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

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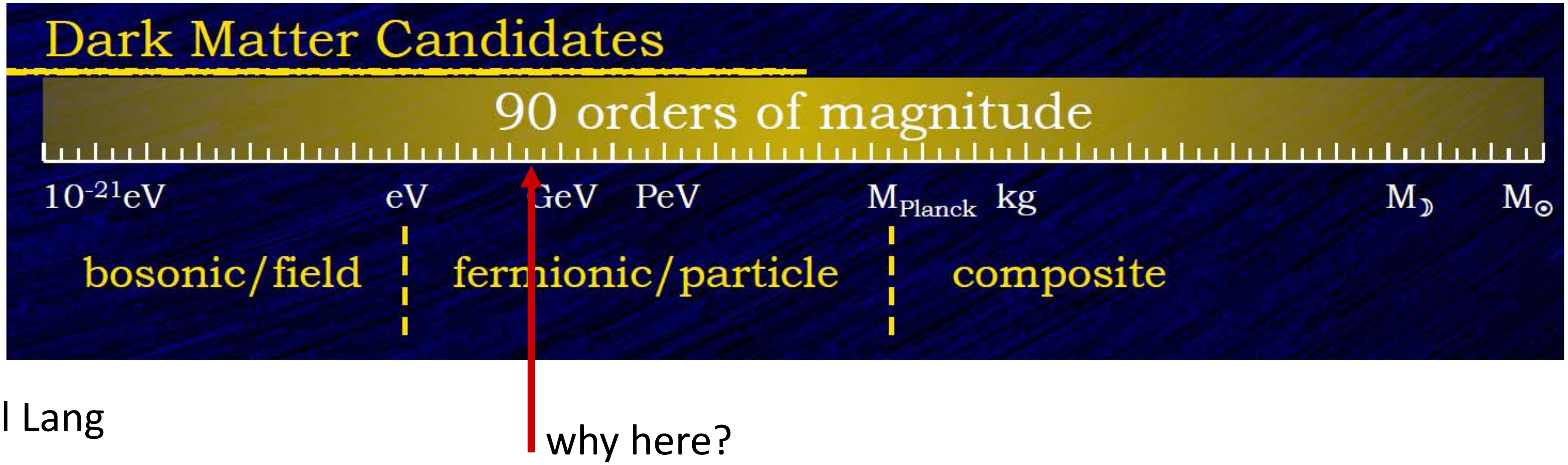
low-mass dark matter

- 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?



Rafael Lang

why here?

why MeV?

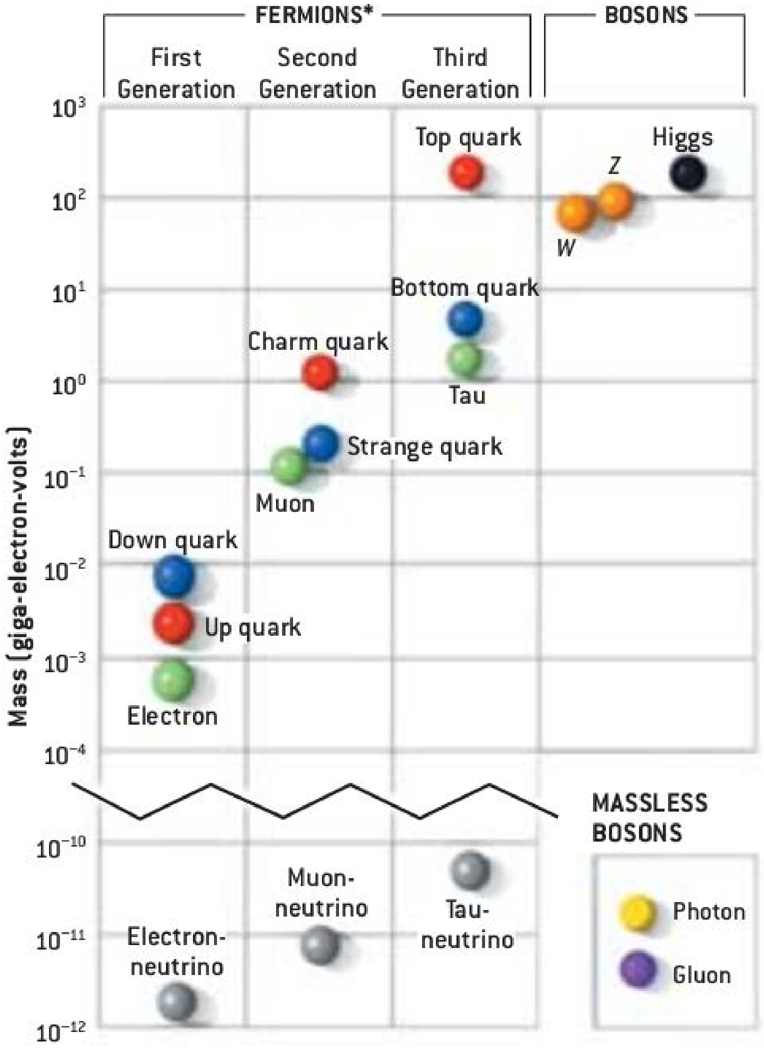
- analogous to the WIMP miracle
  - mechanism for getting TeV-scale particle to have the correct relic density…
  - … and a reason why a new TeV scale particle should arise (new physics associated with EWSB)

- reason for having a particle at the MeV scale?...

- … light flavor physics

measuring scales

- 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 $\mathrm{Tr}\,[\sigma_3]$ and $\mathrm{Tr}[(\sigma_3)^3]$ → 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

blessings and curses

- among choices of new U(1), this makes U(1)$_{T3R}$ special …
- … because symmetry protects fermion masses, dark Higgs must couple to visible sector
- that gives us a few unique phenomenological features
- necessarily have two mediators coupling to SM… dark photon and dark Higgs
- necessarily have reasonably large coupling to dark Higgs and Goldstone mode (longitudinal mode of dark photon)
  - enhancement to production modes
  - but also stronger constraints
  - constrained model… can’t run away to weak coupling
  - possible to rule in or out definitively

game plan

- this is a general framework, but we'll develop an explicit example

- lots of constraints, but open parameter space available
  - upcoming experiments can close most parameter space, but not all

- 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 (p-wave or co-annihilation)

model

- $q^u{}_R$, $q^d{}_R$, ℓ_R, and ν_R → $Q_{T3R} = \pm 2$
  - 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 $\propto V$
  - 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

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

$\tilde{H} \equiv i\sigma_2 H^*$, 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}, $m_{1,2}$, $m_{A'}$, $m_{\phi'} \lesssim V$
- smaller V → lighter DM, with stronger coupling to SM
- taking $V \sim$ 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
  - 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 tuned against each other or heavy new physics
  - even weakly coupled A’ contributes to g-2 via massless Goldstone mode

constraints

- main constraints
  - solar/SN/Glob. Cluster cooling constraints (production of A', $\phi' \rightarrow$ invisible)
  - BBN/CMB → need ΔN_{eff} small ($\lesssim 0.5$)
  - $e^+e^- \rightarrow 4\mu$ (BaBar), anomalous π, η decay (Crystal Barrel)
  - fixed target/beam dump/collider exps.: $A', \phi' \rightarrow \gamma\gamma$, e^+e^- at displaced detector
  - fixed target/beam dump/collider exps.: $A', \phi' \rightarrow$ missed at nearby detector
  - fixed target/beam dump/collider exps.: $A', \phi' \rightarrow$ invisible particles scattering at distant detector
  - fifth force constraints → constrains light mediators

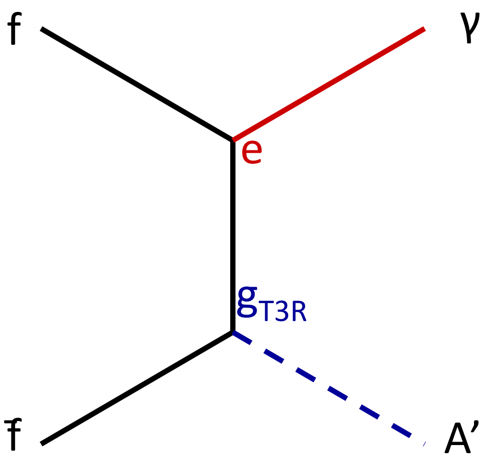
- we'll take $V = 10$ GeV, and will find restrictions on $m_{\phi'}$ and $m_{A'}$
  - not much dependence on dark matter mass
  - take neutrino mixing angle small

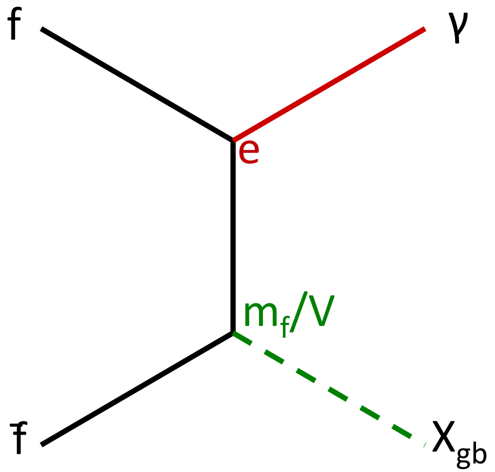
N_{eff} and $U(1)_{T3R}$

- 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 muons
  - 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 $V > \mathcal{O}(10^6)$ GeV
  - result of coupling to chiral fermions

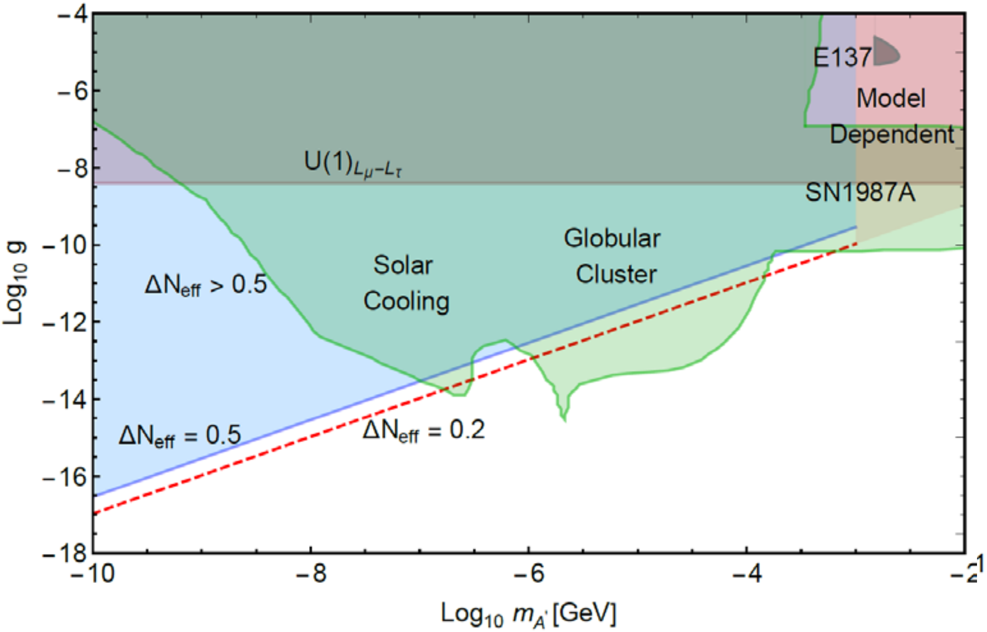
N_{eff} and chiral fermions

- 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



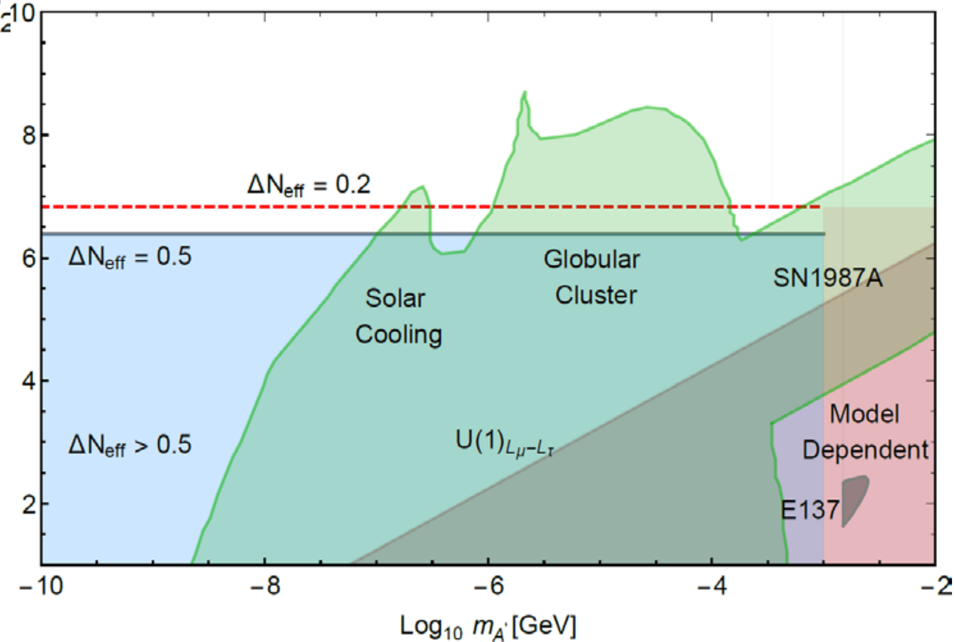
L_μ- L_τ is from Escuedero, Hooper, Krnjaic, Pierre (1901.020210, purple)

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

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

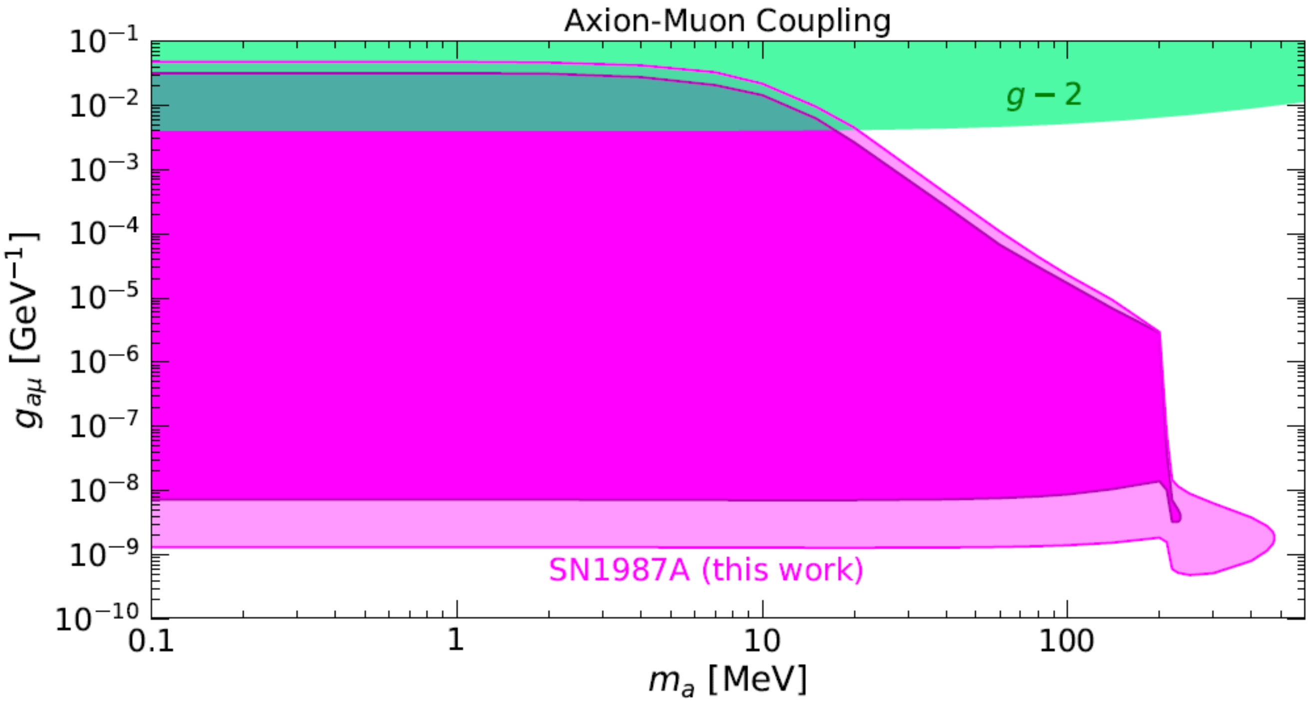
$$\langle \sigma v \rangle_{T=m_f} \eta > H$$

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)



updated bounds from SN1987A

- updated bounds based on direct production from muons in supernovae
- upshot (Bollig, DeRocco, Graham, Janka, 2005.07141; Croon, Elor, Leane, McDermott 2006.13942)
  - new estimates of SN eos indicate higher temperature, so muons produced
  - couple to dark Higgs and Goldstone mode, so they are produced
  - if they decay to invisible states, too much SN cooling



Croon, Elor, Leane, McDermott, 2006.13942

cosmological and astrophysical bounds

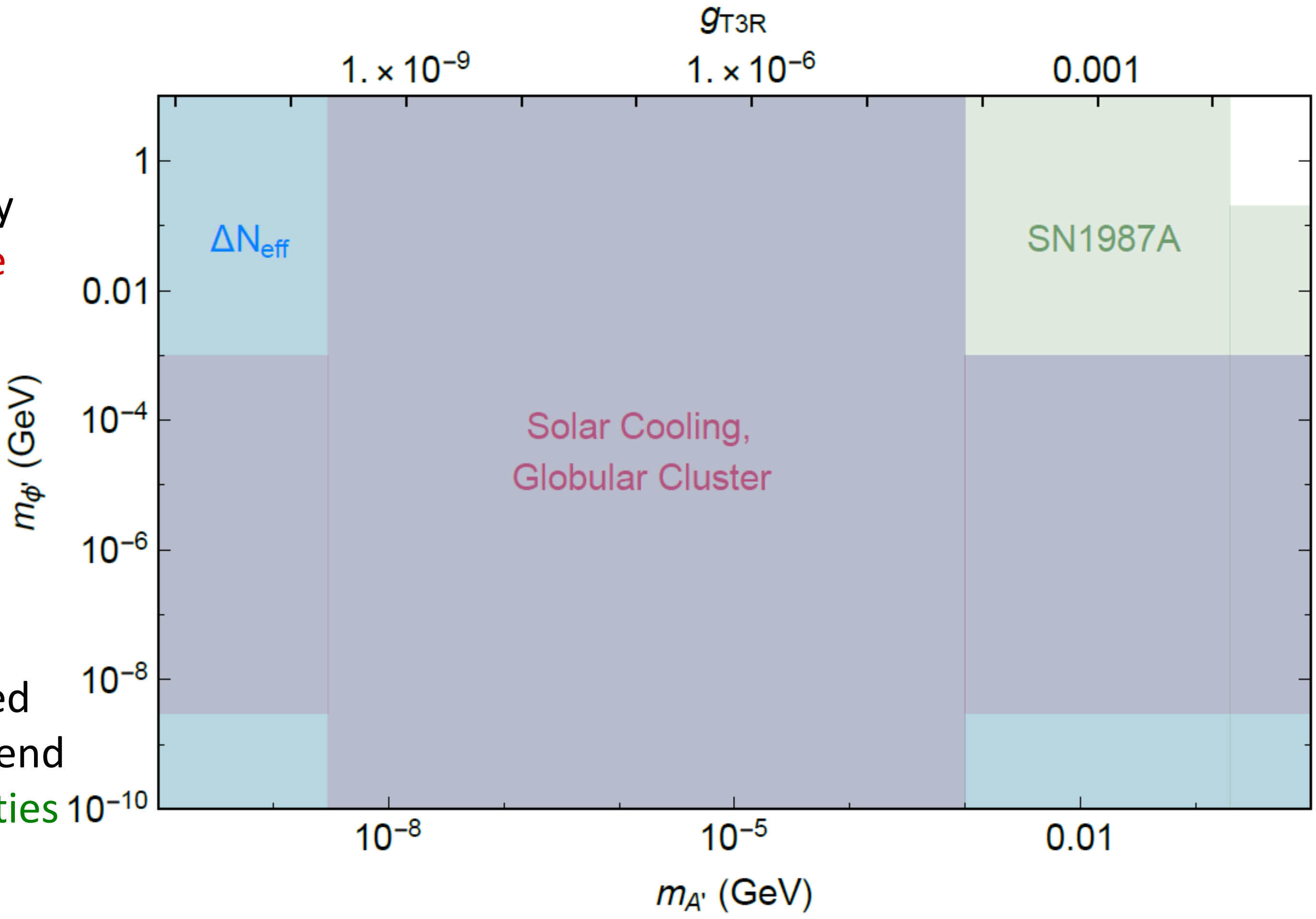
assume m_η, m_ν > 10 MeV, (N_{eff})

tight bounds if A’, ϕ’ decay to invisible states, but one can get around them….

N_{eff} bound goes away if reheat temperature is below 100 MeV…

cooling bounds can be killed by chameleon effects, depend on astrophysical uncertainties

Invisible final states: Astrophysical/cosmological bounds



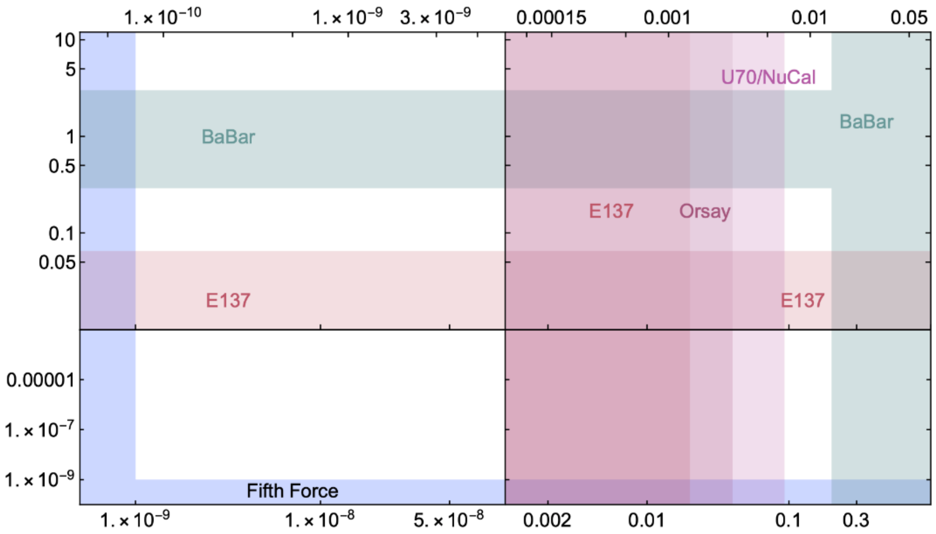
so it’s worth it to look at laboratory probes of this region of parameter space also….

visible decays at displaced detectors

- $\phi' \rightarrow \gamma\gamma$ is always prompt, so no signal at a displaced detector
- $A' \rightarrow \gamma\gamma$ is forbidden (Landau-Yang theorem)
- $A' \rightarrow e^+e^-$ occurs at one-loop though kinetic mixing
  - may dominate branching fraction if $A' \rightarrow \eta\eta, \nu\nu$ (tree-level) are not kinematically allowed
  - may have a long decay length, if kinetic mixing is small enough

- we'll assume no tree-level kinetic mixing
- current and upcoming experiments sensitive to displaced $A' \rightarrow e^+e^-$ if $m_{A'}$ is not too large
- larger $m_{A'} \rightarrow$ larger $g_{T3R} \rightarrow$ shorter decay length → doesn't reach detector

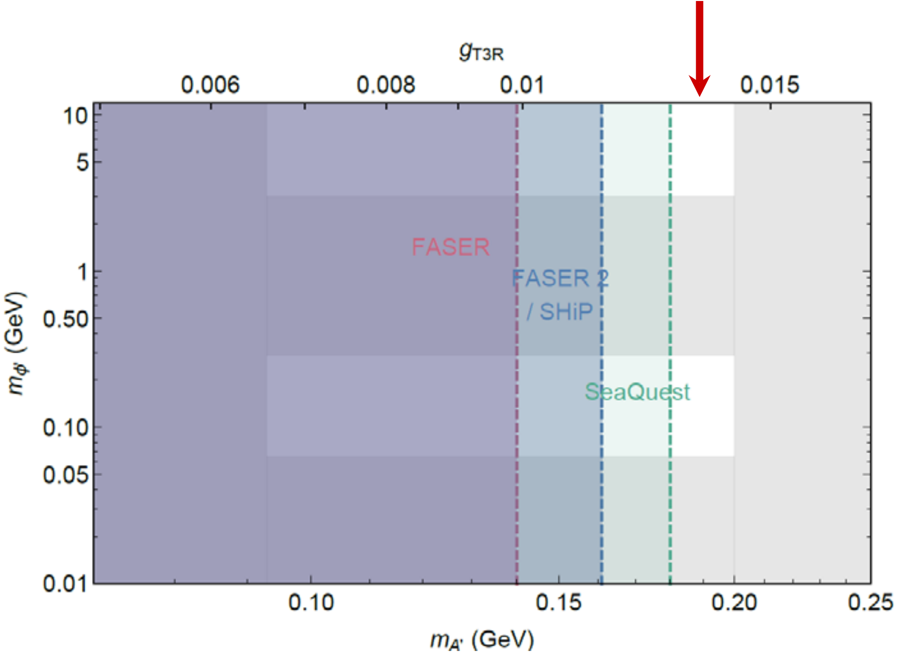
constraints for visible states



$m_{A'}$ = 180-200 MeV → won't be probed by these experiments

maybe DUNE near detector? repurposing neutrino scattering experiments?

two-body visible decays not allowed if $m_{A'} < 1$ MeV



missing energy at nearby detectors

- two ways to see missing energy
  - tree-level decays to invisible states (if kinematically allowed)
  - delayed decays to visible states (decays outside detector)
- strongest constraints from experiments with muons
  - can probe small $m_{A'}$ regime with longitudinal polarization coupling
- NA64μ
- LDMX-M^3

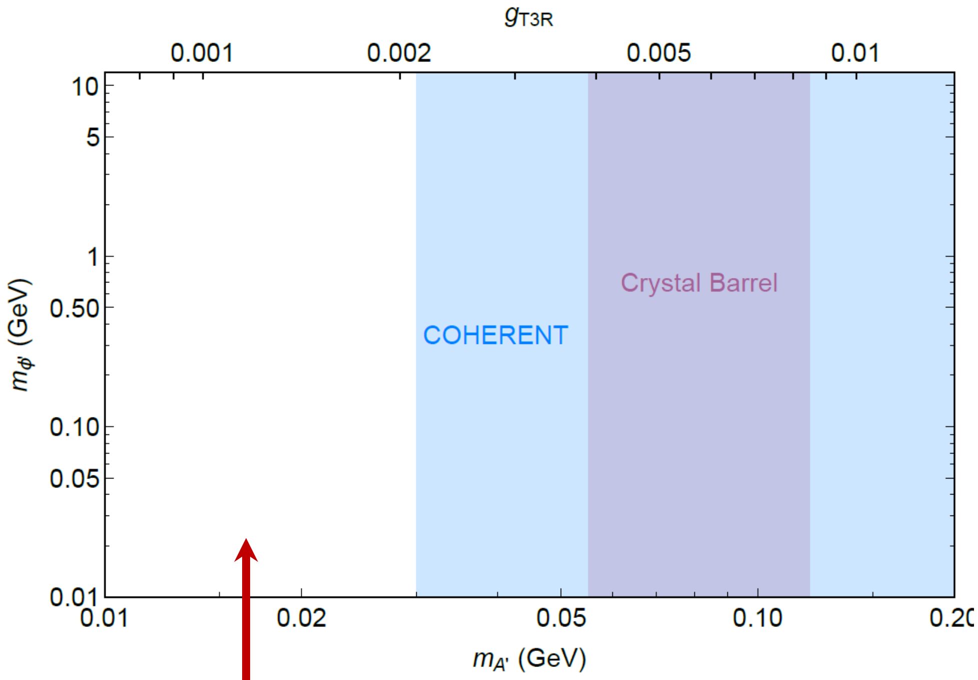
- basic upshot → they are sensitive to all models with invisible final states, because mediators couple to muons with strength ~ 0.01
  - longitudinal polarization A' has the same coupling (Goldstone)
- for visible states, not competitive

scattering at distant detectors

- if decays produce invisible states, they can scatter at distant detectors
  - backgrounds from neutrinos produced by stopped pion decay
  - distinguish by energy spectrum (higher energy) and timing (prompt)
- COHERENT searches for this….
- will focus on A’, since production rates have been computed (pion decay, bremsstrahlung)
- sets bounds….
- but COHERENT also sees a 2.4-3σ excess
  - Dutta, Kim, Liao, Park, Shin, Strigari (1906.10745, 2006.09386)
  - CsI detector (sig. depends on neutron distribution)
  - can explain if $m_{A'} \sim 30$ MeV
- rate scales as $m_{A'}^6$

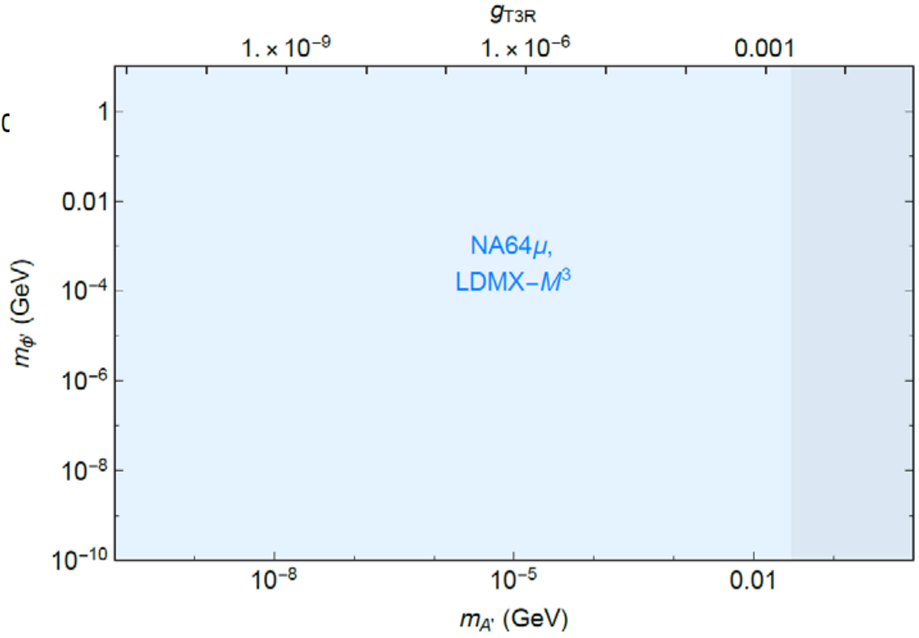
COHERENT CsI detector
COHERENT website

constraints for invisible states



this region can survive current bounds if the astrophysical/cosmological bounds are relaxed by evading assumptions …

… but will be probed by future laboratory experiments

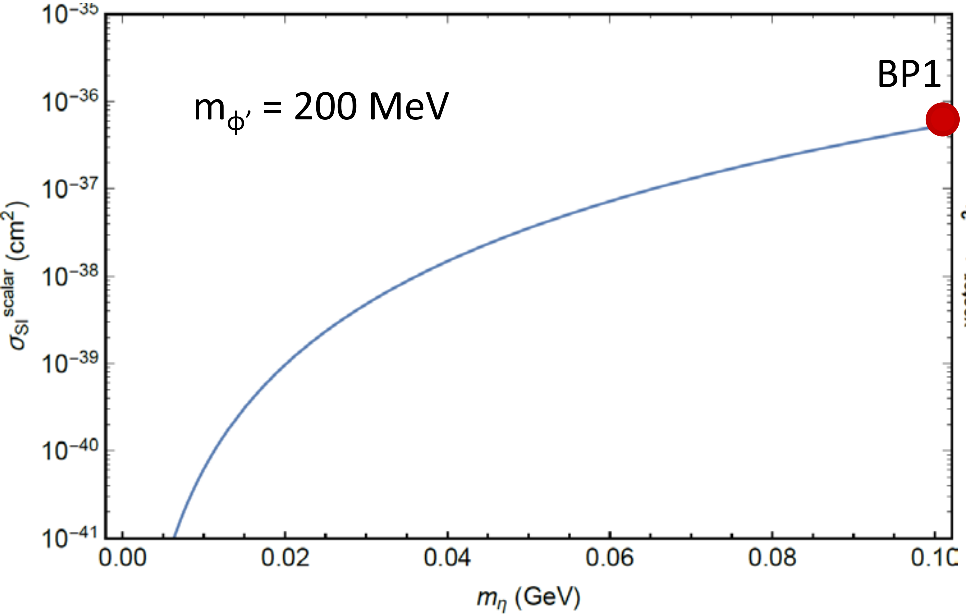


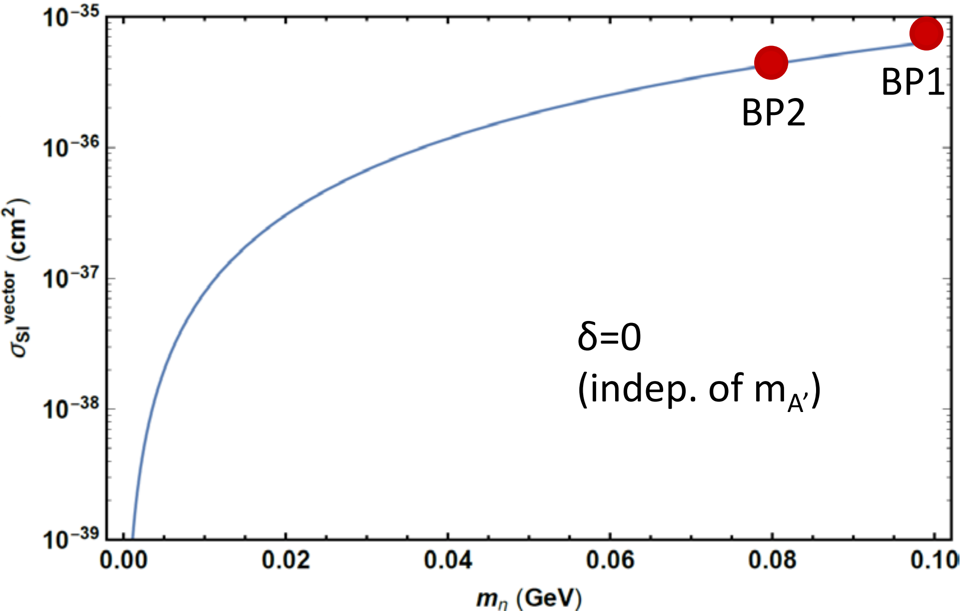
direct detection

- 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
  - CDEX-1B → $\sigma_{SI} \sim 10^{-32\text{-}34}$ cm^2 at m_η = 50-180 MeV
  - XENON1T → $\sigma_{SI} \sim 10^{-29\text{-}30}$ cm^2 over full mass range, up-scattering
    - $\sigma_{SI} \sim 10^{-34}$ cm^2 at m_η = 100 MeV (Migdal effect, 1907.12771)
- benchmark models satisfy all bounds





thermal relic density

- main relevant annihilation channels are s-channel through ϕ' or A'
- a thermal relic cross section would naively violate Planck bounds
- a few 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
- if $m_\eta < m_\mu$, final states particles will be light ($\gamma\gamma$, e^+e^-, etc.)
- ϕ' coupling suppressed by mass of incoming/outgoing particles, or loop
  - 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
  - demand η_2 decay before recombination

two benchmark models

	$m_{A'}$(MeV)	$m_{\phi'}$(MeV)	m_{η}(MeV)	m_{ν_s}(MeV)	$m_{\nu D}$(MeV)	$\langle \sigma v \rangle$ (cm^3/s)	$\sigma_{SI}{}^{S}$ (pb)	$\sigma_{SI}{}^{V}$ (pb)
BP1	95	200	100	10	10^{-3}	3×10^{-26}	0.51	6.50
BP2	125	10^4	80	10	10^{-3}	3×10^{-26}	3.5×10^{-8}	4.32

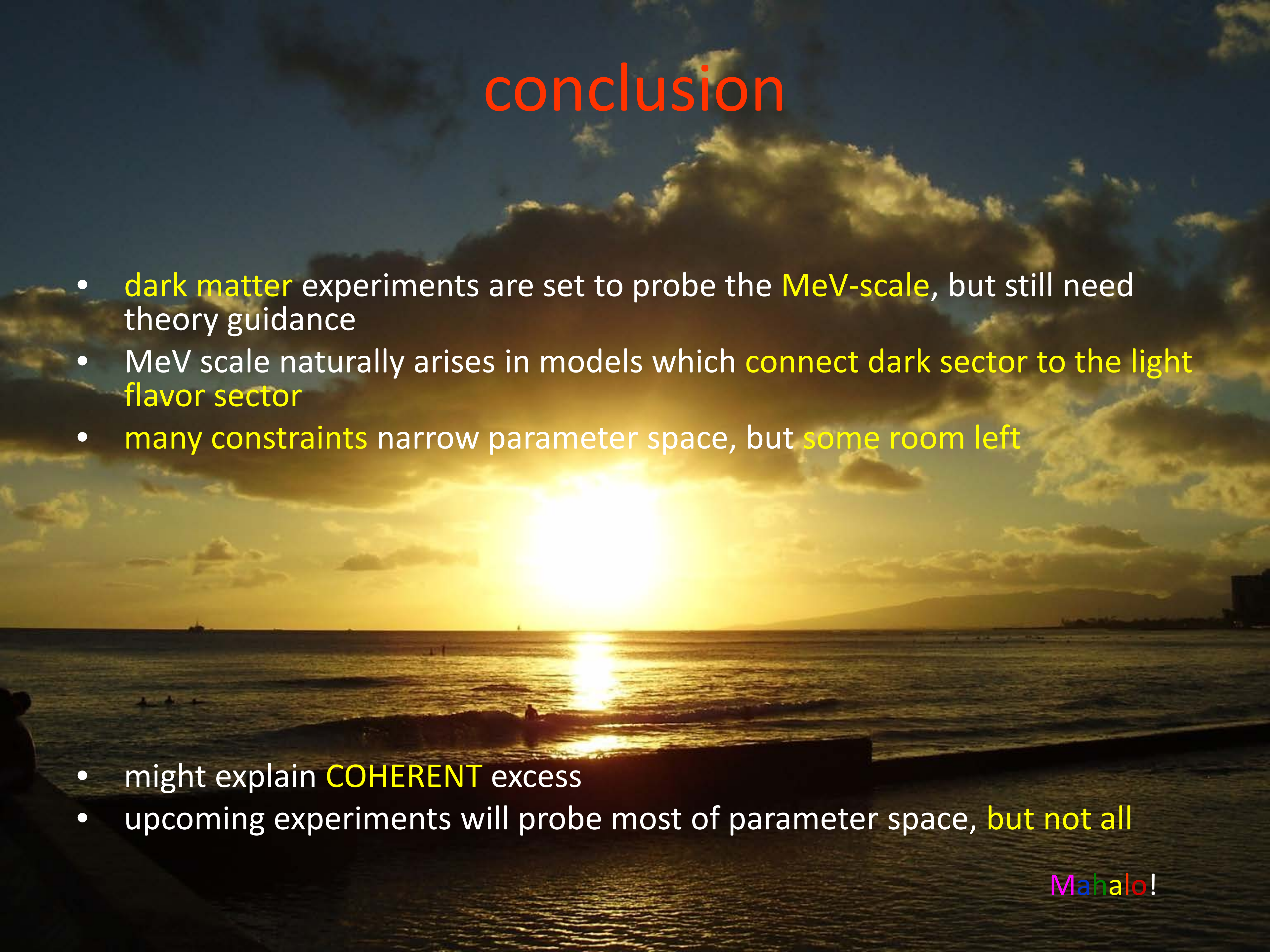
- first benchmark get relic density via ϕ’ resonance
  - a_μ corrections (A’/ϕ’) need to be tuned against new physics to 1%

- 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^- final state (one-loop) can be non-negligible, but rate suppressed if heavier state gone before recombination
    - if splitting small enough (< $\mathcal{O}(1)$ 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 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

- might explain COHERENT excess
- upcoming experiments will probe most of parameter space, but not all

Mahalo!

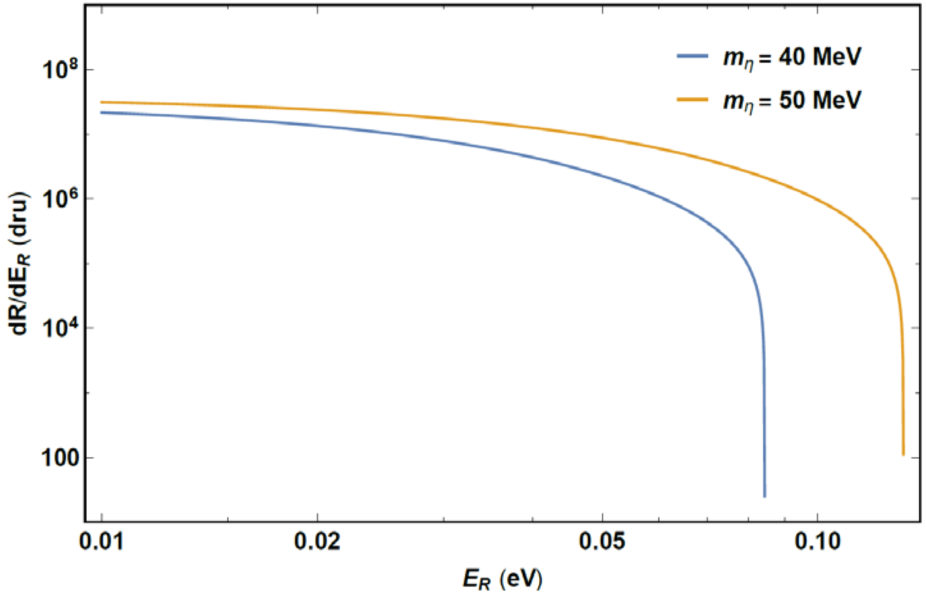
Backup Slides

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} (2002.01137)
  - 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

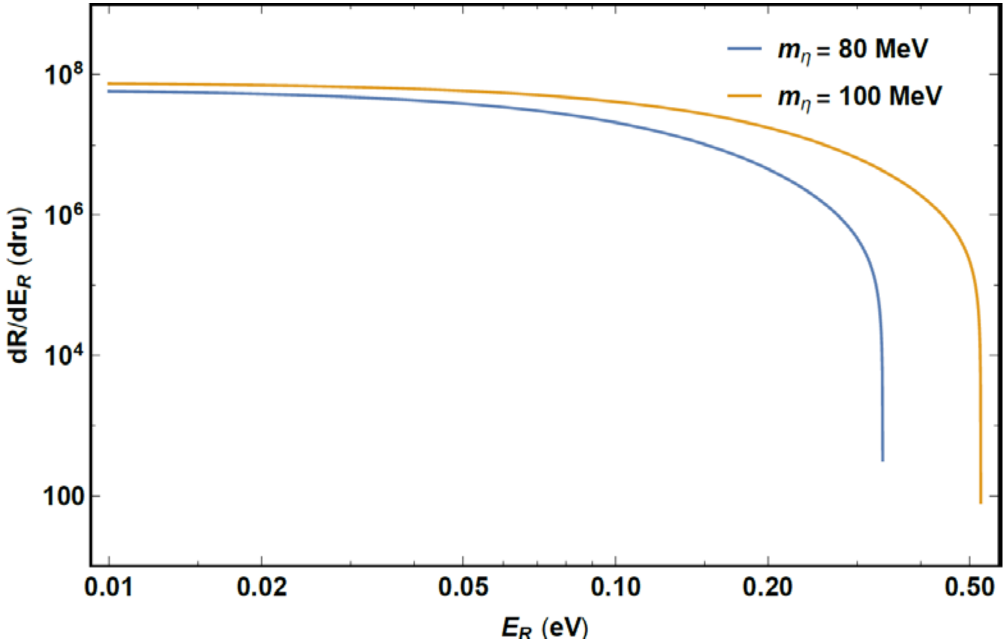
- future work to expand on this….

elastic scattering rates

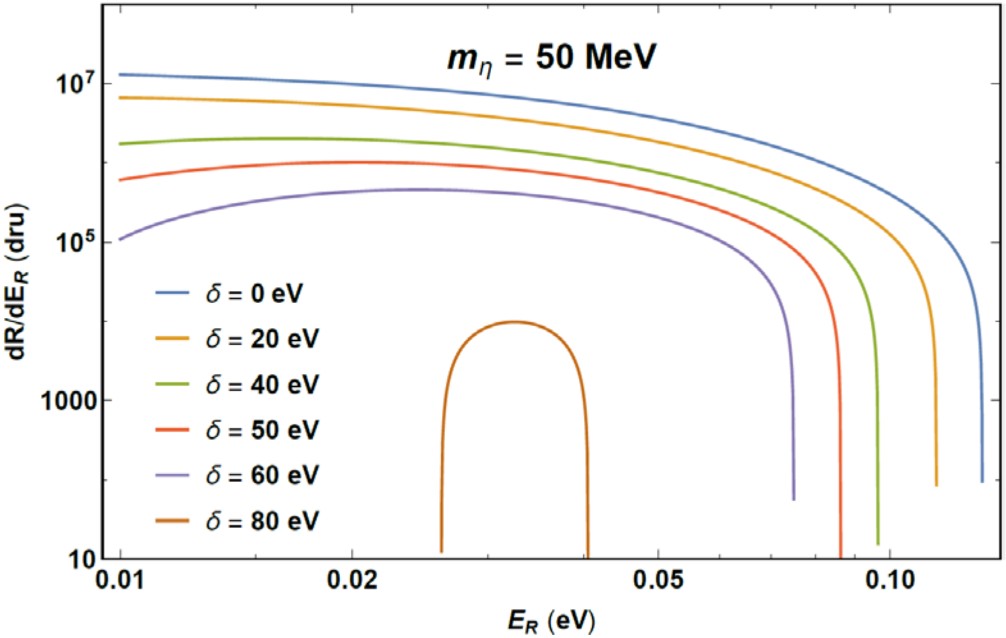


$m_{\phi'}$ = 200 MeV, V=10 GeV

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

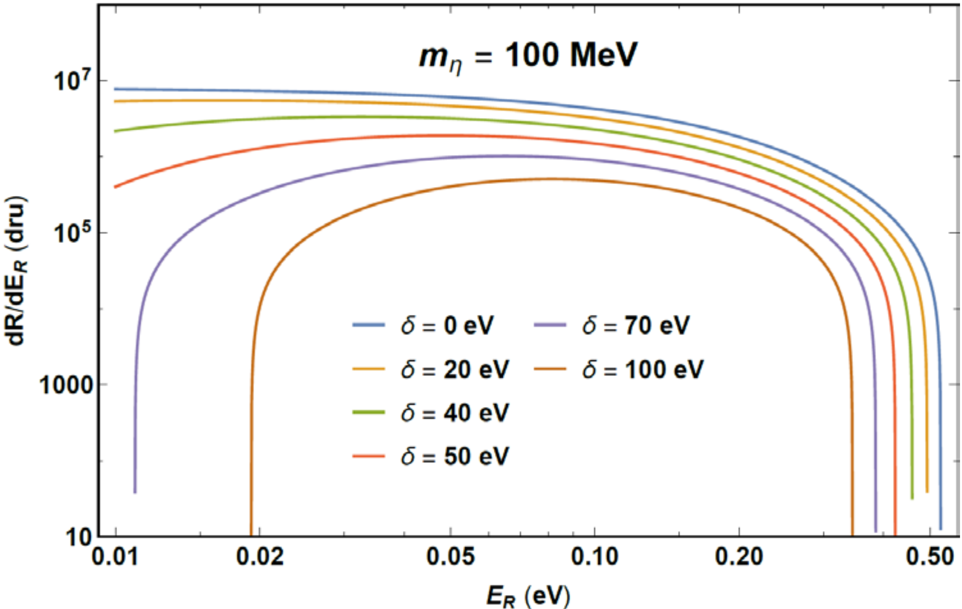


inelastic scattering rates

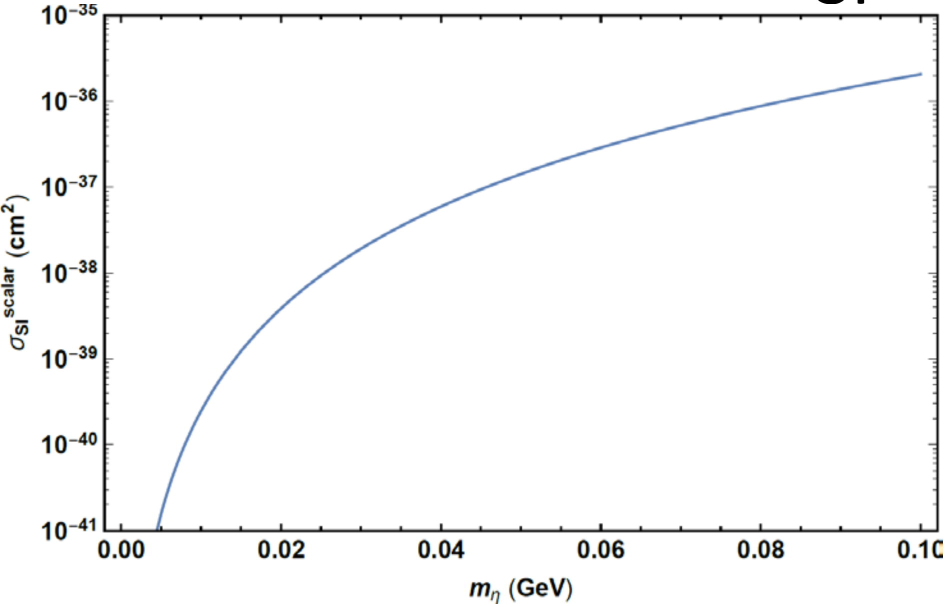


$m_{A'}$ = 55 MeV, V=10 GeV

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



DM-nucleon σ_{SI} (zero-mom. trans.)



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

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

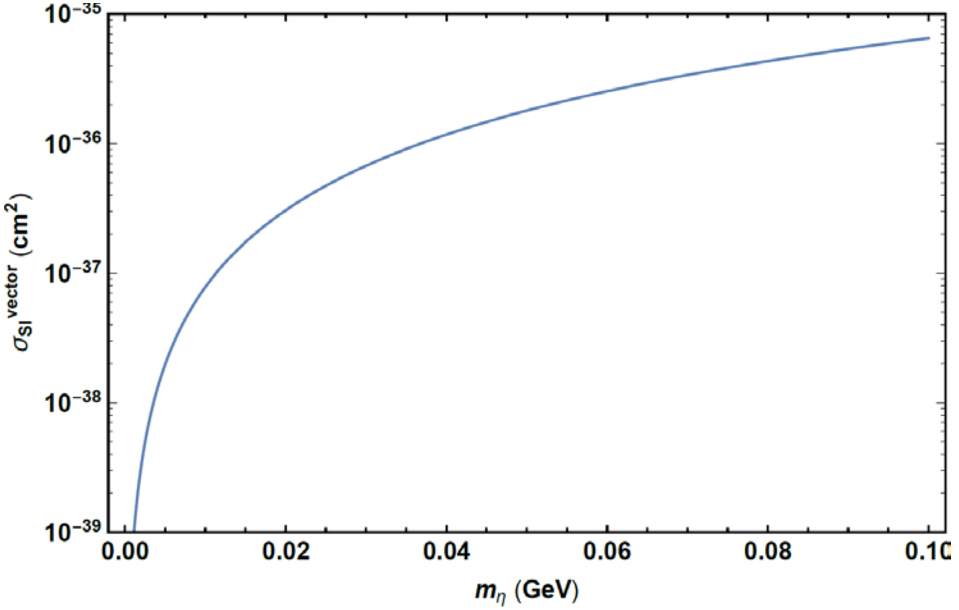
$$f_{p,n} \propto m_N$$

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

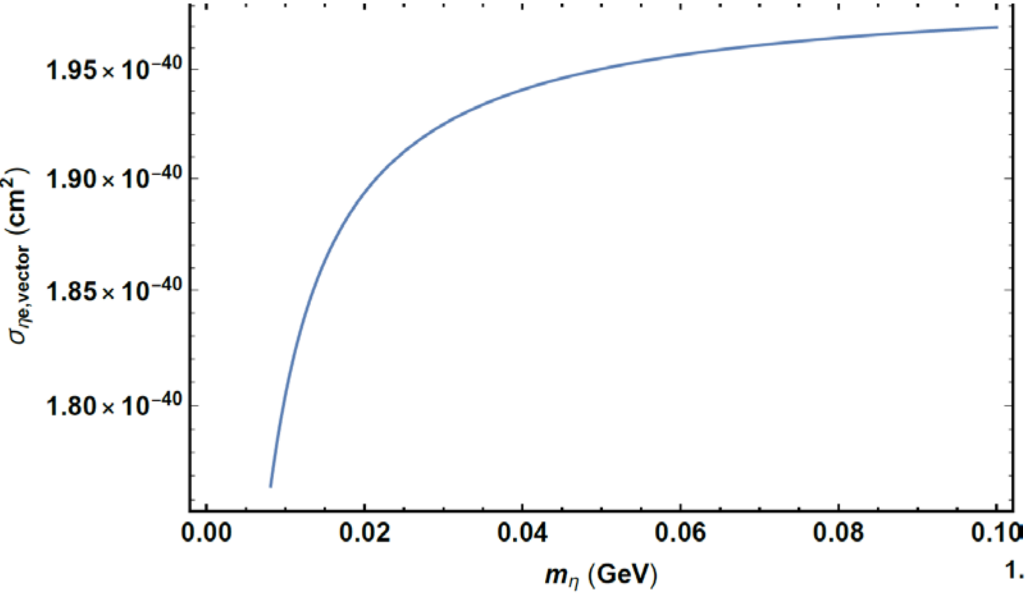
$$\sigma_{SI(0)}^{vector(p,n)} = \frac{\mu_{\eta N}^2}{16\pi V^4}$$

$$\delta = 0$$

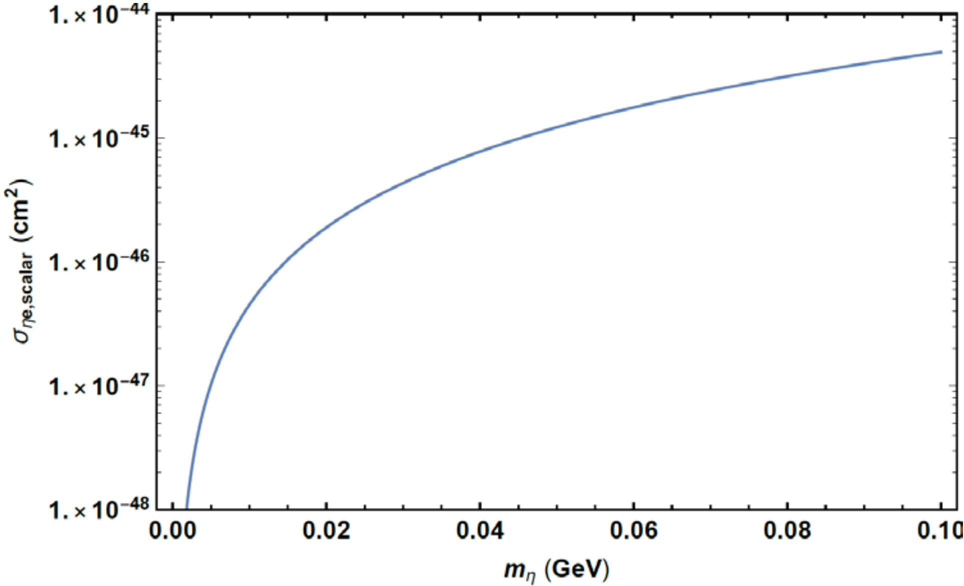
V=10 GeV



DM-electron cross sections

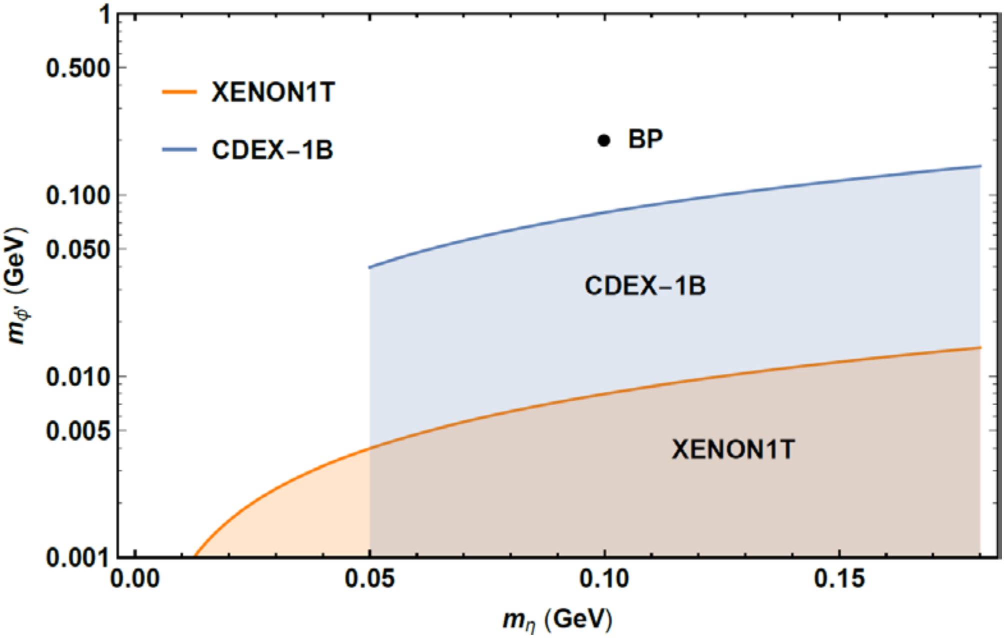


$m_{\phi'}$ = 200 MeV, δ = 0,
V=10 GeV



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

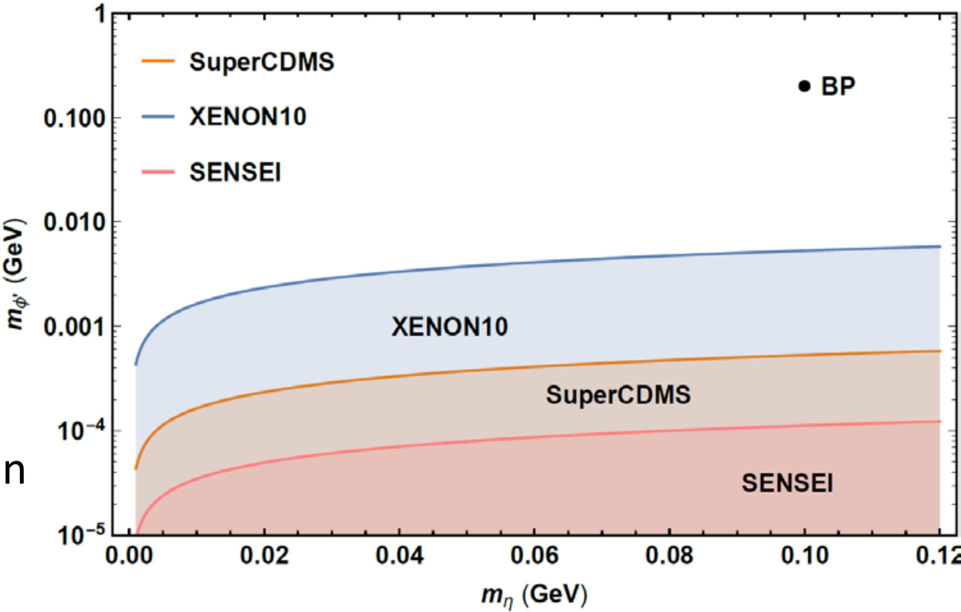


DM-nucleon

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 $m_{A'}$ → 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

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