



# Physics Opportunities at Dark Matter “Colliders”



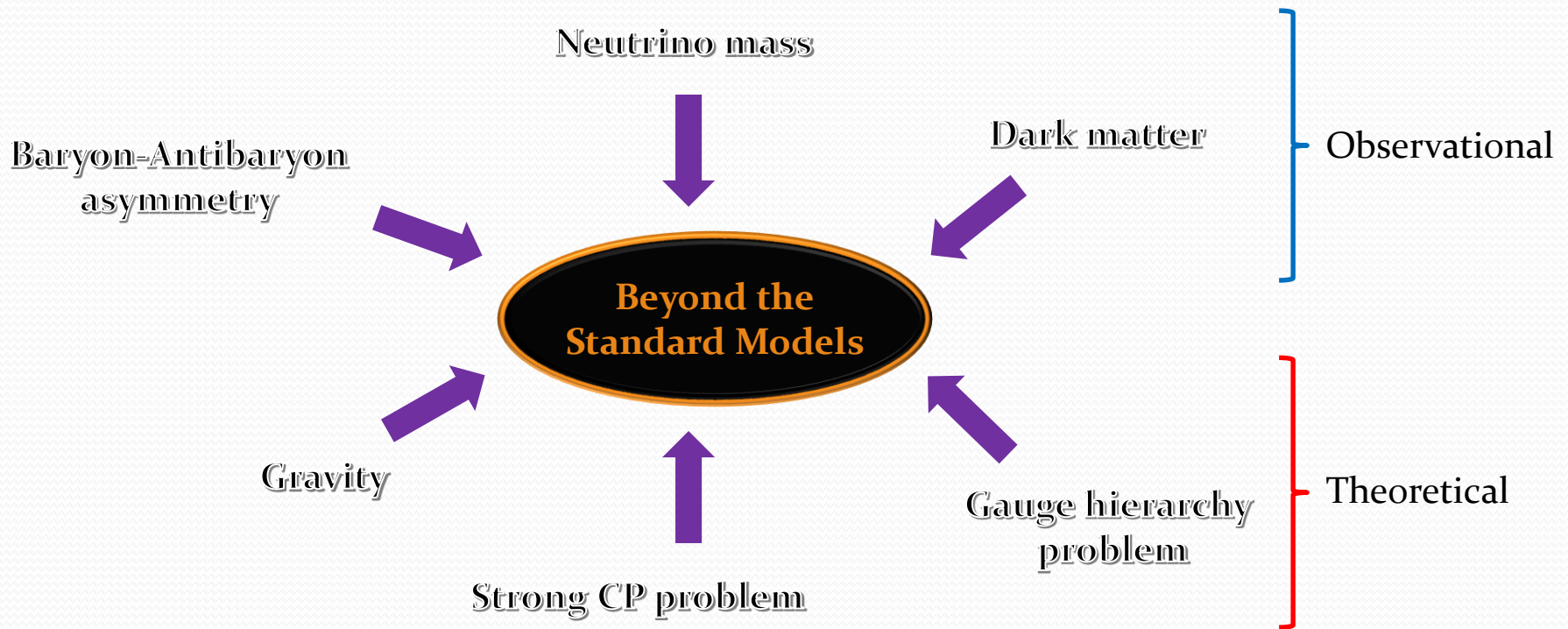
Doojin Kim

Korea-CERN Workshop at Jeju, Korea

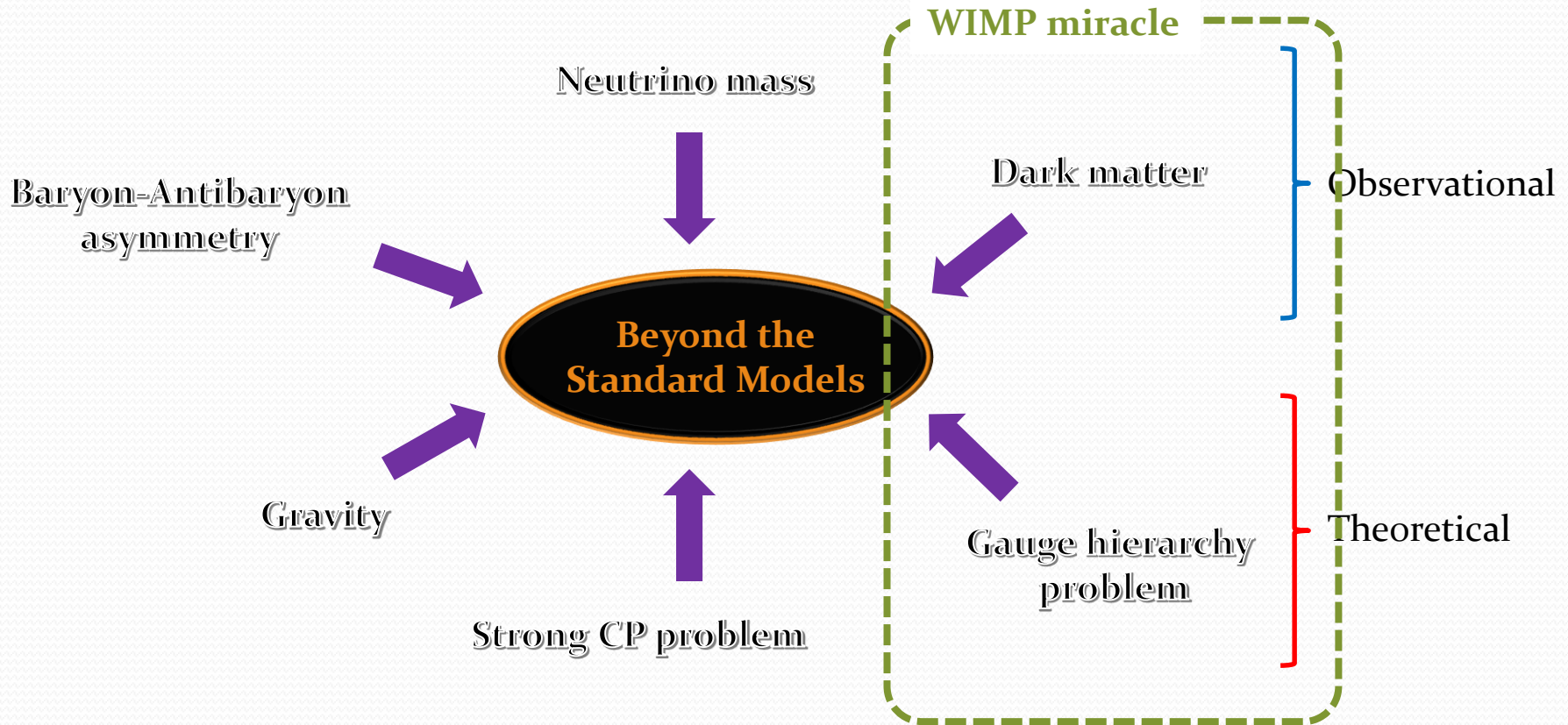
June 1st, 2017

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

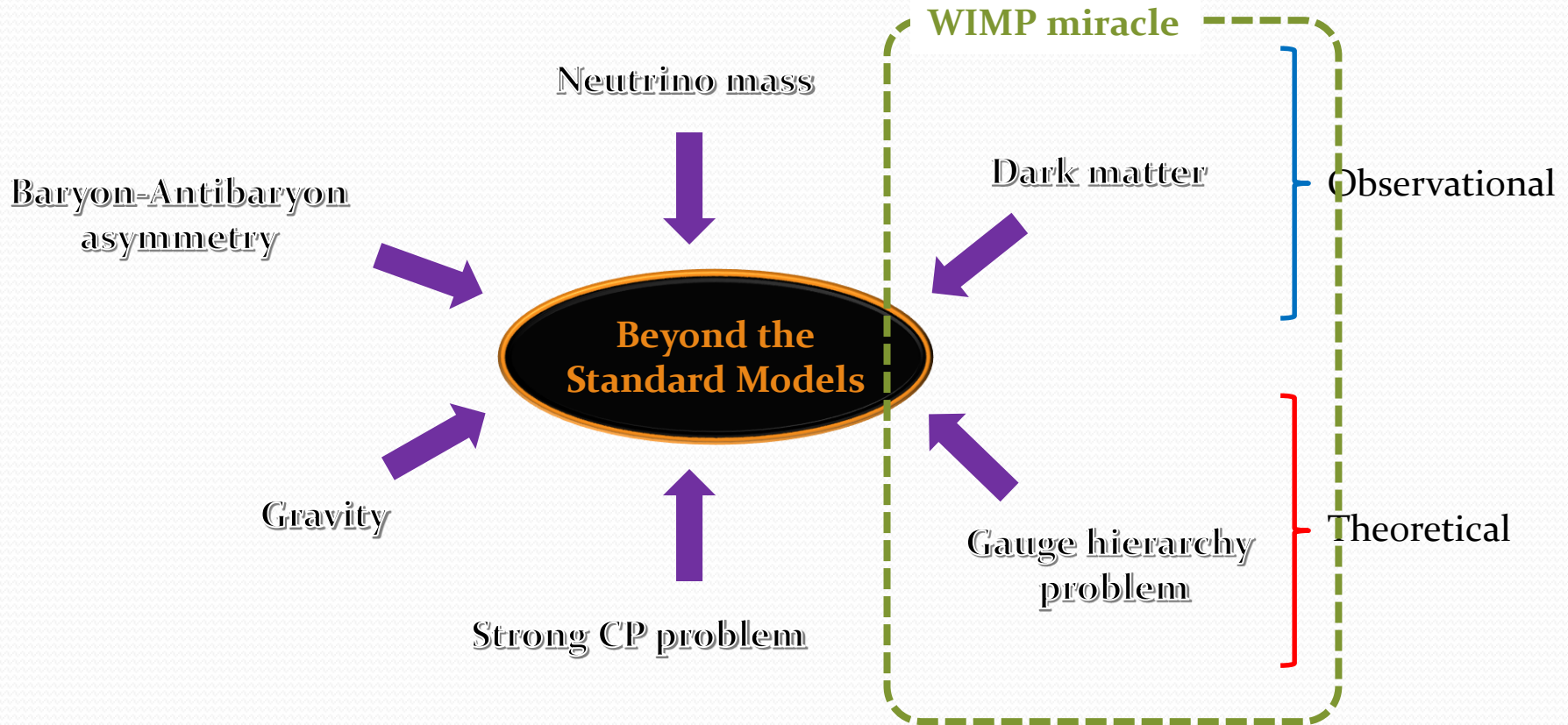
# Need for New Physics



# Need for New Physics at Weak/TeV Scale



# Need for New Physics at Weak/TeV Scale



**Many experiments/searches targeting at Weak/TeV scale**

# Experimental Efforts

## ATLAS SUSY Searches\* - 95% CL Lower Limits

May 2017

## ATLAS Preliminary

$\sqrt{s} = 7, 8, 13 \text{ TeV}$

Model	$\epsilon, \mu, \tau, \gamma$	Jets	$E_{T}^{\text{miss}}$	$[\mathcal{L} d(\text{fb}^{-1})]$	Mass limit	$\sqrt{s} = 7, 8 \text{ TeV}$	$\sqrt{s} = 13 \text{ TeV}$	Reference	
Inclusive Searches	MSUGRA/CMSSM	$0-3 e, \mu, 1-2 \tau$	2-10 jets/0-3	Yes	20.3	1.85 TeV	$m(\tilde{g})=m(\tilde{u}_L)$	1507.0535	
	$\tilde{g}\tilde{g} \rightarrow q\bar{q}$	0	2-6 jets	Yes	36.1	1.57 TeV	$m(\tilde{g})=200 \text{ GeV}, m(\tilde{u}_L)=m(\tilde{t}_1^{(2*)})$ (pre-0)	ATLAS-CONF-2017-022	
	$\tilde{g}\tilde{g} \rightarrow q\bar{q}$ (compressed)	0	1-3 jets	Yes	3.2	608 GeV	$m(\tilde{g})=m(\tilde{t}_1^{(2*)})=5 \text{ GeV}$	1604.0773	
	$\tilde{g}\tilde{g} \rightarrow q\bar{q}$	0	2-6 jets	Yes	36.1	2.09 TeV	$m(\tilde{g})=200 \text{ GeV}$	ATLAS-CONF-2017-022	
	$\tilde{g}\tilde{g} \rightarrow q\bar{q} + \text{sgg} + \text{gg}$	0	2-6 jets	Yes	36.1	2.91 TeV	$m(\tilde{g})=200 \text{ GeV}, m(\tilde{t}_1^{(2*)})=0.5(m(\tilde{t}_1^{(2*)})+m(\tilde{g}))$	ATLAS-CONF-2017-022	
	$\tilde{g}\tilde{g} \rightarrow q\bar{q}(\ell\ell)/\nu\nu(\ell\ell)$	$3 e, \mu$	4 jets	Yes	36.1	1.825 TeV	$m(\tilde{g})=4400 \text{ GeV}$	ATLAS CONF-2017-030	
	$\tilde{g}\tilde{g} \rightarrow q\bar{q}WZ/\ell\ell$	0	7-11 jets	Yes	36.1	1.8 TeV	$m(\tilde{g})=4400 \text{ GeV}$	ATLAS CONF-2017-033	
	GMSB (bino NLSIP)	$1/2 \tau + 0-1 \ell$	0-2 jets	Yes	3.2	2.0 TeV	$m(\tilde{g})=4400 \text{ GeV}$	1607.05979	
	OGM (bino NLSIP)	2 $\gamma$	0	Yes	3.2	1.65 TeV	$m(\tilde{g})=4400 \text{ GeV}$	1606.09150	
	OGM (higgsino-bino NLSIP)	$\gamma$	1 $b$	Yes	20.3	1.37 TeV	$m(\tilde{g})=950 \text{ GeV}, m(\tilde{NLSIP})=0.1 \text{ mm}, \mu=0$	1507.09493	
OGM (higgsino-bino NLSIP)	$\gamma$	2 jets	Yes	13.3	1.8 TeV	$m(\tilde{g})=850 \text{ GeV}, m(\tilde{NLSIP})=0.1 \text{ mm}, \mu=0$	ATLAS-CONF-2016-066		
OGM (higgsino NLSIP)	$2 e, \mu, (\tau)$	0 jets	Yes	20.3	900 GeV	$m(\tilde{g})=850 \text{ GeV}$	1503.03200		
Gravitino LSP	0	mono-jet	Yes	20.3	865 GeV	$m(\tilde{g})=850 \text{ GeV}, m(\tilde{C})=1.8 \times 10^{-11} eV, m(\tilde{g})=m(\tilde{g})=1.5 \text{ TeV}$	1502.01518		
3 $\gamma$ gen. final	$\tilde{g}\tilde{g} \rightarrow h\bar{h}$	0	3 $h$	Yes	36.1	1.92 TeV	$m(\tilde{g})=800 \text{ GeV}$	ATLAS-CONF-2017-021	
	$\tilde{g}\tilde{g} \rightarrow h\bar{h}$	0-1 $e, \mu$	3 $h$	Yes	36.1	1.97 TeV	$m(\tilde{g})=800 \text{ GeV}$	ATLAS CONF-2017-021	
	$\tilde{g}\tilde{g} \rightarrow h\bar{h}$	0-1 $e, \mu$	3 $h$	Yes	20.1	1.37 TeV	$m(\tilde{g})=300 \text{ GeV}$	1407.0050	
3 $\gamma$ gen. squire annihilation	$\tilde{g}\tilde{g} \rightarrow h\bar{h}$	0	2 $h$	Yes	36.1	800 GeV	$m(\tilde{g})=420 \text{ GeV}$	ATLAS-CONF-2017-028	
	$\tilde{g}\tilde{g} \rightarrow h\bar{h}$	$2 e, \mu$ (SS)	1 $h$	Yes	36.1	275-700 GeV	$m(\tilde{g})=200 \text{ GeV}, m(\tilde{t}_1^{(2*)})=m(\tilde{t}_2^{(2*)})=100 \text{ GeV}$	ATLAS-CONF-2017-030	
	$\tilde{g}\tilde{g} \rightarrow h\bar{h}$	0-2 $e, \mu$	1-2 $h$	Yes	4.7/13.3	117-170 GeV	$m(\tilde{g})=1-2 m(\tilde{t}_1^{(2*)}), m(\tilde{t}_1^{(2*)})=35 \text{ GeV}$	1209.2102, ATLAS-CONF-2017-077	
	$\tilde{g}\tilde{g} \rightarrow h\bar{h}$	0-2 $e, \mu$	0-2 jets+1-2 $h$	Yes	20.3/36.1	90-198 GeV	$m(\tilde{g})=1 \text{ GeV}$	1506.0816, ATLAS-CONF-2017-020	
	$\tilde{g}\tilde{g} \rightarrow h\bar{h}$	0	mono-jet	Yes	3.2	90-322 GeV	$m(\tilde{g})=m(\tilde{t}_1^{(2*)})=5 \text{ GeV}$	1604.0773	
	$\tilde{g}\tilde{g} \rightarrow h\bar{h}$	$2 e, \mu$ (Z)	1 $h$	Yes	20.3	150-600 GeV	$m(\tilde{g})=150 \text{ GeV}$	1403.5222	
	$\tilde{g}\tilde{g} \rightarrow h\bar{h}$	$3 e, \mu$ (Z)	1 $h$	Yes	36.1	290-790 GeV	$m(\tilde{g})=0 \text{ GeV}$	ATLAS-CONF-2017-019	
	$\tilde{g}\tilde{g} \rightarrow h\bar{h}$	$1/2 e, \mu$	4 $h$	Yes	36.1	328-980 GeV	$m(\tilde{g})=0 \text{ GeV}$	ATLAS-CONF-2017-019	
	$\tilde{g}\tilde{g} \rightarrow h\bar{h}$	$2 e, \mu$	0	Yes	36.1	90-440 GeV	$m(\tilde{g})=0$	ATLAS-CONF-2017-039	
	$\tilde{g}\tilde{g} \rightarrow h\bar{h}$	$2 e, \mu$	0	Yes	36.1	710 GeV	$m(\tilde{g})=0, m(\tilde{t}_1^{(2*)})=0.5 m(\tilde{t}_2^{(2*)})=m(\tilde{t}_1^{(2*)})$	ATLAS-CONF-2017-038	
EW direct	$\tilde{g}\tilde{g} \rightarrow h\bar{h}$	$2 e, \mu$	0	Yes	36.1	760 GeV	$m(\tilde{g})=0, m(\tilde{t}_1^{(2*)})=0.5 m(\tilde{t}_2^{(2*)})=m(\tilde{t}_1^{(2*)})$	ATLAS CONF-2017-035	
	$\tilde{g}\tilde{g} \rightarrow h\bar{h}$	$2 e, \mu$	0	Yes	36.1	580 GeV	$m(\tilde{g})=m(\tilde{t}_1^{(2*)}), m(\tilde{t}_1^{(2*)})=0, m(\tilde{t}_2^{(2*)})=0.5 m(\tilde{t}_1^{(2*)})=m(\tilde{t}_1^{(2*)})$	ATLAS CONF-2017-039	
	$\tilde{g}\tilde{g} \rightarrow h\bar{h}$	$2 e, \mu$	0-2 jets	Yes	36.1	270 GeV	$m(\tilde{g})=m(\tilde{t}_1^{(2*)}), m(\tilde{t}_1^{(2*)})=0, \text{decoupled}$	ATLAS CONF-2017-038	
	$\tilde{g}\tilde{g} \rightarrow h\bar{h}$	$2 e, \mu$	0-2 jets	Yes	20.3	635 GeV	$m(\tilde{g})=m(\tilde{t}_1^{(2*)}), m(\tilde{t}_1^{(2*)})=0, m(\tilde{t}_2^{(2*)})=0.5 m(\tilde{t}_1^{(2*)})=m(\tilde{t}_1^{(2*)})$	1501.07110	
	$\tilde{g}\tilde{g} \rightarrow h\bar{h}$	$4 e, \mu$	0	Yes	20.3	635 GeV	$m(\tilde{g})=m(\tilde{t}_1^{(2*)}), m(\tilde{t}_1^{(2*)})=0, m(\tilde{t}_2^{(2*)})=0.5 m(\tilde{t}_1^{(2*)})=m(\tilde{t}_1^{(2*)})$	1405.5086	
	OGM (bino NLSIP) weak prod. $\tilde{g}\tilde{g} \rightarrow \gamma\gamma$	$1 e, \mu, \tau$	0	Yes	20.3	115-370 GeV	$c \leq 1 \text{ mm}$	1507.09493	
	OGM (bino NLSIP) weak prod. $\tilde{g}\tilde{g} \rightarrow \gamma\gamma$	$2 \gamma$	0	Yes	20.3	990 GeV	$c \leq 1 \text{ mm}$	1507.09493	
	Compl'd particles	Direct $\tilde{g}\tilde{g} \rightarrow h\bar{h}$ prod., long-lived $\tilde{g}$	Disapp. trk	1 jet	Yes	36.1	430 GeV	$m(\tilde{g})=m(\tilde{t}_1^{(2*)})=140 \text{ MeV}, m(\tilde{g})=0.2 \text{ ns}$	ATLAS-CONF-2017-017
		Direct $\tilde{g}\tilde{g} \rightarrow h\bar{h}$ prod., long-lived $\tilde{g}$	dE/dx trk	0	Yes	18.4	495 GeV	$m(\tilde{g})=m(\tilde{t}_1^{(2*)})=160 \text{ MeV}, m(\tilde{g})=15 \text{ ns}$	1506.03332
		Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	27.9	650 GeV	$m(\tilde{g})=100 \text{ GeV}, 10 \mu\text{s} < \tau(\tilde{g}) < 1000 \text{ s}$	1310.6594
Stable $\tilde{g}$ R-hadron		trk	0	Yes	3.2	1.58 TeV	$m(\tilde{g})=100 \text{ GeV}, r_0=10 \text{ ms}$	1506.05129	
Metastable $\tilde{g}$ R-hadron		dE/dx trk	0	Yes	3.2	1.57 TeV	$m(\tilde{g})=100 \text{ GeV}, r_0=10 \text{ ms}$	1004.04520	
GMSB, stable $\tilde{g}$ R-hadron		1-2 $\mu$	0	Yes	19.1	537 GeV	$10^{-10} \text{ tan}\beta < 50$	1411.8795	
GMSB, $\tilde{g} \rightarrow \gamma\gamma$ , long-lived $\tilde{g}$		2 $\gamma$	0	Yes	20.3	440 GeV	$1 < m(\tilde{g}) < 3 \text{ ns}, \text{GMSB model}$	1409.5442	
$\tilde{g}\tilde{g} \rightarrow \text{any } \nu\bar{\nu}$		displ. vtx + jets	0	Yes	20.3	20.3	$2 < m(\tilde{g}) < 740 \text{ mm}, m(\tilde{g})=1.3 \text{ TeV}$	1504.05162	
OGM $\tilde{g}\tilde{g} \rightarrow \nu\bar{\nu}$		displ. vtx + jets	0	Yes	20.3	1.0 TeV	$6 < m(\tilde{g}) < 480 \text{ mm}, m(\tilde{g})=1.1 \text{ TeV}$	1504.05162	
RPV		LIV $pp \rightarrow \tilde{g}\tilde{g} + X, \tilde{g} \rightarrow \text{jet}/\ell/\mu/\tau$	0	0	Yes	3.2	1.8 TeV	$A_{11} < -0.11, A_{21} < 0.015, \tau_{\tilde{g}}=0.07$	1607.08079
	Bilinear RPV CMSSM	$2 e, \mu$ (SS)	0-3 $b$	Yes	20.3	1.45 TeV	$m(\tilde{g})=0, m(\tilde{t}_1^{(2*)})=m(\tilde{t}_2^{(2*)})=1 \text{ mm}$	1404.2590	
	$\tilde{g}\tilde{g} \rightarrow h\bar{h}$	$2 e, \mu$	0	Yes	13.3	1.14 TeV	$m(\tilde{g})=400 \text{ GeV}, A_{11}=0, \beta_1=1, 2$	ATLAS-CONF-2016-075	
	$\tilde{g}\tilde{g} \rightarrow h\bar{h}$	$3 e, \mu, \tau + \nu$	0	Yes	20.3	450 GeV	$m(\tilde{g})=0.2 m(\tilde{t}_1^{(2*)}), A_{11}=0$	1403.5098	
	$\tilde{g}\tilde{g} \rightarrow h\bar{h}$	0	4-5 large-R jets	Yes	14.8	1.08 TeV	$\text{BR}(\tilde{g} \rightarrow \text{BR})=0$	ATLAS-CONF-2016-067	
	$\tilde{g}\tilde{g} \rightarrow h\bar{h}$	0	4-5 large-R jets	Yes	14.8	1.55 TeV	$m(\tilde{g})=800 \text{ GeV}$	ATLAS CONF-2016-067	
	$\tilde{g}\tilde{g} \rightarrow h\bar{h}$	$1 e, \mu$	B-10 jets/0-4 $b$	Yes	36.1	2.1 TeV	$m(\tilde{g})=1 \text{ TeV}, \mu_{112}=0$	ATLAS CONF-2017-013	
	$\tilde{g}\tilde{g} \rightarrow h\bar{h}$	$1 e, \mu$	B-10 jets/0-4 $b$	Yes	36.1	1.85 TeV	$m(\tilde{g})=1 \text{ TeV}, \mu_{112}=0$	ATLAS CONF-2017-013	
	$\tilde{g}\tilde{g} \rightarrow h\bar{h}$	0	2 jets + 2 $b$	Yes	15.4	410 GeV	$\text{BR}(\tilde{g} \rightarrow h\bar{h})=20\%$	ATLAS-CONF-2016-022, ATLAS-CONF-2016-084	
	$\tilde{g}\tilde{g} \rightarrow h\bar{h}$	$2 e, \mu$	2 $b$	Yes	36.1	0.4, 1.45 TeV	$\text{BR}(\tilde{g} \rightarrow h\bar{h})=20\%$	ATLAS CONF-2017-038	
Other	Scalar charm, $\tilde{c} \rightarrow c\bar{c}$	0	2 $c$	Yes	20.3	510 GeV	$m(\tilde{g})=200 \text{ GeV}$	1501.01325	

\* Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

10<sup>-1</sup> 1 Mass scale [TeV]

# Experimental Efforts

## ATLAS SUSY Searches\* - 95% CL Lower Limits

May 2017

ATLAS Preliminary

## ATLAS Exotics Searches\* - 95% CL Exclusion

Status: August 2016

ATLAS Preliminary  
 $\int \mathcal{L} dt = (3.2 - 20.3) \text{ fb}^{-1}$   $\sqrt{s} = 8, 13 \text{ TeV}$

Model	$\ell, \gamma$	Jets <sup>†</sup>	$E_{T}^{\text{miss}}$	$[\mathcal{L} dt (\text{fb}^{-1})]$	Limit	Reference	
Inclusive Searches MSUGRA/CMSM $\tilde{g}, \tilde{u}, \tilde{d} \rightarrow q\bar{q}$ (compressed) $\tilde{g}, \tilde{u}, \tilde{d} \rightarrow q\bar{q} + \tilde{g}$ $\tilde{g}, \tilde{u}, \tilde{d} \rightarrow q\bar{q} + \tilde{u}, \tilde{d}$ $\tilde{g}, \tilde{u}, \tilde{d} \rightarrow q\bar{q} + \tilde{g}, \tilde{u}, \tilde{d}$ GMSB (NLSP) GGM (bino NLSP) GGM (higgsino-bino NLSP) GGM (higgsino NLSP) Gravitino LSP	ADD $G_{KK} + g/q$	-	$\geq 1j$	Yes	3.2 6.88 TeV	$n=2$ 1604.07773	
	ADD non-resonant $t\bar{t}$	$2 e, \mu$	-	-	20.3 4.7 TeV	$n=3 \text{ Hz}$ 1407.2410	
	ADD CBH $\rightarrow t\bar{t}$	$1 e, \mu$	$1j$	-	20.3 5.2 TeV	$n=6$ 1911.2006	
	ADD CBH	-	$2j$	-	19.7 8.7 TeV	$n=6$ ATLAS-CONF-2016-060	
	ADD BH high $\sum p_T$	$\geq 1 e, \mu$	$\geq 2j$	-	3.2 6.2 TeV	$n=6, M_0 = 3 \text{ TeV, rot BH}$ 1606.02895	
	ADD BH multijet	-	$\geq 3j$	-	3.6 9.95 TeV	$n=6, M_0 = 3 \text{ TeV, rot BH}$ 1512.02586	
	RS1 $G_{KK} \rightarrow t\bar{t}$	$2 e, \mu$	-	-	20.3 2.68 TeV	$k/\tilde{M}_* = 0.1$ 1405.4123	
	RS1 $G_{KK} \rightarrow \gamma\gamma$	$2 \gamma$	-	-	3.2 3.2 TeV	$k/\tilde{M}_* = 0.1$ 1606.03053	
	Bulk RS $G_{KK} \rightarrow WW \rightarrow qq'\nu$	$1 e, \mu$	$1j$	Yes	13.2 1.24 TeV	$k/\tilde{M}_* = 1.0$ ATLAS-CONF-2016-002	
	Bulk RS $G_{KK} \rightarrow HH \rightarrow bbbb$	-	$4b$	-	13.3 360-860 GeV	$k/\tilde{M}_* = 1.0$ ATLAS-CONF-2016-049	
Bulk RS $G_{KK} \rightarrow t\bar{t}$	$1 e, \mu$	$\geq 1 b, \geq 1j, \geq 1\gamma$	Yes	20.3 2.2 TeV	BR = 0.925 1505.07018		
ZUED / RPP	$1 e, \mu$	$\geq 2 b, \geq 4j$	Yes	3.2 1.46 TeV	Tex (1,1), BR(A <sup>1,1</sup> ) $\rightarrow t\bar{t}$ + 1 ATLAS-CONF-2016-013		
3 <sup>rd</sup> gen. squarks (mixed)	SSM $Z' \rightarrow t\bar{t}$	$2 e, \mu$	-	-	13.3 4.05 TeV	ATLAS-CONF-2016-045	
	SSM $Z' \rightarrow \tau\bar{\tau}$	$2 \tau$	-	-	19.5 2.02 TeV	1602.01177	
	Leptophobic $Z' \rightarrow b\bar{b}$	-	$2b$	-	3.2 1.5 TeV	1603.09791	
	SSM $W' \rightarrow t\bar{t}$	$1 e, \mu$	-	Yes	13.3 4.74 TeV	ATLAS-CONF-2016-061	
	HVT $W' \rightarrow WZ \rightarrow qq\nu$ model A	$0 e, \mu$	$1j$	Yes	13.2 2.4 TeV	ATLAS-CONF-2016-052	
	HVT $W' \rightarrow WZ \rightarrow qq\nu$ model B	$0 e, \mu$	$2j$	-	15.5 3.0 TeV	ATLAS-CONF-2016-055	
	HVT $V' \rightarrow WH/ZH$ model B	multi channel	-	-	3.2 2.31 TeV	$g_V = 1$ 1607.05621	
	LRSM $W'_2 \rightarrow t\bar{b}$	$1 e, \mu$	$2 b, 0-1j$	Yes	20.3 1.92 TeV	$g_V = 3$ 1401.4162	
	LRSM $W'_2 \rightarrow t\bar{t}$	$0 e, \mu$	$\geq 1 b, 1j$	-	20.3 1.78 TeV	1408.0886	
	CI $q\bar{q}qqq$	-	$2j$	-	15.7 19.9 TeV	$\alpha_{12} = -1$ ATLAS-CONF-2016-069	
EW direct	CI $l\bar{l}qqq$	$2 e, \mu$	-	-	3.2 28.2 TeV	$\alpha_{12} = -1$ 1607.05059	
	CI $u\bar{u}ttt$	$2(S) \geq 3 e, \mu$	$\geq 1 b, \geq 1j$	Yes	20.3 4.9 TeV	$\alpha_{12} = -1$ 1504.04605	
	DM	Axial-vector mediator (Dirac DM)	$0 e, \mu$	$\geq 1j$	Yes	3.2 1.0 TeV	$g_{\tau} > 0.25, g_{\mu} = 1.0, m(\chi) < 250 \text{ GeV}$ 1604.07773
	Axial-vector mediator (Dirac DM)	$0 e, \mu, 1 \gamma$	$1j$	Yes	3.2 710 GeV	$g_{\tau} > 0.25, g_{\mu} = 1.0, m(\chi) < 150 \text{ GeV}$ 1604.01508	
	$ZZ\chi\chi$ EFT (Dirac DM)	$0 e, \mu$	$1j, \leq 1j$	Yes	3.2 550 GeV	$m(\chi) < 150 \text{ GeV}$ ATLAS-CONF-2015-080	
	LQ	Scalar LQ 1 <sup>st</sup> gen	$2 e$	$\geq 2j$	-	3.2 1.1 TeV	$\beta = 1$ 1605.06035
	Scalar LQ 2 <sup>nd</sup> gen	$2 \mu$	$\geq 2j$	-	3.2 1.05 TeV	$\beta = 1$ 1605.06035	
	Scalar LQ 3 <sup>rd</sup> gen	$1 e, \mu$	$\geq 1 b, \geq 3j$	Yes	20.3 640 GeV	$\beta = 0$ 1508.04735	
	Heavy quarks	VLO $TT \rightarrow Ht + X$	$1 e, \mu$	$\geq 2 b, \geq 3j$	Yes	20.3 955 GeV	T in (T,R) doublet 1505.04308
	VLO $YY \rightarrow Hb + X$	$1 e, \mu$	$\geq 1 b, \geq 3j$	Yes	20.3 770 GeV	Y in (B,Y) doublet 1505.04306	
VLO $BB \rightarrow Hb + X$	$1 e, \mu$	$\geq 2 b, \geq 3j$	Yes	20.3 735 GeV	Isoscalar singlet 1505.04306		
VLO $BB \rightarrow Zb + X$	$2 \geq 3 e, \mu$	$\geq 2 \geq 1 b$	-	20.3 755 GeV	B in (B,Y) doublet 1409.5500		
VLO $QQ \rightarrow WqWq$	$1 e, \mu$	$\geq 4j$	Yes	20.3 590 GeV	1509.04281		
VLO $T_{3/2} T_{3/2} \rightarrow WW\gamma$	$2(S) \geq 3 e, \mu$	$\geq 1 b, \geq 1j$	Yes	3.2 900 GeV	ATLAS-CONF-2016-032		
3 <sup>rd</sup> gen. squarks (aligned)	Excited quark $q' \rightarrow q\gamma$	$1 \gamma$	$1j$	-	3.2 4.4 TeV	only $u'$ and $d'$ , $A = m(q')$ 1512.02810	
	Excited quark $q' \rightarrow qg$	-	$2j$	-	15.7 5.6 TeV	only $u'$ and $d'$ , $A = m(q')$ ATLAS-CONF-2016-009	
	Excited quark $b' \rightarrow bg$	-	$1 b, 1j$	-	8.8 2.3 TeV	ATLAS-CONF-2016-060	
	Excited quark $b' \rightarrow Wt$	$1 \text{ or } 2 e, \mu$	$1 b, 2-3j$	Yes	20.3 1.5 TeV	$f_t = f_b = f_{\tau} = 1$ 1510.02664	
	Excited lepton $\nu'$	$3 e, \mu, \tau$	-	-	20.3 3.0 TeV	$A = 3.0 \text{ TeV}$ 1411.2921	
	Excited lepton $\nu'$	$3 e, \mu, \tau$	-	-	20.3 1.6 TeV	$A = 1.6 \text{ TeV}$ 1411.2921	
	Other	LSTC $\Delta \rightarrow W\gamma$	$1 e, \mu, 1 \gamma$	-	Yes	20.3 960 GeV	1407.8150
		LRSM Majorana $\nu$	$2 e, \mu$	$2j$	-	20.3 570 GeV	$m(W_2) = 2.4 \text{ TeV, no mixing}$ 1506.0620
		Higgs triplet $H \rightarrow \tau\tau$	$2 e$ (SS)	-	-	13.9 870 GeV	DY production, BR( $H^{\pm\pm} \rightarrow \tau\tau$ ) ATLAS-CONF-2016-051
		Higgs triplet $H^{\pm\pm} \rightarrow t\bar{t}$	$3 e, \mu, \tau$	-	-	20.3 400 GeV	DY production, BR( $H^{\pm\pm} \rightarrow t\bar{t}$ ) 1411.2921
Monopole (non-res prod)		$1 e, \mu$	$1b$	Yes	20.3 607 GeV	$\alpha_{\text{em}} = 0.2$ 1510.5494	
Multi-charged particles		-	-	-	20.3 795 GeV	DY production, $ q  = 5e$ 1504.04188	
Magnetic monopoles		-	-	-	7.0 1.34 TeV	DY production, $ g  = 1g_0, \text{spin } 1/2$ 1509.08559	

\*Only a selection of the available mass limits on new states or phenomena is shown. Lower bounds are specified only when explicitly not excluded.

†Small-radius (large-radius) jets are denoted by the letter j (J).









**HEY!**



**WHAT'S GOING ON HERE!**

# Effort Further

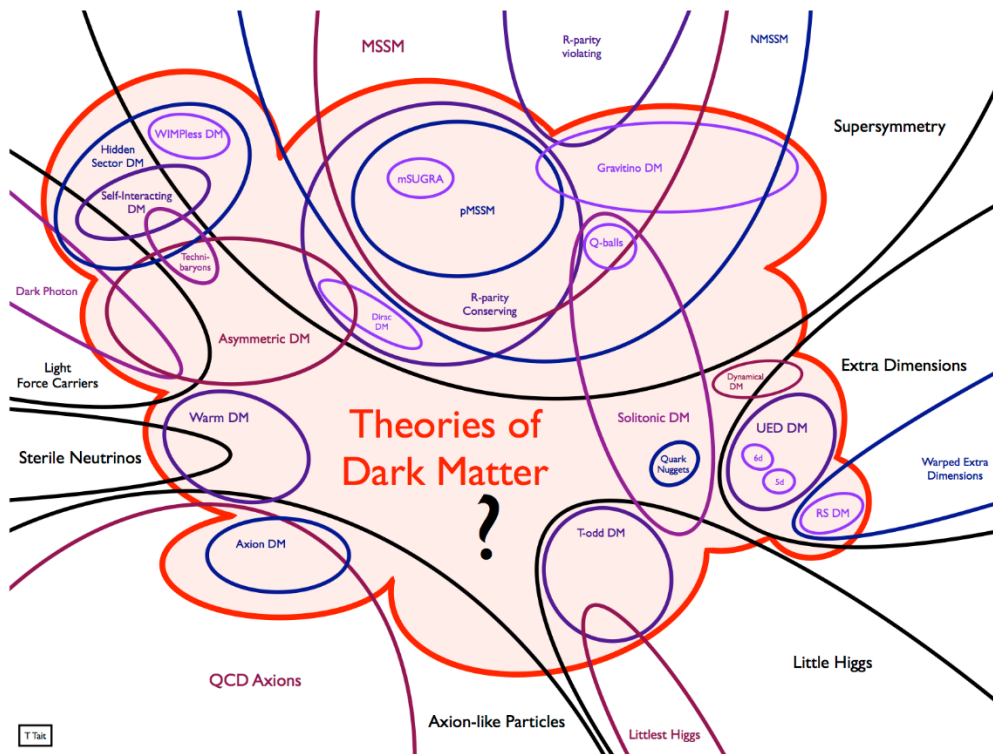
- “Attacking” **every single corner** of parameter space in new physics models and/or probing **unexplored territories**
  - ❖ Filling missing gaps (e.g., compressed mass spectra)
  - ❖ Displaced vertex searches (e.g., MATSULA), disappearing tracks
  - ❖ Exotic final states (e.g., tri-boson searches, “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!

# 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!
  - ❖ **Dark sector particle (including DM) searches at dark matter “colliders”**

# Dark Matter Models

## ● Various DM models



from the talk by Tim Tait

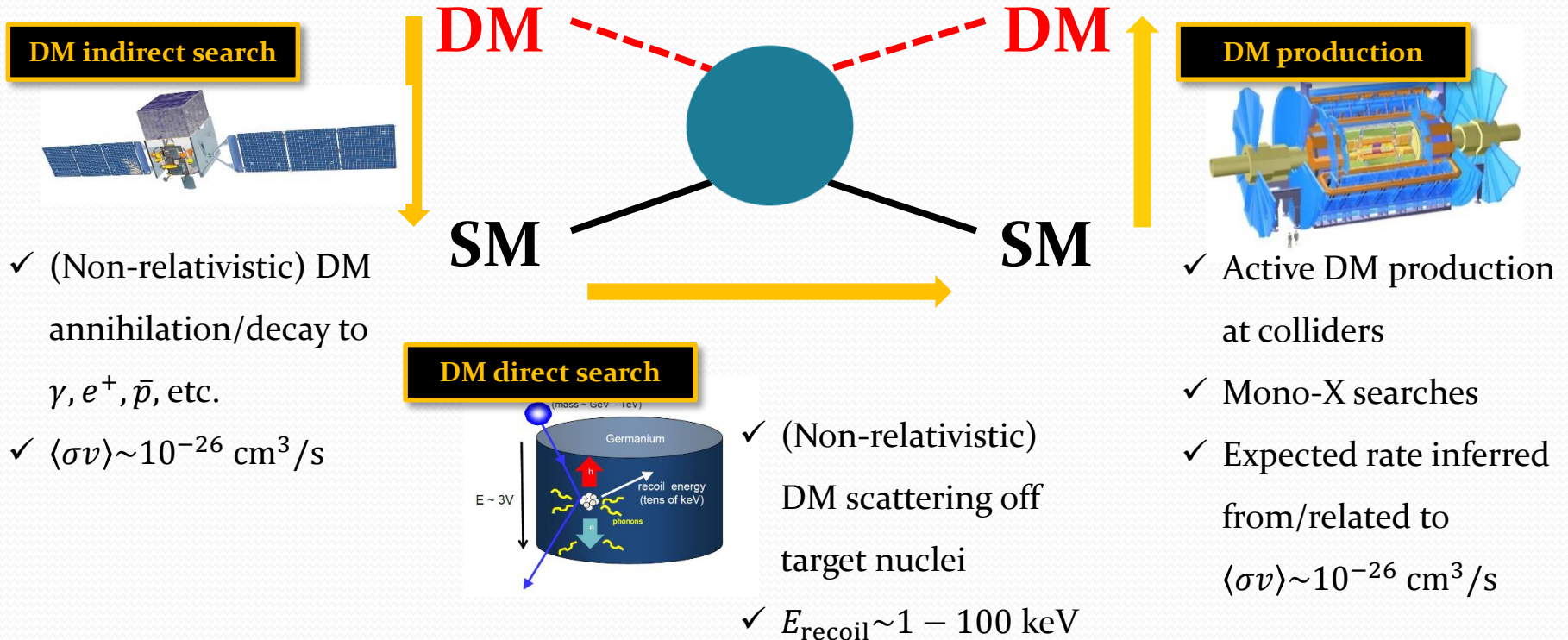
□ Many dark matter simplified models or new physics models including a dark matter candidate proposed

- ❖ 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

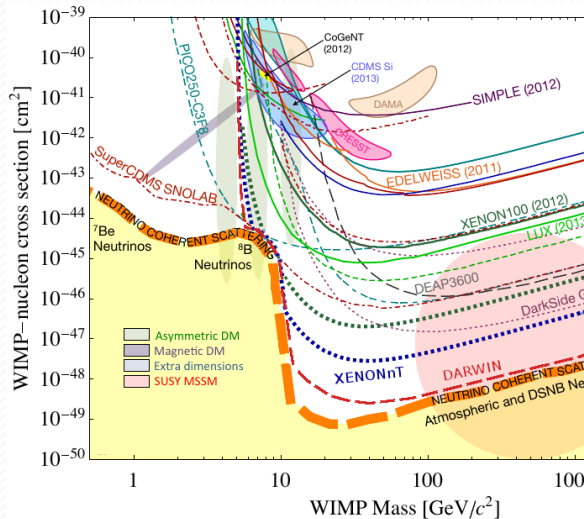
- “Minimal” phenomenological implications in the context of dark matter detection under minimal dark matter scenarios



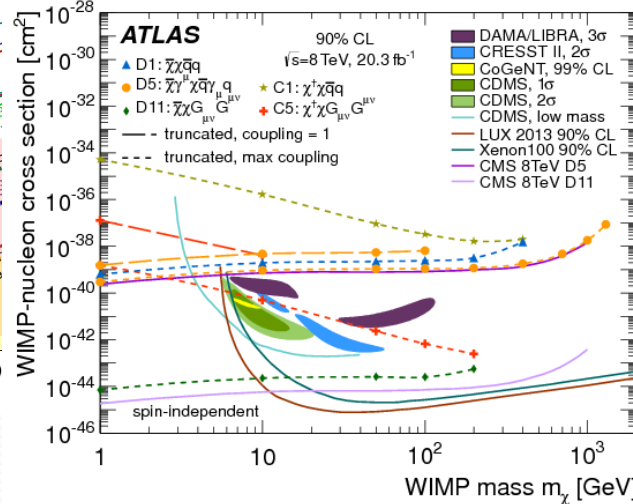
# Dark Matter Searches

## Current status

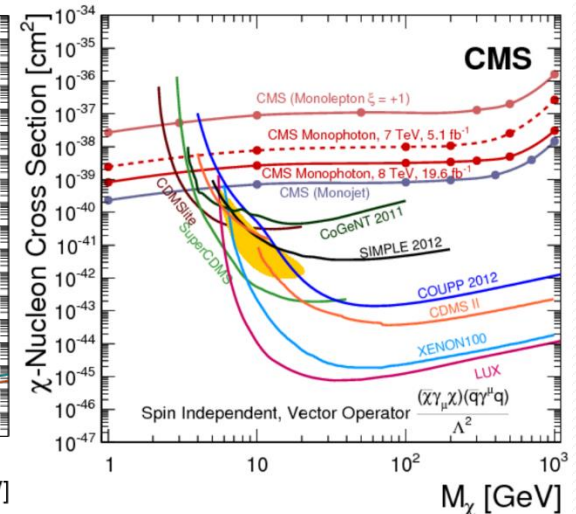
- No “unambiguous” observation of DM signatures via non-gravitational interactions (many searches/interpretations designed under minimal dark-sector scenarios)



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



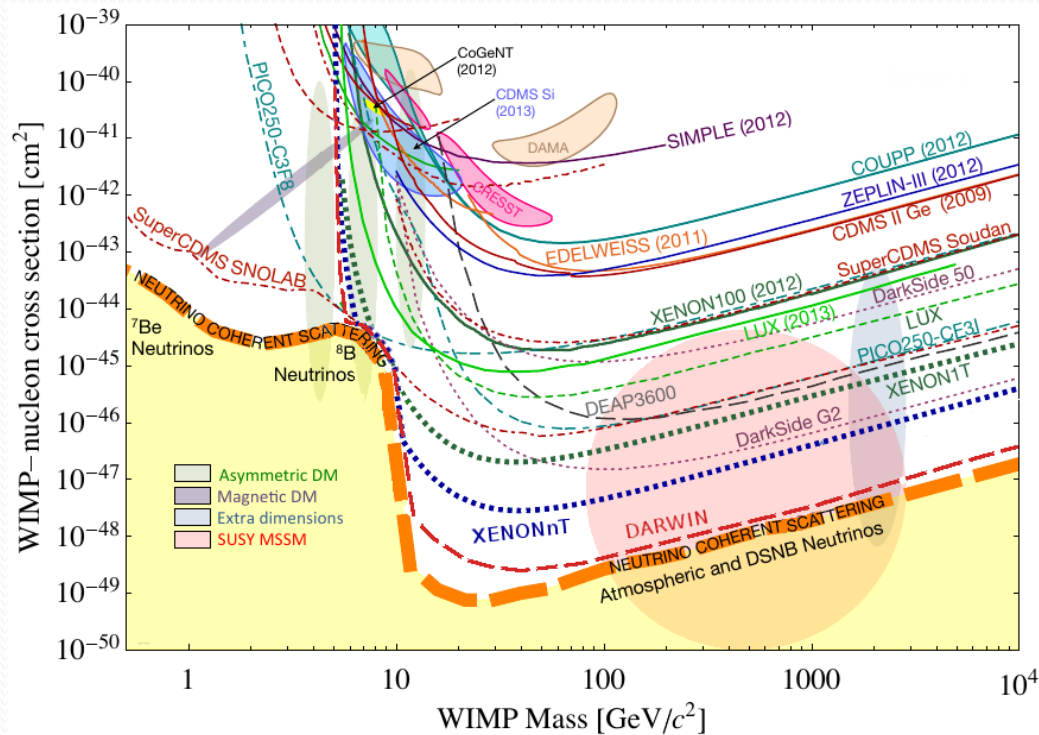
[ATLAS mono-jet search (2015)]



[CMS mono-photon search (2014)]

# Dark Matter Direct Detection

## Current status



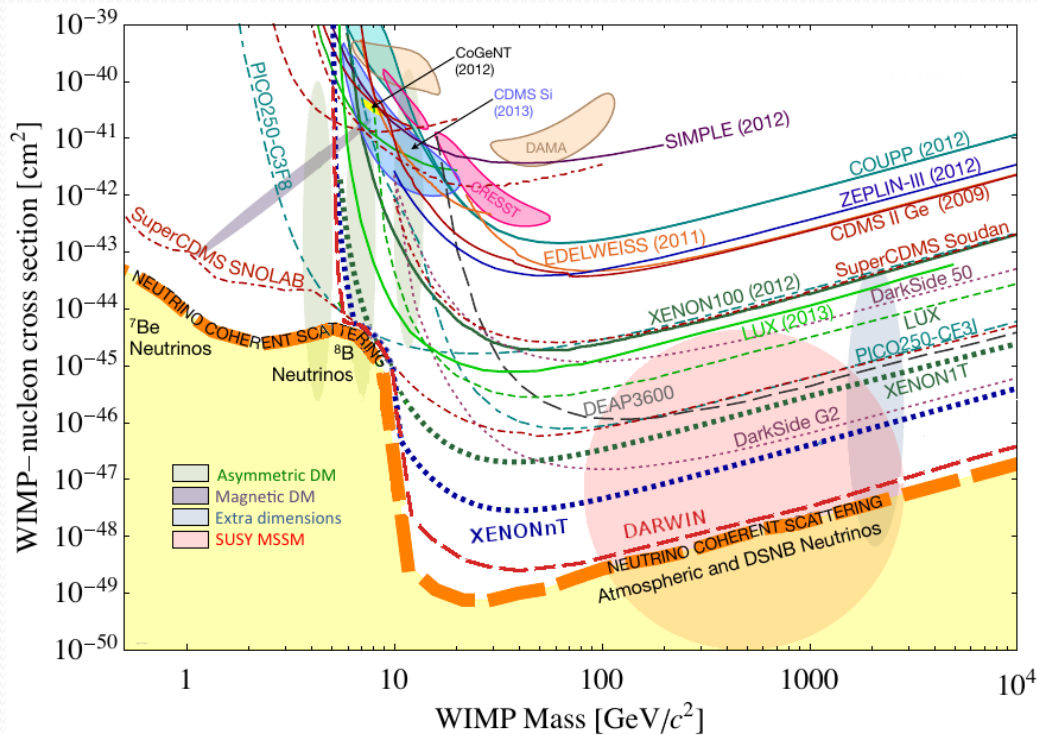
[P. Cushman, C. Calbiati and D. N. McKinsey, (2013); L. Baudis (2014)]

- 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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**New search schemes needed!**

# “Minimal” vs. “Non-minimal”

- “Vanilla” vs. “Flavorful”



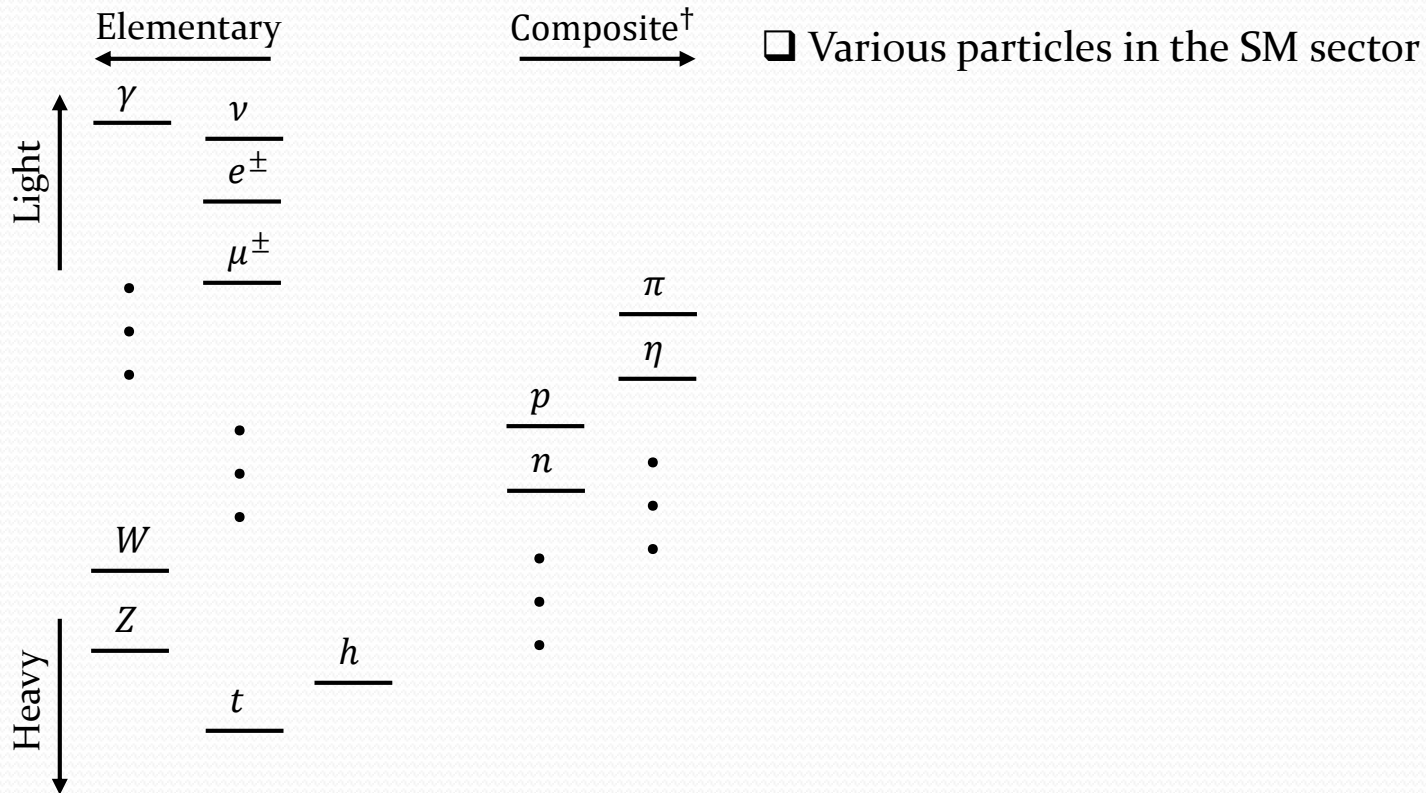
# “Minimal” vs. “Non-minimal”

- “Vanilla” vs. “Flavorful”



# “Flavorful” Dark Sector

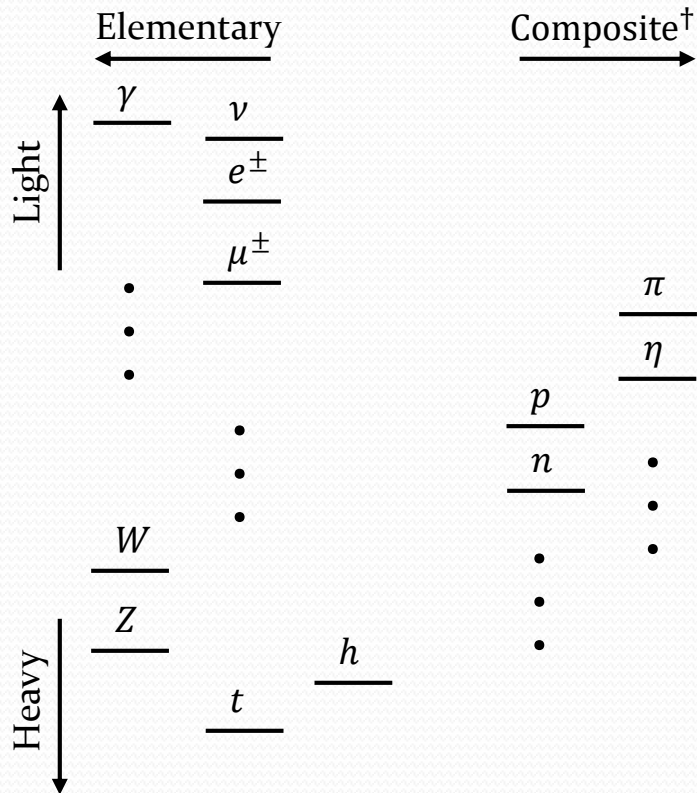
## ● Why flavorful? Flavorful SM!



†: here meaning the particles made of elementary ones

# “Flavorful” Dark Sector

## ● Why flavorful? Flavorful SM!



□ 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)

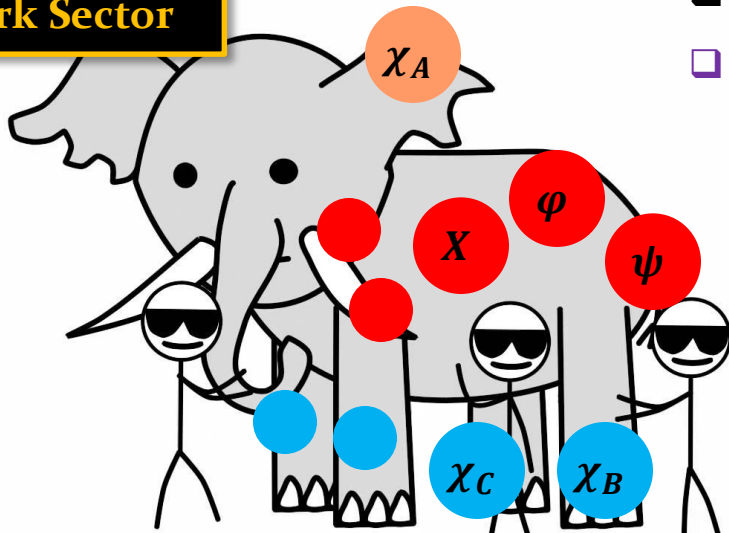
†: here meaning the particles made of elementary ones



# “Flavorful” Dark-sector Scenarios

## ● In what sense?

### Dark Sector

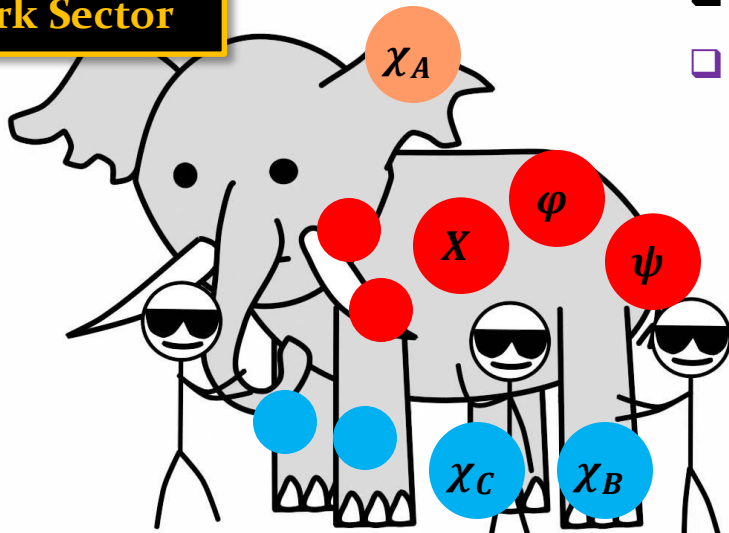


- $\chi_A$ : **dominant relic** (as in the minimal setup)
- **More members** in the dark sector
  - ✓ **Unstable members**, say  $\psi, \varphi, X, \dots$  (e.g., cosmic ray excess interpretations [DK and J.-C. Park (2015)])
  - ✓ **More dark matter species**, say  $\chi_B, \chi_C \dots$  (e.g., dynamical dark matter models [K. Dienes and B. Thomas, (2011)])

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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?

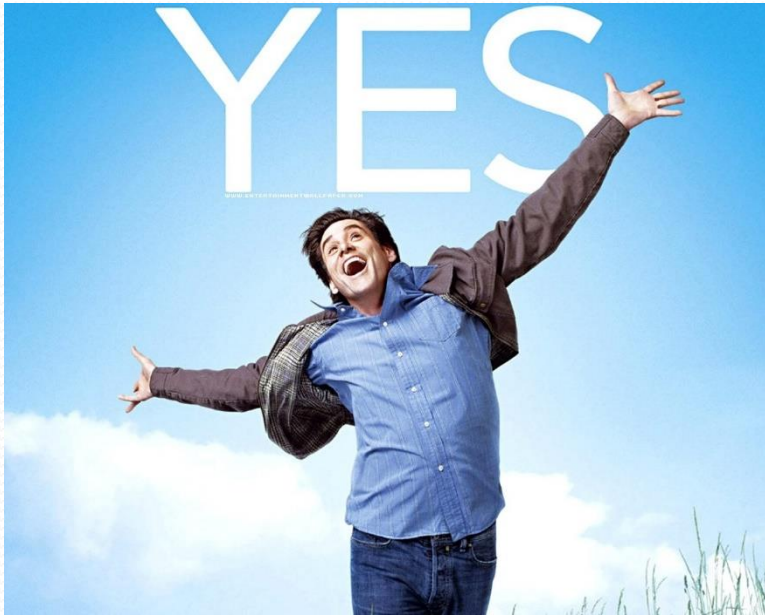
## ● Big question



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

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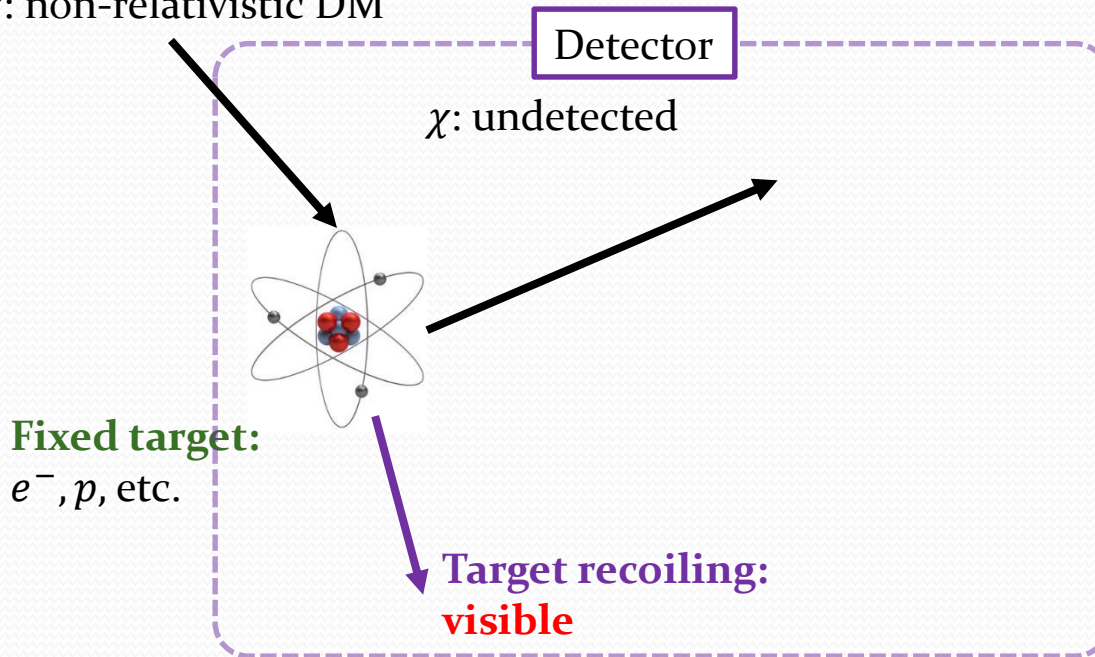
✓ **New dark matter search strategies: dark matter “colliders”** [DK, J.-C. Park and S. Shin (2016)]

# Dark Matter Direct Detection

## ● Basic idea

□ Conventional DM direct detection experiments are considering the situation in which

$\chi$ : non-relativistic DM



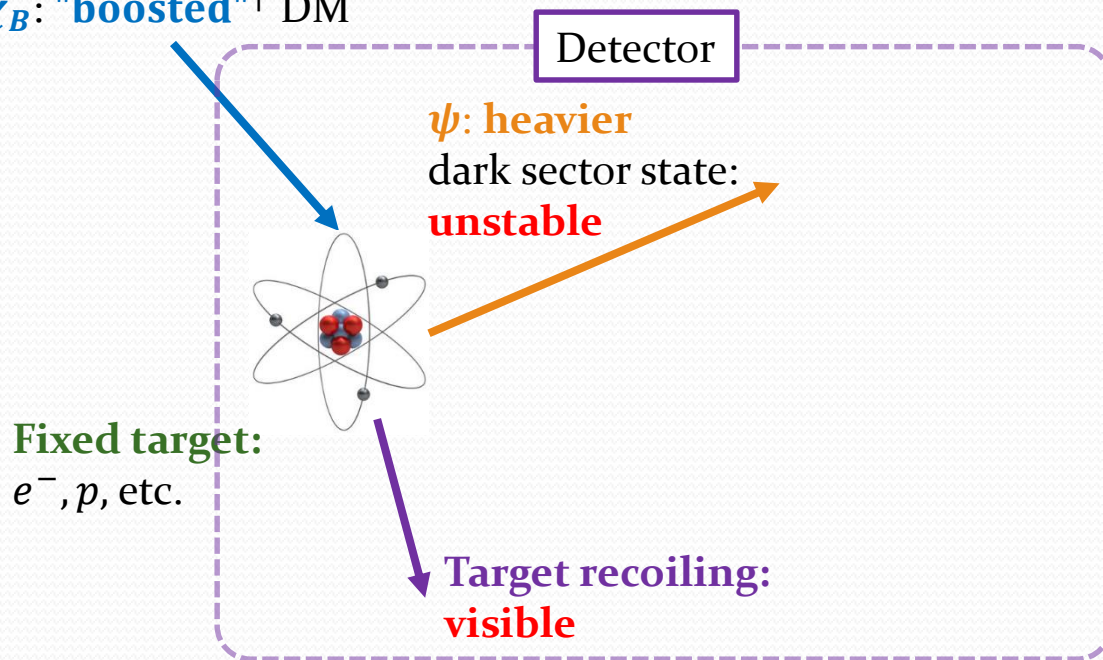
✓ Existence of DM inferred from a target recoiling (1 – 100 keV)

# Dark Matter “Colliders”

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

□ We are imagining the situation in which

$\chi_B$ : “boosted”<sup>†</sup> DM

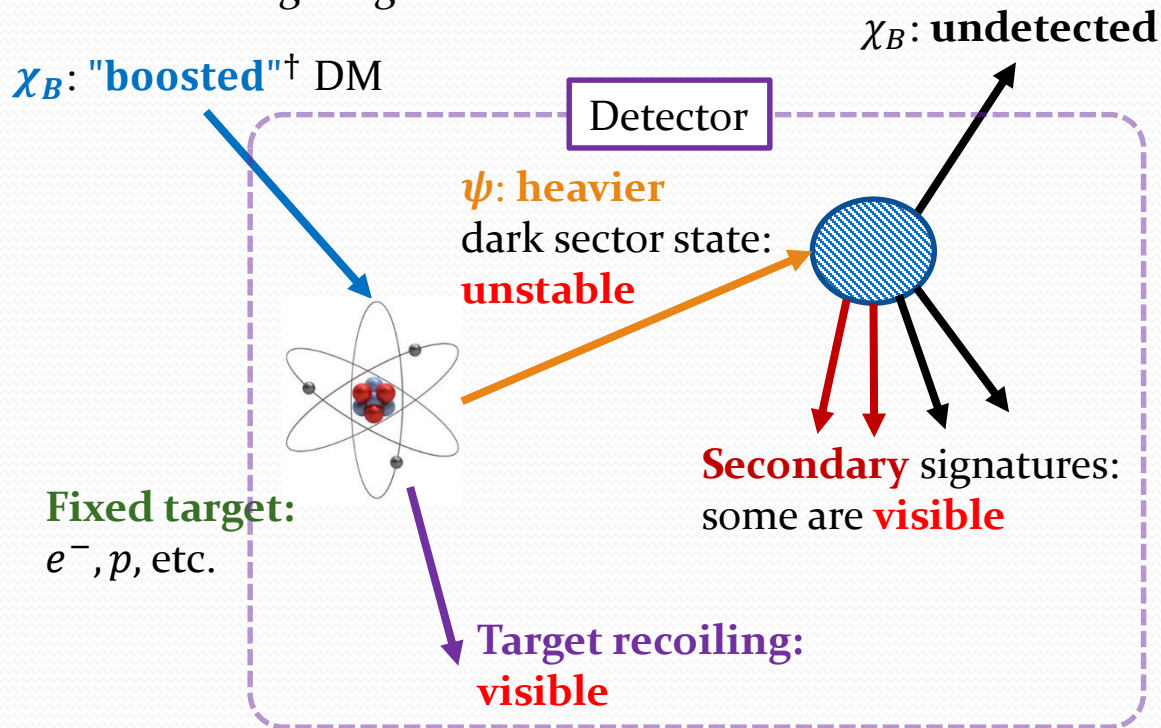


<sup>†</sup>: Production of boosted DM will be discussed in a couple of slides.

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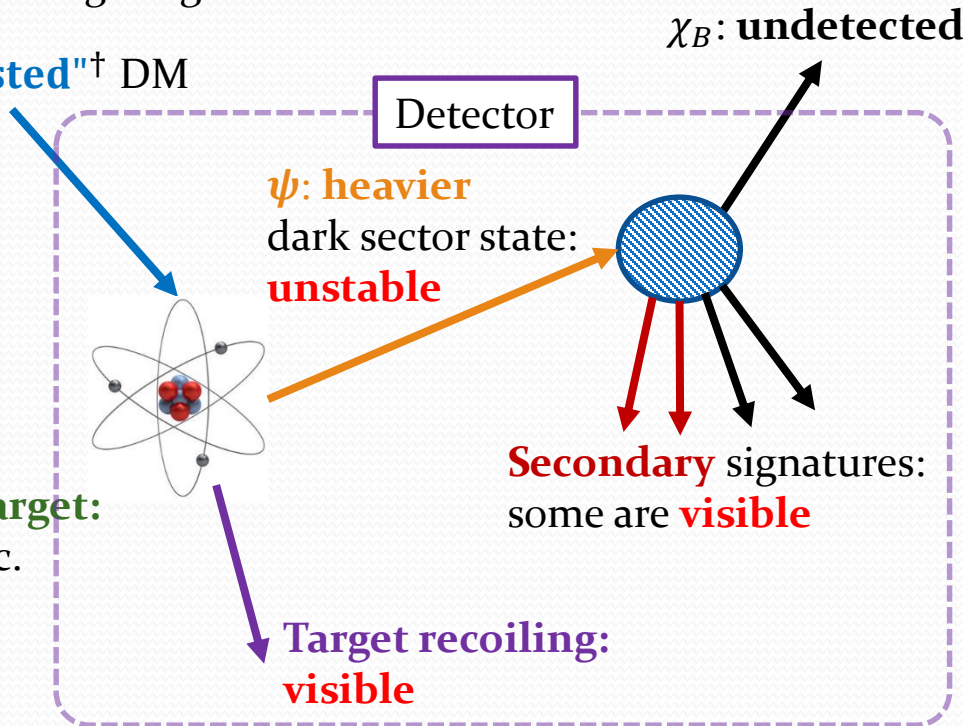
# Dark Matter “Colliders”

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

□ We are imagining the situation in which

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Fixed target:  
 $e^-$ ,  $p$ , etc.

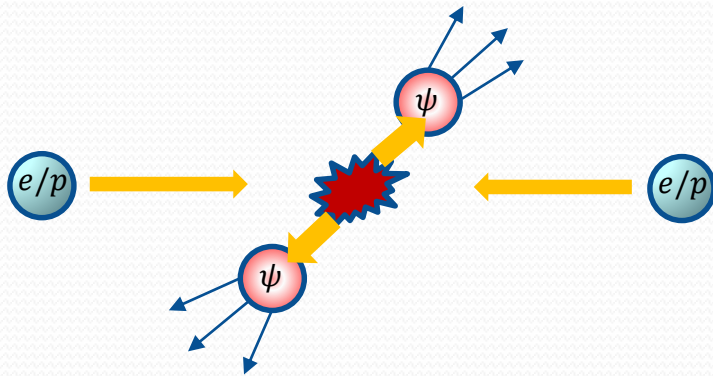


- ✓ Probing **heavier dark/hidden-sector states**
- ✓ Target recoil (like in typical DM direct detection exp.) + secondary visible signatures ⇒ **more** handles, (relatively) **background-free** (no secondary signatures in usual backgrounds)
- ✓ **Complementary** to standard DM direct searches

<sup>†</sup>: Production of boosted DM will be discussed in a couple of slides.

# Dark Matter “Colliders”

- Collider as a heavy-state probe

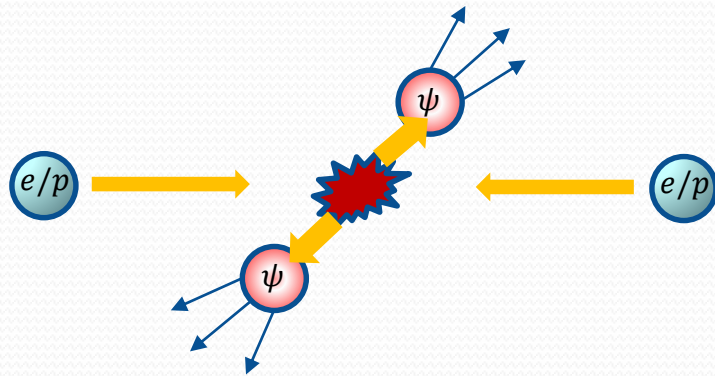


## Conventional colliders

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

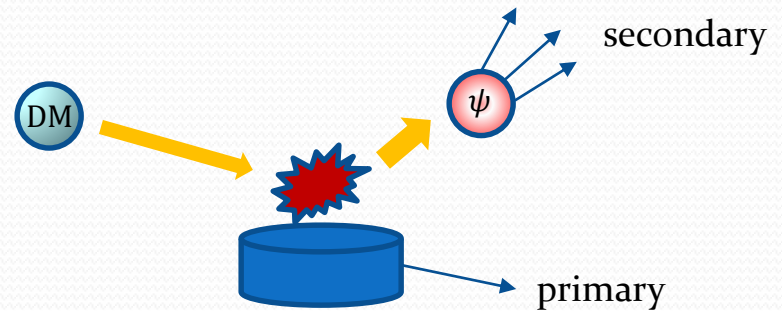
# Dark Matter “Colliders”

## ● 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

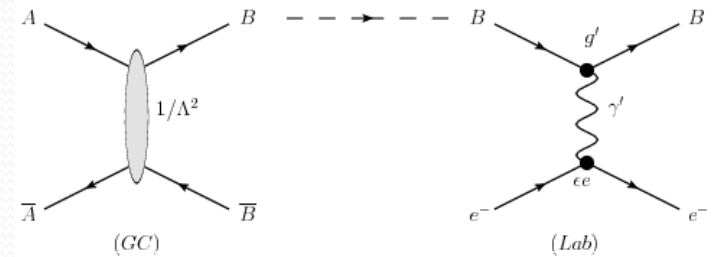


# Boosted Dark Matter

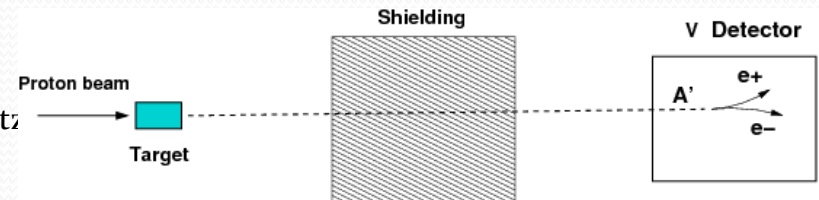
## ● Sources

### ☐ 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)]

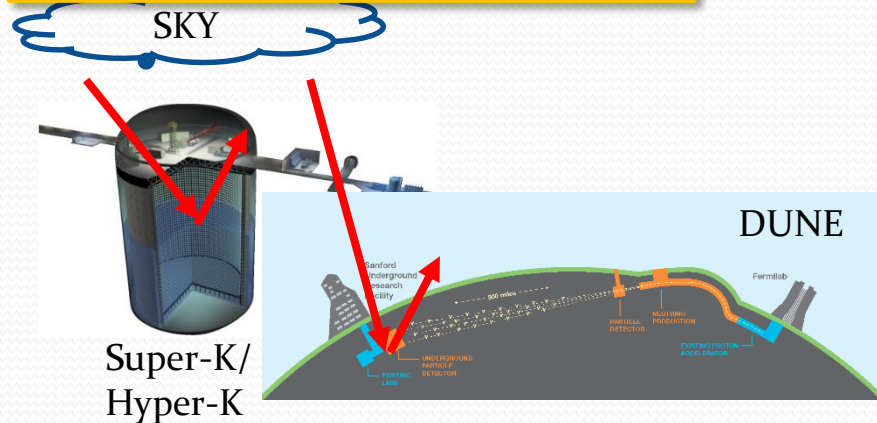


# Signal Detection

## ● Detection strategy

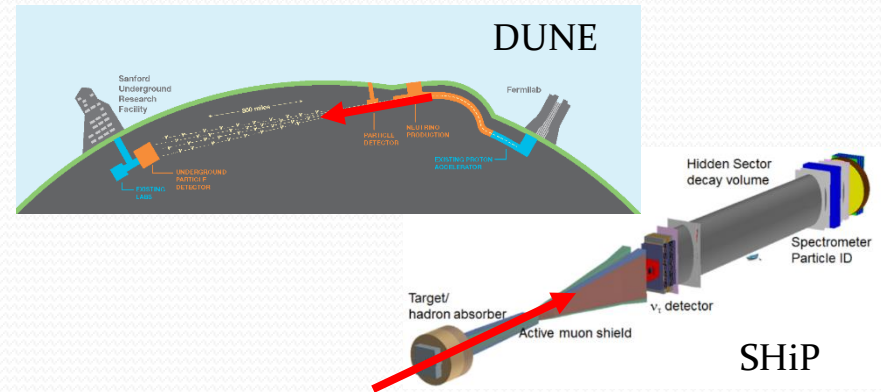
- Null observation of DM signatures may suggest small interaction strengths between SM particles and dark-sector particles (including DM).

### Large-volume (neutrino) detectors



“Passive” searches

### Intensity-frontier experiments



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



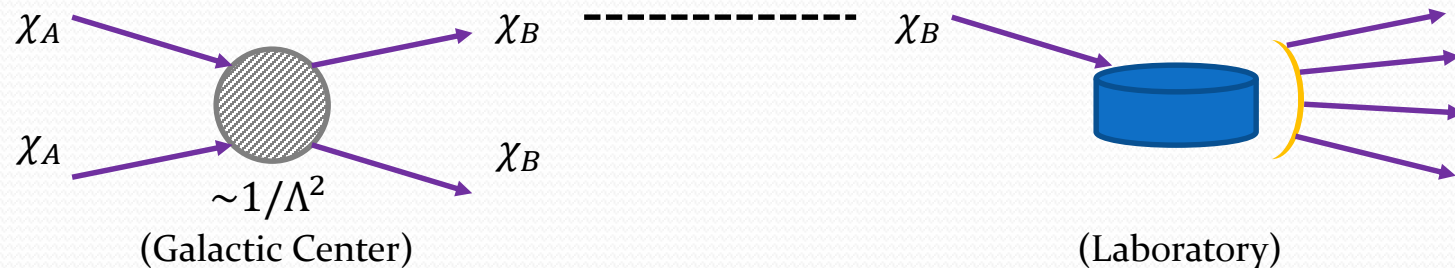
# **DM “Colliders” at the Cosmic Frontier**

# Boosted DM Source: Cosmic Frontier

## ● Boosted DM source

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

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



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

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

# Dark Sector Model

## ● Vector portal

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

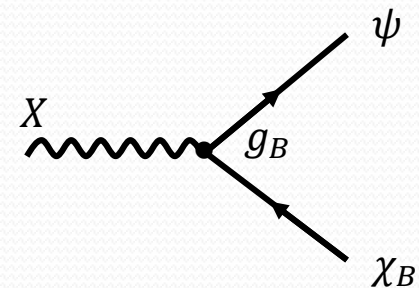
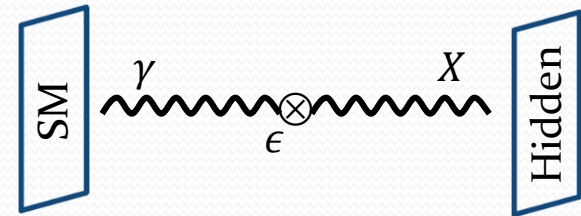
❑ **Vector portal** (e.g., dark “photon” scenario) [Holdom (1986)]

❑ Fermionic DM

❖ **Flavor-changing neutral current** [e.g., J.-E. Kim, M. S. Seo, and S. Shin (2012)]

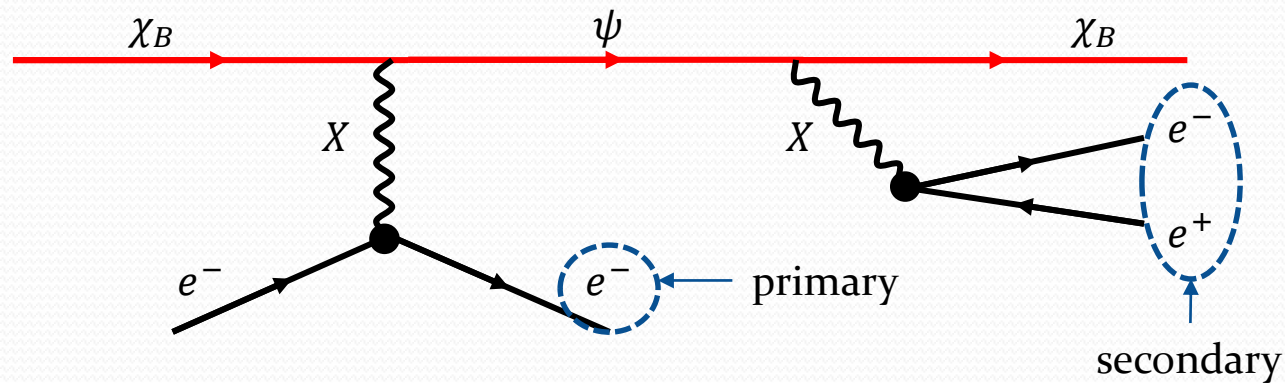
❖ (Relevant models may have flavor-conserving currents as well,  $\bar{\psi} \gamma^\mu \psi X_\mu$ ,  $\bar{\chi}_B \gamma^\mu \chi_B X_\mu$ )

❑ (**NOT restricted** to vector portal scenarios)



# Discovery Potential

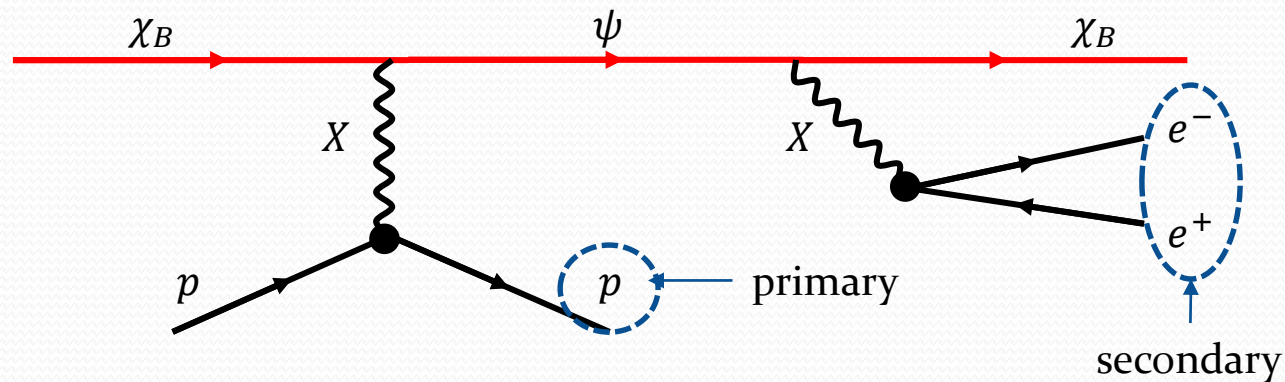
## ● Typical signal features: $e$ -scattering



- ❑ **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  $10^{-7} \text{ cm}^{-2} \text{ s}^{-1}$  with which our reference points become sensitive in various experiments.

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

	$m_{\chi_B}$	$m_\psi$	$m_X$	$\gamma_{\chi_B}$
$e$ -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
- ❖  $\gamma_{\chi_B}$ : boost factor of boosted DM  $\chi_B$
- ❖ “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  $\mathcal{O}(10^{-7}) \text{ cm}^{-2} \text{ s}^{-1}$ , it is **promising and achievable!**

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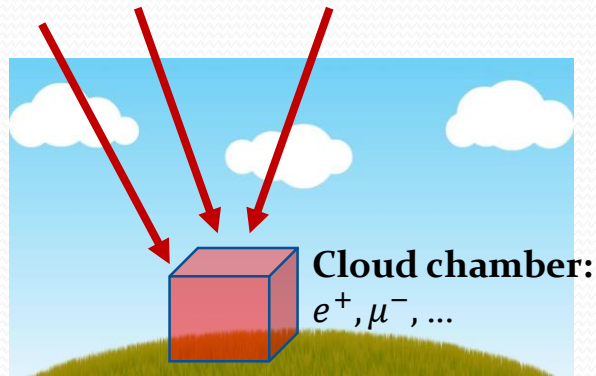
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- ❑ Remind, in a minimal boosted DM scenario, if flux over the whole sky is  $\mathcal{O}(10^{-7}) \text{ cm}^{-2} \text{ s}^{-1}$ , it is **promising and achievable!**
- ❑  $p$ -scattering improved at DUNE due to **smaller threshold energy**



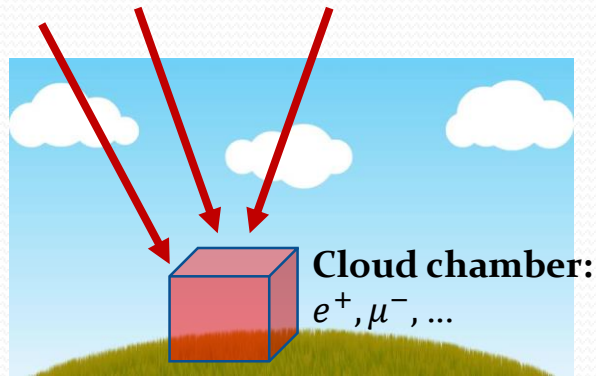
# **DM “Colliders” at the Intensity Frontier**

# New Particles at Cosmic Frontier



Passive searches

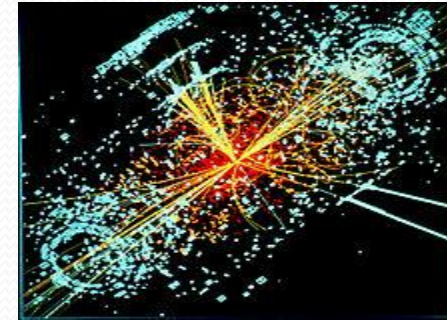
# New Particles at Energy Frontier



Passive searches

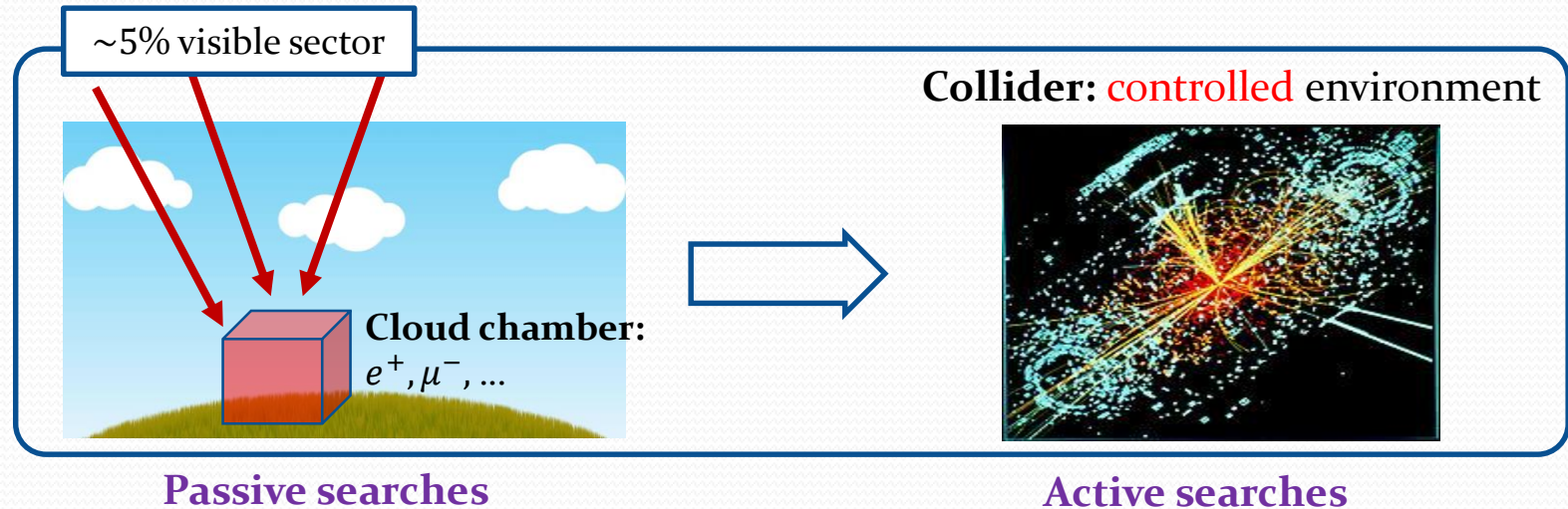


Collider: **controlled** environment

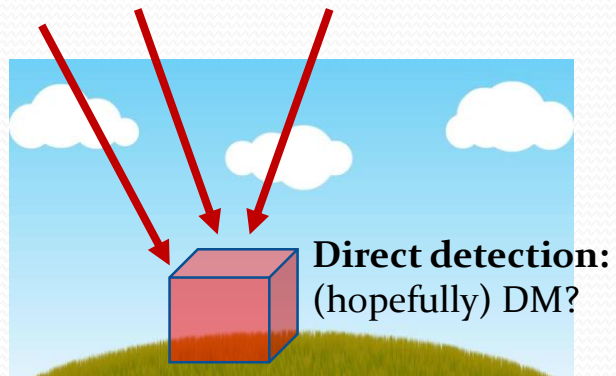
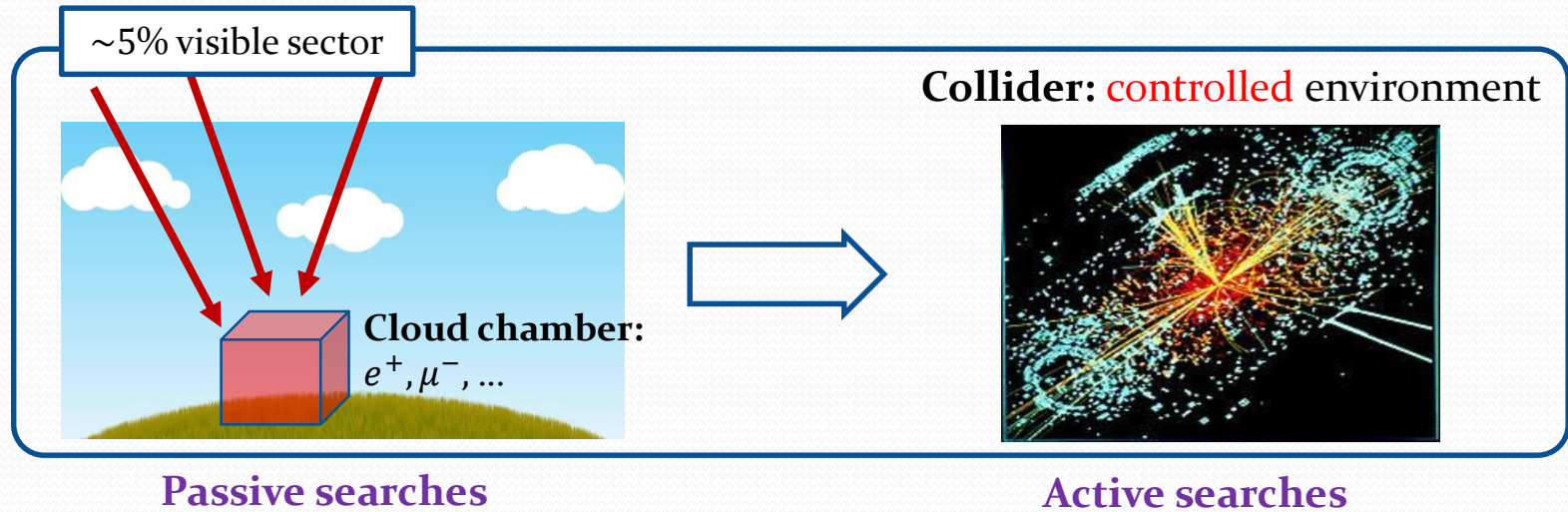


Active searches

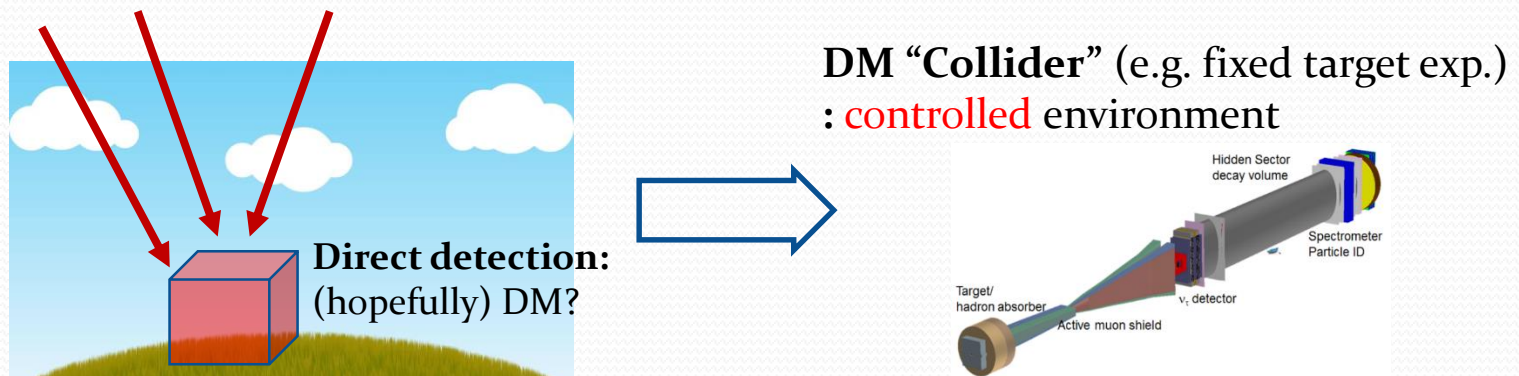
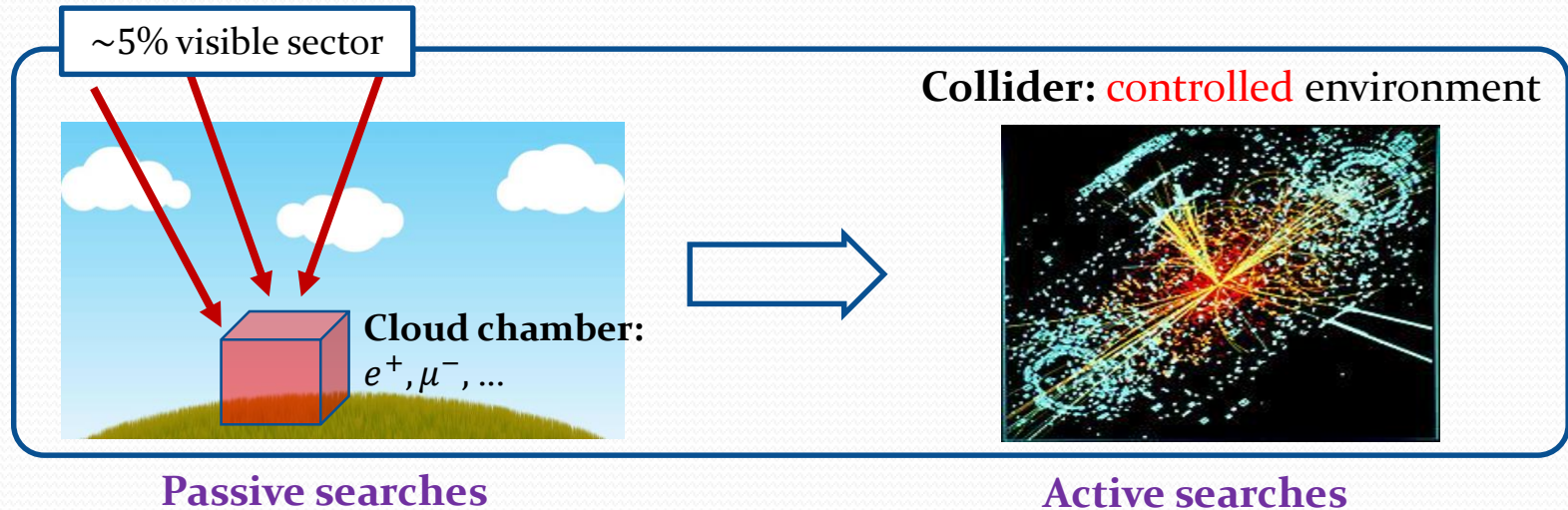
# Exploring the Visible Sector



# DM Searches at Cosmic Frontier

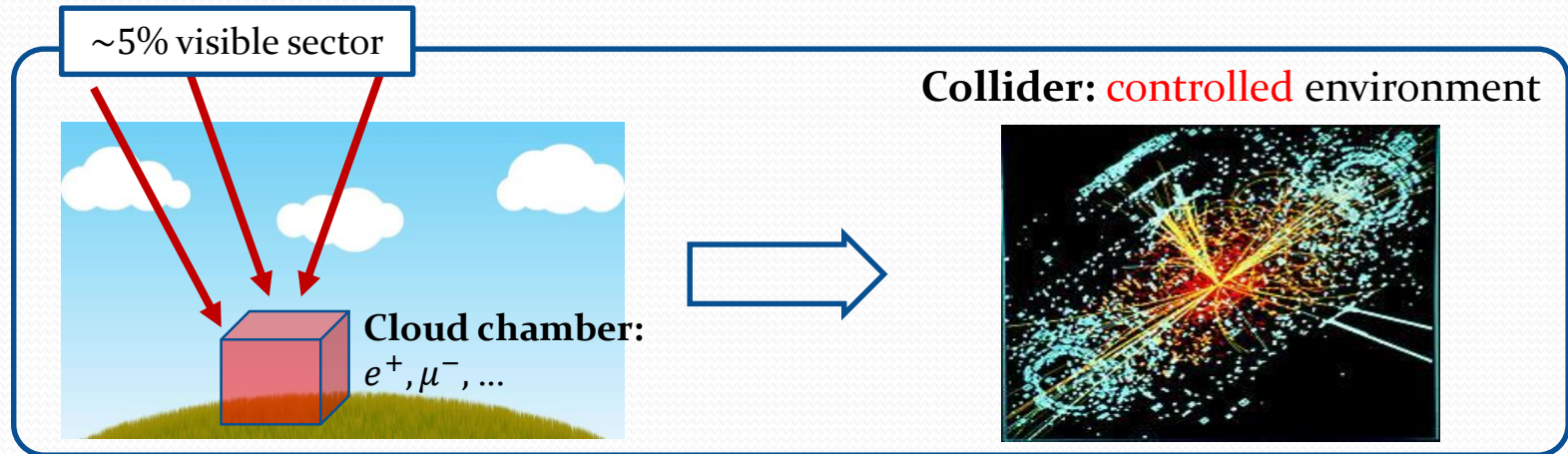


# DM Colliders at Intensity Frontier



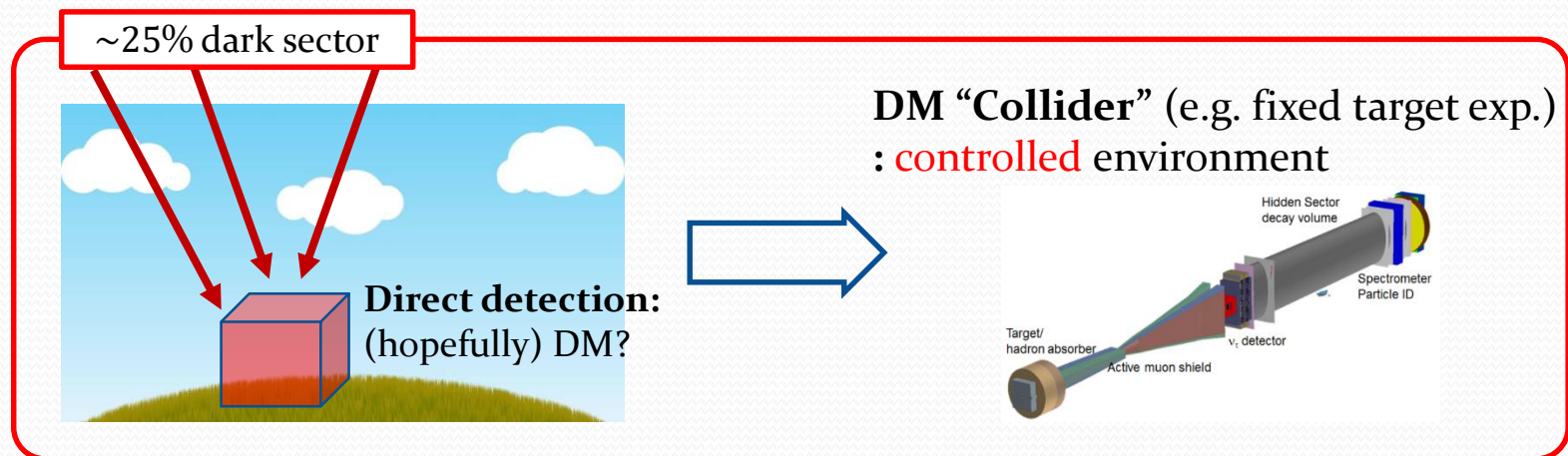


# Exploring the Dark Sector



Passive searches

Active searches



# Candidate Experiments

Exp.	DUNE	SHiP <sup>†</sup>	SK/HK <sup>‡</sup>
Near-far detector	Yes	Yes	(Yes)
Distance b/w detectors	1,300 km	50 m	(700 – 1,000) km
Volume*	8 t/ <b>40</b> kt	9.6 t/NA	<b>(190/190)</b> kt <b>22.5</b> 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	$11 \times 10^{20}$ /year	$0.4 \times 10^{20}$ /year	$48 \times 10^{20}$ /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

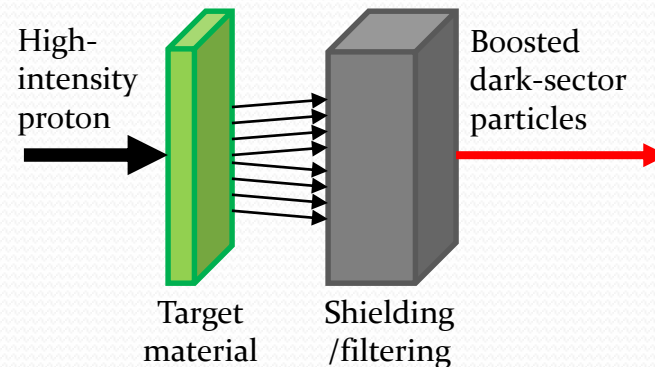
- DUNE/SHiP/Kamiokande **ideal for sub-GeV to GeV hidden sector particle searches**: different exps. require different strategies optimized to the production mechanism and associated detectors.

# Boosted DM Source: Intensity Frontier

## ● Physics opportunities at fixed target exps.

□ **Production by target collision** (e.g., in vector portal scenarios)

- Meson decay:  $pp \rightarrow \pi/\eta + \text{others}$ ,  
 $\pi/\eta \rightarrow X^*\gamma \rightarrow \chi_B\chi_B\gamma$ ;  $\pi/\eta \rightarrow X^*\gamma \rightarrow \chi_B\psi\gamma$ ;  $\pi/\eta \rightarrow X^*\gamma \rightarrow \psi\psi\gamma$
- Drell-Yan:  $pp \rightarrow X^* \rightarrow \chi_B\chi_B, \chi_B\psi, \psi\psi$
- **Boost of  $\chi_B$  given by a distribution**

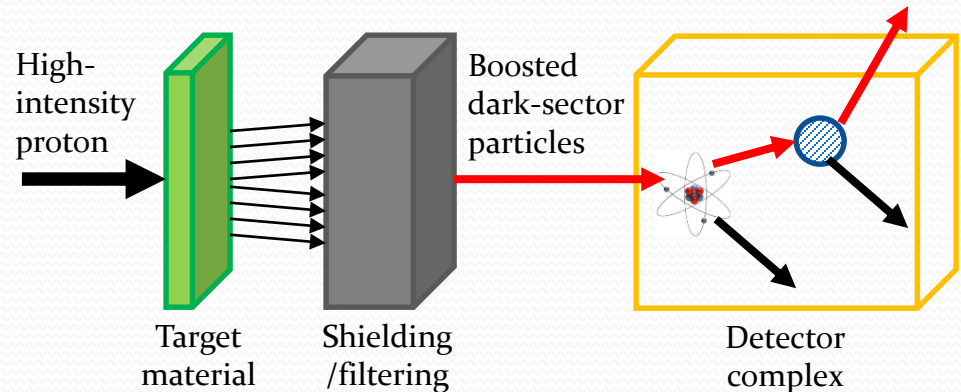


# Signal Detection

## ● Physics opportunities at fixed target exps.

### □ Production by target collision (e.g., in vector portal scenarios)

- Meson decay:  $pp \rightarrow \pi/\eta + \text{others}$ ,  
 $\pi/\eta \rightarrow X^*\gamma \rightarrow \chi_B\chi_B\gamma$ ;  $\pi/\eta \rightarrow X^*\gamma \rightarrow \chi_B\psi\gamma$ ;  $\pi/\eta \rightarrow X^*\gamma \rightarrow \psi\psi\gamma$
- Drell-Yan:  $pp \rightarrow X^* \rightarrow \chi_B\chi_B, \chi_B\psi, \psi\psi$
- **Boost of  $\chi_B$  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)

# Dark Matter “Colliders” and Beyond

**The cosmic  
frontier**

**Monte Carlo  
Simulation**

**The intensity  
frontier**

**Conventional  
DM direct detection**

**The DM “collider”**

**New physics/DM  
model building**

**Collider  
phenomenology**



# 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**

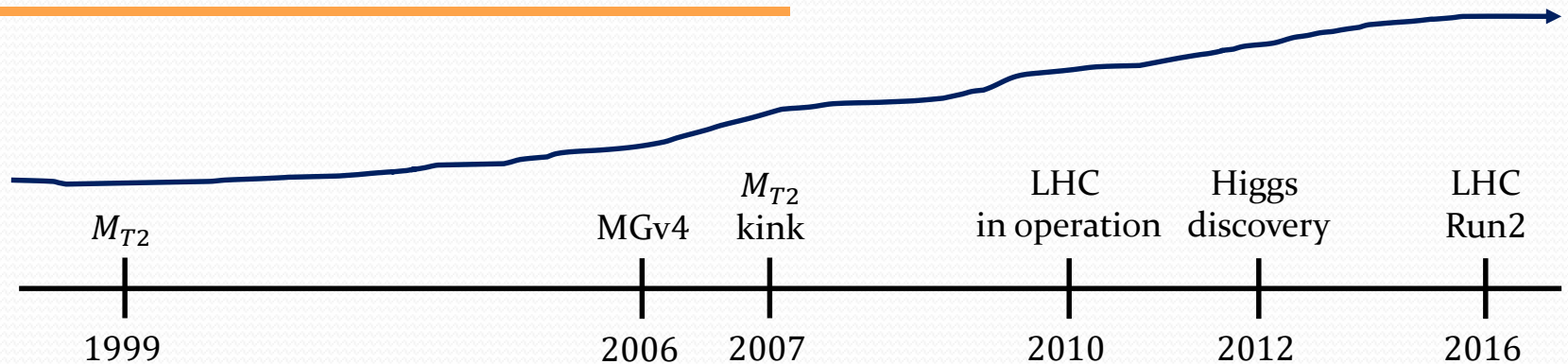
- ✓ Signal detection prospects at standard colliders
- ✓ Applying collider variables to DM colliders
- ✓ Developing optimized variables for DM colliders

## ☐ Constructing **new physics models** probable at DM colliders

- ✓ Light KK graviton model (in progress)
- ✓ UV-completed/effective hidden-sector models

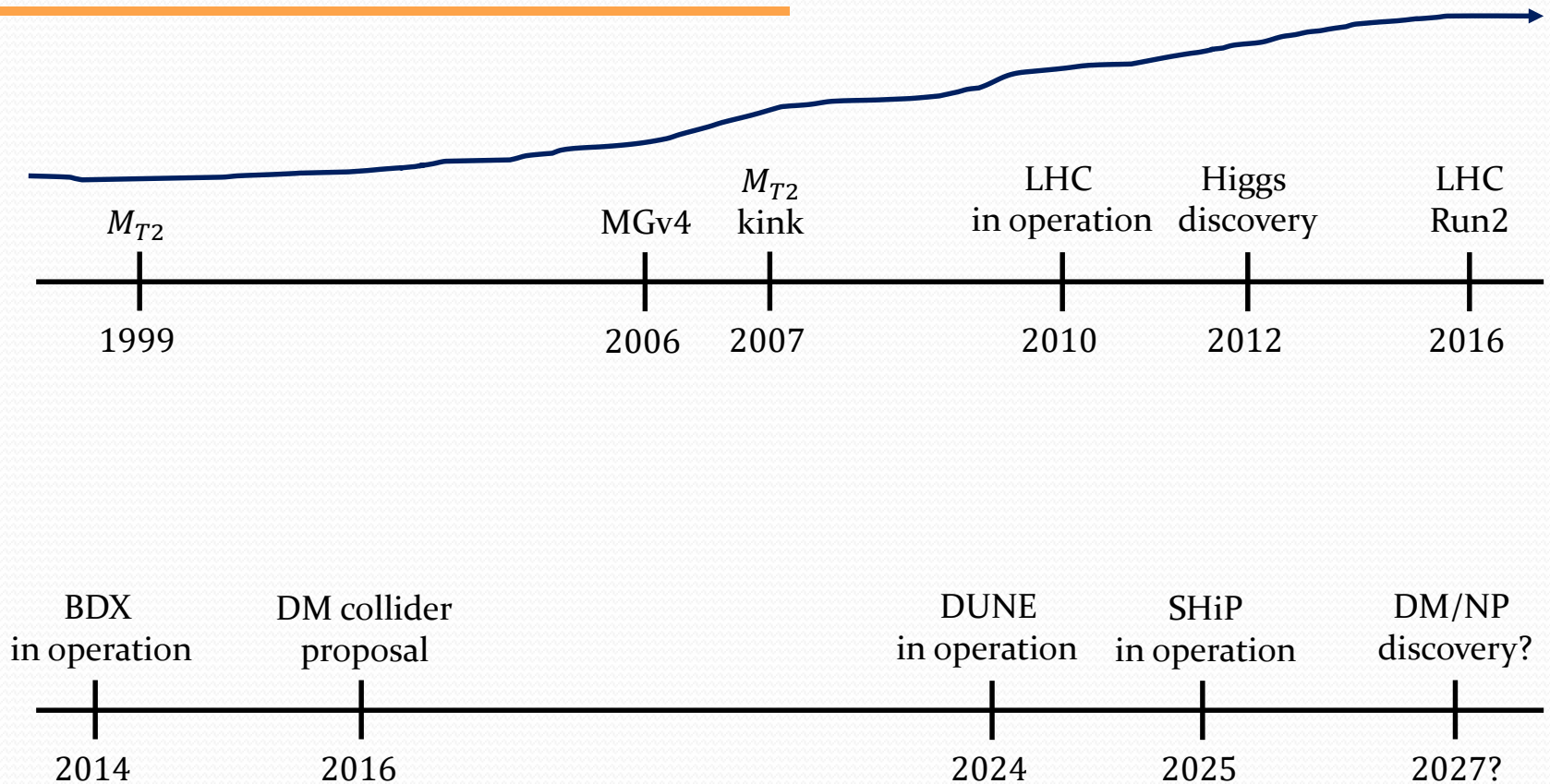
# DM Collider Physics: Take-home Message

## ● Collider physics vs. DM collider physics



# DM Collider Physics: Take-home Message

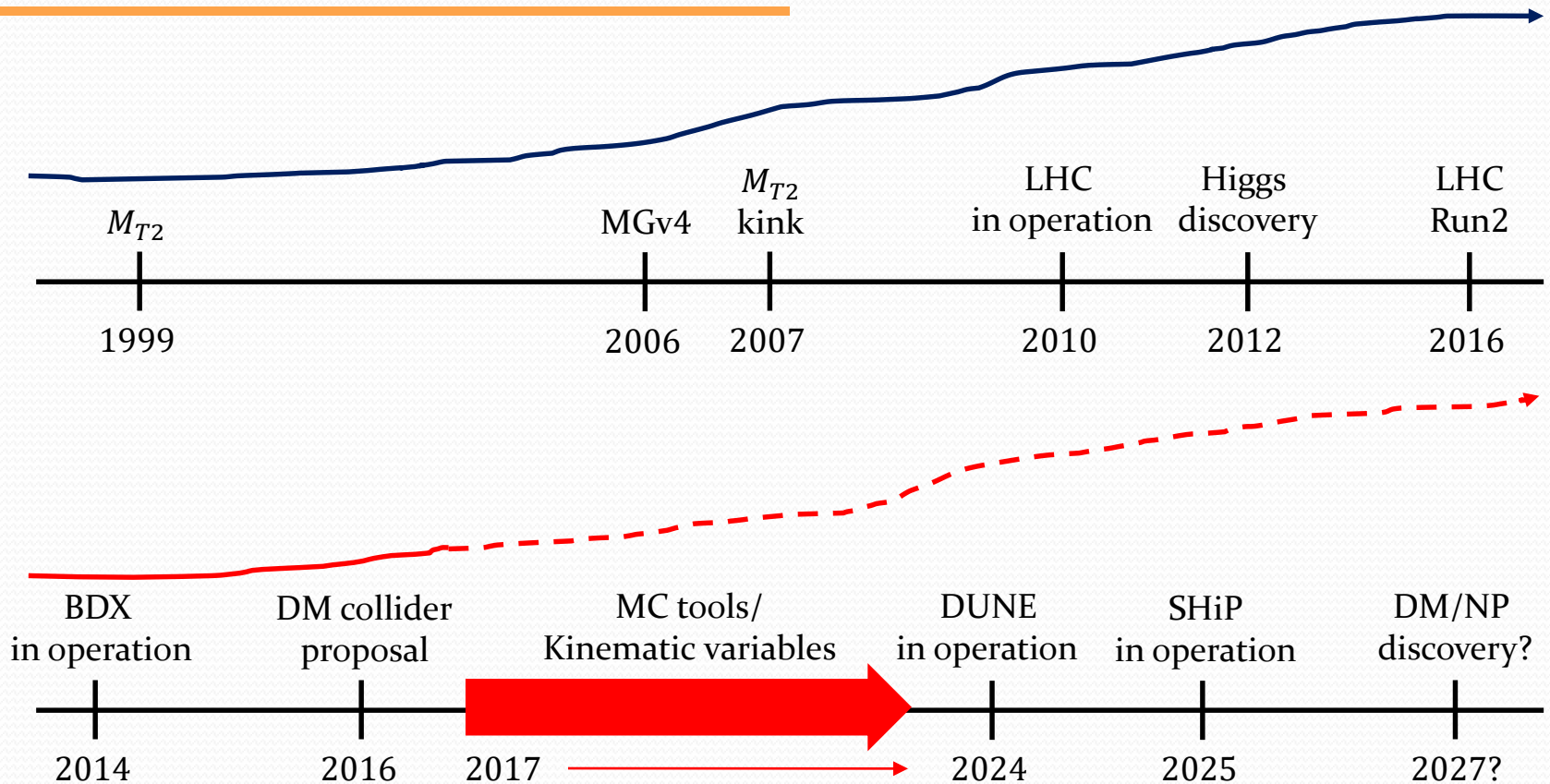
## ● Collider physics vs. DM collider physics





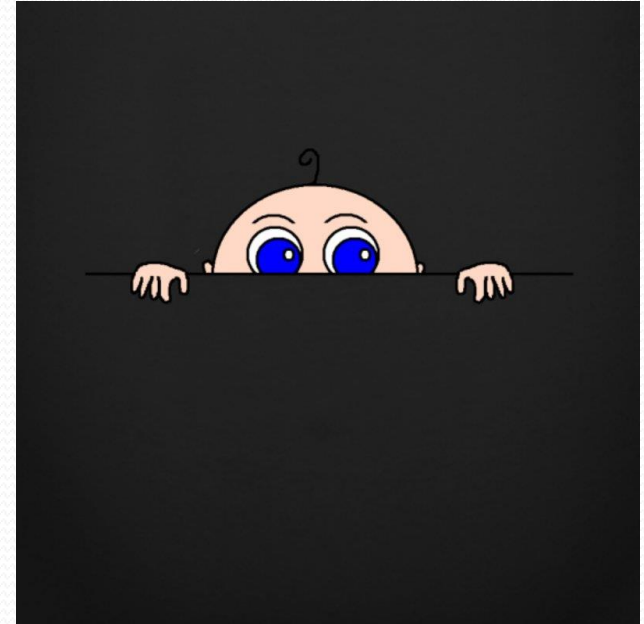
# DM Collider Physics: Take-home Message

## ● Collider physics vs. DM collider physics



# Conclusions

- ❑ What's going on at the weak scale?  $\Rightarrow$  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  $\Rightarrow$  **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  $\rightarrow$  **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!

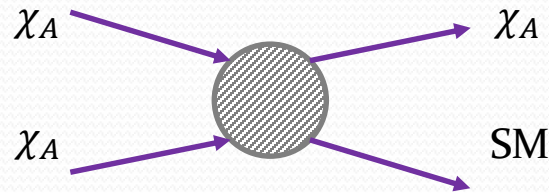


# Back-up

# 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

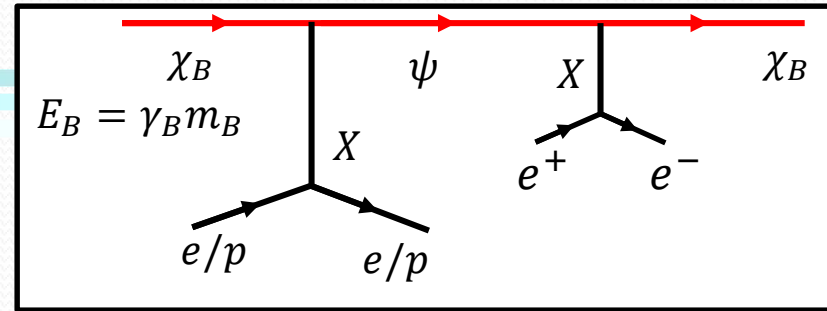


- Under the circumstance in which the mass of SM here is lighter (i.e.,  $m_A > m_{SM}$ ), the outgoing  $\chi_A$  can be boosted and its boost factor is given by

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

# Signal Attributes

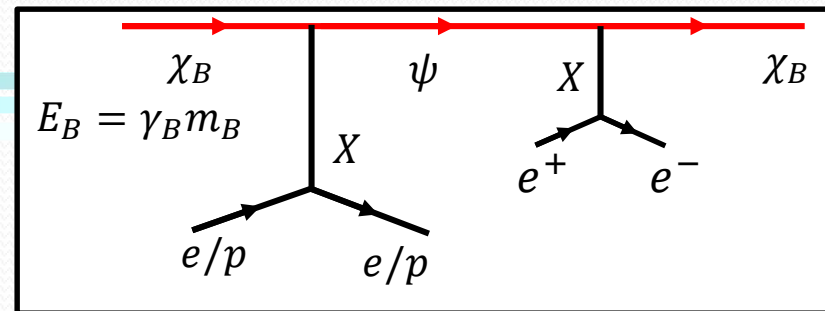
## ● Comparison b/w e- and p-scatterings



Exp.	e-scattering	p-scattering
Energy for primary scattering	Peaking towards smaller momentum transfer	Large for Cherenkov (Small for DUNE/SHiP detectors)
Threshold energy	Small	Yes
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 $\theta_{res} \sim 3^\circ$ , <b>better at DUNE/SHiP</b> )	Reasonably separated (in preferred mass spectra) Recoil proton + well-separated $e^+ e^-$ pair

# Signal Attributes

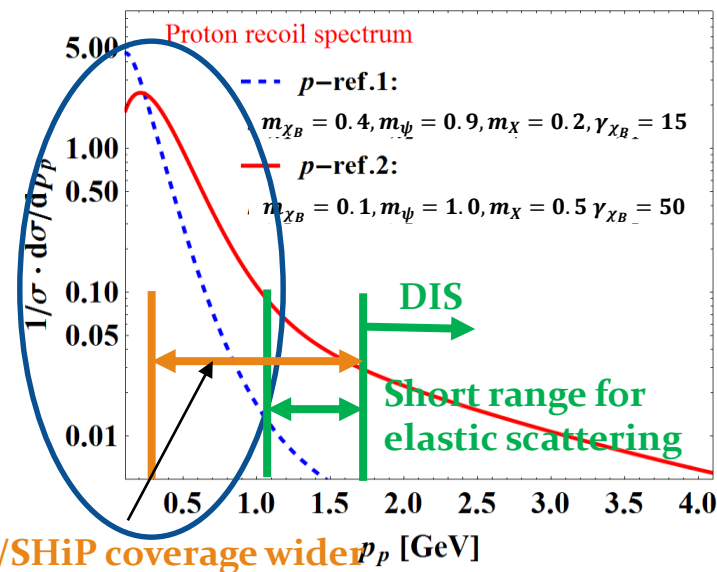
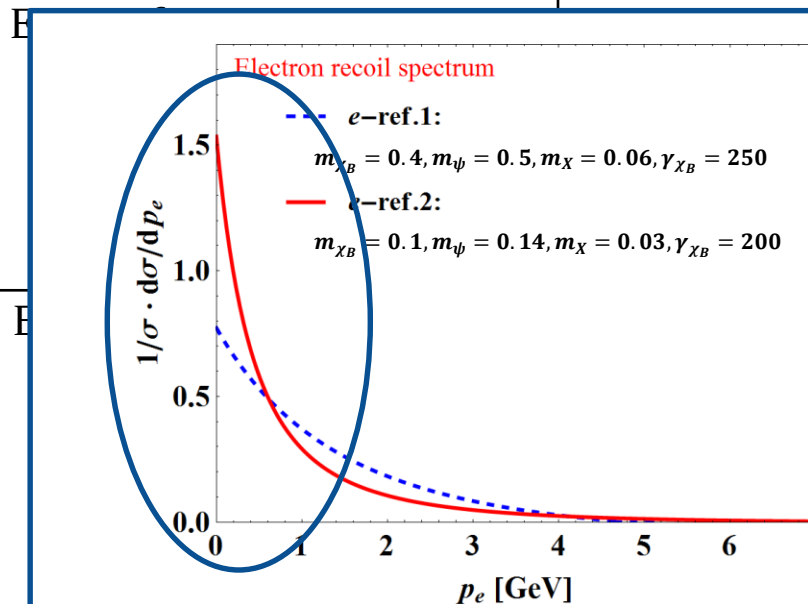
- Comparison b/w e- and p-scatterings



Exp.

e-scattering

p-scattering

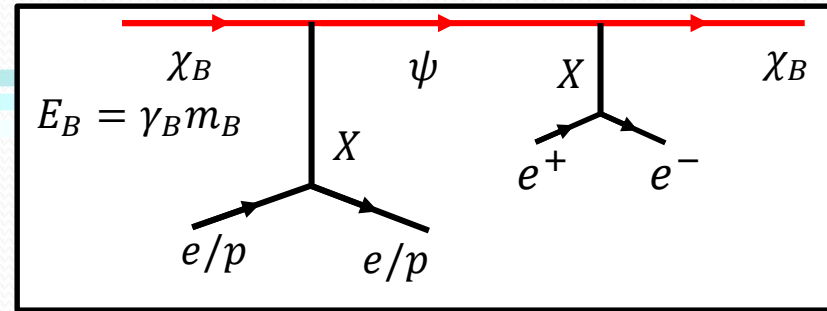


DUNE/SHiP coverage wider

DUNE/SHiP)

# Signal Attributes

## ● Comparison b/w e- and p-scatterings

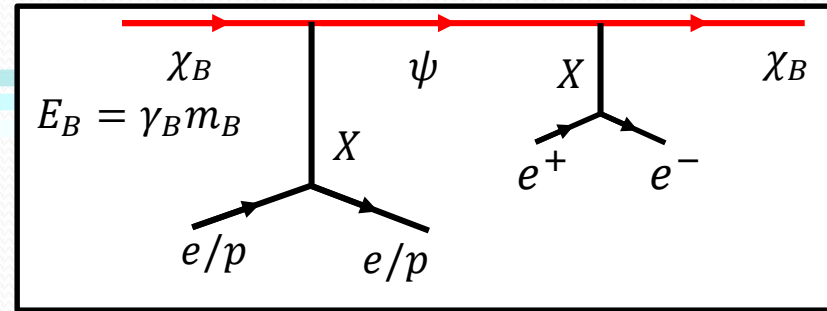


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# Signal Attributes

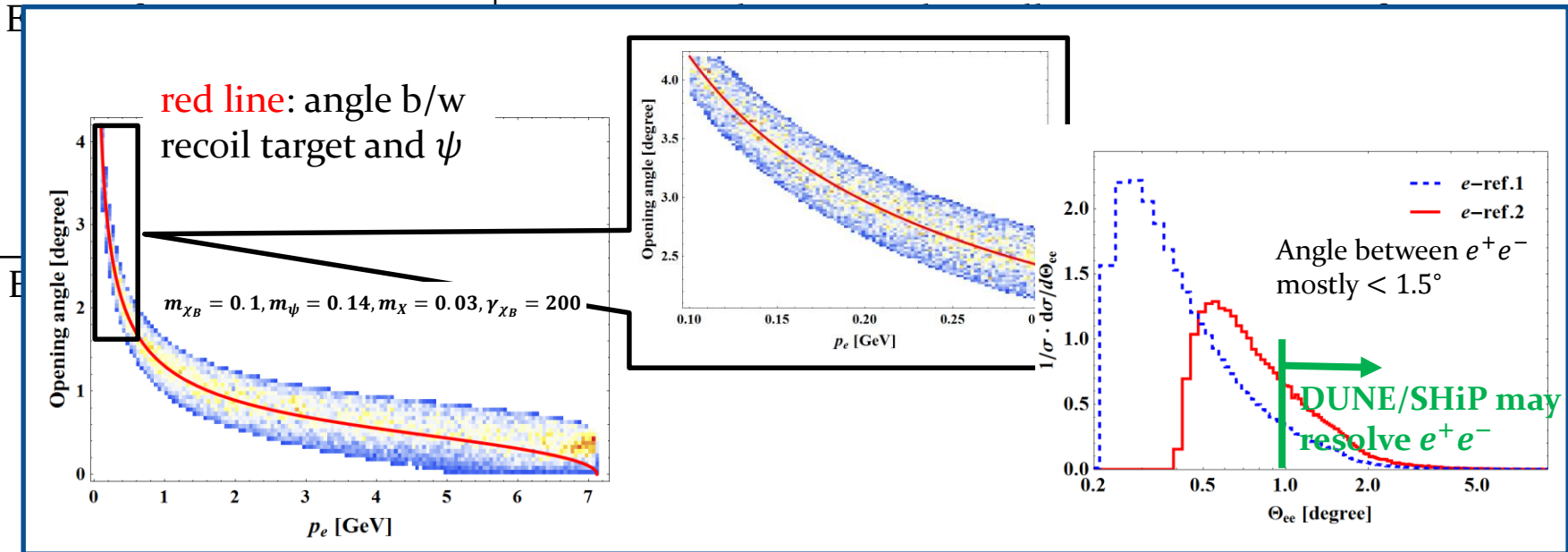
- Comparison b/w e- and p-scatterings



Exp.

e-scattering

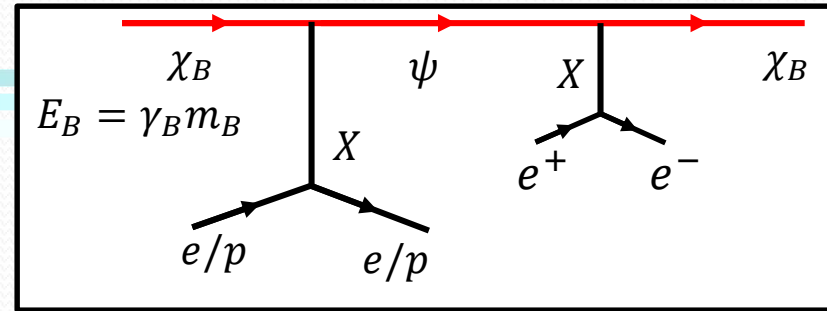
p-scattering



DUNE/SHiP)

# Signal Attributes

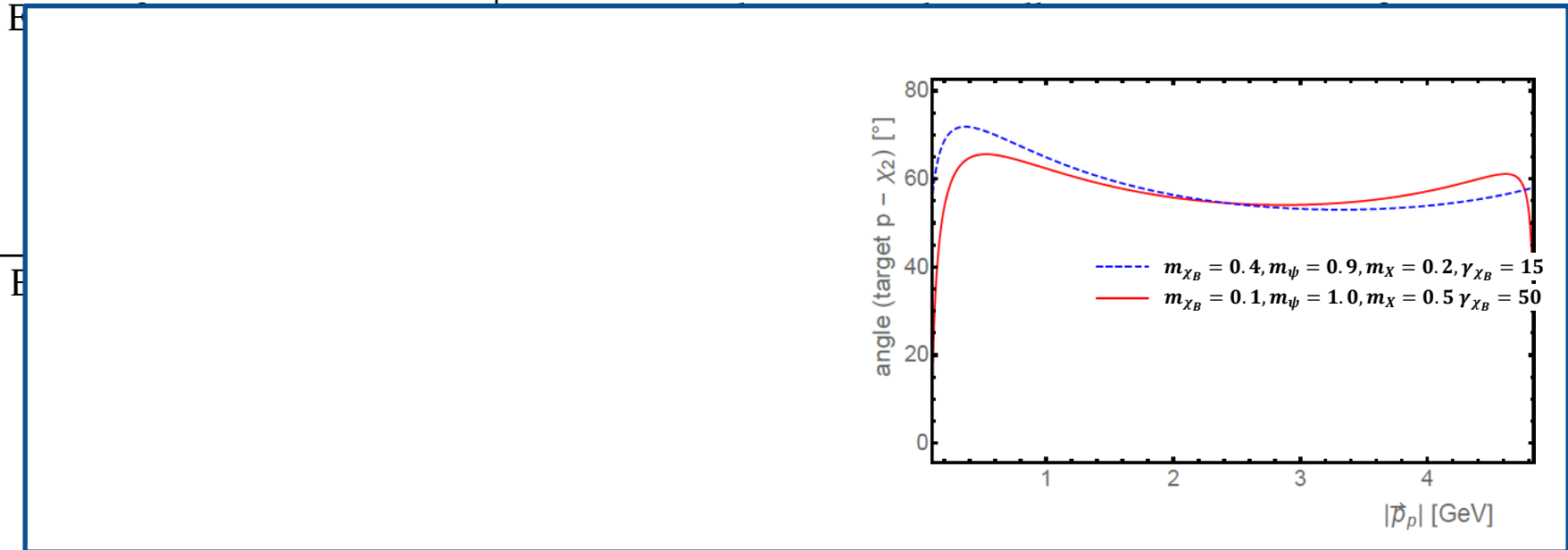
- Comparison b/w e- and p-scatterings



Exp.

e-scattering

p-scattering

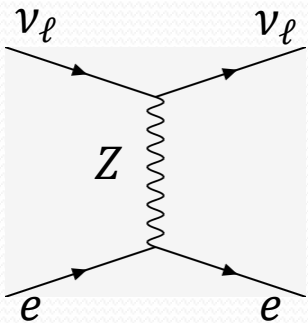


DUNE/SHiP)

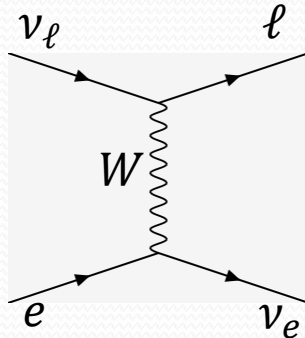
# Background Considerations

## ● Potential sources

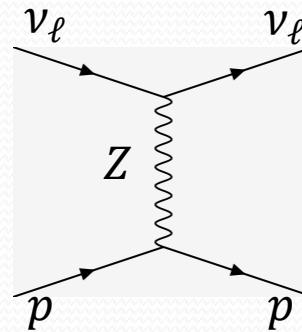
- ❑ Cherenkov radiation (CR) by electron/muon is distinguished from that by proton.
- ❑ Electron-preferred scenarios:



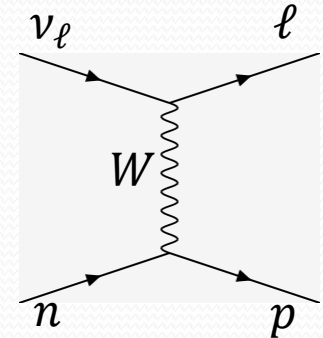
: CR by an N.C.  
electron



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



: CR by an N.C.  
proton unless broken

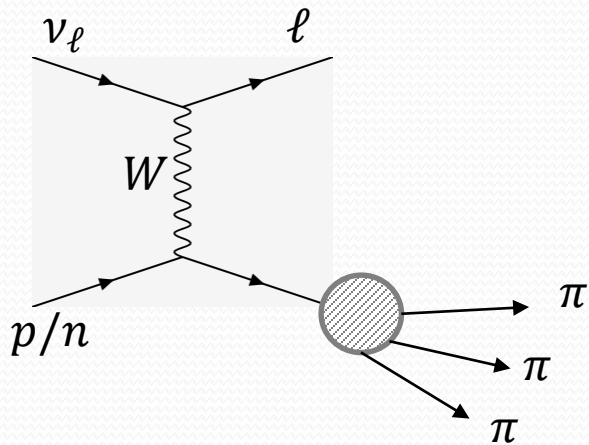


: CR by at least, a C.C.  
proton unless broken

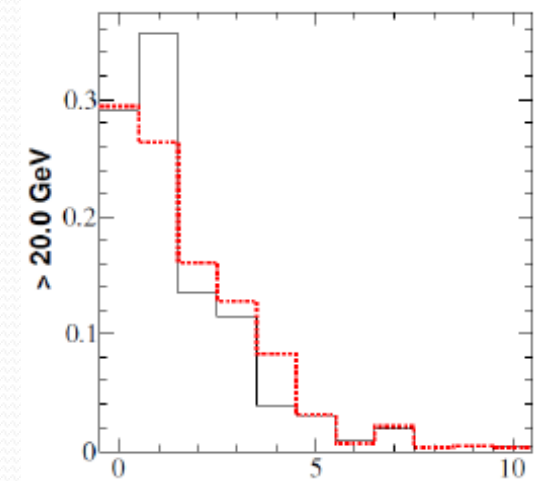
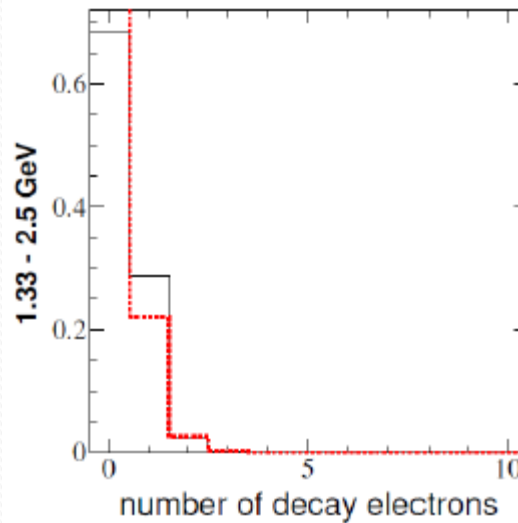
- ❑ Proton-preferred scenarios: opening angles among recoil proton, decayed electrons are large enough to resolve

# Background Considerations

- More challenging cases: broken nuclei



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

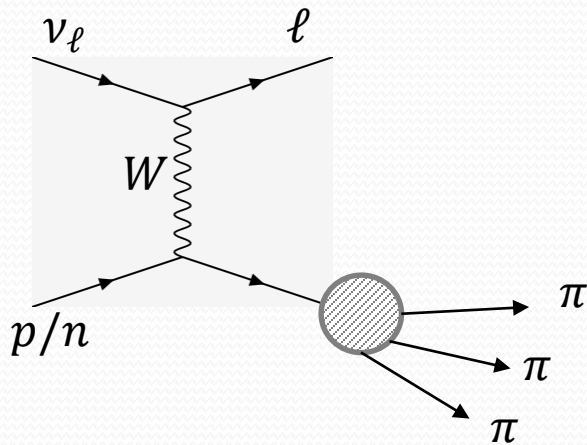


Super-K (2012)

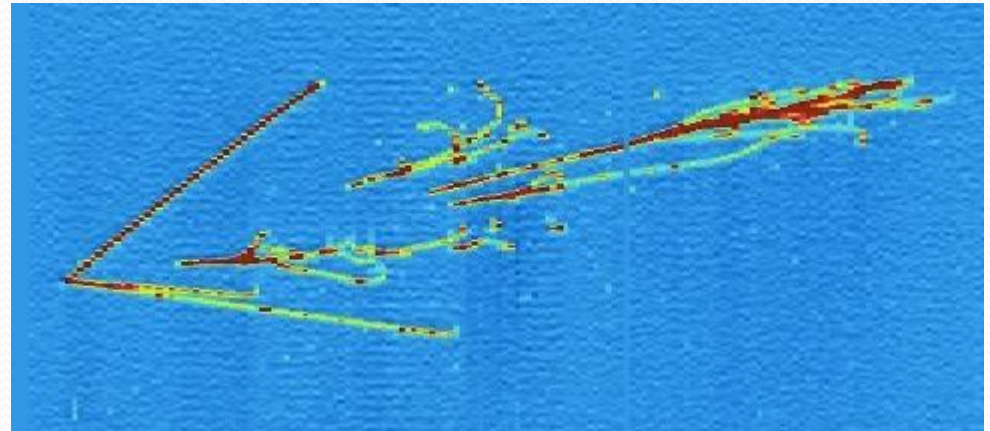
- Similar expectations for neutral currents
- (Dedicated study in progress)

# Background Considerations

- More challenging cases: broken nuclei



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

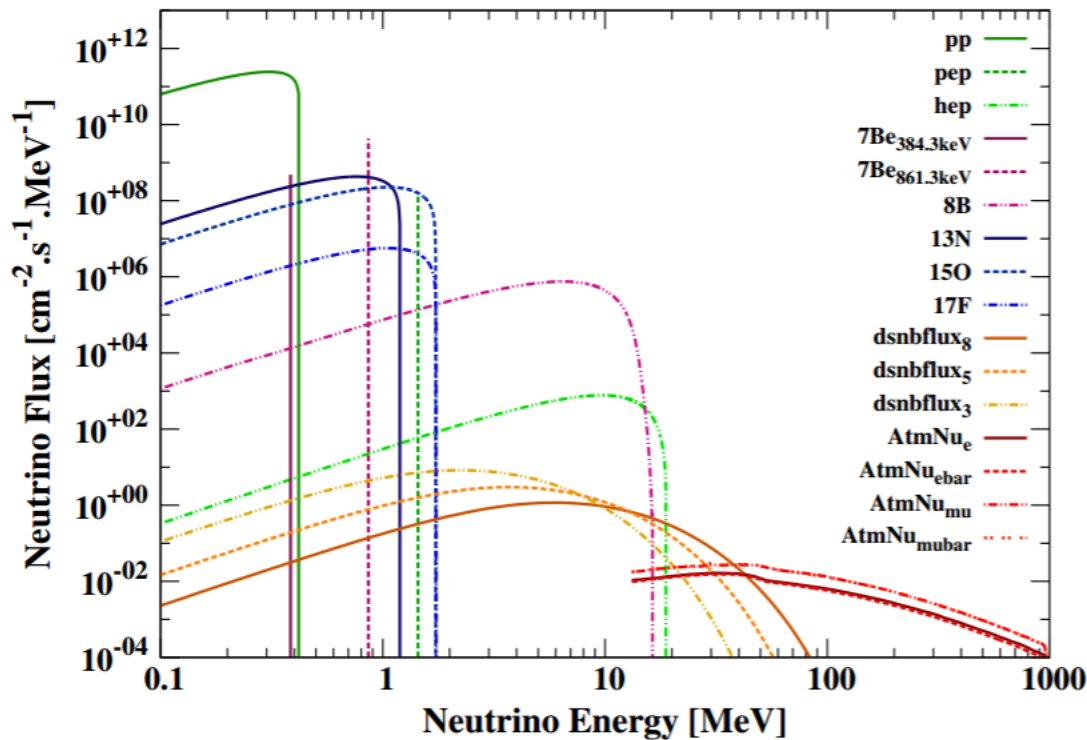


Particle tracks created by a neutrino interaction in liquid argon in the ArgoNeuT

- 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

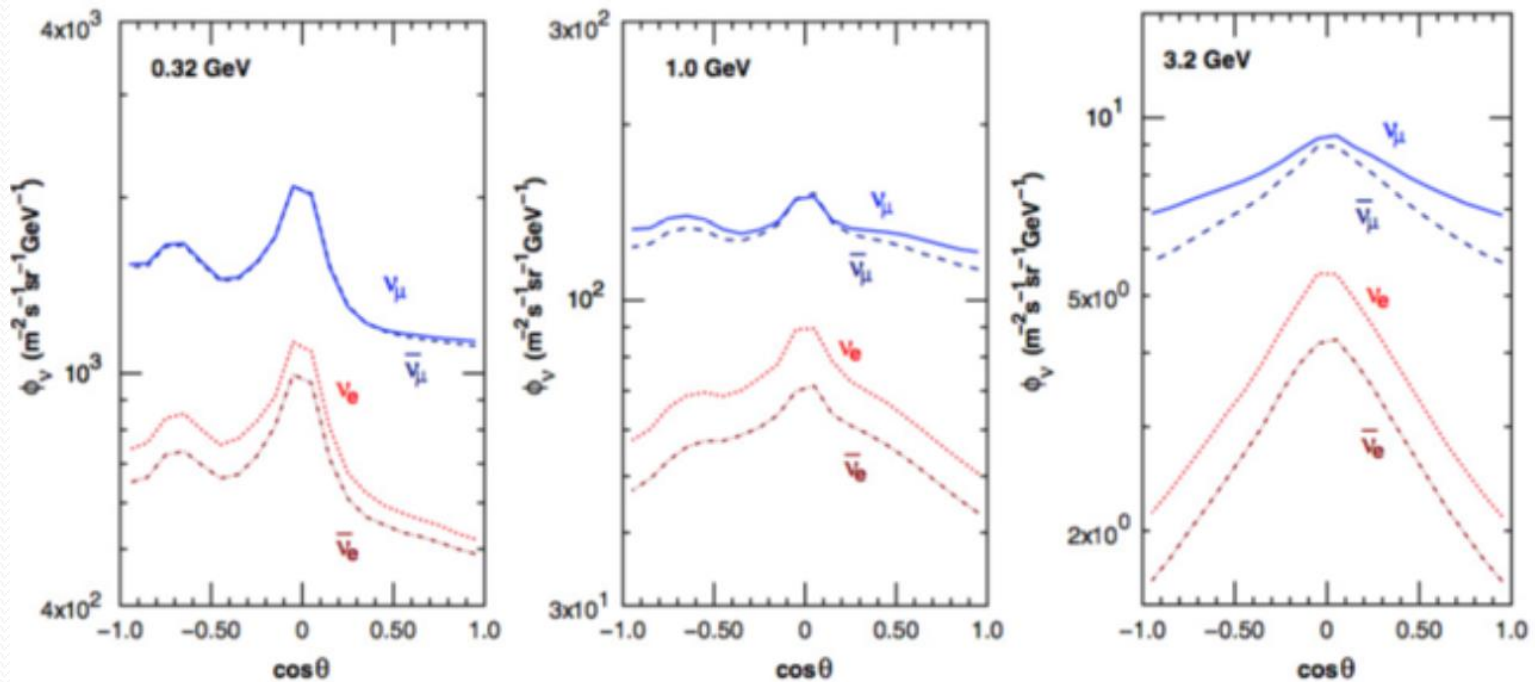


[Ruppin et al., (2014)]

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

# Flux of Atmospheric Neutrino

- Neutrino as a background

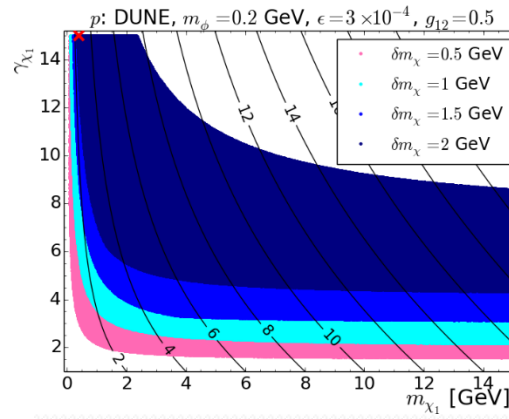
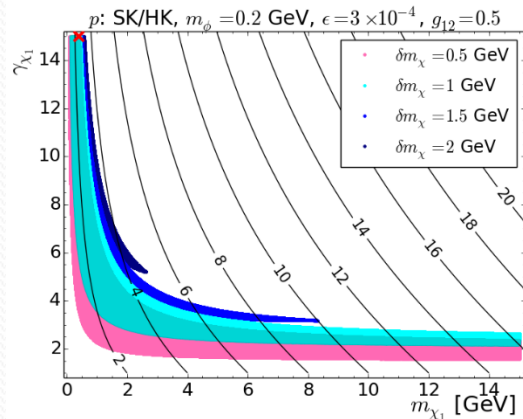
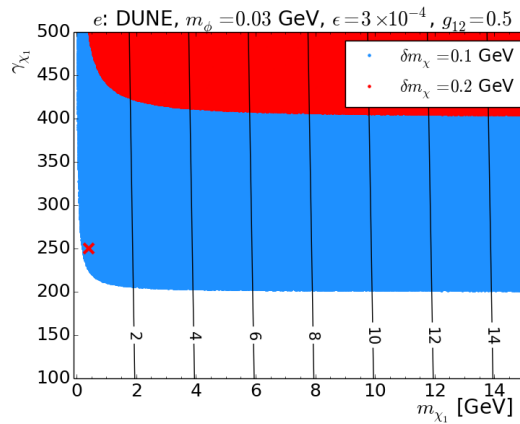
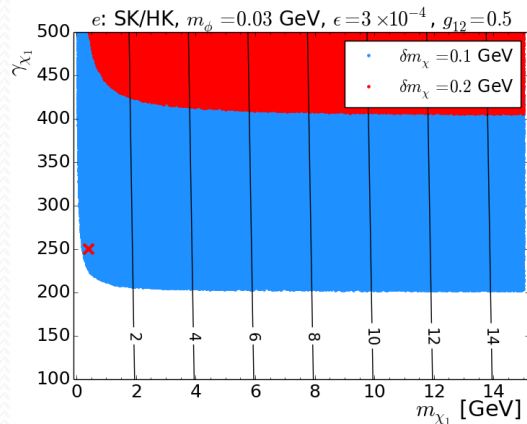


$\theta$ : zenith angle

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
- $m_{\chi_1}$ : mass of incident boosted DM,  $\gamma_{\chi_1}$ : boost factor of incident boosted DM,  $\delta m_\chi$ : mass gap between the DM and the heavier state



# Current Status of Dark Photon Searches

## ● Kinetic mixing parameter choice

