Constraints on Inelastic Dark Matter

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In Collaboration with Kai Schmidt-Hoberg

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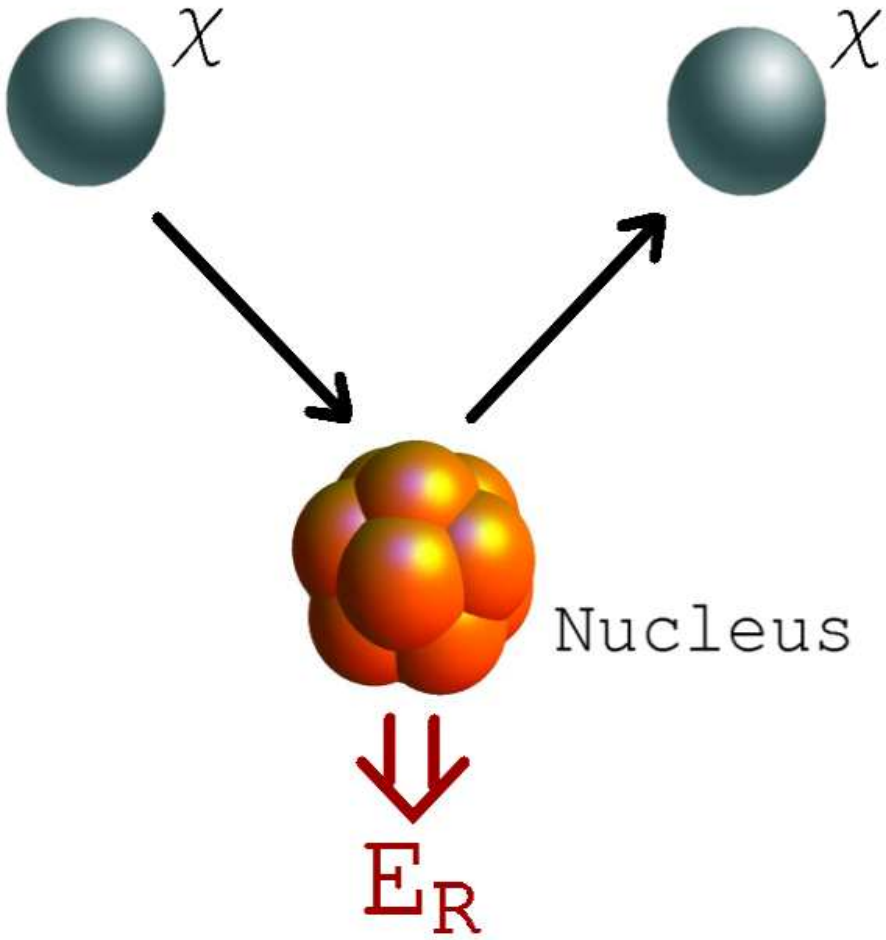
Outline

1. Direct Dark Matter Detection
2. Inelastic Dark Matter
3. Experimental Limits
4. Conclusion

Dark Matter Detection

- WIMP χ passes detector
  - $\rightarrow$ Liquid noble gas (Xenon...)
  - $\rightarrow$ Crystal (CDMS...)
- Scatters off target nucleus
- $E_R \rightsquigarrow$ Light, heat

Detector signal



Annual Modulation

- Reaction rate (spin-independent scattering):

$$\frac{dR}{dE_R} \propto \rho_\chi \; \sigma_n \, A^2 \; F[E_R]^2 \int_{v_{\min}} dv \; \frac{f[v]}{v}$$

Annual Modulation

- Reaction rate (spin-independent scattering):

$$\frac{dR}{dE_R} \propto \rho_\chi \, \sigma_n \, A^2 \, F[E_R]^2 \int_{v_{\min}} dv \, \frac{f[v]}{v}$$

Local WIMP Density

Annual Modulation

- Reaction rate (spin-independent scattering):

$$\frac{dR}{dE_R} \propto \rho_\chi \, \sigma_n A^2 \, F[E_R]^2 \int_{v_{\min}} dv \, \frac{f[v]}{v}$$

Cross Section

Annual Modulation

- Reaction rate (spin-independent scattering):

$$\frac{dR}{dE_R} \propto \rho_\chi \; \sigma_n \, A^2 \; F[E_R]^2 \int_{v_{\min}} dv \; \frac{f[v]}{v}$$

Form Factor

Annual Modulation

- Reaction rate (spin-independent scattering):

$$\frac{dR}{dE_R} \propto \rho_\chi \quad \sigma_n A^2 \quad F[E_R]^2 \quad \int_{v_{\min}} dv \, \frac{f[v]}{v}$$

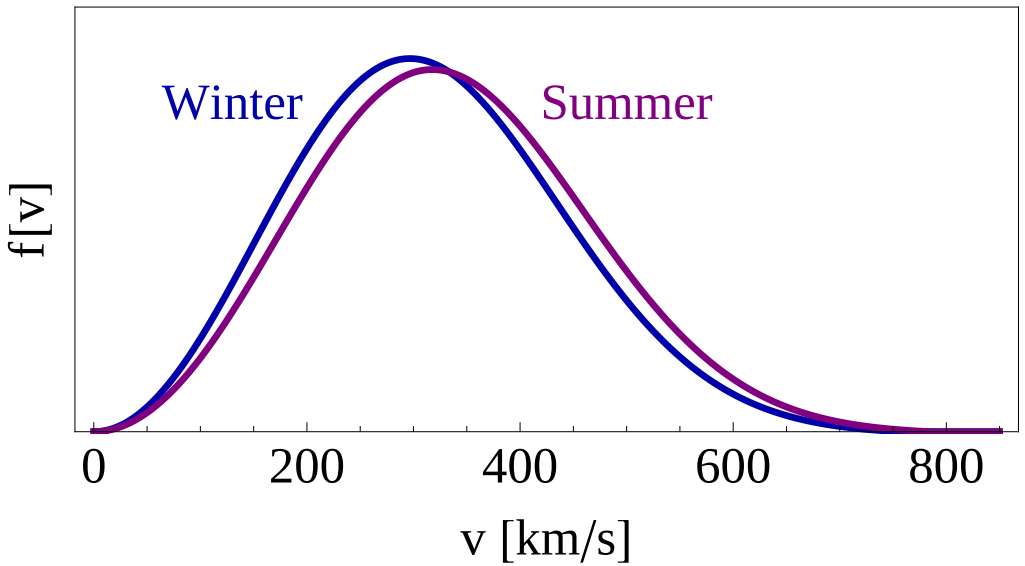
Velocity Distribution

Annual Modulation

- Reaction rate (spin-independent scattering):

$$\frac{dR}{dE_R} \propto \rho_\chi \quad \sigma_n A^2 \quad F[E_R]^2 \quad \int_{v_{\min}} dv \quad \frac{f[v]}{v}$$

- Velocity distribution:



Expected rate:

$$S_0 + S_m \cos\omega(t - t_0)$$

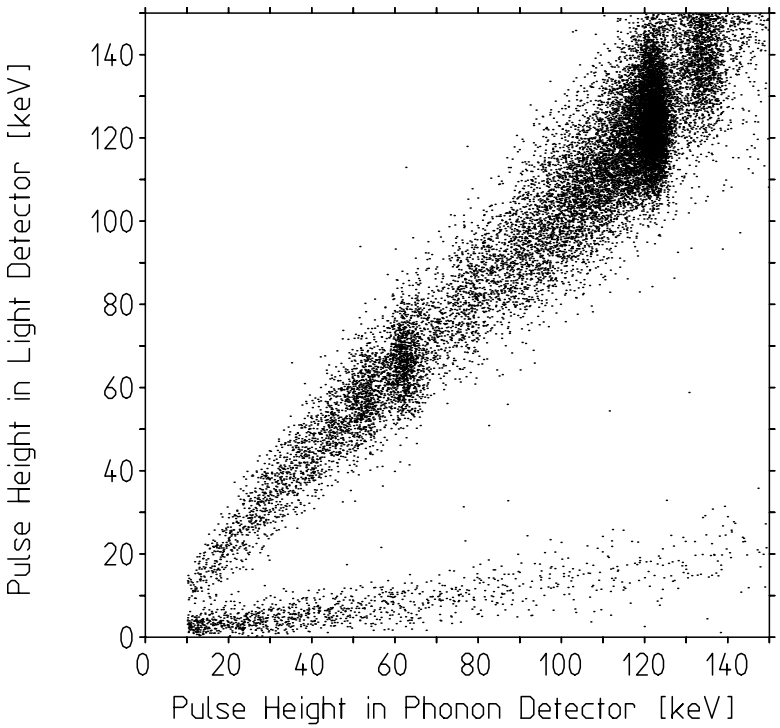
Period and phase:

$$\omega = 2\pi/\text{yr}$$

$$t_0 = \text{June } 2^{\text{nd}}$$

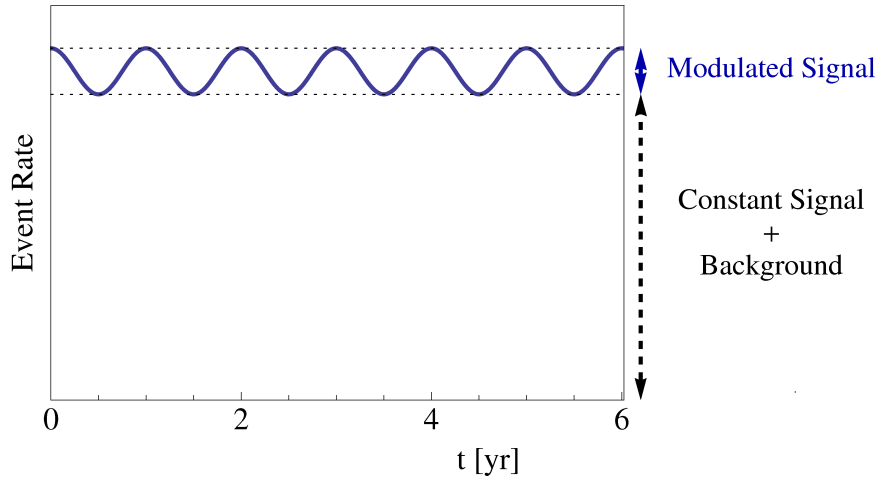
Background Discrimination

CDMS, Xenon, CRESST, ...



- Recoil: $E_R \rightsquigarrow \Delta T, e^-, \gamma$
- Measure 2 of them
  - $\rightarrow$ Energy calibration
  - $\rightarrow$ Event discrimination

DAMA



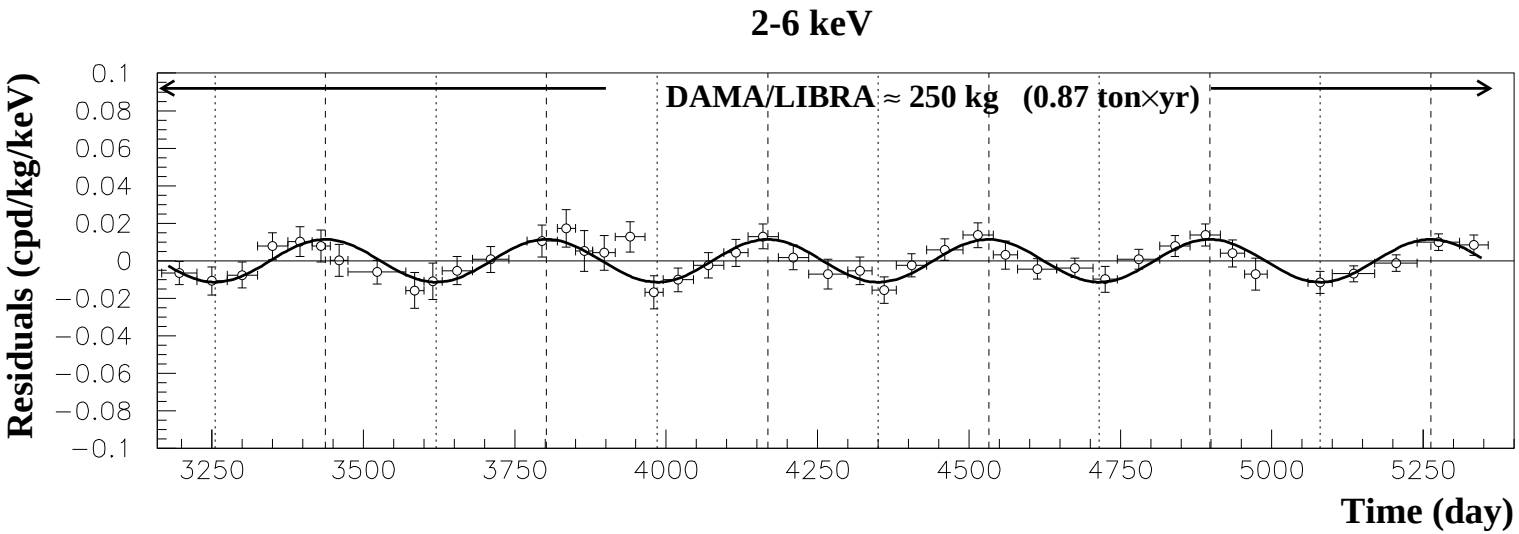
- Only scintillation
- Identify signal through its modulation

Insensitive to const. rate

The DAMA Puzzle

- Modulation signal in DAMA ($> 8\,\sigma$)

  Bernabei et al., Eur. Phys. J. **C67** (2010)



- No clear signal in CDMS, Xenon ...

  Ahmed et al., Phys. Rev. Lett. **102** (2009), Angle et al., Phys. Rev. Lett. **100** (2008)

- Standard WIMP: Rate depends only on σ_n, m_χ

Problem: DAMA Region ↯ Other Searches

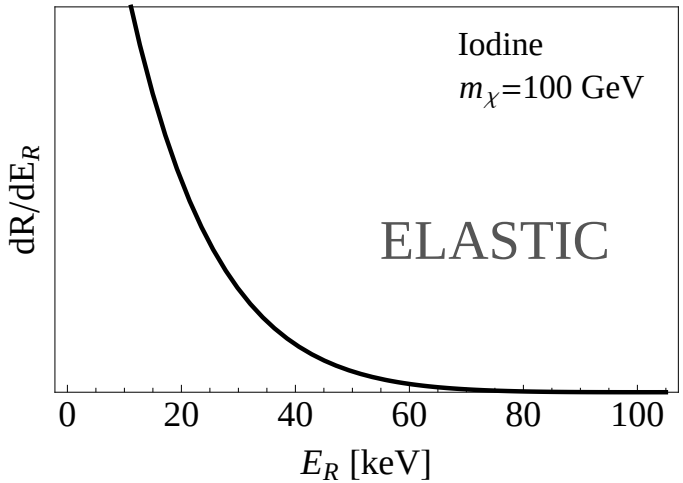
A Solution to the DAMA Puzzle

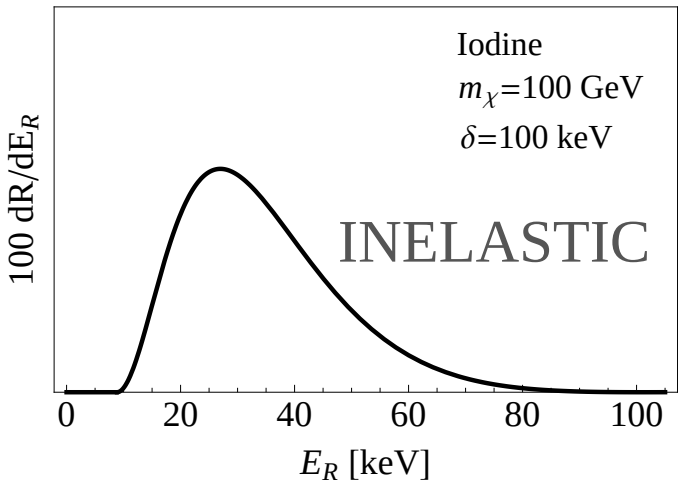
- Inelastic Dark Matter: $\chi + N \to \chi' + N$
  Tucker-Smith, Weiner, Phys. Rev. **D64** (2001)
- Scattering requires higher velocity

$$v_{\text{min}} = v_{\text{min,elastic}} + \frac{\delta}{\sqrt{2 m_N E_R}}$$

δ : Mass Splitting

- Changes spectrum



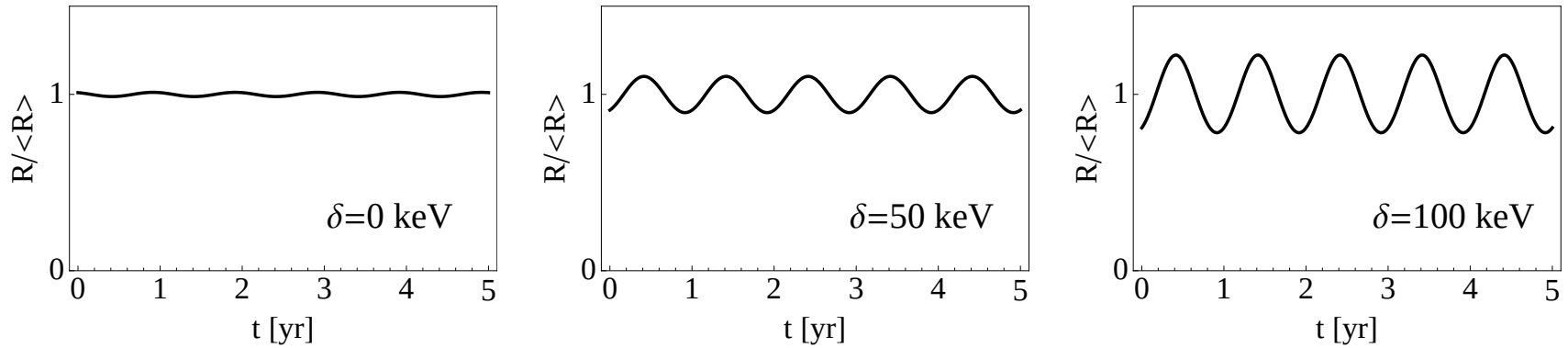


- Heavy targets are favored

Enhanced Modulation

- Sensitive to tail of velocity distribution

  $\Rightarrow$ Modulation gets enhanced



  $\Rightarrow$ DAMA more sensitive!

- Realizations of Inelastic Dark Matter
  - SUSY model with sneutrino
    Arkani-Hamed, Hall, Murayama, Tucker-Smith, Weiner, Phys. Rev. **D64** (2001)
  - Warped extra dimensions
    Cui, Morrissey, Poland, Randall, JHEP **05** (2009)

Our Analysis

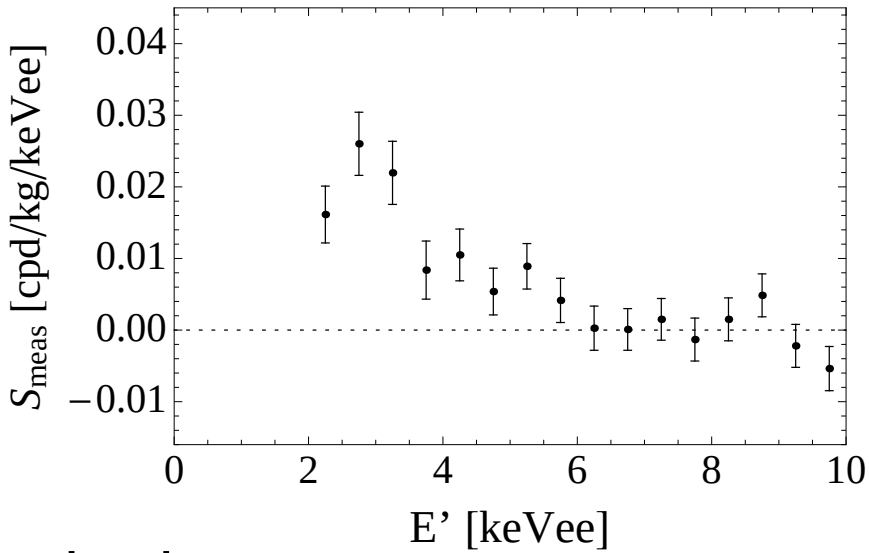
- Experiments:

  DAMA/LIBRA, CDMS I & II, CoGeNT, CRESST I & II, TEXONO, XENON10 & 100, ZEPLIN III

  DAMA/LIBRA, Eur. Phys. J. **C67** (2010), CDMS I, Phys. Rev. **D68** (2003), CDMS II, Phys. Rev. Lett. **102** (2009), CoGeNT, Phys. Rev. Lett. **101** (2008), CRESST I, Astropart. Phys. **18** (2002), CRESST II, Astropart. Phys. **31** (2009) & Talk by Seidel at WONDER 2010, TEXONO, Phys. Rev. **D79** (2009), XENON10, Phys. Rev. Lett. **100** (2008), XENON100, **arXiv:1005.0380** [astro-ph] (2010)

- DAMA allowed region with χ^2 metric

$$\chi^2 = \sum_{\text{bins}} \frac{(S_{\text{pred}} - S_{\text{meas}})^2}{(\sigma_{\text{meas}})^2}$$

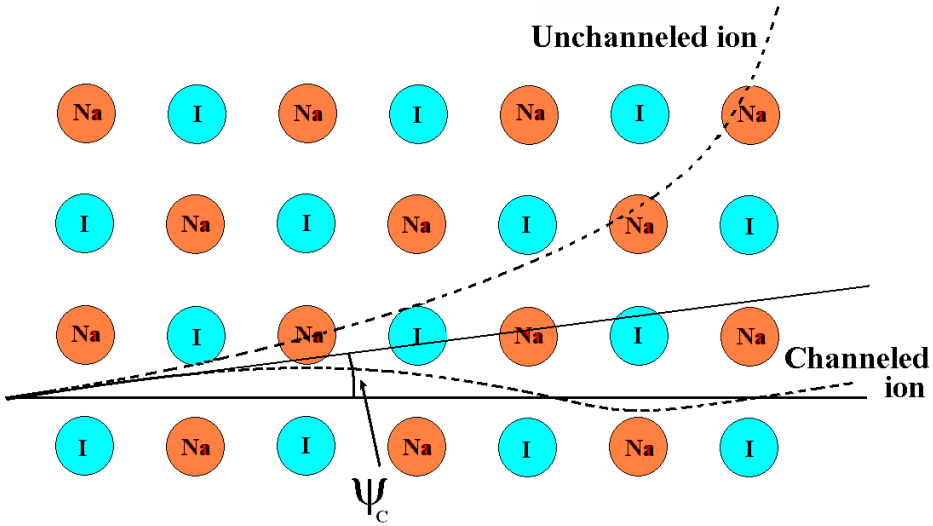


- Limits with Maximum Gap Method

  Yellin, Phys. Rev. **D66** (2002)

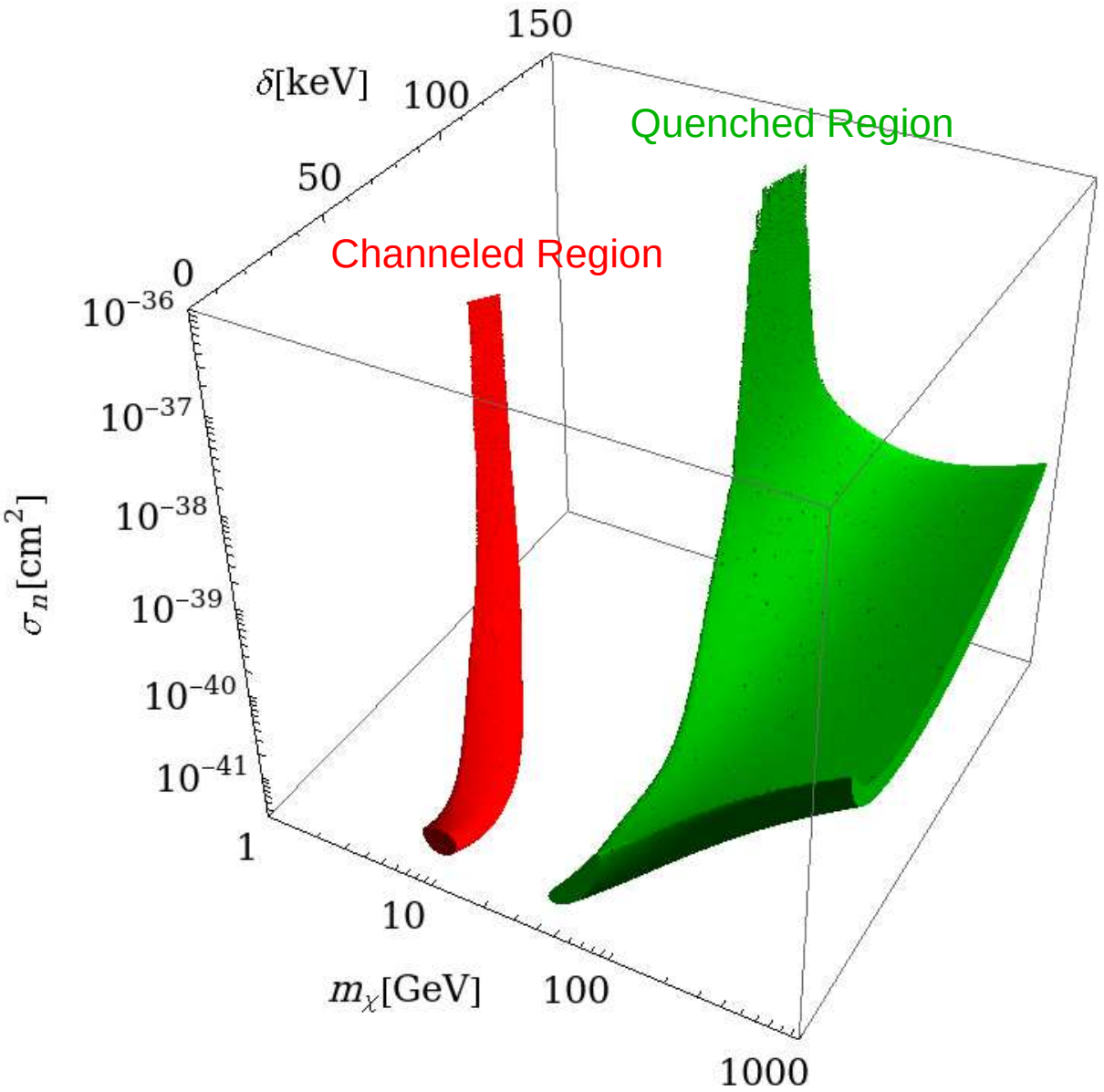
DAMA: Quenching and Channeling

- Quenching factor $\mathbf{Q = E'/E_R}$ (E': Scintillation Energy)
- **Channeling:** Recoil along characteristic axes
  $\Rightarrow E'/E_R = 1$
- Channeling fraction calculated by DAMA
  Bernabei et al., Eur. Phys. J. **C53** (2008)



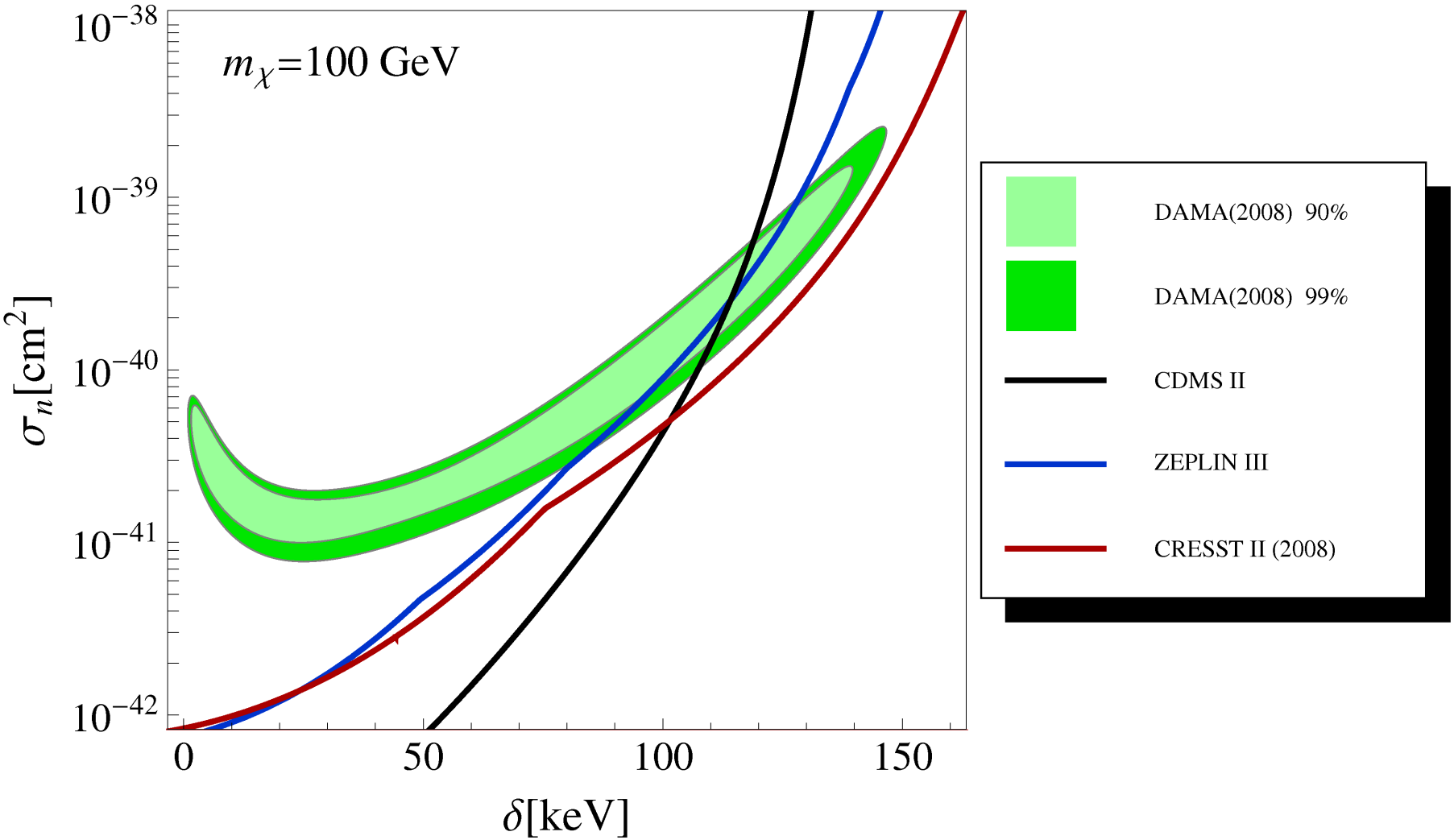
- **But:** DAMA calculation challenged
  Savage, Gelmini, Gondolo, Freese, **arXiv:1006.0972** [astro-ph] (2010)

DAMA Allowed Regions



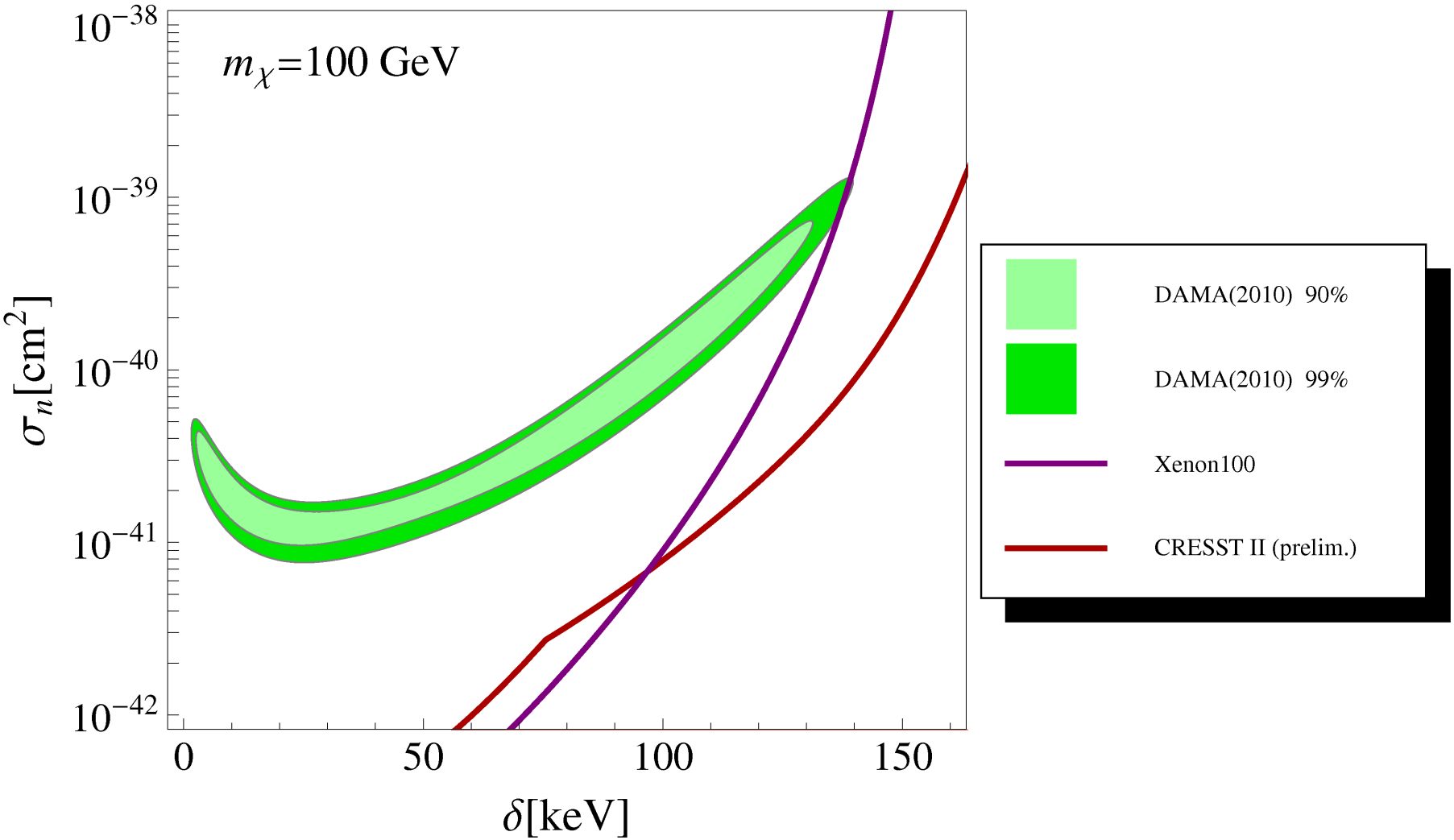
The Quenched Region

- Status 2009: Heavy Inelastic Dark Matter disfavored



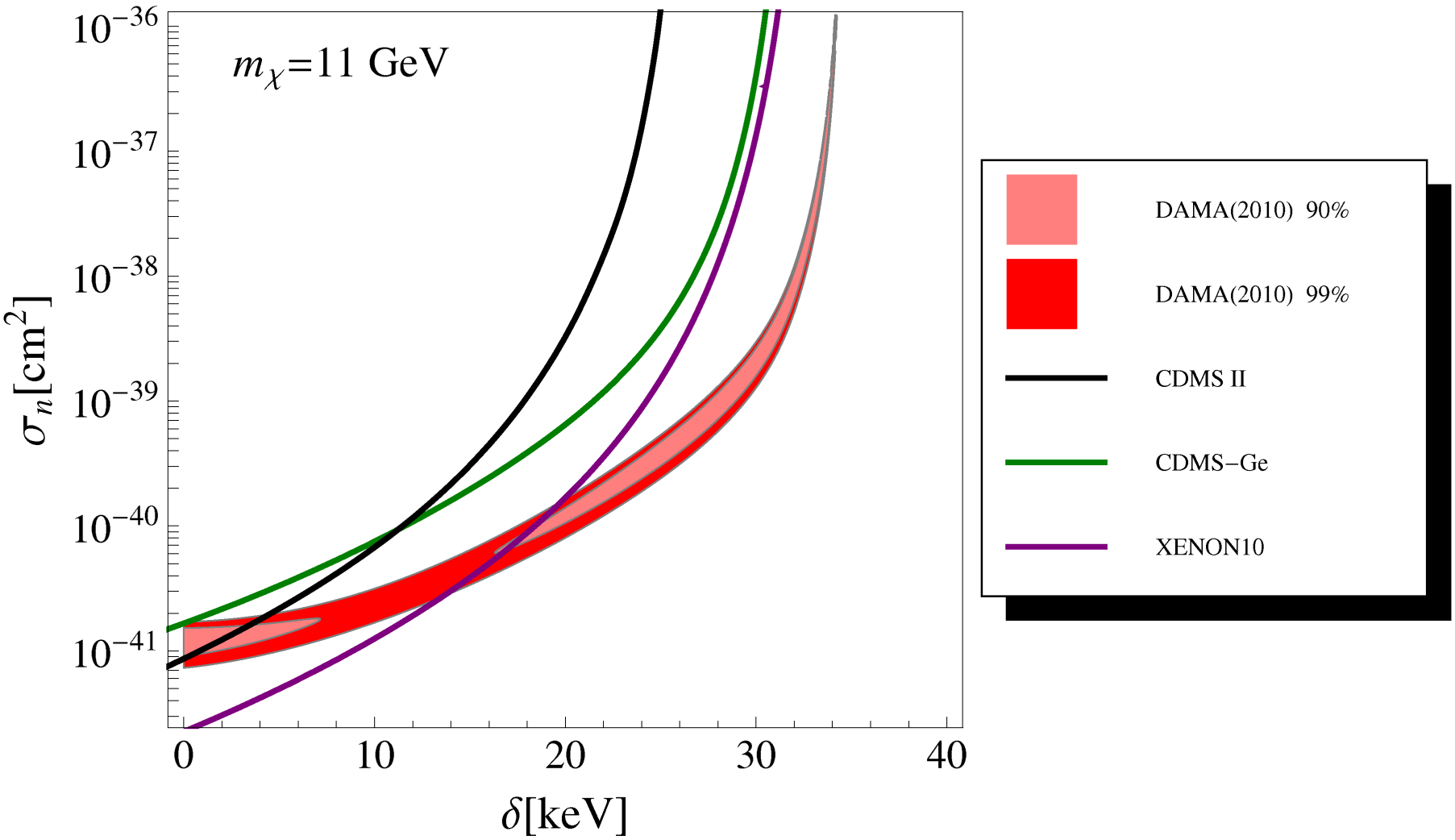
The Quenched Region

- New Results: Heavy Inelastic Dark Matter excluded



The Channeled Region

- Light Inelastic Dark Matter viable (but relies on channeling)



Conclusion

- Inelastic Dark Matter increases the sensitivity of DAMA relative to other direct detection experiments
- But: Inelastic Dark Matter $m_\chi \gtrsim 15$ GeV is now excluded at high significance especially by CRESST II
- Light Inelastic Dark Matter remains a possible solution to the DAMA puzzle if channeling exists.