Inelastic Dark Matter and Directional Detection: Motivations and Prospects

Douglas Finkbeiner (Harvard)
with
Neal Weiner (NYU)
Tongyan Lin (Harvard)

Inelastic dark matter:
Many possible mechanisms, including

- composite WIMPs (analog: nuclei - messy)
- new force in the dark sector (simple, clean, big leap)

How big is the leap?
1/6 of the matter in the Universe interacts via a very complicated SU(3) x SU(2) x U(1) force. One minimal extension is to posit an additional U(1) gauge force that (almost) only interacts with DM: a new “dark force.”

What is the simplest WIMP you can have?

- Majorana fermion or a real scalar.
- Particle is its own anti-particle.
- No conserved quantum numbers.

Suppose the new force is a U(1) gauge force, mediated by a vector boson. (analogy: electromagnetism)

- New boson couples to the "dark charge" but in the Majorana basis they have no charge.
- Any Majorana fermion can be written as a linear combination of 2 Dirac fermions which *do* have the charge.
- These do not have to be mass eigenstates.

Said another way, the WIMP is part of a doublet under the dark U(1) symmetry.
(A spin-1 boson cannot have a coupling to a single neutral state.)
If the symmetry is perfect, the two members of the doublet are degenerate.
Broken symmetry leads to a mass difference.

The important point is, the *mass eigenstate* is not the eigenstate the force couples to. That is, the coupling is *off-diagonal.*

Example from Electromagnetism:

An electron is a doublet (right-handed and left-handed) The force is mediated by a spin-1 boson (photon) which couples off-diagonally, so the vertex joins a RH electron, LH electron, and photon. The RH and LH electron have the same mass, so we "sweep this under the rug."

E/M is a good symmetry, but in general our new symmetry is weakly broken by some amount, leading to a mass splitting, δ, between the two mass eigenstates.

We can think of these as "ground state" and "excited."

See Arkani-Hamed et al. (2009; 0810.0713) for details

Summary: if we assume

- new force in the dark sector (simplest gauge force),
- simple WIMP (no conserved quantum numbers), and
- imperfect symmetry for new force (generic),

we arrive at the startling conclusion that inelastic scattering between the two mass eigenstates is the generic behavior, and elastic scattering is the special case.

This motivates a broad consideration of the effects of inelastic WIMP scattering in both astronomy and physics.

Why consider new forces anyway?

- inelastic scattering (DAMA)
- Sommerfeld enhancements (PAMELA, ATIC, Fermi?)
- annihilation through light (< GeV) channels
- thermal relic scenario still ok.

DAMA has an 8.2 σ measurement of annual modulation. Limits from other experiments (CDMS, XENON10, Zeplin III, CRESST) rule out DAMA by large factors for the *elastic* scattering case. However, iDM (inelastic DM) makes everything consistent. iDM works better because

- heavy nuclei are kinematically favored (Si, Ge too light)
- recoil energies are higher (>~ 40 keVr)
- annual modulation stronger (tail of *v* distribution)

Indeed, if we had expected inelastic scattering with a 100 keV splitting, DAMA probably would be taken as strong evidence for WIMPs.

Because we did not expect it, a different kind of experiment must find them.

XENON100 and LUX will produce results by 2010 (?) and have the sensitivity to get 100s or 1000s of events if DAMA/iDM is correct. If they do not, they will rule out this scenario.

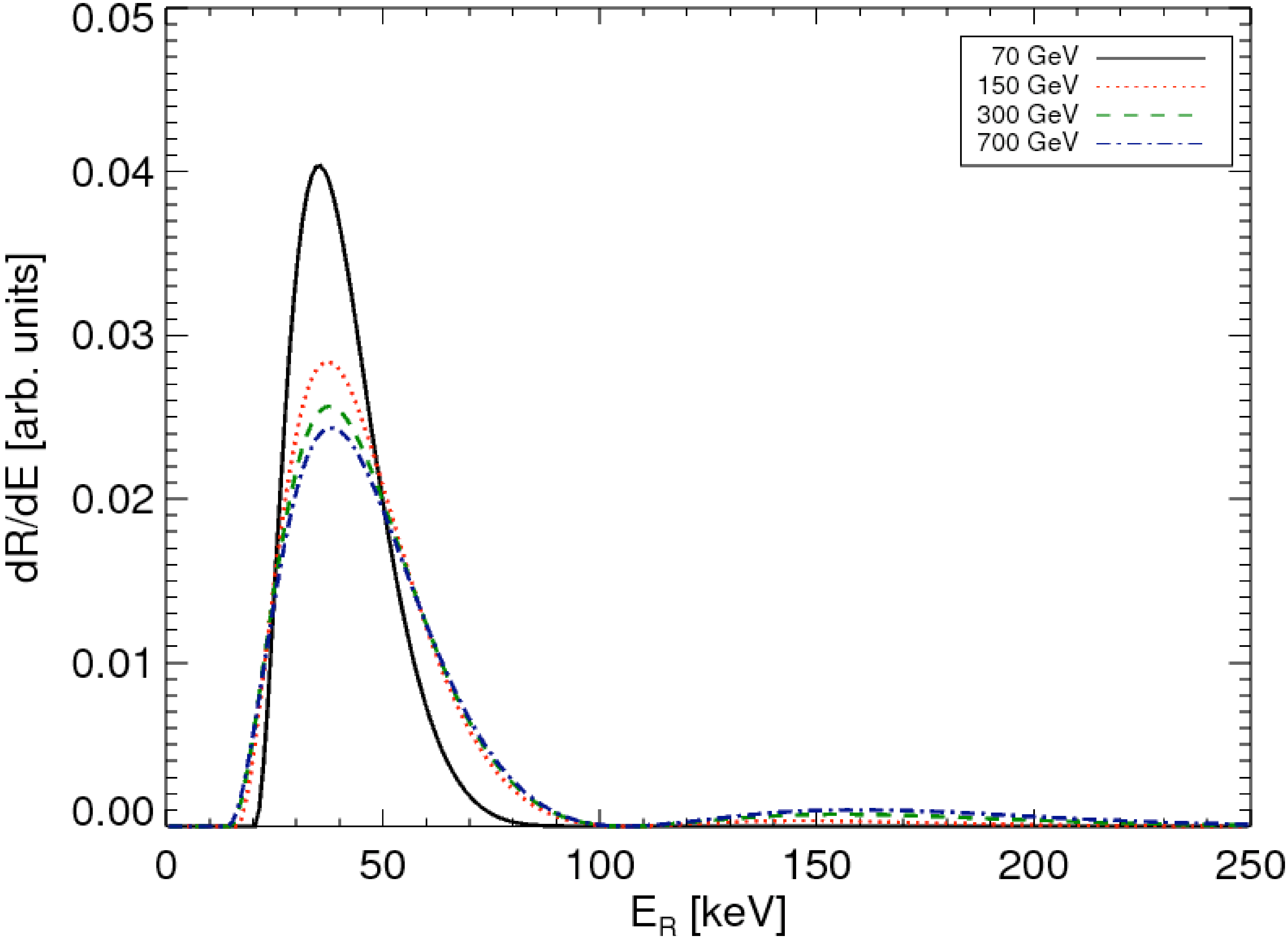
If the events do appear, we need a real smoking gun: Directional detection will begin its heyday!

Conventional wisdom:
directional detection is nearly impossible, because you need ton-scale target mass, so 1000s of cubic meters of gas detector -> expensive!

If DAMA/iDM is correct, you need ~10 cubic meters for 1 year. This is because

- Cross section is higher (factor ~ 100)
- Recoil energy is higher (~ 40 - 80 keVr)
- Directions better preserved

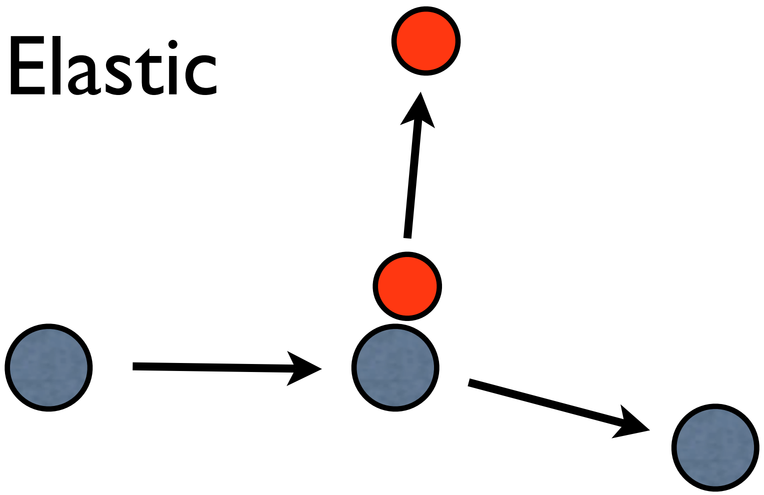
See Finkbeiner, Lin, & Weiner (0906.0002)



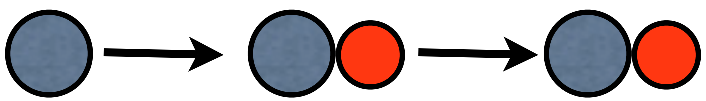
0.05
0.04
0.03
0.02
0.01
0.00
dR/dE [arb. units]
0
50
100
150
200
250
E_R [keV]
70 GeV
150 GeV
300 GeV
700 GeV

Predictions are fairly model independent, because this is merely kinematics.

Elastic

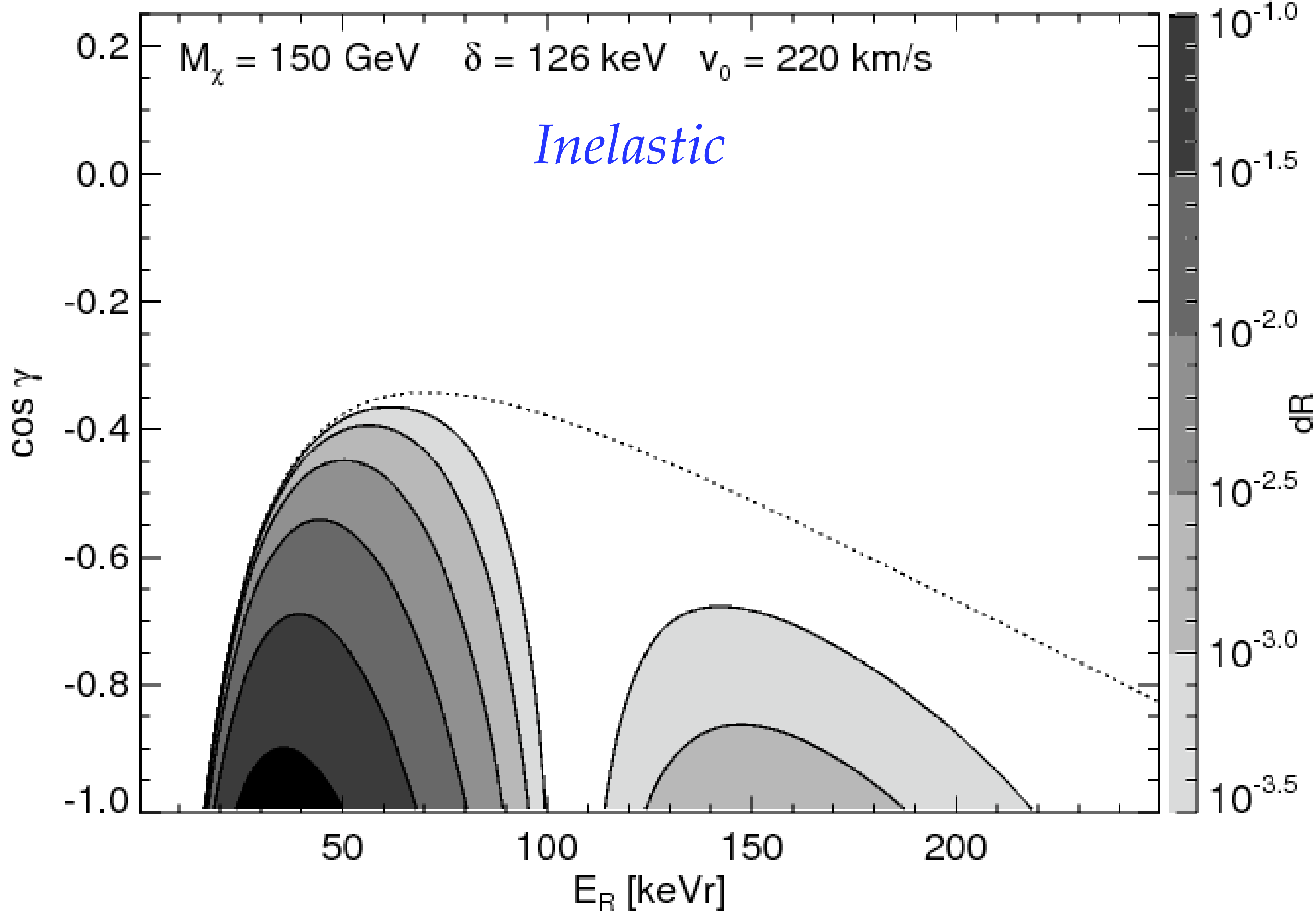


Inelastic (at threshold)



This leads to better preservation of direction:

See Finkbeiner, Lin, & Weiner (0906.0002)



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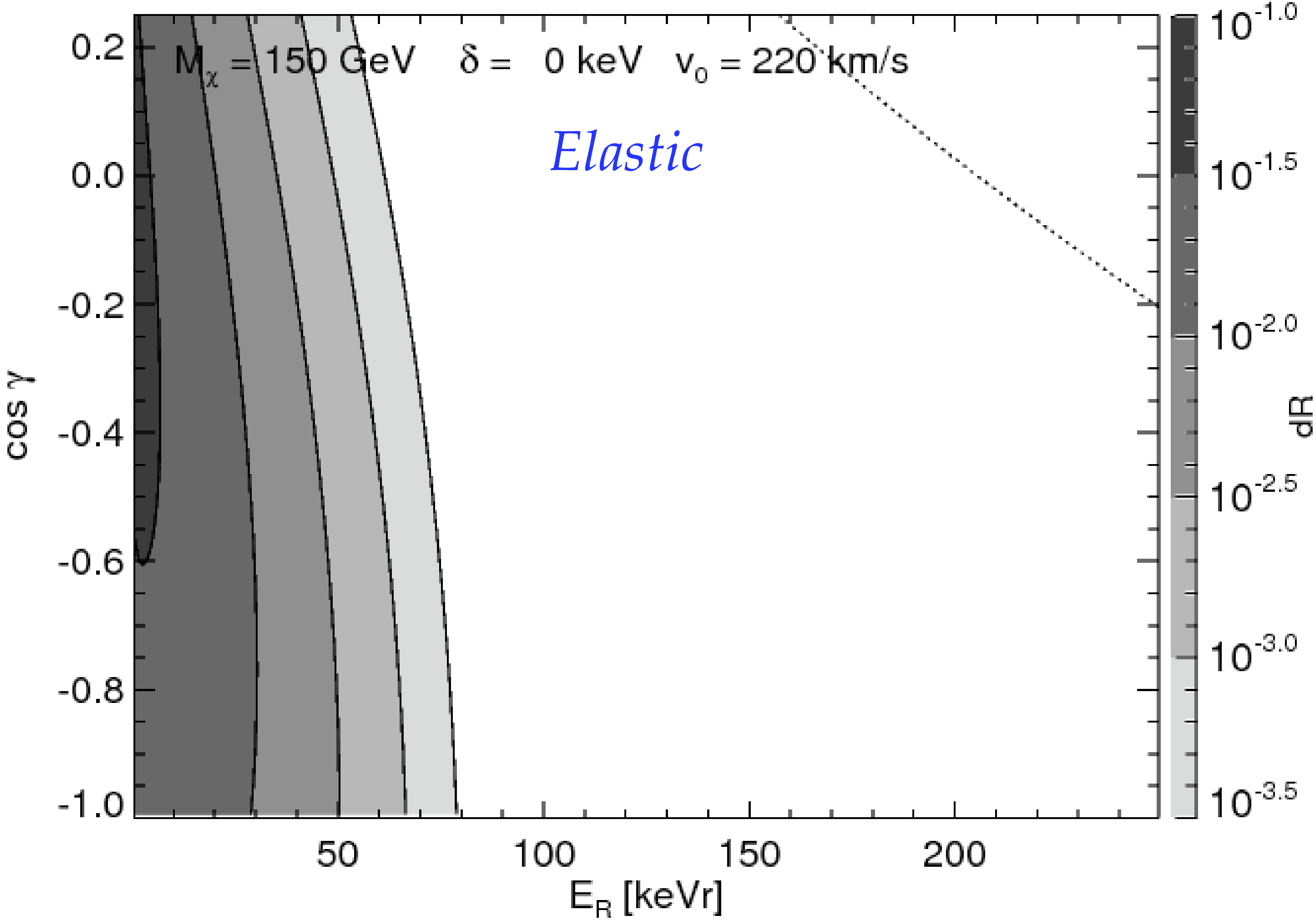
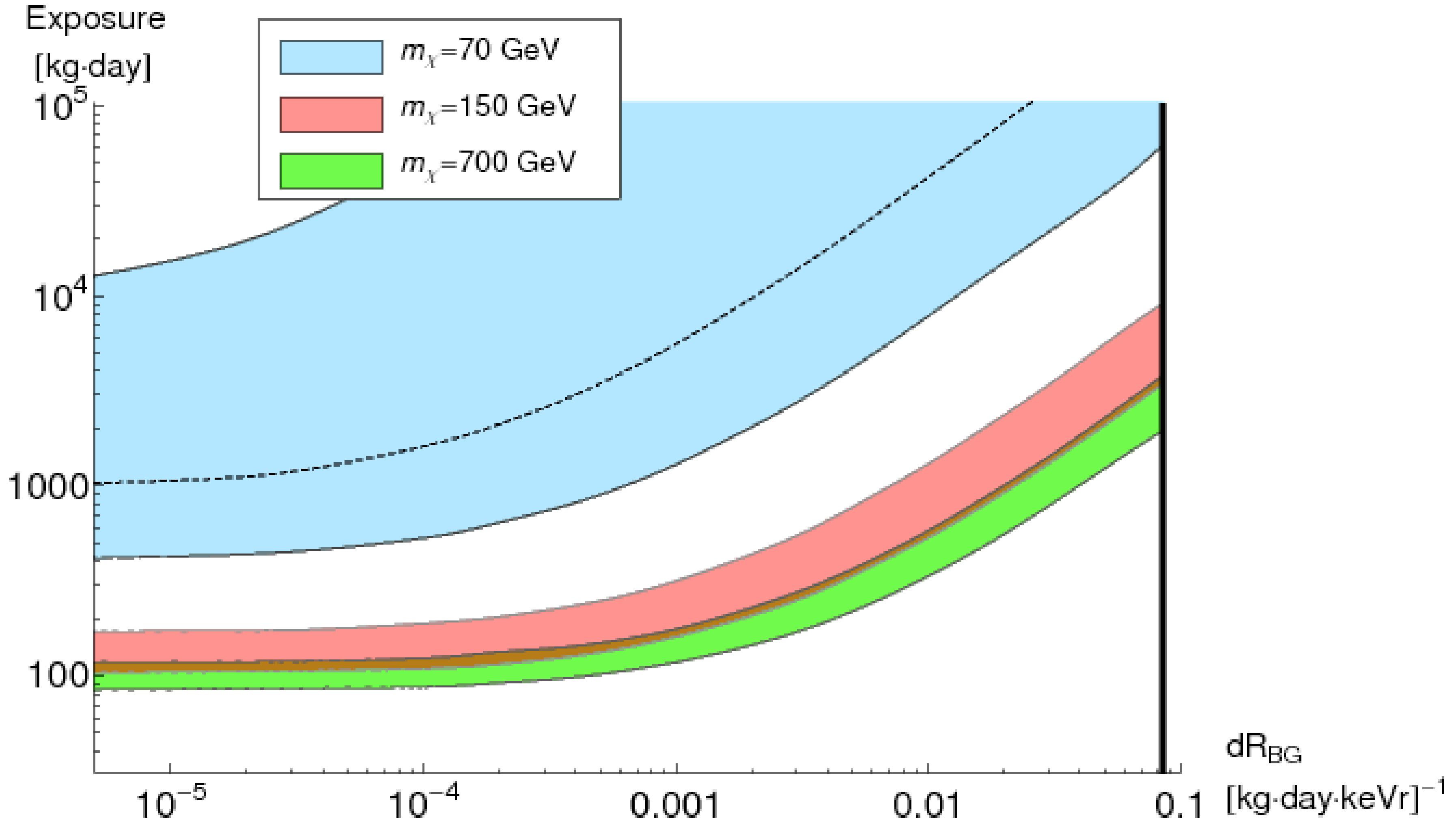


Detectability: exposure for 3σ result 95% of the time, <cos γ>

See Finkbeiner, Lin, & Weiner (0906.0002)



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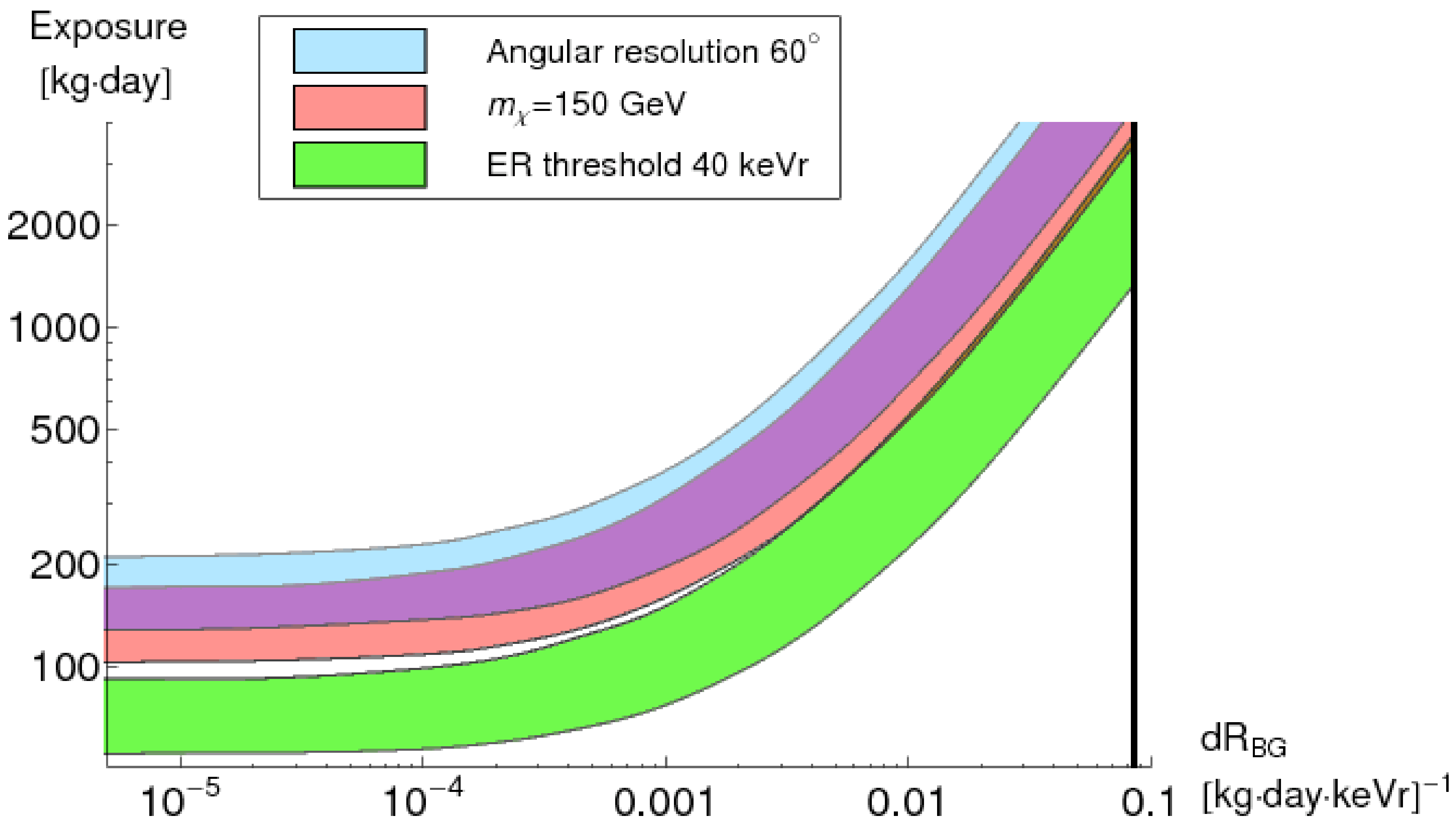

Detectability:

So, a directional detector with:
- large target mass (e.g. Xe),
- low background (< 0.1 cpd/kg/keVr)
- low threshold (40-50 keVr)

can test the DAMA/iDM scenario with exposures of 100 -1000 kg day.

A detection in this way would be a “smoking canon.”

Parameter Estimation: (m,δ) where σ is unknown

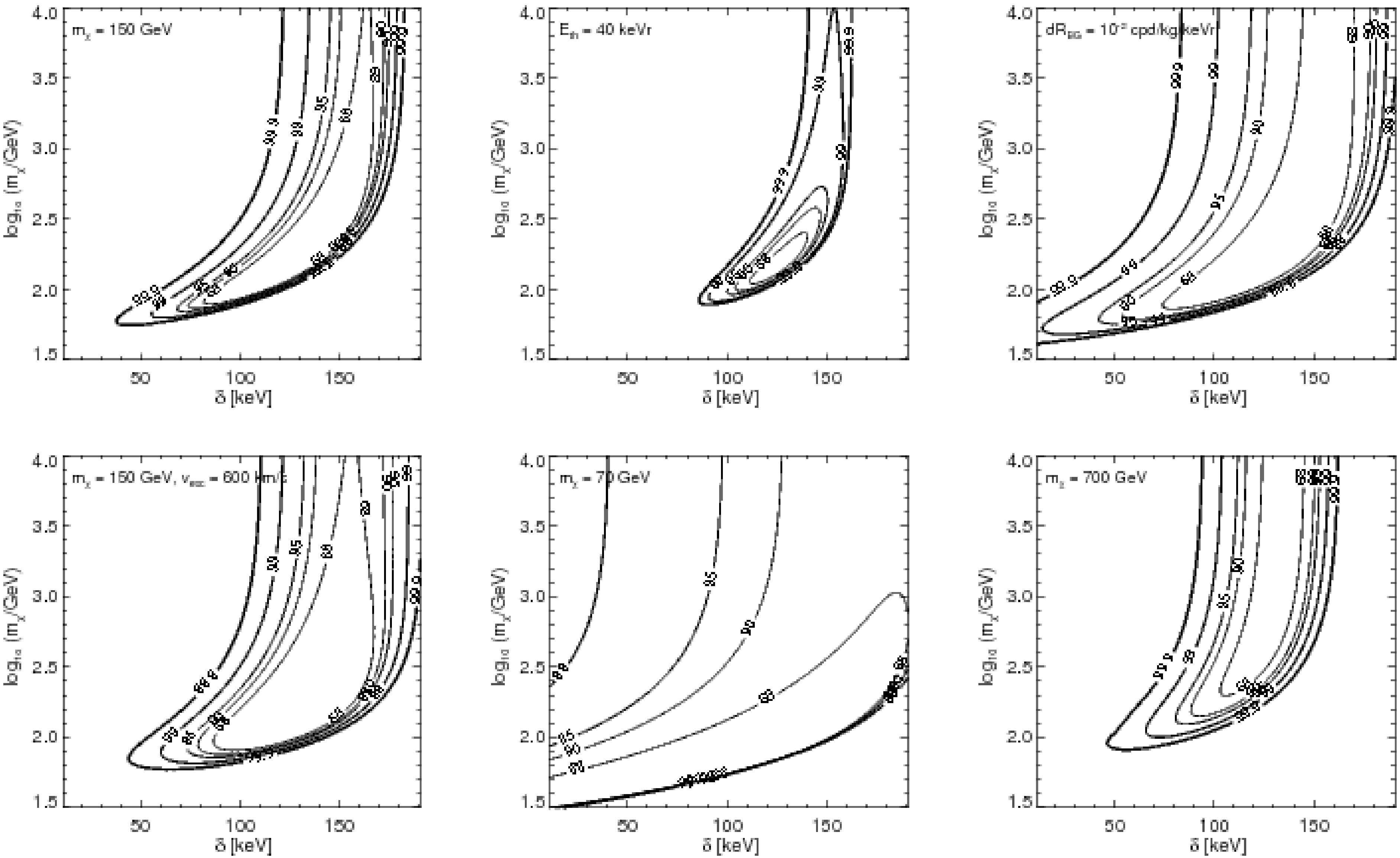

FIG. 5: Confidence levels for determining m_χ and δ, where σ_n is unknown, with an exposure of 1000 kg · day.

Parameter Estimation: (m,δ) where σ is known

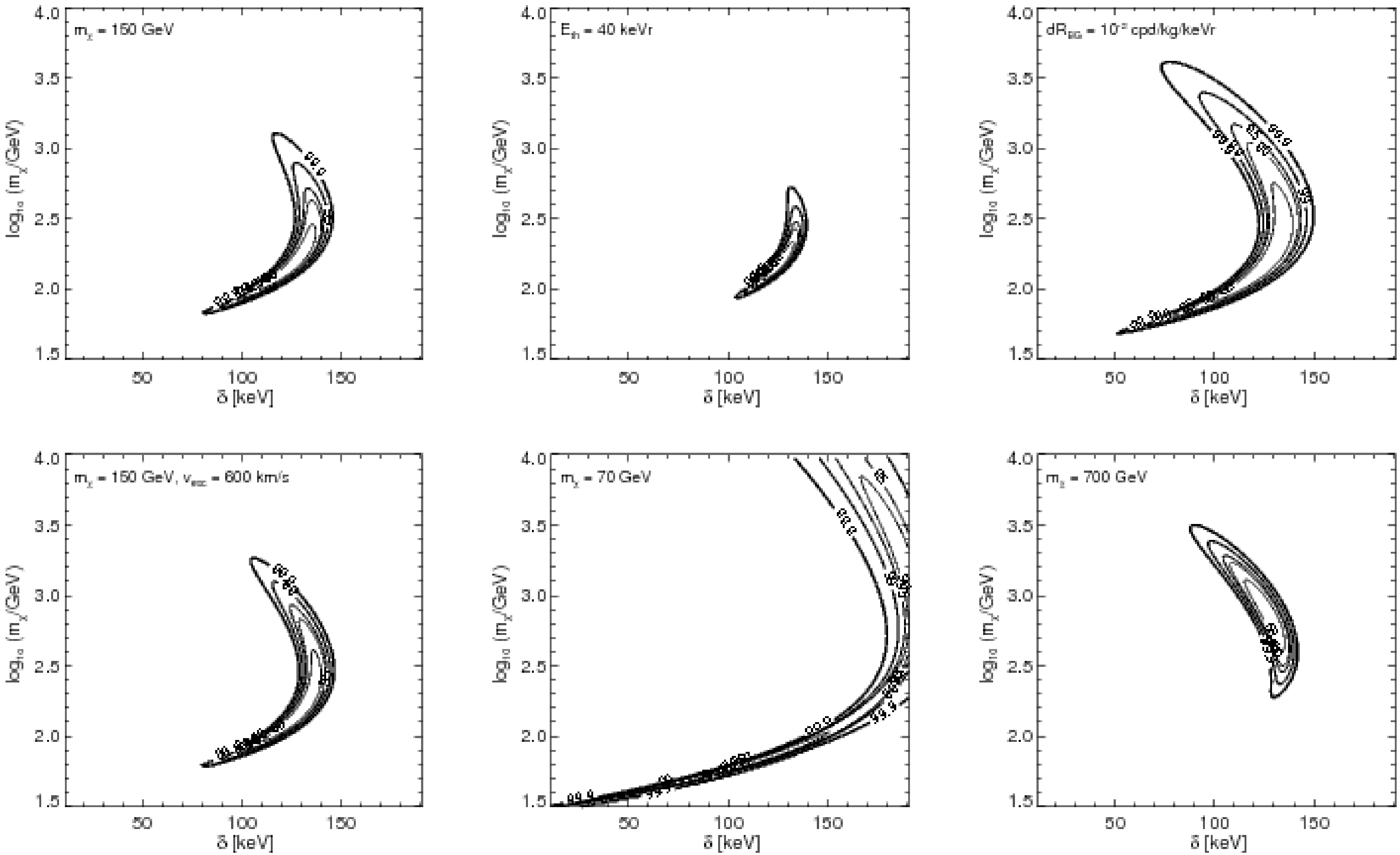

FIG. 6: Confidence levels for determining m_χ and δ, where σ_n is *known*, with an exposure of 1000 kg · day.

Parameter Estimation: (δ, m/σ) where m is unknown

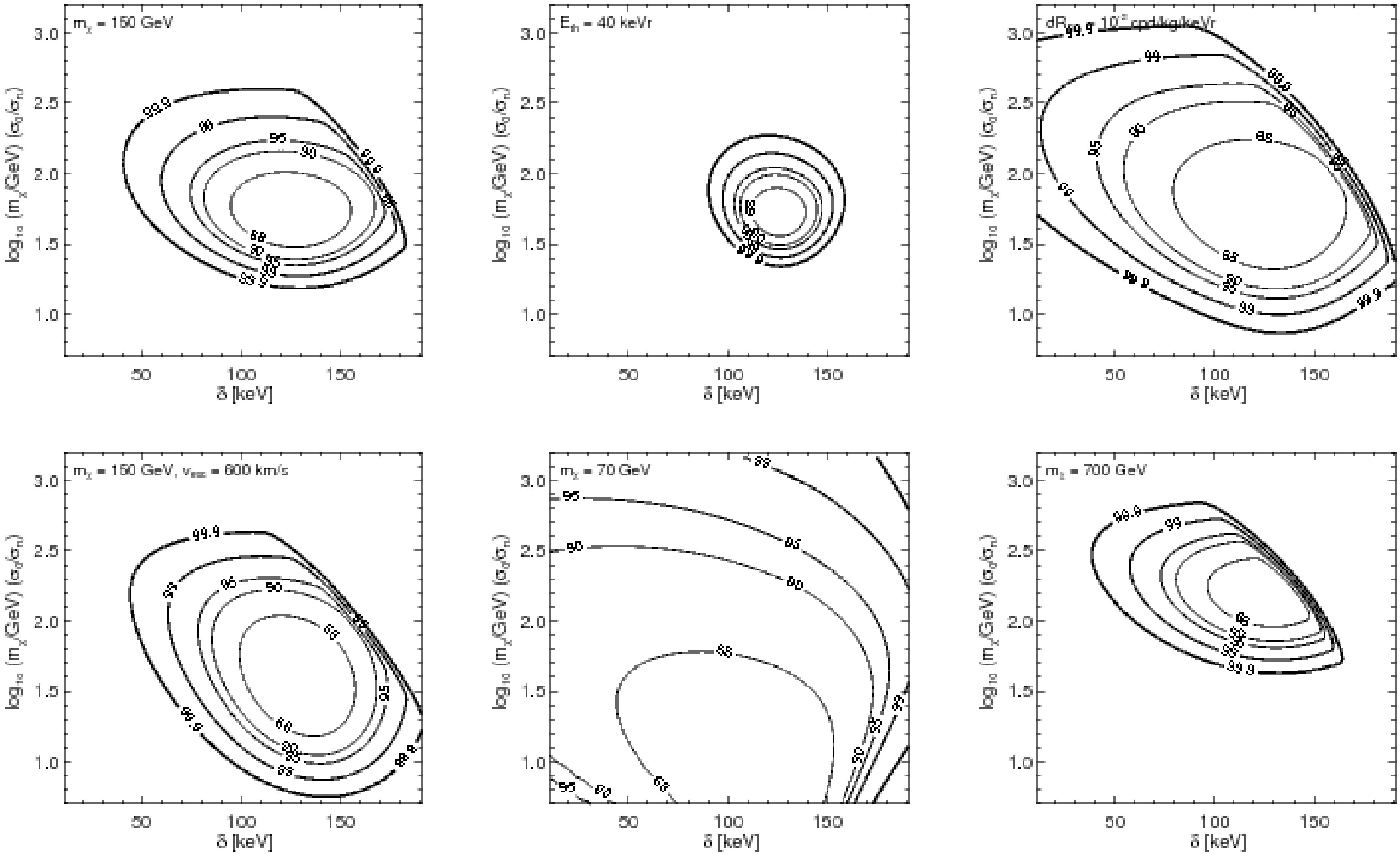

FIG. 9: Confidence levels for determining δ and m_χ/σ_n, where m_χ is unknown, with an exposure of 1000 kg · day, taking $\sigma_0 = 10^{-40}$ cm^2. Over most of the parameter space, some value of m_χ (and therefore σ_n) can be found to produce enough events for the given δ. However, in the case of large δ and large m_χ/σ_n, no solution is possible in some cases.

Outlook:

The near-term prospects are bimodal.

If the DAMA modulation is caused by WIMPs then
- iDM is probably right
- XENON10 events at 40-80 keVr are probably real
- XENON100 will have 200 events in the first 40 day run
- LUX will also detect in first month. (week?)
- Directional detection will come to the forefront
- 2010 will be a very interesting year!

On the other hand, if DAMA is wrong, we have a long way to go.