Shocking Signals from CHAMP Cosmic Rays

BSM Pandemic Seminar
11-17-20

David Dunsky

with Lawrence Hall & Keisuke Harigaya

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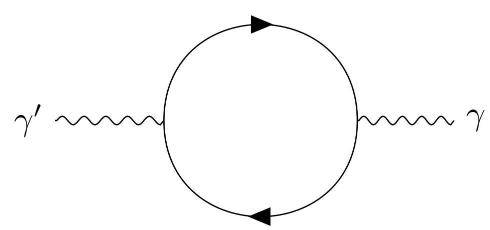
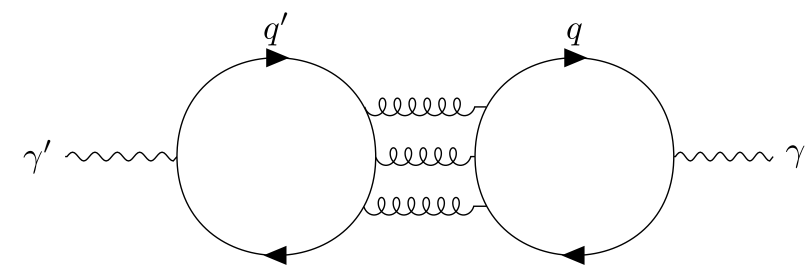
Motivation for CHAMPs

- Particle Physics
  - Kinetic Mixing, $U(1)$ Stability



B. Holdom, 1986



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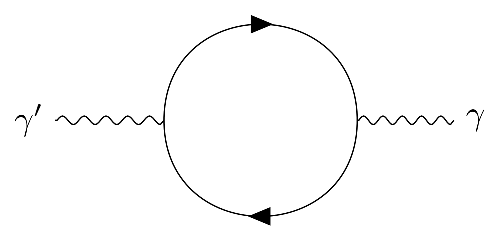

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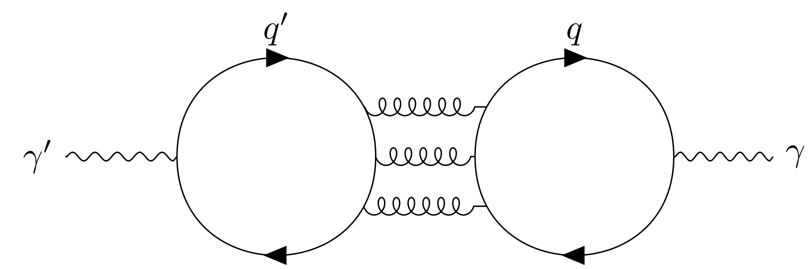

Dunsky, Hall, Harigaya, 2019

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- Effect of supernova shocks on detection of CHAMPs?

L. Chuzhoy, R. Kolb, 2009

J. Li, T. Lin 2020

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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
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- Thermalization dominated by Warm Ionized Medium

$$\Gamma_{\mathrm{therm}} \approx \langle n_{e,p} \sigma v \rangle \times \frac{\Delta p}{p} \times f_{\mathrm{WIM}}$$

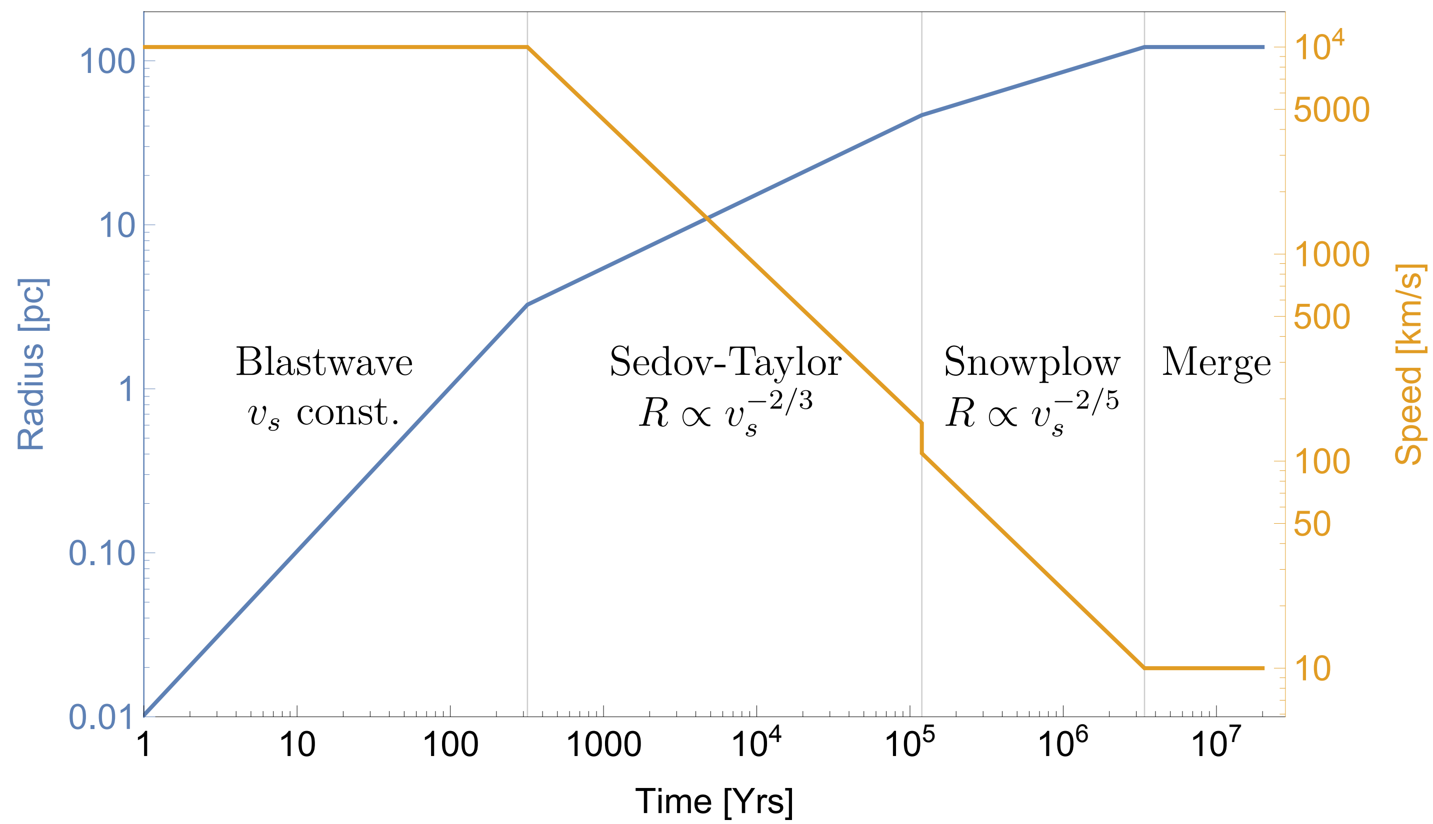
$$\approx (4 \times 10^7\,\mathrm{yr})^{-1} \left(\frac{m/q^2}{10^6\,\mathrm{GeV}} \right)^{-1} \left(\frac{v}{10^3\,\mathrm{km/s}} \right)^{-3} \left(\frac{n_e}{0.2\mathrm{cm}^{-3}} \right) \left(\frac{f_{\mathrm{WIM}}}{0.15} \right)$$

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

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



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

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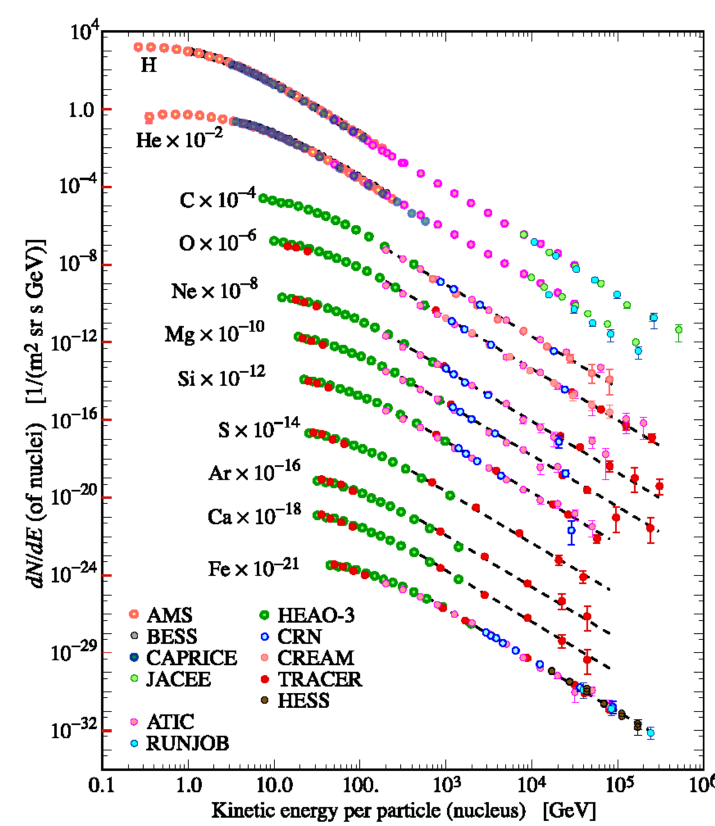
Exponential momentum gain, first-order Fermi acceleration



Ingredients

- Just two:
  - 1) Initially moving faster than the shock

Injection Problem

  - 2) Must reflect backwards

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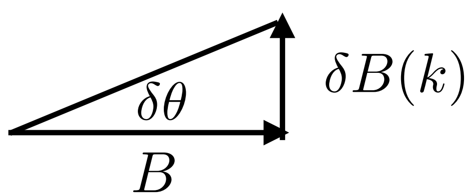
  - 1) Initially moving faster than the shock
    - Easier - CHAMPs can remain supra-thermal between encountering shocks

Injection Problem

  - 2) Must reflect backwards
    - Collisionless. Accomplished by B-fields around shock
    - Ability to reflect linear in q (gyroradius)

Rate 3: Escape from the Disk

- CHAMPs diffuse through the ISM by resonantly scattering off magnetic irregularities δB on scale of $r_{\rm gyro}$



Change in pitch angle $$\delta\theta = \frac{\delta B(k)}{B}$$

Random walk process $$\langle \Delta\theta^2 \rangle = N\delta\theta^2$$

Effective Mean Free Path $$\lambda_{\rm MFP} = N r_{\rm gyro} = r_{\rm gyro}/\delta\theta^2 = \lambda_0 (r_{\rm gyro})^a$$

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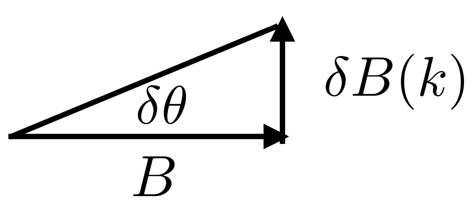

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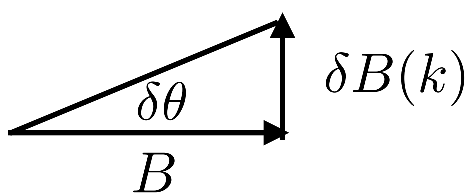

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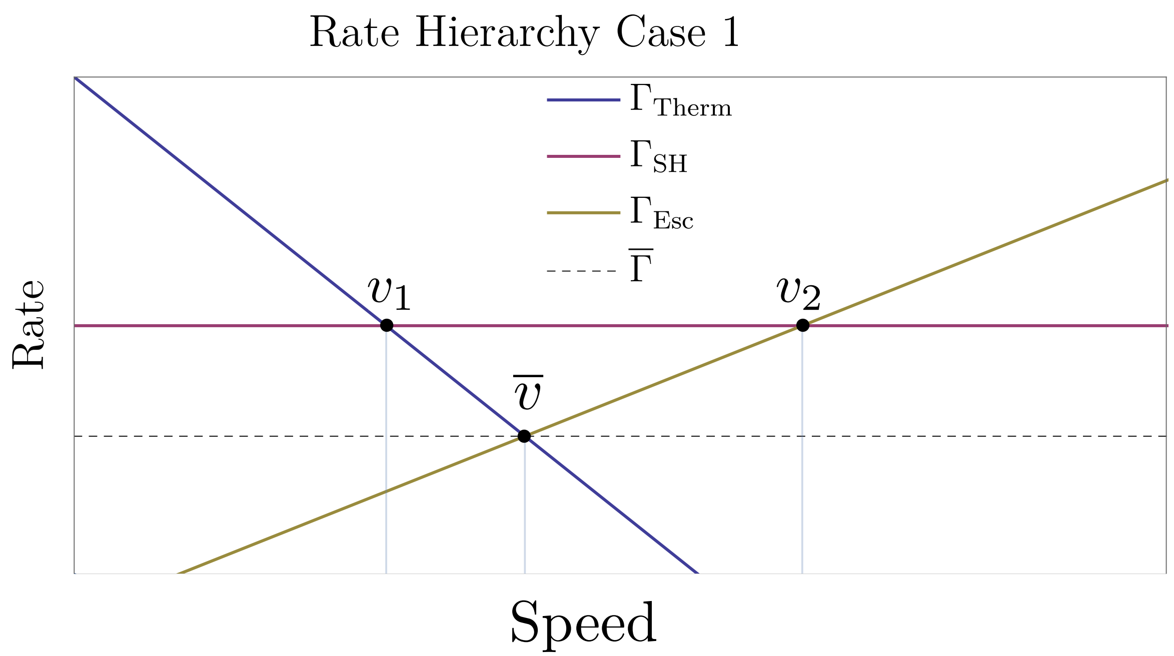
$$\Gamma_{esc} = \frac{2D}{H_{disk}^2} \approx \left(2\times 10^7 \text{ yr}\right)^{-1} \left(\frac{v}{10^3 \text{ km/s}}\right)^{3/2} \left(\frac{m/q}{10^6 \text{ GeV}}\right)^{1/2} \left(\frac{H_{disk}}{300 \text{ pc}}\right)^{-2} \gamma^{1/2}\theta\left(v - v_{esc}\right)$$

Acceleration and Ejection



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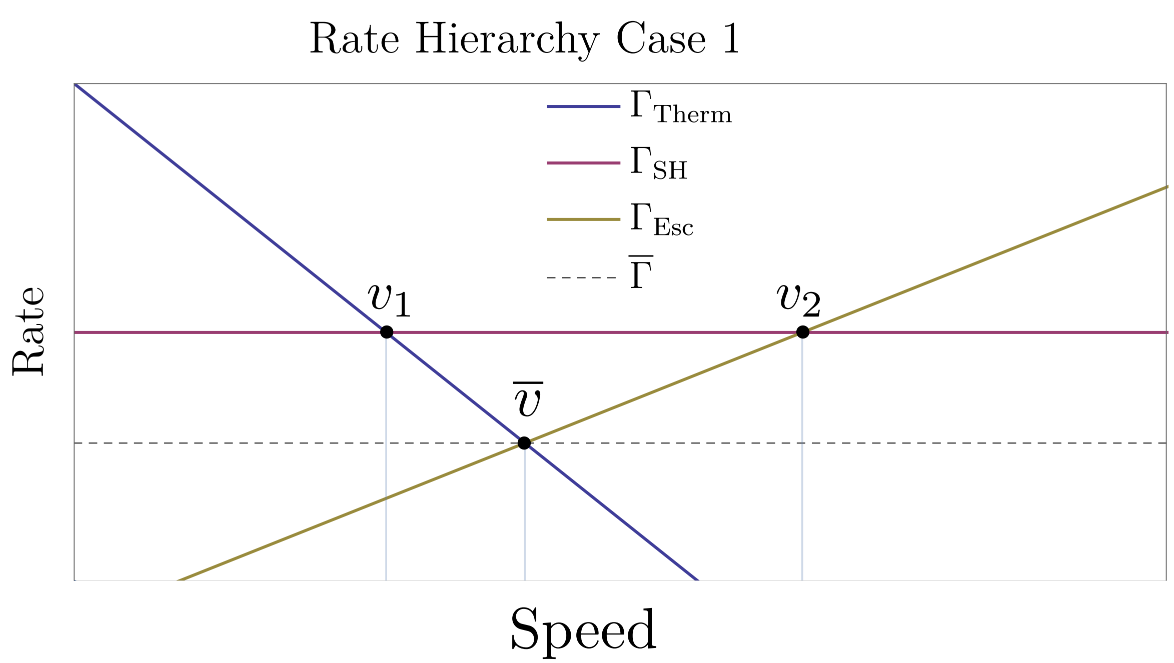

$$\frac{dn}{d\ln v} \propto R_{SN}^3 \propto v^{-2}$$

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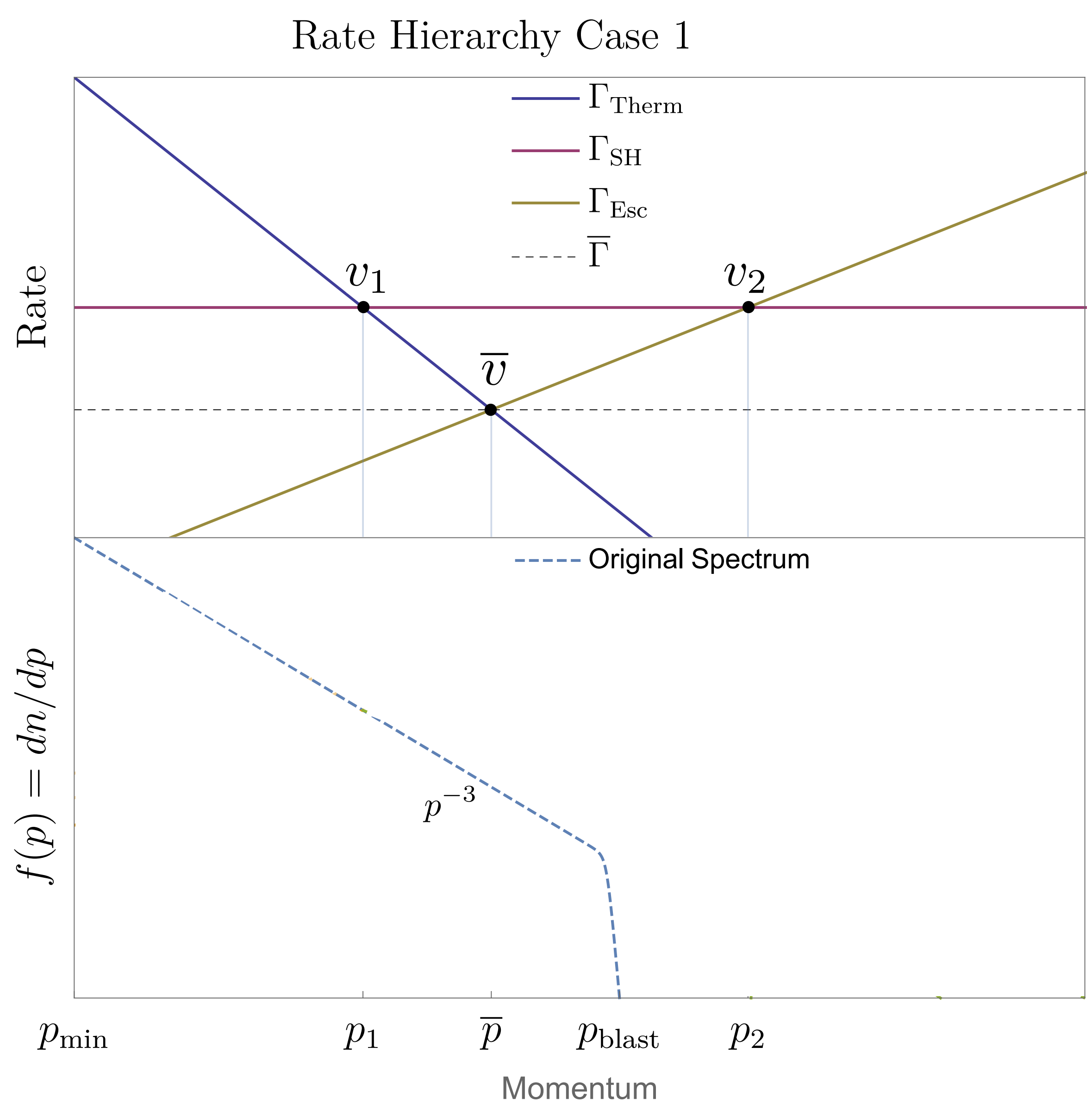

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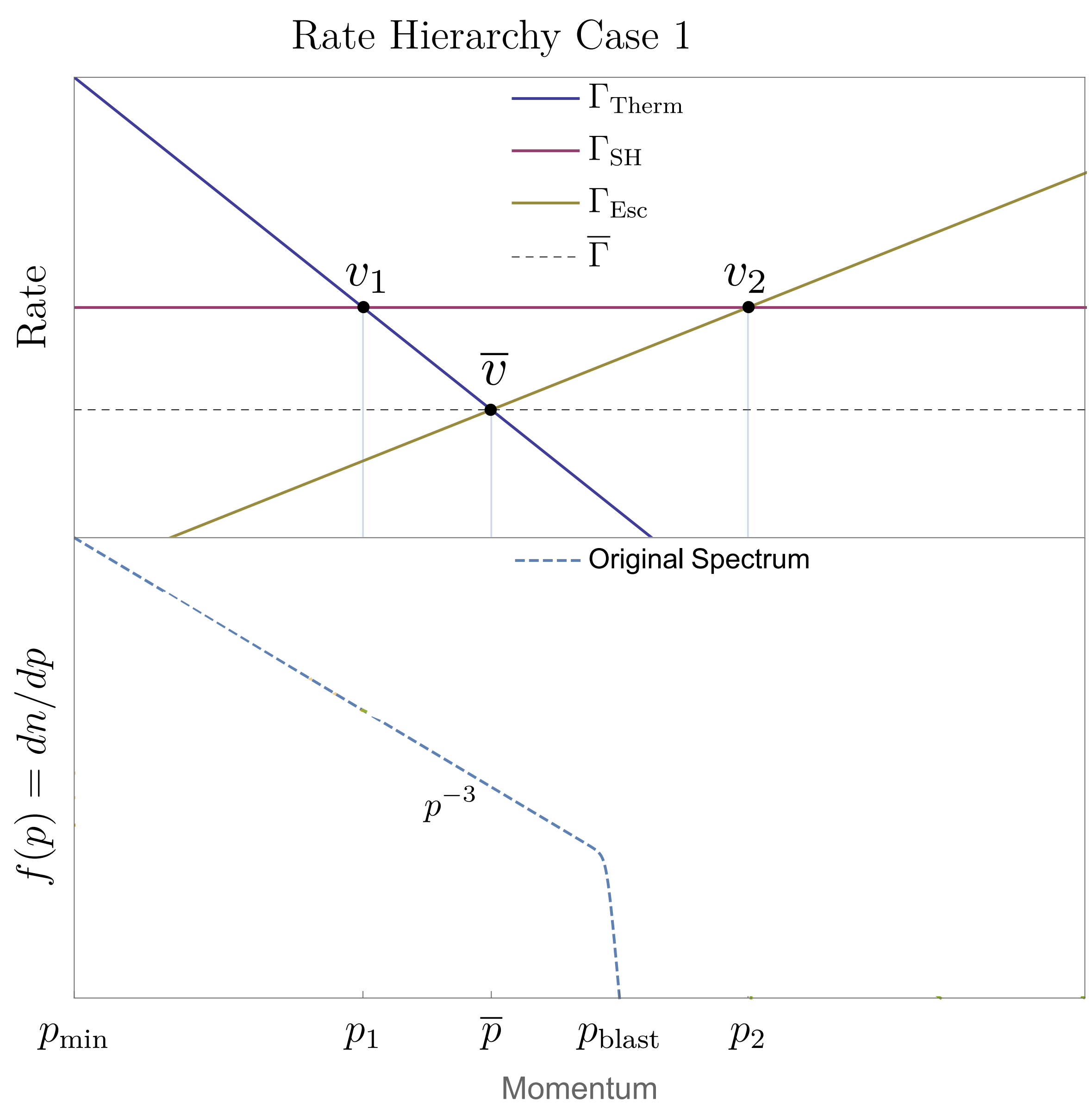

$$\frac{\partial f}{\partial t} = \frac{\partial (p\Gamma_{therm}(p) f)}{\partial p}$$

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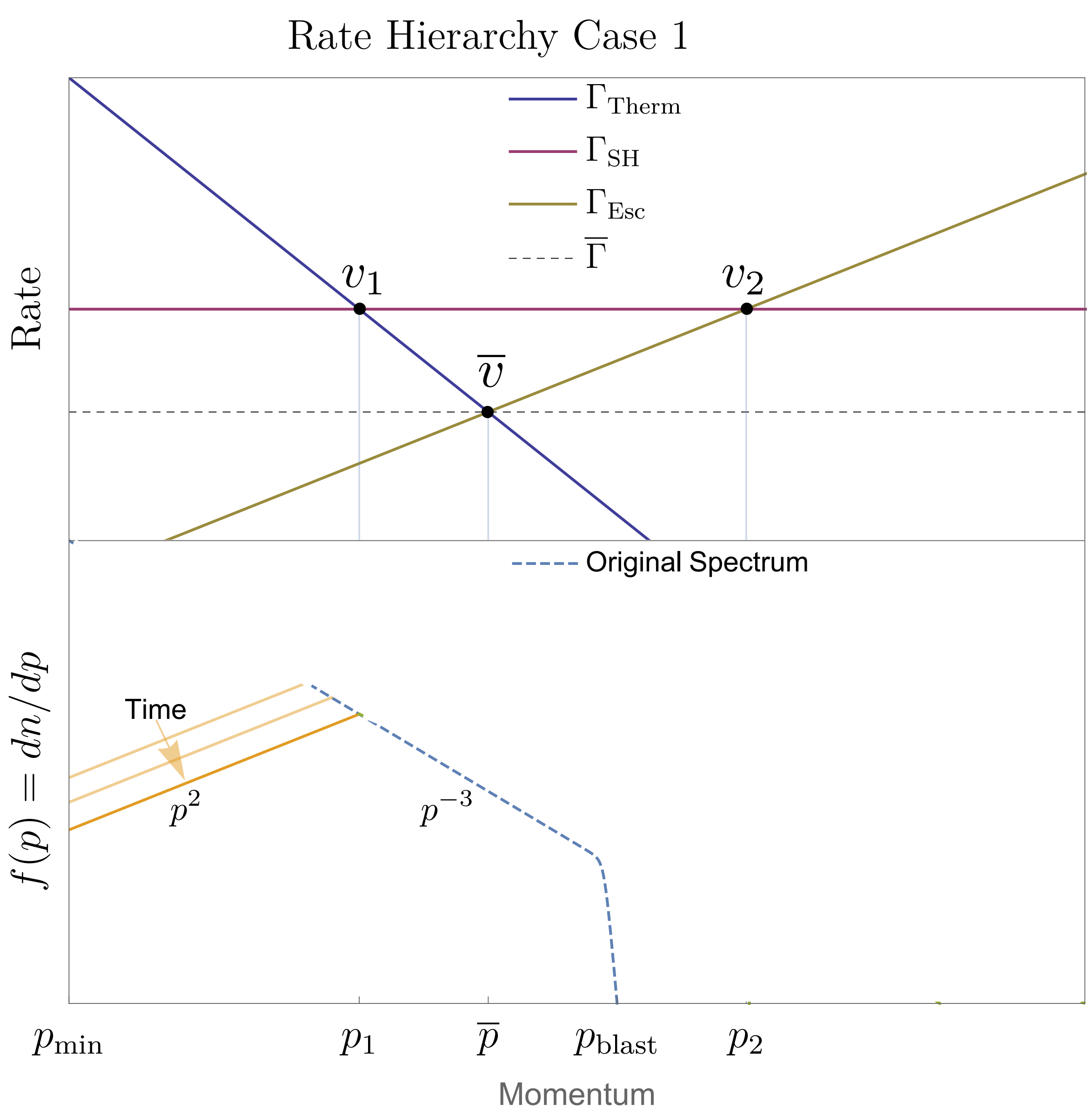

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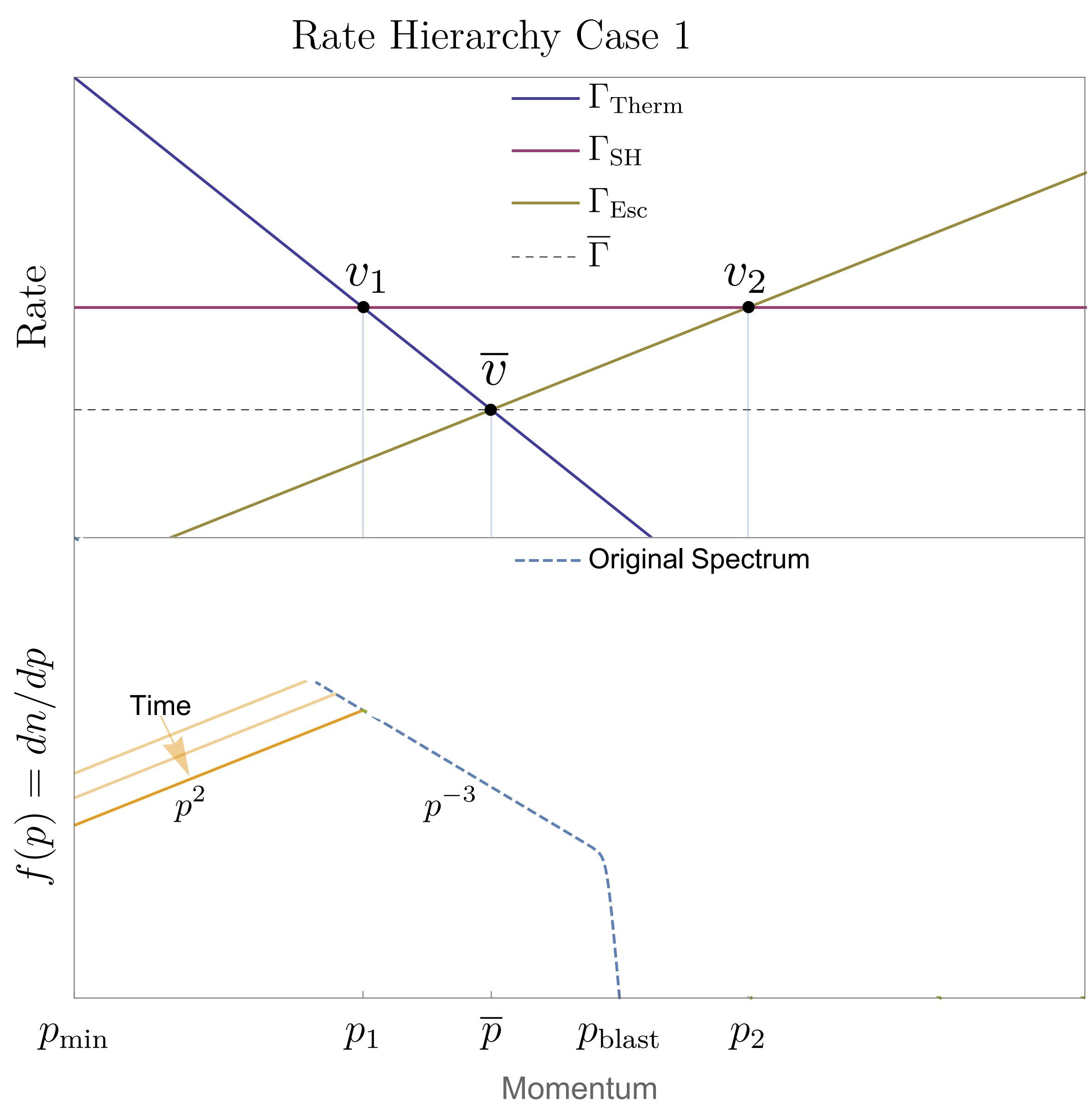

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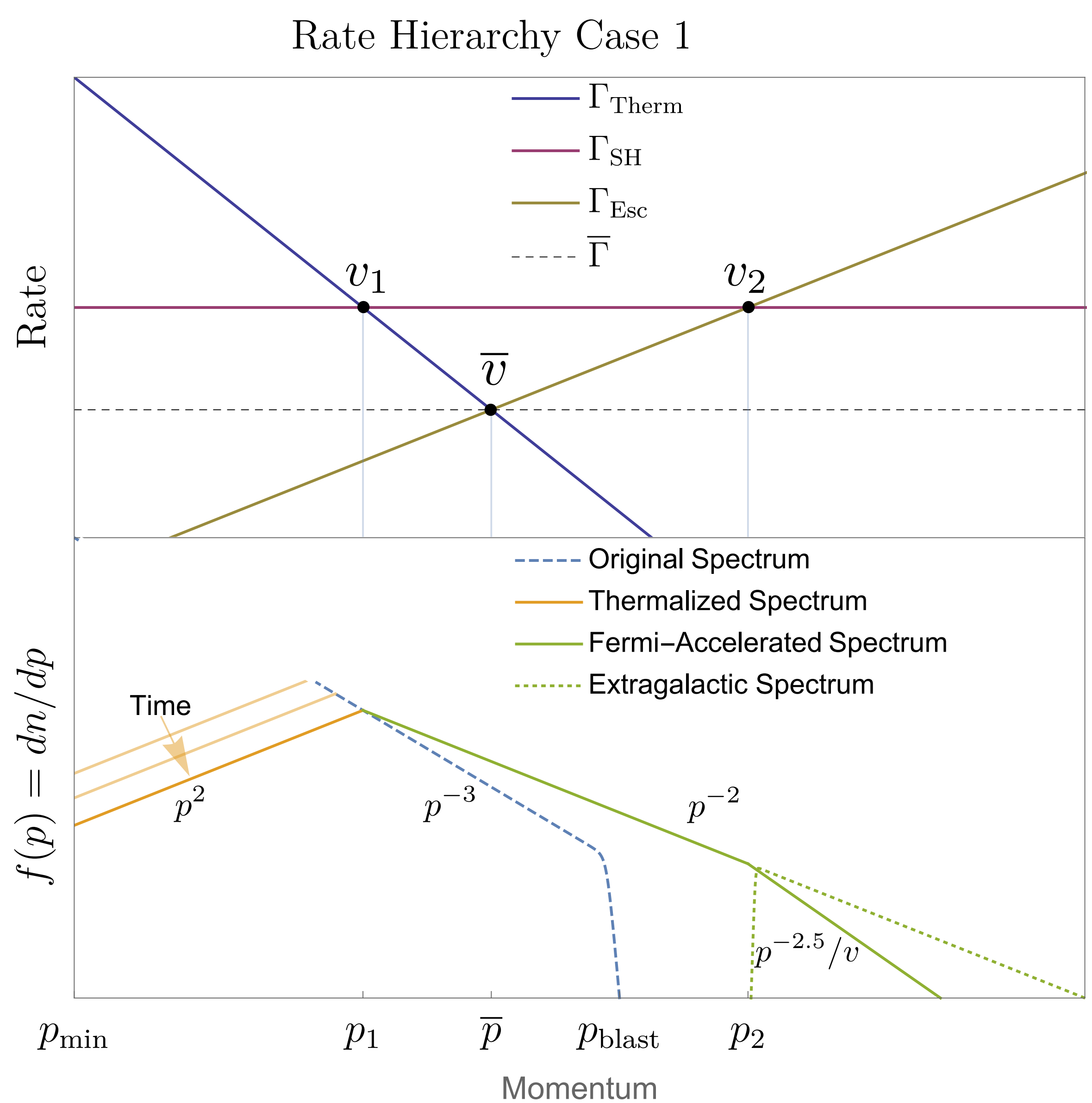

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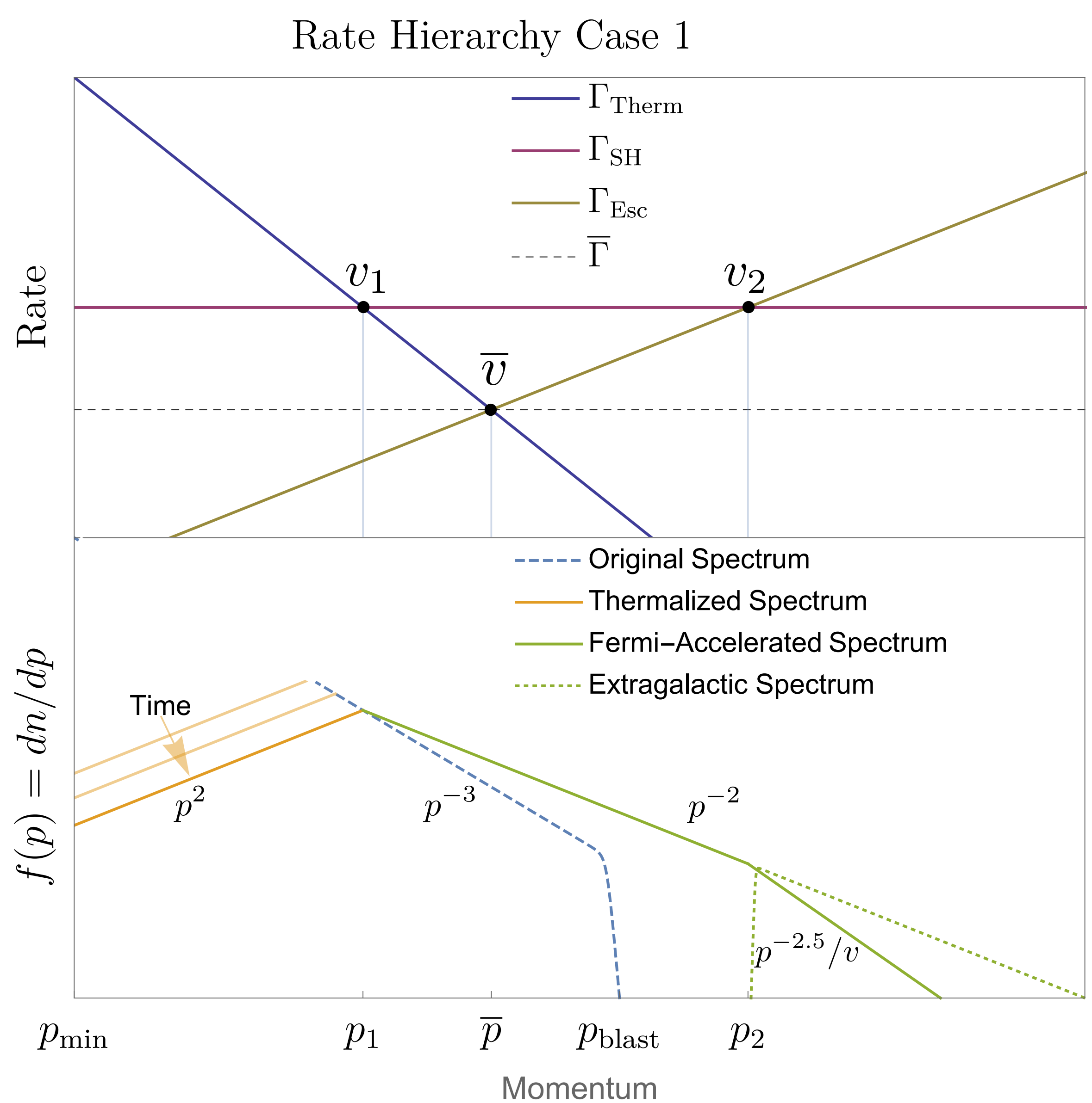

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- To be Fermi-accelerated, CHAMPs must encounter critical shock $v_s = v_1$

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

- CHAMPs with $m/q^2 \gtrsim 10^5\,\text{GeV}$ don't thermalize before encountering shock

(ie $v_1 \lesssim v_{\rm vir}$)

↓

- Efficiently ejected from disk

Diffusion into Disk and Local Flux

- Problem
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- Solution
  - Solve transport equation

Diffusion into Disk and Local Flux

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

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

$$n(0,z) = n(t, \pm H_c/2) = f_X n_0, \qquad n_0 \approx \frac{0.3}{m}\ \mathrm{GeV/cm^3}$$

Direct Detection

- Fermi-accelerated CHAMP background moving faster than typically assumed Dark Matter speeds $\sim 220\ \mathrm{km/s}$
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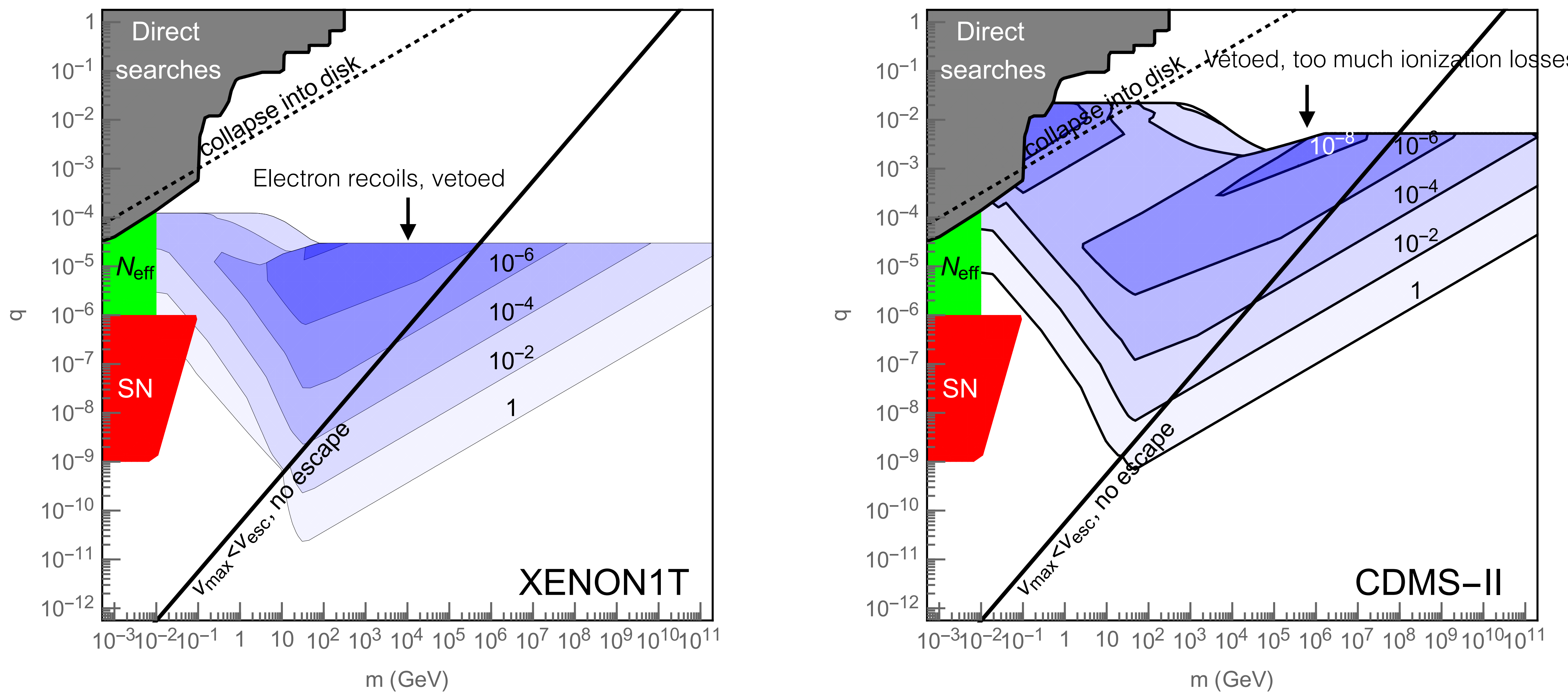
(4) Relativistic CHAMPs emit or induce Cherenkov light when traveling through water detectors like Super Kamiokande

Nuclear Recoil at Underground Detectors

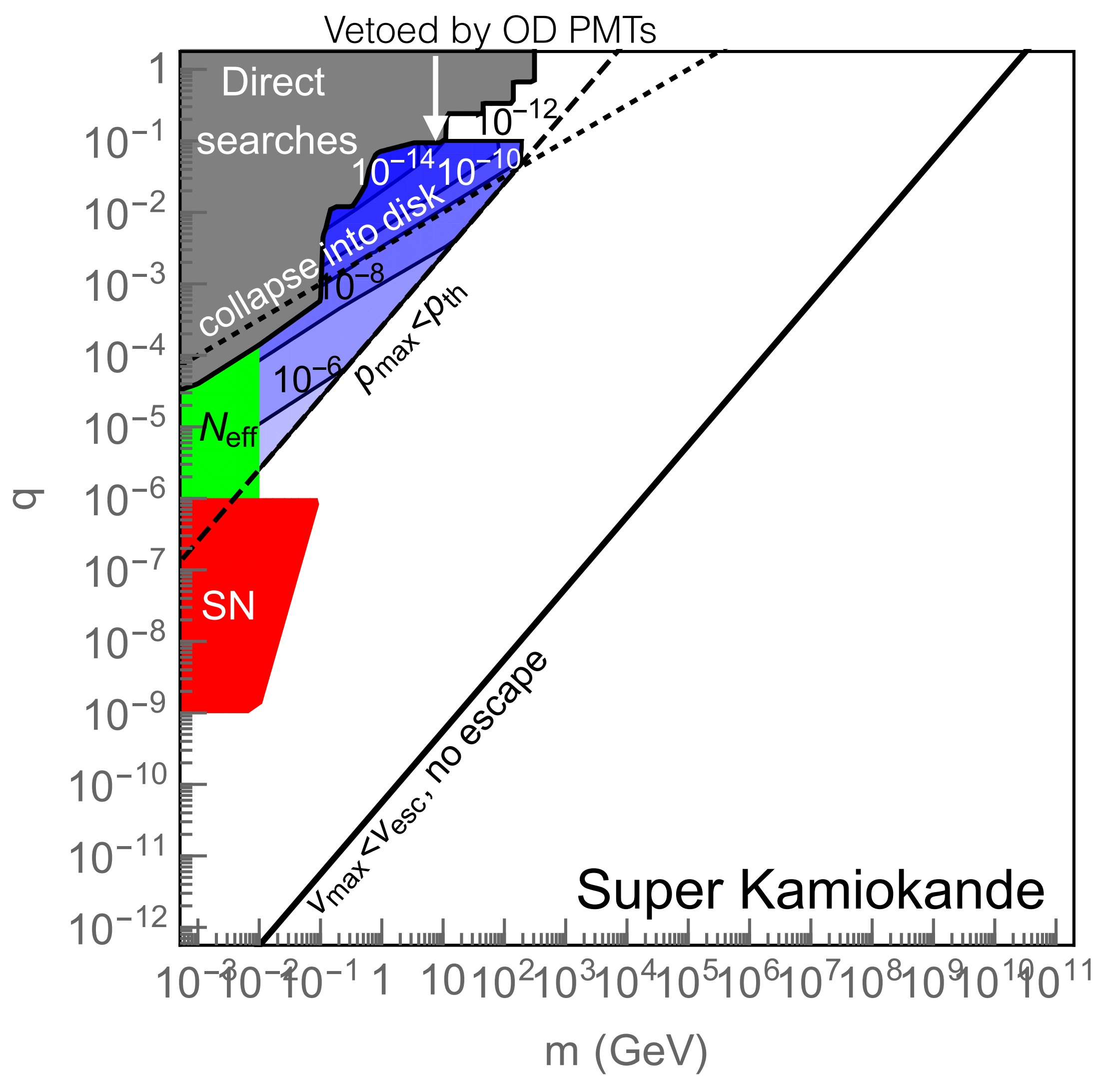
$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2 Z^2 q^2}{\mu^2 v^4 (1-\cos\theta)^2}$$

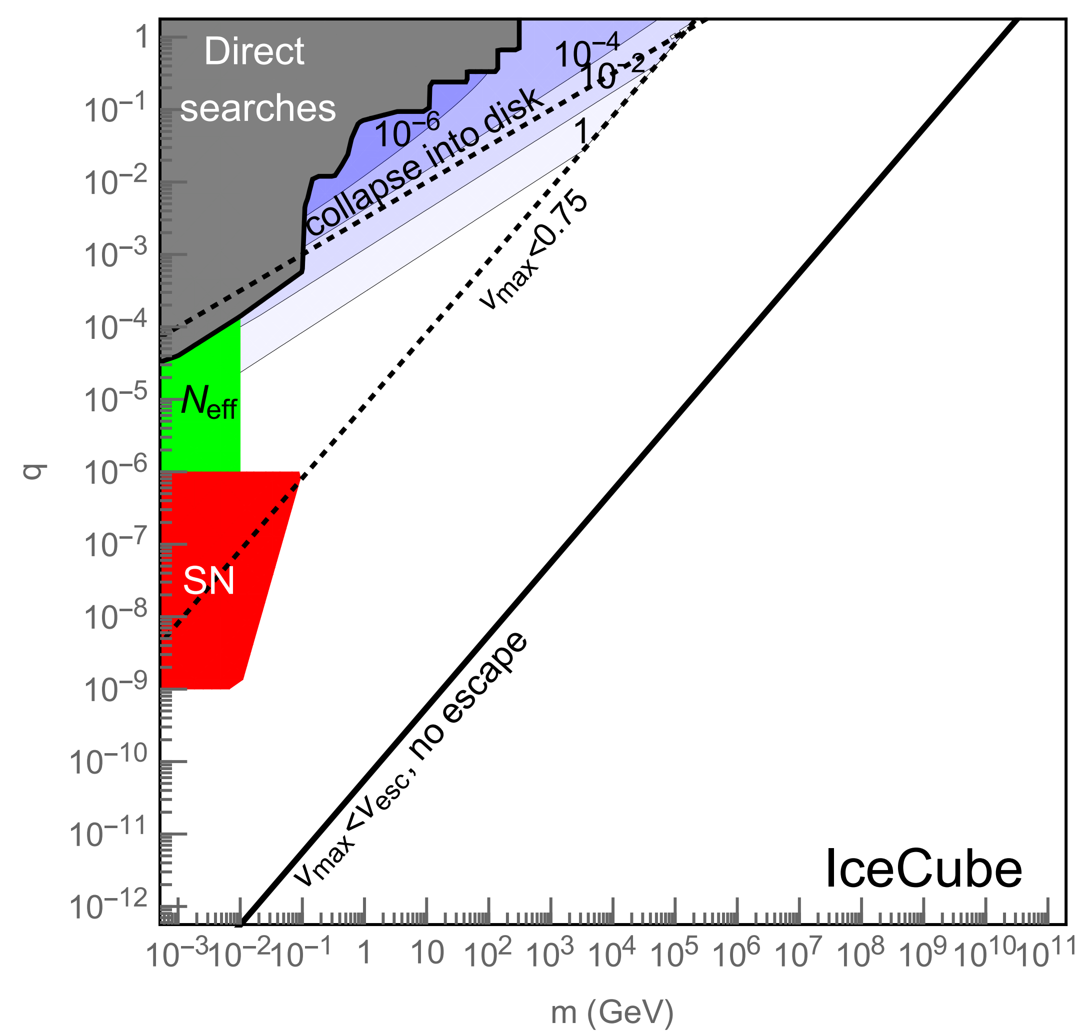
$$\Gamma_{Sig} = N_N \int dv\, \sigma(E_R > E_{R,th}) v \frac{dn_A}{dv} \simeq N_N \left[\sigma(E_R > E_{R,th}) v \frac{dn_A}{d\ln v}\right]_{v=v_-} < \begin{cases} \text{15 events/1 ton-year (Xenon1T)} \\ \text{10 events/600 kg-day (CDMS-II)} \end{cases}$$



Induced/Emitted Cherenkov Light

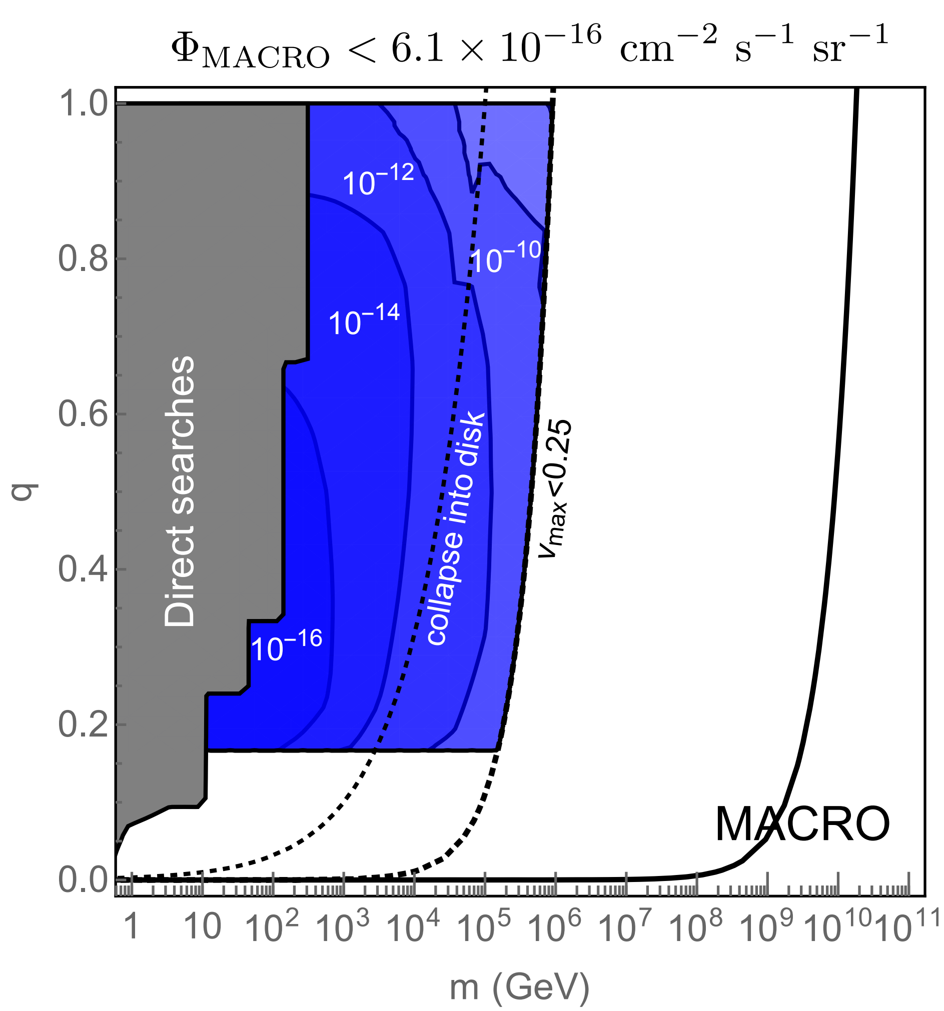
- Recoiling electrons can emit detectable Cherenkov light in Super-K
- Relativistic CHAMPs passing through Antarctic ice may produce more Cherenkov photons than IceCube's dark count

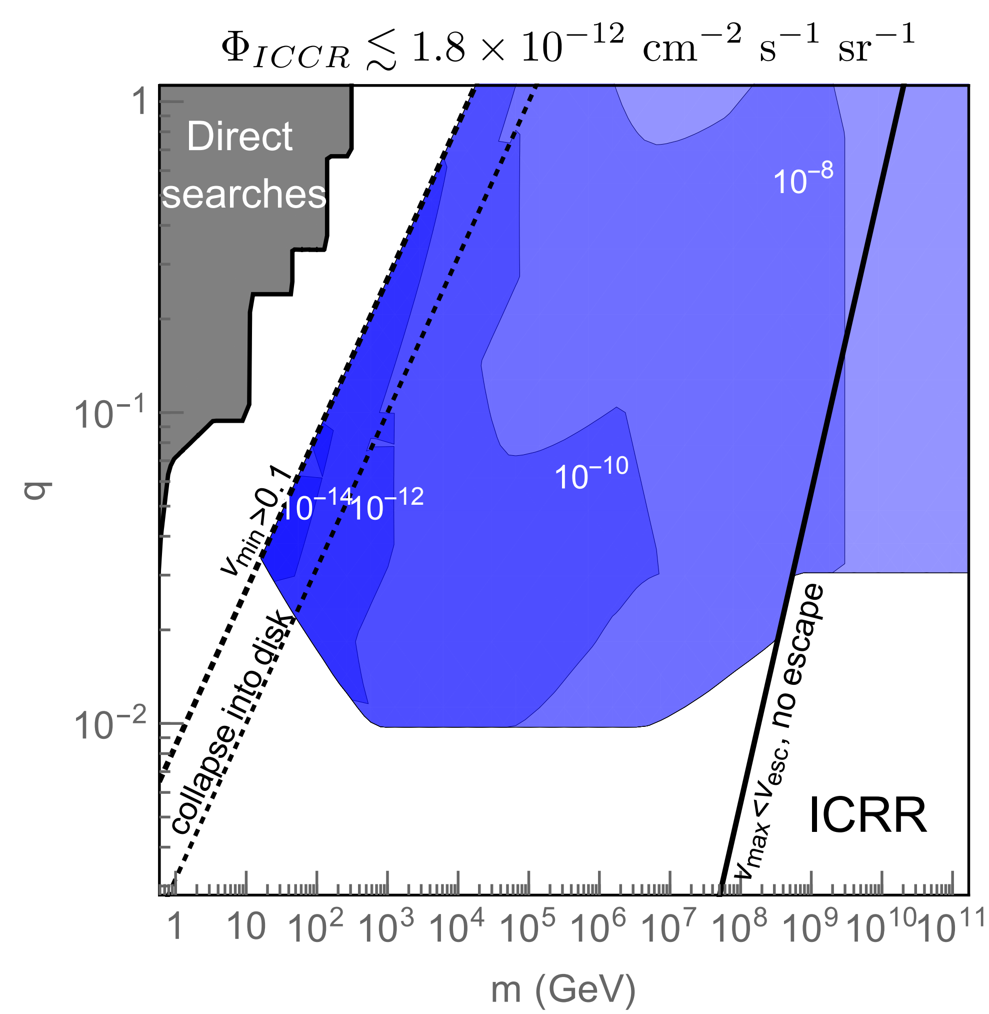




Ionization Particle Searches

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

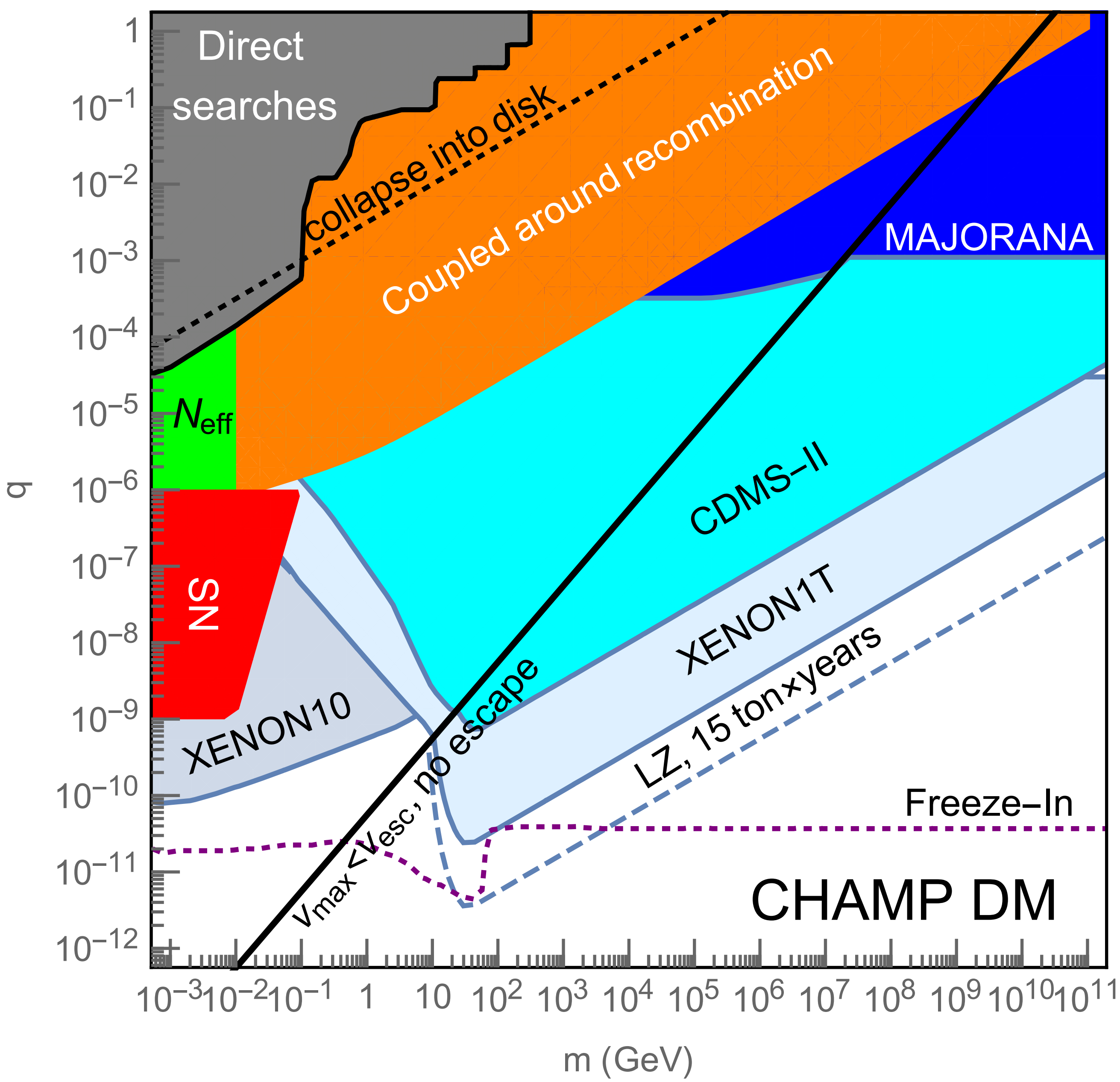




Summary

- $m \lesssim 10^{10} q \ \ \text{GeV}$
  Large flux of accelerated CHAMPs in the disk today

- Nuclear/electron recoil experiments, Cherenkov and ionization detectors place stringent bounds on fraction of CHAMP dark matter



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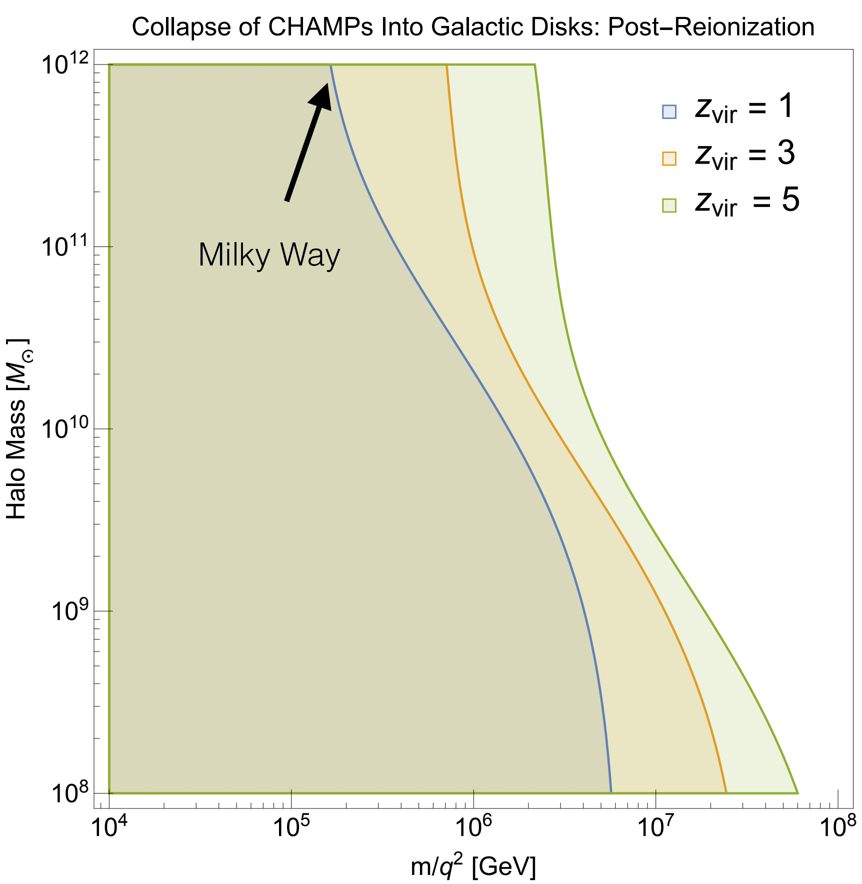
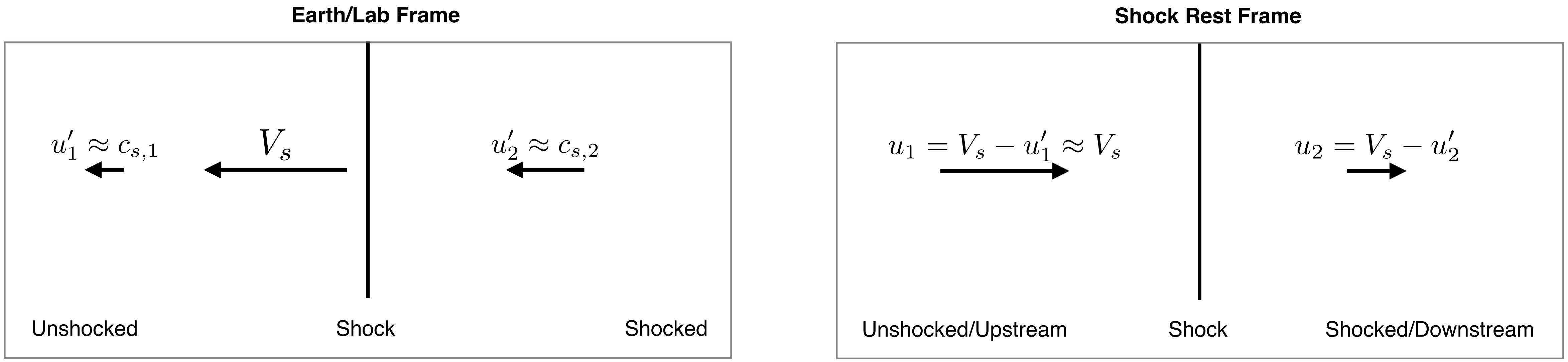


- Collapsing CHAMPs ruled out if $f_X = \frac{\Omega_X}{\Omega_{\rm DM}} = 1$
- If $f_X < 1$, number density of CHAMPs in MW disk about 100x greater if collapse, $m/q^2 \lesssim 10^5\ \mathrm{GeV}$

Fermi Acceleration

A. Bell 1978, L. Drury 1983



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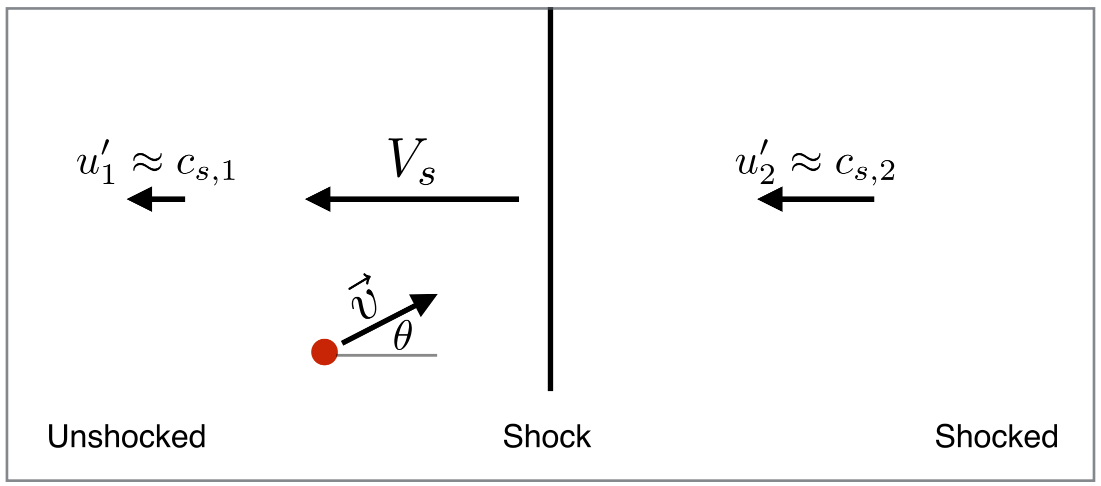
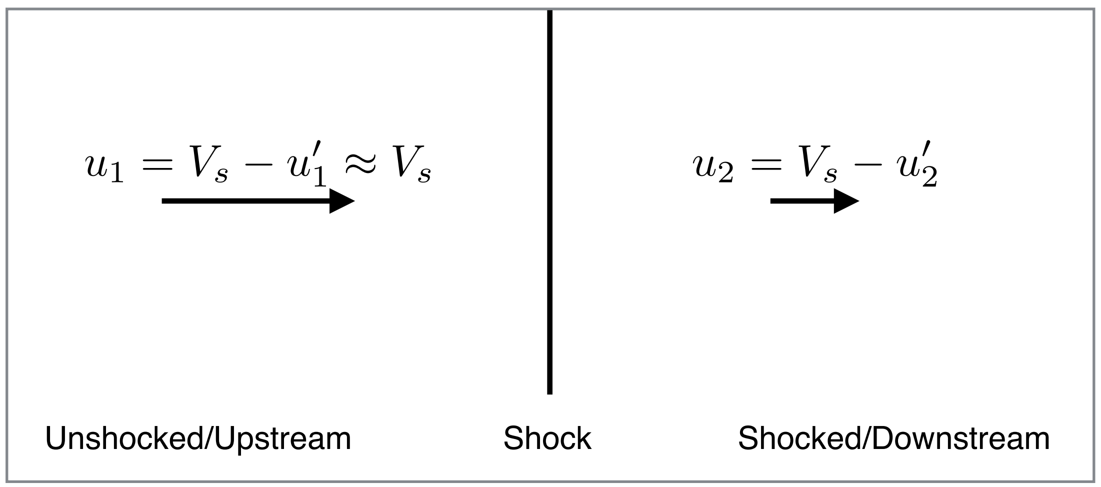
Earth/Lab Frame



Shock Rest Frame

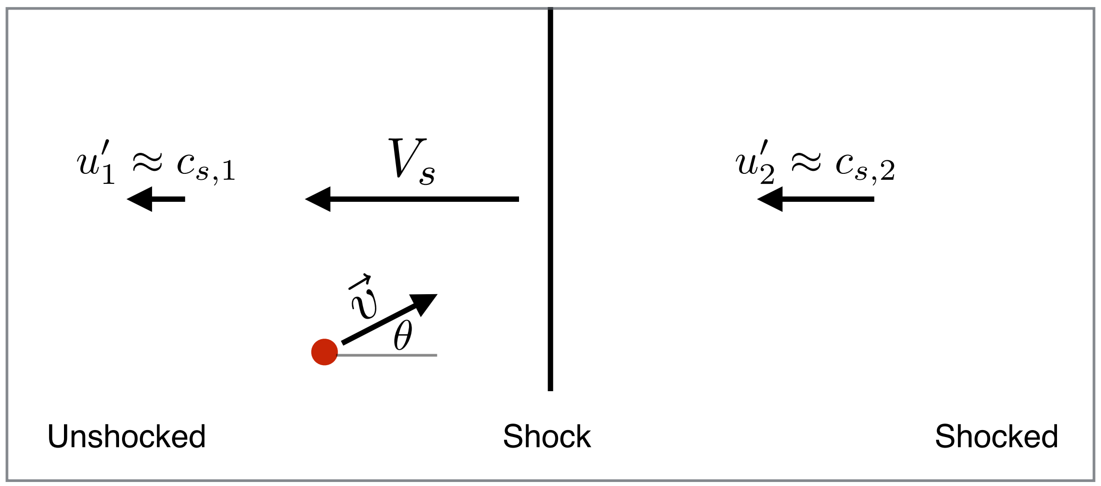


$$\vec{p}_0 = m\vec{v}$$

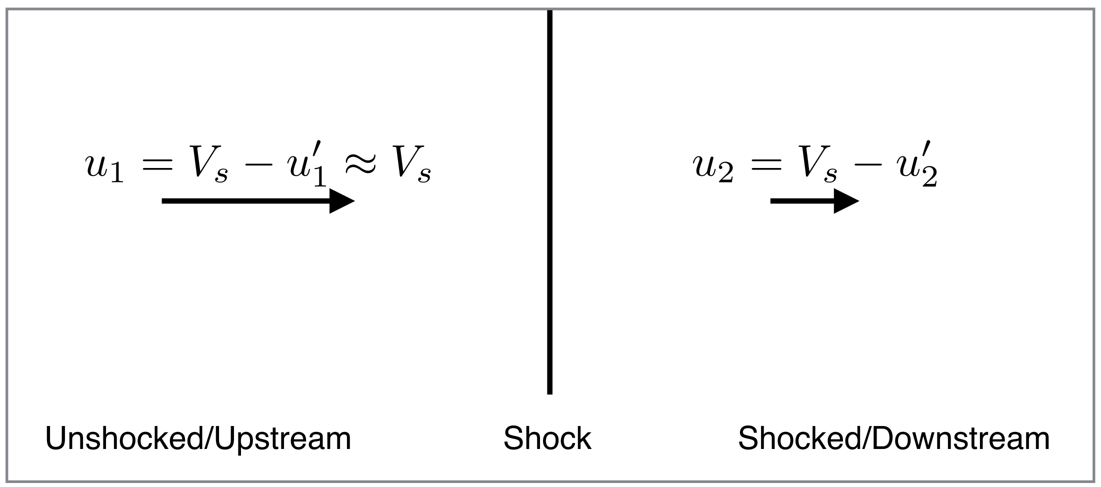
Fermi Acceleration

A. Bell 1978, L. Drury 1983

Earth/Lab Frame



Shock Rest Frame

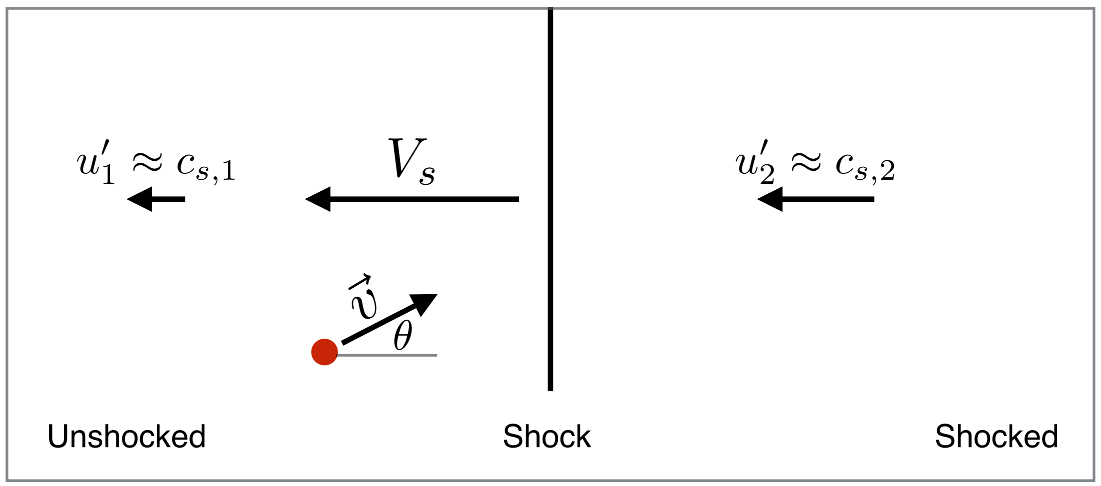


$$\vec{p}_s = m(\vec{v} + \vec{u}_1)$$

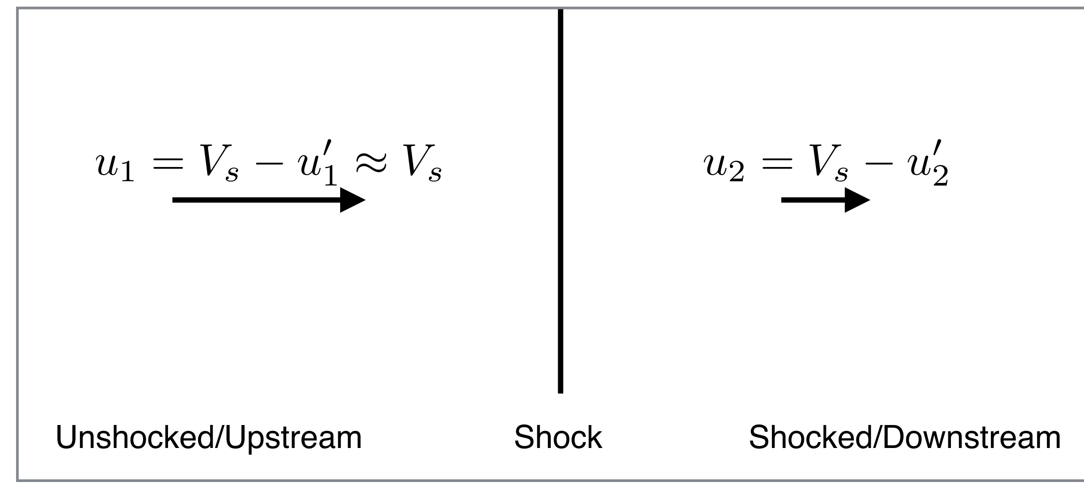
Fermi Acceleration

A. Bell 1978, L. Drury 1983

Earth/Lab Frame



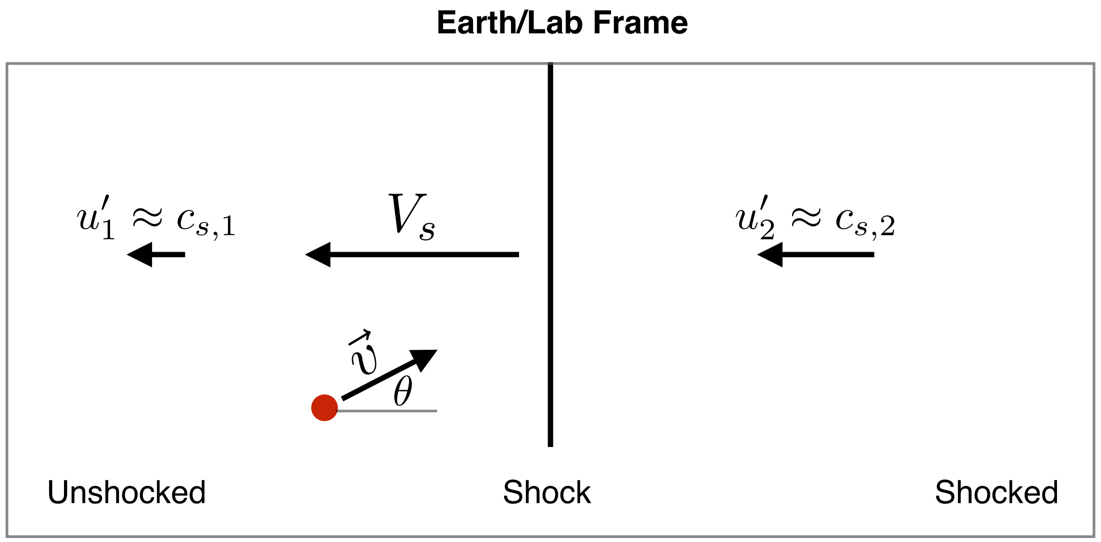
Shock Rest Frame

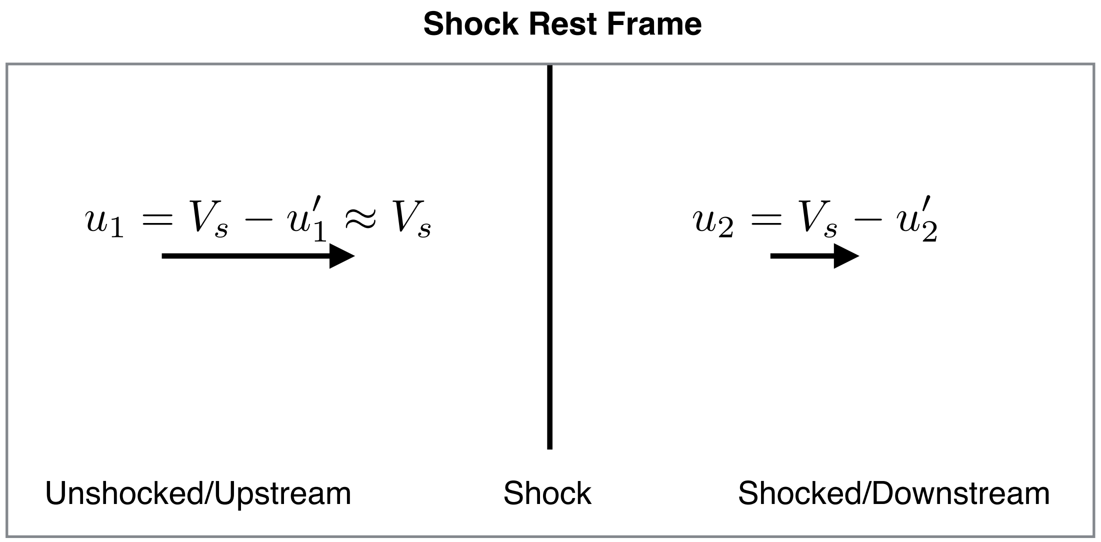


$$\vec{p}_{ds} = m(\vec{v} + \vec{u}_1 - \vec{u}_2)$$

Fermi Acceleration

A. Bell 1978, L. Drury 1983



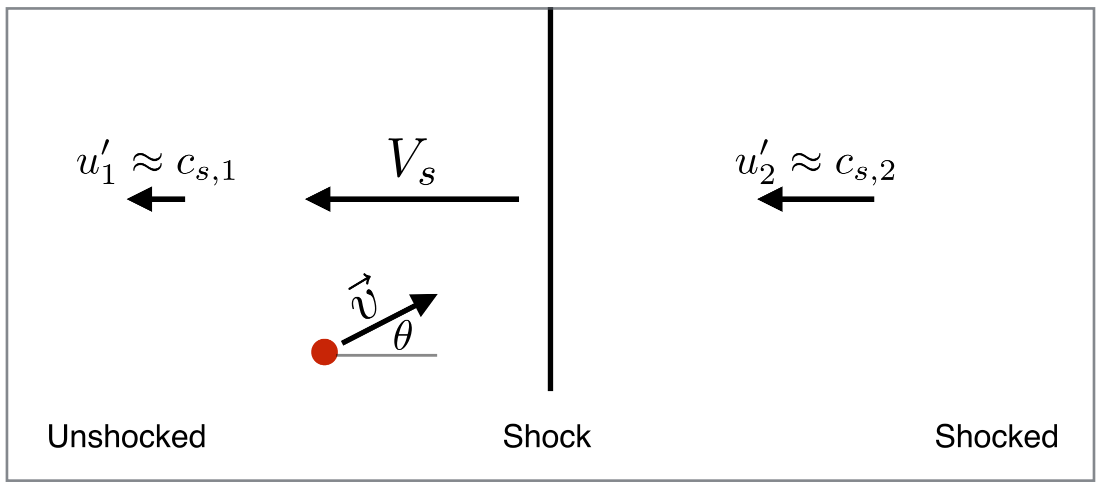


$$p_{ds} = m\sqrt{v^2 + 2v(u_1 - u_2)\cos\theta + (u_1 - u_2)^2}$$

Fermi Acceleration

A. Bell 1978, L. Drury 1983

Earth/Lab Frame



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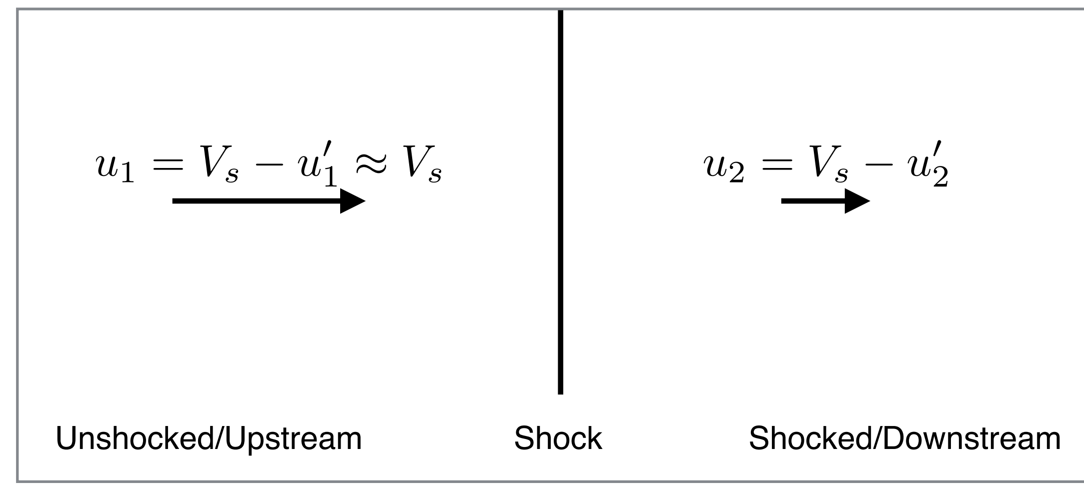
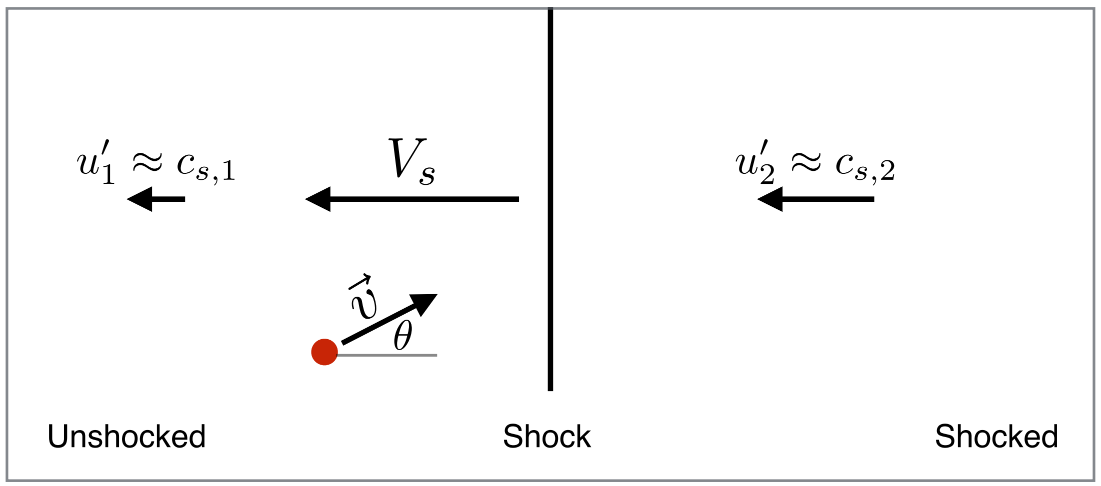


$$p_{ds} \simeq p_0 (1 + \frac{u_1 - u_2}{v} \cos\theta)$$

Fermi Acceleration

A. Bell 1978, L. Drury 1983

Earth/Lab Frame



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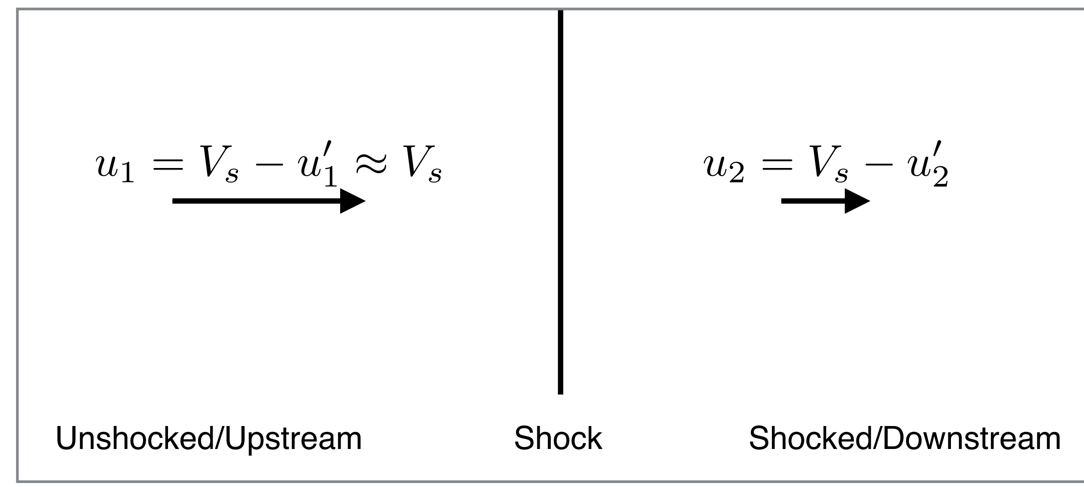
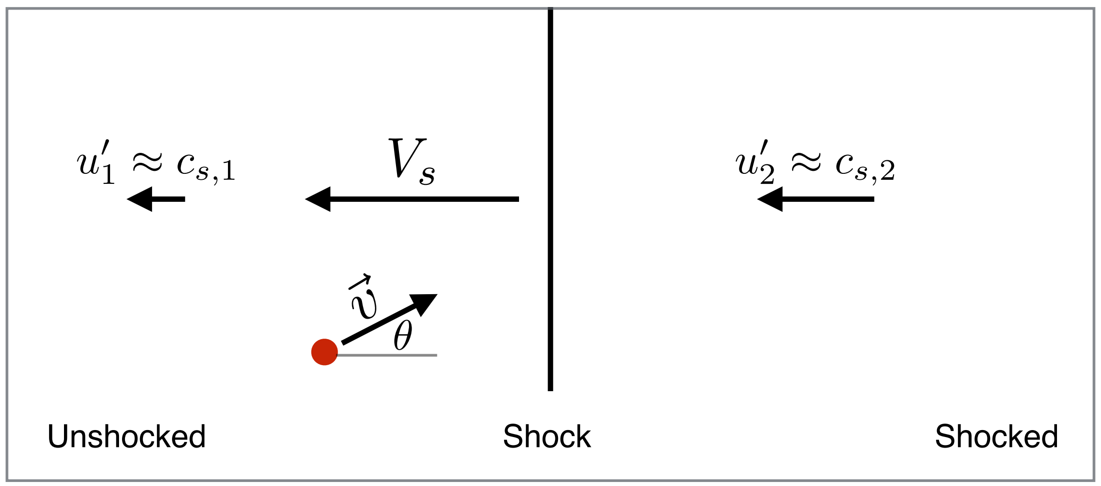


$$p_{ds} \simeq p_0\left(1 + \frac{u_1 - u_2}{v}\cos\theta\right) \longrightarrow$$

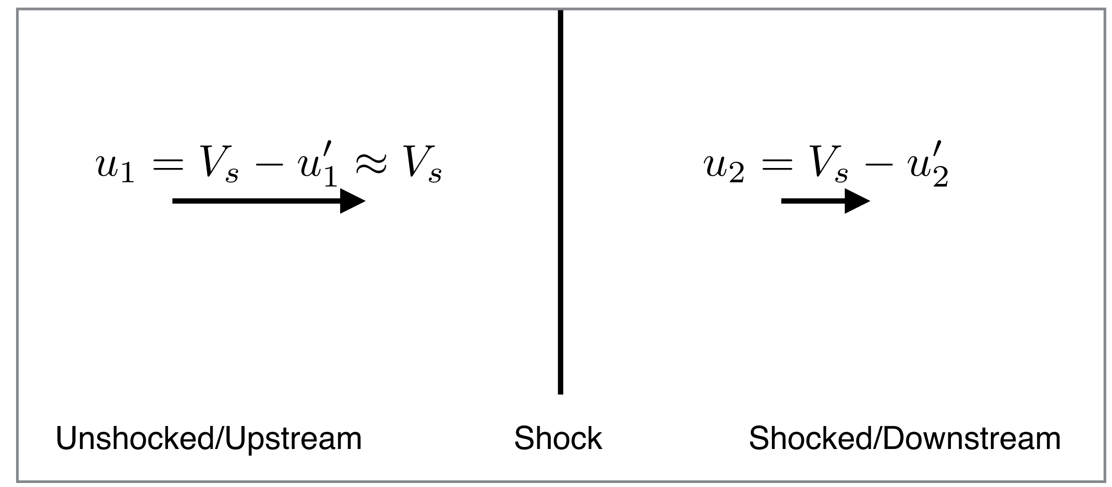
Fermi Acceleration

A. Bell 1978, L. Drury 1983

Earth/Lab Frame



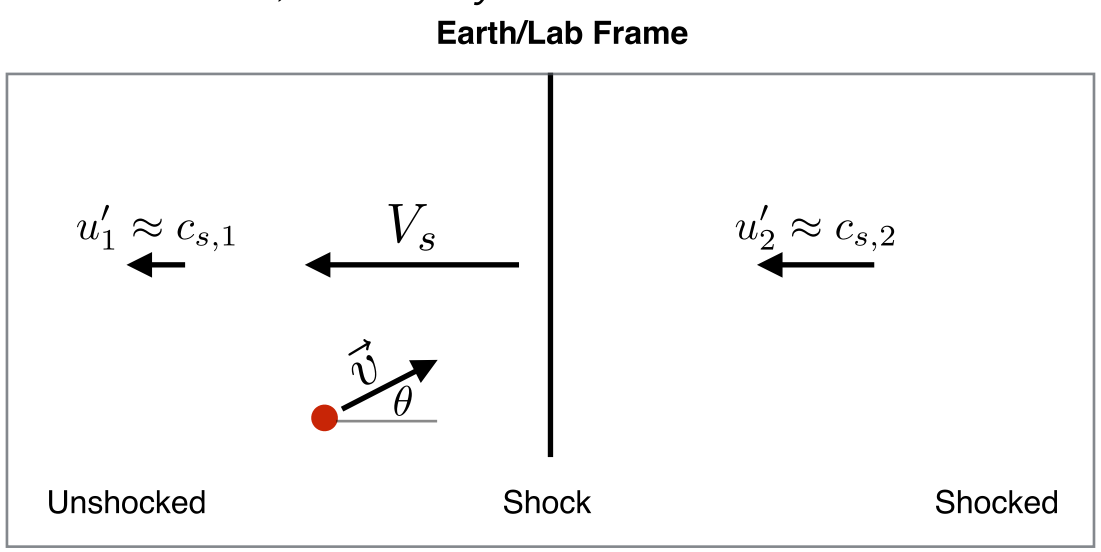
Shock Rest Frame

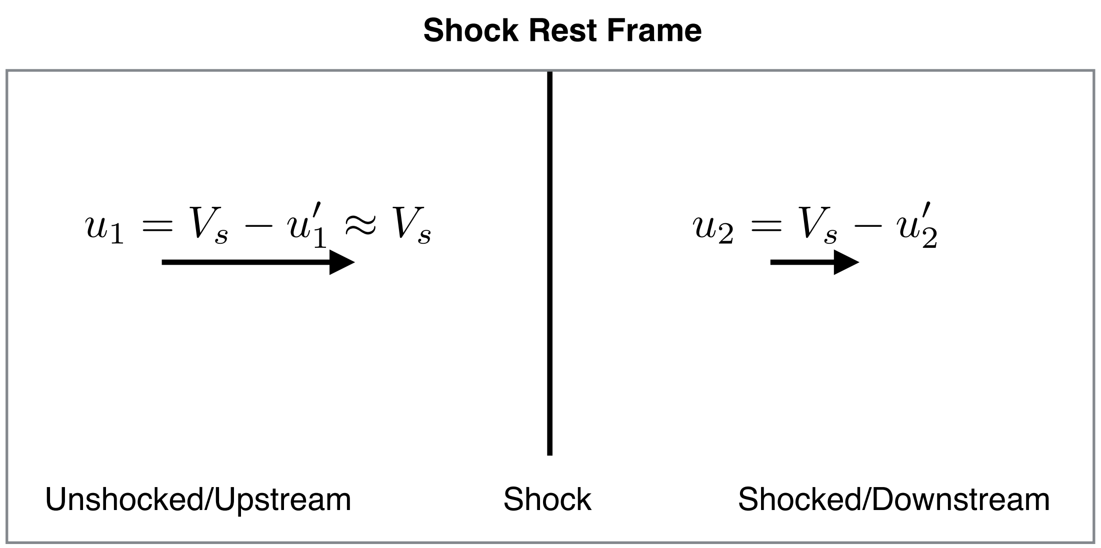


$$p_{ds} \simeq p_0\left(1 + \frac{u_1 - u_2}{v}\cos\theta\right) \longrightarrow \Delta p = p_0 \frac{u_1 - u_2}{v}\cos\theta$$

Fermi Acceleration

A. Bell 1978, L. Drury 1983





$$p_{ds} \simeq p_0 \left(1 + \frac{u_1 - u_2}{v} \cos\theta\right) \longrightarrow \langle \Delta p \rangle = p_0 \frac{u_1 - u_2}{v} \frac{2}{3}$$

Fermi Acceleration

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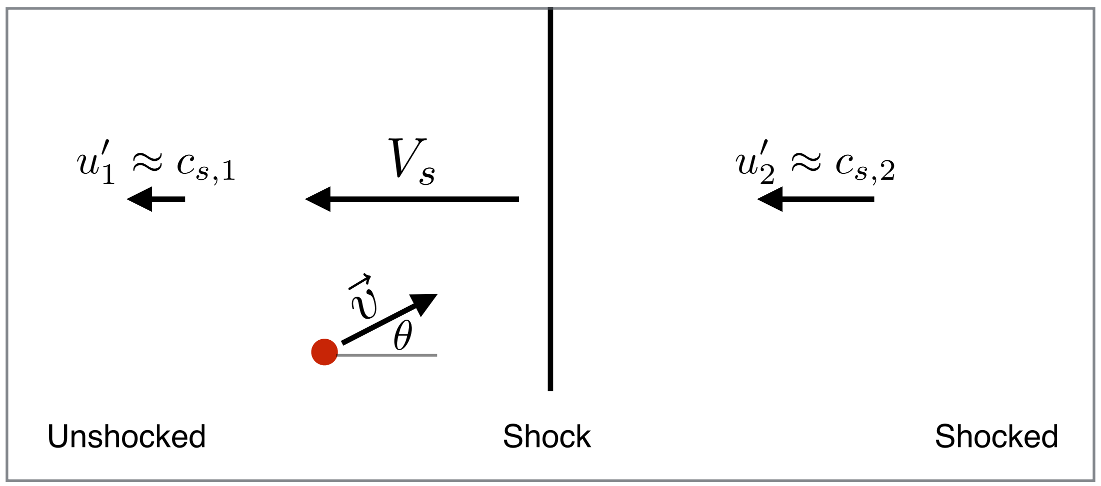
Earth/Lab Frame



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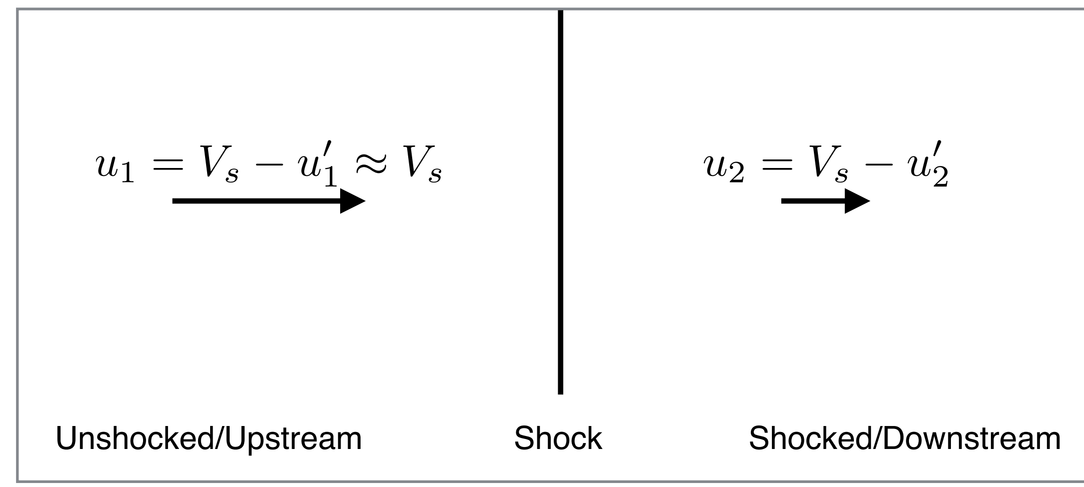

$$p_{ds} \simeq p_0 \left(1 + \frac{u_1 - u_2}{v} \cos\theta\right) \longrightarrow \langle \Delta p \rangle_{cycle} = p_0 \frac{u_1 - u_2}{v} \frac{4}{3}$$

Fermi Acceleration

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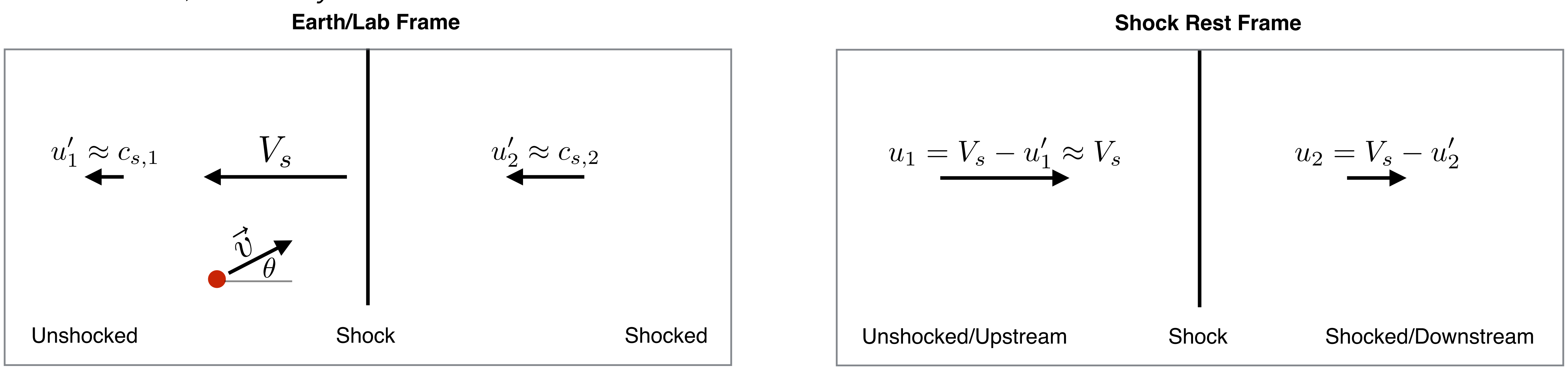

$$p_{ds} \simeq p_0 \left(1 + \frac{u_1 - u_2}{v} \cos\theta\right) \longrightarrow \langle \Delta p \rangle_{cycle} = p_0 \frac{u_1 - u_2}{v} \frac{4}{3}$$

$$p_1 = p_0 + \Delta p_0$$

Fermi Acceleration

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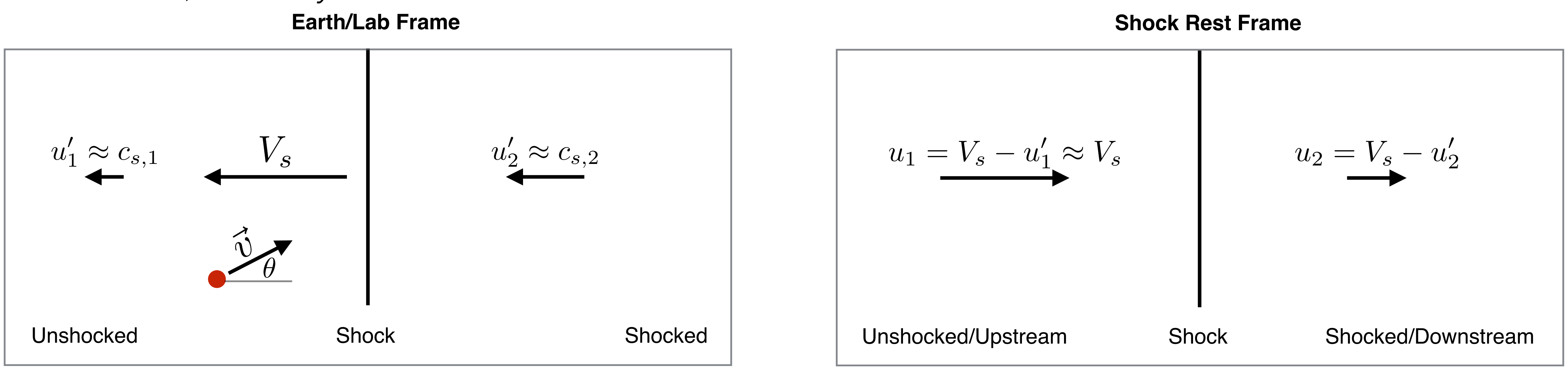

$$p_{ds} \simeq p_0 (1 + \frac{u_1 - u_2}{v} \cos\theta) \longrightarrow \langle \Delta p \rangle_{cycle} = p_0 \frac{u_1 - u_2}{v} \frac{4}{3}$$

$$p_1 = p_0 \left(1 + \frac{4}{3} \frac{u_1 - u_2}{v_0}\right)$$

Fermi Acceleration

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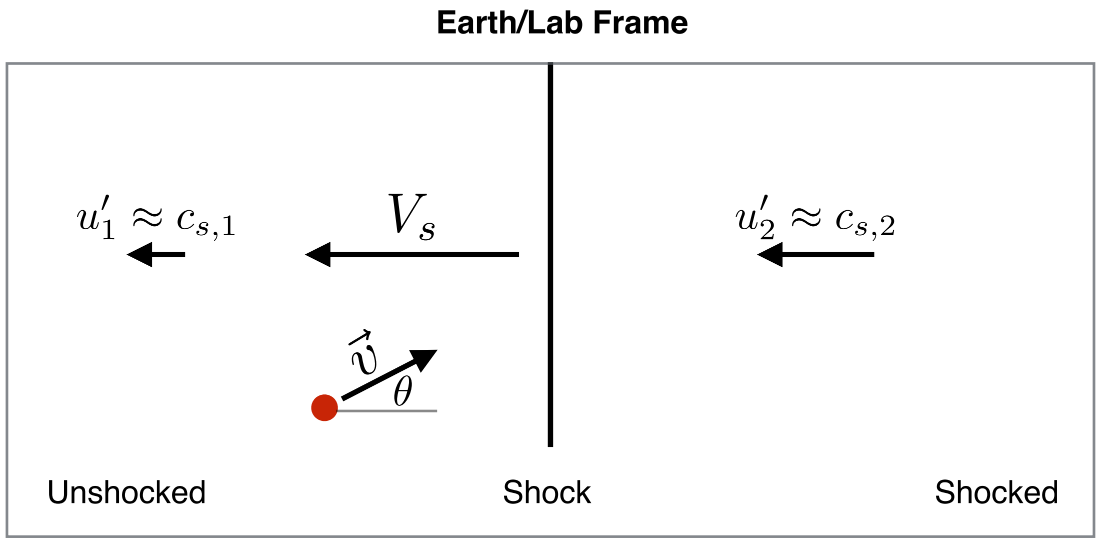
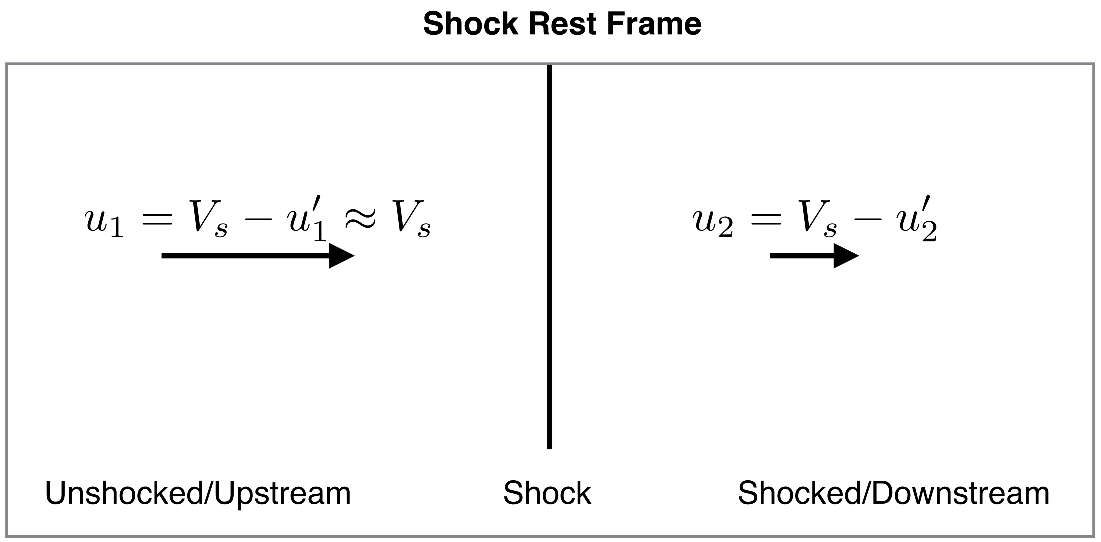




$$p_{ds} \simeq p_0(1 + \frac{u_1 - u_2}{v}\cos\theta) \longrightarrow \langle \Delta p \rangle_{cycle} = p_0 \frac{u_1 - u_2}{v}\frac{4}{3}$$

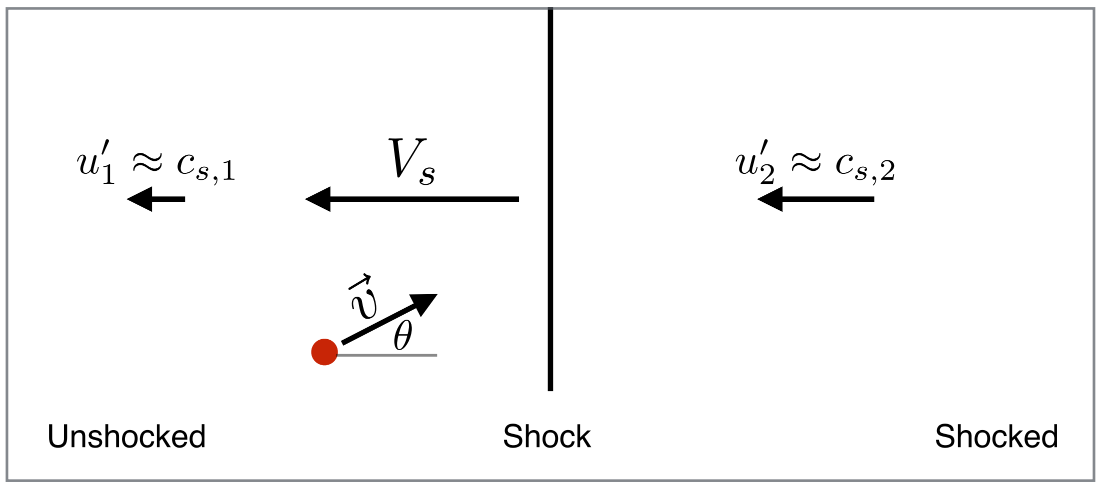
$$p_1 = p_0\left(1 + \frac{4}{3}\frac{u_1 - u_2}{v_0}\right)$$

$$p_2 = p_1 + \Delta p_1$$

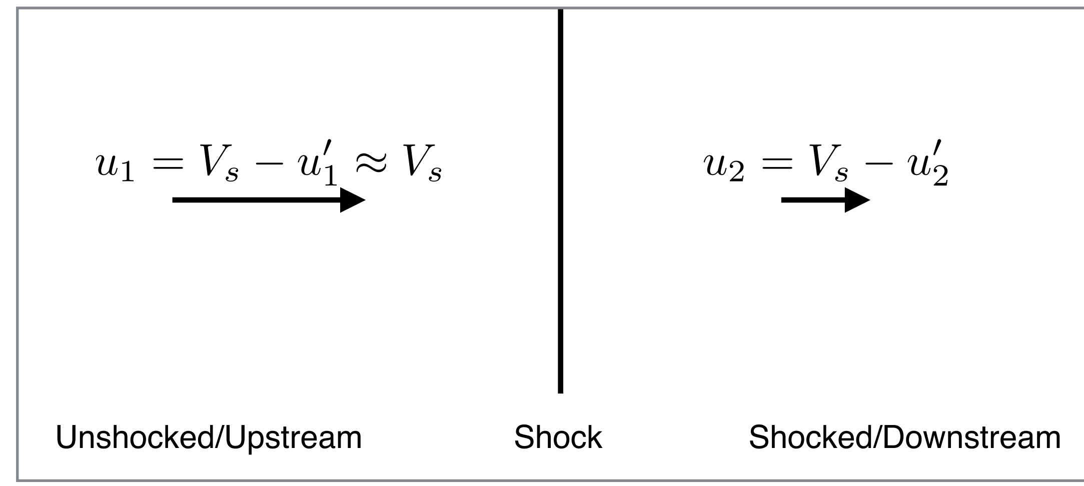
Fermi Acceleration

A. Bell 1978, L. Drury 1983

Earth/Lab Frame



Shock Rest Frame



$$p_{ds} \simeq p_0 (1 + \frac{u_1 - u_2}{v} \cos\theta) \longrightarrow \langle \Delta p \rangle_{cycle} = p_0 \frac{u_1 - u_2}{v} \frac{4}{3}$$

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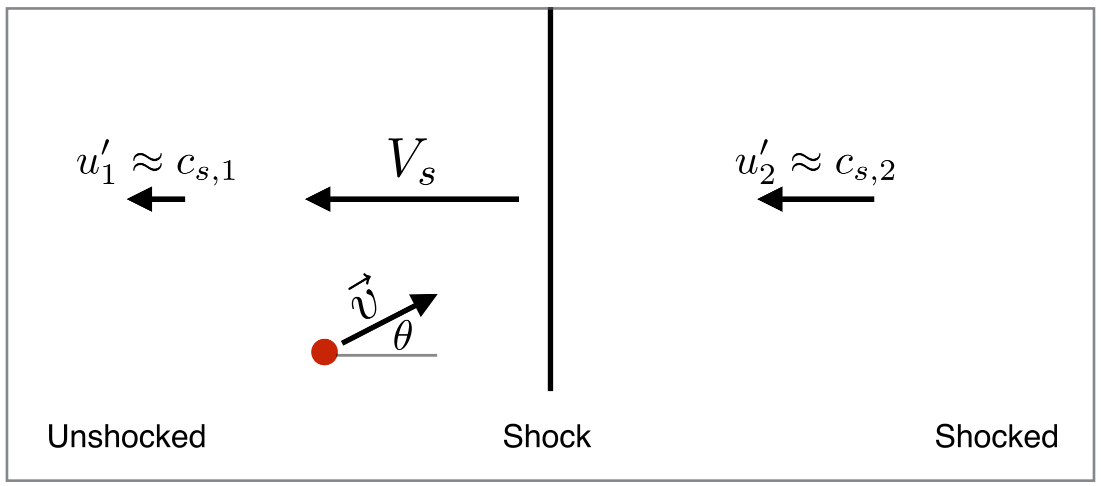
Earth/Lab Frame



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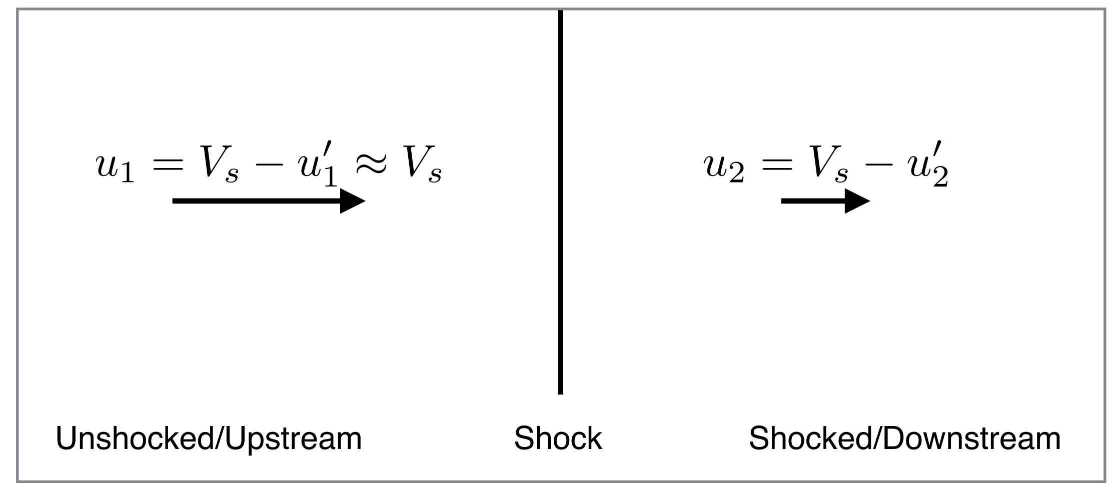

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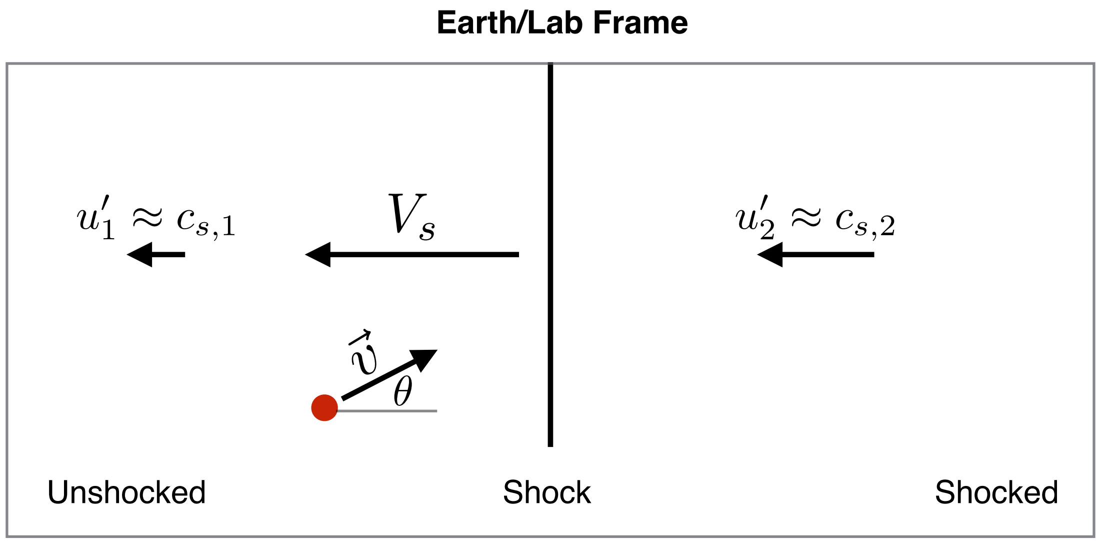

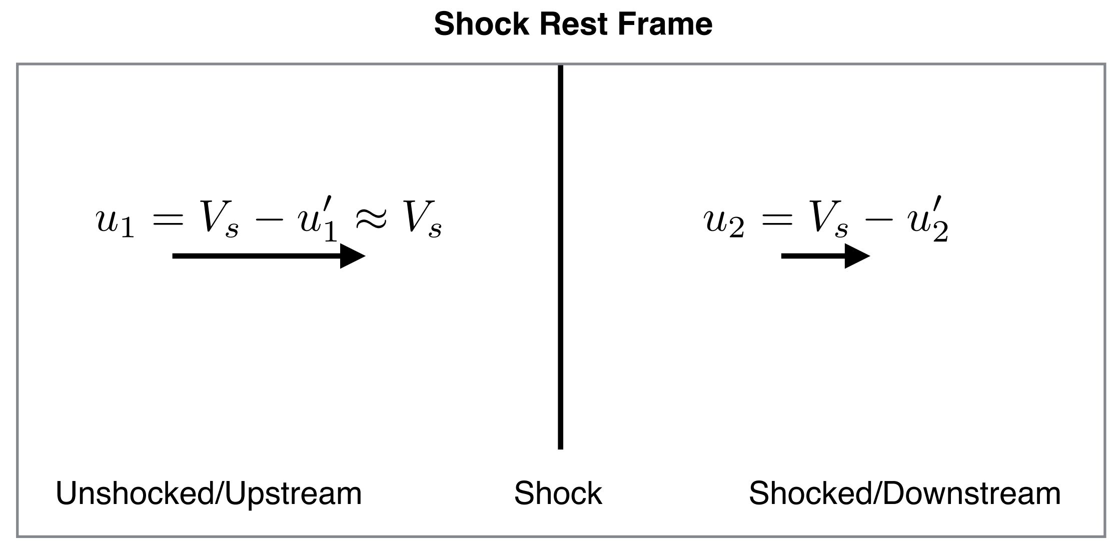

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$$p_n = p_0 \prod_{i=1}^{n} \left(1 + \frac{4}{3} \frac{u_1 - u_2}{v_{i-1}} \right)$$

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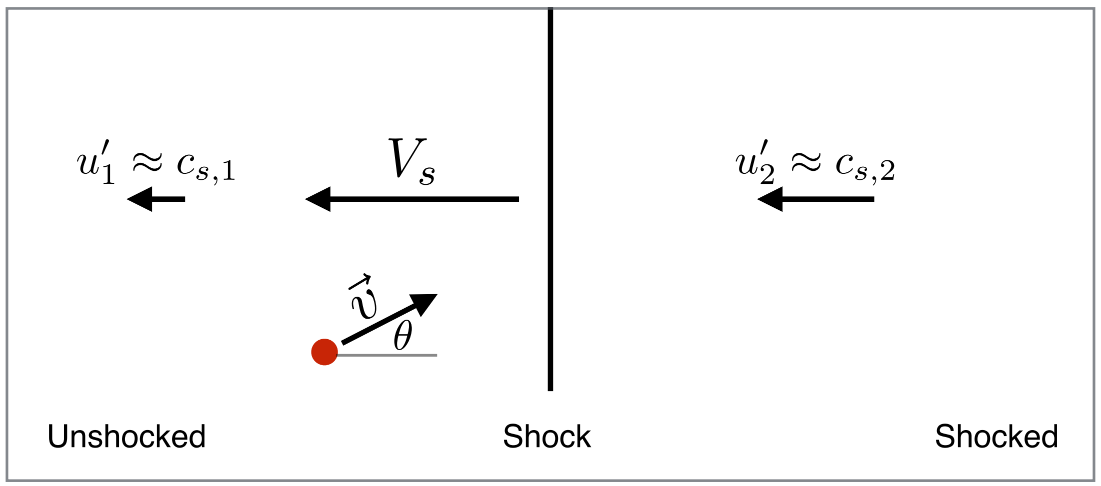
A. Bell 1978, L. Drury 1983

Earth/Lab Frame



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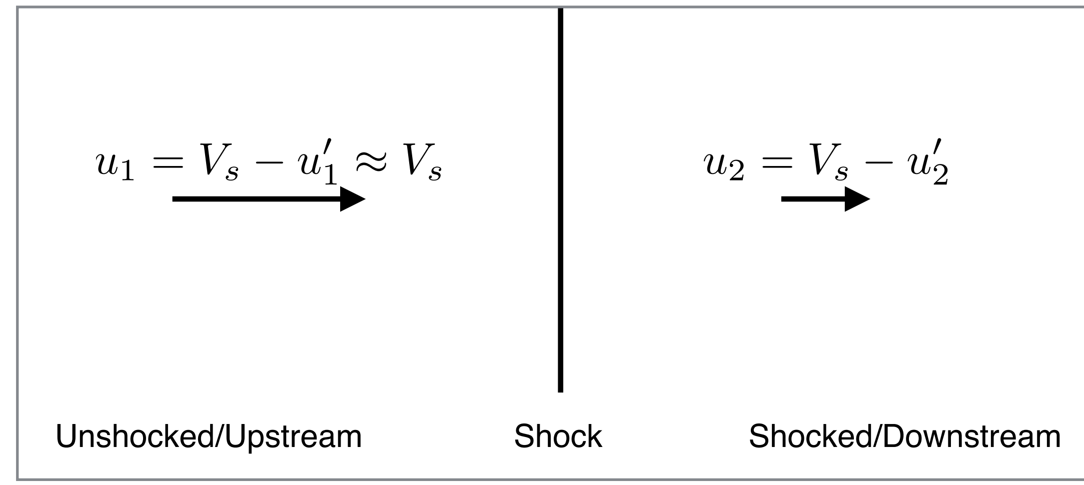
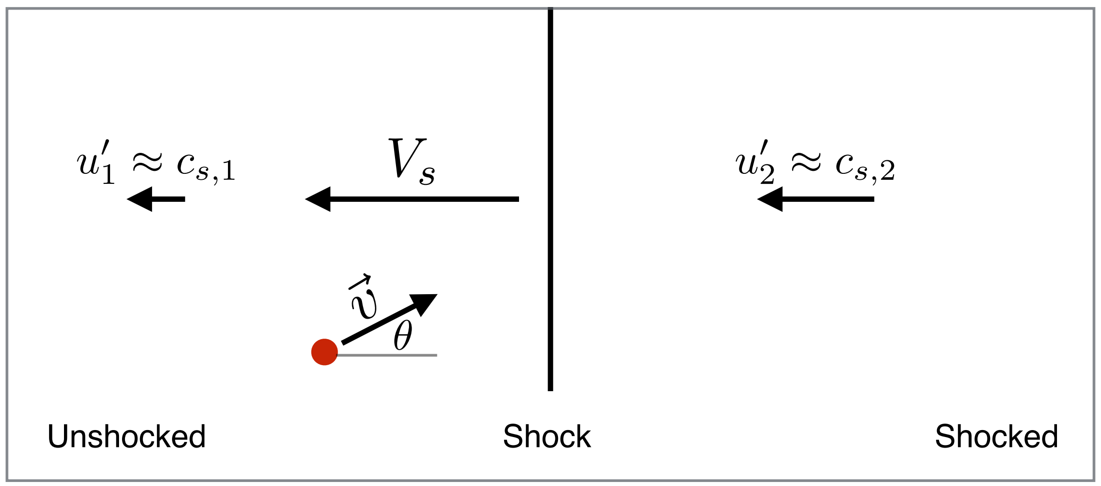


$$P_{goner} = \frac{\Phi_{out}}{\Phi_{in}}$$

Fermi Acceleration

A. Bell 1978, L. Drury 1983

Earth/Lab Frame



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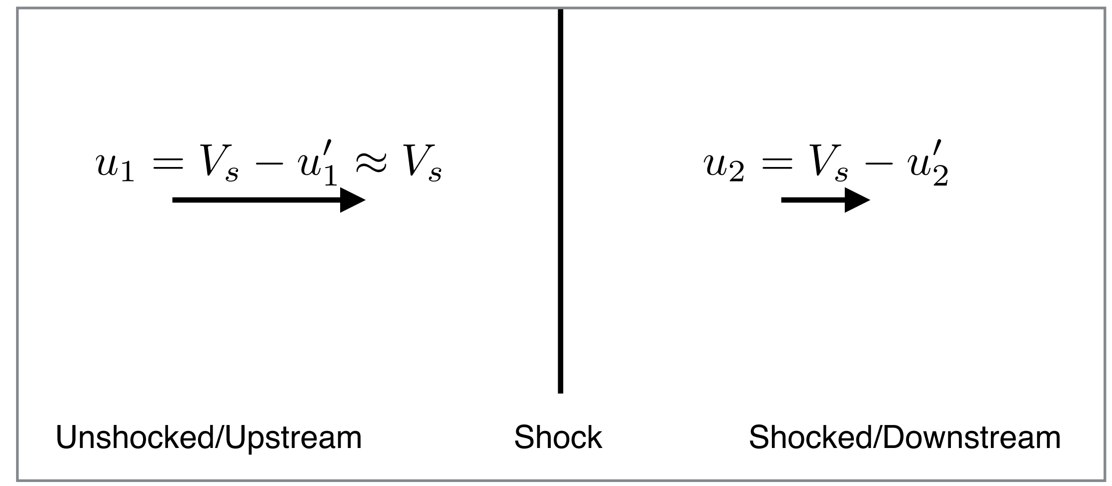

$$P_{goner} = \frac{\Phi_{out}}{\Phi_{in}} \longrightarrow \Phi_{out} = n u_2$$

Fermi Acceleration

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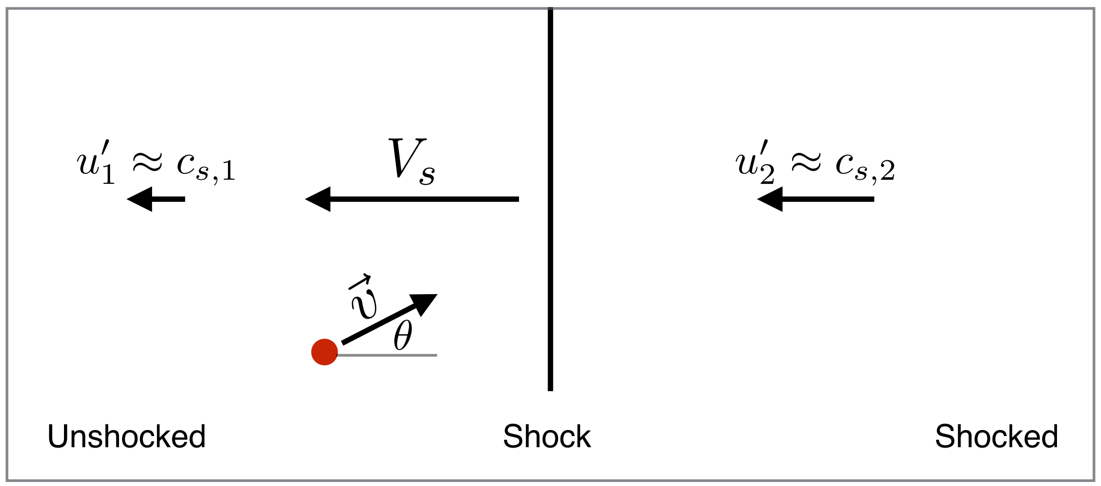
Earth/Lab Frame



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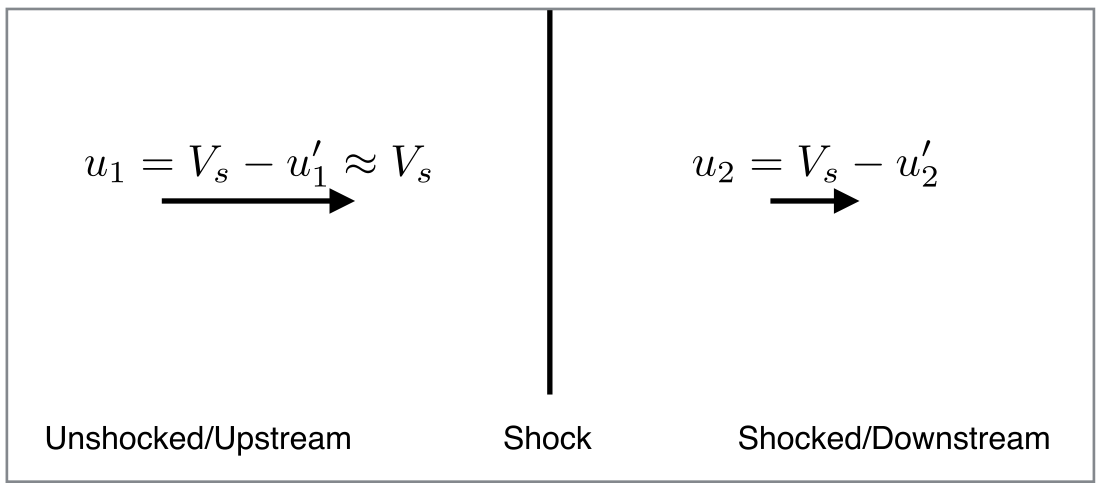


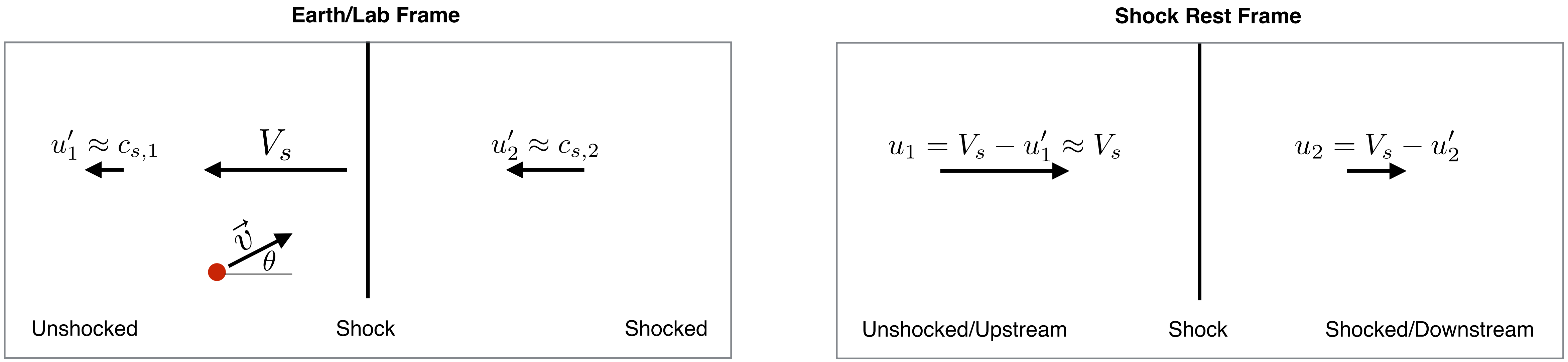
$$P_{goner} = \frac{\Phi_{out}}{\Phi_{in}}$$

$$\longrightarrow \quad \Phi_{out} = n u_2$$

$$\longrightarrow \quad \Phi_{in} = \frac{1}{4\pi R^2} \int_{shock} n\vec{v} \cdot \vec{da} = \frac{nv}{4}$$

Fermi Acceleration

A. Bell 1978, L. Drury 1983



$$P_{goner} = \frac{\Phi_{out}}{\Phi_{in}} \longrightarrow \Phi_{out} = nu_2$$

$$\longrightarrow \Phi_{in} = \frac{1}{4\pi R^2}\int_{shock} n\vec{v}\cdot d\vec{a} = \frac{nv}{4}$$

$$P_n = \prod_{i=1}^{n}\left(1 - \frac{4u_2}{v_{i-1}}\right)$$

Fermi Acceleration

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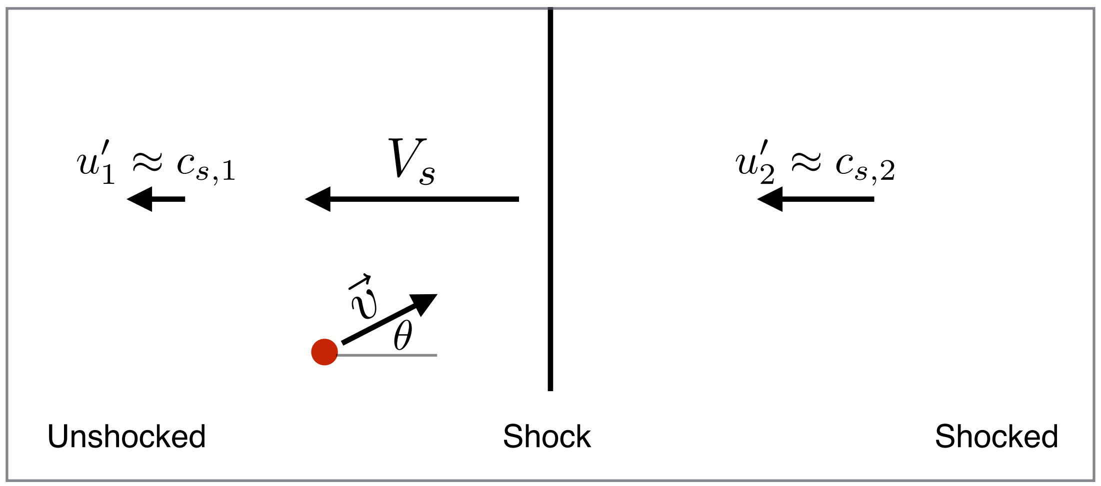
Earth/Lab Frame



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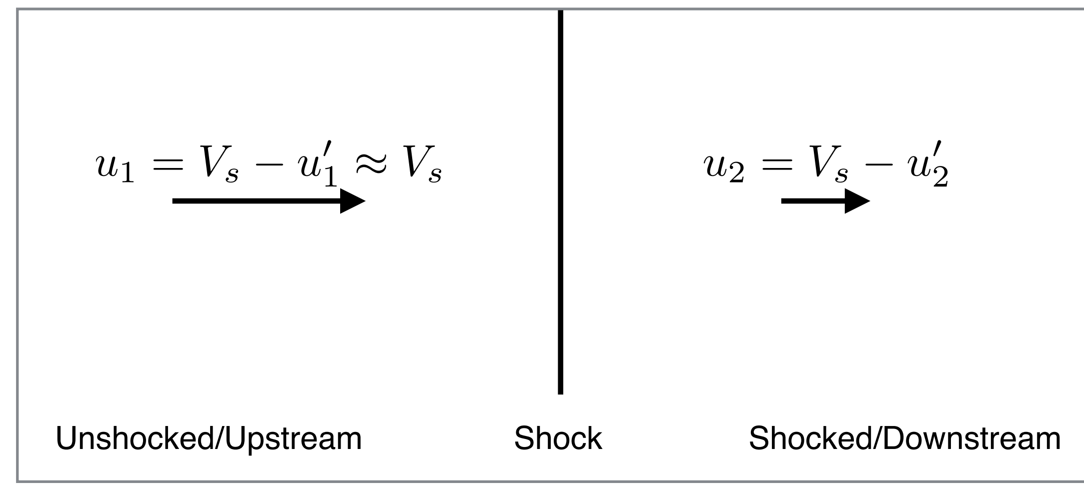

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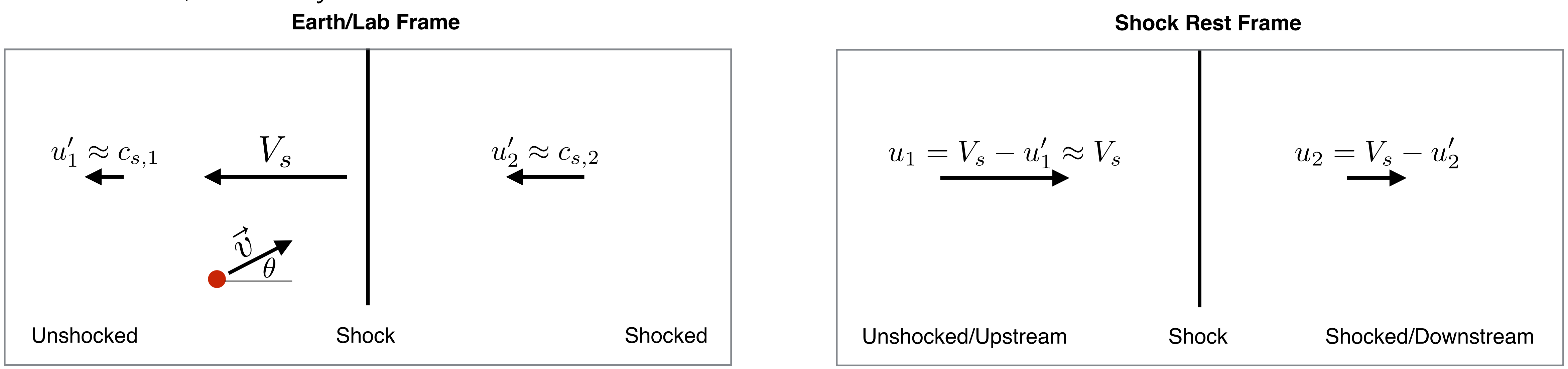

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$$\ln P_n = \sum_{i=1}^{n} \ln\left(1 - \frac{4u_2}{v_{i-1}}\right) \simeq -4u_2 \sum_{i=1}^{n} \frac{1}{v_{i-1}}$$

$$p_n = p_0 \prod_{i=1}^{n} \left(1 + \frac{4}{3} \frac{u_1 - u_2}{v_{i-1}}\right)$$

Fermi Acceleration

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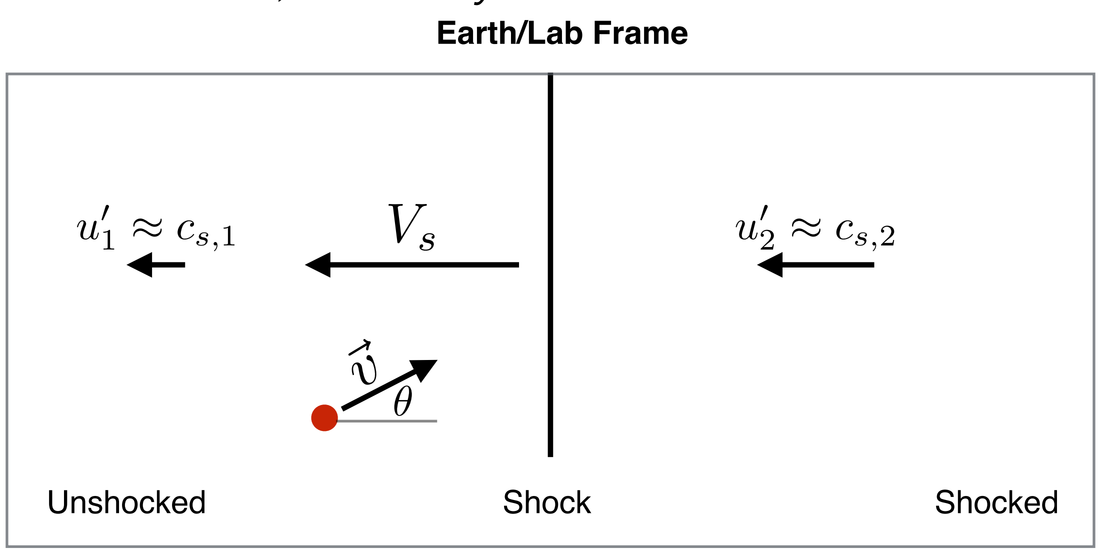

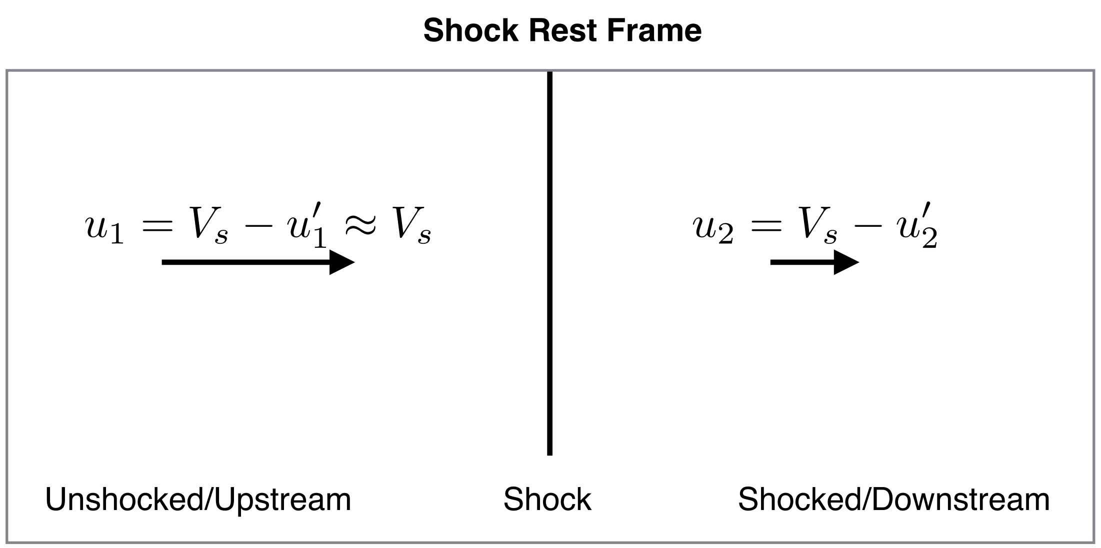

$$P_{goner} = \frac{\Phi_{out}}{\Phi_{in}} \quad \begin{array}{l} \longrightarrow \Phi_{out} = n u_2 \\ \longrightarrow \Phi_{in} = \dfrac{1}{4\pi R^2} \displaystyle\int_{shock} n\vec{v} \cdot d\vec{a} = \dfrac{nv}{4} \end{array}$$

$$\ln P_n = \sum_{i=1}^{n} \ln\left(1 - \frac{4u_2}{v_{i-1}}\right) \simeq -4u_2 \sum_{i=1}^{n} \frac{1}{v_{i-1}}$$

$$\ln\frac{p_n}{p_0} = \sum_{i=1}^{n} \ln\left(1 + \frac{4}{3}\frac{u_1 - u_2}{v_{i-1}}\right) \simeq \frac{4}{3}(u_1 - u_2) \sum_{i=1}^{n} \frac{1}{v_{i-1}}$$

Fermi Acceleration

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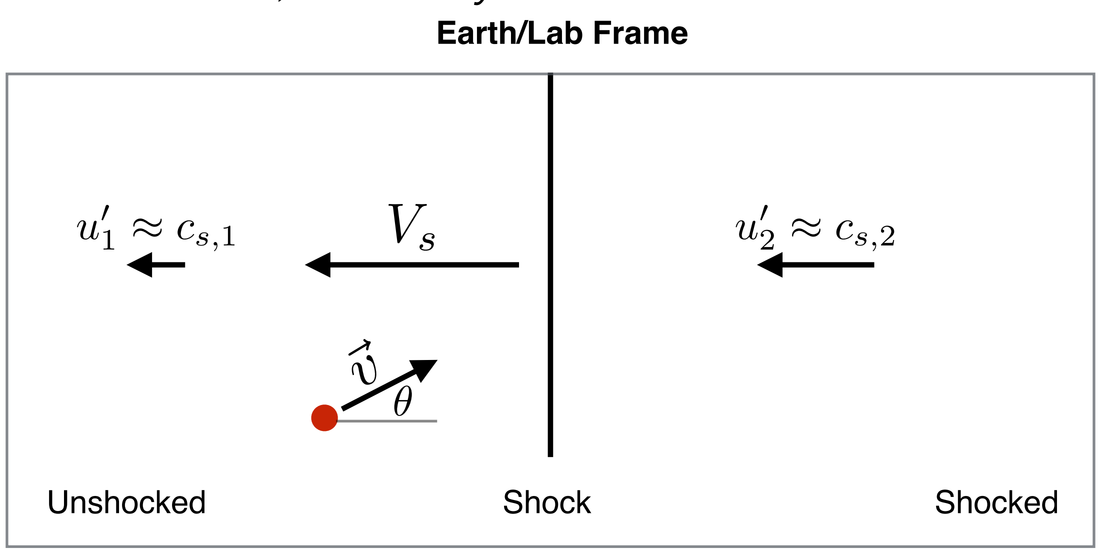
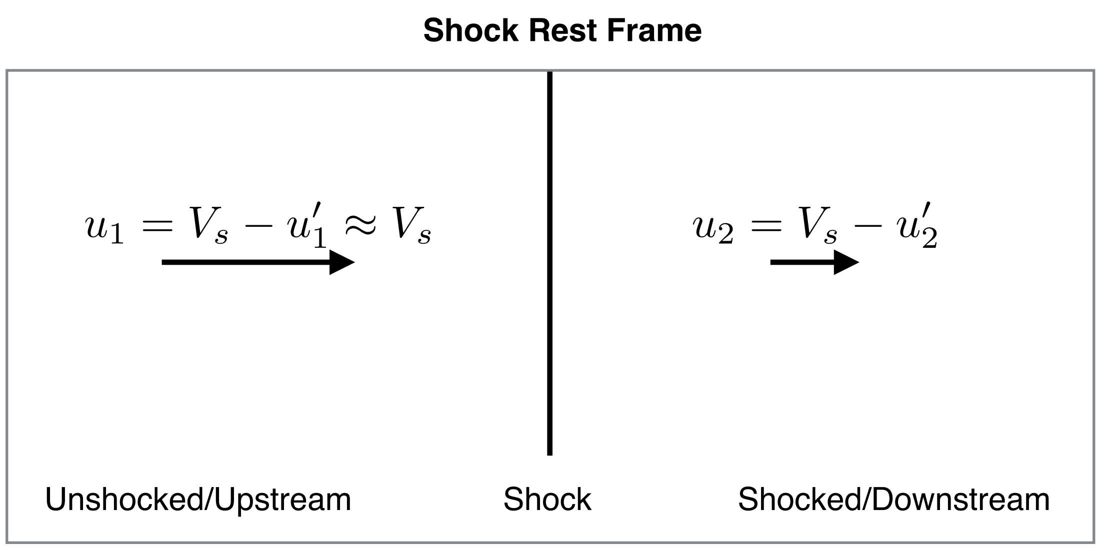
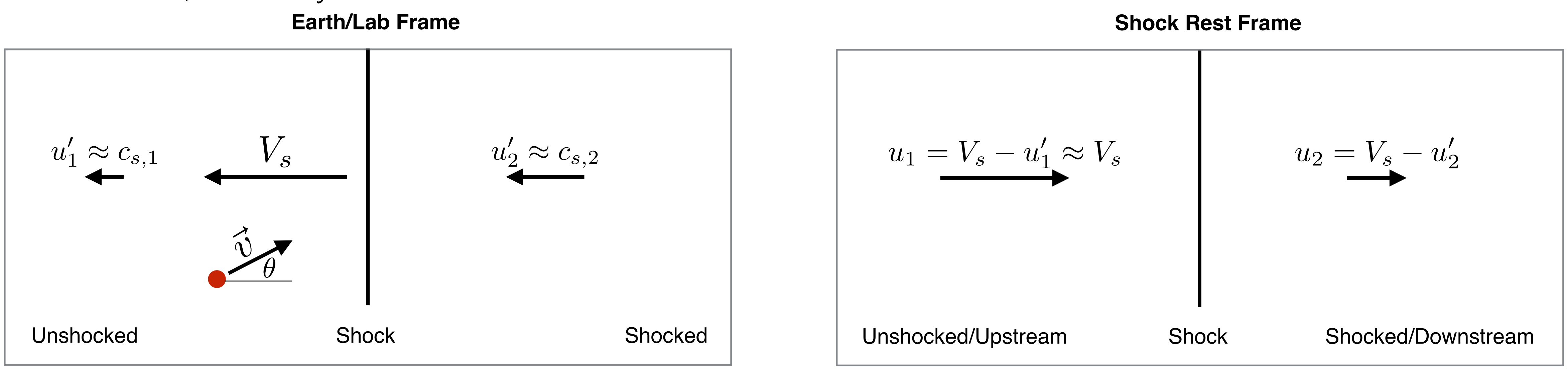




$$\mathrm{Prob}(p|p_0) = \left(\frac{p}{p_0}\right)^{-\frac{3u_2}{u_1 - u_2}}$$

Fermi Acceleration

A. Bell 1978, L. Drury 1983



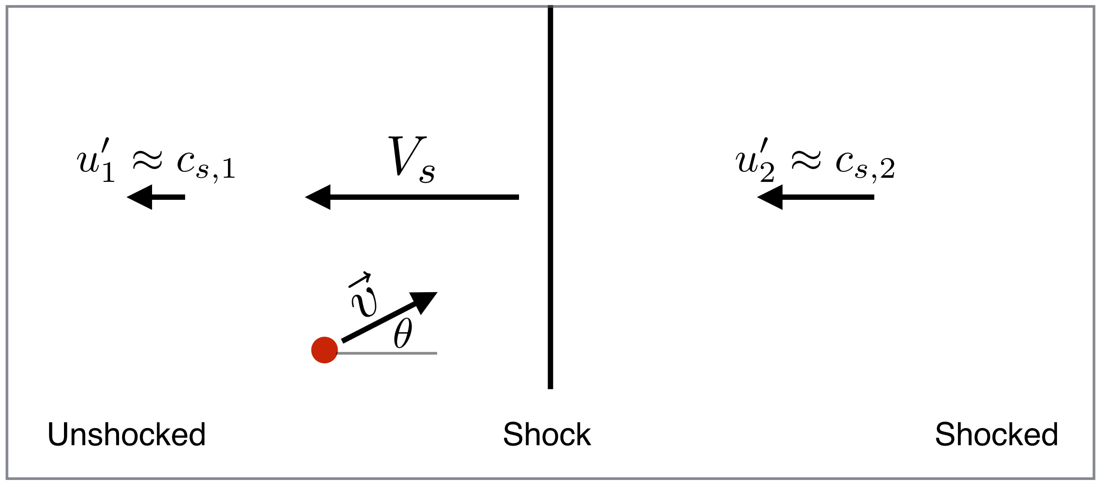
$$\mathrm{Prob}(p|p_0) = \left(\frac{p}{p_0}\right)^{-\frac{3u_2}{u_1 - u_2}}$$

$$\frac{u_1}{u_2} = \frac{\gamma + 1}{\gamma - 1} = 4$$

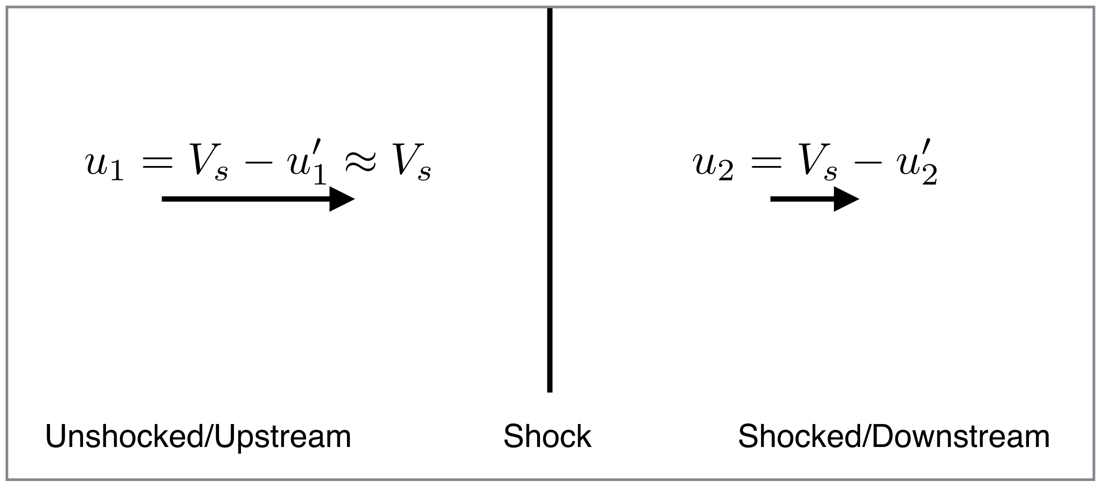
Fermi Acceleration

A. Bell 1978, L. Drury 1983

Earth/Lab Frame



Shock Rest Frame



$$\mathrm{Prob}(p|p_0) = \left(\frac{p}{p_0}\right)^{-\frac{3u_2}{u_1-u_2}} = \frac{p_0}{p}$$

$$\frac{u_1}{u_2} = \frac{\gamma+1}{\gamma-1} = 4$$

Fermi Acceleration

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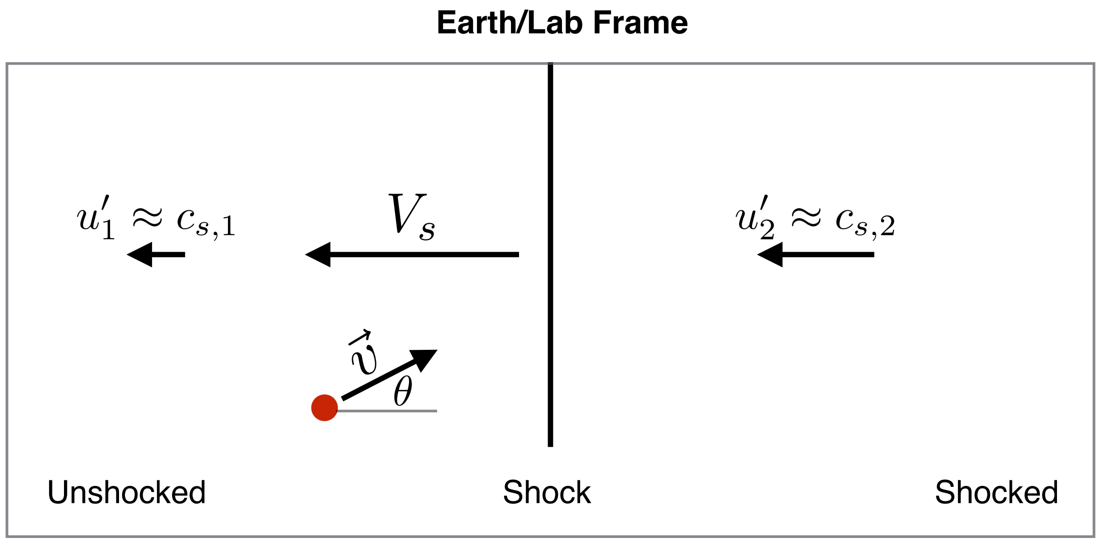

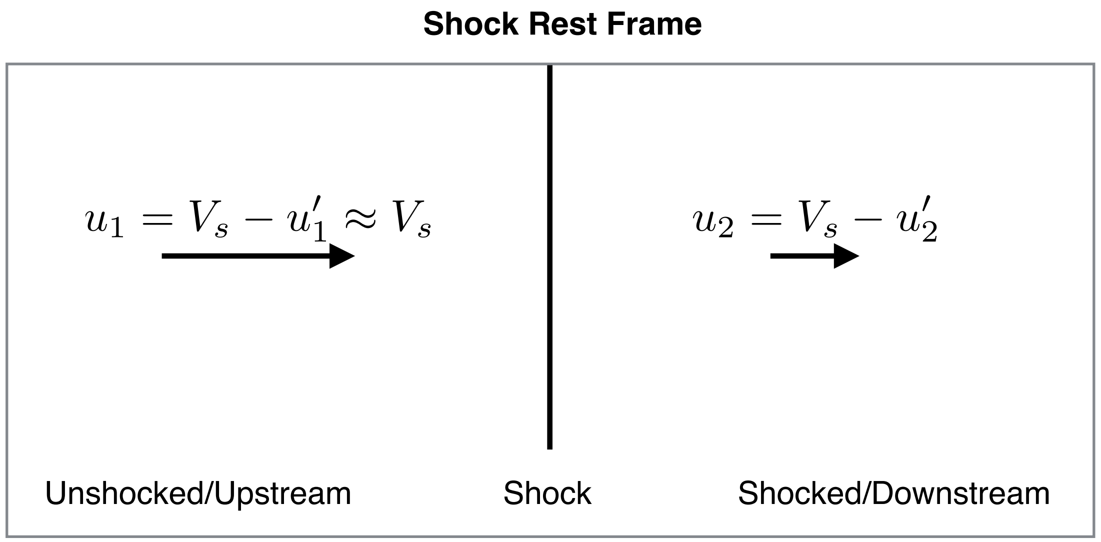

$$\mathrm{Prob}(p|p_0) = \left(\frac{p}{p_0}\right)^{-\frac{3u_2}{u_1 - u_2}} = \frac{p_0}{p} \longrightarrow f = \frac{dn}{dp} = n_0 \frac{p_0}{p^2}$$

$$\frac{u_1}{u_2} = \frac{\gamma + 1}{\gamma - 1} = 4$$

Maximum Acceleration

- Spatial bottleneck - gyroradius larger than magnetic field region
- Temporal bottleneck - acceleration time longer than age of shock

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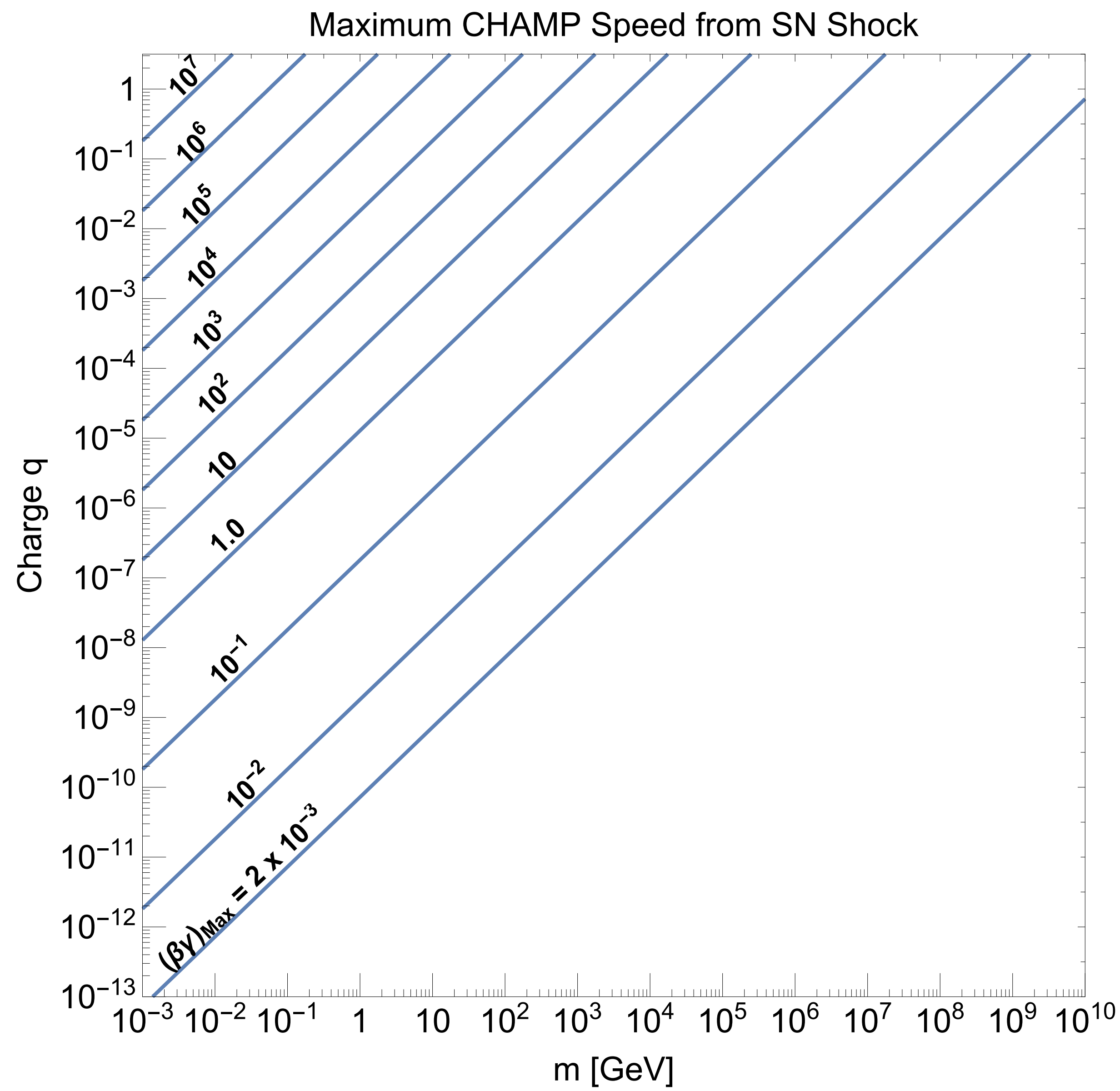
- Max momentum set by $t_{\rm acc} = \frac{8}{3}\frac{r_{gyro}v}{v_s^2} \leq t_{\rm remnant} = \frac{2}{5}\frac{R}{v_s}$

Maximum Acceleration



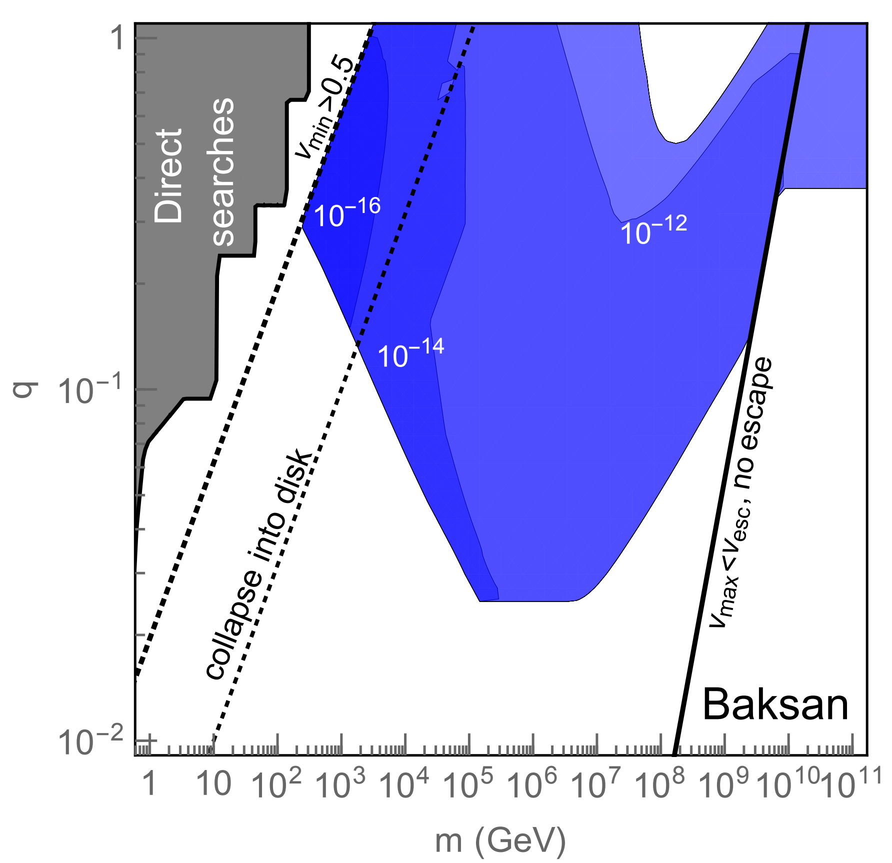
$$\left(\frac{p}{q}\right)_{max} \approx \frac{5.5\times 10^4\ \mathrm{GeV}}{\beta}\left(\frac{B}{15\ \mu\mathrm{G}}\right)\left(\frac{R_{max}}{40\ \mathrm{pc}}\right)\left(\frac{v_s}{200\ \mathrm{km/s}}\right)$$

No acceleration as $q \to 0$

Ionization Particle Searches

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

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



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