Title: New Dark Matter Search Strategies at DUNE

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Abstract:

New Dark Matter Search Strategies at DUNE

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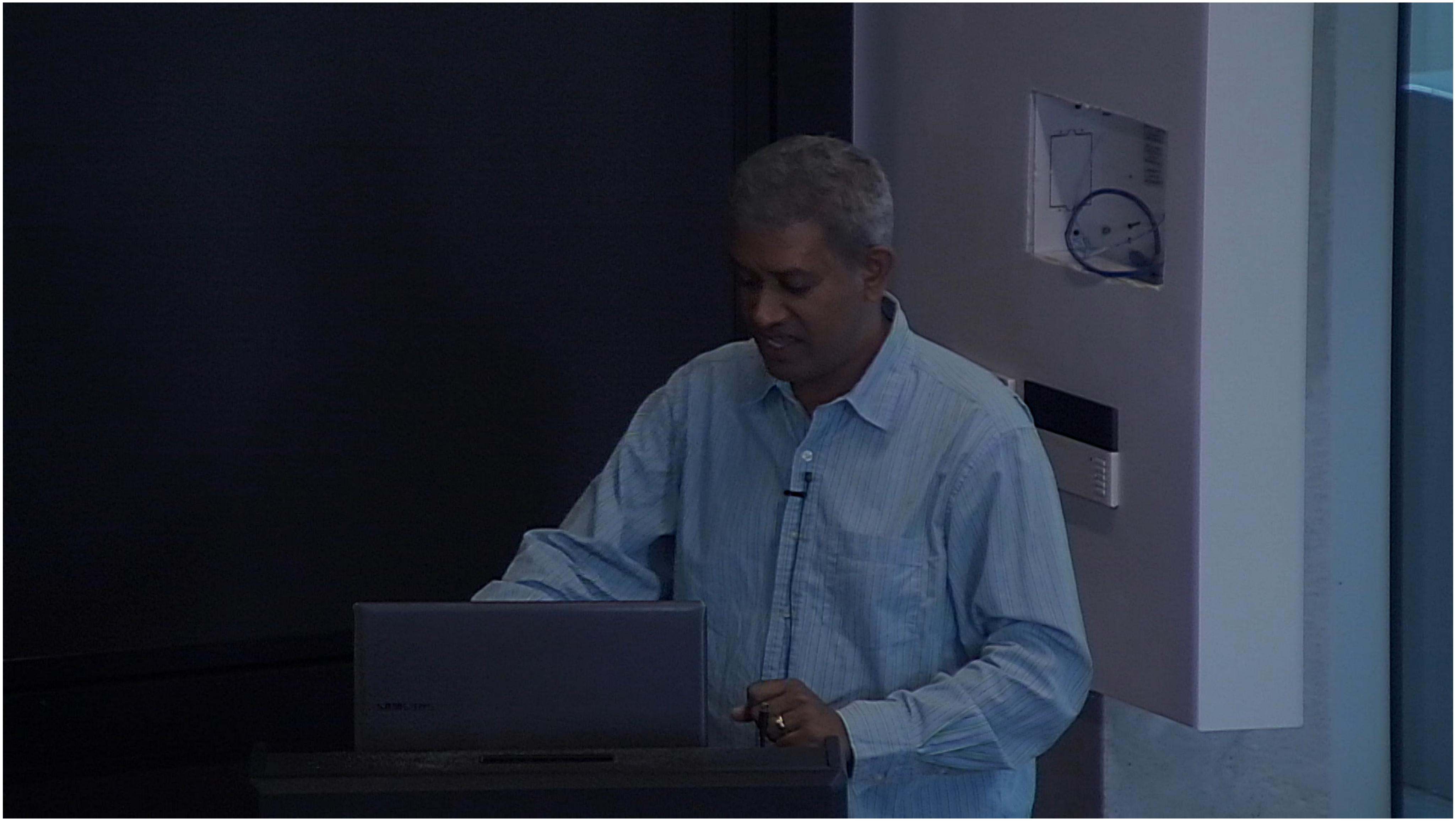


dark matter and monoenergetic neutrinos

- can search for dark matter using neutrino detectors
  - dark matter scatters off solar nuclei and collects in the core of the Sun
  - annihilates to Standard Model products
  - neutrinos get out and reach detector on earth

- focus is typically on a smooth distribution of high-energy events above background
- I'll focus on a different possibility
  - models in which dark matter can produce monoenergetic sub-GeV neutrinos
  - detectors and strategies which can resolve a line signal
  - obtaining direction information about neutrino

- DUNE is an ideal setting for this type of search

standard lore

- expect to get a continuum signal
  - dark matter annihilates to intermediate particles
  - decays give a continuum neutrino spectrum
- look for high energy neutrinos
  - larger cross section with detector
  - smaller background from atmospheric neutrinos
- use directionality, but only for high energy neutrinos
  - try to identify neutrinos arriving from the direction of the Sun
  - looking for charged lepton produced by charged-current interaction
  - points away from source, but only for E > GeV
    - for lower energies, charged lepton is roughly isotropic

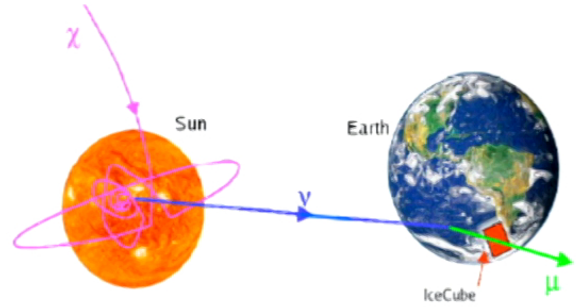
basic points

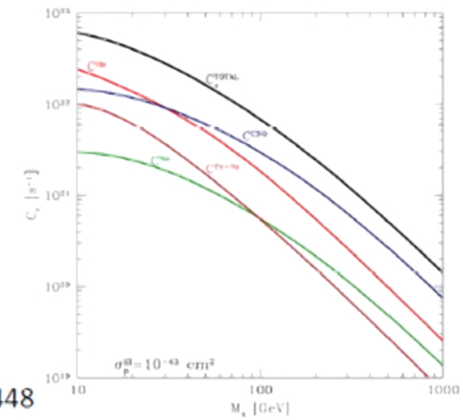
- theory
  - u, d, s final state quarks produce plenty of K^+
    - light hadrons stop before they decay (producing more K^+)
    - decay produces 236 MeV monoenergetic neutrino
- experiment
  - DUNE will do very well at total energy reconstruction for a charged-current interaction
    - sensitive to a line signal
  - DUNE can also get the direction of the neutrino from the nucleon recoil
    - new type of directionality search
    - great for reducing systematic uncertainty

neutrinos from the Sun

- basic idea
  - DM scatters off solar nuclei, loses energy through elastic scattering
  - falls below v_{esc} → captured
    - orbits, eventually collects in core
    - rate depends on mass, σ
  - DM annihilates to SM matter
  - SM decay yields neutrinos → seen at detector
  - DM in equilibrium → $\Gamma_C = 2\,\Gamma_A$
  - so neutrino event rate probes DM capture rate ($\propto \sigma_{SI}, \sigma_{SD}$)
- usually ignore light q final state
  - why?

Dawn Williams





A. Zentner, arXiv:0907.3448

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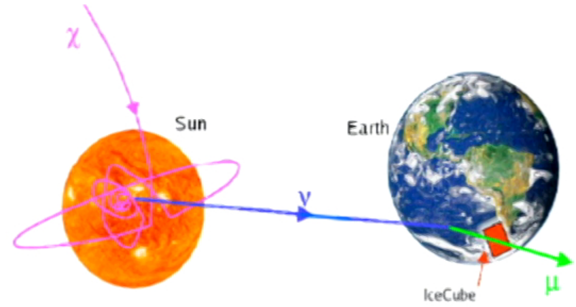

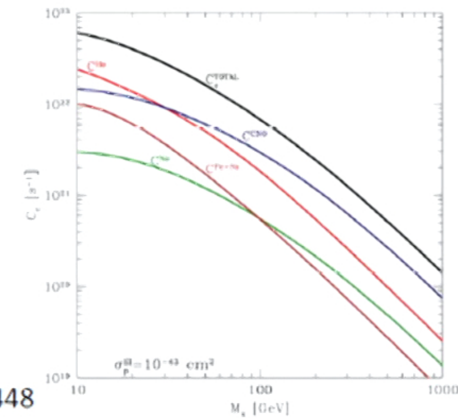

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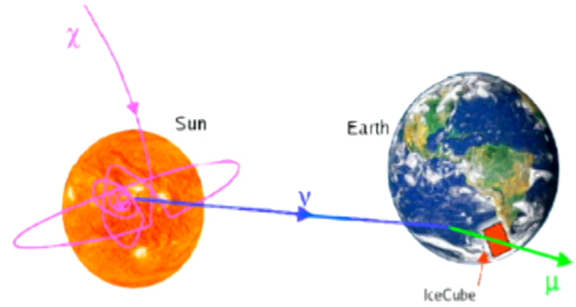

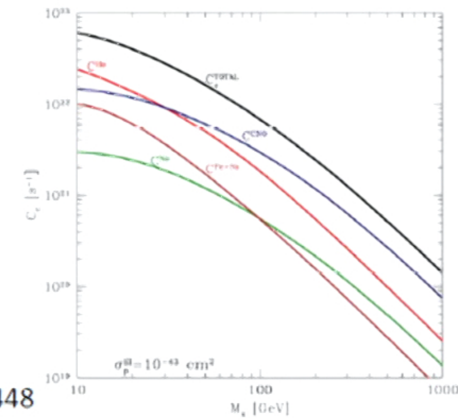

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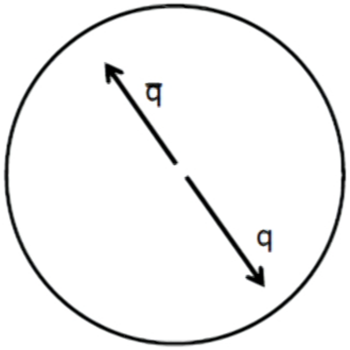
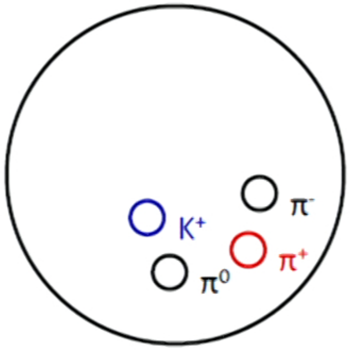
dark matter annihilation to light quarks

- u, d, s final states → hard!
  - u, d, s → light hadrons which stop in the Sun before decay
  - resulting ν spectrum is very soft
  - large background, small detector effective area



- but the stopping process produces a large number of π^+, K^+
  - trade a hard spectrum for a softer one, but with larger flux [Beacom, Rott, Siegal-Gaskins (1208.0827); Bernal, Martin-Albo, Palomares-Ruiz (1208.0834)]



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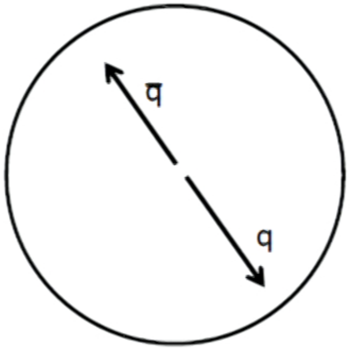
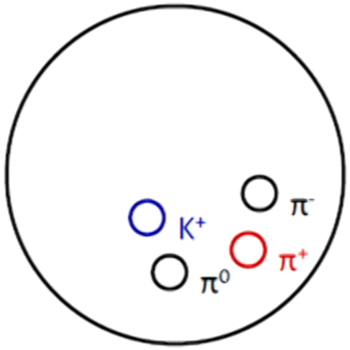




spectrum

- care about π^+ and K^+
  - $\pi^0 \rightarrow \gamma\gamma$
  - π^- Coulomb-captured by nuclei, and absorbed (not a lot of neutrinos)
- main relevant decay is $\pi^+, K^+ \rightarrow \nu_\mu \mu^+$
  - monoenergetic ν with E = 29.8 MeV (π^+ - 100%) or 235.5 MeV (K^+ - 64%)
  - line signal
    - include oscillation effects
- just need the fraction of DM energy which goes into stopped π^+, K^+
  - determine with Pythia/GEANT
  - use Pythia to simulate showering and hadronization; output the spectrum of long-lived hadrons
  - GEANT deals with interaction in dense solar medium

K^+

- I'll focus on the 236 MeV neutrino arising from stopped K^+ decay
- much larger cross section with detector target
  - more than offsets smaller number of kaons per annihilation

- now have all the pieces
  - given dark matter mass, scattering cross section, and annihilation channel, can get the flux of 236 MeV neutrinos from the Sun
  - with the energy resolution, can get the flux from atmospheric neutrino background
  - gives us the signal-to-background ratio
  - with the neutrino-nucleus scattering cross section (numerical) and exposure, can get signal significance

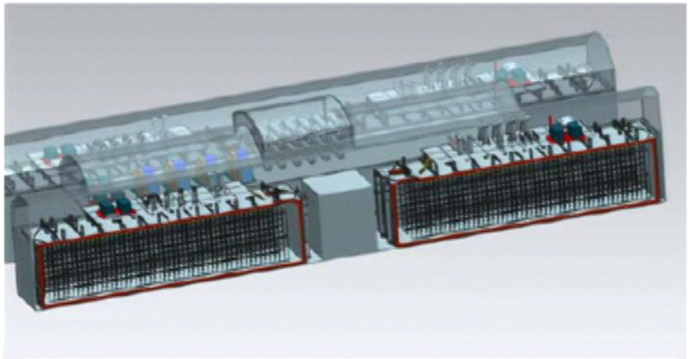
DUNE

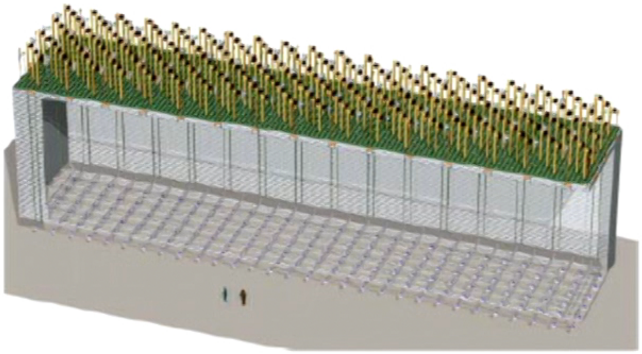
1601.02984

- Deep Underground Neutrino Experiment

- perfect for this type of search
  - large exposure
  - good total energy resolution
  - can identify outgoing particle tracks with good energy and angular resolution

- our benchmarks
  - angular resolution $\sim 5°$
  - total energy res. – $\varepsilon \sim 10\%$



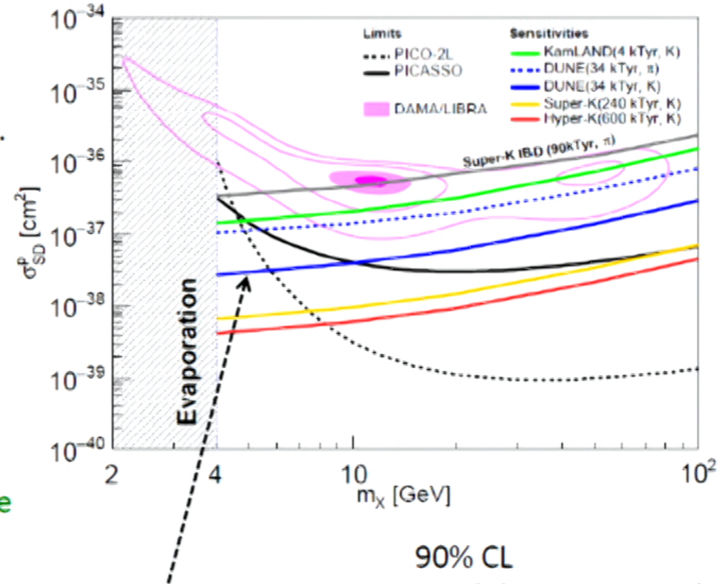


sensitivity for non-directional search

- assume 34 kT yr exposure
  - electron channel
  - ~ 50 bgd. events
  - 90%CL exclusion, assuming observation consistent with bgd.
  - sig. signif. $\propto$ (exposure / ε)$^{1/2}$

- competitive with direct detection at ~ 4-5 GeV (but PICO-60 wins above this)
- SK, HK → win with exposure
  - WC detectors → size advantage
- other neutrino searches not sensitive (focused on high-energy neutrinos)

In, Kumar, Rott, Yaylali - 1510.00170



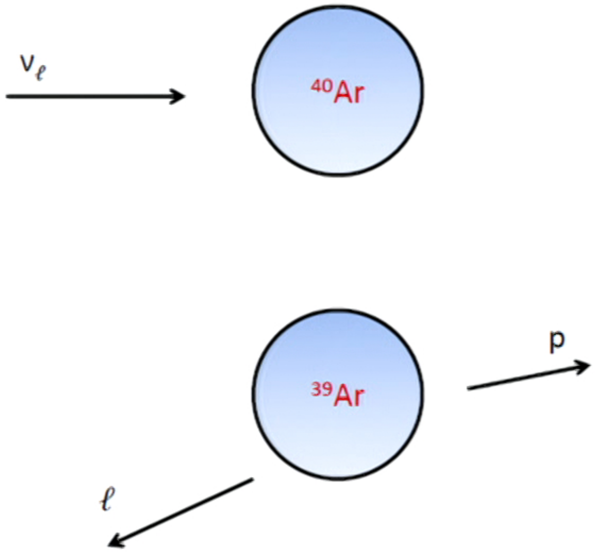
90% CL
annihilation to u or d
spin-dep. scattering

directionality

- for 34 kT yr exposure, DUNE atm. ν background is significant
- would be great to get a directionality cut
  - preferentially select events where ν arrives from the direction of the Sun
- reduces systematic uncertainties in background by comparing on-axis to off-axis event rates
  - want $S / B > \delta B_{sys.} / B$ → excess not just a systematic error
  - can measure B by going off axis (reduces $\delta B_{sys.} / B$)
  - increases S / B by picking events from the direction of the Sun
- can improve statistical significance
- most searches for neutrinos arising from dark matter annihilation utilize directionality...
- ... but usually when looking for a very energetic neutrino
  - CC-interaction produces a forward-peaked charged lepton

directionality for sub-GeV νs

- for sub-GeV ν, the charged lepton produced is mostly isotropic
- but the hadronic recoil is not!
- at this energy, get a lot of events where a single proton is ejected
  - $\nu_\ell + {}^{40}Ar \rightarrow \ell^- + p^+ + {}^{39}Ar$
- ejected in the forward direction
  - cut on proton direction
- but analytic approximations to the cross sections and distributions are lacking
- rely on numerical techniques
- NuWro



NuWro

- generate 10^5 events per flavor (ν_e or ν_μ)
- select events with...
  - one charged lepton track identified
  - one ejected proton track identified (kills $\bar{\nu}$ bgd.)
  - cuts at event generation level (no attempt to model detector)
    - just need particles generated above a threshold
- lepton threshold → 30 MeV
- proton threshold → 50 MeV (according to DUNE CDR...)
  - "tight"
- we'll also consider a more optimistic proton cut → 20 MeV
  - "loose"
- determine efficiency for signal events (η_S) and bgd events (η_B) to satisfy event selection and angular cuts

cuts and efficiencies

$$\frac{S}{B} \to \left(\frac{\eta_S}{\eta_B}\right) \times \frac{S}{B}$$

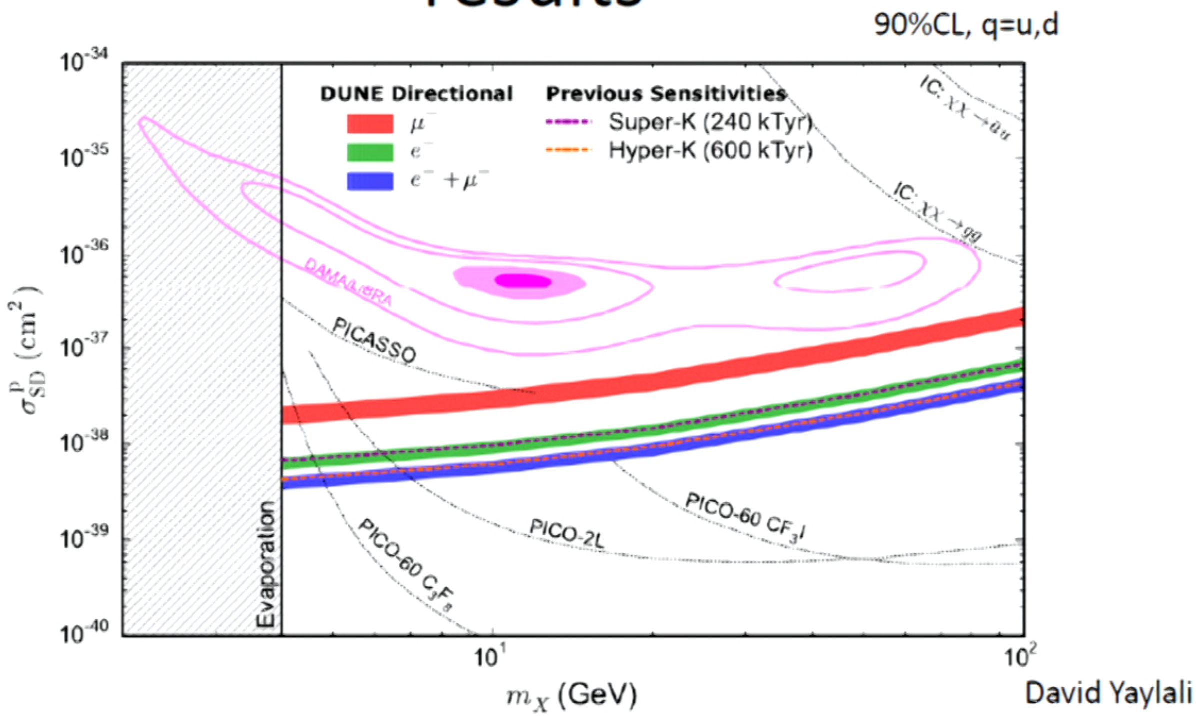
$$\frac{S}{\sqrt{B}} \to \left(\frac{\eta_S}{\eta_B}\sqrt{\eta_B}\right) \times \frac{S}{\sqrt{B}}$$

cut	S/B enhancement	sensitivity enhancement
tight:electron	4.8	1.2
tight: muon	4.5	1.0
loose:electron	3.4	1.4
loose:muon	3.5	1.4

tight → win on S/B (up to S/B ~0.4)
loose → win on sensitivity

- cuts: cone half-angle (≫ ang. res)
- tight: muon → 45°
- tight: electron → 50°
- loose: electron → 55°
- loose: muon → 55°
- S/B can improve by up to × 5
  - very good for on-/off-axis
- but signal significance only sees a modest improvement
  - big hit from small selection efficiencies
- win more on systematics than statistics

results



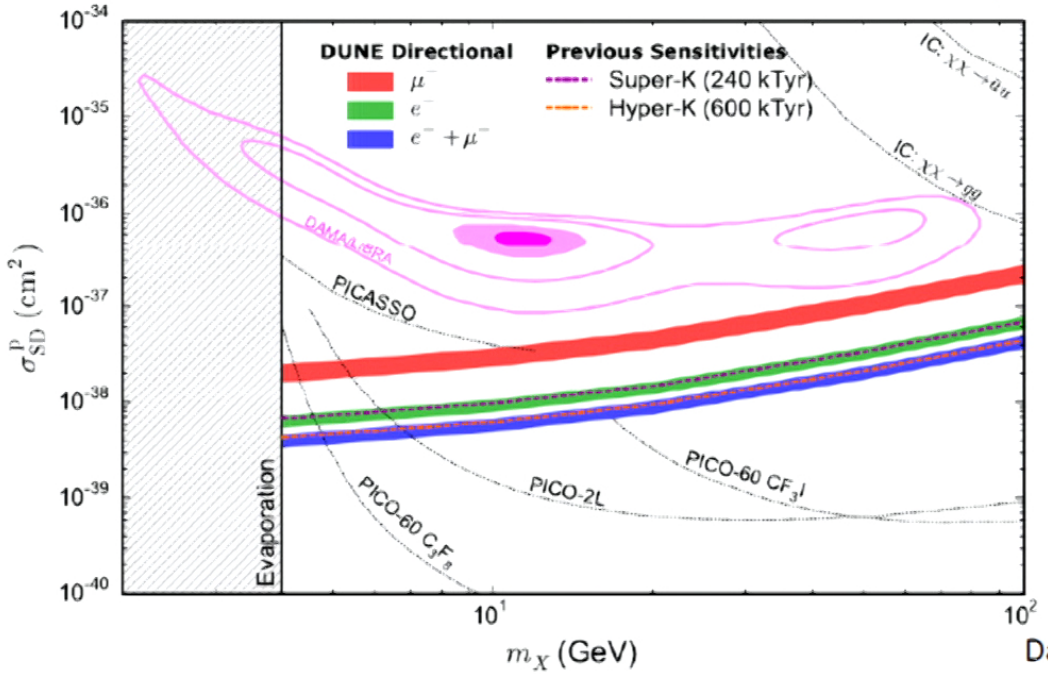
assume 340 kT yr ... need large exposure to offset selection efficiencies
dozens of background events
need a long run-time just to catch up to Super-K and PICO-60

what's the point of doing this at DUNE?

- for signal significance, WC detectors will always win because of exposure
- except for a small mass range, PICO is already winning
- but there are good reasons to search at DUNE
- directionality gives a new handle on systematic uncertainties and bgd.
  - no such directionality possible with WC detectors
  - PICO sensitivity is degrading rapidly < 10 GeV
  - different astrophysics uncertainties than direct detection
- if a signal is seen in the future, can get a handle on annihilation channel
  - is it asymmetric dark matter?
  - a 236 MeV line signal at DUNE from the Sun would be striking evidence of dark matter annihilation producing light quarks
  - cross section could be $\ll$ 1 pb, with Sun still in equilibrium
  - especially for low mass DM, hard to see this any other way
- important as a complementary search strategy

results

90%CL, q=u,d



David Yaylali

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conclusion

- dark matter annihilation in the Sun can produce monoenergetic 236 MeV neutrinos
  - produce numerous stopped K^+
- LArTPC ν-detectors can reconstruct energy and direction of products
  - can detect a neutrino line with good total energy resolution
  - can get directionality from ejected proton

- reduced backgrounds and systematic uncertainties
- sub-GeV ν directionality is a unique capability of DUNE
- stopped kaon experiment would help with calibration
- above all, need lots of exposure

Mahalo!