$U(1)_{T3R}$ model with light mediators

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and arXiv:2105.07655

w/ Bhaskar Dutta, Jason Kumar and Peisi Huang

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Low Mass Dark Matter Model

- Is there any reason to have a new particle at the $\mathcal{O}$(1-100) MeV range?
  - the mass scale associated with the two lightest flavor sector of SM is $\mathcal{O}(1-100)$ MeV
  - analogous to WIMP miracle, if the new physics is related to the light flavor sector of SM, then the DM arises from the new physics will also lie at that scale
  - the new physics can address the Yukawa sector hierarchy in the light flavor sector.

- Our strategy → connect the dark sector to the light flavor sector of SM through a dark photon/Higgs interactions for right handed SM fermions using a new U(1) gauge group

Dark Matter Model Setup

- Implementation → add a new gauge group $U(1)_{T3R}$ (Pati,Salam 74; Mohapatra,Pati 75)
  - couples to the right handed fermions : μ_R, ν_R, u_R, d_R
  - up-type and down-type particles having opposite charges
  - by construction free of all gauge and gravitational anomalies
  - add a fermion pair $\eta_{L,R}$ charged under $U(1)_{T3R}$ and SM singlet: DM candidate
- Yukawa sector needs dark Higgs (ϕ) insertion: protect fermion masses
  - it gets vev V and breaks $U(1)_{T3R}$ down to Z_2 parity
  - only η's are odd under parity: DM
  - $m_f, m_\eta, m_{\phi'}, m_{A'}$ scale as V: A' is the dark photon
  - V = 10 GeV makes all of them sub-GeV

Model Features

- Two light mediators: A' and ϕ'
  - ϕ' coupling to SM fermion is $\propto m_f/V$, A' coupling to SM fermion is $\propto m_{A'}/V$
- Direct detection: satisfy current constraints
  - ϕ' mediated: SI, elastic, isospin-invariant
  - A' mediated: SI, inelastic, isospin-violating
- Relic density: Consistent with Planck bound
  - annihilation through ϕ' resonance (p-wave suppressed)
  - co-annihilation via A'

Constraints

- Qualitatively new constraint: As $U(1)_{T3R}$ couple to chiral fermions, the tree level production of A' longitudinal modes can be enhanced.

- Tightly constrained, but satisfy all the current constraints- open parameter space available

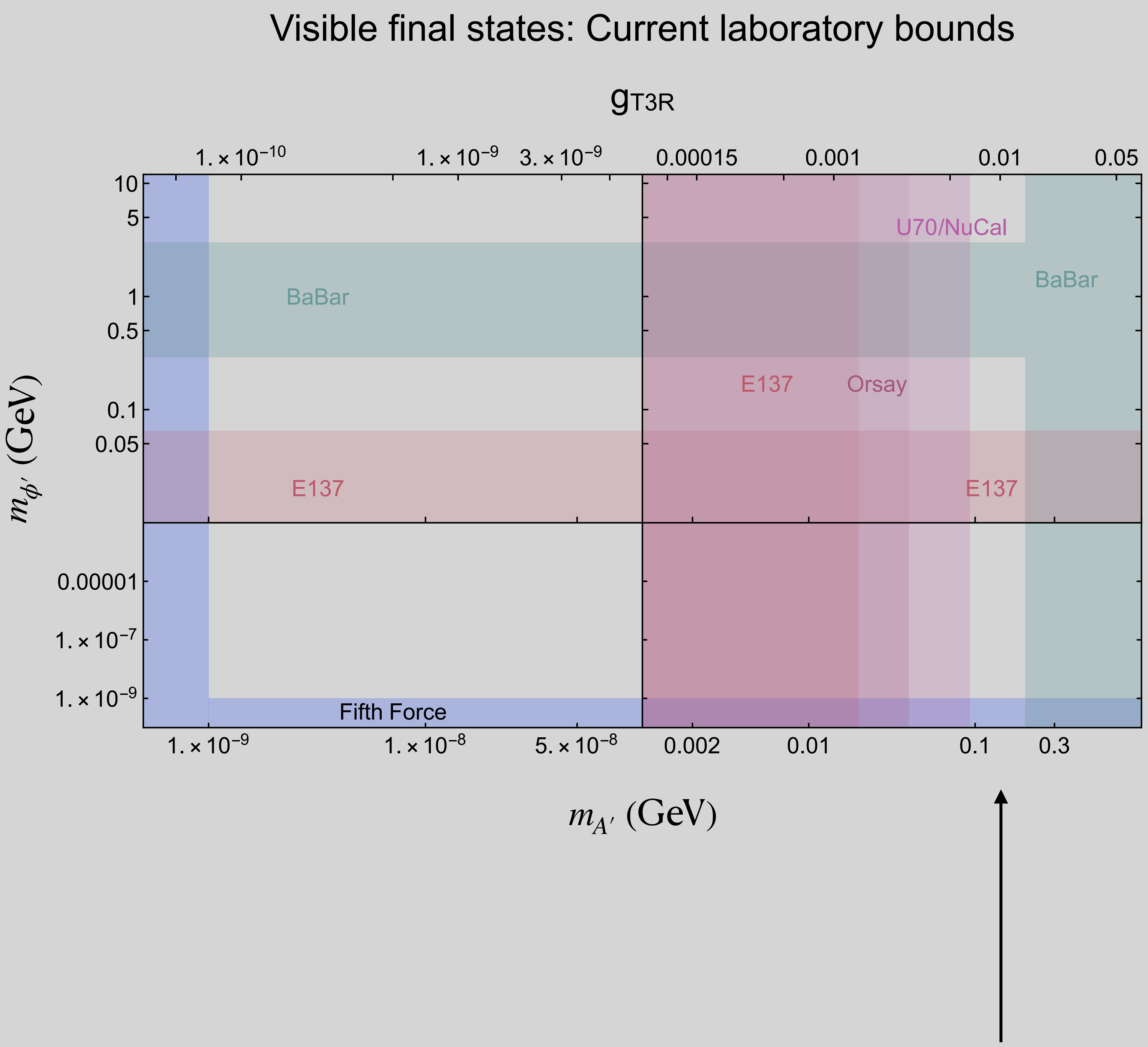
  — the g-2 correction from ϕ'(positive) and A'(negative) can be tuned against each other - Consistent with recent Fermilab results.

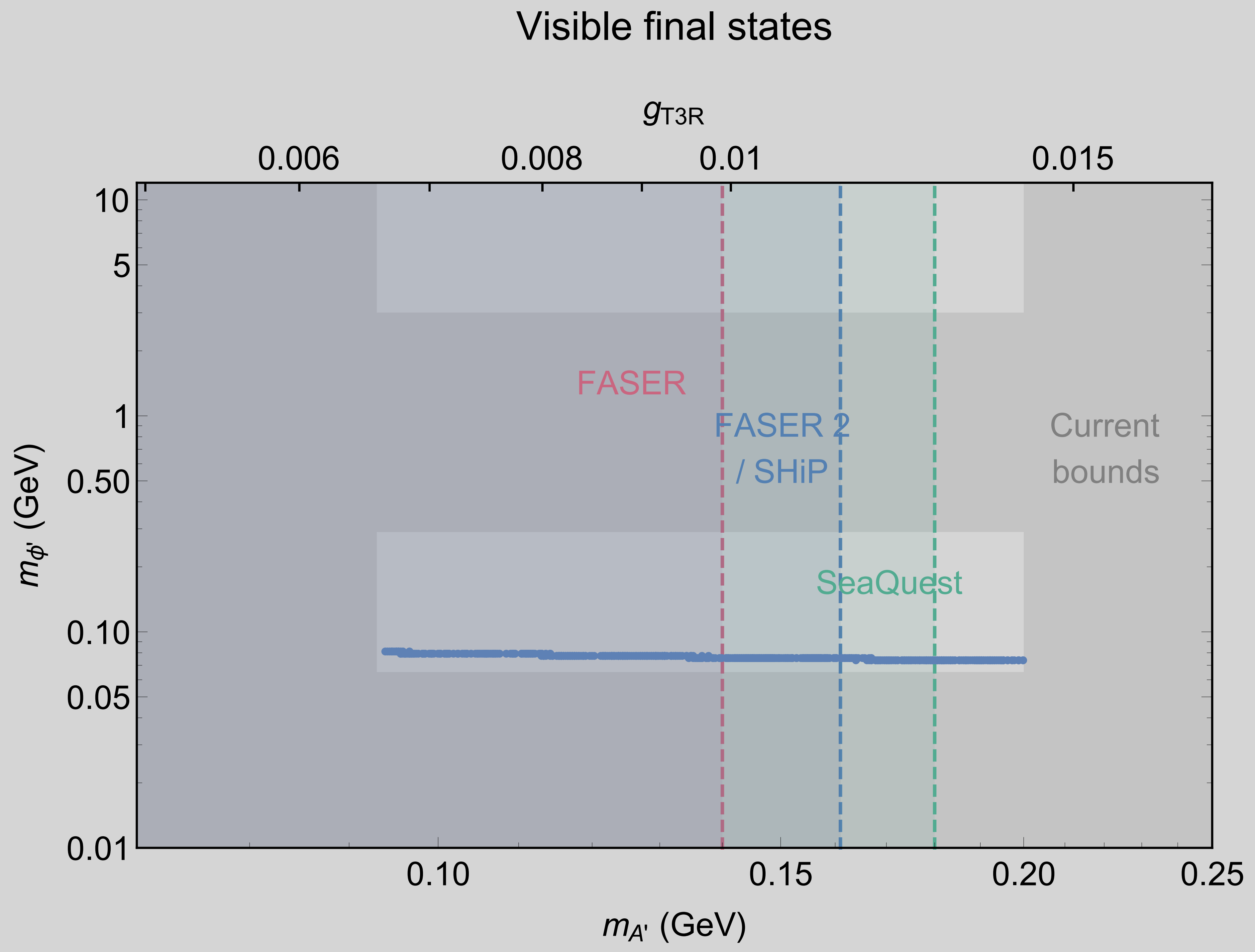
- A variety of upcoming experiments can probe the open parameter space.

  — beam dump/ fixed target, collider, neutrino and direct detection.

- A' does not couple to left-handed neutrino. The light mediators mostly decay to visible final states. Avoid constraints from neutrino measurements.

Parameter space for visible final states





Lepton Flavor Non-Universality and Quark Flavor Violation

- Low energy model induces lepton flavor non-universality as $U(1)_{T3R}$ couples to muon only.

- The mass terms for the fermions charged under $U(1)_{T3R}$ arise from non-renormalizable operators at EW scale.

- UV completion is possible by adding vector-like fermions at high scale.

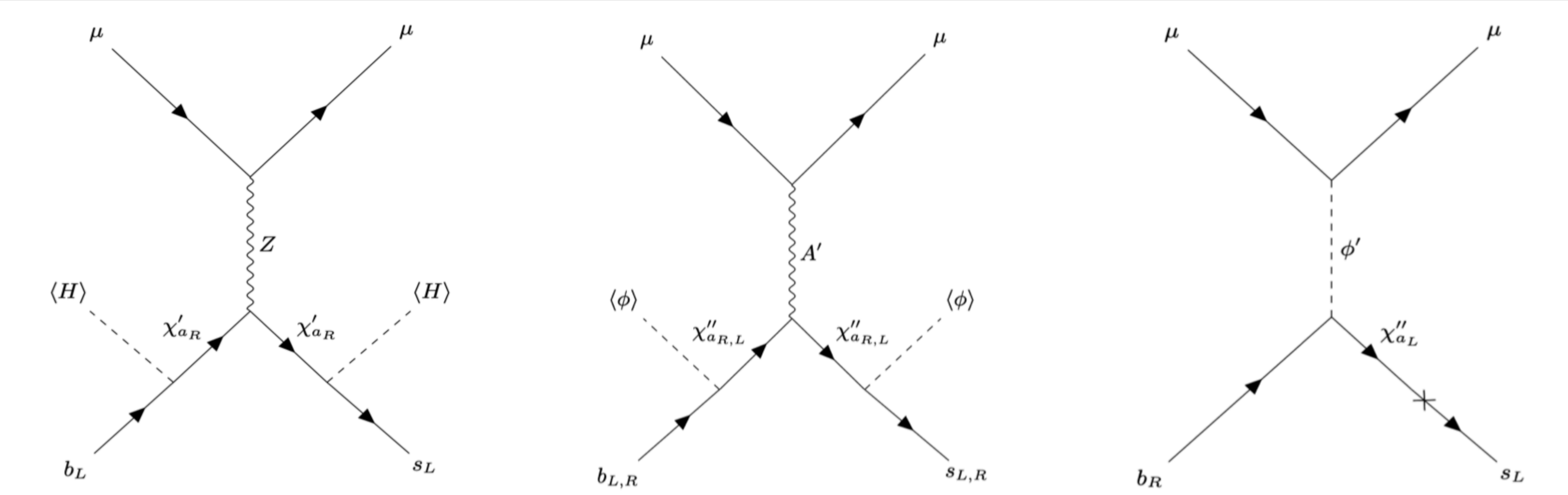
  — Universal seesaw.

  — tree level flavor violation in the quark sector.

Flavor Anomalies

- Opportunity to fit $b \to sl^+l^-$ anomalies.

- No constraints from neutrino measurements due to the lack of left-handed neutrino couplings.



Flavor Anomalies

- On the other hand U(1)$_{T3R}$ imposes $C_9^{(\prime)NU} = C_{10}^{(\prime)NU}$. Also have $C_s^{(\prime)}$ and $C_p^{(\prime)}$.
  - Clean observables: $R_{K^{(*)}}$ and $B_s \to \mu\mu$ with SM pull as high as 4.6 σ.
  - Can get predictions for other related observables, need more accurate theoretical calculation of form factor .

	BMA	BMB	BMC	BMD
C_{10}^U	4.85	-5.86	2.7	-5.67
$C_{9,10}^{NU}$	-0.30	3.65	-0.8	4.55
$\lvert C_s - C_s'\rvert$ GeV^{-1}	0.033	0.024	0.011	-
$\lvert C_p - C_p'\rvert$ GeV^{-1}	-	0.030	0.043	-
$C_{9,10}^{\prime NU}$	-	-	-	-1.28
R_K	0.82	0.87	0.86	0.87
$R_K^*[1.1, 6]$	0.83	0.78	0.97	0.89
$Br(B_s \to \mu\mu)$	3.36×10^{-9}	3.05×10^{-9}	2.67×10^{-9}	3.34×10^{-9}
SM pull	4.4σ	4.6σ	3.8σ	4.2σ

CONCLUSIONS

- $\mathcal{O}(100)$ MeV scale naturally arises in models which connect dark sector to the light flavor sector.
- We implement this by adding anomaly free $U(1)_{T3R}$ gauge group.
- We have two light mediators : elastic and inelastic direct detection channels.
- We get correct relic density.
- Tight constraints, some open parameter space, can be probed by future experiments
- The low energy model together with UV completion can fit the recent flavor anomalies.

THANK YOU!!!

Backup Slides

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)

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

$$L_\phi = -\frac{\lambda_u}{\Lambda}\tilde{H}\phi^*\bar{Q}_L q_R^u - \frac{\lambda_d}{\Lambda}H\phi\bar{Q}_L q_R^d$$

$$-\frac{\lambda_\nu}{\Lambda}\tilde{H}\phi^*\bar{L}_L\nu_R - \frac{\lambda_\ell}{\Lambda}H\phi\bar{L}_L\ell_R$$

$$-m_D\bar{\eta}_R\eta_L - \frac{1}{2}\lambda_L\phi\bar{\eta}_L^c\eta_L - \frac{1}{2}\lambda_R\phi^*\bar{\eta}_R^c\eta_R$$

$$-\mu_\phi^2\phi^*\phi - \lambda_\phi\left(\phi^*\phi\right)^2 + \text{h.c.}$$

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

MODEL

- 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

Constraints

- 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 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, Orsay, U70/NuCal 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 $m_{A'}$

Anomalous Magnetic Moment of Muon

- 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 $m_\ell \ll m_{A'}$
  - Renormalizable heavy physics with vector-like quark can correct this

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

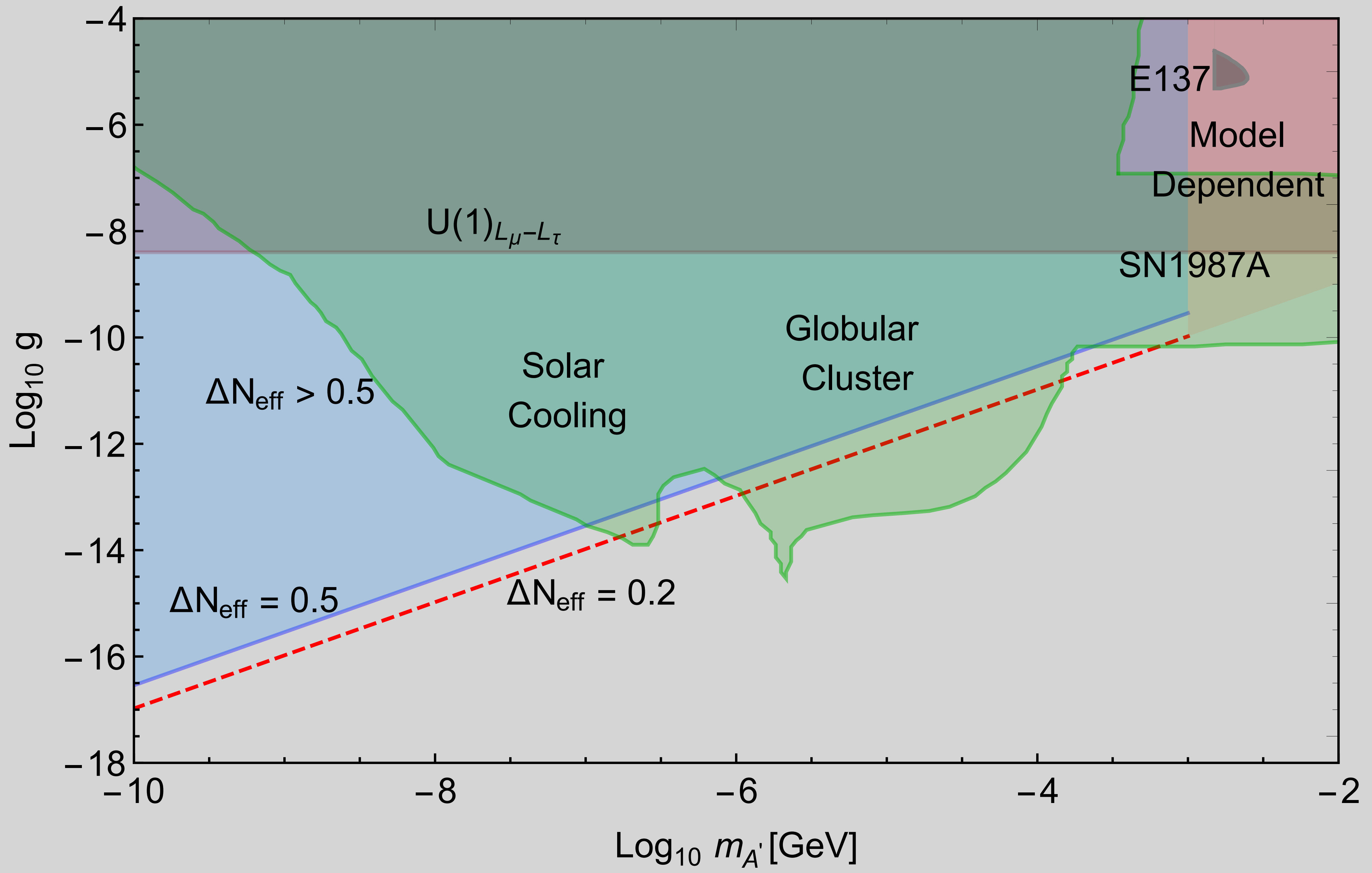
N_{eff} AND $U(1)_{T3R}$

- generally two ways to avoid light A' or ϕ' contributing too much to N_{eff}
- if A' and ϕ' are heavy enough (> 10 MeV), the abundance is Boltzmann suppressed, 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

Longitudinal Mode

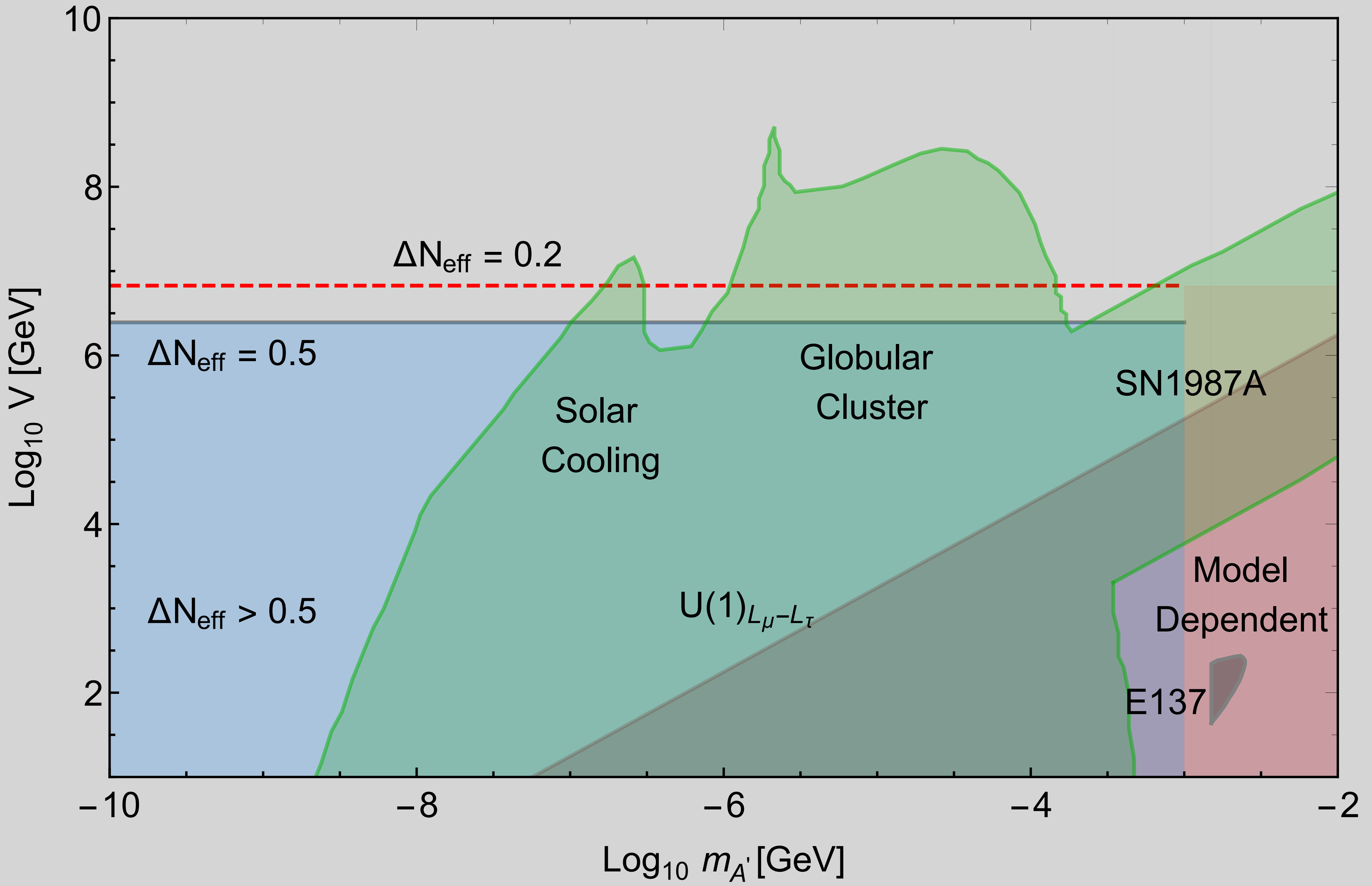
- weak coupling, so dominant A' production mode is inverse decay process
  - $f\bar{f} \rightarrow \gamma A'$
- longitudinal modes get an enhancement, $E/m_{A'}$, so A' thermalizes regardless of how small the mass/coupling is
  - enhancement killed if there is only a vector coupling, due to Ward identity
- 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

CONTRIBUTION TO N_{eff} FROM A'



- The constraints are much more severe than $U(1)_{L_\mu - L_\tau}$
- No matter how weak the coupling, the Goldstone mode (longitudinal polarization) does not decouple and equilibrates in the early universe.

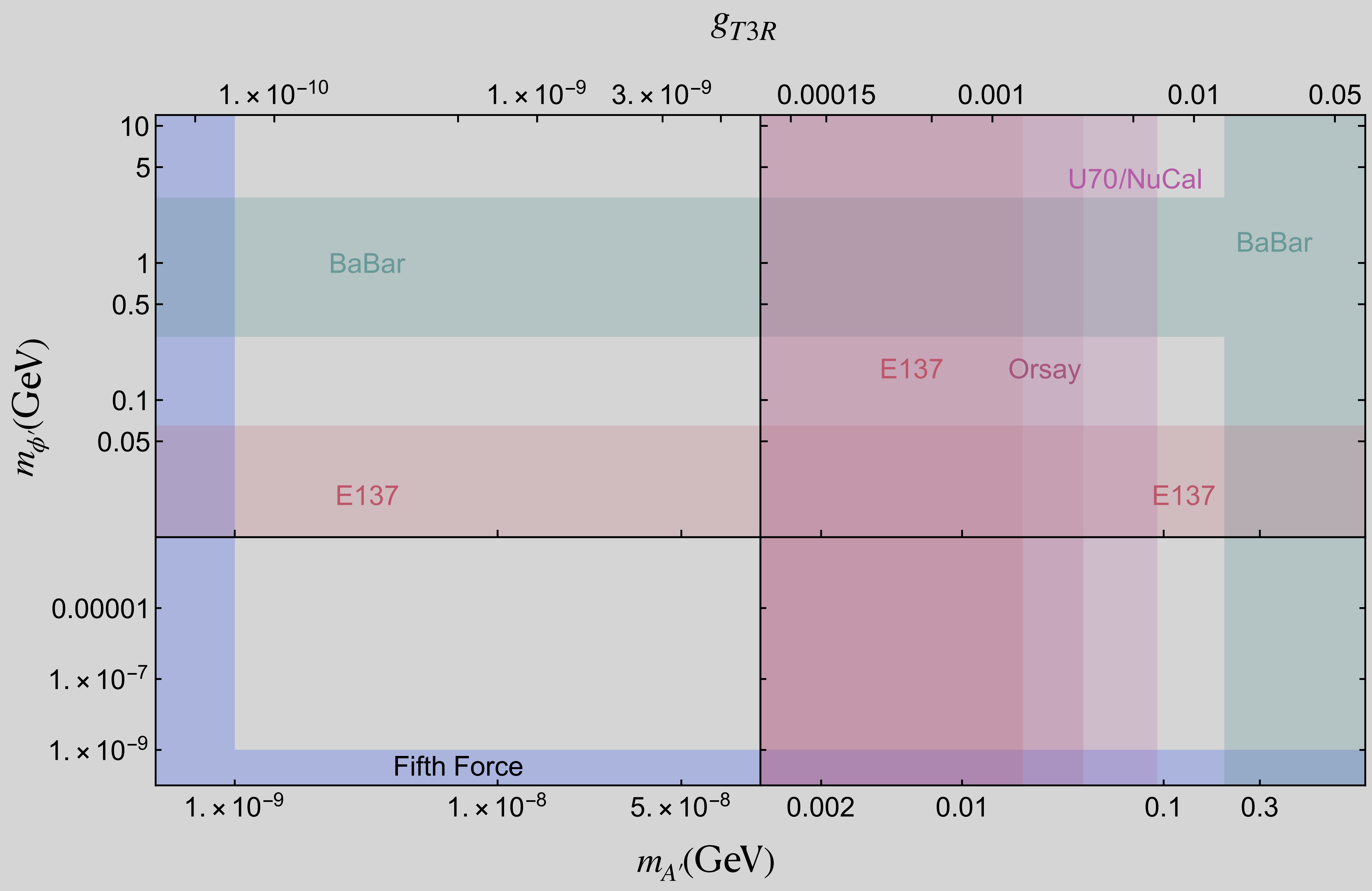
- For $1 \le m_{A'} \le 10$ MeV, this can be done by choosing neutrino mass matrix appropriately.
- H_0 tension can be resolved for $\Delta N_{eff} \simeq 0.2$ by choosing V appropriately for $m_{A'} \le 1$ MeV.



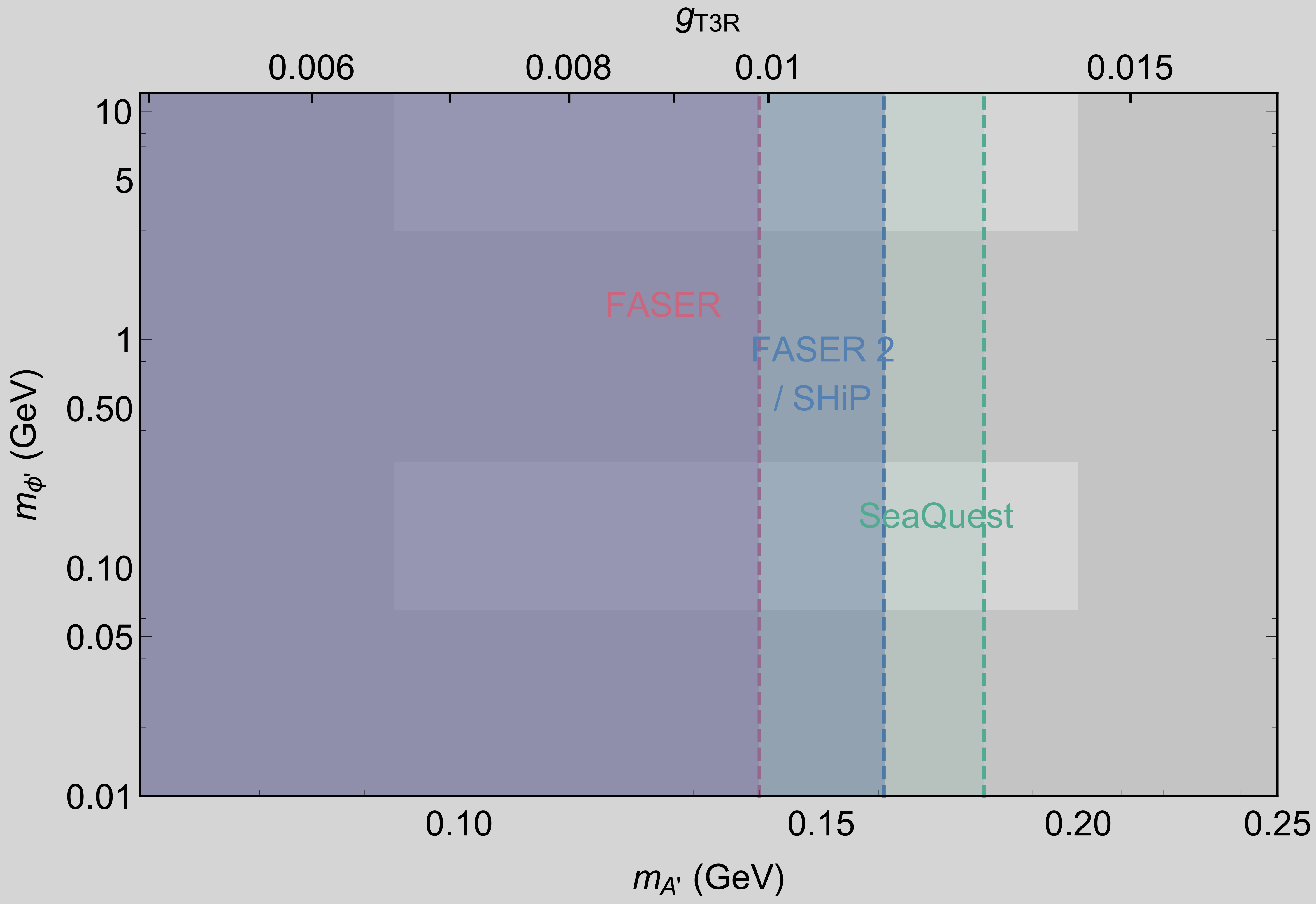
Parameter space: Visible final states

$V = 10$ GeV

Visible final states: Current laboratory bounds



Visible final states: Future laboratory bounds



Visible decays at displaced detectors

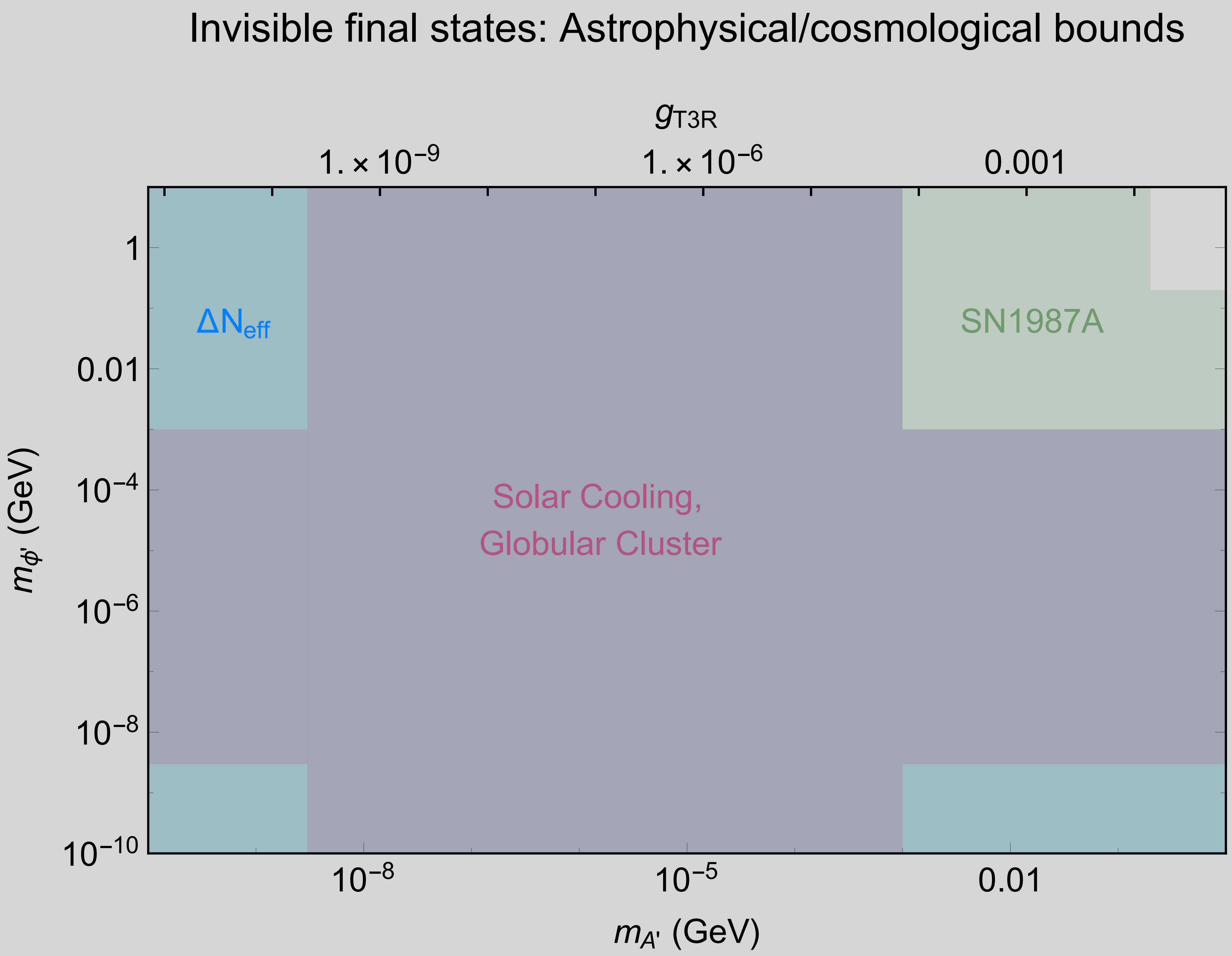
- Experimental strategy: produce light mediators at a proton collider, fixed target or beam dump and search for visible final states
- Production of A'/ϕ': p-bremsstrahlung or meson decay at tree level, production cross section gets enhancement compared to secluded model
- A' mediator is long-lived when decays into visible final states: decays to e^+e^- pair through one loop kinetic mixing: can be probed
- ϕ' decays rapidly into visible final states $\gamma\gamma$ via one loop mixing: can not be probed, decay length too short to produce appreciable number of particles to reach the detector

Probing dark photon in the displaced detectors

- A' decays to visible final states occur if $m_{A'} \geq 1$ MeV, the production cross section for the longitudinal mode is highly suppressed compared to the production cross section of the traverse component as it scales as $m_f/m_{A'}$
- Sensitivity can be obtained by rescaling the sensitivity of the secluded model, but with number of events enhanced to account for the fact that the production is tree level process.
- The sensitivity has a ceiling and floor: below the floor, the coupling is too weak to produce enough A', and above the ceiling, coupling too strong, A' decays rapidly.

Astrophysical/cosmological bounds

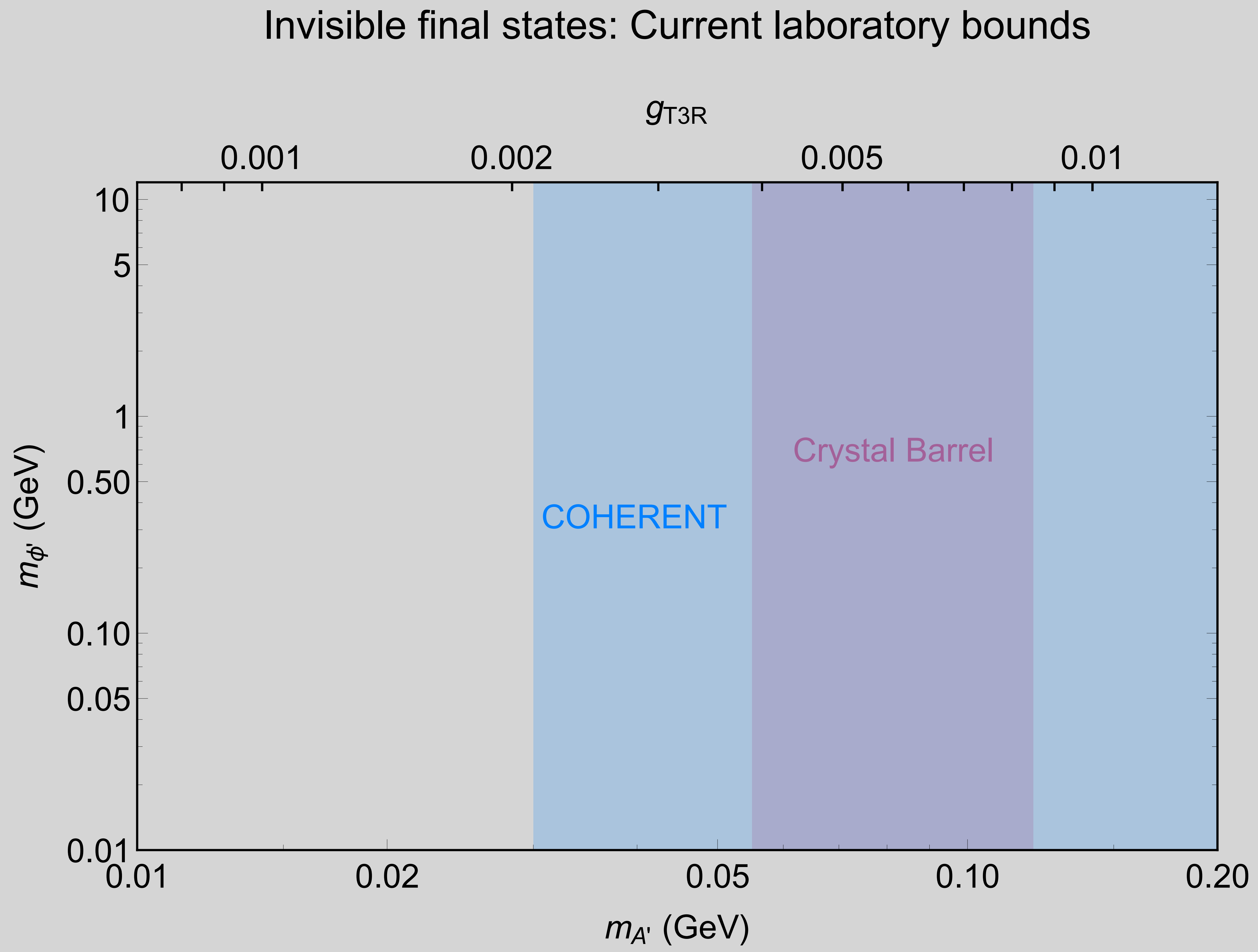
- If the Universe reheats to a lower temperature, then the ΔN_{eff} bound can be evaded.
- All the astrophysical bounds can be evaded by assuming dark photon to be chameleon-type field.
- There are way around, therefore the lab bounds are important

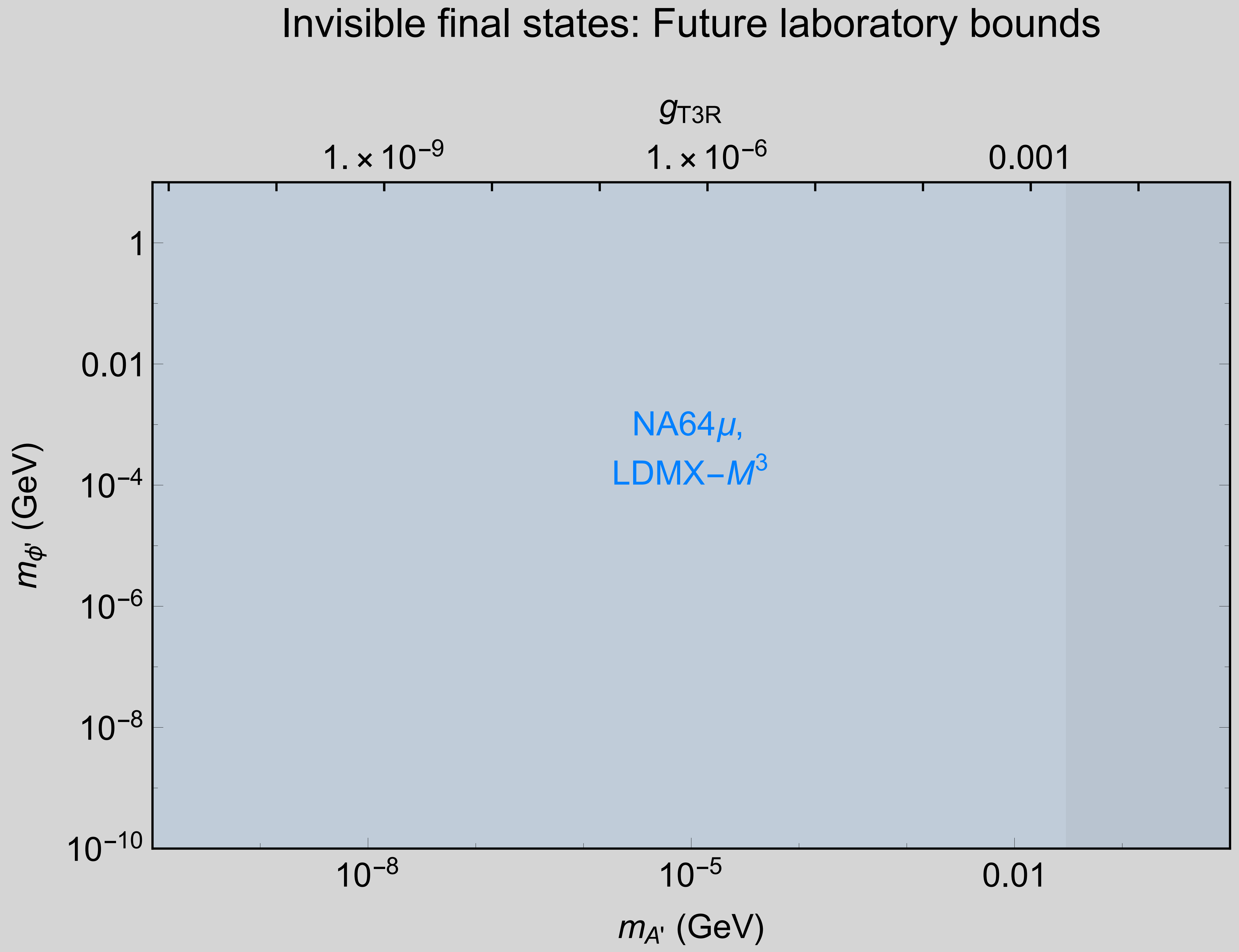


$V = 10$ GeV

Parameter Space: Invisible Final States

$V = 10$ GeV





SUMMARY OF CONSTRAINTS

TABLE I: A summary of the various experiments/probes considered here, their methods for producing and detecting the mediating particles, and the resulting sensitivities.

Type of experiments	Name of the experiment	Production of A'/ϕ'	Final states	Results
Electron beam dump experiments	E137, Orsay	A' : electron bremsstrahlung through kinetic mixing at one-loop, ϕ' : Primakoff production at one-loop.	Both A', ϕ' decay predominantly to visible SM states e^+e^-. ϕ' decay is rapid.	E137 rules out : 1 MeV $\le m_{A'} \le 20$ MeV, 1 MeV$\le m_{\phi'} \le 65$ MeV. Orsay rules out : 1 MeV $\le m_{A'} \le 40$ MeV.
Proton beam dump experiments	U70/NuCal, FASER SHiP, SeaQuest (displaced detector)	p-bremsstrahlung or meson decay at tree level	$A' \to e^+e^-$ through kinetic mixing. $\phi' \to \gamma\gamma$ ϕ' decays rapidly hence cannot be probed.	U70/NuCal rules out : 1 MeV $\le m_{A'} \le 93$ MeV. FASER can probe : 1 MeV $\le m_{A'} \le 140$ MeV. FASER 2/SHiP can probe : 1 MeV $\le m_{A'} \le 161$ MeV. SeaQuest can probe : 1 MeV $\le m_{A'} \le 180$ MeV.
e^+e^- collider experiments	BaBar, Belle-II	$e^+e^- \to \mu^+\mu^- + A'/\phi'$, $e^+e^- \to \gamma A'$	4μ final states, γ + invisible	BaBar rules out for (4μ final states) : 200 MeV $\le m_{A'} \le 1.3$ GeV, 290 MeV $\le m_{\phi'} \le 3$ GeV. Belle-II can probe (γ + invisible): $m_{A'} \ge 30$ MeV.
Fifth force searches experiments	Precision tests of gravitational Casimir, and van der Waals forces	Relevant for extremely light A'/ϕ'. For $m_{A'} \to 0$ limit, the Longitudinal mode will contribute.	n/a	The parameter space is ruled out for : $m_{A'}/m_{\phi'} \le 1$ eV.
Astrophysical probes	SN1987A, Cooling of Sun and globular clusters, White dwarfs	$\gamma + \mu \to A' + \mu$, $\mu + p \to \mu + p + A'$, $\mu^+\mu^- \to A'$ at tree level, $e^+e^- \to A'$ through kinetic mixing.	$A' \to \eta\eta, \nu_s\nu_s$ (if decays to $\nu\nu, e^+e^-$ then can not escape), $\phi' \to \eta\eta, \nu\nu$	SN1987A rules out : $m_{A'}, m_{\phi'} \le 200$ MeV. Stellar cooling rules out: $m_{A'}, m_{\phi'} \le 1$ MeV. WD constraint are negligible if $m_\eta, m_{\nu_s} \ge 0.1$ MeV. (All these astrophysical bounds can be evaded using chameleon effect.)
Cosmological probes	ΔN_{eff} value	$\mu^+\mu^- \to \gamma A'$, production of longitudinal mode get enhanced due to axial vector coupling.	invisible states	If the Universe reheat at a temperature ≥ 100 MeV, $m_{A'}, m_{\phi'} \le 1$ MeV is ruled out. (Can be evaded if reheat occurs at a lower temperature.)
Muon beam experiments	NA64μ, LDMX-M[3] (nearby detectors)	$\mu-$bremsstrahlung	Can probe when A'/ϕ' has a significant decay rate to invisible states such as $\nu\nu, \eta\eta$	NA64μ, LDMX-M[3] can probe the entire parameter space if $m_{A',\phi'} > 2m_{\eta,\nu_s}$ with Br(invisible)$> 10^{-4}$, even if $A'/\phi' \to \mu^+\mu^-$ is allowed still Br(invisible)$> 10^{-4}$ provided $m_{\eta,\nu_s} > 1$ MeV.
Neutrino experiments	COHERENT, CCM JSNS[2]	p/e- bremsstrahlung, meson decay	$A' \to \nu_s\nu_s/\eta\eta$, $\nu_s/\eta_i + N \to \nu_s/\eta_j + N$ generate nuclear recoil, $\nu_s/\eta_i + e \to \nu_s/\eta_j + e$ generate electron recoil	Can be probed by looking at nuclear/electron recoil. $m_{A'} \sim 30$ MeV can explain the 2.4-3σ excess found by COHERENT, $m_{A'} \gtrsim 30$ MeV is ruled out. CCM and JSNS[2] will improve the sensitivity.

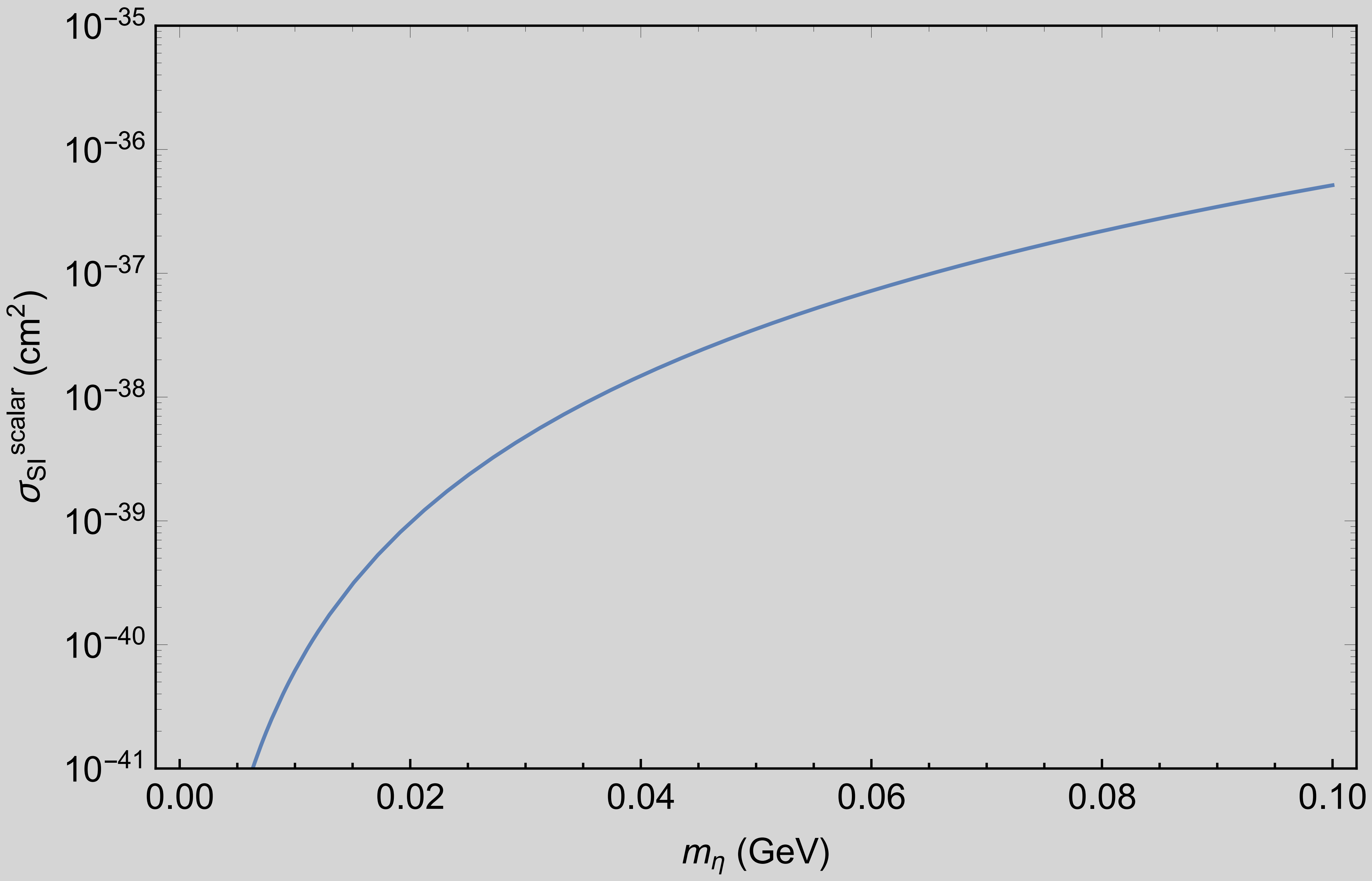
Direct Detection

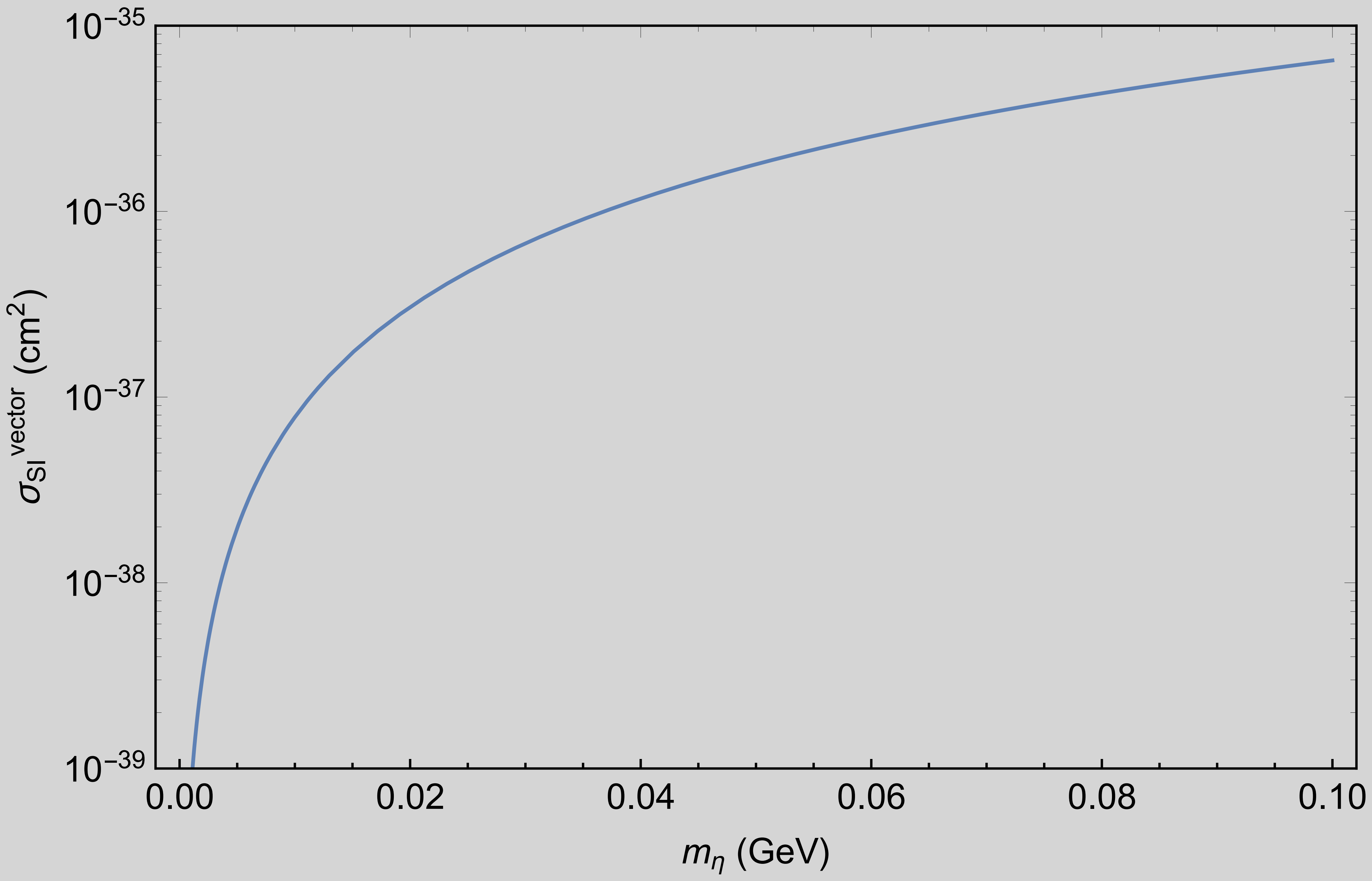
- ϕ' mediated → SI, velocity-independent, elastic, isospin-invariant
- A' mediated → SI, velocity-independent, inelastic, isospin-violating (IVDM)
  - opposite coupling to u and d (thus to p and n)
- mediator mass is of the same order as momentum transfer
  - not a contact interaction, $d\sigma/dE_R$ 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 (1907.12771)
- cosmic rays scatter off DM, boosted DM scatters in XENON1T (1810.10543; 1907.03782)
- DM-electron scattering (one-loop suppressed… not constraining)

DM-Nucleon Cross Section

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

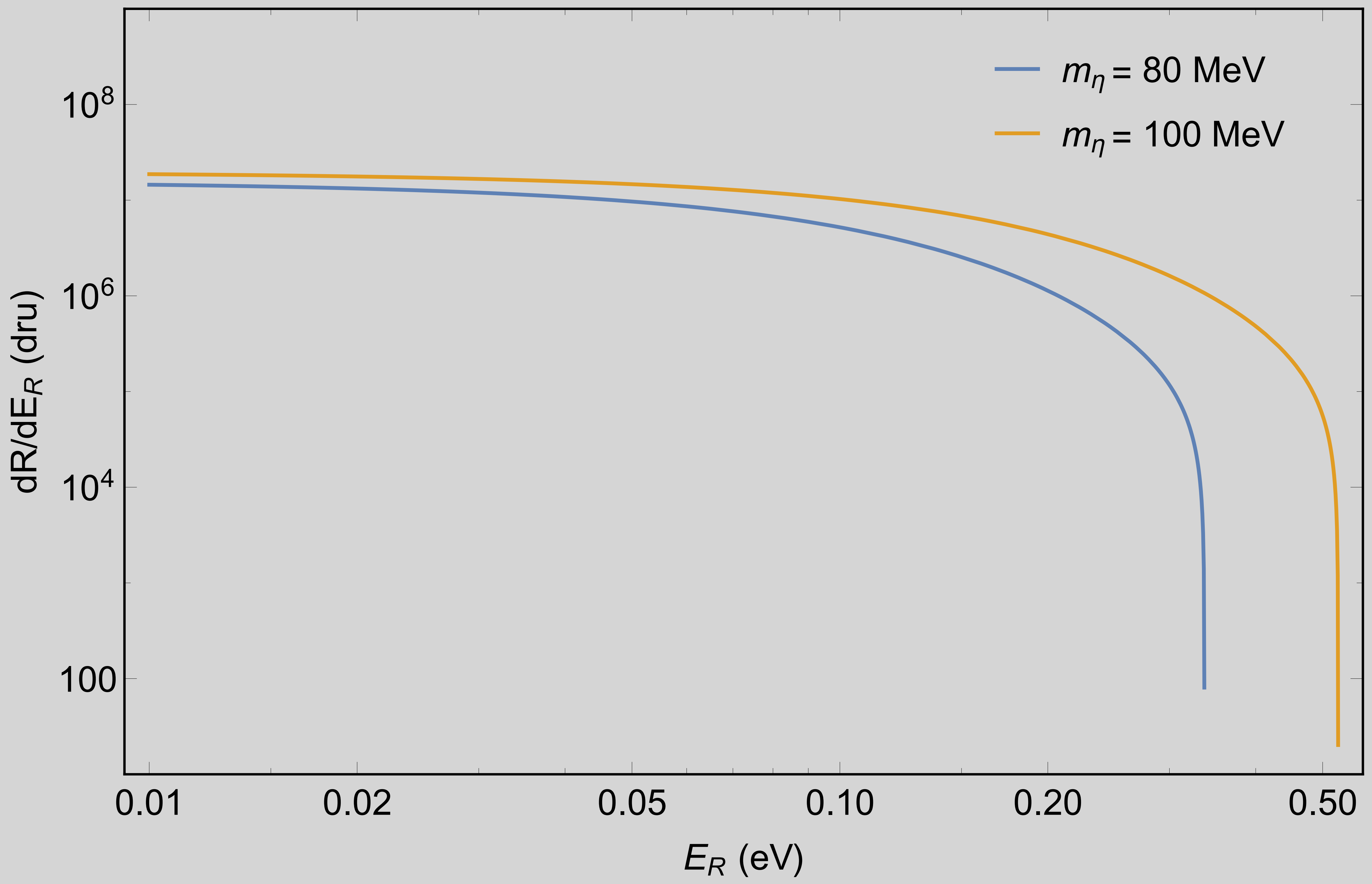
δ= 0, V=10 GeV
Independent of $m_{A'}$



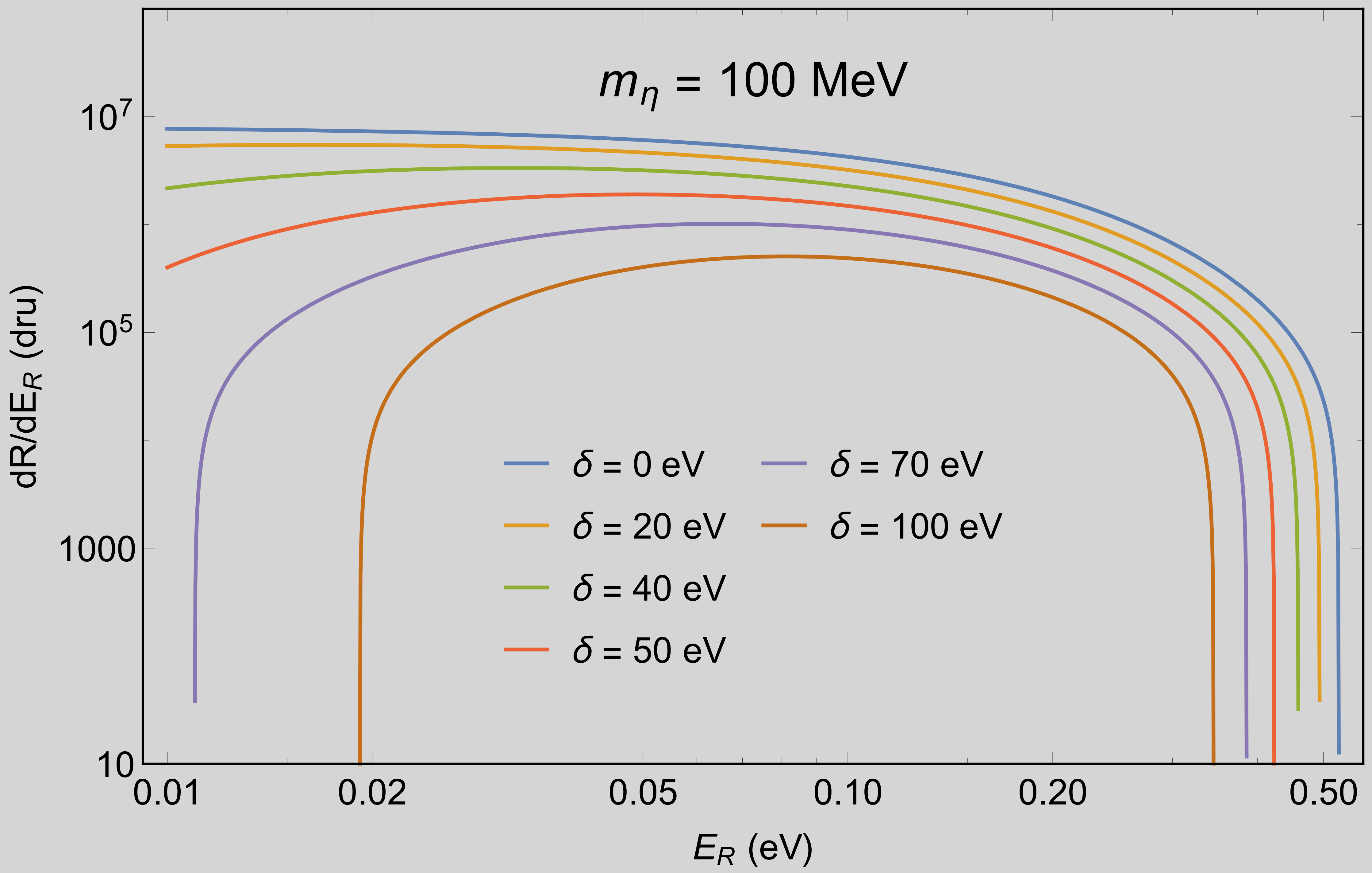


Direct Detection Rate

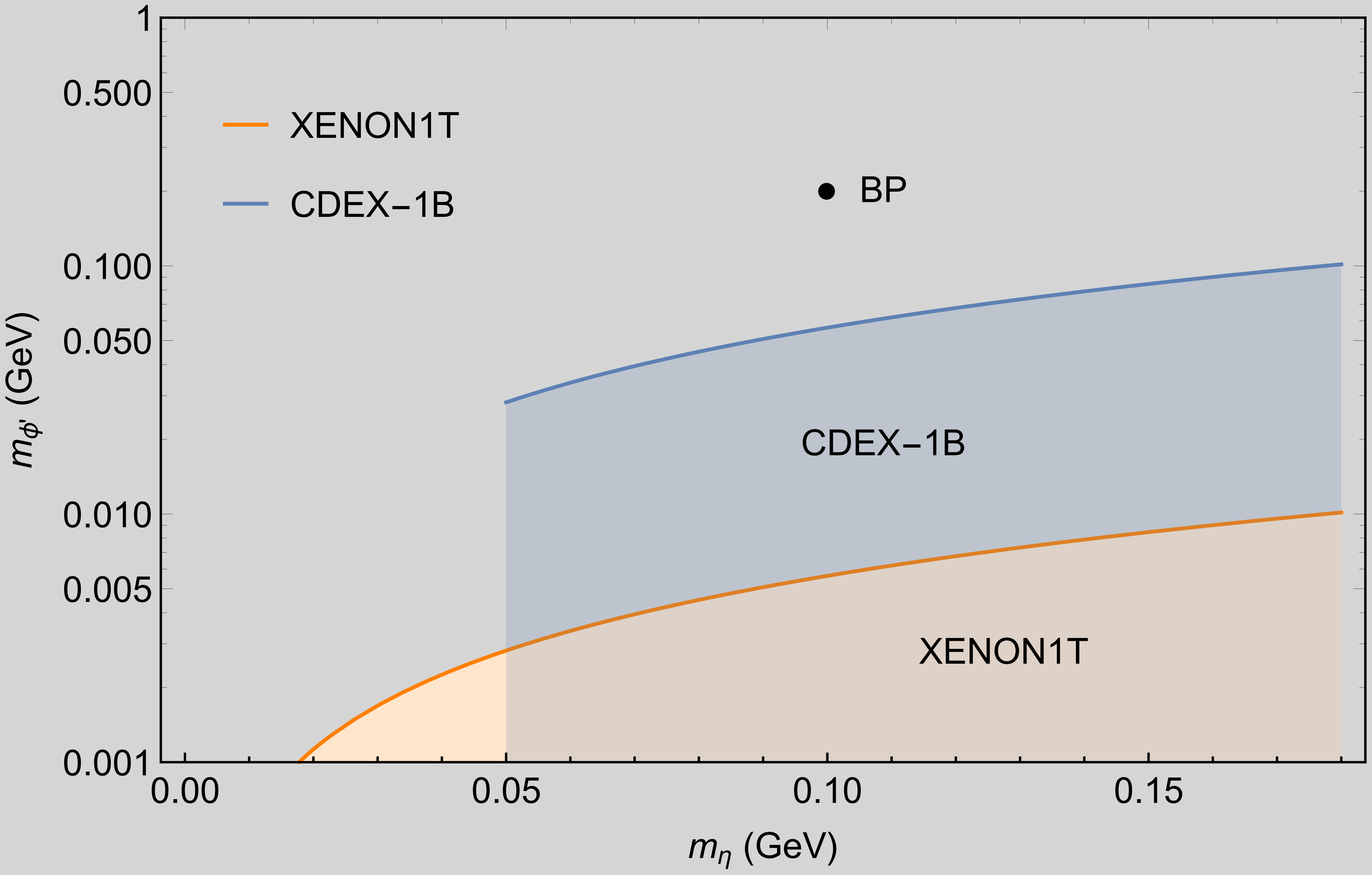
Elastic scattering



Inelastic scattering



Exclusion contour



elastic scattering (ϕ'-mediated)

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

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 model

BP	$m_{A'}$ (MeV)	$m_{\phi'}$ (MeV)	m_η (MeV)	m_{ν_s} (MeV)	m_{ν_D} (MeV)	$<\sigma v>$ (cm^3/sec)	σ_{SI}^{scalar} (pb)	σ_{SI}^{vector} (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}	3.50×10^{-8}	4.32

- first benchmark get relic density via ϕ' resonance
  - a_μ corrections (A'/ϕ') need to be 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

Key points

- 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)

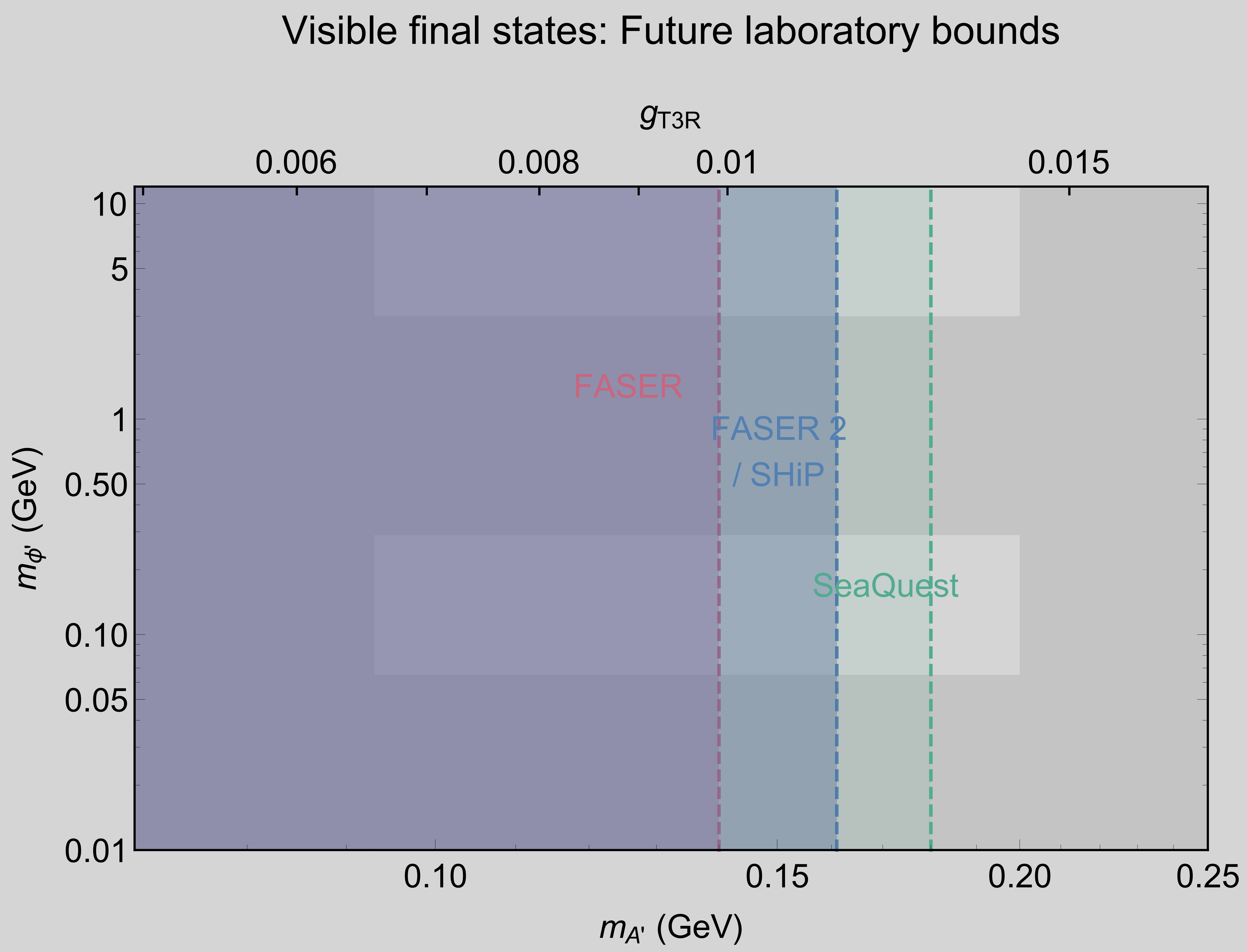
Sensitivities of forward physics facilities

- FASER: Probed if
  $1\ \text{MeV} \leq m_{A'} \leq 140\ \text{MeV}$

- FASER 2/ SHiP: Probed if
  $1\ \text{MeV} \leq m_{A'} \leq 161\ \text{MeV}$

- SeaQuest: Probed if
  $1\ \text{MeV} \leq m_{A'} \leq 180\ \text{MeV}$

$V = 10$ GeV

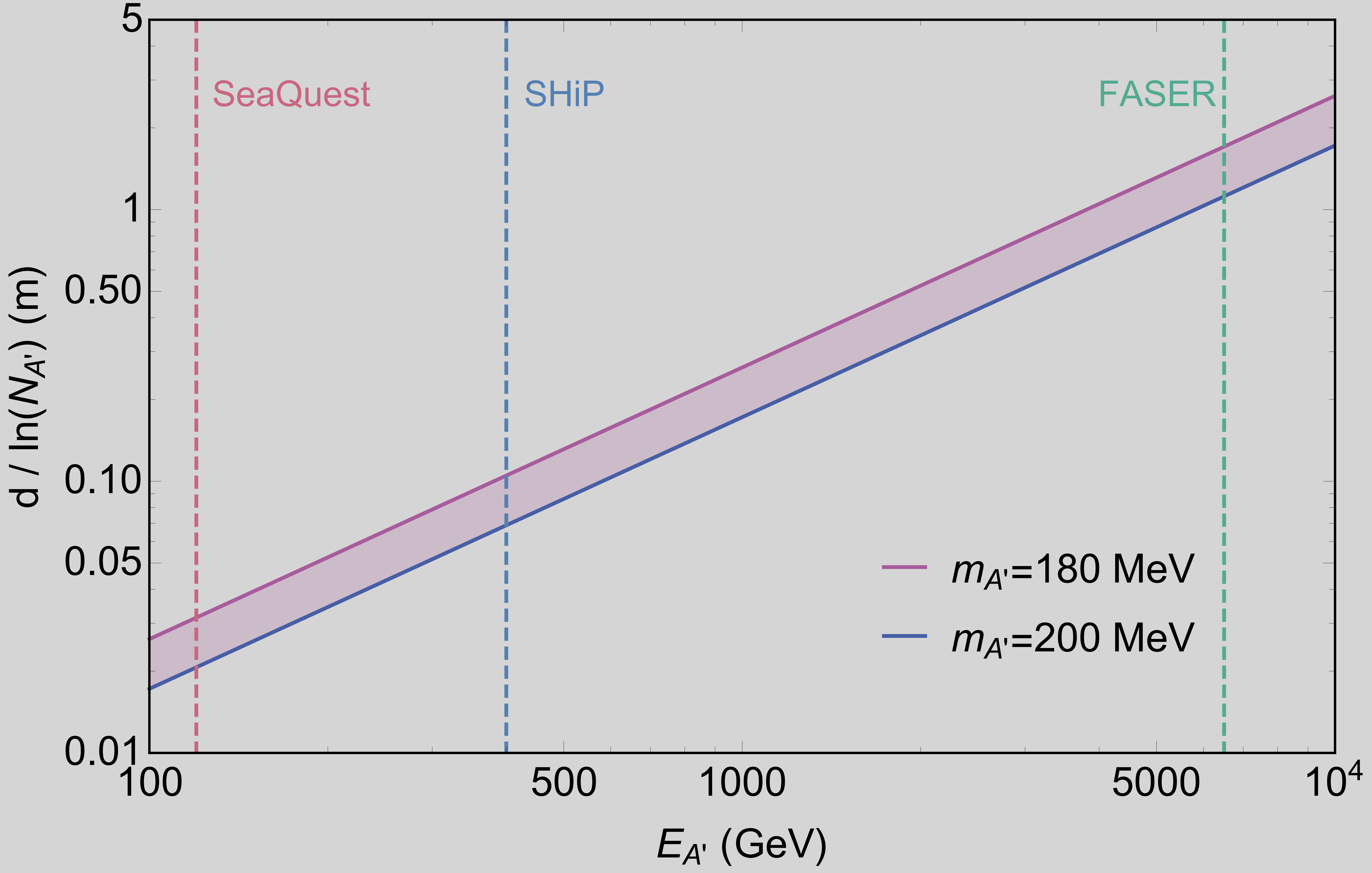


Searching A' in Forward Physics Facilities

- A' mediator is long-lived and can decays into visible final states

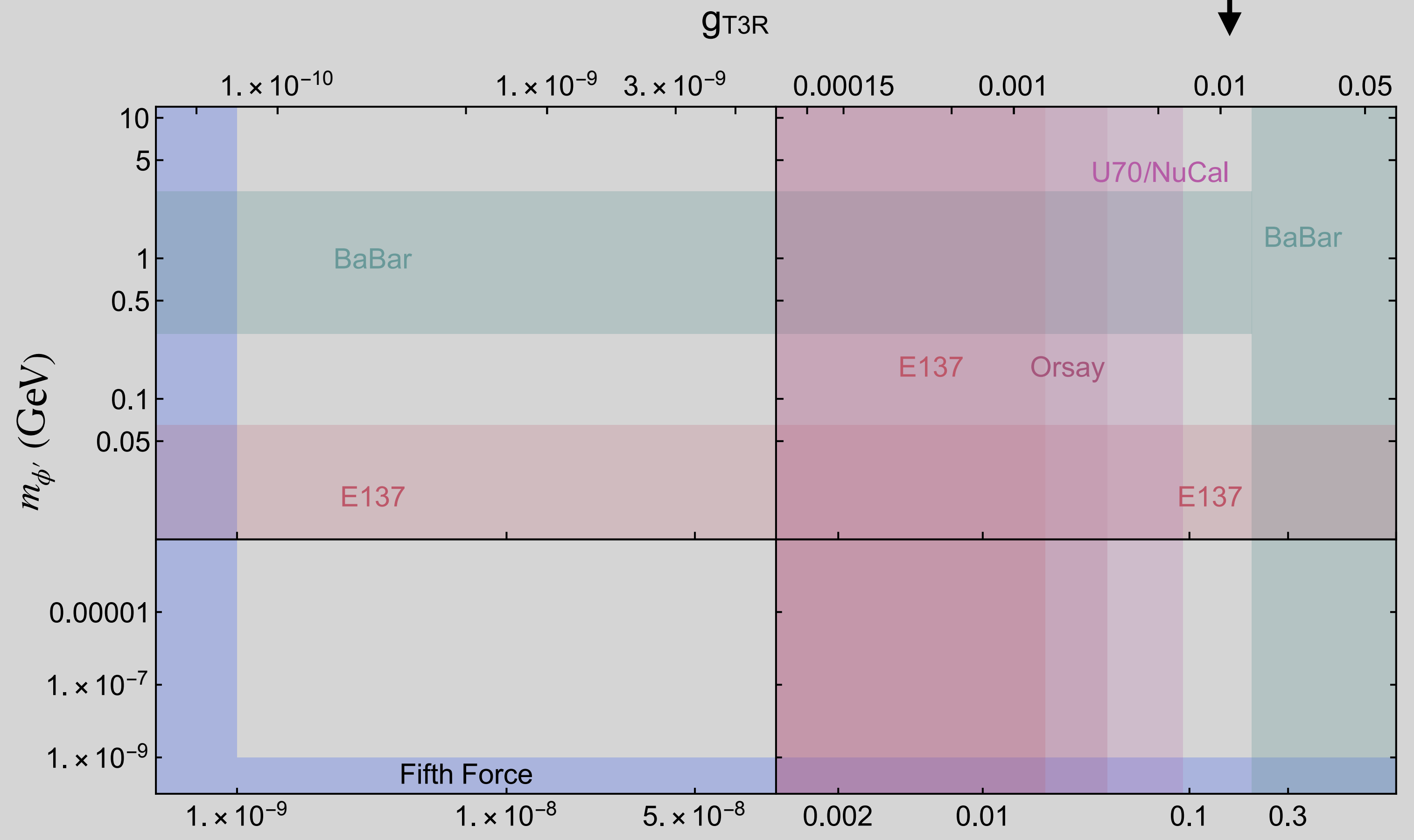
- For $\mathcal{O}(1)$ events, $N_{A'}e^{-d/d_{A'}} \simeq \mathcal{O}(1)$, $d_{A'}$ is the decay length of A'.

- ϕ' decays rapidly, decay length too short for an appreciable number of particles to reach the detector

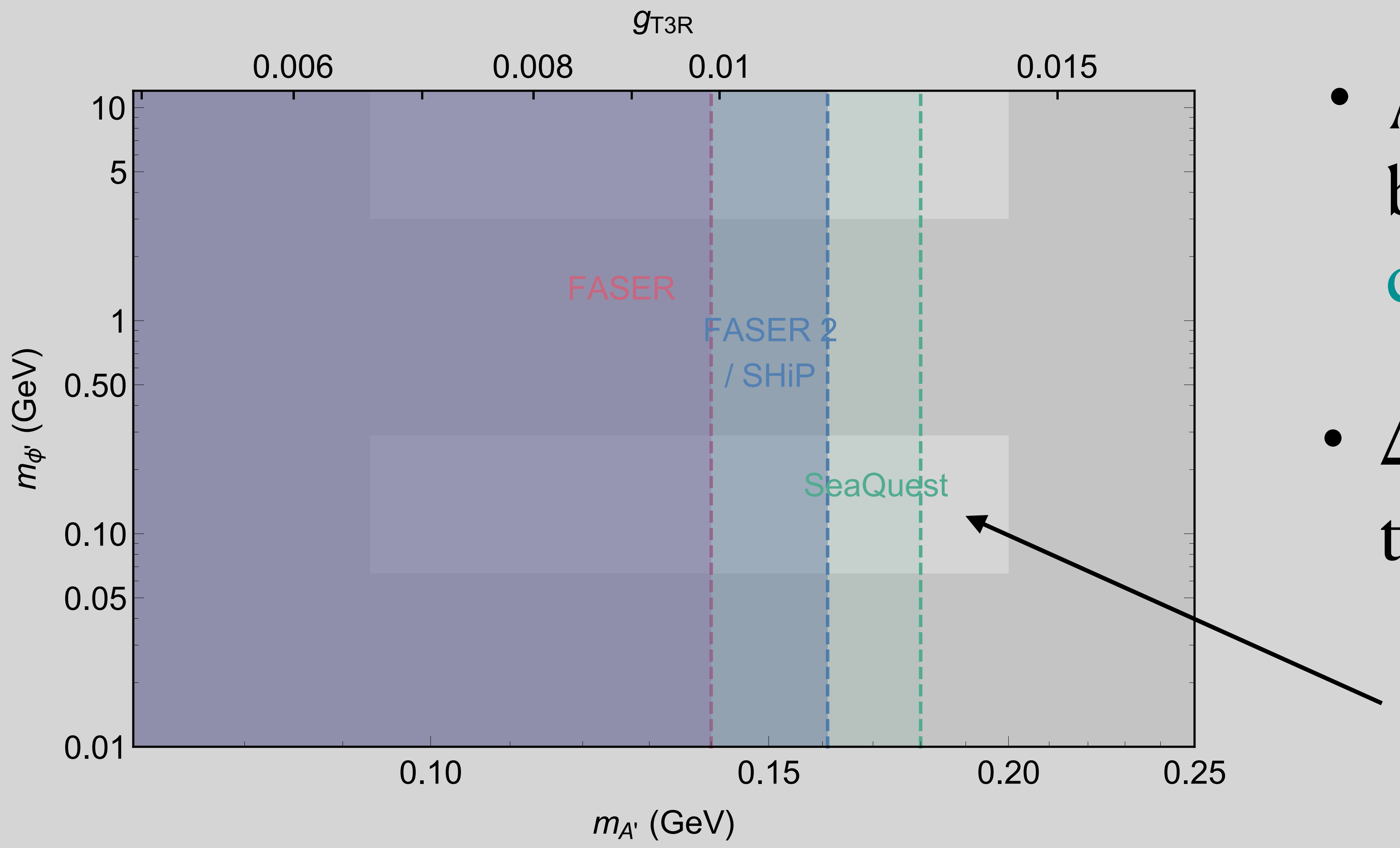


PARAMETER SPACE

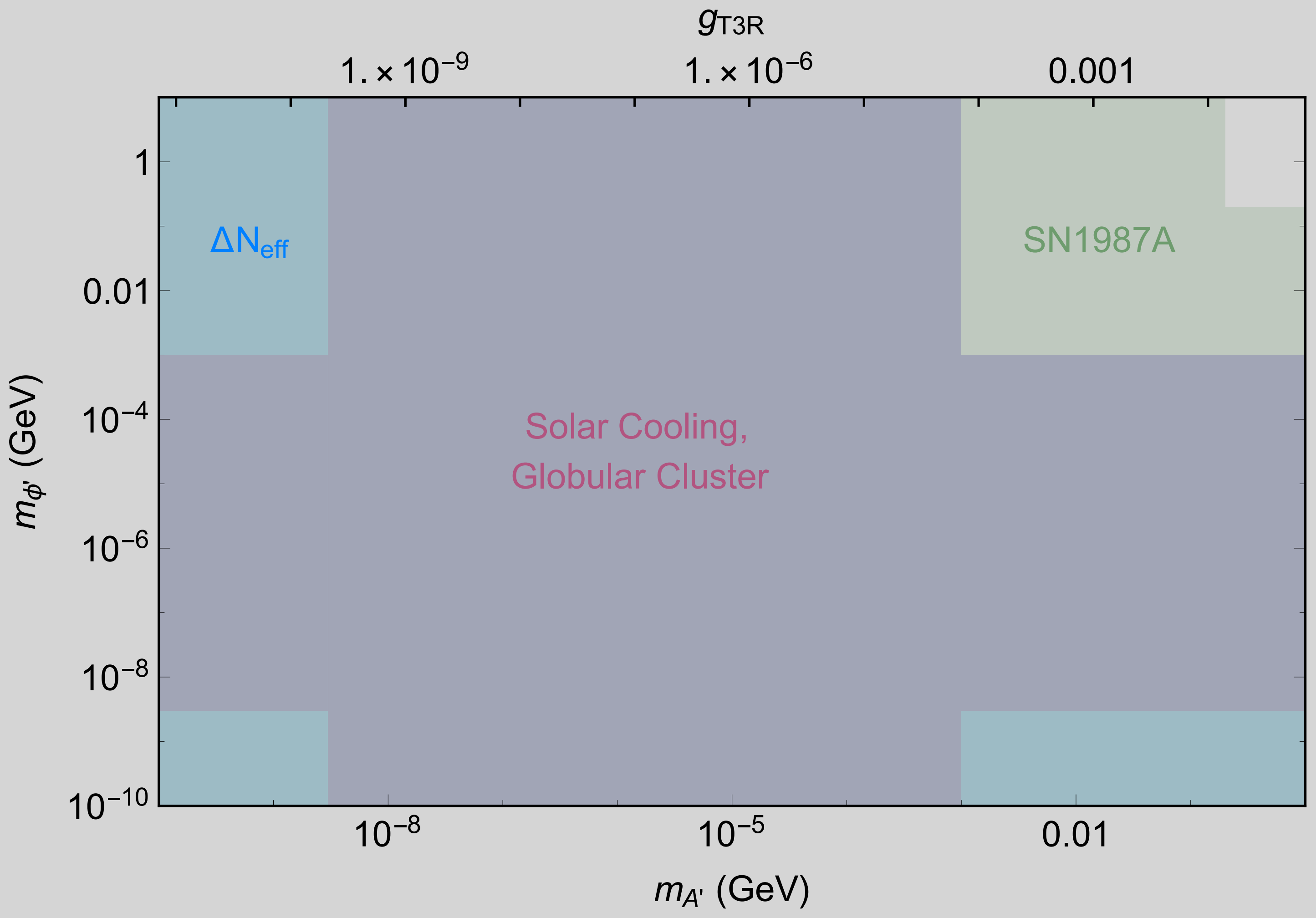
Visible final states: Current laboratory bounds



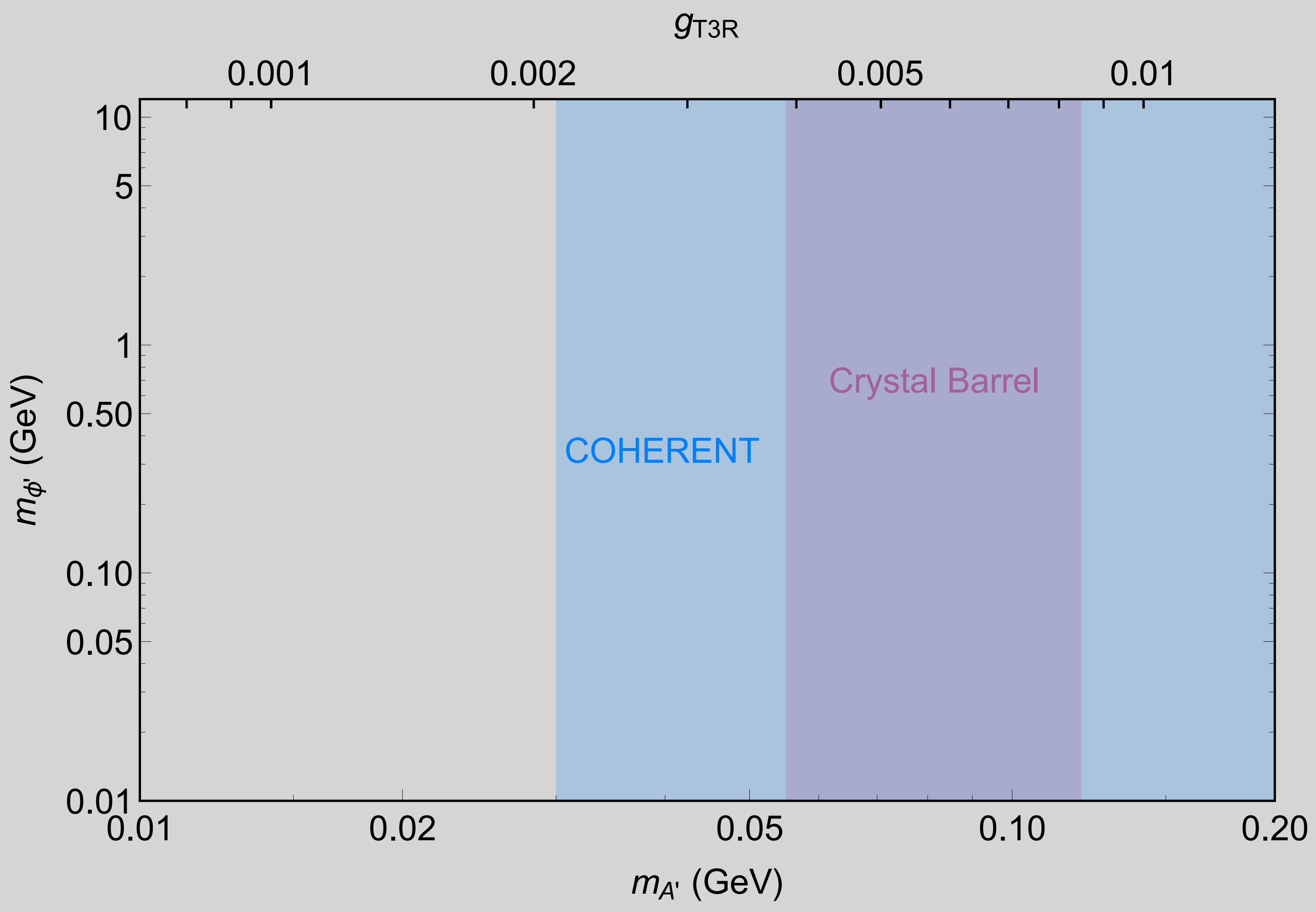
Visible final states: Future laboratory bounds



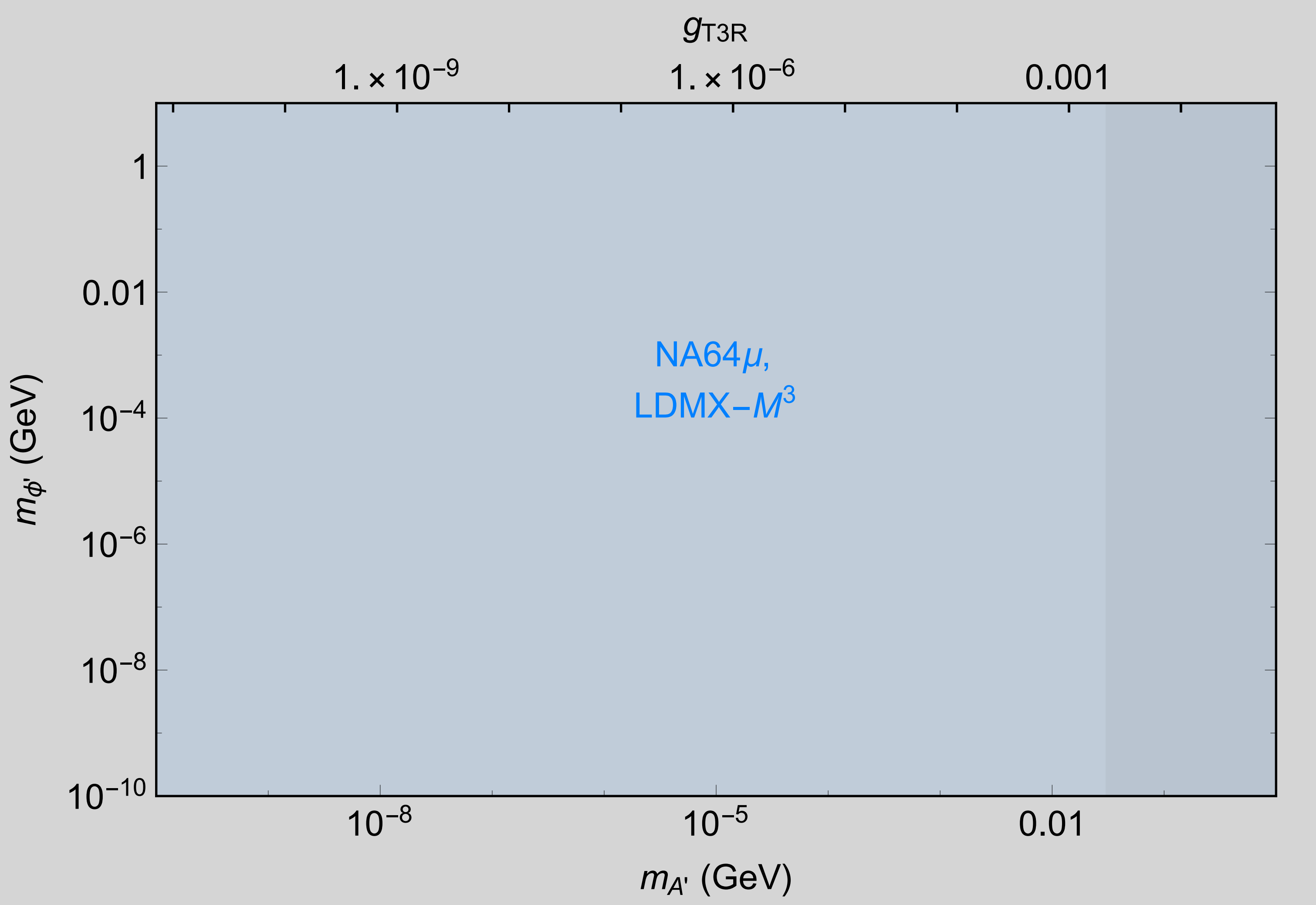
Invisible final states: Astrophysical/cosmological bounds



Invisible final states: Current laboratory bounds



Invisible final states: Future laboratory bounds



- All the astrophysical bounds can be relaxed by assuming dark photon to be chameleon-type field.
- ΔN_{eff} can be evaded if the Universe reheat to a lower temperature <100 MeV.