Interactions **F**ondamentales en **P**hysique et en **A**strophysique
Département d'**A**strophysique, **G**éophysique et **O**céanographie
Université de Liège

Milli-interacting dark matter interpretation of the direct-search experiments

Quentin Wallemacq

Rencontres de Moriond
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Q. Wallemacq, arXiv:1307.7623
Q. Wallemacq, arXiv:1401.5243

Université de Liège

LA LIBERTÉ DE CHERCHER

Introduction
Direct-search experiments

	Operating temperature (K)	Energy interval (keVee)
DAMA/LIBRA (9.3σ)	300	2-6
CoGeNT (2.2σ)	77	0.5-3
CDMS-II/Si (5.4% probability to be due to bg)	cryogenic	3 events at 8.2, 9.5 and 12.3 keVr
CDMS-II/Ge-superCDMS (Ge)	cryogenic	No signal
XENON100-LUX (Xe)	173	No signal

Aim: reconcile **AS MANY** experiments as possible in a unique scenario!

Dependence on:

- Detector composition (nucleus)
- Temperature

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Aim: reconcile **AS MANY** experiments as possible in a unique scenario!

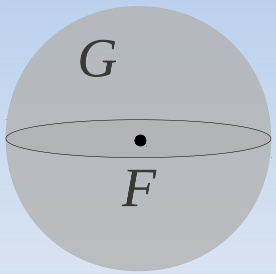
Dependence on:

- Detector composition (nucleus)
- Temperature

→ New interaction mechanism, new dark sector

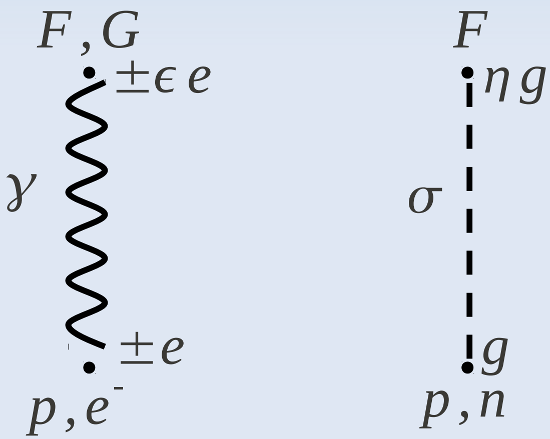
Milli-interacting dark matter
The model

Subdominant dark sector:



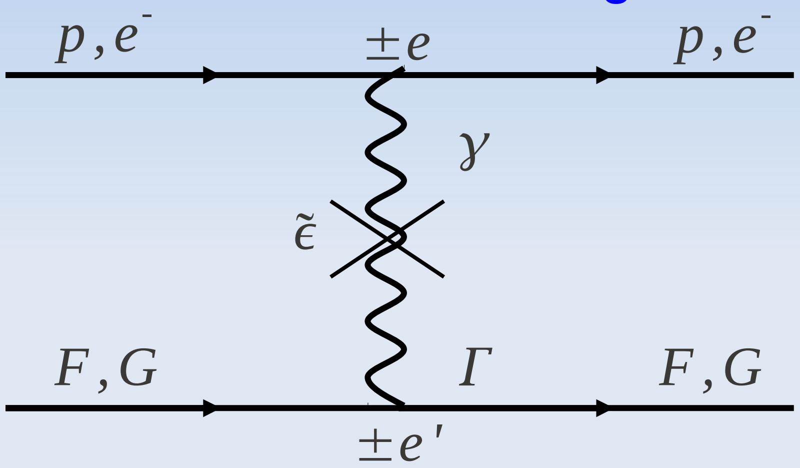
Hydrogen-like dark atoms

- F,G: electric millicharges
- F: new scalar interaction with nucleons



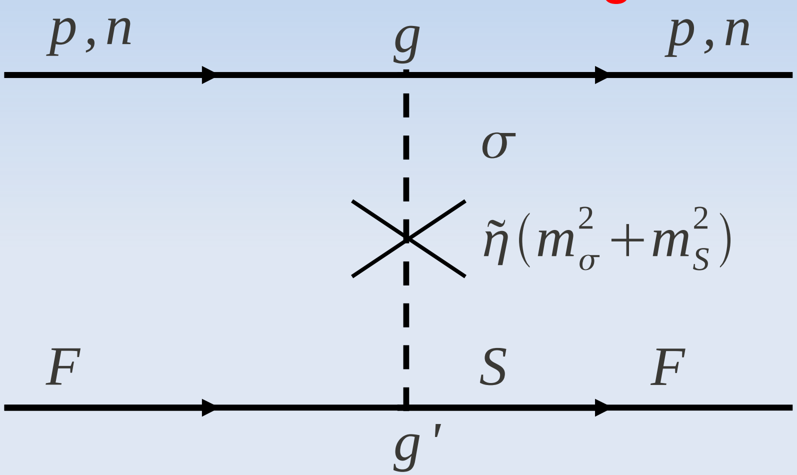
Dark sector = dark fermions F,G + dark photons Γ + dark scalars S

$\Gamma - \gamma$ kinetic mixing:



$$\tilde{\epsilon}\, e' \equiv \epsilon\, e$$
$$\tilde{\eta}\, g' \equiv \eta\, g$$

$S - \sigma$ mass mixing:



Holdom (1986), Foot (2000),
Feldman et al. (2007), Cline (2012)

Milli-interacting dark matter

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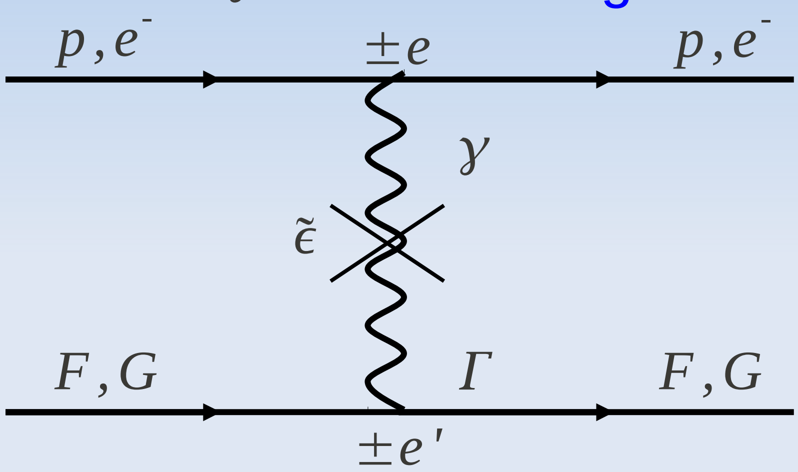

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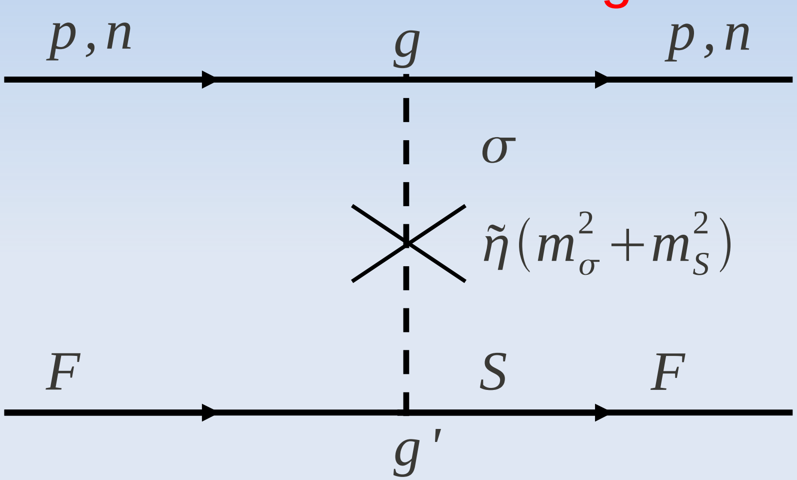

5 constrained parameters: $m_F, m_S, a_0', \epsilon, \eta$

Milli-interacting dark matter

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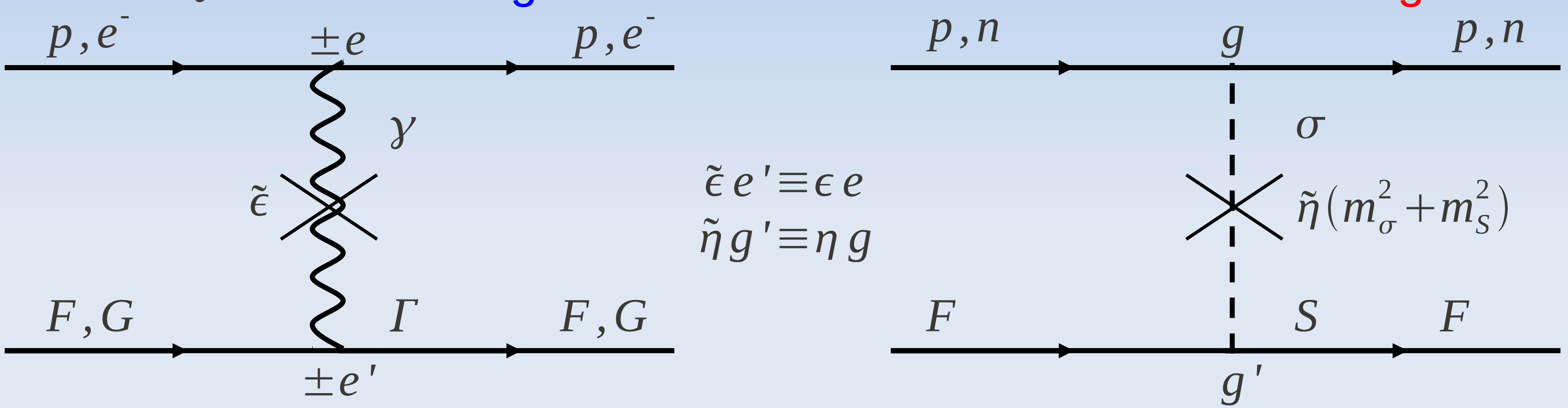
$\Gamma-\gamma$ kinetic mixing: $S-\sigma$ mass mixing:



Holdom (1986), Foot (2000),
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5 constrained parameters: $m_F, m_S, a_0', \epsilon, \eta$

1 Å: typical size of standard atoms

Constraints

- Unseen disintegrations of vector mesons: $Q\bar{Q} \rightarrow \gamma S$

$\Upsilon(1S)$ $\Upsilon(3S)$ $J/\Psi(1S)$

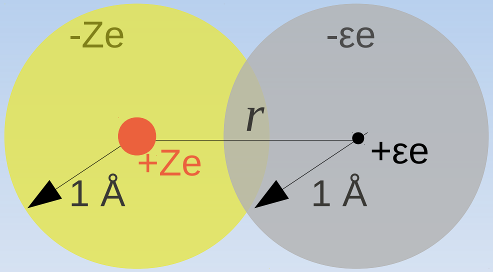
$\longrightarrow \eta < 1.2\,10^{-4}$

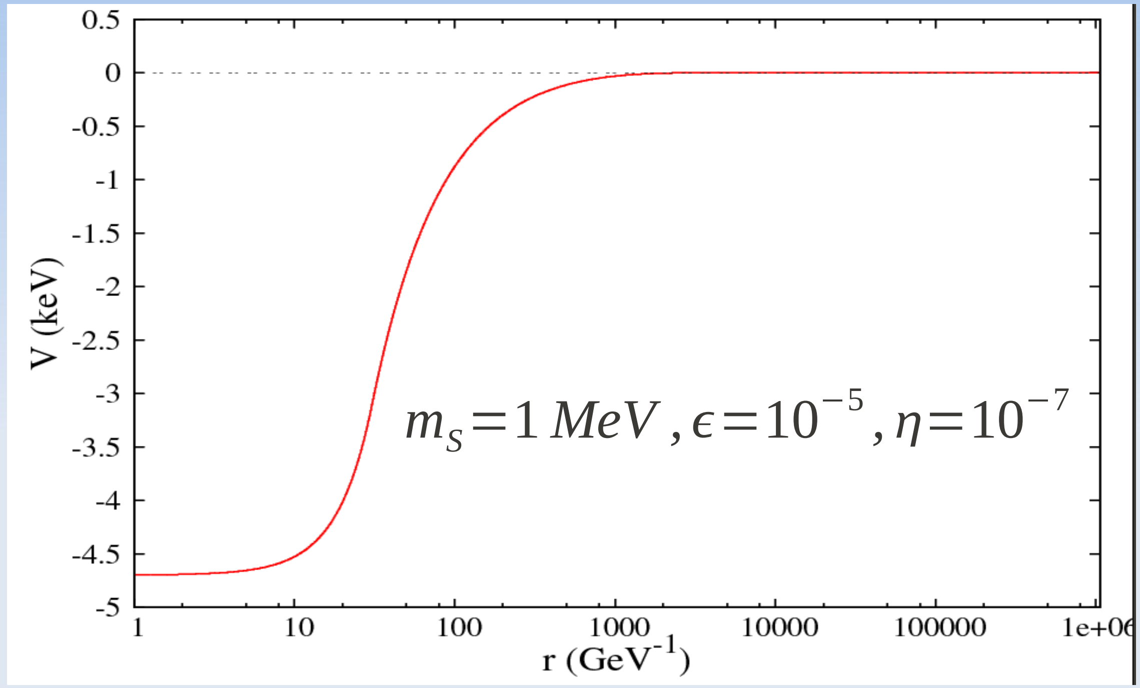
- CMB (Planck): $\Omega_{F,G} h^2 < 0.001 (95\% CL)$ Dolgov et al. (2013)

- Accelerators: $\epsilon < 4.1 \times 10^{-5}$ at $m_G = 1\,MeV$ A.A. Prinz et al. (1998)

Dark-Standard interactions

Atom-dark atom





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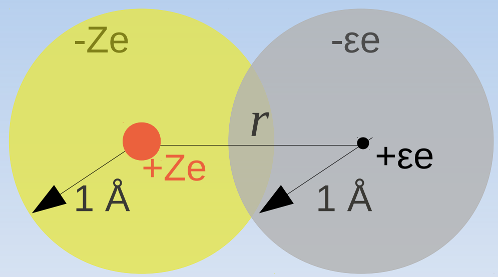
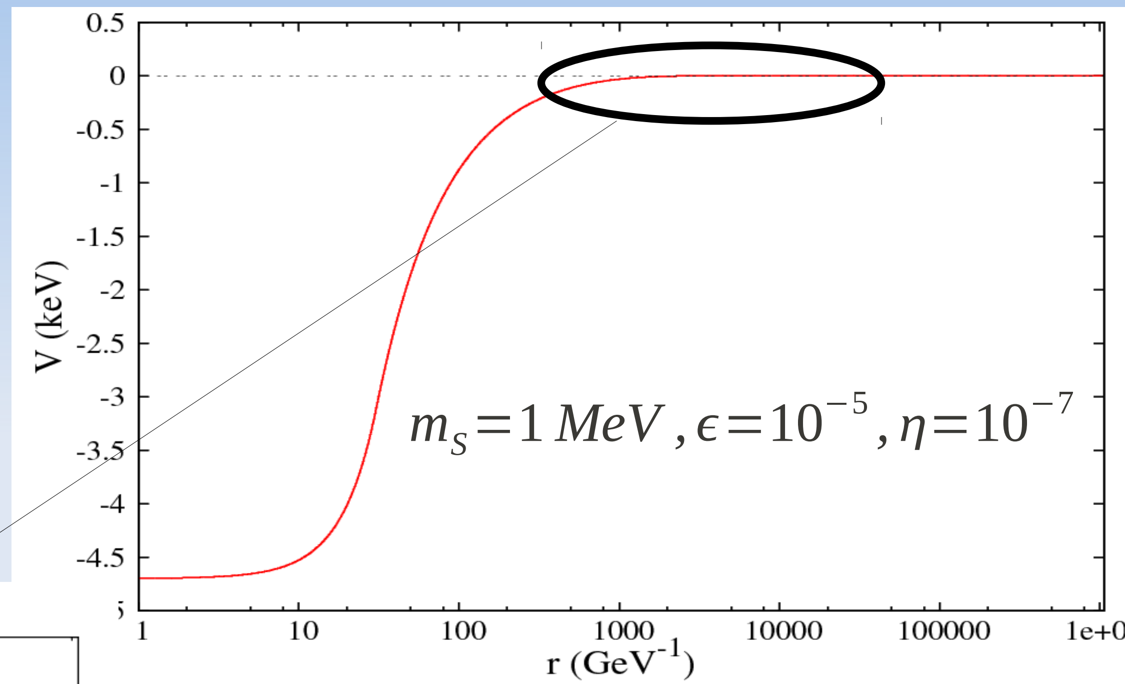
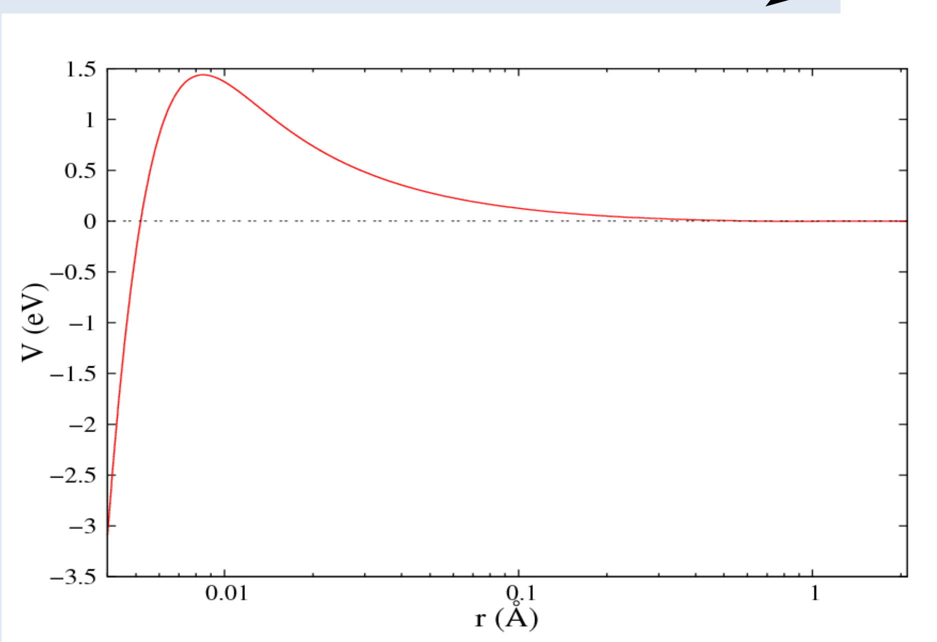






From space to undeground detectors

Thermalization in terrestrial crust

Dark matter « wind » → Dark atoms hit the surface of the Earth

↓

Lose energy ← Undergo elastic collisions with terrestrial atoms

↓

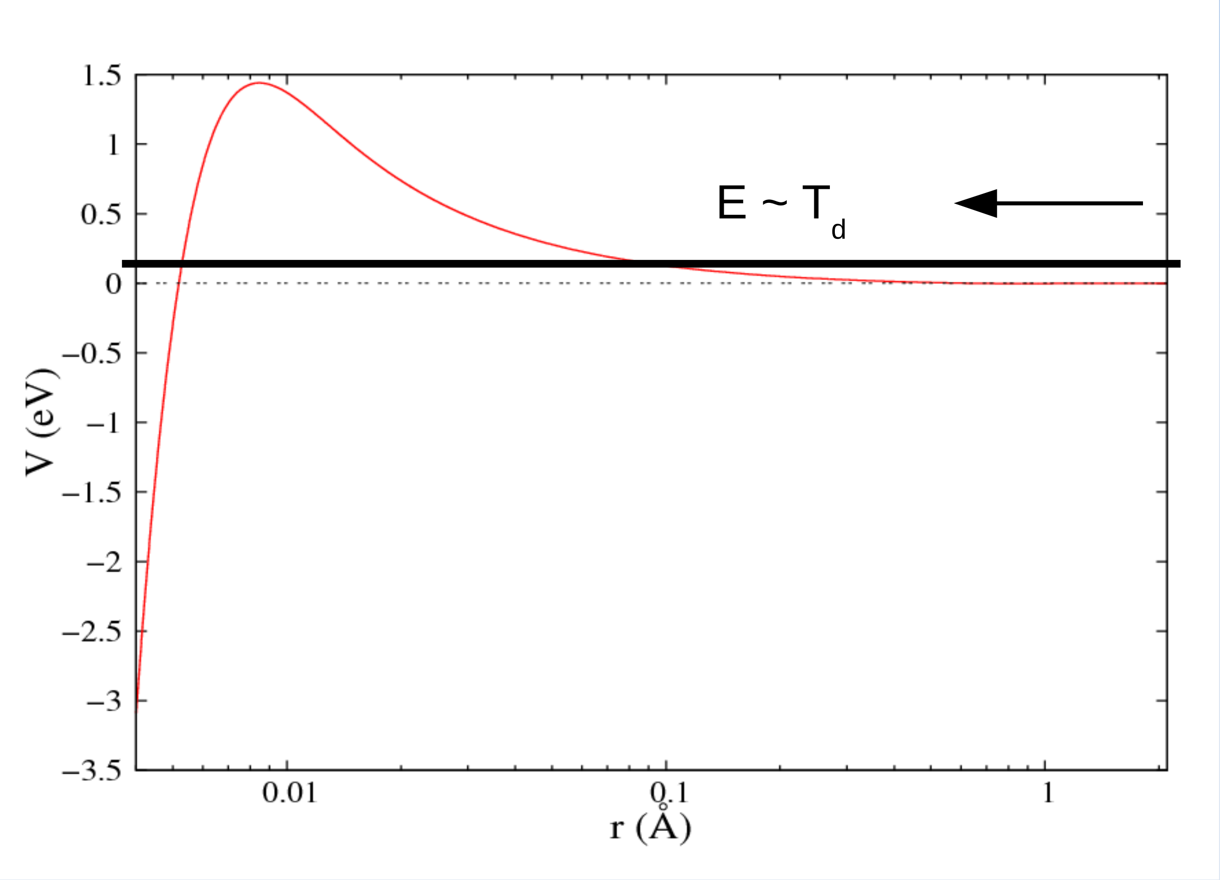
- Energy loss per unit path length: $\frac{dE}{dx}$

- Penetration length: $x = \int_{E_{th}}^{E_0} \frac{dE}{|dE/dx|} < 1\ km, \quad E_{th} = \frac{3}{2} T_{crust}$

Typical depth of underground detectors

From space to undeground detectors
Bound-state-formation events

Radiative capture of **thermal** F particles by atomic nuclei of the active medium:



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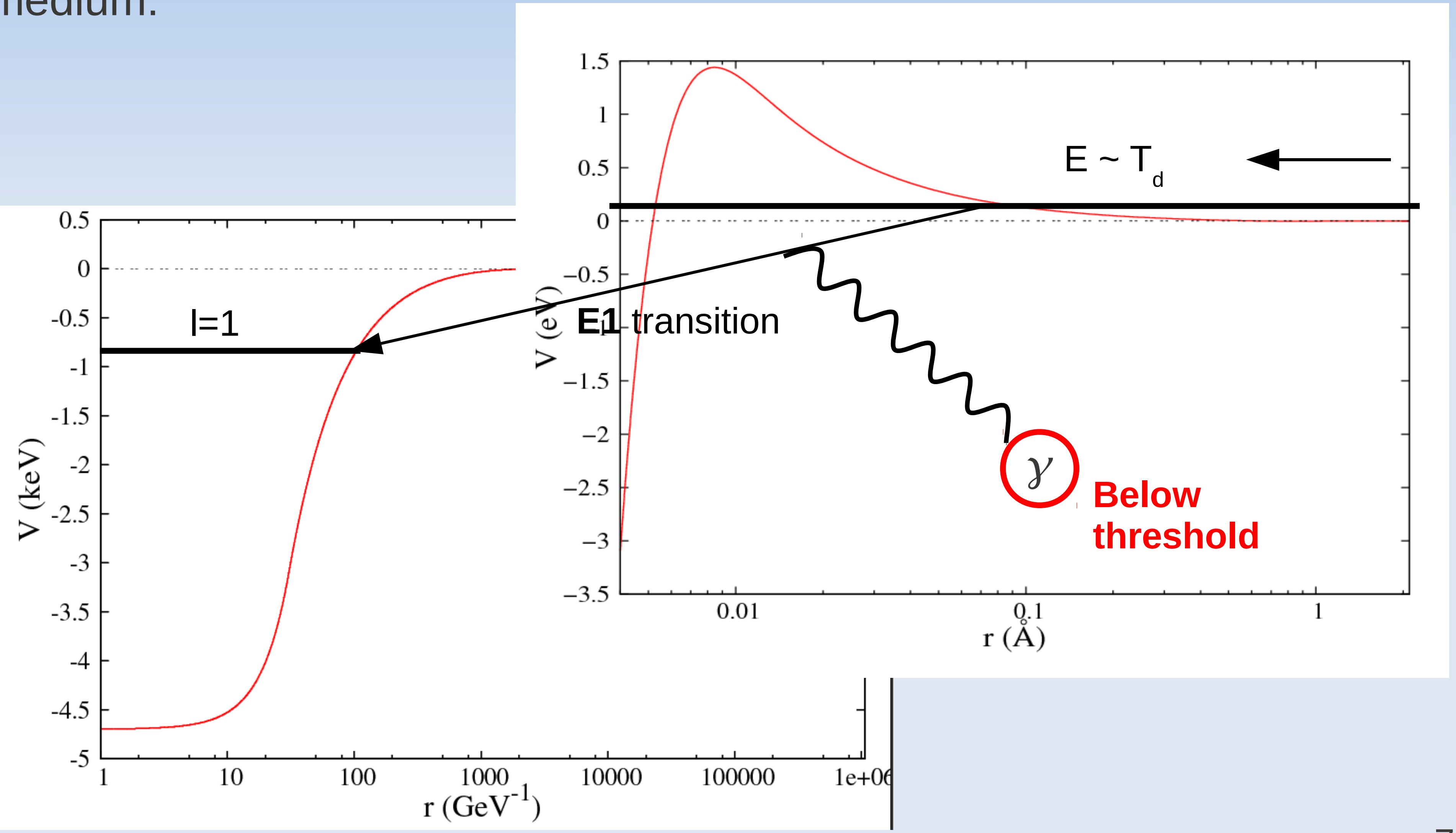

From space to undeground detectors

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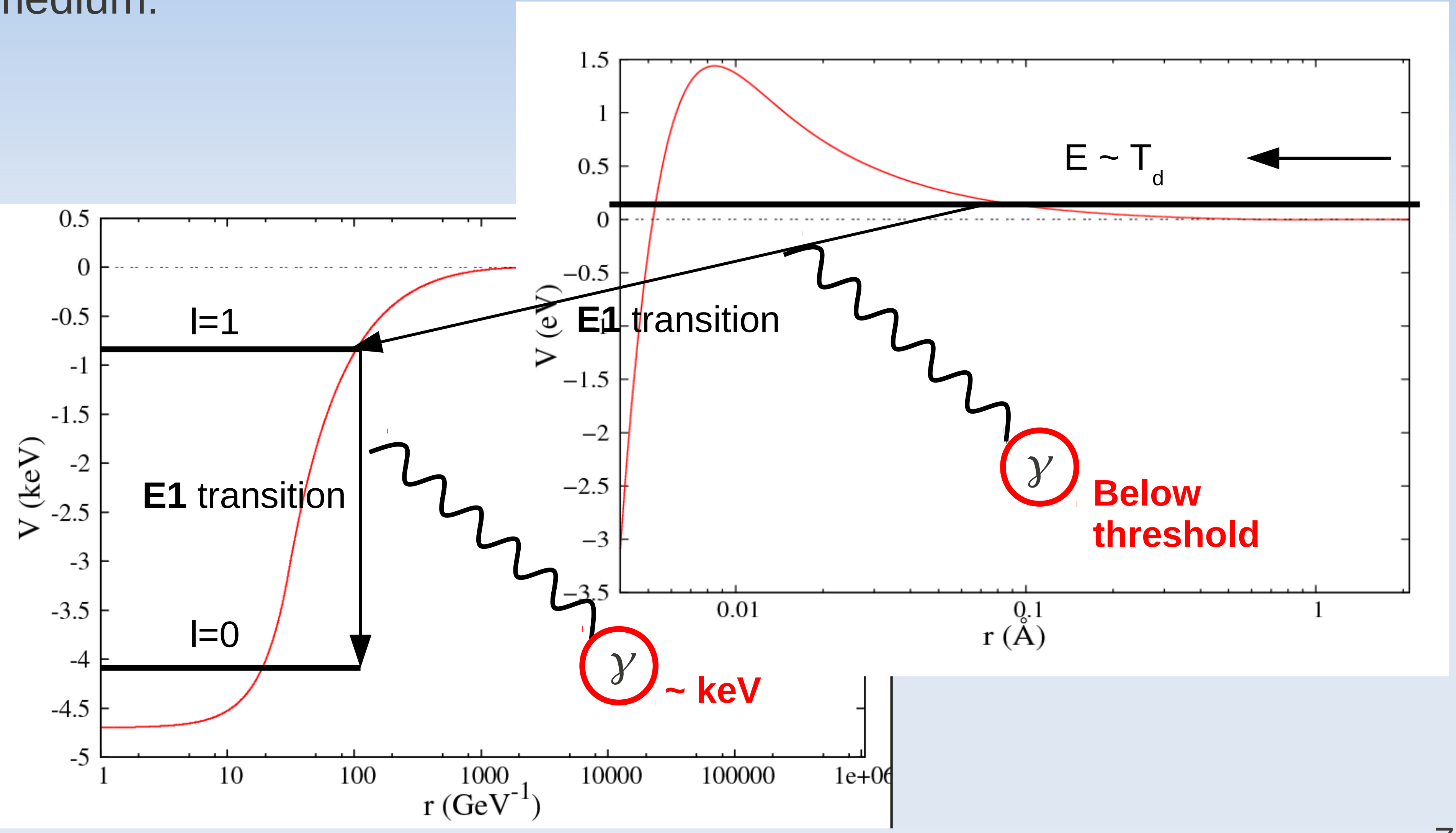

From space to undeground detectors
Bound-state-formation rate

$$R \sim \langle \sigma_{\text{capt}} v \rangle$$

Tunneling: high Z $\longrightarrow R \downarrow$

low $T_d \longrightarrow R \downarrow$

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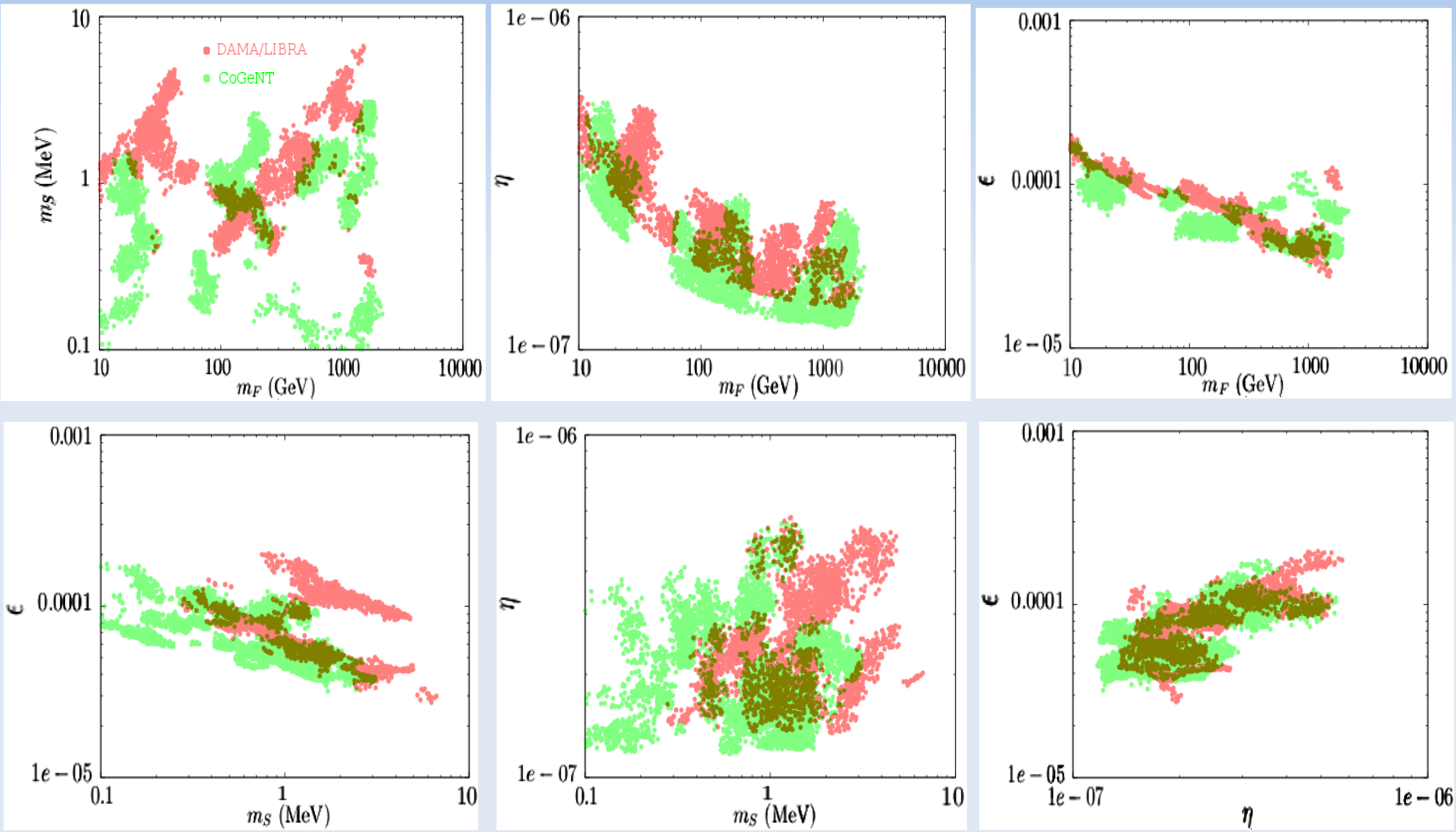
IMPORTANT:
Electron recoils and **NOT** nuclear recoils!

No discrimination power: DAMA, CoGeNT

Discrimination power: XENON100, CDMS, LUX

Exploring the parameter space

Reproduction of DAMA and CoGeNT



Exploring the parameter space

Consistency with XENON100, CDMS-II/Ge, superCDMS, LUX

- XENON100, LUX: - electron vs. nuclear recoil discrimination power
  - No signal

→ Remaining events (if any) are considered as backgrounds and rejected

→ Increased expected electronic background must still be consistent with observed one

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- Problems with CDMS-II/Si and CRESST-II

Conclusion

- Complex and **subdominant** dark sector made of dark atoms interacting with standard sector through electric ($\gamma - \Gamma$) and « nuclear » ($\sigma - S$) **millicharges**.

- Explains: **DAMA/LIBRA, CoGeNT**

- Does not contradict: **XENON100, CDMS-II/Ge, superCDMS, LUX**

- Does not explain: **CDMS-II/Si, CRESST-II**

- Predictions: - one emitted photon below keV
  - contribution to electronic background
  - emission of spectral lines

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Thank you!

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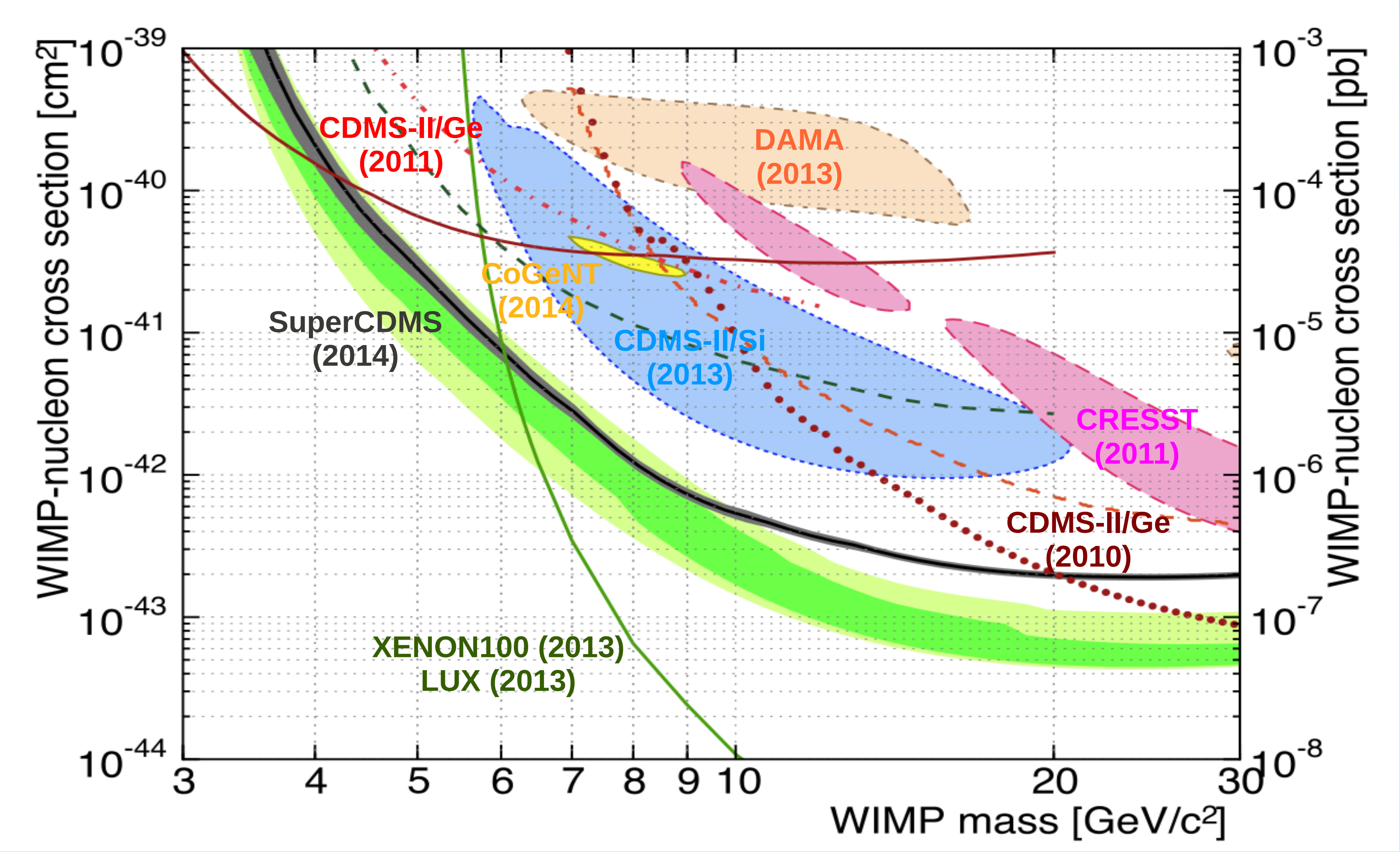
Elastic WIMP-nucleon cross section:



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The model

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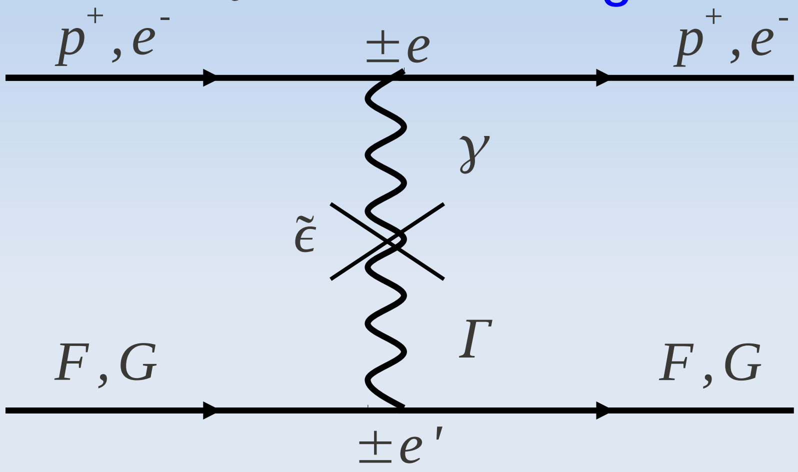
$\Gamma - \gamma$ kinetic mixing:

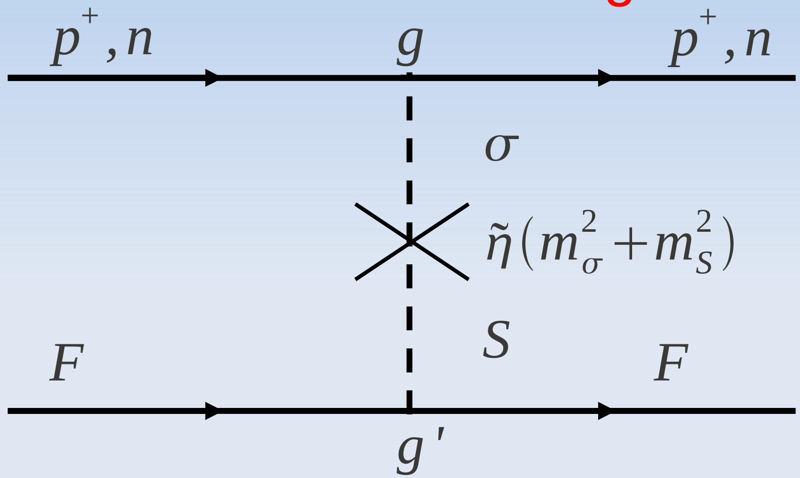


$$V_k = \pm \frac{\epsilon \alpha}{r}, \quad \alpha = \frac{e^2}{4\pi}$$

Pure Coulomb,
attractive or repulsive

Foot (2000), Feldman et al. (2007), Cline (2012)

$S - \sigma$ mass mixing:



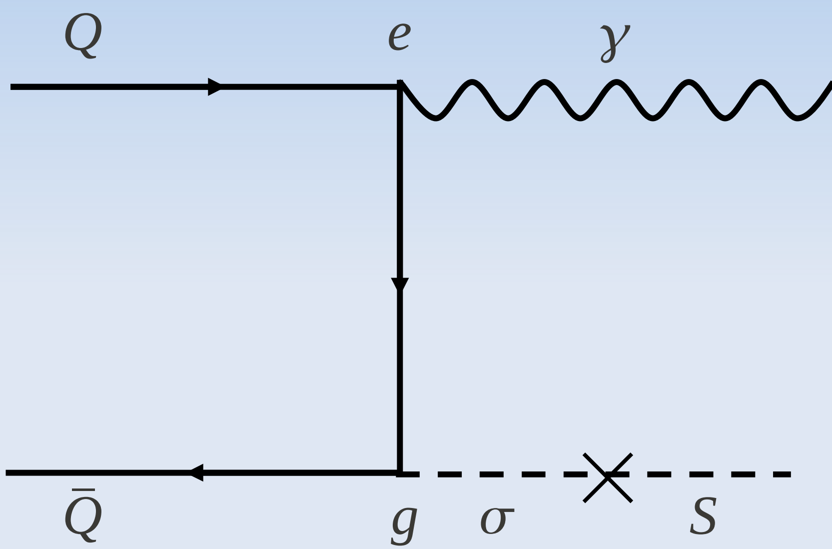
$$V_m = -\frac{\eta (m_\sigma{}^2 + m_S{}^2) \beta}{r} \left(\frac{e^{-m_\sigma r} - e^{-m_S r}}{m_S^2 - m_\sigma^2} \right), \quad \beta = \frac{g^2}{4\pi}$$

« Composed » Yukawa,
attractive

As $m_S \ll m_\sigma$, $V_m \approx -\frac{\eta \beta}{r} e^{-m_S r}$

- Unseen disintegrations of quarkonium states $Q\bar{Q}$: $Q\bar{Q} \rightarrow \gamma S$

$\Upsilon(1S)$ $\quad$ $\Upsilon(3S)$ $\quad$ $J/\Psi(1S)$



$$\frac{B(Q\bar{Q}\rightarrow\gamma S)}{B(Q\bar{Q}\rightarrow e^{+}e^{-})}=\frac{2\beta}{\alpha}\frac{M_{Q\bar{Q}}(M_{Q\bar{Q}}^{2}-m_{S}^{2})}{(M_{Q\bar{Q}}^{2}+2m_{e}^{2})\sqrt{M_{Q\bar{Q}}^{2}-4m_{e}^{2}}}\frac{\tilde{\eta}^{2}(m_{\sigma}^{2}+m_{S}^{2})^{2}}{(m_{S}^{2}-m_{\sigma}^{2})^{2}}$$

$B(\Upsilon(1S)\rightarrow\gamma S)<5.6\,10^{-5}$ Balest et al. (1995)

$B(\Upsilon(3S)\rightarrow\gamma S)<15.9\,10^{-6}$ Aubert et al. (2008)

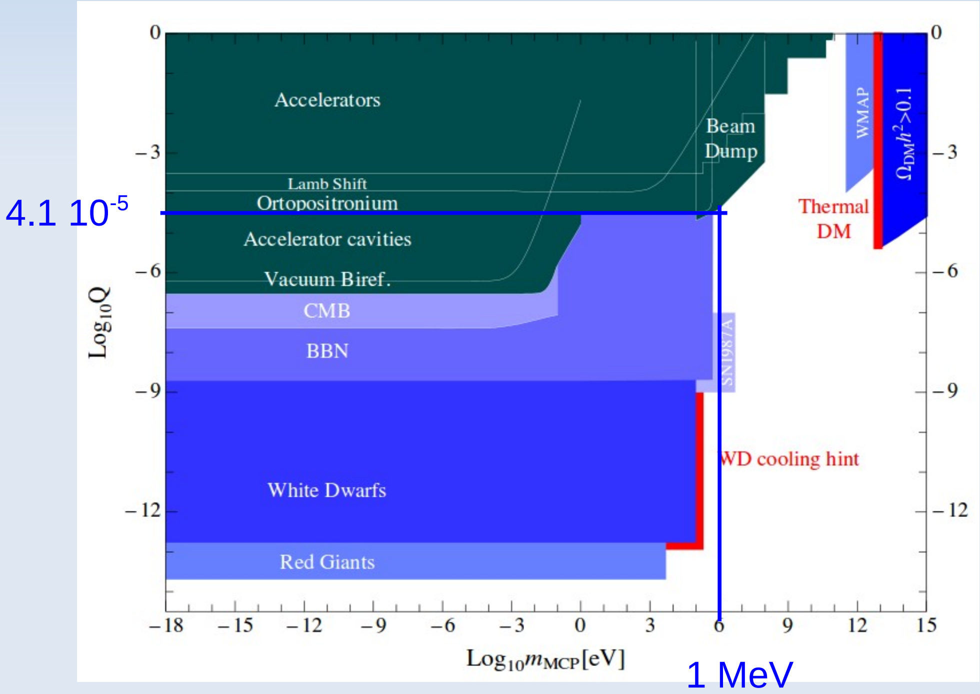
$B(J/\Psi(1S)\rightarrow\gamma S)<4.3\,10^{-6}$ → $\tilde{\eta} < 1.2\,10^{-4}$

→ $\eta < 1.2\,10^{-4} \quad (g'=g)$

Constraints
Electric millicharges

- CMB (Planck): $\Omega_{mcp} h^2 < 0.001 (95\% CL)$

- Accelerators:



Essig et al. (2013)

- $\epsilon < 0.1$ for $m_F > 1 GeV$

- If $\alpha' \approx \alpha$, then $a_0' = 1$ Å

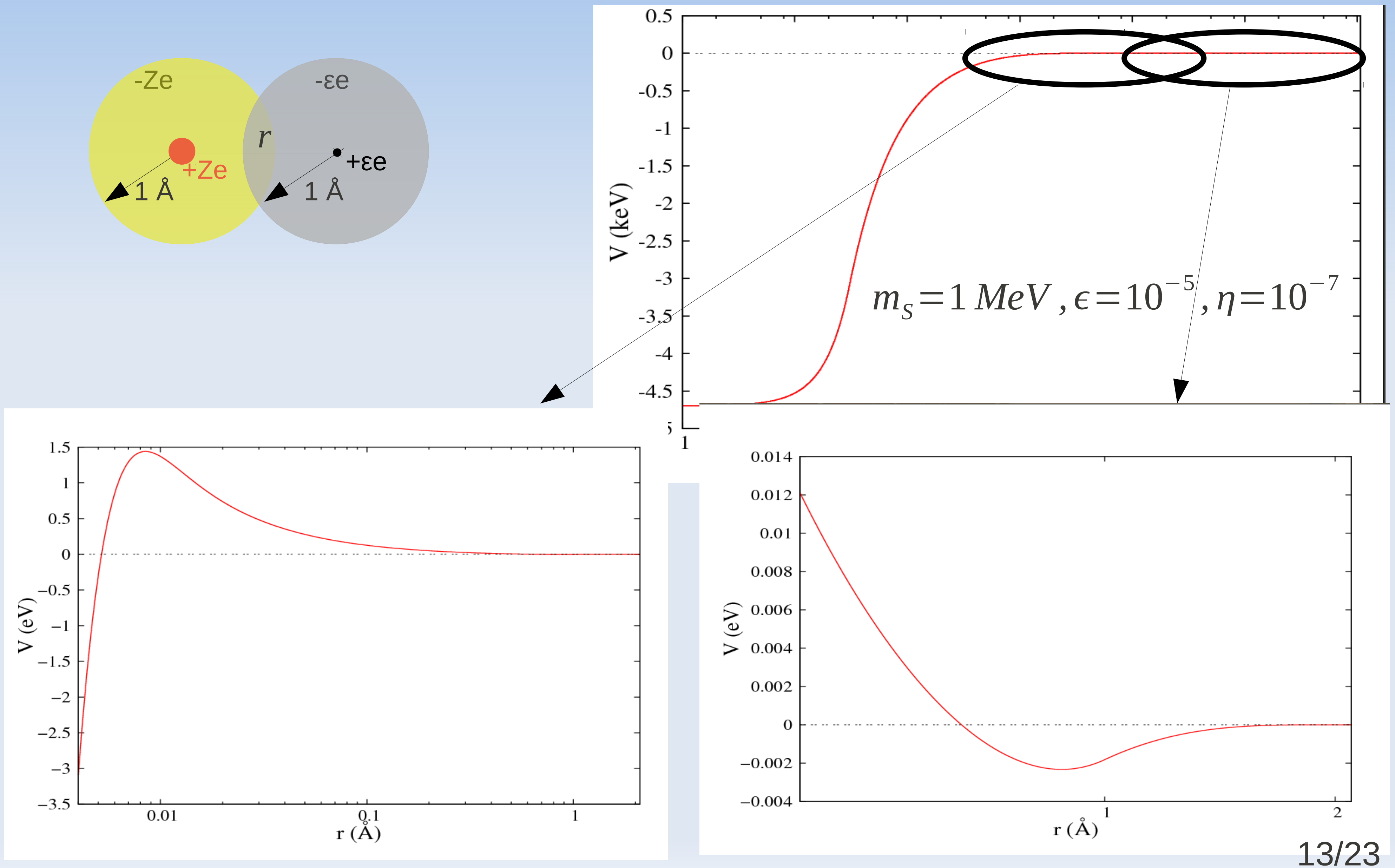
Implies $m_G \approx m_e \sim MeV$

↓

Interesting for light component G

Dark-Standard interactions

Atom-dark atom



From space to undeground detectors

Capture cross section

- **Thermal** F-particles: partial s-wave of the incident plane wave
- Solve radial Schrodinger equation at l=0 for E>0: diffusion eigenstate u_{diff}
- Solve radial Schrodinger equation at l=1 for E_b<0: bound eigenstate u_b

Tunneling

→ **E1 capture cross section**: $\sigma_{capt} \sim \frac{(E-E_b)^3}{E^{3/2}} \left| \int_0^\infty r\, u_b(r)\, u_{diff}(r)\, dr \right|^2$

→ **Event counting rate**: $R = n_F n_N \langle \sigma_{capt} v \rangle$

$\langle$ Mawellian velocity distributions $\rangle$

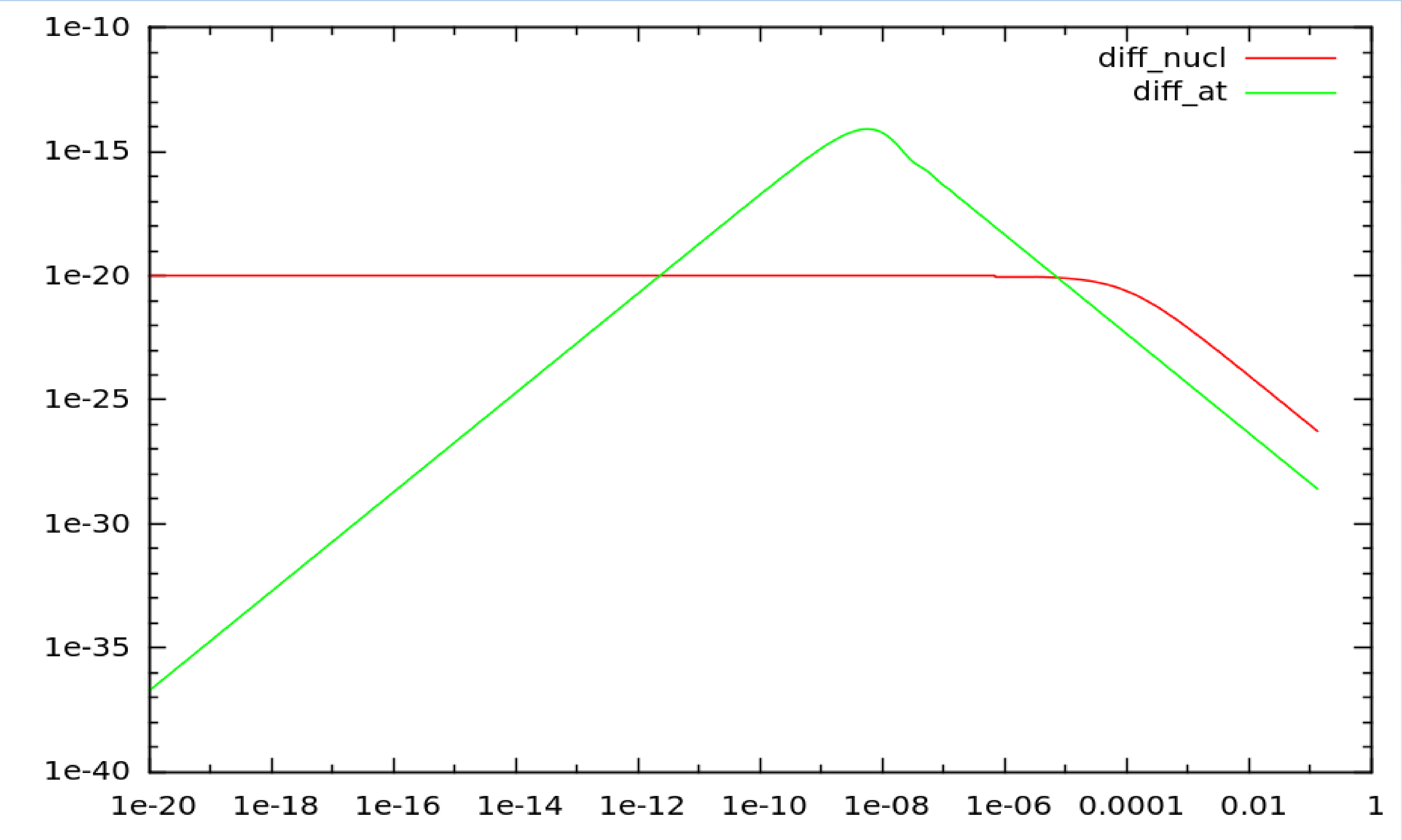
IMPORTANT:
Electron recoils and **NOT** nuclear recoils!

$$R \sim \int_0^\infty \sigma_{capt}(E)\, E\, e^{-E/T_d}\, dE$$

No discrimination power: DAMA, CoGeNT

Discrimination power: XENON100, CDMS, LUX

Operating temperature → $R(cryogenic) \to 0$



1e-10
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1e-20
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1e-16
1e-14
1e-12
1e-10
1e-08
1e-06
0.0001
0.01
1
diff_nucl
diff_at