Millicharged Atomic Dark Matter

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based on arXiv:1201.4858, and arXiv:1205.xxxx

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May 7th, Pheno 2012

Outline

- Millicharged Atomic DM
- Elastic and Inelastic Scatterings
- Constraints on Millicharged Atomic DM
- Fits to CoGeNT, CDMS, Xenon

Atomic Dark Matter

$$\mathcal{L} = \bar{\mathbf{e}}(i\not{D}' - m_{\mathbf{e}})\mathbf{e} + \bar{\mathbf{p}}(i\not{D}' - m_{\mathbf{p}})\mathbf{p} - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}\tilde{F}'_{\mu\nu}\tilde{F}'^{\mu\nu} + \frac{1}{2}\tilde{\epsilon}F_{\mu\nu}\tilde{F}'_{\mu\nu}$$

- ◇ **e**: dark "**electron**" with mass $m_{\mathbf{e}}$
- ◇ **p**: dark "**proton**" with mass $m_{\mathbf{p}}$
- ◇ **H**: dark "**hydrogen atom**" with mass $m_{\mathbf{H}} = m_{\mathbf{e}} + m_{\mathbf{p}} - B$
- ◇ $D' \equiv \partial \pm igA'$: covariant derivative w.r.t. dark gauge boson A'
- ◇ F: electromagnetic field strength
- ◇ $\tilde{F}'$: field strength of the dark gauge field
- ◇ $\tilde{\epsilon}$: gauge kinetic mixing parameter

Cline, ZL, Xue, arXiv:1201.4858

see also: Goldberg, Hall, 86'; Holdom, 86'; Kaplan, Krnjaic, Rehermann, Wells, 09'

interaction to ordinary matter

$$\tilde{F}' = F' + \tilde{\epsilon} F \text{ (1st order in } \tilde{\epsilon})$$

$$\mathcal{L}_{\rm int} = g A'_\mu J^\mu_d + A_\mu (e J^\mu_{em} + \tilde{\epsilon} g J^\mu_d) = g J^\mu_d A'_\mu + e A_\mu (J^\mu_{em} + \epsilon J^\mu_d)$$

J_{em}, SM electromagnetic currents
$J^\mu_d \equiv \bar{\mathbf{p}}\gamma^\mu \mathbf{p} - \bar{\mathbf{e}}\gamma^\mu \mathbf{e}$, hidden sector currents
ϵ, millicharge

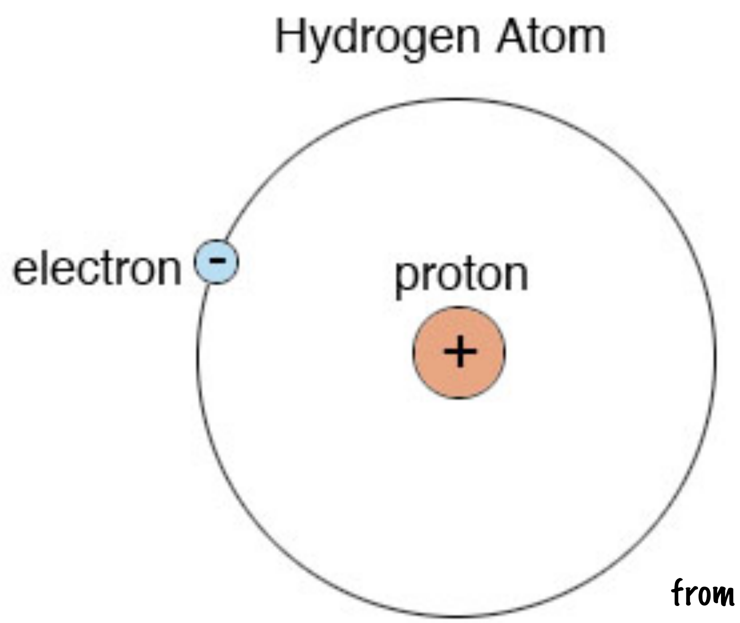
dark electron and dark proton carry e*ε electric charge

Dark matter direct detection is mediated by photon and is controlled by the millicharge ε

atomic bound states

Asymmetry in the hidden sector generates relic abundance of dark electron and dark proton.

Binding energy $B = \frac{1}{2}\alpha'^2 \mu_{\mathbf{H}}$



from nasa.gov

Dark atom recombination results in both neutral and ionized dark matter components

$$m_{\mathbf{e}} \sim 1 \text{ GeV} \; , m_{\mathbf{p}} \sim 10 \text{ GeV} \; , \alpha' \sim 0.1 \Longrightarrow \frac{n_{\mathbf{e}}}{n_{\mathbf{H}}} < 10^{-4}$$

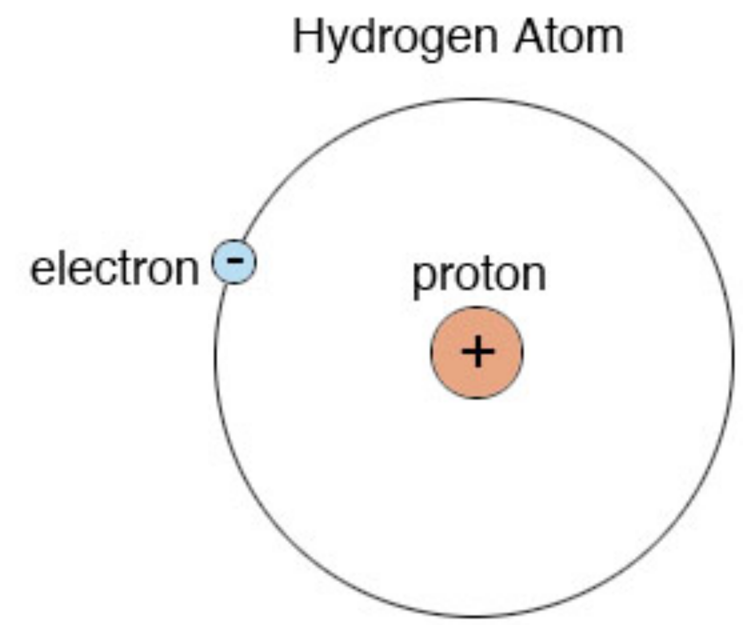
Kaplan, Krnjaic, Rehermann, Wells, 09'

finding dark atoms

$$m_{\mathbf{e}} \ll m_{\mathbf{p}}$$

The electric charge density of the dark atom

$$\rho(\vec{r}) = \epsilon e \left[\delta^3(\vec{r}) - |\Psi_{\mathbf{e}}(\vec{r})|^2\right]$$



The Fourier transform of the charge density

$$\tilde{\rho}(\vec{q}) = \epsilon e \left[1 - \frac{1}{(1 + a_0'^2 q^2/4)^2}\right] \simeq \frac{\epsilon e a_0'^2 q^2}{2}$$

$$q \ll 1/a'$$

Bohr radius: $a' \simeq 1/(\alpha' m_{\mathbf{e}})$

scattering of dark atom and proton in Born approx.

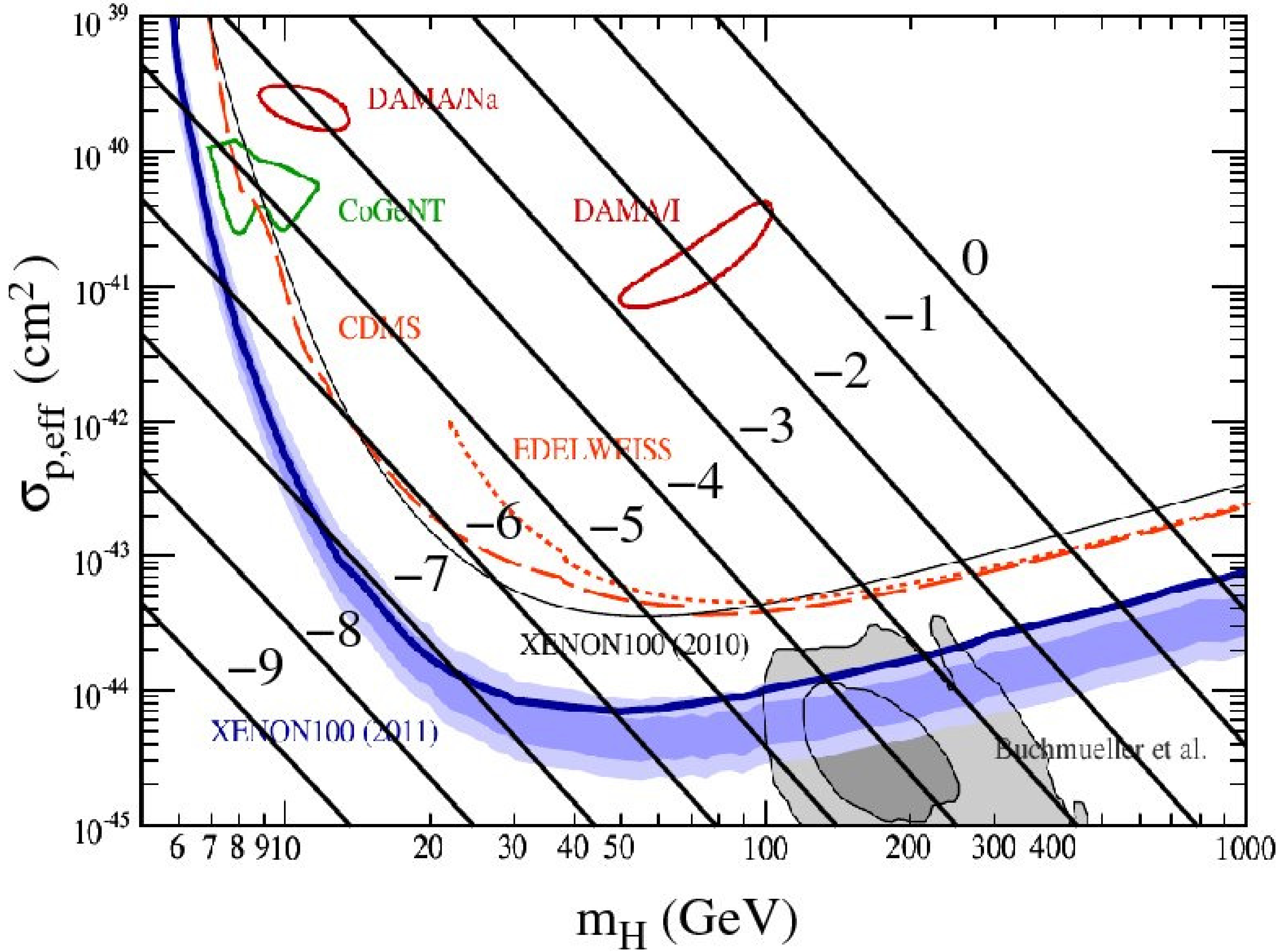
$$\sigma_{\mathbf{H}p} = 4\pi\, \alpha^2 \epsilon^2 \mu_{\mathbf{H}p}^2 {a_0'}^4$$

This x-sec depends on DM mass and β

$$\beta \equiv \frac{\epsilon^2}{\alpha'^4} \frac{(1 + x_{\mathbf{e}})^4}{x_{\mathbf{e}}^4} \qquad x_{\mathbf{e}} \equiv \frac{m_{\mathbf{e}}}{m_{\mathbf{p}}} \simeq \frac{m_{\mathbf{e}}}{m_{\mathbf{H}}}$$

comparison with Xenon100 limits

$$\sigma_{p,\text{eff}} = \left(\frac{Z}{A}\right)^2 \sigma_{\mathbf{H}p}$$



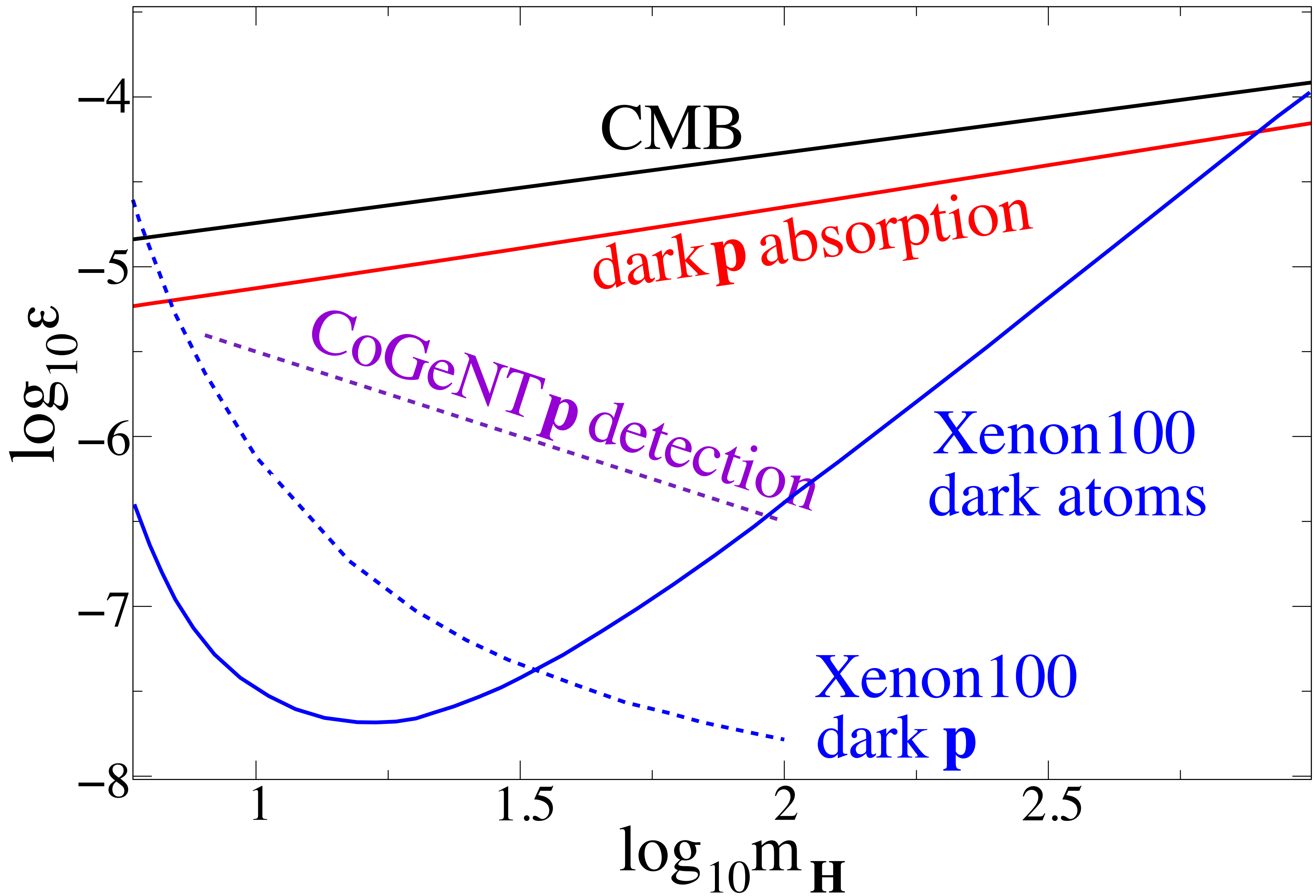
diagonal lines: $\log_{10}\beta$

Cline, ZL, Xue, arXiv:1201.4858

detecting dark ions

$$\alpha' = 0.1$$

$$\frac{m_{\mathbf{e}}}{m_{\mathbf{p}}} = 0.1$$



decoupling dark ions at SM recombination

stopping effects of 1 km rock on dark ions

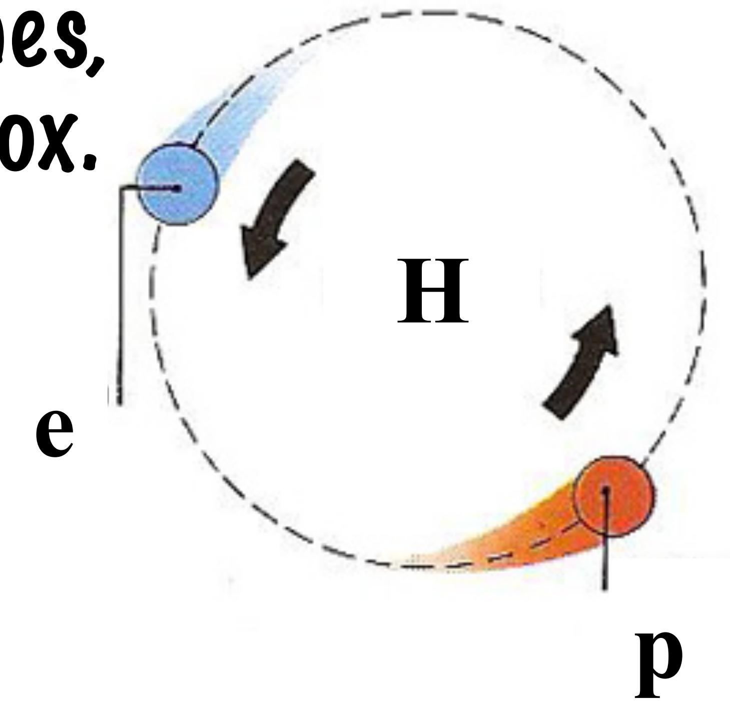
dark ion to explain CoGeNT

Xenon100 limits on dark ions and atoms

special case

$$m_{\mathbf{e}} = m_{\mathbf{p}}$$

Average charge density of the DM atom vanishes, so the elastic scattering vanishes in Born approx.



hyperfine splitting of ground state

$$E_{\rm hf} = \frac{2}{3}\, g_{\mathbf{e}}\, g_{\mathbf{p}}\, \alpha'^4 \frac{m_{\mathbf{e}}^2 m_{\mathbf{p}}^2}{(m_{\mathbf{e}} + m_{\mathbf{p}})^3} \to \frac{1}{6}\alpha'^4 m_{\mathbf{H}}$$

Transitions between the spin singlet and triplet states are dominated by the spin-orbit interaction

$$H_{\rm int} = \frac{\tilde{\epsilon} e}{4\pi\, m_p\, r^3}\vec{L}_p \cdot \vec{\mu}_{\mathbf{e}} + \{\mathbf{e} \to \mathbf{p}\}$$

Inelastic differential cross section

$$\frac{d\sigma_N}{d\Omega} \simeq \frac{(4\epsilon Z)^2\alpha^2}{m_{\mathbf{H}}^2}\, \frac{\mu_N^2}{q^2}\, \frac{p'}{p} |\vec{v} \times \hat{q}|^2 F_H^2$$

CoGeNT events and exotic isotope search

CoGeNT: $E_{\rm hf} \sim 15$ keV, $m_{\mathbf{H}} \sim 6$ GeV, $\alpha' \sim 0.06$, $\epsilon \sim (10^{-3}, 10^{-2})$

dark ions with above ε charge are efficiently stopped in the atmosphere, bound to nucleus, forming the so-called "exotic isotope" with a significant relative abundance.

stable against thermal fluctuation — Goldberg, Hall, 86'; Holdom, 86'

limits on relative abundance in exotic isotope searches from deuterium and helium are much smaller. Muller, Alvarez, Holley, Stephenson, 77' Klein, Middleton, Stephens, 81'

However, such constraints are weakened, because

(1) binding to deuterium is unstable compared to oxygen
(2) binding to helium is unstable against solar x-ray
(3) helium is not primordial
(4) shielding from magnetosphere
(5) expelled by supernovae shock waves from galaxy

other constraints ?

CMB constraints

decoupling millicharged DM at recombination epoch

$$\epsilon \lesssim 10^{-6} \quad \text{for} \quad m_{\rm DM} \sim 10 \text{ GeV}$$ McDermott, Yu, Zurek, 11'

For atomic dark matter models, the ion-component is not the dominant component.

$$\Omega_{\rm ion} h_0^2 < 0.007$$ Dubovsky, Gorbunov, Rubtsov, 03'

decoupling the dark atoms from the baryon-photon plasma

$$\gamma \mathbf{H} \to \gamma \mathbf{H} (\sigma_C = 32\pi\epsilon^2\alpha^2/3m_{\mathbf{e}}^2) \Longrightarrow \epsilon < 0.02$$

Cline, ZL, Xue, arXiv:1201.4858

Neutron star constraints

DM capturing and accumulation in a neutron star can potentially destroy the host star. This puts strong constraints on bosonic asymmetric DM.

McDermott, Yu, Zurek, 11'
Kouvaris, Tinyakov, 11'

The strong constraint on bosonic DM relies on the absence of Fermi pressure.

Chandrasekhar limits $$N_{\rm Cha}^{\rm boson} \simeq \frac{M_{Pl}^2}{m_{\mathbf{H}}^2} \ll N_{\rm Cha}^{\rm fermion} \simeq \frac{M_{Pl}^3}{m_{\mathbf{H}}^3}$$

At the bosonic Chandrasekhar limit, confine atomic DM within the Schwarzschild radius. It starts to behave as Fermi gas.

$$\Delta r = \frac{R_s}{N^{1/3}} = \frac{2Nm_{\mathbf{H}}}{M_{Pl}^2 N^{1/3}} = \frac{2m_{\mathbf{H}}(N_{\rm cha}^{\rm boson})^{2/3}}{M_{Pl}^2} = \frac{2}{M_{Pl}^{2/3} m_{\mathbf{H}}^{1/3}} \ll a_0' = \frac{1}{\alpha' m_{\mathbf{e}}}$$

direct detection rate

event rate via inelastic scattering

$$\frac{dR}{dE_R} = \frac{\pi N_T \rho_{\mathbf{H}}}{m_{\mathbf{H}} E_R} \left(\frac{4\epsilon\alpha Z F_H}{m_{\mathbf{H}}} \right)^2 I(x, y, \vec{v}_e)$$

$$I(x, y, \vec{v}_e) = \int_{v_{\rm min}} \frac{d^3v}{v} \left(v^2 - v_{\rm min}^2\right) f(\vec{v} + \vec{v}_e)$$

minimum velocity

$$v_{\rm min} = \frac{x+y}{2\sqrt{x}}; x \equiv \frac{q^2}{\mu^2}; y \equiv 2\frac{\delta m_{\mathbf{H}}}{\mu}$$

velocity distribution

$$f = N\left(e^{-v^2/v_0^2} - e^{-v_{\rm esc}^2/v_0^2}\right)$$

$$v_0 = 220\ {\rm km/s},\ v_{\rm esc} = 500 - 600\ {\rm km/s},\ v_e = 232 \pm 15\ {\rm km/s}$$

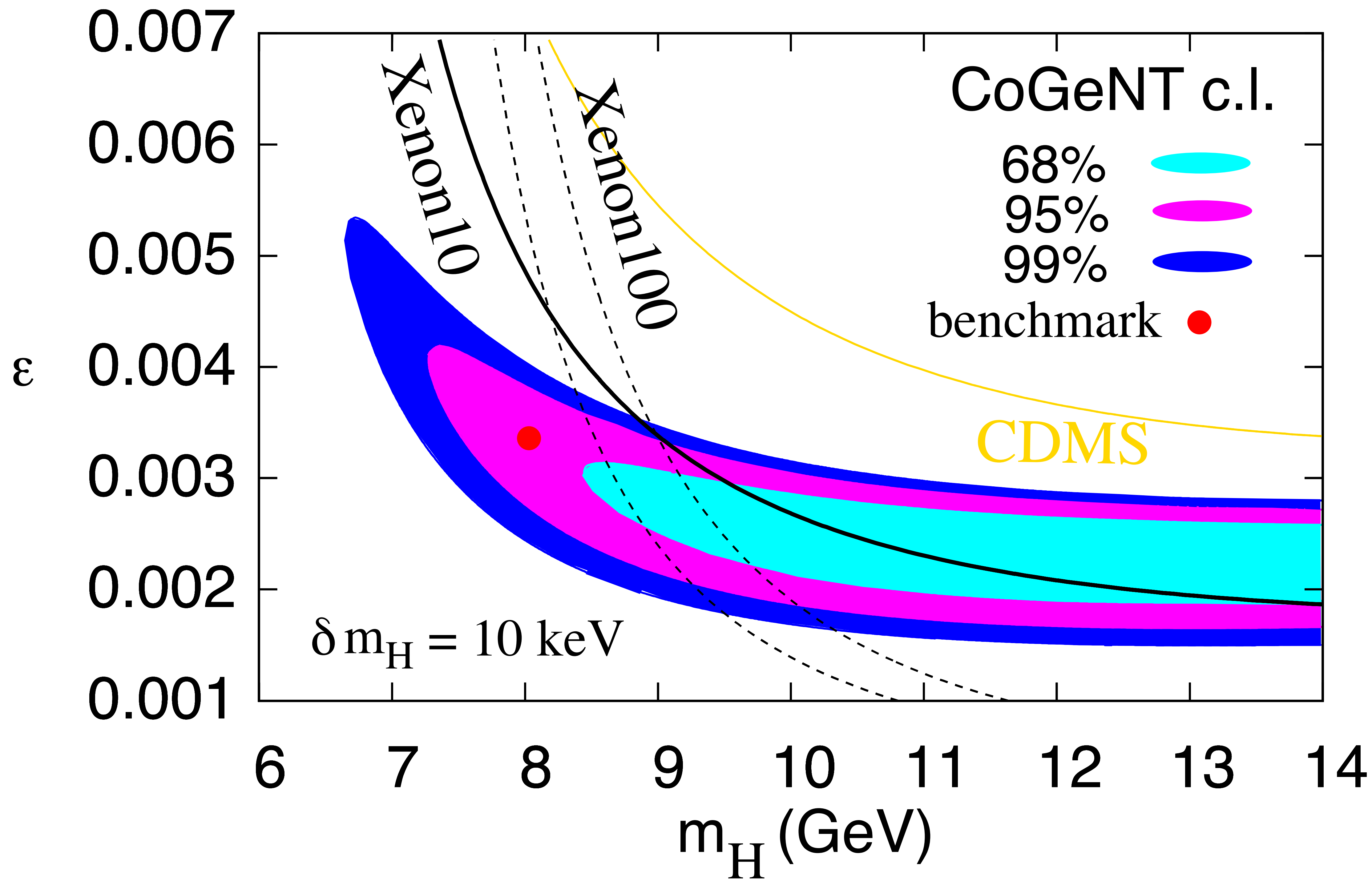
Millicharged Atomic DM model inputs

$m_{\mathbf{H}}$, dark matter mass

$\delta m_{\mathbf{H}}$, hyperfine splitting

ϵ, millicharge

Fit to CoGeNT, Xenon, CDMS



Cline, ZL, Xue, work in process

Summary

- Millicharged atomic dark matter that is consistent with various experimental constraints can produce detectable signal in underground DM experiments.
- Inelastic scattering from atomic hyperfine splitting can generate the observed excess events in CoGeNT.
- The fit to CoGeNT data when considering Xenon and CDMS limits is good. More data from CoGeNT and Xenon will come in the summer which can test our model.

Additional Slides

dark hydrogen atom recombination

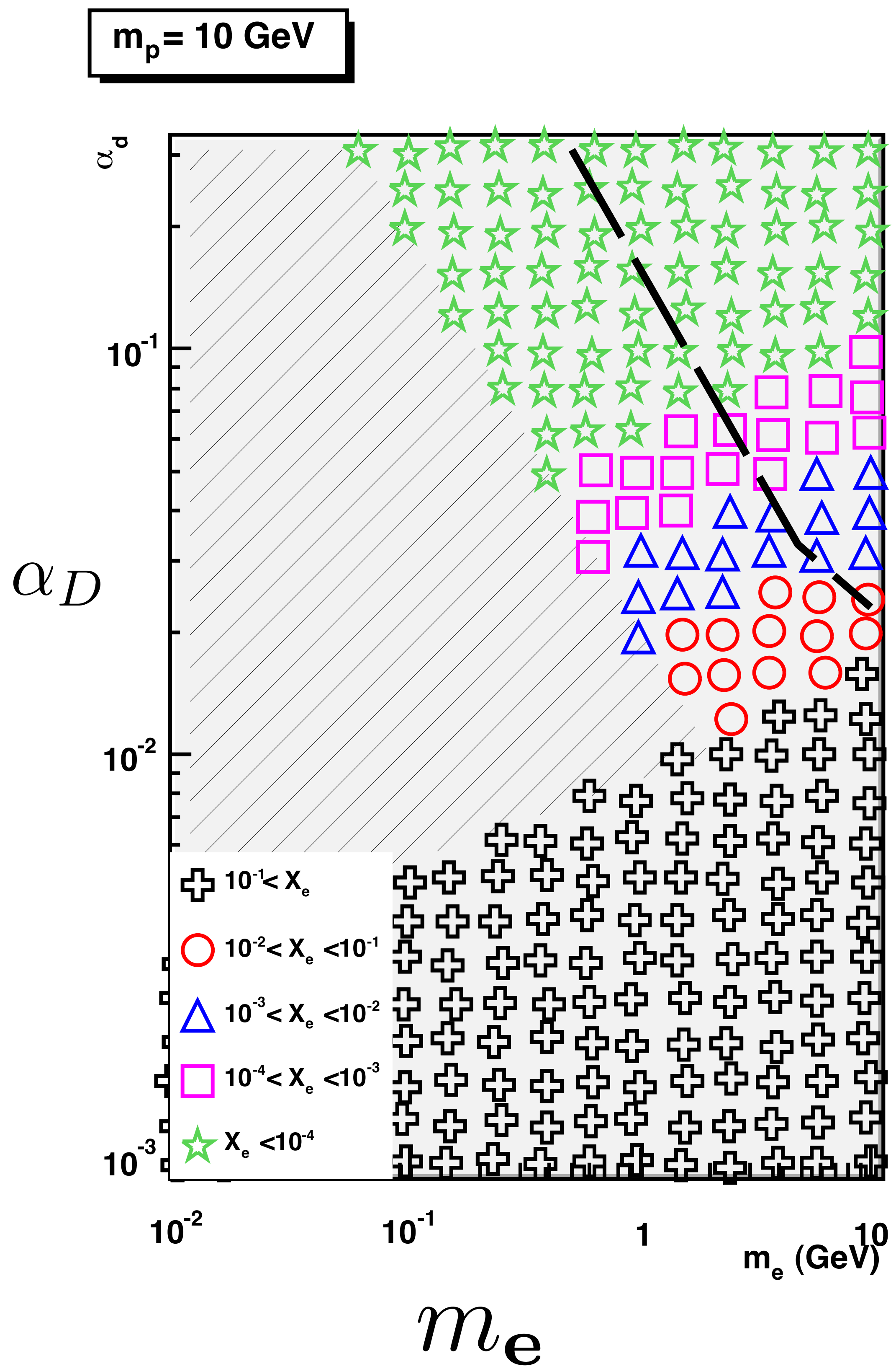
$$\mathbf{e} + \mathbf{p} \leftrightarrow \mathbf{H} + \gamma$$

Presence of both neutral and ionized dark matter components.

$$X_{\mathbf{e}} \equiv \frac{n_{\mathbf{e}}}{n_{\mathbf{e}} + n_{\mathbf{H}}}$$

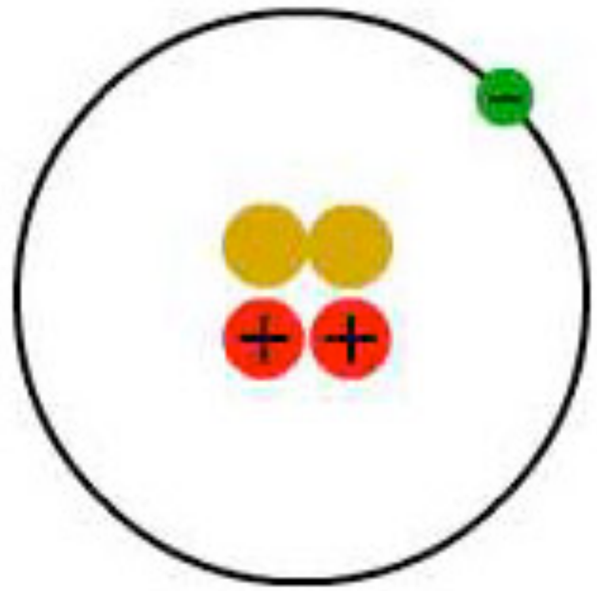
$$\langle \sigma v \rangle = \xi \frac{64\pi}{\sqrt{27\pi}} \frac{\alpha_D^2}{\mu_{\mathbf{H}}^2} x^{1/2} \ln(x)$$

$X_e < 10^{-4}$ when $\alpha_D > 0.1$



Kaplan, Krnjaic, Rehermann, Wells, 09'

Exotic isotope search



- Millicharged dark ions with ionization fraction $f = 10^{-4}$ would have a flux of 2×10^{20}/s on the earth
- With $\epsilon \sim 10^{-2}$, dark ions would be stopped in ~ 1 m of the atmosphere (10^{44} atoms) and produce a relative abundance 10^{-7} of exotic isotopes over 10 Gyr.
- Binding energy with nuclei, $B = (\epsilon\alpha Z)^2 \mu_{\mathbf{e}N}/2$ which is unstable against thermal fluctuations when $\epsilon \lesssim 10^{-3}$. (Goldberg, Hall; Holdom)
- In the mass range covering $m_{\mathbf{e}} = 3$ GeV, heavy isotope searches have excluded abundances of $10^{-18.5}$ for deuterium from D_2O and 10^{-14} for helium. (Muller et.al; Klein et.al)

Evade the "exotic isotope" constraints

- **e** binds much more strongly (400 eV) to oxygen than to deuterium (3 eV) for $\epsilon = 0.01$, making D[D**e**]O highly unstable to decay into D_2[O**e**].

- He on Earth is not primordial, but rather has a lifetime of $\tau = 10^6$ y in the atmosphere, (Lu et.al.) reducing the estimated abundance by a factor of $\tau/(10 \text{ Gyr})$ to 10^{-11}.

- magnetosphere effectively shields the earth from slow charged particles, including 3 GeV dark ions with $\epsilon \sim 10^{-2}$, whose gyroradius at the top of the atmosphere is ~ 0.01 earth radii.

- Solar x-rays are sufficiently energetic to break up the He-**e** bound state (binding energy 5 eV) and allow **e** to rebind much more strongly to N or O in the atmosphere.

- For $\epsilon < 0.005$, supernovae are able to efficiently expel 3 GeV ions from the galaxy (Chuzhoy, Kolb)

Halo shape constraint

The elliptical shape of DM halos put constraints on DM self-interaction

$$\frac{\sigma_{\mathbf{HH}}}{m_{\mathbf{H}}} < 0.02 \frac{\text{cm}^2}{g}$$

Miralda-Escude

Dark atom annihilation $\sigma_{\mathbf{HH}} = 4\pi(\kappa a_0')^2 \quad \text{with} \quad 3 \lesssim \kappa \lesssim 10$

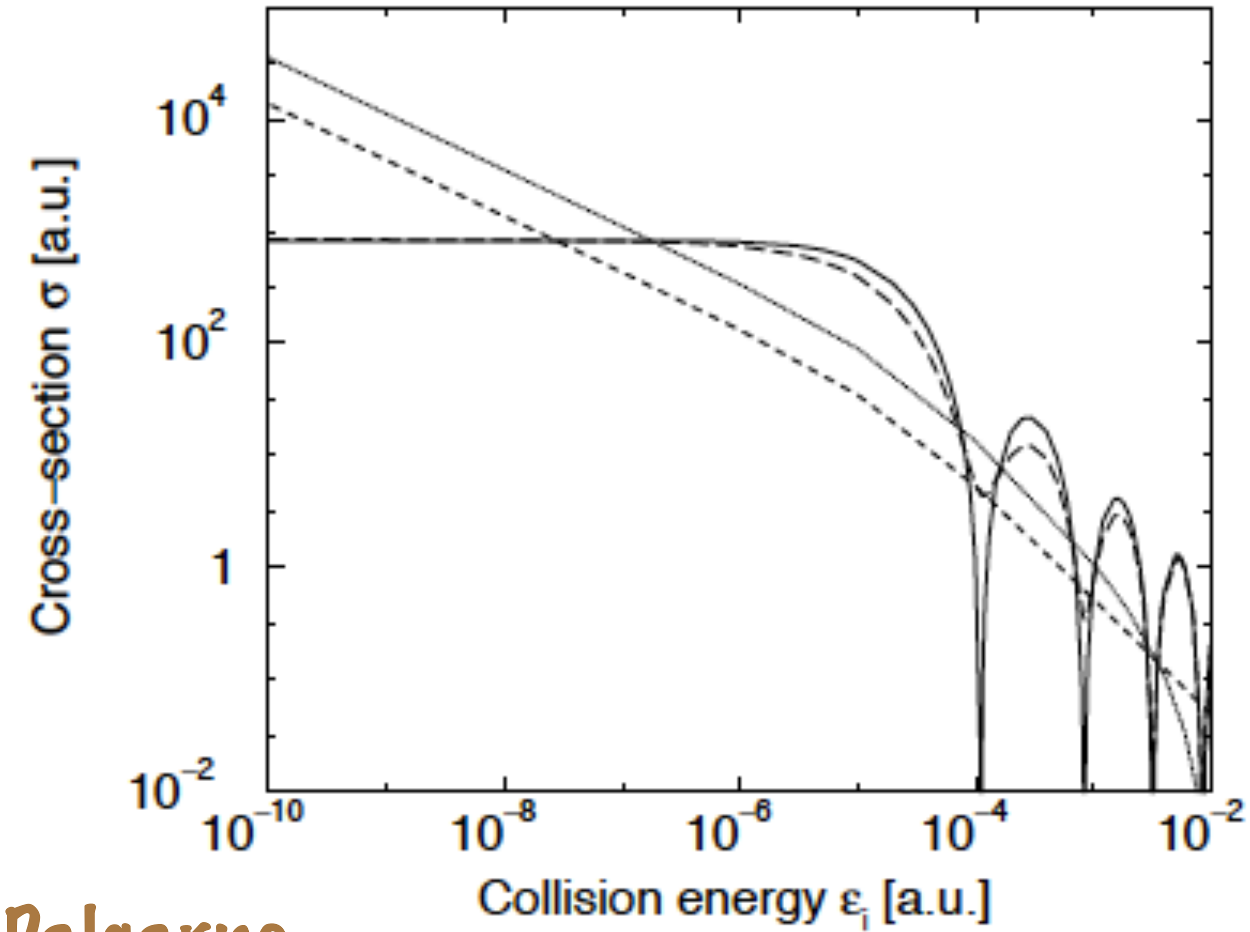
Kaplan, Krnjaic, Rehermann, Wells

Based on analysis on hydrogen-antihydrogen collisions, the interaction cross section is weaker.

$\kappa \cong 0.16$ at $E \sim (v/\alpha')^2 \sim 10^{-3}$

$m_{\mathbf{H}} \gtrsim 2$ GeV when $\alpha' = 0.062$, $m_{\mathbf{e}} = m_{\mathbf{p}}$

$m_{\mathbf{H}} \gtrsim 4$ GeV when $\alpha' = m_{\mathbf{e}}/m_{\mathbf{p}} = 0.1$



Froelich, Jonsell, Saenz, Zygelman, Dalgarno