DPF 2017, Fermilab

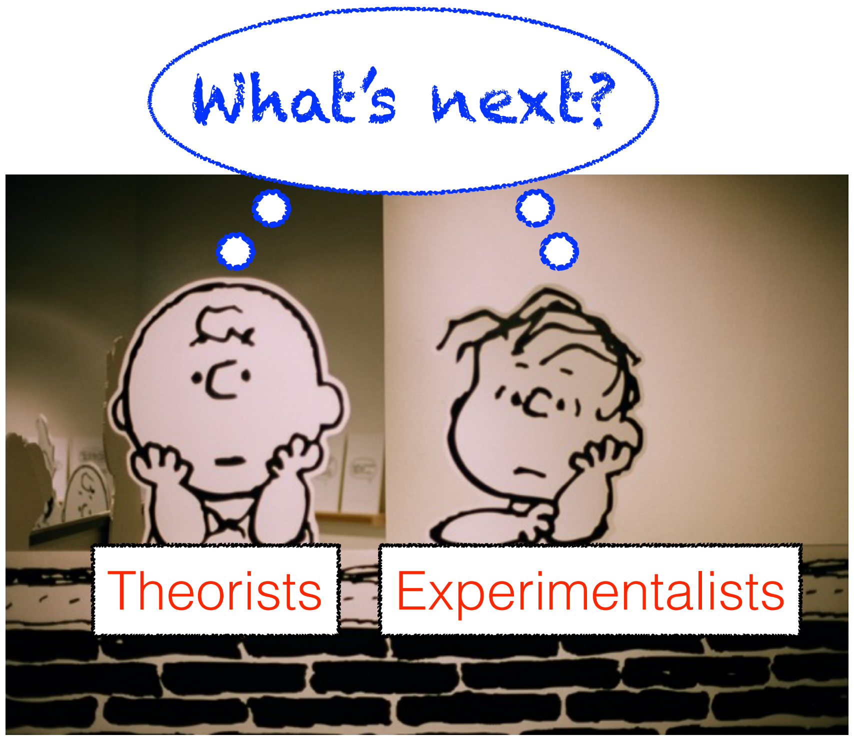
Dark matter collider at DUNE: relativistic scattering of boosted DM

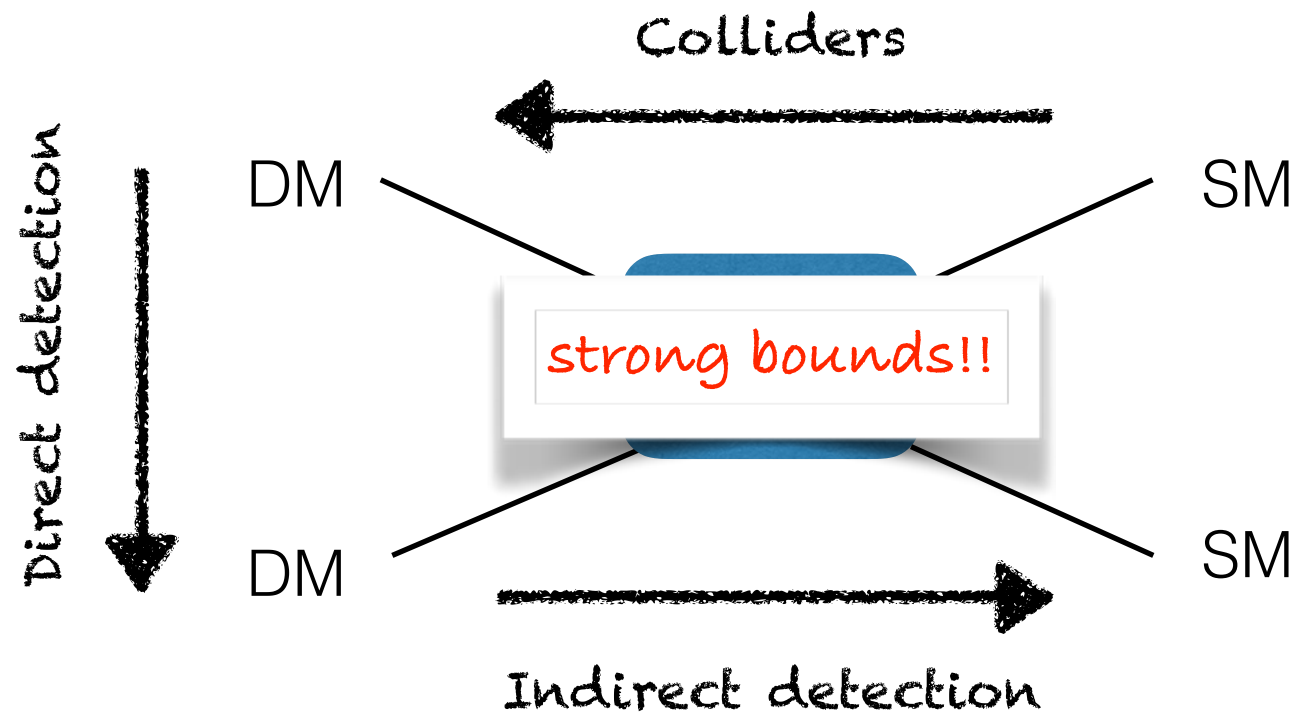
THE UNIVERSITY OF CHICAGO

Seodong Shin

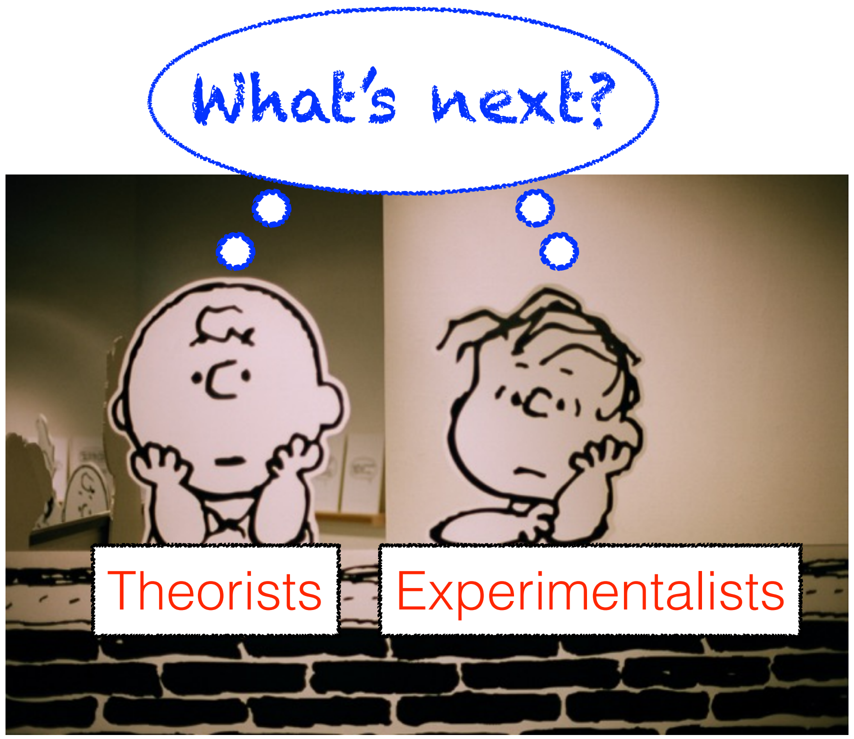
1612.06867 with Doojin Kim, Jong-Chul Park

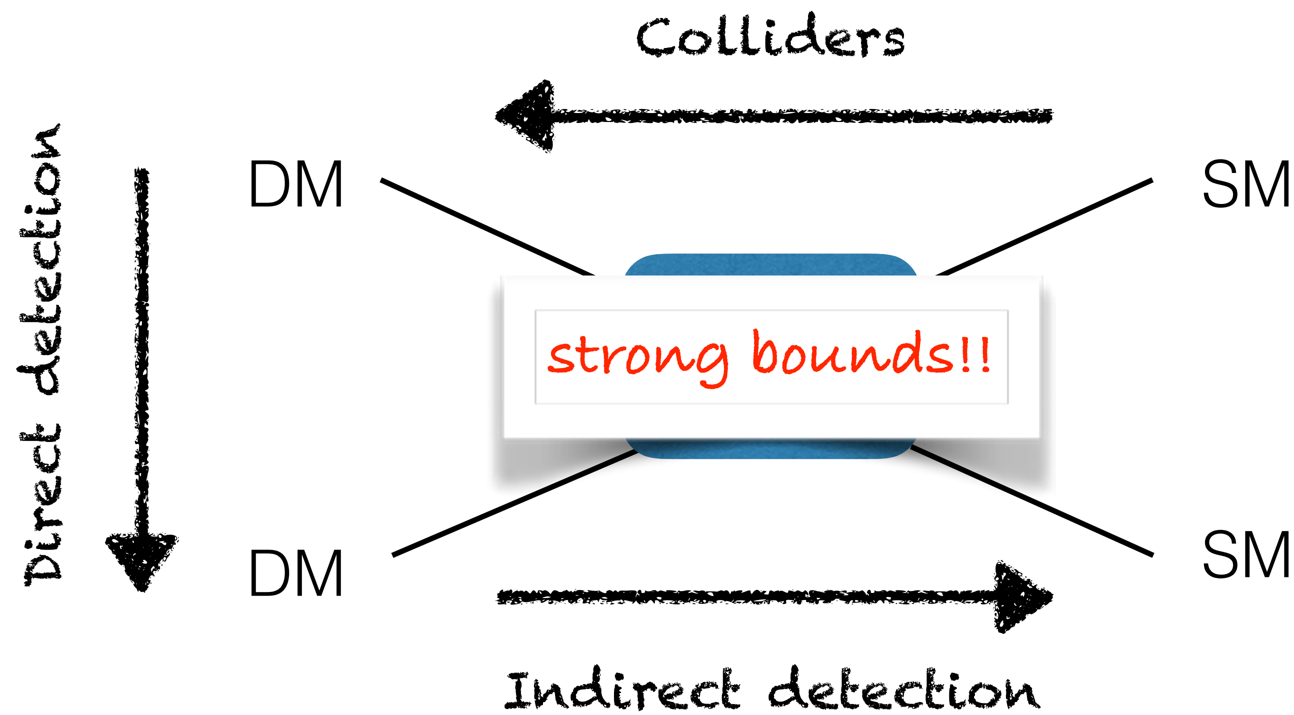
Not easy tasks





Not easy tasks

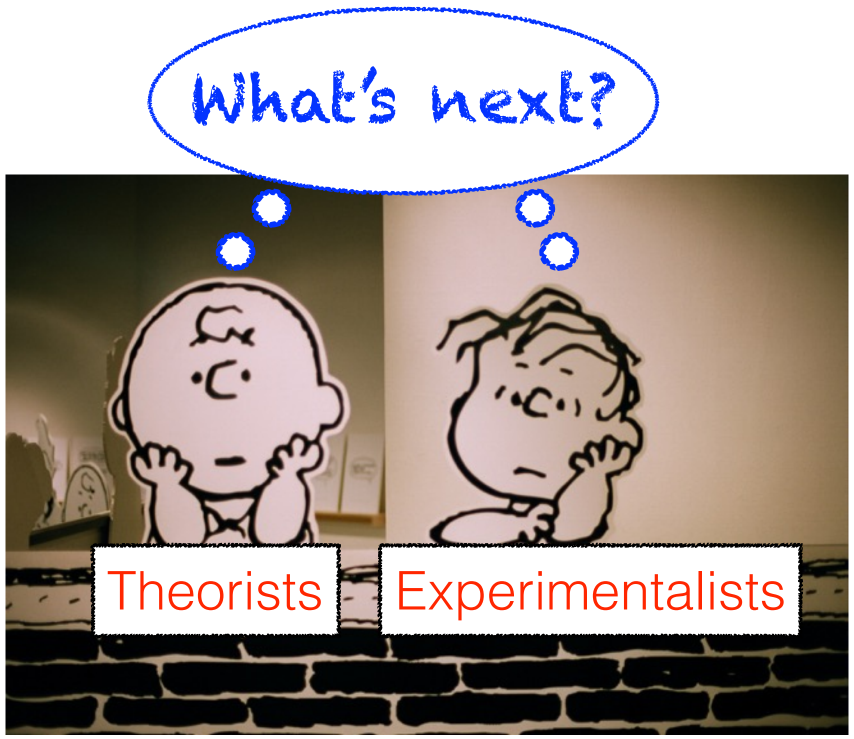


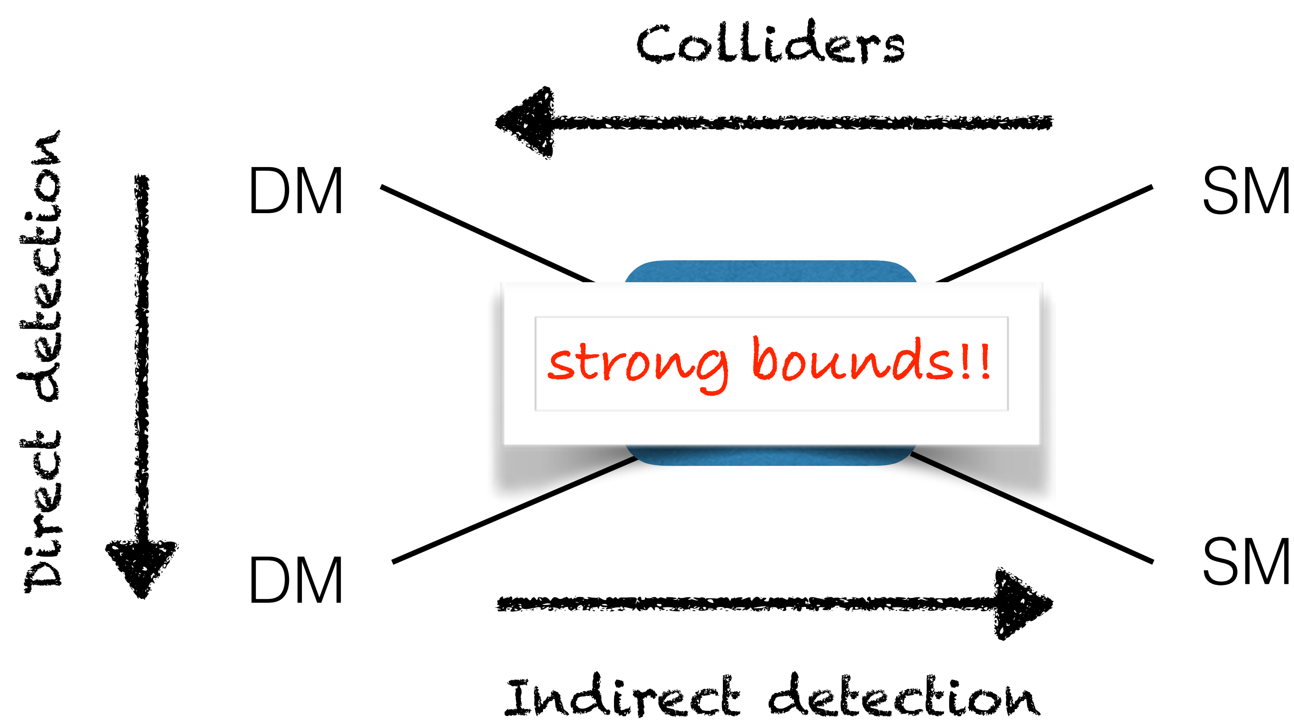


- Keep probing the rest of the corners of parameter space:
  tons of models may be still there!!

- 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 & search strategy can be considered!

Non-conventional DM scenarios

- Secluded WIMP: DM-SM int. suppressed (avoid LHC & DD bounds)

  Huh, Kim, Park, Park, 0711.3528
  Kim, **SS**, 0901.2609
  Pospelov, Ritz, Voloshin, 0711.4866
  Kim, Lee, Park, **SS**, 1601.05089

- Flavorful (non-minimal) dark sector:

  multi-component DM and/or + unstable particles (like SM)

  non-conventional thermal scenario expected

  Belanger, Park, 1112.4491 Agashe, Cui, Necib, Thaler, 1405.7370

  Kim, Park, **SS**, 1612.06867, 1702.02944

- Non-conventional interactions: self-interacting, strongly-interacting

- etc…..

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- Non-conventional interactions: self-interacting, strongly-interacting

- etc…..

Non-conventional search strategy needed!

Non-conventional search strategy

My focus

Relativistic scattering of DM with a target

- 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

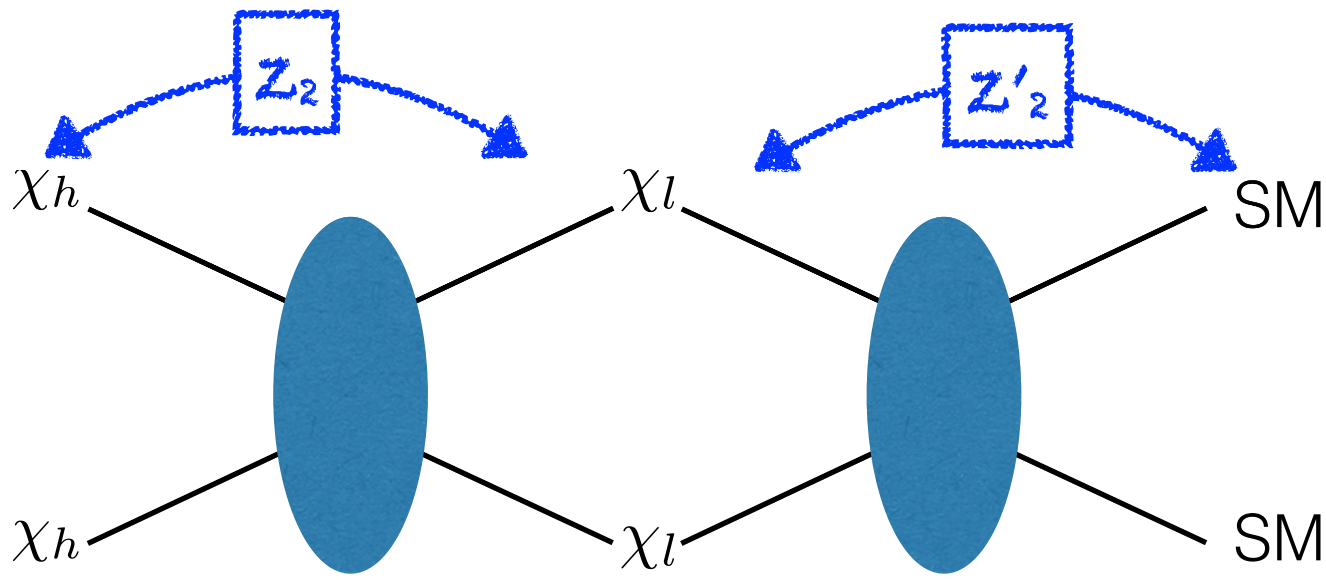
  Bjorken, Essig, Schuster, Toro, 0906.0580

  Batell, Pospelov, Ritz, 0906.5614

  Izaguirre, Krnjaic, Schuster, Toro, 1403.6826

Non-conventional search strategy

e.g., boosted dark matter



Agashe, Cui, Necib, Thaler, 1405.7370

Non-conventional search strategy

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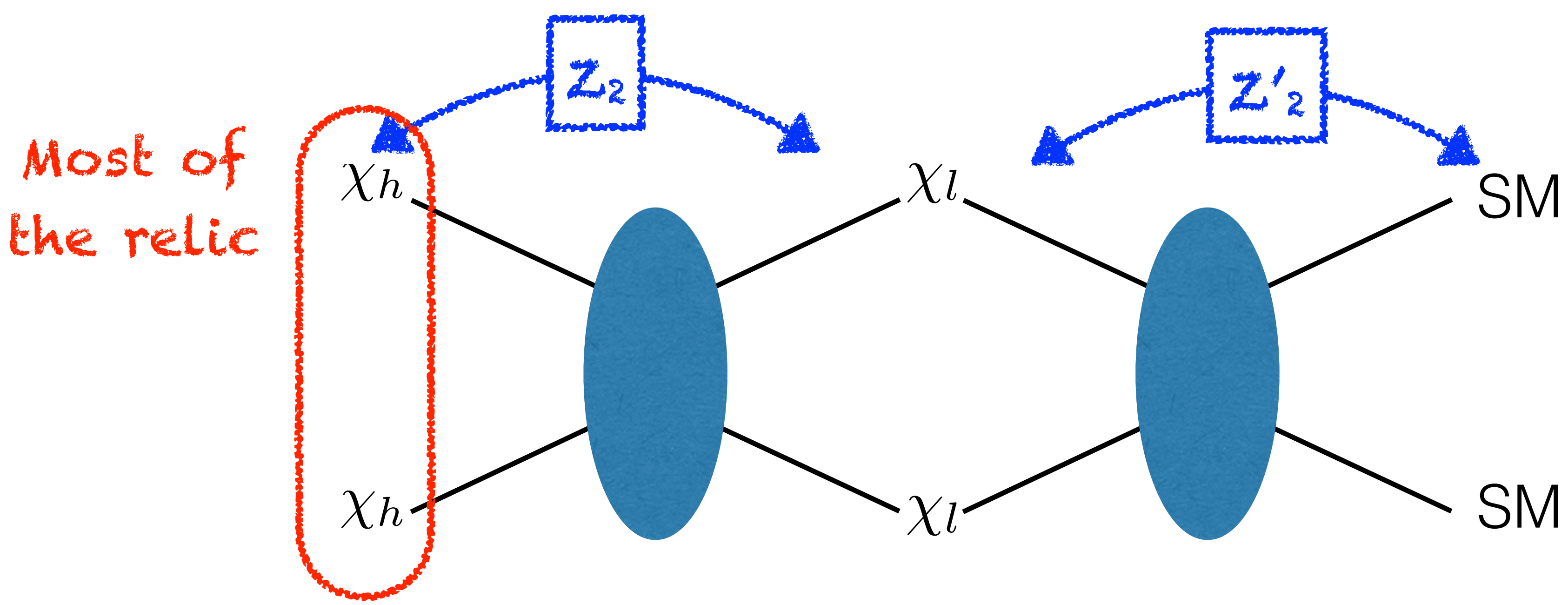


Agashe, Cui, Necib, Thaler, 1405.7370

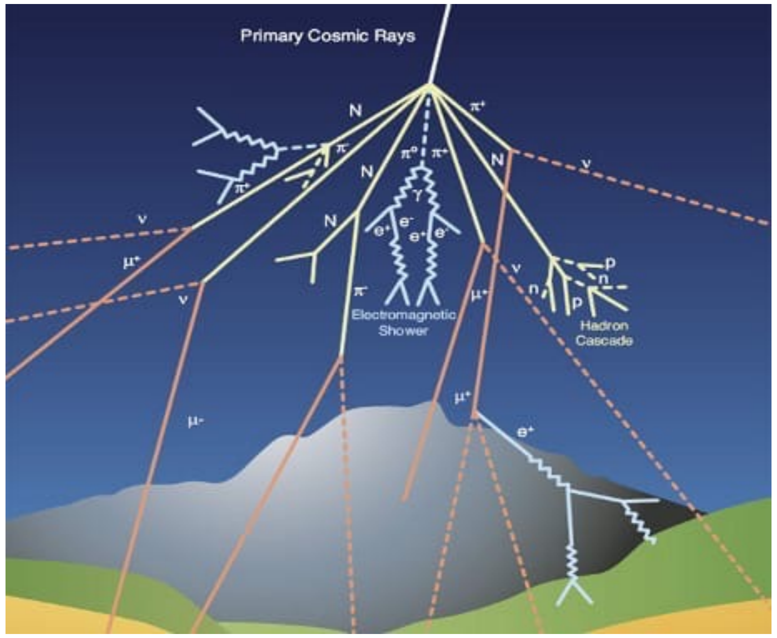
Belanger, Park, 1112.4491 Assisted freeze-out

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

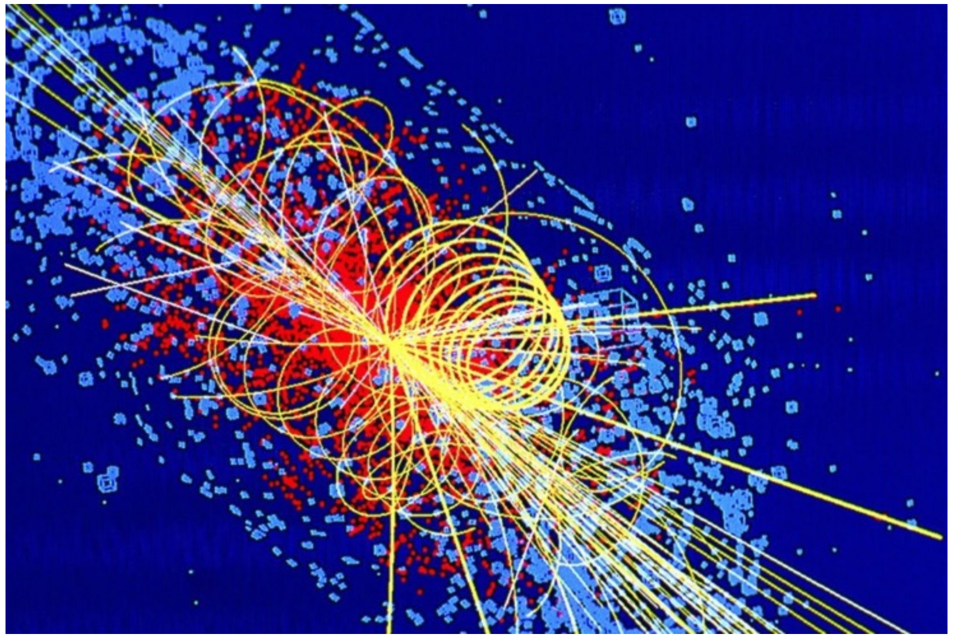
※ relic χ_l is non-relativistic

Categories of search

SM (5% of the Universe)



Cosmic frontier search



Collider search (active search)

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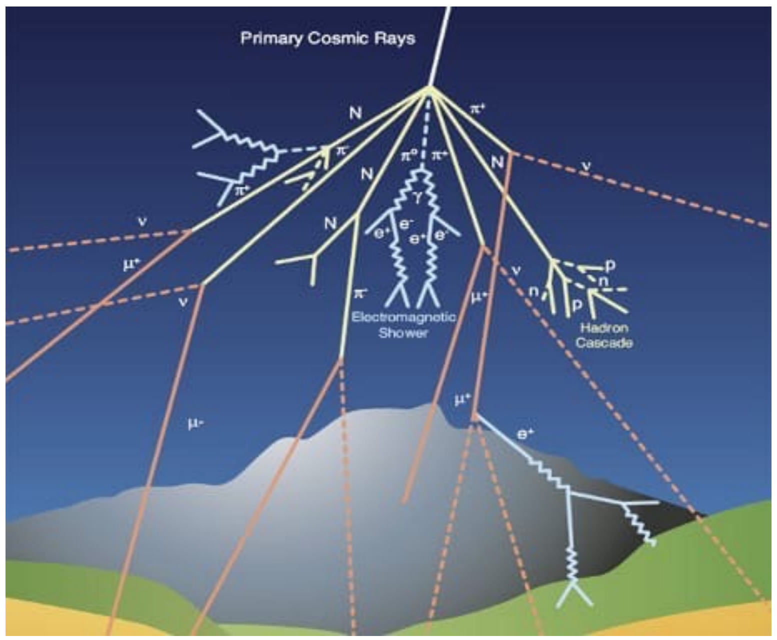

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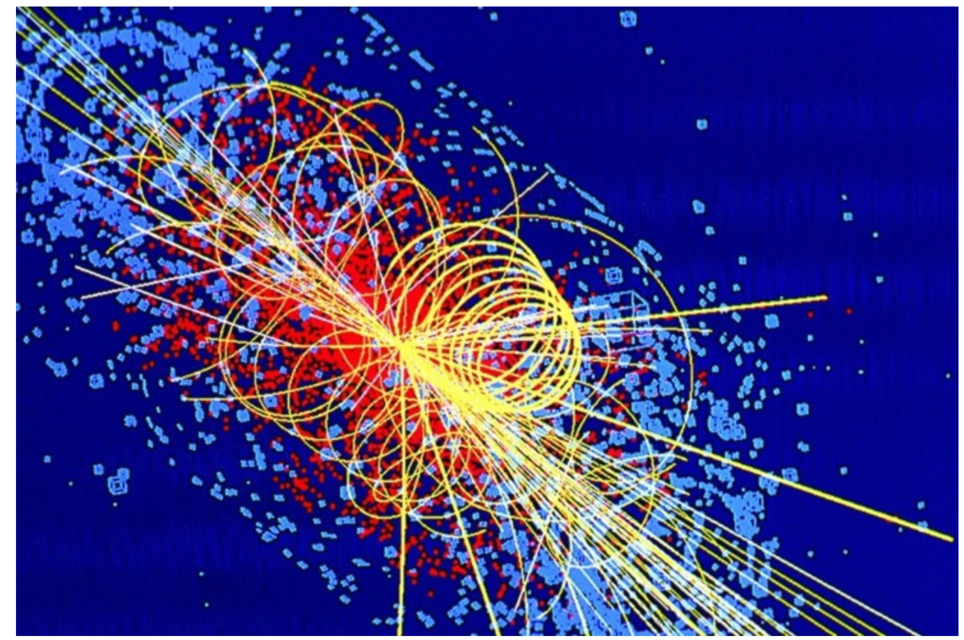
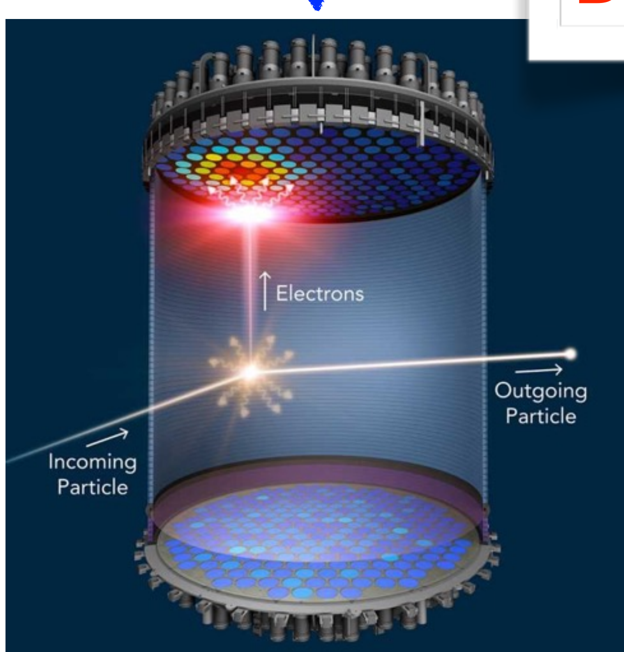


Collider search (active search)

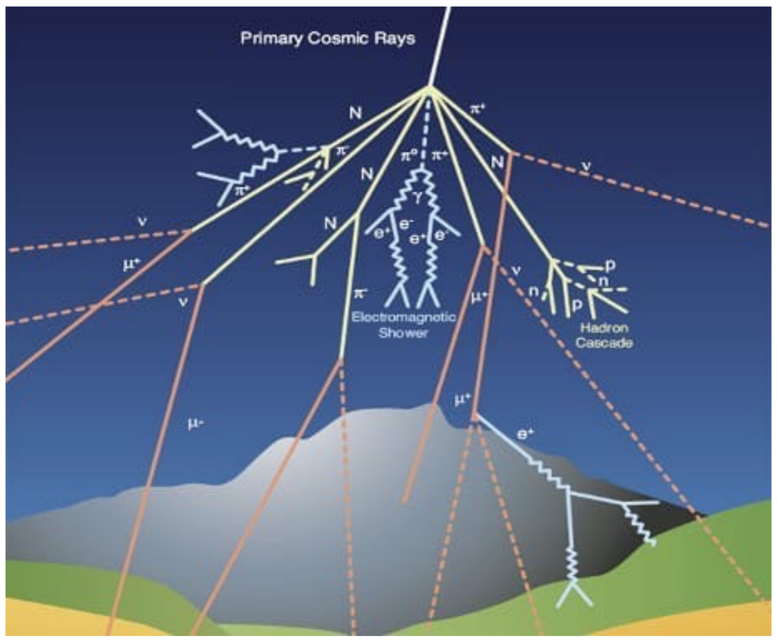
DM (25% of the Universe)



Non-relativistic DM (WIMP) scattering

Categories of search

SM (5% of the Universe)



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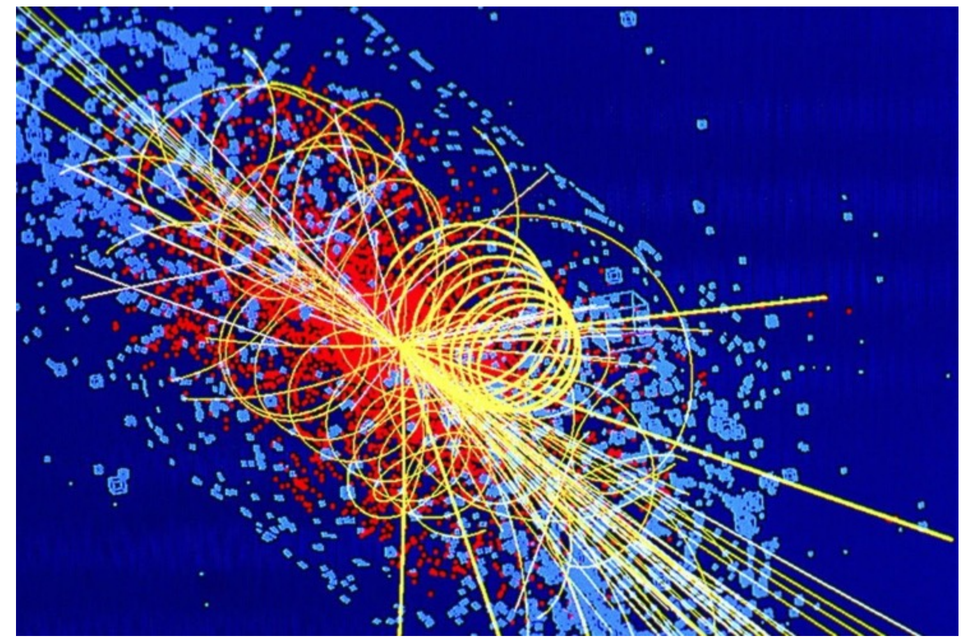
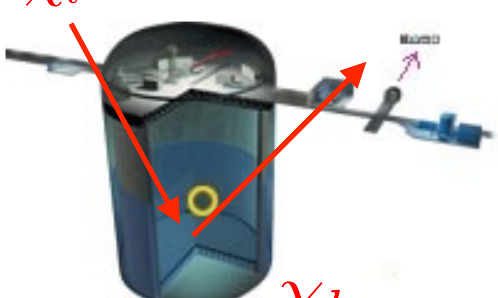


Collider search (active search)

DM (25% of the Universe)

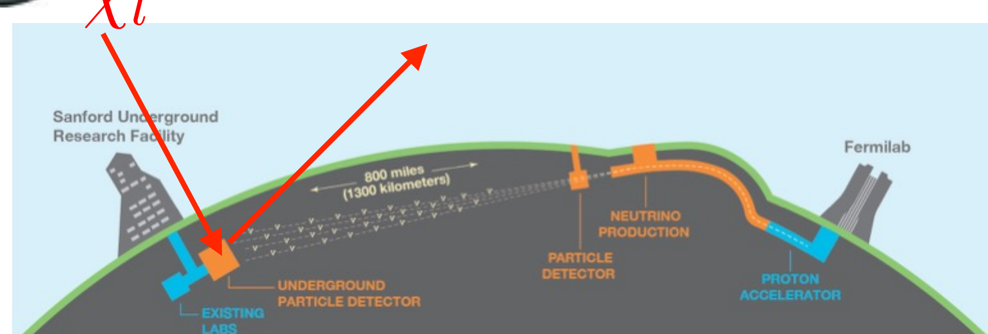
χ_l



Relativistic DM scattering (boosted)

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

χ_l

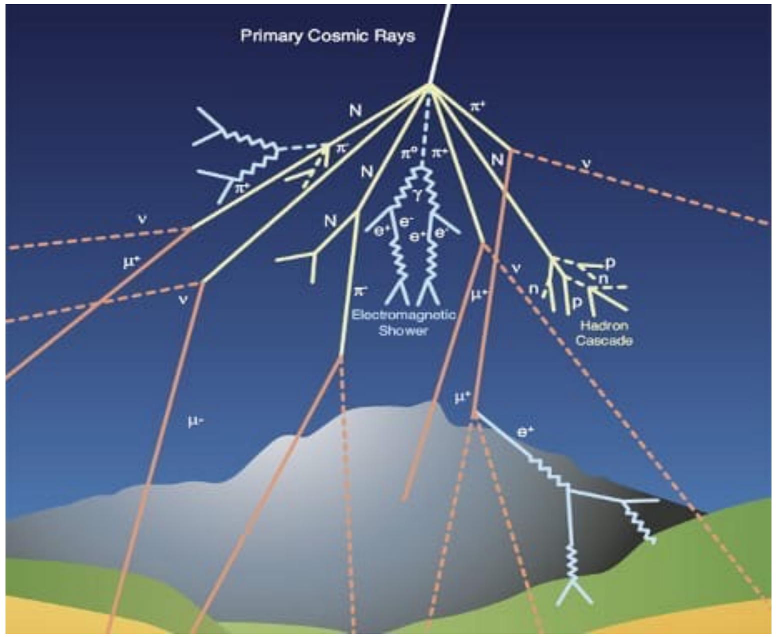


flux $\mathcal{O}(10^{-7}\,\mathrm{cm}^{-2}\mathrm{s}^{-1})$

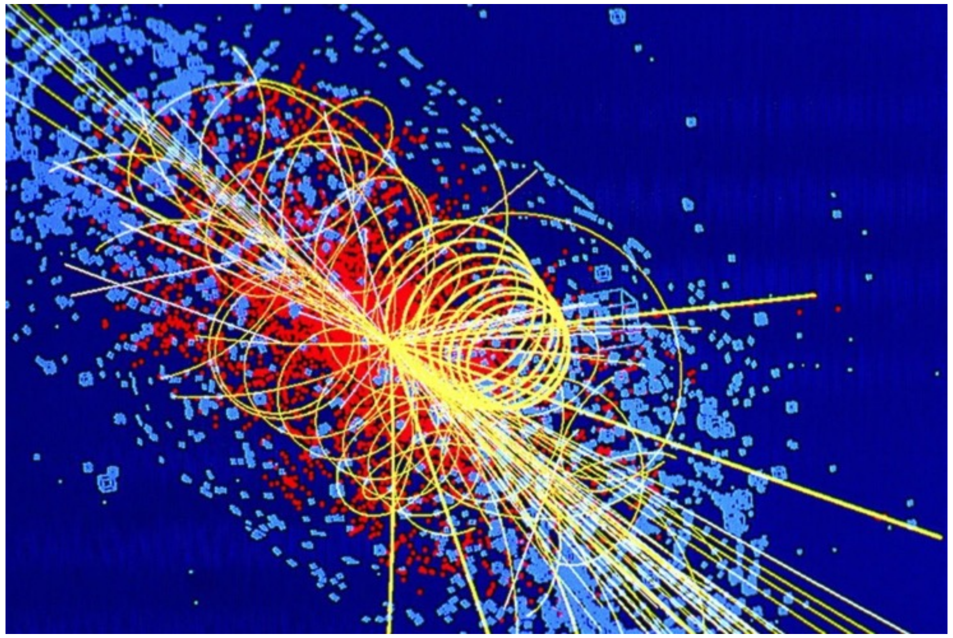
$m_{\chi h}$ ~ O(10 GeV)

Categories of search

SM (5% of the Universe)



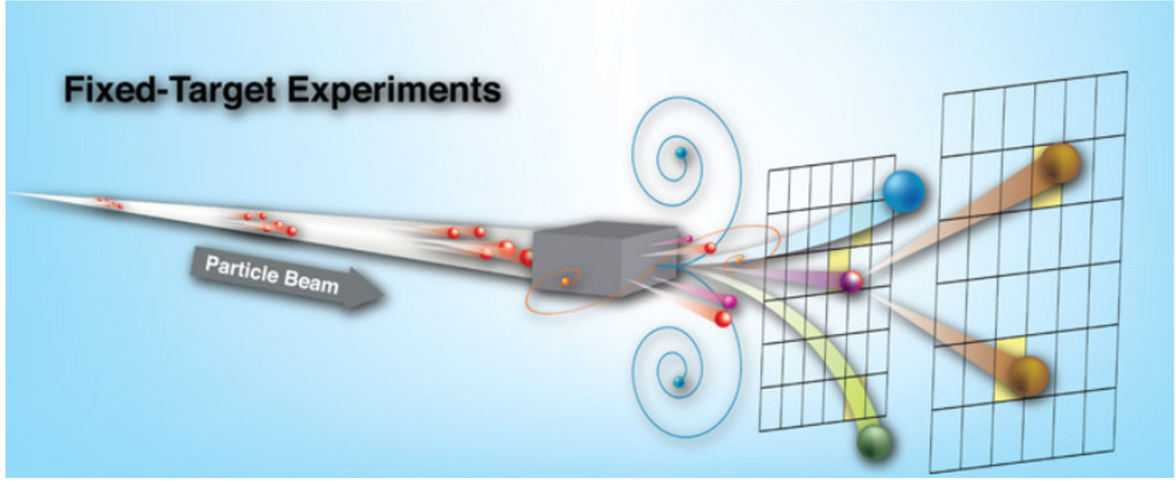
Cosmic frontier search



Collider search: Intensity frontier

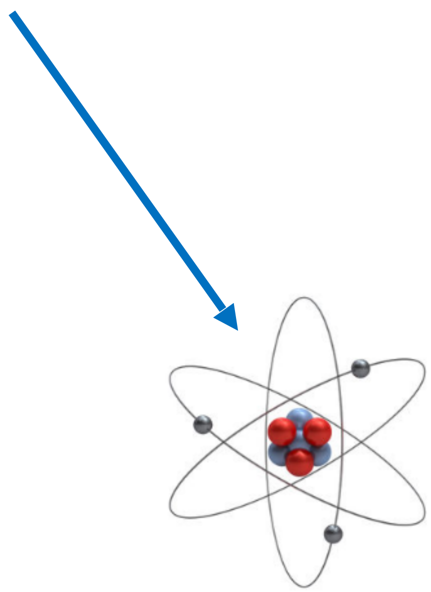
DM (25% of the Universe)

Relativistic DM scattering



Flavorful dark sector

χ_l: **boosted** DM

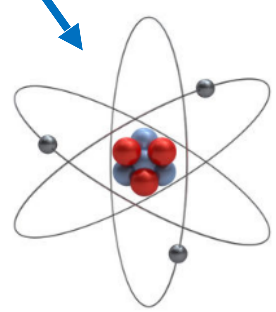


Basic strategy: simple number counting over ν background

Mandatory, Not easy

Flavorful dark sector

χ_l: **boosted** DM



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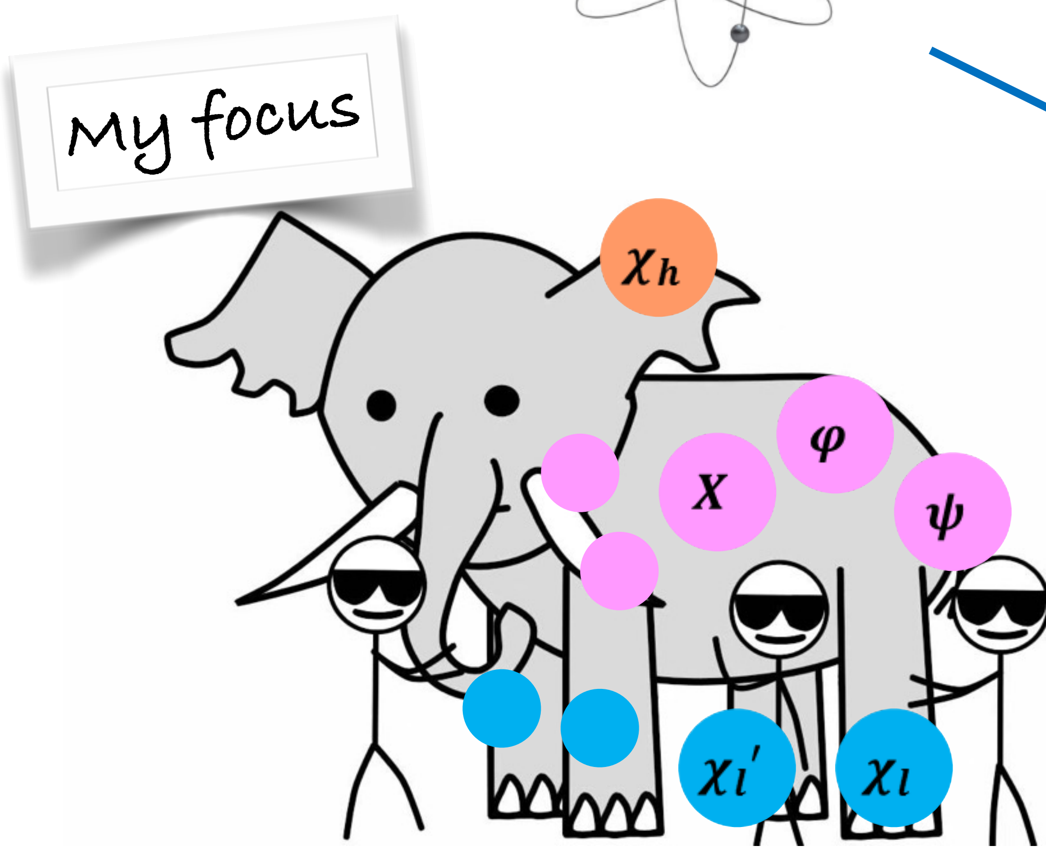
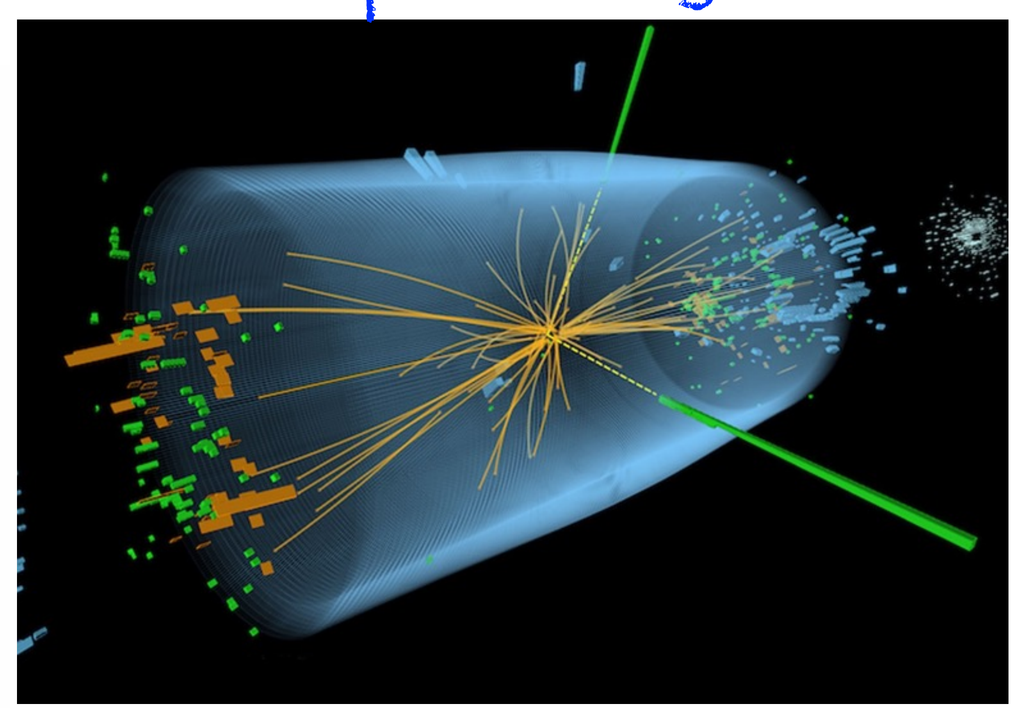
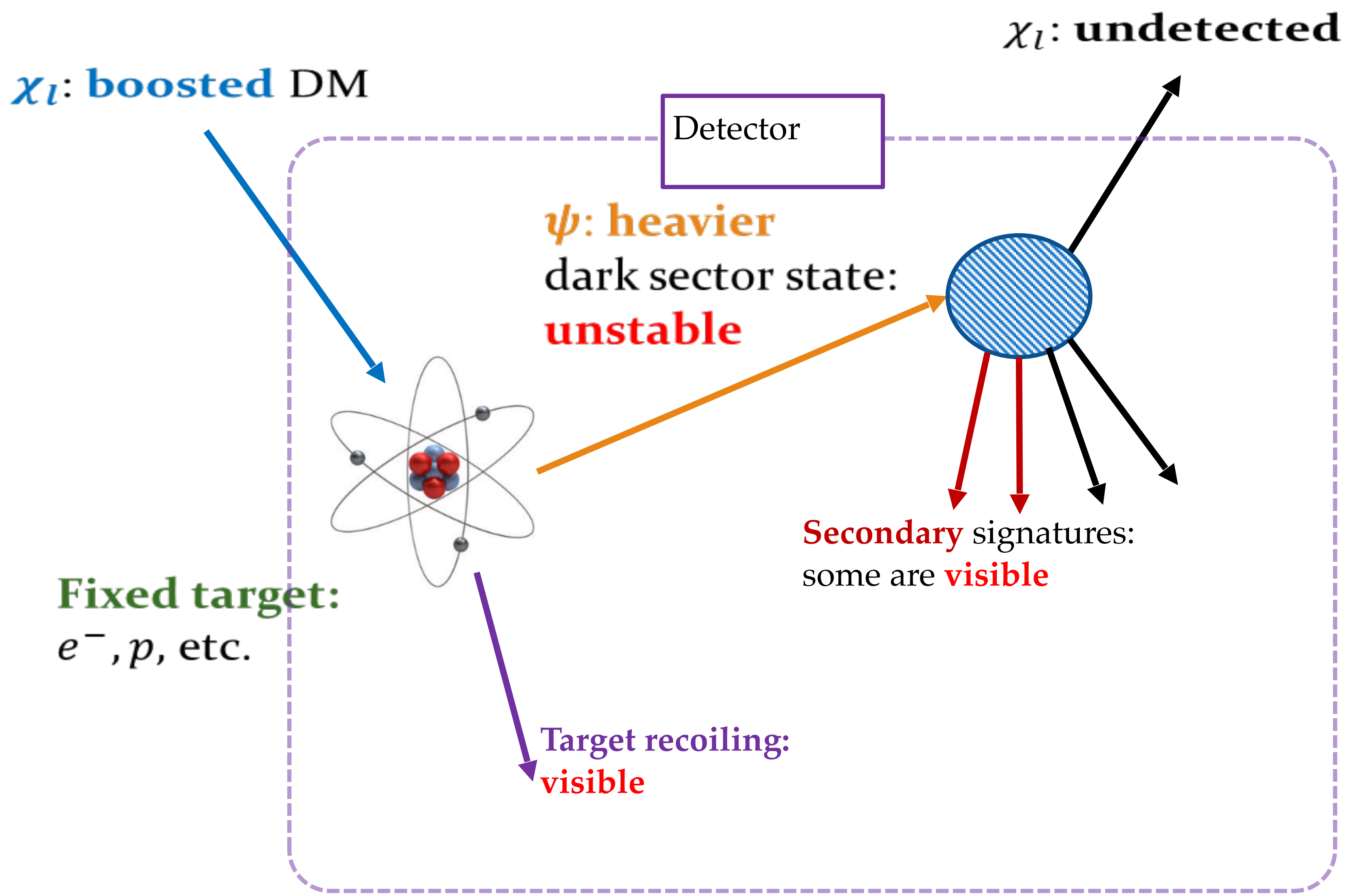


promising



DM “Collider”: flavorful dark sector



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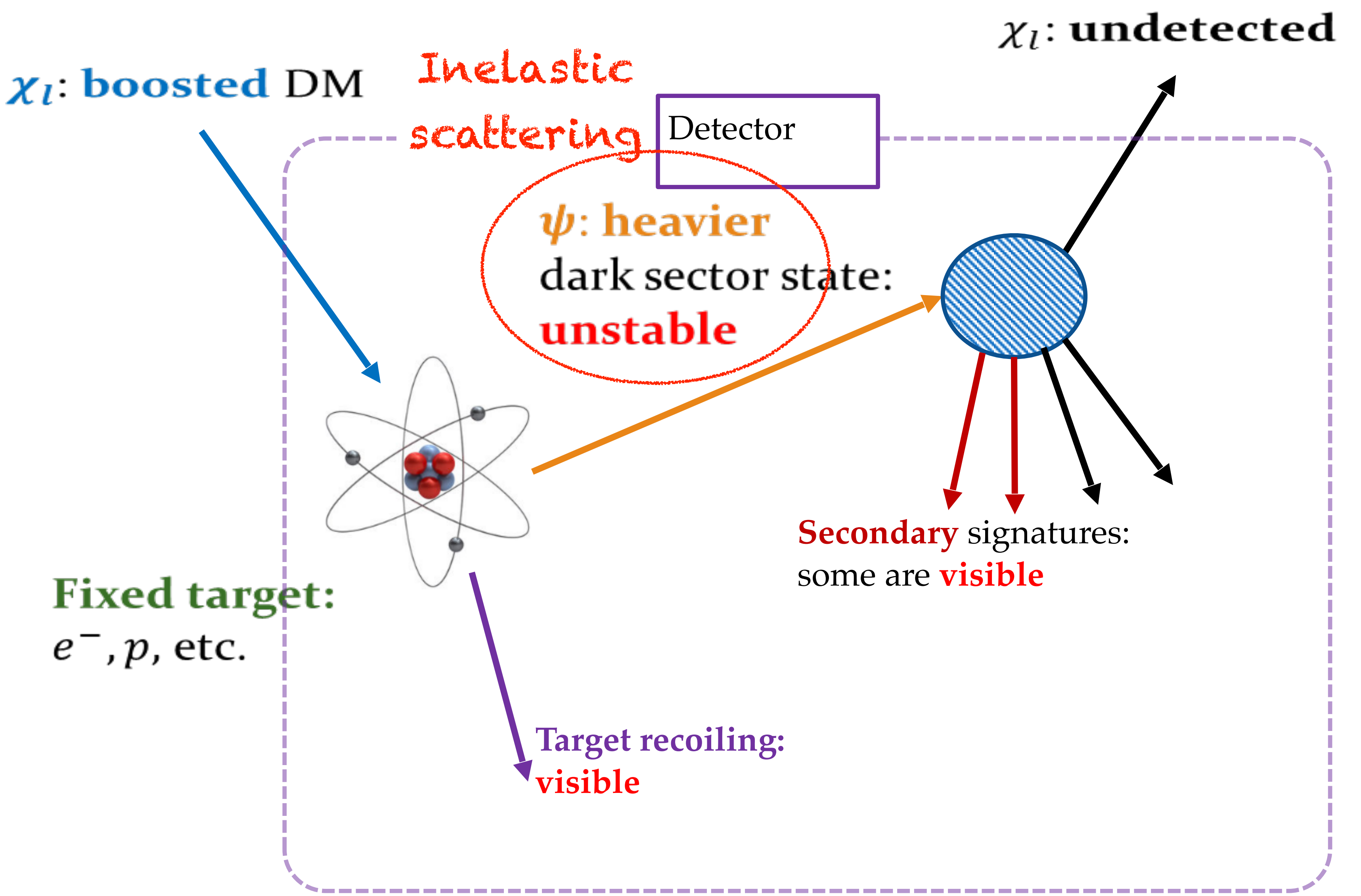
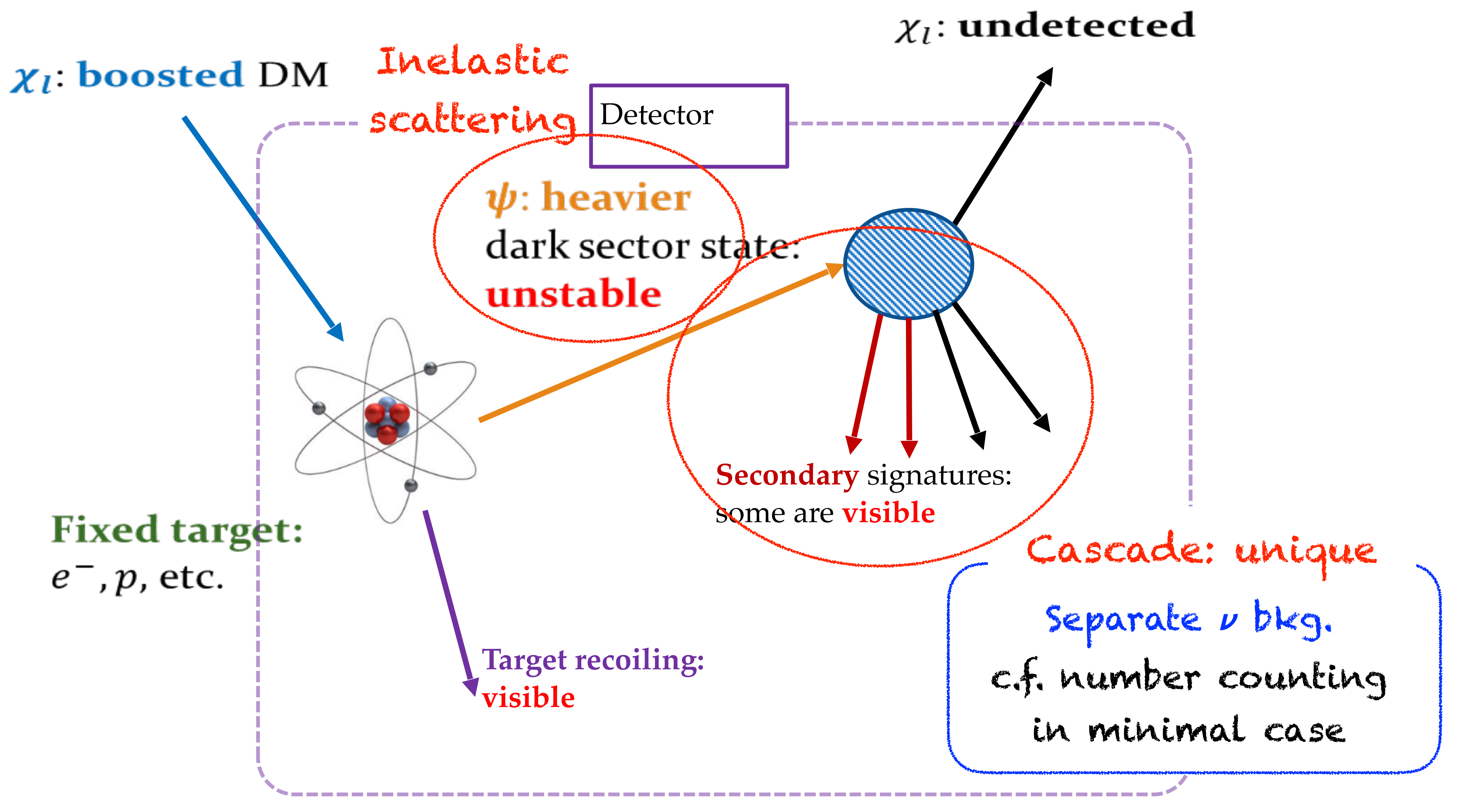


DM “Collider”: flavorful dark sector



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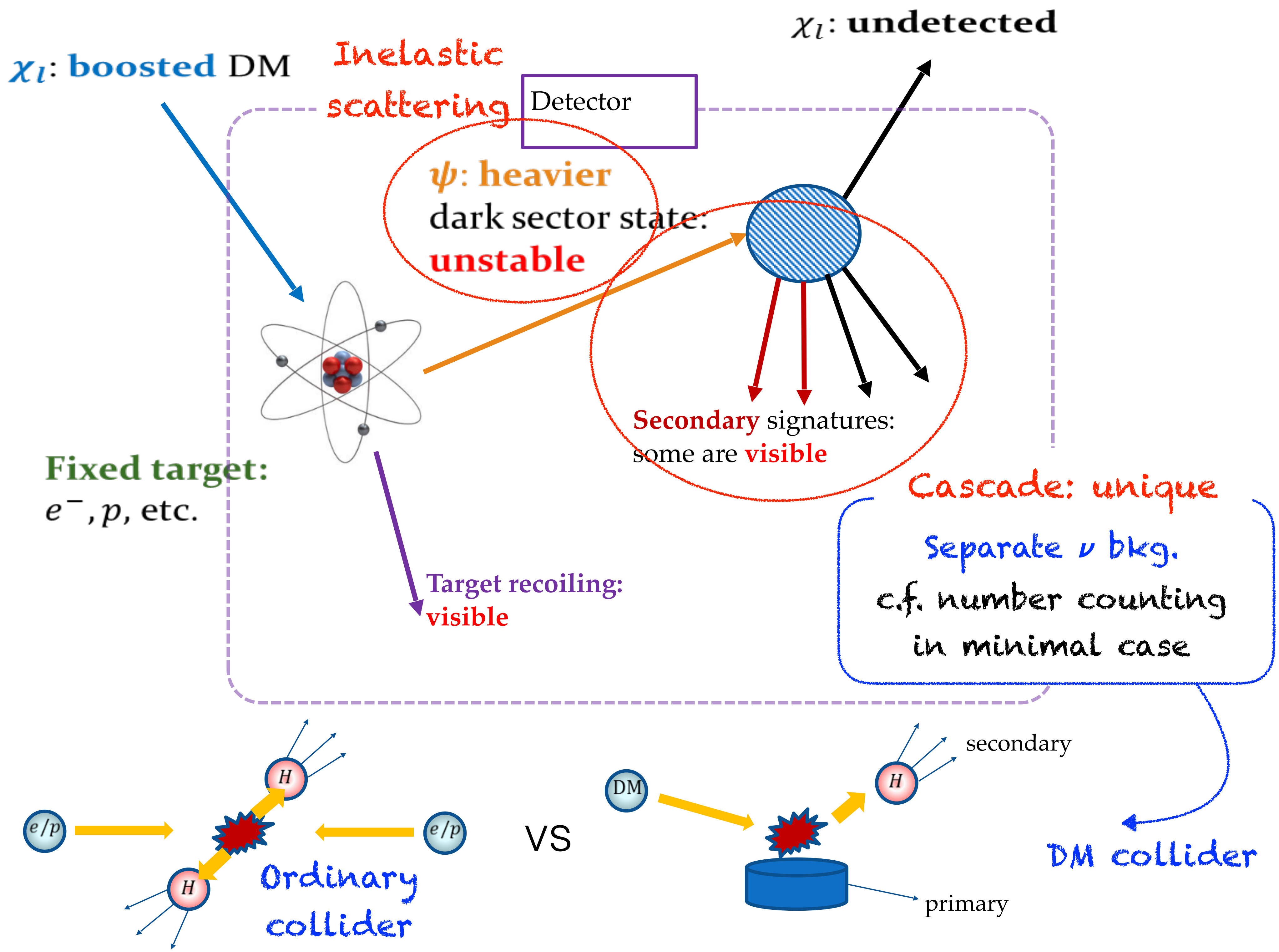
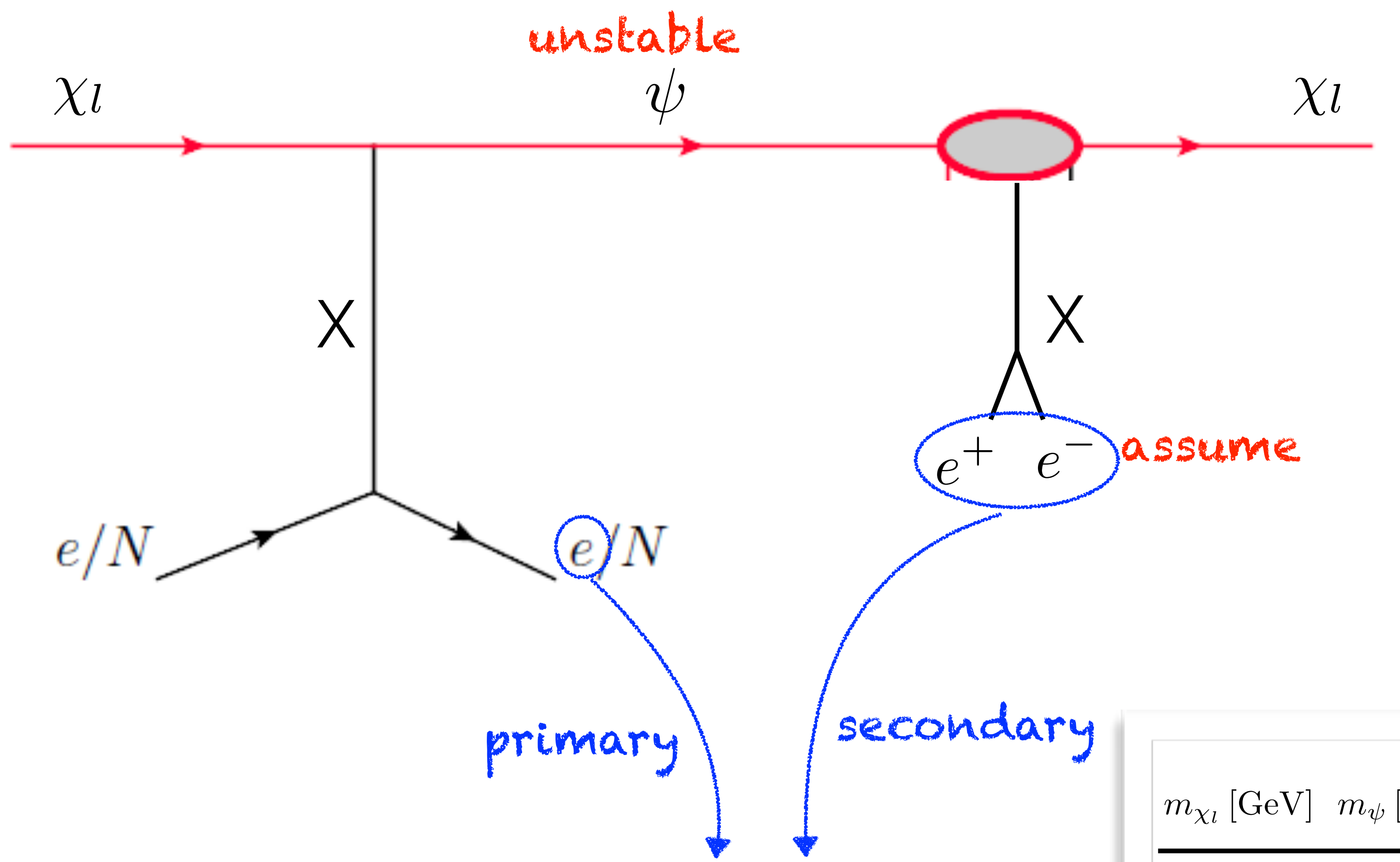


e-scattering: highly boosted



High chance to observe
two separate signals!!

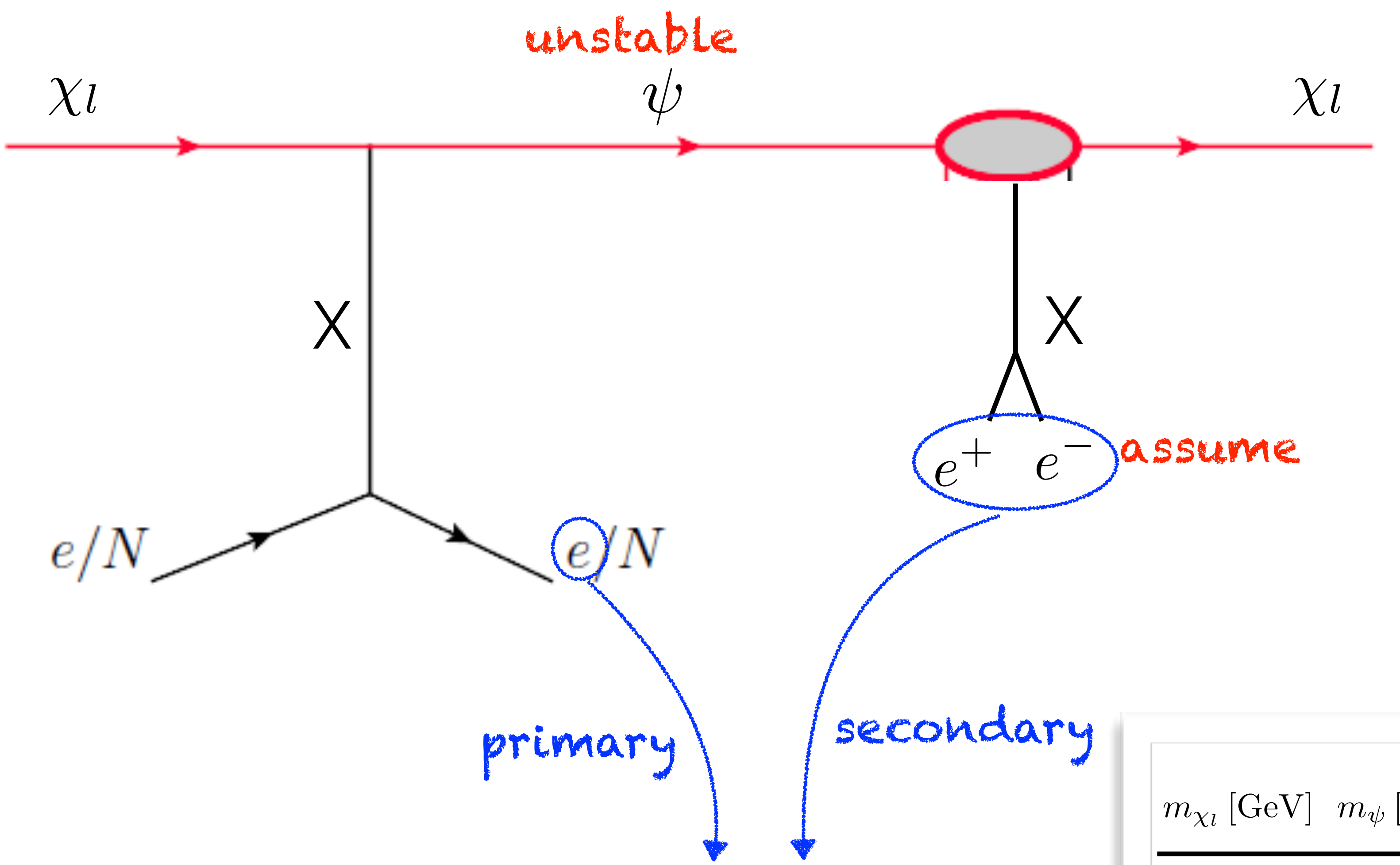
m_{χ_l} [GeV]	m_ψ [GeV]	m_X [GeV]	γ_{χ_l}
0.4	0.5	0.06	250
0.1	0.14	0.03	200

in an experiment with angular resolution ~ 3°

(Super/Hyper Kamiokande) for primary p_e: 0.1 - 0.3 GeV

Moderate recoil E

e-scattering: highly boosted



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0.1	0.14	0.03	200

in an experiment with angular resolution ≲ 1°

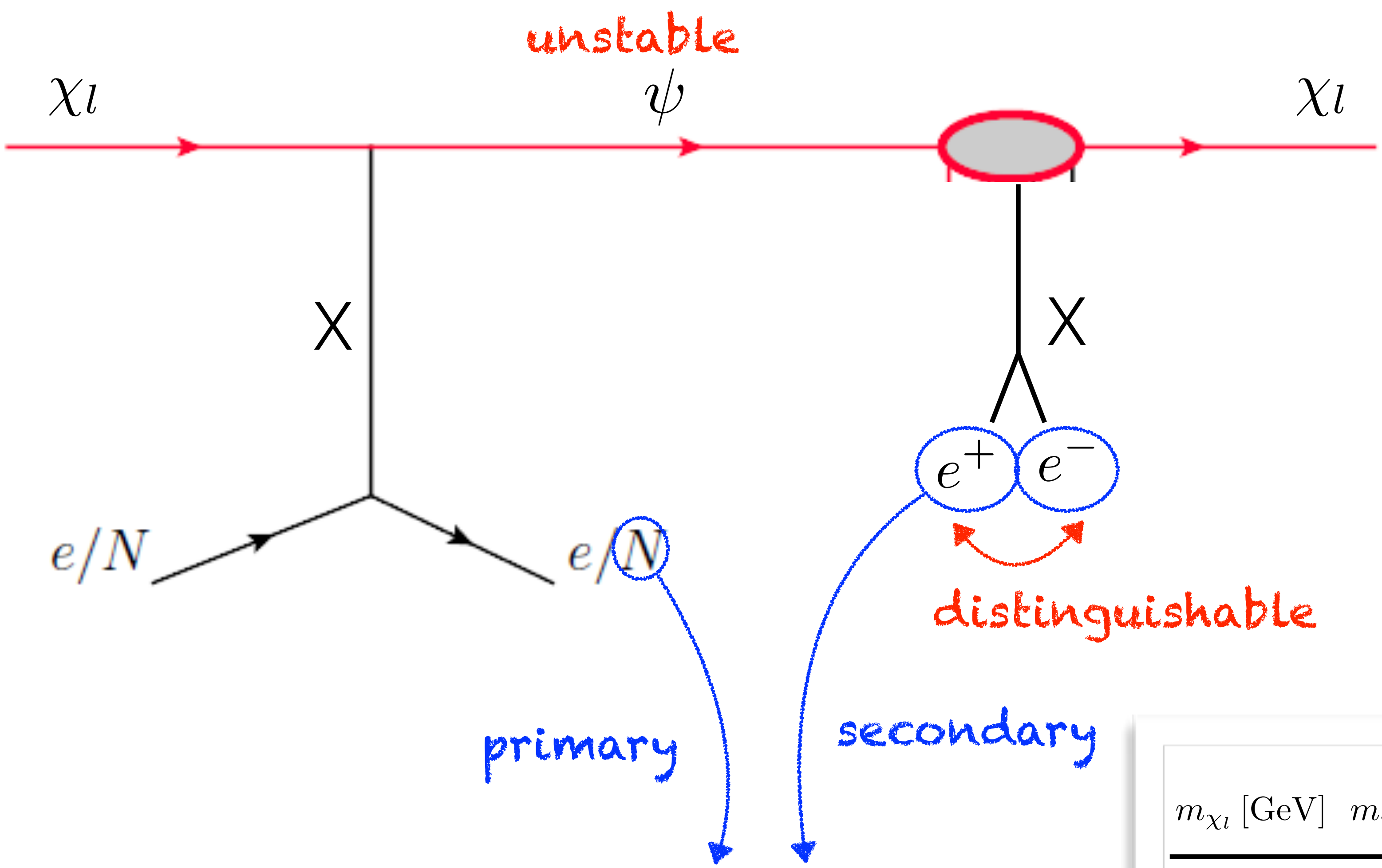
smaller volume

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

cosmic & intensity intensity

Wider range of E

p-scattering: less boosted



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

High chance to observe
three separate signals!!

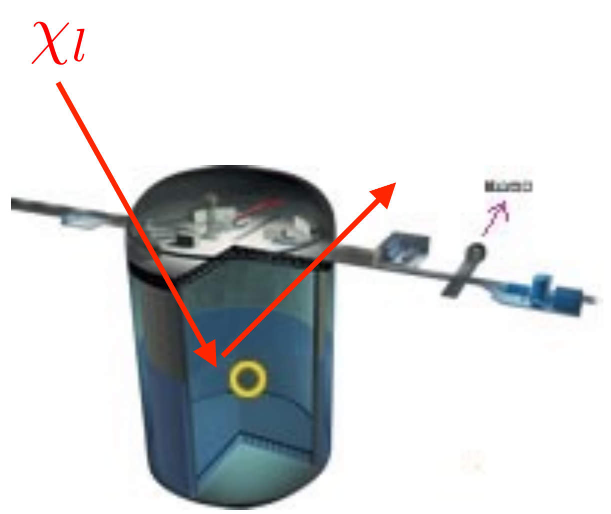
very sensitive!!

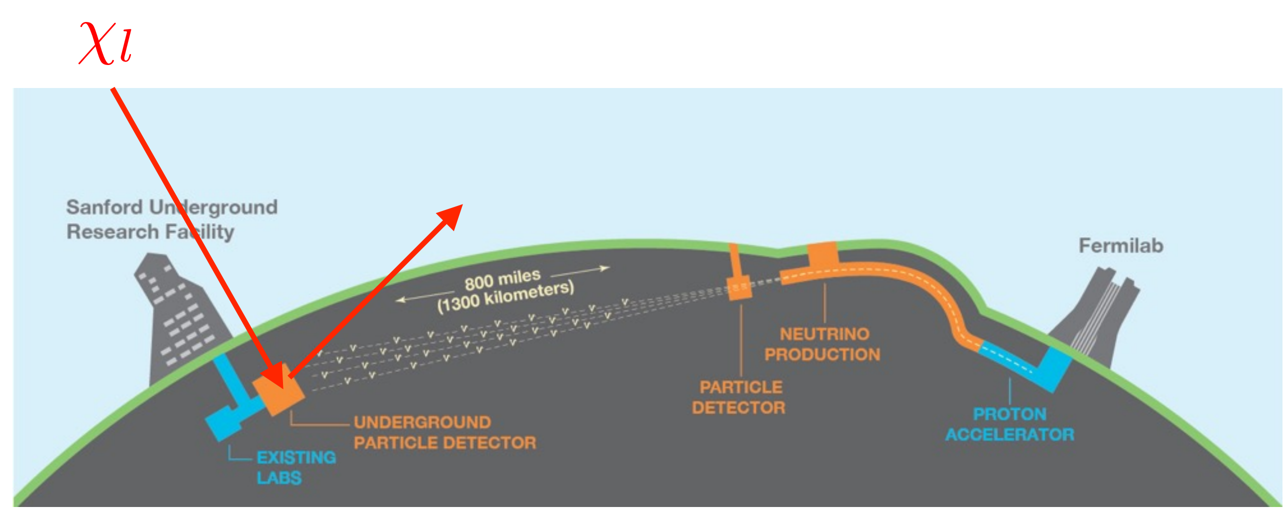
Promising in an experiment with $E_{th} \ll 1$ GeV (**DUNE**, SHiP)

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

Search in cosmic frontier experiments

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





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

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

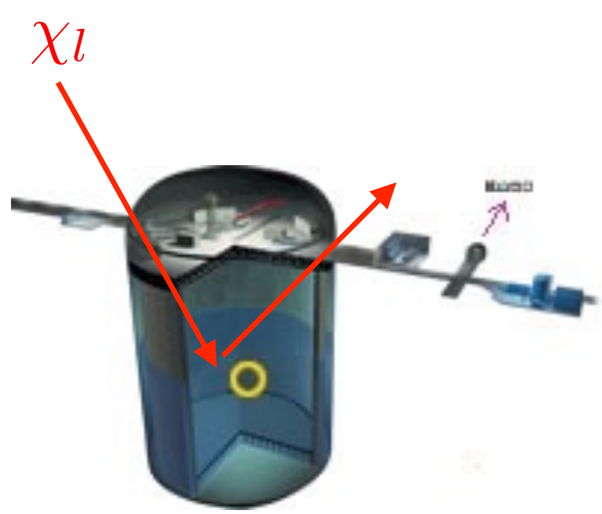
$\mathcal{O}(10^{-7}\,\text{cm}^{-2}\text{s}^{-1})$

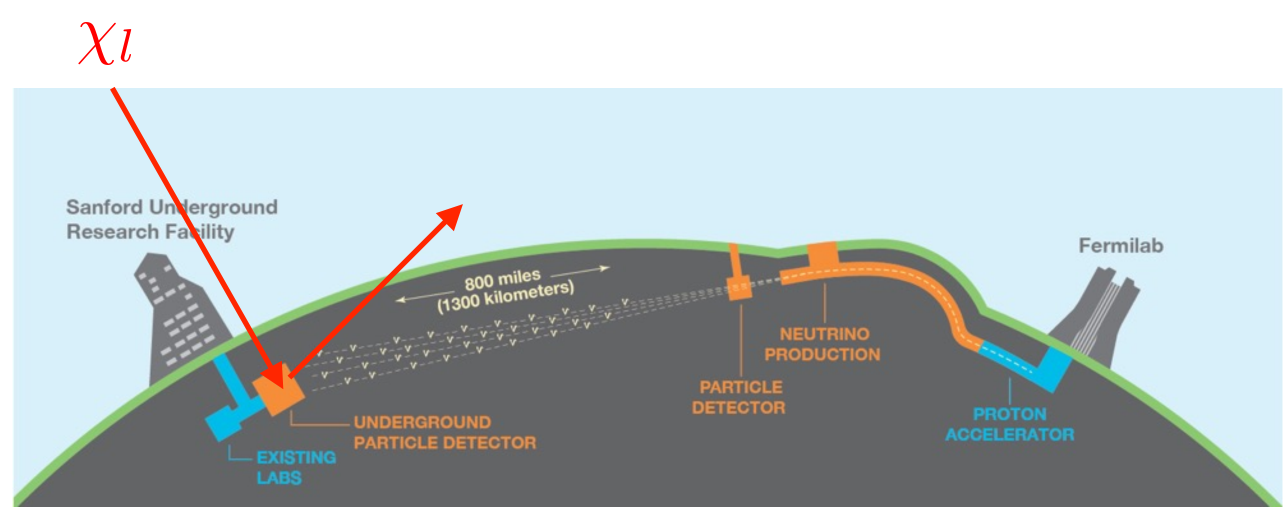
$m_{\chi h} \sim O(10 \text{ GeV})$

Promising example!

Search in cosmic frontier experiments

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





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DUNE	1 yr	190	9.0	150	1600
DUNE	13.6 yr	14	0.69	11	120

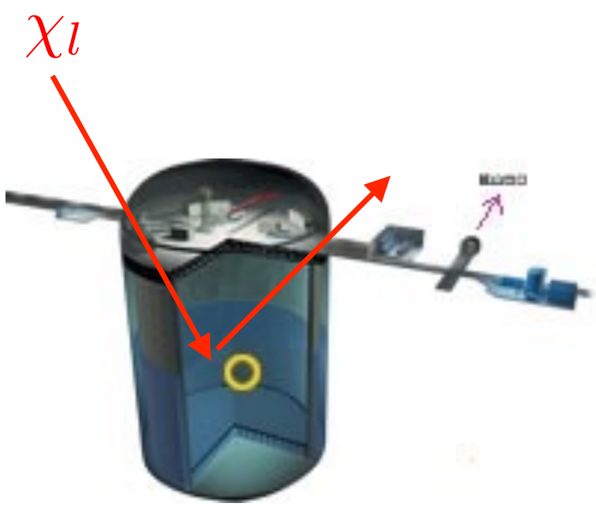
less sensitive than e

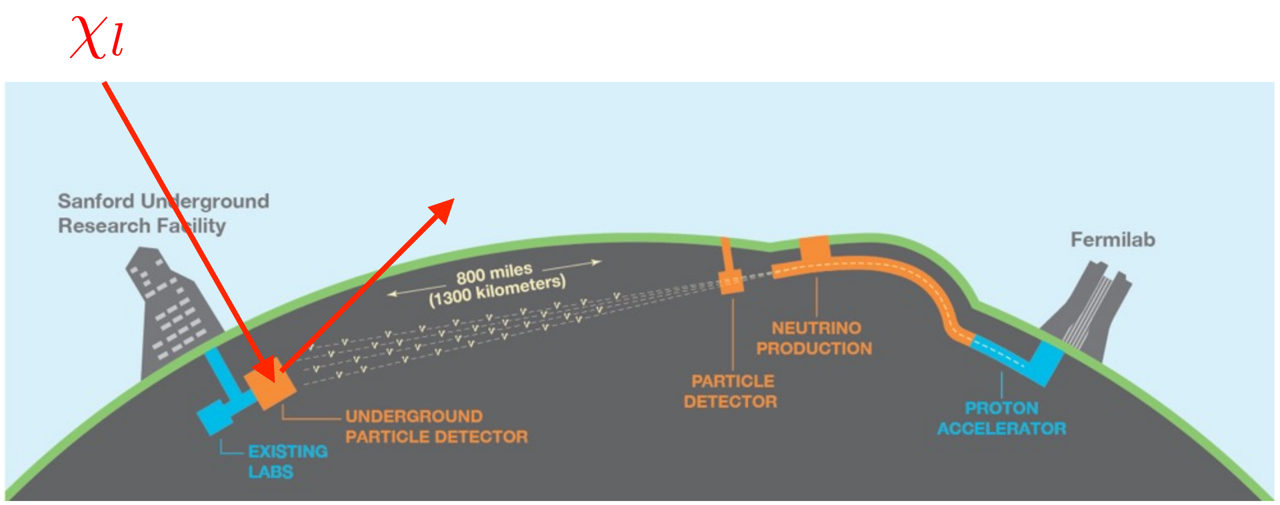
Assume no bkg.

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

Search in cosmic frontier experiments

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





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DUNE	1 yr	190	9.0	150	1600
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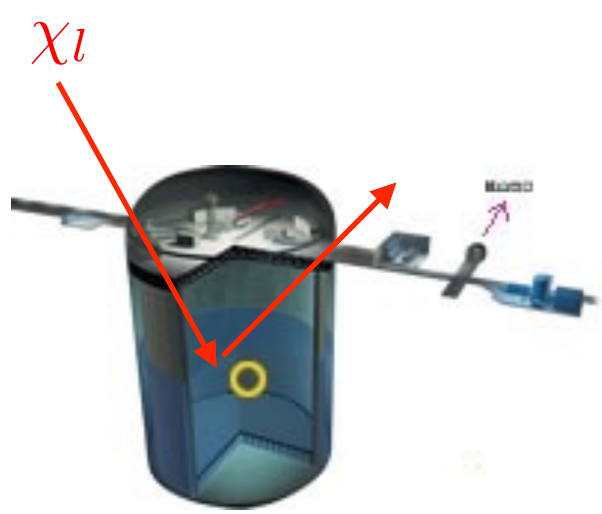
13.6 yr of HK improves the sensitivity

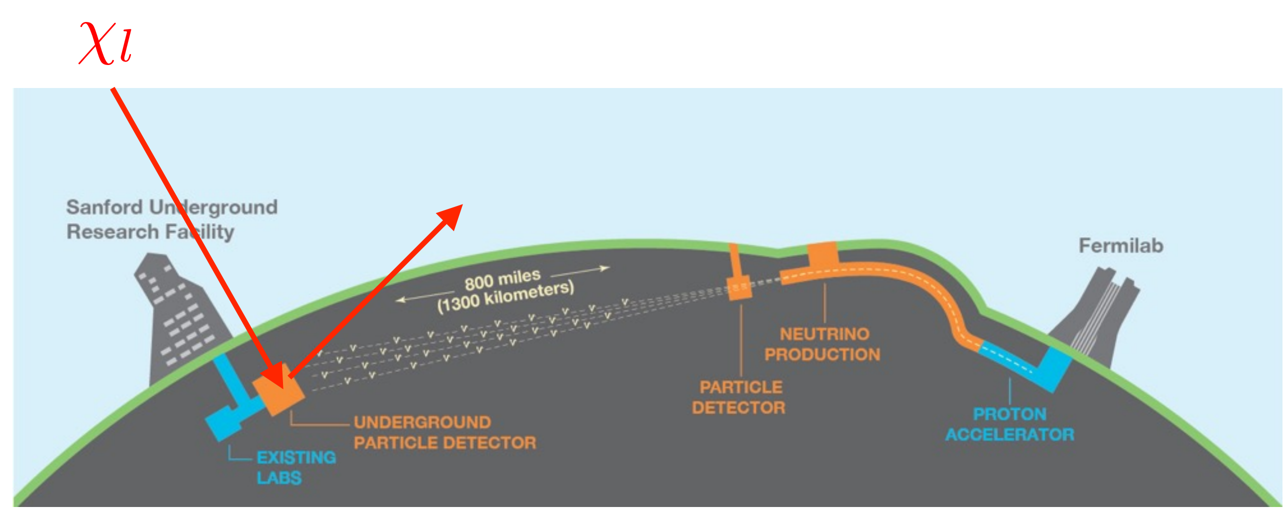
Assume no bkg.

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

Search in cosmic frontier experiments

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





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Assume no bkg.

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

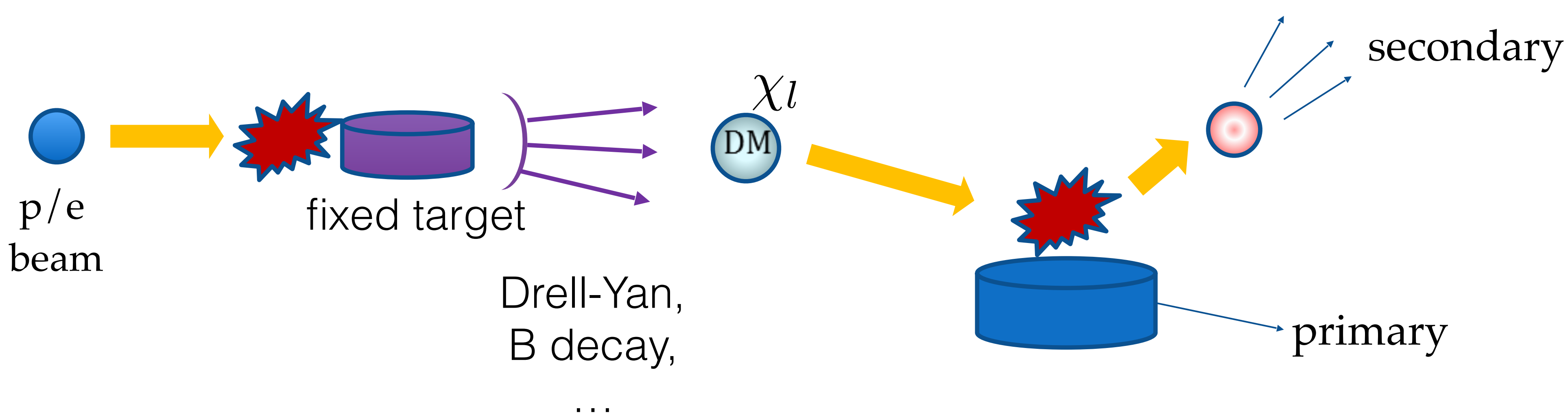
Remarkable improvement in DUNE!!!

Promising (3 simultaneous signals)

Search in intensity frontier experiments

Intensity frontier: increase fluxes of incoming χ_l

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



Search in intensity frontier experiments

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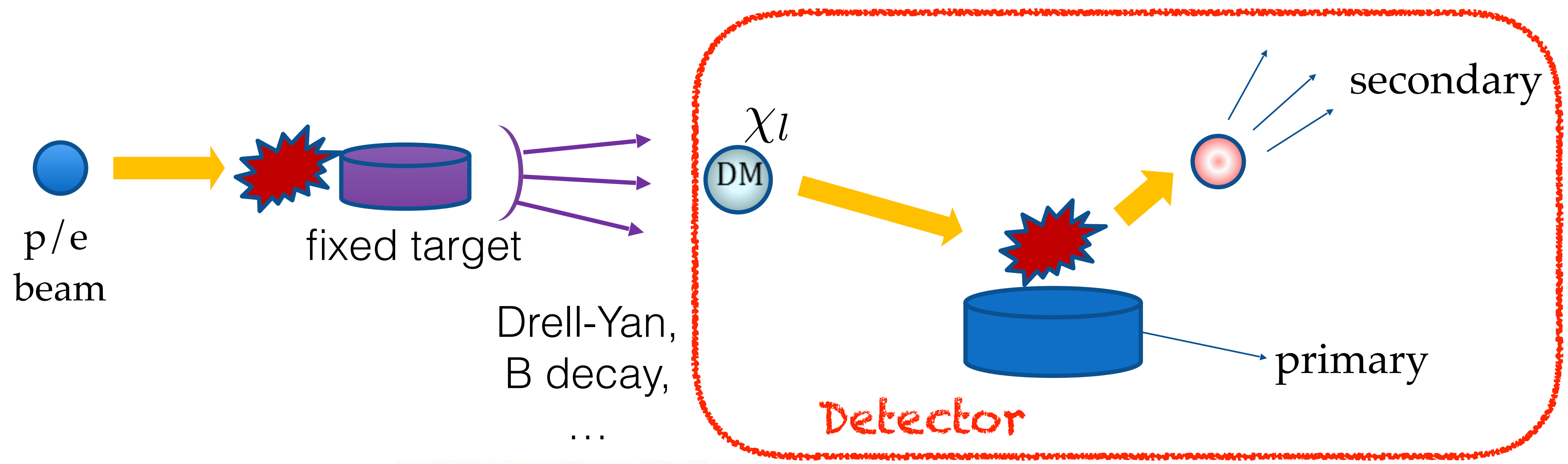
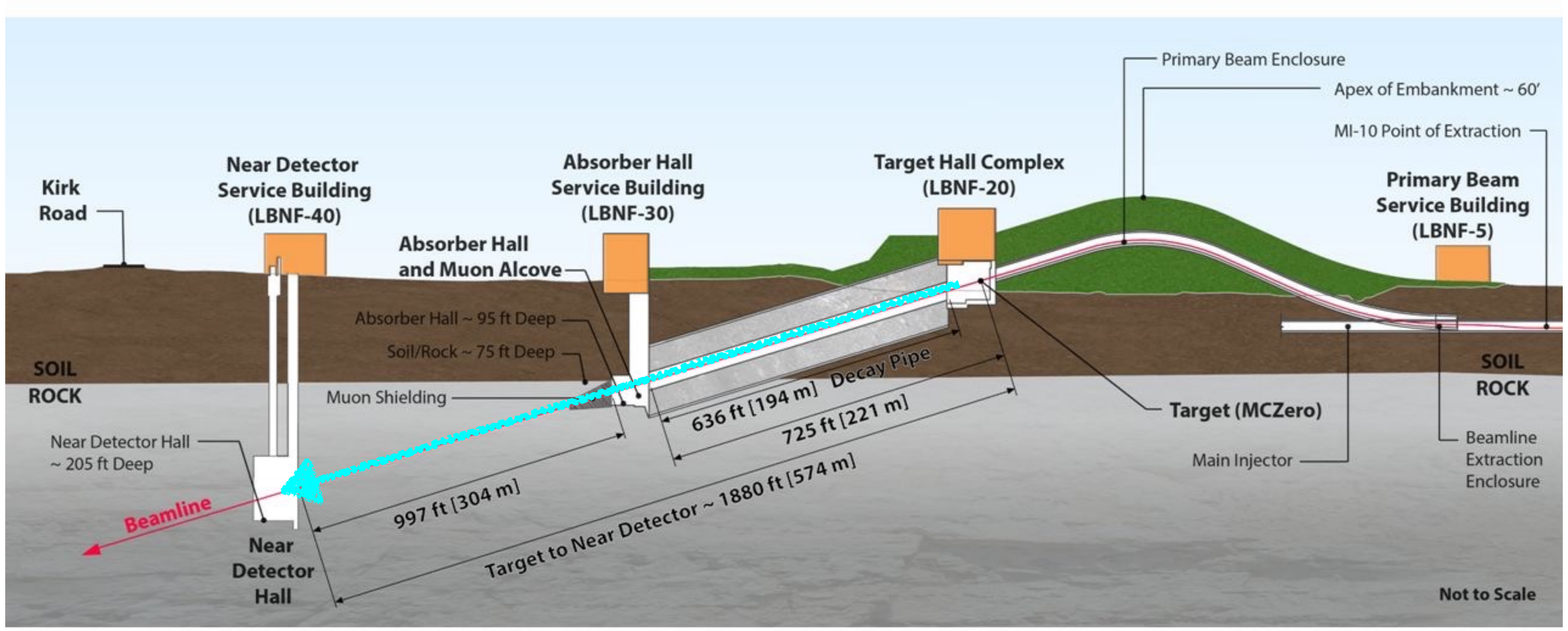


DUNE Beamline with Near Detector



Conclusions

- Flavorful/non-minimal dark sector (χ_l): 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)	E_{th} high in Cherenkov light detectors (low σ)	cons
pros	Sensitive with small flux	Need large flux	cons
cons	Separation of two signals not easy (good for low p_e)	Separation of two signals & 3 visible objects: promising	pros

Conclusions

- Flavorful/non-minimal dark sector (χ_I): cascade process
- Analyzed in current & future large volume ν detectors:
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e-scattering		p-scattering	
pros	Eth low in Cherenkov light detectors (high σ)	Eth high in Cherenkov light detectors (low σ)	cons
pros	Sensitive with small flux	Need large flux	cons
cons	Separation of two signals not easy (good for low p_e)	Separation of two signals & 3 visible objects: promising	pros

DUNE

Conclusions

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

- Analyzed in current & future large volume ν detectors:
  Super-K, Hyper-K, DUNE

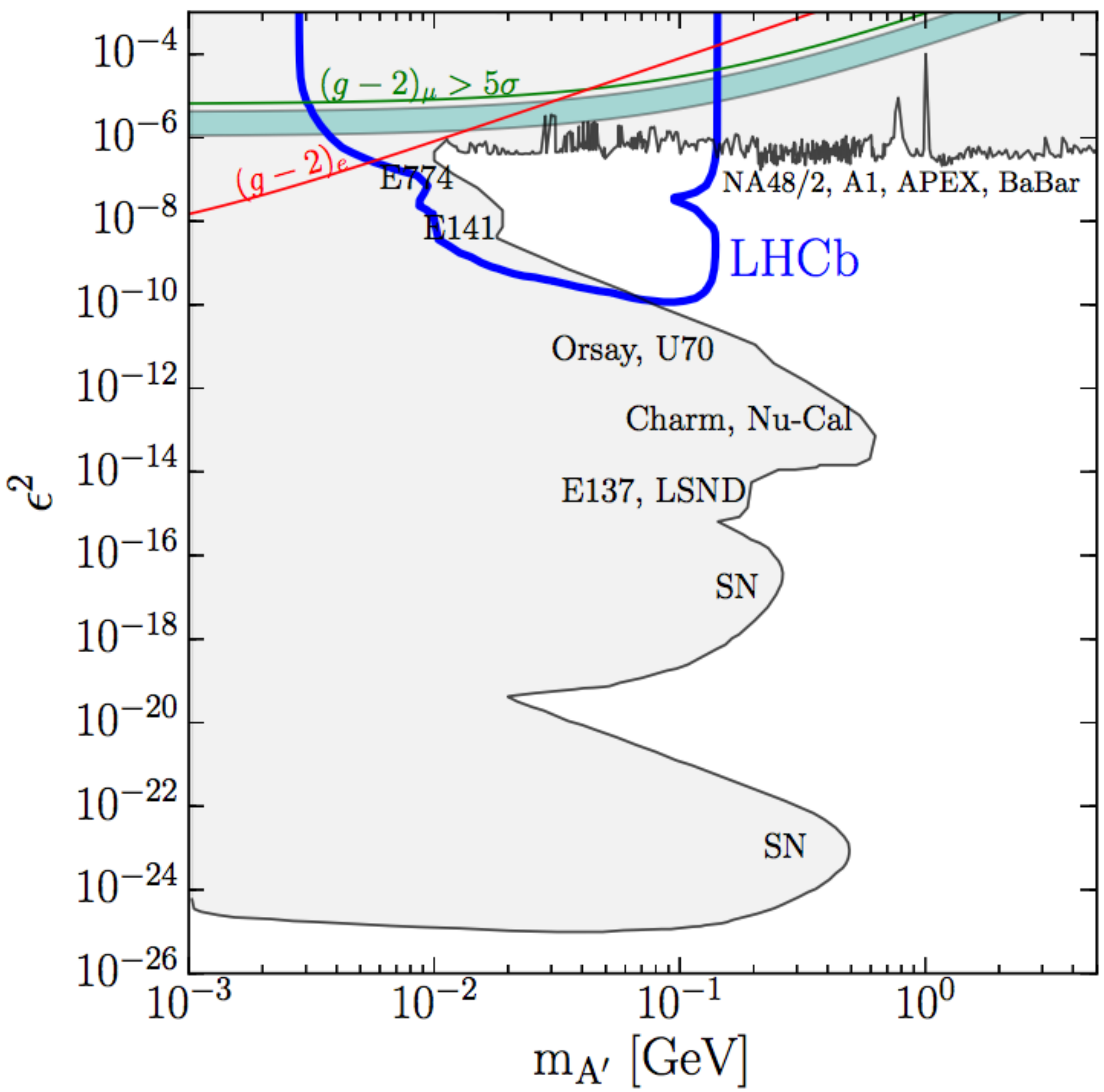
e-scattering	p-scattering
• E_{th} low in Cherenkov light detectors (high σ)	• E_{th} high in Cherenkov light detectors (low σ)
• Sensitive with small flux	• Need large flux Intensity frontier exp.
• Separation of two signals not easy (good for low p_e)	• Separation of two signals & 3 visible objects: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

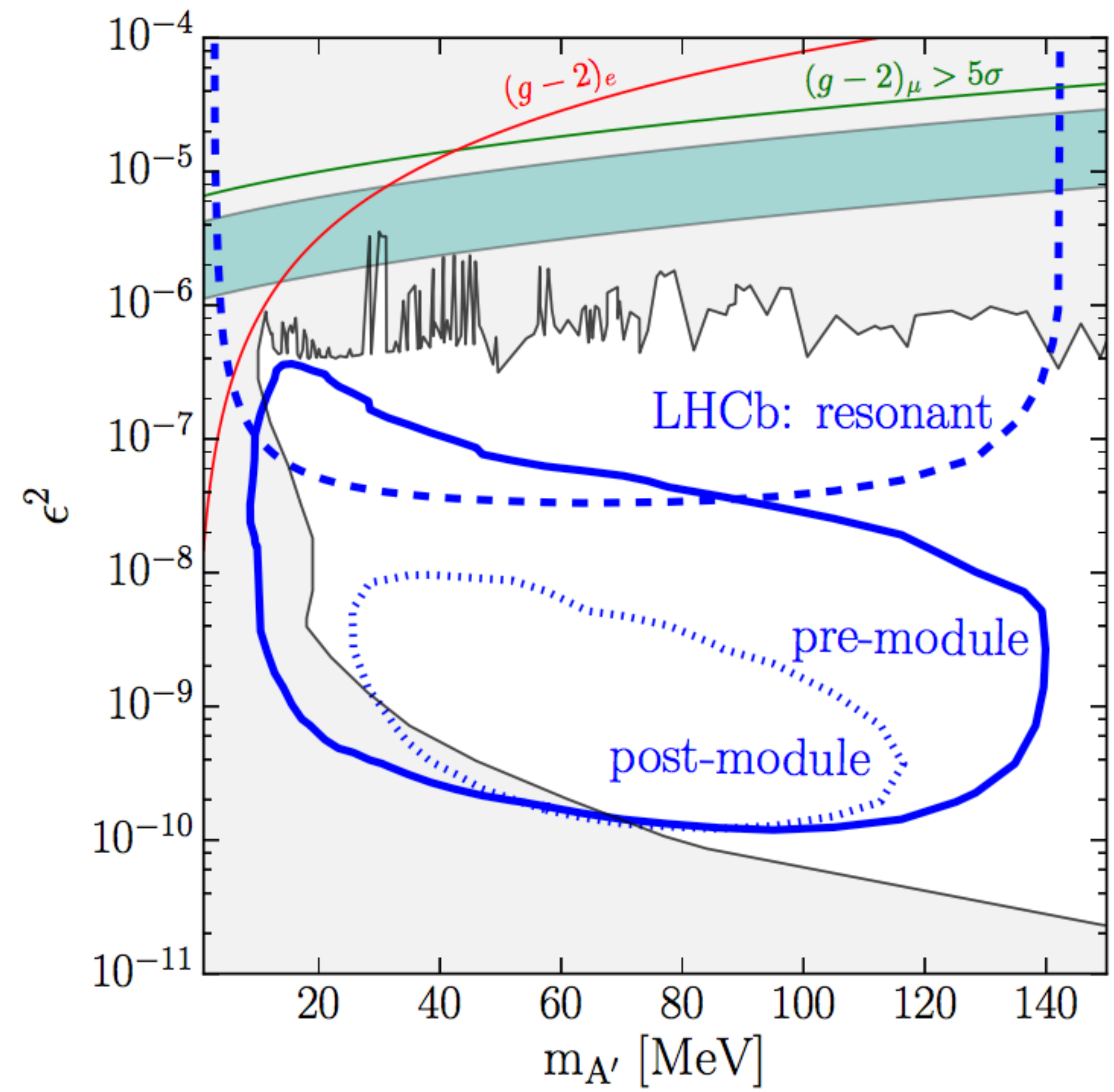
pros (e-scattering, first two items); cons (e-scattering, third item)

cons (p-scattering, first two items); pros (p-scattering, third item)

DUNE

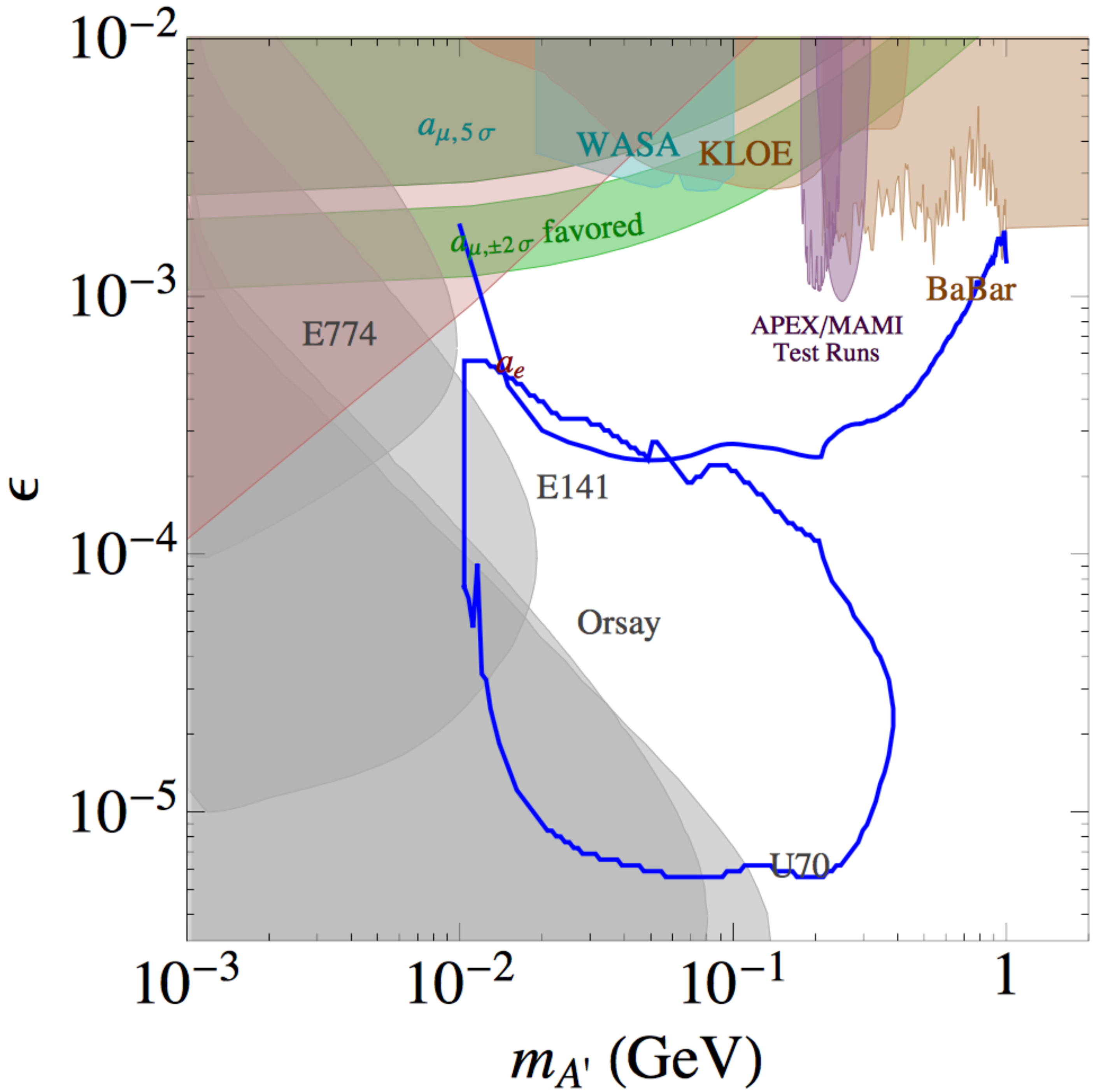
Back up





Ilten, Thaler, Williams, Xue, 1509.06765

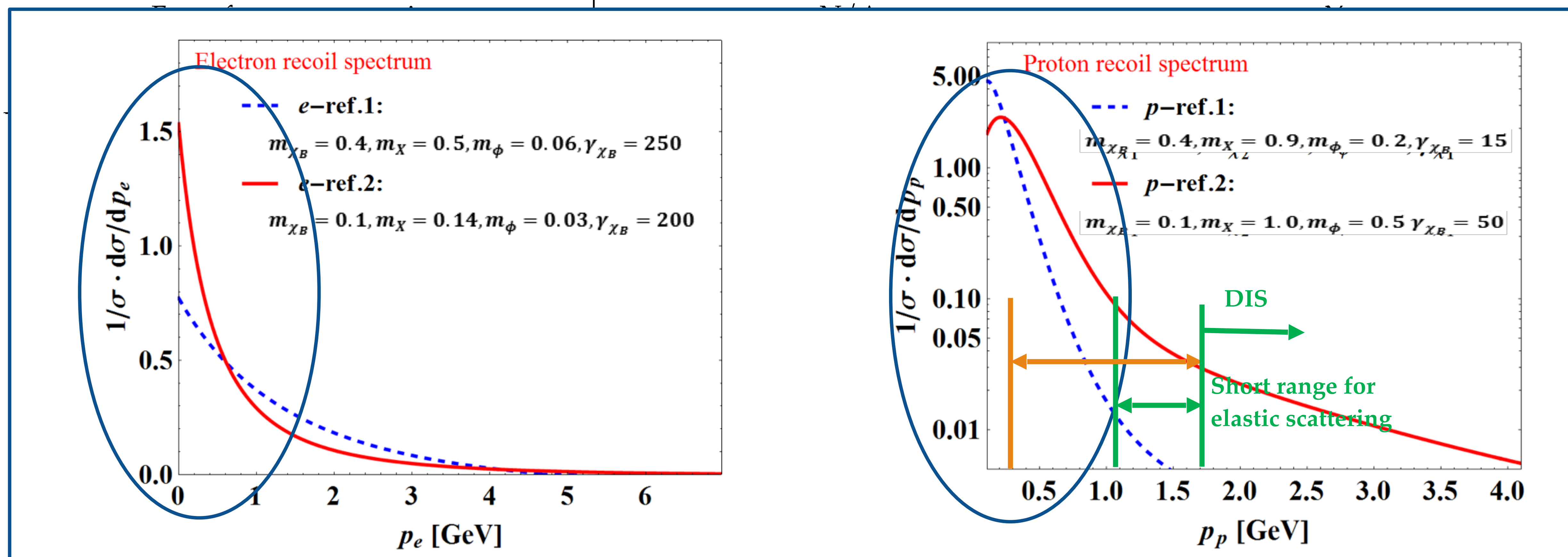
Back up



Essig et al., 1311.0029

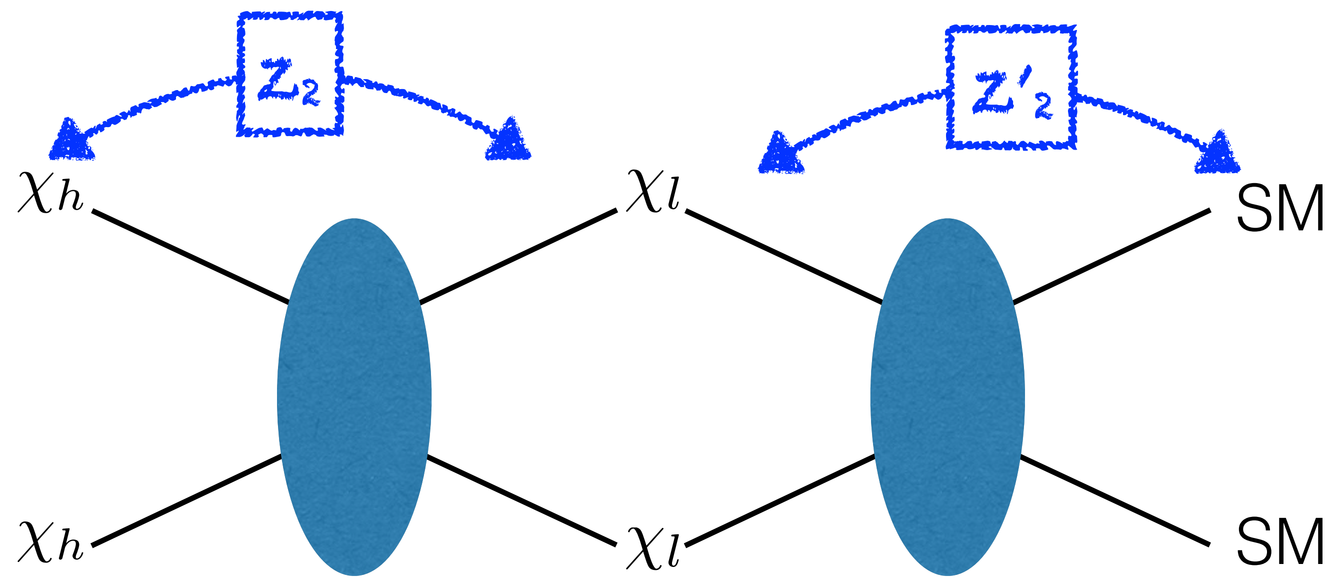
e/N scattering prospects

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

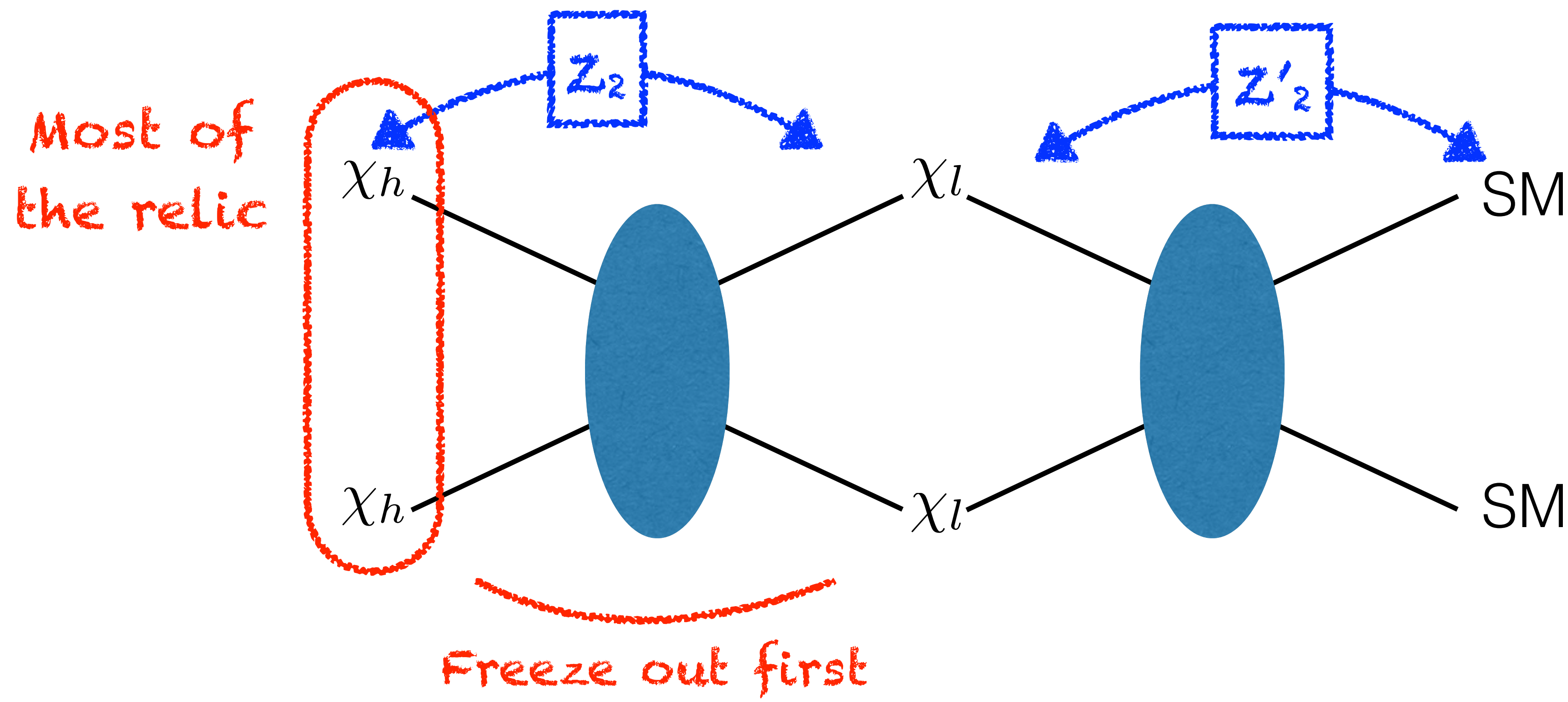


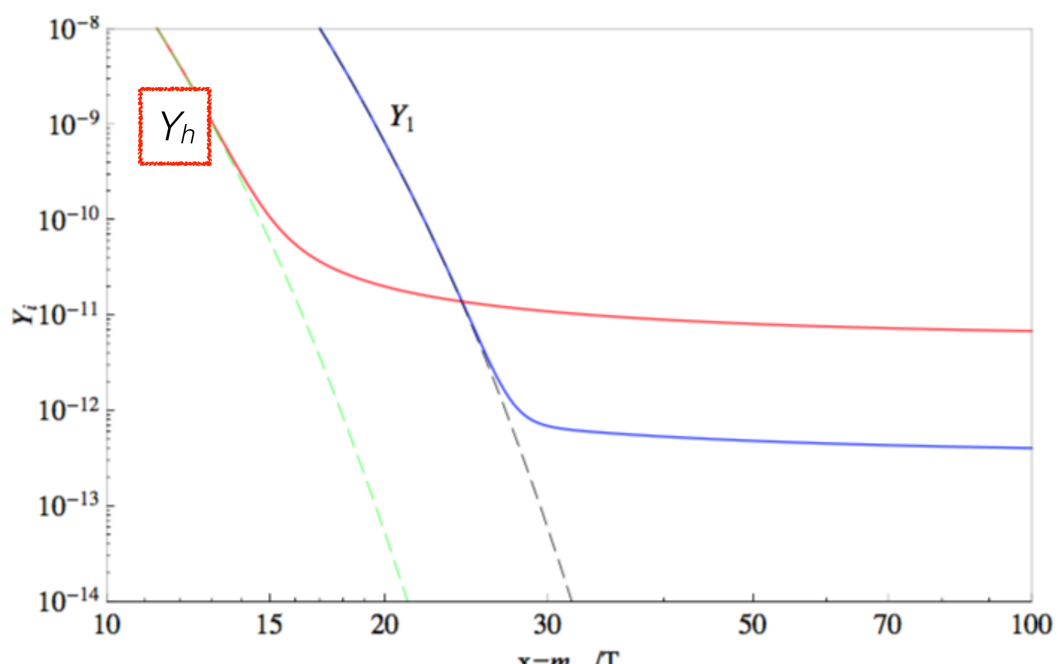
Belanger, Park, 1112.4491

Agashe, Cui, Necib, Thaler, 1405.7370

Boosted DM

Minimal model example





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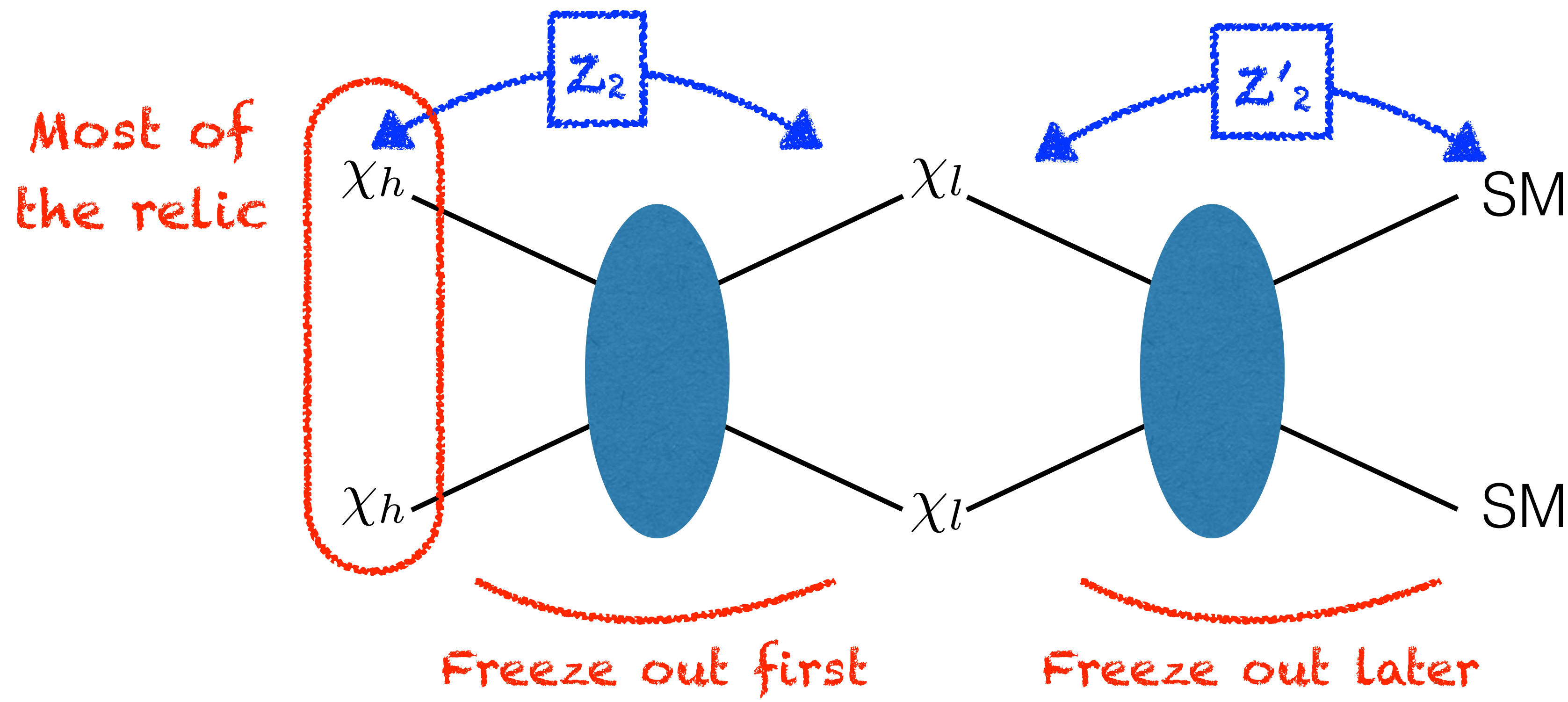
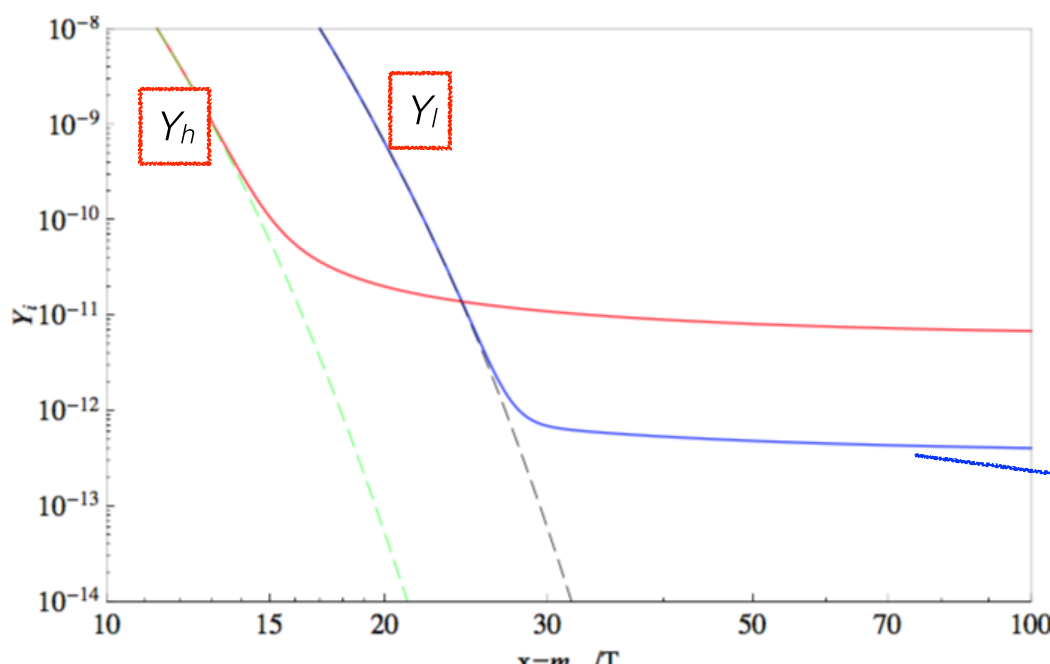
Boosted DM

Minimal model example





Belanger, Park, 1112.4491

Agashe, Cui, Necib, Thaler, 1405.7370

Assisted freeze-out

(Flux of relic χ_1: small)

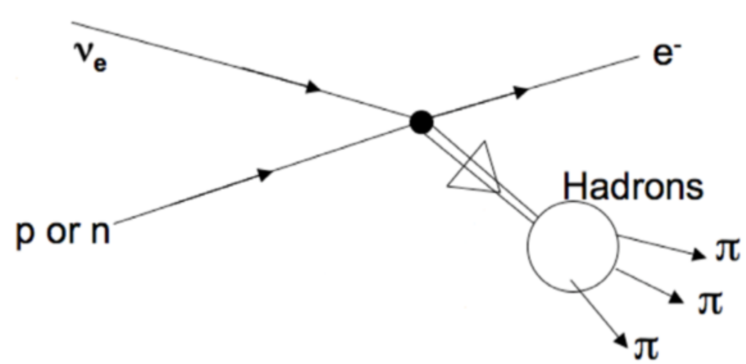
non-relativistic

Really background free?

Background may be negligible (dedicated analysis needed)

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

- Not energetic muon $\mu \rightarrow e \nu_e \nu_\mu$ (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



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

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

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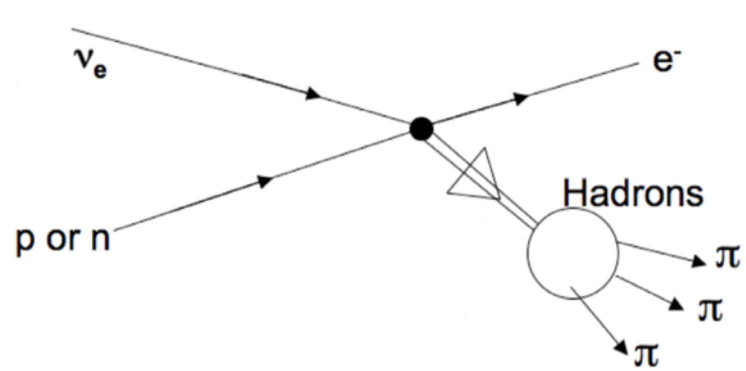

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Kim, Park, **SS**, Work in progress

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
- $n\nu_e \to pe \to 3e + \ldots$ 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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+ 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

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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 + directionality (GC)?

Really background free?

Background may be negligible (dedicated analysis needed)

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

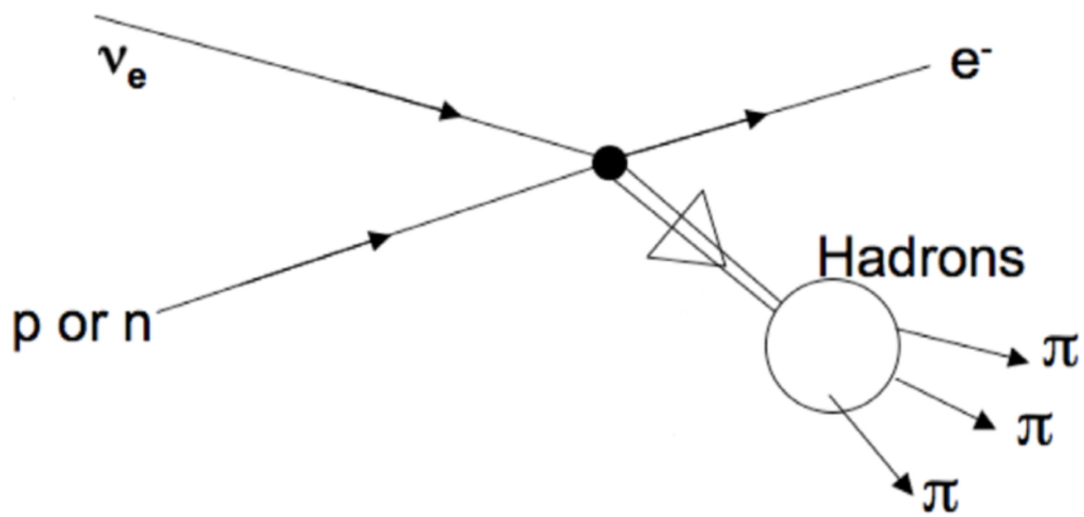
Ionization from the charged track (DUNE)

- 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
- $n \nu_e \to pe \to 3e + \ldots$ by hadronized p (or just by NC): shower can be seen

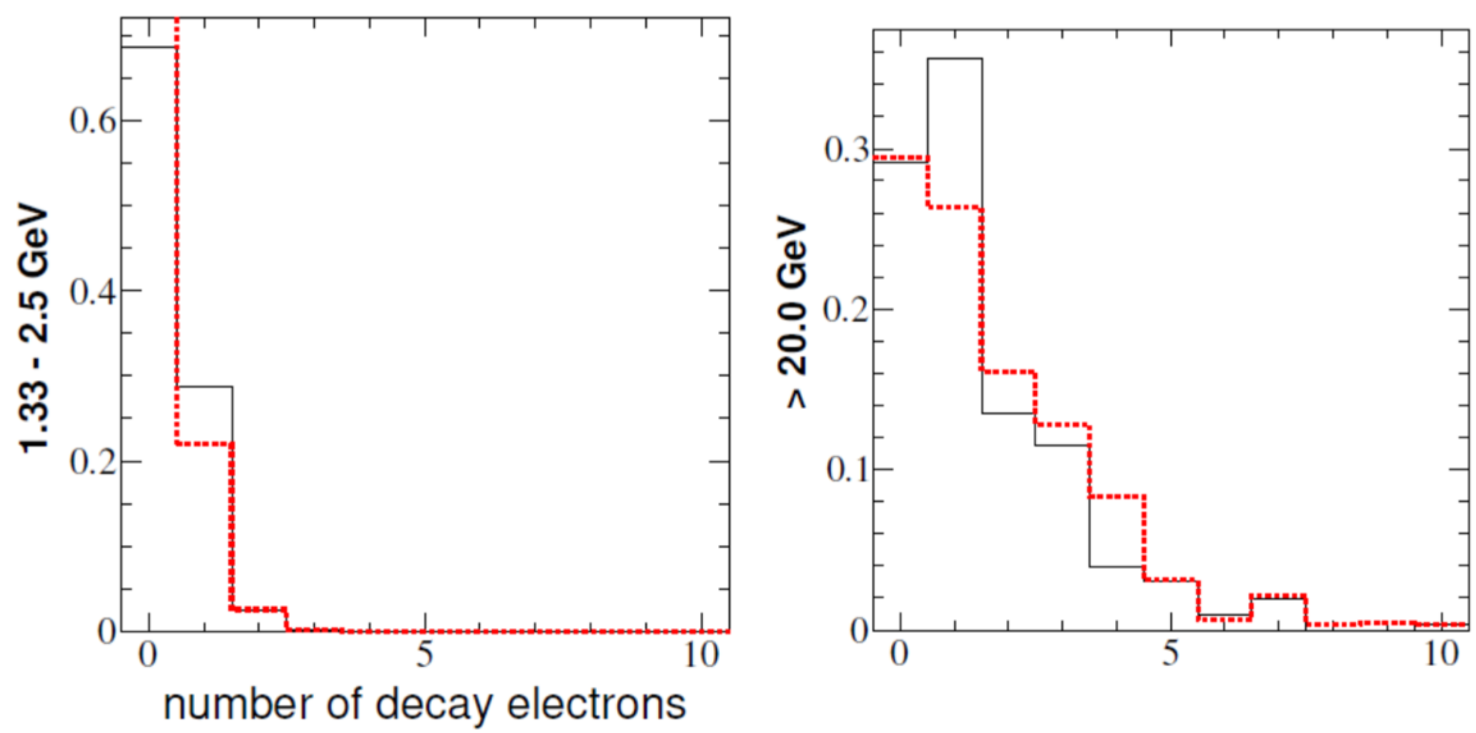
Maybe DUNE can separate all possible backgrounds

Back up

Super-K (2012)

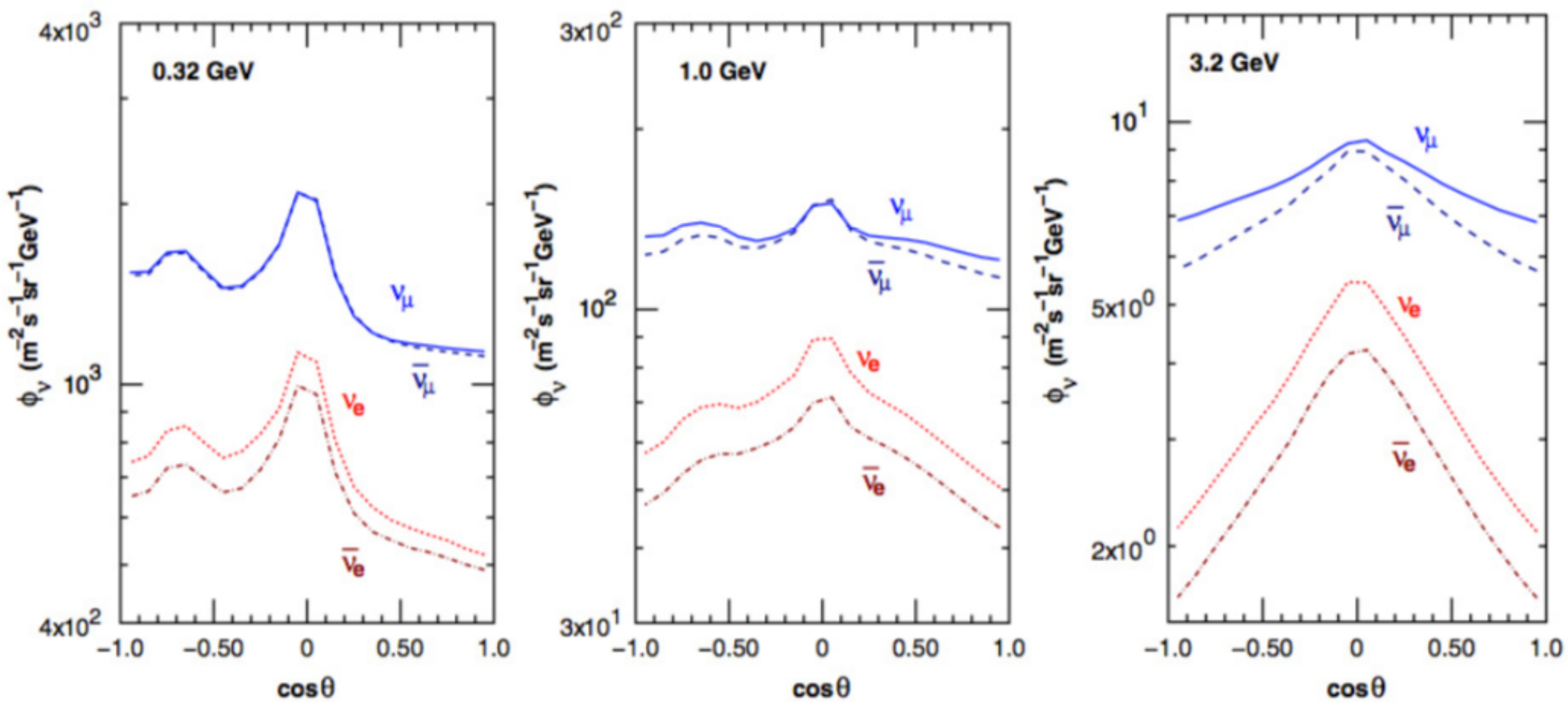


$$\pi^+ \to \mu^+ + \nu + \mu$$
$$\quad\quad \hookrightarrow e^+ + \nu_e + \overline{\nu}_\mu$$



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

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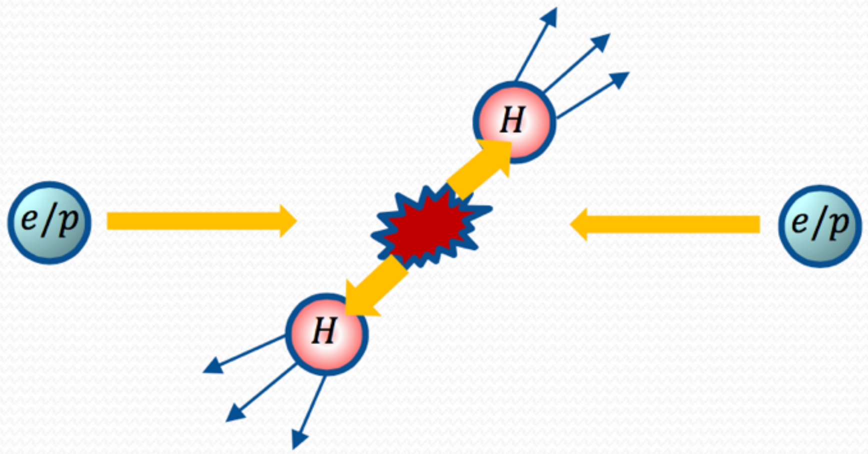
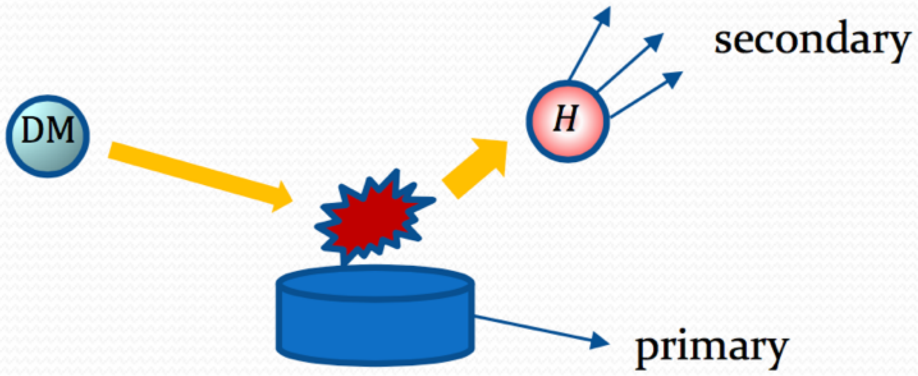
Back up

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

Search in intensity frontier experiments

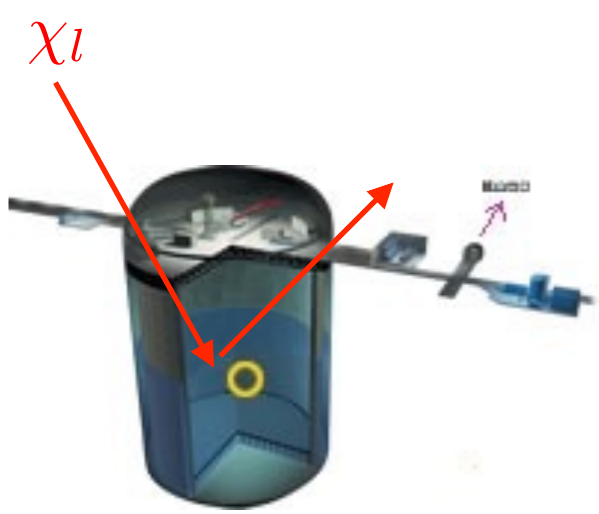
Intensity frontier: increase fluxes of incoming χ_l

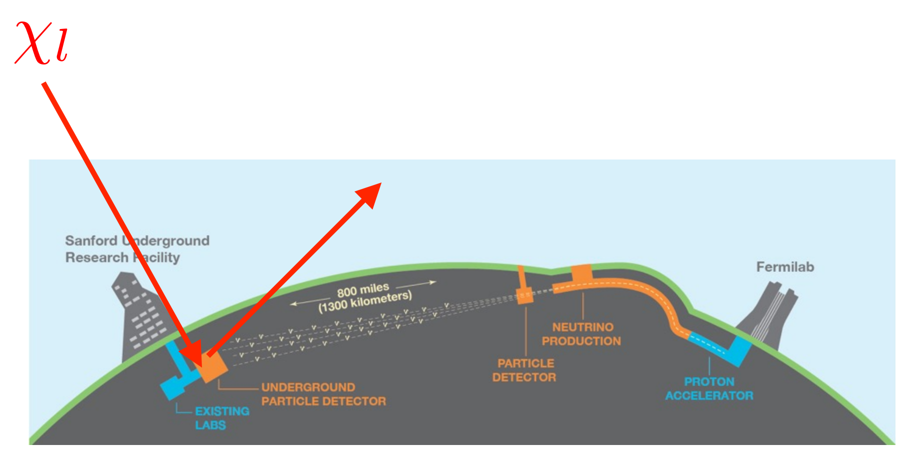
Kim, Park, **SS**, … , Work in progress

Exp.	DUNE	SHiP[†]	SK/HK[‡]
Near-far detector	Yes	Yes	(Yes)
Distance b/w detectors	1,300 km	50 m	800 km
Volume*	8/40 kt	9.6 kt/NA	(190/190) kt 22.5 kt for SK
Detector type	Liquid Ar	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	27×10^{20}/year
Power	1.2 MW	(> 0.16 MW)	1.3 MW
Angular resolution (e/p)	$1^\circ/5^\circ$	(Good)	$3^\circ/3^\circ$
Threshold energy	20 – 30 MeV	(Equally small)	100 – 1000 MeV*
Position resolution	1 – 2 cm	0.1 – 1 mm	Not good

Passive search of relativistic DM scattering

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





Identify the signals by simple counting N_{obs} over the expected bkg.

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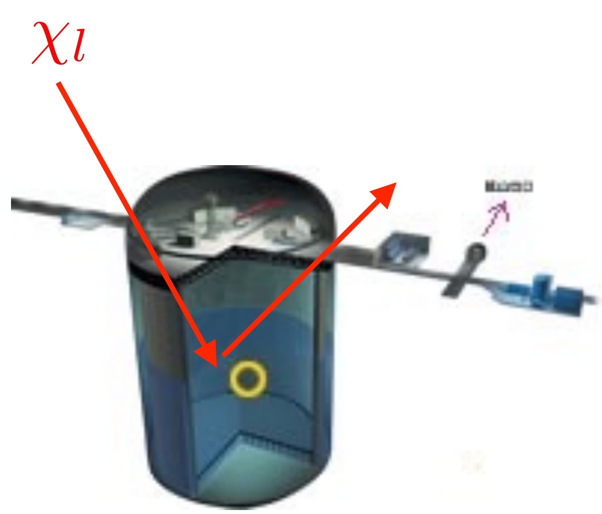
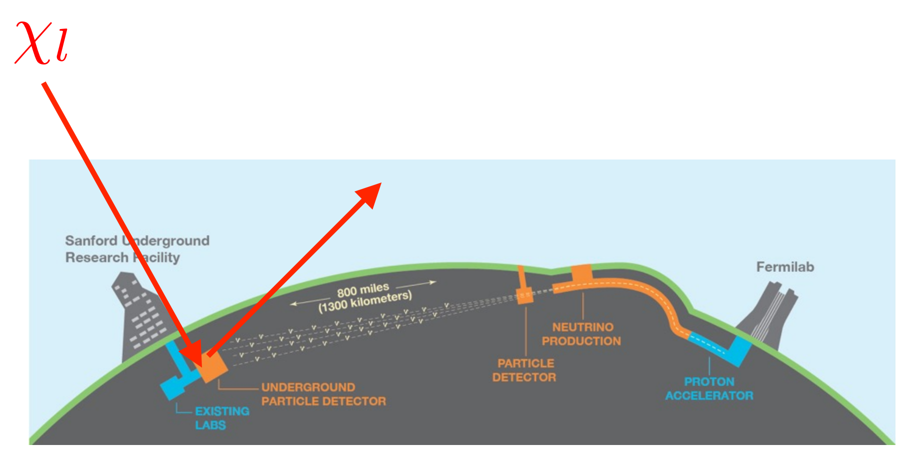
$\chi_h \chi_h \to \chi_l \chi_l$ (current universe) relativistic





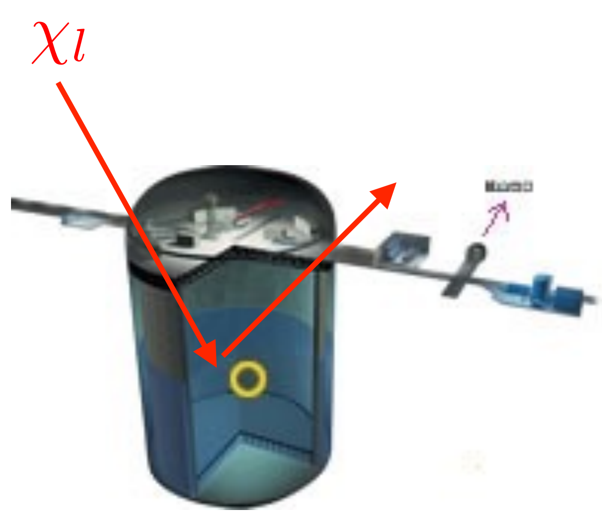
Identify the signals by simple counting N_{obs} over the expected bkg.

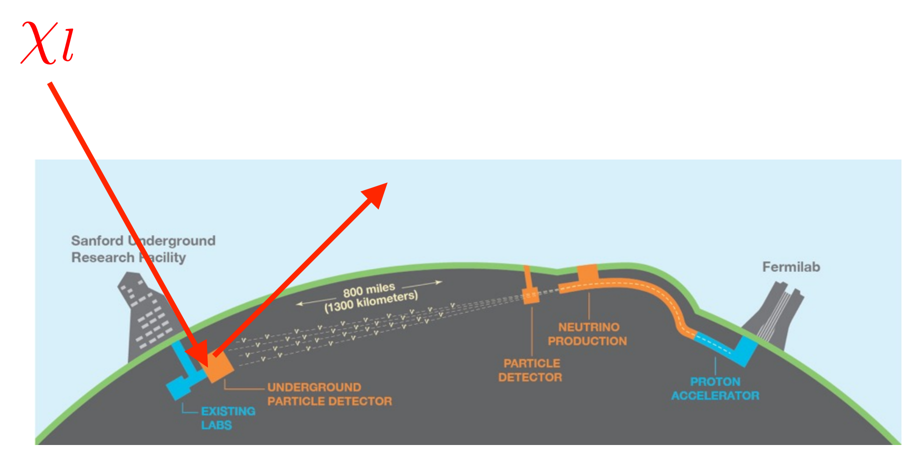
neutrino

Interesting but not easy
to confirm the signals over ν

Passive search of relativistic DM scattering

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

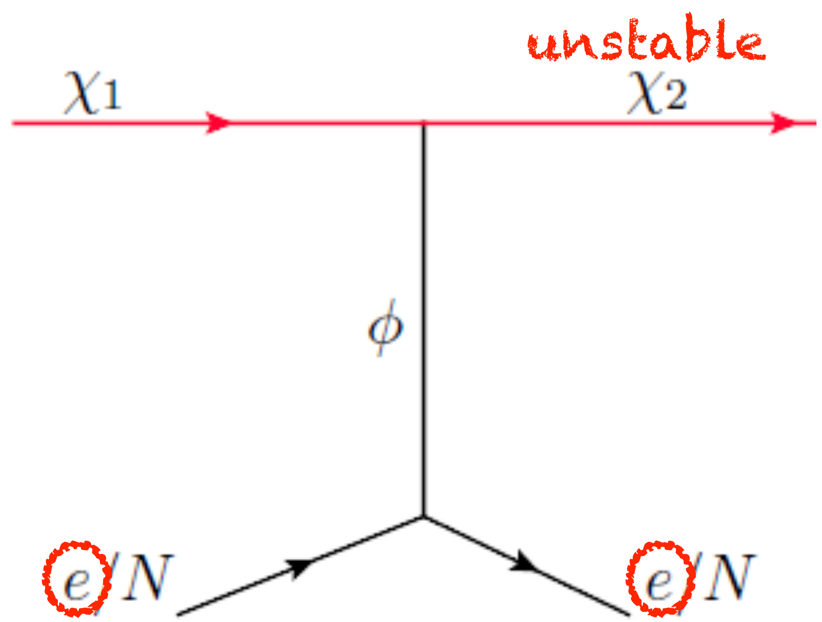
  Berger, Cui, Zhao, 1410.2246 Kong, Mohlaberg, Park, 1411.6632

  Alhazmi, Kong, Mohlaberg, Park, 1611.09866

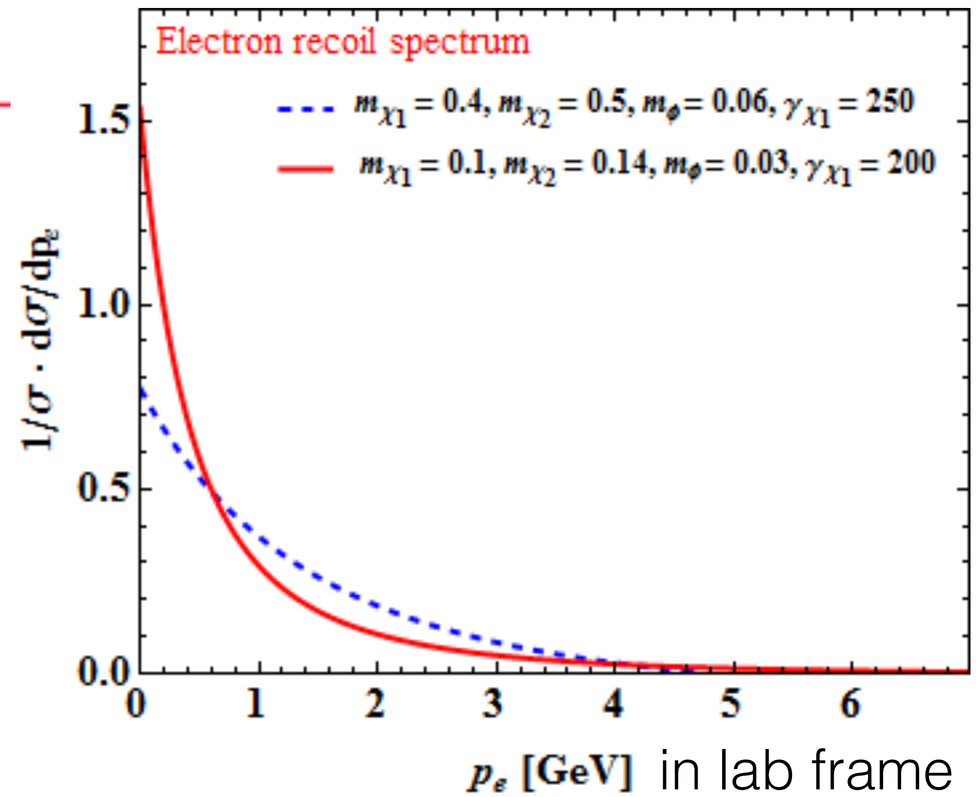
- Non-minimal dark sector (just like SM?): extraordinary signal

  Kim, Park, **SS**, 1612.06867

Energy spectrum: e-scattering



primary scattering

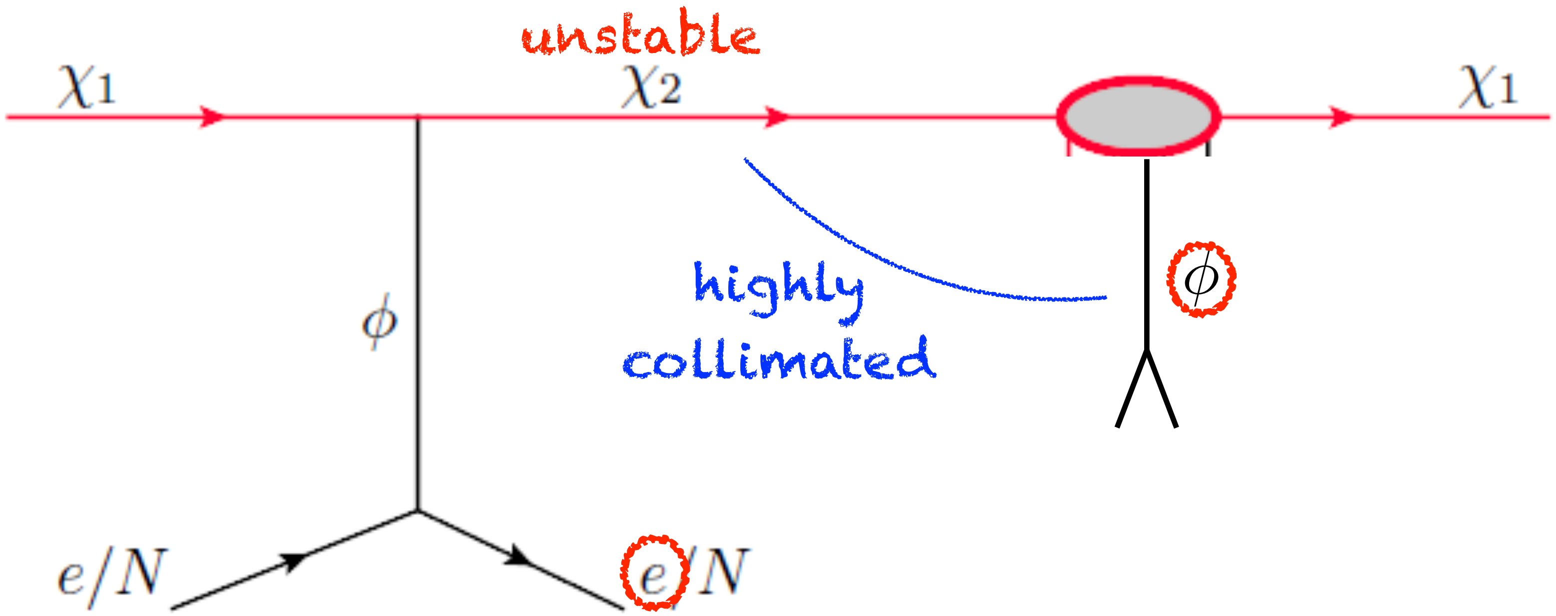


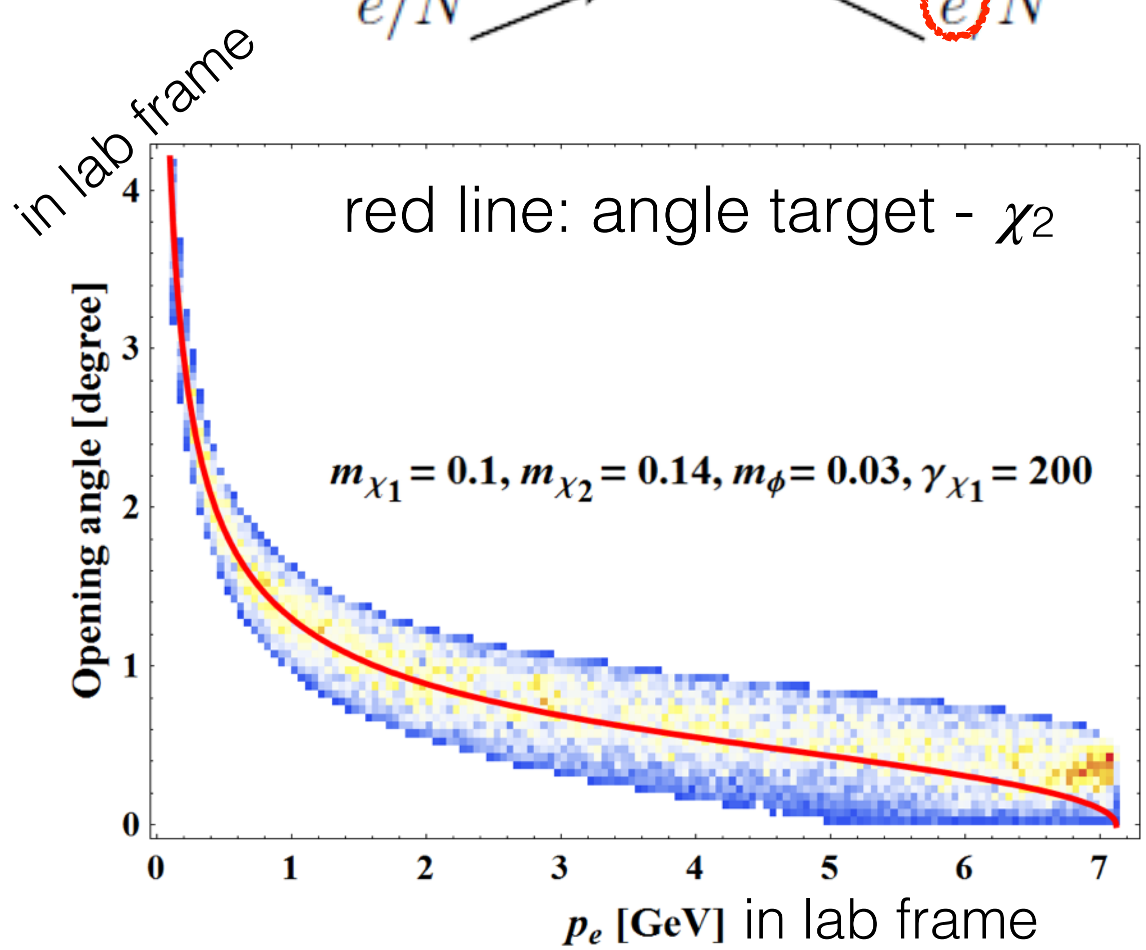
in lab frame

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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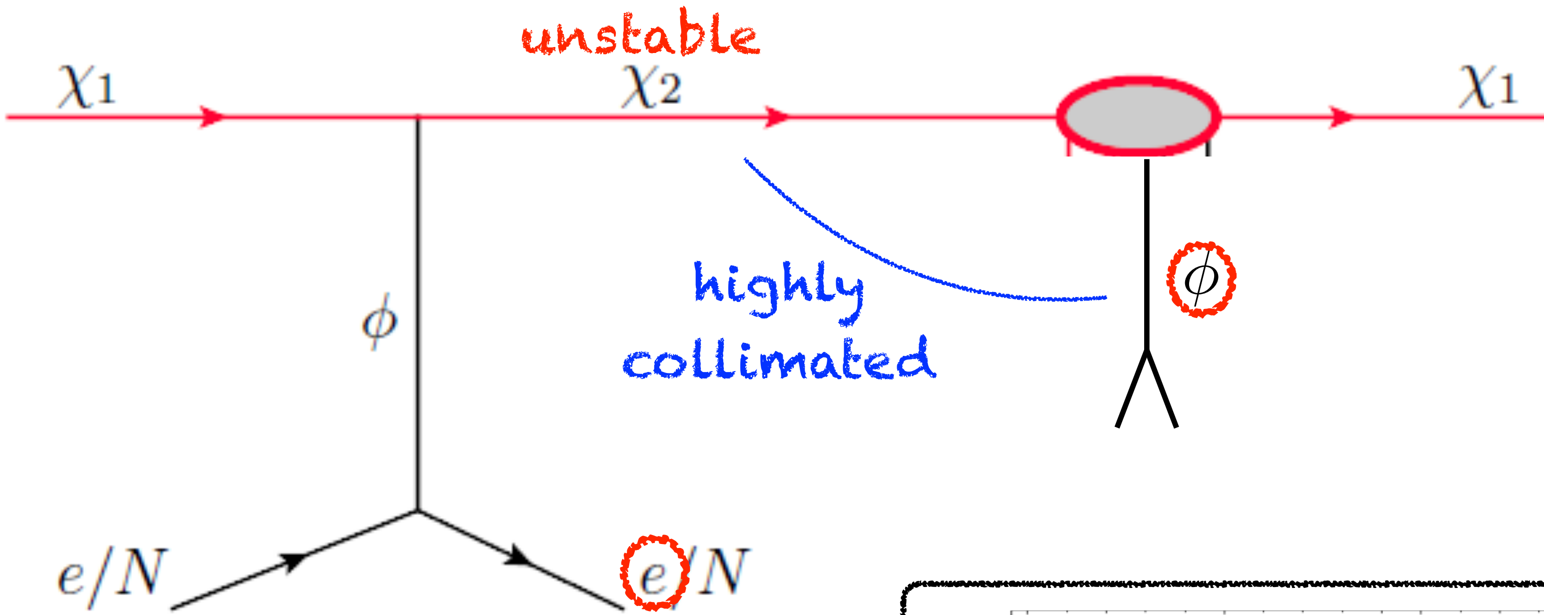
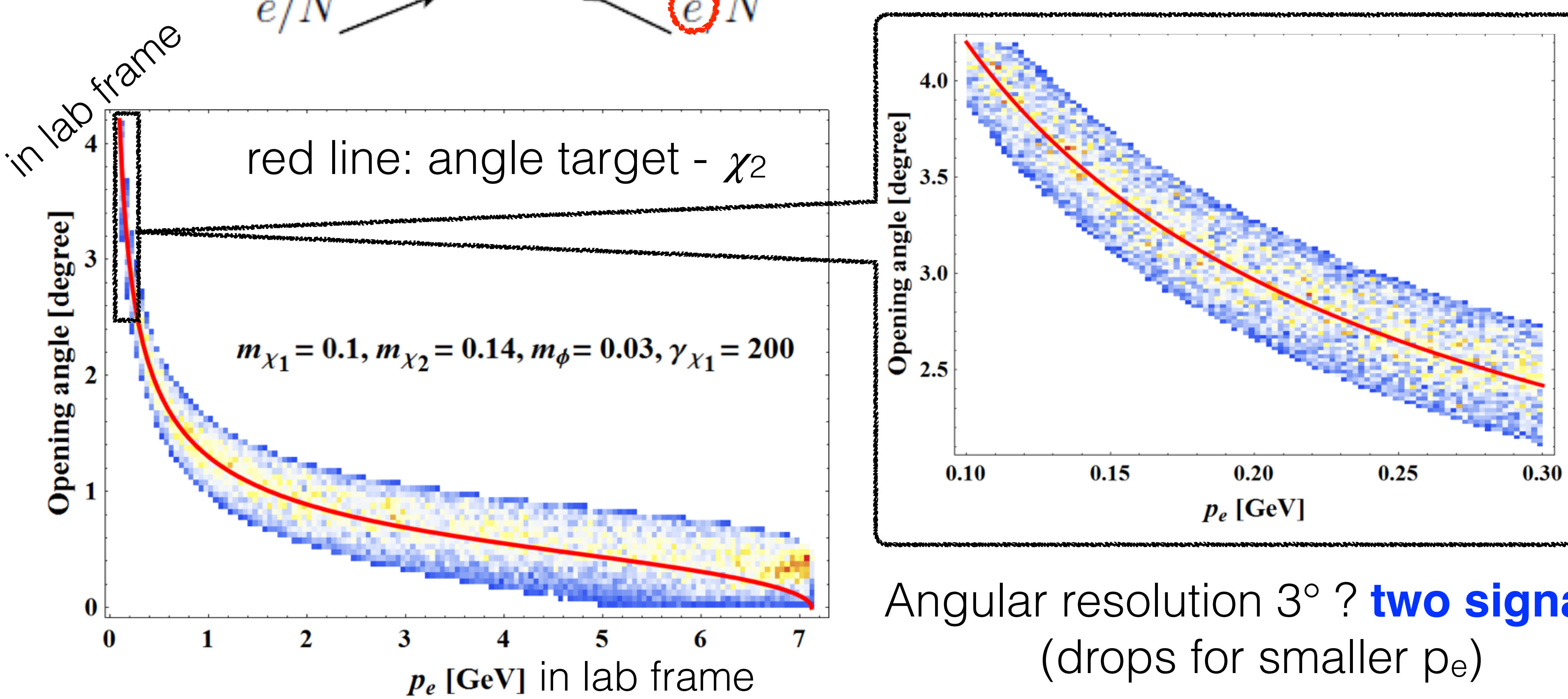
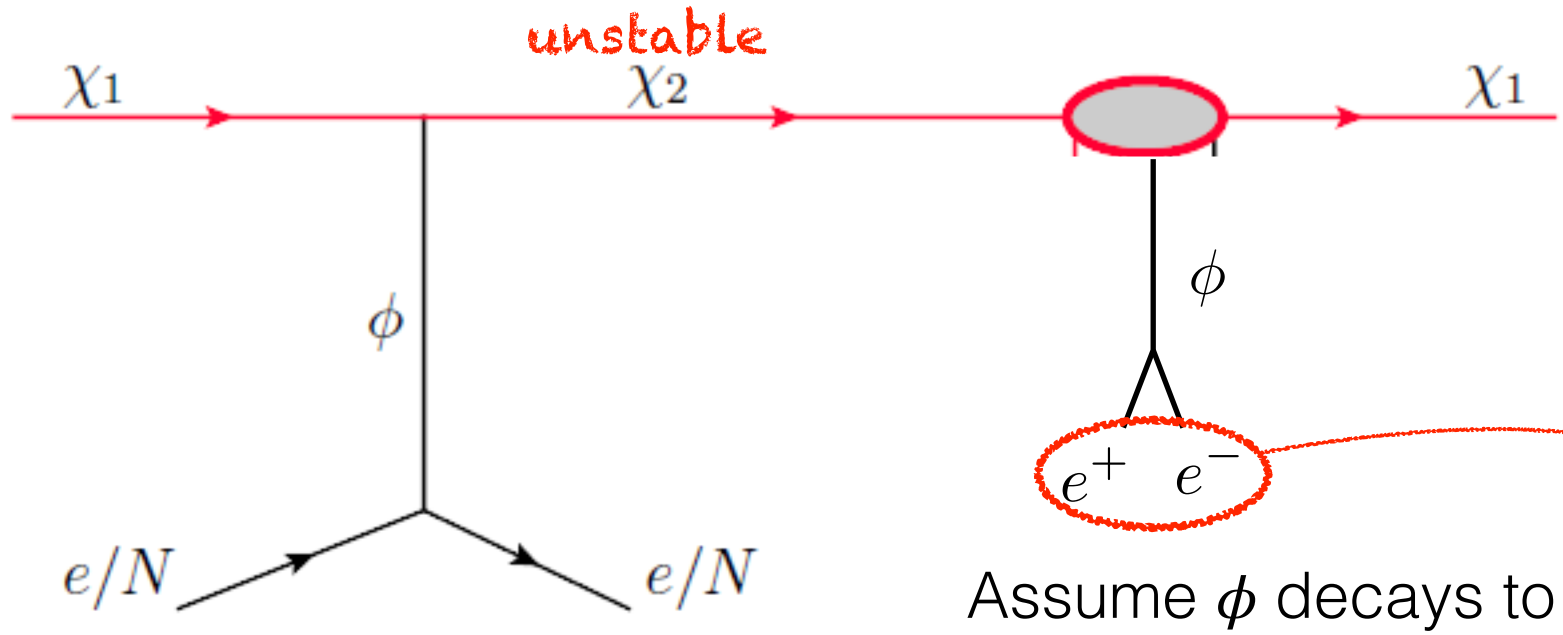


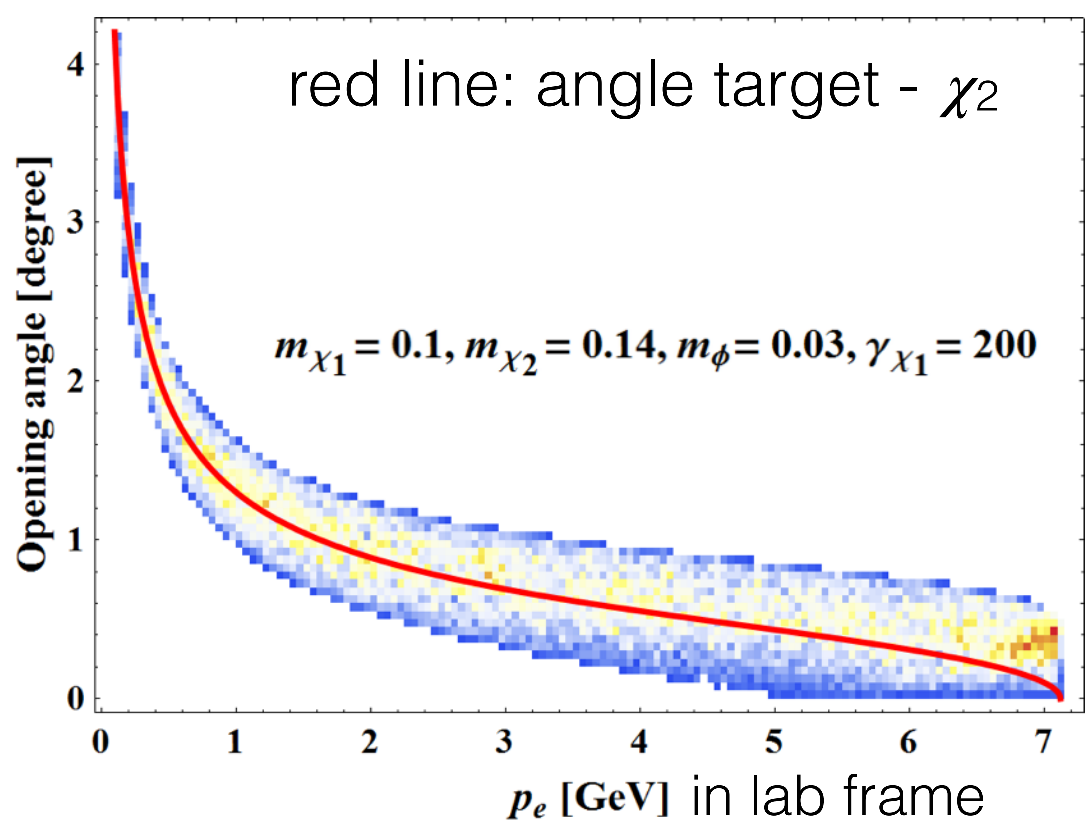


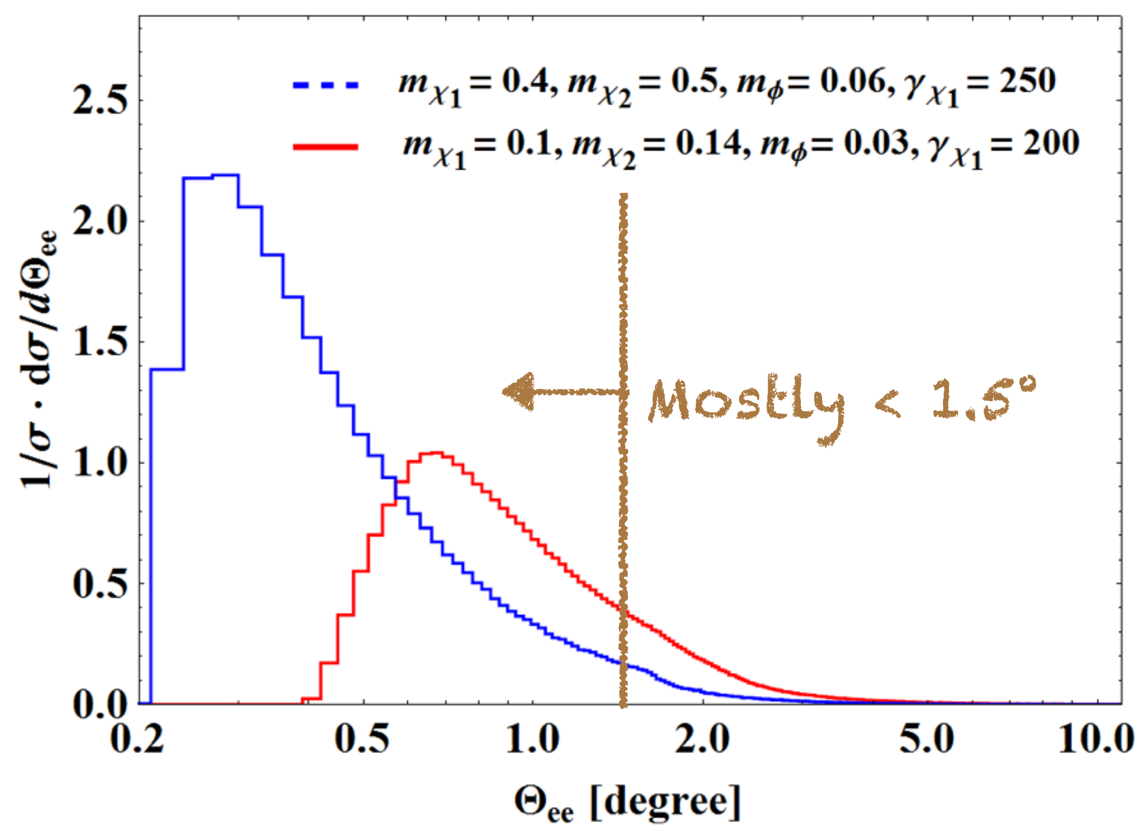
Angular resolution 3° ? **two signals!**
(drops for smaller p_e)

e-scattering: highly collimated

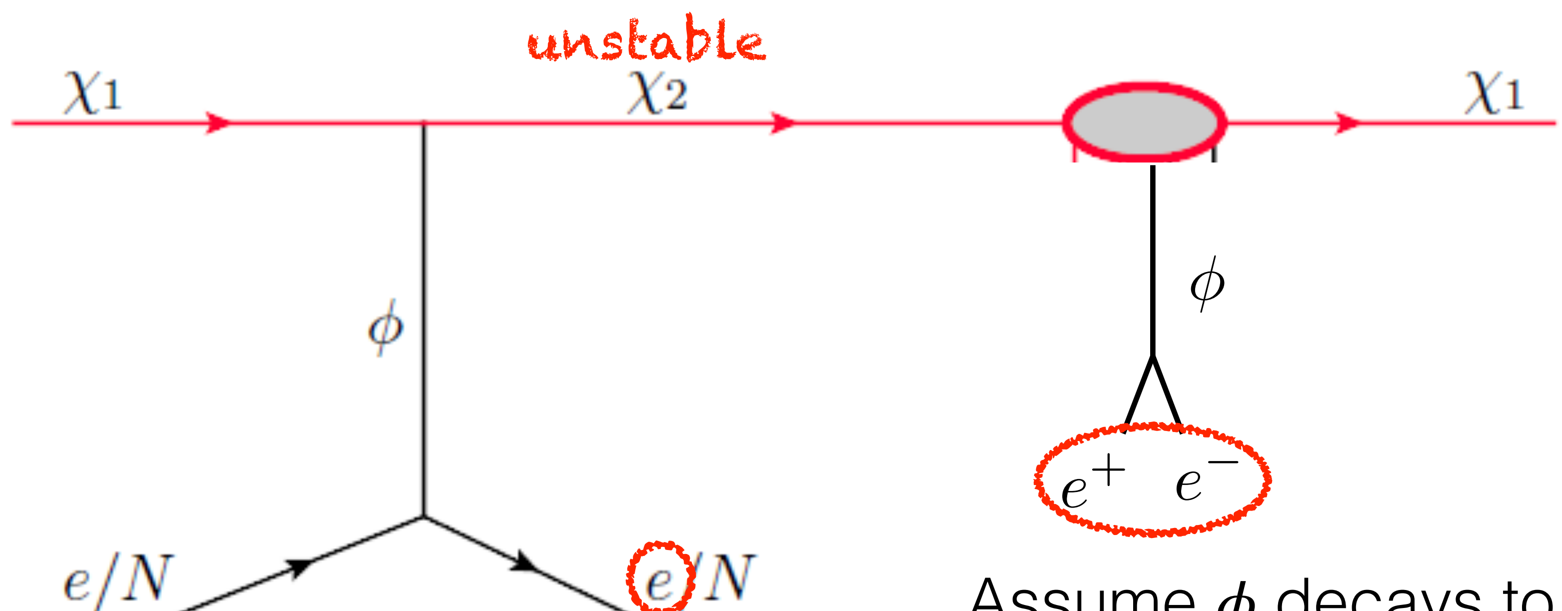


Assume ϕ decays to e^+e^-





e-scattering: detection prospects



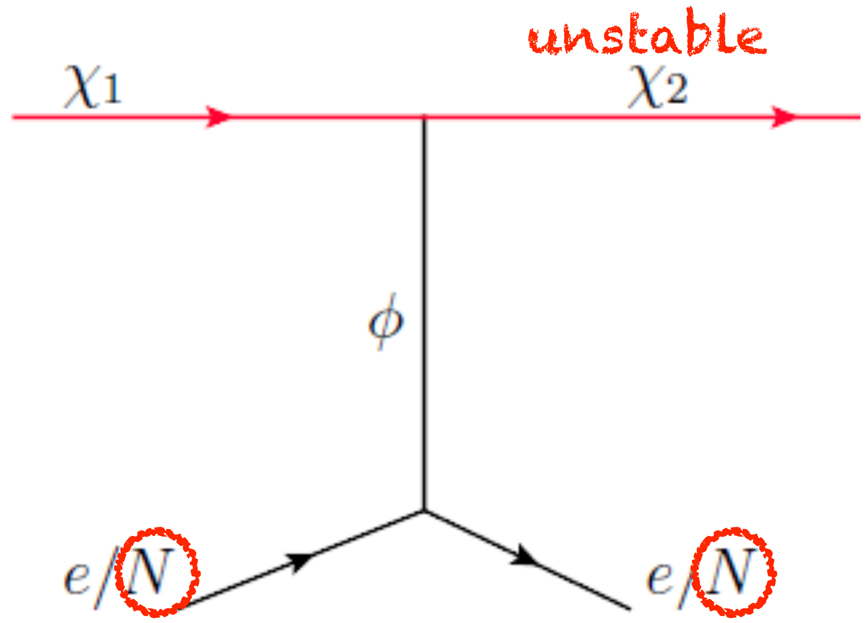
Assume ϕ decays to e^+e^-

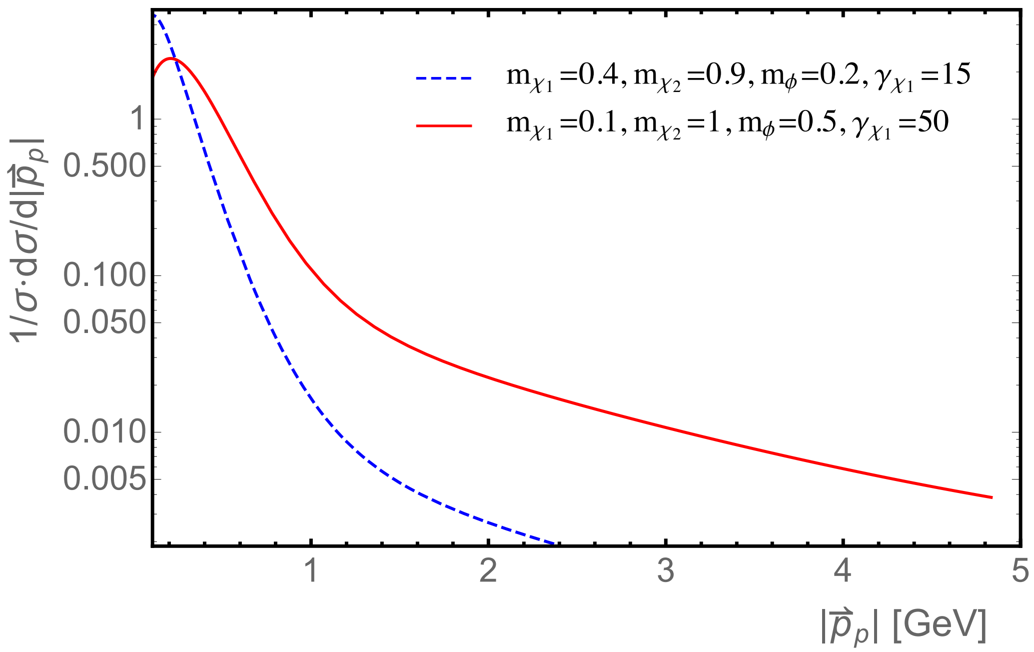
effective for $E > E_{th}$

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

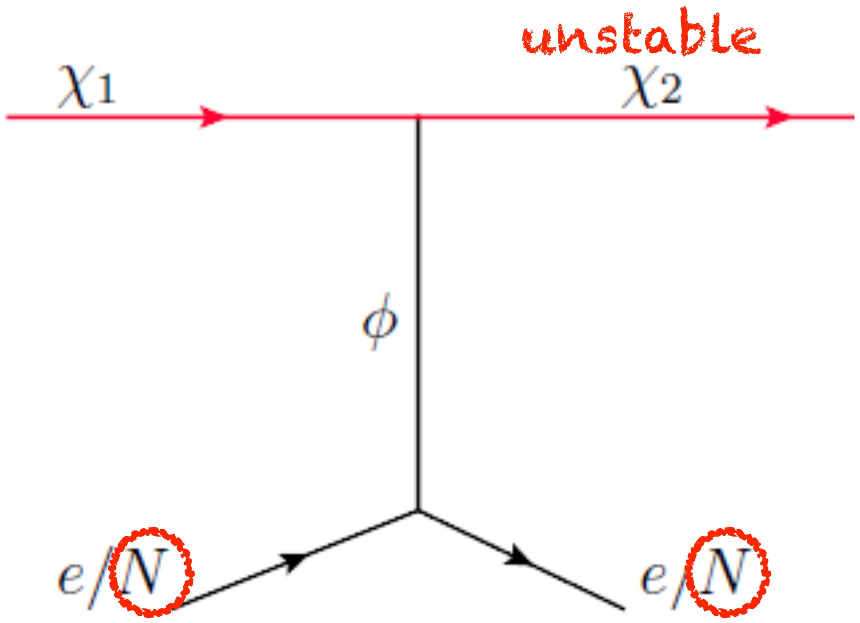


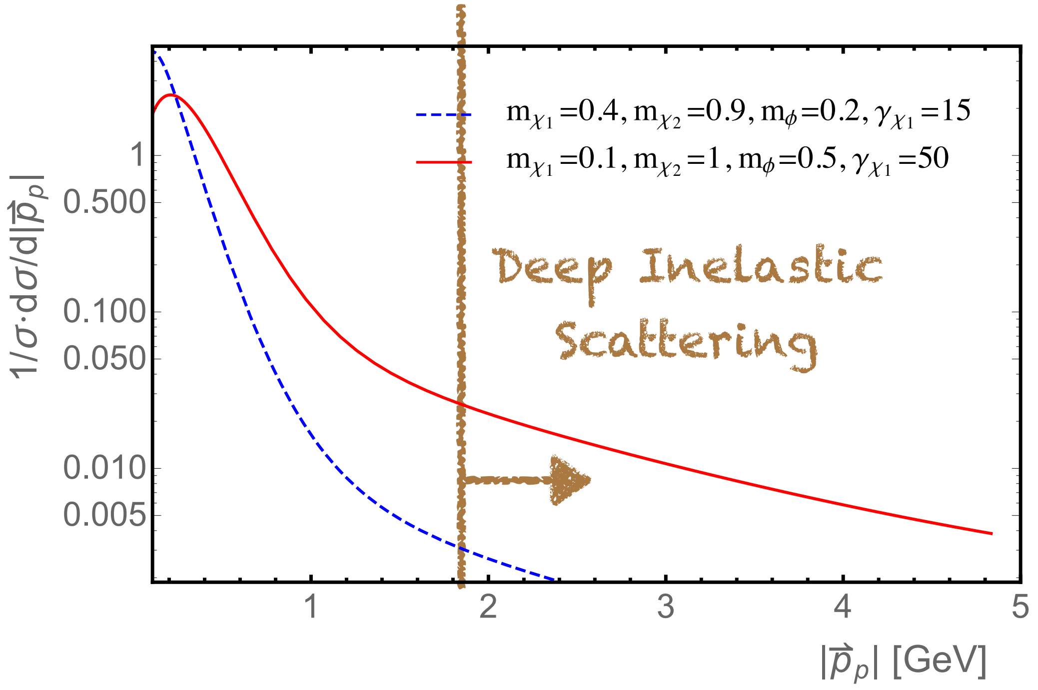


p-scattering NOT preferred over e-scattering (Cherenkov)

- 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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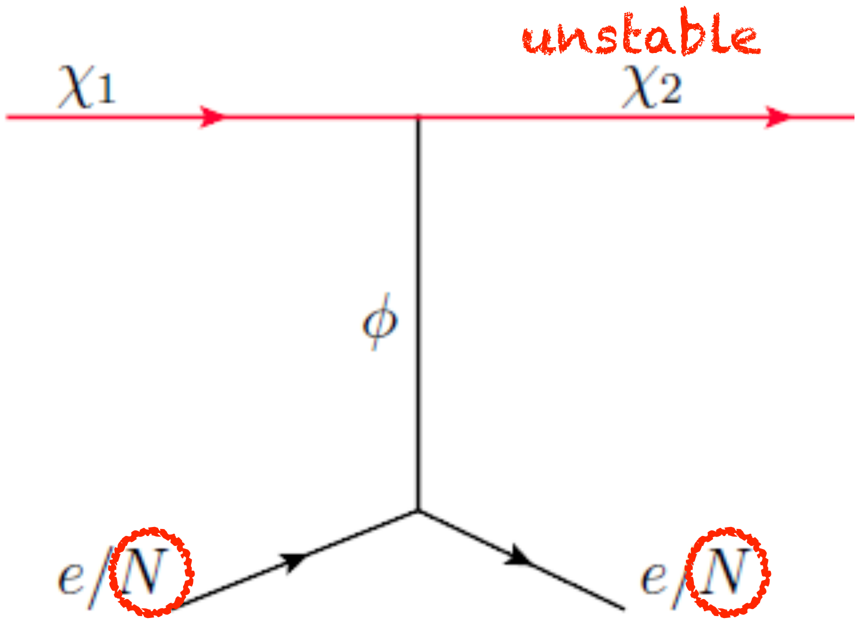
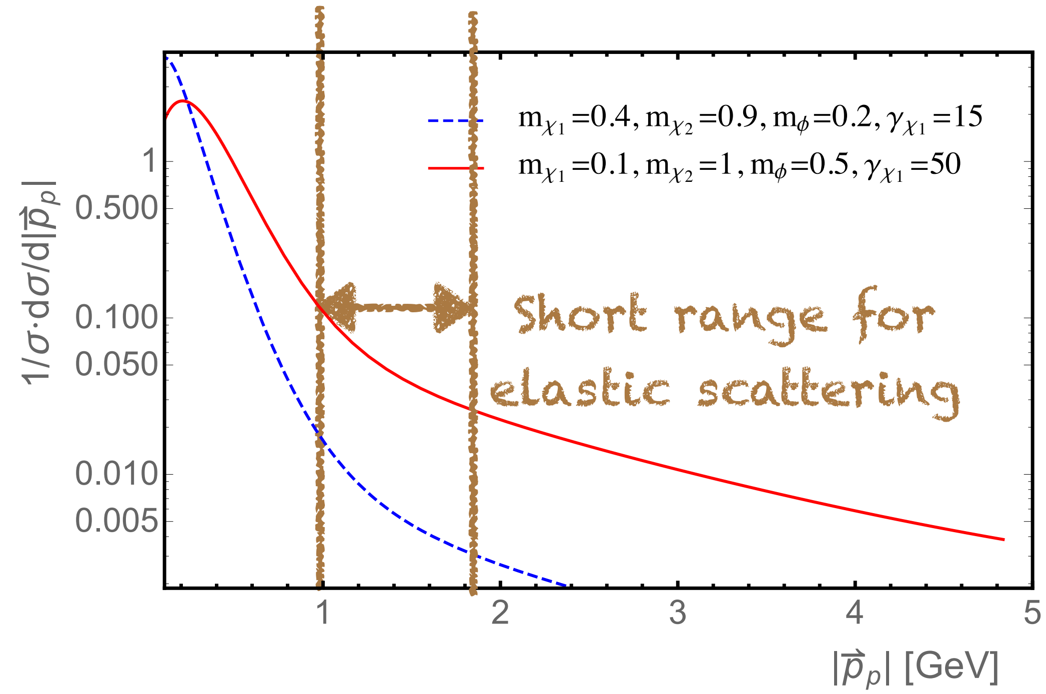
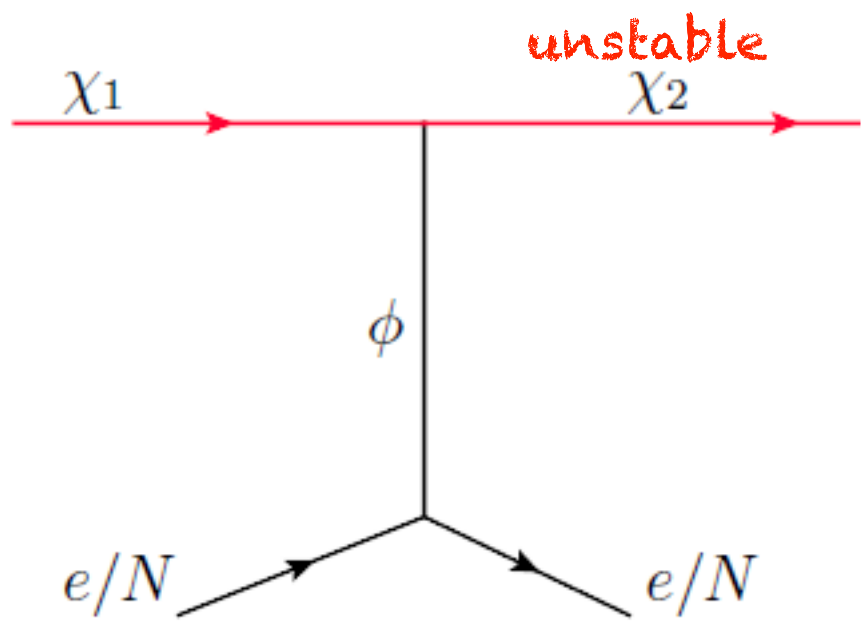


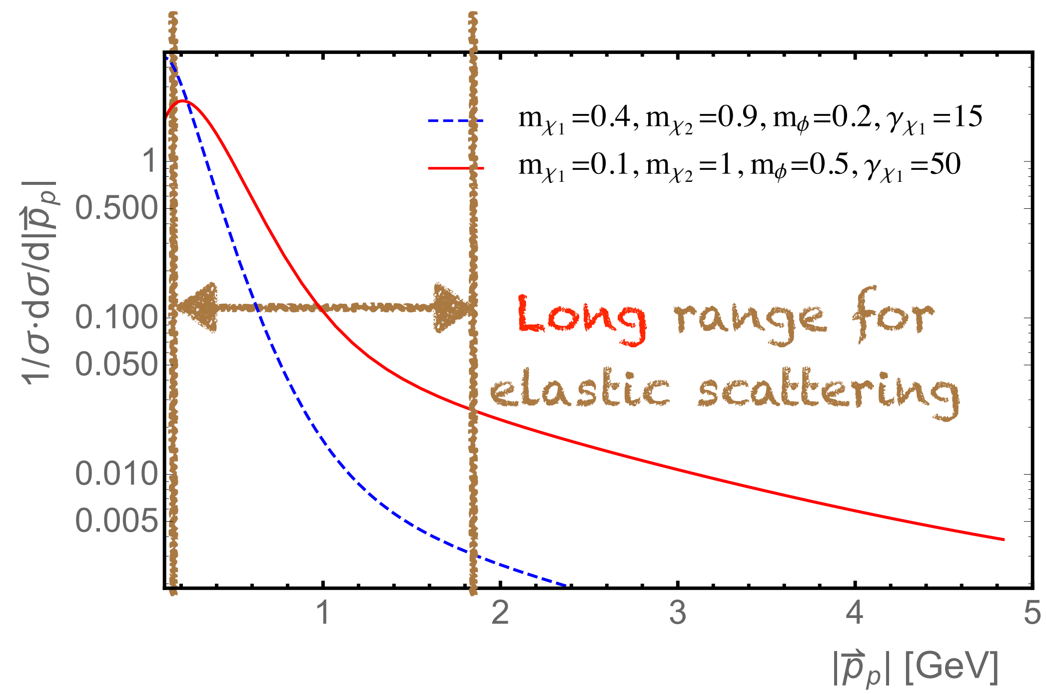


p-scattering NOT preferred over e-scattering (Cherenkov)

- 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

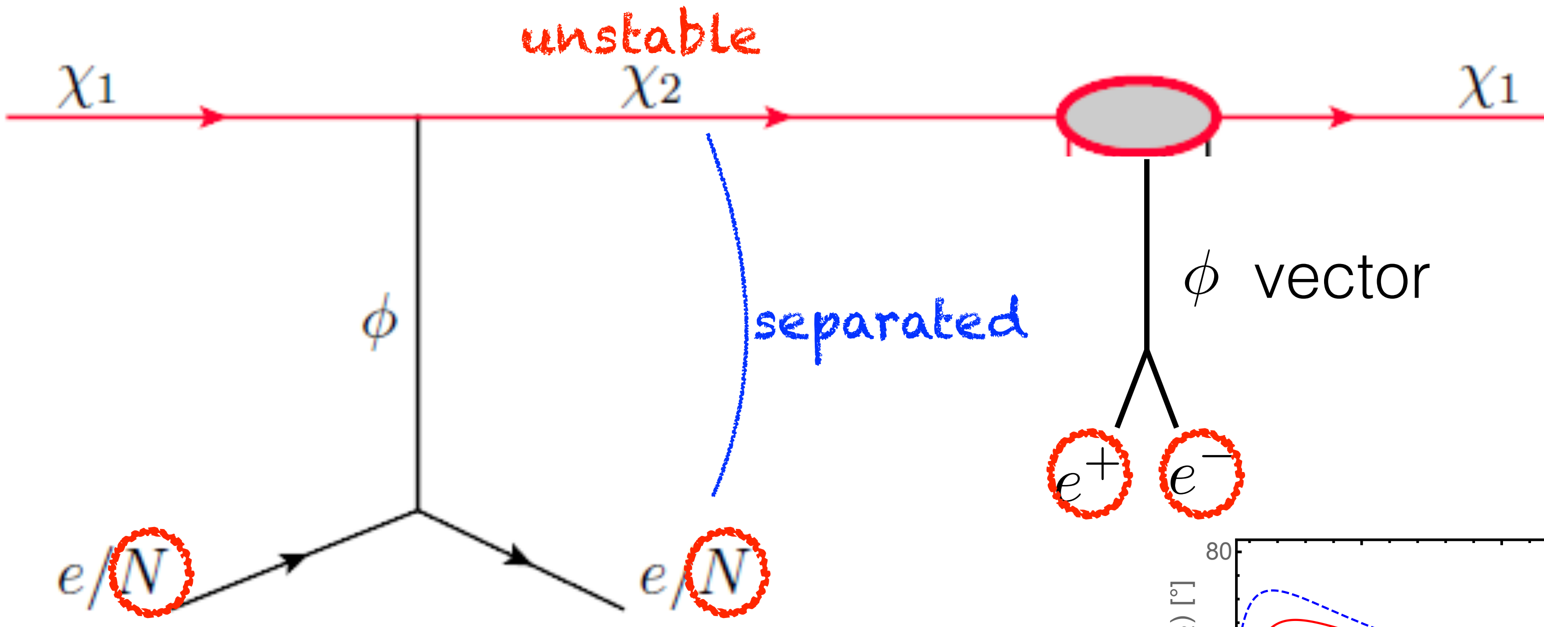




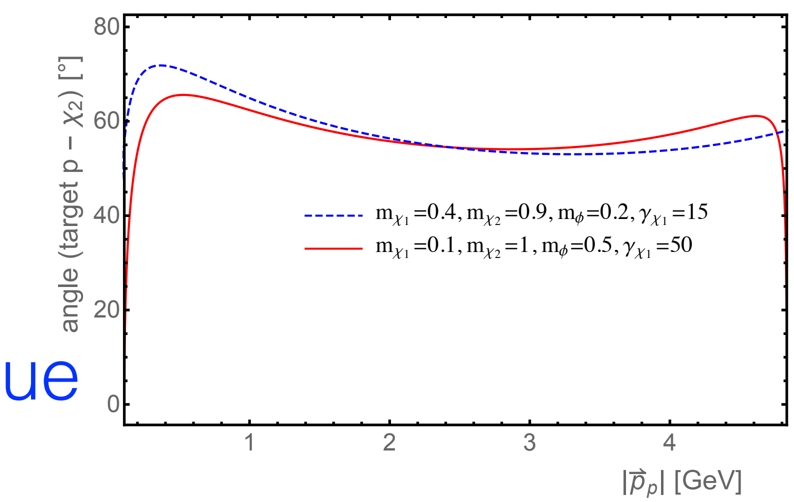
However, the cascade process is still unique

- 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