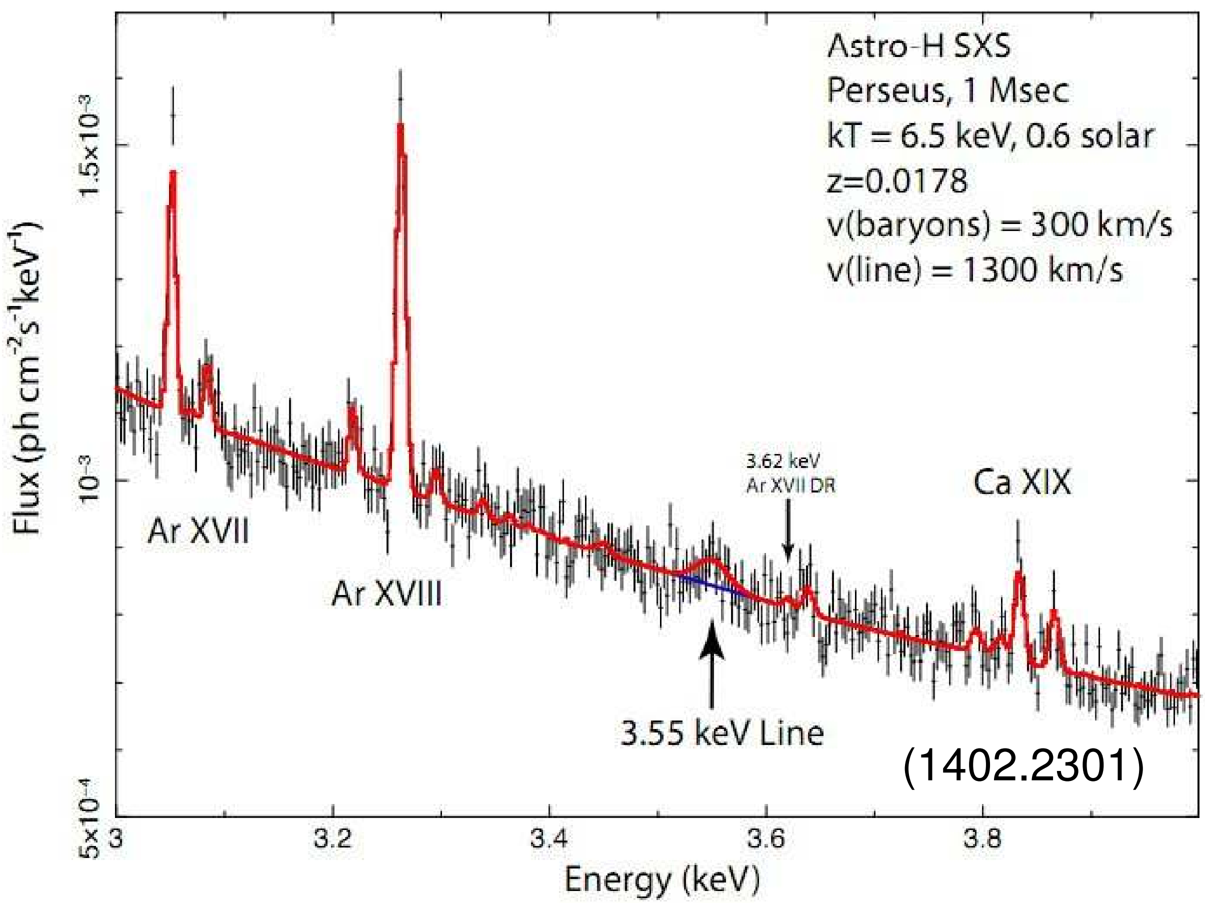
Consistency of dark matter interpretations of the 3.5 keV X-ray line



Jim Cline, McGill University

U. of Toronto, 27 Oct., 2014

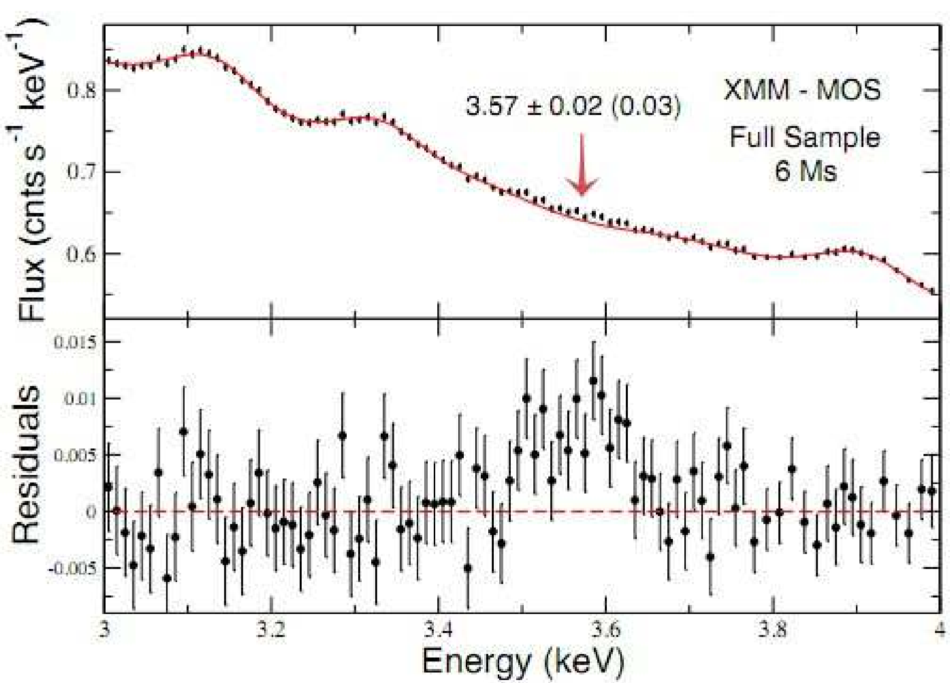
A tentative discovery

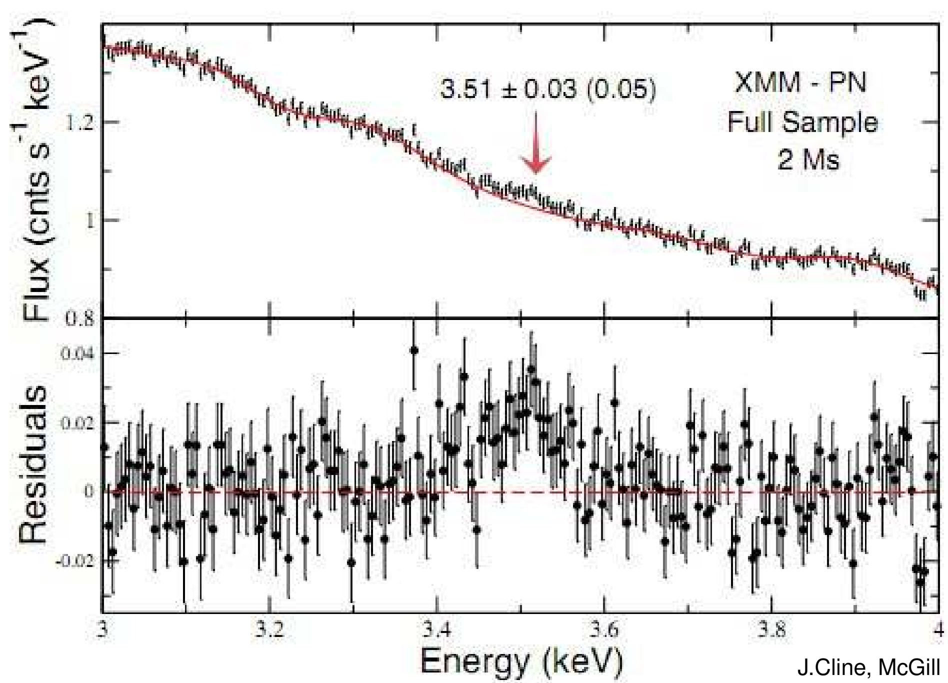
Bulbul *et al.* (1402.2301) find 3.5 keV X-ray line in XMM-Newton data using stacked spectra of 73 galaxy clusters;

Also in Perseus cluster (both with XMM and Chandra data) and Centaurus+Ophiucus+Coma clusters.

They argue it is not consistent with expected strength of known atomic transitions.

Suggest decays of 7 keV sterile neutrinos, $\nu_s \to \nu + \gamma$



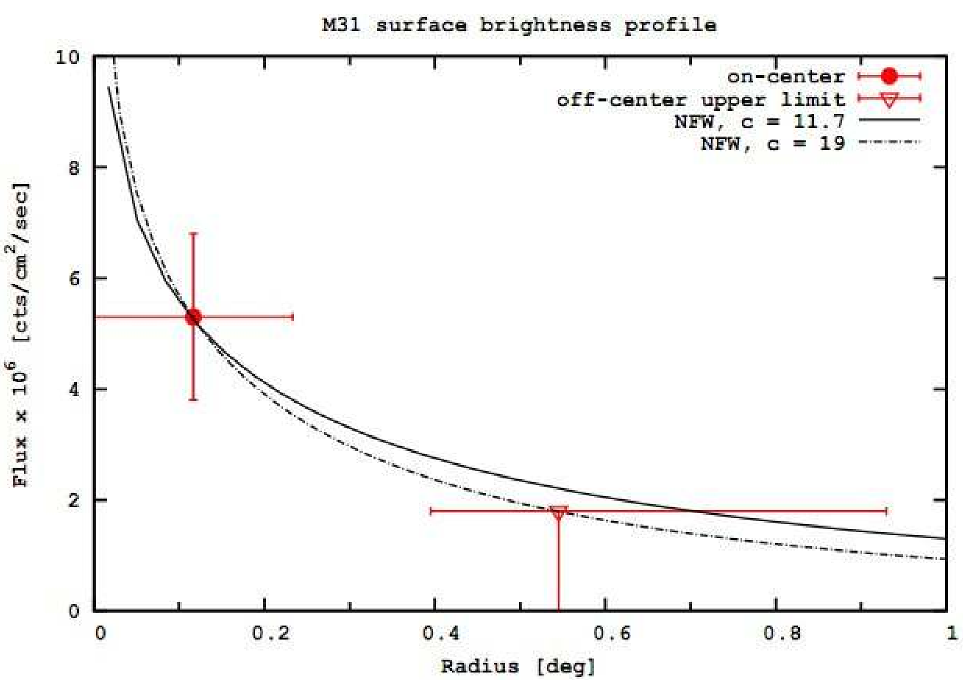


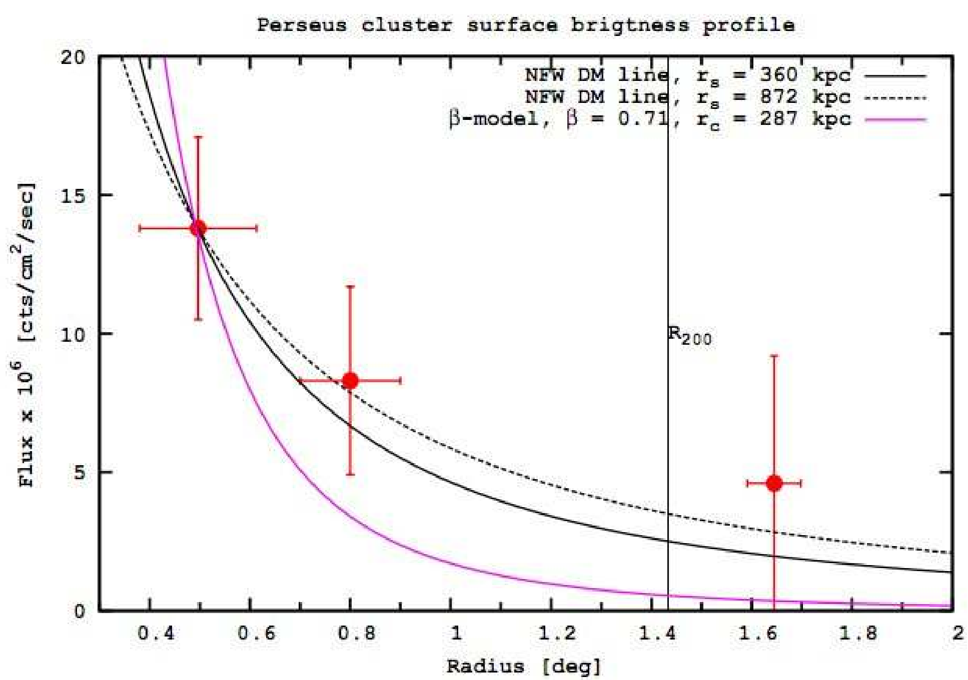
Quickly confirmed by one group

Boyarsky *et al.* (1402.4119) report 3.5 keV line in Andromeda galaxy (M31) and Perseus galaxy cluster using XMM-Newton data.

3.5 keV line has 4.3σ global significance.

Morphology consistent with decaying neutrinos





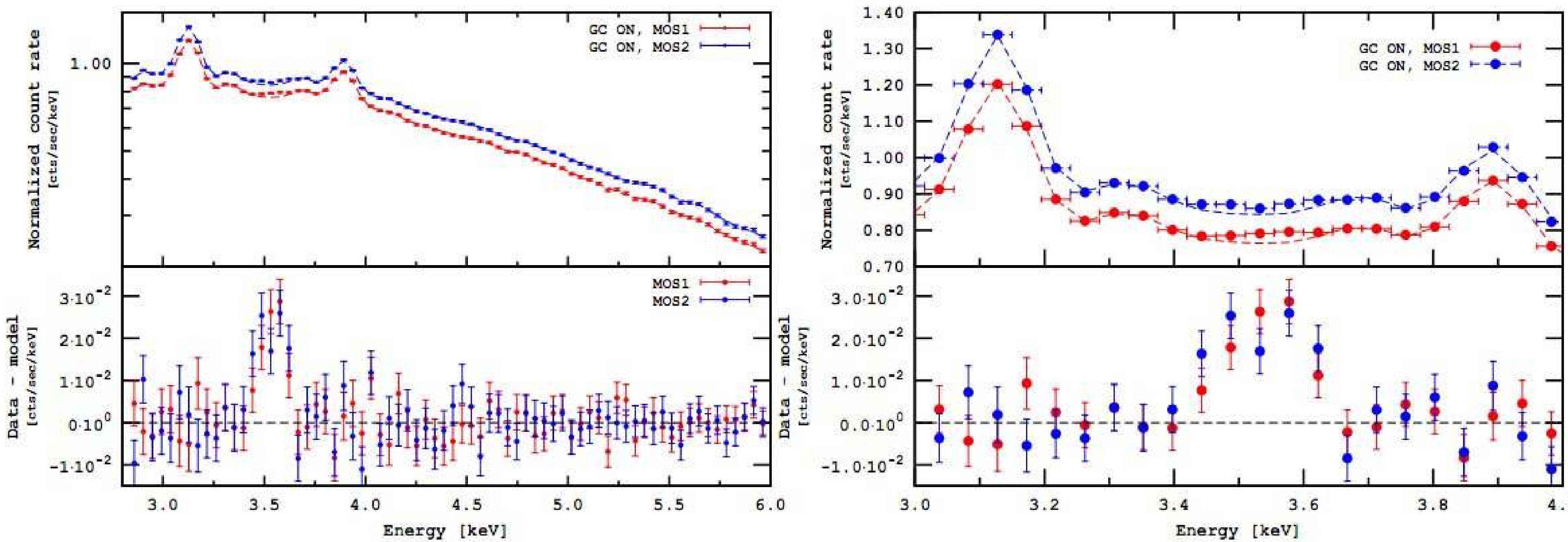
Not confirmed by other searches

- Riemer-Sørensen (1405.7943) finds only upper limit on line strength from galactic center using Chandra data
- Malyshev *et al.* (1408.3531) find no evidence for line in 8 dwarf spheroidals near MW
- Anderson *et al.* (1408.4115) sees no line in stacked spectra of 81 (89) galaxies using Chandra (XMM-Newton) data
- Jeltema, Profumo (1408.1699) claim that in all cases line can be explained by K and Cl transitions

Null searches say they should have seen it if it was decaying dark matter: ruled out at $(3.3\text{-}4.6)\sigma$ (Malyshev)
or $(4.4\text{-}11.8)\sigma$ (Anderson)

The line strikes back

Boyarsky *et al.* (1408.2503) find the line in the galactic center



Bulbul *et al.* (1409.4143) criticize analysis of Jeltema and Profumo

Boyarsky *et al.* (1408.4388) also rebut them

3.5 keV X-rays: DM or atomic line?

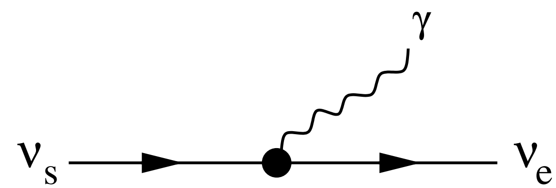
Bulbul *et al.*	1402.2301	73 stacked clusters	not K
Boyarsky *et al.*	1402.4119	M31, Perseus cluster	maybe K?
Riemer-Sørensen	1405.7943	not in Milky Way	lets K float
Jeltema, Profumo	1408.1699	no excess anywhere	it's K & Cl
Boyarsky *et al.*	1408.2503	excess in Milky Way	not K
Malyshev *et al.*	1408.3531	not in dwarf sph.	K irrelevant
Anderson *et al.*	1408.4115	find no lines in clusters, MW, M31	
Boyarsky *et al.* Bulbul *et al.*	1408.4388 1409.4143	arguments against 1408.1699	

Arguments against atomic origin of line sound plausible, but seem to partly depend on what one considers to be a reasonable density of K XVIII in various environments

Dependence on DM model

Interpretation of data depends on nature of DM model.

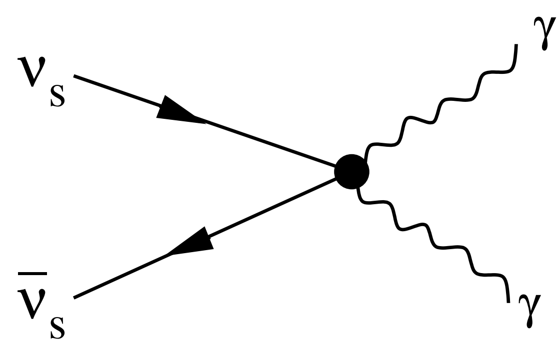
Decays follow DM density ρ. *E.g.,* 7 keV sterile neutrino with transition magnetic moment $\mu\bar{\nu}_s\sigma_{\mu\nu}F^{\mu\nu}\nu_e$;



Decay rate depends on ν_s-ν_e mixing angle θ,

$$\Gamma_\nu = 2.46\times 10^{-28}\mathrm{s}^{-1}\,\frac{\sin^2 2\theta}{10^{-10}}\,\left(\frac{m_\nu}{7.1\,\mathrm{keV}}\right)^5$$

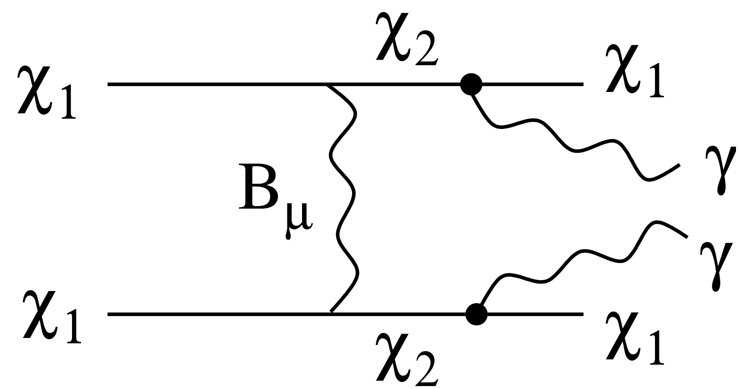
Annihilations go like ρ^2. *E.g.,* 3.5 keV neutrinos:



Or axions, ALPs, axinos, moduli, light superpartners, Majorons . . .

Excited dark matter: XDM

Predicted signal can also be different in excited DM scenario (Finkbeiner & Weiner, 1402.6671):



$\chi_{1,2}$ can be very heavy; only δm_χ need be small (3.5 keV).

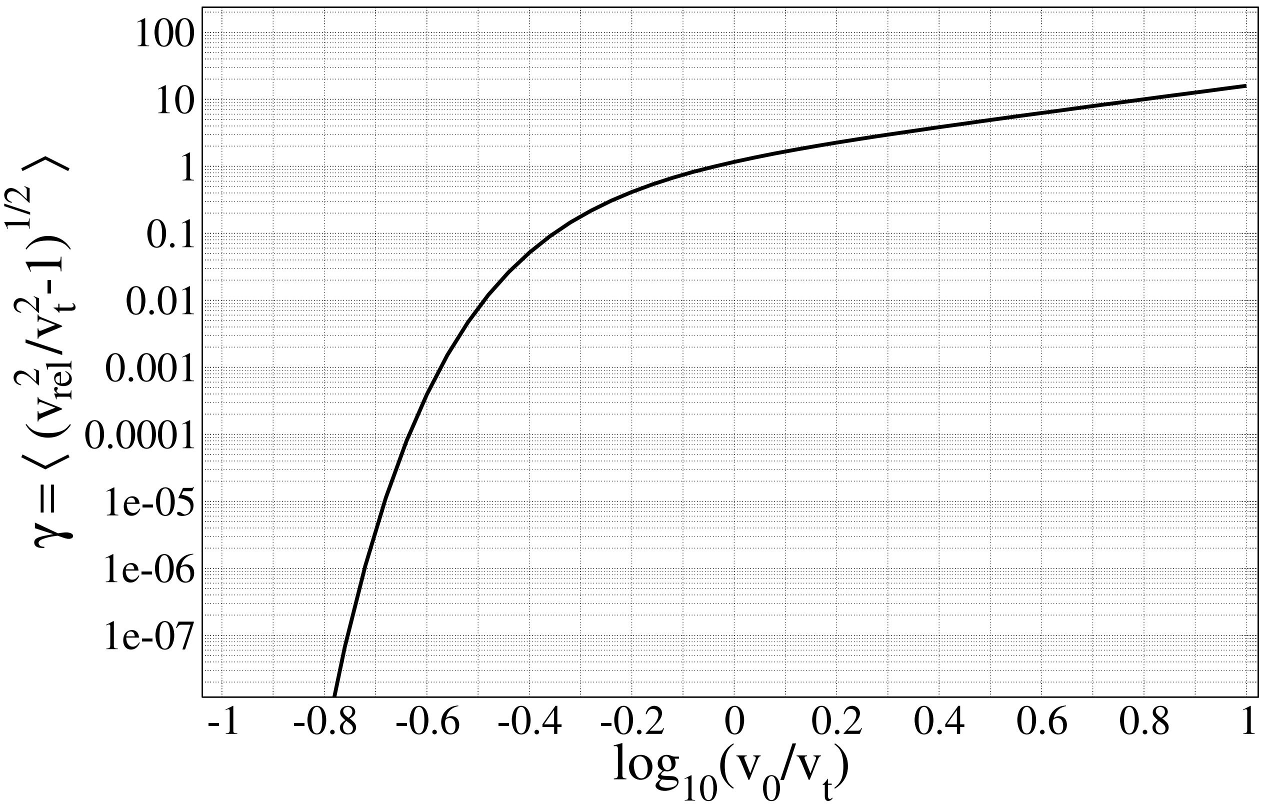
JC & A. Frey, 1408.0233 note that threshold relative velocity

$$v_t = \sqrt{8\,\delta m_\chi / m_\chi}$$

to produce excited states can make signal smaller in objects with lower DM velocity dispersion

Velocity dependence of XDM models

The phase space integral for inelastic scattering contributes velocity dependence $\gamma \equiv \langle (v_{\rm rel}^2/v_t^2 - 1)^{1/2} \rangle$:



X-ray signal can depend sensitively on DM velocity dispersion v_0 in system of interest.

JC, A. Frey 1408.0233

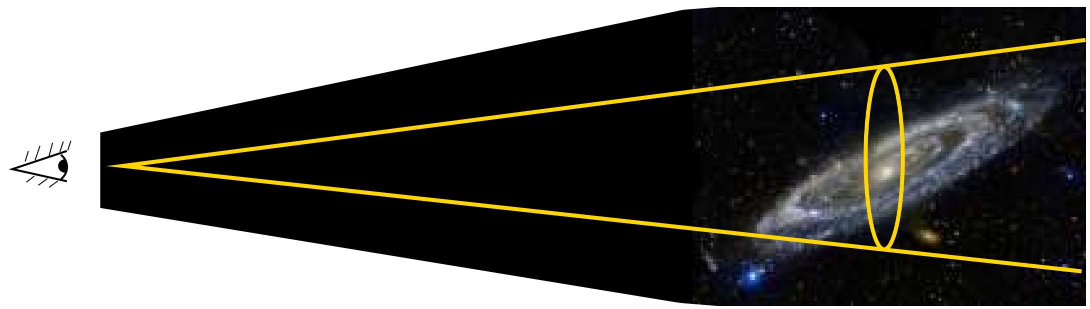
Could explain why some sources (dwarf spheroidals) reveal the line and others not.

A more detailed study

JC, A. Frey, work in progress: Previous fits to DM models focused on decaying DM, where X-ray flux is determined by DM decay rate:

$$F_\gamma = \Gamma_\nu \int \frac{d^3x}{4\pi\, x^2}\,\frac{\rho}{m_\nu}$$

Integral is over conical field of view (FOV).



We reanalyze measured fluxes for scattering (or annihilating) DM,

$$F_\gamma = \int \frac{d^3x}{4\pi\, x^2}\,\frac{\rho^2}{m_\chi^2}\langle\sigma v\rangle$$

accounting for dependence of $\langle\sigma v\rangle$ on the DM velocity dispersion in system of interest

Results

We fit fluxes to decaying DM, and to XDM with fast, intermediate and slow lifetimes of the excited state.

(1) Reference	(2) object	(3) ν mixing $\sin^2 2\theta$ $(\times 10^{-11})$	(4) fast decay $\langle\sigma v\rangle_f \cdot \left(\frac{10\,\mathrm{GeV}}{m_\chi}\right)^2$ $(10^{-22}\,\mathrm{cm^3 s^{-1}})$	(5) intermediate $\tau \sim 2\times 10^6$y or 2×10^7y	(6) slow decay $\langle\sigma v\rangle_s \cdot \left(\frac{10\,\mathrm{GeV}}{m_\chi}\right)^2$ $(10^{-22}\,\mathrm{cm^3 s^{-1}})$	(7) v disp. $\langle\sigma_v\rangle$ (km/s)
Bulbul *et al.* [1]	clusters	6 ± 3	240 ± 120		490 ± 250	1010
Bulbul *et al.* [1]	Perseus	$(22-50)$	$(900-2500)$		$(4100-13000)$	1282
Boyarsky *et al.* [2]	Perseus	$(56-100)$	$(1-2)\times 10^5$		$(1-2)\times 10^4$	1282
Boyarsky *et al.* [2]	M31	$(2-20)$	$(4-12)$	$\to \left\{ \begin{matrix}\text{unchanged} \\ (5-15)\end{matrix}\right\}$	$(25-70)$	98
Boyarsky *et al.* [4]	MW	$(10-30)$	$\left\{\begin{matrix}(0.1-0.7), & \text{NFW} \\ (50-550), & \text{Burkert}\end{matrix}\right.$	$\overset{\text{NFW}}{\to} \left\{\begin{matrix}(2-12) \\ (20-130)\end{matrix}\right\}$	$(400-3000)$	105
Riemer-Sørensen [3]	MW	$<(6-20)$	$< \left\{\begin{matrix}(0.15-1.1), & \text{NFW} \\ (82-1150), & \text{Burkert}\end{matrix}\right.$	$\overset{\text{NFW}}{\to} \left\{\begin{matrix}(2.7-20) \\ (44-330)\end{matrix}\right\}$	$<(190-1700)$	105
Anderson *et al.* [5]	galaxies	$<(1.9-4.7)$	$<(270-620)$		$<(170-420)$	100
Malyshev *et al.* [6]	dwarfs	$<(2.7-4.8)$	$<(0.18-0.26)$		$<(0.10-0.15)$	10

Perseus cluster is a problem for all models. Contaminated by some background (or foreground)?

We treat it as an outlier in our fits.

Results

Decaying DM is not consistent with observations versus upper limits.

What about XDM? We want to correlate $\langle \sigma v \rangle$ with velocity dispersion.

M31 and Milky Way should have similar $\langle \sigma v \rangle$ – requires extra consideration

(1) Reference	(2) object	(3) ν mixing $\sin^2 2\theta$ $(\times 10^{-11})$	(4) fast decay $\langle \sigma v \rangle_f \cdot \left(\frac{10\,\mathrm{GeV}}{m_\chi}\right)^2$ $(10^{-22}\,\mathrm{cm^3 s^{-1}})$	(5) intermediate $\tau \sim 2 \times 10^6$y or 2×10^7y	(6) slow decay $\langle \sigma v \rangle_s \cdot \left(\frac{10\,\mathrm{GeV}}{m_\chi}\right)^2$ $(10^{-22}\,\mathrm{cm^3 s^{-1}})$	(7) v disp. $\langle \sigma_v \rangle$ (km/s)
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Riemer-Sørensen [3]	MW	$< (6 - 20)$	$< \left\{ \begin{matrix} (0.15 - 1.1), & \text{NFW} \\ (82 - 1150), & \text{Burkert} \end{matrix} \right.$	$\overset{\text{NFW}}{\rightarrow} \left\{ \begin{matrix} (2.7-20) \\ (44-330) \end{matrix} \right\}$	$< (190 - 1700)$	105
Anderson *et al.* [5]	galaxies	$< (1.9 - 4.7)$	$< (270 - 620)$		$< (170 - 420)$	100
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M31 versus MW

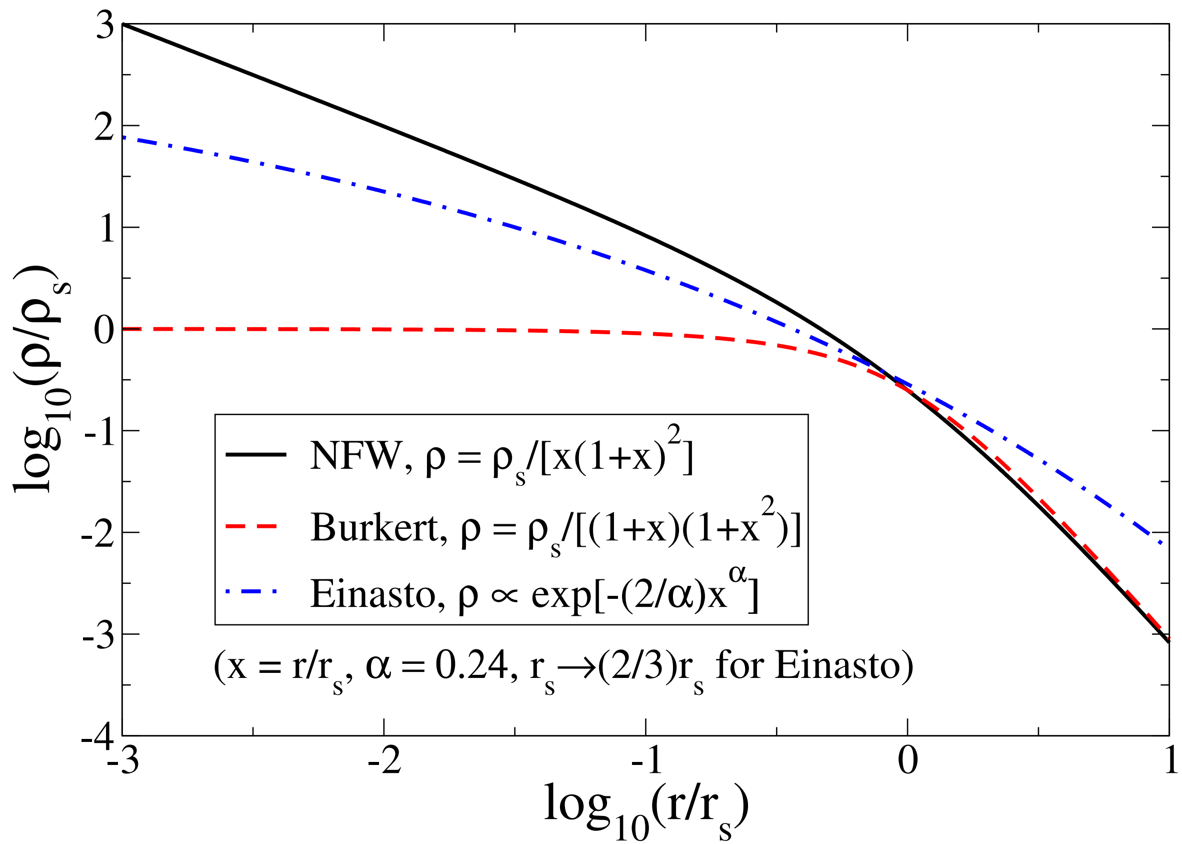
Fields of view for M31 and MW observations cover vastly different fractions of the respective halos:

Reference	object	FOV (radius)	$\langle\sigma v\rangle_f \cdot \left(\frac{10\,\mathrm{GeV}}{m_\chi}\right)^2$ $(10^{-22}\,\mathrm{cm^3 s^{-1}})$	$\tau \sim 2\times10^6$y or 2×10^7y	$\langle\sigma v\rangle_s \cdot \left(\frac{10\,\mathrm{GeV}}{m_\chi}\right)^2$ $(10^{-22}\,\mathrm{cm^3 s^{-1}})$	$\langle\sigma_v\rangle$ (km/s)
Bulbul *et al.*	clusters	0.2°	240 ± 120		490 ± 250	1010
Bulbul *et al.*	Perseus	0.2°	$(900 - 2500)$		$(4100 - 13000)$	1282
Boyarsky *et al.*	Perseus	$0.4 - 0.9^\circ$	$(1-2)\times10^5$		$(1-2)\times10^4$	1282
Boyarsky *et al.*	M31	1.5°	$(4 - 12)$	$\to \left\{ \begin{array}{c}\text{unchanged}\\ (5-15)\end{array}\right\}$	$(25 - 70)$	98
Boyarsky *et al.*	MW	0.16°	$\left\{ \begin{array}{l}(0.1-0.7),\ \text{NFW}\\ (50-550),\ \text{Burkert}\end{array}\right.$	NFW $\to$ $\left\{ \begin{array}{c}(2-12)\\ (20-130)\end{array}\right\}$	$(400 - 3000)$	105
Riemer-Sørensen	MW	$0.04 - 0.15^\circ$	$< \left\{ \begin{array}{l}(0.15-1.1),\ \text{NFW}\\ (82-1150),\ \text{Burkert}\end{array}\right.$	NFW $\to$ $\left\{ \begin{array}{c}(2.7-20)\\ (44-330)\end{array}\right\}$	$< (190 - 1700)$	105
Anderson *et al.*	galaxies	$R_{\rm vir}/d$	$< (270 - 620)$		$< (170 - 420)$	100
Malyshev *et al.*	dwarfs	0.25°	$< (0.18 - 0.26)$		$< (0.10 - 0.15)$	10

Inferred cross section for MW is very sensitive to whether halo profile is cuspy or cored; M31 is insensitive.

Cuspy versus cored profile

DM-only simulations predict cuspy halos; simulations with baryons tend to be cuspy, but can also depend upon details of merger history. Some observations claim evidence for cored halos.



We don't need strong core to reconcile MW and M31 signals–see Einasto profile

Lifetime of excited state

Instead of cored halo, it is possible that excited state streams away from galactic center before decaying, reducing signal in observed field of view. Has similar effect to less cuspy halo.

We smear $\rho^2(x)$ by Gaussian of width

$$\sigma = \sigma_v \tau = \text{velocity dispersion} \times \text{lifetime}.$$

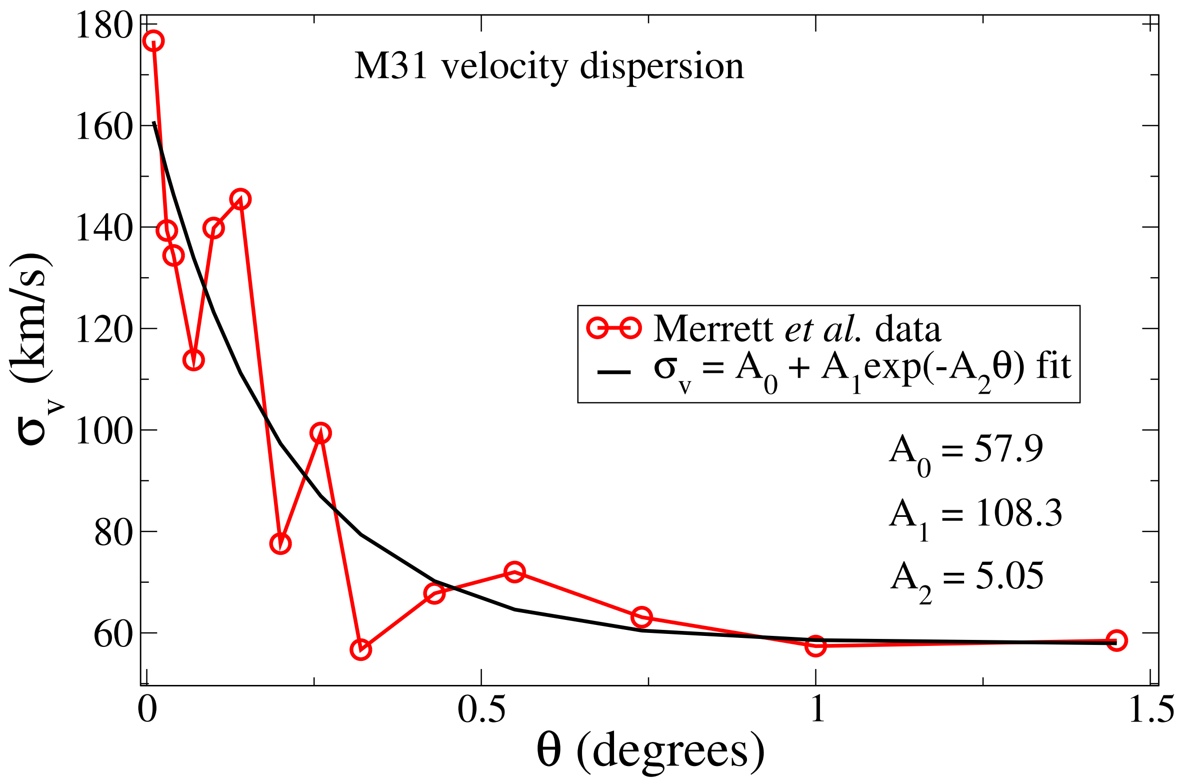
Lifetimes $\tau = 2 \times 10^6 - 2 \times 10^7$ y can reconcile M31 and MW line strengths.

(In limit of very long lifetime, excited states virialize and produce line with same morphology as decaying DM, but different rate

$$\Gamma_{\rm eff} = \frac{\langle \sigma v \rangle}{m_\chi} \frac{\int d^3x\, \rho^2}{\int d^3x\, \rho}\ )$$

M31 velocity dispersion profile

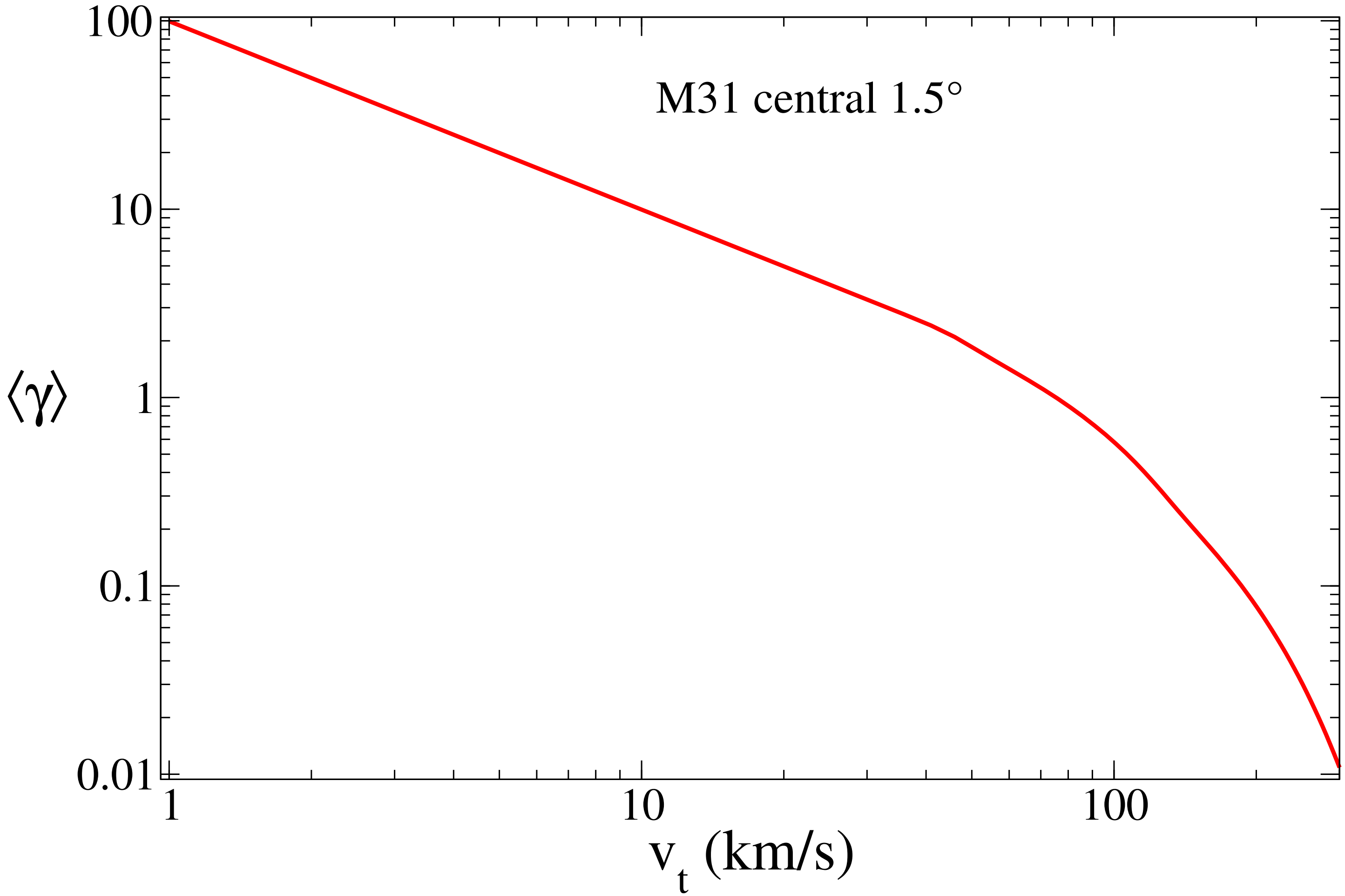
Most sources have approximately constant σ_v over field of view, but not Andromeda galaxy.



Must take $\langle \sigma v \rangle = \sigma_0 v_t \gamma(\sigma_v / v_t)$ inside integral $\int d^3x \, \rho^2 / x^2$ for the flux.

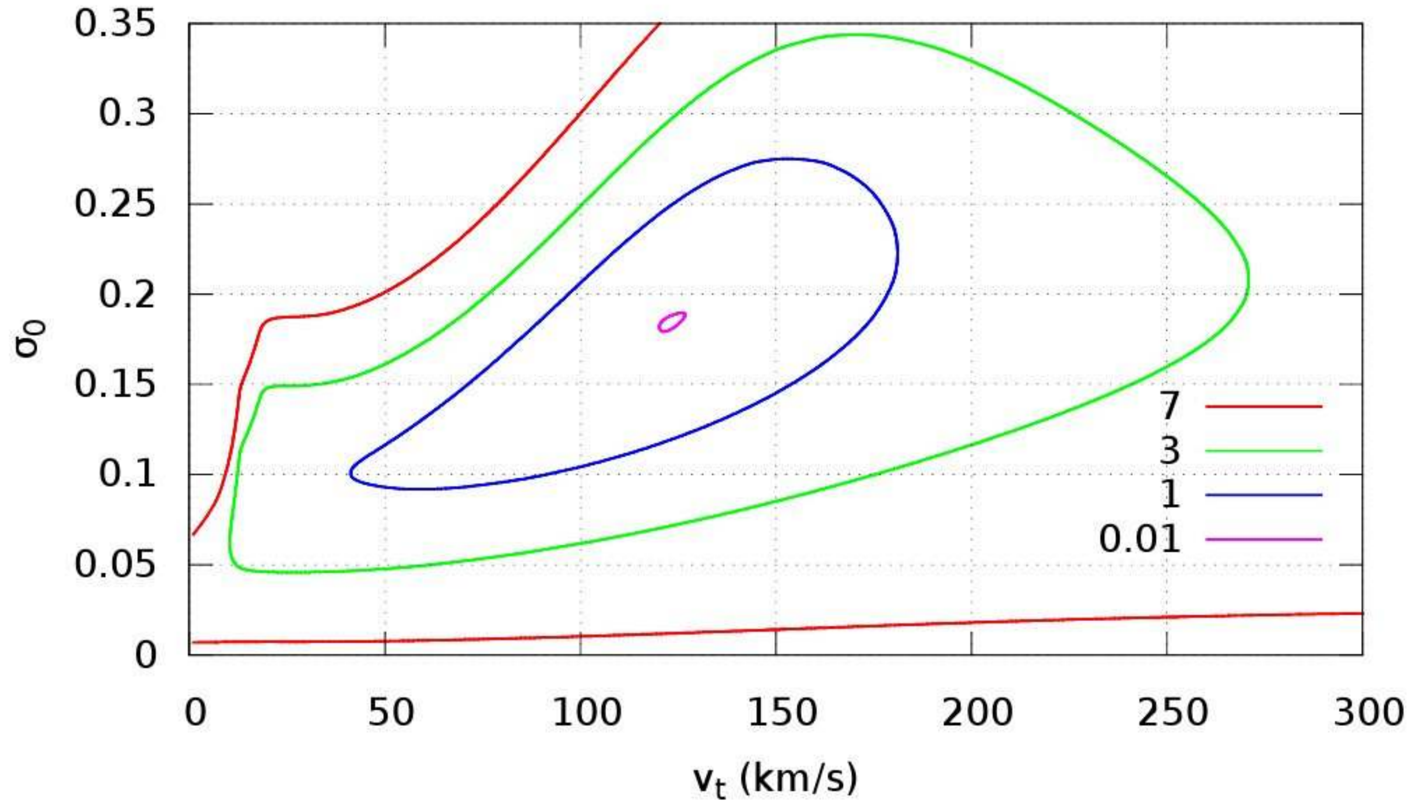
M31 velocity dispersion profile

Leads to this dependence on threshold velocity:



Fits to X-ray line data: fast decays

We parametrize cross section as $\langle\sigma v\rangle = \sigma_0\, v_t\, \gamma(\sigma_v/v_t)$.
XDM model is specified by parameters σ_0, v_t and τ.
We fit σ_0, v_t to observations for short and intermediate τ.
Contours of χ^2 for models with fast decays:

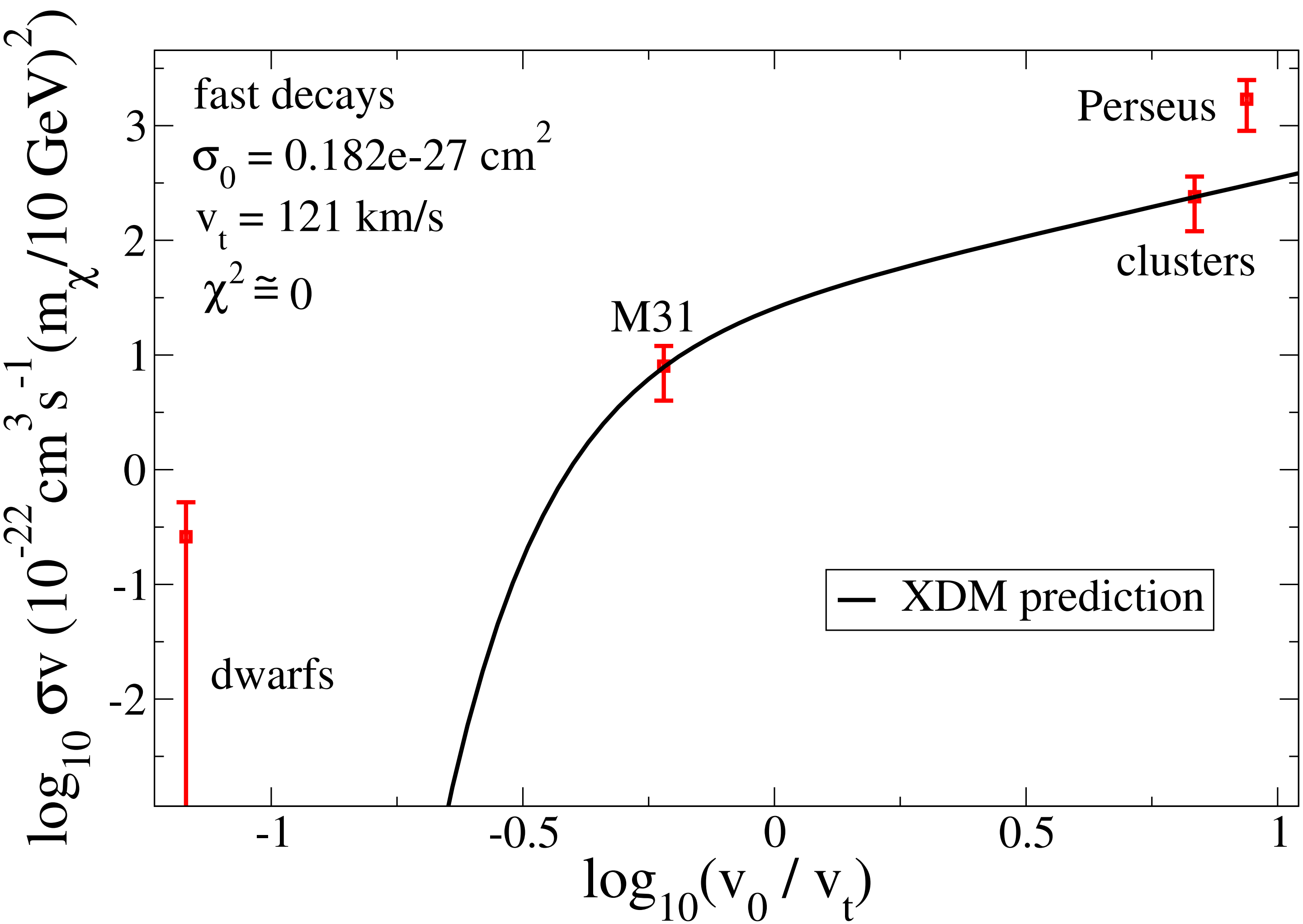


Recall $v_t = (8\,\delta m_\chi/m_\chi)^{1/2}$. Allowed range of v_t implies

$$25\ \mathrm{GeV} \lesssim m_\chi \lesssim 25\ \mathrm{TeV}$$

Cross section versus velocity

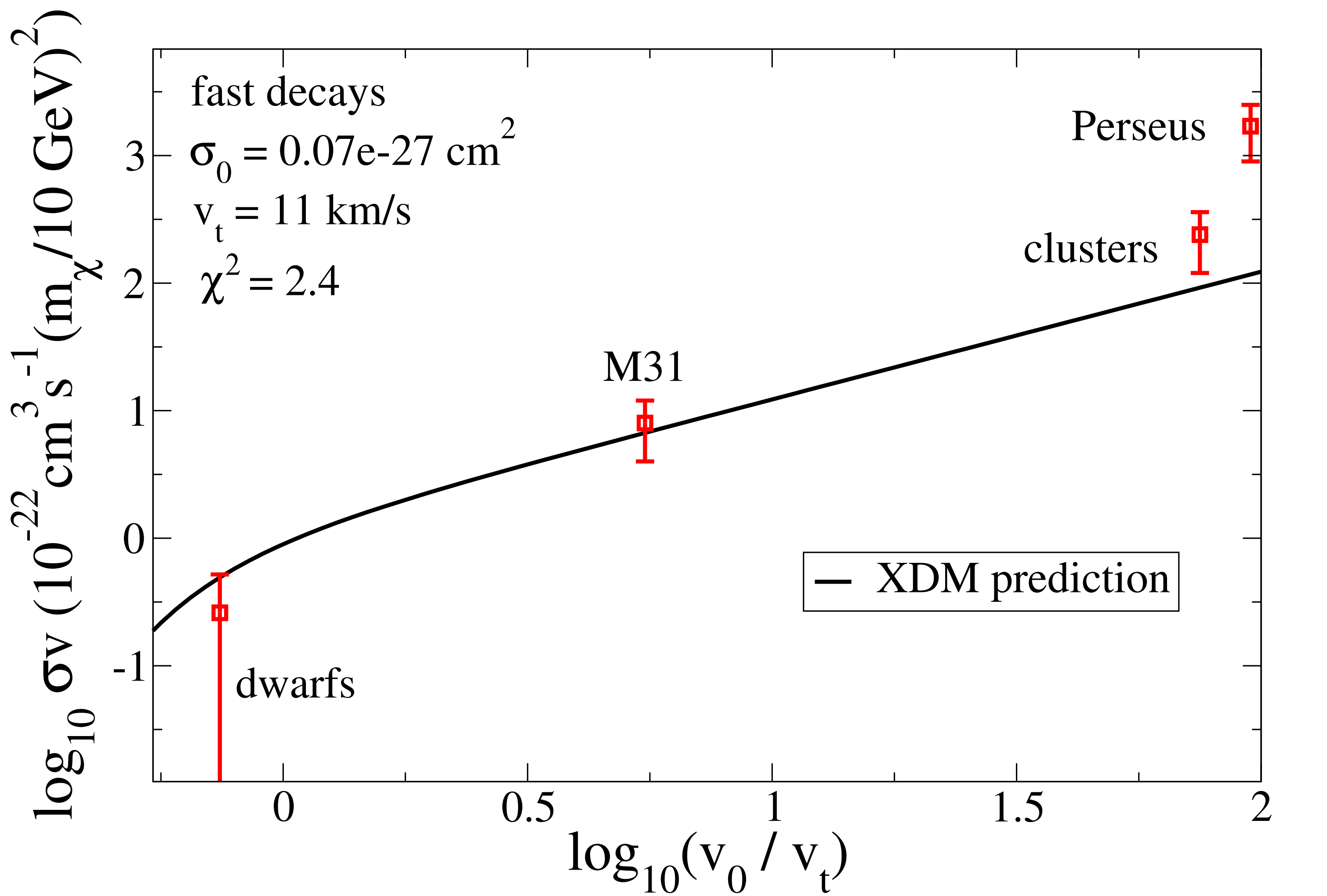
At best fit point, dwarf spheroidal signal is predicted to be far below observed limit



MW signal (not shown) is fitted by adjusting DM halo profile.

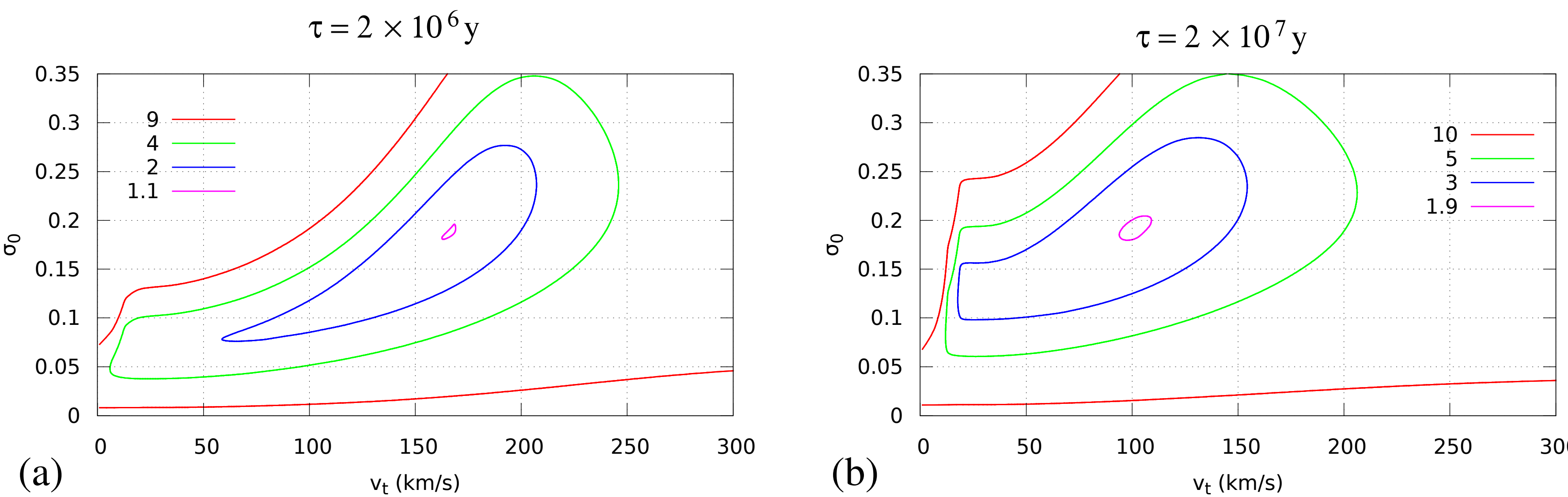
Cross section versus velocity

But for an acceptable fit ($\delta\chi^2 = 3$) with low $v_t \sim 10$ km/s, dwarf spheroidal signal could be just below threshold for detection



Fits to X-ray line data: slower decays

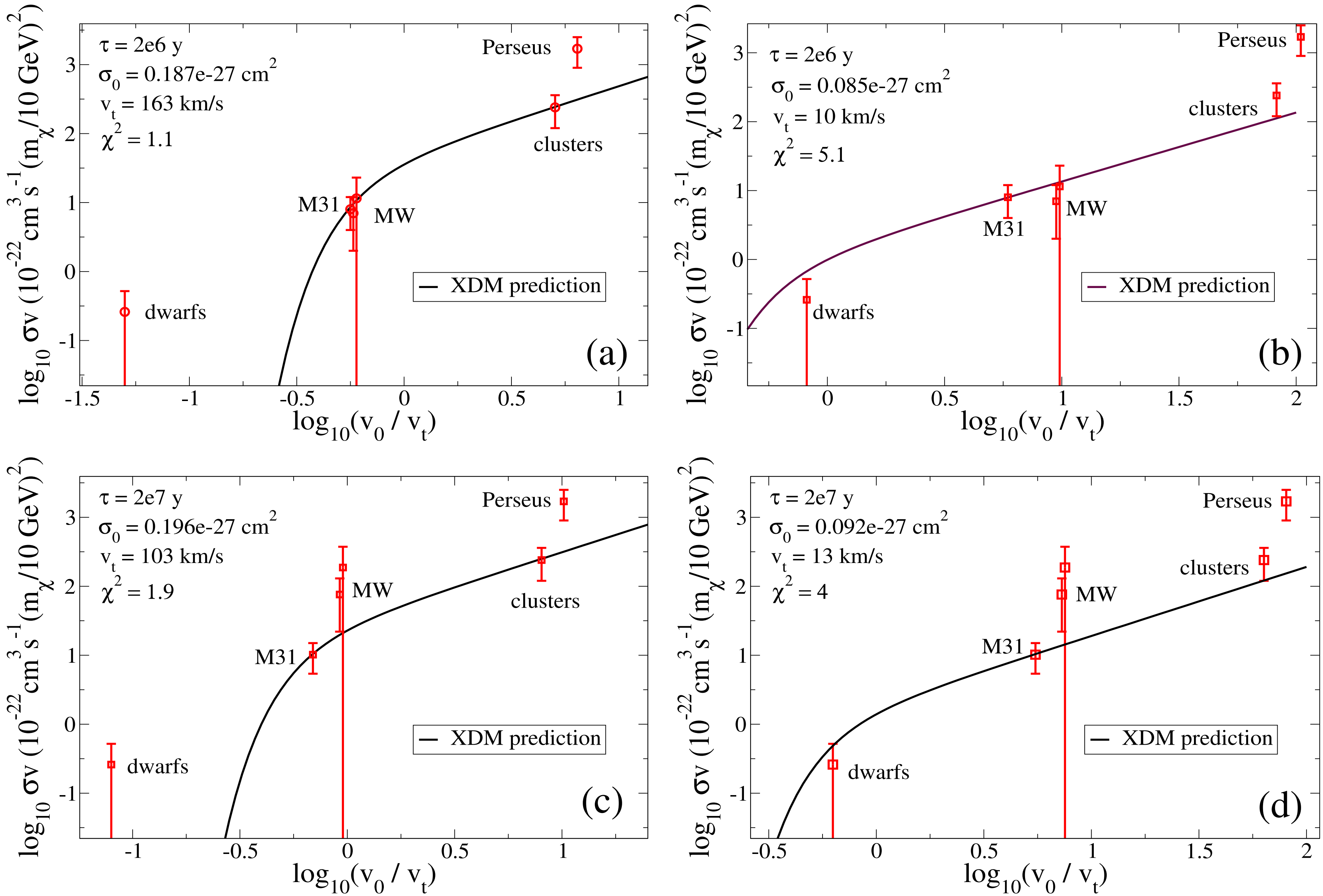
Similar conclusions hold for excited states with longer lifetimes



Shorter lifetime 2×10^6 y gives better fit.

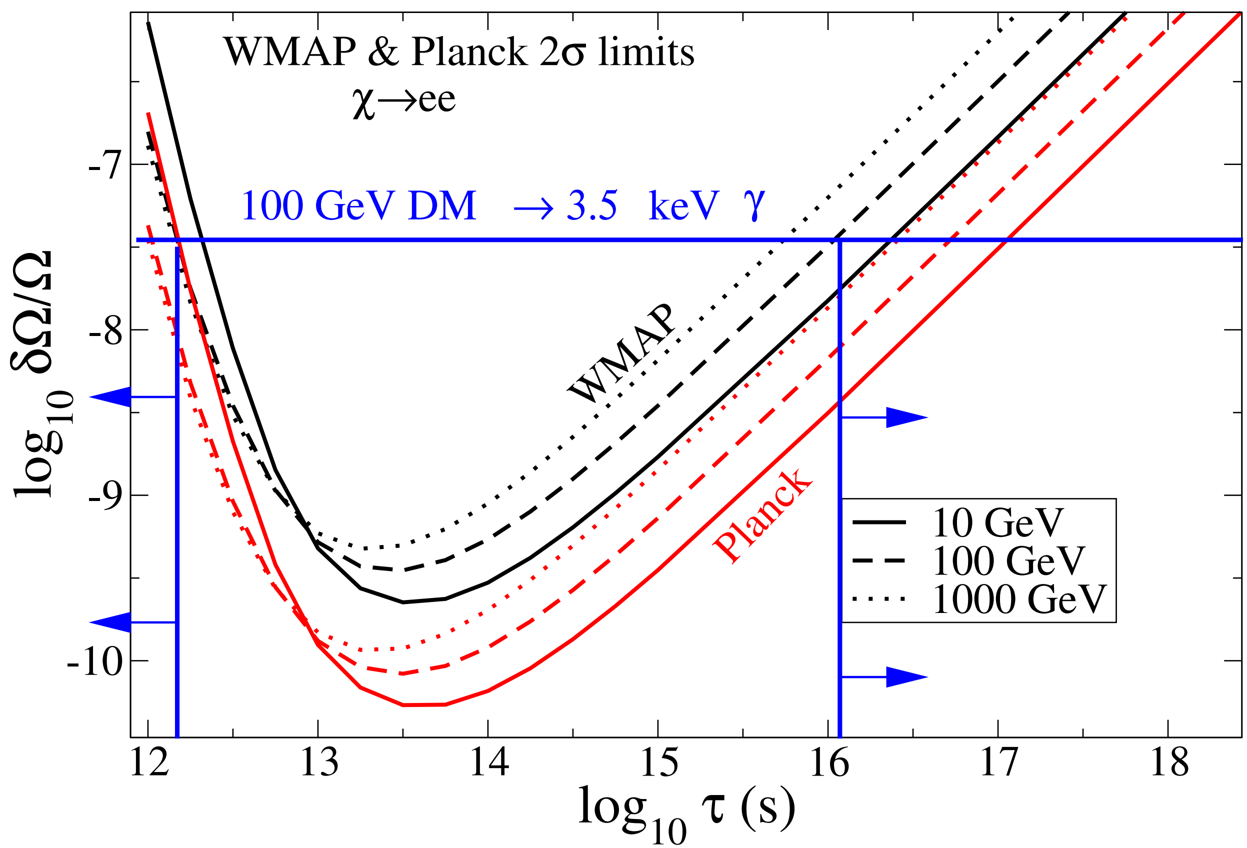
Fits to X-ray line data: slower decays

Here we fit MW data with others



CMB constraint: $\delta\Omega/\Omega$ versus τ

Metastable DM decaying into SM particles can distort the CMB unless lifetime is sufficiently long or short



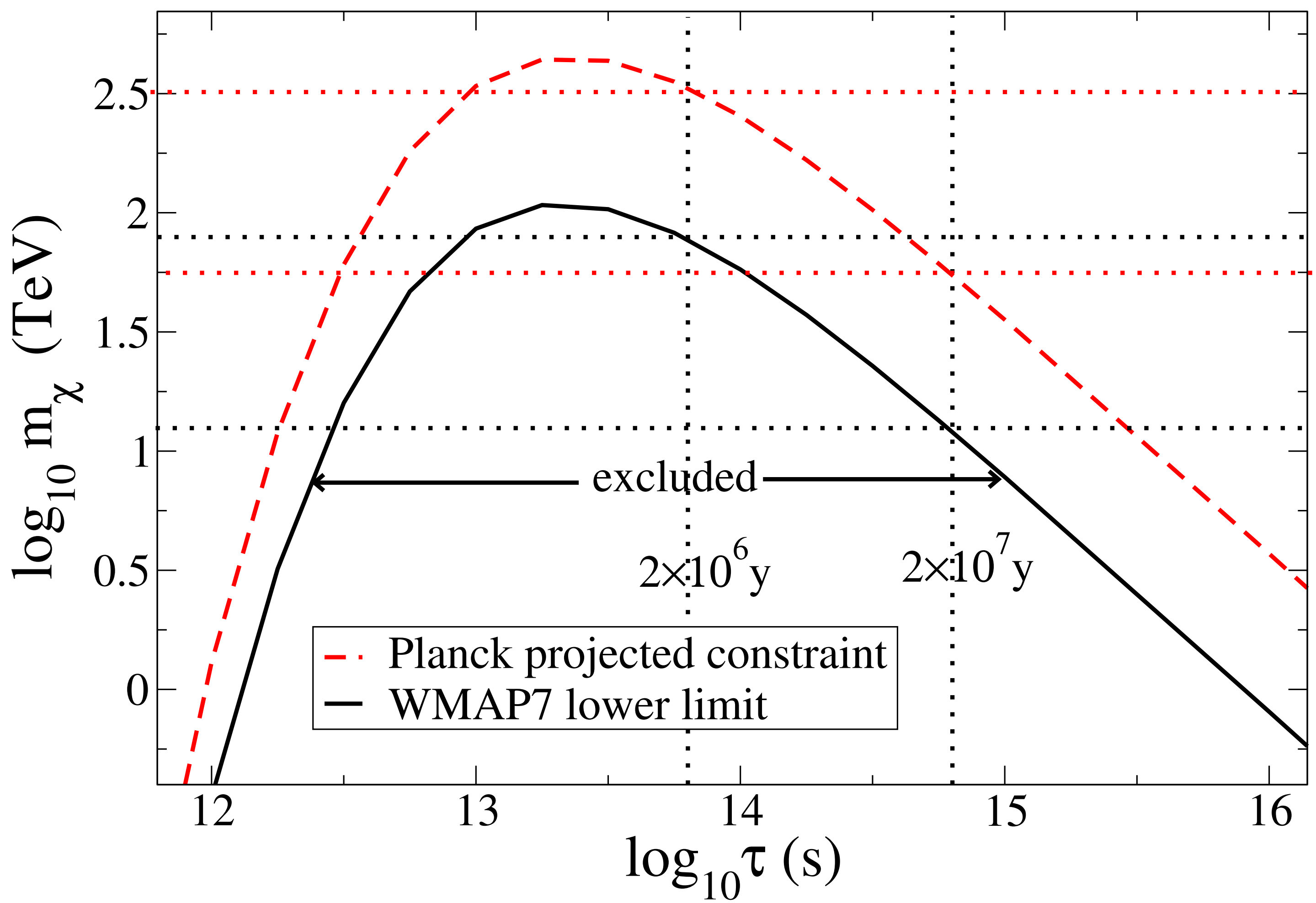
$\delta\Omega/\Omega = \delta m_\chi/m_\chi$ = fraction of DM energy density that decays into electrons (in this example)

JC & P. Scott, (1301.5908)

E.g., 100 GeV DM decaying into 3.5 keV x-ray has $\delta\Omega/\Omega = 3.5\times 10^{-8}$, lifetime must be $\gtrsim 10^{16}$s or $\lesssim 10^{12}$s

CMB constraint: m_χ versus τ

The slow decay scenario is constrained by CMB. Desired lifetime requires large DM mass $m_\chi \gtrsim 5$ TeV in most optimistic case



Planck may eventually exclude the long-lived scenario entirely

X-rays as "21cm lines" of dark atoms

JC, Z. Liu, G.D. Moore, Y. Farzan, W. Xue, 1404.3729

How to generate such a small mass splitting?
Atomic dark matter has hyperfine excited state with

$$\Delta E = \frac{8}{3}\,\alpha'^4\,\frac{m_e^2 m_p^2}{(m_e+m_p)^3} = \frac{8}{3}\,\alpha'^4\,\frac{\mu_H^2}{m_H}$$

suppressed by $\alpha'^4(m_e/m_p)^2$.

With gauge kinetic mixing, $-(\epsilon/2)F'_{\mu\nu}F^{\mu\nu}$, excited state decays into photons with rate

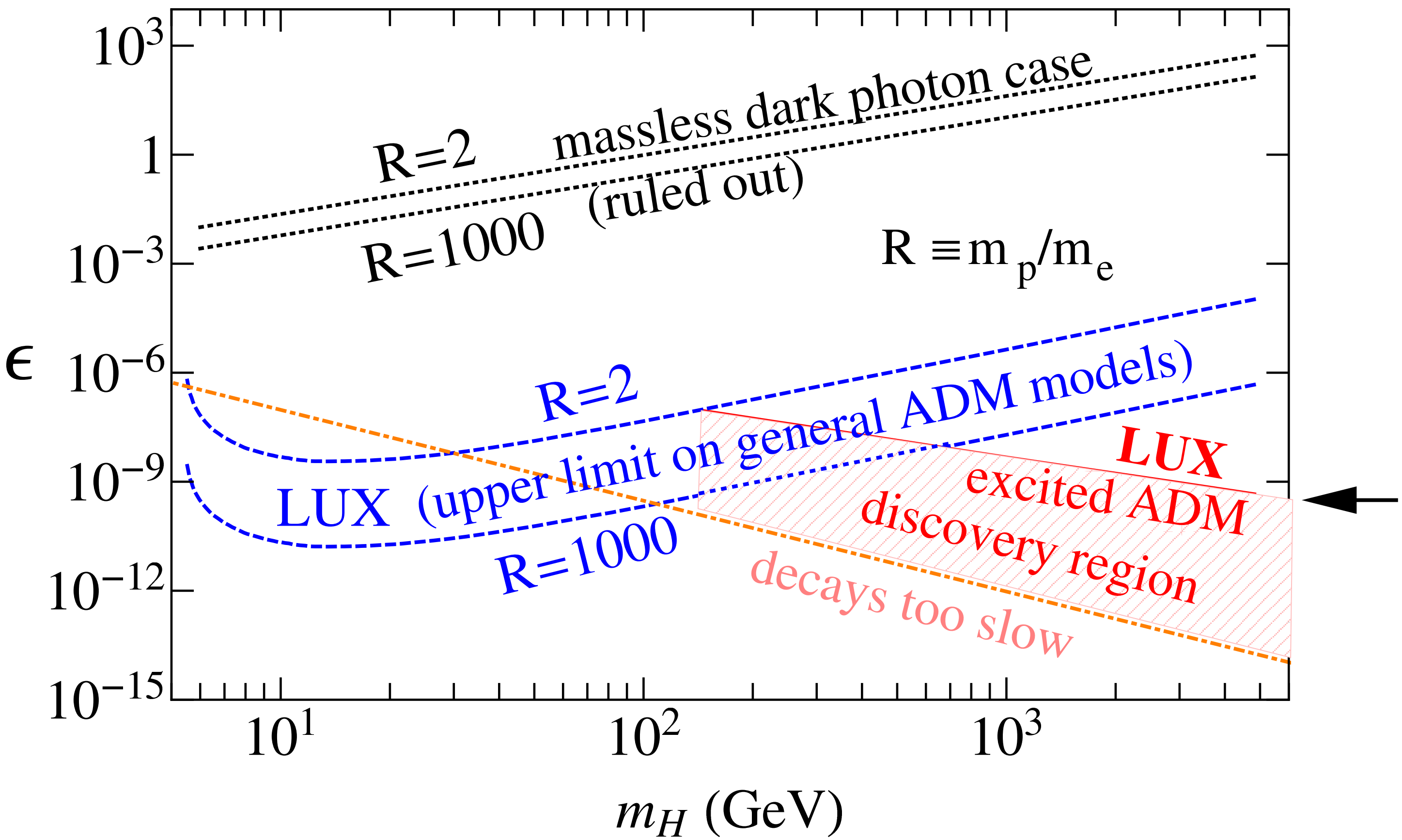
$$\Gamma_{hf} = \frac{3\mu_H^2}{\alpha\epsilon^2\Delta E^3}$$

If dark photon mass $m_{\gamma'} > 3.5\ \mathrm{keV}$, these are the only decays. Analog of 21 cm emission in dark sector.

Direct detection of dark atoms: $m_p \gg m_e$

If excited state is primordial, $\epsilon \sim 10^{-14}\, m_e\, m_p^{1/2}\, \mathrm{GeV}^{-3/2}$ and direct detection is unobservable.

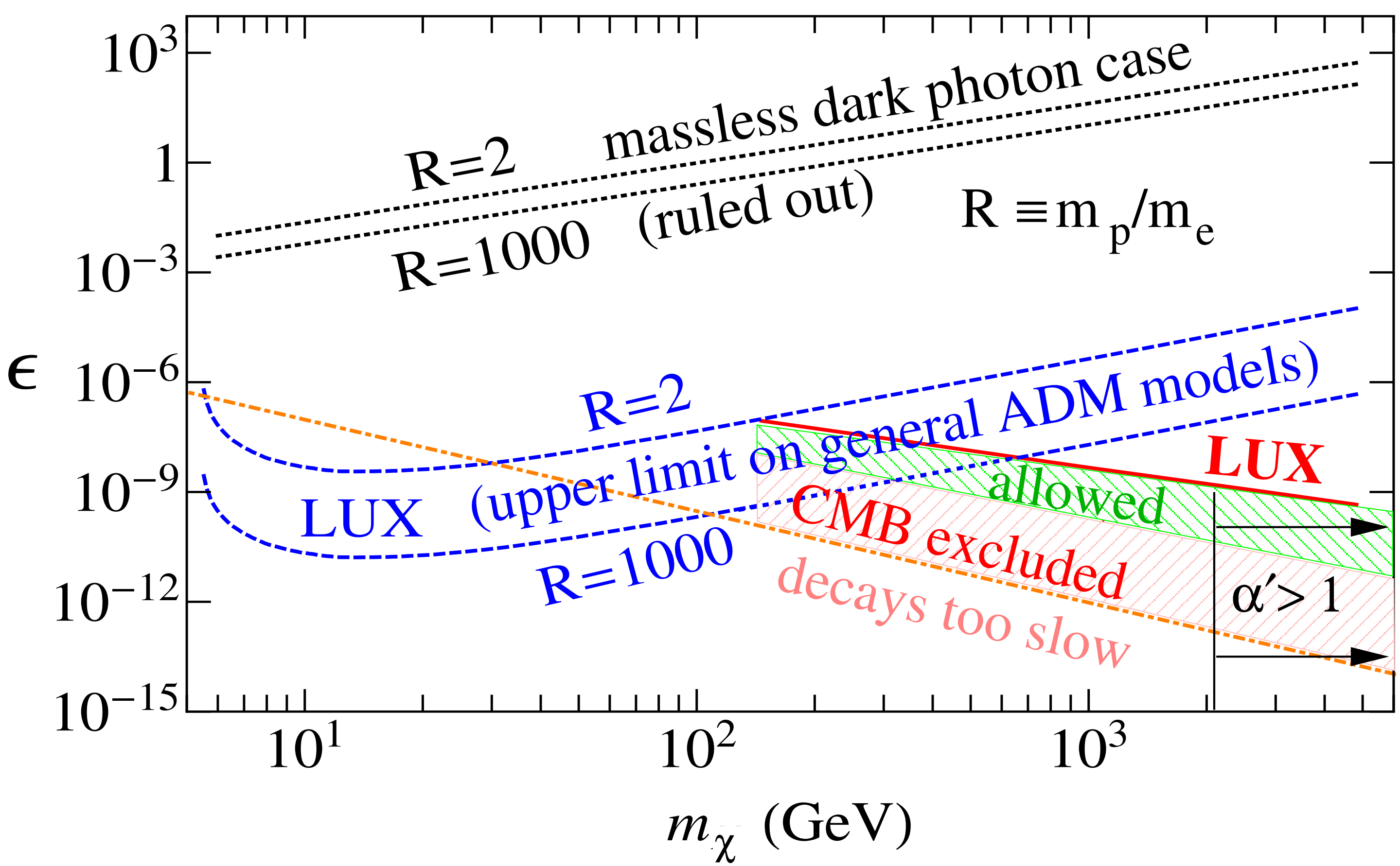
If XDM mechanism $\chi_1\chi_1 \to \chi_2\chi_2 \to \chi_1\chi_1 + 2\gamma$, then ϵ can be much larger, discoverable by direct detection.



Cross section for observed line strength implies relation between R and m_H.

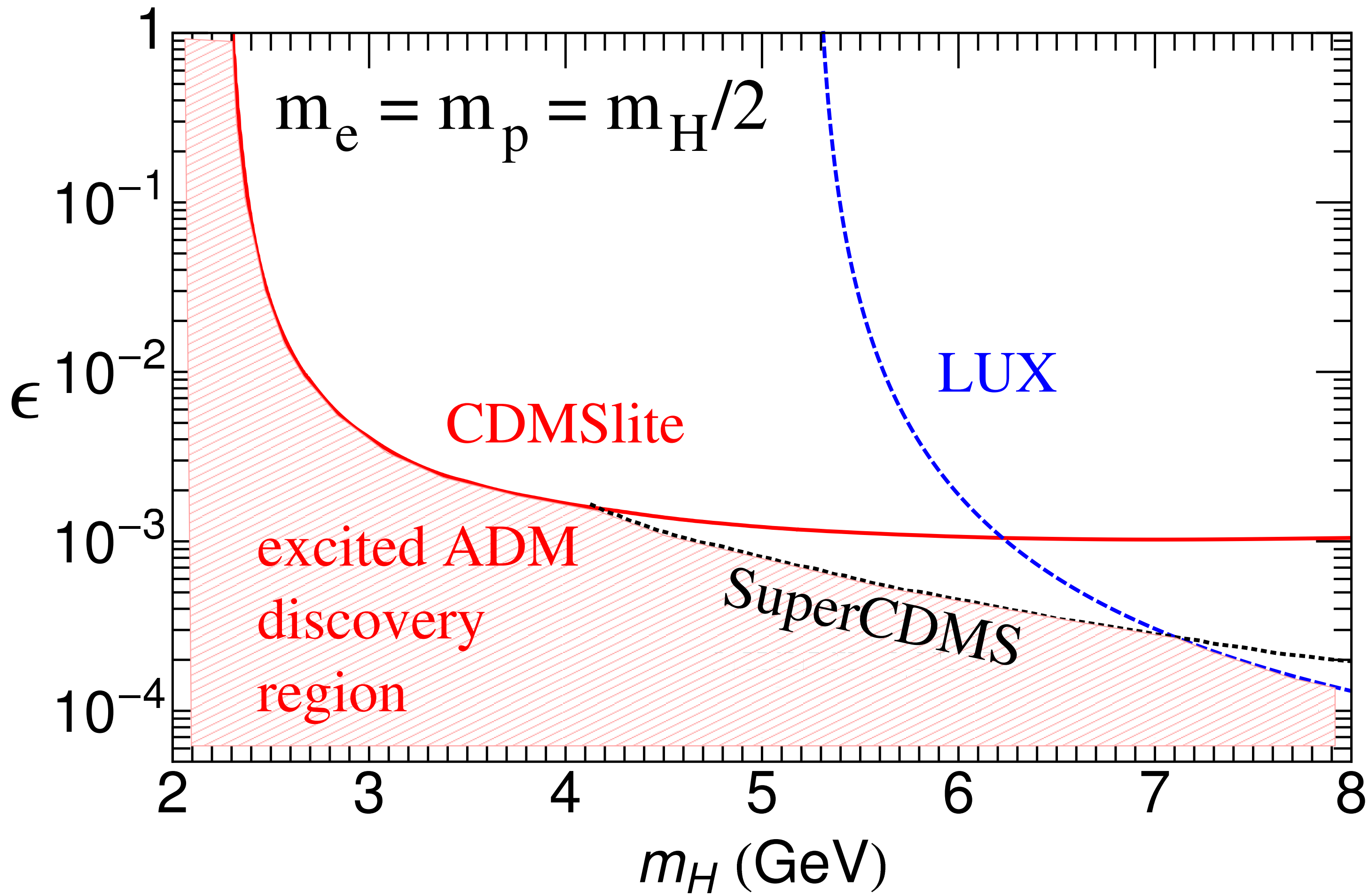
Effect of CMB constraint

Since intermediate/slow decays of excited state are ruled out, the allowed parameter space is reduced



Direct detection of dark atoms: $m_e = m_p$

$m_e = m_p$ is a special case: transitions are magnetic and inelastic $\chi_1\, p \to \chi_2\, p$: much weaker constraint on ϵ.

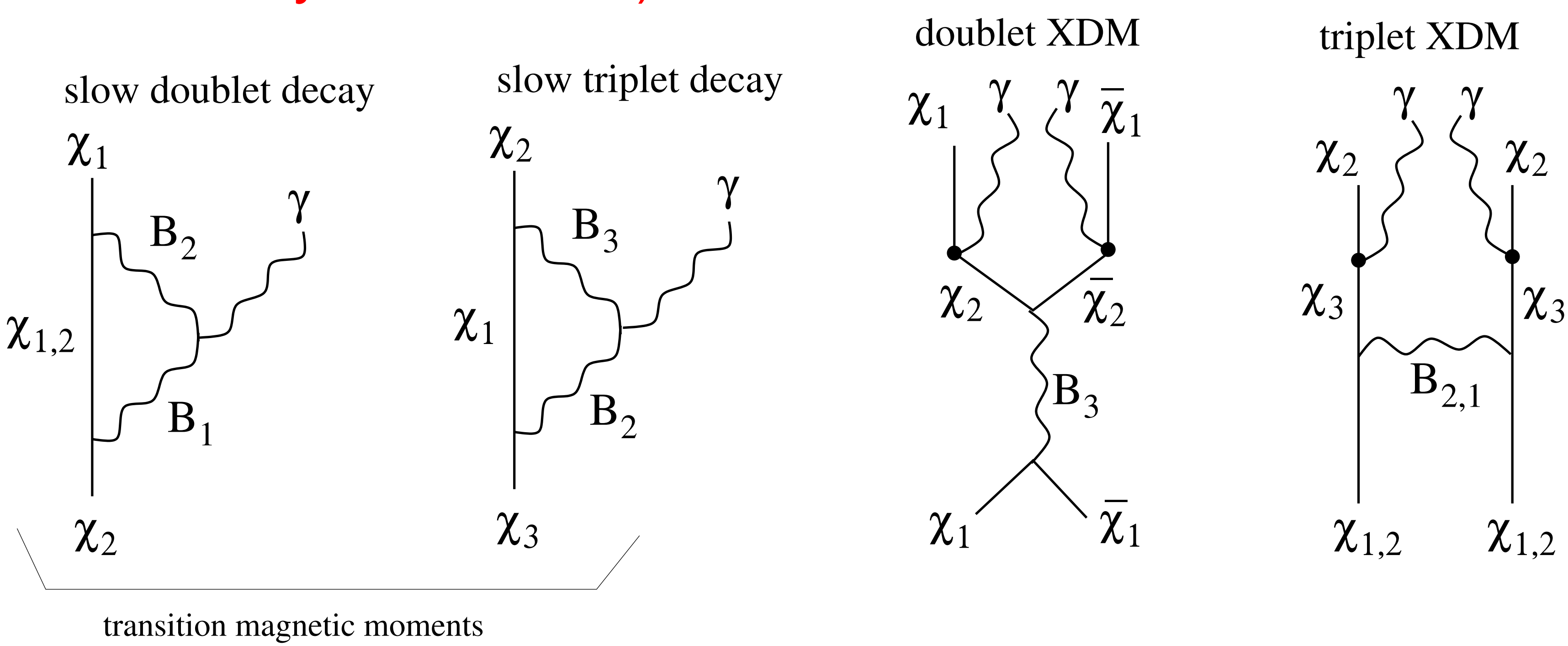


X-rays from nonabelian XDM

Suppose DM transforms under a nonabelian gauge symmetry in the hidden sector, take SU(2).

Broken SU(2) can give small mass splittings of the DM multiplet, $\delta m_\chi = 3.5\ \mathrm{keV}$

Natural setting for XDM models of X-ray line
(JC & A. Frey, 1408.0233)



Nonabelian kinetic mixing

Need dimension-5 or -6 operator for nonabelian kinetic mixing, with dark Higgs triplet Δ or doublet h

$$\frac{1}{2\Lambda}\Delta^a B_a^{\mu\nu} Y_{\mu\nu} \quad \text{or} \quad \frac{1}{2\Lambda^2}(h^\dagger \tau^a h)\, B_a^{\mu\nu} Y_{\mu\nu}$$

Higgs VEV gives kinetic mixing parameter $\epsilon = \langle\Delta\rangle/\Lambda$ or $\langle h\rangle^2/\Lambda^2$ and the interaction

$$\epsilon g B_1^\mu B_2^\nu F_{\mu\nu}$$

that gives χ transition magnetic moment at one loop.

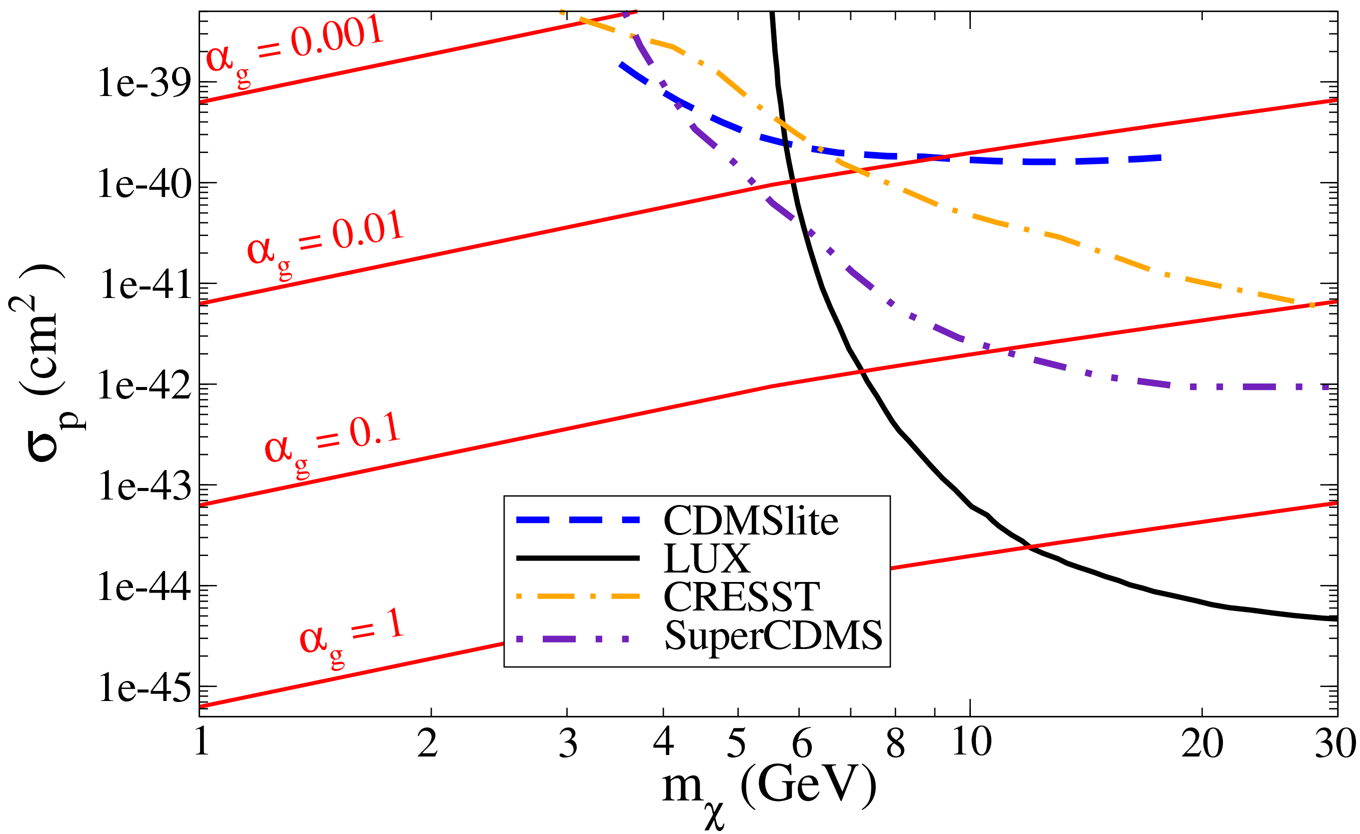
After diagonalizing gauge boson kinetic term, B_3 gets coupling ϵe to protons — mediates χ scattering on nucleons.

B_3 also couples to electrons: can be produced in beam-dump experiments

Direct detection of nonabelian DM

Cross section on protons is $\sigma_p \cong 16\pi^2\,\epsilon^2\,\alpha\,\alpha_g\,m_p^2/m_B^4$

Need $\epsilon = f(\alpha_g, m_\chi, m_B)$ to get observed X-ray line strength from decays. Dependence on m_B cancels in doublet DM model; σ_p depends only on m_χ and α_g:



← Slowly decaying doublet DM model (asymmetric DM) ←

XDM version has $\sigma_p \gtrsim \dfrac{10^{-36}\ \text{cm}^2}{\alpha_g^2}$ requires $m_\chi \lesssim 2$ GeV

Is nonabelian XDM ruled out?

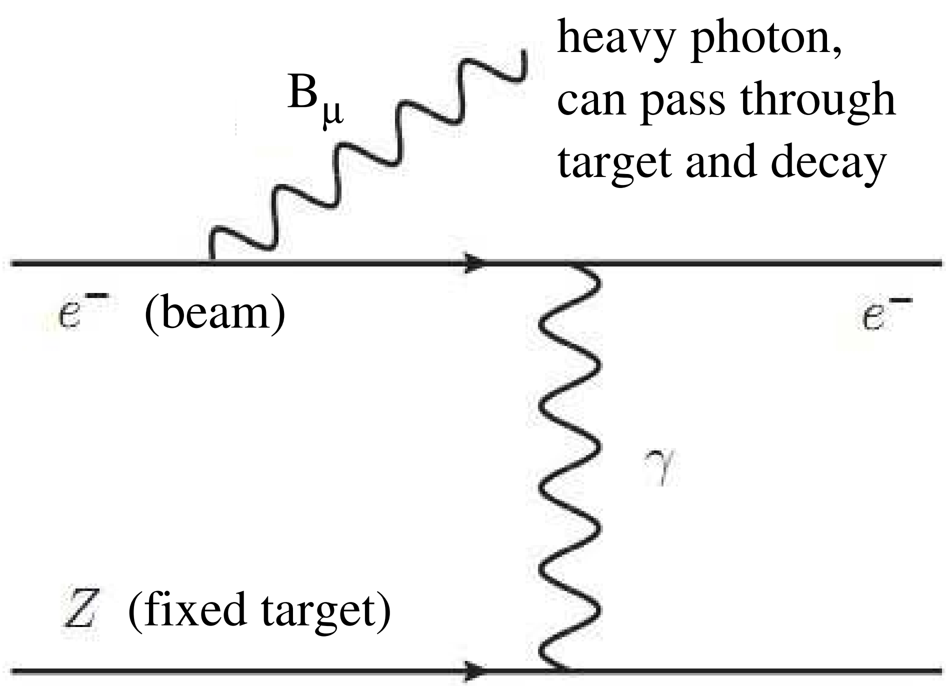
Such small DM mass requires large threshold velocity, $v_t \gtrsim 1100$ km/s

X-ray line would be suppressed in all sources except galaxy clusters.

Let's see how experimental situation develops

Heavy photon searches

The massive B_3 gauge boson can be discovered in beam dump experiments like APEX, DarkLight, HPS (Heavy Photon Search) at Jefferson Lab, or MAMI (Mainz Microtron)

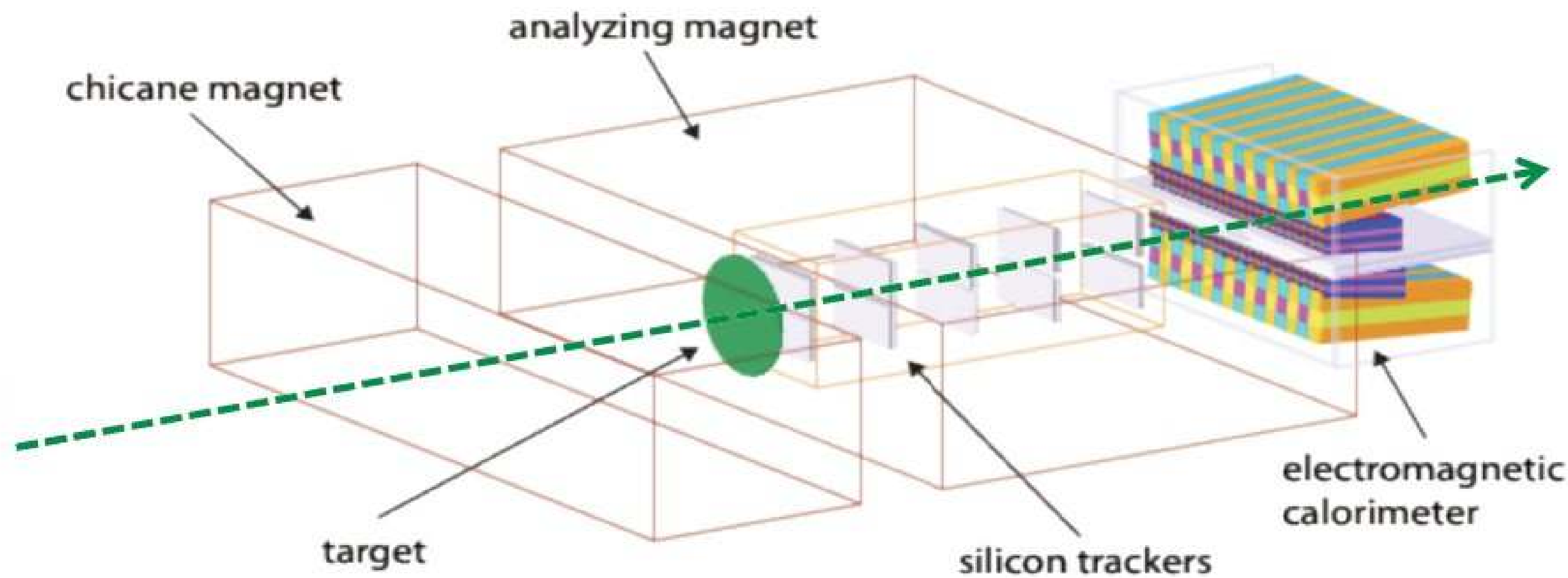


$B \to e^+e^-$ after passing through target, due to kinetic mixing

HPS status (1310.2060)

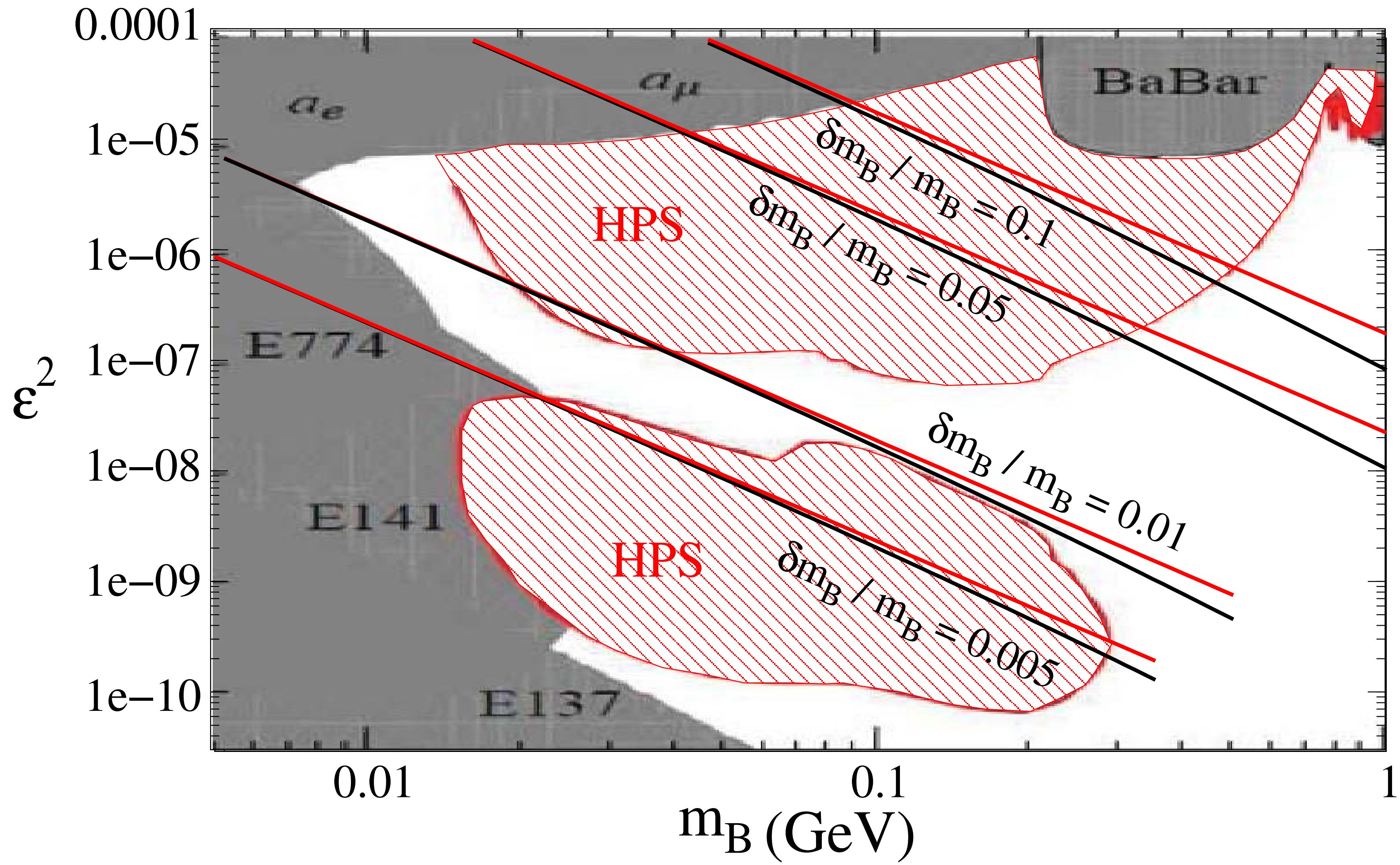
HPS is funded, will be installed in Sept. 2014, beamline in Oct., engineering run through spring 2015.

Includes muon detector (not shown). Searches for bumps in e^+e^- or $\mu^+\mu^-$ spectrum, and also displaced vertices.



HPS discovery potential

XDM doublet model has lower bound on ϵ to satisfy CMB constraints. The bound depends upon α_g, $\delta m_B/m_B$ and (weakly) on m_χ; has significant overlap with HPS regions.



Conclusions

Steady stream of experimental hints for DM detection keeps the field interesting!

3.5 keV X-ray signal is controversial; excited DM models might explain observational discrepancies

Perseus cluster flux too big; presents challenge to all DM models

The other observations can fit XDM predictions if MW halo is not too cuspy, or if XDM lifetime $\sim 10^7$ y and $m_\chi \gtrsim 5$ TeV

For noncuspy MW halo, DM mass can be 25 GeV - 25 TeV. If heavy, dwarf spheroidals could reveal the line

Not only direct detection may confirm nature of dark sector; dark gauge boson may also be discoverable at electron beam experiments