Neutrino Experiments for Dark Matter Detection

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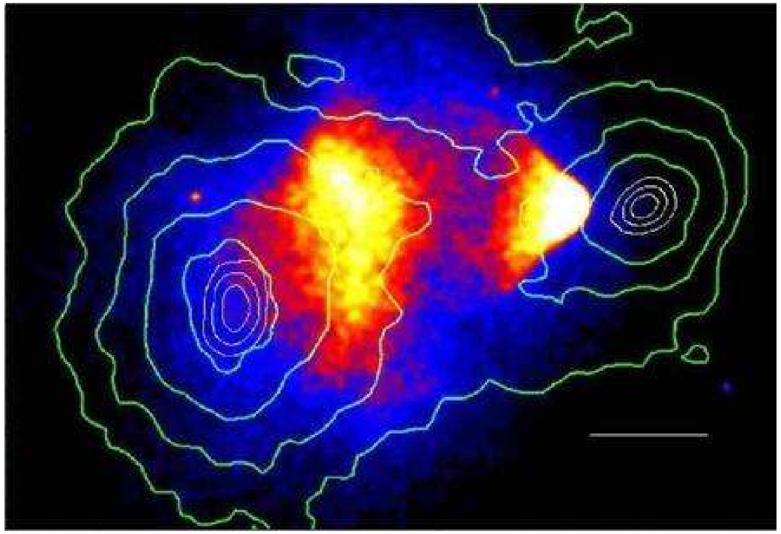
Junwu Huang , Y.Z. JHEP (2014)

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

On-going collaborations with MicroBooNE & DUNE arXiv: hep-ph 1708.xxxxx

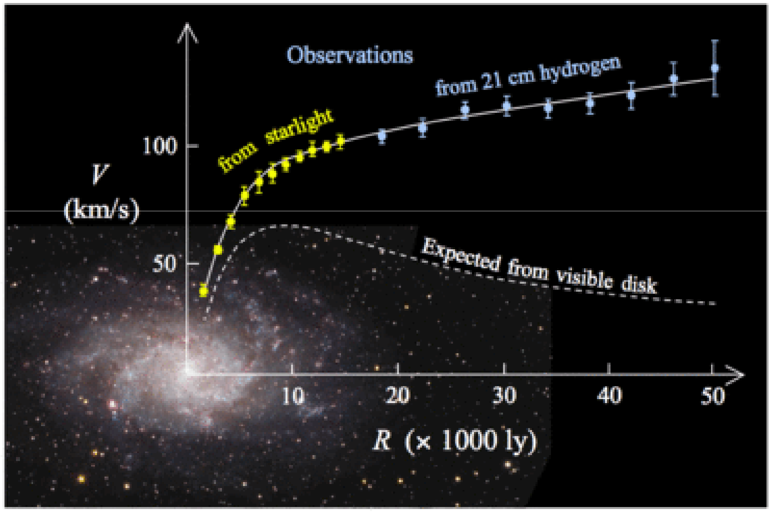
Dark Matter Overview:

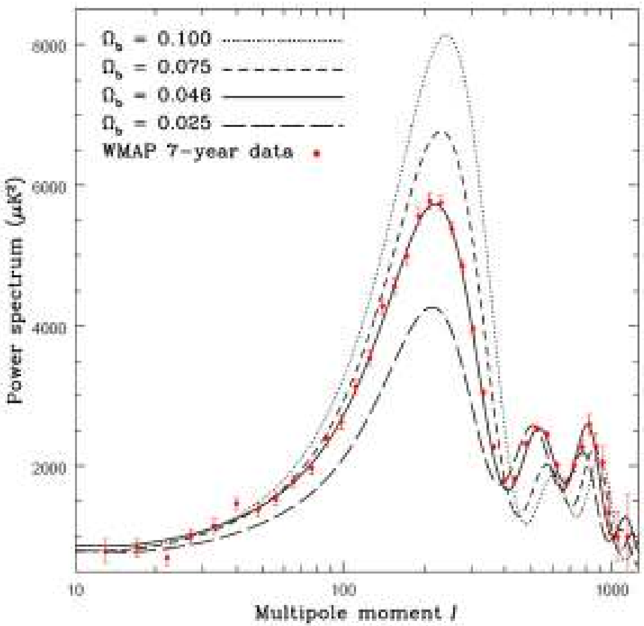
• Bullet Cluster (Deep Chandra)



Why do we need DM?

• Galaxy rotation curve (Wikipedia)

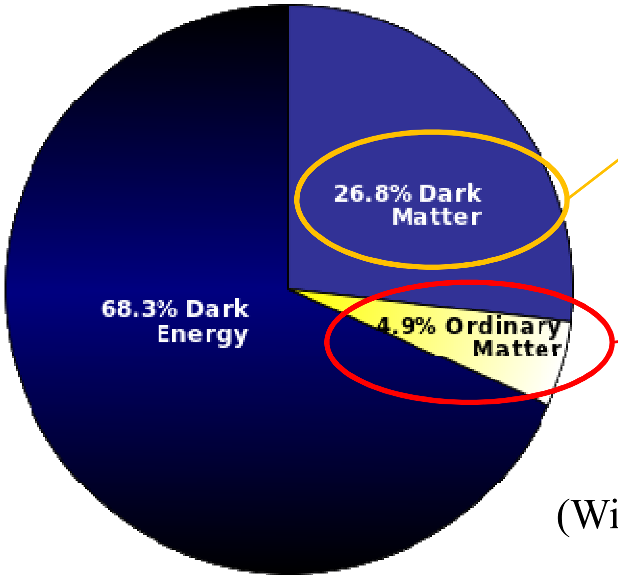




• The CMB Anisotropy Power Spectrum

(WMAP year 5 data)

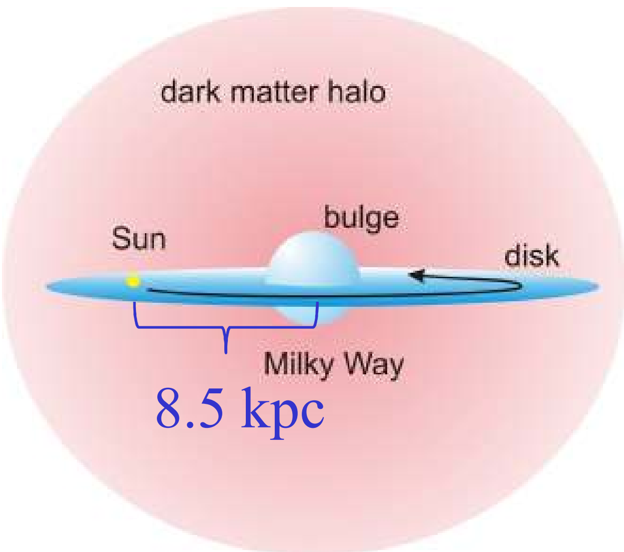
Dark Matter Overview:



We only know DM through its gravitational interaction!

We only understand 5% of the Universe!

(Wikipedia)



Local DM energy density:

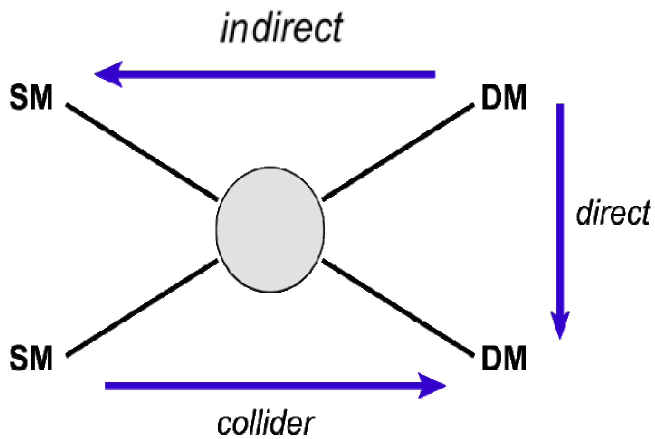
$$\rho_{\rm DM} \simeq 0.4 {\rm GeV/cm^3}$$

Local DM velocity:

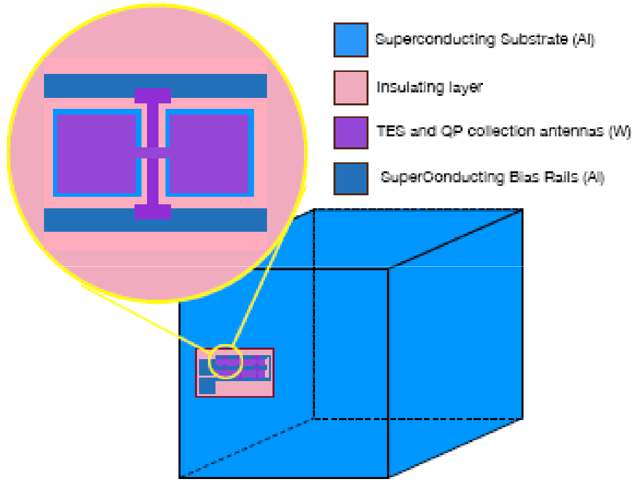
$$v_{\rm vir} \sim 10^{-3} c$$

Deviations away from conventional searches:

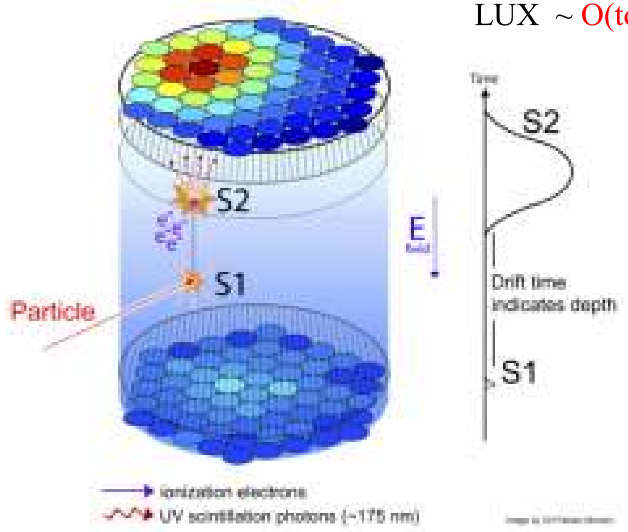
Decades of efforts focused on
conventional WIMP DM detections.
Time to think out of the box!



different
mass regime



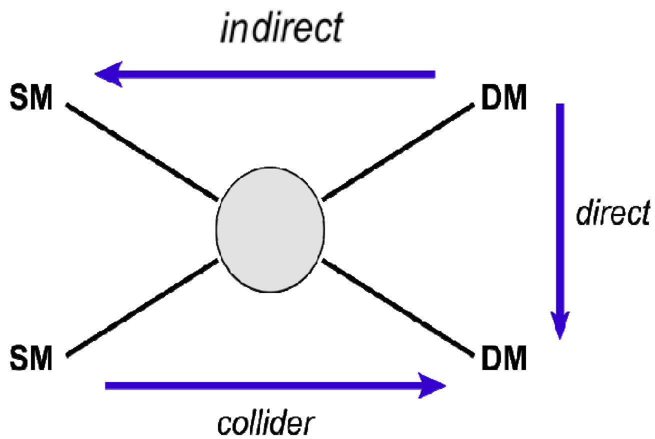
LUX ~ O(ton)



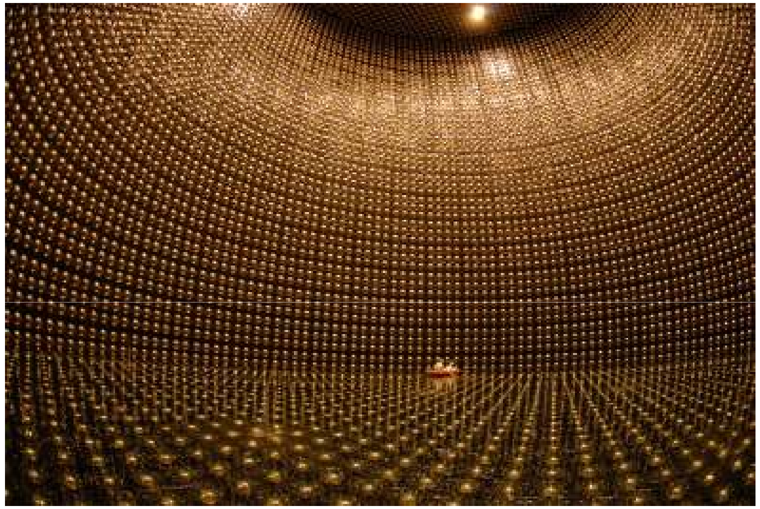
Superconductor ~ O(kg)
Y. Hochberg, M. Pyle, Y.Z., K. Zurek
P.R.L. (2016) JHEP (2016)

Deviations away from conventional searches:

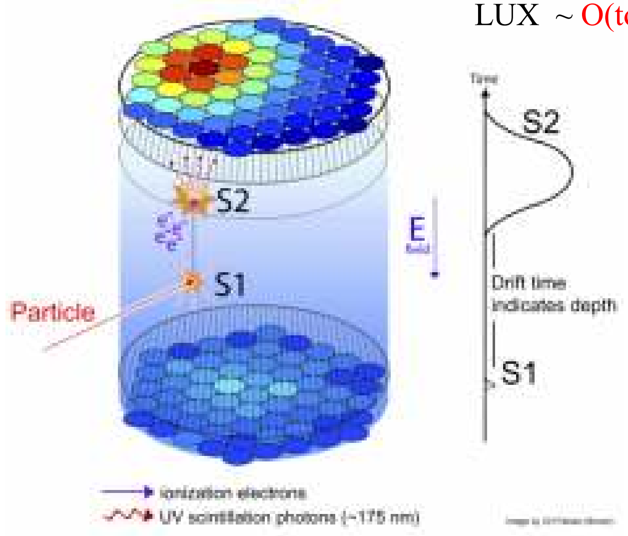
Decades of efforts focused on
conventional WIMP DM directions.
Time to think out of the box!



different
interaction



LUX ~ O(ton)

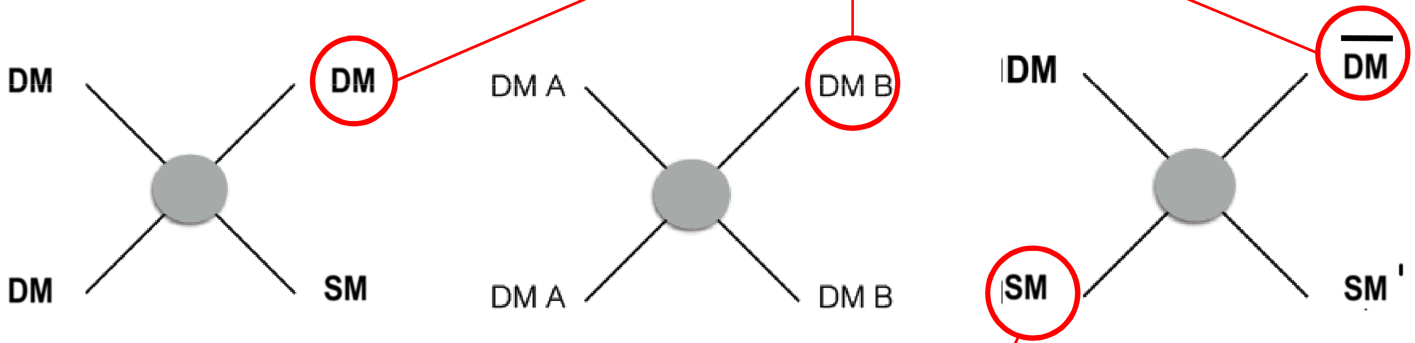


Neutrino experiments ~ O(10^5 ton)
Junwu Huang , Y.Z.
JHEP (2014)
Joshua Berger, Yanou Cui , Y. Z.
JCAP (2015)

Unconventional DM:

- Boosted DM is generic.
- DM-SM interaction can be inelastic.

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)

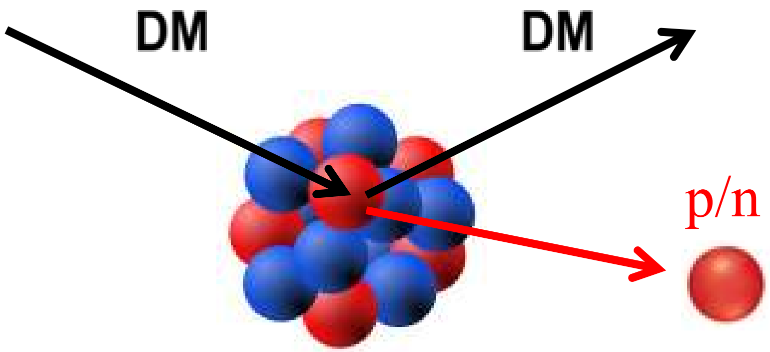
DM induced nucleon decay.

Boosted DM detection strategies:

Boosted DM detection:

⇨ DM particle is energetic enough to knock a nucleon out!

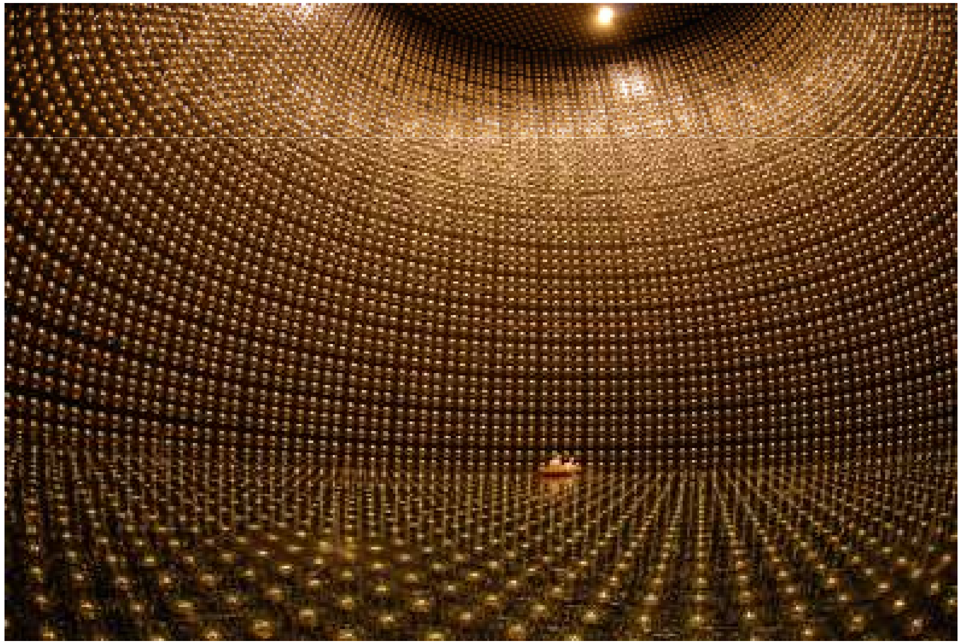
v ~ O(1) c



Looking for proton/neutron
knocked out of a nucleus.
Similar to neutrino neutral current interaction!

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

DM-nucleon scattering cross section
can be less constrained!



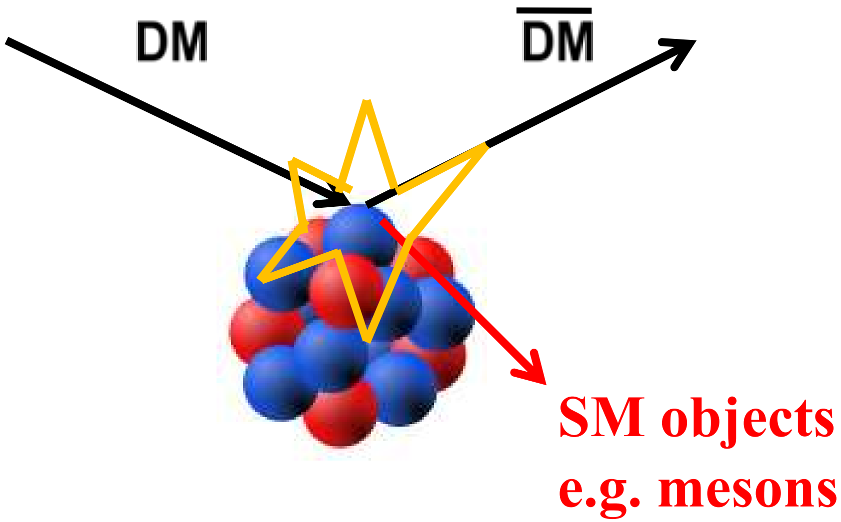
Large Volume Neutrino Experiments
Super-K ~ 50K ton! DUNE ~ 68K ton!

DM IND detection strategies:

DM Induced Nucleon Decay:

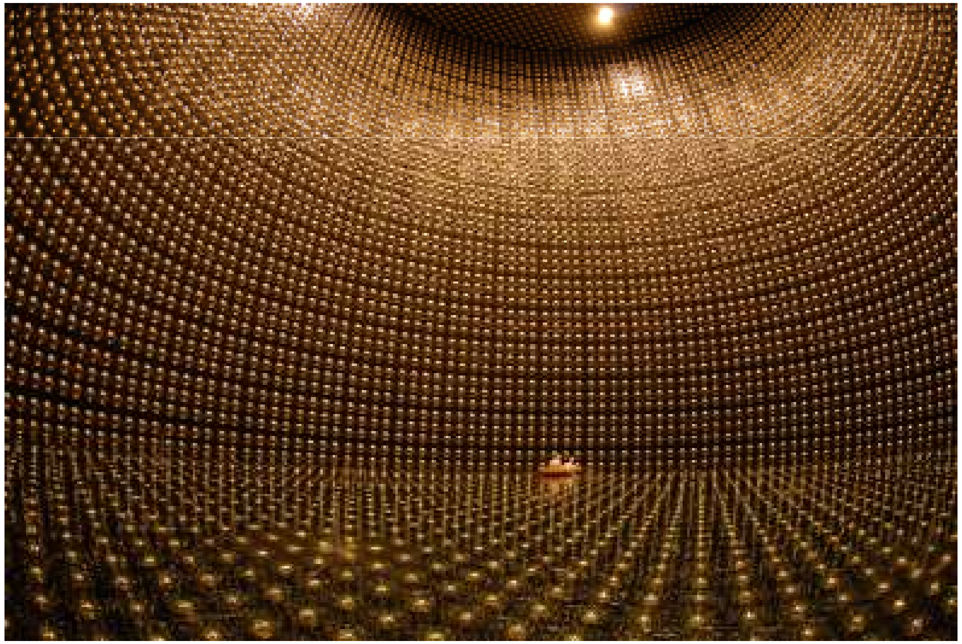
DM as initial state is invisible in nucleon decay experiments.

⇨ The signature can be very similar to a nucleon decay process



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

Similar studies in
Darkogenesis model, J. Shelton, et. al. PRD (2010)
Hylogenesis model, H. Davoudiasl, et. al. PRL (2010)



Large Volume Nucleon Decay Experiments
Super-K ~ 50K ton! DUNE ~ 68K ton!

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)

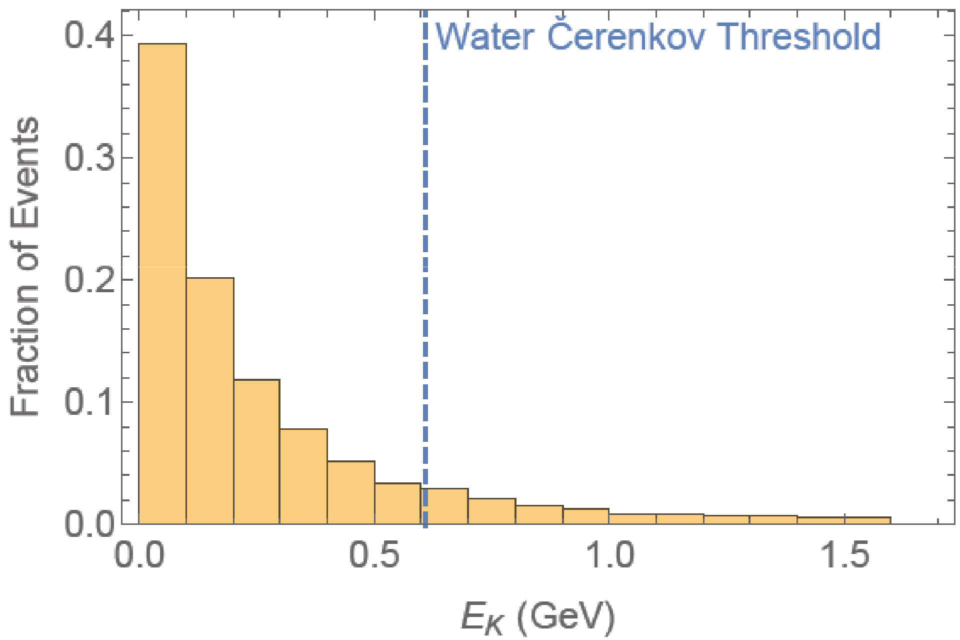
  Photomultiplier Tube

  ⇨ Energy threshold is 100 GeV
  But may be lowered in the future.

Neutrino experiments for boosted DM:

Lowering energy threshold helps a lot!

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



$m_{\rm DM}$ = 100 GeV, v = 0.6 c

It is promising to carry out this search using LArTPCs.

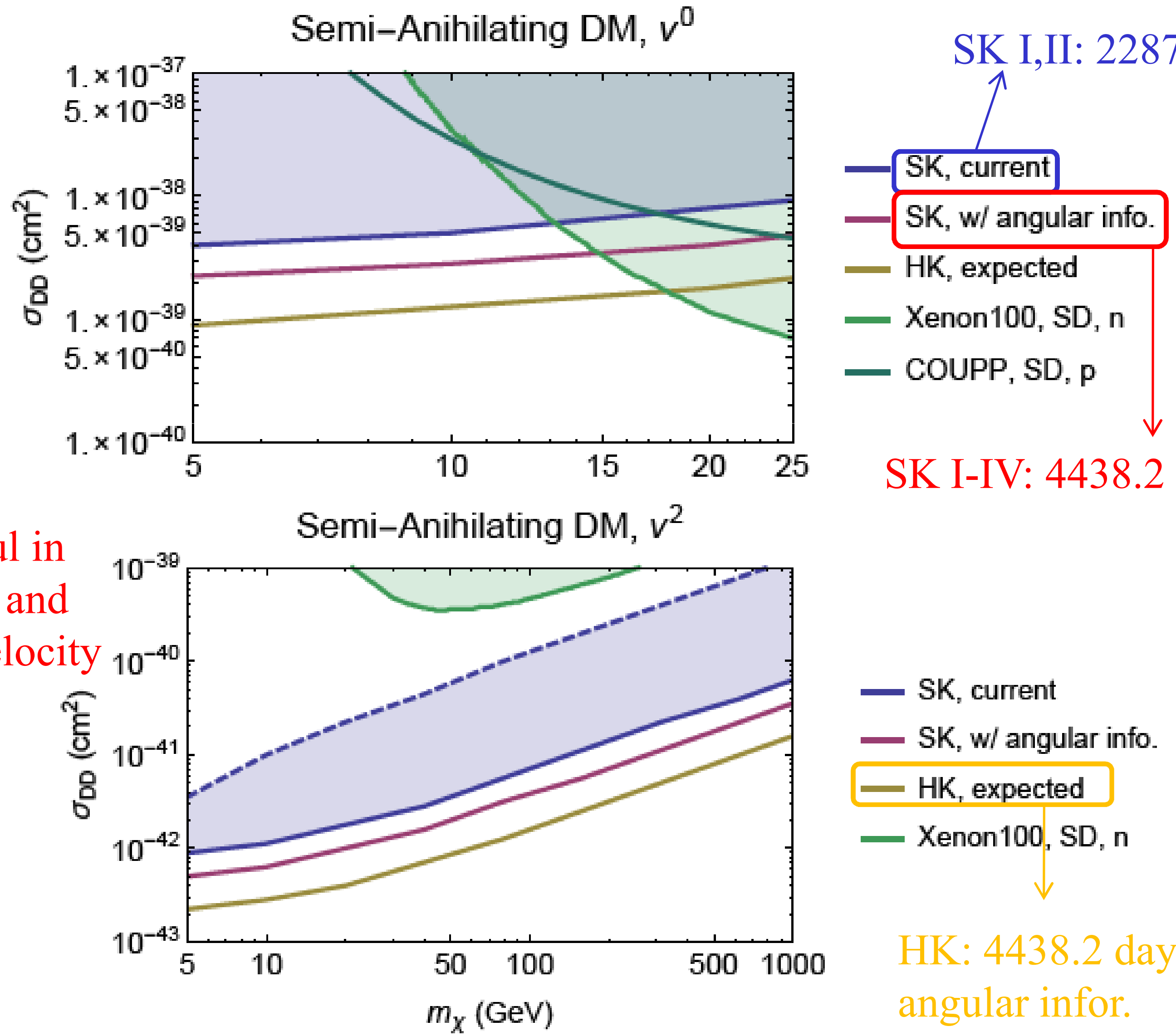
May also be useful to study scatterings through a light mediator.

Results using Super/Hyper-K:

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

Already exceed the limits from DM DD!

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



SK I,II: 2287.8 days

SK I-IV: 4438.2 days

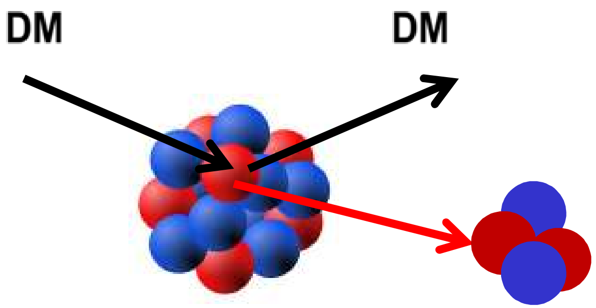
HK: 4438.2 days, angular infor.

On-going collaborations with MicroBooNE/DUNE:

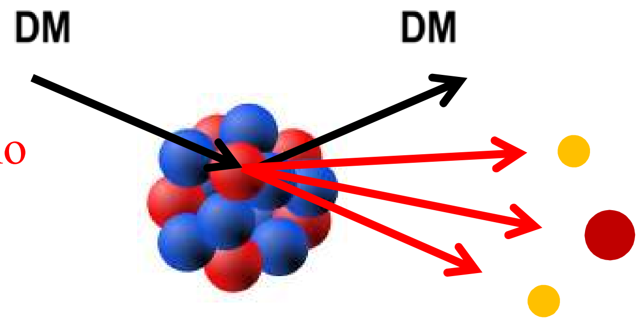
Things to be addressed in MicroBooNE/DUNE:

- 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



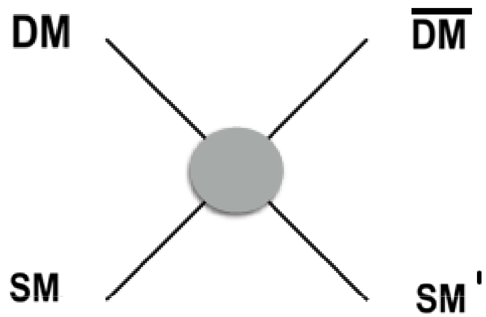
- Detector simulation
  Detector reaction
  Energy/angular resolutions
  Event reconstruction efficiency

DarkGeant4

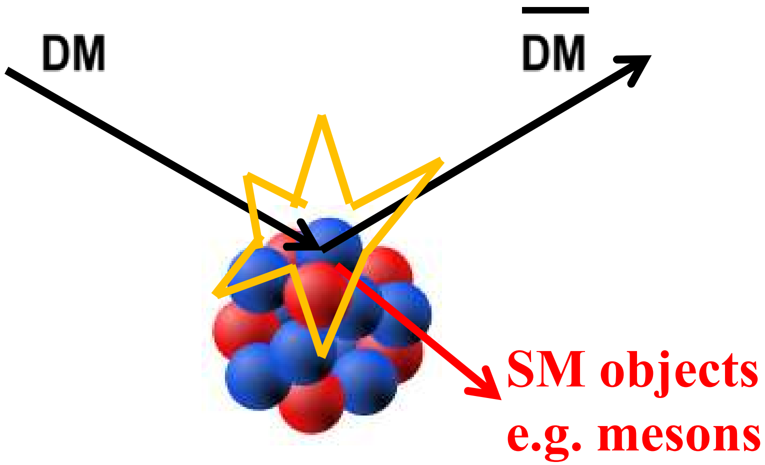
Asaadi, Davenport, (UT-Arlington), Convery (SLAC), Tsai (Fermilab), Russell, Tufanli (Yale) + …

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!

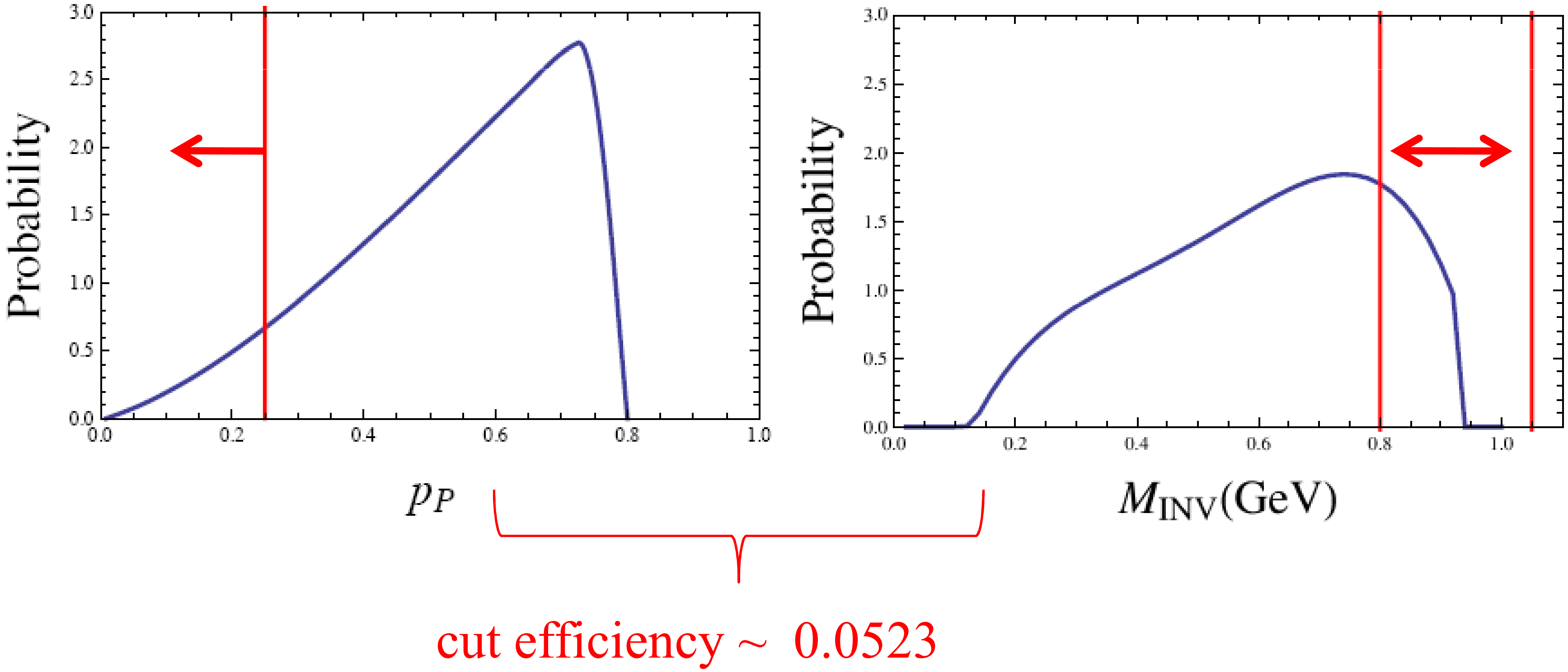
$$p + \phi \to e^+/\mu^+ + \pi^0/K^0 + \bar{\phi}$$

Neutrino experiments for DM IND:

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

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

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



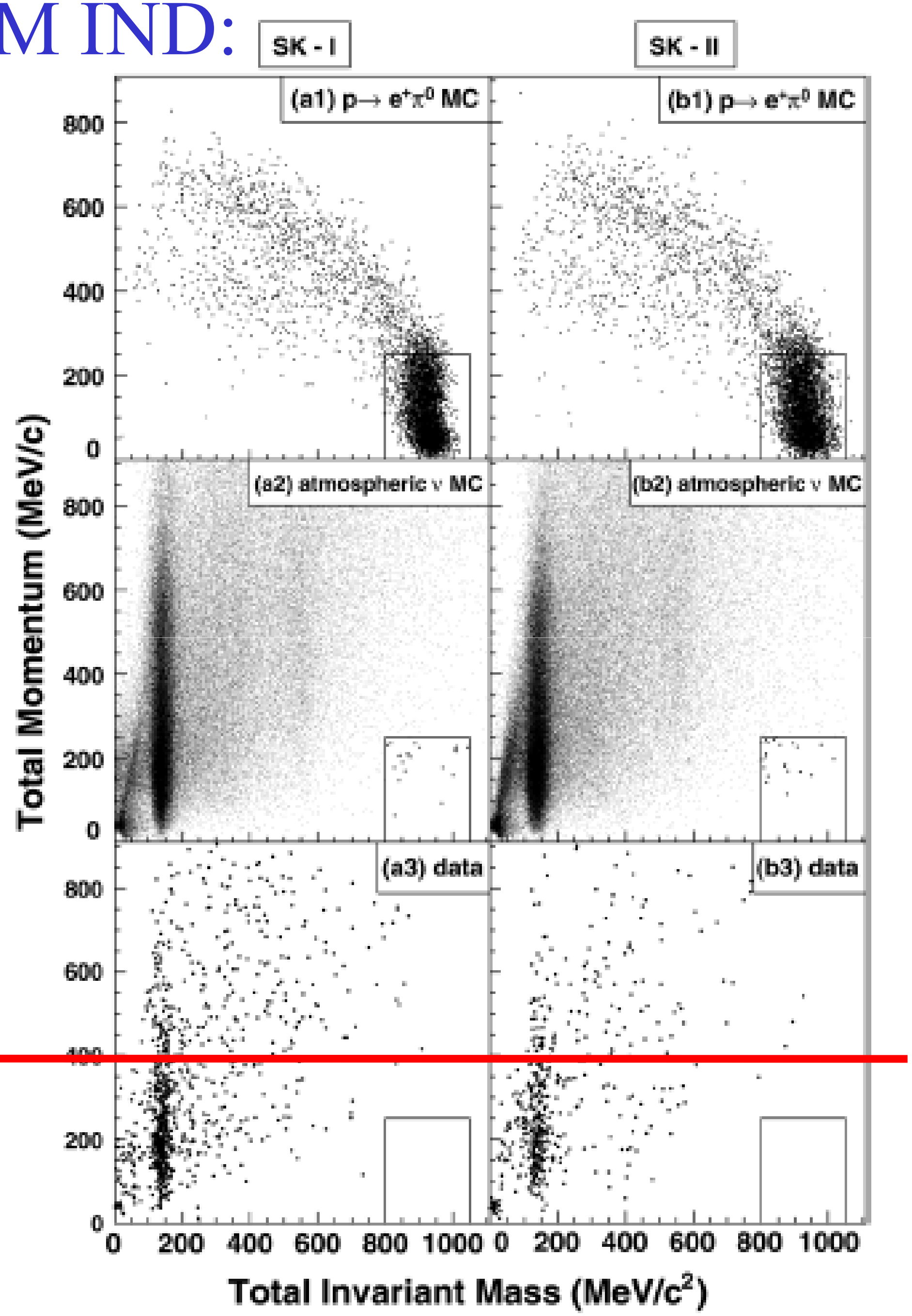
Neutrino experiments for DM IND:

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:

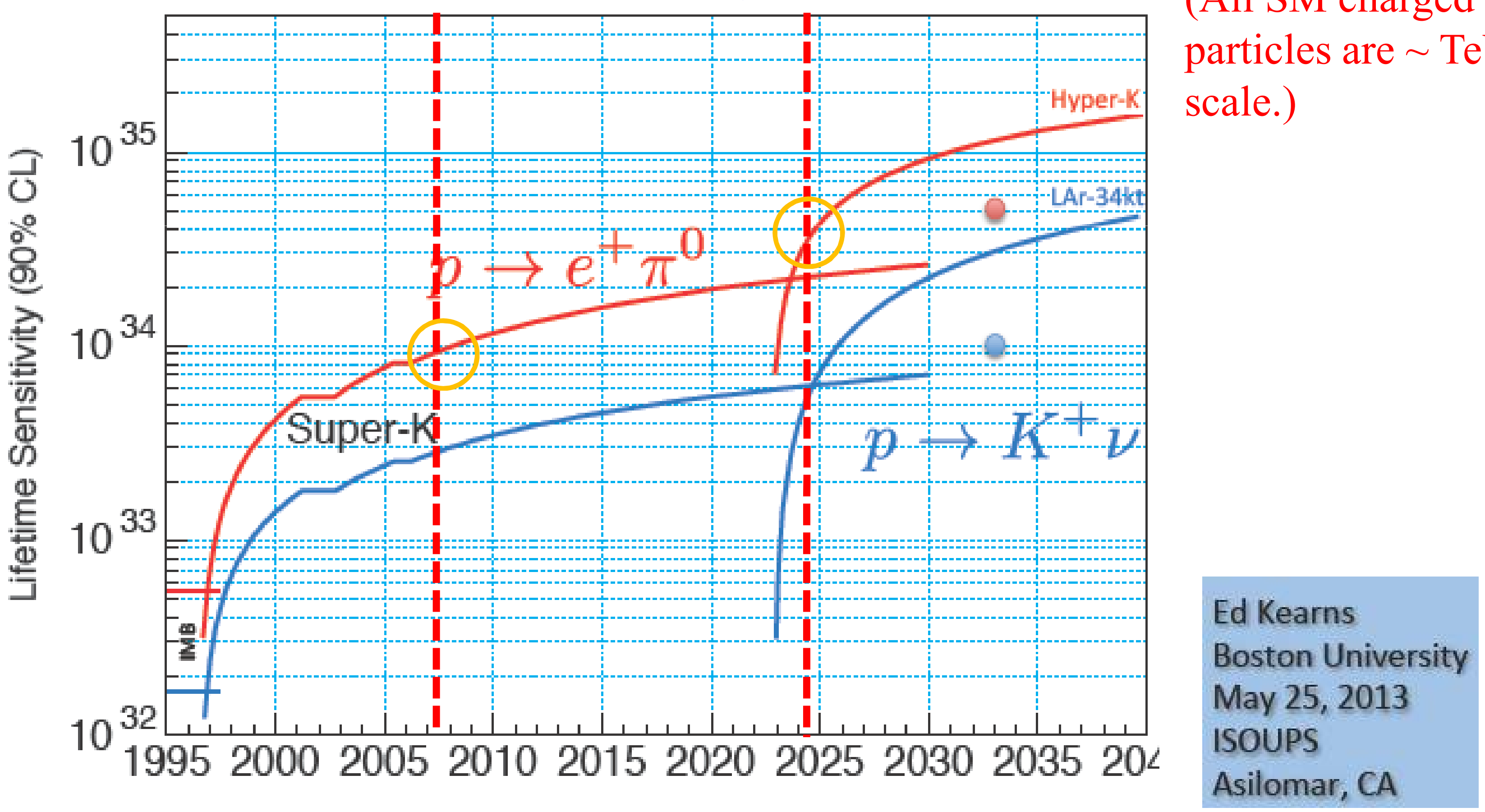
$$\tau_{\rm eff} = 1.5 \times 10^{33}{\rm yr}\left(\frac{0.7\times 10^{-40}{\rm cm}^3/{\rm s}}{(\sigma v)_{\rm IND}}\right)$$

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

with improved efficiency ~ 0.2

with current efficiency ~ 0.05

(All SM charged particles are ~ TeV scale.)



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.

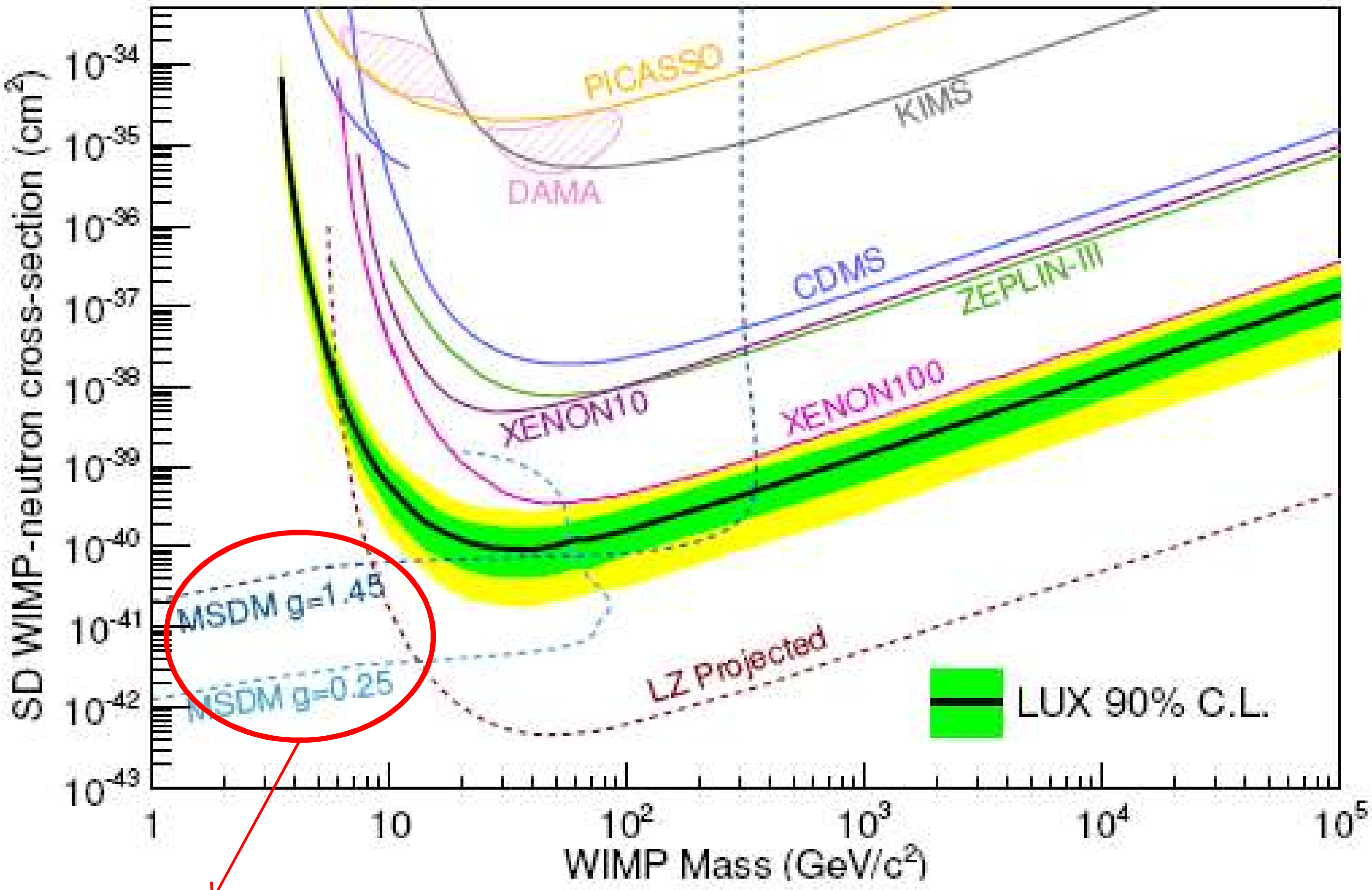
  DM in initial/final states can modify the kinematics.

  ⇨ 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:



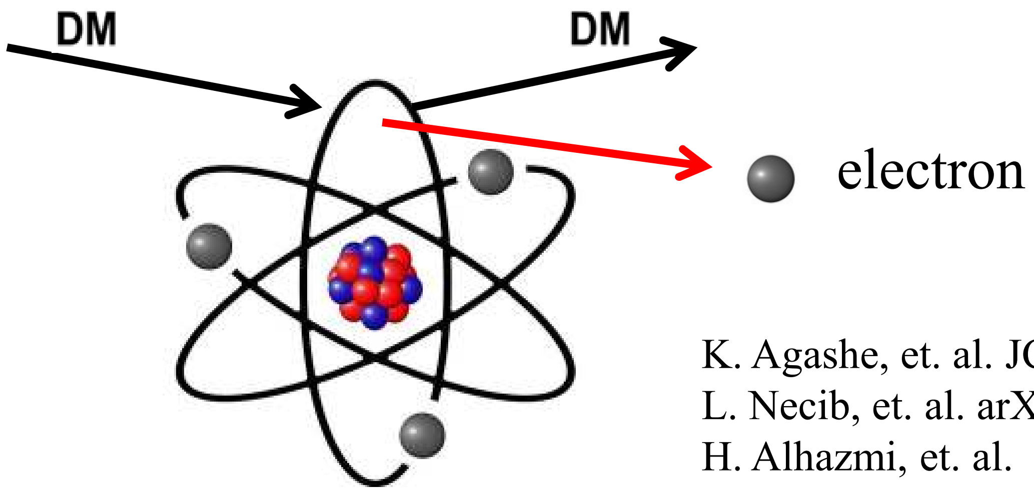
Model dependent:
mediator mass/width/coupling

(LUX arXiv:1602.03489)

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

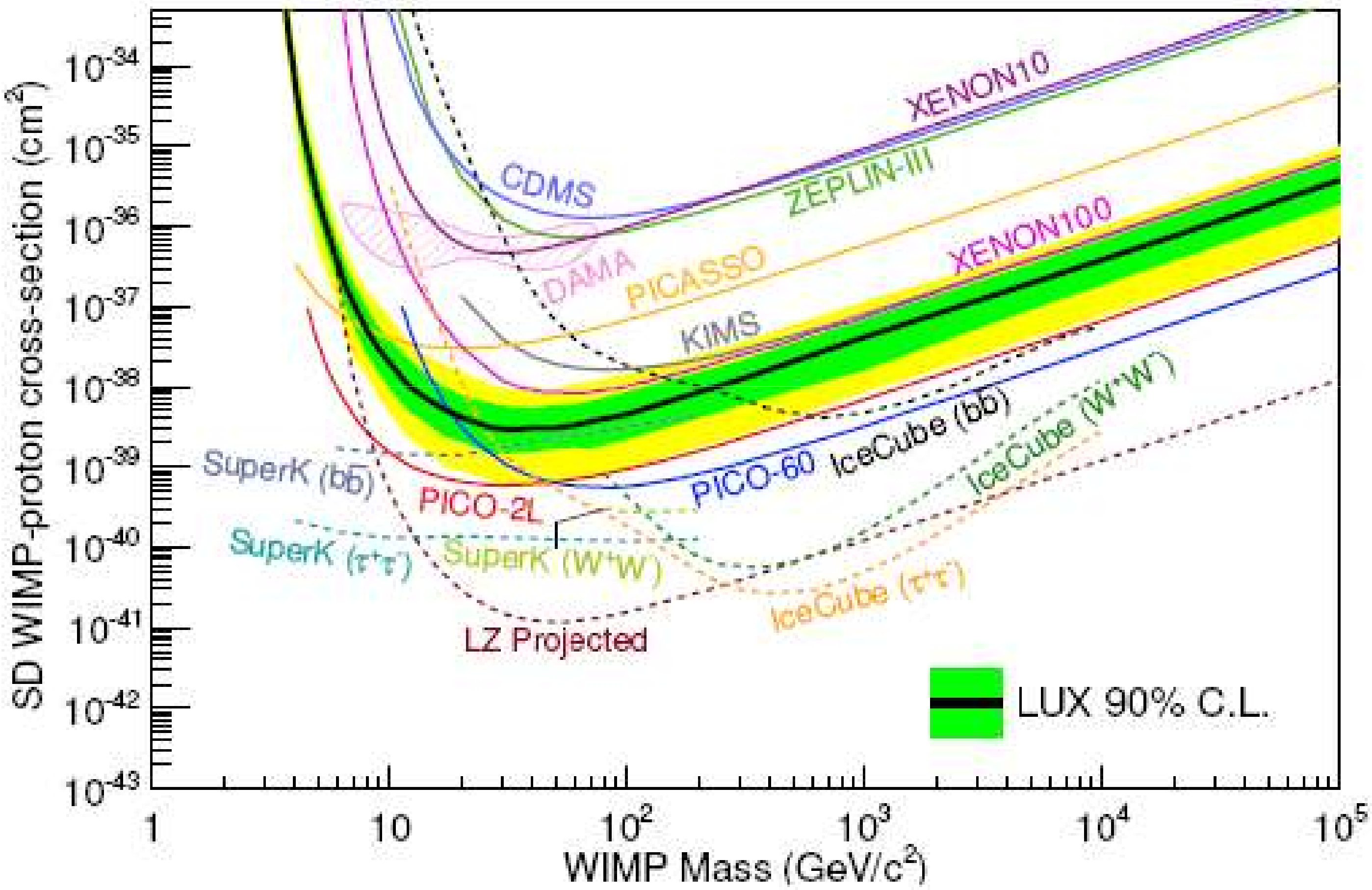


K. Agashe, et. al. JCAP (2014)
L. Necib, et. al. arXiv:1610.03486 [hep-ph]
H. Alhazmi, et. al. arXiv:1611.09866 [hep-ph]
….

Concerns:

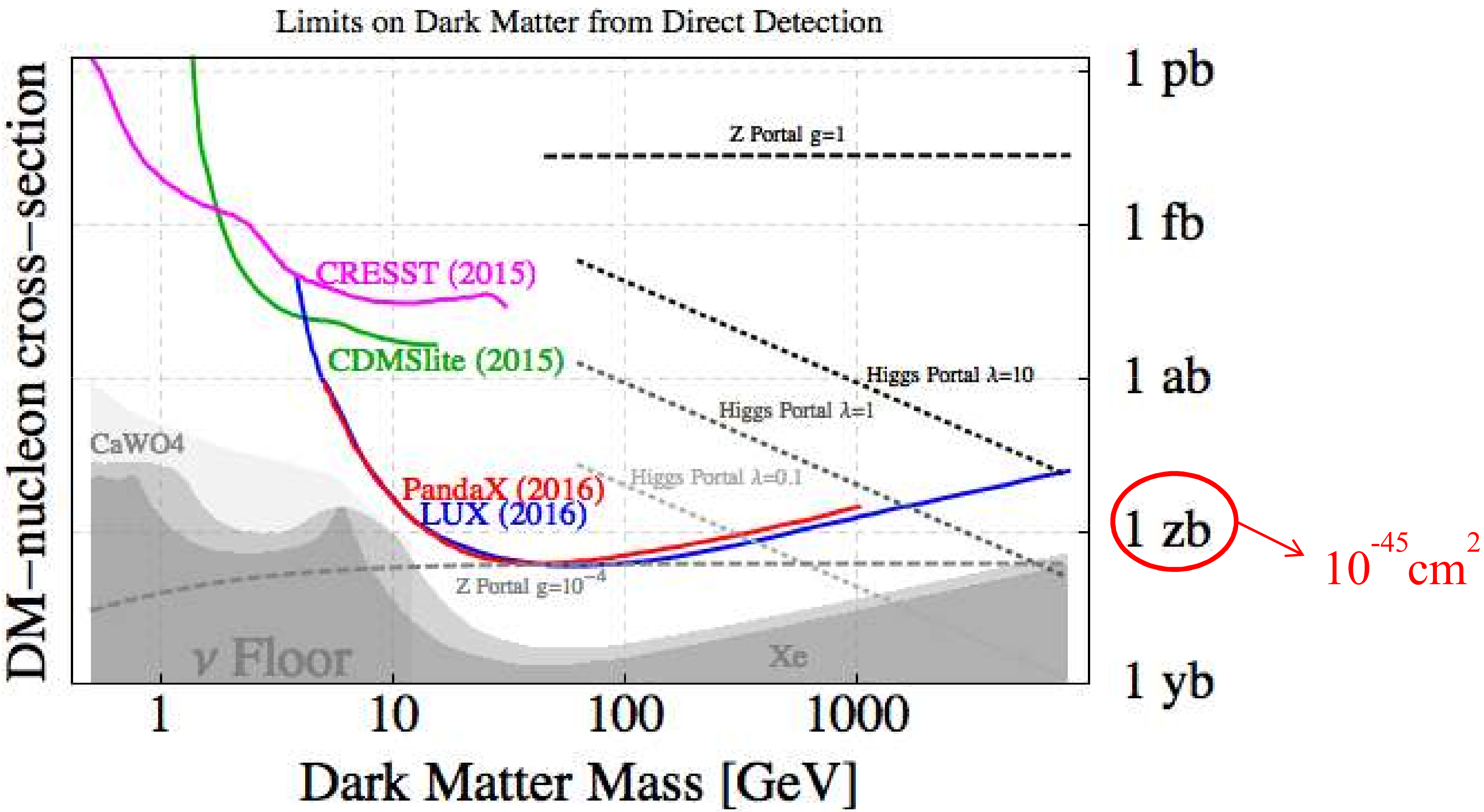
- More model-dependent parameters are needed.
- Larger SM background for electron channel (NC vs CC interaction rate).
- Neutrino beam induced beta decay as additional background.

Backup slides:



(LUX arXiv:1602.03489)

Backup slides:



Backup slides:

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

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

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

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

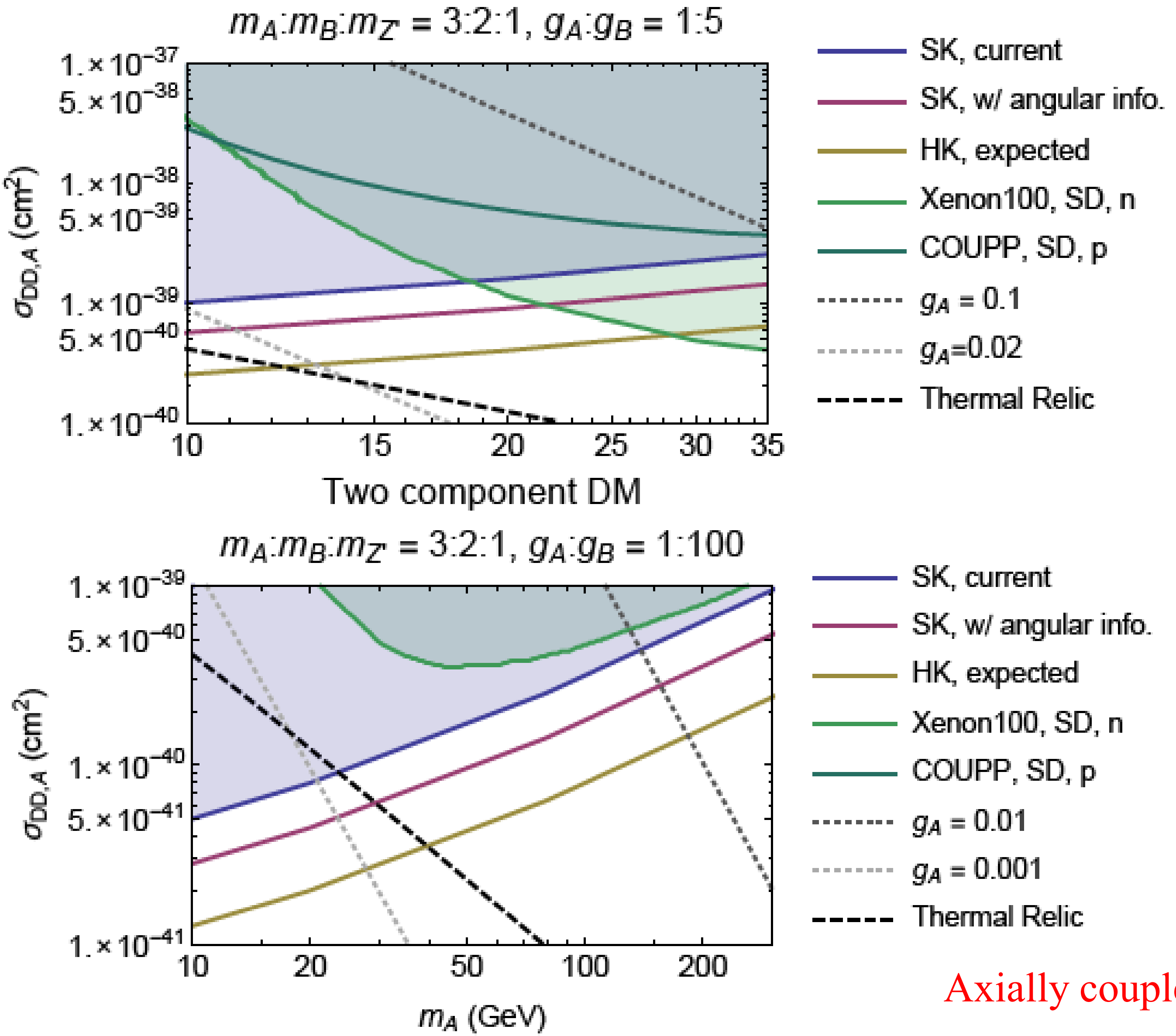
If M_{med} ~ 10 GeV, couplings ~ 0.025.

⇨ 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)