Searching for DM Particles at the STS with CEvNS

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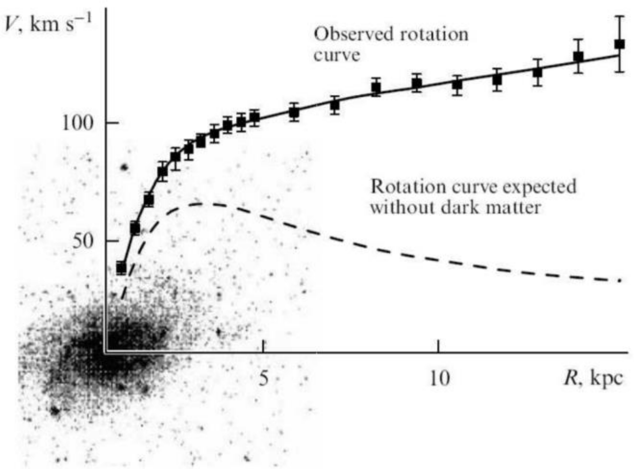
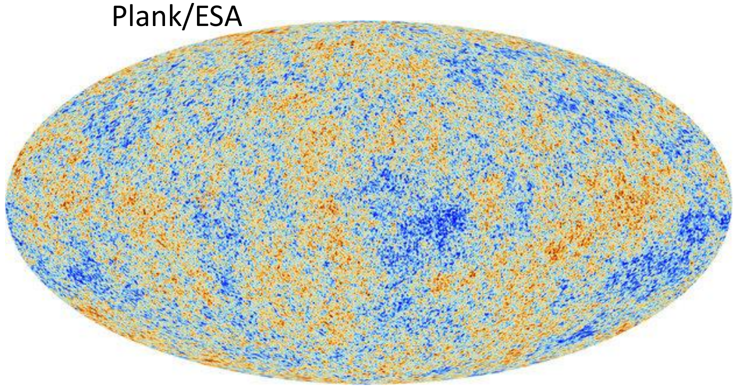
Dark matter in our universe

arXiv 1710:10630



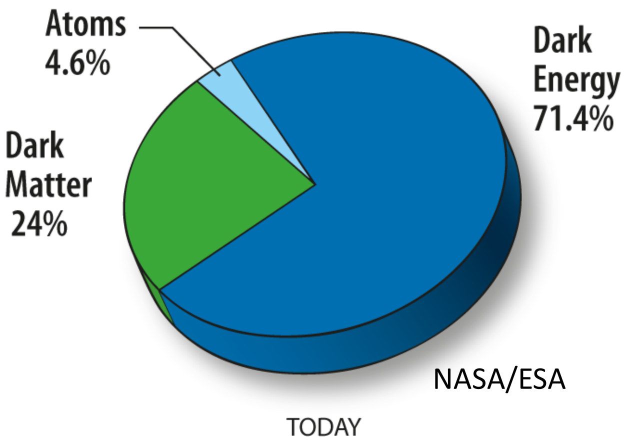
Plank/ESA



ApJ 909 27

- First evidence for dark matter (DM) comes from rotation curves of galaxies in early 20th century (e.g. Zwicky 1933)
- In 2003, precision CMB data confirmed the existence of dark matter and estimated that roughly 80% of matter in the universe is dark matter
- Continuing understanding distribution of dark matter from weak gravitational lensing data

- 100 years since postulation, and we still haven’t found the particle nature of DM despite many attempts – new physics we know exists, we just need to find a new place to look



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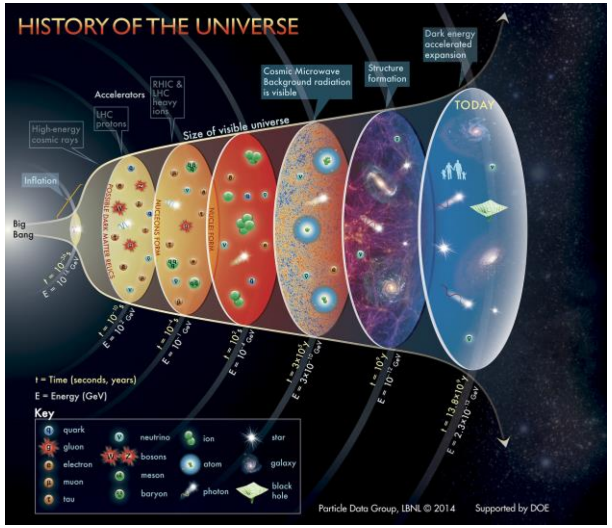
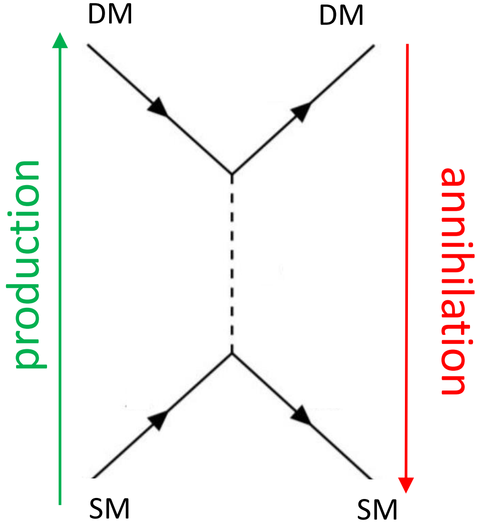
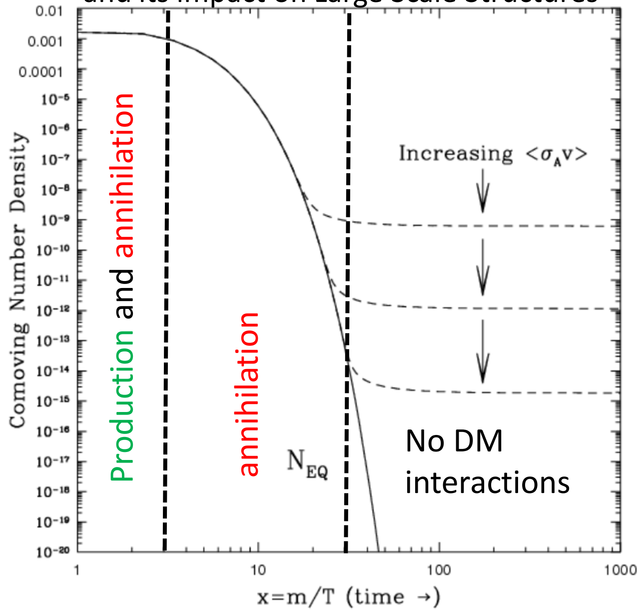
Origin of weakly-interacting dark matter





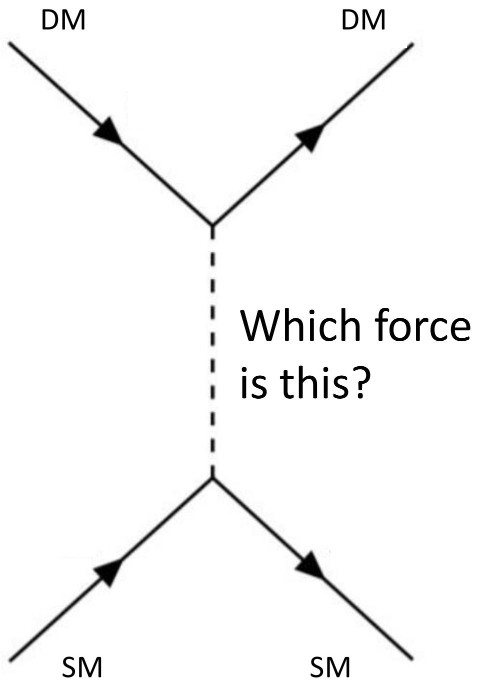
Chatterjee: Dark Matter Self Interaction and its impact on Large Scale Structures



- ❑ Assuming that DM is a particle that interacts weakly with standard-model (SM) matter, in the very early universe, DM was in thermal equilibrium with SM fermions
  - As the universe cools, DM production is no longer kinematically allowed, and the DM concentration falls exponentially
  - Later, as the universe continued expanding, the DM concentration became so low that DM annihilation stopped since DM particles could no longer find partners to annihilate with
- ❑ At this point, the universe “freeze-out” of DM occurred, with the DM concentration fixed to the modern observed value
- ❑ Freeze-out concentration depends on DM cross section – higher cross section implies DM can annihilate even when less dense so that concentration is lower
  - Modern relic abundance tells us what the cross section is (as a function of DM mass)

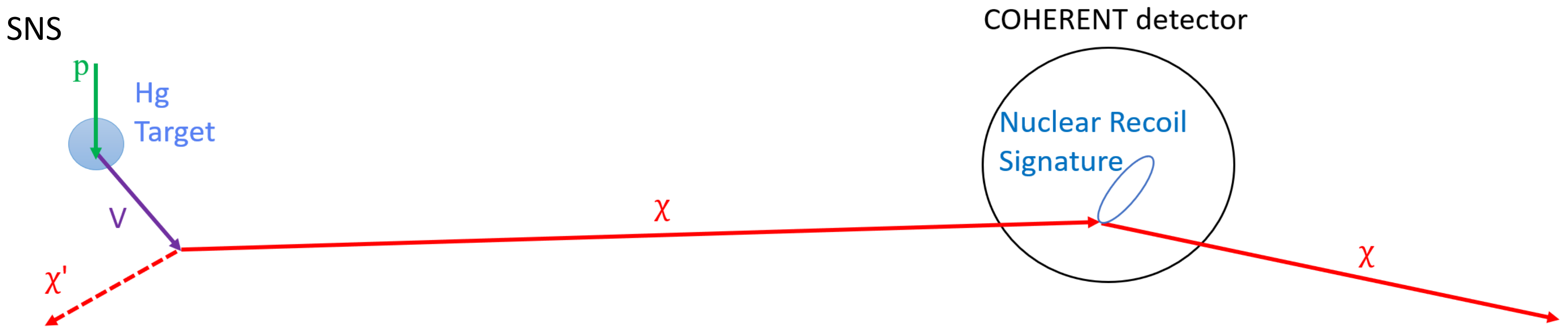
Low-mass DM phenomenology

- For decades, experiments have focused on classic WIMP searches assumed to interact with the weak force
- The DM scattering cross section is $\sigma \sim m_\chi^2/m_z^4$
  - Lower DM mass → lower cross section → higher DM abundance
  - If $m_\chi < 2$ GeV/c^2, predicted relic abundance would be so large it would close the universe, preventing modern the universe
- No longer assume DM interacts with SM particles via the weak force, but some yet unknown hidden sector particle, V
- In this scenario, $\sigma \sim m_\chi^2/m_V^4$ which is consistent with modern cosmology even at low mass scales
- Simplest scenario postulates a vector mediator that kinematically mixes with SM photon: $\mathcal{L} \sim \frac{1}{2}\varepsilon^2 F_{\mu\upsilon}V^{\mu\upsilon}$
- Model parameters
  - DM and mediator masses: m_χ and m_V
  - SM-mediator and DM-mediator couplings: ε and α_D
- Relic abundance given in terms of $Y = \varepsilon^2\alpha_D\left(m_\chi/m_V\right)^4$



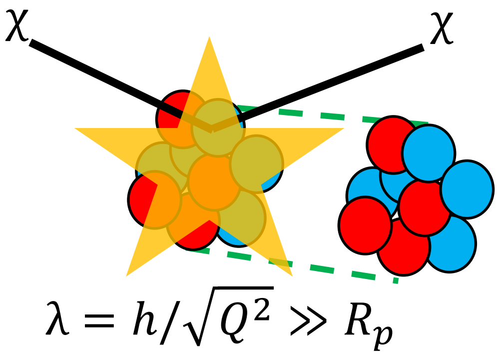
Classical WIMP mass regime:
  Lee and Weinberg, Phys. Rev. Lett. **39** 165 (1977)
Early sub-GeV DM phenomenology:
  Fayet, Phys. Rev. **D70**, 023514 (2004)
  Boehm and Fayet, Nuc. Phys. **B683**, 219 (2004)
  Pospelov et al., Phys. Lett. **B662**, 53 (2008)
Coherent DM scattering / DM at the SNS:
  deNiverville et al., Phys. Rev. **D84**, 075020 (2015)
  Dutta et al., Phys. Rev. Lett. **123**, 061801 (2019)

Direct DM detection at the SNS



- ☐ Any hidden sector particles with masses below ≈ 220 MeV/c^2 could be produced in the many proton-Hg interactions within the SNS target
- ☐ This may include mediator particles between SM and DM particles
- ☐ Mediator decays to a pair of DM particles, sending a flux out of the SNS
  - Suitable detector placed in this flux can directly detect DM particles scattering within the detector

Advantages of low-recoil detectors: cross section



- ☐We're dealing with low enough Q^2 that the deBroglie wavelength is large compared to nuclear radius
- ☐All nucleons within nucleus recoil coherently from neutrino or DM scattering
- ☐Astroparticle direct-detection experiments have exploited this for years – now accelerator experiments can too with CEvNS detectors

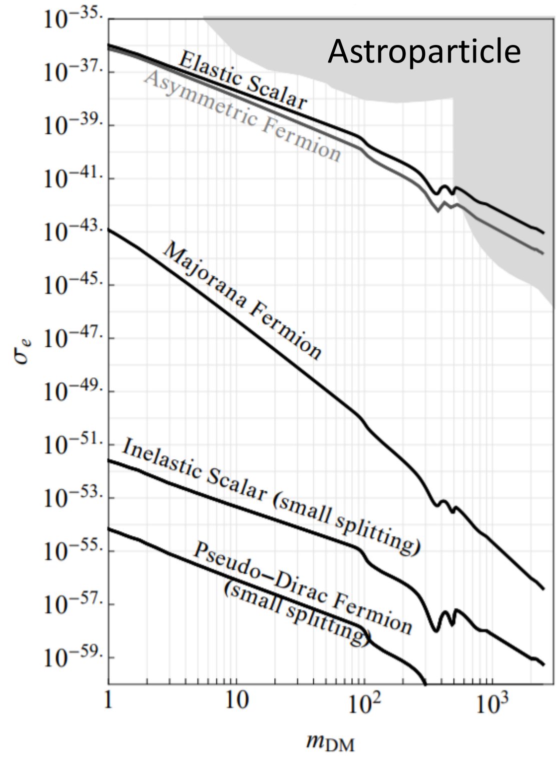
- ☐This coherency gives a Z^2 enhancement in the cross section → big effect for CsI (Z of 53/55)
- ☐Game-changing – investing in a small 14-kg detector can compete with multi-ton detectors and 10-t CEvNS detector can out-compete

Direct-detection experiments searching for light dark matter

	Mass (t)
LSND	167
MiniBooNE	450
COHERENT CsI	0.0146

Advantages of accelerator searches: less model dependent

- Astroparticle experiments are within grasp of the expected dark matter concentration for scalar DM
- But if DM is a fermion, the scattering cross section is heavily suppressed by DM speed $v/c < 0.001$
- Predictions span 20 orders of magnitude


arXiv 1707.04591

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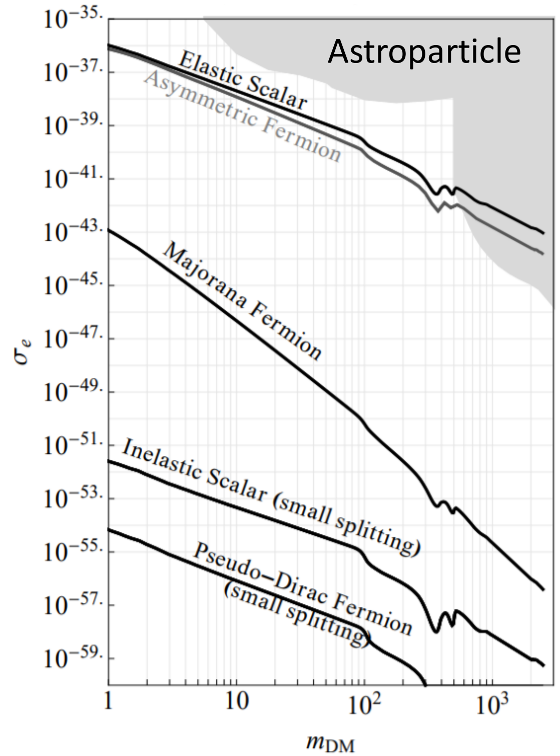
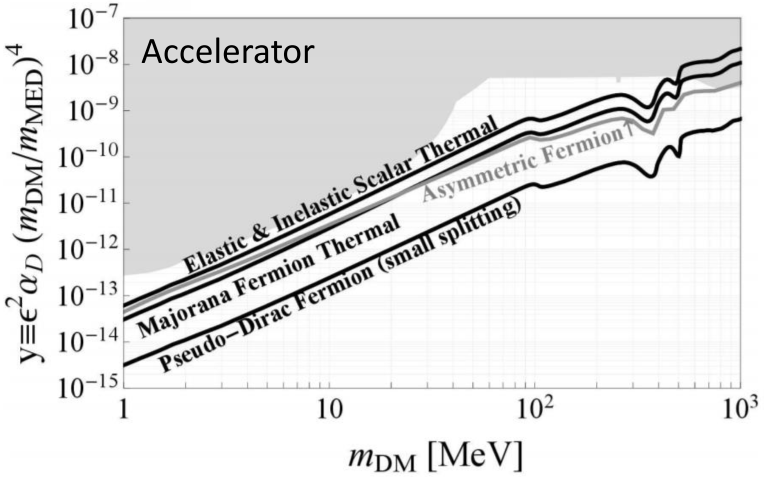


- At accelerators, DM is relativistic with only a factor of 20 between different expectations
  - Accelerator searches only viable options to test fermionic DM
- COHERENT gets the best of both worlds
  - Independent of DM particle nature like accelerator methods
  - Large coherent cross section like astroparticle methods

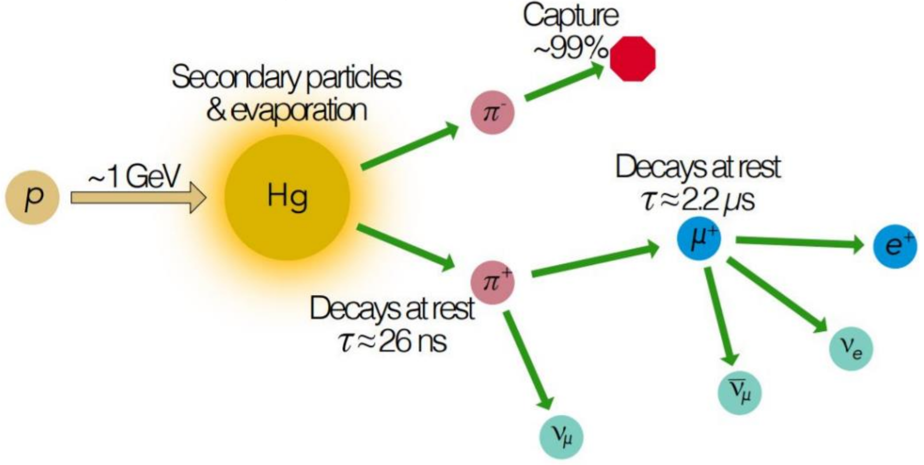


Neutrino flux at the SNS

- Low energy pions are a natural by-product of SNS running
  - π^+ will stop and decay at rest

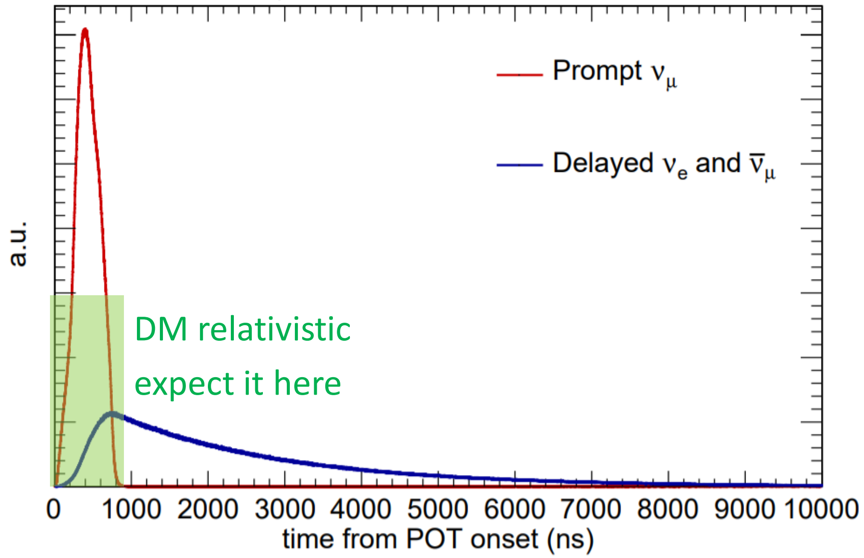
$$\pi^+ \rightarrow \mu^+ + \nu_\mu \quad : \ \tau = 26 \text{ ns}$$
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu \quad : \ \tau = 2200 \text{ ns}$$

  - Flux includes three flavors of neutrinos → can test flavor universality as a BSM signature

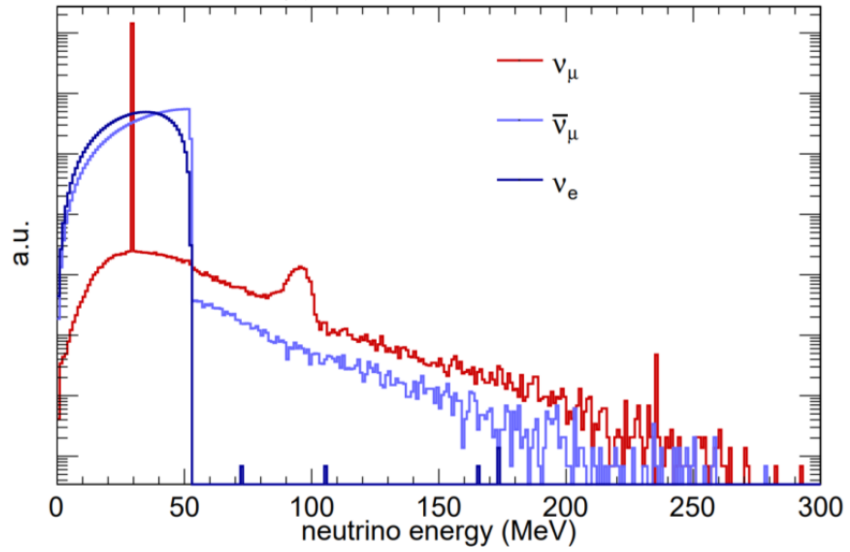


- Flux shape is very well known and very small contribution from decay in flight at the SNS

Timing distribution at SNS



Energy distribution at SNS



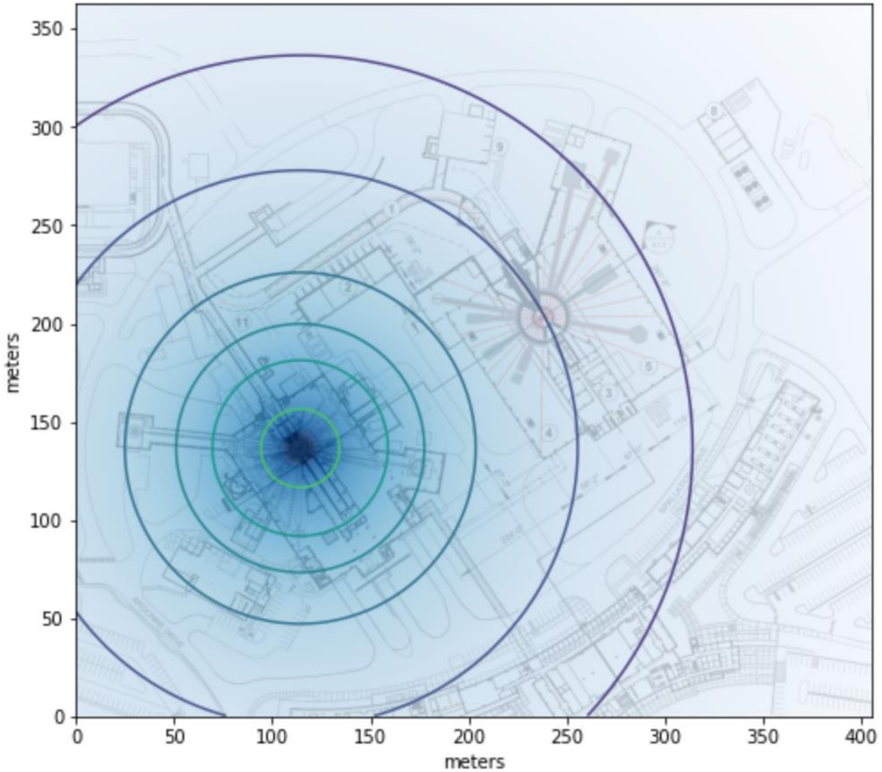
Directionality of flux at the SNS

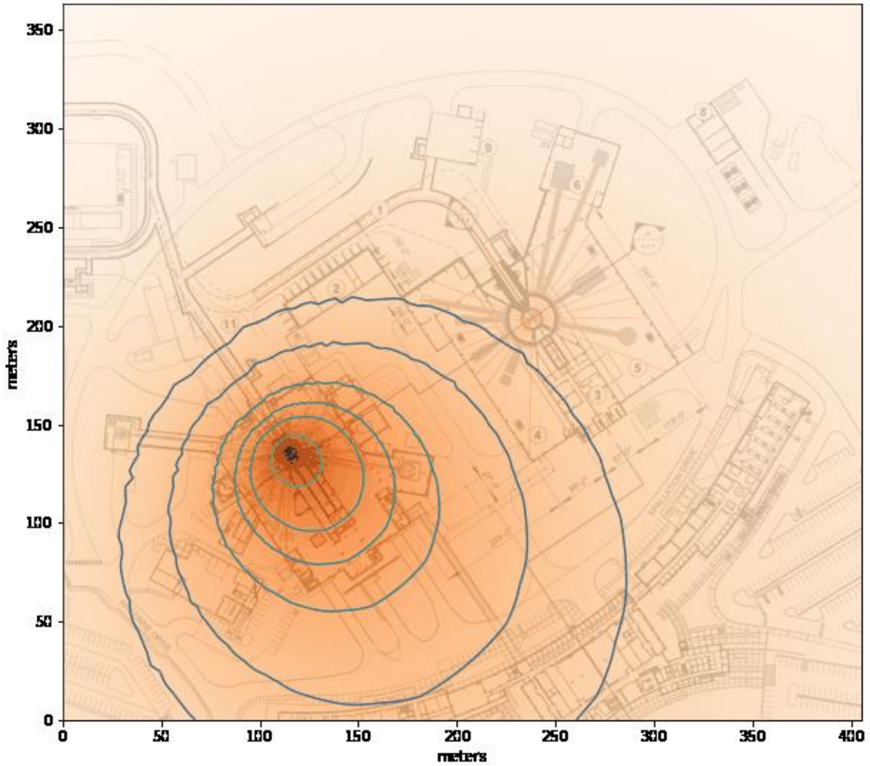
Neutrino flux produced at rest – isotropic

Largest beam-related background for DM searches at the SNS

DM produced in-flight – is boosted

A forward-directed detector would optimize DM / background

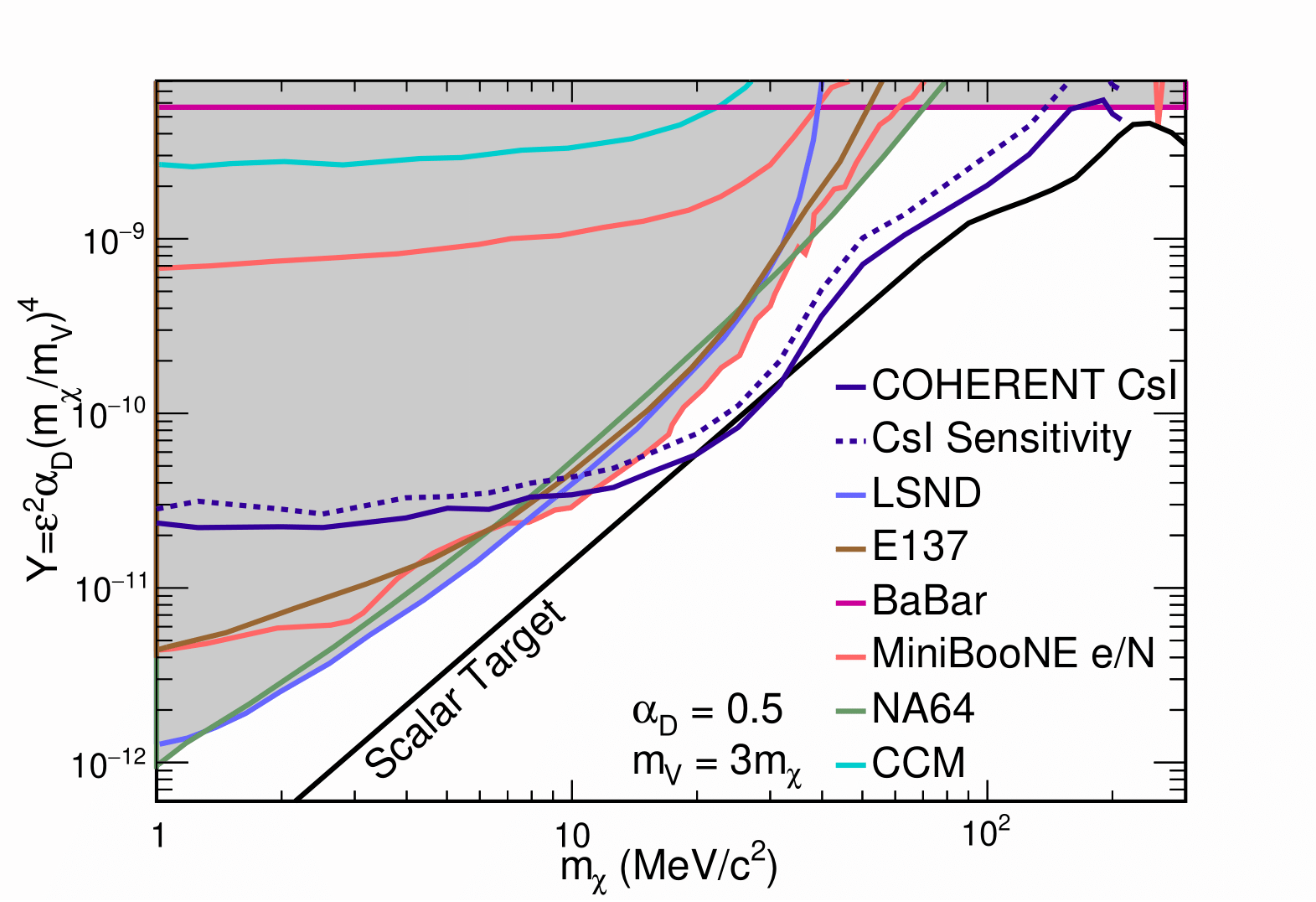




- After STS is built, both targets will operate with 3(1)/4 bunches sent to FTS (STS)
- If DM is in this mass regime, SNS very advantageous – a single detector monitors DM flux from two beams allowing confirmation of the expected angular dependence of the flux

Current COHERENT constraint of WIMP-like DM

- With first CEvNS data from COHERENT, we are already competitive here
- We are first to probe beyond the scalar target that matches the DM relic abundance
- Achieved with small 14.6 kg detector, can do much better at the STS

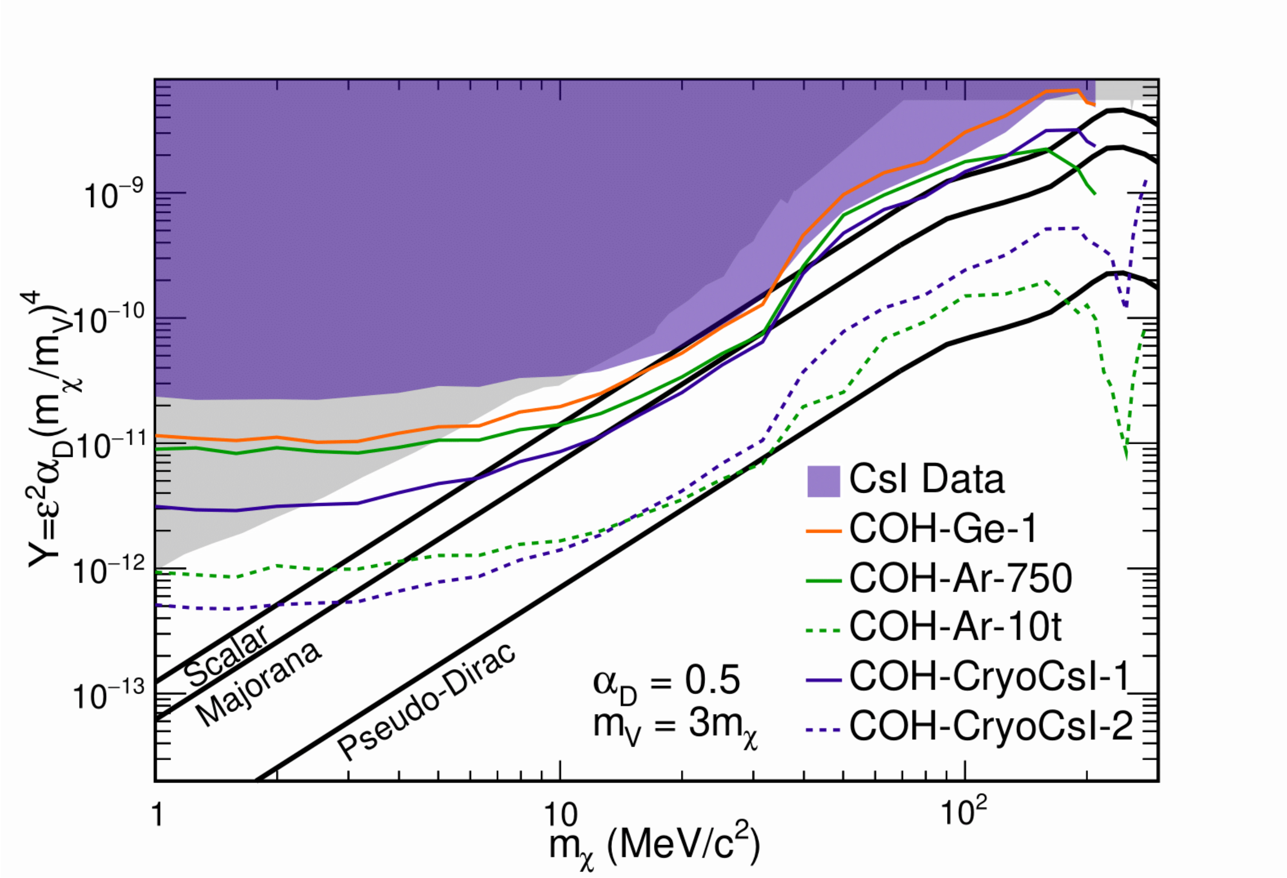


Considerations for a detector at the STS

❑ We consider two straw-person detector concepts at the STS
  - 10t liquid argon calorimeter – scaled up version of CENNS10 which made first CEvNS measurement on Ar
  - 700 kg of cryogenic CsI scintillator – next-generation CsI technology that mitigates random backgrounds and improves light yield for much lower threshold

❑ Three things to consider when placing the detectors:
  - Closer is better – more flux if you can place detector closer to target
  - Sufficient neutron shielding – too close you and your detector is swamped by neutrons
  - Off-axis angle – neutrino flux is isotropic but DM flux is forward-directed so more forward detectors have much better s/b

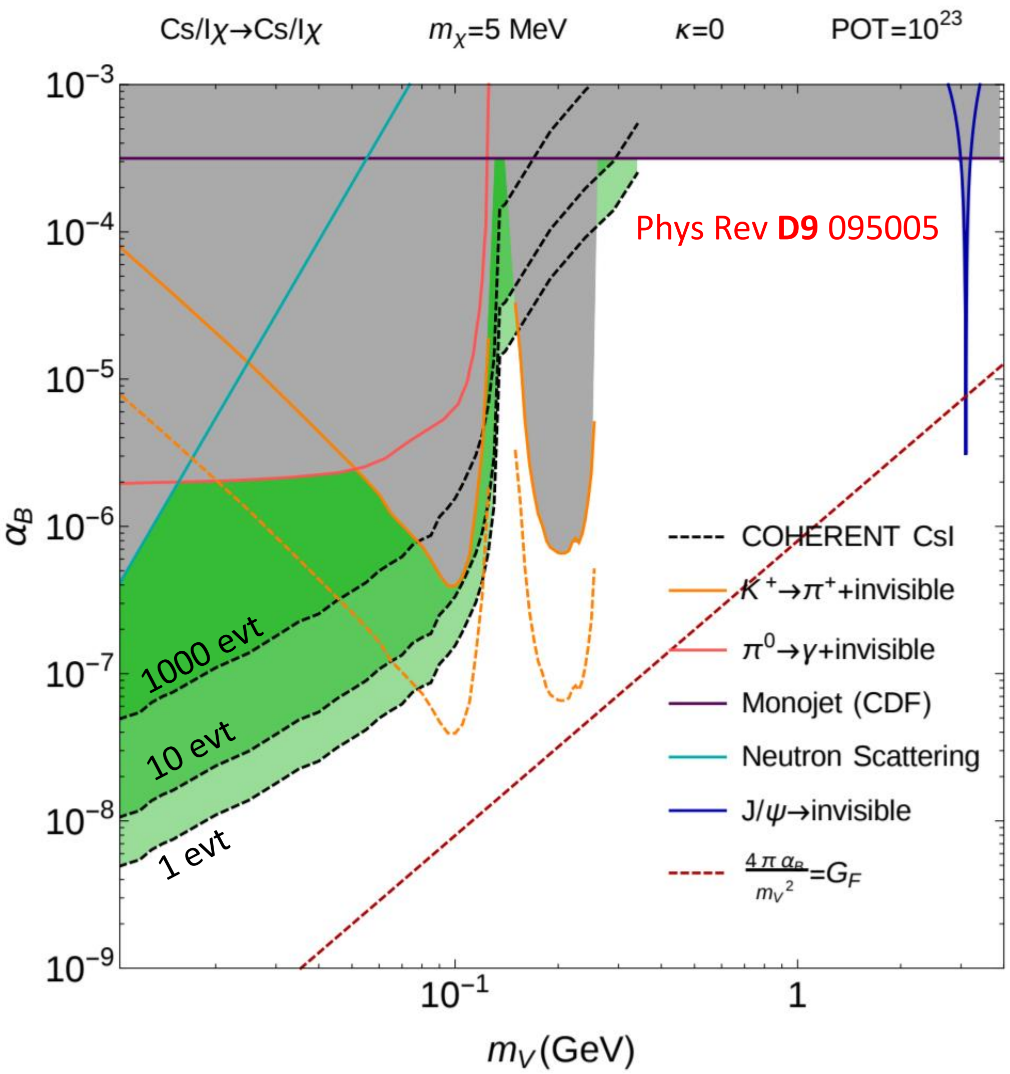
Future COHERENT sensitivitv to dark matter



- In immediate future: germanium detector currently being commissioned – will fully explore scalar target at lower masses
- In coming years: future argon and cryogenic CsI detector – will be sensitive to a lower DM flux and probe the Majorana fermion target
- In next decade: large detectors placed forward at the STS (dashed lines) will begin to ambitiously test even the most pessimistic spin scenarios

Other hidden sector searches: leptophobic DM

- Leptophobic DM could also explain observed cosmology where DM only interacts with SM hadrons
  - DM-e elastic scattering dominant channel for many experiments and aren’t sensitive to this model
  - But CEvNS experiments sensitive through looking at DM-nucleus interactions



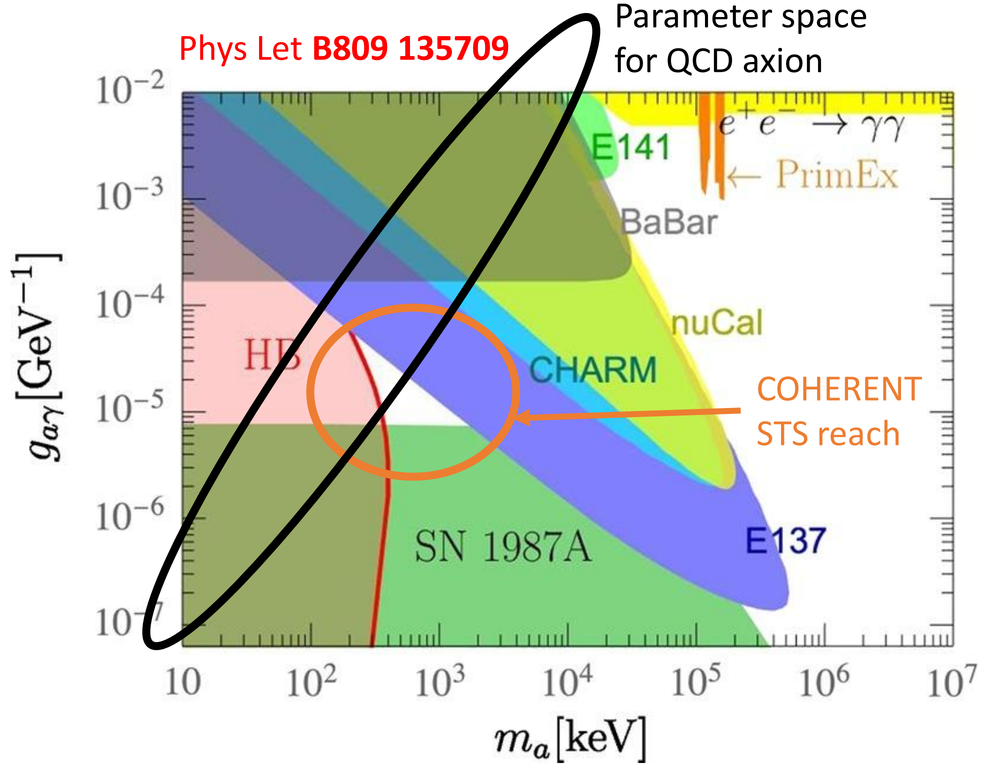
Phys Rev **D9** 095005

- Viable model with recent advances on theory side connecting experimentally observed rates to DM relic abundance
- Sensitivity studies maturing, but preliminary estimates are very favorable for our detectors

Other hidden sector searches: axions

- We will also be sensitive to axion-like particles (ALP) that may be produced at the SNS
    - Primakoff production within target and scattering in detector, e.g. $\gamma Z \rightarrow aZ$ and $aZ \rightarrow \gamma Z$

- Preliminary theory studies calculating event rates show we expect sensitivity for ALP masses above threshold, ≈ 10 keV
    - Should explore open parameter space not yet tested by cosmology or beam dump experiments
    - Unexplored parameters consistent with where you'd expect the QCD axion – strong motivation on theory side for this search



Phys Let **B809 135709**

Parameter space for QCD axion

COHERENT STS reach

Summary

- CEvNS experiments at accelerators are very effective probes of sub-GeV DM
- Initial COHERENT data has placed leading bounds but STS data can cover most of interesting parameter space consistent with the DM thermal abundance

- Other searches for leptophobic DM and axions will also improve on constraints, active work from theory and experiment sides to understand how well we can constrain these models