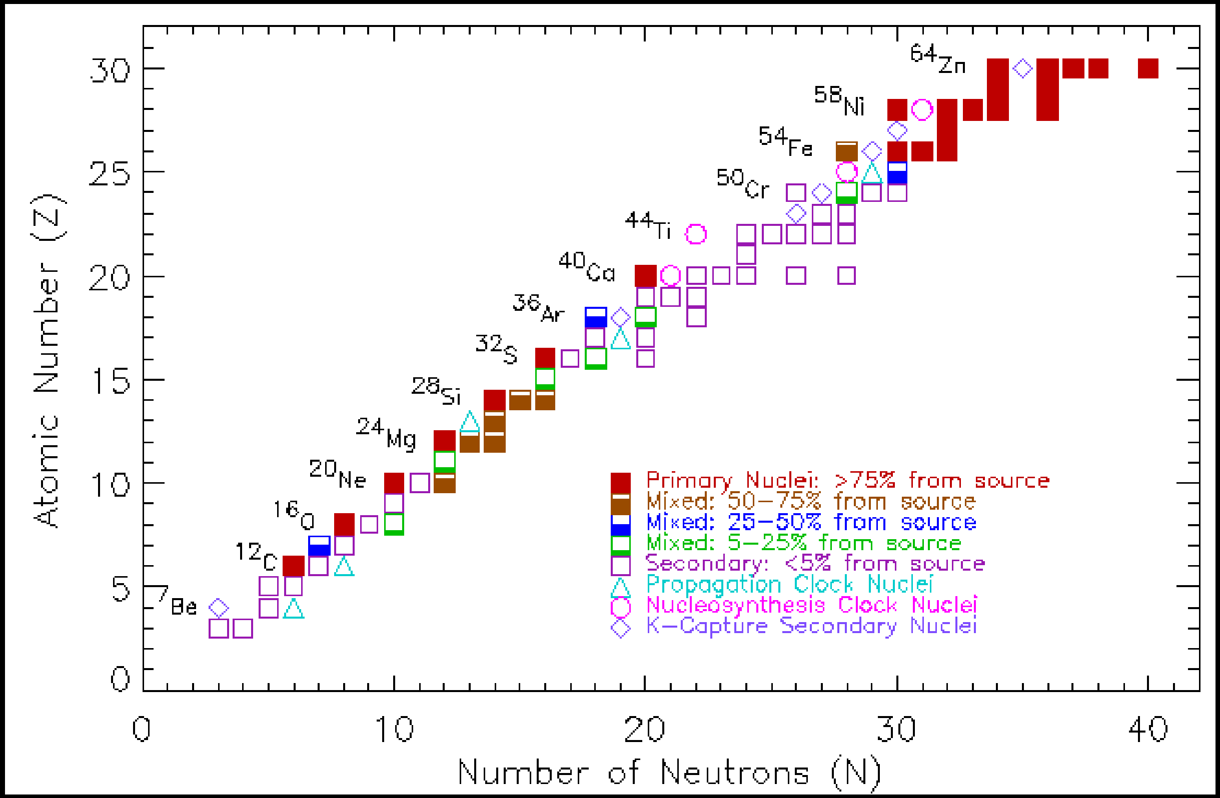
CR composition: isotopic abundances



http://www.srl.caltech.edu/ACE/CRIS_SIS/cris.html

Elemental and Isotopic Composition of the GCRs
J.A. Simpson
ARNPS 33 (1983) 323

CR composition: isotopic abundances



Elemental and Isotopic Composition of the GCRs
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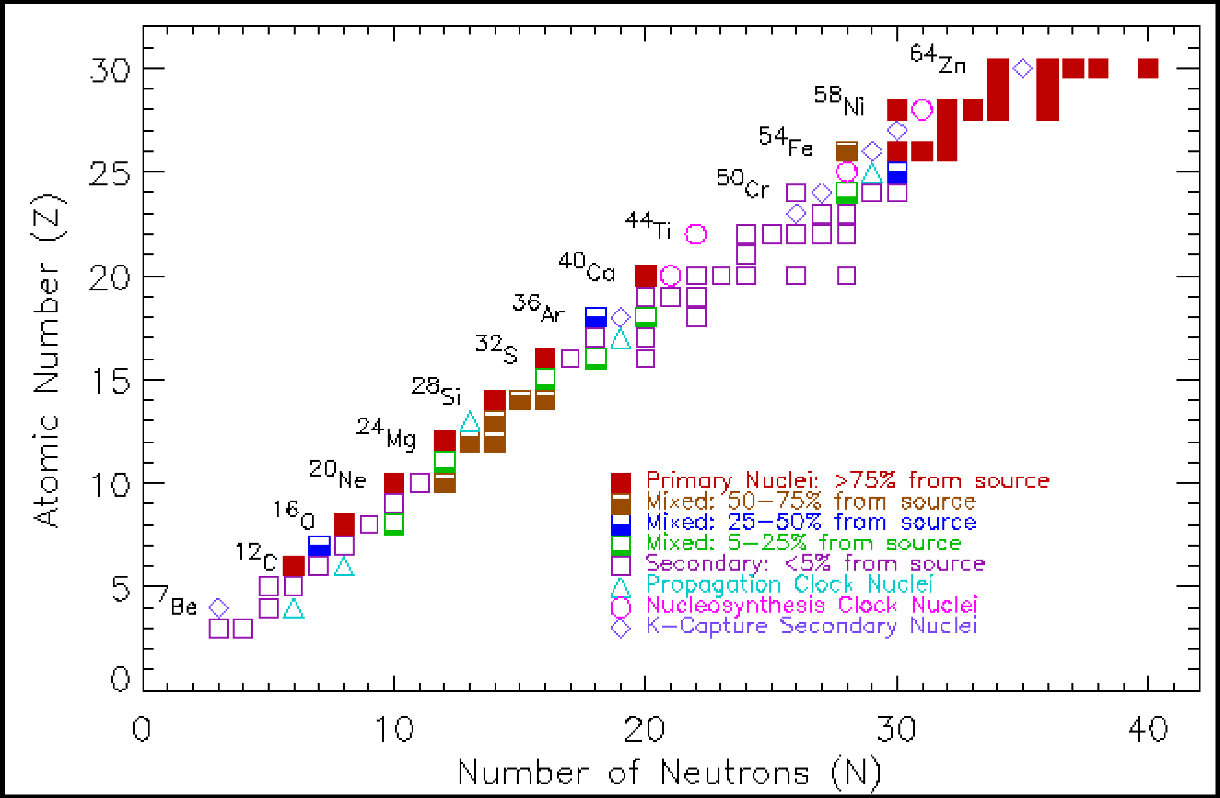
ARNPS 33 (1983) 323

http://www.srl.caltech.edu/ACE/CRIS_SIS/cris.html

CR nuclei probe many effects:

- Stable species: most isotopes… (source and propagation)
  - Isotopic anomaly (e.g., ^{22}Ne): contributions from **Wolf-Rayet stars rich in ^{22}Ne**
  - Refractory vs volatile species: affect abundances → **injection/efficiency at source**

CR composition: isotopic abundances



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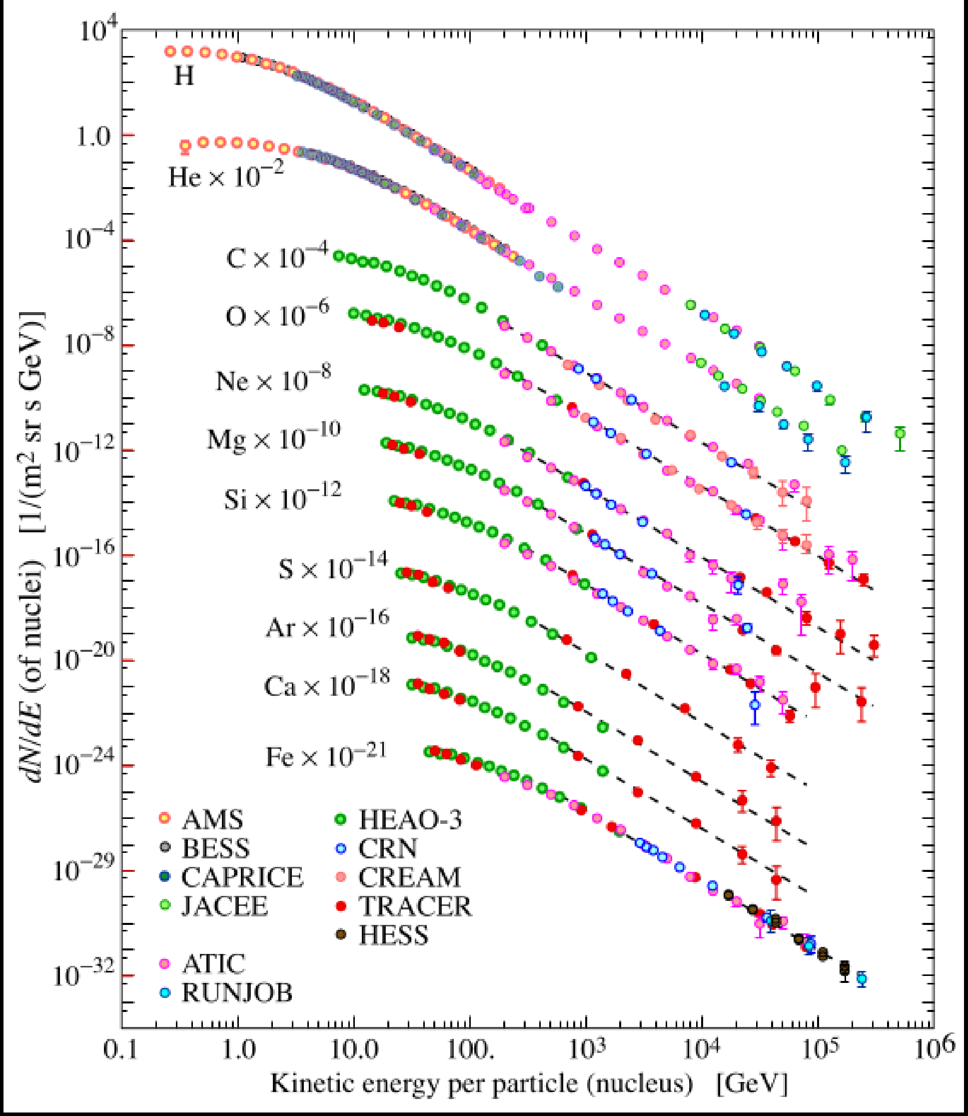
- CR clocks (^{10}Be, ^{26}Al, ^{36}Al, ^{54}Mn): β-unstable secondary species with $t_{1/2} \sim t_{propagation} \sim 10$ Myr
  - EC acceleration clock: ^{59}Co+e$^-$→^{59}Ni+ν_e ($t_{1/2} \sim 7.5\ 10^4$ yr): no ^{59}Co → $t_{delay} \gtrsim 10^5$ years
  - EC re-acceleration (e.g., ^{51}Cr, ^{49}V): gain ~ 100 MeV/n @ 500 MeV/n

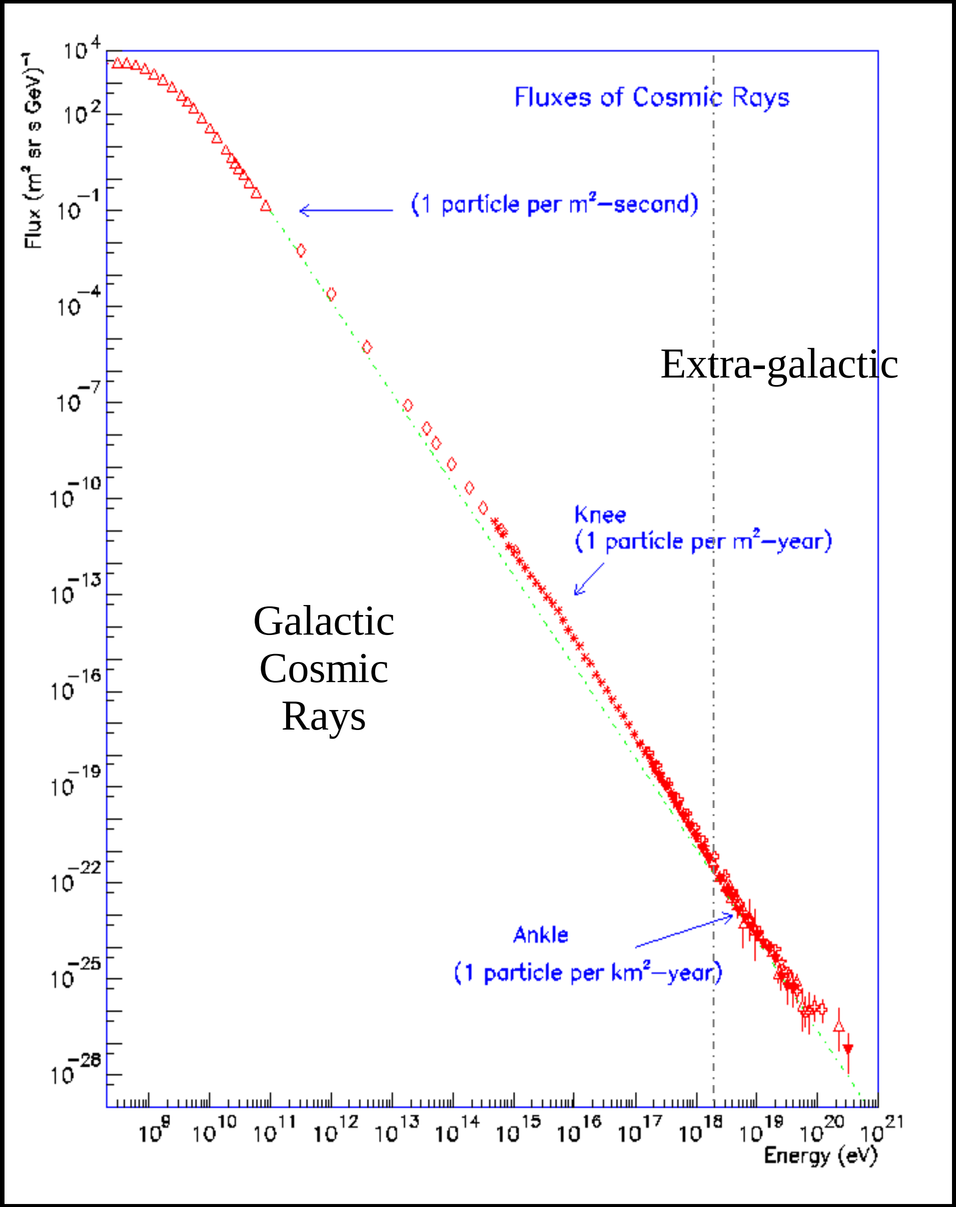
CR spectrum: element by element



Beringer et al. (PDG), PR D86, 010001 (2012)

→ Acceleration mechanisms to provide a power law?
→ Same slope for all primary species?

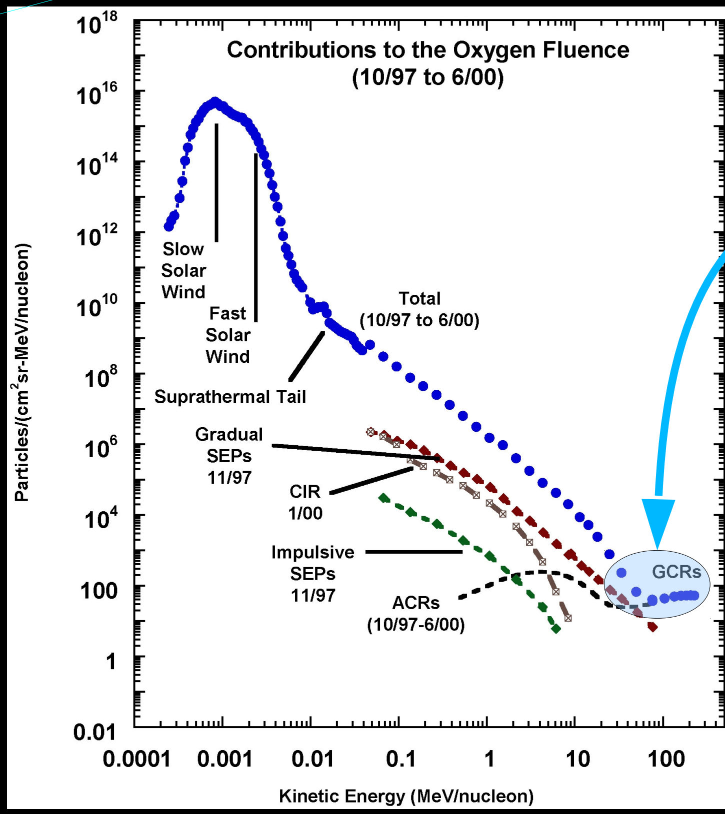
CR spectrum: all spectrum



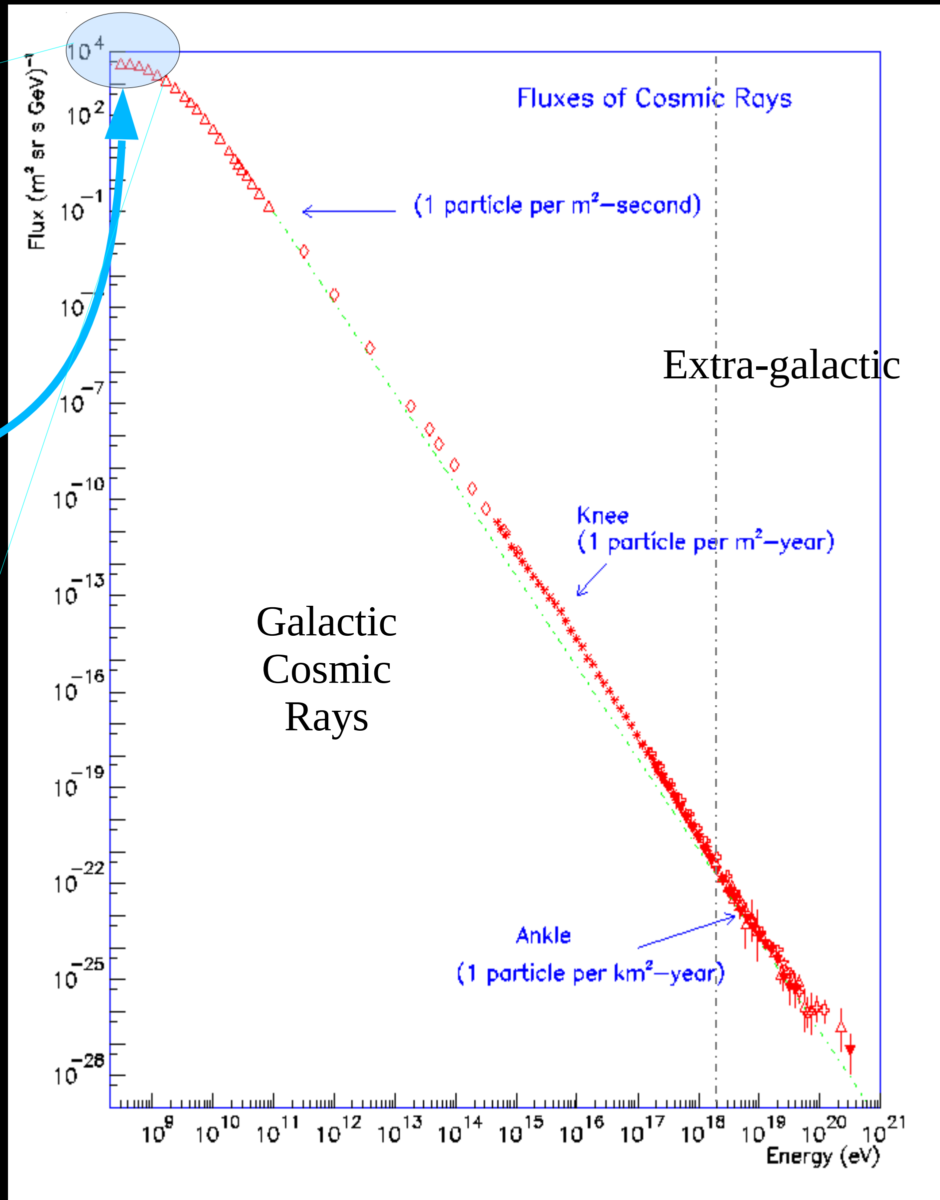
→ Maximum energy for galactic and extragalactic sources?
→ Transition between Solar/Galactic/Extragalactic CRs?

CR spectrum: Solar CRs at low energy

N.B.: the Solar cavity is the first place where acceleration and propagation theories are tested



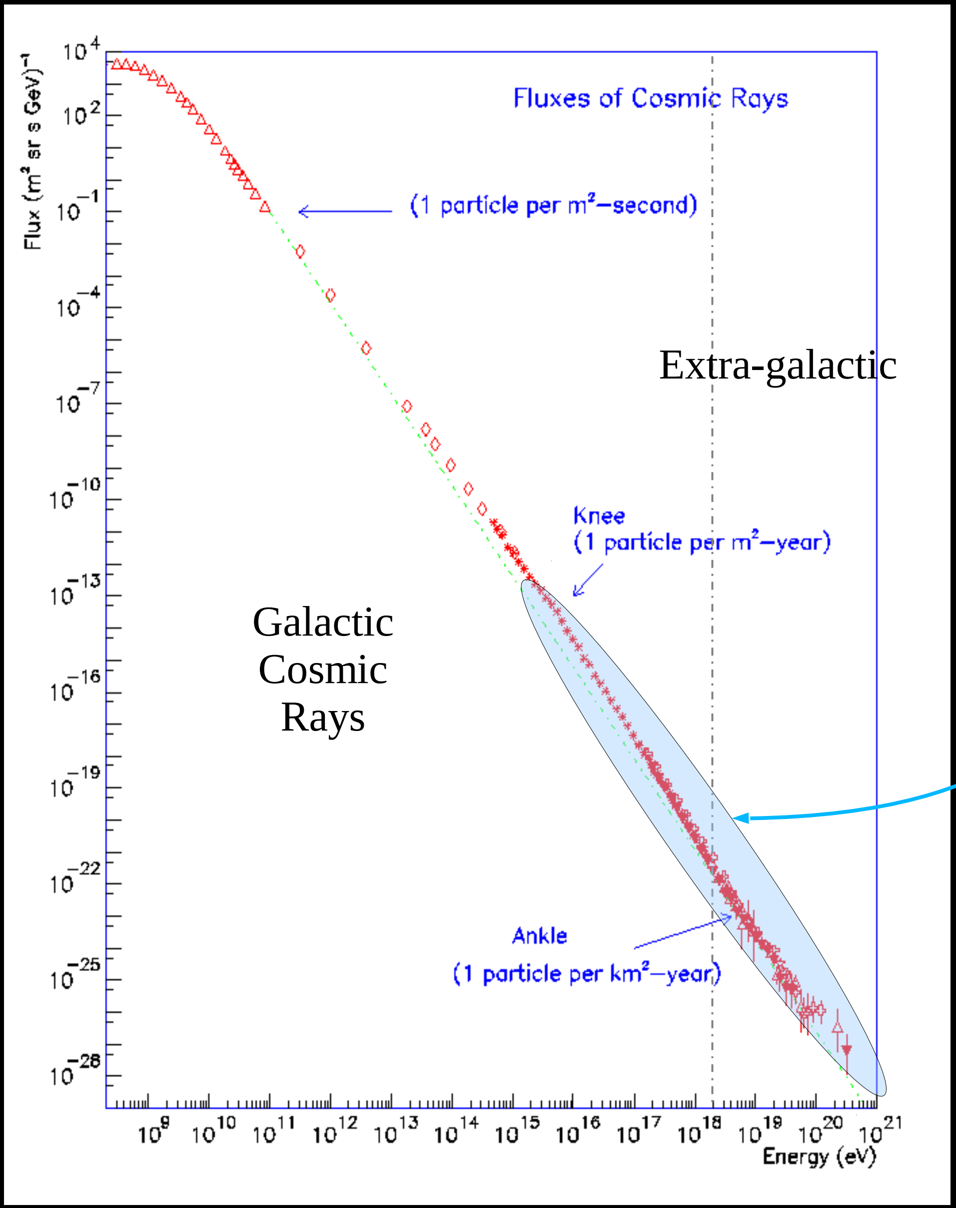
http://www.srl.caltech.edu/ACE/ASC/DATA/level3/fluences/#O_contrib



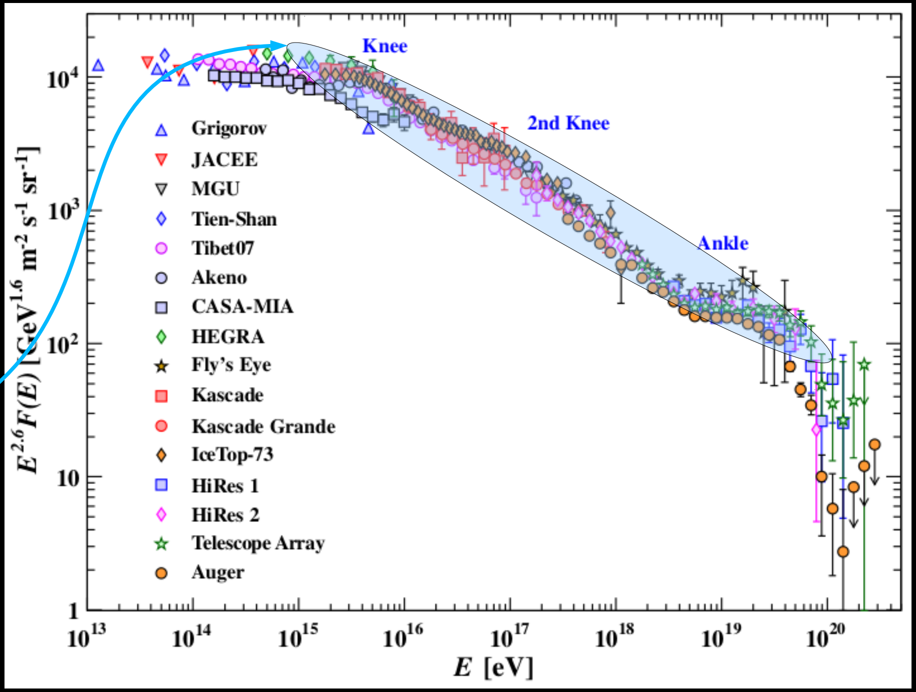
→ Plenty of different components at low energy (transient and continuous)

→ Indirect effect of Solar Cosmic rays: solar modulation

CR spectrum: Ultra High Energy CRs (UHECR)

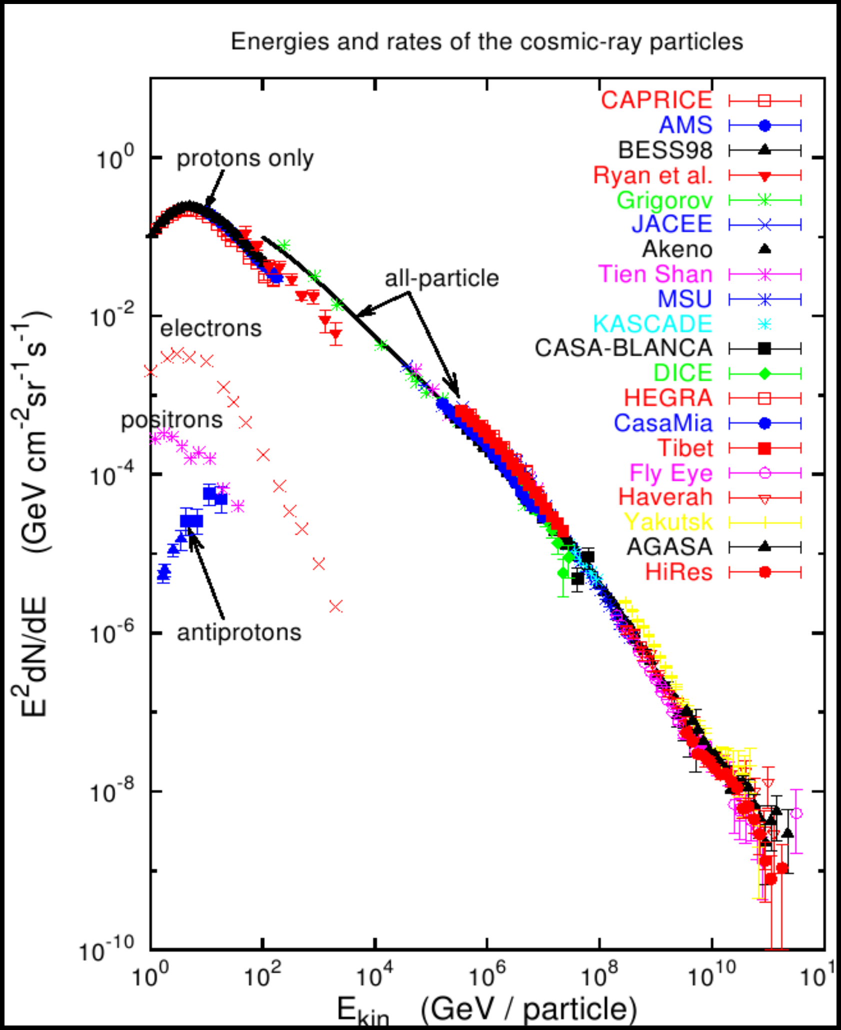


N.B.: UHECRs allow to study the most extreme environments in the Universe



→ Origin of structures in spectrum, composition, anisotropy?
→ Sources of the UHECRs
→ Transport in the cluster and inter-cluster medium

CR spectrum: all species together



Hillas 2006, arXiv:0607109

→ Spectrum of antiprotons, diffuse γ-rays, e^- and e^+ (and sources)

→ CR anisotropy ($\delta<10^{-3}$) for ≠ energies and ≠ species