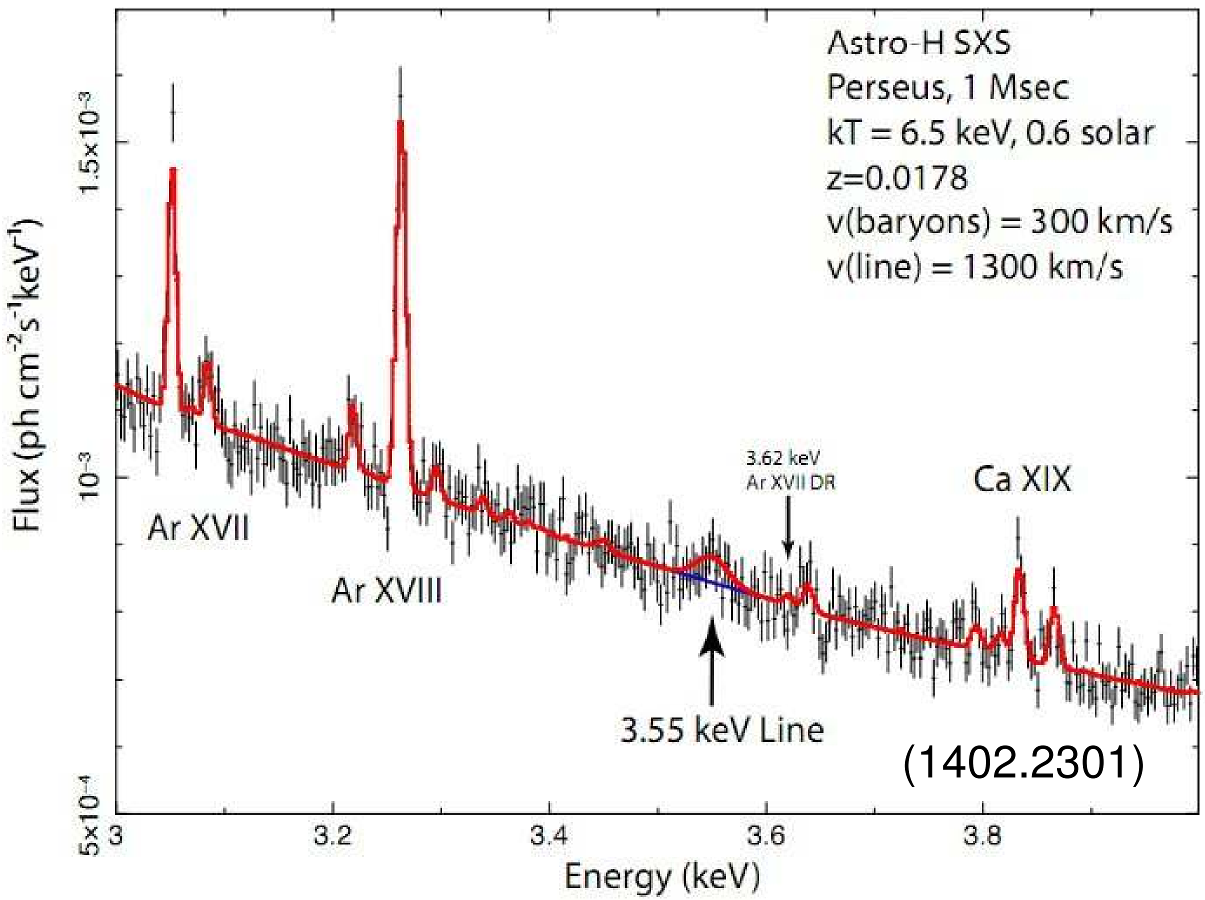
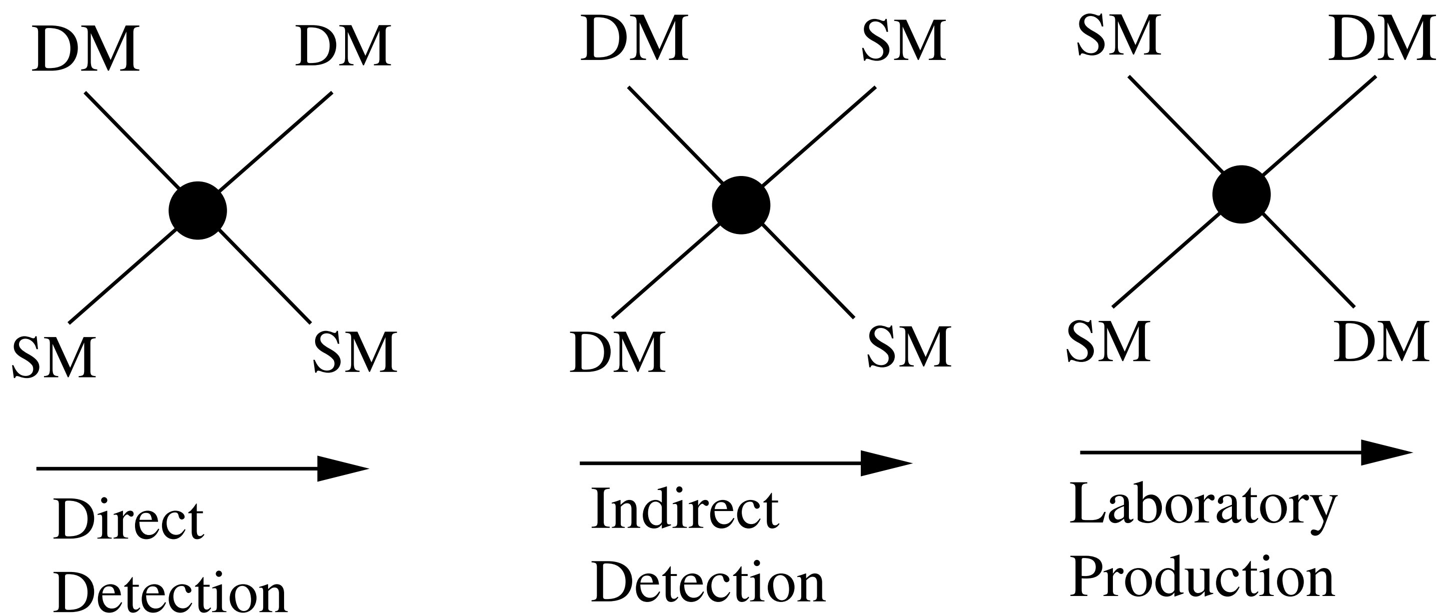
News from the dark side



Jim Cline, McGill University

NBIA-APCTP workshop, 22 Aug. 2014

The dark matter mantra

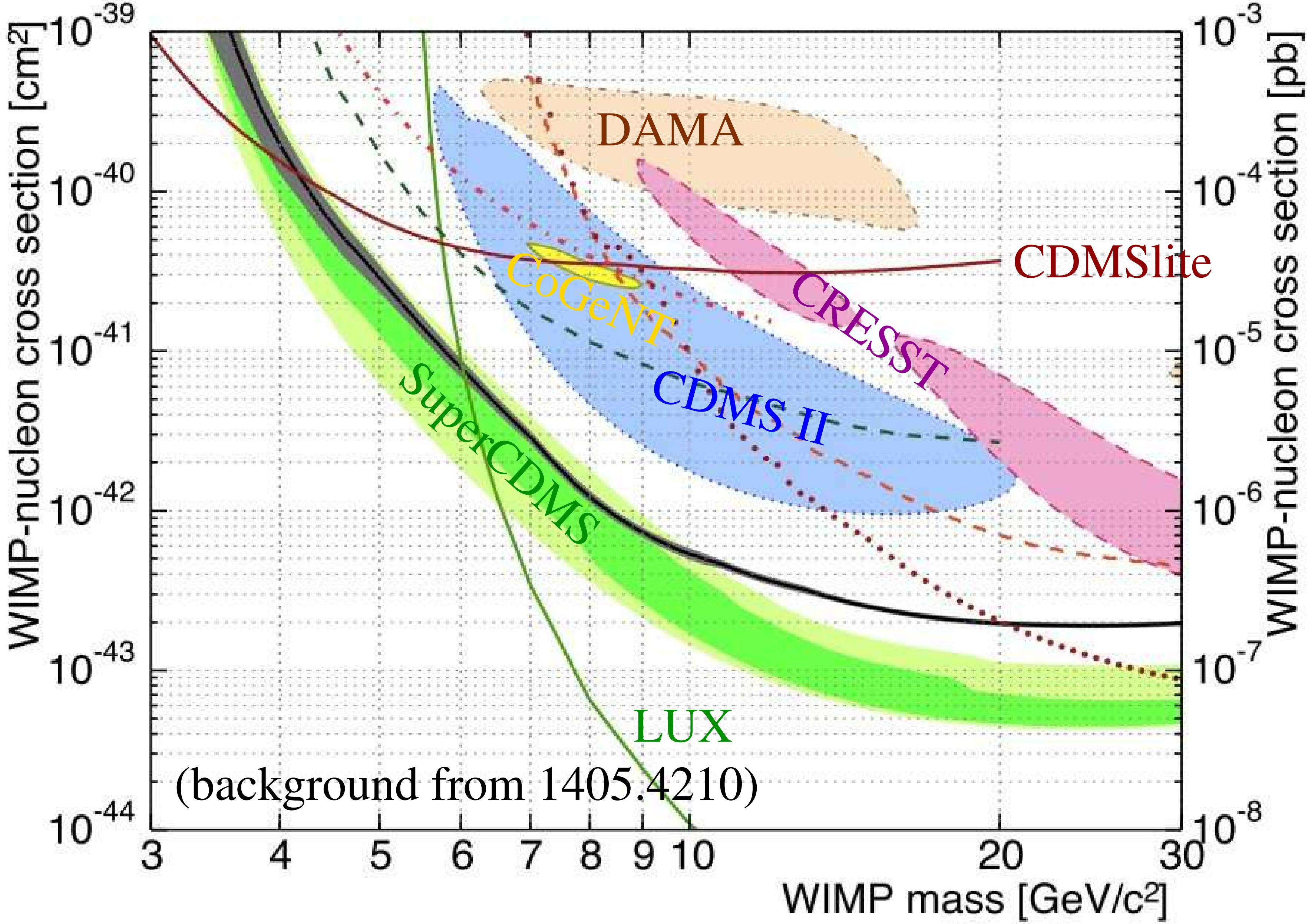


Keep repeating the words, one may eventually come true . . .

Hints of direct detection (come and gone)

- DAMA: never gone but never confirmed
- CoGeNT: modulation persists, amplitude too big for WIMPs (1401.3295)
- CRESST: latest result negates initial hints of detection (1407.3146)
- CDMS II excess events excluded by SuperCDMS (1405.4210)

Hints of direct detection (come and gone)



Spin-dependent scattering limits

If DM interacts with nucleon spin, limits are weaker:

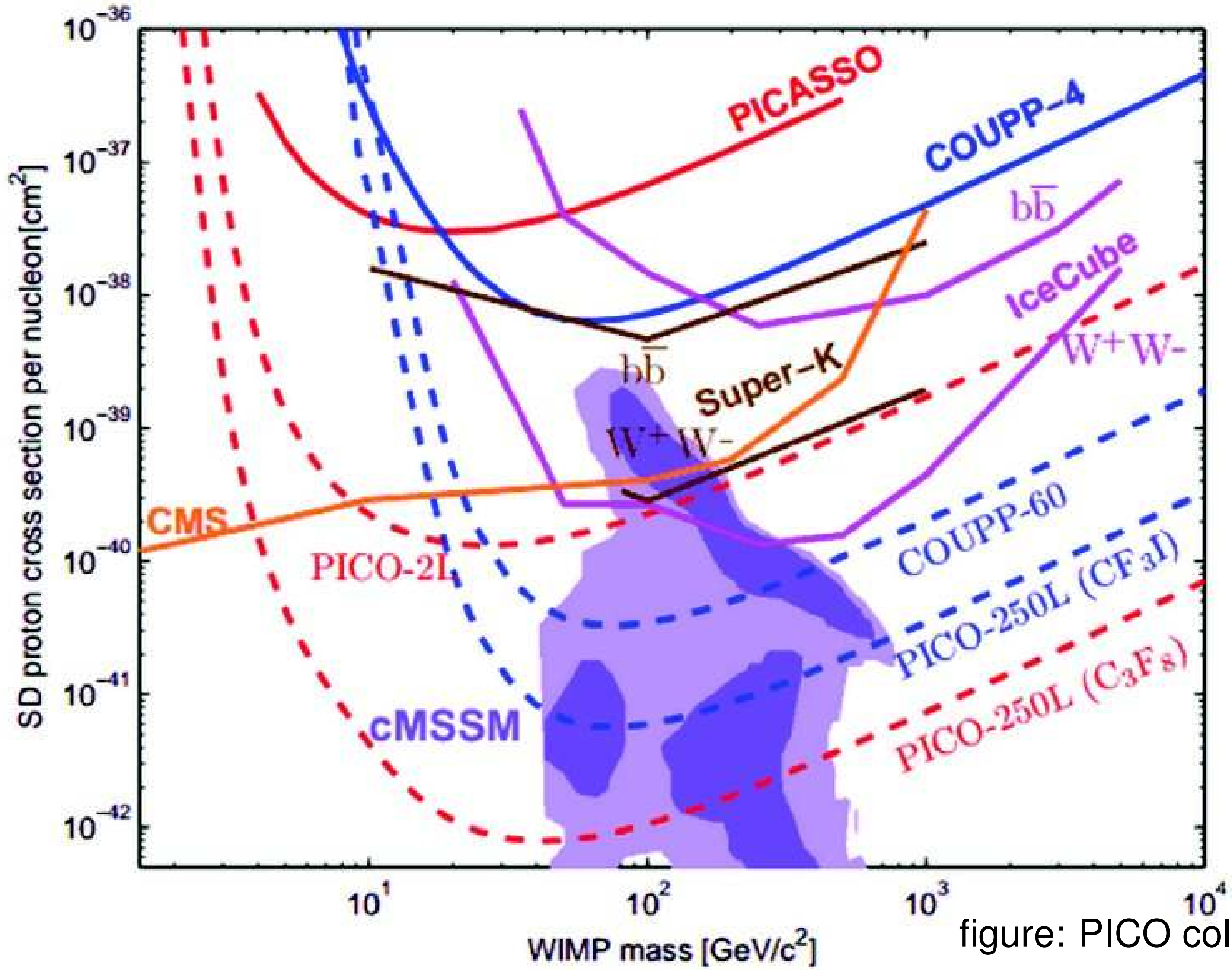


figure: PICO collaboration

PICO collaboration at SNOLAB will push limits (2017)

Hints of indirect detection

- Excess 511 keV gamma rays from galactic center — source still unknown after 40 years
- PAMELA/Fermi/AMS excess positrons (probably pulsars?)
- 130 GeV Fermi line (significance has gone down in Fermi analysis)
- Galactic center gamma ray excess (under pressure from cosmic ray constraints? 1404.3741, 1406.6027, 1407.2173)
- Hints of strong DM self-interactions from structure formation (many caveats, 1306.0913)
- The latest! 3.5 keV X-ray line in XMM-Newton data; seen in M31 and Perseus galaxy cluster (1402.4119), stacked spectra of 73 galaxy clusters (1402.2301), and in Milky Way (1408.2503)

3.5 keV X-rays: DM or potassium?

3.5 keV line has 4.3σ global significance.*

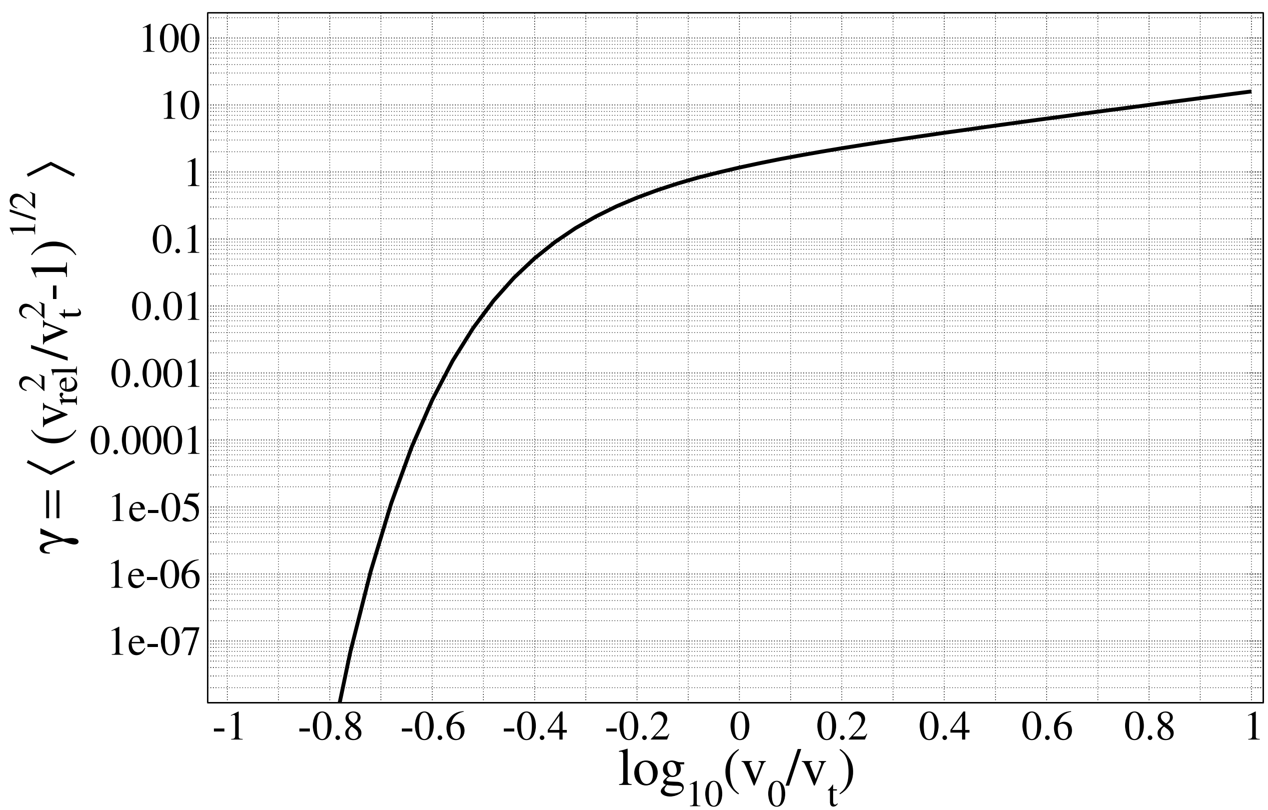
Controversy as to whether K XVIII transition at 3.515 keV (& 3.47 keV) is origin of signal

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
Boyarsky *et al.*	1408.4388	arguments against 1408.1699	
Anderson *et al.*	1408.4115	find no lines in clusters, MW, M31	

3.5 keV X-rays: loophole for DM?

Predictions for DM depend upon whether it's due to decays or annihilations (or inelastic scattering followed by decays—XDM—with threshold velocity v_t)

Inelastic scattering rate goes like $\gamma \equiv \langle (v_{\rm rel}^2/v_t^2 - 1)^{1/2} \rangle$



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 have the line and others not.

Hints of DM self-interactions

Standard cold dark matter seems to get structure wrong at small scales.

N-body simulations predict cuspy density profiles, while observations suggest otherwise.

More large satellite galaxies are predicted for the Milky Way than observed.

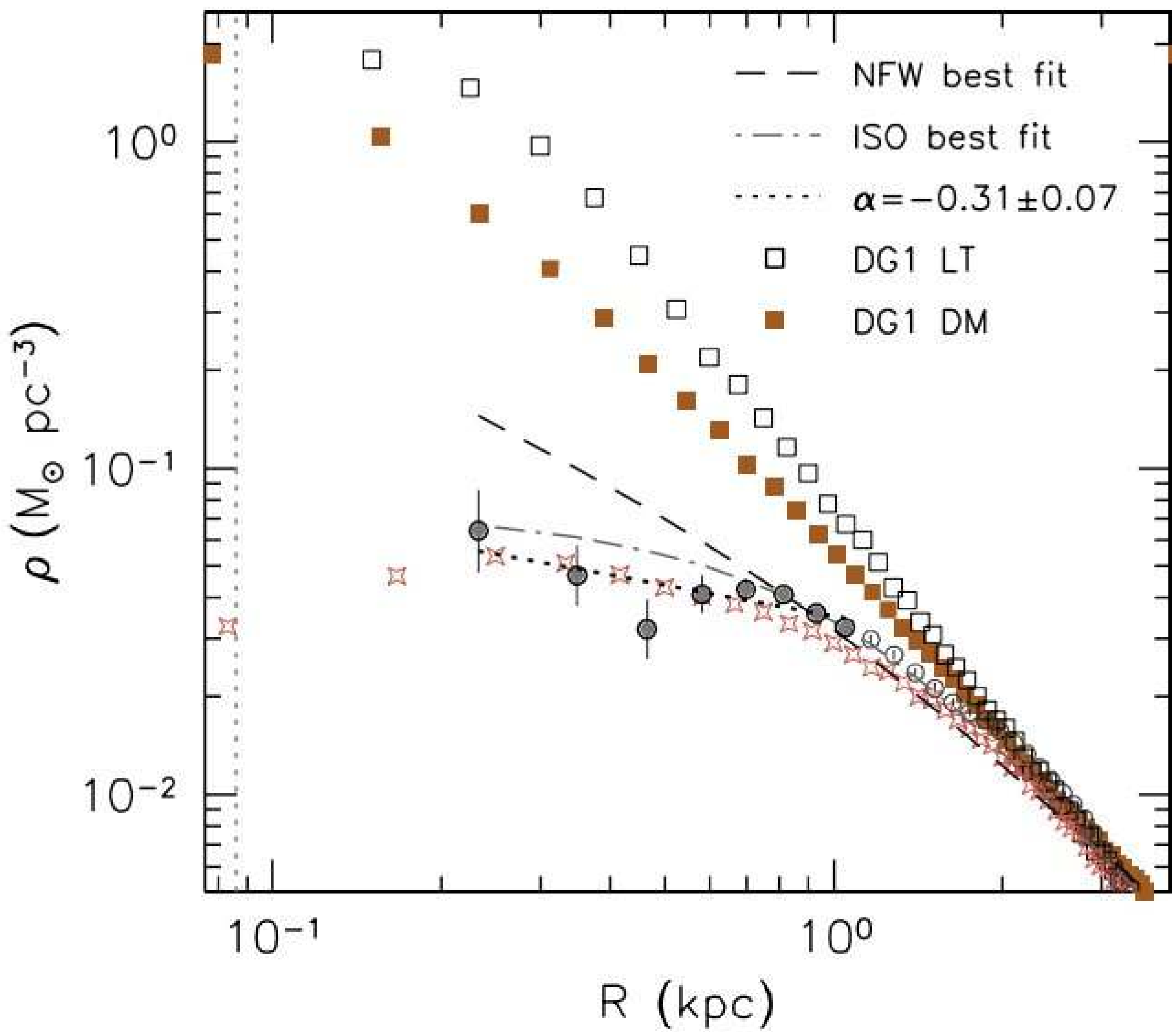
If DM scatters elastically with itself, with

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

these problems are ameliorated. (1b = 100 fm^2)

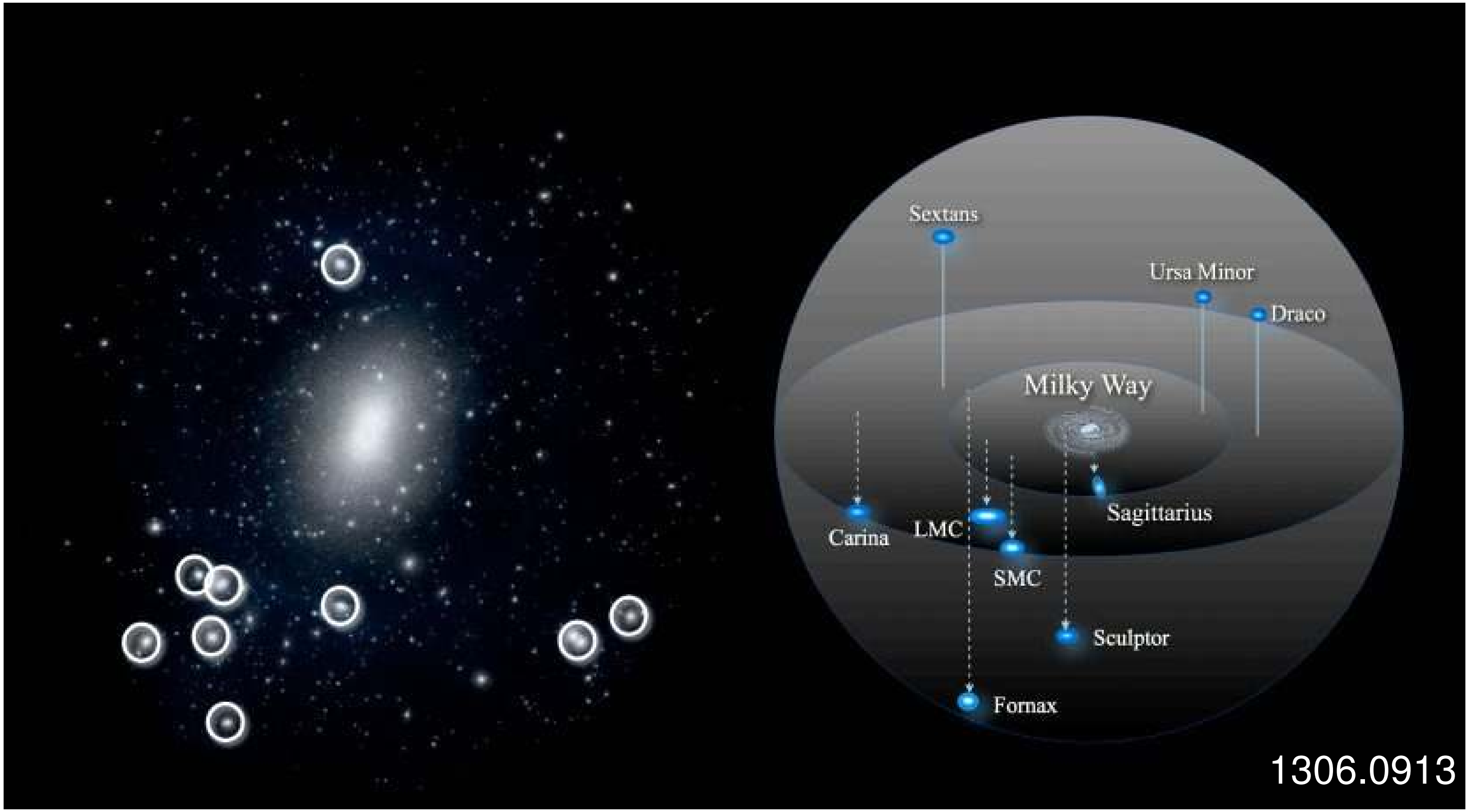
Cusp versus core problem

Oh *et al.*, 1011.2777, compare simulated dwarf galaxies with observed THINGS survey



Too big to fail, missing satellite problems

e.g., Garrison-Kimmel *et al.*, 1404.5313



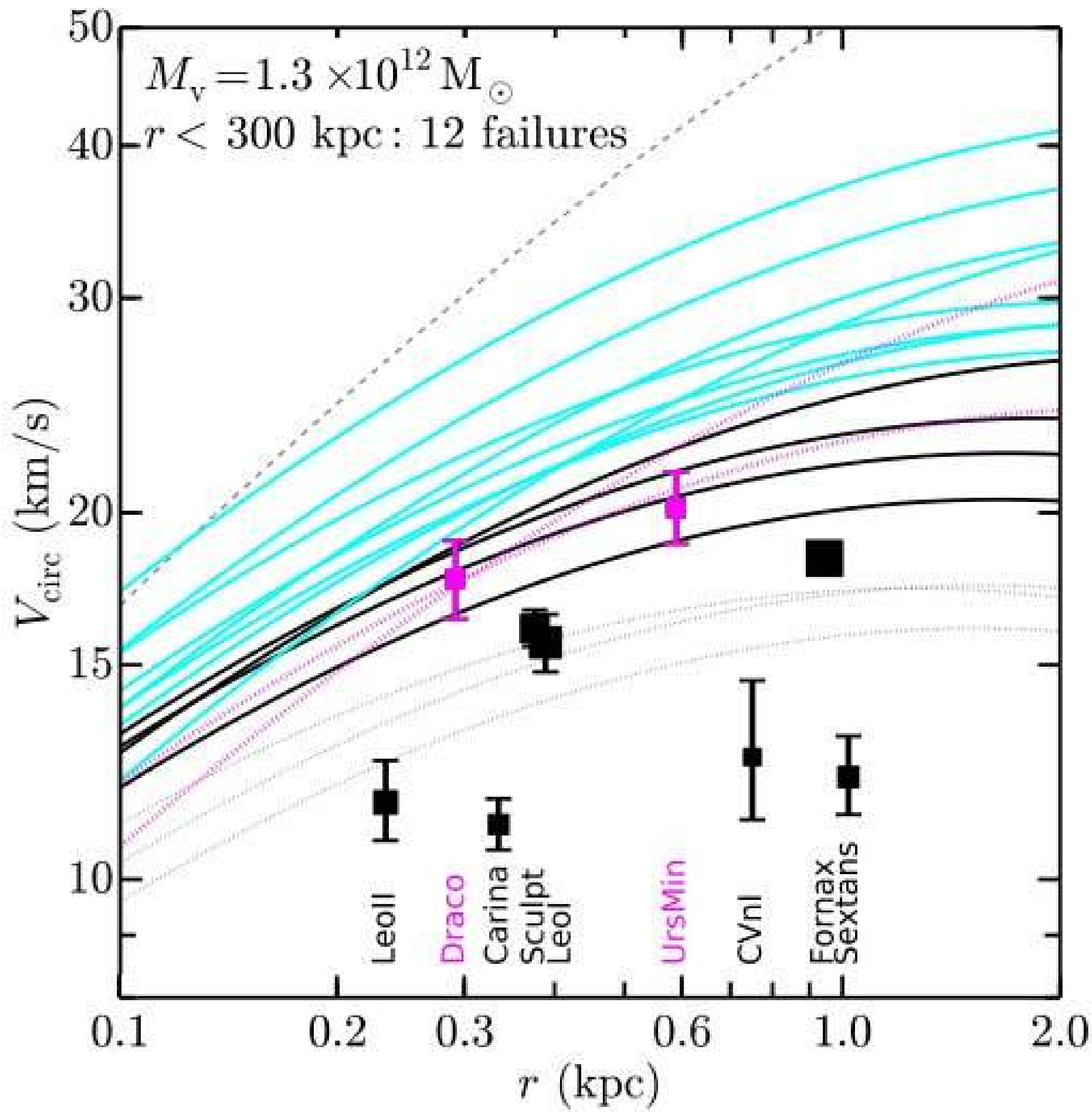
Largest predicted dwarf satellites (left) have too high central densities to match observed ones (right).

And smaller predicted dwarfs outnumber observed ones.

TBTF: simulations vs. Milky Way

1404.5313 counts massive failures around MW-like galaxies in ELVIS simulation; an example $\Longrightarrow$

Measured MW dwarf velocities are well below those of most predicted subhalos.



How self-interactions help

DM particles at larger radii have larger velocity. They scatter with DM particles at smaller radii, heating them up. Initially cuspy profile gets puffed up.

Simulations (Zavala *et al.*, 1211.6426) show that

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

gives the desired effect. Larger values would have too big effect and are ruled out.

E.g., Bullet Cluster simulation requires $\sigma/m < 1.3\,\mathrm{b/GeV}$. (Randall *et al.,* 0704.0261)

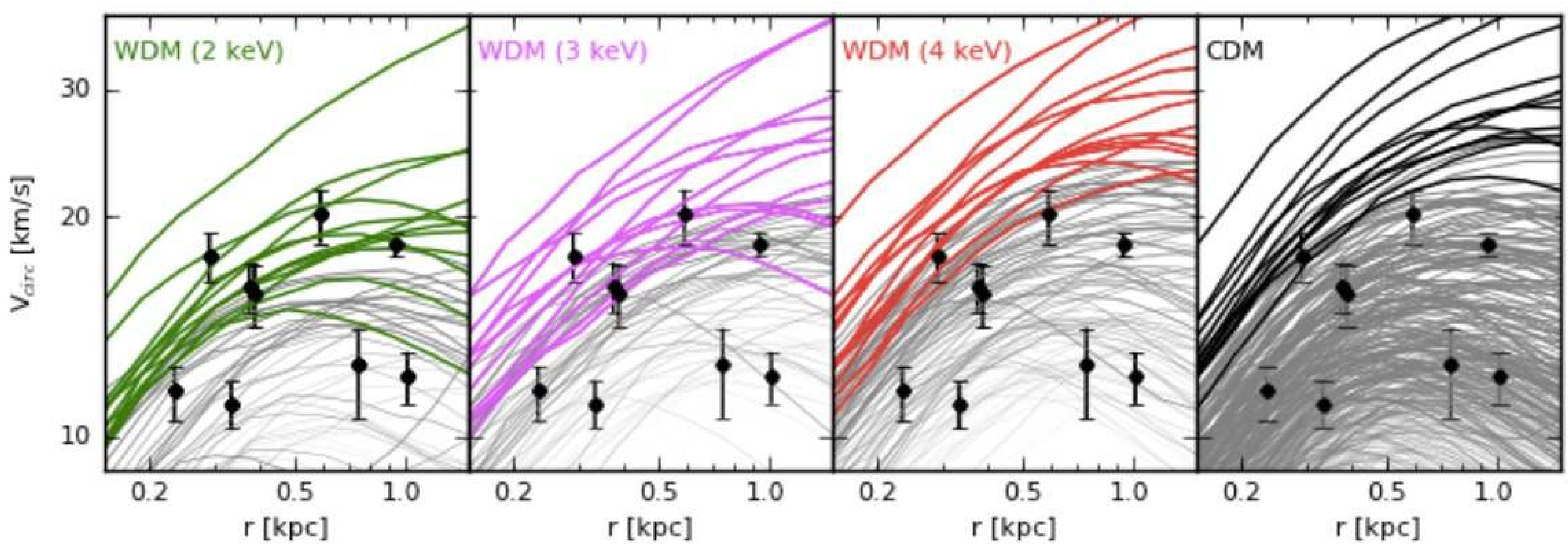
(Warm dark matter as solution to small scale structure problems seems disfavored ...)

Warm dark matter dead?

Streaming of WDM erases small scale structure, reduces number of subhalos and makes halos less cuspy.

But Lyman-α is sensitive to small scale structure: WDM cannot be too warm, $m_\chi > 3.3\ \mathrm{keV}$ (Viel *et al.*, 1306.2314)

Such heavy WDM cannot solve TBTF problem (1309.5960):



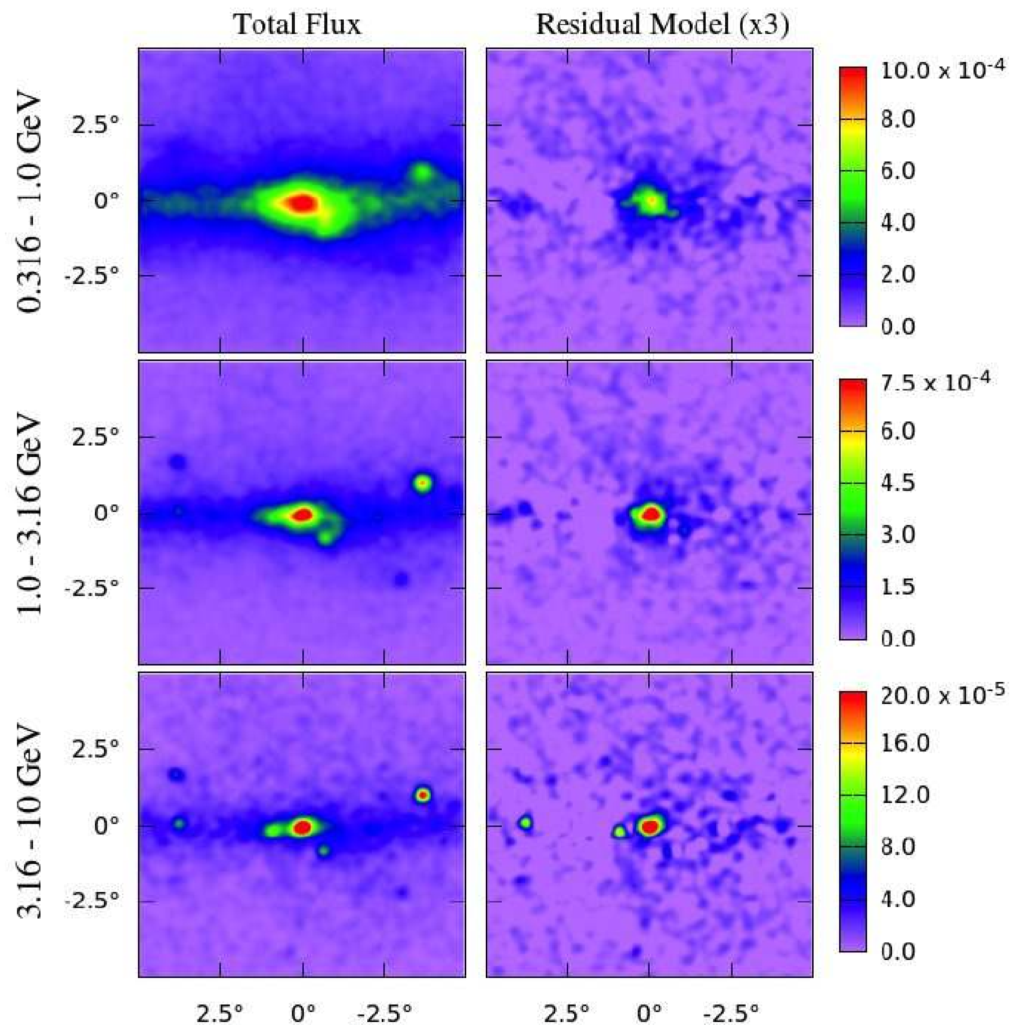
Also does not help cusp-core problem (1306.0913)

Galactic center γ-ray excess

Hooper *et al.* continue to find evidence for excess 0.3-10 GeV γ-rays in inner 10° of galaxy.

raw maps

residual maps



includes point sources, diffuse emission, isotropic template, sources associated with 20 cm synchrotron emission...

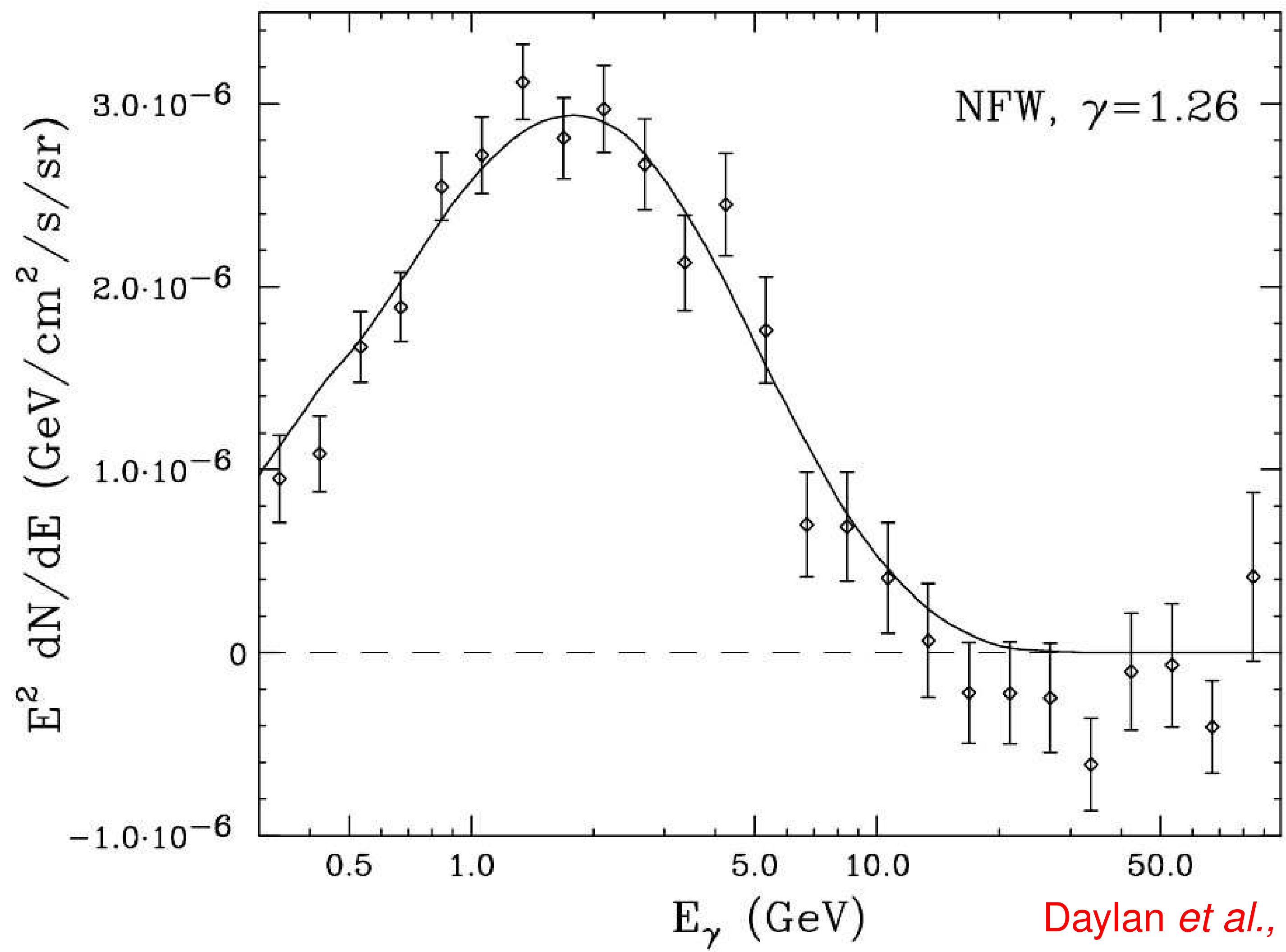
excess is 30% of raw signal

NFW profile fits shape well

Daylan et al., 1402.6783

GC excess spectrum

Spectrum fits 35 GeV DM annihilating to $b\bar{b}$ with $\langle\sigma v\rangle = 1.7\times 10^{-26}\mathrm{cm}^3/\mathrm{s}$ (80% of relic density value)

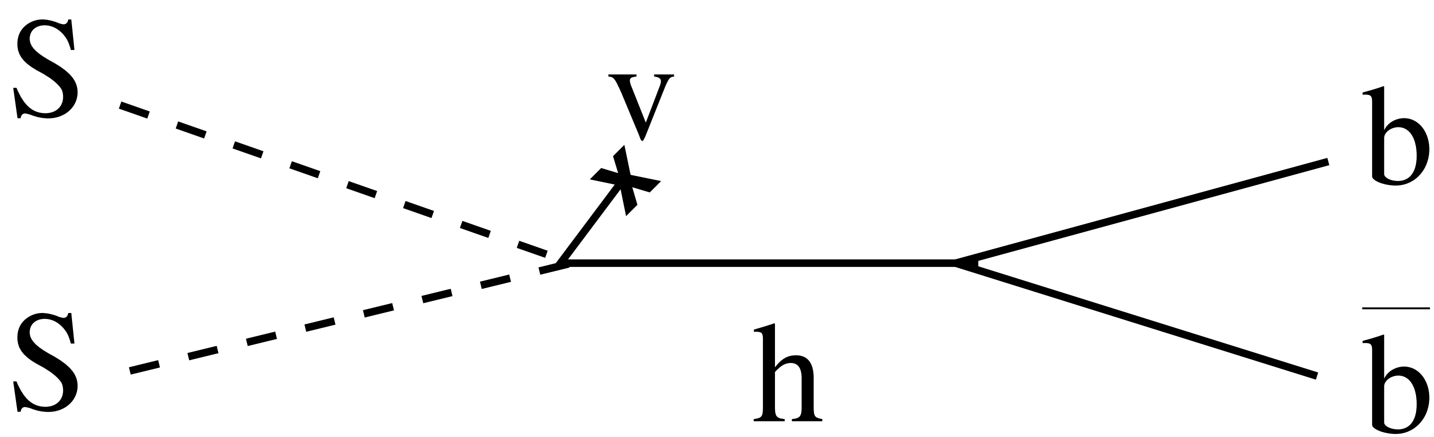


Daylan *et al.,* 1402.6703

GC excess spectrum—prefers $\chi\chi \to b\bar{b}$

Suggests Higgs portal DM, *e.g.,* scalar singlet DM model,

$$\mathcal{L} = \frac{1}{2}\left((\partial_\mu S)^2 - m_S^2 S^2 - \lambda_{hs} S^2 |H|^2\right)$$



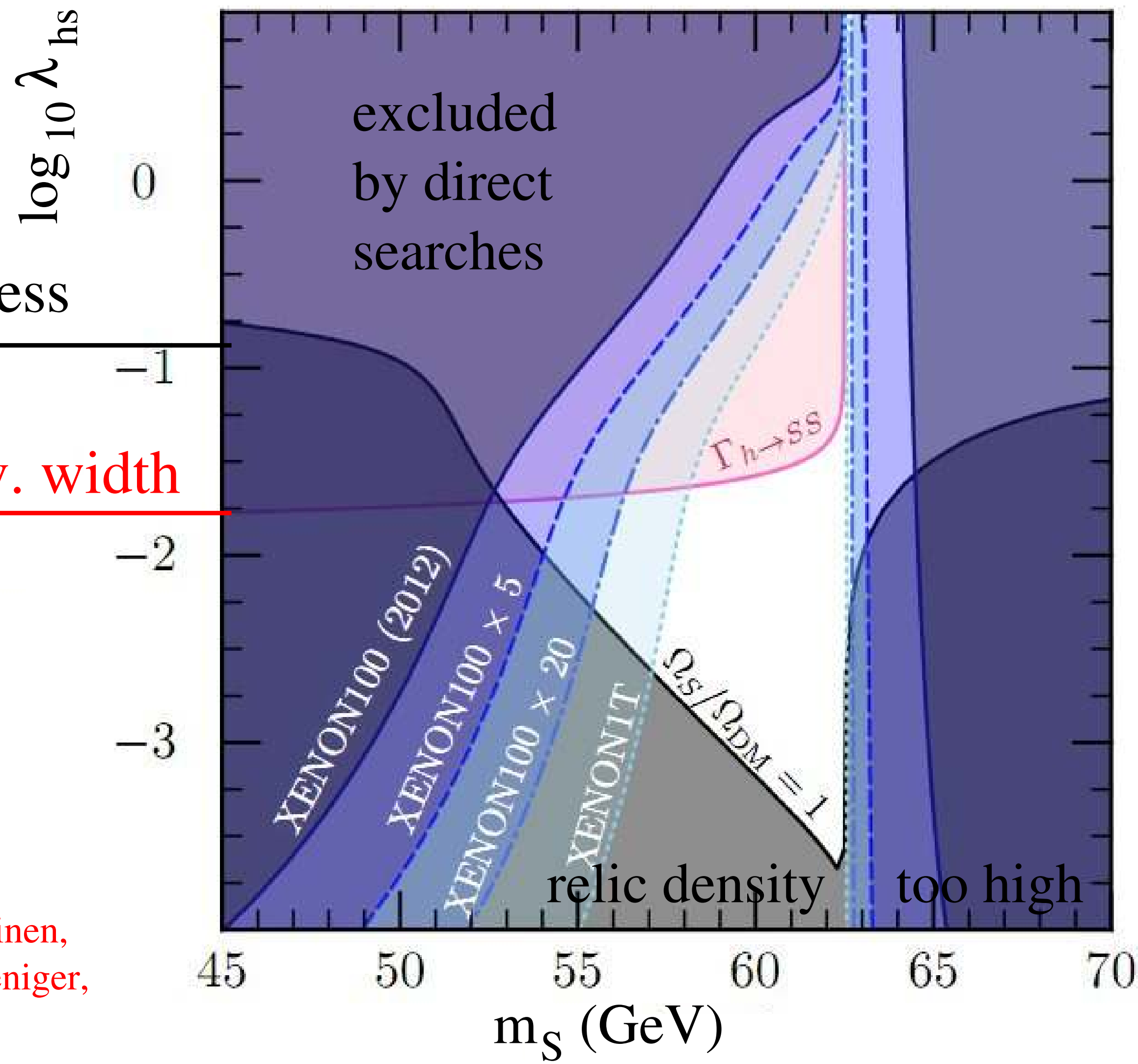
However the required cross section is in conflict with invisible Higgs decays, $h \to SS$, and direct detection constraints . . .

Singlet DM vs. laboratory constraints

Higgs portal does not work:

GC excess

Higgs inv. width

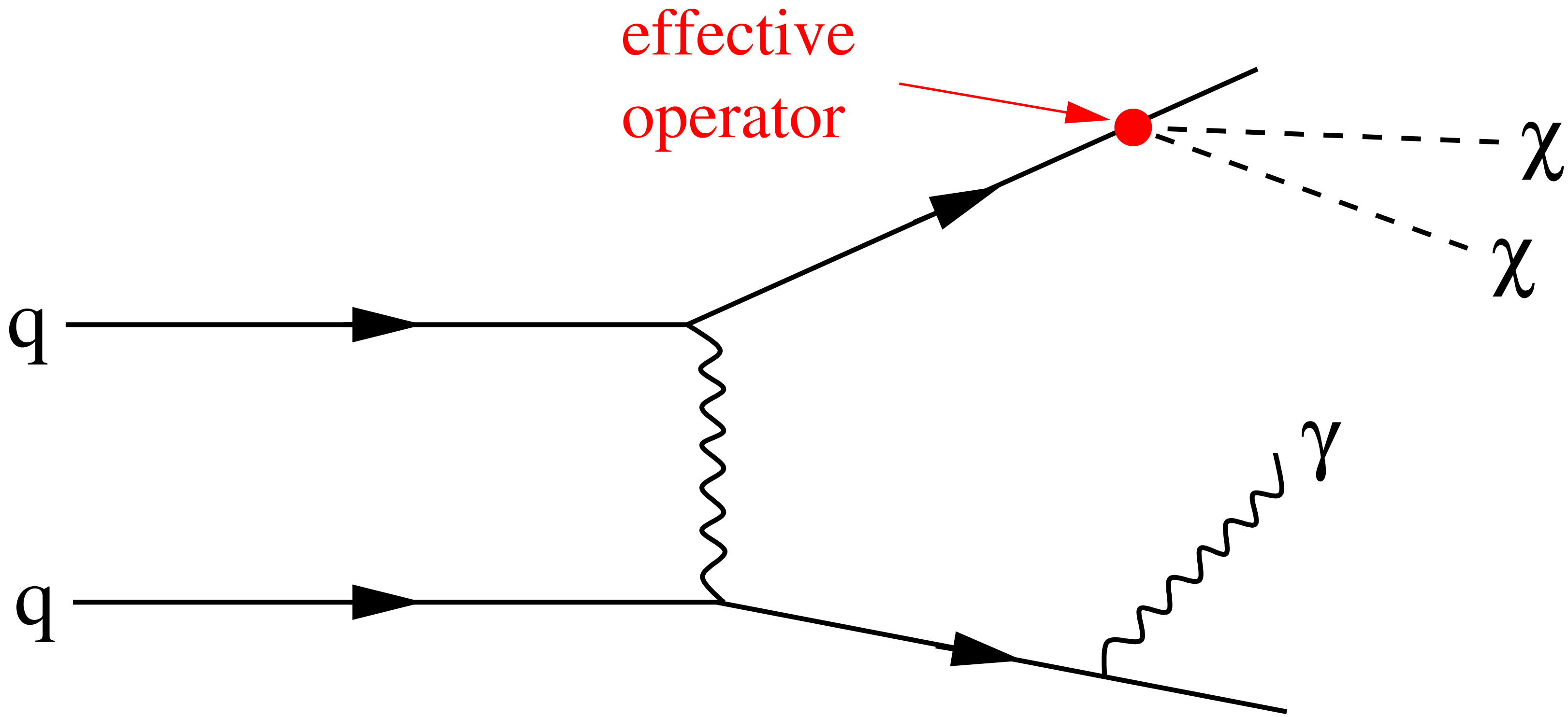


JC, K. Kainulainen,
P. Scott, C. Weniger,
1306.4710

(Will come back to models later)

Searching for DM at colliders

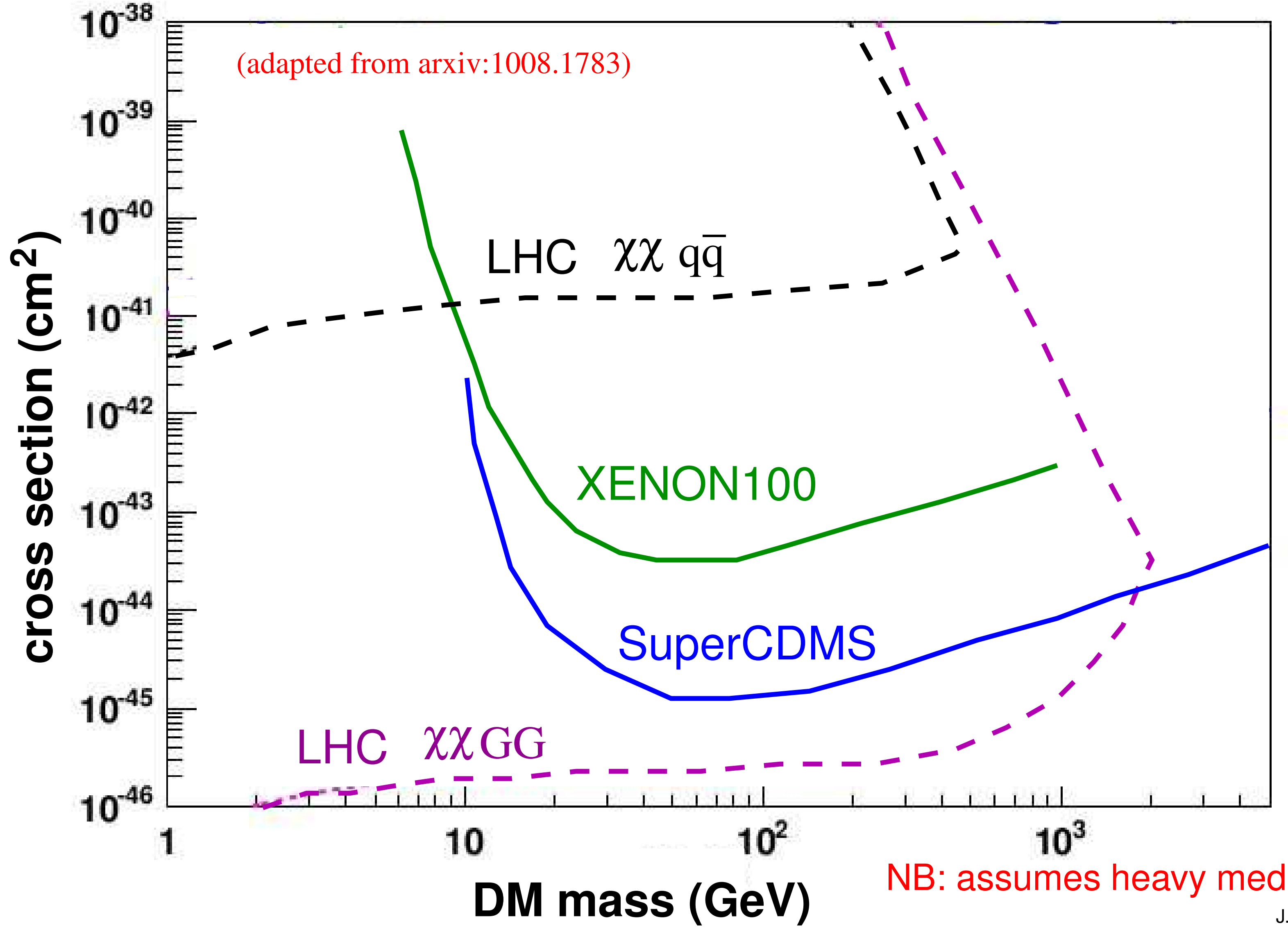
Look for missing transverse energy due to DM pair production:



E.g., monophoton events

LHC sensitivity to DM

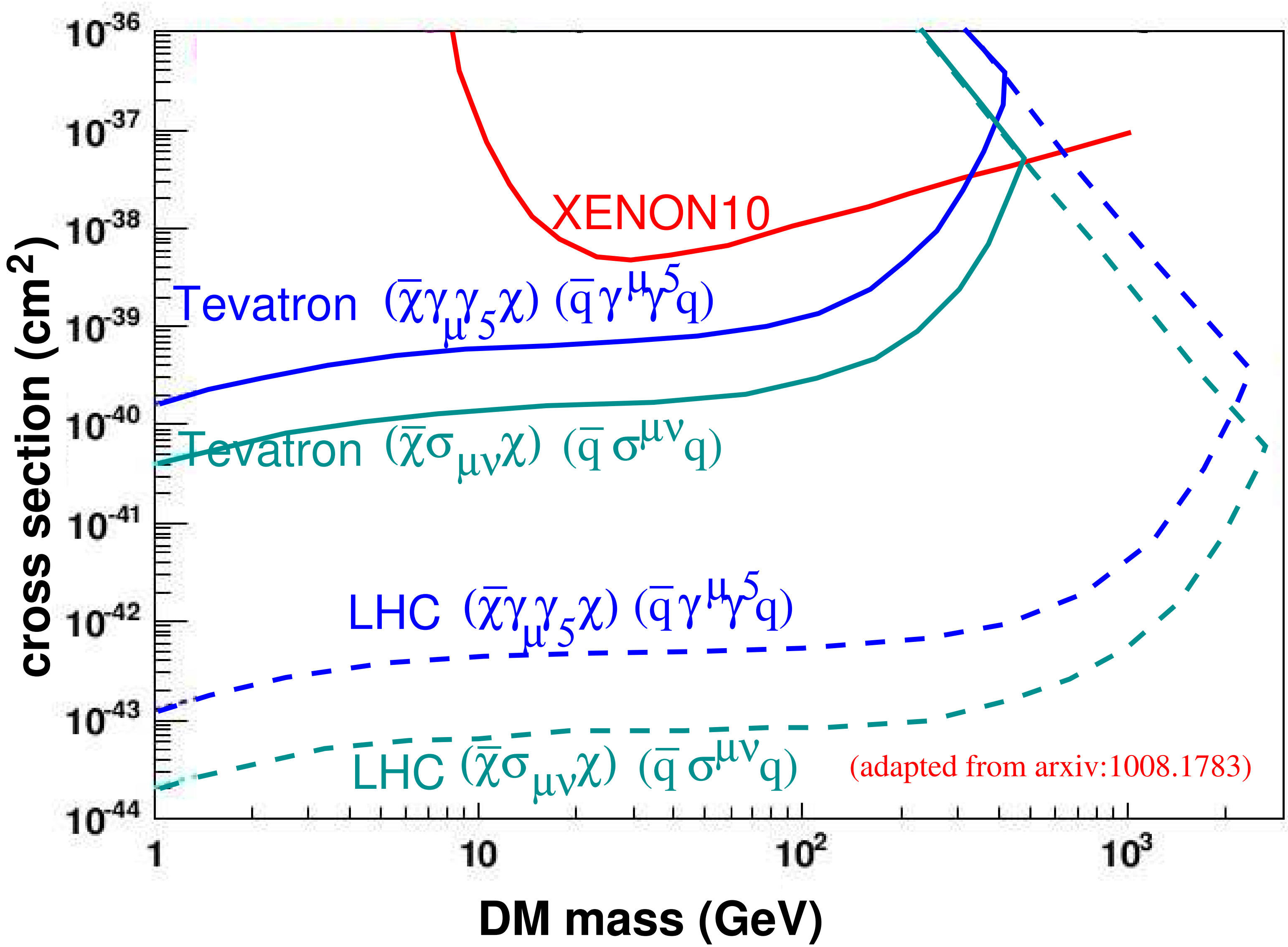
LHC could be more sensitive or less so than direct searches, depending on exactly how DM interacts with quarks.



NB: assumes heavy mediators!

LHC sensitivity to DM

If DM couples to nucleon spin instead of nucleon number,
LHC and Tevatron are more sensitive than direct detectors



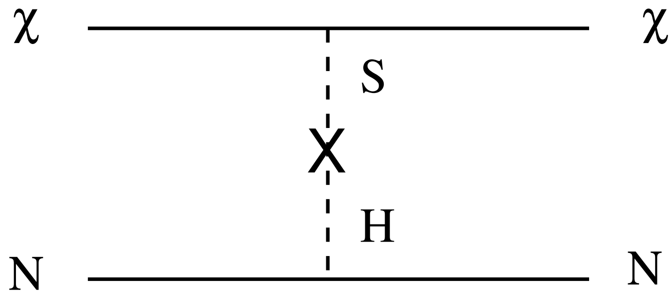
General theoretical DM models

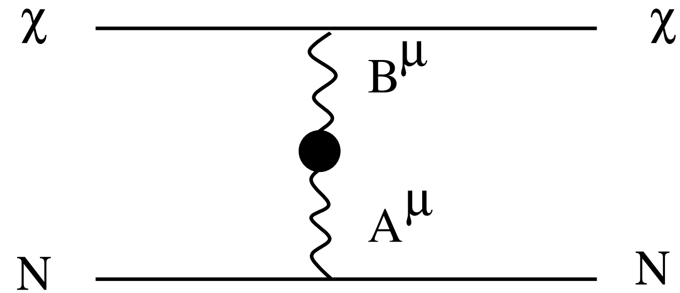
Formerly theoretical ideas for DM were dominated by SUSY WIMPs — the lightest neutralino.

More recently, nonSUSY "hidden sector" models have become popular; dark sector could be complex like the standard model

A "portal" is needed to communicate between the two sectors

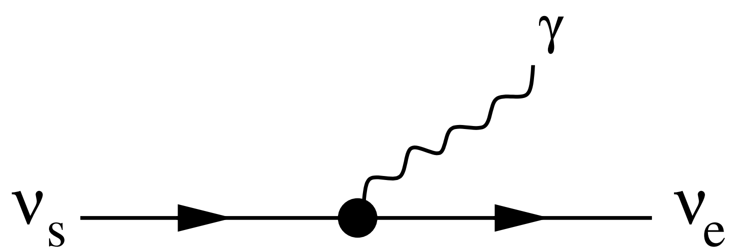
$\lambda\|H\|^2 S^2$	$\epsilon F_{\mu\nu} B^{\mu\nu}$
Higgs portal	gauge kinetic mixing portal



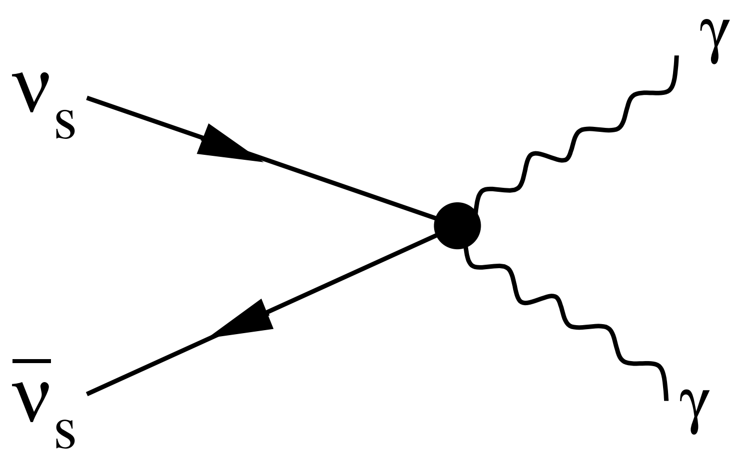


Theoretical DM models for x-rays

Simplest possibility is 7 keV sterile neutrino with transition magnetic moment $\mu\bar{\nu}_s\sigma_{\mu\nu}F^{\mu\nu}\nu_e$; ν_s decays into $\nu_e + \gamma$



Or annihilations of 3.5 keV neutrinos:

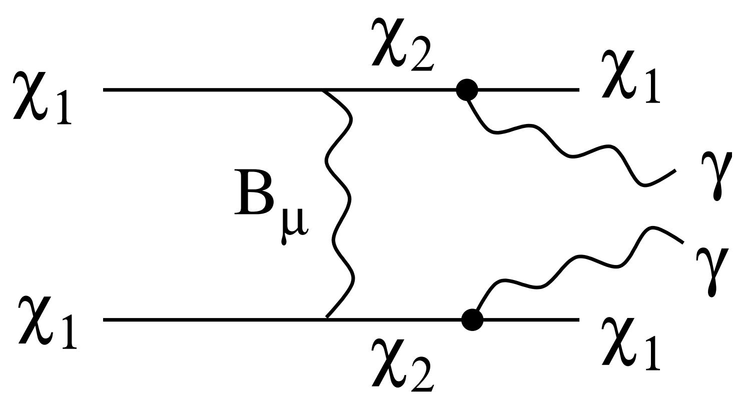


Or axions, ALPs, axinos, moduli, light superpartners, Majorons . . .

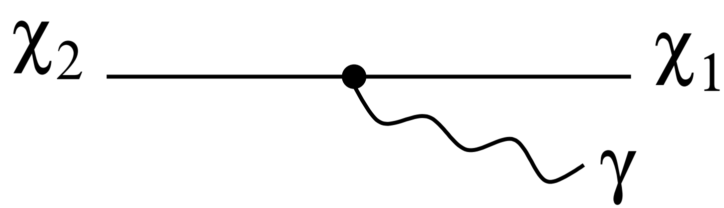
What about WIMPs?

If it's keV-scale DM, no observable direct detection (though maybe still production at LHC). What about WIMPs?

Heavy excited DM models can do the job (1402.6671)[a]



$\chi_{1,2}$ can be very heavy; only δm_χ need be small (3.5 keV). Or χ_2 could be cosmologically long-lived (1403.1570)[b]:



Direct detection may now be possible.

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[a] Finkbeiner & Weiner
[b] Frandsen, Sannino, Shoemaker, Svensen

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, excited state decays into photons with rate

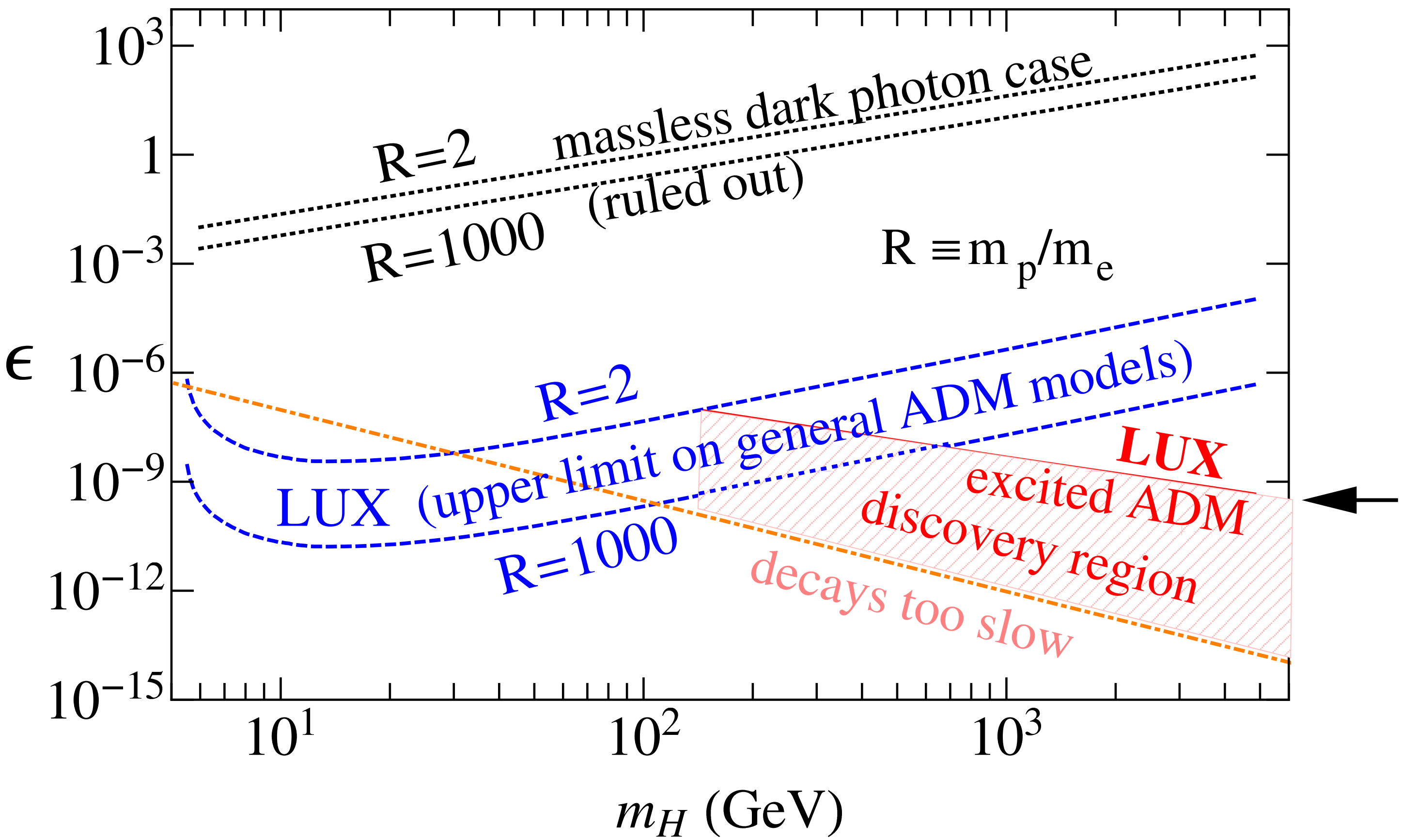
$$\Gamma_{hf} = \frac{3\mu_H^2}{\alpha\epsilon^2\Delta E^3}$$

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.

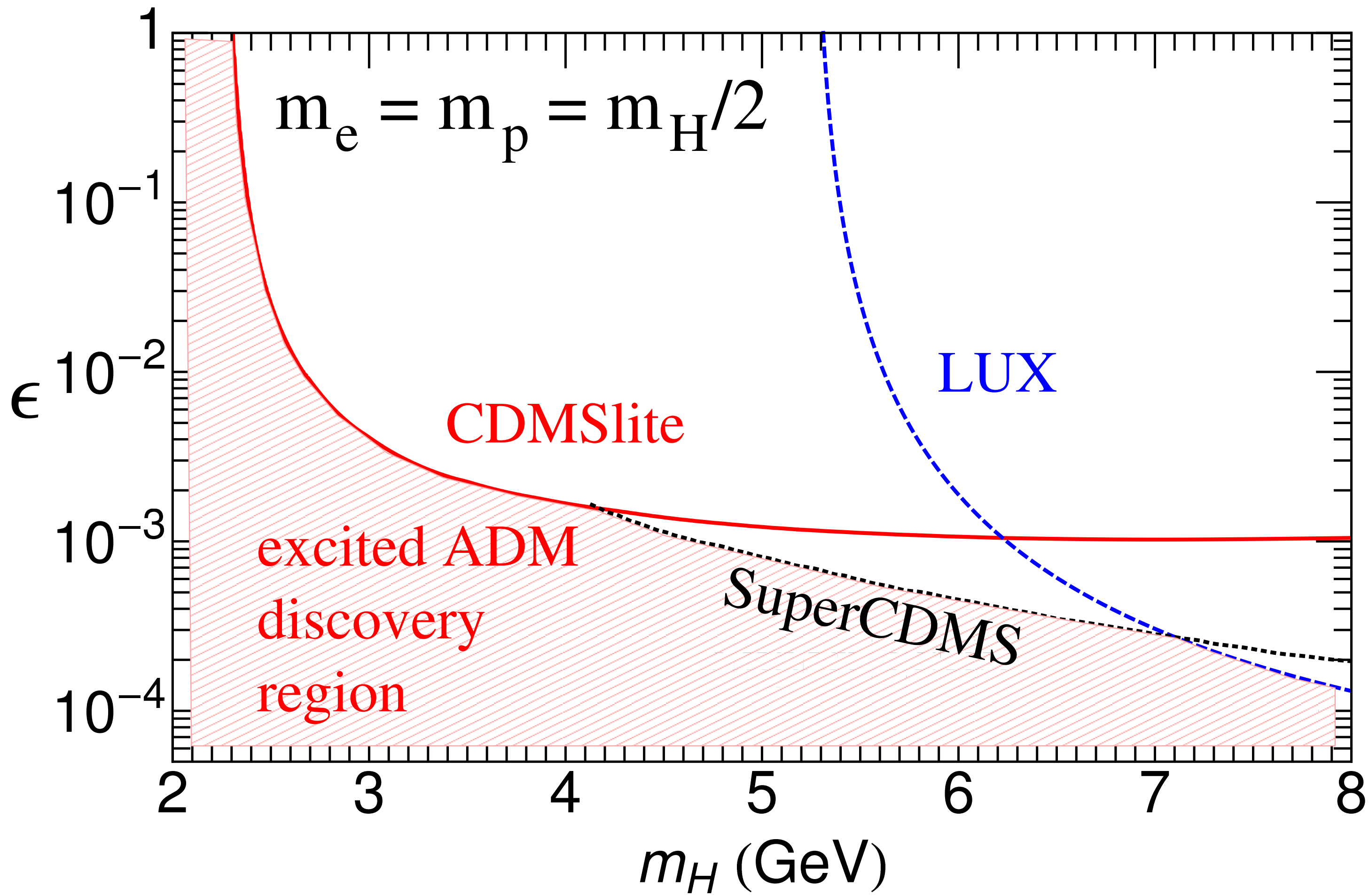
If XDM mechanism $\chi_1\chi_1 \to \chi_2\chi_2 \to \chi_1\chi_1 + 2\gamma$, then ϵ can be much larger, discoverable by direct detection.



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

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.



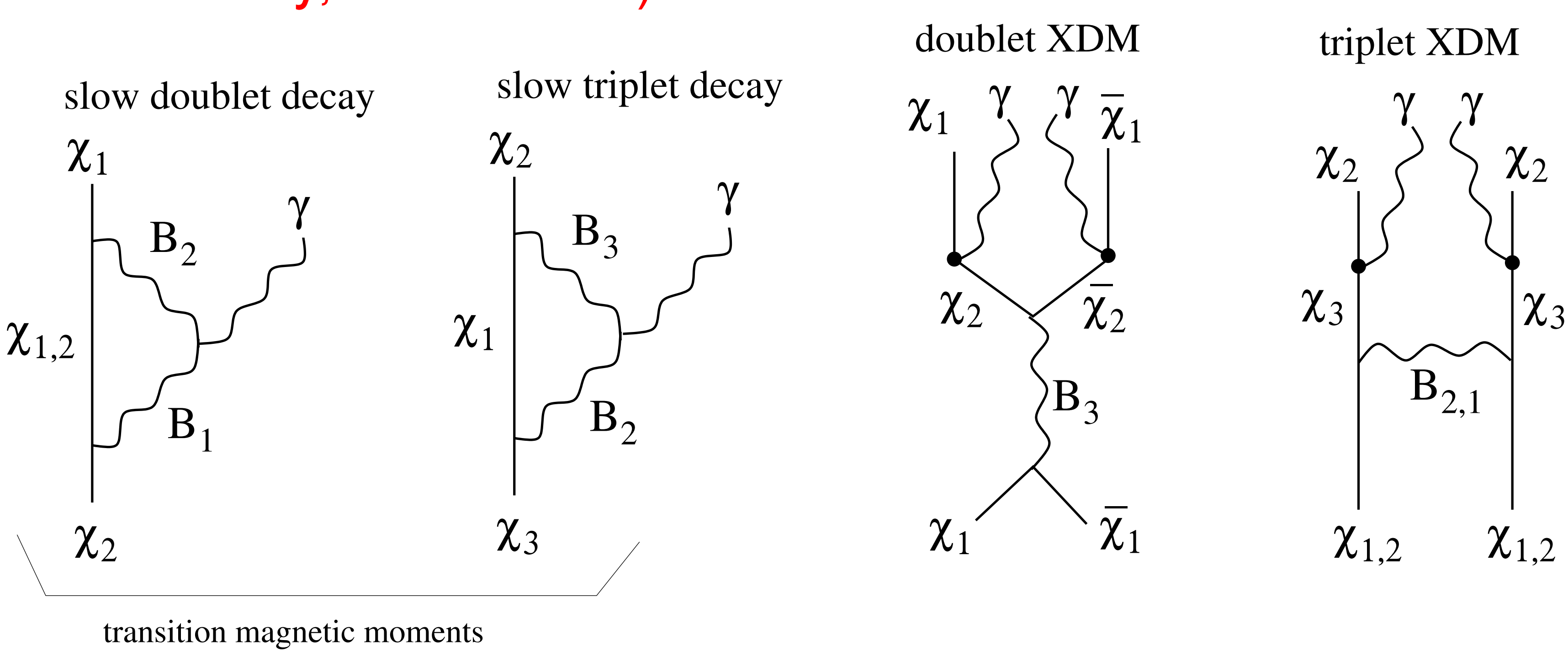
X-rays from nonabelian XDM*

* excited dark matter

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.

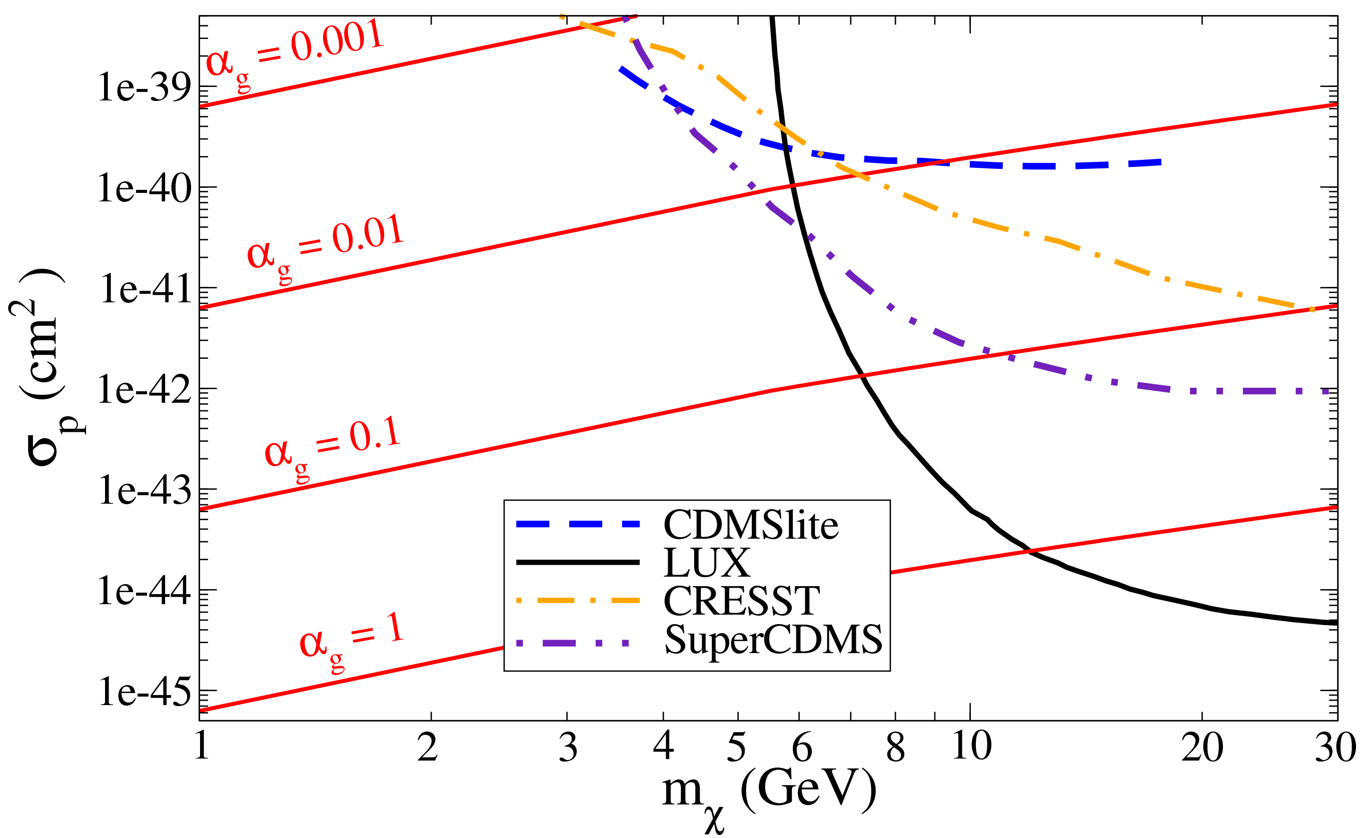
After diagonalizing gauge boson kinetic term, B_3 gets coupling ϵe to protons — mediates χ scattering on nucleons.

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:



$\longleftarrow$

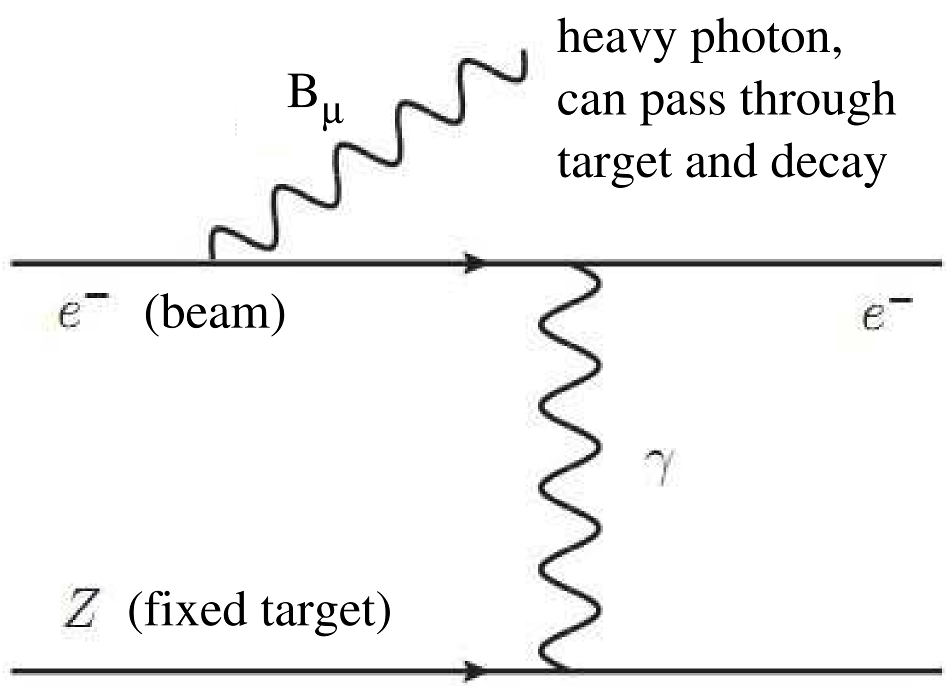
Slowly decaying doublet DM model (asymmetric DM)

$\longleftarrow$

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

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)

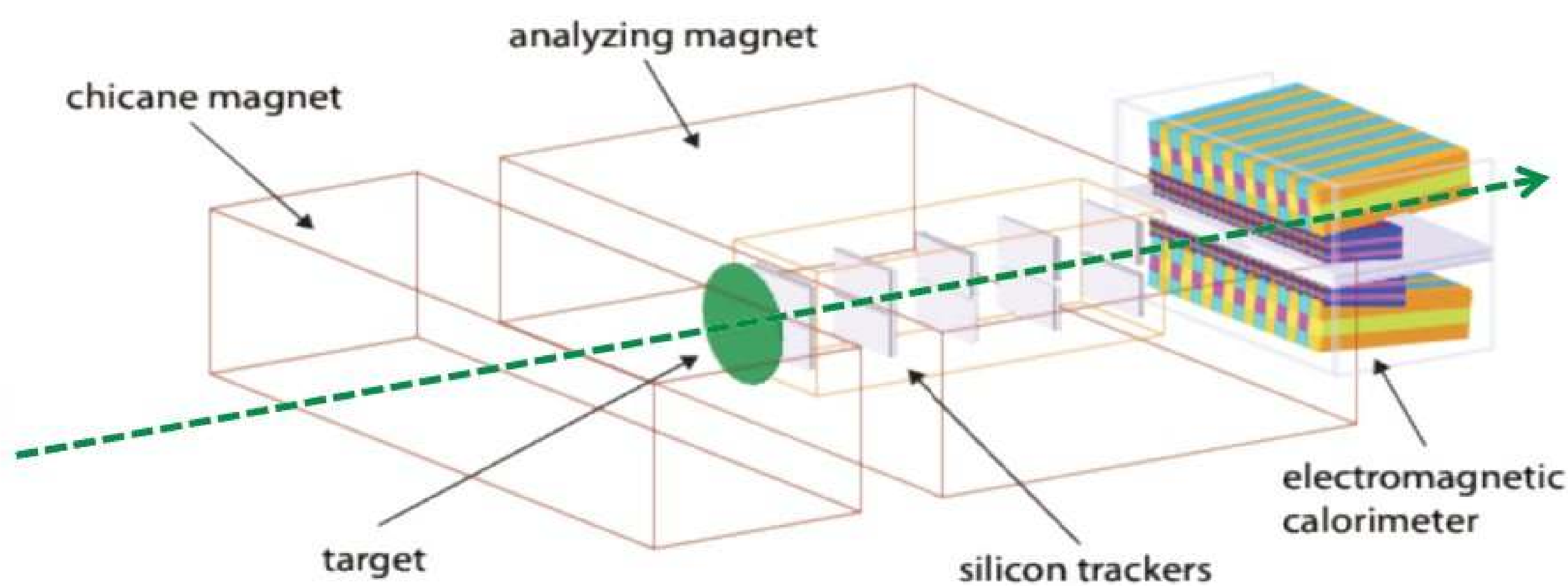


$B \to e^+e^-$ after passing through target, due to kinetic mixing

HPS status (1310.2060)

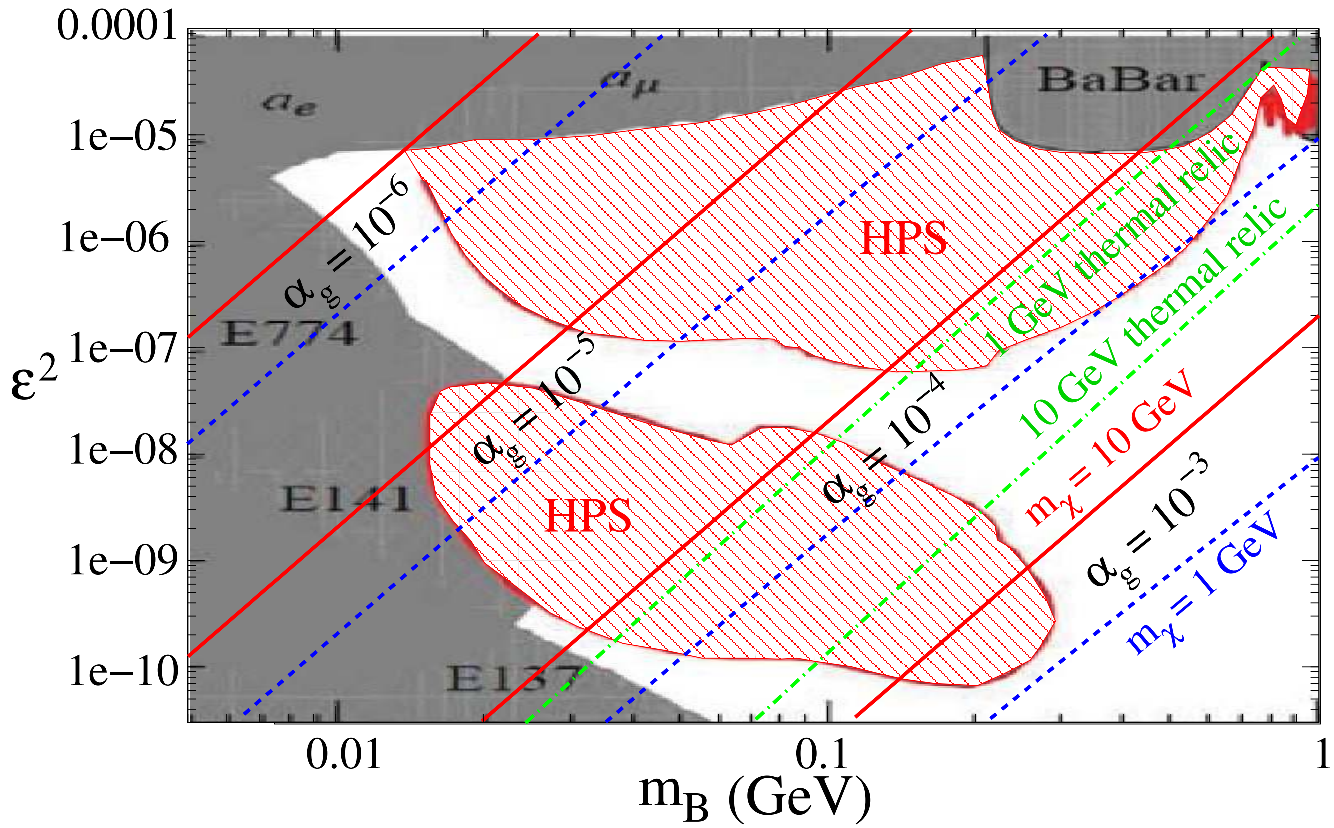
HPS is funded, will be installed in Sept. 2014, beamline in Oct., engineering run through spring 2015.

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



HPS discovery potential

The slowly-decaying doublet model has large overlap with HPS region of sensitivity, depending on α_g and m_χ

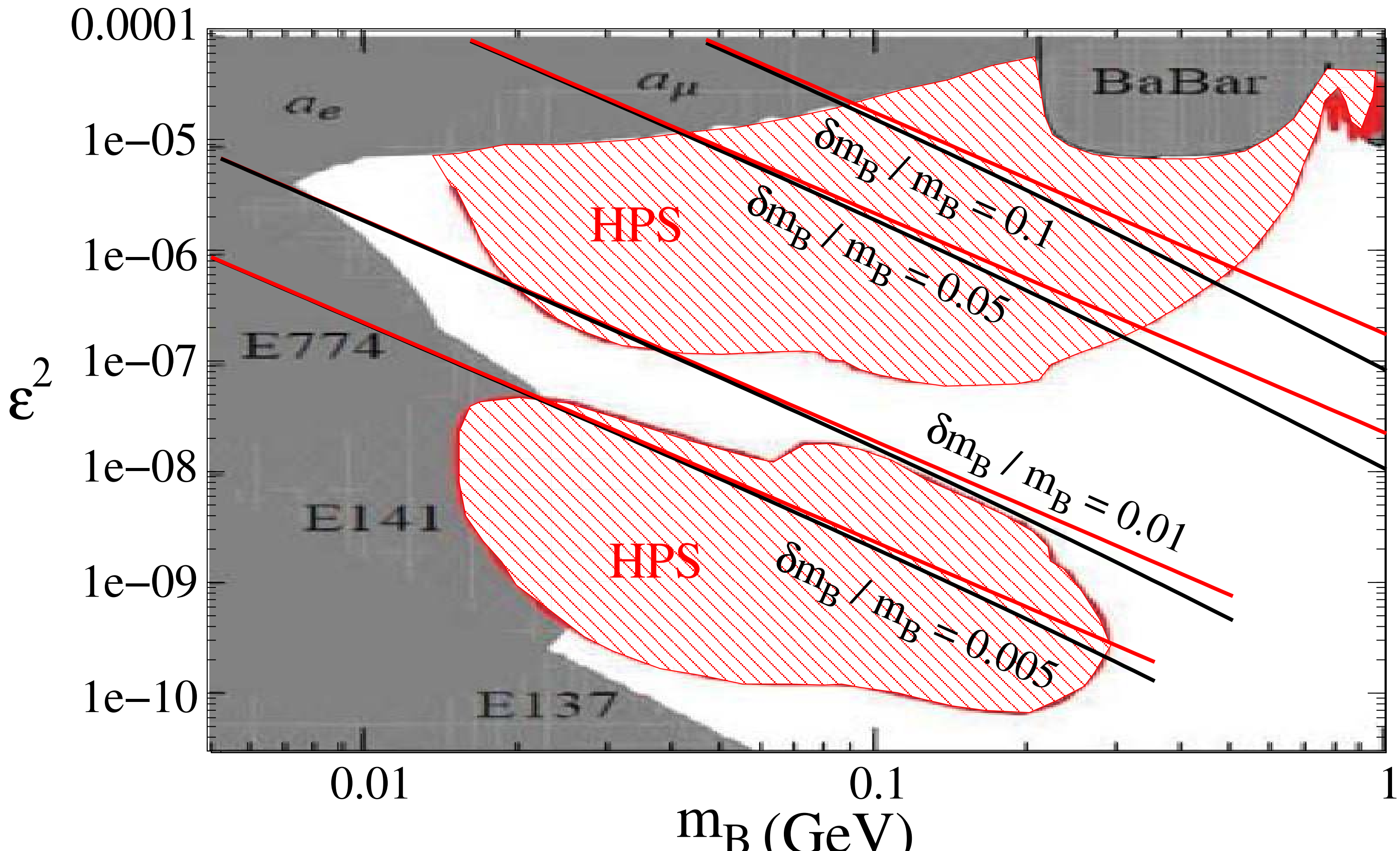


← bump hunt

← bump + displaced vertex

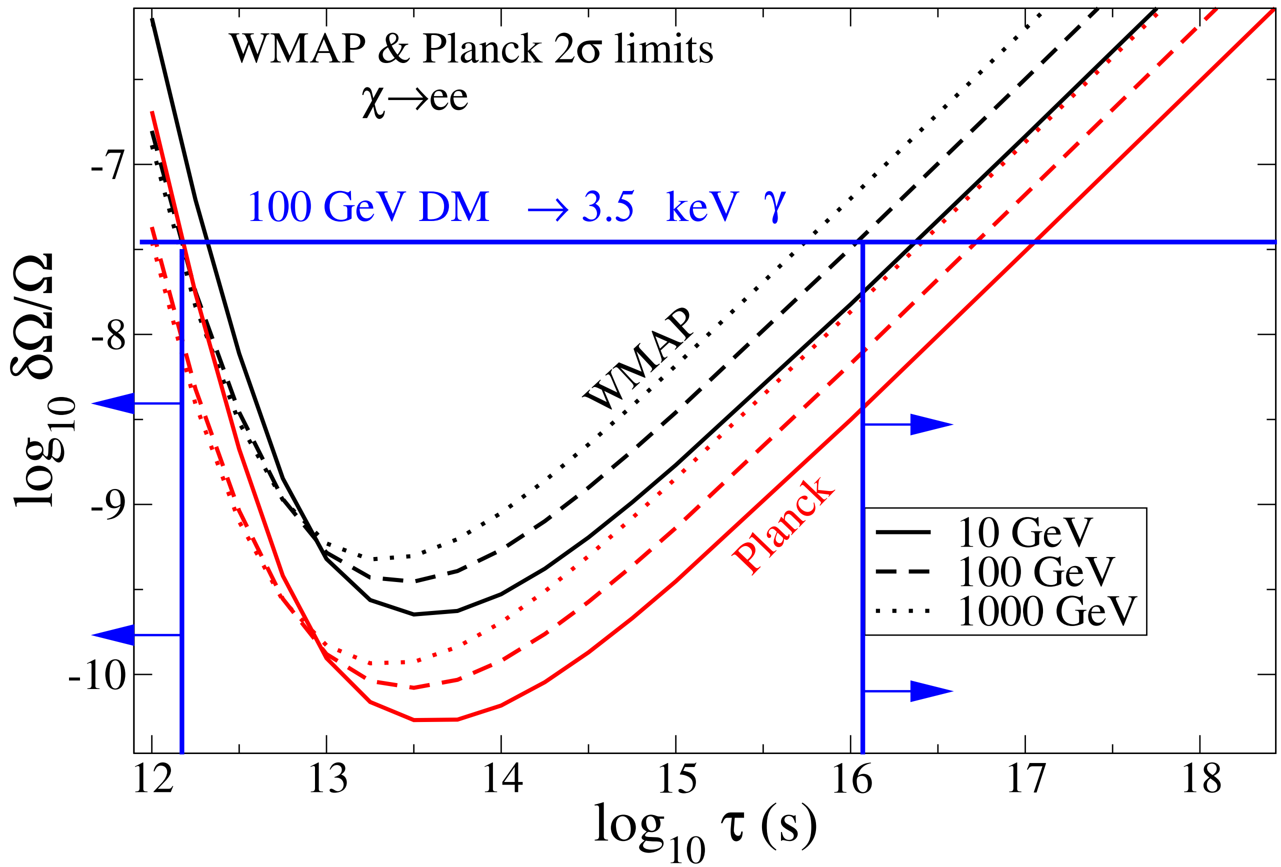
HPS discovery potential

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



CMB constraint

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

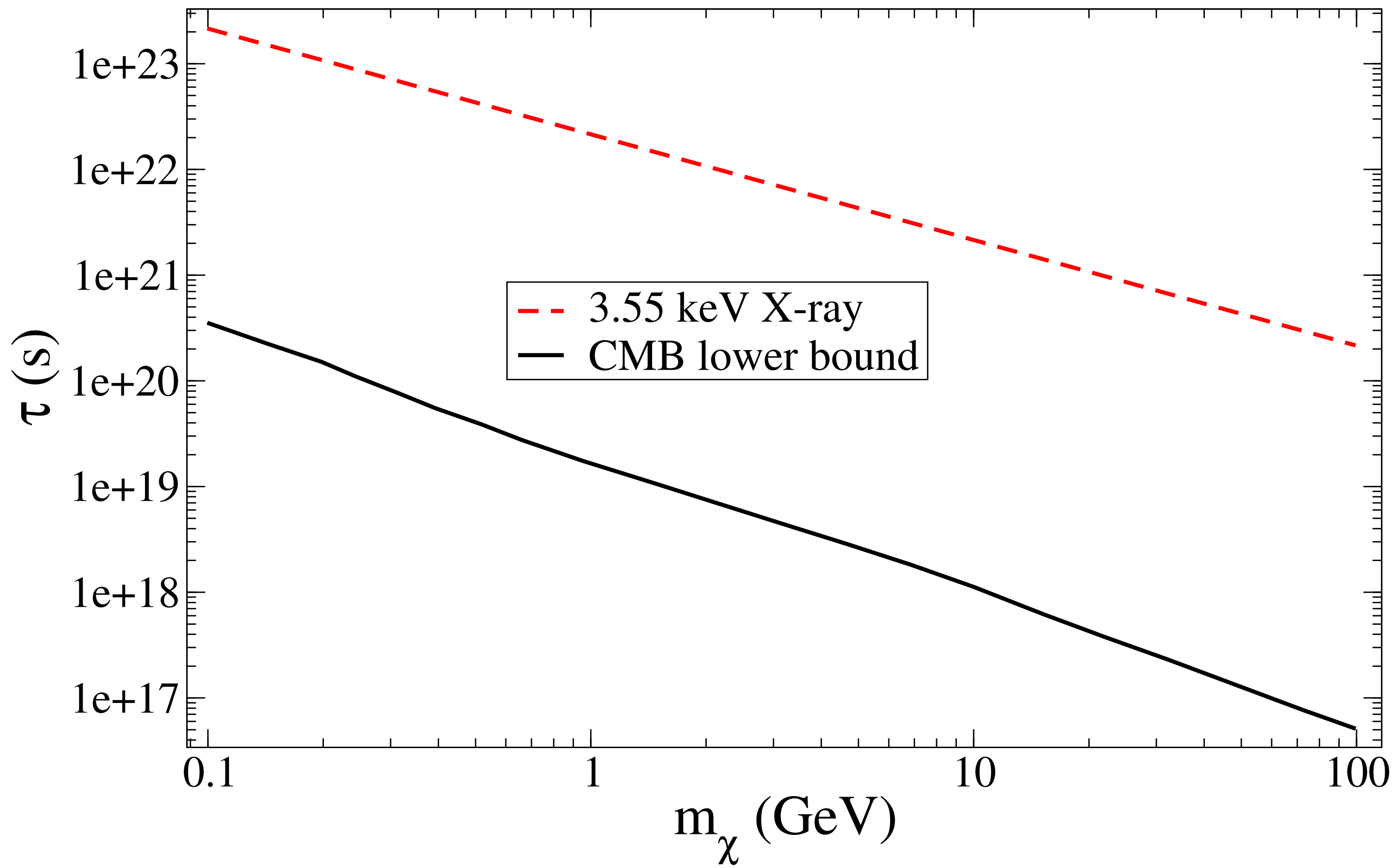


JC & P. Scott, (1301.5908)

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

CMB constraint

Slowly decaying doublet DM easily satisfies the constraint



But XDM doublet DM needs to fall on lower side, $\tau \lesssim 10^{12}\,\mathrm{s}$, leading to much larger values of ϵ than slow decay model.

Composite models of self-interacting DM

How big is 1 b/GeV?

Scalar dark matter with $(\lambda/4!)\phi^4$ interaction and $\lambda = 100$ would need to have $m = 400\,\mathrm{MeV}$ to scatter that strongly.

Normal H atoms have $\sigma/m \sim 30\,a_0^2/m_p \sim 10^9\,\mathrm{b/GeV}!$
Cross section is large because atom is large, $a_0 \sim (\alpha m_e)^{-1}$.

Nucleons have $\sigma/m \sim 10\,\mathrm{b/GeV}$ due to residual strong interactions.

$\to$ Composite dark matter naturally has large self-interactions.

Dark atom self-interactions

Atomic physicists know how to compute H-H elastic scattering. We can use their results/methods to generalize to dark atoms.

Three parameters:

$$\{\alpha',\ m_e,\ m_p\}\ \longrightarrow\ \{\alpha',\ m_H = m_e + m_p,\ R = m_p/m_e\}$$

We can scale out two of them by choice of (atomic) units for distance and energy:

$$a_0 = (\alpha'\mu)^{-1}, \quad \epsilon_0 = \alpha'^2\mu$$

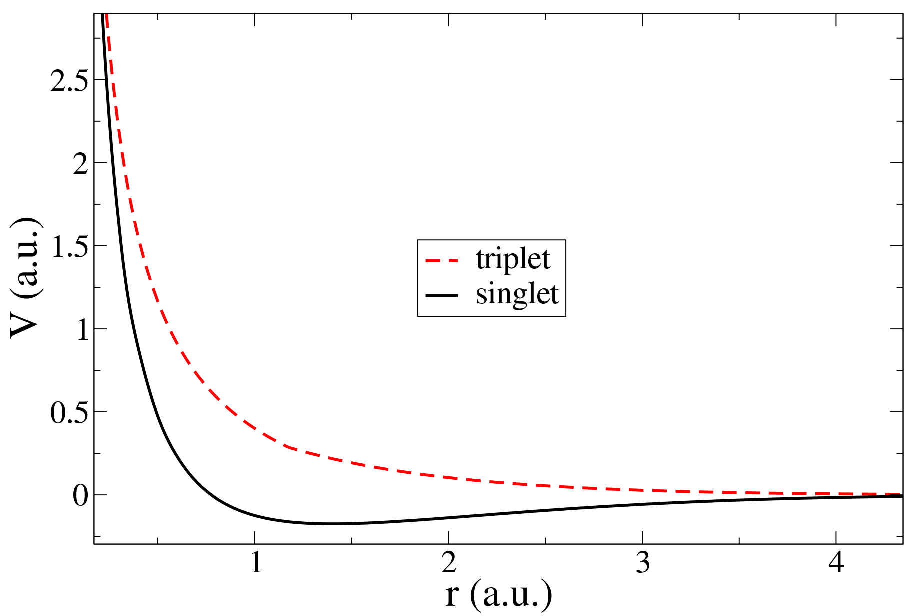
($\mu = \frac{m_e m_p}{m_e+m_p}$ = reduced mass). Only $R \geq 1$ remains as nontrivial parameter.

Partial wave scattering

In atomic units, Schrödinger eq. for partial wave amplitudes is

$$\left(\partial_r^2 - \frac{\ell(\ell+1)}{r^2} + f(R)\,(E - V_{s,t})\right) u_\ell^{s,t}(r) = 0$$

where $f(R) = m_H\,\epsilon_0 = R + 2 + R^{-1}$, and $V_{s,t}$ are potentials for electron spin singlet and triplet channels, determined by atomic physicists:

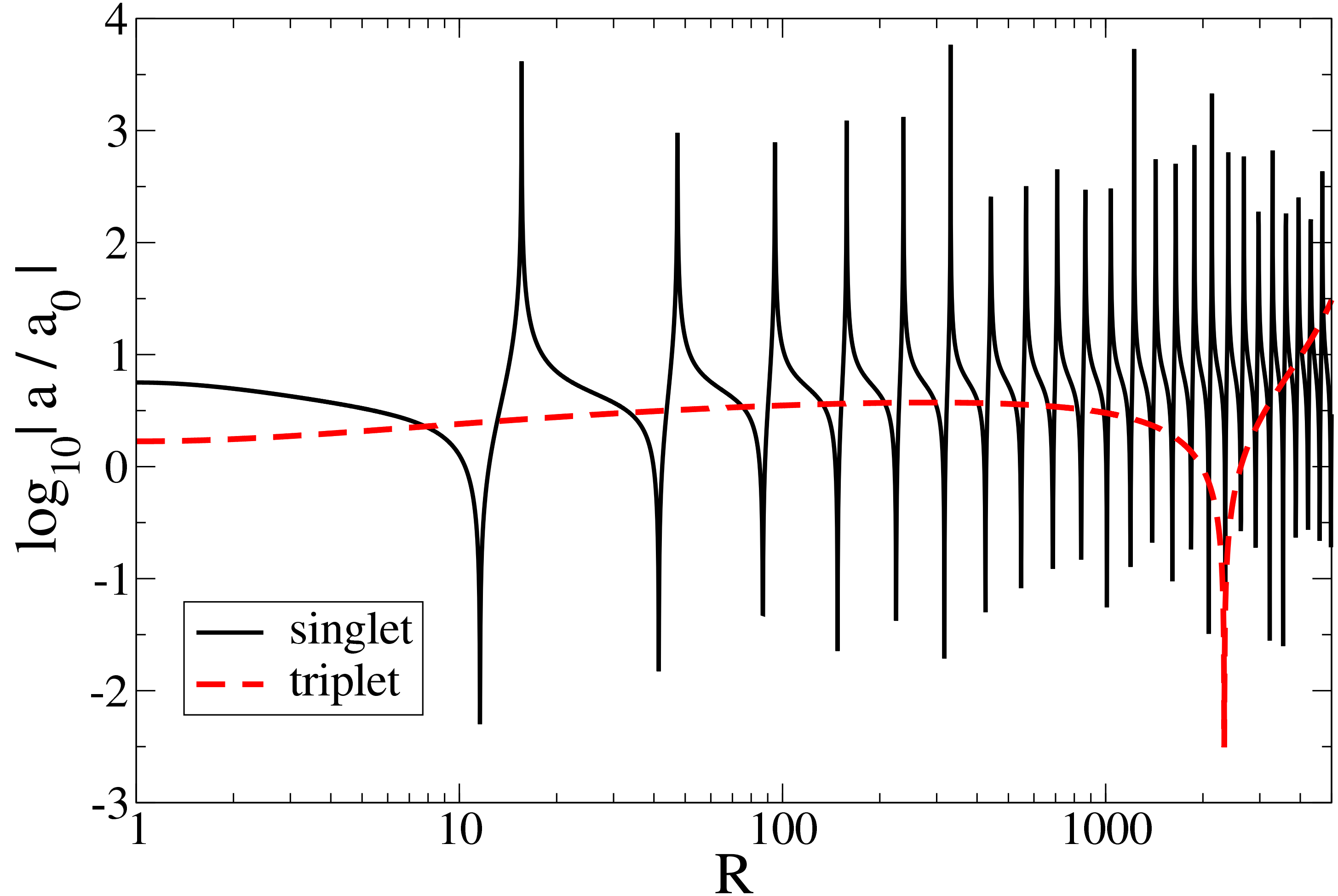


$V_{s,t}$ depend only upon $a_0,\ \epsilon_0$, not R.
We can use them directly for dark atoms!

$f(R)$ acts like particle mass

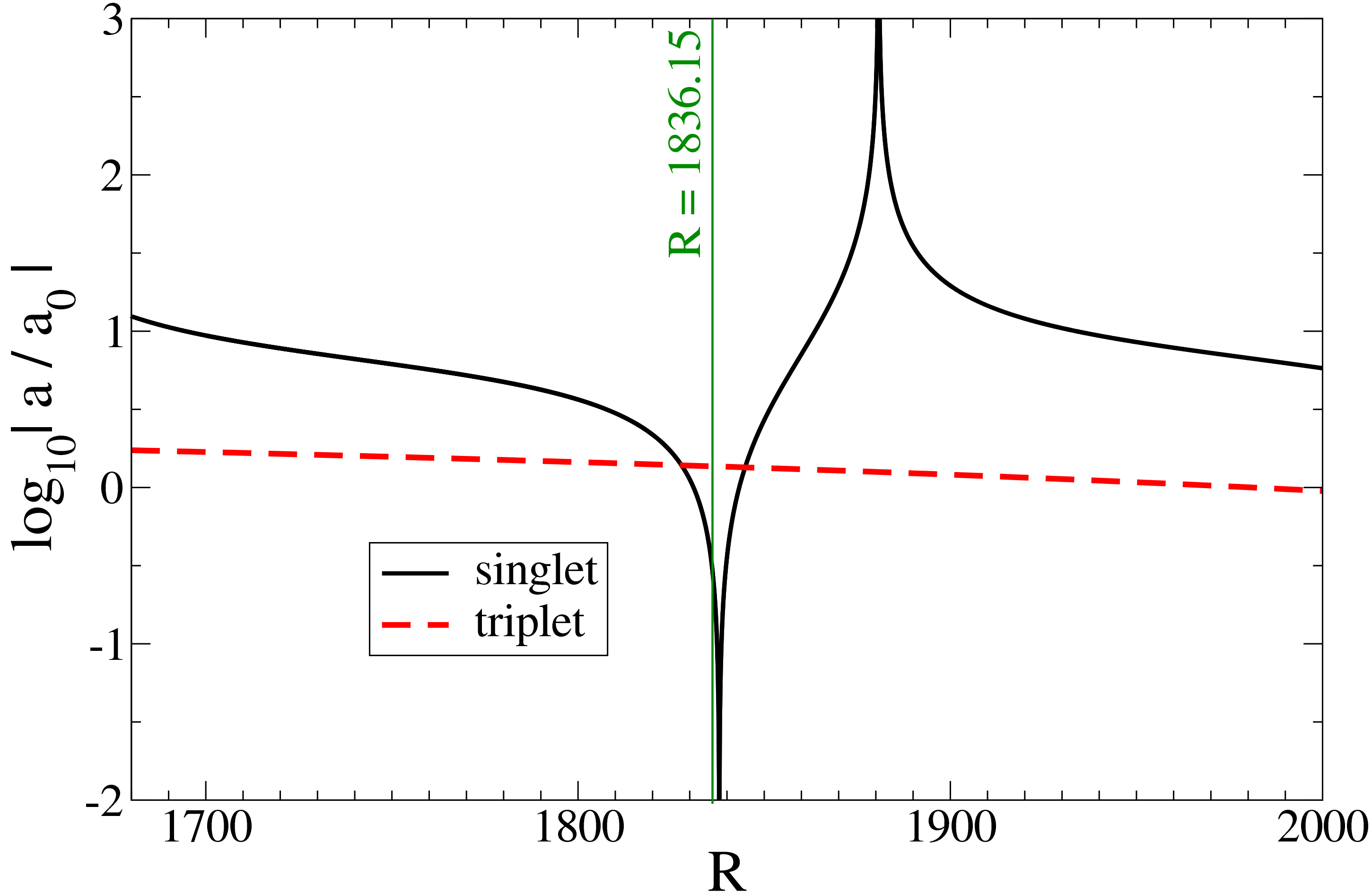
R-dependence of cross section

Effective mass increases with R: deeper potential $\rightarrow$ more bound states $\rightarrow$ divergences in scattering length, $a = \lim_{k\to 0}\sqrt{\sigma(k)/4\pi}$



R-dependence of cross section

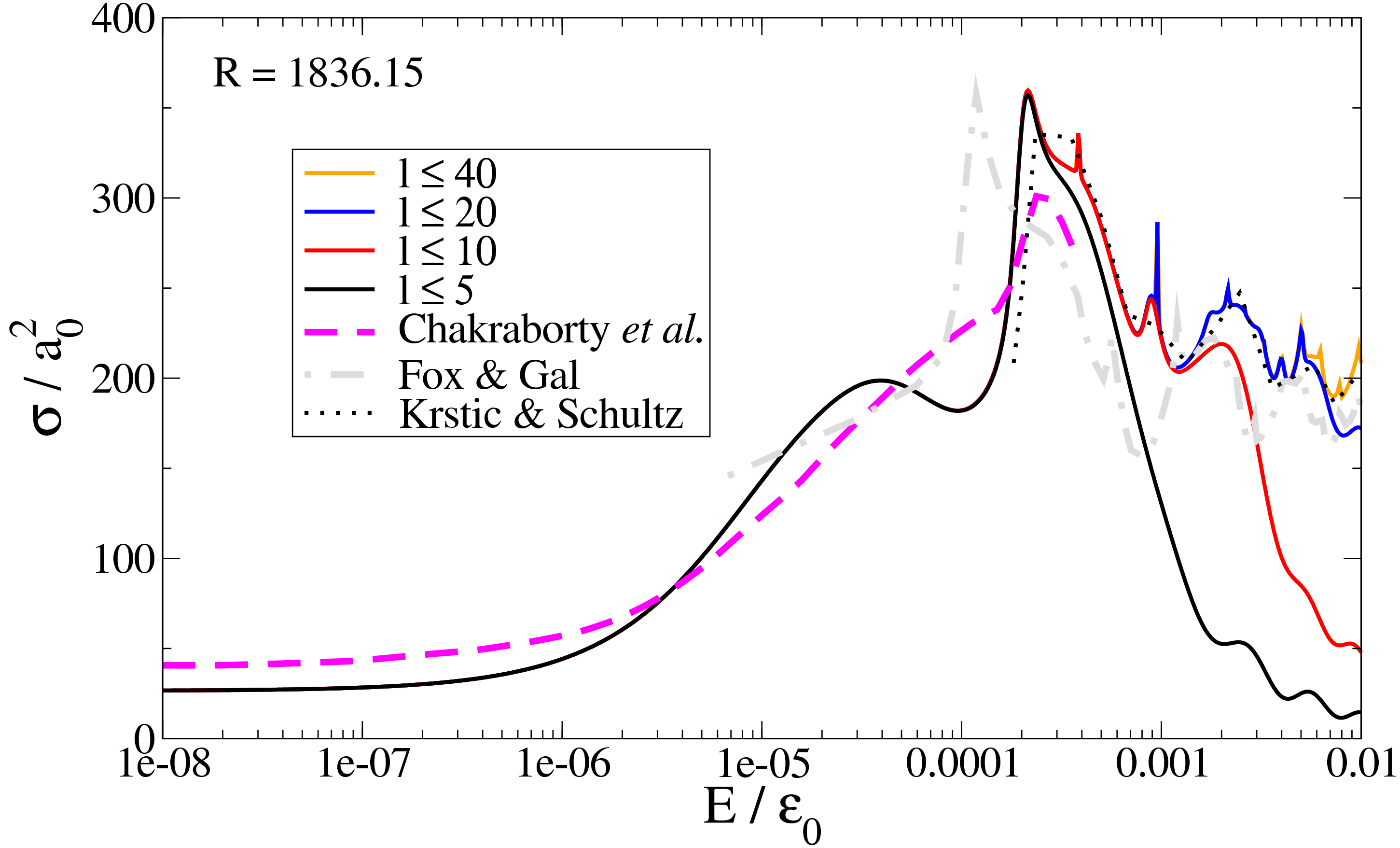
Real world happens to be close to a zero of the singlet channel scattering length:



$\rightarrow$ Real-world cross section $\sigma \sim 30\, a_0^2$ is atypically small.

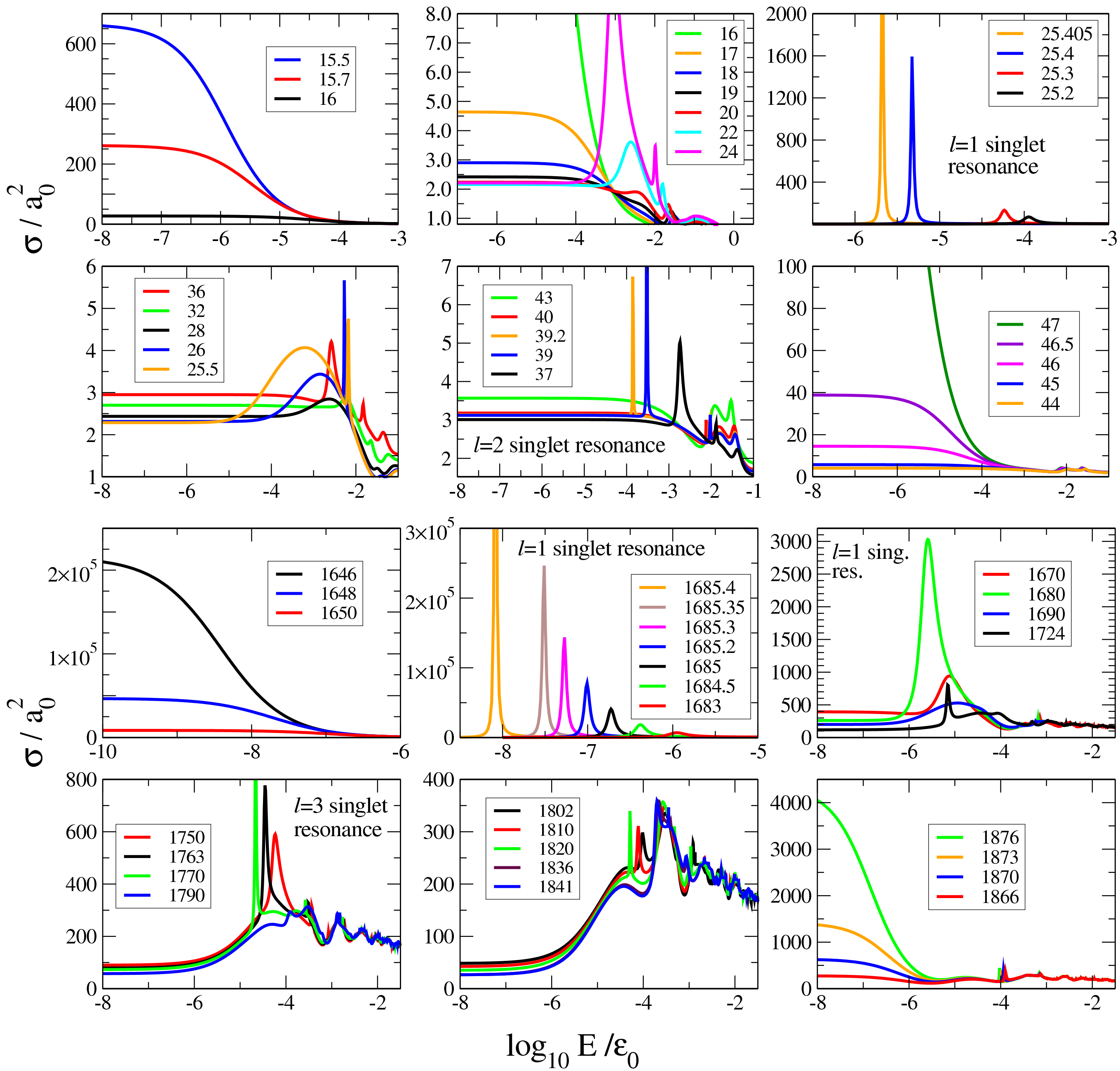
Reproducing known results

We can reproduce the most recent result from the atomic physics literature for $R = 1836.35$:



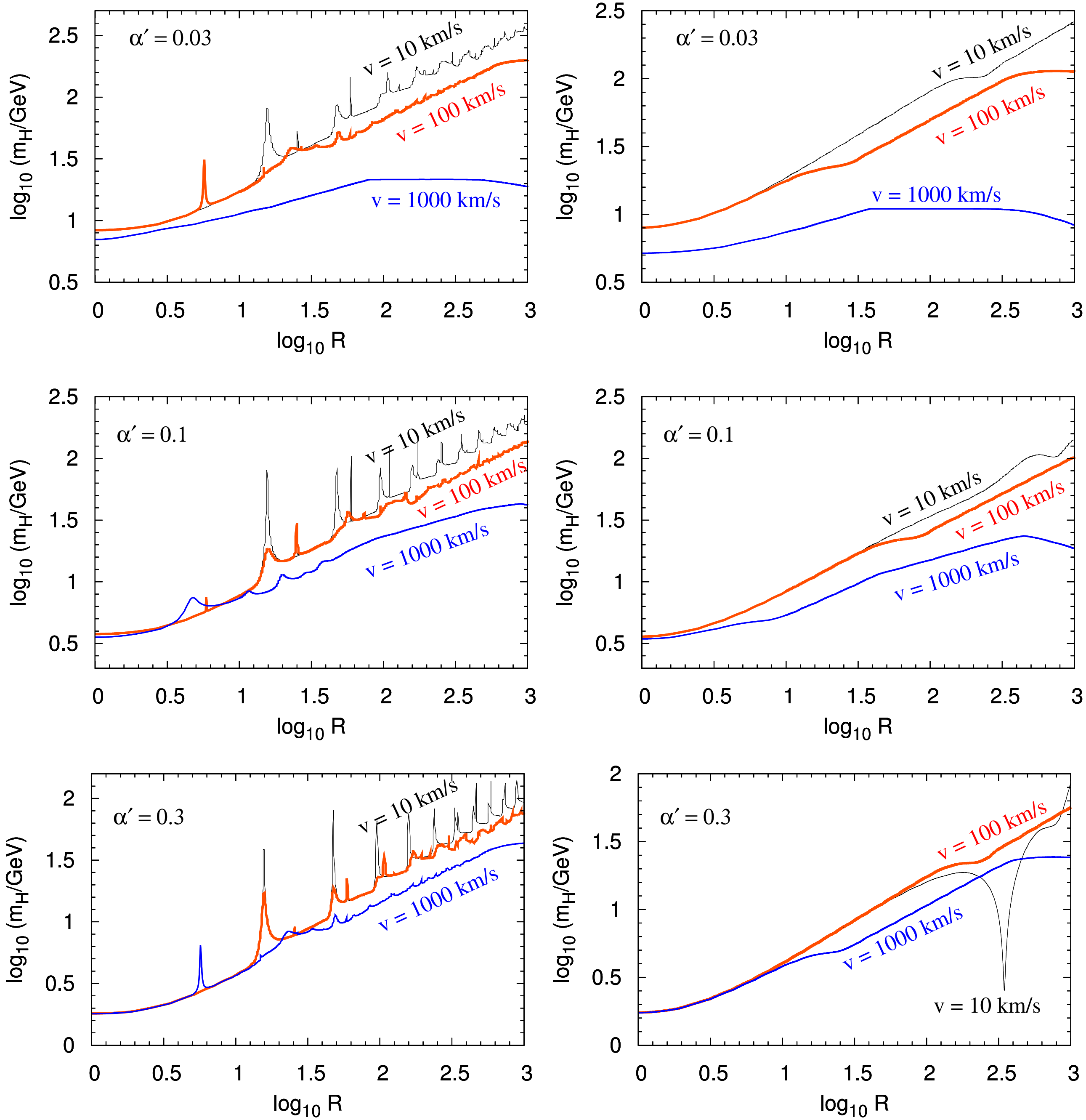
Differences with earlier results are due to refinements in V_s over the years, or some authors' neglect of m_e contribution to m_H.

R-dependence of cross section



We get many intricate features in σ as a function of energy and of R

Preferred regions of parameter space



Left: preferred m_H versus R for different α' and DM velocities.

Right: same for dark H_2 molecules.

Roughly fit by

$$\frac{m_H}{\mathrm{GeV}} \cong \left(\frac{R}{5.3\alpha'}\right)^{2/3}$$

or

$$a_0 \cong 1\,\mathrm{fm}\left(\frac{m_H}{\mathrm{GeV}}\right)$$

Dark molecules?

We can compute scattering of dark H_2 molecules in same way, since intermolecular potential is known.

Could dark atoms bind primarily into H_2 molecules? Residual ionized fraction of dark atoms catalyzes molecule production, *e.g.*,

$$\mathrm{H} + p \to \mathrm{H}_2^+, \quad \mathrm{H}_2^+ + \mathrm{H} \to \mathrm{H}_2 + p$$

No dark stars, no ionizing radiation; dark molecules may dominate.

Danger: rotational excitations are too easy if $R \gg 1$, making dark matter too dissipative. We can quantify:

Electric quadrupole transition requires $\ell = 2$ bound state.

For what value of R do we get the first zero-energy $\ell = 2$ bound state?

We find $R = 15.42$

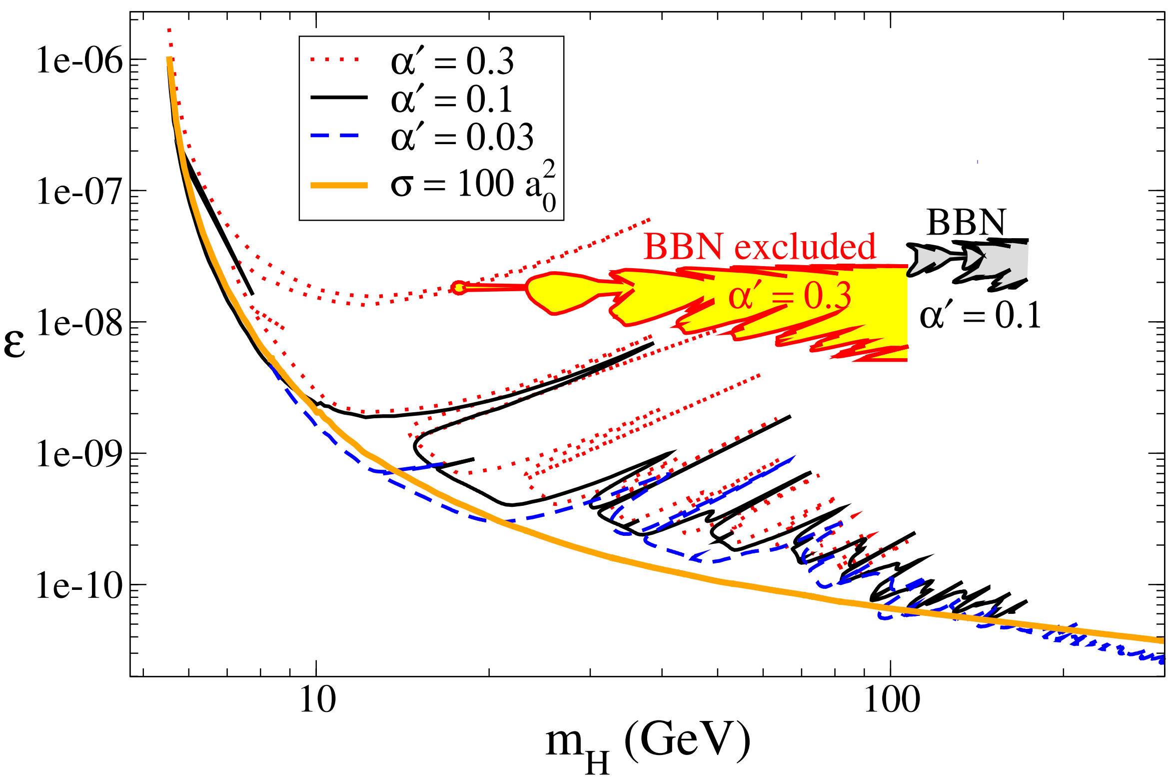
Thus for $R < 15.42$, dark molecules are not dissipative.

Direct detection of dark atoms

If dark photon kinetically mixes with normal photon via

$$\frac{1}{2}\epsilon F^{\mu\nu}F'_{\mu\nu}$$

then dark constituents become millicharged $\pm\epsilon e$ and can scatter on protons with $\sigma_p = 4\pi(\alpha\epsilon\mu_{pH})^2 a_0^4$. Using SIDM constraint to eliminate R, we get LUX upper bound on ϵ:



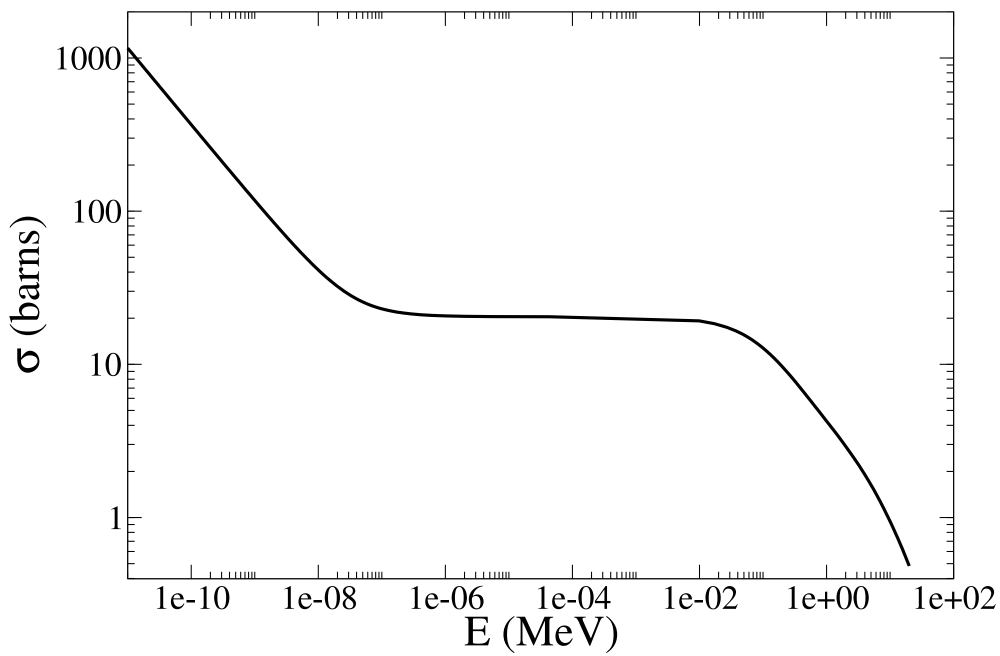
Dark "baryons"

Suppose that nucleons of a strongly-interacting hidden sector are the DM.

How big is σ/m_N for NN scattering? Naive estimate:

$$\sigma \sim 4\pi\Lambda^{-2}, \quad m_N \sim N_c\Lambda$$

for dark confinement scale Λ. Predicts $\sigma/m_N \sim 0.4\,\mathrm{b/GeV}$ for QCD—too low by factor of 50 compared to observed value!



neutron-proton scattering cross section versus energy

(electromagnetic interaction dominates at very low E)

The weakly bound deuteron

p-n scattering is resonantly enhanced by deuteron intermediate state:

$$pn \to D \to pn$$

Enhancement due to small binding energy $E_B = 2.2\,\mathrm{MeV}$ of deuteron:

$$\frac{\sigma}{m_N} \to \frac{2\pi}{N_c \Lambda^2 E_b} \qquad \left(\mathrm{c.f.}\ \frac{4\pi}{N_c \Lambda^3}\right)$$

How to generalize this to other QCD-like theories with different fundamental parameters? How does E_b scale?

Lattice gauge theorists have done it for us! (though not in terms of E_b).

NN scattering lengths

As $E \to 0$, cross section approaches

$$\sigma = \pi(a_s^2 + 3a_t^2)$$

where $a_{s,t}$ are singlet/triplet scattering lengths (deuteron has spin 1 and so is in triplet channel).

Lattice gauge theorists Chen *et al.*, 1012.0453 computed $a_{s,t}$ in QCD as function of m_π. We extract

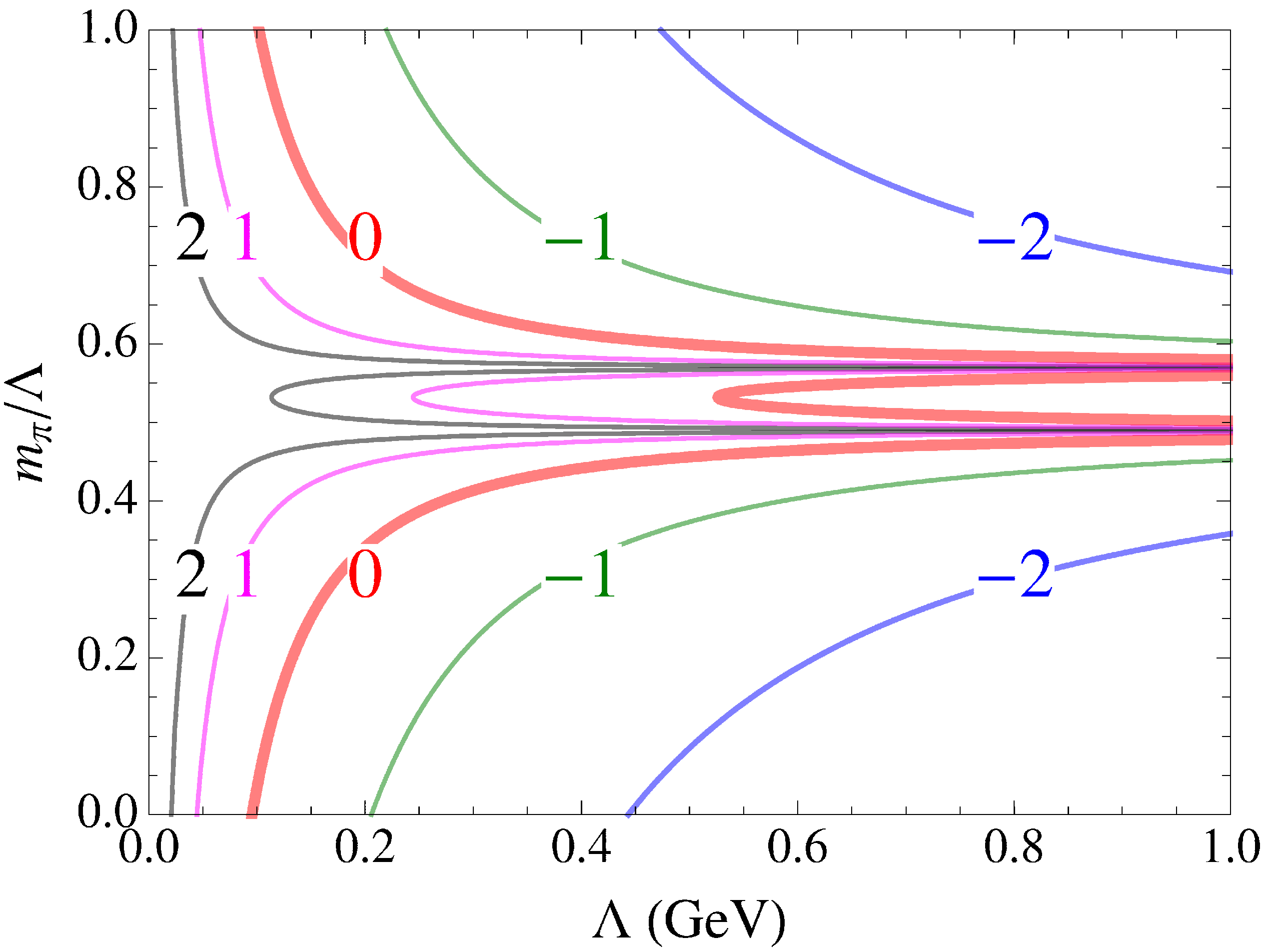
$$a_s = \frac{0.58\,\Lambda^{-1}}{m_\pi/\Lambda - 0.57}, \qquad a_t = \frac{0.39\,\Lambda^{-1}}{m_\pi/\Lambda - 0.49}$$

by dimensional analysis (Λ is only other scale in problem).

We can compute σ/m_N for any m_π, Λ, assuming $m_N = 3.8\,\Lambda$ as in QCD.

SIDM prediction for dark baryons

Contours of $\log_{10}[(\sigma/m)/(1.1\mathrm{b}/\mathrm{GeV})]$



Note that $m_\pi = 0$ is allowed, so that π would contribute only to dark radiation, not dark matter.

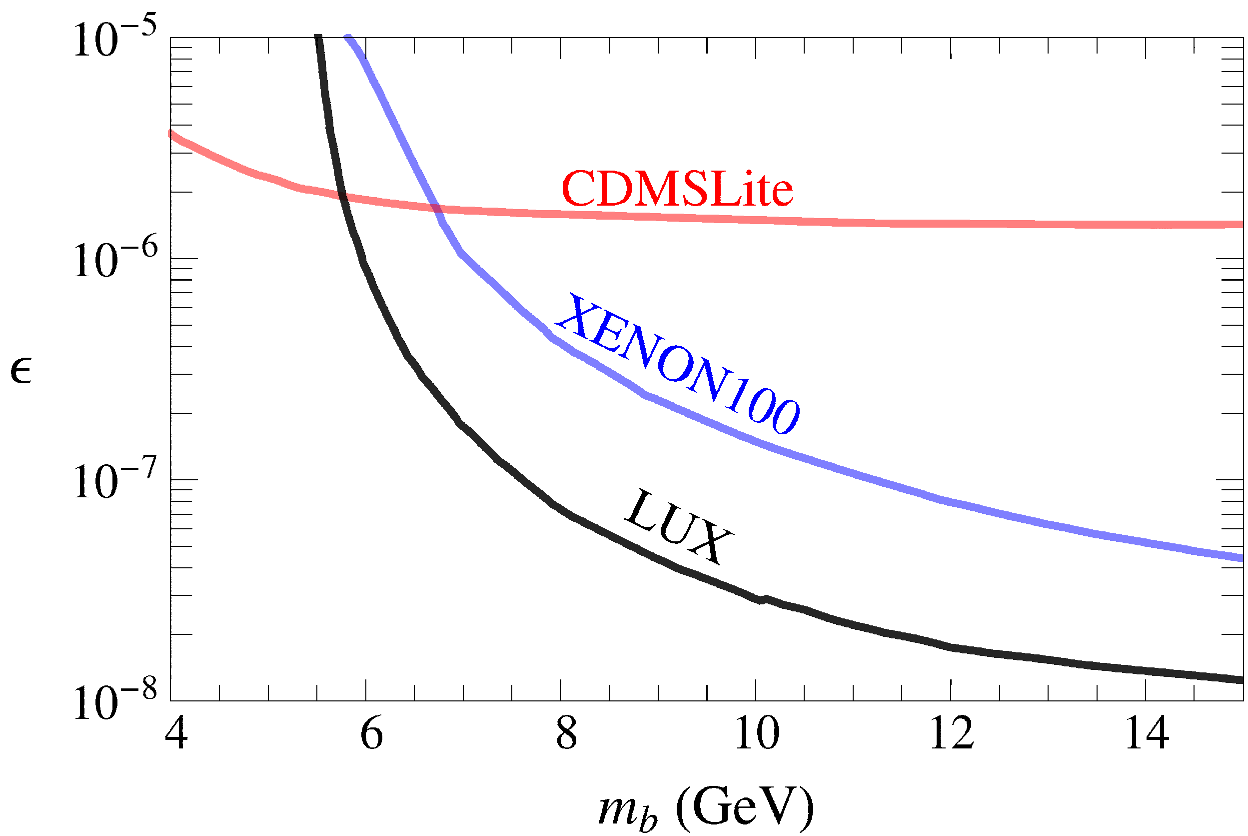
Typical dark baryon mass is O(GeV).

Dark baryon direct detection

If quarks interact with kinetically mixed, massive Z', then dark baryons scatter on protons with cross section

$$\sigma_{pb} = 144\pi\,\alpha\,\alpha'\epsilon^2\frac{\mu^2}{m_{Z'}^4}$$

Direct detection constraints on ϵ:

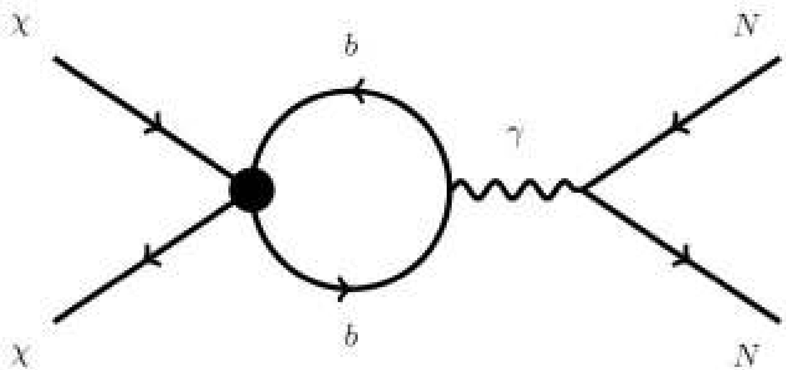


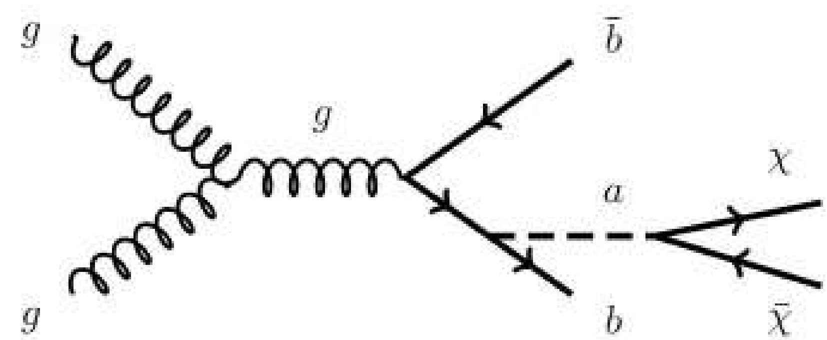
Assuming
$g' = 1$,
$m_{Z'} = 1$ GeV.

Bound scales as $m_{Z'}^2/g'$ for other values.

DM Models for GC γ-ray excess

Higgs portal mediator doesn't work; in fact nearly all s-channel mediators conflict with direct detection and LHC limits (Izaguirre et al., 1404.2018)





CMS searches for bottom squarks, $\tilde{b}\,\tilde{b}^* \to b\,\bar{b} + \chi\chi$ severely constrain these models.

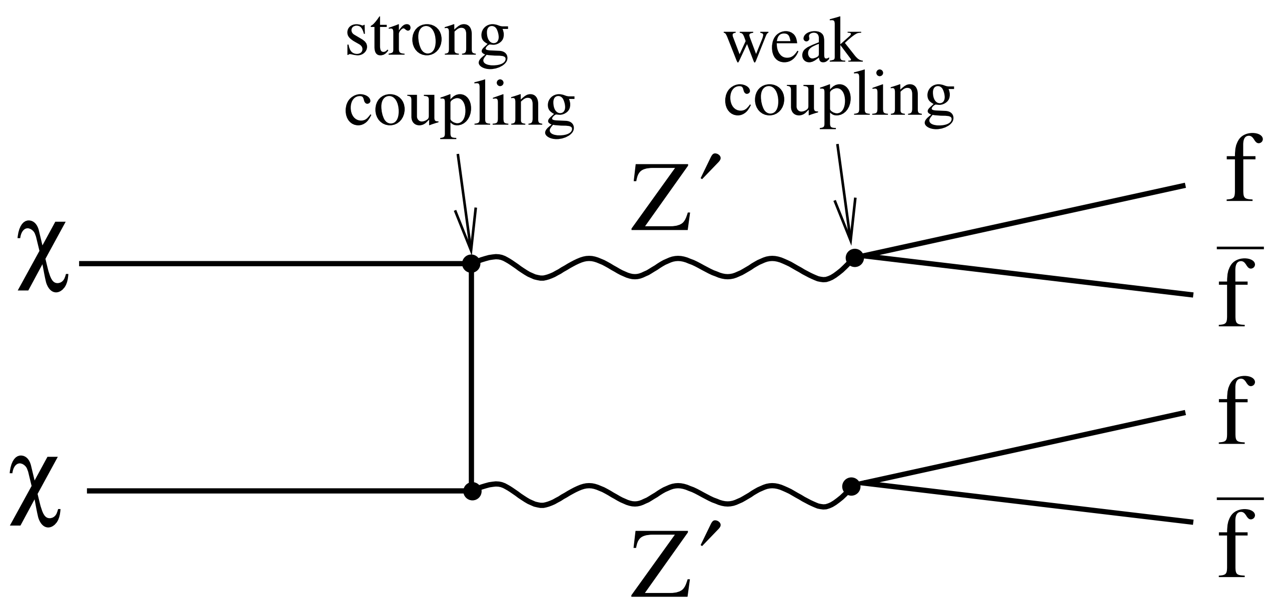
Annihilation into light mediators helps to overcome this problem:

$$\chi\chi \to Z'Z' \to b\,b\,\bar{b}\,\bar{b}$$

(or possibly other final states)

Light mediators for GC γ-ray excess

1405.0272, 1404.2018: annihilation to mediators weakens the constraints; coupling to SM fermions can be very weak:

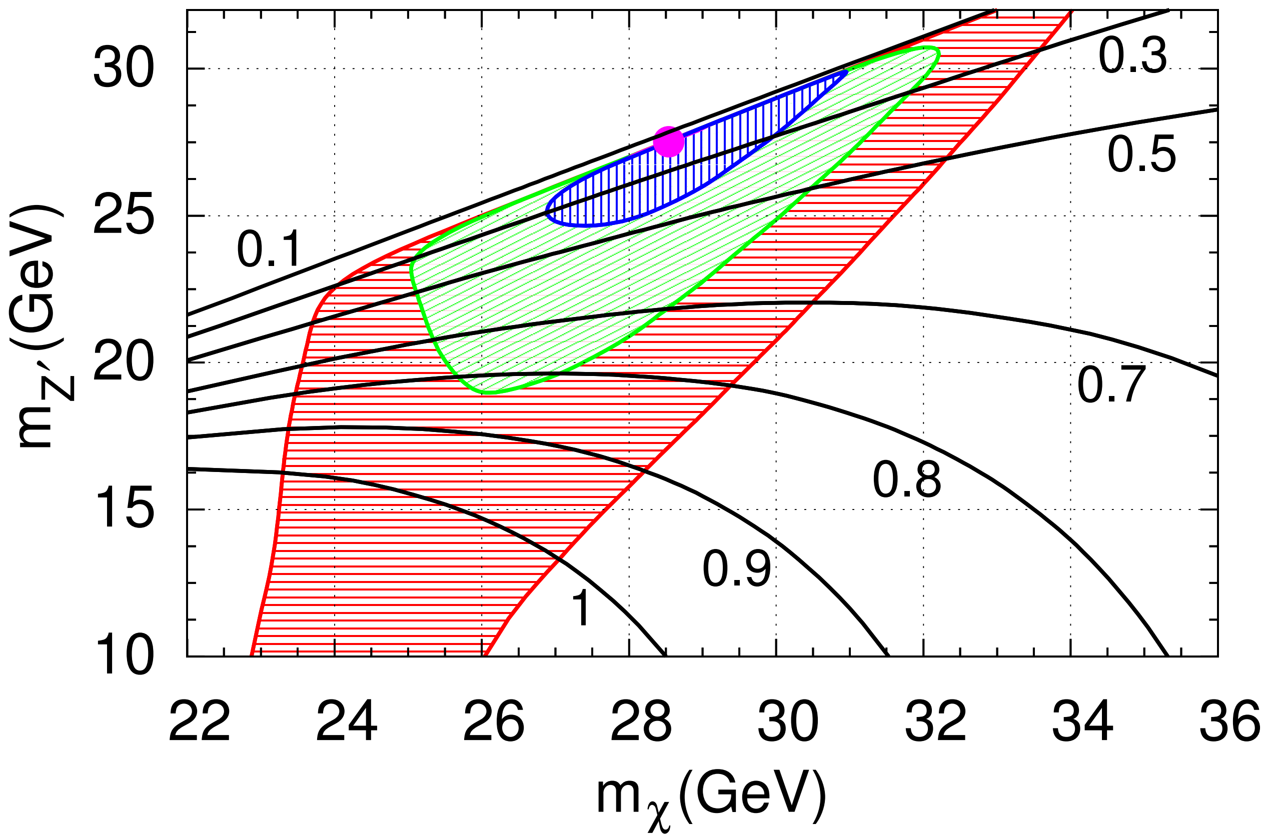


Z' need only decay near the galactic center

But GC signal strength is still related to relic density

DM Models for GC γ-ray excess

An example: kinetically mixed Z' coupled to χ
(JC, G. Dupuis, Z. Liu, W. Xue 1405.7691)



Shaded regions: $1, 2, 3\,\sigma$ intervals for GC excess.

Contours: relic density relative to full CDM value.

There is tension between best fit for GC and for relic density

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

Continuing indications of CDM failure for small-scale structure might indicate DM self-interactions—a more intricate dark sector than the minimal one

The galactic center gamma ray excess continues to attract attention from DM practitioners

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