CHAMP Cosmic Rays

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Motivation

- Theories Beyond the Standard Model may contain exotic stable CHArged Massive Particles, or CHAMPs, of mass m, electric charge qe and abundance $f_X \equiv \Omega_X/\Omega_{\rm DM}$
- May arise from:
  - Exotic color-neutral matter added to SM
  - Exotic heavy colored states that hadronize with SM quarks
  - Hidden $U(1)$. Dark photon kinetically mixed with our photon

Outline

- Collapse of CHAMPs into the Galactic Disk
- Three Key Rates In the Galactic Disk
- Acceleration and Ejection from the Galaxy
- Diffusion into the Disk and the Local CHAMP Flux
- Direct Detection of Accelerated CHAMP Cosmic Rays

Collapse into Disk

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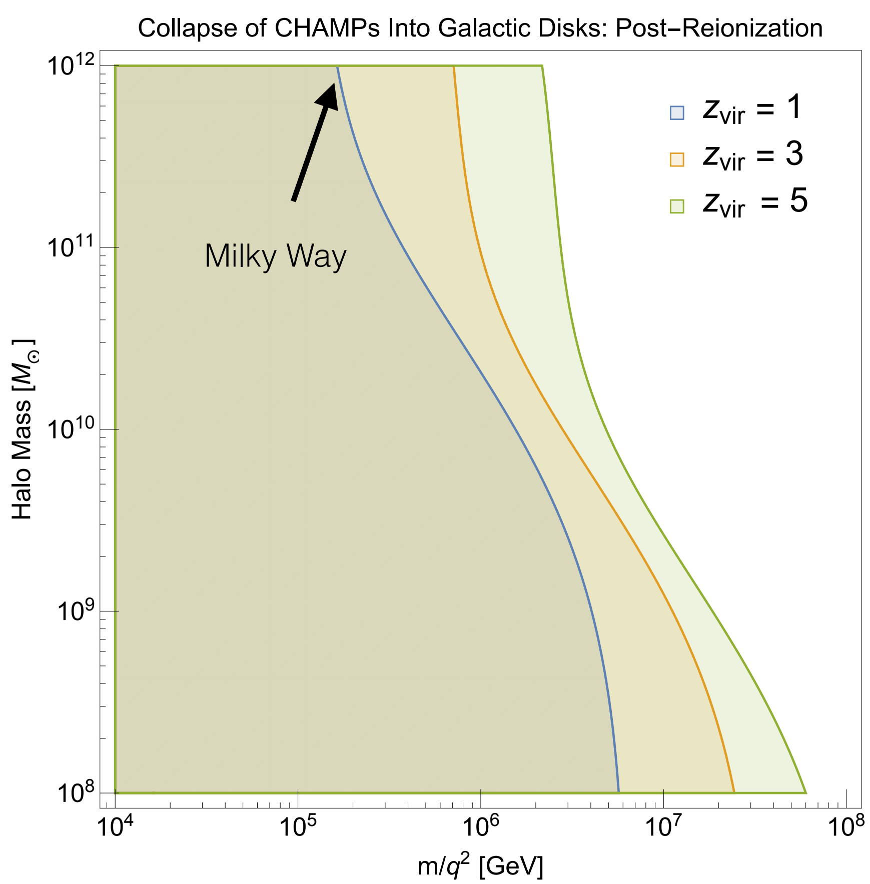

- Collapsing CHAMPs ruled out if $f_X = \frac{\Omega_X}{\Omega_{\rm DM}} = 1$
- If $f_X < 1$, number density of CHAMPs in MW disk about 100x greater if collapse, $m/q^2 \lesssim 10^5$ GeV

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Rate 1: Thermalization in ISM

ISM Phase	n_{tot} (cm^{-3})	n_e (cm^{-3})	T (K)	Fractional Volume f
Hot Ionized	3×10^{-3}	3×10^{-3}	5×10^5	0.5
Warm Ionized	0.3	0.2	8×10^3	0.15
Warm Neutral	0.5	0.05	8×10^3	0.3
Cold Neutral	50	< 0.1	80	0.04
Molecular	> 300	< 0.1	10	0.01

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- Thermalization dominated by Warm Ionized Medium

$$\Gamma_{therm} = \sum_{\text{phase } i} \frac{f_i}{t_{therm,i}} \approx \frac{f_{WIM}}{t_{therm,WIM}}$$

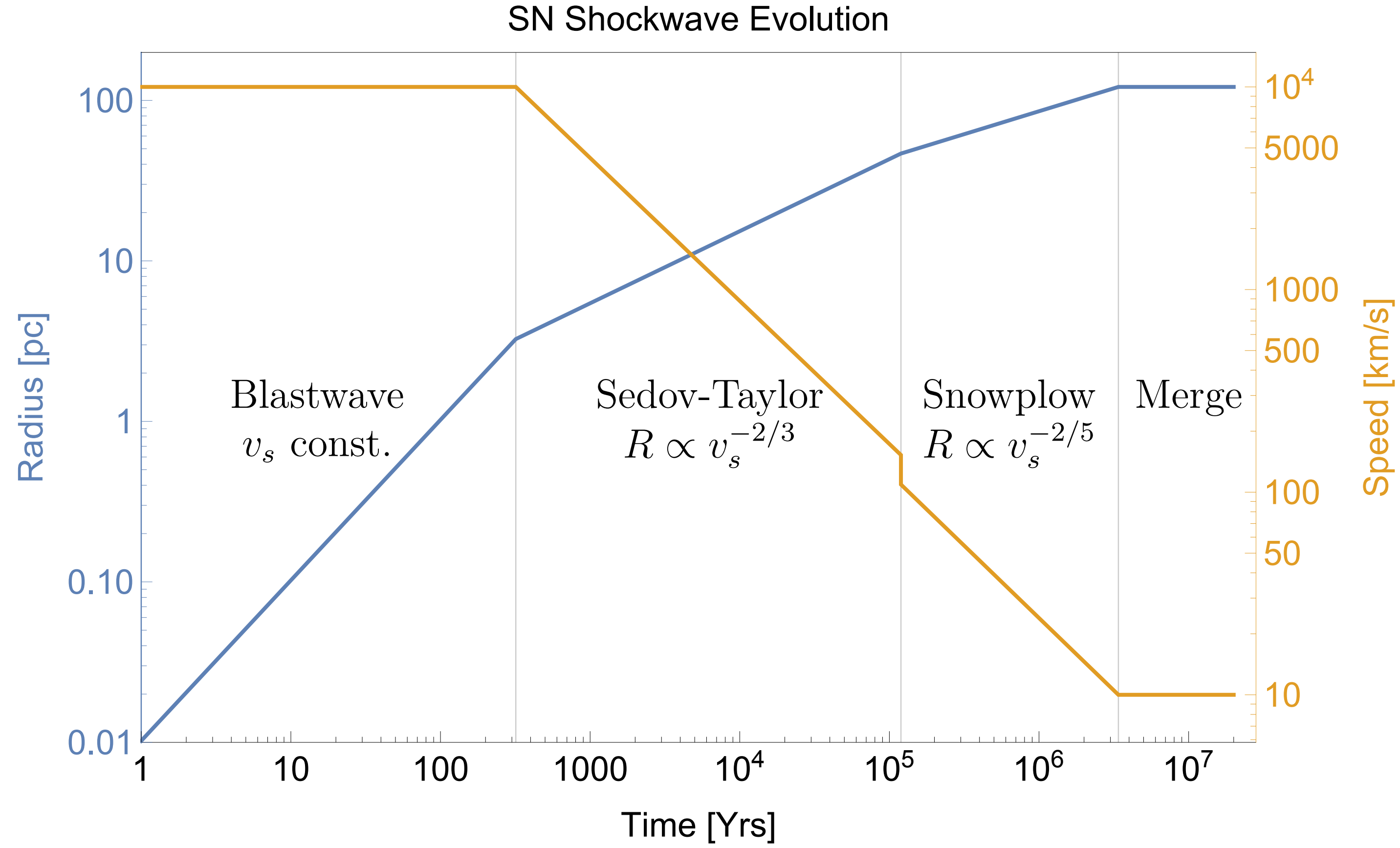
$$\approx (4 \times 10^7 \text{ yr})^{-1} \left(\frac{m/q^2}{10^6 \text{ GeV}}\right)^{-1} \left(\frac{v}{10^3 \text{ km/s}}\right)^{-3} \left(\frac{n_e}{0.2 \text{ cm}^3}\right) \left(\frac{f_{WIM}}{0.15}\right)$$

Rate 2: Shock Encounter

- Rate at which CHAMPs are accelerated is tied to the rate of encountering strong shocks

- Expected rate to encounter a SN shock of speed v_s

$$\Gamma_{Enc}(v_s) = \frac{V_{SN}(v_s)}{V_{Disk}}\Gamma_{SN}$$



$$\Gamma_{\rm SH} = (2.5 \times 10^7 \text{ yr})^{-1} \left(\frac{R_{max}}{40 \text{ pc}}\right)^3 \left(\frac{R_{disk}}{15 \text{ kpc}}\right)^{-2} \left(\frac{H_{disk}}{300 \text{ pc}}\right)^{-1} \left(\frac{\Gamma_{SN}}{.03 \text{ yr}^{-1}}\right)$$

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Exponential momentum gain, first-order Fermi acceleration

$$\mathrm{Probability}(p > p_0 \,|\, p_0) = \frac{p_0}{p} \longrightarrow f = \frac{dn}{dp} = n_0 \frac{p_0}{p^2}$$

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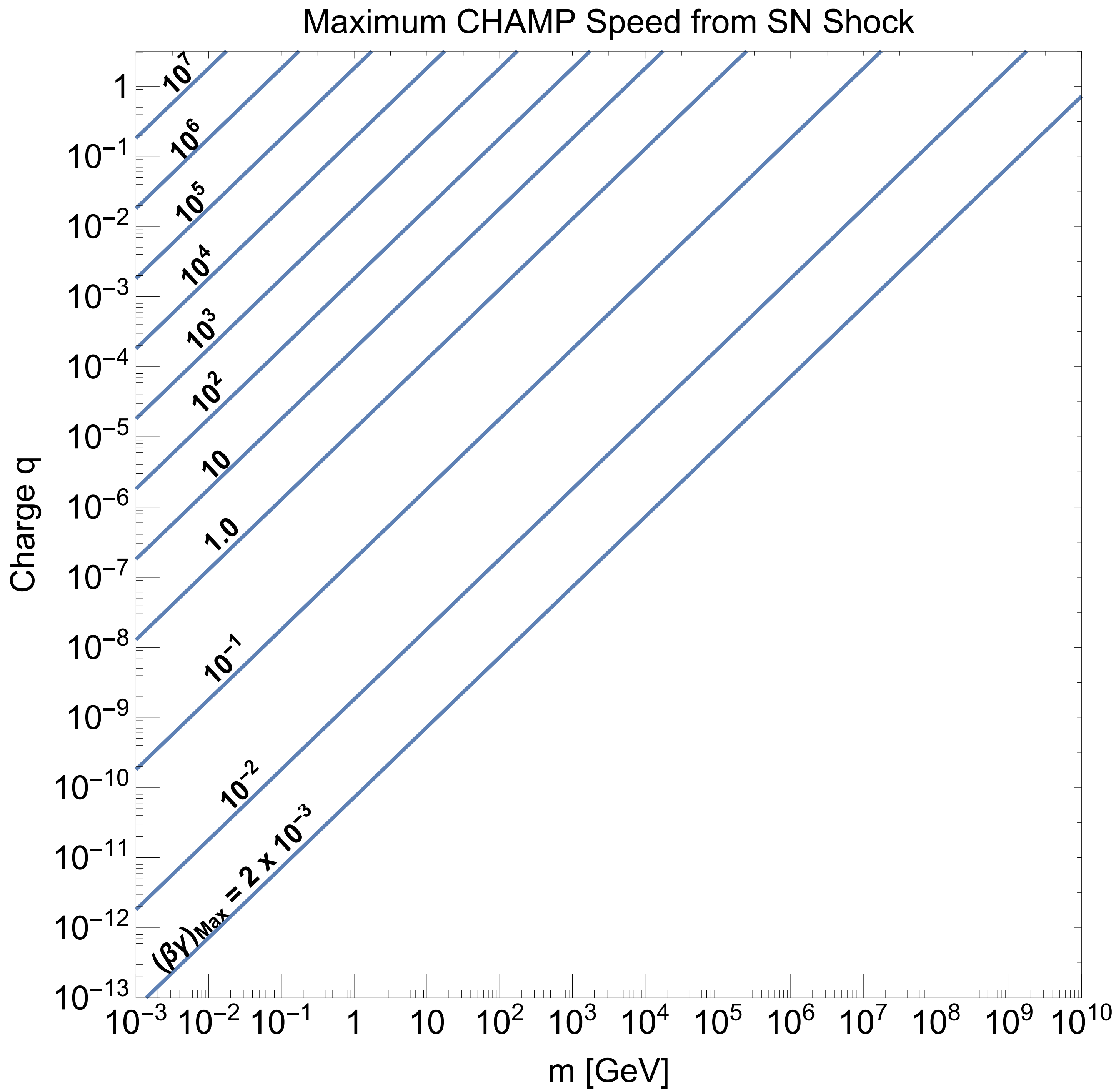

$$\left(\frac{p}{q}\right)_{max} \approx \frac{5.5 \times 10^4 \text{ GeV}}{\beta} \left(\frac{B}{15\ \mu\text{G}}\right) \left(\frac{R_{max}}{40\text{ pc}}\right) \left(\frac{v_s}{200\text{ km/s}}\right)$$

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Rate 3: Escape from the Disk

- CHAMPs diffuse through the ISM by resonantly scattering off magnetic irregularities on the scale

$$k = \frac{2\pi}{r_{gyro}} \qquad r_{gyro} = \frac{\gamma m v}{qB} \longrightarrow \lambda \propto R^a \qquad R \equiv r_{gyro} B = p/q$$

Mean free path — Rigidity

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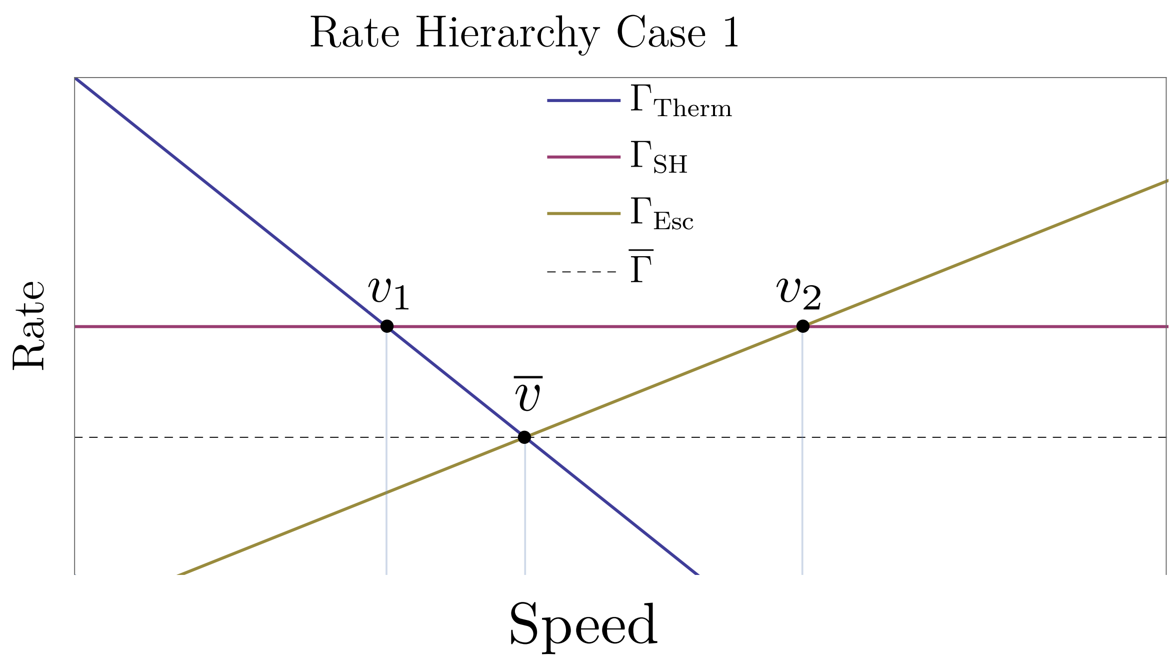
$$\Gamma_{esc} = \frac{2D}{H_{disk}^2} \approx \left(2 \times 10^7\ \text{yr}\right)^{-1} \left(\frac{v}{10^3\ \text{km/s}}\right)^{3/2} \left(\frac{m/q}{10^6\ \text{GeV}}\right)^{1/2} \left(\frac{H_{disk}}{300\ \text{pc}}\right)^{-2} \gamma^{1/2} \theta\left(v - v_{esc}\right)$$

Acceleration and Ejection



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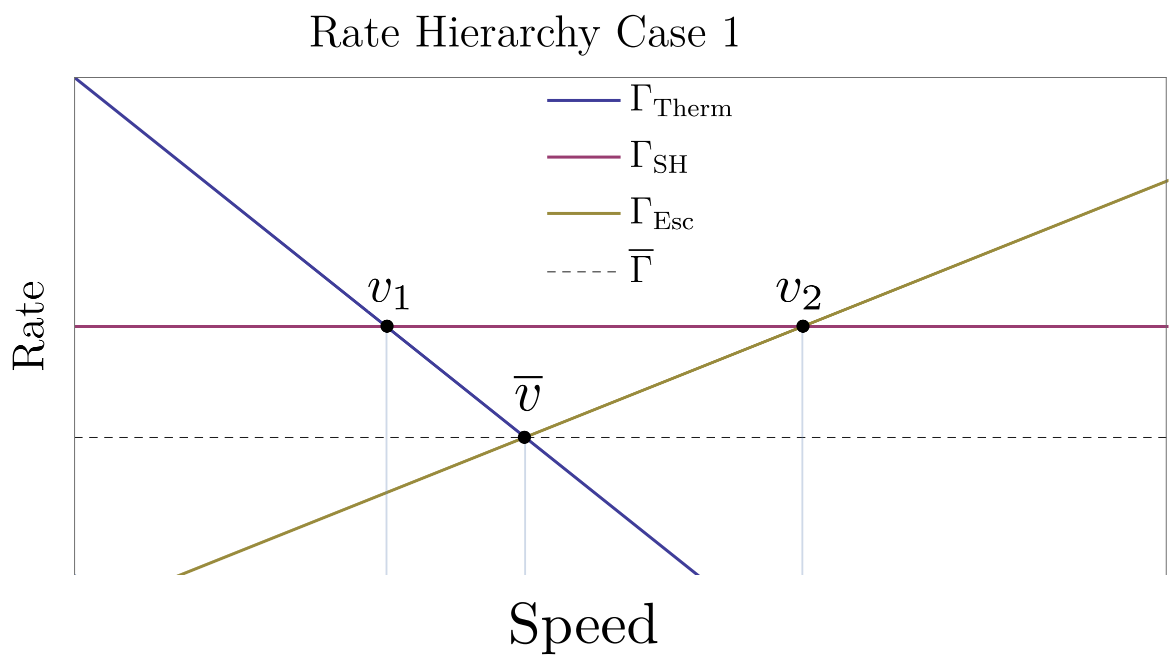

$$\frac{dn}{d\ln v} \propto R_{SN}^3 \propto v^{-2}$$

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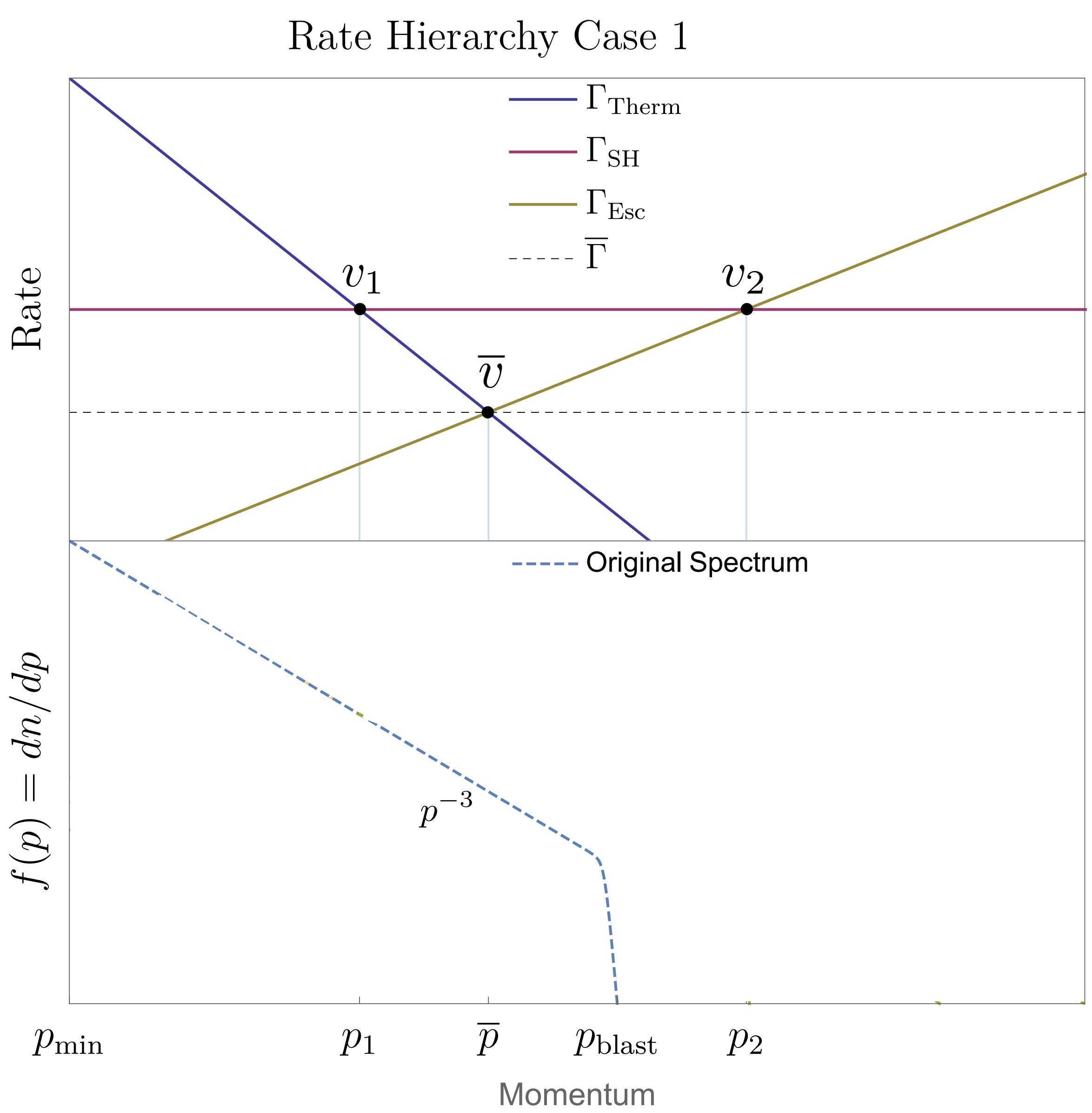

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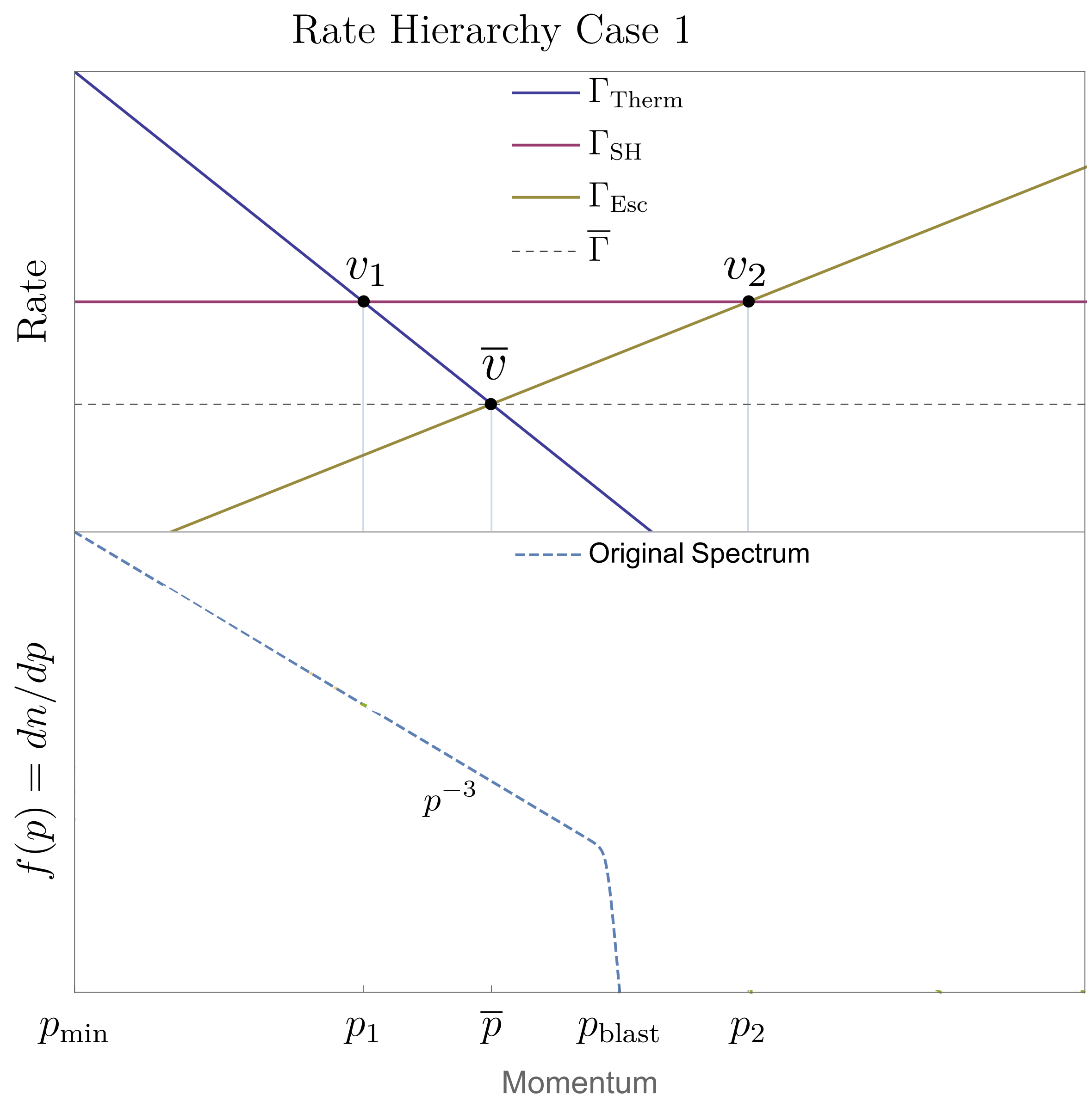

$$\frac{\partial f}{\partial t} = \frac{\partial(p\Gamma_{therm}(p)f)}{\partial p}$$

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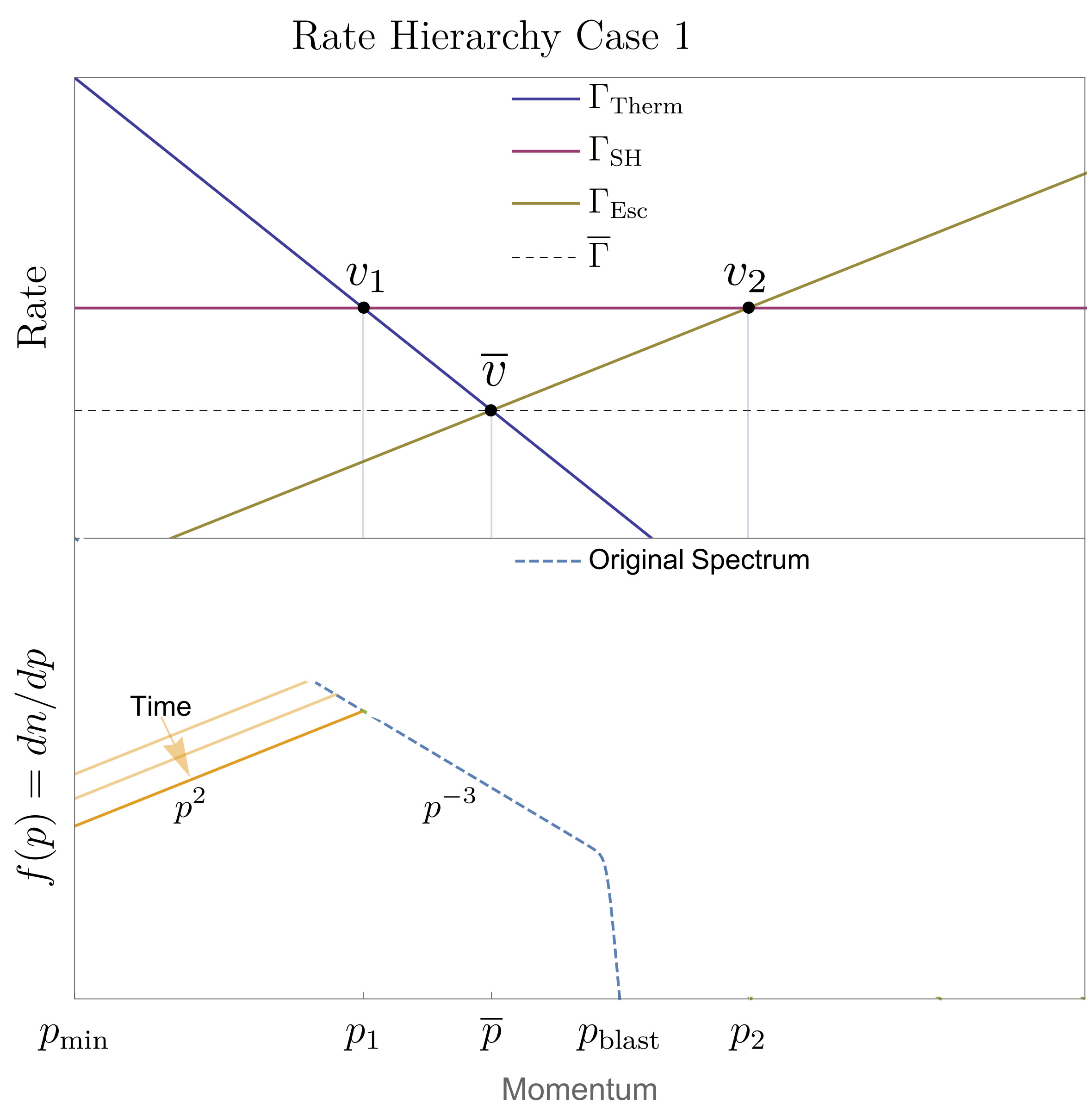

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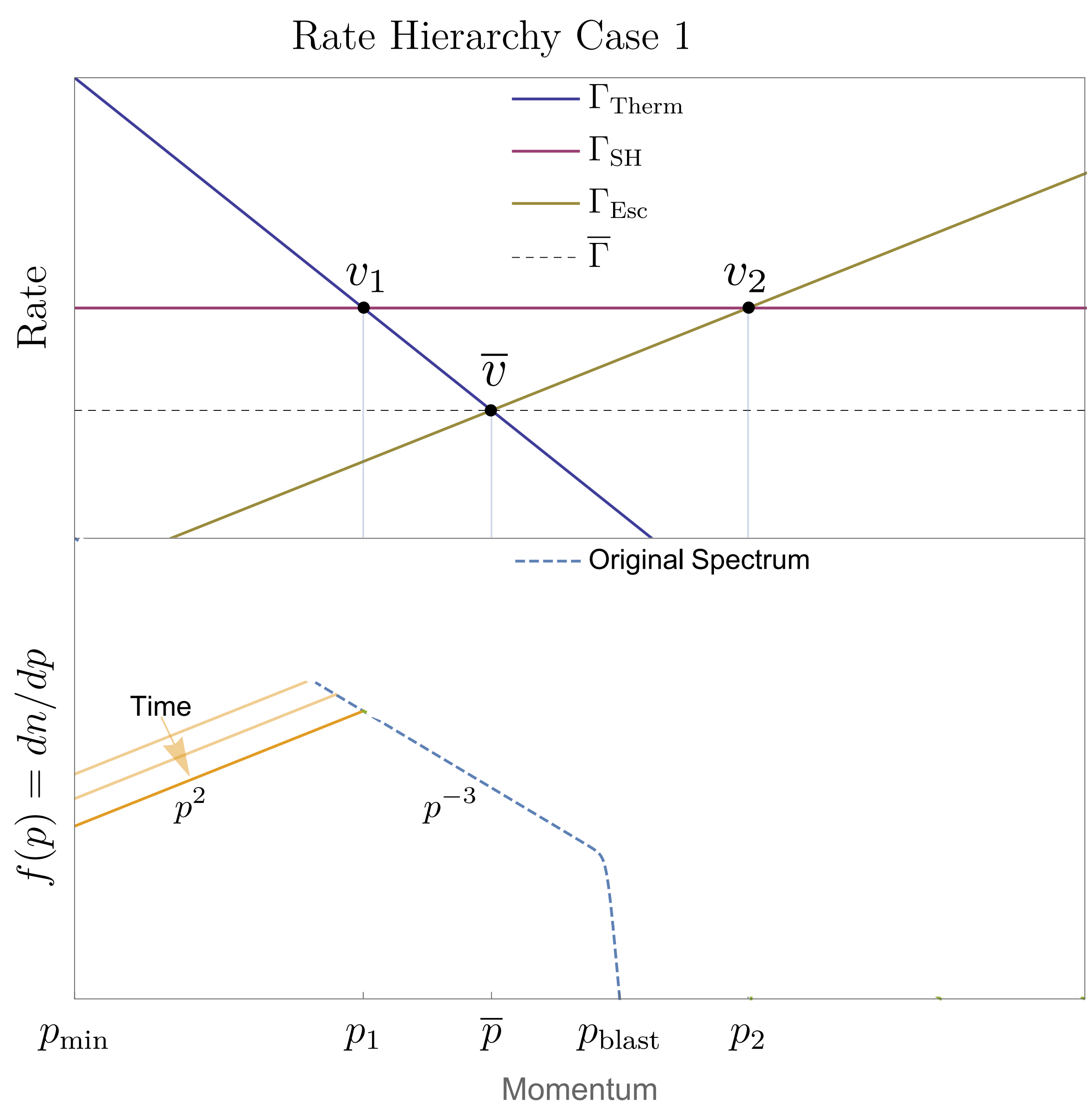

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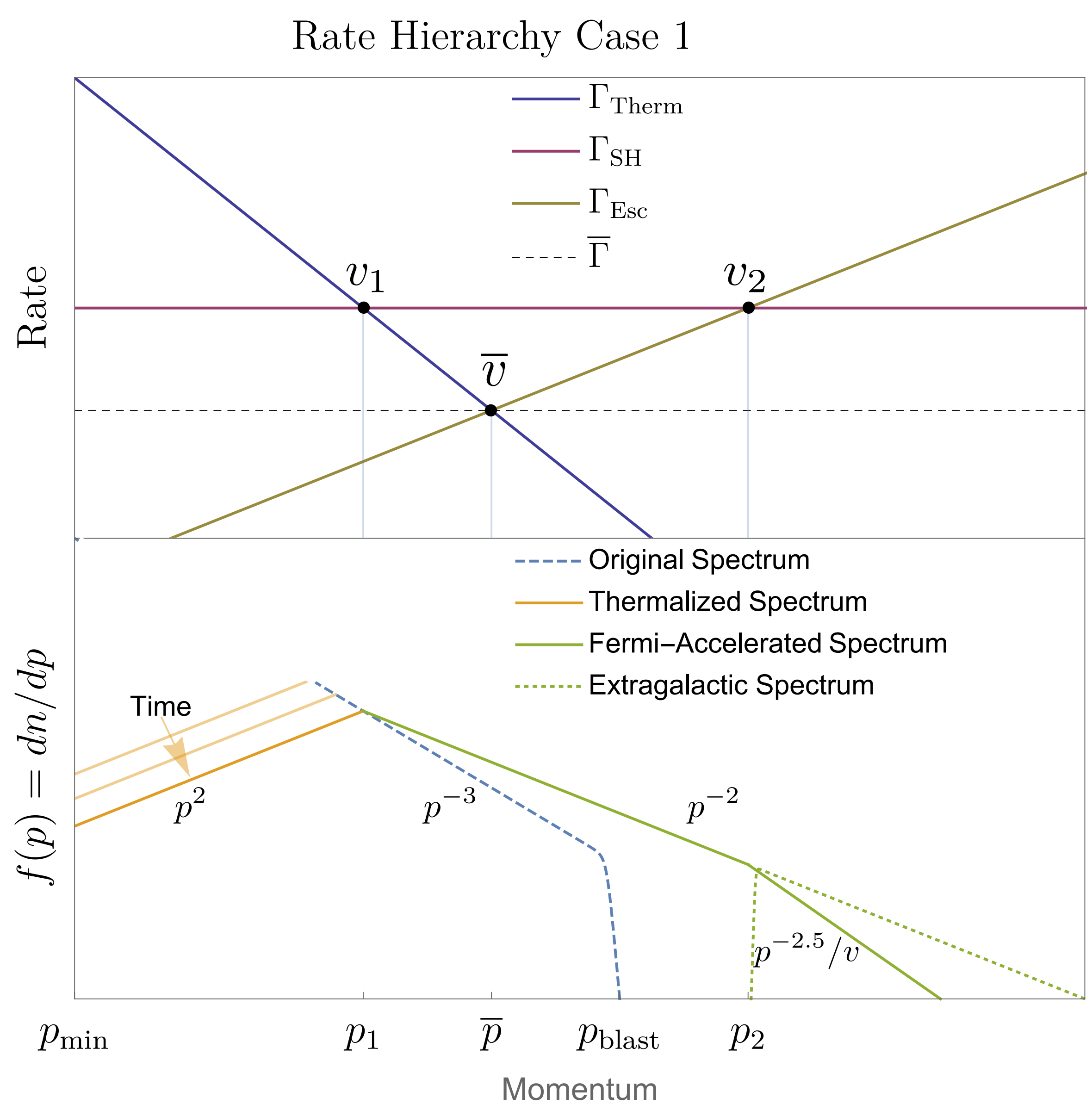

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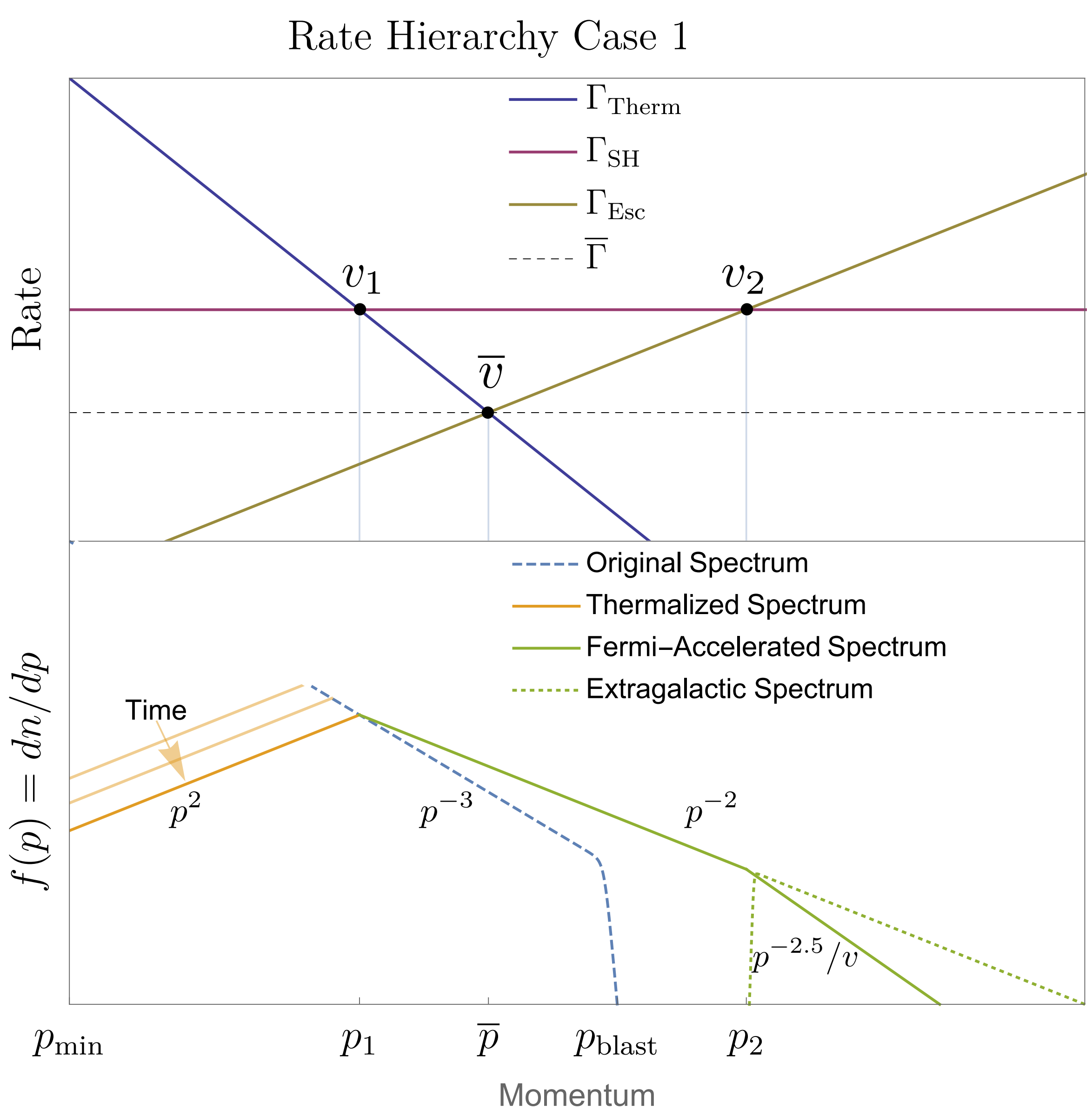

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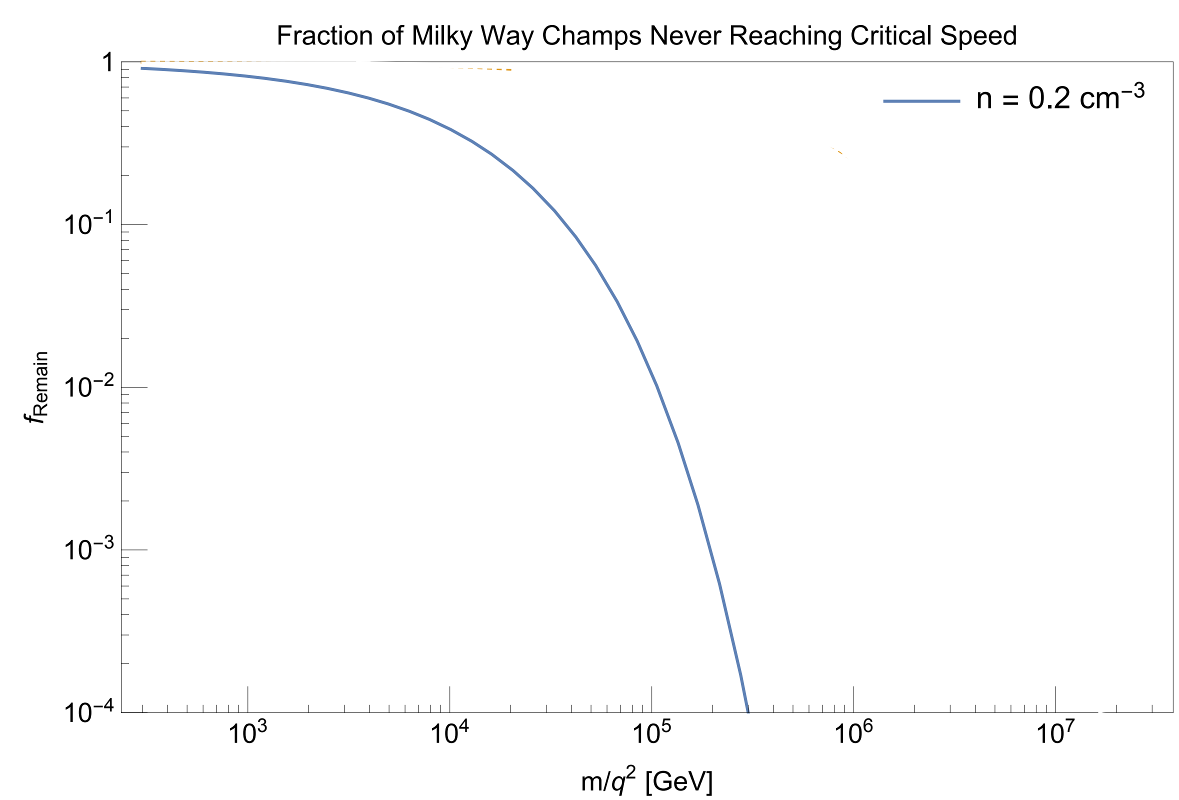
- To be Fermi-accelerated, CHAMPs must encounter critical shock $v_s = v_1$

$$\Gamma_A = \Gamma_{enc}(v_s = v_1)$$

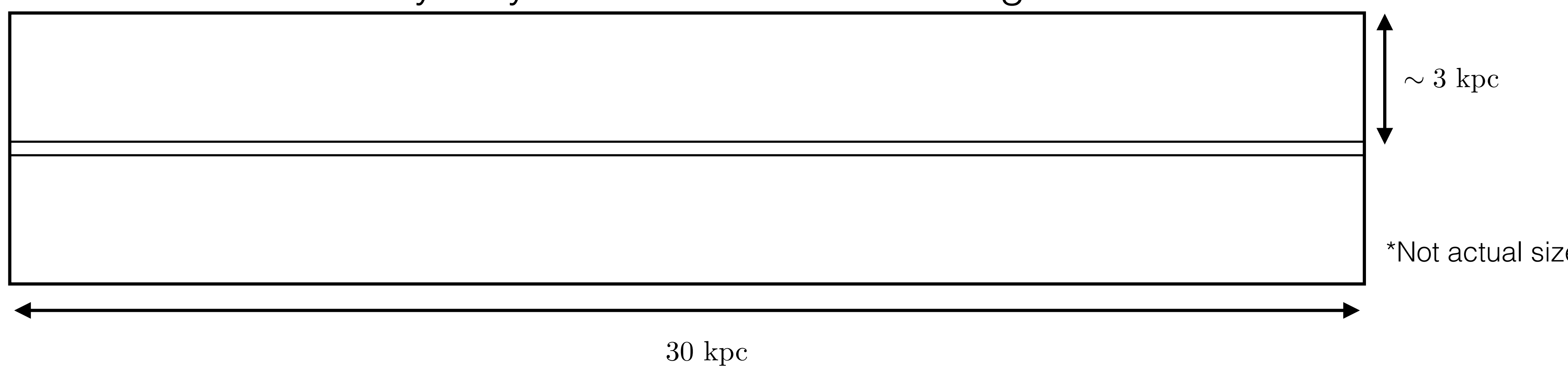
$$\downarrow$$

$$f_{remain} \approx \exp\left(-\Gamma_A \times 10^{10}\ \mathrm{yr}\right)$$



Diffusion into Disk and Local Flux

Milky Way disk and confinement region



$$\frac{\partial n(t,z)}{\partial t} = D\,\frac{\partial^2 n(t,z)}{\partial z^2} - \Gamma_A\,\theta(z + H_{\rm disk}/2)\,\theta(H_{\rm disk}/2 - z)\,n(t,z)$$

$$\frac{dn_A(t)}{dt} = \Gamma_A\,n(t,0) - \Gamma_{esc}\,n_A(t), \quad n_A(0) = 0$$

Don't collapse: $n(0,z) = n(t, \pm H_c/2) = f_X n_0,$ $\quad n_0 \approx \frac{0.3}{m}\ \mathrm{GeV/cm^3}$

Collapse: $n(0,z) = 100\,f_X n_0\,\theta(z + H_{\rm disk}/2)\,\theta(H_{\rm disk}/2 - z), \quad n(t, \pm H_c/2) \lesssim n_0$

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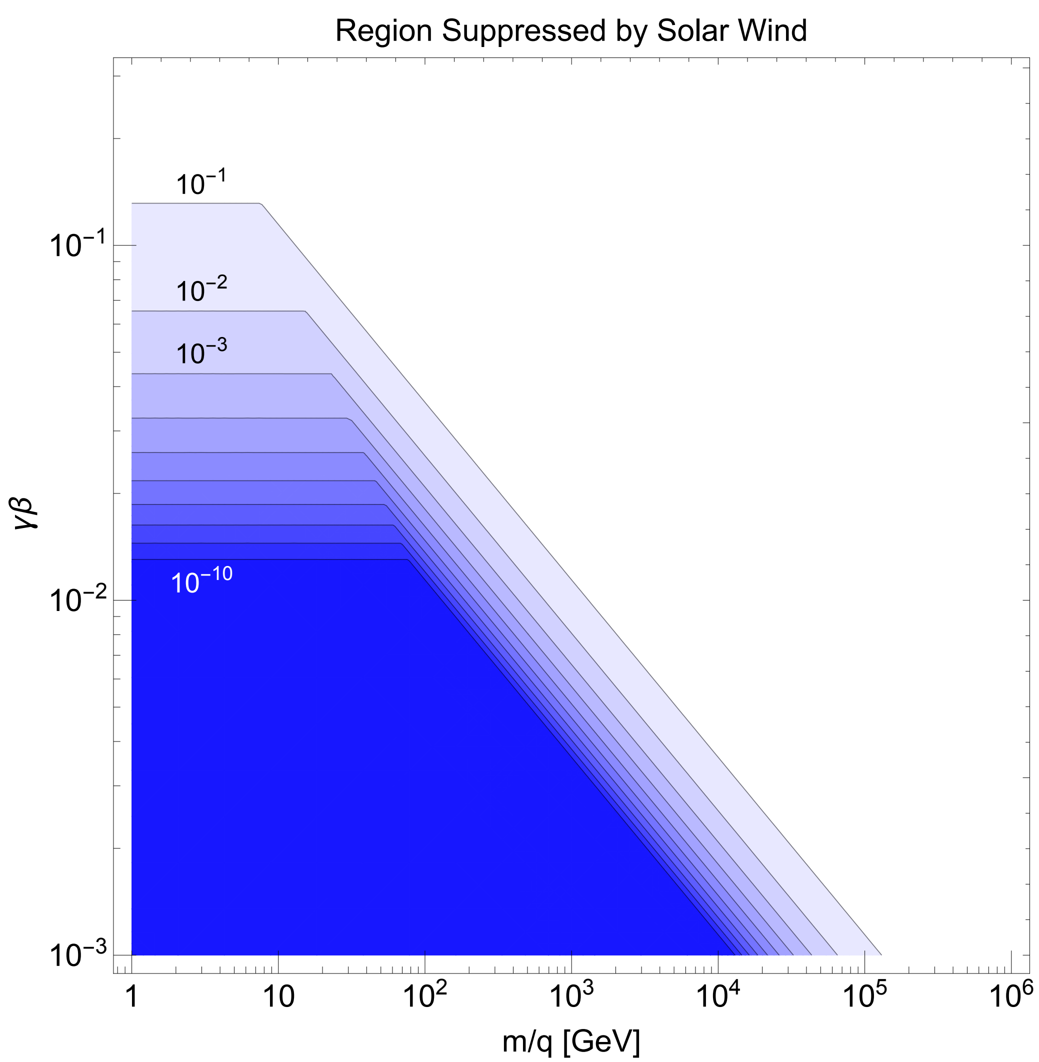
(4) Relativistic CHAMPs emit or induce Cherenkov light when traveling through water detectors like Super Kamiokande

Barriers to Detection

- CHAMPs must travel 'upstream' through solar wind

$$J(r) = n(r)v_w(r) - D\frac{\partial n(r)}{\partial r} \longrightarrow n(r) = n_0(r_0)\exp\left(-\int_r^{r_0} \frac{v_w(r)dr}{\frac{1}{3}\lambda(R)v}\right)$$



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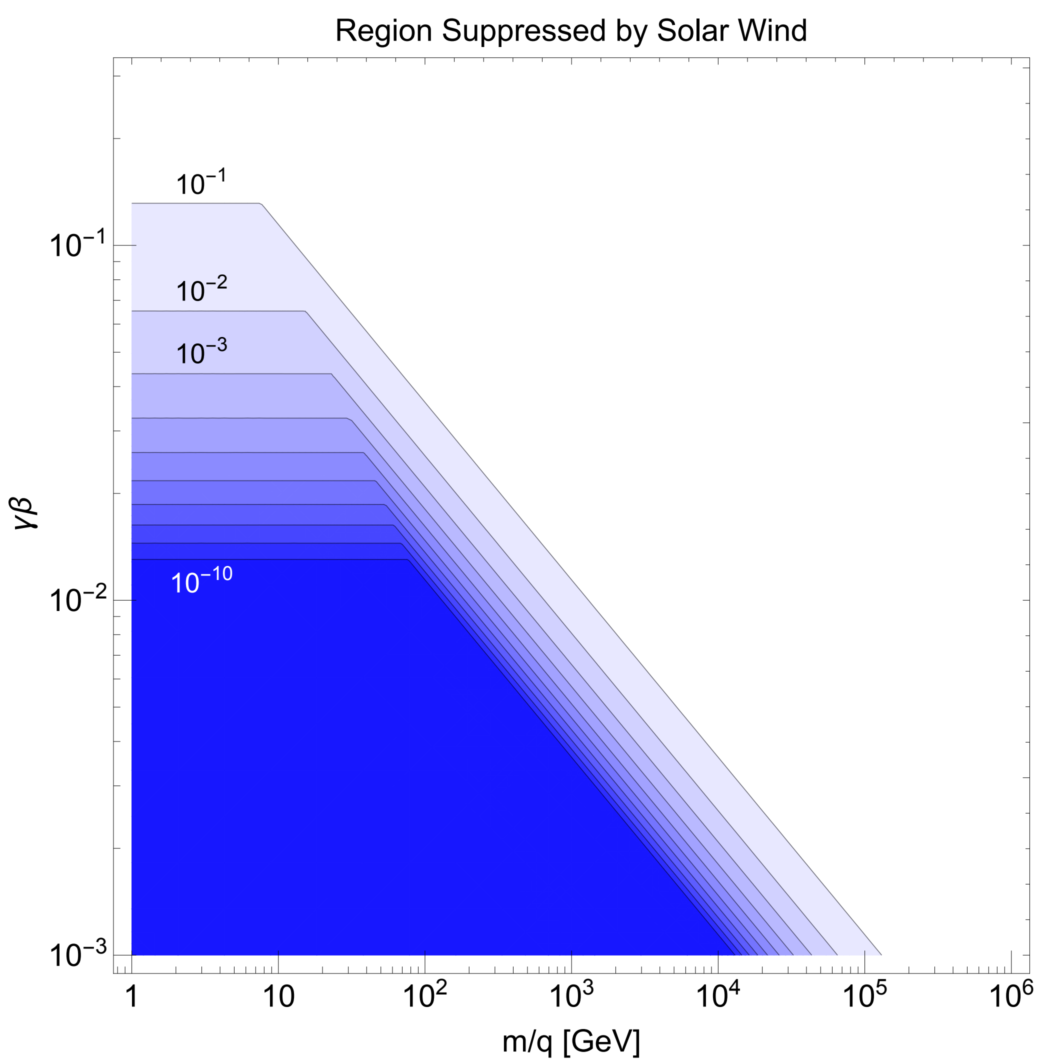
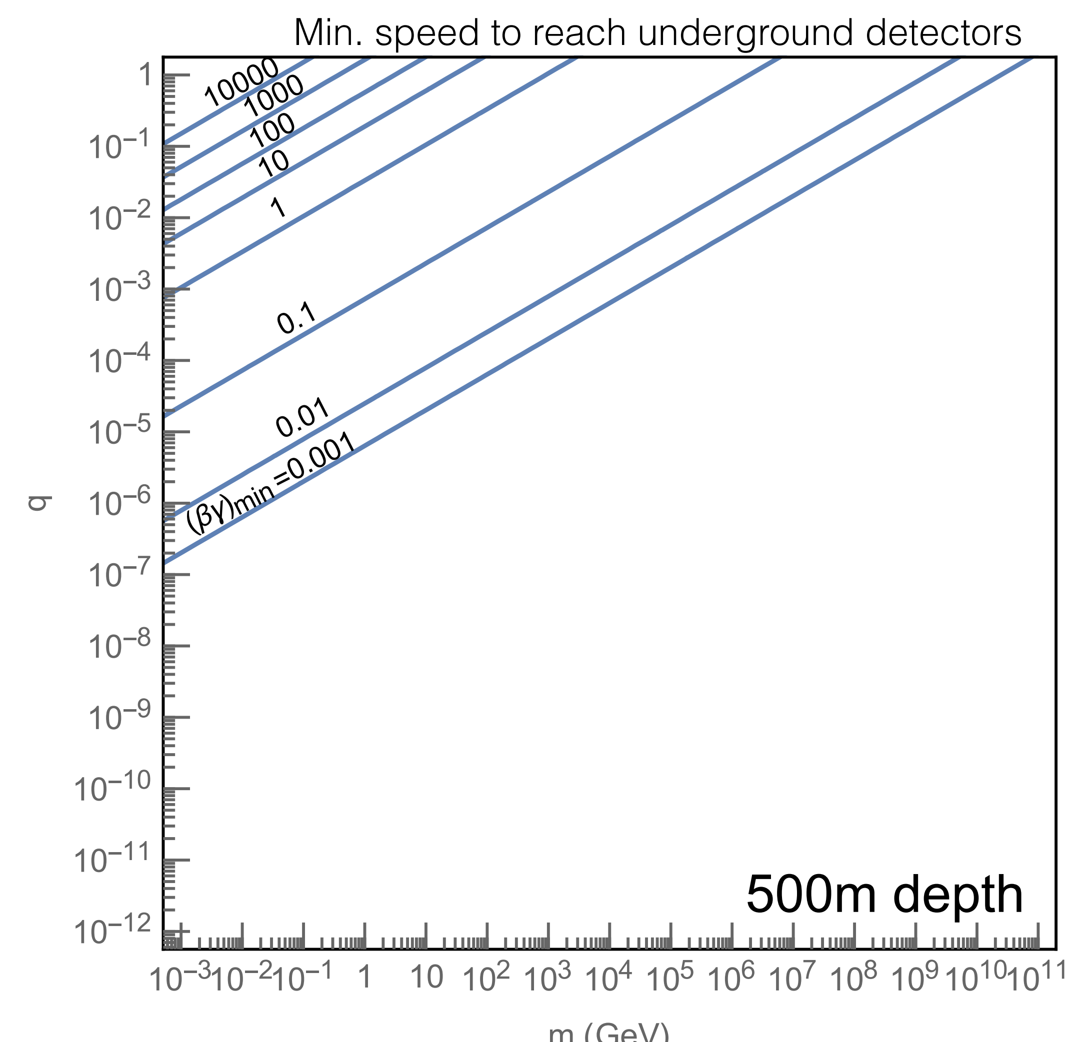
- CHAMPs must travel through Earth’s crust $-\left\langle\frac{dE}{dx}\right\rangle = 0.15\ \mathrm{MeV\ cm^2/g}\left(\frac{q}{\beta}\right)^2\left(\frac{Z/A}{1/2}\right)\ln\left(\frac{2m_e\gamma^2\beta^2}{10Z\ \mathrm{eV}}\right)$

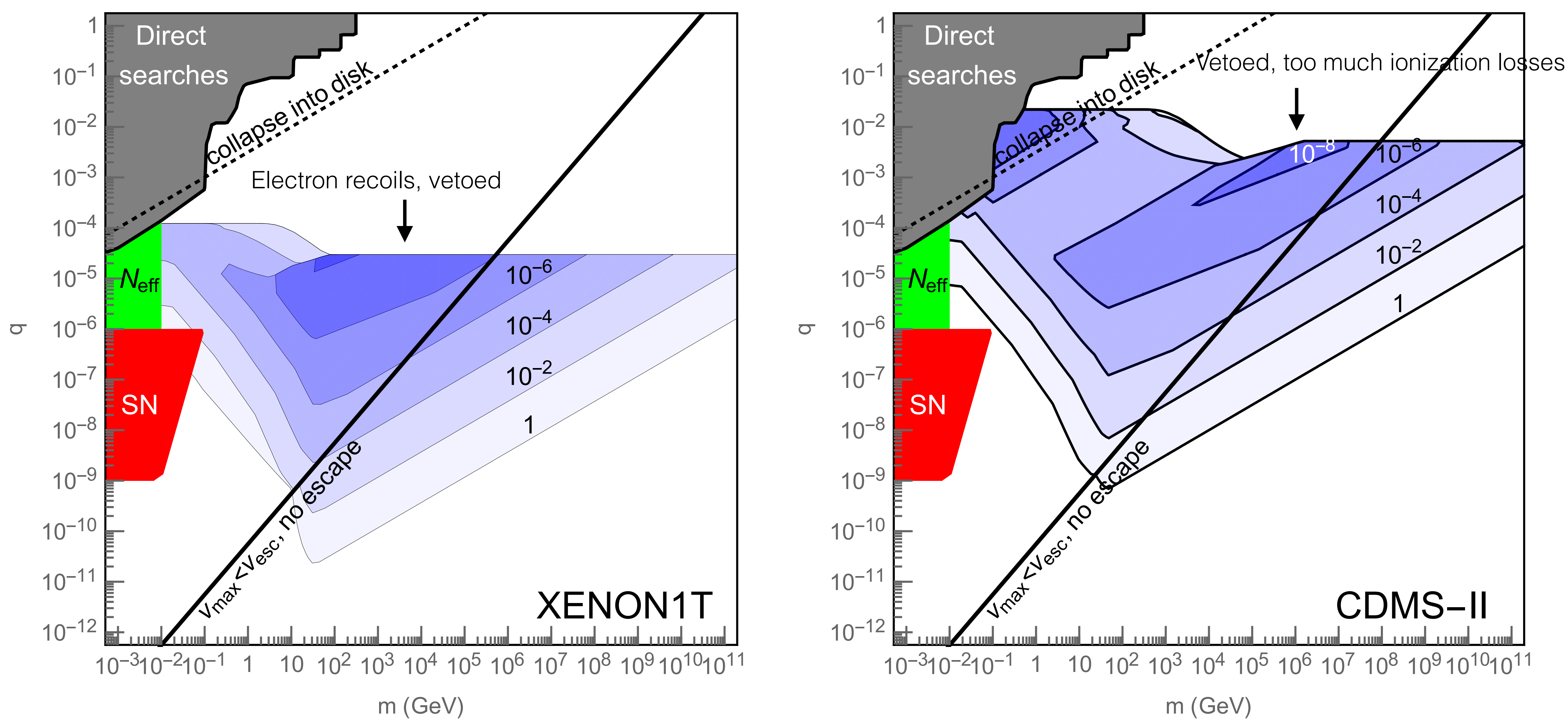




Nuclear Recoil at Underground Detectors

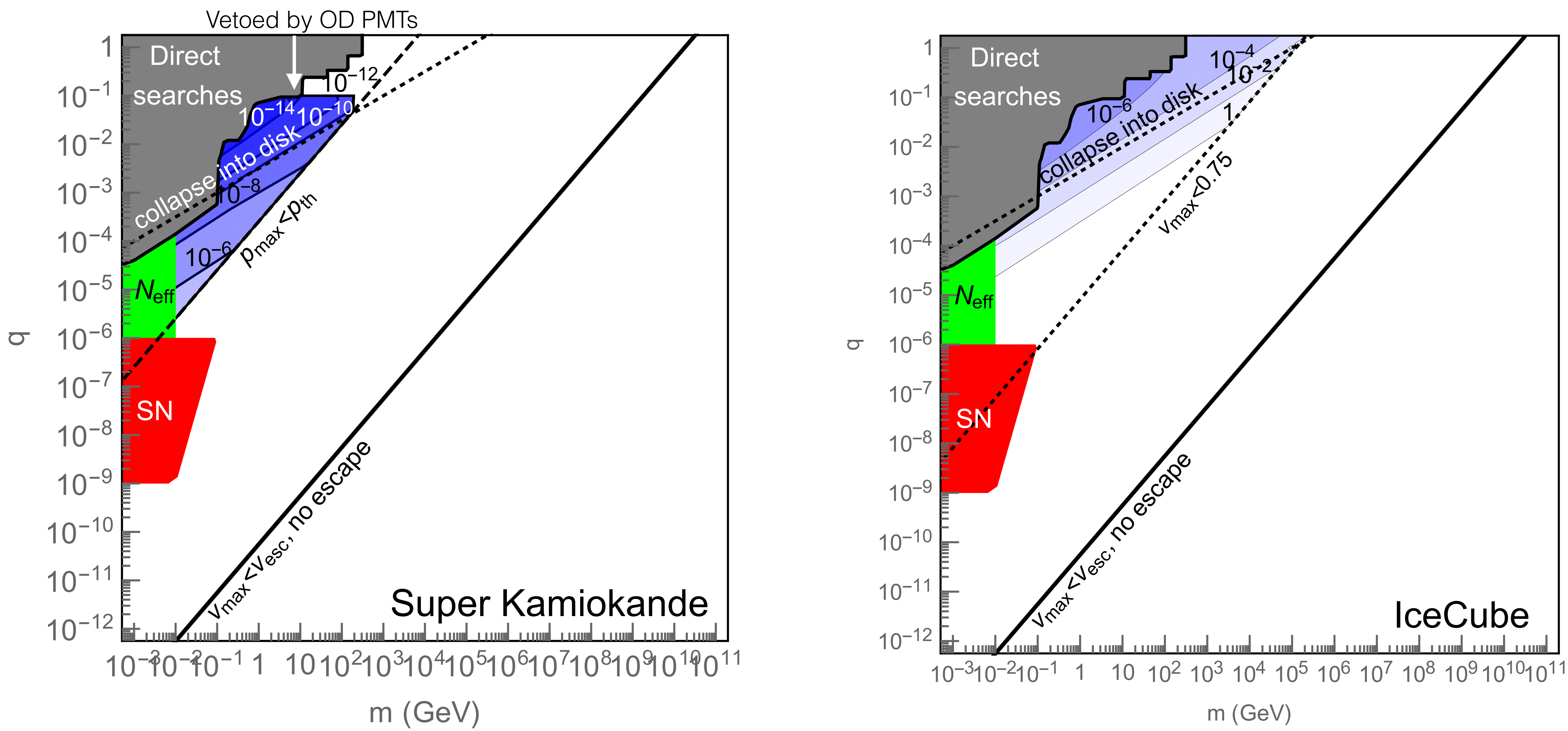
$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2 Z^2 q^2}{\mu^2 v^4 (1-\cos\theta)^2}$$

$$\Gamma_{Sig} = N_N \int dv\, \sigma(E_R > E_{R,th}) v \frac{dn_A}{dv} \simeq N_N \left[\sigma(E_R > E_{R,th}) v \frac{dn_A}{d\ln v}\right]_{v=v_-} < \text{ 15 events/1 ton-year}$$



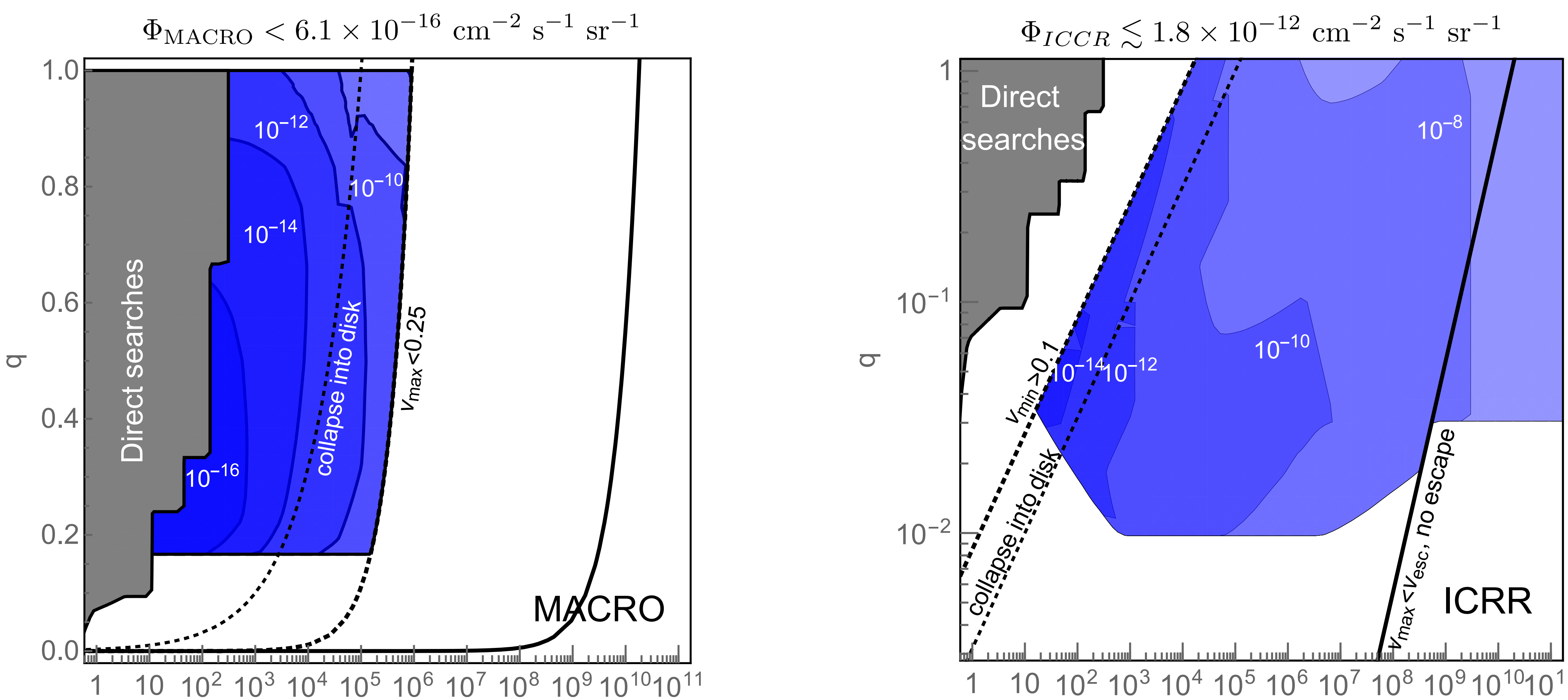
Induced/Emitted Cherenkov Light

- Relativistic CHAMPs passing through water may deposit enough energy to accelerate electrons to speeds > 0.75c, which emit detectable Cherenkov light in Super-K
- Relativistic CHAMPs passing through Antarctic ice may produce more Cherenkov photons than IceCube’s dark count



Ionization Particle Searches

- As q grows, CHAMPs yield significant ionization
- Experiments typically scintillation detectors. with constraints in form of upper bound on CHAMP flux $\Phi(p > p_0) = \int_{p_0}^{p_{max}} \frac{dn_A}{dp} v \, dp$



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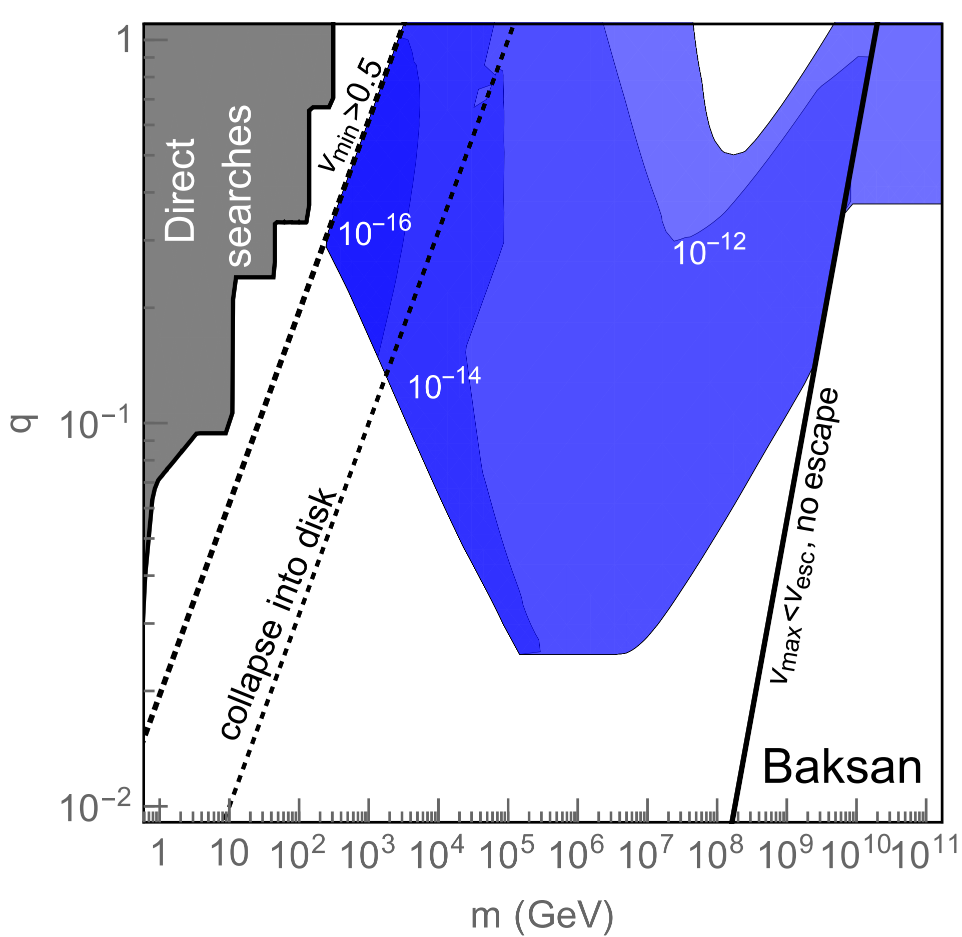
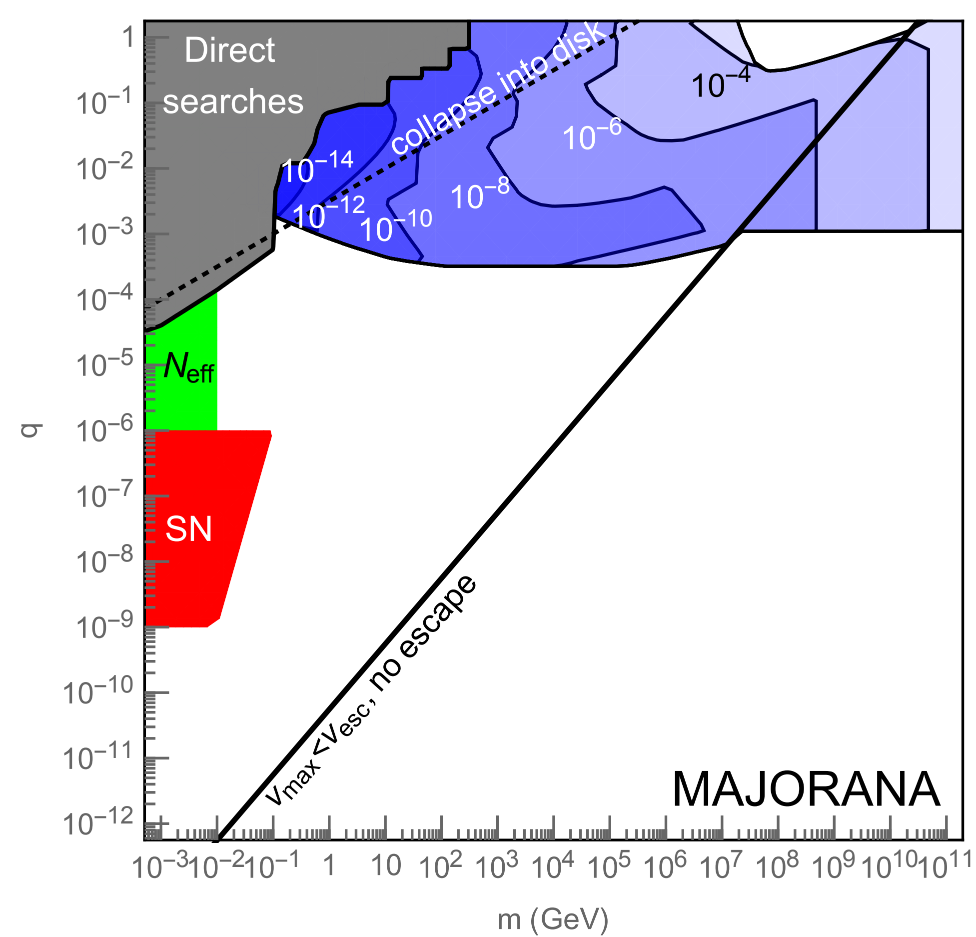
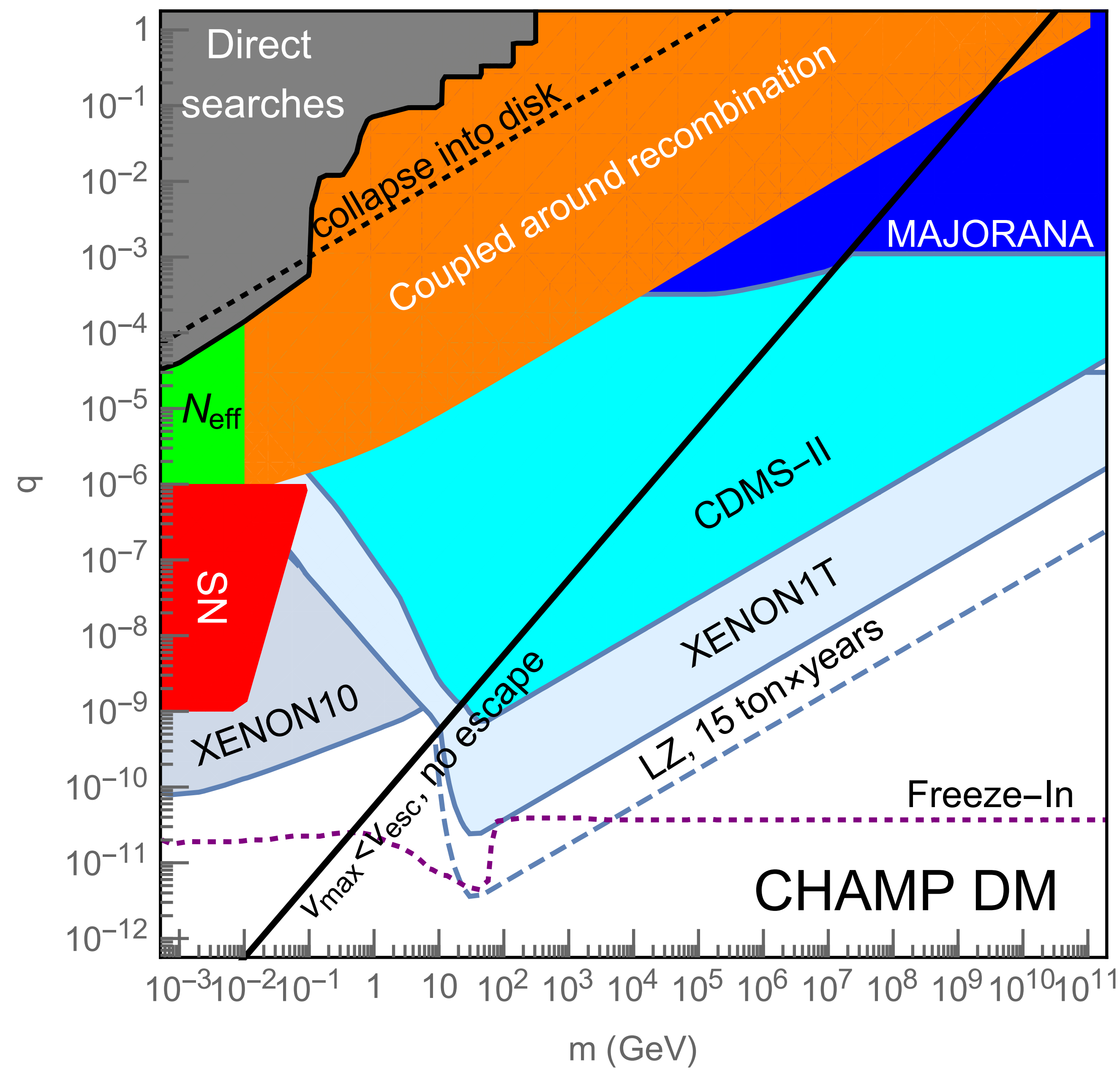
$$\Phi_{\rm Baksan} \lesssim 2 \times 10^{-15}\ {\rm cm}^{-2}\ {\rm s}^{-1}\ {\rm sr}^{-1}$$



$$\Phi_{\rm MAJORANA} < 10^{-9}\ {\rm cm}^{-2}\ {\rm s}^{-1}\ {\rm sr}^{-1}$$



CHAMP Dark Matter



Summary

- For $m \gtrsim 10^{10} q$ GeV, CHAMPS unaffected by thermalization, Fermi acceleration and diffusion

- For $m \lesssim 10^{10} q$ GeV, there is a large flux of accelerated CHAMPs in the disk today

- Nuclear/electron recoil experiments, Cherenkov and ionization detectors place stringent bounds on f_X

- *X* excluded as dark matter for q above 10^{-9} for any m