Sub-GeV Dark Matter

Bhaskar Dutta

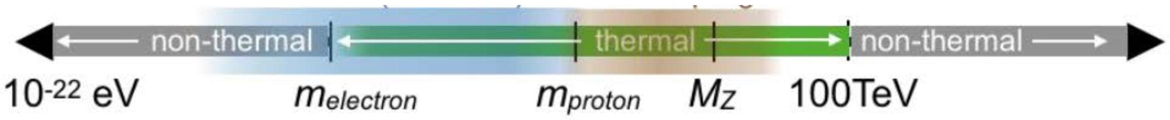
Texas A&M University

The XXVIII International Conference on Supersymmetry and Unification of Fundamental Interactions (SUSY 2021),

23-28 August, Beijing, China

Sub-GeV DM

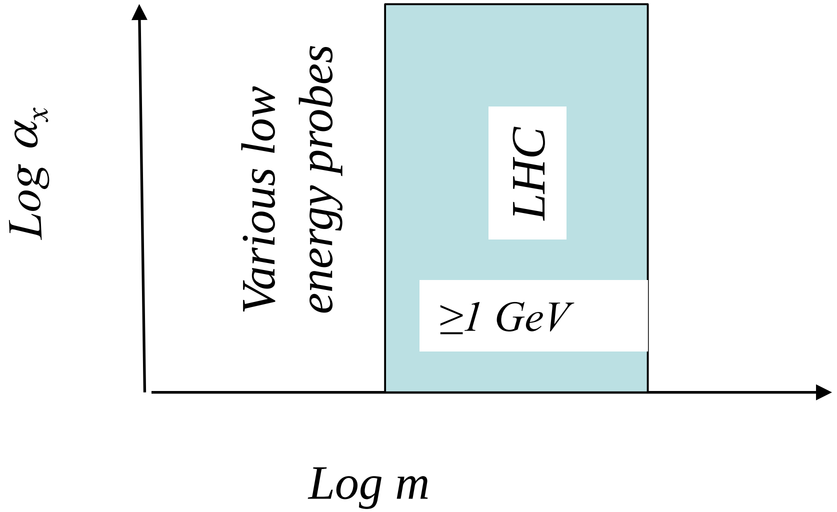
- **DM explanation requires new physics**



DM new initiative report'17

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

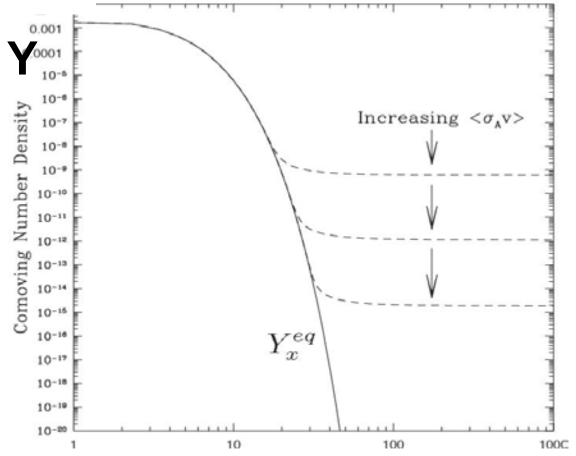
$$\alpha_x = \frac{g_x^2}{4\pi}$$



Thermal DM

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

Y=DM abundance



Mass of DM/Temp.

Outline

Low mass (less than a GeV) dark matter

- **Models (examples)**

- **Detection:**

➢ **DM Direct, Indirect experiments**

➢ **Beam-dump based experiments, specifically for neutrinos**

- **Outlook**

Example: One Specific Model

Model for a sub GeV DM, light mediators

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

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

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

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

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

Dark matter is made out of η_1, η_2:

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

Low mass dark matter, gauge and scalar mediators

Dark Matter (parity odd): $\eta_{1,2}$ and can be inelastic with small mass gap among η_1, η_2

Predictions are testable at various low energy experiments

Dutta, Ghosh, Kumar,
PRD,2019; PRD2020, 2105.07655

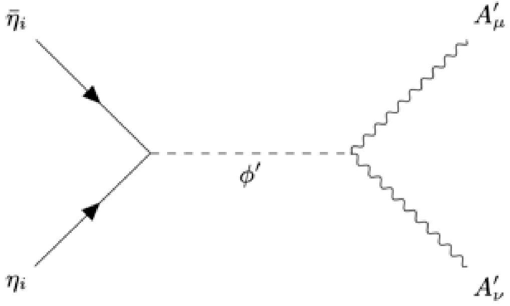
[Ghosh's talk SUSY'21]

- **This model accommodates the 4.2σ anomaly in $(g-2)_\mu$ and 3.1σ anomaly in R_k**

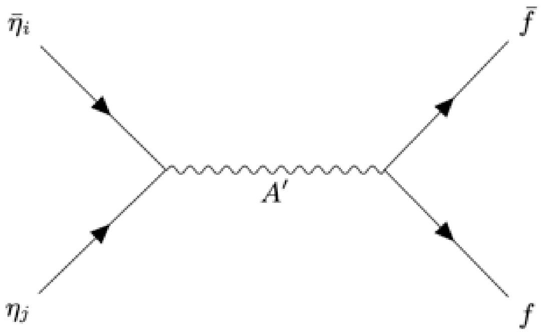
Thermal Relic Abundance

- **Realistic models contains both scalar (ϕ') and vector (A') mediators**

Dominant two body final states: $\bar{l}l, \bar{\nu}\nu, \pi\pi, A'A', \phi'\phi', \phi'A'$



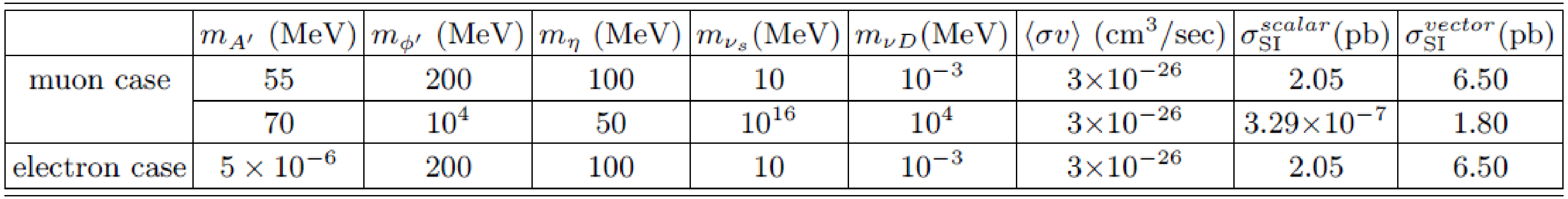
P-wave



S-wave

+ …

Resonance/non-resonance:

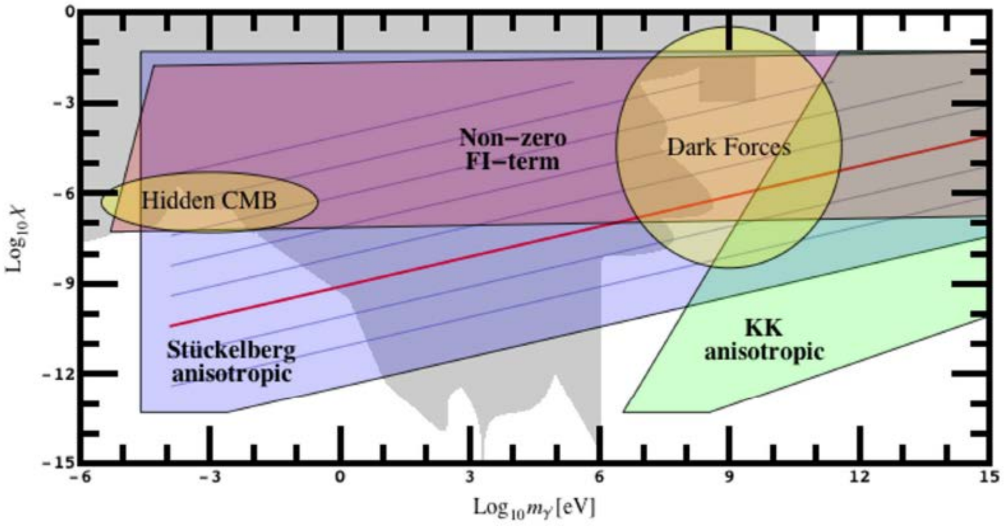


	$m_{A'}$ (MeV)	$m_{\phi'}$ (MeV)	m_η (MeV)	m_{ν_s}(MeV)	$m_{\nu D}$(MeV)	$\langle\sigma v\rangle$ (cm^3/sec)	$\sigma_{\mathrm{SI}}^{scalar}$(pb)	$\sigma_{\mathrm{SI}}^{vector}$(pb)
muon case	55	200	100	10	10^{-3}	3×10^{-26}	2.05	6.50
	70	10^4	50	10^{16}	10^4	3×10^{-26}	3.29×10^{-7}	1.80
electron case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

Models

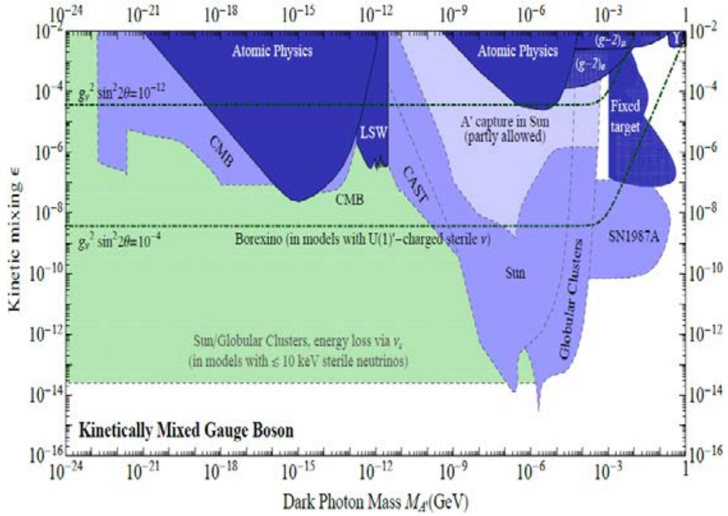
- **Similar models: New Gauge symmetry (E.g., Pospelov, Ritz,Voloshin, PLB, 2008, Chun, Park , Scopel, JHEP 02, 2011, Batell, deNiverville, McKeen, Pospelov, Ritz, PRD 2014, Foldenauer, PRD 2019, Bi, He,Yuan, PLB 2009, Kaplan, Luty, Zurek, PRD 2009, Okada, Raut, Shafi, PLB 2020, Craig, Garcia, Kribs, JHEP'20)**

Extended Higgs sector+ sterile neutrinos (E.g., Dutta, Ghosh, Li, PRD 2020, Adulpravitchai, Schmidt, JHEP 2015, Rose, Khalil, Moretti, PLB, 2021; Zhang, Ji, Mohapatra, JHEP, 2013



Cicoli, Goodsell, Jaeckel, Ringwald, JHEP 2011

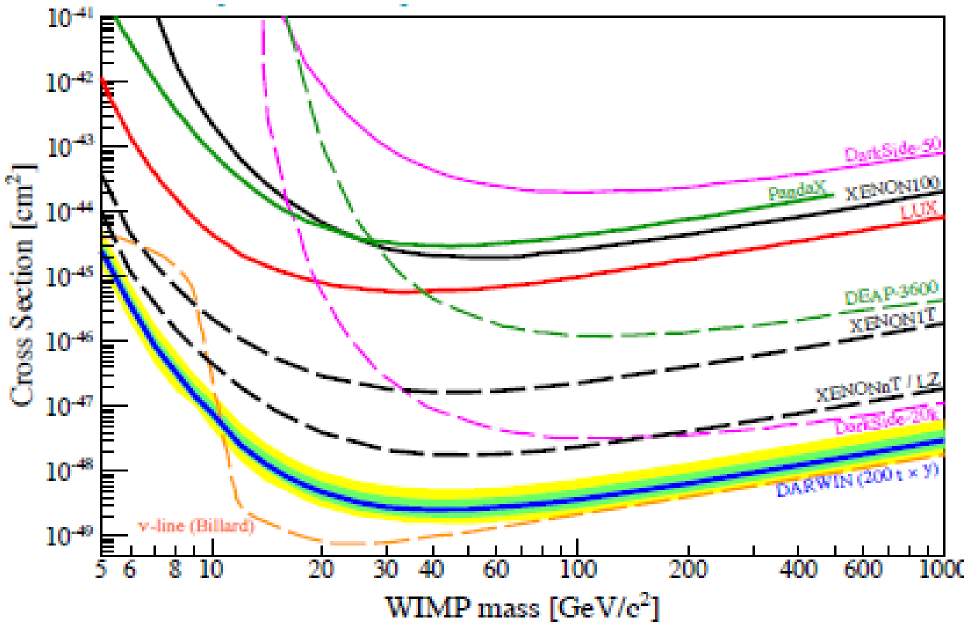
All these models have constraints from beam-dump, low energy accelerators, g-2, astrophysical and cosmological constraints, e.g.,



Harnik, Kopp, Machado, JCAP 2012

DM direct detection

- **The lighter dark matter (less than GeV) does not have much energy (v ~ 10^{-3} cm/s) to produce observable nuclear recoil in the direct detection experiments**



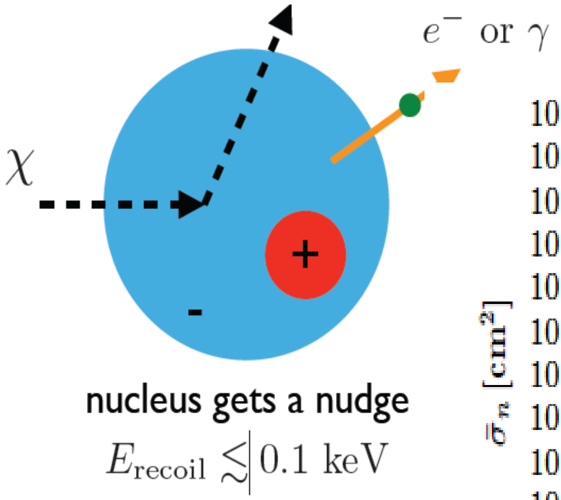
- **New ideas to probe light DM:**
  building low threshold detectors,
  using electron targets, Migdal effect,
  Atomic coherency, photo electric absorption,
  superconductors, Dirac materials etc.

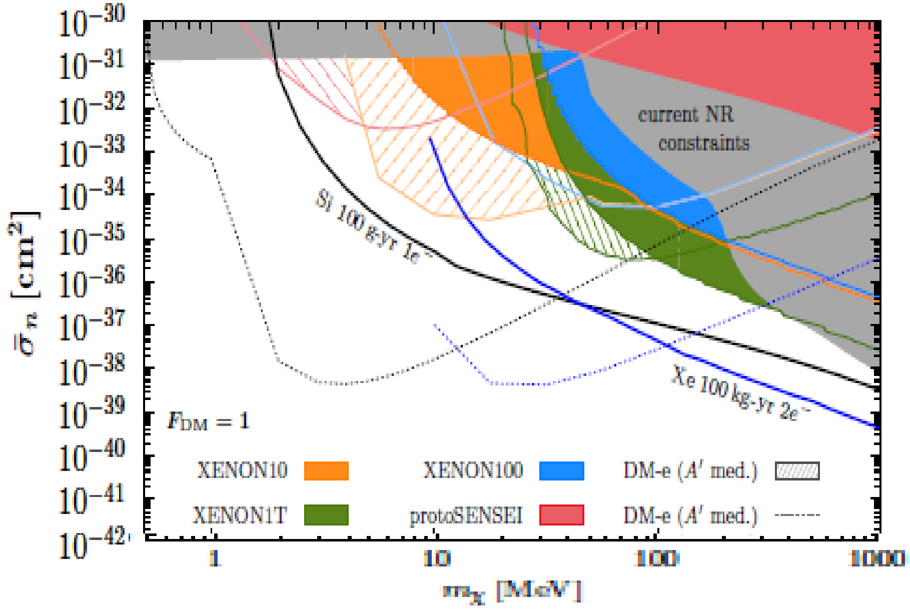
Direct Detection

Various ways of probing Sub-GeV DM:

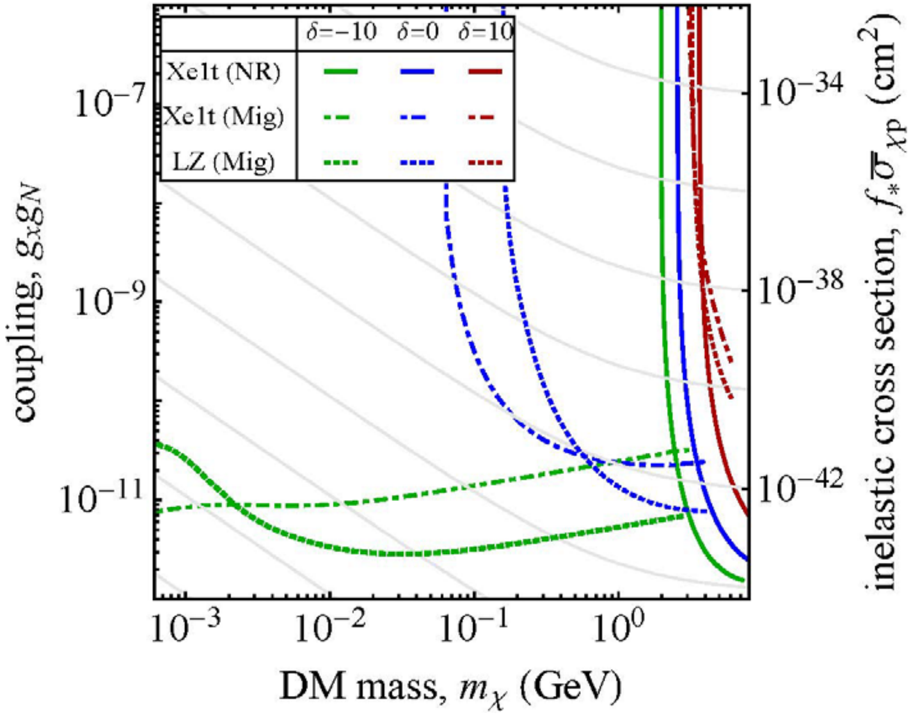
Ibe, Nakano, Shoji, Sujuki, 2018
Dolan, Kahlhoefer, McCabe, 2018

Migdal effect (Ionization and excitation of electron)





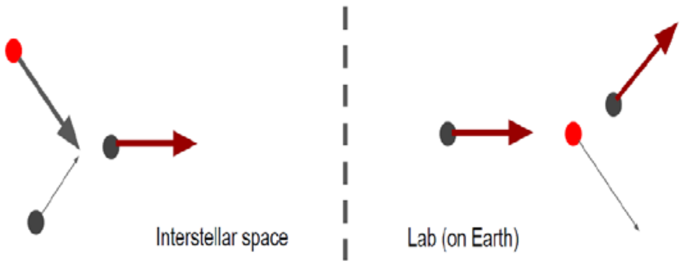
Essig, Prdaler, Sholapurkar, Yu, PRL 2020



Bell, Dent, Dutta, Ghosh, Kumar, Newstead, 2021
Flambaum, Su, Wu, Zhu, 2021

Direct Detection

Cosmic ray scattered



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

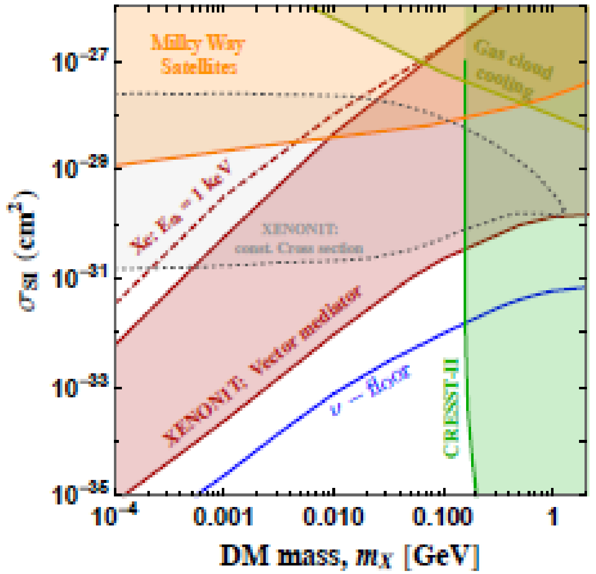
Bringmann, Pospelov, PRL2019

Ema, Sala, Sato, PRL, 2019

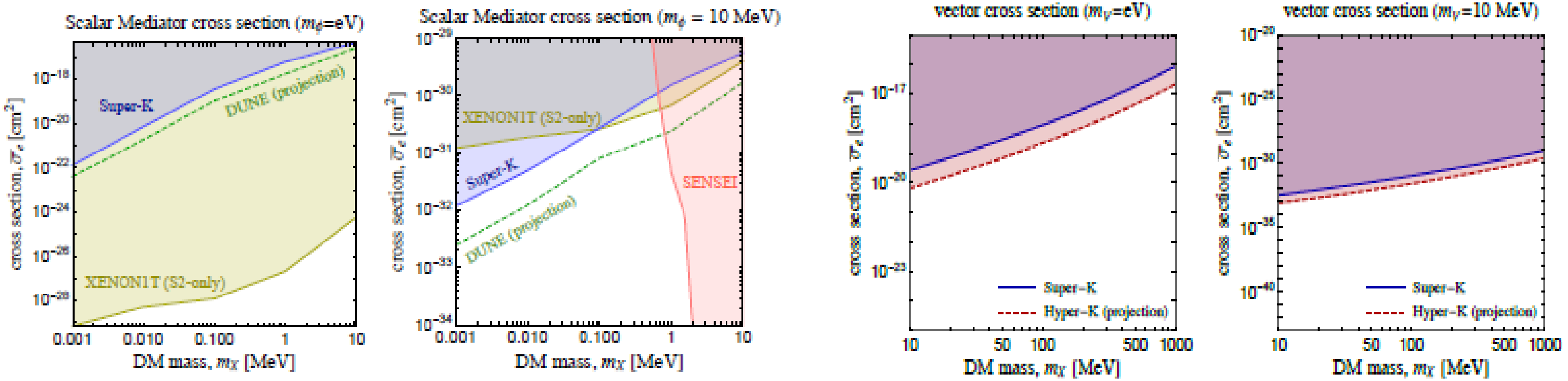
Cappiello, Beacom, PRD 2020

Dent, Dutta, Newstead, Shoemaker, PRD 2020

Nuclear recoil



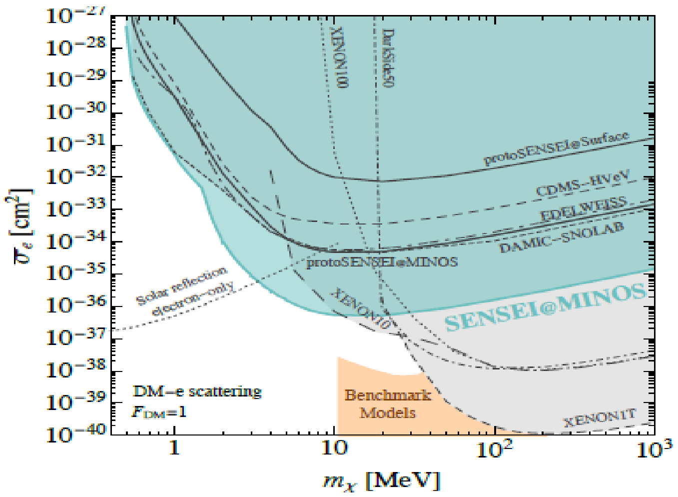
Electron recoil

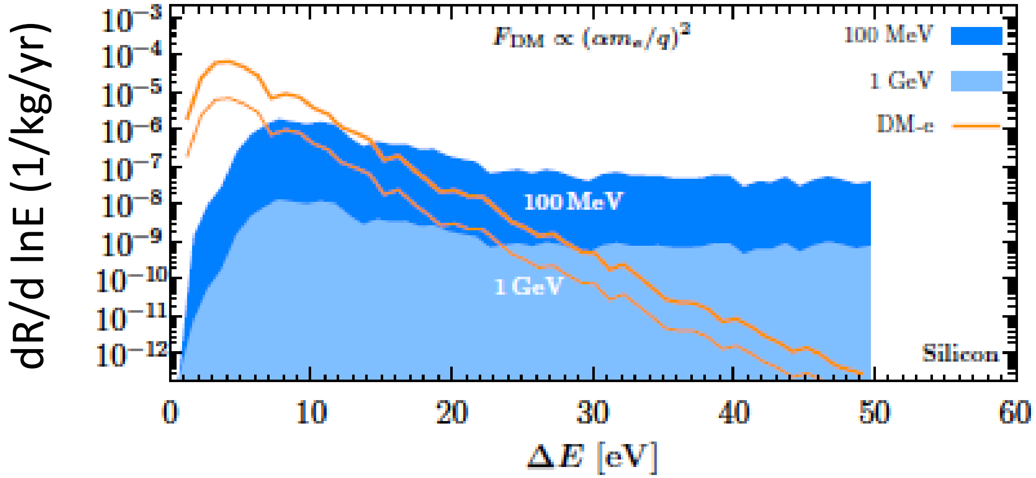


Dent, Dutta, Newstead, Shoemaker, Arellano, PRD, 2021

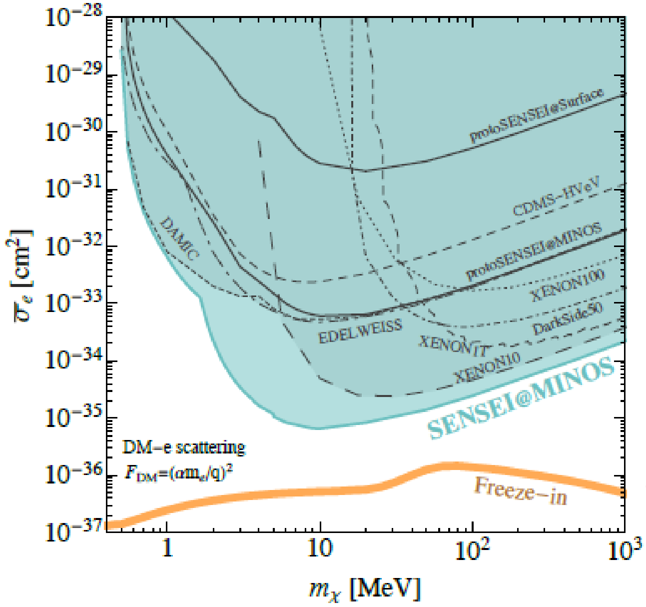
Direct Detection

DM-electron interaction

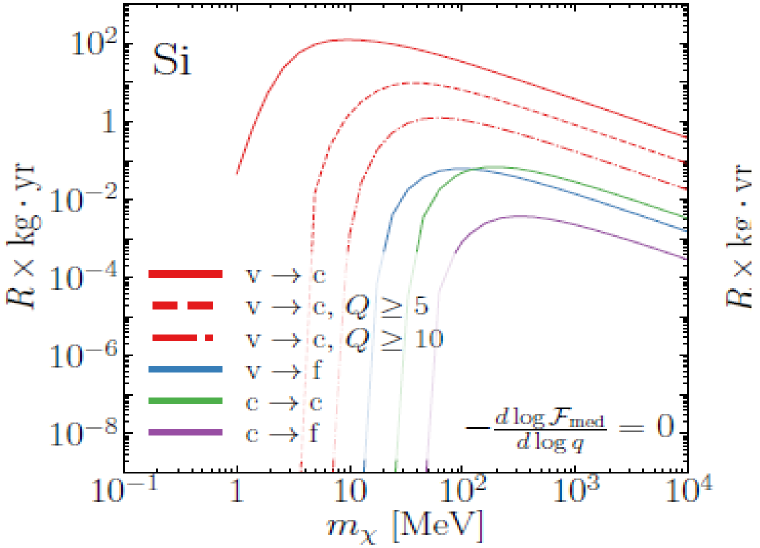




Essig, Prdaler, Sholapurkar, Yu, PRL 2020



Barak et al (SENSEI) 2020



Griffin, Inzani,Trickle, Zhang, Zurek, 2105.05253

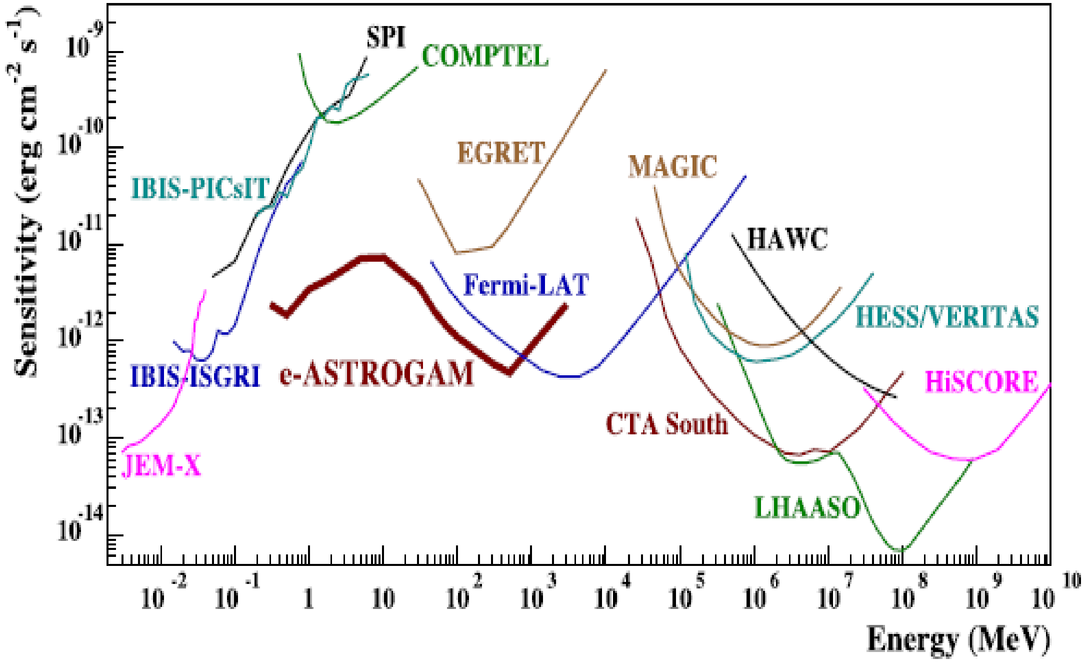
Accurate calculations of dark matter electron scattering rates in semiconductors
➔ Important for superCDMS, SENSEI, DAMIC, EDELWEISS

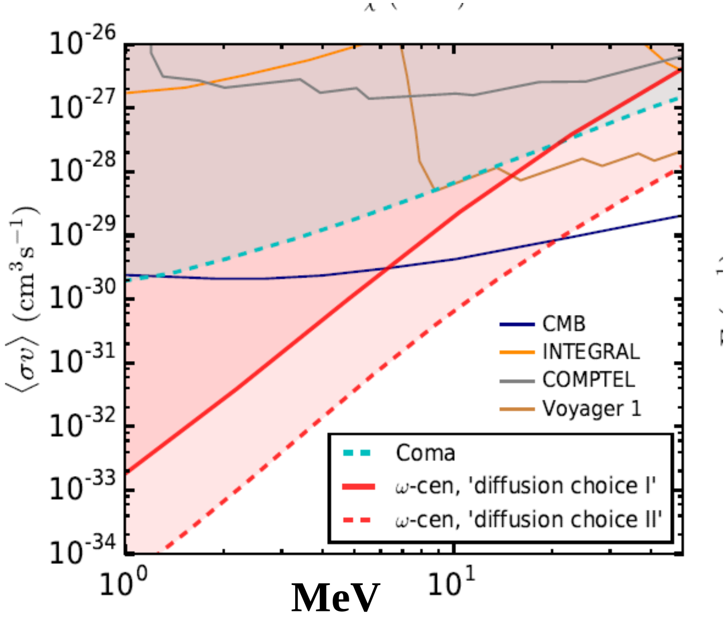
Catena,Emken, Nicola A. Spaldin, Tarantino, PRR 2020
Pandey, Singh, Wu, Chen, Chi, Hsieh, Liu, Wong, PRD 2020,
Baxter, Kahn, Krnjaic ,Griffin, PRD 2020

Sub-MeV DM: superconductors, superfluid He, Dirac materials, polar materials

Griffin, Knappen, Lin, Zurek, 2018

Light DM: Indirect detection





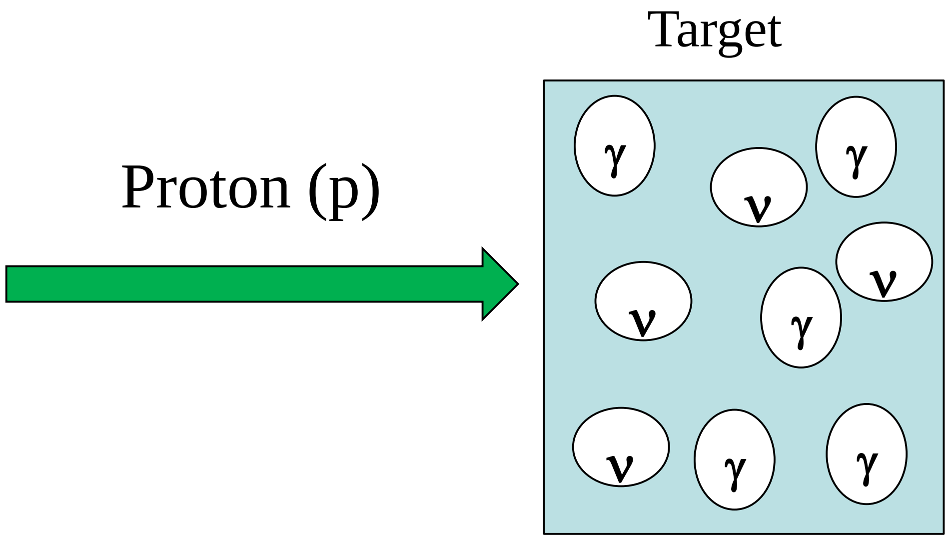
Dutta, Kar, Strigari, JCAP, 2020

- **Lighter than a GeV DM is very difficult to probe at the indirect detection**
- **Future experiments, e.g., AMEGO, e ASTROGRAM should be able to probe DM down to MeV**
- **SKA limits can be strong**

Light DM search: ν experiments

- **Lighter than a GeV DM is very difficult to probe at the LHC, Direct and Indirect detections**

**A new strategy to probe light DM: Use Low energy accelerator,
e.g. proton with energy 1- 100 GeV hitting a target, Beryllium, Mercury, Tungsten, Iron etc.**



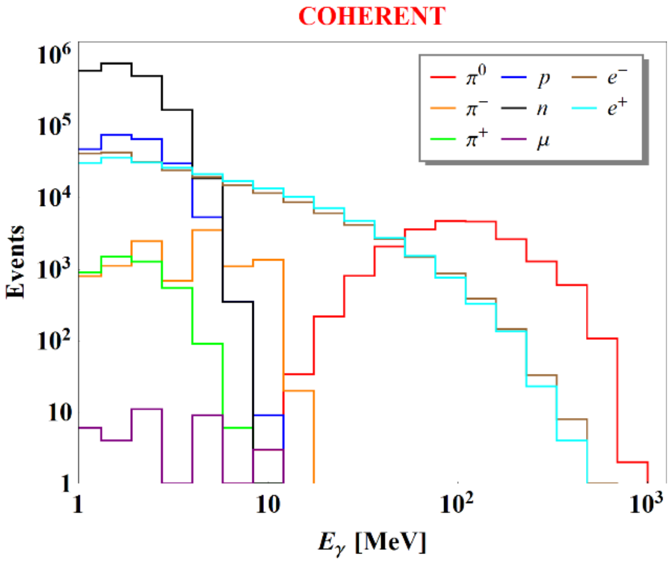
γ’s are produced from proton bremsstrahlung, cascade decays, various Mesons decays

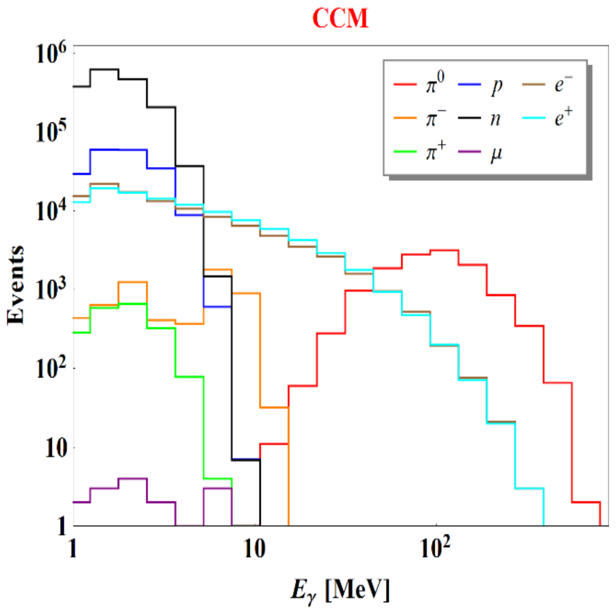
ν’s are produced from various Mesons decays

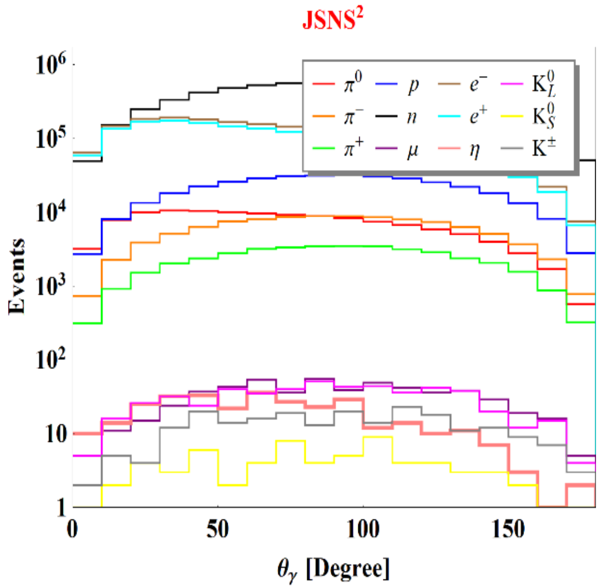
- **Reactor based neutrino experiments are also a high intensity source of photons along with ν’s**

DM at ν experiment

Accelerator based experiments: proton hitting a target produces photons.
For example (using GEANT4 + FTFP BERT library generating 10^5 protons on targets.)







Dutta, Kim, Liao, Park, Shin,
Strigari, Thompson, PRL 2020, 2021

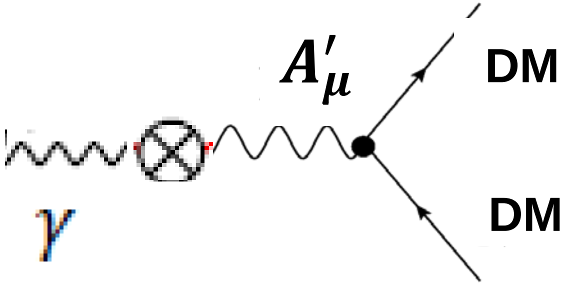
Experiment	E_{beam} [GeV]	POT [yr^{-1}]	Target	Detector: mass, distance, angle, E_r^{th}
COHERENT	1	1.5×10^{23}	Hg	CsI[Na]: 14.6 kg, 19.3 m, 90°, 6.5 keV LAr: 24 kg (0.61 ton), 28.4 m, 137°, 20 keV
JSNS^2	3	3.8×10^{22}	Hg	Gd-LS: 17 ton, 24 m, 29°, 2.6 MeV
CCM	0.8	1.0×10^{22}	W	LAr: 7 ton, 20 m, 90°, 25 keV

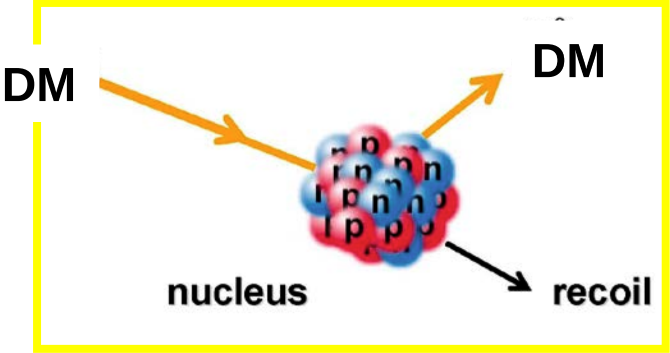
For DUNE, MiniBooNE
Celentano, Darmé, Marsicano, Nardi, PRD,2020
Brdar, Dutta, Jang, Kim, Shoemaker, PRL 2021
Capozzi, Dutta, Gurung, Jang, Shoemaker, 2021

Low mass DM at ν experiments

Dark photon produces dark matter

➔ **Dark matter particles can be produced in the lab**





- **Lot of dark matter particles**
- **Low mass dark matter can be investigated**
- **Problem: Neutrinos also produce same signals**

Dark Photon to DM at ν Expts.

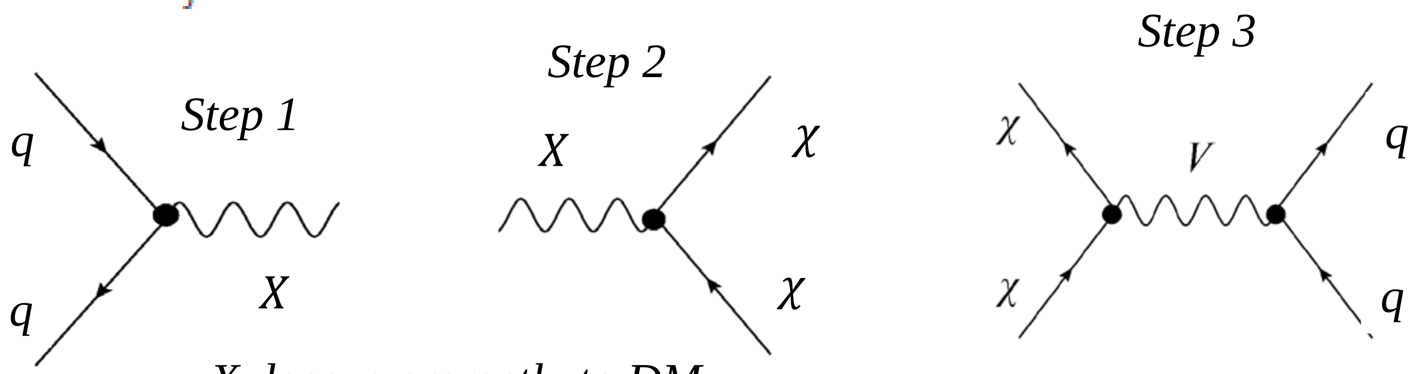
$$\mathcal{L}_{X,\mathrm{prod}} \supset \sum_f \kappa_f^X x_f^X X_\mu \bar{f}\gamma^\mu f + \kappa_D^X X_\mu \bar{\chi}\gamma^\mu \chi \,,$$

$$\mathcal{L}_{V,\mathrm{scatter}} \supset \sum_f \kappa_f^V x_f^V V_\mu \bar{f}\gamma^\mu f + \kappa_D^V V_\mu \bar{\chi}\gamma^\mu \chi \,,$$

X,V**: Dark gauge boson/Dark photon**

We can assume X≡ V

$\kappa_f^X \sim e\epsilon$

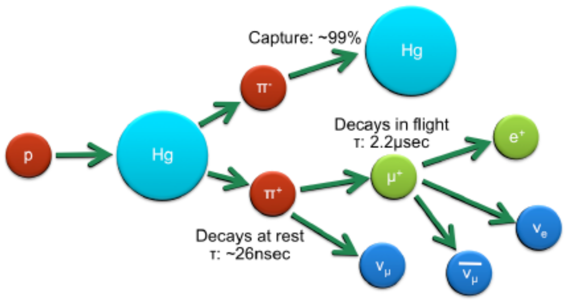


X decays promptly to DM

$$\frac{d\sigma}{dE_{r,N}} = \frac{(\kappa_f^V \kappa_D^V)^2 (Q_{\mathrm{eff}}^V)^2 \cdot |F_V|^2}{4\pi p_\chi^2 (2m_N E_{r,N} + m_V^2)^2} \left\{ 2E_\chi^2 m_N \left(1 - \frac{E_{r,N}}{E_\chi} - \frac{m_N E_{r,N}}{2E_\chi^2}\right) + m_N E_{r,N}^2 \right\} ,$$

- **DM arising from dark photons can be observed from the nuclear/electron recoils**

Example: COHERENT (ongoing)

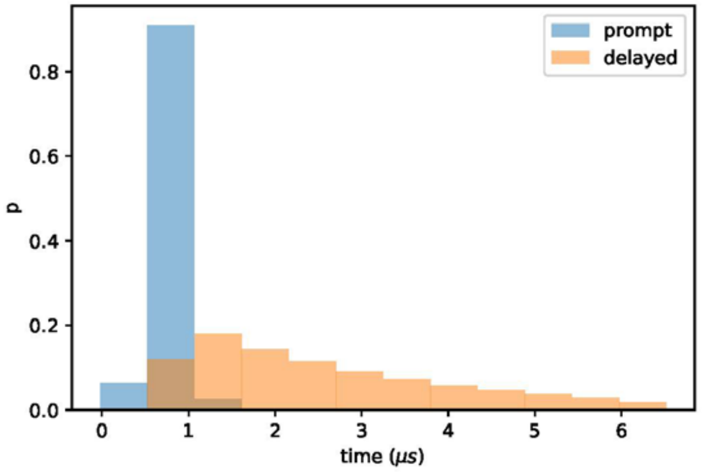


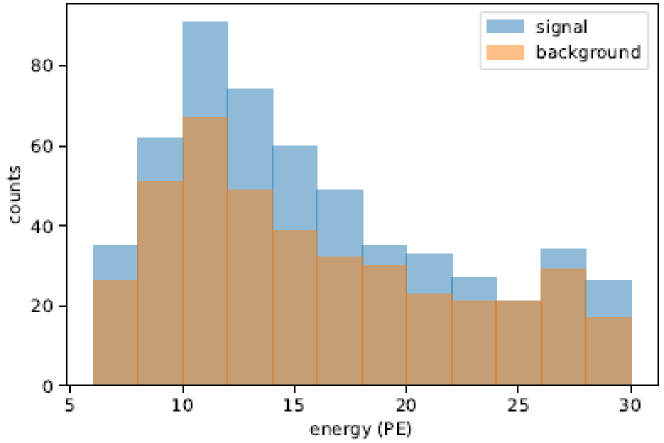
Proton beam hits a target Hg [COHERENT: 1 GeV]

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

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

COHERENT: CsI data:2018





- **Similarly:**

CCM (Los Alamos)
: 800 MeV proton beam,
JSNS2 (J-PARC): 3 GeV beam
CONUS, CONNIE (reactor based)

COHERENT (2017) **No CEνNS rejected at 6.7σ: CsI (2020): 11.6σ**

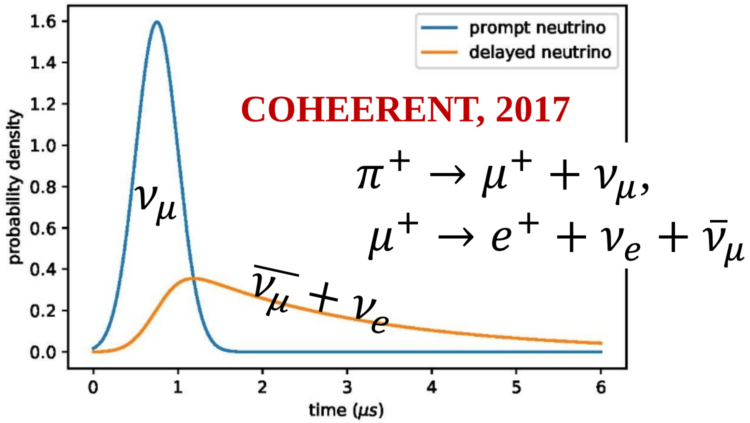
COHERENT (2020) **No CEνNS rejected at 3.8σ : LAr**

CEνNS-DM

The ongoing CEνNS experiments, COHERENT, CCM etc. are probing light DM

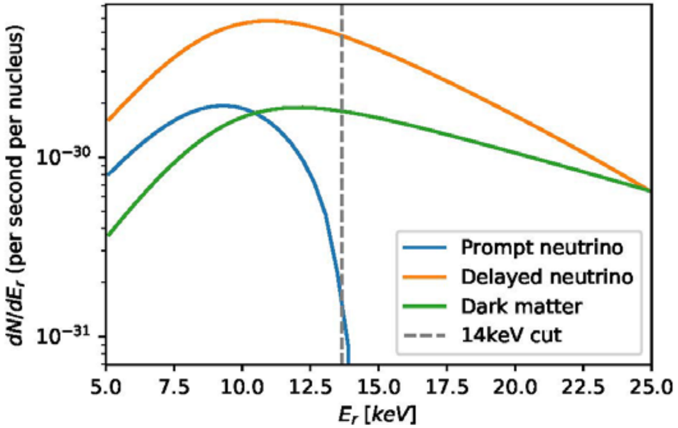
Deniverville, Pospelov, Ritz, PRD, 2015, Ge, Shoemaker, JHEP, 2018, Dutta, Kim, Liao, Park, Shin, Strigari, PRL, 2020

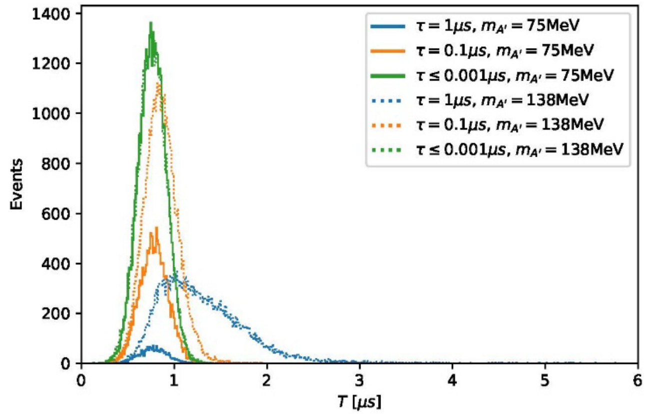
- ***Both neutrinos, DM produce nuclear/electron recoils: how to distinguish them?***
- ***The timing and energy recoil measurement at COHERENT, CCM, JSNS^2 can be used***



COHEERENT, 2017

$$\pi^+ \to \mu^+ + \nu_\mu,$$
$$\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$$



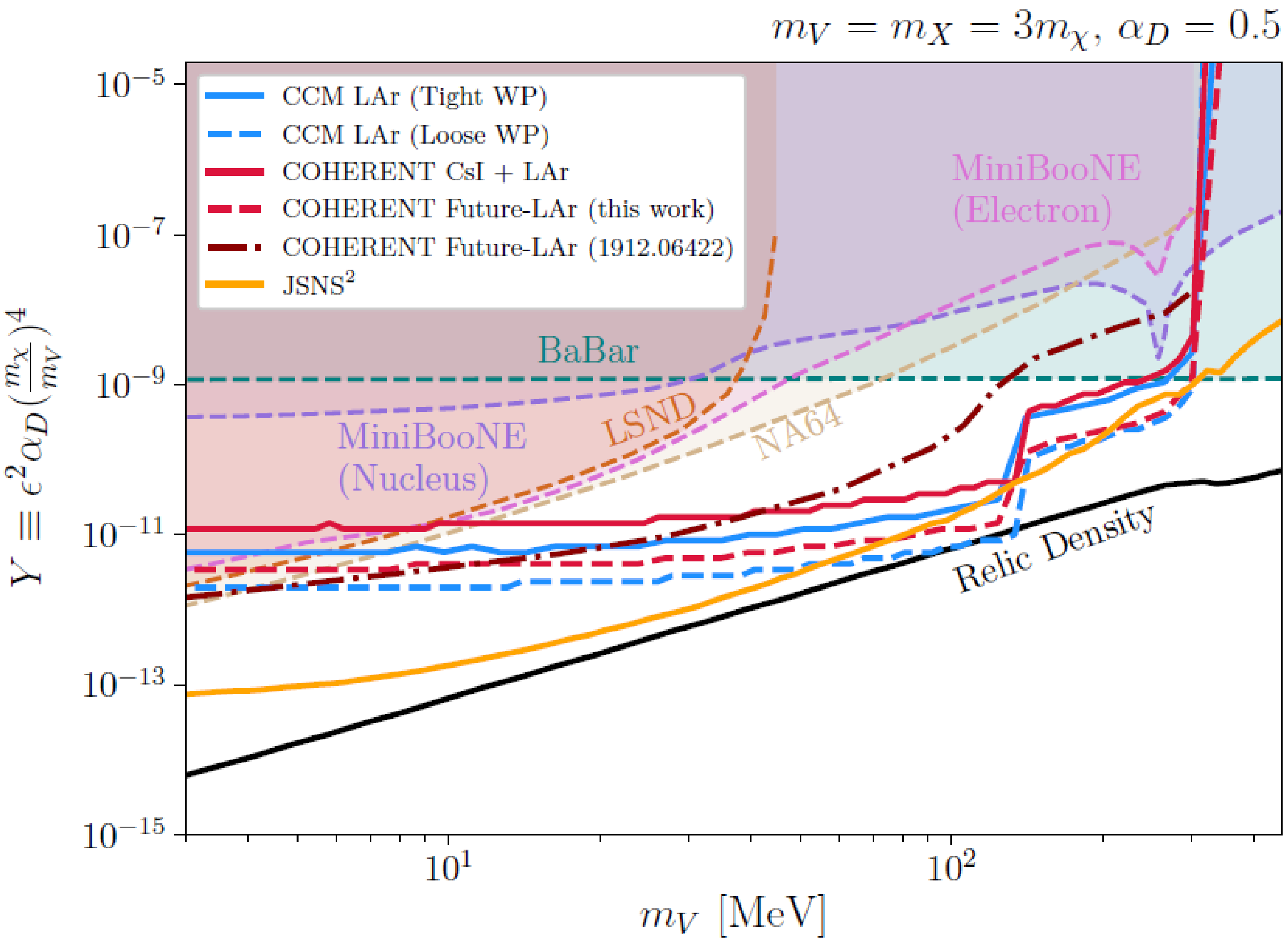


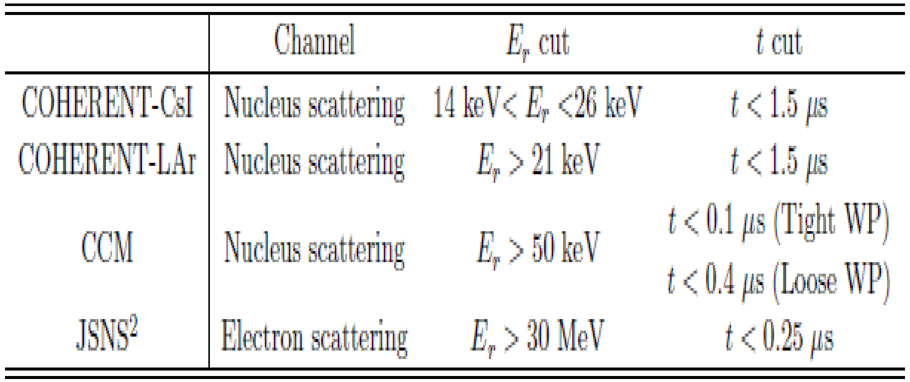
- ***For t < 1.5μs, we have mostly prompt ν***
- ***For E_r >14 KeV (CsI) we remove the prompt ν***

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

➔ ***We need to do the same thing for CCM, JSNS^2***

DM at ν experiments





	Channel	E_r cut	t cut
COHERENT-CsI	Nucleus scattering	14 keV< E_r <26 keV	$t < 1.5$ μs
COHERENT-LAr	Nucleus scattering	$E_r > 21$ keV	$t < 1.5$ μs
CCM	Nucleus scattering	$E_r > 50$ keV	$t < 0.1$ μs (Tight WP) $t < 0.4$ μs (Loose WP)
JSNS^2	Electron scattering	$E_r > 30$ MeV	$t < 0.25$ μs

- **Very Low DM mass can be probed**

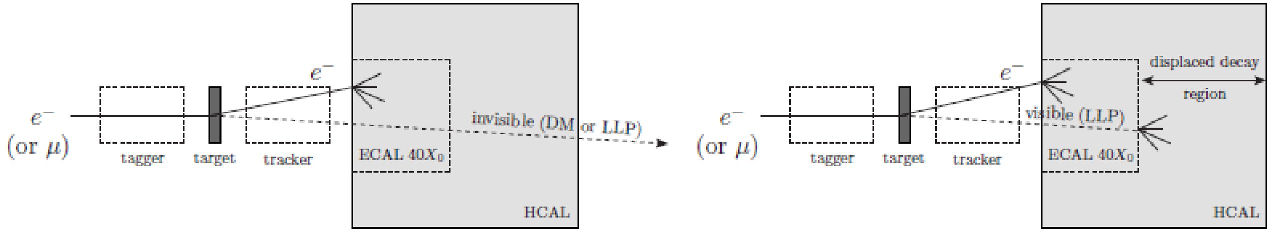
Dutta, Kim, Liao, Park, Shin, Strigari, Thompson, PRL 2020, 2021

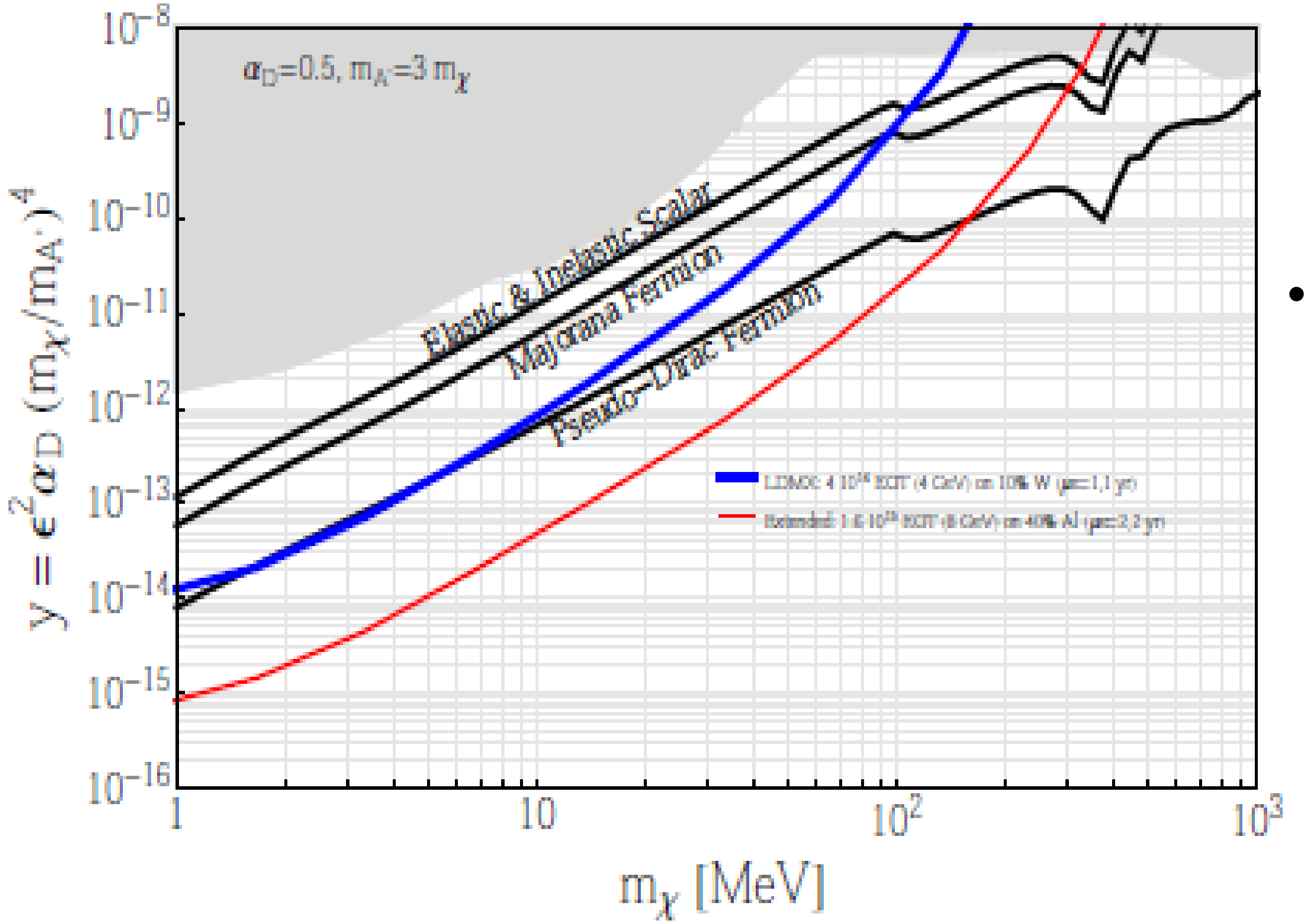
- **For M_V (M_{DM}) < 100 (33) MeV, $g_N g_\chi$ <3.5 10^{-5}**

- **The proton beam-dump based experiments probe the DM quark couplings extensively**

DM at electron experiment

LDMX: :

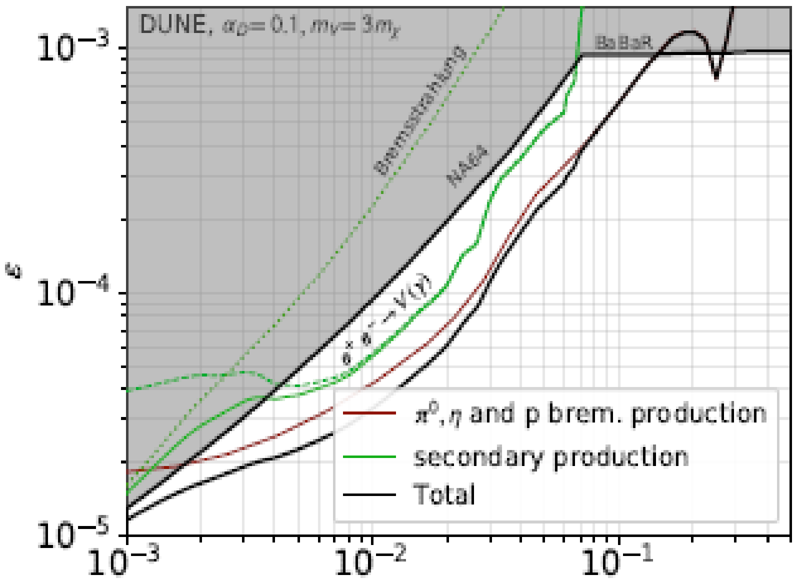


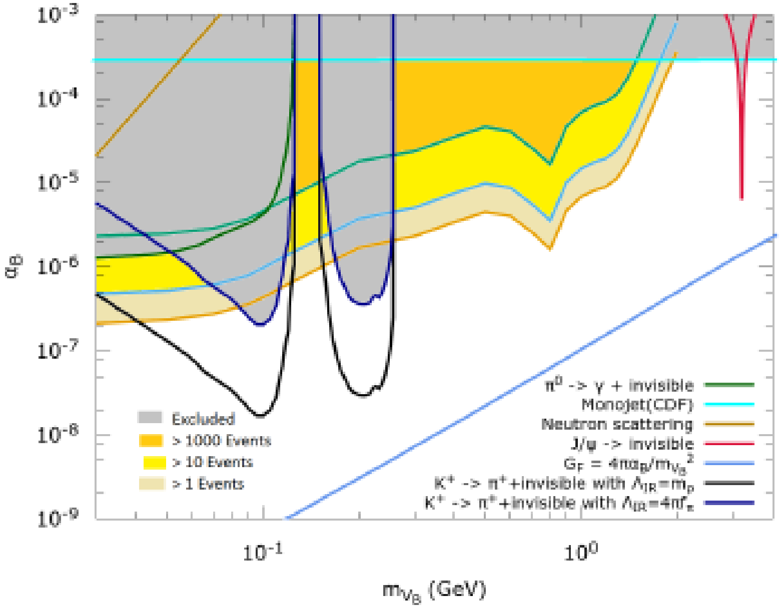


- **For M_V (M_{DM}) = 30 (10) MeV, $g_e\, g_\chi < 7 \times 10^{-6}$**

Berlin, Blinov, Krnjaic, Schuster, Toro, PRD 2020; LDMX, 2018

Light DM at DUNE





DUNE (near detector): Dark Matter parameter space, **Celentano, Darmé, Marsicano, Nardi, 2020**

(Using photons from Mesons) **Romeri, Kelly, Machado, PRD 2020**

Estimations are available for *SBND, ICARUS*

De Gouvea, Fox, Harnik, Kelly, Zhang, JHEP, 2020

Leptophobic models can be probed extensively

Utilizing the DUNE beam-dump: The reach would improved further

Naaz, Singh, Singh, Adv.High Energy Phys. 2020

Outlook

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

- **Models with Sub-GeV DM are very interesting, especially with light mediators**

➔They can explain many anomalies, g-2, R_k, MiniBooNE etc.

- **Models have sufficient allowed parameter space after satisfying various experimental constraints**

- **These models can be probed at direct and indirect detection experiments**

- **Ongoing neutrino experiments COHERENT, CCM etc. are already providing leading constraints on the allowed parameter space**

- **Future DUNE, SBND, ICARUS, LDMX etc. along with the direct and indirect experiments will be important for probing these models**