Searching for Monoenergetic Neutrinos Arising From Dark Matter Annihilation

Jason Kumar

University of Hawaii

collaborators

- Jin In
- Carsten Rott
- Pearl Sandick
- Jennifer Gaskins
- David Yaylali

- 1502. 02091, 15xx.xxxxx

dark matter and monoenergetic neutrinos

- searches for dark matter using neutrino detectors
  - dark matter collects in the core of the sun after scattering off solar nuclei
  - annihilates to Standard Model products, and the neutrinos get out
  - reach neutrino detector on earth
- focus is typically on a smooth distribution of events above background
- why?
  - often assumed no direct annihilation to neutrinos
    - neutrinos arise from decay of other SM states
  - mostly have studied detection strategies in which neutrino energy can't be fully reconstructed anyway
    - see a smooth distribution of charged leptons
- I'll focus on a different possibility
  - models in which dark matter can produce monoenergetic neutrinos
  - detectors and strategies which can resolve a line signal

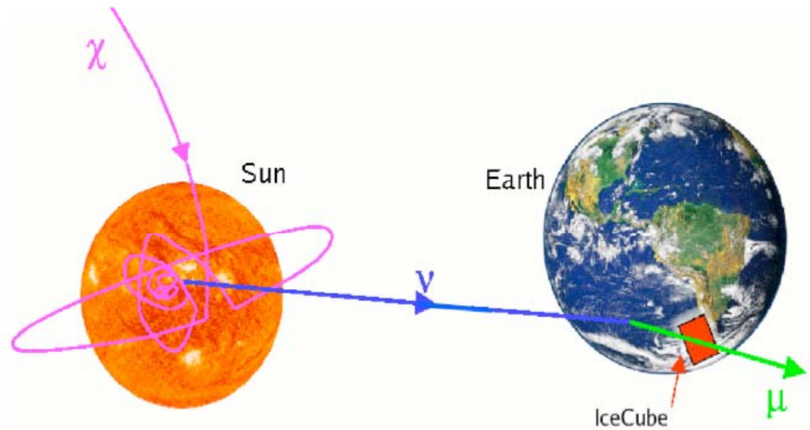
basic points

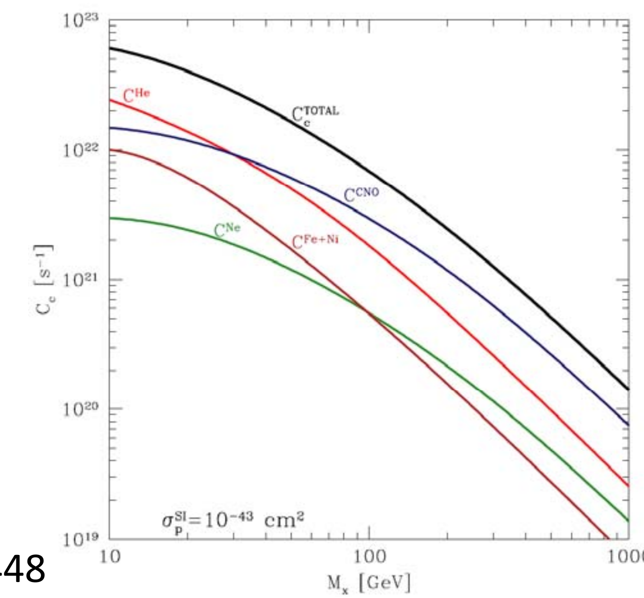
- experiment
  - electron neutrinos undergoing charged-current interaction will deposit almost all energy in the detector
  - some neutrino detectors, like liquid scintillation detectors or liquid argon TPCs, can reconstruct energy and direction of incoming neutrino
    - can determine if neutrino emanates from the sun
  - sensitive to a line signal
- theory
  - in the absence of minimal flavor violation, or with non-Majorana dark matter, can easily have dark matter annihilate to monoenergetic neutrinos
  - dark matter models which annihilate to u, d, s quarks produce plenty of π^+, K^+
    - stop before they decay (producing more π^+)
    - produce monoenergetic neutrino

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
  - 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 look for hard neutrinos
- light hadrons stop before decaying → soft neutrinos

Dawn Williams



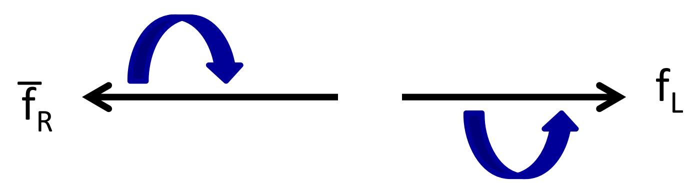


A. Zentner, arXiv:0907.3448

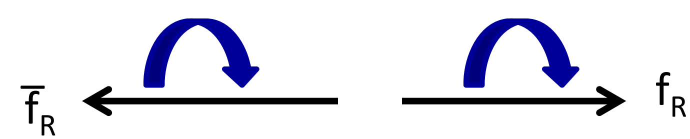
why (not) $\chi\chi \rightarrow \bar{\nu}\nu$?

- 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 $S_z=\pm1$ need f, $\bar{f}$ with opp. helicity
  - no mixing needed

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



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

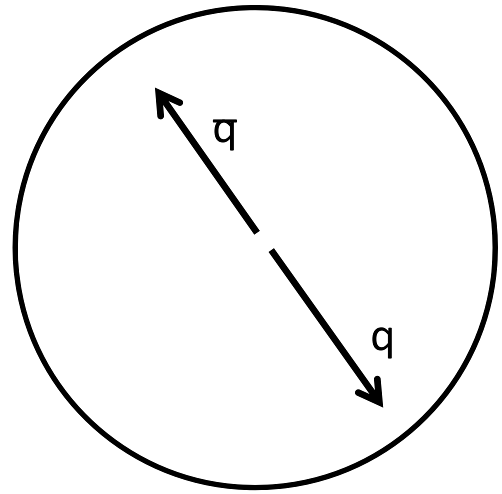


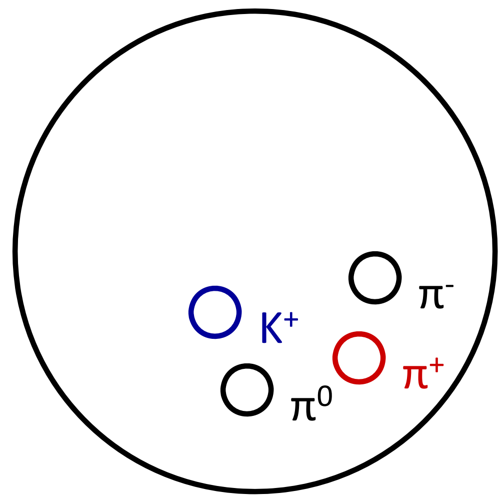
monoenergetic neutrinos

- 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 mass
- either way, $\chi\chi \rightarrow \bar{\nu}\nu$ branching fraction could be O(1)
  - or $\chi\chi \rightarrow \bar{q}q$ for q = u, d, s
- worth studying these annihilation channels

why not light hadrons?

- usually ignore $\chi\chi \to \bar{q}q$ for q=u,d,s
- why? → another reason....
  - u, d, s → light hadrons which stop in the sun before decay
  - care about pions, kaons
  - resulting ν spectrum is very soft
  - large background, small detector effective area
- but the stopping process produces a large number of pions
  - trade a hard spectrum for a softer one, but with larger flux
  - Beacom, Rott, Siegal-Gaskins (1208.0827)



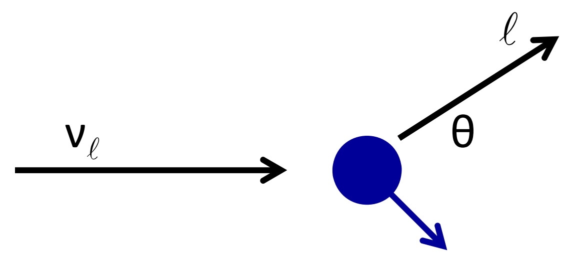


spectrum

- care about π^+ and K^+
  - $\pi^0 \rightarrow \gamma\gamma$
  - π^- Coulomb-captured by nuclei, and absorbed
    - doesn't produce a lot of neutrinos
- main relevant decay is $\pi^+, K^+ \rightarrow \nu_\mu \mu^+$
  - monoenergetic neutrino with E = 29.8 MeV (pion) or 235.5 MeV (kaon)
  - oscillates into monoenergetic ν_e , and can produce a line signal
  - muon stops in sun before decay
    - $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$
    - also get continuum ν_e, $\bar{\nu}_\mu$ from μ^+ decay, but less distinctive
- just need the fraction of DM energy which goes into stopped π^+, K^+
- $r \equiv$ fraction of center-of-mass energy which goes into π^+, K^+
  - determine r in Pythia/GEANT
- $r_\pi \sim 0.1$

resolving a line signal

- essentially need two things
  - full energy containment
  - directionality of charged lepton track (for high energy)
- need ν_e
  - charged current interaction produces $e^{\pm}$
  - produces short-range cascade which is fully-contained in detector
  - at high E_ν, muon is long-range
    - reduces the effective volume
  - at E_ν = 30 MeV, can't produce muon



$$\theta_{cone} = 0.37\sqrt{\frac{10\text{ GeV}}{E_\nu}}$$

f ≡ fraction of events in θ_{cone}

$f_\nu \sim 0.4$

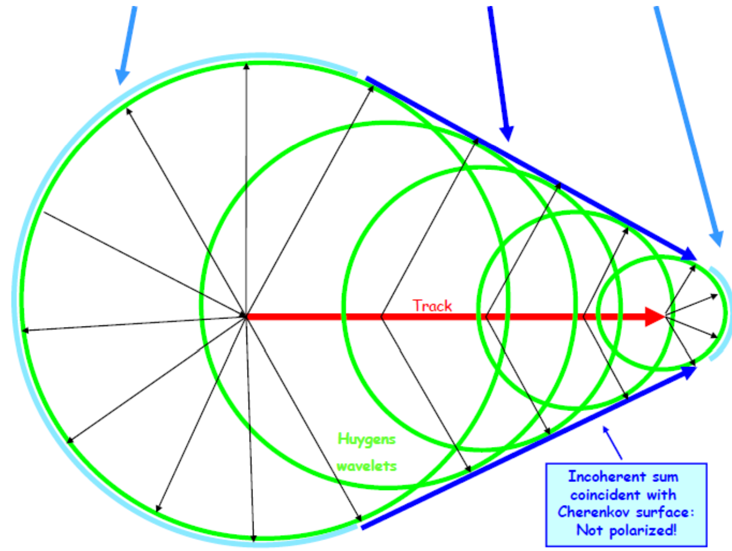
$f_{\bar{\nu}} \sim 0.8$

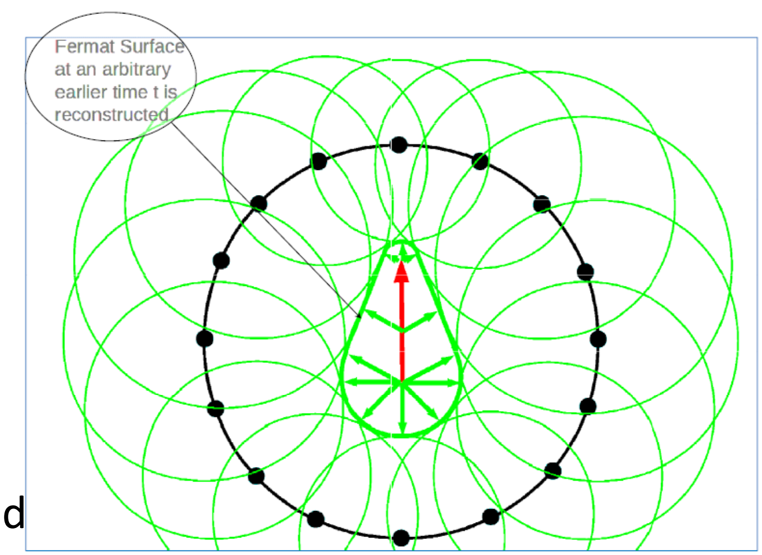
reduces bgd at large E_ν

but at $E_\nu \approx 30$ MeV, no direction

LS detector

- scintillator produces a spherical burst of light
- essentially a calorimeter
  - easy to get total energy
  - harder to get direction from a spherical burst of light
- but timing of when PMTs are illuminated can be used to reconstruct charged lepton track
  - essentially, Huygen's principle
- analysis of KamLAND data is on the way....
- we'll treat it as our benchmark detector ....





figures courtesy of John Learned

what we need....

- we have the neutrino fluxes from the sun arising from DM....
- we have estimates of the ν_e background
  - at E > GeV (for $\chi\chi \rightarrow \bar{\nu}\nu$)
  - at E $\sim$ 30-300 MeV (for meson decay)
- charged current neutrino-nucleus scattering cross section
  - for E > GeV, get $\sigma \propto$ E (DIS)
  - for E $\sim$ 30-300 MeV, more complicated
    - cross sections smaller at low E_ν

Honda

$$\frac{d^2\Phi}{d\Omega dE}(E \gg \text{GeV}) \approx \left(0.04\ \text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}\text{GeV}^{-1}\right)\left(0.8 + \frac{E}{\text{GeV}}\right)^{-3.5}$$

$$\frac{d^2\Phi}{d\Omega dE}(30\ \text{MeV}) \approx 1\ \text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}\text{GeV}^{-1}$$

Battistoni, Ferrari, Montaruli, Sala

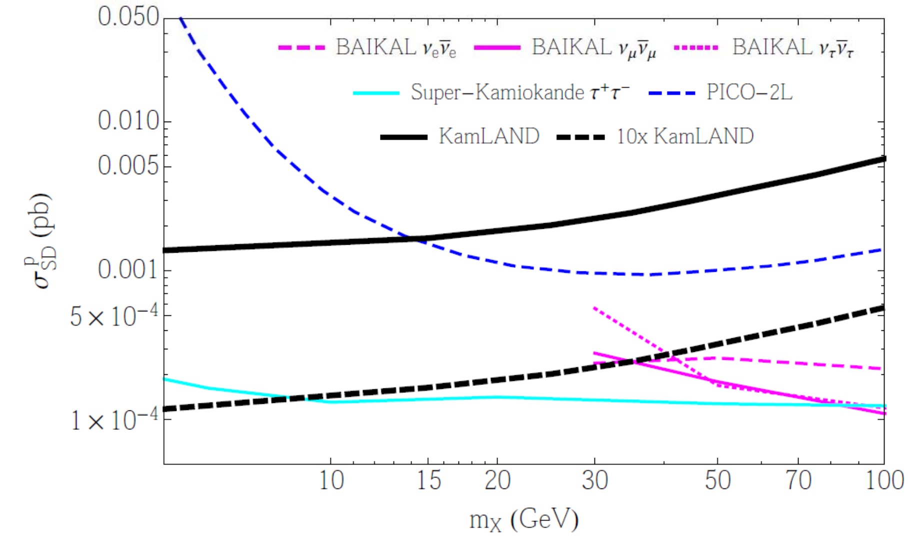
$$\sigma_{\nu N}\left(E \gg \text{GeV}\right) \approx 10^{-39}\,\text{cm}^2\left(E/\text{GeV}\right)$$

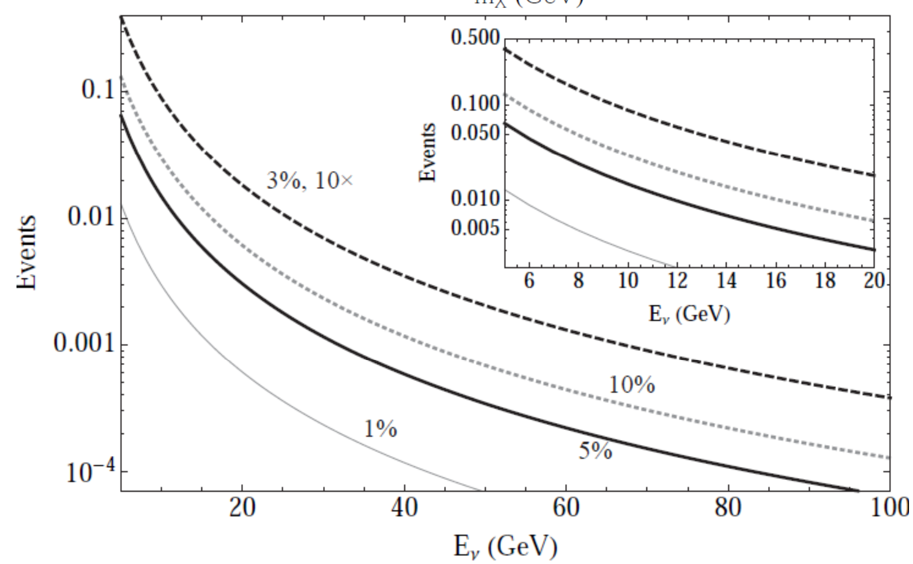
$$\sigma_C\left(30\ \text{MeV}\right) \approx 10^{-41}\,\text{cm}^2$$

$$\sigma_{Ar}\left(30\ \text{MeV}\right) \approx 10^{-40}\,\text{cm}^2$$

sensitivity at high energy

flavor-indep, 90% CL

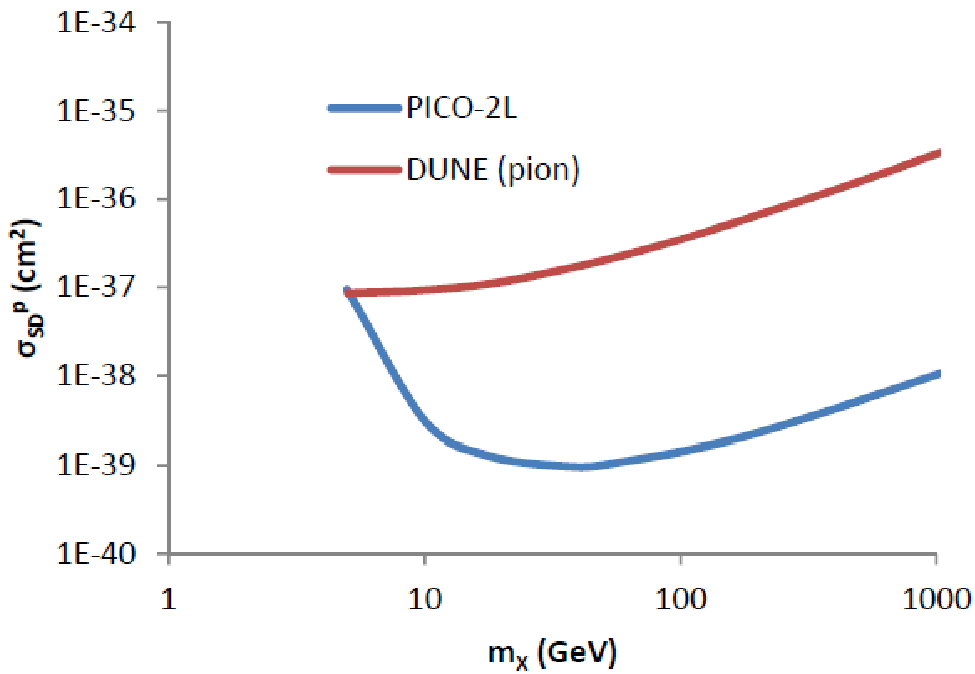




- benchmark = KamLAND
  - V = 500 m^3
  - T = 3600 days
  - ε ~ few % (5 %)
- beats current DD limits
  - no big suppression at low mass, unlike direct detection
- Super-K wins
  - larger exposure due to size
  - SK has larger bgd., but KamLAND is signal limited
    - can't fully benefit from low background yet
- ~~LBNE~~ DUNE? → ε ~ 3 %, 10× exp.

sensitivity for charged meson decay

- at low energy, take $\varepsilon \sim 1\ \%$ for LS
- KamLAND is signal limited
  - viable models produce < 1 event in KamLANDs exposure
  - problem → $\sigma_{\nu A}$ small at low E_ν
- DUNE could do much better (34 kT LAr TPC, 1 year)
  - still negligible background
    - 1 year, $\varepsilon \sim 10\ \%$
  - competitive with direct detection at ~ 5 GeV
- other neutrino searches not sensitive (focused on high-energy neutrinos)



90% CL

signal limited

- look at π^+ decay, 10 GeV, LArTPC
- if $\varepsilon \lesssim 0.1$, would need ~ 10 years to get a single bgd. event in a bin
- S/B doesn't depend on exposure or target, just on fluxes and energy resolution
- if S = B, then $\sigma_{SD}{}^p \approx 0.07$ pb × ε
- E_{crit} exposure needed to get a single signal event at S = B (= 1)
  - exposure = (M/kT) (T/yr)
- to fully realize potential at 5% energy resolution, need 625 kT yr LArTPC detector
  - LS → factor 8× larger

$$N_{bgd.}^{DUNE} \approx (1.1)\varepsilon \left(\frac{M_{Ar}}{34\ \mathrm{kT}}\right)\left(\frac{T}{\mathrm{yr}}\right)$$

$$\frac{S}{B} \approx \frac{14}{\varepsilon}\frac{\sigma_{SD}^{p}}{\mathrm{pb}}$$

$$E_{crit}^{Ar} \approx \frac{31}{\varepsilon} \qquad E_{crit}^{C} \approx \frac{250}{\varepsilon}$$

signal limited

- consider monoenergetic neutrino signal at $m = 10$ GeV
  - again at LArTPC, $\varepsilon \sim 5\%$
- compare to analysis of monoenergetic neutrinos from π^+ decay
  - background neutrino rate is about ~ 4900 smaller
  - signal neutrino rate about ~ 13 times smaller (fixed σ_{SD}^p)
    - no enhancement arising from multiple pions
  - effective area $\sim 10^4 \times$ larger
    - energy dependence of scattering cross section
- at S/B = 1 limit, would have $\sigma_{SD}^p \approx 10^{-5}$ pb
  - need a ~ 270 kT yr detector exposure to get ~ 1 signal event
- $\chi\chi \rightarrow \bar{\nu}\nu$ channel has better sensitivity, smaller exposure, ... if it's there
- but to fully exploit either strategy, one would need an exposure similar to a 34 kT DUNE running for 10 – 20 years

conclusion

- dark matter annihilation in the sun can produce monoenergetic neutrinos
    - need non-Majorana, or non-MFV, for direct annihilation to neutrinos
    - or decays of numerous stopped π^+

- LS or LArTPC neutrino detectors can reconstruct energy and direction
    - need electron neutrinos for fully-contained shower

- reduced backgrounds
- but current detectors are signal-limited, so need bigger detectors and larger run-times.... (DUNE? THEIA?)

Mahalo!

Back-up slides