What can we learn from GCR observations near the Earth

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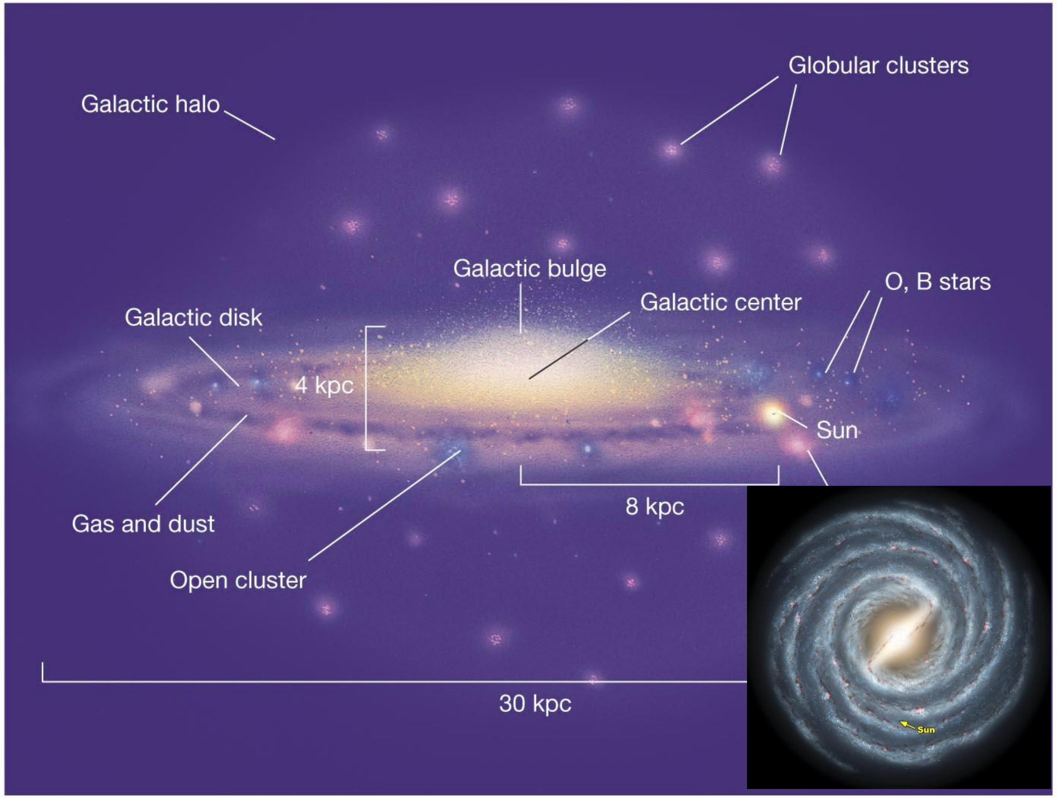
2026.4.21

Collaboration with Zhenning Shen and Zhe Li

Milky Way Basic Fact



Astrophysics II by Fiveable

Rotation period of Sun: 220 million years.
Number of stars: 200 billion

Typical diffusion coefficient of GCR is,

$$D(E) \approx D_0 \left(\frac{E}{1\ \mathrm{GeV}} \right)^{\delta} \ \mathrm{cm}^2/\mathrm{s}$$

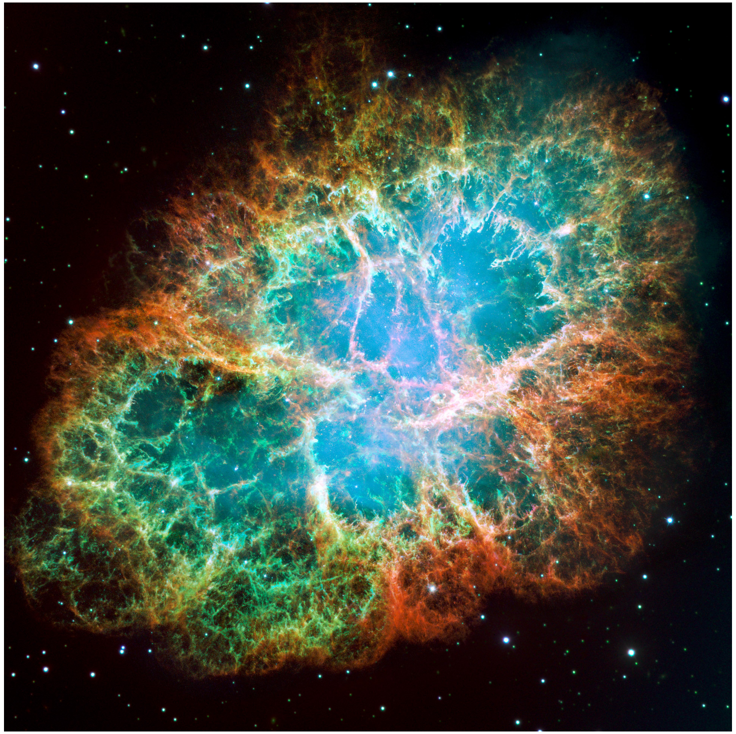
D_0 ~ 1-4 * 10^28 cm^2/s and delta=1/3 or 1/2 depending on turbulence spectral index.

$$\lambda_c(E_{\mathrm{GeV}}) \approx 0.3\, D_{0,28} E_{\mathrm{GeV}}^{\delta}\ \mathrm{pc}$$
$$\tau_c(E_{\mathrm{GeV}}) \approx 1.0\, D_{0,28} E_{\mathrm{GeV}}^{\delta}\ \mathrm{yr},$$

Average ISM: 10^29-10^30 cm^2/s for TeV-scale particles.

TeV Halos: In specific regions like "TeV halos" around pulsars (e.g., Geminga), the diffusion coefficient can be suppressed by a factor of 100.

SNR Shocks as the Accelerator



SN 1054 remnant (Crab Nebula)

Power Required to Maintain GCRs in the Galaxy:

GCR Energy Density: ~ (1 eV/cm³).
GCR Confinement Volume: Cylinder with $R \approx 15$ kpc, $H \approx 4$ kpc
=> Total energy E_{total}: $\sim(1.6\times10^{-12}$ ergs/cm$^3)\times(8\times10^{67}$ cm$^3)\approx1.3\times10^{56}$ ergs

GCR Residence Time τ_{esc}: from the Beryllium-10 clock, we know their average residence time is about 15 million years (for 1 GeV/nul particle).

=>the power needed to replenish it is: **$P_{GCR}=E_{total}/\tau_{esc}\approx2.6\times10^{41}$ergs/sec**

Power Supplied by Supernovae:

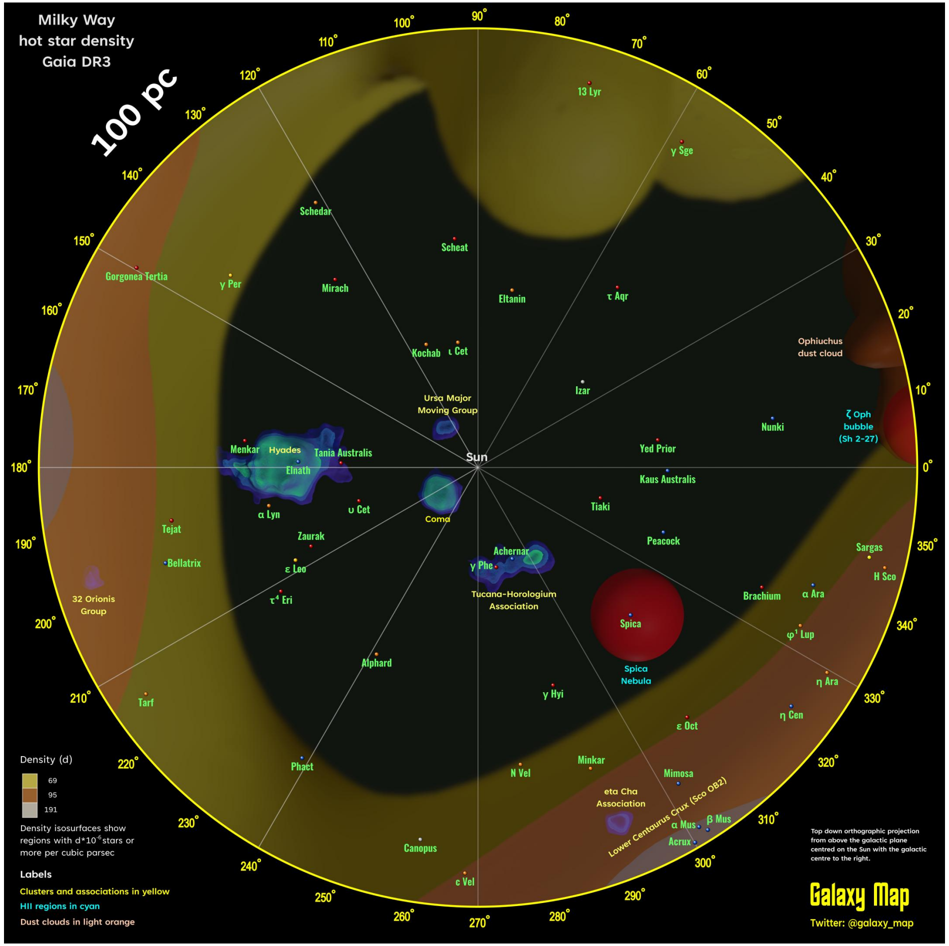
Kinetic Energy per Supernova (ESN): Roughly 1% explosion energy goes to the kinetic energy of the ejecta, which is 10^{51} ergs.

SN occurs about 3 times per centry.

=>the power of SN $\approx10^{42}$ergs/sec

Surprisingly close, suggesting that SNR shocks are the power houses for GCRs!

Local Bubble as the elephant in the room?



Local Bubble: low-density, hot cavity in the interstellar medium, roughly 300 parsecs across, formed by roughly 15 to 20 supernova (SN) explosions over the past 14 million years. B field ~ 0.2-0.6 muG.

The Sun is currently located near its center, having passed into this region about 5 to 6 million years ago.

If kappa is the same as in ISM, then:
TeV particles stay in local bubble ~330 yrs;
GeV particles stay ~3300 yrs.

If kappa is 10-times smaller, then:
TeV particles stay in local bubble ~3300 yrs;
GeV particles stay ~33,000 yrs.

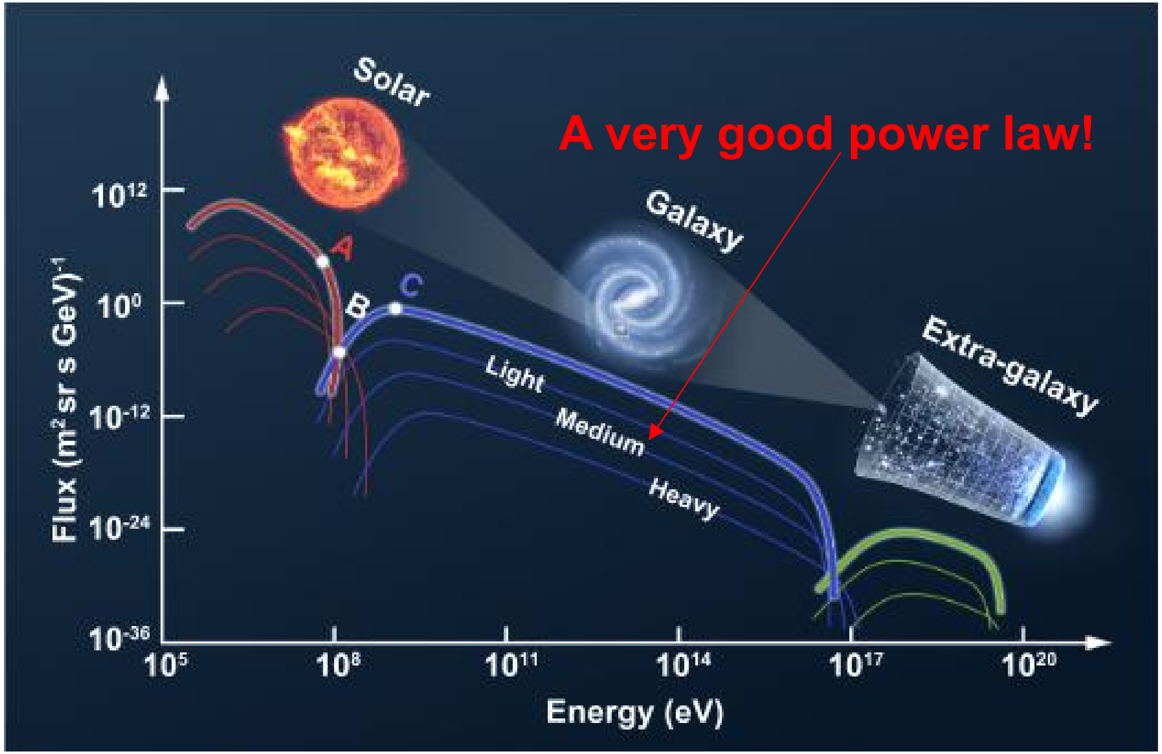
Past SNs: **60Fe sentiments** indicate that:
1.5 to 3 million years ago: One or more supernovae, likely in the Upper Centaurus Lupus (UCL) subgroup of the Scorpius-Centaurus association.

6 to 9 million years ago (Previous): A previous explosion, possibly associated with the Tucana-Horologium association or an earlier event as the solar system entered the bubble.

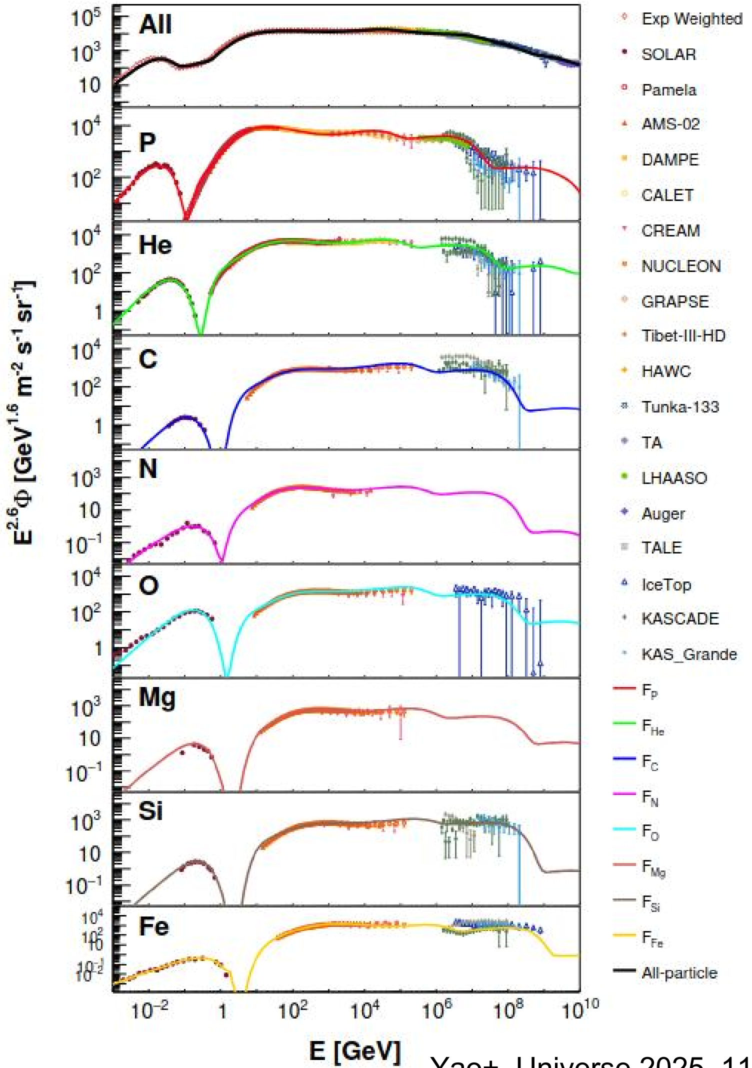
So the GCR spectrum we see is ***unlikely*** a local feature.

Nojiri et al 2025 ApJL 979 L18. doi: 10.3847/2041-8213/ada27a

Understanding Solar Modulation



A very good power law!



Yao+, Universe 2025, 11, 96.

1) to obtain the genuine ***global*** GCR spectra
2) to understand/track the solar activity

Particle Transport in the solar system --Parker's transport equation

$$\frac{\partial f}{\partial t} = -V_{w,i}\frac{\partial f}{\partial x_i} + \frac{\partial}{\partial x_i}\kappa_{ij}\frac{\partial f}{\partial x_j} - V_{D,i}\frac{\partial f}{\partial x_i} + \frac{1}{3}\frac{\partial V_{w,i}}{\partial x_i}\frac{\partial f}{\partial \ln p} + Q$$

advection ***diffusion*** ***drift*** ***energy change***

Propagation of GCRs in the Galaxy is an advection-diffusion process

Turbulence

QLT Jokipii, (1966)

$$\kappa = \frac{v^2}{8}\int_{-1}^{+1} d\mu \frac{(1-\mu^2)^2}{D_{\mu\mu}} = \frac{vp^2c^2}{8\pi Q^2 e^2}\frac{1}{I(k=\Omega/v)}.$$

Eugene Parker 1927-2022

$$\frac{\partial f}{\partial t} + (u\cos\psi + \mu v)\cdot\frac{\partial f}{\partial z} - \frac{v(1-\mu^2)}{2B}\frac{\partial B}{\partial z}\frac{\partial f}{\partial \mu} - \frac{\partial}{\partial \mu}\left(D_{\mu\mu}\frac{\partial f}{\partial \mu}\right) = Q$$

deterministic
characteristic

stochastic
"scattering"–random walk

If retain pitch angle info, => **Focused Transport Equation**, describing, e.g. SEP in the solar wind.

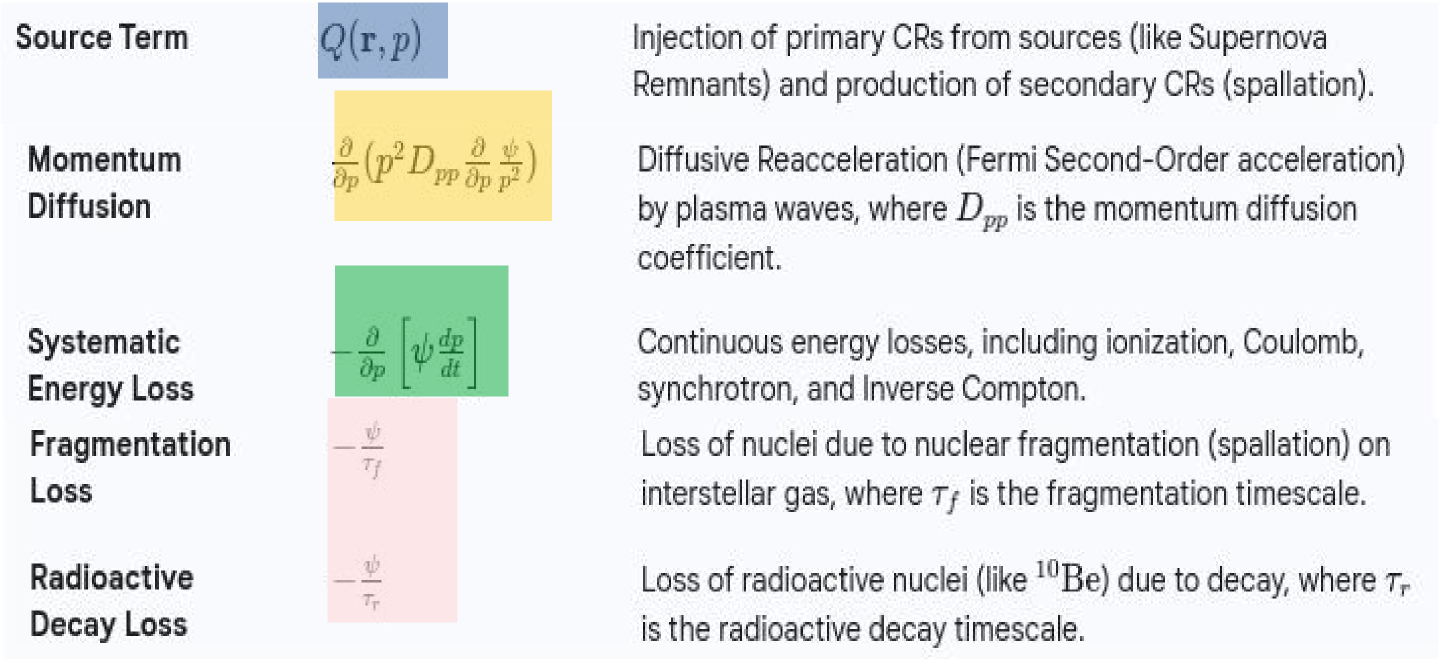
From Solar system to the Galaxy : adding Nuclear Physics to the Picture

$$\frac{\partial \psi}{\partial t} = q(\vec{r},p) + \vec{\nabla}\cdot(D_{xx}\vec{\nabla}\psi - \vec{V}\psi) + \frac{\partial}{\partial p}p^2 D_{pp}\frac{\partial}{\partial p}\frac{1}{p^2}\psi - \frac{\partial}{\partial p}\left[\dot{p}\psi - \frac{p}{3}(\vec{\nabla}\cdot\vec{V})\psi\right] - \frac{1}{\tau_f}\psi - \frac{1}{\tau_r}\psi\ ,$$

$$\psi(p) = 4\pi p^2 f(\mathbf{r},p,t)$$

Ginzburg-Syrovatskii Equation

Spallation leads to the creation of secondary CR, so the system is a coupled equation for elements from H, to 64Ni, plus positron and anti-proton.



Source Term	$Q(\mathbf{r},p)$	Injection of primary CRs from sources (like Supernova Remnants) and production of secondary CRs (spallation).
Momentum Diffusion	$\frac{\partial}{\partial p}(p^2 D_{pp}\frac{\partial}{\partial p}\frac{\psi}{p^2})$	Diffusive Reacceleration (Fermi Second-Order acceleration) by plasma waves, where D_{pp} is the momentum diffusion coefficient.
Systematic Energy Loss	$-\frac{\partial}{\partial p}\left[\psi\frac{dp}{dt}\right]$	Continuous energy losses, including ionization, Coulomb, synchrotron, and Inverse Compton.
Fragmentation Loss	$-\frac{\psi}{\tau_f}$	Loss of nuclei due to nuclear fragmentation (spallation) on interstellar gas, where τ_f is the fragmentation timescale.
Radioactive Decay Loss	$-\frac{\psi}{\tau_r}$	Loss of radioactive nuclei (like $^{10}\mathrm{Be}$) due to decay, where τ_r is the radioactive decay timescale.

The GALPROP code: https://galprop.stanford.edu/index.php

Secondary to Primary Ratios

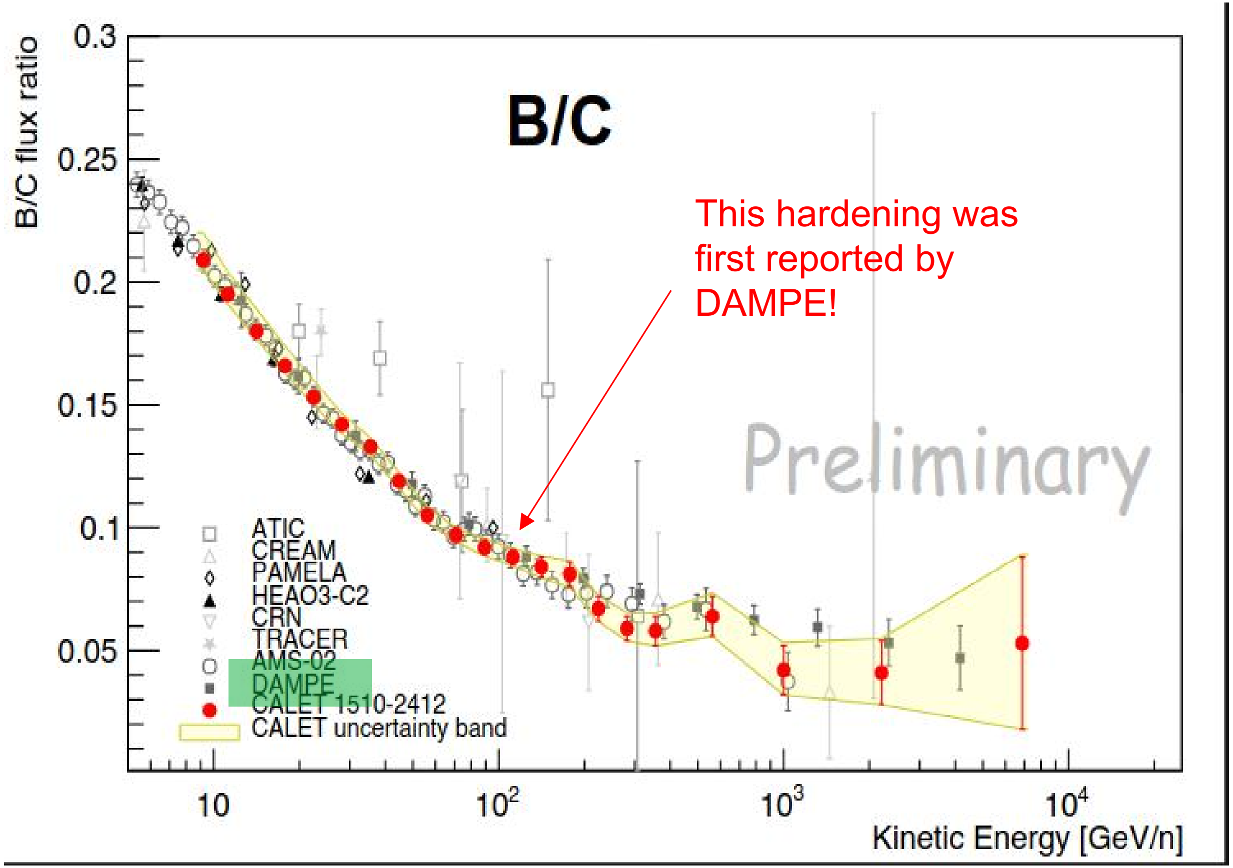
As an example: Boron-to-Carbon ratio (B/C)

Production of the secondary Boron depends on the amount of interstellar matter traversed by primary Carbon (before escaping the Milky Way).

At higher energies, the residence time decreases since,

$\tau \sim (H/\lambda)^2 * (\lambda/v) \sim 1/\kappa \sim R^{-\delta}$

So the ratio decreases with energy.



This hardening was first reported by DAMPE!

CALET 2025 ICRC

Cosmogenic Nuclei as Cosmic Ray Clock

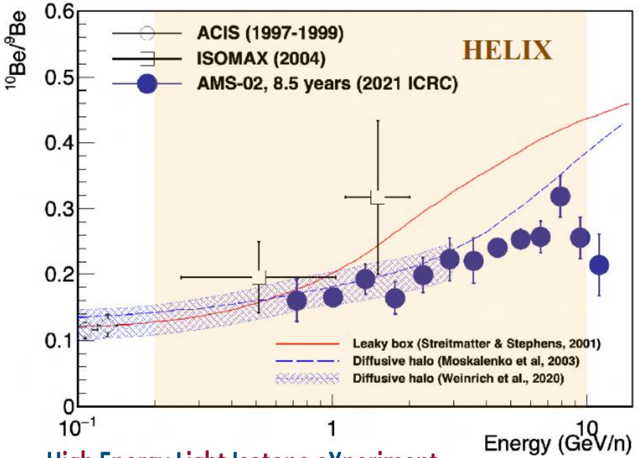
As an example: Be-10/Be-9

Produced by spallation:

$$\left(\frac{{}^{10}\mathrm{Be}}{{}^{9}\mathrm{Be}}\right)_{\mathrm{production}} \equiv \frac{Q_{10}}{Q_9} = \frac{\sum_i \sigma_{i\to{}^{10}\mathrm{Be}} N_i}{\sum_i \sigma_{i\to{}^{9}\mathrm{Be}} N_i}$$

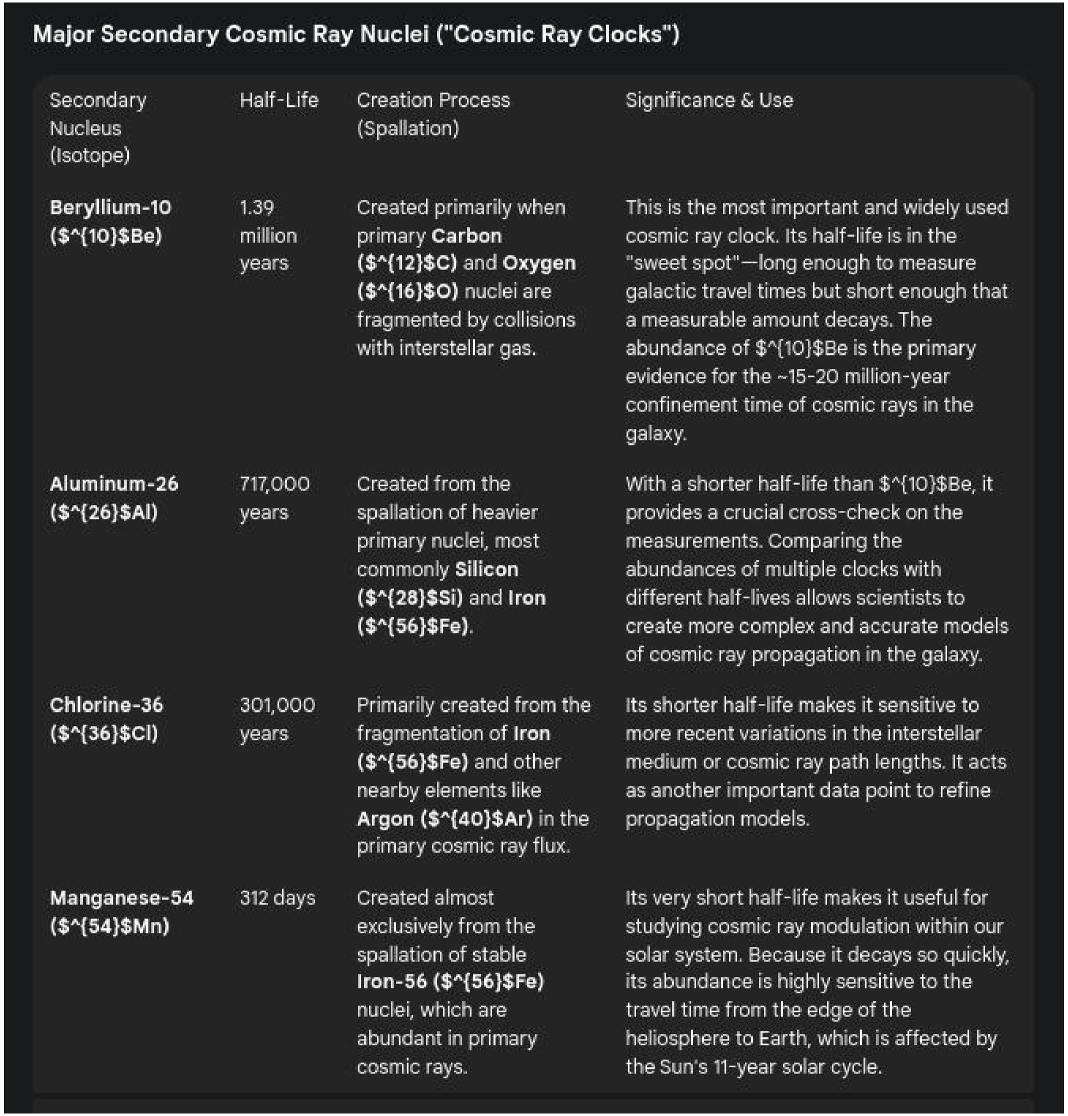
$$\approx \frac{\sigma_{\mathrm{C}\to{}^{10}\mathrm{Be}} N_{\mathrm{C}} + \sigma_{\mathrm{O}\to{}^{10}\mathrm{Be}} N_{\mathrm{O}}}{\sigma_{\mathrm{C}\to{}^{9}\mathrm{Be}} N_{\mathrm{C}} + \sigma_{\mathrm{O}\to{}^{9}\mathrm{Be}} N_{\mathrm{O}}} \approx \mathbf{0.35} \pm 0.05$$

Ratio of Be10/Be9 can discriminize different propagation scenarios.



High Energy Light Isotope eXperiment

http://helix.uchicago.edu/index.html



Major Secondary Cosmic Ray Nuclei ("Cosmic Ray Clocks")

Secondary Nucleus (Isotope)	Half-Life	Creation Process (Spallation)	Significance & Use
Beryllium-10 (^{10}Be)	1.39 million years	Created primarily when primary **Carbon (^{12}C)** and **Oxygen (^{16}O)** nuclei are fragmented by collisions with interstellar gas.	This is the most important and widely used cosmic ray clock. Its half-life is in the "sweet spot"—long enough to measure galactic travel times but short enough that a measurable amount decays. The abundance of ^{10}Be is the primary evidence for the ~15-20 million-year confinement time of cosmic rays in the galaxy.
Aluminum-26 (^{26}Al)	717,000 years	Created from the spallation of heavier primary nuclei, most commonly **Silicon (^{28}Si)** and **Iron (^{56}Fe)**.	With a shorter half-life than ^{10}Be, it provides a crucial cross-check on the measurements. Comparing the abundances of multiple clocks with different half-lives allows scientists to create more complex and accurate models of cosmic ray propagation in the galaxy.
Chlorine-36 (^{36}Cl)	301,000 years	Primarily created from the fragmentation of **Iron (^{56}Fe)** and other nearby elements like **Argon (^{40}Ar)** in the primary cosmic ray flux.	Its shorter half-life makes it sensitive to more recent variations in the interstellar medium or cosmic ray path lengths. It acts as another important data point to refine propagation models.
Manganese-54 (^{54}Mn)	312 days	Created almost exclusively from the spallation of stable **Iron-56 (^{56}Fe)** nuclei, which are abundant in primary cosmic rays.	Its very short half-life makes it useful for studying cosmic ray modulation within our solar system. Because it decays so quickly, its abundance is highly sensitive to the travel time from the edge of the heliosphere to Earth, which is affected by the Sun's 11-year solar cycle.

Solar Modulation

Heliosphere as a shield preventing Galactic Cosmic Ray from direct “compacting” on Earth.

Transport equation

(in conservation form)

$$\frac{\partial f}{\partial t} + \nabla \cdot S + \frac{1}{p^2}\frac{\partial}{\partial p}(p^2 J) = 0$$

$$\mathbf{S} = -\frac{p}{3}\mathbf{u}\frac{\partial f}{\partial p} - \kappa \nabla f$$

$$J = \frac{p}{3}\boldsymbol{u} \cdot \nabla f$$

S: current in r space
J: current in p space

Solar Modulation:

- Heliosheath
- TS
- **Solar wind**

effects of magnetic field turbulence on GCRs.

Gleeson-Axford 1967

Force-Field Model

Period of solar cycle is ~ 11 years, assuming all physical quantities change gradually => steady state as a 1st approximation

Furthermore, if $\mathbf{S} = -\frac{p}{3}\mathbf{u}\frac{\partial f}{\partial p} - \kappa \nabla f = 0$

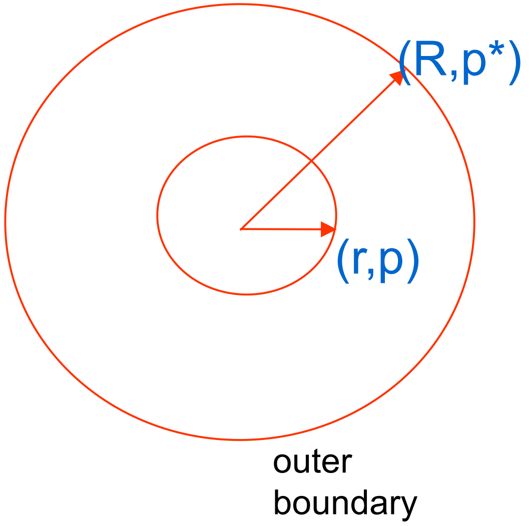
1st order differential equation, use method of characteristics, $\frac{dp}{pu} = \frac{dr}{3\kappa}$

Assuming k =**k1(r)***k2(P)*b ==> f(r, p) = f(R, p*)

$$\int_r^R \frac{V(r')}{3\kappa_1(r')}\,dr' = \int_p^{p^*} \frac{\kappa_2(p')\beta(p')}{p'}\,dp' \equiv \phi(r)$$

Further assuming $\kappa_2(P) = P$

k1(r) depends on solar wind turbulence property and has a 11-22 solar cycle period.



Force-field model: Zeϕ is the energy loss

Why is the (1D) Force-Field Model quite good?

Implication of the steady state and S=0 assumption

$$\frac{\partial f}{\partial t} + \nabla \cdot S + \frac{1}{p^2}\frac{\partial}{\partial p}(p^2 J) = 0$$

==> J ~ p^-3!

$$\mathbf{S} = -\frac{p}{3}\mathbf{u}\frac{\partial f}{\partial p} - \kappa \nabla f$$

$$J = \frac{p}{3}\mathbf{u} \cdot \nabla f$$

Beyond the FF model: Generalized Force-Field Model

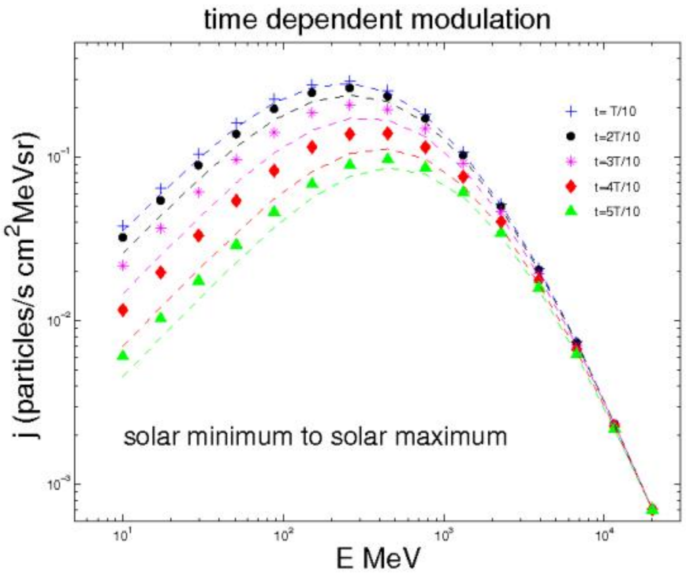
Keep k =k1(r)*k2(P)*b, but relax k2(P)=p

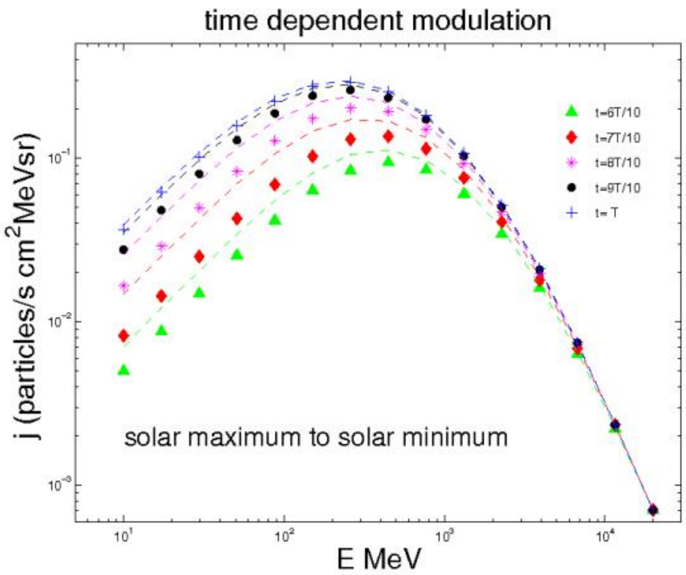
$$\int_r^R \frac{V(r')}{3\kappa_1(r')} dr' = \int_p^{p^*} \frac{\kappa_2(p')\beta(p')}{p'} dp' \equiv \phi(r)$$

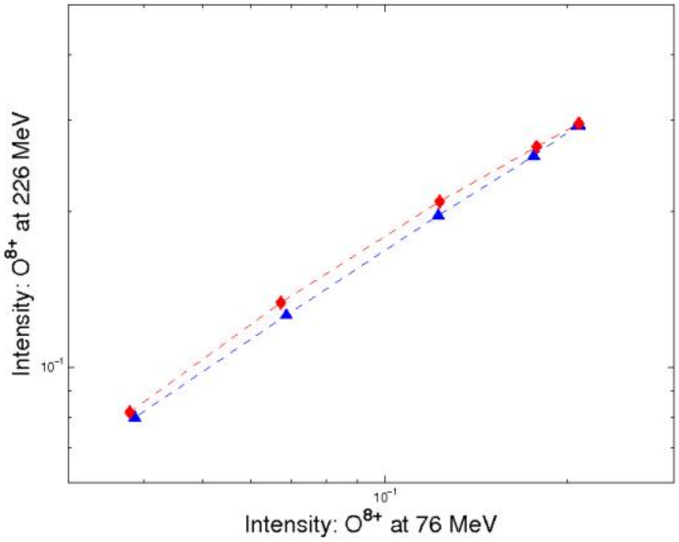
See Zhenning Shen’s talk @ this meeting, Shen+ (2026)

Beyond Steady State

Time-dependent modulation (Hysteresis Effect)







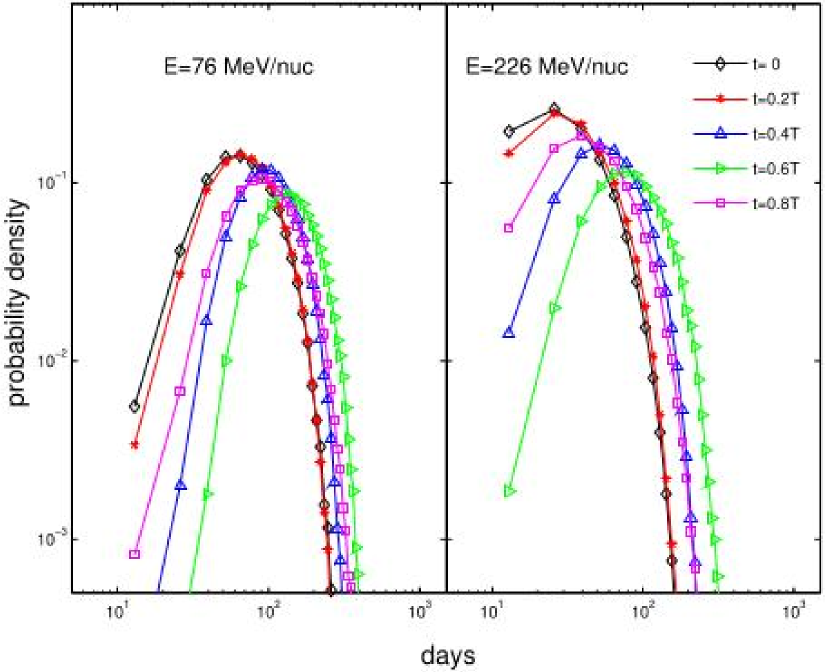
$$\kappa_{rr}(r) = \frac{\kappa_B + \kappa_S}{2} + \frac{\kappa_B - \kappa_S}{2} * cos(2\pi \frac{t - r/V_{sw}}{T})$$

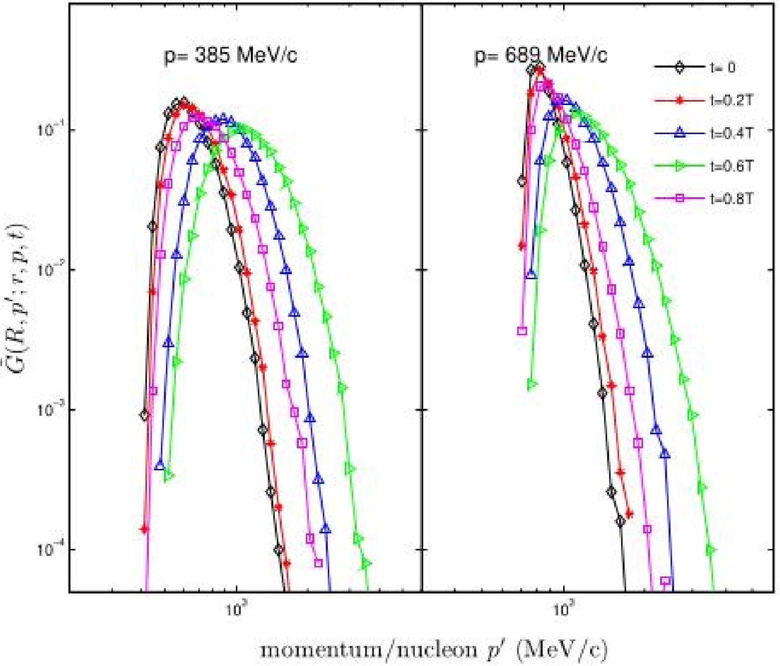
Li+ (2009)

Probability Distribution of the travel time and Green’s function G̃(R, p0 ; r, p, t)

$$
\begin{aligned}
f(r,p,t) &= \int\int G(R,p',t';r,p,t) f_b(p') dp' dt' \\
&= \int \tilde{G}(R,p';r,p,t) f_b(p',t') dp'.
\end{aligned}
$$

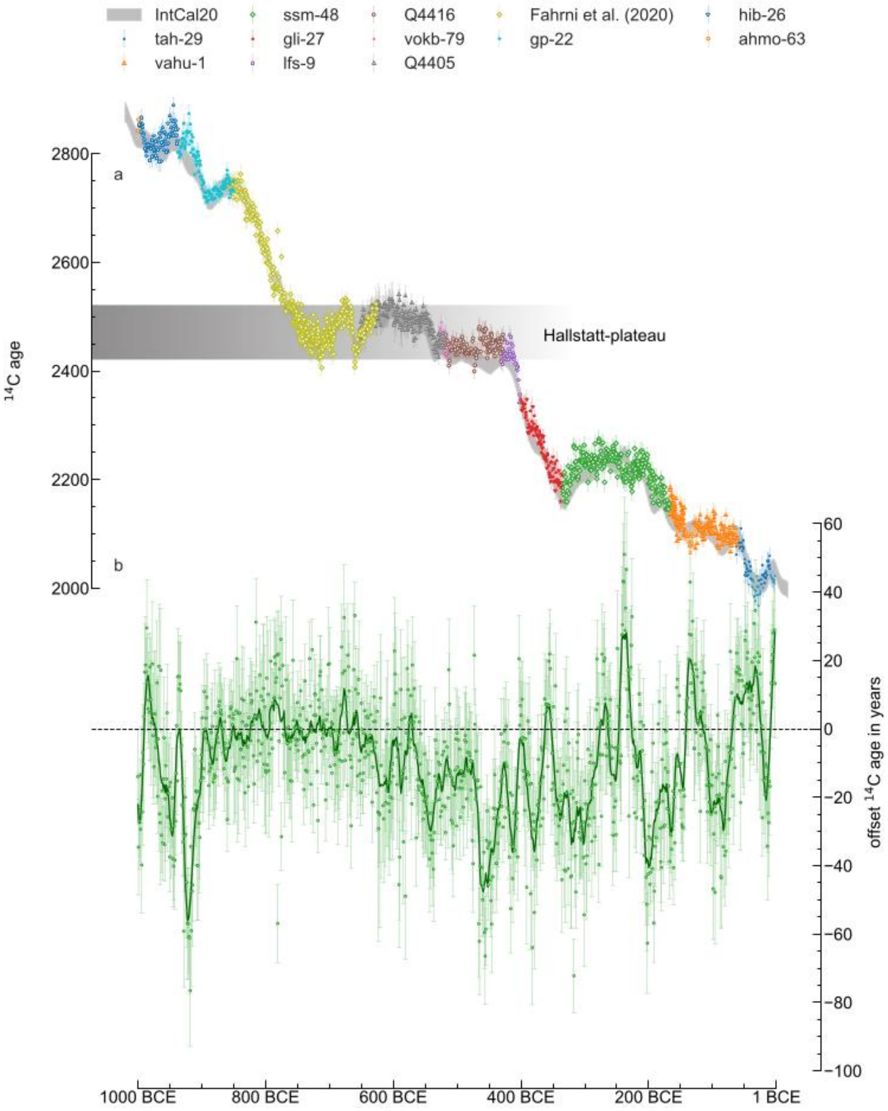
$$
\frac{\partial G}{\partial t} + V_{sw}\cdot\nabla G - \nabla\cdot(\kappa\cdot\nabla G) - \frac{1}{3}\nabla\cdot V_{sw}\frac{\partial G}{\partial lnp} = \delta(r-r')\delta(p-p')\delta(t-t').
$$

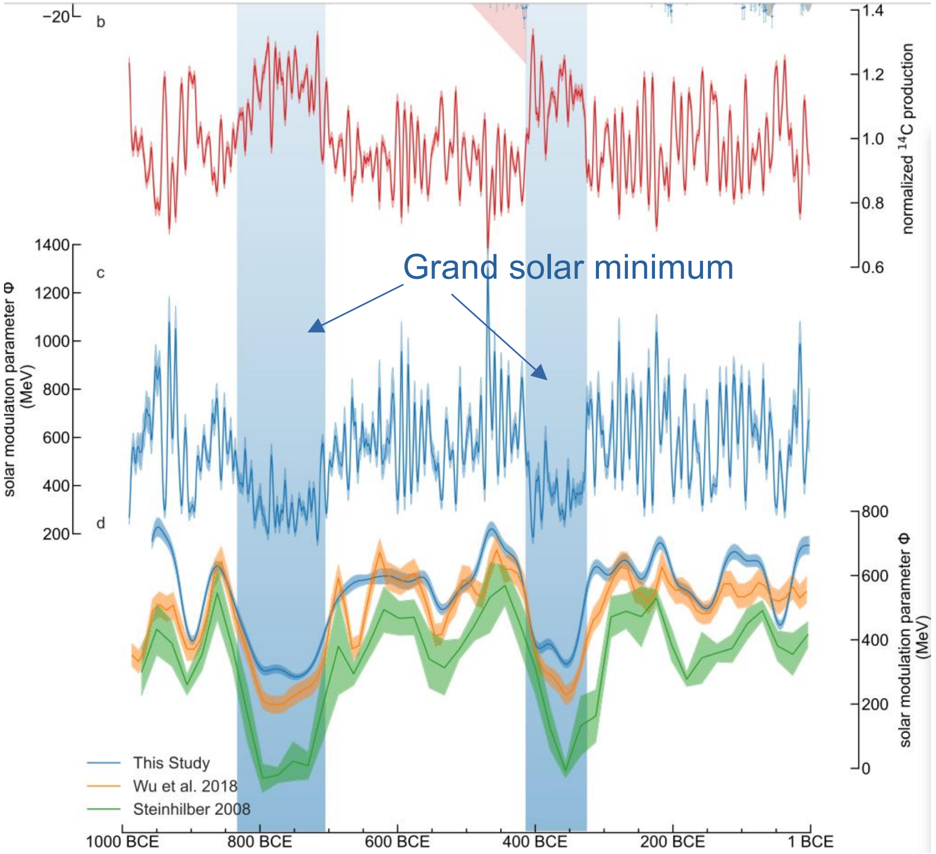




Li+ (2009)

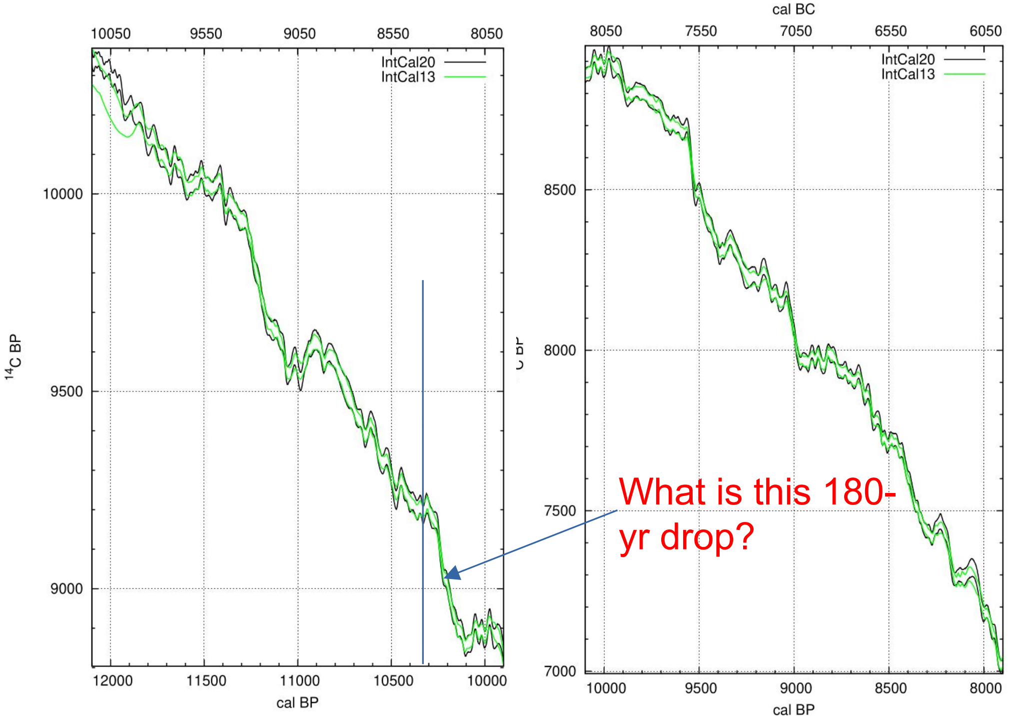
Variation of phi on a longer time scale



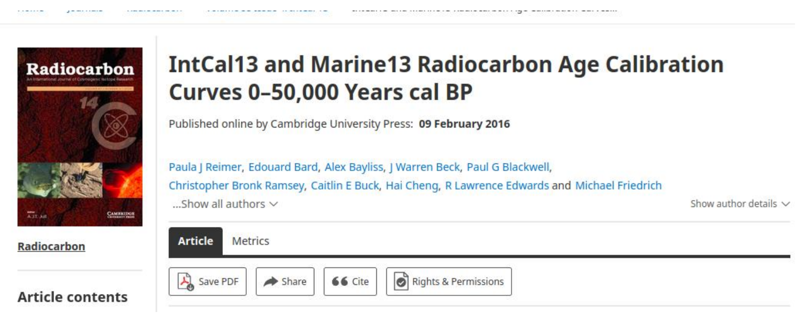


Grand solar minimum

History of GCR from ^{14}C radiocarbon age curve – inferring solar system’s environment



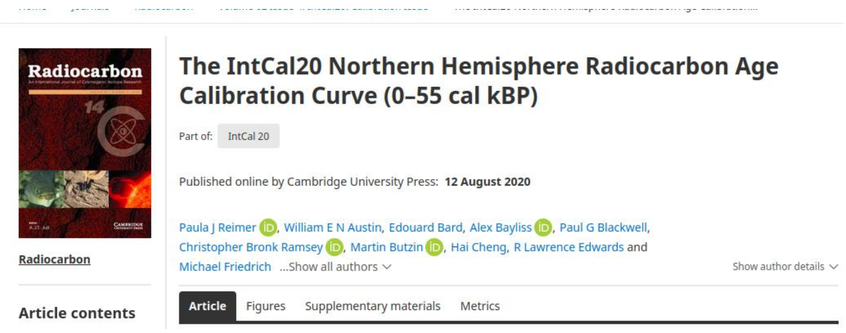
What is this 180-yr drop?



Radiocarbon

IntCal13 and Marine13 Radiocarbon Age Calibration Curves 0–50,000 Years cal BP

Paula J Reimer, Edouard Bard, Alex Bayliss, J Warren Beck, Paul G Blackwell, Christopher Bronk Ramsey, Caitlin E Buck, Hai Cheng, R Lawrence Edwards and Michael Friedrich



Radiocarbon

The IntCal20 Northern Hemisphere Radiocarbon Age Calibration Curve (0–55 cal kBP)

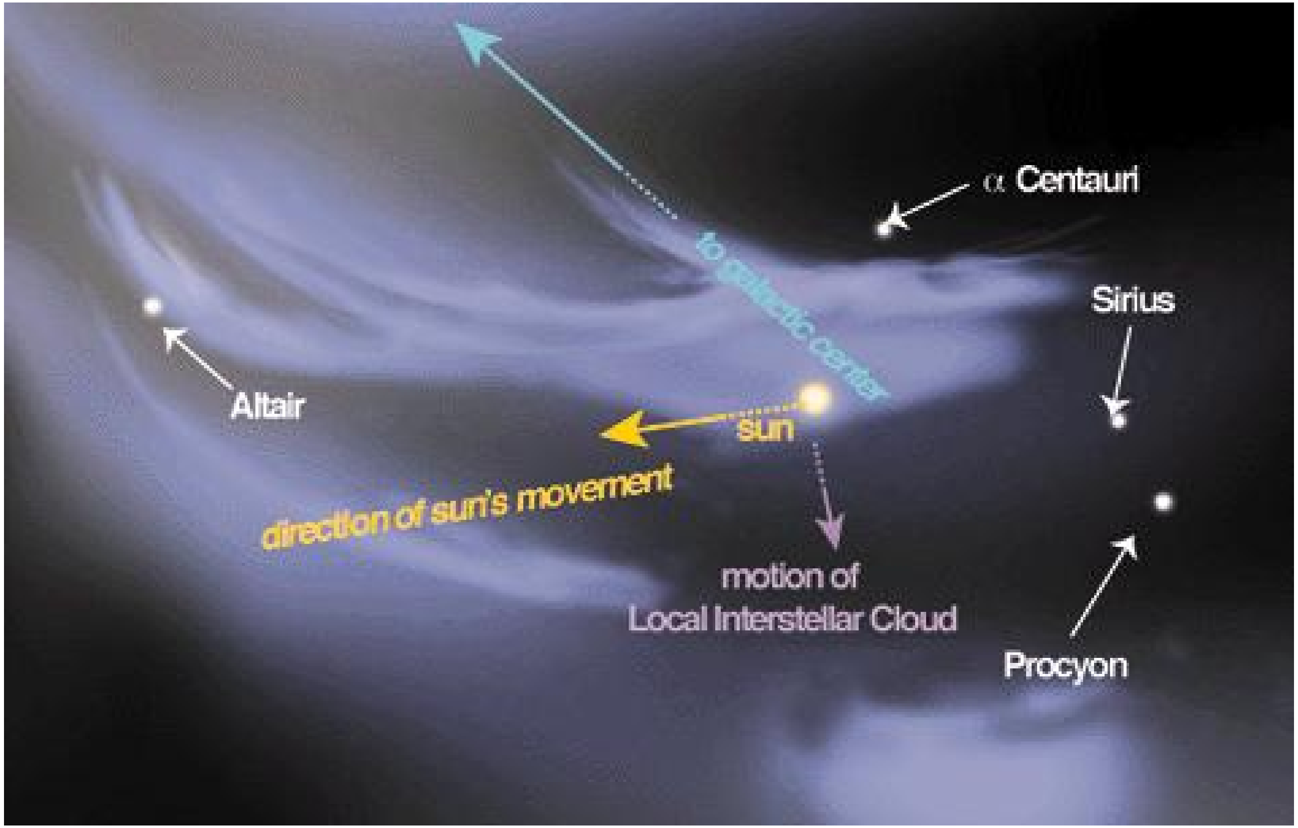
Part of: IntCal 20

Paula J Reimer, William E N Austin, Edouard Bard, Alex Bayliss, Paul G Blackwell, Christopher Bronk Ramsey, Martin Butzin, Hai Cheng, R Lawrence Edwards and Michael Friedrich

Sudden changes in the age curve can be due to single SEP event. What if the change is gradual, lasting 200 yrs?

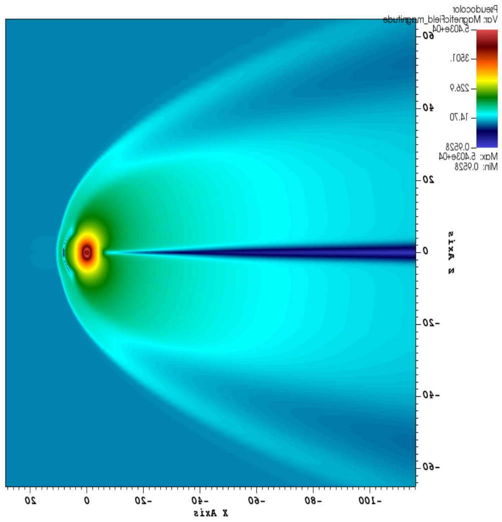
https://c14.arch.ox.ac.uk/calibration.html

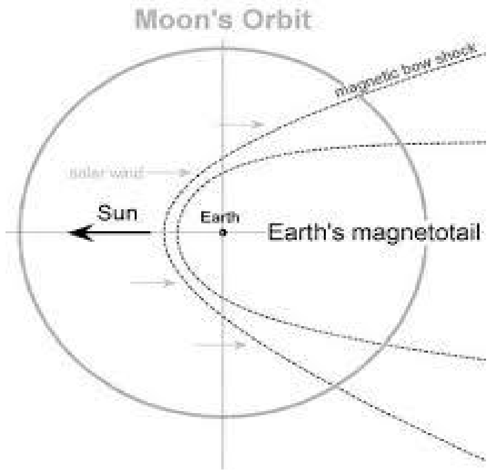
Deciphering Local Fluff with ^{14}C record

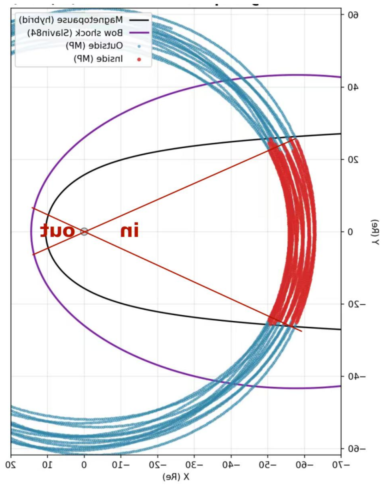


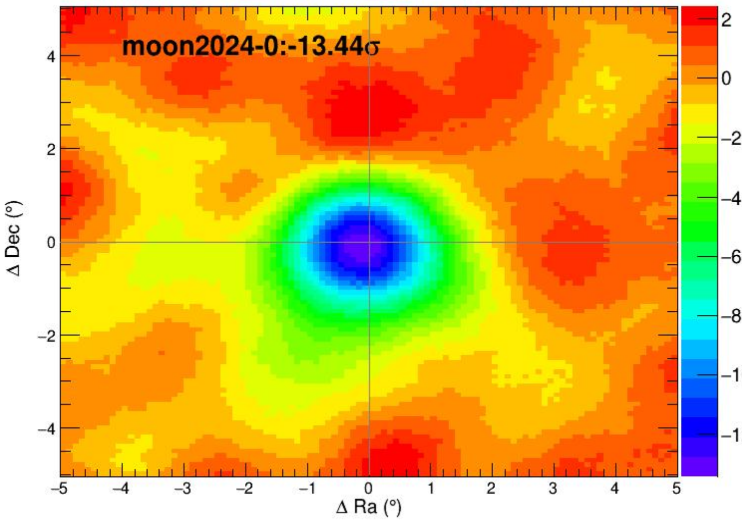
About 10,000 yrs ago, solar system enters local fluff (0.3/cm^3) from local Bubble (0.05/cm^3). **Size of the Heliosphere drops**, GCR flux @1au increases, 14C increases and 14C age drops. With 26km/s, solar system travels 5.4 au/year, and travels 1000 au in 180 years.

Moon Shadow –collaboration with Zhe Li et al.



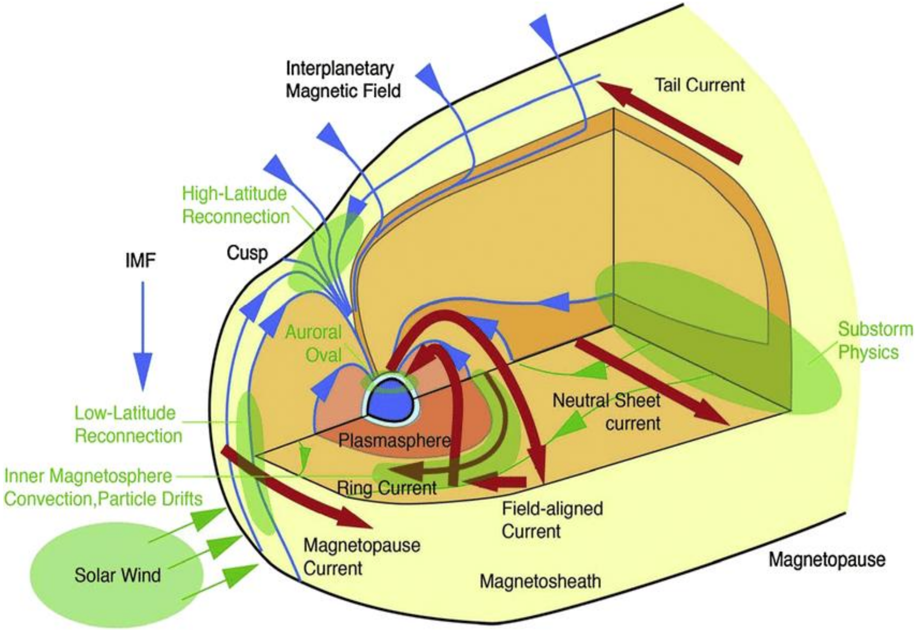






Center offset: ~0.3 deg

Size (spreading) ~ 0.2-0.5 deg (energy dependent)

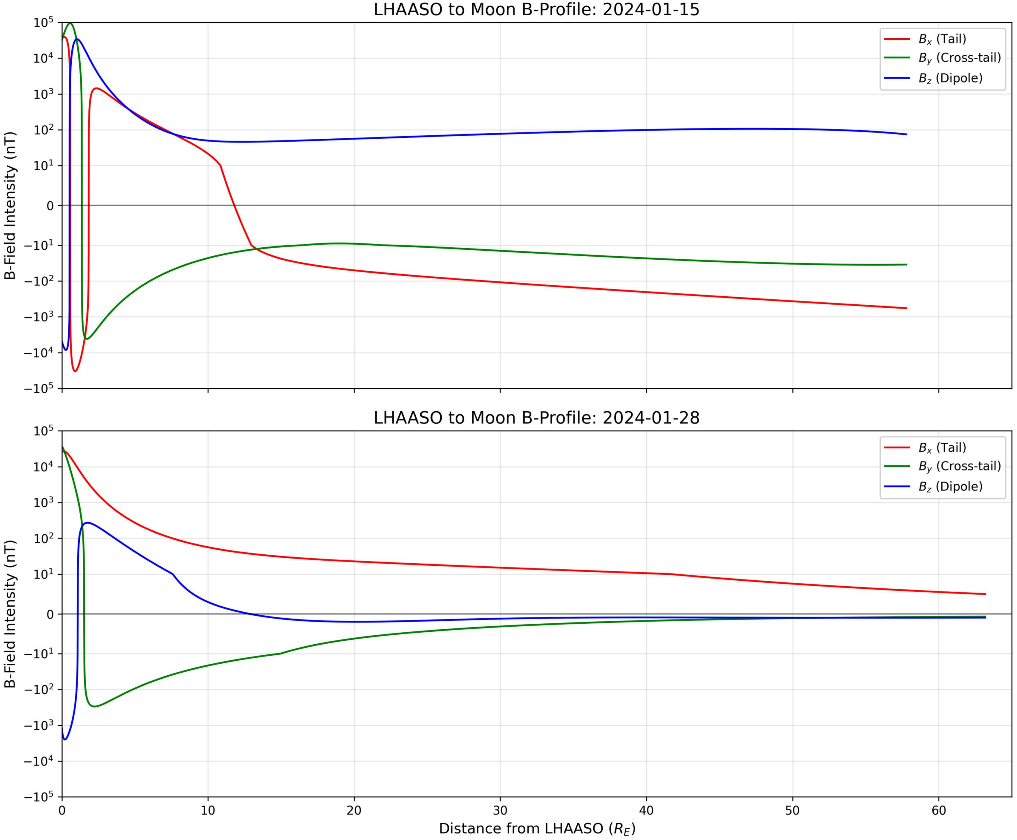


Mironova+, 2015

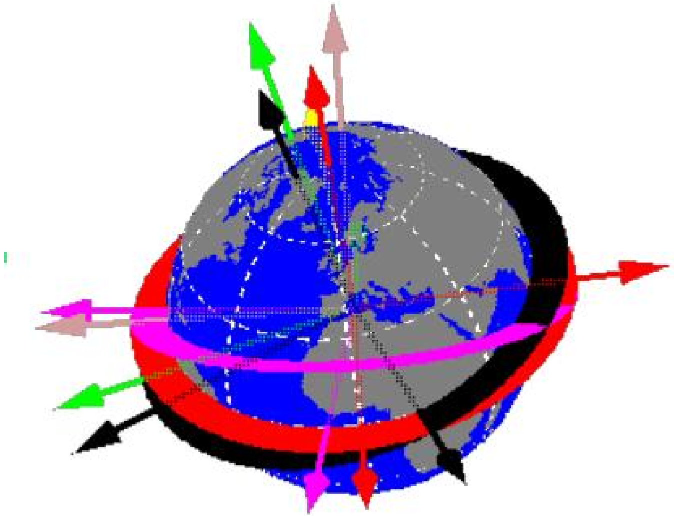
The B field along the Moon-LHASSO line has very ***complicated*** pattern

This can affect, but of less effect, on the Sun shadow observation as well

Magnetic Field along the LHASSO-Moon line of sight



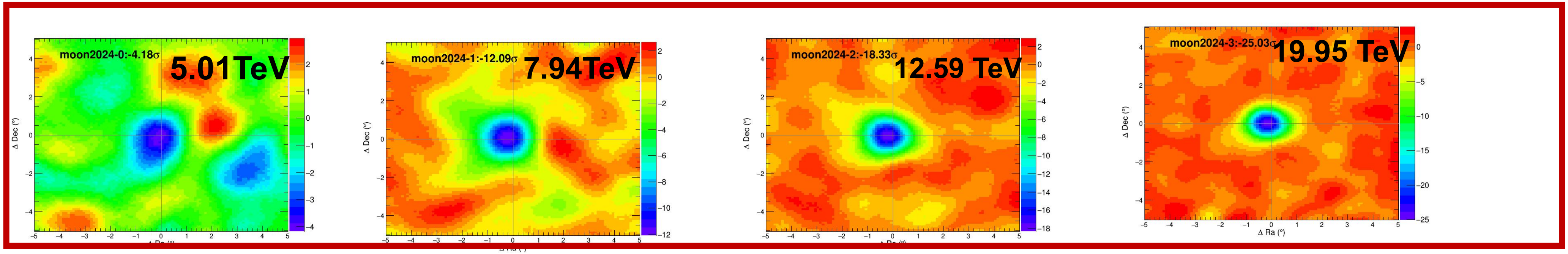
Dipole field change sign across magnetic equator

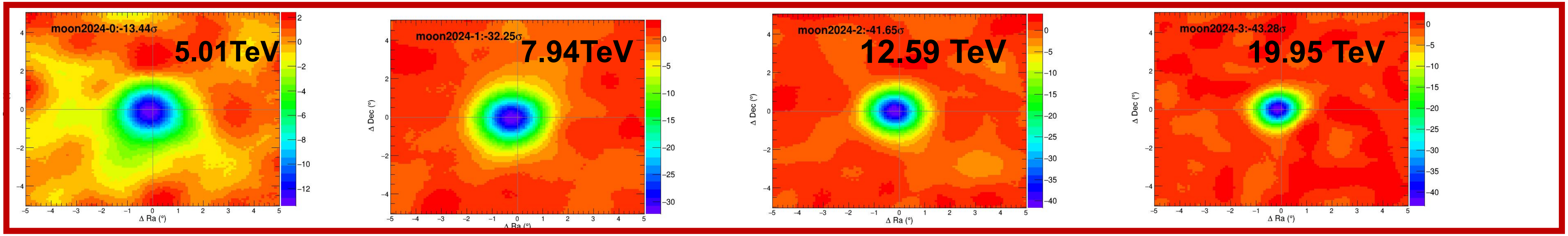


Moonshadow observed in the year 2024 with LHAASO-KM2A

--preliminary results

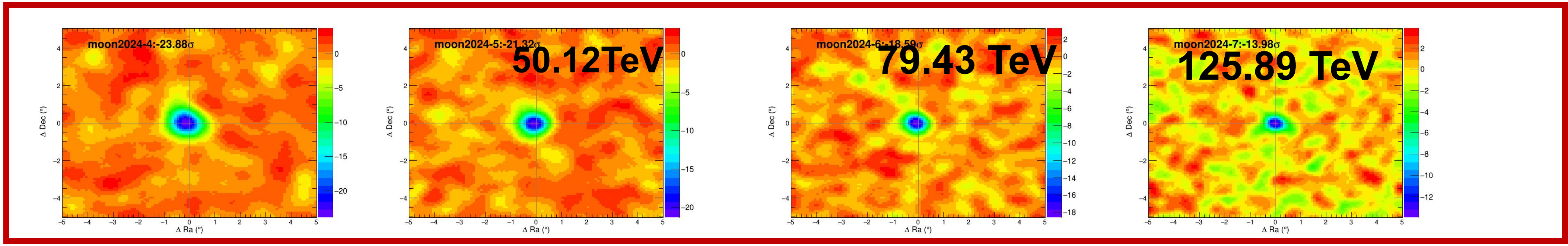
above

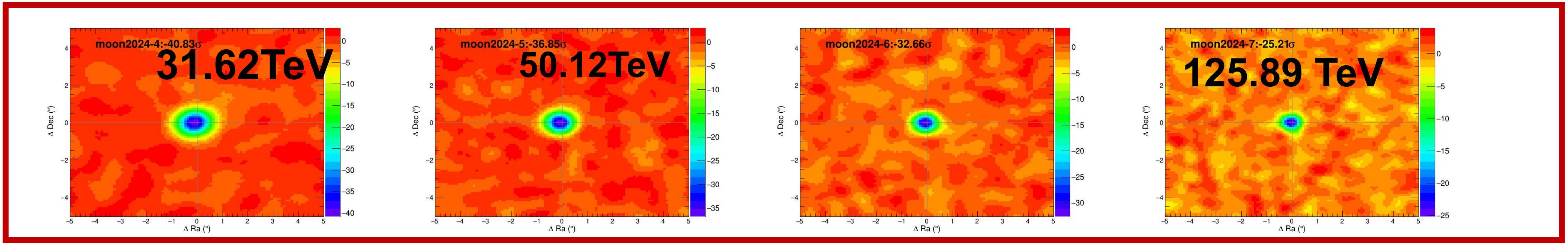




bellow

above





bellow

2024 Magnetic Latitude Calendar (The "BR Plane" Cycle)

On average, each month follows this rhythm:

- **~9 Days ABOVE (> +10°):** The Moon is "high" in the Northern Magnetic Hemisphere.
- **~4.5 Days CROSSING:** Moving from North to South.
- **~9 Days BELOW (< -10°):** The Moon is "low" in the Southern Magnetic Hemisphere.
- **~4.5 Days CROSSING:** Moving from South back to North.

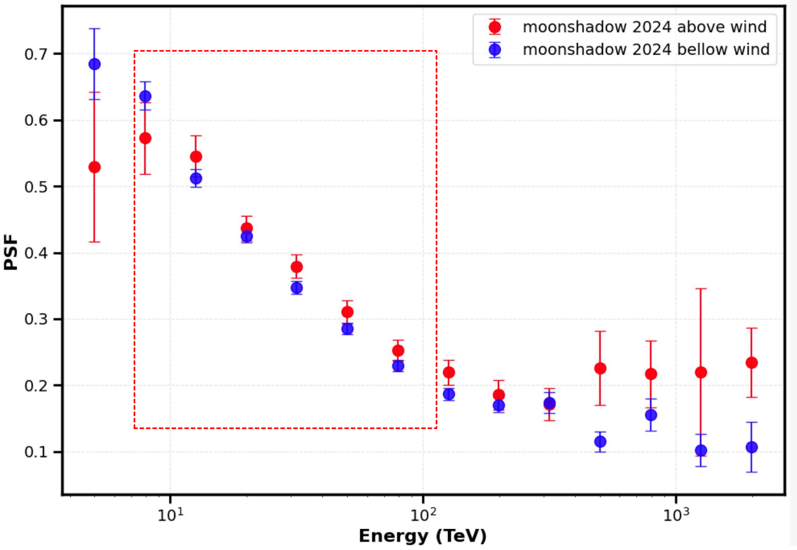
Month (2024)	"ABOVE" Window (> +10°)	"BELOW" Window (< -10°)
January	Jan 09 – Jan 18	Jan 23 – Feb 01
February	Feb 05 – Feb 14	Feb 19 – Feb 28
March	Mar 04 – Mar 13	Mar 18 – Mar 27
April	Mar 31 – Apr 09	Apr 14 – Apr 23
May	Apr 27 – May 06	May 11 – May 20
June	May 25 – Jun 03	Jun 08 – Jun 17
July	Jun 21 – Jun 30	Jul 05 – Jul 14
August	Jul 18 – Jul 27	Aug 01 – Aug 10
September	Aug 14 – Aug 23	Aug 28 – Sep 06
October	Sep 10 – Sep 19	Sep 24 – Oct 03
November	Oct 08 – Oct 17	Oct 22 – Oct 31
December	Nov 04 – Nov 13	Nov 18 – Nov 27

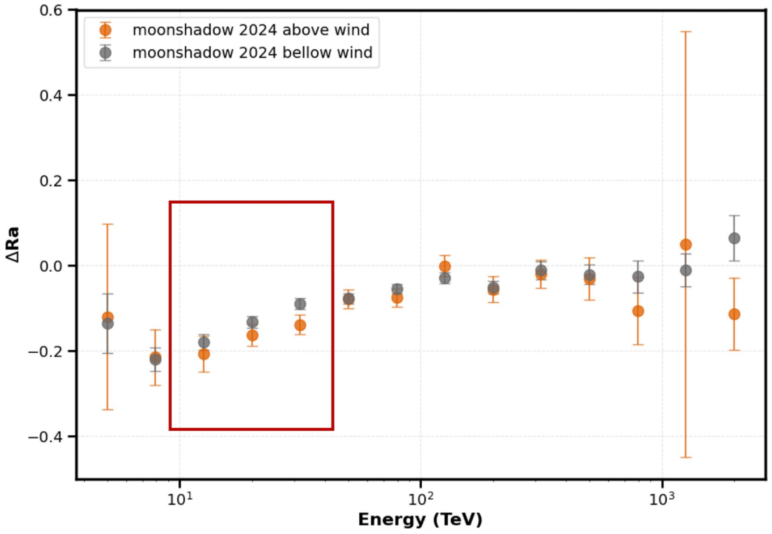
Need Ensemble Analysis with LHASSO-Moon configuration as the selection criteria

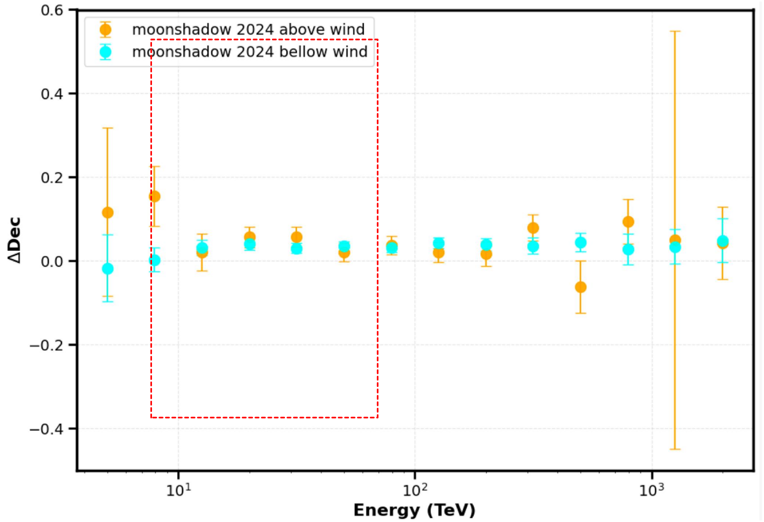
Center displacement depends on more sign of polar field;

Spreading may depend on solar wind residence fraction

Preliminary Results







Backup

What affects phi?

Do electrons behave differently in A>0 and A<0 cycles? Electrons are good tracer of field lines with fewer cross field diffusion, so in A>0 cycle, the travel time is shorter (longer)? Can this be seen from observations?

Acceleration time scale and maximum particle energy

the acceleration time scale

$$\Delta t = \frac{3s}{s-1}\frac{\kappa(p)}{u_{sh}^2}\frac{\Delta p}{p}$$

Axford (1981),
Drury (1983)

the dynamic time scale.

$$t_{dyn} = \min\{\frac{\mathrm{R(t)}}{\mathrm{dR(t)/dt}}, \frac{\mathrm{B(t)}}{\mathrm{dB(t)/dt}}, \frac{\mathrm{n(t)}}{\mathrm{dn(t)/dt}}\}$$

the highest energy is decided by

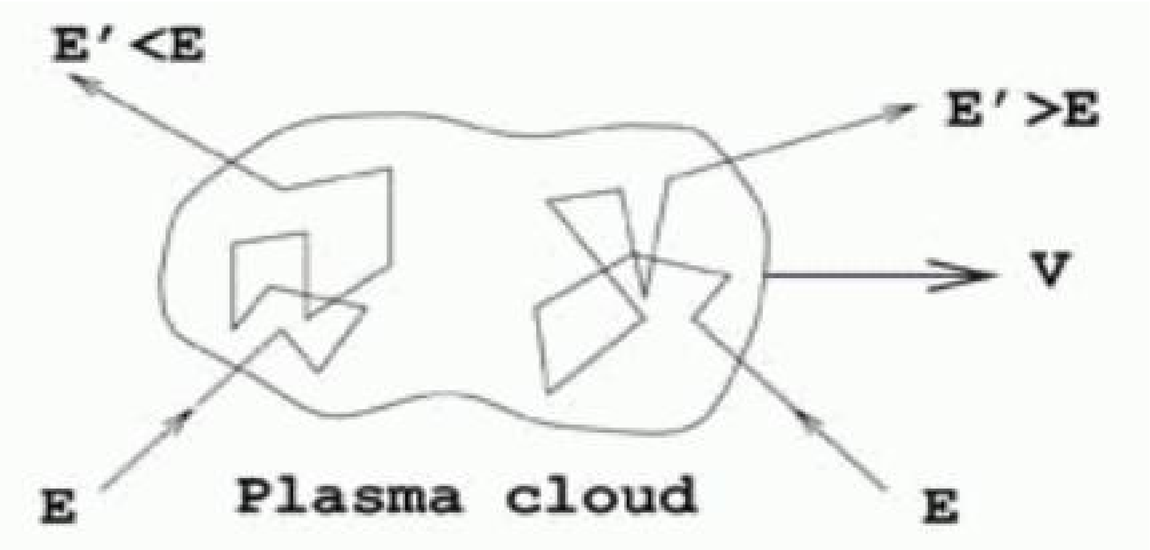
$$t_{dyn} = \int_{p_1}^{p_{max}} \beta\frac{\kappa}{u_{sh}^2}\frac{1}{p}dp.$$

$$\kappa = \kappa_{up}(p) + s\kappa_{dn}(p).$$

smaller k lead to higher energy

compression ratio

Second order Fermi Acceleration (stochastic acceleration)



Fermi 1901-1954

Random flow velocity => diffusion in energy

[Fermi, 1949]

Transport equation from different points of view

Fokker-Planck equation

Forward Kolmogorov equation

Adriann Fokker

Max Planck

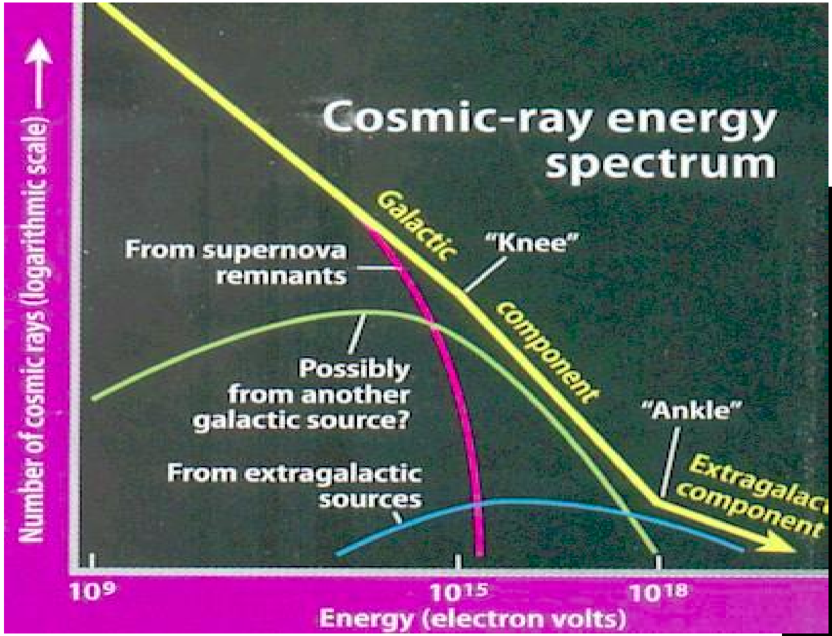
Andrey Kolmogorov

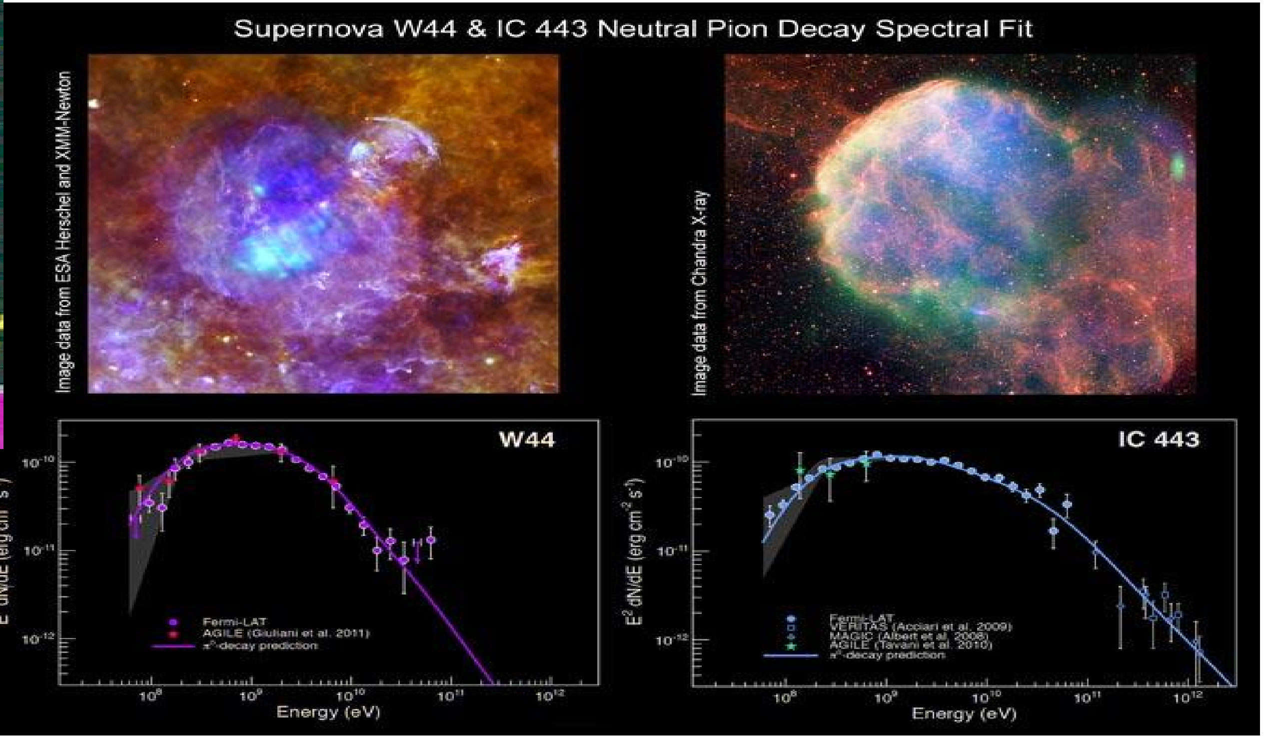
Feynman-Kac Formula

Richard Feynman

Mark Kac

SNR shock: birth place of GCR





Ackermann+, 2013

Fermi LAT gamma ray observation agrees well with pion decay calculation => SNR as birth place of GCR