DARK ATOMS AS A SOLUTION FOR THE MYSTERY OF 3.5 KEV LINE FROM GALAXY CLUSTERS

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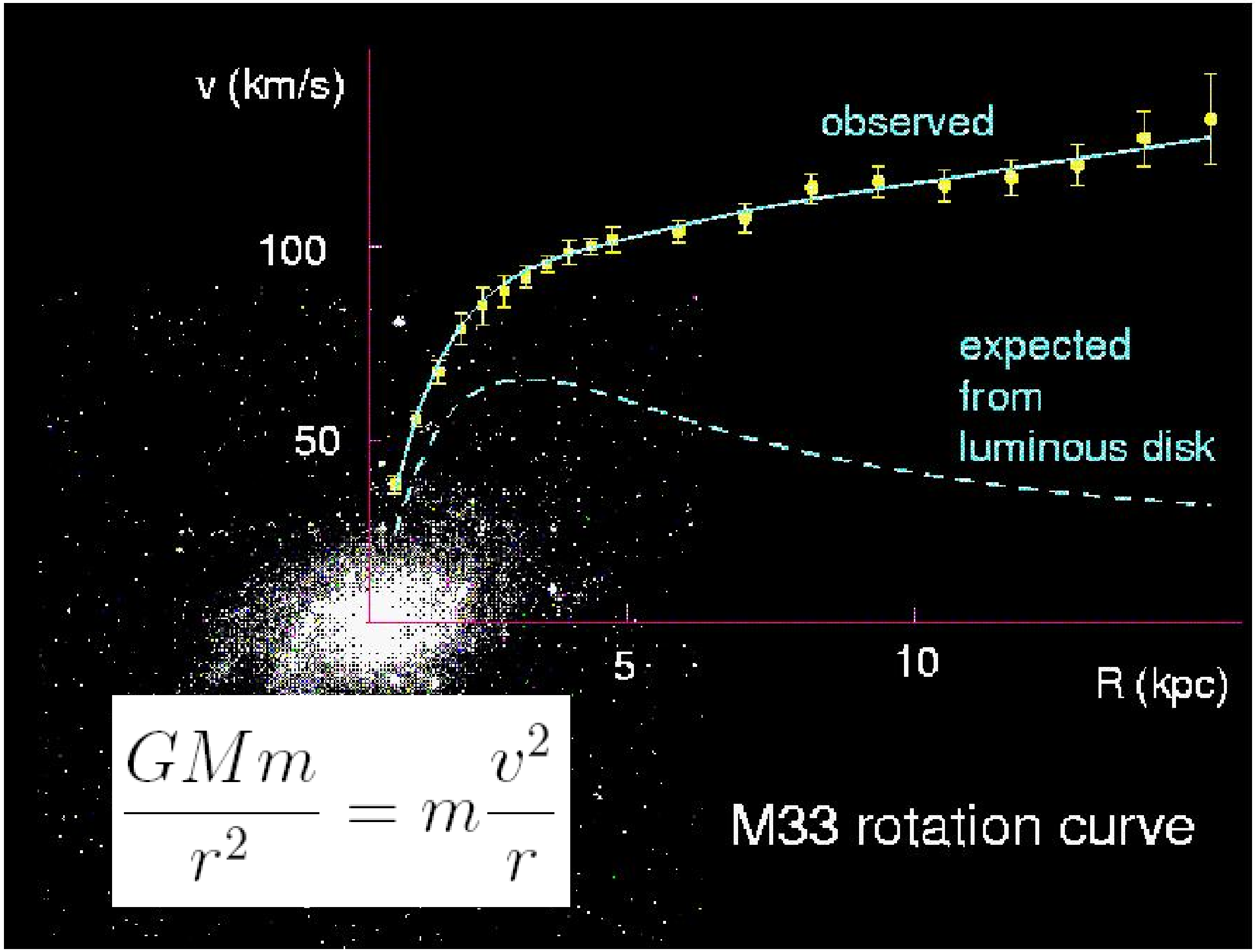
invisibles
neutrinos, dark matter & dark energy physics

WHY DARK MATTER?

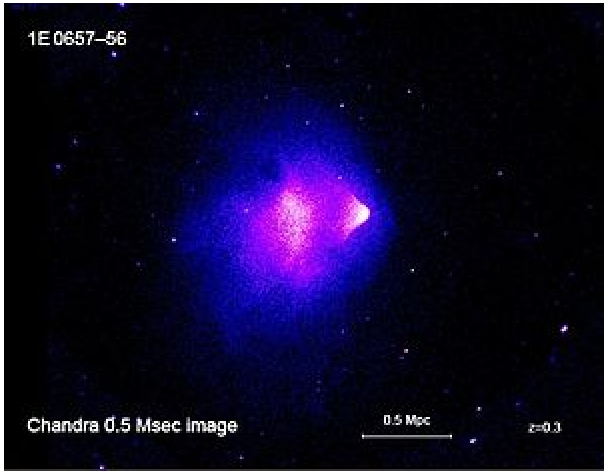
- Rotation curve
- Galaxy clusters
- Bullet clusters
- Cosmic Microwave background
- Structure Formation

ROTATION CURVE

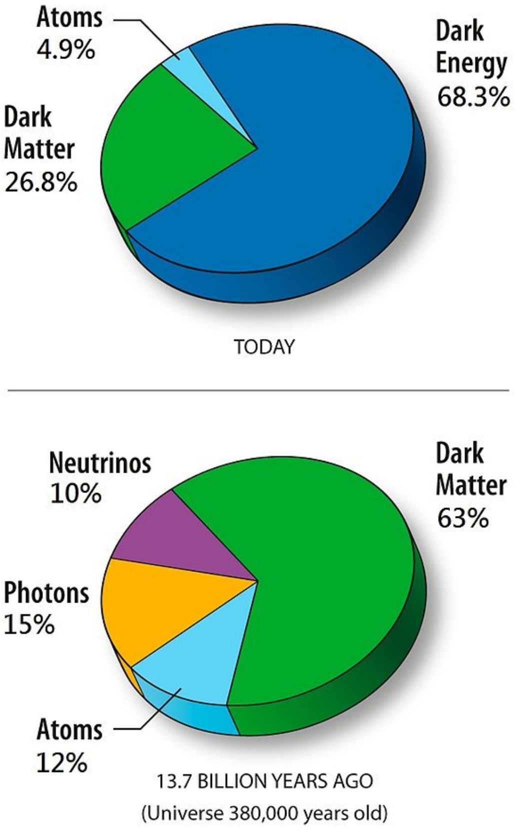


$$\frac{GMm}{r^2} = m\frac{v^2}{r}$$

BULLET CLUSTER



DARK MATTER ABUNDANCE



TYPES OF DARK MATTER

- Cold Dark Matter: M>100 keV

- Warm Dark matter: M=few keV to few 10 keV

- Hot Dark matter: M<<keV

COLD DARK MATTER

- WIMP=Weakly Interacting Massive Particle

- FIMP=Feebly Interacting Massive Particle

- SuperWIMP

WIMP

- Lightest supersymmetric particle (LSP)
- Lightest KK mode in extra large dimension models
- …..
- AMEND and SLIM : Y.F, S. Pascoli and Schimdt, **JHEP 1010 (2010); Y.F., Phys.Rev. D80 (2009)**

DIRECT DM DETECTION

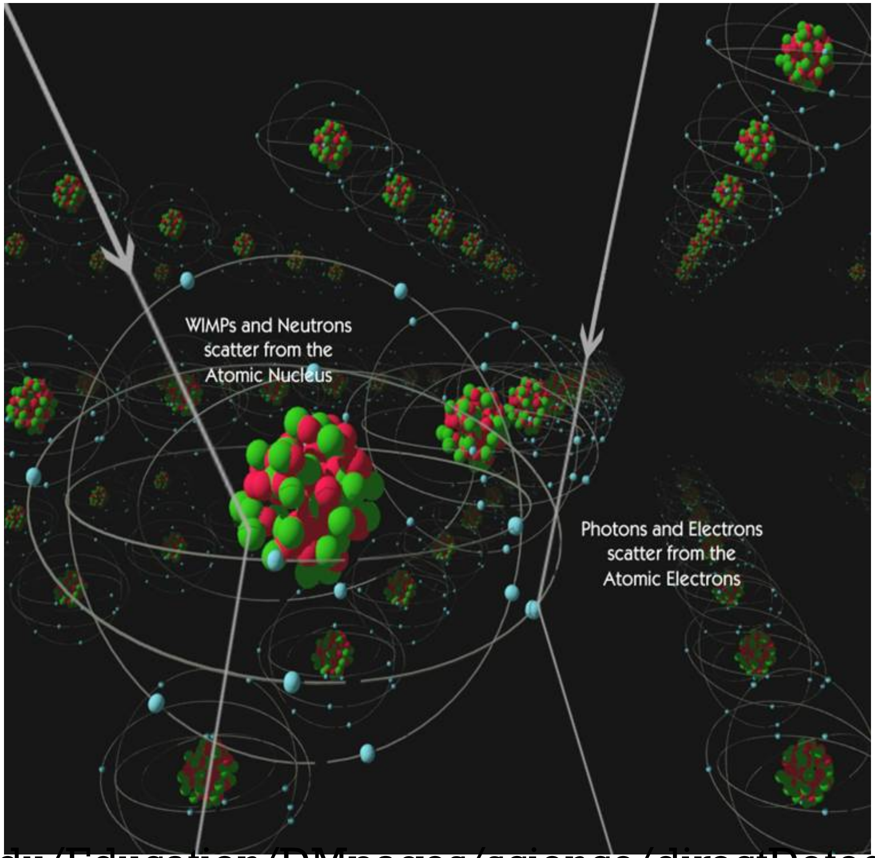
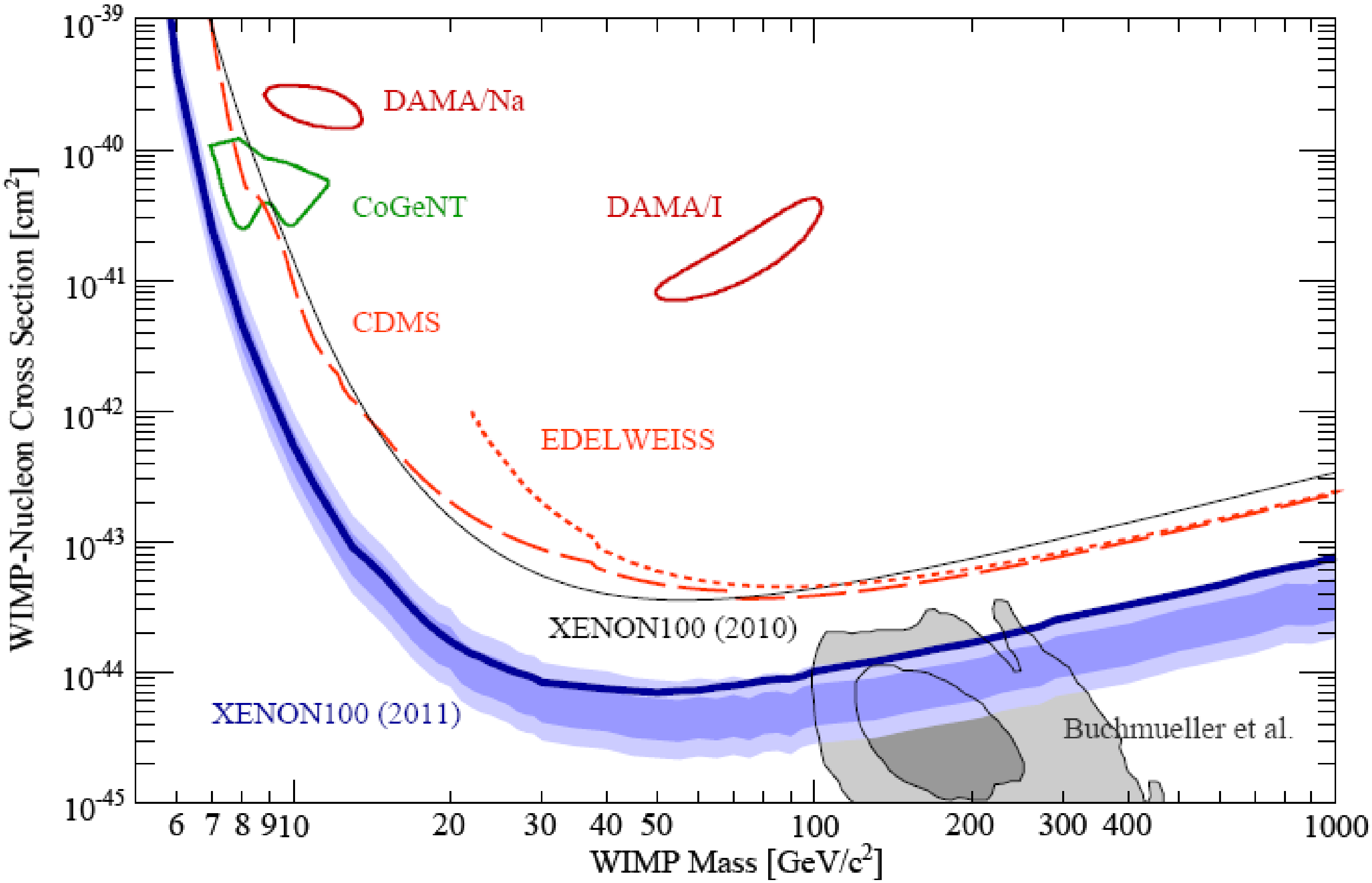
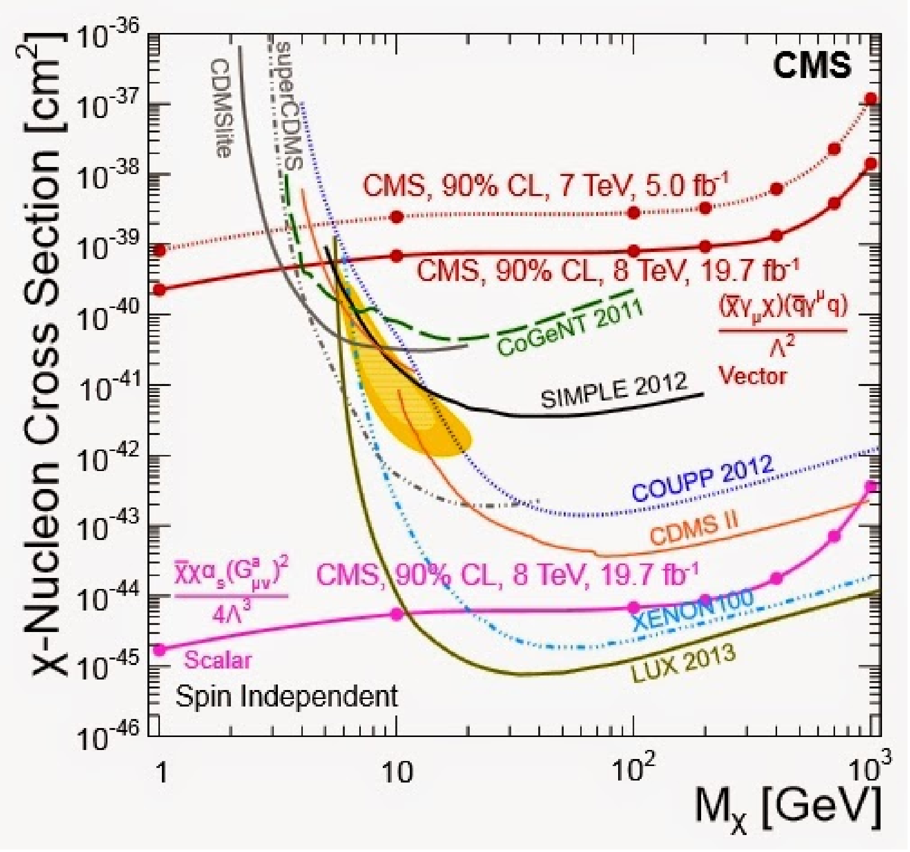


Image courtesy of:
http://cdms.berkeley.edu/Education/DMpages/science/directDetection.shtml

DAMA SIGNAL AND DIRECT BOUNDS



LUX BOUNDS



CMS
X-Nucleon Cross Section [cm^2]
M_χ [GeV]
CDMSlite
superCDMS
CMS, 90% CL, 7 TeV, 5.0 fb^{-1}
CMS, 90% CL, 8 TeV, 19.7 fb^{-1}
CoGeNT 2011
$\frac{(\bar{\chi}\gamma_\mu\chi)(\bar{q}\gamma^\mu q)}{\Lambda^2}$
Vector
SIMPLE 2012
COUPP 2012
CDMS II
$\frac{\bar{\chi}\chi\alpha_s(G^a_{\mu\nu})^2}{4\Lambda^3}$
CMS, 90% CL, 8 TeV, 19.7 fb^{-1}
XENON100
Scalar
LUX 2013
Spin Independent

INDIRECT DETECTION

- Detection of the products of DM pair annihilation (or DM decay)

in the DM halo, galaxy center, Sun, Earth ….

Stable particles: Neutrinos, positrons, anti-protons, anti-Helium, Anti-Deuteron, photon

PHOTON WITH CONTINUOUS SPECTRUM

$$\mathrm{DM} + \mathrm{DM} \to e^- e^+$$

$$\text{Inverse Compton}: \quad e^\pm + \gamma \to e^\pm + \gamma$$

$$\text{pair annihilation}: \quad e^+ e^- \to \gamma\gamma$$

MONOCHROMATIC PHOTON LINE

$$\mathrm{DM} + \mathrm{DM} \rightarrow \gamma\gamma$$

$$E_\gamma = m_{DM}$$

$$\mathrm{DM} \rightarrow X + \gamma$$

$$E_\gamma = \frac{m_{DM}^2 - m_X^2}{2m_{DM}}$$

X-RAY OBSERVATORIES

- XMM-Newton observatory

- Chandra X-ray observatory

CLAIM: 3.5 KEV LINE

- Detection of An Unidentified Emission Line in the Stacked X-ray spectrum of Galaxy Clusters

Bulbul et al, Astrophys. J 791 (2014) 104; arXiv:1402.2301

An unidentified line in X-ray spectra of the Andromeda galaxy and Perseus galaxy cluster

Boyarsky et al, arXiv:1402.4119

BULBUL RESULTS

- XMM-Newton data on 73 galaxy clusters: redshifts 0.01-0.35

$$E = (3.55 - 3.57) \pm 0.03 \text{ keV}$$

$$> 3\sigma \text{ statistical significance}$$

BULBUL RESULTS

- Chandra results on Perseus

- Chandra results on Virgo

REDSHIFT

- Removes doubts about detector response features.

BOYARSKY RESULTS

- Andromeda galaxy (M31)
- Perseus cluster

Observed by XMM-Newton

Stronger towards the center

($\sim 4\sigma$ in the combined dataset)

ATOMIC LINES

- Hydrogen atom: $E_b = 13.6\ \mathrm{eV}$
- Hydrogen-like ions: $E = -\dfrac{m_e \alpha^2 Z^2}{2n^2}$

$$\alpha = \frac{e^2}{4\pi}$$

$$E \propto \frac{Ze^2}{r} \qquad \frac{1}{r} \propto Ze^2$$

ATOMIC LINES CLOSE TO 3.5 KEV?

- Careful analysis by Bulbul et al:
- He-like Cl XVI

n=5 → 1 E=3.52 keV

Stronger lines n=3 → 1, n=4 → 1

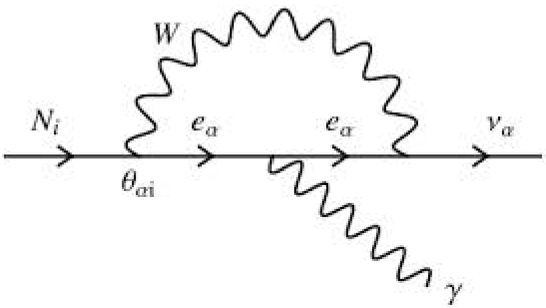
K XVIII $1s^1\ 2p^1 \to 1s^2$ E=3.51 keV

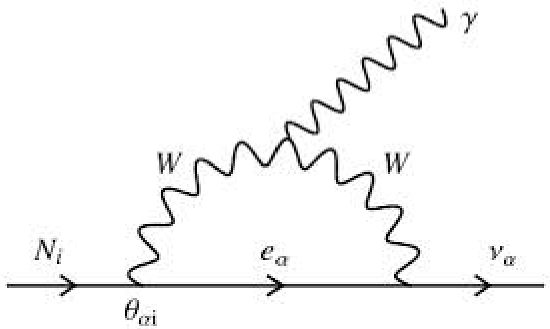
DARK MATTER SIGNAL?

- Sterile neutrino as DM

$$m_s = 2E = 7.1 \text{ keV}$$

$$\nu_s \to \nu\gamma$$





$$\Gamma_\gamma(m_s, \theta) = 1.38 \times 10^{-29} \text{ s}^{-1} \left(\frac{\sin^2 2\theta}{10^{-7}}\right)\left(\frac{m_s}{1 \text{ keV}}\right)^5$$

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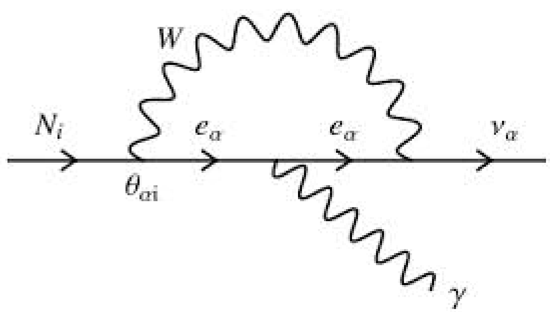

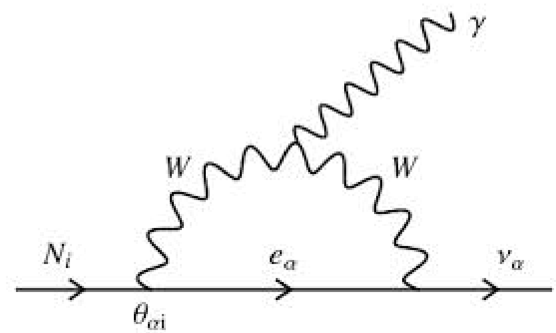

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$$\sin^2(2\theta) \approx 7 \times 10^{-11},$$

DM VS ATOMIC TRANSITION

- Astro-H
- To be launched in 2015
- Better energy resolution
- Higher velocity of DM → Higher broadening of line (Doppler effect)
- Virial velocity of DM: $1300\ \mathrm{km\ s^{-1}}$
- Width of the line $\sim$15 eV

DARK MATTER DECAY

H. Ishida, K. S. Jeong and F. Takahashi, Phys. Lett. B **732** (2014) 196 [arXiv:1402.5837 [hep-ph]]; D. P. Finkbeiner and N. Weiner, arXiv:1402.6671 [hep-ph]; J. -C. Park, S. C. Park and K. Kong, Phys. Lett. B **733** (2014) 217 [arXiv:1403.1536 [hep-ph]]; N. -E. Bomark and L. Roszkowski, Phys. Rev. D **90** (2014) 011701 [arXiv:1403.6503 [hep-ph]]; S. Baek and H. Okada, arXiv:1403.1710 [hep-ph]; T. Tsuyuki, Phys. Rev. D **90** (2014) 013007 [arXiv:1403.5053 [hep-ph]]; K. -Y. Choi and O. Seto, Phys. Lett. B **735** (2014) 92 [arXiv:1403.1782 [hep-ph]]; Z. Kang, P. Ko, T. Li and Y. Liu, arXiv:1403.7742 [hep-ph]; R. Allahverdi, B. Dutta and Y. Gao, Phys. Rev. D **89** (2014) 127305 [arXiv:1403.5717 [hep-ph]]; C. Kolda and J. Unwin, Phys. Rev. D **90** (2014) 023535 [arXiv:1403.5580 [hep-ph]]; F. S. Queiroz and K. Sinha, Phys. Lett. B **735** (2014) 69 [arXiv:1404.1400 [hep-ph]]; K. S. Babu and R. N. Mohapatra, Phys. Rev. D **89** (2014) 115011 [arXiv:1404.2220 [hep-ph]]; H. M. Lee, arXiv:1404.5446 [hep-ph]; H. Okada and T. Toma, arXiv:1404.4795 [hep-ph]; S. V. Demidov and D. S. Gorbunov, arXiv:1404.1339 [hep-ph]; K. P. Modak, arXiv:1404.3676 [hep-ph]; N. Chen, Z. Liu and P. Nath, arXiv:1406.0687 [hep-ph]; B. Dutta, I. Gogoladze, R. Khalid and Q. Shafi, arXiv:1407.0863 [hep-ph]. J. M. Cline and A. R. Frey, arXiv:1408.0233 [hep-ph].

DARK MATTER ANNIHILATION

E. Dudas, L. Heurtier and Y. Mambrini, arXiv:1404.1927 [hep-ph]; S. Baek, P. Ko and W. -I. Park, arXiv:1405.3730 [hep-ph]; C. -W. Chiang and T. Yamada, arXiv:1407.0460 [hep-ph]; H. Okada and Y. Orikasa, arXiv:1407.2543 [hep-ph].

AXION-LIKE DM CONVERSION

J. Jaeckel, J. Redondo and A. Ringwald, Phys. Rev. D **89** (2014) 103511 [arXiv:1402.7335 [hep-ph]]; T. Higaki, K. S. Jeong and F. Takahashi, Phys. Lett. B **733** (2014) 25 [arXiv:1402.6965 [hep-ph]]; H. M. Lee, S. C. Park and W. -I. Park, arXiv:1403.0865 [astro-ph.CO]; M. Cicoli, J. P. Conlon, M. C. D. Marsh and M. Rummel, Phys. Rev. D **90** (2014) 023540 [arXiv:1403.2370 [hep-ph]]; J. P. Conlon and F. V. Day, arXiv:1404.7741 [hep-ph].

OUR PAPERS

- 3.5 keV X-ray as the "21 cm line" of dark atoms and a link to light sterile neutrinos

J. Cline, Y.F., Z. Liu, G.D. Moore and W. Xue, PRD 89 (2014) 121302

- Decaying Vector Dark Matter as an Explanation for the 3.5 keV line from galaxy clusters,

Y.F. and Amin Rezaei Akbarieh, arXiv:1408.2950

DISPUTES OF THE EXISTENCE OF THE LINE

- Reimer-Sorensen, arXiv:1405.7943

No line from Milky Way (MW) in Chandra data

Consistent only if most conservative DM density profile in the innermost part of galaxy is taken.

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Boyarsky et al, arXiv:1408.2503

Line from Milky Way (MW) in XMM-Newton data

Source of difference between two results: Free Potassium abundance taken by Reimer-Sorensen

SECOND DISPUTE

- Dark matter searches going bananas: the contribution of Potassium (and Chlorine) to 3.5 keV line, Jeltema and Profumo,

arXiv:1408.1699

XMM-Newton on: MW, M31, clusters

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arXiv:1408.1699

XMM-Newton on: MW, M31, clusters

Boyarsky et al., 1408.4388

They should not have restricted to analysis to 3-4 keV

Analysis up to 8 keV

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- Dark matter searches going bananas: the contribution of Potassium (and Chlorine) to 3.5 keV line, Jeltema and Profumo,

arXiv:1408.1699

XMM-Newton on: MW, M31, clusters

Bulbul et al., Comment on "Dark matter searches going bananas:..", arXiv:1404.4143

Incorrect atomic data

Inconsistent spectroscopic modeling

THIRD DISPUTE

- Constraints on 3.5 keV line emission from stacked observations of dward Spheroidal (dSph) galaxies, Malyshev, Neronov and Eckert, arXiv:1408.3531
- dSph: high mass/light ratio
- Inconsistent with Bulbul result unless MW halo is taken into account.
- Consistent with Boyarsky within uncertainty
- Claim can be tested by longer XMM-Newton exposure

FOURTH DISPUTE

- Non-detection of X-ray Emission from Sterile Neutrinos in Stacked Galaxy Spectra, M. E. Anderson, E. Churazov and J. N. Bregman, arXiv:1408.4115
- Galaxies T<2 keV; making central regions
- Chandra (81 galaxies) and XMM-Newton (89 galaxies)
- No signal
- The line was expected to be seen at $> 4\sigma$

SOME BACKGROUND

- Shaposhnikov

$\nu\ \mathrm{SM}$

- Warm Dark matter: better explaining small scale structure

(abundance of dwarf galaxies+halo core)

DARK ATOMS

- Mirror Models: dark counterpart for any SM particle
- R. Foot, Intl J Mod Phys D 13, 2162 (2004) [astro-ph/0407623]

- Dark quarks → Dark nucleons
-
- Dark electrons

→ Dark atoms

OUR IDEA

- Transition in dark atoms lead to the 3.5 keV line.
- Simplest idea: $2\mathrm{P} \rightarrow 1\mathrm{S}$ transition

Splitting=3.5 keV AND right intensity

Upper bound from bullet clusters

$$\frac{\sigma}{m} \sim 0.1 \frac{\mathrm{cm}^2}{\mathrm{gr}} \left(\frac{\alpha'}{2 \times 10^{-4}} \right)^4 < 1 \frac{\mathrm{cm}^2}{\mathrm{gr}}$$

$$\alpha' \ll 0.02 \Rightarrow T_{DM}^{virial} \gg \text{ionization energy}$$

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HYPERFINE TRANSITION

- Famous 21 cm line

$$\Delta E = \frac{8}{3}\alpha^4 \frac{m_e^2 m_p^2}{m_H^3}$$

$$\boxed{H \propto \frac{\mu_e \cdot \mu_p}{r^3}}$$

$$\boxed{\mu_e \propto \frac{e}{m_e} \quad \mu_p \propto \frac{e}{m_p}}$$

$$\boxed{\frac{1}{r} \propto \frac{m_e m_p}{m_e + m_p}\alpha}$$

$$\boxed{m_H = m_e + m_p}$$

OUR IDEA

- 3.5 keV X-ray as the "21 cm line" of dark atoms and a link to light sterile neutrinos

J. Cline, Y.F., Z. Liu, G.D. Moore and W. Xue, PRD 89 (2014) 121302

HYPERFINE TRANSITION IN DARK ATOMS

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

Here **e**, **p** and **H** respectively denote the dark electron, proton (assumed to be elementary particles), and hydrogen atom, with fine structure constant α' and $m_{\mathbf{H}} = m_{\mathbf{e}} + m_{\mathbf{p}}$.

TRANSITION RATE EMITTING AN ORDINARY PHOTON

$$\boxed{\tau_{hf}^{-1} = \frac{\alpha\epsilon^2}{3}\frac{\Delta E^3}{\mu_{\mathbf{H}}^2}}$$

Electric charge of dark proton and dark electron $\mp\epsilon e$

MASS OF DARK PHOTON

- Dark photon is massless or has a mass smaller than 3.5 keV.

- Dark photon has a mass larger than 3.5 keV

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Frandsen, JCAP 1405 (2014) 33

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MASS OF DARK PHOTON

- Dark photon is massless or has a mass smaller than 3.5 keV.

Frandsen, JCAP 1405 (2014) 33

- Dark photon has a mass larger than 3.5 keV

Only emitting ordinary photon

TWO REGIMES

- Lifetime of excited states < lifetime of universe

Fast decay scenario

- Lifetime of excited states > lifetime of universe

Slow decay scenario

LIFETIME OF EXCITED STATES < LIFETIME OF UNIVERSE

- Scattering of dark particles off each other

- Excited states

- Subsequent decay producing 3.5 keV line

A X-ray line from eXciting dark matter, D. Finkbeiner and N Weiner, arXiv:1402.6671

STRENGTH OF X-RAY LINE FROM SCATTERING

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

$m_{\gamma'} < 3.5\ \mathrm{keV}$ → $BR = \epsilon^2 \alpha/\alpha'$

$m_{\gamma'} > 3.5\ \mathrm{keV}$ → $BR = 1$

SCATTERING CROSS SECTION

$$\sigma_{\mathrm{el}} \cong 100\, a_0^2 \equiv \frac{100}{(\alpha' \mu_{\mathbf{H}})^2} \equiv \frac{100\, f(R)^2}{(\alpha' m_{\mathbf{H}})^2}$$

$$R = m_{\mathbf{p}}/m_{\mathbf{e}} \geq 1$$

$$f(R) = m_{\mathbf{H}}/\mu_{\mathbf{H}} = R + 2 + R^{-1}$$

- Cline et al., PRD89 (2014)4314

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

$$\Downarrow$$

$$\alpha' = 0.034\,(m_{\mathbf{H}}/\mathrm{GeV})^{-1/4}\, f(R)^{1/2}$$

$$\sigma_{\rm el} \cong 100\, a_0^2 \equiv \frac{100}{(\alpha' \mu_{\mathbf{H}})^2} \equiv \frac{100\, f(R)^2}{(\alpha' m_{\mathbf{H}})^2}$$

$$+$$

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

$$\Downarrow$$

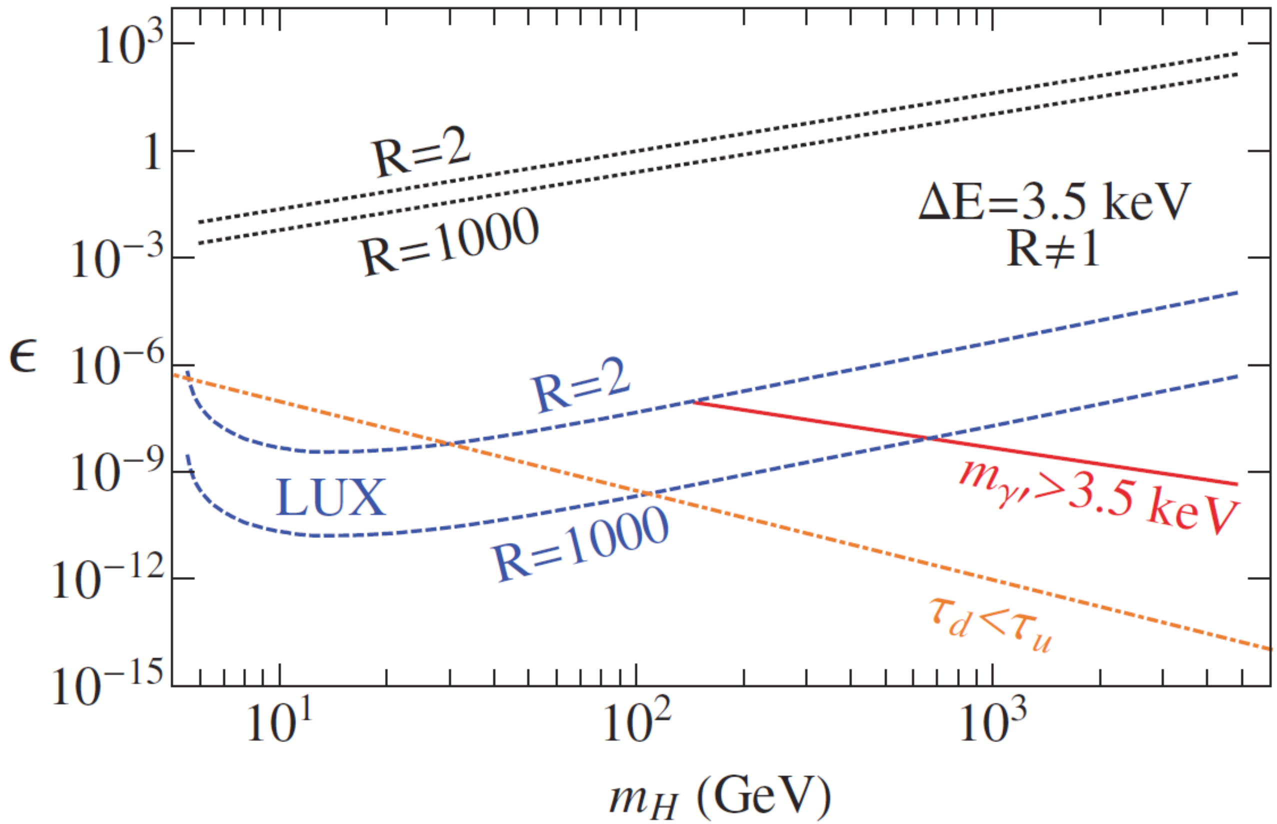
$$m_{\mathbf{H}} = 137\, [f(R)/4]^{2/7}\, {\rm GeV}$$

BOUNDS

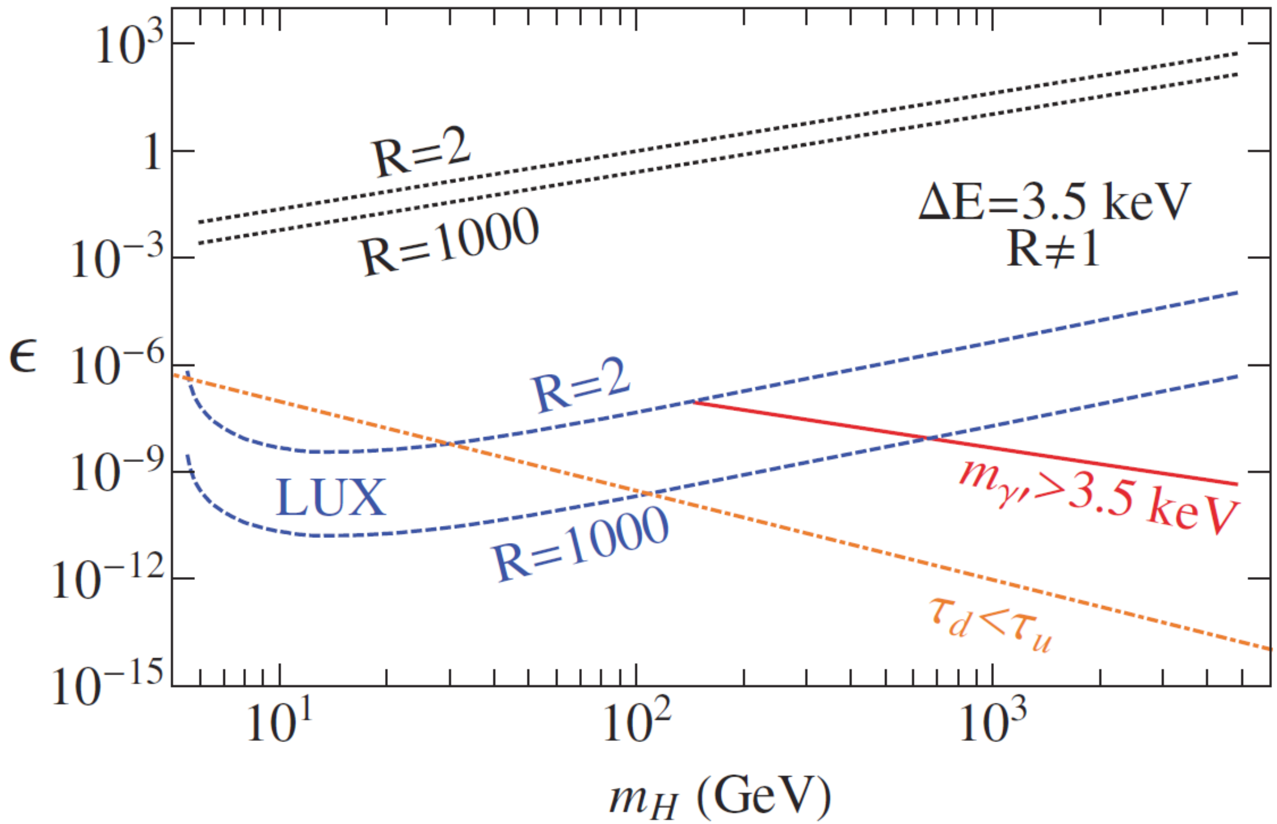
$$\tau_d < \tau_u \Rightarrow \qquad \epsilon > 3 \times 10^{-10} \left(m_{\mathbf{H}}/100\ \mathrm{GeV}\right)^{-5/2}$$

Interaction of Dark atom with proton via photon exchange:

$$\epsilon < 1.5 \times 10^{-7} \left(\frac{100\ \mathrm{GeV}}{m_{\mathbf{H}}}\right)^{3/2} = 1.7 \times 10^{-7} R^{-3/7}$$



10^3
1
10^{-3}
10^{-6}
10^{-9}
10^{-12}
10^{-15}
ϵ
R=2
R=1000
ΔE=3.5 keV
R≠1
R=2
LUX
R=1000
$m_{\gamma'}>3.5$ keV
$\tau_d<\tau_u$
10^1
10^2
10^3
m_H (GeV)



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LIFETIME OF EXCITED STATES > LIFETIME OF UNIVERSE

- The fraction of excited states remaining from dark atom recombination era 1

LIFETIME OF EXCITED STATES > LIFETIME OF UNIVERSE

- The fraction of excited states remaining from dark atom recombination era $\sim$ 1

Strength of the 3.5 keV line:

$$\tau_d^{-1} = 2.3 \times 10^{-21}\,\mathrm{s}^{-1}\,(m_{\mathbf{H}}/100\,\mathrm{GeV})$$

$$=$$

$$\tau_{hf}^{-1} = \frac{\alpha\epsilon^2}{3}\,\frac{\Delta E^3}{\mu_{\mathbf{H}}^2}$$

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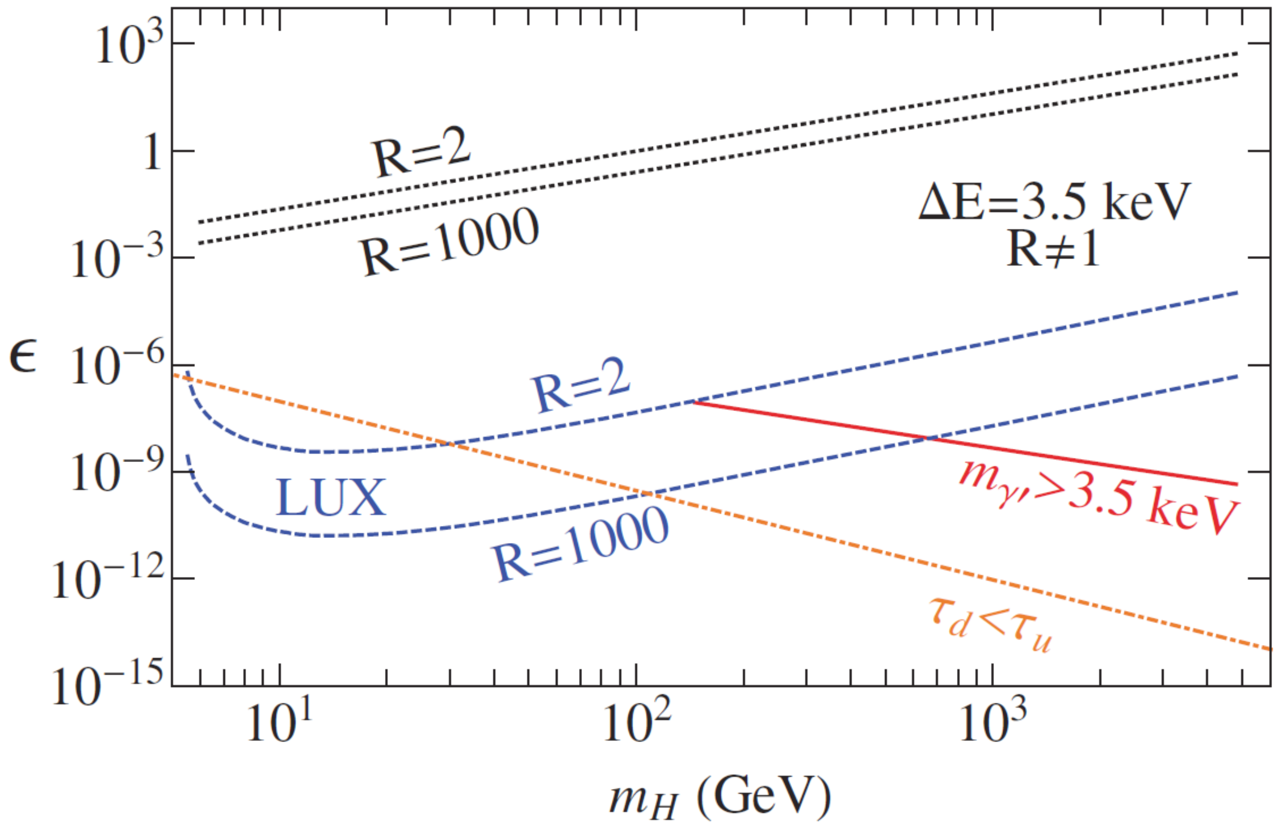
$$=$$

$$\tau_{hf}^{-1} = \frac{\alpha\epsilon^2}{3}\frac{\Delta E^3}{\mu_{\mathbf{H}}^2}$$

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



10^{3}
1
10^{-3}
ϵ
10^{-6}
10^{-9}
10^{-12}
10^{-15}
10^{1}
10^{2}
10^{3}
m_H (GeV)
R=2
R=1000
ΔE=3.5 keV
R≠1
R=2
LUX
R=1000
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$$\Delta E = 3.5\ \mathrm{keV} \Rightarrow \alpha' = 0.034\,(m_{\mathbf{H}}/\mathrm{GeV})^{-1/4} f(R)^{1/2}$$

MORPHOLOGY OF THE LINE INTENSITY

$\tau_d > \tau_U$ ⟹ $I \propto \rho$

$\tau_d \ll (\text{galaxy size})/v \sim 10^8\ \text{yr}$ ⟹ $I \propto \rho^2$

$\tau_d \sim (\text{galaxy size})/v \sim 10^8\ \text{yr}$ ⟹ $I??$

MORPHOLOGY OF THE LINE INTENSITY

$\tau_d > \tau_U \quad \Rightarrow \quad I \propto \rho$

Boyarsky et al, results on Andromeda

$\tau_d \ll (\text{galaxy size})/v \sim 10^8 \text{ yr} \quad \Rightarrow \quad I \propto \rho^2$

$\tau_d \sim (\text{galaxy size})/v \sim 10^8 \text{ yr} \quad \Rightarrow \quad I??$

DARK RECOMBINATION

- Kaplan et al, JCAP 1005, 21 (2010); Cyr-Racine and Sigurdson, PRD 87 103515 (2013); Cline et al., PRD 85 101302 (2012)
- Ionization fraction

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

Shape of dark matter halos $\Longrightarrow$ $X_{\mathrm{e}} < 3 \times 10^{-3}$

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

Further bound in fast decay scenario:

$$m_{\mathbf{H}} = 137\,[f(R)/4]^{2/7}\,\mathrm{GeV}$$

$$X_{\mathrm{e}} \sim 60\, R^{-15/7},$$

$$X_{\mathrm{e}} < 3 \times 10^{-3}$$

$$\boxed{R > 100}$$

DARK RECOMBINATION

- Kaplan et al, JCAP 1005, 21 (2010); Cyr-Racine and Sigurdson, PRD 87 103515 (2013); Cline et al., PRD 85 101302 (2012)
- Ionization fraction

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

No such restriction for slow decay scenario

DARK MATTER SELF INTERACTION

- Structure formation
- Cold dark matter: controversies in small scale, D. H. Weinberg et al., arXiv:1306.0913

$$\sigma/m \lesssim 1\ \mathrm{b/GeV}$$

- Strongly Interacting Dark Matter (SIDM)

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

DARK ATOM SELF INTERACTION

- Fast decay scenario

$\boxed{m_{\mathrm{H}} \sim 350 - 700\ \mathrm{GeV}}$ $\boxed{R \sim 100 - 1000,}$

$$\sigma_{\mathrm{el}}/m_{\mathrm{H}} = 1.5 - 3\ \mathrm{mb/GeV}$$

- Slow decay scenario

More freedom to realize SIDM with $\boxed{\sigma/m \sim 1\ \mathrm{b/GeV}}$

CONSTRAINTS ON DARK PHOTON

- Compton wavelength of dark photon> dark atom size

$$m_{\gamma'} \ll a_0^{-1} = \alpha' m_{\mathbf{H}}/f$$

Preferred parameter range: $m_{\gamma'} \ll 100 \text{ MeV}.$

- De-excitation: Dark photon mass < binding energy of dark atom

$$m_{\gamma'} \ll \frac{1}{2}\alpha'^2 m_{\mathbf{e}} \cong 7 \text{ MeV}$$

STUECKELNERG MASSES

$$A'_\mu(J'^\mu + (\tilde{\epsilon} - \tilde{\delta})J^\mu) + A_\mu(J^\mu - \tilde{\epsilon} J'_\mu)$$

$$\tilde{\epsilon} = (e/g)\epsilon \qquad (\tilde{\epsilon} - \tilde{\delta})e \equiv \delta e$$

- Natural range: $\delta \gg \epsilon$
- Fine tuned: $\delta \ll \epsilon$ $\boxed{\tilde{\epsilon} \to \tilde{\delta}}$

BOUND ON COUPLING OF DARK PHOTON TO CHARGED PARTICLES

- Supernova cooling:

$$m_{\gamma'} \sim 1 \text{ MeV} \quad \Rightarrow \quad \delta \lesssim 6 \times 10^{-11}$$

Dreiner et al, arXiv:1310.3826

- Stronger bounds for lower $m_{\gamma'}$

DARK PHOTON DECAY

$$m_{\gamma'} \ > \ 2m_e$$

$$\Gamma_{ee} = (1/3)\alpha\,\delta^2\, m_{\gamma'}\, g(x)$$

$$x \ = \ (m_e/m_{\gamma'})^2$$

$$g(x) \ = \ (1 + 2x)(1 - 4x)^{1/2} \ \sim \ 1$$

Life time ~50 sec

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Life time ~50 sec $\Rightarrow$ BBN

WILL DARK PHOTONS BE POPULATED?

- Too slow $\gamma e \leftrightarrow \gamma' e$ and $\gamma \mathrm{e} \leftrightarrow \gamma' \mathrm{e}$.

- Higher temperatures?

- Other decay modes?

LINK TO STERILE NEUTRINO

- ν_s couples to e and a W' boson with strength g'_w

$$\boxed{\frac{1}{2} a_\nu \, \bar{\nu}_s \gamma^\mu \gamma_5 \nu_s \, \partial^\alpha F'_{\alpha\mu}}$$

$$a_\nu \cong {g'_w}^2 g' / (16\pi^2 m^2_{W'})$$

$$\gamma' \to \nu_s \bar{\nu}_s \text{ of } \Gamma_{\nu\bar{\nu}} = a^2_\nu m^5_{\gamma'} / 24\pi .$$

NEED FOR EXTRA RADIATION

- Tension between BICEP2 and Planck

Giusarma et al., arXiv:1403.4852; Zhang et al., arXiv:1403.7028; Dvorkin et al., arXiv:1403.8049; Archidiacono et al., arXiv:1404.1794

- Sterile neutrinos with a mass ~0.5 eV

$$\Delta N_{\rm eff} \sim 1$$

SUMMARY

- A 3.5 keV line from Andromeda and certain galaxy clusters has been observed.
- This might be due to dark matter.
- We presented a model in which dark matter is composed of dark atoms and this 3.5 keV line is equivalent of the 21 cm line of the dark atoms.

- **Thank you for your attention!**

BACKUP SLIDES

CAN RELIC NEUTRINOS PLAY THE ROLE OF DM?

NO

$$m_{\nu_e} < 2.2 \text{ eV}$$

$$\Omega_\nu \approx \frac{m_\nu}{91.5 h^2 \text{ eV}} . \qquad h \equiv H_0/(100 \text{ km/sec Mpc})$$

$$(\Omega_\nu / \Omega_m \lesssim 0.2)$$