Dark Matter without Astrophysics

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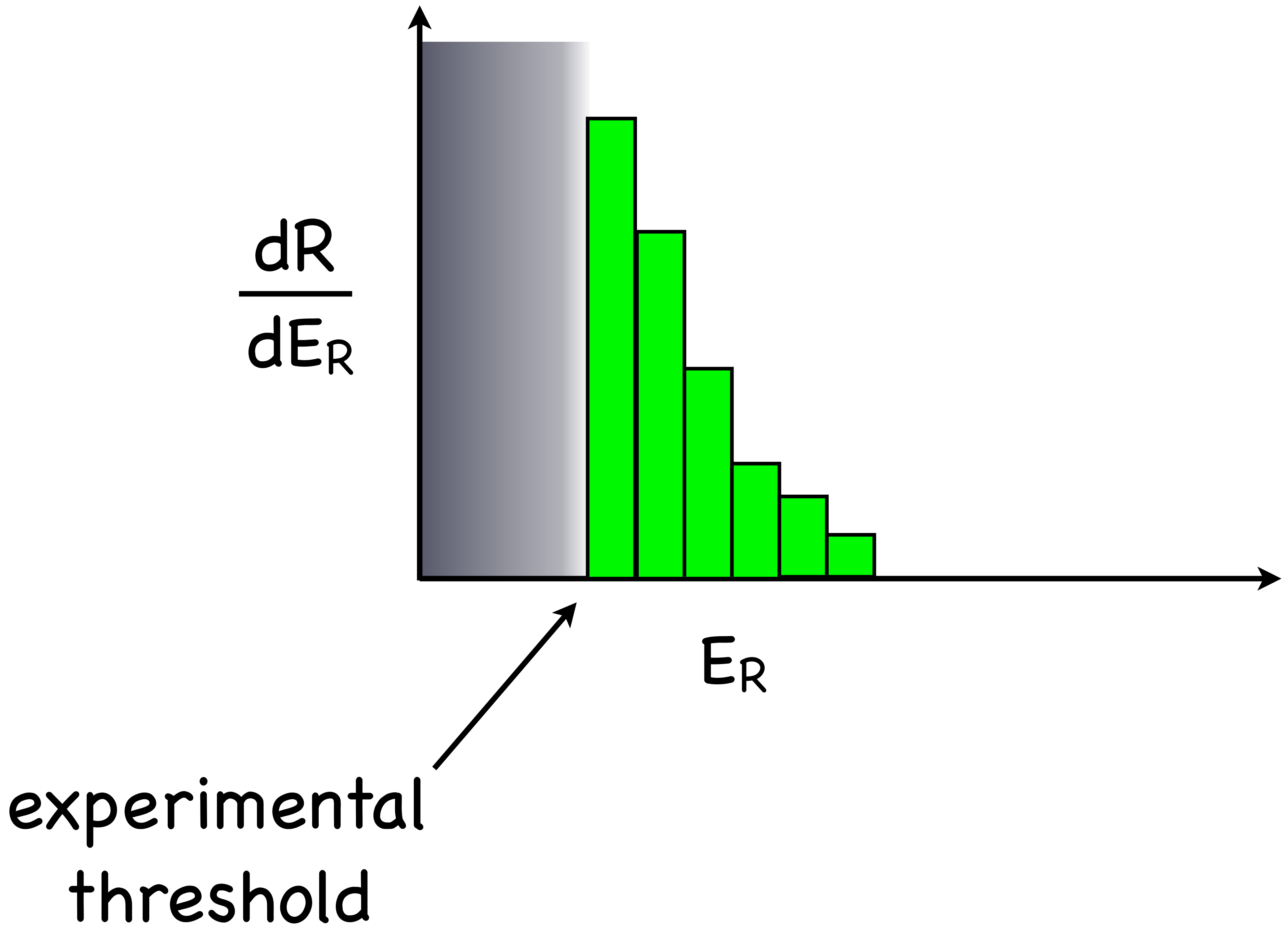
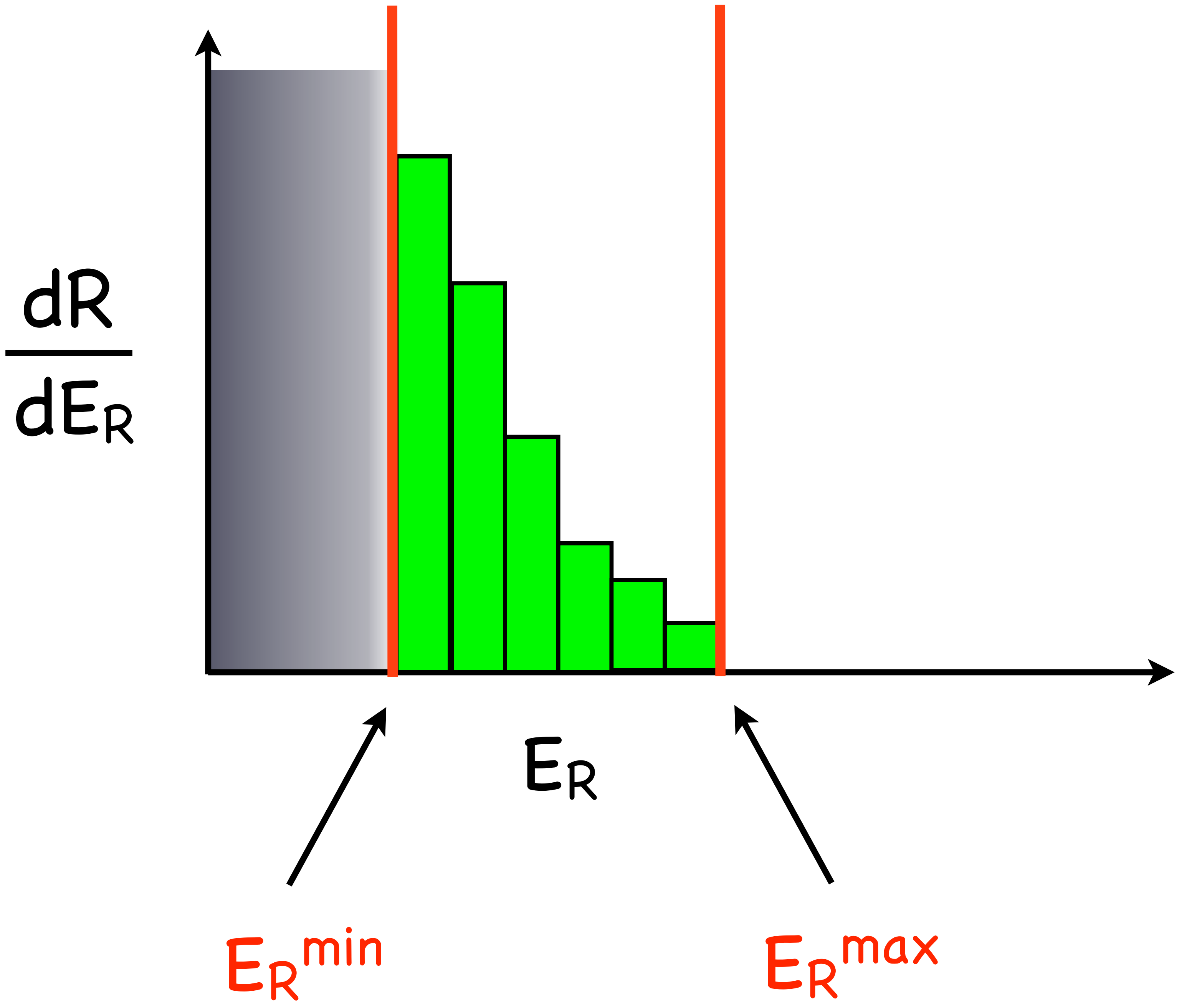
Aspen 10 Feb 2011

Is there f(v)-independent particle physics information in a single recoil spectrum?



Kinematics

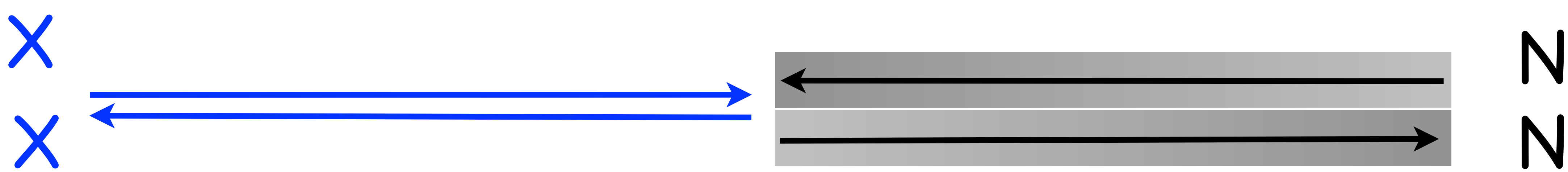


Elastic Kinematics

$$E_R = \frac{\mu^2 v^2 (1 - \cos\theta_{cm})}{m_N}$$

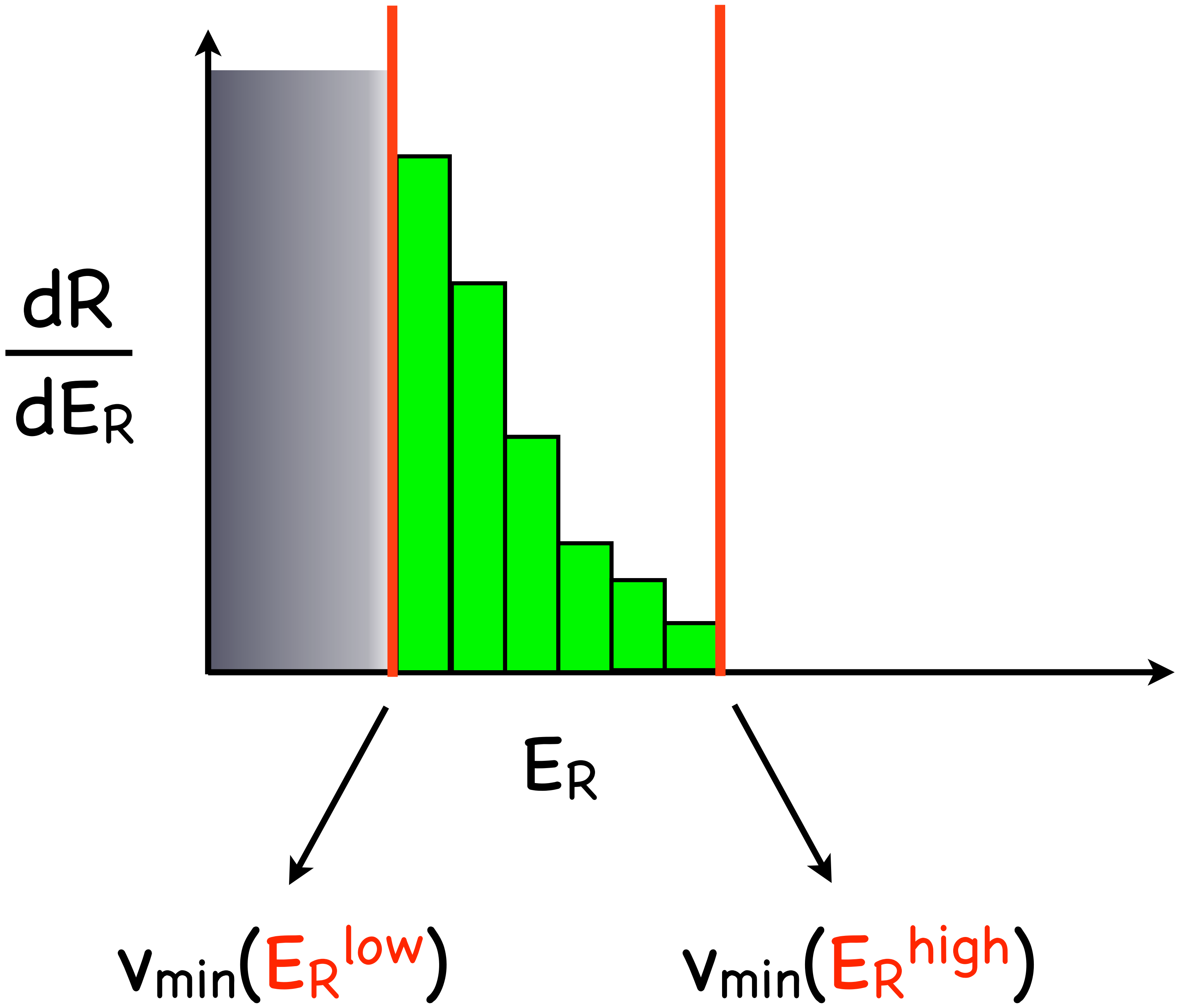
relative velocity!!!
(Earth frame)

For fixed E_R, smallest v at $\theta_{cm} = \pi$
(head-on collision)



$$v_{min}(E_R) = \left(\frac{m_N\, E_R}{2\,\mu^2}\right)^{1/2}$$

Elastic Kinematics



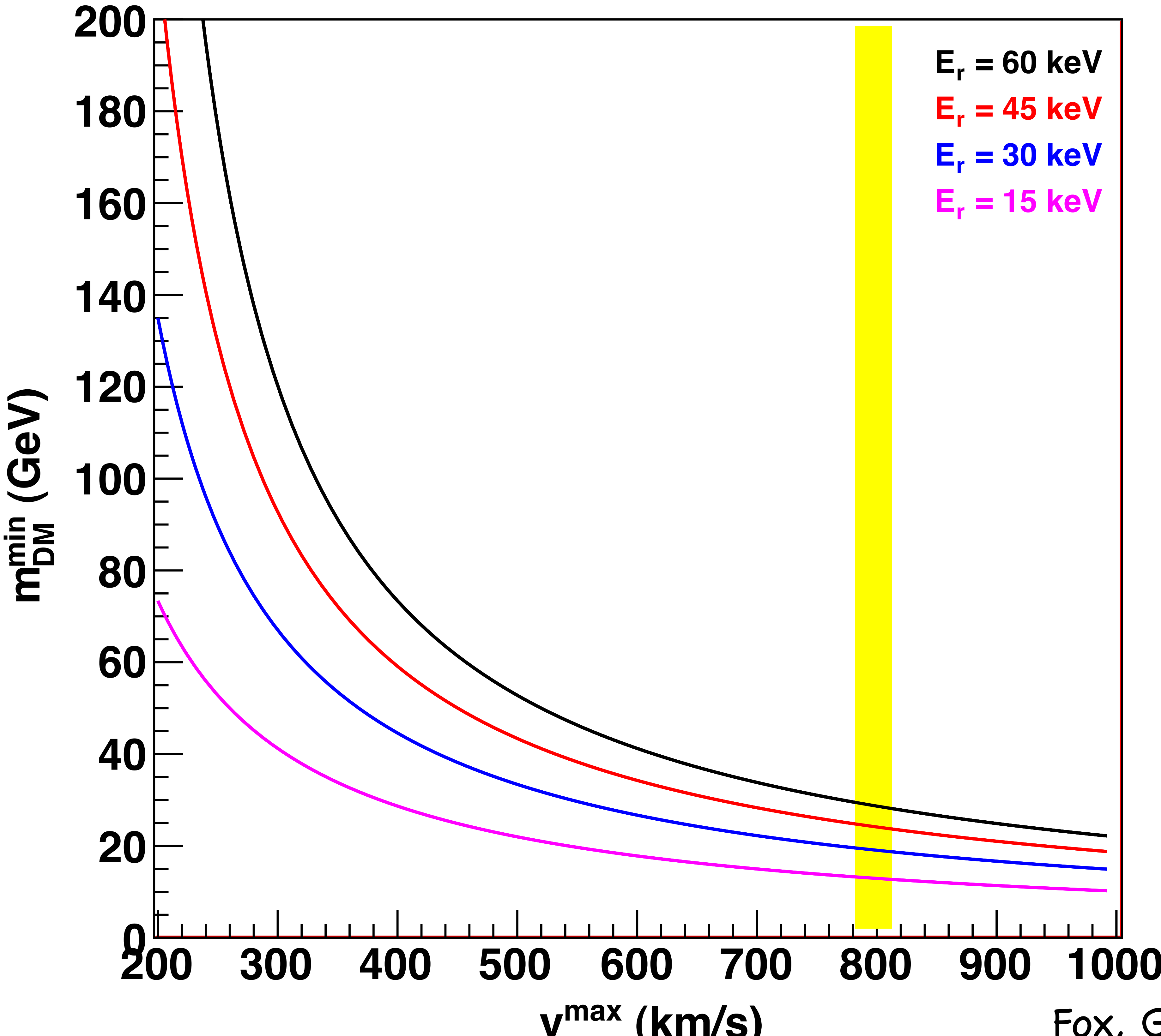
Elastic Kinematics

Obviously

$$v_{min}(E_R^{low}) \quad < \quad v_{min}(E_R^{high})$$

for elastic scattering

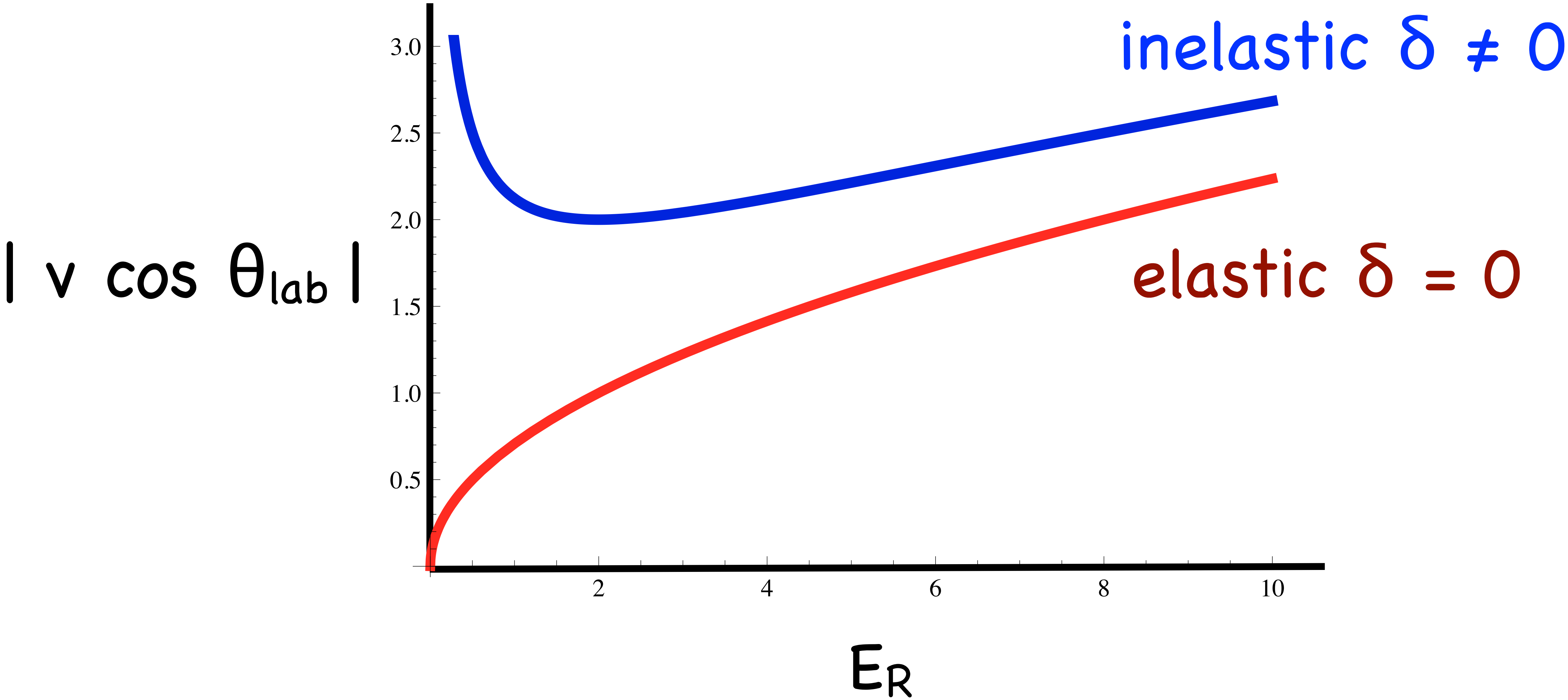
Assume v_{max} exists, with $v_{min}(E_R^{high}) < v_{max}$, then:



Target example: Xe

Fox, GK, Tait; 1011.1910

Inelastic Kinematics



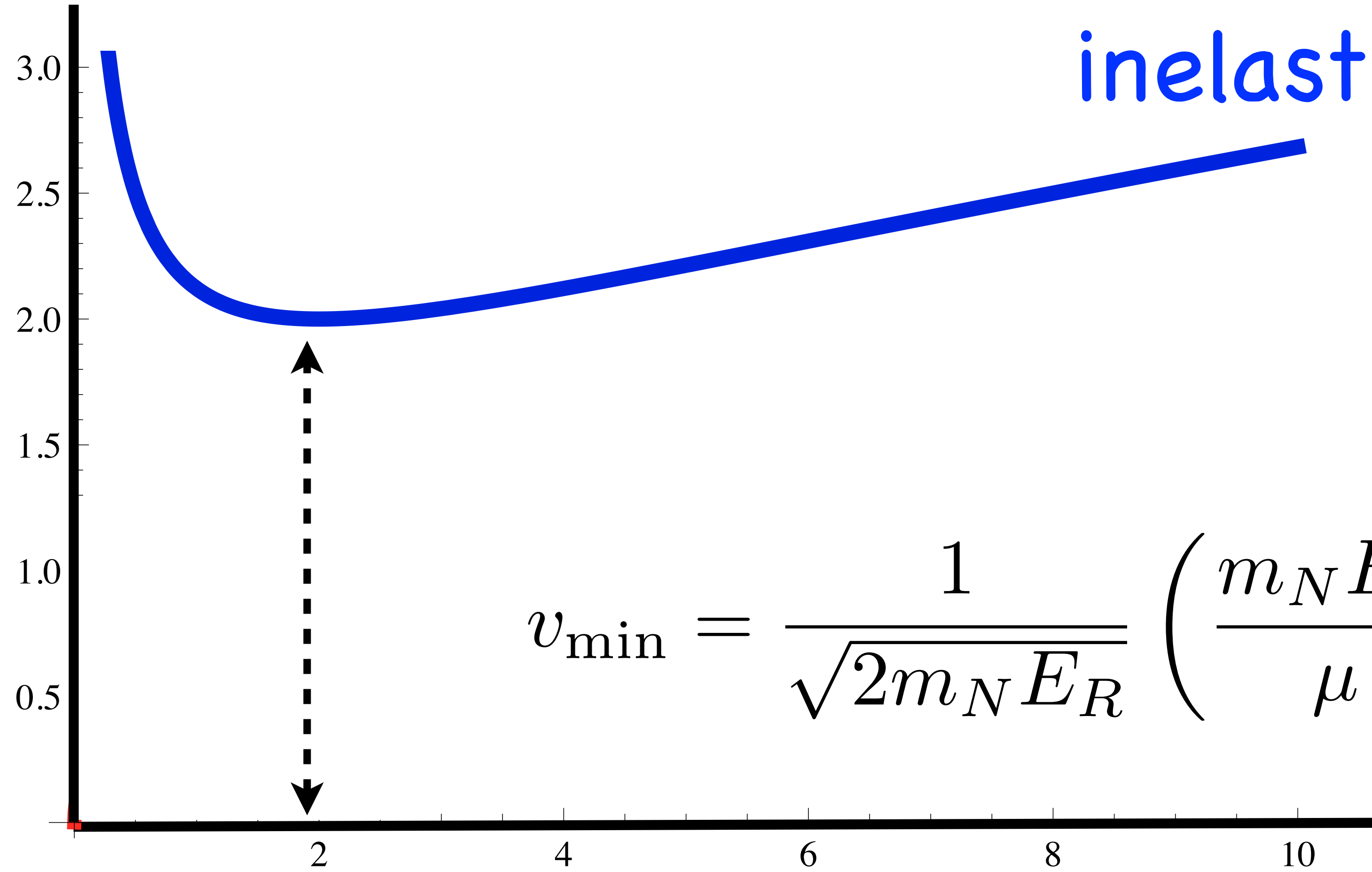
$$E_R^2 + 2E_R\frac{\mu}{m_N}(\delta - \mu v^2\cos^2\theta_{\rm lab}) + \frac{\mu^2}{m_N^2}\delta^2 = 0$$

Minimum Velocity to Scatter

$|\cos\theta_{lab}| = 1$

inelastic $\delta \neq 0$

v_{min}



$$v_{\rm min} = \frac{1}{\sqrt{2 m_N E_R}} \left(\frac{m_N E_R}{\mu} + \delta \right)$$

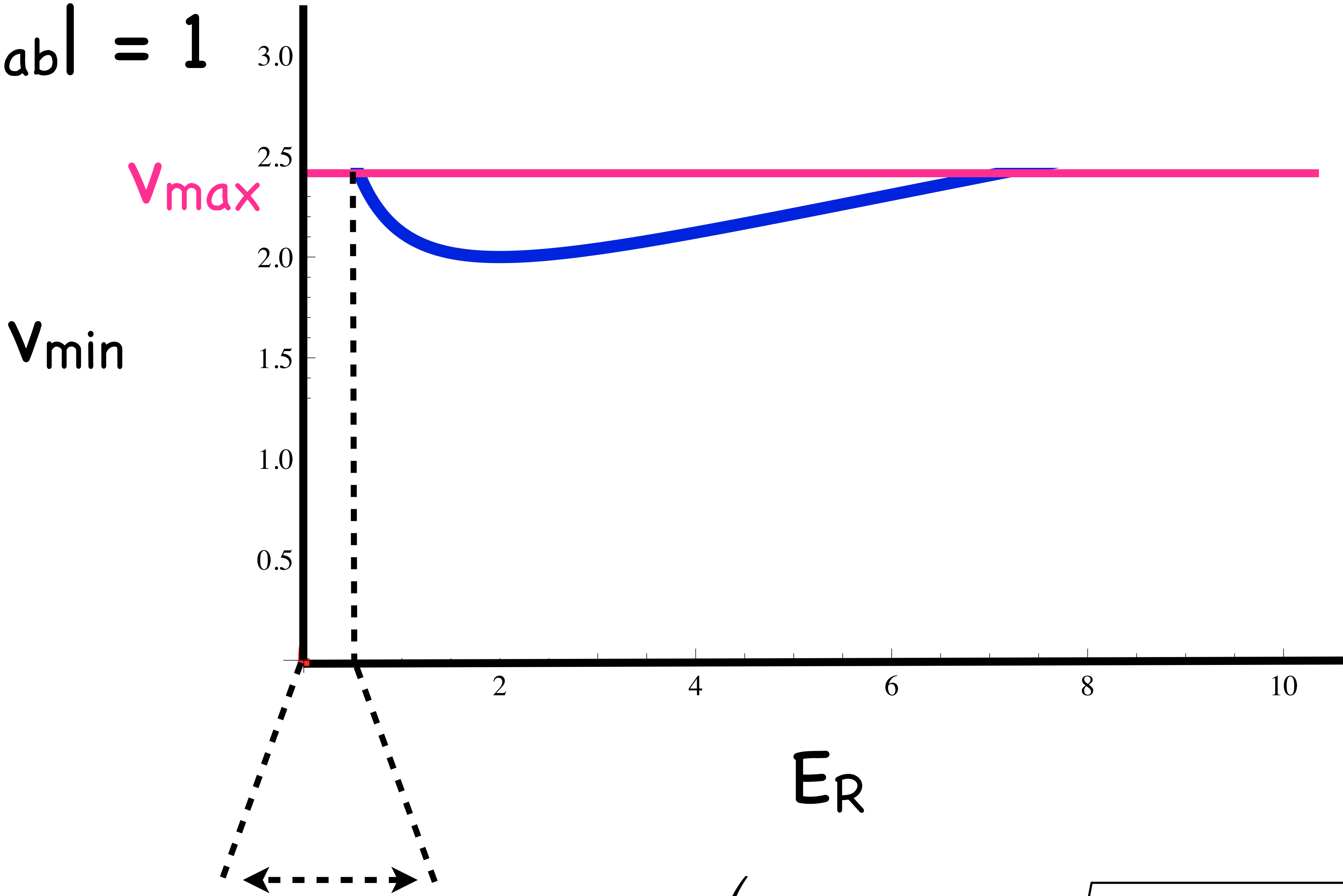
E_R

$$v_{min}(E_R^{low}) \nless v_{min}(E_R^{high})$$

Not! (necessarily)

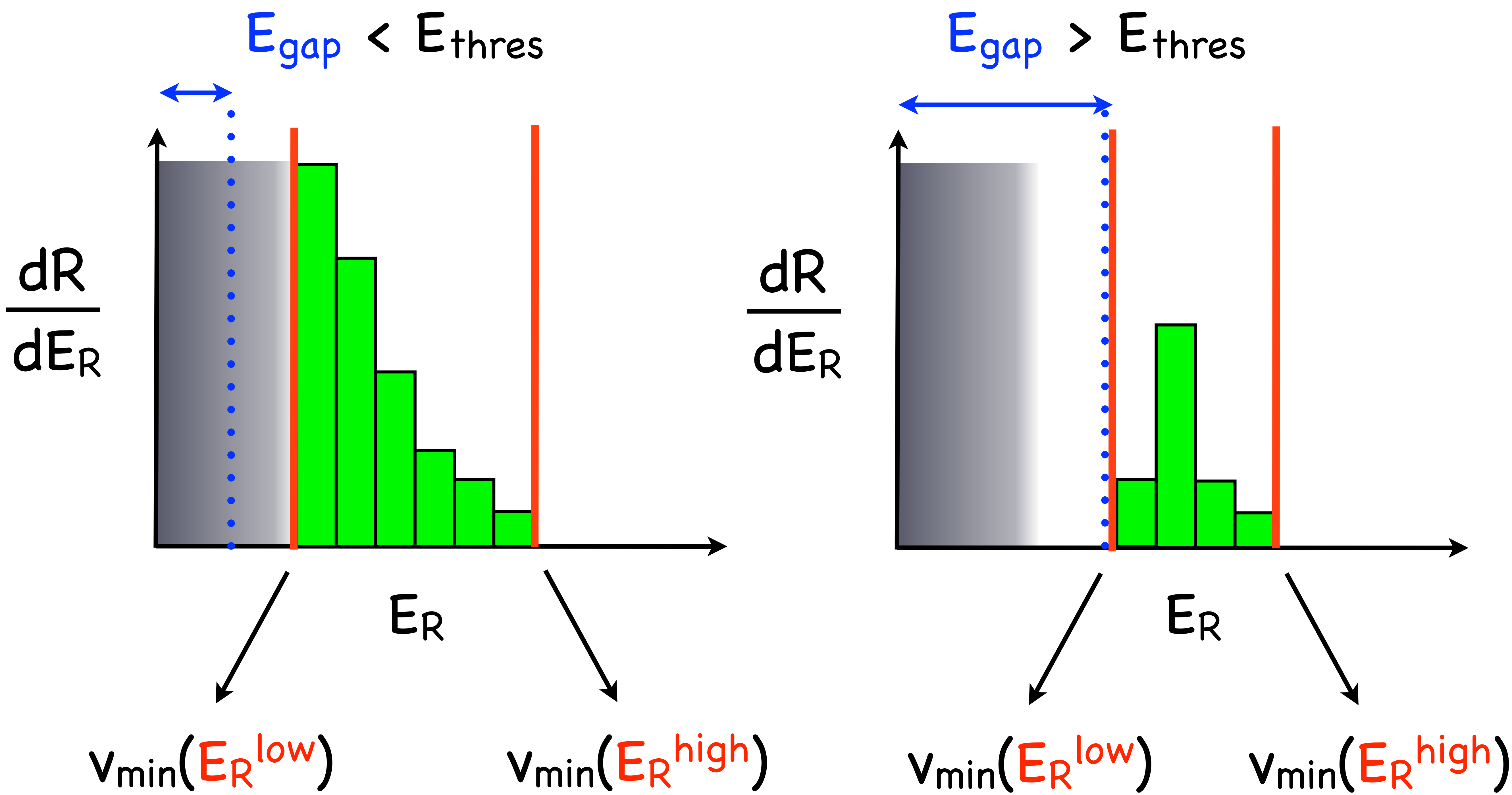
E_R Gap
(region of E_R with NO recoil events)

$|\cos\theta_{lab}| = 1$

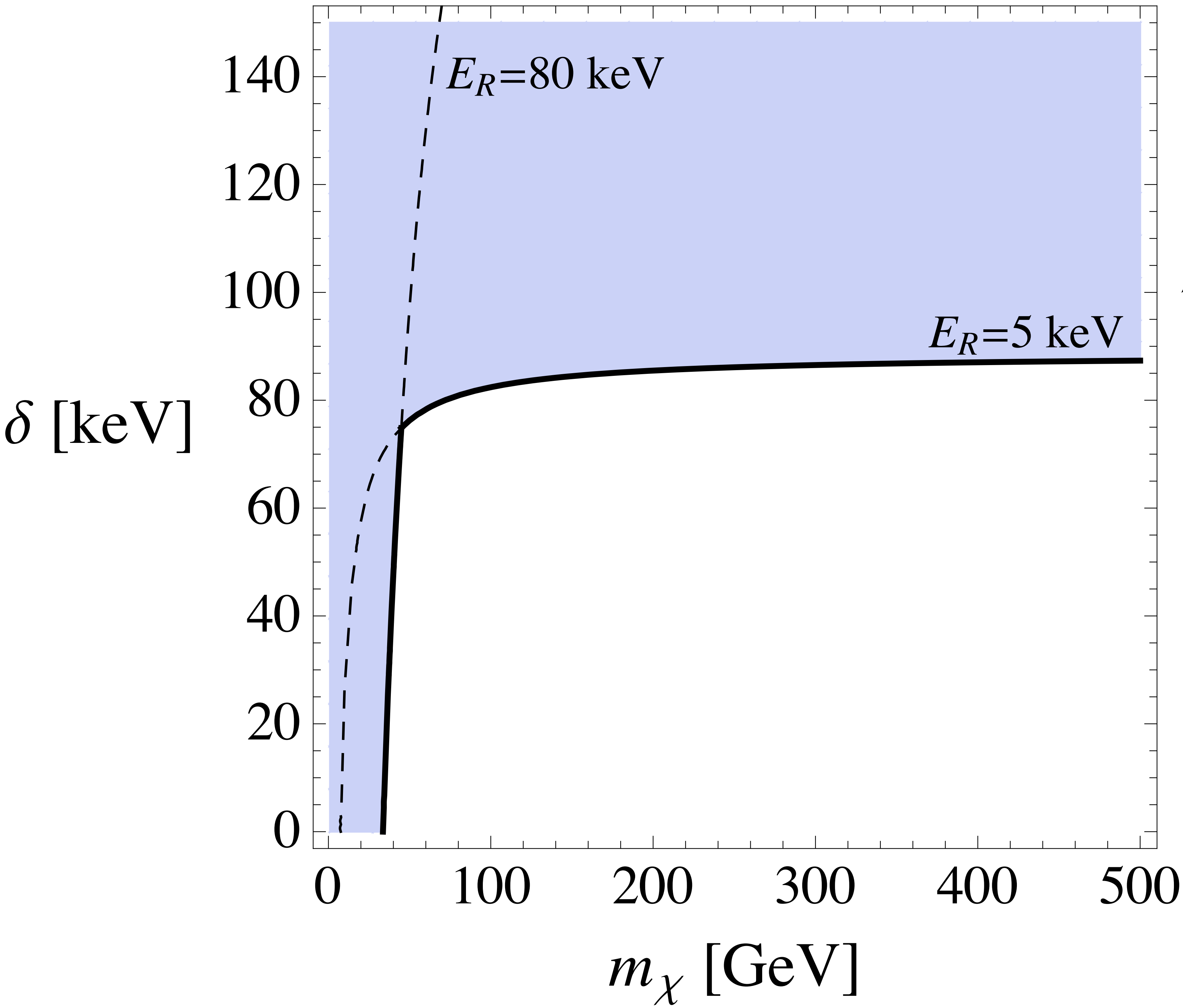


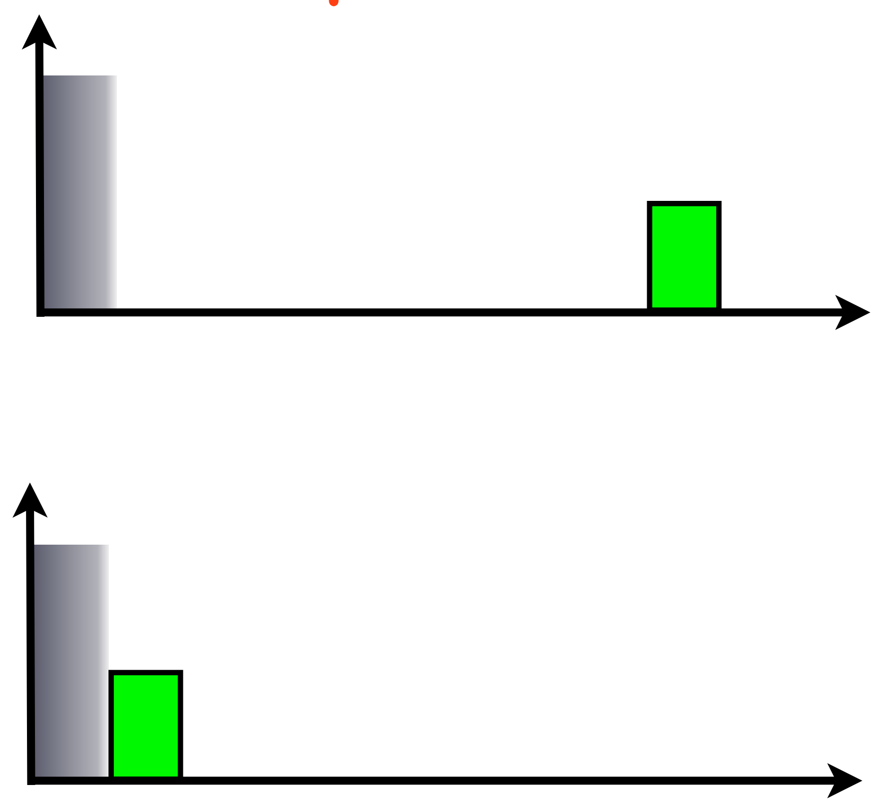
$$E_R^{\text{gap}} = \frac{\mu^2}{m_N}\left(v_{\max}^2 - \frac{\delta}{\mu} - \sqrt{\left(v_{\max}^2 - \frac{\delta}{\mu}\right)^2 - \frac{\delta^2}{\mu^2}}\right)$$

Inelastic Kinematics



Inelastic Constraints (Xenon Example)

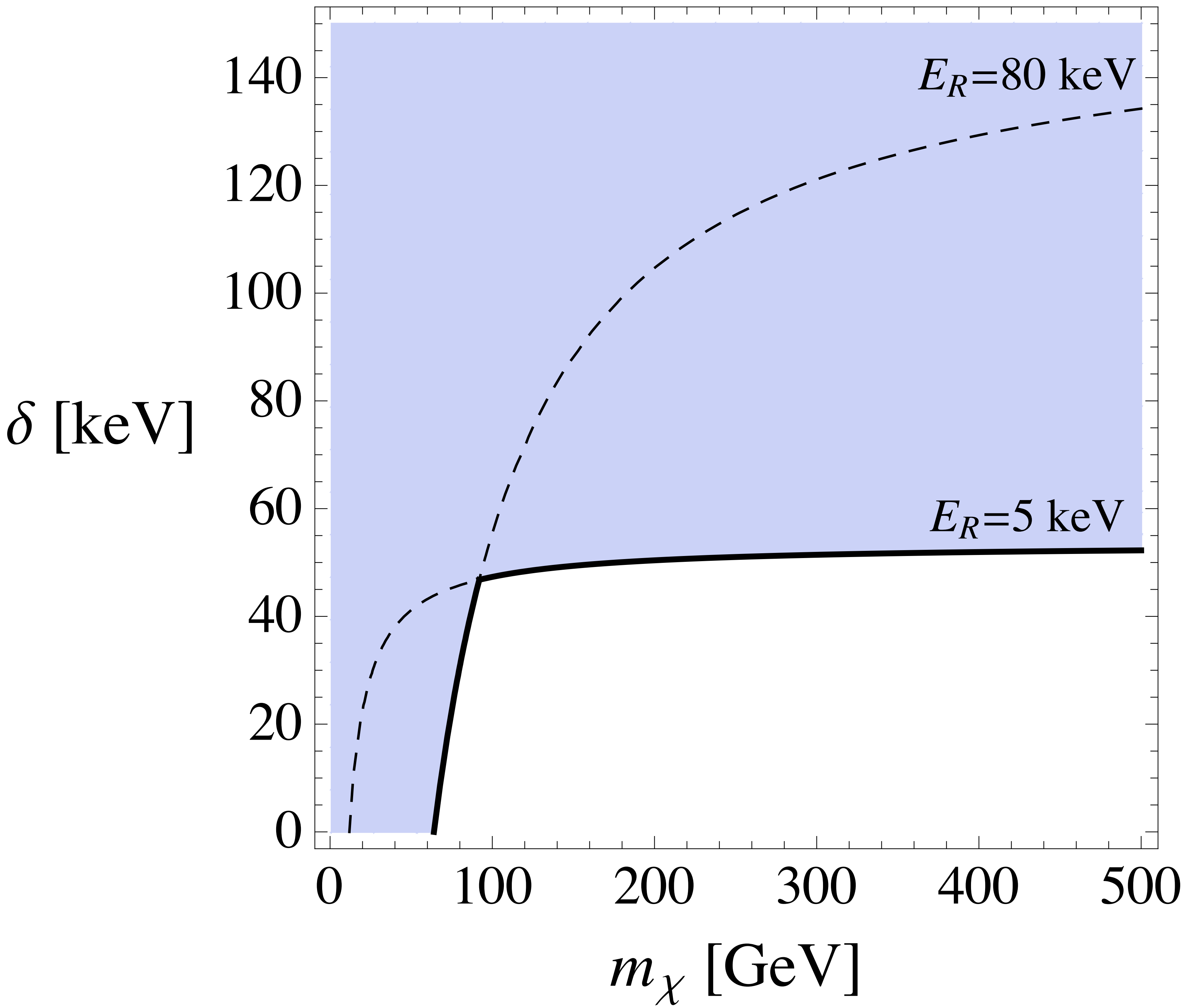




v_{max} = 800 km/s

Fox, GK, Tait; 1011.1910

Inelastic Constraints (Xenon Example)



v_{max} = 500 km/s

Fox, GK, Tait; 1011.1910

Rates

Differential Rate for Scattering Experiment

$$\frac{dR}{dE_R} = \left(\begin{array}{c} \#\ \text{target} \\ \text{nuclei} \end{array} \right) \times \left(\begin{array}{c} \text{DM} \\ \text{flux} \end{array} \right) \times \frac{d\sigma}{dE_R}$$

$$\frac{dR}{dE_R} = \sum_i N_T \; n_{\chi i} \int_{v_{i,min}}^{v_{max}} d^3v_i \; f(v_i(t)) \; |v_i| \; \frac{d\sigma_{\chi i}}{dE_R}$$

Sum over multiple DM particles

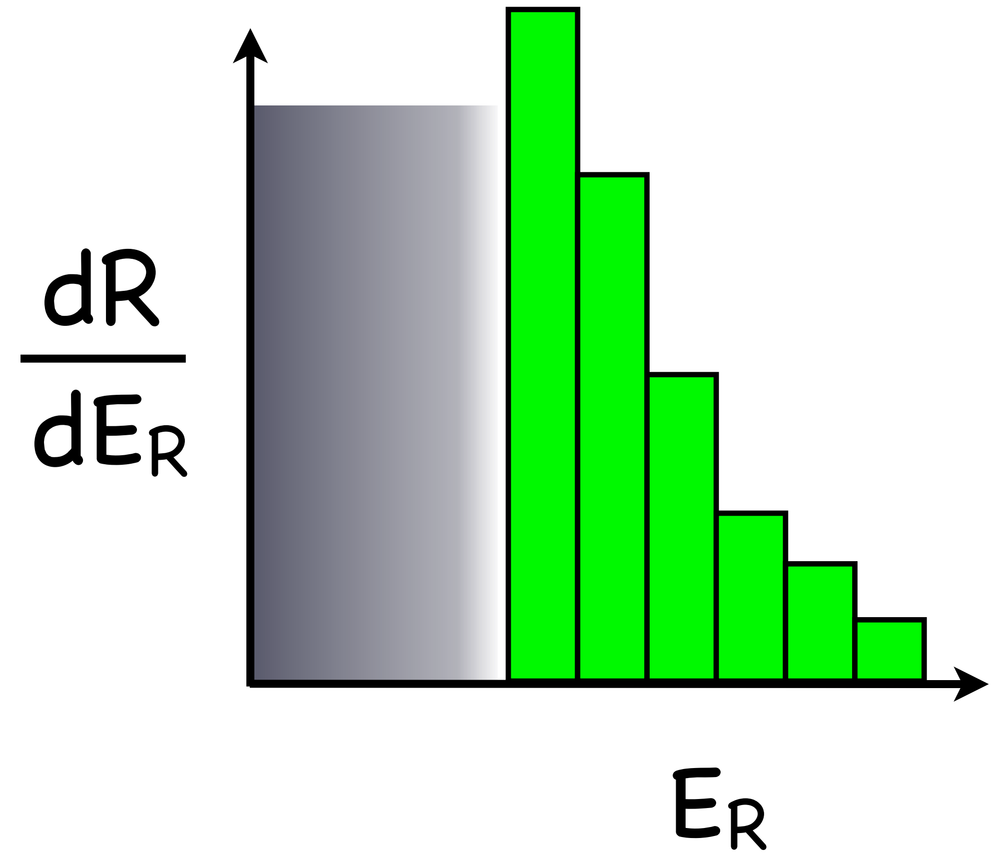
Normalization of Rate

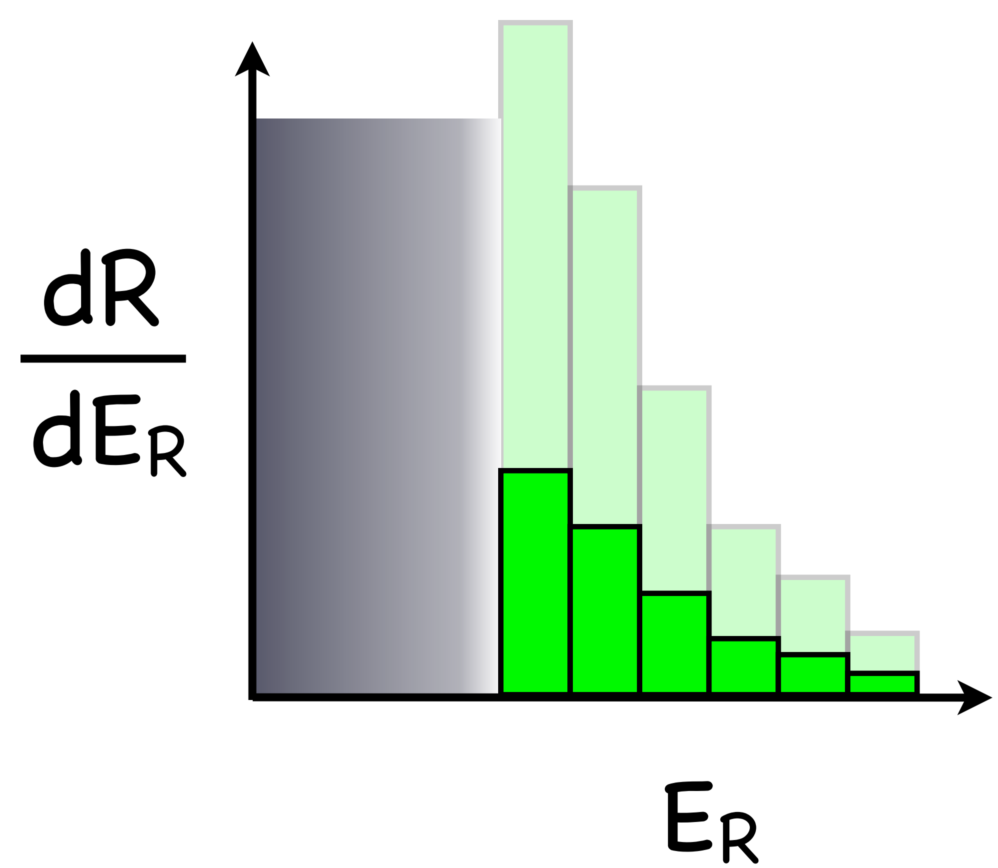
Given

$$\int d^3v_i \; f(v_i) = 1$$

Total degeneracy between $n_{\chi i}$ and normalization of f(v).

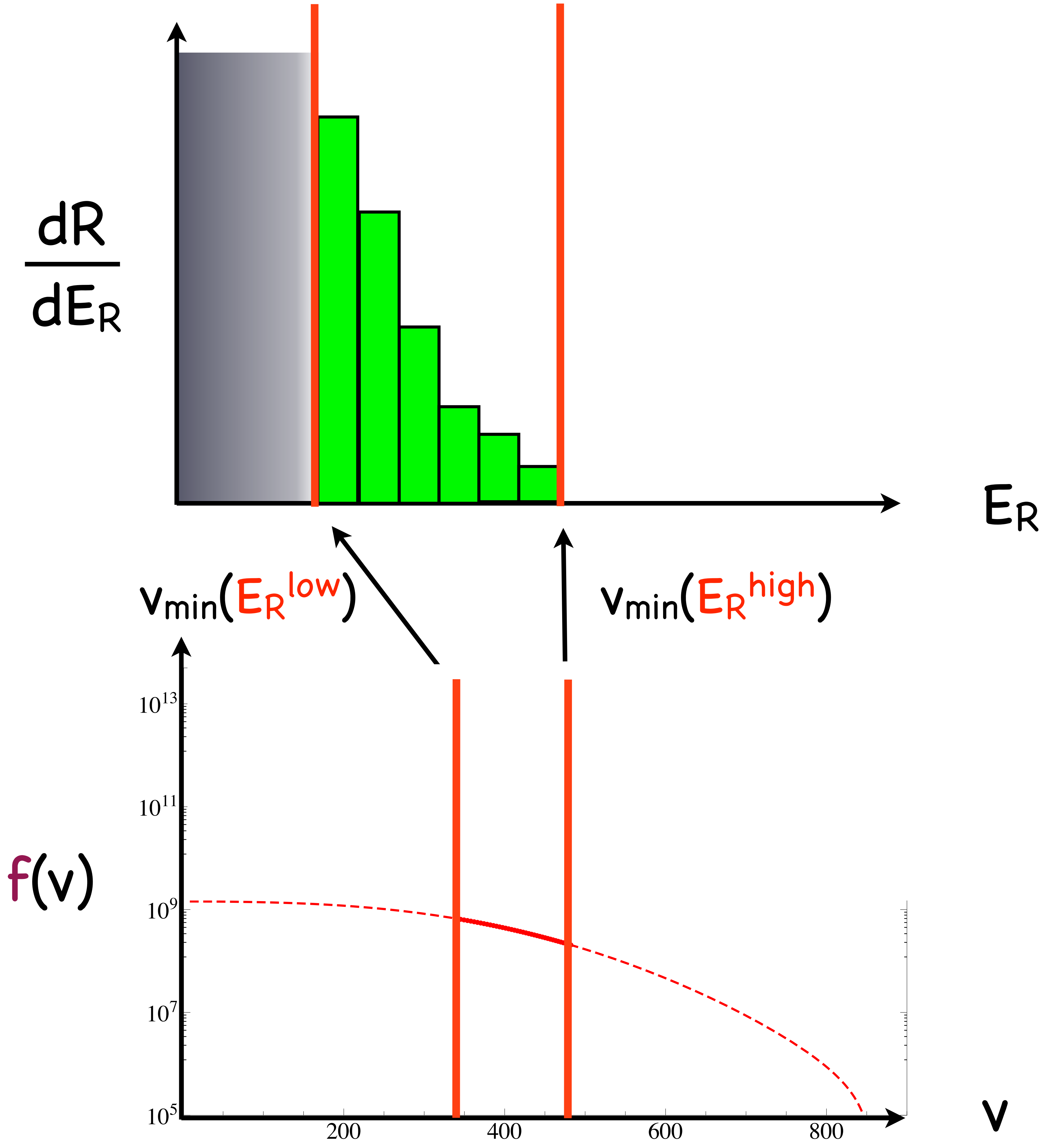
Hence, no information from total rate R.





Worse still, an experimental threshold means cannot probe f(v) for $v < v_{min}(E_R^{low})$.

So normalization "doubly" unknown.

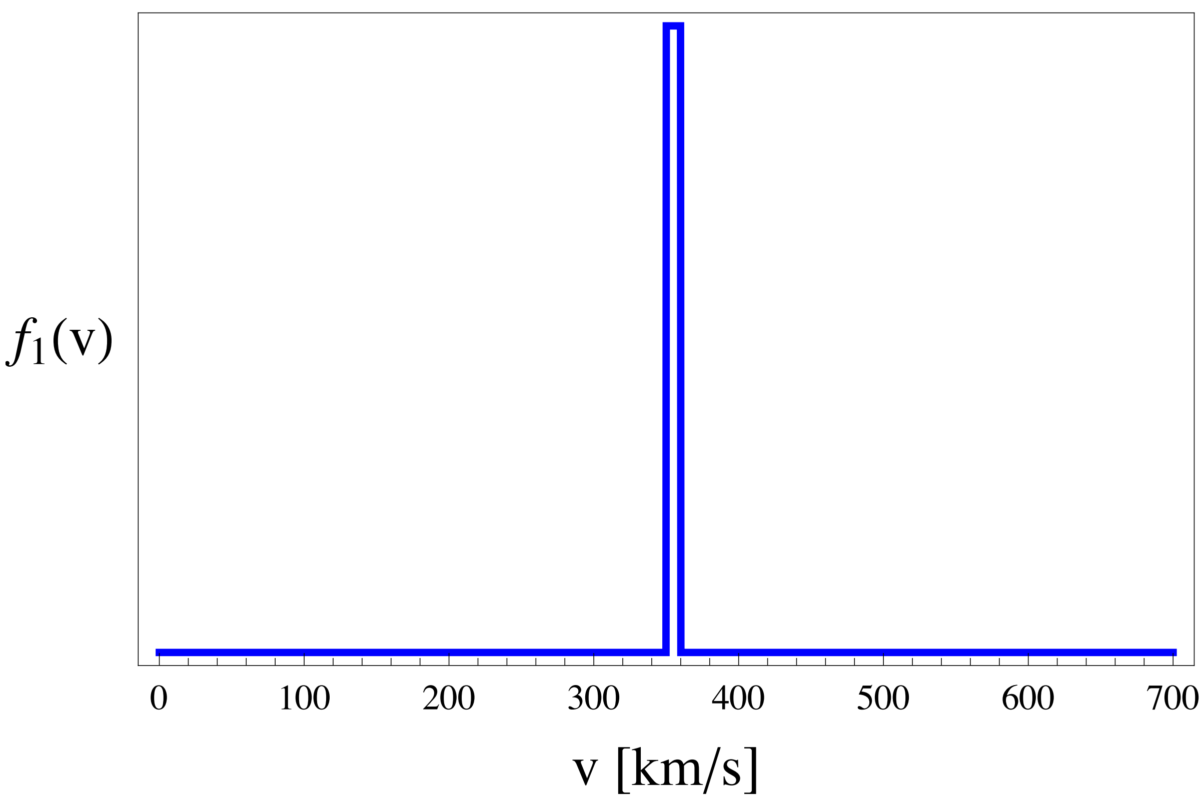


So, at best, f(v)-independent information is to be found in the shape.

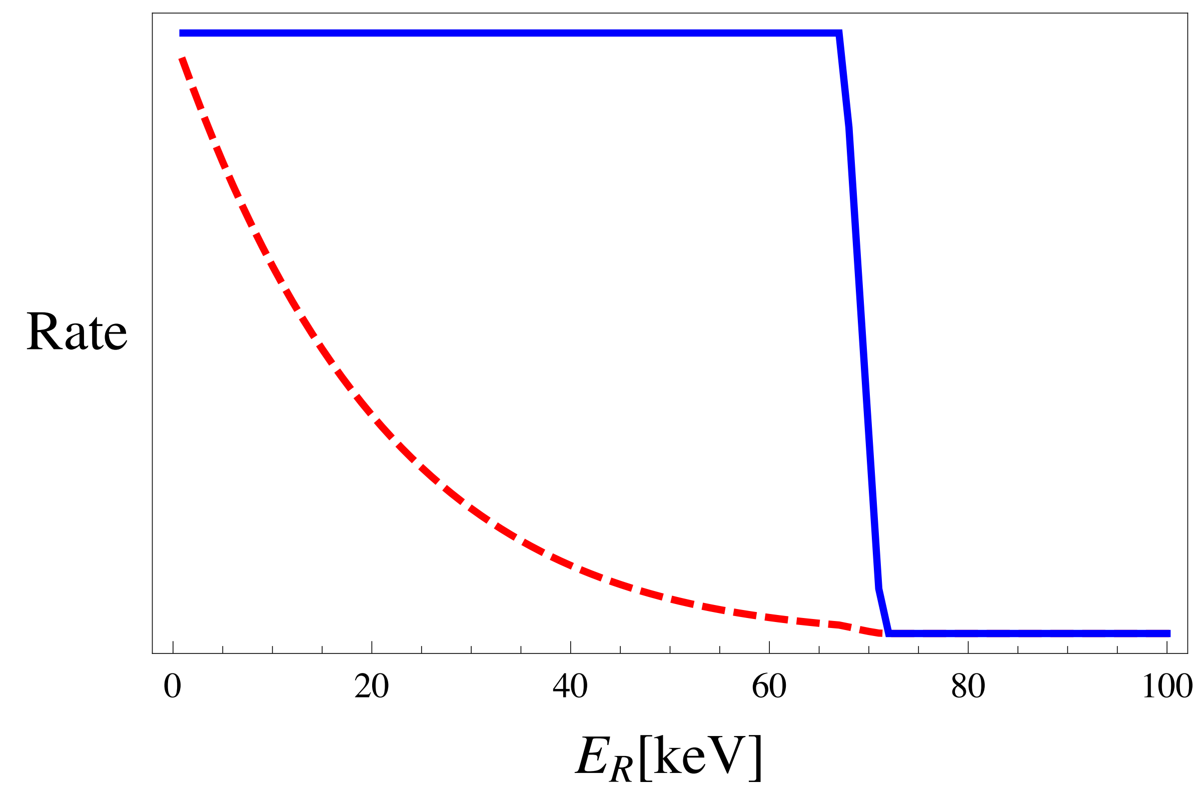
Claim #1: Shapes are much easier to "read off" when recoil spectrum is "deconvoluted" of the nuclear form factor.

$$\mathcal{R} \equiv \frac{1}{F_N^2(E_R)} \frac{dR}{dE_R} \qquad\qquad \frac{dR}{dE_R}$$

deconvoluted convoluted



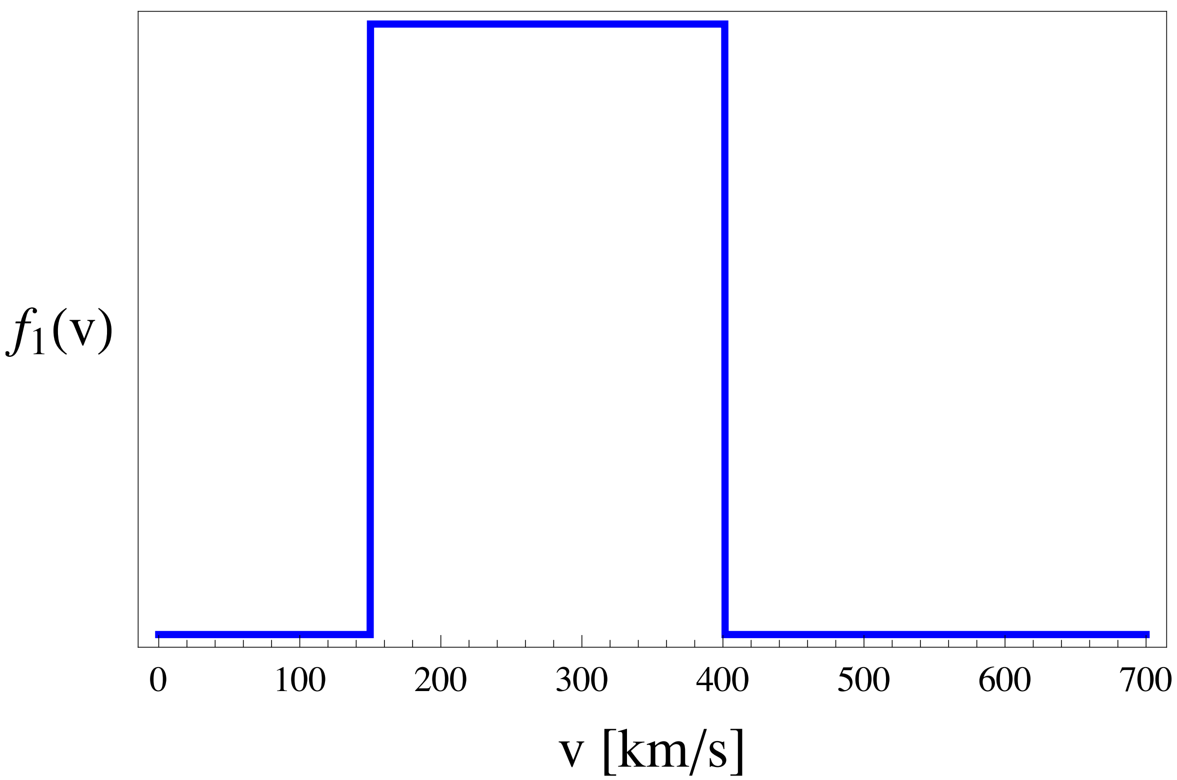
deconvoluted

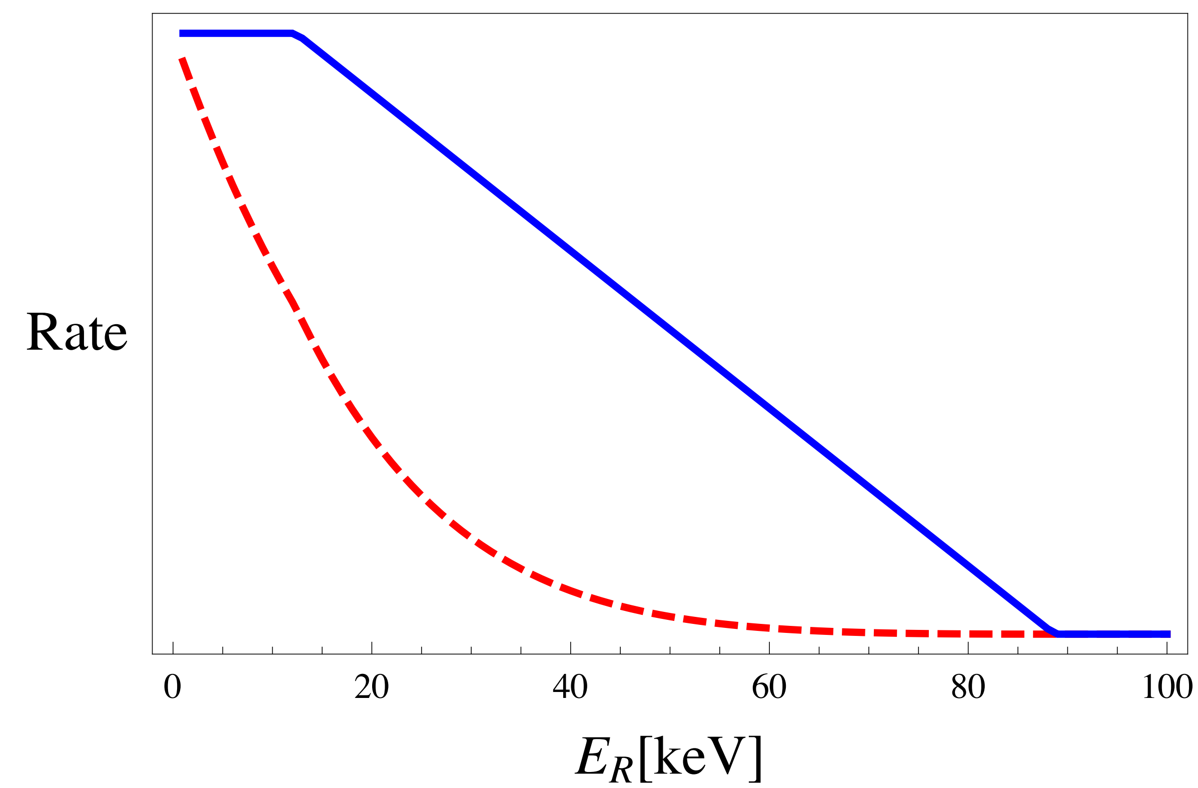


convoluted

(example rate is Xenon)

deconvoluted

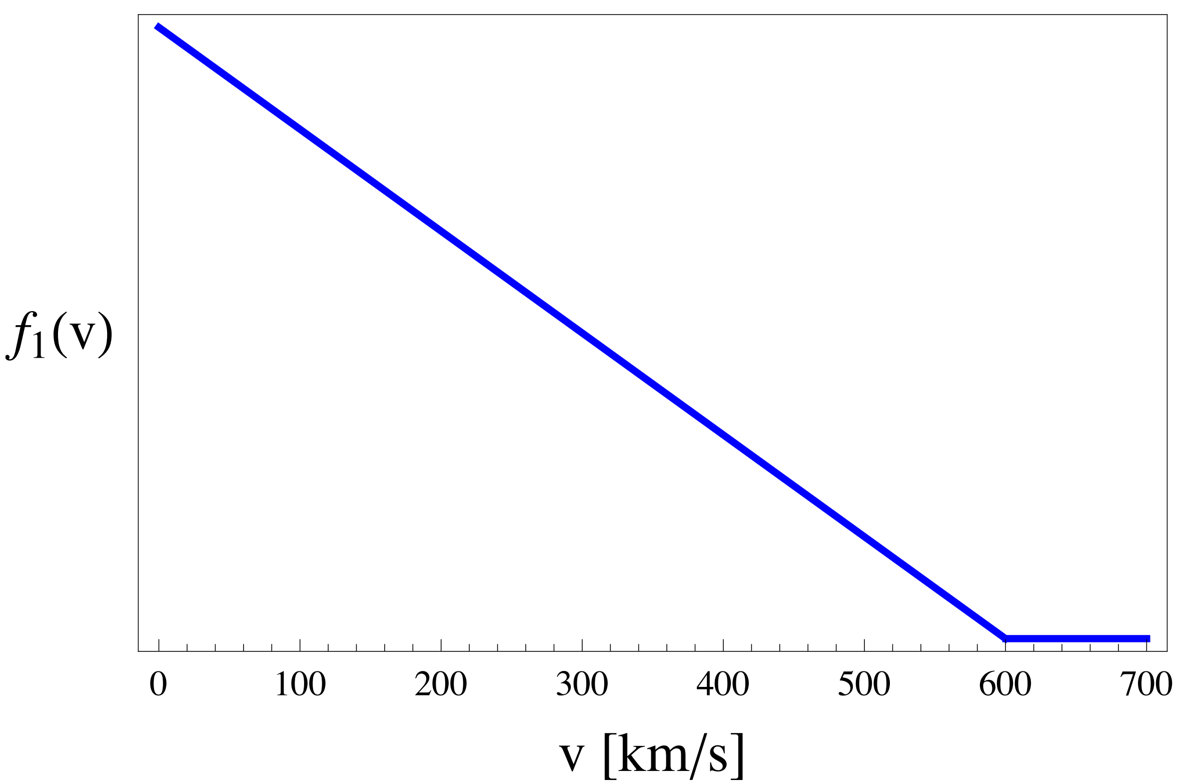


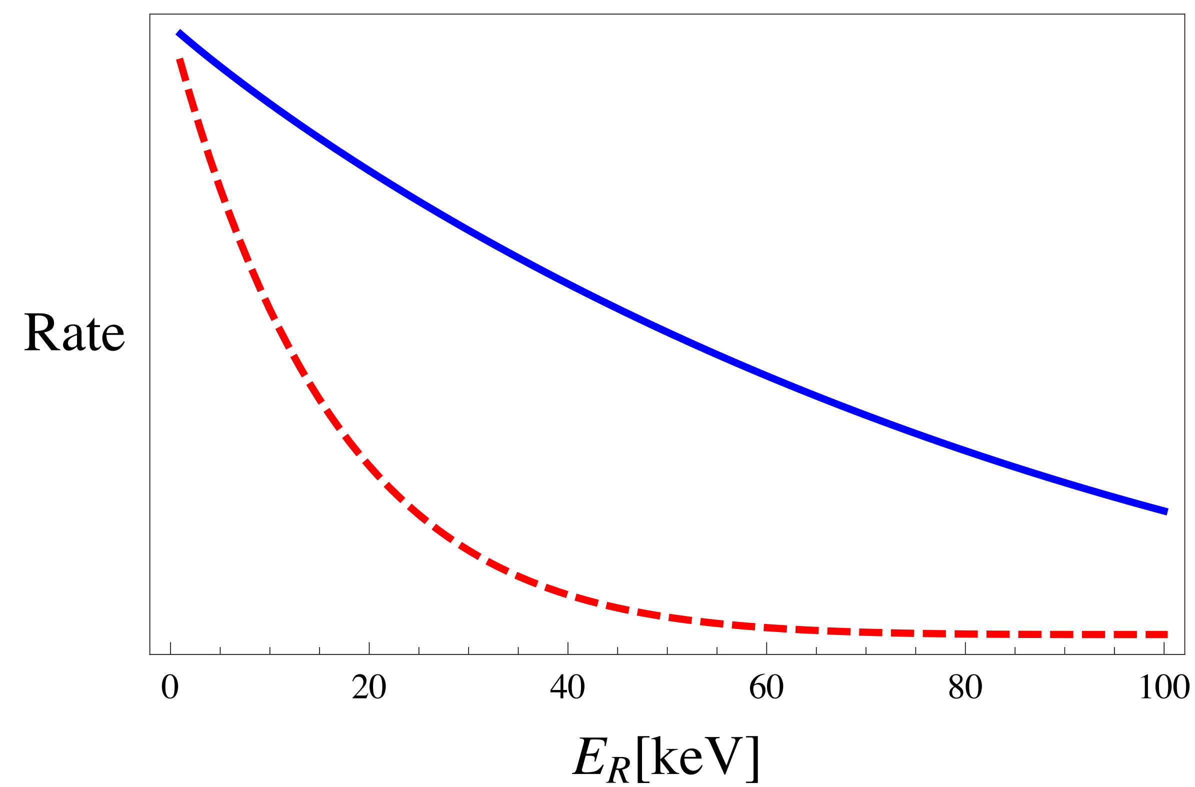


convoluted

(example rate is Xenon)

deconvoluted





convoluted

(example rate is Xenon)

What shapes/features are f(v)-independent?

Formally Solve for f(v)

Concrete statements can be made about general case.

Here, consider one DM particle scattering elastic *or* inelastic with a "factorizable" $\sigma(v,E_R) = \sigma(v)F_\chi^2(E_R)$.

We obtain:

$$f_1(v_{\min}(E_R)) = - \frac{4\mu^2 E_R^2}{m_N^2 E_R^2 - \mu^2\delta^2} \frac{1}{\mathcal{N}\sigma_0(v_{\min}(E_R))F_\chi^2(E_R)} \left(\frac{d\mathcal{R}}{dE_R} - \mathcal{R}\frac{1}{F_\chi^2(E_R)} \frac{dF_\chi^2(E_R)}{dE_R} \right)$$

f-condition

Central result: f(v) > 0 must be satisfied!

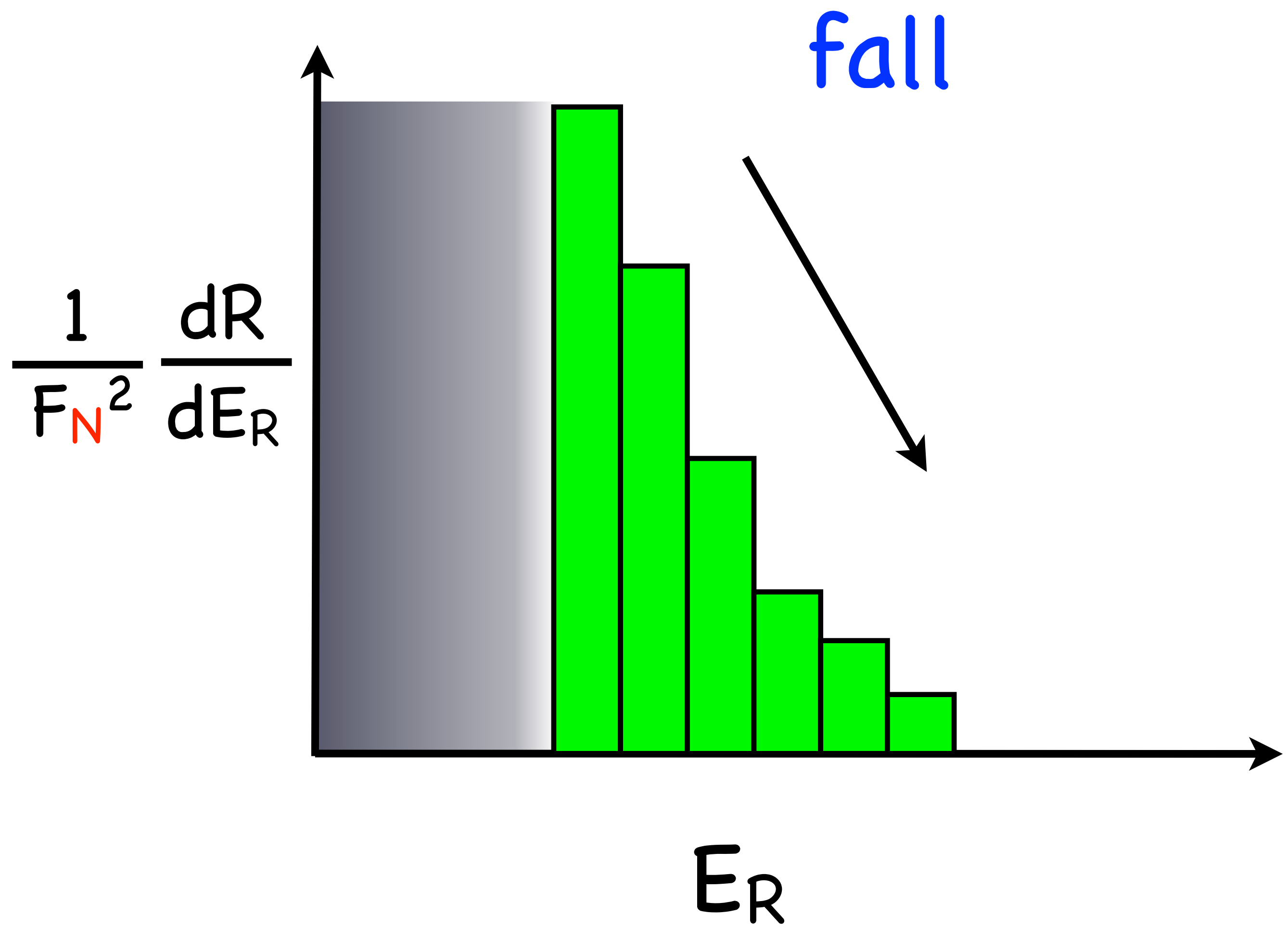
Implies rise must be particle physics.

Cannot be "faked" by unusual f(v).

$$f_1(v_{\min}(E_R)) = -\frac{4\mu^2 E_R^2}{m_N^2 E_R^2 - \mu^2\delta^2} \frac{1}{\mathcal{N}\sigma_0(v_{\min}(E_R))F_\chi^2(E_R)} \left(\frac{d\mathcal{R}}{dE_R} - \mathcal{R}\frac{1}{F_\chi^2(E_R)} \frac{dF_\chi^2(E_R)}{dE_R} \right)$$

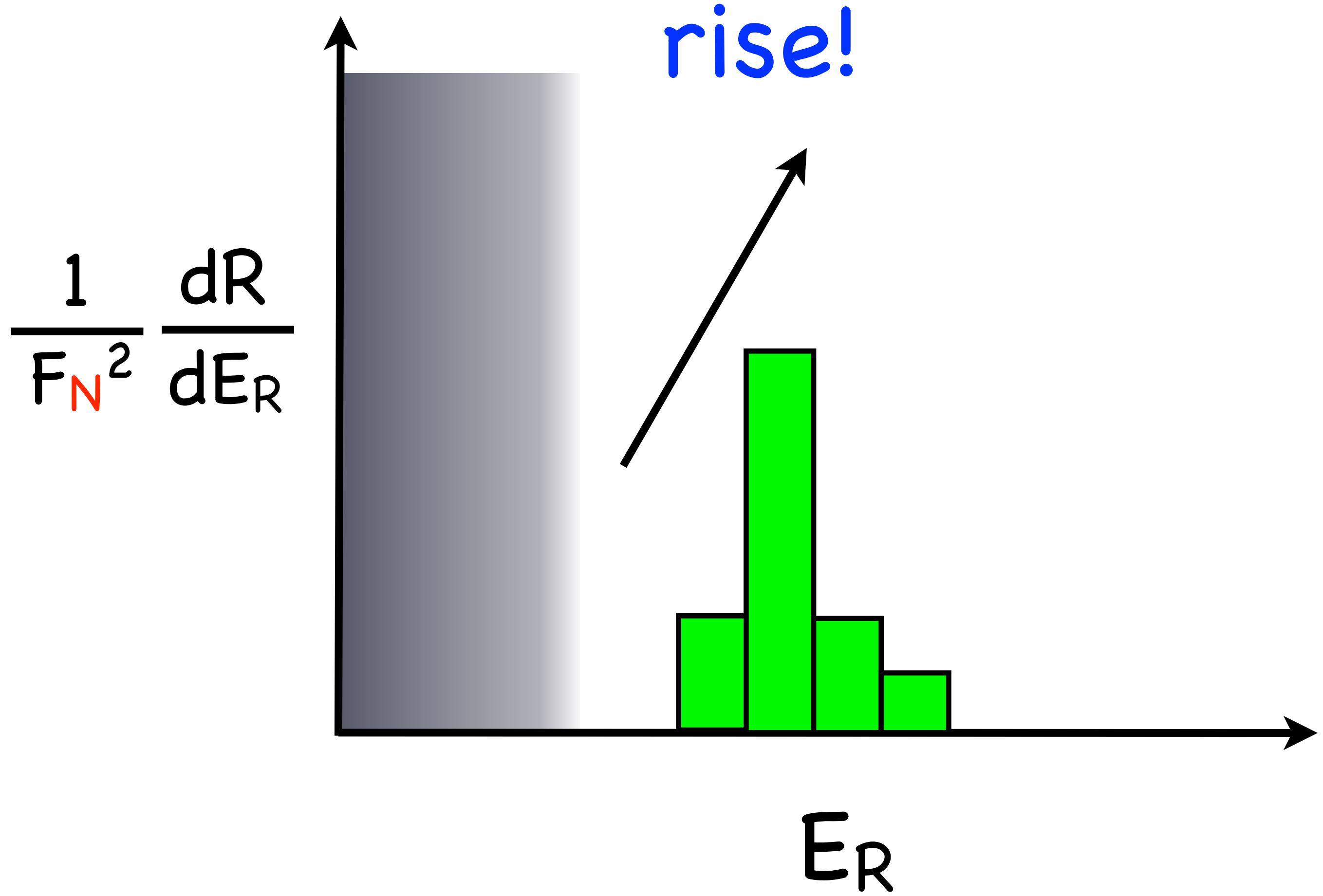
Examples

Ordinary Elastic Scattering



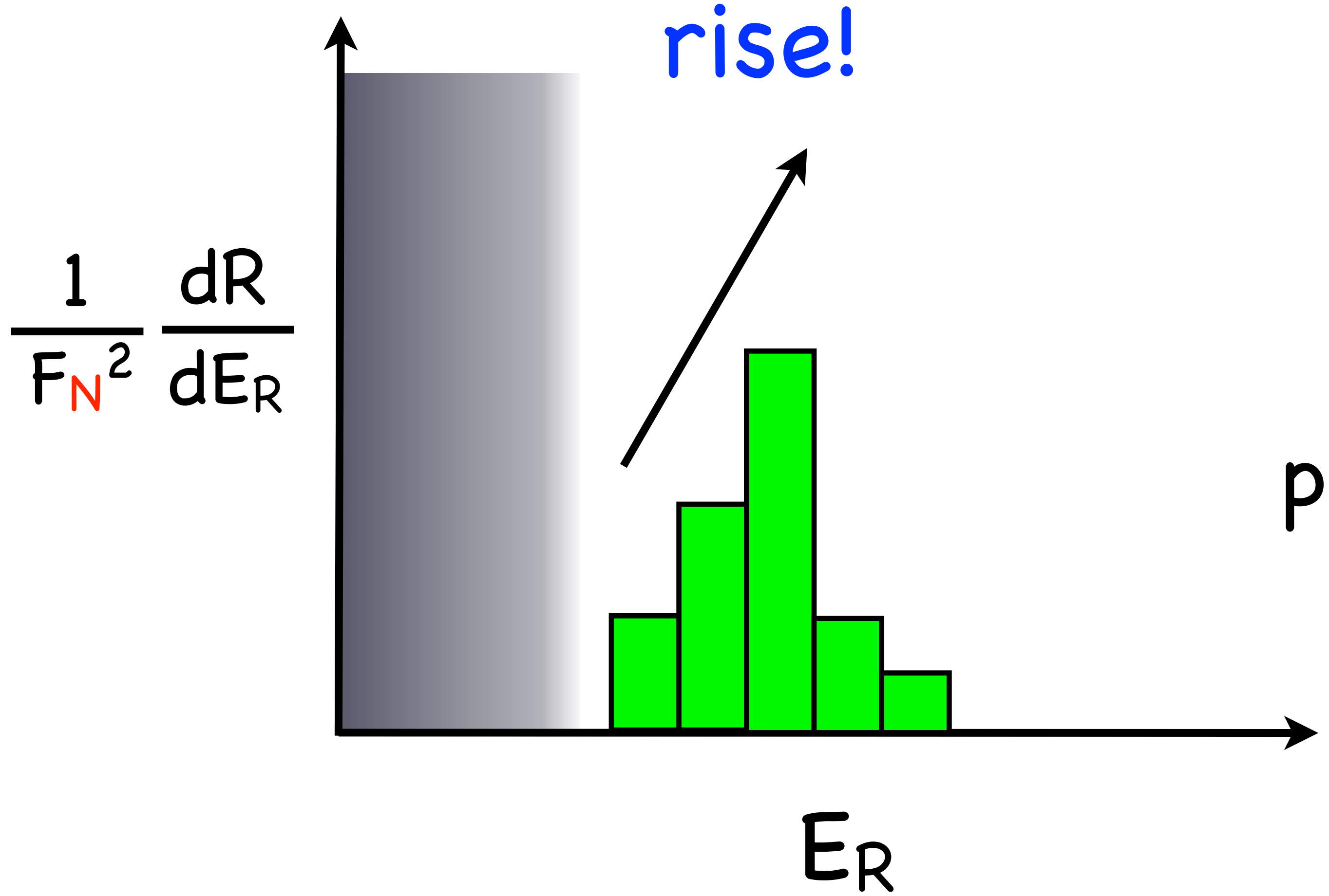
$$f_1(v_{\min}(E_R)) = - \frac{4\mu^2 E_R^2}{m_N^2 E_R^2} \frac{1}{\mathcal{N}\sigma_0(v_{\min}(E_R))F_\chi^2(E_R)} \left(\frac{d\mathcal{R}}{dE_R} \right)$$

Inelastic; no form factor



$$f_1(v_{\min}(E_R)) = -\frac{4\mu^2 E_R^2}{m_N^2 E_R^2 - \mu^2\delta^2}\frac{1}{\mathcal{N}\sigma_0(v_{\min}(E_R))F_\chi^2(E_R)}\left(\frac{d\mathcal{R}}{dE_R}\quad\right)$$

Dark Matter Form Factor



$F_\chi(E_R) \approx (E_R)^n$

positive powers

$$f_1(v_{\min}(E_R)) = -\frac{4\mu^2 E_R^2}{m_N^2 E_R^2 \boxed{}} \frac{1}{\mathcal{N}\sigma_0(v_{\min}(E_R))F_\chi^2(E_R)} \left(\frac{d\mathcal{R}}{dE_R} - \mathcal{R}\frac{1}{F_\chi^2(E_R)}\frac{dF_\chi^2(E_R)}{dE_R} \right)$$

Anything goes for $f(v)$?

If no priors on f(v), then using

$$v_{min} = \left(\frac{m_N \, E_R}{2\,\mu^2}\right)^{1/2}$$

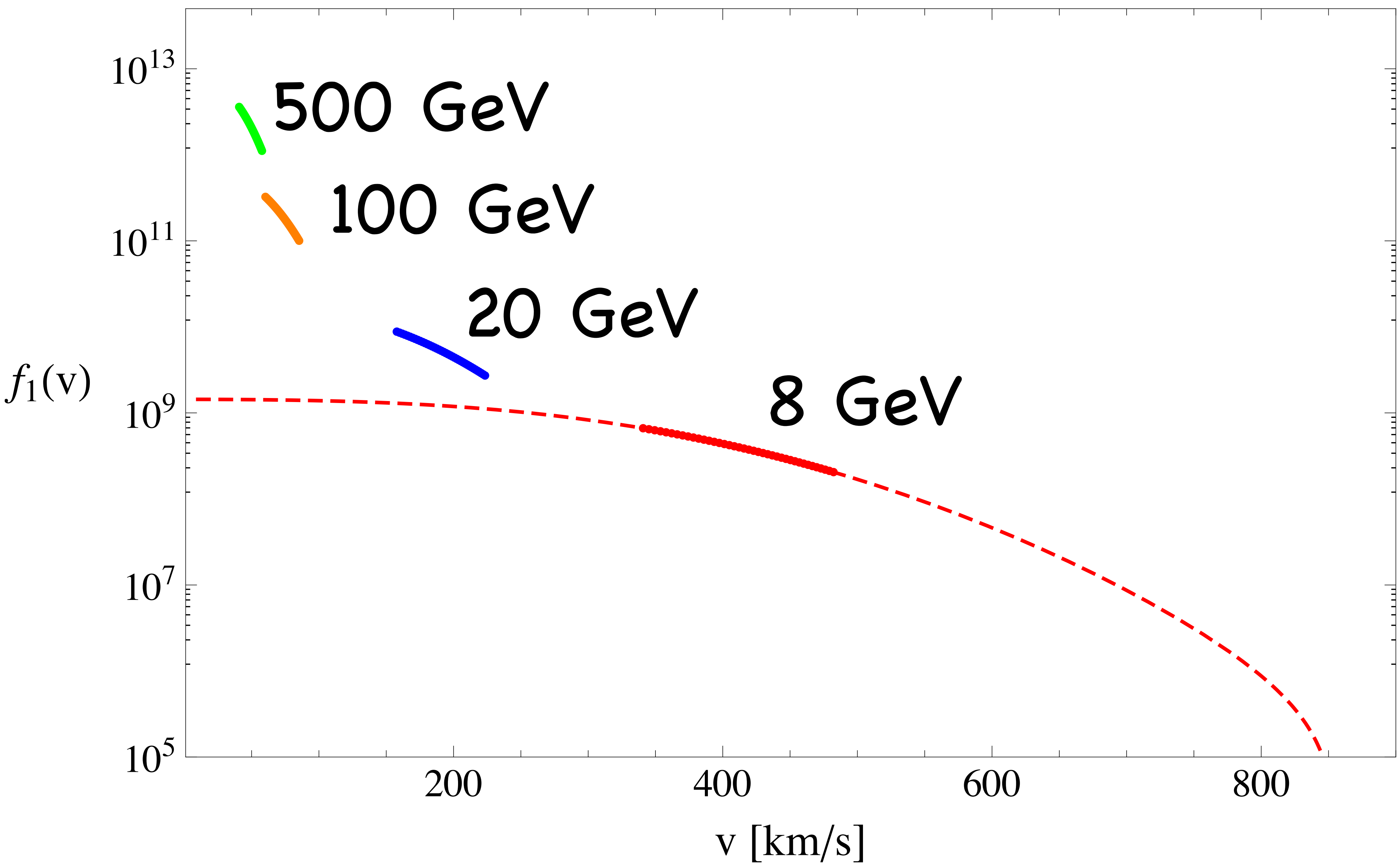
can increase m_X

while

decreasing velocity range

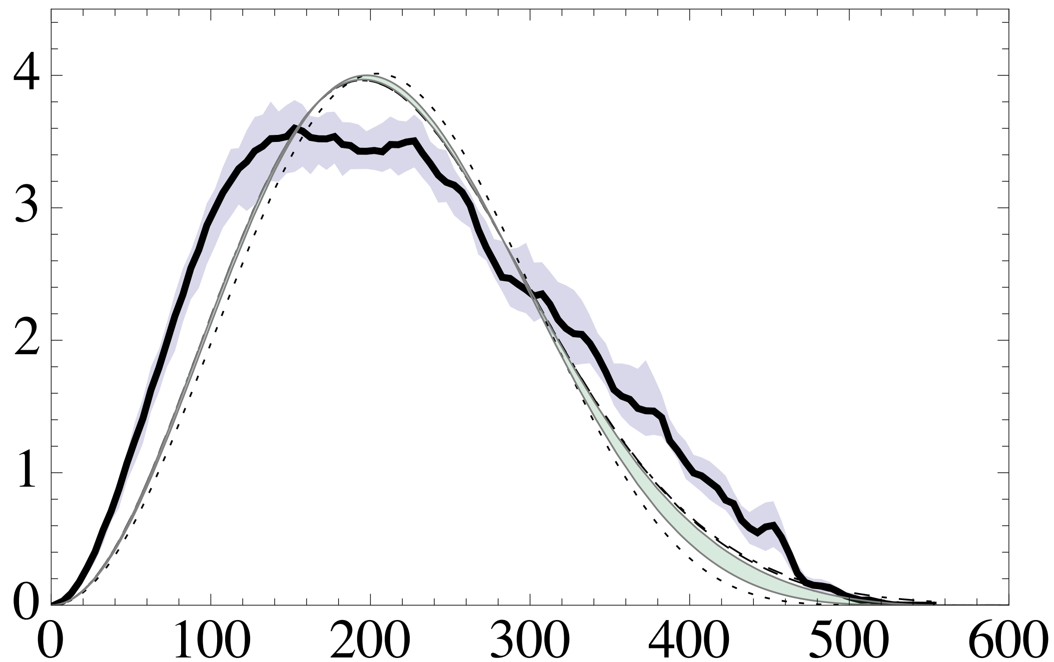
$$\frac{v_{min}(m_{Xlow})}{v_{min}(m_{Xhigh})} = \frac{\mu_{high}}{\mu_{low}} \quad \text{asymptotes to } (m_{Xhigh} \gg m_{Ge}) \longrightarrow \quad \frac{m_{Ge}}{m_{Xlow}}$$

Example: Range of f(v) that fit CoGeNT excess

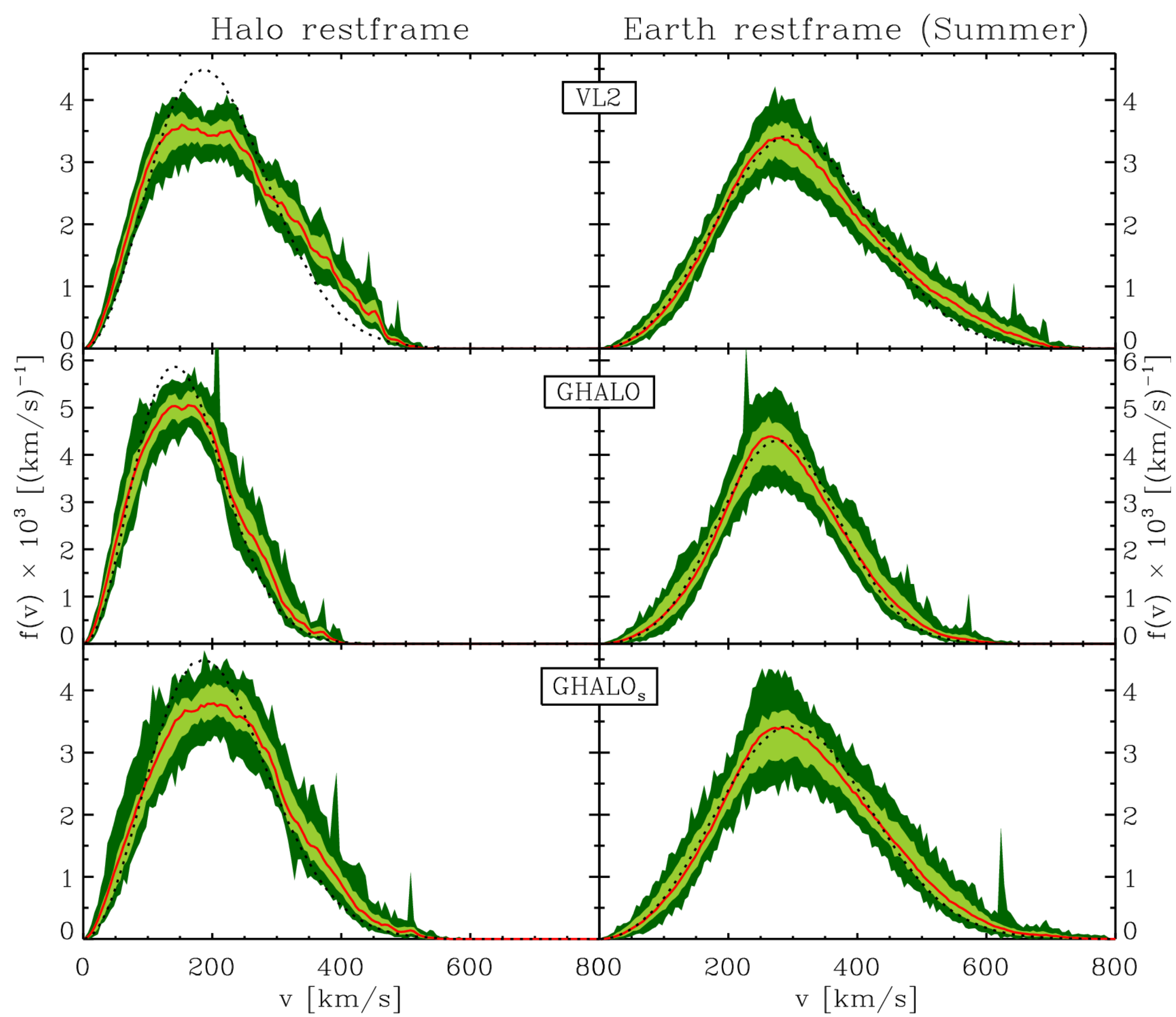


Earth frame!

Surely, you're crazy...



Lisanti et al 1010.4300

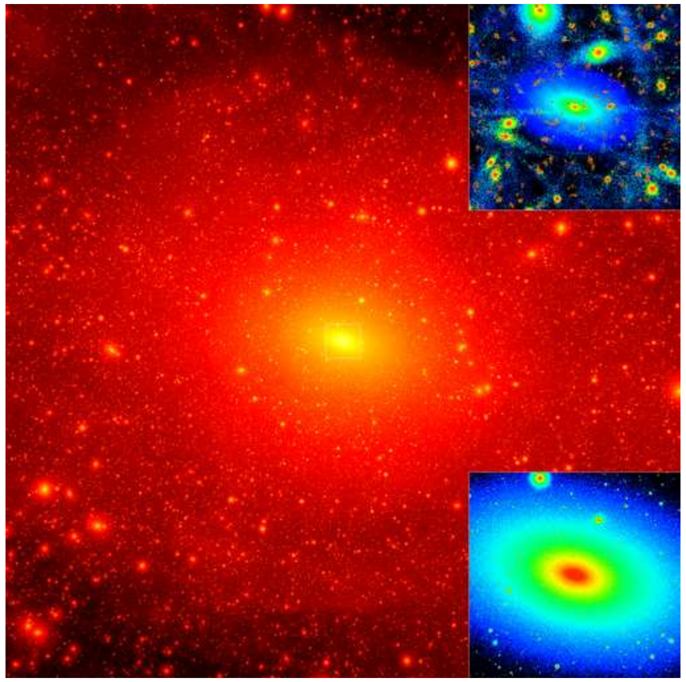


Kuhlen et al 0912.2358

Local Distribution?

N body simulations such as Via Lactea, GHALO, etc give excellent average properties for a galaxy like the Milky Way.

0808.2981 (GHALO)



astro-ph/0611370 (Via Lactea)

Resolution ≈ 1000 M_{solar}/pc^3 ≈ 1 particle/(50 pc^3); while 25 years of dark matter experiments have sampled L ≈ 230 km/s x 25 years ≈ 0.006 pc

Local Distribution?

0812.2033

The Graininess of Dark Matter Haloes

Marcel Zemp[1,2⋆], Jürg Diemand[2,6], Michael Kuhlen[3], Piero Madau[2], Ben Moore[4], Doug Potter[4], Joachim Stadel[4] and Lawrence Widrow[5]

ABSTRACT
We use the recently completed one billion particle *Via Lactea II* ΛCDM simulation to investigate local properties like density, mean velocity, velocity dispersion, anisotropy, orientation and shape of the velocity dispersion ellipsoid, as well as structure in velocity space of dark matter haloes. We show that at the same radial distance from the halo centre, these properties can deviate by orders of magnitude from the canonical, spherically averaged values, a variation that can only be partly explained by triaxiality and the presence of subhaloes. The mass density appears smooth in the central relaxed

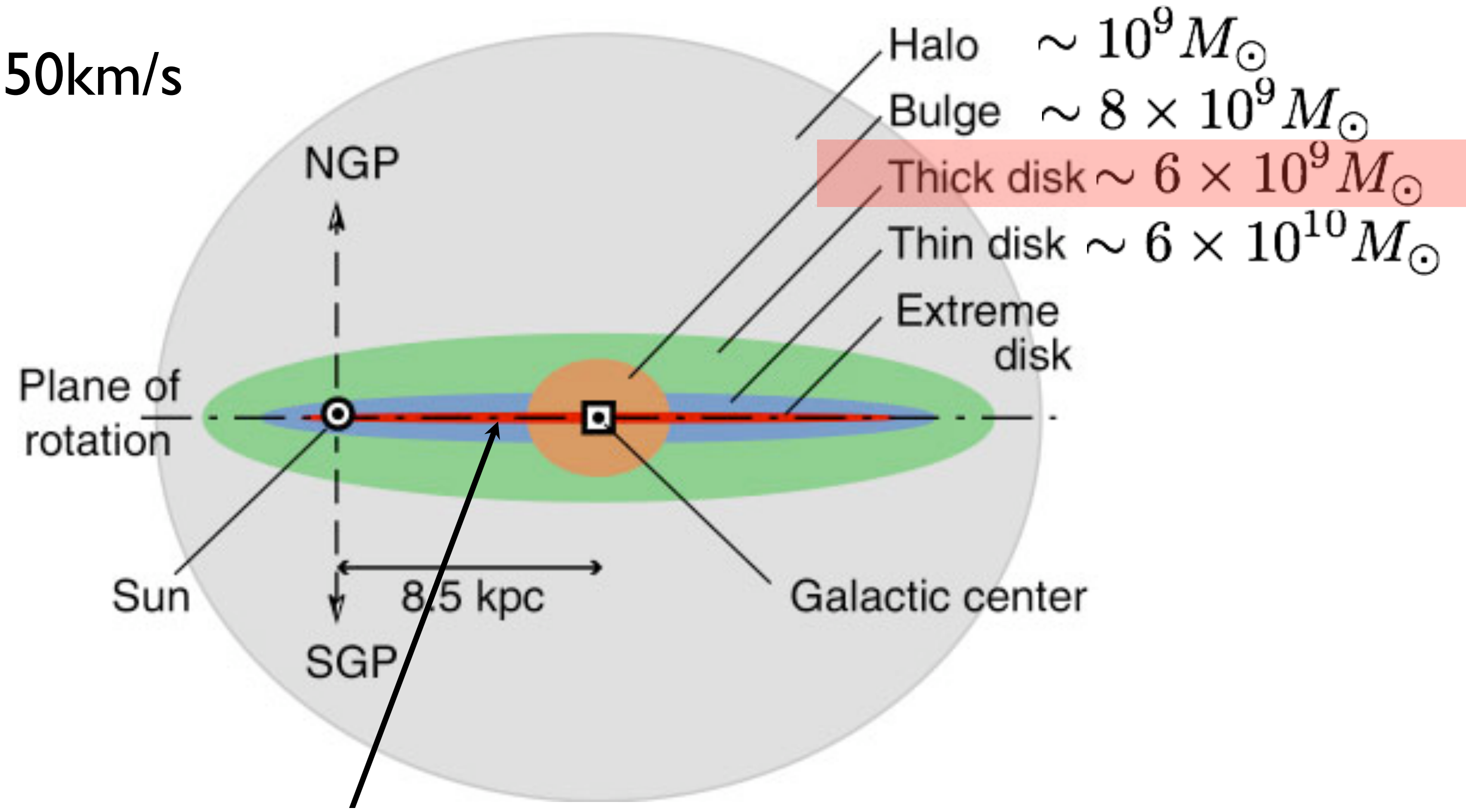
Conclusions

the local phase space structure. Also the missing baryonic physics in Via Lactea II like adiabatic contraction, stellar disk and bulge, inspiralling compact objects like black holes etc. can modify the central dark matter structure in either way. Therefore, it is still not clear what the detailed structure of the dark matter locally is.

Dark Disk in Simulations with Baryon Disk

$\rho_{dd} = 0.25\text{-}1.5\rho_{shm}$; $v_{lag} = 0\text{-}150$km/s ; $\sigma = 50\text{-}90$km/s

Fiducial values: $\rho_{dd} = 0.5\rho_{shm}$; $v_{lag} = \sigma = 50$km/s



- The precise dark disc properties are not known since these depend on the detailed merger history of the Milky Way. We can hope to detect and characterise the dark disc astrophysically by hunting for accreted stars in the solar neighbourhood.

Read et al 0803.2714; 0901.2938

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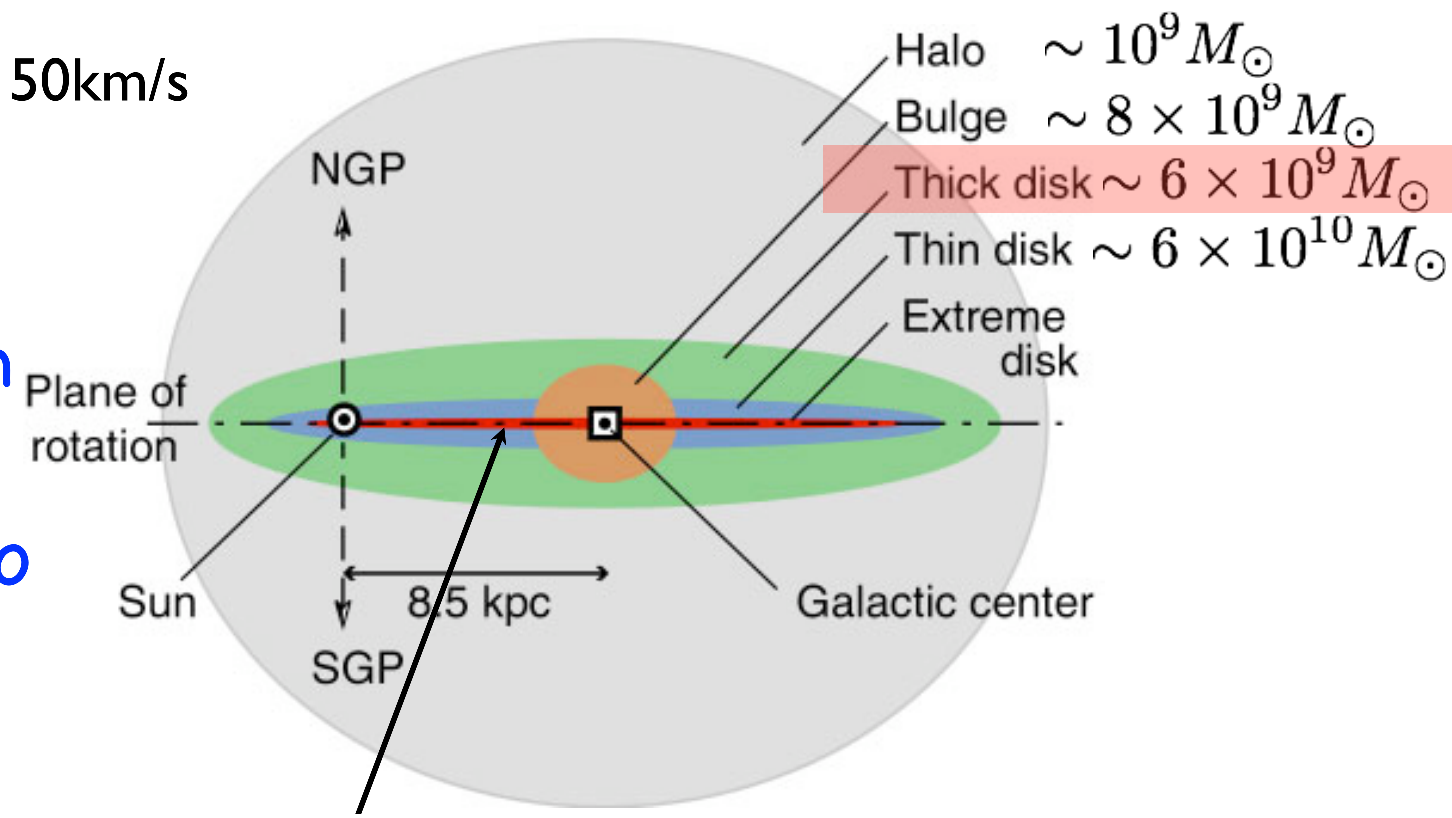
Densities comparable to halo

velocities much smaller than Maxwellian halo



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Summary

- There are astrophysics-independent signals of particle physics -- rise(s) in deconvoluted spectrum!
- Lower bounds on m_X robust (kinematics), and get better with data at high E_R (inelastic low and high E_R)
- Upper bounds on m_X nonexistent with arbitrary f(v) (CoGeNT not necessarily light DM)
- Smaller range for f(v) in Earth frame physically realizable (dark disk, etc.)
- Healthy degree of skepticism of local f(v) is essential to avoid "jumping to conclusions"