A Sub-GeV DM model

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DPF, Boston 28th July – 2nd August, 2019

Based on: Dutta, Ghosh, Kumar, 1905.02692

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**

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

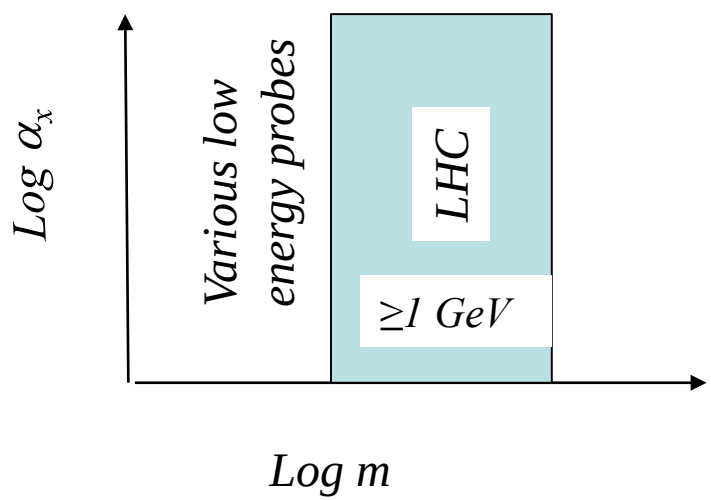
- **Similarly, DM explanation (with M_{DM} anywhere between 1 KeV to 100 TeV) requires new physics**

Thermal DM

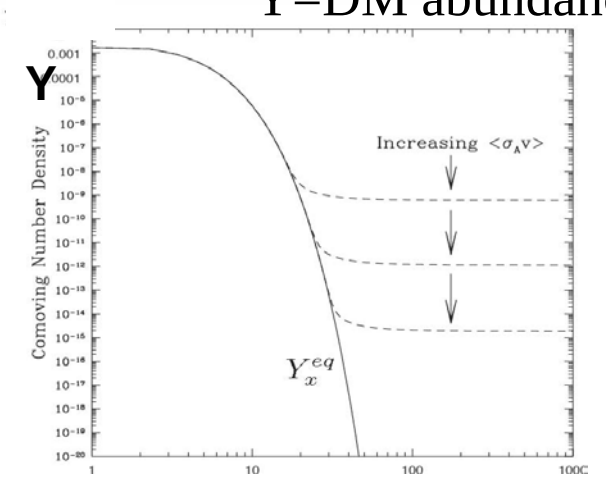
$$H = n\langle\sigma v\rangle \quad \sigma \sim 1\,pb$$

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

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



Y=DM abundance



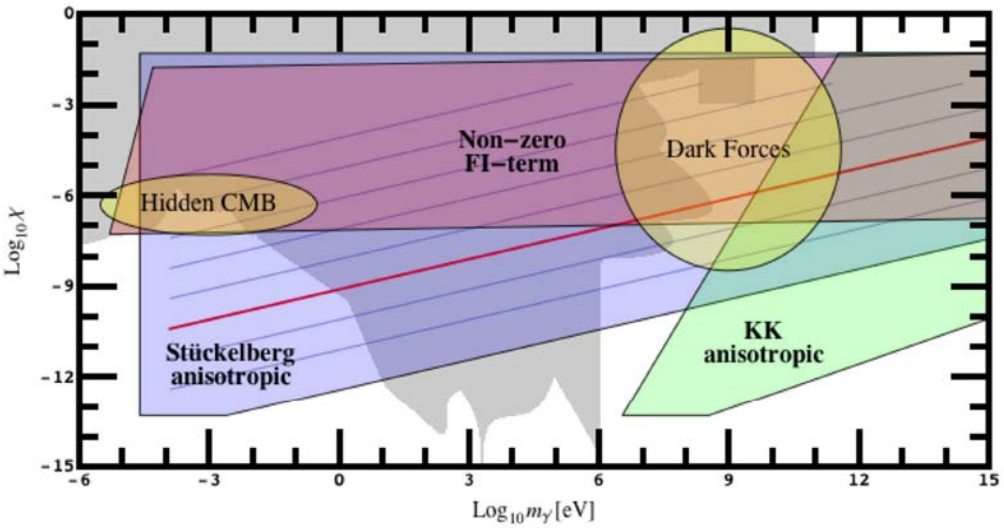
Mass of DM/Temp.

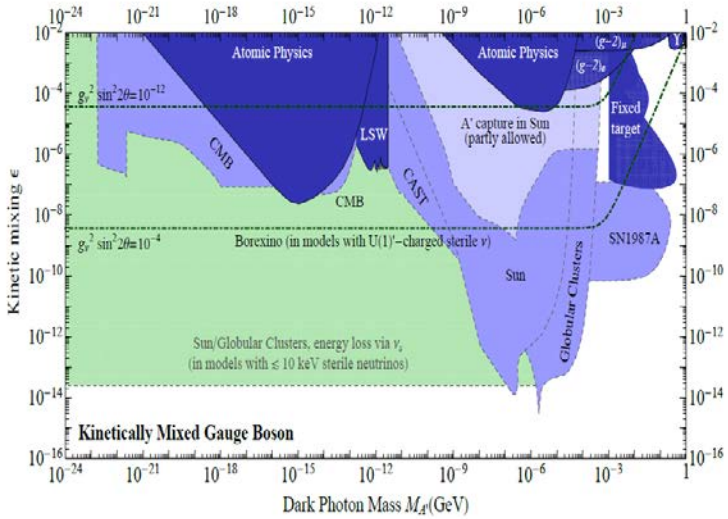
Low scales

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: Models

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

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

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** $m_{\phi'}=2\lambda_\phi^{1/2}V.$

Vector-like quarks with mass 1 TeV or higher can generate this Lagrangian

➔ ***Larger Yukawa couplings for first two generations are possible***

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

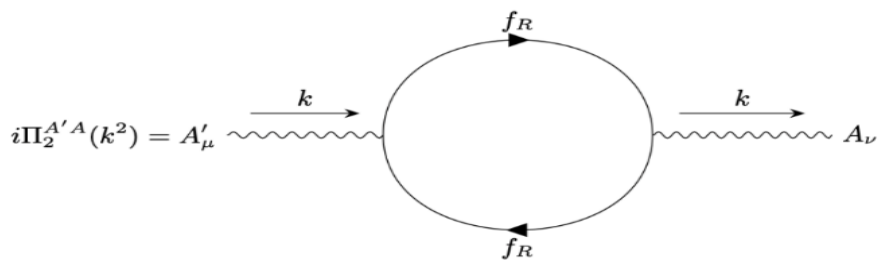
$$\eta_1 = -\frac{i}{\sqrt{2}}\begin{pmatrix}\eta_L - \eta_R^c \\ -\eta_L^c + \eta_R\end{pmatrix} \qquad \eta_2 = \frac{1}{\sqrt{2}}\begin{pmatrix}\eta_L + \eta_R^c \\ \eta_L^c + \eta_R\end{pmatrix}$$

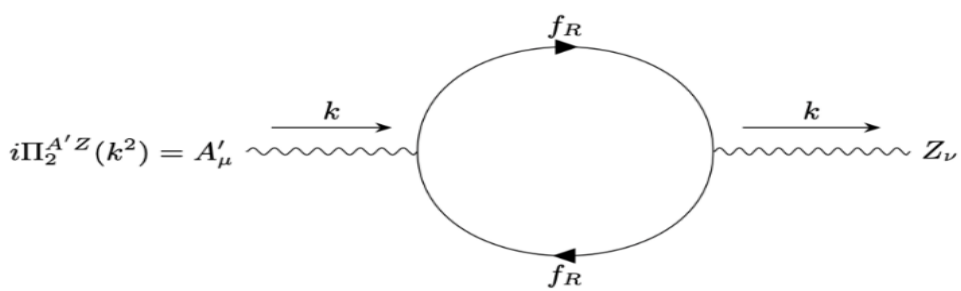
Dark Matter (parity odd): $\eta_{1,2}$

$U(1)_{T3R}$

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

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





$U(1)_{T3R}$

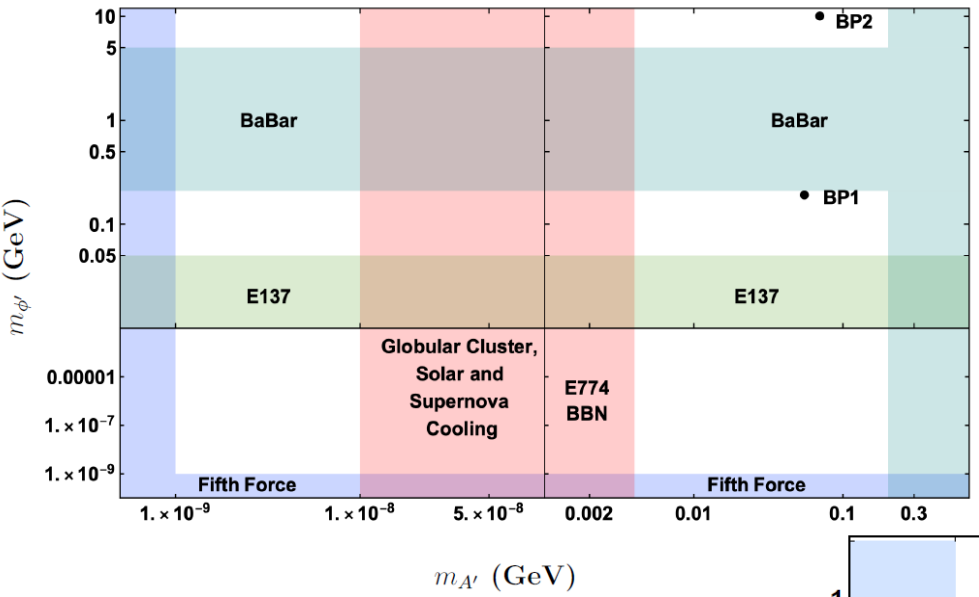
- ϕ': $\phi' \to \bar{l}l$, $\nu_s\nu_A$, $\pi\pi$, $A'A'$: **dominate, if kinematically allowed. Otherwise,** $\phi' \to \gamma\gamma$ ***(one loop diagram)*** **dominates**

- 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

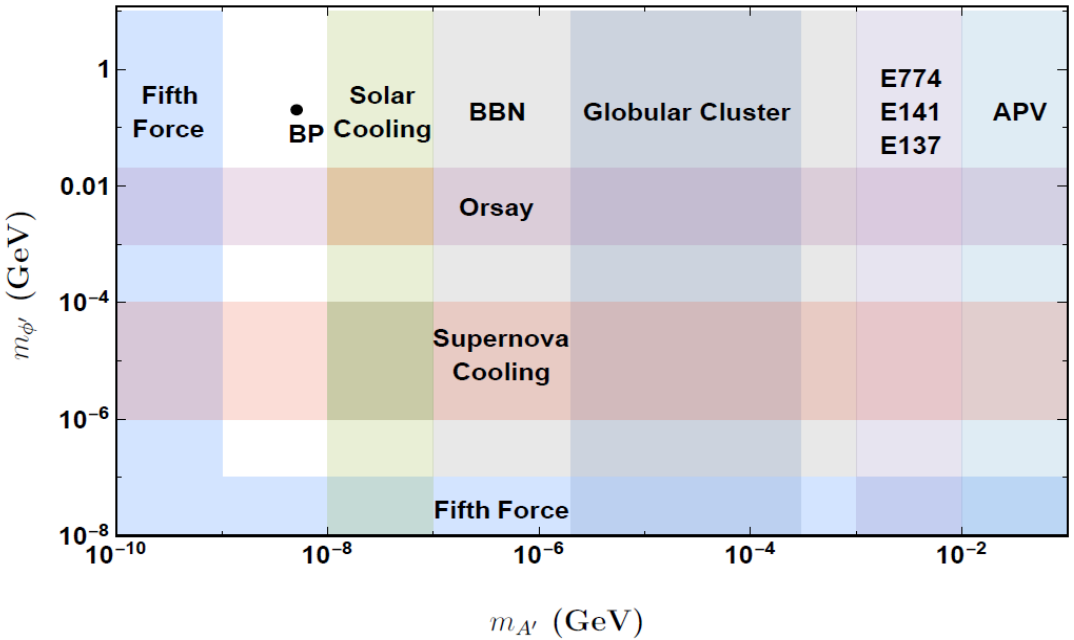
Various scenarios: Gauge boson (A')-scalar (ϕ') mediators parameter space



- ***Muon model:*** u_R, d_R, ν_R, μ_R

- ***Electron model:***
  Muon model: u_R, d_R, ν_R, e_R

- ***Similarly, models with second generation quarks***



Direct Detection: Light DM&Med

Various ways of probing Sub-GeV DM:

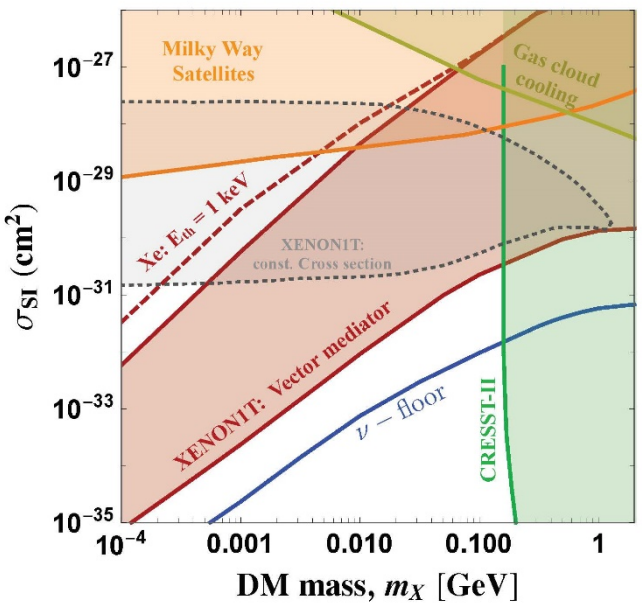
Cosmic ray scattered

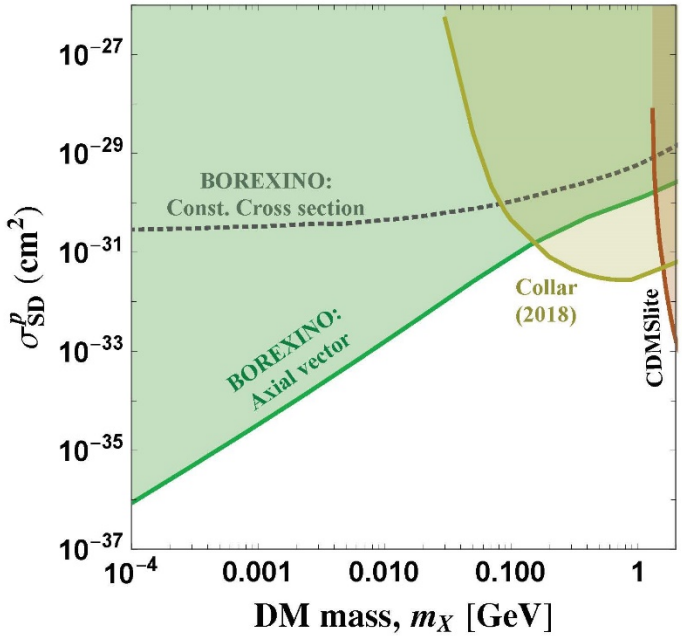
Bringmann, Pospelov, 2018

Ema, Sala, Sato, 2018

Dent, Dutta, Newstead, Shoemaker, 2019

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



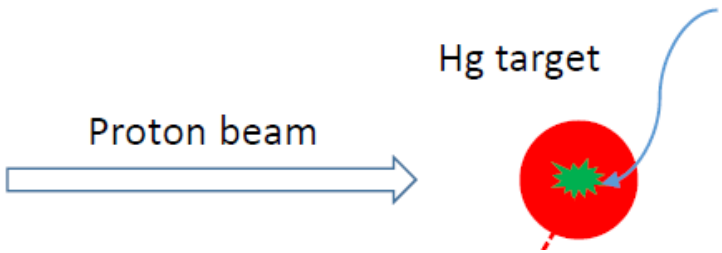


Dent, Dutta, Newstead, Shoemaker, 2019

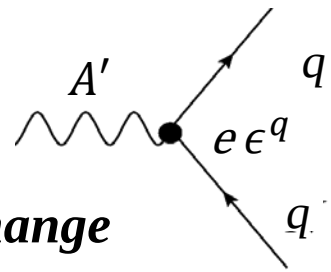
DM in ν experiments

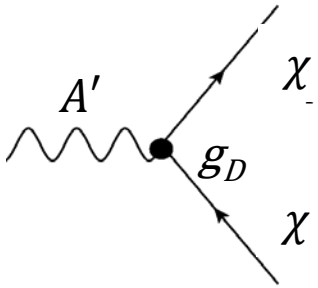
Production of DM(χ_1) at COHERENT

Deniverville, Pospelov, Ritz,'15



- $\pi^- + p \to n + A', \; A' \to \chi\chi$





There is also another process: Charge exchange

- $\pi^- + p \to \pi^0 + n$

$\pi^0 \to \gamma + A'$ [**JSNS^2 TDR**]

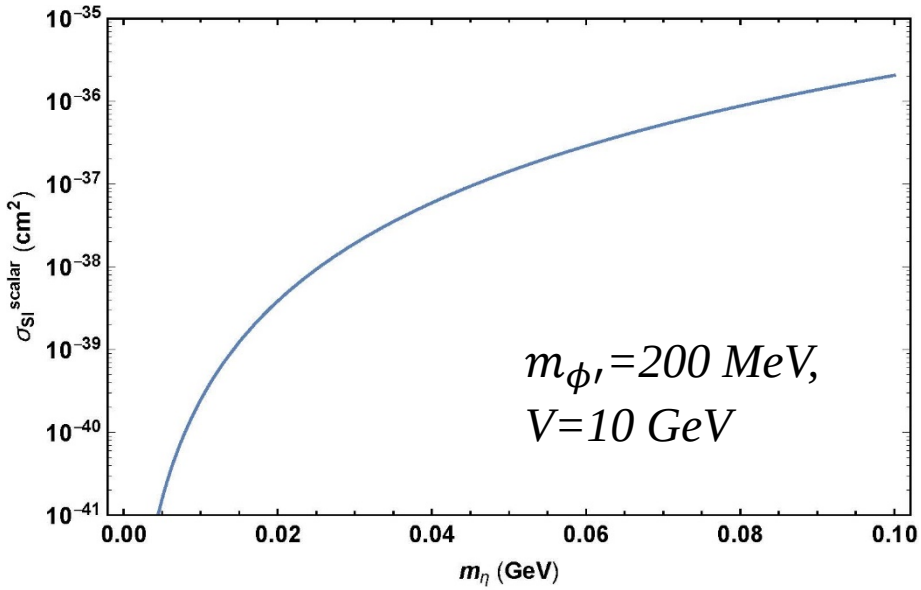
Probe Dark Photon (A') decay into DM utilizing: timing measurements

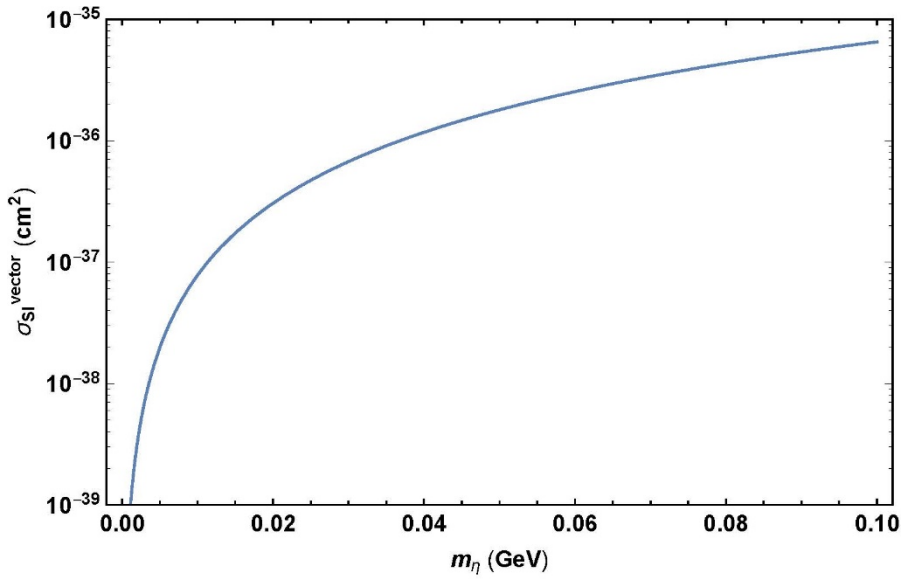
- ***DM mass needs to be less than 70 MeV***

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

direct detection

Constraints from CRESST, Xenon1T **(cosmic ray scattered,**
Dent Dutta, Newstead, Shoemaker, 2019)





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

ϕ' ***mediated***

$$\sigma_{\rm SI}^{scalar(p,n)} = \frac{\mu_{\eta N}^2 m_\eta^2}{\pi V^4 m_{\phi'}^4} f_{p,n}^2$$

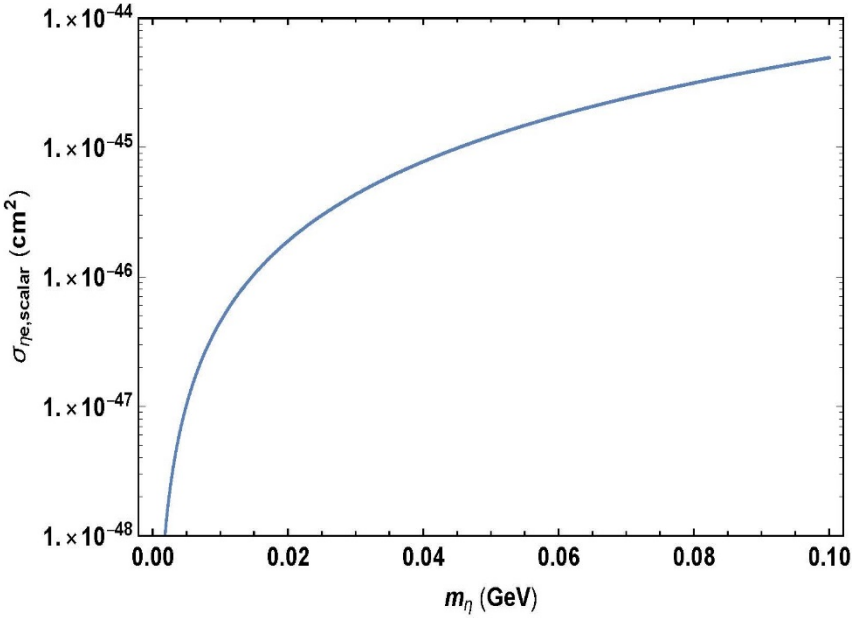
Inelastic scattering: $\bar{\eta}_1\gamma^\mu\eta_2\bar{q}_L\gamma^\mu q_L$

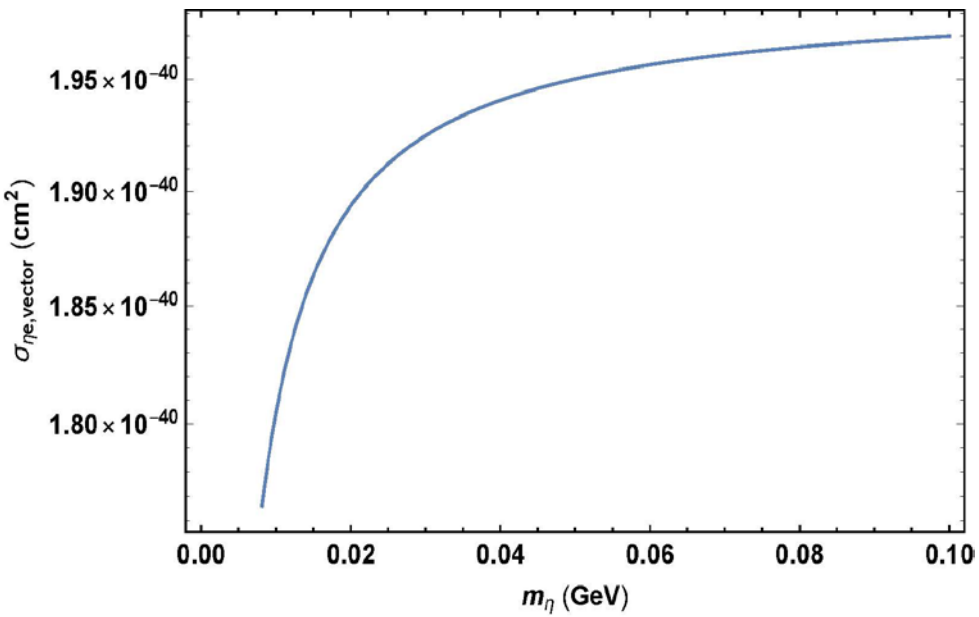
A' ***mediated***

$$\sigma_{\rm SI}^{vector(p,n)} = \frac{\mu_{\eta N}^2}{16\pi V^4}$$

direct detection

Dark Matter-electron Scattering

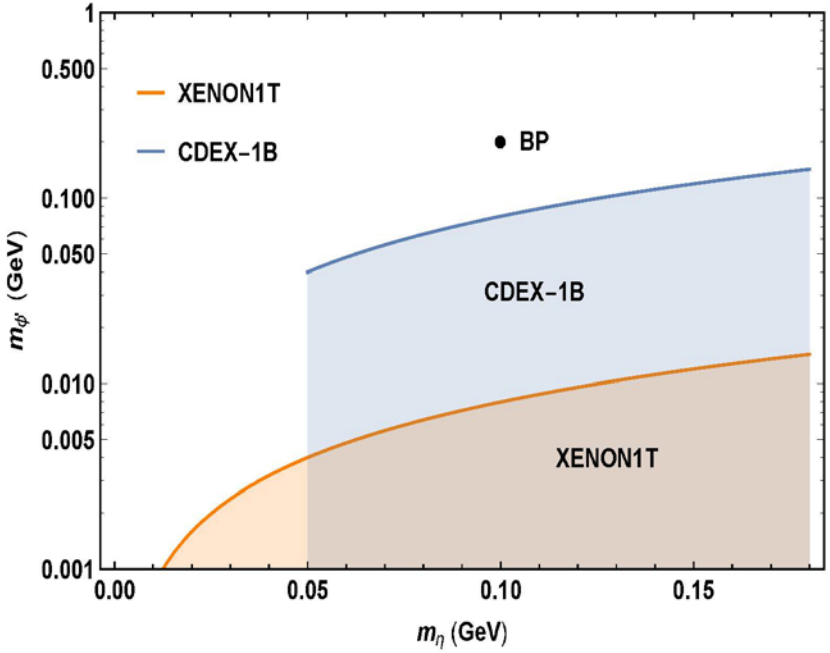




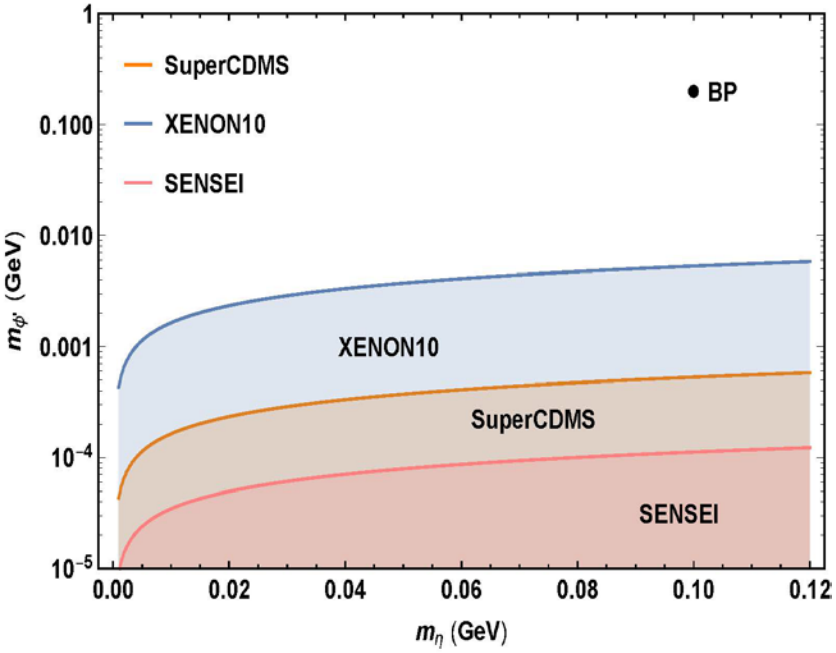
The allowed cross-section ≤ 10^{-40} cm^2

Ema, Sala, Sato, 2018
Xenon 1T, 1906.04717

direct detection



Dark Matter-nucleon



Dark Matter-electron

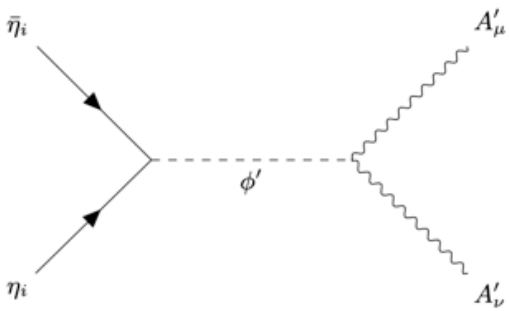
Thermal Relic Abundance

Dominant two body final states:

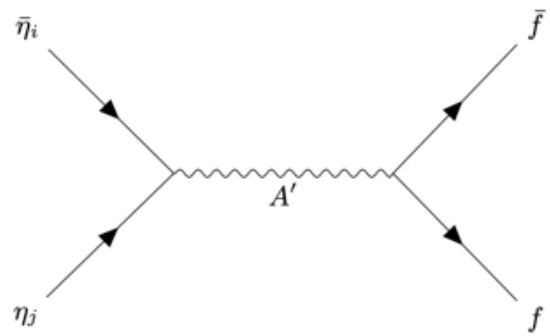
$$\bar{\ell}\ell,\ \bar{\nu}\nu,\ \pi\pi,\ \pi^0(\phi', A', \gamma)$$

$$+$$

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



P-wave



S-wave

+ …

Resonance/non-resonance:

	$m_{A'}$ (MeV)	$m_{\phi'}$ (MeV)	m_η (MeV)	m_{ν_s}(MeV)	$m_{\nu D}$(MeV)	$\langle\sigma v\rangle$ (cm^3/sec)	$\sigma_{\rm SI}^{scalar}$(pb)	$\sigma_{\rm SI}^{vector}$(pb)
muon case	55	200	100	10	10^{-3}	3×10^{-26}	2.05	6.50
	70	10^4	50	10^{16}	10^4	3×10^{-26}	3.29×10^{-7}	1.80
electron case	5×10^{-6}	200	100	10	10^{-3}	3×10^{-26}	2.05	6.50

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

- **We constructed a model, where DM mass ~ 100 MeV,**
  two light mediators: scalar and gauge boson

- **The model has sufficient allowed parameter space after satisfying various experimental constraints**

- **DM relic abundance can occur thermally**