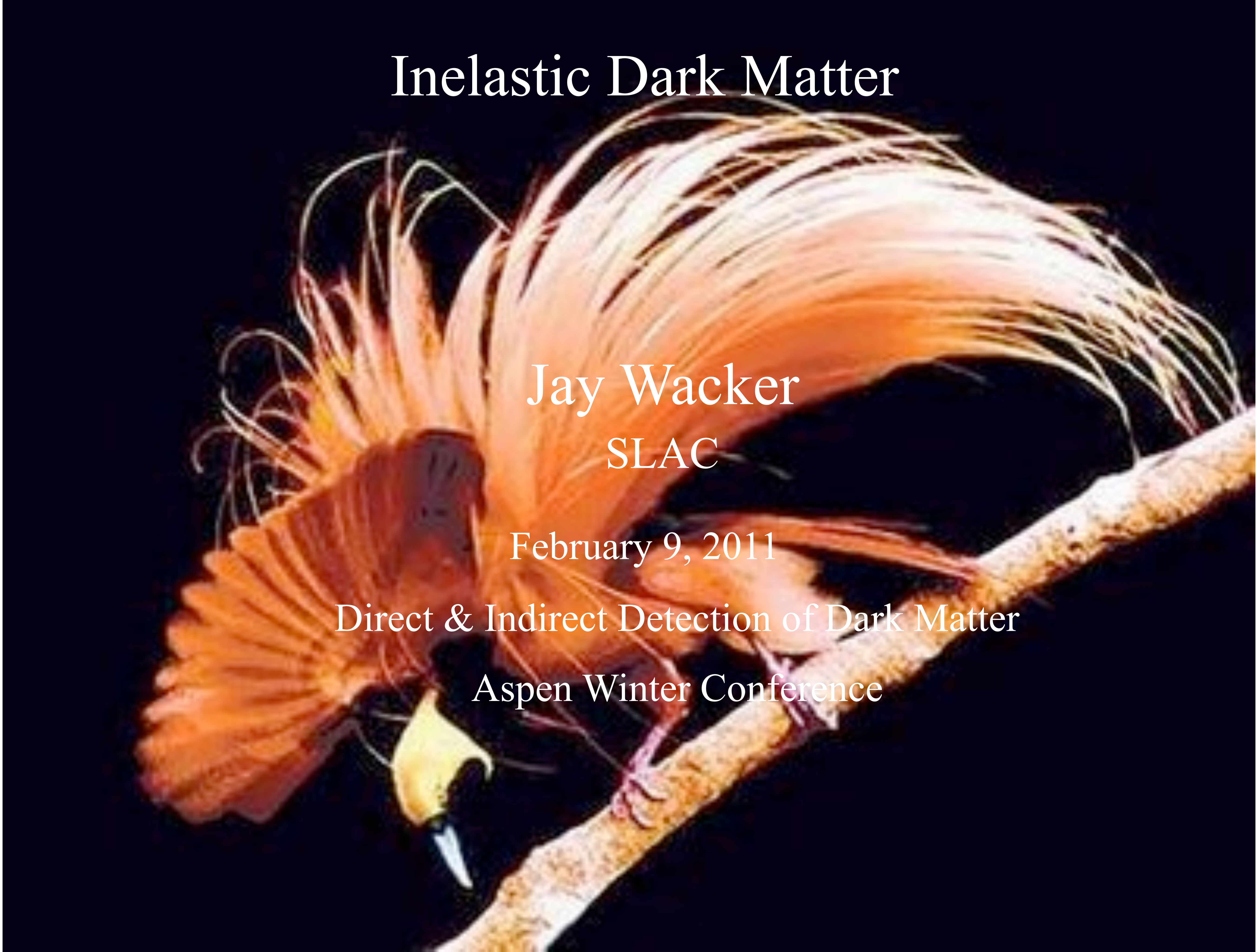
Inelastic Dark Matter



Jay Wacker

SLAC

February 9, 2011

Direct & Indirect Detection of Dark Matter

Aspen Winter Conference

Inelastic Dark Matter is a Weird Bird

Requires believing DAMA at face value

Non-minimal Dark Sectors

Inelastic Dark Matter is a Weird Bird

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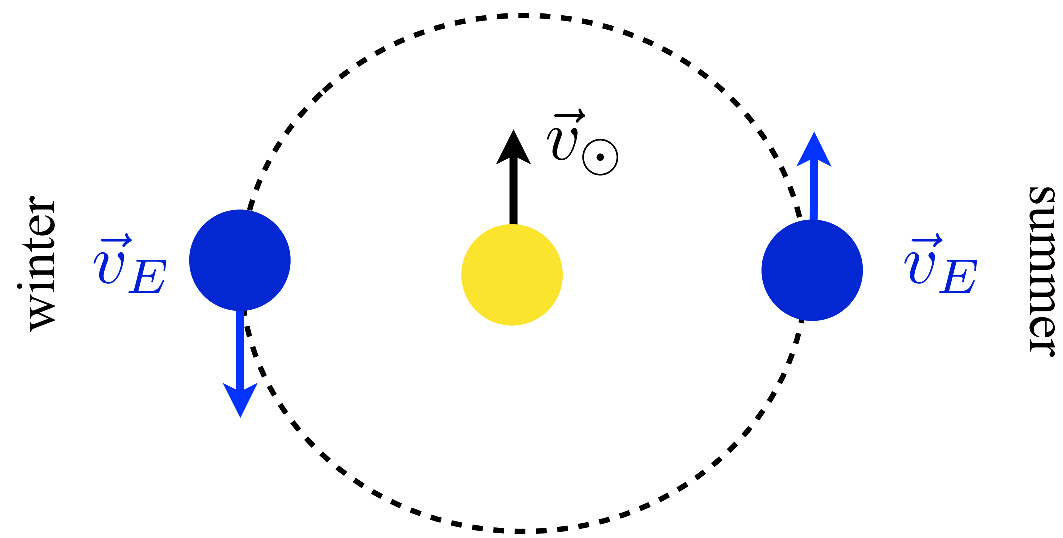
Non-minimal Dark Sectors

DAMA

NaI Annual Modulation Experiment running for 13 years

Galactic Dark Matter



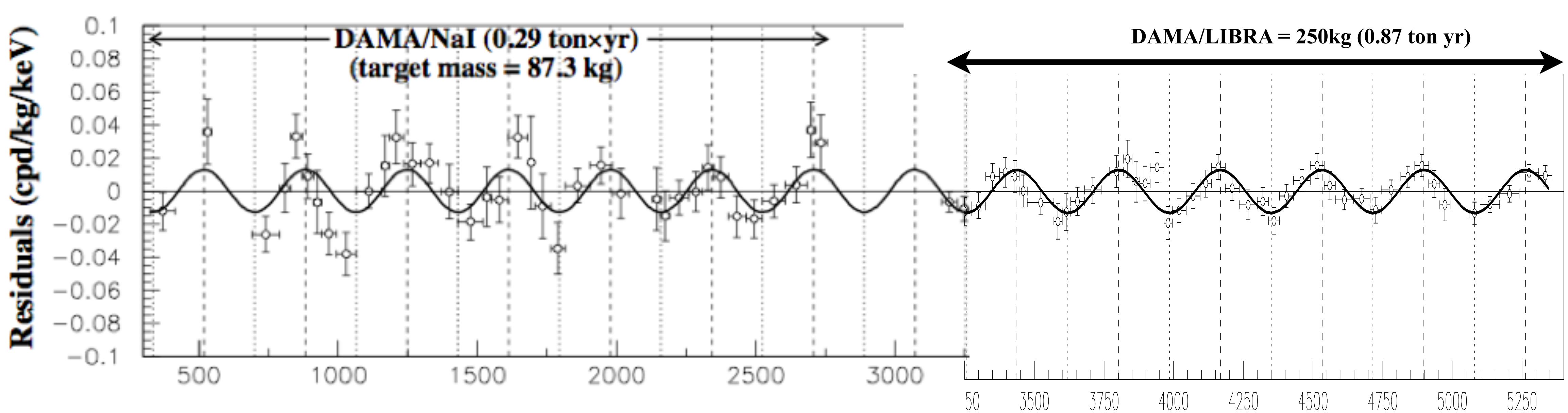
$v \le v_{\rm esc} + |\vec{v_E} - \vec{v_\odot}|$ $v \le v_{\rm esc} + |\vec{v_E} + \vec{v_\odot}|$

Annual modulation in WIMP signal

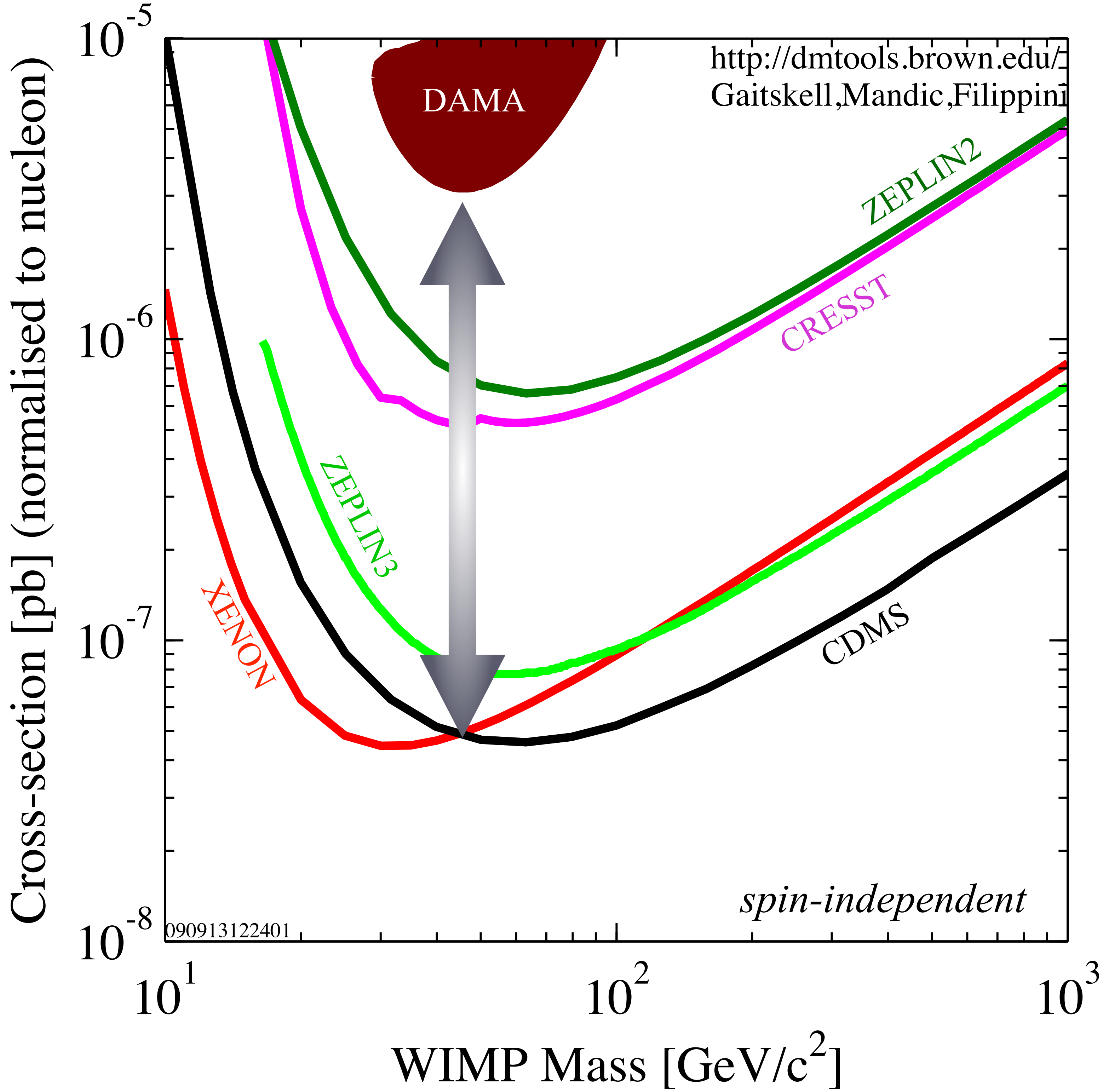
$$\Phi_{\rm dm} = n_{\rm dm}\, v$$

$$A_{\rm mod} = R_{\rm Sum} - R_{\rm Win}$$

Modulation amplitude ~2.5% for elastic scattering



“Normal” Dark Matter is in conflict



Excluded
by a factor
of 30

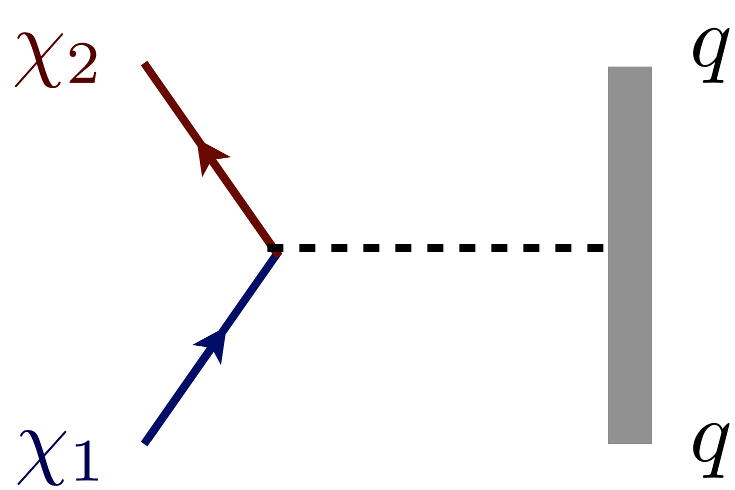
Inelastic Dark Matter

Dark matter has two nearly degenerate states

$$\delta m \sim (100 \text{ keV})$$

Tucker-Smith and Weiner, hep-ph/0101138.

Scattering off SM transitions between states



Higher threshold velocity necessary to scatter,

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

Rate Calculation

Minimum DM velocity to scatter cause E_R recoil

Fast particles not bound to galaxy

Velocity Distribution

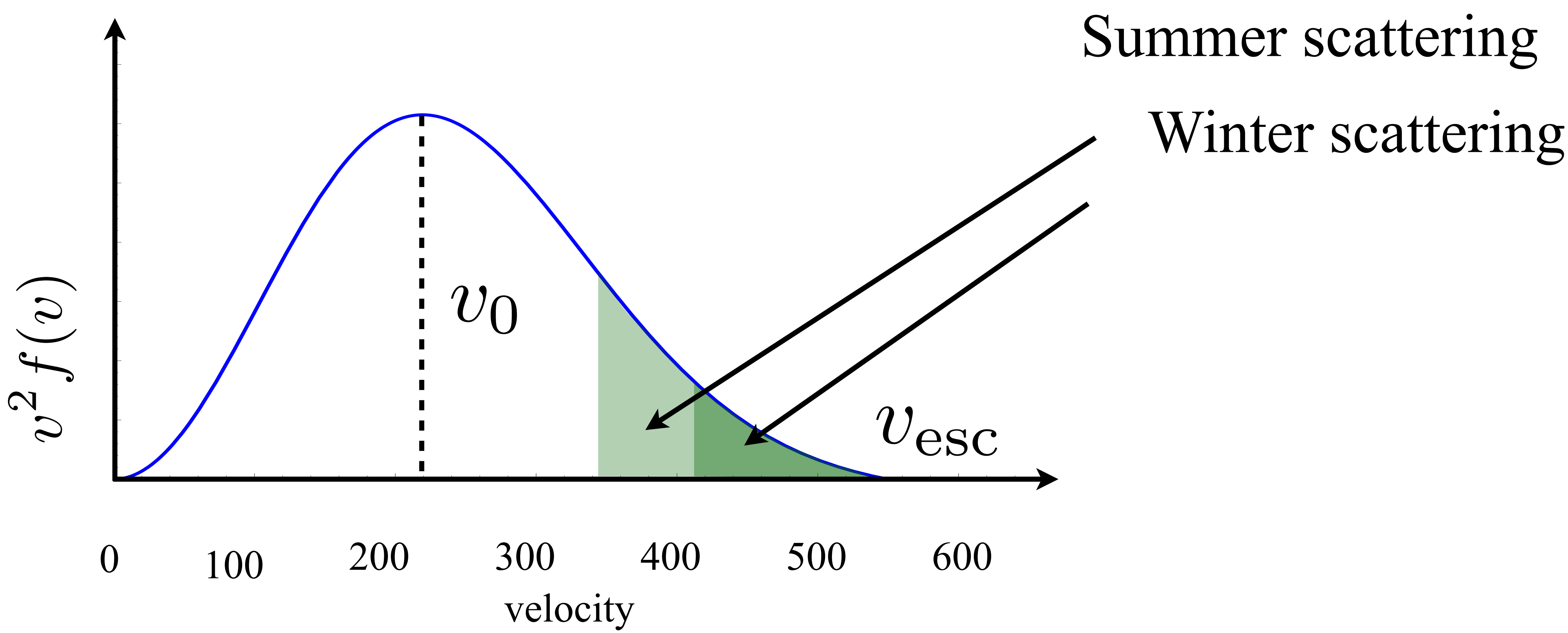
$$\frac{dR}{dE_R} \propto \int_{v_{\rm min}}^{v_{\rm esc}} d^3v \, \frac{d\sigma}{dE_R} v \, e^{-v^2/v_0^2}$$

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

Larger Modulation Fraction

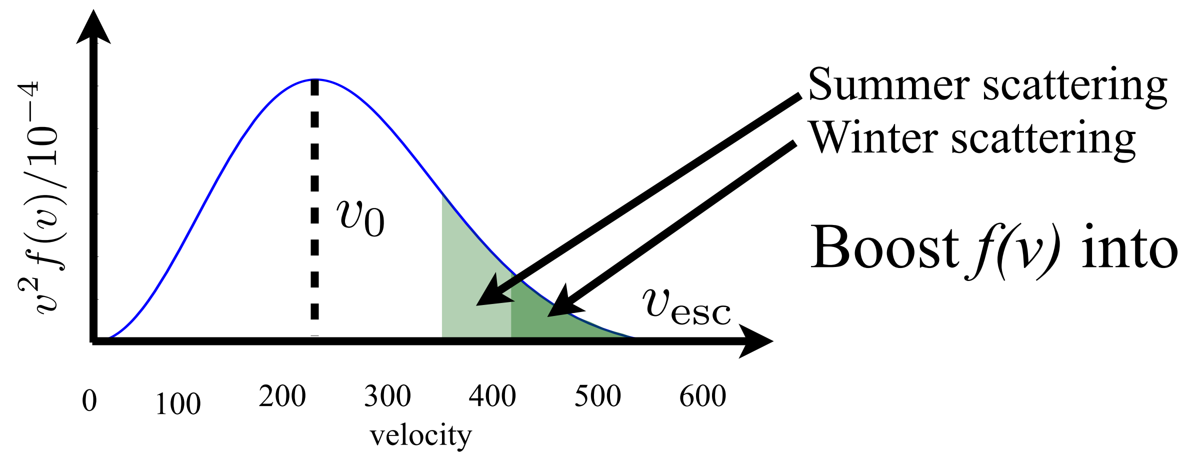
Boost *f(v)* into Earth's frame

Fraction of DM that can scatter inelastically changes dramatically

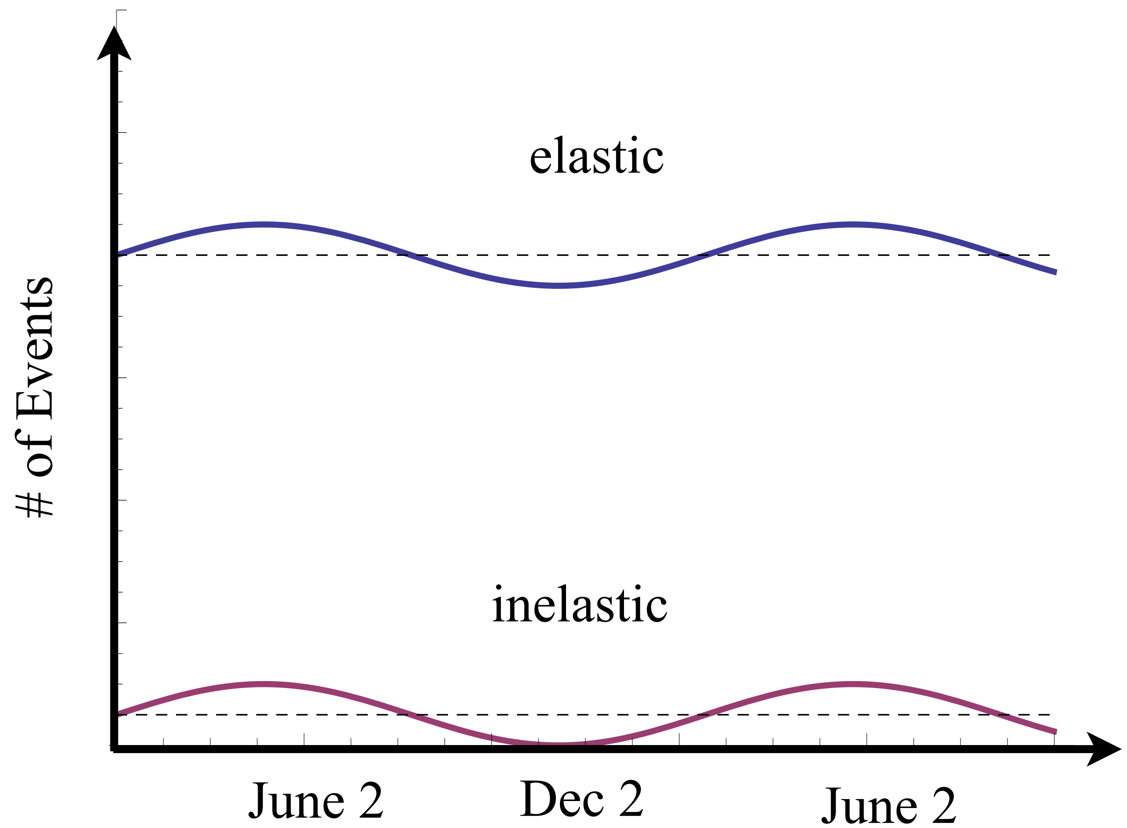


Larger Modulation Fraction

Smaller rate to fit DAMA's modulation



Boost *f(v)* into Earth's frame



2.5% modulation

Factor of 20 difference in translating modulated to unmodulated rate!

100% modulation

Extreme sensitivity to *when* the experiment ran

Running in winter can reduce sensitivity

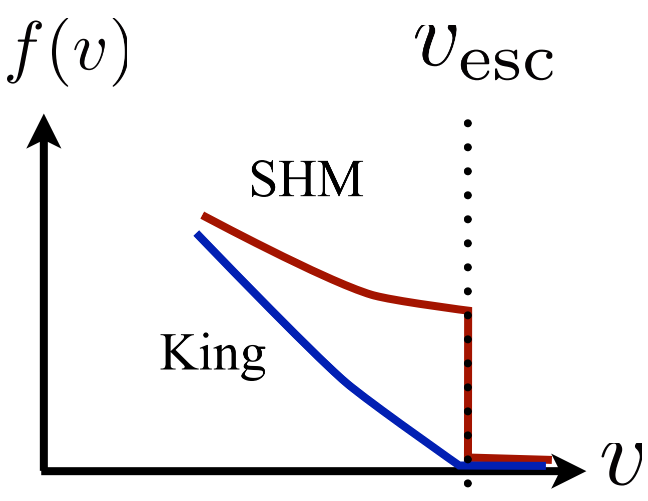
How Many Particles near Escape Velocity?

Want to know about the high velocity tails for
dark matter scattering

Long running debate between:

$$f_{\rm SHM} = e^{-v^2/v_0^2}\,\Theta(v_{\rm esc} - v)$$

$$f_{\rm King} = \left(e^{-v^2/v_0^2} - e^{-v_{\rm esc}^2/v_0^2}\right)\Theta(v_{\rm esc} - v)$$



eg Petriello & Zurek 0806.3989 vs Chang, Kribs, Tucker-Smith & Weiner 0807.2250

How many particles are near the escape velocity?

Velocity Distribution Ansatz

Lisanti, Strigari, JW, Weschler 1010.4300

The functional form of the velocity distribution must satisfy

$$\text{Isotropy} + \text{Equilibrium} \Longrightarrow f(\mathcal{E})$$

$$\mathcal{E} = v_{\rm esc}^2 - v^2$$

The ansatz for the phase space distribution is

power-law index

$$f(\mathcal{E}) \propto \left(e^{\mathcal{E}/\mathcal{E}_0} - 1\right)^{k} \Theta(\mathcal{E})$$

Goes smoothly to zero at low binding energy (i.e., near $v_{\rm esc}$)

$$f(v) \rightarrow (v_{\rm esc} - v)^k$$

Satisfies Jeans Theorem

Scattering Rate

Spatial density profiles: $\rho \propto r^{-\alpha}(a+r)^{-\gamma+\alpha}$

$$\mathrm{NFW}: \qquad \alpha = 1 \quad \gamma = 3$$

$$k = \gamma - 3/2 \qquad (\gamma > 3)$$

Scattering Rate

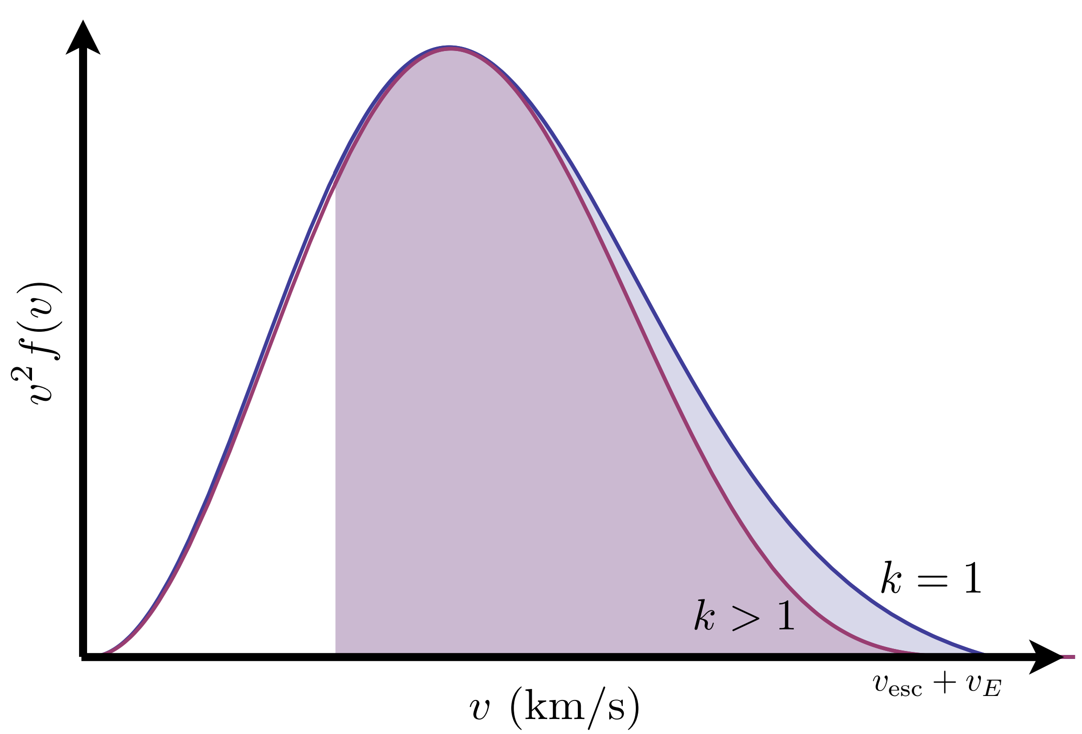
Spatial density profiles: $$\rho \propto r^{-\alpha}(a+r)^{-\gamma+\alpha}$$

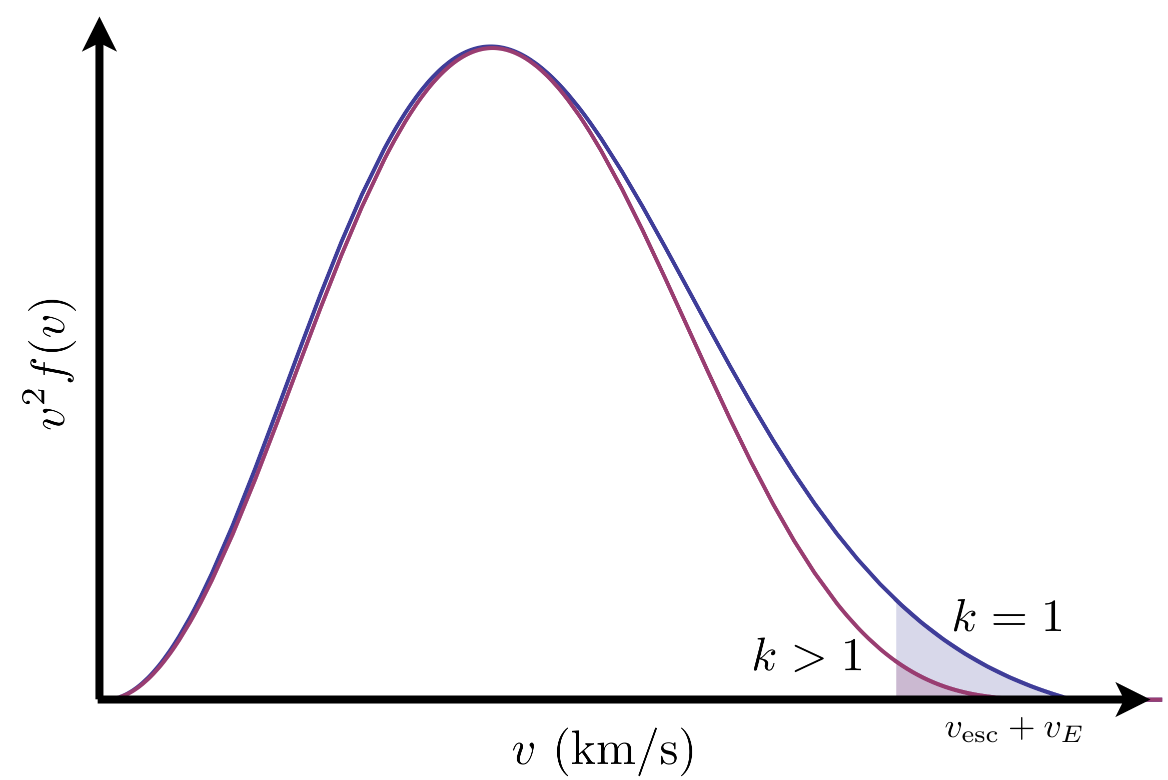
$$\text{NFW}: \quad \alpha = 1 \quad \gamma = 3$$

$$k = \gamma - 3/2 \qquad (\gamma > 3)$$

For low v_{min}, small differences between rates for different k

Rates for large v_{min} are significantly altered



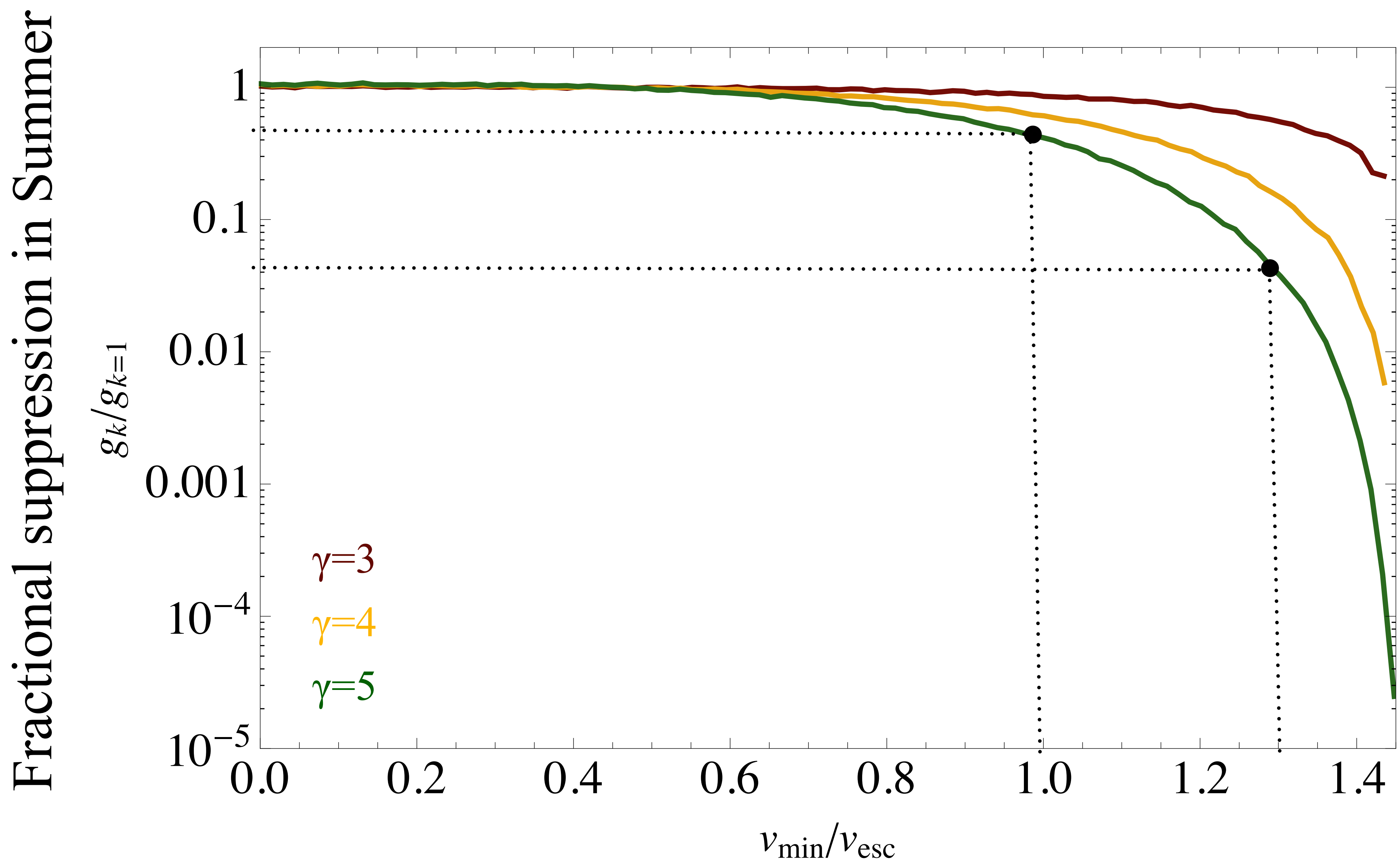


Scattering Rate

Using lighter nuclei problematic

$$v_{\min} \sim \frac{\delta m}{\sqrt{m_N E_R}}$$

Replacing ^{127}I with ^{72}Ge raises $v_{\min}$ by 30%



Light nuclei can only confirm

Too much theoretical uncertainty

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Heavy nuclei are necessary to exclude

Much heavier usually results in lower modulation fraction

CRESST

$CaWO_4$ Detector

XENON100

COUPP

KIMS

Light nuclei can only confirm

Too much theoretical uncertainty

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CRESST

$CaWO_4$ Detector

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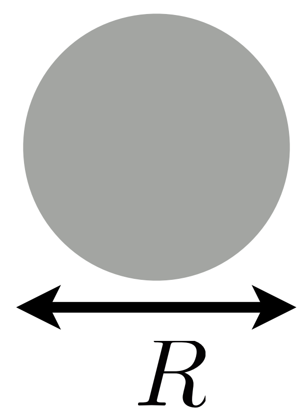
Going too heavy is problematic too

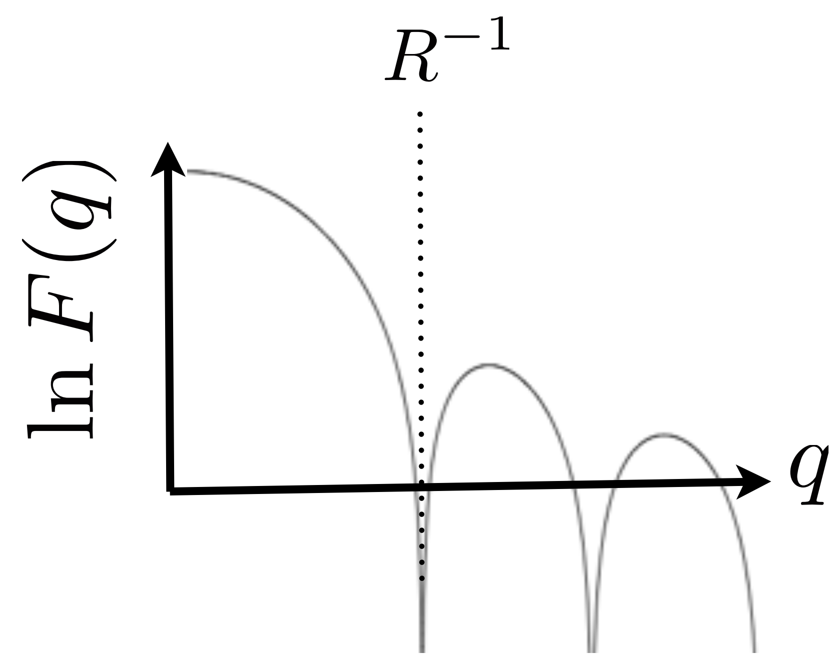
Nuclear Form Factors

Heavier in mass, larger in size



Fourier transforming the mass distribution gives the form factor

$$F_{\mathrm{Helm}}(q) \sim \frac{j_1(qR)}{qR}$$

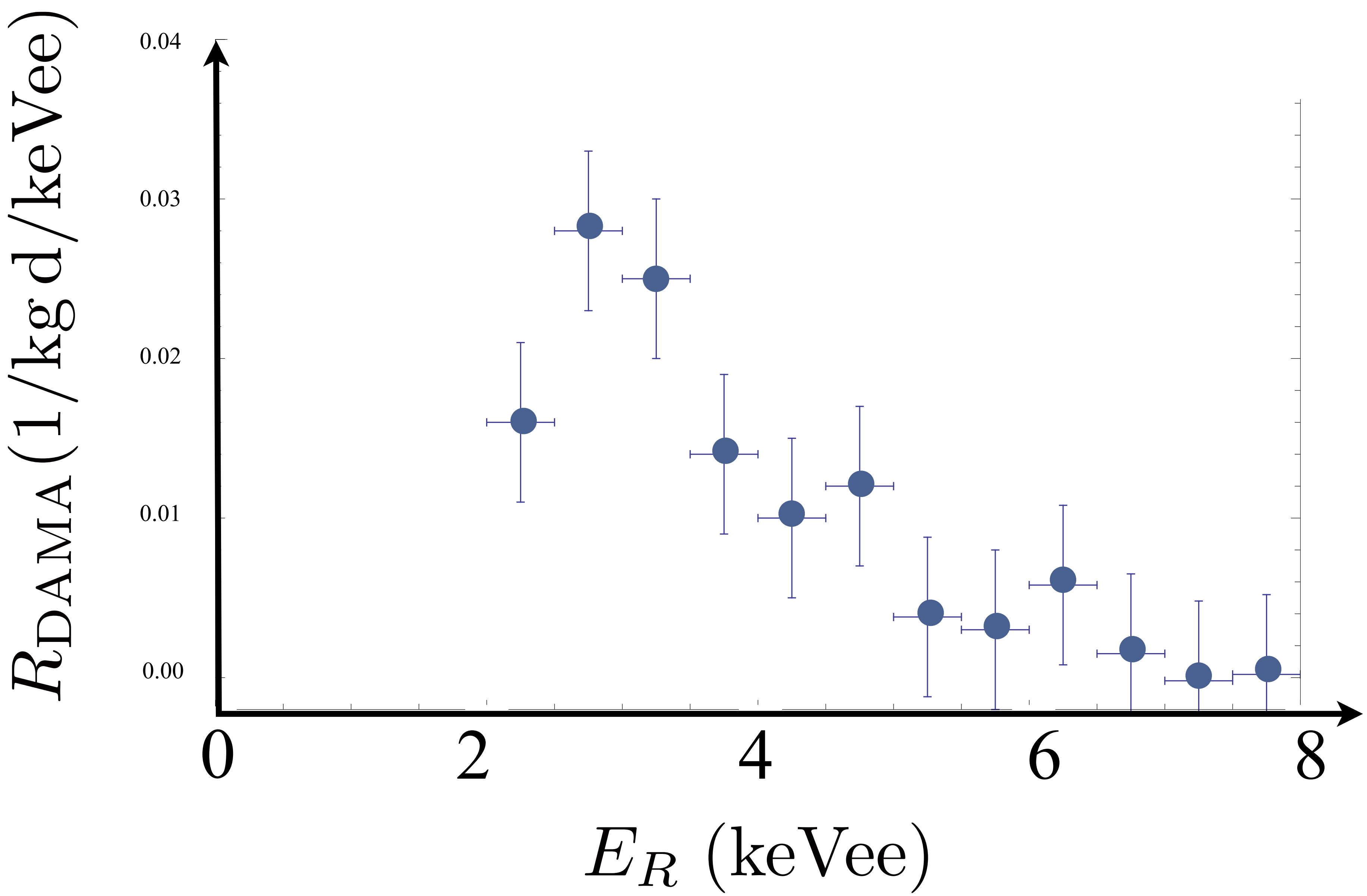


If size is too large, zero of form factor can suppress signal

Quenching factors

DAMA measure scintillation, only a fraction of the energy

$$E_{\rm ee} = Q_{\rm I} E_{\rm nr} \qquad\qquad 5\% \lesssim Q_I \lesssim 10\%$$



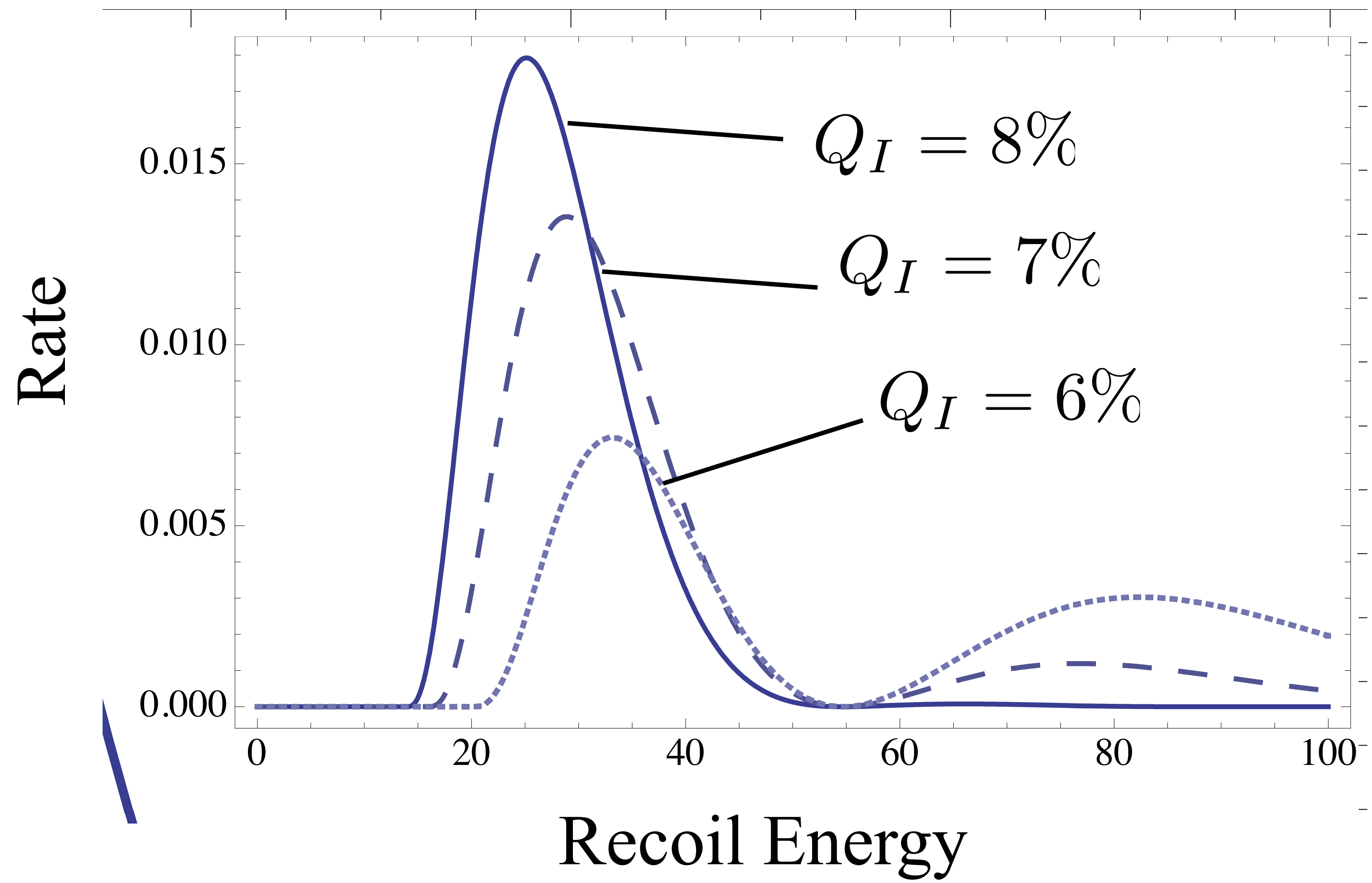
$$3 \text{ keVee} = 30 \text{ keVnr} \rightarrow 60 \text{ keVnr}$$

CRESST-II

^{184}W has nuclear form factor zero at 50 keVnr

$$10\text{keV} \leq E \leq 40 \text{ keV}$$

DAMA signal can lie on top of the zero



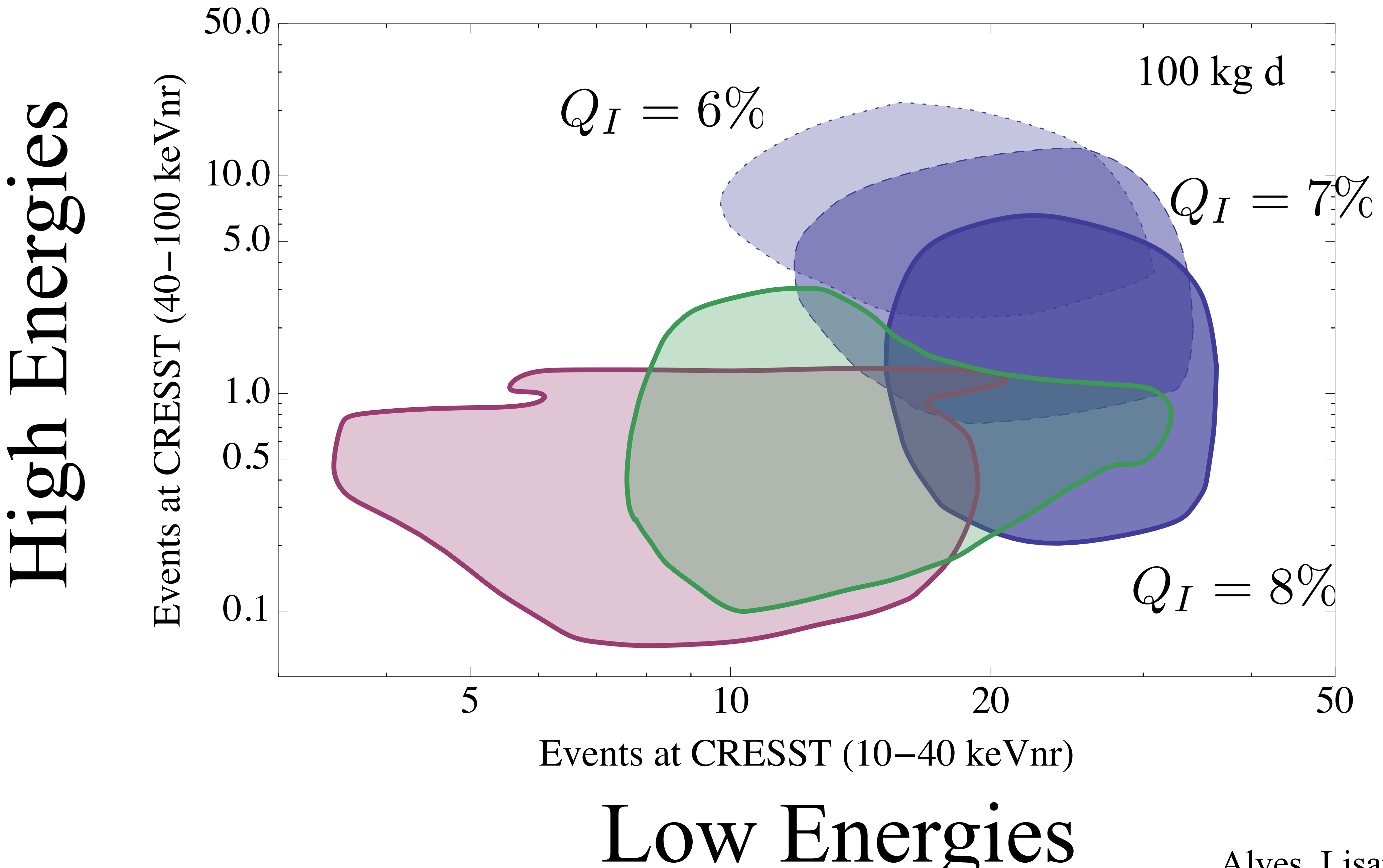
Alves, Lisanti, JW 1005.5421

CRESST-II

Fitting DAMA

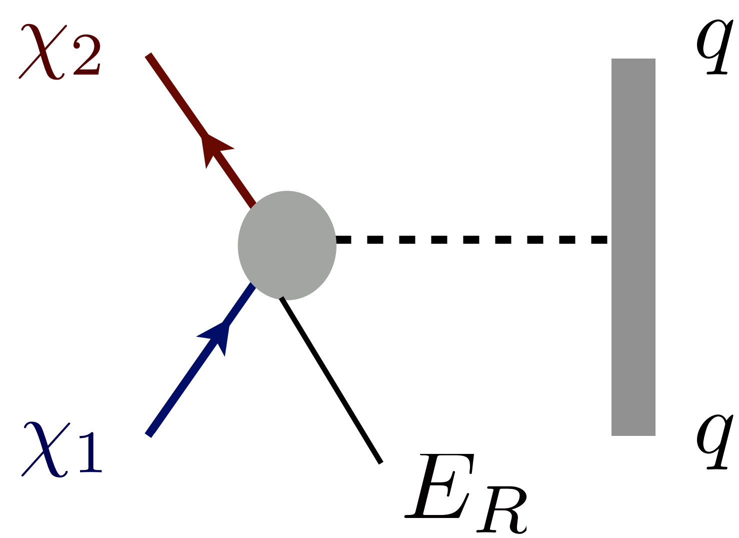
Fit other experiments (including XENON100)

Marginalizing over astrophysics



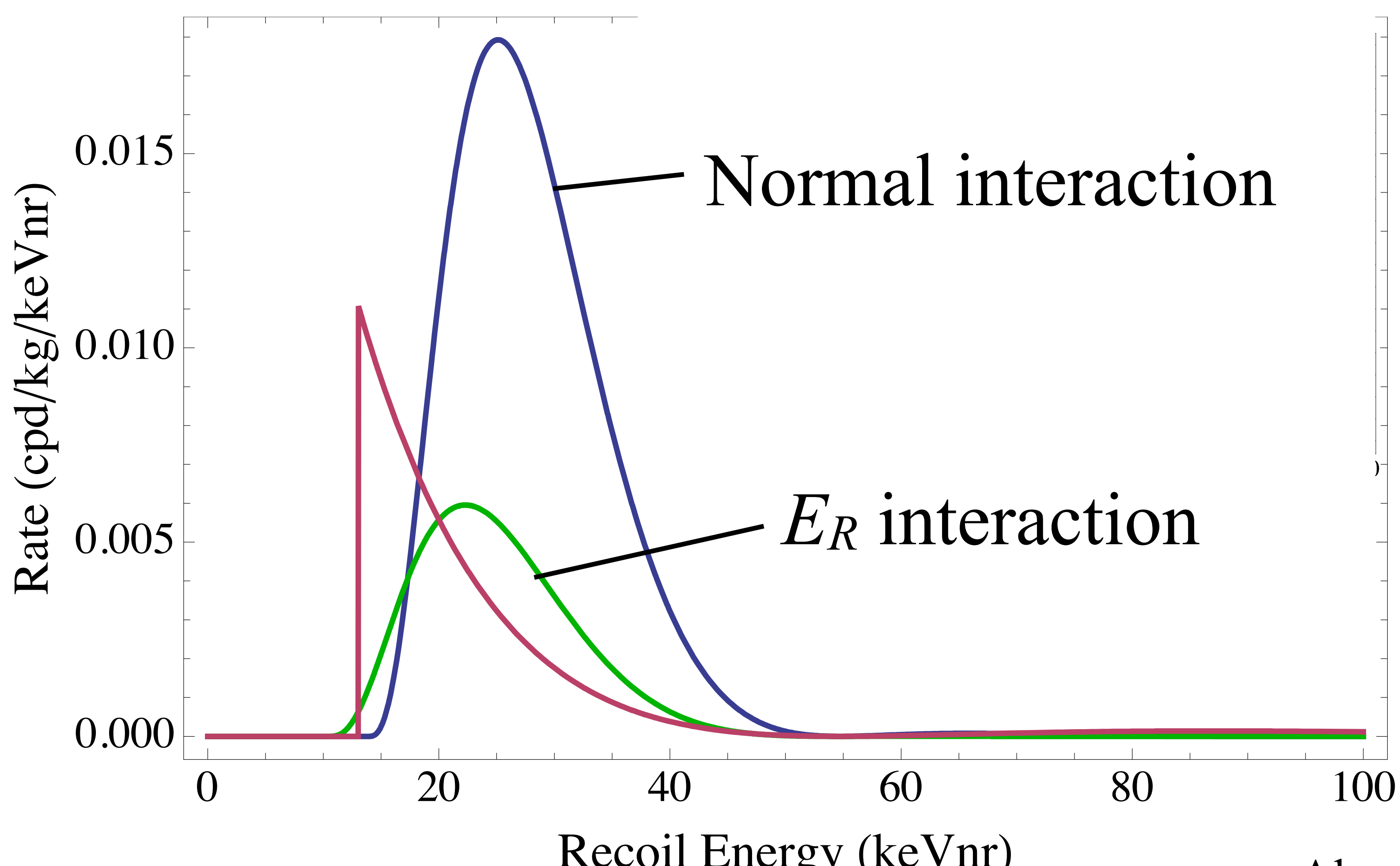
Alves, Lisanti, JW 1005.5421

Dark Matter Interactions



W form factor causes recoil energies to be lower than I

$E_R(W) \sim 25$ keV $\qquad E_R(I) \sim 35$ keVnr

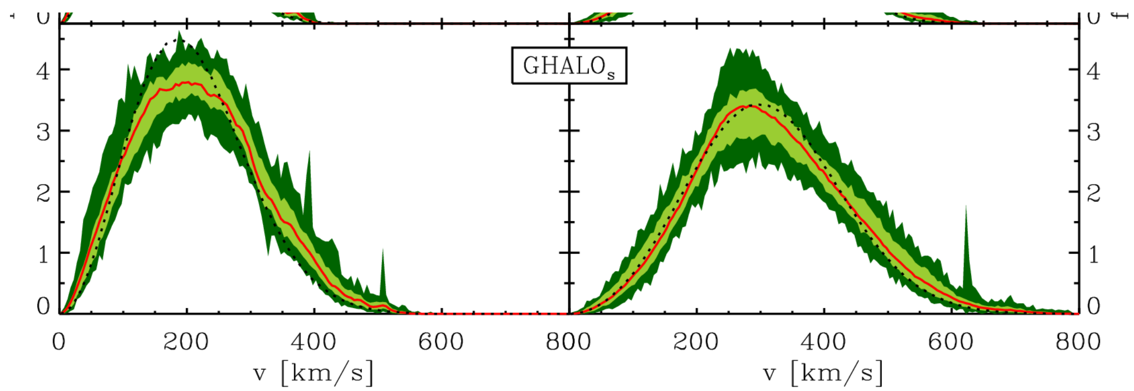


Alves, Lisanti, JW 1005.5421

Designer Velocity Distribution Functions

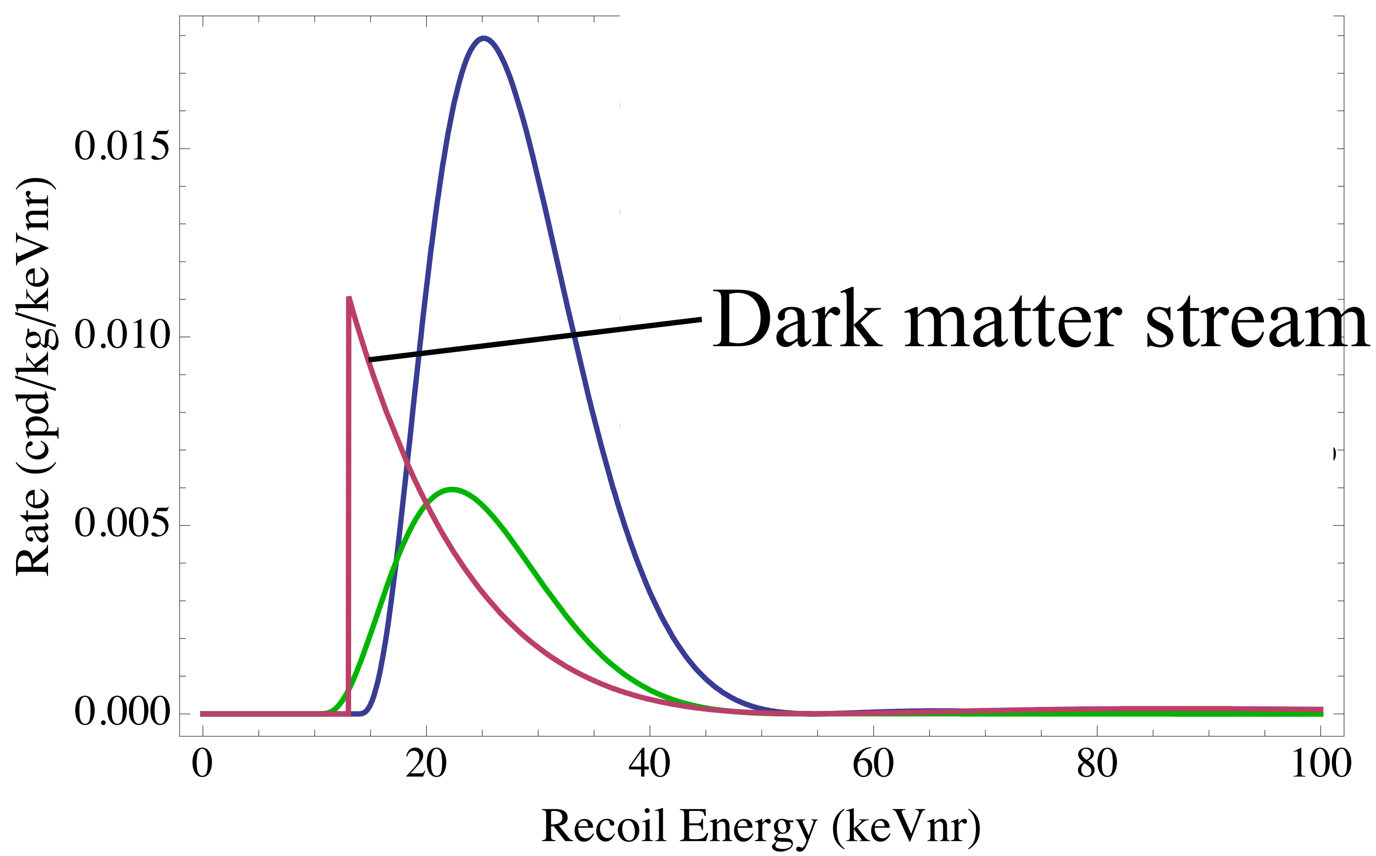
High velocity tail could be dominated by a stream of dark matter

$$f(v) = f_0(v) + \epsilon\delta^3(\vec{v} - \vec{v}_{\rm str})$$



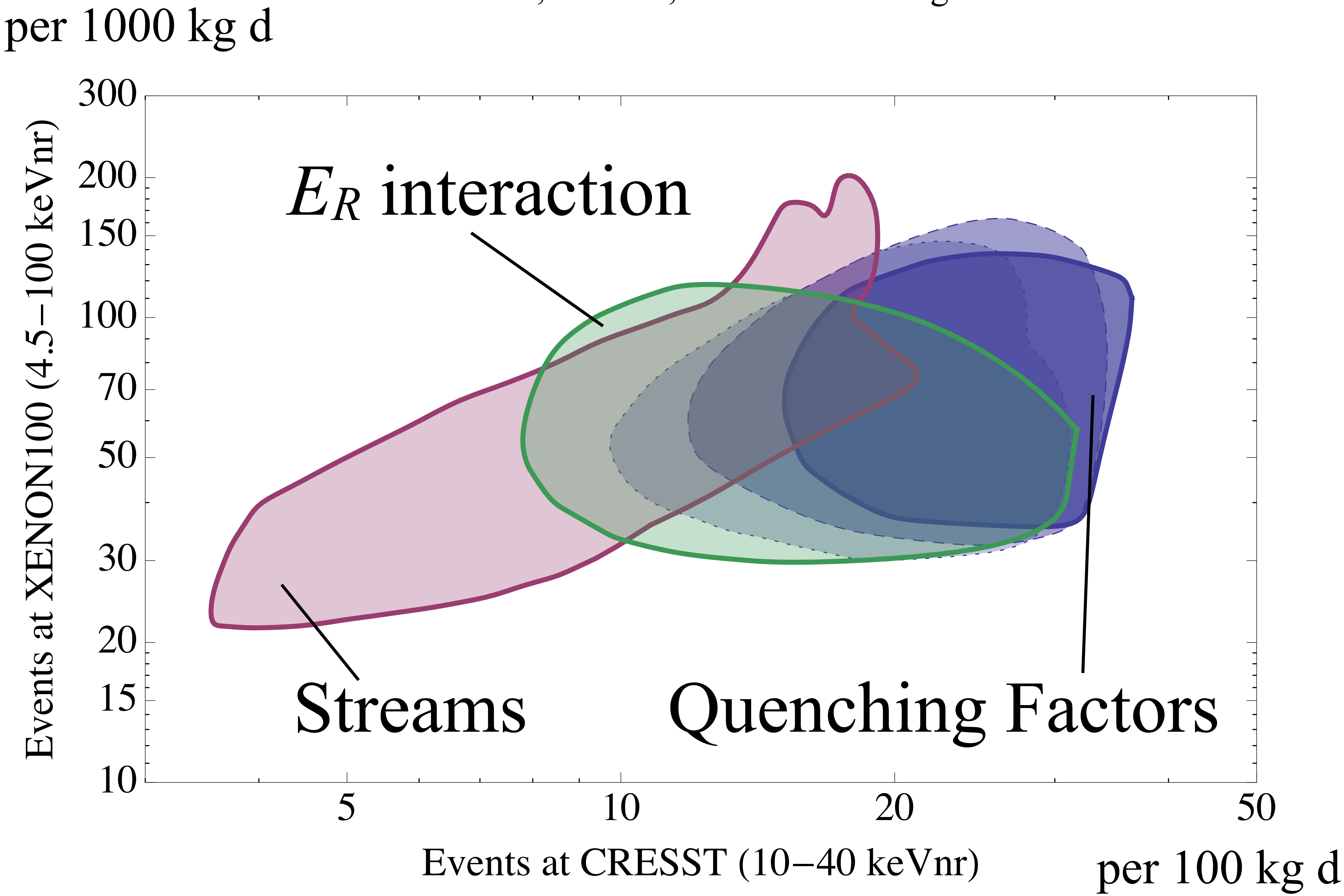
Kuhlen, Weiner et al 0912.2358

Gives larger modulation for W



Waiting for Godot

XENON100, COUPP, KIMS are coming



(Notice XENON predictions don't change significantly)

Alves, Lisanti, JW 1005.5421

Narrowing in on iDM

Shows there is extreme challenges in changing target nuclei

Velocity Distribution Function

Experimental Unknowns

Dark Matter Model Dependence

Shows the need for a broad experimental program in order to discover dark matter