Low Energy Neutrinos from Dark Matter Annihilation in the Sun

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University of Arizona

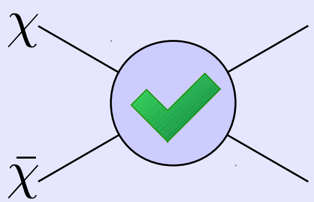
Based on work in collaboration with C.Rott and S.In (Sungkyunkwan U), and J.Kumar (UHawaii): 1510.00170

Main points of this talk

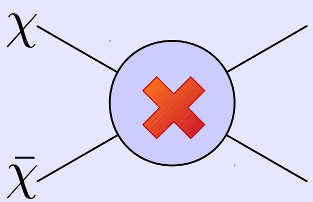
- DM can annihilate in the Sun to neutrinos which can be detected here on Earth.

- The common perception was that only channels which give rise to high energy neutrinos can be probed by this method, due to large backgrounds at low energy.

These searches were thought to be insensitive to models where DM annihilates to light quarks.



$\Big\} \; W^{\pm}, \tau^{\pm}, \bar{b}b, \ldots$



$\Big\} \; \bar{u}u, \bar{d}d, \bar{s}s, \ldots$

However...

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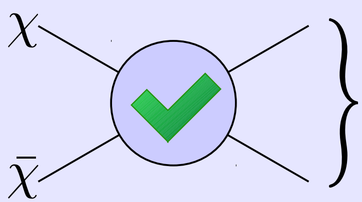

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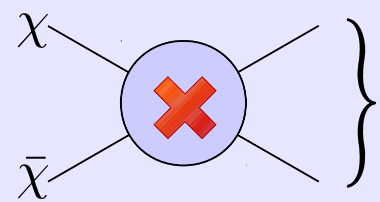
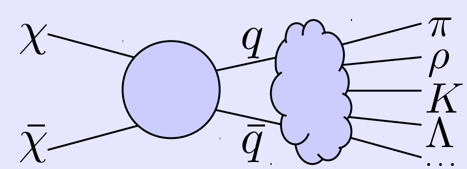


$\bar{u}u, \bar{d}d, \bar{s}s, \ldots$

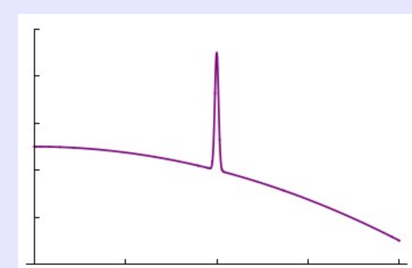
However...

- We will show that annihilation to most SM final states (including light quarks) creates ***particle showers in the Sun***



  ⇨ *We trade the high energy of DM annihilations for a large flux of neutrinos at low energy. These can be detected above background*

- Focusing on **monoenergetic neutrinos** can provide very good sensitivity to these models at LS, LArTPC, and WC detectors



Dark Matter Annihilation in the Sun – Basic Idea

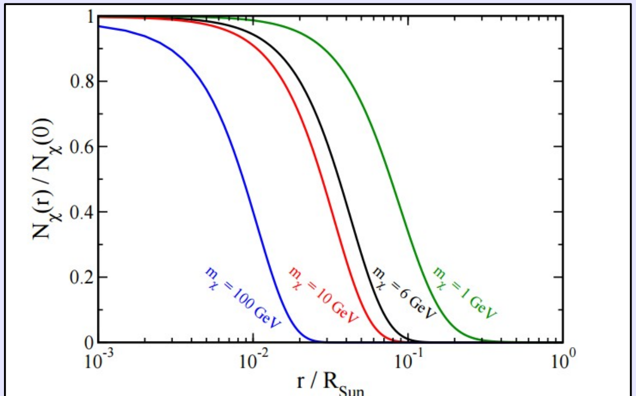
- DM can scatter off nuclei in the sun and lose energy, becoming gravitationally trapped.
- Subsequent scatterings will cause DM to accumulate in the core.

As long as $m_x \gtrsim 4\ \mathrm{GeV}$*, evaporation will be negligible.*

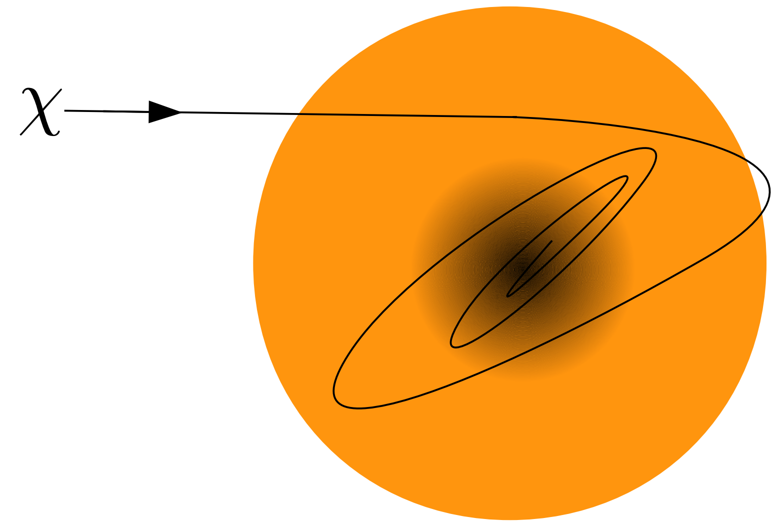
Capture rate:

$$\Gamma_{\mathrm{C}} \propto \sigma^{p}_{\mathrm{SD}}$$

DM core size



Taken from N. Bernal et. al., 1208.0834



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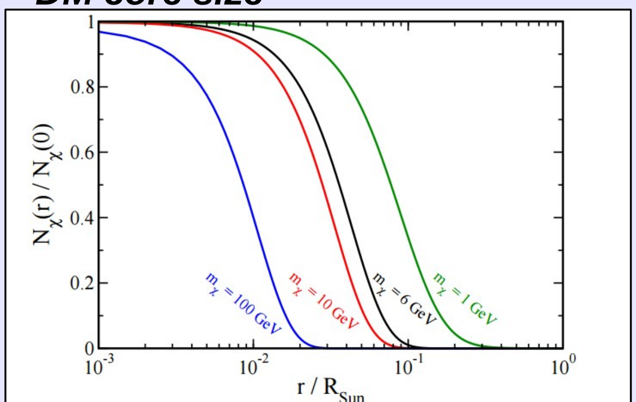

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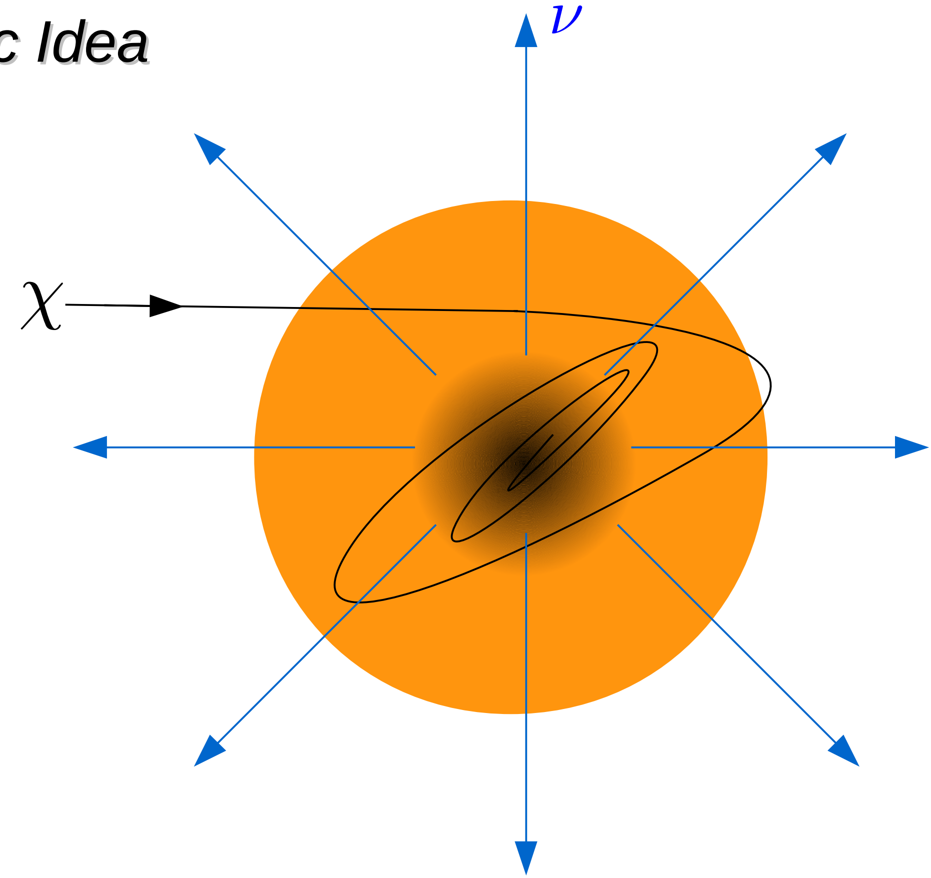


As DM density in core increases, annihilation rate increases. *Equilibrium reached generally*:

$$\Gamma_{\mathrm{A}} = \frac{1}{2}\Gamma_{\mathrm{C}}$$

Dark matter out from annihilation $=$ *Dark matter in from capture*

If some annihilation products are neutrinos, they will leave the Sun and can be detected.

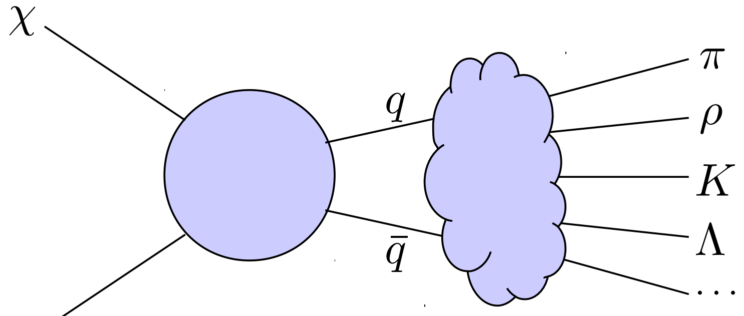
A constraint on flux from neutrinos from DM annihilation provides a constraint on DM-nucleon scattering cross section.

Easy to place constraints on high-energy neutrinos... backgrounds are low

How do we probe models which do not produce high energy neutrinos?

For example, annihilation to light quarks...

Annihilations to light quarks will produce a number of hadrons. The **number density** and **energy spectrum** of each hadron species is found in PYTHIA.



Physics 101

All hadrons except nucleons will decay. We can find the ***average path length*** of the produced particle based on its lifetime and average energy:

$$l = v\tau_{\text{lab}} = v\gamma\tau$$

Thus some of the hadrons will travel farther than others before decaying....

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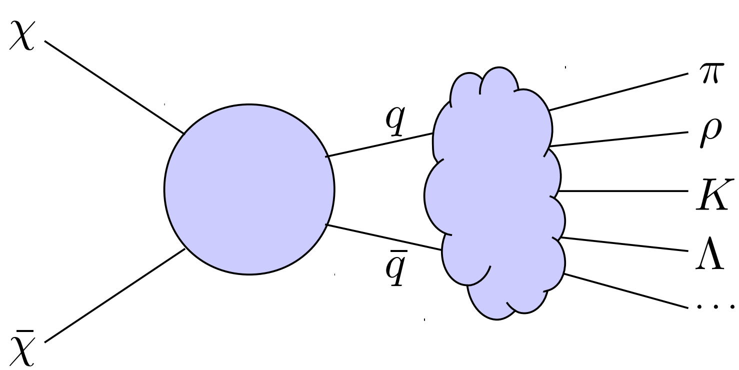

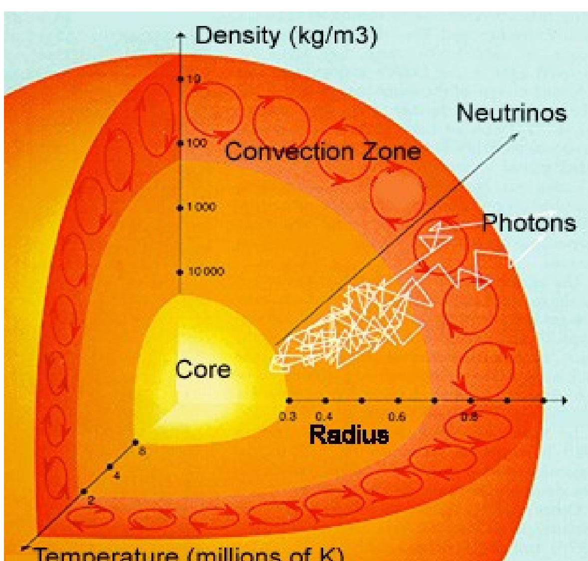

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What happens when this occurs within the dense core of the Sun?

Decay Product Propagation in the Sun

Number density of solar core:

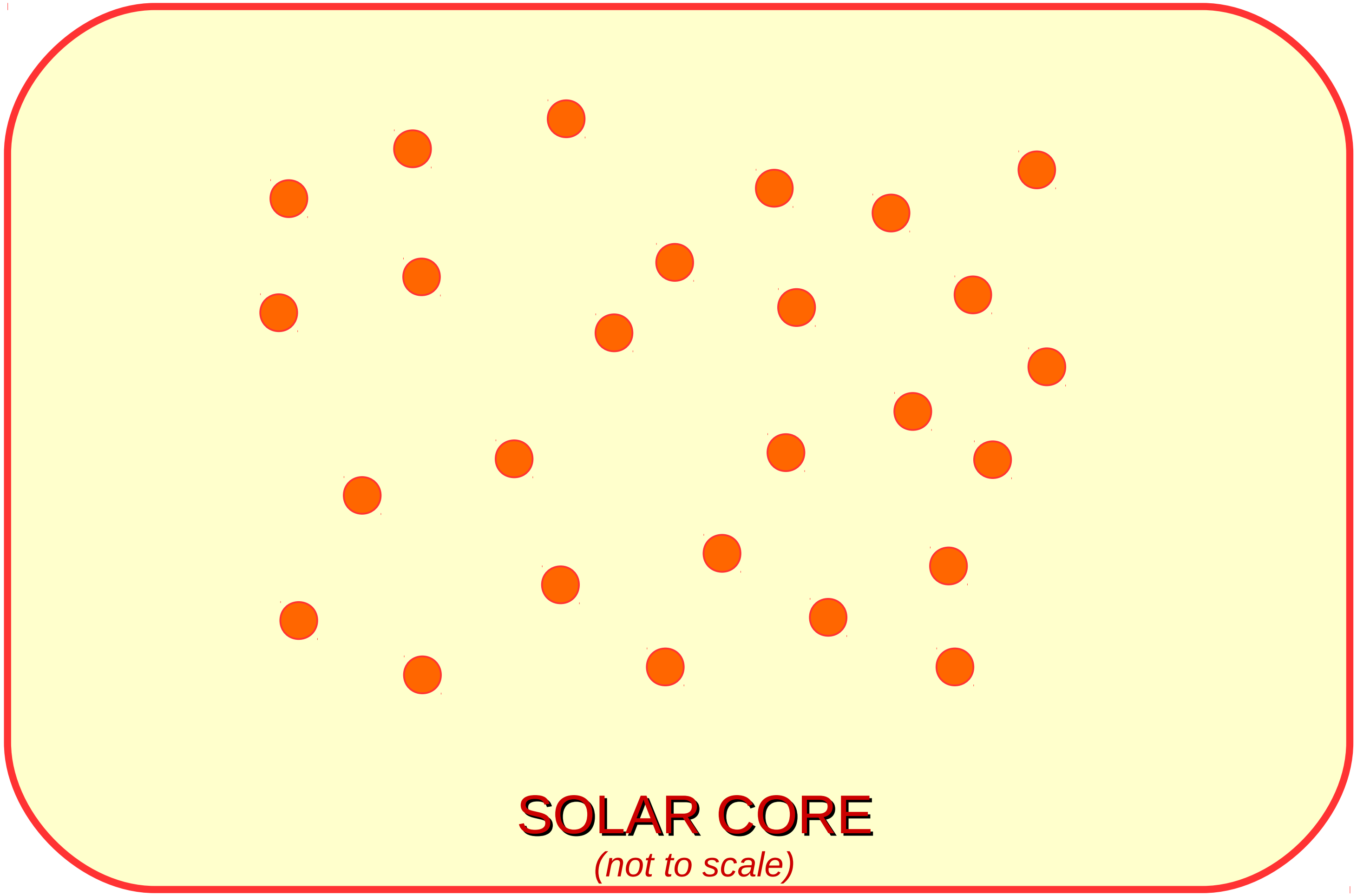
$$n \sim 10^{23}\ \mathrm{nuclei/cm^3}$$

Hadron-hadron cross section:

$$\sigma \sim 10\ \mathrm{mb}$$

Hadron ***mean free path*** length in the sun:

$$l_{\mathrm{mfp}} \sim \frac{1}{\sigma n} \sim 1\ \mathrm{mm}$$



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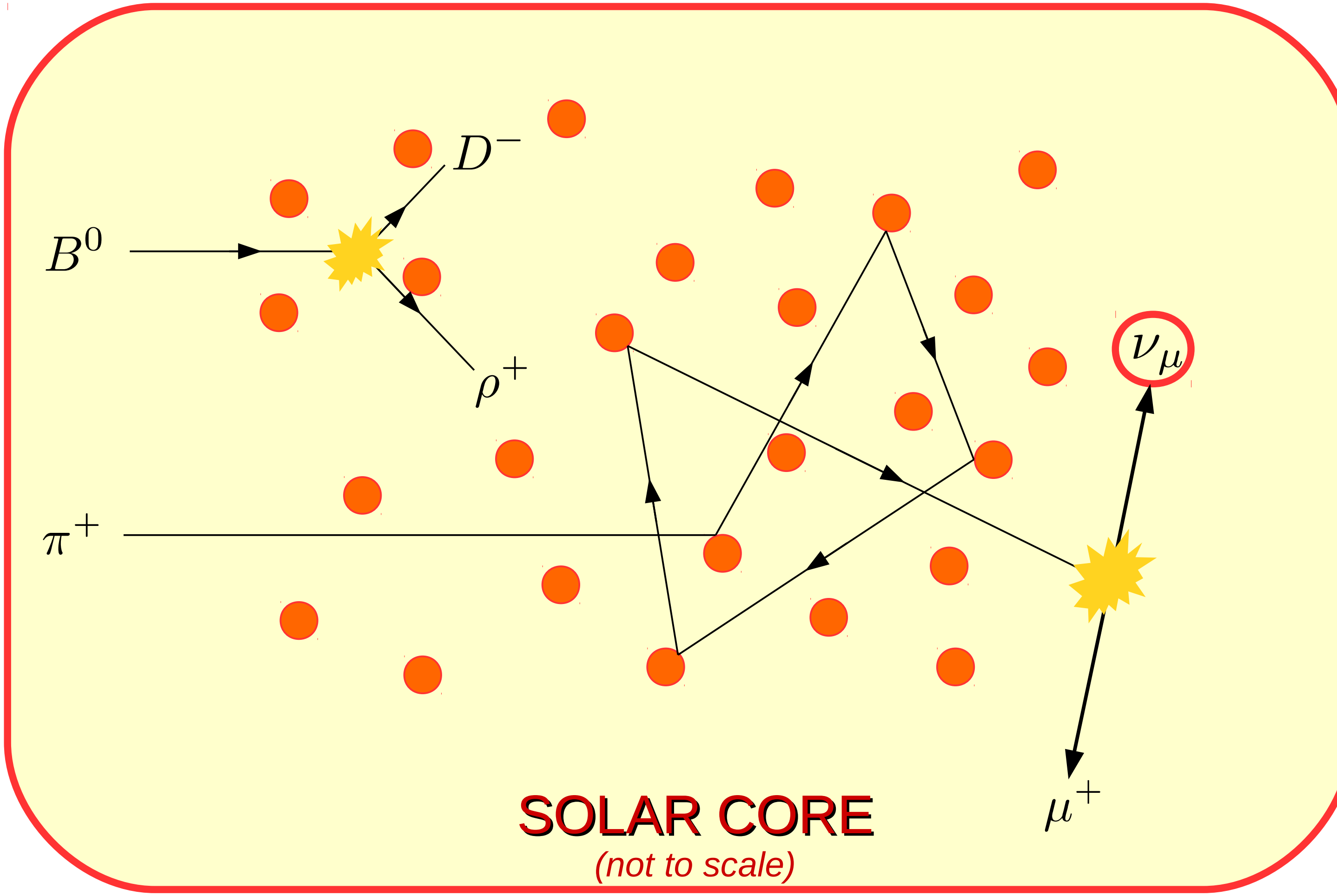

For a given annihilation product hadron species....

$l < l_{\mathrm{mfp}}$: Hadron species decays promptly before interacting with solar medium
$\pi^0, D^\pm, D^0, B^\pm, \Xi^c, \Xi^b, \Sigma^0, \Omega, \ldots$

$l > l_{\mathrm{mfp}}$: Hadron interacts with nuclei (H and He) in solar core before decaying

$l \gg l_{\mathrm{mfp}}$: Hadron will **come to rest** in solar core, then decay.
$\pi^\pm, K^\pm$ ***These decay to monoenergetic neutrinos***

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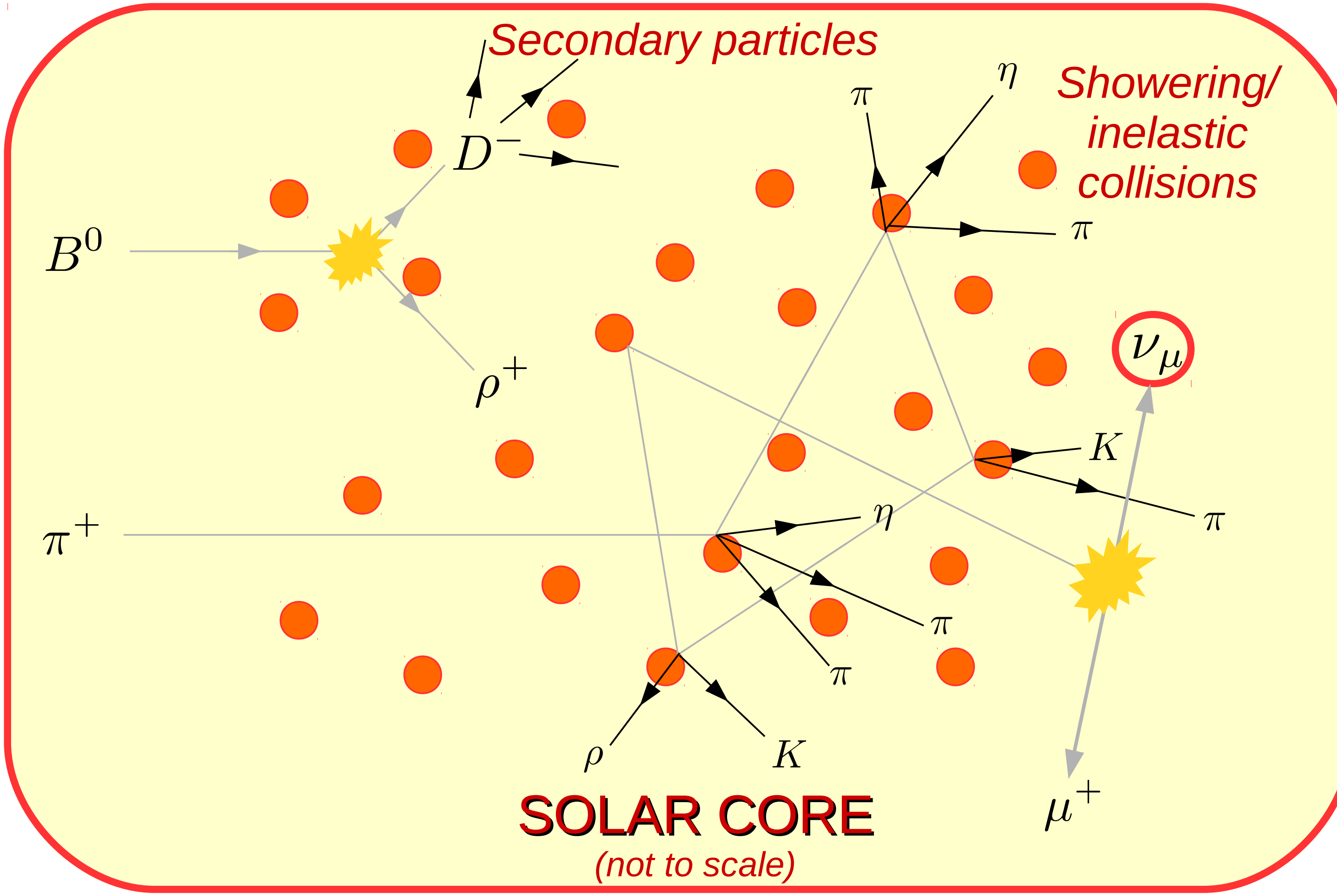


Meanwhile, the longer lived particles produce showers of additional hadrons as they lose energy through inelastic collisions.

- The small number of initial high energy annihilation products are converted to a ***large number of low energy hadrons.*** Their subsequent decay to neutrinos can then be detected over background.

First proposed by my collaborator C.Rott, with Siegal-Gaskins and Beacom, [1208.0827]
Simultaneously proposed by Bernal, Martin-Albo,Palomares-Ruiz [1208.0834]

Posted on the very same day!

We care about charged pions and kaons... all other hadrons either decay before stopping or are produced in much lower numbers.

Furthermore, pi- and K- do not contribute because they are almost always captured in atomic orbits and are absorbed.

Thus we are interested only in

$$\pi^+ \to \mu^+ + \nu_\mu \qquad \mathrm{BR} \approx 100\%$$
$$K^+ \to \mu^+ + \nu_\mu \qquad \mathrm{BR} \approx 64\%$$

Yields monoenergetic neutrinos at:

$$E_\nu = \frac{m_{\pi,K}^2 - m_\mu^2}{2m_{\pi,K}} = \begin{cases} 29.8 \text{ MeV} & (\pi^+ \text{ decay}) \\ 236 \text{ MeV} & (K^+ \text{ decay}) \end{cases}$$

At the detector end, we need charged current reactions from ν_e, not ν_μ

- Pion decay: $\nu_\mu + A \to \mu^- + A'$ kinematically forbidden
- Kaon decay: muon not always contained within detector $\Longrightarrow$ Energy not fully reconstructed.

$\Rightarrow$ Muon neutrinos must oscillate to electron neutrinos:

$$F_{\nu_\mu \to \nu_e}(E = 30 \text{ MeV}) \approx 0.36$$
$$F_{\nu_\mu \to \nu_e}(E = 236 \text{ MeV}) \approx 0.46$$

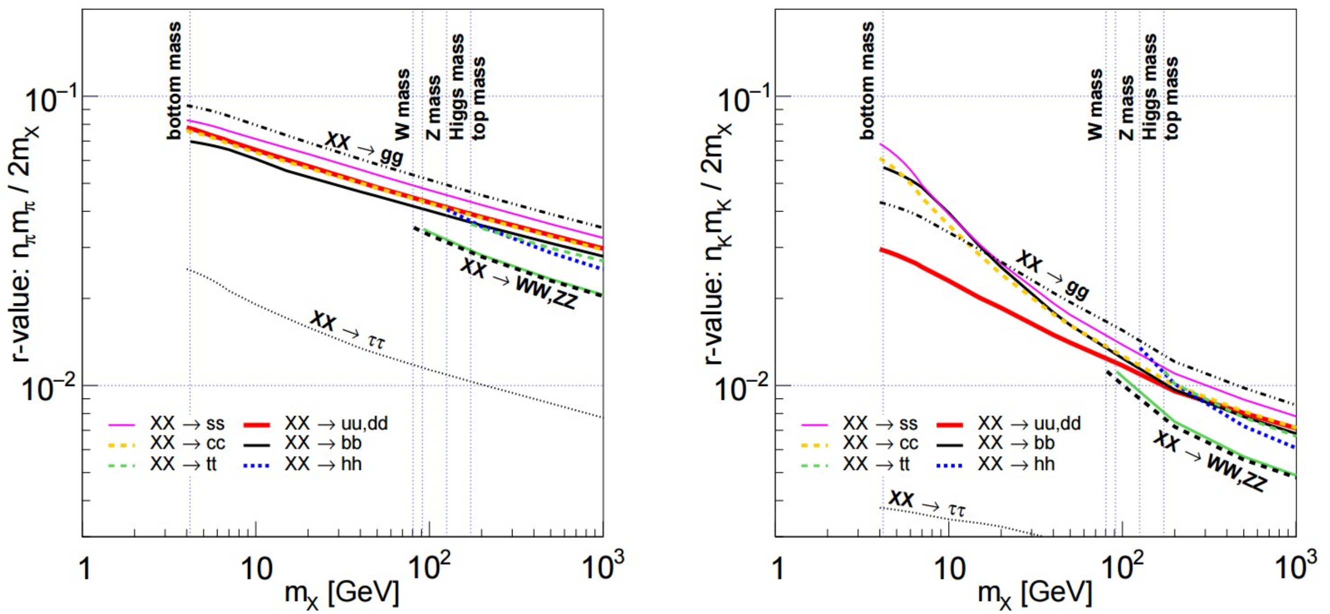
(Normal hierarchy)

Intrasolar Propagation

GEANT is used to propagate the “pseudostable” hadrons through the dense solar medium. This provides us with the number of stopped pions and kaons per DM annihilation. We can represent this with *r-fractions*.

Fraction of annihilation energy which goes into stopped pions or kaons:

$$r_\pi \equiv \frac{m_\pi n_\pi}{2m_X}$$



~0.1–10% of annihilation energy goes to stopped pions and kaons.

Most pions and kaons are produced through hadronic cascade showers, thus r-fractions largely insensitive to initial state.

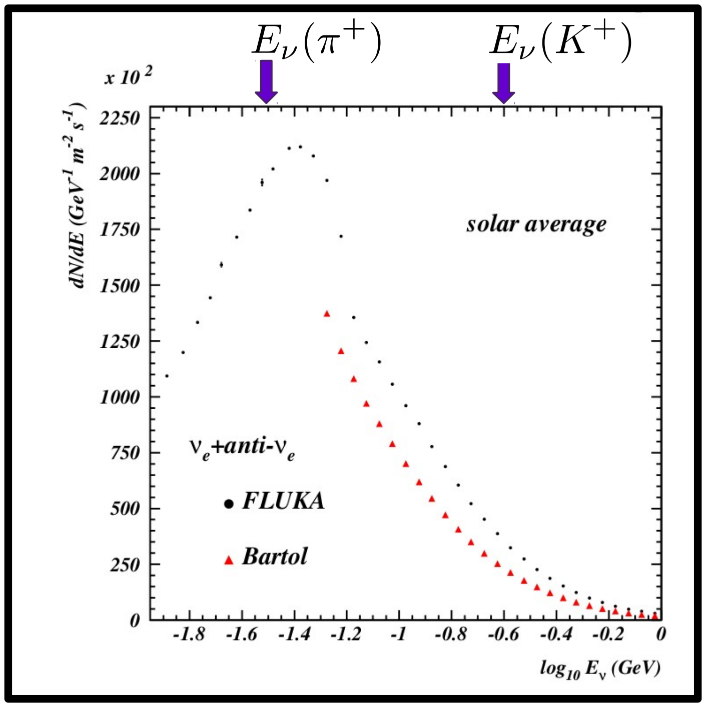
Strategy presented in this talk is widely applicable to many different DM models

Neutrino flux from signal now in hand:

$$\frac{d^2\Phi_{\pi,K}}{dE\,d\Omega} = \frac{(1/2)\Gamma_C(\sigma_{\rm SD})F_\nu}{4\pi r_\oplus^2}\left(\frac{2m_X r_{\pi,K}}{m_{\pi,K}}\right)\delta(E-E_0)\delta(\Omega)$$

Backgrounds

Atmospheric electron neutrino background



G.Battistoni, A.Ferrari, T.Montaruli and P.~R.~Sala, Astropart. Phys. 23, 526 (2005).

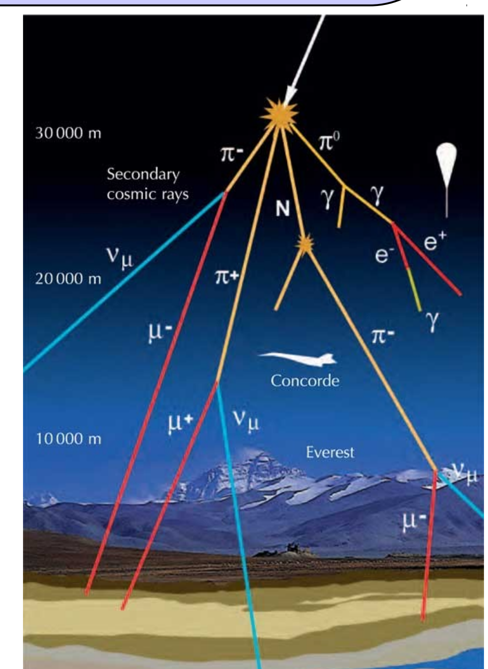
Main background: Atmospheric electron neutrinos.

$$\frac{d^2\Phi}{dE d\Omega}(E = 30\ \mathrm{MeV}) \sim 10\ \mathrm{m}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}\mathrm{MeV}^{-1}$$

$$\frac{d^2\Phi}{dE d\Omega}(E = 236\ \mathrm{MeV}) \sim 1\ \mathrm{m}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}\mathrm{MeV}^{-1}$$

Backgrounds for kaon channel order of magnitude smaller

Other backgrounds:
Cosmic rays which strike the Earth, Moon, or Sun will also produce pions and kaons which come to rest and decay.



Earth: Small number of pions reach the earth surface. Assume 10% are converted to stopped pions/kaons. Resulting monoenergetic ν_e flux (i.e. after oscillation) an ***order of magnitude smaller*** than atmospheric neutrino flux in the same energy range.

Sun/Moon: All cosmic rays strike the surface. So 100% give rise to particle showers in the regolith/plasma. Assume 10% to stopped pions/kaons decaying at rest. ***Background insignificant*** due to small solid angle.

→ *Contributions subleading*

Additional Backgrounds and Uncertainty – Detector specific

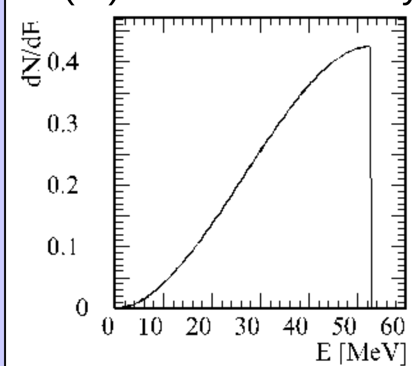
Note that since our signal is $\nu_e + A \to e^- + A'$, the electron will have an energy $E_e \approx E_\nu - \Delta m$ where $\Delta m = m_A - m_{A'}$

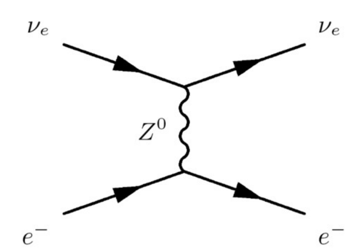
	Δm	$E_e(\pi)$	$E_e(K)$	
Argon	1.5	28.5	234.5	LArTPC
Carbon	17.5	12.5	218.5	LS
Oxygen	15.5	14.5	220.5	WC

For pion-decay neutrino detection, there are a few other backgrounds....

- Invisible muons: atmospheric $\nu_\mu/\bar{\nu}_\mu$ can interact via CC to create a muon. This muon can be below the Cherenkov threshold, thus escaping detection... it can then come to rest and decay to an electron which is below 52 MeV: $\mu^- \to e^- + \bar{\nu}_e + \nu_\mu$
    - At WC detectors, can be larger than atm. ν_e background by factor of 10
    - Not an issue for LS/LarTPC... good lepton identification at low energy
- Neutral-current elastic scattering
- Neutral-current charged pion production
- Uncertainty in nuclear physics/scattering simulation at low energy

E(e-) from muon decay

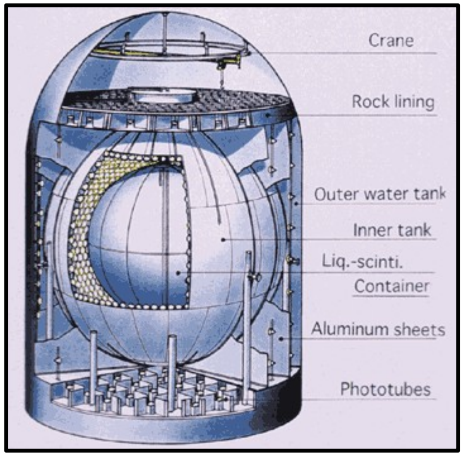




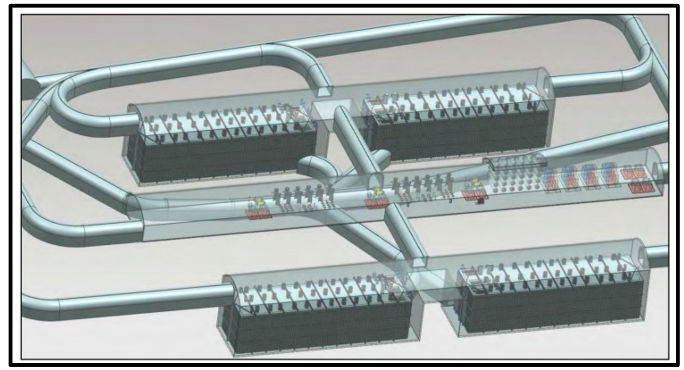
We will not calculate constraints from the pion-decay neutrino for LS and WC detectors.
(These constraints are most likely weaker than those from kaon-decay neutrinos, anyways...)

For the kaon-decay neutrino, these backgrounds are much less of an issue...

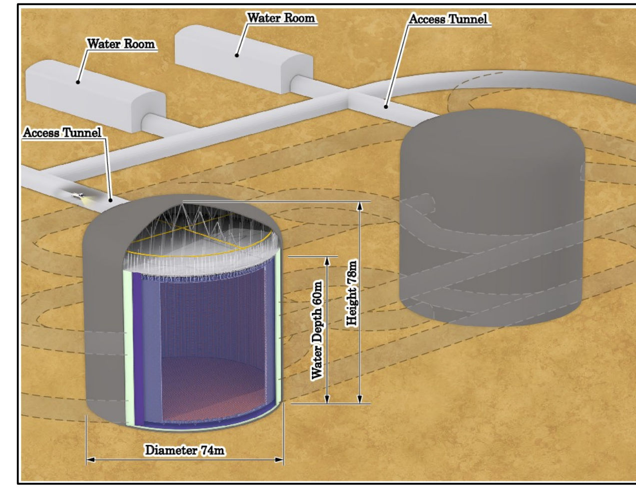
Liquid Scintillator
KamLAND



LAr Time Projection Chamber
DUNE



Water Cherenkov
Super-K/Hyper-K

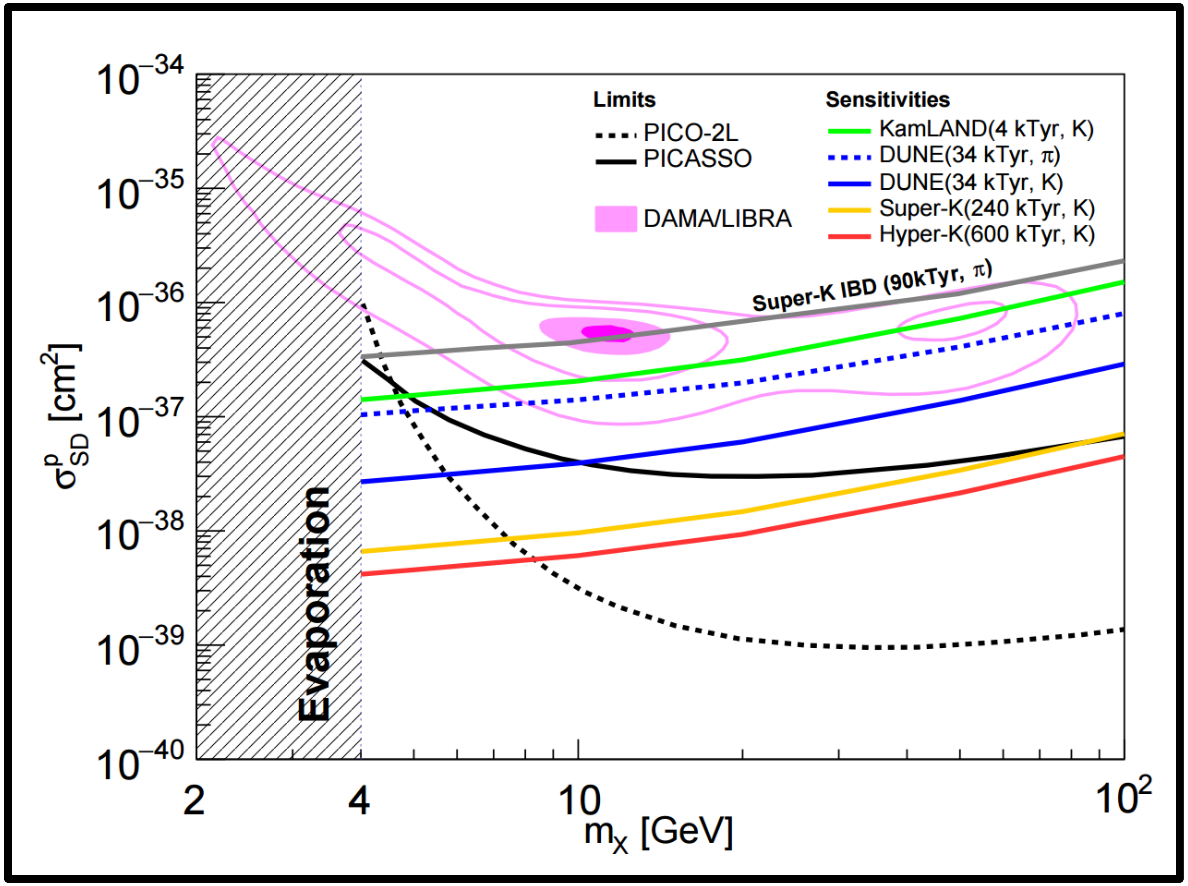


With conservative estimates of energy resolution for each detector, we can find the number of background and allowed signal events within the neutrino energy bin centered on 30 and 236 MeV.

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	S/B
KamLAND	current	4 kT yr	—	—	—	—	5.1	6	0.68	5.5	~1
DUNE	future	34 kT yr	0.2	0	1	2.3	50	50	0.68	10.3	~10 ~1/5
Super-K	current	240 kT yr	—	—	—	—	305	305	0.68	28.7	~1/10
Hyper-K	future	600 kT yr	—	—	—	—	762.5	763	0.68	45.4	~1/15

- Monoenergetic searches in general significantly increase S/B ratio.
- LS/LarTPC detectors have much better S/B than WC.
  For pion channel, DUNE has S/B >>1 => sensitivity grows linearly with exposure
  (However, more difficult to get larger exposures than for WC detectors.)

Results



Previous study (grey line)

Tightest constraint from considering anti-ν from stopped muons at SuperK:

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

where $\bar{\nu}_\mu$ is detected through IBD after oscillation:

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

Beacom, Rott, Siegal-Gaskins [1208.0827]

This work: Main takeaways

- Monoenergetic neutrino line searches generally more sensitive than previous studies.
- Current bounds from KamLAND already tighter than DD for Mx<5.
- As of now, prospects for detection best for WC detectors, due to large exposures.

Why the kaon line does so well...

- At MeV energies, $\sigma \propto E_\nu^2$, so kaon line more detectable despite 1/10 kaons to pions.
- Oscillation more favorable for kaon ν_μ (F~1/2) than for pion ν_μ (F~1/3) or $\bar{\nu}_\mu$ from IBD (F~1/6)
- Background lower by factor of 10 for kaon line versus pion line.
  (though energy resolution worse at 230 MeV)

Large increase in sensitivity by searching for monoenergetic neutrino.
K-decay line better than pion decay line, despite smaller number of stopped kaons.

Conclusions

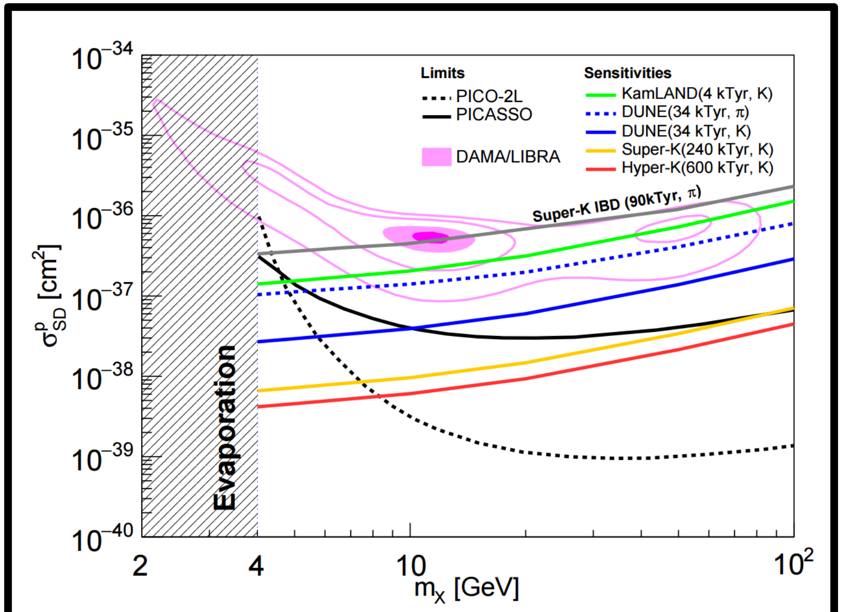
- Dark matter can be captured by the sun, providing a high density target for DM indirect detection through neutrinos.
- Contrary to previous thinking, models in which DM annihilates to light quarks can be probed using this method.

  Previously, only high energy neutrinos from heavy decay channels (W+W-, tau tau, …) were thought to be distinguishable from background. However,

  - Light hadrons can shower in the sun, greatly increasing their multiplicities. They then decay, producing a large number of low energy neutrinos.

    Energy is traded for a large flux, which can be seen over background.

- Focusing on the monoenergetic neutrinos from stopped DM annihilation products (specifically pions and kaons) gives rise to competitive constraints on dark matter models, and is **more competitive than direct detection experiments** for low mass DM.
- For larger mass DM, this provides an important complementary probe to direct detection experiments.



Backup

Neutrino Oscillations

Normal mass hierarchy

R. Lehnert and T. J.Weiler, Phys. Rev. D 77, 125004 (2008) [arXiv:0708.1035 [hep-ph]].

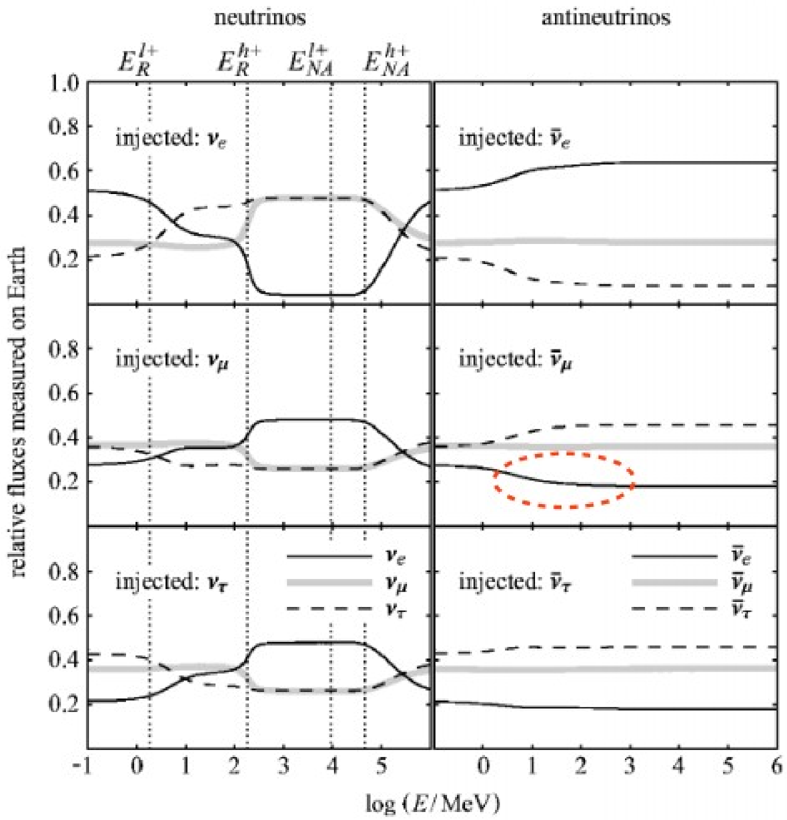


FIG. 3: Solar neutrino and antineutrino flavor probabilities at Earth versus energy, for a single injection flavor and fc normal mass hierarchy. Here, we have taken $\theta_{13} = 12°$, $\delta = 0$. All other neutrino parameters are as in Fig. 2. The ν_μ a spectra and $\bar{\nu}_\mu$ and $\bar{\nu}_\tau$ spectra are interchanged if $\delta = \pi$ is chosen. Vertical dotted lines mark the characteristic scales fc lower-energy resonance given by Eqs. (50) and (52) and the higher-energy resonance given by Eqs. (53) and (54).

Inverted mass hierarchy

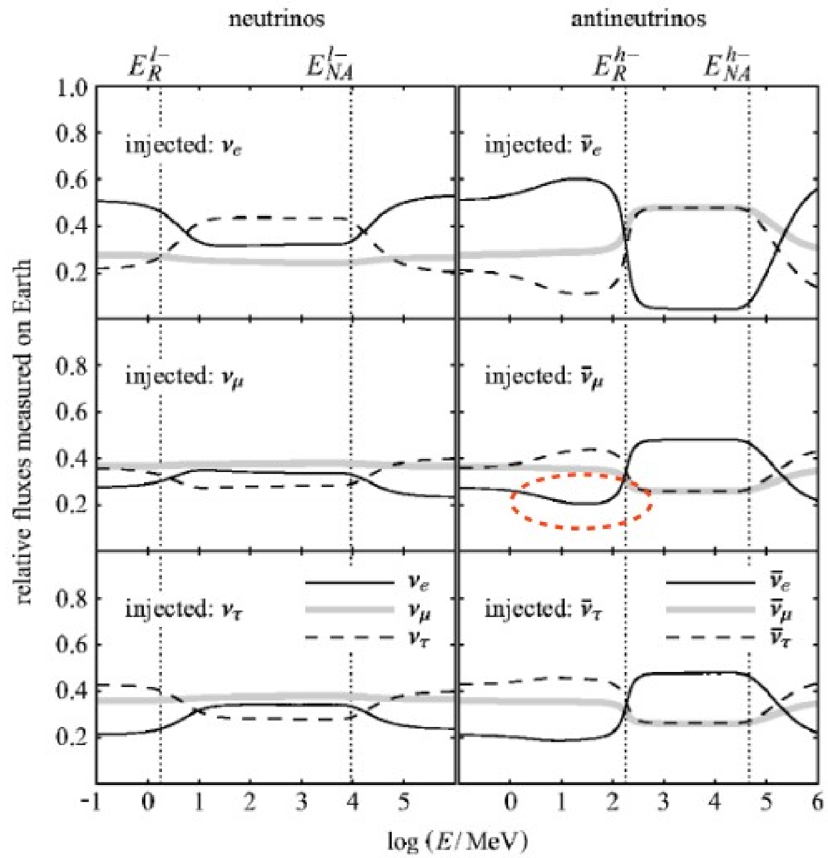
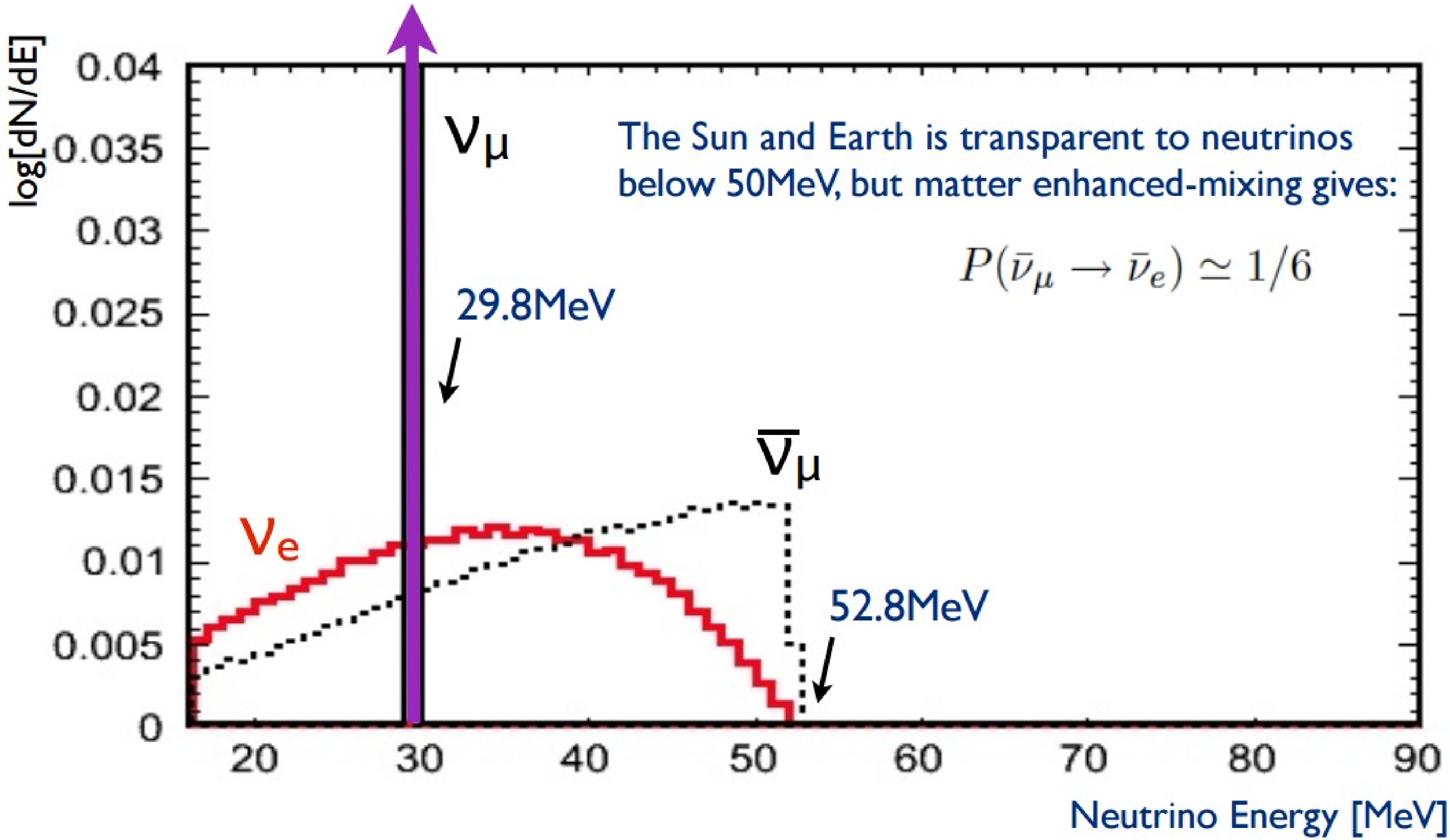


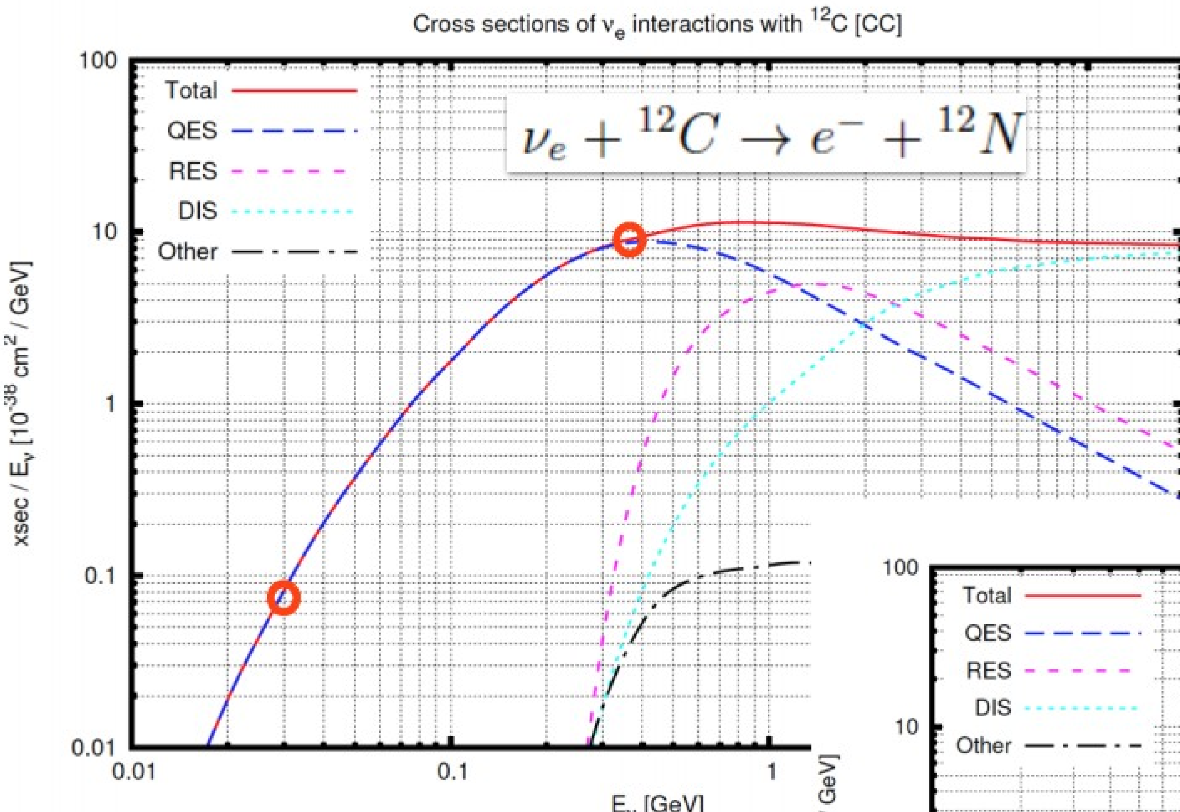
FIG. 4: Neutrino and antineutrino flavor probabilities on Earth versus energy, for the inverted hierarchy. Here, we have taken $\delta m^2_{32} = -3.0 \times 10^{-3}\,\text{eV}^2$. All other neutrino parameters are as in Fig. 3 (including $\theta_{13} = 12°$ and $\delta = 0$). The ν_μ and ν_τ spectra and $\bar{\nu}_\mu$ and $\bar{\nu}_\tau$ spectra are interchanged if $\delta = \pi$ is chosen.

Expected low-energy Neutrino Signal

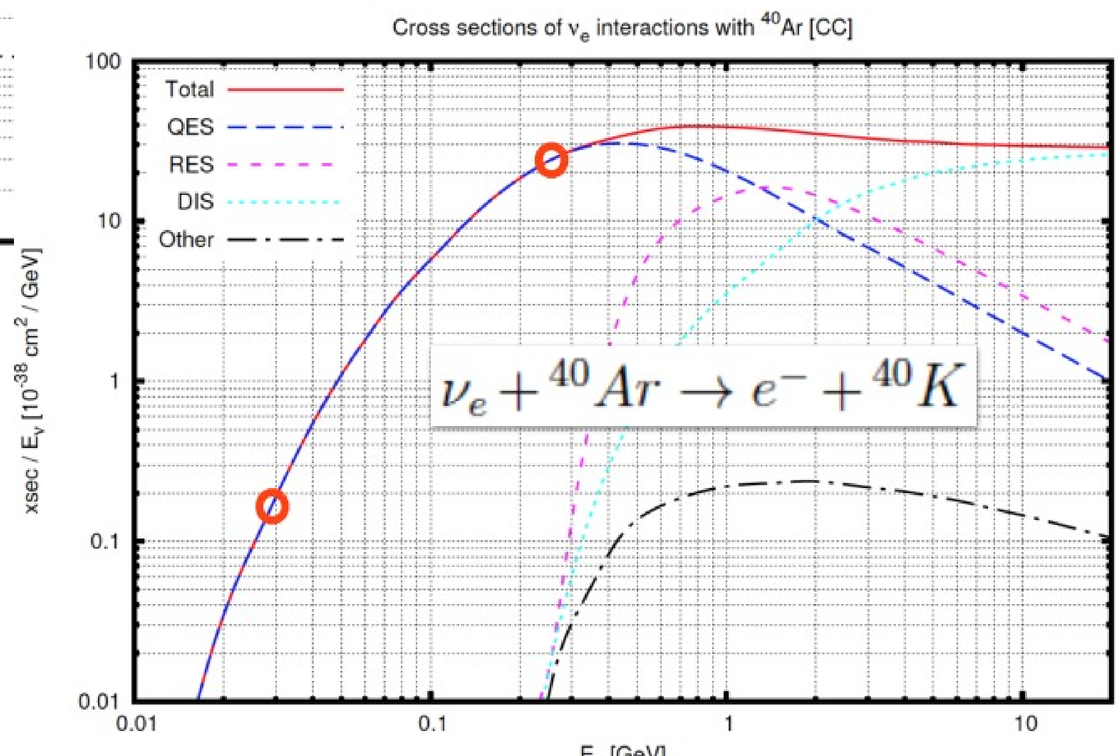
Neutrino Spectrum from pion decay at rest (normalized to unity)



Neutrino cross section

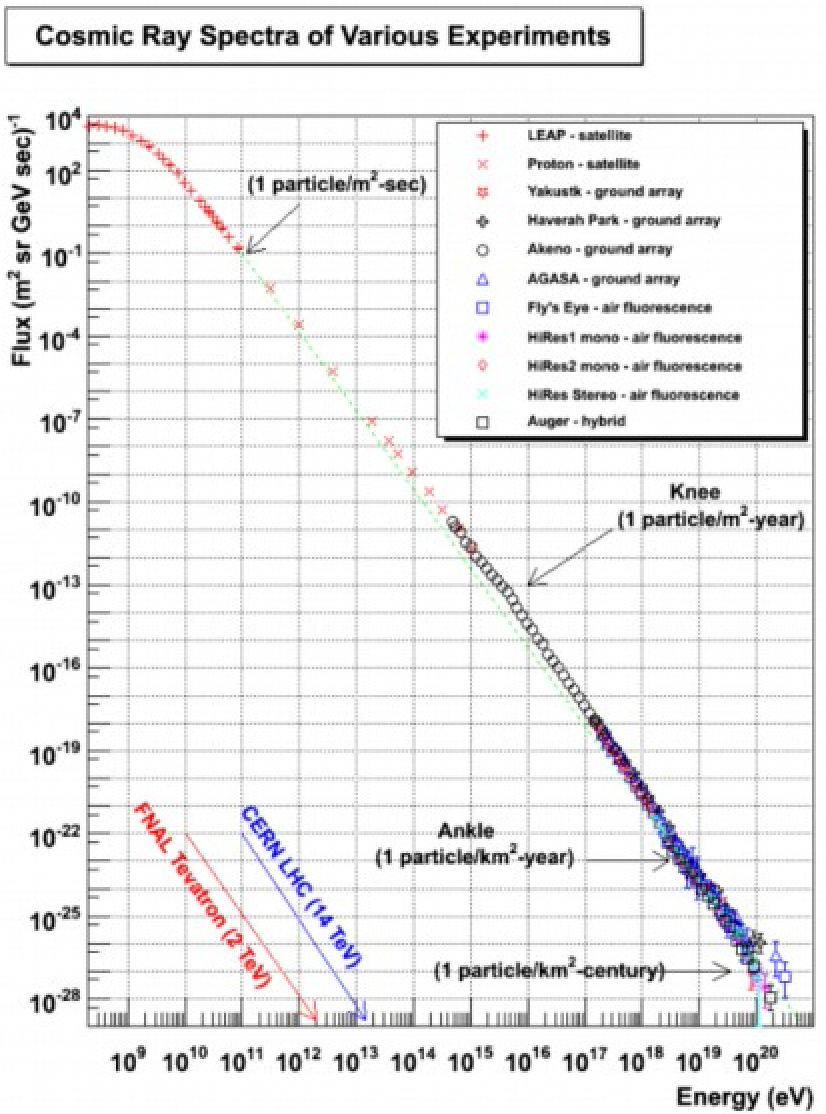


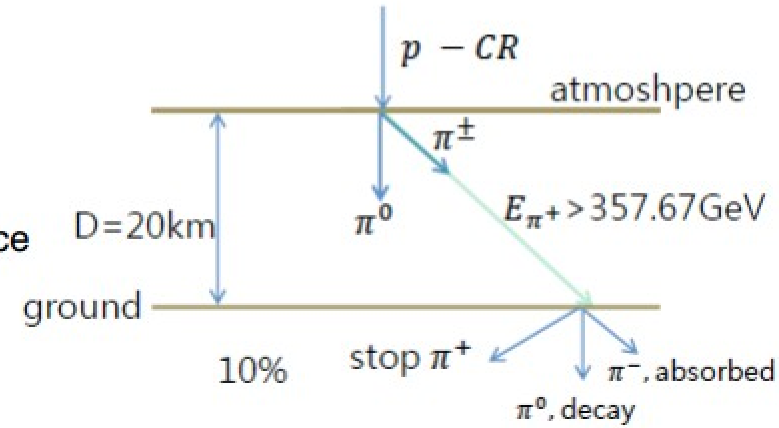
- 29.8MeV
  - charged current quasi-elastic
- 235.5MeV
  - charged current quasi-elastic,
  - just at the edge of pion production, deep inelastic scattering, resonance, coherent



thanks to Shao-Feng Ge for Genie cross sections

Pions from CR airshowers





π^+ - reaching surface

$c\tau$=7.8045 m

d=20,000m

$m_{\pi^+}c^2$=139.57 MeV

$$E^2 = m^2c^4 + \frac{d^2}{c^2\tau^2}m^2c^4 \rightarrow E = mc^2\sqrt{1+\left(\frac{d}{c\tau}\right)^2}$$

- Estimate background from stopped pions from CR's hitting the Earth surface... very conservative estimate (no interaction in the atmosphere assumed)
- Pion at rest decay rate:

$$1.6 \times 10^{16}\,[pions][s]^{-1}$$

- The corresponding neutrino rate is that of a 100GeV WIMP at 3x10^{-39}cm^2