Cosmic Rays' Energy Dependent Injection Time (CREDIT)

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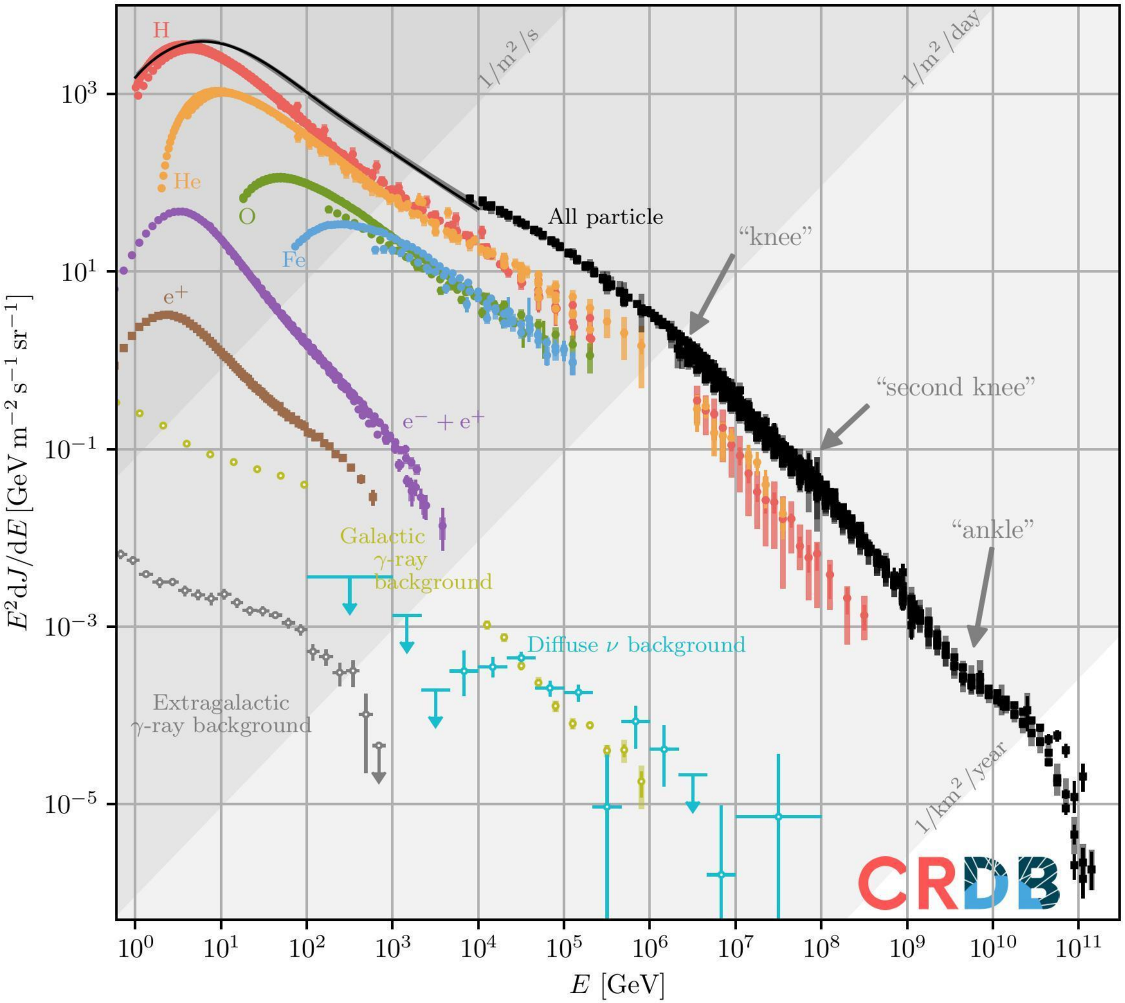
Sexten - Advances in Modeling High-Energy Astrophysical Sources: Insights from recent multimessenger discoveries - 04/07/2025

[2409.11012] Investigating the CREDIT history of supernova remnants as cosmic-ray sources



H
He
O
Fe
e+
e− + e+
All particle
"knee"
"second knee"
"ankle"
Galactic γ-ray background
Extragalactic γ-ray background
Diffuse ν background
1/m²/s
1/m²/day
1/km²/year
CRDB
$E^2 \mathrm{d}J/\mathrm{d}E\,[\mathrm{GeV\,m^{-2}\,s^{-1}\,sr^{-1}}]$
E [GeV]

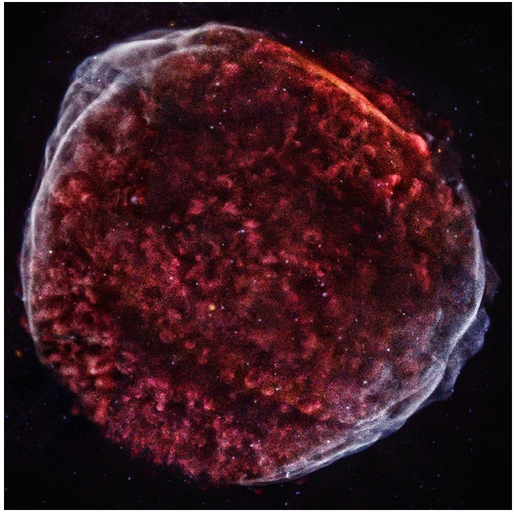
SuperNova Remnant (SNR)

Good candidate for Galactic Cosmic Ray (GCR):

- Fulfil energy density of GCR (10% efficiency)
- Diffusive shock acceleration possible at shock front
- Synchrotron photon show power law dependence

Problem

- Where are they?
- Can they accelerate GCR up to sufficient energy?



Chandra :: Photo Album :: SN 1006 :: April 17, 2013 (harvard.edu)

Maximum Energy from SNR

$$\nabla \times \boldsymbol{E} = -\frac{1}{c}\frac{\partial \boldsymbol{B}}{\partial t} \qquad E = q\int \boldsymbol{E}\cdot \mathrm{d}l$$

Dimensional analysis:

$$\frac{\boldsymbol{E}}{d} \sim \frac{1}{c}\frac{\boldsymbol{B}}{t} \implies \boldsymbol{E} \sim \frac{u}{c}\boldsymbol{B} \implies E_{\mathrm{max}} \sim q\frac{u}{c}\boldsymbol{B}L$$

Analysing acceleration time:

$$t_{\mathrm{accel}} \approx \frac{D(E)}{u_s^2} \implies D(E_{\mathrm{max}}) \approx u_s R_s$$

$$D_{\mathrm{Bohm}}(E) = \frac{r_L c}{3} = \frac{Ec}{3qB} \implies E_{\mathrm{max}} \sim q\frac{u_s}{c}\boldsymbol{B}R_s$$

$$E_{\mathrm{max}} \approx 10\mathrm{TeV}\left(\frac{\boldsymbol{B}}{1\mu\mathrm{G}}\right)\left(\frac{u_{\mathrm{shock}}}{10^4\mathrm{kms}^{-1}}\right)\left(\frac{R_{\mathrm{SNR}}}{10\mathrm{pc}}\right)$$

[Lagage, Cesarsky 1983, Bell 2013]

Evolution of Maximum Energy

$$E_{max} \approx 10\mathrm{TeV}\left(\frac{B}{1\mu\mathrm{G}}\right)\left(\frac{u_{\mathrm{shock}}}{10^4\mathrm{kms}^{-1}}\right)\left(\frac{R_{\mathrm{SNR}}}{10\mathrm{pc}}\right)$$

E_{max} is also the maximum energy confinable in the source

Ejecta-dominated phase:

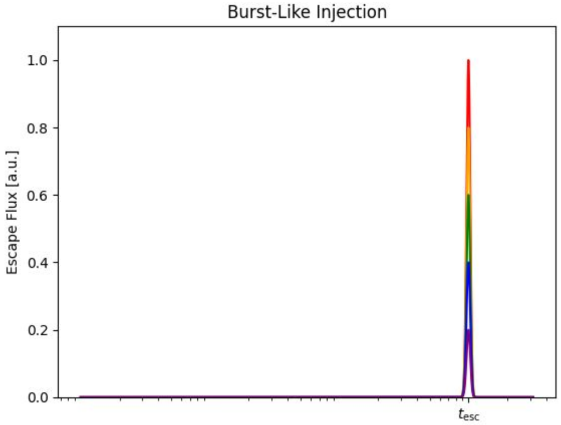
- u_s constant, $R_{\mathrm{SNR}} \propto t \Rightarrow$ good acceleration
- Non-resonant hybrid ([Bell 2004]) instability amplifies B-field, PeV energies?

Sedov-Taylor phase:

- Shock slows down: $R_{\mathrm{SNR}} \propto t^{2/5} \Rightarrow u_s \propto t^{-3/5} \Rightarrow R_{\mathrm{SNR}} u_s \propto t^{-1/5}$
- B-field amplification likely diminishes
- Particles with $E > E_{max}$ escape from SNR, injected into ISM

$\Rightarrow$ Cosmic Rays' Energy Dependent Injection Time (CREDIT)

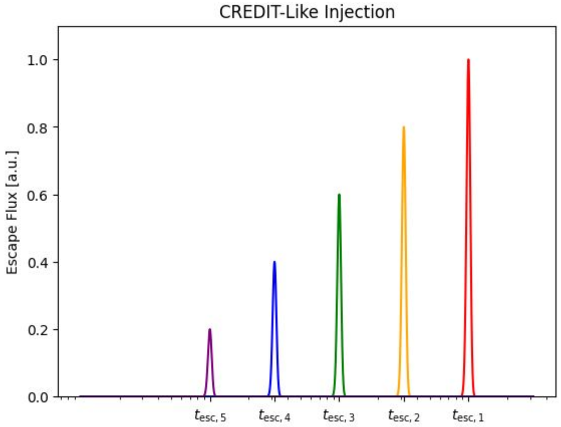
Rigidity Dependent Escape Time

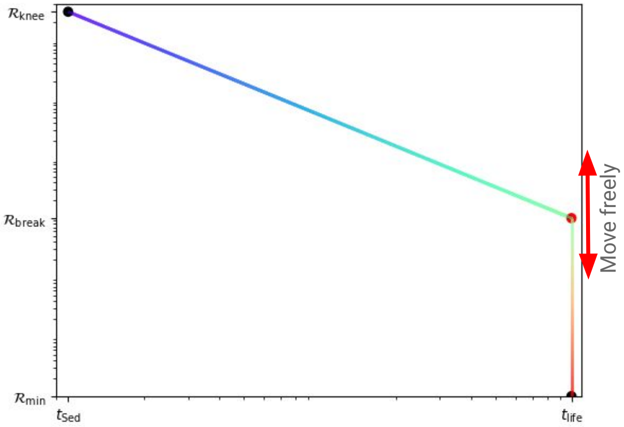


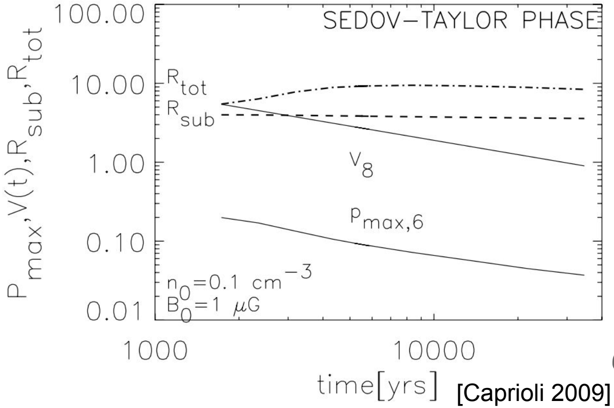
Rigidity $\mathcal{R} = \frac{p}{q} = \frac{p}{Ze}$

Broken power law in escape time

End of lifetime: all CR of lower rigidity ($<R_{break}$) escape at once







[Caprioli 2009]

Cosmic Ray Transport Equation

Simplest case $\frac{\partial \psi}{\partial t} = \nabla(D\nabla\psi) + Q$, assume *D* is isotropic

Boundary condition $\psi(z = \pm H) = 0$

Use delta functions for *Q* to get Green's function

$$G(r, t \leftarrow r_0, t_0) = \frac{\Theta(c\tau - d)}{(4\pi D\tau)^{3/2}} e^{-\frac{d^2}{4D\tau}} \sum_{n=-\infty}^{\infty} (-1)^n e^{-\frac{(2nH)^2}{4D\tau}}$$

$$\tau = \tau(R) = t - t_0(\mathcal{R})$$
$$t_0(\mathcal{R}) = t_{\rm age} - t_{\rm esc}(\mathcal{R})$$
$$d^2 = (r - r_0)^2$$

Flux from 1 point source

$$\psi = G(r, t \leftarrow r_0, t_0) Q_0(\mathcal{R})$$

Cosmic Ray Flux Measured on Earth

Q is not known precisely

Use smooth source approximation to compensate

$$\bar{\psi} = \int \mathrm{d}t_0 \int \mathrm{d}R_0 \int \mathrm{d}\theta_0 G(r, t \leftarrow r_0(R_0, \theta_0), t_0) f(R_0) Q_0(\mathcal{R})$$

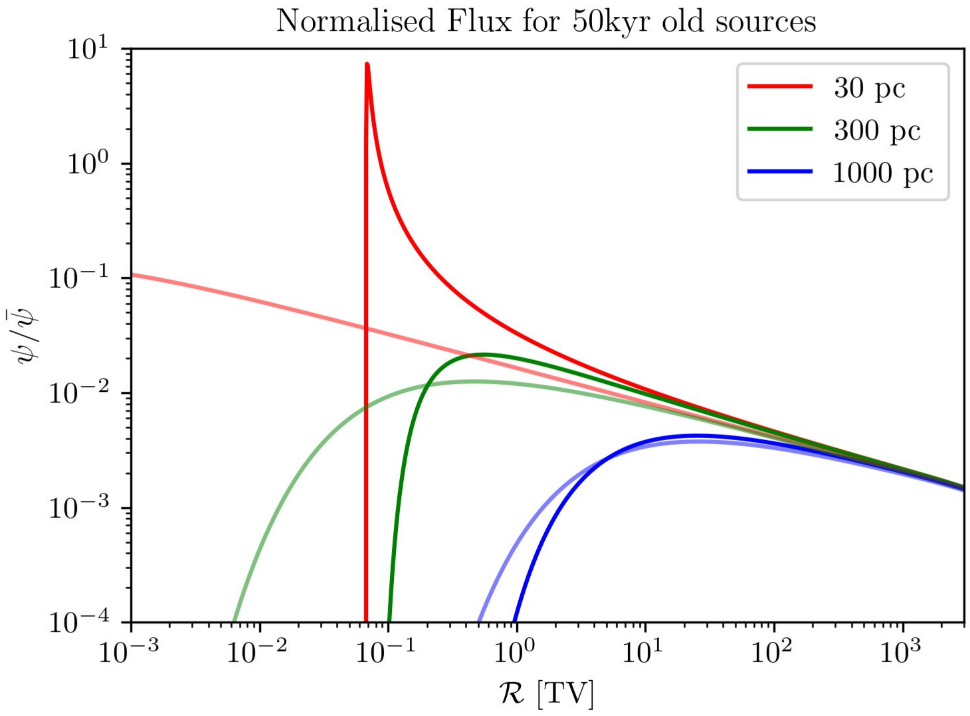
Add up fluxes from individual sources (t_0 and r_0 chosen at random)

$$\psi = \sum_i G(r, t \leftarrow r_{0,i}, t_{0,i}) Q_0(\mathcal{R})$$

Take normalised flux: dimensionless and Q_0 factors out

$$\mathbf{\Psi} = \frac{\psi}{\bar{\psi}}$$

Green's Function with and without CREDIT



$D(R) = D_0\, R^{0.6}$

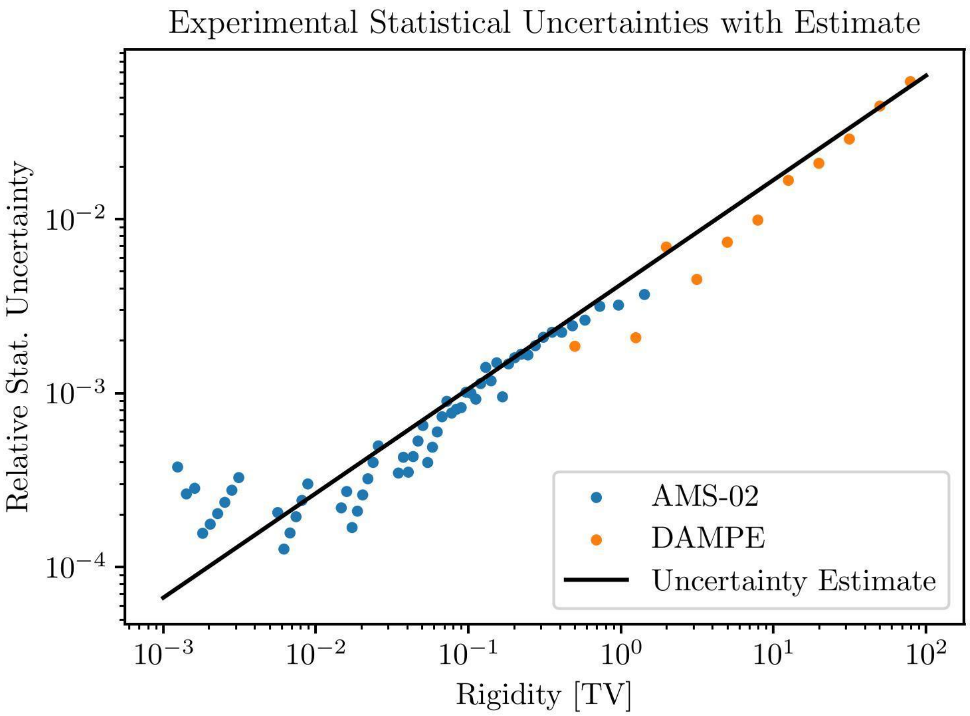
Cutoff at low rigidity

HUGE peak after cutoff

At high rigidities, CREDIT makes little to no difference

Large distances suppress peak

Experiments



Flux measured in bins, with associated statistical uncertainty

Parametrise $\sigma_{\text{stat}} = 0.42(R[\text{TV}])^{0.6}\ \%$

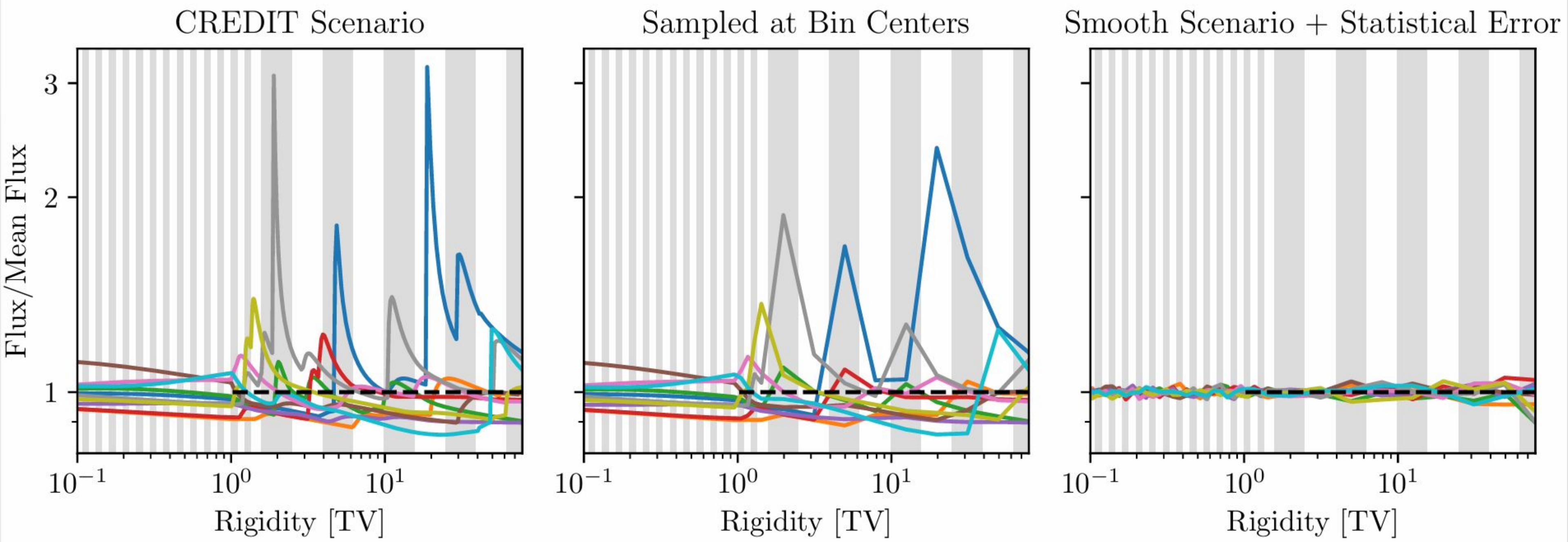
Bins go up to only ~ 100TV

Ignore systematic uncertainties since their correlation is unknown

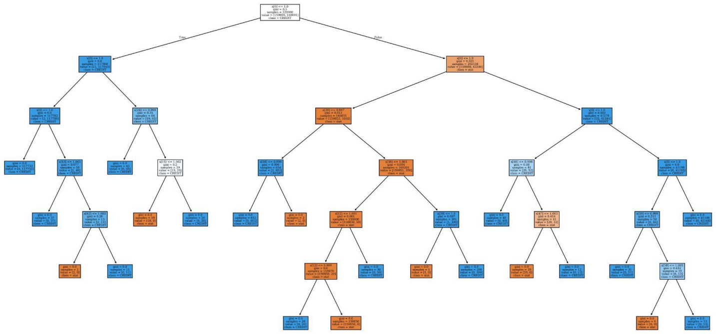
[The Alpha Magnetic Spectrometer (AMS) on the international space station: Part II — Results from the first seven years - ScienceDirect]
[Measurement of the cosmic ray proton spectrum from 40 GeV to 100 TeV with the DAMPE satellite | Science Advances]

Predicted Fluxes from Simulations

10 random realisations chosen, each sum of contributions of many random sources



Machine Learning (Decision Tree)



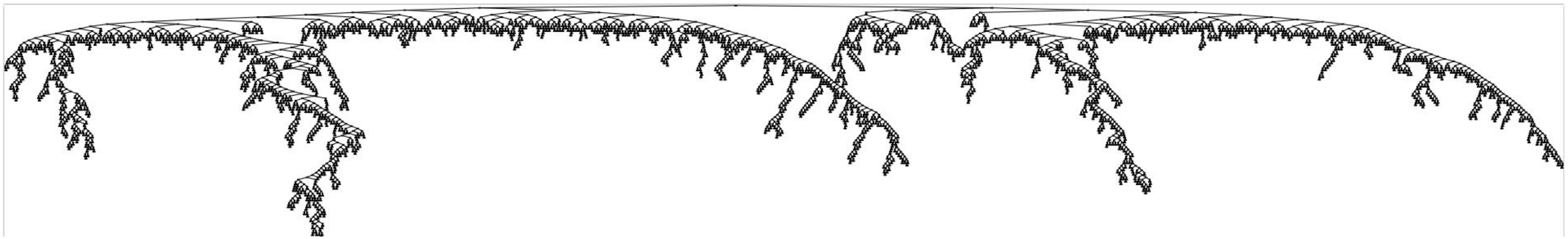
Split dataset into subsets by looking at 1 bin

If condition on value of the bin (larger or smaller)

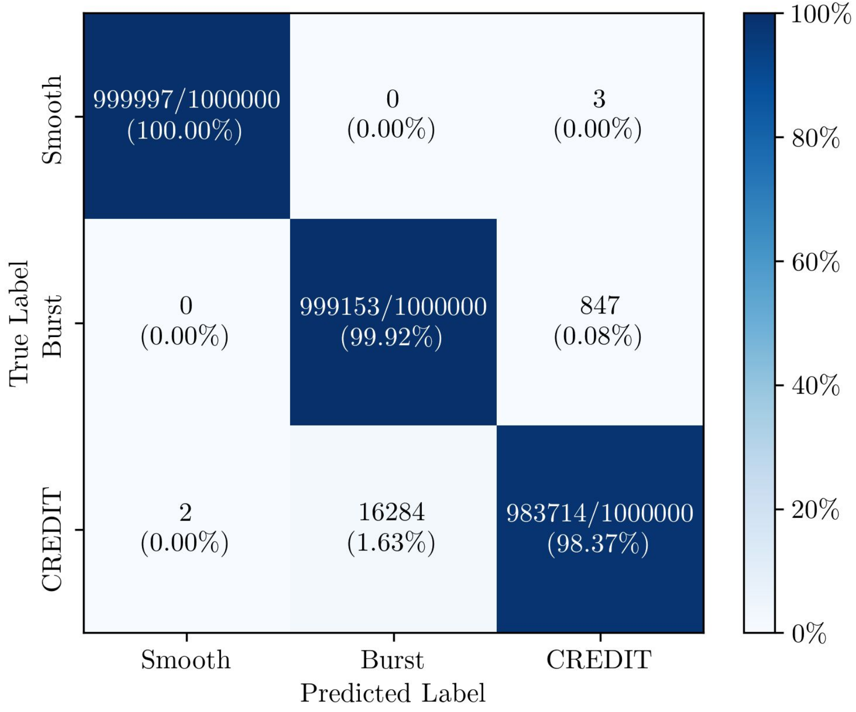
Repeat until all subsets have same label

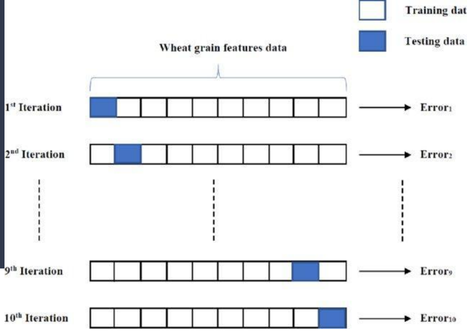
Predict label for new data following if-conditions

Take directly from **sklearn**, no optimising needed



Decision Tree Accuracy





[Agarwal 2023]

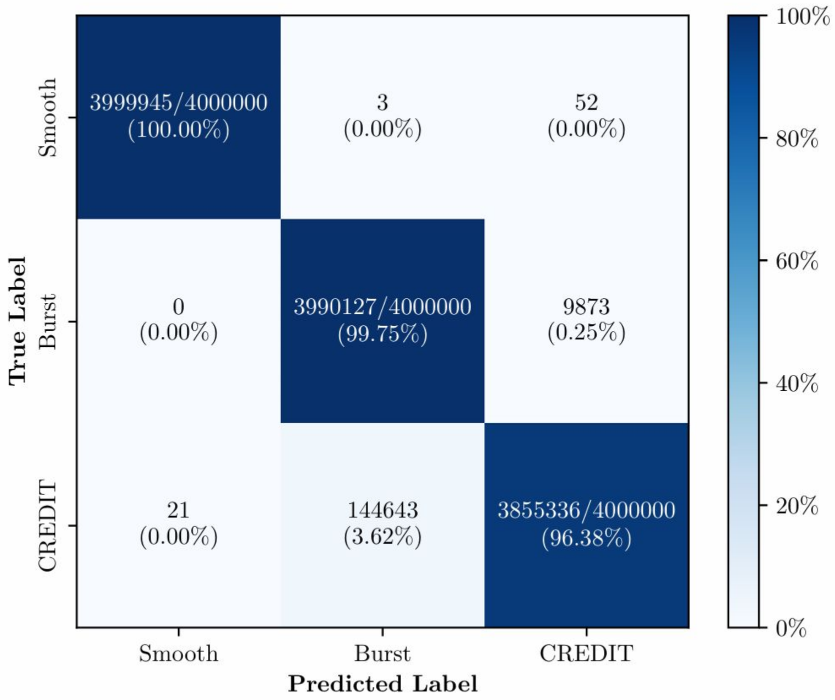
10-fold cross validation to maximise use of dataset

Add predictions from all 10 iterations to get confusion matrix

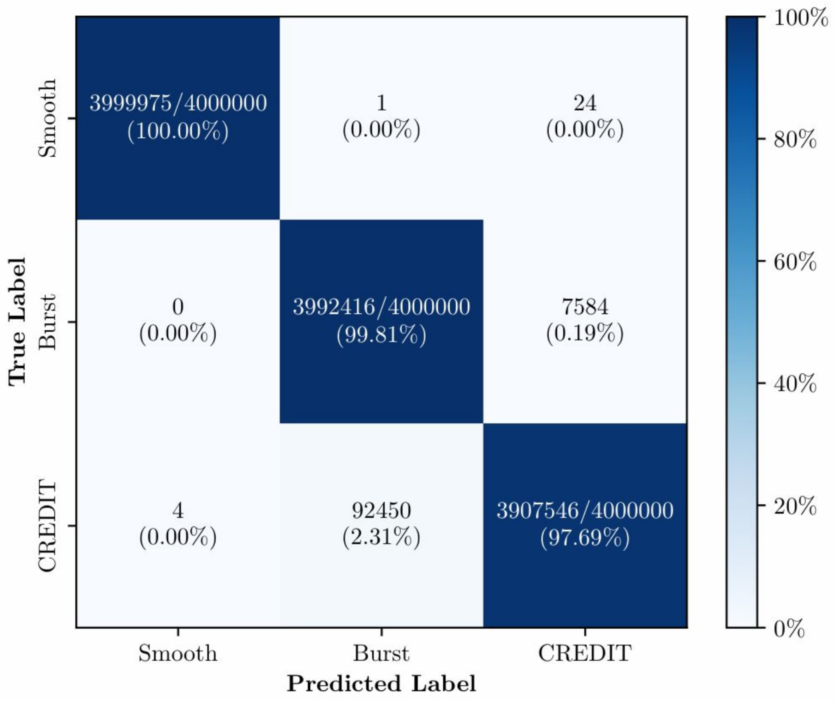
Use 10TV break rigidity as a benchmark

Very good performance

Including More Break Rigidities

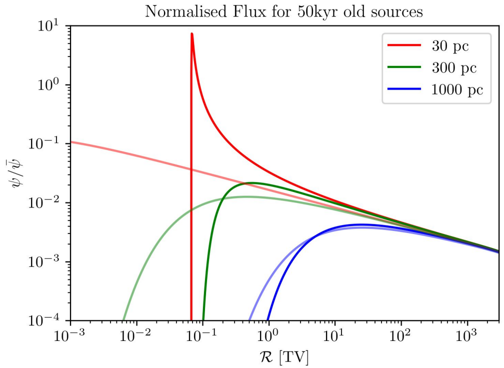


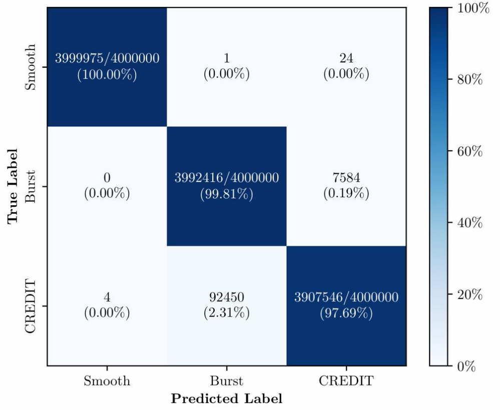
20 values of $R_{break} \in [1,25]$ TV



Individual $R_{break} \in [1,25]$ TV for each source with $P \propto R_{break}^{-1}$

Conclusion and Outlook





CREDIT follows from generic arguments for accelerated energies, especially high maximum ones (knee)

Peaks from CREDIT can be significant

Apply machine learning to improve accuracy in determining the injection scenario

Need for better understanding of correlation between bins (modelling or systematic error) to apply to data

-CREDIT: Constrain parameters

-Burst : Rethink sources for high energy GCR

-Smooth: Catastrophic error has occurred

Thank You for Your Attention