Physics Opportunities at Dark Matter "Colliders"

Doojin Kim

Planck Conference at Warsaw, Poland

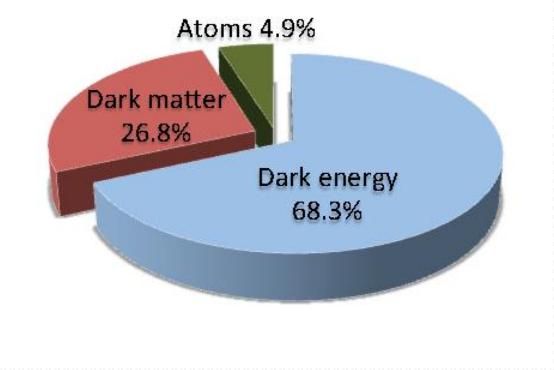
May 25th, 2017

Based on DK, J.-C. Park, and S. Shin, arXiv:1612.06867
G. Giudice, DK, J.-C. Park, S. Shin, ..., in progress

Dark Matter

Existence of dark matter

- Dark Matter (DM): **~25% of our universe**, existence supported by rotation curves, gravitational lensing, cosmic microwave background etc.



Dark Matter

Known properties

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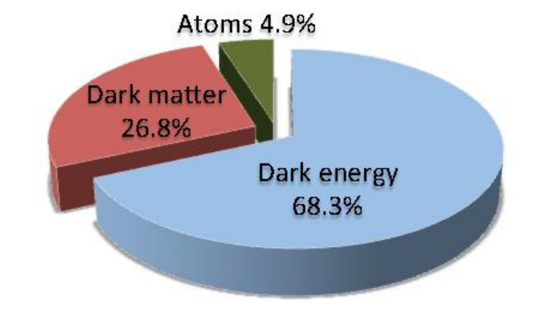
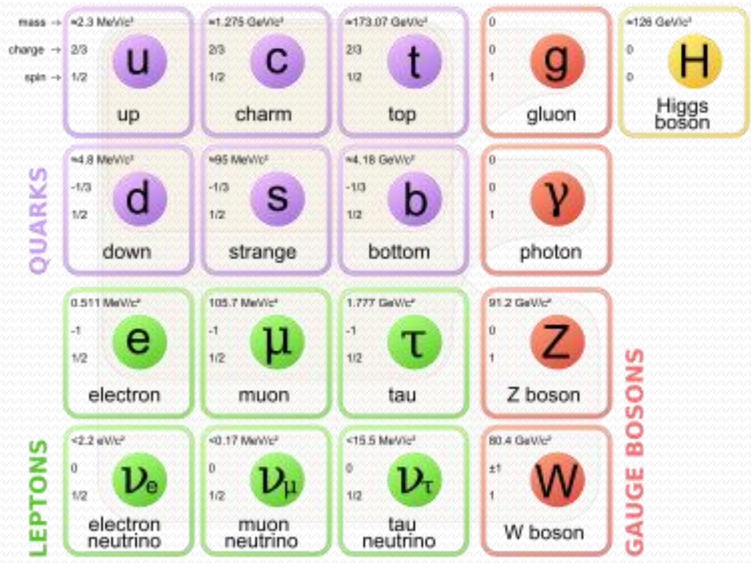


- Known DM properties (albeit few):
  - gravitationally interacting
  - not short-lived
  - not hot
  - not baryonic
  - not electrically charged



Dark Matter

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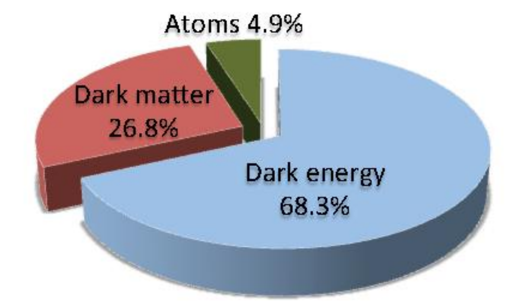

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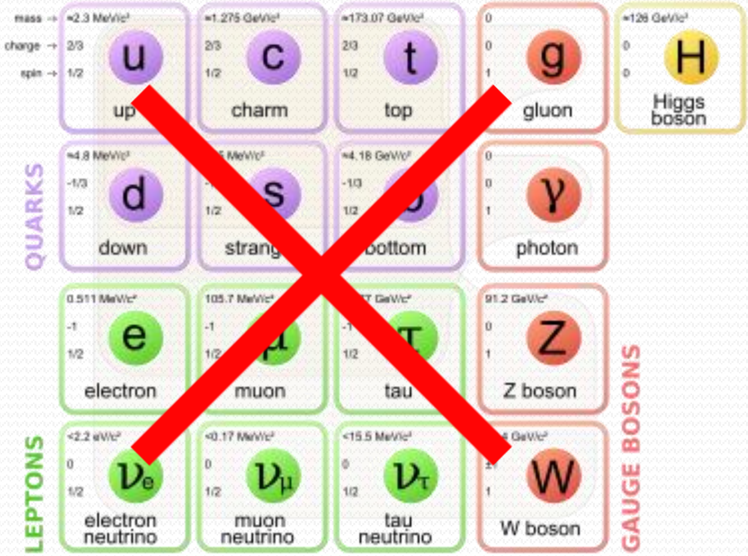
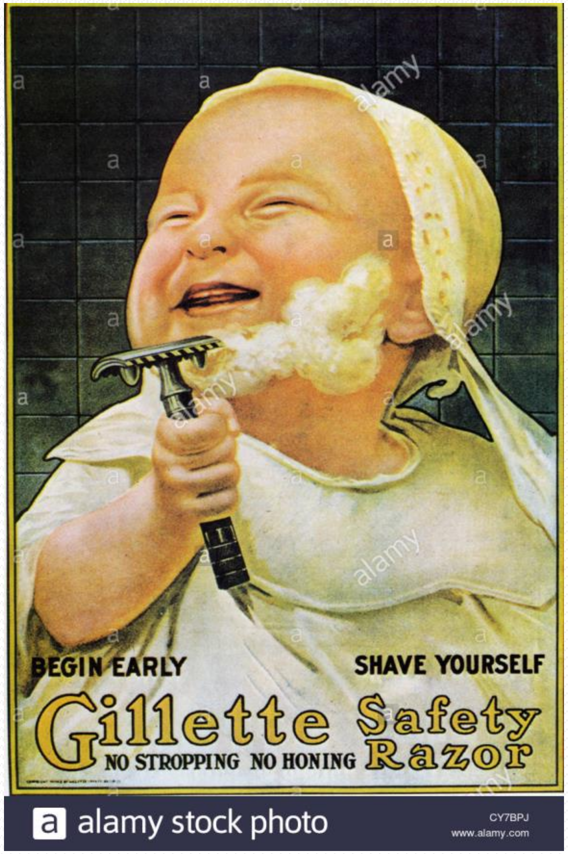
  ⇒ Need for **new physics/particles**



“Minimal” Dark Sector

Occam's razor(?)

- Many DM simplified models or new physics models including a DM candidate proposed:
  - ✓ Positing **single DM species**/focusing on **dominant DM** (with other dark sector particles put aside)
  - ✓ Good and economical approach toward the truth in the earlier stage!
  - ✓ Concentrating on **DM itself** and relevant **phenomenological implications**

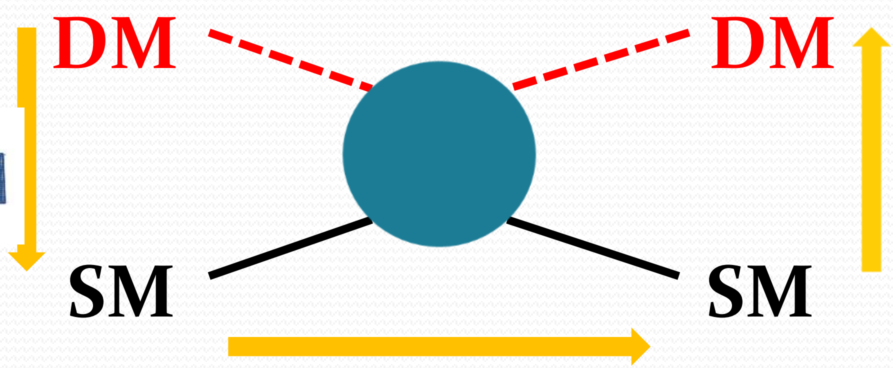


"Minimal" Dark Sector

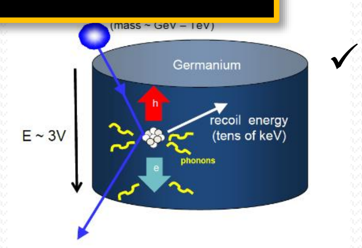
"Minimal" phenomenological implications

DM indirect search

- ✓ (Non-relativistic) DM annihilation/decay to $\gamma, e^+, \bar{p}$, etc.
- ✓ $\langle \sigma v \rangle \sim 10^{-26}\ \mathrm{cm}^3/\mathrm{s}$



DM direct search



- ✓ (Non-relativistic) DM scattering off target nuclei
- ✓ $E_{\mathrm{recoil}} \sim 1 - 100\ \mathrm{keV}$

DM production

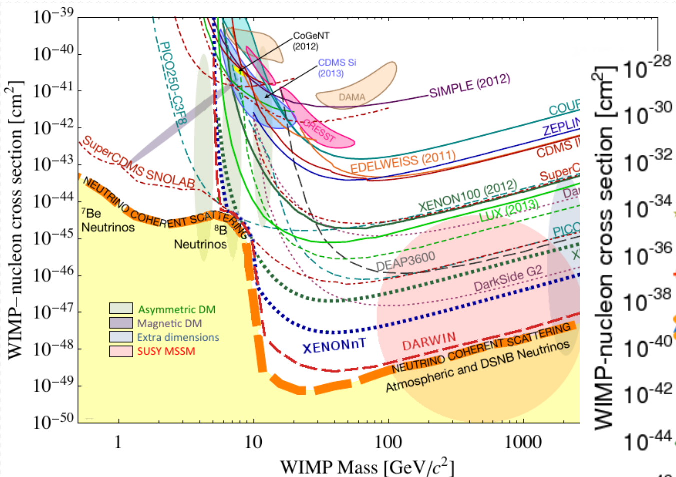
- ✓ Active DM production at colliders
- ✓ Mono-X searches
- ✓ Expected rate inferred from/related to $\langle \sigma v \rangle \sim 10^{-26}\ \mathrm{cm}^3/\mathrm{s}$

“Non-minimal” Dark Sector

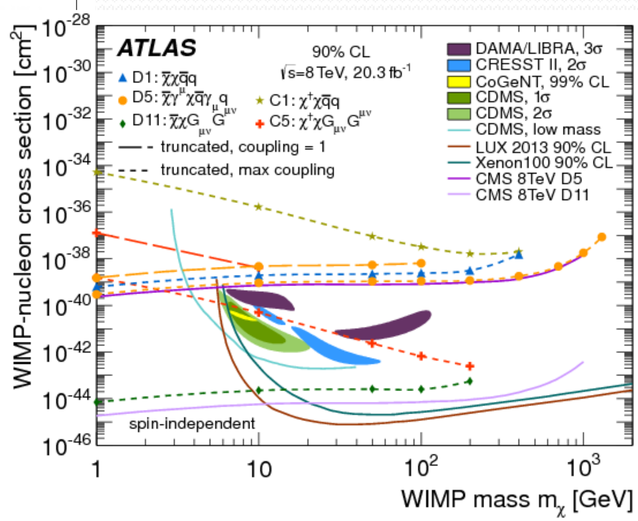
Why flavorful?

- **No “unambiguous” observation** of DM signatures via non-gravitational interactions

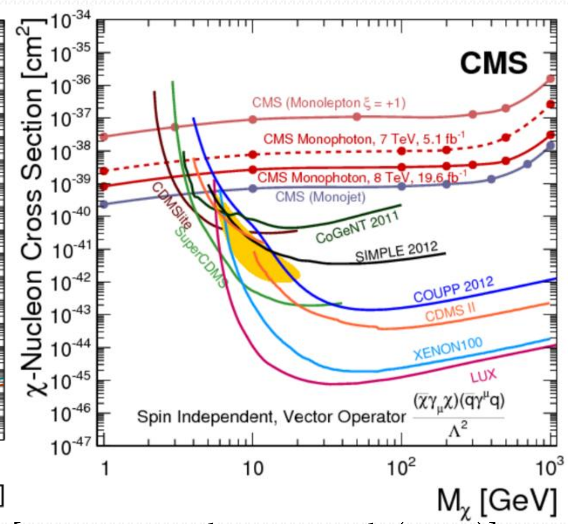
  (many searches/interpretations designed under minimal dark-sector scenarios)



[P. Cushman, C. Calbiati and D. N. McKinsey, (2013); L. Baudis (2014)]



[ATLAS mono-jet search (2015)]



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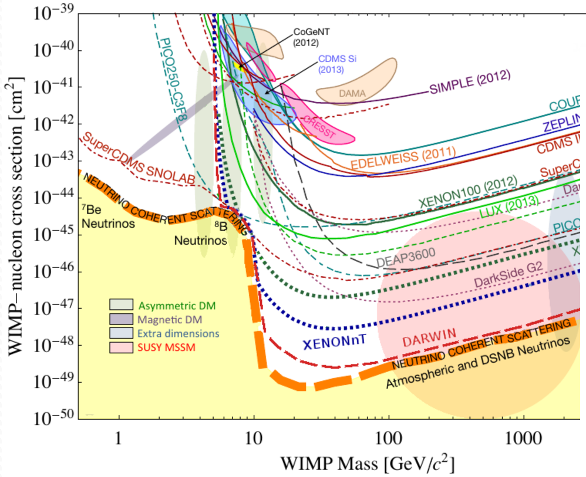

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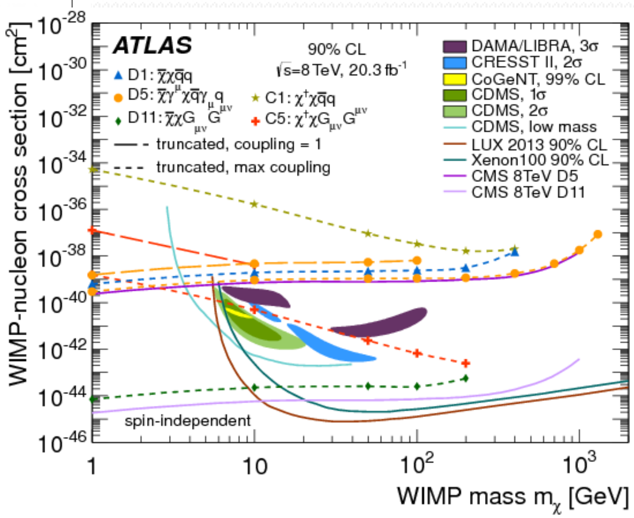

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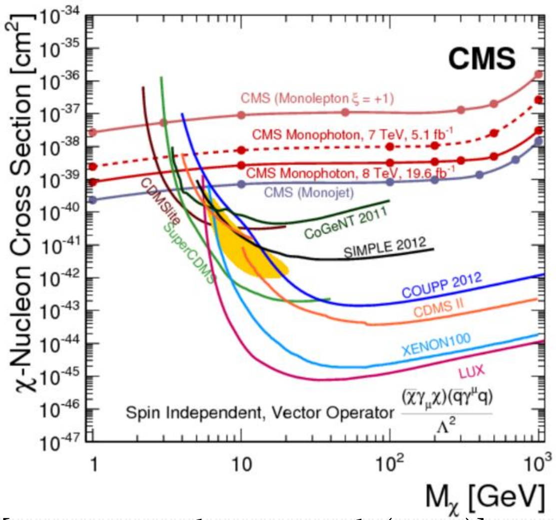

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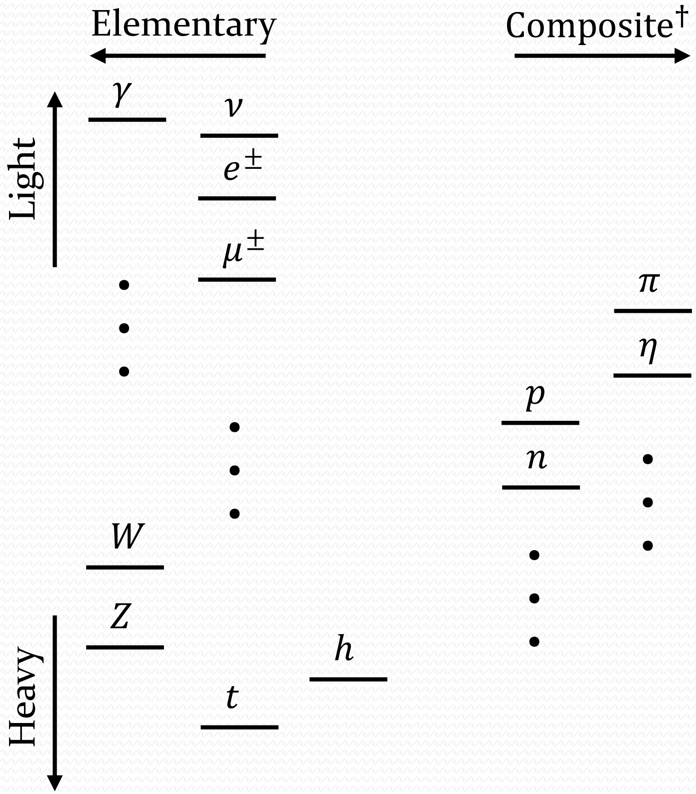
Time to (seriously) **consider non-minimal/flavorful** dark-sector scenarios?!

"Flavorful" Dark Sector

Why flavorful?

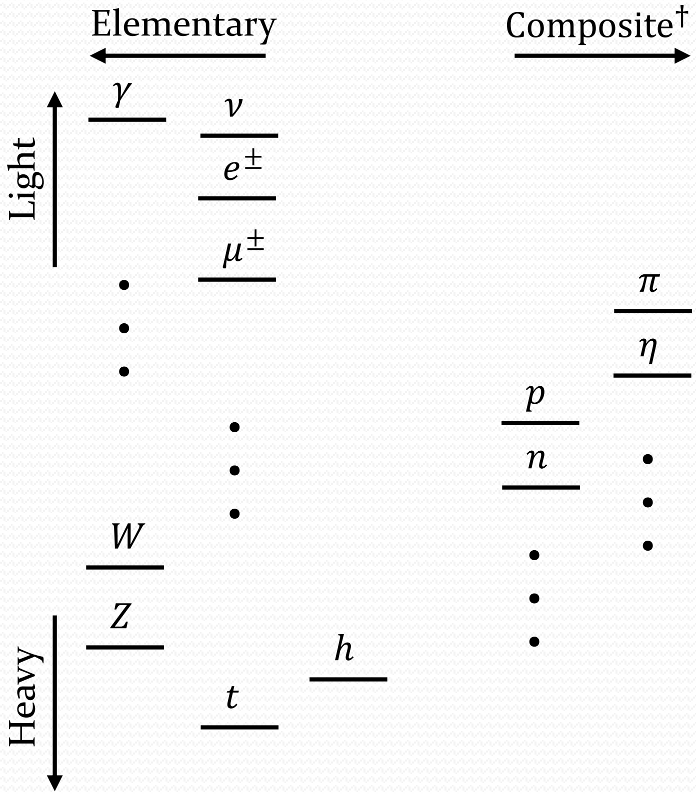


❑ Various particles in the SM sector

†: here meaning the particles made of elementary ones

"Flavorful" Dark Sector

Why flavorful?



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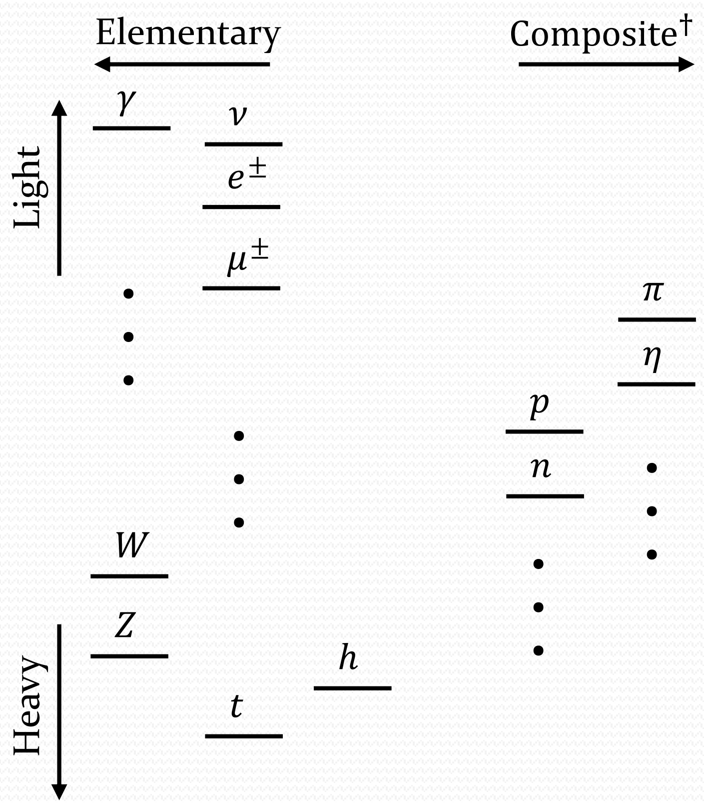

- ❑ Various particles in the SM sector
  - ✓ **Multiple stable particles** → **interesting physics** from other stable members which are **not difficult to detect** albeit not dominant (proton is dominant in the visible sector)
  - ✓ **Many heavier (unstable) states** → **interesting signatures/phenomenology** stemming from their decays (e.g., at lepton/hadron colliders)

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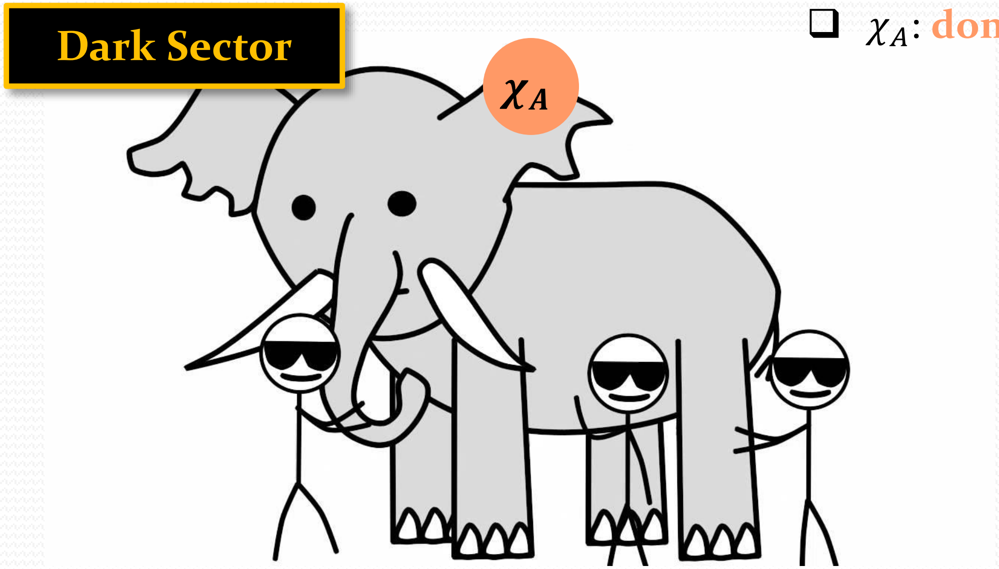
"Flavorful" Dark-sector Scenarios

In what sense?



- ❑ χ_A: **dominant relic** (as in the minimal setup)

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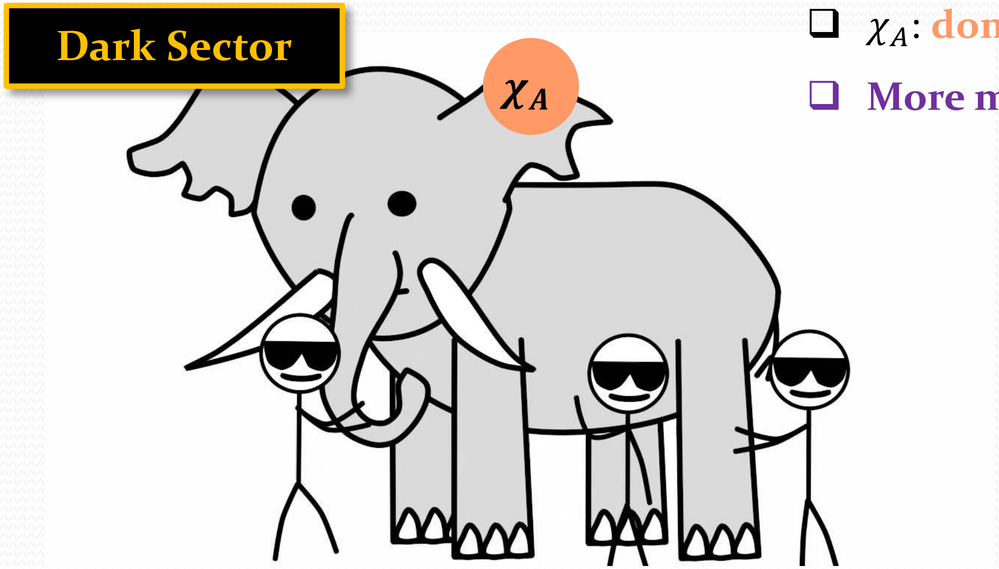

- χ_A: **dominant relic** (as in the minimal setup)
- **More members** in the dark sector

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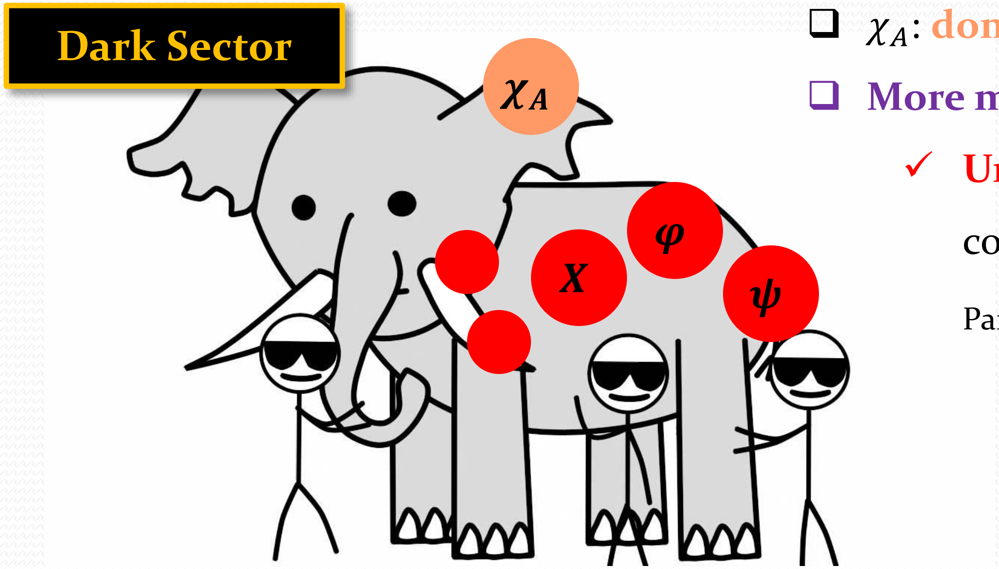

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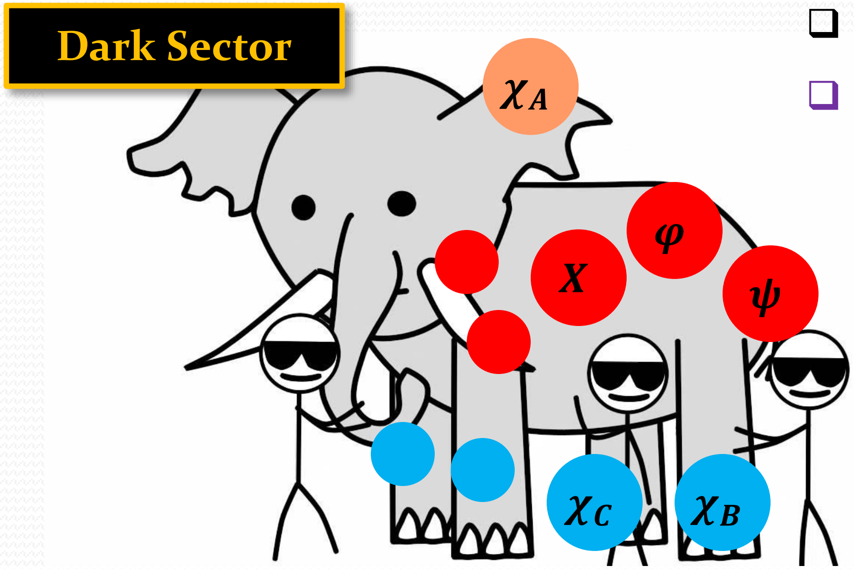

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  - ✓ **More dark matter species**, say χ_B, χ_C ... (e.g., dynamical dark matter models [K. Dienes and B. Thomas, (2011)])

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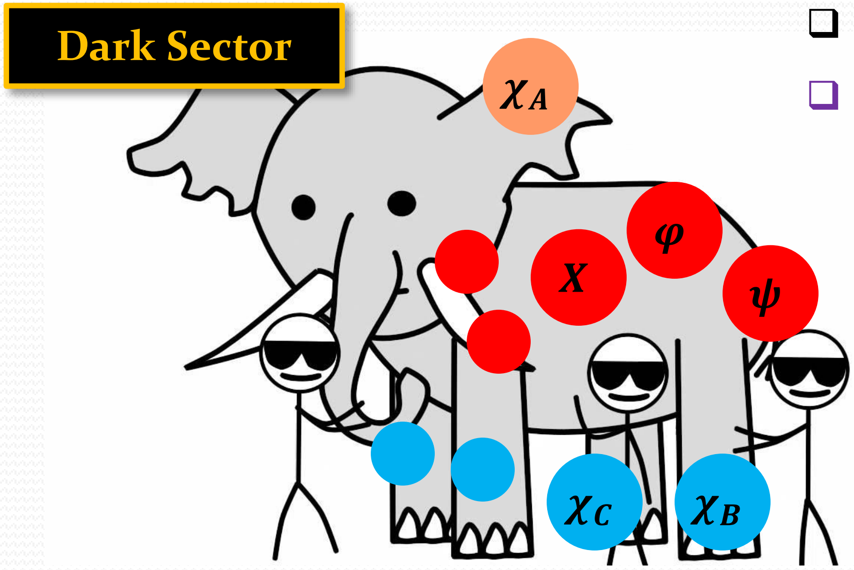

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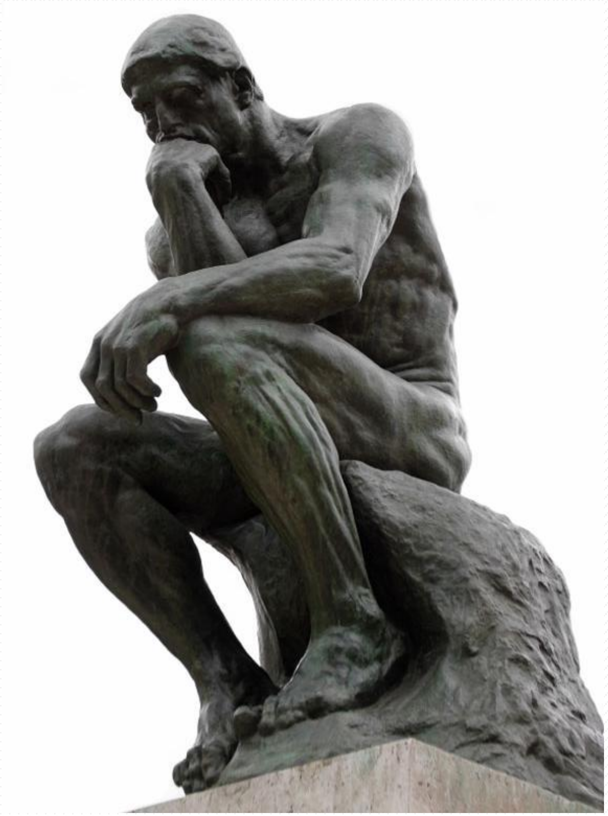
❑ **Rising interest**

- ❖ Boosted dark matter scenarios [K. Agashe et al., (2014); K. Kong, G. Mohlabeng, J.-C. Park (2014)]
- ❖ Assisted freeze-out mechanism [G. Belanger and J.-C. Park (2011)]
- ❖ Dark matter "transporting" mechanism [**DK**, J.-C. Park and S. Shin (2017)]

"Non-conventional" Implications?

Big question

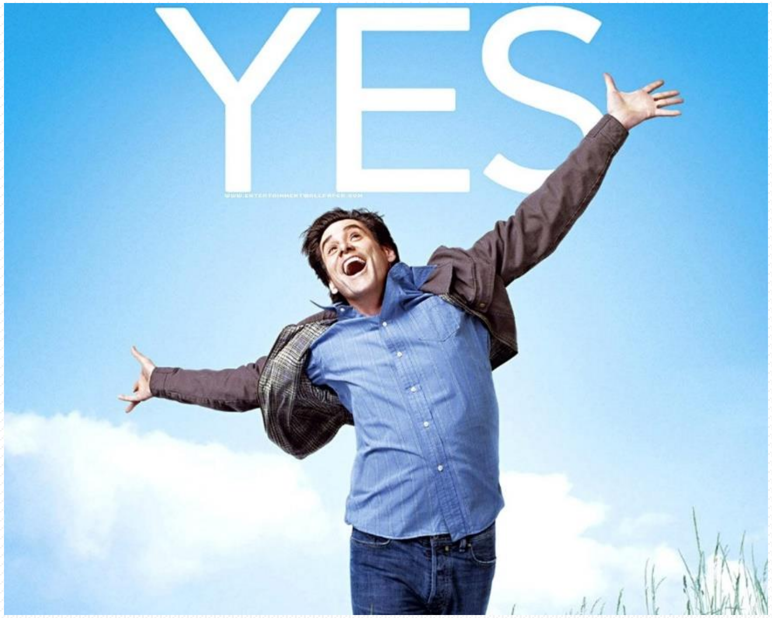


- ❑ Existence of more members in the dark sector

  → are there any **non-trivial/non-conventional implications not available in the minimal setup**?

“Non-conventional” Implications!

Big question



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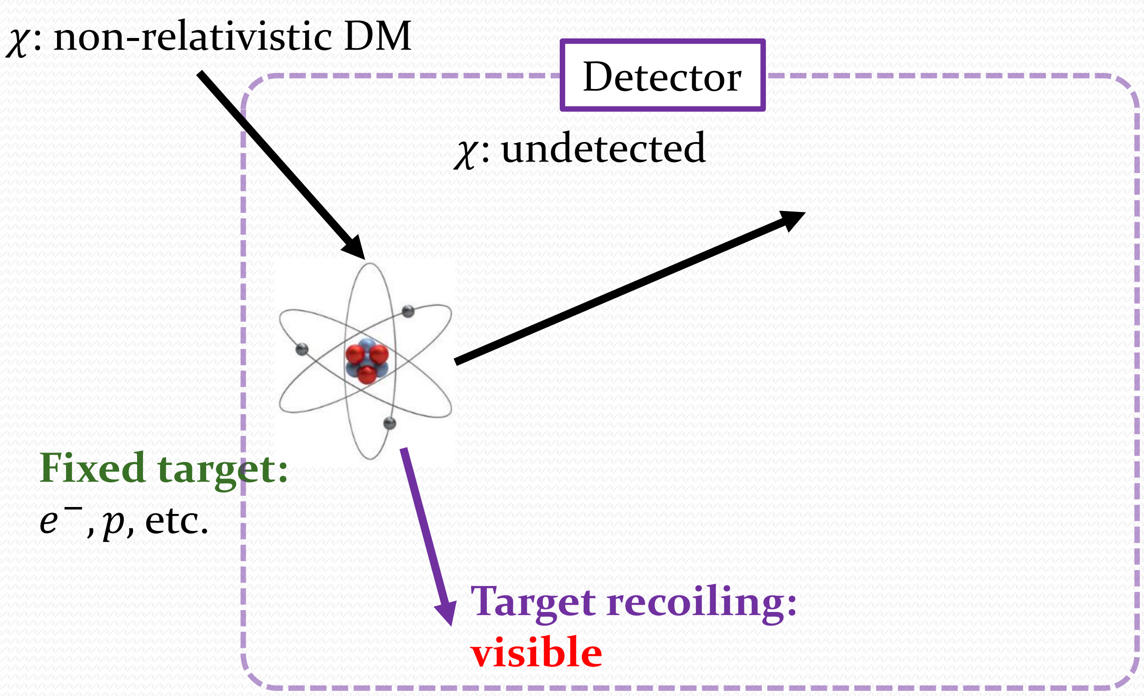
  → are there any **non-trivial/non-conventional implications not available in the minimal setup**?

  - ✓ **New dark matter search strategies: dark matter “colliders”** [**DK**, J.-C. Park and S. Shin (2016)]

Dark Matter Direct Detection

Basic idea

- ❑ Conventional DM direct detection experiments are considering the situation in which

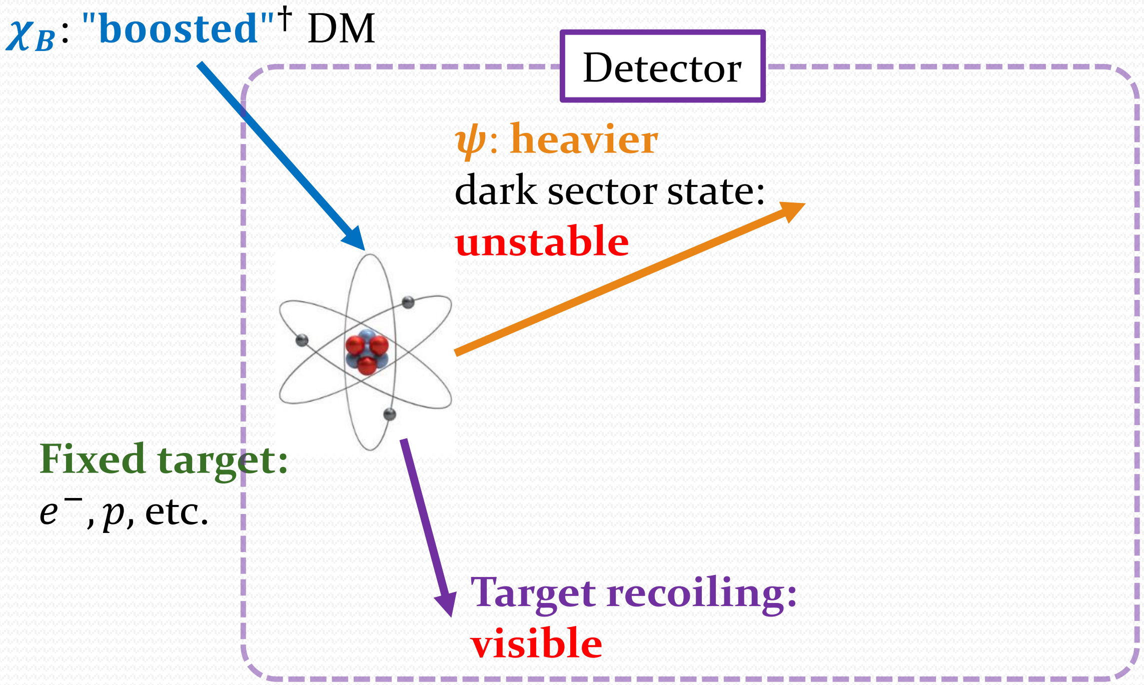


✓ Existence of DM inferred from a target recoiling ($1 - 100$ keV)

Dark Matter "Colliders"

Basic idea [DK, J.-C. Park and S. Shin (2016)]

- We are imagining the situation in which



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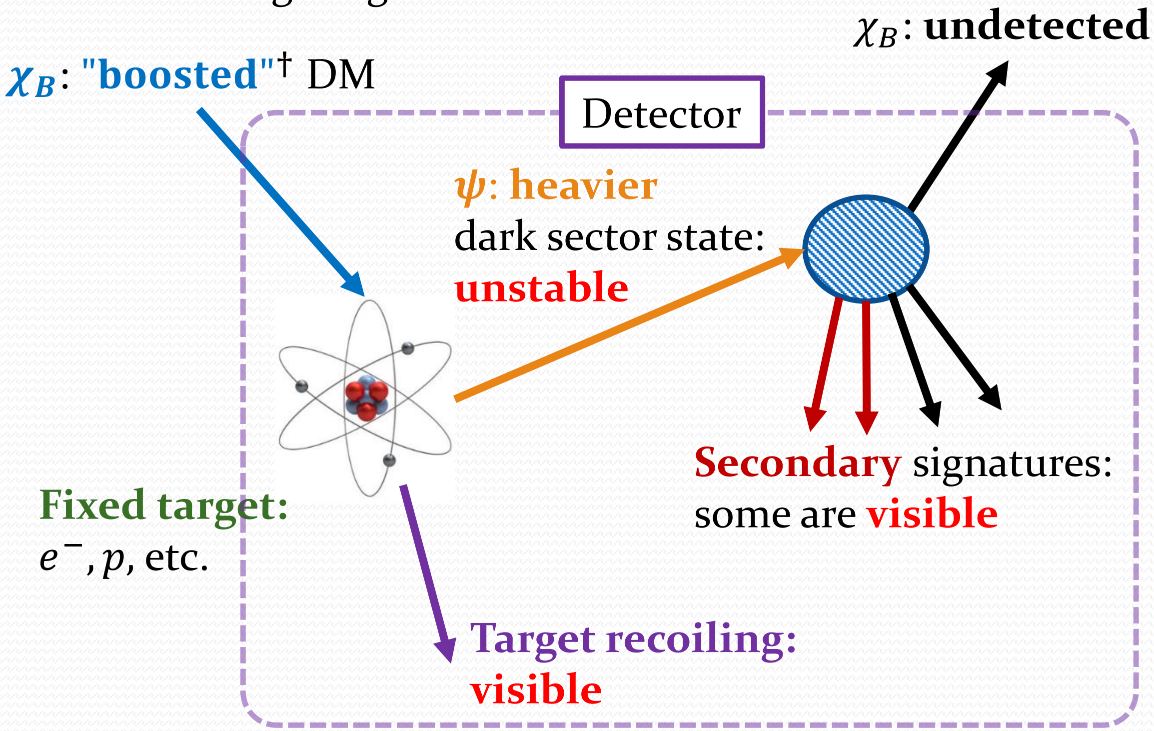

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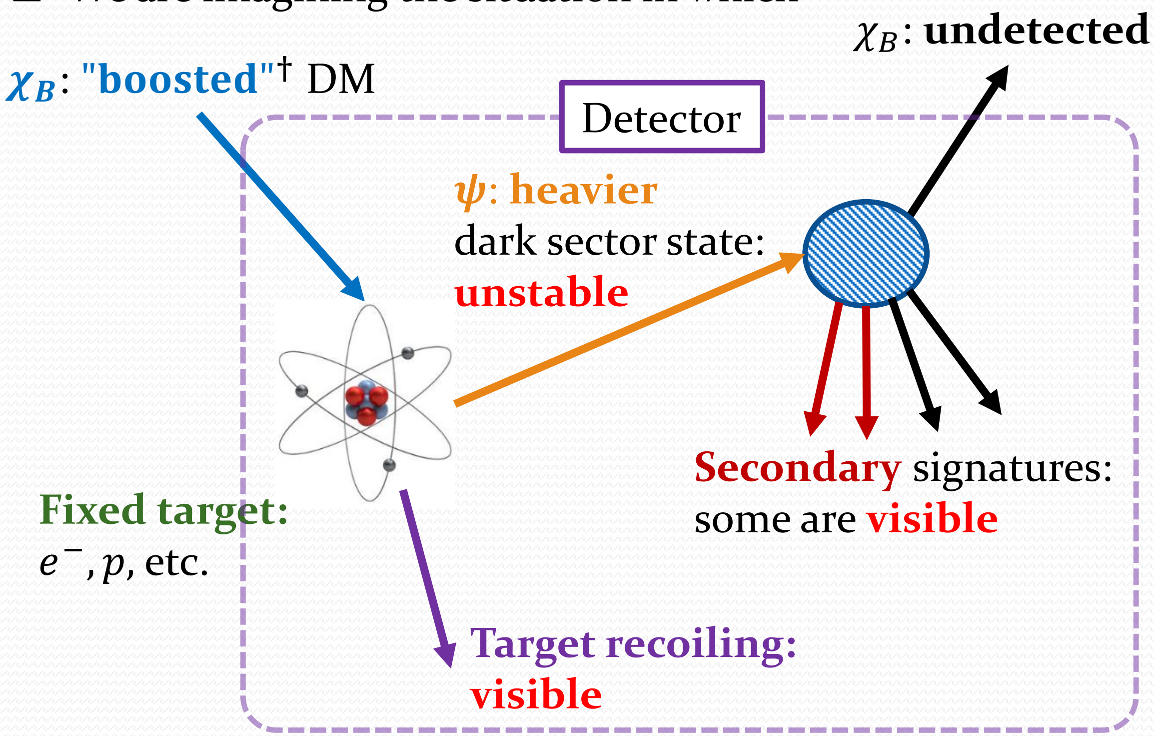

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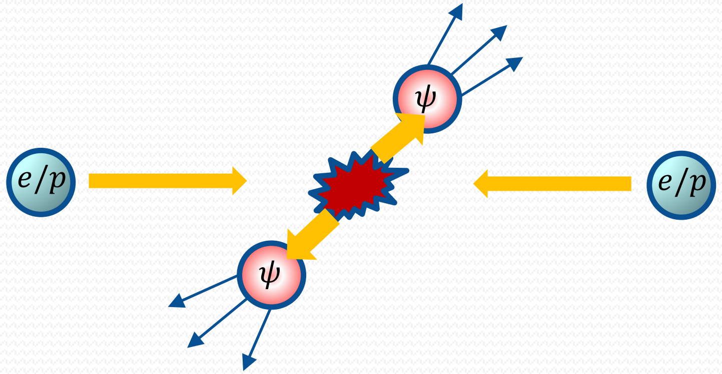
- ✓ Probing **heavier dark/ hidden-sector states**
- ✓ Target recoil (like in typical DM direct detection exp.) + secondary visible signatures $\Rightarrow$ **more** handles, (relatively) **background-free** (no secondary signatures in usual backgrounds)
- ✓ **Complementary** to standard DM direct searches

Dark Matter “Colliders”

Collider as a heavy-state probe



Conventional colliders

- Head-on collision of light SM-sector (stable) particles
- to produce heavier states
- and study resulting phenomenology

Dark Matter "Colliders"

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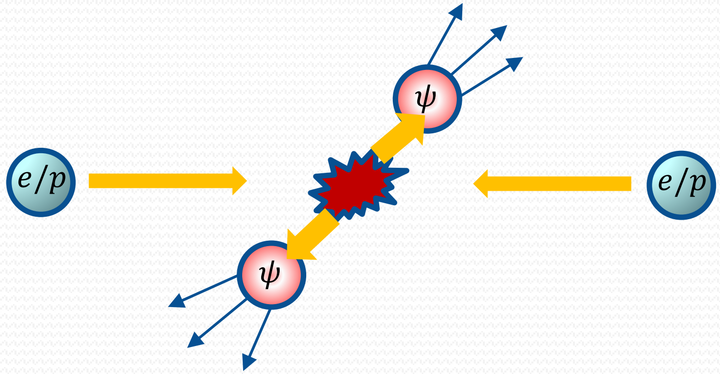
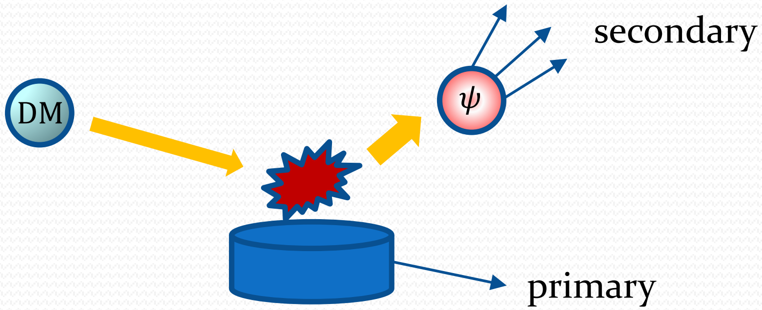




Conventional colliders

- ❑ Head-on collision of light SM-sector (stable) particles
- ❑ to produce heavier states
- ❑ and study resulting phenomenology

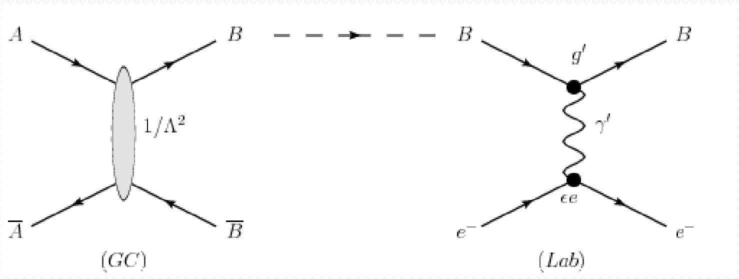
Dark matter colliders

- ❑ Collision of light hidden-sector (stable) particles onto a target
- ❑ to produce heavier hidden-sector states
- ❑ and study resulting phenomenology

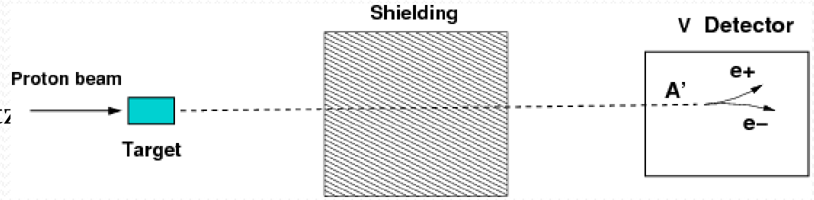
Boosted Dark Matter

Sources

- Boosted DM needed
  - ✓ The cosmic frontier: Boosted Dark Matter (BDM) scenarios (in a couple of slides) [K. Agashe et al., (2014); K. Kong, G. Mohlabeng, J.-C. Park (2014)]



  - ✓ The intensity frontier: fixed target experiments [Bjorken et al. (2009); Batell, Pospelov, Ritz (2009); Izaquirre et al. (2014)]

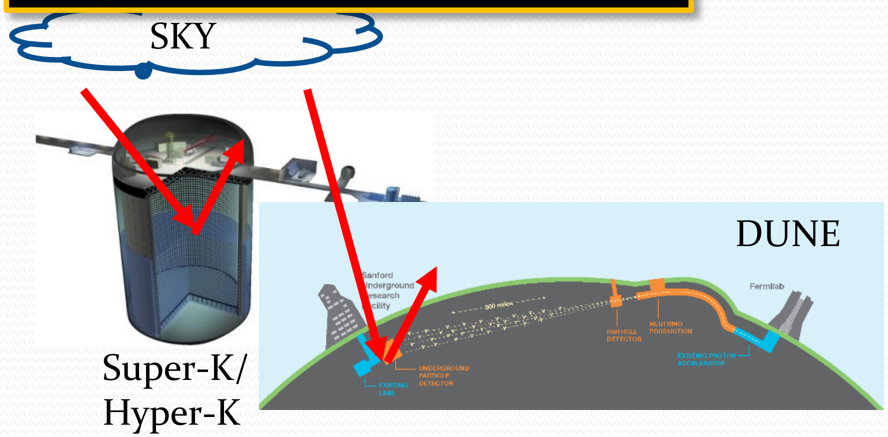


Signal Detection

Detection strategy

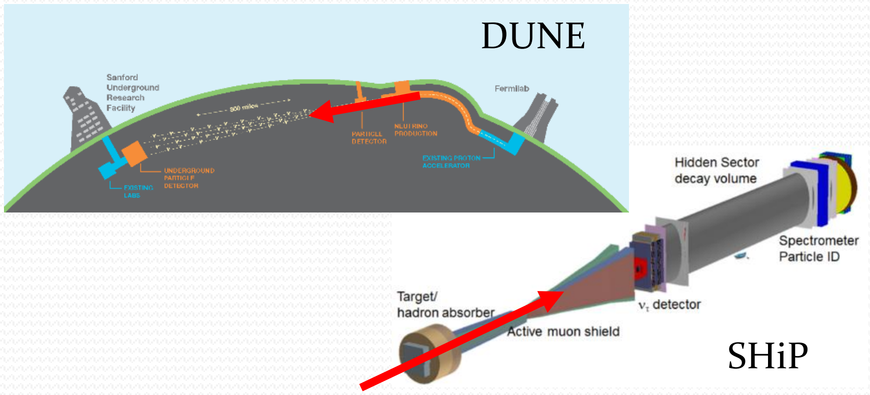
- Null observation of DM signatures may suggest small interaction strengths between SM particles and dark-sector particles (including DM).

Large-volume (neutrino) detectors



"Passive" searches

Intensity-frontier experiments



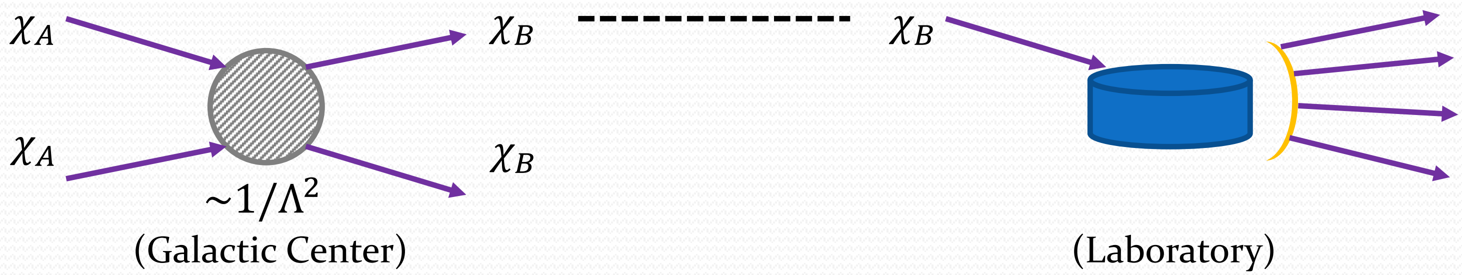
"Active" searches: more generic [G. Giudice, **DK**, J.-C. Park, S. Shin, ..., in progress]

Boosted DM Source: Cosmic Frontier

Boosted DM source

- Boosted DM scenarios [K. Agashe et al., (2014); K. Kong, G. Mohlabeng, J.-C. Park (2014)]

  $Z_2 \otimes Z_2', U(1) \otimes U(1)'$, etc.



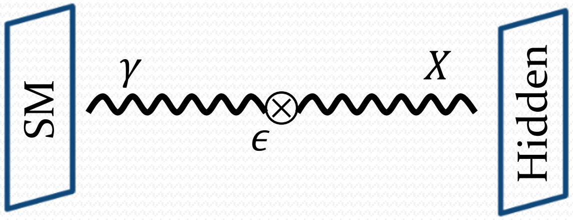
  - χ_A: heavier DM, dominant relic, non-relativistic, **not directly** communicating with SM
  - χ_B: lighter DM, subdominant relic, **relativistic** at the current universe (non-relativistic at the early universe), **directly** communicating with SM
  - Typical flux of χ_B: $\sim 10^{-7}\text{cm}^{-2}\text{s}^{-1}$ for $\mathcal{O}(10-100)$ GeV χ_A

- (**NOT the only way** of having boosted DM particles)

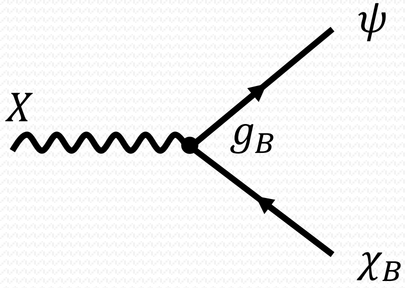
Dark Sector Model

Vector portal

$$\mathcal{L}_{\rm int} \ni -\frac{\epsilon}{2} F_{\mu\nu} X^{\mu\nu} + g_B \bar{\psi} \gamma^\mu \chi_B X_\mu + h.c.$$

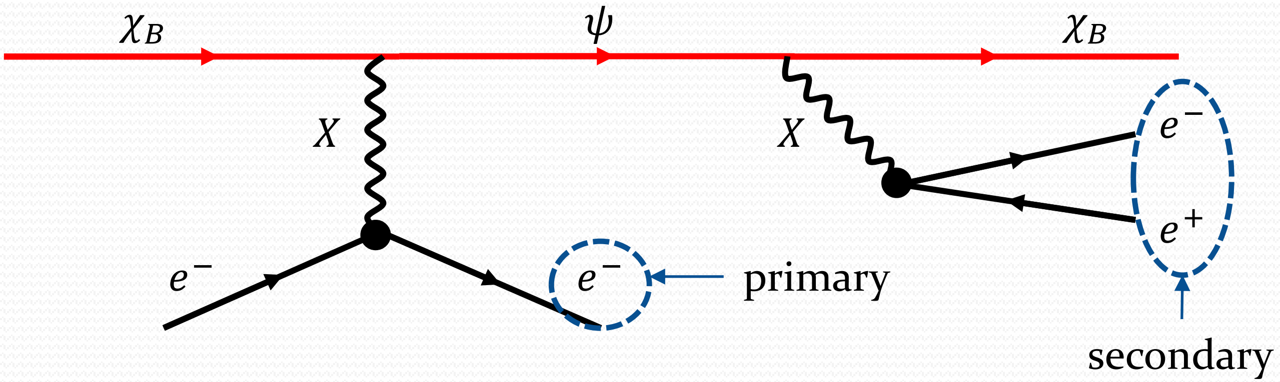


- **Vector portal** (e.g., dark "photon" scenario) [Holdom (1986)]
- Fermionic DM
  - **Flavor-changing neutral current** [e.g., J.-E. Kim, M. S. Seo, and S. Shin (2012)]
  - (Relevant models may have flavor-conserving currents as well, $\bar{\psi}\gamma^\mu\psi X_\mu$, $\bar{\chi}_B\gamma^\mu\chi_B X_\mu$)
- (**NOT restricted** to vector portal scenarios)



Discovery Potential

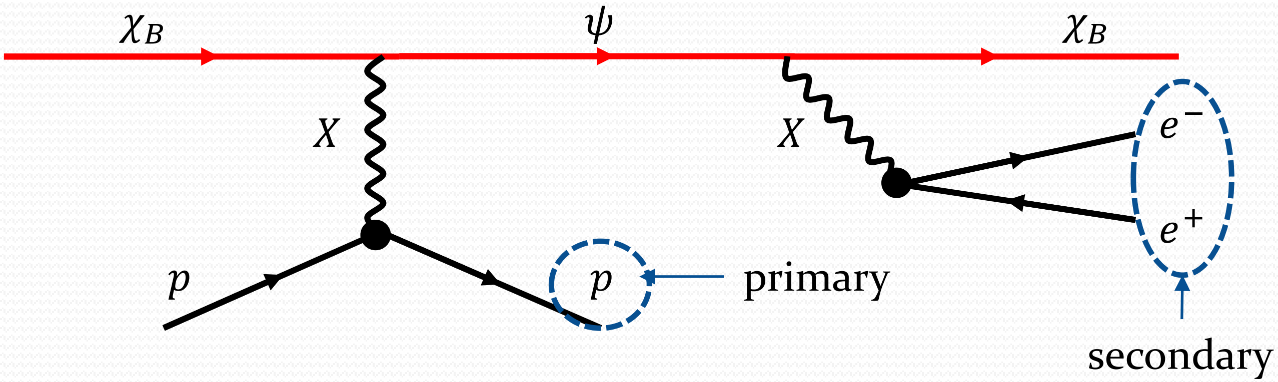
Typical signal features: *e*-scattering



- **GeV/sub-GeV mass** and **sizable boost factor** of hidden-sector particles preferred by kinematics
- e-scattering preferred ← smaller threshold energy, e^- as a fundamental particle
- e^+e^- from the secondary: **highly collimated** (not separable in most favored parameter region)
- e^- from the primary: collimated, but separable with detectors of good angular resolution
- High chance to observe **two separable charged tracks**

Discovery Potential

Typical signal features: p-scattering



- **GeV/sub-GeV mass** and **decent boost factor** of hidden-sector particles preferred by kinematics
- (Typically) Larger threshold energy, p could be broken apart, atomic form factor
- e^+e^- from the secondary: **separated**
- p from the primary: **separated** from the secondary particles
- High chance to observe **three separable charged tracks**

Discovery Potential

Results and outlook

Exp.	Run time	e-ref.1	e-ref.2	p-ref.1	p-ref.2
SK	13.6 yr	170	7.1	3500	5200
HK	1 yr	88	3.7	1900	2800
HK	13.6 yr	6.7	0.28	140	210
DUNE	1 yr	190	9.0	150	1600
DUNE	13.6 yr	14	0.69	11	120

TABLE II: Required fluxes in unit of 10^{-7} cm^{-2} s^{-1} with which our reference points become sensitive in various experiments.

[**DK**, J.-C. Park and S. Shin (2016)]

	m_{χ_B}	m_ψ	m_X	γ_{χ_B}
e-ref1	0.4	0.5	0.06	250
e-ref2	0.1	0.14	0.03	200
p-ref1	0.4	0.9	0.2	15
p-ref2	0.1	1.0	0.5	50

- $\epsilon^2 = (3 \times 10^{-4})^2$ and $g_B = 0.5$ for all reference points
- γ_{χ_B}: boost factor of boosted DM χ_B
- "Zero" background assumed
- Every mass in GeV

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- Remind, in a minimal boosted DM scenario, if flux over the whole sky is $\mathcal{O}(10^{-7})$ cm^{-2}s^{-1}, it is **promising and achiev**able!

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[**DK**, J.-C. Park and S. Shin (2016)]

	m_{χ_B}	m_ψ	m_X	γ_{χ_B}
e-ref1	0.4	0.5	0.06	250
e-ref2	0.1	0.14	0.03	200
p-ref1	0.4	0.9	0.2	15
p-ref2	0.1	1.0	0.5	50

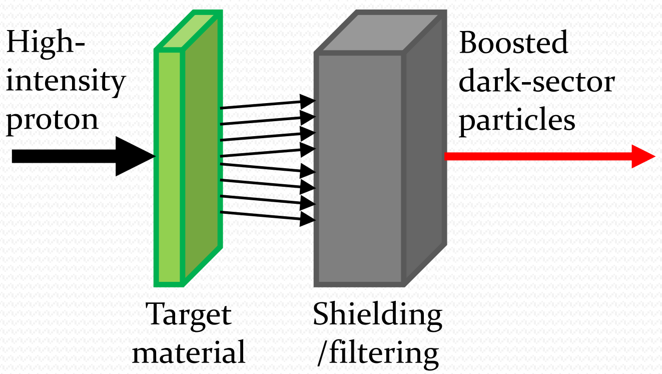
- $\epsilon^2 = (3 \times 10^{-4})^2$ and $g_B = 0.5$ for all reference points
- γ_{χ_B}: boost factor of boosted DM χ_B
- "Zero" background assumed
- Every mass in GeV

- Remind, in a minimal boosted DM scenario, if flux over the whole sky is $\mathcal{O}(10^{-7})$ cm^{-2}s^{-1}, it is **promising and achievable**!
- p-scattering improved at DUNE due to **smaller threshold energy**

Boosted DM Source: Intensity Frontier

Physics opportunities at fixed target exps.

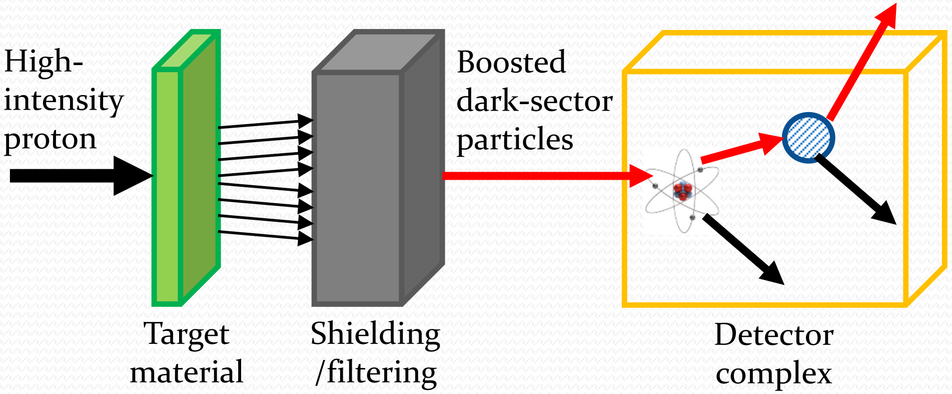
- **Production by target collision** (e.g., in vector portal scenarios)
  - Meson decay: $pp \to \pi/\eta + \text{others}$, $\pi/\eta \to X^*\gamma \to \chi_B\chi_B\gamma$; $\pi/\eta \to X^*\gamma \to \chi_B\psi\gamma$; $\pi/\eta \to X^*\gamma \to \psi\psi\gamma$
  - Drell-Yan: $pp \to X^* \to \chi_B\chi_B, \chi_B\psi, \psi\psi$
  - **Boost of χ_B given by a distribution**



Signal Detection

Physics opportunities at fixed target exps.

- **Production by target collision** (e.g., in vector portal scenarios)
  - Meson decay: $pp \rightarrow \pi/\eta$ + others, $\pi/\eta \rightarrow X^*\gamma \rightarrow \chi_B\chi_B\gamma$; $\pi/\eta \rightarrow X^*\gamma \rightarrow \chi_B\psi\gamma$; $\pi/\eta \rightarrow X^*\gamma \rightarrow \psi\psi\gamma$
  - Drell-Yan: $pp \rightarrow X^* \rightarrow \chi_B\chi_B, \chi_B\psi, \psi\psi$
  - **Boost of χ_B given by a distribution**

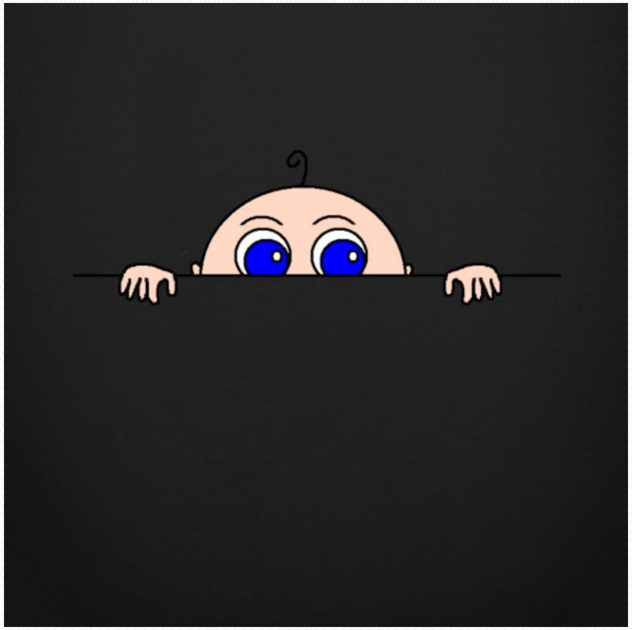


- **Detection by detector complex** (e.g., DM "colliders") [G. Giudice, **DK**, J.-C. Park, S. Shin, …, in progress]
  - Detector-specific strategies required
  - Far/near detector system at e.g., DUNE, T2HKK: **ratio of $N_{\text{near}}^{\text{signal}}$ to $N_{\text{far}}^{\text{signal}}$** available/useful for further DM signal confirmation
  - Signal events with **displaced secondary vertex**: better signal identification (e.g., SHiP)

Take-home Messages

Summary and lessons

- The more, the messier? The more, the merrier! ⇒ **Peeping into the hidden sector** through flavorful scenarios
- Rising interest in “flavorful” dark sector physics
- Physics opportunities at dark matter “colliders”
  - ***Orthogonal***: (relatively) **background-free** due to secondary signatures → **new direct DM search paradigm**!
  - ***Inexpensive***: exclusion limit/detection prospects at neutrino detectors such as Super/Hyper-K, DUNE, SHiP, etc. **without extra apparatus**
  - ***Complementary***: constraining parameters for various DM scenarios/models
  - ***Interdisciplinary***: if this scenario is the truth, **many ideas in collider phenomenology directly apply**!



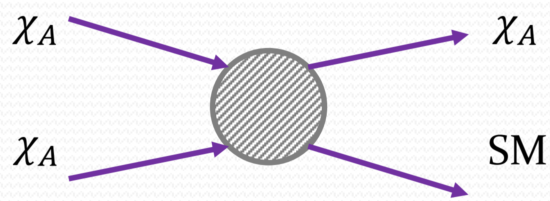

thank you!

Back-up

Boosted DM from the Sky

Semi-annihilation

- In DM models where relevant DM is stabilized by e.g., Z_3 symmetry, one may have a process like



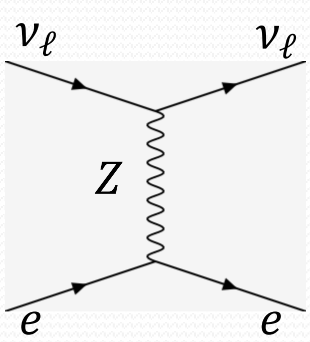
- Under the circumstance in which the mass of SM here is lighter (i.e., $m_A > m_{\rm SM}$), the outgoing χ_A can be boosted and its boost factor is given by

$$\gamma_A = \frac{5m_A^2 - m_{\rm SM}^2}{4m_A^2}$$

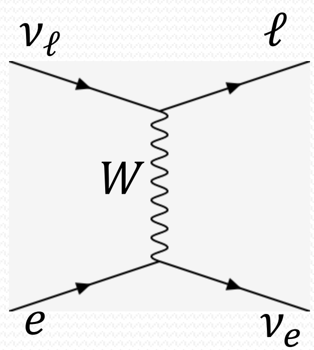
Background Considerations

Potential sources

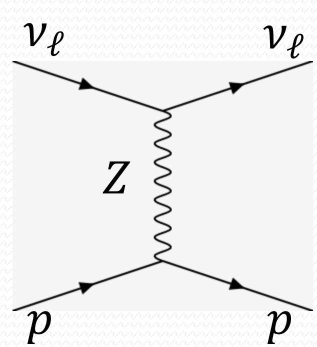
- Cherenkov radiation (CR) by electron/muon is distinguished from that by proton.
- Electron-preferred scenarios:



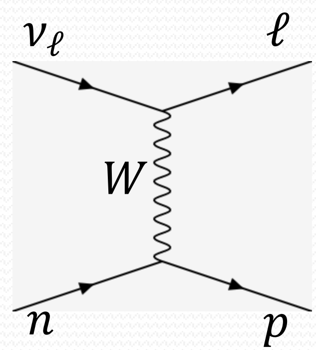
: CR by an N.C. electron



: CR by a C.C. electron/muon/tau



: CR by an N.C. proton unless broken

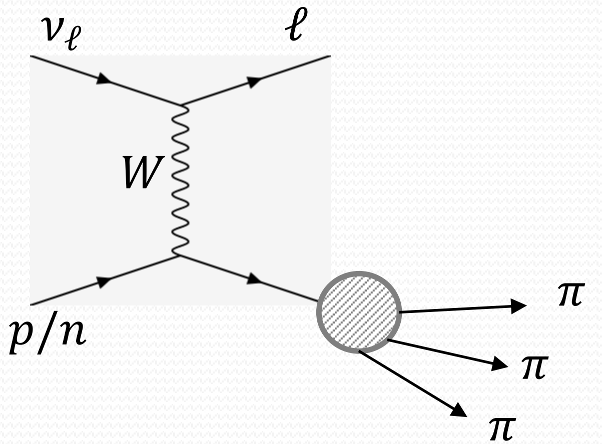


: CR by at least, a C.C. proton unless broken

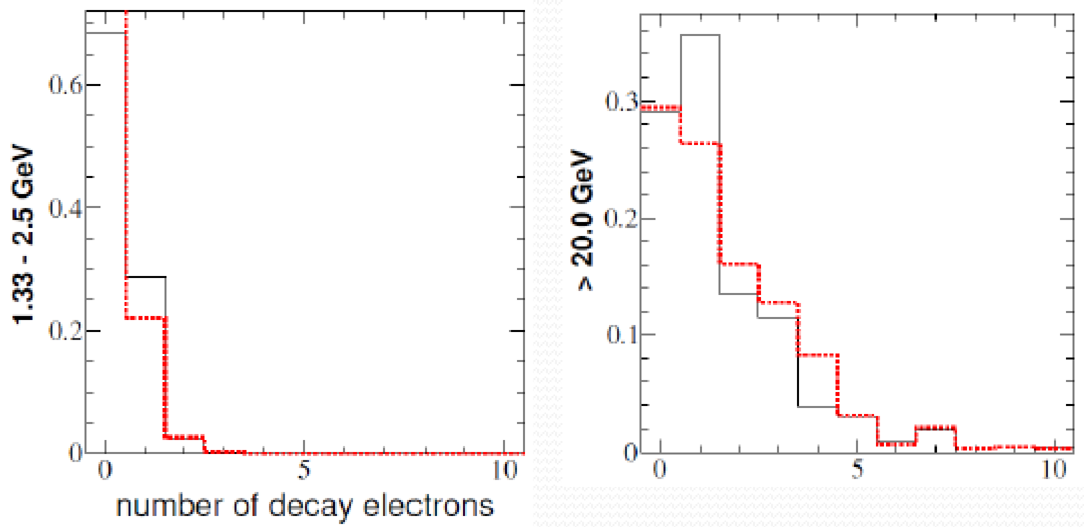
- Proton-preferred scenarios: opening angles among recoil proton, decayed electrons are large enough to resolve

Background Considerations

More challenging cases: broken nuclei



$\pi^+ \to \mu^+\nu \to e^+\nu\nu\nu$

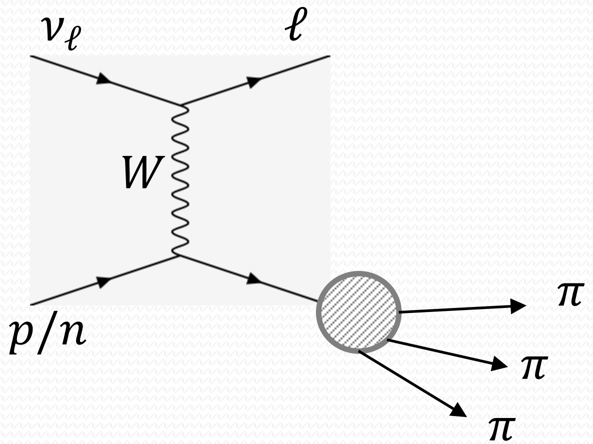


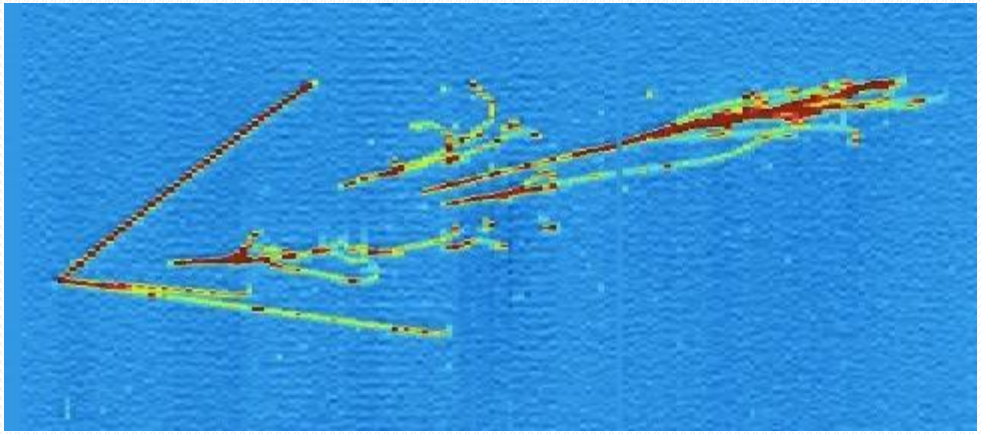
Super-K (2012)

- ❑ Similar expectations for neutral currents
- ❑ (Dedicated study in progress)

Background Considerations

- More challenging cases: broken nuclei





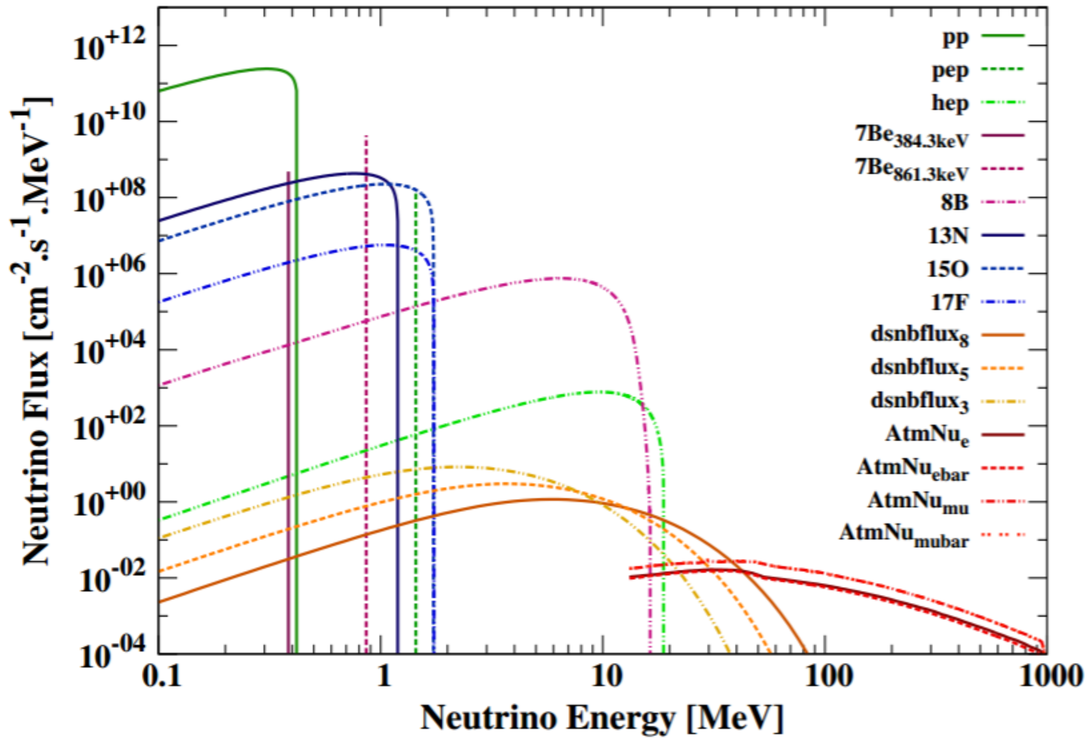
Particle tracks created by a neutrino interaction in liquid argon in the ArgoNeuT

e.g. $\pi^+ \to \mu^+ \nu \to e^+ \nu\nu\nu$

- ❑ Expecting again that **(quality) track-based particle identification** allows us to distinguish multi-track background events from signal ones
- ❑ A dedicated study is needed

Flux of Neutrino

Neutrino as a background

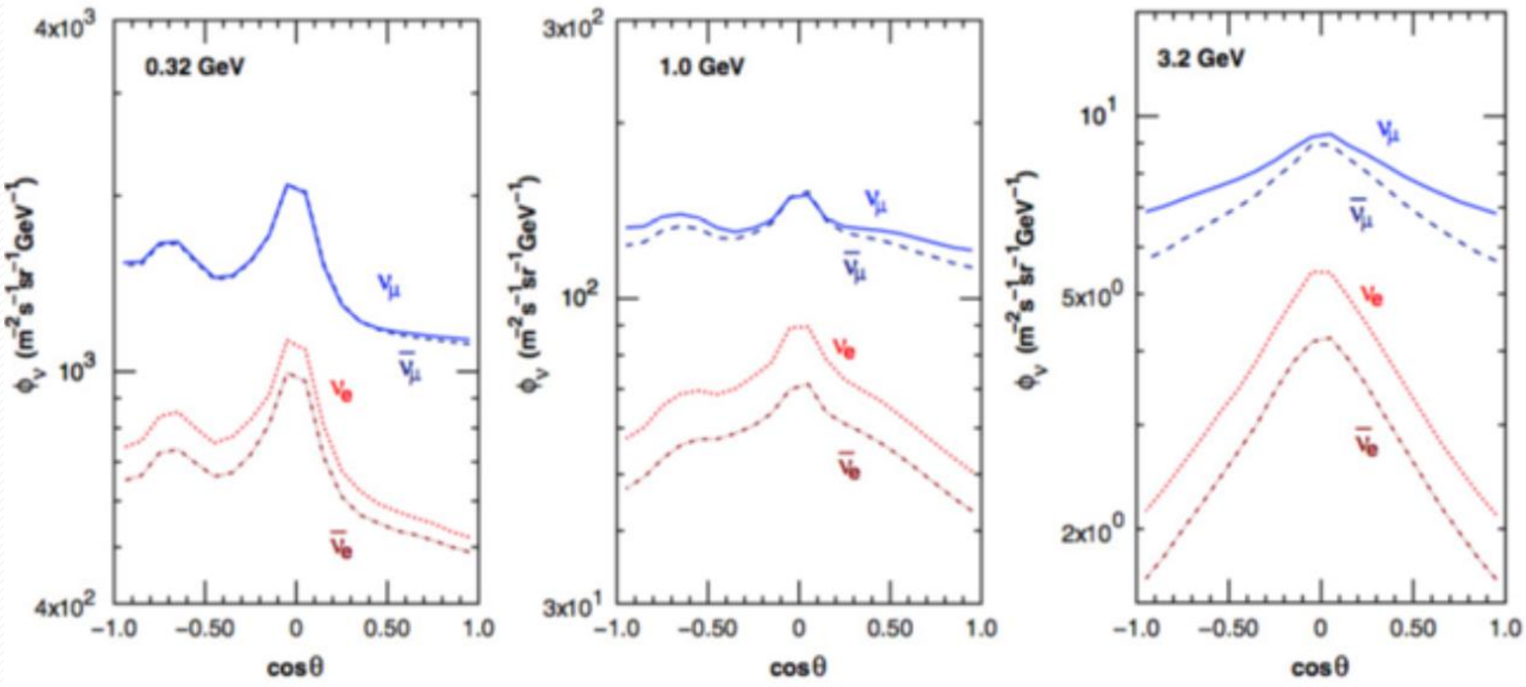


[Ruppin et al., (2014)]

- Relevant neutrino fluxes to the background of direct DM detection experiments: solar, atmospheric, and diffuse supernovae

Flux of Atmospheric Neutrino

Neutrino as a background

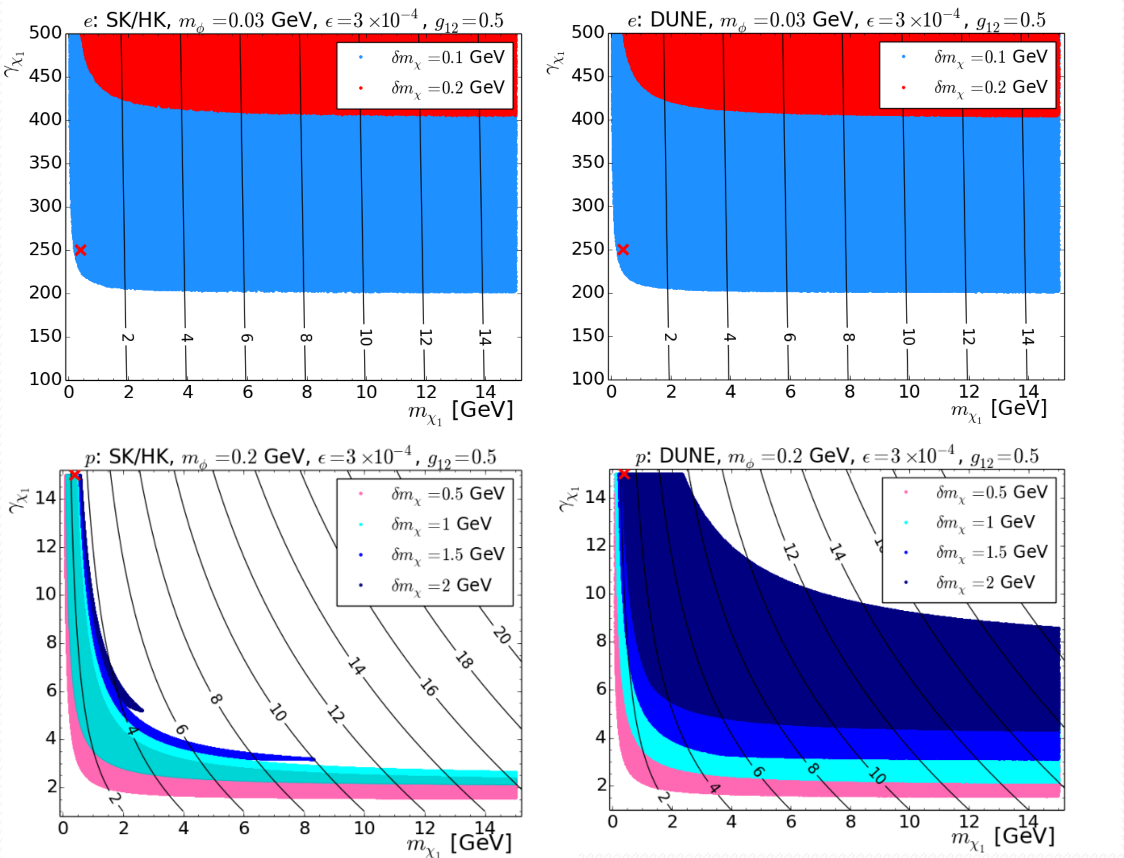


θ: zenith angle

Energetic neutrino flux $\sim 10^{-4}\text{cm}^{-2}\text{s}^{-1}$

Accessible Parameter Region

Parameter scanning

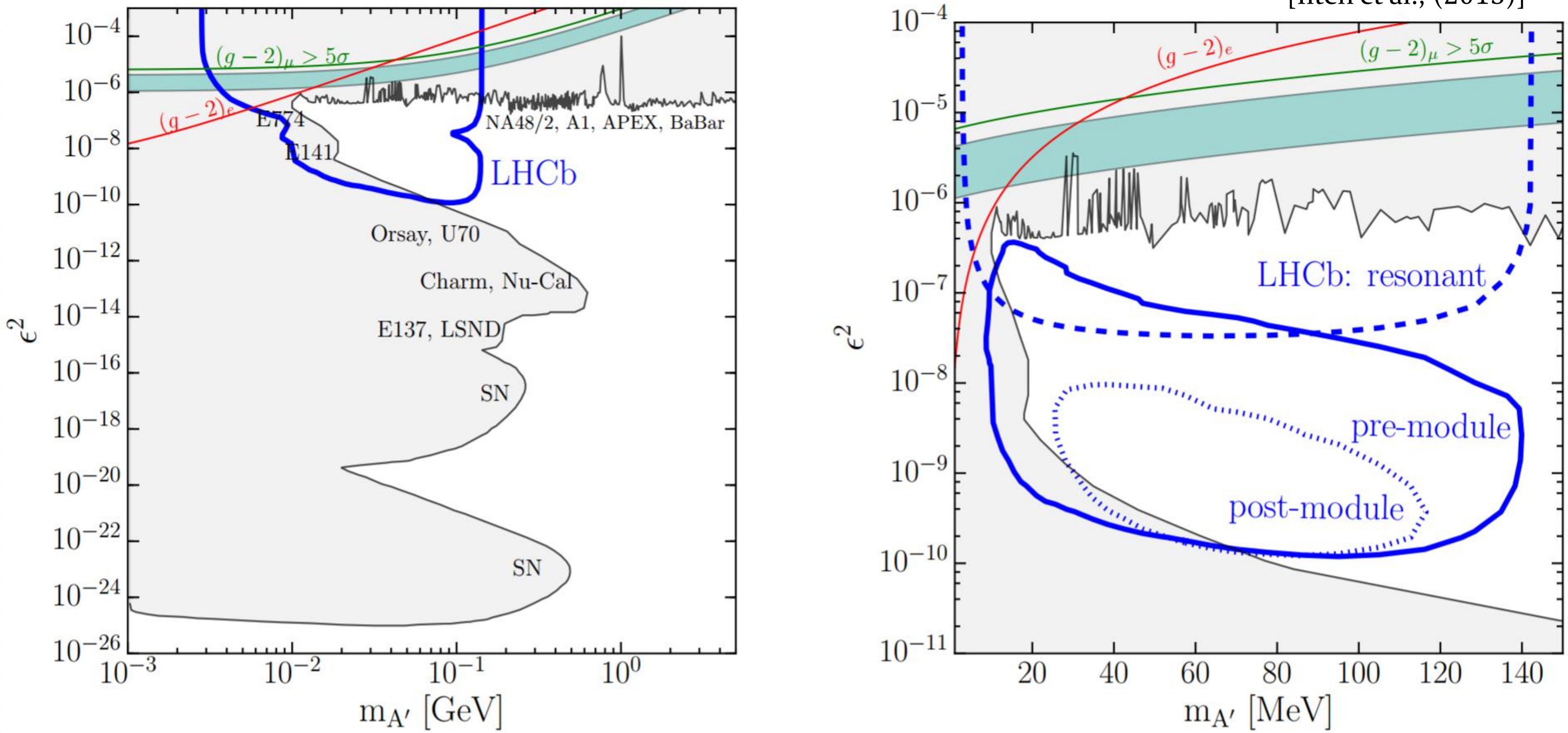


- e-scattering (upper panels) and p-scattering (lower panels)
- Black solid lines: kinematically allowed maximum mass of heavier hidden-sector states
- m_{χ_1}: mass of incident boosted DM, γ_{χ_1}: boost factor of incident boosted DM, δm_χ: mass gap between the DM and the heavier state

Current Status of Dark Photon Searches

- **Kinetic mixing parameter choice**

[Ilten et al., (2015)]



Comparison among Neutrino Detectors

Exp.	DUNE	SHiP†	SK/HK‡
Near-far detector	Yes	Yes	(Yes)
Distance b/w detectors	1,300 km	50 m	(700 – 1,000) km
Volume*	8 t/40 kt	9.6 t/NA	(190/190) kt 22.5 kt for SK
Detector type	LArTPC	Emulsion/Calorimeter	Cherenkov
Particle identification	Very good	Very good	Good
Beam energy	120 GeV	400 GeV	30 GeV
PoT	11×10^{20}/year	0.4×10^{20}/year	48×10^{20}/year
Power	1.2 MW	(> 0.15 MW)	1.3 MW
Angular resolution (e/p)	$1^\circ/5^\circ$	(Good)	$3^\circ/3^\circ$
Threshold energy (e/p)	30/50 MeV	(Equally small)	0.1/1 GeV⋆
Position resolution	1 – 2 cm	0.1 – 1 mm	Not good

†: Numbers in parentheses are our estimation.
‡: Numbers in parentheses are relevant to T2HKK.
∗: Red-font numbers are fiducial volume.
⋆: Threshold energy for the "good" angular resolution above

- DUNE/SHiP/Kamiokande **ideal for sub-GeV to GeV hidden sector particle searches**: different experiments require different strategies optimized to the associated detectors.