Light Mediators

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Neutrino-Electron Scattering at Low Energies,
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Introduction

- **ν sector of SM (SU(3) x SU(2) x U(1)) requires new physics for understanding the experimental results on masses and mixing angles**

$$\textit{tiny } \nu \textit{ mass: } \frac{m_{\nu_D}^2}{m_{Maj}}$$

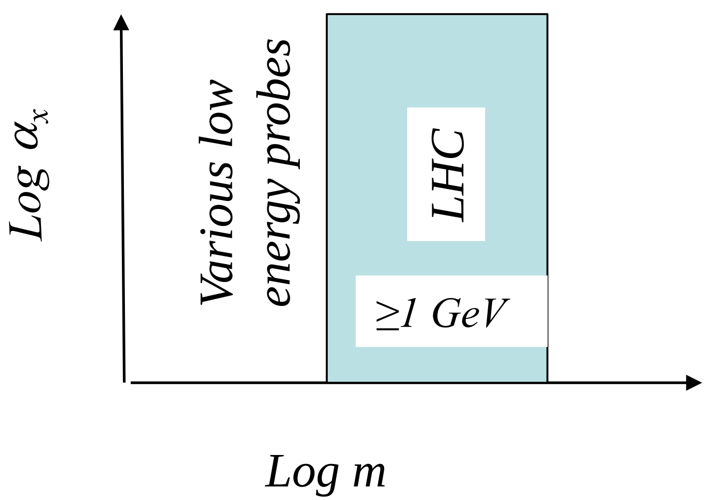
- **Similarly, DM explanation (with M_{DM} anywhere between 1 KeV to 100 TeV) requires new physics**

Thermal DM

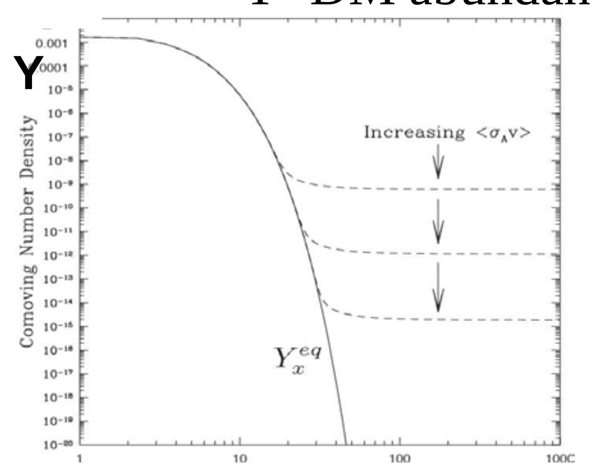
$$H = n\langle\sigma v\rangle \quad \sigma \sim 1\,pb$$

- **The new physics: new mass scales and new couplings**

$$\alpha_x = \frac{g_x^2}{4\pi}$$



Y=DM abundance



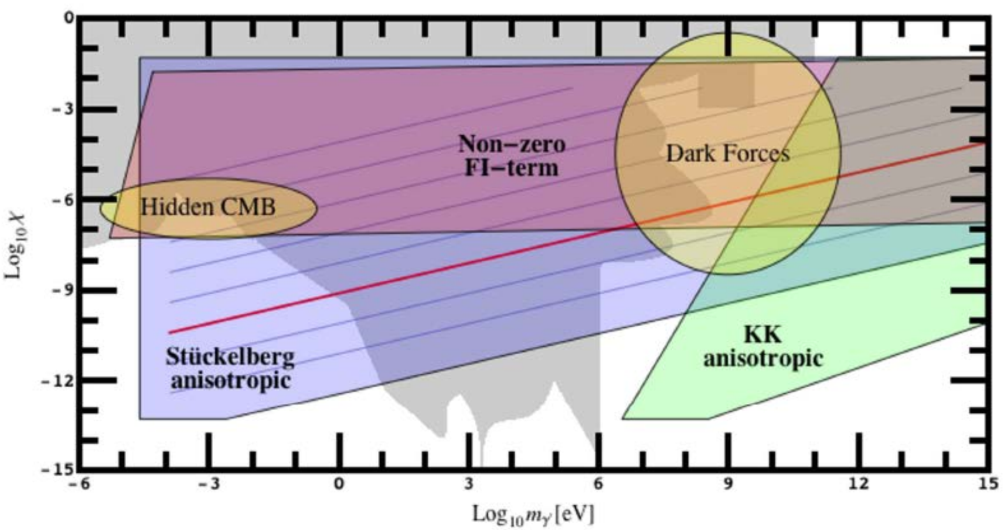
Mass of DM/Temp.

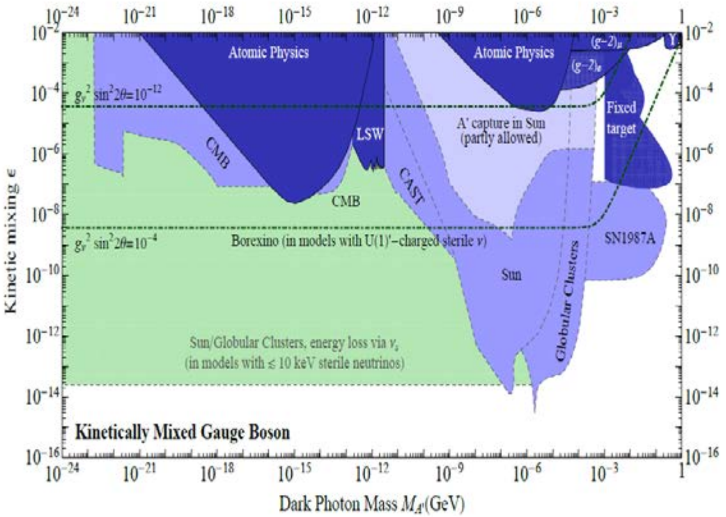
Low scales

New physics: new symmetry breaking scale

Existence of new scales above or below the SM in many theories
Intermediate scale, GUT scale etc.

String theory: Many U(1) symmetry with the symmetry breaking scale can be anywhere





Cicoli, Goodsell, Jaeckel, Ringwald, 2011

Harnik, Kopp, Machado, 2012

Light mediator scenarios

Various interesting Light mediators scenarios:

- **Various Dark Matter scenarios based on hidden sectors:**
  e.g., Models with Light Dark Matter,
  Sommerfeld enhancements motivated by SIMP, Decay of the observable sector DM into hidden sector, models of asymmetric DM

- **g-2 of electron: Recent observed excess (smaller than the SM prediction)**

- **Neutrino sector physics.**
  New Neutrino interactions to satisfy MiniBoone excess

- **Solutions of Yukawa couplings hierarchies problem**

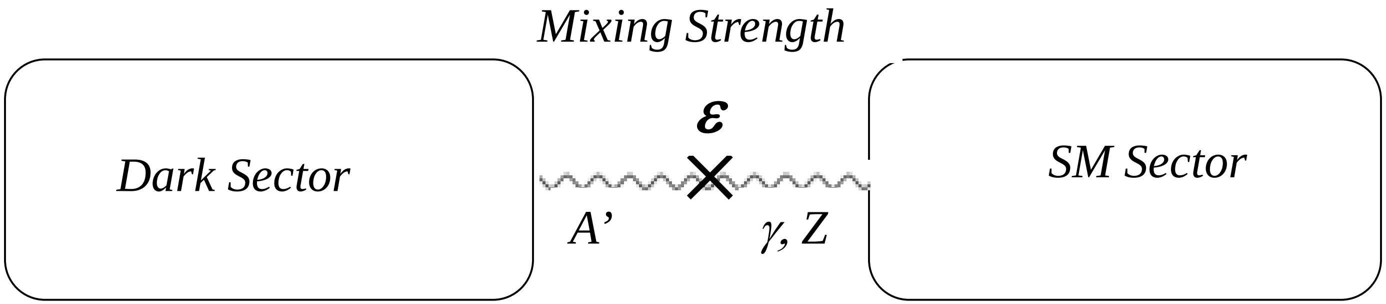
Various Models

- **Parameter space of Z- Z' mixing, L_μ-L_τ models**
- **Hidden sector model**
- **Low mass DM models associated with new symmetry scale**
- **DM and neutrino scenarios with interesting signatures**

Models: Kinetic mixing

Simplest idea: Assume a "dark sector" with U(1) symmetry

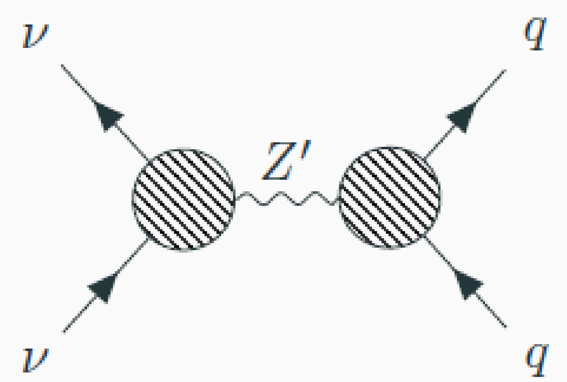
The "Dark sector" sector mixes with the SM via kinetic mixing (loop generated by particles containing charges from both sectors)



Holdom, 1986

ε *:can be generated from a loop containing particles with charges belong to both sectors*

Models: Kinetic mixing



$$L_{\text{gauge}} = -\frac{1}{4}F_a^{\mu\nu}F_{a\mu\nu} - \frac{1}{4}F_b^{\mu\nu}F_{b\mu\nu} - \frac{\epsilon}{2}F_a^{\mu\nu}F_{b\mu\nu}$$

$$L_{int} = -\frac{g}{c_w}c_\alpha(t_\alpha - \epsilon\, s_w)(\tau_{3L} - \frac{t_\alpha - \epsilon/\, s_w}{t_\alpha - \epsilon\, s_w}s_w^2 Q)Z'_\mu \bar{f}\gamma^\mu f$$

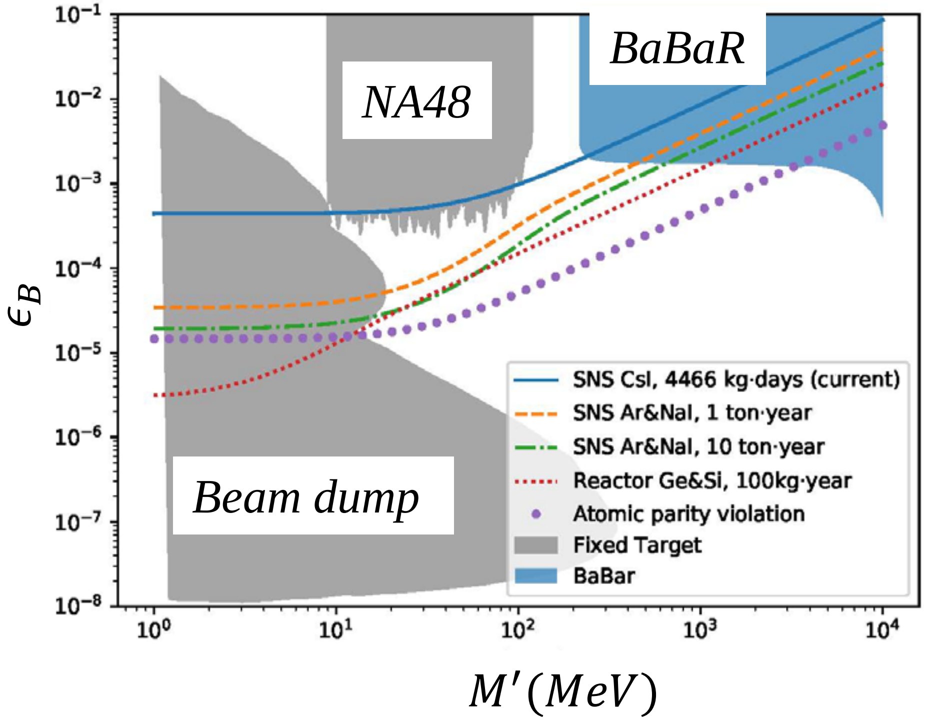
s_α : Z-Z' mass mixing

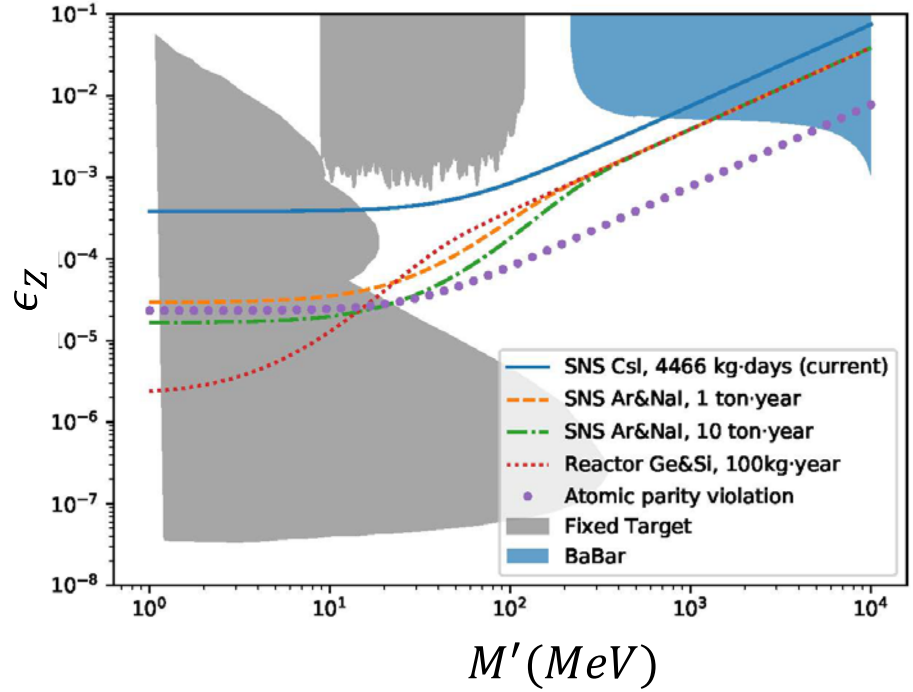
1. Dark Z boson: α small, coupling: $ig tan\theta_w (Y_f/2)\epsilon_B$

2. Dark hypercharge boson: ϵ small, coupling: $-\frac{ig}{c_w}\epsilon_Z(\tau_{3L} - s_w^2 Q)$

$\epsilon_Z \equiv s_\alpha$

Kinetic mixing





Abdullah, Dent, Dutta, Liao, Kane, Strigari, 2018

Models: Kinetic mixing

Kinetic mixing arises in many models.

Visible sector DM decays to hidden sector

$$\tau_{2-\mathrm{body}}^{\chi_i \to Z\ \chi_j} \sim 10^{-17}\ s \times \left(\frac{10^{-3}}{\epsilon}\right)^2 \left(\frac{0.01}{|N_{i3}N_{j3}^*|}\right)^2$$

Lifetime of the dark matter particle in the observable sector depends on the mixing with the hidden sector

Acharya, Ellis, Kane, Nelson, Perry, 2018

Hidden Sector: Form factor

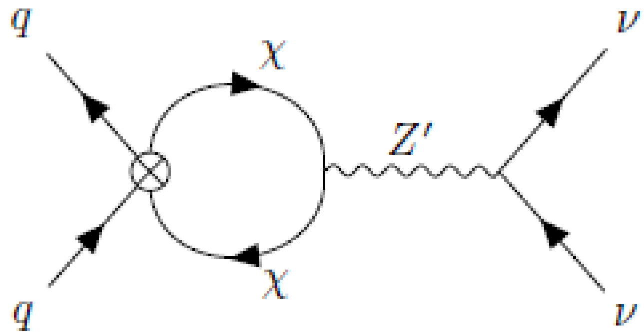
Hidden sector fermions χ:

$$\mathcal{L} = \frac{g}{\Lambda^2}\bar{q}'\gamma^\mu P_{L,R}q'\bar{\chi}\gamma_\mu(1\pm\gamma_5)\chi + i\bar{\chi}\gamma^\nu\left[\partial_\nu - ig_\chi Z'^\nu\right]\chi - m_\chi\bar{\chi}\chi + \frac{1}{2}m_{Z'}^2 Z'_\mu Z'^\mu$$

Datta, Duraisamy, Ghosh'13,
Datta, Kumar, Liao, Marfatia, '17
Elor, Liu, Slatyer, Soreq, '18

Z' couples directly to χ and leptons

Quark coupling with χ is due to this operator:

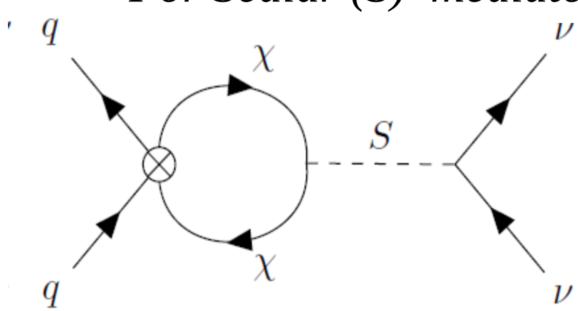


$$\mathcal{L}_{HD} = \frac{g_{L,R}}{\Lambda^2}\bar{q}'\gamma^\mu P_{L,R}q'\partial^\nu Z'_{\mu\nu},$$

$$\mathcal{L}_{q'q'} = \bar{q}'\hat{\gamma}^\mu\left[P_L F_L(q^2) + P_R F_R(q^2)\right]q'\, Z'_\mu$$

$$F_{L,R}(q^2) = \frac{q^2}{\Lambda^2}g_{L,R}(q^2)$$

For Scalar (S) mediator



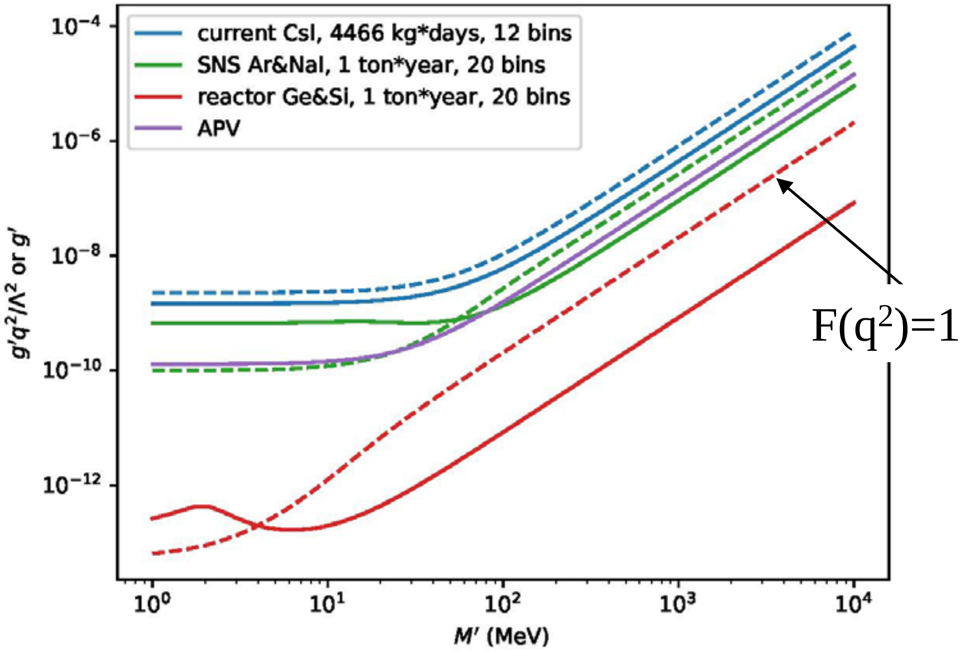
$$F_{L,R}(q^2) = \frac{q^2}{\Lambda^2}g_{L,R}(q^2)$$

Form factor

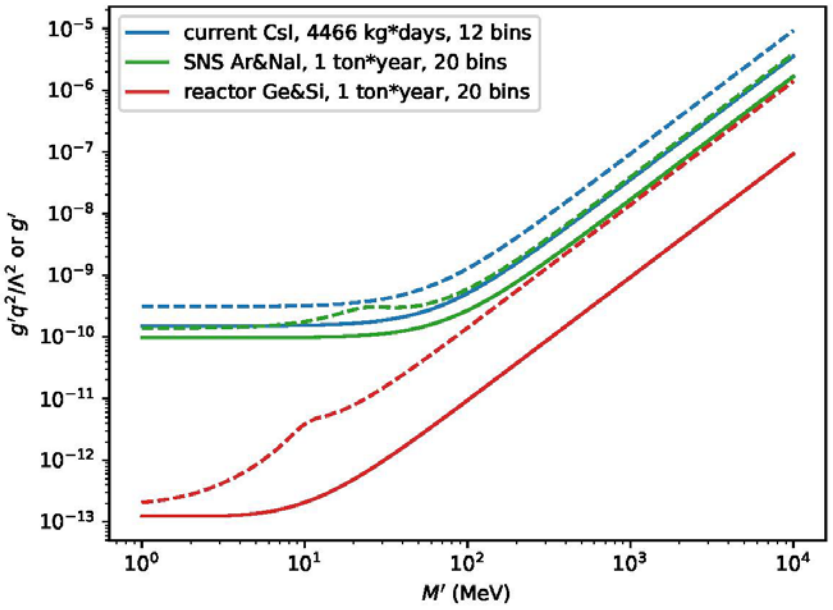
$$\mathcal{L}_{\rm BSM} = -\sqrt{2} G_F \bar{\nu}_L \gamma^\mu \nu_L \bar{f} \gamma_\mu f \frac{g F(q^2, \Lambda^2)}{q^2 + m'^2} \frac{1}{2\sqrt{2} G_F}$$

$$F(q^2, \Lambda^2) = \frac{q^2}{\Lambda^2}$$

vector



Scalar



Datta, Dutta, Liao, Marfatia, Strigari, 2018

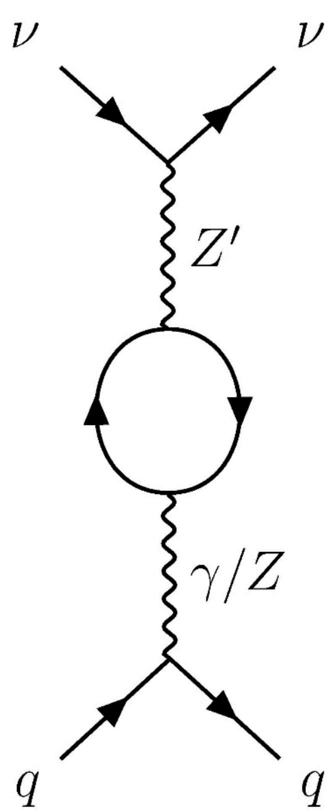
Lμ-Lτ

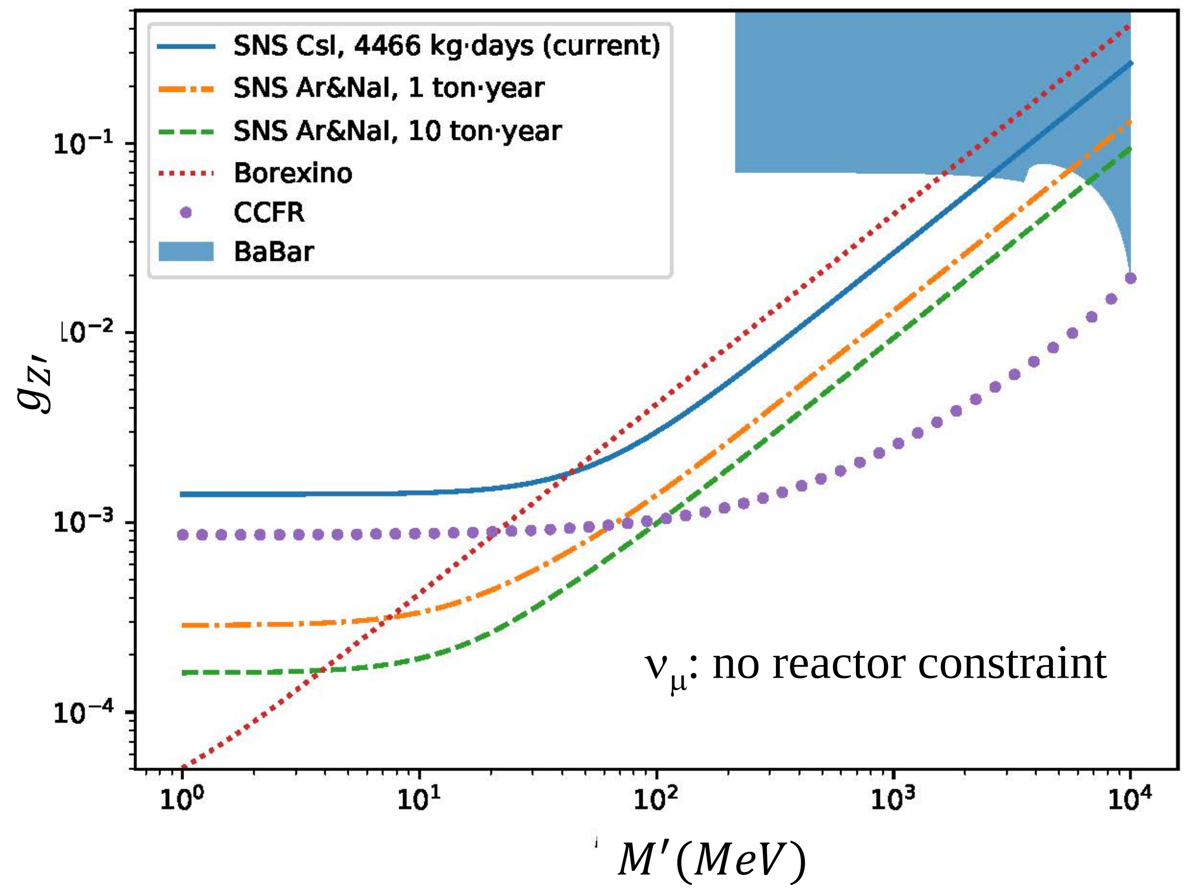
$U(1)_{\mu-\tau}$ symmetry Models

[Neutrino flavor structures:
He, Joshi, Lew, Volkas,'91]

$$\mathcal{L}_{Z'} = -\frac{1}{4}F_{Z'\mu\nu}F^{\mu\nu}_{Z'} + \frac{1}{2}m^2_{Z'}Z'_\mu Z'^\mu - g_{Z'}Z'_\mu j^\mu_{Z'} \,,$$

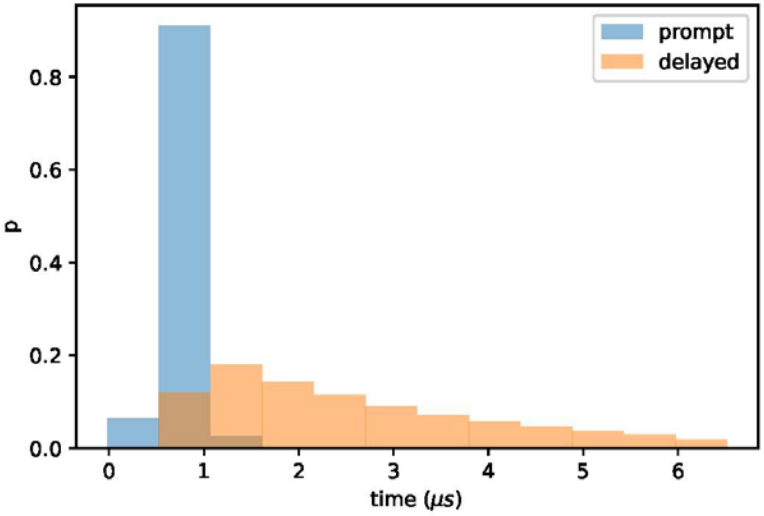
$$j^\mu_{Z'} = \ell^\dagger_{\mu L}\bar{\sigma}^\mu \ell_{\mu L} - \ell^\dagger_{\tau L}\bar{\sigma}^\mu \ell_{\tau L} - \bar{\mu}^\dagger_R \bar{\sigma}^\mu \bar{\mu}_R + \bar{\tau}^\dagger_R \bar{\sigma}^\mu \bar{\tau}_R - \bar{N}^\dagger_{\mu R}\bar{\sigma}^\mu \bar{N}_{\mu R} + \bar{N}^\dagger_{\tau R}\bar{\sigma}^\mu \bar{N}_{\tau R} \,,$$



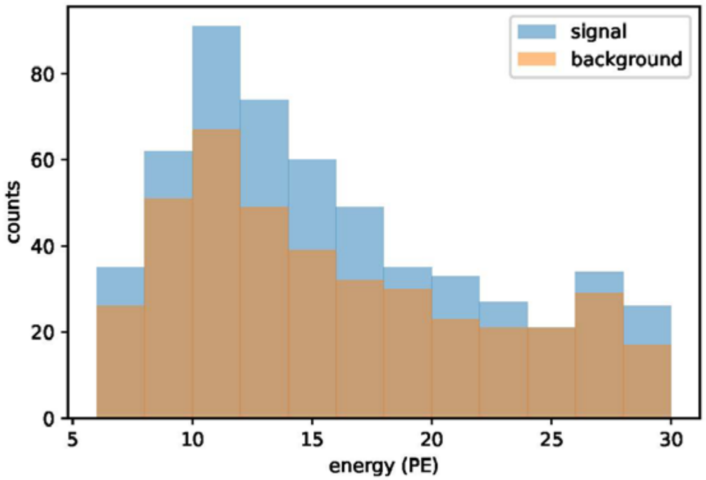


Abdullah, Dent, Dutta, Liao, Kane, Strigari, 2018

COHERENT : timing+Energy data



Timing data



Energy data

Prompt: $\pi^+ \to \mu^+ + \nu_\mu$

Delayed: $\mu^+ \to e^+ + \overline{\nu_\mu} + \nu_e$

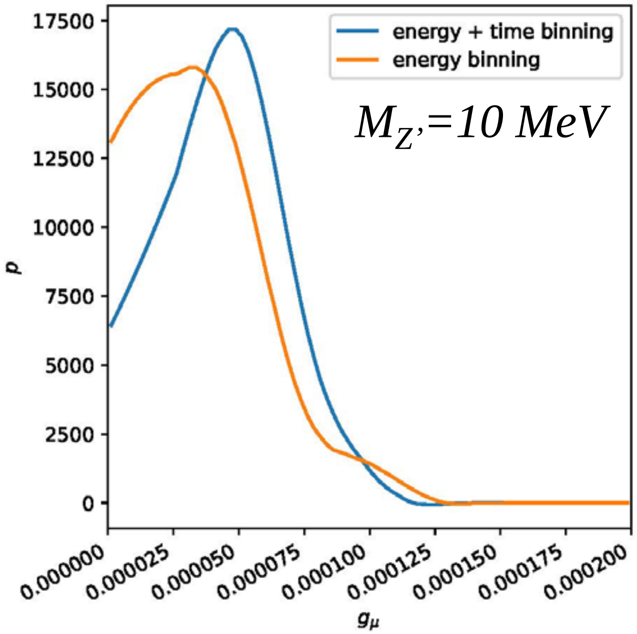
COHERENT, 2018

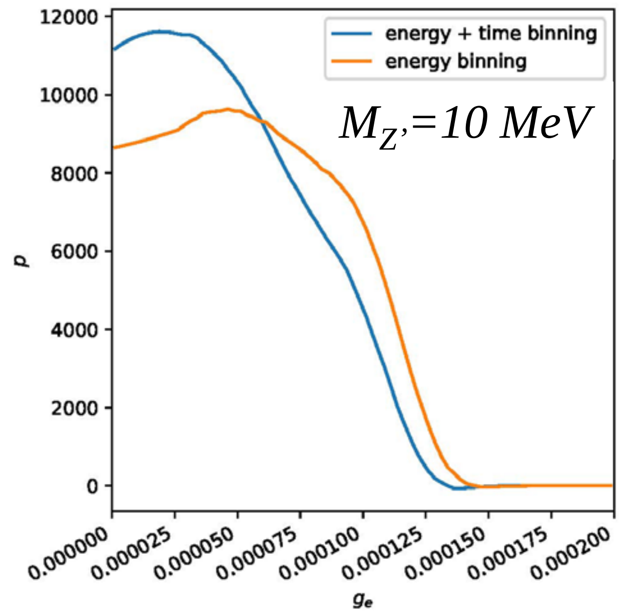
Timing+Energy: Z'

$$\frac{d\sigma}{dE} = \frac{G_F^2 m}{2\pi}\left((g_v+g_a)^2 + (g_v-g_a)^2\left(1-\frac{E}{E_\nu}\right)^2 + (g_a^2-g_v^2)\frac{mE}{E_\nu^2}\right)$$

$$\mathcal{L} \supset Z'_\mu(g'_\nu \bar{\nu}_L\gamma^\mu\nu_L + g'_{f,v}\bar{f}\gamma^\mu f + g'_{f,a}\bar{f}\gamma^\mu\gamma^5 f) \qquad (g_v, g_a) \Rightarrow (g_v, g_a) + \frac{g'_\nu\,(g'_{f,v}, \pm g'_{f,a})}{2\sqrt{2}G_F\,(q^2+M_{Z'}^2)}$$

Posterior probabilities in a log-liklihood analysis





g_μ=0

g_e=0

g_u=g_d=g_ν=g', R_n

Dutta, Liao, Sinha, Strigari, 2019

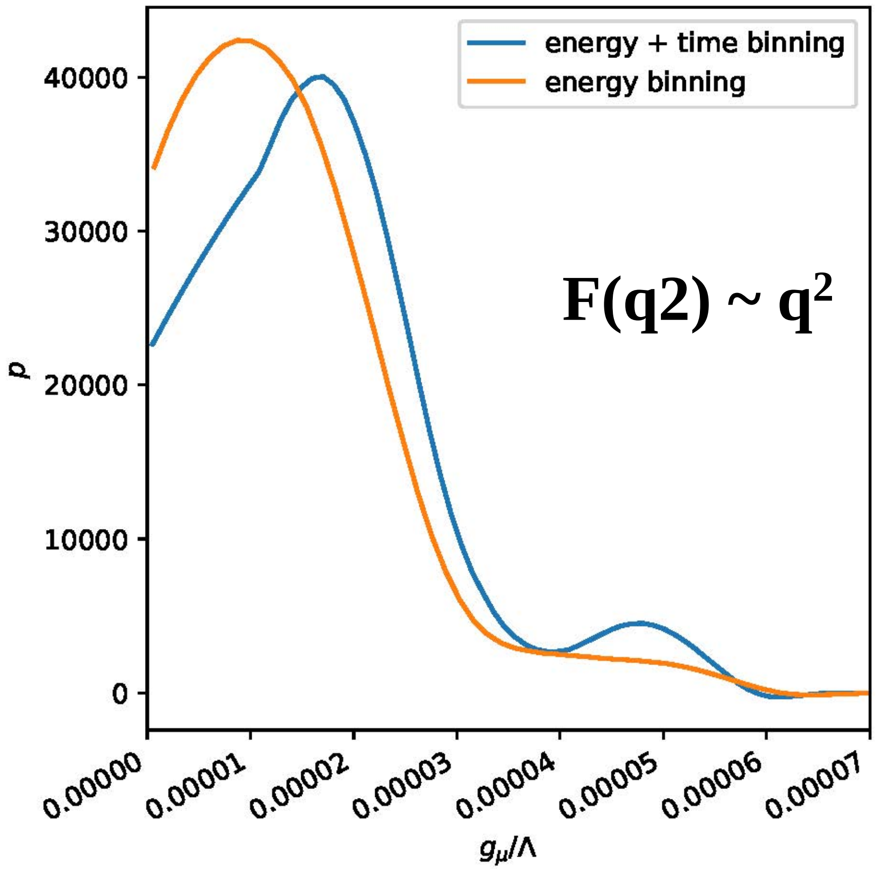
Timing+Energy: Z'

Mediator mass, $M_{Z'}$ (MeV)	Fixed (model (a))	Fixed shape (model (b))	Varying (model (c))
free	1.4(0.7)	0.9(0.6)	1.1(0.6)
10	1.9(1.2)	1.4(1.1)	1.6(1.0)
100	1.9(1.1)	1.4(1.1)	1.6(1.1)
1000	1.9(1.2)	1.4(1.1)	1.6(1.1)

$M_{Z'}$ (MeV)	10	100	1000
g_μ	$[1.87, 6.65] \times 10^{-5}$	$[0.41, 1.47] \times 10^{-4} \oplus [2.47, 2.66] \times 10^{-4}$	$[0.48, 1.32] \times 10^{-3} \oplus [2.17, 2.47] \times 10^{-3}$
g_e	$[0, 6.12] \times 10^{-5}$	$[0, 1.53] \times 10^{-4} \oplus [2.53, 2.84] \times 10^{-4}$	$[0, 1.22] \times 10^{-3} \oplus [2.22, 2.77] \times 10^{-3}$

Dutta, Liao, Sinha, Strigari, 2019

Timing+Energy: Z'



$g_e=0$

Timing+Energy: Z'

Nuclear form factor

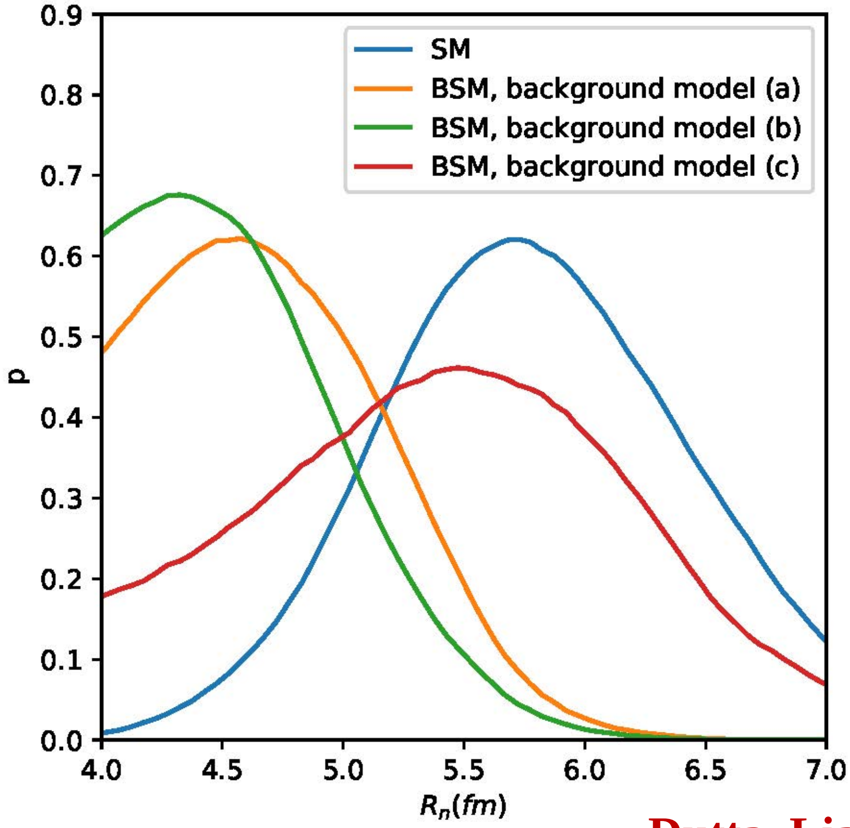
Helm factor

$$\frac{\mathrm{d}\sigma}{\mathrm{d}E} = \frac{G_F^2 Q_V^2}{2\pi} m_N \left(1 - \left(\frac{m_N E}{E_\nu^2}\right) + \left(1 - \frac{E}{E_\nu}\right)^2\right) F(q^2)$$

$$F_N^{\mathrm{Helm}}(q^2) = 3\,\frac{j_1(qR_0)}{qR_0}\,e^{-q^2 s^2/2},$$

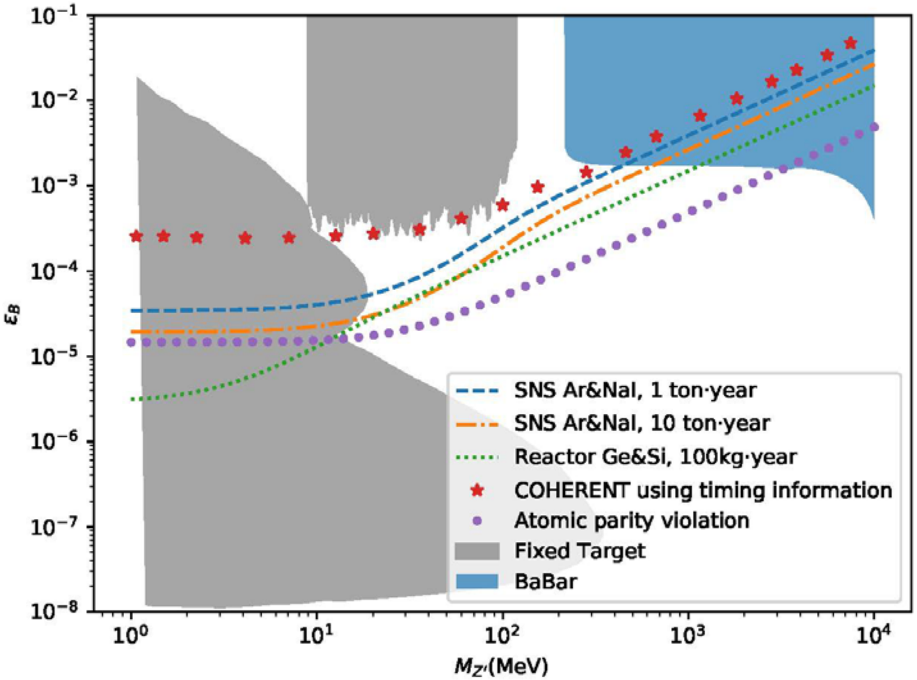
$$R_n^2 = R_0^2 + 5s^2$$

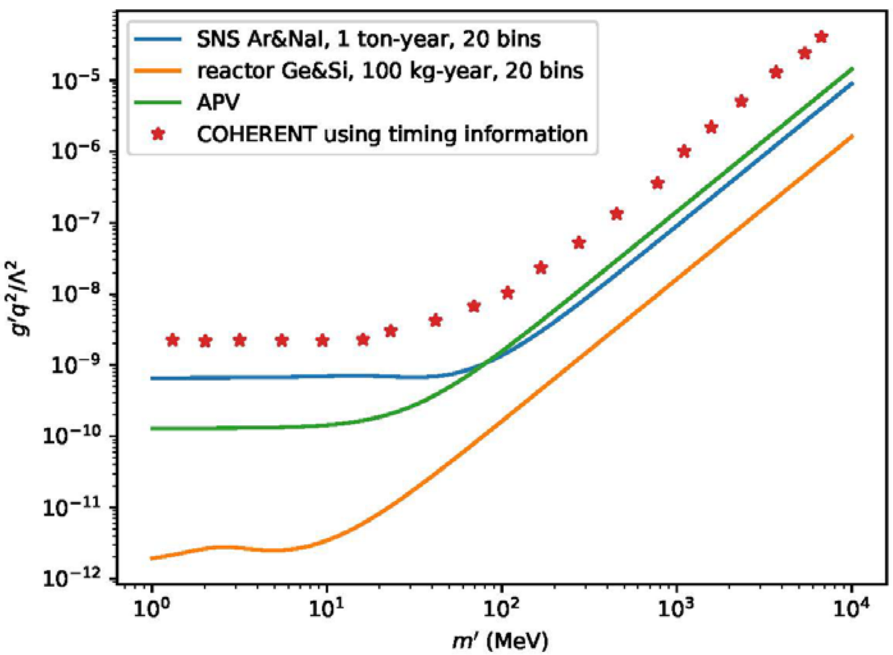
$g_e = g_\mu$



Dutta, Liao, Sinha, Strigari, 2019

Timing + Energy data: Impact





~ 1.6 σ points for kinetic mixing (left) and $F(q^2) \sim q^2$ (right)

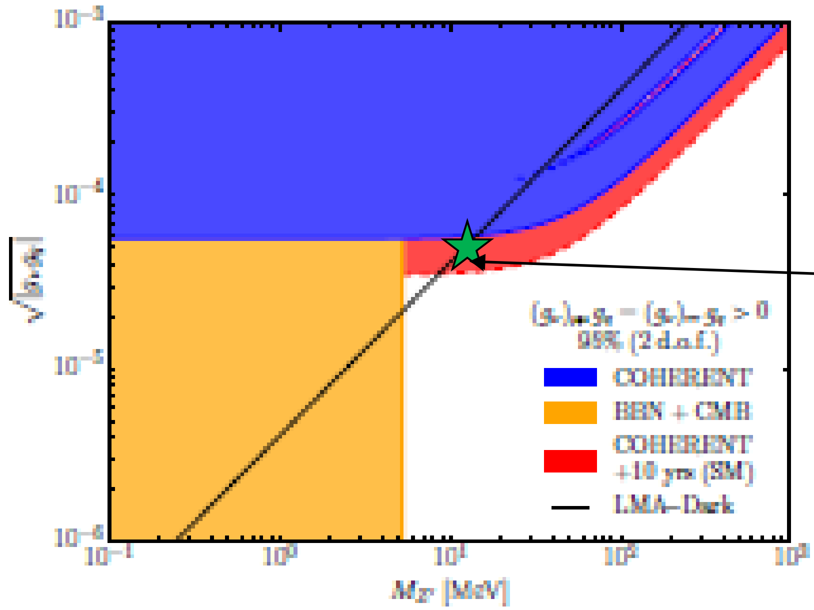
Dutta, Liao, Sinha, Strigari, 2019

LMA-D

ν – oscillation data allows large NSI in the LMA-dark region

Standard LMA: 34^0 ⟺ ***LMA-Dark: 45^0 < θ <90^0 with ε ~1***

Large ε ⇨ ***small $M_{Z'}$***



The significance is about 1.6σ using timing + energy data

COHERENT

Dutta, Liao, Strigari, 2019

Denton, Farzan, Shumaker, 2018

$SU(2)_L \times U(1)_Y \times U(1)_{T3R}$

Model for a sub GeV DM

E.g., there may be a new symmetry breaking scale around GeV
➔2nd and 1st generation fermion masses (~MeV to few GeV)

Anomaly free

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

$SU(2)_L \times U(1)_Y \times U(1)_{T3R}$

$U(1)_{T3R}$ *is broken at 1-10 GeV down to* Z_2

Low mass dark matter, gauge Boson, scalar

Predictions are testable at various low energy experiments

Dutta, Ghosh, Kumar, 2019

Similar model for with 3rd generation: Dutta, Kumar, 2011

$U(1)_{T3R}$

$$\mathcal{L}_{Yuk} = -\frac{\lambda_u}{\Lambda}\tilde{H}\phi^*\bar{Q}_L q_R^u - \frac{\lambda_d}{\Lambda}H\phi\bar{Q}_L q_R^d - \frac{\lambda_\nu}{\Lambda}\tilde{H}\phi^*\bar{L}_L\nu_R - \frac{\lambda_l}{\Lambda}H\phi\bar{L}_L\ell_R - \lambda\phi\bar{\eta}_R\eta_L - \frac{1}{2}\lambda_L\phi\bar{\eta}_L^c\eta_L - \frac{1}{2}\lambda_R\phi^*\bar{\eta}_R^c\eta_R - \mu_\phi^2\phi^*\phi - \lambda_\phi(\phi^*\phi)^2 + H.c.,$$

- **Scalar ϕ vev** $V=(-\mu_\phi^2/2\lambda_\phi)^{1/2}$ **breaks $U(1)_{T3R}$ to Z_2 , vev is around 1-10 GeV with** $m_{\phi'}=2\lambda_\phi^{1/2}V$.

$$\mathcal{L}_{Yuk} = -m_u\bar{q}_L^u q_R^u - m_d\bar{q}_L^d q_R^d - m_\nu\bar{\nu}_L\nu_R - m_\ell\bar{\ell}_L\ell_R - \frac{1}{2}m_1\bar{\eta}_1\eta_1 - \frac{1}{2}m_2\bar{\eta}_2\eta_2 - \frac{m_u}{V}\bar{q}_L^u q_R^u\phi' - \frac{m_d}{V}\bar{q}_L^d q_R^d\phi' - \frac{m_{\nu D}}{V}\bar{\nu}_L\nu_R\phi' - \frac{m_\ell}{V}\bar{\ell}_L\ell_R\phi' - \frac{1}{2}\frac{m_1}{V}\bar{\eta}_1\eta_1\phi' - \frac{1}{2}\frac{m_2}{V}\bar{\eta}_2\eta_2\phi' + ...$$

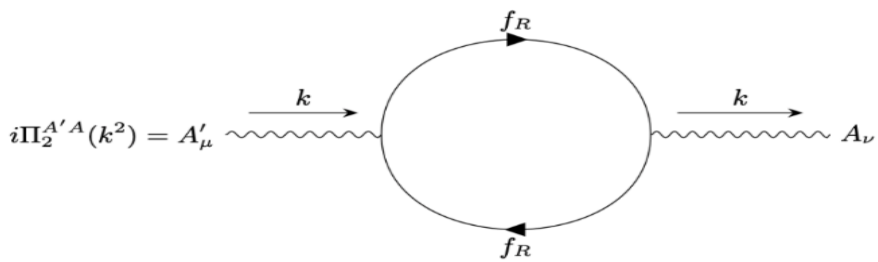
$$\eta_1 = -\frac{i}{\sqrt{2}}\begin{pmatrix}\eta_L - \eta_R^c \\ -\eta_L^c + \eta_R\end{pmatrix} \qquad \eta_2 = \frac{1}{\sqrt{2}}\begin{pmatrix}\eta_L + \eta_R^c \\ \eta_L^c + \eta_R\end{pmatrix}$$

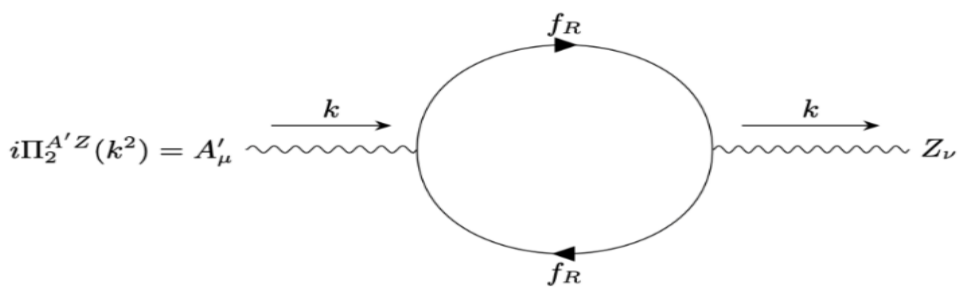
Dark Matter (parity odd): $\eta_{1,2}$

$U(1)_{T3R}$

$$\mathcal{L}_{gauge} = \frac{i}{4} g_{T_{3R}} A'_\mu (\bar{\eta}_1 \gamma^\mu \eta_2 - \bar{\eta}_2 \gamma^\mu \eta_1) + \frac{m_{A'}^2}{V} \phi' A'_\mu A'^\mu + i g_{T3R} A'_\mu (\phi' \partial^\mu \phi'^* - \phi'^* \partial^\mu \phi) - \frac{1}{2} g_{T_{3R}} j^\mu_{A'} A'_\mu,$$

$$j^\mu_{A'} = \sum_f Q^f_{T_{3R}} \bar{f} \gamma^\mu f. \qquad m_{A'}^2 = 2 g_{T_{3R}}^2 V^2$$





$U(1)_{T3R}$

- ϕ': $\phi' \to \bar{l}l$, $\nu_s\nu_A, \pi\pi, A'A'$: **dominate, if kinematically allowed. Otherwise,** $\phi' \to \gamma\gamma$ ***(one loop diagram)*** **dominates**

- A': $A' \to \bar{l}l$, $\nu_s\nu_s, \pi\pi, \phi'\phi'$: **dominate, if kinematically allowed. Otherwise,** $A' \to \nu_L\nu_L$***(one loop diagram)*** **dominates**

- ν_s: $\nu_s \to \nu_A\gamma\gamma$: **mediated by an offshell** ϕ'**dominate**

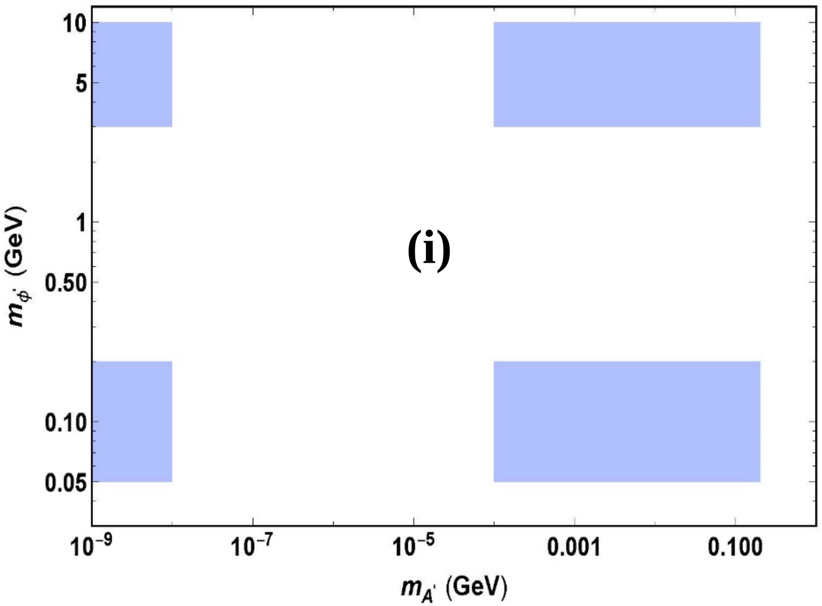
Parameter Space

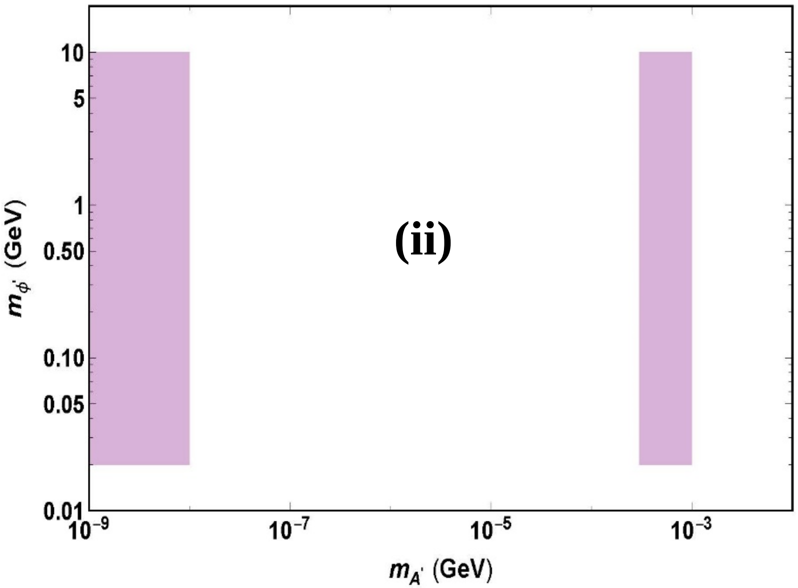
Various scenarios: Gauge boson (A')-scalar (ϕ') mediators parameter space

(ι) μ_R, u_R, d_R, ν_R, η_R, η_L, ϕ : E137, Babar, BBN, Globular cluster, Sun, supernova etc

(ii) e_R, u_R, d_R, ν_R, η_R, η_L, ϕ : Atomic parity, BBN, Globular cluster, Sun, supernova etc

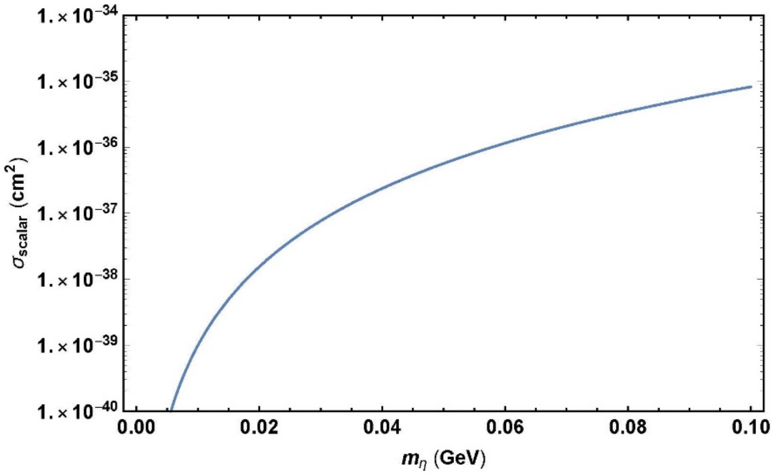
(iii) μ_R, c_R, s_R, ν_R, η_R, η_L, ϕ: E137, Babar, , BBN, Globular cluster, Sun etc

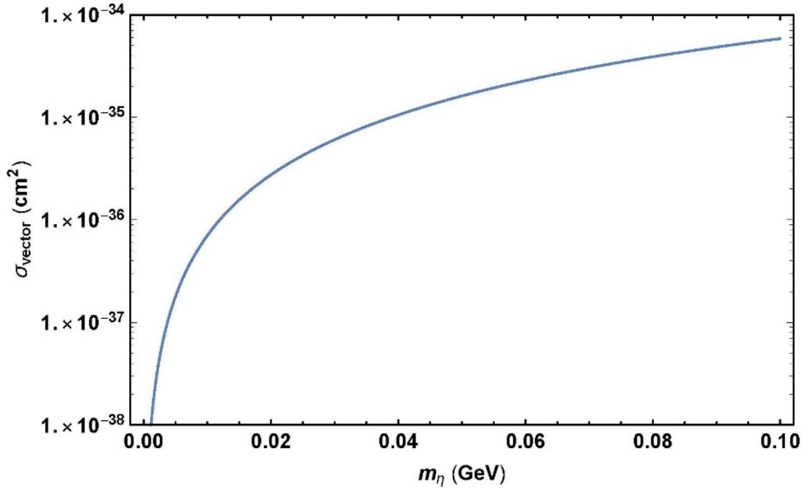




direct detection

Constraints from CRESST, Xenon1T **(cosmic ray scattered, Bringmann, Pospelov, 2018)**





Elastic scattering: $\bar{\eta}\eta\,\bar{q}_L q_R$

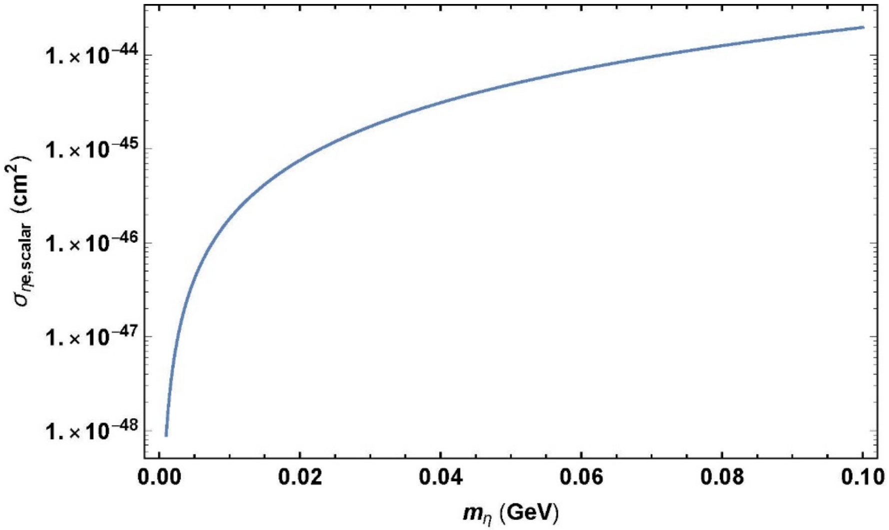
ϕ' *mediated*

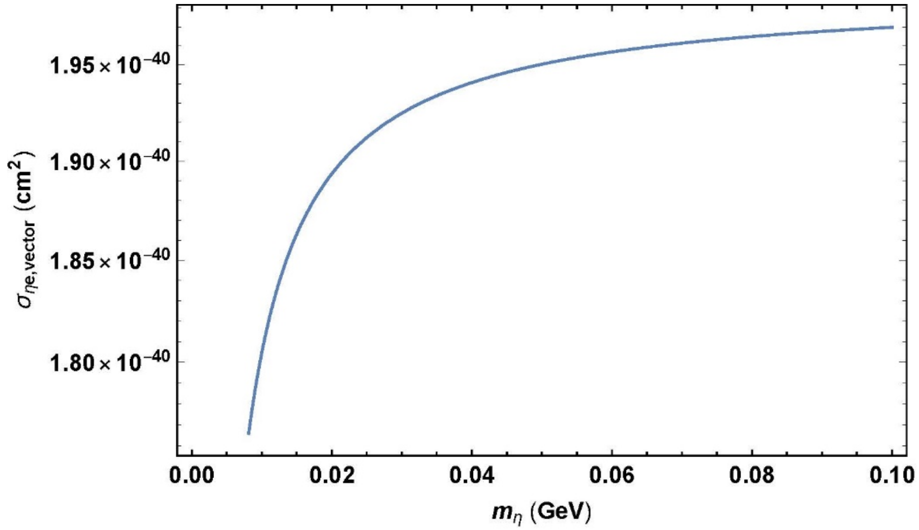
Inelastic scattering: $\bar{\eta}_1\gamma^\mu\eta_2\bar{q}_L\gamma^\mu q_L$

A' *mediated*

direct detection

Dark Matter-electron Scattering





The allowed cross-section ≤ 10^{-38} cm^2

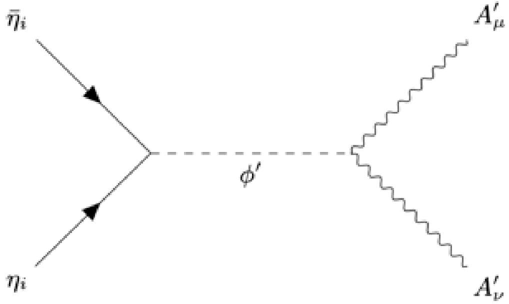
Ema, Sala, Sato, 2018

Thermal Relic Abundance

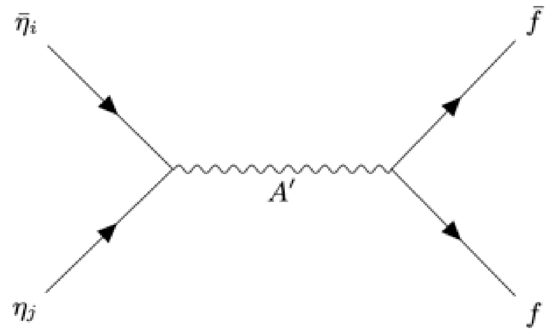
Dominant two body final states: $\bar{\ell}\ell,\ \bar{\nu}\nu,\ \pi\pi,\ \pi^0(\phi', A', \gamma)$

$$+$$

$$A'A',\ \phi'\phi' \text{ and } \phi'A'$$



P-wave



S-wave

+ …

Resonance/non-resonance:

	m'_A (MeV)	m'_ϕ (MeV)	m_η (MeV)	$\langle\sigma v\rangle$ cm^3/sec	$\sigma^{scalar}_{0\eta n}$(pb)	$\sigma^{vector}_{0\eta n}$(pb)
muon case	40	102	50	3×10^{-26}	0.56	16.14
	70	10^4	50	3×10^{-26}	5.6×10^{-9}	16.14
electron case	0.4	100	50	3×10^{-26}	0.56	16.14

Models: e$^+$e$^-$ from the scattering

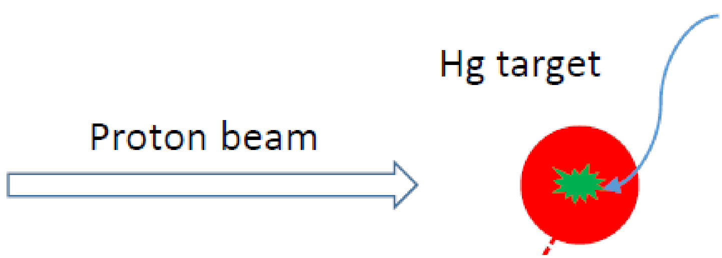
Dark sector consists of dark matter particle χ_1 and an unstable particle χ_2
χ_2 is heavier than χ_1 and decays into SM particles + χ_1

Many authors: Finkbeiner, Weiner, Chang, Kribs, Tucker-Smith, Slatyer, Pospelov, Yavin, Poland, Randall, Cui, Morissey, Dienes, Thomas, Kumar, Kim, Park, Shin…

$$\mathcal{L}_X \supset -\frac{\sin\epsilon}{2} F_{\mu\nu} X^{\mu\nu} + g_{12} \bar{\chi}_2 \gamma^\mu \chi_1 X_\mu + h.c.$$

Production of χ_1 at COHERENT

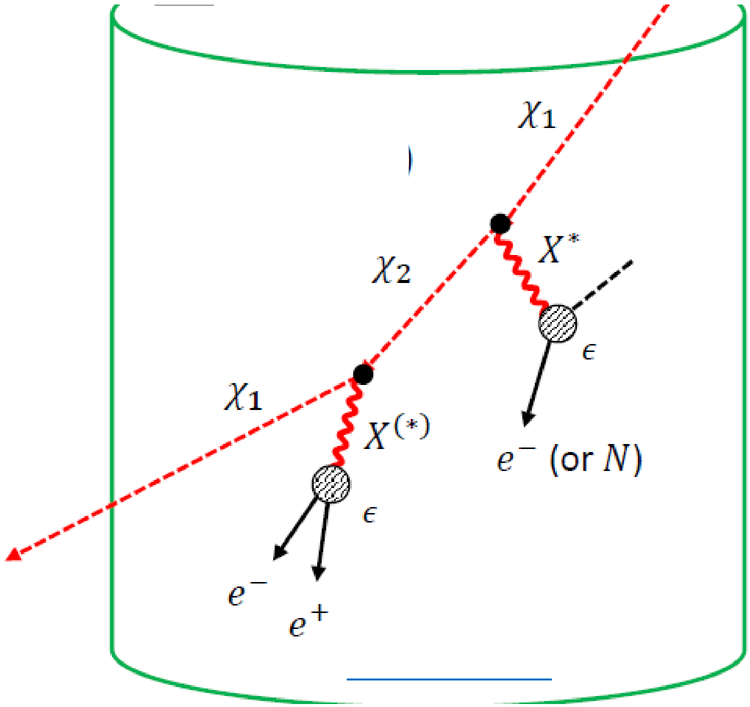
Deniverville, Pospelov, Ritz,'15



$$\pi^- + p \rightarrow n + X^{(*)} \rightarrow \begin{cases} n + \chi_1 + \chi_1 \\ n + \chi_1 + \chi_2 \end{cases}$$

(χ_2: **not** DM, a heavier dark-sector state!)

Models: e^+e^- from the scattering



χ_1 : **Dark Matter**

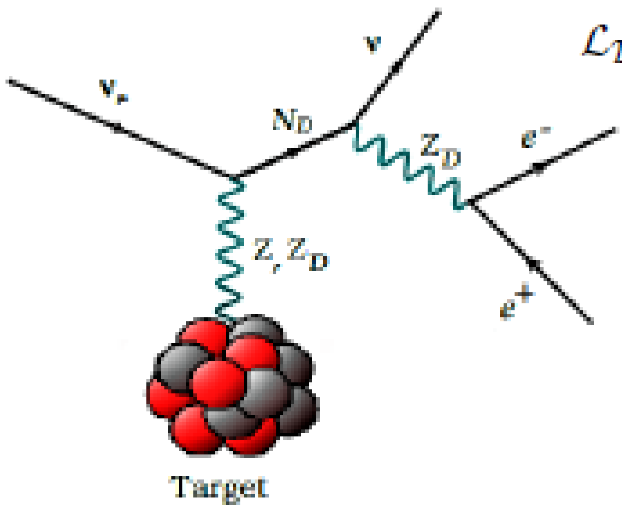
- ***Three visible particles (recoil ~ 1-20 MeV)***
- ***e^+e^- pair can be displaced (parameter choice)***

Dutta, Kim, Park, Shin, Tayloe, In Progress

Models: e^+e^- from the scattering

MiniBoone observation of excess ν_e $\overline{\nu}_e$ in charged current event (excess electron-like events)

$$\nu_\alpha = \sum_{i=1} U_{\alpha i}\,\nu_i + U_{\alpha 4}\,N_{\mathcal{D}}\,,$$



$$\mathcal{L}_{\mathcal{D}} \supset \frac{m^2_{Z_{\mathcal{D}}}}{2}\,Z_{\mathcal{D}\mu}Z^\mu_{\mathcal{D}} + g_{\mathcal{D}} Z^\mu_{\mathcal{D}}\overline{\nu}_{\mathcal{D}}\gamma_\mu\nu_{\mathcal{D}} + e\epsilon\,Z^\mu_{\mathcal{D}}\,J^{\rm em}_\mu + \frac{g}{c_W}\epsilon'\,Z^\mu_{\mathcal{D}}\,J^Z_\mu\,,$$

Bertuzzo, Jana, Machado, Funchal, 2018

- **Similar scenarios can be constructed with neutrino-dark matter interaction as well.**

Outlook

- **What is the scale of new physics?**

- **Models with light mediators are very interesting:**
  Dark Matter, g-2 of electron, neutrino masses,
  Yukawa coupling hierarchy, MiniBoone excess

- **Mediators masses ≤ 10 GeV are mostly not constrained by the**
  collider bounds are not applicable

- **Many interesting ideas, e.g., L_μ-L_τ , Hidden sector, U(1)-T_{3R}**
  Low mass DM etc.

- **Many experiments are probing this region**