Searches for DM Induced Nucleon Decay

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arXiv:1312.0011
with Yue Zhao

Outline:

- Motivation and Review
- Effective operators & Parameters
- Relating to Chiral Lagrangian
- Possible Signatures
  - Induced nucleon decay in SuperK
  - Constraining by atmospheric neutrino data
  - Detecting boosted DM from the Sun
- Summary

References

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Motivation & Review

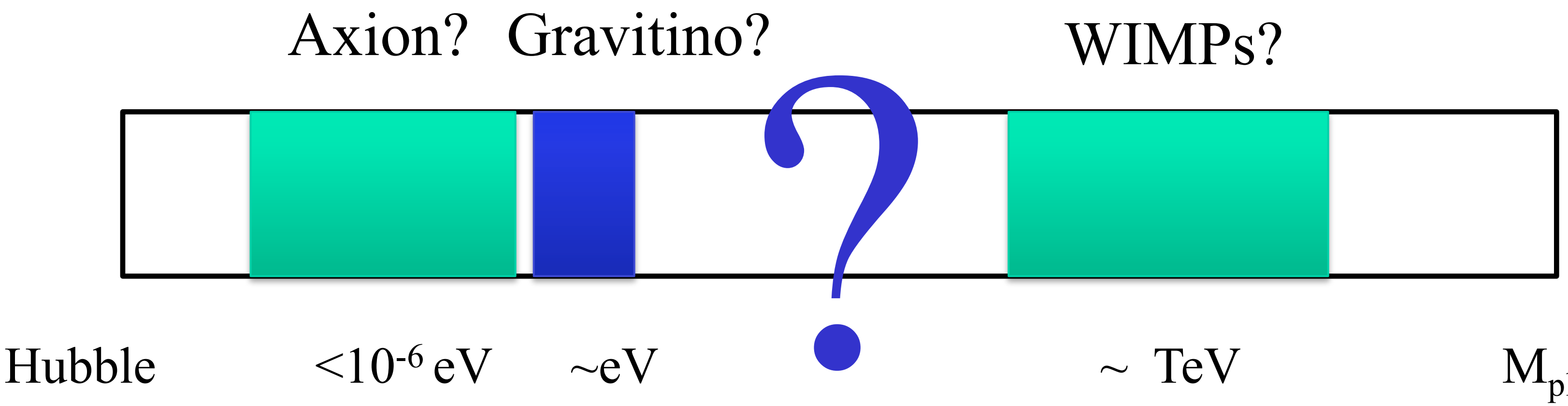
DM Candidates:

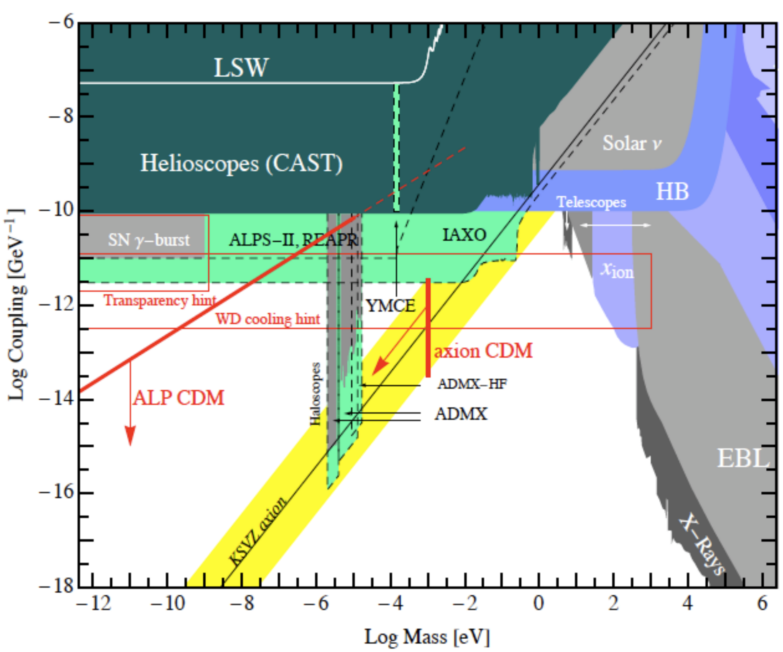
WIMPS? (T.T)
- WIMP Miracle?
- SUSY?
- ADD or RS BHs, KK states?
- Prob: CDMS, Xenon100, LUX, LHC...

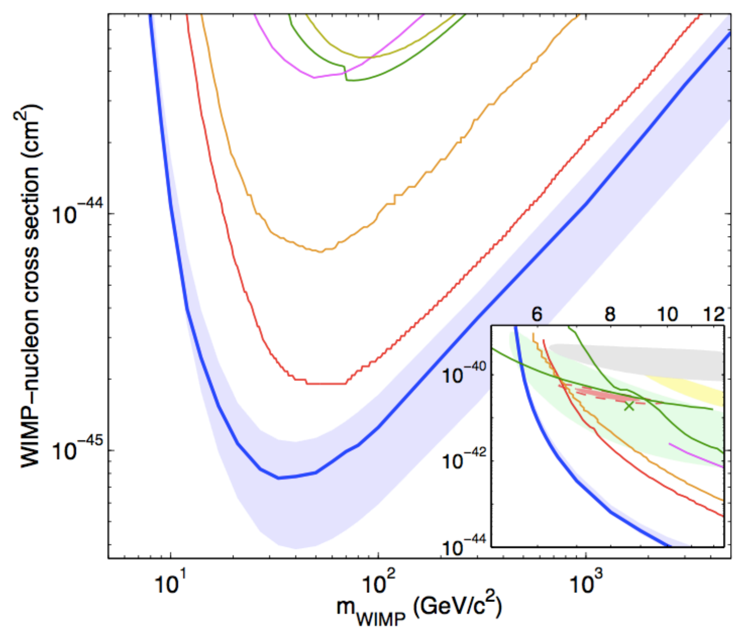
Light Boson?
- QCD Axion?
- String Axion, Moduli, Dilaton?
- Dark Photon?
- Prob: ADMX, CMB, Cooling?

Not so Light Fermion?
- Gravitino?
- Sterio Neutrino?

Motivation & Review







Motivation & Review

Asymmetric DM… *Kaplan, Luty, Zurek [0901.4117 [hep-ph]]*

Thinking behind $\Omega_{DM}/\Omega_B \sim 5$, just like when we think behind Strong CP and the hierarchy problem! Mirror Universe?

DM carries (+/-) baryon number.

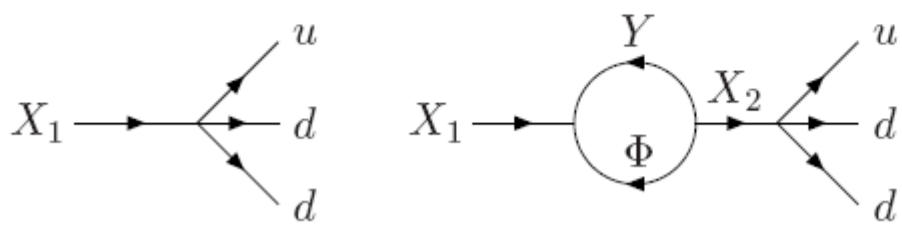
- Starting from non-zero (B/L), distribute to SM and DM sectors through chemical equilibrium. DM carries positive baryon number.

- Introducing non-zero CP phase during non-equilibrium phase. No requirement for non-zero (B-L) is needed. DM carries negative baryon number.

Motivation & Review

N. Blinov, H. Davoudiasl, D. Morrissey, K. Sigurdson, S. Tulin
arXiv:1008.2399 [hep-ph]
arXiv:1106.4320 [hep-ph]
arXiv:1206.3304 [hep-ph]

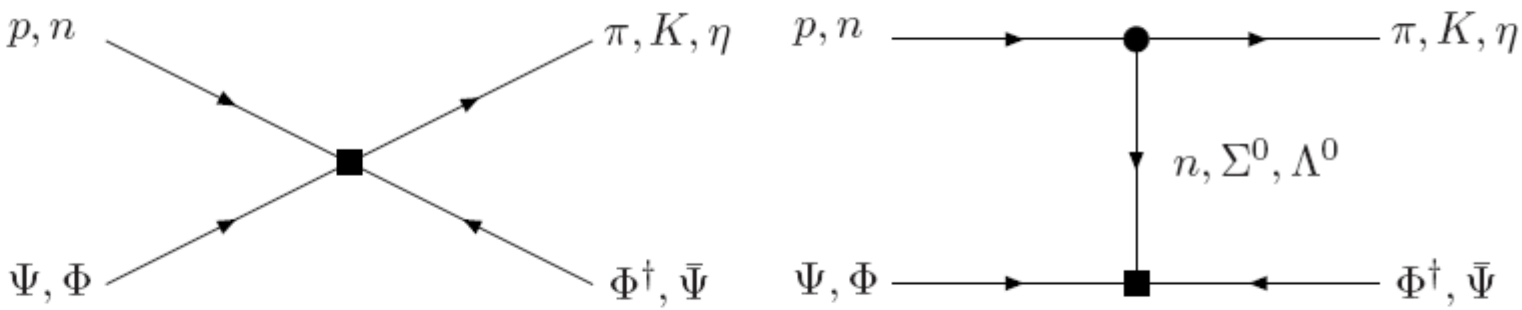
$$-\mathscr{L} \supset \frac{\lambda_a}{M^2} \bar{X}_a P_R d \, \bar{u}^c P_R d + \zeta_a \, \bar{X}_a Y^c \Phi^* + \text{h.c.}$$



CP violating phase ⟹ ADM carries anti-baryon number

Motivation & Review

$$\mathscr{L}_{\text{eff}} \sim \frac{1}{\Lambda^3} u_R^i d_R^j d_R^k \Psi_R \Phi + \text{h.c.}$$



To make sure this process happens:

$\Longrightarrow$ $|m_Y - m_\Phi| < m_p + m_e < m_Y + m_\Phi$

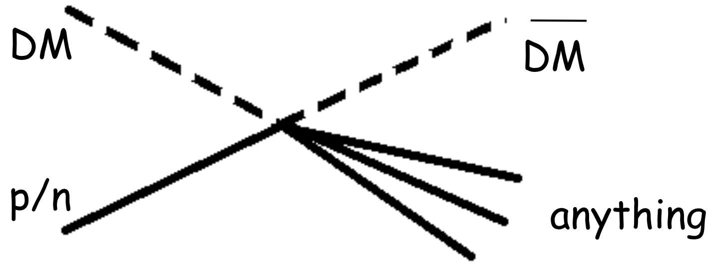
Nucleon is stable due to the conservation of baryon number.
Induced decay can happen since DM carry Baryon Number.

Motivation & Review

- Only one component of DM?
  no degeneracy between scalar and fermionic DM

- Different particles in final state (leptons)?
  different proton decay search channel
  more interesting signatures one could study

Effective operators:



- Just one component of DM: DM -> $\overline{\text{DM}}$, and induce nucleon decay

- To transfer baryon number and keep SU(3) singlet, 3 quarks are needed.

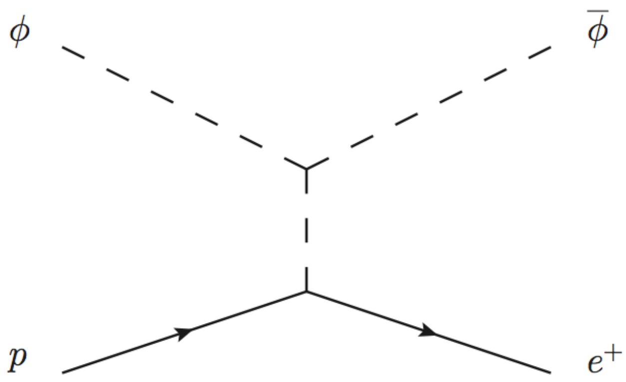
- To keep Lorentz symmetry, one more fermion is needed.

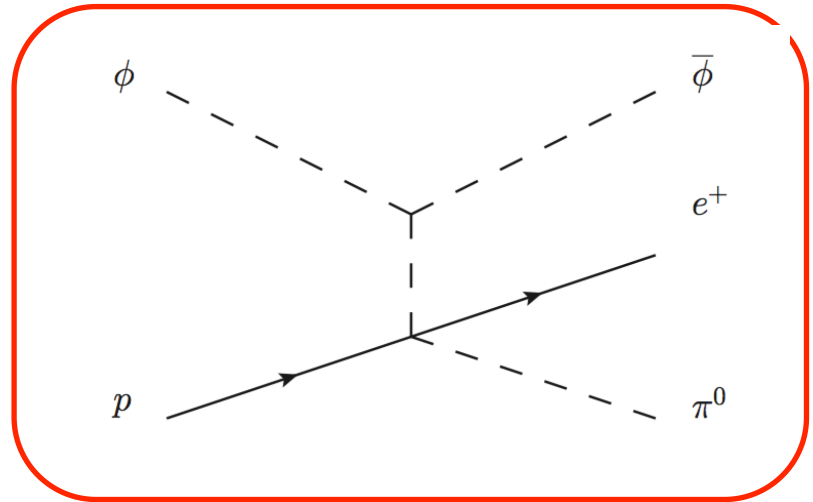
- Keep the lowest dimension.

⇨ Minimal version with a scalar DM particle:

$$\mathscr{L}_{eff} \supset \frac{1}{\Lambda^4}\phi^{*2}(e^c u^c)(d^c u^c) \quad \text{or} \quad \mathscr{L}_{eff} \supset \frac{1}{\Lambda^4}\phi^{*2}(L^\dagger Q^\dagger)(u^c d^c)$$

Effective operators:





Comparison with arXiv:1106.4320 [hep-ph] :

Pros:

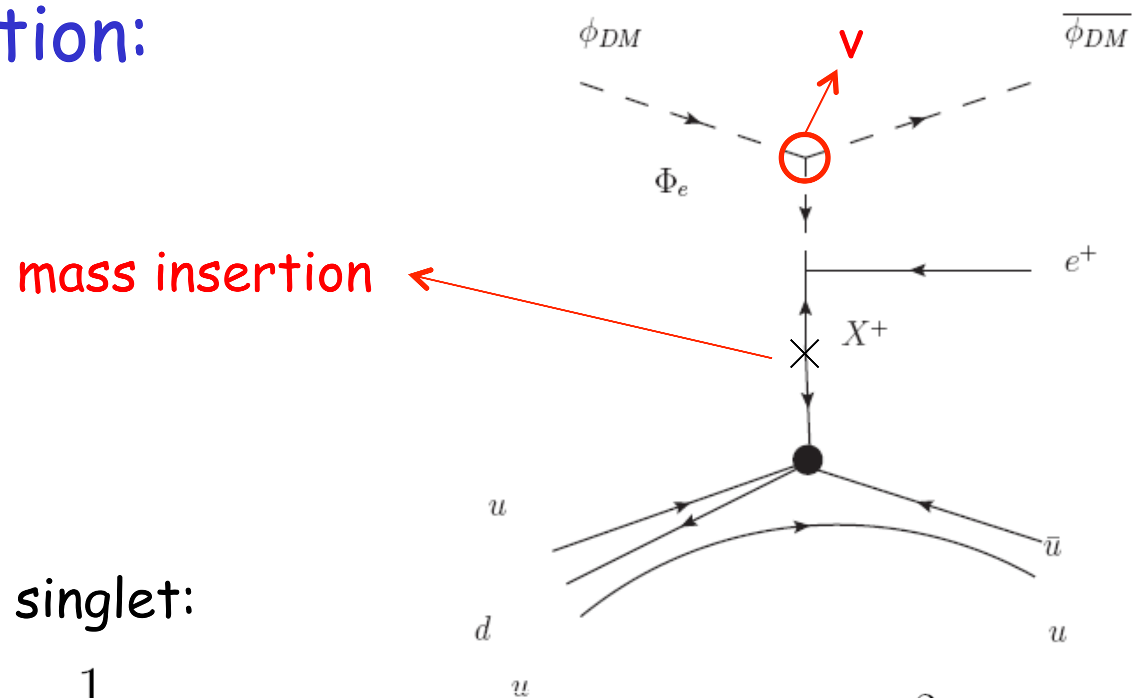
- only one component of DM, no degeneracy between scalar and fermion
- one more diagram to play with
- one lepton in the final state, more interesting phenomenology

Cons:

Naively more difficult for this process to happen, due to:

- dim is higher by 1
- For SuperK study, one more particle in final state (2 -> 3 Process)

UV Completion:



X as SU(2) singlet:

$$\mathscr{L}_c \supset \frac{1}{\Lambda^2}(X u^c)(d^c u^c) \qquad \mathscr{L}_{DM} \supset v\phi^{*2}\Phi_e^* + \Phi_e(X^c e^c)$$

X as SU(2) doublet:

$$\mathscr{L}_c \supset \frac{1}{\Lambda^2}(X^c Q)(u^{c\dagger} d^{c\dagger}) \qquad \mathscr{L}_{DM} \supset v\phi^{2}\Phi_e + \Phi_e^*(XL)$$

UV Completion:

Summary:

φ_{DM} : the only DM particle in our model B = -½ L = -½ Q = 0

$X_{1,2}$: Heavy B = +1 L = 0 Q = +1 (0)
1 and 2 are for Hylogenesis ⇨ Not the focus of this talk
Focus on the phenomenology of anti-baryonic DM

Φ_e : color singlet B = +1 L = +1 Q = 0
Mediating the interaction between DM and SM particles.

$$-\mathcal{L}_e \supset \frac{\lambda_c}{\Lambda^2}(Xu^c)(u^c d^c) + \lambda_s X^c e^c \Phi_e + v\phi^*\phi^*\Phi_e^* + h.c.$$

$$\Rightarrow \quad \mathscr{L}_{e,eff} \supset \frac{v}{\Lambda^2 M_X M_{\Phi_e}^2}\phi^{*2}(e^c u^c)(d^c u^c)$$

$$-\mathcal{L}_L \supset \frac{\lambda_c}{\Lambda^2}(X^c Q)(u^{c\dagger} d^{c\dagger}) + \lambda_s X L \Phi_e^* + v\phi\phi\Phi_e + h.c.$$

$$\Rightarrow \quad \mathscr{L}_{L,eff} \supset \frac{v}{\Lambda^2 M_X M_{\Phi_e}^2}\phi^{*2}(L^\dagger Q^\dagger)(u^c d^c)$$

Parameters :

- $m_{DM} \sim 3$ GeV
- $m_{\Phi e} \sim m_{DM}$
- $v < 4\pi\, m_{DM}$
- $M_X > \lambda_s\, 500$ GeV
- $M_X \sim \Lambda \sim 1000$ GeV → conservative choice

Benchmark point

- $m_{DM} = 3$ GeV
- $m_{\Phi e} = 3$ GeV
- $v = 38$ GeV
- $\lambda_s = 2$
- $M_X = \Lambda = 1000$ GeV

* Effective Suppression Scale: M = 104 GeV

Relating to Chiral Lagrangian

Parton level operator:

$$O_{R1} = \epsilon_{\alpha\beta\gamma}\phi\phi(d_R^\alpha u_R^\beta)(u_R^\gamma e_R)$$

$$O_{R2} = \epsilon_{\alpha\beta\gamma}\phi\phi(s_R^\alpha u_R^\beta)(u_R^\gamma e_R)$$

for $\Phi_e(X^c e^c)$ operator

$$O_{L1} = \epsilon_{\alpha\beta\gamma}\phi\phi(d_R^\alpha u_R^\beta)(u_L^\gamma e_L - d_L^\gamma \nu_L)$$

$$O_{L2} = \epsilon_{\alpha\beta\gamma}\phi\phi(s_R^\alpha u_R^\beta)(u_L^\gamma e_L - d_L^\gamma \nu_L)$$

$$O_{L3} = \epsilon_{\alpha\beta\gamma}\phi\phi(d_R^\alpha u_R^\beta)(s_L^\gamma \nu_L)$$

for $\Phi_e^*(XL)$ operator

$(s_L^\gamma \nu_L)$ → not including charm due to its mass

Use chiral Lagrangian to relate parton level process to nuclei/ meson process (*Claudson, Wise and Hall*)

Relating to Chiral Lagrangian

Chiral Lagrangian:

$\Phi_e(X^c e^c) \Rightarrow$

$$\mathcal{L}_{int} \supset C_{L1}\beta \mathrm{Tr}\left[O\xi^\dagger(B_R e_R)\xi\phi\phi\right] + C_{L2}\beta \mathrm{Tr}\left[\tilde{O}\xi^\dagger(B_R e_R)\xi\phi\phi\right]$$

$\Phi_e^*(XL) \Rightarrow$

$$\begin{aligned}\mathcal{L}_{int} \supset\; & C_{R1}\alpha \mathrm{Tr}\left[O\xi(B_L e_L)\xi\phi\phi - O'\xi(B_L \nu_L)\xi\phi\phi\right] \\ + \; & C_{R2}\alpha \mathrm{Tr}\left[\tilde{O}\xi(B_L e_L)\xi\phi\phi - \tilde{O}'\xi(B_L \nu_L)\xi\phi\phi\right] + C_{R3}\alpha \mathrm{Tr}\left[\tilde{O}''\xi(B_L \nu_L)\xi\phi\phi\right]\end{aligned}$$

$\alpha \sim -0.015\ GeV^3$ and $\beta \sim 0.014\ GeV^3$ from Lattice calculation

Leading order expansion in $p_{\pi^0}/(4\pi f)$ ~ 0.3, with f ~ 139 MeV.

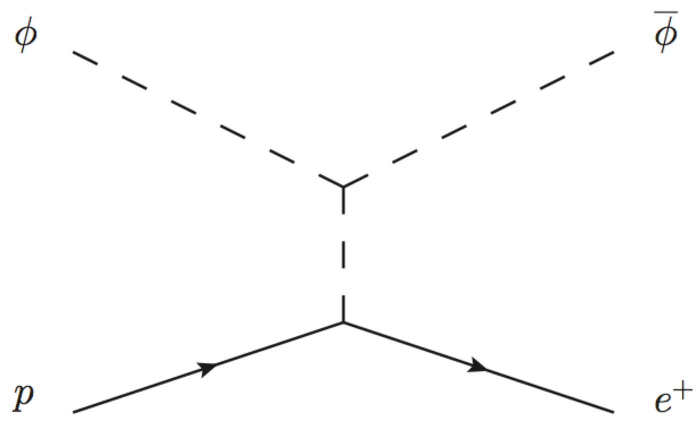
$$\mathcal{L}_{\rm int} = \sum_i C_i O_i$$

Relating to Chiral Lagrangian

After expansion:

Leading order

$$\mathcal{L}_{\rm int} \supset C_{R1}\beta p_R e_R \phi\phi \quad \text{or} \quad C_{L1}\alpha(p_L e_L - n_L \nu_L)\phi\phi$$



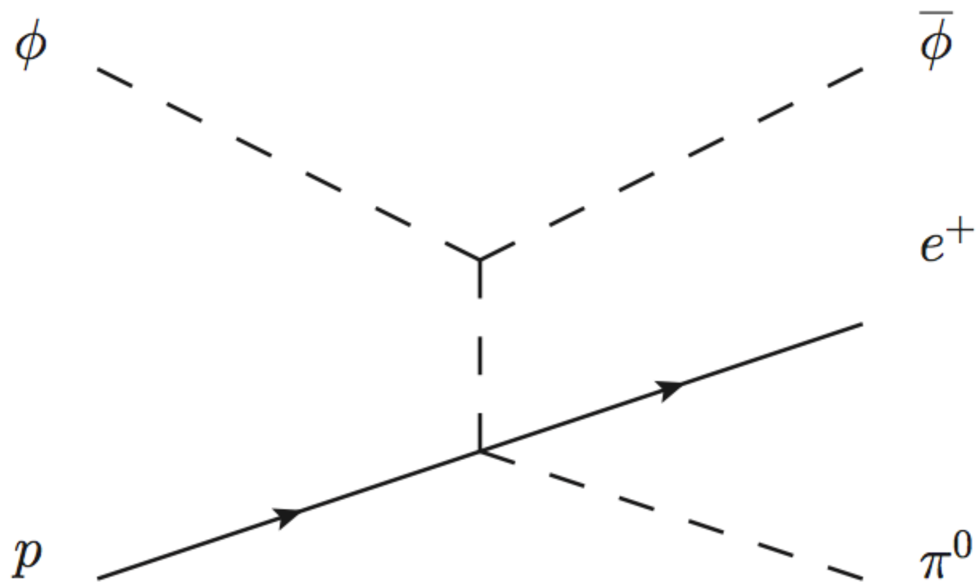
$$E_{e/\nu} \simeq \frac{2m_{DM} + m_P}{2(m_{DM} + m_P)} m_P$$

Relating to Chiral Lagrangian

After expansion:

Next leading order

$$\mathcal{L}_{\text{int}} \supset i\frac{C_{R1}\beta}{\sqrt{2}f}\pi^0 p_R e_R \phi\phi \text{ or } i\frac{C_{L1}\alpha}{\sqrt{2}f}\pi^0(p_L e_L - n_L \nu_L)\phi\phi$$



Signatures – Induced nucleon decay

A similar signature has been studied in detail by

N. Blinov, H. Davoudiasl, D. Morrissey, K. Sigurdson, S. Tulin
arXiv:1008.2399 [hep-ph]
arXiv:1106.4320 [hep-ph]
arXiv:1206.3304 [hep-ph]

We have charged lepton in the final state.

Although the leading order expansion induces 2-to-2 process

$$p + \phi \to e^+ + \tilde{\phi}$$

The atmospheric neutrino background is large.

Currently no searches optimize for such channel, but may be doable in near future.

- Energy resolution is very good for charged leptons.
- Veto on fast moving proton/neutron. (Doping Gd Ion in SuperK)

Signatures - Induced nucleon decay

Currently the most sensitive channel:

$$p + \phi \rightarrow \pi^0 + e^+ + \tilde{\phi}$$

Translating the cross section to proton decay lifetime:

$$\tau_N^{-1} \approx (10^{32}\,\mathrm{yrs})^{-1} \times \left(\frac{\rho_{DM}}{0.3\,\mathrm{GeV/cm^3}}\right)\left(\frac{(\sigma v)_{IND}}{10^{-39}\,\mathrm{cm^3/s}}\right)$$

Benchmark point

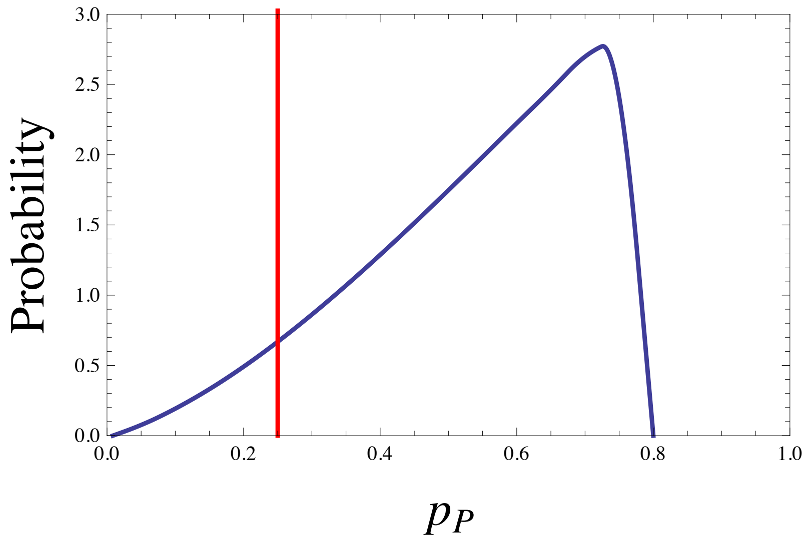
- m_{DM} = 3 GeV
- $m_{\Phi e}$ = 3 GeV
- v = 38 GeV
- λ_s = 2
- Mx = Λ = 1000 GeV

⇨ σ_{IND} v ~ $0.7*10^{-40}$ cm^3/s
τ ~ $1.5*10^{33}$ yr

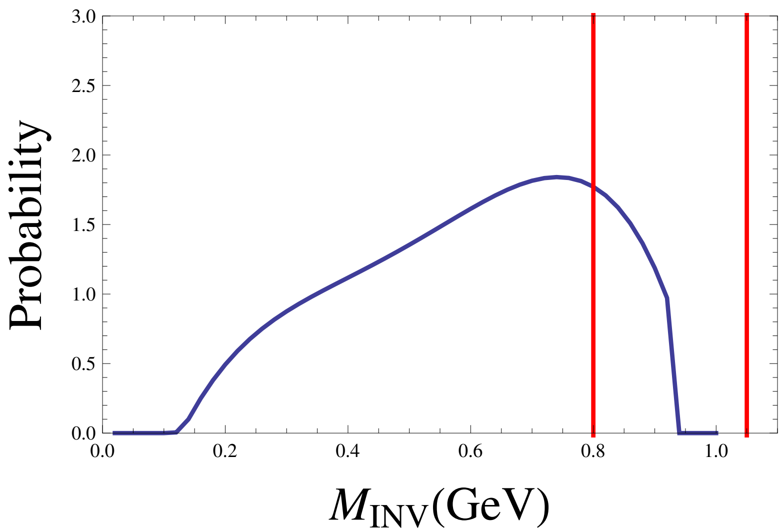
Signatures – Induced nucleon decay

Reconstruction efficiency:

P cut < 250 MeV



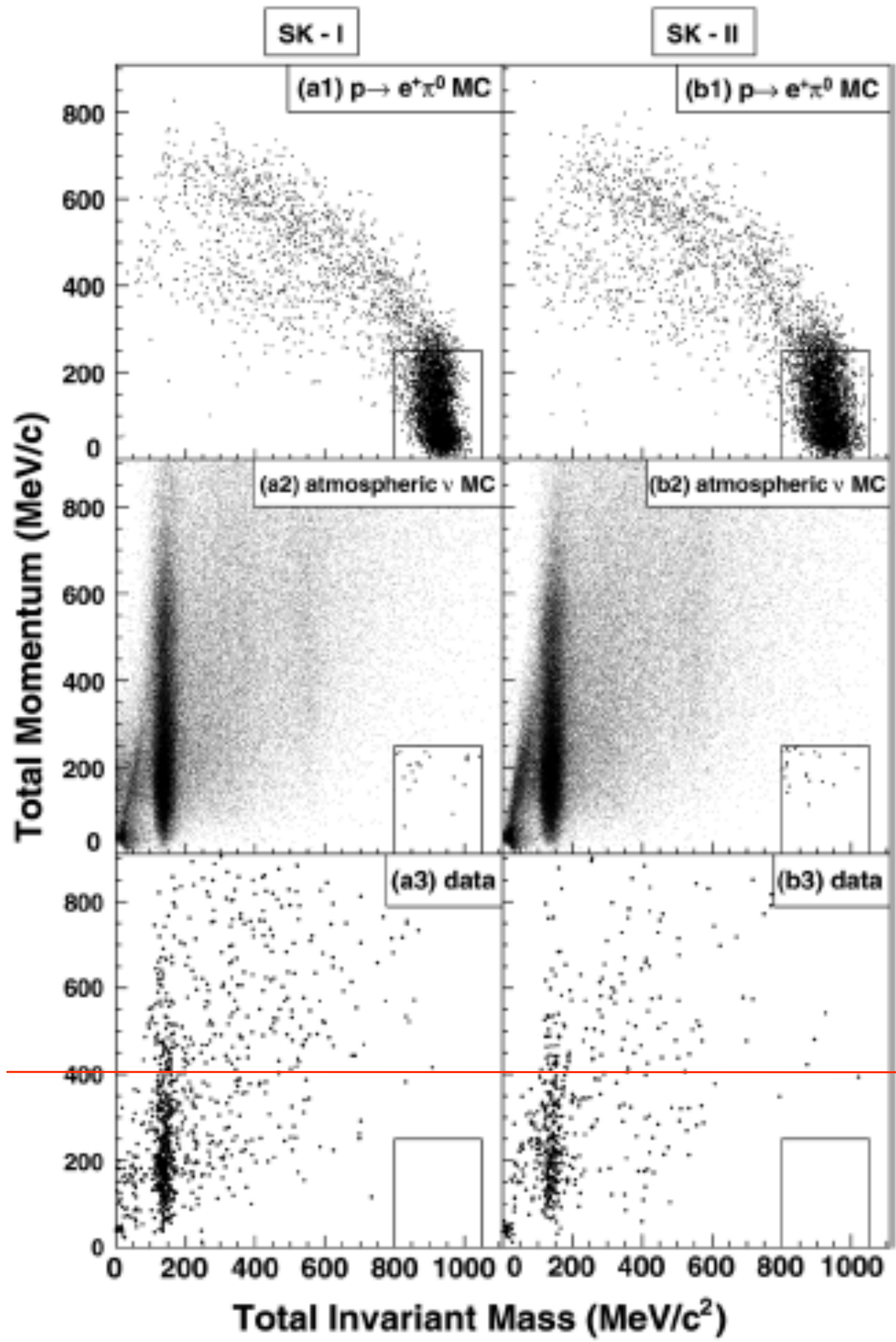
Inv mass cut (800~1050 MeV)



cut efficiency ~ 0.61*0.0523 ⇨ τ ~ $2.9*10^{34}$ yr

detector efficiency

Near Future



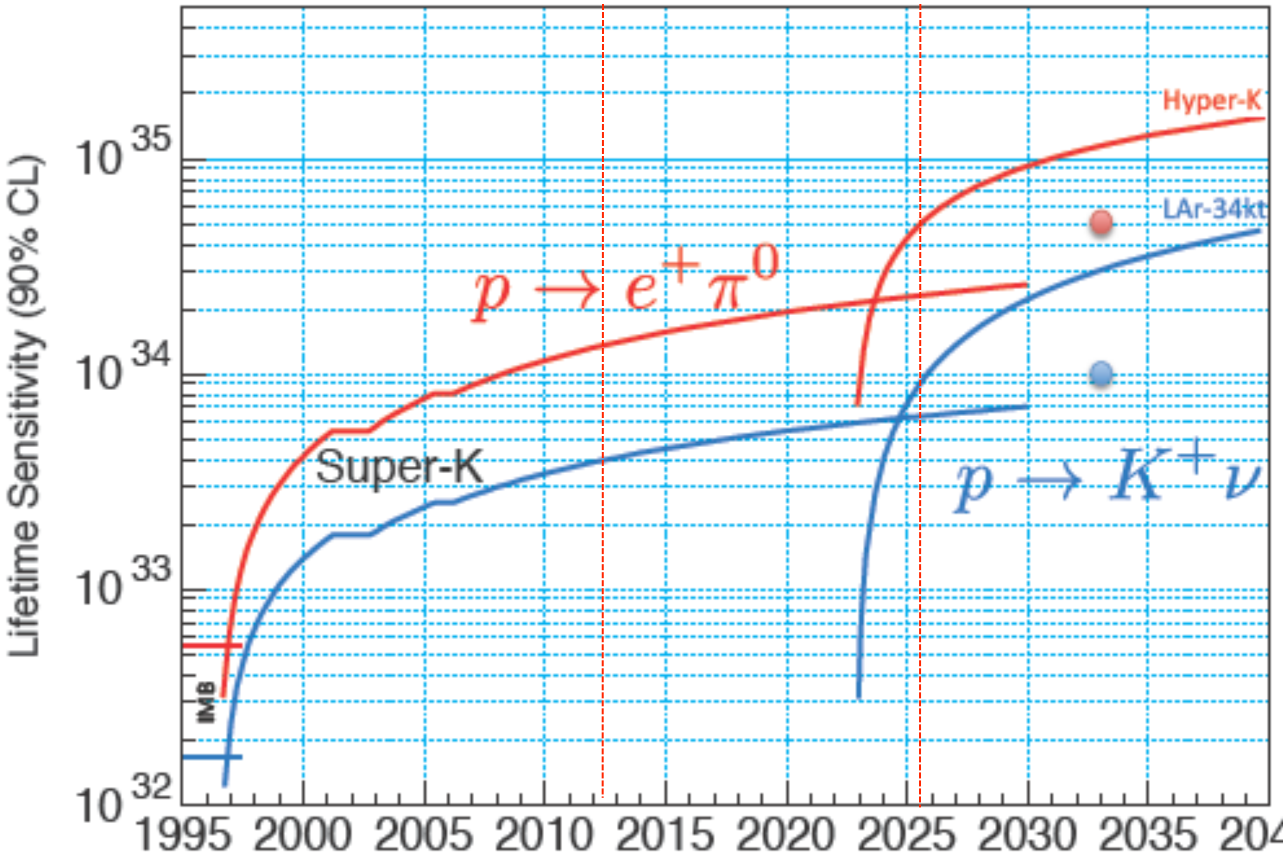
$\tau \sim 7.5*10^{33}$ yr (2007 data)

cut efficiency ~ 0.61*0.2

cut efficiency mildly changes with DM mass

not crazy to cut on Pt < 400 MeV

Signatures – Induced nucleon decay



Ed Kearns
Boston University
May 25, 2013
ISOUPS
Asilomar, CA

Capture in the Sun:

In IND, we benefit by having a charged lepton in the final state.

We also have neutrinos in the final state, it helps us for detection as well!

Every inelastic scattering between DM and nucleon induces a neutrino: 1 GeV

⇨ Neutrino experiment may help for the search.

No need to reconstruct proton/neutron.

⇨ Leading order process dominates, with a much higher IND Xsec.
Only annihilating with neutron generates neutrino.

ADM does not annihilate with each other, thus the Sun accumulates DM.

⇨ Neutrino flux from the Sun.

Due to conversion from DM to anti-DM, Neutron Star bounds do not apply, even our ADM is a scalar.

Capture in the Sun:

Capture rate:

$$C^{\odot} \simeq 1.3 \times 10^{25}\,\mathrm{s}^{-1} \left(\frac{\rho_{\mathrm{DM}}}{0.3\,\mathrm{GeV/cm^3}}\right)\left(\frac{270\,\mathrm{km/s}}{\bar{v}}\right)\left(\frac{1\,\mathrm{GeV}}{m_{\mathrm{DM}}}\right)$$
$$\times\left[\left(\frac{\sigma_{\mathrm{H}}}{10^{-40}\,\mathrm{cm}^2}\right)S(m_{\mathrm{DM}}/m_{\mathrm{H}}) + 1.1\left(\frac{\sigma_{\mathrm{He}}}{16\times 10^{-40}\,\mathrm{cm}^2}\right)S(m_{\mathrm{DM}}/m_{\mathrm{He}})\right]$$

For DM lighter than 5 GeV:

additional input to the model

- Spin independent: 10^{-39} cm^2
- Spin dependent: 10^{-36} cm^2

⇒

- Spin independent: $C^{\odot} \sim 10^{26} s^{-1} (\frac{5GeV}{m_{DM}})$
- Spin dependent: $C^{\odot} \sim 10^{29} s^{-1} (\frac{5GeV}{m_{DM}})$

Capture in the Sun:

Thermal escape rate:

$$E^{\odot} \approx 10^{-\left(\frac{7}{2}(m_{\rm DM}/{\rm GeV})+4\right)}\,{\rm s}^{-1}\left(\frac{\sigma_{\rm H}}{5\times 10^{-39}\,{\rm cm}^2}\right)$$

Anti-DM after conversion:

$$p_{\tilde{\phi}} \simeq \frac{2m_{DM}+m_N}{2(m_{DM}+m_N)}m_N$$ ~ 0.8 GeV for 3 GeV DM

As long as DM mass is smaller than few TeV,
it will fly away from the Sun.

⇩

(leads to interesting signature one could look for)

Capture in the Sun:

Equation for accumulation:

$$\frac{dN_{DM}}{dt} = C^{\odot} - (\sigma v)_{IND}\, n_{c,n} N_{DM} - E^{\odot} N_{DM}$$

Anti-DM will be boosted after the conversion. No DM-anti-DM annihilation term is included.

Dominated by 2-to-2 process! Unlike in SuperK, one does not need to reconstruct proton.

Only annihilating with neutron can produce neutrinos

28% mass of the Sun is Helium

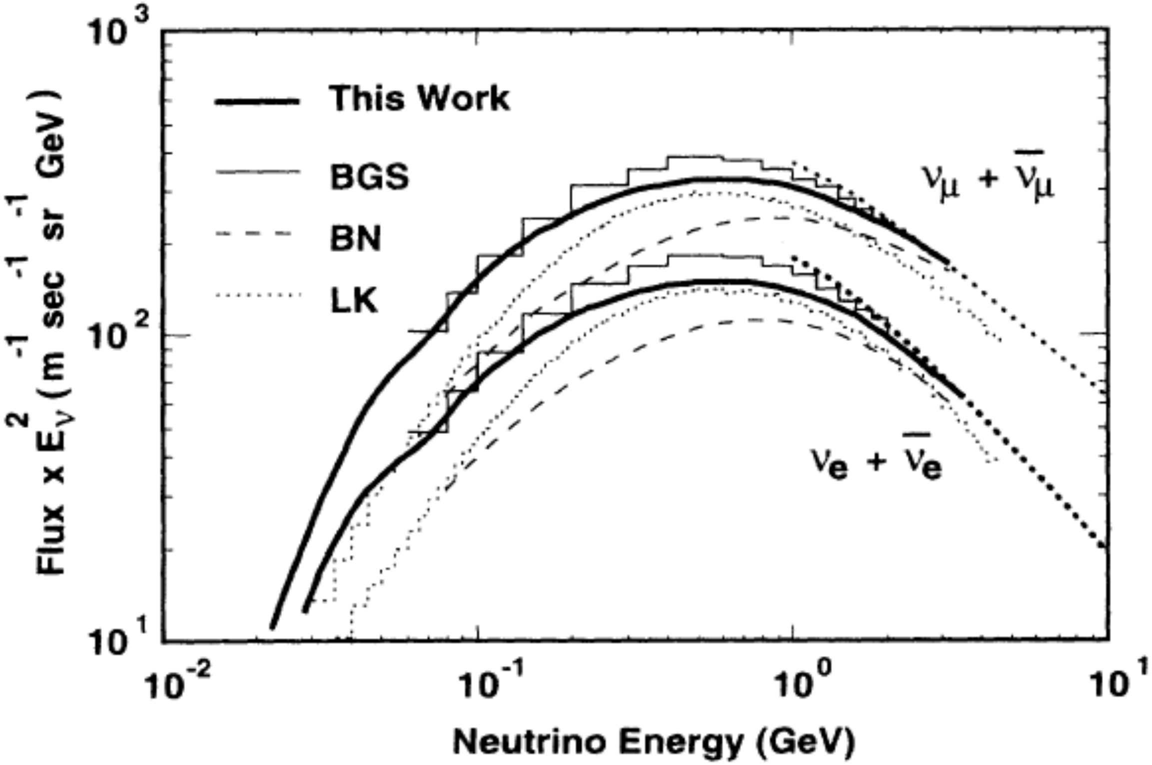
Benchmark point

- m_{DM} = 3 GeV
- $m_{\Phi e}$ = 3 GeV
- v = 38 GeV
- λ_s = 2
- Mx = Λ = 1000 GeV

⇨ $\sigma_{IND}\, v \sim 5.6*10^{-36}$ cm^3/s

Capture in the Sun:

Neutrino Flux



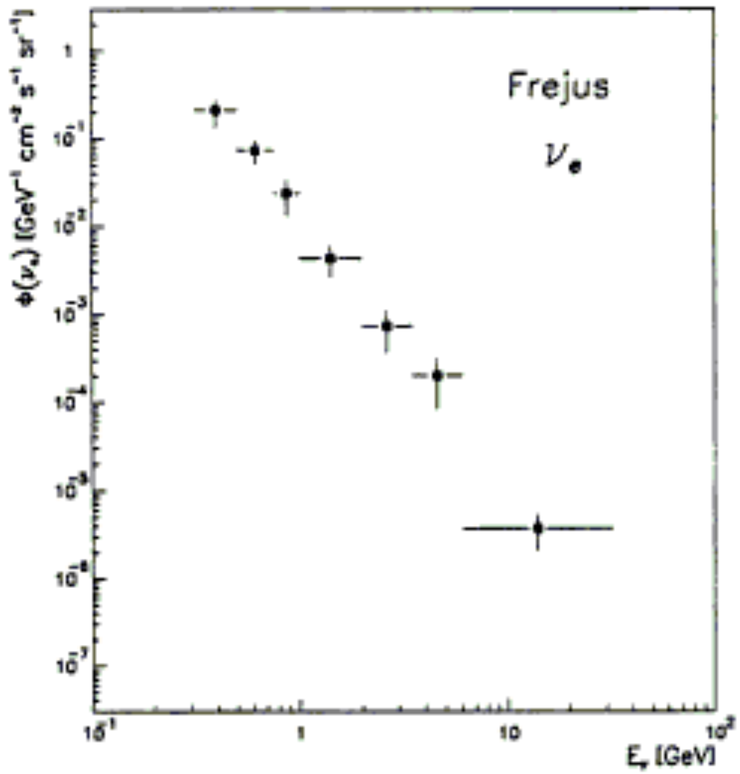
M. Honda, T. Kajita,
K. Kasahara, S. Midorikawa
2006, 2011

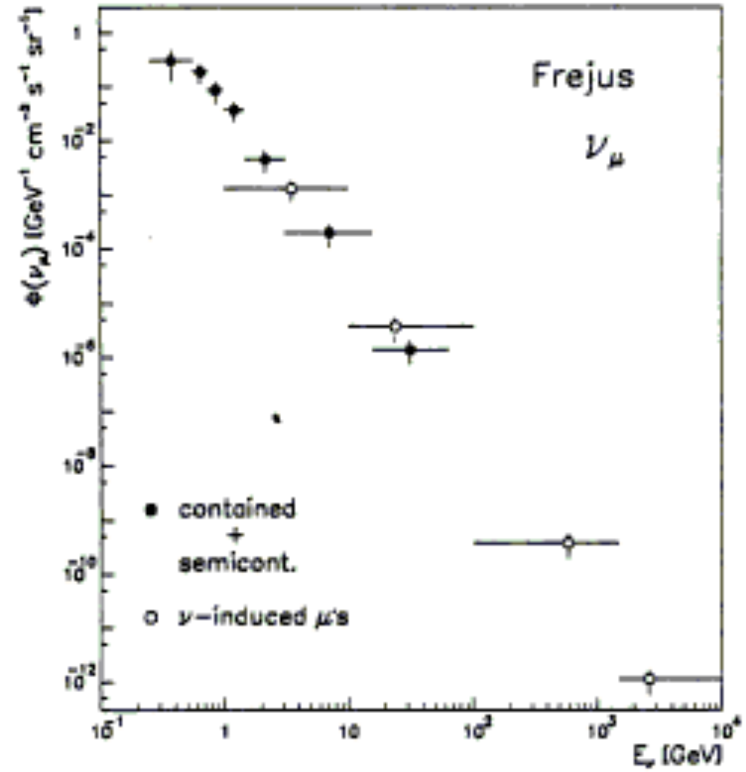
Theoretical uncertainty is the dominant uncertainty for neutrino flux spectrum ~ 20%.

Capture in the Sun:

Neutrino Flux

1995ICRC....1..726F





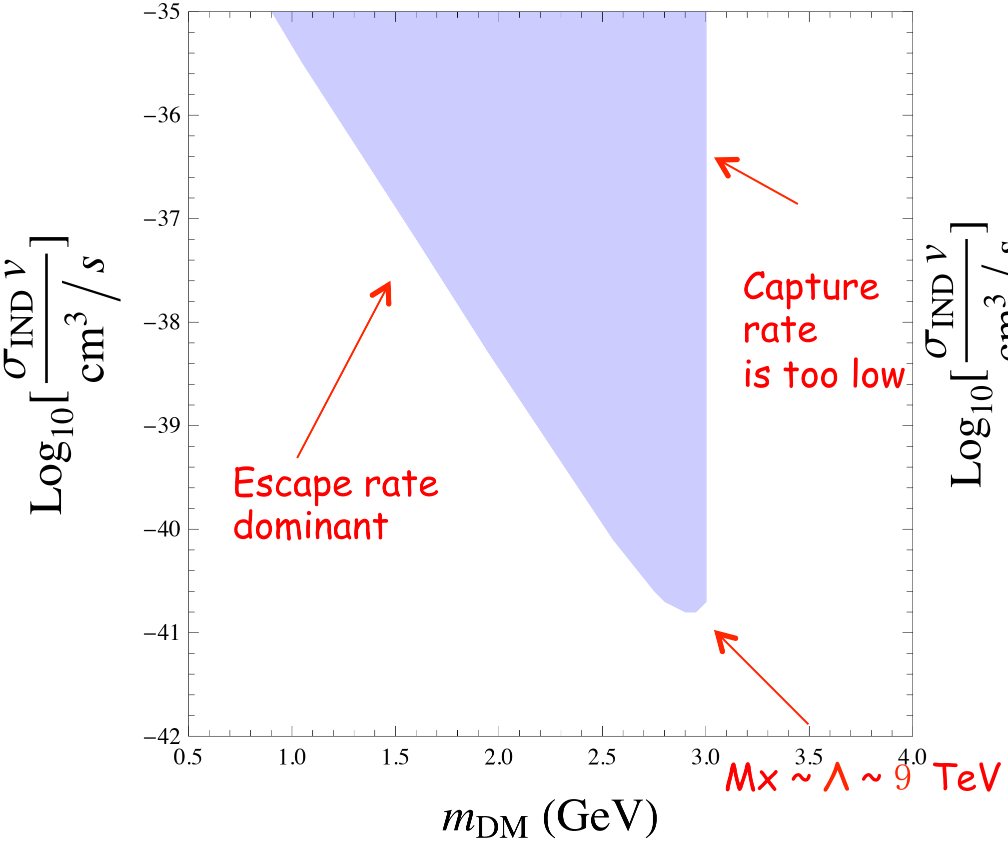
not sensitive to DM mass

⇨ anti-electron neutrino from the Sun < 1.25 * 10^{24} /s

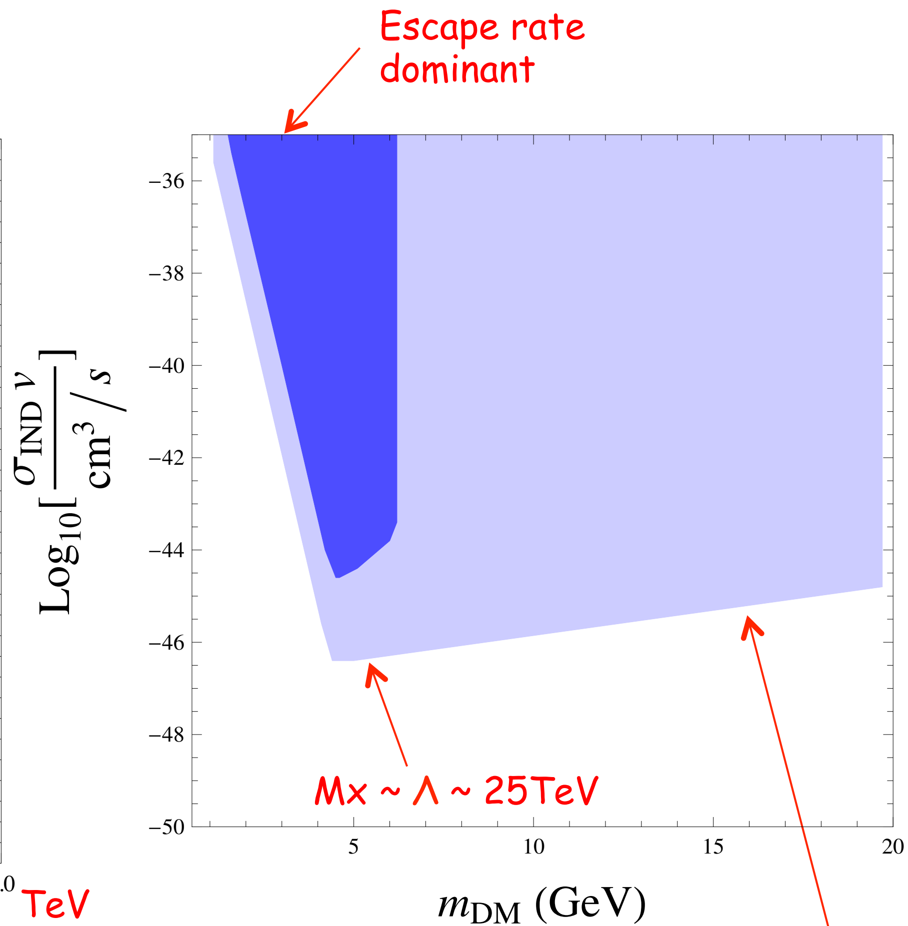
One can further apply directional information to reduce atmospheric neutrino BG. Not done yet for sub-GeV neutrino.

Capture in the Sun:

Neutrino Flux



Spin Independent

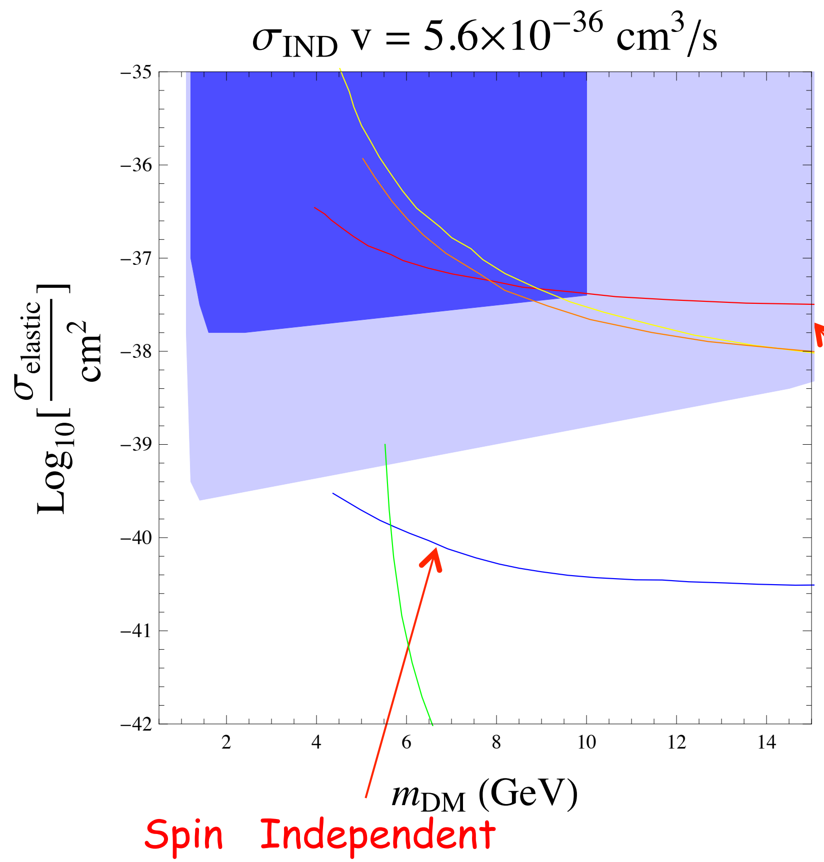


Spin Dependent

If DM is too heavy, it cannot be stopped in the Sun.

Capture in the Sun:

Neutrino Flux



Taking the benchmark mark point, one can use neutrino flux to constrain the elastic scattering cross section.

Capture in the Sun:

Anti-DM Flux

DM converts to Anti-DM and is boosted to high velocity.

$$p_{\tilde{\phi}} \simeq \frac{2m_{DM} + m_N}{2(m_{DM} + m_N)} m_N$$

~ 0.86 GeV for 3 GeV DM

⇨ v ~ 0.3 c >> escape velocity

Both proton/neutron can annihilate with DM to boost anti-DM.

Can we see those anti-DM flux on any ground experiments?

Capture in the Sun:

Anti-DM Flux

Colliding with proton/neutron momentum transfer ~ 600 MeV.

⇨ Large enough to kick out the proton/neutron from the nucleus.

Similar to NC elastic scattering between atmospheric neutrino and proton/neutron.

The flux is comparable to atmospheric neutrino flux, but might have a higher scattering Xsec comparing to neutrinos (10^{-39} cm^2).

Proton is not boosted enough for Cherenkov ring (just a little bit below the threshold).

Neutron will be captured by hydrogen and emit 2.2 MeV gamma ray.

⇨ Only 20% efficiency to detect.

Capture in the Sun:

Anti-DM Flux

Doping SK with Gd ion, neutron capture gives 8 MeV gamma ray.

Combine the gamma ray from prompt nuclear de-excitation to reduce the background.

Large liquid scintillator, Daya Bay II: Directional information (20 kton)

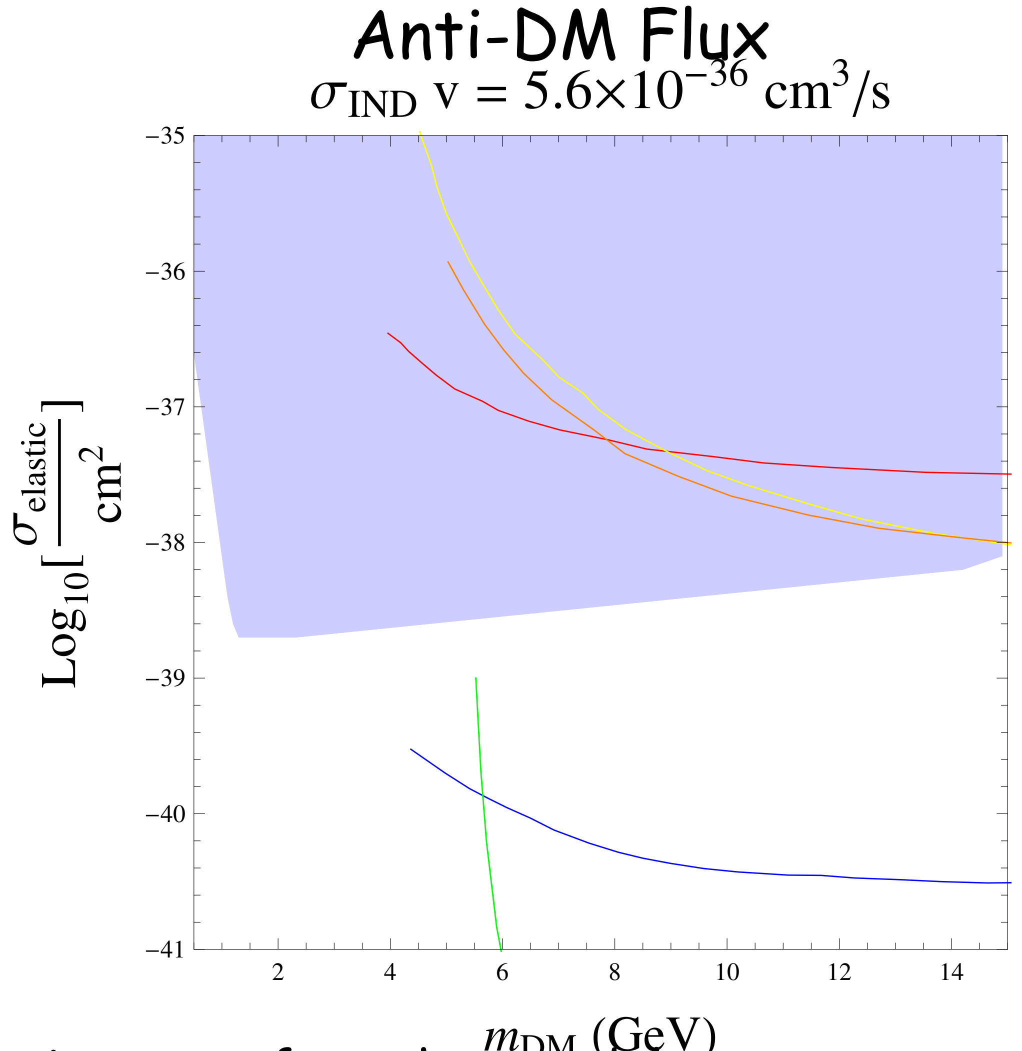
Energy resolution may not be good

⇒ We require: $Flux_{DMbar} * \sigma_{elastic} \sim Flux_{\nu} * \sigma_{NC} * 20\%$
for $10\ MeV < E_{\nu}$

too low to kick out neutron in oxygen (← 10 MeV)

uncertainty dominated by theoretical ones (← 20%)

Capture in the Sun:



Generic signature for other models:

Semi-annihilation:

proton/neutron may be even boosted enough for Cherenkov ring

Summary:

- When DM carries anti-baryon number, it is possible to annihilate with nucleon.

- We propose a single component DM model where DM carries $\frac{1}{2}$ baryon and lepton number, and it can induce nucleon decay.

- Signatures in this model:

  - Induced nucleon decay in SuperK (charged lepton, 2-to-3)
    the best search channel in SuperK can be applied
    current cuts ⇨ probe parameter space in very near future.
    Loosing mildly ⇨ probe the parameter space right now.

  - Neutrino flux from the Sun (neutrino, 2-to-2)
    constraining IND Xsec-Elastic Xsec-Mass space

  - Anti-DM flux from the Sun (anti-DM, 2-to-2)
    constraining IND Xsec-Elastic Xsec-Mass space
    generically applicable to other models.

Thank all!

Parameters:

- φ_{DM} :
  For Hylogenesis, m_{DM} ~ 3 GeV
  can be anything, model dependent

- Φ_e : SM gauge singlet.
  Mass needs to be larger than 1 GeV, to avoid proton decay.

  Mass preferred to be larger than 3 GeV to avoid wash out

  - If larger than 6 GeV, then decay to 2 DM

  - If smaller than 6 GeV, then in equilibrium with DM, and decay to pbar and e+ later. Decay lifetime is small enough to not mess up BBN.

$$\Gamma \sim (\frac{1}{16\pi^2})^2 \frac{m_{\phi_e}^7}{m_X^2 \Lambda^4}$$

$$M_X \sim \Lambda \sim 1000\ GeV$$

$$\tau \sim 7.5 \times 10^{-6} s$$

⇒ Decay when T ~ 1 GeV

Parameters:

- 3-scalar vertex:

$\delta m^2 < m^2$ $\Longrightarrow$ $v < 4\pi m_{DM}$

- X :

coupling to the leptonic sector

$$\Phi_e(X^c e^c) \text{ or } \Phi_e^*(XL)$$

LEP mono-photon constraint:
Effective operator is dim 6 due to chirality of lepton operator.

photon Energy > 10 GeV $\Longrightarrow$ $\sigma * A < 0.1$ pb

$\Longrightarrow$ $M_X > \lambda_s$ 500 GeV

Parameters :

- X :
  - Coupling to the strong sector: $\frac{1}{\Lambda^2}(Xu^c)(d^cu^c)$

The search channels depend on how X decays.

For model with $\Phi_e^*(XL)$:

1 jet + 1 charged lepton + MET or 1 jet + MET

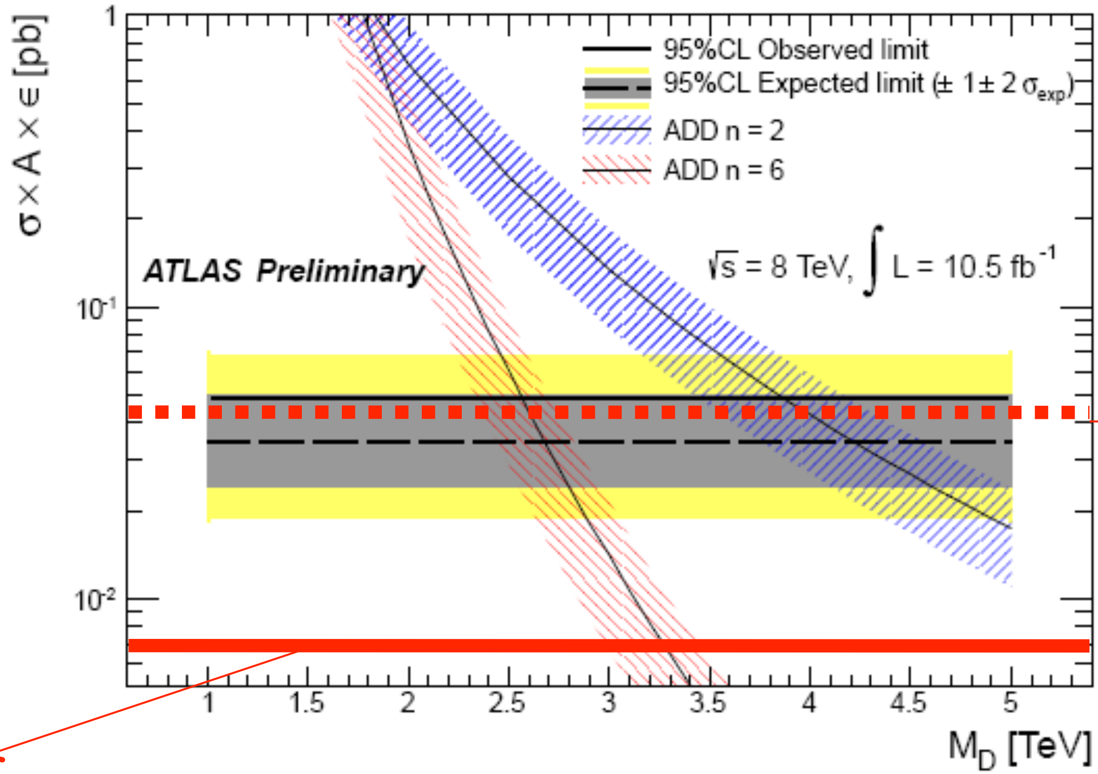
Monojet search can be applied to the second channel.

Assuming Mx ~ Λ, we do a very simple parton level estimation on the LHC constraints.

Parameters:

$$\Phi_e^*(XL)$$

ATLAS monojet search
Pt of leading jet > 350 GeV



Mx ~ Λ ~ 500 GeV
Only cut on PT at parton level

Xsec * A ~ 45 fb
Marginally OK
Need to be more careful!

Mx ~ Λ ~ 1000 GeV
Only cut on PT at parton level
Xsec * A ~ 7 fb

⇨ Without further detector simulation, just cutting on the Pt of leading jet, our Xsec * A is safely smaller than experiment constraint.

Parameters:

For model with $\Phi_e(X^c e^c)$ and $\Phi_e^*(XL)$:

The decay product is 1 jet + 1 charged lepton + MET.

Large SM background in this channel as q + W.

No concrete search optimized for this channel yet!

Most relevant search W', cut on

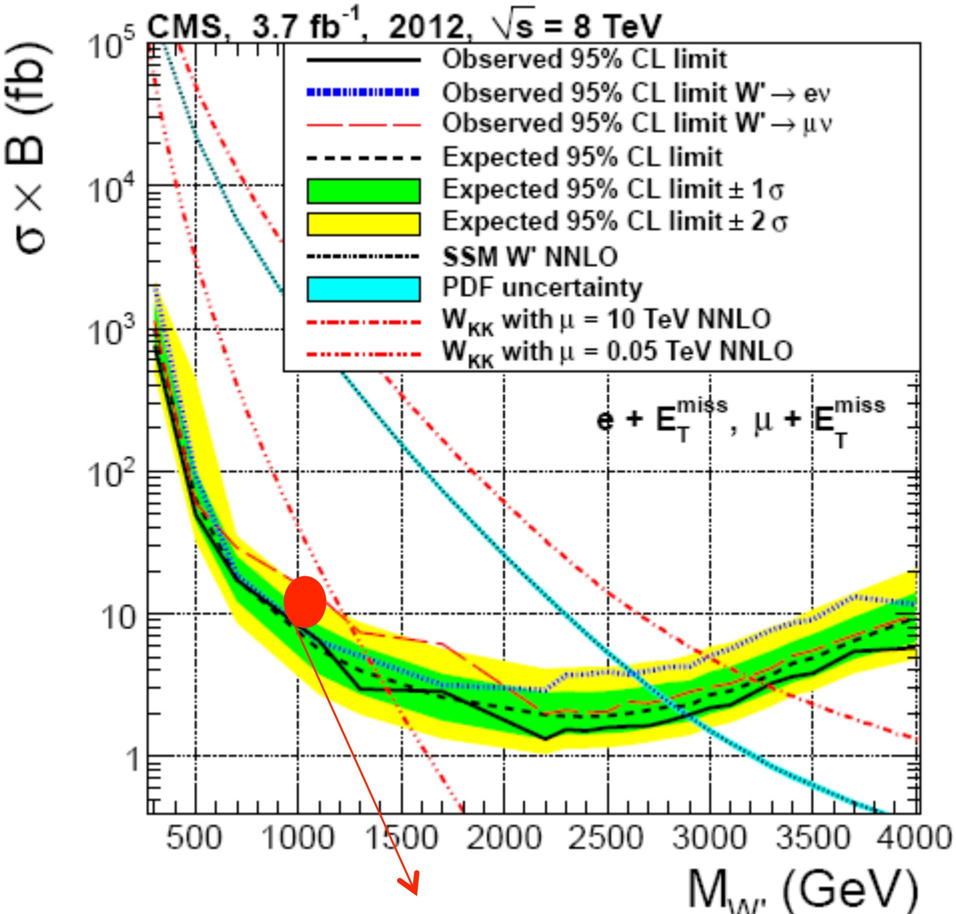
$$0.4 < p_{\mathrm{T}}^{\ell} / E_{\mathrm{T}}^{\mathrm{miss}} < 1.5$$

$$|\Delta\phi_{\ell,\nu} - \pi| < 0.2\pi$$

Parameters :

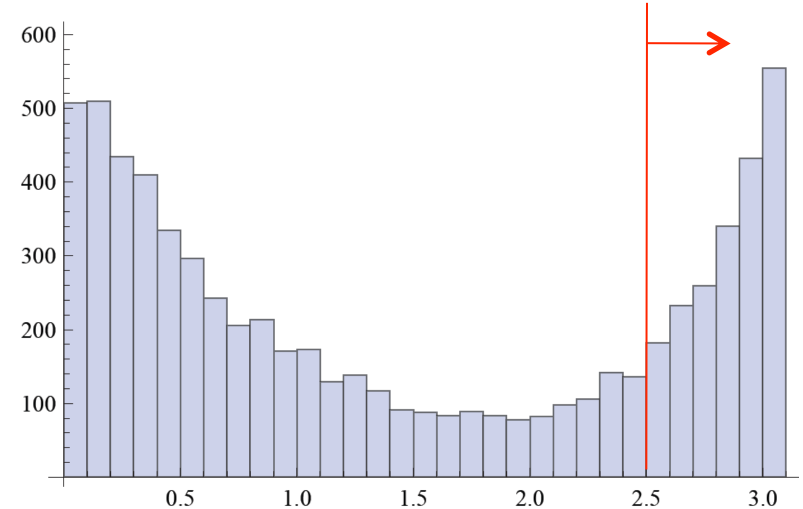
$$\Phi_e(X^c e^c)$$

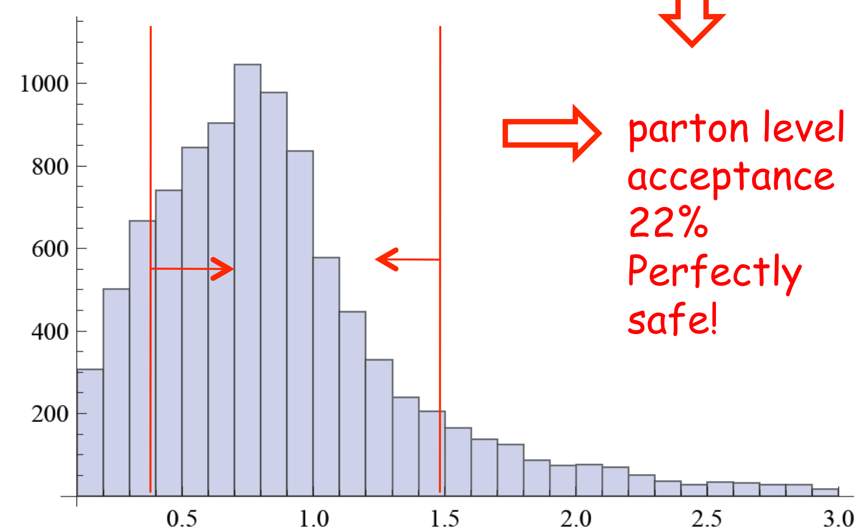
CMS W' search



Mx ~ Λ ~ 1000 GeV
parton level Xsec, without putting in cuts yet!

$$|\Delta\phi_{\ell,\nu} - \pi| < 0.2\pi$$



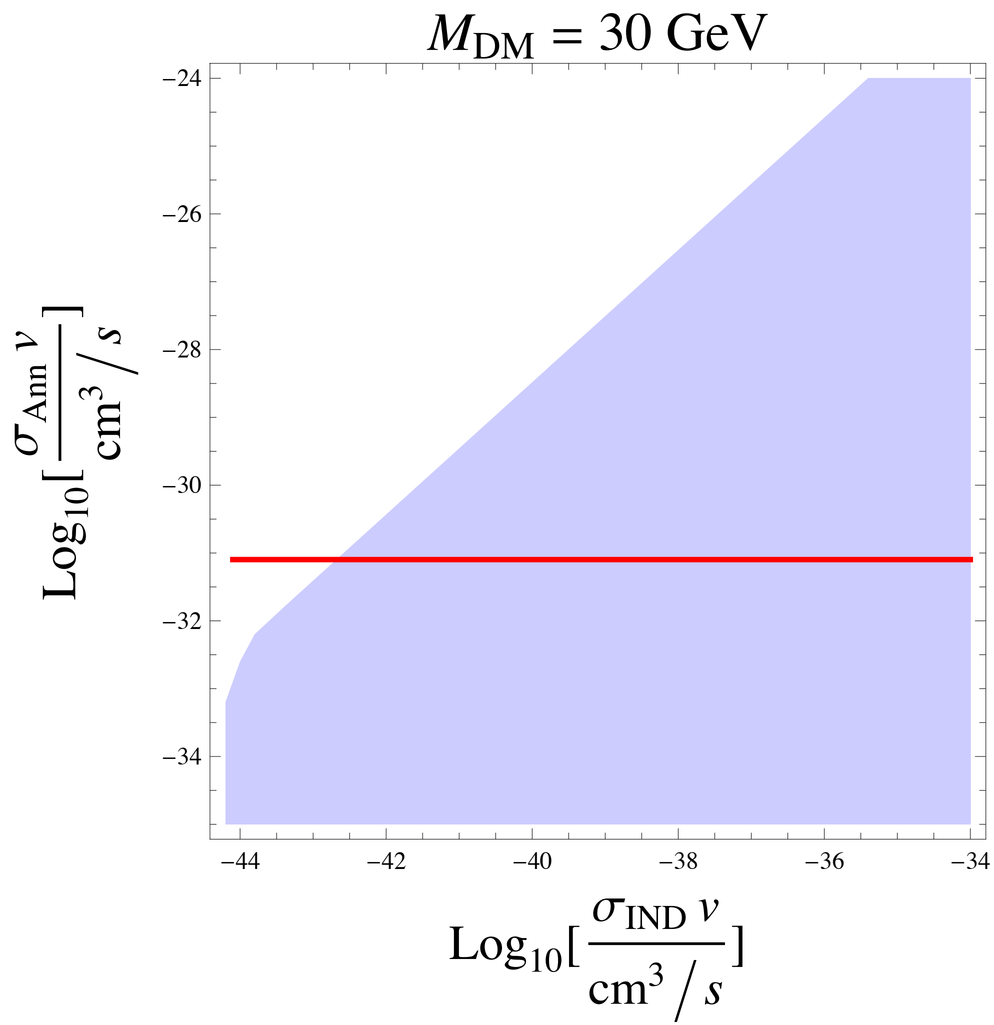


parton level acceptance 22%

Perfectly safe!

Capture in the Sun:

Neutrino Flux



assuming the largest elastic scattering cross section allowed from direct detection

much higher than n_{DM}

IND rate ~ n_{DM} * n_{nuclei}

DM-anti-DM annihilation ~ n_{DM} * $n_{anti\text{-}DM}$

Even for symmetric DM, Neutrino flux from IND could be interesting if annihilation Xsec is small enough. (σ_{ann}~ $v^{\#}$ or co-annihilation)

$$\frac{1}{\Lambda^2}\phi^\dagger\partial^\mu\phi\overline{f}\gamma_\mu\gamma^5 f$$