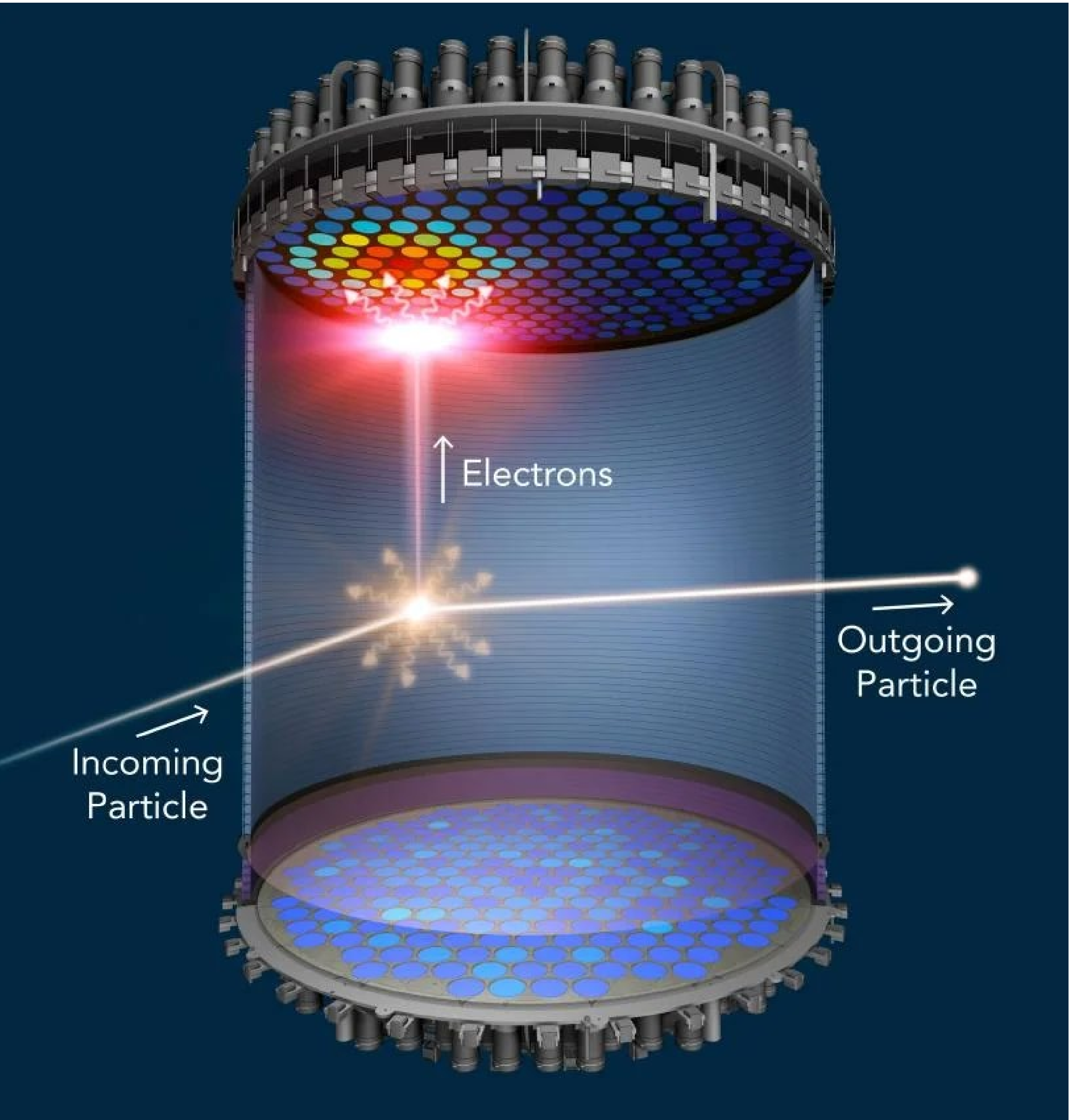
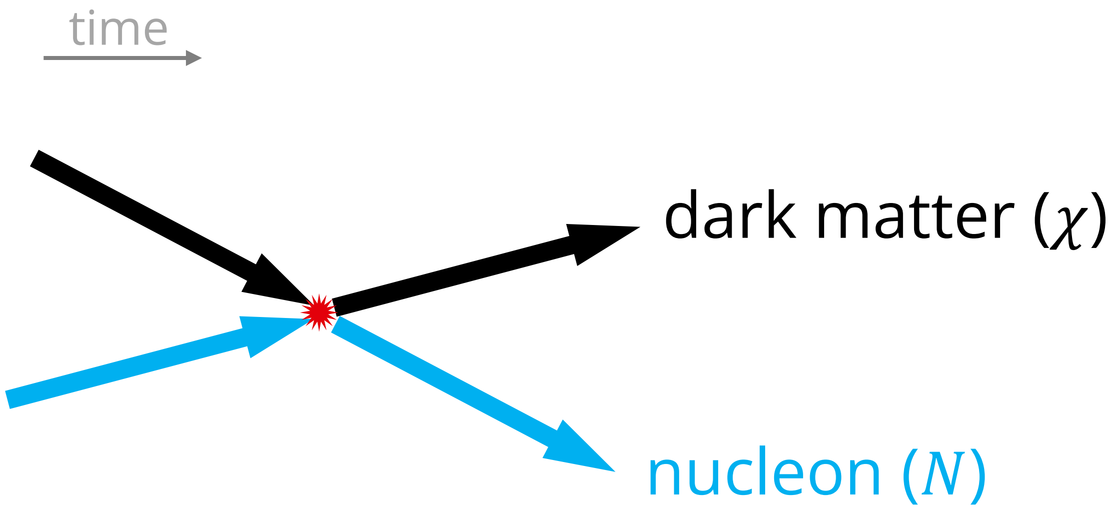
Axion-mediated dark matter direct detection

Anh Vu Phan (Vu)
NNV meeting, 7 November 2025

Radboud University
Nikhef

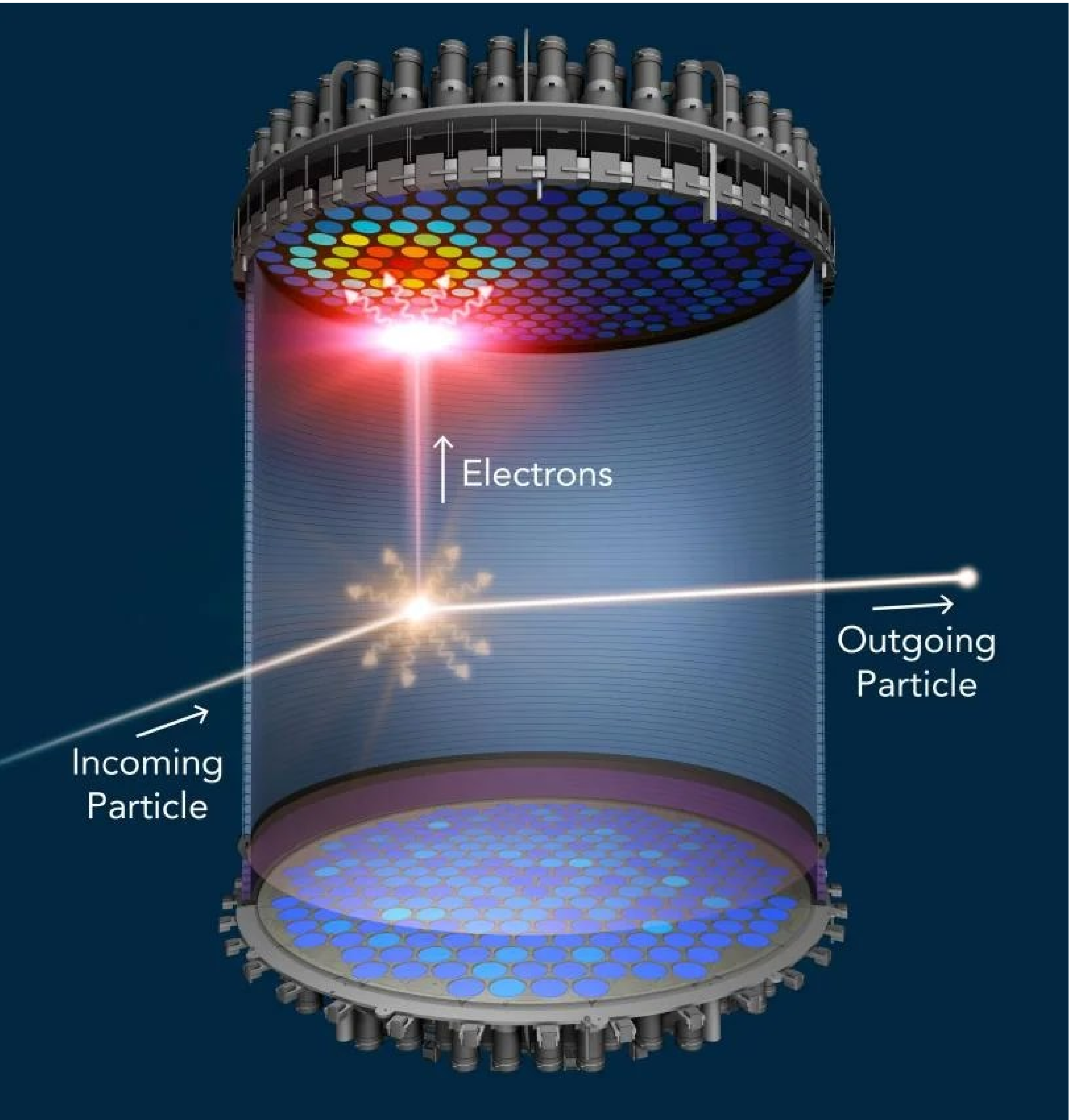
DARK MATTER

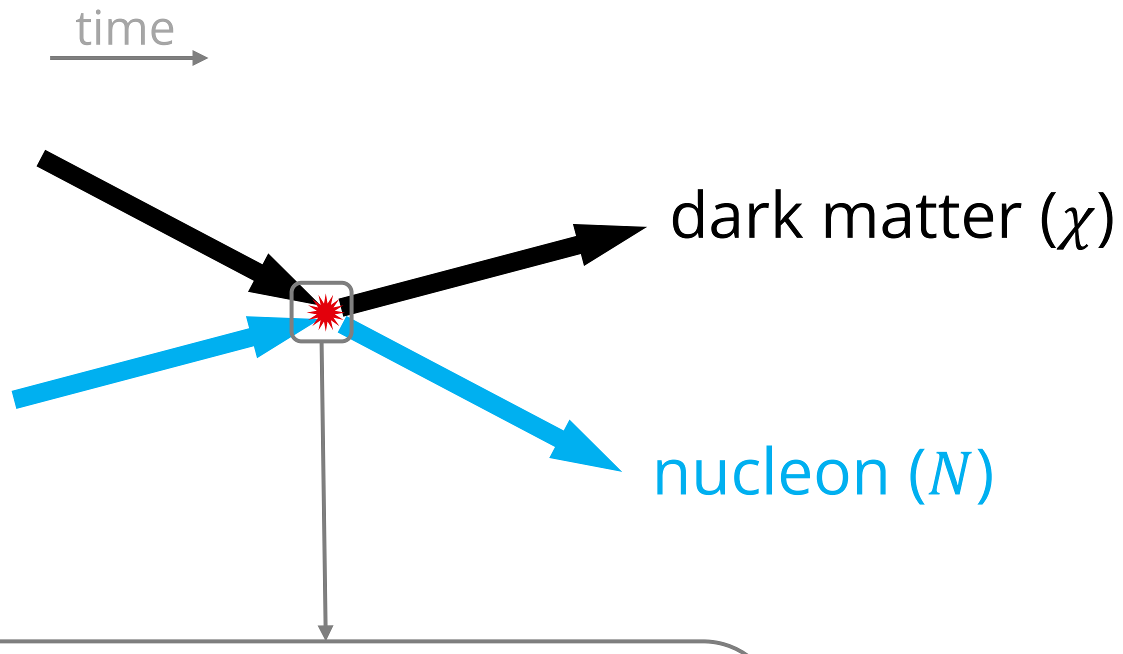




LZ experiment. Credit: *SLAC National Accelerator Laboratory*

DARK MATTER





- Scalar $\bar{N}N$
- Pseudoscalar $\bar{N}i\gamma^5 N$
- Vector $\bar{N}\gamma^\mu N$
- Axial-vector $\bar{N}\gamma^\mu\gamma^5 N$
- Tensor $\bar{N}\sigma^{\mu\nu}N$

LZ experiment. Credit: *SLAC National Accelerator Laboratory*

SPIN-INDEPENDENT SCATTERING

Scalar	$\bar{N}N$	Non-relativistic limit $\longrightarrow$	$2m_N\delta_{ss'}$
Vector	$\bar{N}\gamma^\mu N$		

s, s' are nucleon's spins before and after scattering with DM

SPIN-INDEPENDENT SCATTERING

Scalar	$\bar{N}N$	Non-relativistic limit $\longrightarrow$	$2m_N\delta_{ss'}$	s, s' are nucleon's spins before and after scattering with DM
Vector	$\bar{N}\gamma^{\mu}N$			

independent of the nucleon's spin orientation

SPIN-INDEPENDENT SCATTERING

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Non-relativistic limit → $2m_N\delta_{ss'}$

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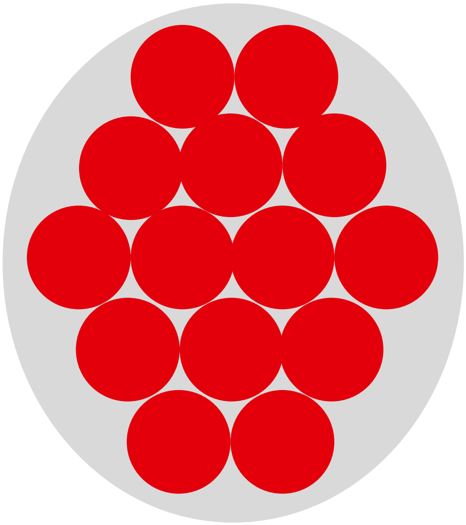
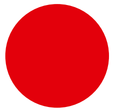
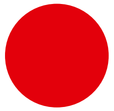
Amplitude DM  scattering $\sim$ Number of  $\times$ Amplitude DM 

SPIN-INDEPENDENT SCATTERING

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Vector	$\bar{N}\gamma^\mu N$			

$\delta_{ss'}$ → independent of the nucleon's spin orientation

DM-nucleus scattering probability $\sim A^2 \times$ DM-nucleon scattering probability

SPIN-INDEPENDENT SCATTERING

Scalar $\bar{N}N$

Vector $\bar{N}\gamma^{\mu}N$

Non-relativistic limit → $2m_N\delta_{ss'}$

s, s' are nucleon's spins before and after scattering with DM

independent of the nucleon's spin orientation

DM-nucleus scattering probability $\sim A^2 \times$ DM-nucleon scattering probability

For Xenon, $A \sim 130 \Longrightarrow 10^4$ enhancement of cross section

SPIN-DEPENDENT SCATTERING

Axial-vector $\bar{N}\gamma^{\mu}\gamma^{5}N$ —Non-relativistic limit→ $4m_N \boldsymbol{S}_{ss'}$

s, s' are nucleon's spins before and after scattering with DM

depends on the nucleon's spin orientation

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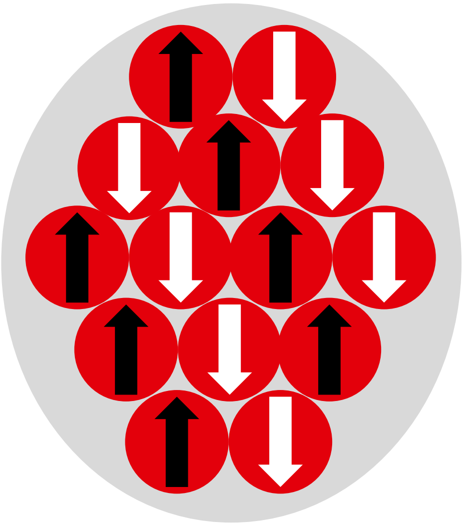
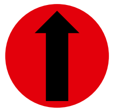
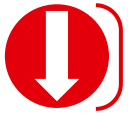
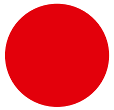
Amplitude DM  scattering ~ [Number of  − Number of ] × Amplitude DM 

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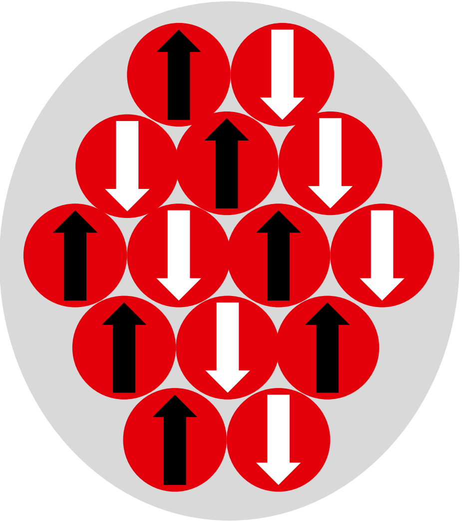
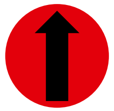
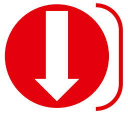
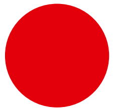
Amplitude DM  scattering $\sim$ [Number of  – Number of ] $\times$ Amplitude DM 

0 for even atomic number (^{132}Xe, ^{134}Xe, …)
± 1 for odd atomic number (^{129}Xe, ^{131}Xe)

SPIN-DEPENDENT SCATTERING

Axial-vector $\bar{N}\gamma^{\mu}\gamma^{5}N$ —Non-relativistic limit→ $4m_N\boldsymbol{S}_{ss'}$

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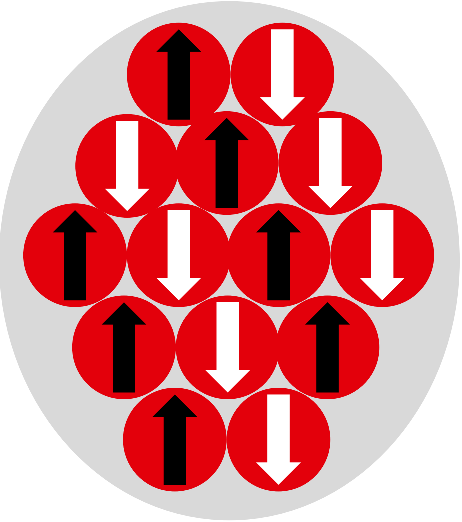
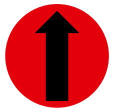
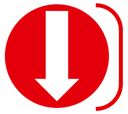
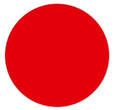
Amplitude DM  scattering ~ (Number of  − Number of ) × Amplitude DM 

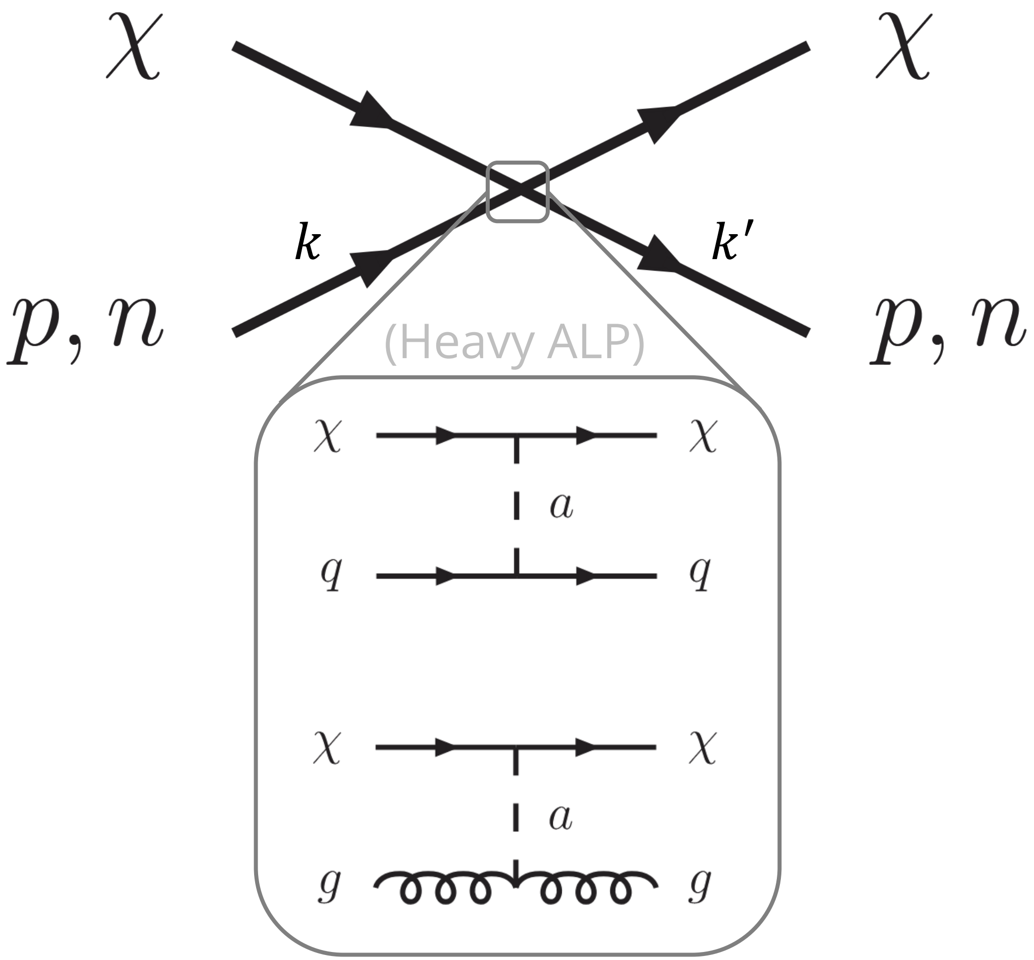
0 for even atomic number (^{132}Xe, ^{134}Xe, …)

± 1 for odd atomic number (^{129}Xe, ^{131}Xe)

Spin-dependent scattering is ~ $\mathbf{10^{-4}}$ as likely as spin-independent scattering for Xenon

ALP-MEDIATED SCATTERING

Pseudoscalar $\bar{N} i\gamma^5 N$

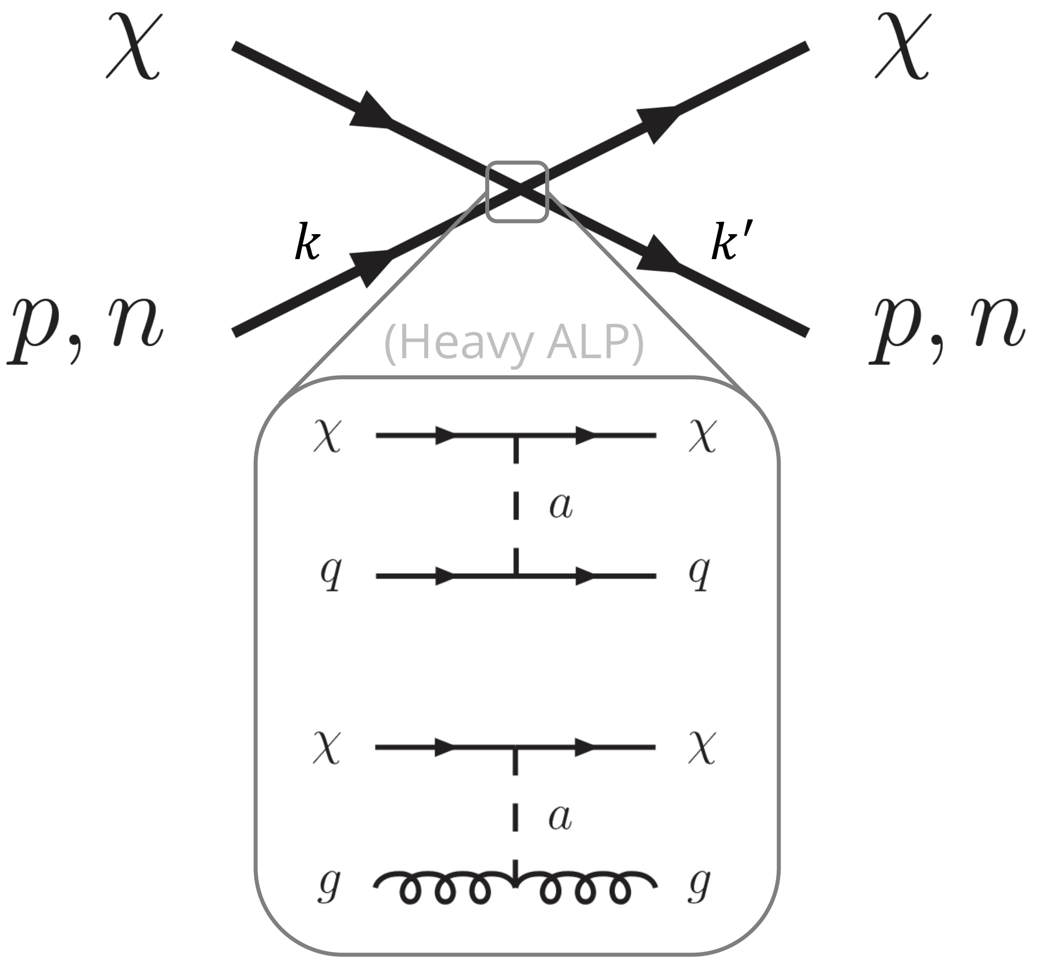


ALP-MEDIATED SCATTERING

recoil momentum $\boldsymbol{q} = \boldsymbol{k}' - \boldsymbol{k}$

Pseudoscalar $\bar{N} i\gamma^5 N$ $\xrightarrow{\text{Non-relativistic limit}}$ $2\boldsymbol{q} \cdot \boldsymbol{S}_{ss'}$

s, s' are nucleon's spins before and after scattering with DM



ALP-MEDIATED SCATTERING

recoil momentum

Pseudoscalar $\bar{N} i \gamma^5 N$ → (Non-relativistic limit) $2\boldsymbol{q} \cdot \boldsymbol{S}_{ss'}$

s, s' are nucleon's spins before and after scattering with DM

spin-dependent

$$\frac{|\boldsymbol{q}|}{m_N} \sim \text{DM velocity} \sim 10^{-3}$$

ALP-mediated scattering is $\sim \left(\frac{|q|}{m_N}\right)^4 \frac{1}{A^2} \sim \mathbf{10^{-16}}$ as likely as spin-independent scattering!

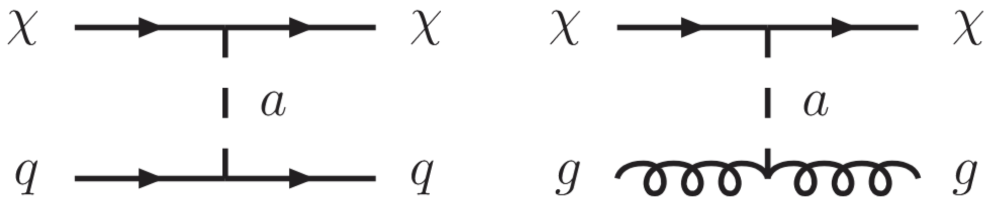
ENHANCEMENT MECHANISM

Light ALP $(m_a \ll |\boldsymbol{q}|)$

Loop effects

ENHANCEMENT MECHANISM

Light ALP $(m_a \ll |\boldsymbol{q}|)$



$$\sim \frac{m_N^2}{\boldsymbol{q}^2 + m_a^2} \sim \frac{m_N^2}{\boldsymbol{q}^2}$$

→ scattering probability is enhanced by $\left(\frac{m_N^2}{\boldsymbol{q}^2}\right)^2 \sim \mathbf{10^{12}}$

Loop effects

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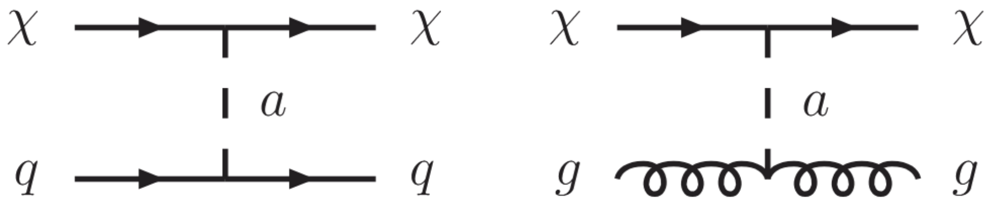

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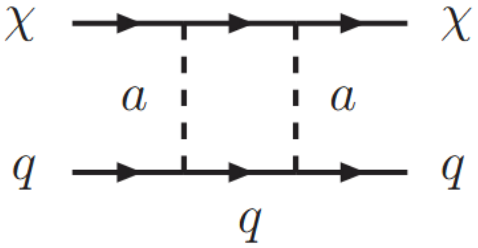
Loop effects

Flavor-conserving

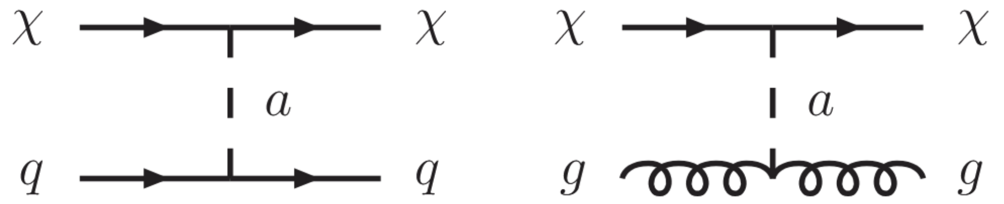


$\sim (\bar{\chi}\chi)(\bar{N}N)$

spin-independent!

ENHANCEMENT MECHANISM

Light ALP $(m_a \ll |\boldsymbol{q}|)$



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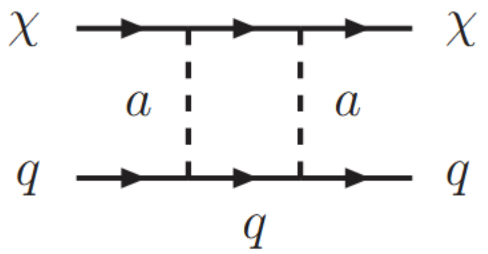


$$\sim (\bar{\chi}\chi)(\bar{N}N)$$

spin-independent!

→ enhanced by $A^2 \left(\frac{m_N}{|\boldsymbol{q}|}\right)^4 \left(\frac{c_\chi c_{qq}}{16\pi^2} \frac{m_\chi^2}{f_a^2}\right)^2 \sim \mathbf{10^{11}} \left(c_\chi c_{qq} \frac{m_\chi^2}{f_a^2}\right)^2$

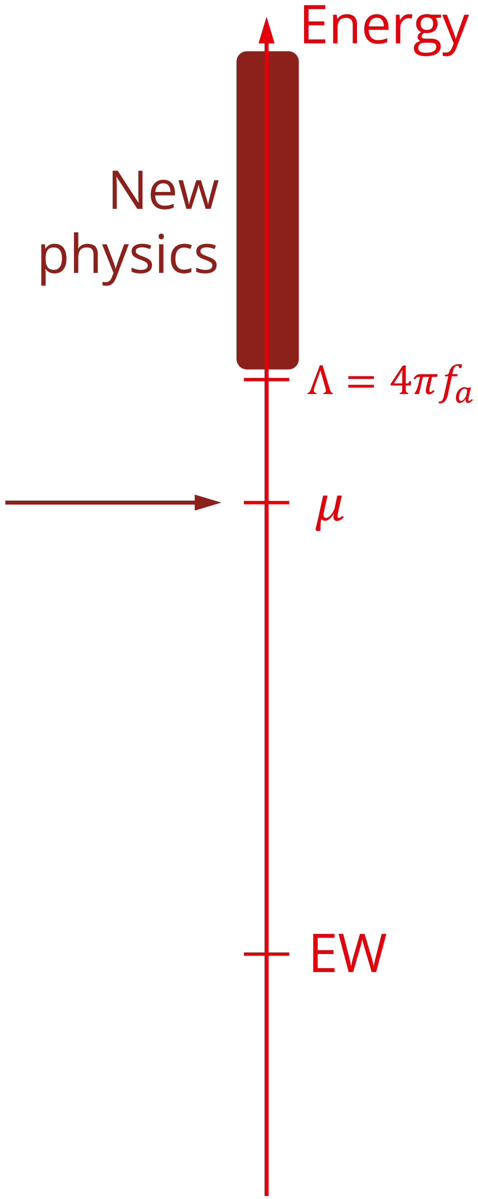
$\frac{\text{spin-independent}}{\text{spin-dependent}}$

Loop-suppressed (heavy ALP limit)

ALP-FERMION INTERACTION

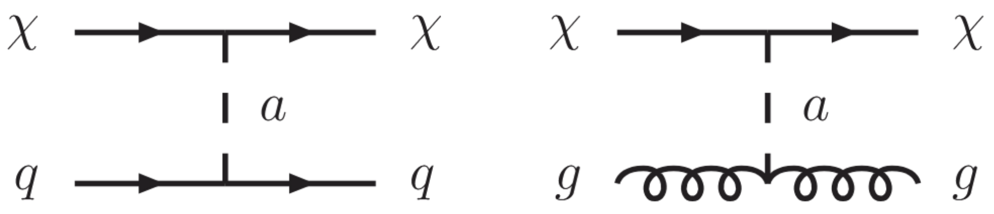
$$\mathcal{L}_{\text{eff}}(\mu) \supset -\sum_f m_f c_{ff} \frac{a}{f_a} \bar{f} i\gamma^5 f$$

Interaction strength ∝ fermion mass



ENHANCEMENT MECHANISM

Light ALP ($m_a \ll |\boldsymbol{q}|$)



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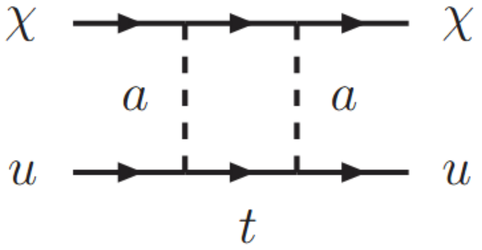
Loop effects

Flavor-changing



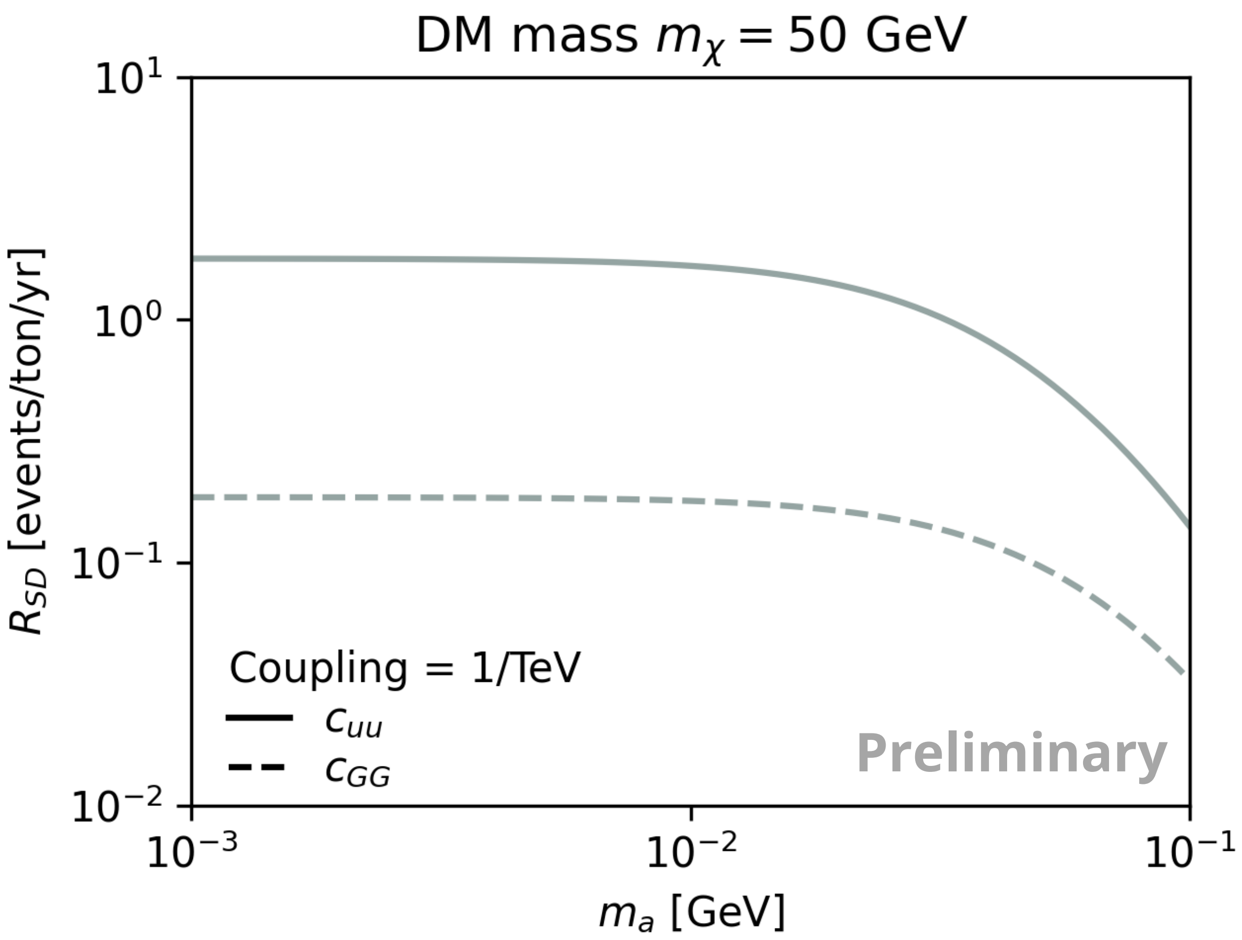
$\sim (\bar{\chi}\chi)(\bar{N}N)$

spin-independent!

→ enhanced by $A^2 \left(\frac{m_N}{|\boldsymbol{q}|}\right)^4 \left(\frac{c_\chi \bar{c}_{ut}}{16\pi^2} \frac{m_\chi^2}{f_a^2}\right)^2 \left(\frac{m_t}{m_u}\right)^2 \sim \mathbf{10^{20}} \left(c_\chi \bar{c}_{ut} \frac{m_\chi^2}{f_a^2}\right)^2$

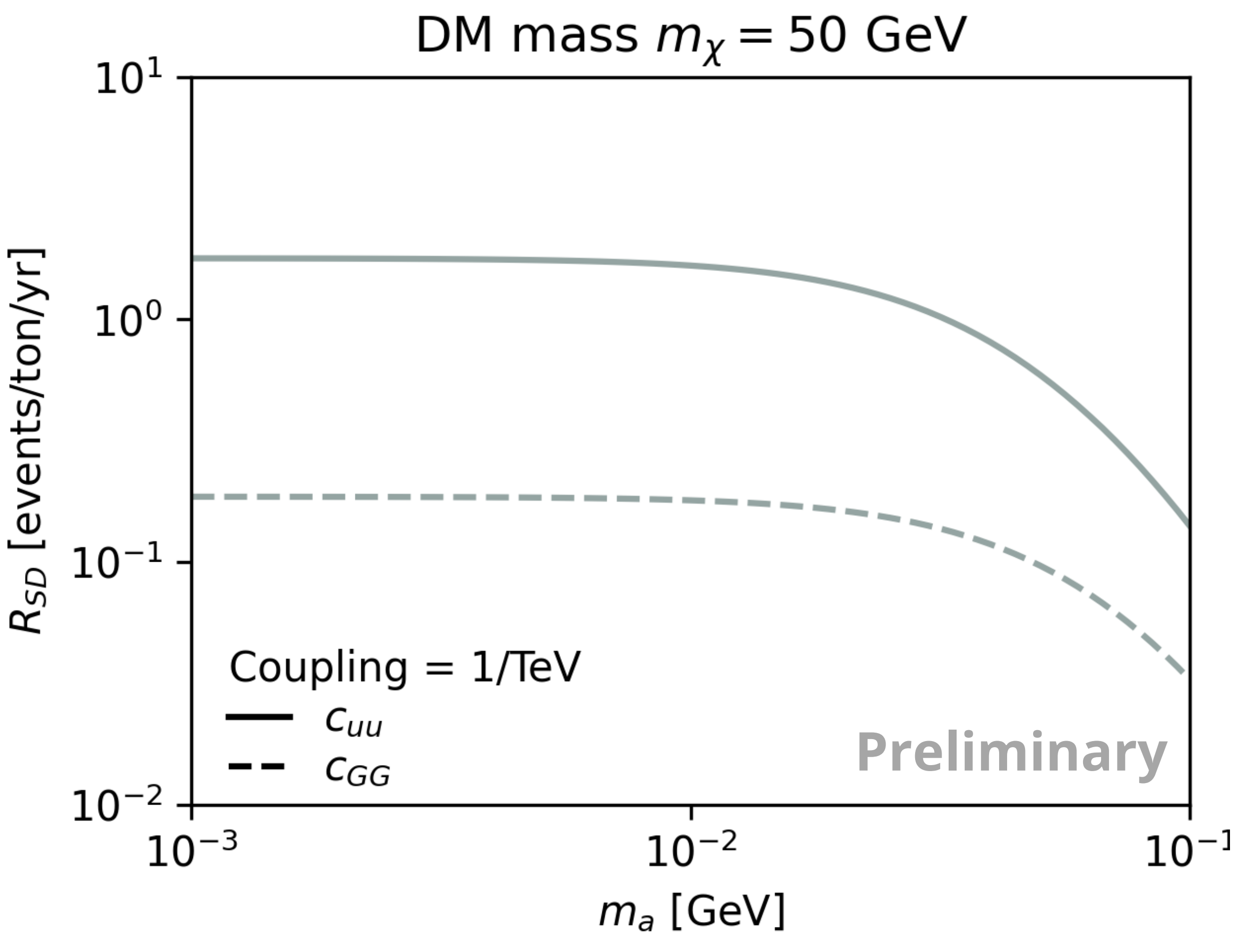
Top mass enhancement

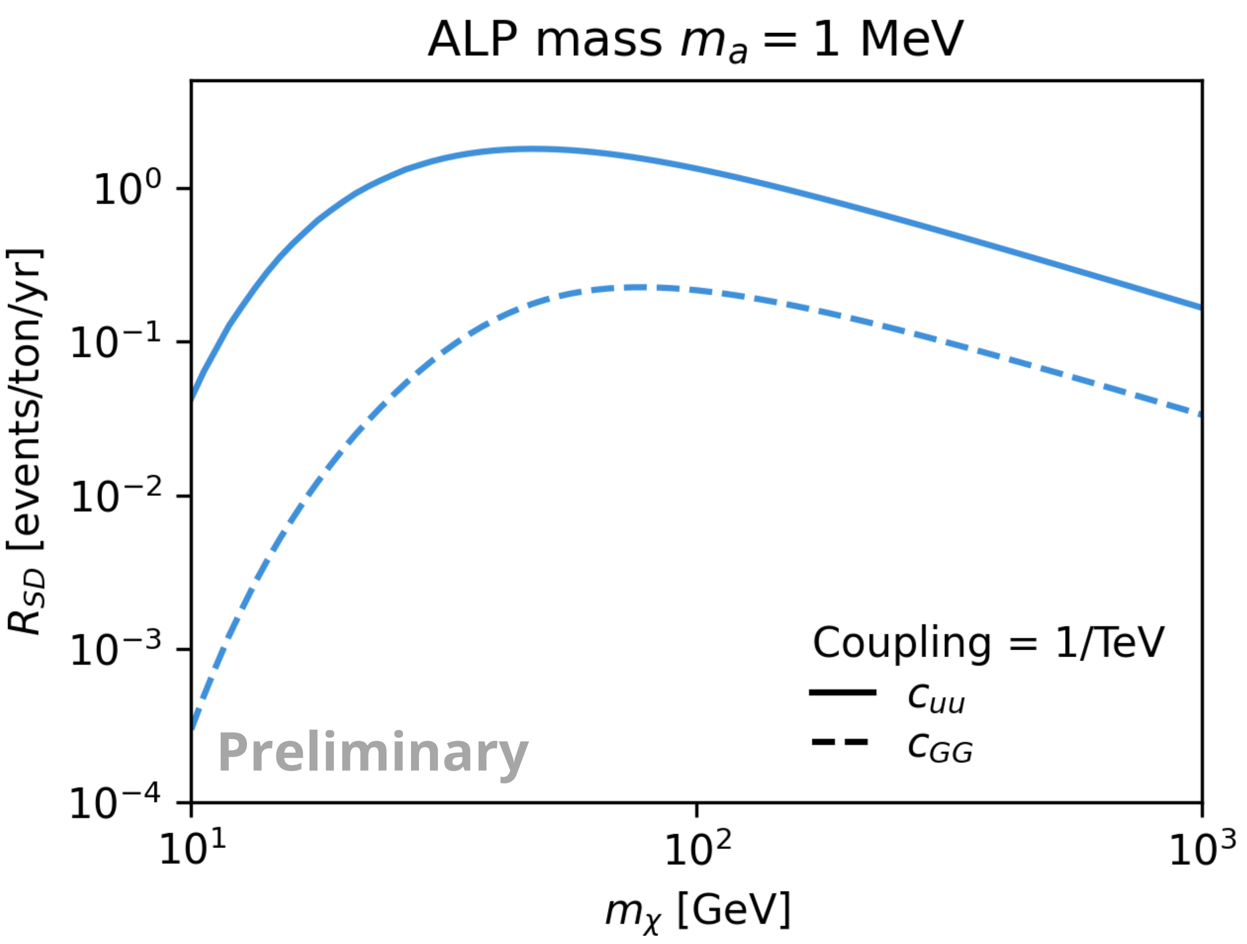
LIGHT ALP $(m_a < 1\ \text{GeV})$



$$\frac{c_{uu} c_\chi}{f_a^2} = \frac{1}{\text{TeV}^2} \quad \text{or} \quad \frac{c_{GG} c_\chi}{f_a^2} = \frac{1}{\text{TeV}^2} \quad \text{@ XENONnT}$$

LIGHT ALP $(m_a < 1 \text{ GeV})$





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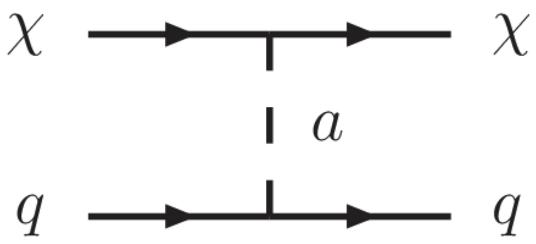

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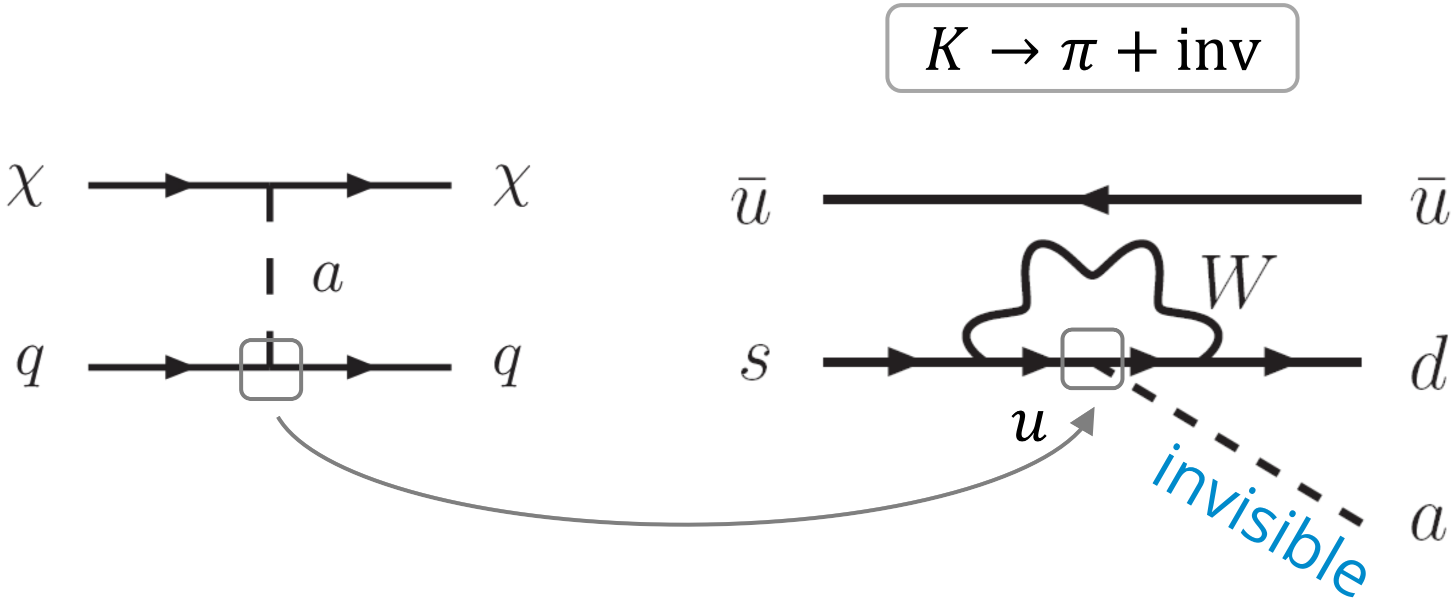

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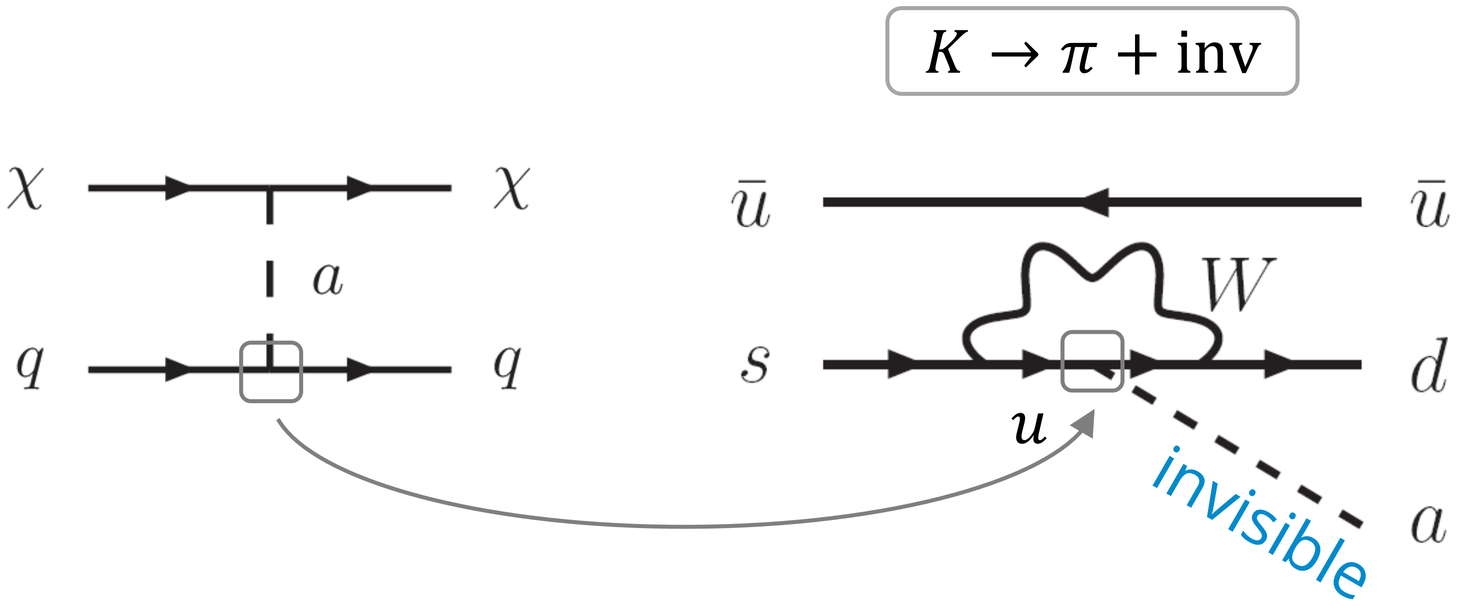
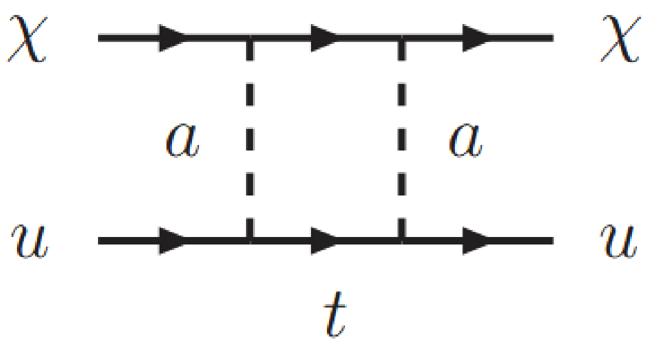


$\text{BR}(K^+ \to \pi^+ + \text{inv}) \lesssim 10^{-11}$

NA62 (2025) [2507.17286]

Excluded by invisible meson decay searches

FLAVOR-CHANGING SCATTERING



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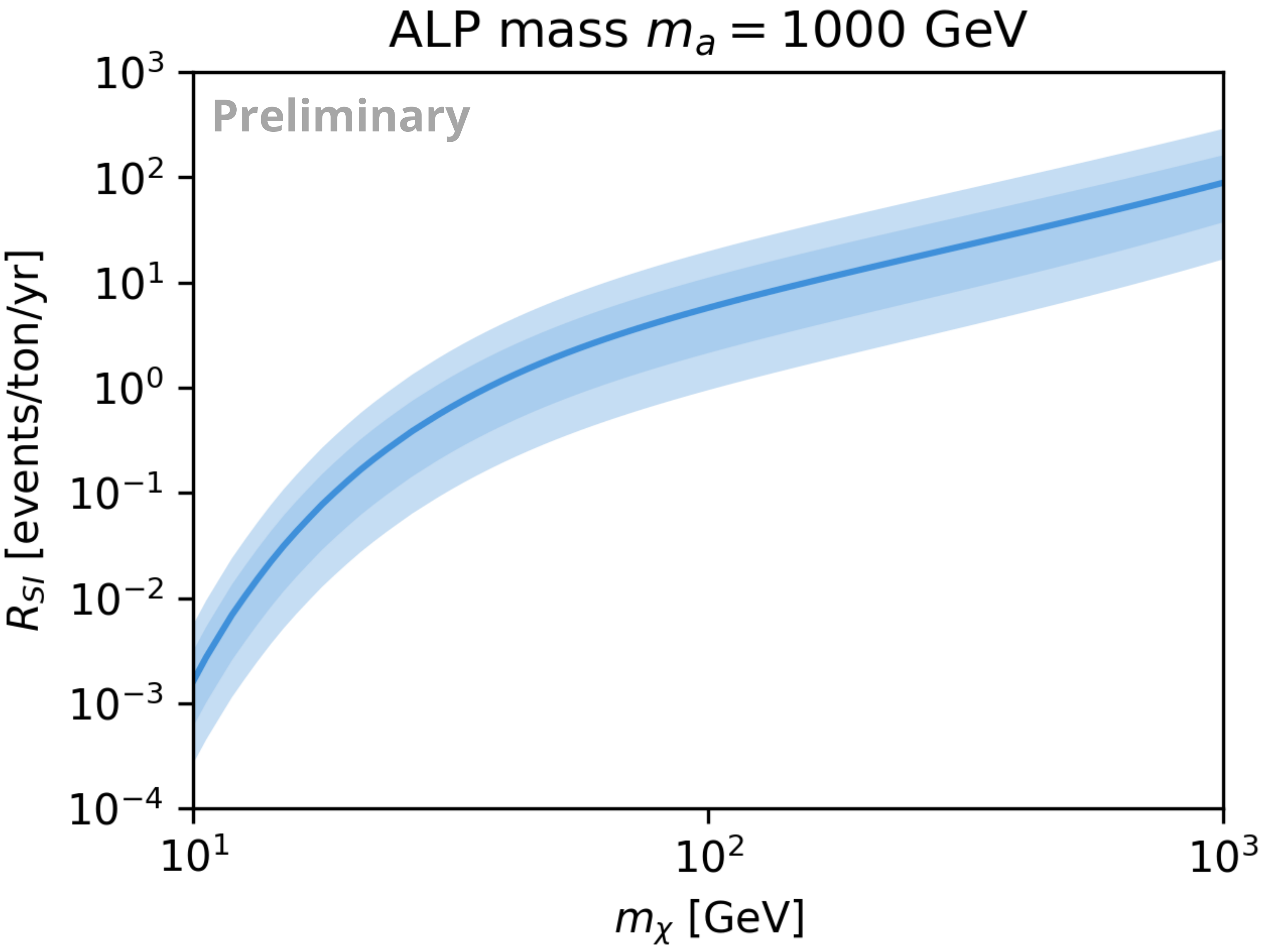

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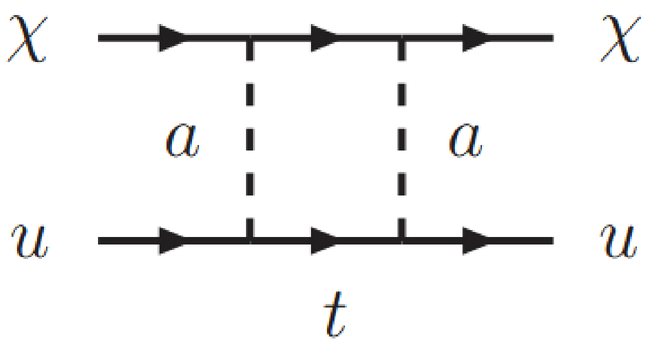

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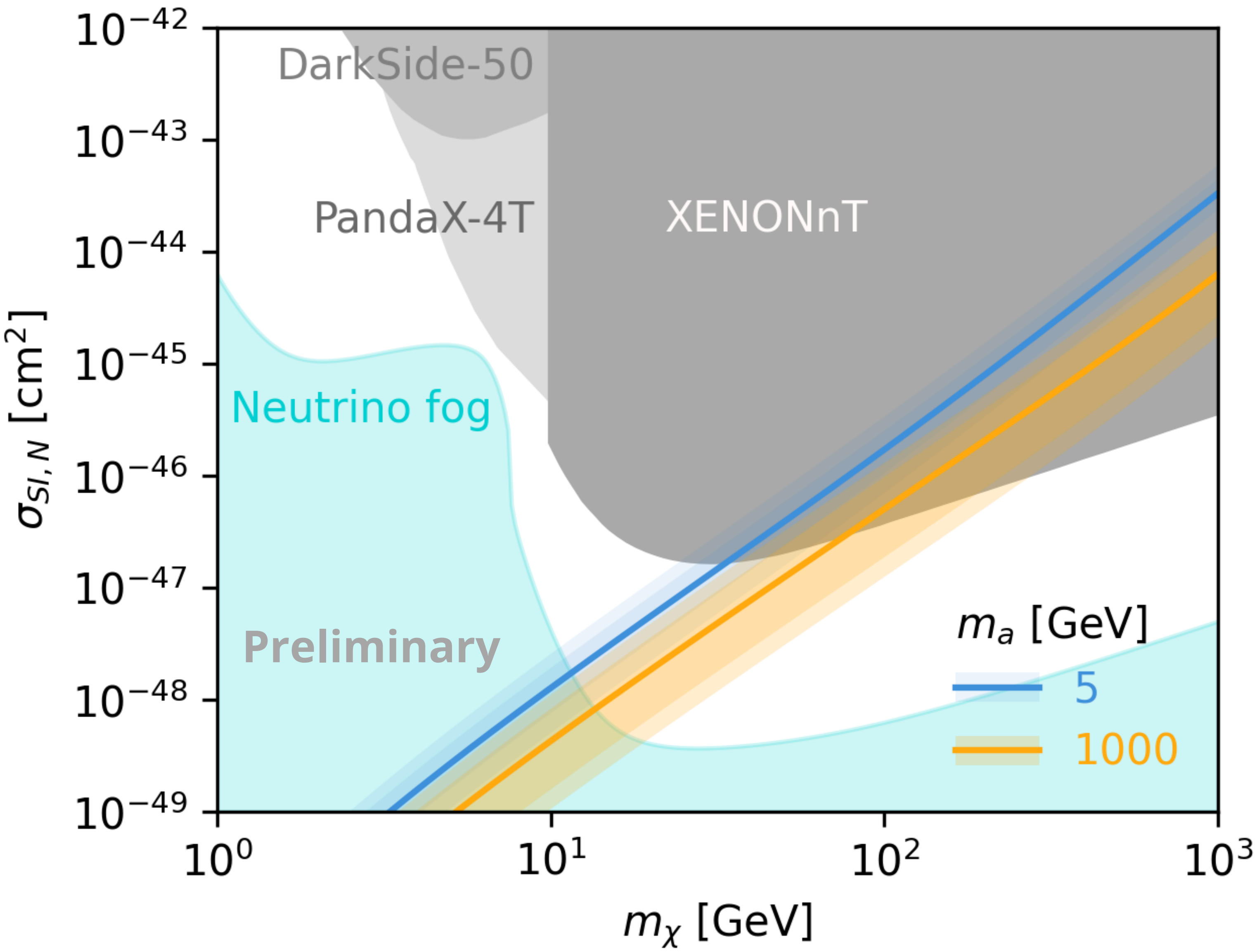


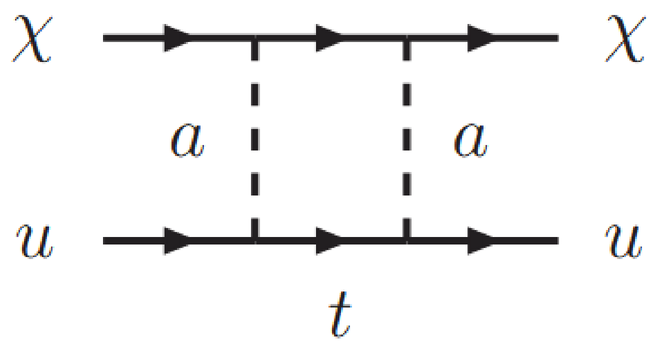
Conclusions

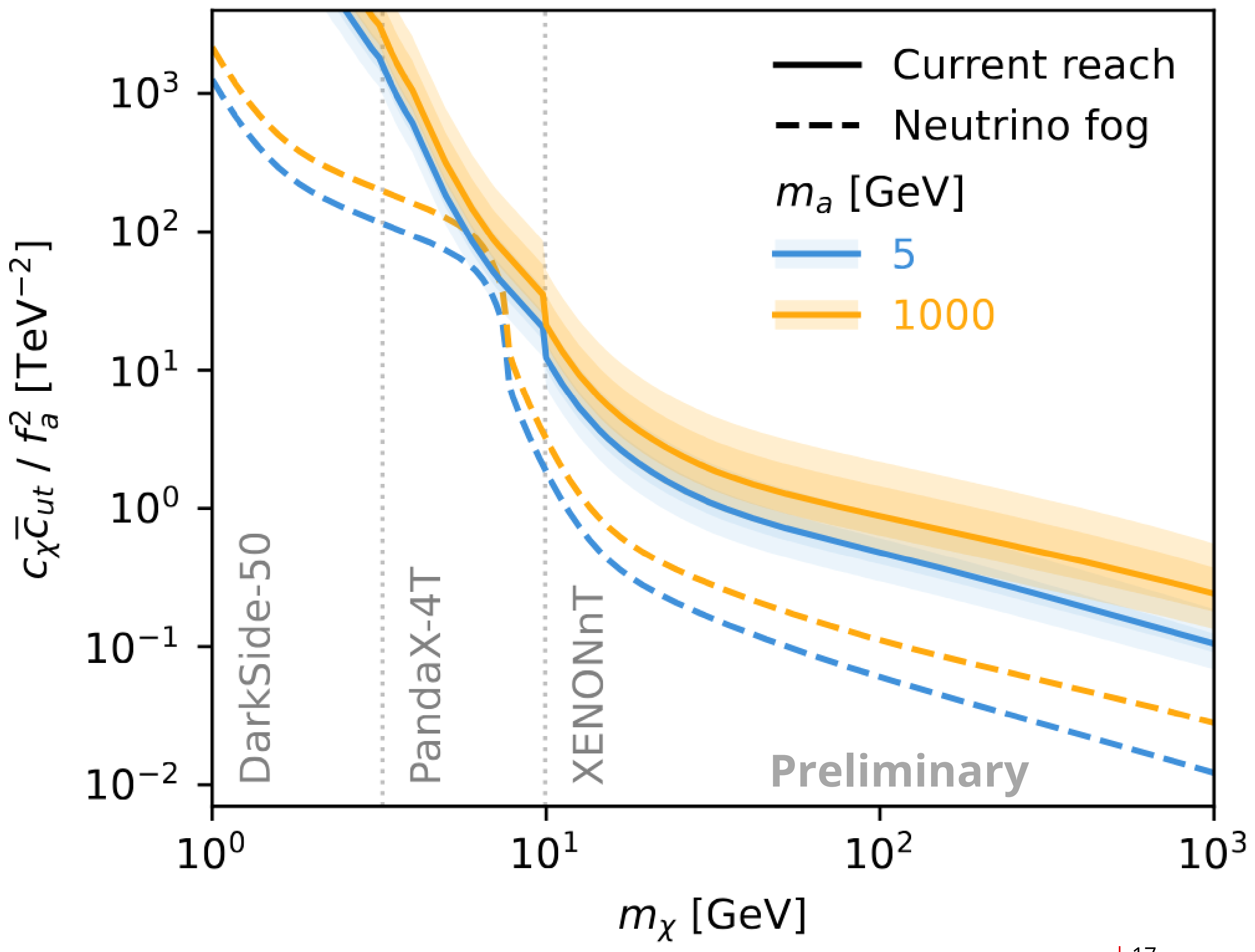
- ALP-mediated scattering is spin-dependent and momentum-suppressed.
- Light ALPs can lift momentum suppression.
- Loop effects can lift both spin- and momentum suppression.
- **XENON-nT is already sensitive to ALP-mediated DM scattering**.

Thank you for listening!

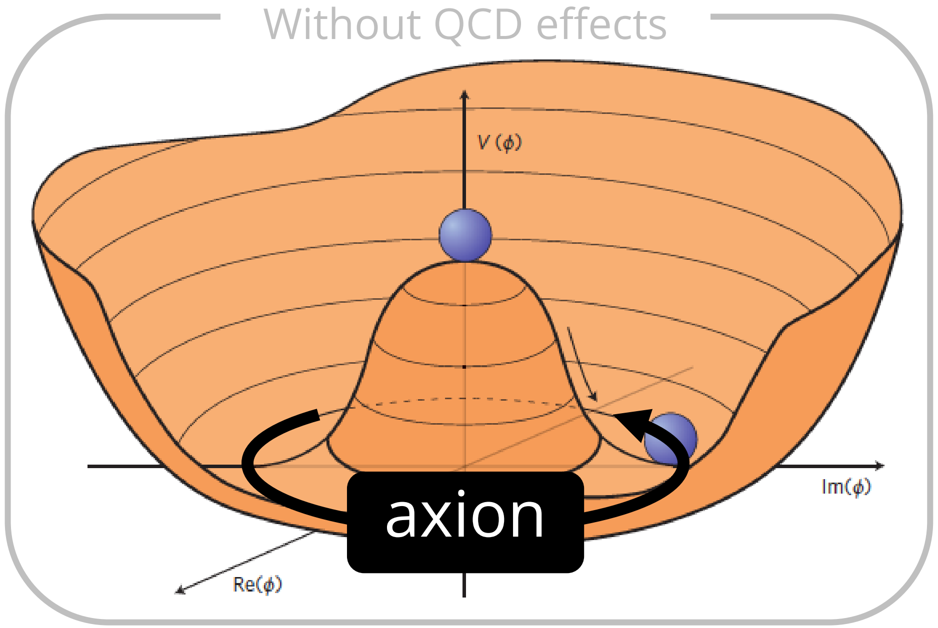
BACKUP SLIDES

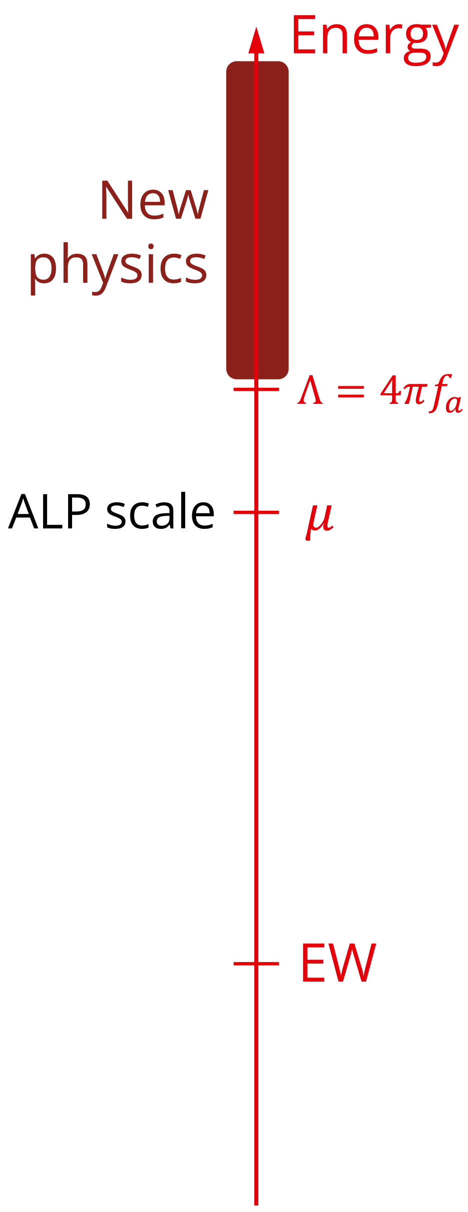
FLAVOR-CHANGING SCATTERING





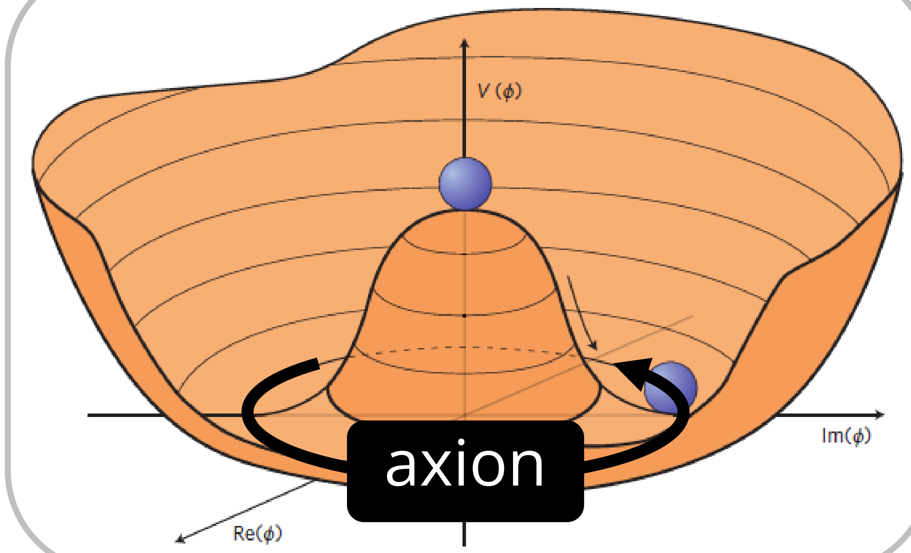
AXION-LIKE PARTICLE (ALP)



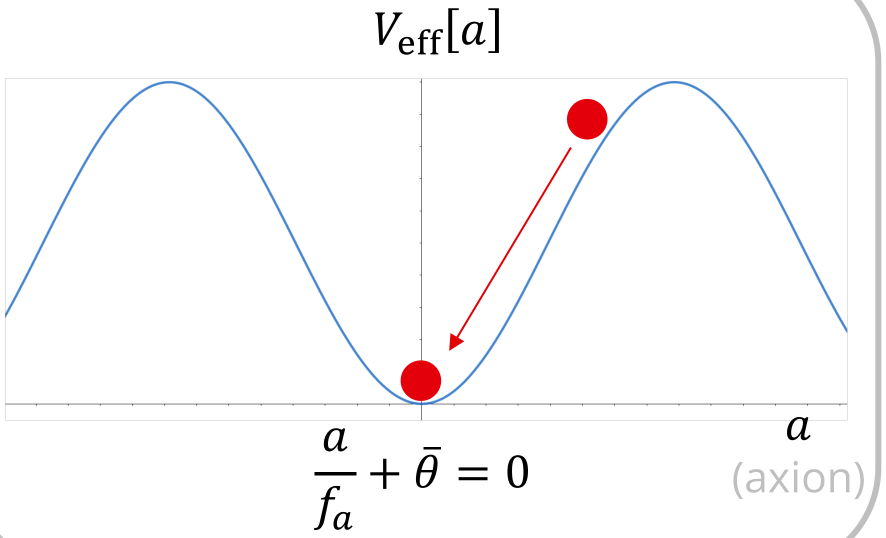


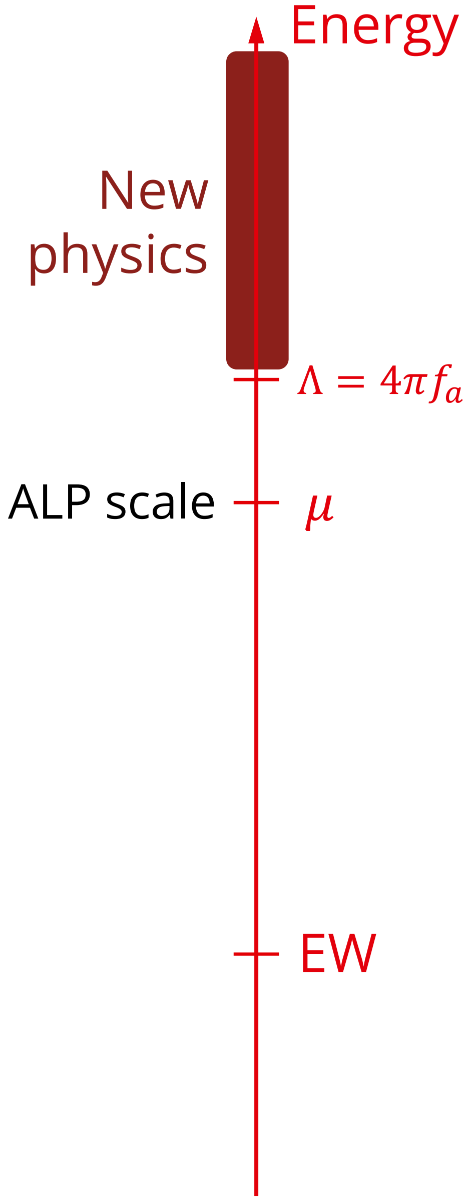
AXION-LIKE PARTICLE (ALP)

Without QCD effects



With QCD effects





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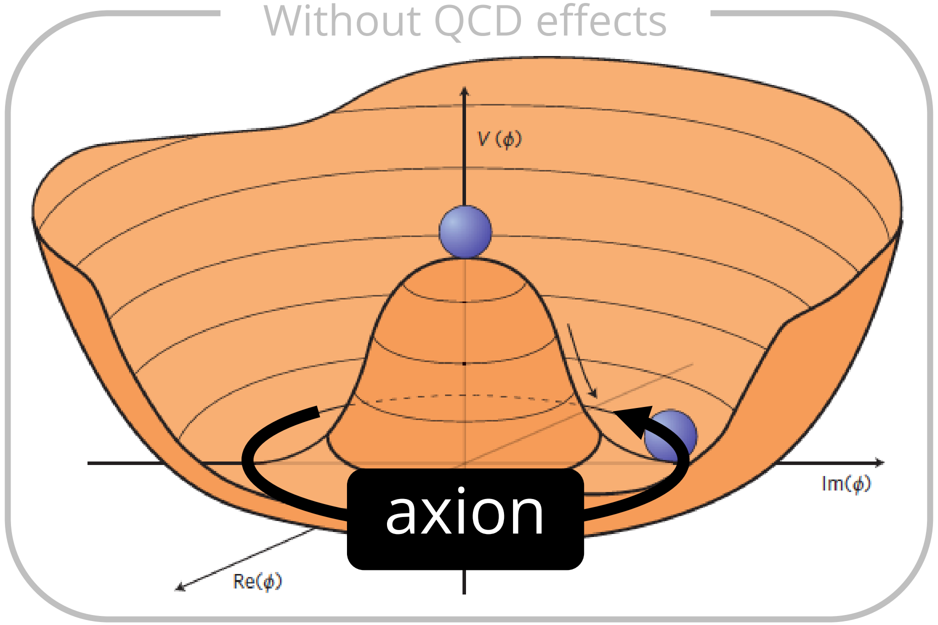
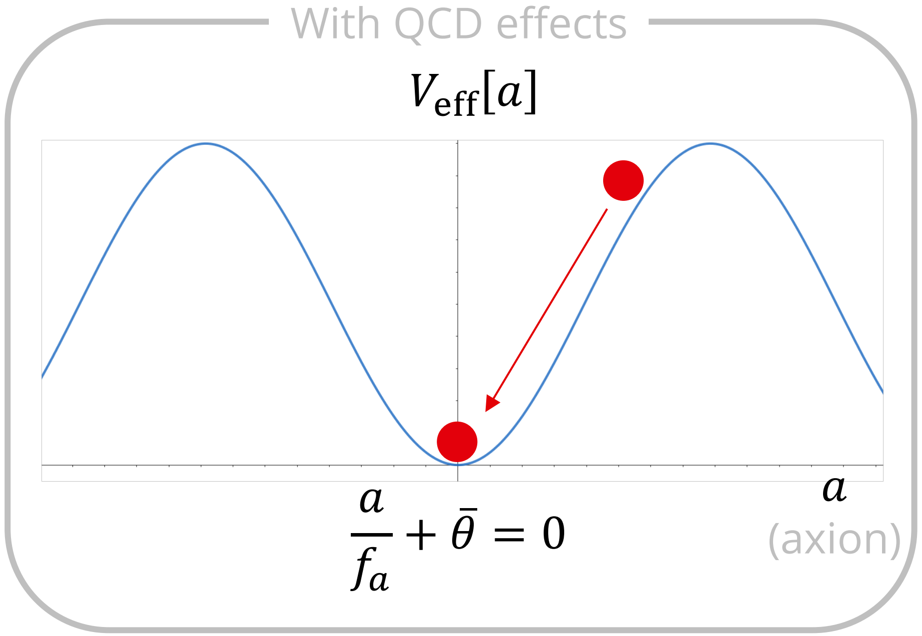
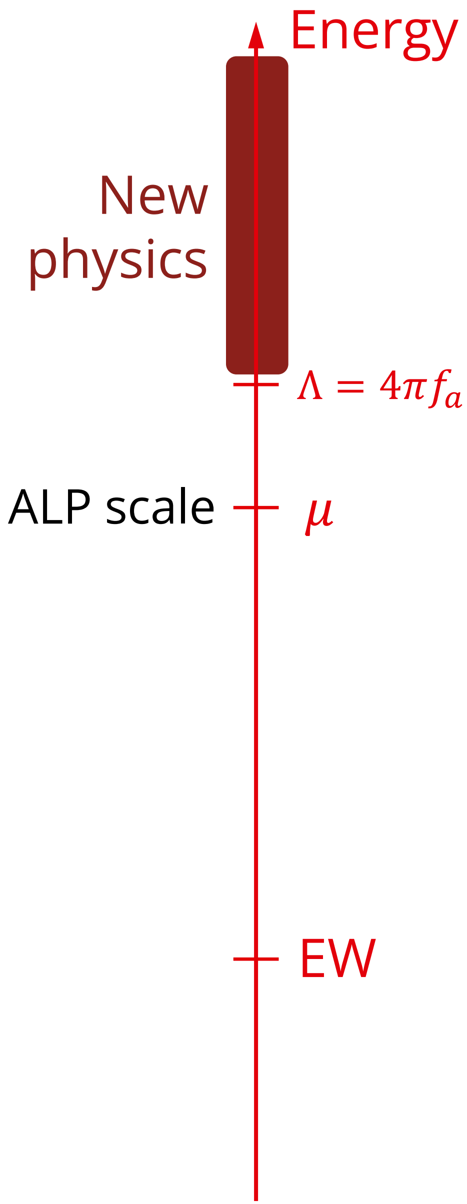
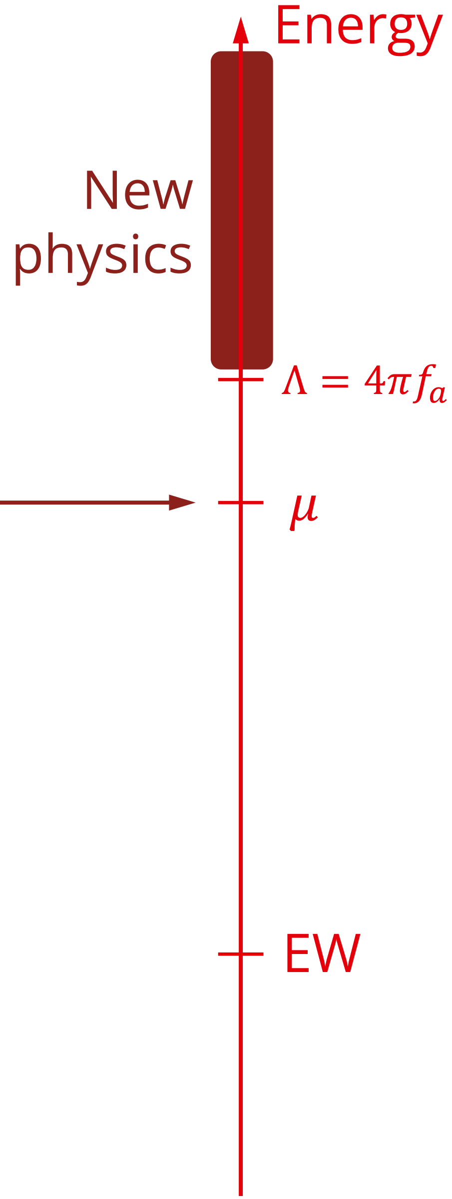




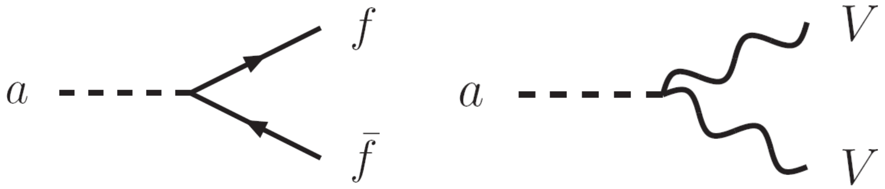


- Pseudoscalar
- Has shift symmetry $a \to a + 2\pi f_a$
- Need not solve strong CP problem

ALP EFFECTIVE THEORY



$$\mathcal{L}_{\text{eff}}(\mu) \supset \frac{1}{2}\partial_\mu a\, \partial^\mu a - \frac{m_a^2}{2} a^2 - \frac{\partial^\mu a}{f_a}\sum_F \bar{F} c_F \gamma_\mu F + \frac{a}{f_a}\sum_V c_{VV}\frac{\alpha_V}{4\pi} V^A_{\mu\nu}\tilde{V}^{A,\mu\nu}$$



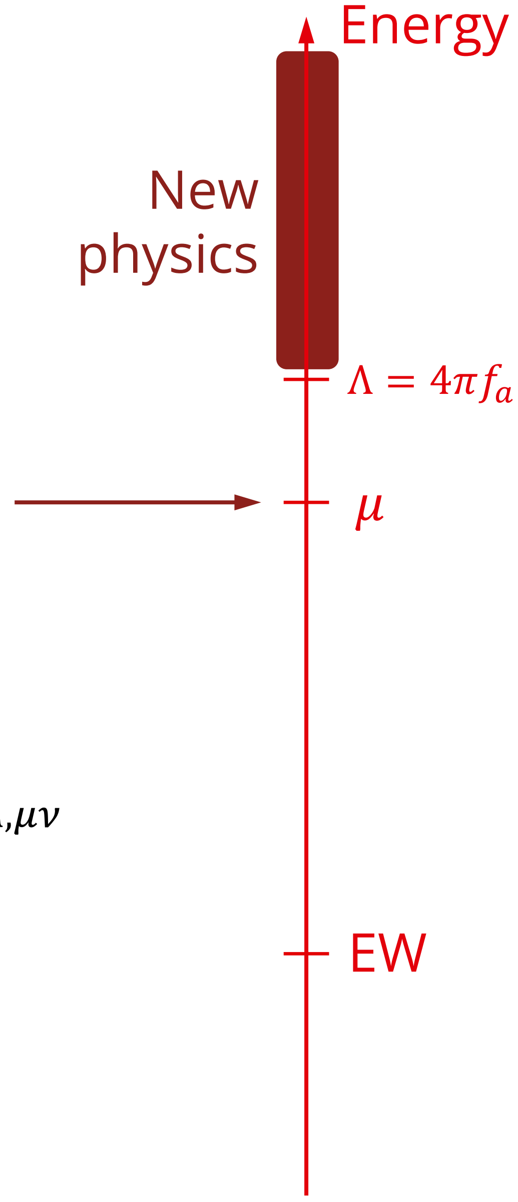
breaks
$a \to a + c$

invariant under $a \to a + 2\pi f_a$

ALP EFFECTIVE THEORY

$$\mathcal{L}_{\text{eff}}(\mu) \supset \frac{1}{2}\partial_\mu a\,\partial^\mu a - \frac{m_a^2}{2}a^2 - \frac{\partial^\mu a}{f_a}\sum_F \bar{F}\boldsymbol{c}_F\gamma_\mu F + \frac{a}{f_a}\sum_V c_{VV}\frac{\alpha_V}{4\pi}V^A_{\mu\nu}\tilde{V}^{A,\mu\nu}$$

$$\to \frac{1}{2}\partial_\mu a\,\partial^\mu a - \frac{m_a^2}{2}a^2 - \sum_f m_f c_{ff}\frac{a}{f_a}\bar{f}i\gamma^5 f + \frac{a}{f_a}\sum_V \tilde{c}_{VV}\frac{\alpha_V}{4\pi}V^A_{\mu\nu}\tilde{V}^{A,\mu\nu}$$

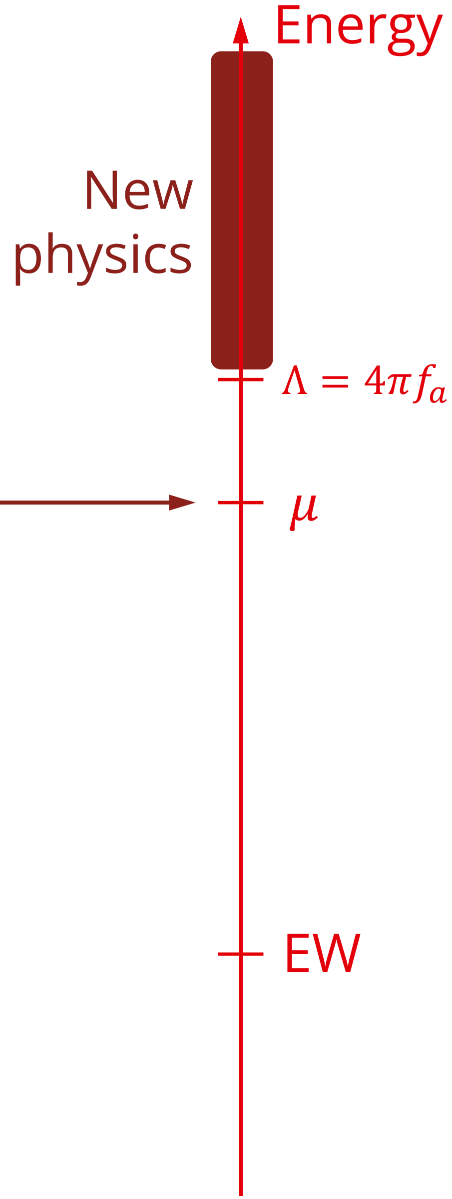


ALP EFFECTIVE THEORY

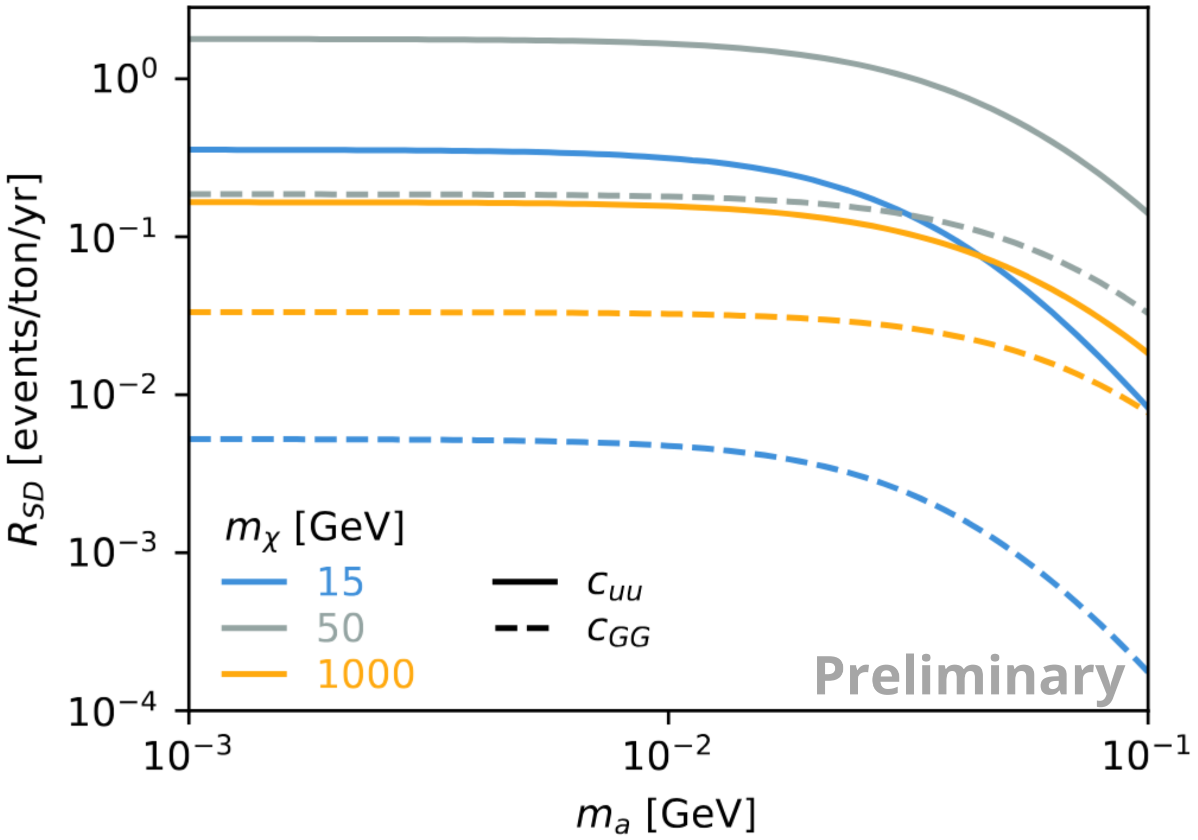
$$\mathcal{L}_{\text{eff}}(\mu) \supset \frac{1}{2}\partial_\mu a\,\partial^\mu a - \frac{m_a^2}{2}a^2 - \frac{\partial^\mu a}{f_a}\sum_F \bar{F}\boldsymbol{c}_F\gamma_\mu F + \frac{a}{f_a}\sum_V c_{VV}\frac{\alpha_V}{4\pi}V_{\mu\nu}^A\tilde{V}^{A,\mu\nu}$$

$$\to \frac{1}{2}\partial_\mu a\,\partial^\mu a - \frac{m_a^2}{2}a^2 - \sum_f m_f c_{ff}\frac{a}{f_a}\bar{f}i\gamma^5 f + \frac{a}{f_a}\sum_V \tilde{c}_{VV}\frac{\alpha_V}{4\pi}V_{\mu\nu}^A\tilde{V}^{A,\mu\nu}$$

Interaction strength ∝ fermion mass

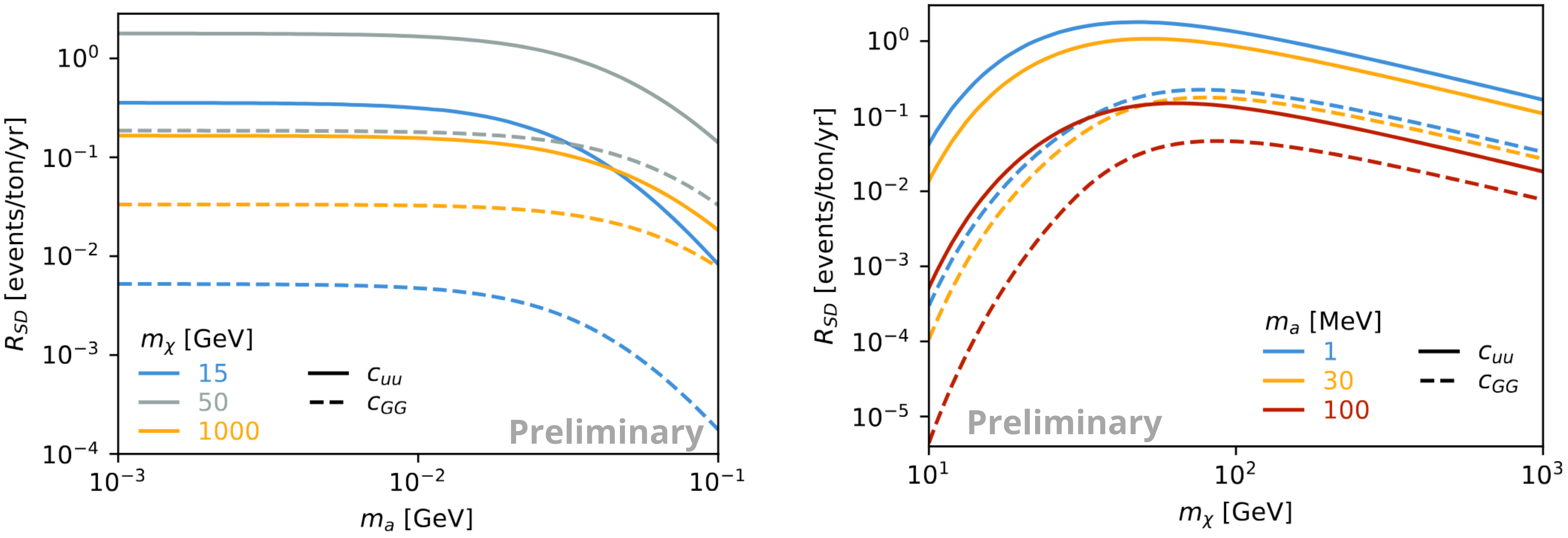


LIGHT ALP $(m_a < 1\ \text{GeV})$



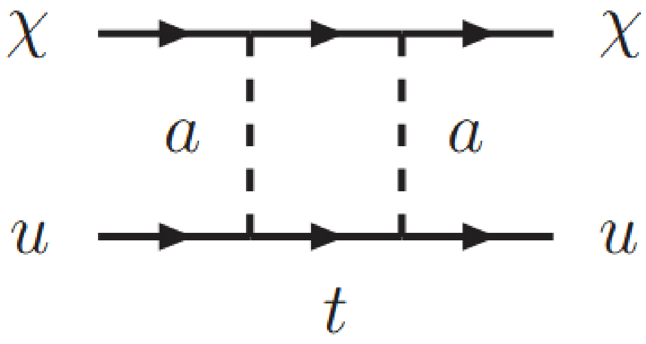
$$\frac{c_{uu}c_\chi}{f_a^2} = \frac{1}{\text{TeV}^2} \quad \text{or} \quad \frac{c_{GG}c_\chi}{f_a^2} = \frac{1}{\text{TeV}^2} \quad \text{@ XENONnT}$$

LIGHT ALP $(m_a < 1\ \text{GeV})$



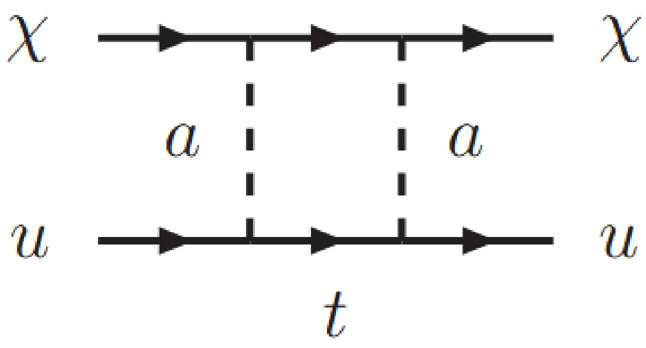
$$\frac{c_{uu}c_\chi}{f_a^2} = \frac{1}{\mathrm{TeV}^2} \quad \text{or} \quad \frac{c_{GG}c_\chi}{f_a^2} = \frac{1}{\mathrm{TeV}^2}$$ @ XENONnT

FLAVOR-CHANGING SCATTERING

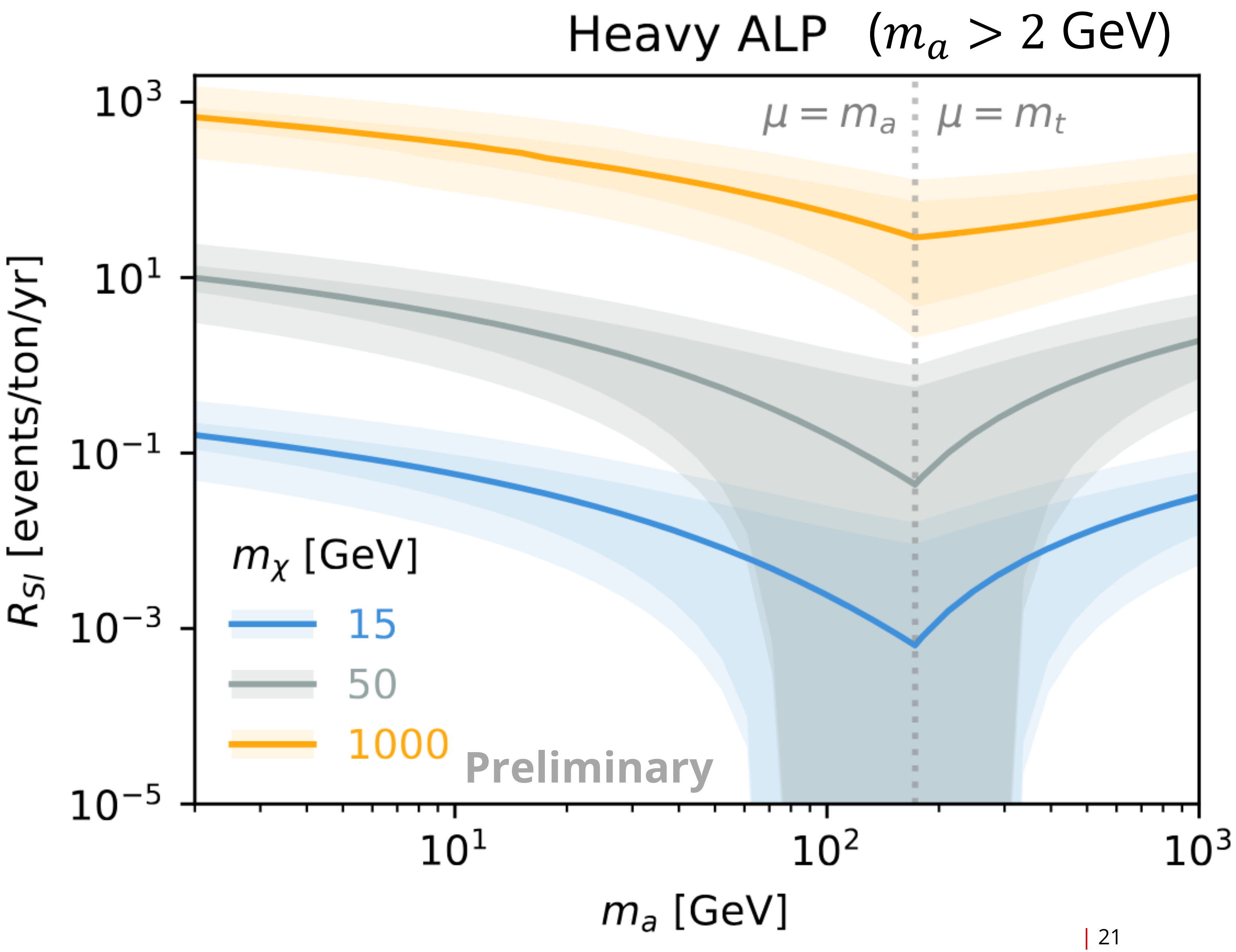


$$\frac{\bar{c}_{ut} c_\chi}{f_a^2} = \frac{1}{\mathrm{TeV}^2}$$

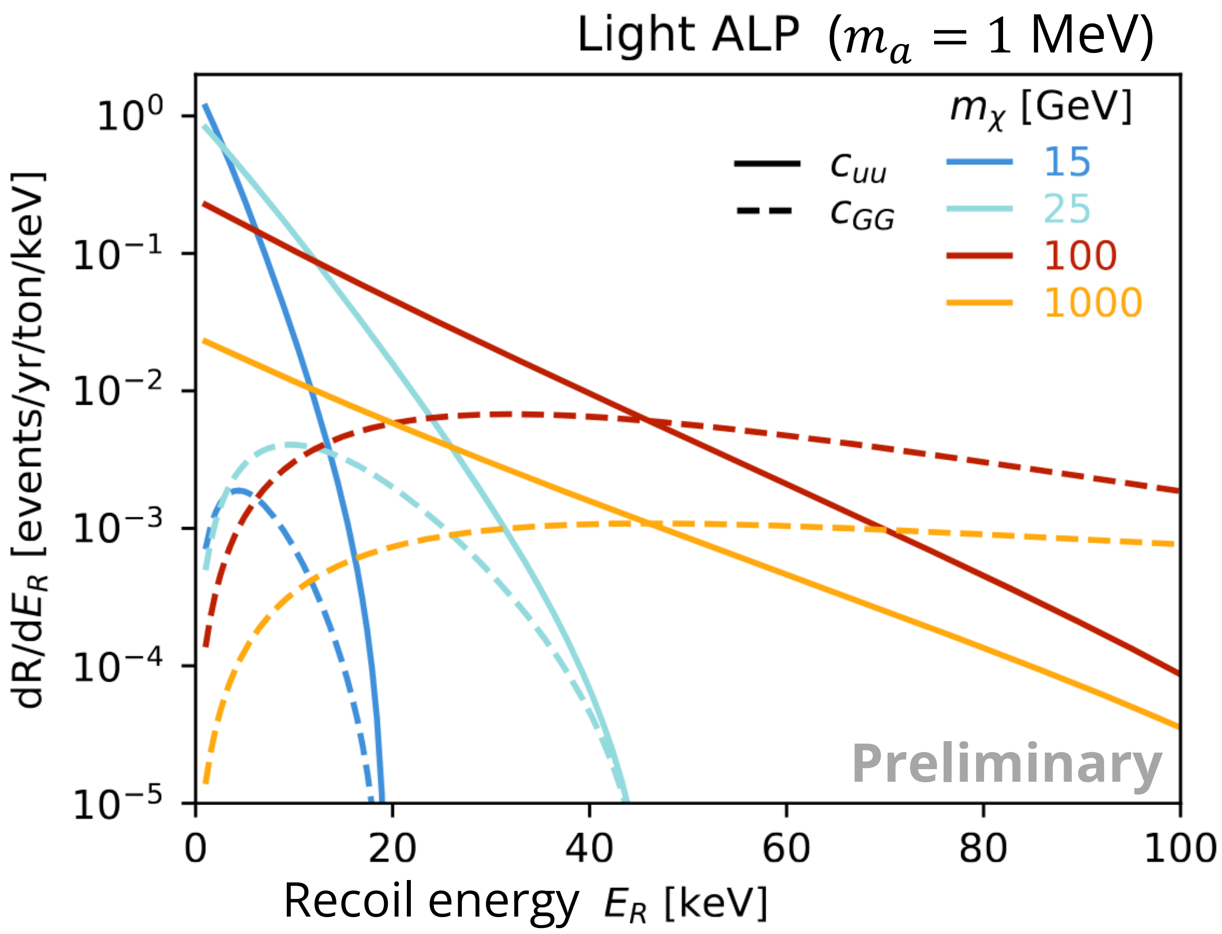
FLAVOR-CHANGING SCATTERING

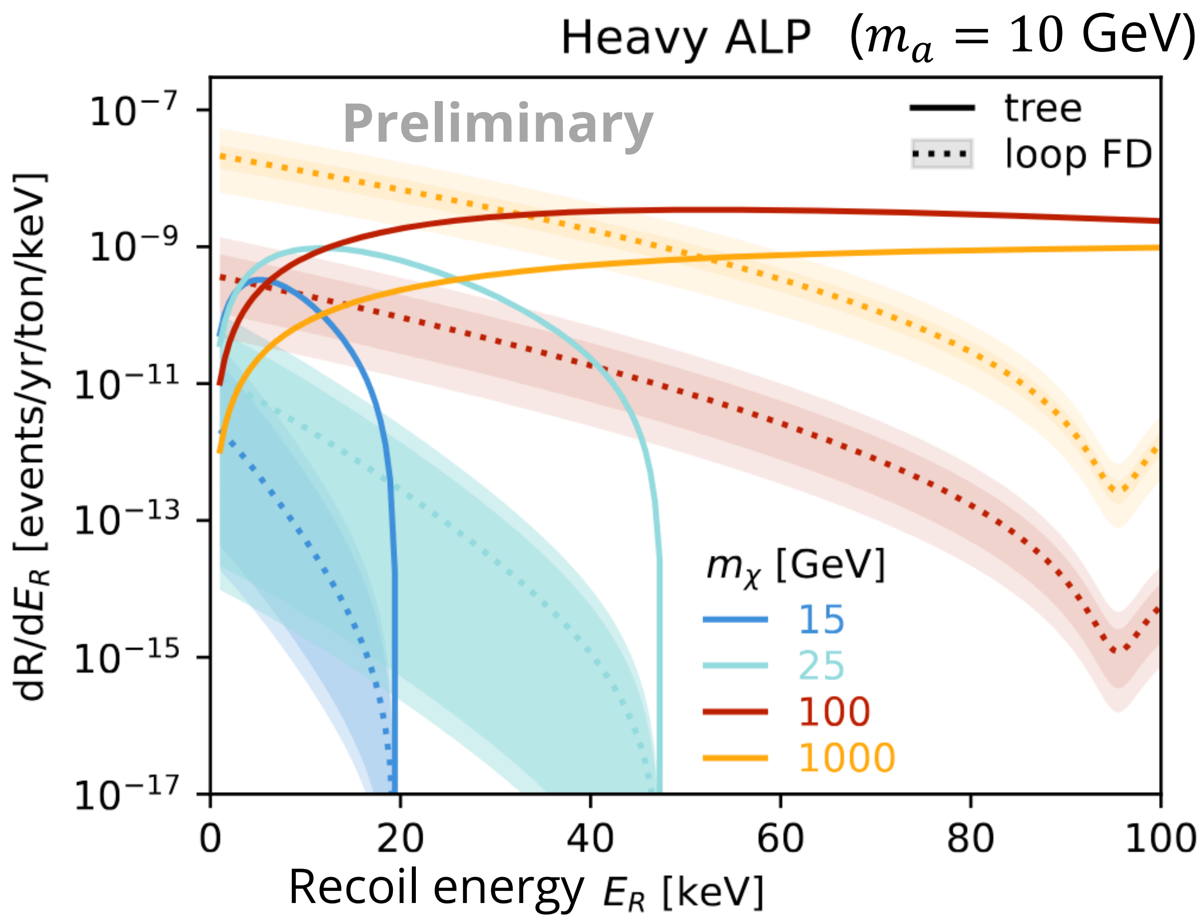


$$\frac{\bar{c}_{ut} c_\chi}{f_a^2} = \frac{1}{\text{TeV}^2}$$



FLAVOR-CONSERVING SCATTERING



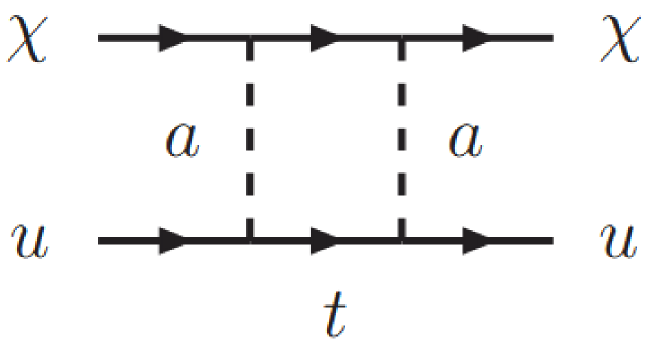


$$\frac{c_{uu}c_\chi}{f_a^2} = \frac{1}{\text{TeV}^2}$$ or $$\frac{c_{GG}c_\chi}{f_a^2} = \frac{1}{\text{TeV}^2}$$

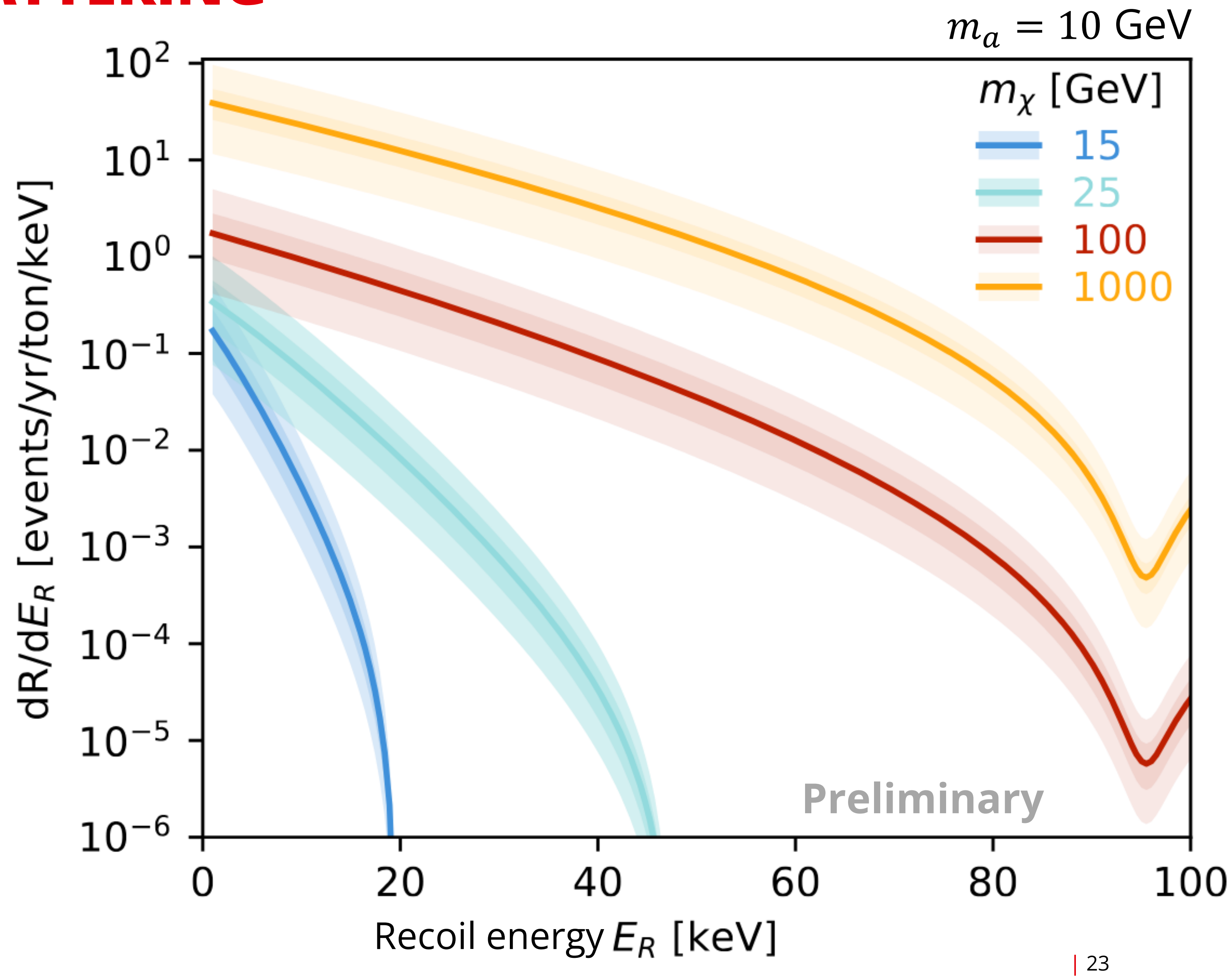
$$\frac{c_{uu}c_\chi}{f_a^2} = \frac{1}{\text{TeV}^2}$$

FLAVOR-CHANGING SCATTERING

See Daniel Mikker's Master's thesis



$$\frac{\bar{c}_{ut} c_\chi}{f_a^2} = \frac{1}{\mathrm{TeV}^2}$$



FROM AMPLITUDE TO ENERGY SPECTRUM

For DM-nucleus scattering

DM-quark amplitude $\mathcal{M}_{\chi q}^{\mathrm{NR}}(\vec{q} = \vec{0})$

Lin (2019)

FROM AMPLITUDE TO ENERGY SPECTRUM

For DM-nucleus scattering

$$\mathcal{M}_{\chi N}^{\mathrm{NR}}(\vec{q} = \vec{0})$$

DM-nucleon amplitude

EFT-matching

DM-quark amplitude $\mathcal{M}_{\chi q}^{\mathrm{NR}}(\vec{q} = \vec{0})$

FROM AMPLITUDE TO ENERGY SPECTRUM

For DM-nucleus scattering

DM-nucleon **reference** cross section, what experiments report

$$\bar{\sigma}_n = \frac{\mu_{\chi n}^2}{\pi} \overline{\left|\mathcal{M}_{\chi N}^{\mathrm{NR}}(\vec{q} = \vec{0})\right|^2}$$

DM-nucleon amplitude

EFT-matching

DM-quark amplitude $\mathcal{M}_{\chi q}^{\mathrm{NR}}(\vec{q} = \vec{0})$

FROM AMPLITUDE TO ENERGY SPECTRUM

For DM-nucleus scattering

$$\sigma_n = \bar{\sigma}_n F^2(q^2)$$

All momentum dependence is factored out

DM-nucleon **reference** cross section, what experiments report

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DM-nucleon amplitude

EFT-matching

DM-quark amplitude $\mathcal{M}_{\chi q}^{\mathrm{NR}}(\vec{q} = \vec{0})$

FROM AMPLITUDE TO ENERGY SPECTRUM

For DM-nucleus scattering

$$\frac{d\sigma_A}{dE_R} \equiv \frac{m_A}{2v^2\mu_{\chi A}^2}\sigma_n F_A^2(q)$$

DM-nucleon "cross section"

Recoil energy $E_R = \frac{q^2}{2m_A}$

Phase space integration

Nuclear form factor

$$\sigma_n = \bar{\sigma}_n F^2(q^2)$$

All momentum dependence is factored out

$$\bar{\sigma}_n = \frac{\mu_{\chi n}^2}{\pi}\overline{\left|\mathcal{M}_{\chi N}^{\mathrm{NR}}\left(\vec{q}=\vec{0}\right)\right|^2}$$

DM-nucleon **reference** cross section, what experiments report

DM-nucleon amplitude

EFT-matching

DM-quark amplitude $\mathcal{M}_{\chi q}^{\mathrm{NR}}\left(\vec{q}=\vec{0}\right)$

FROM AMPLITUDE TO ENERGY SPECTRUM

For DM-nucleus scattering

Luminosity

DM-nucleus cross section

$$\frac{\mathrm{d}R}{\mathrm{d}E_R} = n_\chi N_A \int d^3\vec{v}\, v f(\vec{v}) \frac{\mathrm{d}\sigma_A}{\mathrm{d}E_R}$$

DM-nucleon “cross section”

$$\frac{\mathrm{d}\sigma_A}{\mathrm{d}E_R} \equiv \frac{m_A}{2v^2\mu_{\chi A}^2} \sigma_n F_A^2(q)$$

Recoil energy $E_R = \frac{q^2}{2m_A}$

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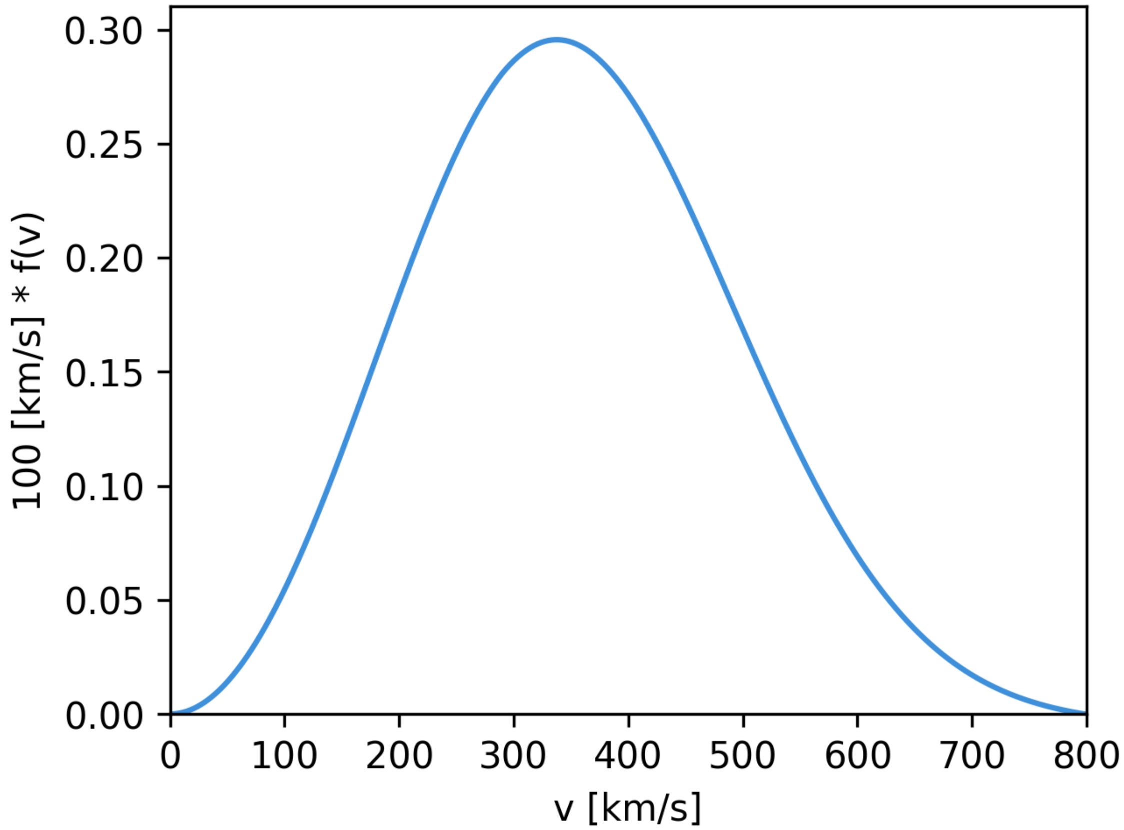
DM-quark amplitude $\mathcal{M}_{\chi q}^{\mathrm{NR}}(\vec{q} = \vec{0})$

FROM AMPLITUDE TO ENERGY SPECTRUM

$$\frac{\mathrm{d}R}{\mathrm{d}E_R} = n_\chi N_A \int d^3\vec{v}\; v f(\vec{v}) \frac{\mathrm{d}\sigma_A}{\mathrm{d}E_R}$$

DM velocity distribution in detector's frame



Standard DM Halo Model

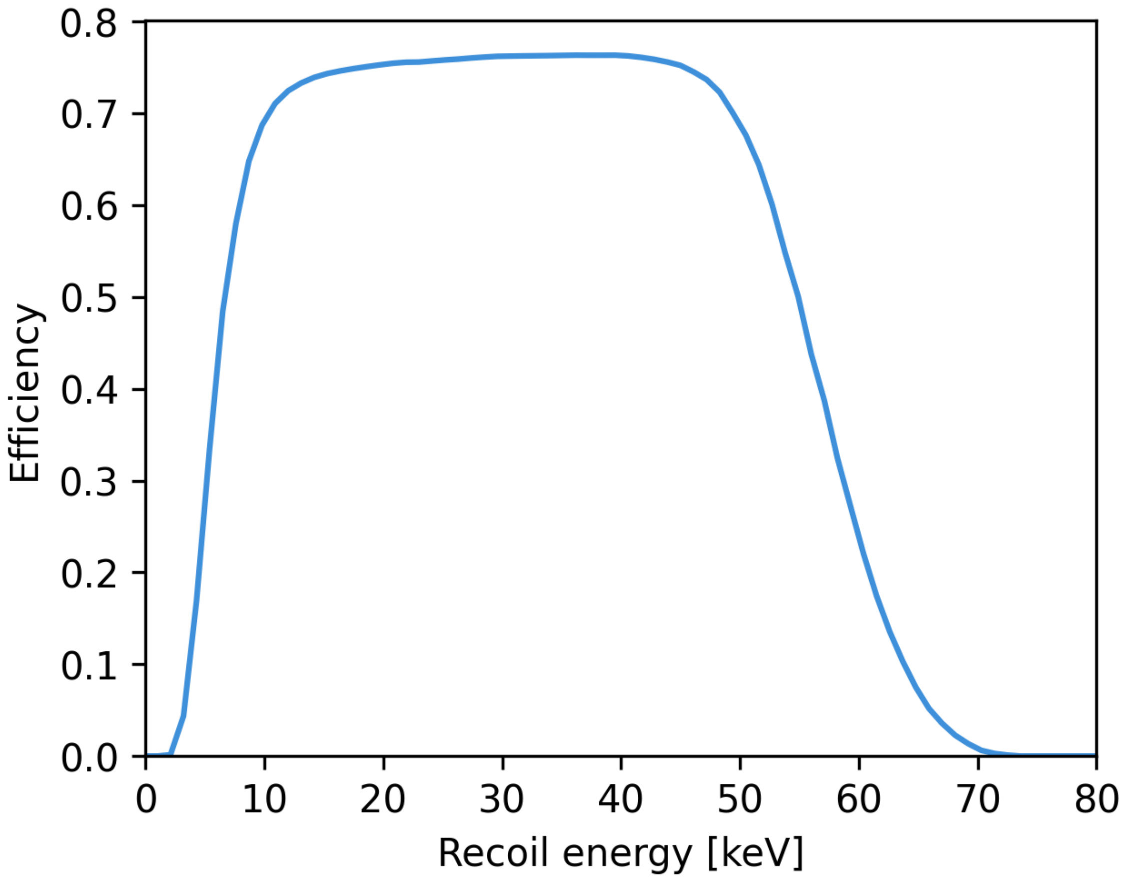
Isotropic Maxwell-Boltzmann distribution

Baxter et al. (2021) [2105.00599]

FROM AMPLITUDE TO ENERGY SPECTRUM

Total rate $R = \int \frac{\mathrm{d}R}{\mathrm{d}E_R} \times$

XENONnT (2025) [2502.18005]

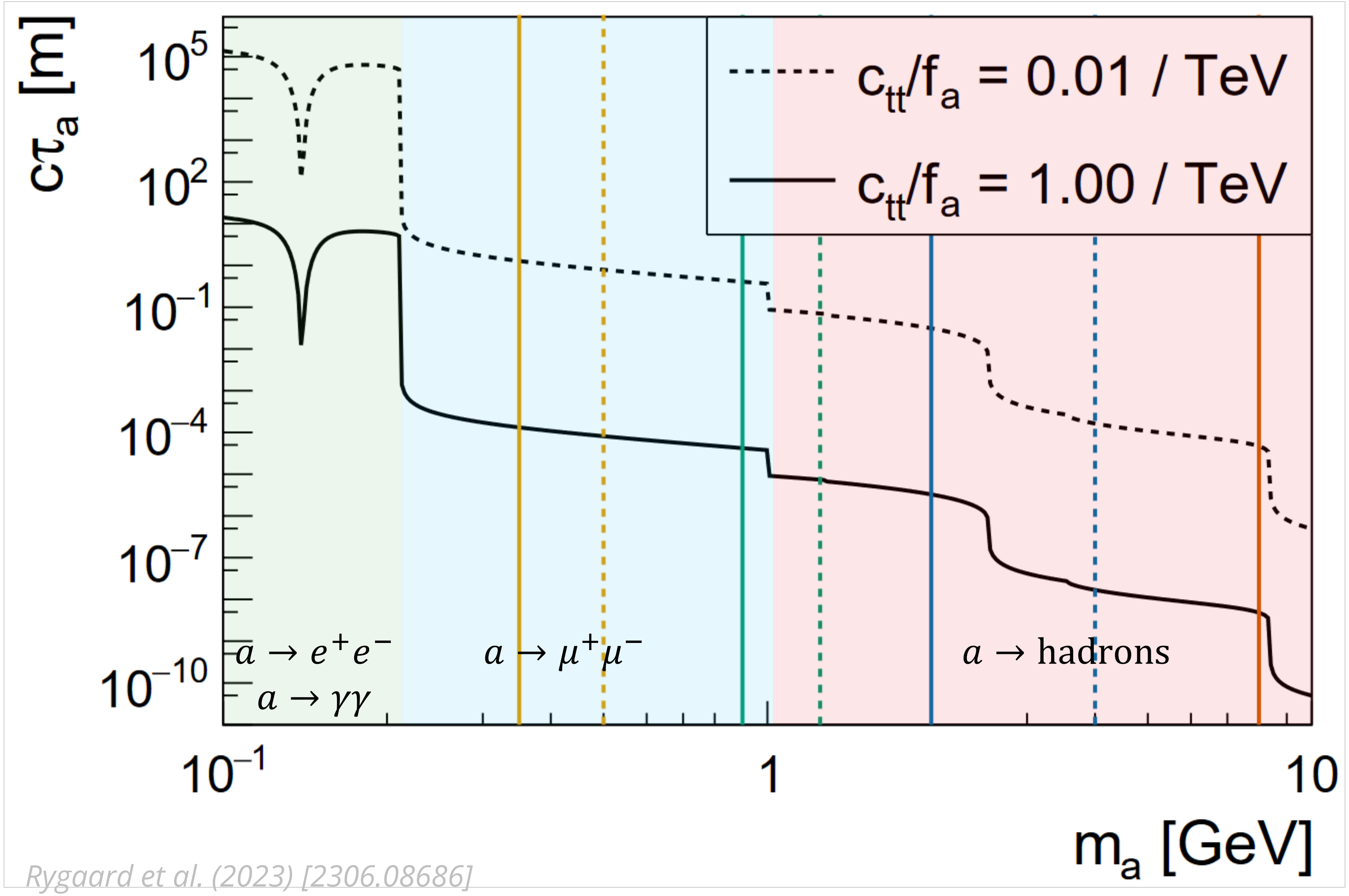


HOW TO FIND ALPS?

It depends. How long can they live?

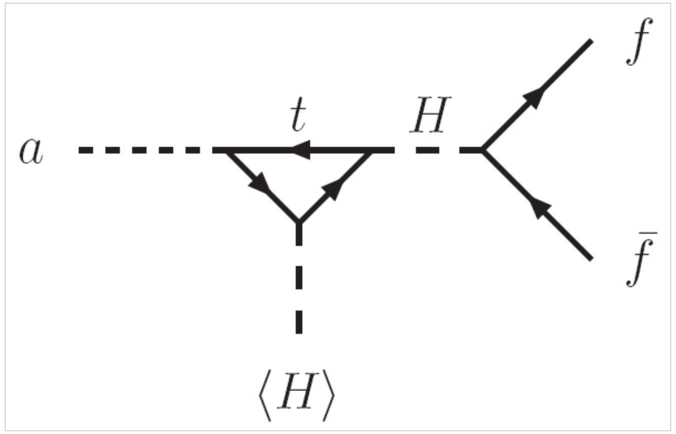
HOW TO FIND ALPS?

It depends. How long can they live?



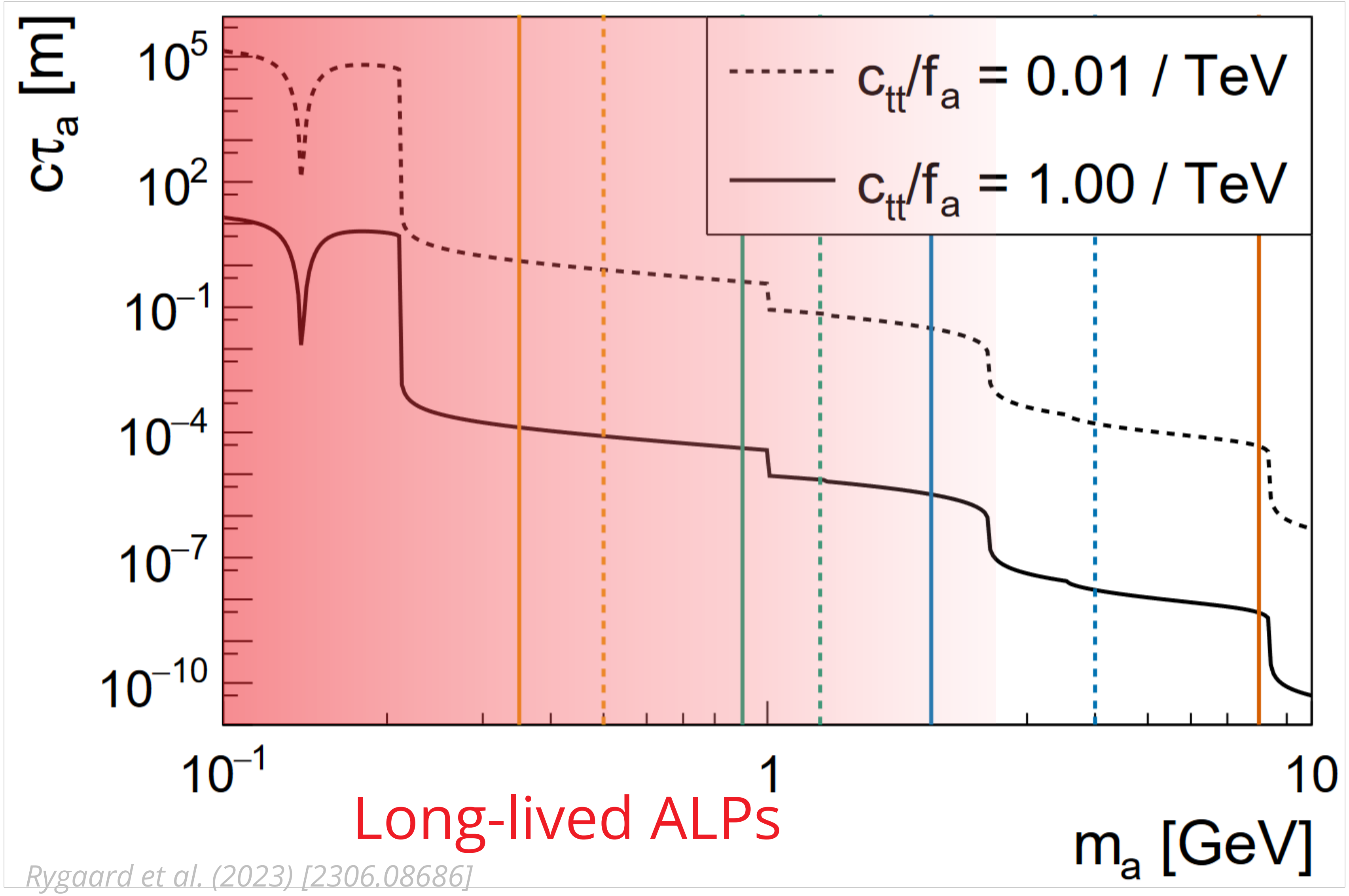
Rygaard et al. (2023) [2306.08686]

$$c_{GG}(\Lambda) = 0, c_{ff\neq tt}(\Lambda) = 0$$



HOW TO FIND ALPS?

It depends. How long can they live?



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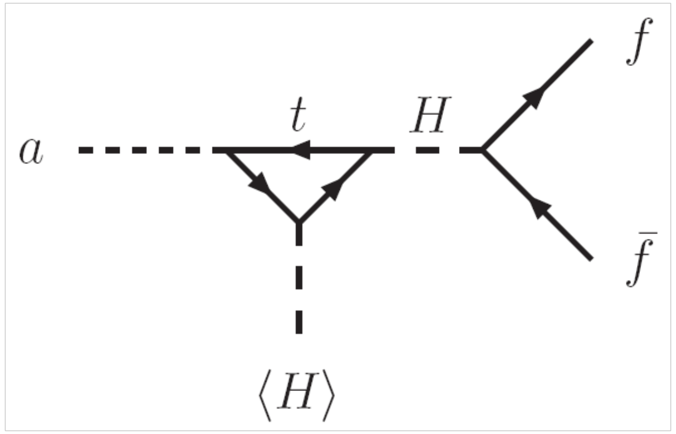
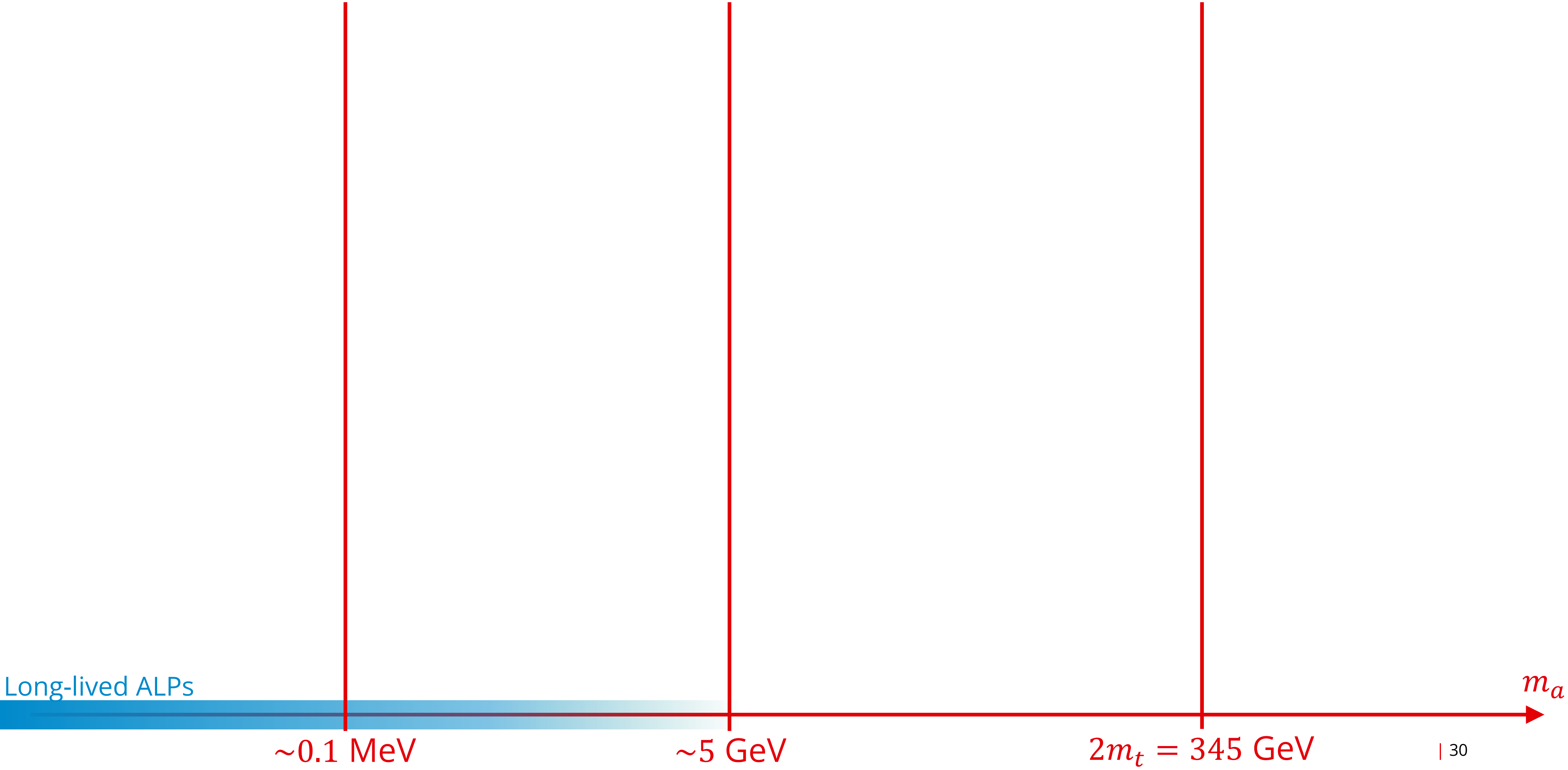


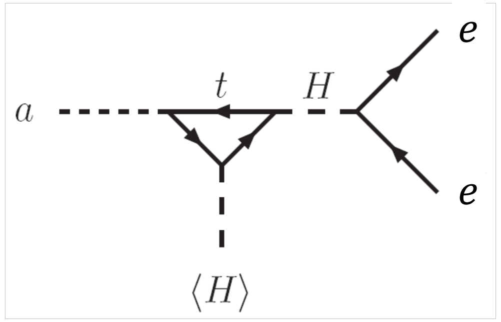
HOW TO FIND ALPS?



HOW TO FIND ALPS?

Astrophysics

ALP-electron



Bonilla et al. (2021) [2107.11392]

Long-lived ALPs

m_a

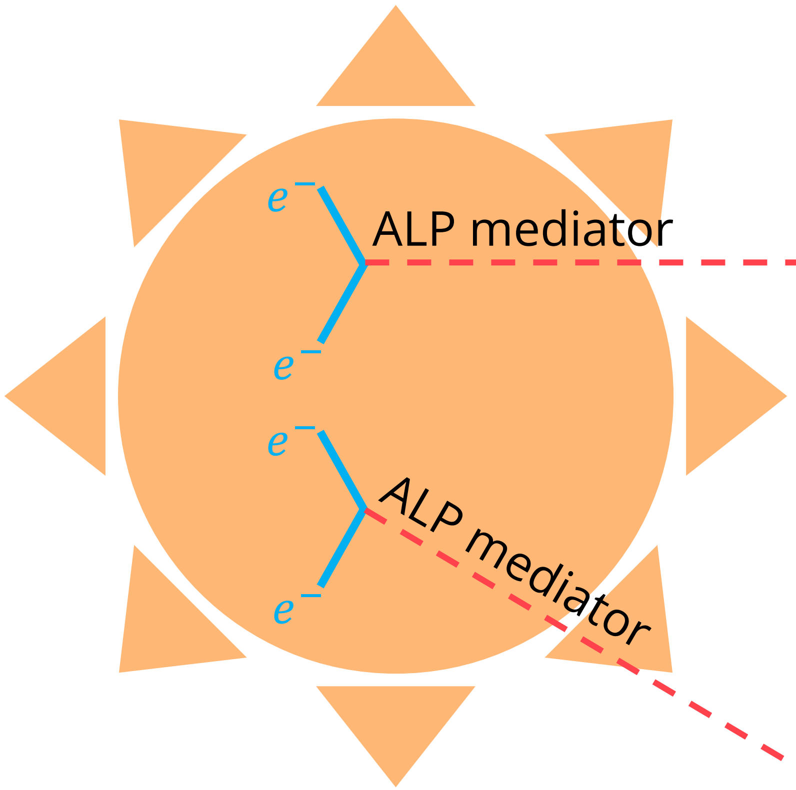
~0.1 MeV

~5 GeV

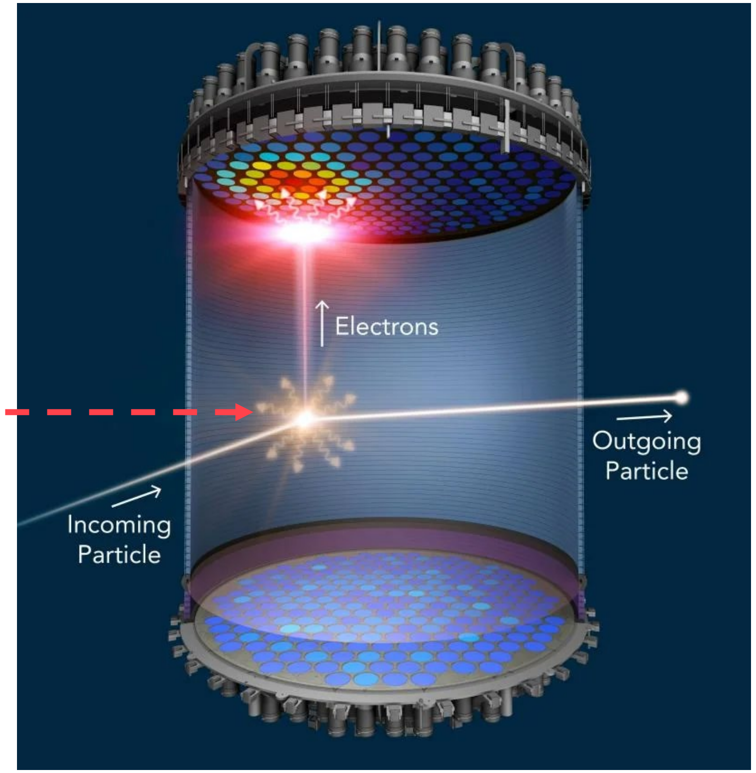
$2m_t = 345$ GeV

STELLAR ALPS

Bonilla et al. (2021) [2107.11392]



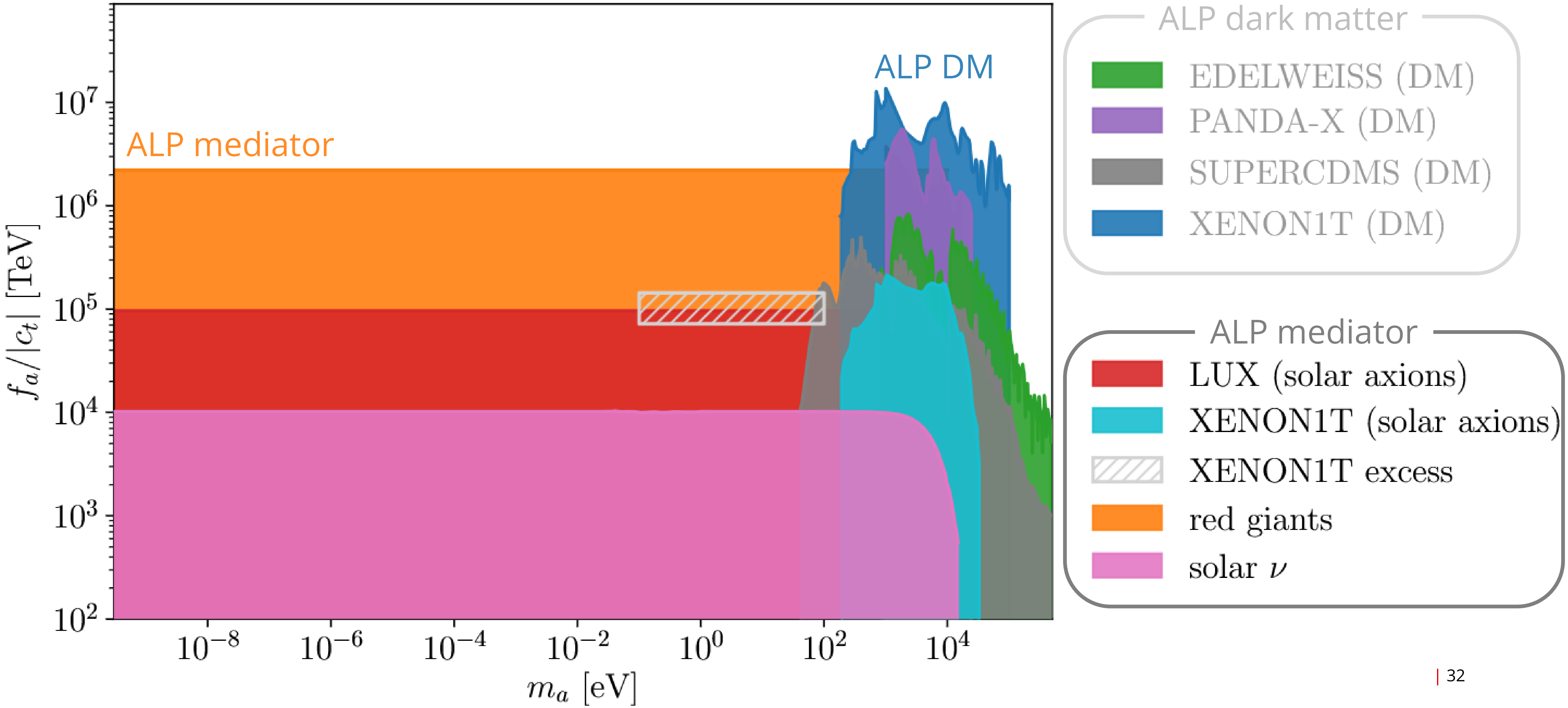
LZ experiment



Change solar luminosity

STELLAR ALPS

Bonilla et al. (2021) [2107.11392]

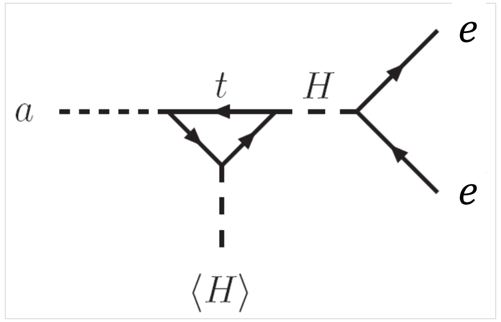


HOW TO FIND ALPS?

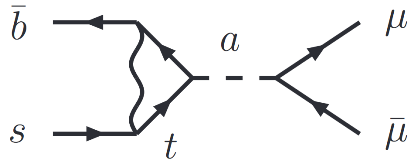
Astrophysics

In meson decays

ALP-electron

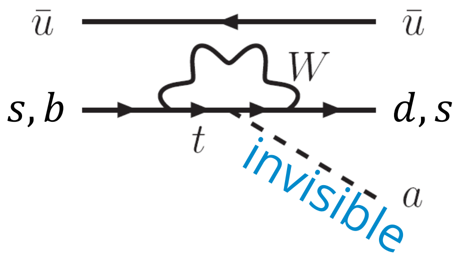


$B_s \to \mu^+\mu^-$



$K \to \pi + \text{inv}$

$B \to K + \text{inv}$



Bonilla et al. (2021) [2107.11392]

Bauer et al. (2021) [2110.10698]

Rygaard et al. (2023) [2306.08686]

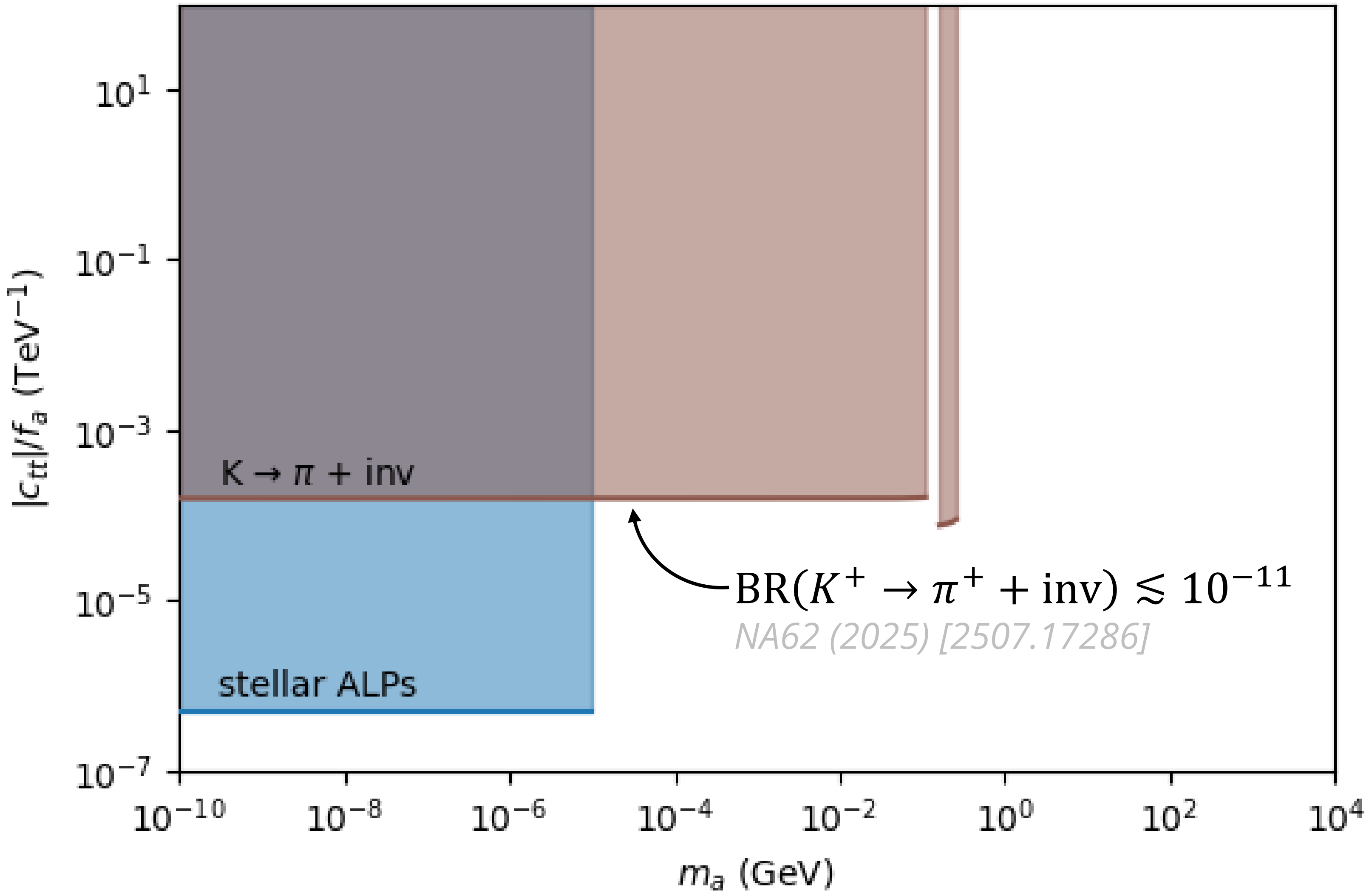
Long-lived ALPs

m_a

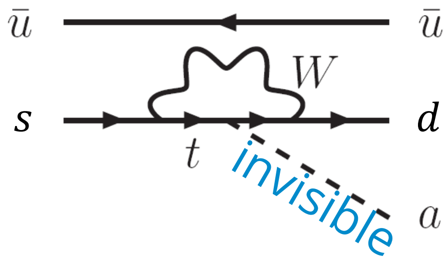
~0.1 MeV ~5 GeV $2m_t = 345$ GeV

IN KAON DECAY

Bauer et al. (2021) [2110.10698]



$c_{GG}(\Lambda) = 0, c_{ff\neq tt}(\Lambda) = 0$

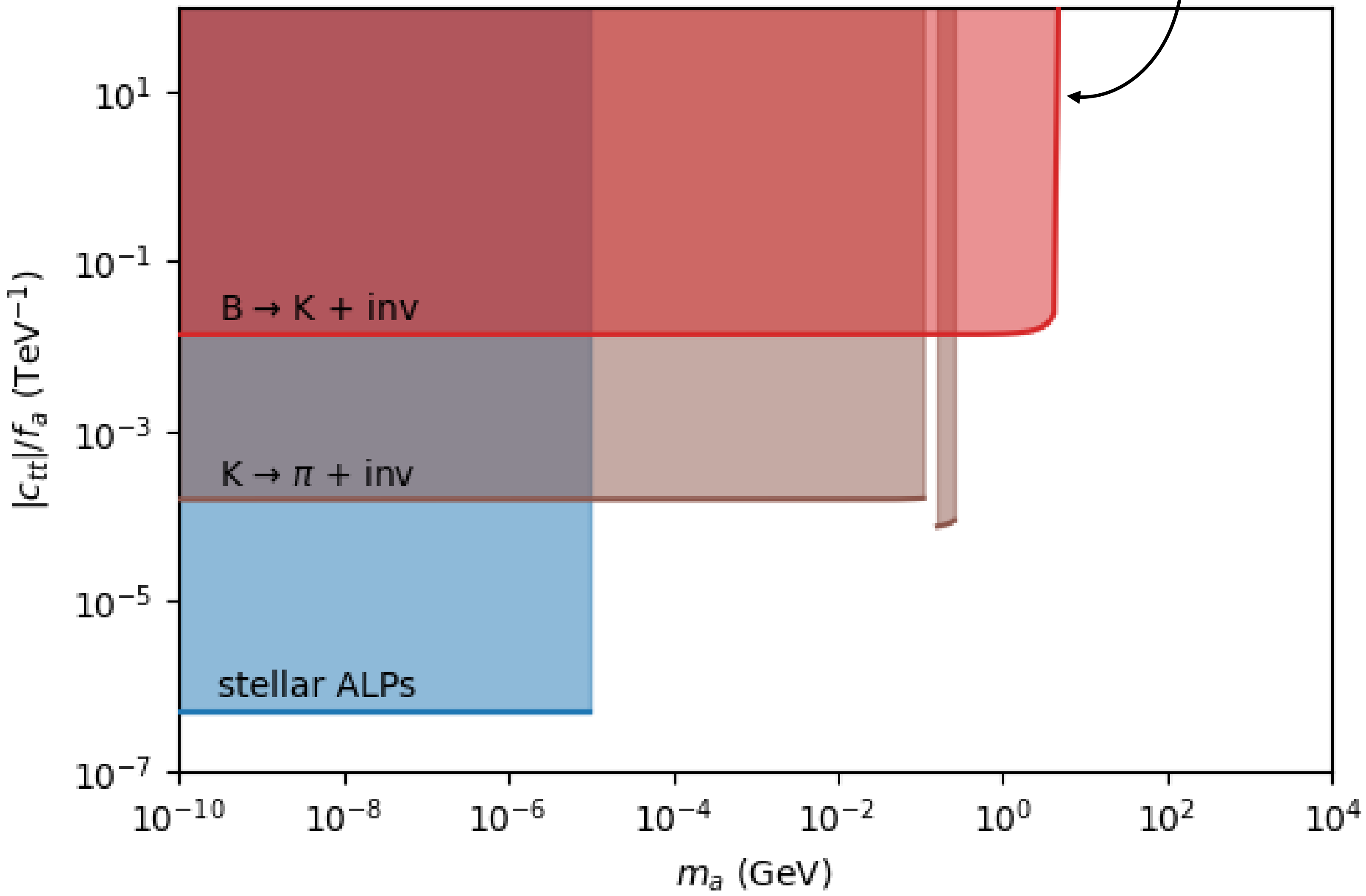


IN B MESON DECAY

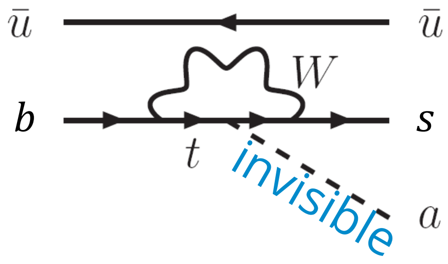
Bauer et al. (2021) [2110.10698]

$\mathrm{BR}(B^+ \to K^+ + \mathrm{inv}) \lesssim \mathrm{BR}(B^+ \to K^+ \nu\bar{\nu}) \cong 2.3 \times 10^{-5}$

Belle II (2023) [2311.14647]

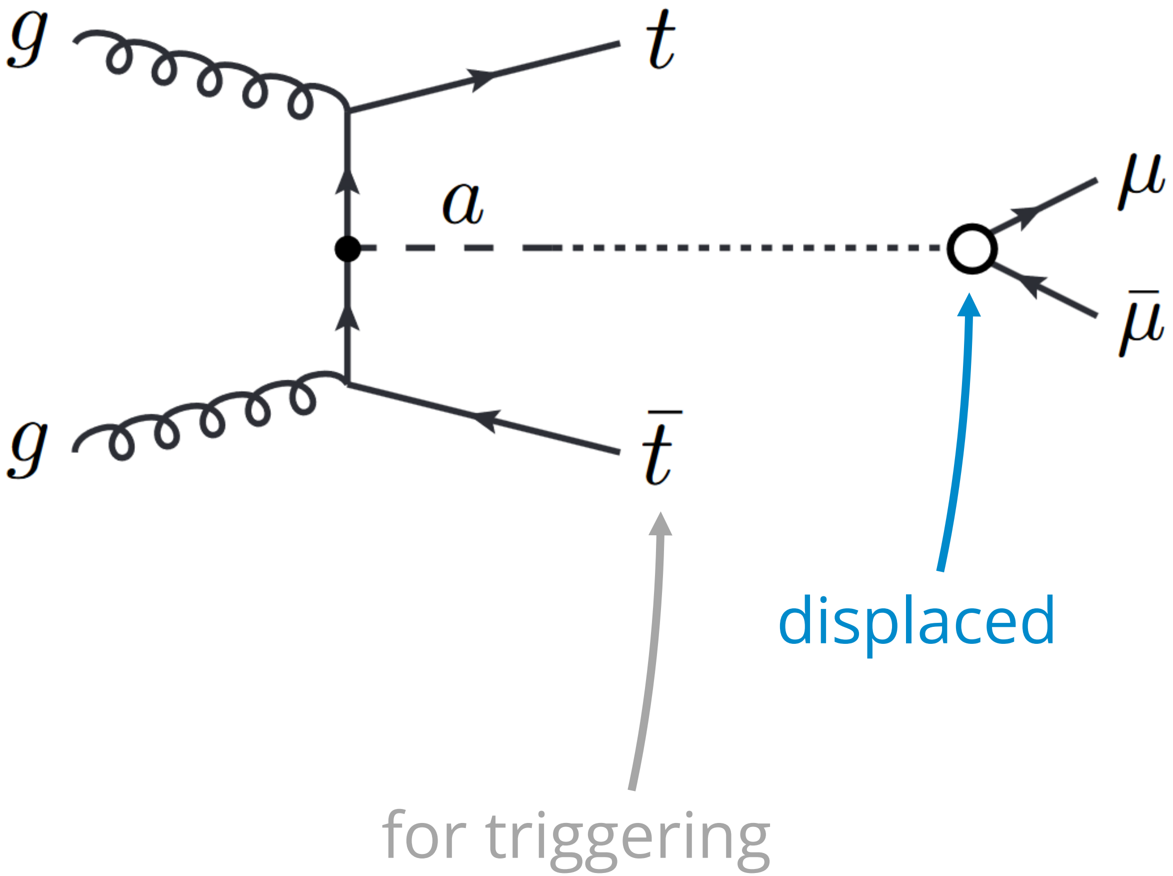


$c_{GG}(\Lambda) = 0, c_{ff\neq tt}(\Lambda) = 0$



DISPLACED ALPS AT THE LHC

Rygaard et al. (2023) [2306.08686]



DISPLACED ALPS AT THE LHC

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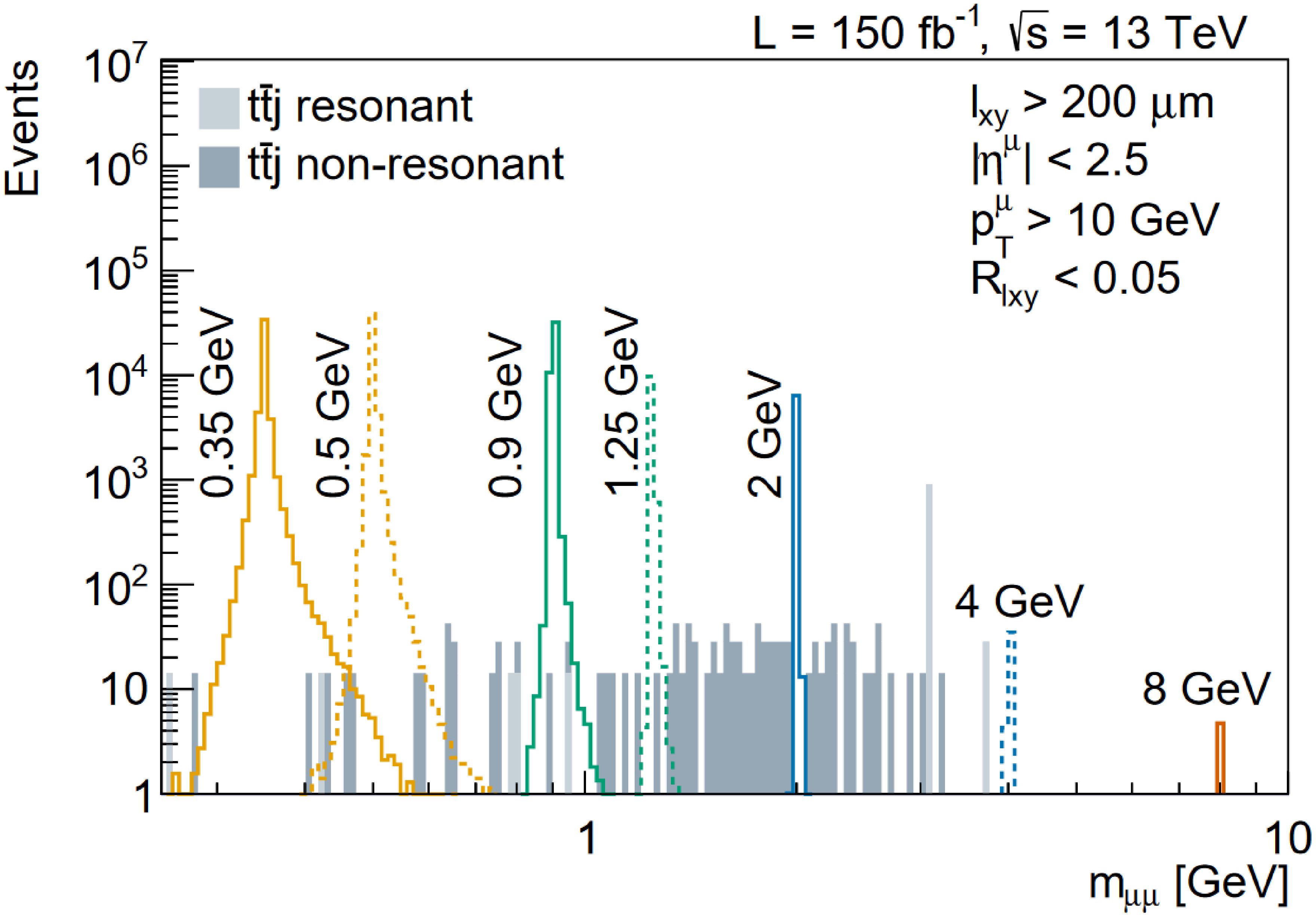
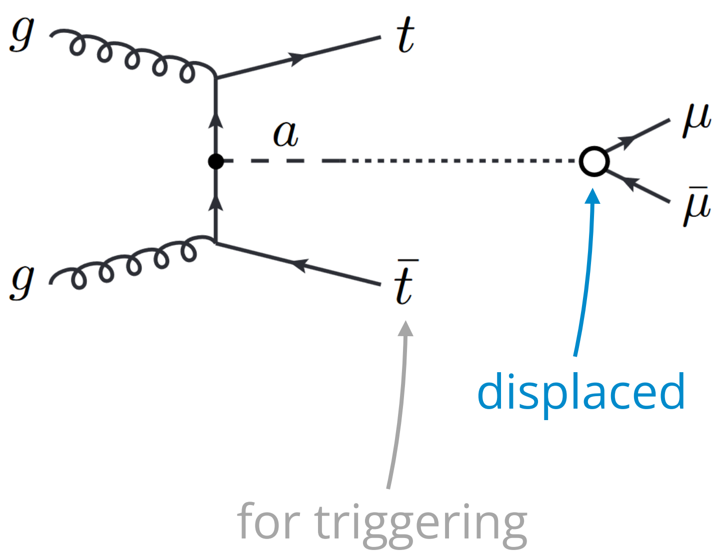
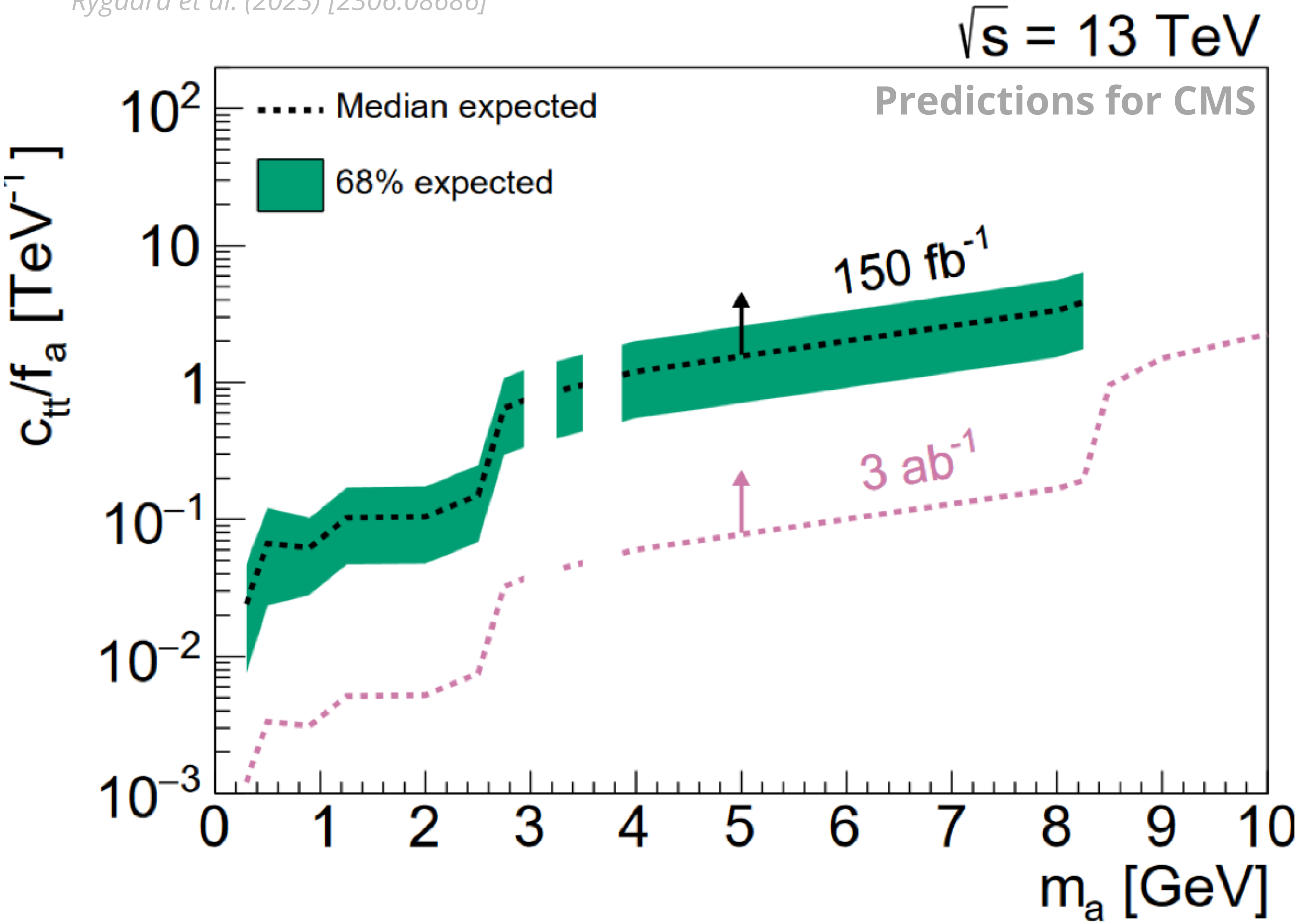


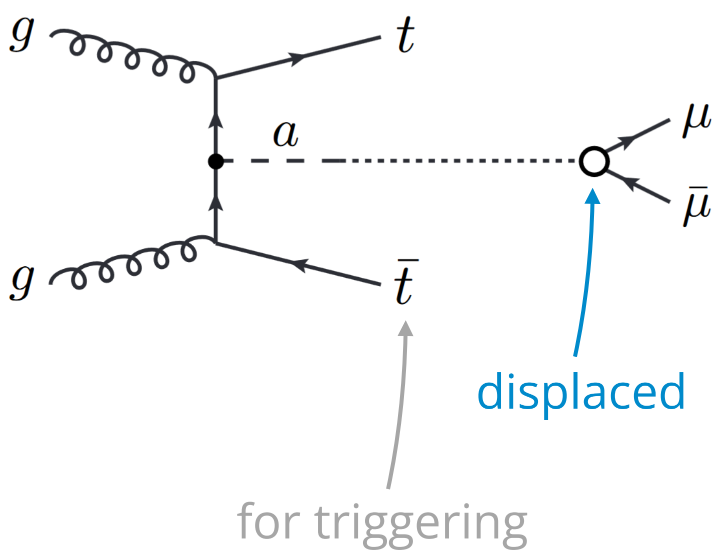


$$\frac{c_{tt}(\Lambda)}{f_a} = \frac{1}{\text{TeV}}, \; c_{\mu\mu}(\Lambda) = 0$$

DISPLACED ALPS

Rygaard et al. (2023) [2306.08686]





HOW TO FIND ALPS?

Astrophysics | **In meson decays** | **In top observables**

ALP-electron

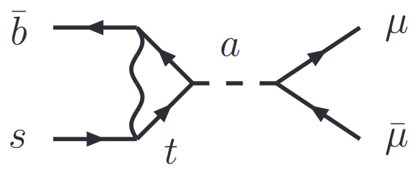
$pp \to t\bar{t}t\bar{t}$

e

e

Bonilla et al. (2021) [2107.11392]

$B_s \to \mu^+\mu^-$



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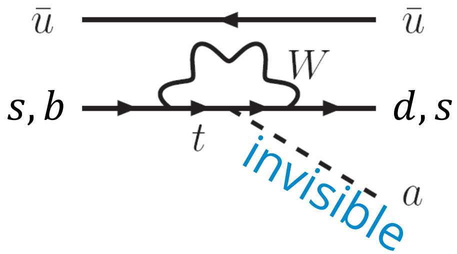
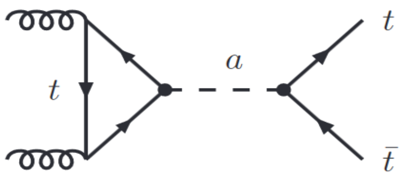


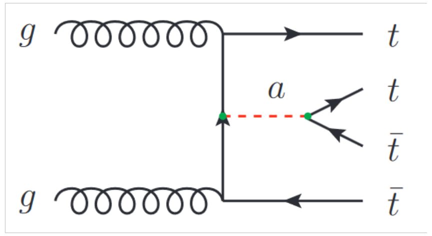
Bauer et al. (2021) [2110.10698]
Rygaard et al. (2023) [2306.08686]

virtual corrections

$pp \to t\bar{t}$



$pp \to t\bar{t}t\bar{t}$



AVP, Westhoff (2023) [2312.00872]
Esser et al. (2024) [2404.08062]
Blasi et al. (2023) [2311.16048]
Bruggisser et al. (2023) [2308.11703]
Biekoetter et al. (2023) [2307.10372]

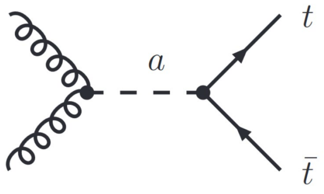
Long-lived ALPs

m_a

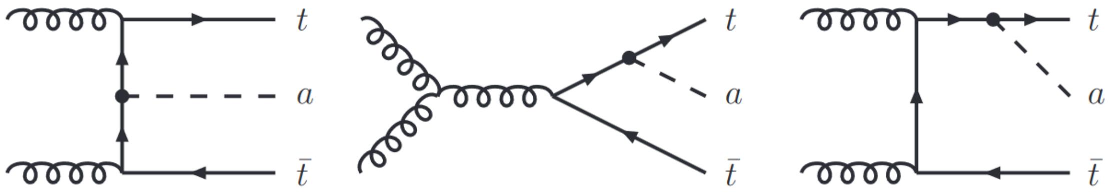
~ 0.1 MeV | ~ 5 GeV | $2m_t = 345$ GeV

ALPS IN $t\bar{t}$ PRODUCTION

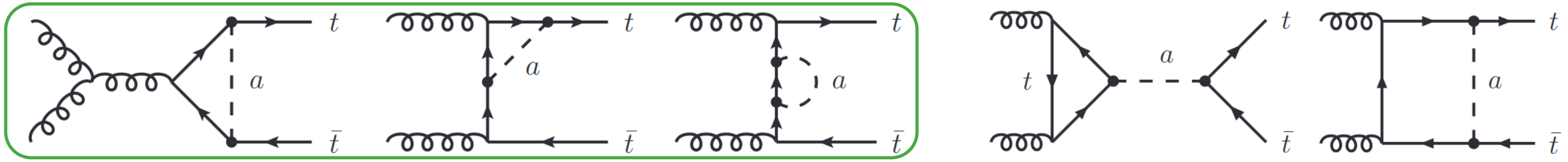
Tree-level



Real ALP radiation



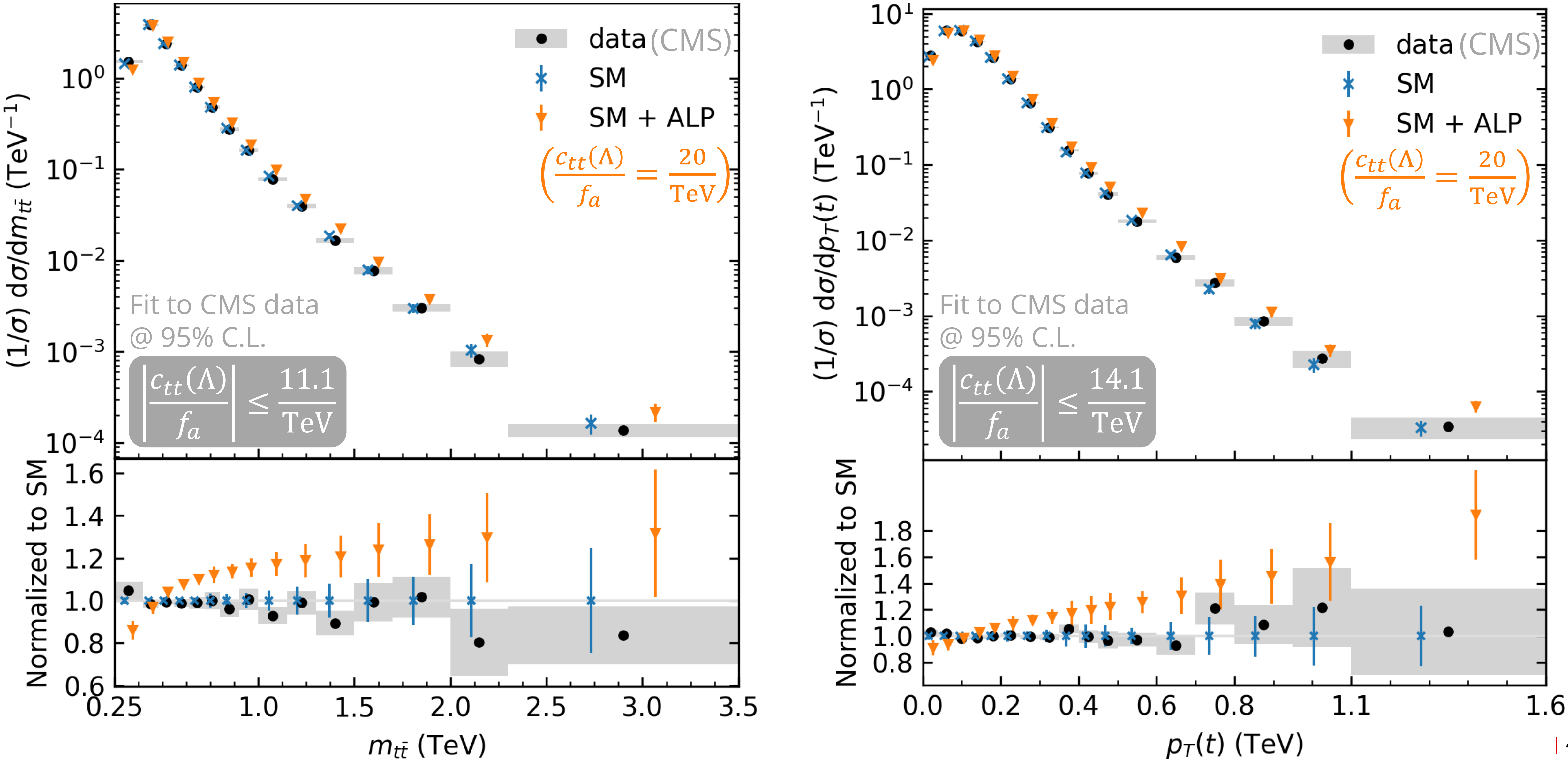
Virtual corrections



Needs renormalization

$c_{GG}(\Lambda) = 0\,;\, m_a = 10$ GeV

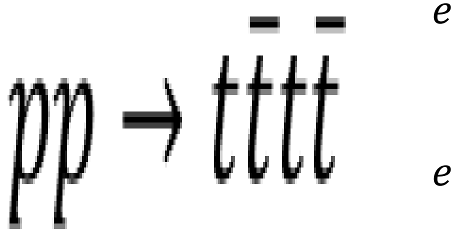
Data: *PRD 104 (2021) 092013*
AVP, *Westhoff (2023) [2312.00872]*
ALP theory uncertainty: 10%



HOW TO FIND ALPS?

Astrophysics

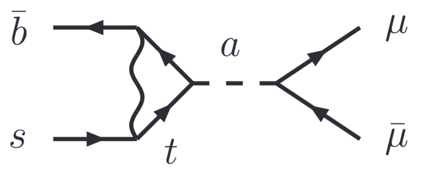
ALP-electron



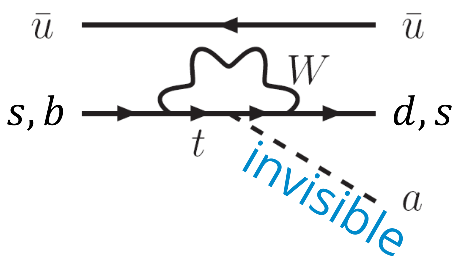
Bonilla et al. (2021) [2107.11392]

In meson decays

$B_s \to \mu^+\mu^-$



$K \to \pi + \text{inv}$
$B \to K + \text{inv}$

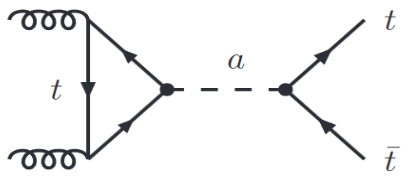


Bauer et al. (2021) [2110.10698]
Rygaard et al. (2023) [2306.08686]

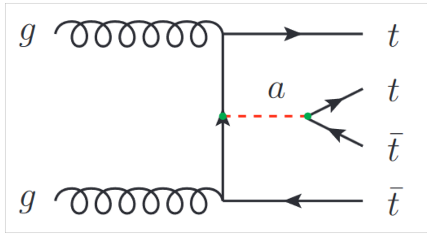
In top observables

virtual corrections

$pp \to t\bar{t}$

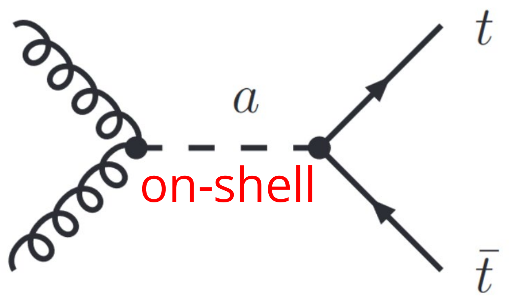


$pp \to t\bar{t}t\bar{t}$



AVP, Westhoff (2023) [2312.00872]
Esser et al. (2024) [2404.08062]
Blasi et al. (2023) [2311.16048]
Bruggisser et al. (2023) [2308.11703]
Biekoetter et al. (2023) [2307.10372]

resonance ALPs



Anuar et al. (2024) [2404.19014]

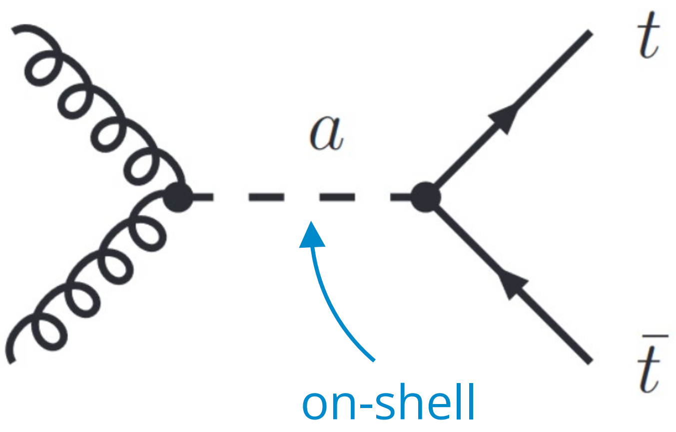
Long-lived ALPs

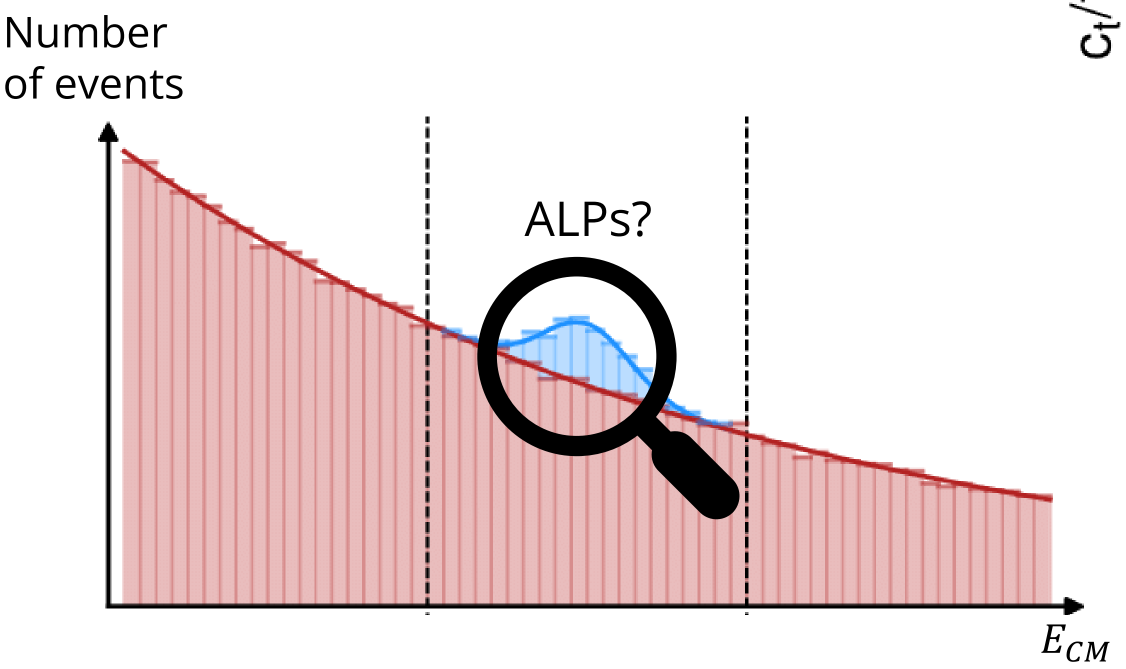
m_a

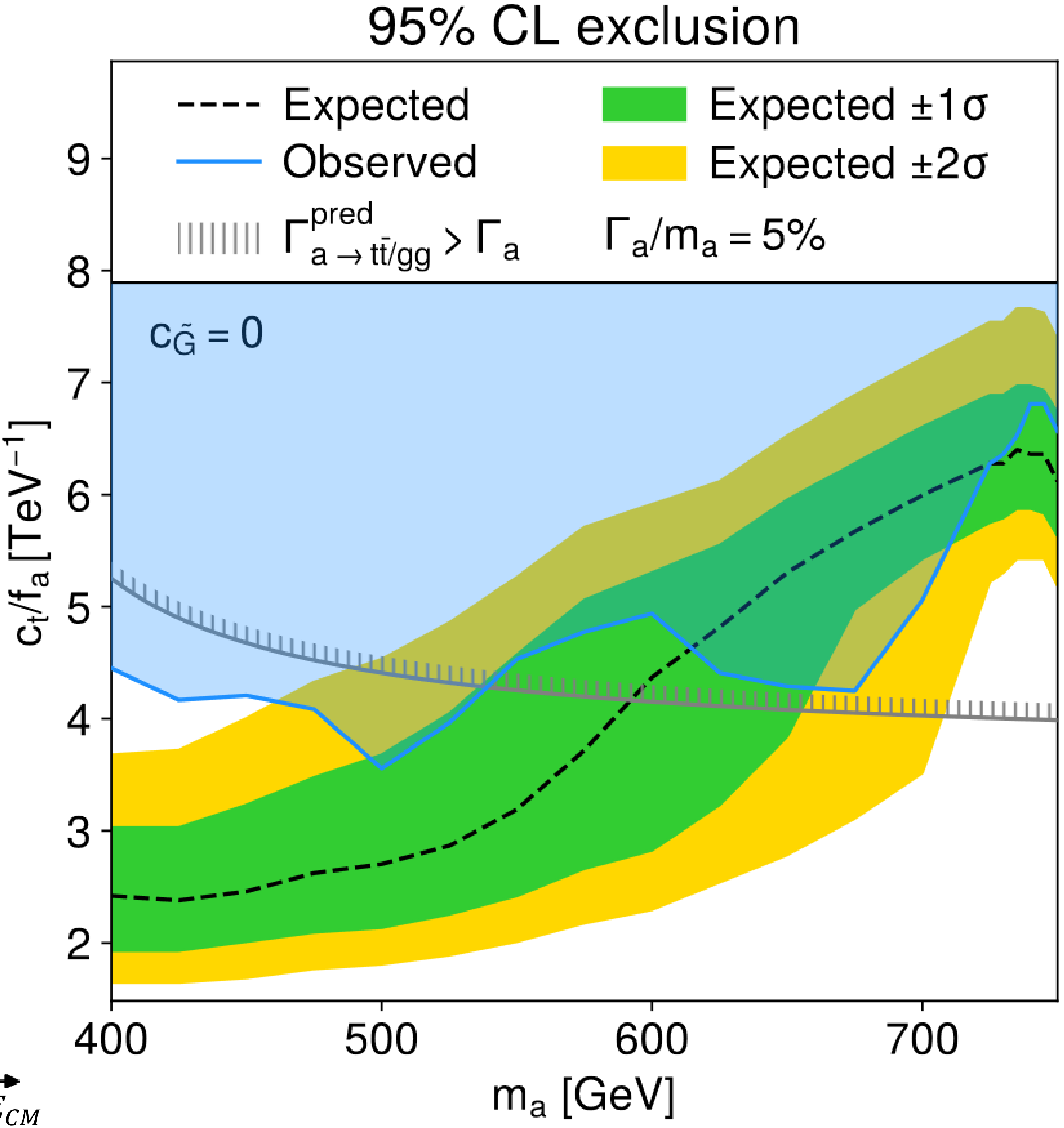
~ 0.1 MeV | ~ 5 GeV | $2m_t = 345$ GeV

RESONANCE SEARCHES

Anuar et al. (2024) [2404.19014]

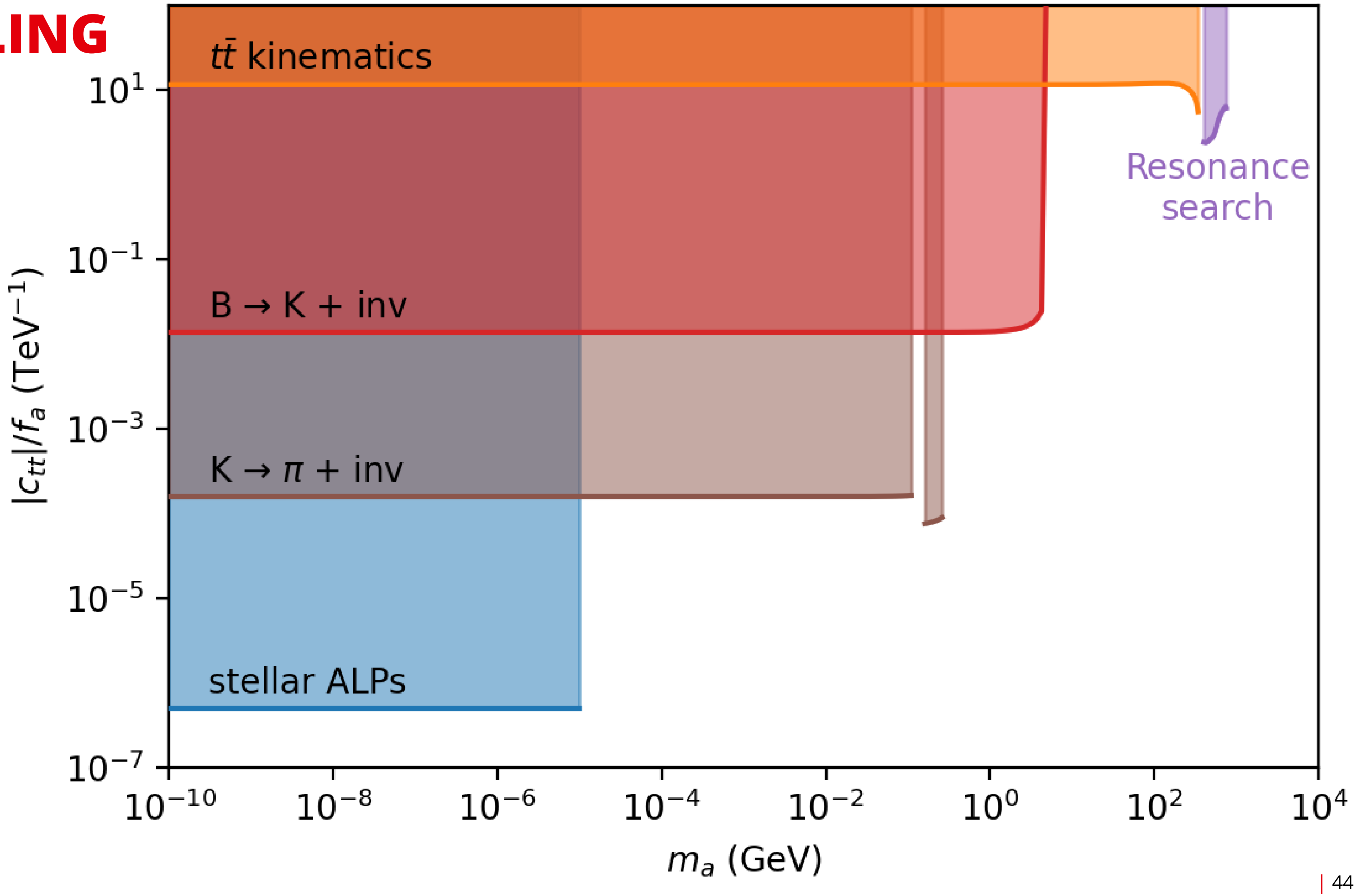






CONSTRAINTS ON ALP-TOP COUPLING

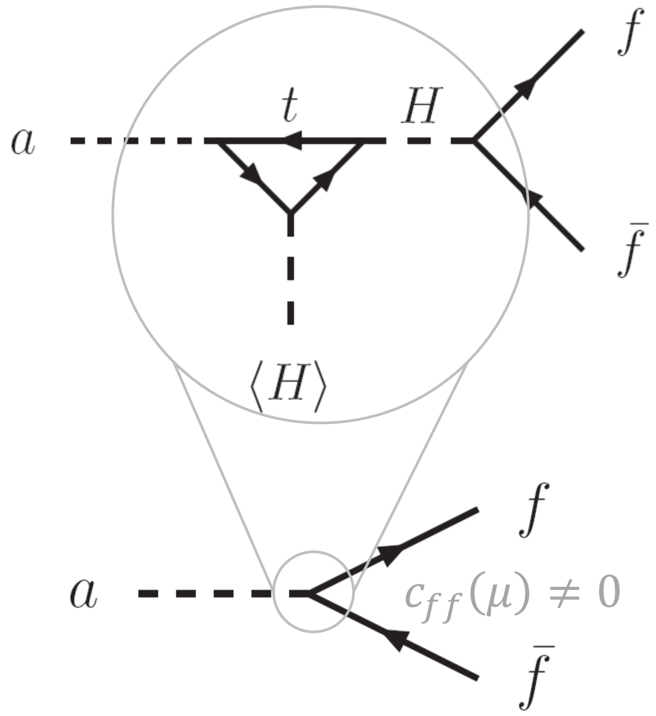
Bonilla et al. (2021) [2107.11392]
Bauer et al. (2021) [2110.10698]
Phan et al. (2023) [2312.00872]
Anuar et al. (2024) [2404.19014]



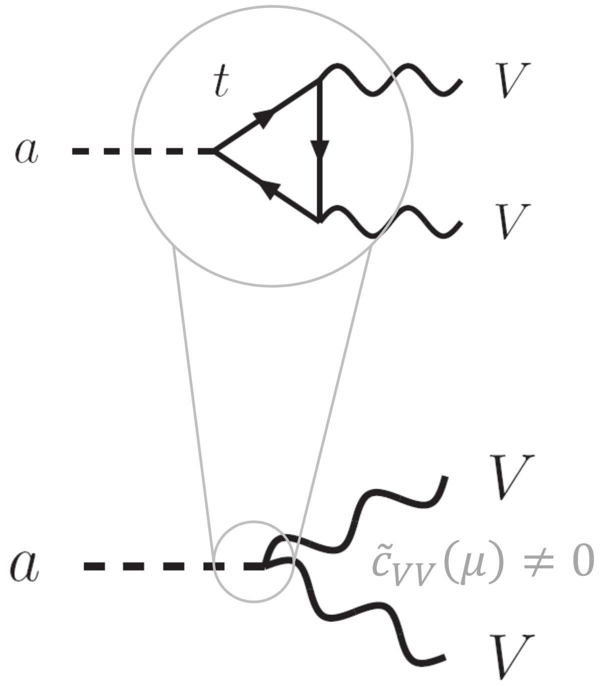
TOP-INDUCED EFFECTIVE COUPLINGS

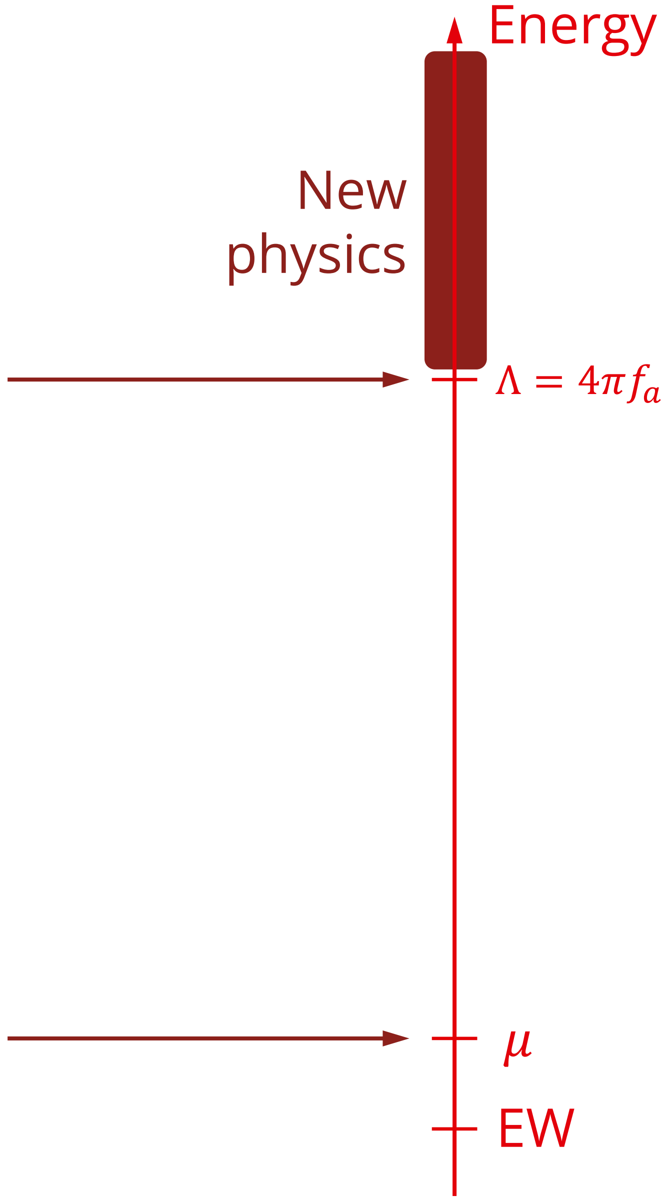
- Tops can induce other couplings via loop corrections

$c_{f\bar{f}}(\Lambda) = 0$ $(f \neq t)$



$\tilde{c}_{VV}(\Lambda) = 0$





ALP EFFECTIVE THEORY

Why top?

$$\mathcal{L}_{\text{eff}}(\mu) \supset \frac{1}{2}\partial_\mu a\, \partial^\mu a - \frac{m_a^2}{2}a^2 - \frac{\partial^\mu a}{f_a}\sum_F \bar{F}\boldsymbol{c}_F\gamma_\mu F + \frac{a}{f_a}\sum_V c_{VV}\frac{\alpha_V}{4\pi}V_{\mu\nu}^A\tilde{V}^{A,\mu\nu}$$

$$Q_L \to e^{-i\boldsymbol{c}_Q\frac{a}{f_a}}Q_L$$

$$u_R \to e^{-i\boldsymbol{c}_U\frac{a}{f_a}}u_R$$

$$c_{qq} = \left(\boldsymbol{c}_U - \boldsymbol{c}_Q\right)_{qq}$$

$$\tilde{c}_{GG} = c_{GG} + \frac{1}{2}\text{Tr}\left(\boldsymbol{c}_D + \boldsymbol{c}_U - 2\boldsymbol{c}_Q\right)$$

$$\to \frac{1}{2}\partial_\mu a\, \partial^\mu a - \frac{m_a^2}{2}a^2 - \sum_f m_f c_{ff}\frac{a}{f_a}\bar{f}i\gamma^5 f + \frac{a}{f_a}\sum_V \tilde{c}_{VV}\frac{\alpha_V}{4\pi}V_{\mu\nu}^A\tilde{V}^{A,\mu\nu}$$