Searching for New Physics Signals from Timing Spectra @ ν Experiments

with B. Dutta, D. Kim, S. Liao, S. Shin & L. Strigari
[1906.10745 & work in progress]

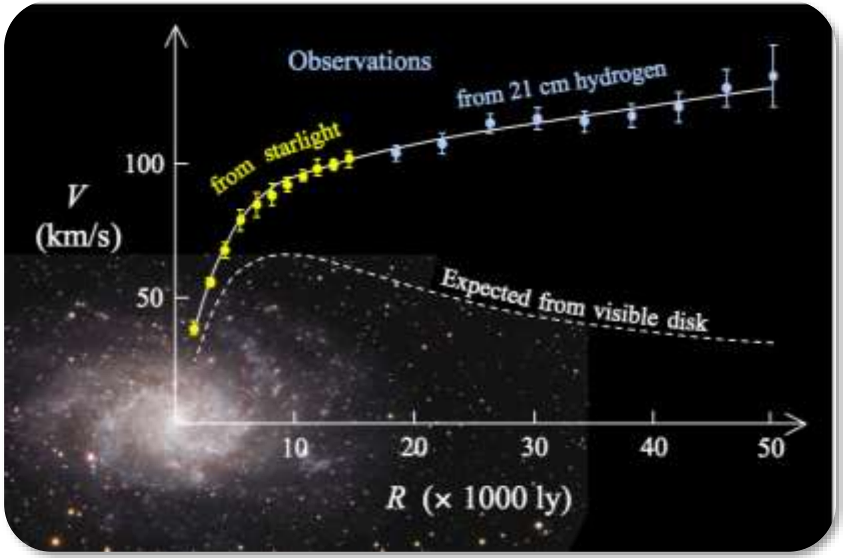
Jong-Chul Park

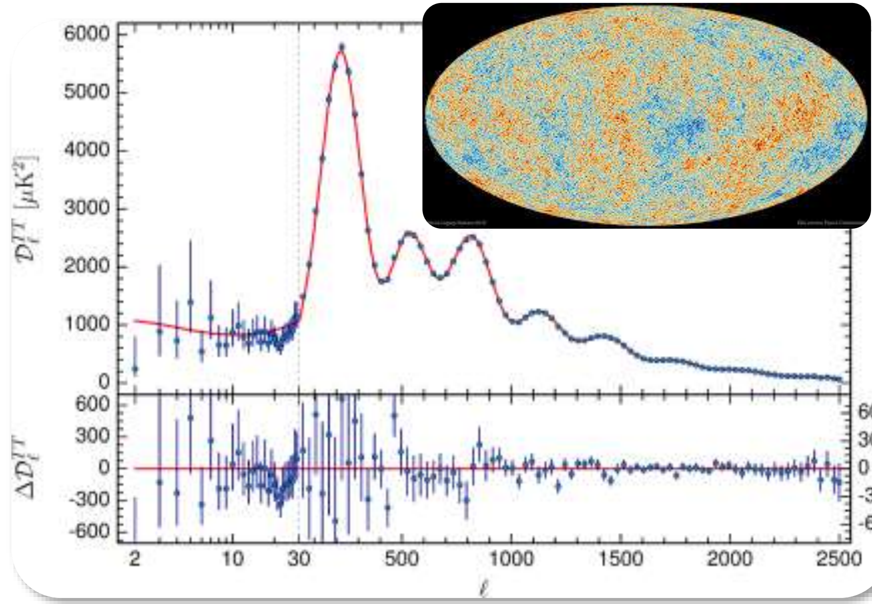
CNU 충남대학교
CHUNGNAM NATIONAL UNIVERSITY

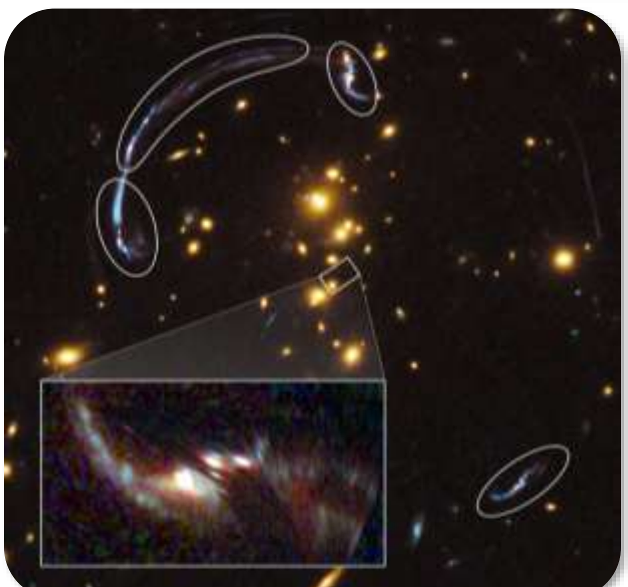
IBS-PNU Join Workshop

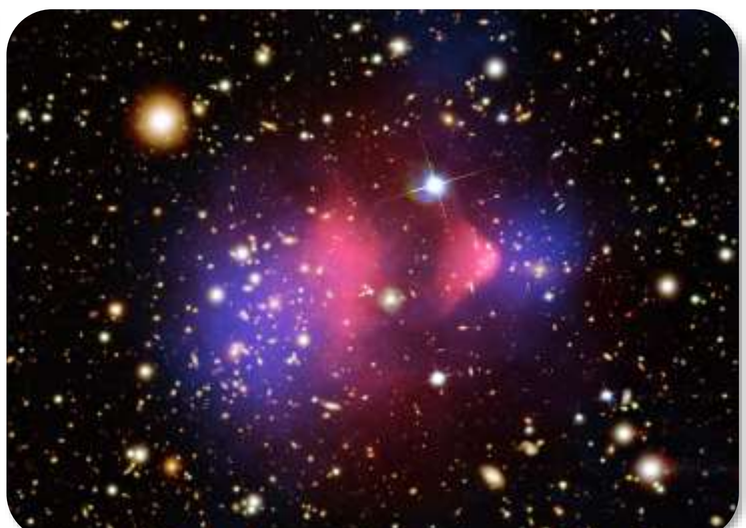
Dec. 06 (2019)

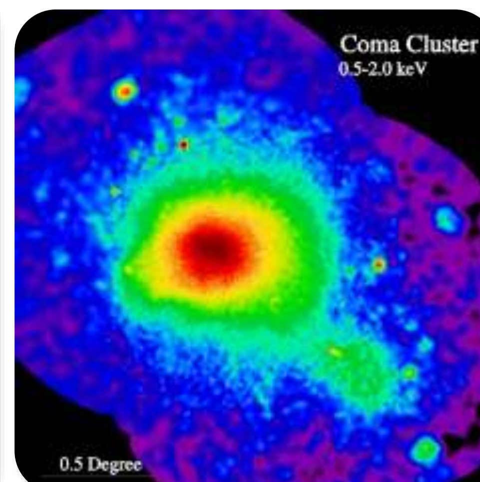
Observational Evidence for DM



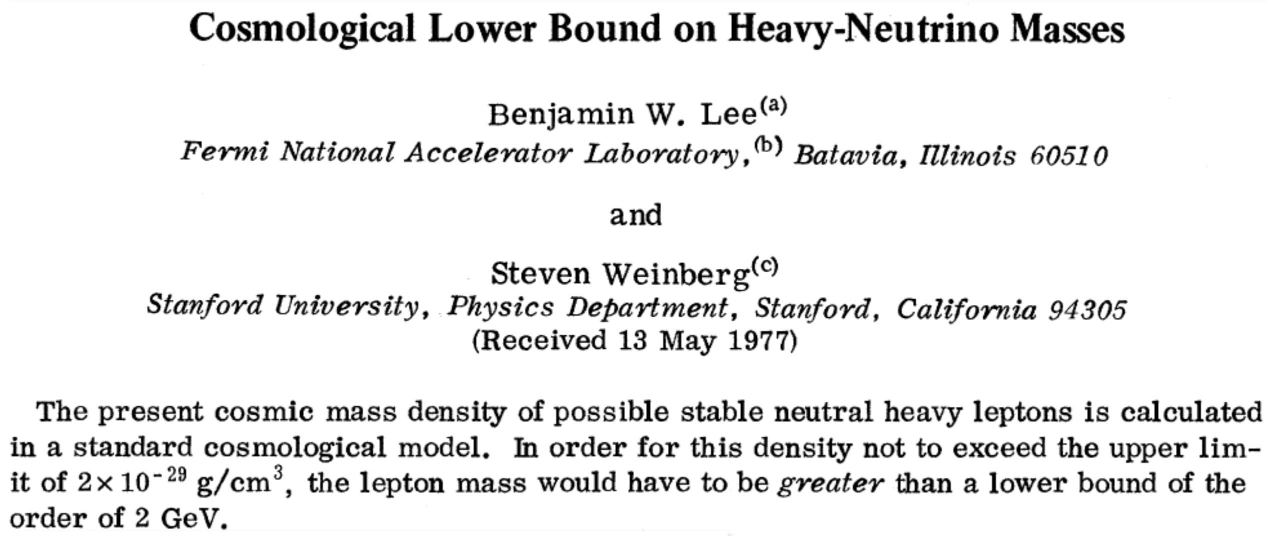








Classic Solution*: WIMP



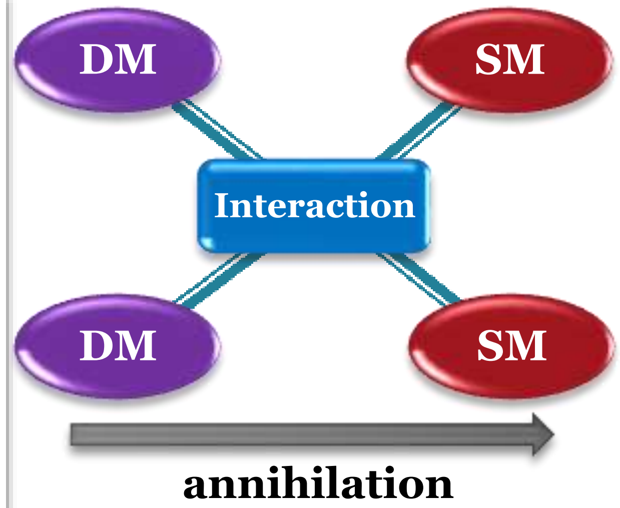
Cosmological Lower Bound on Heavy-Neutrino Masses

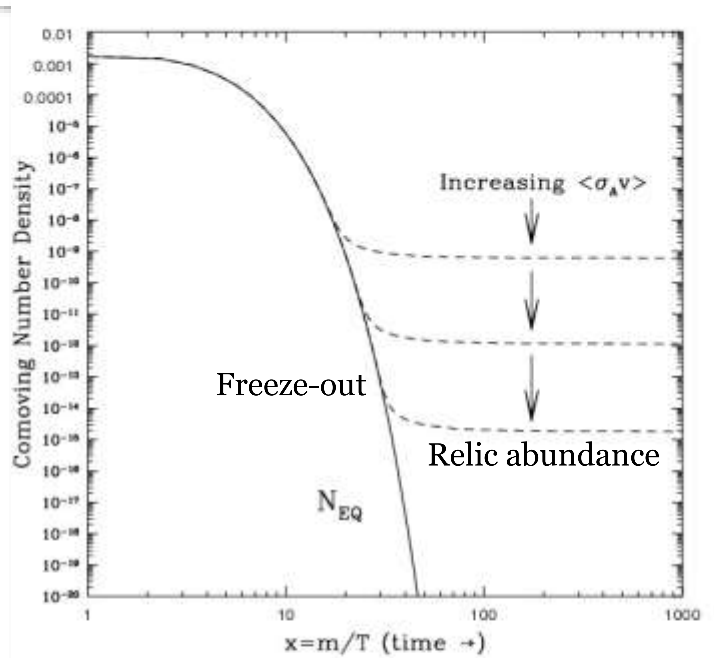
Benjamin W. Lee[a]
Fermi National Accelerator Laboratory,[b] *Batavia, Illinois 60510*

and

Steven Weinberg[c]
Stanford University, Physics Department, Stanford, California 94305
(Received 13 May 1977)

The present cosmic mass density of possible stable neutral heavy leptons is calculated in a standard cosmological model. In order for this density not to exceed the upper limit of 2×10^{-29} g/cm^3, the lepton mass would have to be *greater* than a lower bound of the order of 2 GeV.





- Correct thermal relic abundance:

$$\Omega h^2 \sim \frac{0.1\,pb}{\langle\sigma v\rangle} \text{ with } \langle\sigma v\rangle \sim \frac{\alpha_\chi^2 m_\chi^2}{M^4} \text{ (}M\text{: dark scale/mediator)}$$

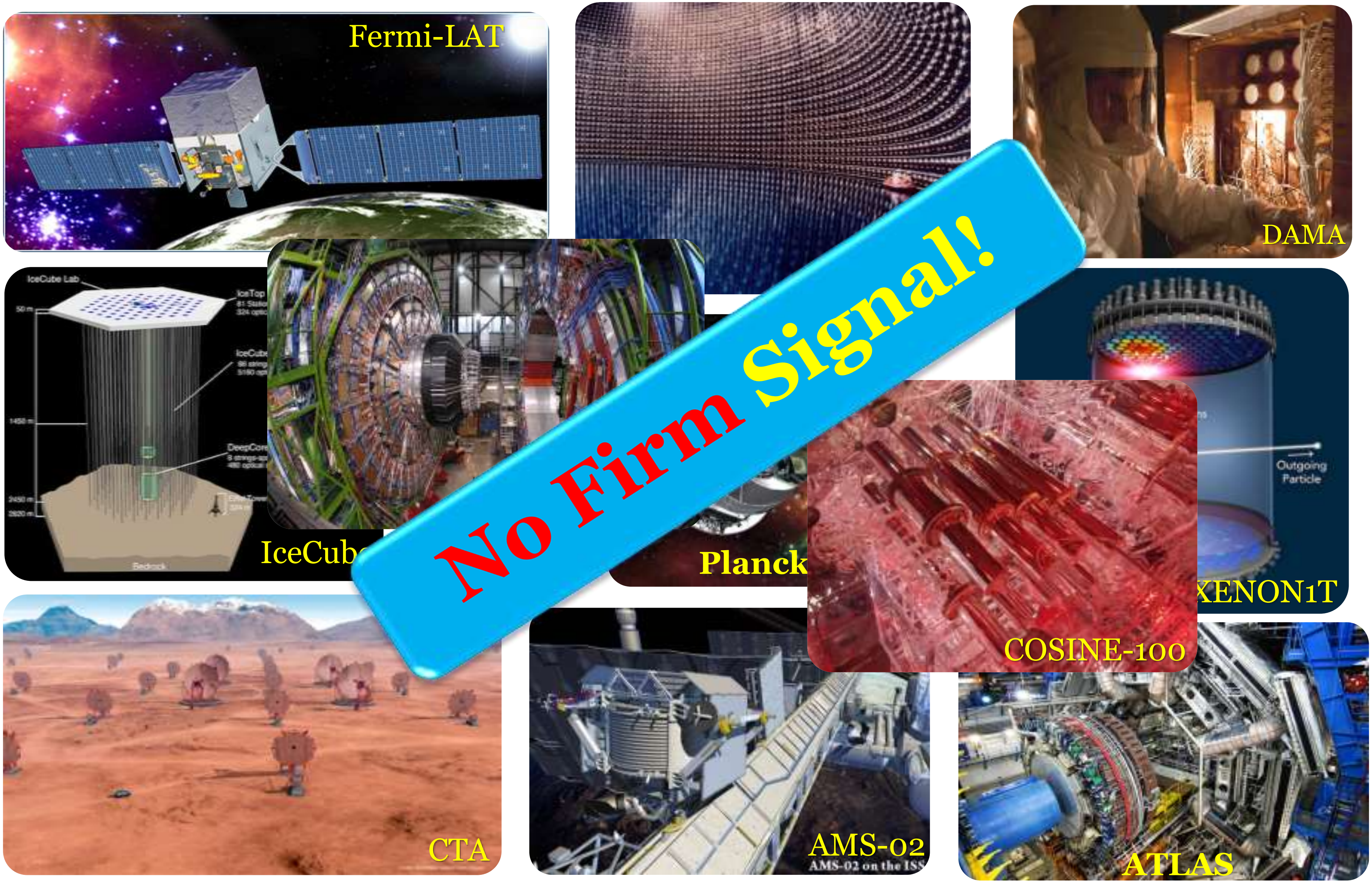
- Weak coupling ➔ naturally weak scale mass:

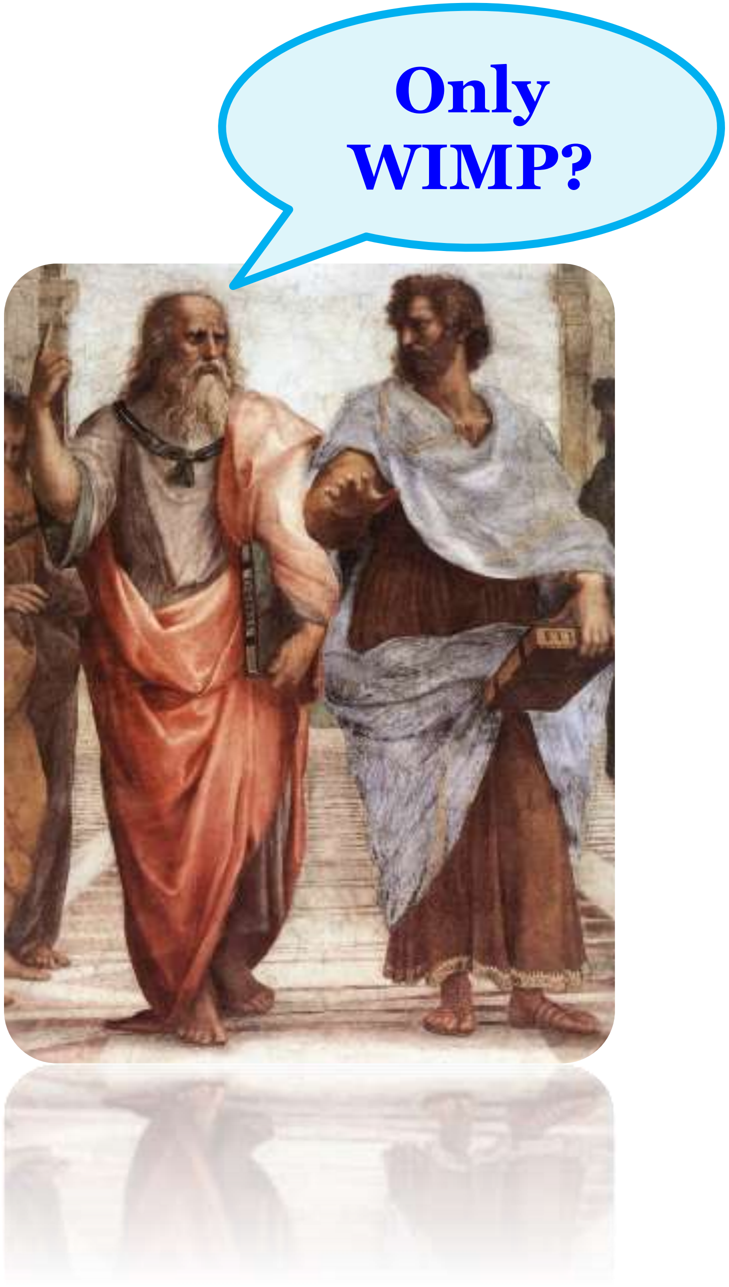
~1 GeV – 10 TeV mass range favored

➔ weak scale (new) physics

* Of course, **axion** is another classic solution.

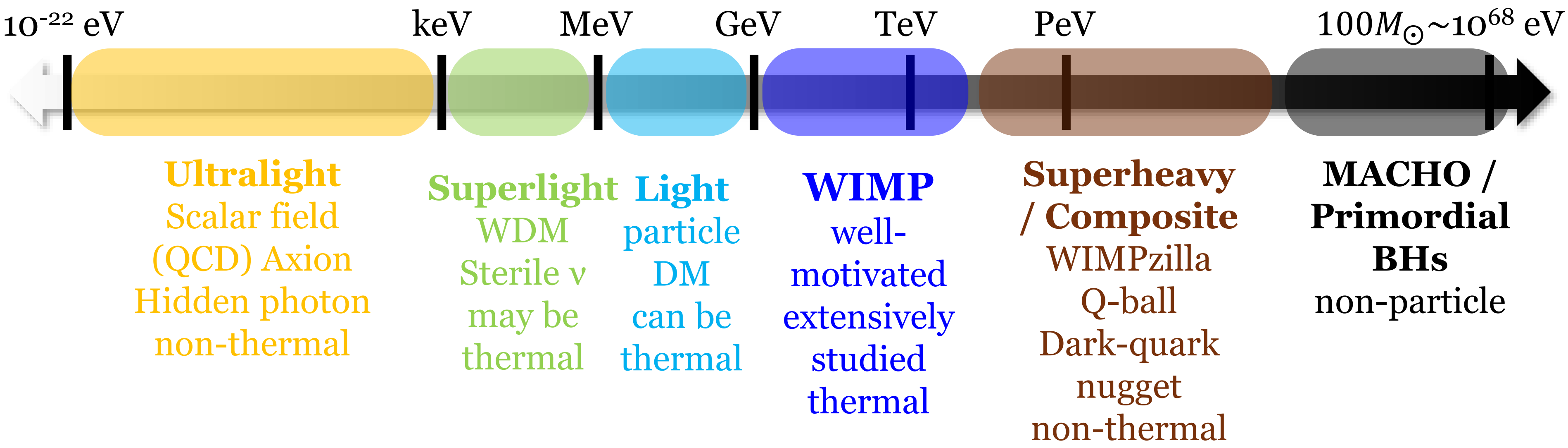
Diverging Efforts for WIMP Searches



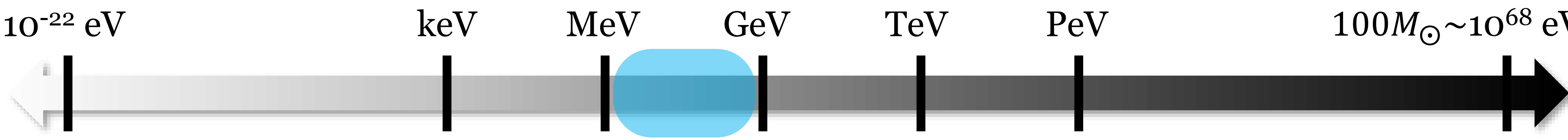

Only
WIMP?

Very Very Wide DM Mass Range

Very Very Wide DM Mass Range



Light Dark-Sector Models



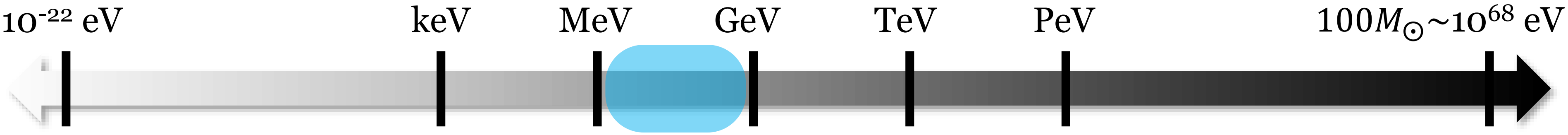
- For heavy mediator, $\langle \sigma v \rangle \sim \frac{\alpha_\chi^2 m_\chi^2}{M^4}$
- For weak scale physics, **sub-GeV DM overproduction** (Lee-Weinberg limit)➔ New mediator $\lesssim M_W$ for freeze-out or freeze-in
- Various light mediator scenarios:
  - ✓ Sommerfeld enhancement [arXiv:0810.0713]
  - ✓ $g-2$ of e/μ: $\sim 2-3\sigma$ discrepancy [arXiv:1806.10252]
  - ✓ New ν interactions for the MiniBooNE excess [arXiv:1807.09877]
  - ✓ Solutions of Yukawa coupling hierarchy prob. [arXiv:1905.02692]

Light particle DM can be thermal

- New DM relic determination mechanisms:
  - ✓ assisted freeze-out [arXiv:1112.4491]
  - ✓ cannibal DM [arXiv:1602.04219, 1607.03108]
  - ✓ co-decaying [arXiv:1105.1652, 1607.03110]
  - ✓ semi-annihilation [arXiv:0811.0172, 1003.5912]
  - ✓ SIMP [arXiv:1402.5143]
  - ✓ …

- Various light DM-involving phenomenology has been studied:
  - ✓ Boosted DM scenarios [arXiv:1405.7370, 1411.6632, 1612.06867]
  - ✓ Fast-moving DM via DM-induced nucleon decays [arXiv:1312.0011]
  - ✓ Energetic cosmic-ray induced relativistic DM [arXiv:1810.10543]
  - ✓ Ultra high E cosmic-ray phenomena [arXiv:1407.3280, 1905.13223]

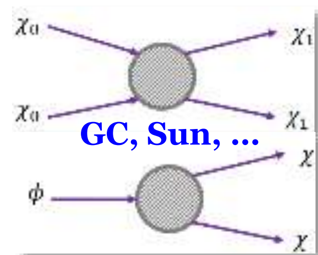
Light Dark-Sector Searches

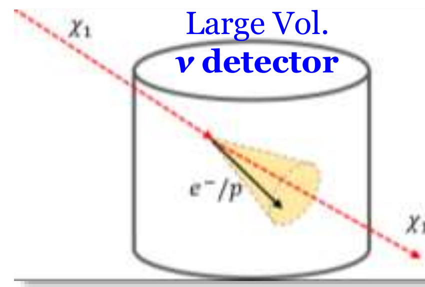


- ❖ $E_k \sim mv^2$<keV with $v\sim10^{-3}$ ➔ $< E_{th}$ of typical DM direct detectors
- ❖ New ideas are required! ➔ graphene, superconducting target, nanowire, superfluid He, 3-D Dirac material, Polar material, … (w/ TES, MKID, SNSPD)

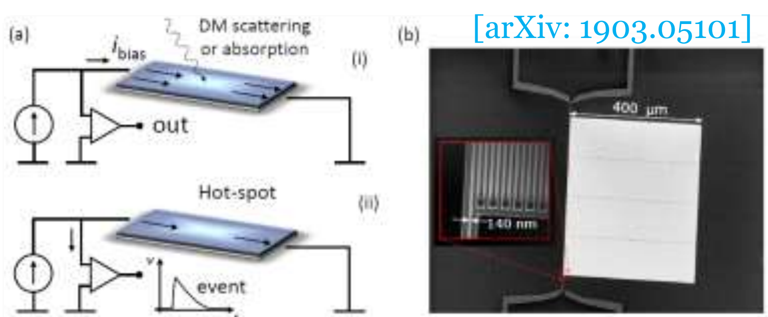
Light particle DM can be thermal

- ❖ Cosmogenic light DM searches: COSINE-100, DUNE, IceCube, ProtoDUNE, SK/HK, …



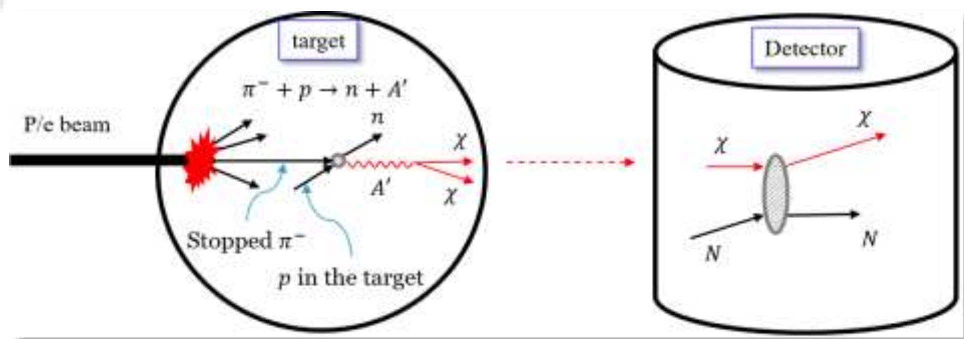


[arXiv: 1606.08849]



[arXiv: 1903.05101]

- ❖ Beam-produced light mediator/DM searches: Babar, BDX, Belle, DUNE, FASER, LDMX, MATHSULA, NA48/2, NA64, SeaQuest, SHiP, T2SK/HK, …



$$\pi^0 \rightarrow \gamma + A', \pi^{-/+} + p/n \rightarrow \pi^0 + n/p$$

Key Points of Our Work!

- A novel strategy to search for new physics signals:

  we can **efficiently isolate** new physics signals **from the SM $\boldsymbol{\nu}$ BGs** using **timing spectra** at (certain kinds of) neutrino experiments, "CEνNS".

- Application: the **measured CsI data** of the COHERENT experiment

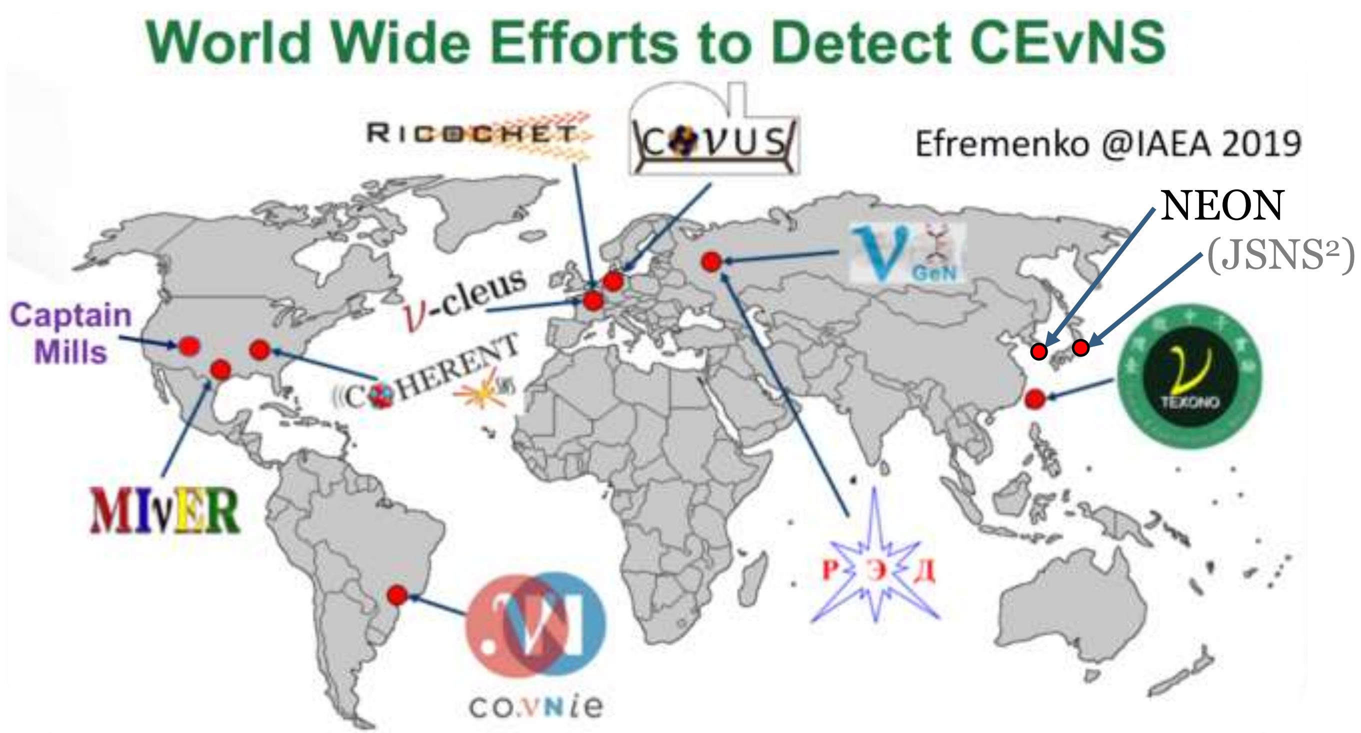
- Result: $\mathbf{2.4 - 3\sigma}$ **excess**!

  ➔ The excess can be explained by light DM arising from dark photon decay.

CEνNS Experiments

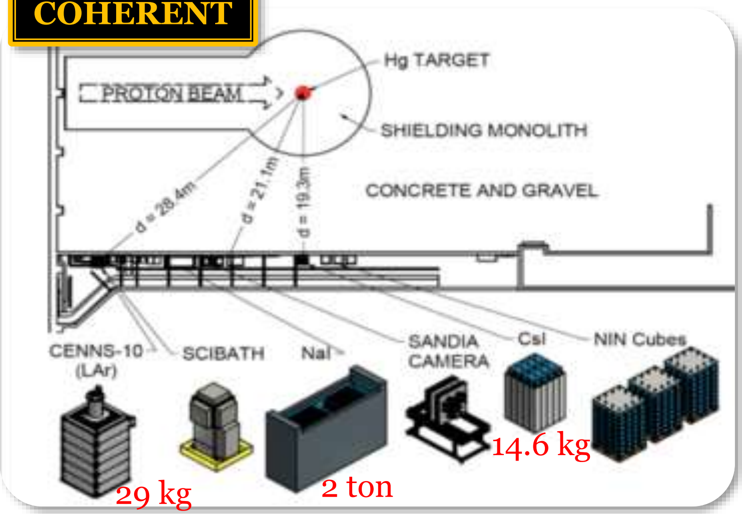
❖ Various current/future Coherent Elastic ν-Nucleus Scattering (CEνNS) experiments

- ✓ Beam-induced ν: CCM, COHERENT, (JSNS²), …
- ✓ Reactor ν: CONNIE, CONUS, MINER, NEON, Nu-Cleus, ν GEN, RED-100, Ricochet, TEXONO, …

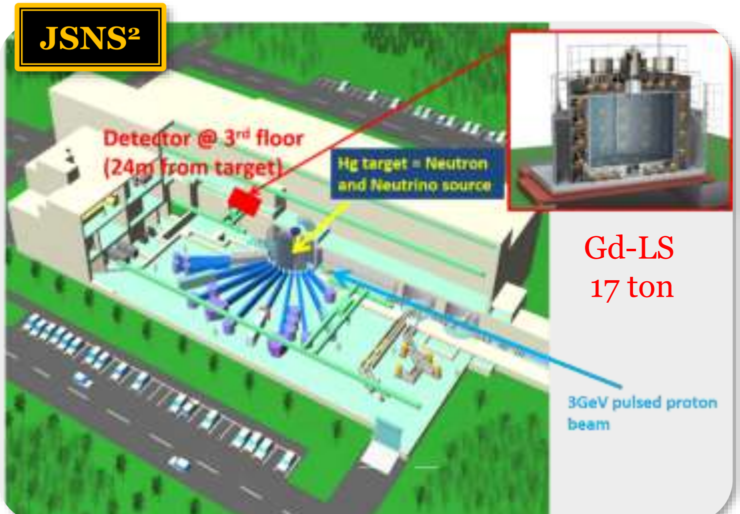


CEνNS Experiments: Beam-induced

COHERENT

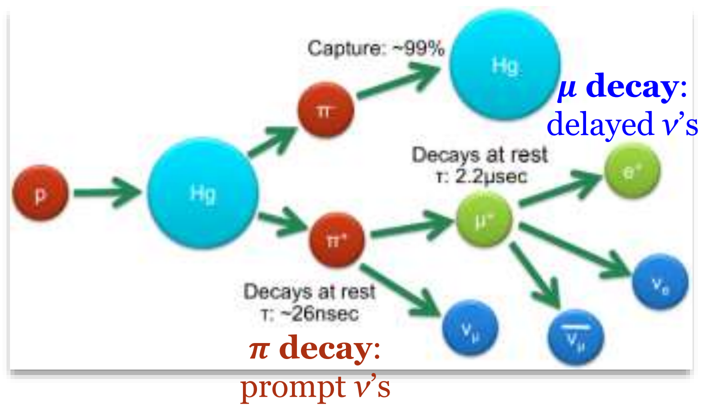


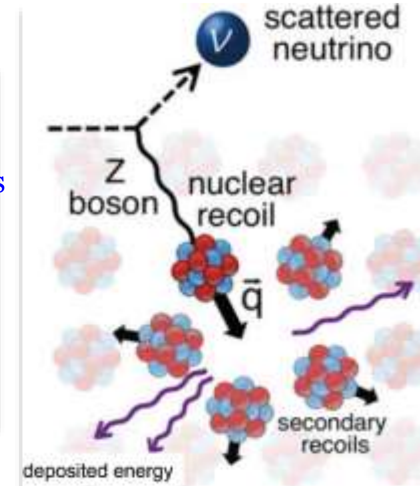
JSNS²



- ❖ Main goal: direct measurement of coherent elastic ν-nucleus scattering (CEνNS)

  ➔ dominant interaction for $E_\nu < 100$ MeV



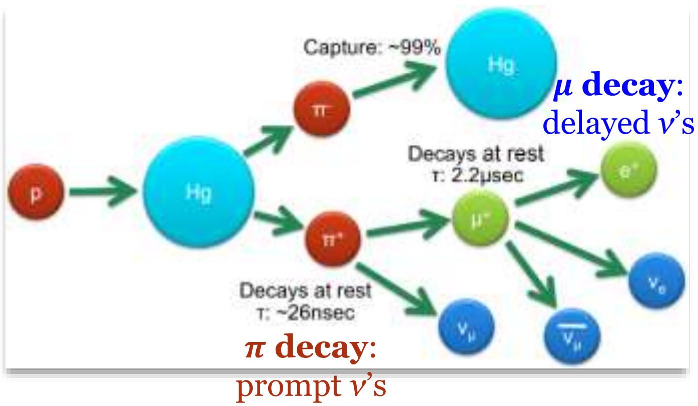


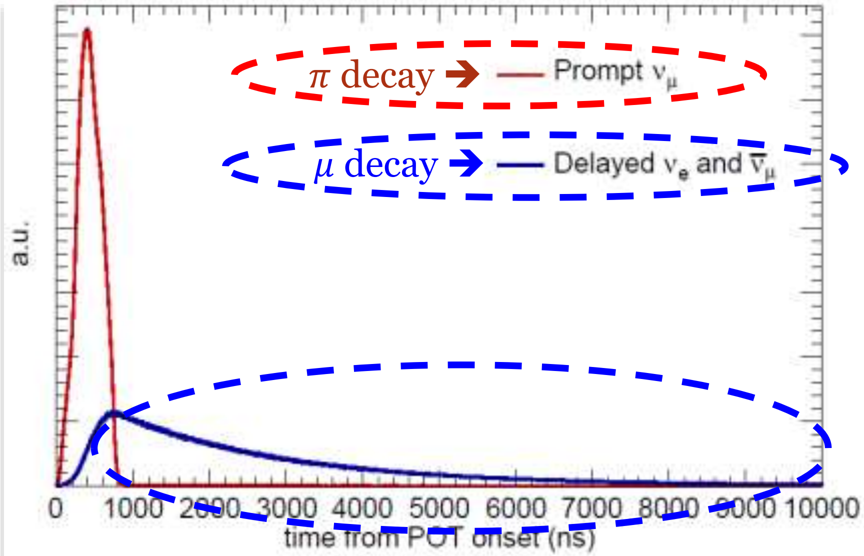
- ✓ COHERENT: 1 GeV p beam on Hg target, 360 ns FWHM (pulse duration) & 60 Hz, $\sim 5 \times 10^{20}$ POT/day
- ✓ (JSNS²): 3 GeV p beam on Hg target, two 100 ns pulses separated by 440 ns & 25 Hz, 1.8×10^{20} POT/day

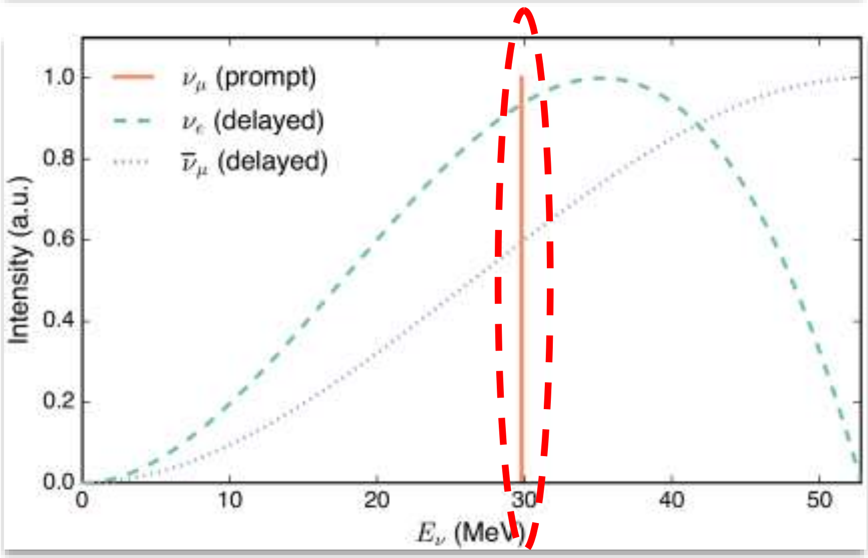
(POT: protons-on-target)

COHERENT [arXiv:1803.09183] & JSNS2 [arXiv:1705.08629]

CEνNS Experiments: E/T-Spectra of ν





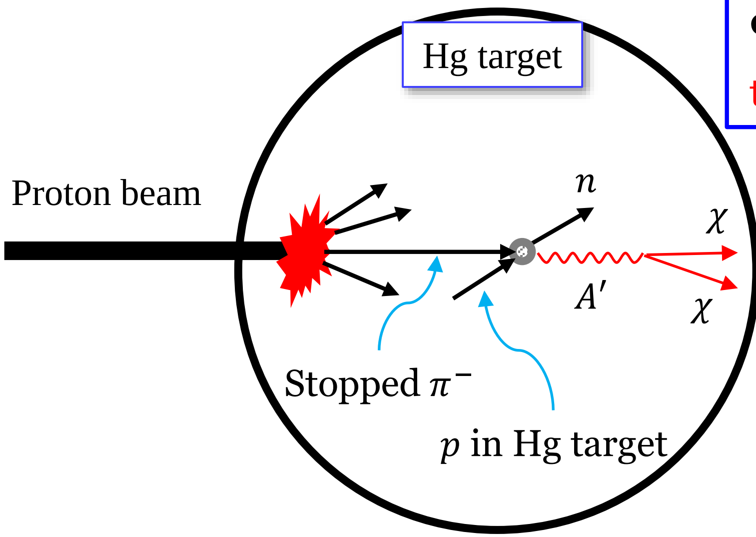


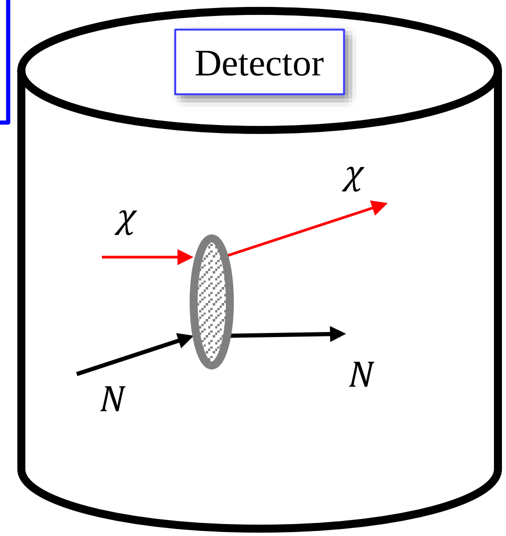
- ✓ Prompt ν's: $T < \sim 1\ \mu s$ & $E_\nu = 29.8$ MeV
- ✓ Delayed ν's: mostly $T > \sim 1\ \mu s$ & $E_\nu = 0 - 53$ MeV (mostly $> \sim 30$ MeV)

COHERENT [arXiv:1803.09183 & 1804.09459]

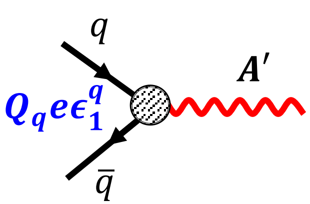
CEνNS Experiments: DM Searches

Probe dark mediator (A') decay into DM utilizing timing measurements!

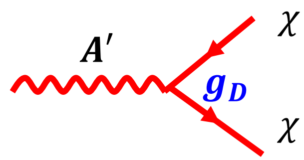




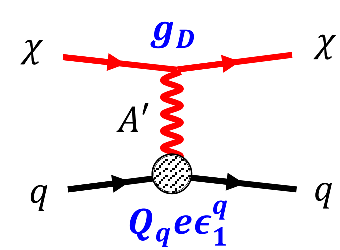
$\pi^- + p \to n + \gamma/\boldsymbol{A'}$ (capture)
[arXiv:1505.07805]



$\boldsymbol{A'} \to \chi + \chi$

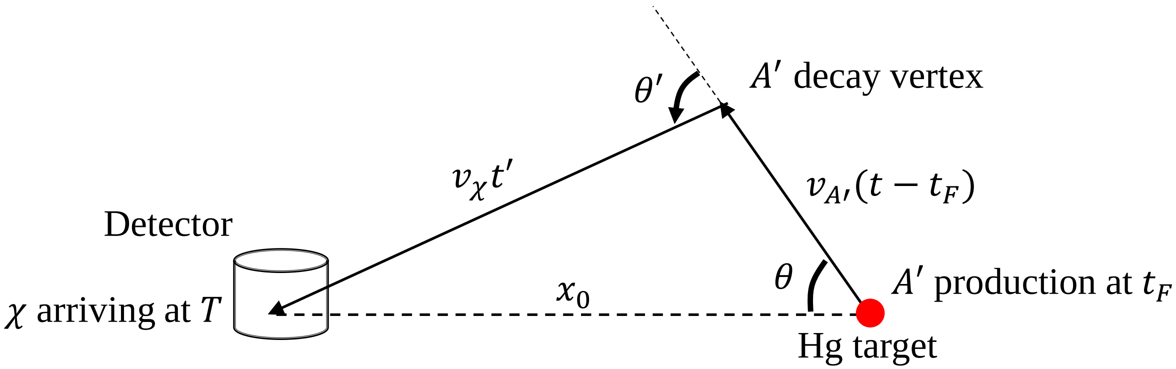


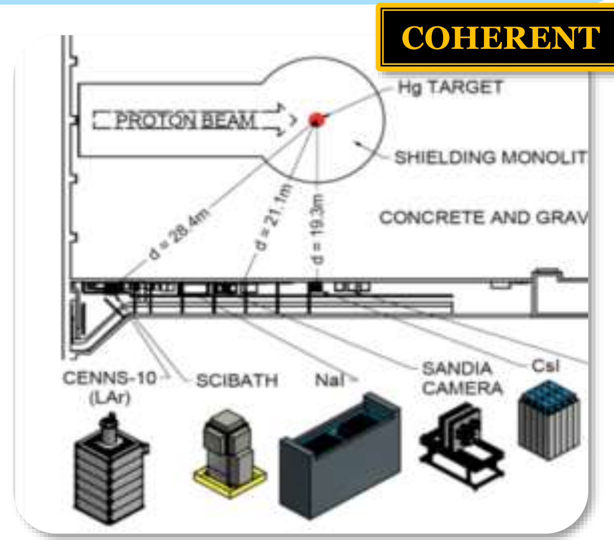
$\chi + N \to \chi + N$



- Other (subdominant) production processes: $\pi^0 \to \gamma + \gamma/\boldsymbol{A'}$ (via conventional direct π^0 production), $\pi^{-/+} + p/n \to \pi^0 + n/p$ & $\pi^0 \to \gamma + \gamma/\boldsymbol{A'}$ (charge exchange)

Timing Spectra of DM Events





Dark matter flux at the detector: $f(T) = dN_\chi/dT$

$$f(T) = \int_{-1}^{1} d\cos\theta \int_0^{t_F^{\max}} dt_F \left|\frac{dT}{dt}\right|^{-1} \frac{d^2N_{A'}}{dt\,d\cos\theta} \cdot w(\cos\theta') \cdot \mathcal{F}(t_F)$$

Model of π^- production timing ($\propto$ POT)

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

t'

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

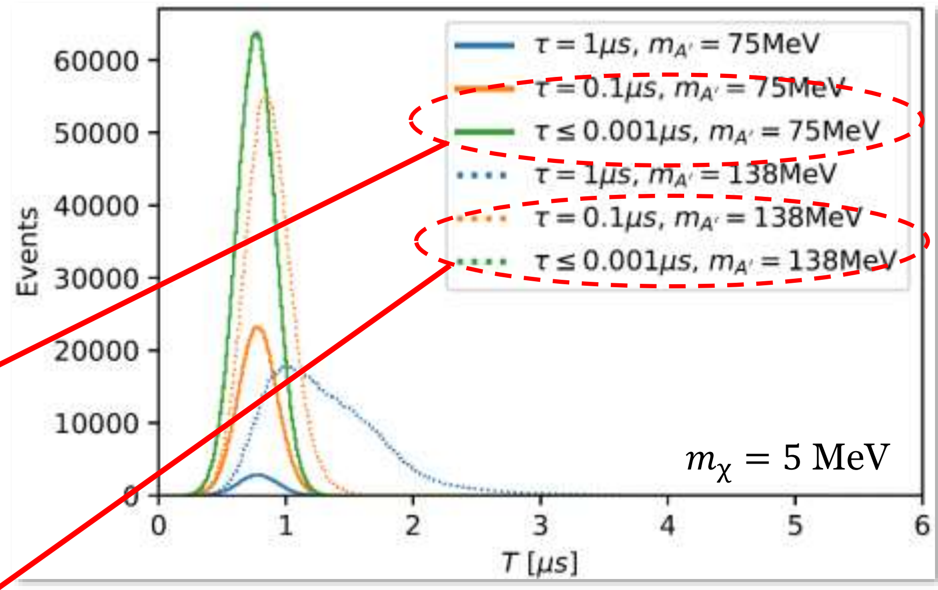
$$w(\cos\theta') = \frac{1}{2\pi(v_\chi t')^2}\left|\frac{d\cos\theta'}{d\cos\theta^*}\right|^{-1}\frac{dN_{A'\to\chi}}{d\cos\theta^*}$$ $\leftarrow$ Probability that DM travels towards the detector

Cf.) Search strategy with timing information at the LHC [arXiv:1805.05957]

Timing Spectra: Dark Photon Scenario

❖ Various possibilities for a dark photon A'

- ✓ Relativistic (solid) vs. Non-relativistic (dotted)
- ✓ Short-lived vs. Long-lived



➢ Relativistic:

DM flux maximized for $\tau <$ a few $\times$ 10 ns

➢ Non-relativistic:

only for $m_{A'} \approx 138$ MeV ($\approx m_{\pi^-} + m_p - m_n$),

DM flux maximized for $\tau <$ a few ns

➢ m_χ: 5 MeV is assumed,

but OK for any values $< m_{A'}/2$

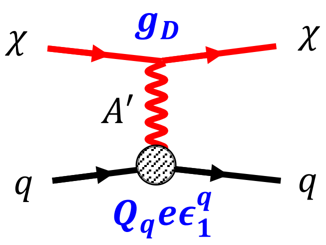
DM Scattering vs Production Parameters

❖ DM scatters off nucleus

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

❖ In general, the scattering could be mediated by a different particle,

e.g., gauged $U(1)_B$ gauge boson:



DM Scattering vs Production Parameters

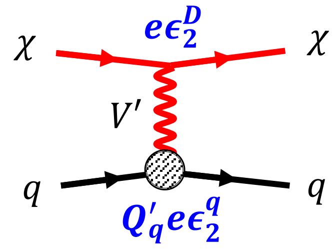
❖ DM scatters off nucleus

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

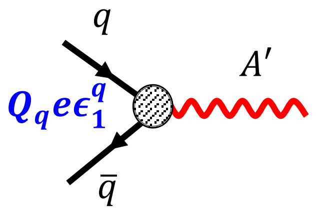
❖ In general, the scattering could be mediated by a different particle,

e.g., gauged $U(1)_B$ gauge boson:

$$A' \to V', m_{A'} \to M', Q_q e\epsilon_1^q \to Q'_q e\epsilon_2^q, g_D = e\epsilon_1^D \to e\epsilon_2^D$$



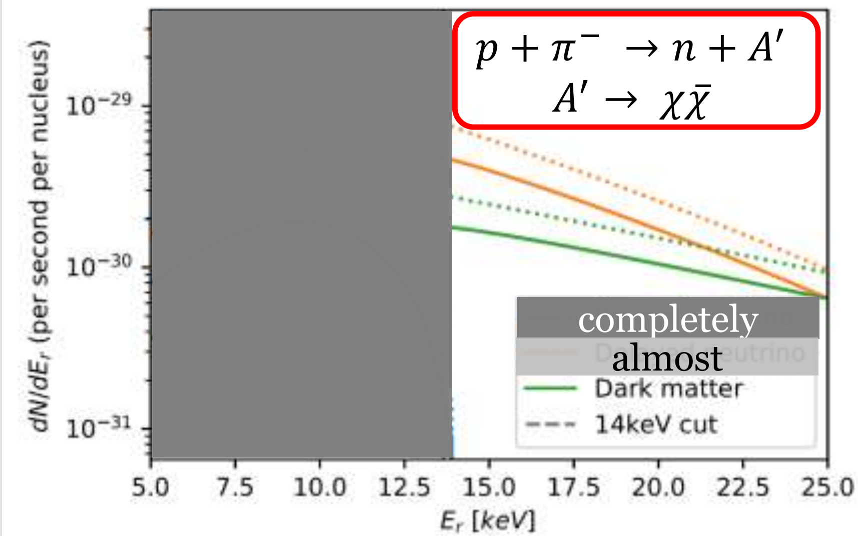
❖ Dark photon A' production to DM scattering can be described by two variables.

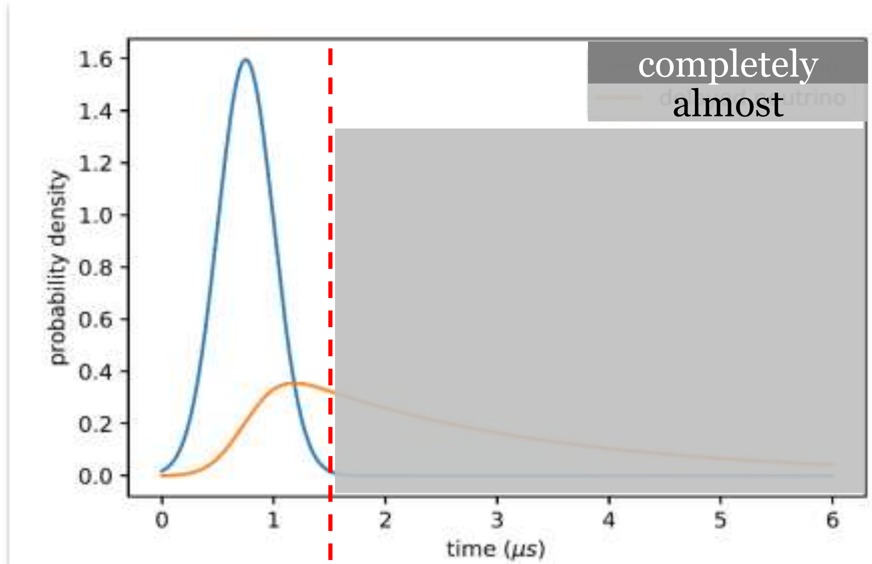


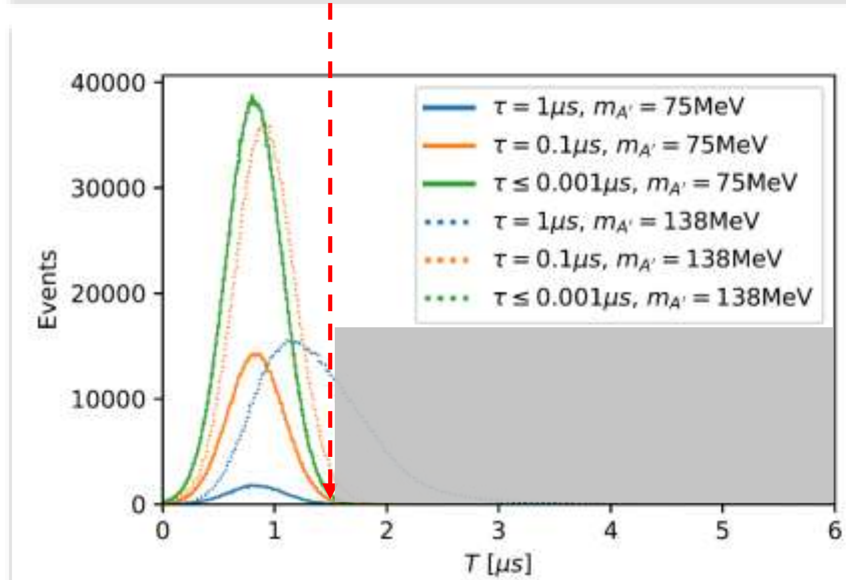
$$\epsilon \equiv \epsilon_1^q \epsilon_2^q \epsilon_2^D \sqrt{\mathrm{BR}_{A'\to\chi\chi}} \text{ and } M'$$

Proposed Search Strategy: *E* & *T*-cuts

for CsI







- $E_r > 14$ keV ($E_r^{max} \simeq 2E_\nu^2/M_T$ for CsI)
  - ✓ Prompt ν: **completed** removed
  - ✓ Delayed ν (& DM signal): still remains
- $T < 1.5$ μs
  - ✓ Delayed ν: **almost** removed
  - ✓ DM signal: **still remains**

Application to Existing Data

- Data released by COHERENT: CsI detector ➔ 14.57 kg×308.1 days [arXiv:1804.09459]
- Analysis scheme
  - ✓ Fix the average rms radius of the neutron distribution to $R_n = 4.7$ fm
  - ✓ 14 keV $< E_r <$ 28 keV & $T < 1.5$ μs

$$F_N^{\text{Helm}}(q^2) = \frac{3 j_1(qR_0)}{qR_0} \exp\left(-\frac{q^2 s^2}{2}\right)$$
$$R_n^2 = 3R_0^2/5 + 3s^2$$

97 : total events
– 49 : classified as steady-state (SS) backgrounds
– 19 : identified as delayed (SM) neutrino events (due to E_r & T-cuts)
– 0 : identified as prompt (SM) neutrino events (due to E_r-cut)
– 3 : beam-related neutron (BRN) backgrounds

---

26 : "Excess!!"

Significance ($R_n = 4.7$ fm): **$2.4\,\sigma$**
Significance ($R_n = 5.5$ fm): **$3.0\,\sigma$**

$$\text{Significance} = \frac{\text{Excess}}{\sqrt{2\text{SS}+\text{BRN}+\text{SM}}}$$ [arXiv:1801.05546]

[arXiv:1801.05546]

DM Search Efforts by COHERENT

Sensitivity of the COHERENT Experiment to Accelerator-Produced Dark Matter

COHERENT Collaboration
[arXiv:1911.06422]

The COHERENT experiment is well poised to test sub-GeV dark matter models using low-energy recoil detectors sensitive to coherent elastic neutrino-nucleus scattering (CEvNS) in the π-DAR neutrino beam produced by the Spallation Neutron Source. We show how a planned 750-kg liquid argon scintillation detector would place leading limits on scalar light dark matter models, over two orders of magnitude of dark matter mass, for dark matter particles produced through vector and leptophobic portals in the absence of other effects beyond the standard model. The characteristic timing structure of a π-DAR beam allows a unique opportunity for constraining systematic uncertainties on the standard model background in a time window where signal is not expected, enhancing expected sensitivity. Additionally, we discuss future prospects, further increasing the discovery potential of CEvNS detectors. Such methods would test the calculated thermal dark matter abundance for all couplings $\alpha' \leq 1$ within the vector portal model over an order of magnitude of dark matter masses.

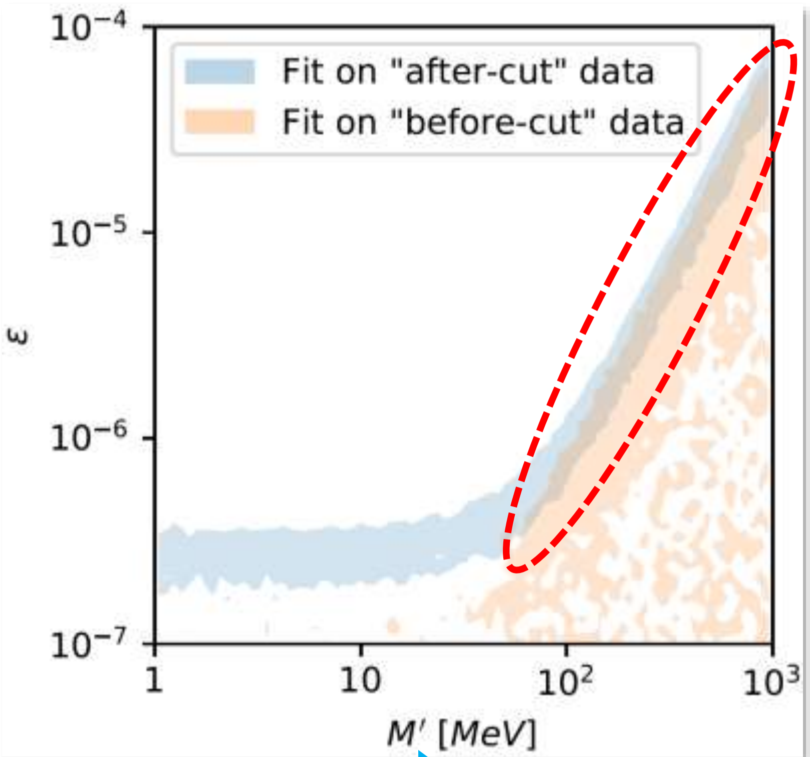
model. A recent analysis of released COHERENT CsI data [13] hints at a roughly 2σ excess in the region where dark matter scatters would be expected, suggesting this is an exciting area to pursue.

Our Work!

[arXiv: 1906.10745]

Excess? DM Interpretation

❖ Fits to the data after the cuts vs. before cuts (=the full data)



$$\epsilon = \epsilon_1^q \epsilon_2^q \epsilon_2^D \sqrt{\mathrm{BR}_{A' \to \chi\chi}}$$

The mass of the DM-nucleus interaction mediator

➢ Baseline model point for the figure in the left:

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

➢ Nevertheless, the figure holds for

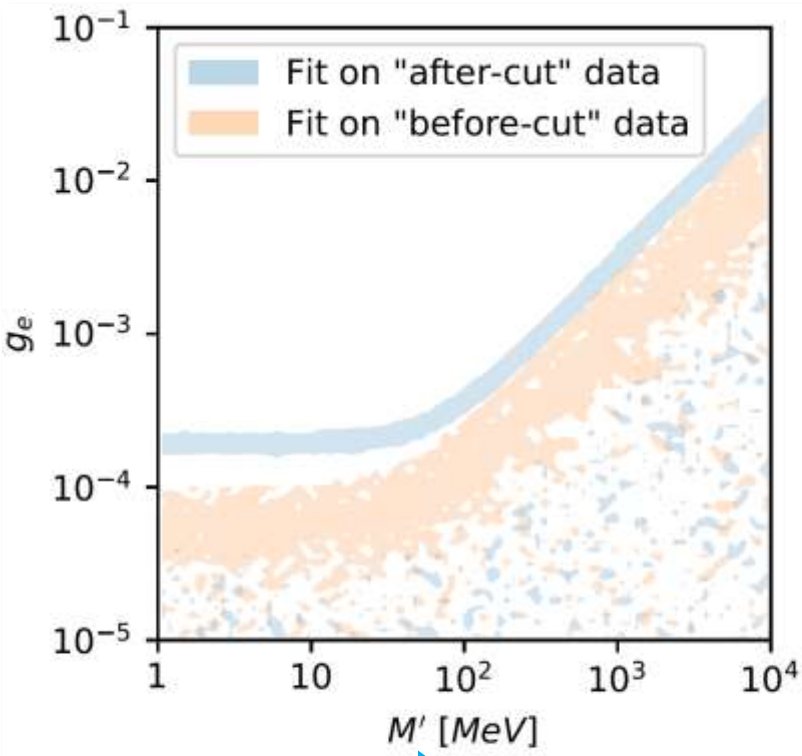
✓ $\tau \lesssim 4$ ns, $m_{A'} < 138$ MeV

✓ $\tau \lesssim 30$ ns, $m_{A'} \cong 138$ MeV (non-relativistic dark photon case)

✓ Any $m_\chi < m_{A'}/2$

Excess? Alternative - NSI Interpretation

❖ An example alternative new physics possibility: non-standard interaction (NSI) of ν

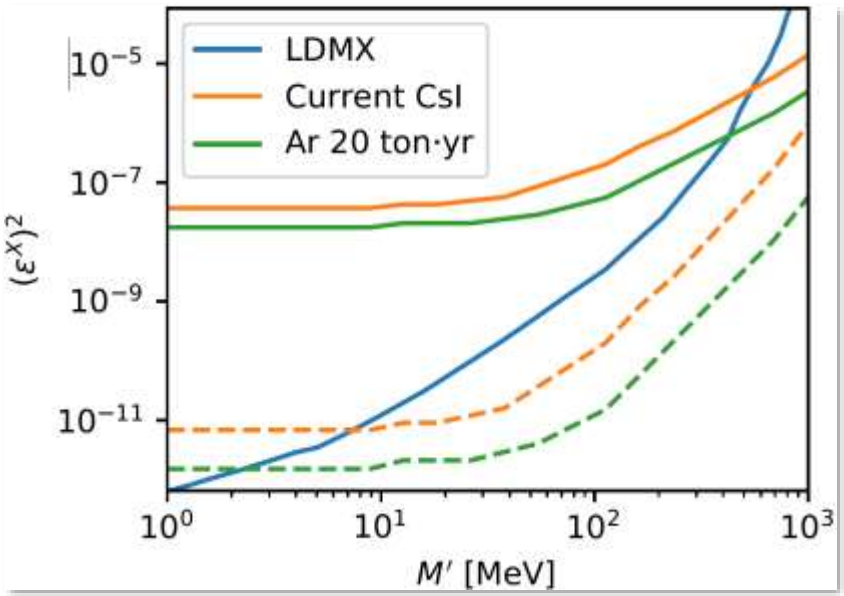


The mass of the new ν_e interaction mediator

- ✓ Benchmark case: non-zero coupling g_e, the NSI in the ν_e neutral-current interaction (along with a new mediator).
  - ➔ No overlapping regions, especially the prompt timing bin (i.e., $T < 1.5\ \mu$s) doesn't show a good fit. NSI affects the overall normalization of neutrino flux!
- ✓ The situation becomes even worse with $g_\mu \neq 0$, since it affects not only the delayed but the prompt spectrum.

No Excess? Constraining Parameters

❖ Assuming no excess is observed, we can constrain parameter space.



- ✓ $\alpha_D \equiv \frac{(e\epsilon_2^q)^2}{4\pi} = 0.5$
- ✓ M': the mass of the DM-nucleus interaction mediator
- ✓ Solid orange and green lines: single mediator scenario, i.e., $\epsilon^X = \epsilon_1^q = \epsilon_2^q$
- ✓ Dashed orange and green lines: multi-mediator scenario. One of them is fixed to 10^{-2} (e.g., gauged $U(1)_B$ gauge boson)
- ✓ For LDMX, ϵ^e in [arXiv:1808.05219] identified as ϵ^X.
- ✓ Sensitivity reach is already better than DUNE, compared to the result in [arXiv:1903.10505].

Conclusion

- No firm signal observation at conventional DM searches motivates us to look into possibilities **other than WIMP**, e.g., light dark sector.
- A novel strategy to search for new physics signals: A combination of ***T* & *E*-cuts** can **efficiently eliminate SM ν BGs** at neutrino experiments, e.g., CEνNS.
- Application: the **measured CsI data** of the COHERENT experiment
- Result: $\mathbf{2.4 - 3\sigma}$ **excess**!

  ➔ The excess can be explained by DM arising from dark photon decay.
- Sensitivities of COHERENT: already better than DUNE & comparable to LDMX

Thank you