New Dark Matter Search Strategies at DUNE

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collaborators

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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

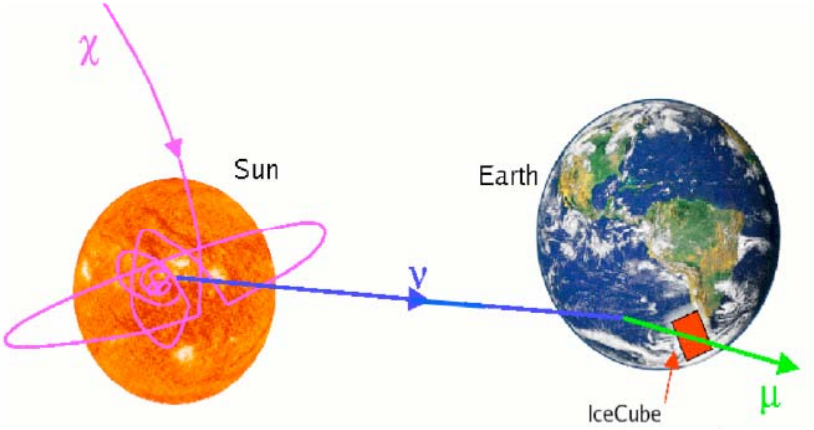
- experiment
  - DUNE will do very well at total energy reconstruction for a charged-current interaction
    - sensitive to a line signal
  - DUNE can also get the direction of the neutrino from the nucleon recoil
    - new type of directionality search
    - great for reducing systematic uncertainty

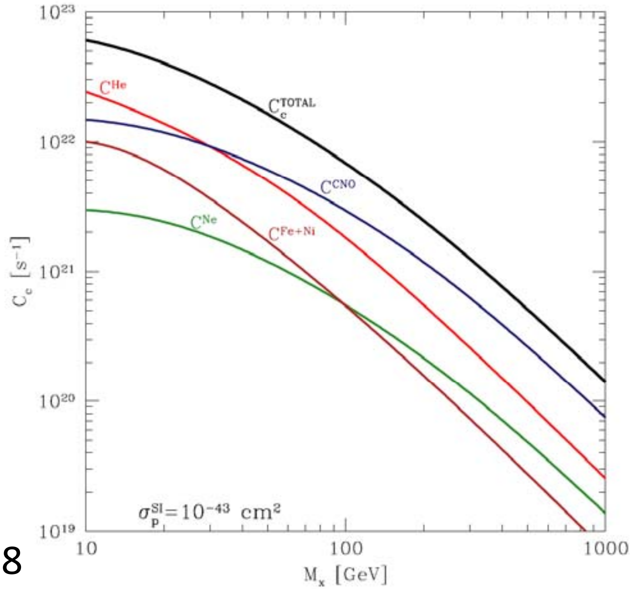
neutrinos from the Sun

(see Carsten Rott's talk....)

- 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



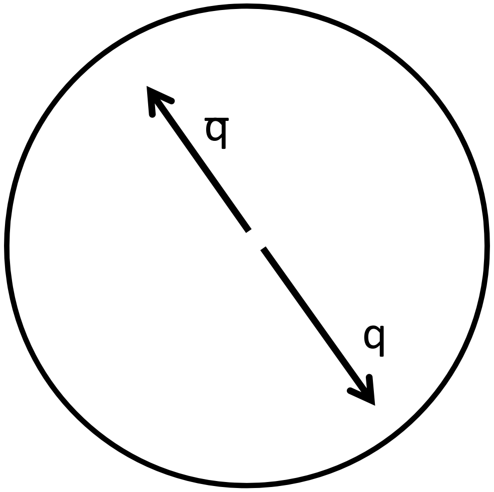


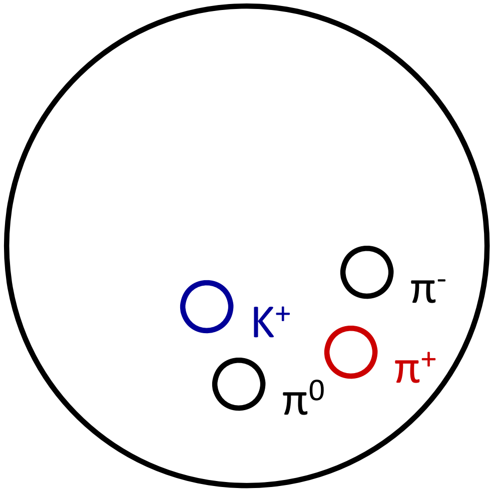
A. Zentner, arXiv:0907.3448

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)]





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

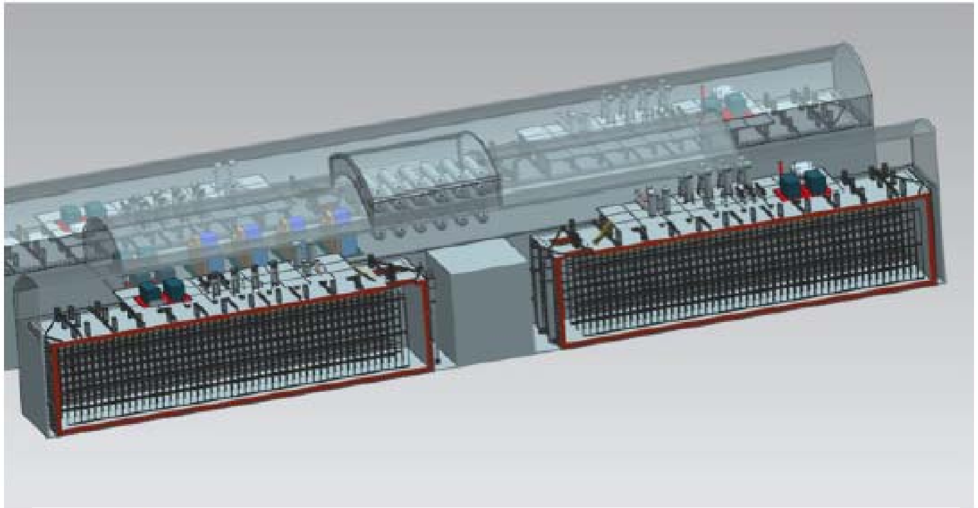
DUNE

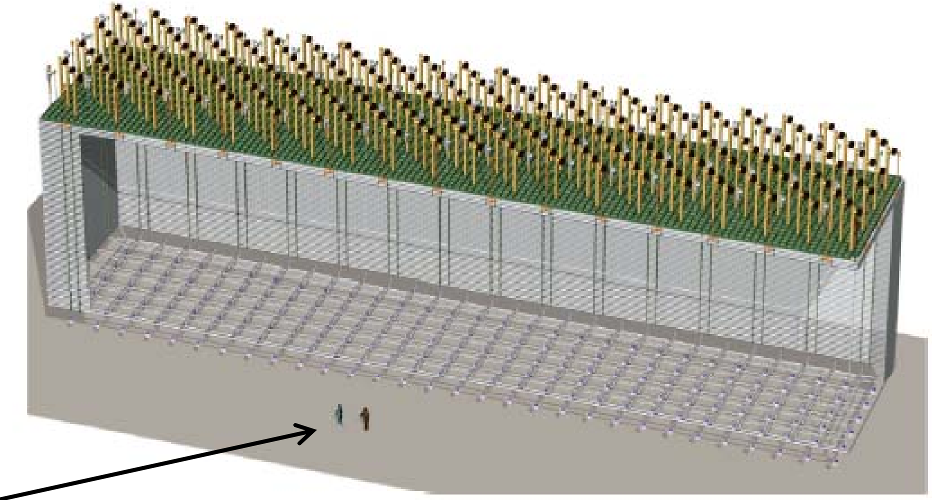
1601.02984

- 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 ~ 5°
  - total energy res. – $\varepsilon \sim 10\%$



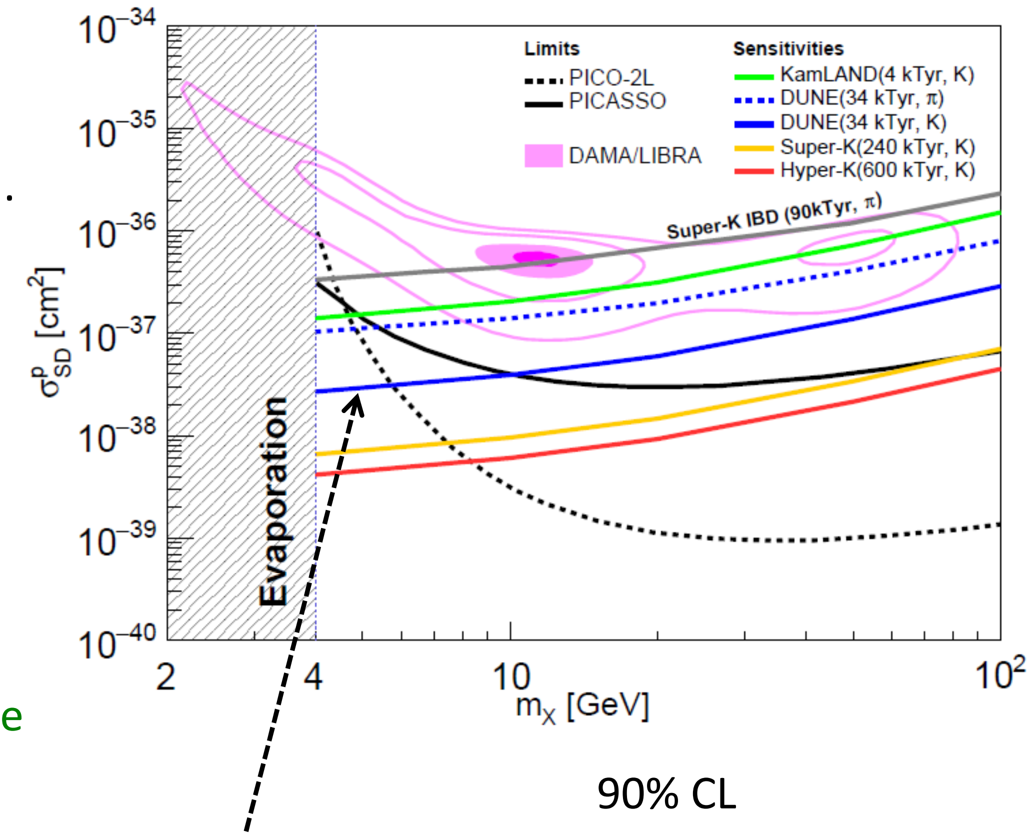


a theorist, for scale

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

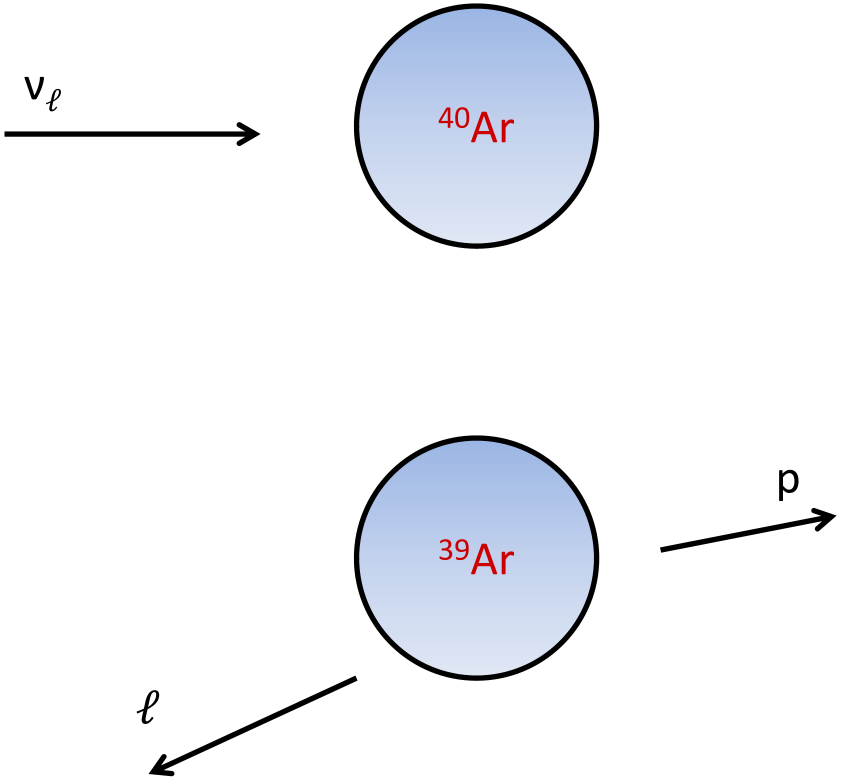
90% CL
annihilation to u or d
spin-dep. scattering

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
  - $\nu_\ell + {}^{40}\mathrm{Ar} \rightarrow \ell^- + p^+ + {}^{39}\mathrm{Ar}$
- 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



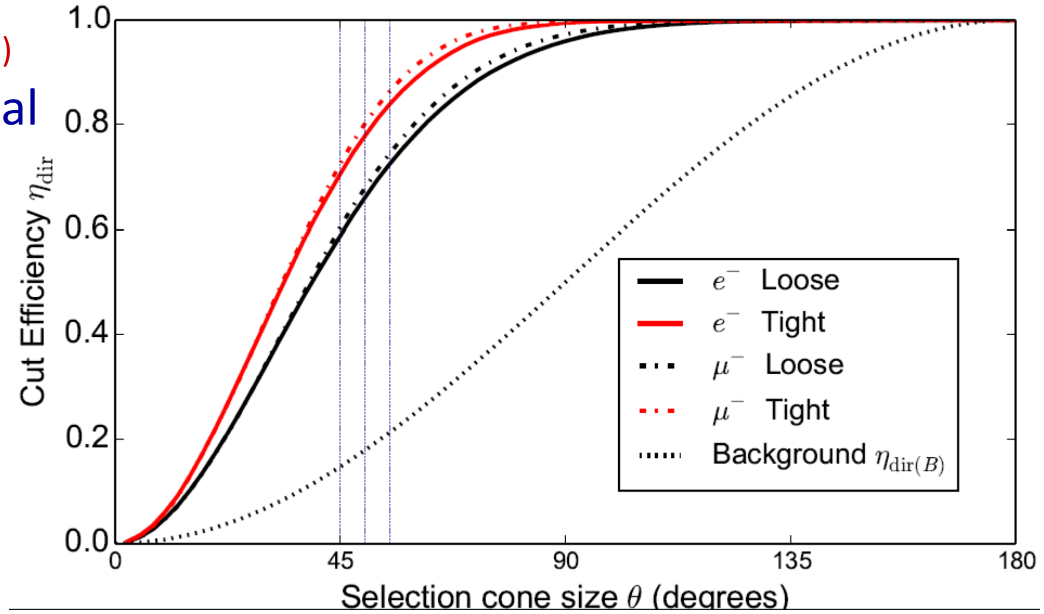
NuWro

- 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

sensitivity and systematics

- two efficiencies
  - event selection (η_{sel})
    - common to S and B
  - directional (η_{dir})
    - fraction of events in forward cone from the Sun
    - better for S than for B
- total efficiency $\eta_{S,B} = \eta_{sel} \times \eta_{dir(S,B)}$
- care about improvement to signal significance, and to S-to-B ratio
- we'll choose cuts to maximize improvement for signal significance for fixed exposure
  - other choices possible...

cut	proton threshold	selection efficiency (η_{sel})
tight:electron tight:muon	$E_{kin} > 50$ MeV $E_{kin} > 50$ MeV	0.43 0.28
loose:electron loose:muon	$E_{kin} > 20$ MeV $E_{kin} > 20$ MeV	0.83 0.75



cuts and efficiencies

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

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

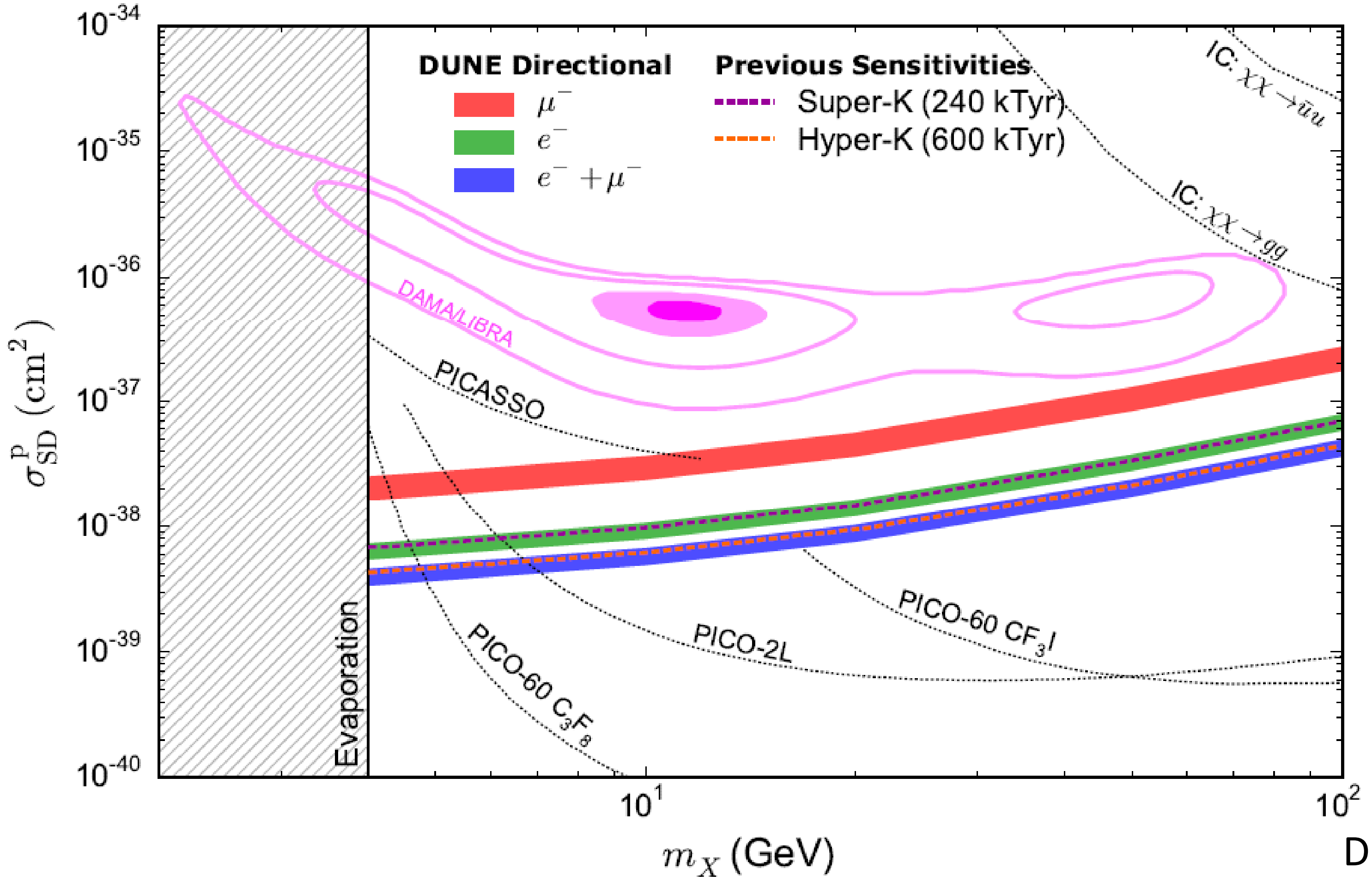
cut	**S/B enhancement**	**sensitivity enhancement**
tight:electron	4.8	1.2
tight: muon	4.5	1.0
loose:electron	3.4	1.4
loose:muon	3.5	1.4

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

90%CL, q=u,d



David Yaylali

assume 340 kT yr ... need large exposure to offset selection efficiencies

dozens of background events

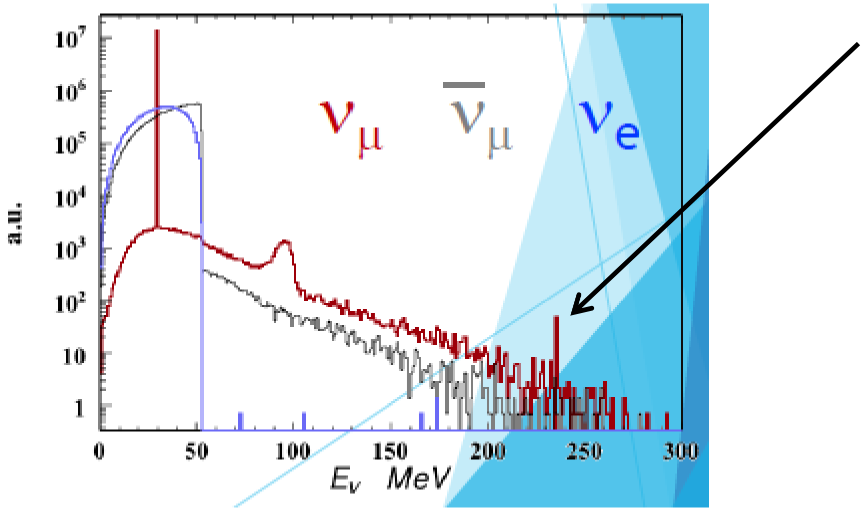
need a long run-time just to catch up to Super-K and PICO-60

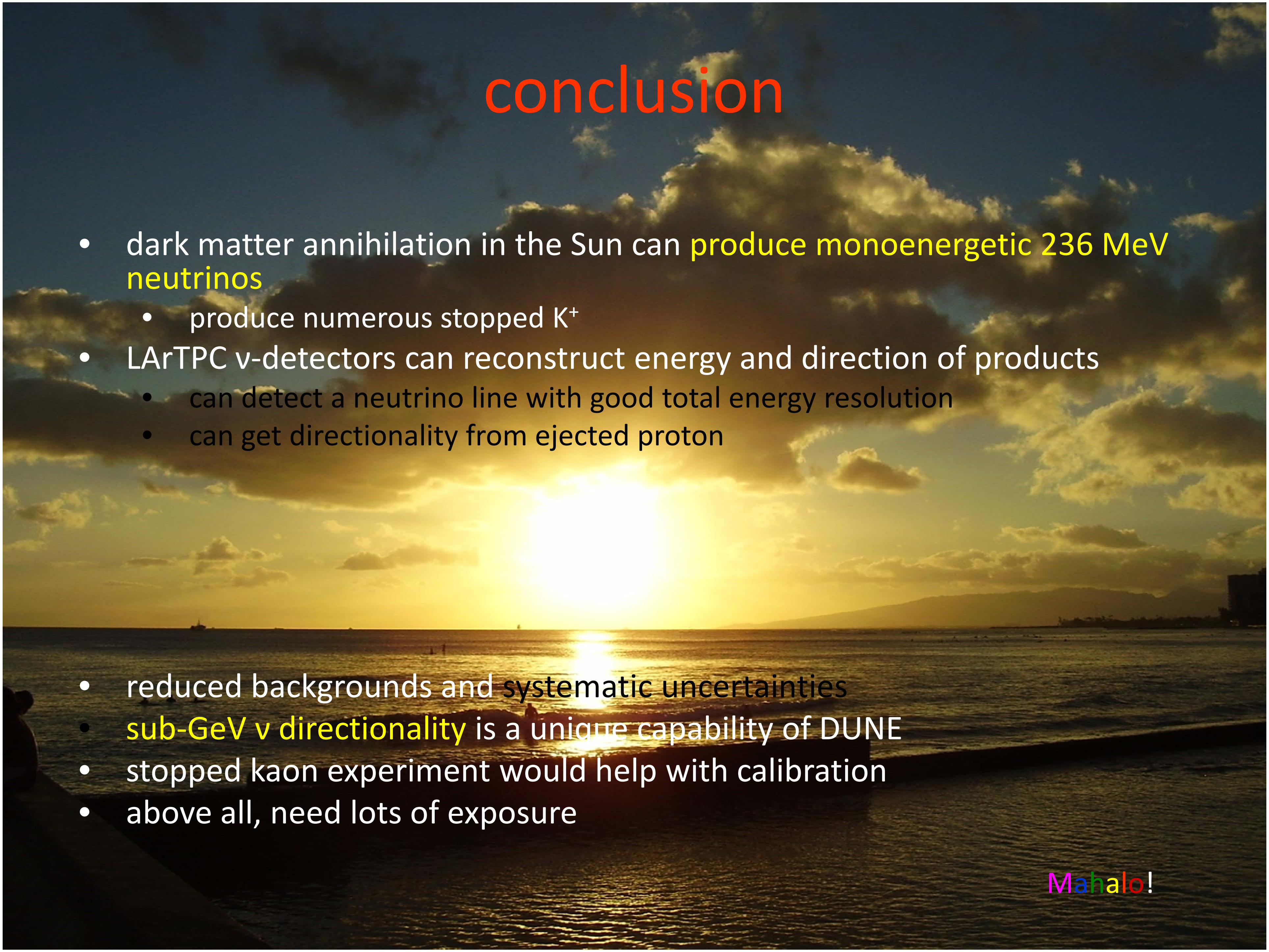
what's the point of doing this at DUNE?

- 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

resolving uncertainties

- a lot of uncertainty in the neutrino-nucleus scattering cross section, etc.
  - really a proof-of-principle
- can “calibrate” by comparing rates on-axis vs. background off-axis
- but can also calibrate directly with a stopped kaon experiment
- a stopped pion experiment is also a stopped kaon experiment
- stopped pion proposals like DAEδALUS are under consideration for DUNE
- can also put an LArTPC at a stopped pion experiment
  - CAPTAIN at SNS (see Lisa Whitehead Koerner’s parallel talk....)





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

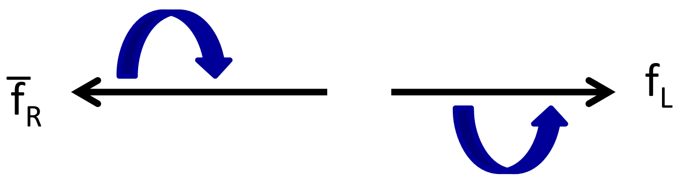
Mahalo!

Back-up slides

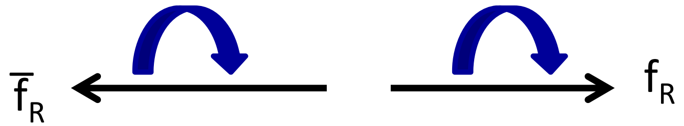
why (not) $\chi\chi \rightarrow \bar{f}f$ (f=u,d,s)?

- can understand just from angular momentum
- for Majorana fermion, wavefunction is anti-symmetric
  - L=0, S=0 or L=1, S=1
- if outgoing fermions on z-axis
  - $L_z=0$ ($Y_{lm}(\theta=0,\phi)\neq 0$ only if m=0)
  - $S_z = J_z$
- if $S_z=0$ need f, $\bar{f}$ with same helicity
  - not CP-conjugate
  - need Weyl spinor mixing
  - in MFV, mixing scales with mass
- if $S_z=\pm 1$ need f, $\bar{f}$ with opp. helicity
  - no mixing needed

J=0, $L_Z=0 \rightarrow S_Z=0$



$J_Z=1$, $L_Z=0 \rightarrow S_Z=1$



monoenergetic neutrinos

- this argument underlies the theoretical prejudice towards searches for the $\bar{b}\,b$, $\bar{\tau}\,\tau$ and $W^+\,W^-$ channels
- but the chirality suppression arises from the assumption of Majorana fermion dark matter and minimal flavor violation
  - certainly true for the CMSSM, but need not be true in general
  - WIMPs need not be Majorana, and MFV can fail even in the general MSSM
- if dark matter is a Dirac fermion, then the initial state can be L=0, S=1, J=1, so s-wave annihilation, but no mixing needed
- if we drop minimal flavor violation, then mixing need not scale with quark mass
- either way, $\chi\chi \rightarrow \bar{q}q$ ($q = u, d, s$) branching fraction could be $\mathcal{O}(1)$
- worth studying these annihilation channels

signal limited – K^+

- compare to π^+ channel
- larger cross section
  - larger effective area (> ×100)
  - need smaller exposure to get signal (or bgd.) events
- fewer K^+ per annihilation
  - backgrounds similar
    - smaller flux, larger bin
  - factor 5-10 smaller S/B
- upshot
  - better sensitivity with small exposure
  - leaves linear regime first
  - ultimate sensitivity comparable

$$N^{\mathrm{DUNE}}_{\mathrm{bgd.,236\ MeV}} \approx (486)\varepsilon\left(\frac{M_{\mathrm{Ar}}}{34\ \mathrm{kT}}\right)\left(\frac{T}{\mathrm{yr}}\right)$$

$$\frac{S}{B} \approx \frac{0.83}{\varepsilon}\frac{\sigma^{p}_{\mathrm{SD}}}{\mathrm{pb}}$$

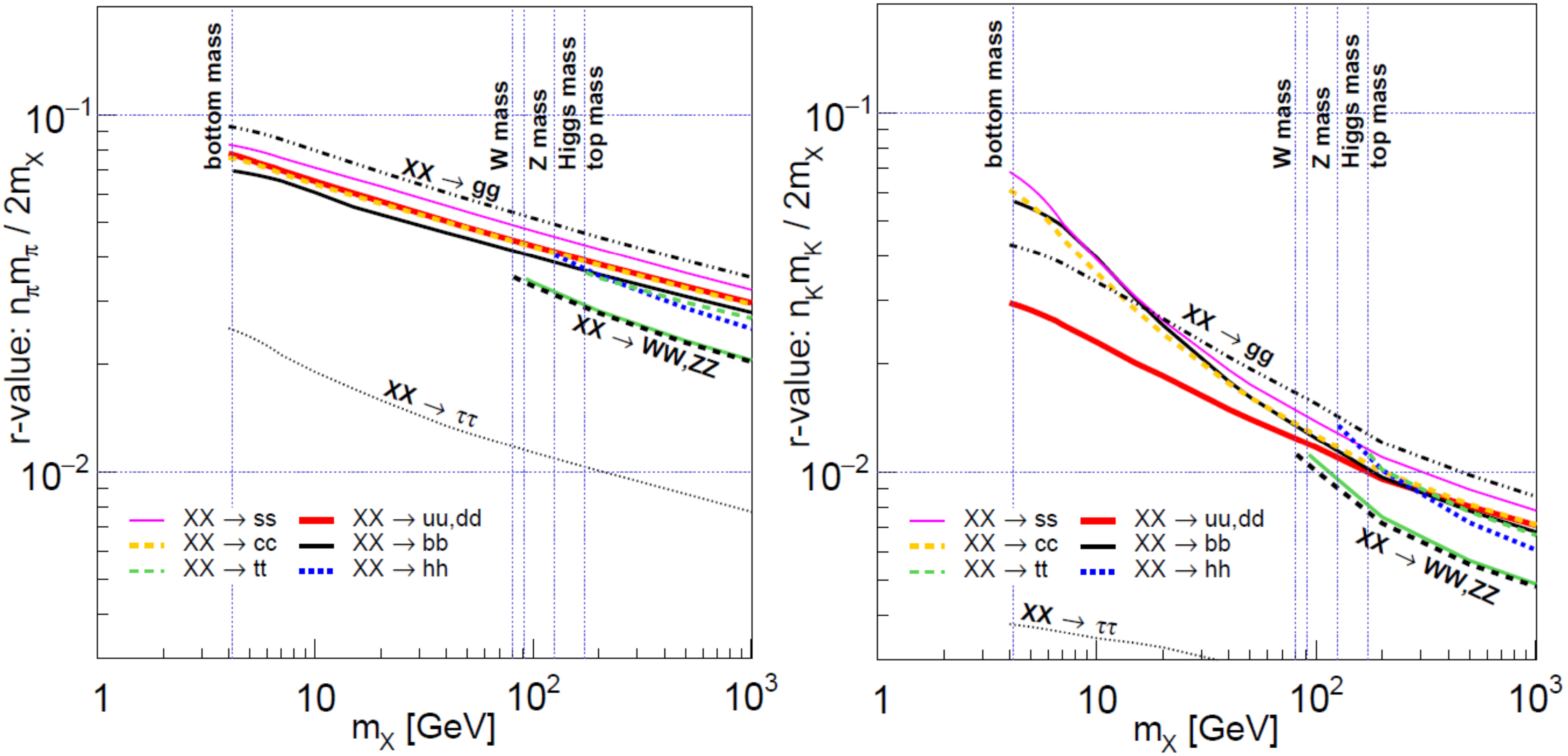
$$E^{\mathrm{Ar}}_{\mathrm{opt}} \approx \frac{0.07}{\varepsilon}$$

issues with the cross section at $\mathcal{O}(100)$ MeV (a novice's view)

- basic idea → impulse approximation (IA)
  - neutrino interacts with a single struck nucleon
  - subsequent interactions between struck nucleon and rest of nucleus
- can model the nucleus state as...
  - Fermi gas
  - using a more detailed spectral function obtained from theory and electron scattering experiments
- spectral function is a better model...
- ...but analysis still based on IA
- IA becomes less valid an approximation for $E_\nu < 100$ MeV
  - Ankowski, Soczyk -- 0709.2139
  - no good tool for going beyond IA, though
  - best to just calibrate

r-factors

1510.00170



r decreases with m_X

about ×10 more 30 MeV vs than 236 MeV vs per annihilation for u and d channels

the pieces we need....

- we have the neutrino fluxes from the Sun arising from DM....
- we have estimates of the $\nu_{e,\mu}$ background at E ~ 236 MeV (atm. ν)
- charged current neutrino-nucleus scattering cross section ($\nu_\ell + n \rightarrow \ell + p$)
  - for E ~ 236 MeV, theory complicated
    - dominant contribution is quasi-elastic
    - not very well understood
    - rely on numerical packages
    - NuWro

Battistoni, Ferrari, Montaruli, Sala

$$\frac{d^2\Phi^e_B}{d\Omega dE} \approx 1.2\ \mathrm{m^{-2}s^{-1}sr^{-1}MeV^{-1}}$$

$$\frac{d^2\Phi^\mu_B}{d\Omega dE} \approx 2.3\ \mathrm{m^{-2}s^{-1}sr^{-1}MeV^{-1}}$$

($\bar{\nu}$ similar)

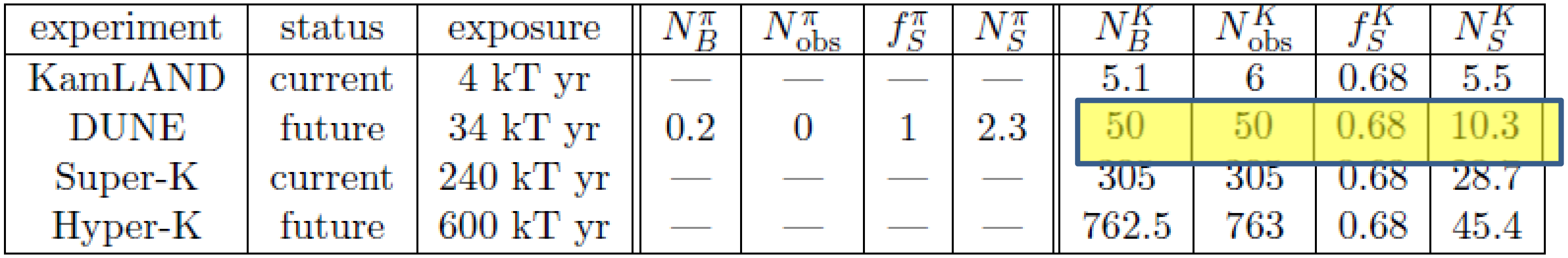
$$\sigma^e_{CC}\left(236\ \mathrm{MeV}\right) \approx 4.2 \times 10^{-38}\ \mathrm{cm}^2$$

$$\sigma^\mu_{CC}\left(236\ \mathrm{MeV}\right) \approx 2.7 \times 10^{-38}\ \mathrm{cm}^2$$

NuWro

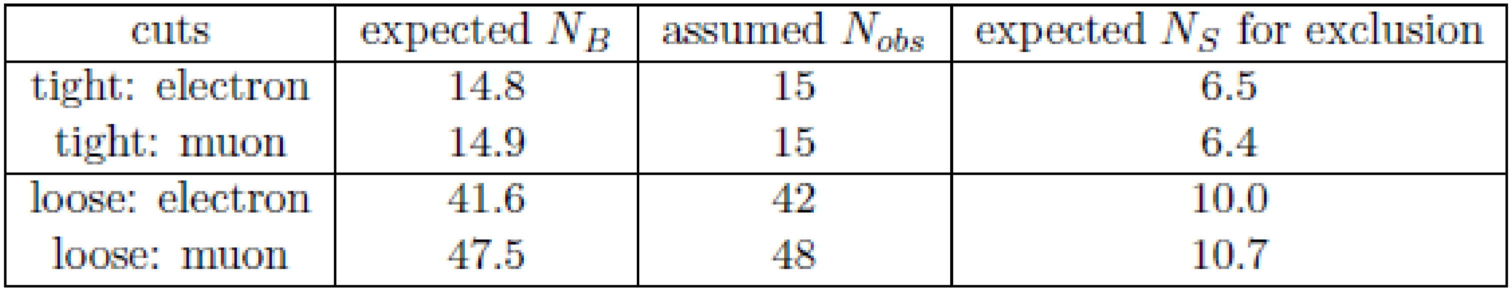
90% CL numbers

non-directional search, electron channel



experiment	status	exposure	N_B^π	$N_{\rm obs}^\pi$	f_S^π	N_S^π	N_B^K	$N_{\rm obs}^K$	f_S^K	N_S^K
KamLAND	current	4 kT yr	—	—	—	—	5.1	6	0.68	5.5
DUNE	future	34 kT yr	0.2	0	1	2.3	50	50	0.68	10.3
Super-K	current	240 kT yr	—	—	—	—	305	305	0.68	28.7
Hyper-K	future	600 kT yr	—	—	—	—	762.5	763	0.68	45.4

directional search, 340 kT yr exposure



cuts	expected N_B	assumed N_{obs}	expected N_S for exclusion
tight: electron	14.8	15	6.5
tight: muon	14.9	15	6.4
loose: electron	41.6	42	10.0
loose: muon	47.5	48	10.7