Accelerator DM at the SNS

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Based on: Dutta, Kim, Liao, Park, Shin, Strigari: 1906.10745

Fundamental Physics at the Second Target Station- FPSTS19
July 26-27, 2019

Light Mediators: Why Not?

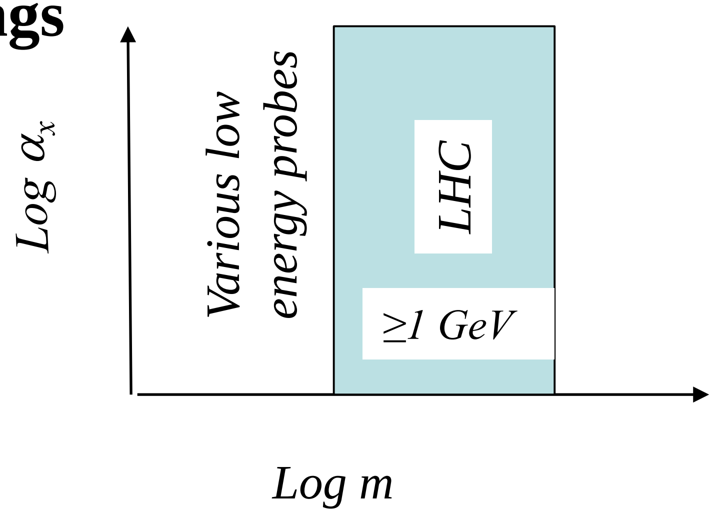
- ν sector of SM (SU(3) x SU(2) x U(1)) requires new physics for understanding the experimental results on masses and mixing angles

tiny ν 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

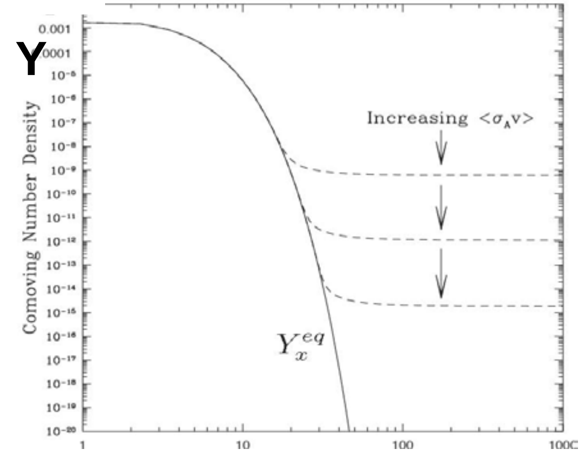
$\alpha_x = \frac{g_x^2}{4\pi}$



Thermal DM

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

Y=DM abundance



Mass of DM/Temp.

Light mediators: Why?

Various light mediators scenarios proposed:

- **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

Essig et al, 2013 Review

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

Marciano, Davoudiasl, 2018

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

Bertuzzo, Jana, Machado, Funchal, 2018

- **Solutions of Yukawa couplings hierarchies problem**

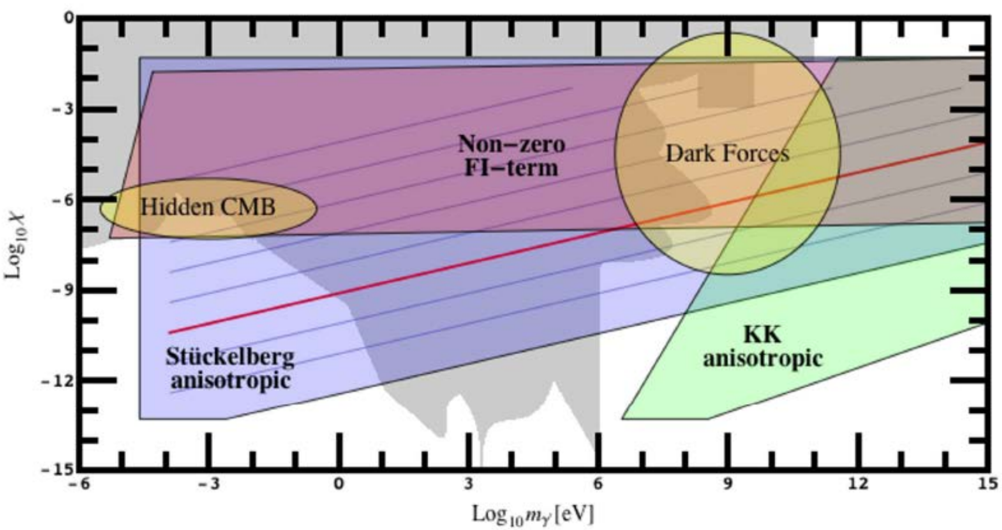
Dutta, Ghosh, Kumar, 2019

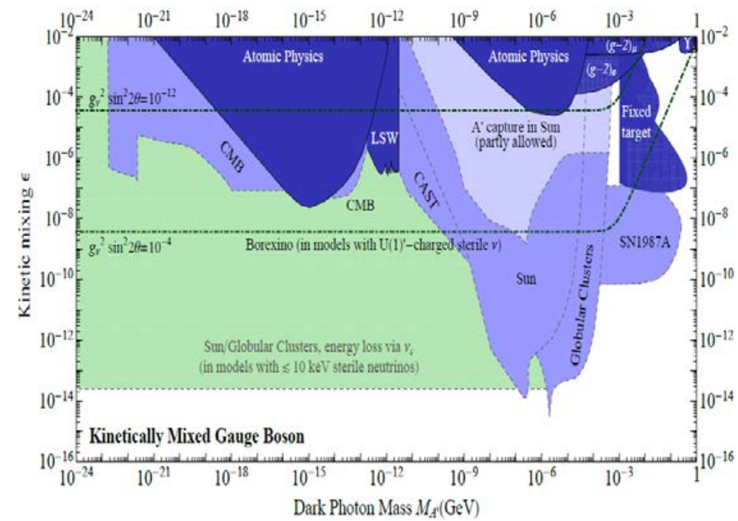
Low scales

New physics: new symmetry breaking scale

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

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





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

Harnik, Kopp, Machado, 2012

Probing Various Models

Two interesting ways to probe these models:

Neutrino (Louie Strigari's talk), Dark Matter (this talk)

Dutta, Kim, Liao, Park, Shin, Strigari: 1906.10745

Direct Detection: Light DM&Med

Various ways of probing Sub-GeV DM:

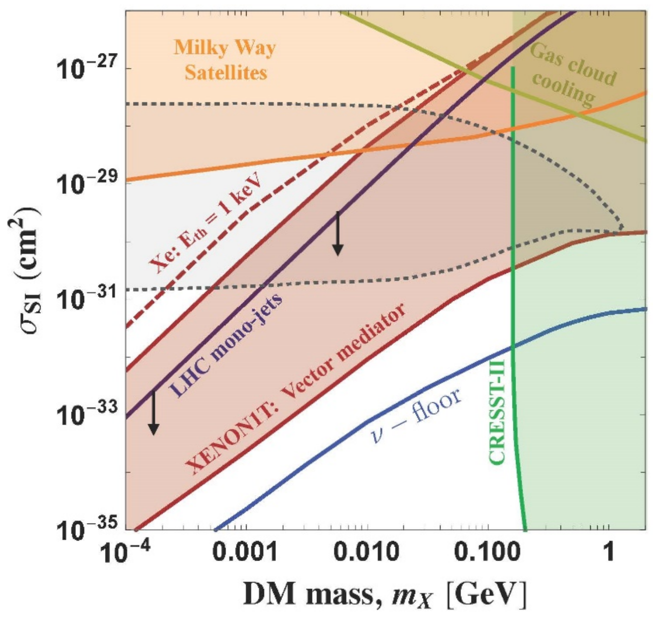
Cosmic ray scattered

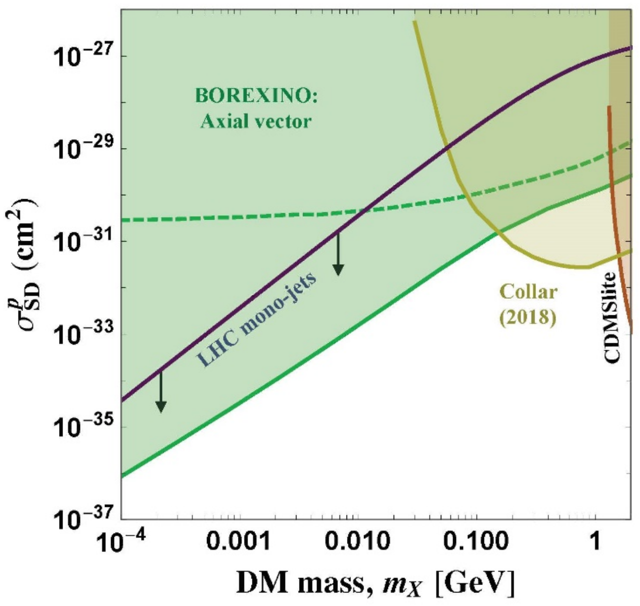
Bringmann, Pospelov, 2018

Ema, Sala, Sato, 2018

Dent, Dutta, Newstead, Shoemaker, 2019

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





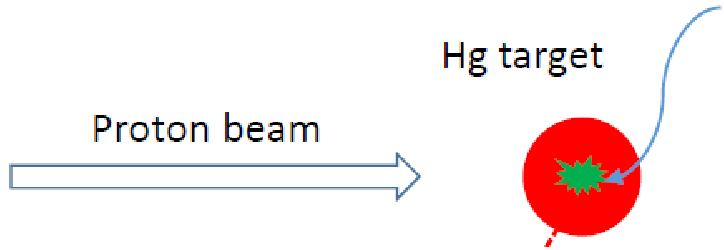
Dent, Dutta, Newstead, Shoemaker, 2019

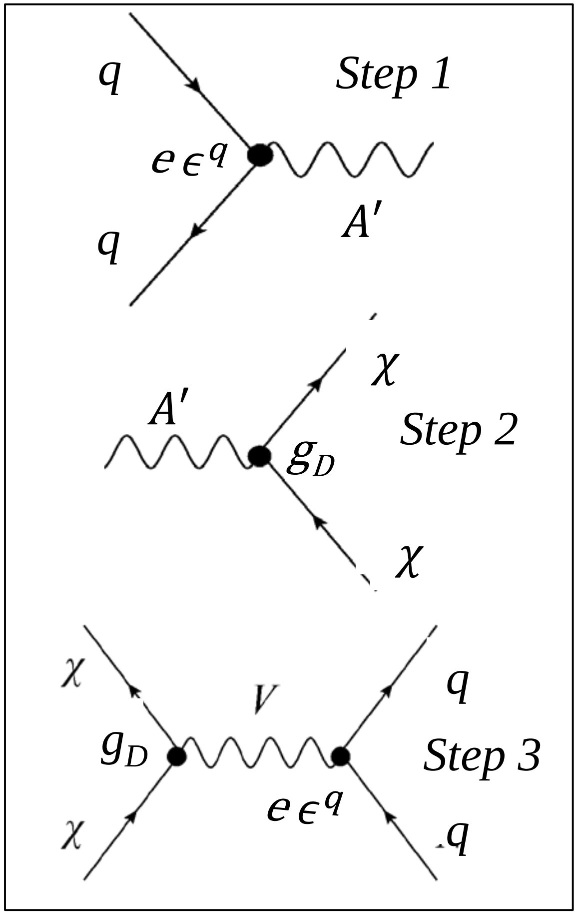
DM in ν experiments

Production of DM(χ_1) at COHERENT

Deniverville, Pospelov, Ritz,'15

- $\boldsymbol{\pi^- + p \to n + A',\ A' \to \chi\chi}$





There is also another process: Charge exchange

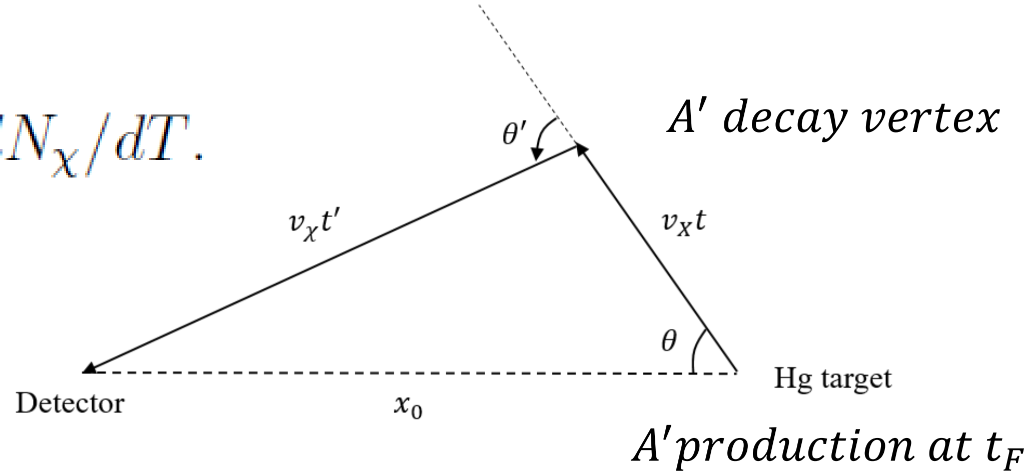
- $\boldsymbol{\pi^- + p \to \pi^0 + n}$

$\boldsymbol{\pi^0 \to \gamma + A'}$ [**JSNS² TDR**]

Probe Dark Photon (A′) decay into DM utilizing: timing measurements

DM Models in ν experiments

DM flux at the detector: $f(T) = dN_\chi / dT\,.$



$$\frac{d^2 N_{A'}}{dt\,d\cos\theta} = \frac{1}{2} \cdot \frac{1}{\tau_{A'}} e^{-\frac{t-t_F}{\tau_{A'}}} \Theta(t - t_F)$$

$$f(T) = \int_{-1}^{1} d\cos\theta \int_{0}^{t_F^{\max}} dt_F \left| \frac{dT}{dt} \right|^{-1} \frac{d^2 N_{A'}}{dt\,d\cos\theta} \cdot w(\cos\theta') \cdot \mathcal{F}(t_F)\,.$$

$$T = t + v_\chi^{-1} \sqrt{x_0^2 + v_{A'}^2 (t - t_F)^2 - 2 x_0 v_{A'} (t - t_F) \cos\theta}$$

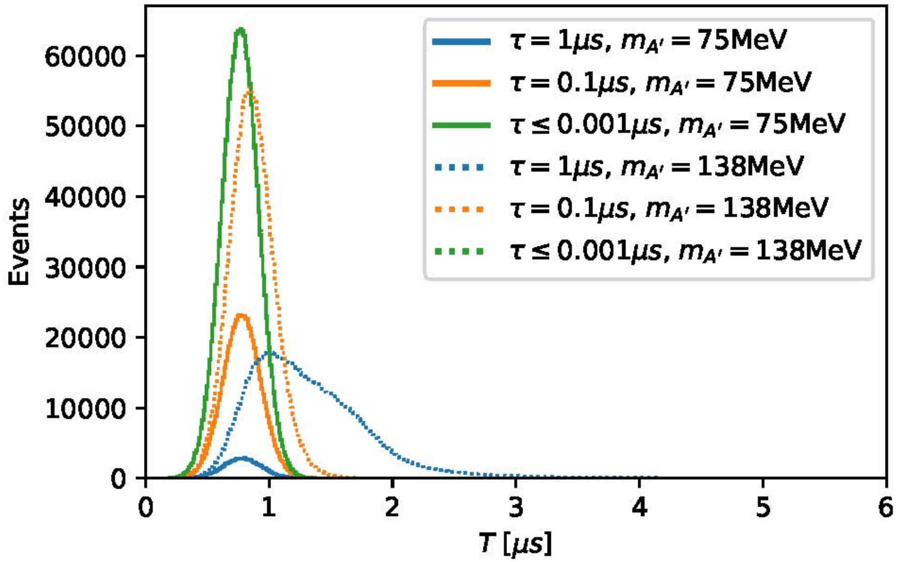
Parameter space: Dark Photon

$$\mathcal{L}_{\rm int} \supset g_\chi A'_\mu \bar{\chi}\gamma^\mu\chi + e_q\epsilon_q A'_\mu \bar{q}\gamma^\mu q\,,$$

Various possibilities for A'

(depending on ϵ^q and M')

- ***Short lived (large ϵ^q)***
- ***Long lived***
- ***Relativistic***
- ***Nonrelativistic (M'~138 MeV)***

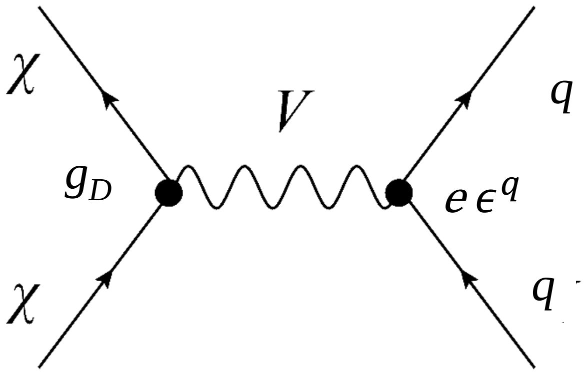


- ***For τ < a few ns, we get maximum number of events***

Parameter space: Dark Matter

Dark Matter scatters off nucleus:

$$\frac{d\sigma}{dE_r} = \frac{e^2\epsilon_q^2 g_D^2 Z^2 \cdot |F(2m_N E_r)|^2}{4\pi p_\chi^2 (2m_N E_r + M'^2)^2} \left\{ 2E_\chi^2 m_N \left(1 - \frac{E_r}{E_\chi} - \frac{m_N E_r}{2E_\chi^2}\right) + E_r^2 m_N \right\},$$

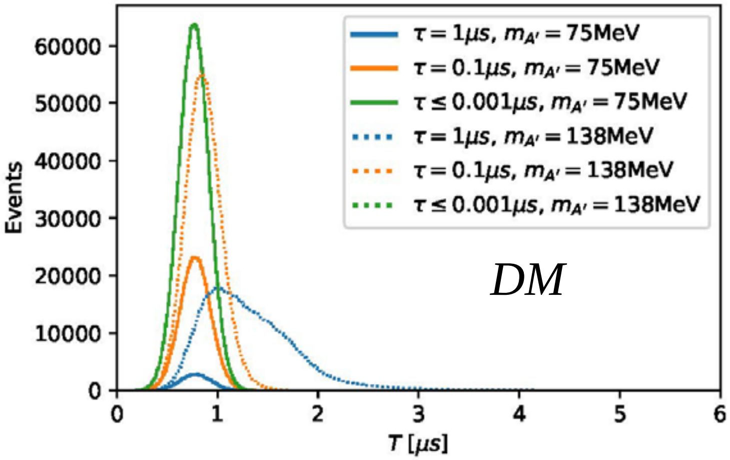


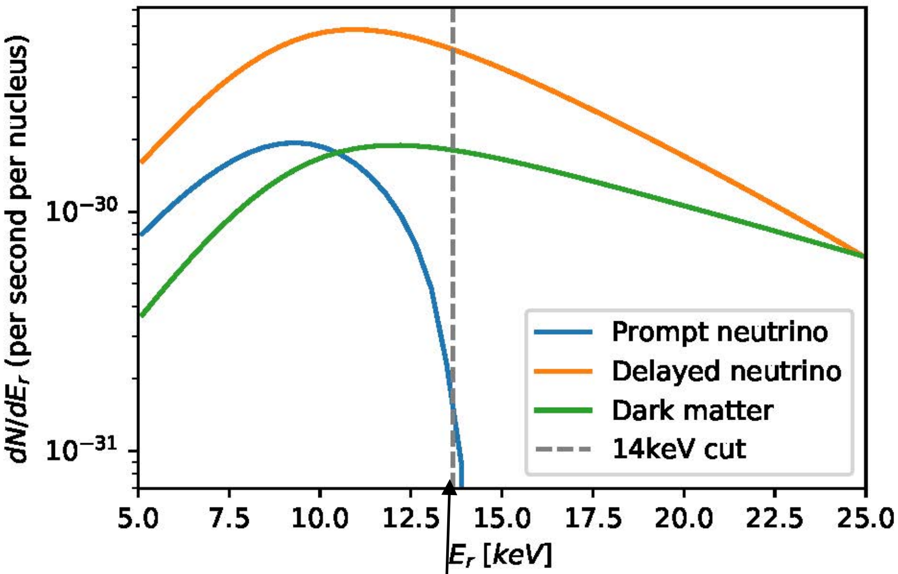
- $g_D = e\,\epsilon_D$
- *If* $A' \equiv V$, *then we have* $e\,\epsilon^q$ *other wise* $e\epsilon_2^q$

Two variables:

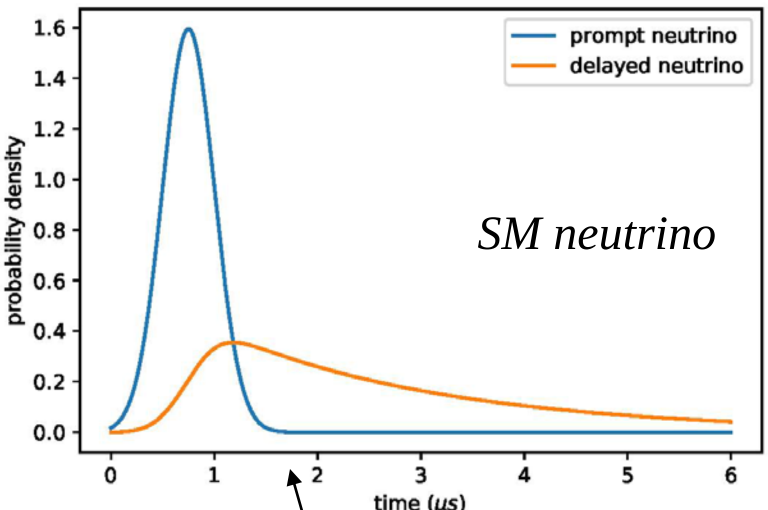
$\epsilon \quad = \epsilon_1^q\,\epsilon_2^q\,\epsilon_D\sqrt{BR_{A'\to\chi\chi}}$ *and M'*

Parameter space: Dark Matter





14 KeV



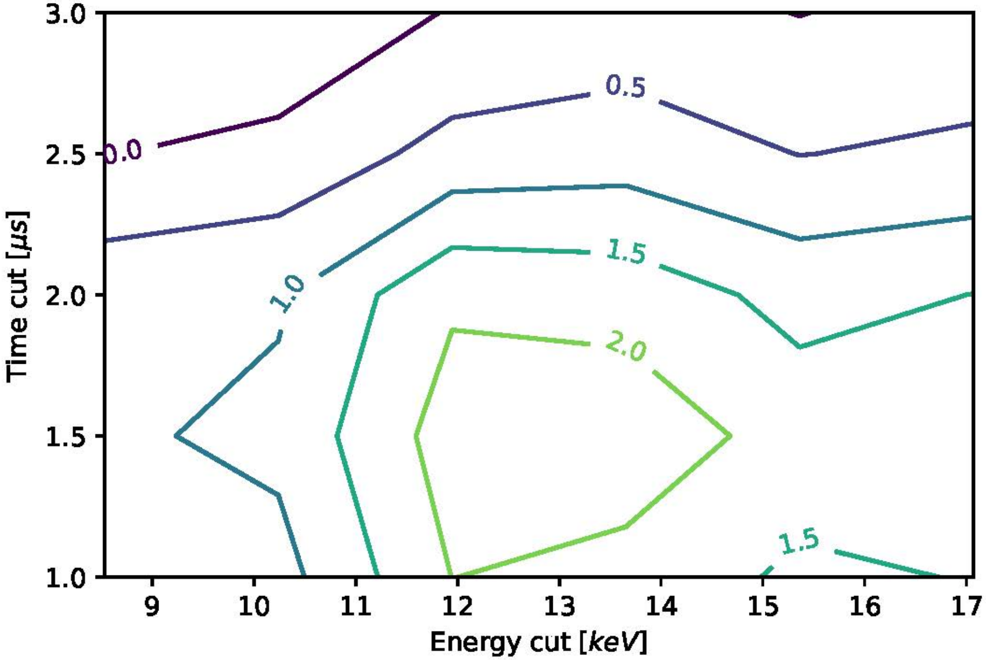
1.5 μs

- ***Fot t < 1.5μ s, we have mostly prompt ν***
- ***For E_r >14 KeV we remove the prompt ν***

➔ ***We can remove the SM ν backgrounds***

COHERENT

Significance Contours



- ***14 KeV <E_r< 26 KeV***
- ***t <1.5 μ s***

Independent of R_n

$$Significance = \frac{Excess}{\sqrt{2\,SS + BRN + SM}}$$

Excess=Signal – BRN – SS - SM

SS=Steady State
BRN=beam related neutron

COHERENT

$$Significance = \frac{Excess}{\sqrt{2\,SS + BRN + SM}}$$

- 14 KeV < E_r < 26 KeV
- $t < 1.5\ \mu s$

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

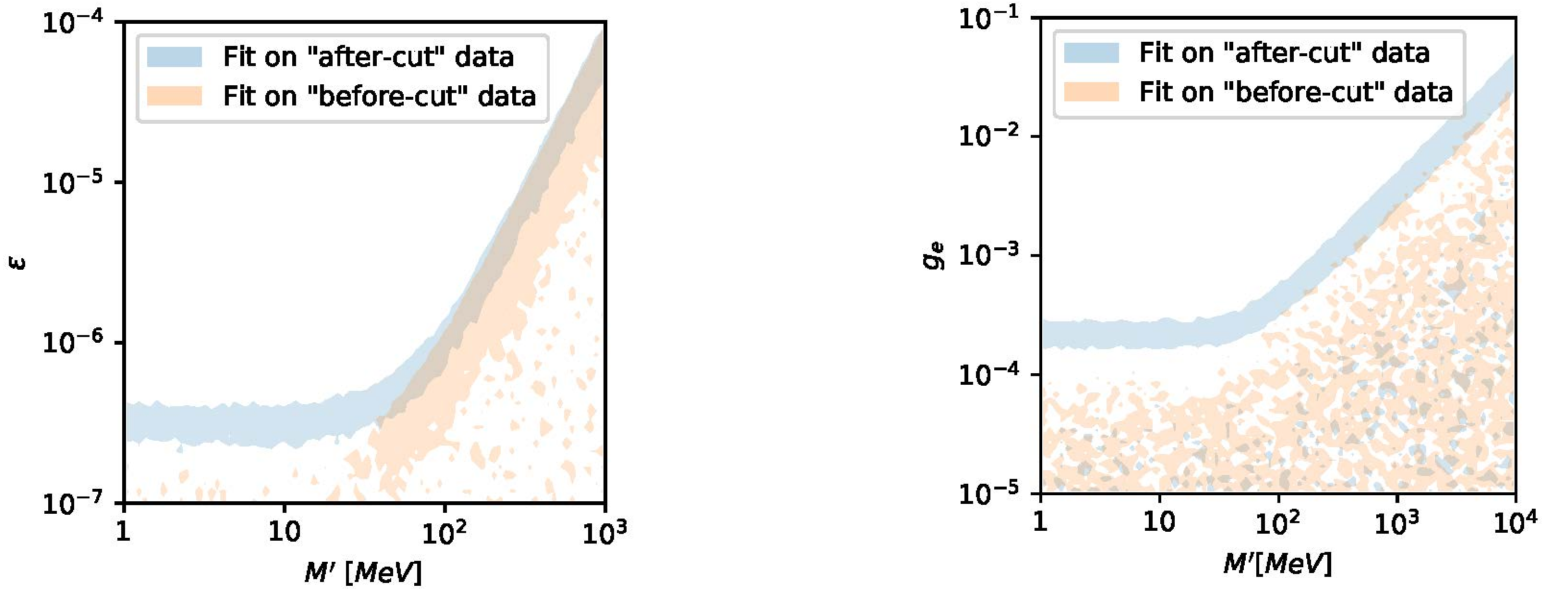
$$R_n^2 = R_0^2 + 5s^2$$

Significance (R_n=4.7 fm): 2.4 σ

Significance(R_n = 5.5 fm): 3 σ

COHERENT

Fit to the excess after the cuts needs to fit the full dataset



$\tau = 1\, ns, m_{A\prime} = 75\ MeV, m_{\chi} = 5\ MeV$

The DM figure holds for:

- $\tau \leq 4\, ns, m_{A'} < 138\ MeV$
- $\tau \leq 30\, ns, m_{A'} = 138\ MeV\ (non-relativistic\ case)$
- $for\ any\ \ m_{\chi} < m_{A'}/2$

Parameter space: Dark Matter

$$\epsilon \quad = \epsilon_1^q \, \epsilon_2^q \, \epsilon_D \sqrt{BR_{A' \to \chi\chi}}$$

Single mediator: $\epsilon_D = 1/e$ ***and*** $\epsilon_1^q = \epsilon_2^q = \epsilon^q$

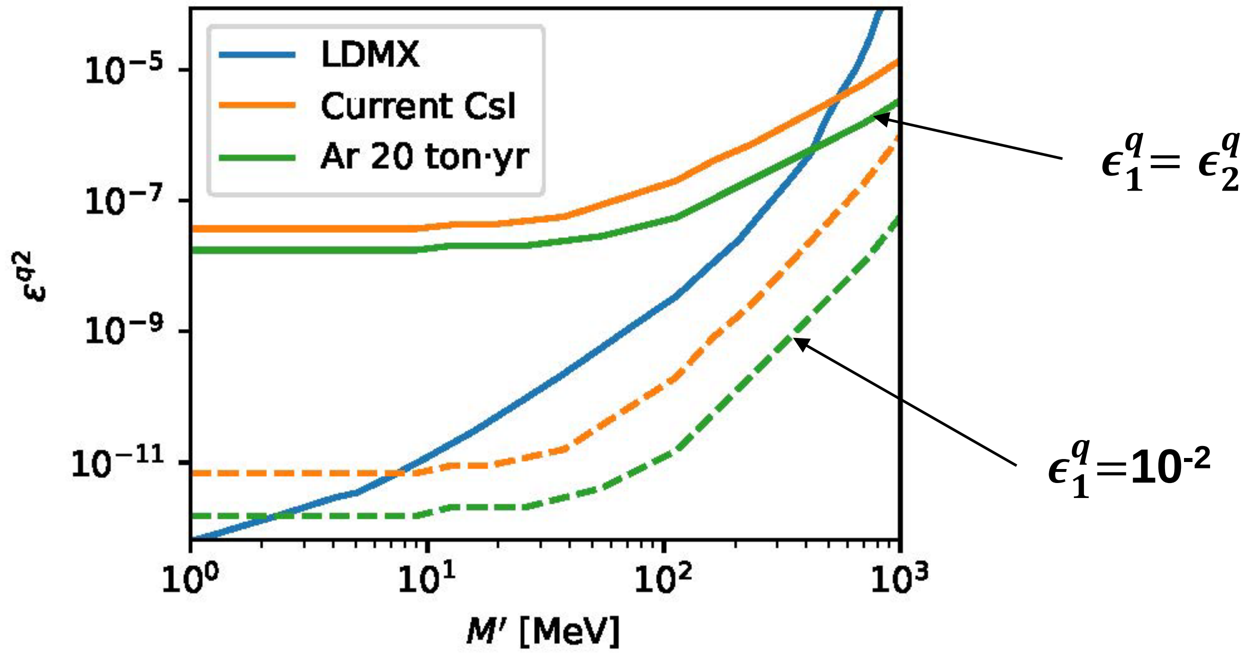
M'(MeV)	50	75	100	1000
ϵ^q	3.5×10^{-4}	4.4×10^{-4}	5.5×10^{-4}	4.6×10^{-3}

Multiple mediators: $\epsilon^q \to \sqrt{(\epsilon_1^q \, \epsilon_2^q e \, \epsilon_D)}$

Dark photon can be long lived

LDMX and COHERENT

$\alpha_D = 0.5$

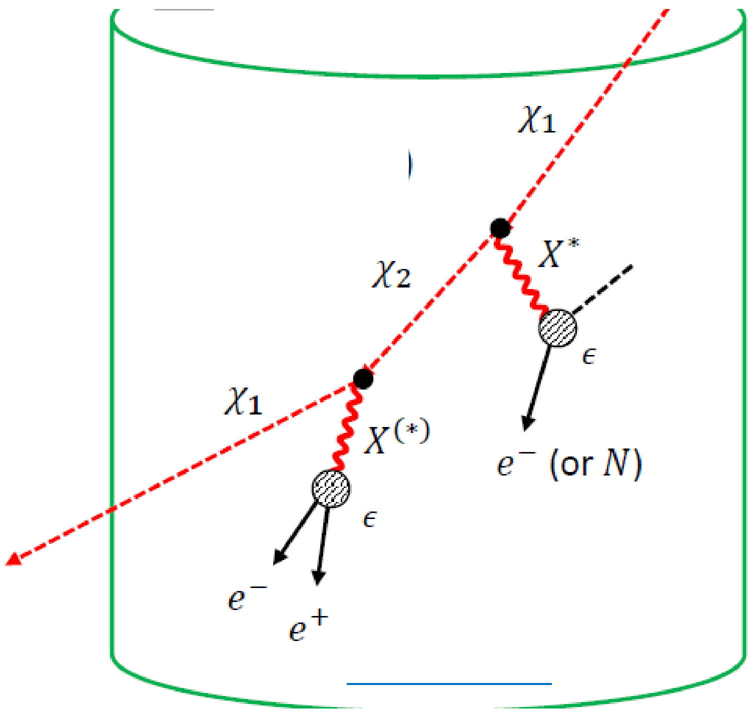


M' is the DM-nucleus interaction mediator

To compare with LDMX, we assume:
$\boldsymbol{\varepsilon^q = \varepsilon^e}$

Reach is already better than DUNE!

Other Models: e^+e^- from the scat.



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

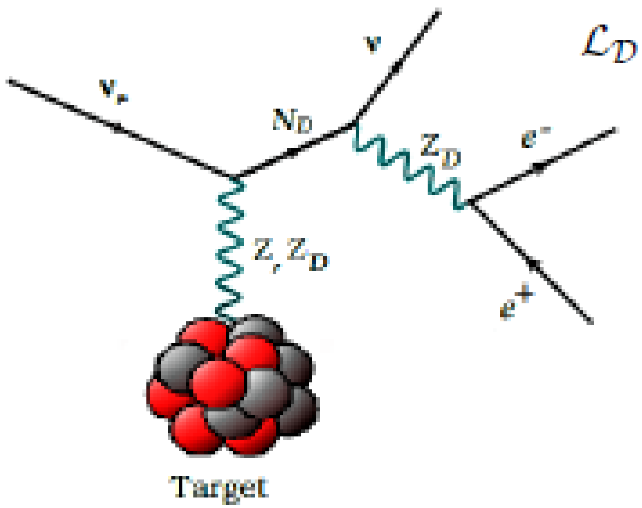
- **Removal of the SM background would be helpful to investigate this scenario**

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**
- **Removal of the SM background would be helpful to investigate this scenario**

Outlook

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

- **Models with light mediators and DM are very interesting**

- **Timing plus energy spectrum from COHERENT experiment can be utilized to probe light DM**

- **A combination of timing and energy cuts can eliminate the SM background**

- **The current data shows a 2.4-3σ excess which can be explained by DM arising from dark photon decay**

- **Reach for DM parameter space is already better than DUNE, comparable to LDMX**