Title: Novel signatures for direct detection of WIMP dark matter

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Abstract: Dark sectors with multi-component WIMP states, with small MeV- to GeV-scale splittings, can lead to more complex signatures in direct detection experiments. I'll discuss some scenarios with excited states charged under either the Standard Model or hidden sector gauge groups, and the ensuing constraints.

Novel signatures for direct detection of WIMP dark matter

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What (don't) we know about dark matter

…aside from gravitational interactions

Assuming a thermal WIMP ➔ $\langle\sigma_{ann}v\rangle_{f.o.} \simeq 1\, pbn$

plus (often stringent) upper bounds $\left\{ \langle\sigma_{ann}v\rangle_{gal} \quad \langle\sigma_{scat}v\rangle_{dec} \quad \langle\sigma_{scat}v\rangle_{N} \right.$

$\langle\sigma_{ann}v\rangle_{gal}$	$\langle\sigma_{scat}v\rangle_{dec}$	$\langle\sigma_{scat}v\rangle_{N}$
↓ Indirect detection	↓ Phase space	↓ Direct detection

Motivations for exploring dark matter as part of a larger (interacting, multi-component) hidden sector?

- a more generic setting to explore experimental sensitivity
- allows for possible enhancement/suppression, that could explain existing anomalies: DAMA, PAMELA, etc.

Expanding the WIMP parameter space

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plus (often stringent) upper bounds $\left\{ \begin{array}{ccc} \langle \sigma_{ann} v \rangle_{gal} & \langle \sigma_{scat} v \rangle_{dec} & \langle \sigma_{scat} v \rangle_{N} \\ \downarrow & \downarrow & \downarrow \\ \text{Indirect detection} & \text{Phase space} & \text{Direct detection} \end{array} \right.$

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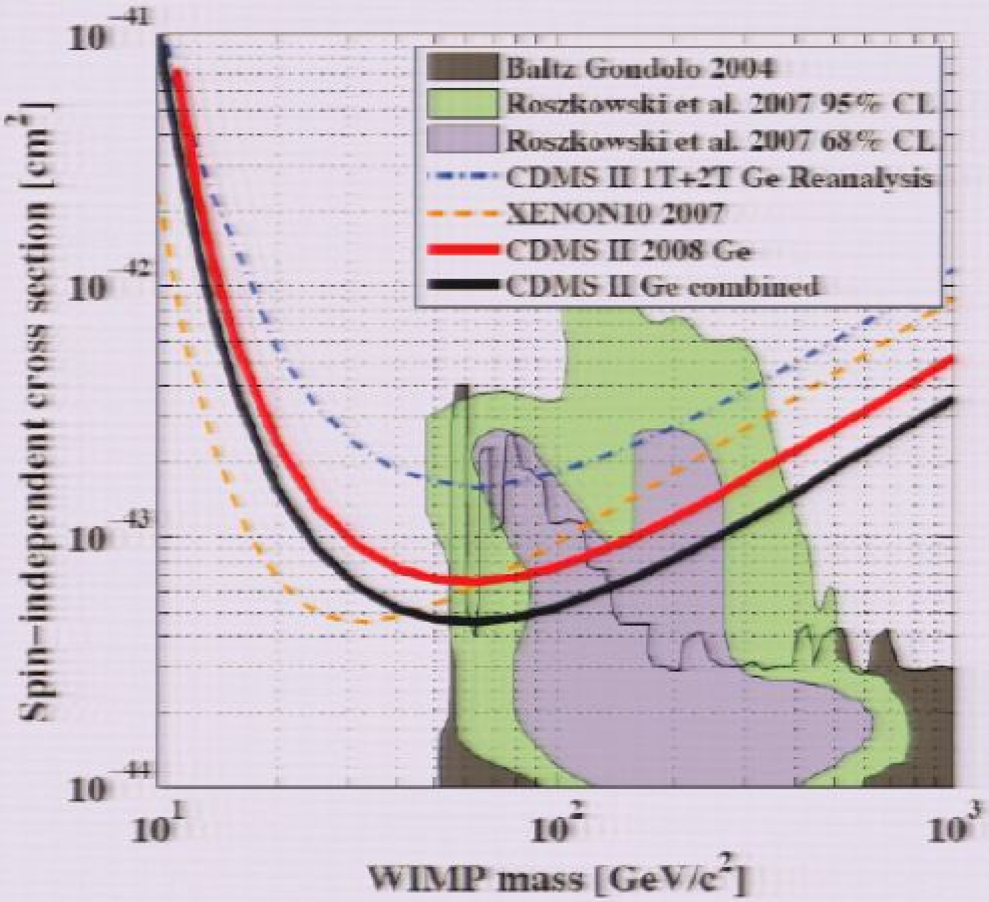
Constraints on scattering

Existing limits test elastic scattering with10-100 keV nuclear recoil energy

$\frac{1}{2}m_\chi v_\chi^2 \sim 50$ keV

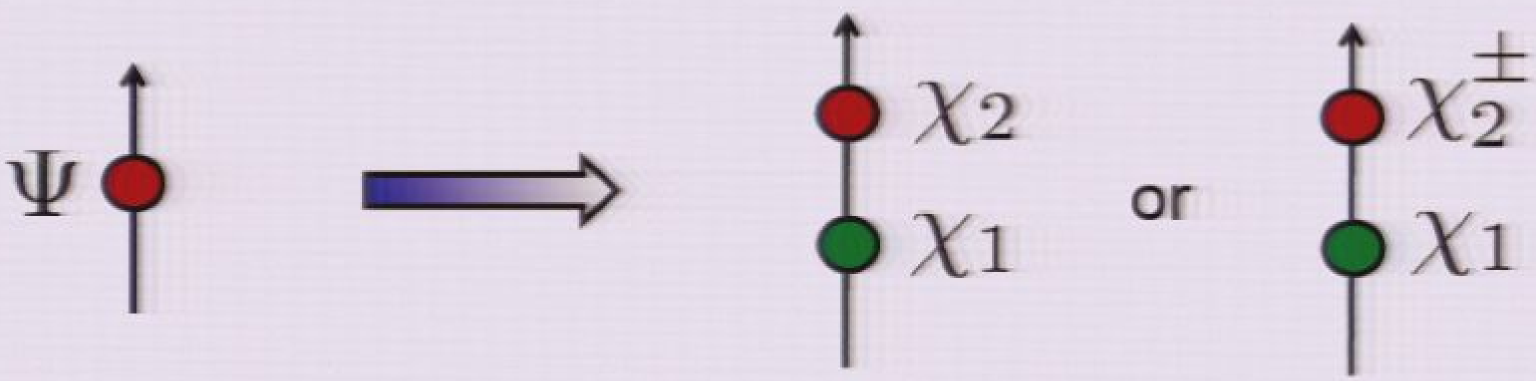


[CDMS '08]

Constraints on scattering and split DM

- Vector and axial-vector couplings to Y, Z are strongly constrained even at loop-level, suggesting a singlet state...
- However, recent motivation for enhancing annihilation (e.g. Sommerfeld enhancement), generally requires multi-component (e.g. Dirac) states with vector currents...

➔ consider the intermediate near-degenerate regime



Outline

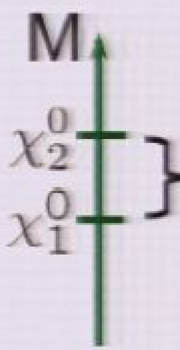
- Split neutral states
  - endothermic and exothermic scattering
- Split charged states
  - recombination and resonant scattering
- Discussion

1. Split neutral states

Multi-component secluded WIMPs

$$\mathcal{L} = -\frac{1}{4}V_{\mu\nu}^2 - \frac{\kappa}{2}V_{\mu\nu}F^{\mu\nu} + |D_\mu\phi|^2 - V(\phi)$$ [Holdom '86]

- A multi-component state charged under $U(1)_S$ is a thermal WIMP dark matter candidate [Pospelov, AR, Voloshin '07; Hooper & Zurek '08; Arkani-Hamed et al '08; Pospelov, AR '08; Batell, Pospelov, AR '09]



$$\Delta m \sim \mathcal{O}(0.1 - 100\,\mathrm{MeV})$$

$$\alpha' \simeq 10^{-2} \times \left(\frac{m_\chi}{270\,\mathrm{GeV}}\right)$$

$$\mathcal{L}_{\mathrm{int}} = e' V_\mu (\chi_1 \partial_\mu \chi_2 - \chi_2 \partial_\mu \chi_1)$$

- If kinetic mixing arises from integrating out heavy charged states at 1-loop ⇒ $\kappa \sim 10^{-3}$, SUSY D-terms then imply a GeV mass scale for V [Arkani-Hamed & Weiner '08, Baumgart et al. '09; Cheung et al '09; Katz & Sundrum '09]

- We fix the secluded U(1) coupling via the relic density, so the parameter space = $\{m_V, m_{h'}, \kappa\}$

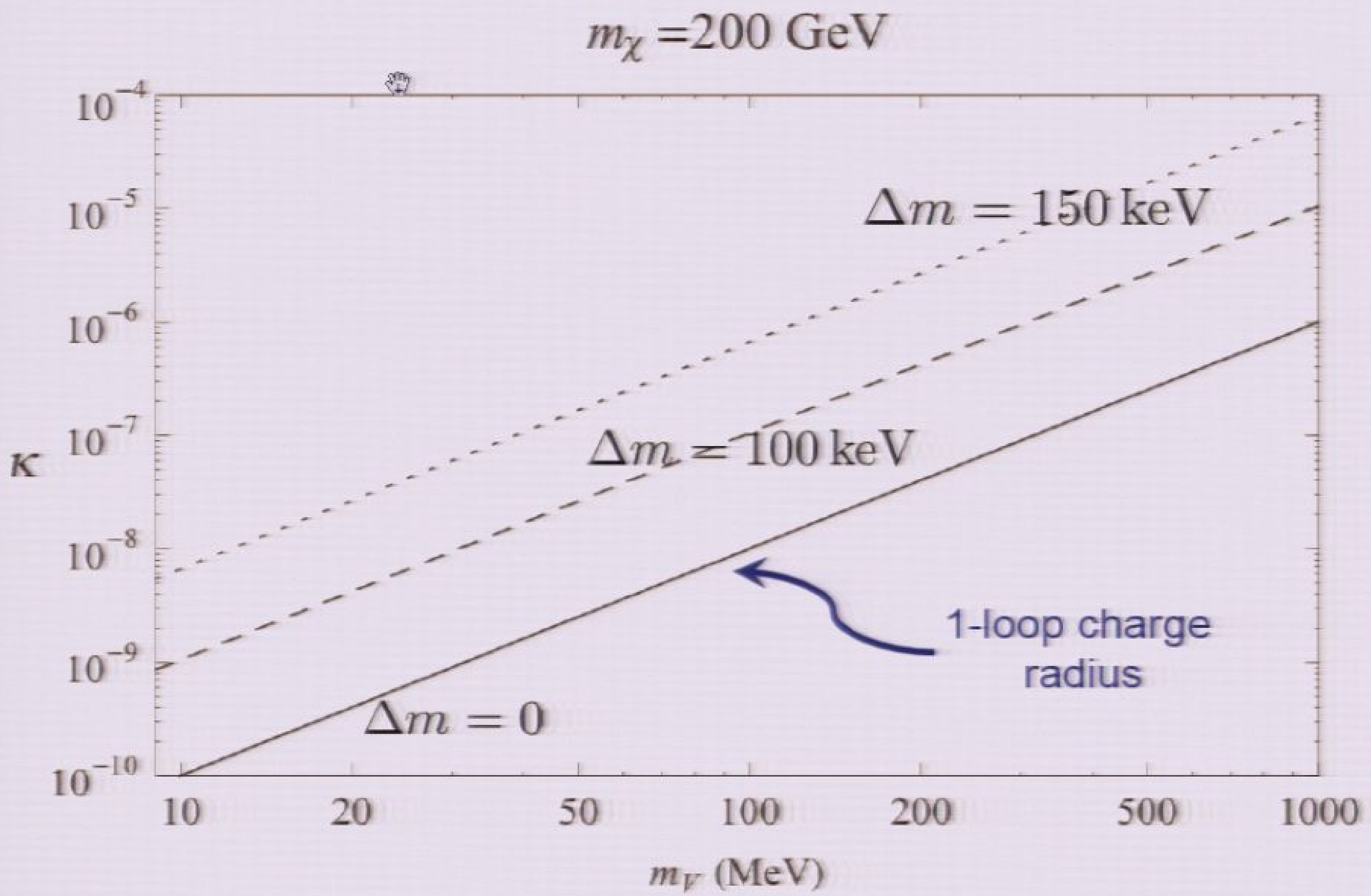
Nuclear scattering

(a)	*elastic scattering :*	$\chi_{(1,2)}N \to \chi_{(1,2)}N.$
(b)	*endothermic scattering* $(Q = -\Delta m)$:	$\chi_1 N \to \chi_2 N.$
(c)	*exothermic scattering* $(Q = \Delta m)$:	$\chi_2 N \to \chi_1 N.$

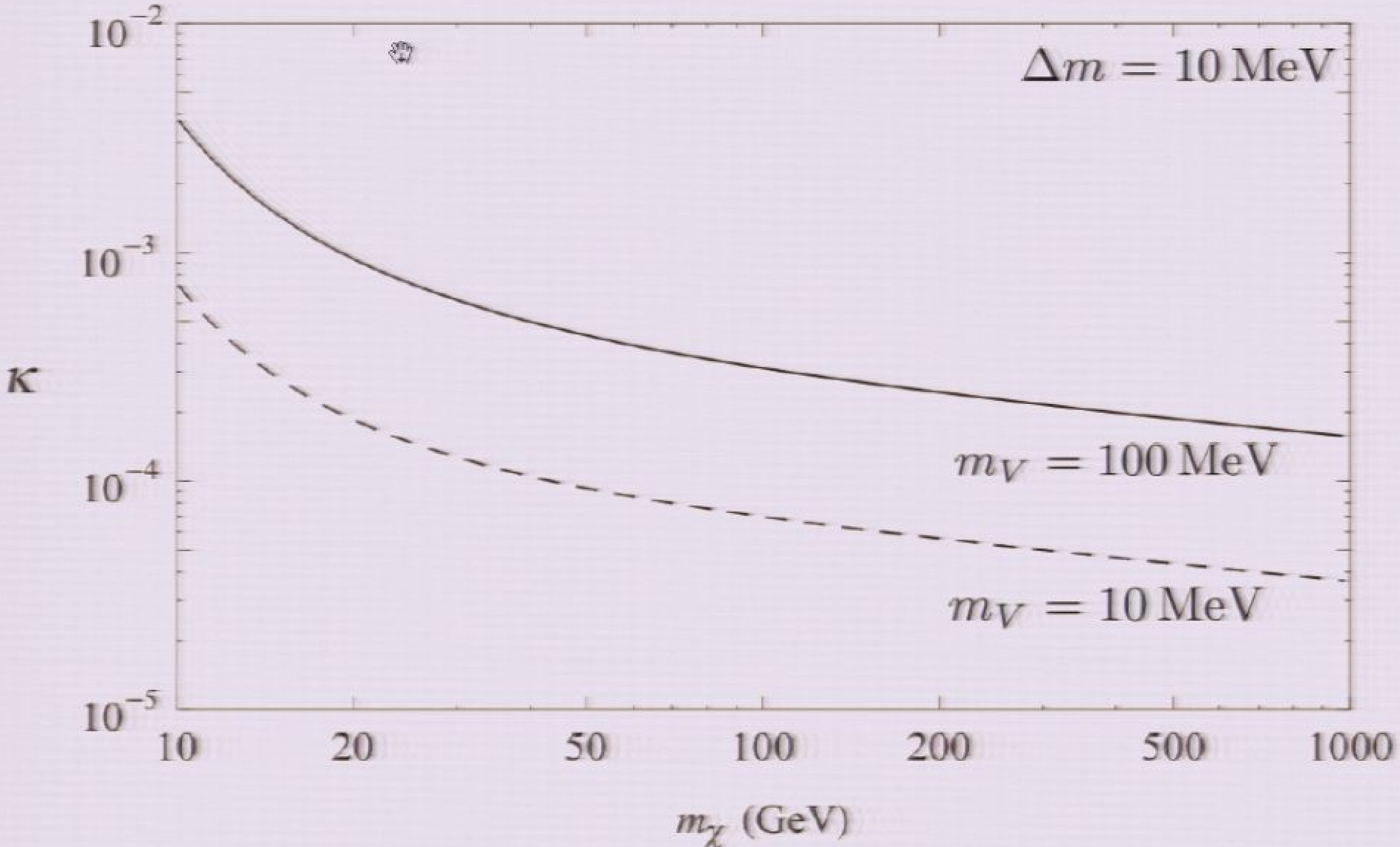
[as in `inelastic dark matter' Tucker-Smith & Weiner '01]

[also: Han & Hempfling '97; Hall, Moroi, Murayama '97]

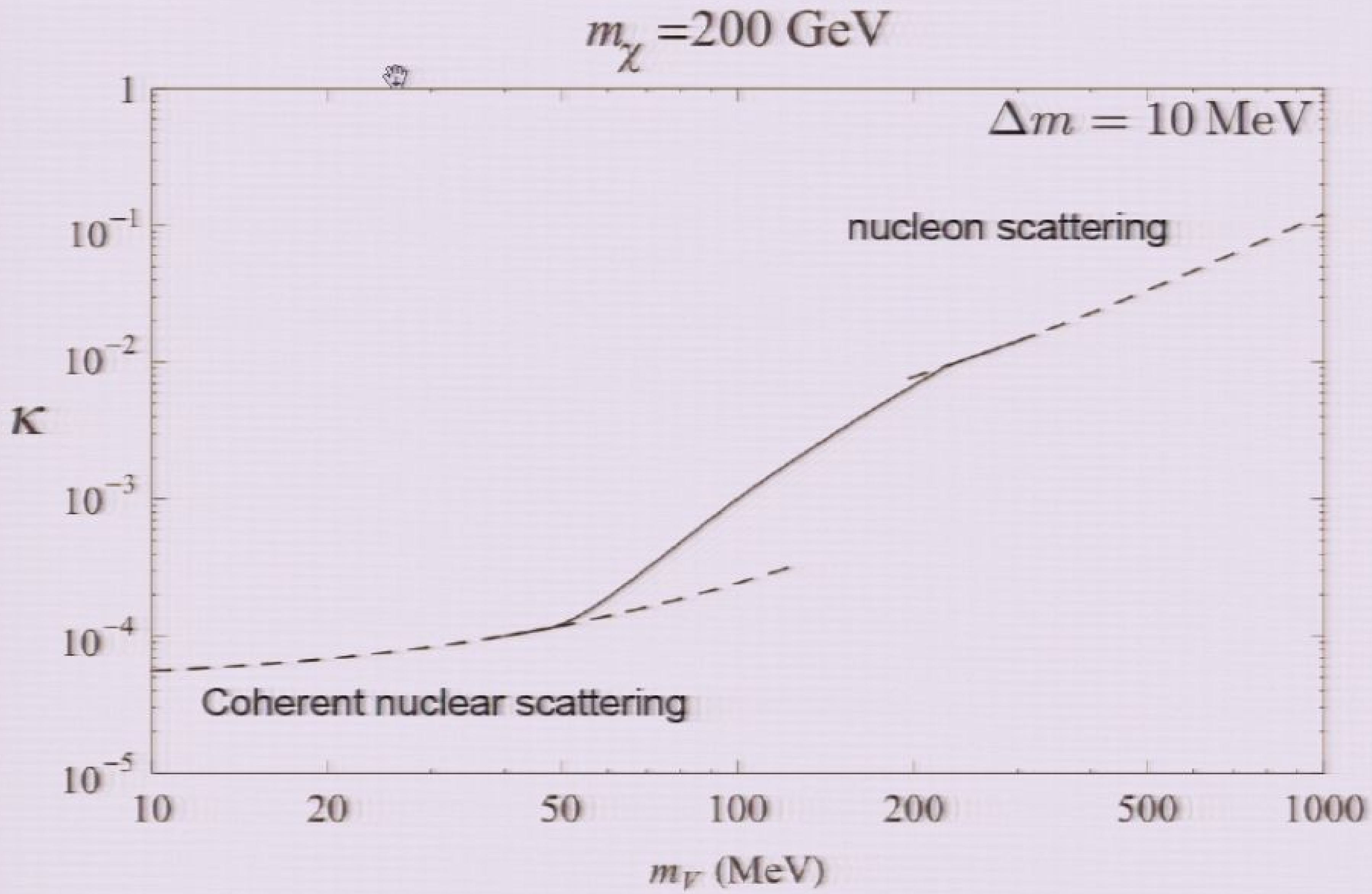
Endothermic inelastic scattering



Elastic scattering



Elastic scattering



Relic χ_2 & exothermic scattering

- After thermal decoupling:

$$\left[\frac{n_2}{n_1}\right]_{\min} \simeq 10^{-2} \times \left(\frac{m_\chi}{300\,\mathrm{GeV}}\right)^{5/2} \left(\frac{10\,\mathrm{MeV}}{T_*}\right)^{1/2}$$

[further upscattering in the galaxy, but generally subdominant, as in XDM Finkbeiner, Weiner '07; Pospelov, AR '07]

- Decays are highly suppressed (for $\Delta m < 2m_e$):

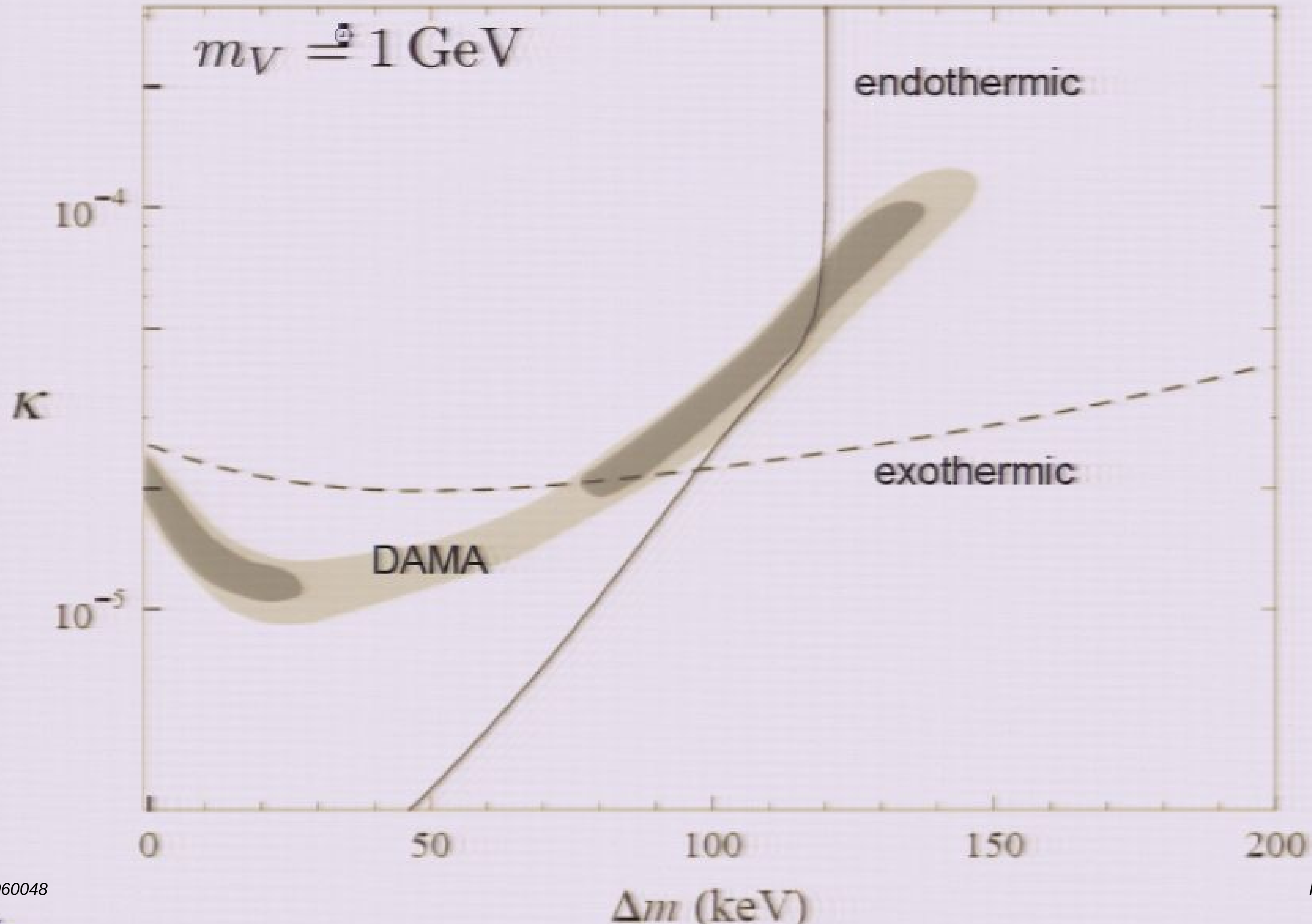
$$\Gamma_{\chi_2 \to \chi_1 + 3\gamma} \gg \frac{1}{\tau_U}, \qquad \Gamma_{\chi_2 \to \chi_1 \nu\bar{\nu}} \gg \frac{1}{\tau_U}$$

→ Exothermic down-scattering is a possible direct detection signature!

[see also Finkbeiner, Slatyer, Weiner and Yavin '09]

Exothermic scattering

$m_\chi = 100$ GeV, $v_E = 500$ km/s



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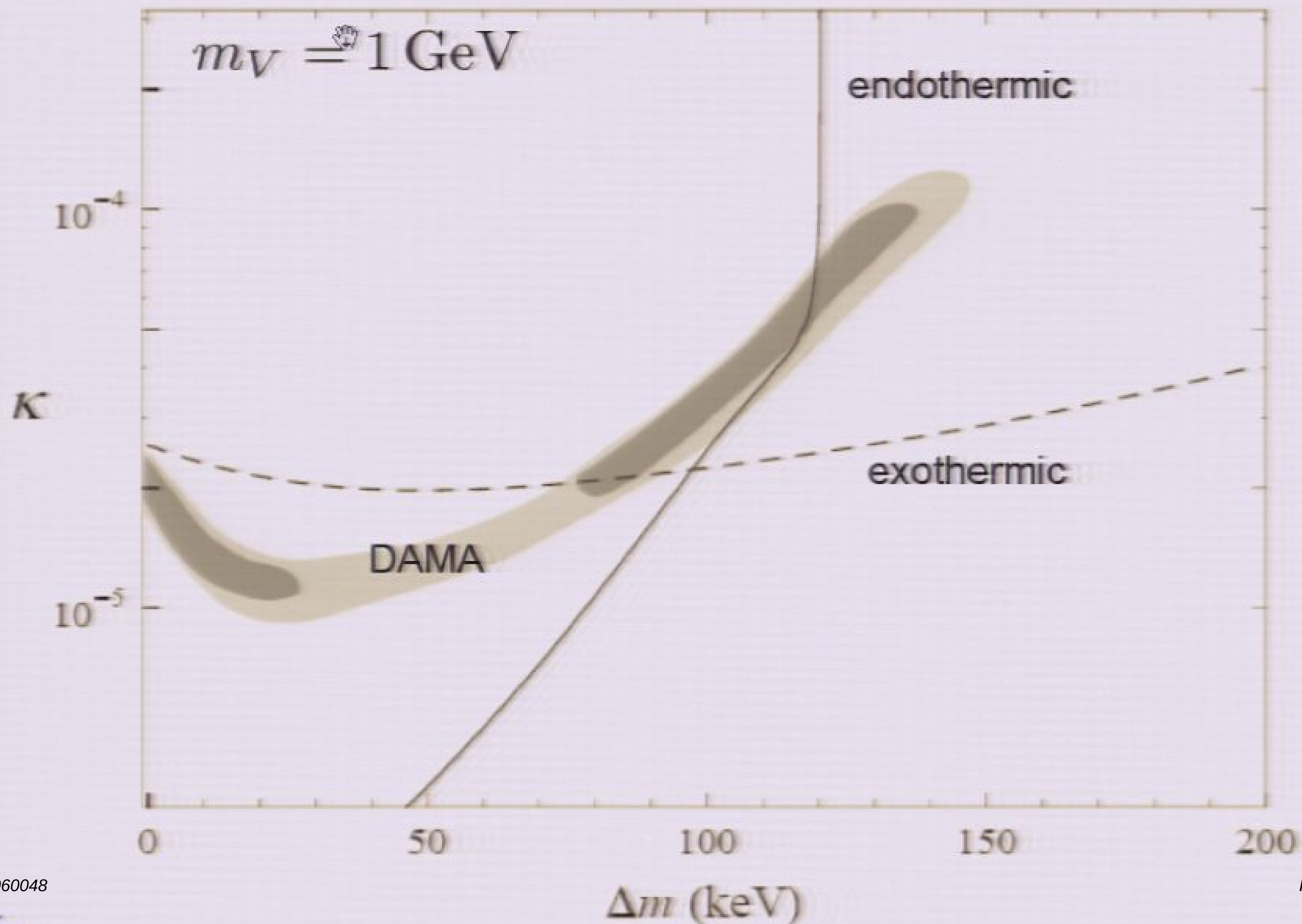
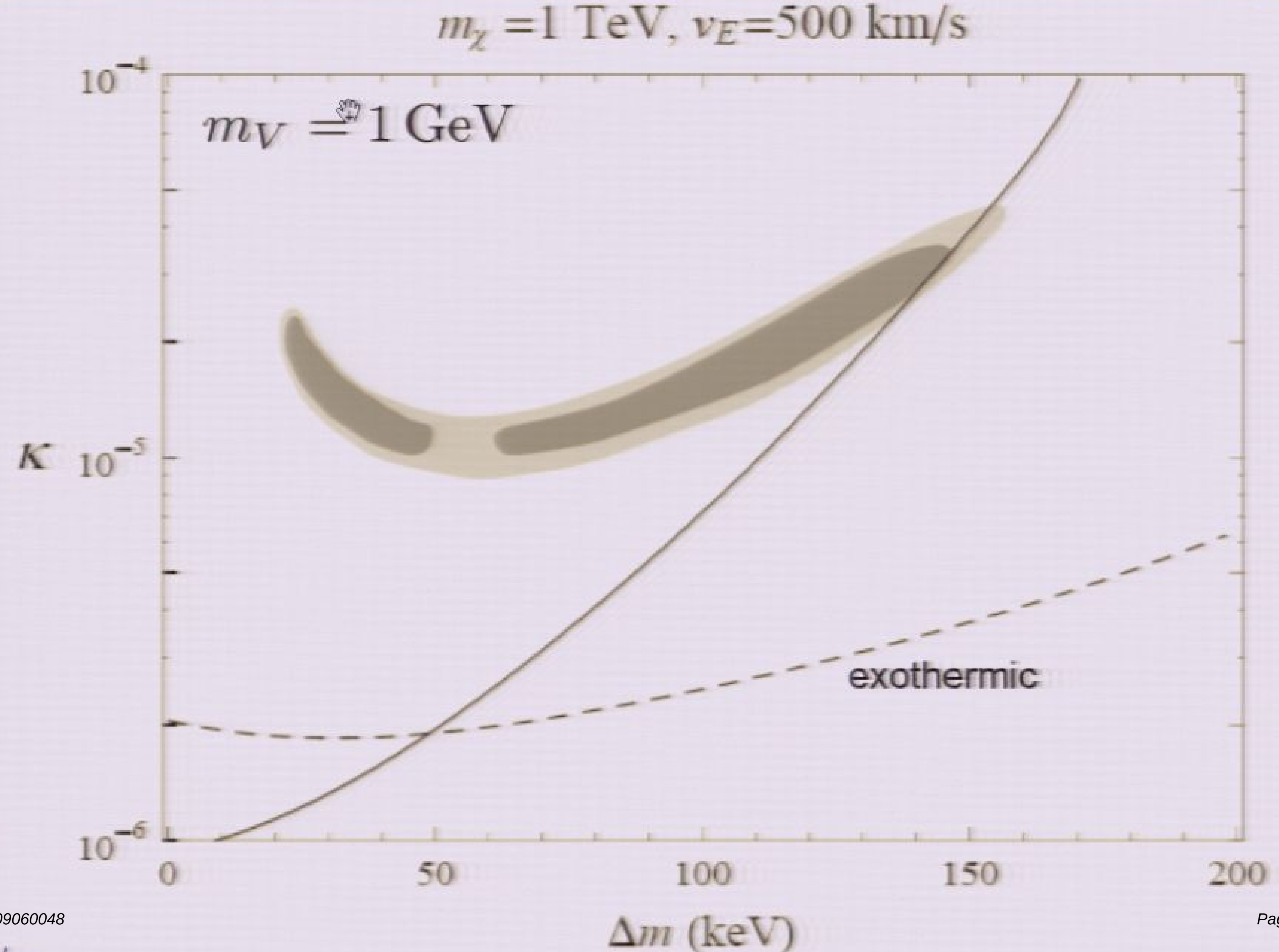
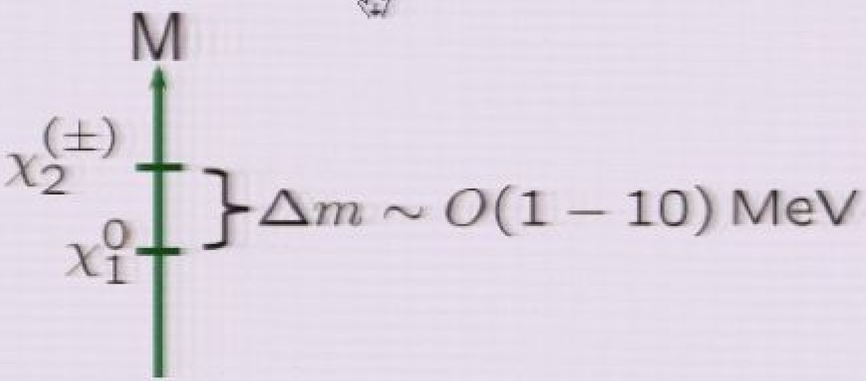


Exothermic scattering



2. Split charged states

Split charged states



NB: "natural" EM or EW splitting of charged and neutral states $\Delta m \sim \frac{\alpha}{\pi} m \sim 100\,\mathrm{MeV}$

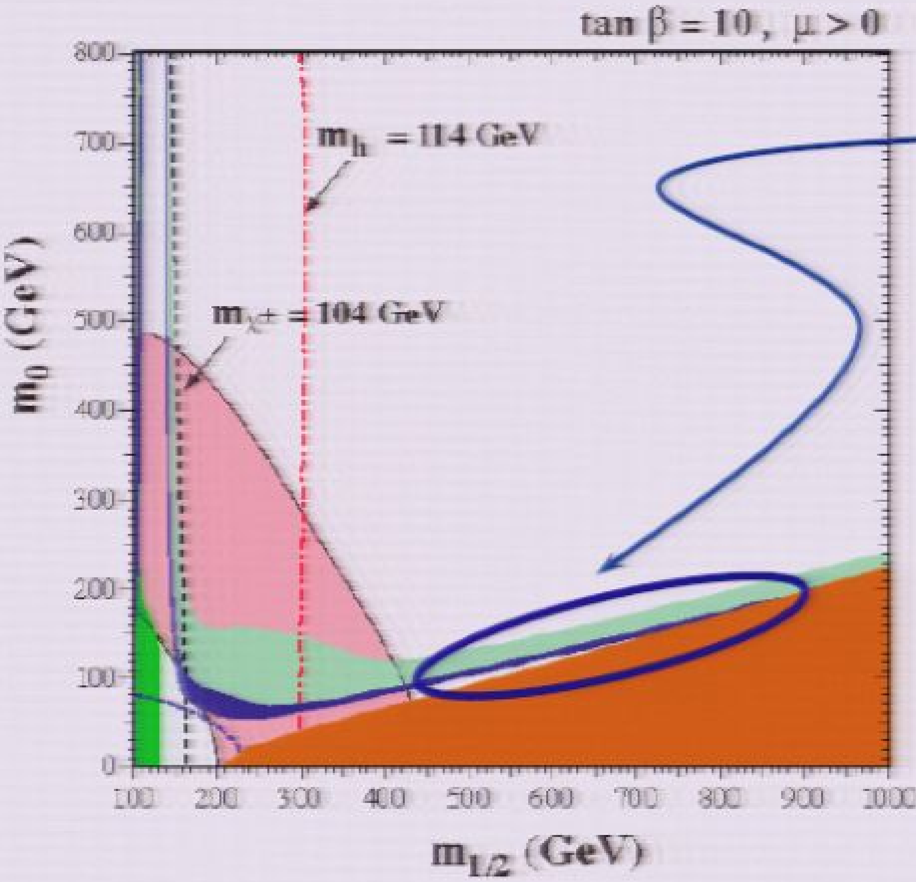
[cf. Cirelli, Fornengo, Strumia '05]

- Type A: charged current $\mathcal{L}_{int} = g J^{\mu -}_{\chi_1 \chi_2} W^+_\mu + h.c.$
- Type B: leptonic current $\mathcal{L}_{int} = g \chi_1 \bar{e} \chi_2^- + h.c.$

NB: Free excited states may decay rapidly, e.g. $\chi_2^\pm \to \chi_1^0 + e^\pm$

Not so exotic…

For the CMSSM…

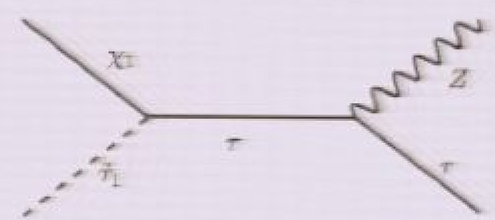


[J. Ellis et al. '03]

WMAP strip

$\Delta(m_{\tilde{\tau}} - m_\chi) \leq 5\,GeV$

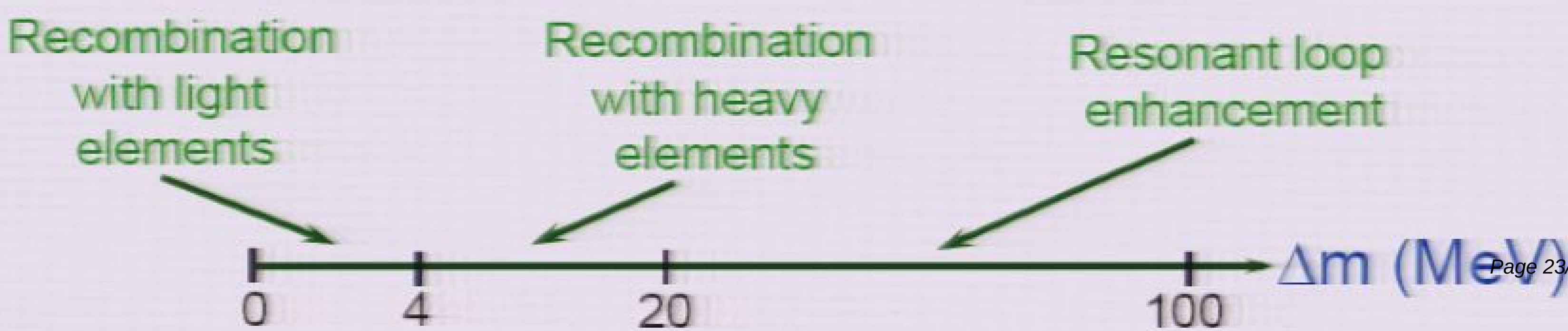
relic density requires efficient co-annihilation



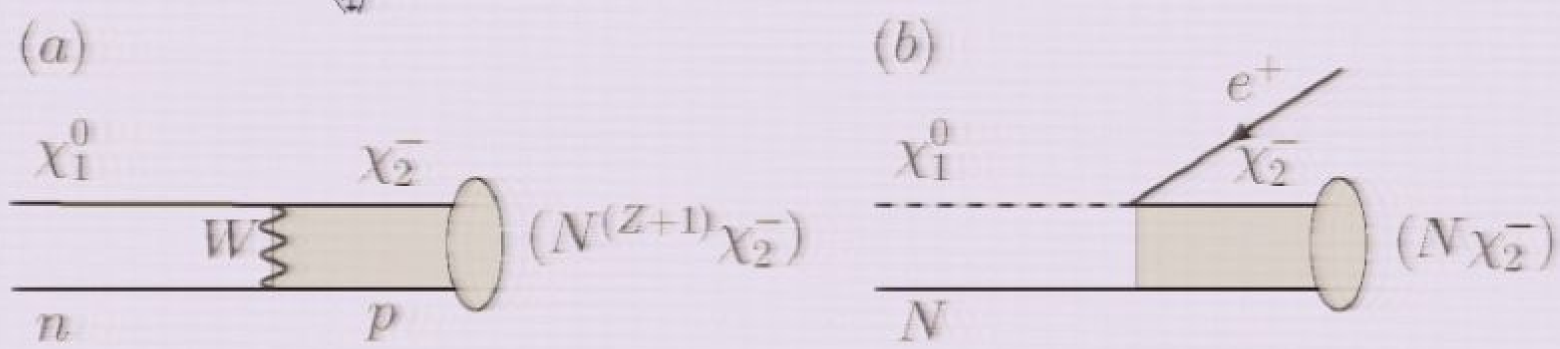
…or is it?

If $\Delta m < E_b$ then "recombination" with nuclei is possible

$(N\chi_2^-)$	Z	E_b^{Gaussian} (MeV)	E_b^{Const} (MeV)
$(^1\text{H}\chi_2^-)$	1	0.025	-
$(^4\text{He}\chi_2^-)$	2	0.346	-
$(^{11}\text{B}\chi_2^-)$	5	2.24	2.13
$(^{12}\text{C}\chi_2^-)$	6	2.8	2.7
$(^{14}\text{N}\chi_2^-)$	7	3.5	3.2
$(^{16}\text{O}\chi_2^-)$	8	4.0	3.7
$(^{40}\text{Ar}\chi_2^-)$	18	9.1	8.0
$(^{74}\text{Ge}\chi_2^-)$	32	14.6	12.5
$(^{132}\text{Xe}\chi_2^-)$	54	21.7	18.4



Direct probes - impact of recombination



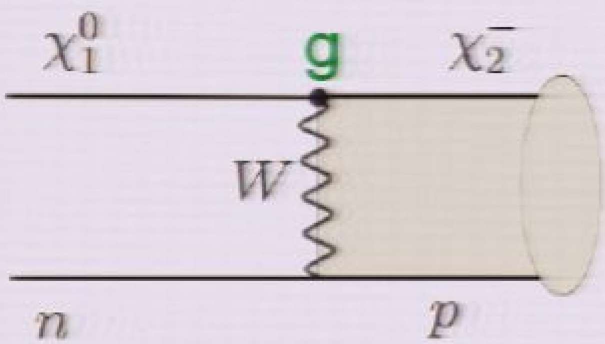
Crucial point: MeV-scale energy release

↓

Distinct signatures for direct detection experiments

Direct probes - CC recombination

Type A:



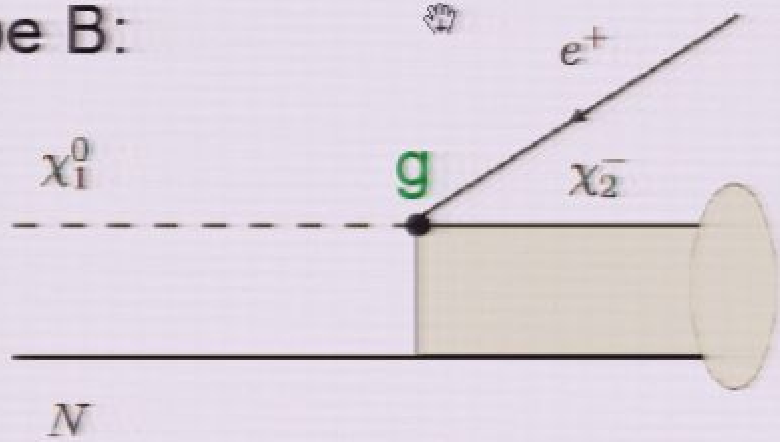
$$(N^{(Z+1)}\chi_2^-)^* \longrightarrow (N^{(Z+1)}\chi_2^-) + (\gamma, n, \ldots)$$

$$\sigma \sim \sigma_{\rm res} \sim \sum_R \frac{\pi g_*}{q_{\rm cm}^2} \frac{\Gamma_W \Gamma}{(E - E_R)^2 + \Gamma^2/4} \qquad \Gamma_W \sim g^2 \frac{G_F^2 M_R^2 v}{r_0^3}$$

$$\sigma_n \sim 10^{-44} \left(\frac{g^2}{4\pi\alpha_2} \right) \mathrm{cm}^2$$

Direct probes - EM recombination

Type B:



$$\sigma \sim \Gamma_{\chi_1 \to \chi_2} |\langle \psi_N^{\text{scat}} | \psi_N^{\text{bound}} \rangle| \times F_G$$

$$\langle \sigma_{\text{rec}} v \rangle \sim g^2 \frac{(E_e + m_e)|p_e|}{m_\chi} R_N^3 \left(\frac{a_B}{R_N} \right)^{3/4} \times F_G$$

$$\sigma_n \sim 10^{-39} \left(\frac{g^2}{4\pi\alpha} \right) \text{cm}^2$$

For heavy nuclei

Rare isotope searches

- No binding to H, He for $\Delta m > 0.5 MeV$
- Strongest constraints on B, C and O if $0.5 MeV < \Delta m < 4 MeV$

$$f_C < 10^{-20} \quad for \quad (N\chi_2^-)$$
$$f_B < 10^{-14} \quad for \quad (C\chi_2^-)$$

[Hemmick et al. '90]

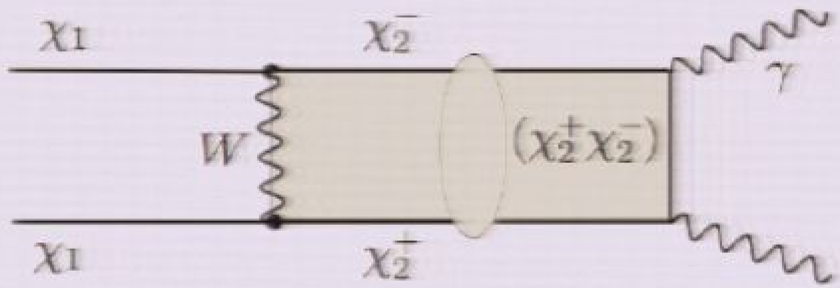
$$\langle \sigma_{\rm rec} v \rangle|_{\rm max} < 10^{-43}{\rm cm}^2 \left(\frac{f_{\rm exp}}{10^{-20}}\right)\left(\frac{10^9{\rm yr}}{\tau_{\rm exp}}\right)$$

But only applies for EM capture (type B) as the nuclear levels do not permit the CC capture in these cases

No significant constraint for $\Delta m > 5 MeV$!!

Comments on indirect Probes

- Gamma rays from annihilation e.g. in the Galactic center



Enhanced mono-energetic gamma flux

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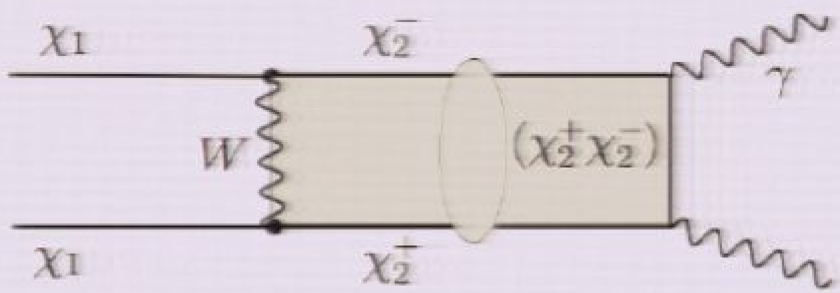

Enhanced mono-energetic gamma flux

- Neutrinos from annihilation e.g. in the sun

This is highly suppressed for pseudo-degenerate WIMPs due capture by Fe

Discussion

A multi-component dark matter sector, with near-degeneracies, can significantly modify the signatures for (in)direct detection:

- Neutral excited states: endothermic and exothermic nuclear scattering is possible
- Charged excited states: For O(10 MeV) splitting, recombination processes may dominate the cross-section in direct detection experiments.
- Charged excited states: For O(100 MeV) splitting, resonant scattering mediated via higher multipoles at 1-loop is possible
- Other (in)direct effects …?

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$$f_C < 10^{-20} \quad for \quad (N\chi_2^-)$$
$$f_B < 10^{-14} \quad for \quad (C\chi_2^-)$$

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