Neutrino Experiments for Dark Matter Detection

Yue Zhao

MCTP, University of Michigan

DUNE BSM meeting 2016

Junwu Huang , Y.Z. JHEP (2014)

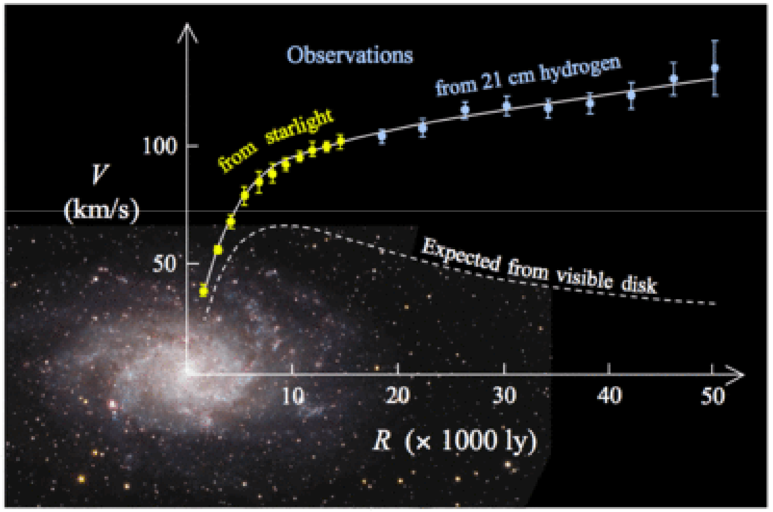
Joshua Berger, Yanou Cui , Y. Z. JCAP (2015)

On-going collaborations with MicroBooNE & DUNE

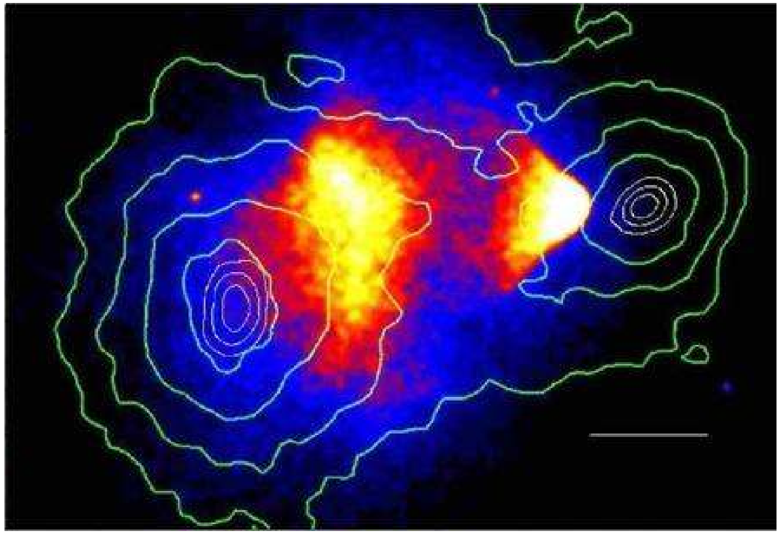
Dark Matter Overview:

Why do we need DM?

• Galaxy rotation curve (Wikipedia)

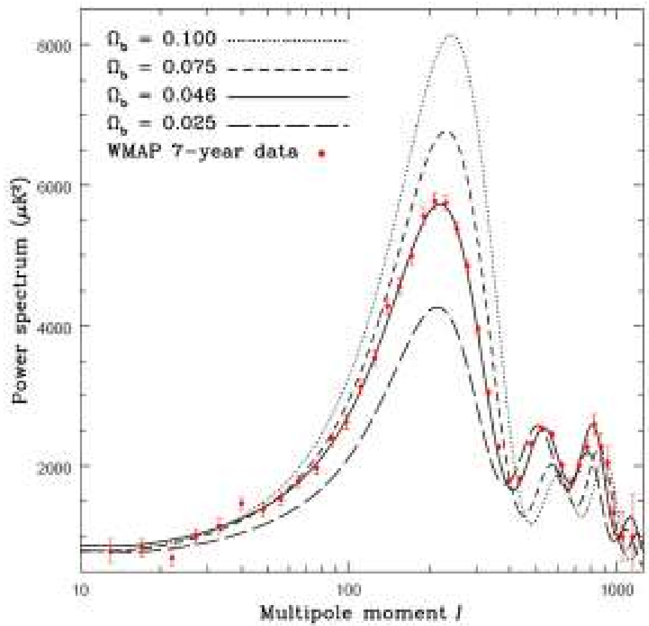


• Bullet Cluster (Deep Chandra)

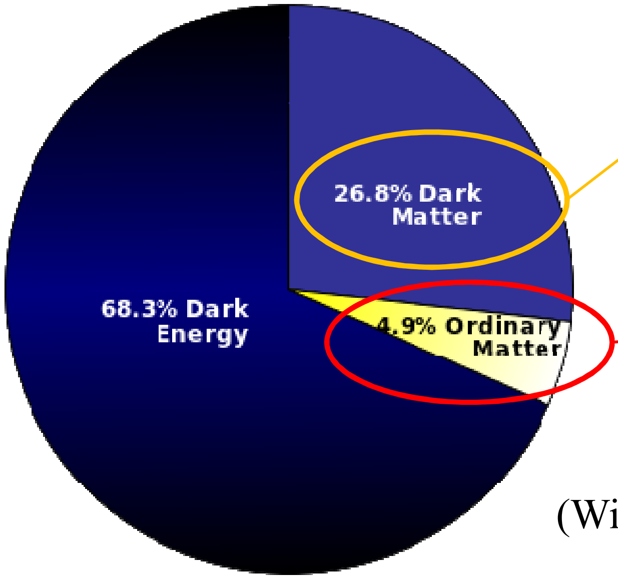


• The CMB Anisotropy Power Spectrum

(WMAP year 5 data)



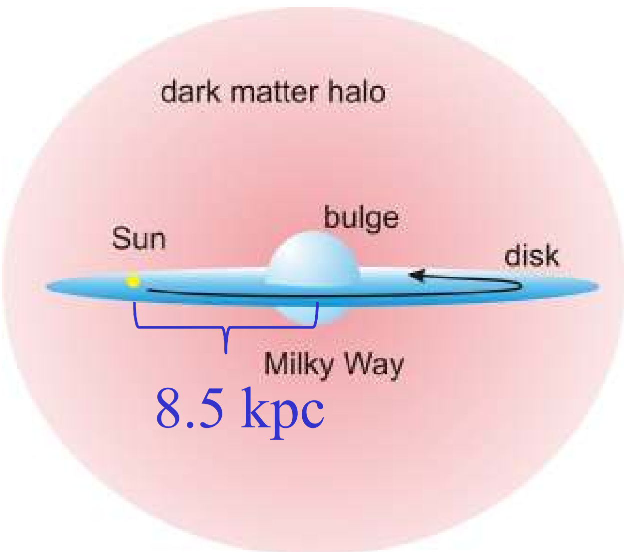
Dark Matter Overview:



We only know DM through its gravitational interaction!

We only understand 5% of the Universe!

(Wikipedia)



Local DM energy density:

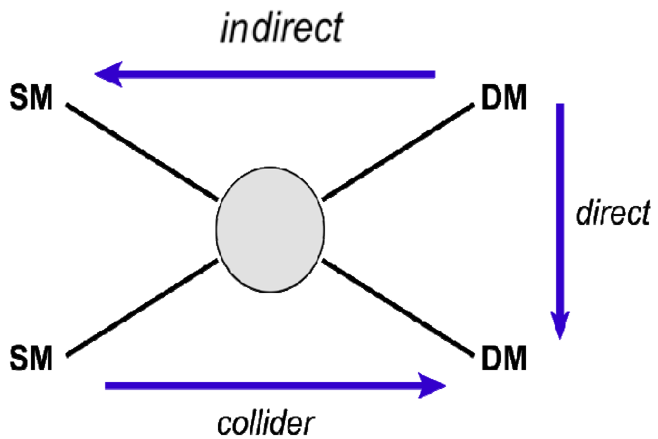
$$\rho_{\rm DM} \simeq 0.4 {\rm GeV/cm}^3$$

Local DM velocity:

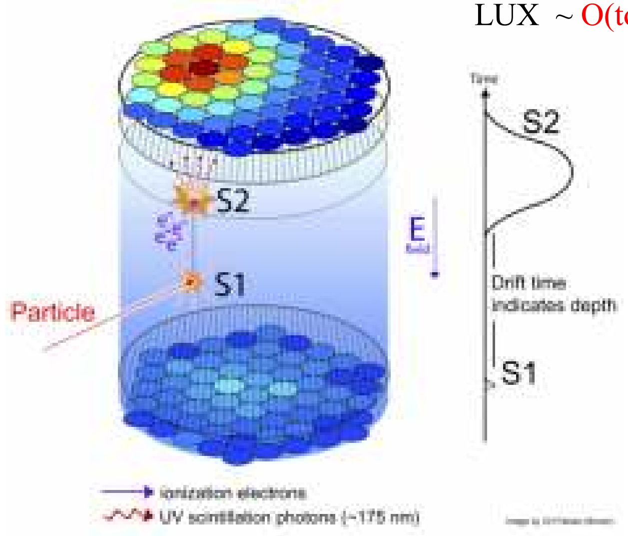
$$v_{\rm vir} \sim 10^{-3} c$$

Deviations away from conventional searches:

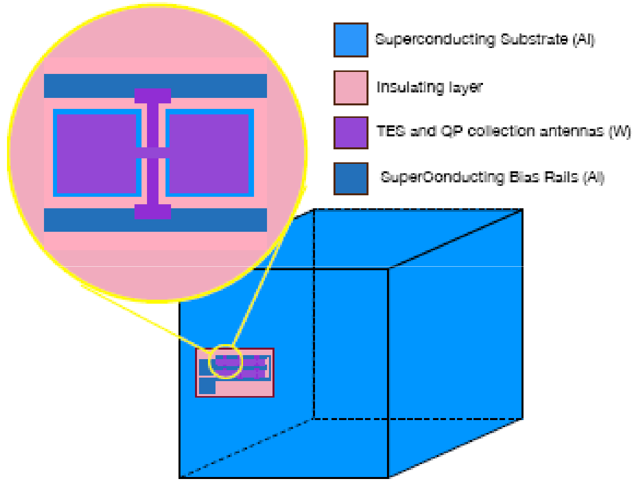
Decades of efforts focused on
conventional WIMP DM detections.
Time to think out of the box!



LUX ~ O(ton)



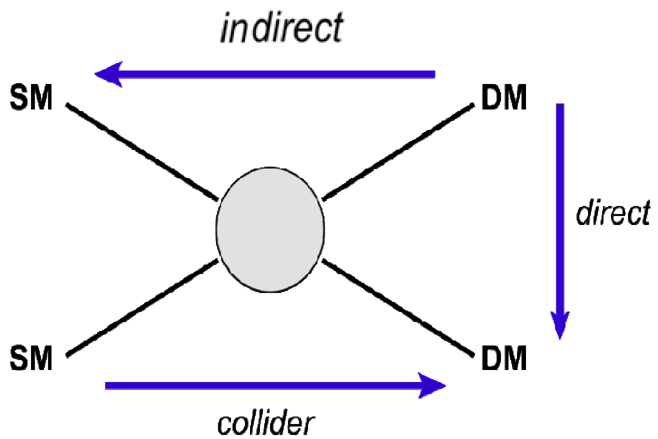
different
mass regime



Superconductor ~ O(kg)
Y. Hochberg, M. Pyle, Y.Z., K. Zurek
P.R.L. (2016) JHEP (2016)

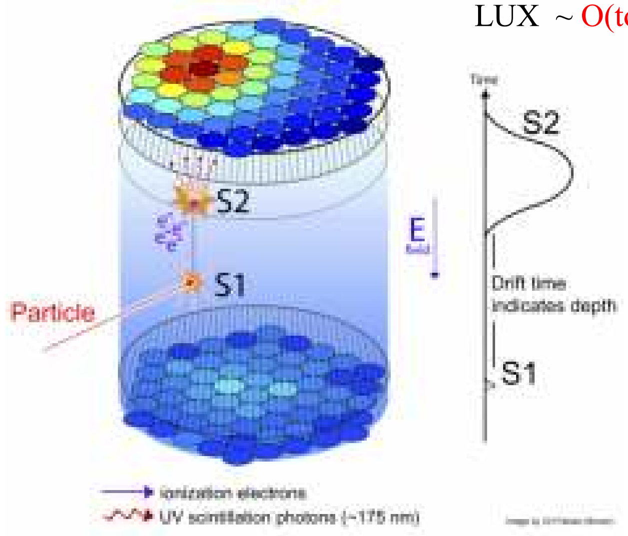
Deviations away from conventional searches:

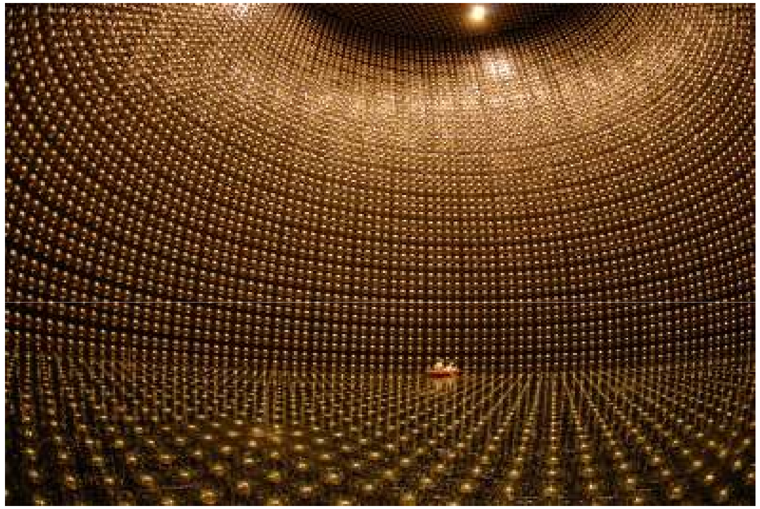
Decades of efforts focused on
conventional WIMP DM directions.
Time to think out of the box!



different
interaction

LUX ~ O(ton)





Neutrino experiments ~ O(10^5 ton)

Junwu Huang , Y.Z.

JHEP (2014)

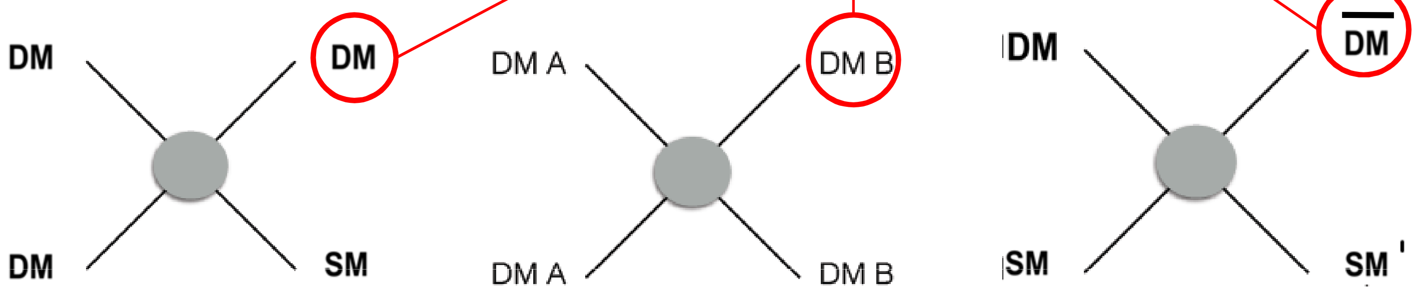
Joshua Berger, Yanou Cui , Y. Z.

JCAP (2015)

Detect BDM:

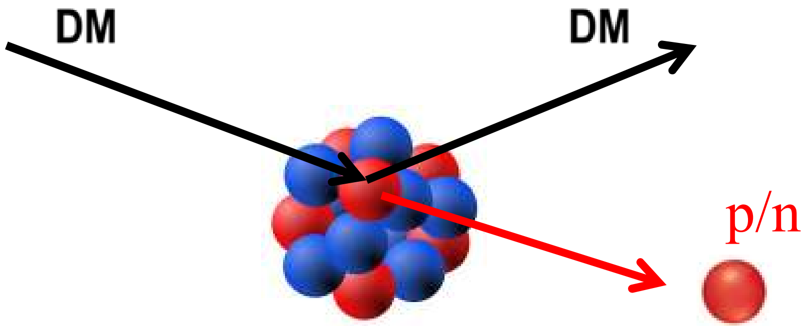
Boosted DM is generic!

DM particle in the final state is moderately boosted.



J. Berger, Y. Cui, Y.Z. JCAP, (2015)
The Sun as the source, DM-p/n scattering.

Junwu Huang , Y.Z.
JHEP (2014)



Looking for proton/neutron knocked out of a nucleus.

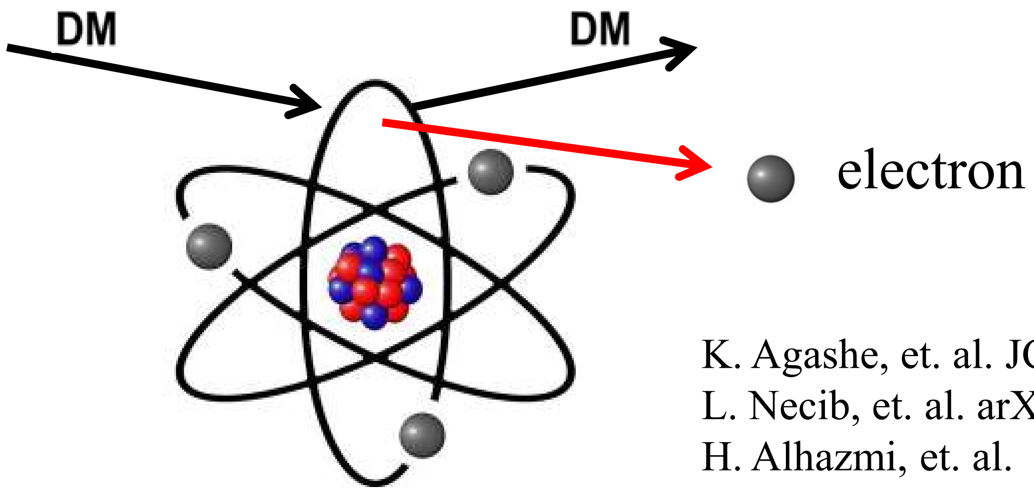
$$\sigma_{\nu p \to \nu p}(E) \simeq 6 \times 10^{-46} \mathrm{cm}^2 \left(\frac{E_\nu}{\mathrm{MeV}}\right)^2$$

DM-nucleon scattering cross section can be less constrained and dramatically enhanced after boosting!

Detect BDM:

Our studies focus on the Sun as the source and DM-p/n scattering.

Variations on this idea: Galaxy as the source and/or DM-electron scattering



K. Agashe, et. al. JCAP (2014)
L. Necib, et. al. arXiv:1610.03486 [hep-ph]
H. Alhazmi, et. al. arXiv:1611.09866 [hep-ph]
….

Concerns:

- More model-dependent parameters are needed.
- Larger SM background for electron channel (NC vs CC interaction rate).
- Neutrino beam induced beta decay as additional background.

Neutrino experiments for boosted DM:

Multiple choices:

- Super/Hyper-Kamiokande (50~1000K ton)

  Cherenkov ring detector

  ⇨ Limited energy range

  not too low: proton momentum > 1.07 GeV (no signal)

  not too high: proton momentum < 2 GeV

  (inelastic scattering, messy final states)

- MicroBooNE/DUNE (0.17~68K ton)

  Liquid Argon Time Projection Chambers (LArTPCs)

  ⇨ Lower energy threshold

  Better control/identification on hadronic activity

  Better angular resolution

- IceCube/PINGU/MICA (?) (~1M ton)

  Photomultiplier Tube

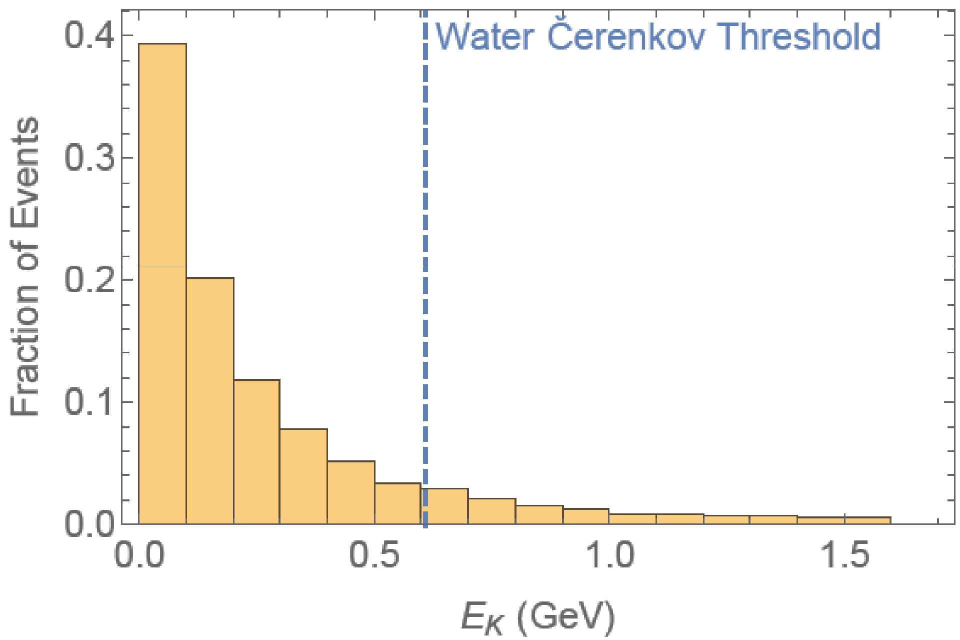
  ⇨ Energy threshold is 100 GeV

  But may be lowered in the future.

Neutrino experiments for boosted DM:

Lowering energy threshold helps a lot!

$$\mathcal{O}_{SD,v^0} = \frac{1}{M^2}\bar{\chi}\gamma^5\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$$



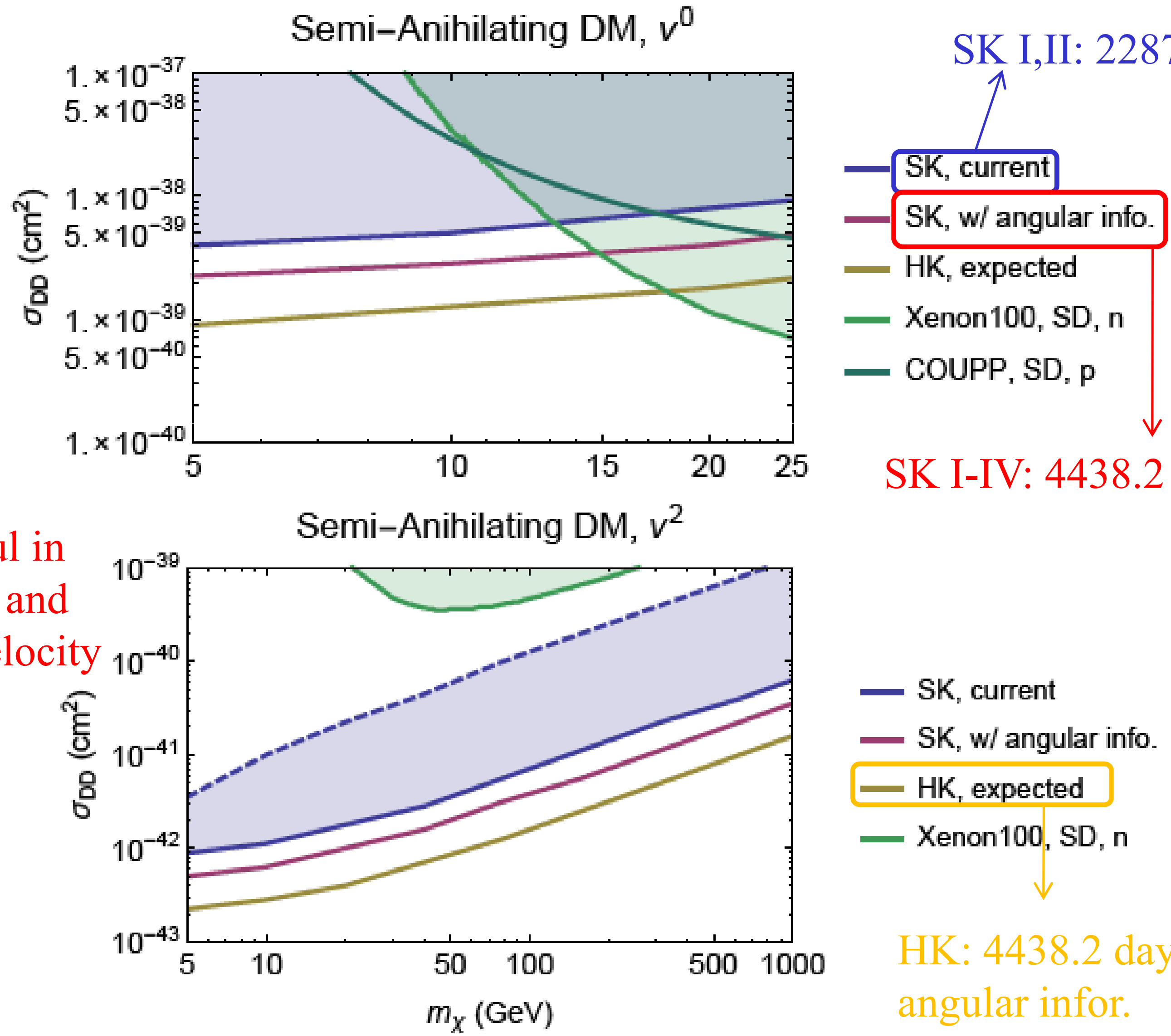
m_{DM} = 100 GeV, v = 0.6 c

It is promising to carry out this search using LArTPCs.

May also be useful to study scatterings through a light mediator.

Results using Super/Hyper-K:

Joshua Berger, Yanou Cui , Y. Z.
JCAP (2015)



SK I,II: 2287.8 days

SK I-IV: 4438.2 days

HK: 4438.2 days, angular infor.

Already exceed the limits from DM DD!

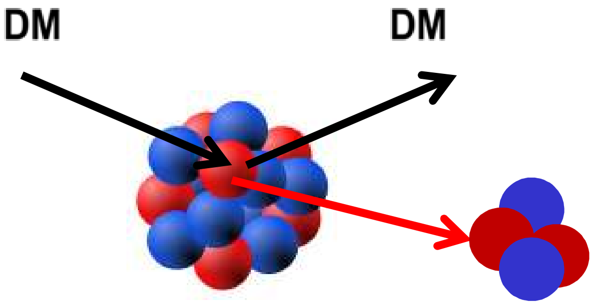
Particularly useful in low mass regime and operators with velocity suppression!

On-going collaborations with MicroBooNE/DUNE:

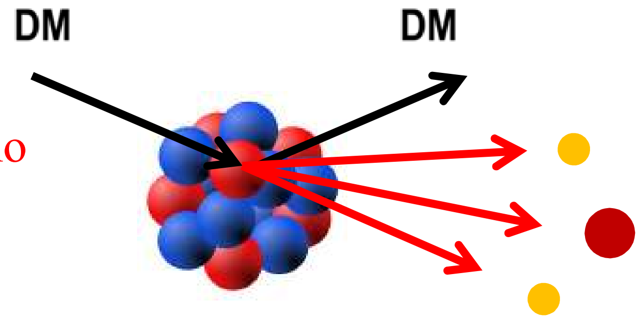
Things to be addressed in MicroBooNE/DUNE:

- Low energy scattering
  Collision may be partial collective.

- High energy scattering
  More likely to be inelastic scattering.
  Multiple particles in final states.



GENIE Neutrino
Monte Carlo



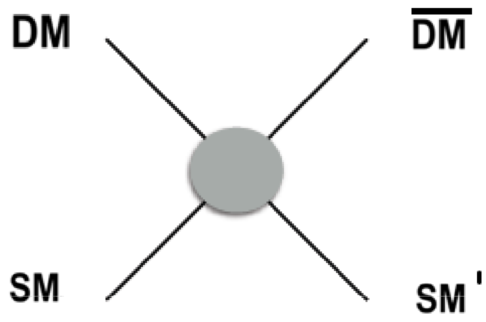
- Detector simulation
  Detector reaction
  Energy/angular resolutions
  Event reconstruction efficiency

} DarkGeant4

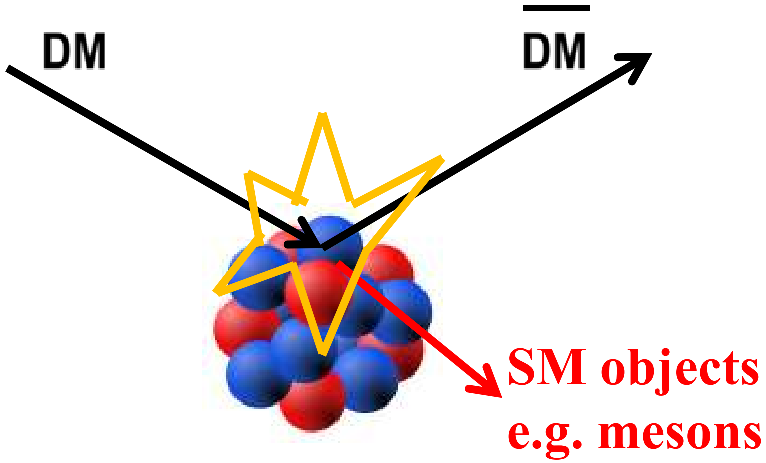
Asaadi, Davenport, (UT-Arlington), Convery (SLAC), Tsai (Fermilab), Russell, Tufanli (Yale) + …

Neutrino experiments for DM IND:

DM can induce nucleon decay like processes!



Junwu Huang , Y.Z.
JHEP (2014)



Looking for proton/neutron decay events.
But kinematics is very different!

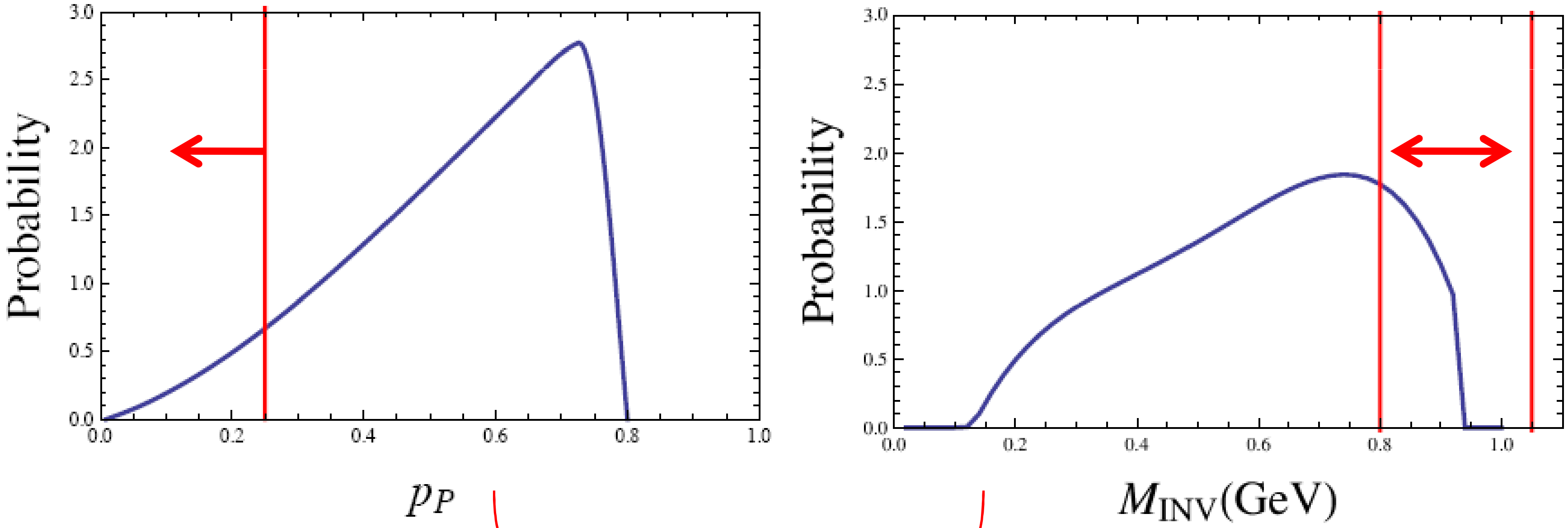
$$p + \phi \to e^+/\mu^+ + \pi^0/K^0 + \bar{\phi}$$

Neutrino experiments for DM IND:

The existence of DM in initial/final states modifies kinematics.

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

- Reconstructed proton momentum < 250 MeV.
- Reconstructed proton inv mass within (800 MeV, 1050 MeV).



cut efficiency ~ 0.0523

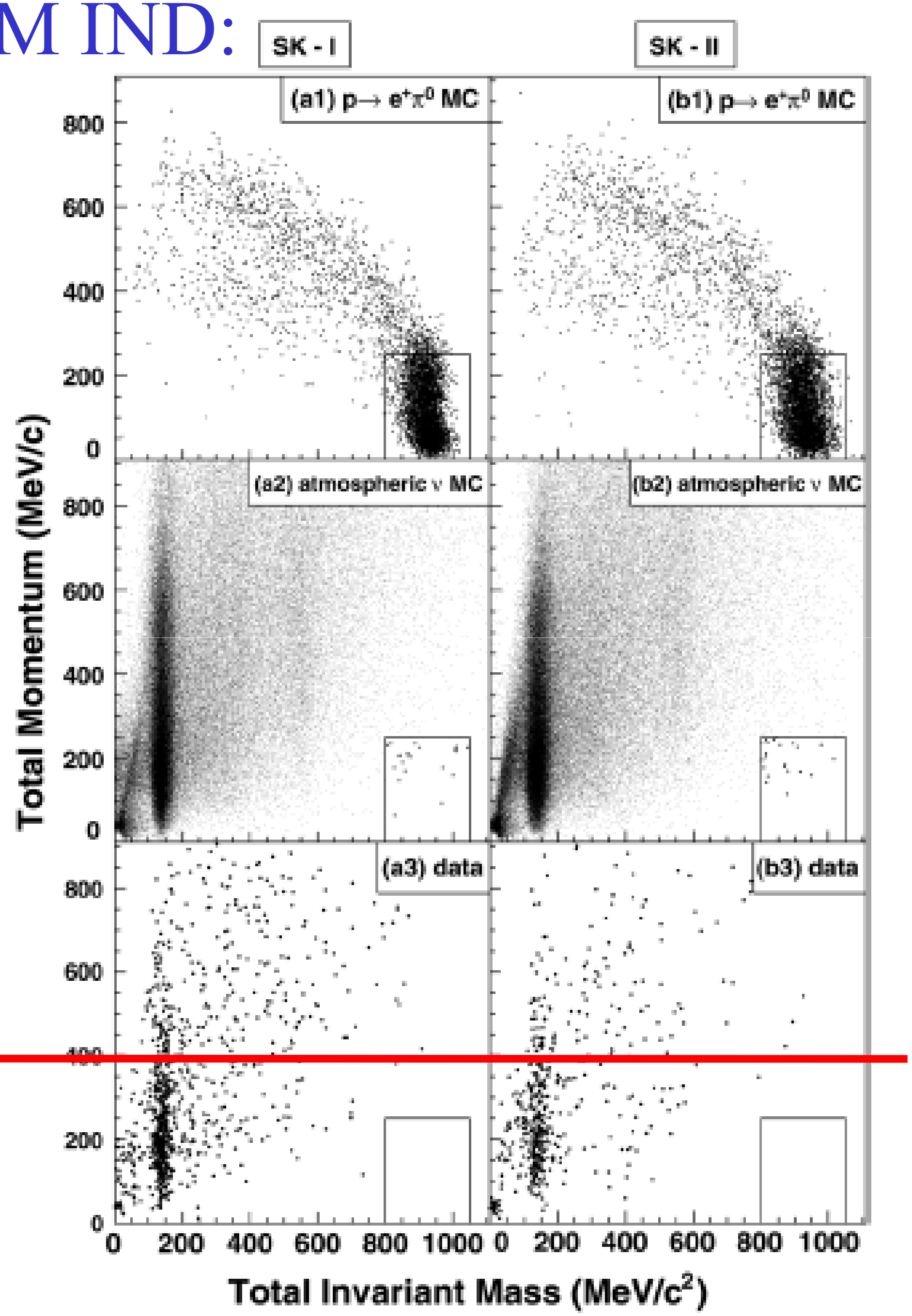
Neutrino experiments for DM IND:

One may want to optimize the cuts respect to DM IND processes.

cut efficiency mildly changes with DM mass

cut efficiency ~ 0.2

not crazy to cut on P < 400 MeV



Neutrino experiments for DM IND:

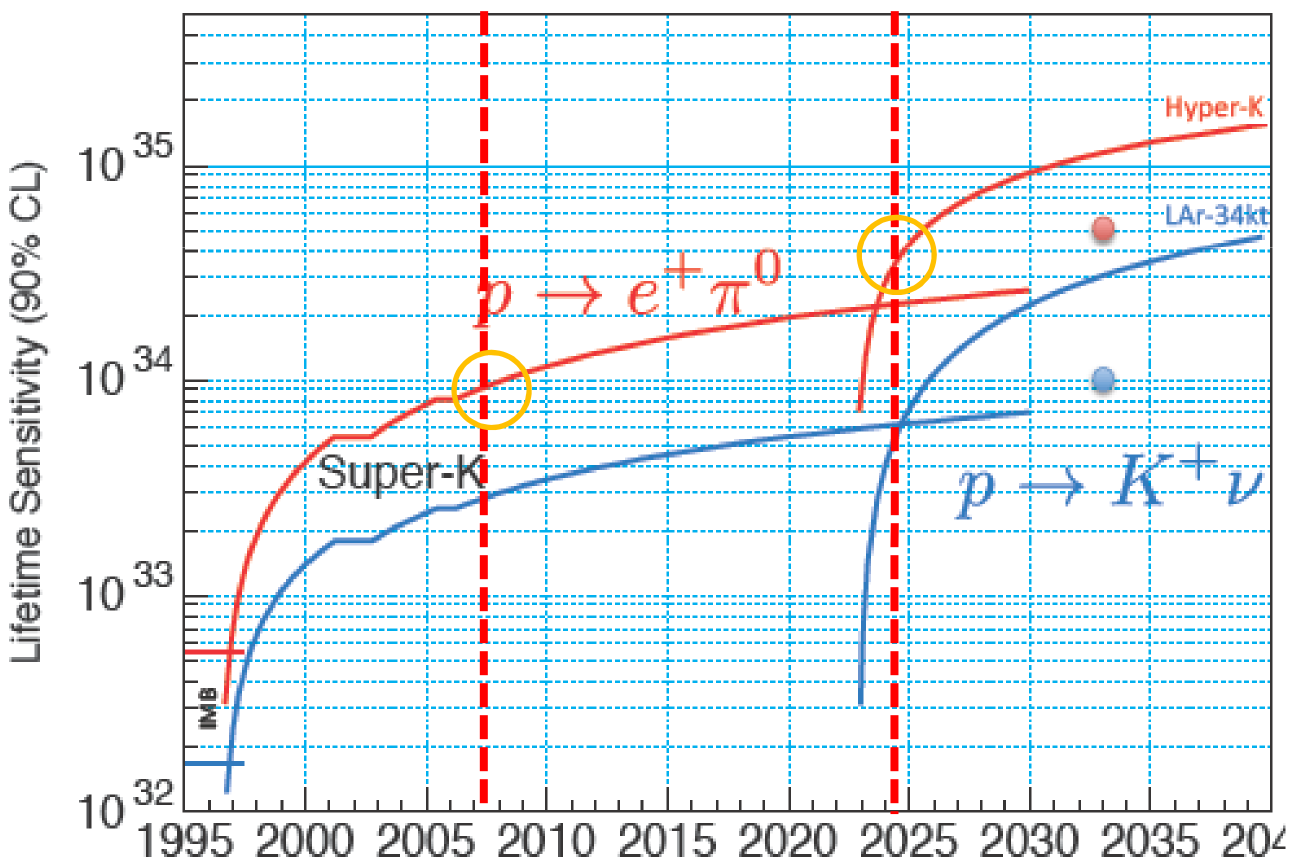
$$\tau_{\rm eff} = 1.5 \times 10^{33}{\rm yr}\left(\frac{0.7\times 10^{-40}{\rm cm}^3/{\rm s}}{(\sigma v)_{\rm IND}}\right)$$

⇨ A benchmark point in our model consistent with all experiments.

(All SM charged particles are ~ TeV scale.)

with improved efficiency ~ 0.2

with current efficiency ~ 0.05



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

Conclusion

The purposes of Neutrino/Proton decay experiments can be extended.

- Boosted DM

  Striking signatures can be induced in well-motivated DM models.

  A wide range of parameter space has been or can be probed.

  ⇨ Super-K is suitable for particular kinetic regime

  ⇨ MicroBooNE/DUNE can extend both high and low energy regimes.

- DM induced nucleon decay

  Easy to fake a proton/neutron decay signal.

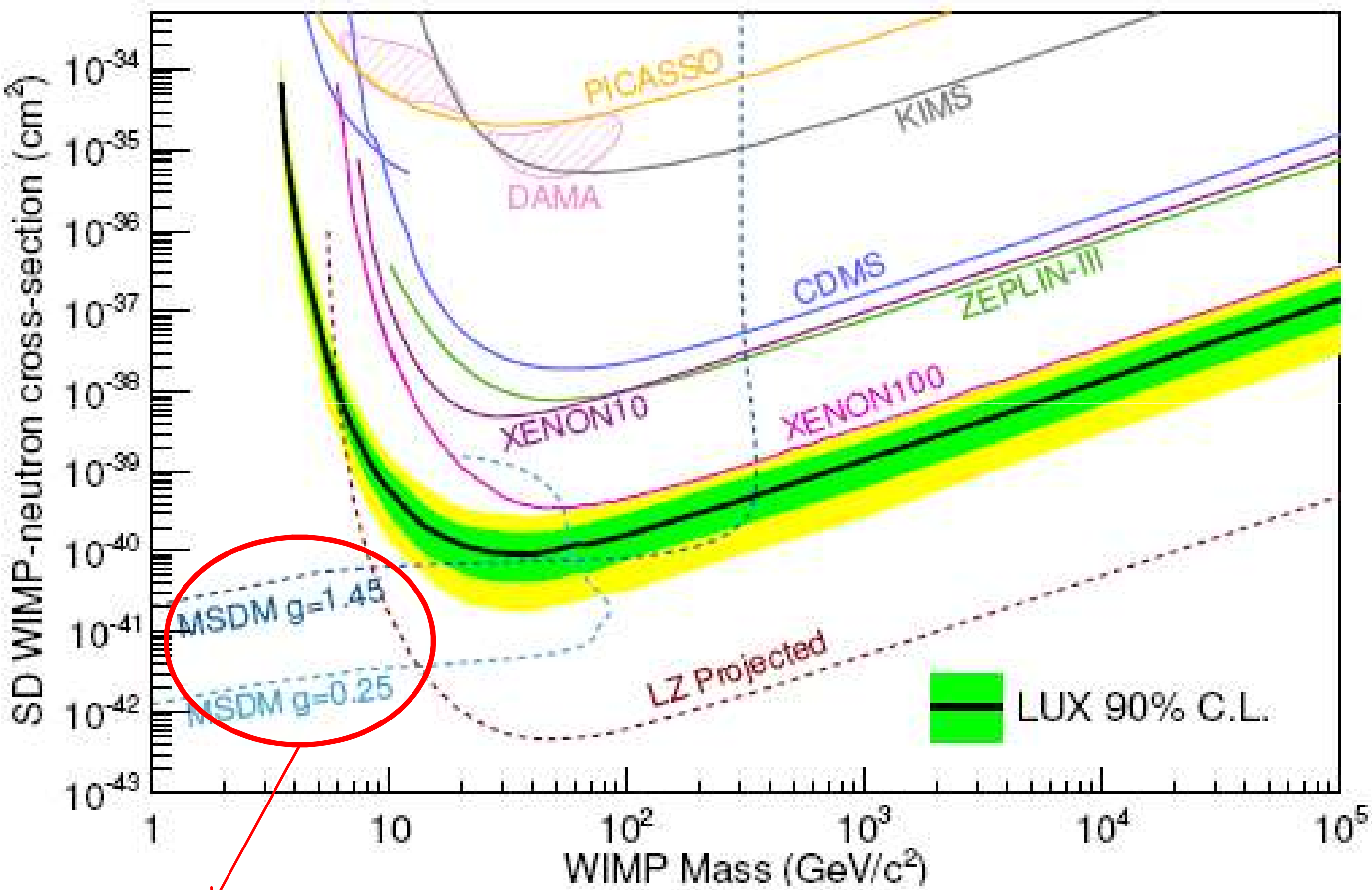
  DM in initial/final states can modify the kinematics.

  ⇨ The current event selection has coverage in our model.

  ⇨ An optimization is necessary to improve signal efficiency.

  ⇨ Complimentary channels between Super/Hype-K and Dune.

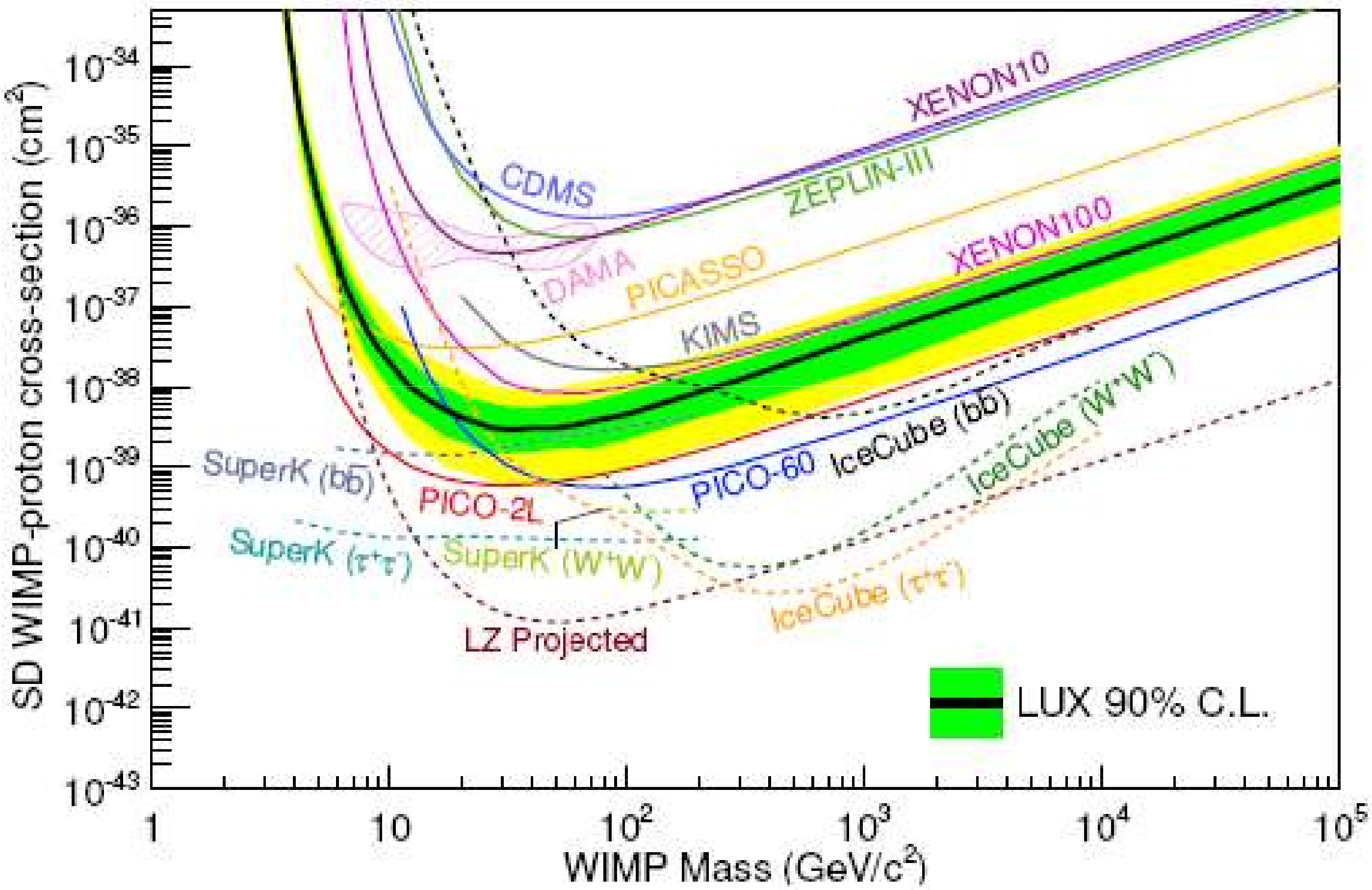
Backup slides:



Model dependent:
mediator mass/width/coupling

(LUX arXiv:1602.03489)

Backup slides:



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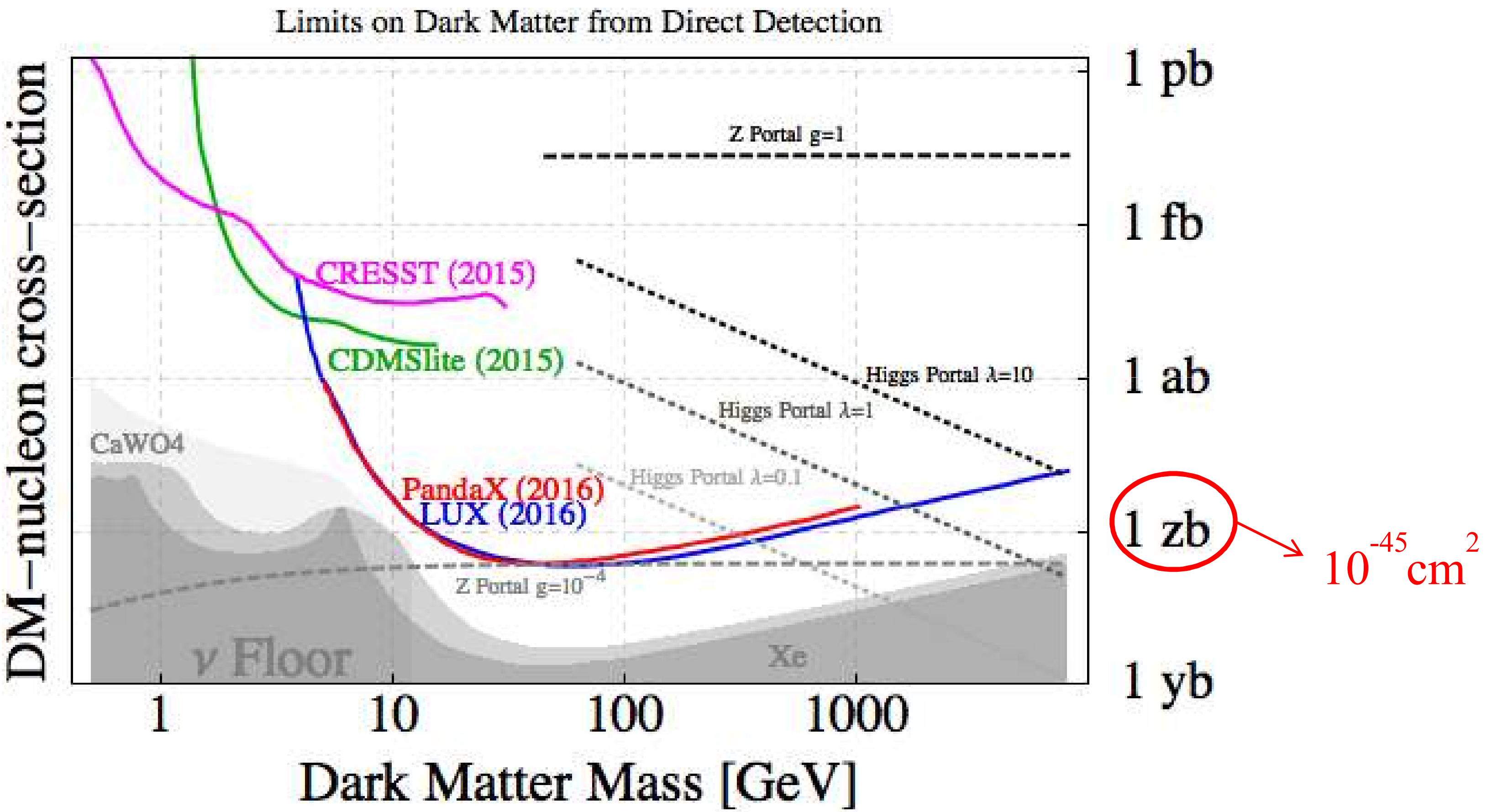


Backup slides:

$$\mathcal{O}_{Xq,S} = \frac{1}{\Lambda^2}(Xu^c)(d^c u^c)$$

$$\mathcal{L}_{\Phi_e,S} = v\bar{\phi}^2\Phi_e^* + \lambda_s \Phi_e (X^c e^c)$$

$$\mathcal{O}_{Xq,D} = \frac{1}{\Lambda^2}(X^c Q)(u^{c\dagger} d^{c\dagger})$$

$$\mathcal{L}_{\Phi_e,D} = v\phi^2\Phi_e + \lambda_s \Phi_e^* (XL)$$

⇩ ⇩

$$\mathcal{L}_{e,S} \supset \frac{\lambda_s v}{\Lambda^2 M_X M_{\Phi_e}^2}\bar{\phi}^2 (e^c u^c)(d^c u^c)$$

$$\mathcal{L}_{L,\mathrm{eff}} \supset \frac{\lambda_s v}{\Lambda^2 M_X M_{\Phi_e}^2}\bar{\phi}^2 (L^\dagger Q^\dagger)(u^c d^c)$$

$$\begin{aligned} m_\phi &= 3 \text{ GeV}, \\ m_{\Phi_e} &= 3 \text{ GeV}, \\ v &= 4\pi m_{\Phi_e} = 3 \times 4\pi \text{ GeV} \\ \lambda_s &= 2, \\ m_X &= \Lambda = 1 \text{ TeV}. \end{aligned}$$

Backup slides:

$$\sigma_{\chi,N} = \frac{3m_N^2 m_\chi^2}{\pi M^4 (m_\chi + m_N)^2} \left(\sum_q \Delta_q \right)^2 F(Q^2)$$

$10^{-38} \mathrm{cm}^2$ ⇨ M ~ 400 GeV

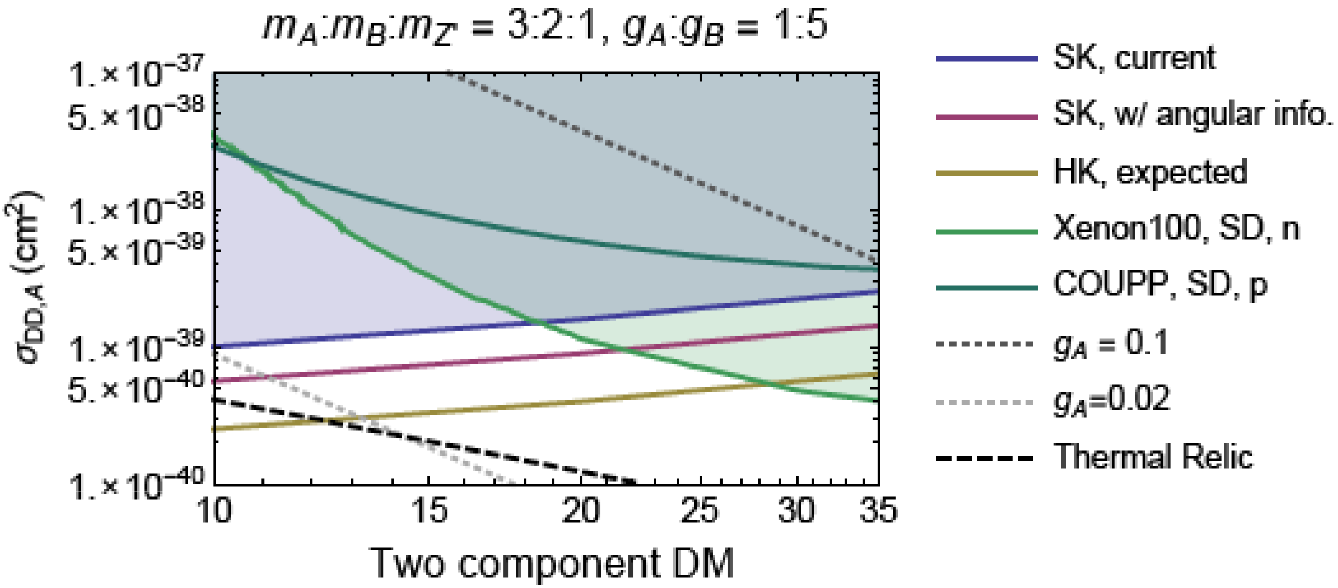
If M_{med} ~ 10 GeV, couplings ~ 0.025.

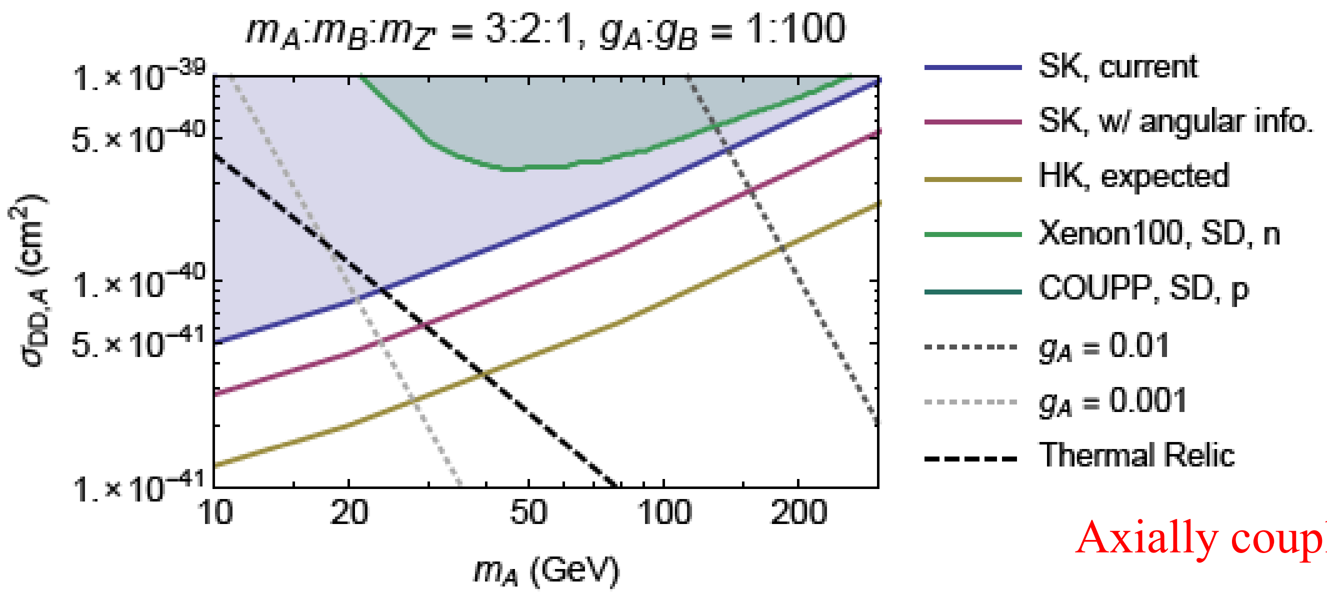
⇨ Both Z' being off-shell and small couplings are helping.

⇨ Mono-jet cross section is too small to be relevant!

Neutrino experiments for boosted DM:

Results:





Axially coupled Z’, ν^0

Neutrino experiments for boosted DM:

Results: for a fixed DM IND cross section (only important for turning point)