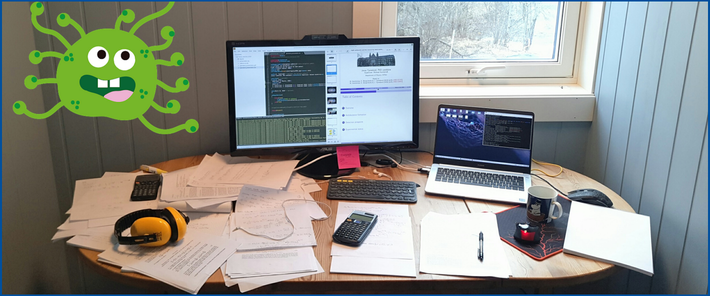
REACCELERATION OF CHARGED DARK MATTER

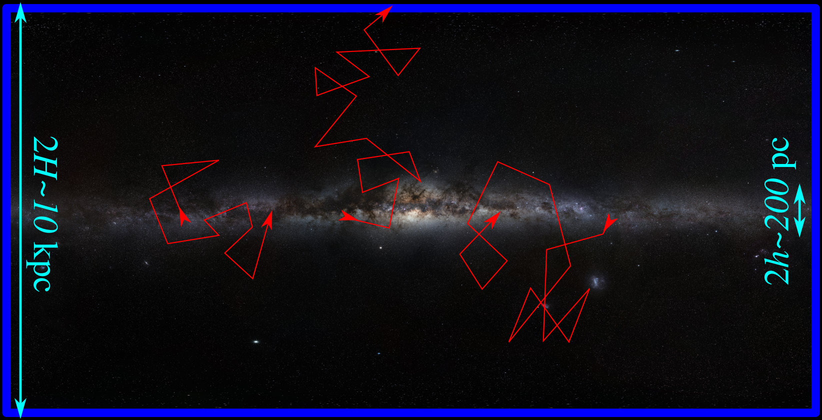
Based on M. Kachelrieß and J. Tjemsland [2006.10479]



Jonas Tjemsland, PhD candidate

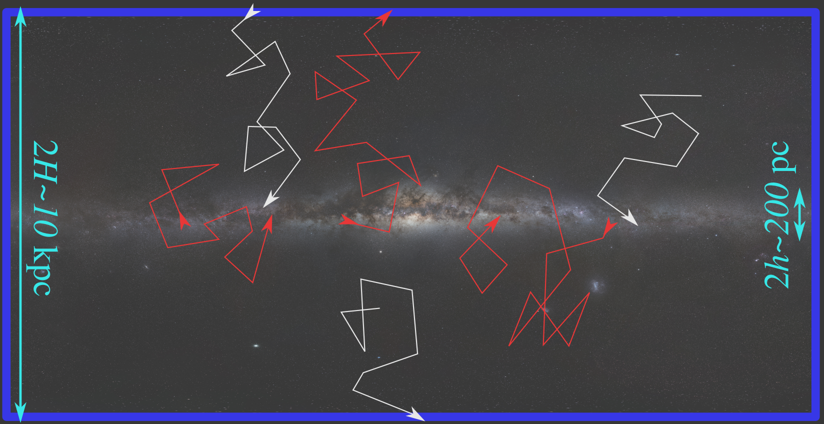
Department of Physics
Norwegian University of Science and Technology

NPACT, 4.–6. August 2020


2H~10 kpc
2h~200 pc

Mass m, charge qe

Charged Dark Matter



Propagation of cosmic rays

$$\frac{\partial f}{\partial t} = \underbrace{Q}_{\text{Source}} + \underbrace{\nabla(D(p)\nabla f)}_{\text{Diffusion}} + \dots$$

with

$$D(p) \sim 3 \times 10^{28} v \left(\frac{p}{m}\right)^{\delta} \ \mathrm{cm^2/s}$$

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Diffusion occurs due to resonant interactions ($k_{res} \sim 1/R_L$) with turbulent magnetic field modes

$$D(p) \approx \frac{1}{3} l_0 v = \frac{1}{3} v \frac{R_L}{2kW_k(k)}$$

W_k: spectral density of turbulent field modes

Reacceleration

$$\frac{\partial f}{\partial t} = \underbrace{Q}_{\text{Source}} + \underbrace{\nabla(D(p)\nabla f)}_{\text{Diffusion}} + \underbrace{\frac{1}{4\pi p^2}\frac{\partial}{\partial p}\left(4\pi p^2 D_{pp}(p)\frac{\partial f}{\partial p}\right)}_{\text{Diffusion in momentum space}} + \ldots$$

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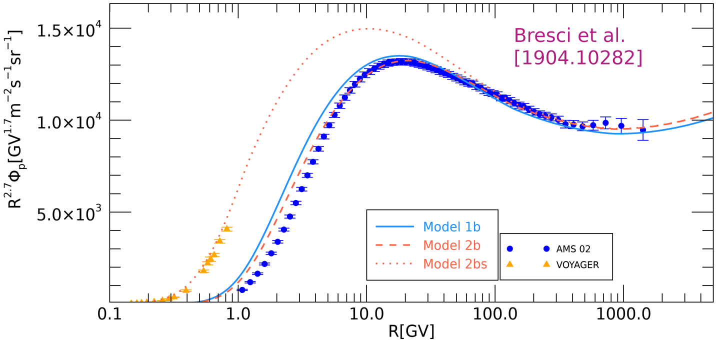
- Improves cosmic ray fits



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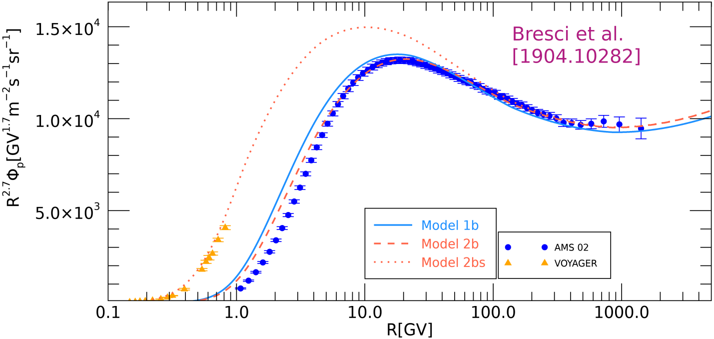
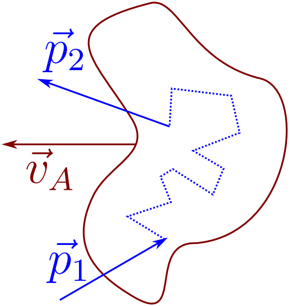
- Improves cosmic ray fits
- Unavoidable consequence of second order Fermi acceleration



Simplified picture: scattering on magnetic clouds

- Mean free path length $l_0 = \tau v \sim 2\,\mathrm{pc}$

$$D(p) \approx \frac{1}{3} l_0 v = \frac{1}{3} \frac{\lambda^2}{\tau} = \frac{1}{3} v^2 \tau$$



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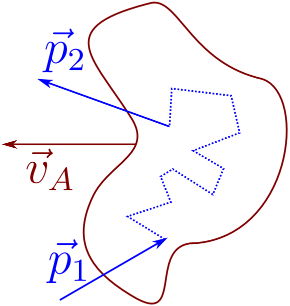

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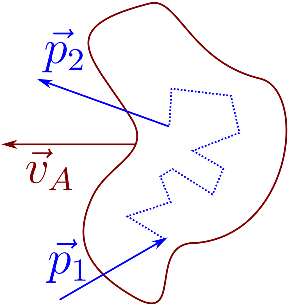

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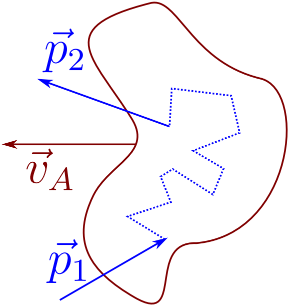
- A net energy gain $\Delta E \propto (v_A/v)^2$



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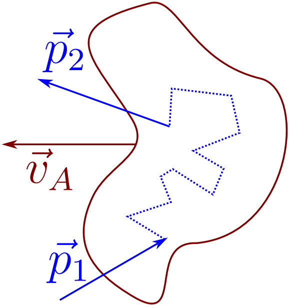

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- A net energy gain $\Delta E \propto (v_A/v)^2$

Elaborate calculations give essentially the same results (Skilling 1975; Melrose 1968)

Power absorbed by reacceleration

$$P_R \sim \int_0^\infty \mathrm{d}p \quad 4\pi p^2 f(p) \; \frac{v_A^2 p v}{9D(p)}$$

Relativistic protons (Thornbury and Drury [1404.2104])

$$P_R^{\mathrm{protons}} \approx \frac{0.1\ \mathrm{eV/cm^3}}{10^7\ \mathrm{yr}} \qquad E_{\mathrm{tot}}^{\mathrm{protons}} \approx 1.0\ \mathrm{eV/cm^3}$$

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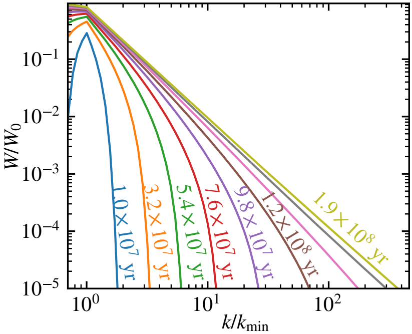
Charged dark matter with Maxwellian phase space density

$$f(v) = \frac{0.3(\mathrm{GeV}/m)/\mathrm{cm^3}}{(\pi p_{\mathrm{vir}}^2)^{-3/2}} \exp\left\{-\frac{p^2}{p_{\mathrm{vir}}^2}\right\}; \quad p_{\mathrm{vir}} \sim m \times 300\ \mathrm{km/s}$$

$$\frac{P_R^{\mathrm{DM}}}{P_R^{\mathrm{protons}}} \approx 10^6 q^{1/3} \left(\frac{m}{10^6\ \mathrm{GeV}}\right)^{2/3}$$

Turbulence

1. Injected at $L_{\max} \sim 100$ pc



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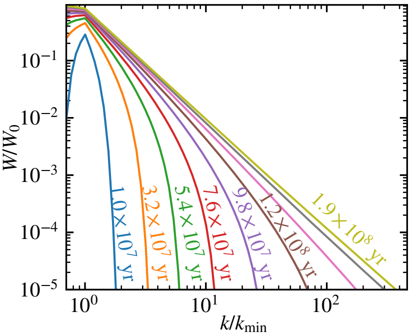
2. Energy cascade to smaller scales

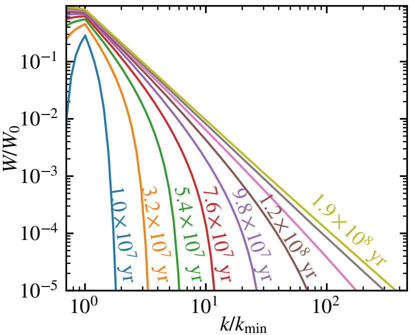


Turbulence

1. Injected at $L_{\mathrm{max}} \sim 100\ \mathrm{pc}$

2. Energy cascade to smaller scales

3. Dissipate at $R_L^{\mathrm{p}} \sim L_{\mathrm{min}} \sim 10^8\ \mathrm{cm}$



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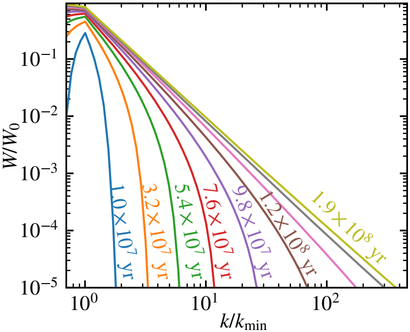
4. Kolmogorov spectrum $W_k(t) \propto k^{-5/3}$



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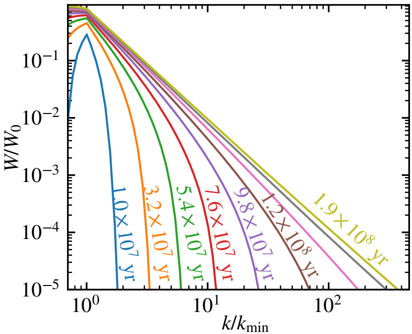

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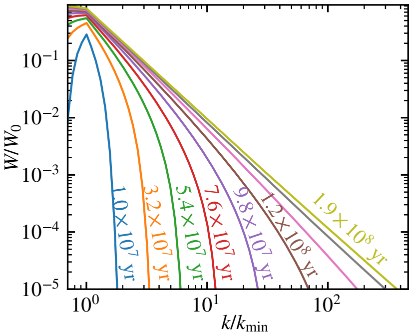
   - $q_W \propto \delta(k - 2\pi/L_{\max})$



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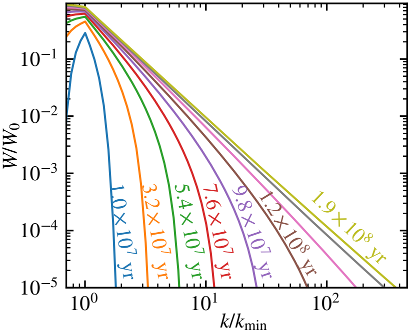

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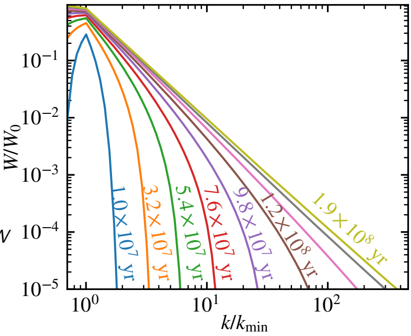

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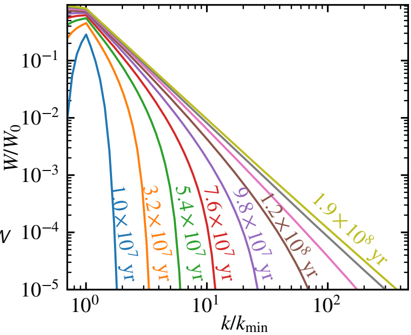

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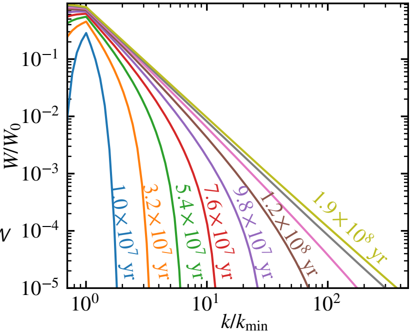
   - $D_{kk} \propto v_A k^{7/2} W_k(t)^{1/2}$



Back-reaction

Particle diffusion

$$\frac{\partial f}{\partial t} = Q + \nabla(D(p)\nabla f) + \frac{1}{4\pi p^2}\frac{\partial}{\partial p}\left(4\pi p^2 D_{pp}(p)\frac{\partial f}{\partial p}\right) + \ldots$$

$$D(p) = \frac{1}{3}v\frac{R_L}{2kW_k(t)}; \qquad D(p)D_{pp}(p) \approx \frac{1}{9}p^2 v_A^2$$

Energy cascade of wave spectrum

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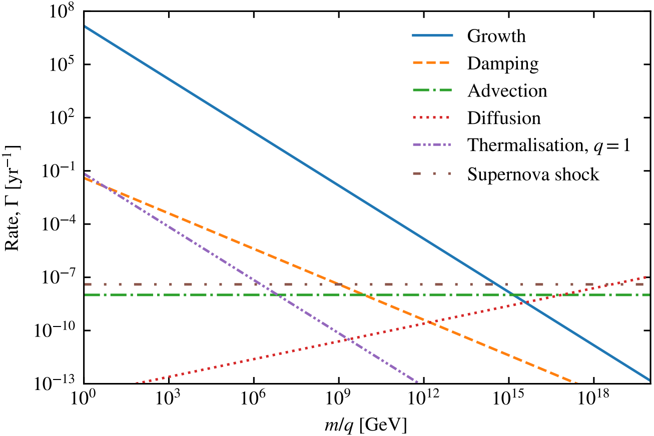
$$\frac{\partial W_k(t)}{\partial k} = \frac{\partial}{\partial k}\left(D_{kk}\frac{\partial W_k(t)}{\partial k}\right) + q_W - \Gamma_{\mathrm{growth}}(k,t)W_k(t)$$

$$D_{kk}(k) = C_{\mathrm{K}} v_A k^{7/2} W_k(t)^{1/2}$$

$$\Gamma_{\mathrm{growth}} = \frac{16\pi^2}{3}\frac{p^4 v_A}{kW_k(t)B_0^2}\left(v\hat{n}\cdot\nabla f - \frac{\pi}{2}m\Omega v_A k W_k(t)\frac{\partial f}{\partial p}\right)$$

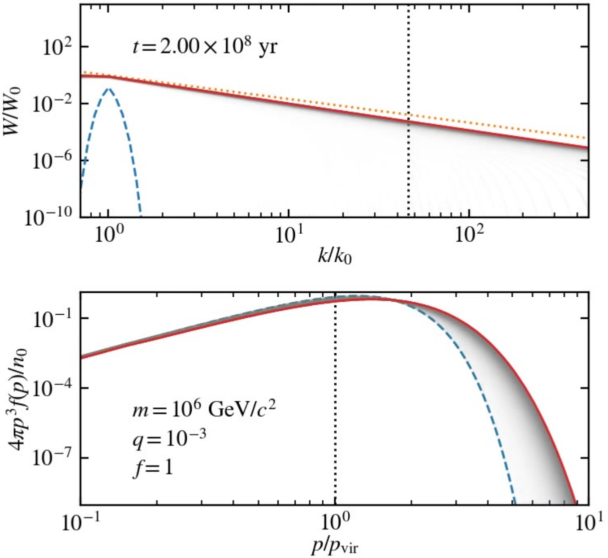
Key rates in charged dark matter propagation



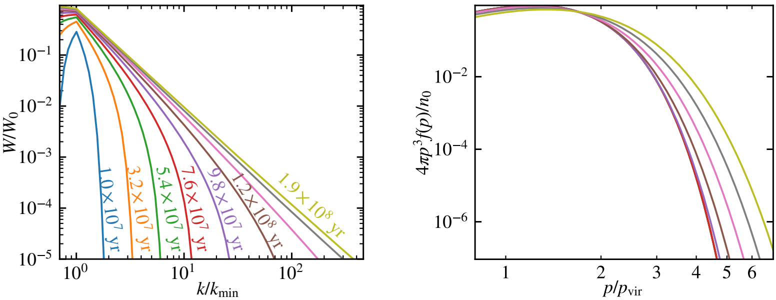
(See Dunsky et al. [1812.11116] for more)

- The growth rate is dominant within the resonance condition $m/q \lesssim 10^{11}$ GeV

Animation: Without back-reaction



Animations never work: Without back-reaction



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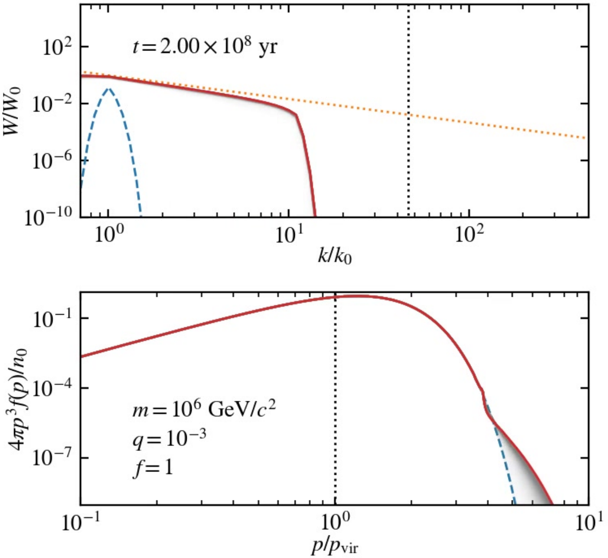

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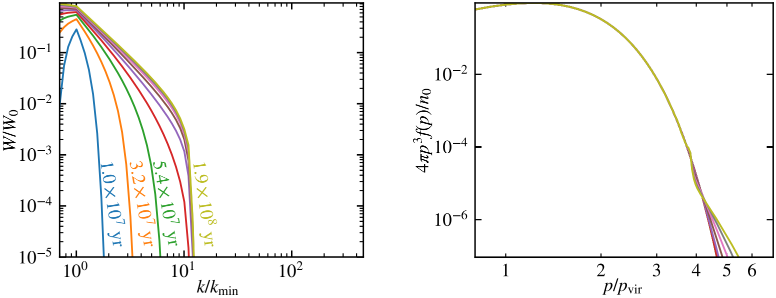
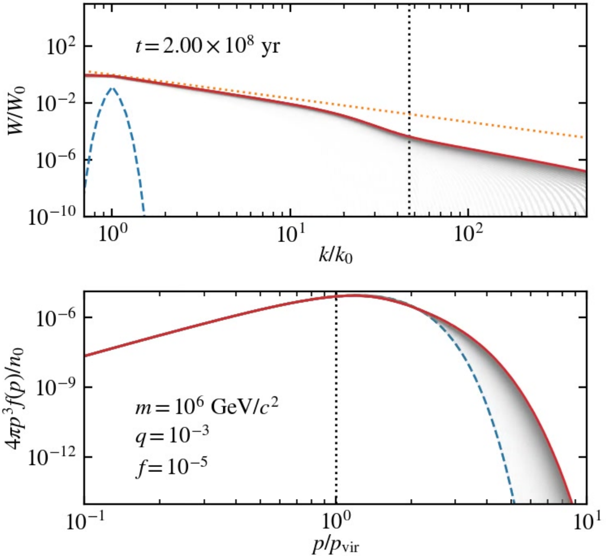


Animation: $\Omega_{\rm cDM}/\Omega_{\rm DM} \sim 10^{-5}$



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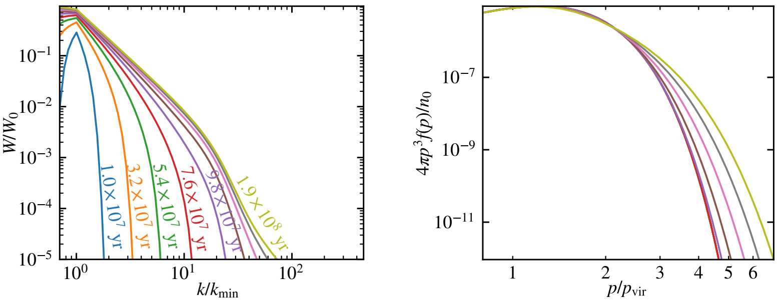

Observable consequences

- No cascade below $k_{\mathrm{vir}} \sim qeB_0/p_{\mathrm{vir}}$
- No diffusion above k_{vir}

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$$\Downarrow$$

Sudden change in spectrum and in anisotropies

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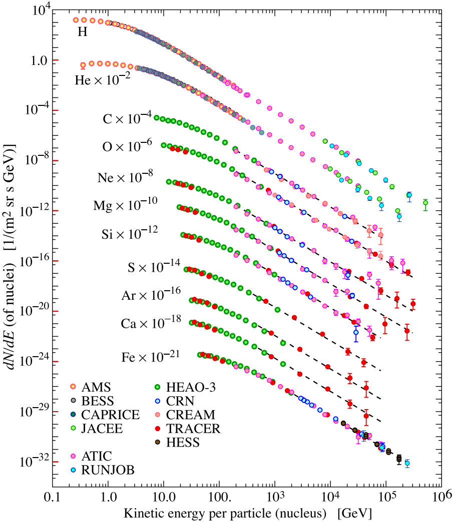

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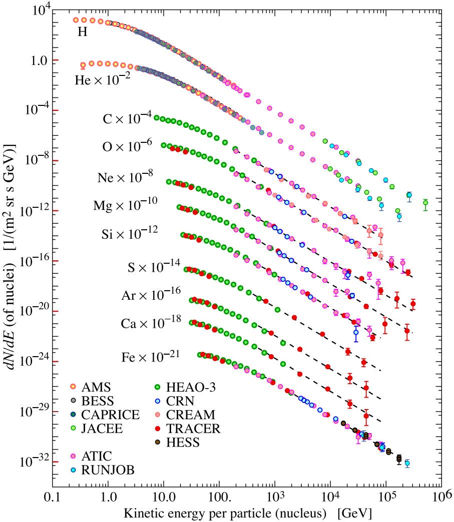
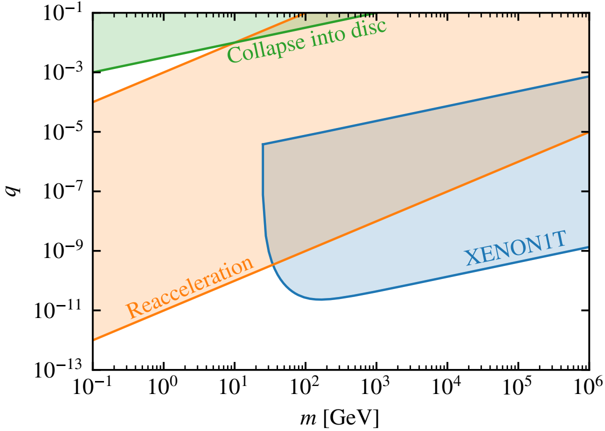
Sudden change in spectrum and in anisotropies

Excluded region

$10^3\ \mathrm{GeV} \lesssim m/q \lesssim 10^{11}\ \mathrm{GeV}$
$f_{\rm cDM}^{-1} m/q \lesssim 10^{12}\ \mathrm{GeV}$



Results



(See e.g. Dunsky et al. [1812.11116] for additional constraints)

$$f_{\mathrm{cDM}}^{-1} m/q \lesssim 10^{12}\ \mathrm{GeV}$$

Summary

- Cosmic rays diffuse on magnetic field irregularities
- Cosmic rays absorb a power $P_R \propto v_A^2$ from the turbulent field modes at $k_{\rm res} \sim 1/R_L$
- If for dark matter $f_{\rm cDM}^{-1} m/q \lesssim 10^{12}$ GeV and $m/q \lesssim 10^{11}$ GeV all wave power will be absorbed at $k_{\rm res} \sim 1/R_L$
- This is not observed

$$\Downarrow$$

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$$10^3 \ {\rm GeV} \lesssim m/q \lesssim 10^{11} \ {\rm GeV}$$

$$f_{\rm cDM}^{-1} m/q \lesssim 10^{12} \ {\rm GeV}$$