Prospects for Direct Detection of Light Dark Matter in Semiconductors

Chiu-Tien Yu
YITP - Stony Brook

with Rouven Essig, Marivi Fernandez Serra, Jeremy Mardon, Adrián Soto, Tomer Volansky

May 1, 2014 New Perspectives on Dark Matter, Fermilab

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work in progress

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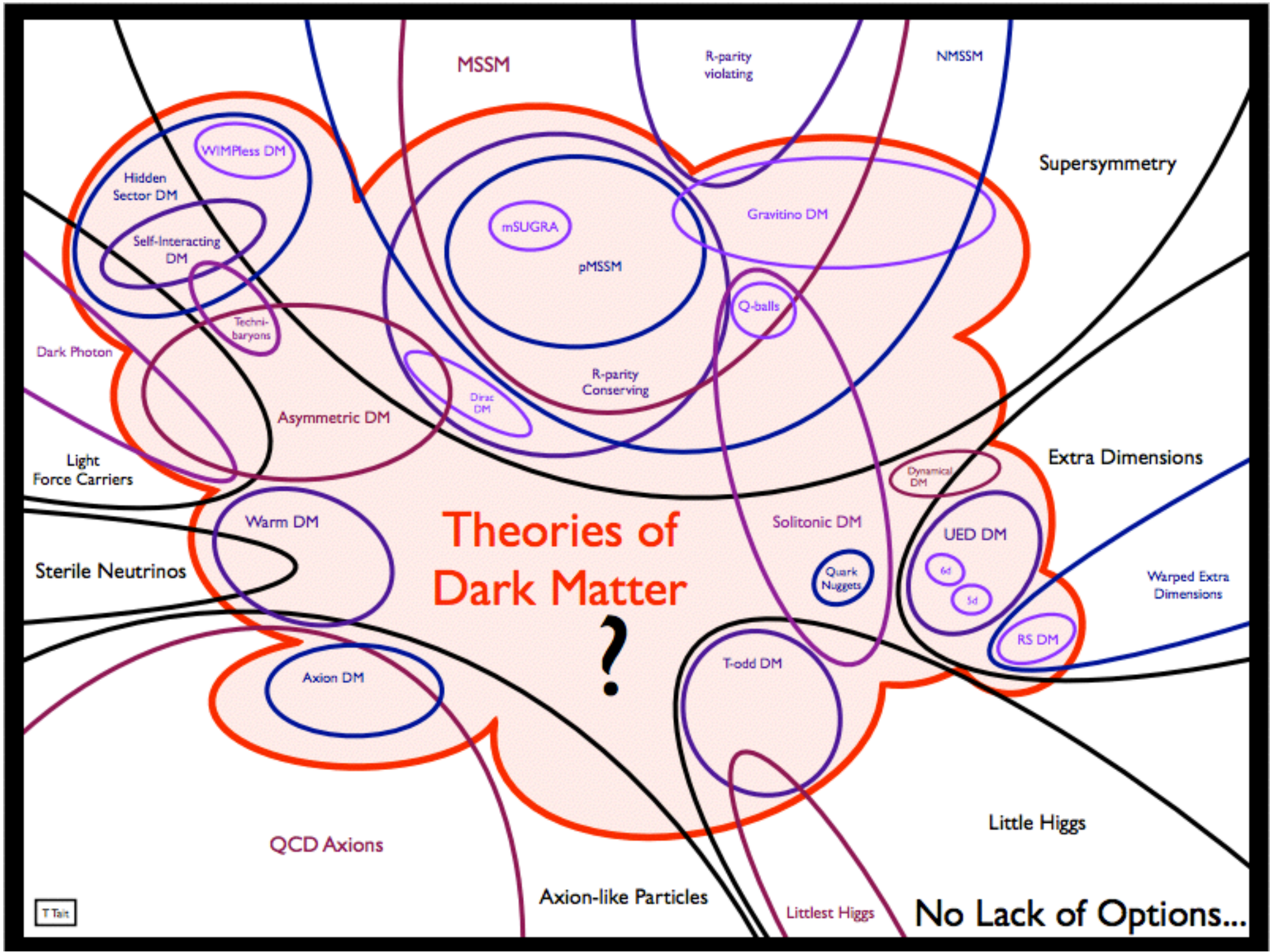
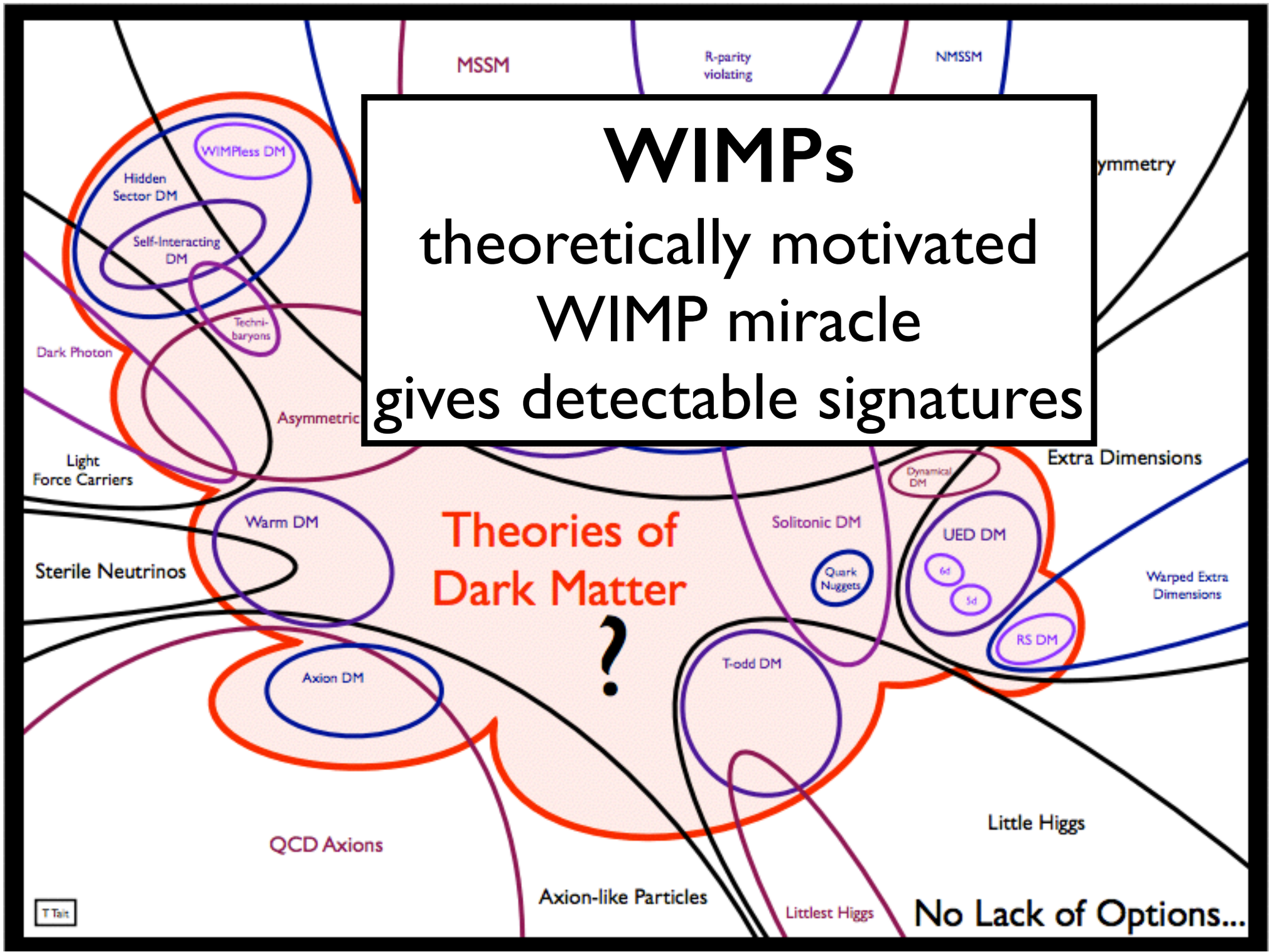
candidates for DM



candidates for DM



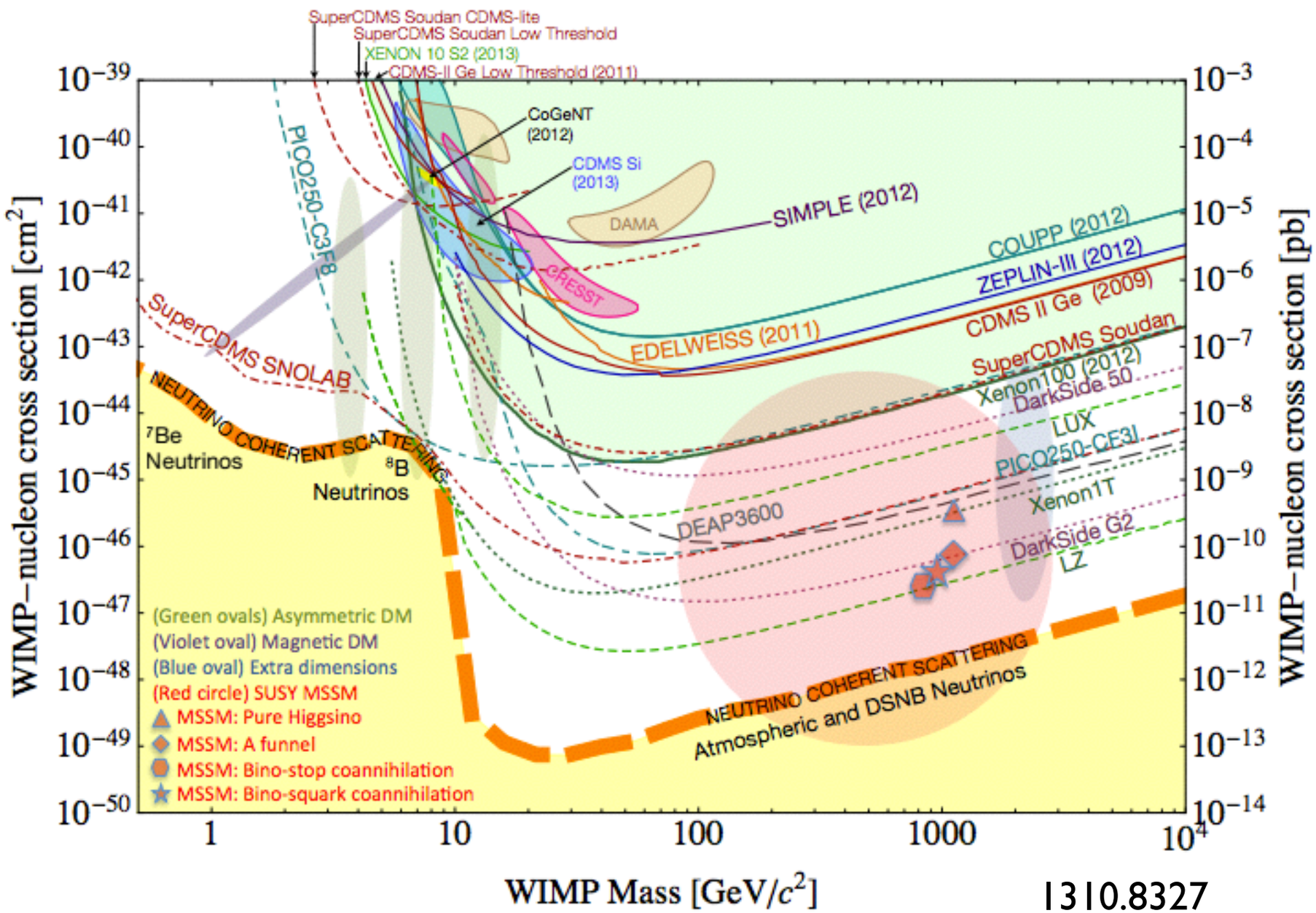
WIMPs

theoretically motivated

WIMP miracle

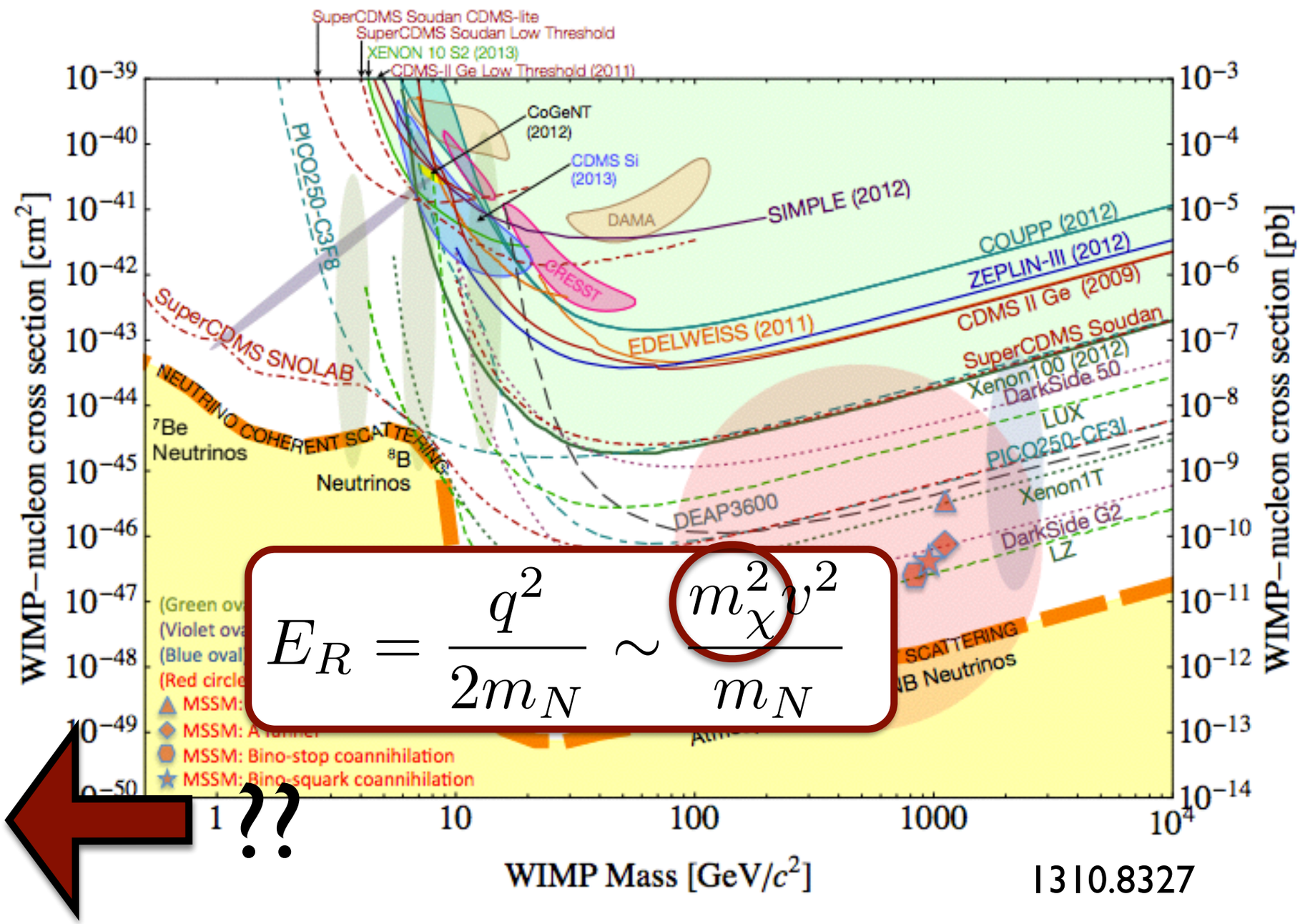
gives detectable signatures

current state of affairs

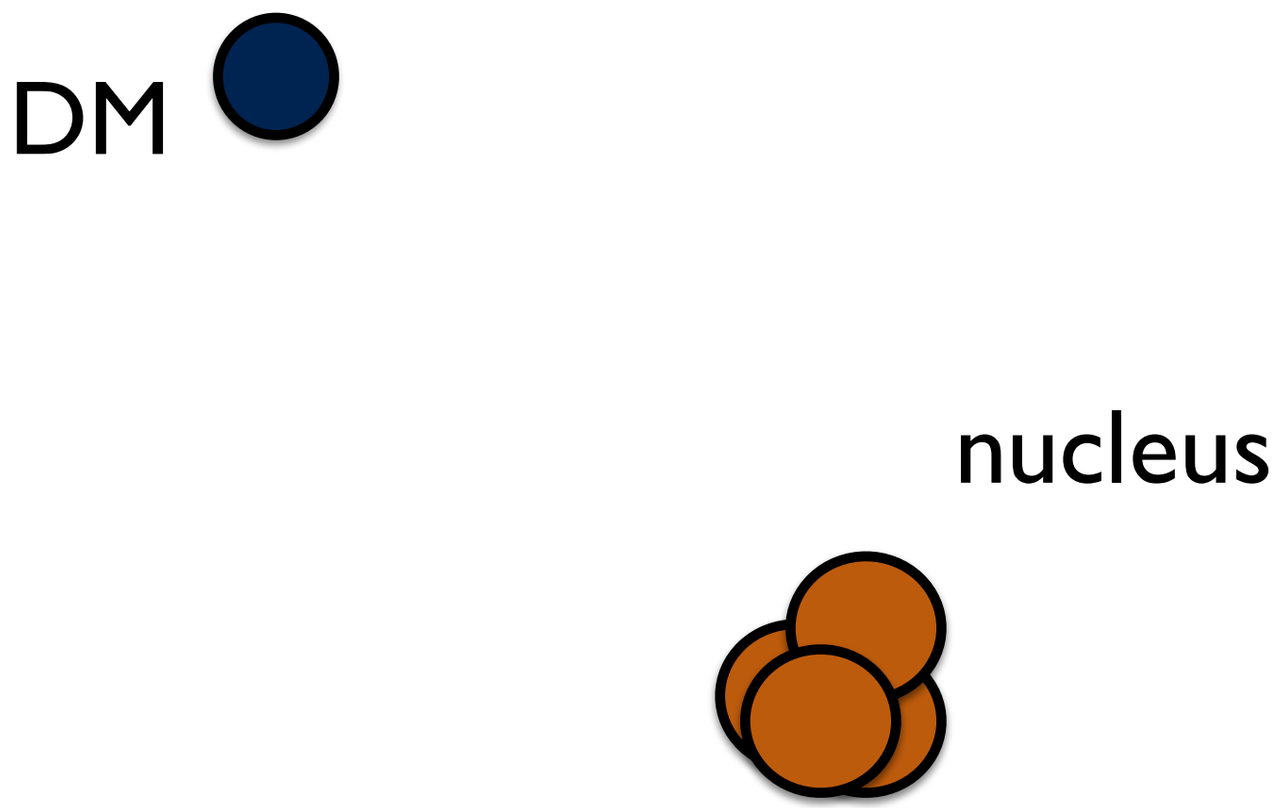


1310.8327

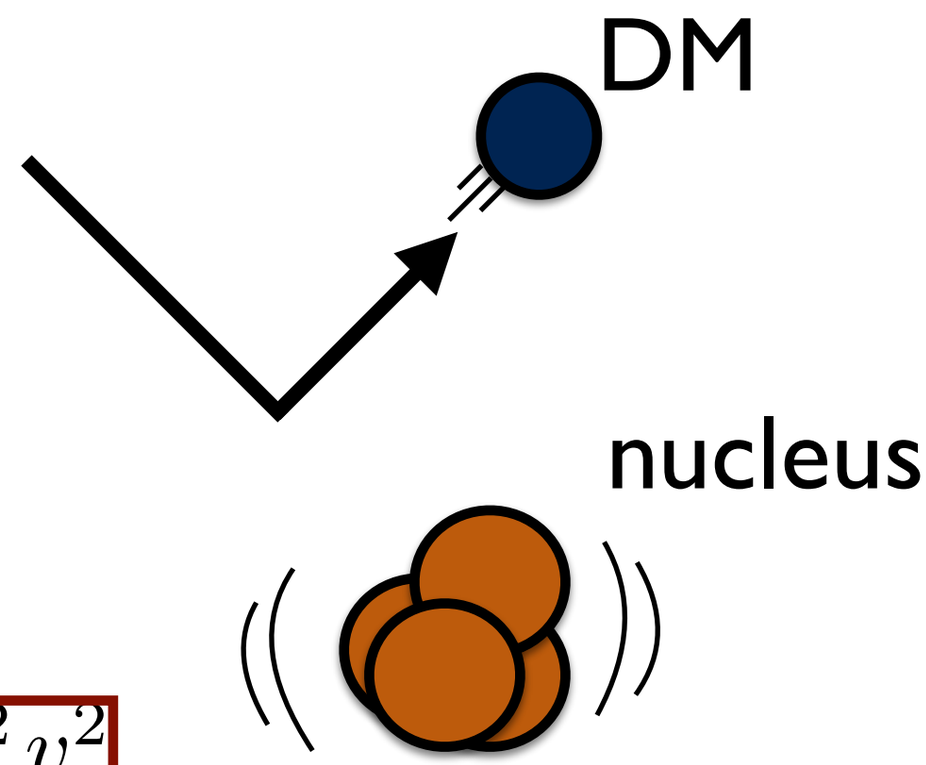
current state of affairs



$$E_R = \frac{q^2}{2m_N} \sim \frac{m_\chi^2 v^2}{m_N}$$



*not to scale



*not to scale

$$E_R = \frac{q^2}{2m_N} \sim \frac{m_\chi^2 v^2}{m_N}$$

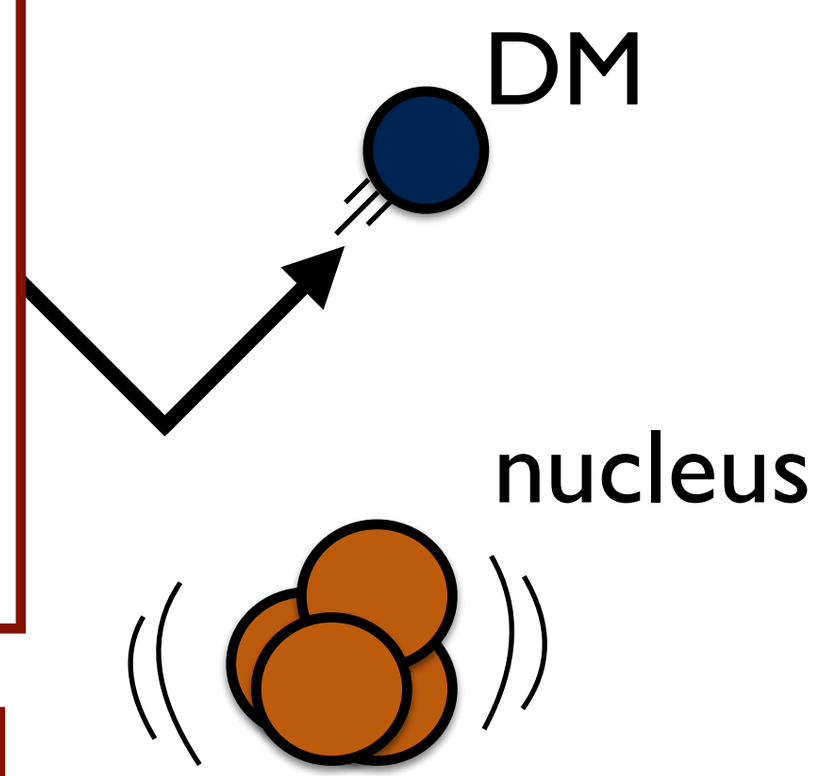
signal:

heat

phonons

scintillation photons

ionization electrons



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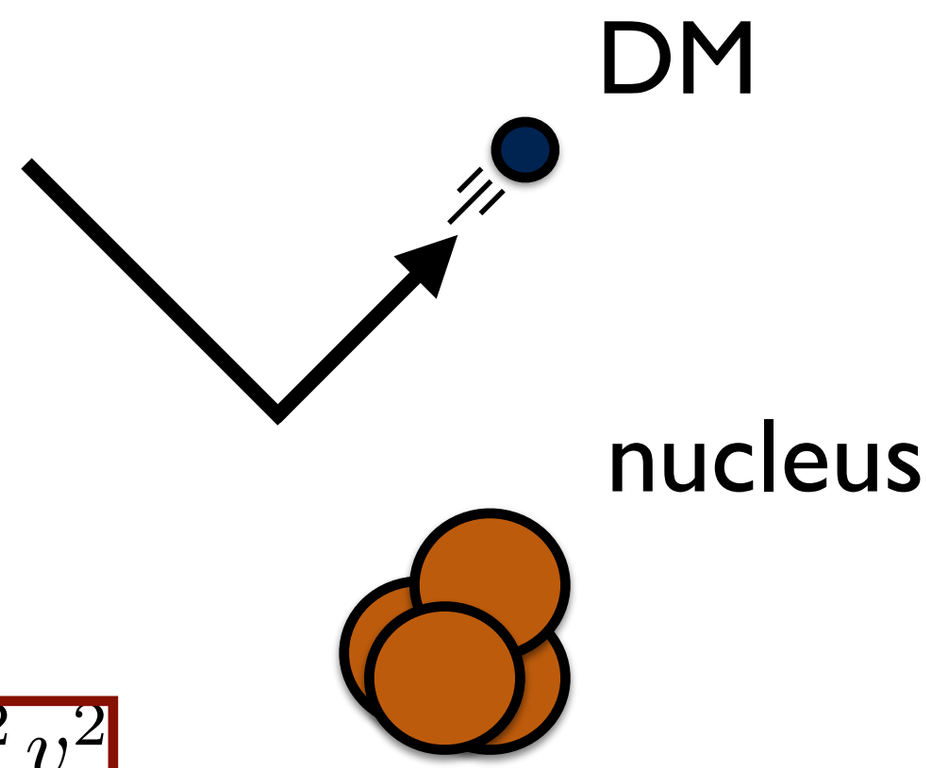
$$E_R = \frac{q^2}{2m_N} \sim \frac{m_\chi^2 v^2}{m_N}$$

$$m_\chi = 100 \text{ GeV}, E_R \sim 1 \text{ MeV}$$



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$$E_R = \frac{q^2}{2m_N} \sim \frac{m_\chi^2 v^2}{m_N}$$

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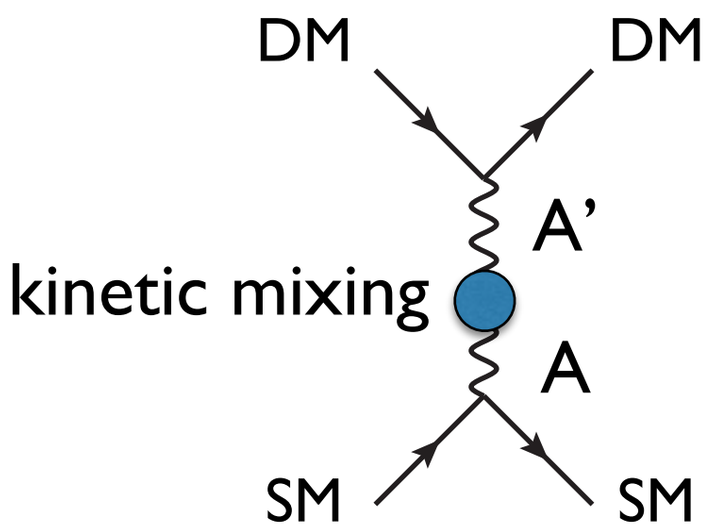
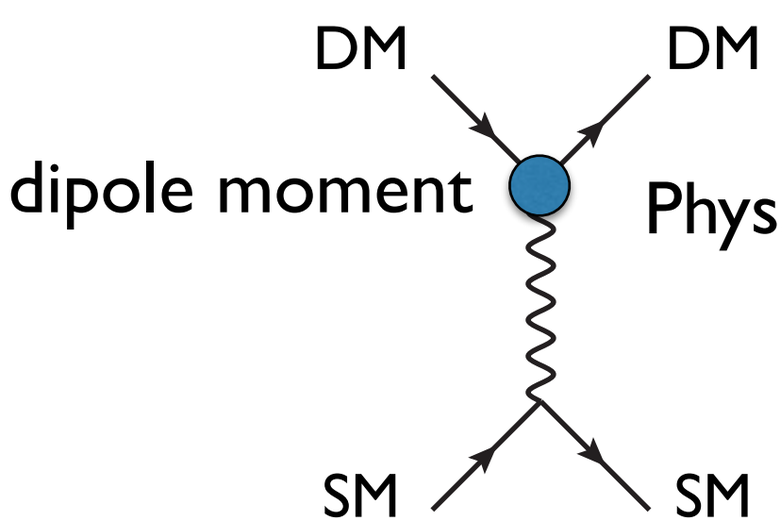
sub-GeV DM is theoretically motivated

Hidden Photon Mediator



Hall et al [0911.1120]
Essig et al [1108.5383]
Lin et al [1111.0293]
Chu et al [1112.0493]

MDM/EDM



Sigurdson et al,
Phys. Rev. D70 (2004) 083501 + Erratum-ibid.
Banks et al [1007.5515]
Graham et al [1203.2531]
Kadota and Silk [1402.7295]

	Monday *Room: 1 West*	Tuesday *Room: 1 West*	Wednesday *Room: 1 West*	Thursday *Room: Curia II*	Friday *Room: Curia II*
9:20-9:30	Workshop opening and welcome				
9:30-10:05	Dave McKeen (U.Washington) "Light Dark Matter and Proton Beam Dumps"	Maxim Pospelov (U.Victoria/Perimeter) "Search for New Physics Below 10 MeV with Underground Accelerators"	Lauren Hsu (FNAL) "Low Mass WIMP searches with SuperCDMS"	Claudia Frugiuele (FNAL) "Light dark matter discovery prospects with NOvA and MINOS "	Tien-Tien Yu (Stony Brook) "Prospects for Direct Detection of Light Dark Matter in Semiconductors"
10:05-10:40	Ranjan Dharmapalan (ANL) "Dark Matter Searches at MiniBooNE"	Surjeet Rajendran (Stanford) "Cosmic Axion Spin Precession Experiment (CASPEr)"	Juan Estrada (FNAL) "DAMIC: Direct Search for Low Mass Dark Matter with CCDs"	Jae Yu (U.Texas at Arlington) "Searching for Dark Matter at LBNE"	Jong-Chul Park (U. Kansas) "3.5 keV line observation and its dark matter interpretation"
10:40-11:20	**Coffee**				
11:20-11:55	Richard Van de Water (LANL) "Probing the Dark Sector with Liquid Argon TPC Detectors"	Gray Rybka (U.Washington) "New Results and New Perspectives from ADMX"	Juan Collar (U. Chicago)	Dave Soper (U. Oregon) "Parton model and color dipole model for dark matter detection in the DIS regime"	Dan Hooper (FNAL/U.Chicago) "Dark matter annihilations in the Galactic Center"
12:00-1:30	**Lunch**				
1:30-2:05	Hooman Davoudiasl (BNL) "Dark Matter from Hidden Forces"	Jeremy Mardon (Stanford) "Ultra-light hidden photon dark matter"	Yuhsin Tsai (U.C. Davis) "Direct Detection with Dark Mediators"	Gordan Krnjaic (Perimeter) "Next Generation Beam Dump Experiments to Search for Light Dark Matter"	
2:05-2:40	Matt Graham (SLAC) "Searching for dark photons in electron beams"	Adam Para (FNAL) Discussion on Directional Dark Matter Detection"	David Curtin (Stony Brook) "Constraining Doubly Dark Portals"	Ze'ev Surujon (Stony Brook) "Strong Constraints on Sub-GeV Dark Matter and Other Light States From E137"	
2:40-3:20	**Coffee**				
3:20-3:55	Daniel Grin (U. Chicago) "Axion dark matter and the CMB"	Discussion/Collaboration	Discussion/Collaboration	Discussion/Collaboration	
4:00-5:00			Wick Haxton (U.C. Berkeley) *Colloquium* "The Nuclear Physics of Direct Dark Matter Detection"		Maxim Pospelov (U.Victoria/Perimeter) *Wine and Cheese* "Broadening the Search for New Physics at Intensity Frontier Experiments"

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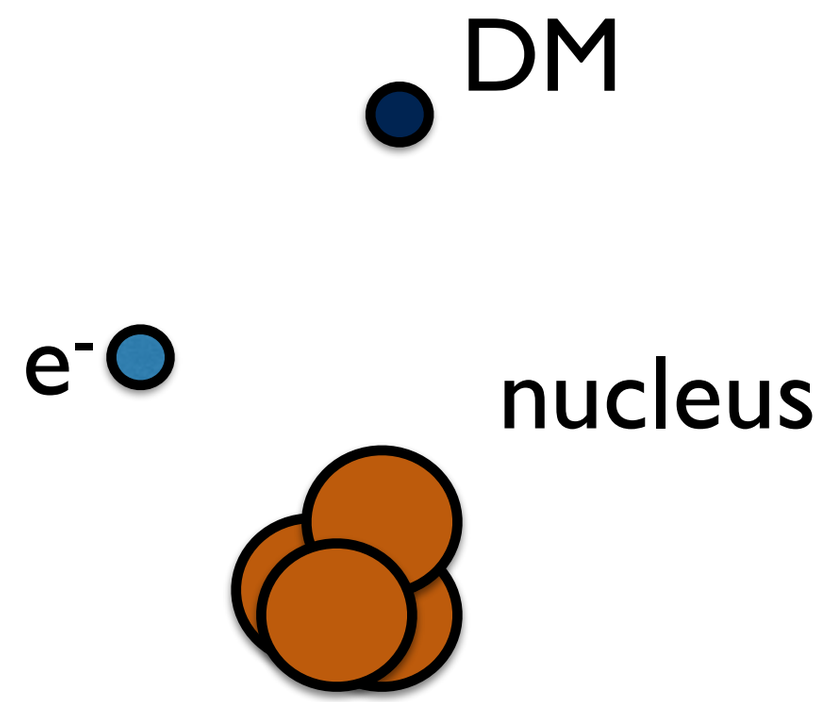
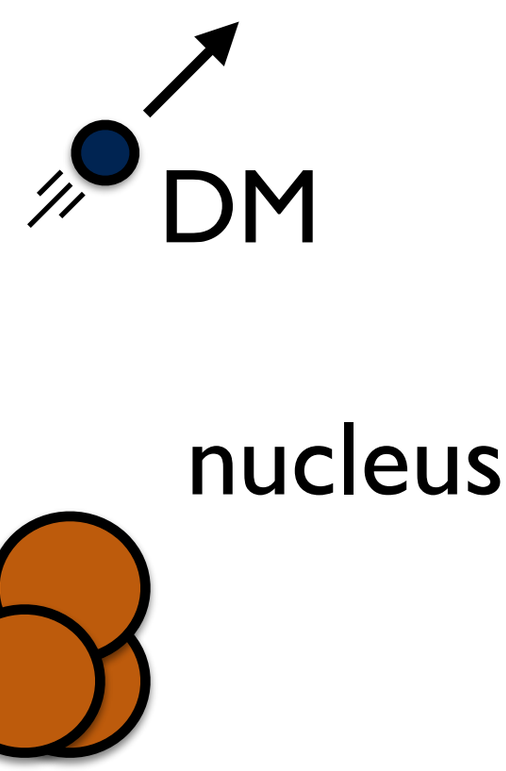


$$E_R = \frac{q^2}{2m_e} \sim \frac{m_\chi^2 v^2}{m_e}$$

*not to scale

signal:
a few ionized electrons



$$E_R = \frac{q^2}{2m_e} \sim \frac{m_\chi^2 v^2}{m_e}$$

*not to scale

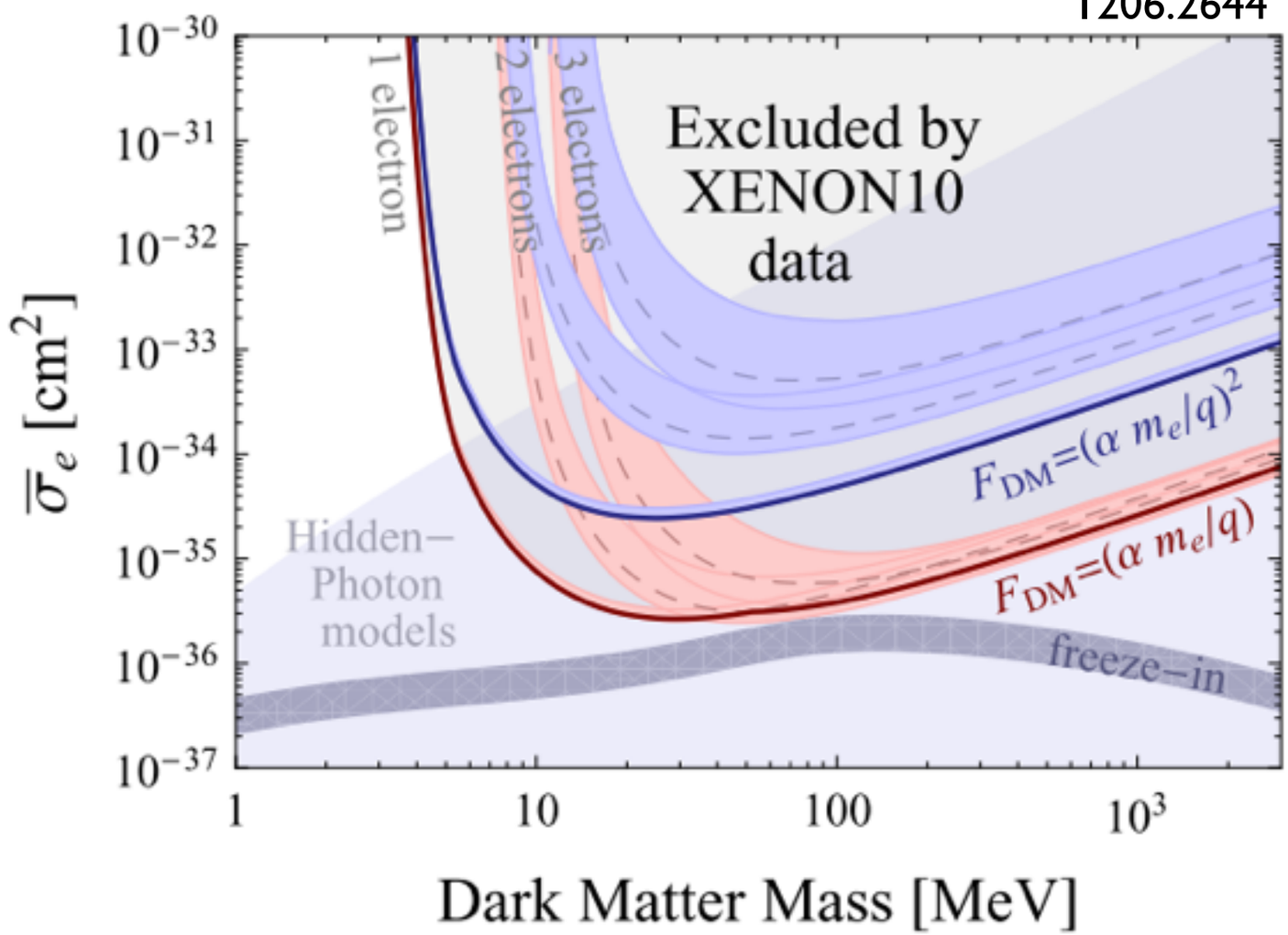
$$m_\chi = 100 \text{ MeV}, E_R \sim 50 \text{ eV}$$

electron scattering

XENON10 limits

R. Essig, A. Manalaysay, J. Mardon, P. Sorenson, T. Volansky

1206.2644

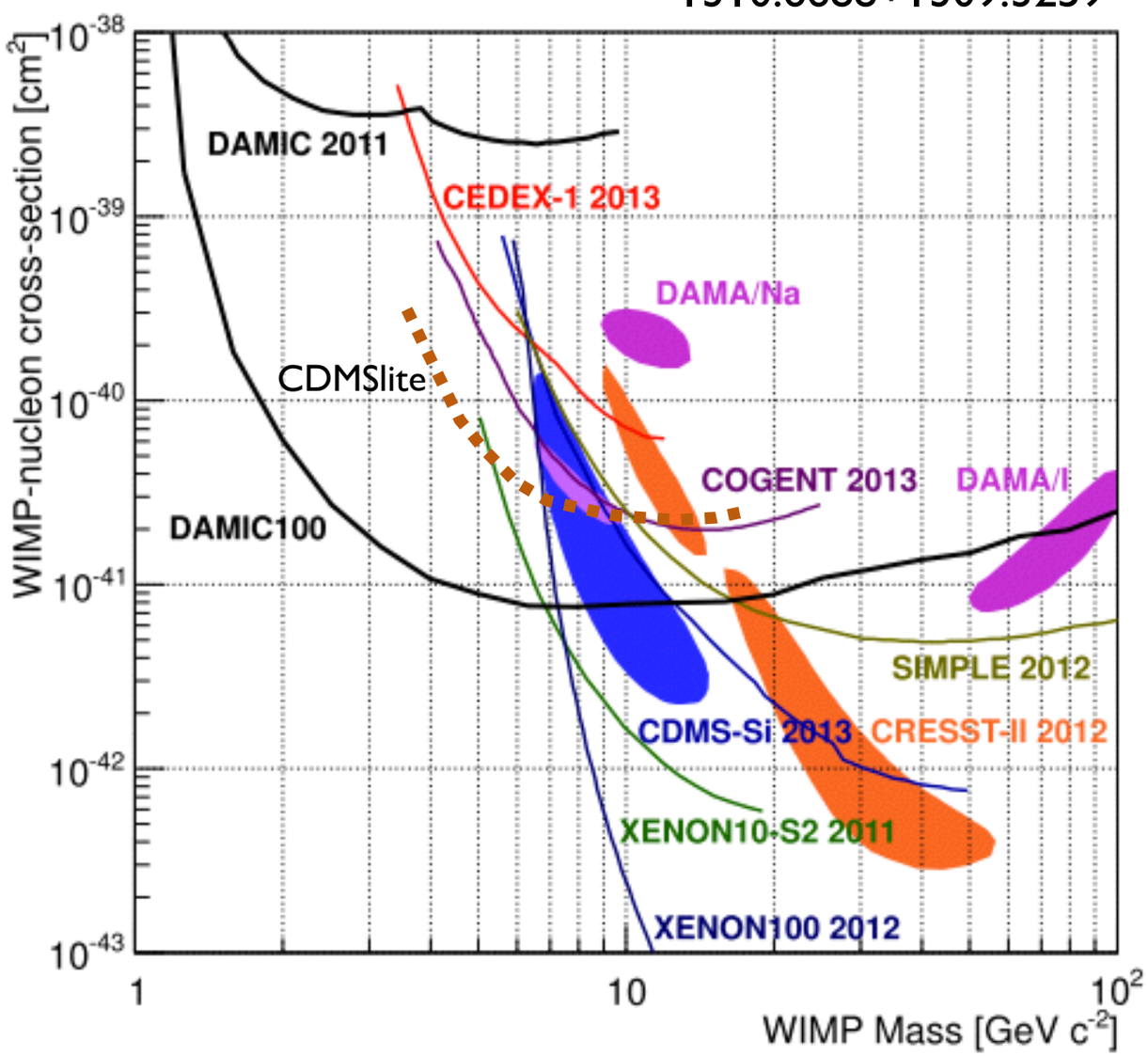


electron energy

- noble gases: ~10 eV
- semiconductors: ~1 eV

current experimental results

1310.6688+1309.3259



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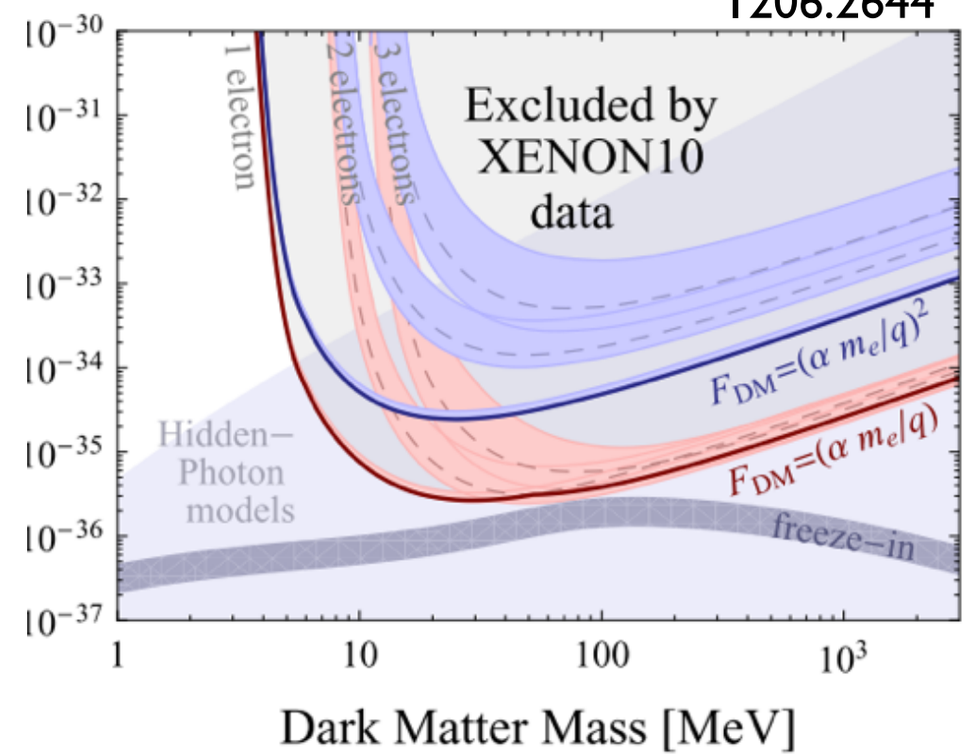
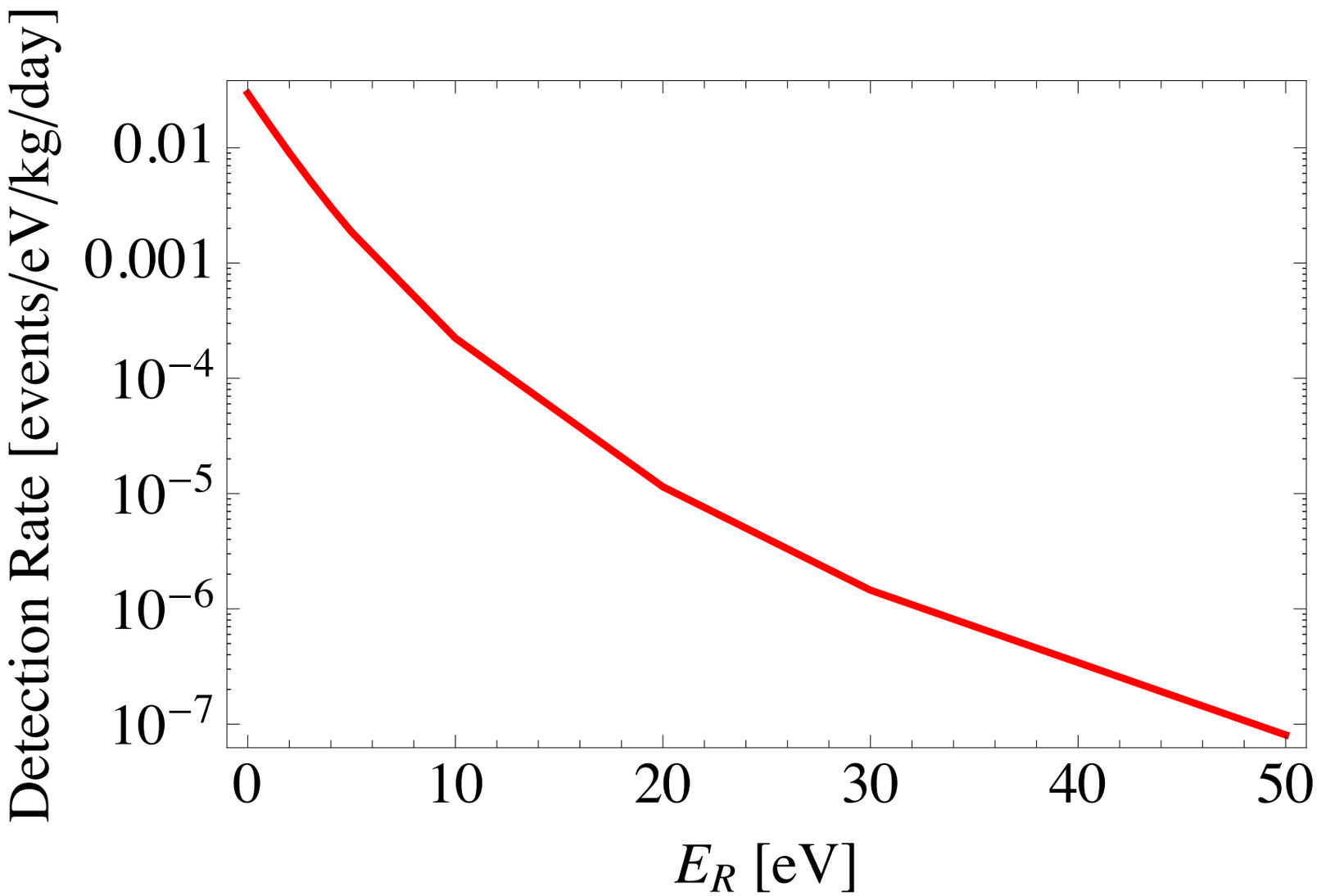
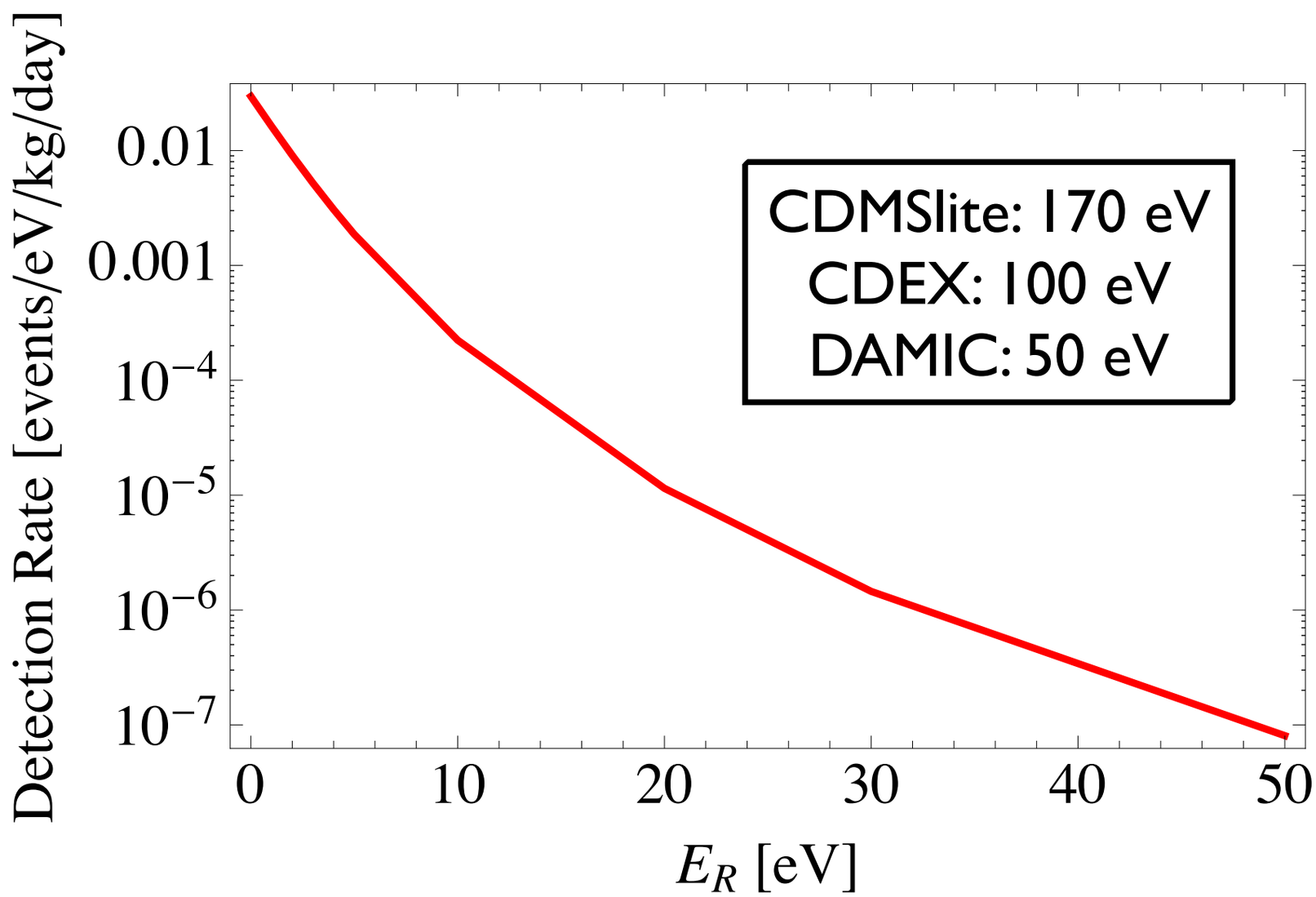


What does it take for semiconductors to reach lower DM mass?

recoil energy spectrum



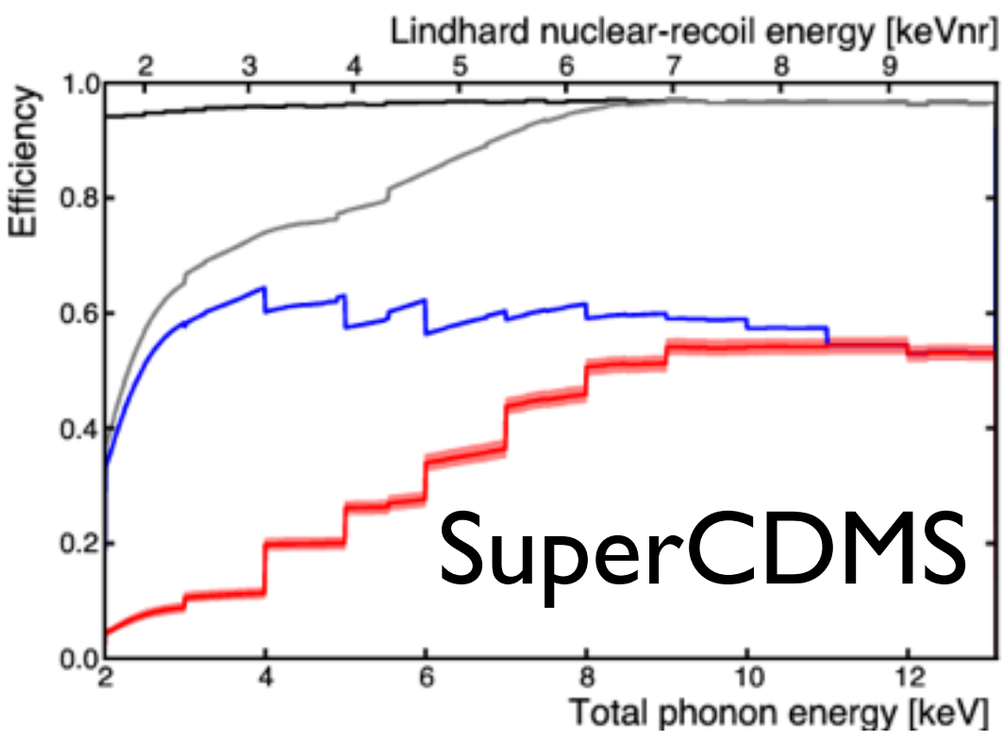
recoil energy spectrum



Q: How low do we need to push the threshold?

experimental efficiencies

1402.7137



1403.5421

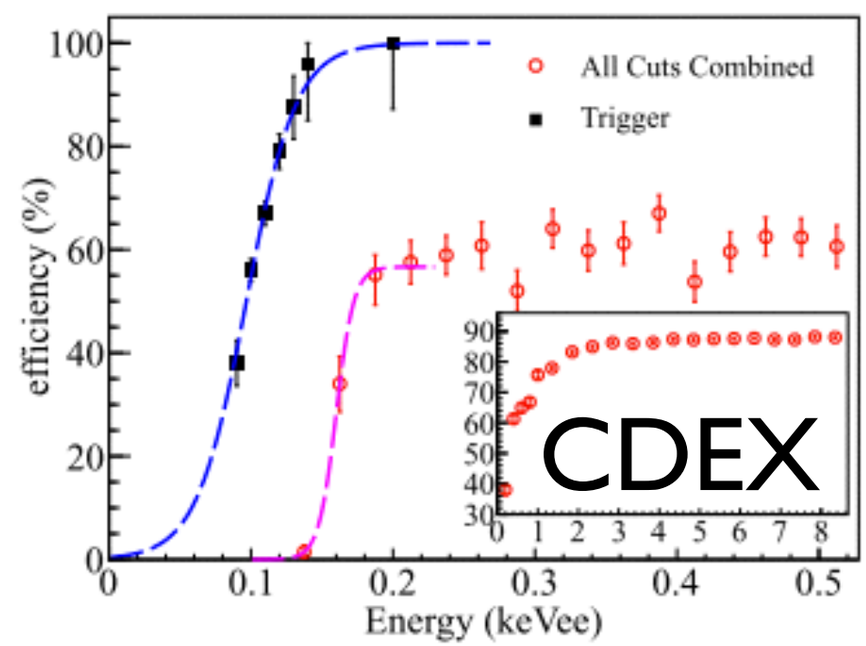


FIG. 9. The trigger efficiencies and those of all selection procedures combined. The combined efficiencies in an extended energy range are depicted in the inset, in which the error bars are smaller than the data point size.

Q: How low do we need to push the threshold?

Calculation Ingredients

ingredients

particle physics

$$\frac{\mathrm{d}\langle\sigma v\rangle}{\mathrm{d}\ln E_R} = \frac{\boxed{\overline{\sigma}_e}}{8\mu_{\chi e}^2}\int q\ \mathrm{d}q|f(k,q)|^2\boxed{|F_{DM}(q)|^2}\eta(v_{min})$$

$$\overline{\sigma}_e = \frac{\mu_{\chi e}^2}{16\pi m_\chi^2 m_e^2}\overline{|\mathcal{M}_{\chi e}(q)|}^2_{q^2=\alpha^2 m_e^2}$$

$$\sigma(q) = \overline{\sigma}_e \times |F_{DM}(q)|^2$$

ingredients

astrophysics

$$\frac{\mathrm{d}\langle\sigma v\rangle}{\mathrm{d}\ln E_R} = \frac{\overline{\sigma}_e}{8\mu_{\chi e}^2}\int q\ \mathrm{d}q|f(k,q)|^2|F_{DM}(q)|^2\boxed{\eta(v_{min})}$$

$$\eta(v_{min}) = \int_{v_{min}} \frac{\mathrm{d}^3 v}{v} f_{MB}(\vec{v})$$

$$v_{min} = \frac{E_B + E_R}{q} + \frac{q}{2m_\chi}$$

ingredients

solid state physics

$$\frac{\mathrm{d}\langle\sigma v\rangle}{\mathrm{d}\ln E_R} = \frac{\overline{\sigma}_e}{8\mu_{\chi e}^2}\int q\ \mathrm{d}q\,\boxed{|f(k,q)|^2}\,|F_{DM}(q)|^2\eta(v_{min})$$

$$\left|f_{i\to i'}(\vec{q},\vec{k})\right|^2 = \frac{V}{(2\pi)^3}\int_{\mathrm{BZ}}\mathrm{d}^3k'\left|\int\mathrm{d}^3x\psi^*_{i',\vec{k}'}(\vec{x})\psi_{i,\vec{k}}(\vec{x})e^{i\vec{q}\cdot\vec{x}}\right|^2$$

ingredients

$$\frac{\mathrm{d}\langle\sigma v\rangle}{\mathrm{d}\ln E_R} = \frac{\overline{\sigma}_e}{8\mu_{\chi e}^2}\int q\ \mathrm{d}q|f(k,q)|^2|F_{DM}(q)|^2\eta(v_{min})$$

local DM density

$$R = N_T\frac{\rho_\chi}{m_\chi}\int_{E_{R,cut}}\mathrm{d}\ln E_R\frac{\mathrm{d}\langle\sigma v\rangle}{\mathrm{d}\ln E_R}$$

number of target nuclei per unit mass

energy threshold

ingredients

solid state physics

$$\frac{\mathrm{d}\langle\sigma v\rangle}{\mathrm{d}\ln E_R} = \frac{\overline{\sigma}_e}{8\mu_{\chi e}^2}\int q\ \mathrm{d}q\,|f(k,q)|^2|F_{DM}(q)|^2\eta(v_{min})$$

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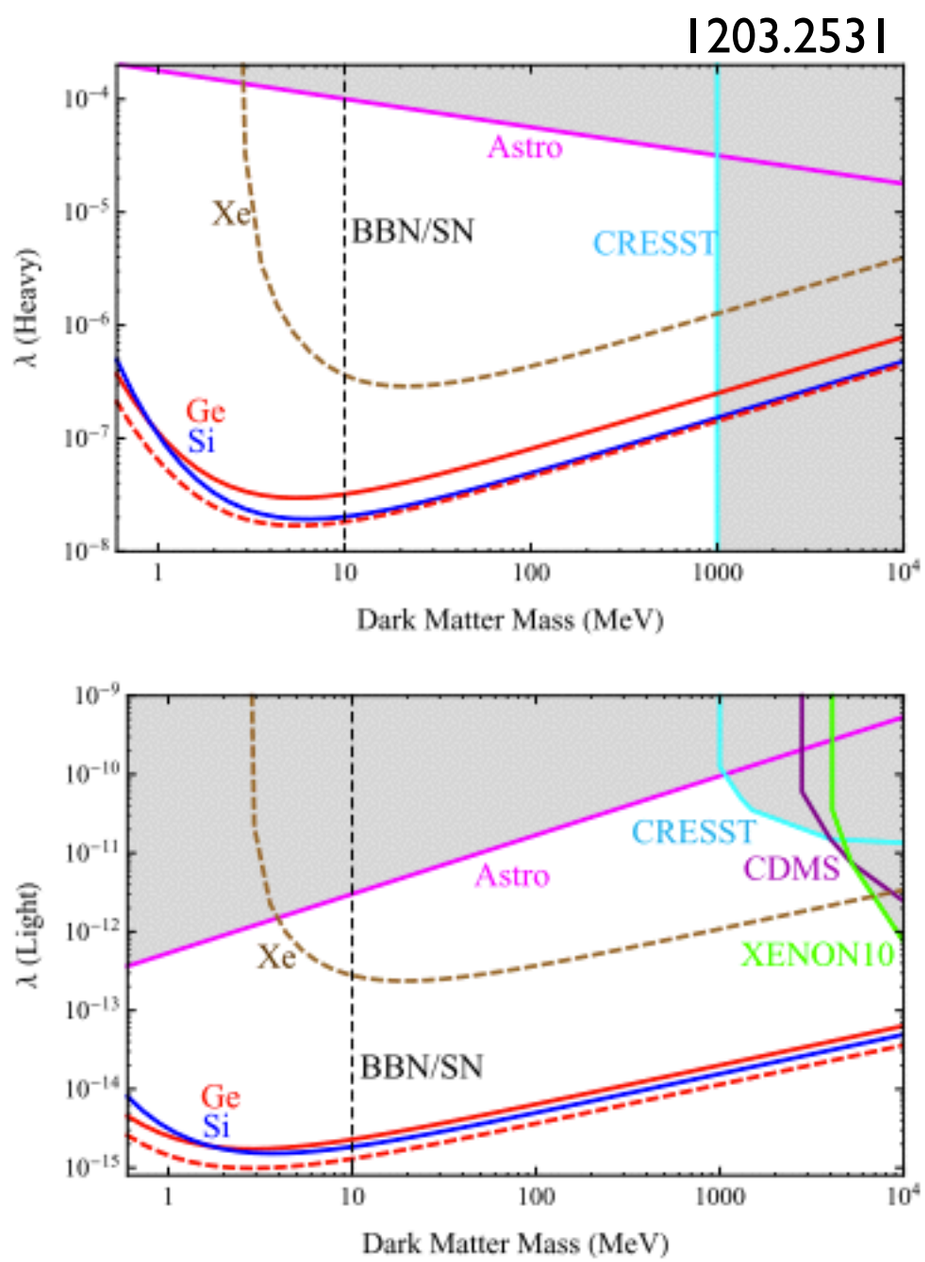
computationally difficult!

analytic

numerical

analytic approximations

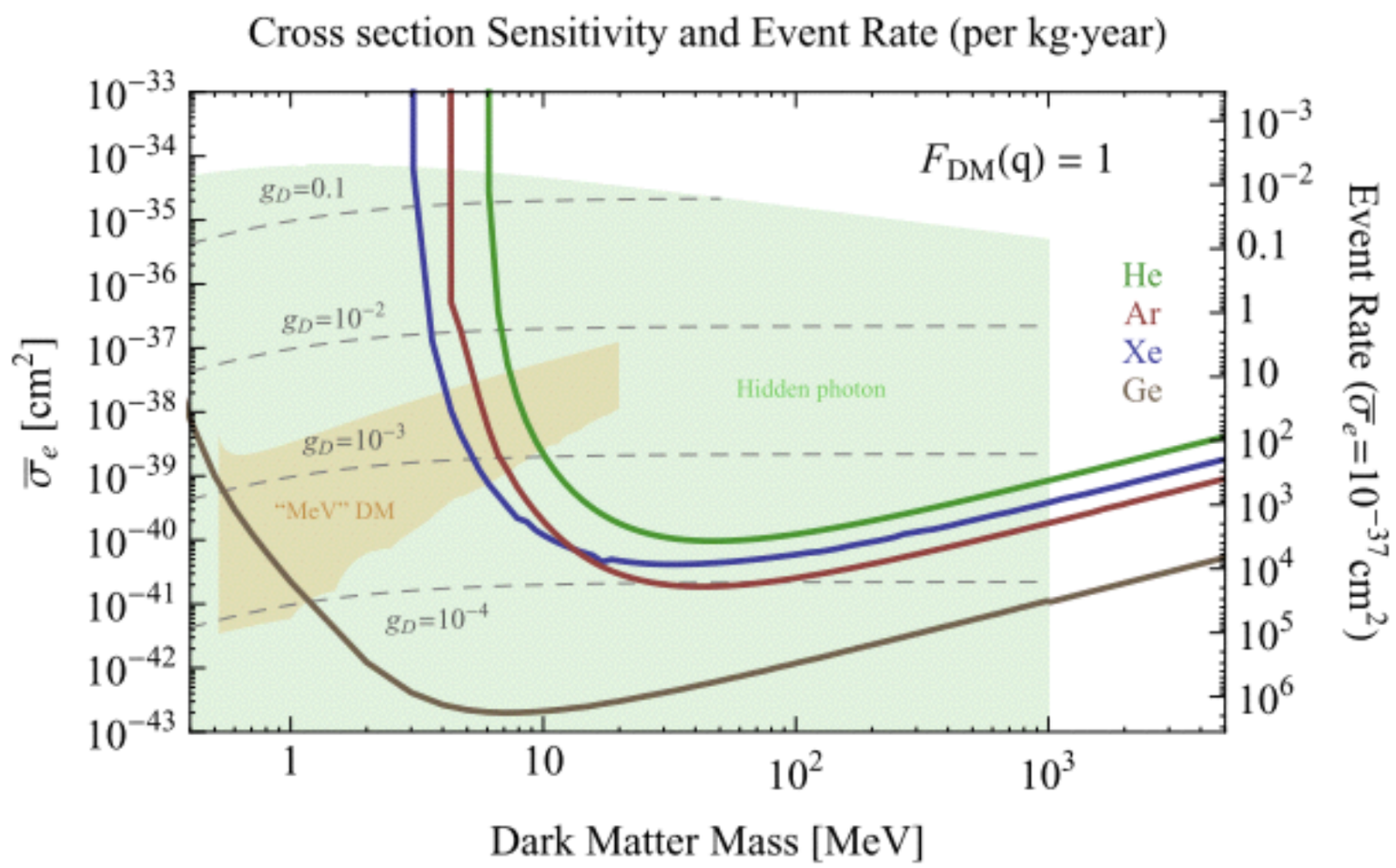


- semi-classical approach
- initial wave functions are spherical
- plane wave final states with altered mass
- no interference
- good for high q

Direct Detection of Sub-GeV Dark Matter

R. Essig, J. Mardon, T. Volansky

1108.5383



assumes zero threshold energy

Direct Detection of Sub-GeV Dark Matter

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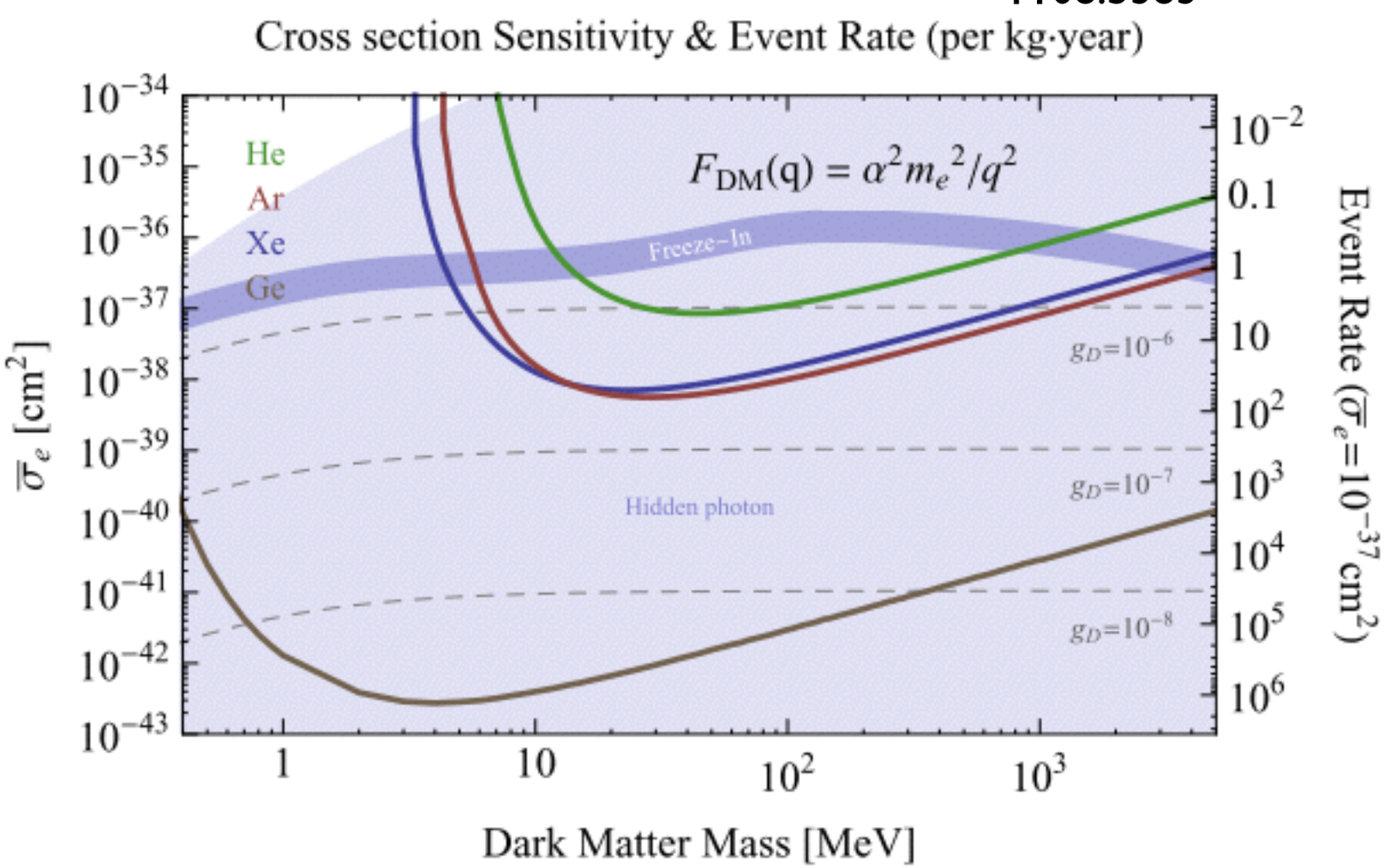
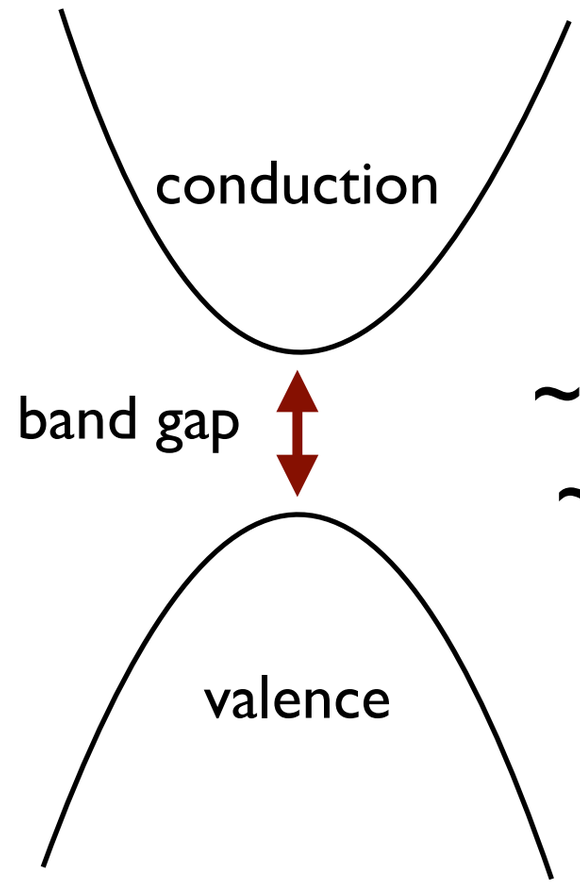
1108.5383



interlude

semiconductors



~0.67 eV for Ge
~1.11 eV for Si

semiconductors

- electron wave functions inside a crystal are complicated, but there are methods to approximate them
- we assume a wavefunction of the form:

$$\psi_{i,\vec{k}}(\vec{x}) = \frac{1}{\sqrt{V}} \sum_{G} \psi_i(\vec{k} + \vec{G}) e^{i(\vec{k}+\vec{G})\vec{x}}$$

lives in Brillouin Zone

reciprocal lattice vector

ingredients

solid state physics

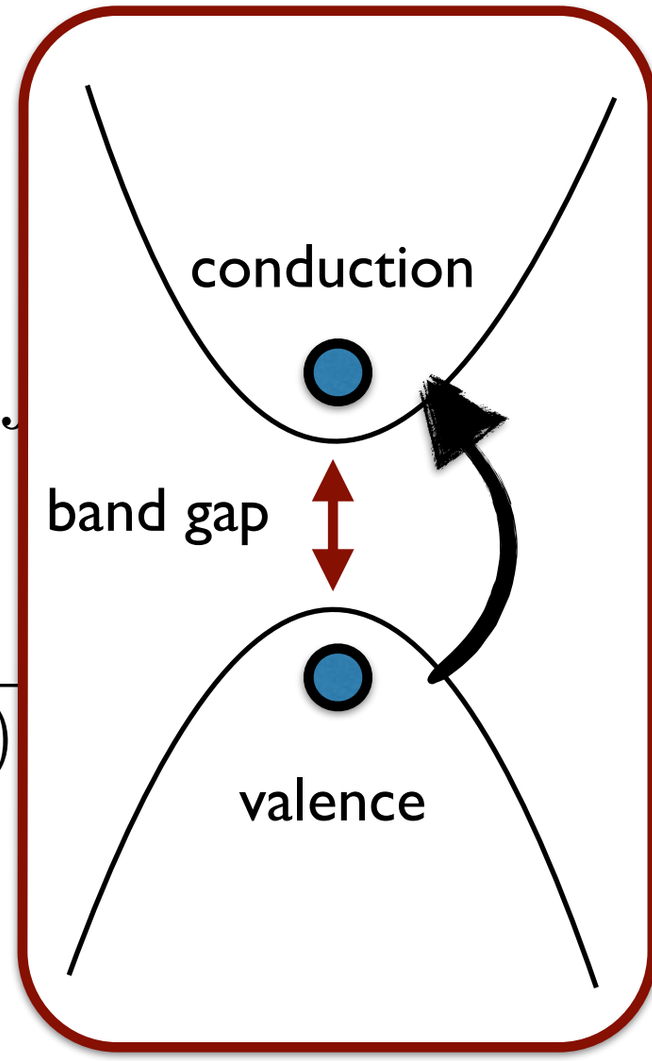
$$\frac{\mathrm{d}\langle\sigma v\rangle}{\mathrm{d}\ln E_R} = \frac{\overline{\sigma}_e}{8\mu_{\chi e}^2}\int q\ \mathrm{d}q\,|f(k,q)|^2|F_{DM}(q)|^2\eta(v_{min})$$

$$\left|f_{i\to i'}(\vec{q},\vec{k})\right|^2 = \frac{V}{(2\pi)^3}\int_{\mathrm{BZ}}\mathrm{d}^3k'\left|\int \mathrm{d}^3x\psi^*_{i',\vec{k}'}(\vec{x})\psi_{i,\vec{k}}(\vec{x})e^{i\vec{q}\cdot\vec{x}}\right|^2$$

probability of exciting an electron from valence band i to conduction band i'

ingredients

$$\frac{\mathrm{d}\langle\sigma v\rangle}{\mathrm{d}\ln E_R} = \frac{\overline{\sigma}_e}{8\mu_{\chi e}^2} \cdot$$



ysics

$$F_{DM}(q)|^2\eta(v_{min})$$

$$\left|f_{i\to i'}(\vec{q},\vec{k})\right|^2 = \frac{V}{(2\pi)}$$

$$\psi^*_{i',\vec{k}'}(\vec{x})\psi_{i,\vec{k}}(\vec{x})e^{i\vec{q}\cdot\vec{x}}\Big|^2$$

probability of exciting an electron from valence band i to conduction band i'

ingredients

solid state physics

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$$\left|f_{i\to i'}(\vec{q},\vec{k})\right|^2 = \left|\sum_G \psi^*_{i'}(\vec{k}+\vec{G}+\vec{q})\psi_i(\vec{k}+\vec{G})\right|^2$$

mild directional dependence
we ignore for now

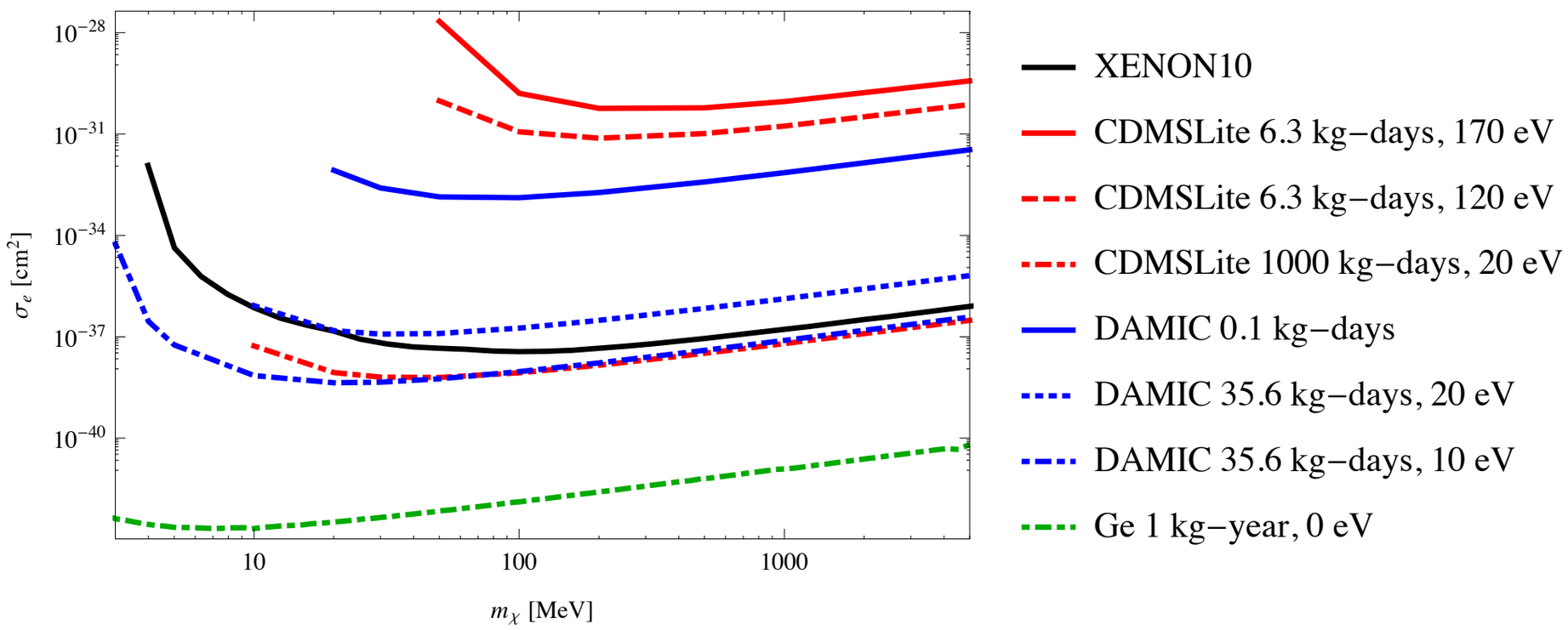
http://www.quantum-espresso.org/

- open source code that calculates electronic structure within density functional theory (DFT) using plane waves and pseudopotentials
- use a mesh of 64 k-vectors, 18 bands, and a regular grid of G-vectors

$$\frac{\left|\vec{k}+\vec{G}\right|^2}{2m_e} < E_c$$ cut-off energy ~40 Ry

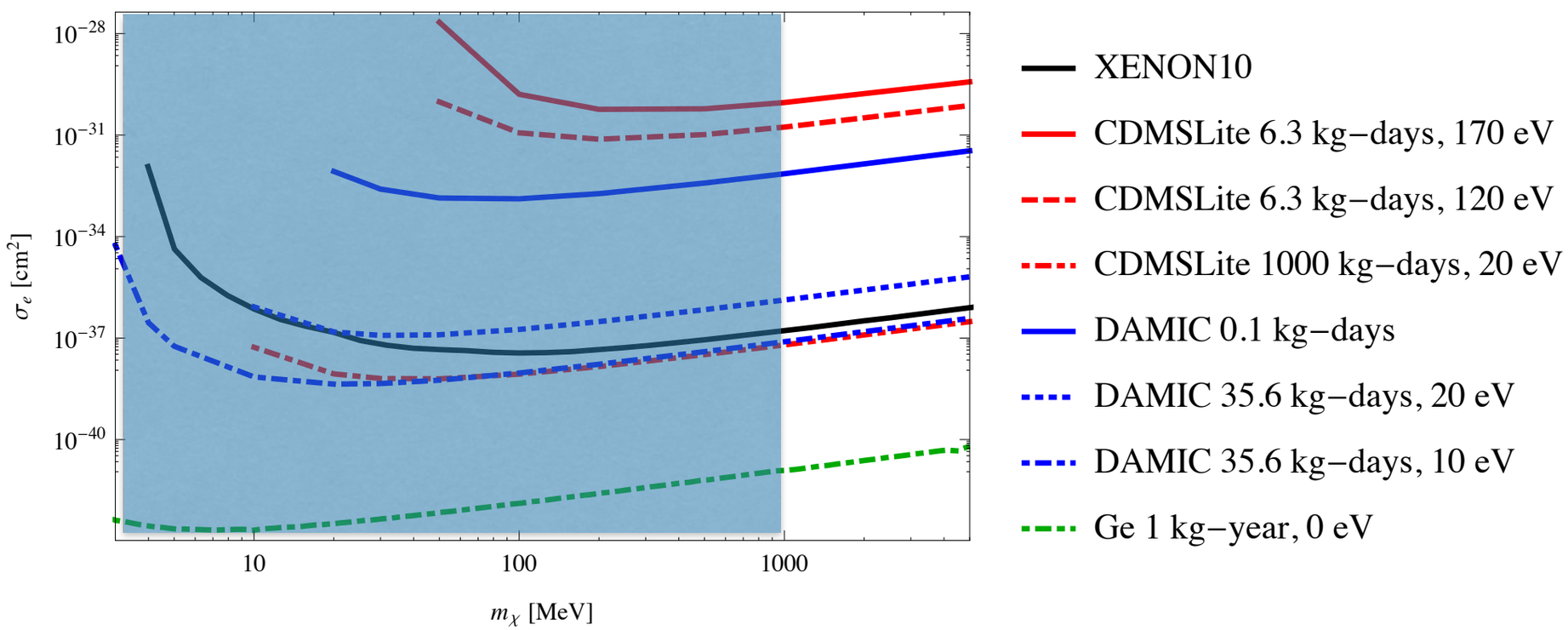
end of interlude

(very)preliminary results



*analytic approximation

(very)preliminary results



*analytic approximation

conclusions

- sub-GeV dark matter is theoretically motivated
- but this mass range is currently unexplored by direct detection experiments, which rely on nuclear recoil.
- exchanging nuclear recoil for electron recoil is a possible resolution
- The best projections so far are theory predictions for noble gases
- semiconductor experiments have the potential to have a further reach due to the small band gap
- ongoing discussions with CDMS and DAMIC