Light Mediators

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Light Mediators: Why Not?

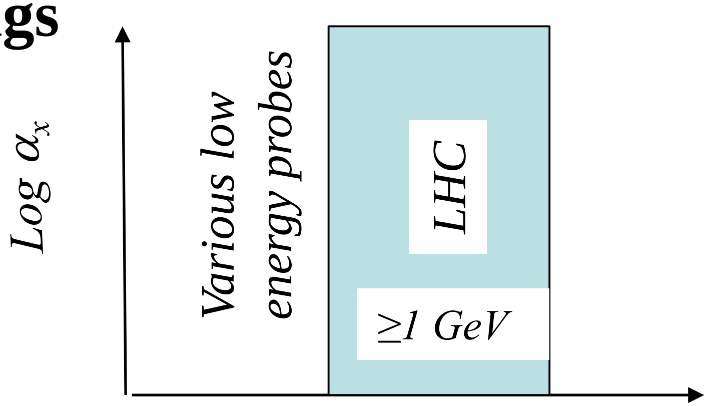
- **ν sector of SM (SU(3) x SU(2) x U(1)) requires new physics for understanding the experimental results on masses and mixing angles**

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

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

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

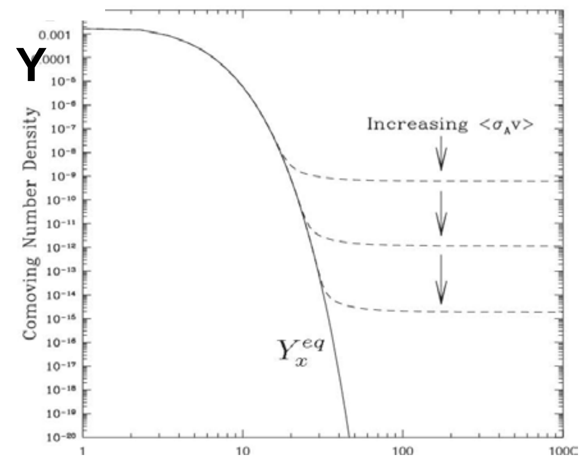
$$\alpha_x = \frac{g_x^2}{4\pi}$$



Thermal DM

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

Y=DM abundance



Mass of DM/Temp.

Light mediators: Why?

Various Light mediators scenarios:

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

- **g-2 of electron: 2.4 σ descripency (recent)**

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

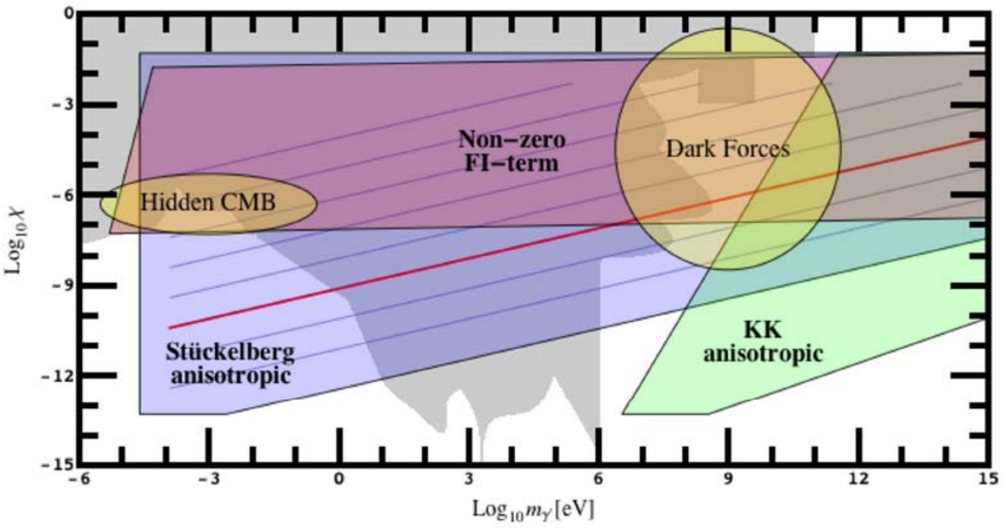
- **Solutions of Yukawa couplings hierarchies problem**

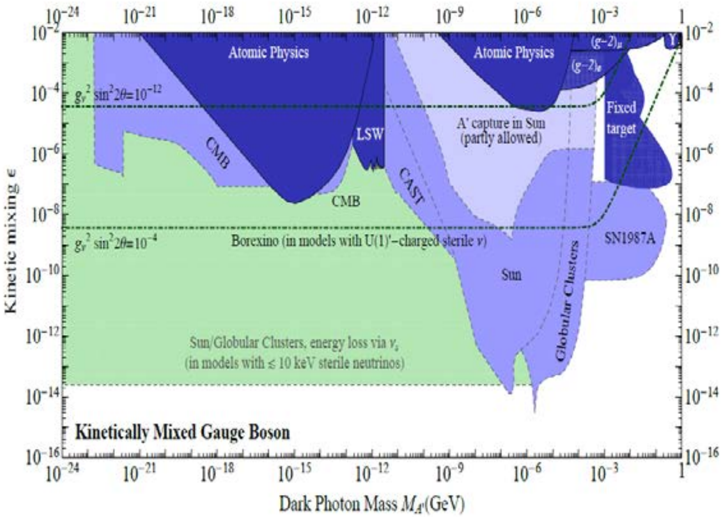
Low scales

New physics: new symmetry breaking scale

Existence of new scales above or below the SM in many theories

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





Cicoli, Goodsell, Jaeckel, Ringwald, 2011
Acharya, Ellis, Kane, Nelson, Perry, 2016

Harnik, Kopp, Machado, 2012

Various Models

- **Kinetic mixing, L_μ-L_τ models**
- **Hidden sector model**
- **B-L for the 3rd generation**
- **A Low mass DM model associated with a new symmetry scale**

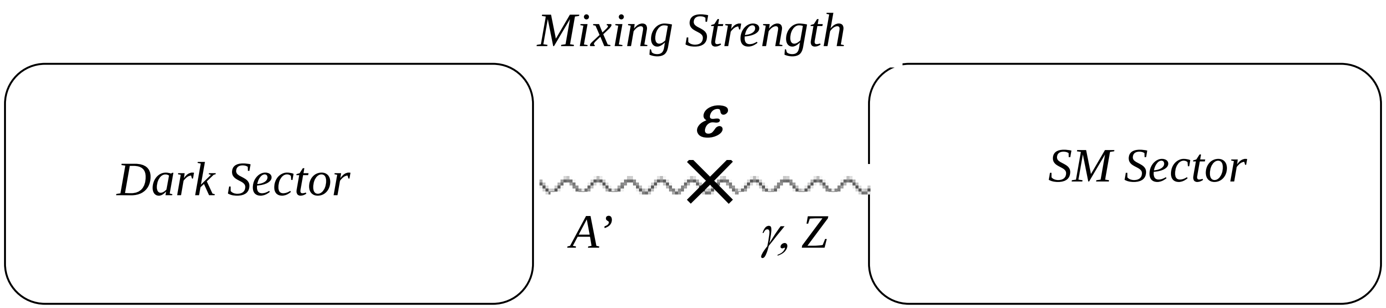
Two ways to probe these models (in this talk):

Neutrino, Dark Matter

Models: Kinetic mixing

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

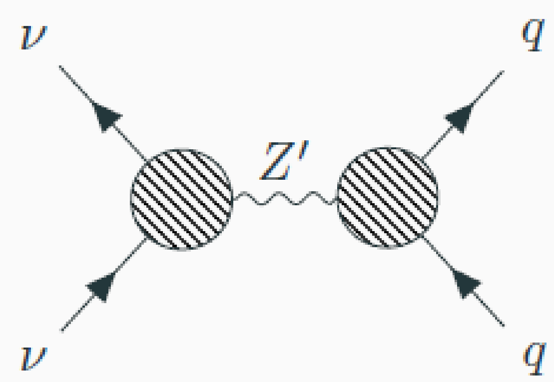
The "Dark sector" sector mixes with the SM via kinetic mixing (loop generated by particles containing charges from both sectors)



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

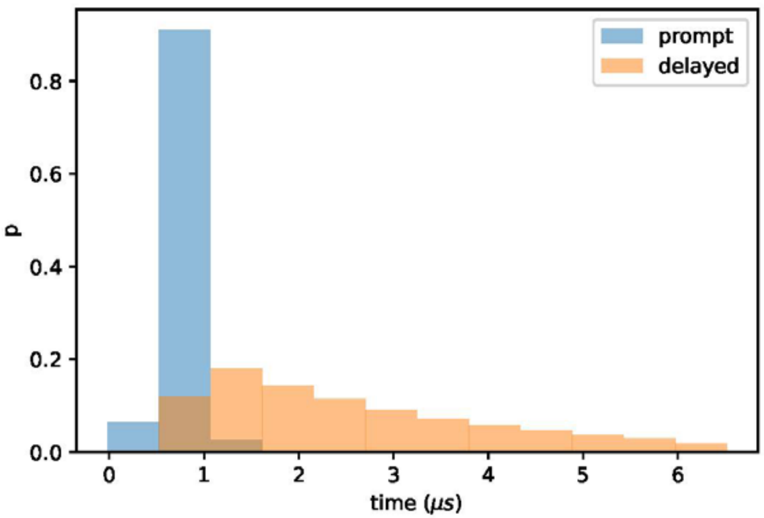
1. Dark Z boson: α small, coupling: $igtan\theta_W(Y_f/2)\epsilon_B$

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

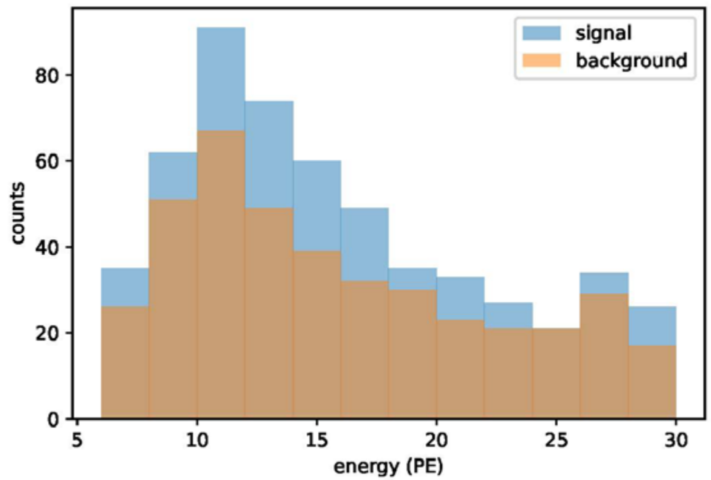
$\epsilon_Z \equiv s_\alpha$

COHERENT : timing+Energy data

COHERENT AT THE SNS: 1 GeV proton beam hits a Hg target: produces pions



Timing data



Energy data

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

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

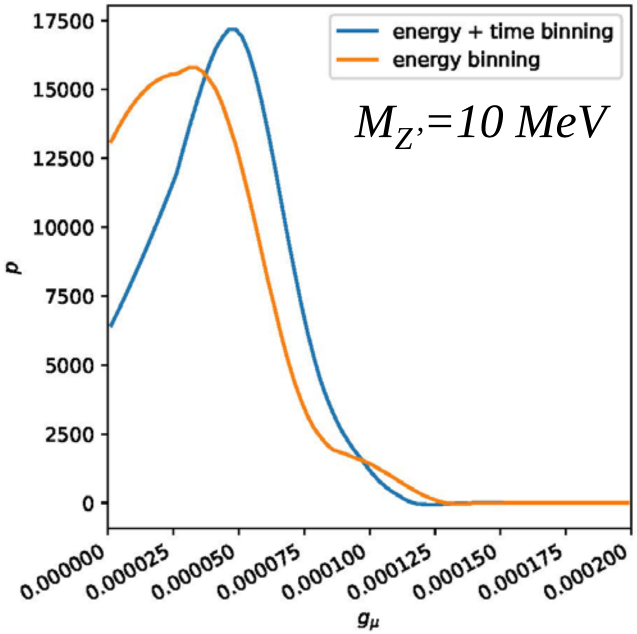
COHERENT, 2018

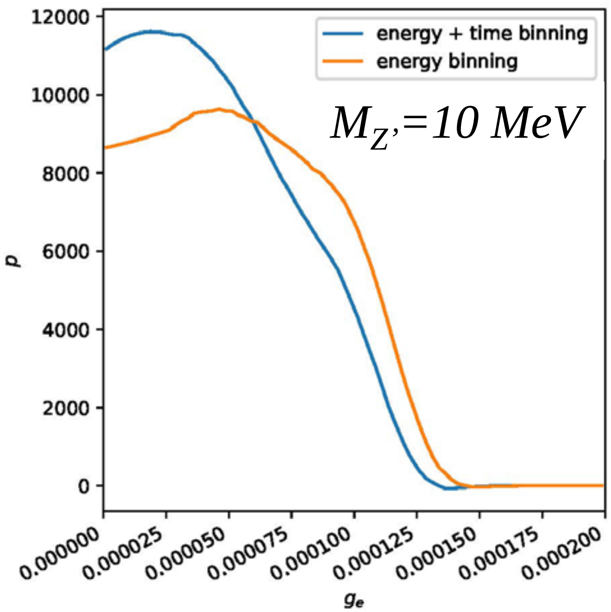
Timing+Energy: Z’

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

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

Posterior probabilities in a log-liklihood analysis





g_μ=0

g_e=0

$g_u=g_d=g_\nu=g'$, 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'

Nuclear form factor

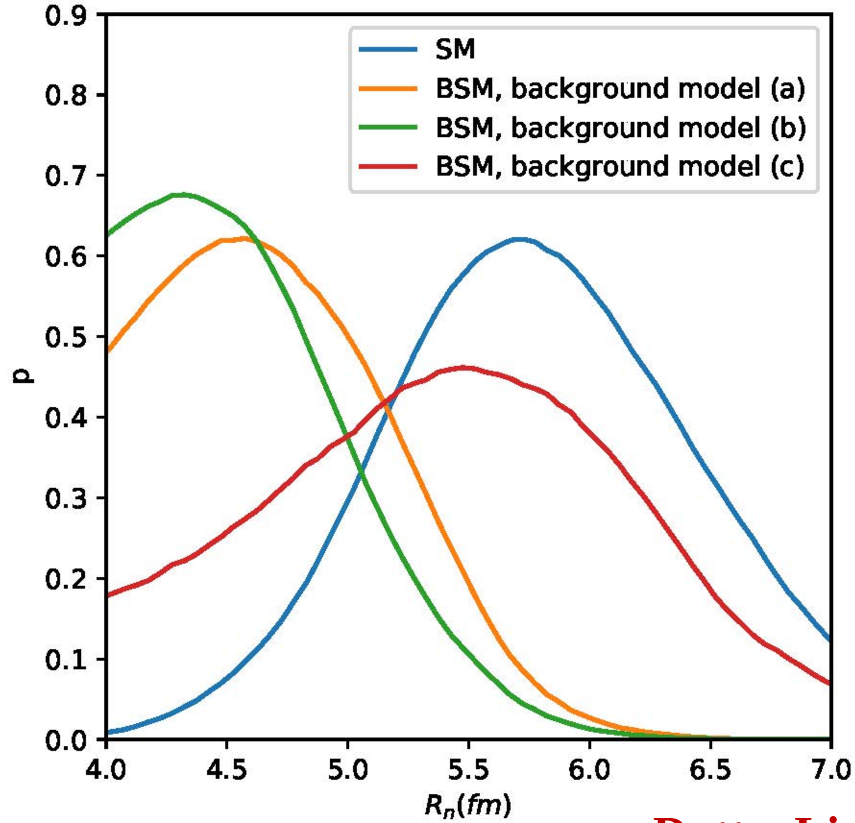
$$\frac{\mathrm{d}\sigma}{\mathrm{d}E} = \frac{G_F^2 Q_V^2}{2\pi} m_N \left(1 - \left(\frac{m_N E}{E_\nu^2}\right) + \left(1 - \frac{E}{E_\nu}\right)^2\right) F(q^2)$$

Helm factor

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

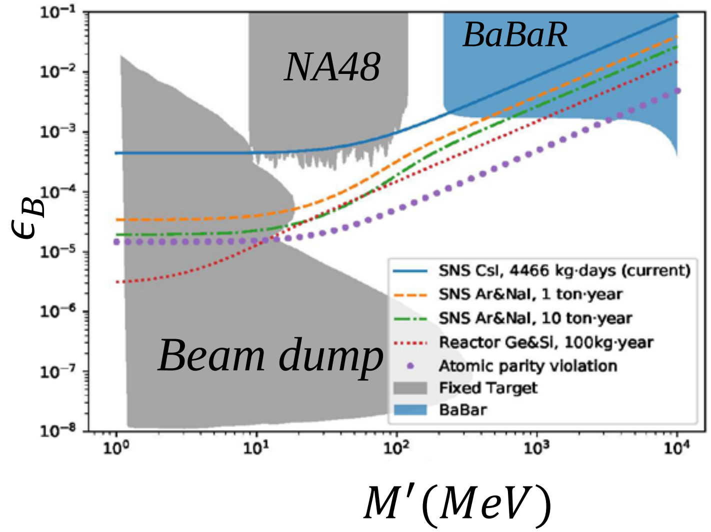
$$R_n^2 = R_0^2 + 5s^2$$

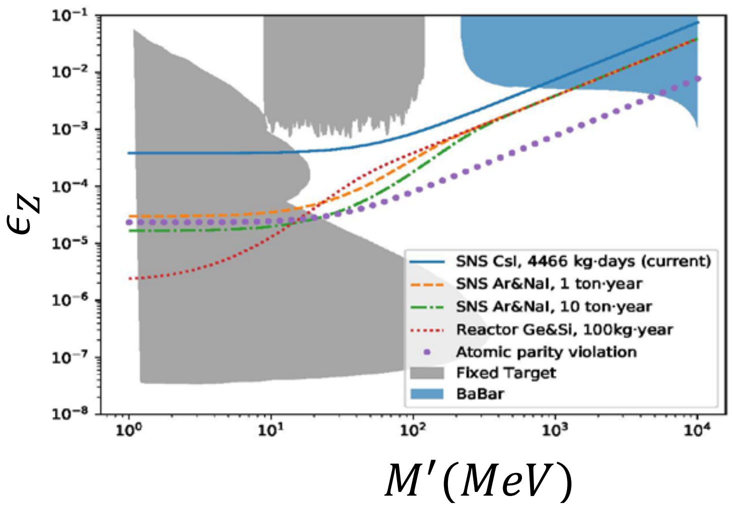
$g_e = g_\mu$



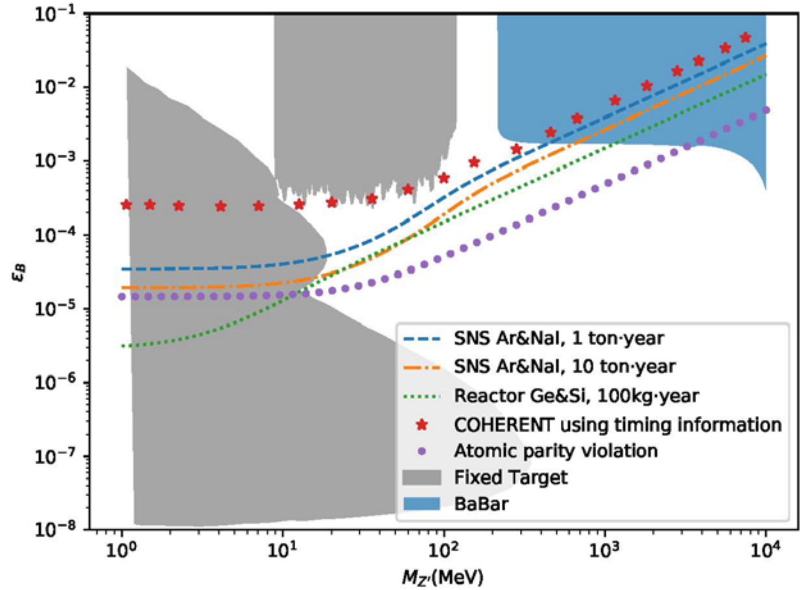
Dutta, Liao, Sinha, Strigari, 2019

Kinetic mixing





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



Dutta, Liao, Sinha, Strigari, 2019

Hidden Sector: Form factor

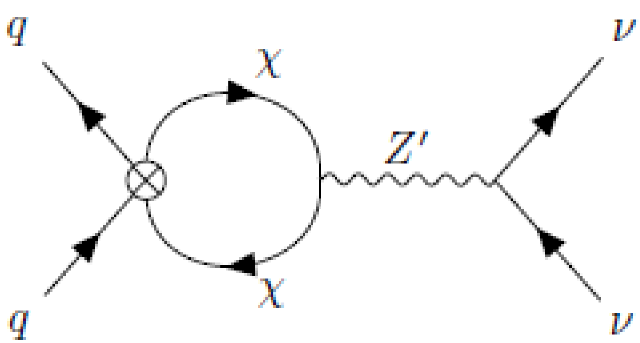
Hidden sector fermions χ:

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

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:

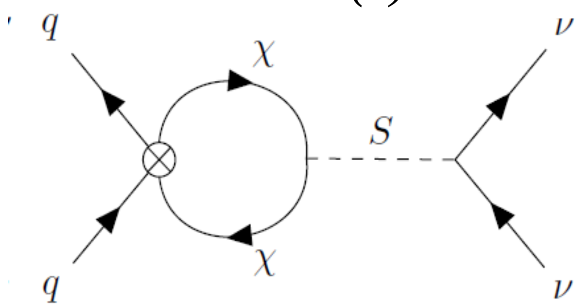


$$\mathcal{L}_{HD} = \frac{g_{L,R}}{\Lambda^2}\bar{q}'\gamma^\mu P_{L,R}q'\partial^\nu Z'_{\mu\nu},$$

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

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

For Scalar (S) mediator



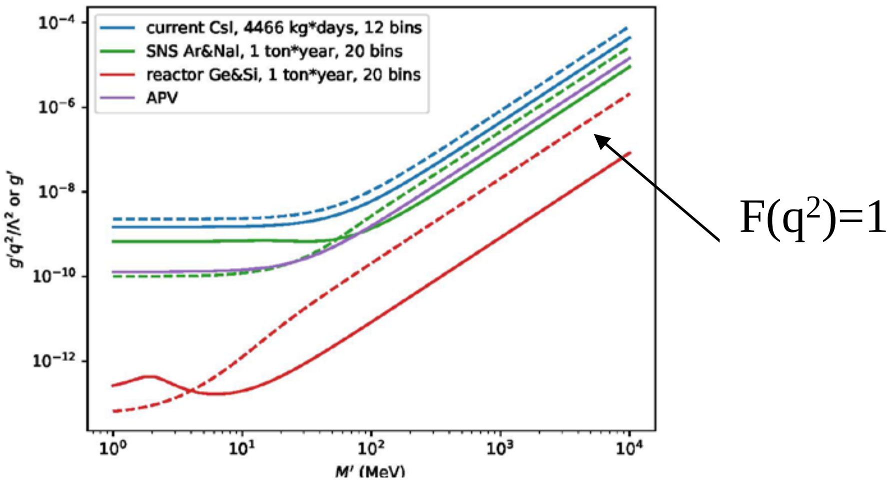
$$F_{L,R}(q^2) = \frac{q^2}{\Lambda^2}g_{L,R}(q^2)$$

Form factor

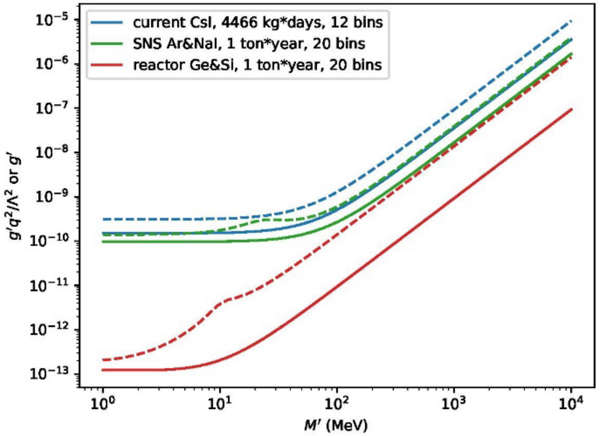
$$\mathcal{L}_{\rm BSM} = -\sqrt{2}G_F\bar{\nu}_L\gamma^\mu\nu_L\bar{f}\gamma_\mu f\frac{gF(q^2,\Lambda^2)}{q^2+m'^2}\frac{1}{2\sqrt{2}G_F}$$

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

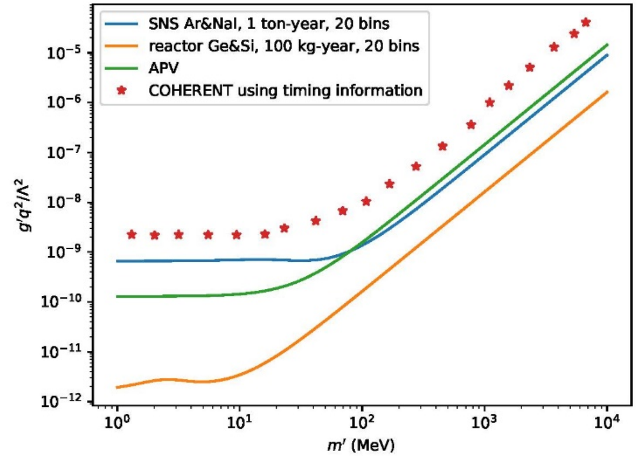
vector



Scalar



Datta, Dutta, Liao, Marfatia, Strigari, 2018



Dutta, Liao, Sinha, Strigari, 2019

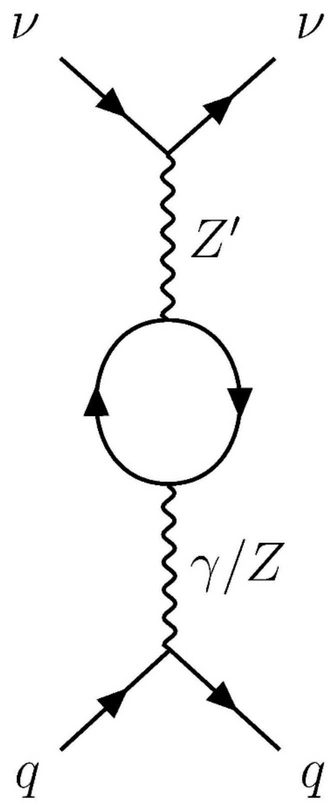
Lμ-Lτ

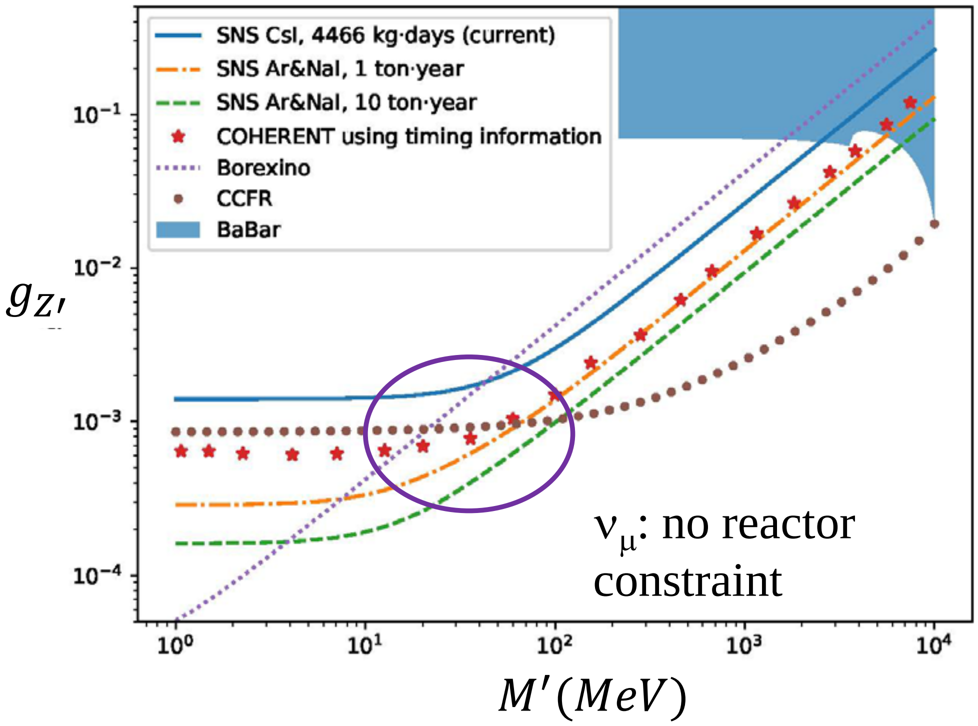
$U(1)_{\mu-\tau}$ symmetry Models

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

$$\mathscr{L}_{\rm int} = g_{Z'} Q_{\alpha\beta} (\overline{\ell_\alpha} \gamma^\rho \ell_\beta + \overline{\nu_\alpha} \gamma^\rho P_L \nu_\beta) Z'_\rho$$

$$\mathscr{L}_{\rm mass} = \frac{1}{2} M_{Z'}^2 Z'^\rho Z'_\rho. \qquad Q_{\alpha\beta} = {\rm diag}(0,1,-1)$$



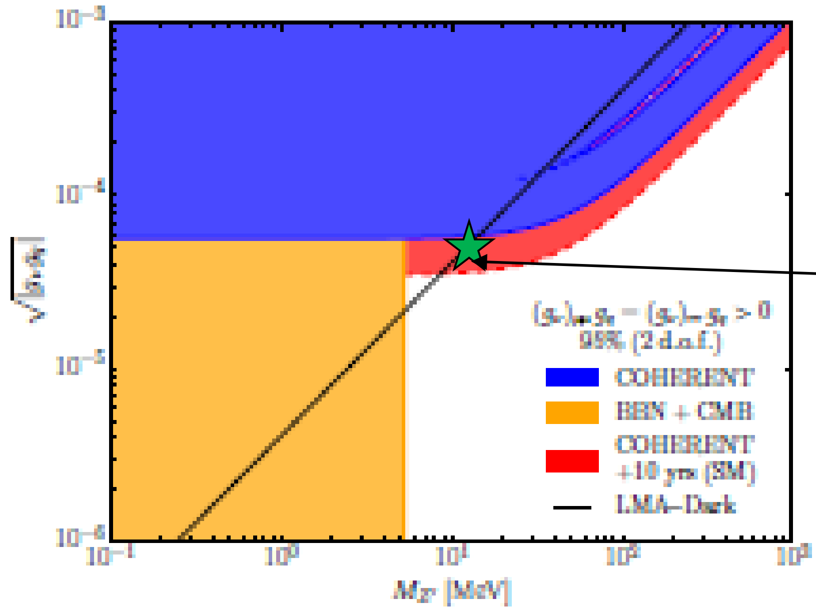


Dutta, Liao, Sinha, Strigari, 2019

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

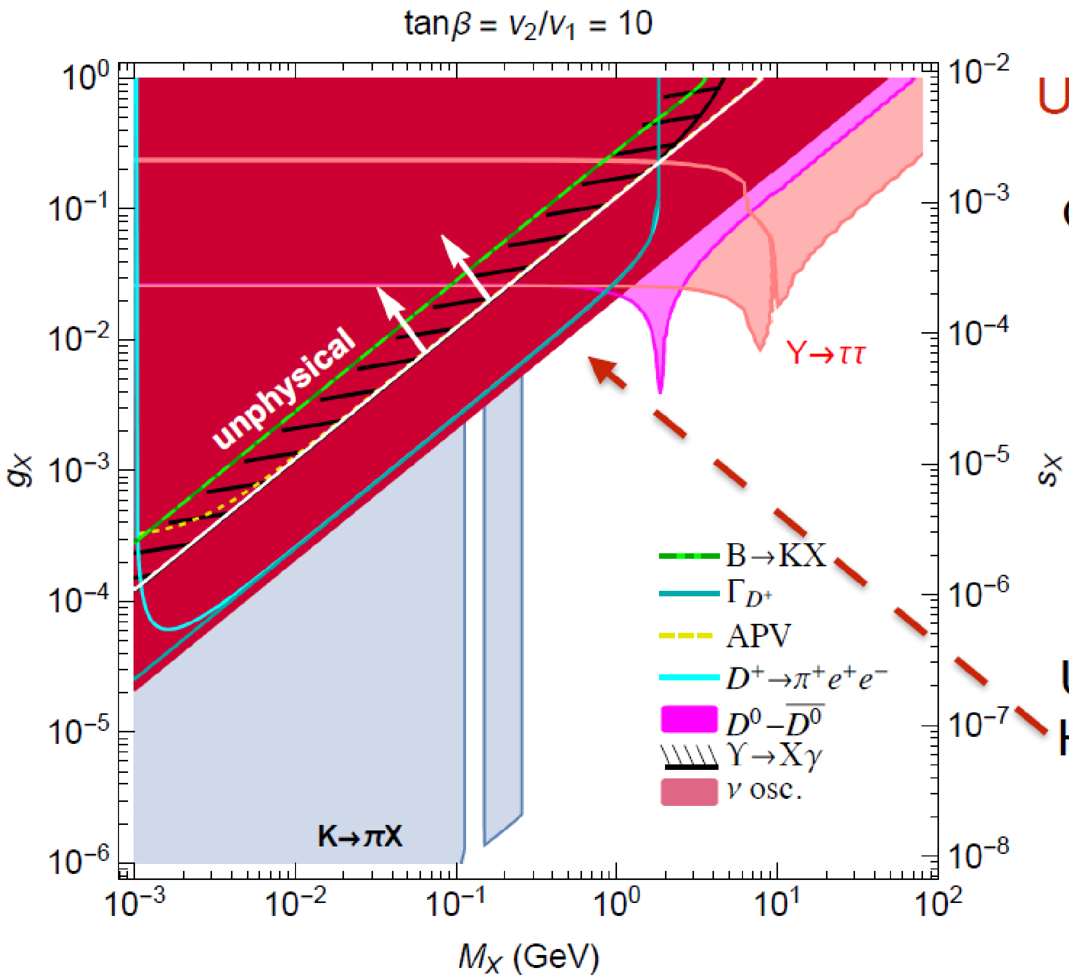
Dutta, Liao, Sinha, Strigari, 2019

Denton, Farzan, Shoemaker, 2018

B-L for the 3rd generation

Neutrinos and low scale new Physics

Can there be a flavor mediators at low scale???



U(1) B – L of the third family

Complete model, including scalar sector and CKM generation

Vast phenomenology:
Z-X mixing (s_X)
D oscillations
Atomic Parity Violation
Upsilon, B, D, and K decays
Higgs, top, Z, and W decays
Neutrino oscillations
…

Babu Friedland Machado Mocioiu 1705.01822

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

Model for a sub GeV DM

E.g., there may be a new symmetry breaking scale around GeV
➔ 2^{nd} and 1^{st} 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 3^{rd} 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** $m_{\phi'}=2\lambda_\phi^{1/2}V$.

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

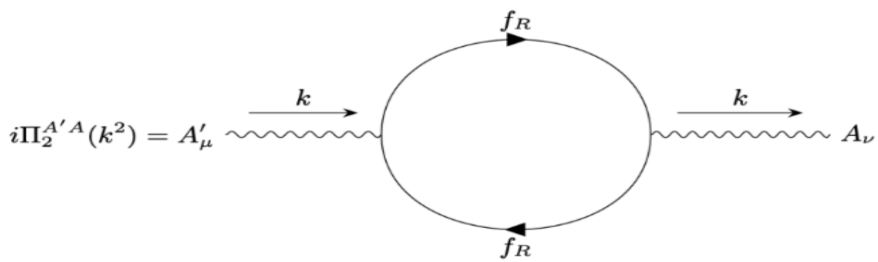
$$\eta_1 = -\frac{i}{\sqrt{2}}\begin{pmatrix} \eta_L - \eta_R^c \\ -\eta_L^c + \eta_R \end{pmatrix} \qquad \eta_2 = \frac{1}{\sqrt{2}}\begin{pmatrix} \eta_L + \eta_R^c \\ \eta_L^c + \eta_R \end{pmatrix}$$

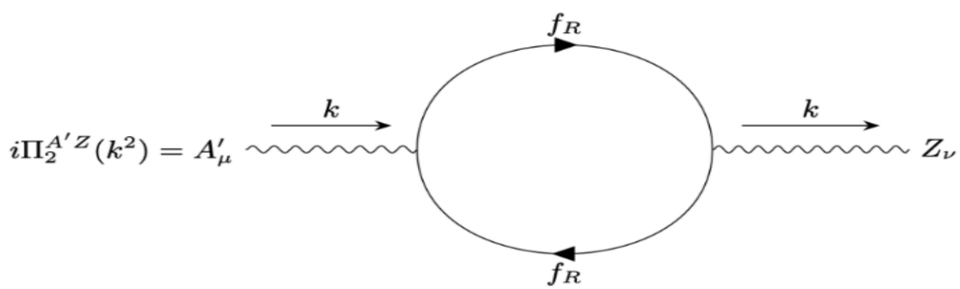
Dark Matter (parity odd): $\eta_{1,2}$

$U(1)_{T3R}$

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

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





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

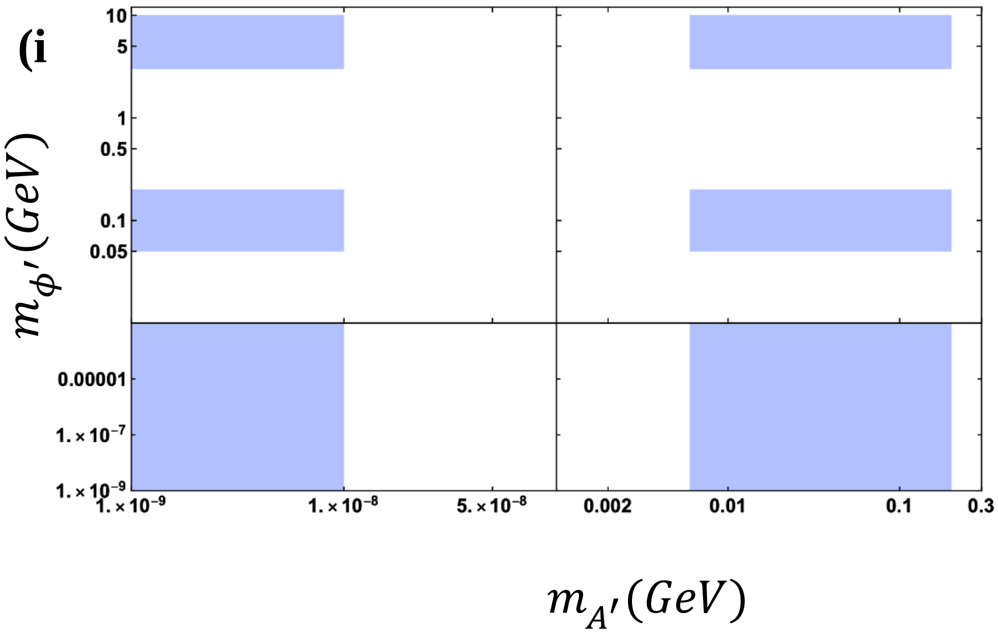
Various scenarios: Gauge boson (A')-scalar (ϕ') mediators parameter space

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

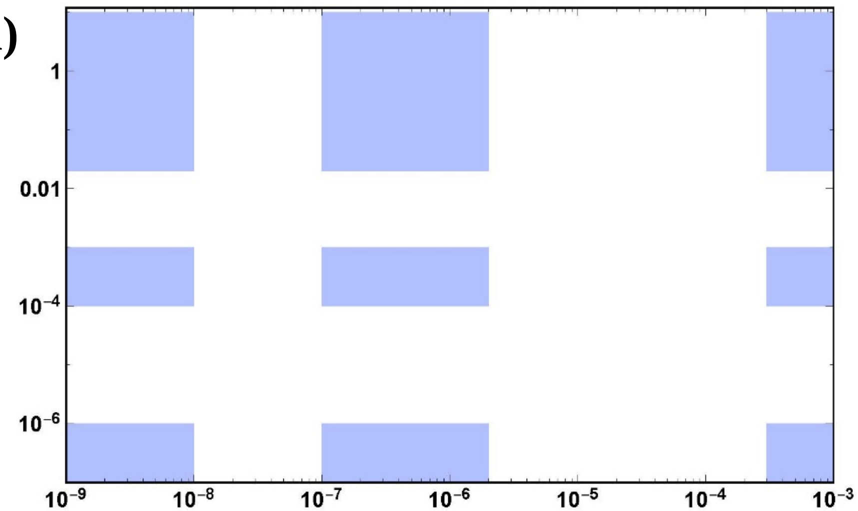
(ii) e_R, u_R, d_R, ν_R, η_R, η_L, ϕ : Atomic parity, BBN, Globular cluster, Sun, supernova etc

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

(i



(ii)



Direct Detection

Various ways of probing Sub-GeV DM:

Migdal effect (Ionization and excitation of electron)

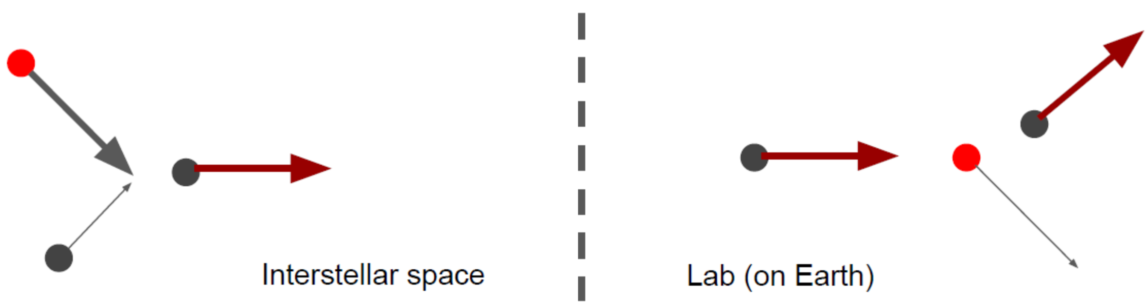
Ibe, Nakano, Shoji, Sujuki, 2018
Dolan, Kahlhoefer, McCabe, 2018

Cosmic ray scattered

Bringmann, Pospelov, 2018

Ema, Sala, Sato, 2018

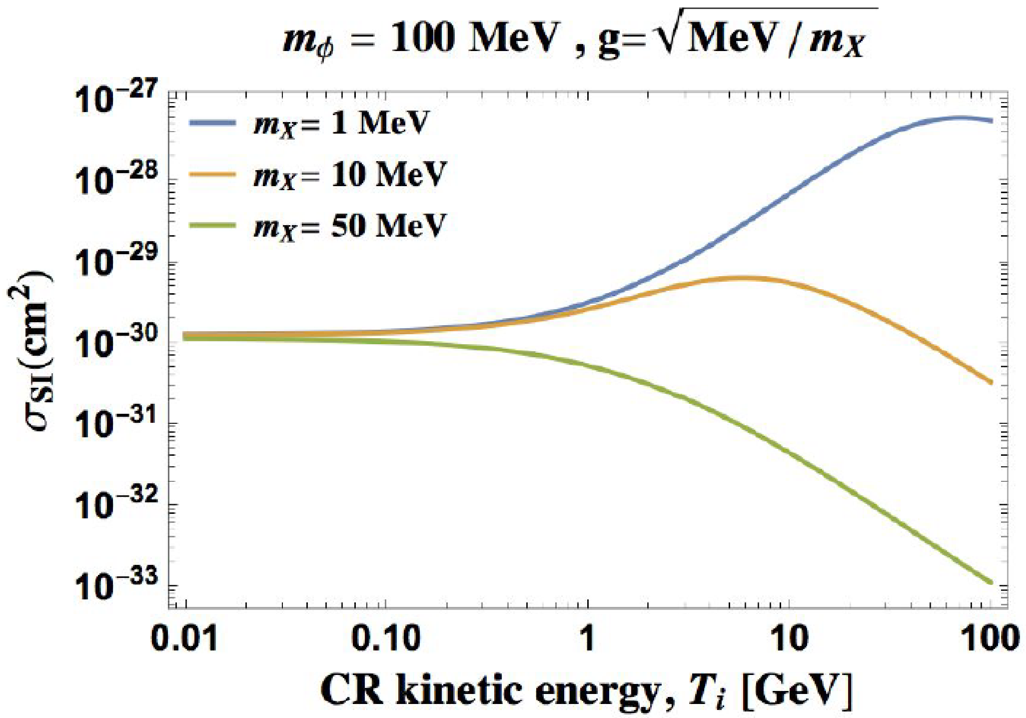
Dent, Dutta, Newstead, Shoemaker, to appear



Low mass DM (up to 10 GeV) become energetic ➔ *detection becomes easier*

Direct Detection

$$\mathscr{L}_{\text{int}} \supset g_{\chi s}\phi\bar{\chi}\chi + g_{Ns}\phi\bar{N}N$$

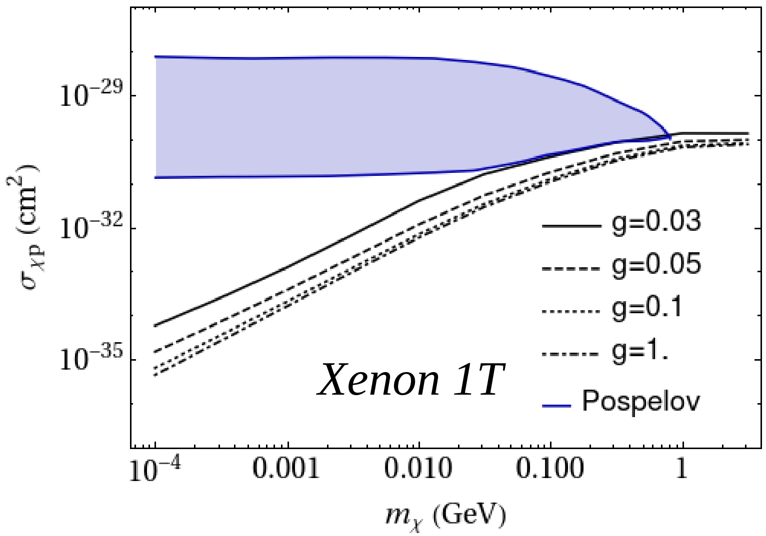


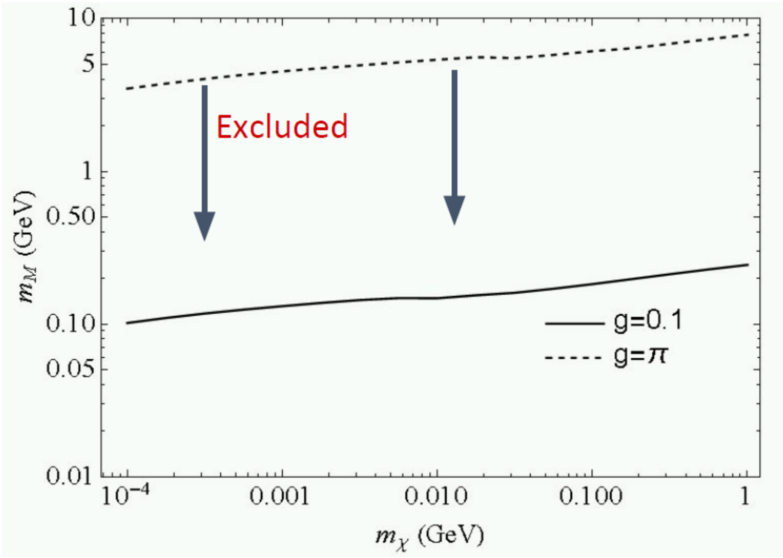
$$\left(\frac{d\sigma}{dT_\chi}\right)_{\text{scalar,CR}} = g^2_{\chi s}g^2_{Ns}\frac{(4m_\chi m_N^2 + 2T_\chi(m_\chi^2 + m_N^2) + m_\chi T_\chi^2)}{8\pi(2m_\chi T_\chi + m_\phi^2)^2(T_i^2 + 2m_T T_i)}$$

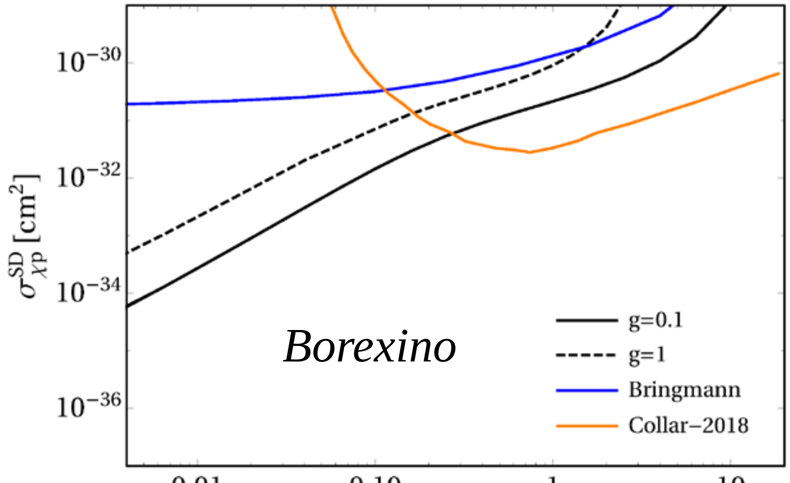
Dent, Dutta, Newstead, Shoemaker, to appear

Direct Detection

Low mass mediator scenarios ➔ Larger cross-section: get constrained





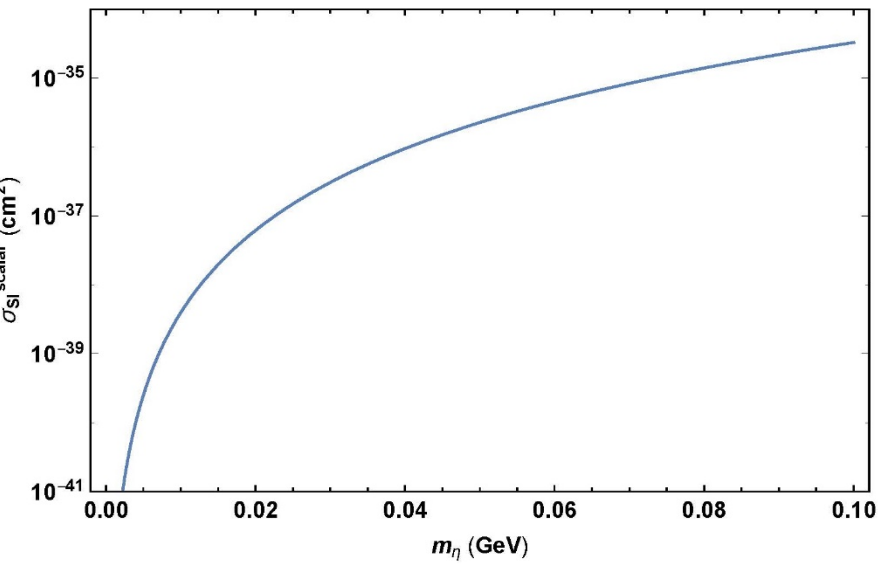


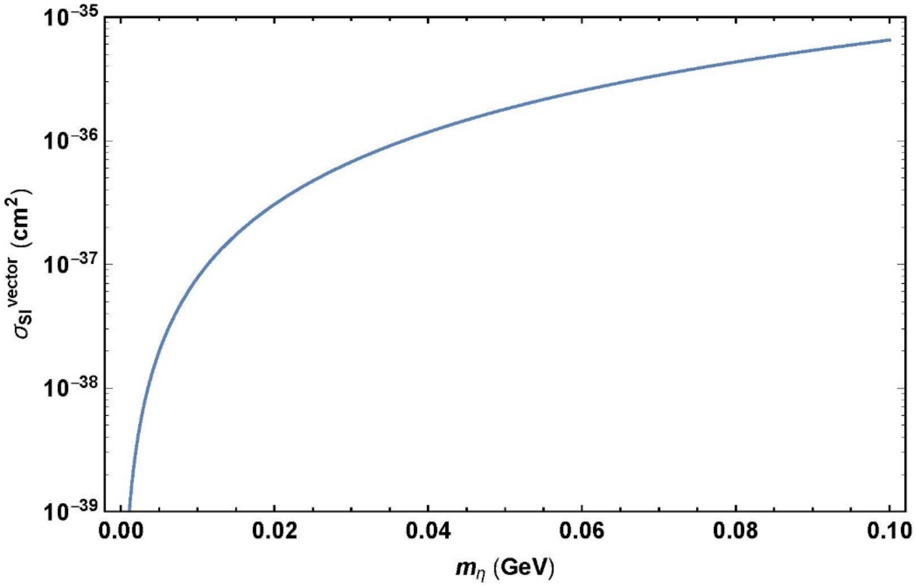
Dent, Dutta, Newstead, Shoemaker, to appear

Direct Detection

For the T_{3R} model

Couplings are fixed for fixed DM and A' masses





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

ϕ' ***mediated***

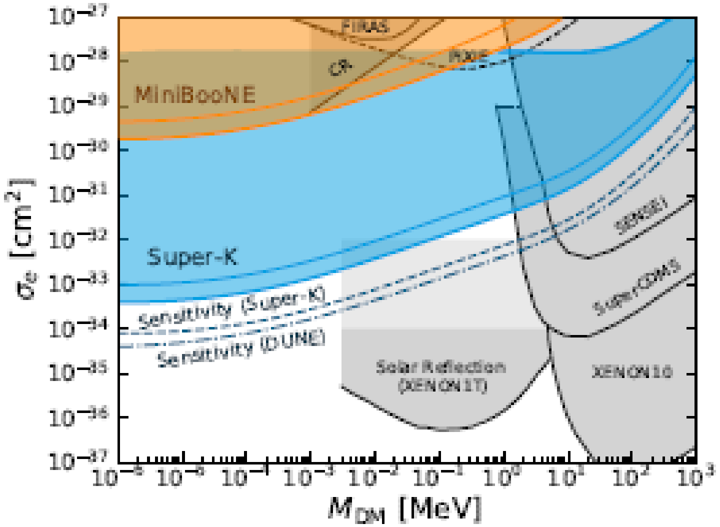
Inelastic scattering: $\bar{\eta}_1\gamma^\mu\eta_2\bar{q}_L\gamma^\mu q_L$

A' ***mediated***

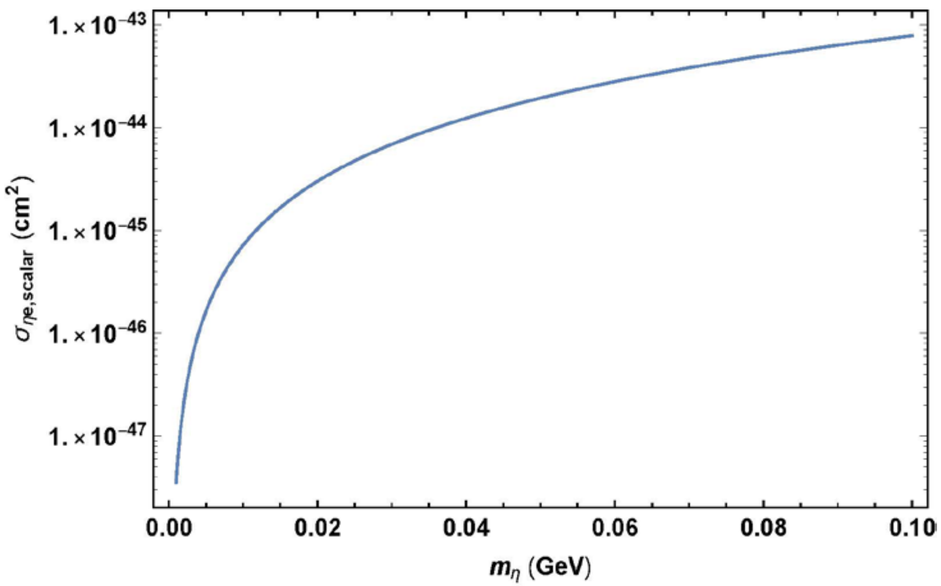
V=10 GeV, m(ϕ')=100 MeV

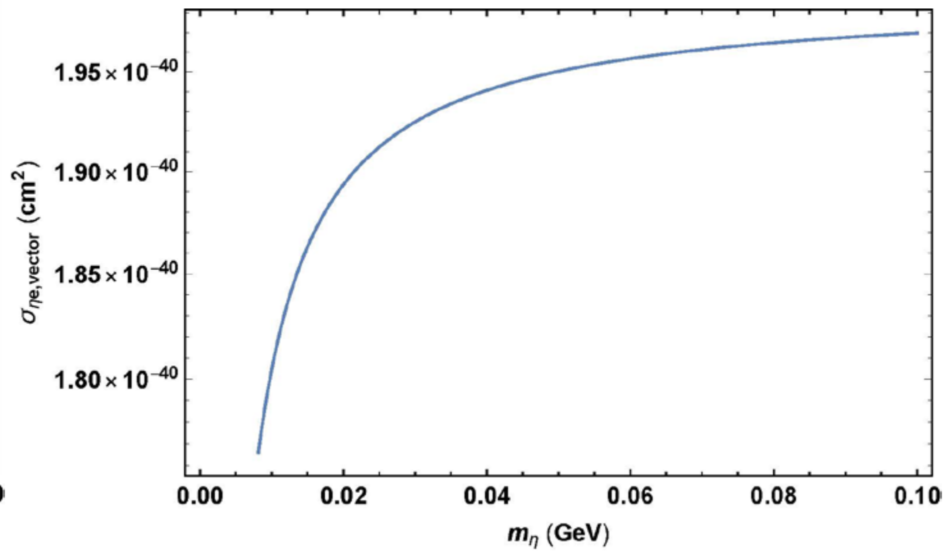
Direct Detection

Dark Matter-electron Scattering



Ema, Sala, Sato, 2018



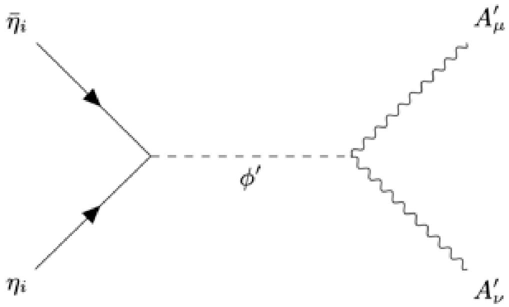


Thermal Relic Abundance

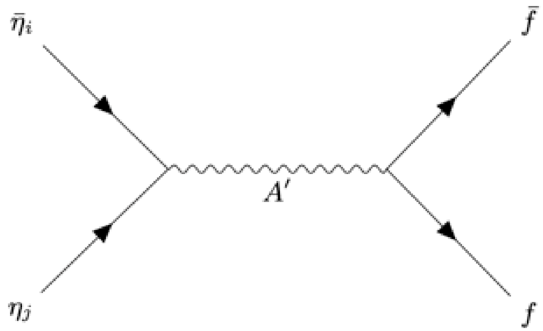
Dominant two body final states: $\bar{\ell}\ell,\ \bar{\nu}\nu,\ \pi\pi,\ \pi^0$

$+$

$A'A',\ \phi'\phi'$ and $\phi'A'$



P-wave



S-wave

+ …

Resonance/non-resonance:

P-wave: CMB is satisfied

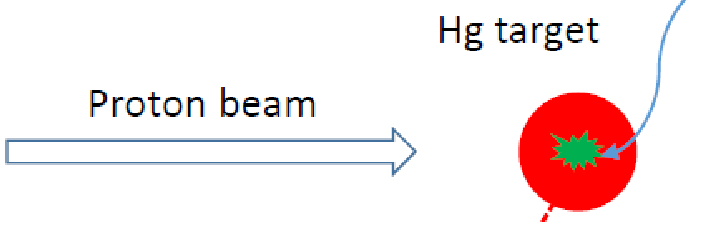
	m'_A (MeV)	m'_ϕ (MeV)	m_η (MeV)	$\langle\sigma v\rangle$ cm^3/sec	$\sigma^{scalar}_{0\eta n}$(pb)	$\sigma^{vector}_{0\eta n}$(pb)
muon case	40	102	50	3×10^{-26}	0.56	16.14
	70	10^4	50	3×10^{-26}	5.6×10^{-9}	16.14
electron case	0.4	100	50	3×10^{-26}	0.56	16.14

S-wave: $A' \rightarrow \nu_A \nu_A$

DM Models in ν experiments

Production of DM(χ_1) at COHERENT

Deniverville, Pospelov, Ritz,'15



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

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

There is also another process:

Charge exchange: $\boldsymbol{\pi^- + p \to \pi^0 + n}$ $\qquad \boldsymbol{\pi^0 \to \gamma + X^{(*)}}$

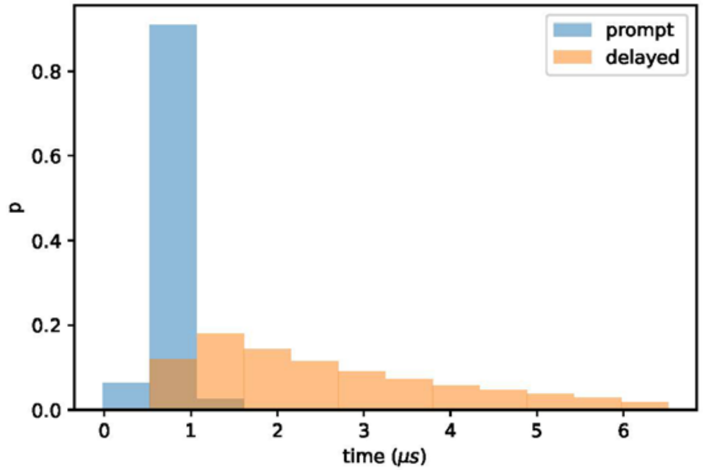
[**JSNS^2 TDR**]

Probe Dark Photon ($X^{(*)}$) utilizing:

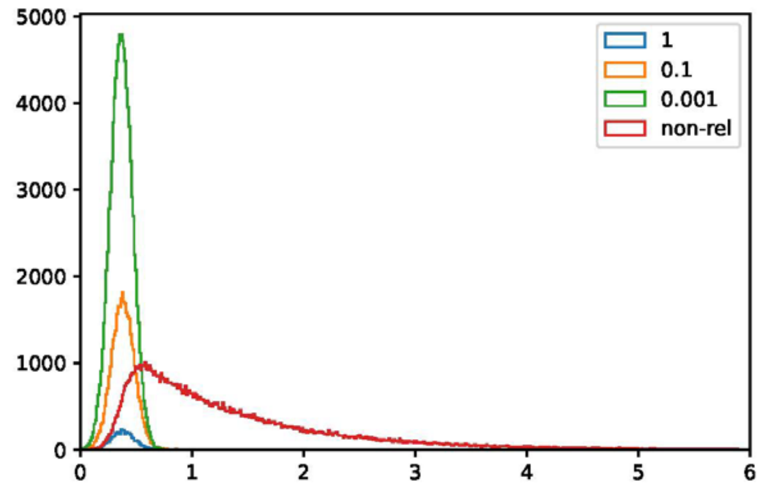
timing, *additional electrons, positrons*

Models: timing

Compare with the timing spectra at COHERENT



Dark Gauge boson with various lifetimes and masses

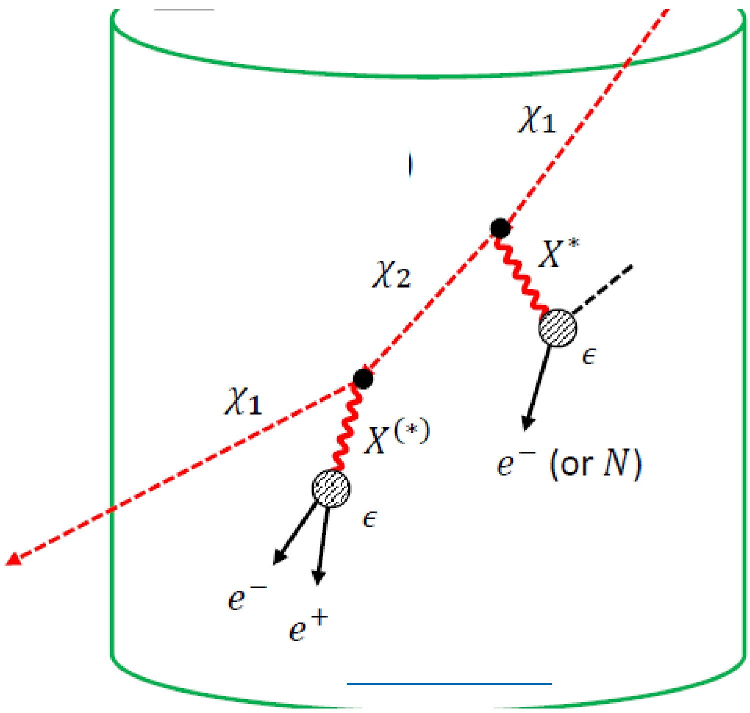


1. ***Energy Cut***

2. ***Select time window***

Dutta, Kim, Park, Shin, Shu, Strigari, In Progress

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

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**

- **Many interesting ideas, e.g., L_μ-L_τ , Hidden sector, $U(1)_{T3R,B-L}$ etc. light mediators (low mass DM)**

- **Both ν and DM experiments are probing light mediators in complimentary ways**