Sub-GeV Dark Matter and $U(1)_{T3R}$

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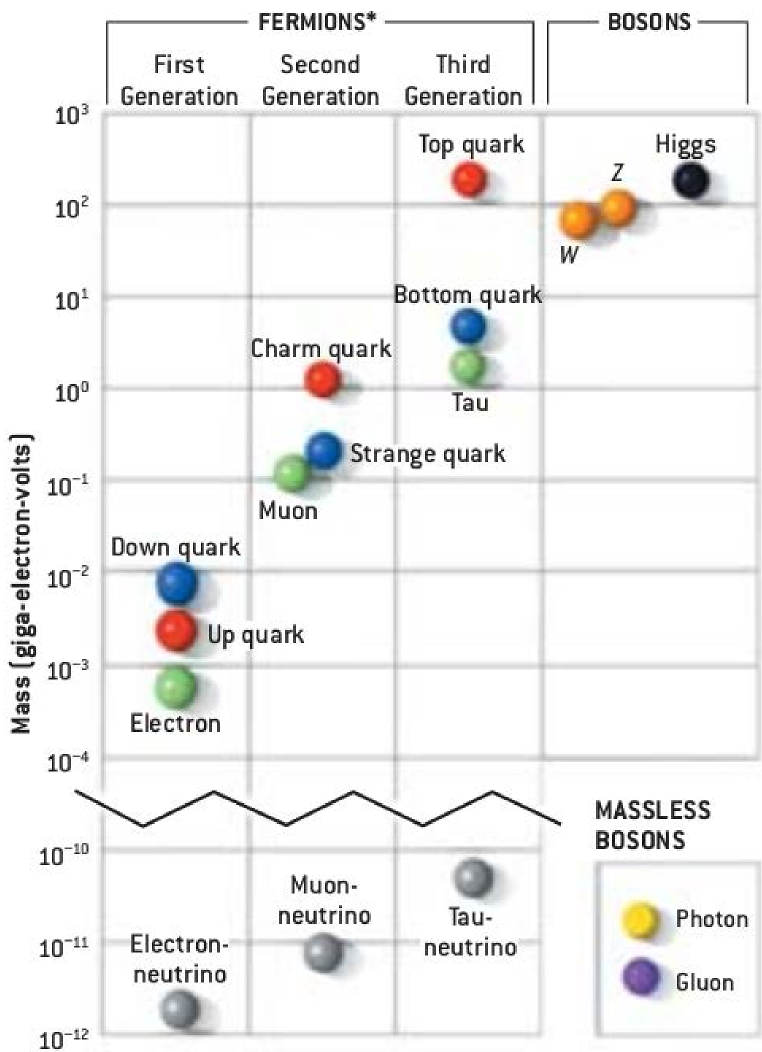
low-mass dark matter

- there has been recent interest in sub-GeV dark matter
  - evades tight constraints from current direct detection experiments
  - can get the right relic density through a variety of mechanisms in which DM is in thermal contact with SM (SIMPs, ELDERs)
  - most of all, can be explored by new, relatively inexpensive experiments
- but is there any reason for a particle at the MeV scale?
- analogous to the WIMP miracle
  - mechanism for getting TeV-scale particle to have the correct relic density…
  - … and a reason why a new TeV scale particle should arise (new physics associated with EWSB)
- reason for having a particle at the MeV scale?...
- … light flavor physics

why MeV?

- electroweak scale is a notch on the ruler, and W, Z, h, (WIMPs?) are all around there
- there is another notch on the ruler at MeV scale....
- 1st and 2nd generation charged particle mass parameters all lie in MeV-GeV range
- can the light flavor sector feed into dark sector?
- our idea → connect DM to light flavor physics through a dark photon/Higgs interaction for right-handed SM fermions



Gordy Kane, Scientific American, May 2003

new U(1) gauge group

- many scenarios of new physics involve new U(1) gauge symmetry under which SM fermions are charged
- since SM is chiral, need to make sure U(1) anomalies are cancelled
- examples studied recently
  - B-L
  - L_i-L_j
  - secluded U(1) → SM charges induced at one-loop through kinetic mixing
- but we want chiral SM charges, so we use $U(1)_{T3R}$ (Pati,Salam 74; Mohapatra,Pati 75)
  - couples to RH fermions, with up-type and down-type having opposite charge
  - originally considered in left-right models, where RH fermions are charged under $SU(2)_R$, and $U(1)_{T3R}$ is subgroup generated by diagonal generator (σ_3)
  - descends from $SU(2)_R$, so manifestly anomaly free
    - anomalies proportional to Tr $[\sigma_3]$ and $Tr[(\sigma_3)^3]$ → vanish
    - won't embed in $SU(2)_R$

$U(1)_{T3R}$ and dark matter

- strategy → charge a generation of right-handed SM fermions under $U(1)_{T3R}$
- in EFT below electroweak scale, the $U(1)_{T3R}$ protects fermion masses
  - $U(1)_{T3R}$ spontaneously broken down to parity by dark Higgs
  - fermion masses now scale with symmetry-breaking parameter V
- if DM is a fermion also charged under $U(1)_{T3R}$, and odd under surviving parity
  - stabilized by parity (it's the only odd particle)
  - gets Majorana mass proportional to symmetry-breaking parameter (V)
- upshot → two dark sector Majorana fermions with mass scale proportional to V, just as with SM light fermions
  - lightest is stable (DM), heavier particle may still be around
  - if V is small, SM fermion scale explained, and DM naturally sub-GeV

game plan

- this is a general framework, but we'll develop an explicit example
  - 1st/2nd generation RH fermions charged under $U(1)_{T3R}$
  - dark matter couples to Standard Model particles through a dark photon (A') and a dark Higgs (ϕ')
- lots of constraints, but open parameter space available
- interesting phenomenological features…
- … spin-independent, velocity-independent DM-nucleon scattering
  - elastic scattering mediated by dark Higgs
  - inelastic isospin-violating scattering mediated by dark photon
- get correct relic density through (co-)annihilation via intermediate A' or ϕ'
- consistent with Planck bounds (invisible, p-wave, or co-annihilation)

model

- $q^u{}_R$, $q^d{}_R$, ℓ_R, and ν_R → Q_{T3R} =±2
  - need not be in same generation
  - anomalies cancel
  - Yukawa terms need ϕ insertion
- $\langle\phi\rangle = V = (-\mu_\phi^2/2\lambda_\phi)^{1/2}$
  - SM fermion masses ∝ V
  - breaks $U(1)_{T3R}$ to a Z_2 parity
  - SM particles even under parity
  - dark sector fermion η is odd
- new particles
  - A′ (dark photon), ϕ′ (dark Higgs)
  - ν_S (mostly ν_R)
  - $\eta_{1,2}$ (Majorana fermion DM)

charges of left-handed component of Weyl spinor

field	$q_R{}^u$	$q_R{}^d$	ℓ_R	ν_R	η_L	η_R	ϕ
q_{T3R}	-2	+2	+2	-2	1	-1	-2

$$L_\phi = -\frac{\lambda_u}{\Lambda}\tilde{H}\phi^*\overline{Q}_L q_R^u - \frac{\lambda_d}{\Lambda}H\phi\overline{Q}_L q_R^d$$
$$-\frac{\lambda_\nu}{\Lambda}\tilde{H}\phi^*\overline{L}_L\nu_R - \frac{\lambda_\ell}{\Lambda}H\phi\overline{L}_L\ell_R$$
$$-m_D\overline{\eta}_R\eta_L - \frac{1}{2}\lambda_L\phi\overline{\eta}_L^c\eta_L - \frac{1}{2}\lambda_R\phi^*\overline{\eta}_R^c\eta_R$$
$$-\mu_\phi^2\phi^*\phi - \lambda_\phi\left(\phi^*\phi\right)^2 + \text{h.c.}$$

$\tilde{H} \equiv i\sigma_2 H^*$, and we take $\lambda_L = \lambda_R \equiv \lambda_M$

masses and couplings

- EFT below EWSB scale….
  - $\phi'\bar{f}f$ → coupling ∝ m_f / V
  - $A'\bar{f}f$ → coupling ∝ $Q_f\, m_{A'} / V$
- η has Maj. and Dirac mass terms
  - take $m_D \ll \lambda_M V$
  - $m_{1,2} \propto V$, with small splitting
  - SM and DM masses scale with V
  - if V~1-10 GeV, naturally get sub-GeV SM and DM fermions, as well as sub-GeV A', ϕ'
- A' coupling to $\eta_{1,2}$ is off-diagonal
  - inelastic scattering, co-annih.
- A' kinetically mixes with γ, Z

$$M_\eta = \begin{bmatrix} \lambda_M V & m_D \\ m_D & \lambda_M V \end{bmatrix}$$

$$M_\nu = \begin{bmatrix} 0 & \lambda_\nu V \\ \lambda_\nu V & M \end{bmatrix}$$

$$m_{A'} = \sqrt{2} g_{T3R} V, \qquad m_{\phi'} = 2\lambda_\phi^{1/2} V$$

$$j^\mu_{T3R} = \frac{i}{2}\left(\bar{\eta}_1 \gamma^\mu \eta_2 - \bar{\eta}_2 \gamma^\mu \eta_1\right) + j^\mu_{T3R,\phi'} + j^\mu_{T3R,SM(R)}$$

setup

- we can choose q^d_R, ℓ_R to be mass eigenstates, since this is technically natural (extra $U(1)^2$ flavor symmetry)
  - see Batell, Freitas, Ismail, McKeen (1712.10022)
- no symmetry reason to assume q^u_R a mass eigenstate, but we'll assume for simplicity that dominant coupling is to one mass eigenstate
- so we take the SM fermions charged under $U(1)_{T3R}$ to be μ_R, u_R, and d_R
  - flavor diagonal
  - other choices possible, but we'll pick this for simplicity and phenomenology
- assuming perturbativity, we get m_{SM}, $m_{1,2}$, $m_{A'}$, $m_{\phi'} < V$
- smaller V → lighter DM, with stronger coupling to SM
- taking V ~ GeV would give us $\mathcal{O}(1)$ couplings, but in tension with data
- need some modest hierarchies

constraints

Batell, Freitas, Ismail, McKeen (1712.10022); Bauer, Foldenauer, Jaeckel (1803.05466)

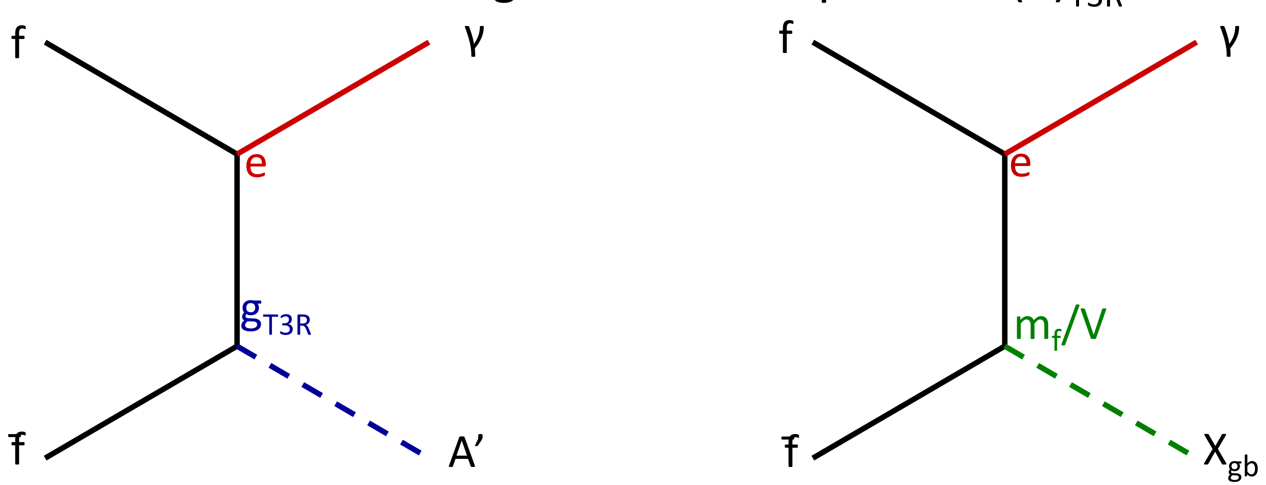
- but lots of constraints on A′, ϕ′ coupling to SM fermions
- main differences between our scenario and others
  - no coupling to $\bar{\nu}_L \nu_L$ (ν_R/ν_A mixing taken small), affects ν exp./cooling constraints
  - direct coupling to μ, not e (1-loop) → affects some e^+e^- collider constraints
  - chiral coupling of A′ to fermions → even at weak coupling, Goldstone couples
- g-2 corrections from ϕ′ (positive) and A′ (negative) running in loop
  - corrections can be fine-tuned against each other or heavy new physics
- main constraints
  - $e^+e^- \to 4\mu$ (BaBar)
  - fixed target/beam dump exps.: A′,ϕ′ → γγ, e^+e^- (E137, E774, E141, Orsay, etc.)
  - solar/SN/Glob. Cluster cooling constraints (production of A′, ϕ′)
  - fifth force constraints/N_{eff}
- we'll take V = 10 GeV, and will find restrictions on $m_{\phi'}$ and $m_{A'}$
  - not much dependence on dark matter mass (take m_η, $m_{\nu S}$ > 10 MeV)

N_{eff} and $U(1)_{T3R}$ (2002.00137)

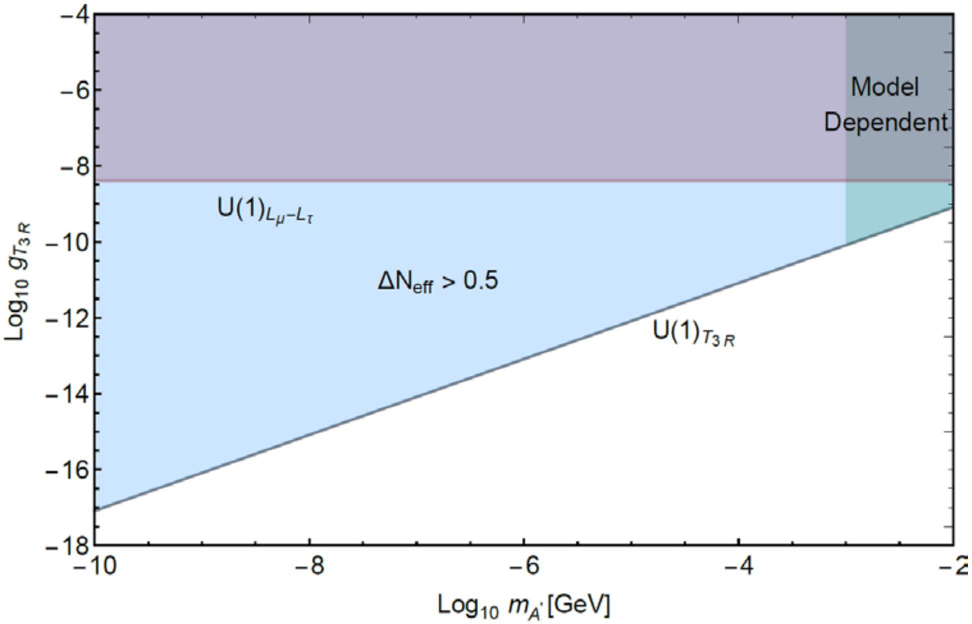
- generally two ways to avoid light A' or ϕ' contributing too much to N_{eff}
- if A' and ϕ' are heavy enough (> 10 MeV), they are gone before neutrino decoupling and don't affect N_{eff}
- if coupling is weak enough, then A' and ϕ' are never in equilibrium with SM → never produced, so also don't affect N_{eff}
- for our case, $U(1)_{T3R}$ coupled to second-generation
  - for ϕ', coupling $m_f/V \sim 0.01$, so never weakly coupled enough
  - for A', coupling $m_{A'}/V$, so can make weakly coupled just by making it light
- but $U(1)_{T3R}$ case is very different from B-L, L_i-L_j, kinetic mixing, etc.
  - no matter how weak the coupling, always produced in the early Universe unless $V > \mathcal{O}(10^7)$ GeV
  - result of coupling to chiral fermions

N_{eff} and chiral fermions

- weak coupling, so dominant A' production mode is inverse decay process
  - $f\bar{f} \rightarrow \gamma A'$
- longitudinal modes get an enhancement, $E/m_{A'}$, so A' thermalizes regardless of how small the mass/coupling is
  - enhancement killed if there is only a vector coupling, due to Ward identity
- another way to see it… as $m_{A'}/V \rightarrow 0$, $U(1)_{T3R}$ becomes a global symmetry
  - massless Goldstone mode couples as m_f/V, always thermalizes
  - for B-L, L_i-L_j, etc., … no need for Goldstone to couple of charged SM fermions
- we'll consider case where 2nd generation couples to $U(1)_{T3R}$



comparing $U(1)_{T3R}$ to L_μ- L_τ



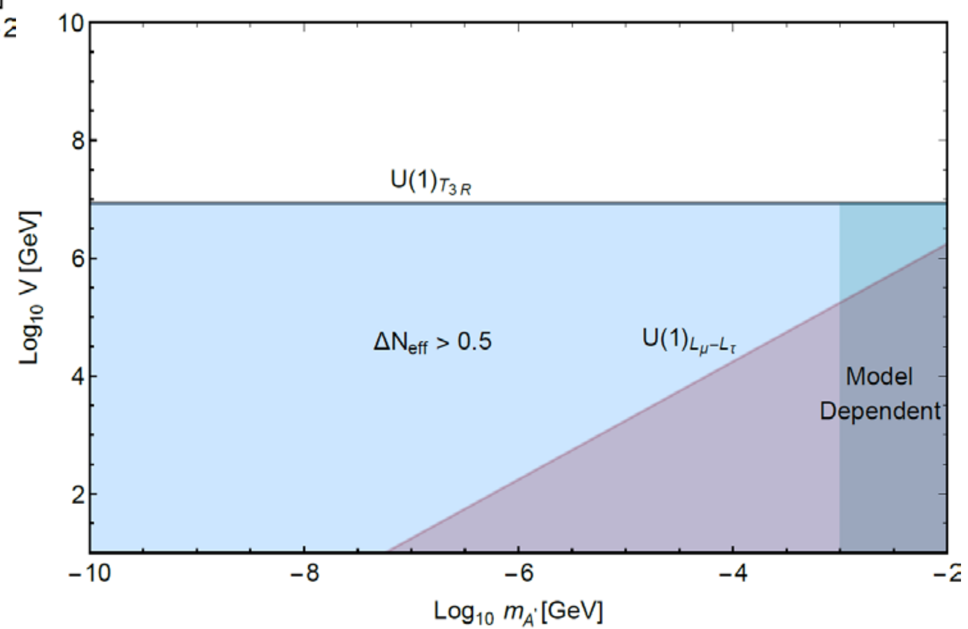
L_μ- L_τ is from Escuedero, Hooper, Krnjaic, Pierre (1901.020210, purple)

between 1-10 MeV, A' can decay to $\nu_A \nu_A$ or e^+e^- at one-loop, so effect on ΔN_{eff} depends on neutrino mass matrix

$$\sigma v \propto \frac{\alpha_{em} m_f^2}{s V^2}$$

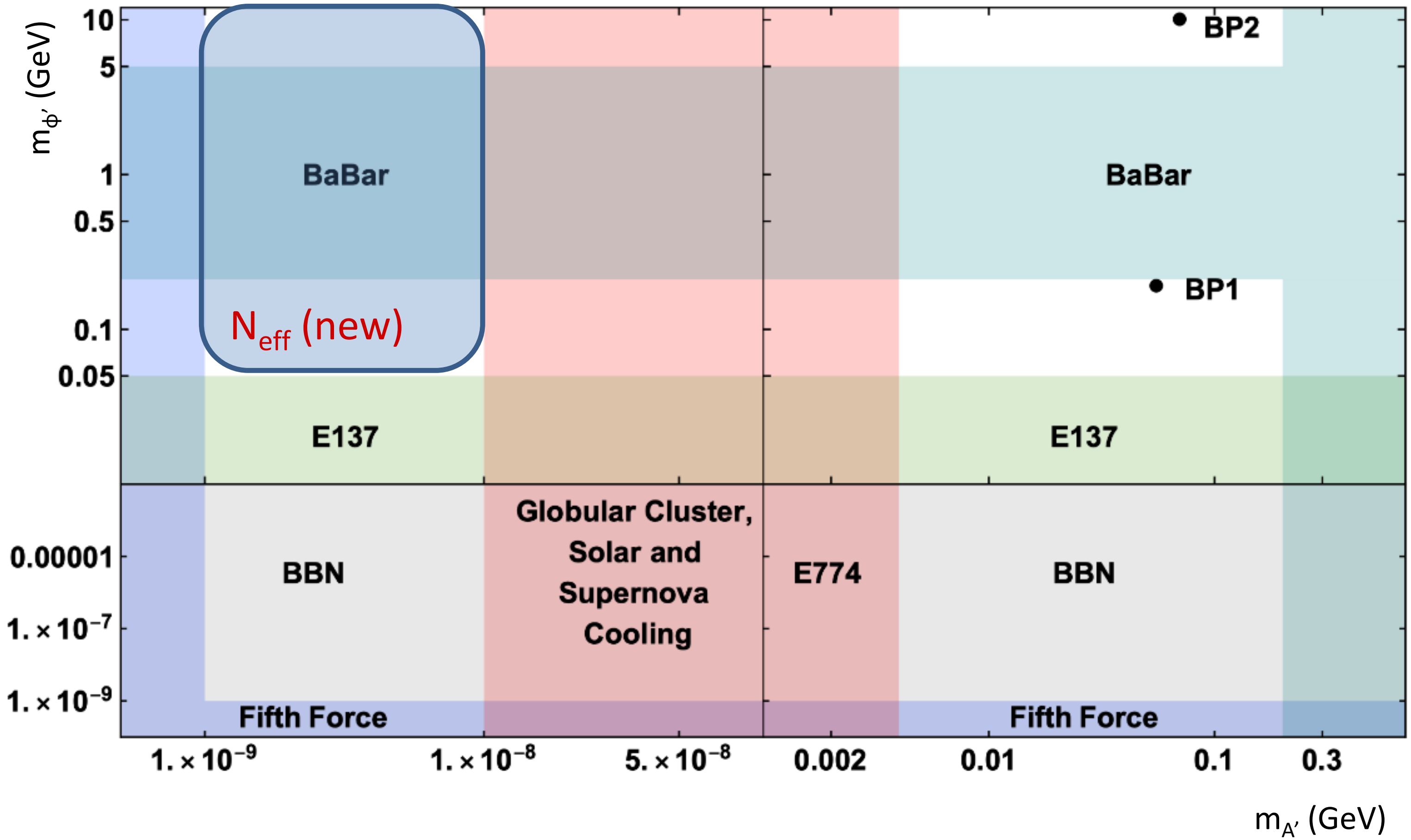
$$\langle \sigma v \rangle_{T=m_f} \eta > H$$

just outside excluded region, can get small ΔN_{eff}, which might help with H_0 tension (Bernal, Verde, Riess 1604.0617; Escuedero, Hooper, Krnjaic, Pierre, 1901.02010, for example)



constraints

two benchmark points which we will see get the relic density right also



open parameter space limited, can be closed with future experiments!

but parameter space can also be opened up by increasing V....

direct detection

- ϕ' mediated → SI, velocity-independent, elastic, isospin-invariant
- A' mediated → SI, velocity-independent, inelastic, isospin-violating (IVDM)
  - opposite coupling to u and d (thus to p and n)
- mediator mass is of the same order as momentum transfer
  - not a contact interaction, $d\sigma/dE_R$ suppressed by $[1+(2m_A E_R/m_{\phi',A'}{}^2)]^{-2}$
- current constraints (contact interaction, isospin-invariant)
  - CRESST III → $\sigma_{SI} \sim 10^{-35}$ cm^2 at m_η = 200 MeV
  - CDEX-1B → $\sigma_{SI} \sim 10^{-32-34}$ cm^2 at m_η = 50-180 MeV
  - XENON1T → $\sigma_{SI} \sim 10^{-29-30}$ cm^2 over full mass range, $\sigma_{SI} \sim 10^{-34}$ cm^2 at m_η = 100 MeV (Migdal effect, 1907.12771)
    - cosmic rays scatter off DM, boosted DM scatters in XENON1T (Bringmann, Pospelov -1810.10543; Dent, Dutta, Newstead, Shoemaker – 1907.03782)
- benchmark models satisfy all bounds (including electron scattering)

thermal relic density

- main relevant annihilation channels are s-channel through ϕ' or A'
- a thermal relic cross section would naively violate Planck bounds
- three ways out which we can use
  - p-wave: factor 10 suppression at freeze-out, but much more at recombination
    - kills Planck bounds for ϕ'-mediated case
  - co-annihilation: heavier state around at freeze-out, but decayed before recombination
    - can rescue A'-mediated co-annihilation case, if DM splitting is set right
  - invisible final states: if annihilation products predominantly produce $\nu_{s,A}$
- ϕ' coupling suppressed by mass of incoming/outgoing particles
  - need to be near resonance to get correct relic density for ϕ' mediator
- A' coupling not suppressed if A' is not light…, need not be on resonance
  - final state is $\nu_{s,A}$ $\nu_{s,A}$, or demand η_2 decay before recombination

two benchmark models

$\ell=\mu$	$m_{A'}$(MeV)	$m_{\phi'}$(MeV)	m_η(MeV)	m_{ν_S}(MeV)	$m_{\nu D}$(MeV)	$\langle\sigma v\rangle$ (cm^3/s)	σ_{SI}^S (pb)	σ_{SI}^V (pb)
BP1	55	200	100	10	10^{-3}	3×10^{-26}	0.51	6.50
BP2	70	10^4	50	10	10^{-3}	3×10^{-26}	5.7×10^{-9}	1.80

- first benchmark get relic density via ϕ' resonance
  - a_μ corrections (A'/ϕ') need to be fine-tuned against each other to 1%
  - need a contribution from new physics for cancellation
- for second benchmark, get relic density from co-annihilation via A'
  - ϕ' corrections to a_μ small, so need to cancel δa_μ correction from A' against heavy new physics to 1%
  - e^+e^- rate (one-loop) can be non-negligible, but can suppress if heavier state gone before recombination
    - if splitting small enough (< 1 MeV), doesn't affect BBN

upshot

- sub-GeV dark matter is a target which experiments are focusing on….
- points to either high-scale new physics with a suppressed coupling to DM, or low-scale new physics with less suppressed couplings
- best-case scenario is a GeV scale dynamically-generated parameter from new physics coupled to DM and SM
  - natural SM coupling is the light-flavor sector
- but the very best-case scenario is in tension with data…
- … need to push the parameter scale up, and the couplings down, to avoid tight constraints → need some fine-tuning (V, g-2)
- but points to a window where we get the correct relic density, and have interesting future prospects for experiments
- inelastic scattering is a generic feature whenever DM is charged under a broken continuous symmetry (mediated by dark gauge boson)

conclusion

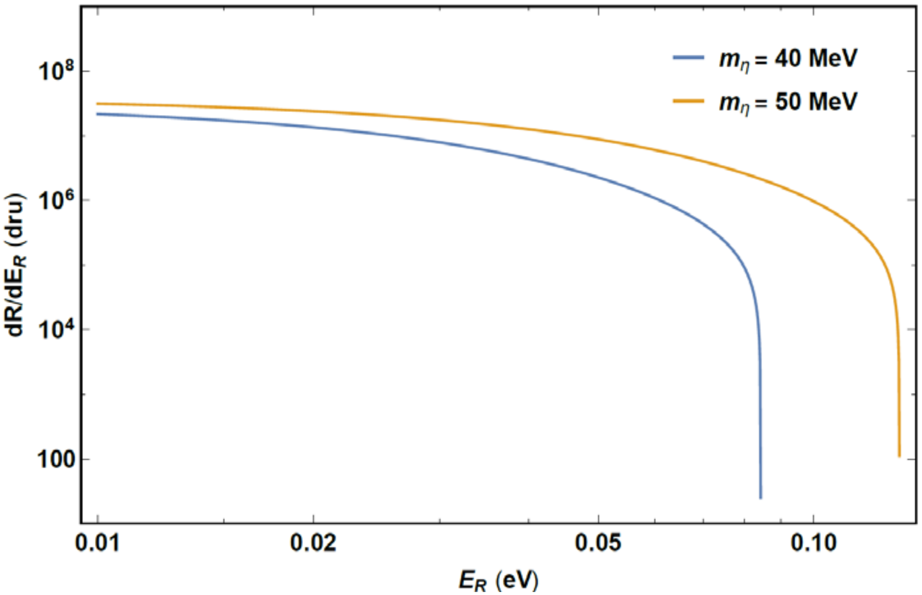
- dark matter experiments are set to probe the MeV-scale, but still need theory guidance
- MeV scale naturally arises in models which connect dark sector to the light flavor sector
- many constraints narrow parameter space, but some room left

- implications for MeV-range searches, including inelastic scat. of IVDM
- future work → prospects for future experiments to definitively test, coupling to electrons while avoiding atomic parity violation exps.

Mahalo!

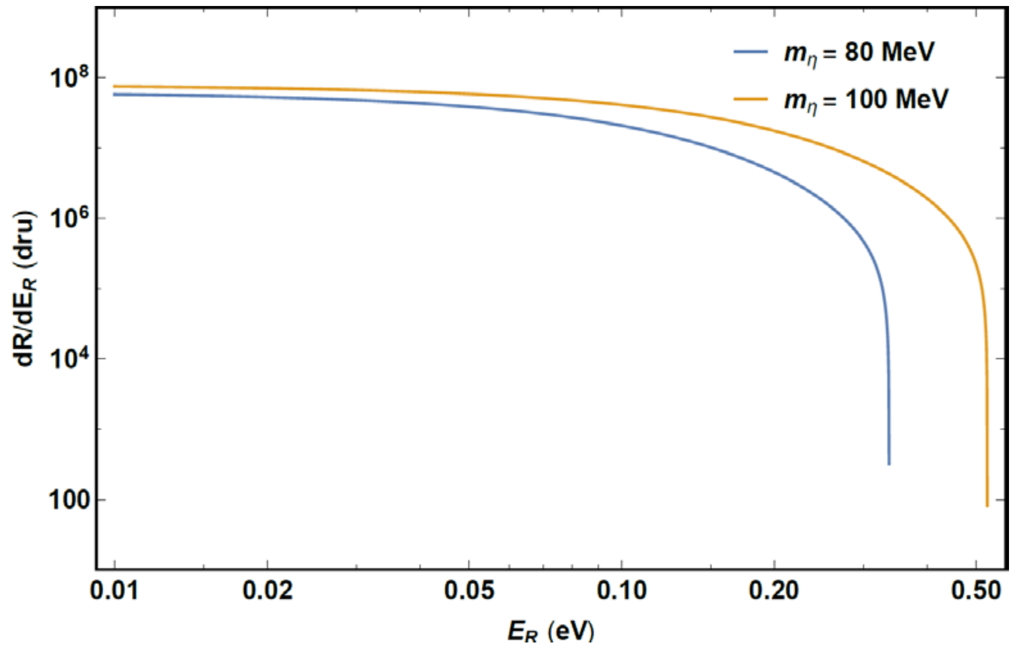
Backup Slides

elastic scattering rates

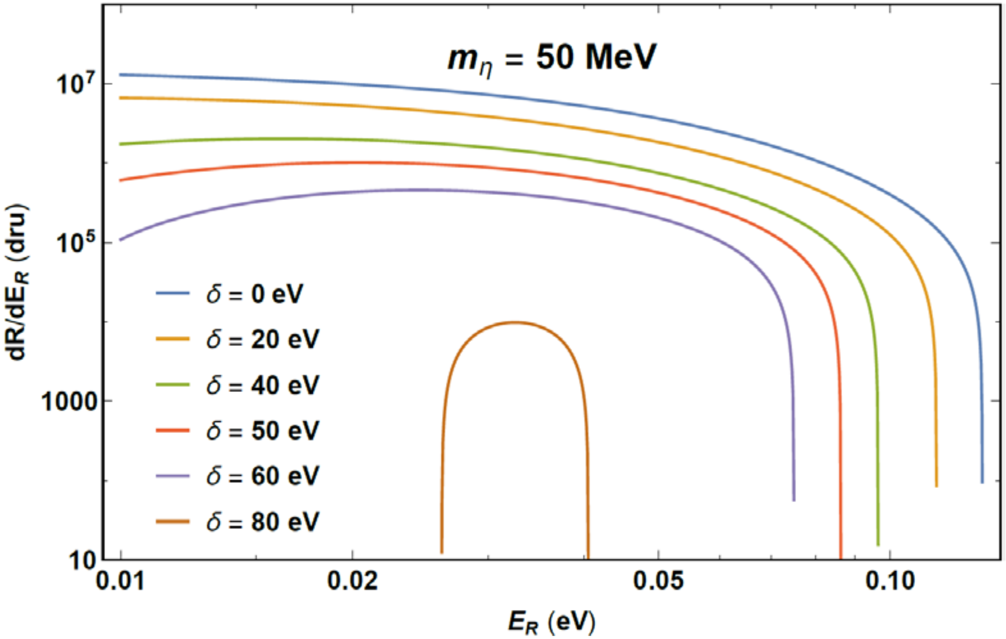


$m_{\phi'}$ = 200 MeV, V=10 GeV

differential cross section suppressed by $[1+(2m_A E_R/m_{\phi',A'}{}^2)]^{-2}$

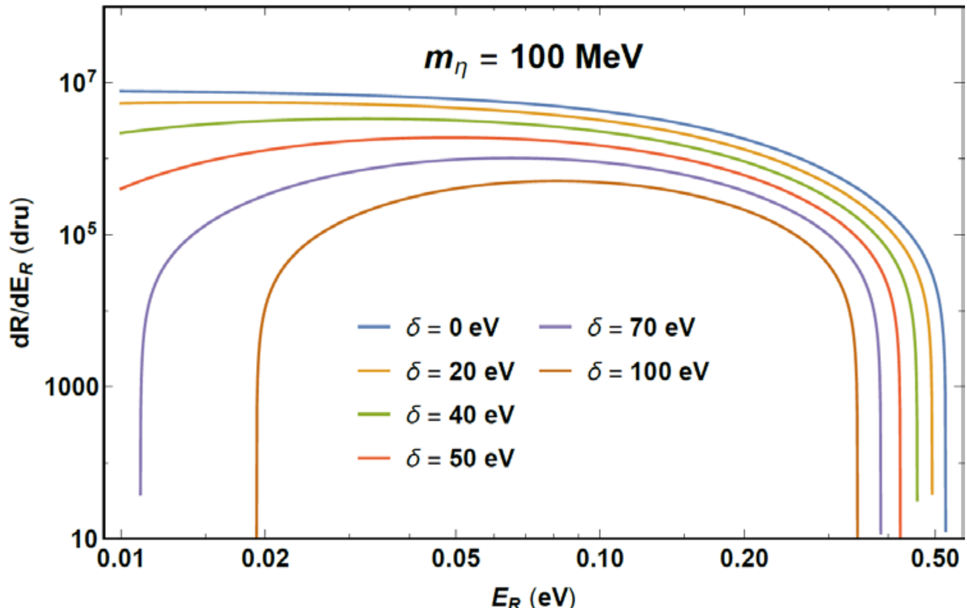


inelastic scattering rates

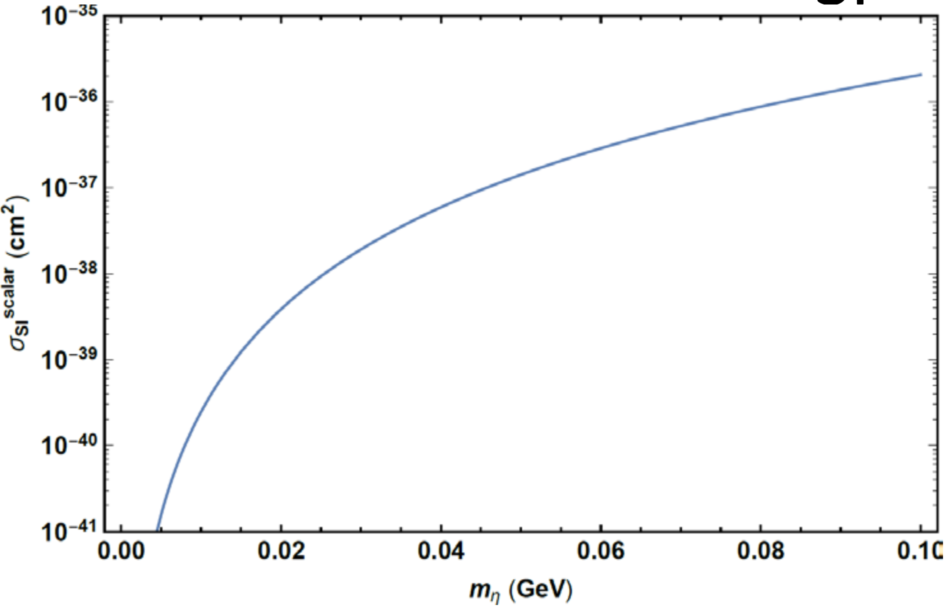


$m_{A'}$ = 55 MeV, V=10 GeV

differential cross section suppressed by $[1+(2m_A E_R/m_{\phi',A'}{}^2)]^{-2}$



DM-nucleon σ_{SI} (zero-mom. trans.)

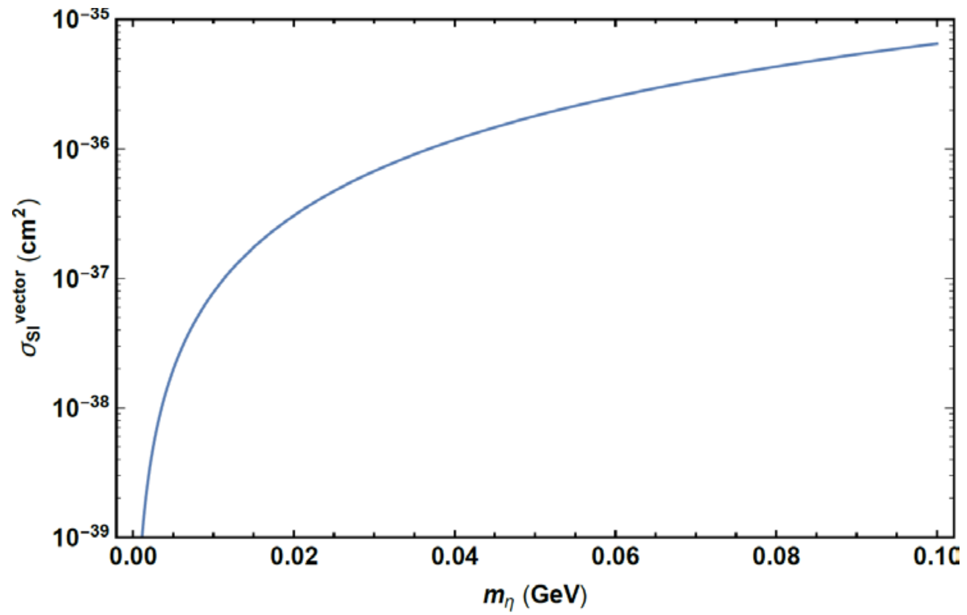


actual differential cross section suppressed by $[1+(2m_A E_R/m_{\phi',A'}{}^2)]^{-2}$

$$\sigma_{SI(0)}^{vector(p,n)} = \frac{\mu_{\eta N}^2}{16\pi V^4}$$

$$\delta = 0$$

V=10 GeV

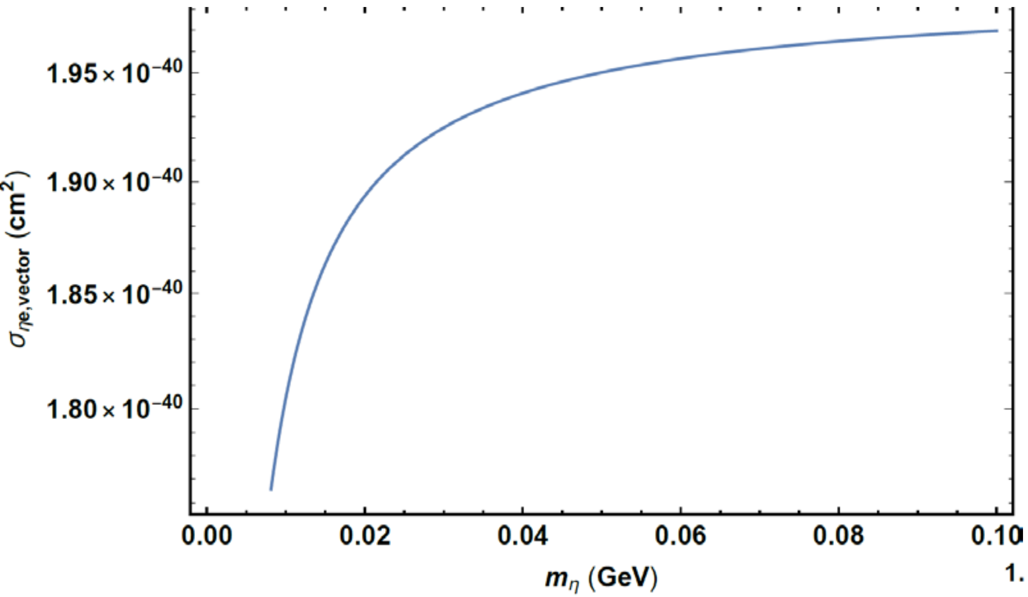


$m_{\phi'}$ = 200 MeV, V=10 GeV

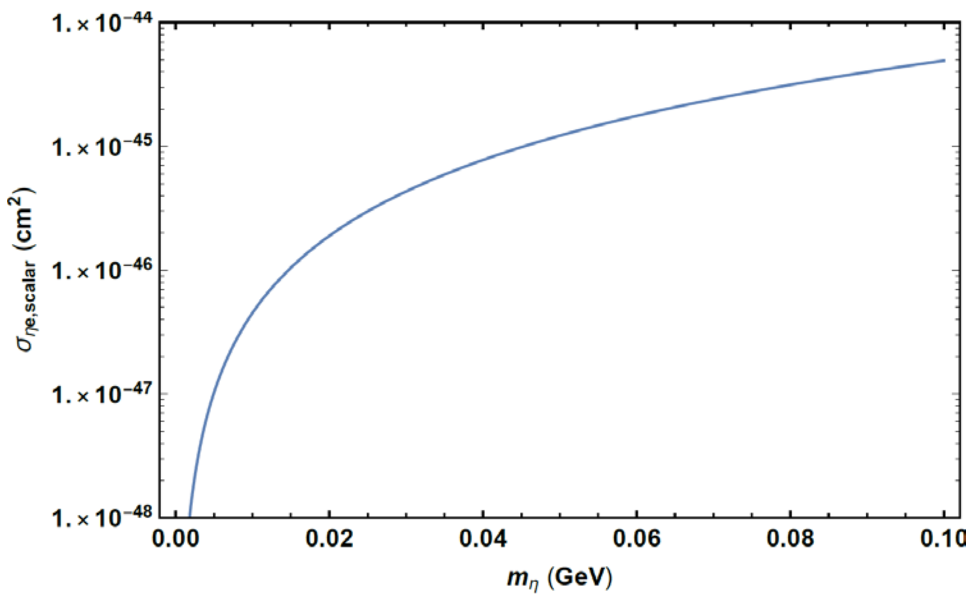
$$\sigma_{SI(0)}^{scalar(p,n)} = \frac{\mu_{\eta N}^2 m_\eta^2}{4\pi V^4 m_{\phi'}^4} f_{p,n}^2$$

$$f_{p,n} \propto m_N$$

DM-electron cross sections

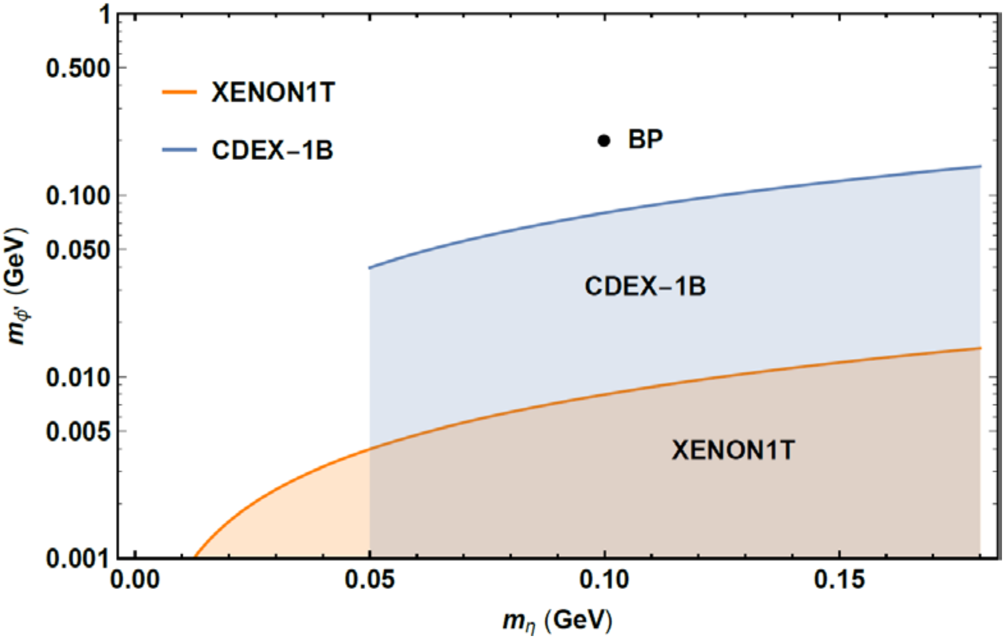


$m_{\phi'}$ = 200 MeV, δ = 0, V=10 GeV



at zero mass splitting and momentum transfer, A'-mediated scattering gets close to recent XENON1T bound (2E-40 cm^2, 1907.11485) but suppression from mass splitting can ease tension

exclusion contours

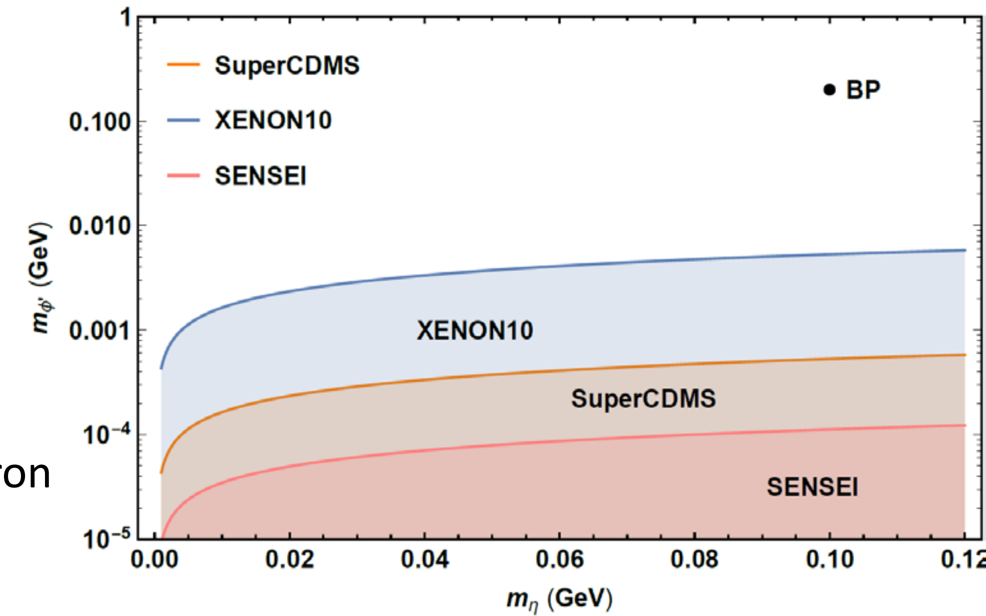


DM-nucleon

elastic scattering (ϕ'-mediated)

BP: $m_{\phi'}$=200 MeV, m_η=100 MeV, V=10 GeV

DM-electron



g-2 correction

- correction from ϕ' is positive, but correction from A' is negative
  - vector + axial
- as $m_{A'} \rightarrow 0$, coupling goes to zero and transverse polarizations decouple, but longitudinal polarization does not
  - becomes massless Goldstone mode of a global symmetry
  - g-2 correction becomes that of pseudoscalar with Goldstone's coupling
- all corrections go away as $m_\ell \ll m_{A'}$

$$\delta a_\ell = \frac{m_\ell^4}{16\pi^2 V^2}\int_0^1 \frac{(1-x)^2(1+x)}{(1-x)^2 m_\ell^2 + x m_{\phi'}^2} + \frac{m_\ell^2}{32\pi^2 V^2}\int_0^1 \frac{2x(1-x)(x-2)m_{A'}^2 - 2x^3 m_\ell^2}{x^2 m_\ell^2 + (1-x)m_{A'}^2}$$

constraint considerations

- $\ell=\mu$
  - $\phi'^{(*)} \rightarrow \gamma\gamma$ through a μ loop is always open, dominates if ν_s heavy enough
    - kills cooling bounds through off-shell ϕ', gives beam-dump bounds
  - $A' \rightarrow \gamma\gamma$ forbidden by Landau-Yang theorem
    - cooling through A' has to be killed by heavy A', weak coupling, or suppressed by heavy ν_s (coupling to ν_A is one-loop)
    - $A' \rightarrow e^+e^-$ proceeds through one loop kinetic mixing, but subdominant to $\nu_A \nu_A$
      - $A' \rightarrow \nu_A \nu_A$ allowed because of γ^5 coupling
      - gives beam dump bounds
- $\ell=e$
  - $\phi'^{(*)} \rightarrow e^+e^-$ tree-level, but suppressed by small coupling, beam dump bounds
  - $\phi'^{(*)} \rightarrow \gamma\gamma$ kills cooling bounds if ν_s is heavy enough to suppress invis. decay
  - $A' \rightarrow e^+e^-$ at tree-level gives beam dump bounds
  - if A' light enough, get cooling bounds from $A' \rightarrow \nu_A \nu_A$

direct detection

- ϕ' mediated → SI, velocity-independent, elastic, isospin-invariant
- A' mediated → SI, velocity-independent, inelastic, isospin-violating (IVDM)
  - opposite coupling to u and d (thus to p and n)
- mediator mass can be of the same order as momentum transfer
  - not a contact interaction, $d\sigma/dE_R$ suppressed by $[1+(2m_A E_R/m_{\phi',A'}^2)]^{-2}$
- current strategies for direct detection of low-mass DM
  - low threshold
  - Migdal effect – nuclear recoil results in electrons being kicked out
  - DM upscattered by cosmic ray interactions
    - boosted relativistic DM well above threshold (Bringmann, Pospelov -1810.10543; Dent, Dutta, Newstead, Shoemaker – 1907.03782)
  - DM-electron scattering (one-loop suppressed… not constraining)
- future experiments upcoming

direct detection

- current constraints (contact interaction, isospin-invariant, δ=0)
  - CRESST III → $\sigma_{SI} \sim 10^{-35}$ cm^2 at m_η = 200 MeV
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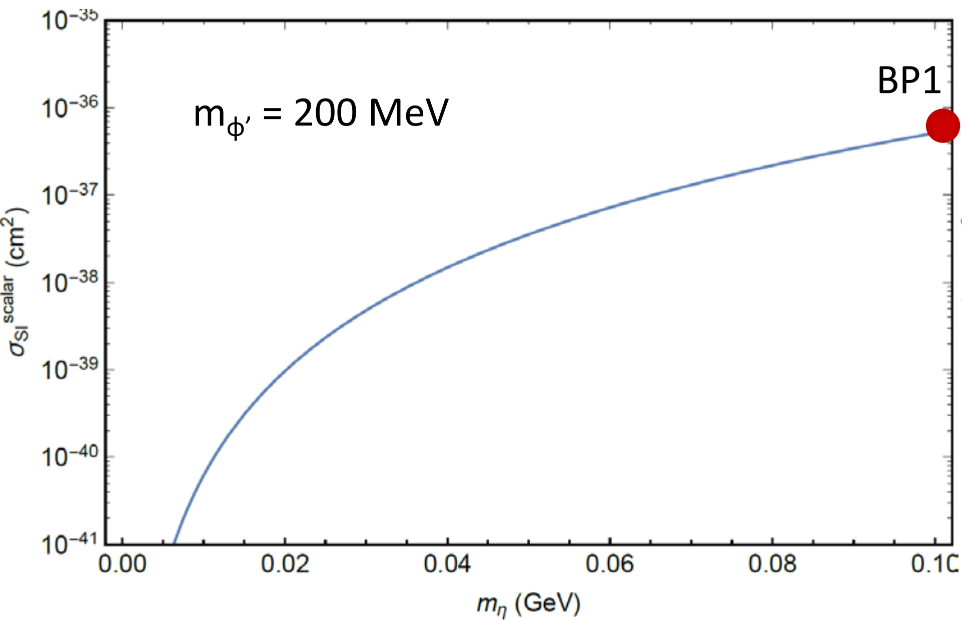
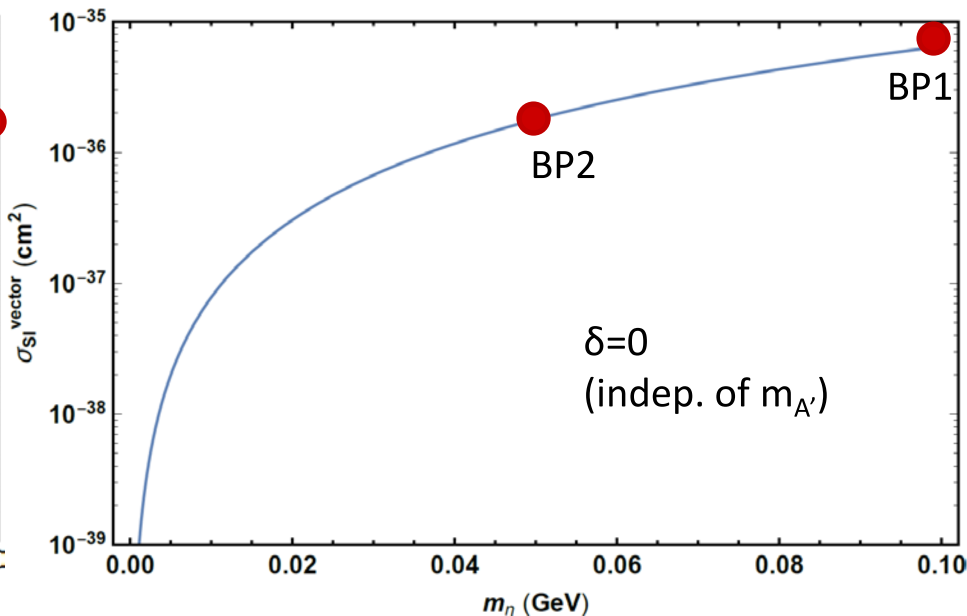




constraints

Batell, Freitas, Ismail, McKeen (1712.10022); Bauer, Foldenauer, Jaeckel (1803.05466)

- but lots of constraints on A', ϕ' coupling to SM fermions
  - couplings fixed in terms of masses and V
- main differences between our scenario and others
  - no coupling to $\bar{\nu}_L \nu_L$ (ν_R/ν_A mixing taken small),
    - suppresses ν experiment and astrophysical cooling constraints when ν_A involved
  - no direct coupling to e
    - some e^+e^- collider constraints suppressed at one-loop
  - chiral coupling of A' to SM fermions
    - even at weak coupling ($g_{T3R} \rightarrow 0$), longitudinal mode (Goldstone) does not decouple
- g_μ-2 corrections from ϕ' (positive) and A' (negative) running in loop
  - corrections can be fine-tuned against each other or heavy new physics
  - even weakly coupled A' contributes to g-2 via massless Goldstone mode

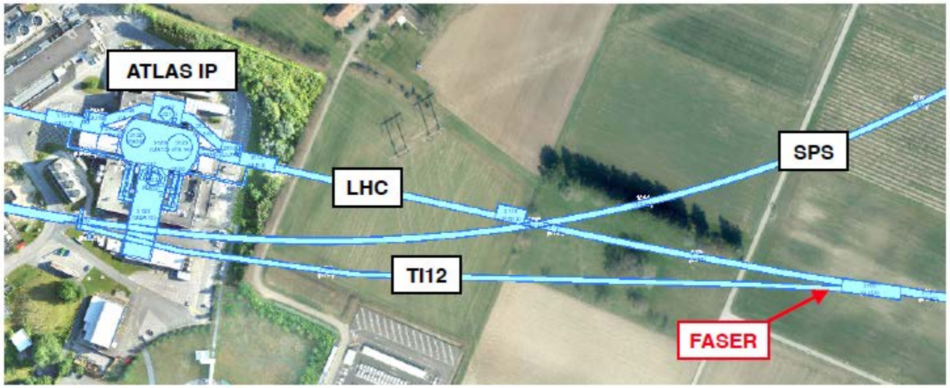
constraints

- main constraints
  - e^+e^- → 4μ (BaBar)
  - fixed target/beam dump exps.: A′,ϕ′ → γγ, e^+e^- (E137, E774, E141, Orsay, etc.)
  - solar/SN/Glob. Cluster cooling constraints (production of A′, ϕ′)
  - fifth force constraints → constrains light mediators
    - when A′ light, longitudinal mode still coupled like a Goldstone boson
  - BBN/CMB → need ΔN_{eff} small ($\lesssim 0.5$)

- we'll take V = 10 GeV, and will find restrictions on $m_{\phi'}$ and $m_{A'}$
  - not much dependence on dark matter mass
  - take neutrino mixing angle small
  - take $m_{\nu s} > 10$ MeV also (doesn't affect N_{eff})
  - take $m_\eta > 40$ MeV (freezeout before BBN, doesn't affect N_{eff})

future experiments

- laboratory production of A’, ϕ’
  - FASER, SHiP, SeaQuest, Mathusla
  - DUNE, COHERENT, CCM
  - LDMX
  - NA64μ
  - COMPASS



FASER (1811.12522)

- dark matter direct detection
  - LZ, CDEX
  - SuperCDMS, CRESST, NEWS-G
  - LBECA, SENSEI

LZ

laboratory production

- produce A', ϕ' from a p beam
  - FASER, SHiP, SeaQuest, Mathusla
    - detect visible decay at distant detector
  - DUNE, COHERENT, CCM
    - decay to DM, which scatters in distant detector
- NA64μ → A', ϕ' produced by μ-beam, and decay invisibly
- LDMX → electrons scattering off nuclei, producing MET
- reanalysis of COMPASS data
  - muon beam strikes a thin target

- plots in progress!

direct detection

- need to account for DM mass splitting for A'-mediated case
  - not such a big effect for CR-upscattering, since already above threshold
  - more important for low-threshold searches
- new solid-state detectors can lower thresholds further
- when detectors are within reach of models, need to address recoil spectrum (non-contact interaction) and isospin violation

- analysis in progress!

electron coupling

- what if the electron is coupled to $U(1)_{T3R}$, not muon?
- basic problem is A'
  - if low-mass, ruled out by constraints on N_{eff} (preliminary)
  - if higher-mass, decays early, but ruled out by atomic parity violation experiments
  - right-handed coupling violates parity
- can potentially fine-tune this away, either by cancelling against new physics, or scaling up V
- other constraints modified by direct coupling to e
- DM-electron scattering becomes more important

- future work to expand on this....