Atomic Dark Matter Signals

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Particles, Cosmology and Strings

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Outline

Millicharged atomic dark matter & direct detection

Cline, ZL, Xue, 1201.4858 (cites 107)
Cline, ZL, Xue, 1207.3039 (cites 21)

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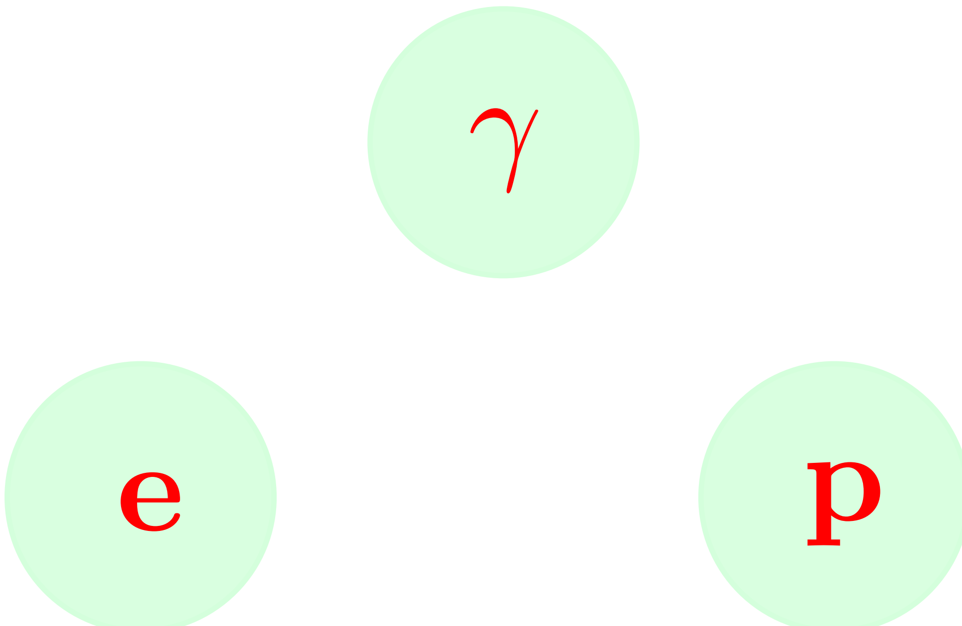
3.5 keV X-ray in atomic dark matter

Cline, Farzan, ZL, Moore, Xue, 1404.3729 (cites 55)

Atomic dark matter setup

visible sector



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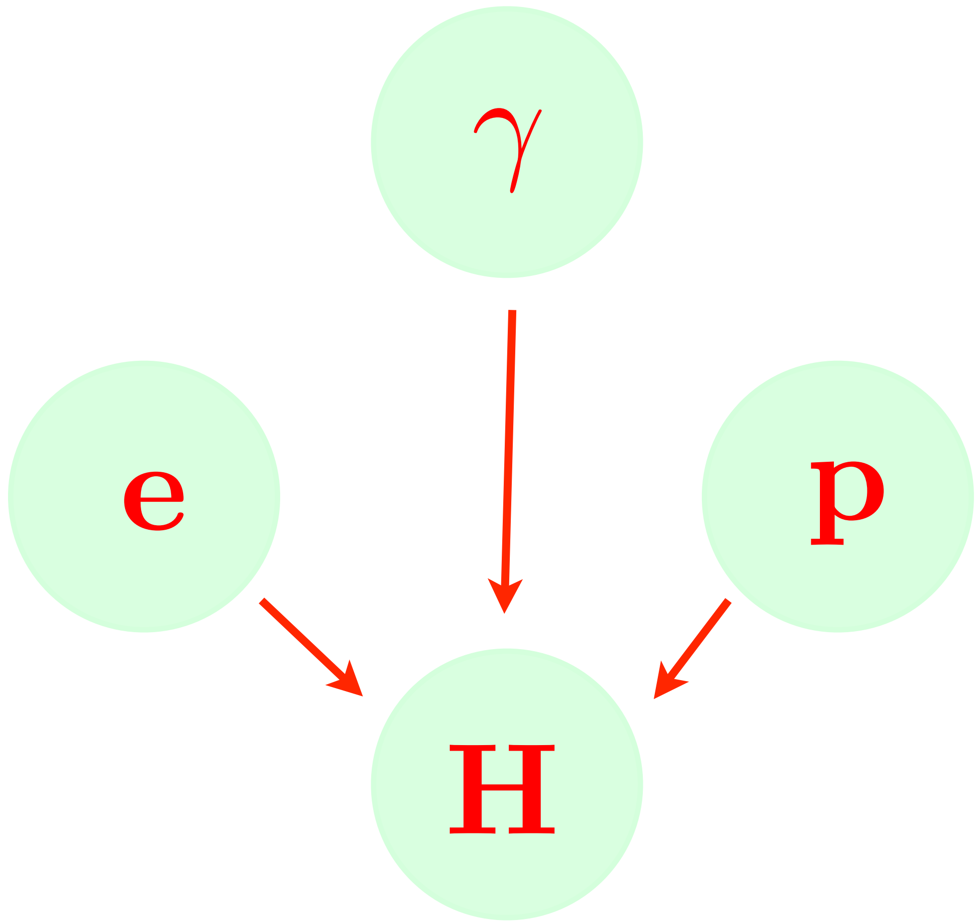

hydrogen recombination

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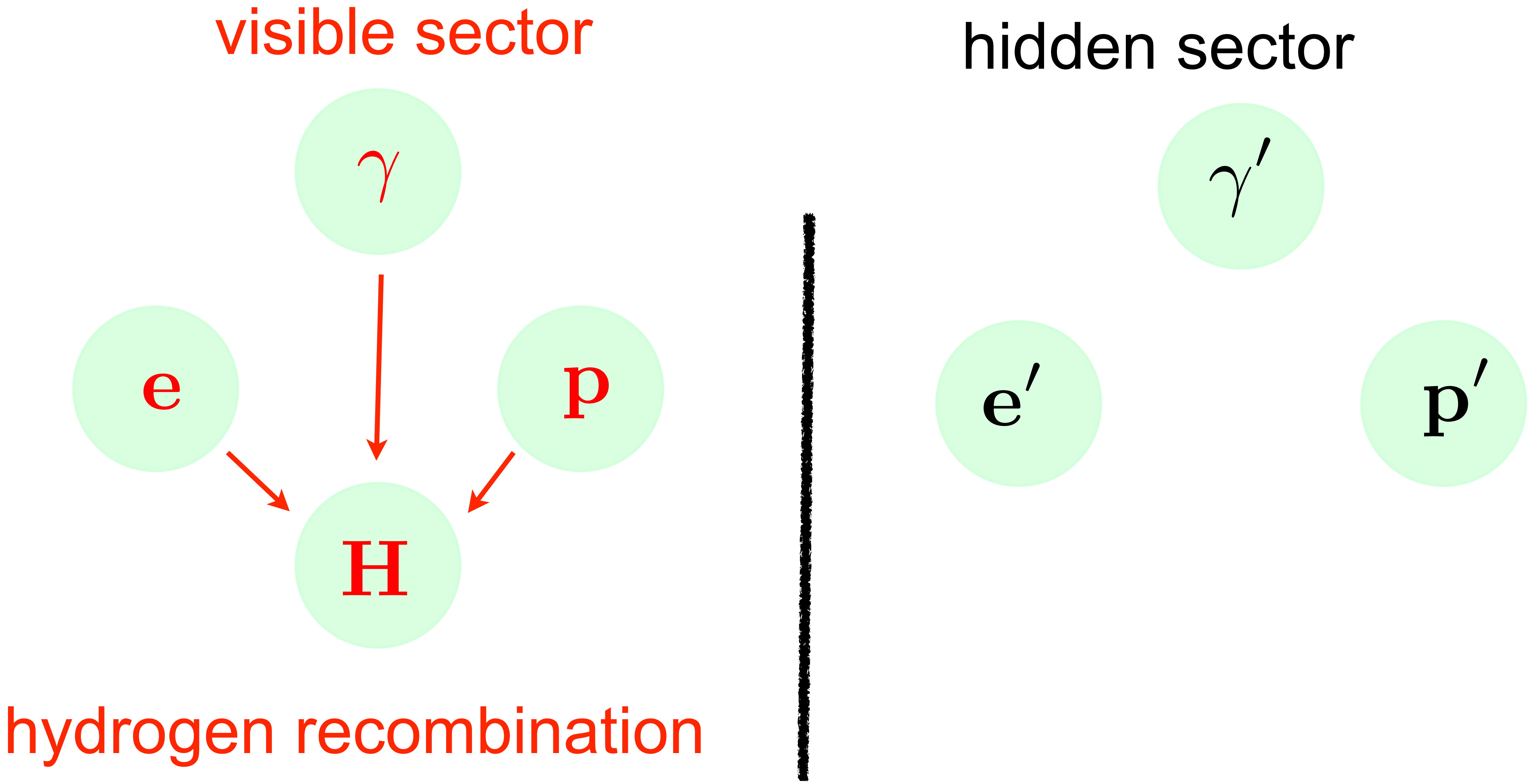

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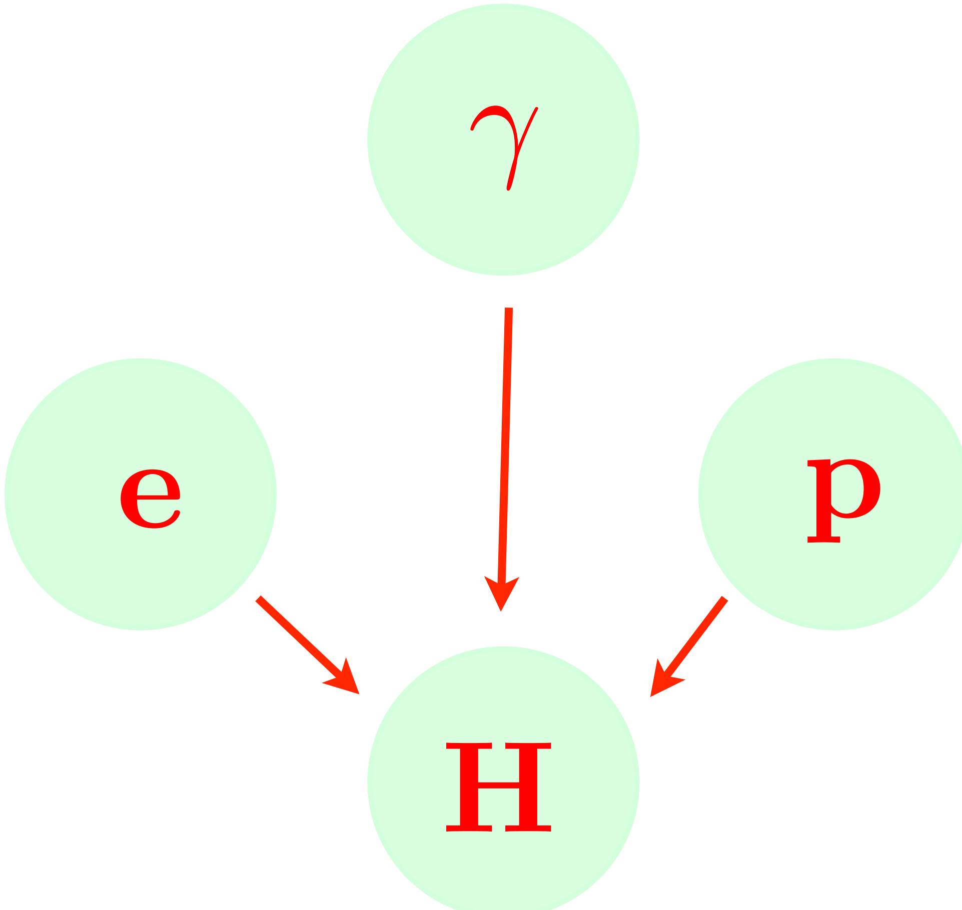

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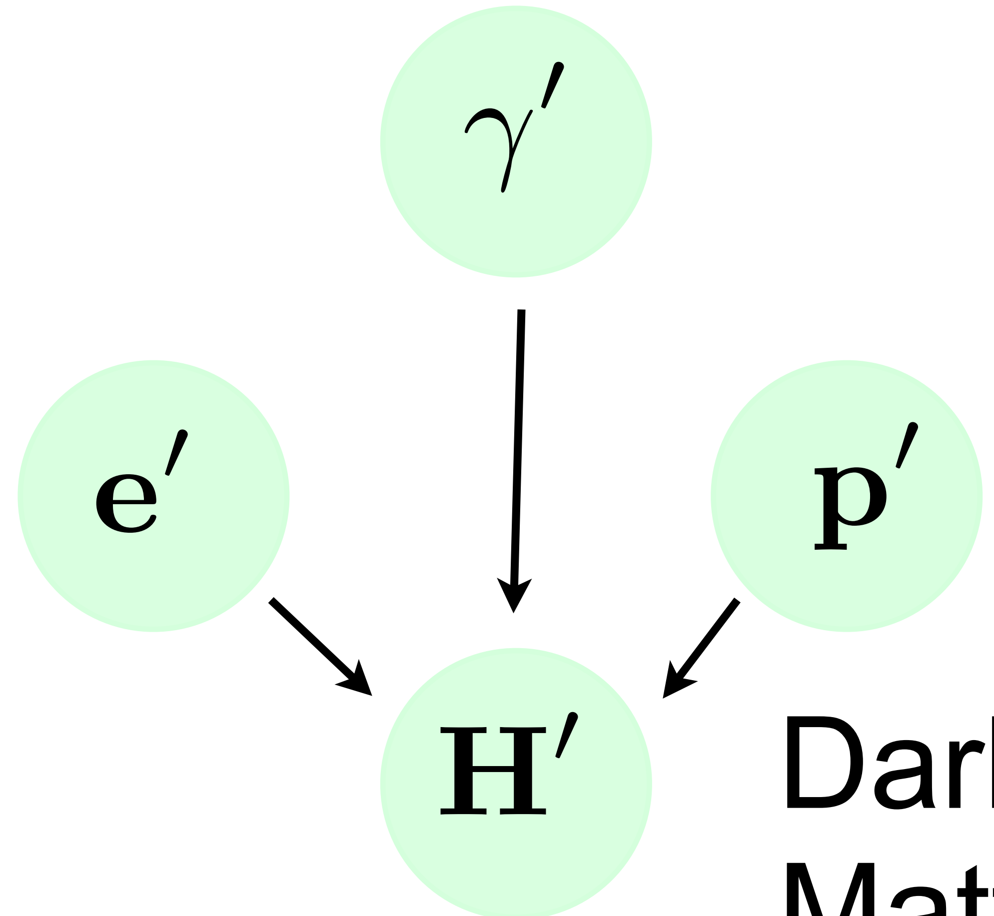
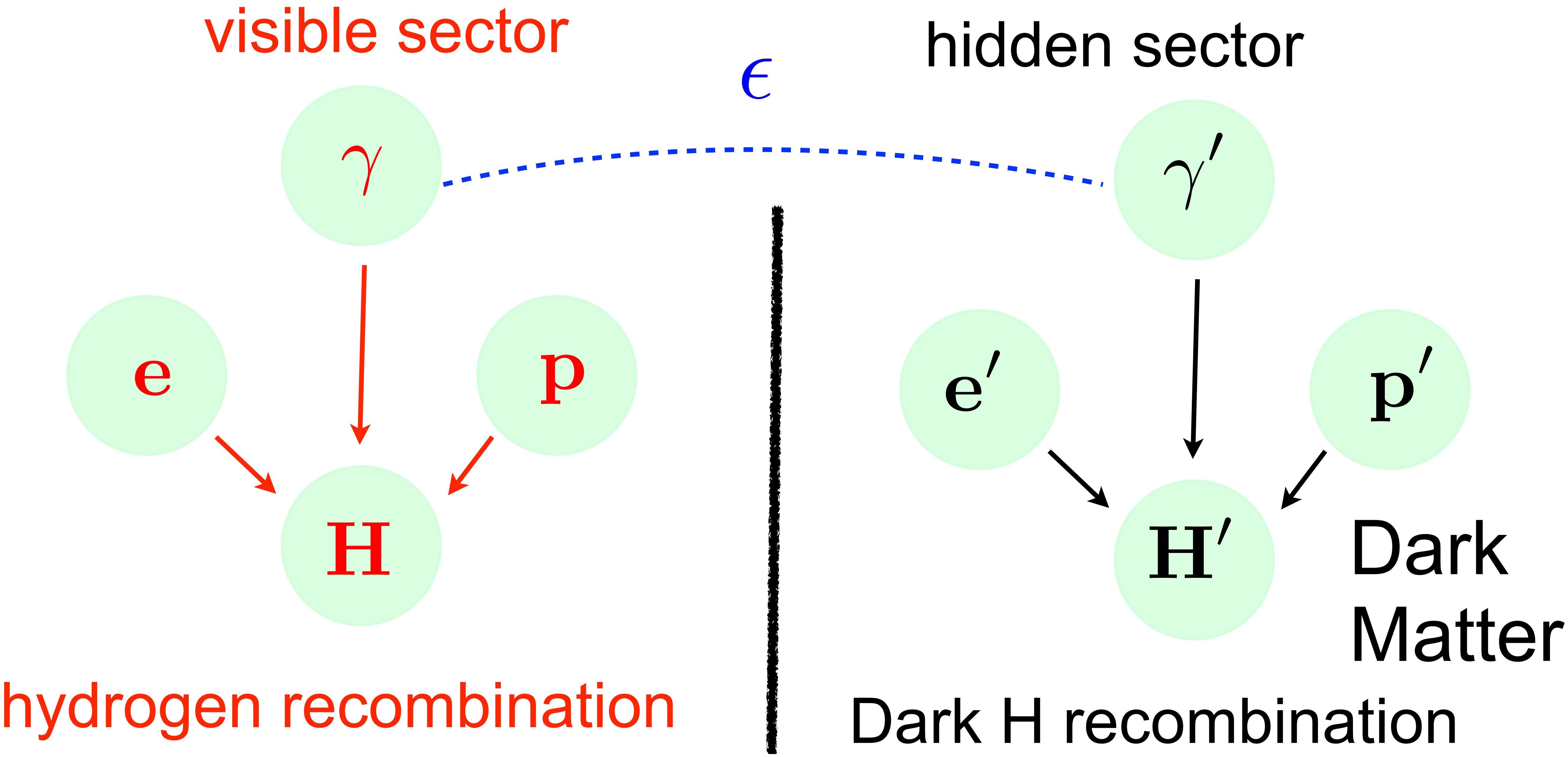


Dark H recombination

Atomic dark matter setup



$$\mathcal{L} = \mathcal{L}_{\mathbf{SM}} + \bar{\mathbf{e}}'(\mathbf{i}\gamma^\mu \mathbf{D}'_\mu - \mathbf{m}_{\mathbf{e}'})\mathbf{e}' + \bar{\mathbf{p}}'(\mathbf{i}\gamma^\mu \mathbf{D}'_\mu - \mathbf{m}_{\mathbf{p}'})\mathbf{p}'$$
$$-\frac{\mathbf{1}}{\mathbf{4}}\mathbf{F}_{\mu\nu}\mathbf{F}^{\mu\nu} - \frac{\mathbf{1}}{\mathbf{4}}\mathbf{F}'_{\mu\nu}\mathbf{F}'^{\mu\nu} + \frac{\epsilon}{\mathbf{2}}\mathbf{F}_{\mu\nu}\mathbf{F}'^{\mu\nu}$$

Field redefinition

$$\mathcal{L} = \mathcal{L}_{SM} + \bar{e}'(i\gamma^\mu D'_\mu - m_{e'})e' + \bar{p}'(i\gamma^\mu D'_\mu - m_{p'})p' - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}\tilde{F}'_{\mu\nu}\tilde{F}'^{\mu\nu} + \frac{\tilde{\epsilon}}{2}F_{\mu\nu}\tilde{F}'^{\mu\nu}$$

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Field redefinition (rotating away the mixing term)

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

$$\mathcal{L}_{\text{int}} = gA'_\mu J^\mu_d + A_\mu(eJ^\mu_{em} + \tilde{\epsilon}gJ^\mu_d)$$
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photon

dark photon does not couple to SM

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hidden current

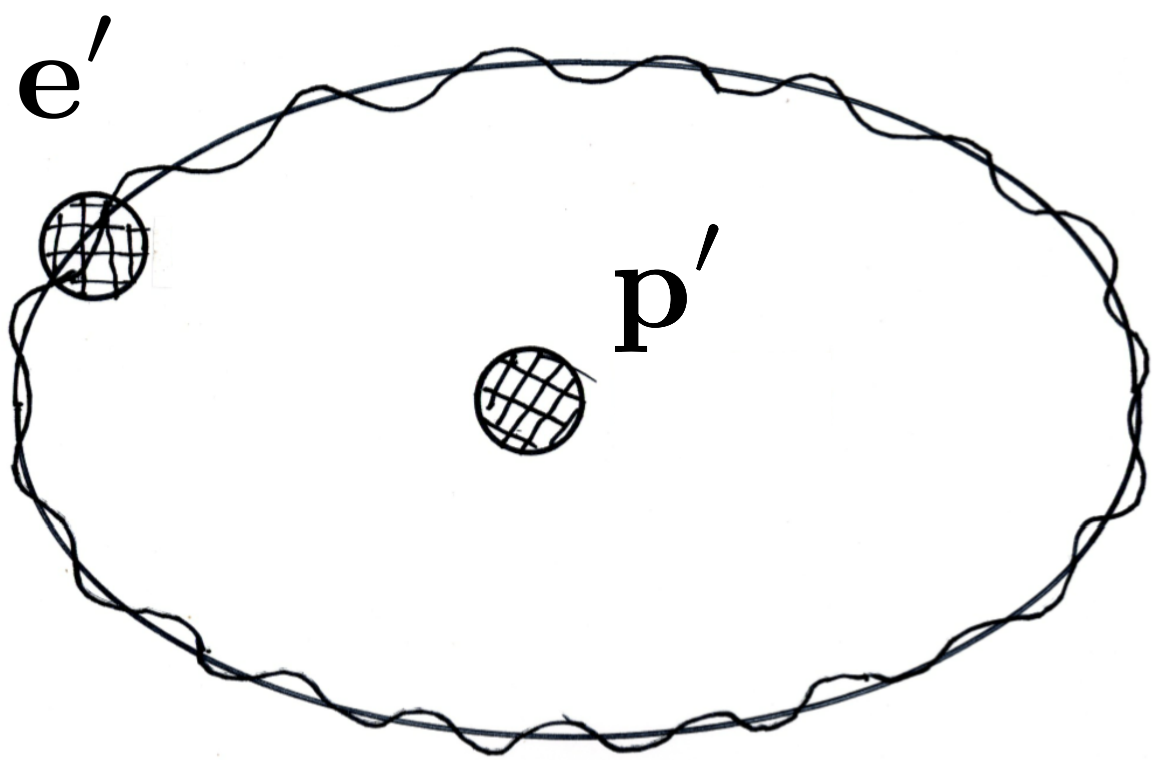
photon

dark photon does not couple to SM

Hidden fermions carry millicharge ε

What does the dark atom look like?

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



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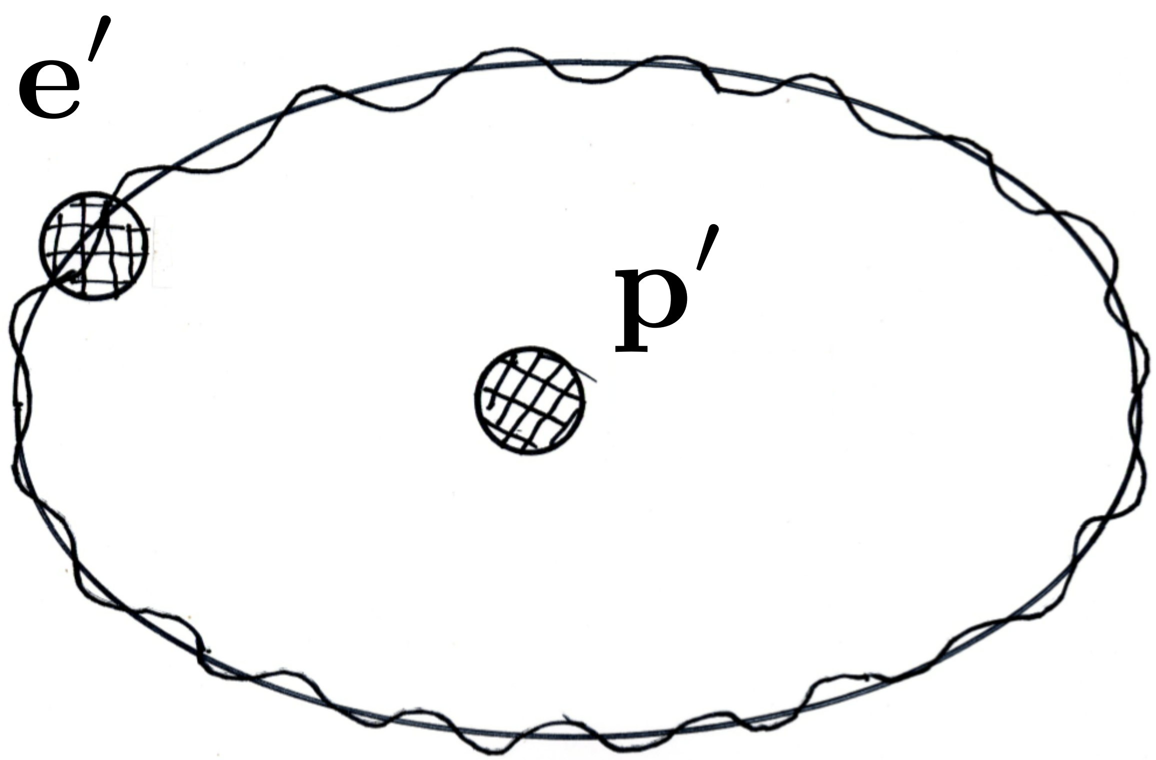

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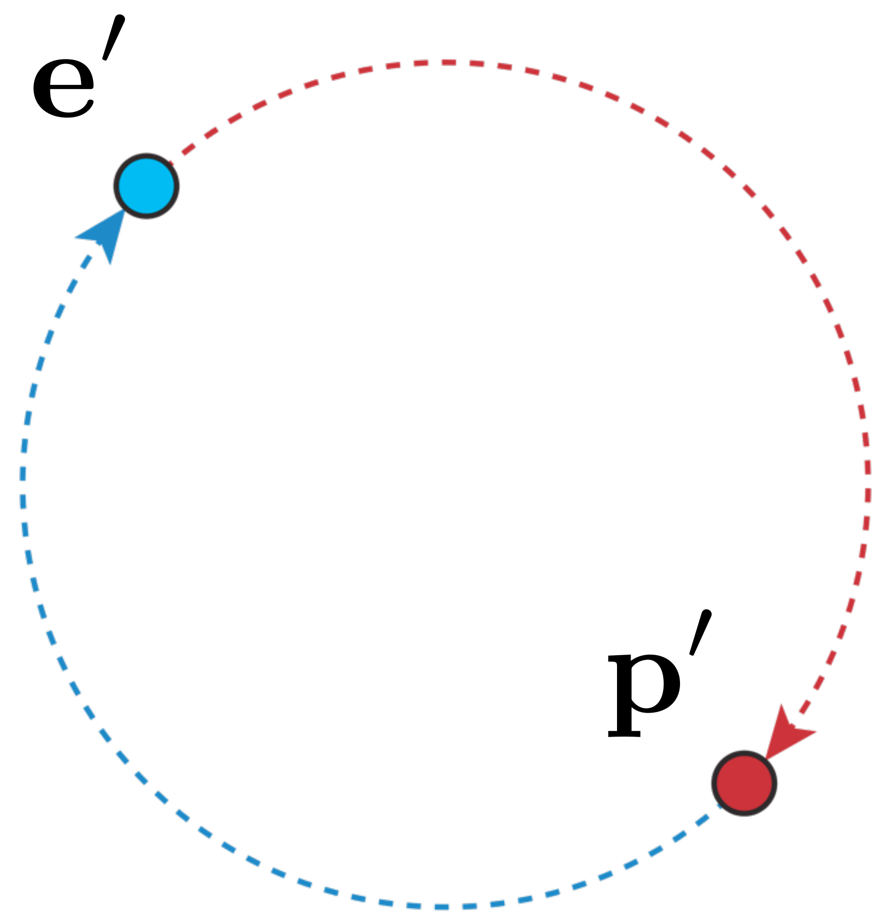

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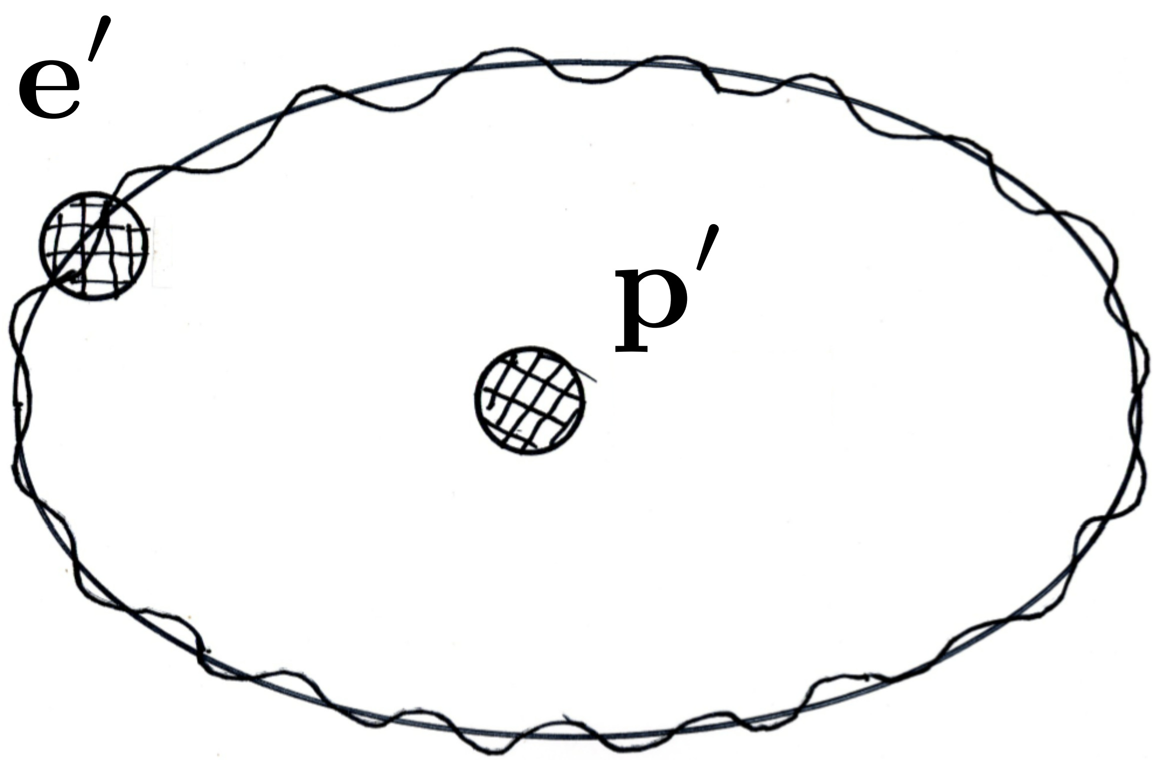

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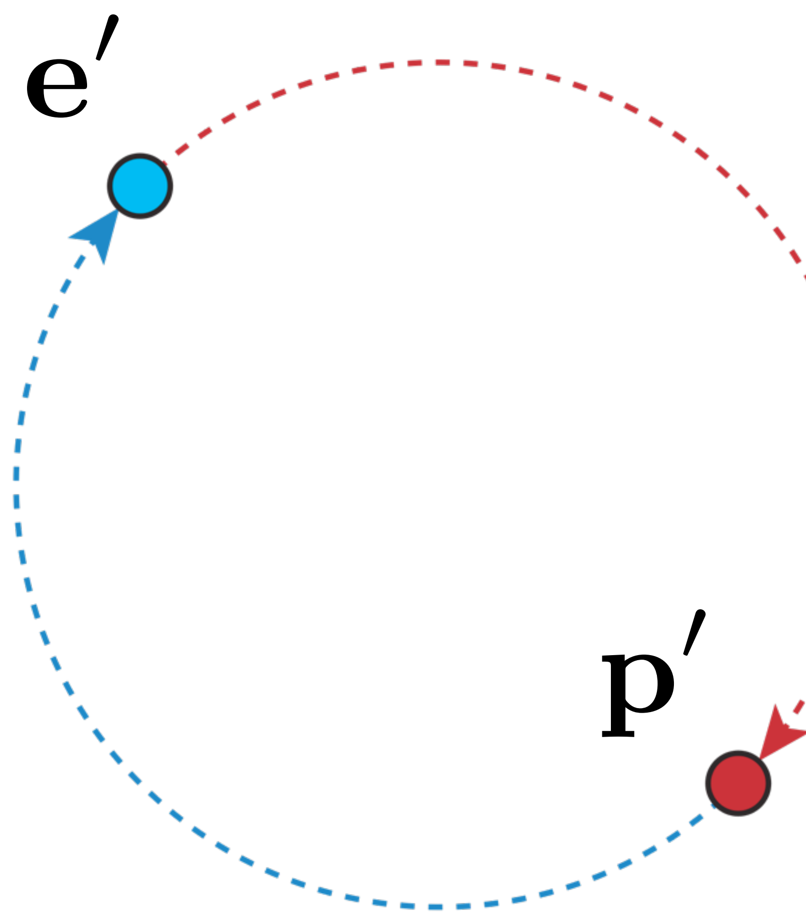

normal hydrogen-like

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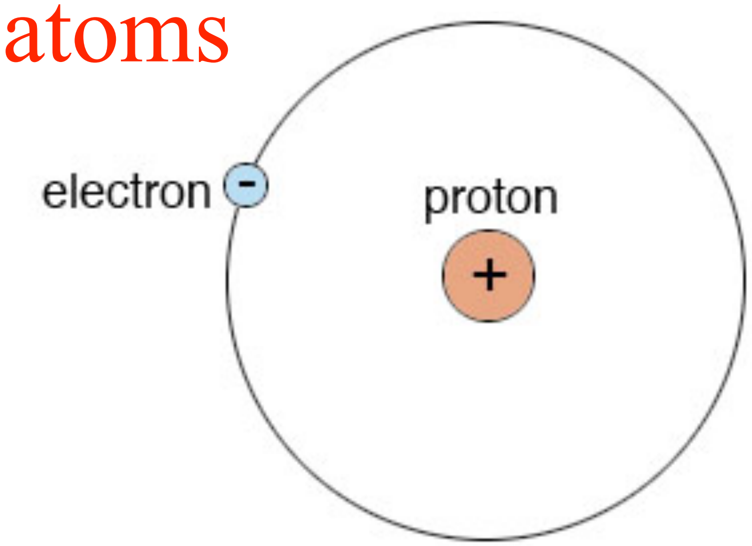
dark electron & dark proton are elementary

Dark genesis

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

ions

atoms



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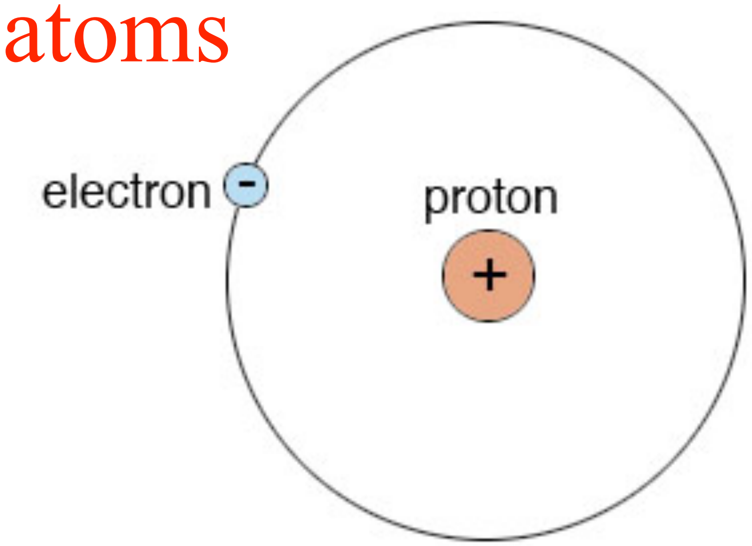


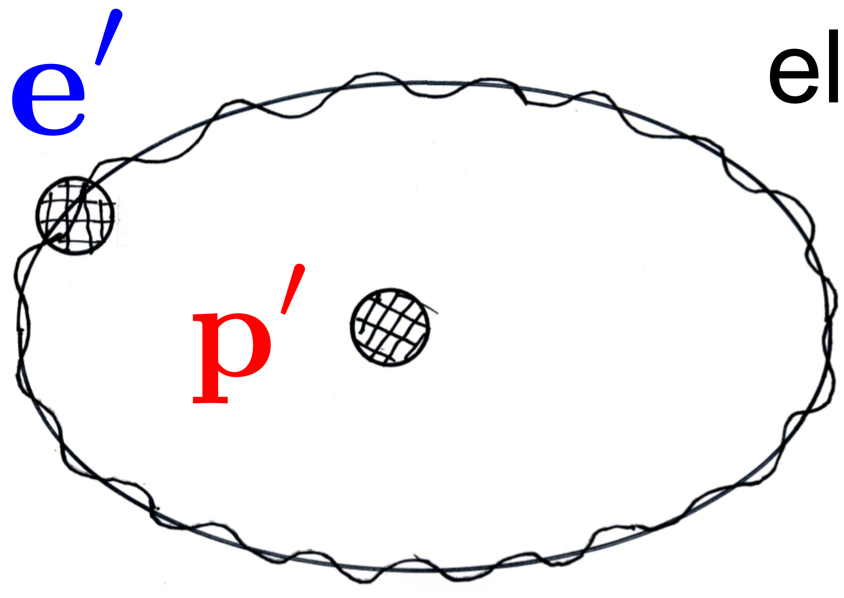
Dark atom recombination results in both neutral and ionized dark matter components

Kaplan, Krnjaic, Rehermann, Wells, '09

ionization fraction
$$X_{e'} \sim \left(1 + 10^{10}\alpha'^4 \frac{\mathrm{GeV}^2}{m_{e'}\, m_{p'}}\right)^{-1}$$

If both fermions are at GeV scale, the hidden coupling strength cannot be much less than 0.01 in order to have $X_{e'} \ll 1$

Directly detecting dark atom



electric charge density of dark atom

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

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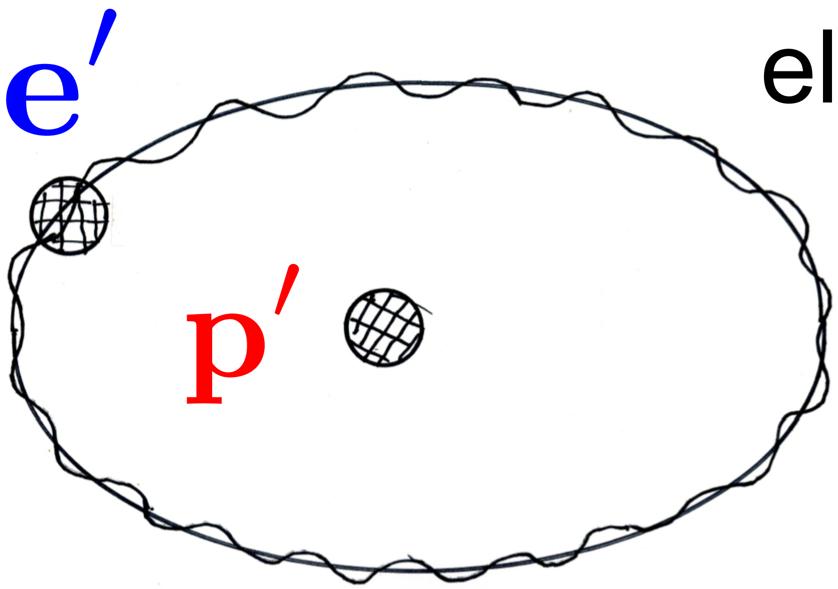

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dark proton

dark electron

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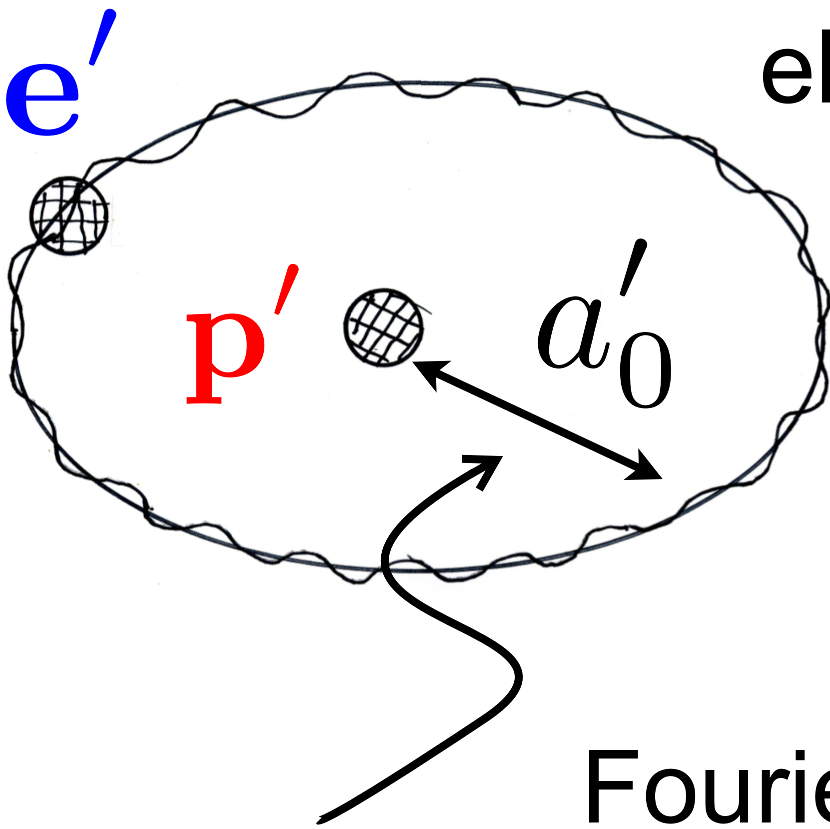


electric charge density of dark atom

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

Bohr radius

$a_0' \sim 1/(\alpha' m_{e'})$

Fourier transform of the charge density

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

for ground state at low wave-number

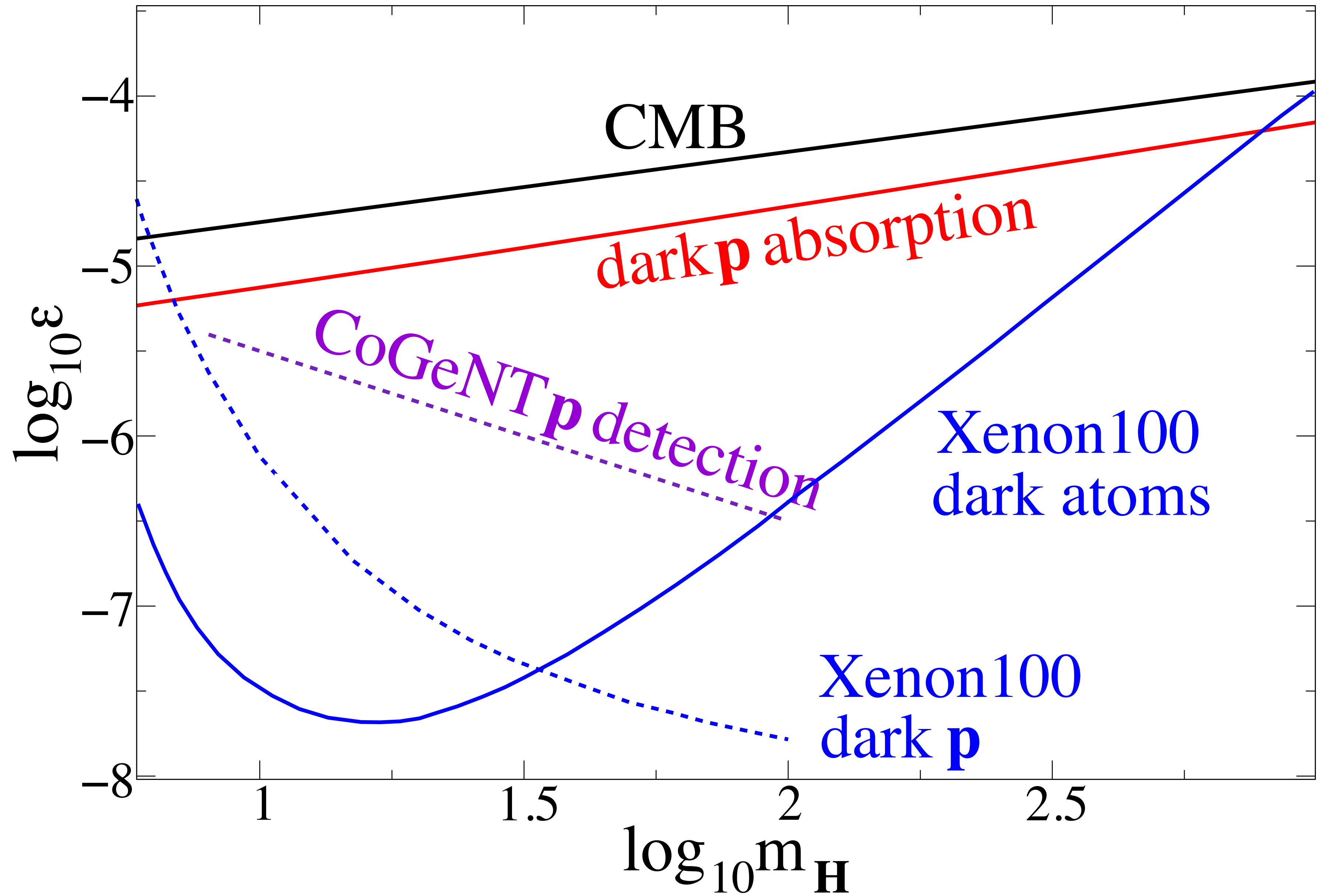
scattering x-sec of dark atom and proton (Born approx.)

$$\sigma_{H'\text{-proton}} = 4\pi\, \alpha^2 \epsilon^2 \mu^2_{H'\text{-proton}} a_0'^{\,4}$$

Detecting dark atom and ions

$$\alpha' = 0.1$$

$$\frac{m_e}{m_p} = 0.1$$



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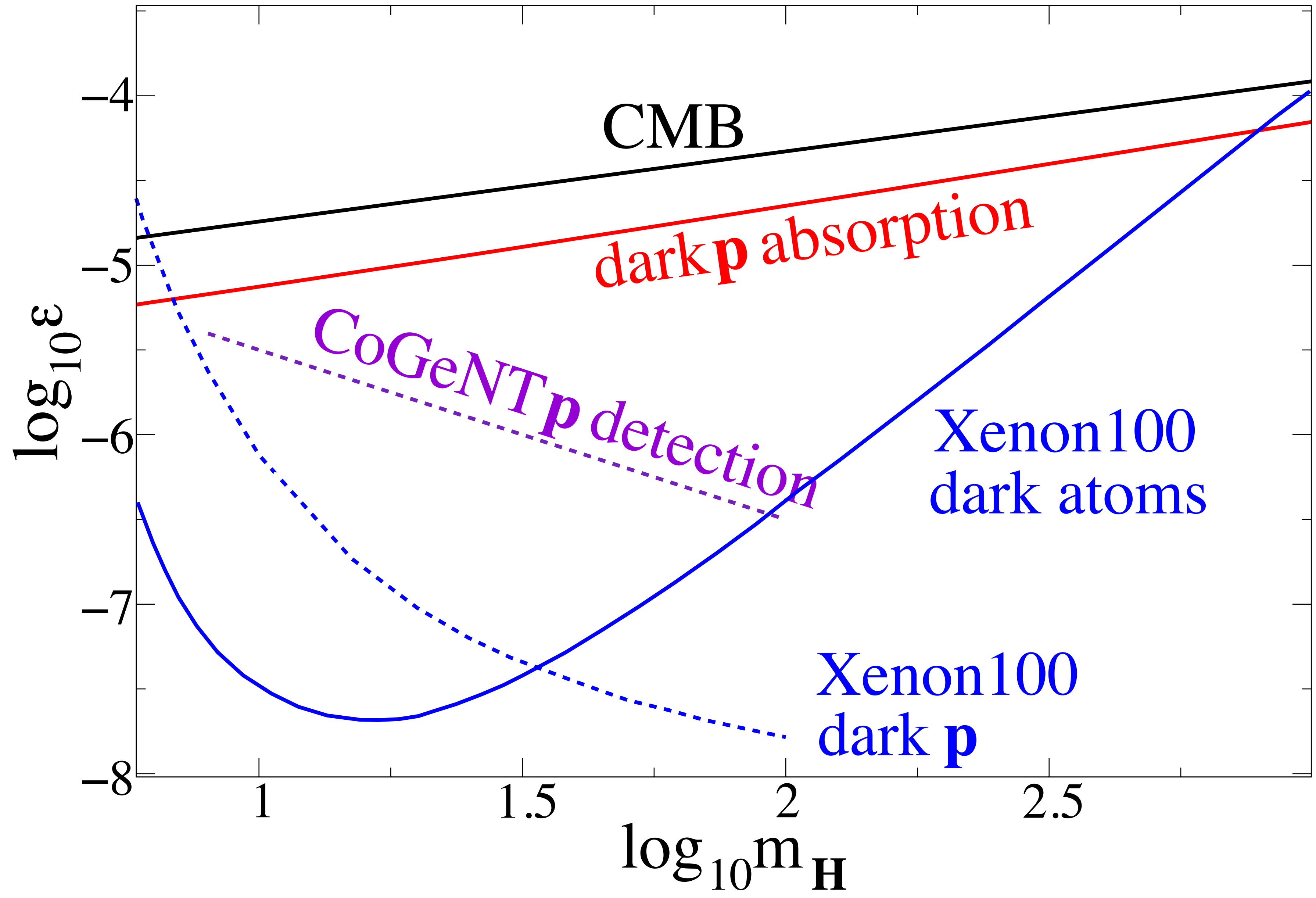

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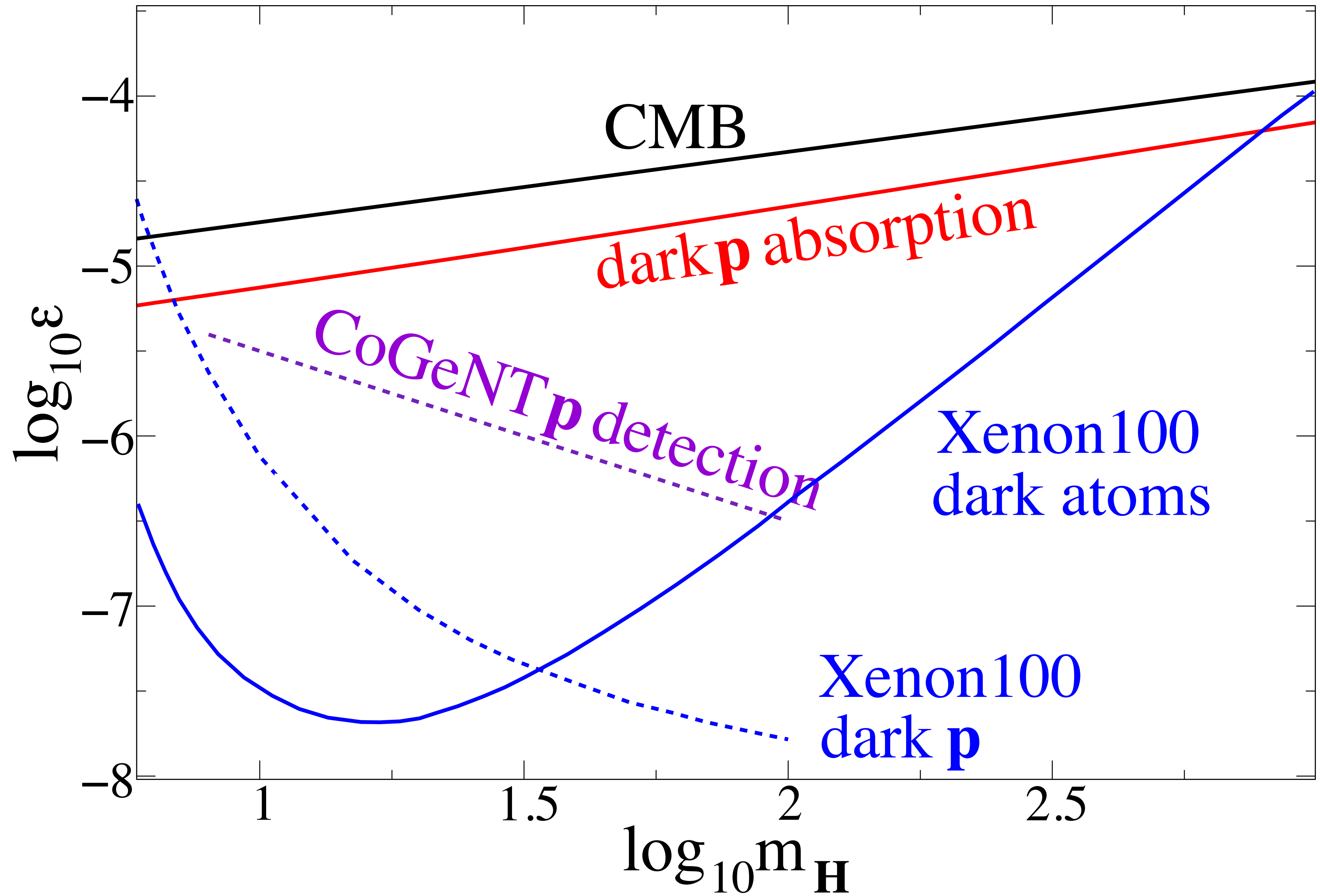

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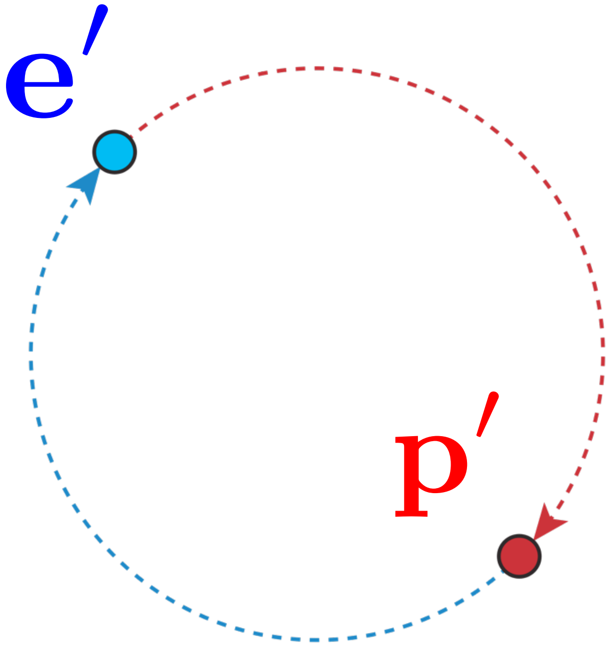
dark ions to explain CoGeNT (2011)

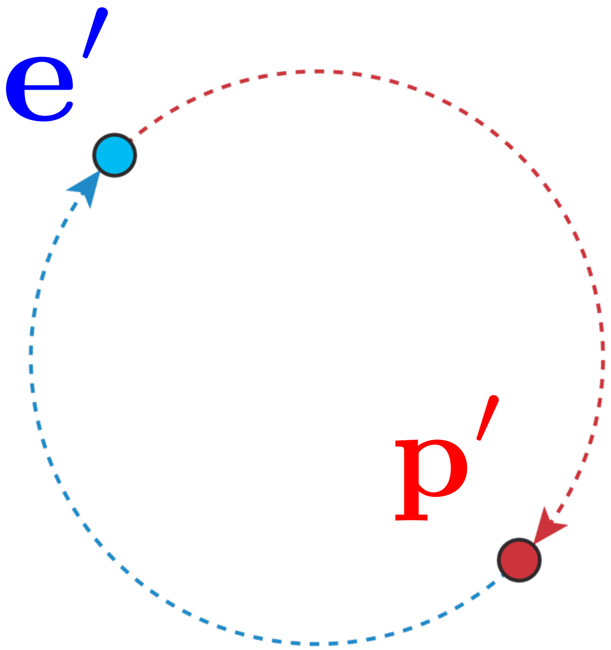
XENON100 (2011) limits on dark ions & dark atoms



Degenerate mass

charge density vanishes (cancellations between dark electron and dark proton)

elastic scattering vanishes in Born approx.



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spin-orbit interaction

$$H_{\rm int} = \frac{\epsilon e^2}{8\pi\, m_{e'}\, m_p\, r^3} \vec{L}_p \cdot (\vec{\sigma}_{e'} - \vec{\sigma}_{p'})$$

spin-spin interaction

$$H_{\rm int} = \frac{\epsilon e}{3m_{e'}} (\vec{\sigma}_{e'} - \vec{\sigma}_{p'}) \cdot \vec{\mu}_N\, \delta^{(3)}(\vec{r}_{H'} - \vec{r}_N)$$

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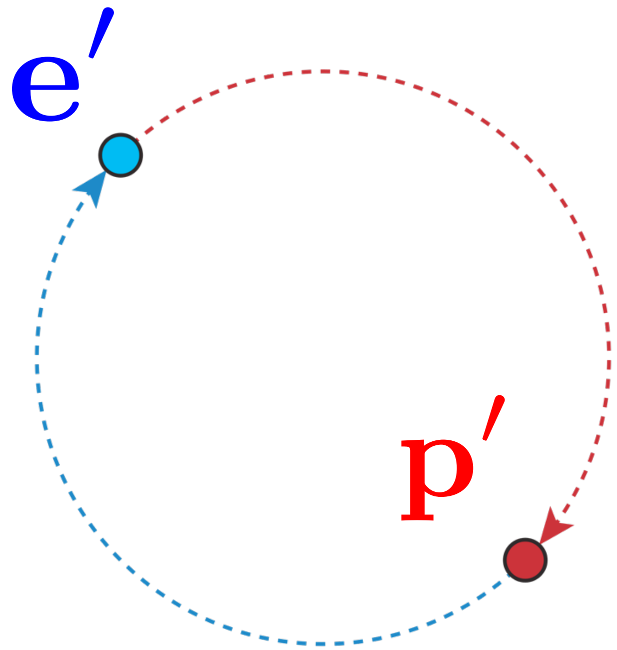

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differential detection rate in underground DM experiments

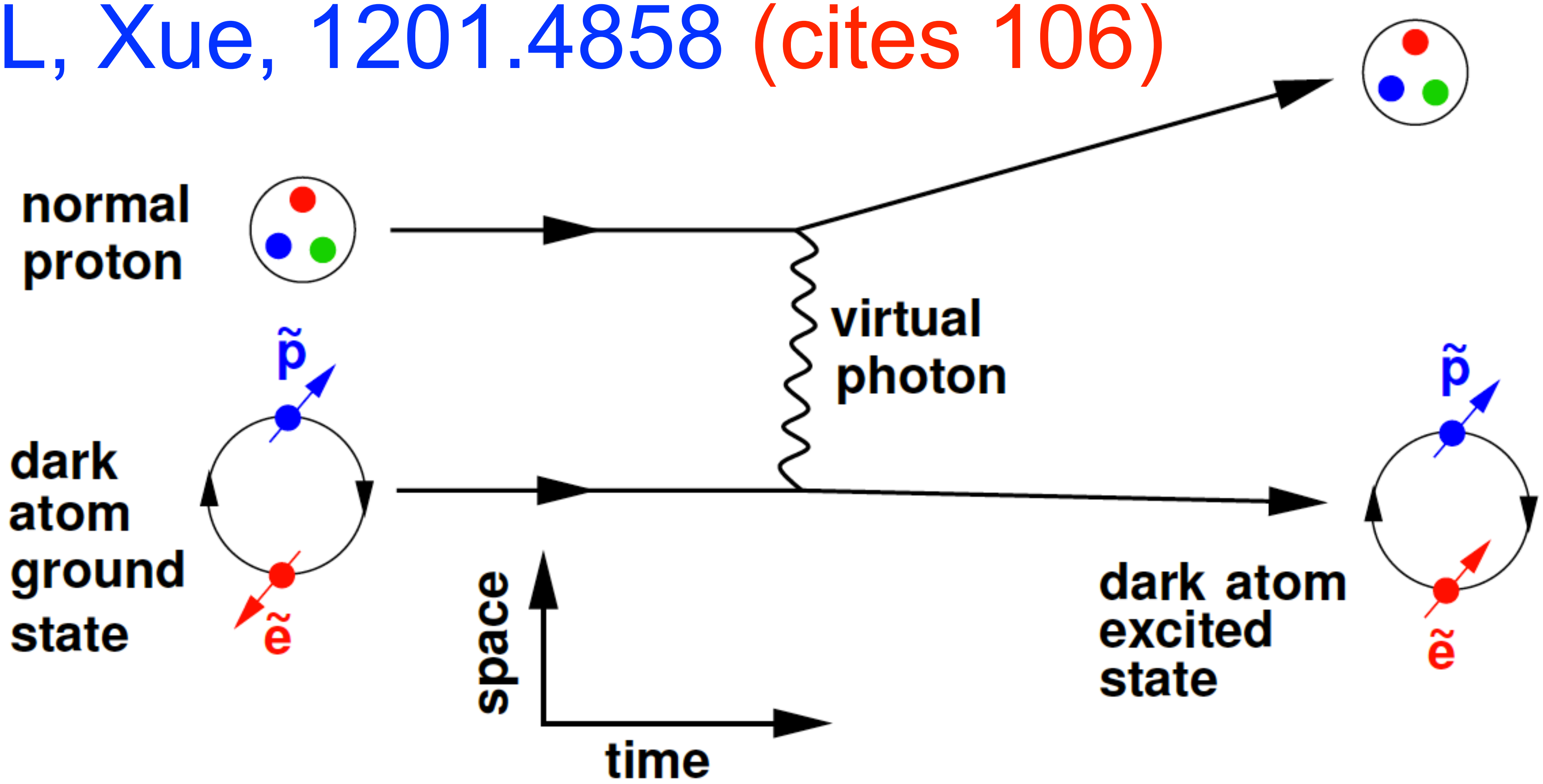
$$\frac{dR}{dE_R} = \frac{N_T \rho_{H'} \pi}{m_{H'}} \left(\frac{4\epsilon\alpha}{m_{H'}}\right)^2 \left[\frac{Z^2 F_H^2}{E_R} \left\langle \frac{v^2 - v_{\rm min}^2}{v} \right\rangle + \frac{2 m_N F_M^2}{9 m_p^2} \left\langle \frac{1}{v} \right\rangle \sum_i f_i \hat{\mu}_i^2 \frac{I_i + 1}{I_i} \right]$$

spin-orbit

spin-spin

Dark hyperfine transitions

Cline, ZL, Xue, 1201.4858 (cites 106)



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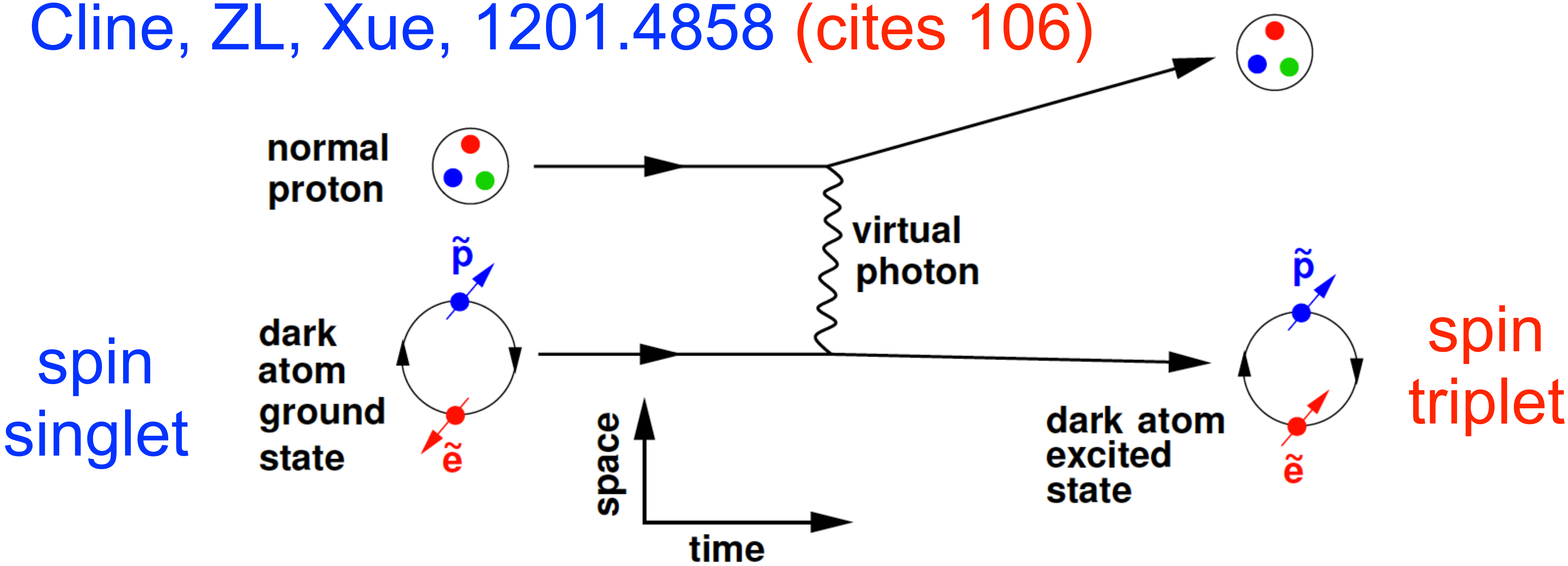

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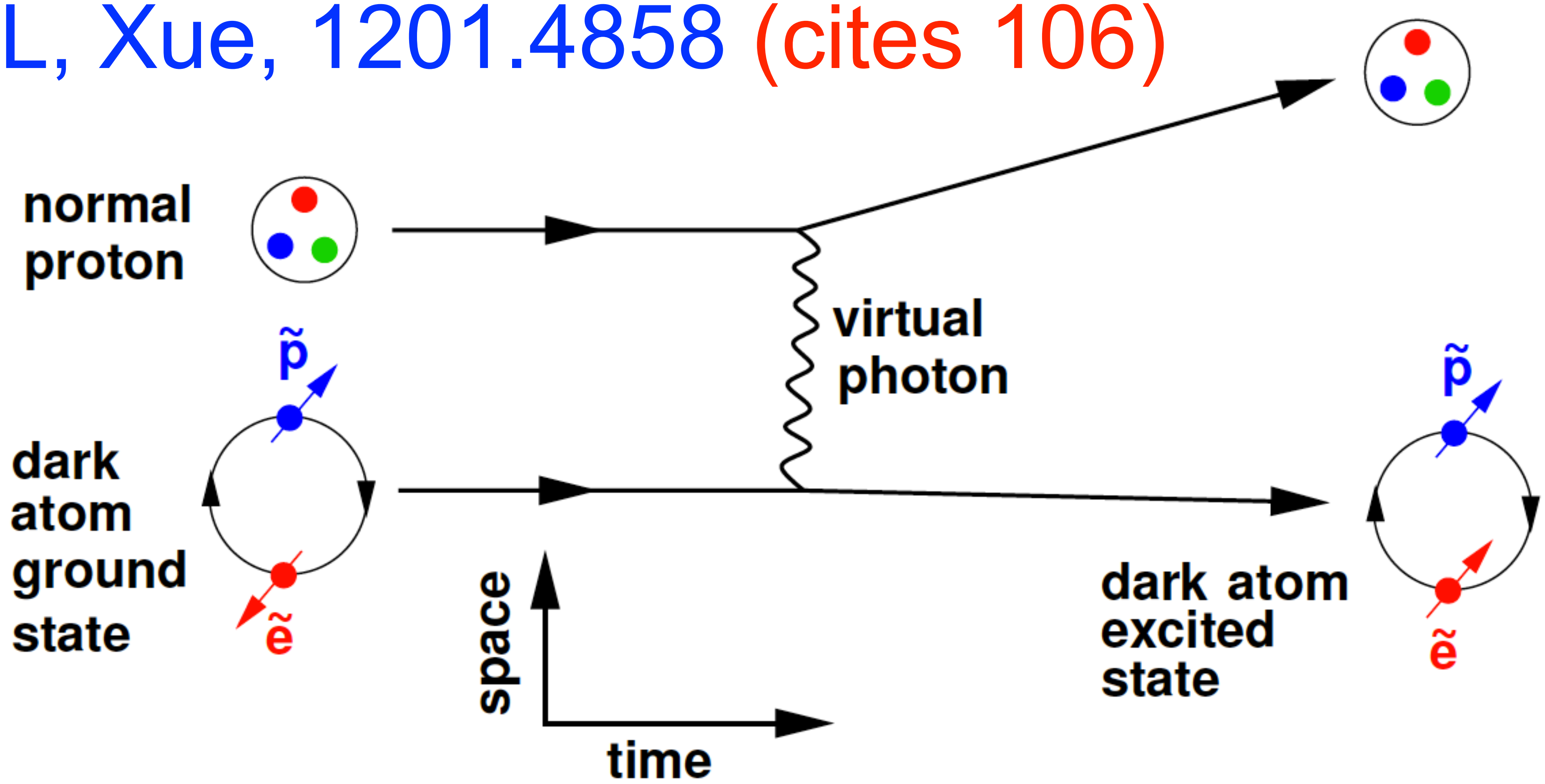


spin singlet

spin triplet

hyperfine splitting of the ground state

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

magnetic DM

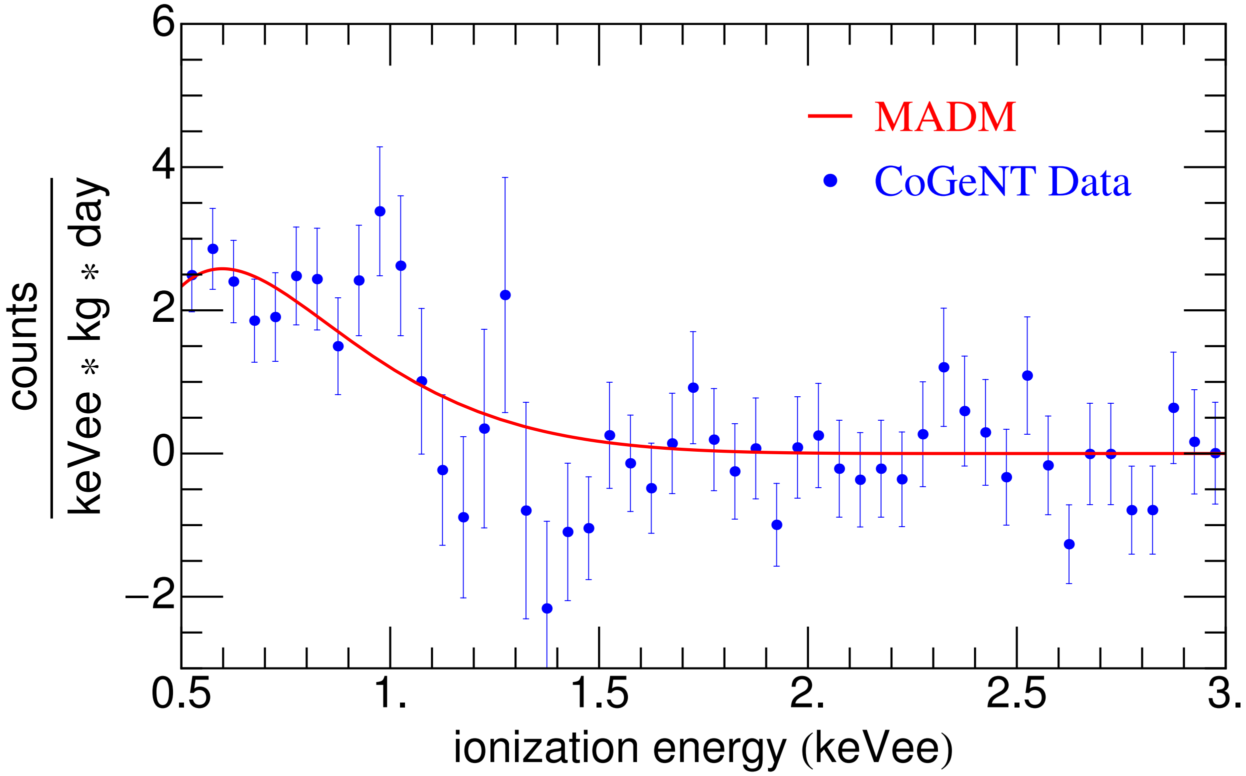
isospin violation

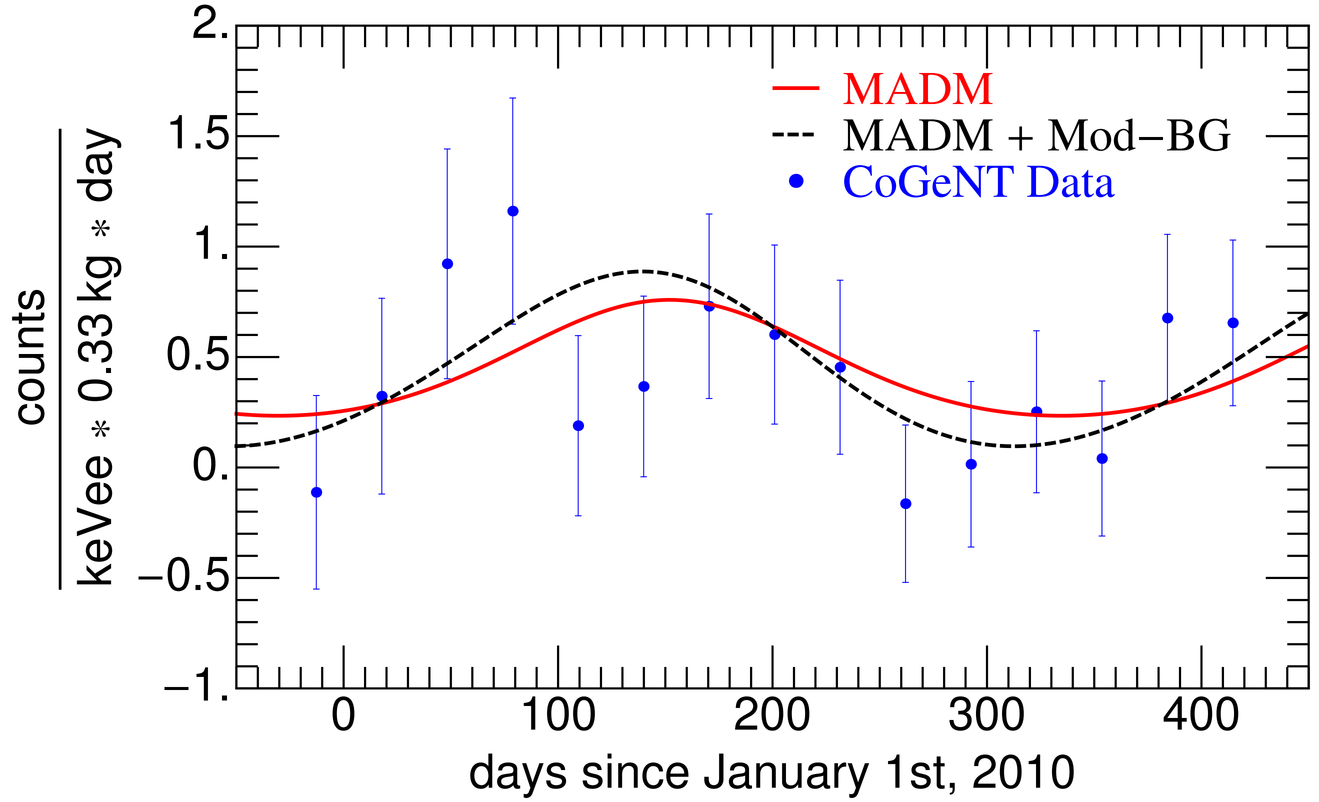
inelastic scattering

non-trivial velocity form factor

Fitting to CoGeNT excess

Cline, ZL, Xue, 1207.3039





$$(m_{H'}, \delta_{H'}, \epsilon) = (9.9 \text{ GeV}, 24.7 \text{ keV}, 0.029)$$

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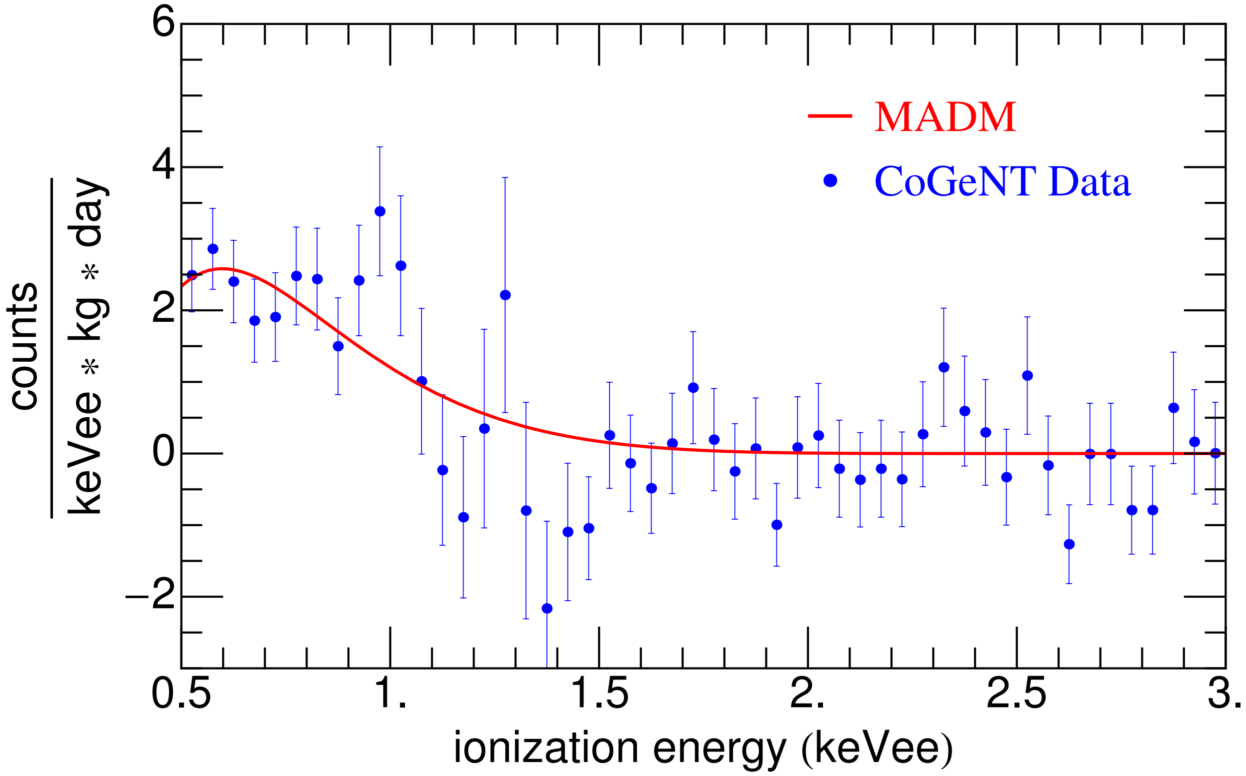

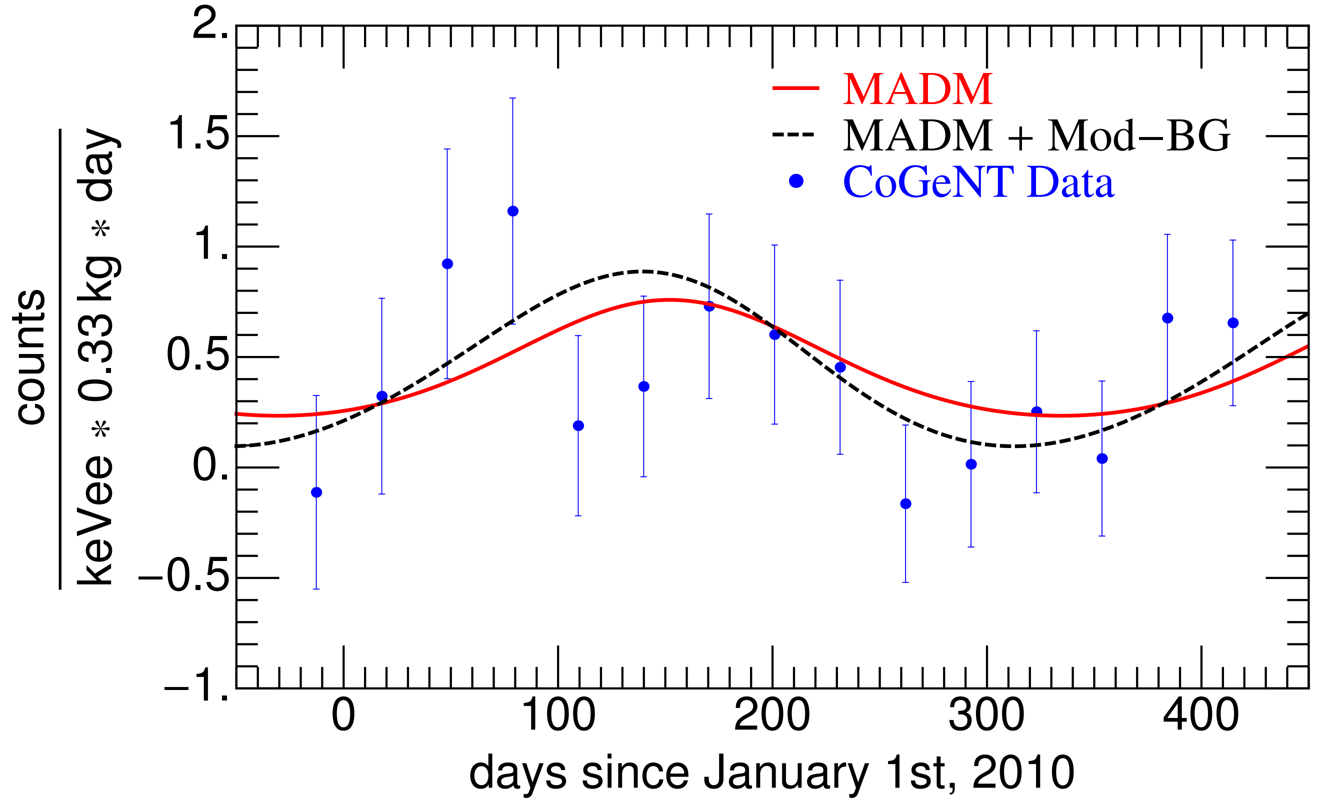

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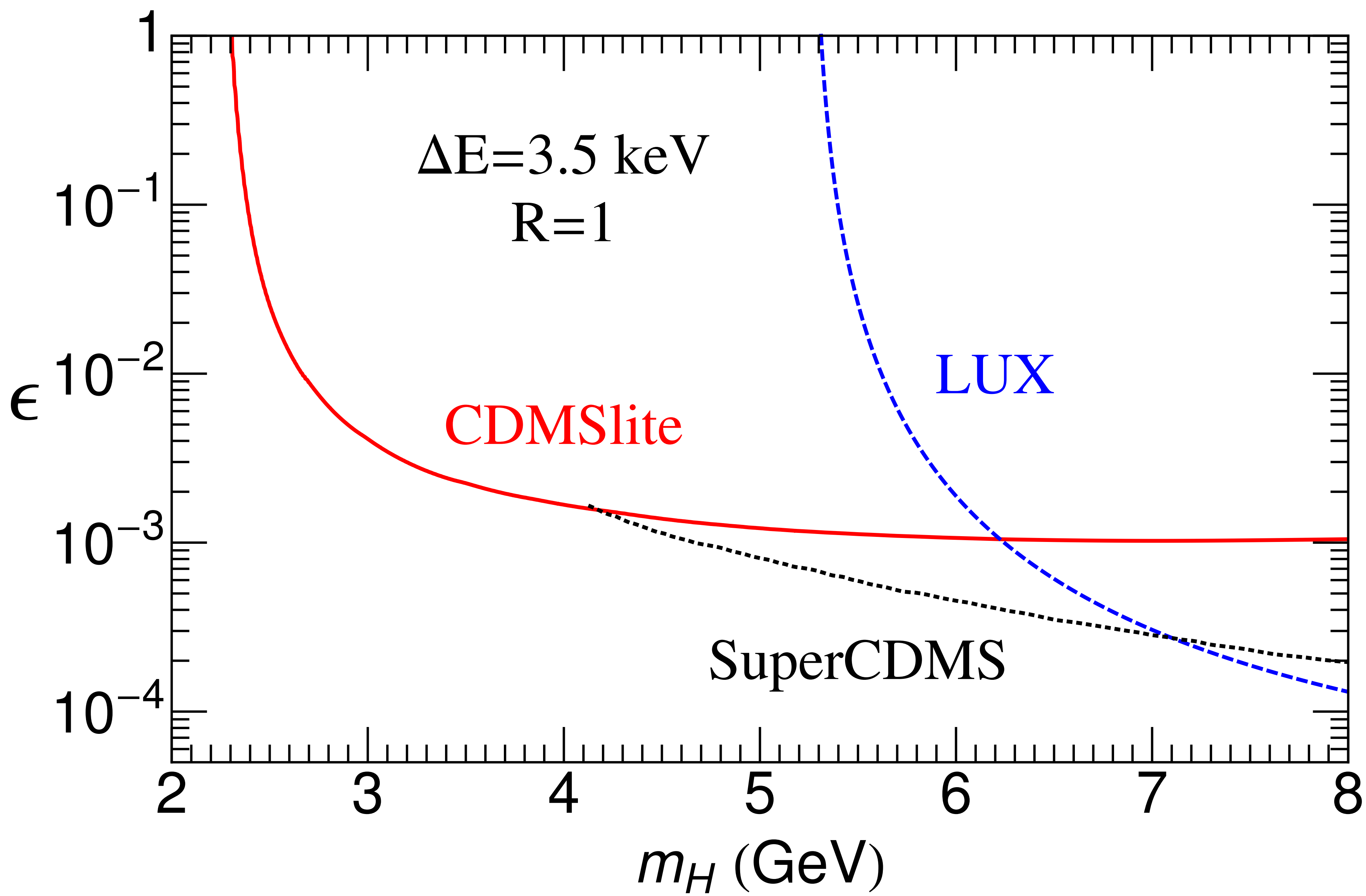
CoGeNT excess is not so promising now.

the coupling ε should be smaller

Constraints (2014)



CoGeNT

Small scale puzzles of CDM

ΛCDM faces 3 problems in small scales

- The cusp/core problem
- The missing satellite problem
- The "too big to fail" problem

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If DM scatters with itself elastically, with

$$\sigma/m \sim \ 1\ \mathrm{barn/GeV}$$

Spergel, Steinhardt '99

these problems are ameliorated.

Dark atom self-interaction

Dark atoms can scatter with each other (self interaction).

Due to the composite structure of the dark atom, the self scattering cross section can be sizeable.

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To compute the dark atom scattering cross section, we solve he Schrodinger equation for the radial wave function R(r)

$$\left[-\frac{1}{r}\frac{d^2}{dr^2}r + \frac{\ell(\ell+1)}{r^2} + 2\mu_{\mathrm{H'H'}}\,V(r)\right]R_\ell(r) = 2\mu_{\mathrm{H'H'}}\,E\,R_\ell(r)$$

The atom-atom reduced mass $\mu_{\mathrm{H'H'}} = m_{\mathrm{H'}}/2$

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The problem depends on **three** free parameters only

$$\{\alpha', m_{e'}, m_{p'}\} \longrightarrow \{\alpha', m_{H'} = m_{e'} + m_{p'} - B, R = m_{p'}/m_{e'}\}$$

Schrodinger Eq. in atomic units

$$\left[\frac{d^2}{dr^2} - \frac{\ell(\ell+1)}{r^2} + m_{\mathrm{H}'}(E - V(r))\right]\underline{[rR_\ell(r)]} = 0$$

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Work in the atomic unit system

Distance in unit of Bohr radius $\quad a_0 = \dfrac{1}{\alpha' \mu}$

Energy in unit of binding energy $\quad \epsilon_0 = 2B = {\alpha'}^2 \mu$

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Change to atomic units

$$r = r_{\mathrm{au}}\, a_0$$

$$E = E_{\mathrm{au}}\, \epsilon_0$$

$$V = V_{\mathrm{au}}\, \epsilon_0$$

$$\left[\frac{d^2}{dr_{\mathrm{au}}^2} - \frac{\ell(\ell+1)}{r_{\mathrm{au}}^2} + m_{\mathrm{H}'} a_0^2 \epsilon_0 \left(E_{\mathrm{au}} - V_{\mathrm{au}}\right)\right] u_\ell(r_{\mathrm{au}}) = 0$$

New Physics

Only R Dependence

In atomic units, the Schrodinger equation becomes

$$\left[\partial_r^2 - \frac{\ell(\ell+1)}{r^2} + f(R,\alpha')\,(E-V)\right][rR_\ell(r)] = 0$$

$$f(R,\alpha') \equiv m_{\mathrm{H}'} a_0^2 \epsilon_0 = \frac{m_{\mathrm{H}'}}{\mu} = R + 2 + \frac{1}{R} - \frac{\alpha'^2}{2} \simeq R + 2 + \frac{1}{R}$$

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In atomic units, both the coupling constant and atomic mass disappear when neglecting the atomic binding energy.

Only R appears! f(R) acts like a particle mass.

Electron Spin States

The electrons in the two scattering atoms can be either in the spin triplet or the spin singlet states.

$$\left[\partial_r^2 - \frac{\ell(\ell+1)}{r^2} + f(R,\alpha')\,(E - V_{s,t})\right]\left[r R_\ell^{s,t}(r)\right] = 0$$

potentials for electron spin singlet and triplet channels $\mathbf{V_{s,t}}$

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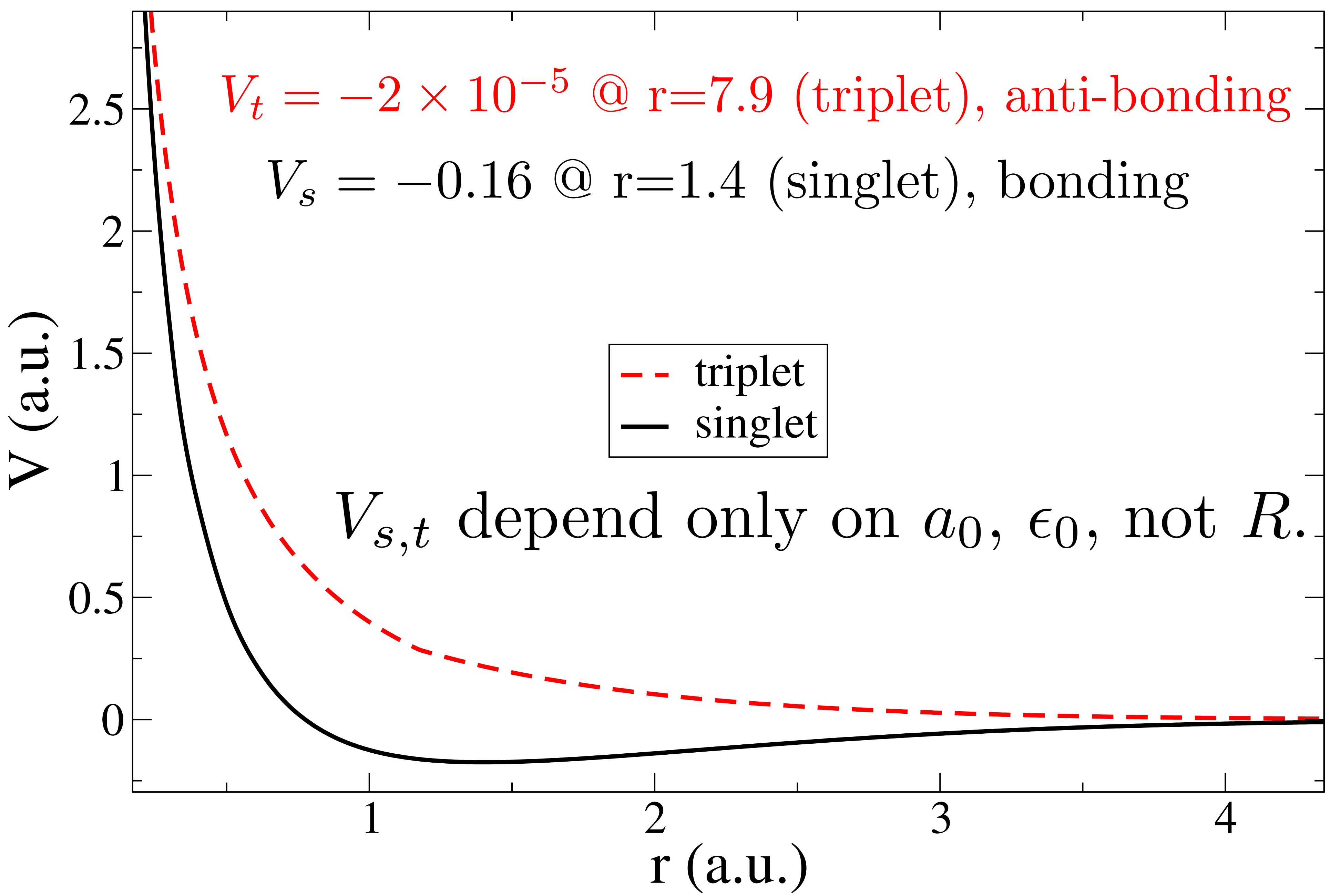
potentials for electron spin singlet and triplet channels $\mathbf{V_{s,t}}$

The singlet state has a symmetric spatial wave function, leading to a much deeper potential well

The triplet state must have a spatially antisymmetric electronic wave function, leading to a potential with a very shallow minimum.

Atomic Hydrogen Potentials



Triplet

Kolos, Wolniewicz '74

Silvera '80

Silvera, Walraven '86

Singlet

Wolniewicz '93

The singlet potential is responsible for Hydrogen molecule formation

Scatterings are more sensitive to the singlet potential than the triplet

We use both potentials to compute dark atom scatterings

Partial Wave Method

asymptotically $rR_\ell^{s,t} \to \sin(kr - \ell\pi/2 + \delta_\ell^{s,t}(k))$

cross section $\sigma_\ell = 4\pi/k^2(2\ell+1)\sin^2(\delta_\ell)$

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$$\sigma = 2\,\frac{4\pi}{k^2}\sum_\ell (2\ell+1)\begin{cases} \frac{1}{16}\sin^2\delta_\ell^s + \frac{9}{16}\sin^2\delta_\ell^t, & \ell \text{ even} \\ \frac{3}{16}\sin^2\delta_\ell^s + \frac{3}{16}\sin^2\delta_\ell^t, & \ell \text{ odd} \end{cases}$$

Jamieson et al. ‘99

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Identical particles

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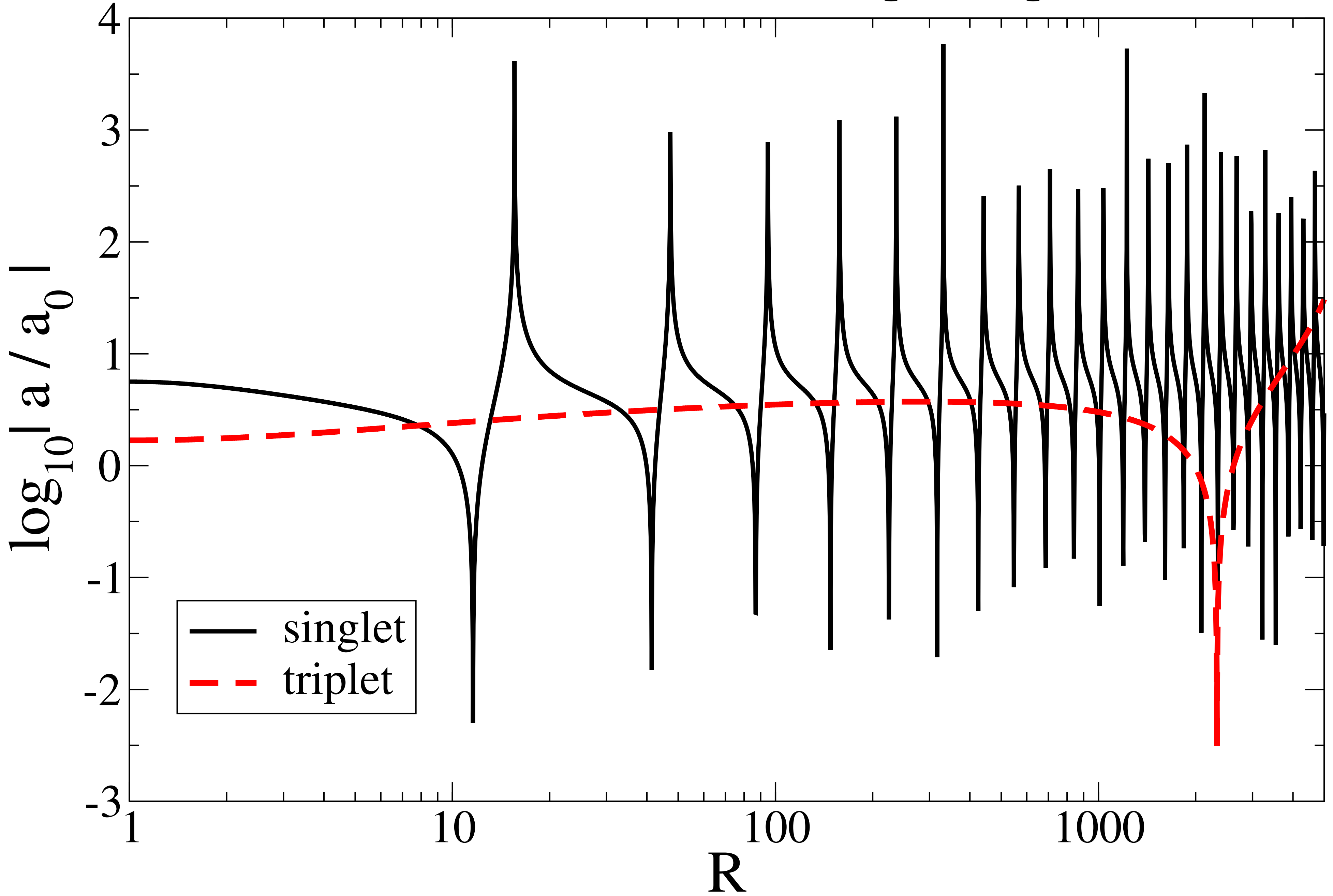
Jamieson et al. '99

R-dependence of scattering length

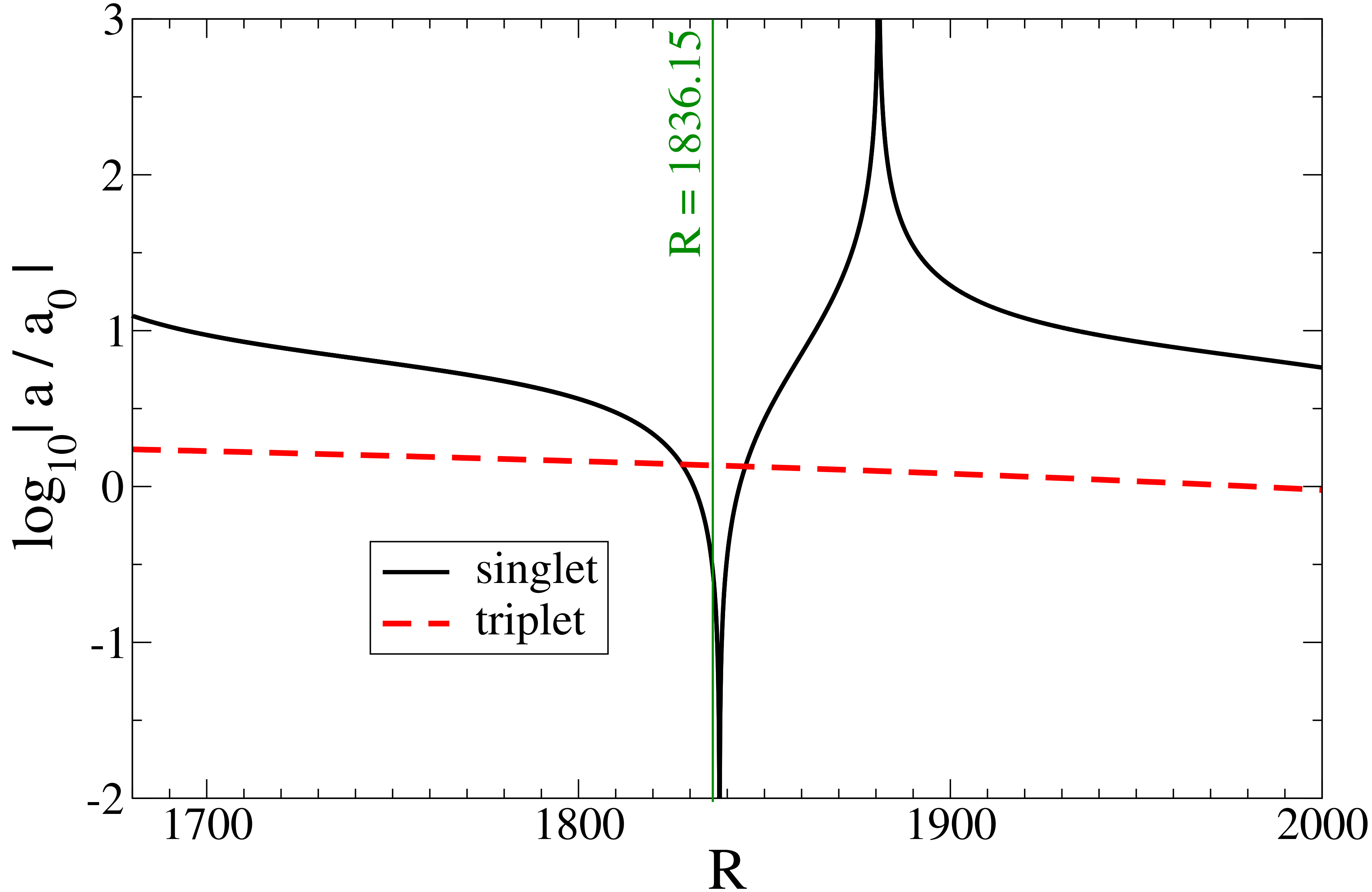
scattering length $a = \lim_{k\to 0}\sqrt{\frac{\sigma(k)}{4\pi}}$



effective mass increases with R: deeper potential causes more bound states, which produce divergences in scattering length

Our real world: R=1836.15

Real world happens to be dominated by the triplet potential



$a_s = 0.28$

$a_t = 1.37$

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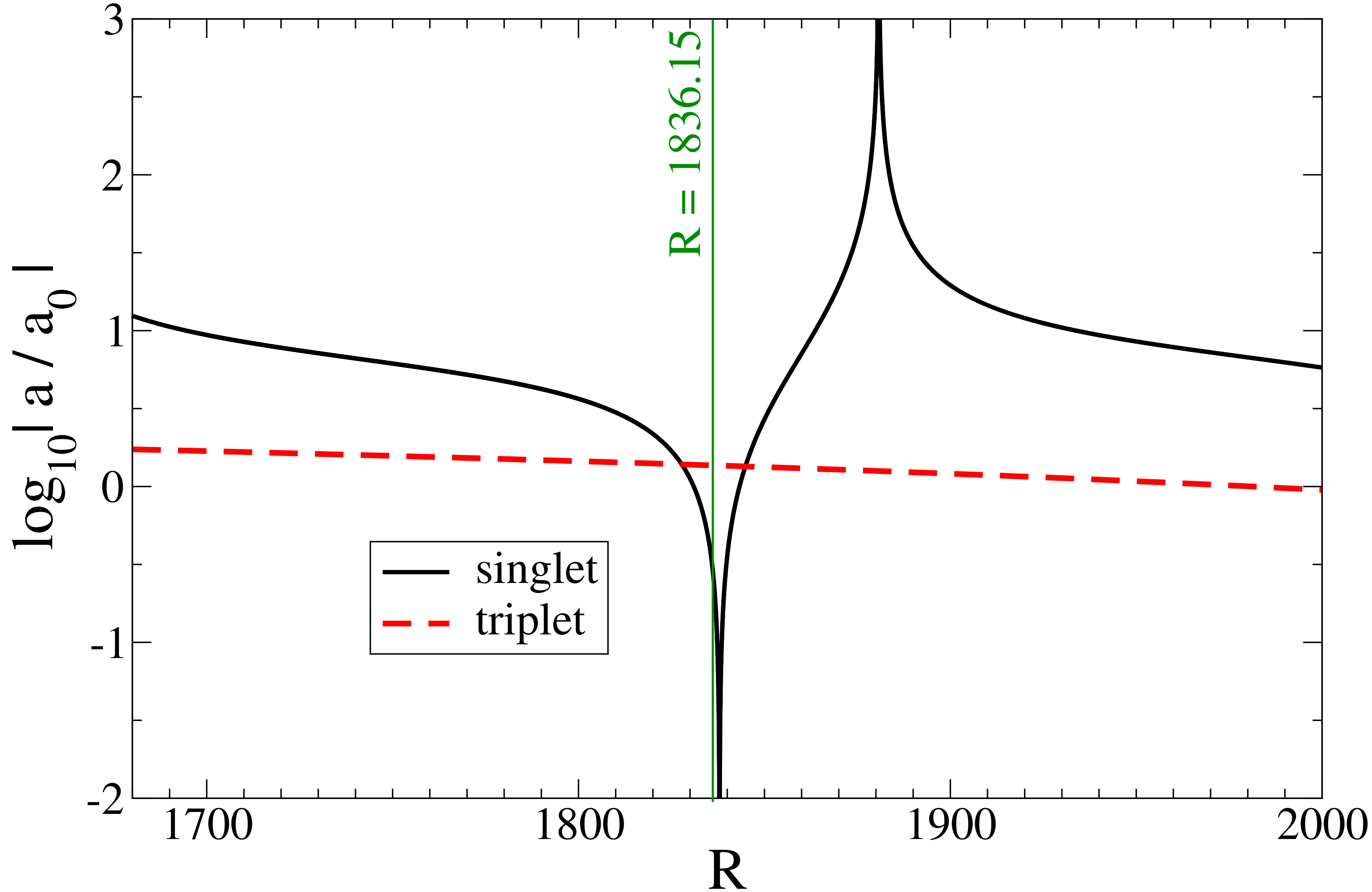


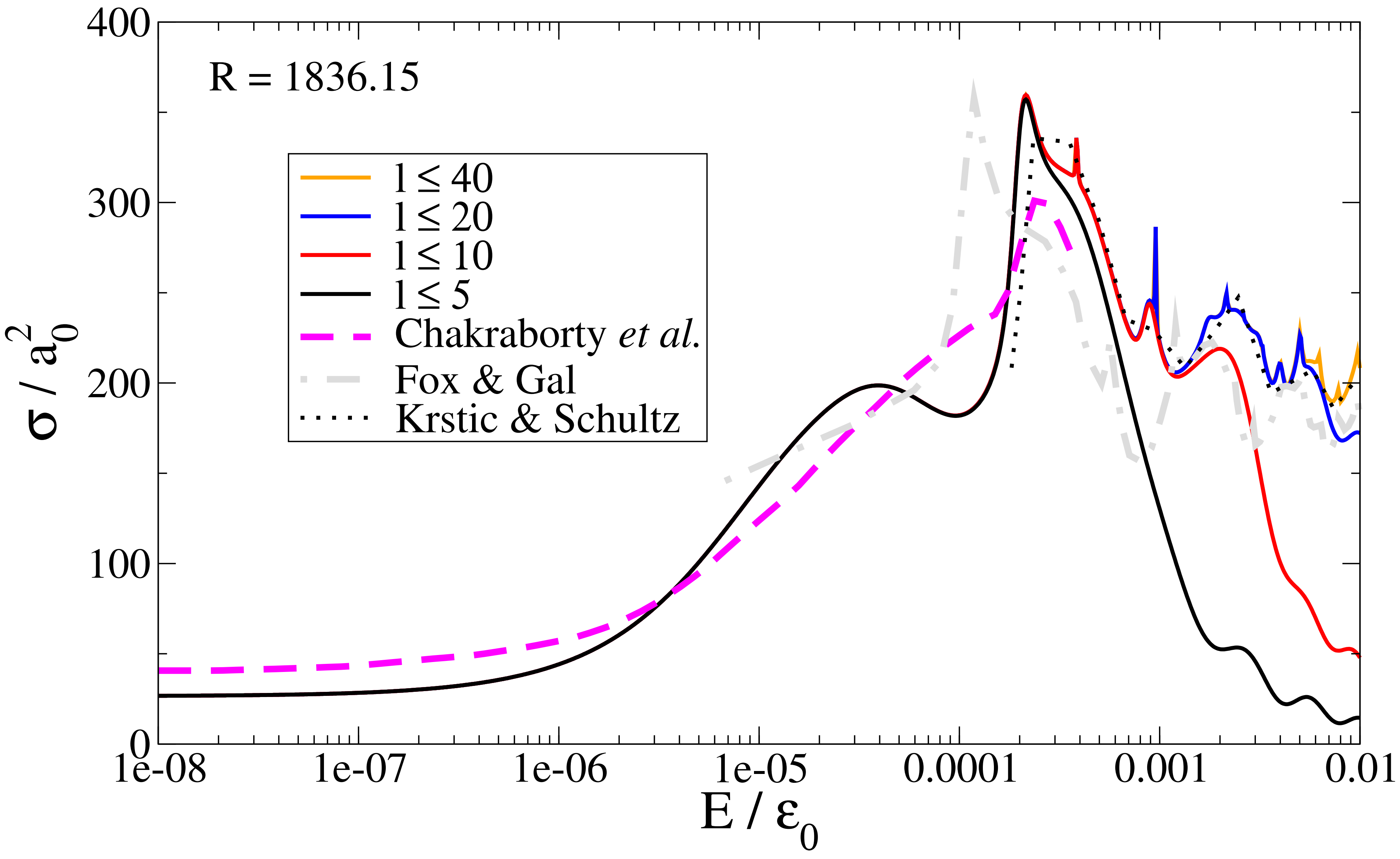
$$a_s = 0.28$$

$$a_t = 1.37$$

Real world cross section, σ~25 (atomic unit) is much smaller than the typical cross section, σ~(100-1000)

Reproducing known results

Recent result from the atomic physics literature: R=1836.35



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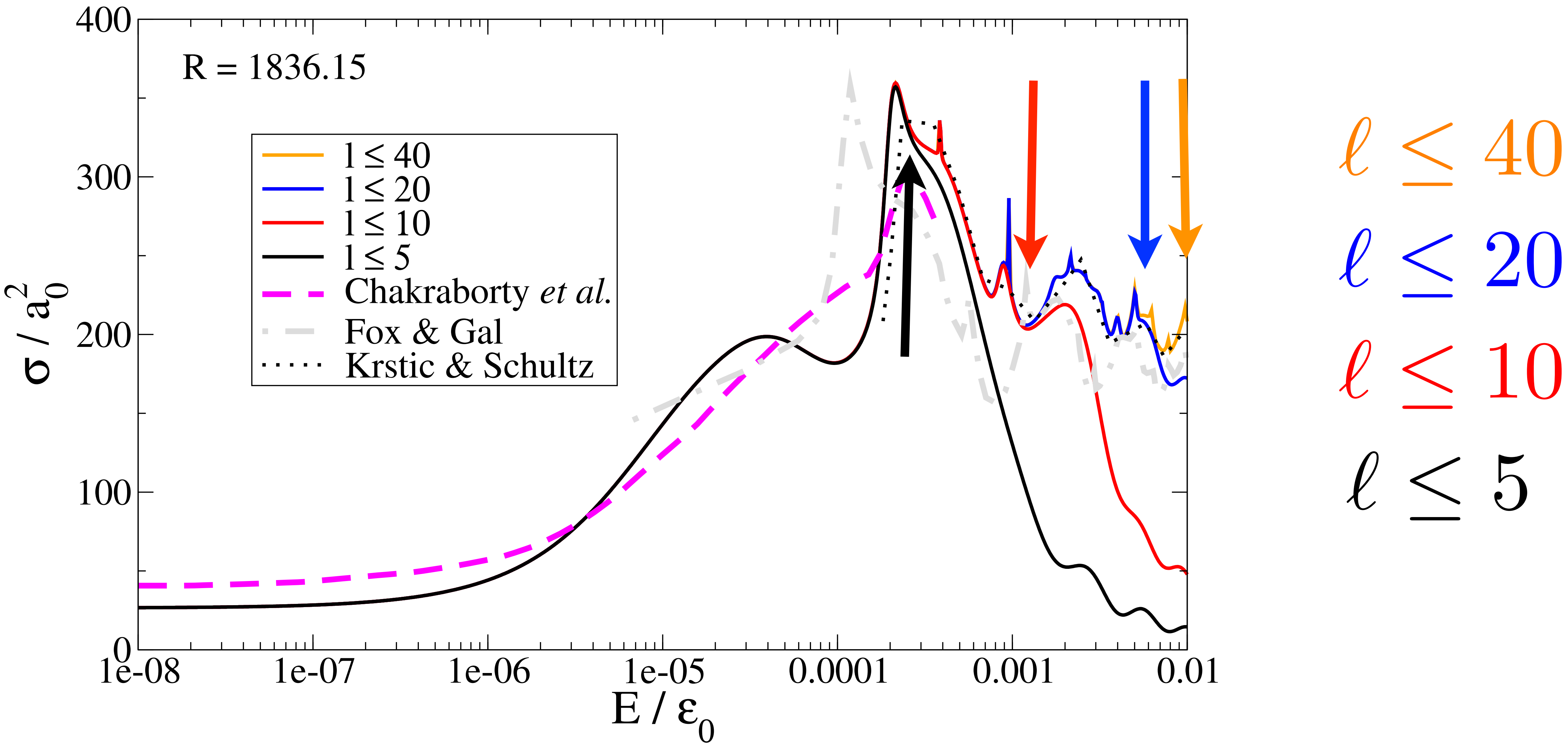

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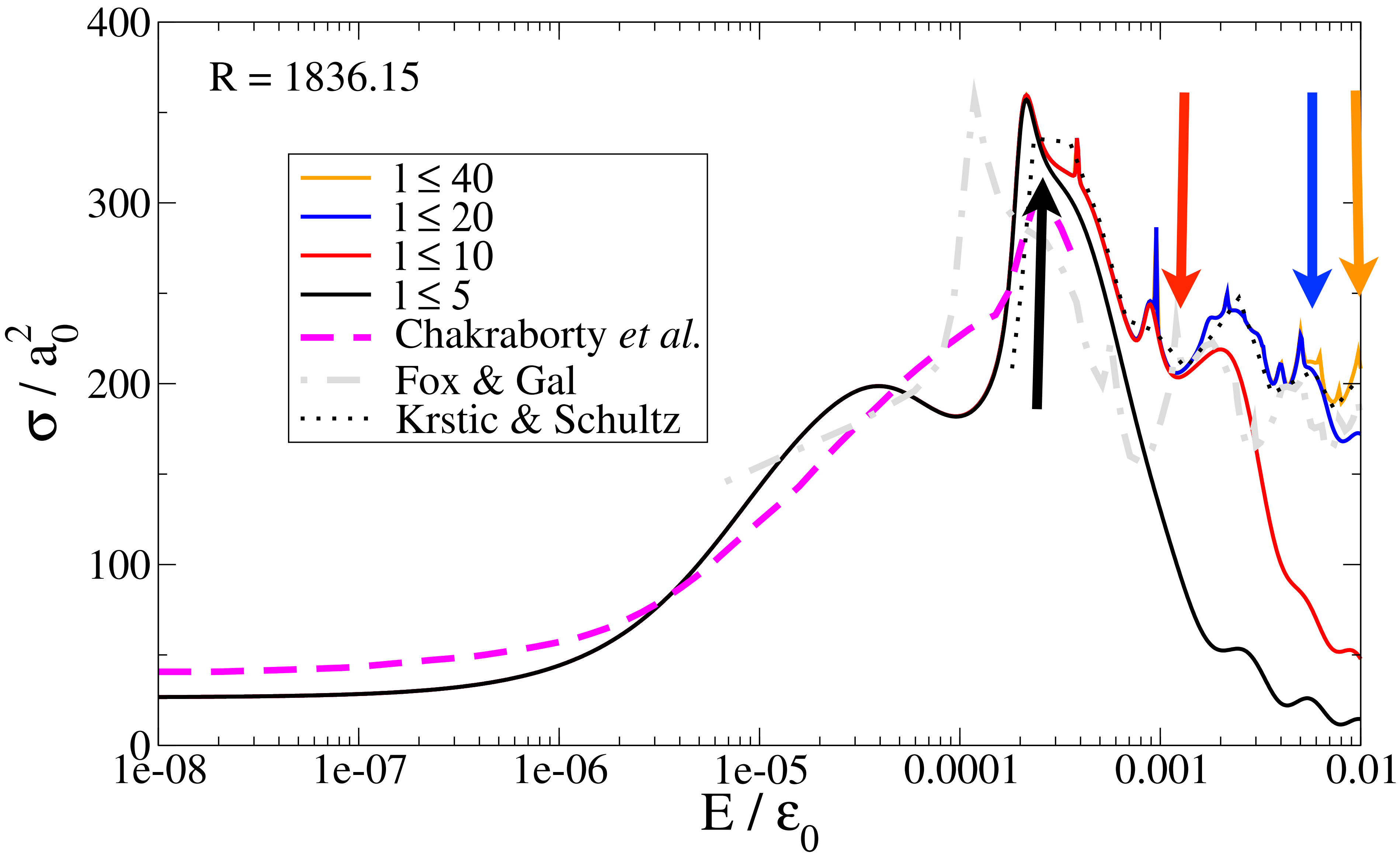


$\ell \leq 40$

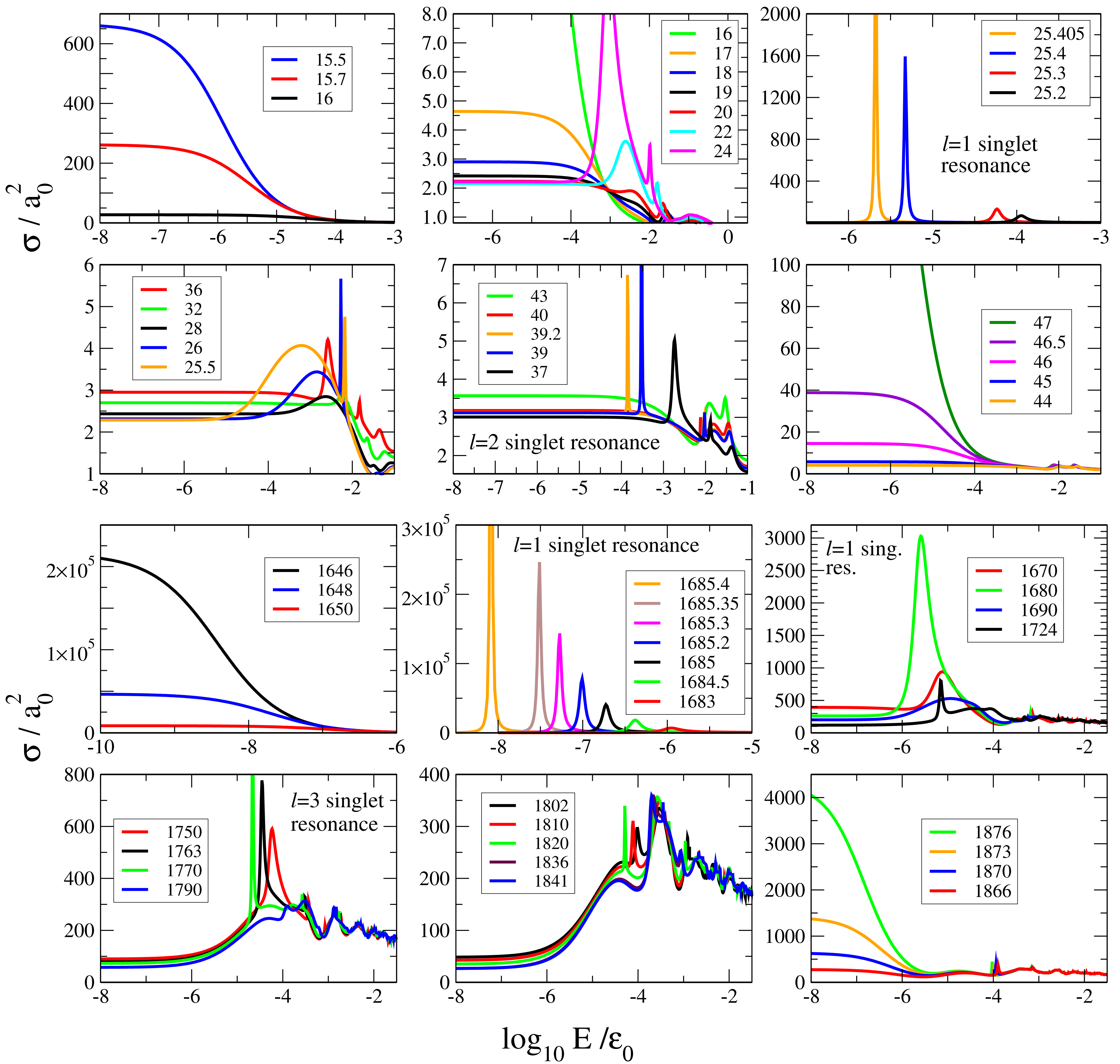
$\ell \leq 20$

$\ell \leq 10$

$\ell \leq 5$

We are interested in the low energy scattering, E<0.01 $(\ell \leq 40)$

R-dependence of cross section



Many intricate features in cross section as a function of energy and of R

Transport cross section

Transport cross section

We compute transport sec instead of elastic xsec, since forward scattering does not exchange energy much.

Commonly used transport cross section

$$\sigma_t = 2\pi \int d(\cos\theta)(1-\cos\theta)\frac{d\sigma}{d\Omega}$$

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Commonly used transport cross section

$$\sigma_t = 2\pi \int d(\cos\theta)(1-\cos\theta)\frac{d\sigma}{d\Omega}$$

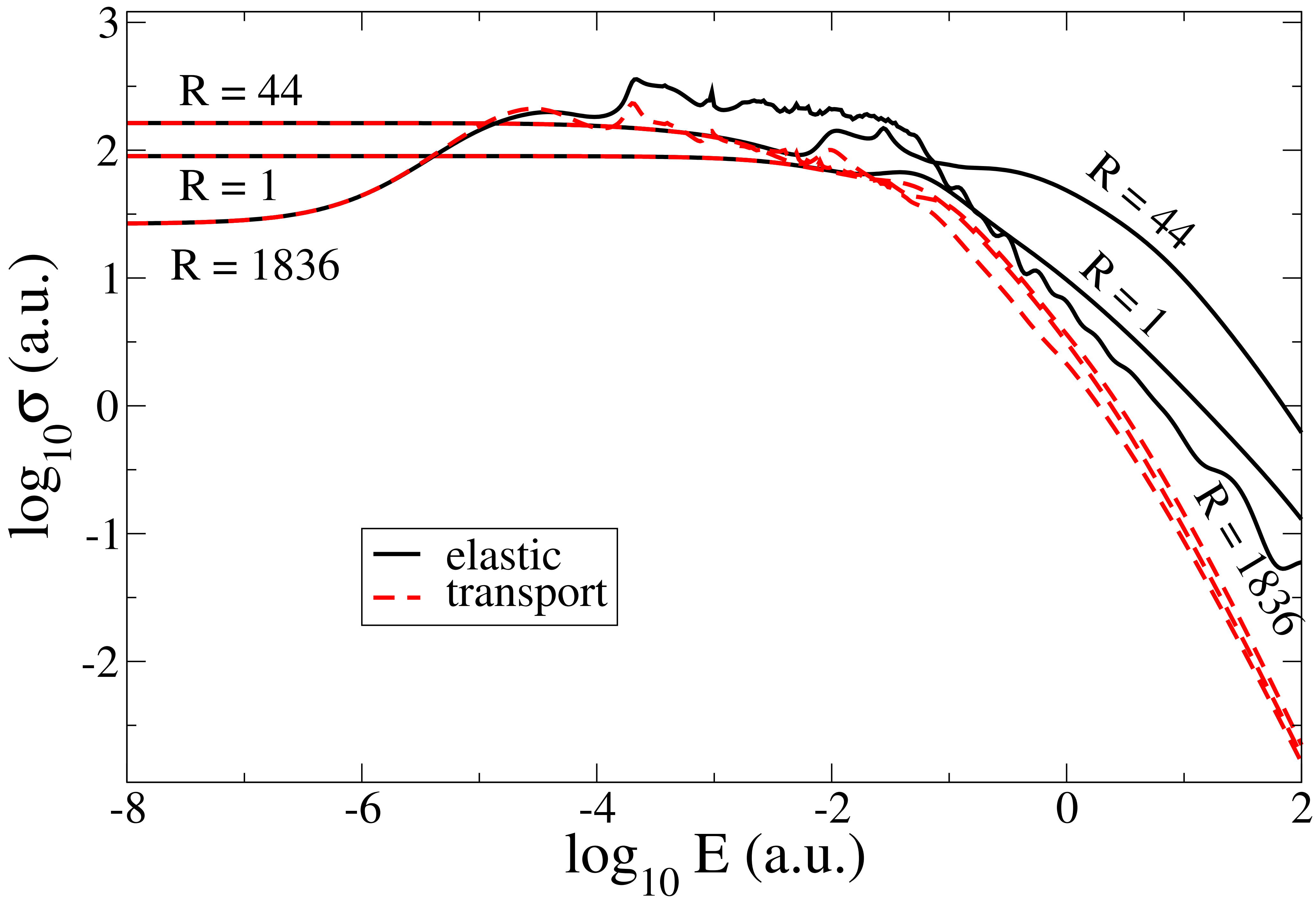
To treat forward and backward scatterings as equivalent (for identical particles), it is more appropriate to use

$$\sigma_t' = 2\pi \int d(\cos\theta)(1-\cos^2\theta)\frac{d\sigma}{d\Omega}$$

The transport x-sec in terms of partial waves

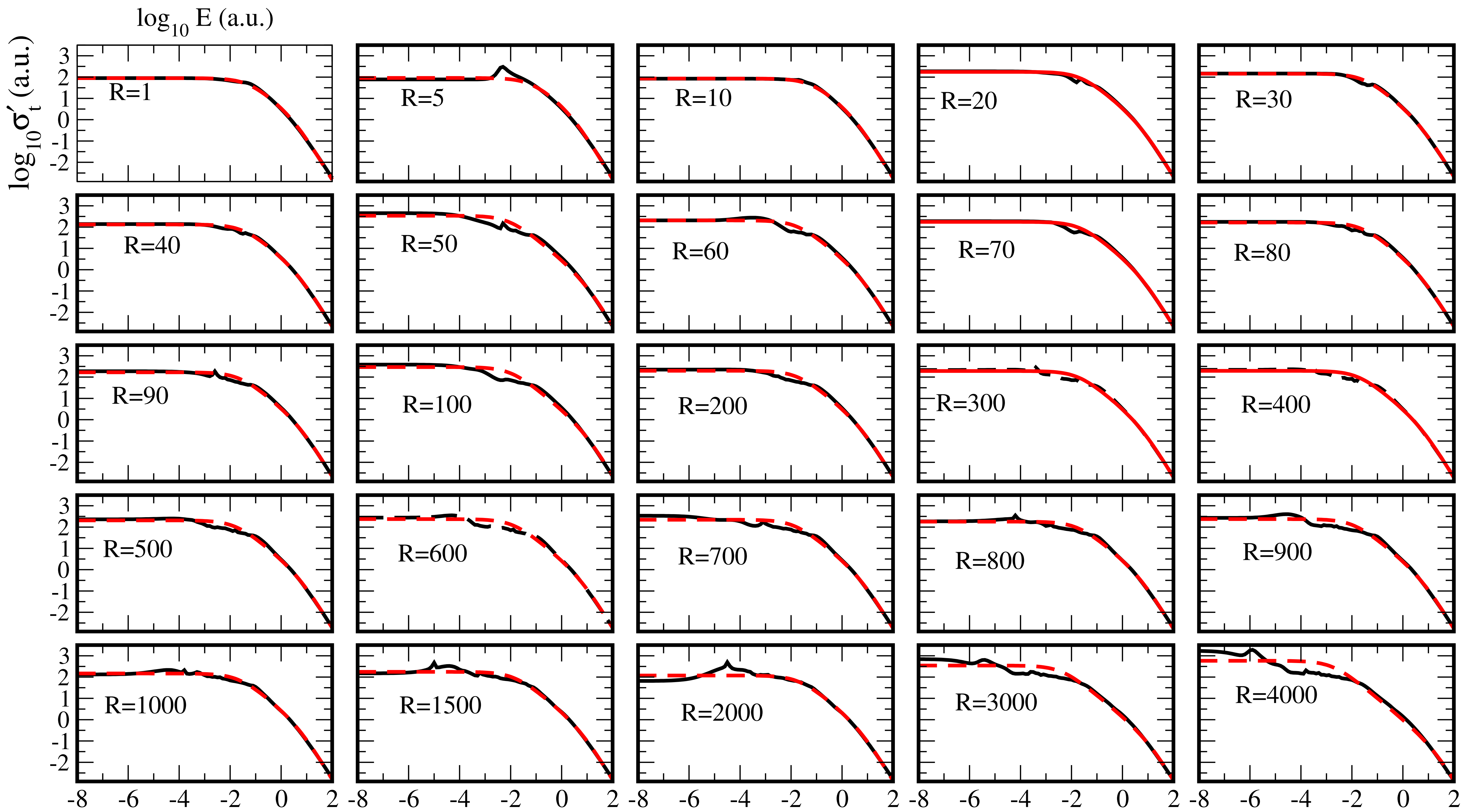
$$\sigma_t' = \frac{6\pi}{k^2}\sum_\ell \frac{(\ell+1)(\ell+2)}{(2\ell+3)}\sin^2(\delta_\ell - \delta_{\ell+2})$$

Transport vs. Elastic



The transport cross section deviates from the elastic case at E = 0.1 a.u., where higher partial waves becomes important.

Energy dependence for different R



solid: momentum transfer cross section;
dashed: fit by the ansatz

$$\sigma'_t \cong (a_0 + a_1 E + a_2 E^2)^{-1}$$

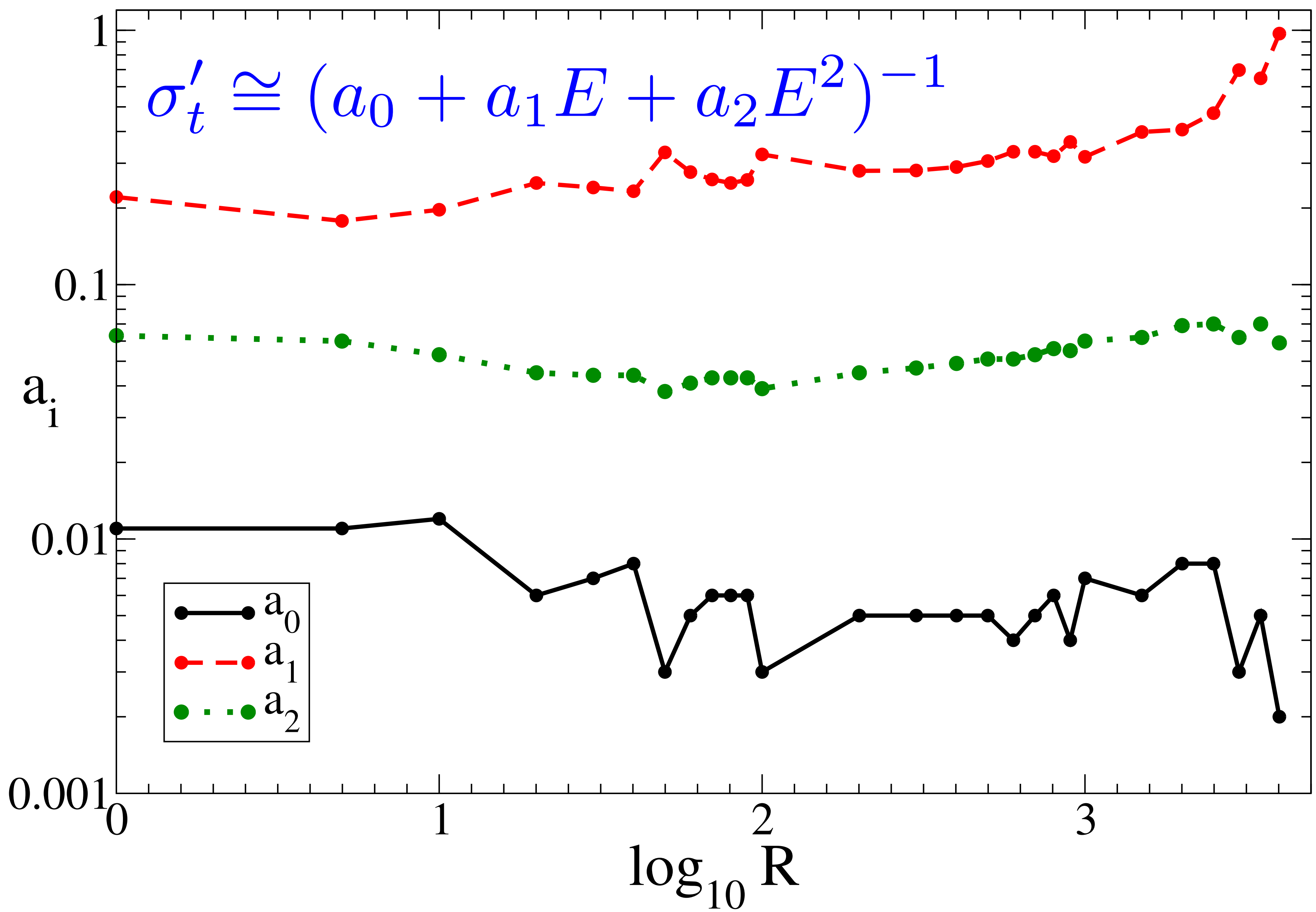
Coefficients of the fit ansatz

$$\sigma_t' \cong (a_0 + a_1 E + a_2 E^2)^{-1}$$

R	a_0	a_1	a_2	χ^2	R	a_0	a_1	a_2	χ^2
1	0.011	0.221	0.063	0.084	400	0.005	0.290	0.049	1.000
5	0.011	0.178	0.060	1.696	500	0.005	0.306	0.051	1.157
10	0.012	0.197	0.053	0.056	600	0.004	0.333	0.051	2.065
20	0.006	0.251	0.045	0.288	700	0.005	0.333	0.053	2.120
30	0.007	0.241	0.044	0.208	800	0.006	0.320	0.056	0.876
40	0.008	0.233	0.044	0.194	900	0.004	0.364	0.055	2.208
50	0.003	0.331	0.038	2.599	1000	0.007	0.318	0.060	0.593
60	0.005	0.277	0.041	1.026	1500	0.006	0.398	0.062	1.351
70	0.006	0.259	0.043	0.567	2000	0.008	0.407	0.069	2.964
80	0.006	0.251	0.043	0.412	2500	0.008	0.472	0.070	2.272
90	0.006	0.258	0.043	0.631	3000	0.003	0.697	0.062	4.531
100	0.003	0.325	0.039	2.726	3500	0.005	0.647	0.070	3.677
200	0.005	0.280	0.045	0.942	4000	0.002	0.970	0.059	10.014
300	0.005	0.281	0.047	0.972	4500	0.002	1.045	0.060	15.530

$$\chi^2 = \sum_{i=1}^{101} \log_{10}^2(\sigma_t'/\mathrm{fit})$$ for 101 uniformly spaced points in $\log_{10}(E) \in [-8, 2]$

Energy dependence for different R



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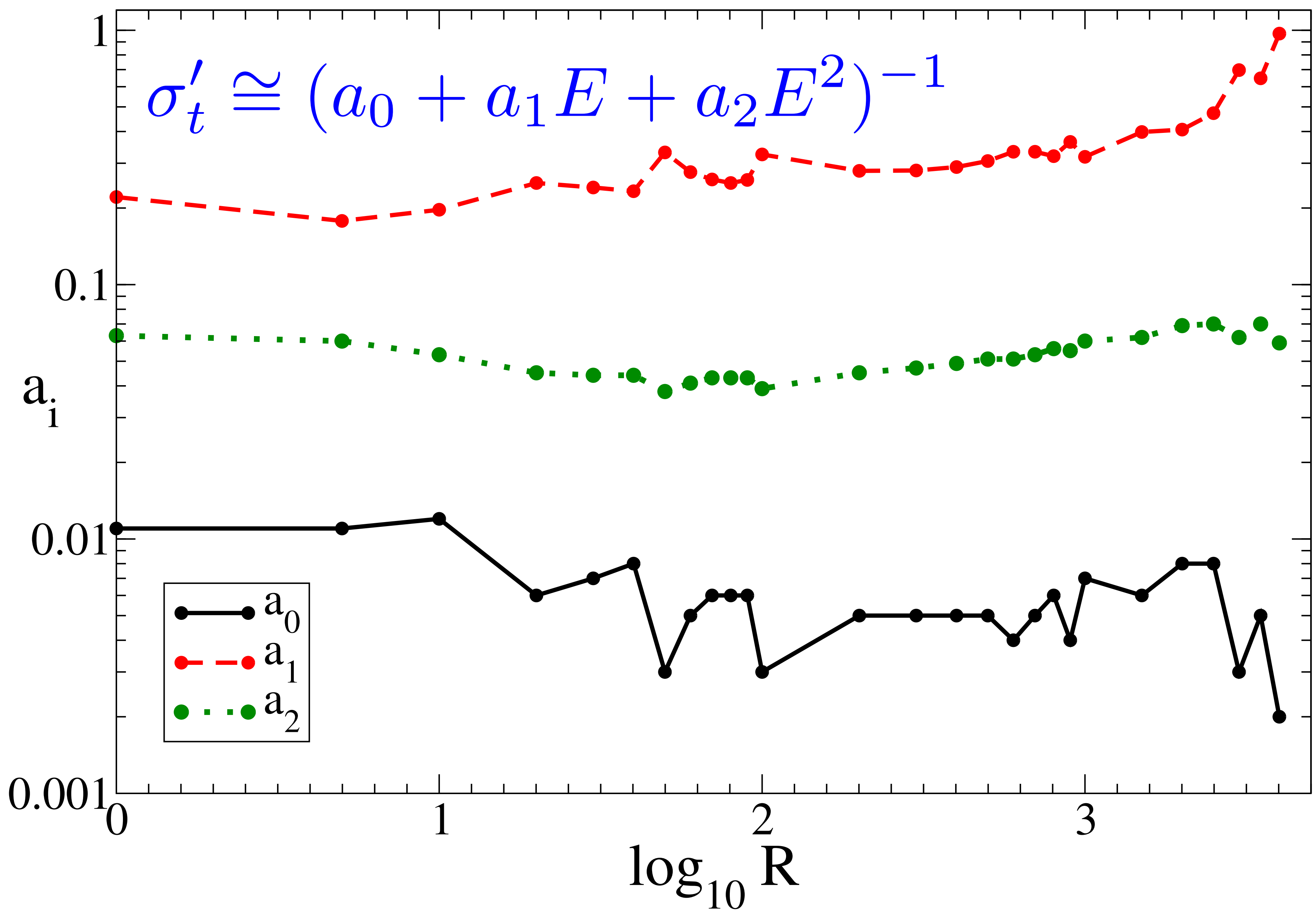
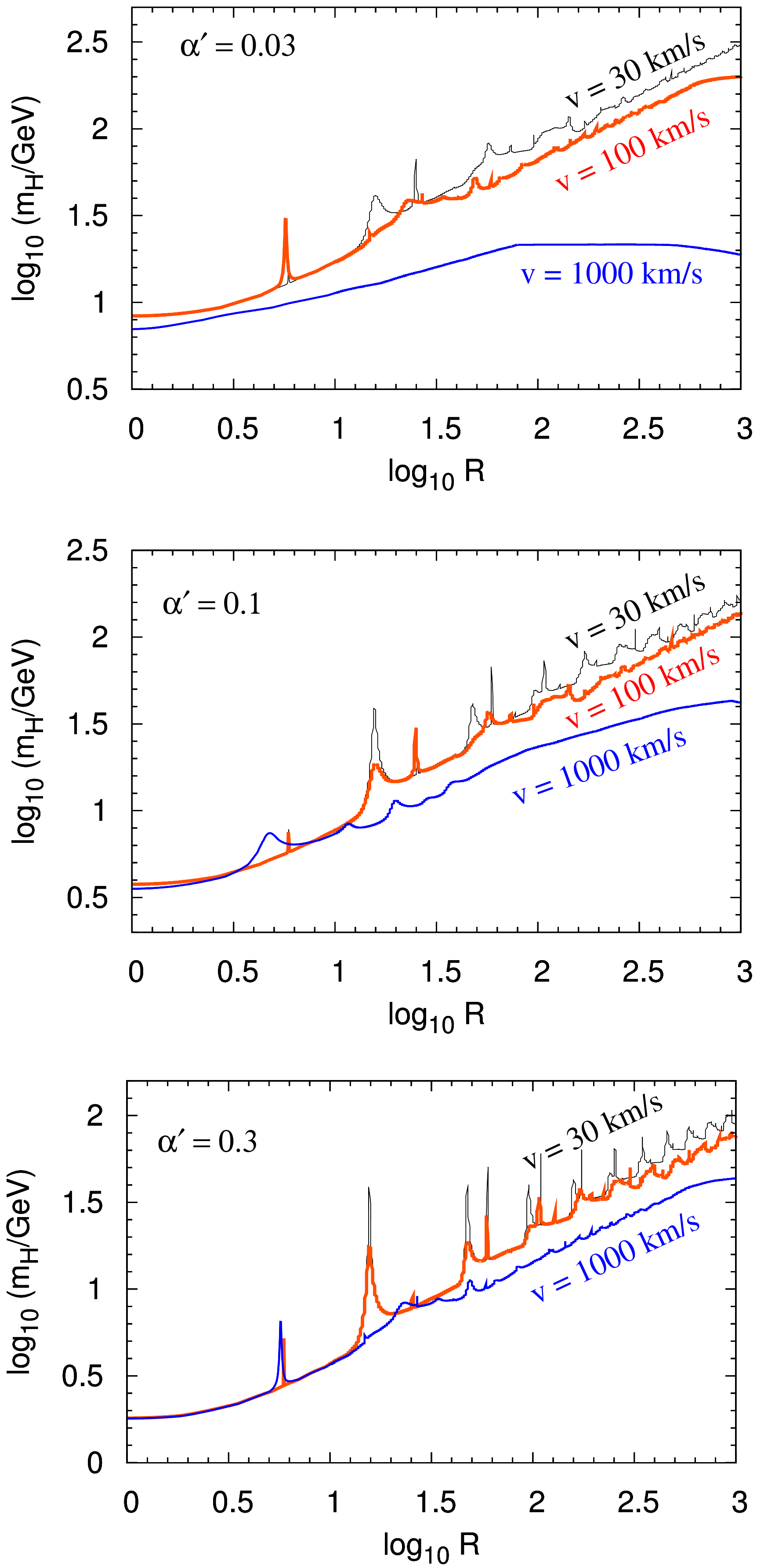


Rough estimates: $\sigma'_t \simeq \frac{1}{a_0} \sim 100(a'_0)^2$ at low energy.

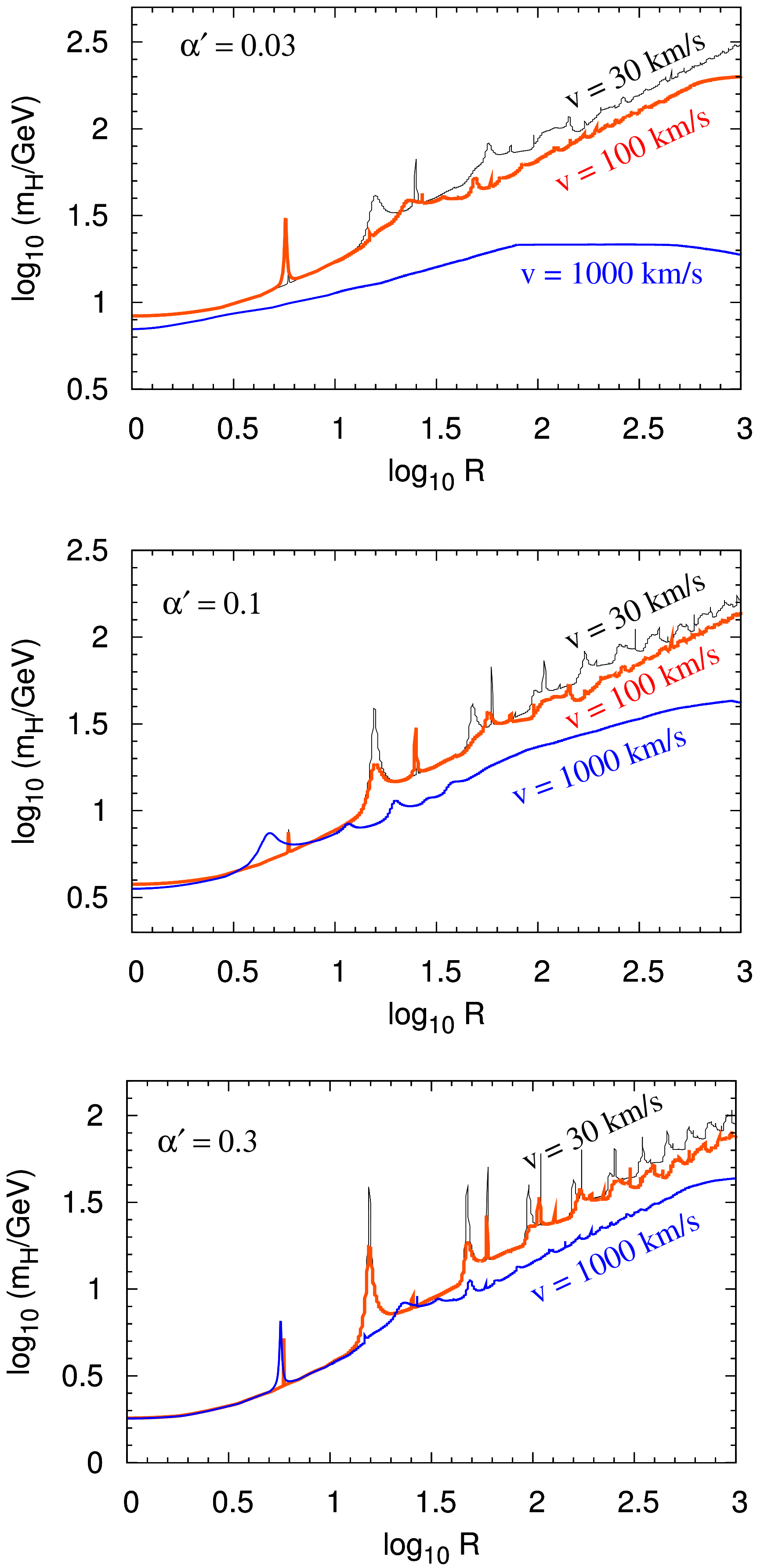
$$\frac{\sigma'_t}{m'_{\mathrm{H}}} \sim 100\frac{{a'_0}^2}{m'_{\mathrm{H}}} = 100\frac{1}{\alpha'^2\mu^2 m'_{\mathrm{H}}} = 100\frac{f^2}{\alpha'^2 m'^3_{\mathrm{H}}} \sim 100\frac{R^2}{\alpha'^2 m'^3_{\mathrm{H}}}$$



Preferred regions of parameter space

$$\frac{\sigma_{\mathrm{H'H'}}}{m'_{\mathrm{H}}} = 0.6\ \frac{\mathrm{cm}^2}{\mathrm{gram}} \sim \frac{\mathrm{barn}}{\mathrm{GeV}}$$

mass versus $R = m_{p'}/m_{e'}$ for different couplings and velocities



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mass versus $R = m_{p'}/m_{e'}$ for different couplings and velocities

30 km/s ⇒ dwarfs

100 km/s ⇒ Milky-Way-like galaxies

1000 km/s ⇒ galactic clusters

3.5 keV X-ray line anomaly

Boyarsky et al., arXiv:1402.4119

XMM-Newton X-ray observatory data from
Andromeda galaxy and Perseus galaxy cluster.

Bulbul, et al., arXiv:1402.2301

stacked spectra of 73 galaxy clusters

Boyarsky et al., arXiv:1408.2503

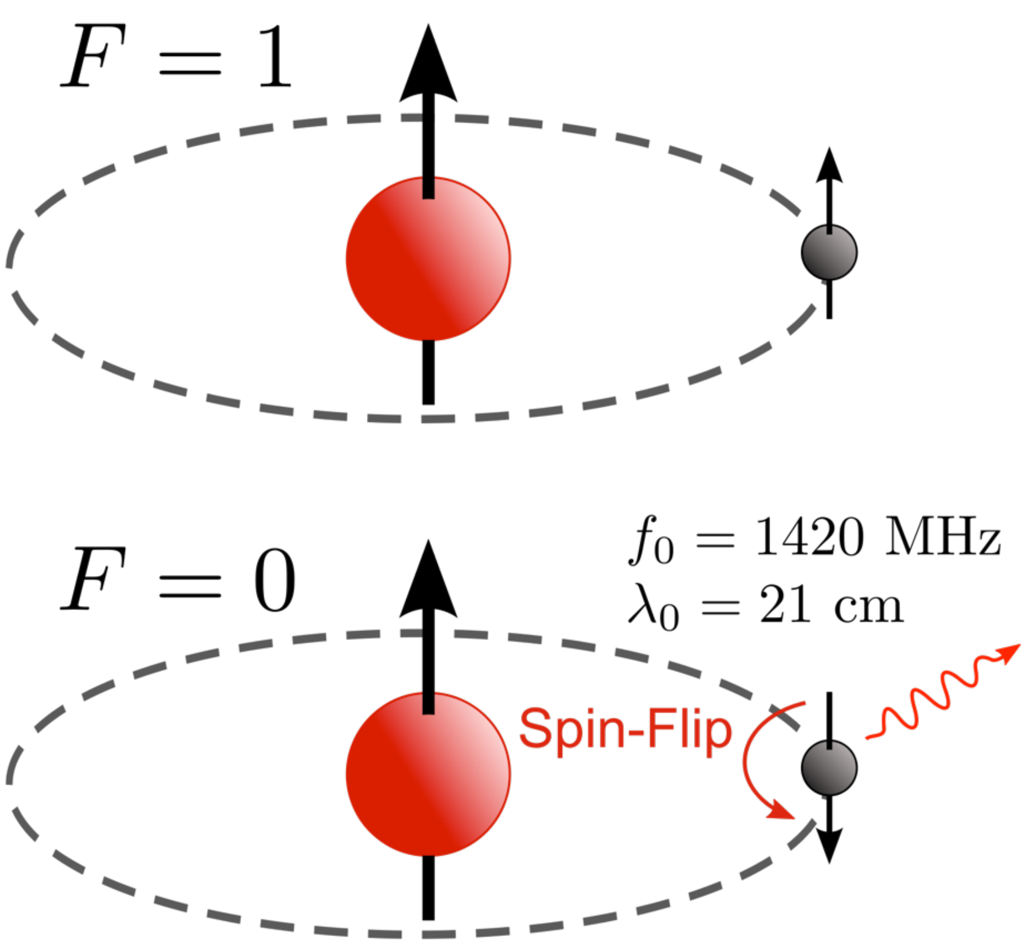
seen in the Galactic Center region in MW

+ others

Dark atom line

The 3.5 keV line can be the hyperfine splitting of the dark atom

$$\Delta E_{\mathrm{hyperfine}} = \frac{8}{3}\alpha'^4 \frac{m_{e'}^2 m_{p'}^2}{m_{H'}^3} = 3.5 \text{ keV}$$



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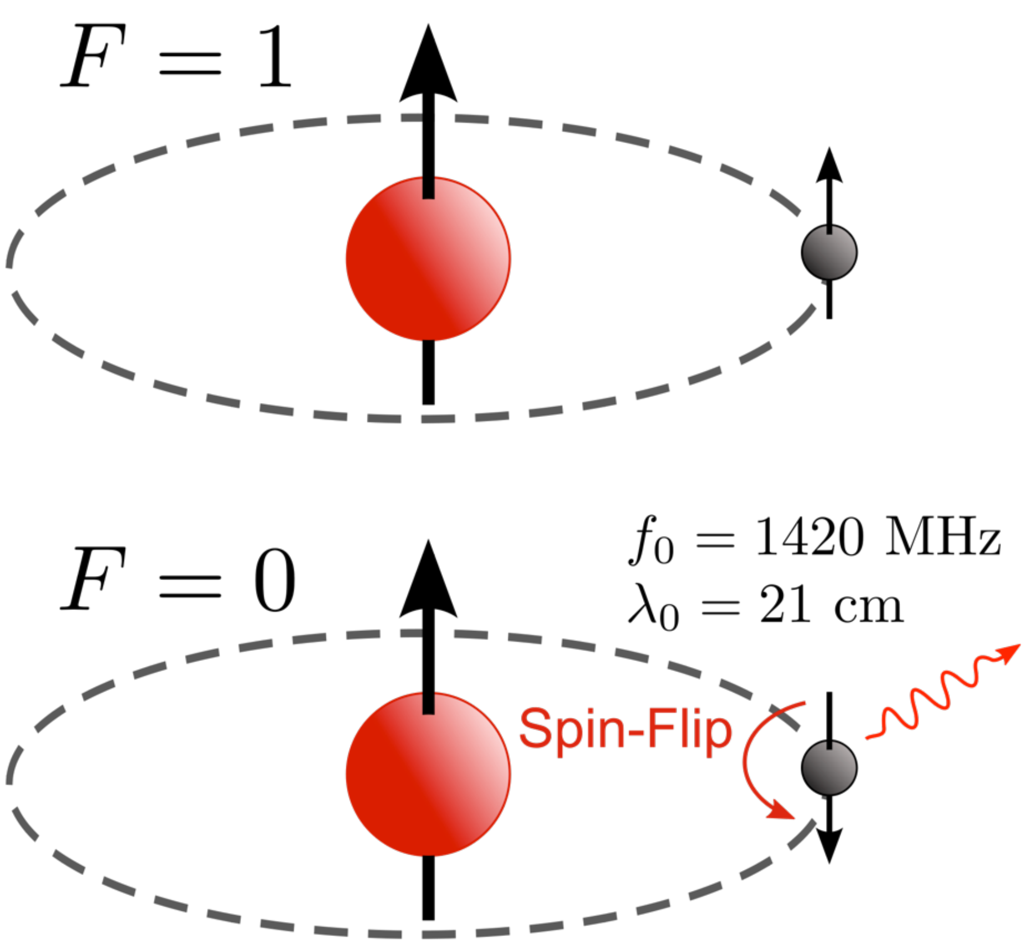

Two scenarios:

(1) Slow inelastic DM scattering followed by **FAST** decays of the excited states

(2) Fast inelastic DM scattering followed by **SLOW** decays of the excited states

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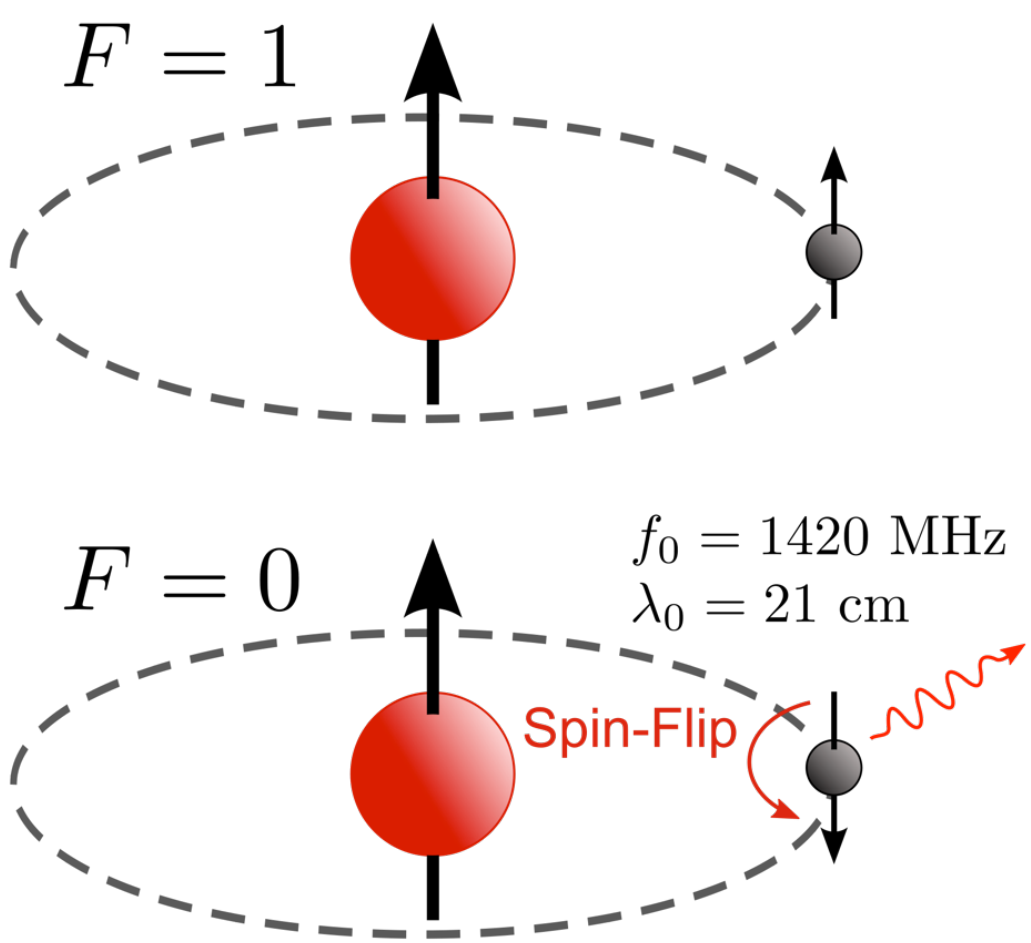

Two scenarios:

(1) Slow inelastic DM scattering followed by **FAST** decays of the excited states

(2) Fast inelastic DM scattering followed by **SLOW** decays of the excited states

The 3.5 keV x-ray flux is determined by the slower process.

Fast decay of excited states

Signal strength requires $\langle \sigma v \rangle \, BR \sim 10^{-21} \, \mathrm{cm}^3 \, \mathrm{s}^{-1} \left(\frac{m_{H'}}{\mathrm{GeV}} \right)^2$

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$$\langle \sigma v \rangle_{\mathrm{spin}} \sim \sigma_{\mathrm{el}} \cong 100 \, a_0^2 \equiv \frac{100}{(\alpha' \mu)^2} \equiv \frac{100 \, f(R)^2}{(\alpha' m_{H'})^2}$$

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For massless dark photons, the branching ratio

$$BR = \epsilon^2 \alpha / \alpha'$$

It turns out that the massless dark photon case either violates the direct detection limits ($\boldsymbol{\varepsilon}$) or produce too big a self interaction cross section ($\boldsymbol{\sigma}$).

For dark photon heavier than 3.5 keV, we have BR=100%.

Kinetic & Stueckelberg mixings

For massive dark photon, one has to introduce Stueckelberg mixings; otherwise, millicharge goes to zero with only kinetic mixing

Kinetic & Stueckelberg mixings

For massive dark photon, one has to introduce Stueckelberg mixings; otherwise, millicharge goes to zero with only kinetic mixing

$$A'_\mu(J'^\mu + (\epsilon_{\rm St} - \epsilon_{\rm km})J^\mu) + A_\mu(J^\mu - \epsilon_{\rm St} J'_\mu)$$

A' (A) denotes the dark (visible) photon vector potential

J' (J) the current of the dark (visible) constituents

$\epsilon_{\rm km}$ $(\epsilon_{\rm St})$ is kinetic (Stueckelberg) mixing parameter

If $\epsilon_{\rm St} = 0$, DM does not couple to photon.
Dark atom does not radiate visible photon.

Constraints on millicharge

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In order to explain the 3.5 x-ray flux, we have

$$\frac{100\, f(R)^2}{(\alpha' m_{H'})^2} = 10^{-21}\,\mathrm{cm}^3\,\mathrm{s}^{-1}\left(\frac{m_{H'}}{\mathrm{GeV}}\right)^2 \qquad f(R) = \frac{m_{H'}}{\mu_{H'}}$$

$$\frac{8}{3}\alpha'^4\frac{m_{e'}^2 m_{p'}^2}{m_{H'}^3} = 3.5\ \mathrm{keV} \qquad \mu_{H'} = \frac{m_{e'} m_{p'}}{m_{e'} + m_{p'}} \simeq \frac{m_{e'} m_{p'}}{m_{H'}}$$

$$\Rightarrow \quad m_{H'} = 137\left[\frac{f(R)}{4}\right]^{2/7}\mathrm{GeV}$$

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For given dark matter mass and R value, we can compute the allowed millicharge value from LUX constraints

$$\sigma_{H'\mathrm{p}} = 4\pi\,\alpha^2 \epsilon^2 \mu_{H'\mathrm{p}}^2 a_0'^4 \qquad a_0' = \frac{1}{\alpha' \mu}$$

$$\Rightarrow \quad \epsilon \lesssim 2.4\times 10^{-7}\sqrt{\frac{\sigma_{\mathrm{LUX}}}{10^{-44}\ \mathrm{cm}^2}}\left[\frac{137\ \mathrm{GeV}}{m_{H'}}\right]^2$$

Slow decay of excited states

If the lifetime of the excited state is greater than the Universe age, dark atoms form a 3:1 ratio of spin states (triplet, singlet). The flux is determined by the decay rate of the excited state.

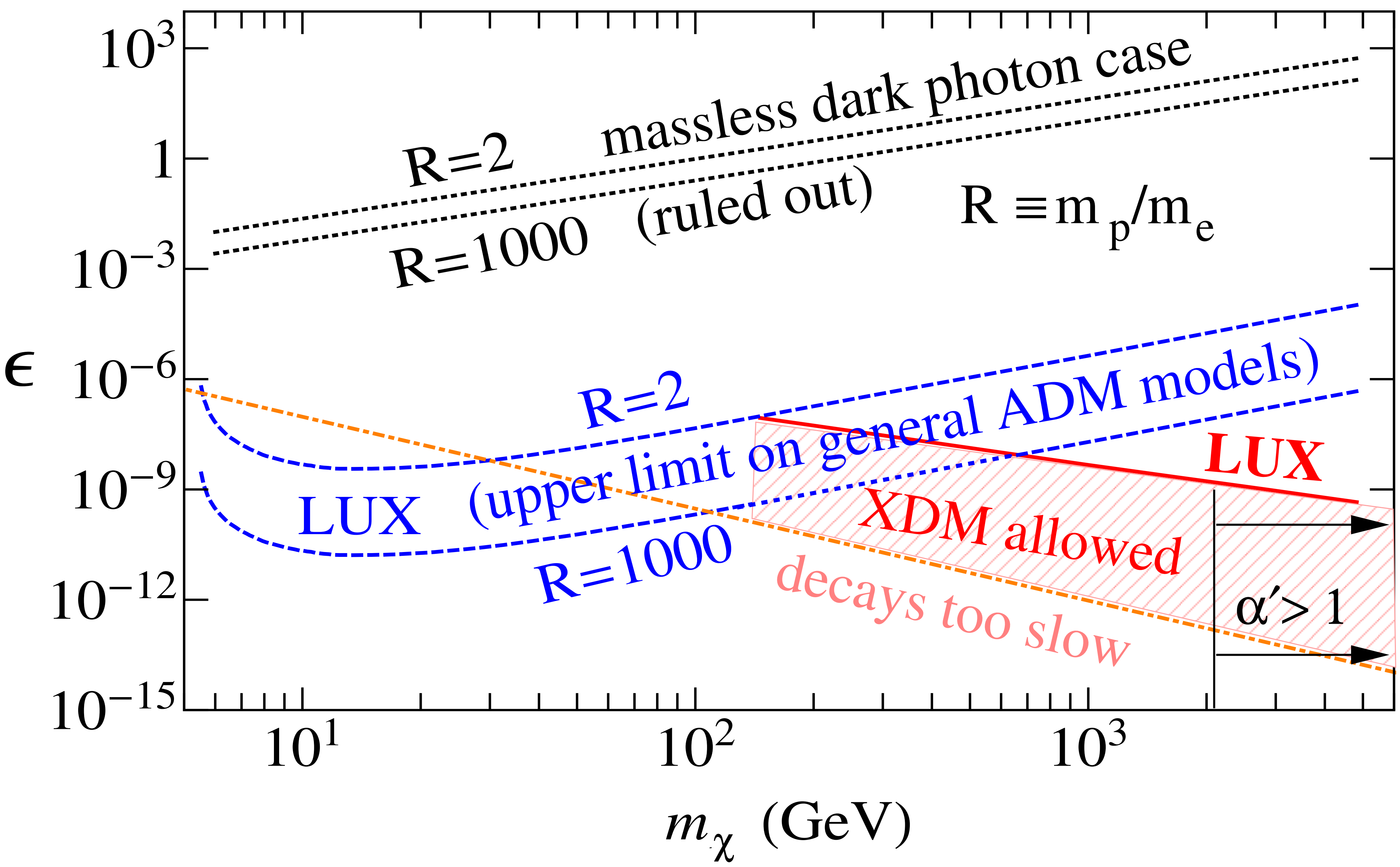
Decay rate of the excited state $\tau_{hf}^{-1} = \frac{\alpha\epsilon^2}{3}\frac{\Delta E^3}{\mu_{H'}^2}$

Signal requires $\tau^{-1} = 2.3 \times 10^{-21} s^{-1} (m_{H'}/100GeV)$

The required millicharge is very small.

$$\epsilon = 1.2 \times 10^{-14} \, (m_{H'}/\mathrm{GeV})^{3/2} \, f(R)^{-1}$$

Constraints on fast decays



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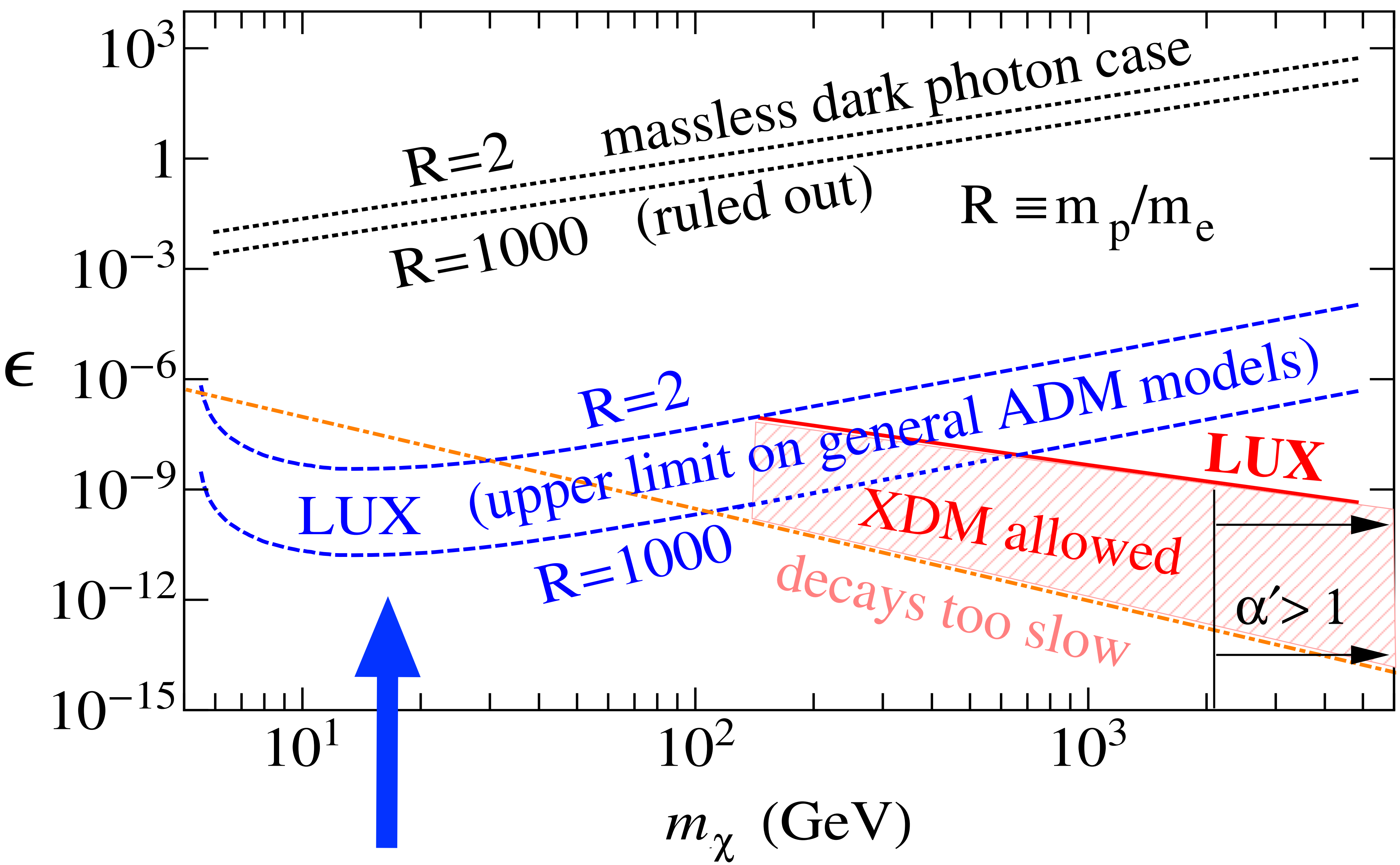
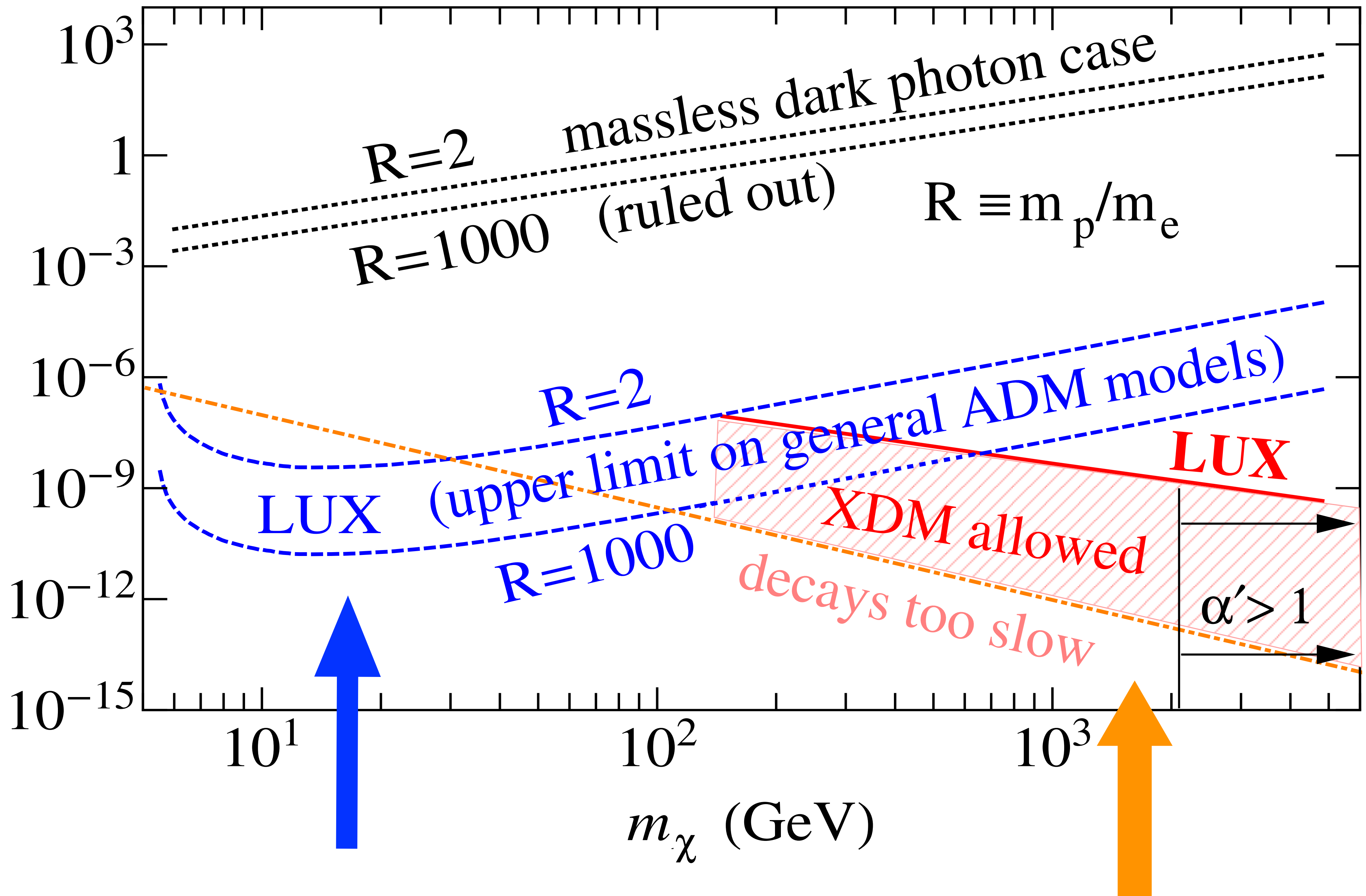


LUX-2013 constraints

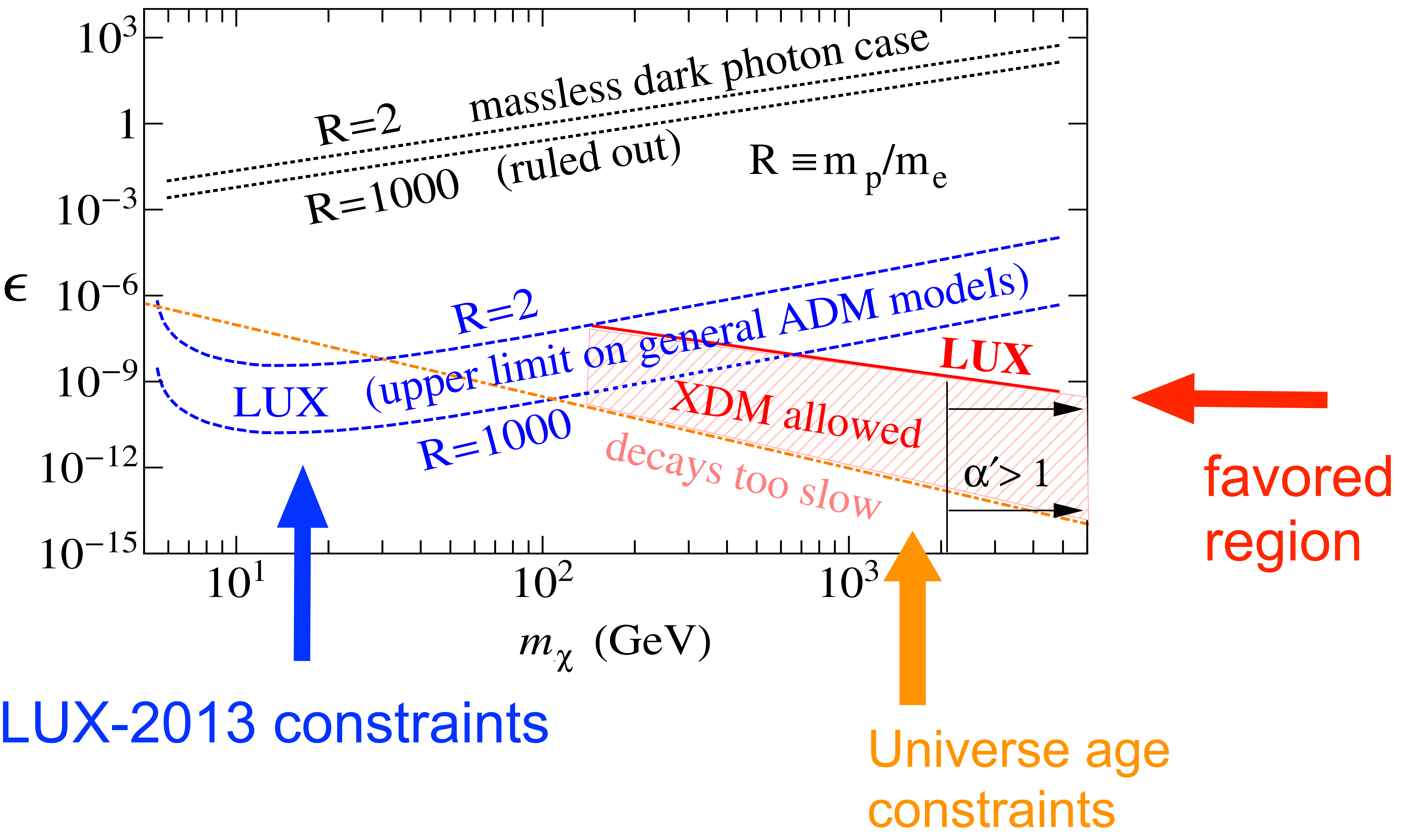
Constraints on fast decays



LUX-2013 constraints

Universe age constraints

Constraints on fast decays



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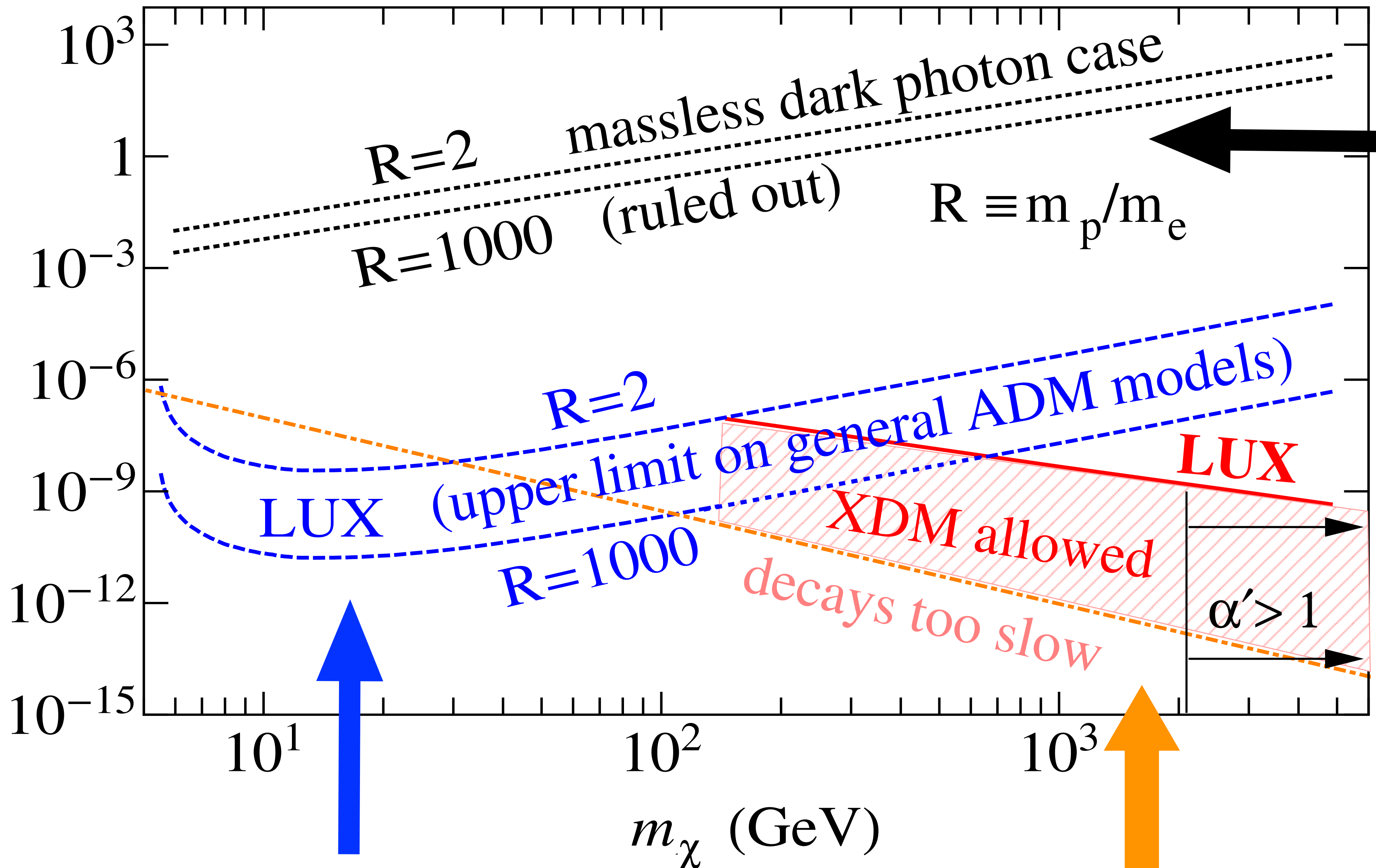

massless dark photon excluded

favored region

LUX-2013 constraints

Universe age constraints

Summary

Atomic dark matter models are interesting for dark matter phenomenology studies.

We can directly detect the atomic dark matter via millicharge which naturally arises via a generic kinetic mixing term (or Stueckelberg mass terms).

Dark atom is an excellent candidate for self-interacting dark matter (SIDM) to solve the small scale problems.

Unidentified 3.5 keV photon line could be due to the hyperfine transitions in atomic dark matter.

Thank you!