Brookhaven Forum 2017

Dark matter collider: relativistic scattering of boosted DM

Seodong Shin

1612.06867 (PRL) with Doojin Kim, Jong-Chul Park

Work in progress with Gian Giudice, Kim + Park

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THE UNIVERSITY OF CHICAGO

Thanks to BF2015

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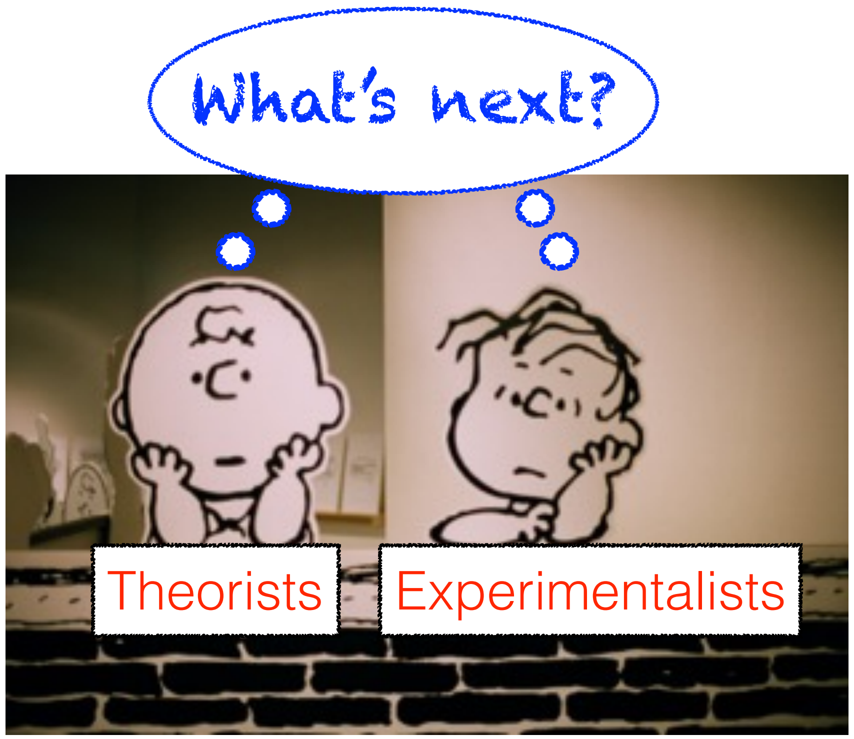
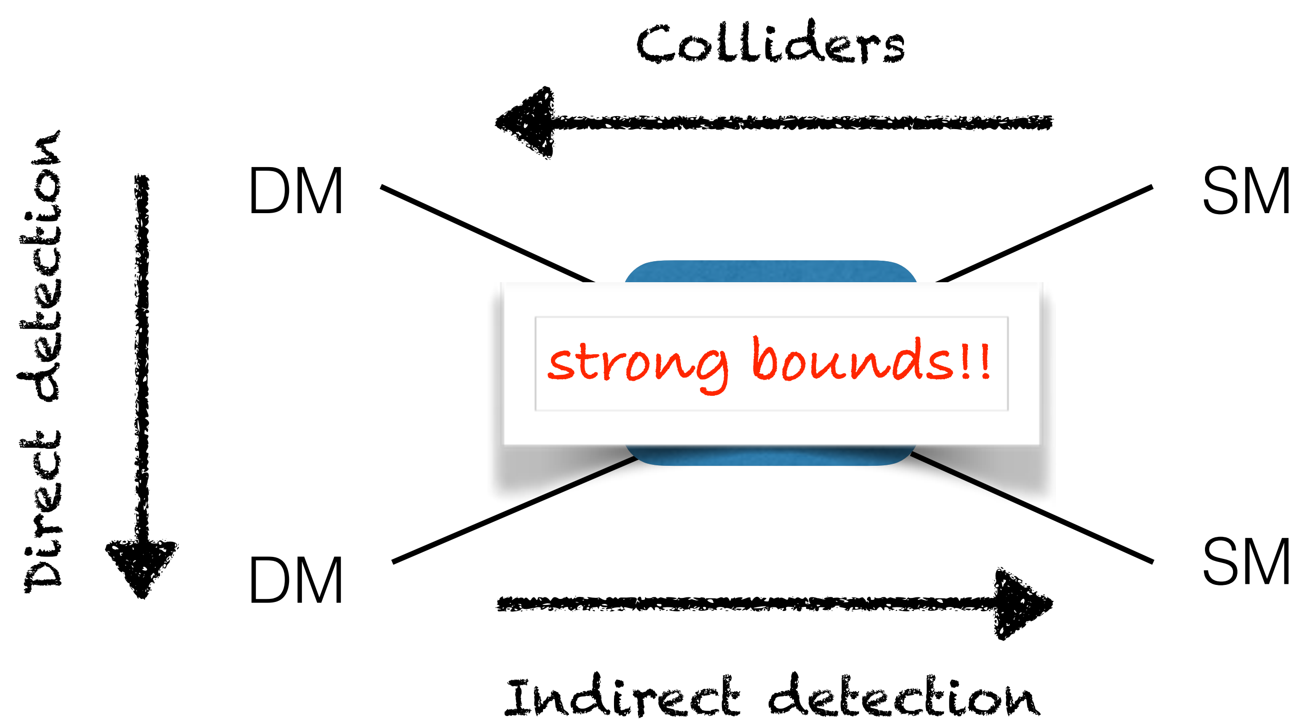
Not easy tasks





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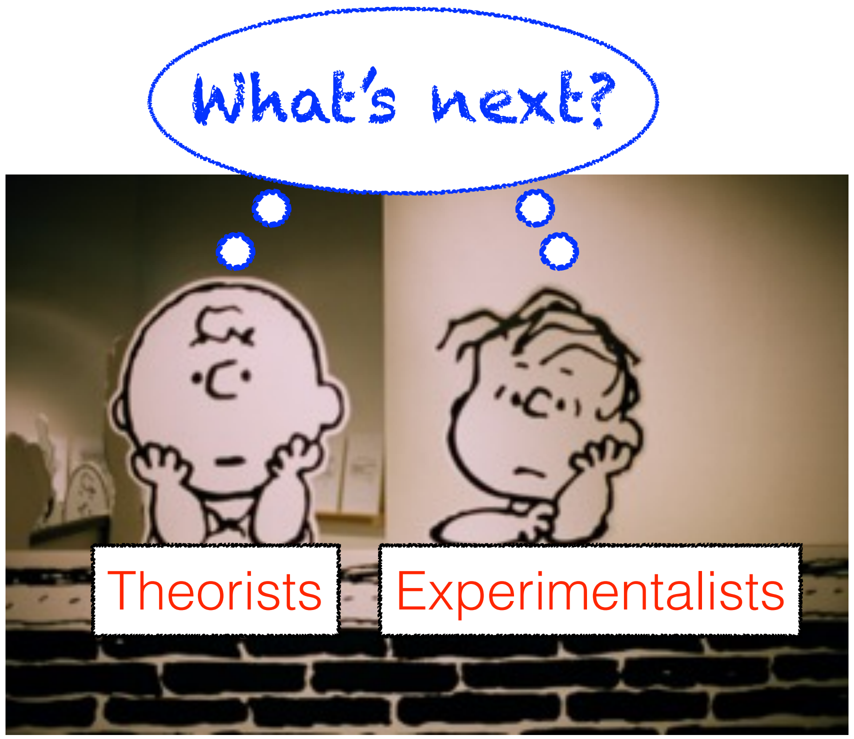
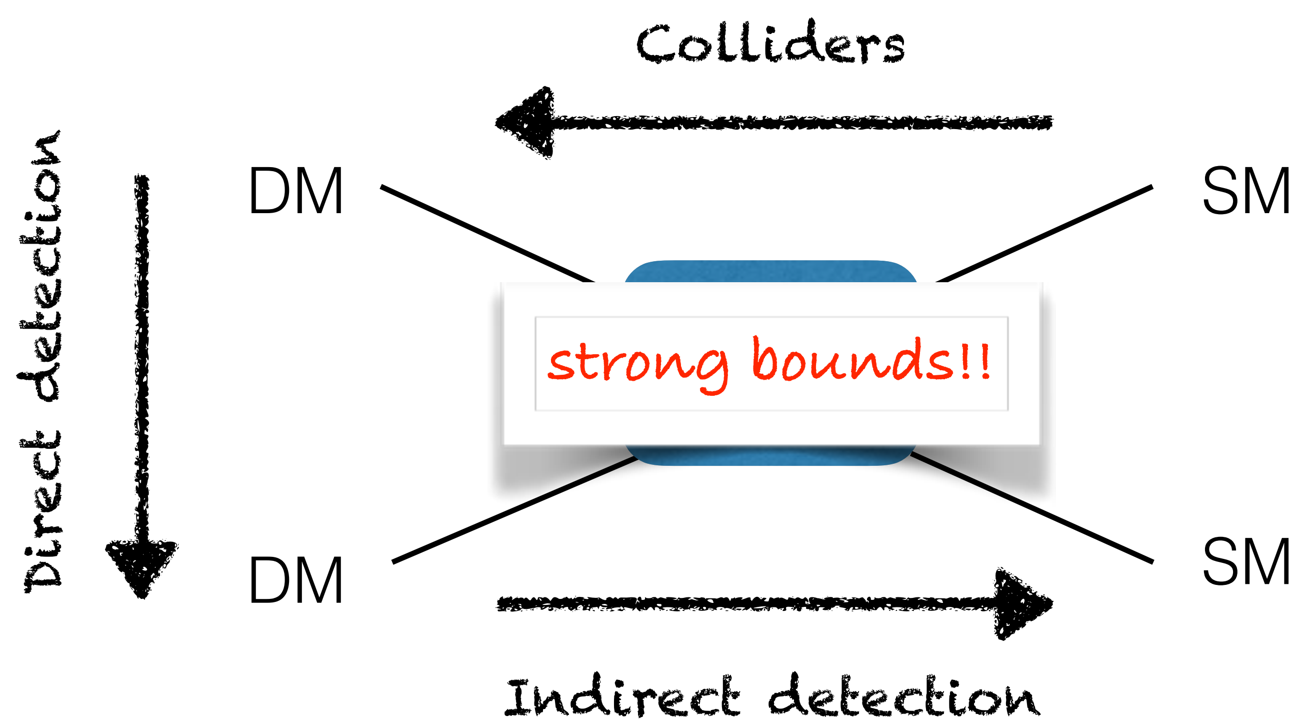
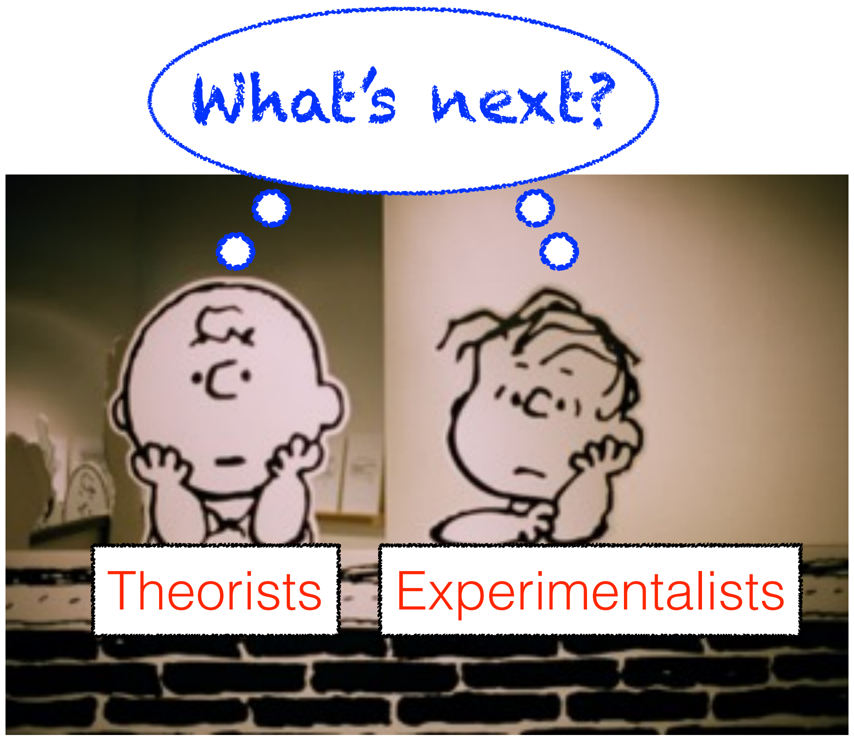


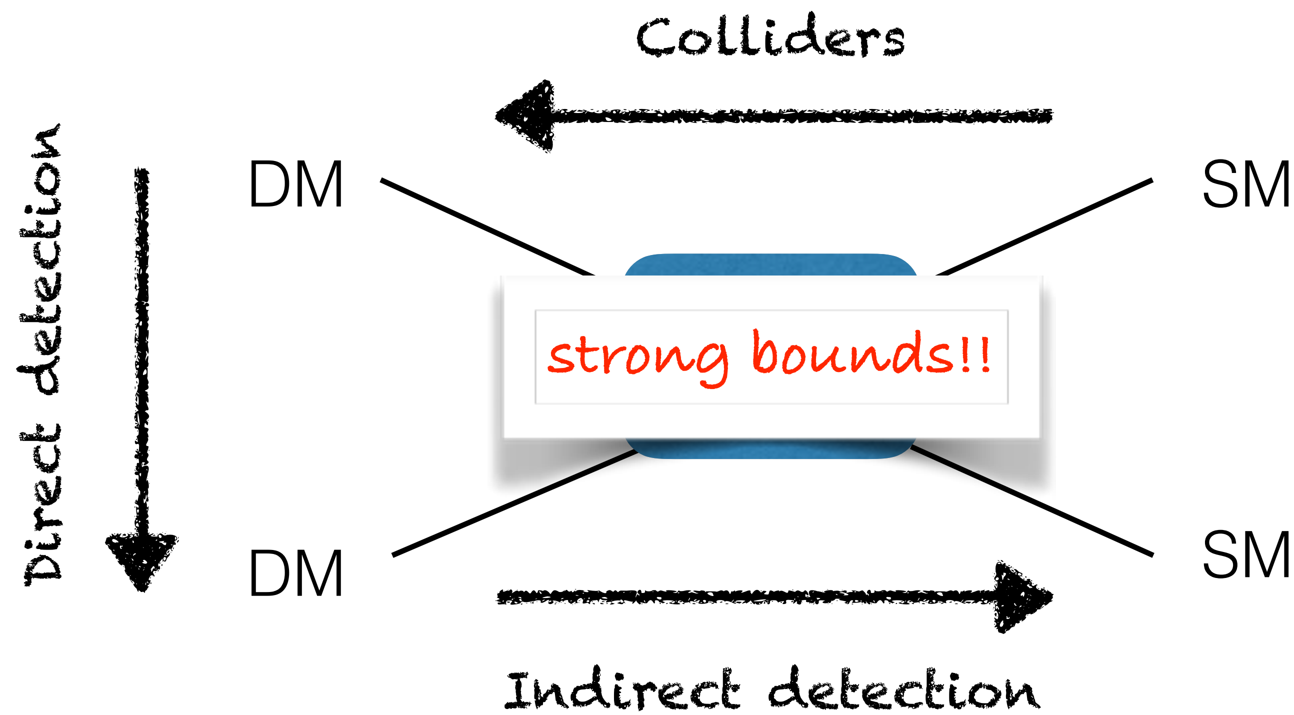


- Keep probing the rest of the corners of parameter space: tons of models may be still there!!

- Non-conventional DM & search strategy must be considered!

Not easy tasks





- Keep probing the rest of the corners of parameter space:
  tons of models may be still there!!

- Non-conventional DM scenario & search strategy

  Conventional WIMP (weak scale mass and int. with SM)

Non-conventional DM scenarios

- Flavorful (non-minimal) dark sector:
  multi-component DM and/or + unstable particles (like SM)
  e.g., inelastic DM, boosted DM, …
- Secluded WIMP: DM-SM int. suppressed (avoid LHC & DD bounds)
- Non-conventional interactions of DM-DM: self-int., strongly-int.
- Very light DM ($\ll$ GeV)

Non-conventional DM scenarios

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- Very light DM ($\ll$ GeV)

Non-conventional search strategy needed!

Non-conventional search strategy

My focus

Relativistic scattering of DM with target in LAB
(non-conventional direct detection)

- Some components of DM relativistically produced: **boosted DM**

  Agashe, Cui, Necib, Thaler, 1405.7370

  Kong, Mohlaberg, Park, 1411.6632

- (Light) DM can be produced in fixed target experiments

  Bjorken, Essig, Schuster, Toro, 0906.0580

  Batell, Pospelov, Ritz, 0906.5614

  Izaguirre, Krnjaic, Schuster, Toro, 1403.6826

Many talks in this workshop

Non-conventional search strategy

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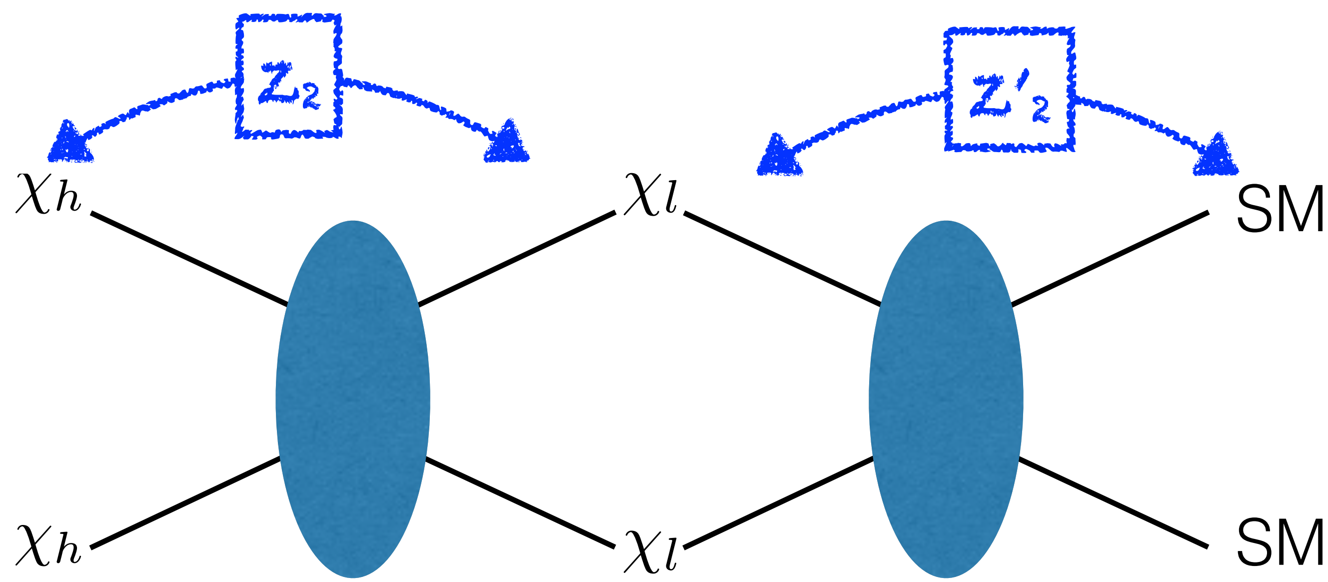
In this talk: Cosmic frontier search

Non-conventional search strategy

e.g., boosted dark matter



Agashe, Cui, Necib, Thaler, 1405.7370

Non-conventional search strategy

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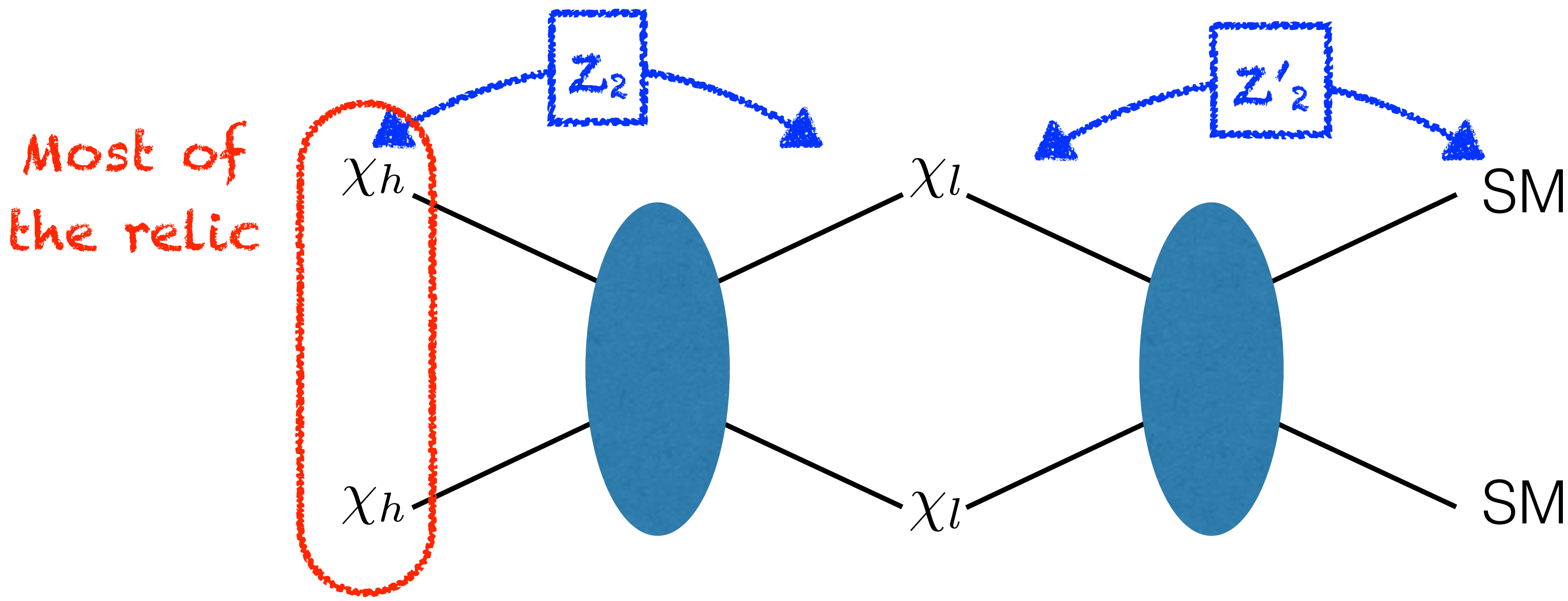


Agashe, Cui, Necib, Thaler, 1405.7370

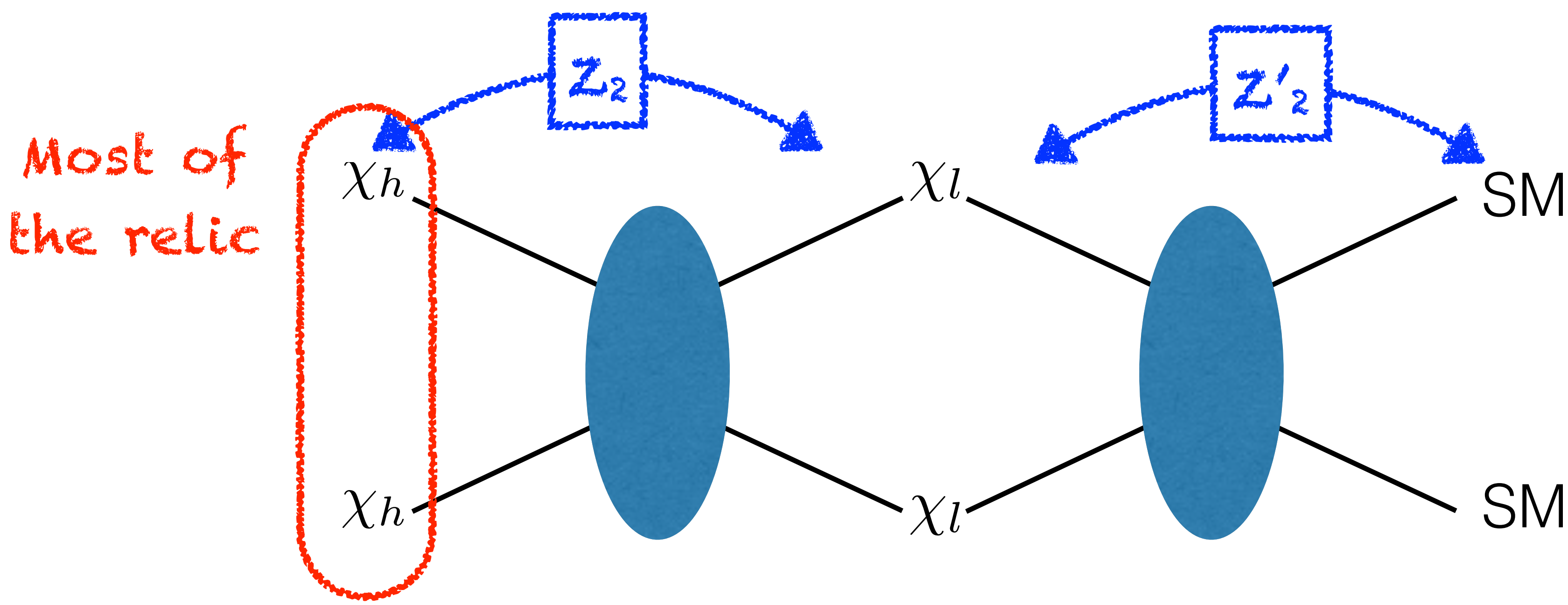
Belanger, Park, 1112.4491 Assisted freeze-out

$\chi_h \chi_h \rightarrow \chi_l \chi_l$ (current universe) relativistic

※ relic χ_l is non-relativistic

Non-conventional search strategy

e.g., boosted dark matter



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Belanger, Park, 1112.4491 Assisted freeze-out

$\chi_h \chi_h \rightarrow \chi_l \chi_l$ (current universe) relativistic

※ relic χ_l is non-relativistic

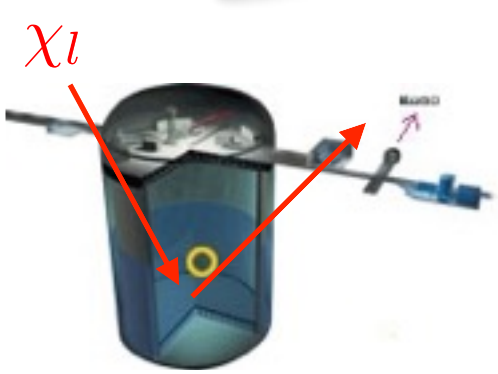
Observe relativistic χ_l scattering with target

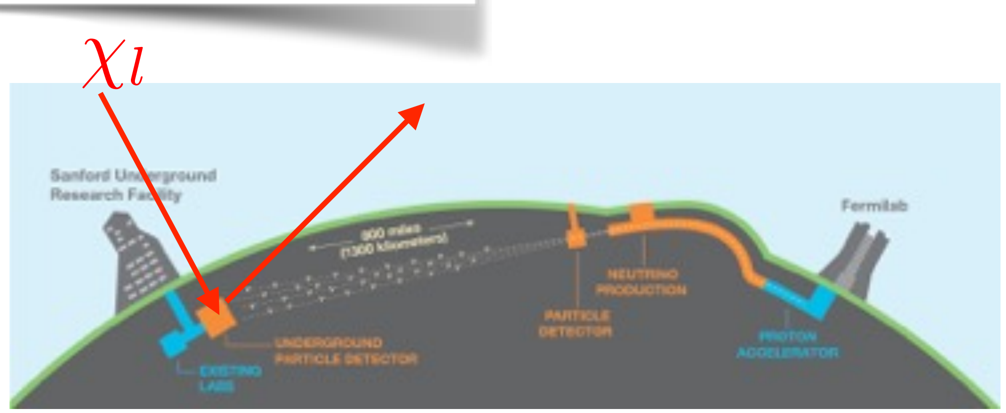
Relativistic scattering of BDM

$\chi_h \chi_h \to$ χ_l χ_l

- similar to NC ν scattering
- small flux $\mathcal{O}(10^{-7}\,\mathrm{cm}^{-2}\mathrm{s}^{-1})$
  $m_{\chi h}$ ~ O(10 GeV)

Large volume ν experiments





- Basic model: count N_{events} over the expected background (ν) challenging
  Directional information of GC (SK preliminary)

- Modified model: additional directional information (Sun) or process promising

Kim, Park, **SS**, 1612.06867

Relativistic scattering of BDM

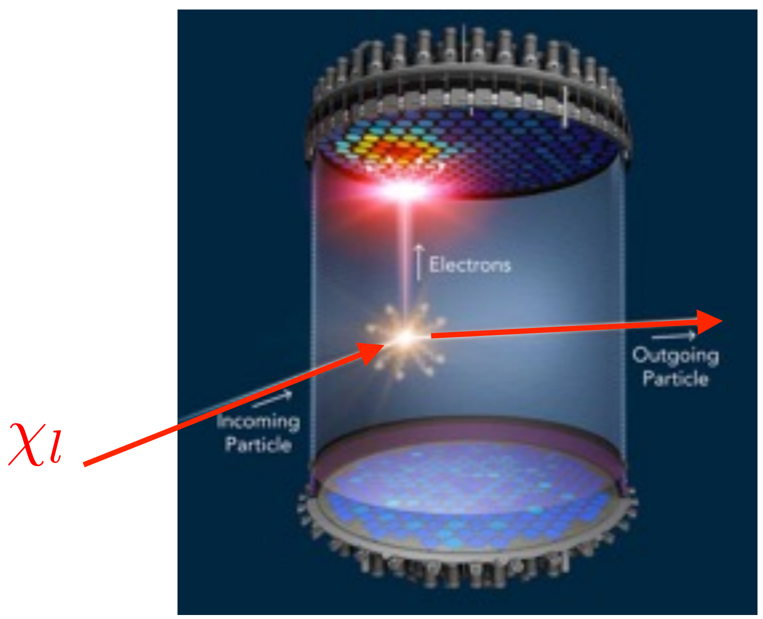
$\chi_h \chi_h \rightarrow \chi_l \chi_l$

- similar to NC ν scattering
- ~~small~~ increase flux

$\mathcal{O}(10^{-3}\,\mathrm{cm}^{-2}\mathrm{s}^{-1})$

$m_{\chi h} \sim O(0.1\ \mathrm{GeV})$

WIMP direct detection exp.



- Nucleon scattering: small cross section ($E_{\chi l}$ sub GeV)

Cherry, Frandsen, Shoemaker, 1501.03166

- Electron scattering: larger cross section background subtraction?

Relativistic scattering of BDM

$\chi_h \chi_h \to \chi_l \chi_l$

- similar to NC ν scattering
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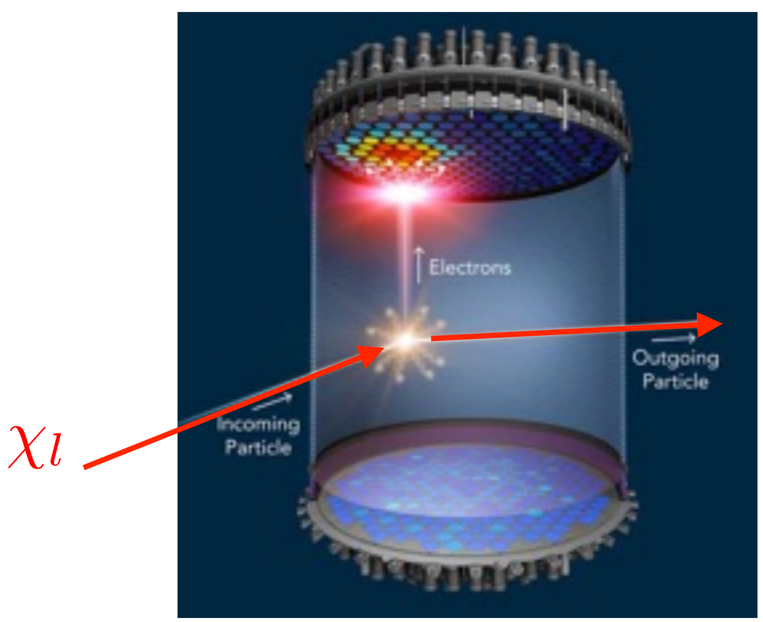
WIMP direct detection exp.



- Nucleon scattering: small cross section ($E_{\chi l}$ sub GeV)

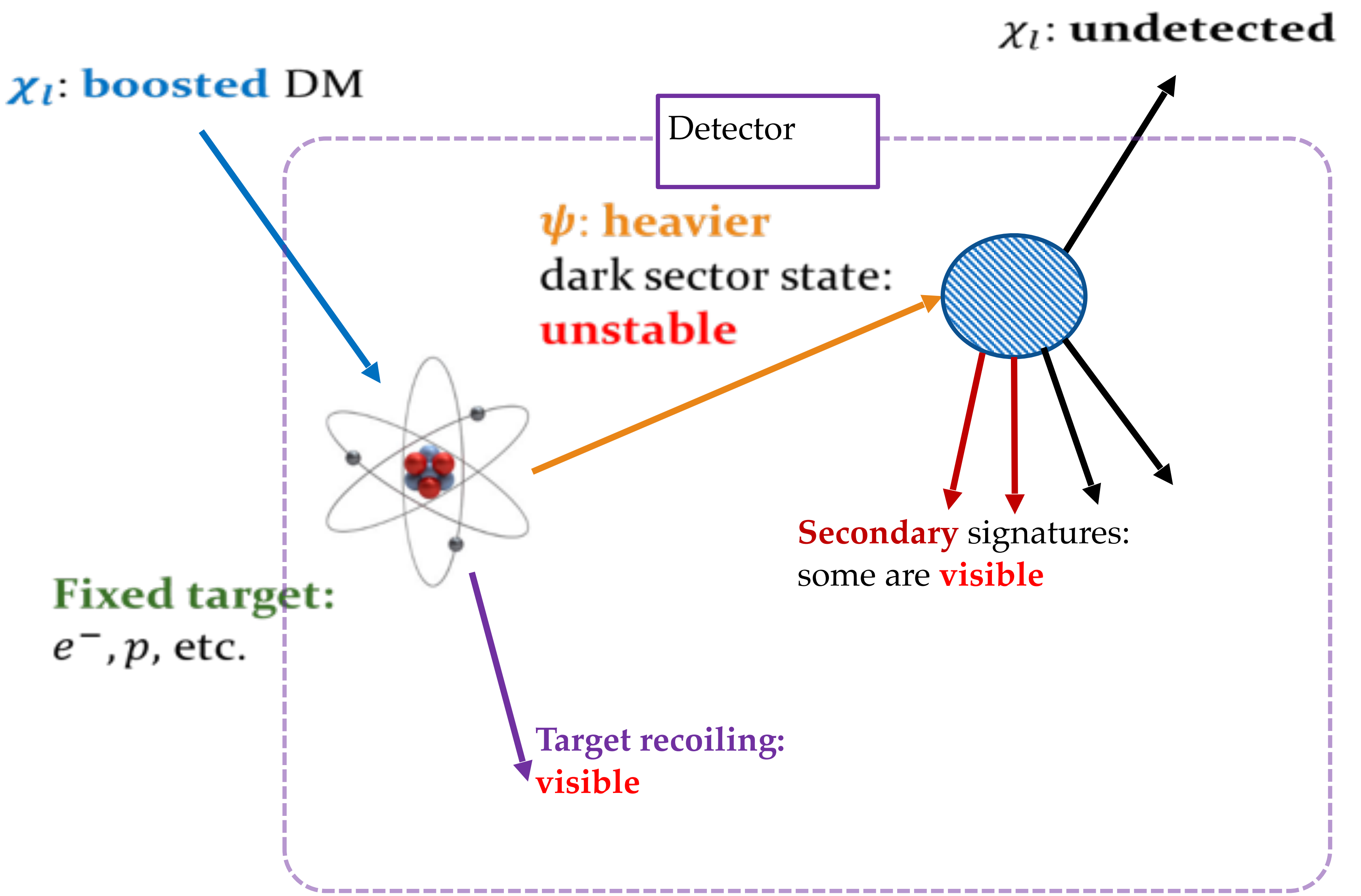
Cherry, Frandsen, Shoemaker, 1501.03166

- Electron scattering: larger cross section
  background subtraction? energetic scattering

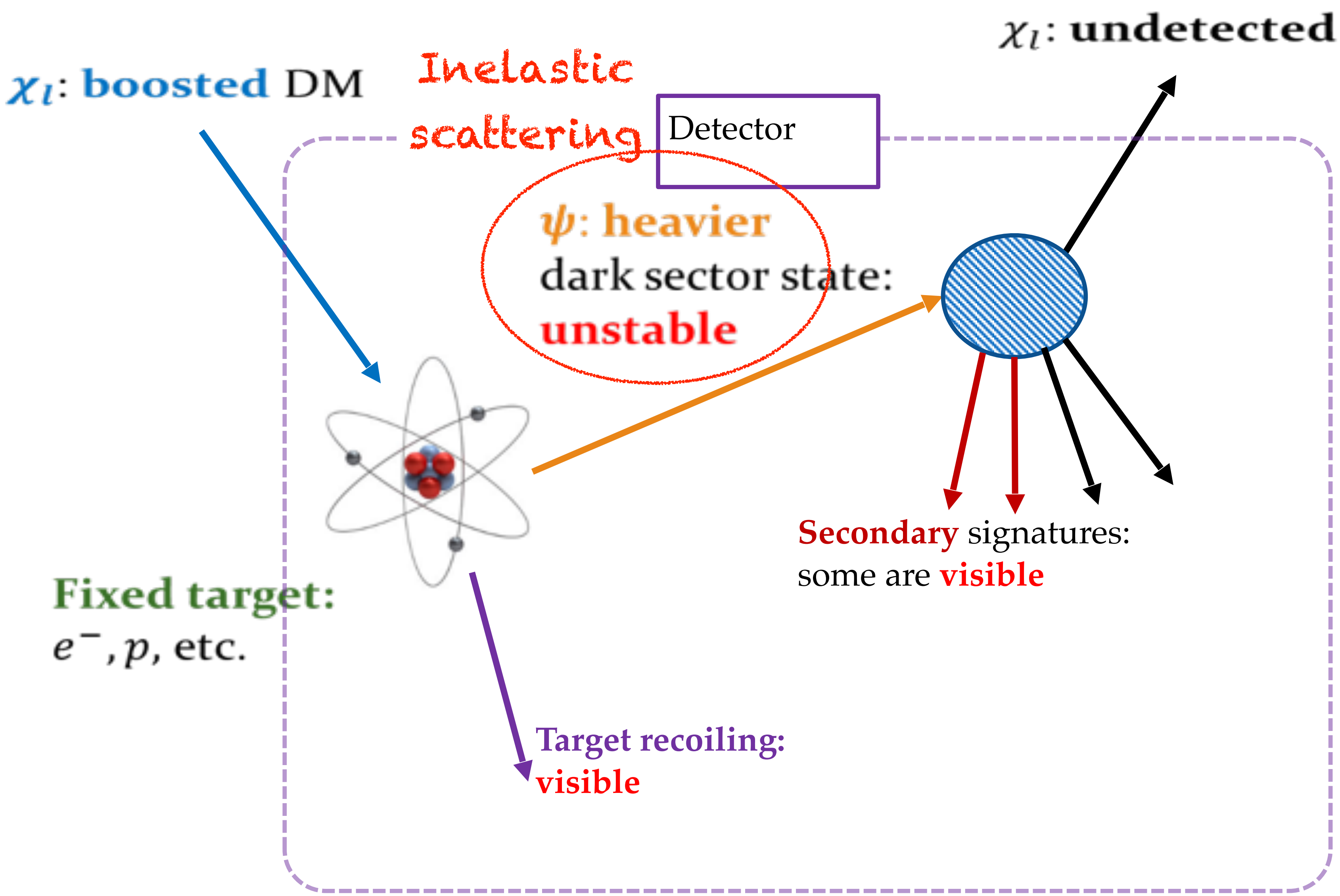
Giudice, Kim, Park, **SS**

Modified model with additional process ← more promising

Modified model: inelastic BDM



Modified model: inelastic BDM



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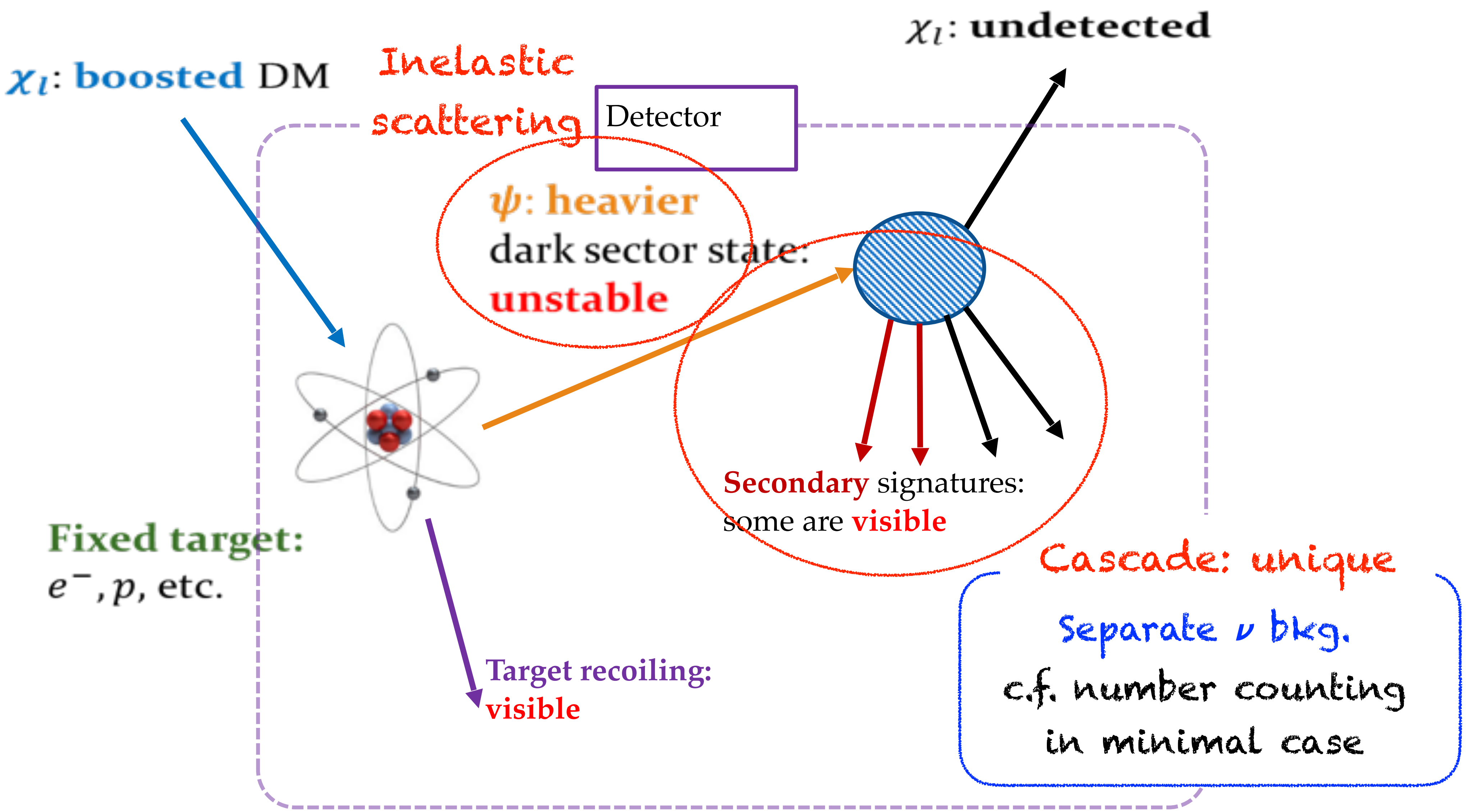

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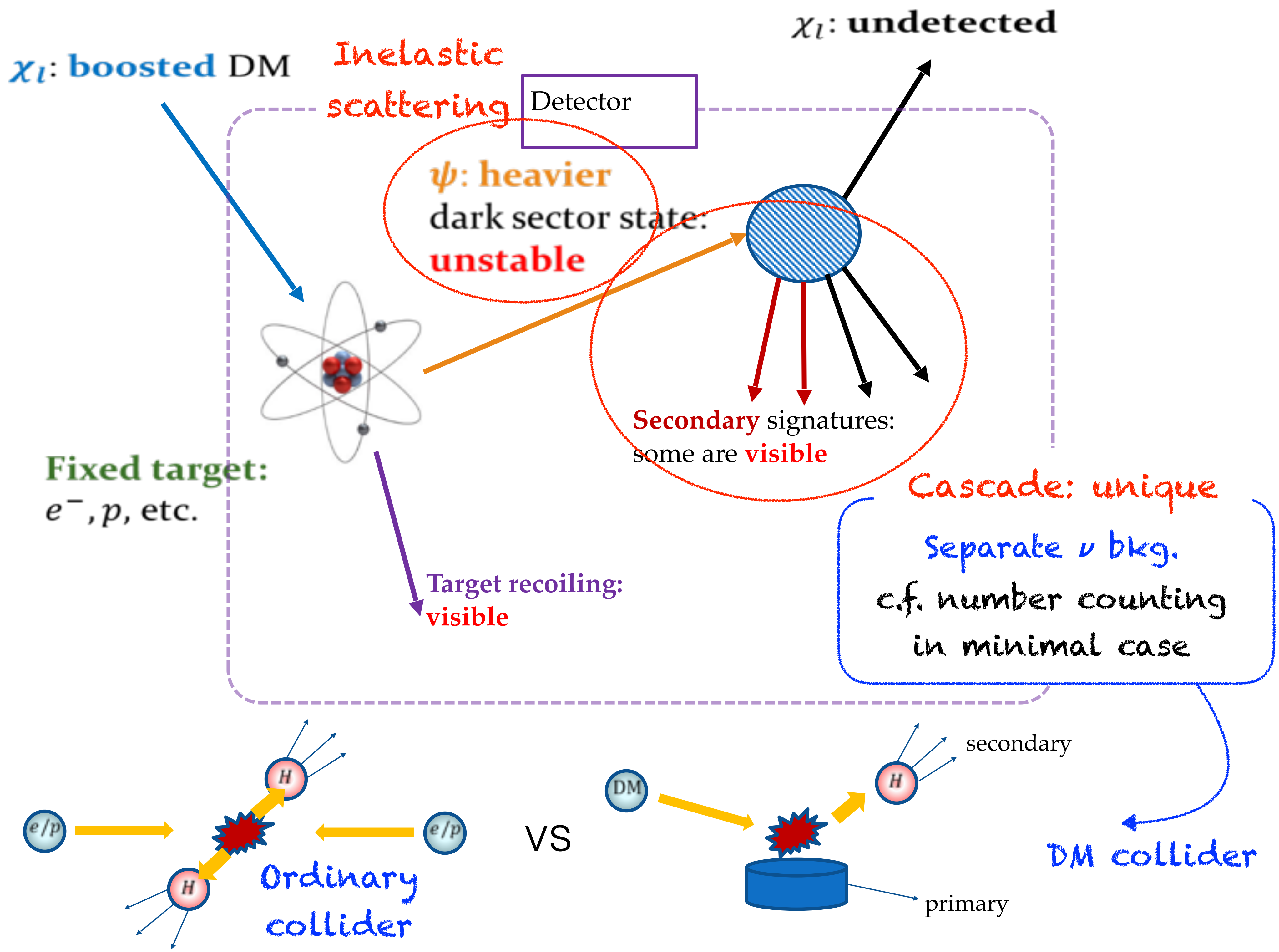
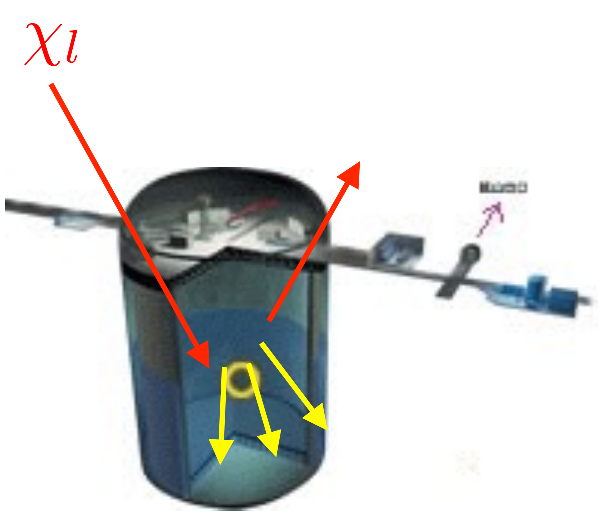
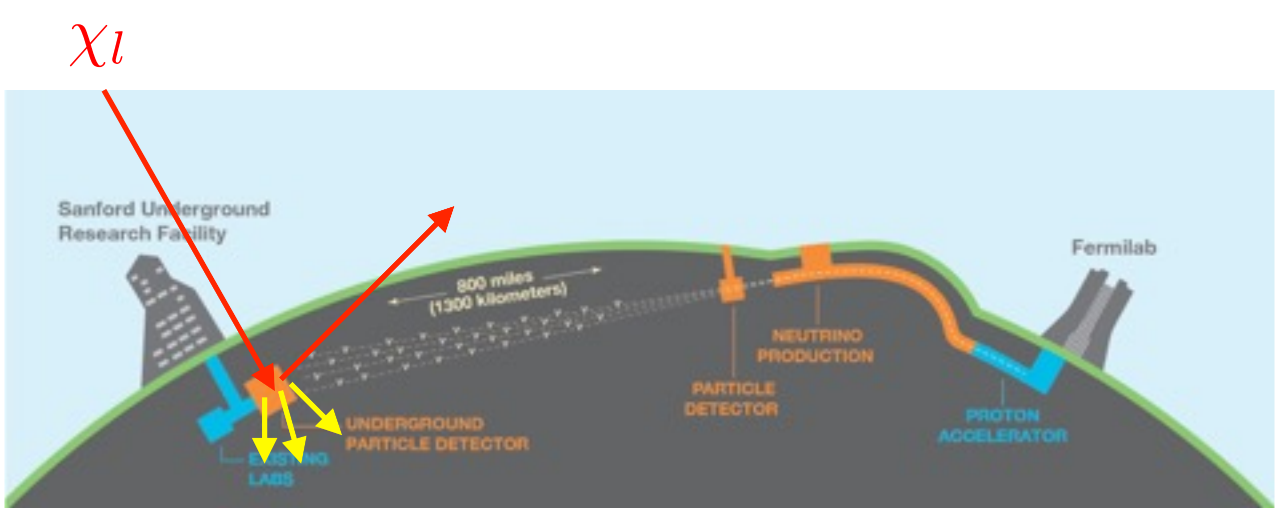
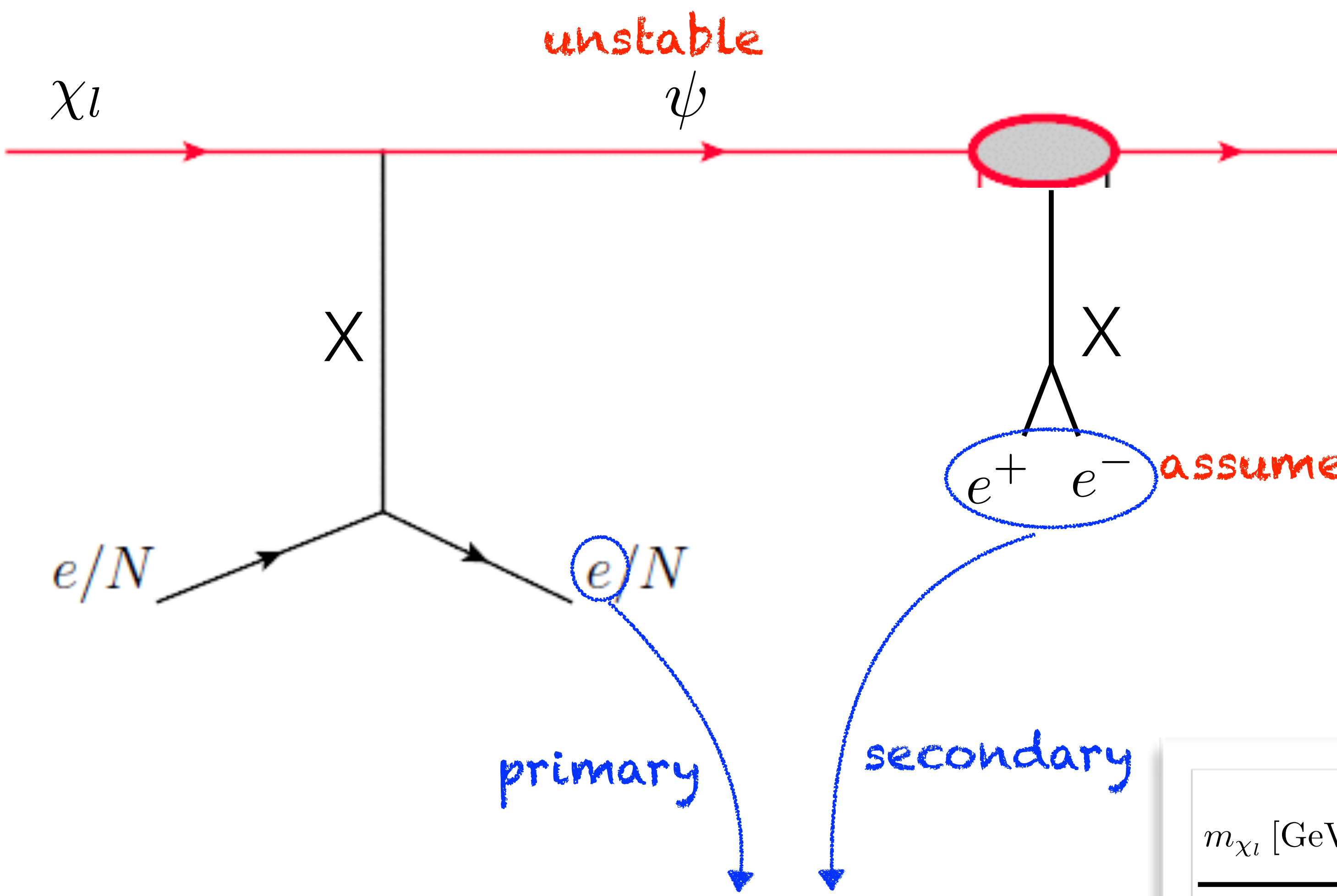


Search in large volume ν experiments





e-scattering at ν exp: highly boosted



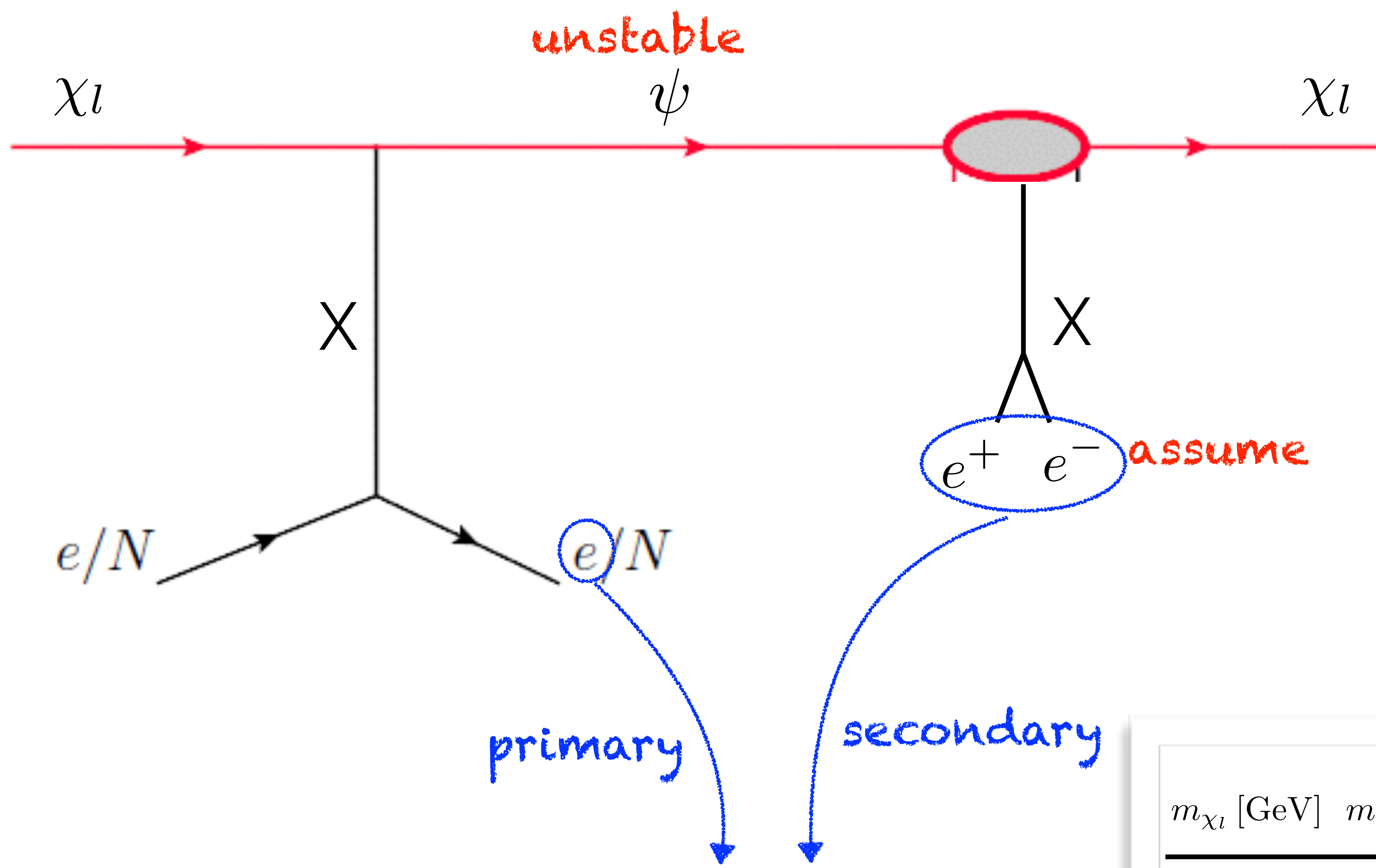
m_{χ_l} [GeV]	m_ψ [GeV]	m_X [GeV]	γ_{χ_l}
0.4	0.5	0.06	250
0.1	0.14	0.03	200

High chance to observe
two separate signals!!

in an experiment with angular resolution ~ 3°
(Super/Hyper Kamiokande) for primary p_e: 0.1 - 0.3 GeV

Moderate recoil E

e-scattering at ν exp: highly boosted



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m_{χ_l} [GeV]	m_ψ [GeV]	m_X [GeV]	γ_{χ_l}
0.4	0.5	0.06	250
0.1	0.14	0.03	200

in an experiment with angular resolution ≲ 1°

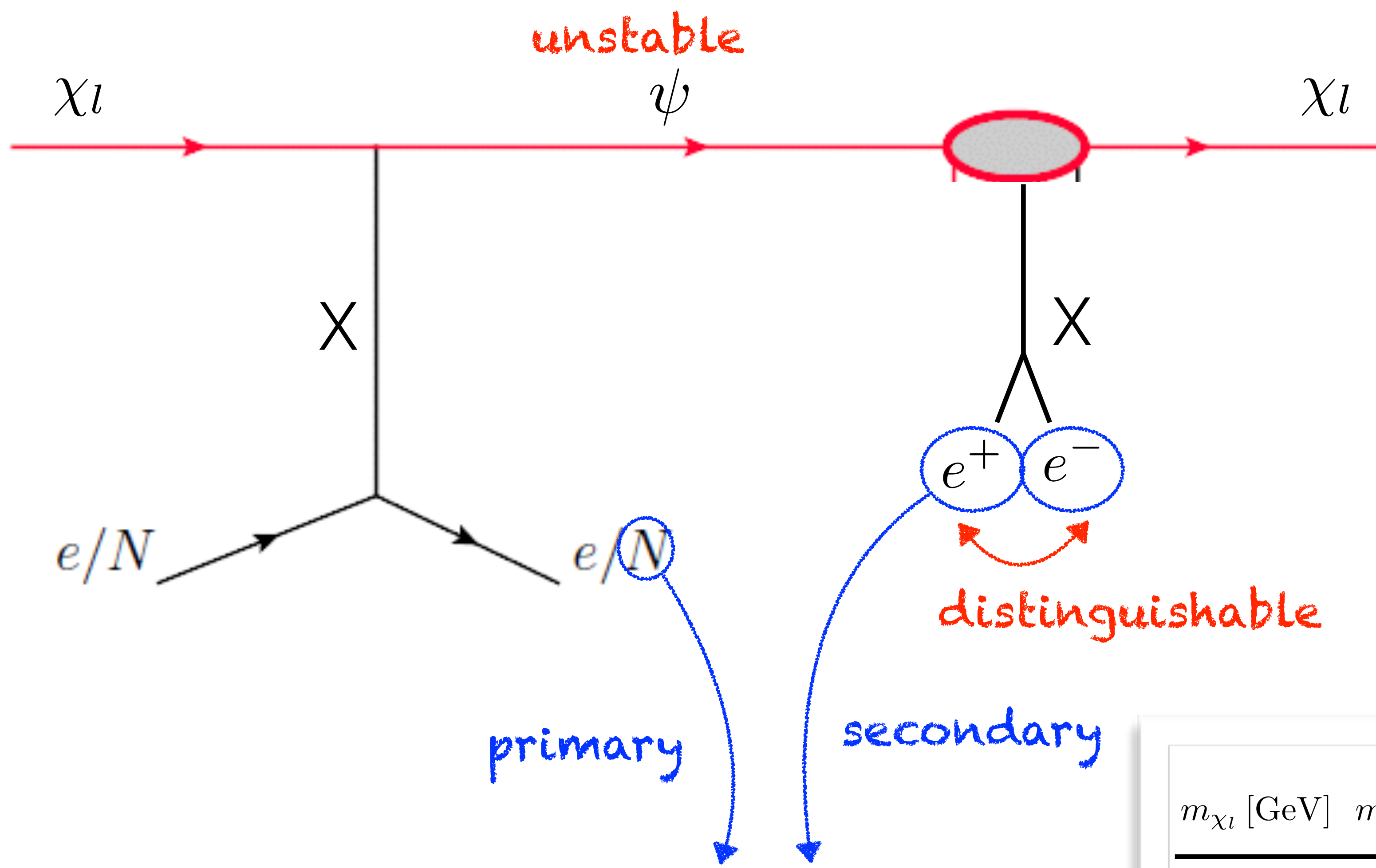
smaller volume

(DUNE, SHiP better) for primary p_e: 0.03 - 1 GeV

cosmic & intensity intensity

Wider range of E

p-scattering at ν exp: highly boosted



High chance to observe
three separate signals!!

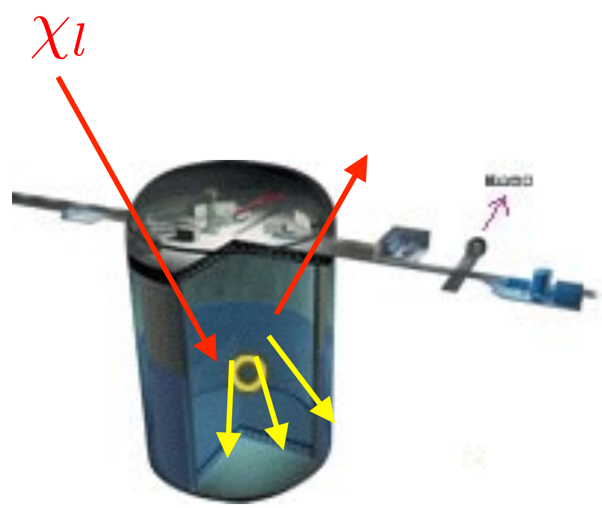
m_{χ_l} [GeV]	m_ψ [GeV]	m_X [GeV]	γ_{χ_l}
0.4	0.9	0.2	15
0.1	1.0	0.5	50

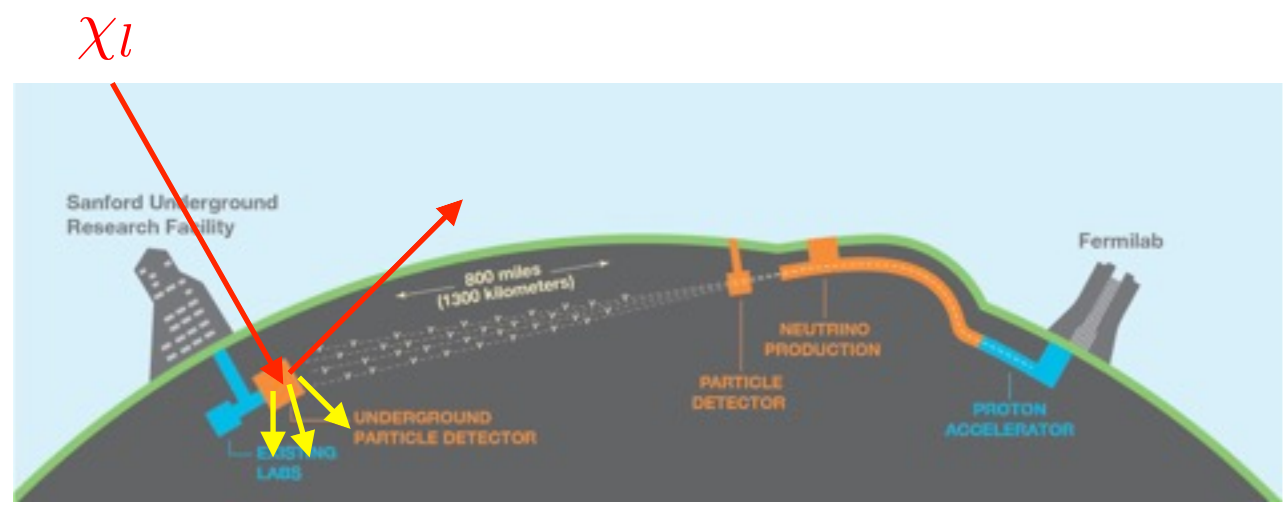
very sensitive!!

Promising in an experiment with $E_{th} \ll 1$ GeV (**DUNE**, SHiP)

Need much larger flux for higher $E_{th} > 1$ GeV (SK/HK)

Search in large volume ν experiments





toy model: dark gauge boson X

$$g_{12} = 0.5,\ \epsilon = 0.0003$$

Required flux

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

Assume no bkg.

unit: $10^{-7}\mathrm{cm}^{-2}\mathrm{s}^{-1}$

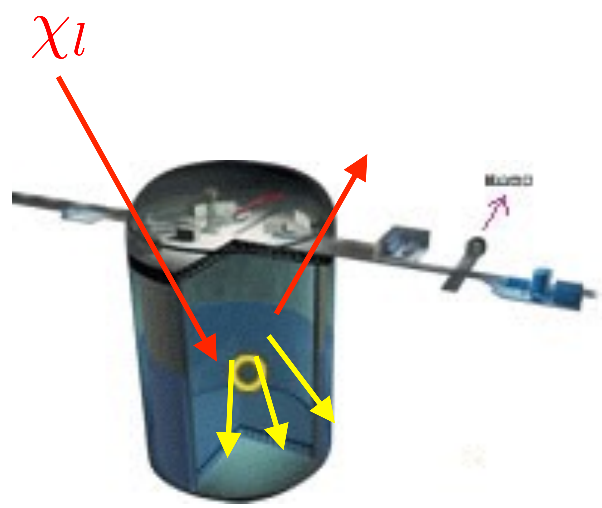
Remind, in a minimal BDM, flux over the whole sky

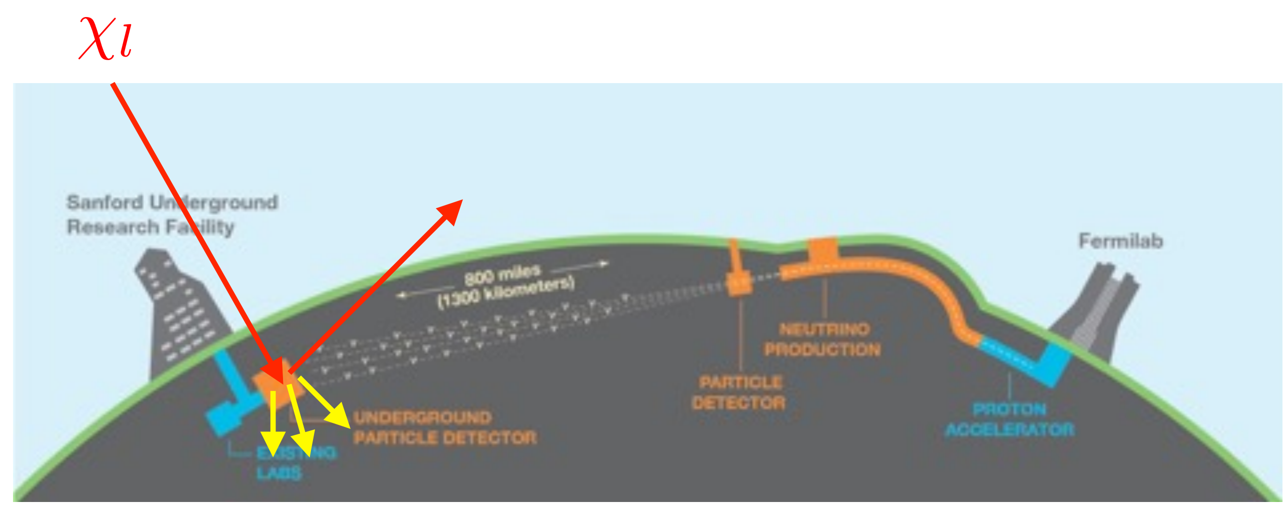
$\mathcal{O}(10^{-7}\,\mathrm{cm}^{-2}\mathrm{s}^{-1})$

$m_{\chi h} \sim O(10\ \mathrm{GeV})$

Promising example!

Search in large volume ν experiments





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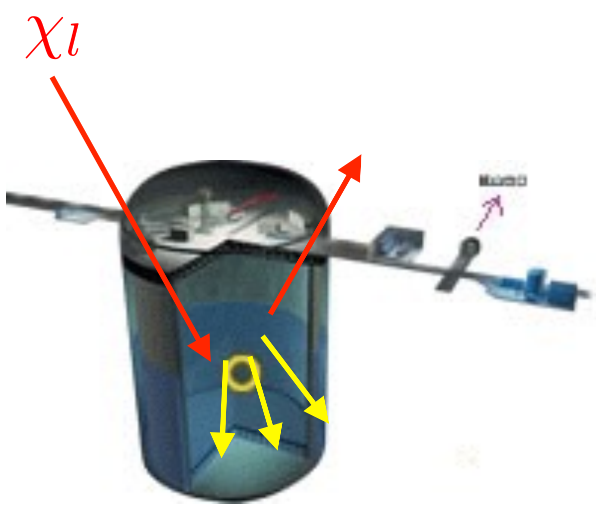
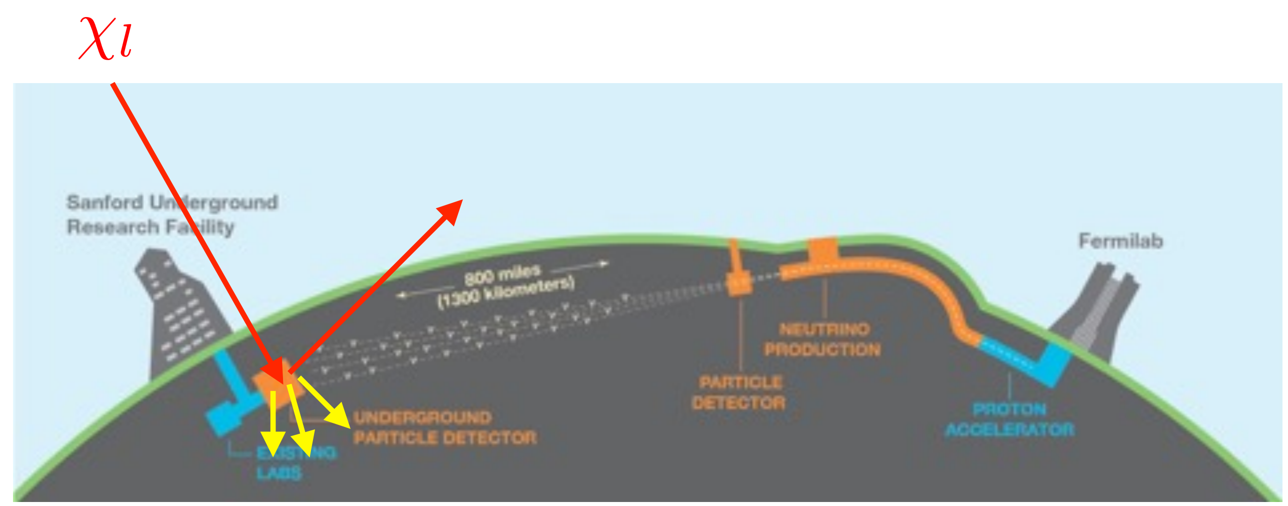
less sensitive than e

Assume no bkg.

unit: $10^{-7}\mathrm{cm}^{-2}\mathrm{s}^{-1}$

Search in large volume ν experiments





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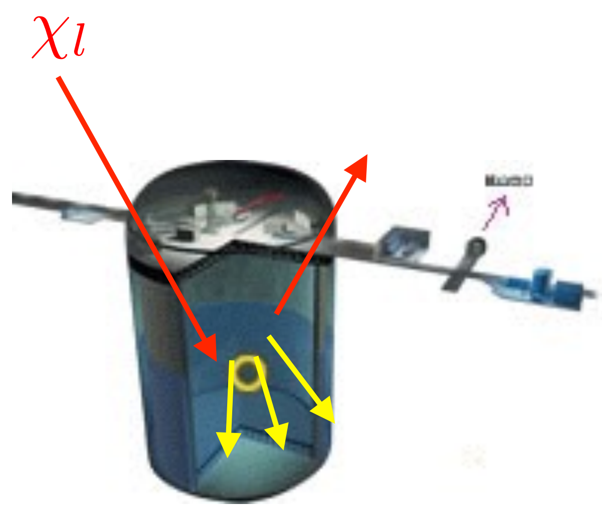
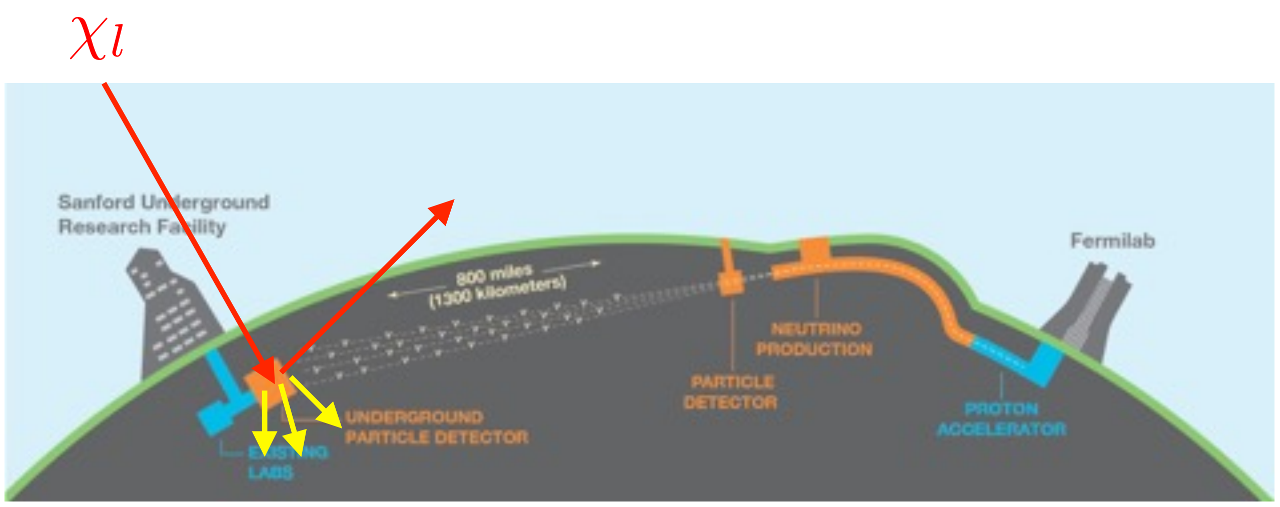
13.6 yr of HK improves the sensitivity

Assume no bkg.

unit: $10^{-7}\mathrm{cm}^{-2}\mathrm{s}^{-1}$

Search in large volume ν experiments





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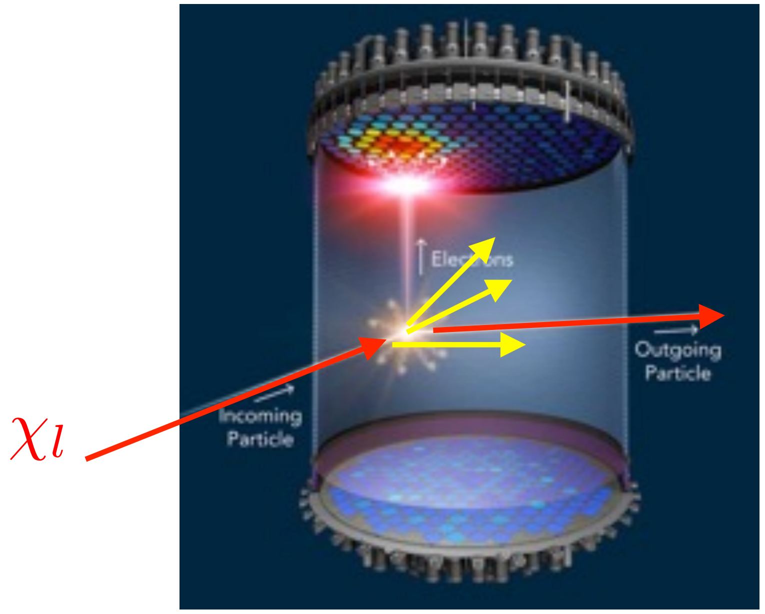
Assume no bkg.

unit: $10^{-7}\mathrm{cm}^{-2}\mathrm{s}^{-1}$

Remarkable improvement in DUNE!!!

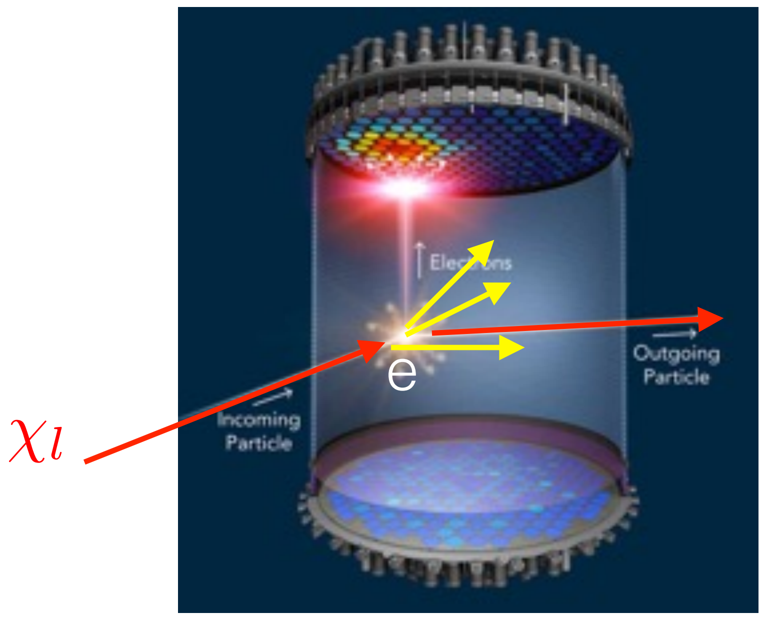
Promising (3 simultaneous signals)

Search in WIMP direct detection experiments



Search in WIMP direct detection exp

Xenon1T, DEAP3600, LZ, XenonNT, …



High energetic (> 10 MeV)
e^- + e^-/e^+ signals

$m_{\chi h} \sim O(0.1 - 1\ \text{GeV})$

$m_{\chi l} \sim O(1 - 10\ \text{MeV})$

- Displaced decay: two time-correlated signals

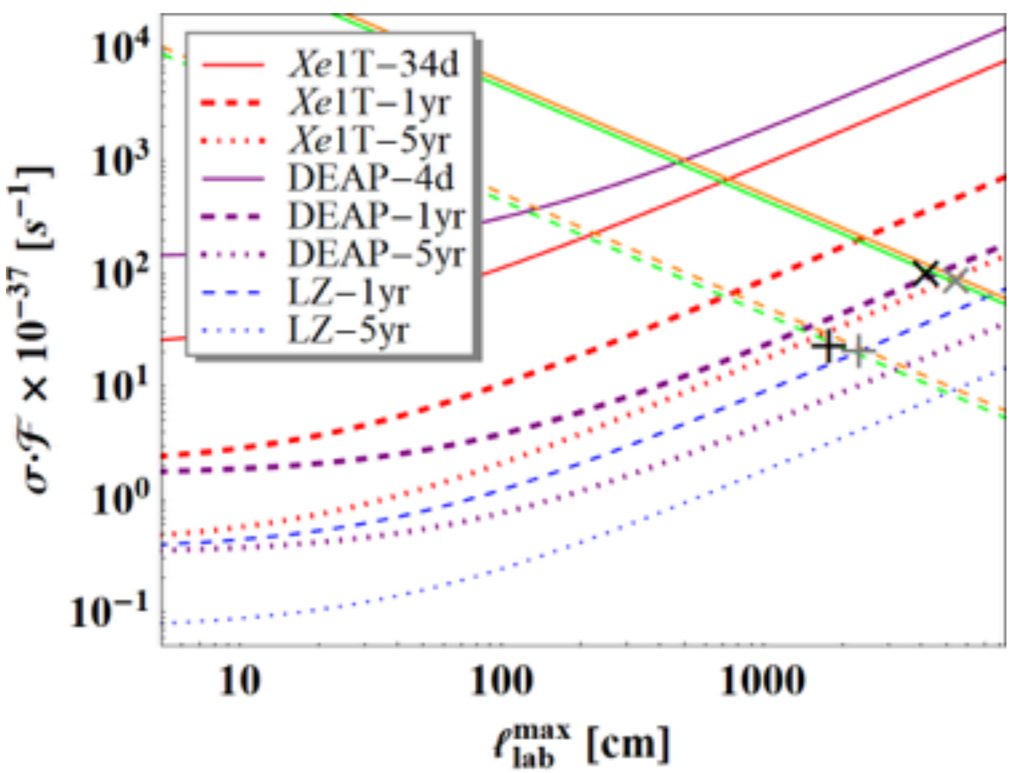
Easier to observe

- Prompt (within resolution) decay: not easy to separate with minimal BDM if e^-/e^+ highly collimated

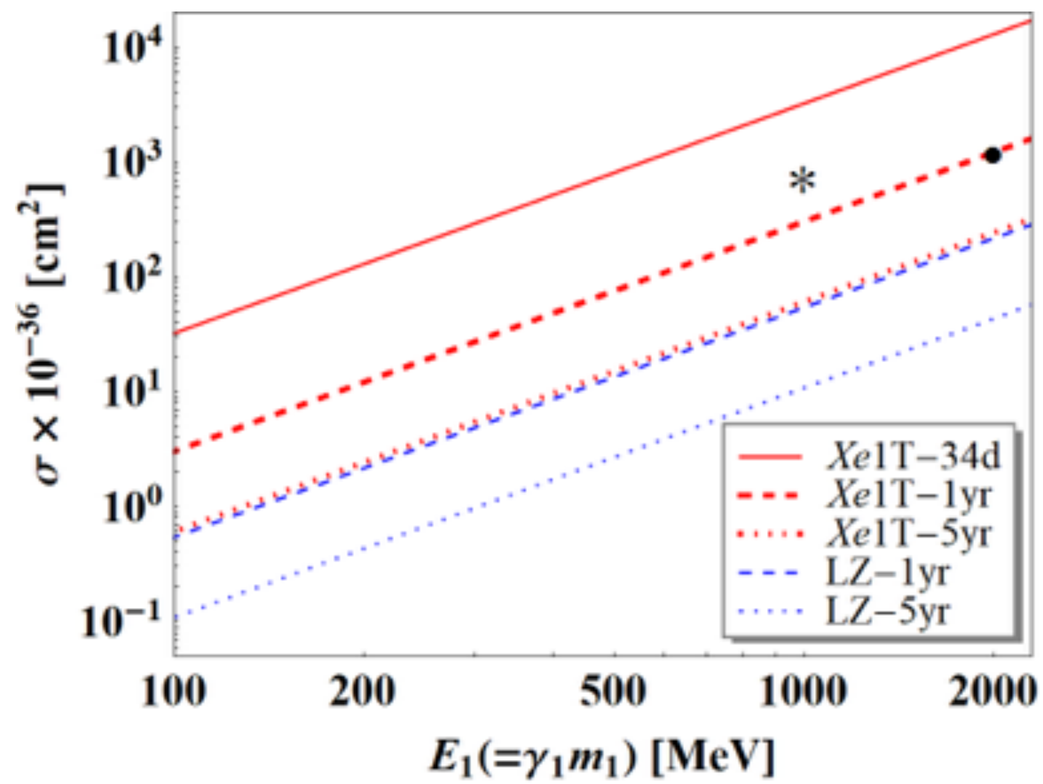
Sensitivities on WIMP DD exp.

Cross section of the primary (inelastic) scattering $\chi_l - e$

Displaced decay



Prompt decay/mBDM



Assume no bkg.

Black point: Pseudo-Dirac

Gray point: Scalar

Green line: Pseudo-Dirac toy ϵ change

Orange line: Scalar toy ϵ change

		m_1	m_2	m_X	γ_1	ϵ
X	ref1 (red solid)	2	5.5	5	20	4.5×10^{-5}
+	ref2 (green dashed)	3	8.5	7	50	6×10^{-5}
*	ref3 (blue dot-dashed)	20	35	11	50	7×10^{-4}
●	ref4 (orange dotted)	20	40	15	100	6×10^{-4}

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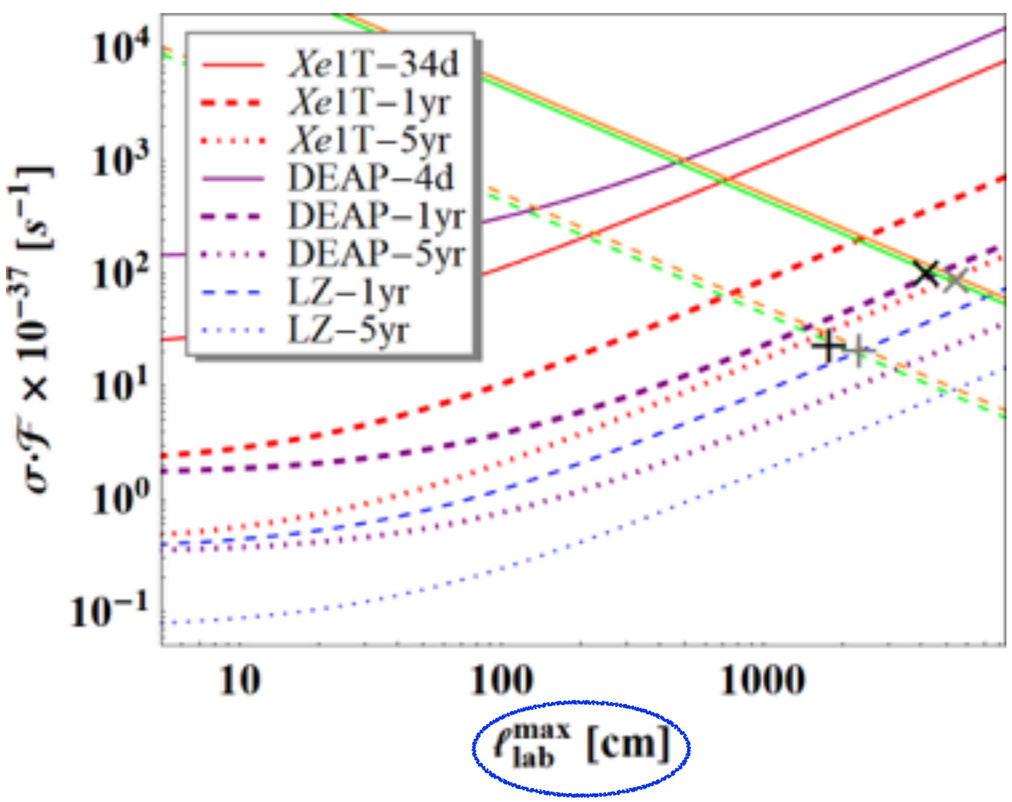

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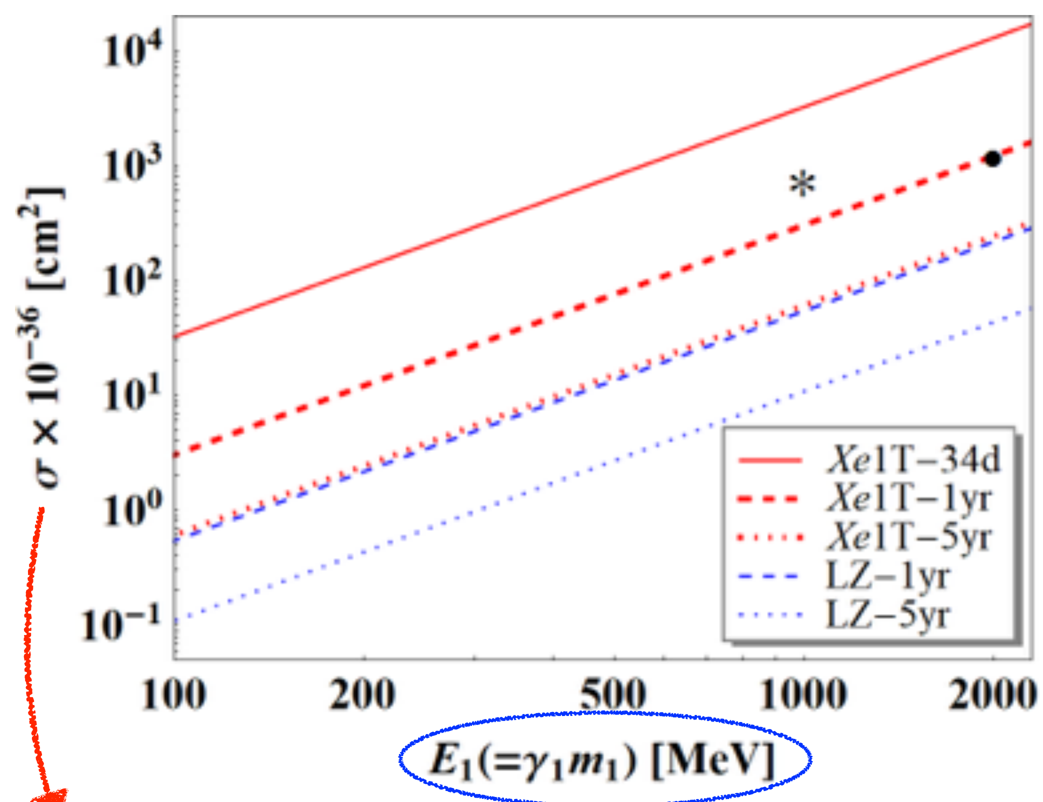

$\chi_h - e$

Flux = $F(E_1 = m_{\chi h})$

Assume no bkg.

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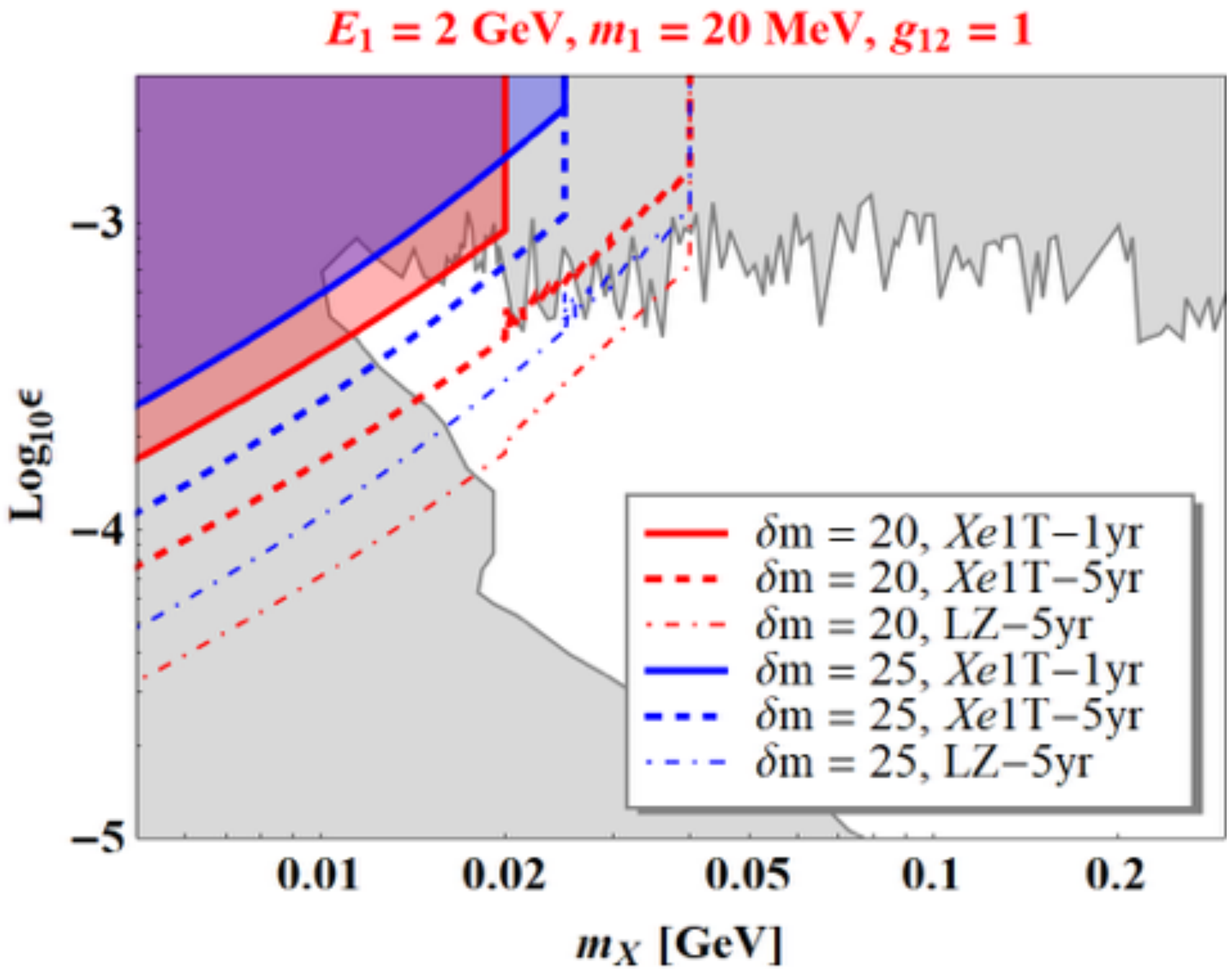
Search in WIMP direct detection exp

Toy model: dark gauge boson X



X decays visibly

Assume no bkg.

Conclusions

- Flavorful/non-minimal dark sector (χ_I): cascade process
- Analyzed in current & future large volume ν detectors:
  Super-K, Hyper-K, DUNE

e-scattering	p-scattering
(pros) • E_{th} low in Cherenkov light detectors (high σ)	(cons) • E_{th} high in Cherenkov light detectors (low σ)
(pros) • Sensitive with small flux	(cons) • Need large flux — Intensity frontier exp.
(cons) • Separation of two signals not easy (good for low p_e)	(pros) • Separation of two signals & 3 visible objects: promising

DUNE

Conclusions

- Flavorful/non-minimal dark sector (χ_l): cascade process

- Analyzed in current & future large volume ν detectors:

  Super-K, Hyper-K, DUNE

- WIMP direct detection experiments for the lighter DM

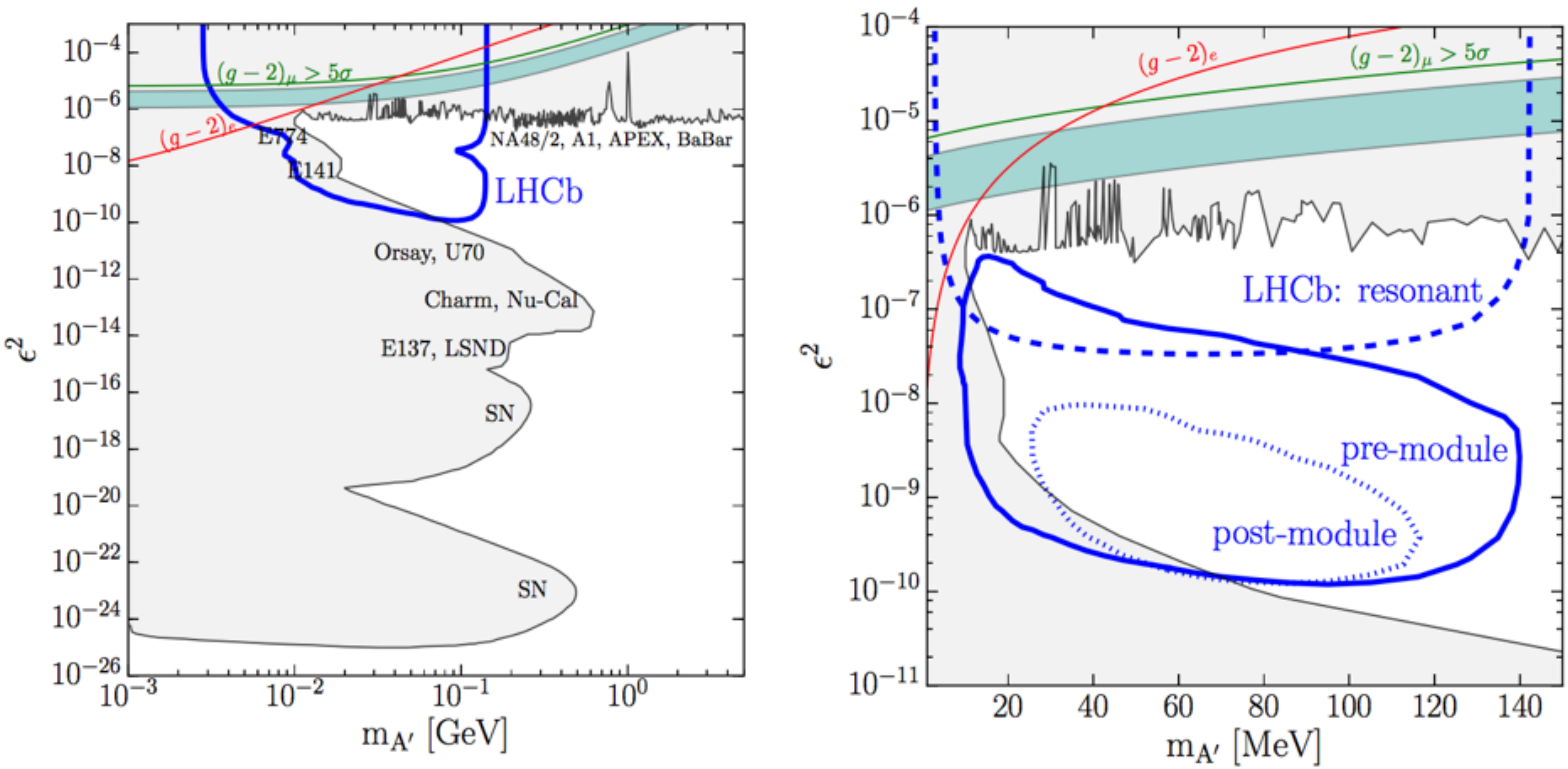
  (Xenon1T, LZ, …)

$m_{\chi_h} \sim O(0.1 - 1\ \text{GeV})$

$m_{\chi_l} \sim O(1 - 10\ \text{MeV})$

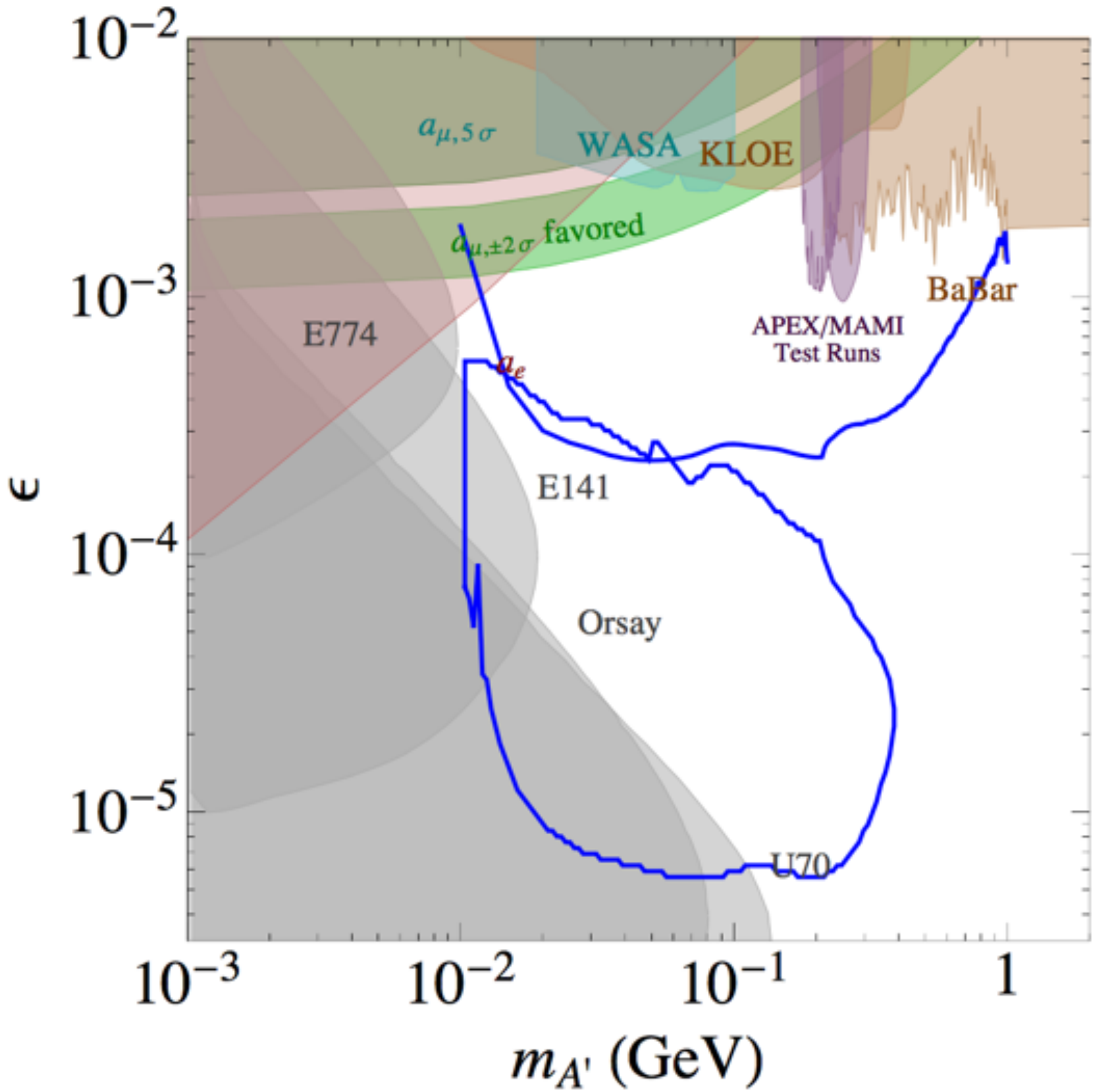
Depends on the detector resolutions much

Back up



Ilten, Thaler, Williams, Xue, 1509.06765

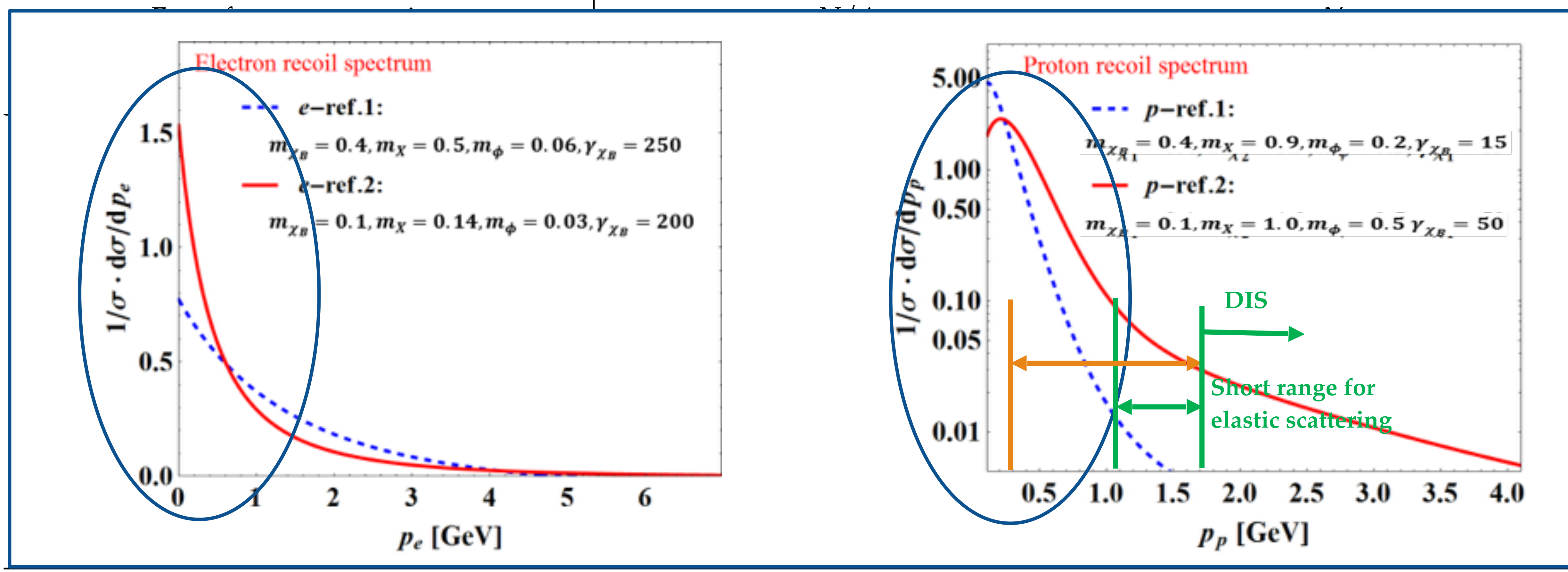
Back up



Essig et al., 1311.0029

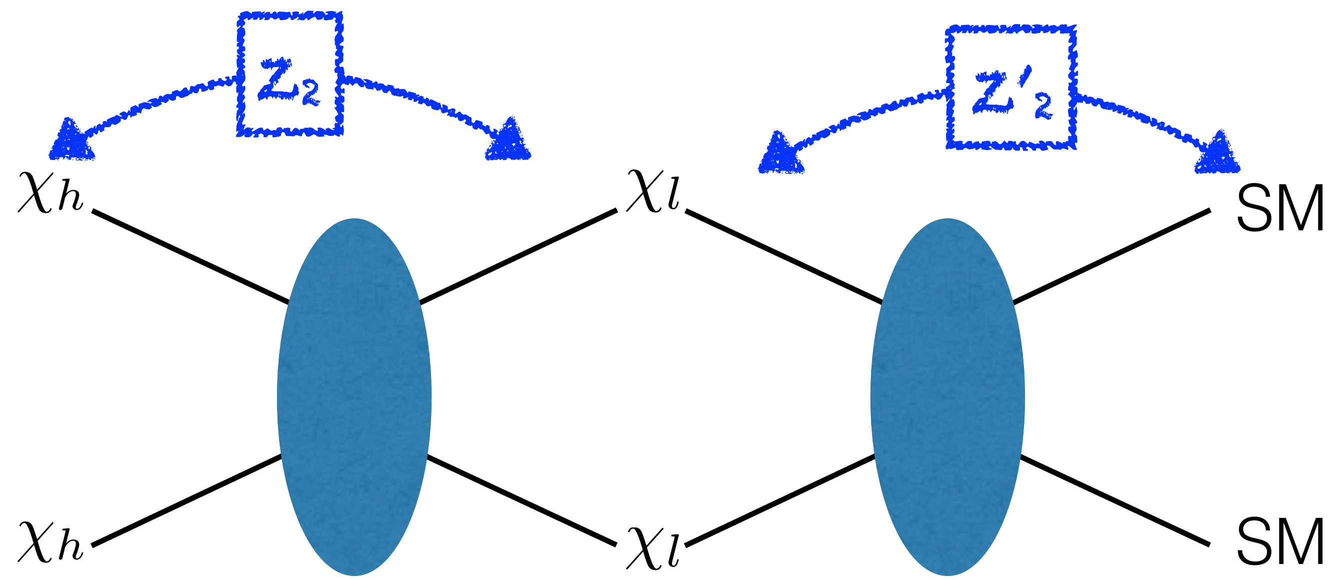
e/N scattering prospects

Exp.	e-scattering	p-scattering
Energy for primary scattering	Peaking towards smaller momentum transfer	
Threshold energy	Small	Large for Cherenkov Small for LArTPC



Boosted DM

Minimal model example

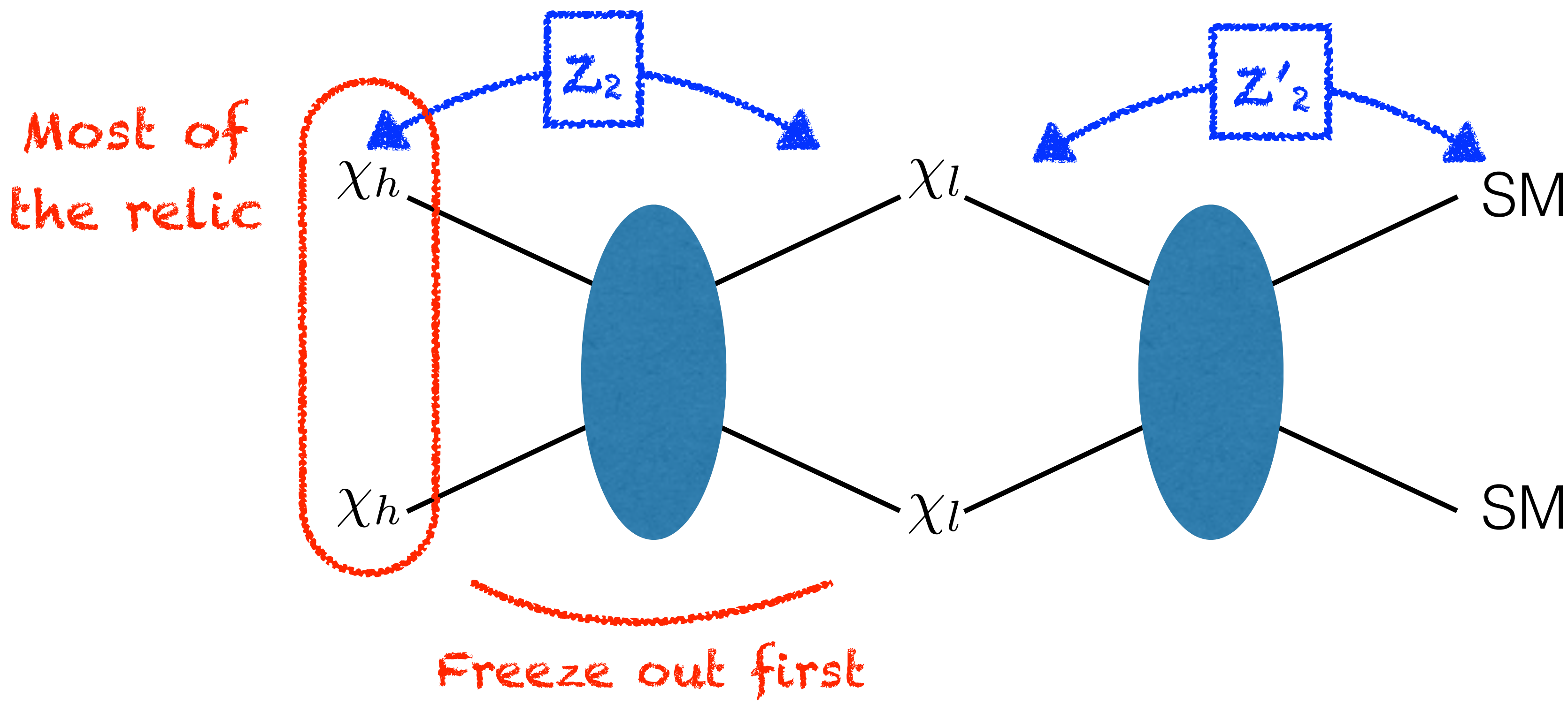


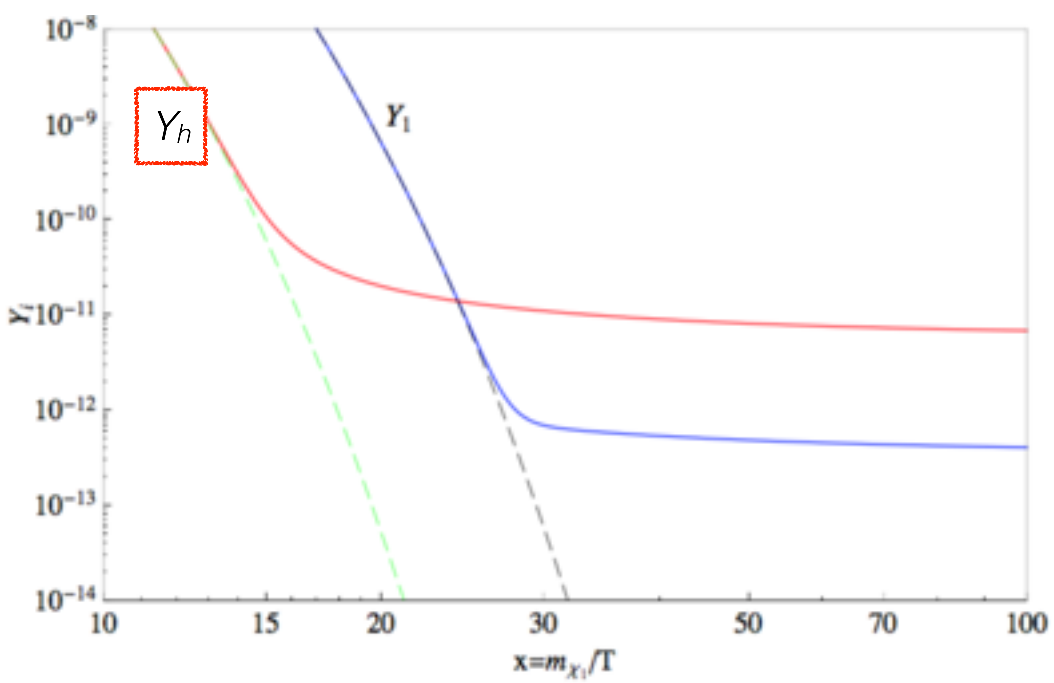
Belanger, Park, 1112.4491

Agashe, Cui, Necib, Thaler, 1405.7370

Boosted DM

Minimal model example



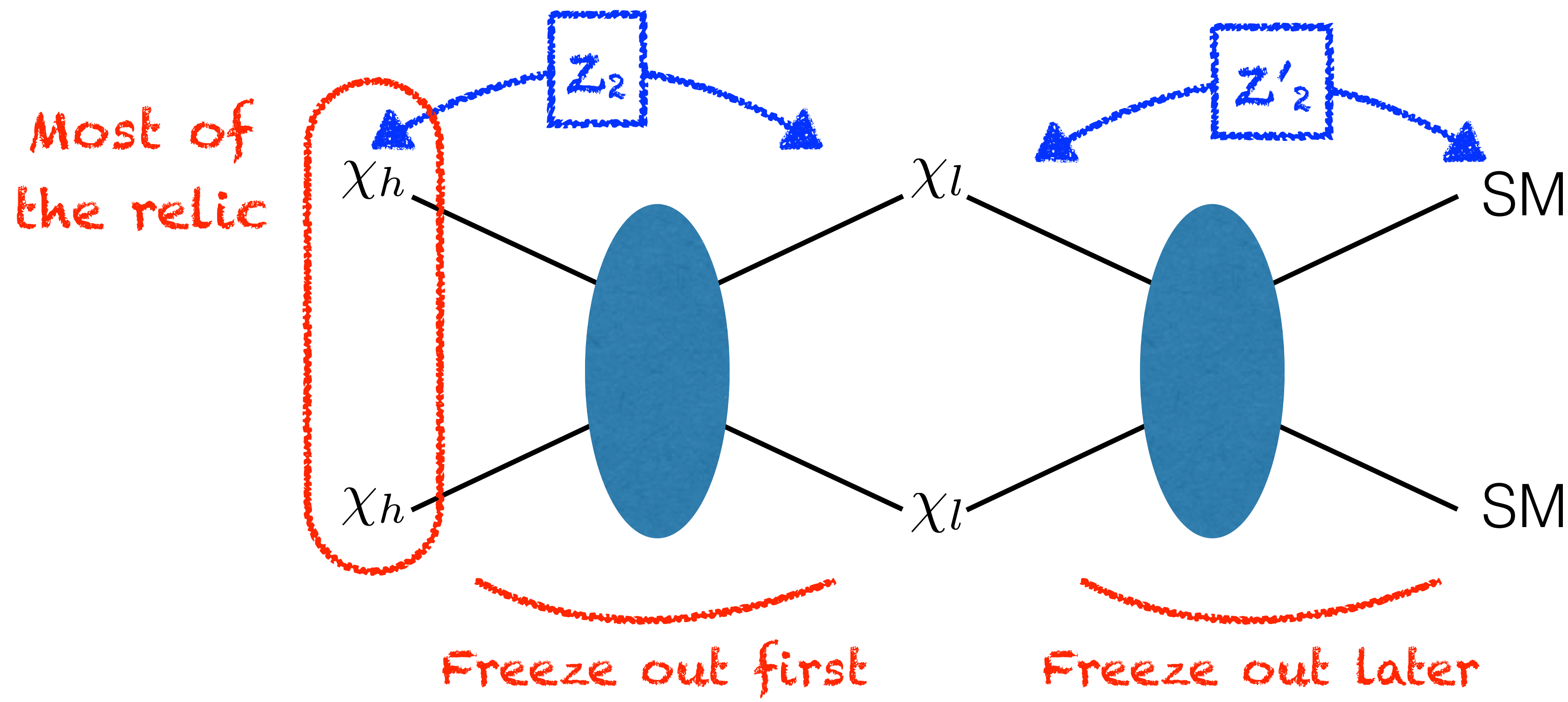


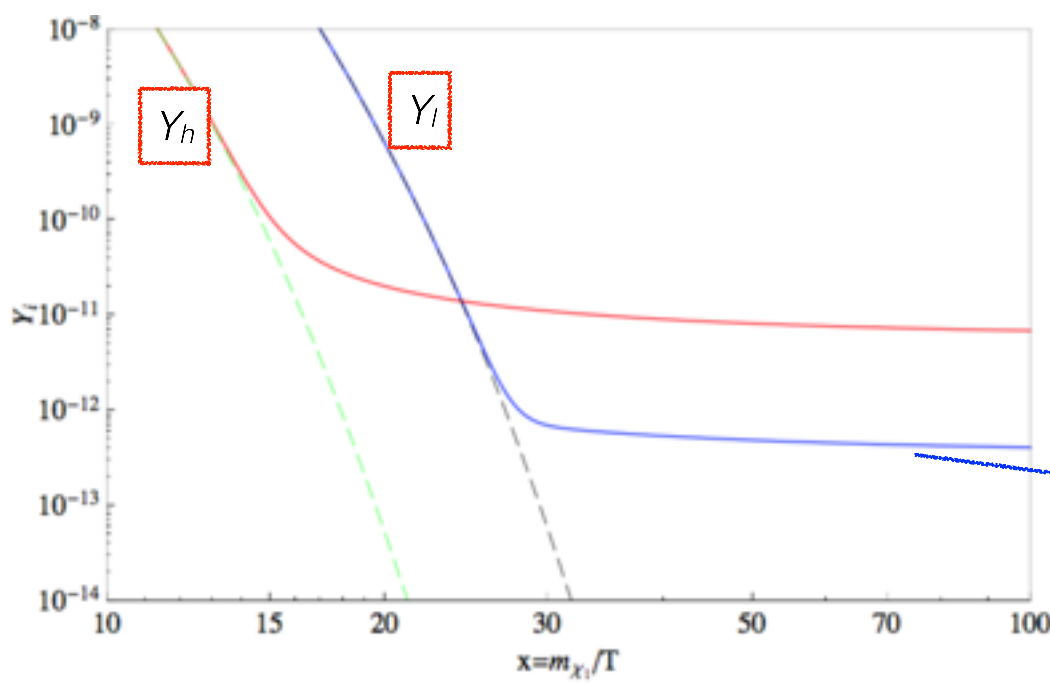
Belanger, Park, 1112.4491

Agashe, Cui, Necib, Thaler, 1405.7370

Boosted DM

Minimal model example





Belanger, Park, 1112.4491

Agashe, Cui, Necib, Thaler, 1405.7370

Assisted freeze-out

(Flux of relic χ_1: small)

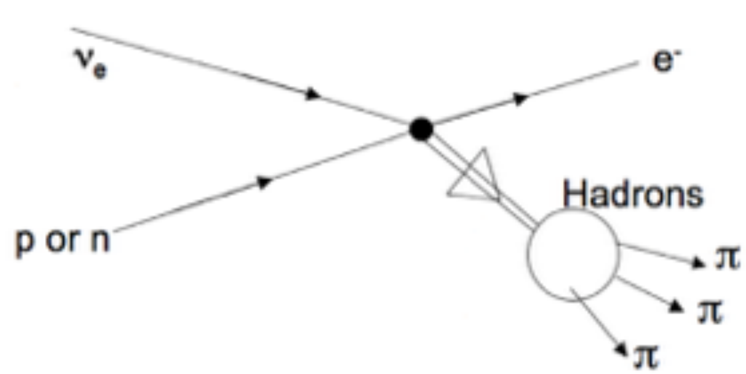
non-relativistic

Really background free?

Background may be negligible (dedicated analysis needed)

Kim, Park, **SS**, Work in progress

- Not energetic muon $\mu \to e \nu_e \nu_\mu$ (e + ℓ): cut out by requiring E > 0.1 GeV
- nν_τ → pτ → p$\ell \nu_\ell \nu_\tau$ (p + ℓ): cut out by requiring 3 visible objects
- nν_e → pe → 3e + … by hadronized p (or just by NC): ring shape & energy



$$\pi^+ \to \mu^+ + \nu + \mu$$
$$\hookrightarrow e^+ + \nu_e + \overline{\nu}_\mu$$

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Kim, Park, **SS**, Work in progress

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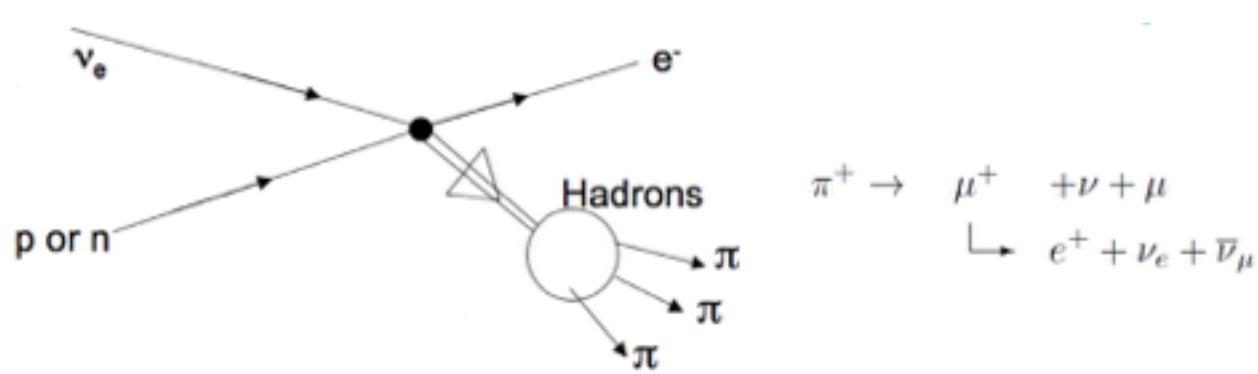
- $n \nu_e \to p e \to 3e + \ldots$ by hadronized p (or just by NC): ring shape & energy



Really background free?

Background may be negligible (dedicated analysis needed)

Kim, Park, **SS**, Work in progress

Cherenkov light detectors (Kamiokande)

- Not energetic muon $\mu \to e \nu_e \nu_\mu$ ($e + \ell$): cut out by requiring $E > 0.1$ GeV
- $n \nu_\tau \to p \tau \to p \ell \nu_\ell \nu_\tau$ ($p + \ell$): cut out by requiring 3 visible objects
- $n \nu_e \to p e \to 3e + \ldots$ by hadronized p (or just by NC): ring shape & energy

Our signal (e-scattering)	Hadronized background
Primary signal (clean): 0.1 - 0.3 GeV	e from CC (clean): higher E
Secondary signal (vague): higher E	e from p/n (vague): lower E

Really background free?

Background may be negligible (dedicated analysis needed)

Kim, Park, **SS**, Work in progress

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- Not energetic muon $\mu \to e \nu_e \nu_\mu$ ($e + \ell$): cut out by requiring $E > 0.1$ GeV
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Our signal (e-scattering)	Hadronized background
Primary signal (clean): 0.1 - 0.3 GeV	e from CC (clean): higher E
Secondary signal (vague): higher E	e from p/n (vague): lower E

+ Number of events of $p(n) \to (2)e$ small

Really background free?

Background may be negligible (dedicated analysis needed)

Kim, Park, **SS**, Work in progress

Cherenkov light detectors (Kamiokande)

- Not energetic muon $\mu \to e \nu_e \nu_\mu$ (e + ℓ): cut out by requiring E > 0.1 GeV
- nν_τ ➝ pτ ➝ p$\ell \nu_\ell \nu_\tau$ (p + ℓ): cut out by requiring 3 visible objects
- nν_e ➝ pe ➝ 3e + … by hadronized p (or just by NC): ring shape & energy

Our signal (e-scattering)	Hadronized background
Primary signal (clean): 0.1 - 0.3 GeV	e from CC (clean): higher E
Secondary signal (vague): higher E	e from p/n (vague): lower E

\+ Number of events of p(n) ➝ (2)e small + directionality (GC)?

Really background free?

Background may be negligible (dedicated analysis needed)

Kim, Park, **SS**, Work in progress

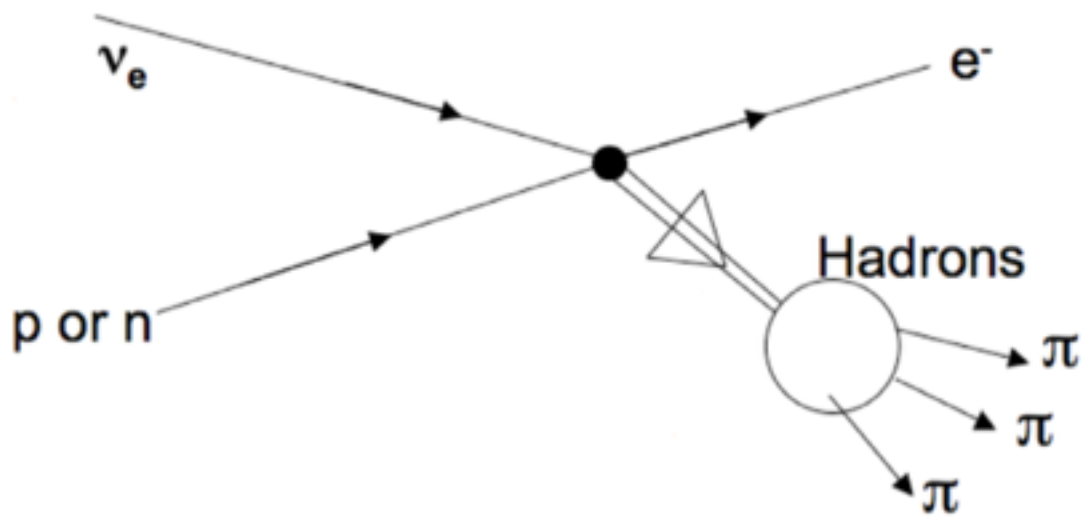
Ionization from the charged track (DUNE)

- Not energetic muon $\mu \to e \nu_e \nu_\mu$ ($e + \ell$): cut out by requiring $E > 0.1$ GeV
- $n \nu_\tau \to p \tau \to p \ell \nu_\ell \nu_\tau$ ($p + \ell$): cut out by requiring 3 visible objects
- $n \nu_e \to p e \to 3e + \ldots$ by hadronized p (or just by NC): shower can be seen

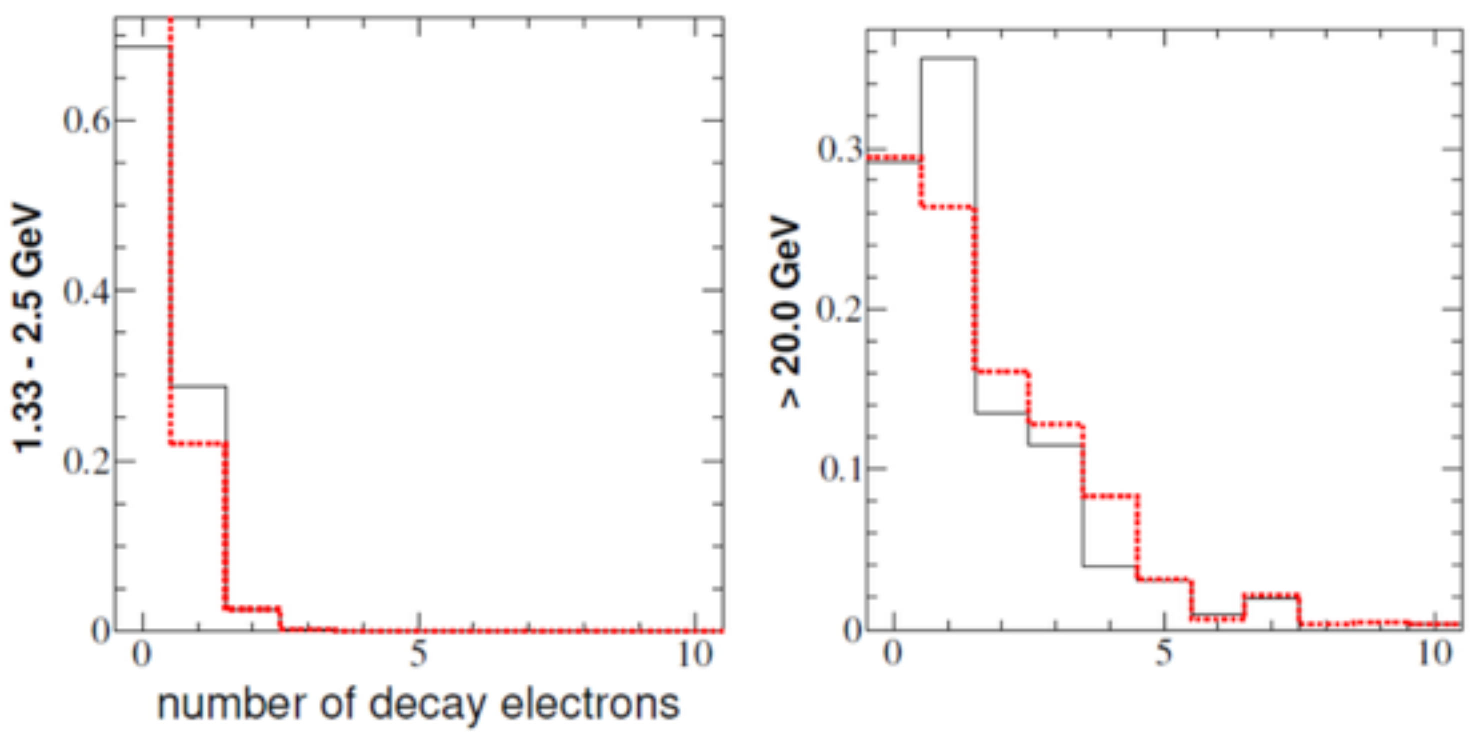
Maybe DUNE can separate all possible backgrounds

Back up

Super-K (2012)

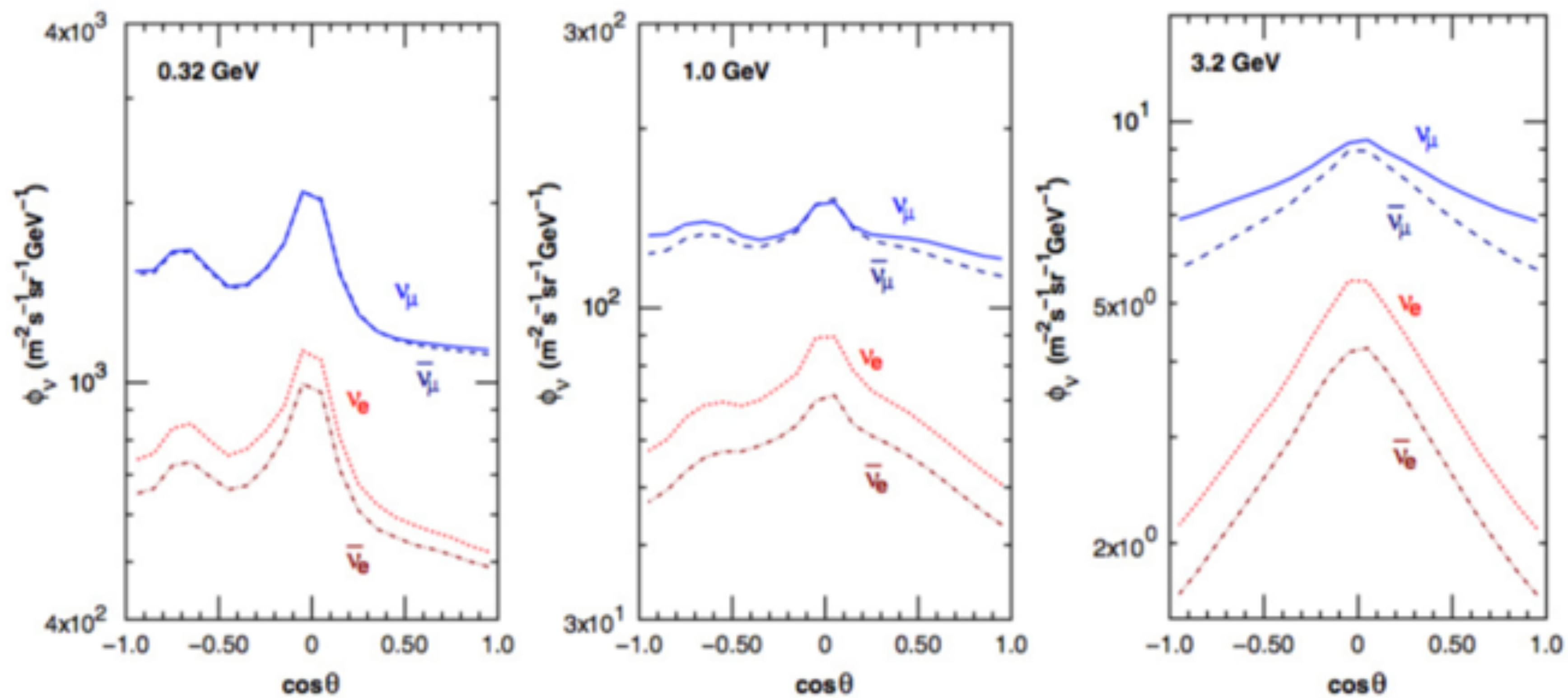


$$\pi^+ \to \mu^+ + \nu + \mu$$
$$\quad \hookrightarrow e^+ + \nu_e + \overline{\nu}_\mu$$



Back up

Flux of atmospheric neutrino



θ: zenith angle

Energetic neutrino ~ 10^{-4} cm^{-2} s^{-1}

Back up

x 0.1 or smaller

Sub-Sample	SK-I	SK-II	SK-III	SK-IV	Total			
	Livetime (days)							
FC and PC	1489	799	518	1993	4799			
UPMU	1646	828	636	1993	5103			
	Number of Events					Interaction [%]		
						ν_eCC	ν_μCC	NC
FC *e*-like								
sub-GeV single-ring	3288 (3104.7)	1745 (1632.8)	1209 (1100.7)	4251 (4072.8)	10493 (9911.0)	94.1	1.5	4.4
multi-GeV single-ring	856 (842.8)	396 (443.7)	274 (299.5)	1060 (1080.0)	2586 (2666.0)	86.3	3.2	10.5
multi-GeV multi-ring	449 (470.1)	267 (252.1)	140 (161.9)	634 (654.9)	1490 (1539.0)	73.0	7.6	19.4
FC μ-like								
sub-GeV single-ring	3184 (3235.6)	1684 (1731.8)	1139 (1152.0)	4379 (4394.7)	10386 (10514.0)	0.9	94.2	4.9
multi-GeV single-ring	712 (795.4)	400 (423.9)	238 (273.9)	989 (1051.5)	2339 (2544.7)	0.4	99.1	0.5
multi-GeV multi-ring	603 (656.5)	337 (343.8)	228 (237.9)	863 (927.8)	2031 (2166.0)	3.4	90.5	6.1
PC								
stop	143 (145.3)	77 (73.2)	54 (53.3)	237 (229.0)	511 (500.8)	12.7	81.7	5.6
thru	759 (783.8)	350 (383.0)	290 (308.8)	1093 (1146.7)	2492 (2622.3)	0.8	98.2	1.0
UPMU								
stop	432.0 (433.7)	206.4 (215.7)	193.7 (168.3)	492.7 (504.1)	1324.8 (1321.8)	1.0	97.7	1.3
non-showering	1564.4 (1352.4)	726.3 (697.5)	612.9 (504.1)	1960.7 (1690.3)	4864.3 (4244.4)	0.2	99.4	0.3
showering	271.7 (291.6)	110.1 (107.0)	110.0 (126.0)	350.1 (274.4)	841.9 (799.0)	0.1	99.8	0.1

Back up

x 0.1 or smaller

Sub-Sample	SK-I		SK-II		SK-III		SK-IV		Total				
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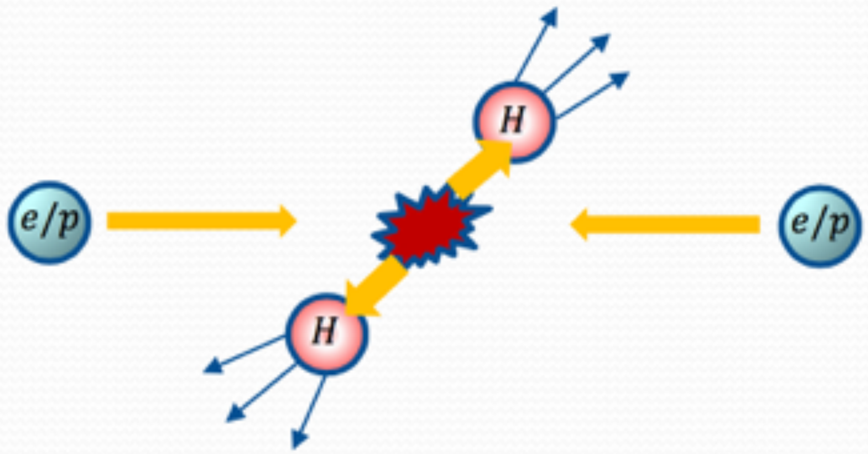
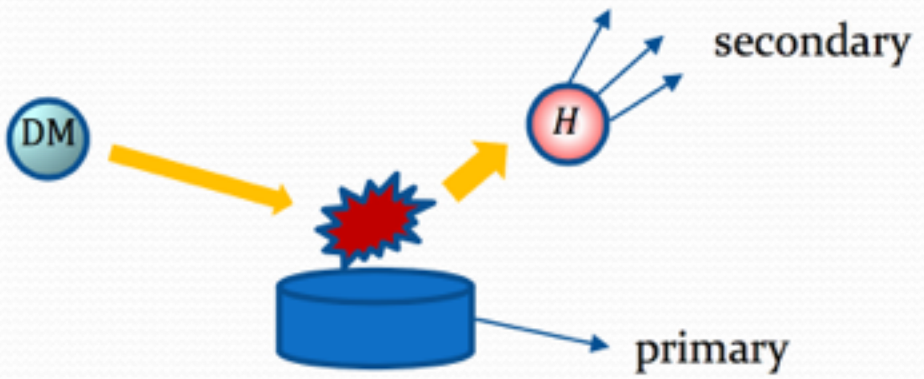
Back up

Collider as a heavy-state probe





Conventional colliders

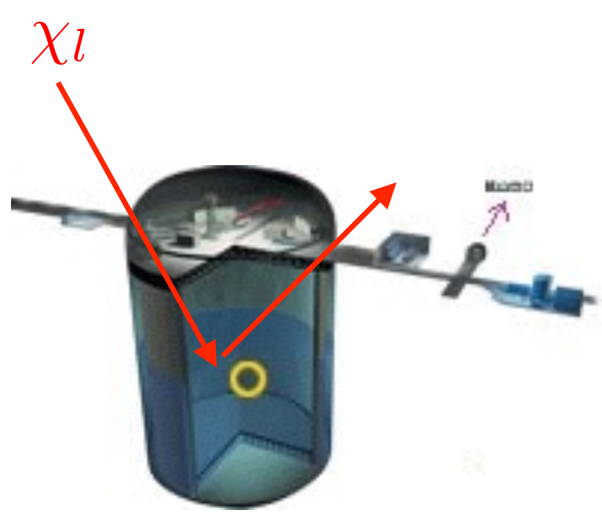
- ❑ Head-on collision of light SM-sector (stable) particles
- ❑ to produce heavier states
- ❑ and study resulting phenomenology

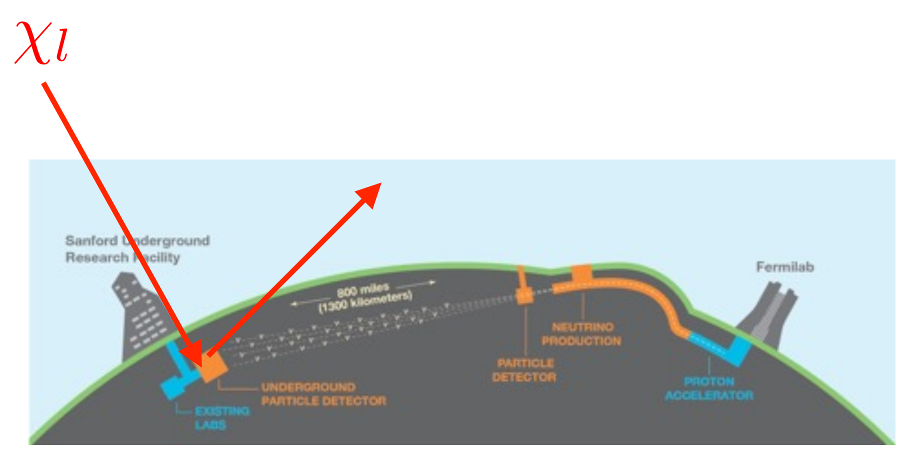
Dark matter colliders

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

Passive search of relativistic DM scattering

$\chi_h \chi_h \rightarrow \chi_l \, \chi_l$ (current universe) relativistic





Modification of minimal models make them *super promising*

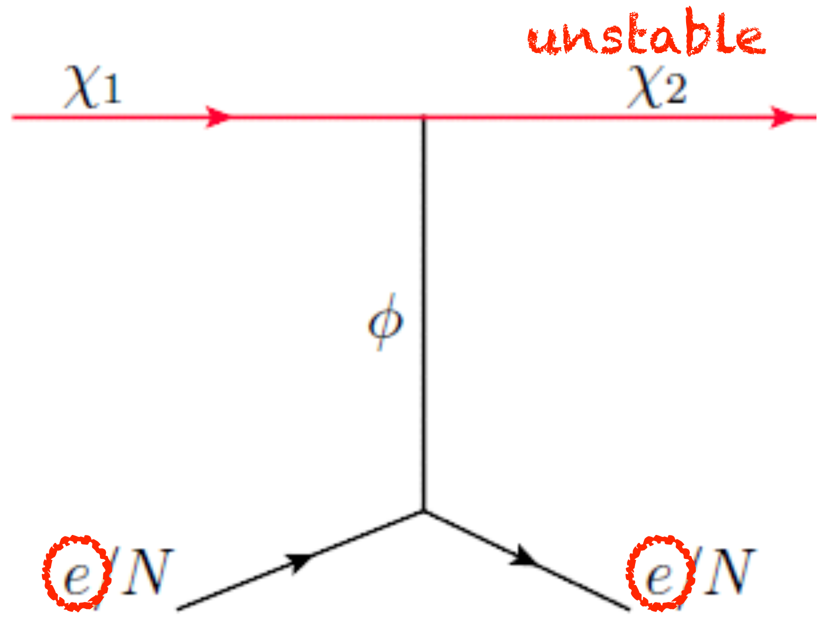
- From Sun: a small coupling of χ_h - SM or self-interaction of χ_h

  Berger, Cui, Zhao, 1410.2246 Kong, Mohlaberg, Park, 1411.6632
  Alhazmi, Kong, Mohlaberg, Park, 1611.09866

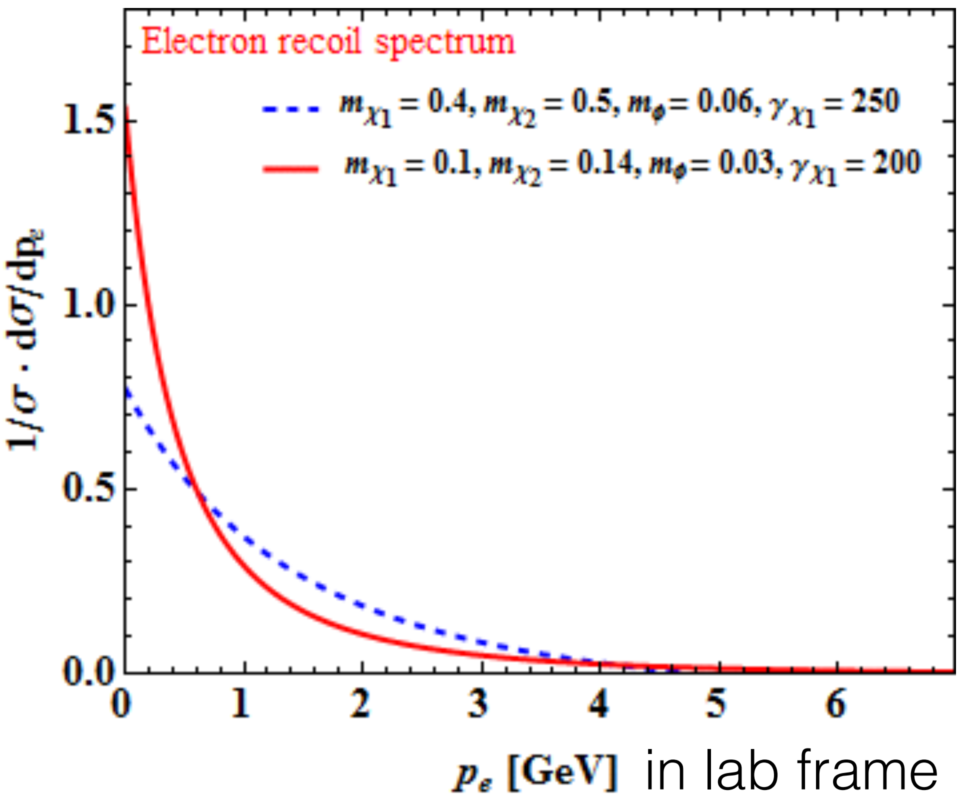
- Non-minimal dark sector (just like SM?): extraordinary signal

  Kim, Park, **SS**, 1612.06867

Energy spectrum: e-scattering



primary scattering

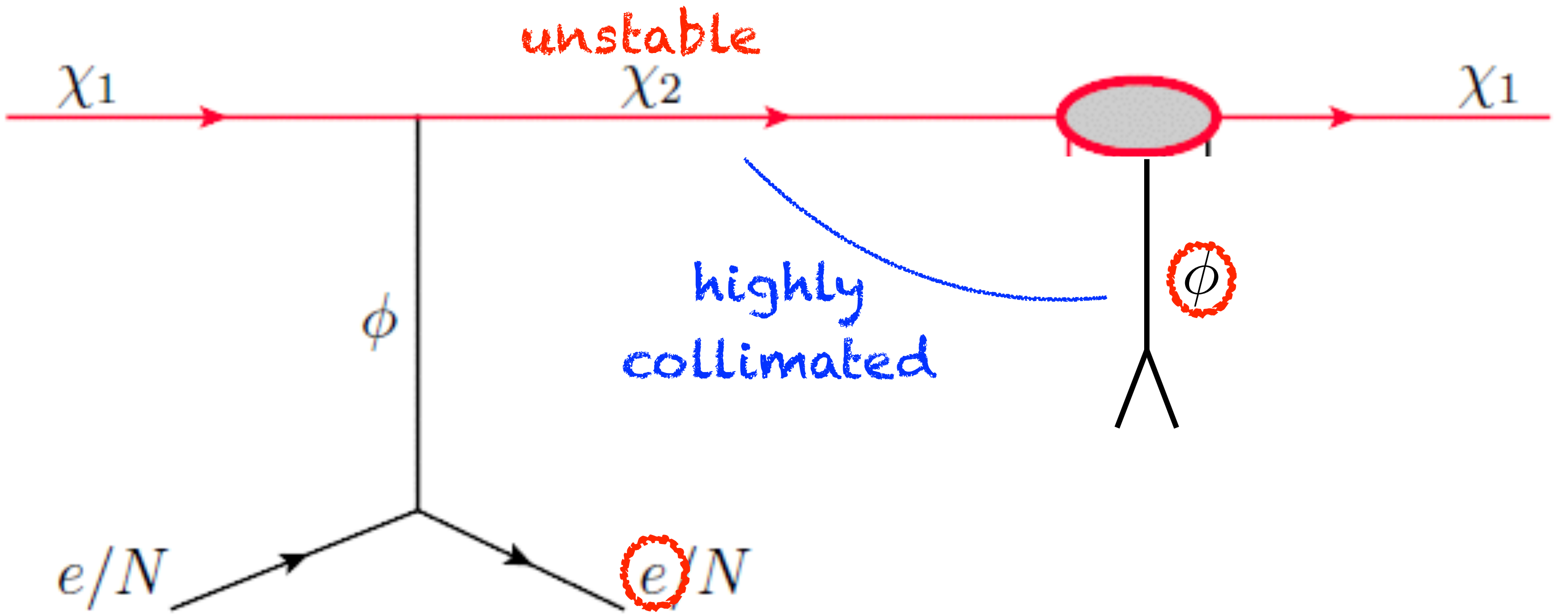


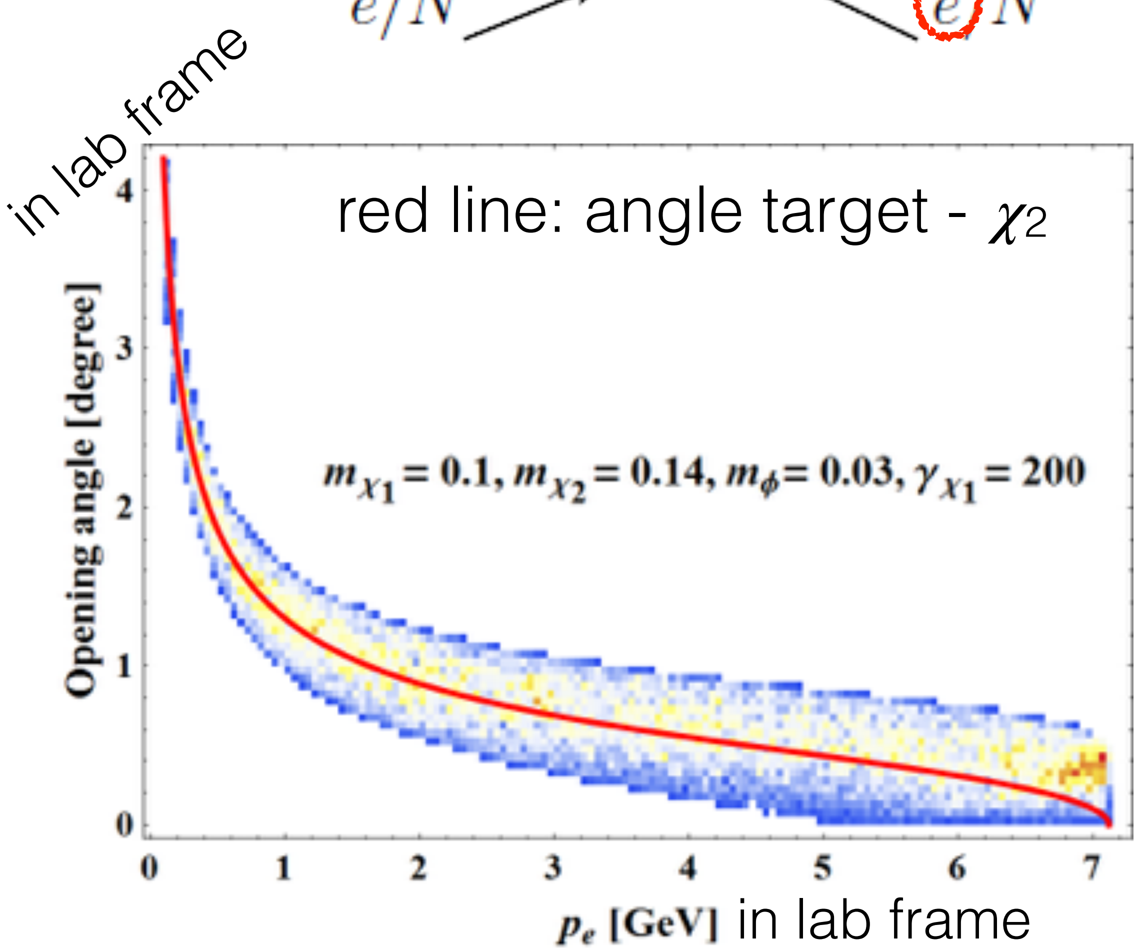
in lab frame

e-scattering preferred over p-scattering

- Primary scattering cross section large when <u>momentum transfer small</u>
- <u>E_{th} low</u> for e-scattering but high for p-scattering (Cherenkov detectors) Kamiokande
- Proton scattering is suppressed by atomic form factor

e-scattering: highly collimated





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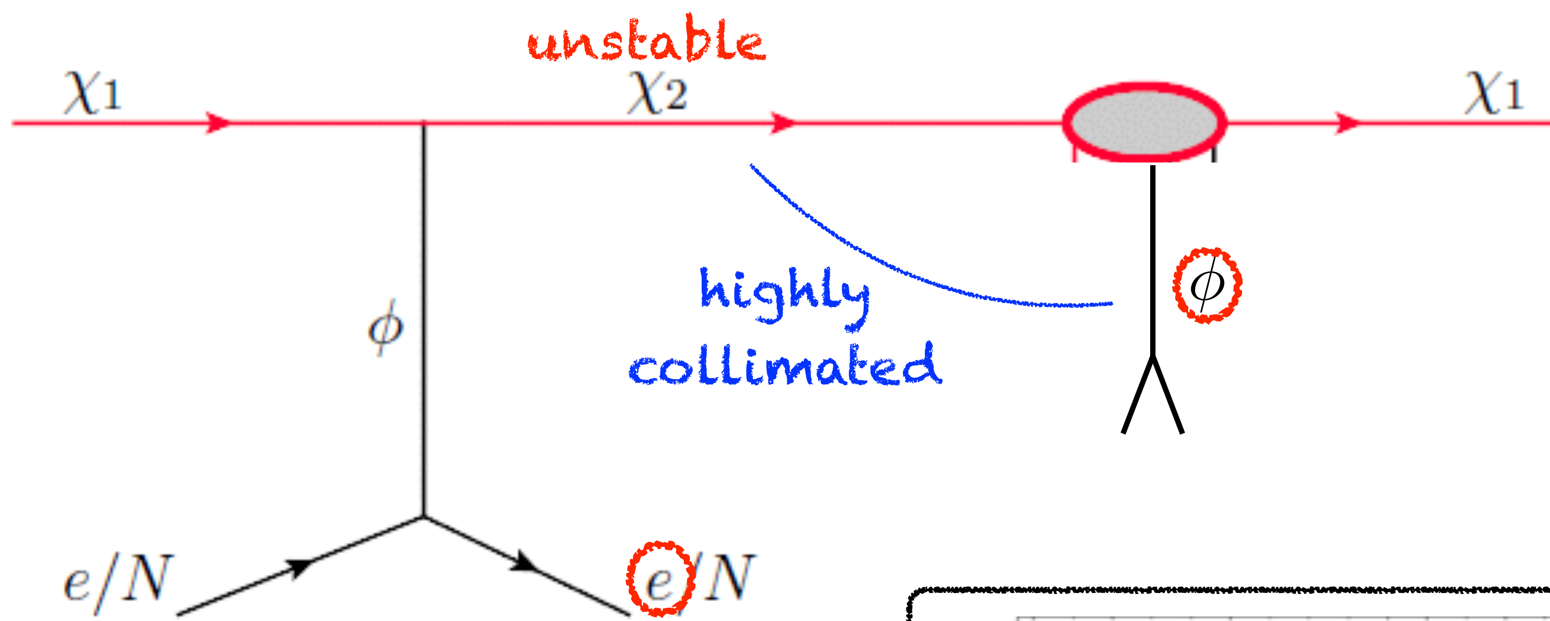
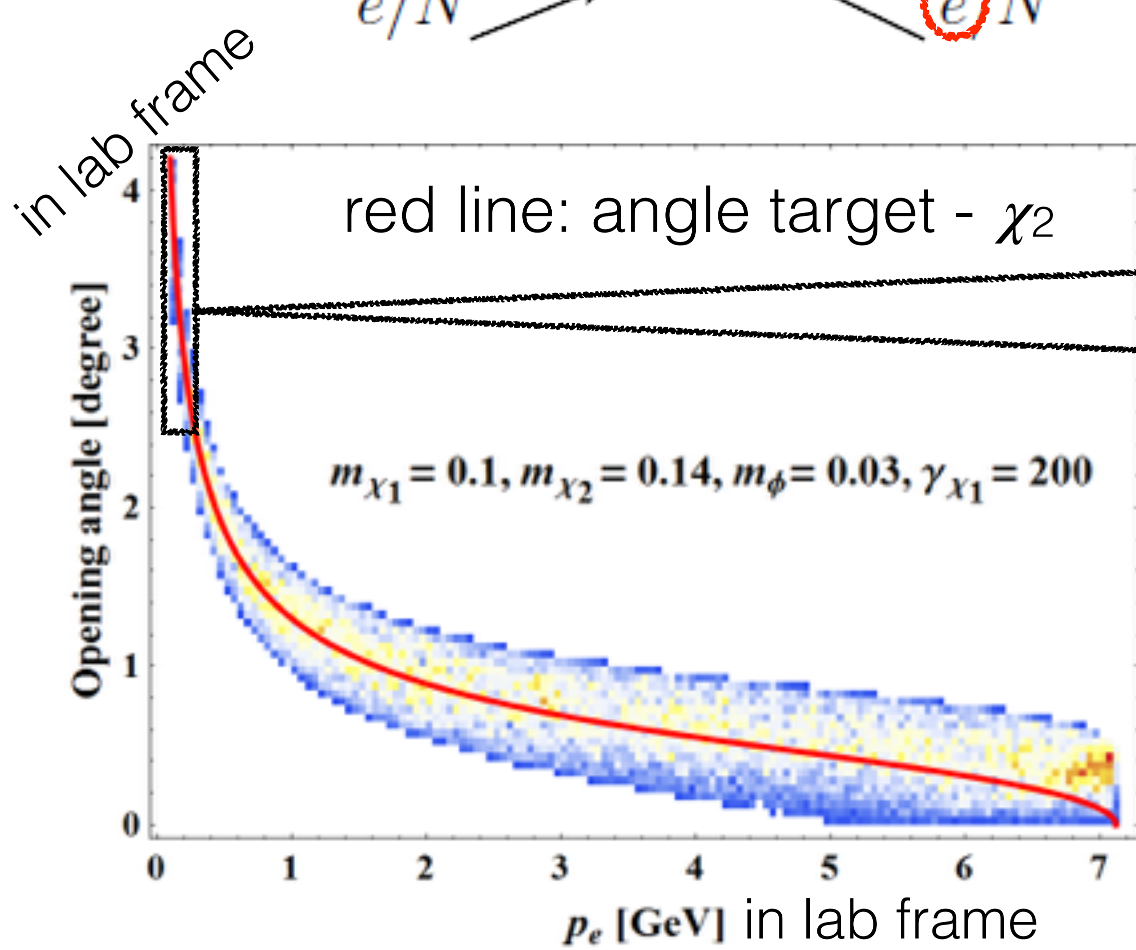
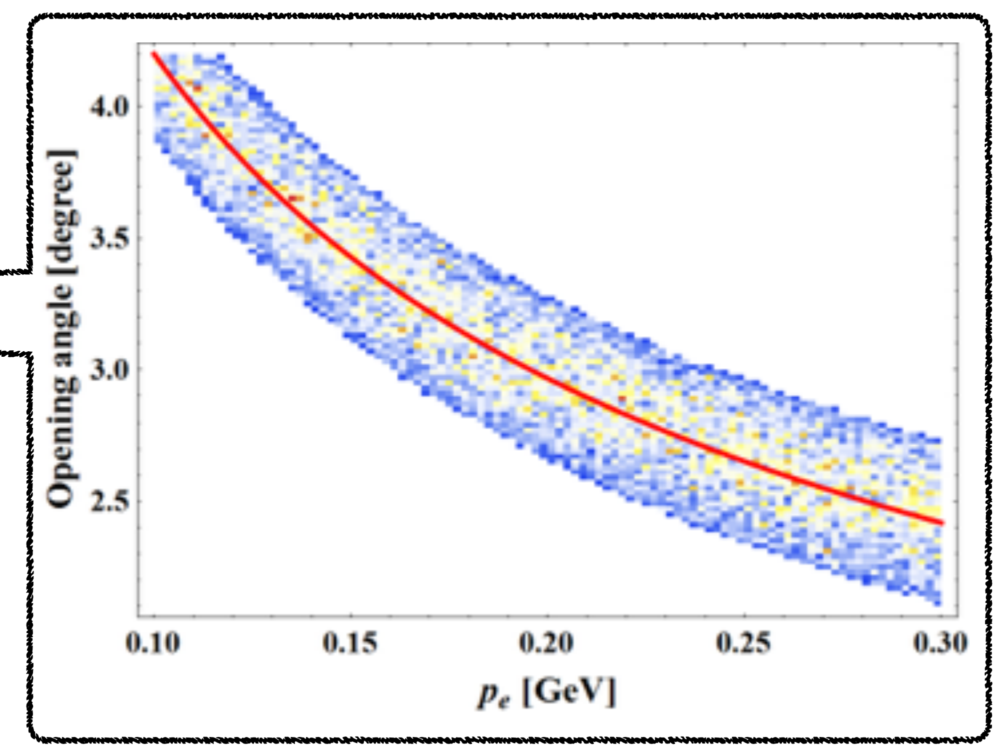
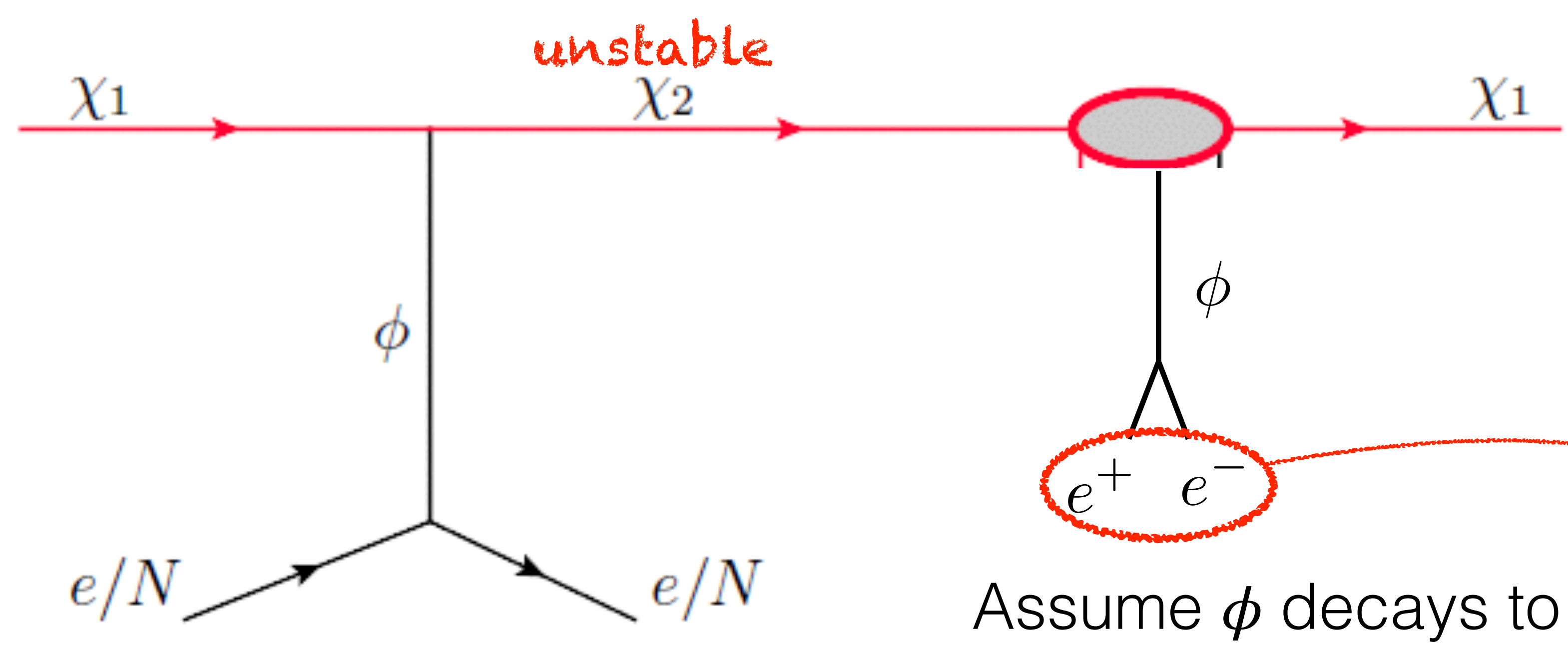




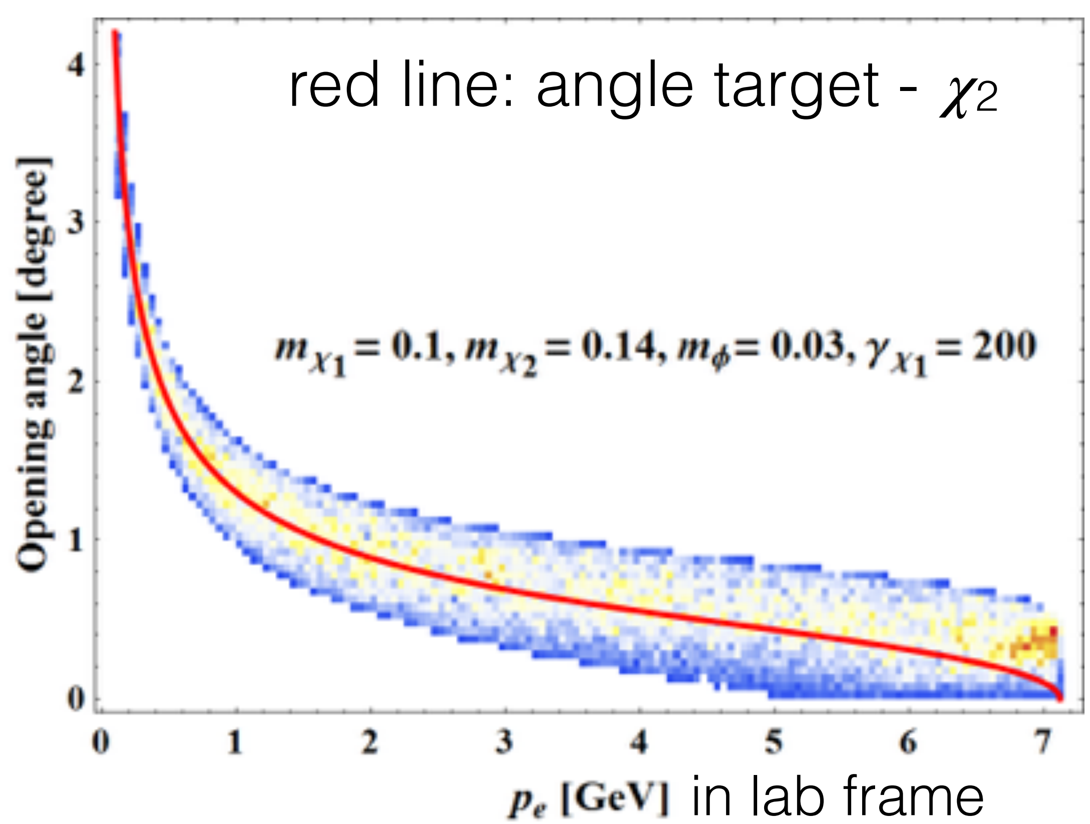


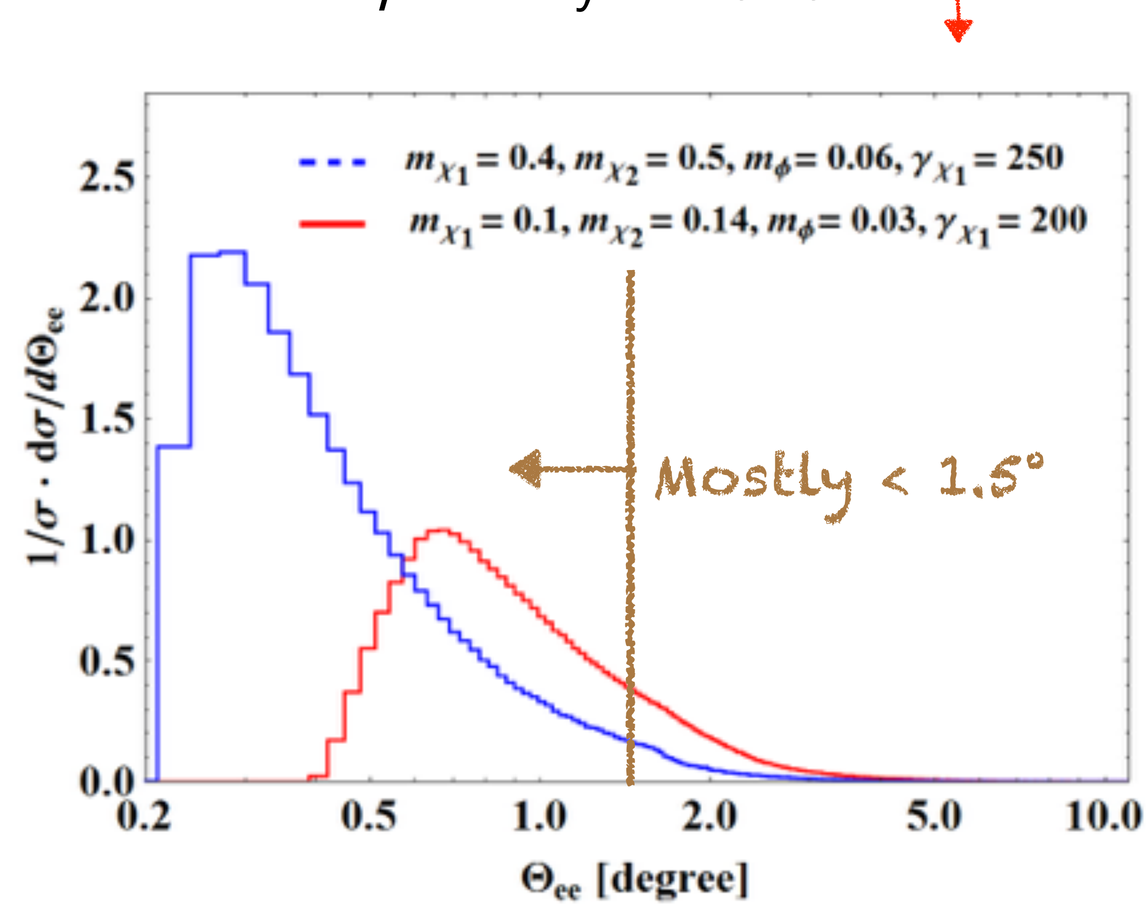
Angular resolution 3° ? **two signals!**
(drops for smaller p_e)

e-scattering: highly collimated

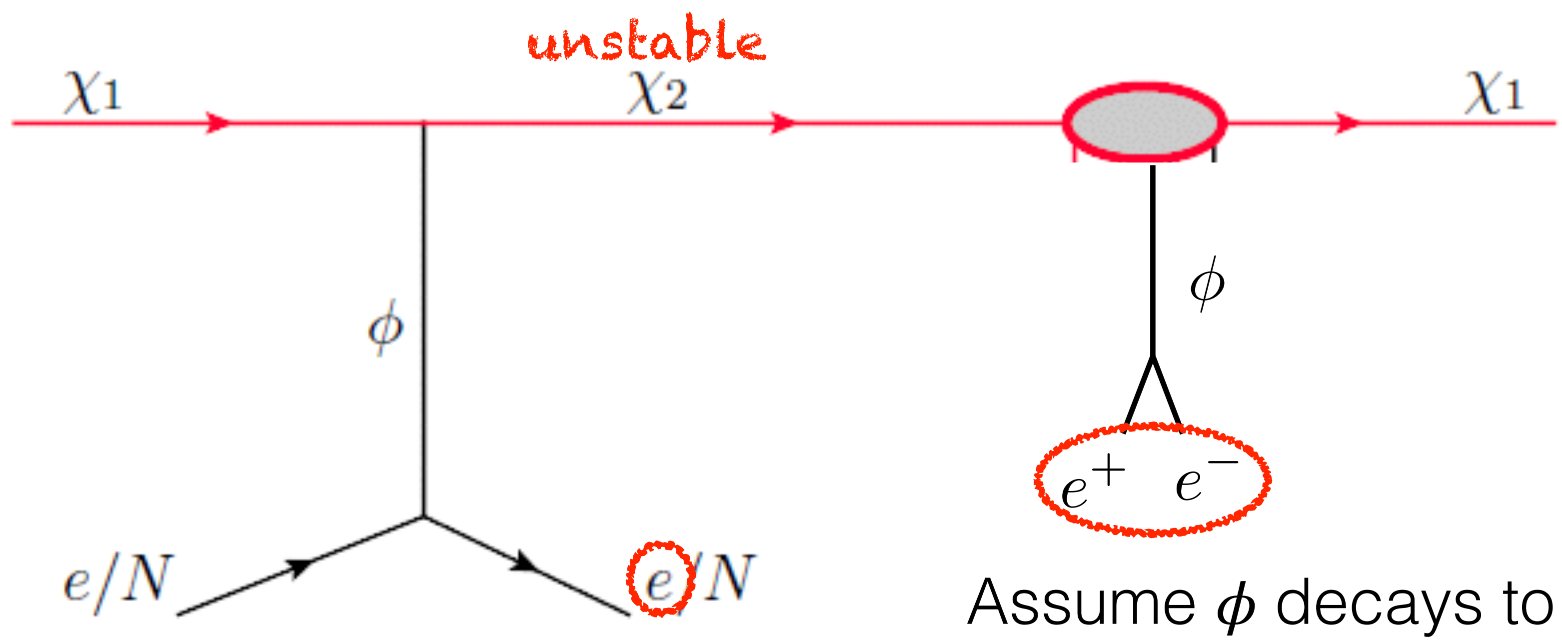


Assume ϕ decays to e^+e^-





e-scattering: detection prospects



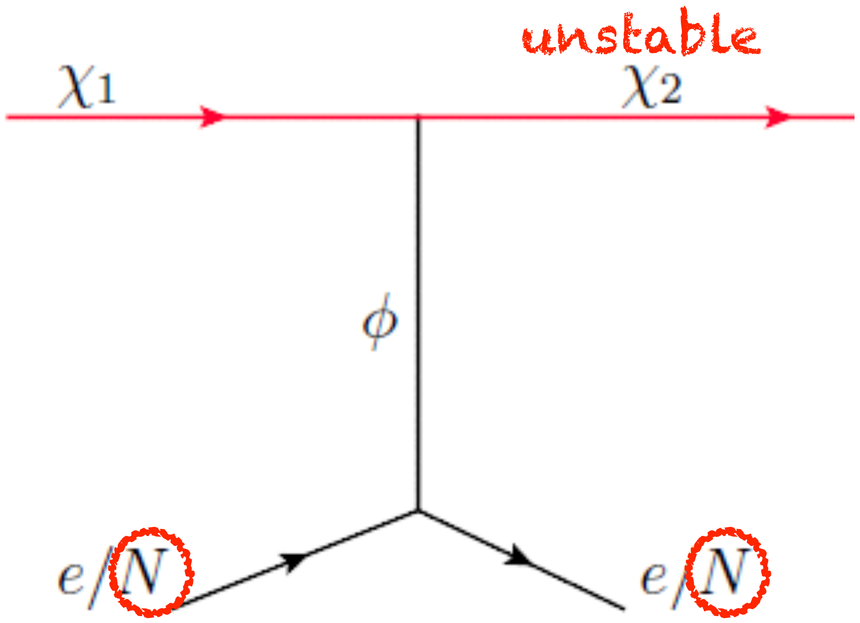
Assume ϕ decays to e^+e^-

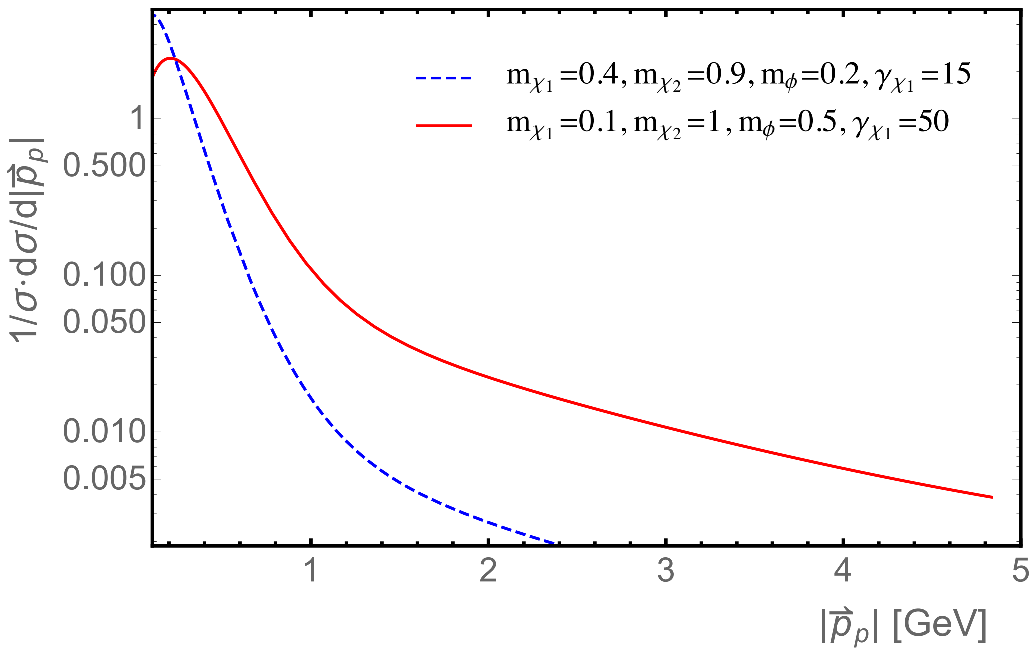
effective for $E > E_{th}$

We need good res.

	Volume [Mt]	E_e[GeV]	E_p^{thres} [GeV]	θ_e^{res}	θ_p^{res}
Super-K	0.0224	0.1	1.07	3°	3°
Hyper-K	0.56	0.1	1.07	3°	3°
DUNE	0.04	0.03	0.05	1°	5°

p-scattering: energy spectrum

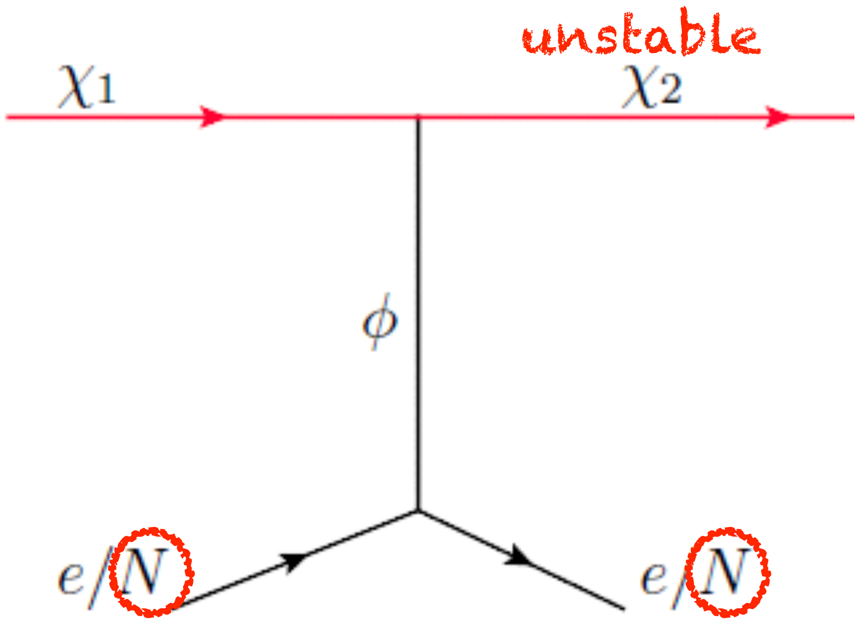


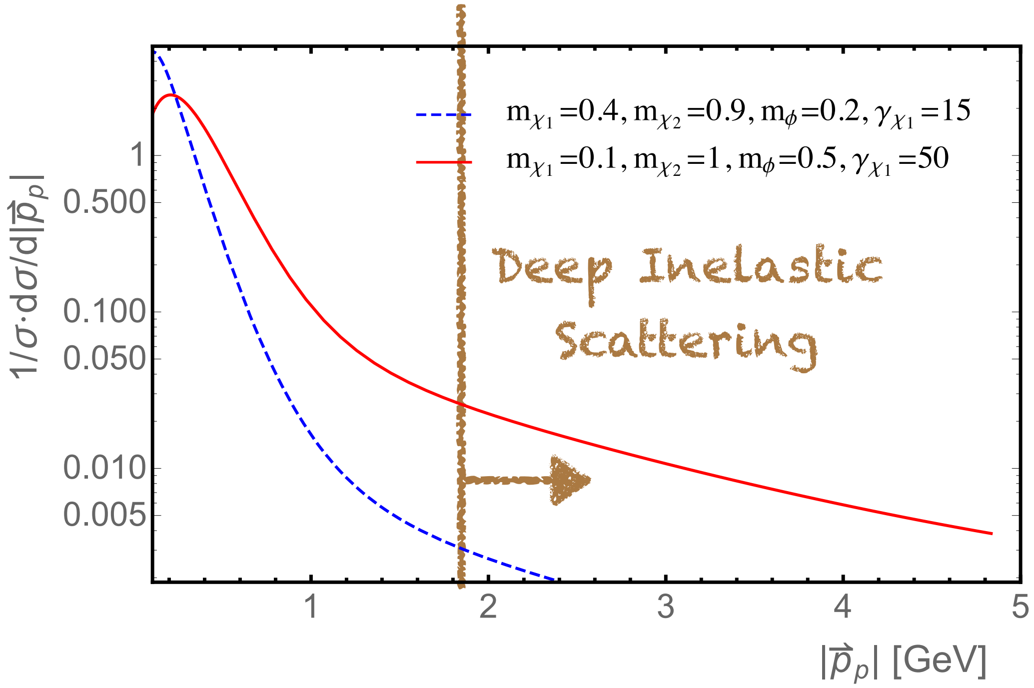


p-scattering NOT preferred over e-scattering (Cherenkov)

- Primary scattering cross section large when momentum transfer small
- E_{th} high for proton scattering (for Cherenkov)
- Proton scattering is suppressed by atomic form factor

p-scattering: energy spectrum





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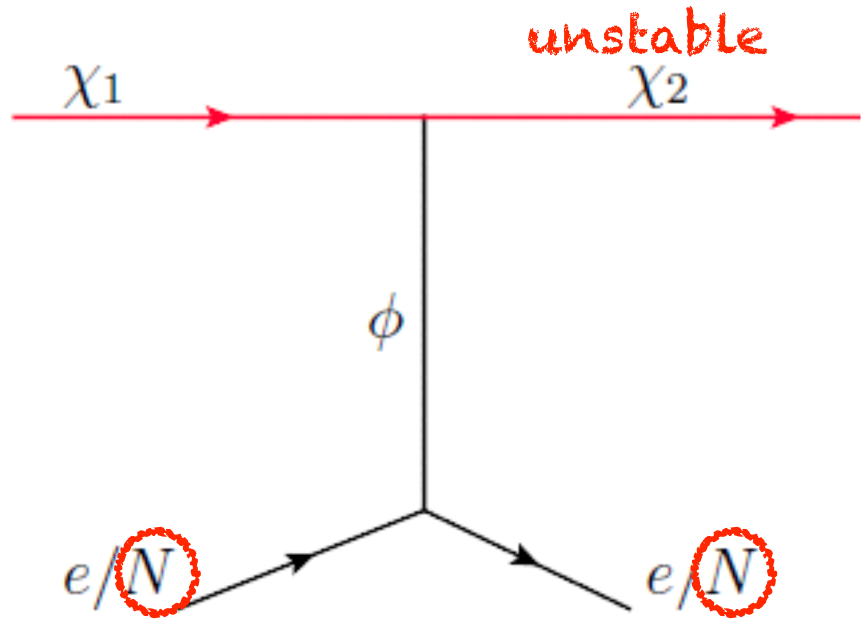
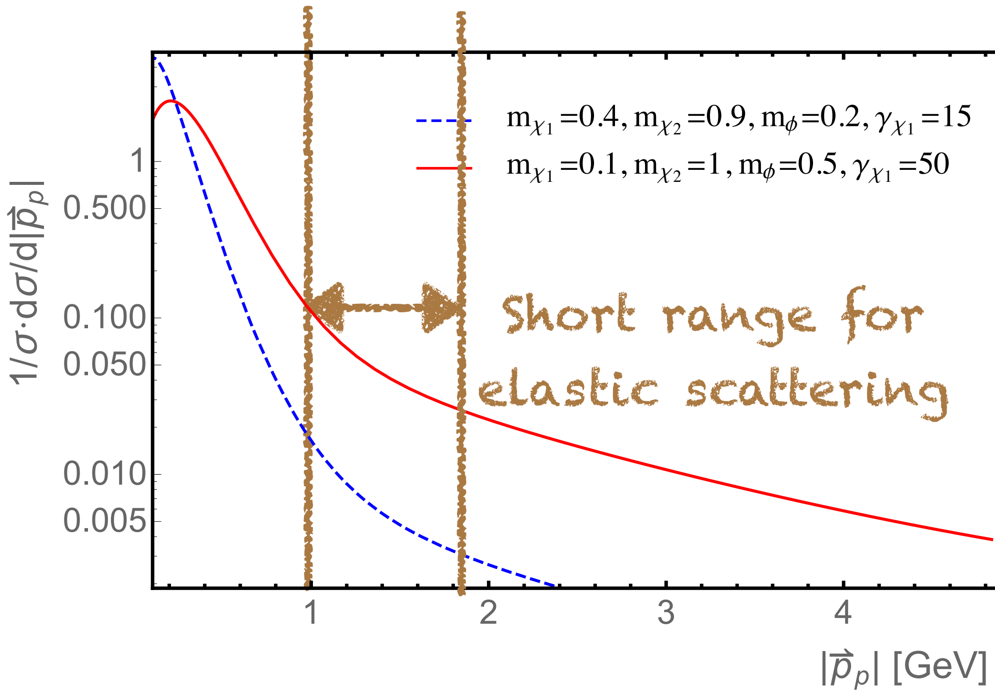
p-scattering: energy spectrum

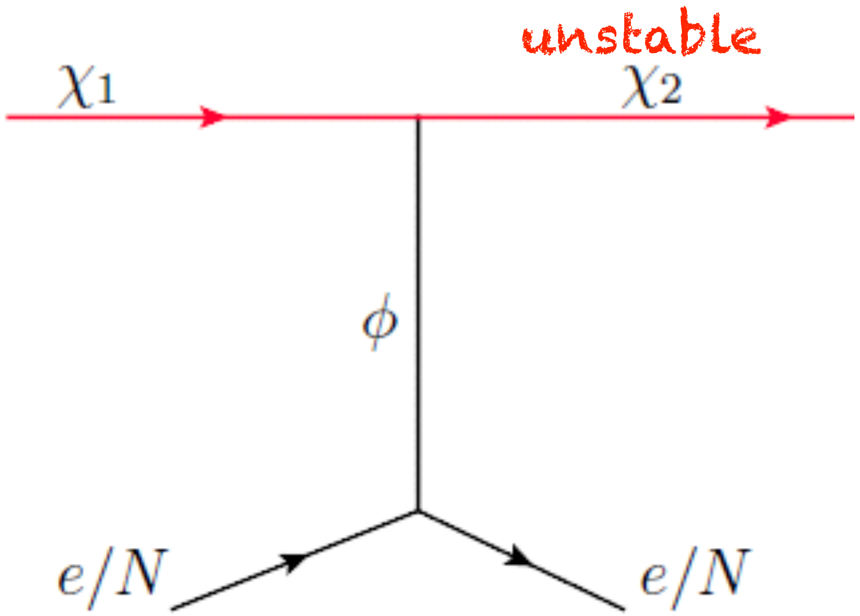


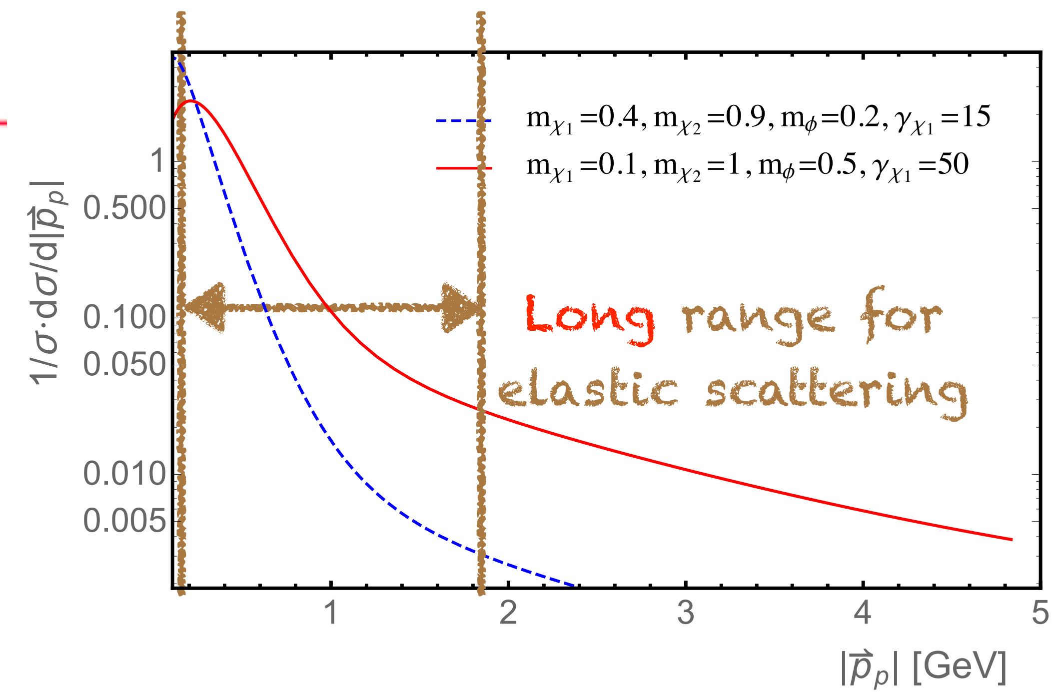


p-scattering NOT preferred over e-scattering (Cherenkov)

- Primary scattering cross section large when <u>momentum transfer small</u>
- E_{th} high for proton scattering (for Cherenkov)
- Suppression by atomic form factor: <u>not so severe for p_p < 2 GeV</u>

p-scattering: energy spectrum

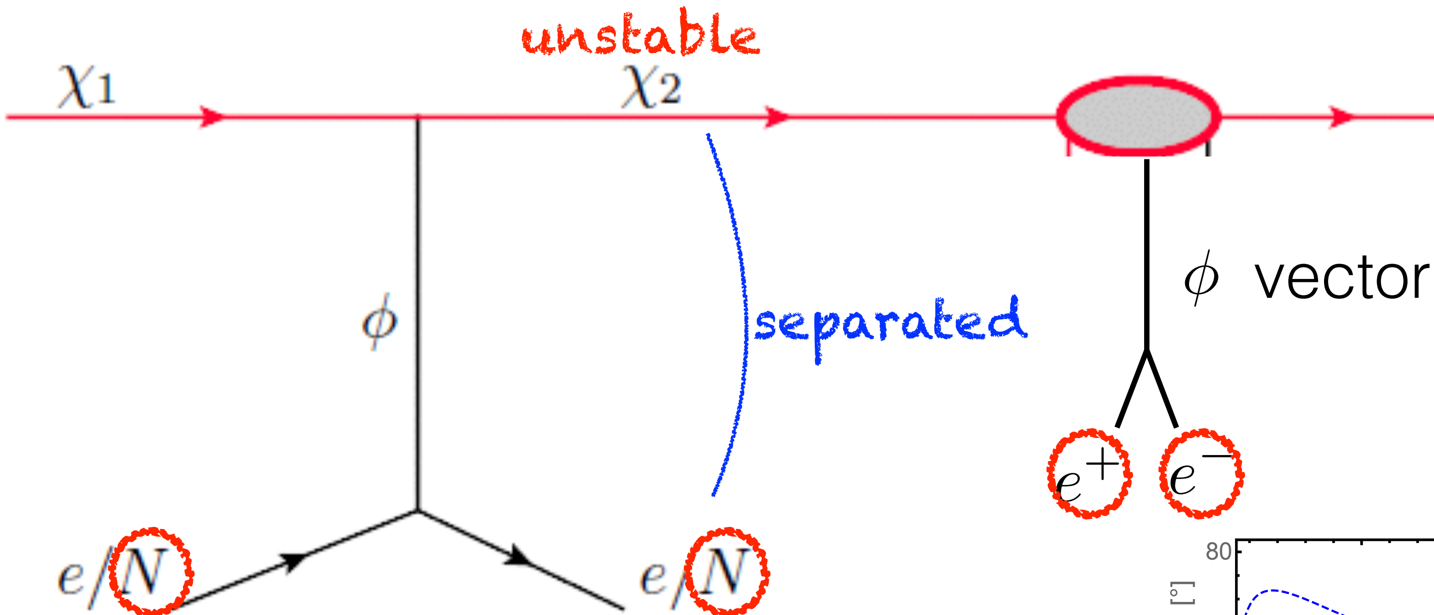


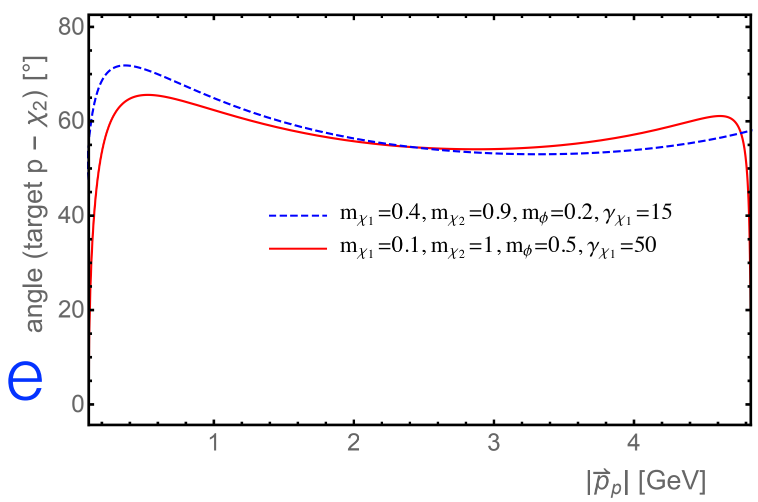


However, the cascade process is still unique

- E_{th} low for proton scattering for liquid Ar detectors (DUNE: E_{th} 50 MeV)
- Separation of two signals are more promising than e-scattering

p-scattering: energy spectrum





However, the cascade process is still unique

- E_{th} low for proton scattering for liquid Ar detectors (DUNE: E_{th} 50 MeV)
- Separation of two signals super good & **3 visible objects**

for both Kamiokande & DUNE