Searching for DM Signals from Timing Spectra @ ν Experiments

with B. Dutta, D. Kim, S. Liao, S. Shin & L. Strigari

[1906.10745 & 1910.xxxxx]

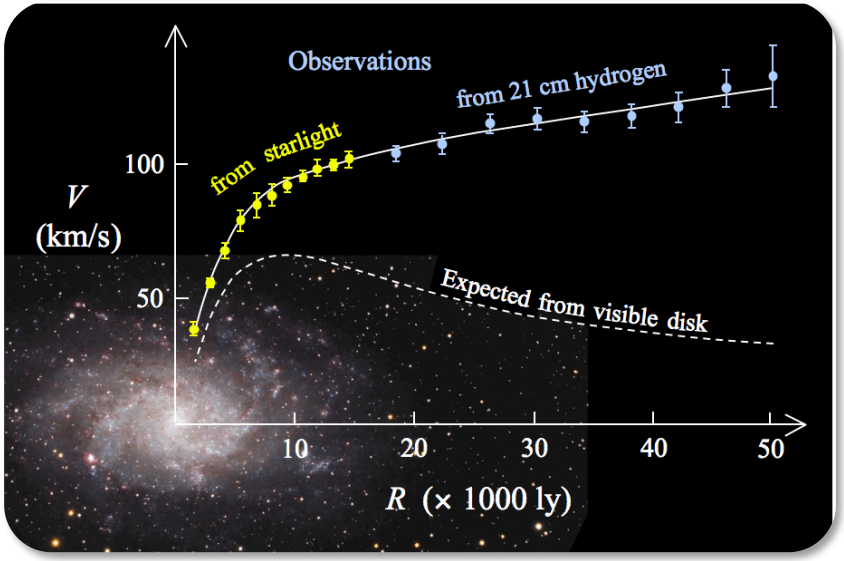
Jong-Chul Park

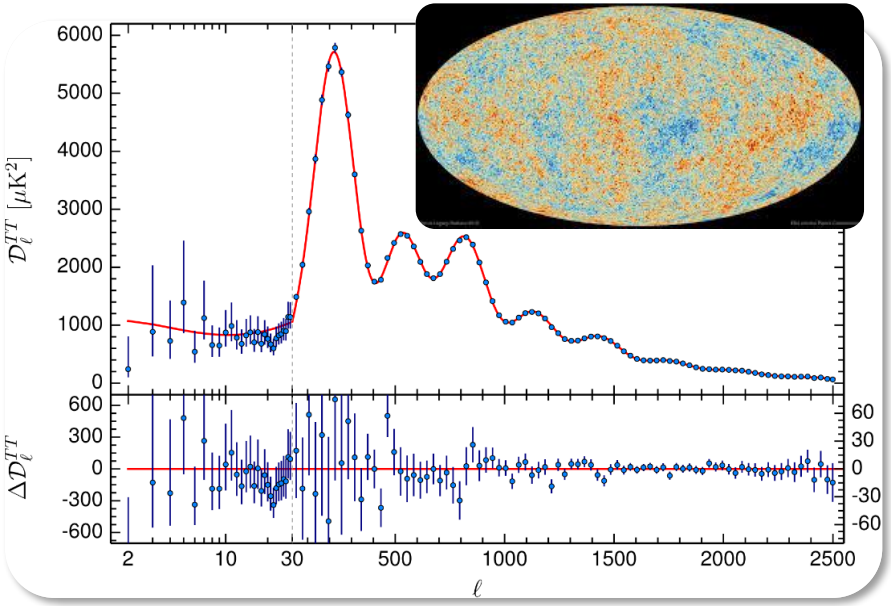
CNU 충남대학교 CHUNGNAM NATIONAL UNIVERSITY

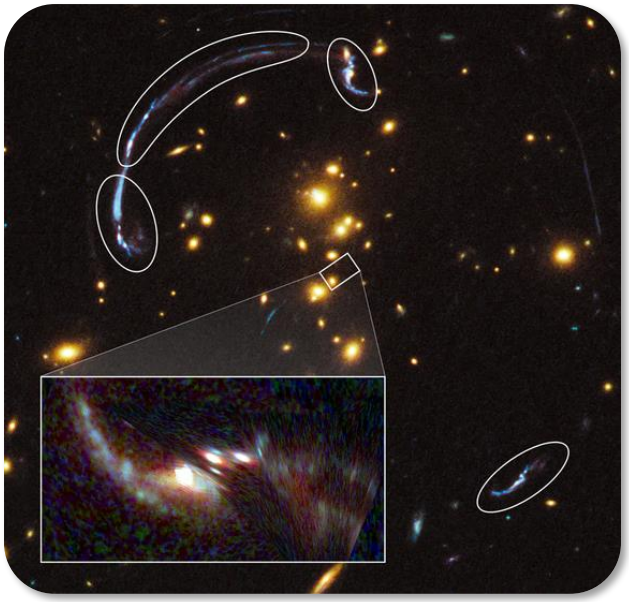
4th IBS-MultiDark-IPPP Workshop

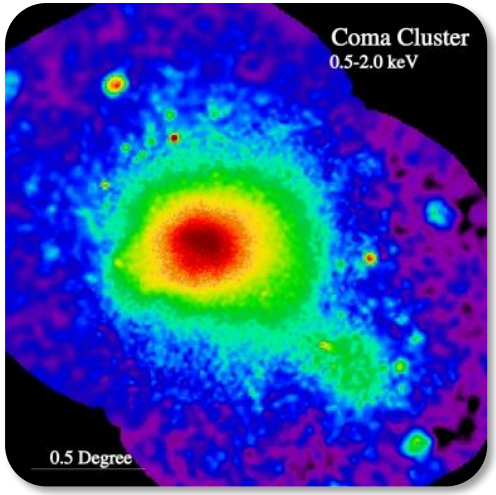
Oct. 11 (2019)

Observational Evidence for DM









Observational Evidence for DM

- ✓ Galaxy rotation curve
- ✓ Coma cluster
- ✓ Gravitational lensing
- ✓ Bullet cluster
- ✓ Structure formation
- ✓ Cosmic microwave background radiation (CMBR)
- ✓ Sky surveys
- ✓ Type Ia supervovae
- ✓ Baryonic acoustic oscillation (BAO)
- ✓ …

Classic Solution*: WIMP

Cosmological Lower Bound on Heavy-Neutrino Masses

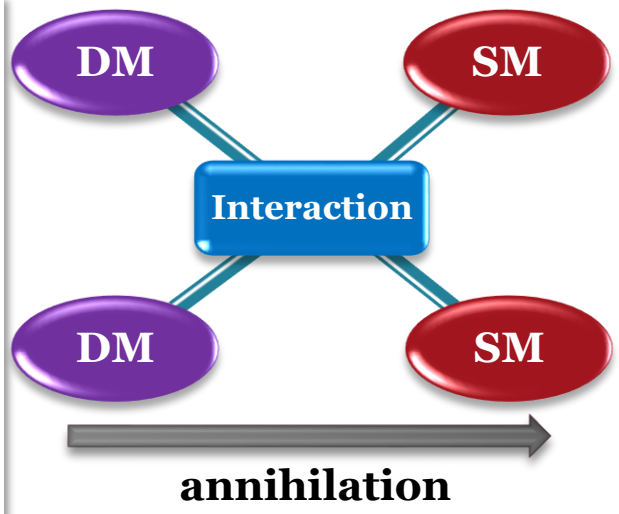
Benjamin W. Lee[(a)]
Fermi National Accelerator Laboratory,[(b)] *Batavia, Illinois 60510*

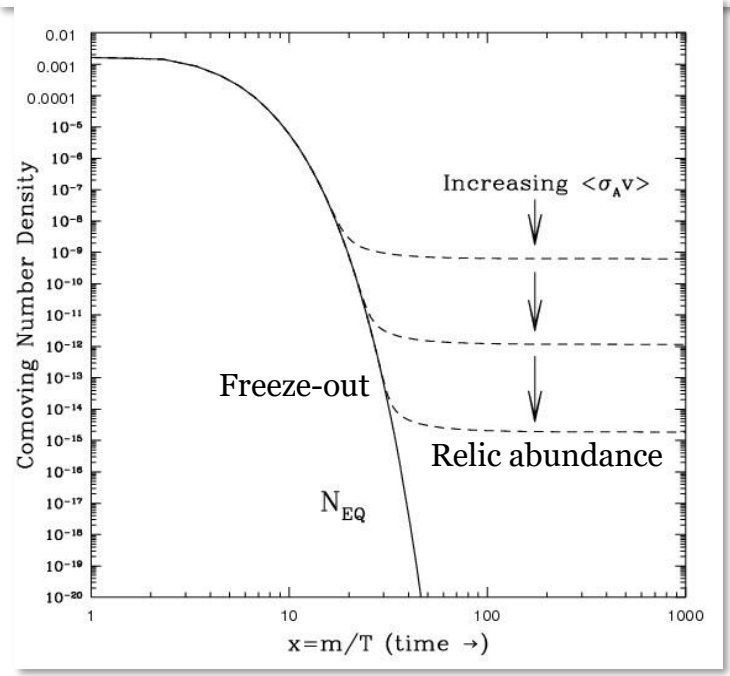
and

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:

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

- Weak coupling ➔ naturally weak scale mass:

  ~1 GeV – 10 TeV mass range favored

  ➔ weak scale (new) physics

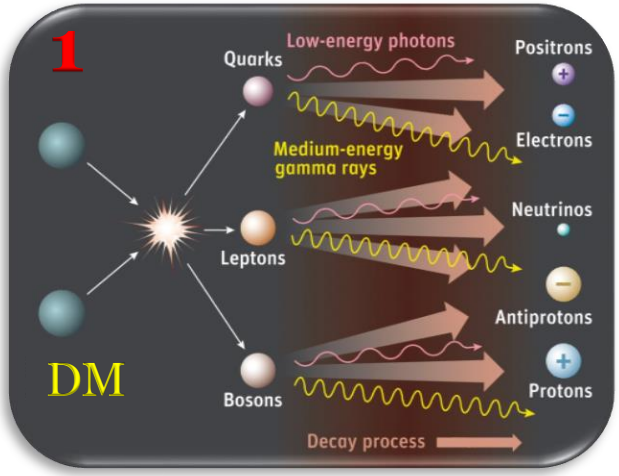
* Of course also **axion**: SungWoo's talk

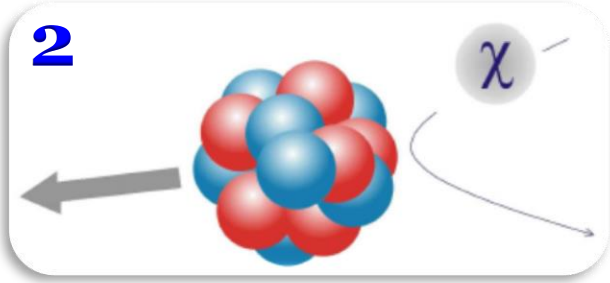
Observational Evidence for DM

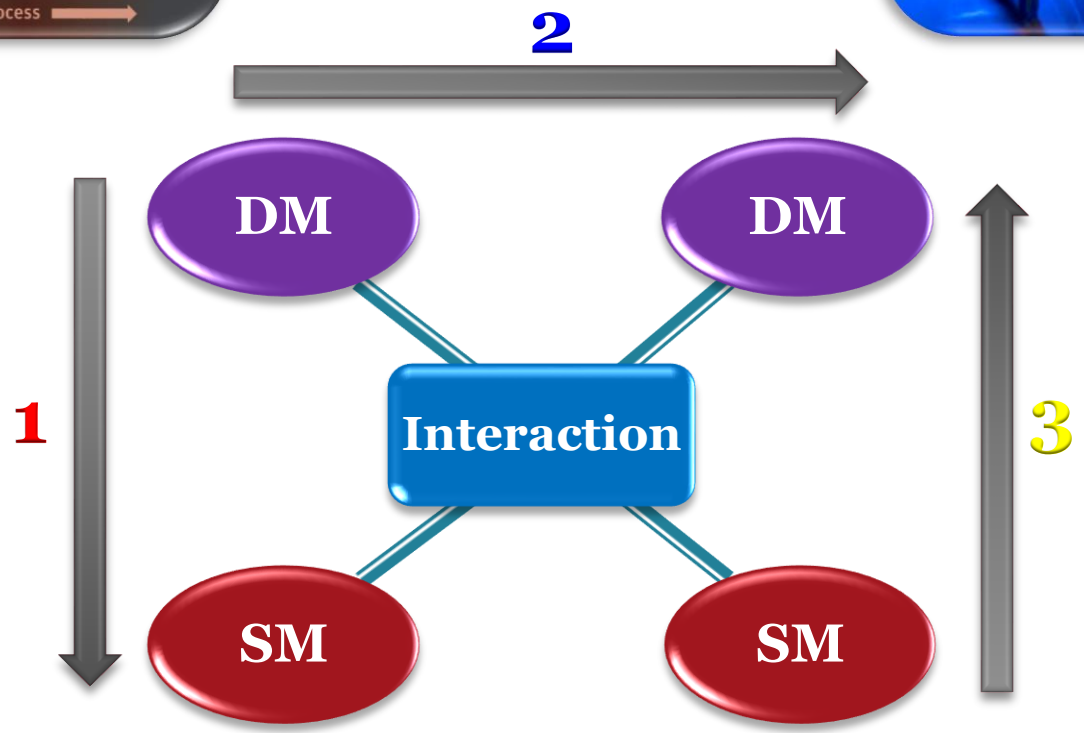
- ✓ Galaxy rotation curve
- ✓ Coma cluster
- ✓ Gravitational lensing
- ✓ Bullet cluster
- ✓ Structure formation
- ✓ Cosmic microwav… radiation (CMBR)
- ✓ Sky survey
- ✓ Type Ia supe… vae
- ✓ Baryonic acoustic oscillation (BAO)
- ✓ …

Only Gravitational

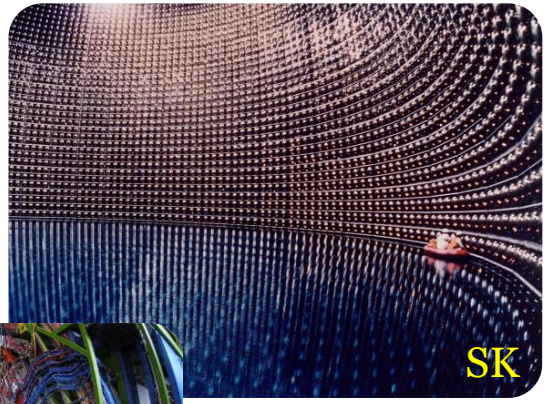
DM (WIMP) Search Strategies

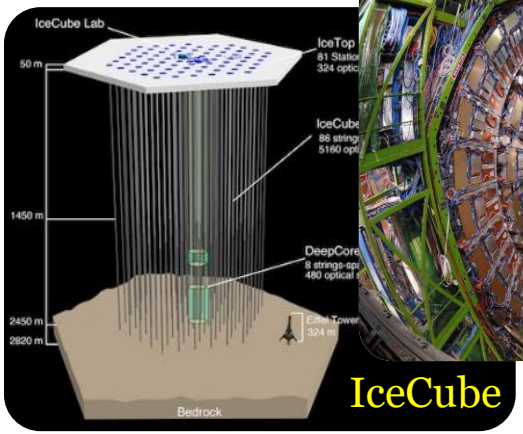


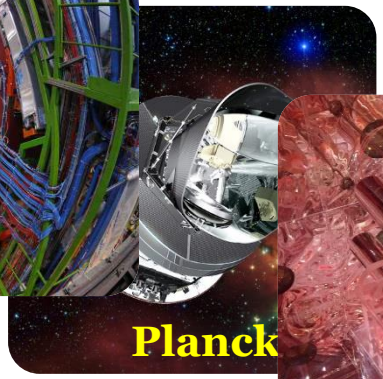


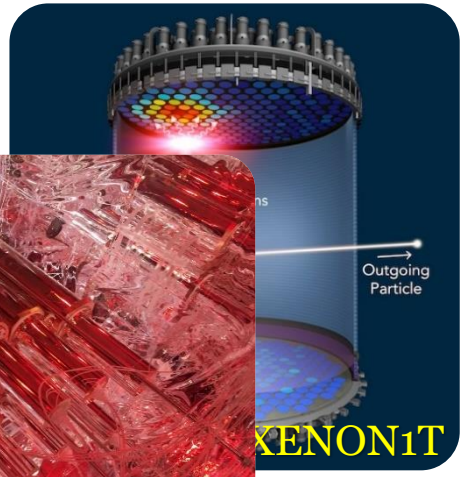


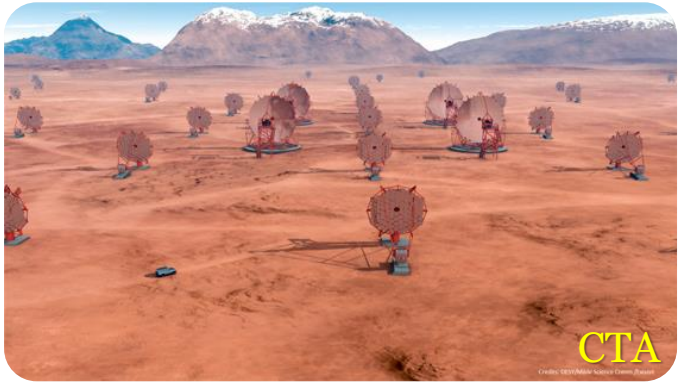
Diverging Efforts for WIMP Searches

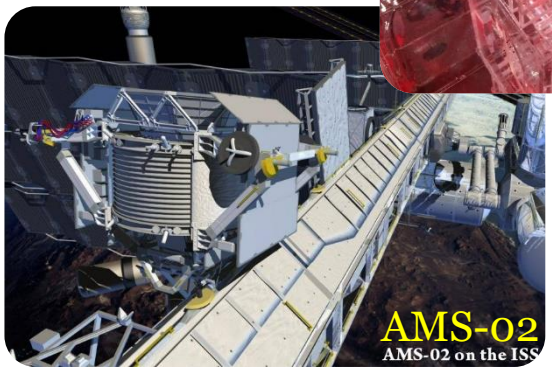


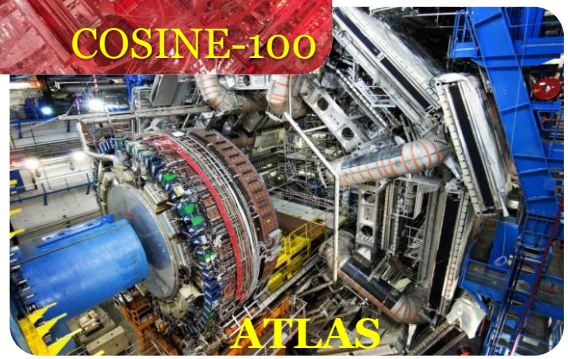




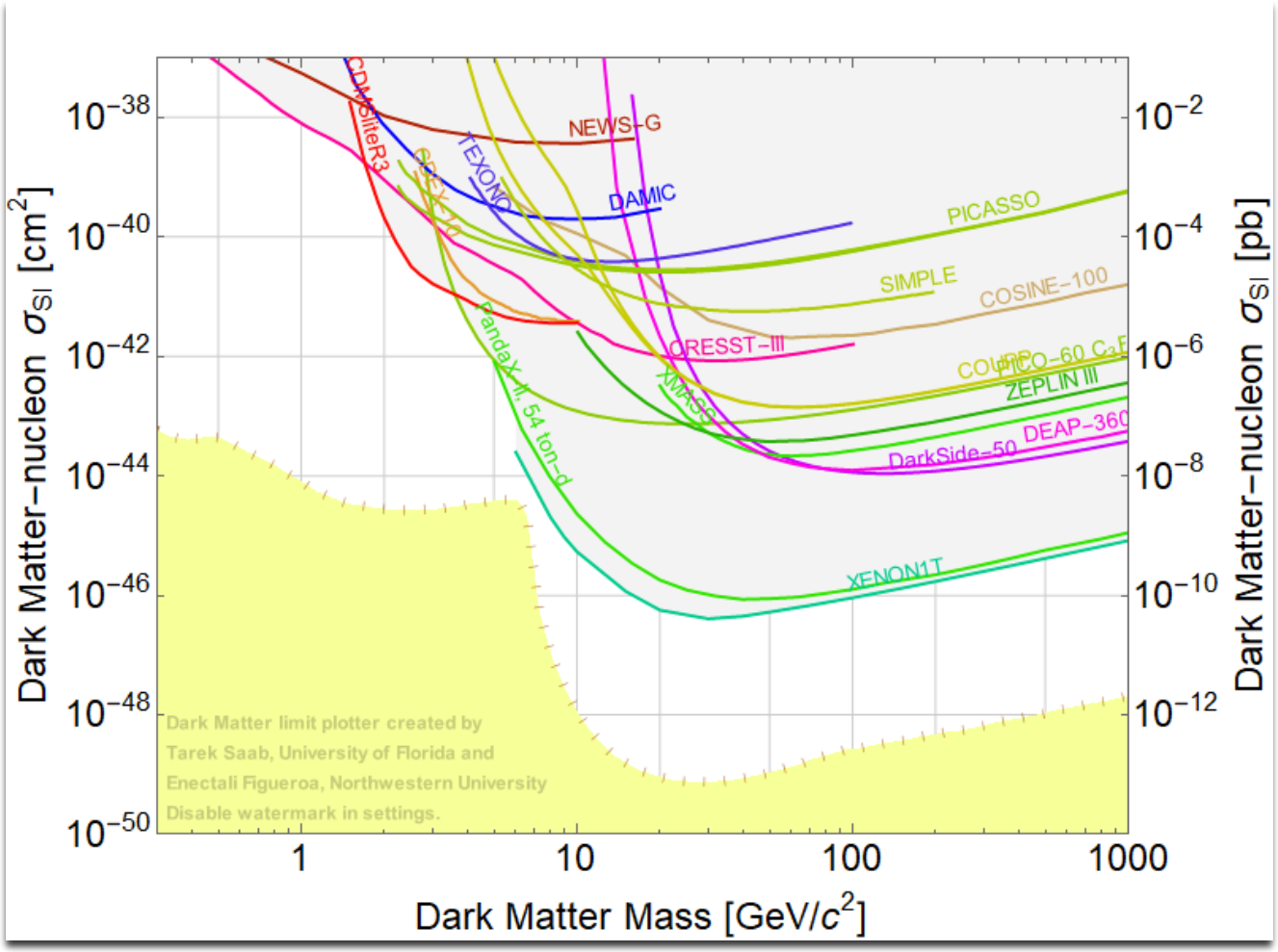






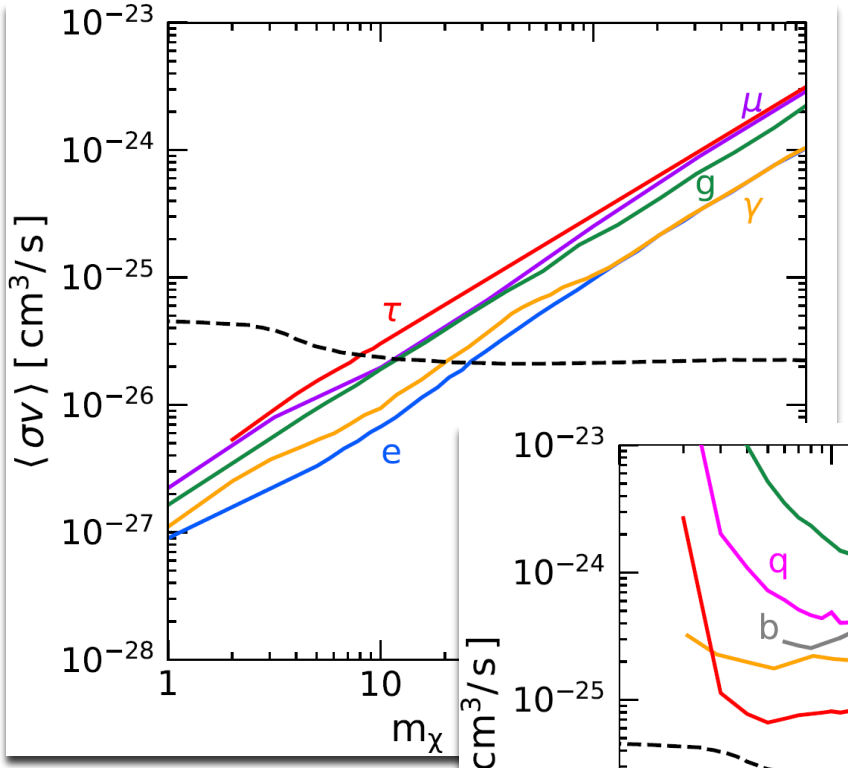


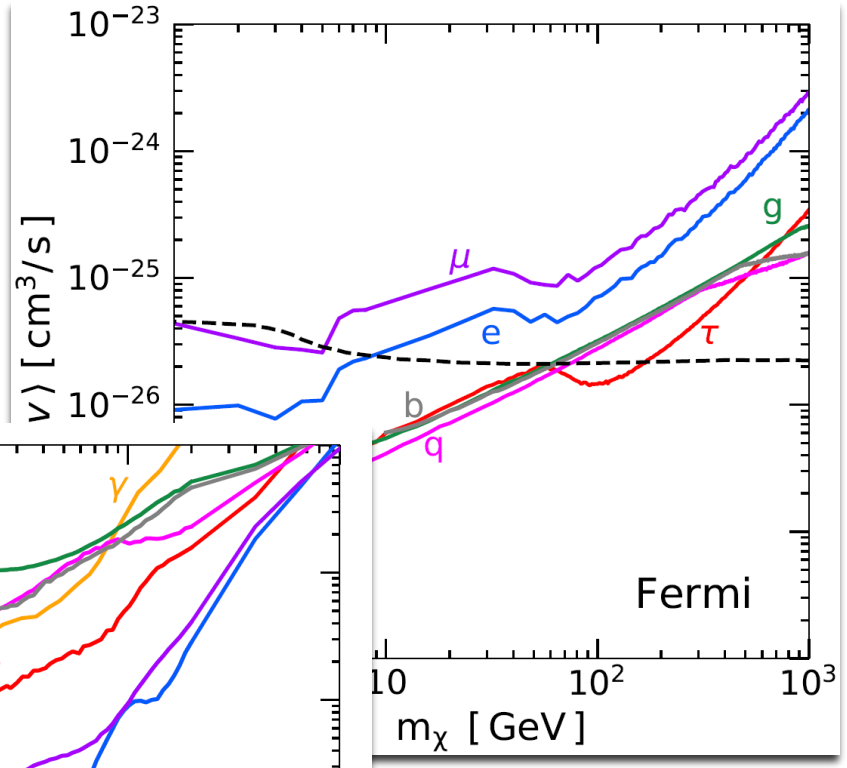
Current Status of Direct Searches

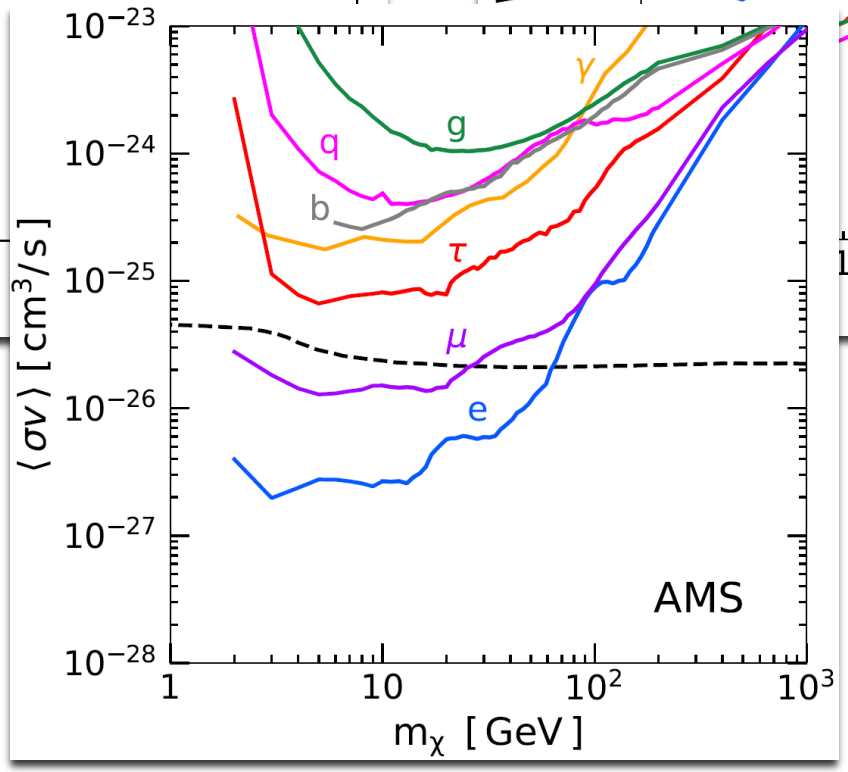


Dark Matter Limit Plotter v5.12, updated May 16, 2019

Current Status of Indirect Searches

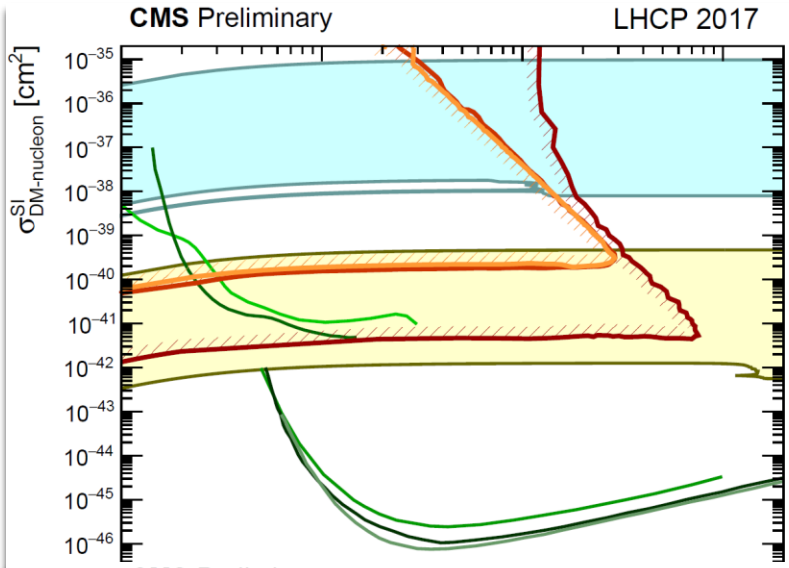


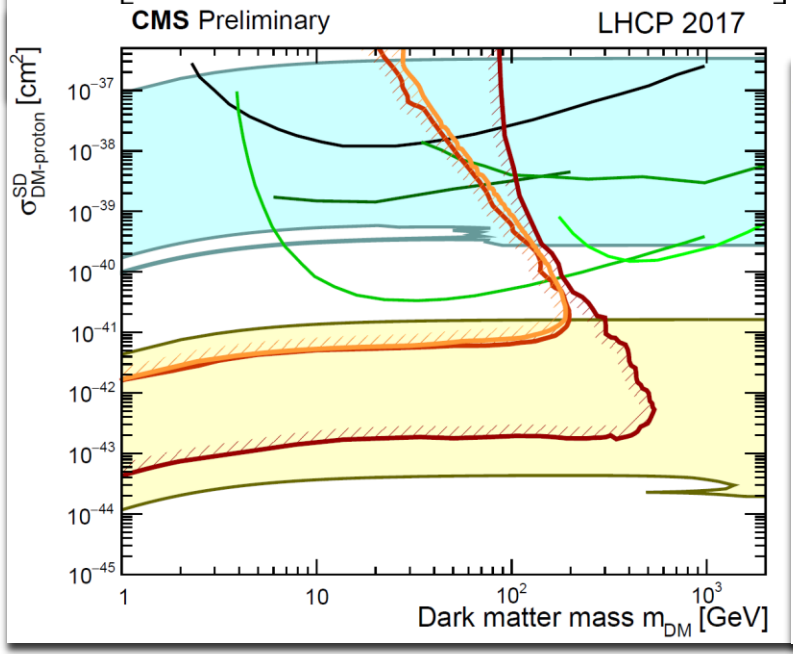


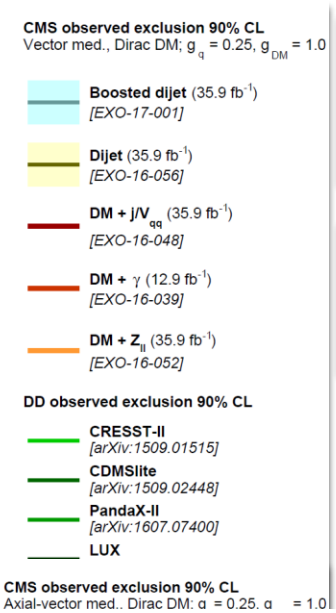


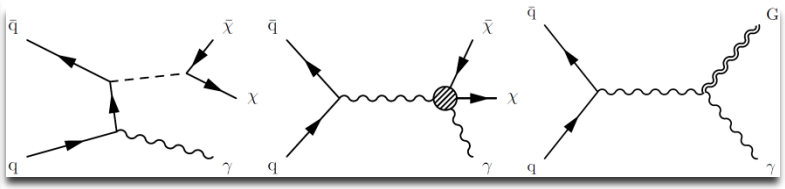
[arXiv: 1805.10305]

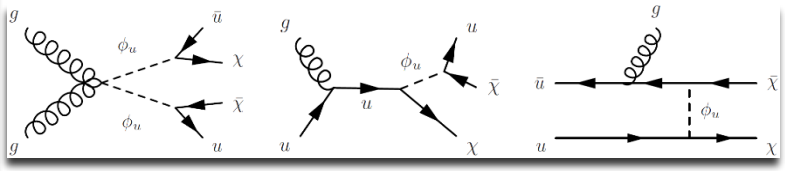
Current Status of LHC Searches

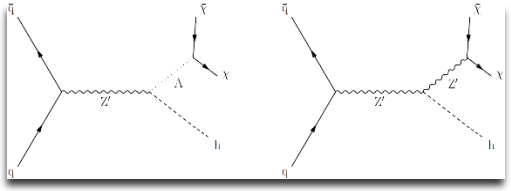


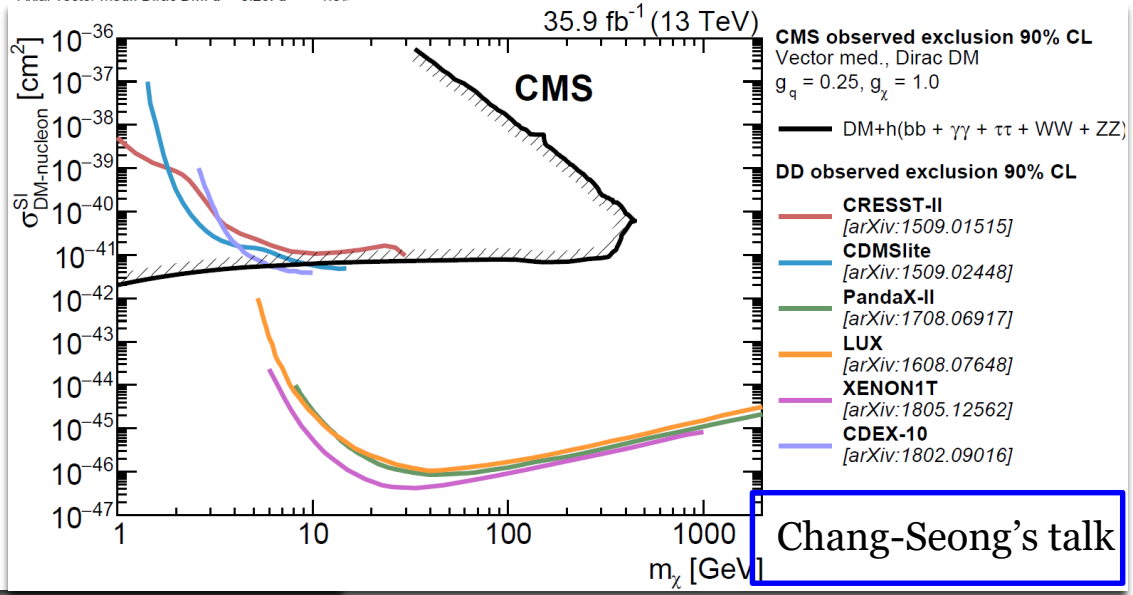




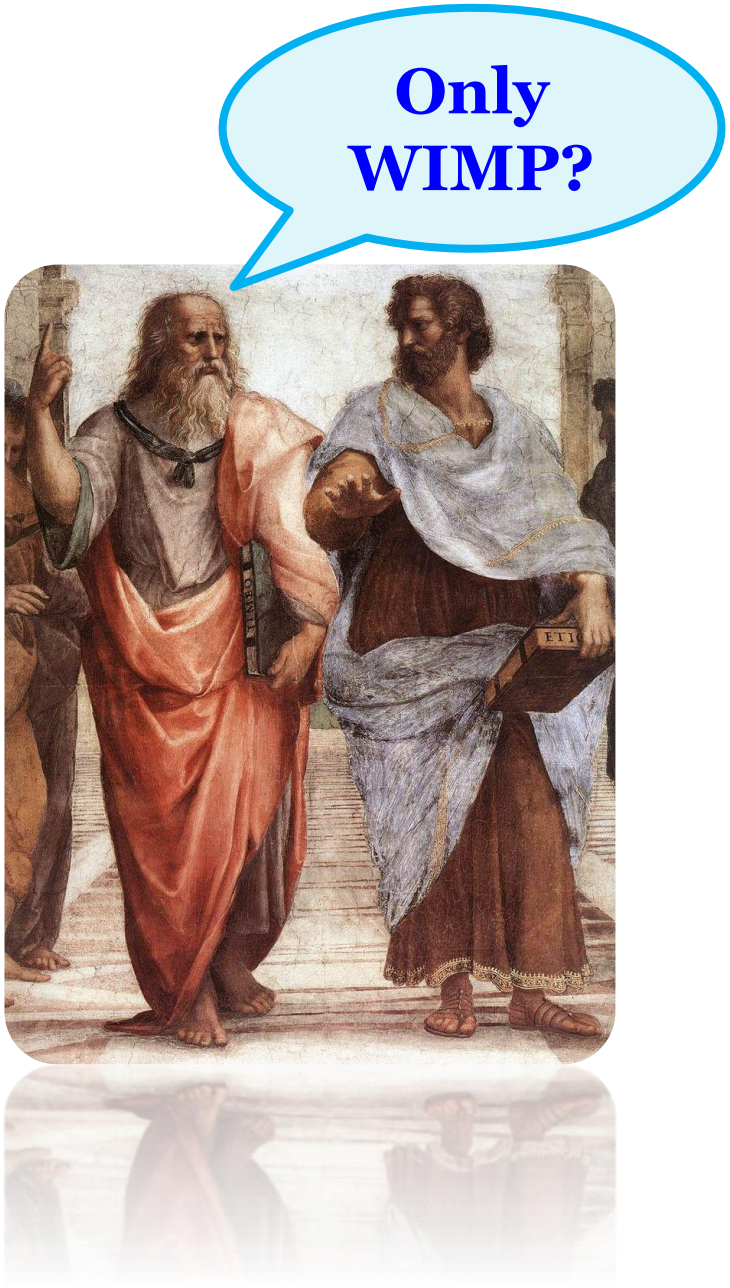






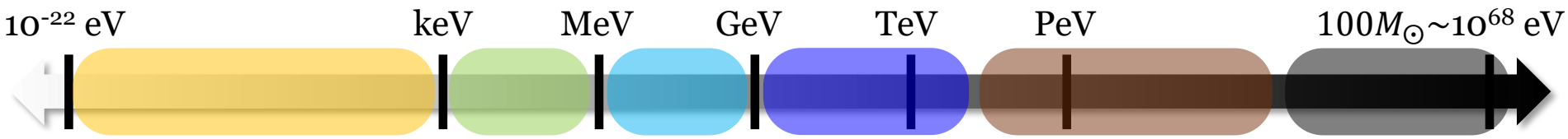


Chang-Seong's talk


Only
WIMP?

Very Very Wide DM Mass Range

Very Very Wide DM Mass Range



Ultralight
Scalar field
(QCD) Axion
Hidden photon
non-thermal

Superlight
WDM
Sterile ν
may be
thermal

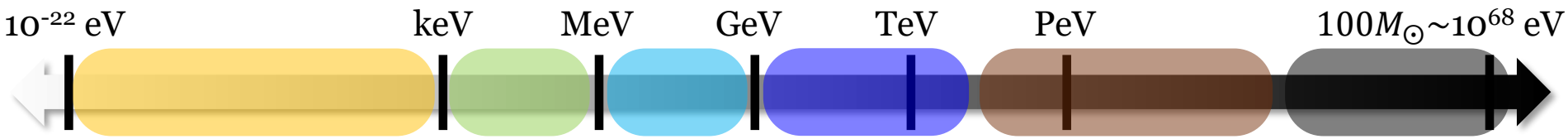
Light
particle
DM
can be
thermal

WIMP
well-
motivated
extensively
studied
thermal

Superheavy / Composite
WIMPzilla
Q-ball
Dark-quark
nugget
non-thermal

MACHO / Primordial BHs
non-particle

Very Very Wide DM Mass Range



Ultralight
Scalar field
(QCD) Axion
Hidden photon
non-thermal

KiYoung Choi
Kenji Kadota
SungWoo Youn
ChangSub Shin
EungJin Chun

Superlight
WDM
Sterile ν
may be
thermal

Light
particle
DM
can be
thermal

Carlos Munoz

Mathias Pierre

David Cerdeno
Stephen Lonsdale

WIMP
well-
motivated
extensively
studied
thermal

ChangHyon Ha
Maria Martinez
Stefano Scopel
Mario Gomez
ChangSeong Moon
Sven Heinemeyer
Osamu Seto
(Inaki Lara Perez)
(Manuel Masip)
(Eibun Senaha)

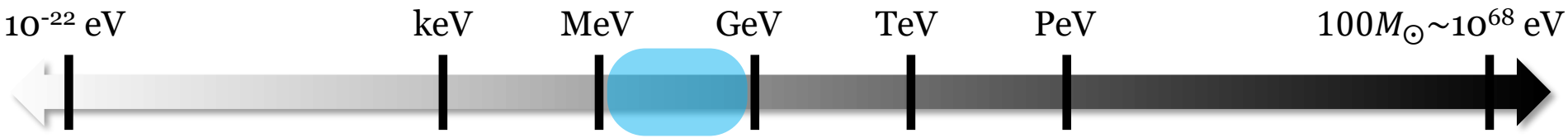
Superheavy
/ Composite
WIMPzilla
Q-ball
Dark-quark
nugget
non-thermal

Viviana Gammaldi
Carsten Rott

MACHO /
Primordial
BHs
non-particle

Daniele Gaggero

Light Dark-Sector Models

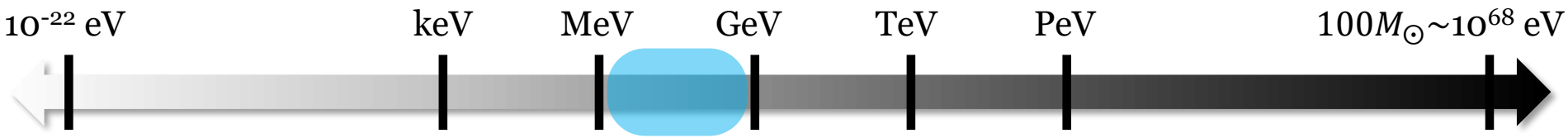


- For heavy mediator, $\langle\sigma v\rangle \sim \frac{\alpha_X^2 m_\chi^2}{M^4}$
- For weak scale physics, sub-GeV DM overproduction (Lee-Weinberg limit)➔ New mediator $< M_W$ for freeze-out or freeze-in
- Various light mediator scenarios:
  - ✓ Sommerfeld enhancement [arXiv:0810.0713]
  - ✓ $g-2$ 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]
- 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 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]
  - ✓ …

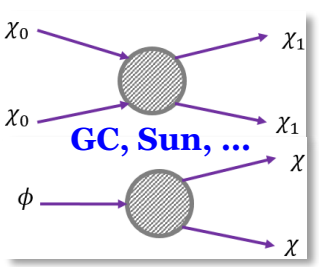
Light Dark-Sector Searches

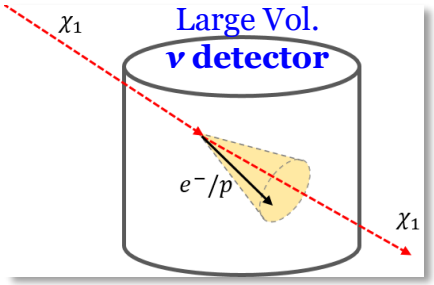


- $E_k \sim mv^2$ < keV with $v \sim 10^{-3}$ ➔ < E_{th} of typical DM direct detectors
- New ideas are required! ➔ graphene, superconducting target, nanowire, superfluid He, 3-D Dirac material, Polar material, … (w/ TES, MKID, SNSPD)

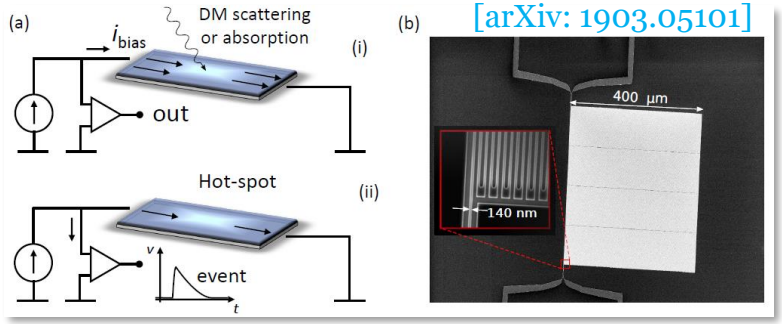
Light particle DM can be thermal

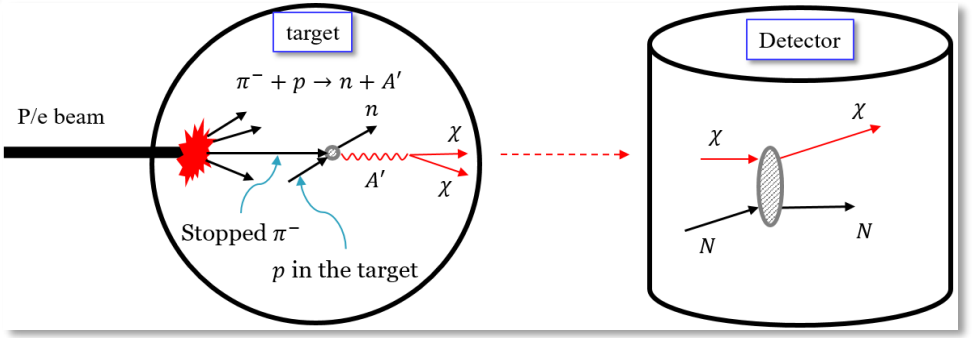
- Cosmogenic light DM searches: COSINE-100, DUNE, IceCube, ProtoDUNE, SK/HK, …





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





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

Summary!

- A novel strategy to search for new physics signals:

  we can **efficiently isolate** (light) DM signals **from the SM ν BGs** using **timing spectra** at (certain kinds of) neutrino experiments.

- Application: the measured CsI data of the COHERENT experiment

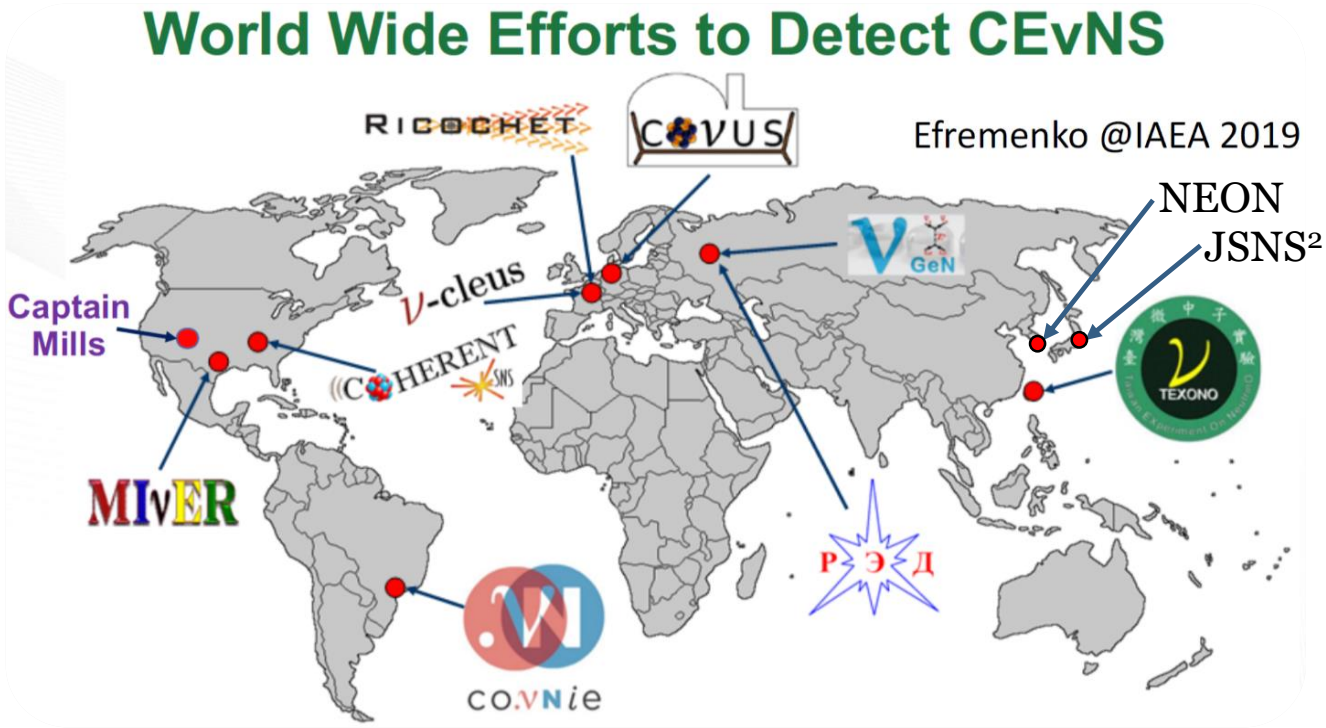
- Result: **$2.4-3\sigma$ excess**!

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

CEνNS Experiments

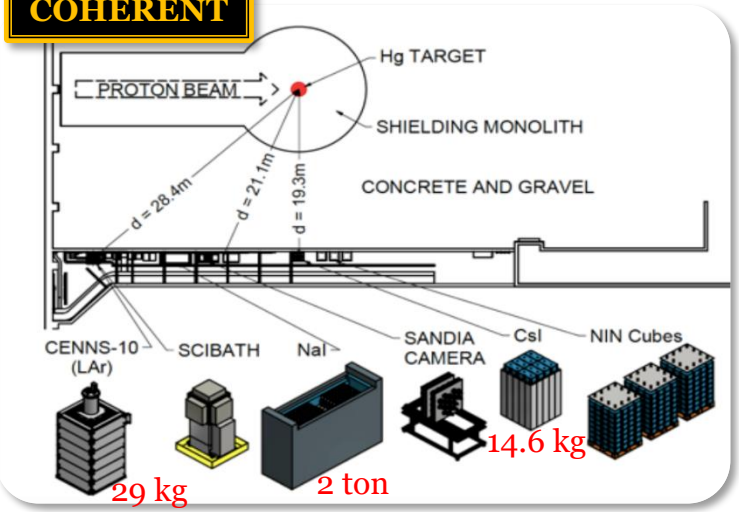
❖ Various current/future Coherent Elastic ν Nucleus Scattering (CEνNS) experiments

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

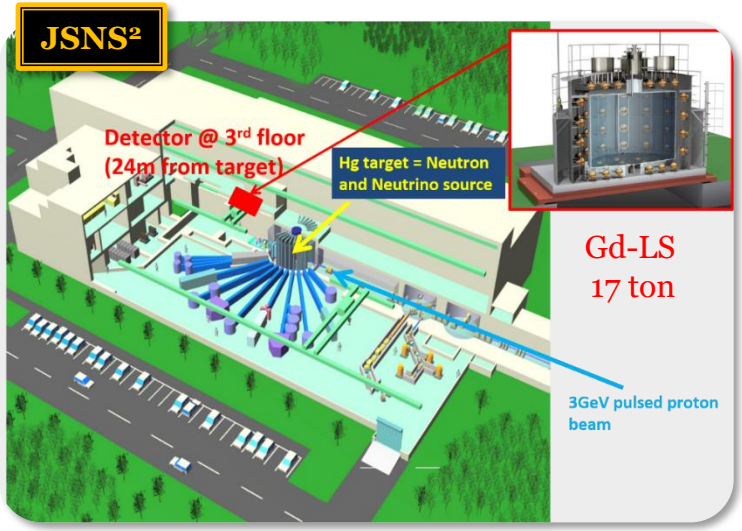


CEνNS Experiments: Beam-induced

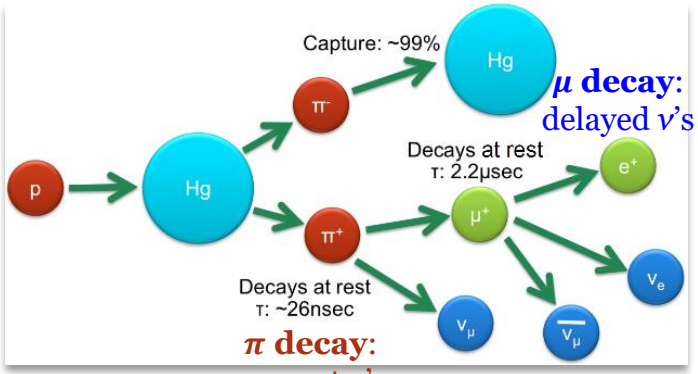
COHERENT

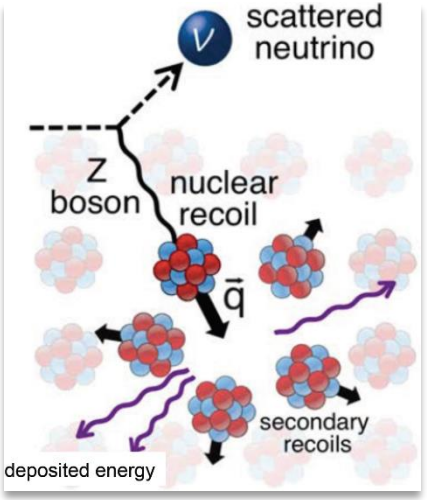


JSNS²



❖ Main goal: direct measurement of CEνNS



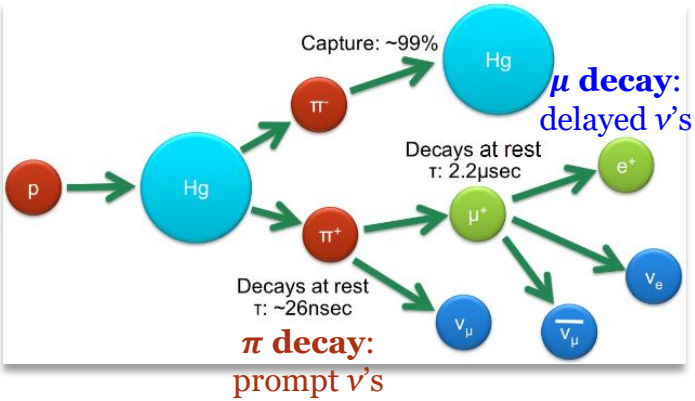


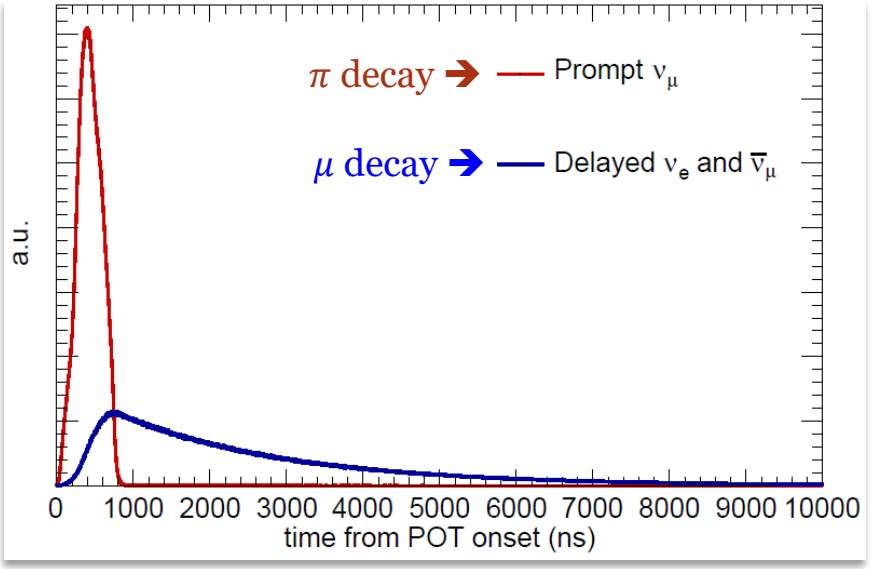
✓ COHERENT: 1 GeV p beam on Hg target, 380 ns FWHM (pulse duration) & 60 Hz, 1.8×10^{23} POT/yr

✓ JSNS²: 3 GeV p beam on Hg target, 700 ns (pulse duration) & 25 Hz, 3.8×10^{22} POT/yr

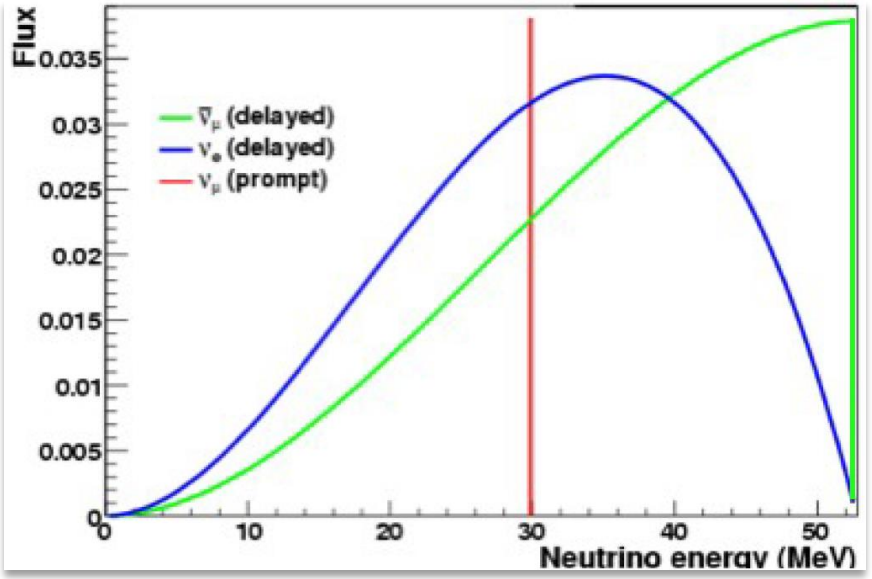
(POT: protons-on-target)

CEνNS Experiments: E/T-Spectra of ν



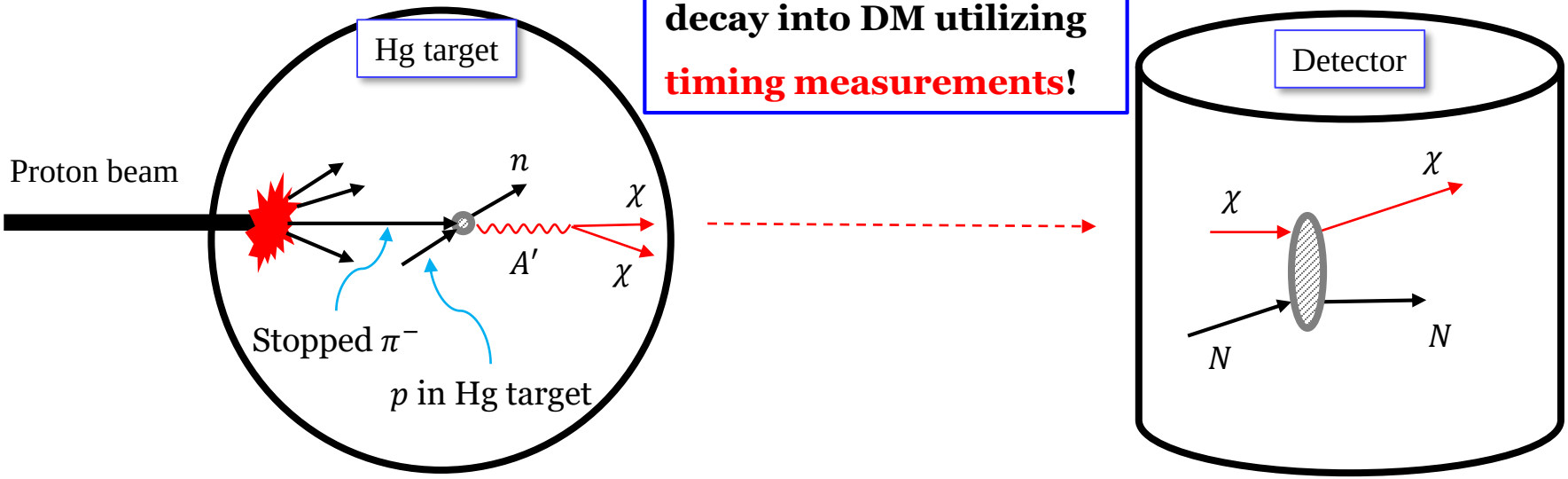


- ✓ Prompt ν's: $T <$ ~1 μs & $E_\nu = 30$ MeV
- ✓ Delayed ν's: mostly $T >$ ~1 μs &
  $E_\nu = 0 - 52$ MeV (mostly > ~30 MeV)

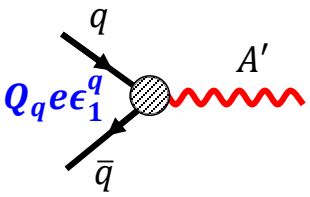


CEνNS Experiments: DM Searches

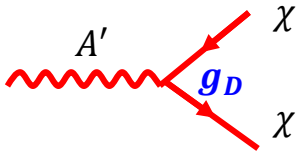
Probe dark mediator (A') decay into DM utilizing timing measurements!



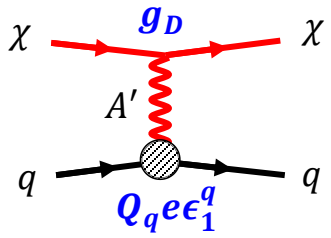
$\pi^- + p \rightarrow n + A'$ (capture)
[arXiv:1505.07805]



$A' \rightarrow \chi + \chi$



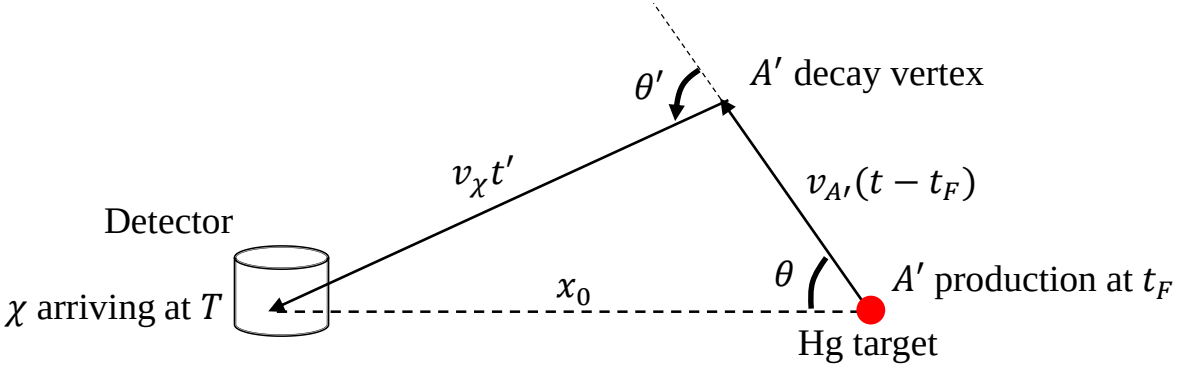
$\chi + N \rightarrow \chi + N$



❖ Other (subdominant) production processes: $\pi^0 \rightarrow \gamma + A'$ (via conventional direct π^0 production),

$\pi^{-/+} + p/n \rightarrow \pi^0 + n/p$ & $\pi^0 \rightarrow \gamma + A'$ (charge exchange)

Timing Spectra of DM Events



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

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

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

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

t'

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

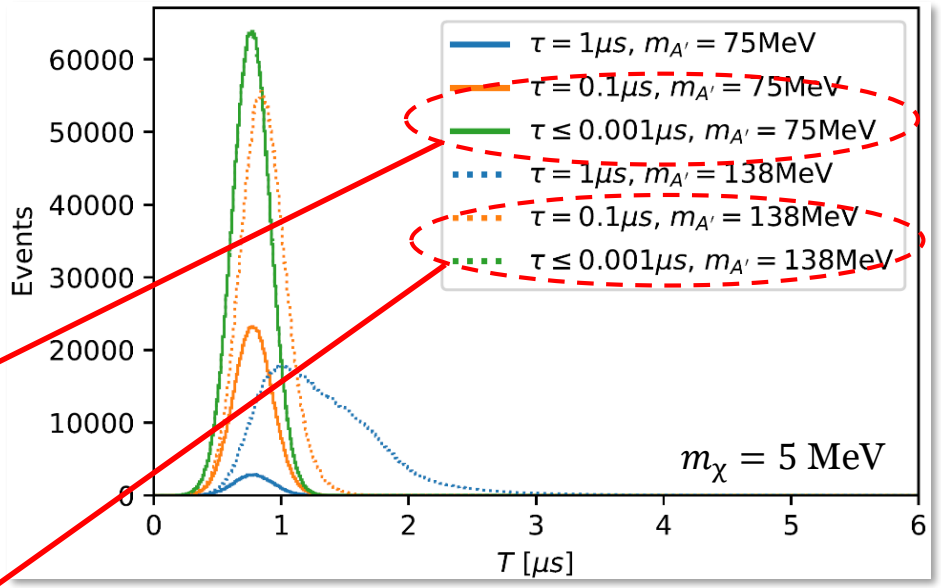
$$w(\cos\theta') = \frac{1}{2\pi (v_\chi t')^2} \left|\frac{d\cos\theta'}{d\cos\theta^*}\right|^{-1} \frac{dN_{A' \to \chi}}{d\cos\theta^*}$$ ← Probability that DM travels towards the detector

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 $< m_{A'}/2$

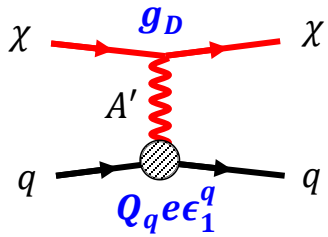
DM Scattering vs Production Parameters

❖ 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

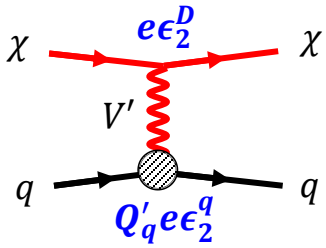
❖ DM scatters off nucleus

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

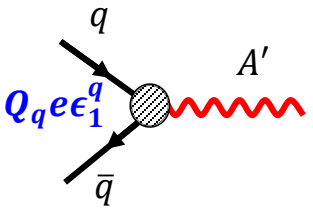
❖ In general, the scattering could be mediated by a different particle,

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

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

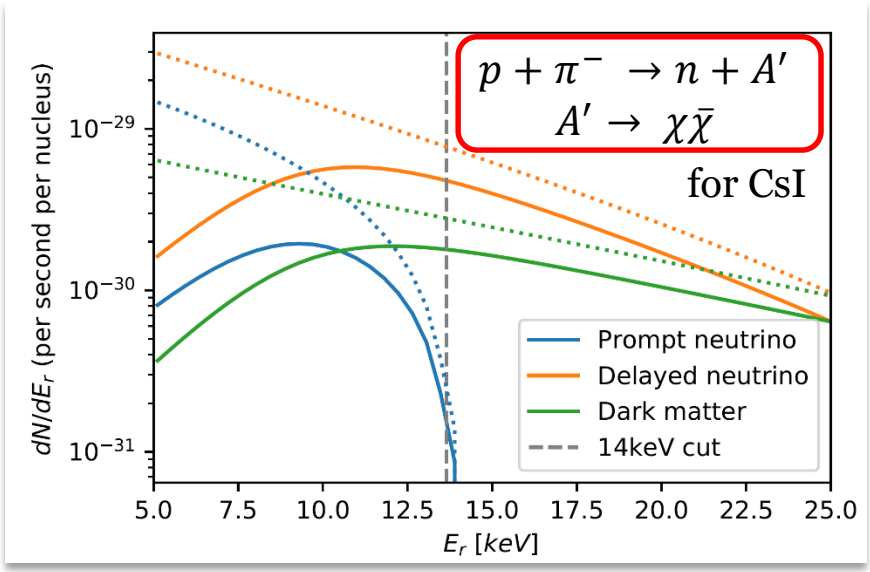


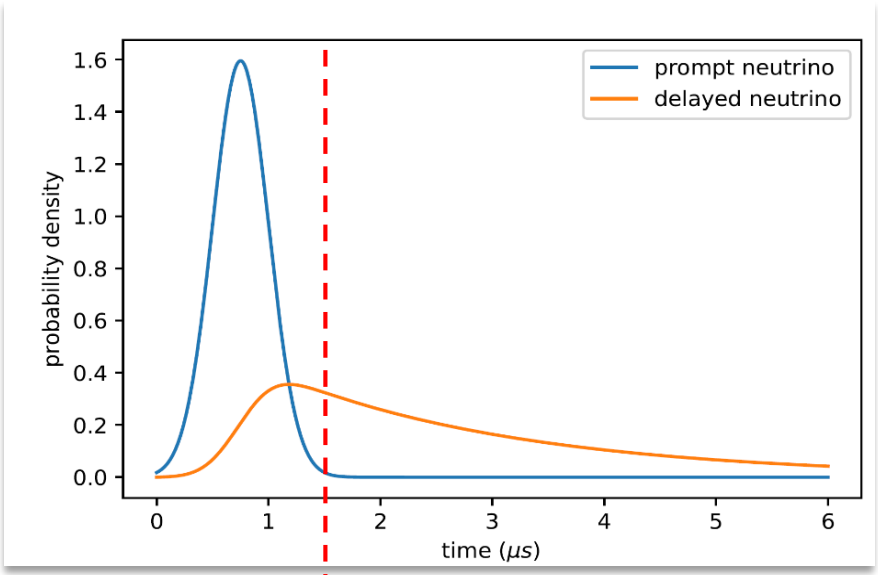
❖ Dark photon A' production to DM scattering can be described by two variables.

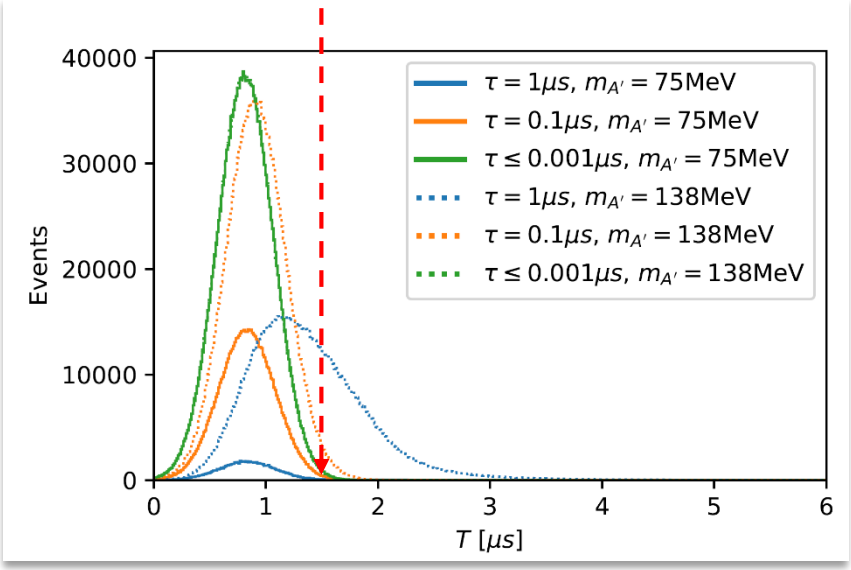


$$\epsilon \equiv \epsilon_1^q \epsilon_2^q \epsilon_2^D \sqrt{\mathrm{BR}_{A' \to \chi\chi}} \text{ and } M'$$

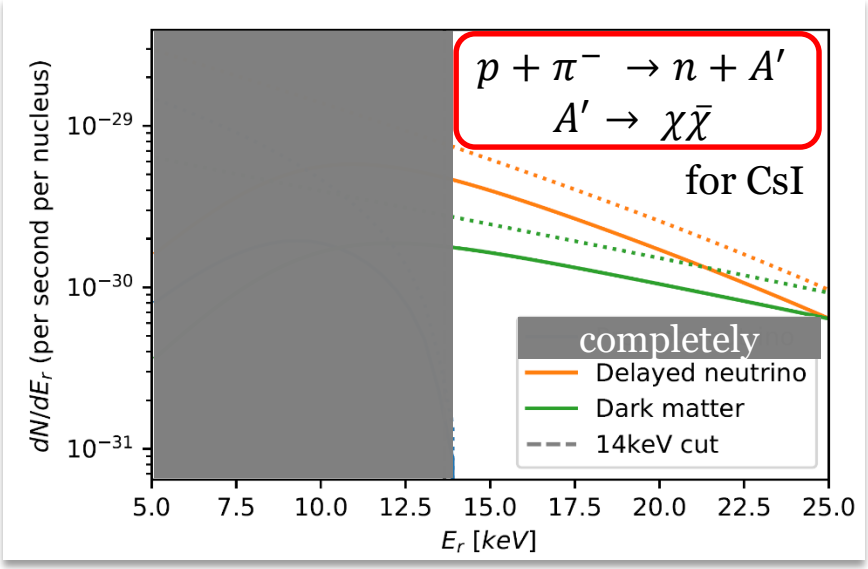
Proposed Search Strategy: E & T-cuts

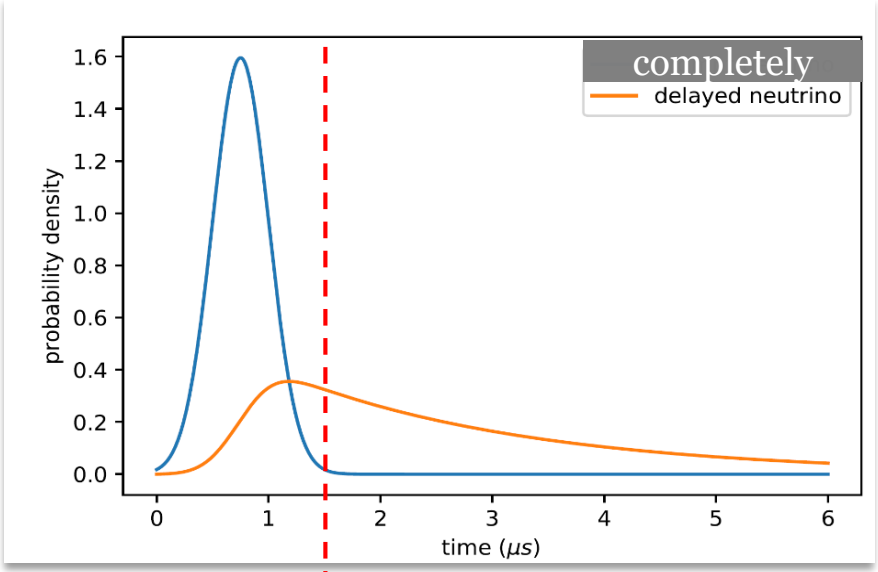




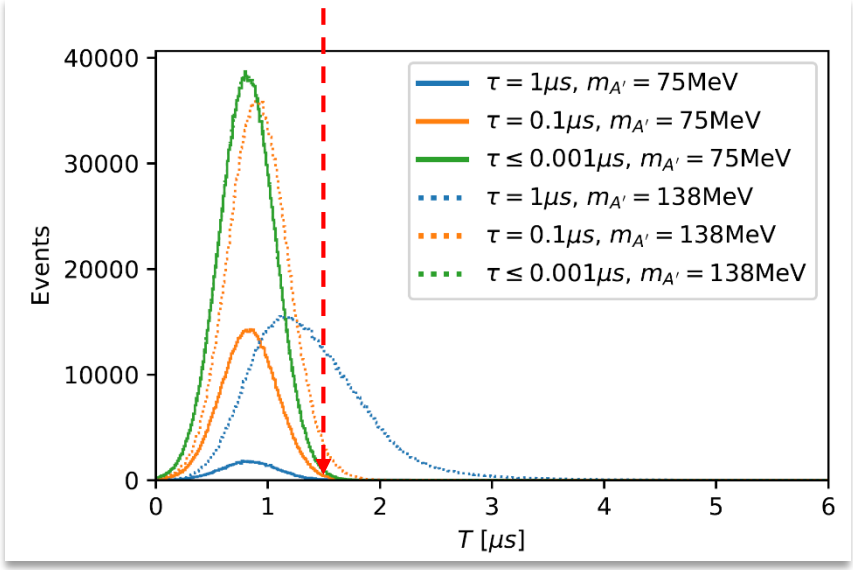


Proposed Search Strategy: E & T-cuts

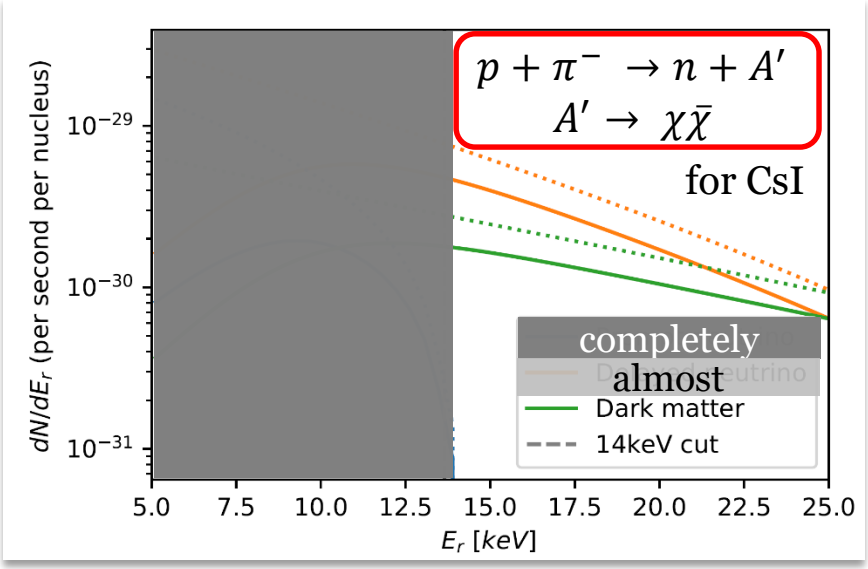


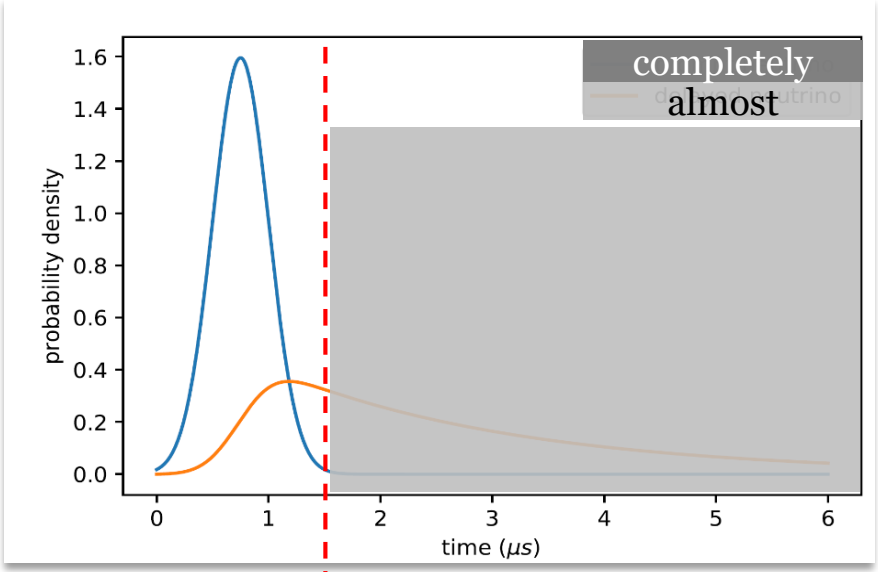


- $E_r > 14$ keV (for CsI)
  - ✓ Prompt ν: **completed** removed
  - ✓ Delayed ν (& DM signal): still remains

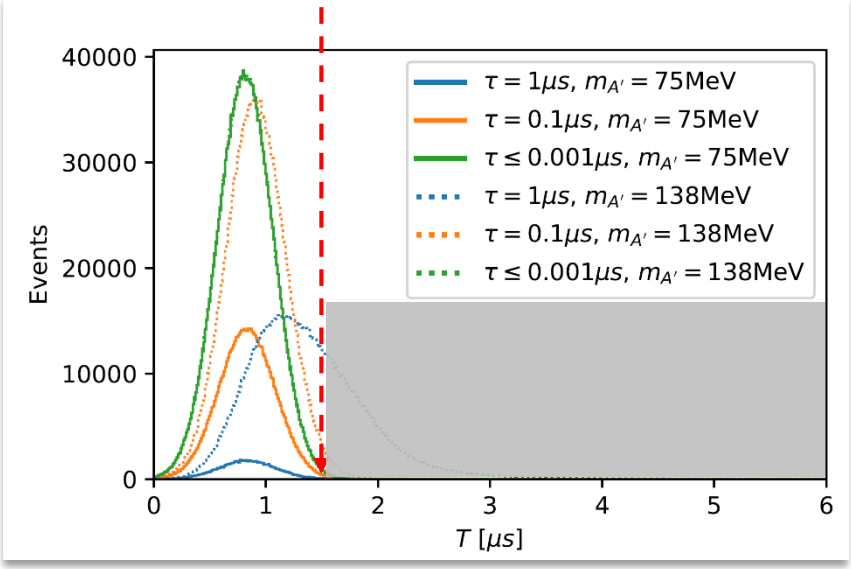


Proposed Search Strategy: E & T-cuts





- $E_r > 14$ keV (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 ➔ 14.5 kg×308 days [arXiv:1804.09459]

❖ Analysis scheme

✓ Fix the average rms radius of the neutron distribution to $R_n = 4.7$ fm

✓ $14\ \text{keV} < E_r < 28\ \text{keV}$ & $T < 1.5\ \mu\text{s}$

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

97 : total events

– 49 : classified as the steady-state (SS) background

– 19 : identified as delayed neutrino events (SM)

– 0 : identified as prompt neutrino events (SM)

– 3 : beam-related neutrino (BRN) backgrounds

26 : "Excess!!"

Significance ($R_n = 4.7$ fm): **2.4 σ**

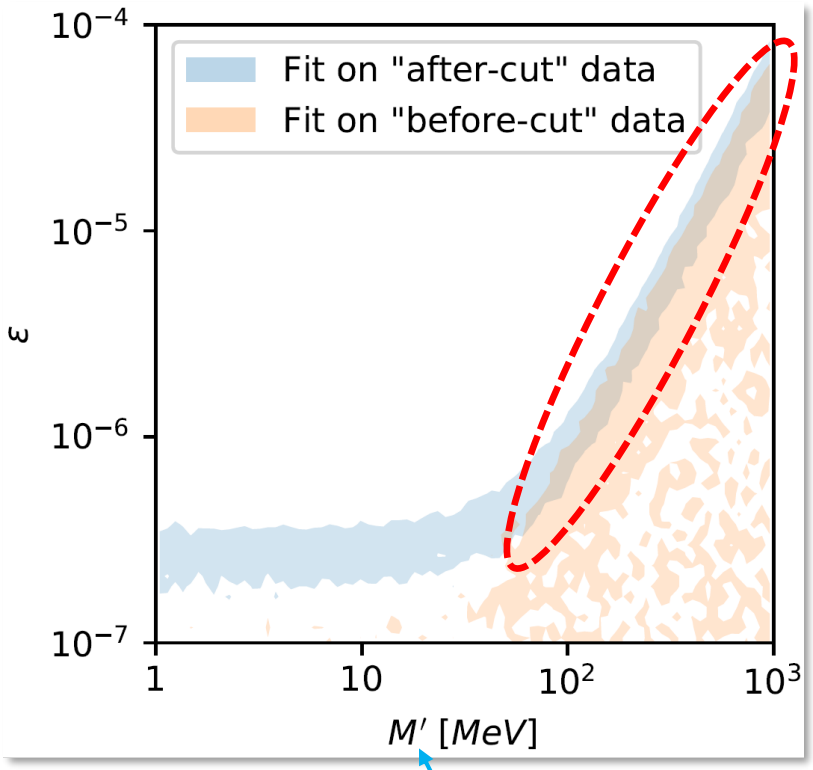
Significance ($R_n = 5.5$ fm): **3.0 σ**

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

[arXiv:1801.05546]

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

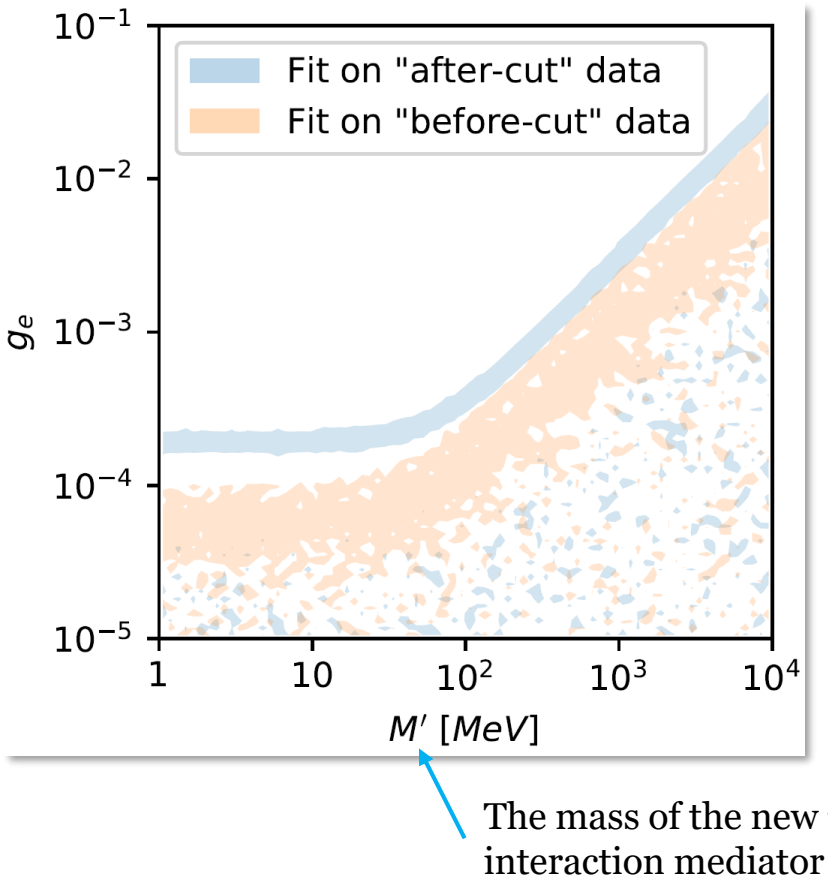
- Baseline model point for the figure in the left:

  $\tau = 1$ 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

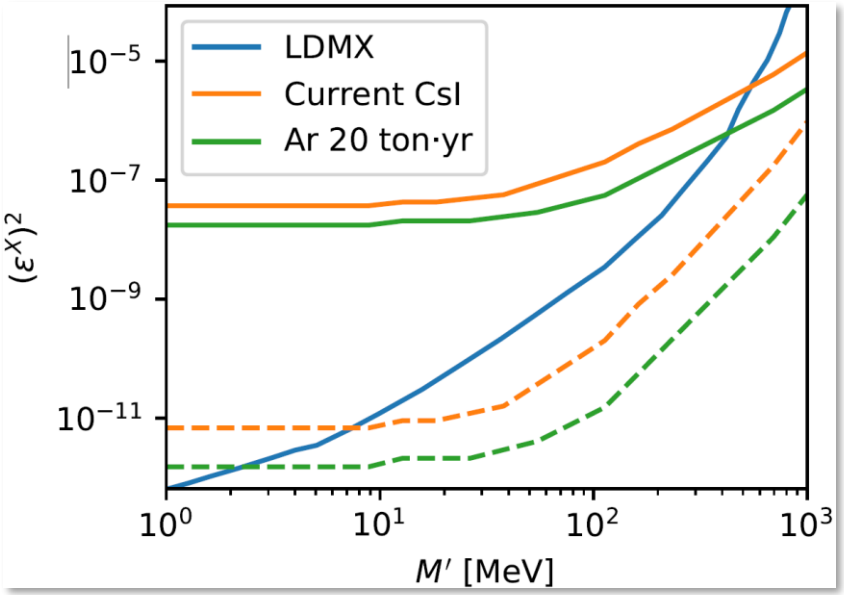
❖ An example alternative new physics possibility: non-standard interaction (NSI) of ν



- ✓ 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: **$2.4 - 3\sigma$ 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

Back-Up

R_n & R_p

❖ R_p: average rms radius of the proton distribution ➔ measurable

$$R_p(^{133}\mathrm{Cs}) = 4.804 \text{ fm}, \quad R_p(^{127}\mathrm{I}) = 4.749 \text{ fm}$$

determined from muonic atom spectroscopy [Atom Data Nucl Data Table (1995)]

❖ R_n: average rms radius of the neutron distribution ➔ indirectly measurable

$$R_n(^{133}\mathrm{Cs}) = 5.04 \pm 0.31 \text{ fm}$$

By combining APV and COHERENT measurements [arXiv:1908.06045]

➔ R_n=4.7 fm for the CSI of COHERENT is very conservative choice!