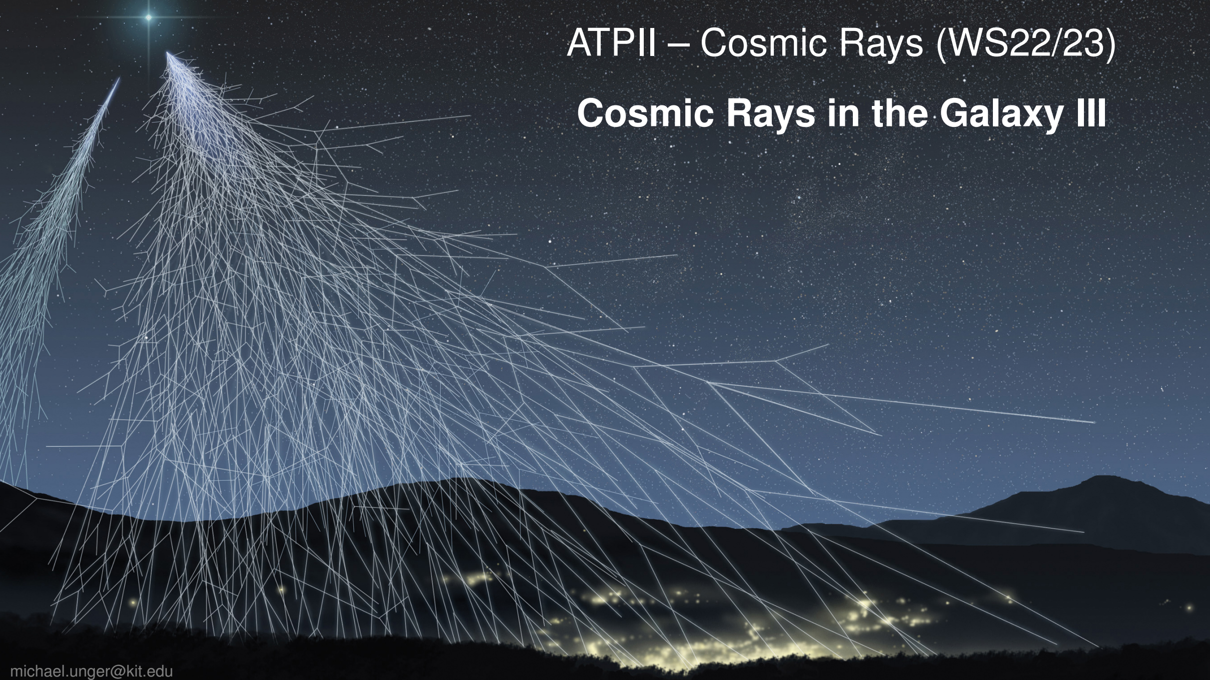

ATPII – Cosmic Rays (WS22/23)

Cosmic Rays in the Galaxy III

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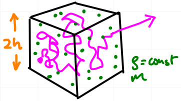
Propagation of stable nuclei

transport equation:
(see last lecture!)

$$\boxed{\frac{\partial n_i}{\partial t} = \overset{\text{source}}{Q_i} + \overset{\text{diffusion}}{\nabla(D_i \nabla n_i)} - \overset{\text{advection}}{\nabla \vec{u} n_i} - \overset{\text{energy loss/gain}}{\frac{\partial}{\partial E}(b_i n_i)} - \left(\overset{\text{decay}}{\frac{1}{\gamma \tau_i}} + \overset{\text{absorption}}{\frac{v \rho}{\lambda_i}}\right) n_i + \overset{\text{production}}{\frac{v \rho}{m} \sum_k \int \frac{d\sigma_{ki}(E,E')}{dE} n_k(E')\, dE'}}$$

Simplifications:

- $\nabla(D_i \nabla n_i) - \nabla \vec{u} n_i \rightarrow n_i / \tau_{esc,i}$ → escape probability $P_{esc} = 1 - e^{-t/\tau_{esc}}$
- $v = c$ relativistic motion
- $\frac{\partial n_i}{\partial t} = 0$ steady state
- energy loss time $\left(\frac{b}{E}\right)^{-1} \ll \tau_{esc}$
- particle production via fragmentation $\sum_k \int \frac{d\sigma_{ki}(E,E')}{dE} n_k(E')\, dE' = \sum_k \sigma_{ki} n_k(E)$ with energy per nucleon $E = E_{tot}/A$
- rigidity dependent propagation → $\tau_{esc,i} = f(R_i) = f(E_0/Z_i) \approx f(E_0/(A_i/2)) \equiv \tau_{esc}(E)$ (independent of type of nucleus i since $A/Z \approx 2$ for all $A>1$)



e.g. $^{12}C \rightarrow {}^{11}B + p$

E:	E_0	$\frac{11}{12} E_0$	$\frac{1}{12} E_0$
A:	12	11	1
E/A:	$E_0/12$	$E_0/12$	$E_0/12$

$$\boxed{\frac{n_i(E)}{\tau_{esc}(E)} = \underset{\text{source}}{Q_i(E)} - \left(\underset{\text{absorption}}{\frac{c \rho}{\lambda_i}} + \underset{\text{decay}}{\frac{1}{\gamma \tau_i}}\right) n_i(E) + \underset{\text{nuclear fragmentation}}{\frac{c \rho}{m} \sum_{k>i} \sigma_{ki} n_k(E)}}$$

"Leaky Box" Model

Propagation of stable nuclei

$$\boxed{\frac{n_i(E)}{\tau_{esc}(E)} = Q_i(E) - \left(\frac{c\rho}{\lambda_i} + \frac{1}{\gamma\tau_i}\right) n_i(E) + \frac{c\rho}{m} \sum_{k>i} \sigma_{ki}\, n_k(E)}$$

source absorption decay nuclear fragmentation

- **primary nuclei**: $Q_p \neq 0$, neglect gain from fragmentation $A_k > A_p$, stable $(\tau_p = \infty)$

$$\rightarrow \quad \frac{n_p(E)}{\tau_{esc}(E)} = Q_p(E) - \frac{c\rho}{\lambda_p} n_p(E) \quad \Rightarrow \quad \boxed{n_p(E) = \frac{Q(E)\,\tau_{esc}(E)}{1 + \lambda_{esc}(E)/\lambda_p}}$$

$\left(\lambda_{esc} = c\rho\tau_{esc},\ \lambda_p = \frac{m}{\sigma_p},\ \text{both } [\mathrm{g/cm^2}]\right)$

- **secondary nuclei**: $Q_s = 0$, assume stable

$$\rightarrow \quad \frac{n_s(E)}{\tau_{esc}(E)} = -\frac{c\rho}{\lambda_s} n_s(E) + \frac{c\rho}{m} \sum_{p>s} \sigma_{ps}\, n_p(E) \quad \Rightarrow \quad \boxed{n_s(E) = \frac{\lambda_{esc} \sum_p \sigma_{ps} n_p / m}{1 + \lambda_{esc}/\lambda_s}}$$

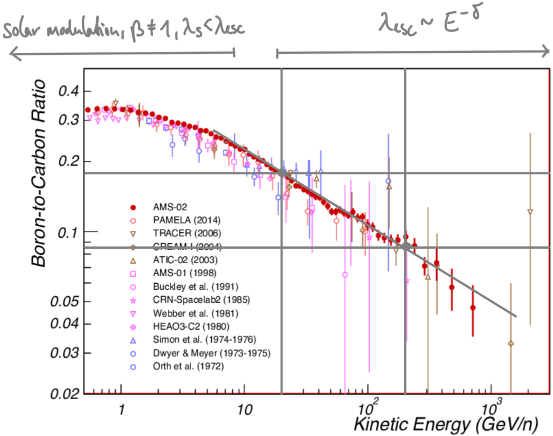
- **escape time**: $h^2 = \langle z^2 \rangle \sim D \cdot t$, $D \sim R^\delta$ (see lecture 4) $R \sim E \Rightarrow \boxed{\tau_{esc} \sim E^{-\delta}}$

↘ half-height of box

Boron to Carbon Ratio

$$\boxed{n_s(E) = \frac{\lambda_{esc} \sum_p \sigma_{ps} n_p / m}{1 + \lambda_{esc}/\lambda_s}}$$

$$\boxed{\tau_{esc} \sim E^{-\delta}}$$



AMS Collaboration, PRL 117 (2016) 231102

- main primary nuclei for boron: ^{12}C and ^{16}O
- $n_C \approx n_O$ (see page 2)
- $\Rightarrow \frac{B}{C} = \frac{n_B}{n_C} = \frac{\lambda_{esc}}{1 + \lambda_{esc}/\lambda_B} \, \frac{\sigma_{C\to B} + \sigma_{O\to B}}{m}$
- lab measurements: $\sigma_{C\to B} = 80\,\text{mb}$, $\sigma_{O\to B} \approx 30\,\text{mb}$, $\lambda_B = 7.1\,\text{g/cm}^2$

  $\Rightarrow \left(\frac{\sigma_{C\to B} + \sigma_{O\to B}}{m}\right)^{-1} \approx 15\,\text{g/cm}^2$

- AMS: $B/C(20\,\text{GeV/n}) / B/C(200\,\text{GeV/n}) \approx 2 \equiv \left(\frac{20}{200}\right)^{-\delta} \Rightarrow \delta \approx 1/3$

  $B/C \approx 0.18$ @ $20\,\text{GeV/n} \;\hat{=}\; R = 40\,\text{GV}$

$$\Rightarrow \lambda_{esc} = \frac{0.18 \cdot 15\,\text{g/cm}^2}{1 - 0.18 \cdot 15/7.1} \left(\frac{R}{40\,\text{GV}}\right)^{-1/3} \rightarrow \boxed{\lambda_{esc} \approx 7 \cdot \left(\frac{R}{10\,\text{GV}}\right)^{-1/3} \text{g/cm}^2}$$

Propagation of unstable nuclei

"cosmic clocks"

$$\boxed{\frac{n_i(E)}{\tau_{esc}(E)} = \underset{\text{source}}{Q_i(E)} - \Big(\underset{\text{absorption}}{\frac{c\varrho}{\lambda_i}} + \underset{\text{decay}}{\frac{1}{\gamma\tau_i}}\Big) n_i(E) + \underset{\text{nuclear fragmentation}}{\frac{c\varrho}{m}\sum_{k>i}\sigma_{ki}\, n_k(E)}}$$

- stable and unstable secondary isotopes

  e.g. ^{10}Be: $\tau = 1.5 \cdot 10^6$ yr, ^{9}Be: stable

- secondary nuclei: $Q_i(E) = 0$ $\Rightarrow$

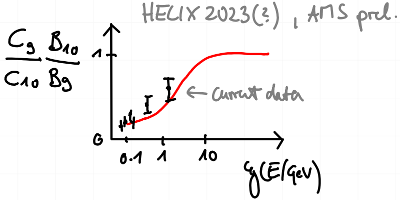
$$n_i(E) = \overbrace{\Big(\frac{c\varrho}{m}\sum_{k>i}\sigma_{ki}\, n_k(E)\Big)}^{C_i} \cdot \Big(\frac{1}{\tau_{esc}} + \overbrace{\frac{c\varrho}{\lambda_i}}^{\equiv \frac{1}{\tau_{int}}} + \frac{1}{\gamma\tau_i}\Big)^{-1}$$

- ratio of unstable (u) to stable (s) isotope: $\frac{n_u}{n_s} = \frac{\tau_{esc}^{-1} + \tau_{int,s}^{-1}}{\tau_{esc}^{-1} + \tau_{int,u}^{-1} + (\gamma\tau_u)^{-1}} \frac{C_u}{C_s}$

$E \to \infty$, $(\gamma\tau_u)^{-1} \to 0$, $\tau_{esc} \ll \tau_{int}$

$\Rightarrow \frac{n_u}{n_s} \to \frac{C_u}{C_s}$

$\Rightarrow \tau_{esc} \approx 2 \cdot 10^7$ yr $(E \sim 1\,\text{GeV/nucl})$

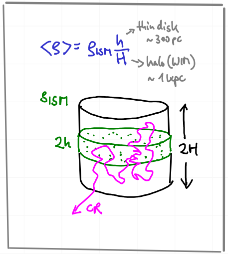


Summary

propagation of nuclei in the galaxy:

- $\lambda_{esc}(R) \sim R^{-\delta}$ B/C ⇒ $\delta \simeq 1/3 \dots 1/2$ [Kolmogorov, Kraichnan] turbulence
- primary nuclei: $n_p \sim Q \cdot \lambda_{esc} \sim R^{-\alpha} \cdot R^{-\delta} = R^{-\alpha-\delta} \underset{\text{obs.}}{\approx} R^{-\gamma}$ $\gamma = 2.6 \dots 2.7$

⇒ <u>injection spectrum</u> $R^{-\alpha}$ $\boxed{Q_{CR}(E) \sim E^{-(2.1\dots2.4)}}$



$\langle \rho \rangle = \rho_{ISM} \frac{h}{H}$

- secondary nuclei: $n_s \sim n_p \cdot \lambda_{esc} \sim \underline{R^{-\alpha-2\delta}}$

stable secondaries ⇒ $\lambda_{esc}(R)$ e.g. B/C

unstable secondaries ⇒ $\tau_{esc}(R)$ e.g. ^{10}Be/^{9}Be

⇒ at R≈GV

$\tau_{esc} \approx 10^7\,\text{yr} \gg \frac{R_{galaxy}}{c}$ ⇒ $\boxed{\text{diffusive motion in Galaxy}}$

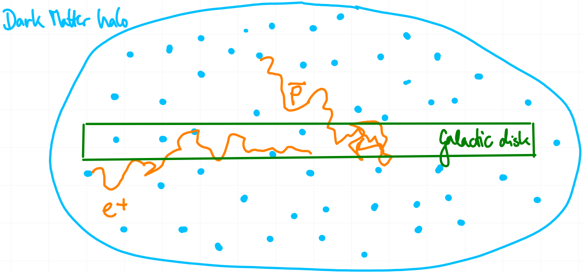
$Q_{CR} = u_{CR} \frac{V}{\tau_{esc}} = 10^{41}\,\text{erg/s}$ $\hat{=}$ $\boxed{0.1\, Q_{SN}}$ (see lecture 1)

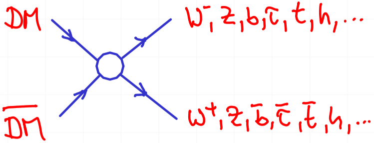
$\langle \rho \rangle = \frac{\lambda_{esc}}{\tau_{esc}} \approx 0.3 \frac{m_p}{\text{cm}^3}$ $< \rho_{ISM} = \frac{1 m_p}{\text{cm}^3}$ ⇒ $\boxed{\text{diffusion in halo}}$

Astrophysical Dark Matter Signals?

- Sources Q_i $\boxed{\text{WIMP}^* \text{ annihilations?}}$

* weakly interacting massive particles

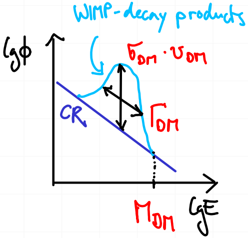




$\xRightarrow{\text{decay}}$ $\pi^0, \pi^\pm, p, e^-, \boxed{e^+, \bar{p}}$

$\gamma\gamma$ $\quad$ $\mu\nu_\mu \to e\nu_e\nu_\mu$

anti-matter from DM annihilation ↔ excess above standard CR background?



Astrophysical Anti-Protons

- secondary production (no anti-stars!?!)

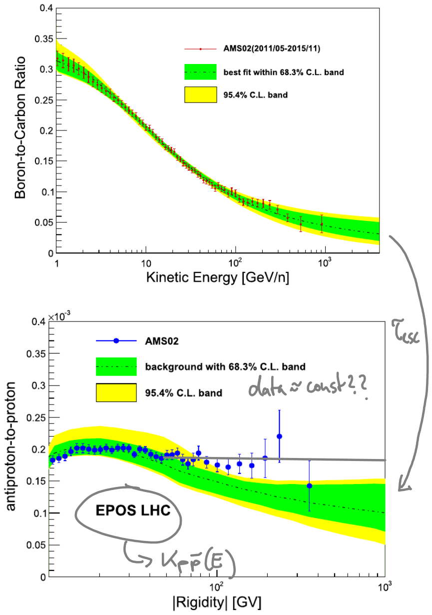
e.g. $\boxed{p_{CR} + p_{ISM} \to p + p + p + \bar{p} + X}$

- spectrum from leaky box

$$\frac{cS}{m}\int_{E_-}^{\infty}\frac{d\sigma_{p\bar{p}}}{dE_p}\, n_p\, dE_p \approx K_{p\bar{p}}(E)\cdot n_p$$

$\Rightarrow$ anti-proton to proton ratio

$$\frac{n_{\bar{p}}}{n_p} = \tau_{esc}(E)\, K_{p\bar{p}}(E) \qquad (\lambda_{esc} < \lambda_{\bar{p}})$$



τ_{esc}

data ≈ const??

$\to K_{p\bar{p}}(E)$

Feng&Zhang ApJ 2018

Electrons and Positrons

- primary:

  → SNR: e^- acceleration in shock

  → Pulsar: e^+ and e^- from pair production

  (curvature radiation $\gamma_{syn} + \gamma_B \rightarrow e^+e^-$)

- secondary:

e.g.

$$\begin{tikzcd} & & e^+e^-\gamma\ (1\%) & \\ P_{CR}+P_{ISM} \arrow[r] & \pi^{\pm} \arrow[d] & +\pi^0 \arrow[u] & +X \\ & \mu^{+/-}+\nu \arrow[d] & & \\ & e^{+/-}+2\nu & & \end{tikzcd}$$

- energy losses important! ionization, bremsstrahlung, synchrotron, inverse Compton

→ $$Q(E) \underset{\lambda_{esc} \gg \lambda_{loss}}{=} \frac{\partial}{\partial E}\left(b(E)\,n\right)$$

$$Q(E) = \kappa E^{-p},\quad b(E) = -\frac{dE}{dt} = \overbrace{b_0 \cdot E^2}^{\text{syn}+\text{IC}}$$ (high energy)

energy loss time $\left(\frac{1}{E}\frac{dE}{dt}\right)^{-1} \sim \frac{1}{E}$

→ $\underline{n(E) \sim E^{-(p+1)}}$

- positron fraction $f_{e^+} = \frac{n_+}{n_+ + n_-}$

  - primary e^- SNR:

    $Q_-^{SNR} \sim E^{-p}$, $n_-^{SNR} \sim E^{-(p+1)}$

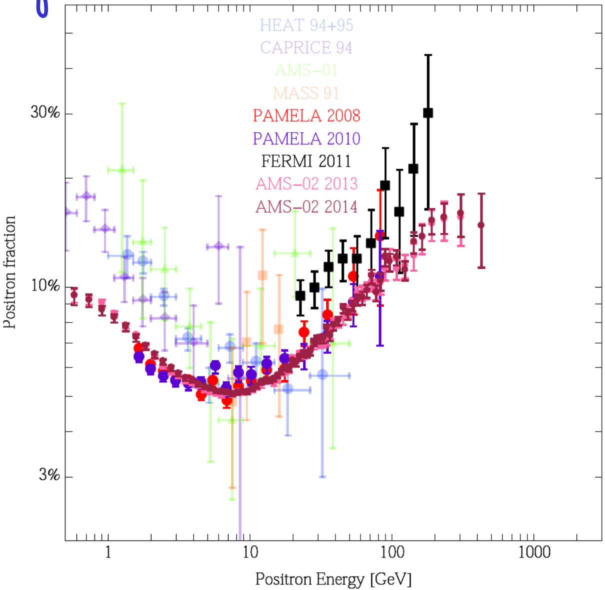
  - secondary $e^{+/-}$:

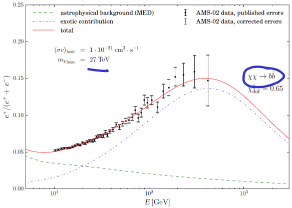
    $Q_\pm^{sec} \sim n_p \sim E^{-(p+\delta)}$

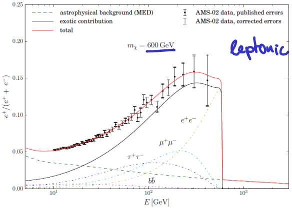
    $n_\pm^{sec} \sim E^{-(p+\delta+1)}$

$$\Rightarrow \boxed{f_{e^+}^{SNR} \approx \frac{n_+^{sec}}{n_-^{SNR}} \sim E^{-\delta}}$$

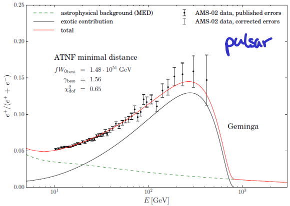
Positron fraction







leptonic



pulsar

M. Boudaud et al., Astron.Astrophys. **575** (2015) A67

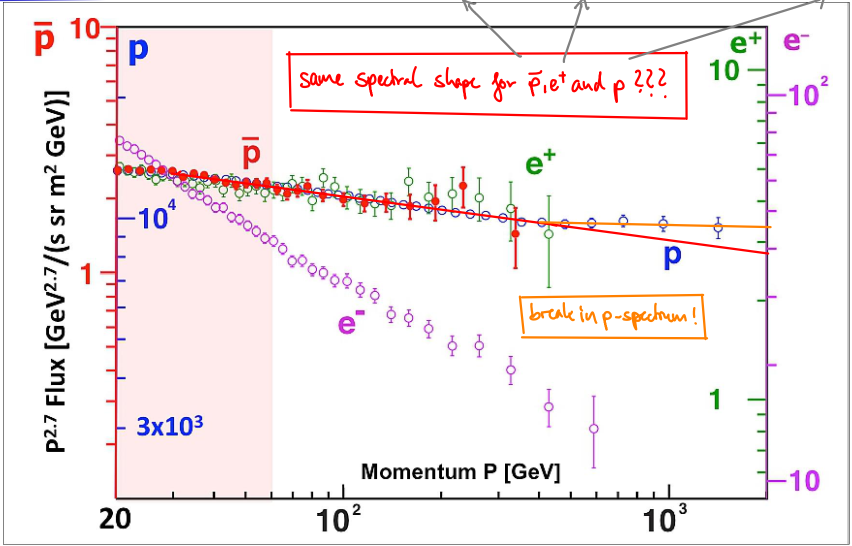
leptonic: $\langle\sigma v\rangle = 10^{-23}\ {\rm cm^3/s} \Leftrightarrow \sigma \sim 10^{-5}\,\sigma_{pp} \Rightarrow$ huge!! ($v \approx 100$ km/s)

Coincidences and Oddities

$\bar{p}$: secondary, $K_{p\bar{p}}(E)$

e^+ secondary + primary or exotic

p: primary



same spectral shape for $\bar{p}, e^+$ and p ???

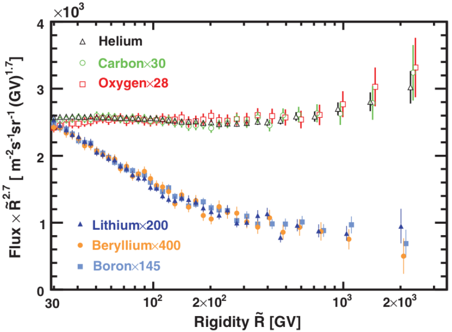
break in p-spectrum!

Summary of AMS measurements

Origin of spectral break?

- break in source spectrum: break in secondaries similar

- break in diffusion coefficient: break in secondaries $\sim 2\times$ as strong



top: P. Mertsch 2018, bottom: AMS PRL 2018