Dark Matter Search with MeV Neutrinos from the Sun

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BSM Physics parallel session

DUNE Collaboration meeting

Outline

- *Executive Summary / Motivation*
- *Dark Matter capture in the Sun and current indirect searches*
- *Signal from low-energy (MeV) neutrinos from Dark Matter annihilations in the Sun*
- *Sensitivity*
  - *Estimate based on detector volume*
  - *Estimate using directionality*
- *Conclusions*

- *New Sensitivity to Solar WIMP Annihilation using Low-Energy Neutrinos* C. Rott, J. Siegal-Gaskins, J. F. Beacom Phys.Rev. D88 (2013) 055005 / arXiv:1208.0827
- *A novel way of constraining WIMPs annihilations in the Sun: MeV neutrinos* N. Bernal, J. Martín-Albo, S. Palomares-Ruiz JCAP 1308 (2013) 011 / arXiv:1208.0834
- *Dark Matter Searches for Monoenergetic Neutrinos Arising from Stopped Meson Decay in the Sun* C. Rott, S. In, J. Kumar, D. Yaylali JCAP 1511 (2015) no.11, 039 / arXiv:1510.00170
- *Directional Searches at DUNE for Sub-GeV Monoenergetic Neutrinos Arising from Dark Matter Annihilation in the Sun* C. Rott, S. In, J. Kumar, D. Yaylali JCAP 1701 (2017) no.01, 016 / arXiv:1609.04876
- *New Dark Matter Search Strategies at DUNE*, C. Rott, S. In, J. Kumar, D. Yaylali, TAUP2017 Proceedings contribution / arXiv:1710.03822

Executive Summary I

- DUNE can have important scientific impact in the search for dark matter annihilation in the Sun
  - Dark matter scatters off solar nuclei, collects in core of the Sun, and annihilation produces neutrinos detectable on Earth
  - DUNE's excellent energy resolution, angular resolution, and particle identification can provide unique capabilities to search for this signal
- Scientific target → $\mathcal{O}$(GeV) dark matter with spin-dependent (SD) scattering off nuclei, annihilating to light quarks
  - Most interesting signal: Monoenergetic $\mathcal{O}$(10-100) MeV neutrinos produced by π^+ and K^+ decay at rest
    - DUNE can do well in reconstructing these event
    - for $K^+ \to \nu_\mu \mu^+$, 236 MeV neutrinos will typically eject an argon proton in the forward direction, giving directionality from hadronic recoil
      - Directionality from hadronic recoil is a unique capability for DUNE

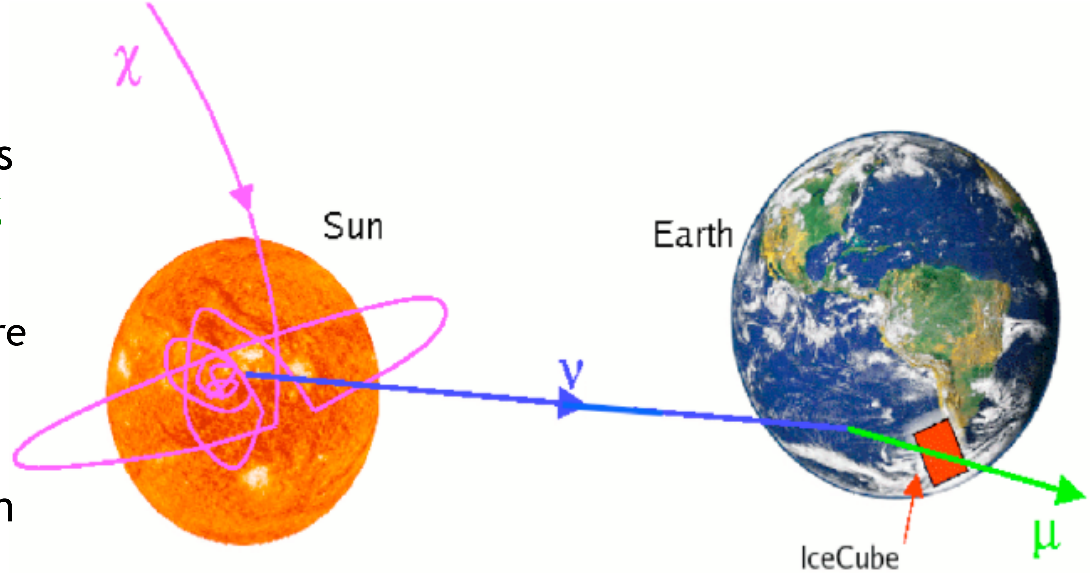
Executive Summary II

- Broader motivation
  - Direct detection (foremost PICO) and WC detectors can also cover much of this parameter space, but DUNE complements them
    - Direct detection is losing sensitivity at low recoil energy
    - Avoids some astrophysical uncertainties which face direct detection
    - Directionality from DUNE provides on/off-source background estimation
- Scenarios of interest
  - Can determine if DM annihilates to light quarks, even at very small cross section → unique capability
  - If a signal for $\mathcal{O}$(GeV) DM is seen in any experiment, it could be asymmetric dark matter → DUNE can rule this out
  - If there is a local DM underdensity, DUNE can beat direct detection

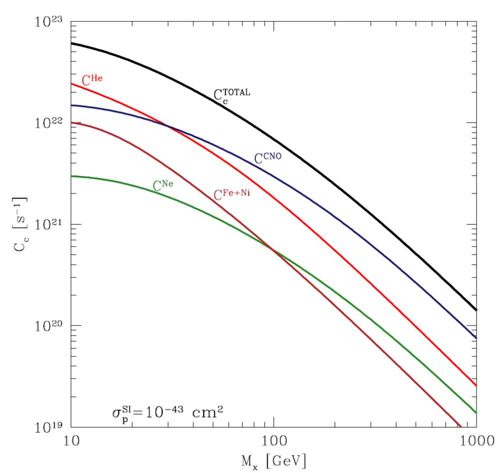
Dark Matter capture in the Sun and current searches

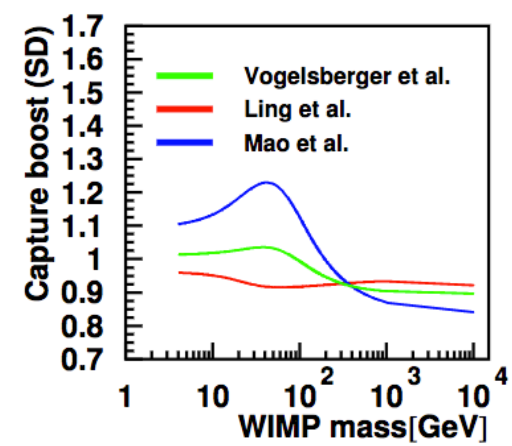
Dark Matter Capture in the Sun

- 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 particles
  - SM decay yields neutrinos → seen at detector
  - DM in equilibrium → $\Gamma_C = 2\,\Gamma_A$
  - So neutrino event rate probes DM capture rate ($\propto \sigma_{SI}$, σ_{SD})
  - Dark Matter capture in the Sun has little dependence on underlying dark matter halo models



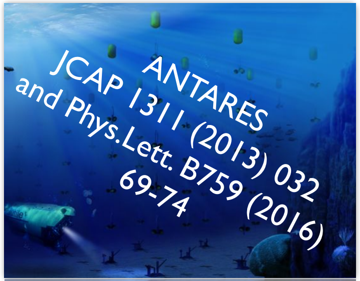
K. Choi, C. Rott and Y. Itow JCAP05(2014)049

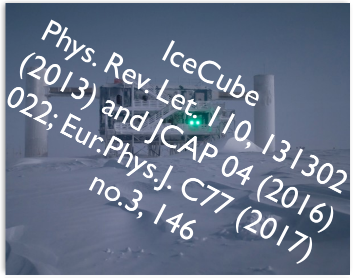


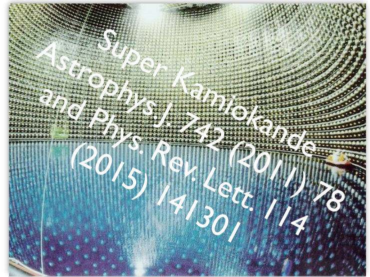


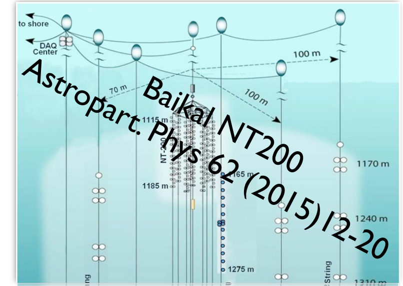
A. Zentner, arXiv:0907.3448

Solar Dark Matter Summary



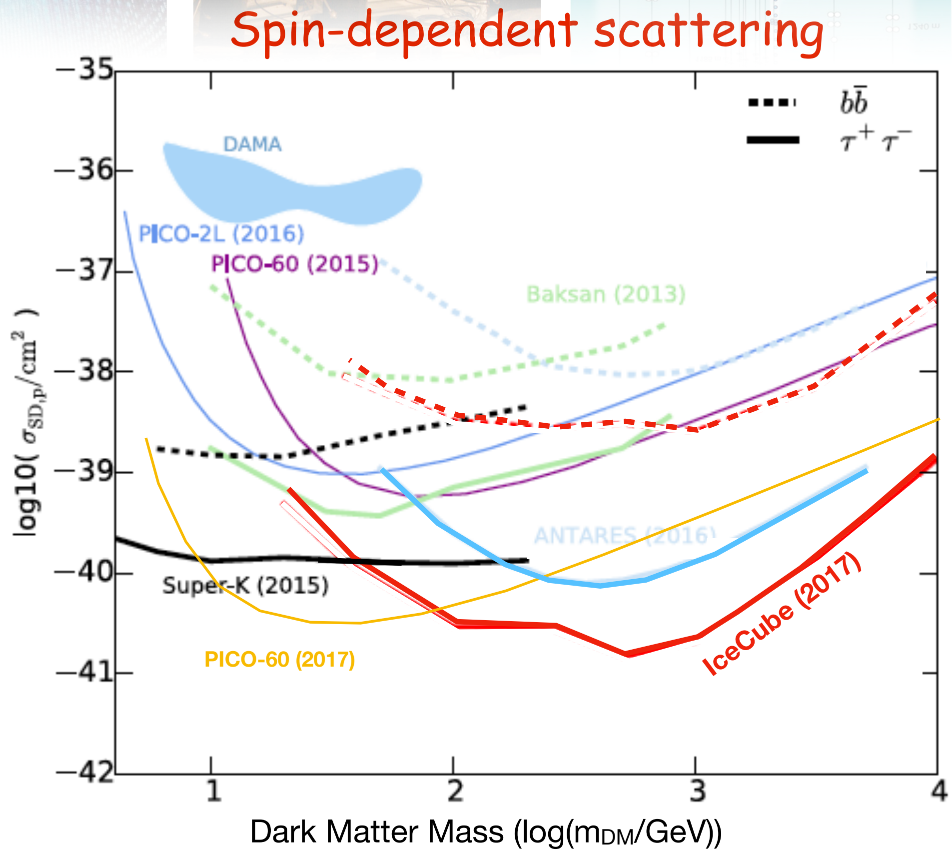






The Sun has been a target for dark matter searches for a long time

- Some of the the world's strongest bounds on dark matter scattering with nucleons have been obtained
- Dark Matter searches from the Sun are complementary to direct dark matter searches.
  - Dark matter capture in the Sun depends very differently on underlying dark matter distributions compared to rates at direct detection experiments



Signal from low-energy (MeV) neutrinos from Dark Matter annihilations in the Sun

MeV Neutrinos from the Sun

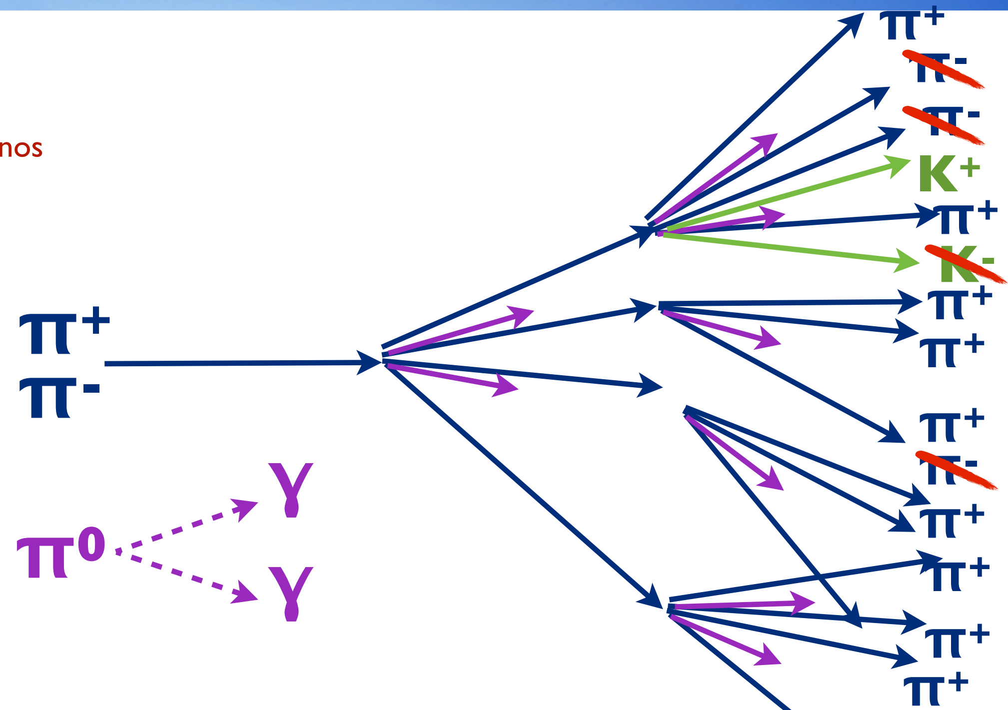
Possible annihilation channels:

$q\bar{q}, gg, c\bar{c}, s\bar{s}, b\bar{b}, t\bar{t}, W^+W^-, ZZ, \tau^+\tau^-, \mu^+\mu^-, \nu\nu, e^+e^-, \gamma\gamma$

few neutrinos

some "high energy" neutrinos in decays
⇒ basis of present day searches

dominant decay into hadrons



decay at rest

- Hadrons in the Sun …
  - interaction length short compared to energy loss length
  - produces secondary particles in collision with protons
  - Dominant energy loss term is π^0 production
  - At the end of the shower charged (+) pion and kaon decay at rest
- π^0 lifetime too short to interact

Simulation (Pythia + GEANT4) to determine pion and kaon yields per channel. Define r-value as the fraction of center-of-mass energy that goes into pions (π^+) or kaons(K^+) decaying at rest.

Charged pions and kaons decay at rest producing mono-energetic neutrinos

$\pi^+ \rightarrow \mu^+ \nu_\mu$ E_ν = 29.8MeV

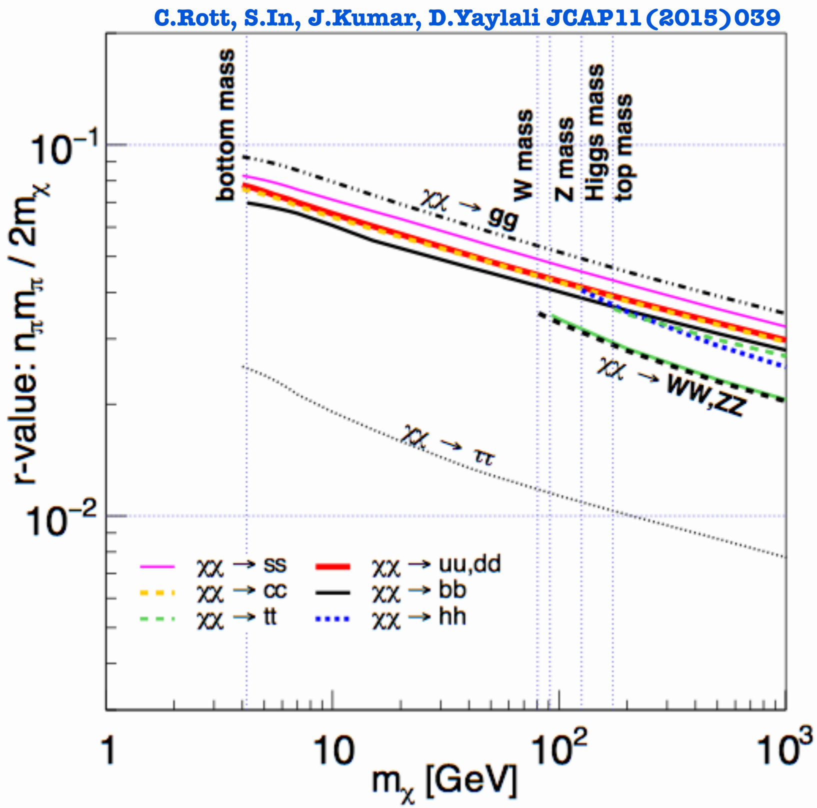
$K^+ \rightarrow \nu_\mu \mu^+$ E_ν=235.5MeV

$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$

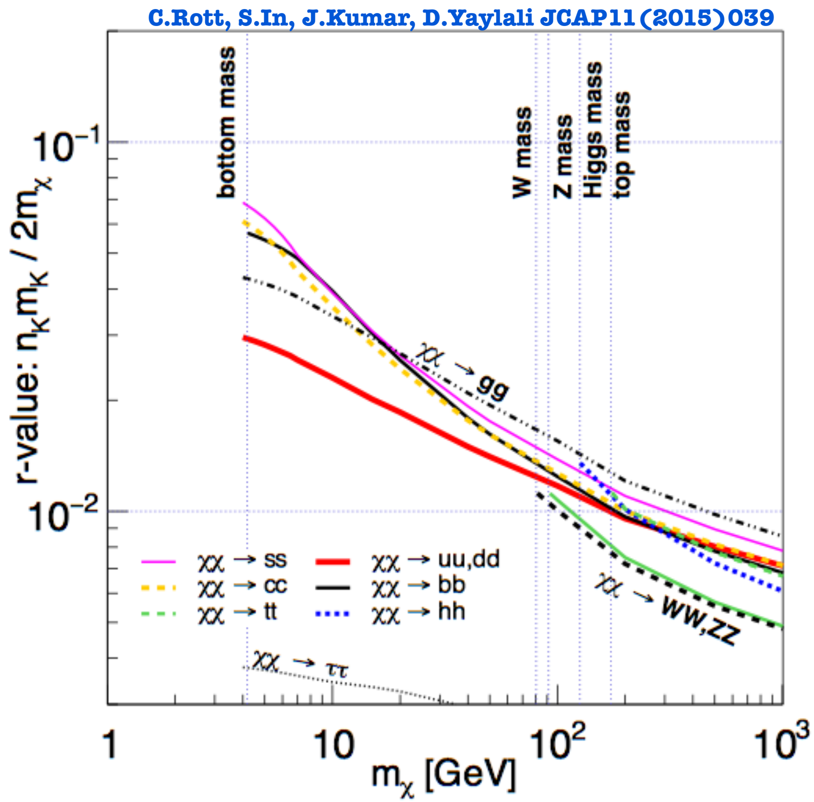
- C. Rott, J. Siegal-Gaskins, J. F. Beacom Phys.Rev. D88 (2013) 055005 / arXiv:1208.0827
- N. Bernal, J. Martín-Albo, S. Palomares-Ruiz JCAP 1308 (2013) 011 / arXiv:1208.0834

Pion and Kaon yields

π^+ r-value - fraction of center-of-mass energy which goes into π^+



K^+ r-value - fraction of center-of-mass energy which goes into K^+



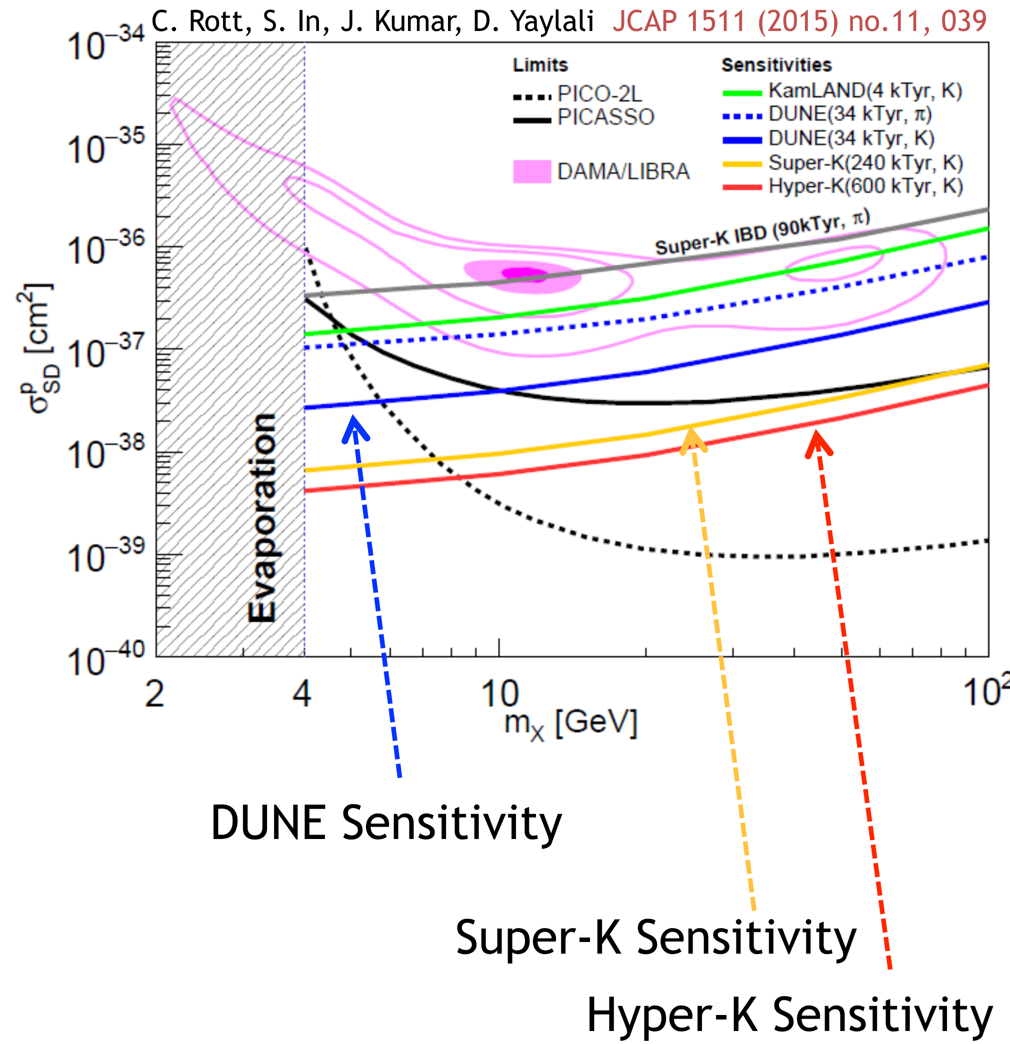
For low dark matter masses difference between flux from stopped pion and kaon decay at rest can be used to disentangle annihilation final states

Sensitivity estimate based on detector volume

sensitivity for non-directional search

- Assume 34 kT yr exposure, e-channel
  - ~ 50 bgd. events (K^+)
  - 90%CL exclusion, assuming observation consistent with bgd.
  - sig. signif. $\propto$ (exposure / ε)$^{1/2}$
- our benchmarks
  - total energy res. – ε ~ 10%
- competitive with direct detection at ~ 4-5 GeV (but PICO-60 wins above)
- SK, HK → win with exposure
  - WC detectors → size advantage
- Other current neutrino searches not sensitive (focused on high-energy neutrinos) and different annihilation channels

Annihilation to u or d quarks



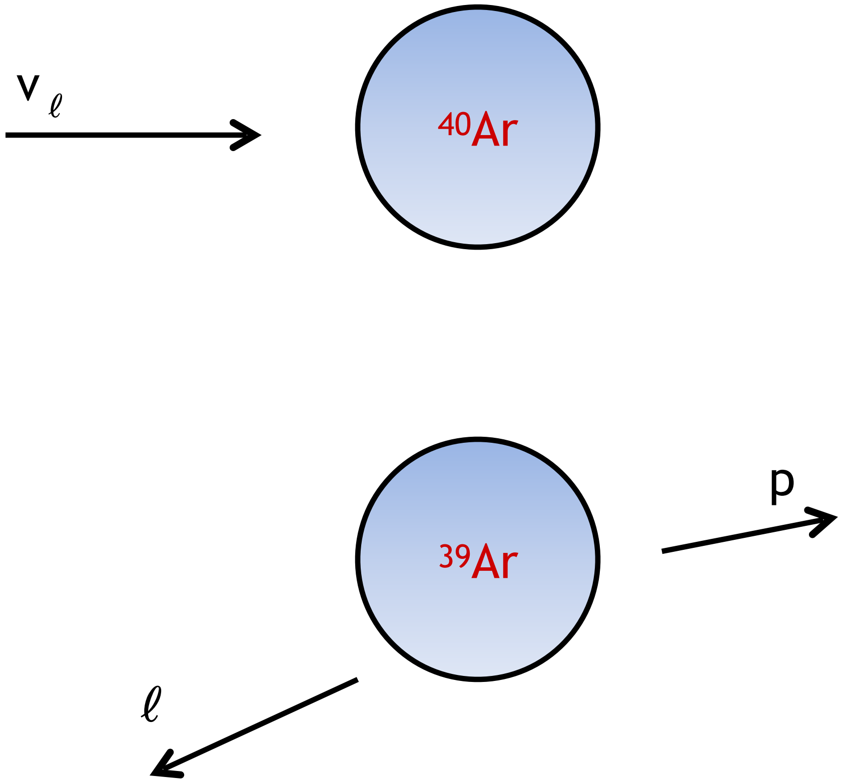
Sensitivity estimate using directionality

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 $S / B > \delta B_{sys.} / B \rightarrow$ 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 Neutrinos

- for sub-GeV ν, the charged lepton produced is mostly isotropic
- but the hadronic recoil is not!
- at 236 MeV, 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

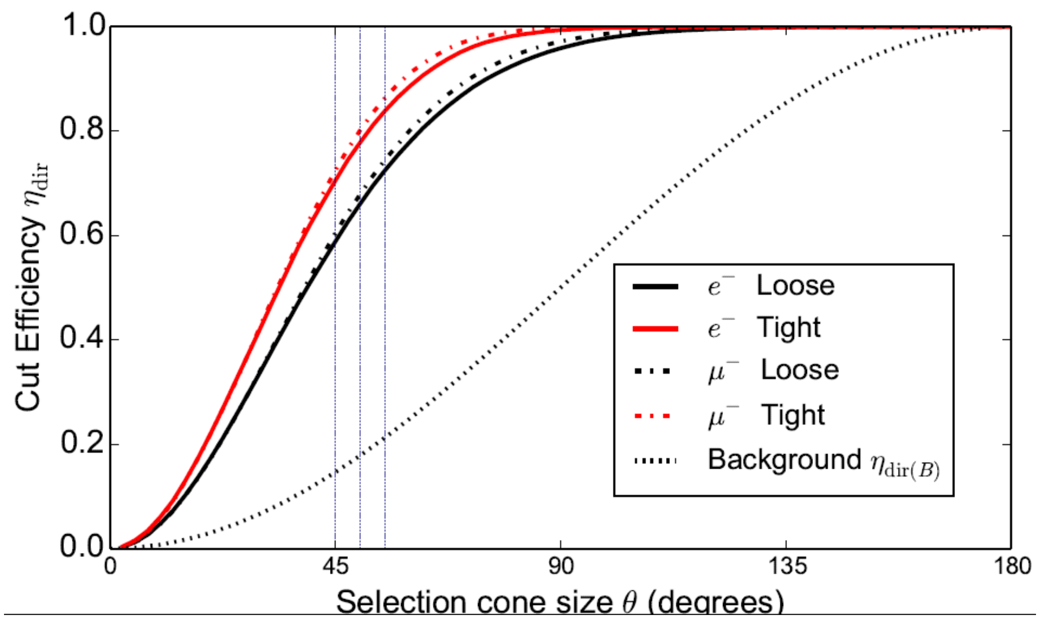
- generate 10^5 events per flavor (ν_e or ν_μ)
- select events with...
  - one charged lepton track identified
  - one ejected proton track identified (kills $\bar{\nu}$ bgd.)
  - cuts at event generation level (no attempt to model detector)
    - just need particles generated above a threshold
- lepton threshold → 30 MeV
- proton threshold →
  - "tight" (50MeV) … according to DUNE CDR
  - "loose" (20MeV) … optimistic scenario

- determine efficiency for signal events (η_S) and bgd events (η_B) to satisfy event selection and angular cuts

sensitivity and systematics

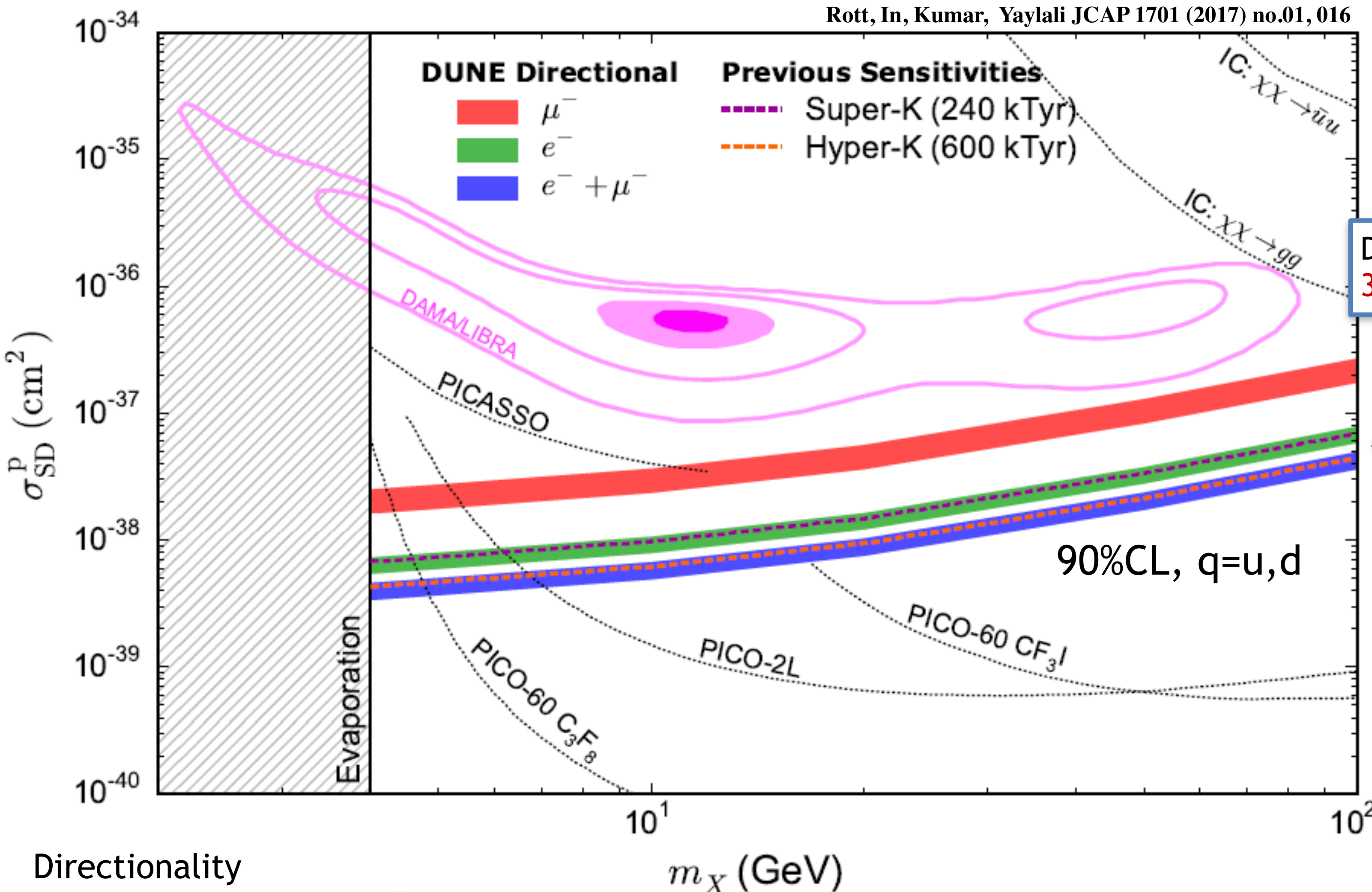
- Two efficiencies
  - event selection (η_{sel})
    - common to S and B
  - directional (η_{dir})
    - fraction of events in forward cone from the Sun
    - better for S than for B
- Total efficiency $\eta_{S,B} = \eta_{sel} \times \eta_{dir(S,B)}$
- Care about improvement to signal significance, and 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



Sensitivities

Rott, In, Kumar, Yaylali JCAP 1701 (2017) no.01, 016



DUNE Sensitivity
340 kT yr

Directionality

- S/B can improve by up to × 5
- Improves sensitivity by 10 - 40%

Conclusion

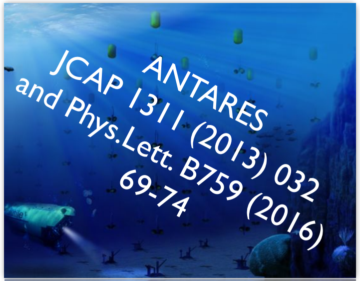
- dark matter annihilation in the Sun can produce monoenergetic 30 MeV and 236 MeV neutrinos
  - produce numerous stopped π^+ and K^+
- LArTPC ν-detectors can reconstruct energy and direction of products
  - can detect a neutrino line with good total energy resolution
  - can get directionality from ejected proton

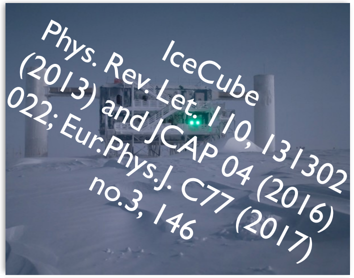
- reduced backgrounds and systematic uncertainties
- sub-GeV ν directionality is a unique capability of DUNE
- stopped pion/kaon experiment would help with calibration
- above all, need lots of exposure
- We have prepared a draft summary for the TDR

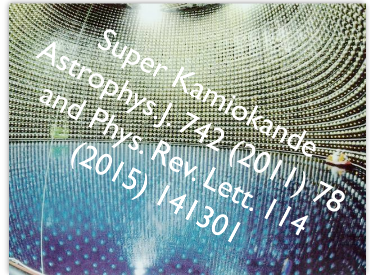
Mahalo!

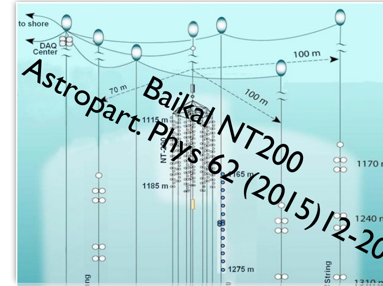
Back-up slides

Solar Dark Matter Summary



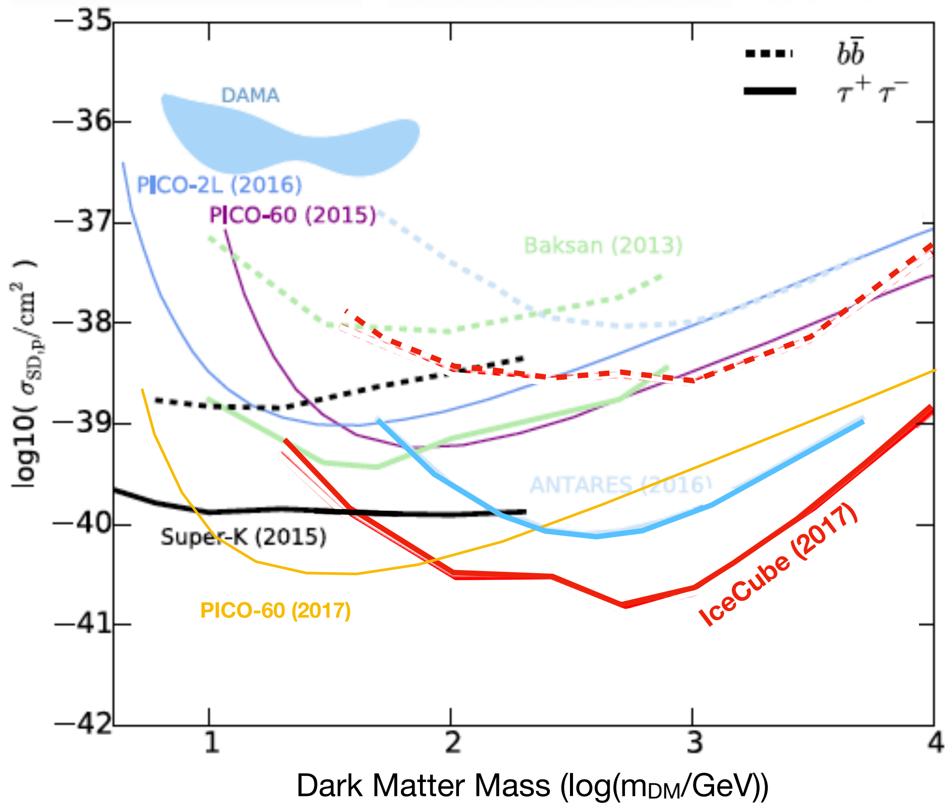


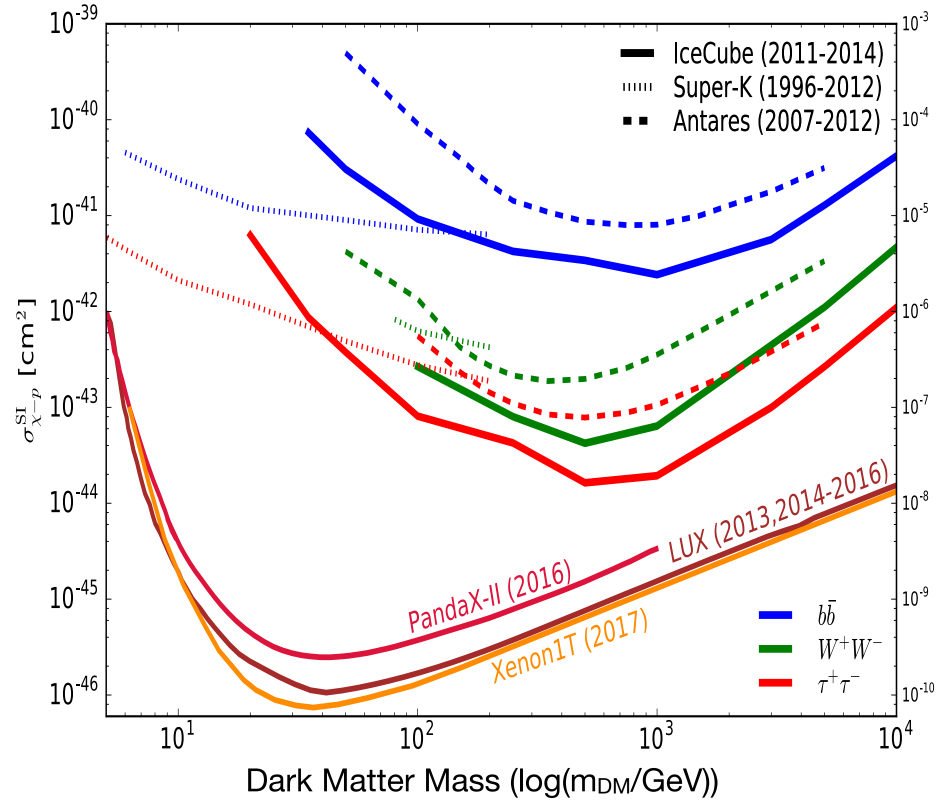




Spin-dependent scattering

Spin-independent scattering



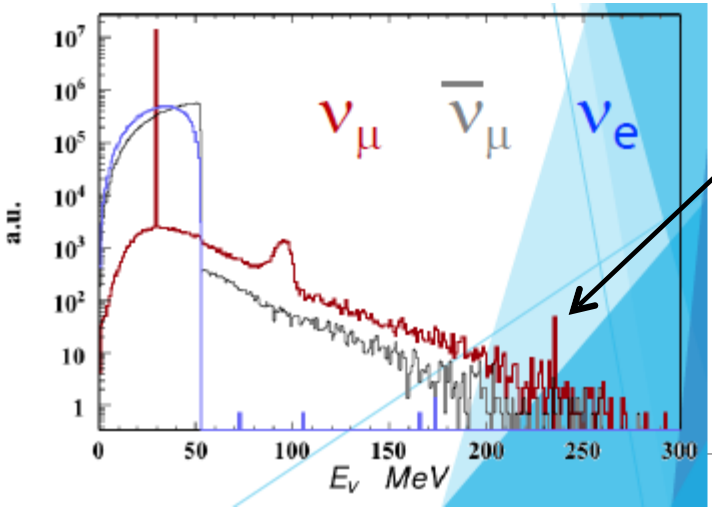


what's the point of doing this at DUNE?

- There are good reasons to search at DUNE
- Directionality gives a new handle on systematic uncertainties and bgd.
  - no directionality possible with WC detectors in IBD detection channel
  - 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 producing light quarks
  - cross section could be ≪ 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
- 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



Note: total KDAR cross section recently measured at MiniBooNE 1801.08348

cuts and efficiencies - directional DM Search

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

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

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: muon → 55°
- loose: electron → 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

references

- *New Sensitivity to Solar WIMP Annihilation using Low-Energy Neutrinos* C. Rott, J. Siegal-Gaskins, J. F. Beacom Phys.Rev. D88 (2013) 055005 / arXiv:1208.0827
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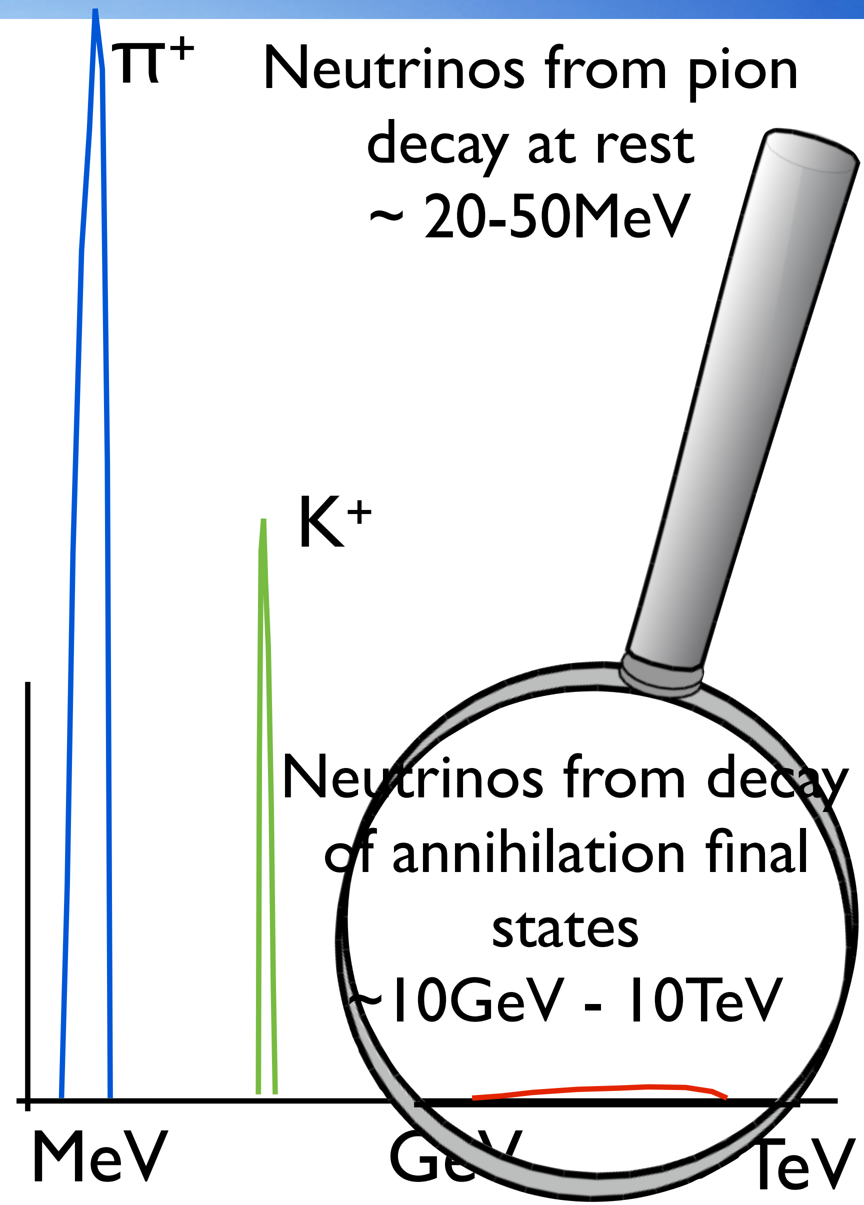
Neutrino signals - Example W-Boson

$W^+ \longrightarrow e^+\nu_e, \mu^+\nu_\mu, \tau^+\nu_\tau$ ~33%

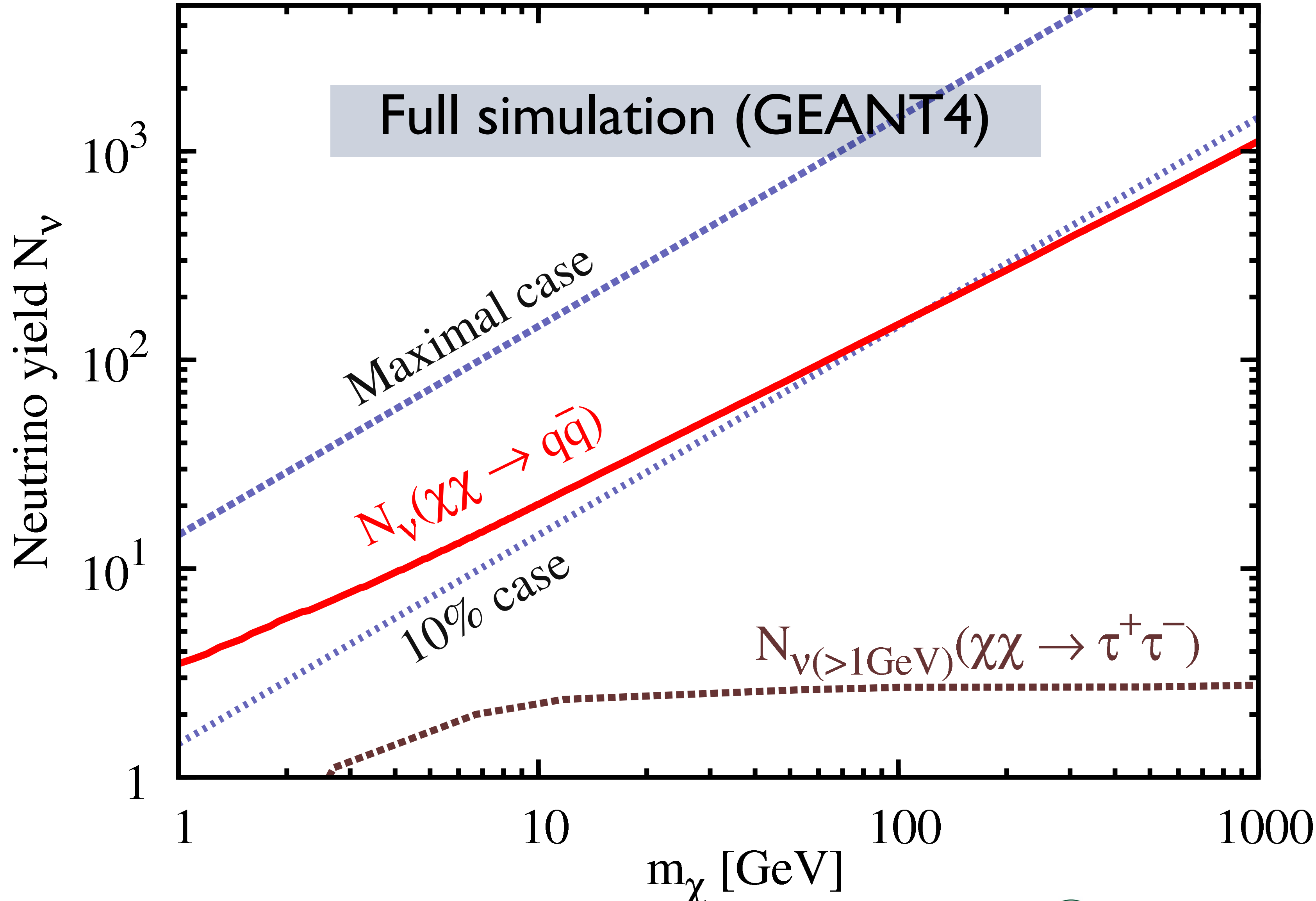
$\longrightarrow qq$ ~67%

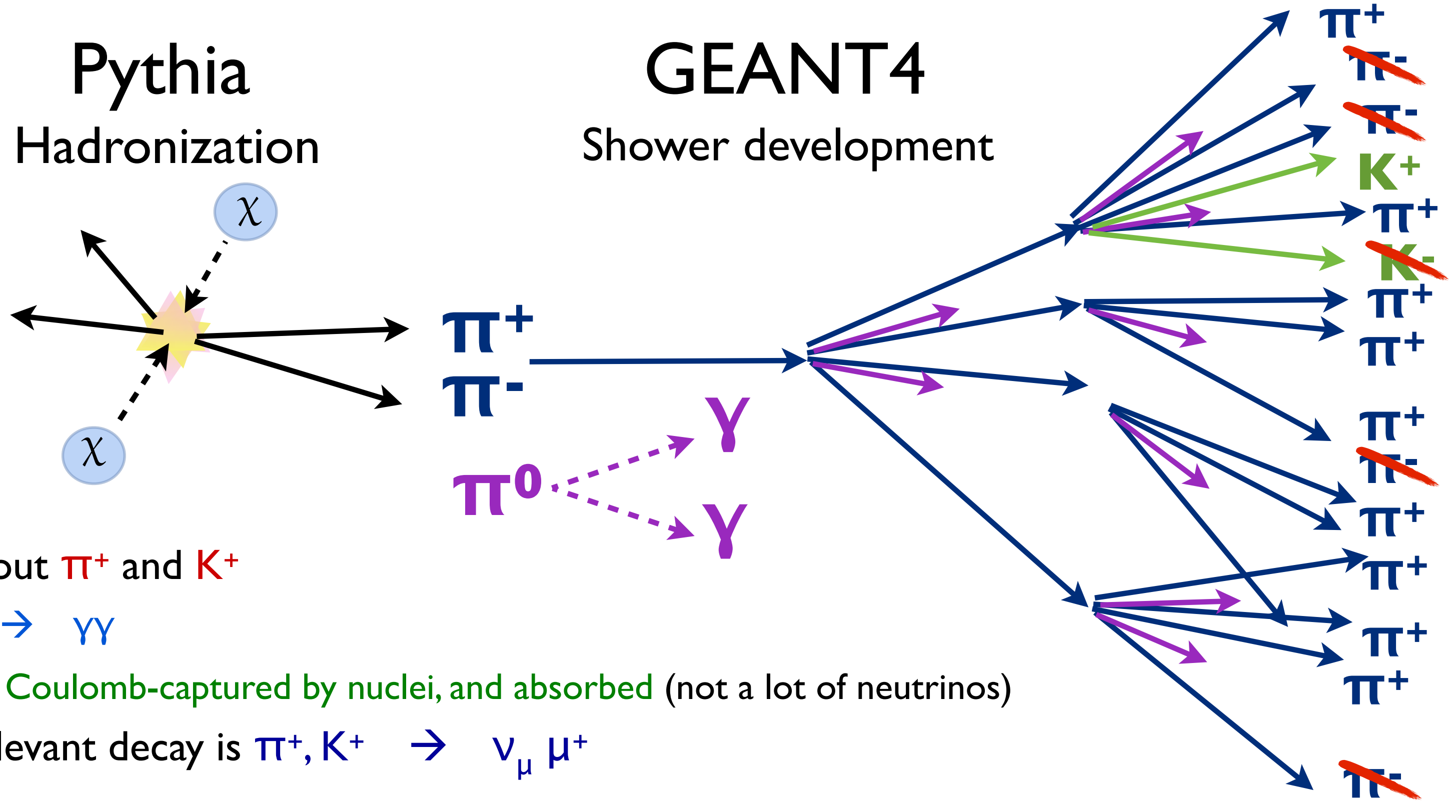
Let's have a closer look at this:

$e^+\nu_e$	1 high energy ν + em shower
$\mu^+\nu_\mu$	1 high energy ν + muon
$\tau^+\nu_\tau$	1 high energy ν + tau decay
qq	hadronic shower



Neutrino yield



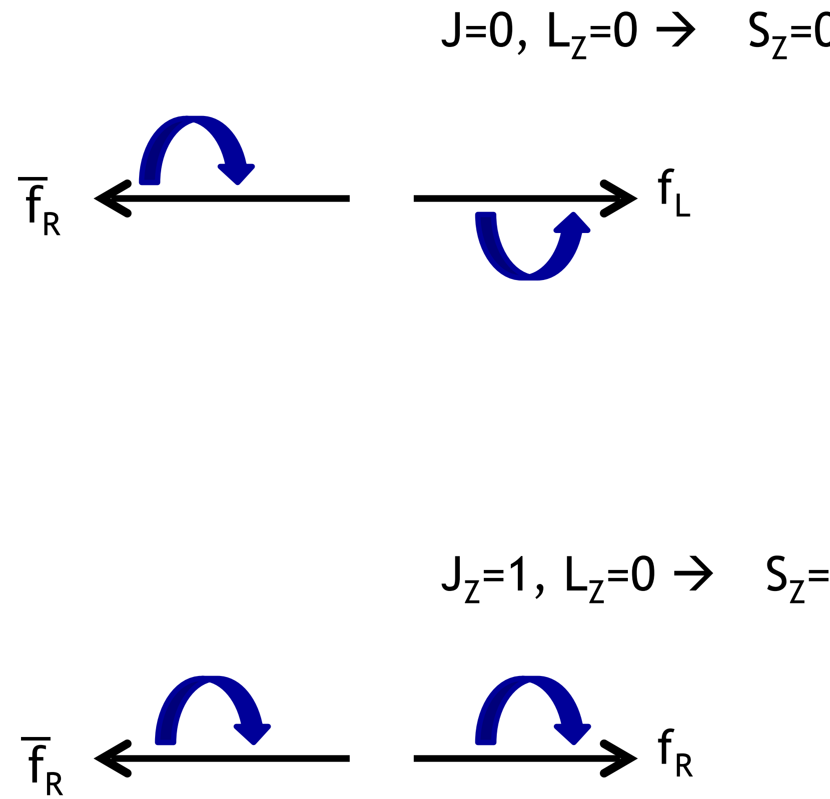


- care about π^+ and K^+
  - $\pi^0 \rightarrow \gamma\gamma$
  - π^- Coulomb-captured by nuclei, and absorbed (not a lot of neutrinos)
- main relevant decay is $\pi^+, K^+ \rightarrow \nu_\mu \mu^+$
  - monoenergetic ν with E = 29.8 MeV (π^+ - 100%) or 235.5 MeV (K^+ - 64%)
  - line signal
    - include 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

Simulation to determine pion and kaon yields per channel Define r-value as the fraction of center-of-mass energy that goes into pions (π^+) or kaons(K^+) decaying at rest.

why (not) $xx \to \bar{f}f$ (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



monoenergetic neutrinos

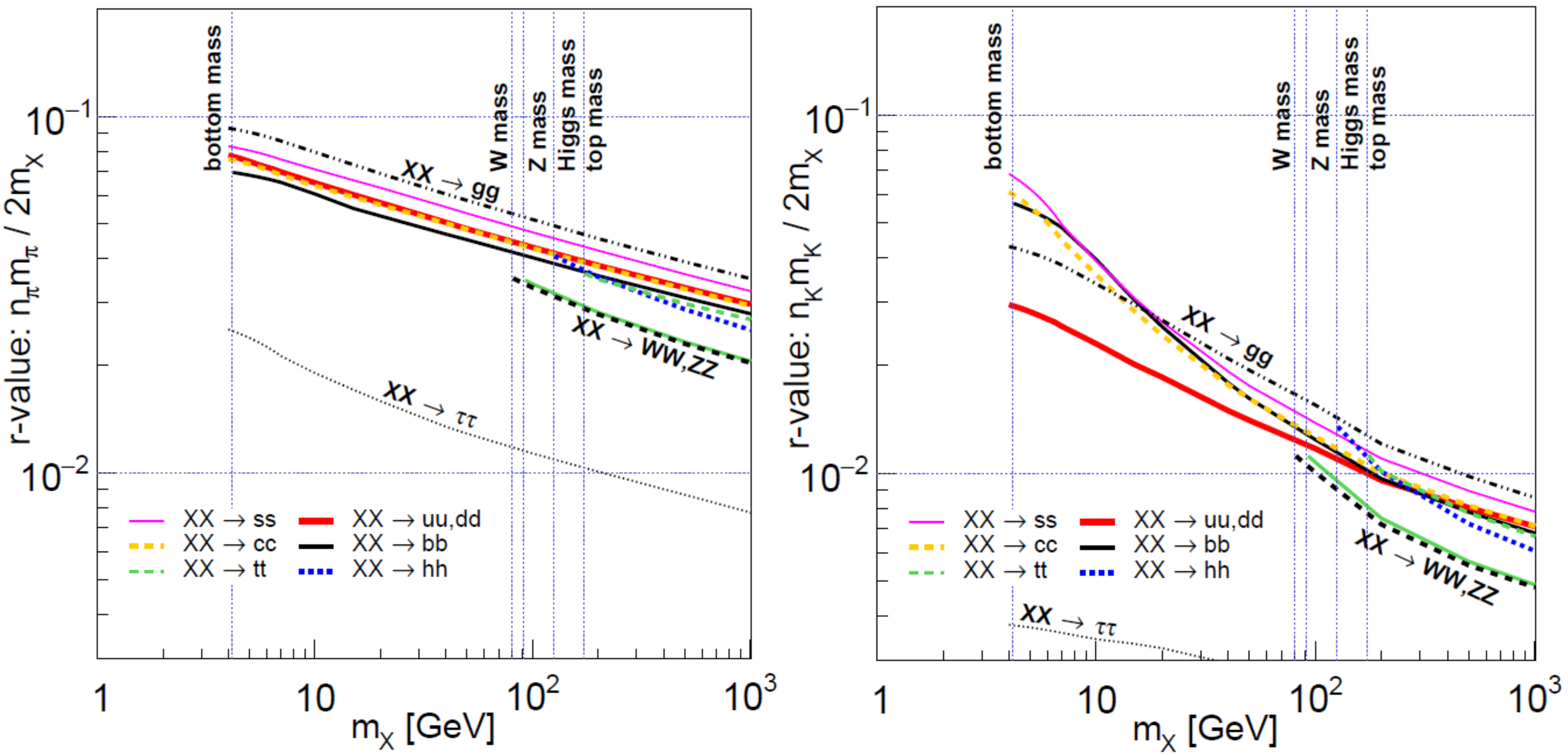
- this argument underlies the theoretical prejudice towards searches for the $\bar{b}b$, $\bar{\tau}\tau$ and W^+W^- channels
- but the chirality suppression arises from the assumption of Majorana fermion dark matter and minimal flavor violation
  - certainly true for the CMSSM, but need not be true 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, $xx \rightarrow \bar{q}q$ ($q = u, d, s$) branching fraction could be $\mathcal{O}(1)$
- worth studying these annihilation channels

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

$$\frac{d^2\Phi_B^e}{d\Omega\, dE} \approx 1.2\ m^{-2}\, s^{-1}\, sr^{-1}\, MeV^{-1}$$

$$\frac{d^2\Phi_B^\mu}{d\Omega\, dE} \approx 2.3\ m^{-2}\, s^{-1}\, sr^{-1}\, MeV^{-1}$$

($\bar{\nu}$ similar)

$$\sigma_{CC}^e(236\ MeV) \approx 4.2 \times 10^{-38}\ cm^2$$

$$\sigma_{CC}^\mu(236\ MeV) \approx 2.7 \times 10^{-38}\ cm^2$$

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

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

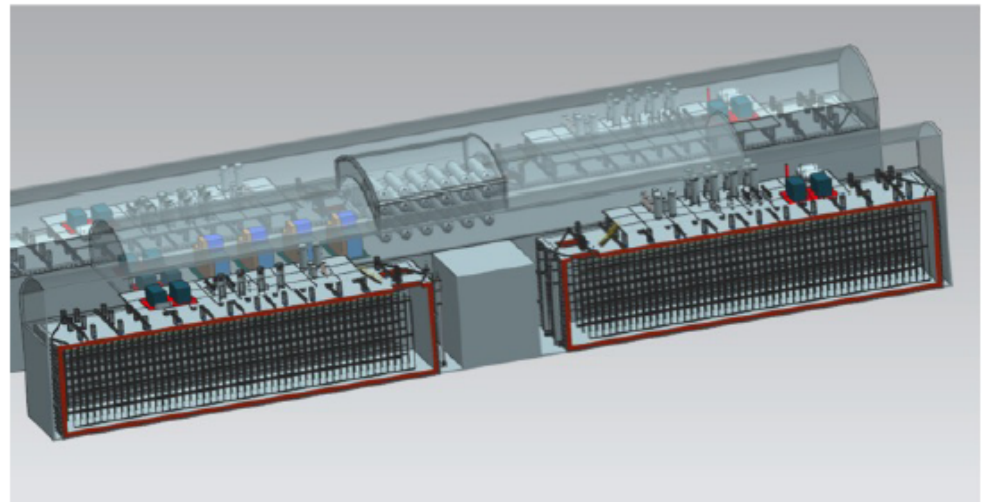
DUNE

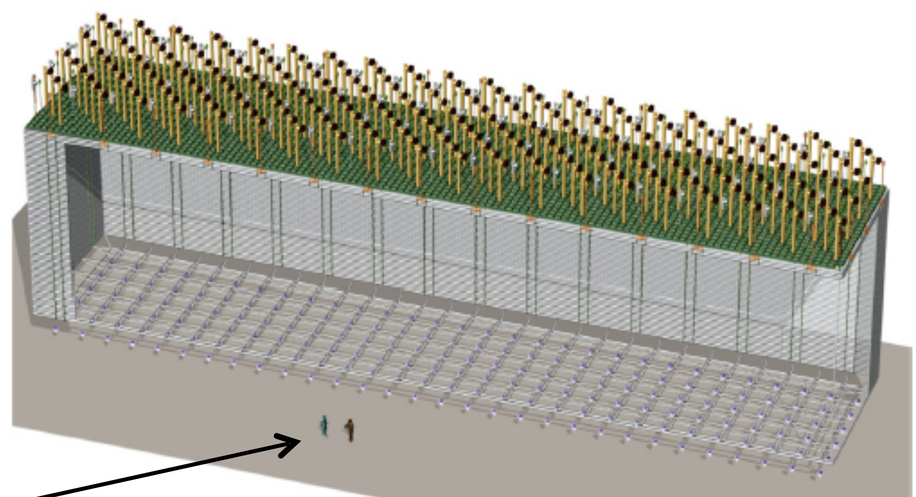
1601.02984

- 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 $\sim 5^\circ$
  - total energy res. – $\varepsilon \sim 10\%$





a theorist, for scale