Physics Opportunities at Dark Matter "Colliders"

Doojin Kim

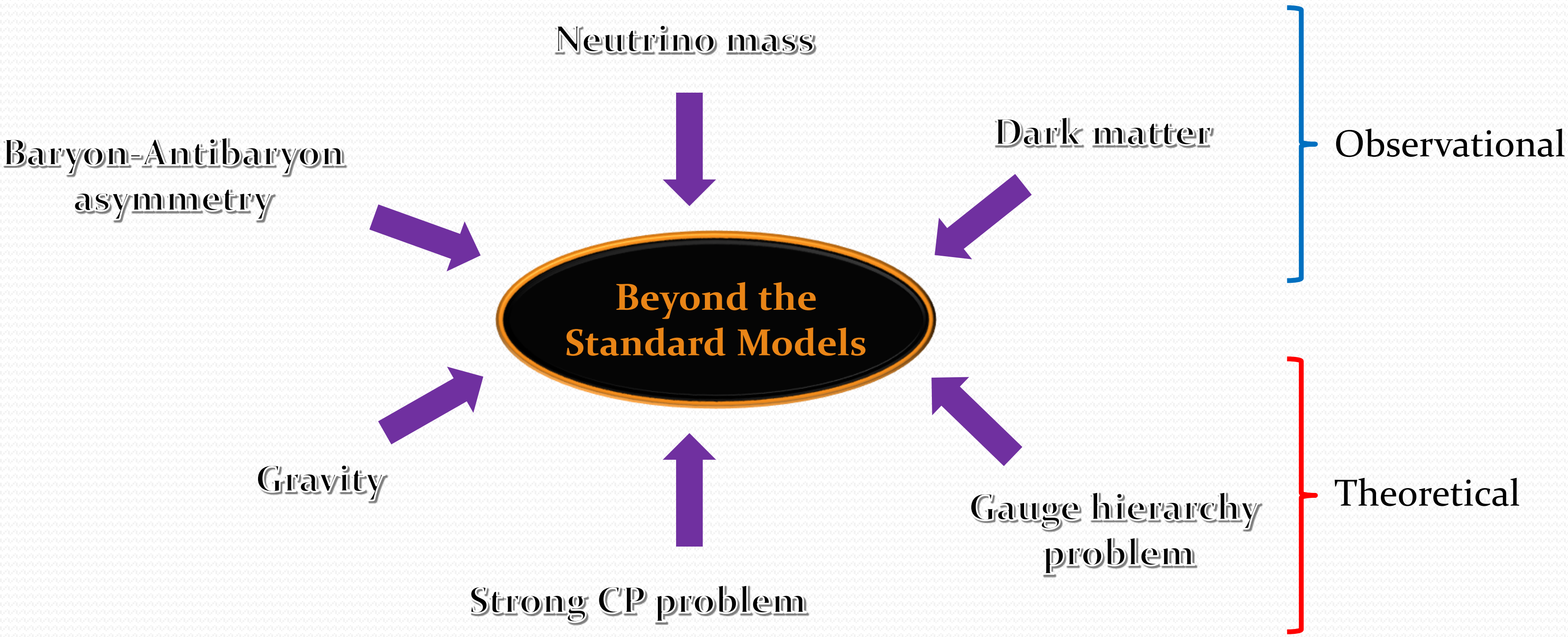
Korea-CERN Workshop at Jeju, Korea

June 1st, 2017

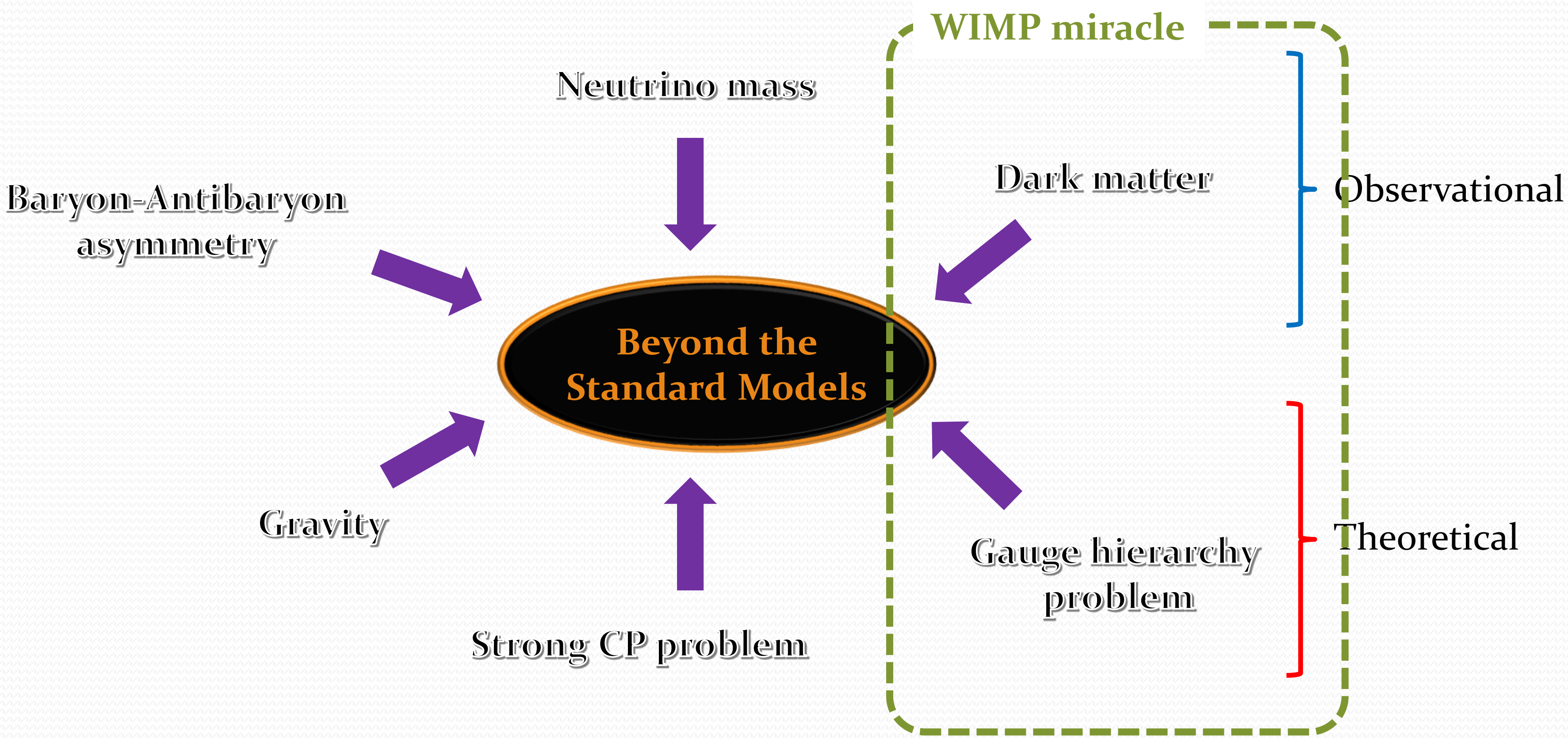
Based on DK, J.-C. Park, and S. Shin, arXiv:1612.06867

G. Giudice, DK, J.-C. Park, S. Shin, …, in progress

Need for New Physics



Need for New Physics at Weak/TeV Scale



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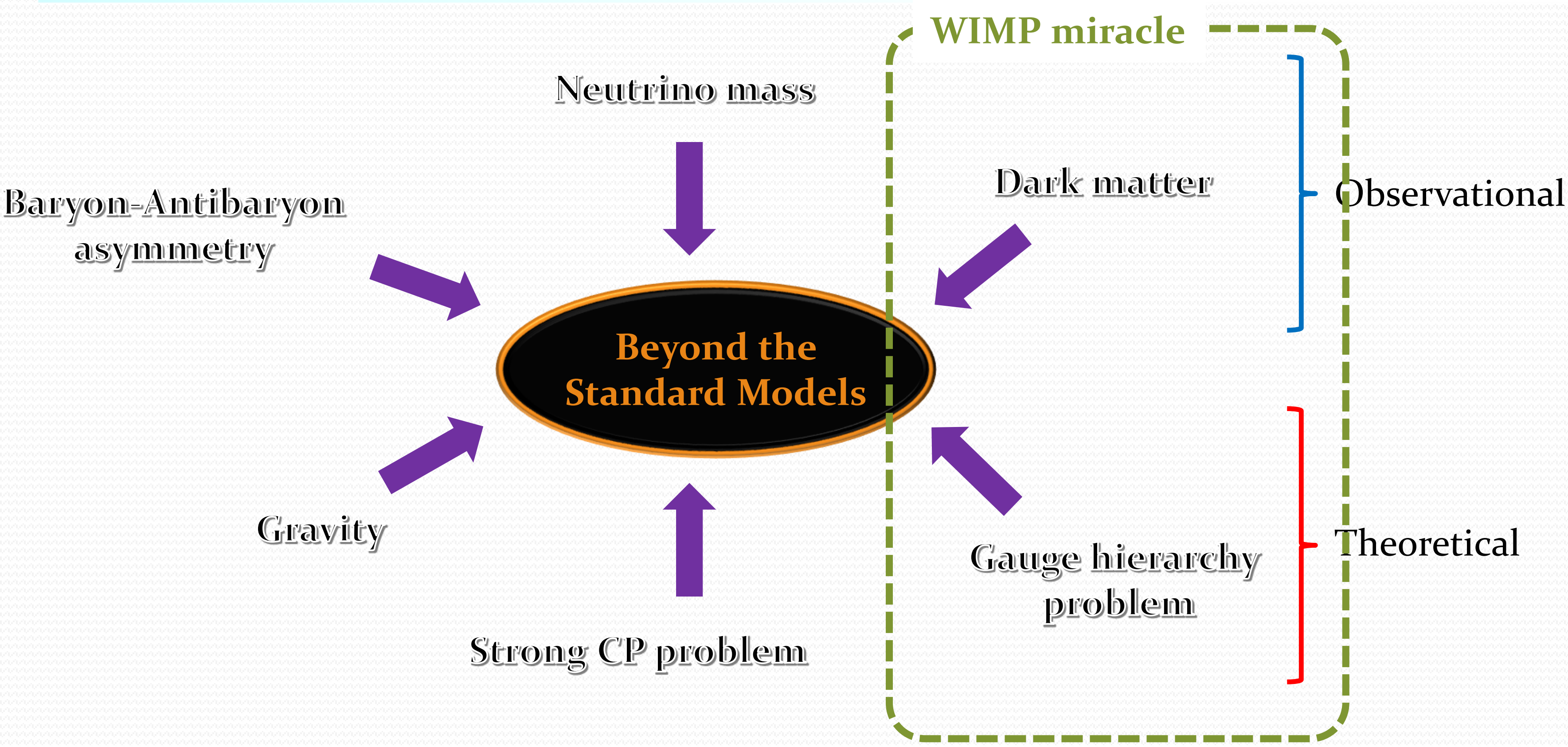
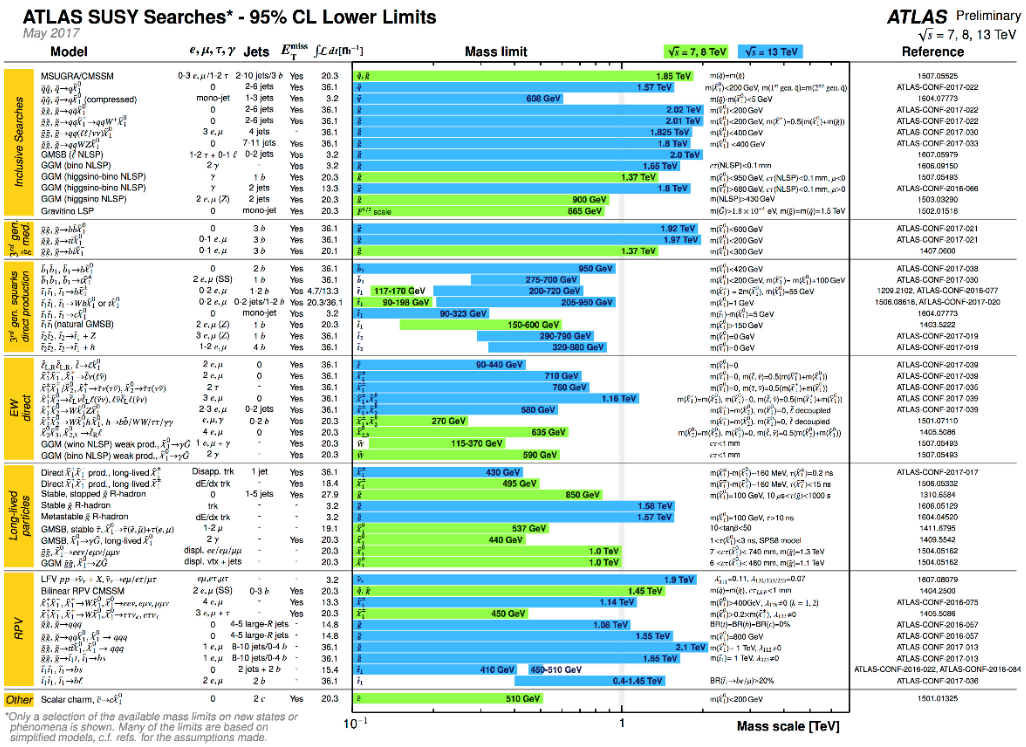


Many experiments/searches targeting at Weak/TeV scale

Experimental Efforts



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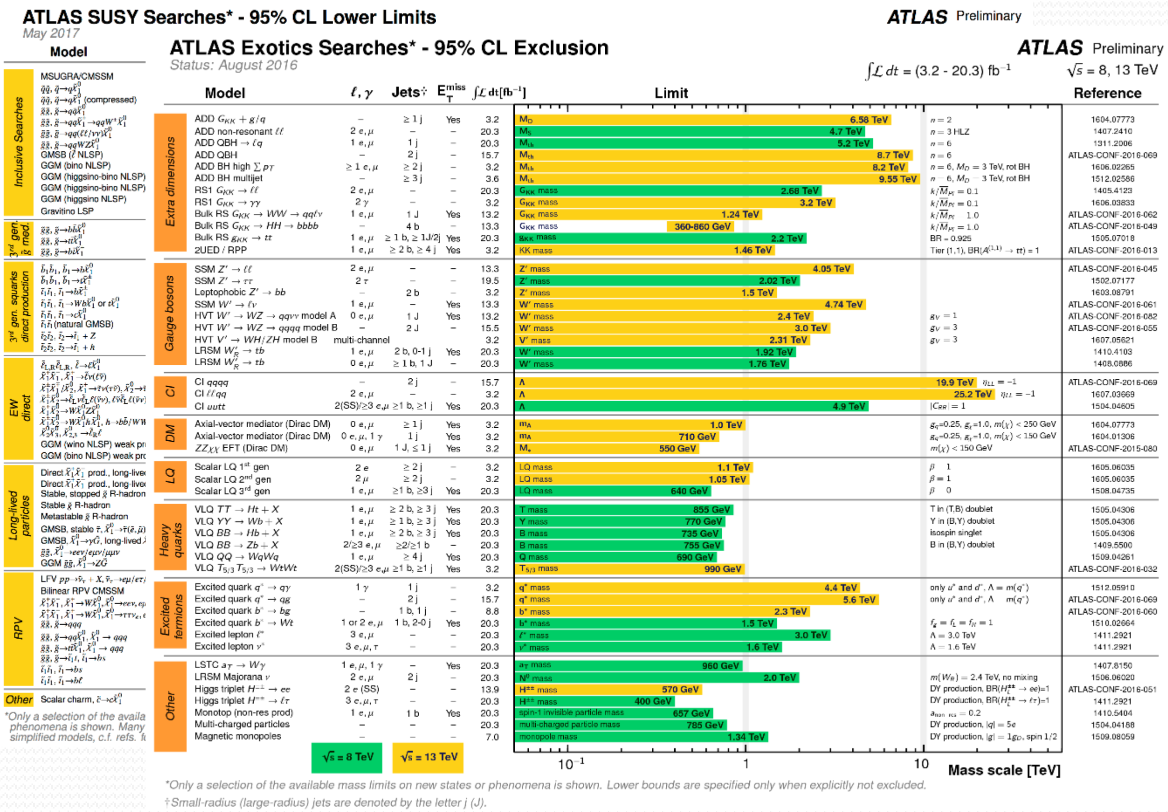

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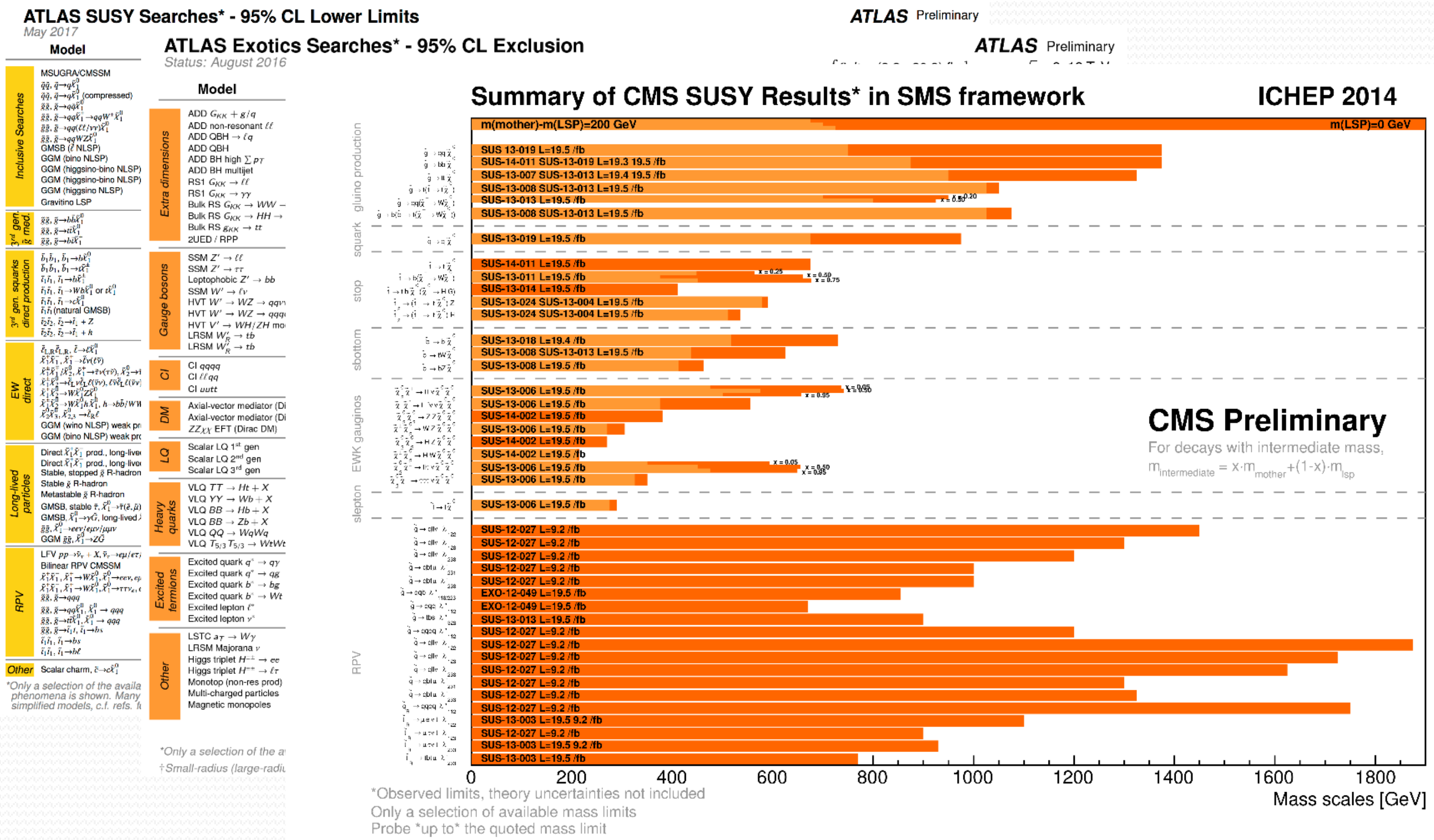

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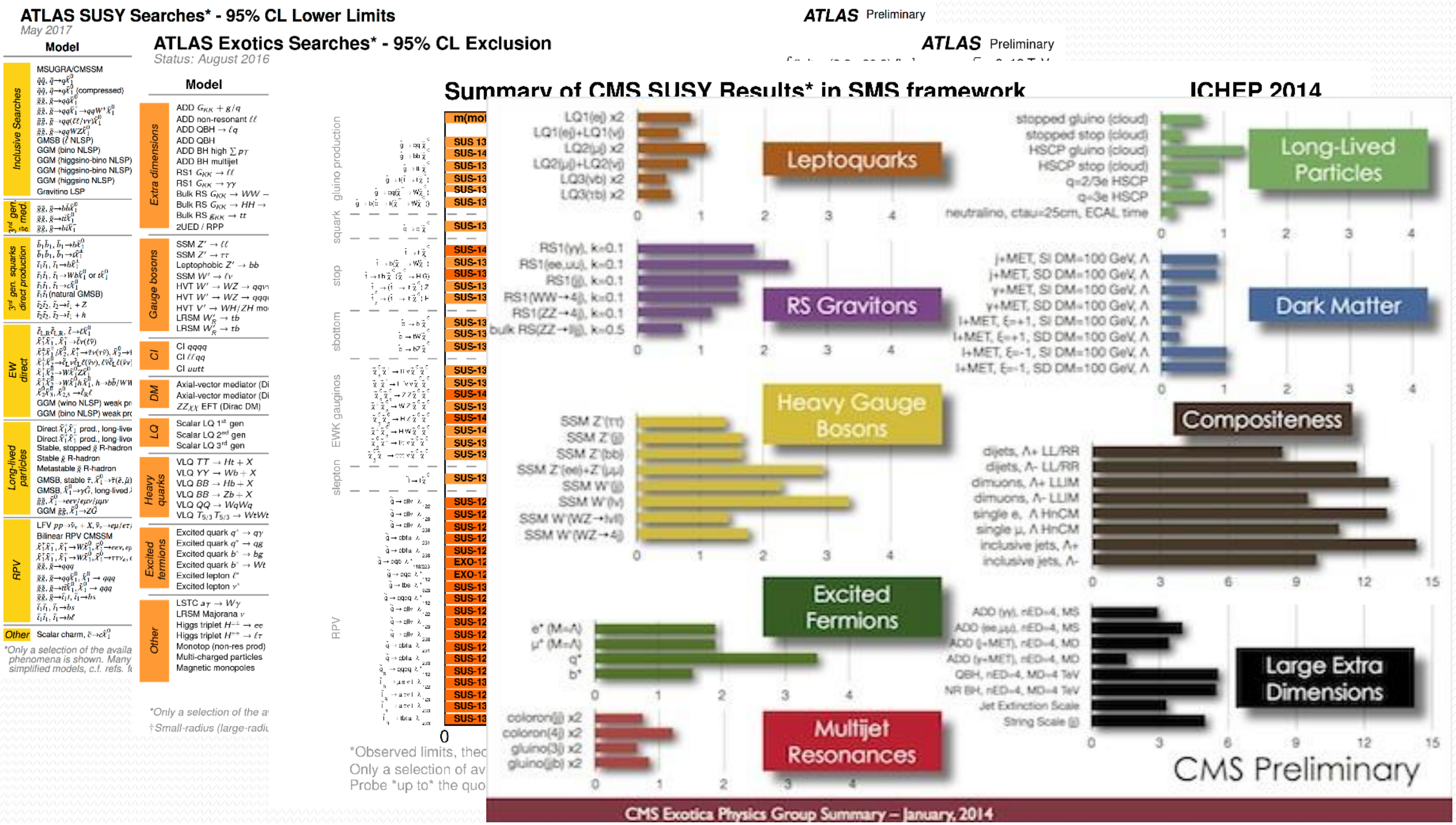

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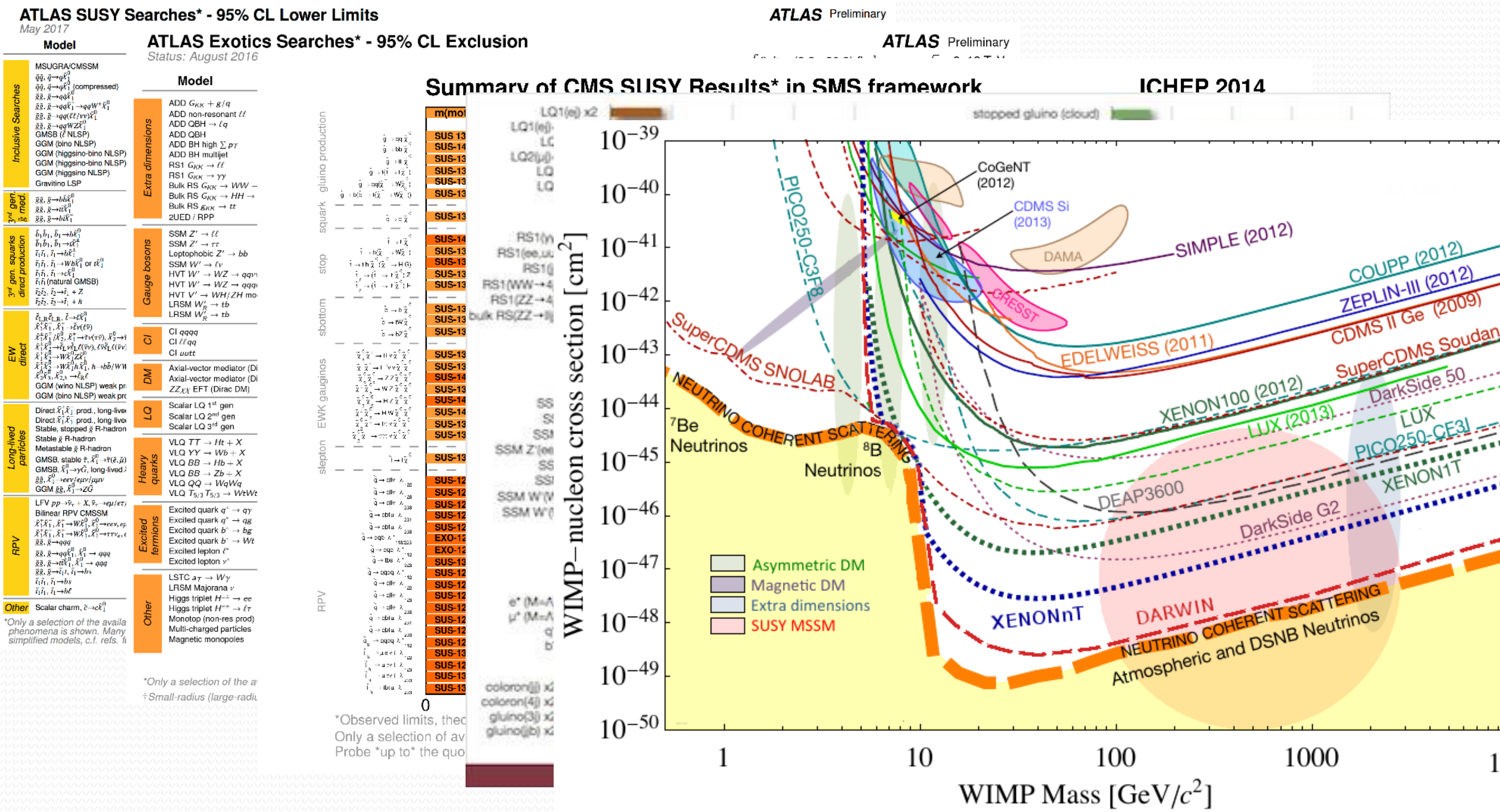


HEY!
WHAT'S GOING ON HERE!
quickmeme.com

Effort Further

- "Attacking" **every single corner** of parameter space in new physics models and/or probing **unexplored territories**
  - Filling missing gaps (e.g., compressed mass spectra)
  - Displaced vertex searches (e.g., MATSULA), disappearing tracks
  - Exotic final states (e.g., tri-boson searches, "dark" showering)
  - SM precision studies (e.g., top quark sector, higgs sector)
  - Improving signal sensitivity in DM direct detection experiments
  - Light mediators (e.g., dark photon) and their "relatives" searches
  - Ultra-light dark matter searches (e.g., CCD, semi-conductors)
  - New satellites with better energy resolution
  - Many more part of which will be covered at this workshop!

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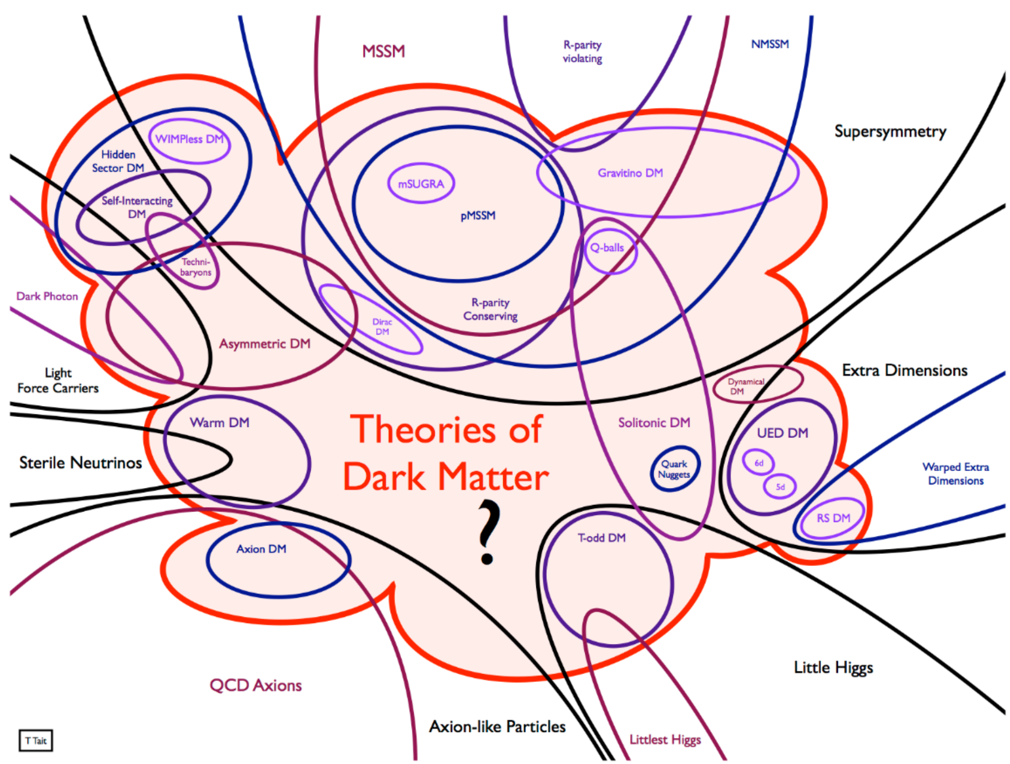
  - **Dark sector particle (including DM) searches at dark matter "colliders"**

Dark Matter Models

Various DM models



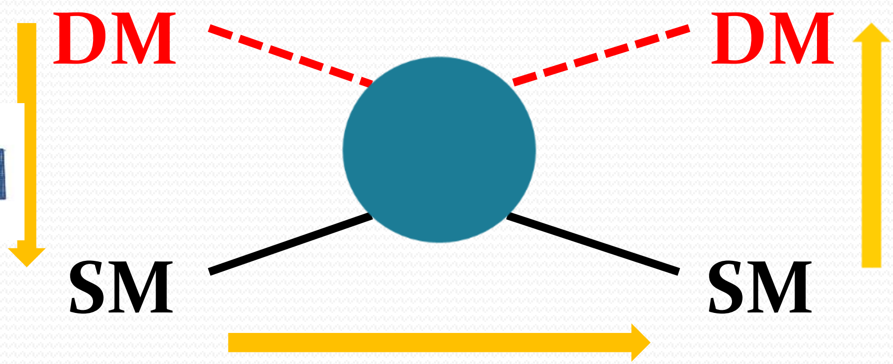
from the talk by Tim Tait

- ❑ Many dark matter simplified models or new physics models including a dark matter candidate proposed
  - ❖ Supersymmetric
  - ❖ Extra-dimensional
  - ❖ Low-energy effective
  - ❖ Many others …
- ❑ Many of them constructed under the **minimality assumption** (as we know very little about DM)

"Minimal" Dark Sector

❑ "Minimal" phenomenological implications in the context of dark matter detection under minimal dark matter scenarios

DM indirect search

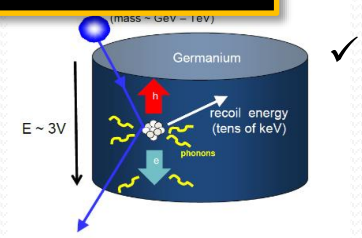


DM production

✓ (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

✓ $E_{\mathrm{recoil}} \sim 1 - 100\ \mathrm{keV}$

✓ Active DM production at colliders

✓ Mono-X searches

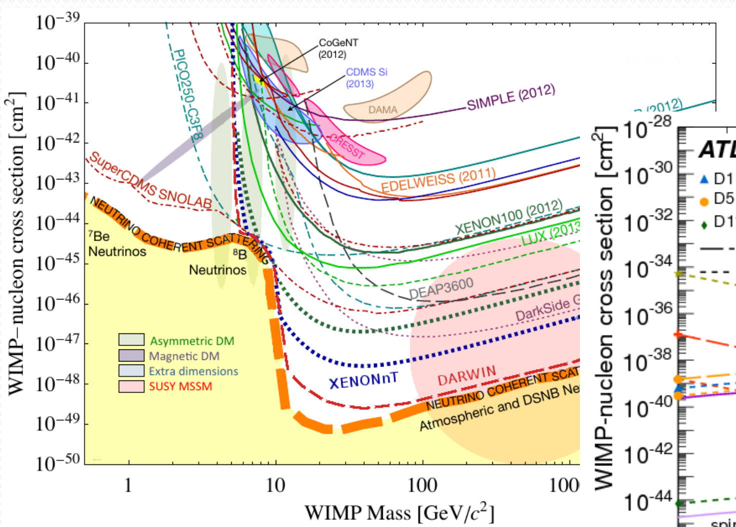
✓ Expected rate inferred from/related to $\langle\sigma v\rangle \sim 10^{-26}\ \mathrm{cm}^3/\mathrm{s}$

Dark Matter Searches

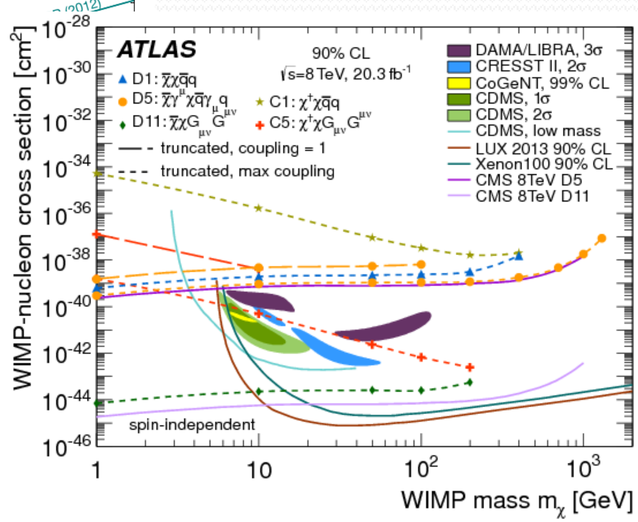
Current status

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

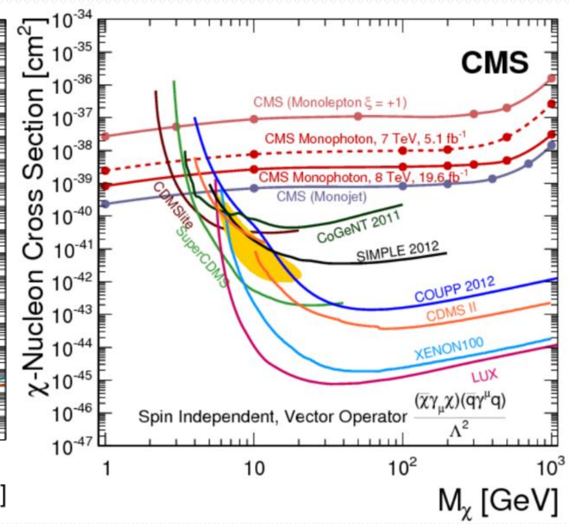
  (many searches/interpretations designed under minimal dark-sector scenarios)



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



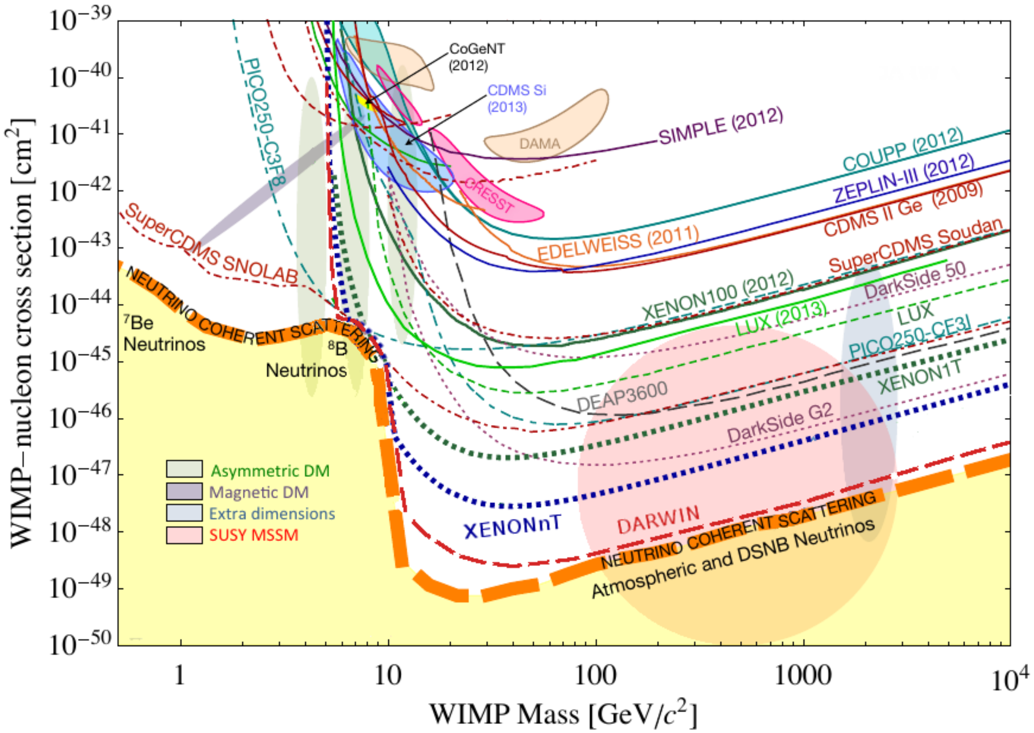
[ATLAS mono-jet search (2015)]



[CMS mono-photon search (2014)]

Dark Matter Direct Detection

Current status



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

- ❑ Weakly Interacting Massive Particles (WIMPs): a well-motivated DM candidate (motivated by DM relic measurement and weak-scale new physics models)
- ❑ Different exp. → Different tech. → Different sensitivity
- ❑ **A wide range of parameter space probed** already and facing eventually irreducible neutrino backgrounds

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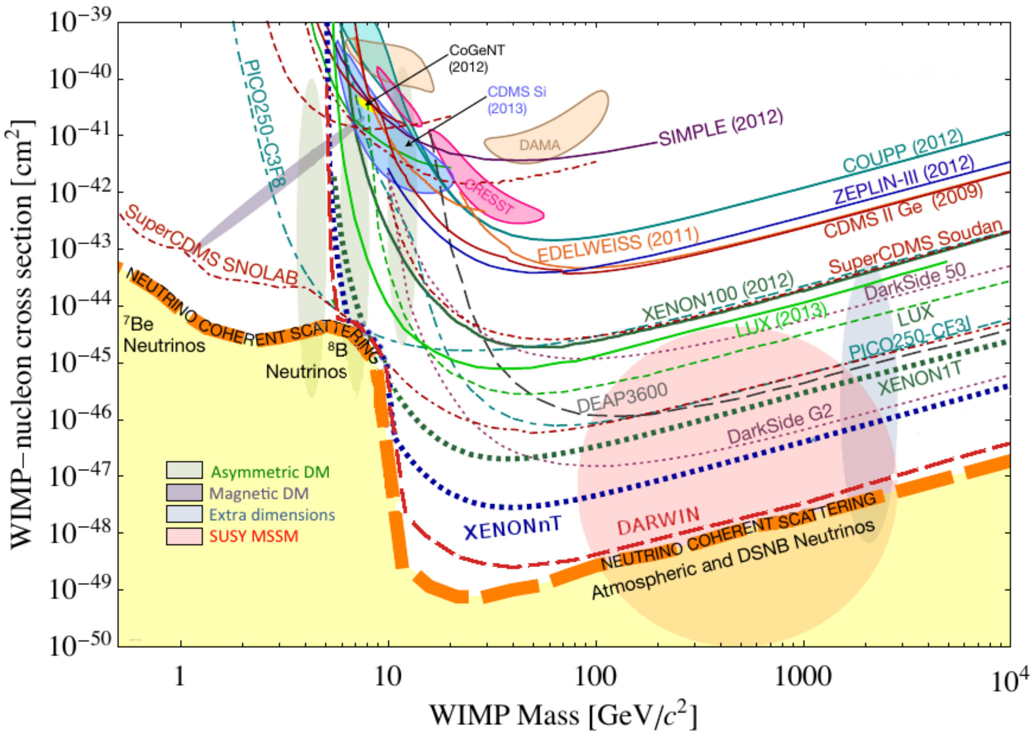

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New search schemes needed!

“Minimal” vs. “Non-minimal”

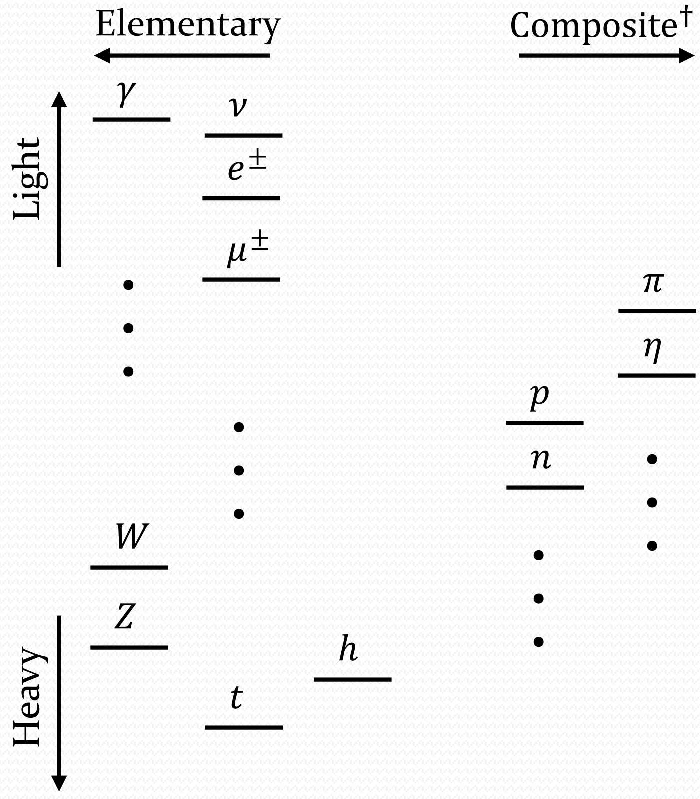
- **“Vanilla” vs. “Flavorful”**

“Minimal” vs. “Non-minimal”

- “Vanilla” vs. “Flavorful”

“Flavorful” Dark Sector

Why flavorful? Flavorful SM!



- ❑ Various particles in the SM sector

†: here meaning the particles made of elementary ones

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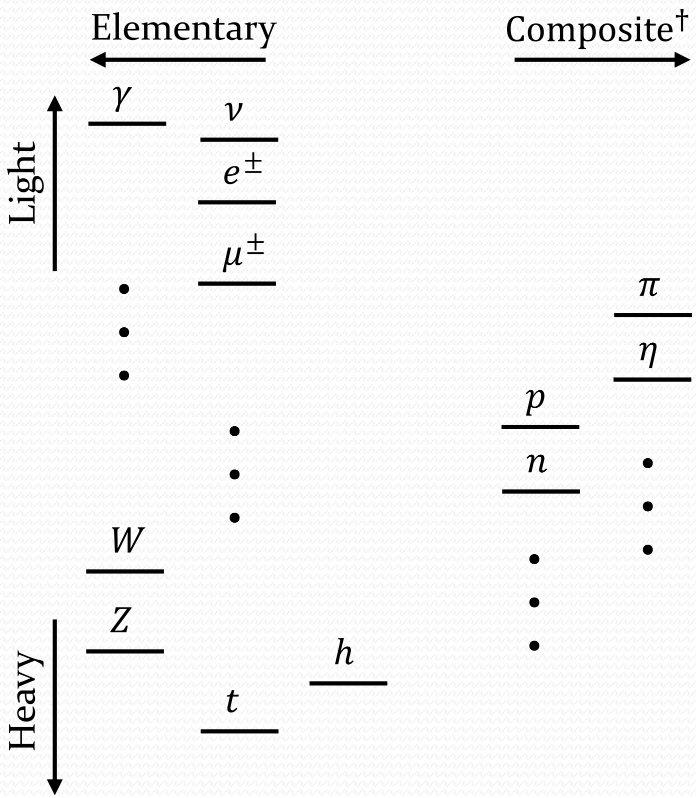

- ❑ Various particles in the SM sector
  - ✓ **Multiple stable particles** → **interesting physics** from other stable members which are **not difficult to detect** albeit not dominant (proton is dominant in the visible sector)

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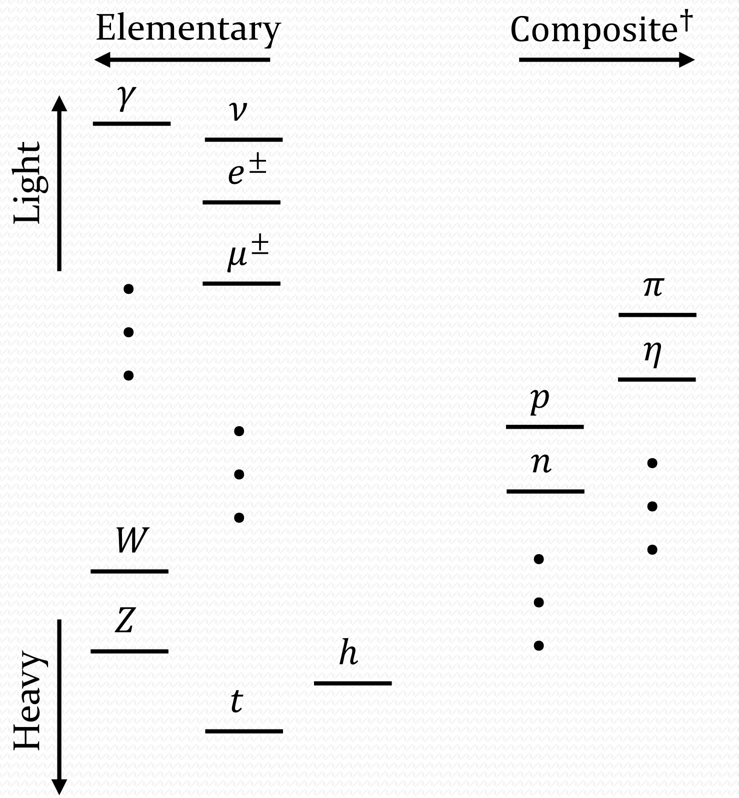

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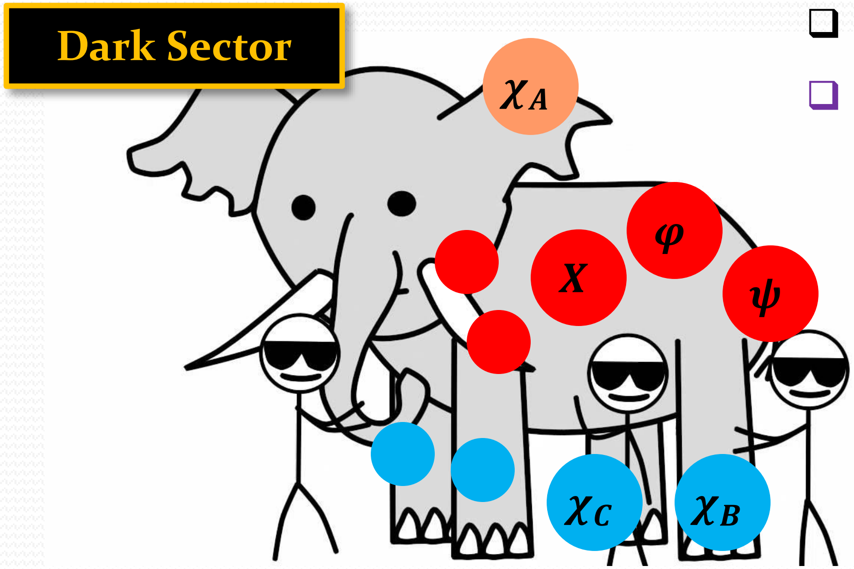
- ❑ Various particles in the SM sector
  - ✓ **Multiple stable particles** → **interesting physics** from other stable members which are **not difficult to detect** albeit not dominant (proton is dominant in the visible sector)
  - ✓ **Many heavier (unstable) states** → **interesting signatures/phenomenology**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

“Flavorful” Dark-sector Scenarios

In what sense?



- χ_A: **dominant relic** (as in the minimal setup)
- **More members** in the dark sector
  - ✓ **Unstable members**, say ψ, φ, X, ... (e.g., cosmic ray excess interpretations [**DK** and J.-C. Park (2015)])
  - ✓ **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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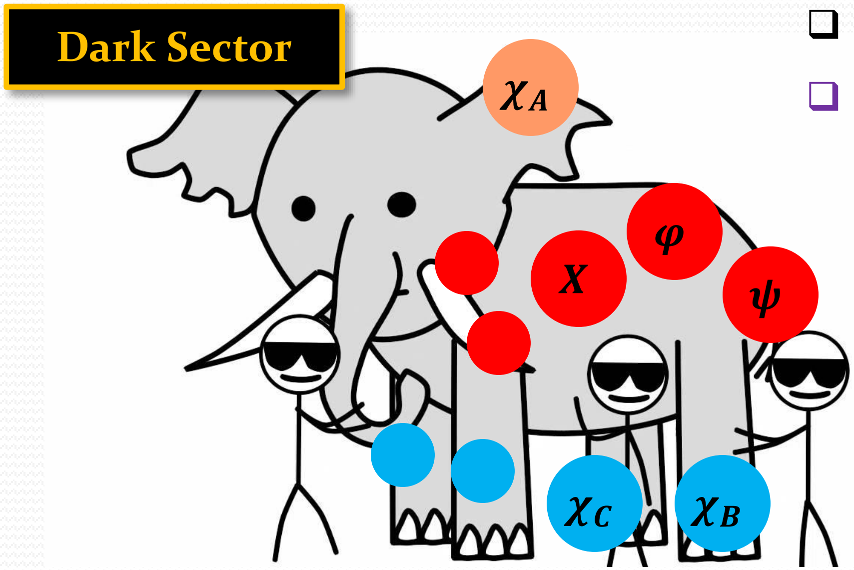

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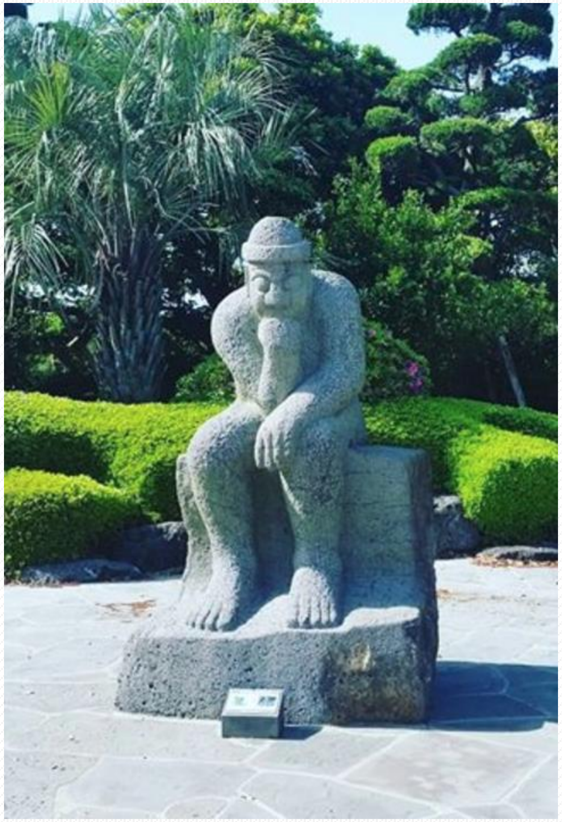
❑ **Rising interest**

- ❖ 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)]

See Jong-Chul's talk

"Non-conventional" Implications?

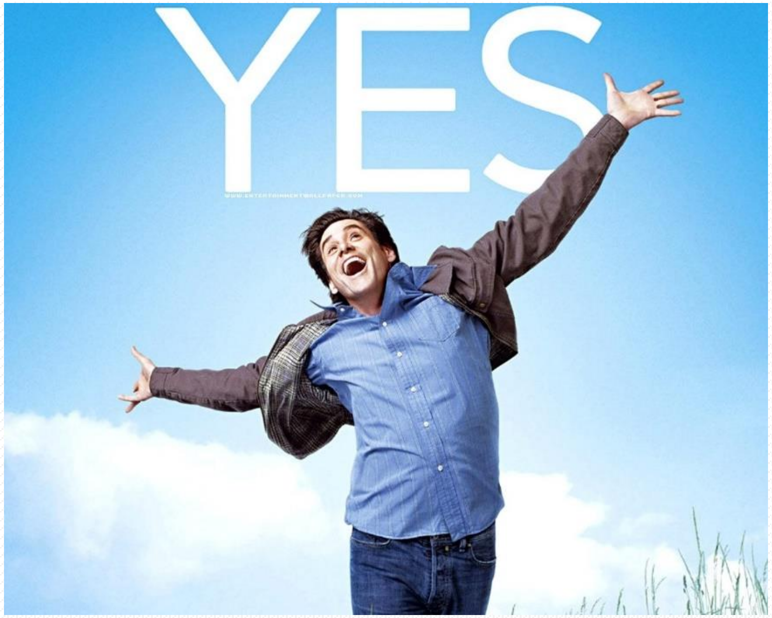
Big question



- ❑ 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



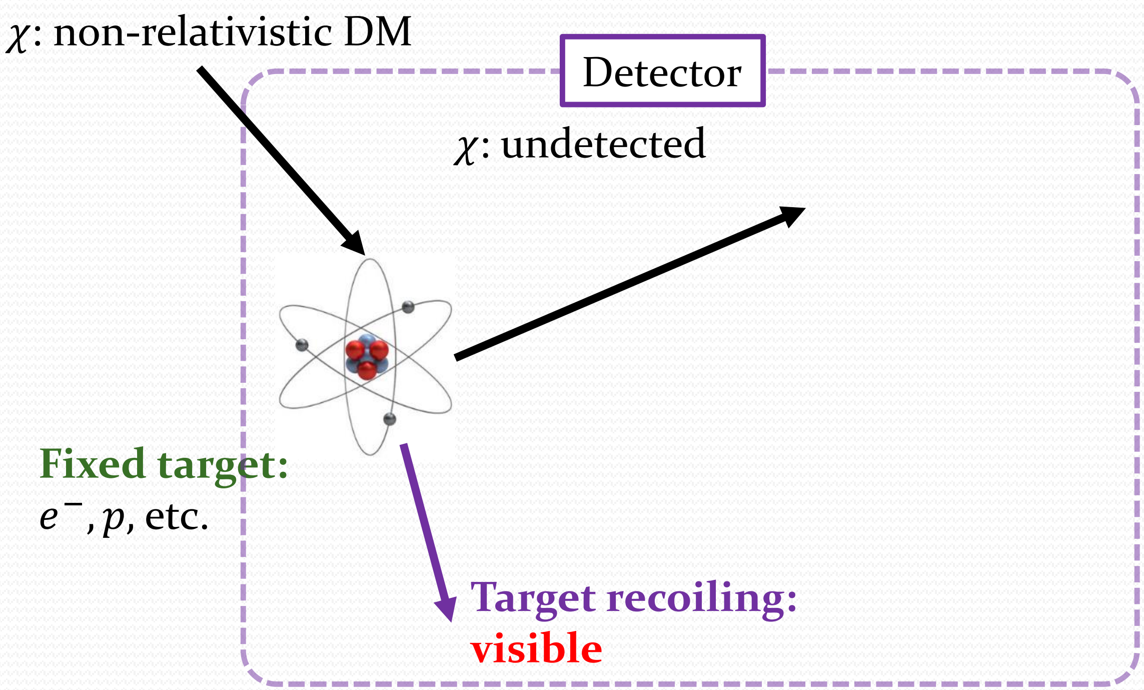
- Existence of more members in the dark sector
  → are there any **non-trivial/non-conventional implications not available in the minimal setup**?

  ✓ **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

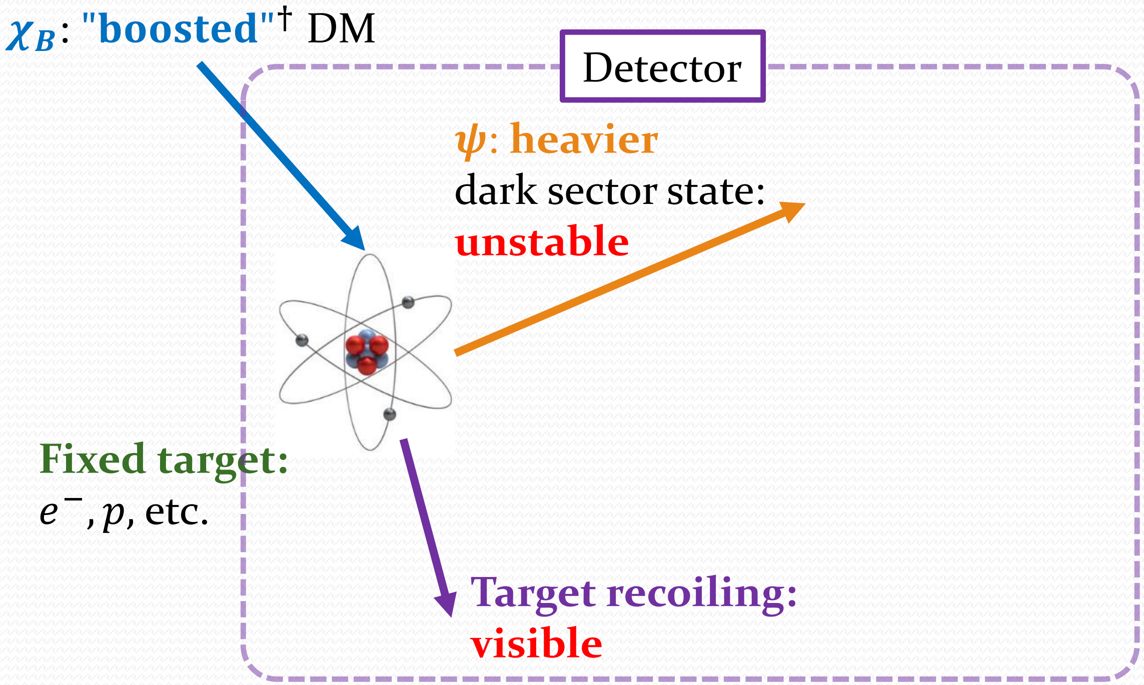


✓ Existence of DM inferred from a target recoiling ($1-100$ keV)

Dark Matter "Colliders"

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

- We are imagining the situation in which



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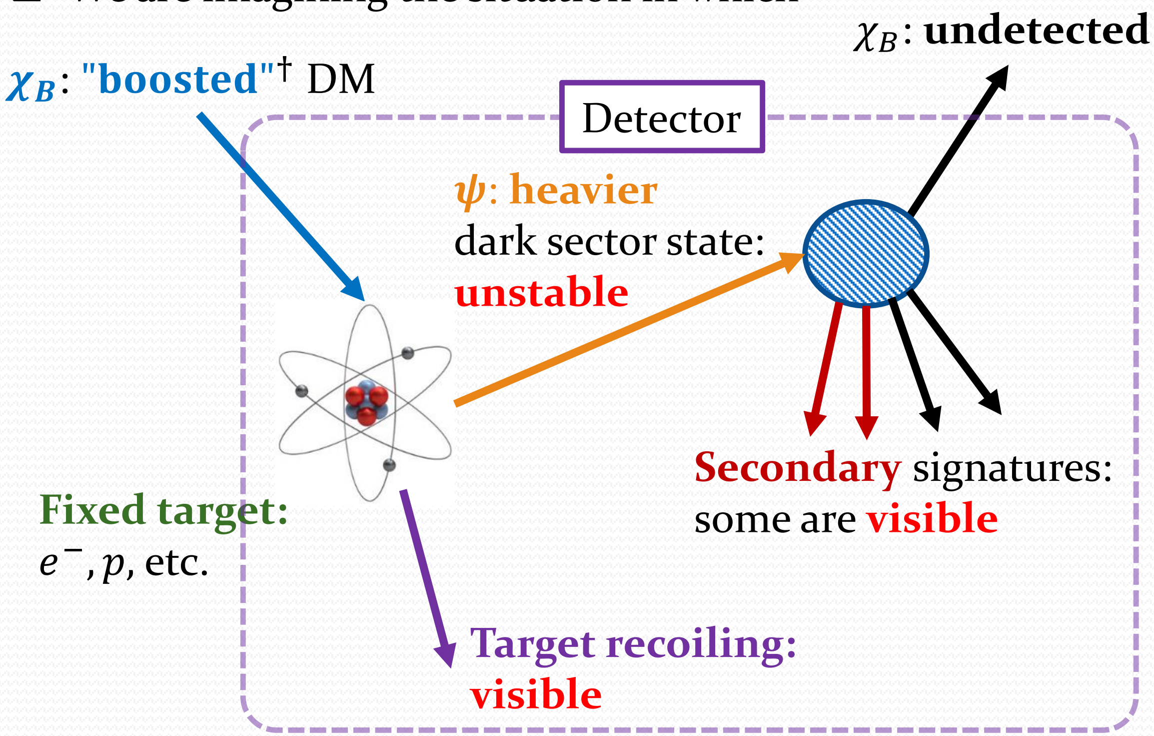

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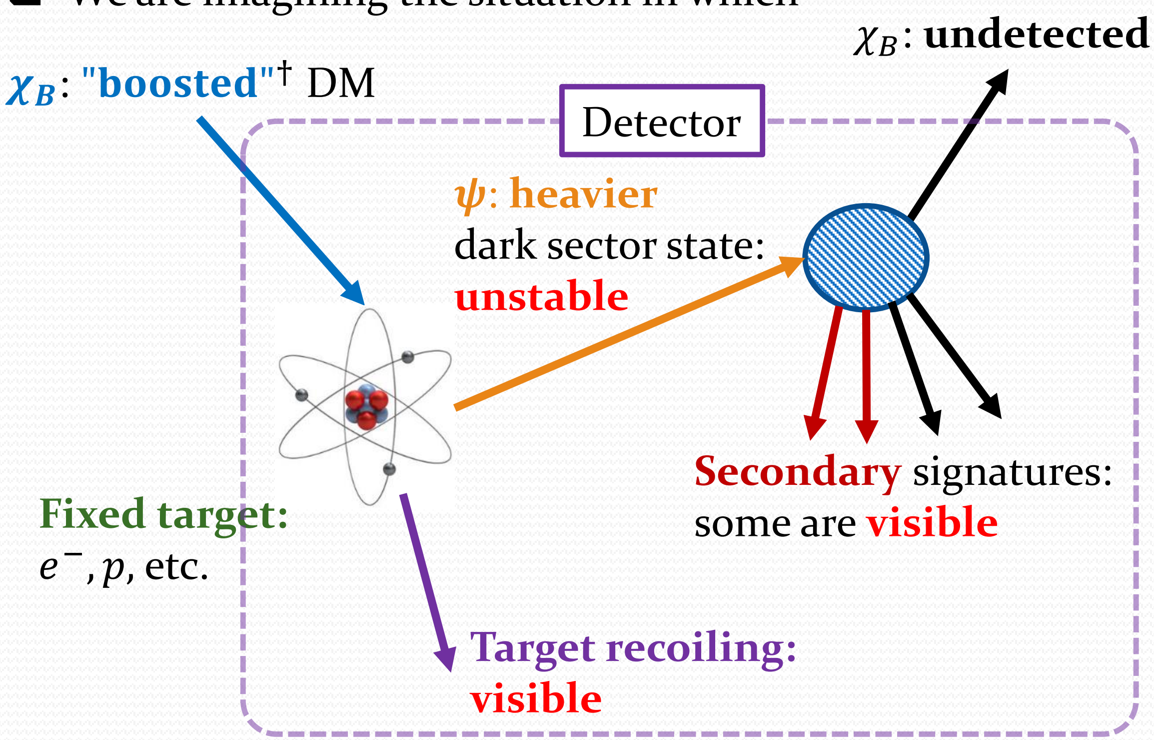

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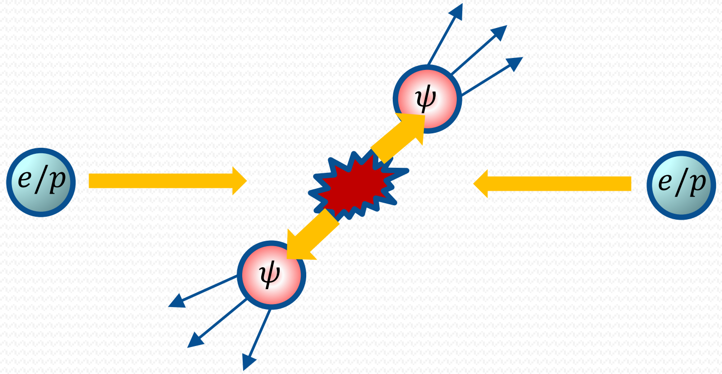
- ✓ Probing **heavier dark/ hidden-sector states**
- ✓ Target recoil (like in typical DM direct detection exp.) + secondary visible signatures $\Rightarrow$ **more** handles, (relatively) **background-free** (no secondary signatures in usual backgrounds)
- ✓ **Complementary** to standard DM direct searches

Dark Matter "Colliders"

Collider as a heavy-state probe

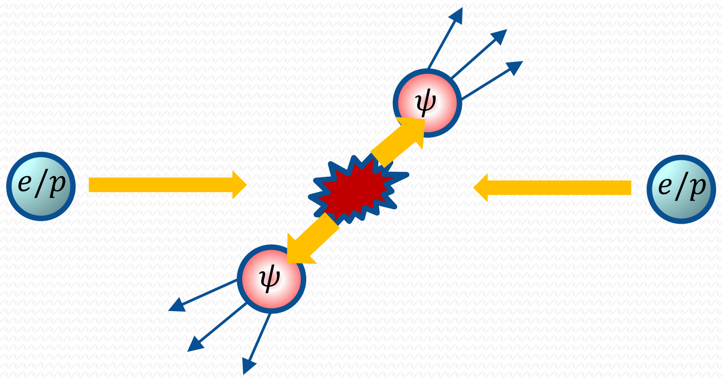


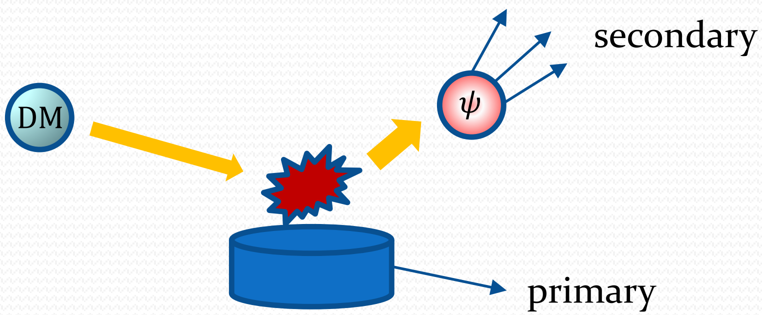
Conventional colliders

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

Dark Matter "Colliders"

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

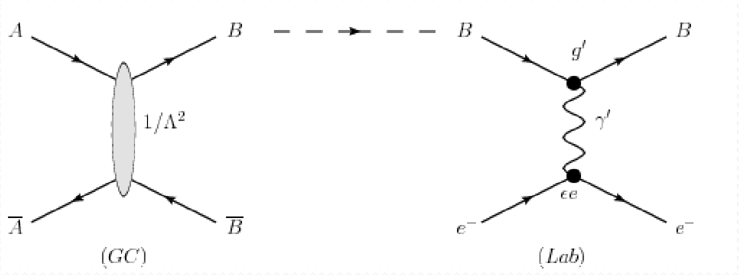
Dark matter colliders

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

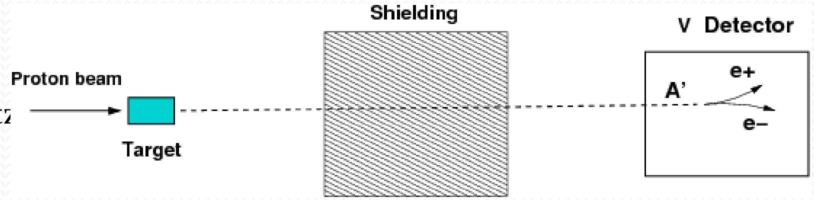
Boosted Dark Matter

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)]

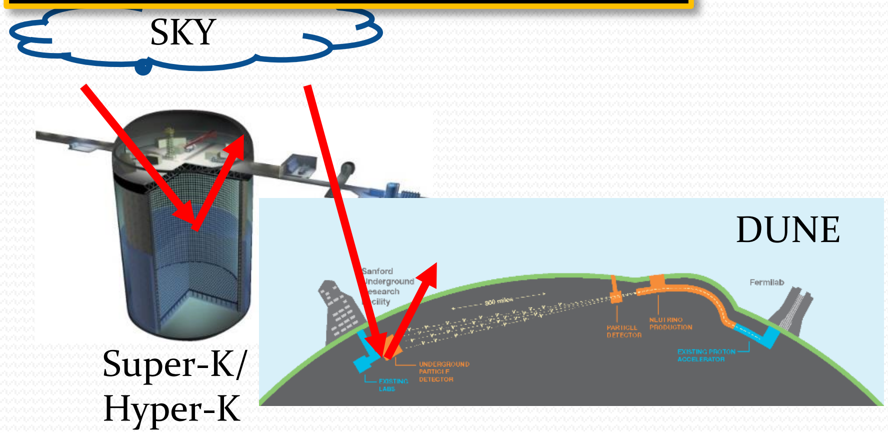


Signal Detection

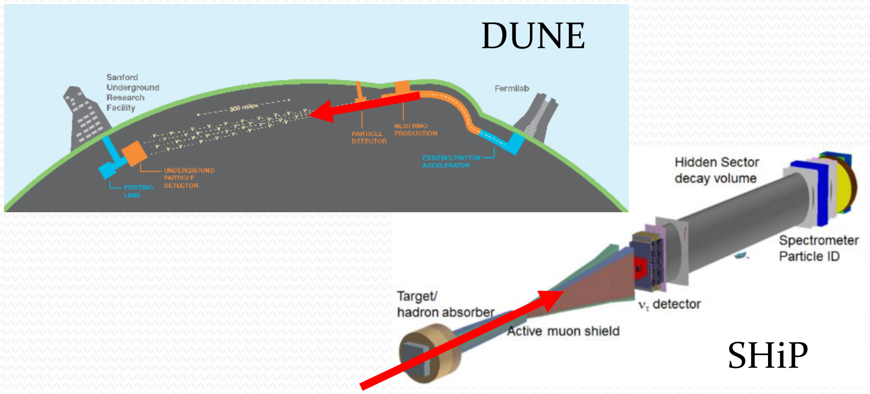
Detection strategy

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

Large-volume (neutrino) detectors



Intensity-frontier experiments



"Passive" searches

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

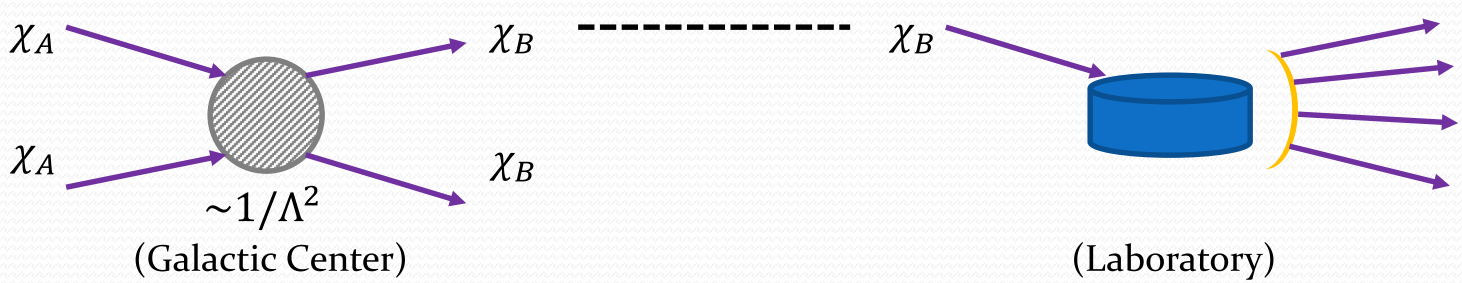
DM “Colliders” at the Cosmic Frontier

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.



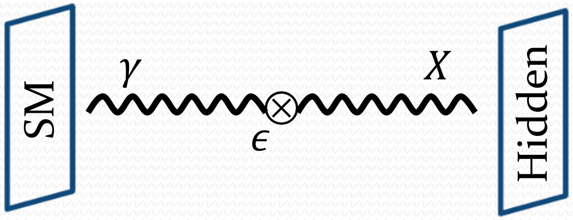
- ❖ χ_A: heavier DM, dominant relic, non-relativistic, **not directly** communicating with SM
- ❖ χ_B: lighter DM, subdominant relic, **relativistic** at the current universe (non-relativistic at the early universe), **directly** communicating with SM
- ❖ Typical flux of χ_B: $\sim 10^{-7}\text{cm}^{-2}\text{s}^{-1}$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

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

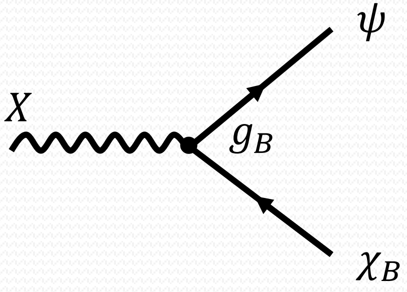
Dark Sector Model

Vector portal

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

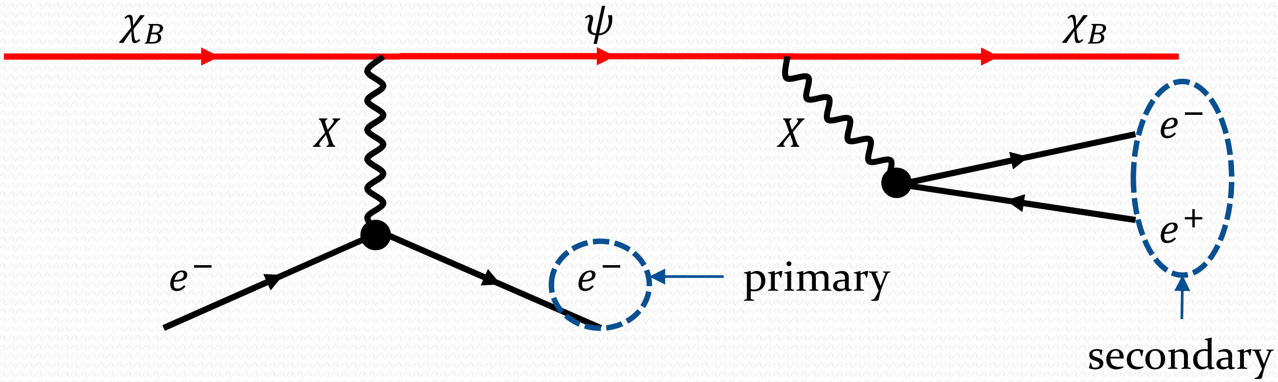


- **Vector portal** (e.g., dark "photon" scenario) [Holdom (1986)]
- Fermionic DM
  - **Flavor-changing neutral current** [e.g., J.-E. Kim, M. S. Seo, and S. Shin (2012)]
  - (Relevant models may have flavor-conserving currents as well, $\bar{\psi}\gamma^{\mu}\psi X_{\mu}$, $\bar{\chi}_B \gamma^{\mu}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



Discovery Potential

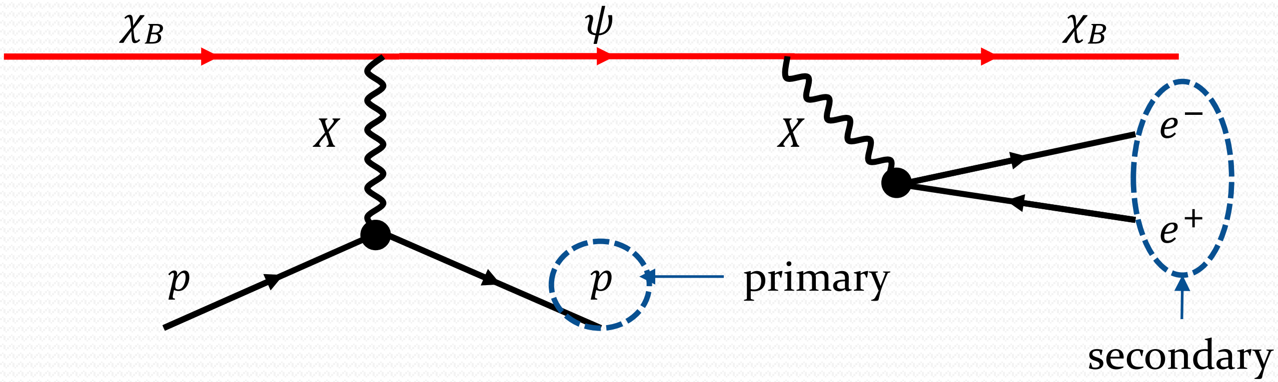
Typical signal features: *e*-scattering



- **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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- "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 achiev**able!

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)]

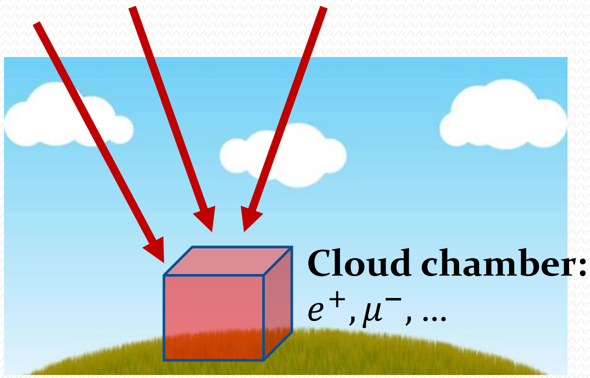
	m_{χ_B}	m_ψ	m_X	γ_{χ_B}
e-ref1	0.4	0.5	0.06	250
e-ref2	0.1	0.14	0.03	200
p-ref1	0.4	0.9	0.2	15
p-ref2	0.1	1.0	0.5	50

- $\epsilon^2 = (3\times10^{-4})^2$ 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**

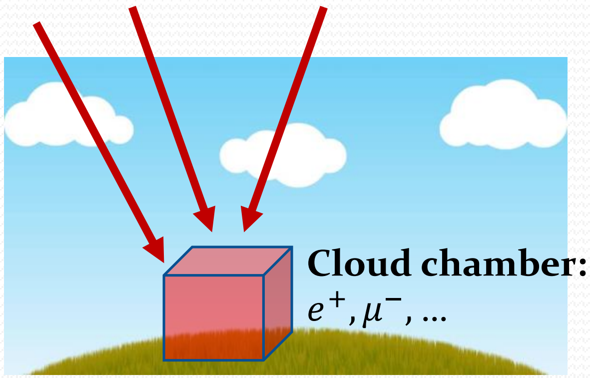
DM “Colliders” at the Intensity Frontier

New Particles at Cosmic Frontier



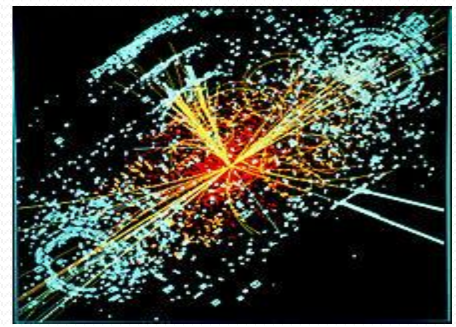
Passive searches

New Particles at Energy Frontier



Passive searches

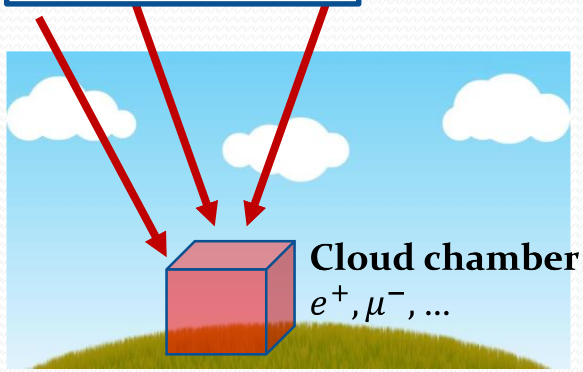
Collider: controlled environment



Active searches

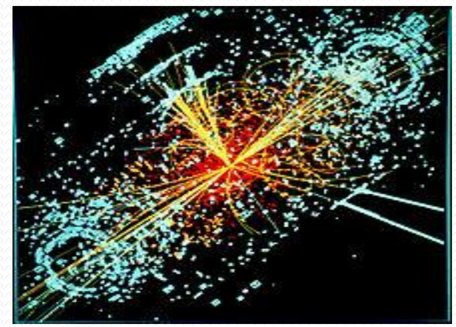
Exploring the Visible Sector

~5% visible sector



Cloud chamber:
$e^+, \mu^-, \ldots$

Collider: controlled environment

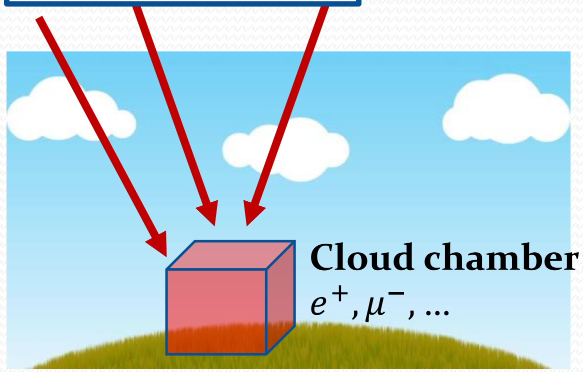


Passive searches

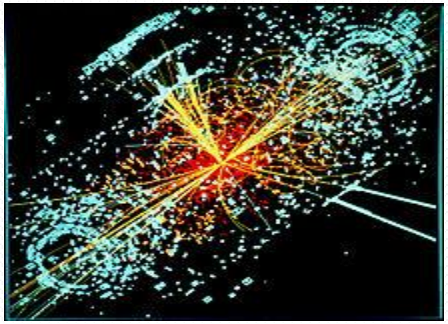
Active searches

DM Searches at Cosmic Frontier

~5% visible sector

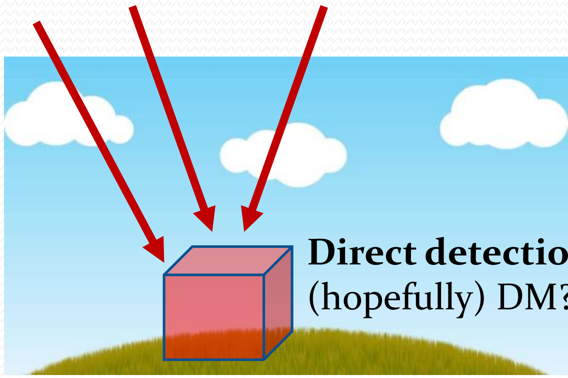


Collider: controlled environment



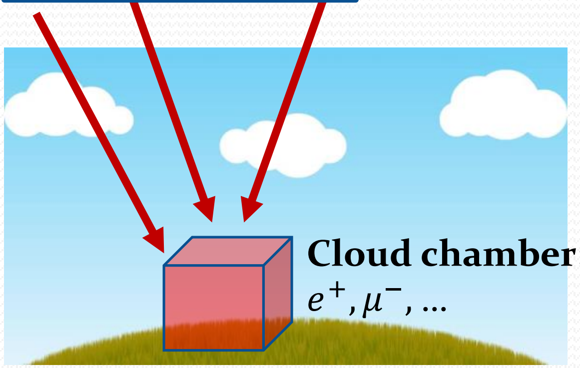
Passive searches

Active searches



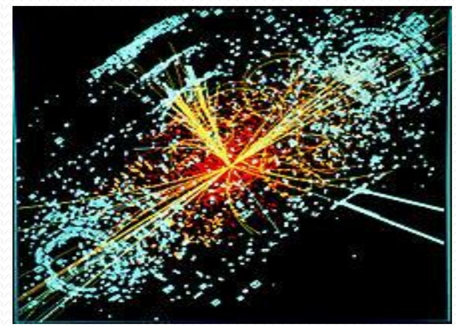
DM Colliders at Intensity Frontier

~5% visible sector



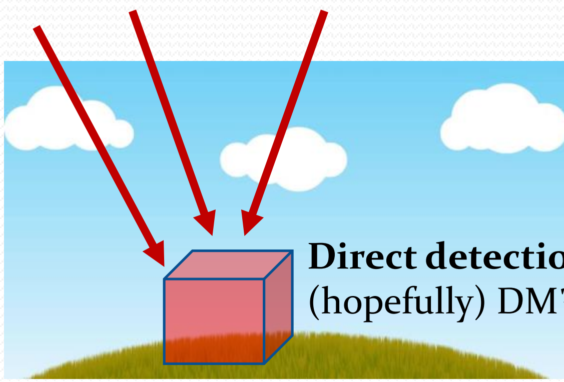
Cloud chamber:
$e^{+}, \mu^{-}, \ldots$

Collider: controlled environment



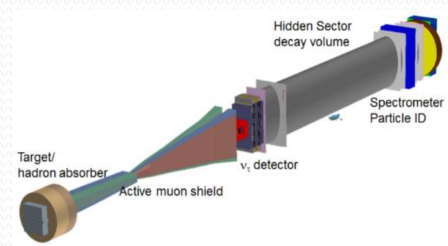
Passive searches

Active searches



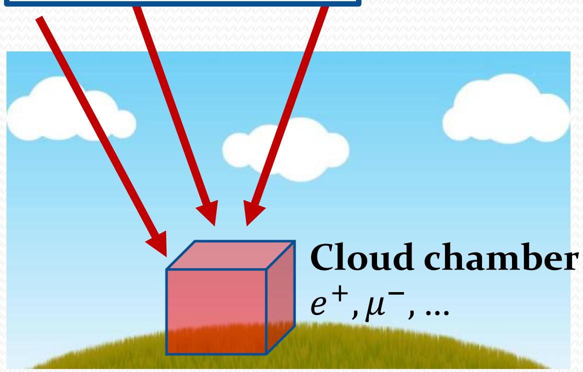
Direct detection:
(hopefully) DM?

DM "Collider" (e.g. fixed target exp.)
: controlled environment



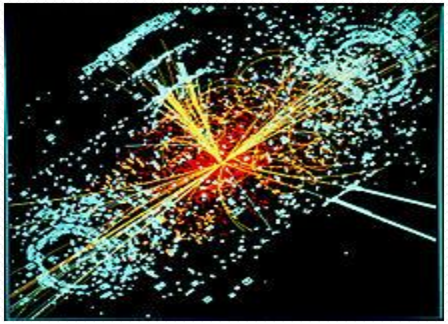
Exploring the Dark Sector

~5% visible sector



Cloud chamber:
$e^+, \mu^-, \dots$

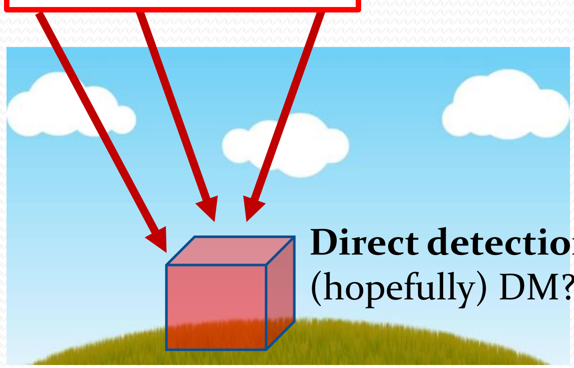
Collider: controlled environment



Passive searches

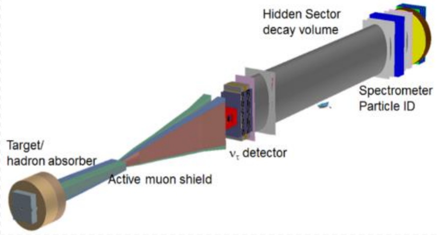
Active searches

~25% dark sector



Direct detection:
(hopefully) DM?

DM "Collider" (e.g. fixed target exp.)
: controlled environment



Candidate Experiments

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

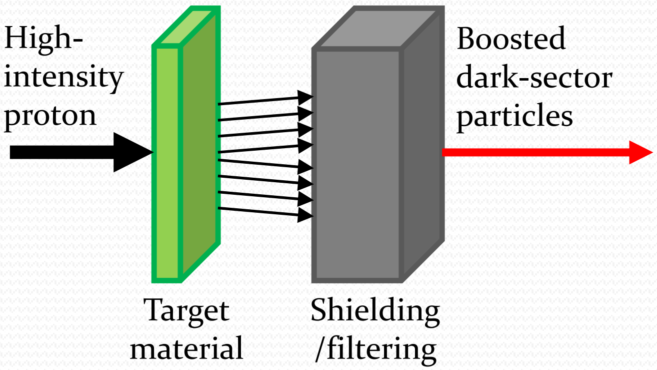
†: Numbers in parentheses are our estimation.
‡: Numbers in parentheses are relevant to T2HKK.
∗: Red-font numbers are fiducial volume.
⋆: Threshold energy for the "good" angular resolution above

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

Boosted DM Source: Intensity Frontier

Physics opportunities at fixed target exps.

- **Production by target collision** (e.g., in vector portal scenarios)
  - Meson decay: $pp \to \pi/\eta +$ 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, $\pi/\eta \rightarrow X^*\gamma \rightarrow \chi_B\chi_B\gamma; \pi/\eta \rightarrow X^*\gamma \rightarrow \chi_B\psi\gamma; \pi/\eta \rightarrow X^*\gamma \rightarrow \psi\psi\gamma$
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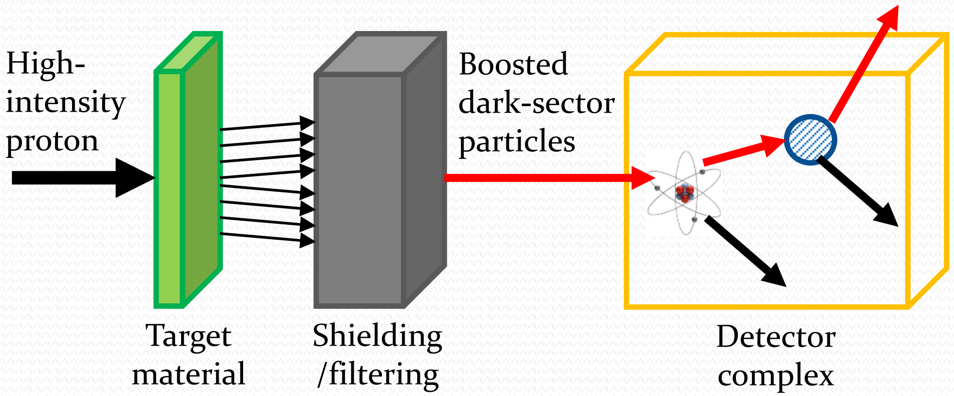
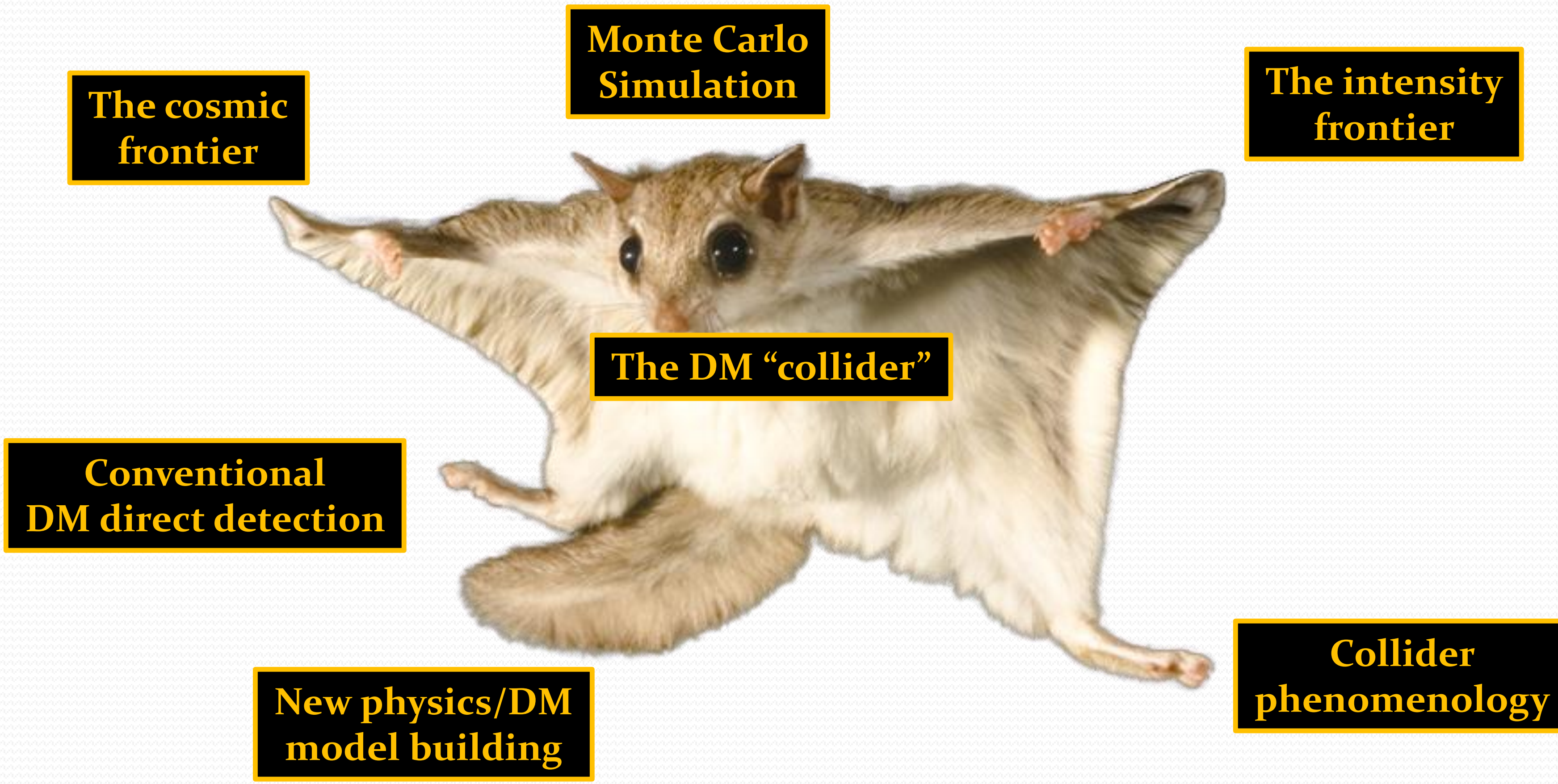


- **Detection by detector complex** (e.g., DM "colliders") [G. Giudice, **DK**, J.-C. Park, S. Shin, …, in progress]
  - Detector-specific strategies required
  - Far/near detector system at e.g., DUNE, T2HKK: **ratio of $N_{\mathrm{near}}^{\mathrm{signal}}$ to $N_{\mathrm{far}}^{\mathrm{signal}}$**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

Dark Matter "Colliders" and Beyond



Research Opportunities

- ❑ Physics opportunities at the **intensity frontier**
  - ✓ The DUNE experiment (in progress)
  - ✓ The SHiP experiment (in progress)
  - ✓ The T2HKK experiment
  - ✓ Other existing/prospective fixed target experiments

- ❑ Physics opportunities at DM **direct detection experiments**
  - ✓ Signal (coming from the sky) detection by a displaced vertex (e.g. SuperCDMS)
  - ✓ New experiment proposal

- ❑ Physics opportunities at the **cosmic frontier**
  - ✓ Potential of cosmic ray excesses
  - ✓ Cosmology: relic abundance, impact on the evolution of the universe

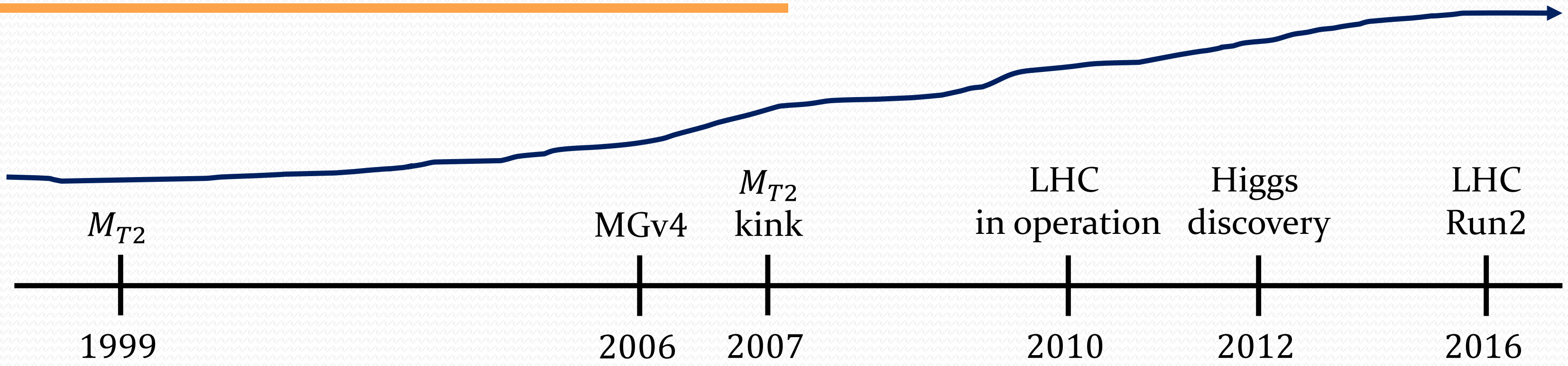
- ❑ **Monte Carlo simulation** for DM "colliders"
  - ✓ "Pre-calculated" boosted DM generator
  - ✓ Developing MC simulation packages for fixed target experiments in collaboration with MC-tool authors

- ❑ **"Collider" phenomenology**
  - ✓ Signal detection prospects at standard colliders
  - ✓ Applying collider variables to DM colliders
  - ✓ Developing optimized variables for DM colliders

- ❑ Constructing **new physics models** probable at DM colliders
  - ✓ Light KK graviton model (in progress)
  - ✓ UV-completed/effective hidden-sector models

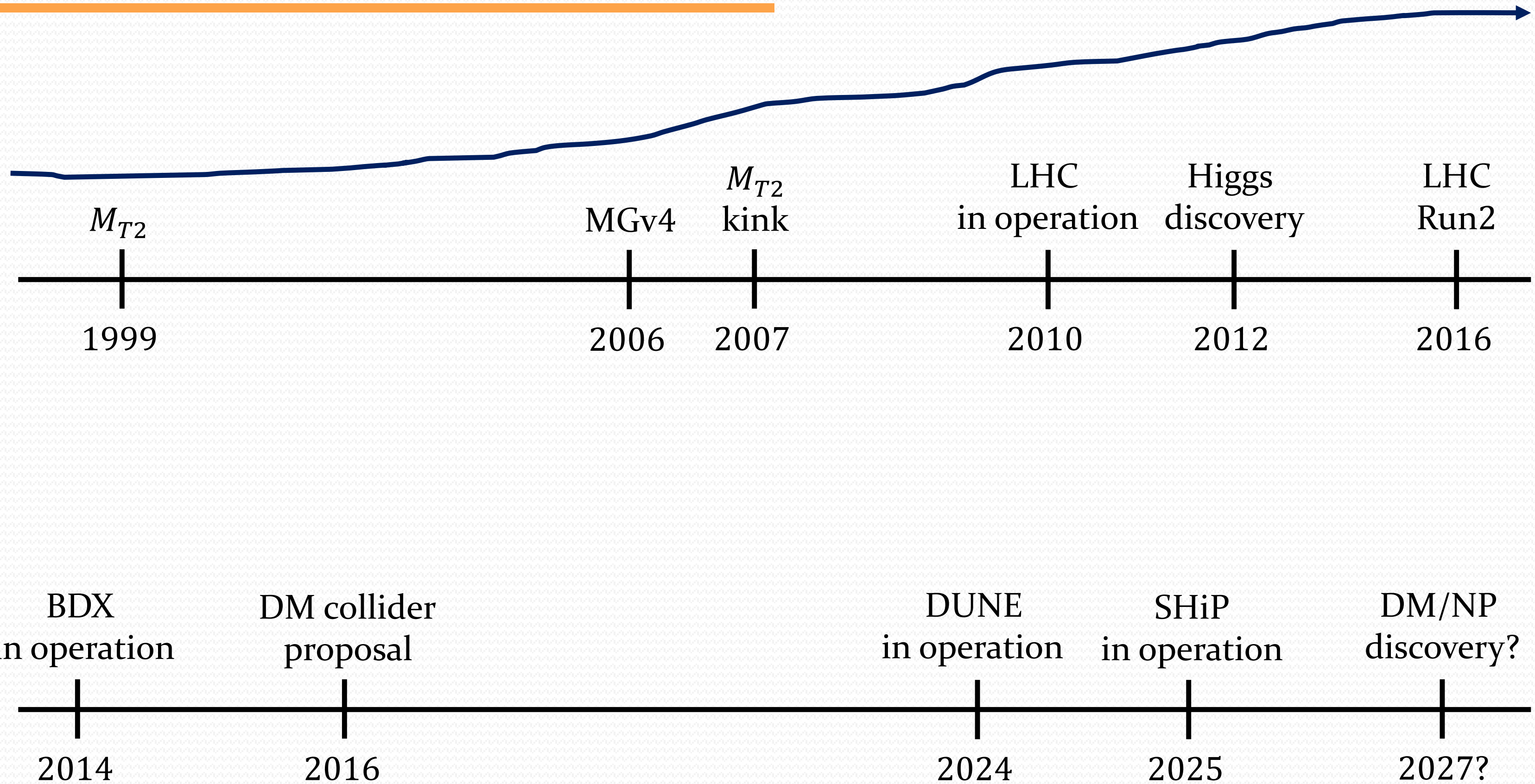
DM Collider Physics: Take-home Message

- Collider physics vs. DM collider physics



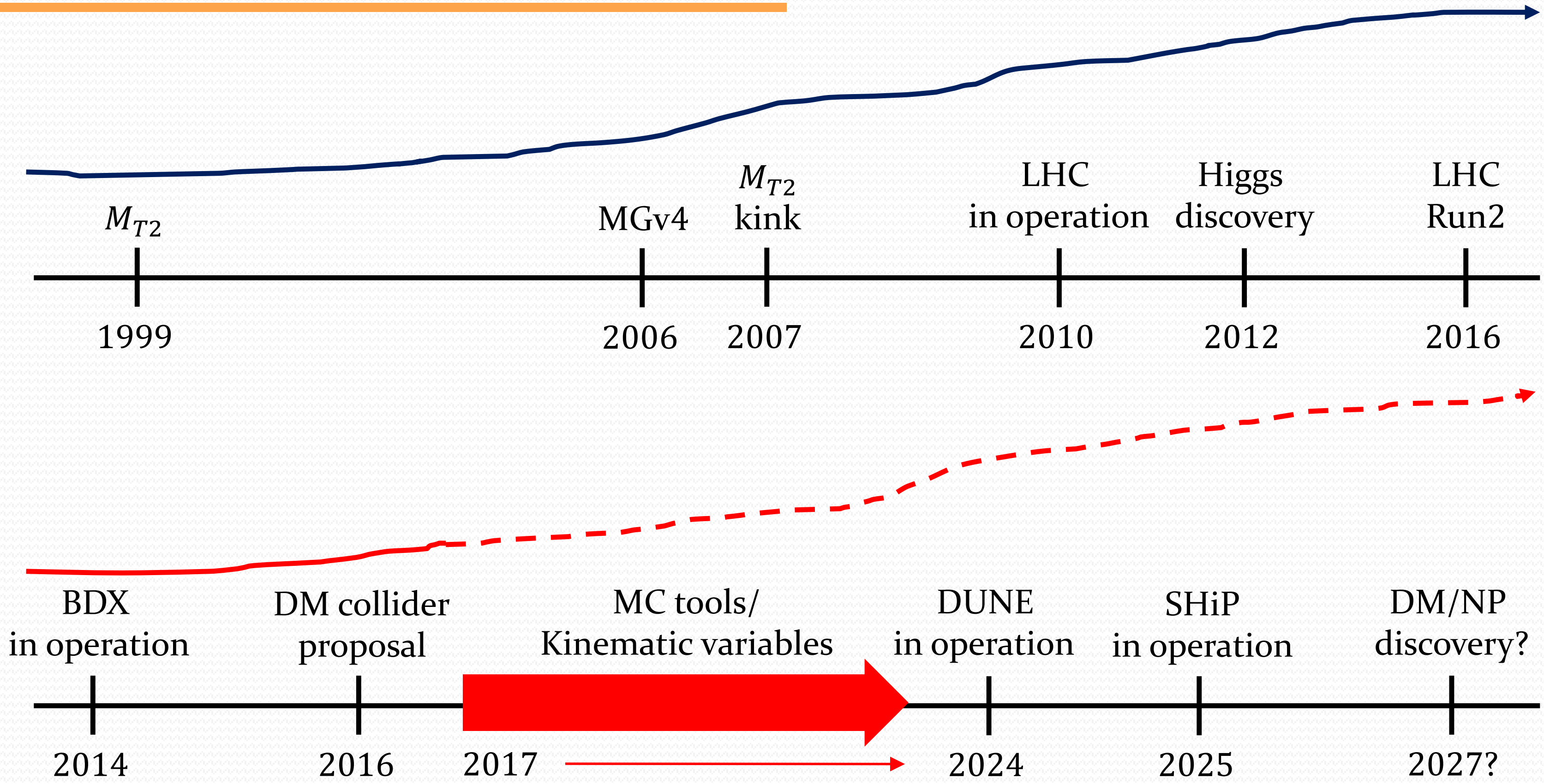
DM Collider Physics: Take-home Message

- **Collider physics vs. DM collider physics**

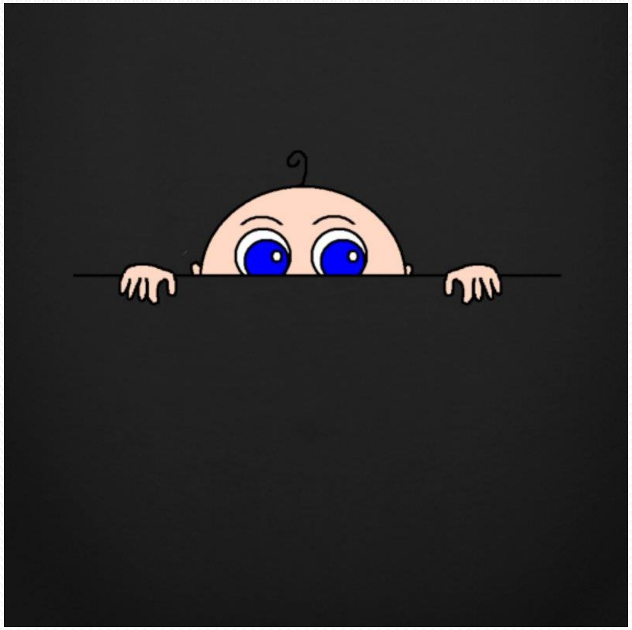


DM Collider Physics: Take-home Message

- Collider physics vs. DM collider physics



Conclusions



- What's going on at the weak scale? ⇒ our Nature might be "shy" so hide herself
- The more, the messier? The more, the merrier!
  - Don't be shy to explore "flavorful" hidden/dark sector scenarios ⇒ **Peeping into the hidden/dark sector** through them
  - 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**!

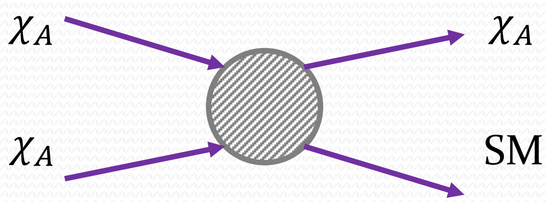

thank you!

Back-up

Boosted DM from the Sky

Semi-annihilation

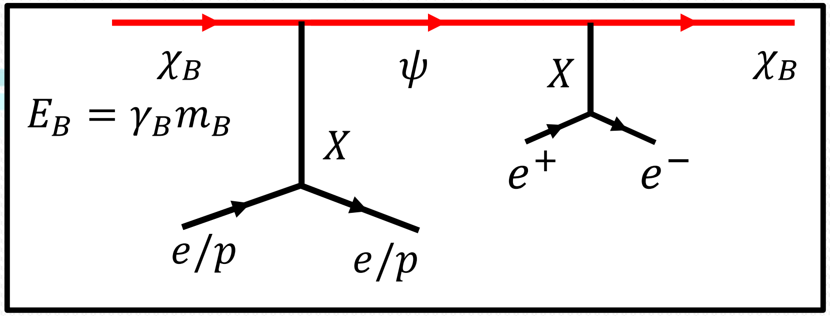
- In DM models where relevant DM is stabilized by e.g., Z_3 symmetry, one may have a process like



- 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

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

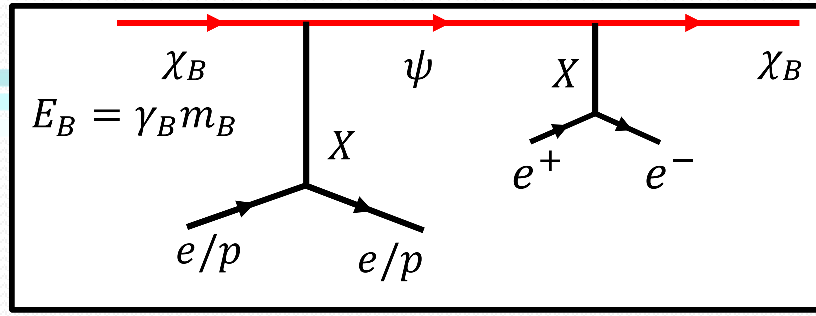
Signal Attributes



Comparison b/w e- and p-scatterings

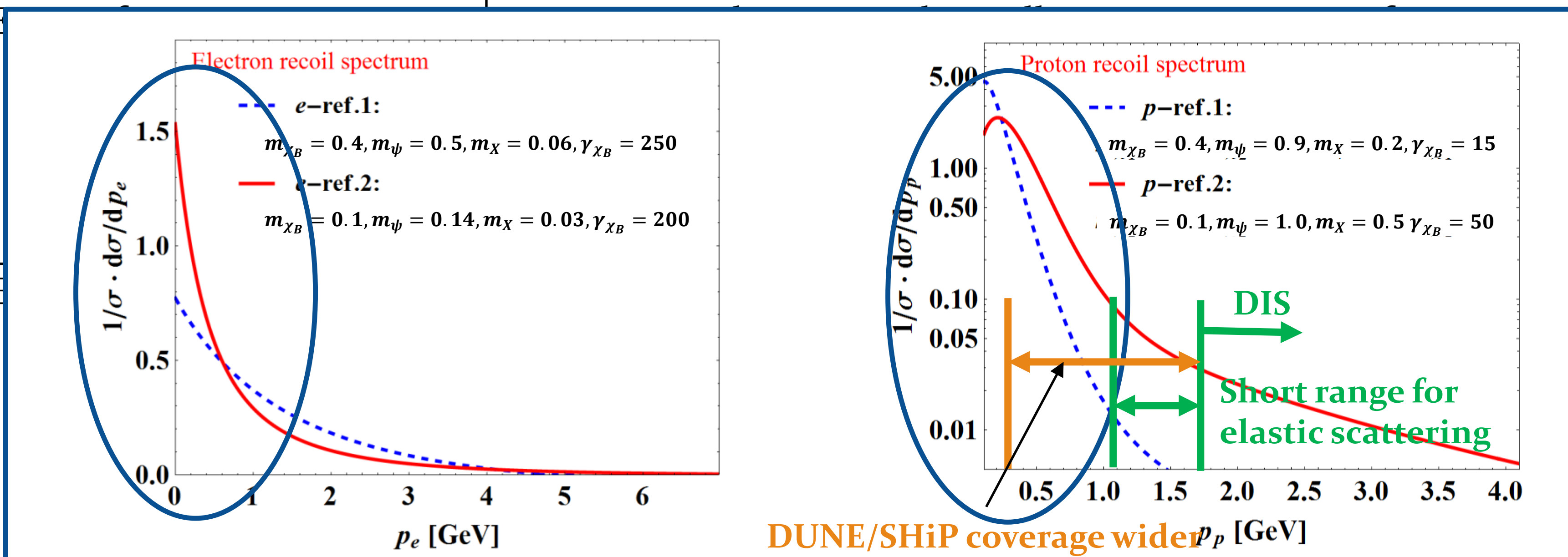
Exp.	e-scattering	p-scattering
Energy for primary scattering	Peaking towards smaller momentum transfer	Peaking towards smaller momentum transfer
Threshold energy	Small	Large for Cherenkov (Small for DUNE/SHiP detectors)
Form factor suppression	N/A	Yes
Deep inelastic scattering	N/A	Yes
Energy for secondary process	(Typically) highly boosted	(Typically) less boosted
Object identification	Highly collimated (in preferred mass spectra) Recoil electron + single object-like e^+e^- pair (assuming $\theta_{res}\sim 3^\circ$, **better at DUNE/SHiP**)	Reasonably separated (in preferred mass spectra) Recoil proton + well-separated e^+e^- pair

Signal Attributes

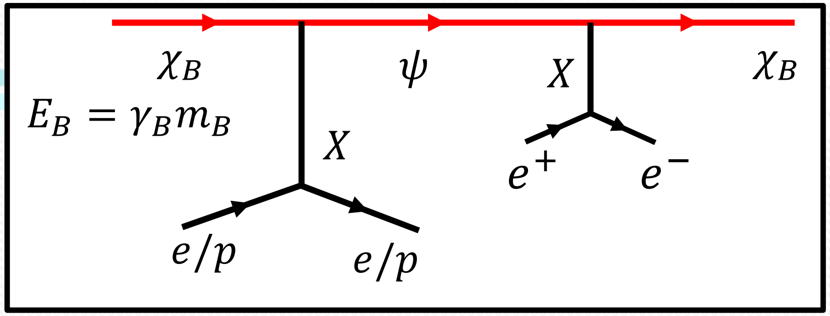


- **Comparison b/w e- and p-scatterings**

Exp.	e-scattering	p-scattering
E		
E		
	DUNE/SHiP)	



Signal Attributes



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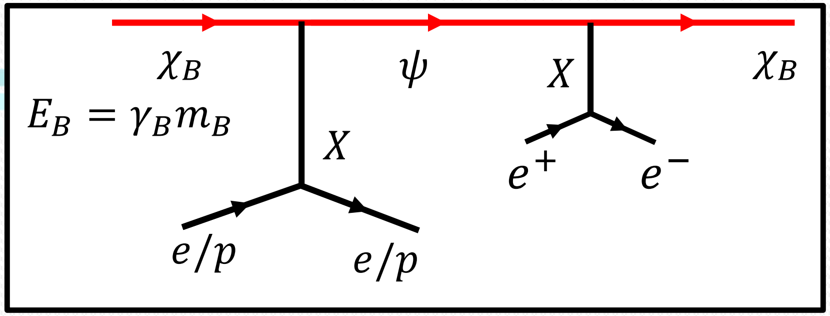
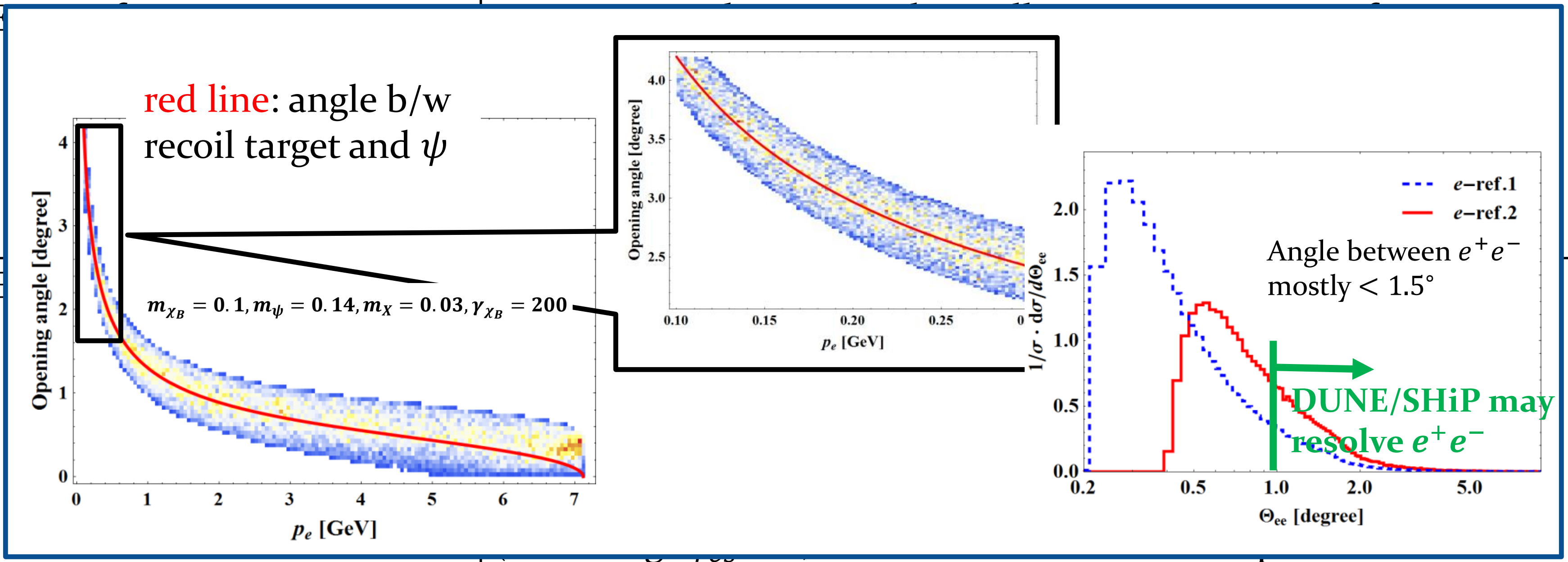


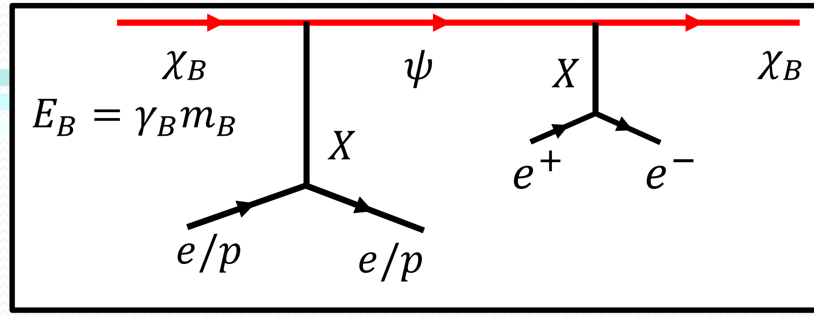
Comparison b/w e- and p-scatterings

Exp.	e-scattering	p-scattering
E		
E	DUNE/SHiP)	

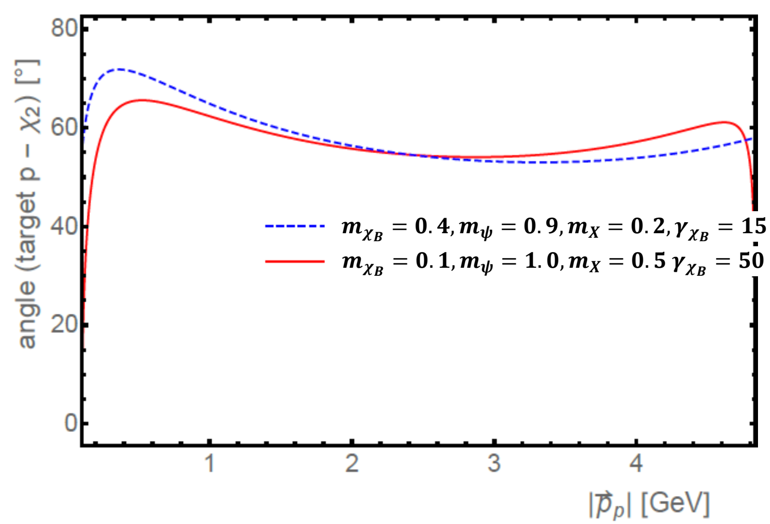


Signal Attributes

- **Comparison b/w e- and p-scatterings**



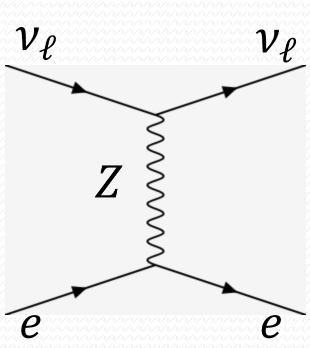
Exp.	e-scattering	p-scattering
E		
E	DUNE/SHiP)	



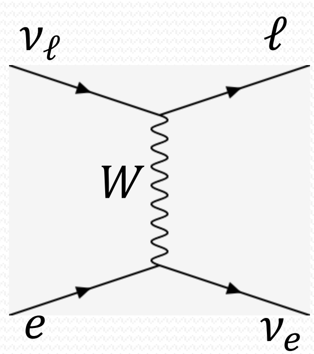
Background Considerations

Potential sources

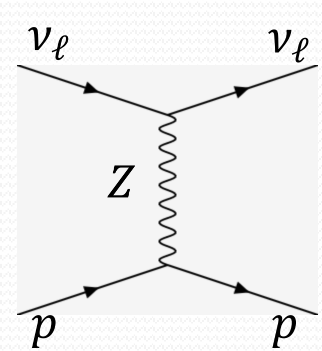
- Cherenkov radiation (CR) by electron/muon is distinguished from that by proton.
- Electron-preferred scenarios:



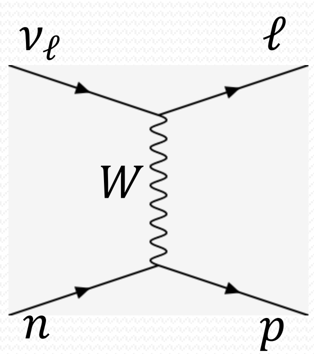
: CR by an N.C.
electron



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



: CR by an N.C.
proton unless broken

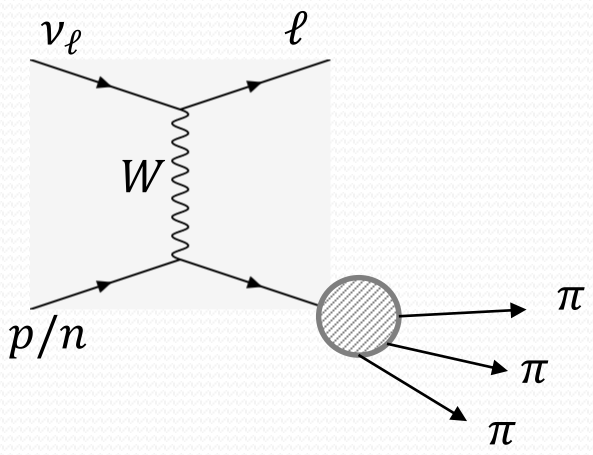


: CR by at least, a C.C.
proton unless broken

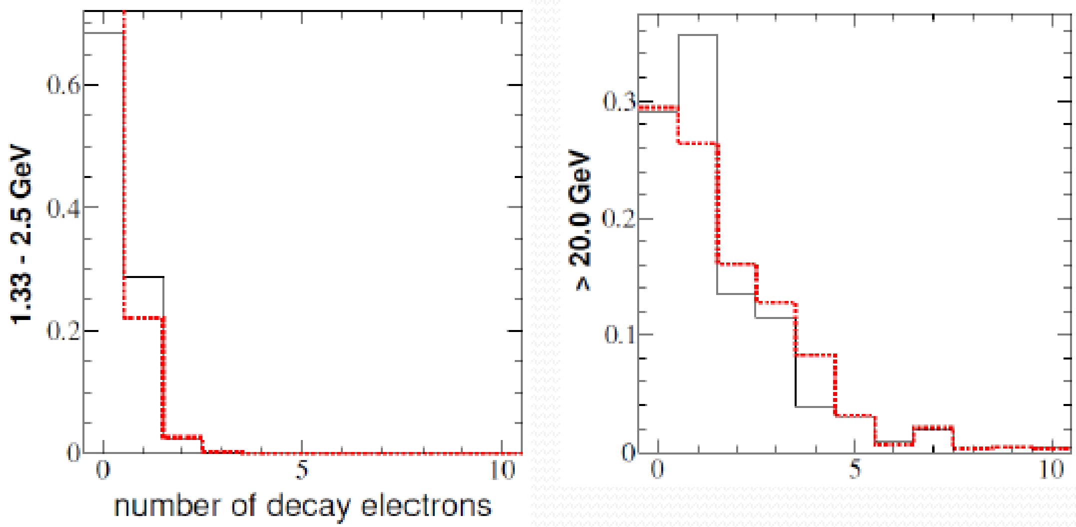
- Proton-preferred scenarios: opening angles among recoil proton, decayed electrons are large enough to resolve

Background Considerations

More challenging cases: broken nuclei



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

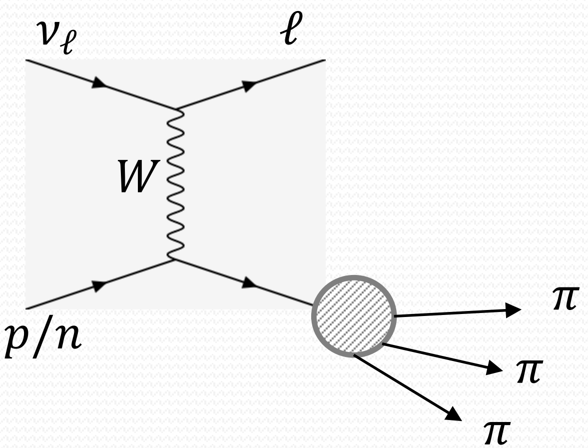


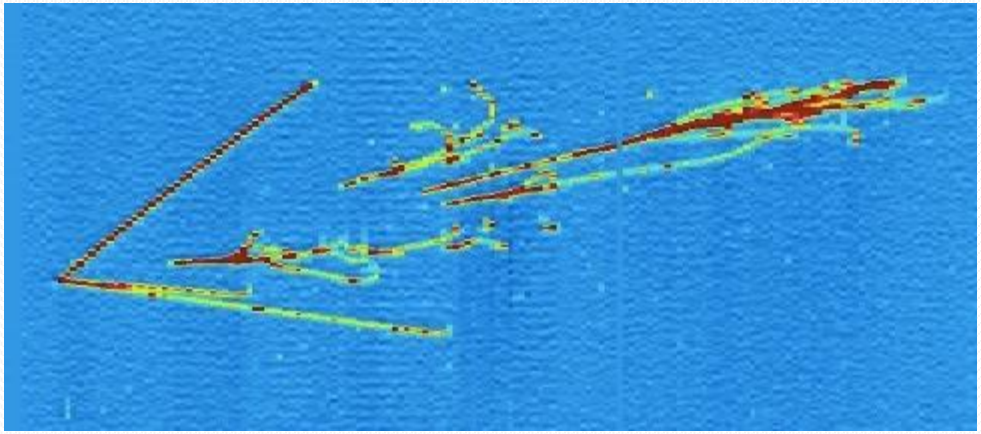
Super-K (2012)

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

Background Considerations

More challenging cases: broken nuclei





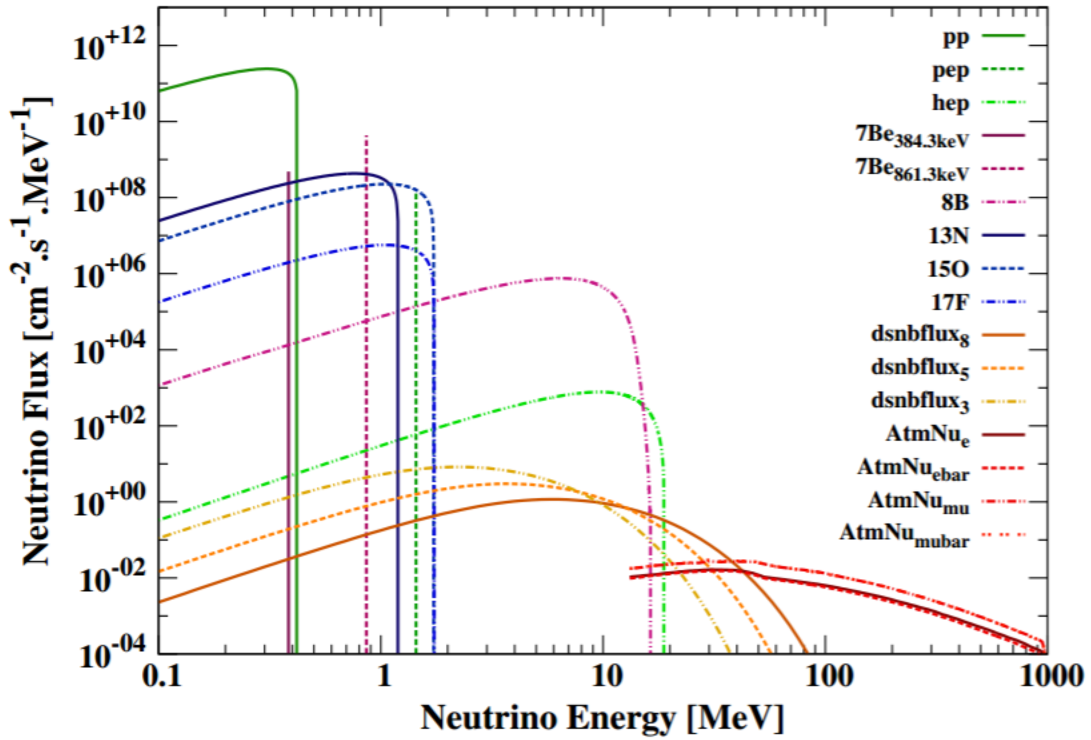
Particle tracks created by a neutrino interaction in liquid argon in the ArgoNeuT

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

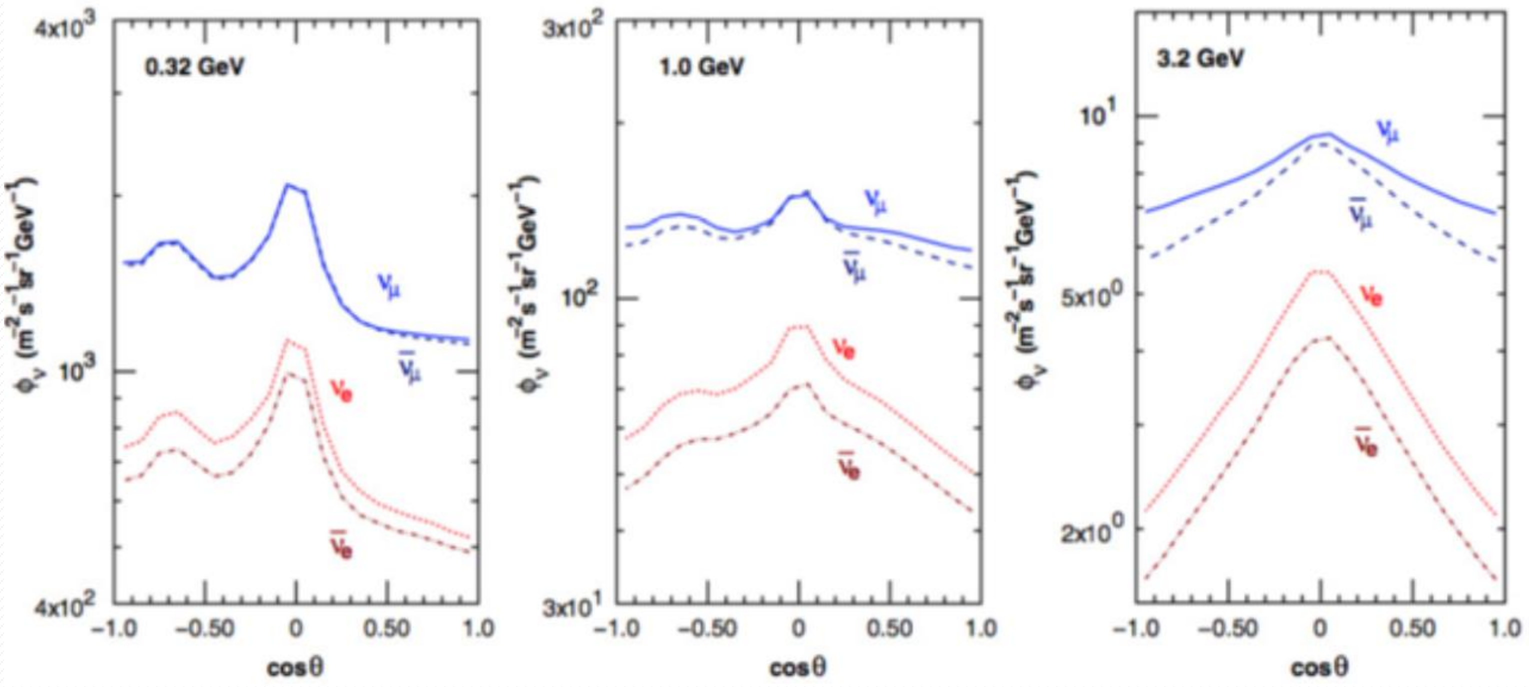


[Ruppin et al., (2014)]

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

Flux of Atmospheric Neutrino

- Neutrino as a background

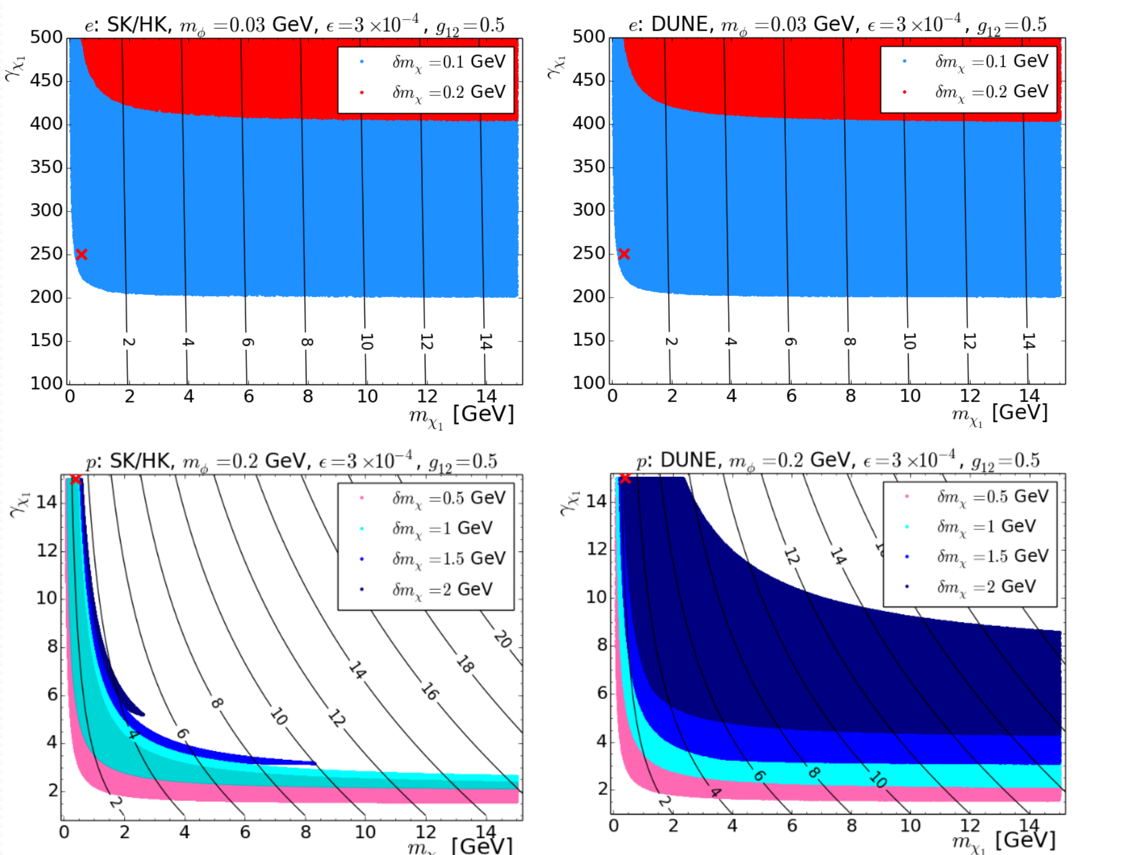


θ: zenith angle

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

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)]