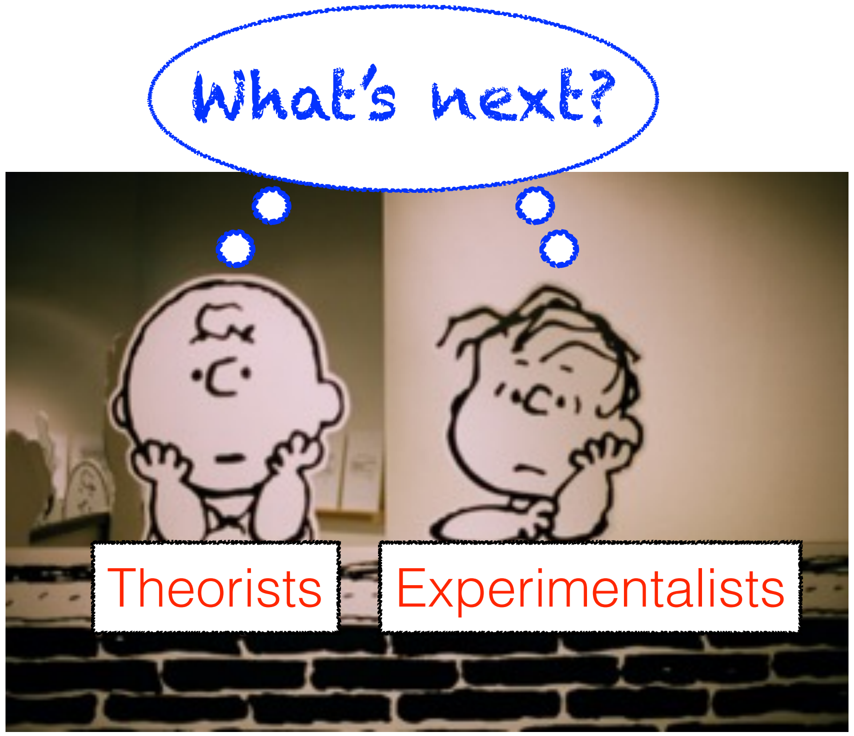
Non-minimal Dark Sector Phenomenology
Dark Matter "Collider"

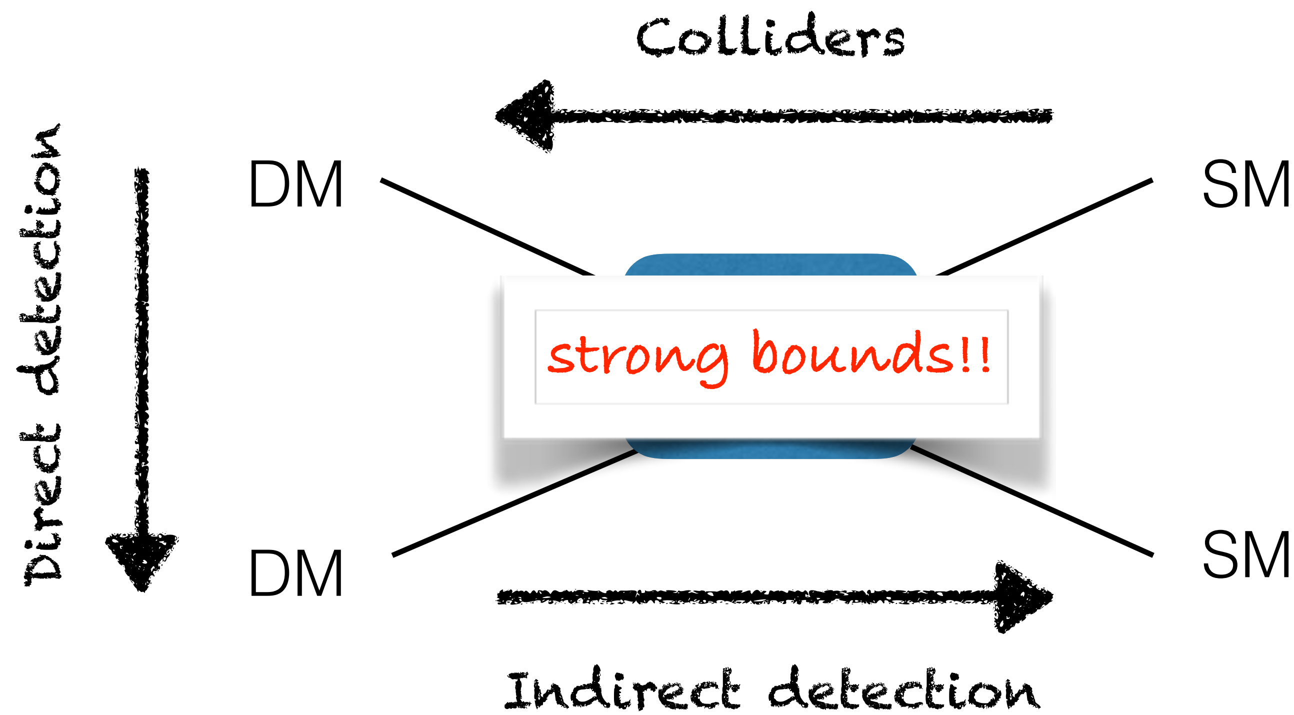
arXiv:1612.06867

Seodong Shin

05.09.17

Not easy tasks

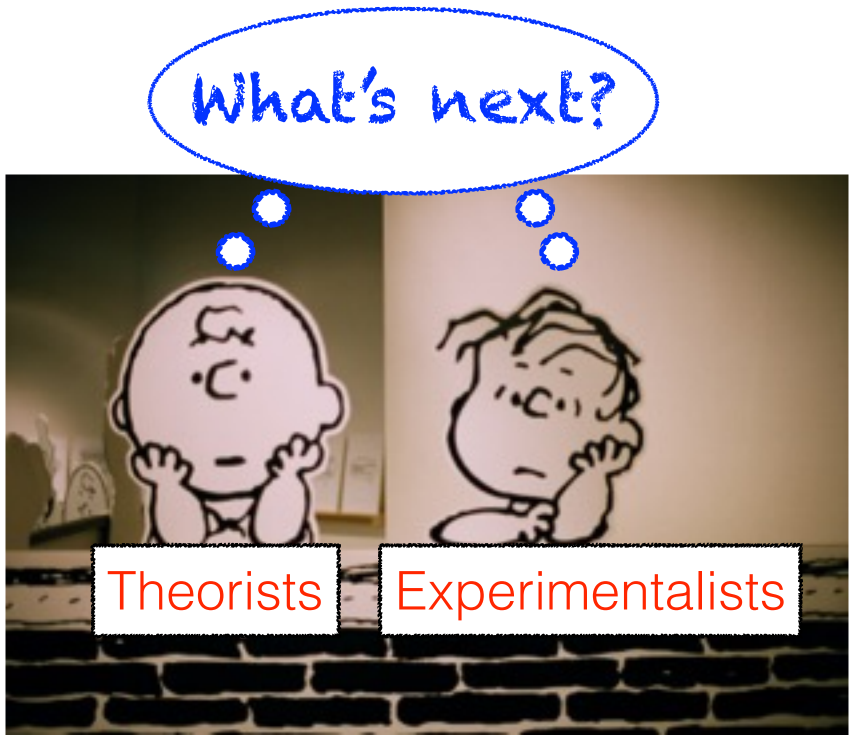


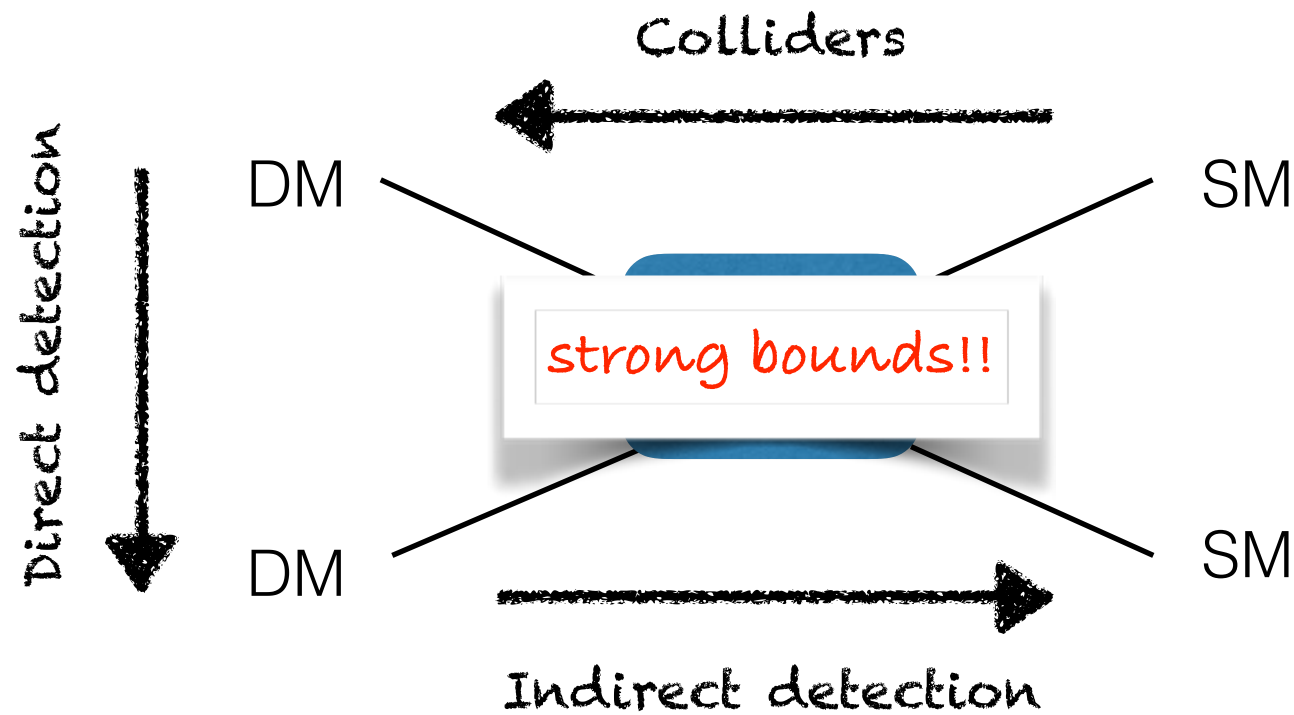


- Keep probing the rest of the corners of parameter space:
  tons of models may be still there!!

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

Not easy tasks





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  tons of models may be still there!!

- Non-conventional DM & search strategy can be considered!
  Doojin's talk

Non-conventional search strategy

My focus

Relativistic scattering of DM with a target
(in a non-minimal scenario)

Non-conventional search strategy

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Relativistic scattering of DM with a target
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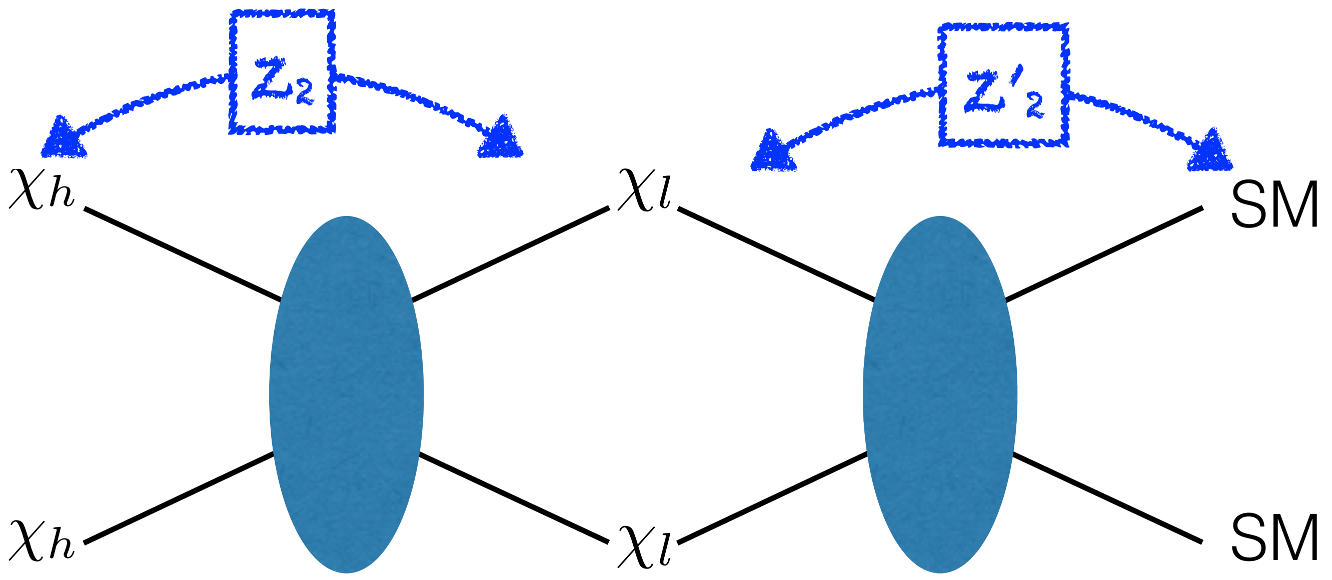
e.g., boosted dark matter



Agashe, Cui, Necib, Thaler, 1405.7370

Non-conventional search strategy

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Relativistic scattering of DM with a target
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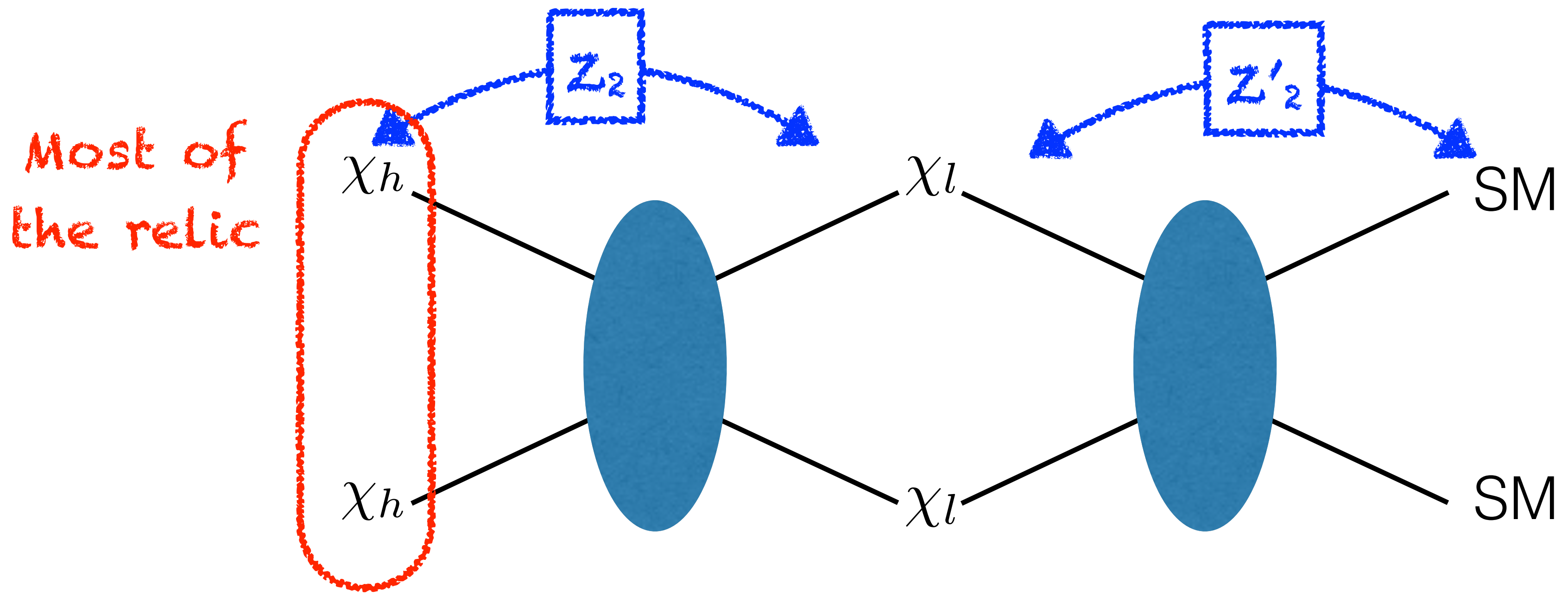


Agashe, Cui, Necib, Thaler, 1405.7370

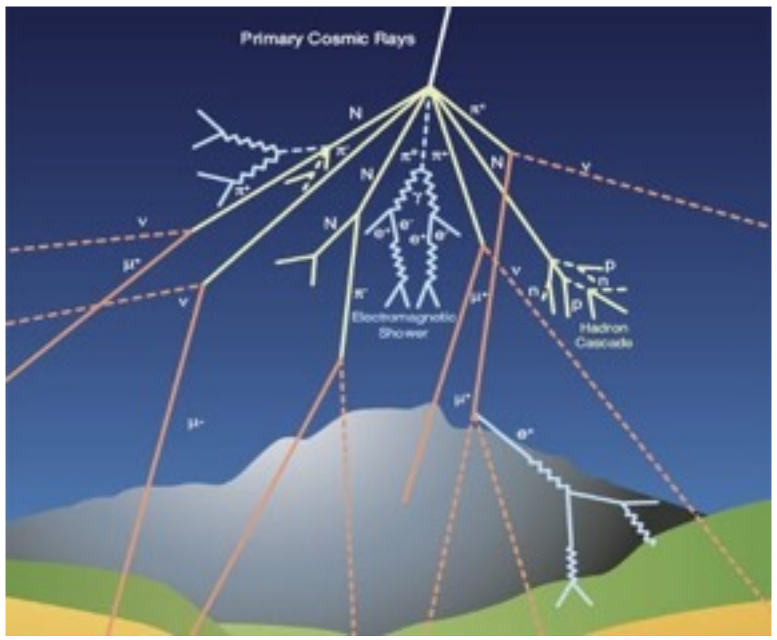
Belanger, Park, 1112.4491 Assisted freeze-out

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

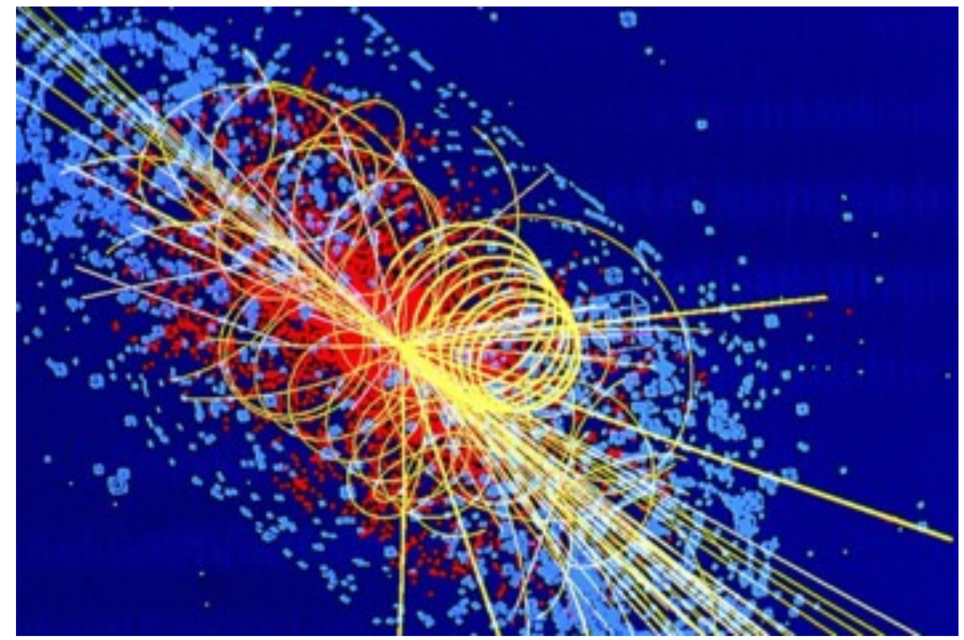
※ relic χ_l is non-relativistic

Relativistic scattering of DM

SM (5% of the Universe)



Passive search



Active search

Relativistic scattering of DM

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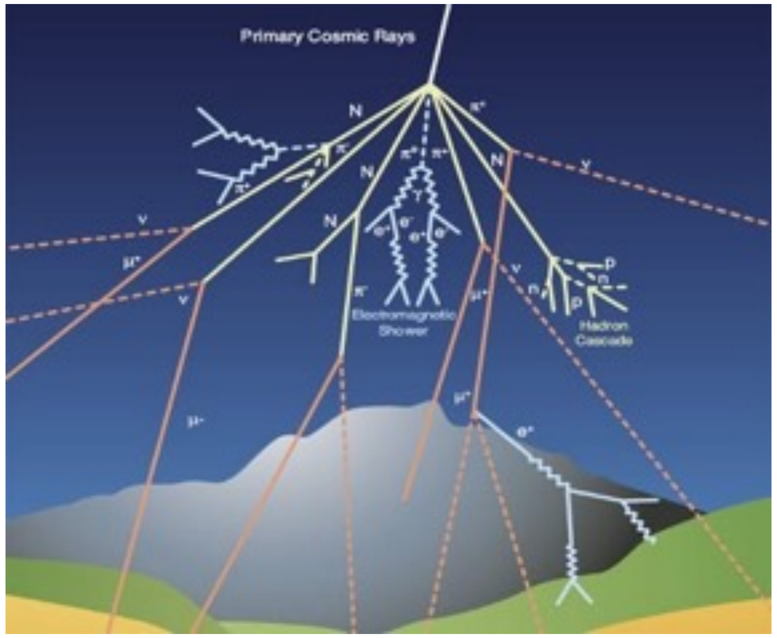

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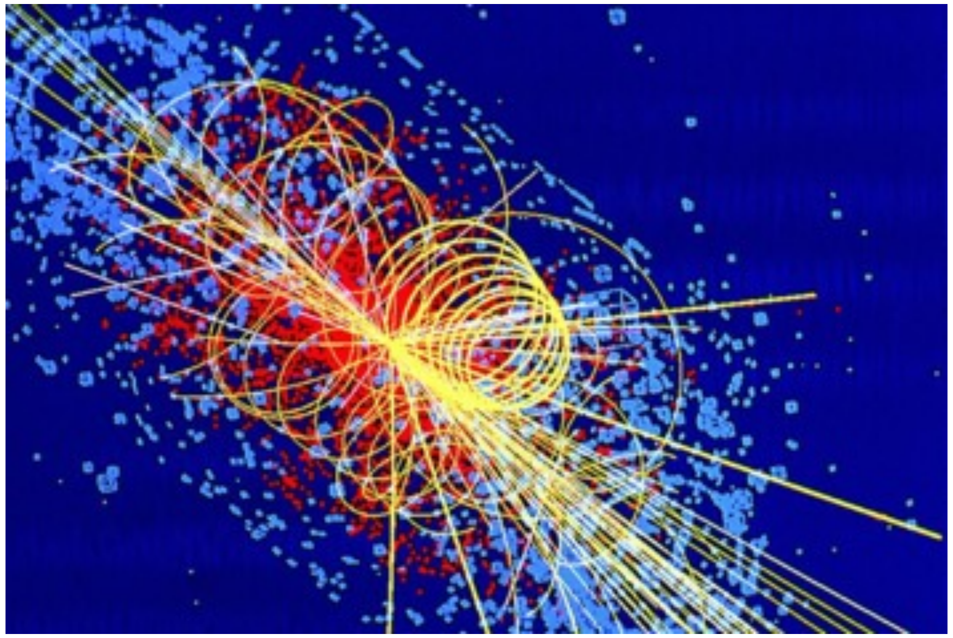
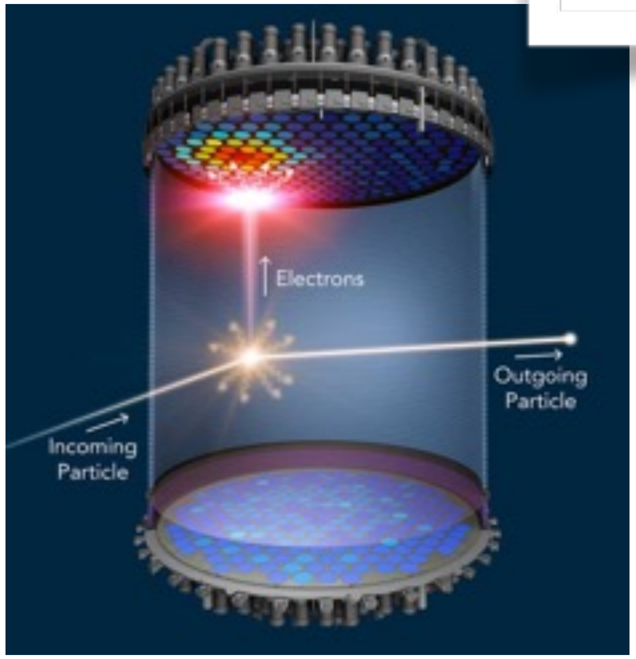


Active search

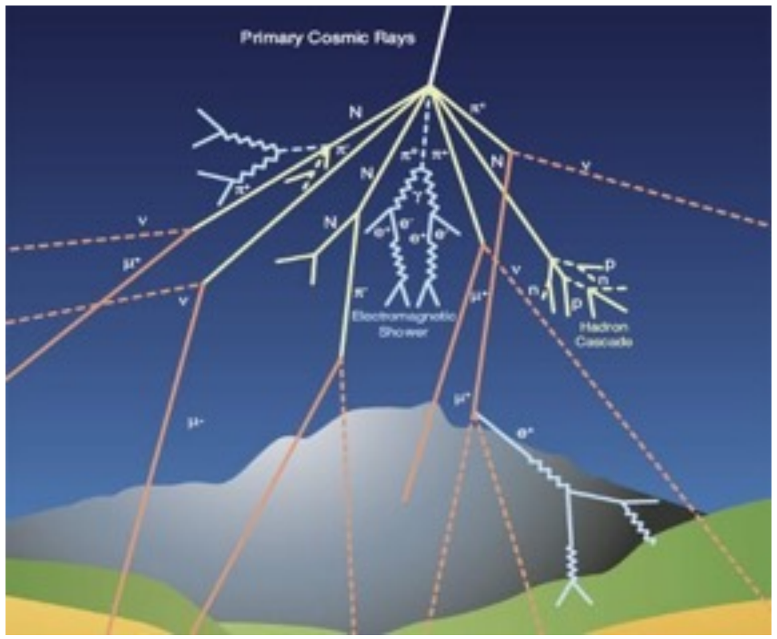
DM (25% of the Universe)

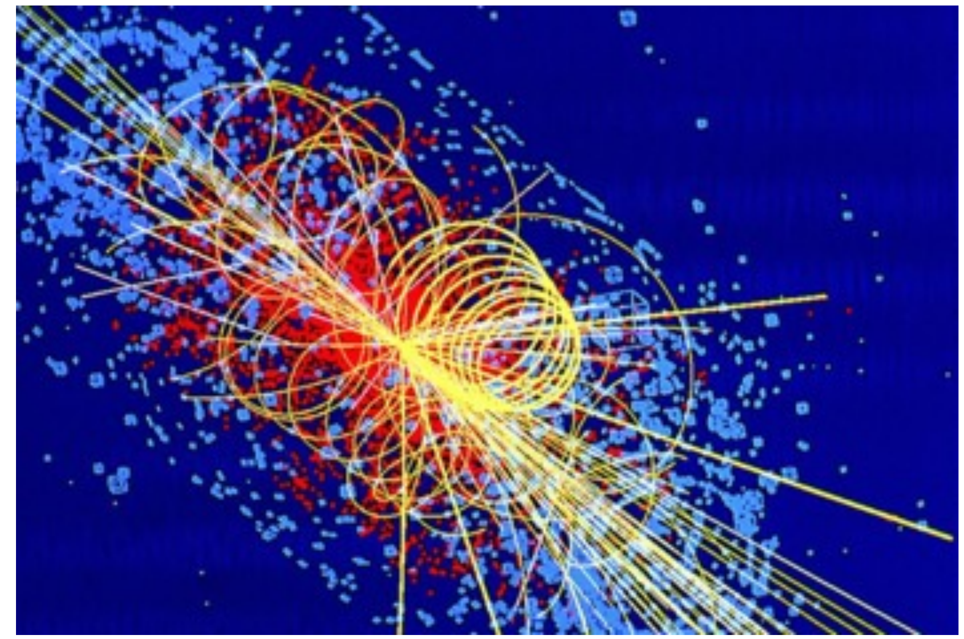


Non-relativistic DM (WIMP) scattering

Relativistic scattering of DM

SM (5% of the Universe)



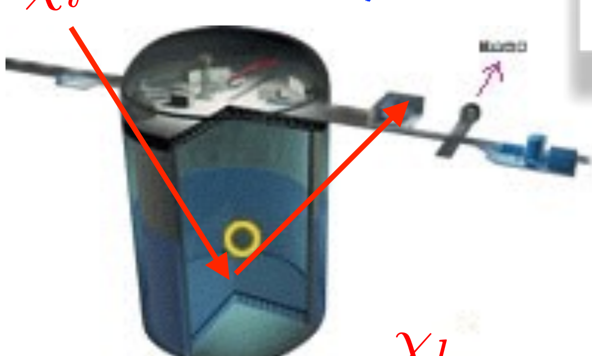


Passive search

Active search

DM (25% of the Universe)

χ_l



χ_l

Relativistic DM scattering (boosted)

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

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

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

Relativistic scattering of DM

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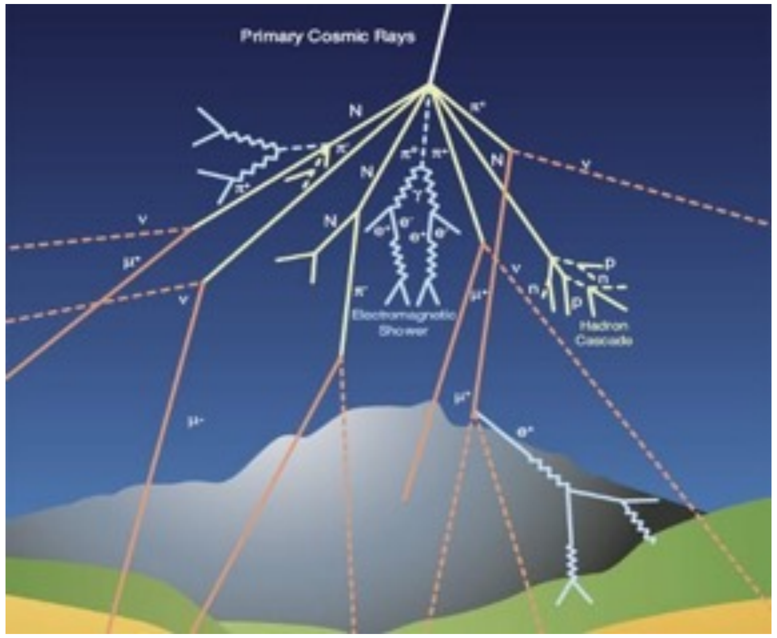

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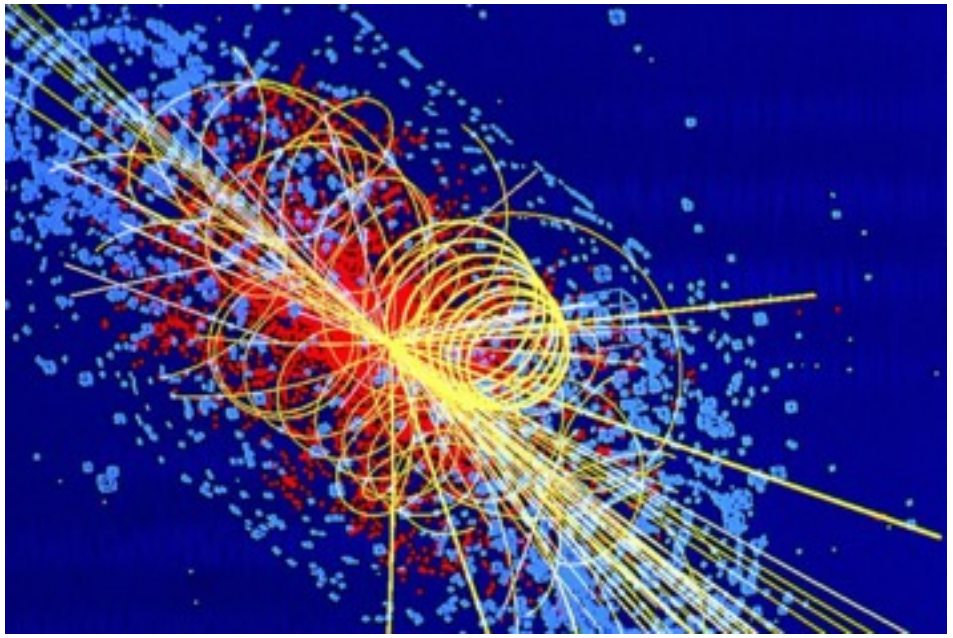
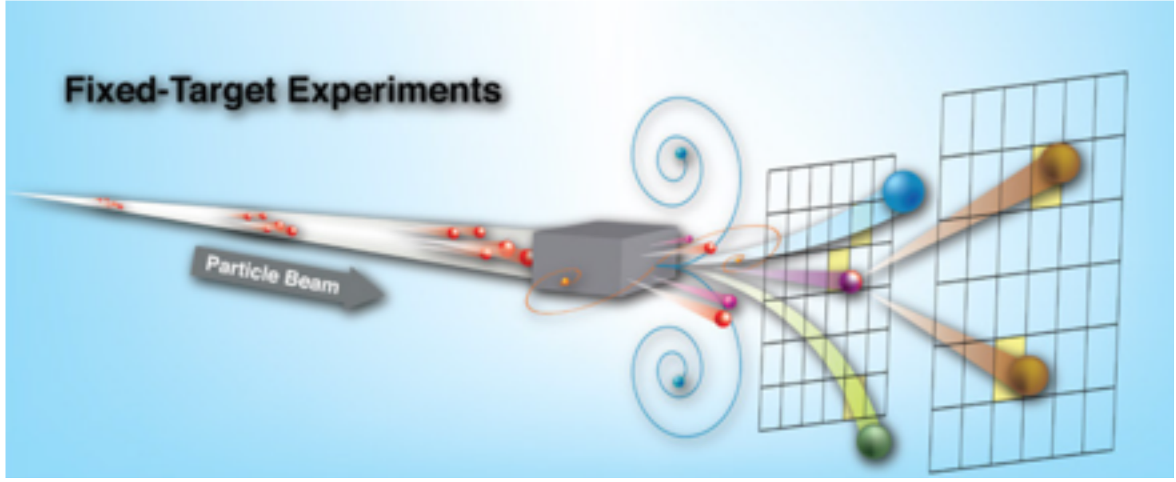


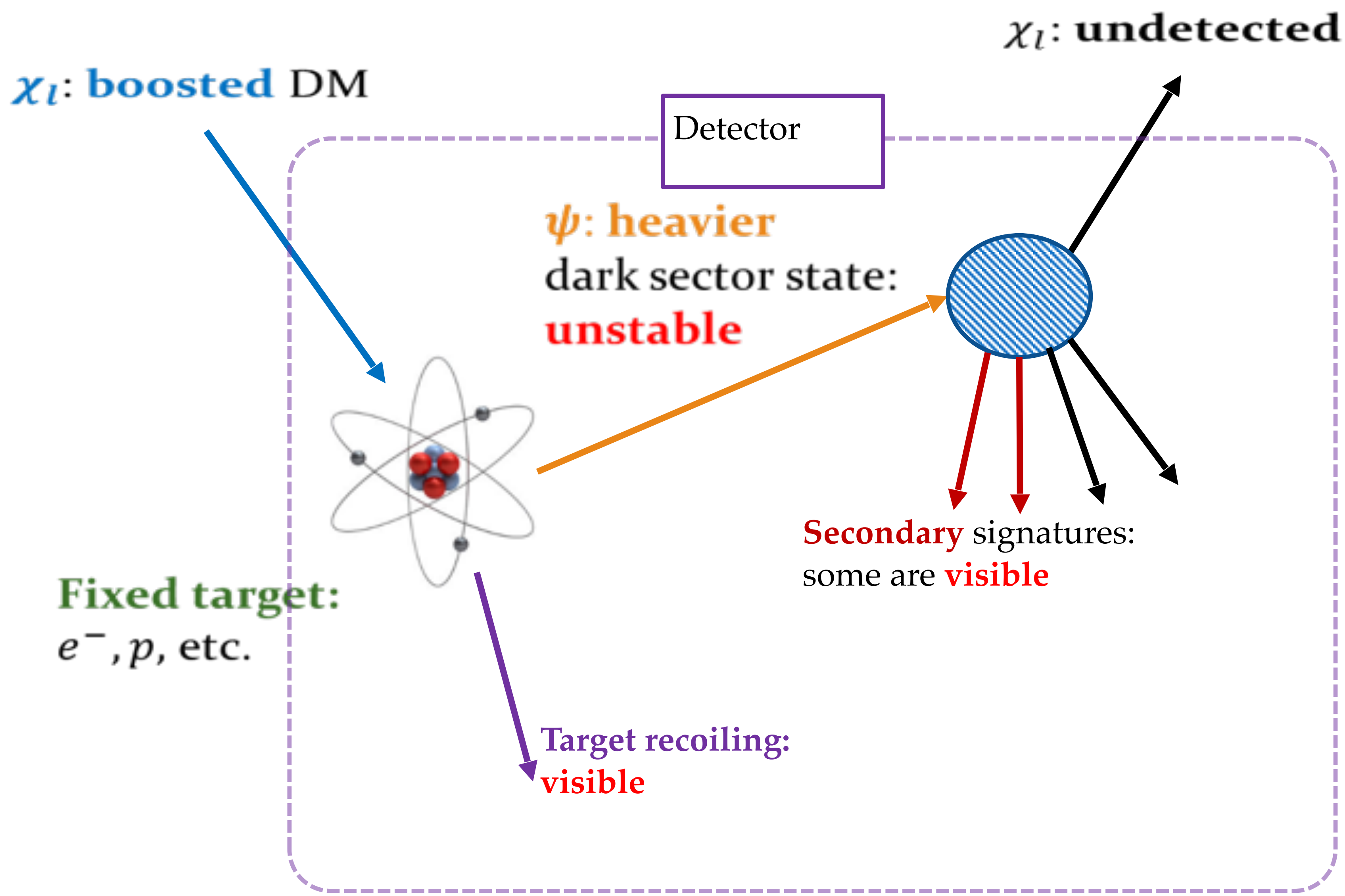
Active search

DM (25% of the Universe)

Relativistic DM scattering



DM “Collider”: non-minimal dark sector



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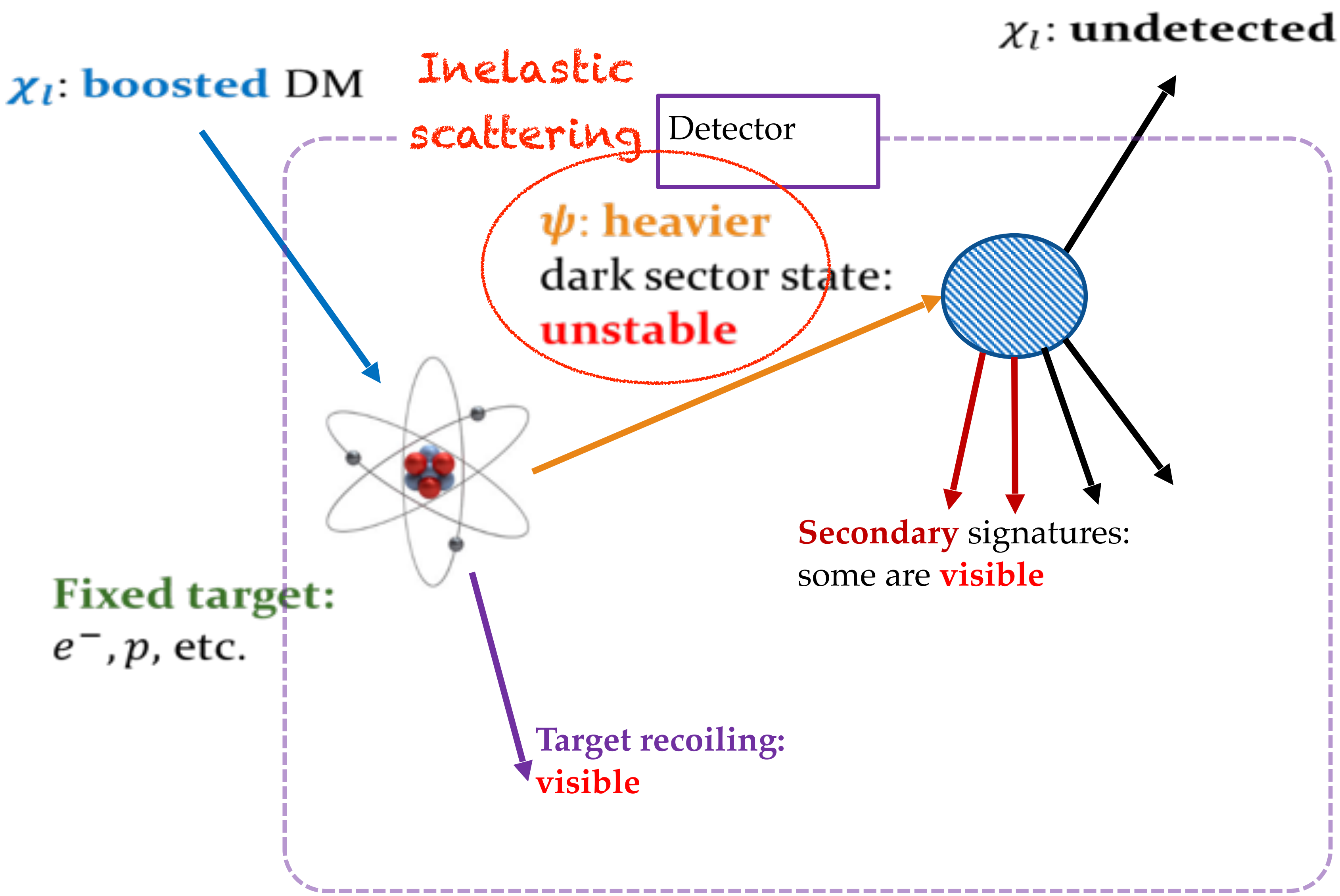

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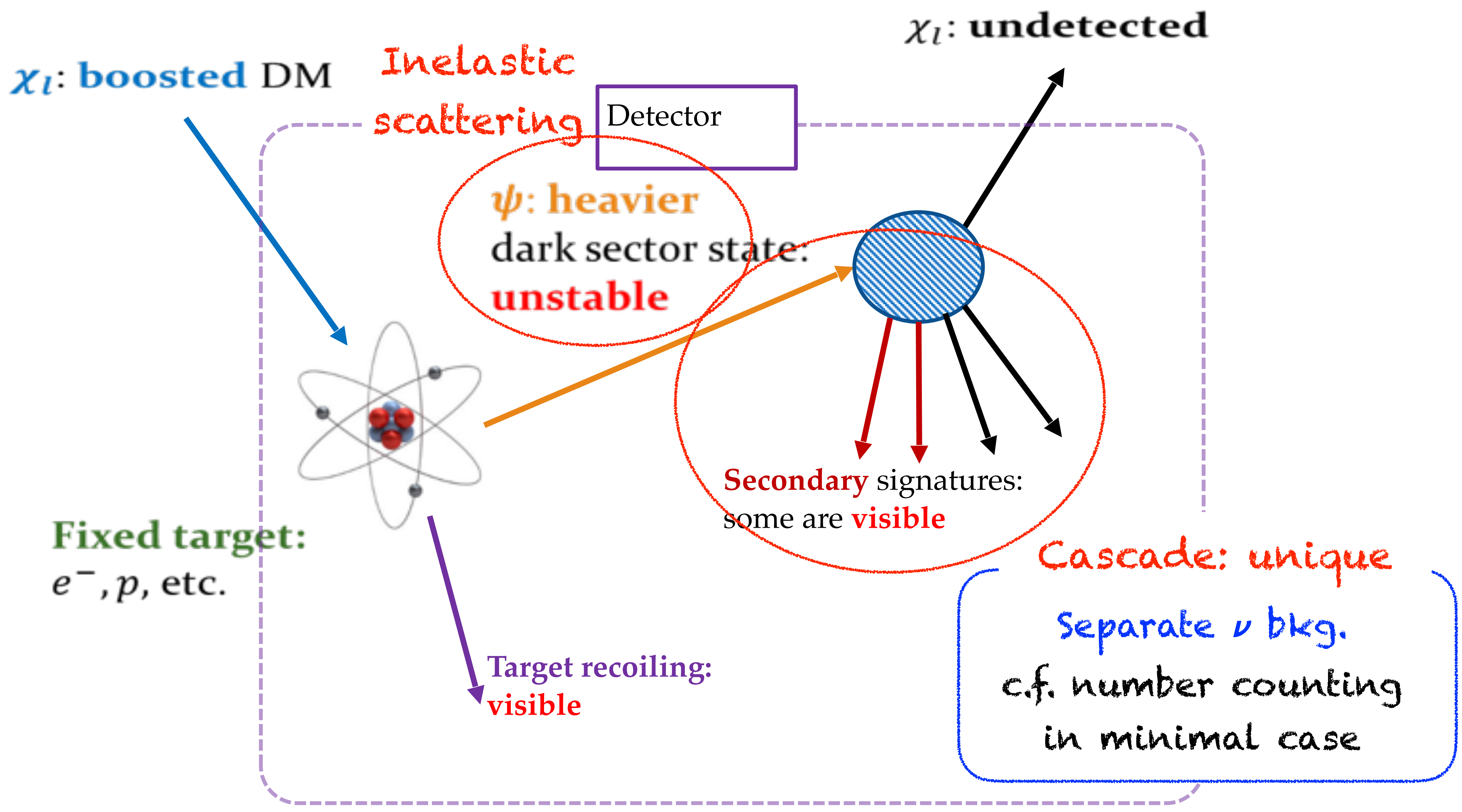

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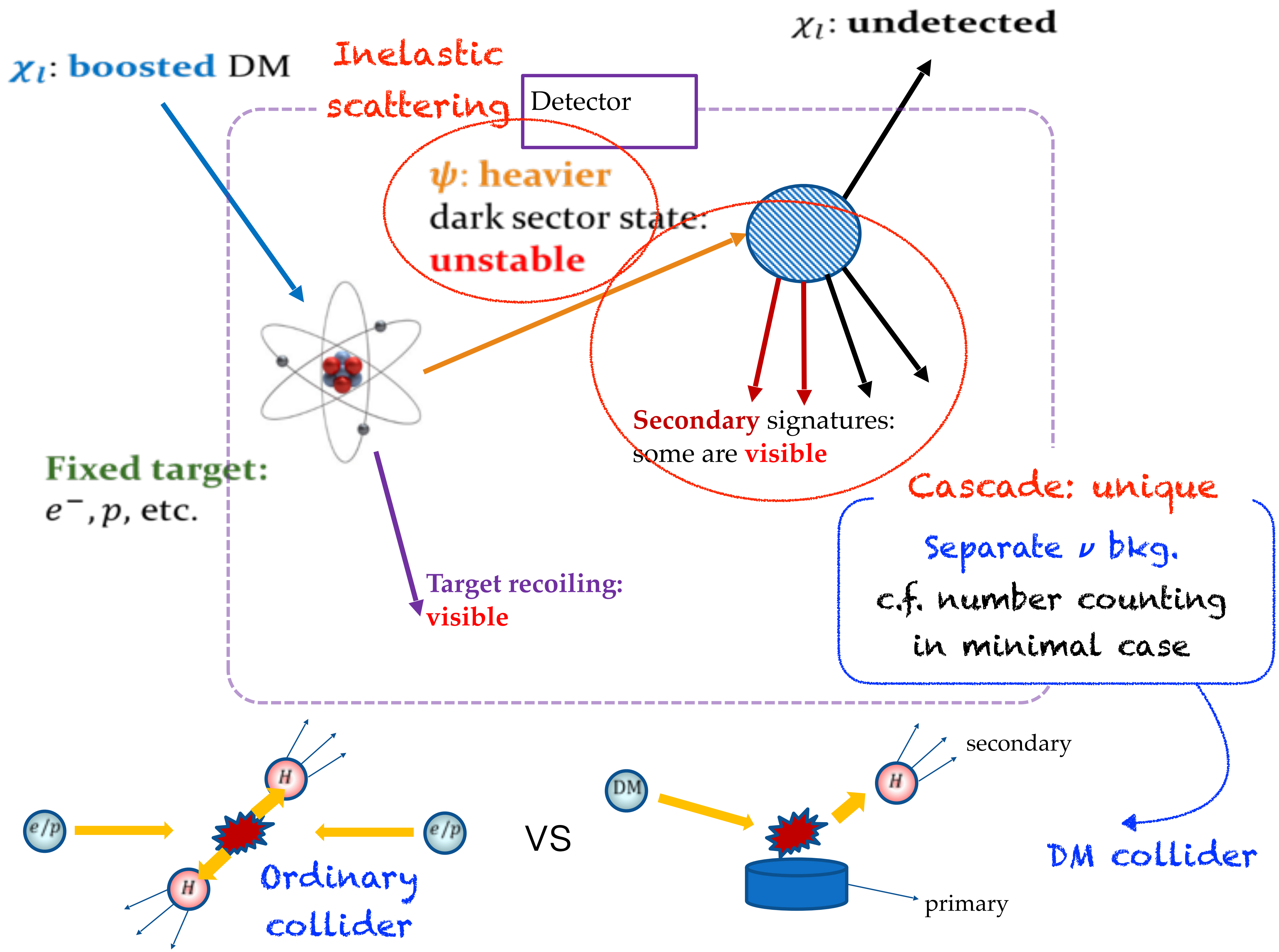
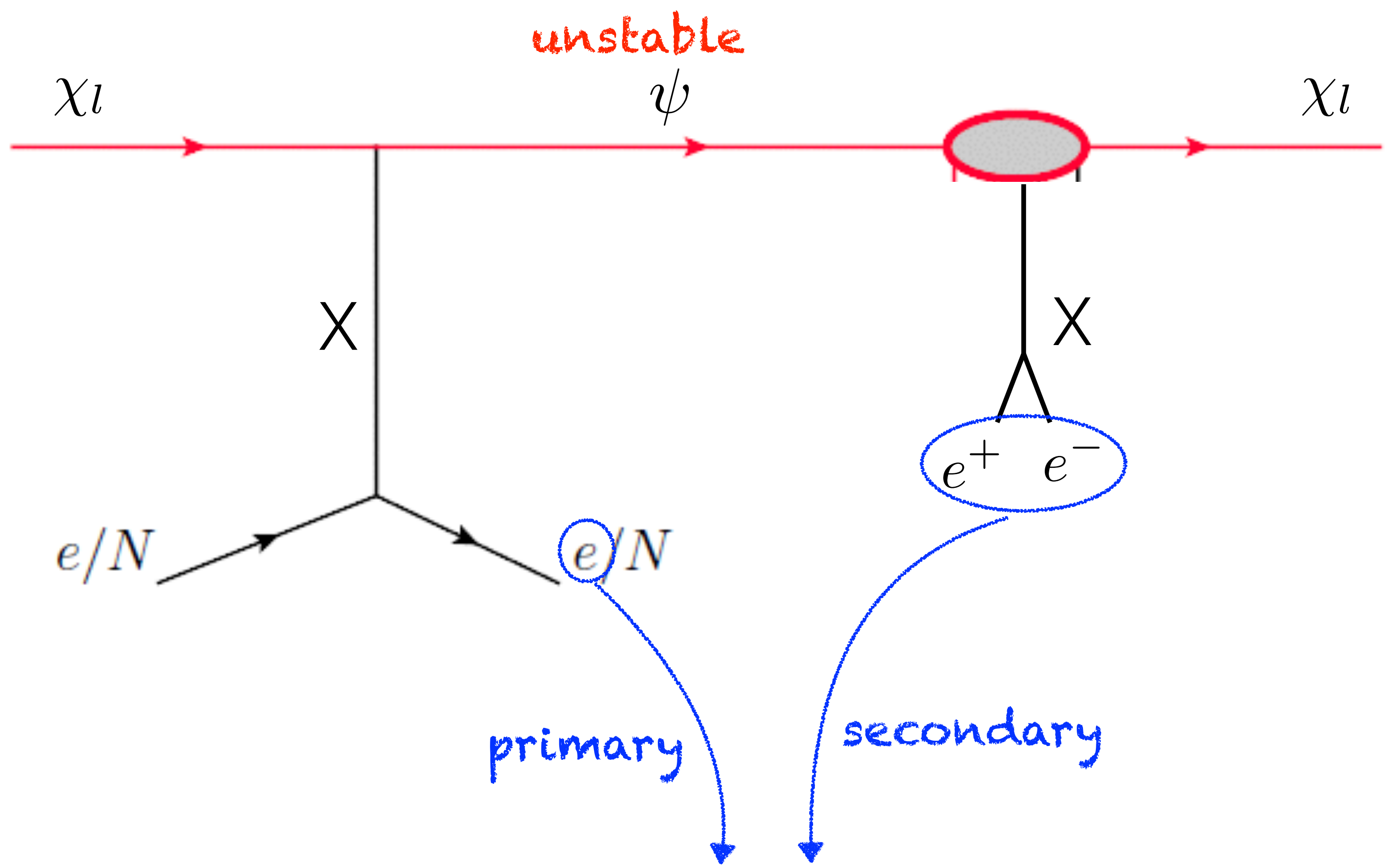


e-scattering: highly boosted

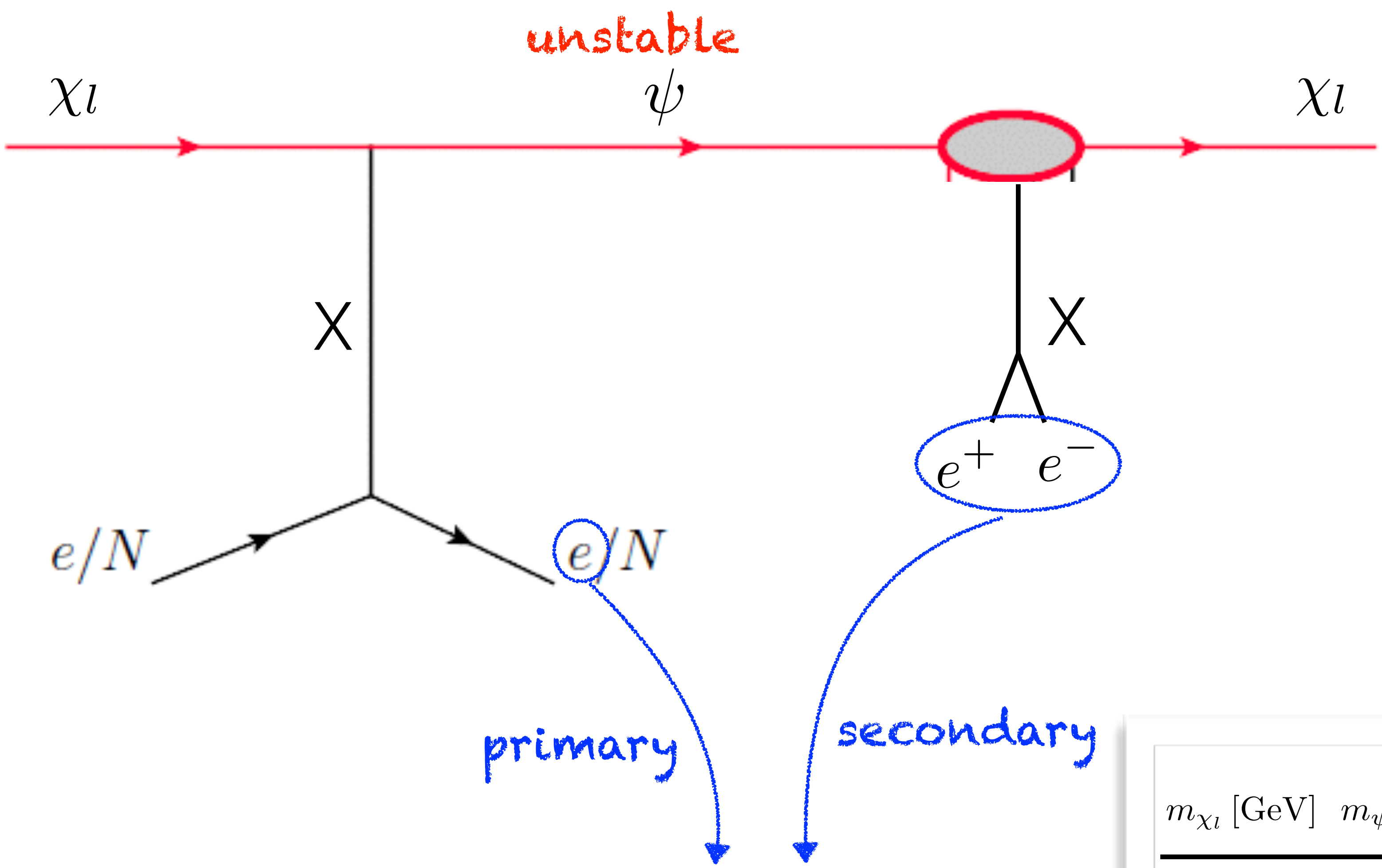


High chance to observe
two separate signals!!

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

Moderate recoil E

e-scattering: 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

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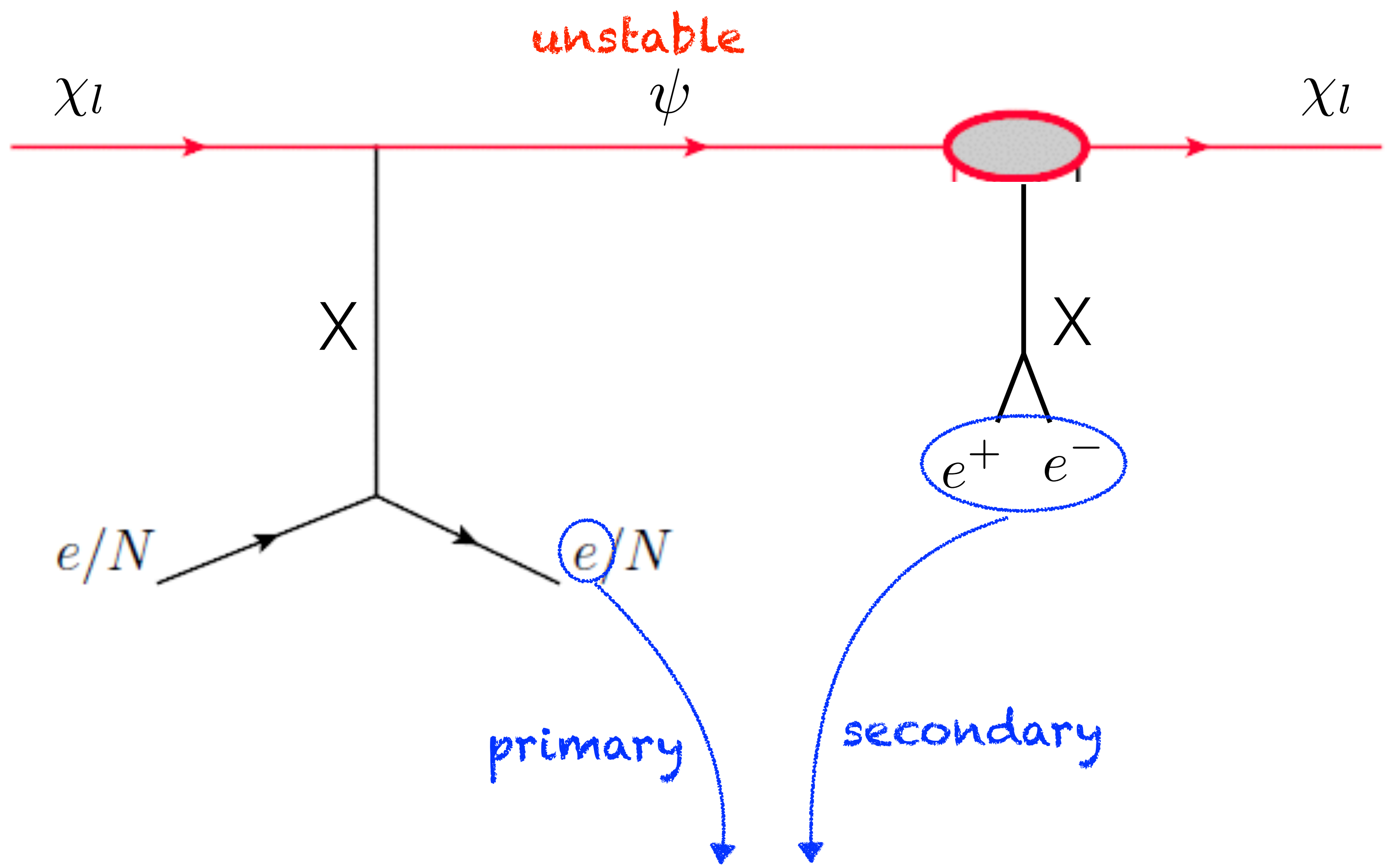


High chance to observe
two separate signals!!

in an experiment with angular resolution ≲ 1°

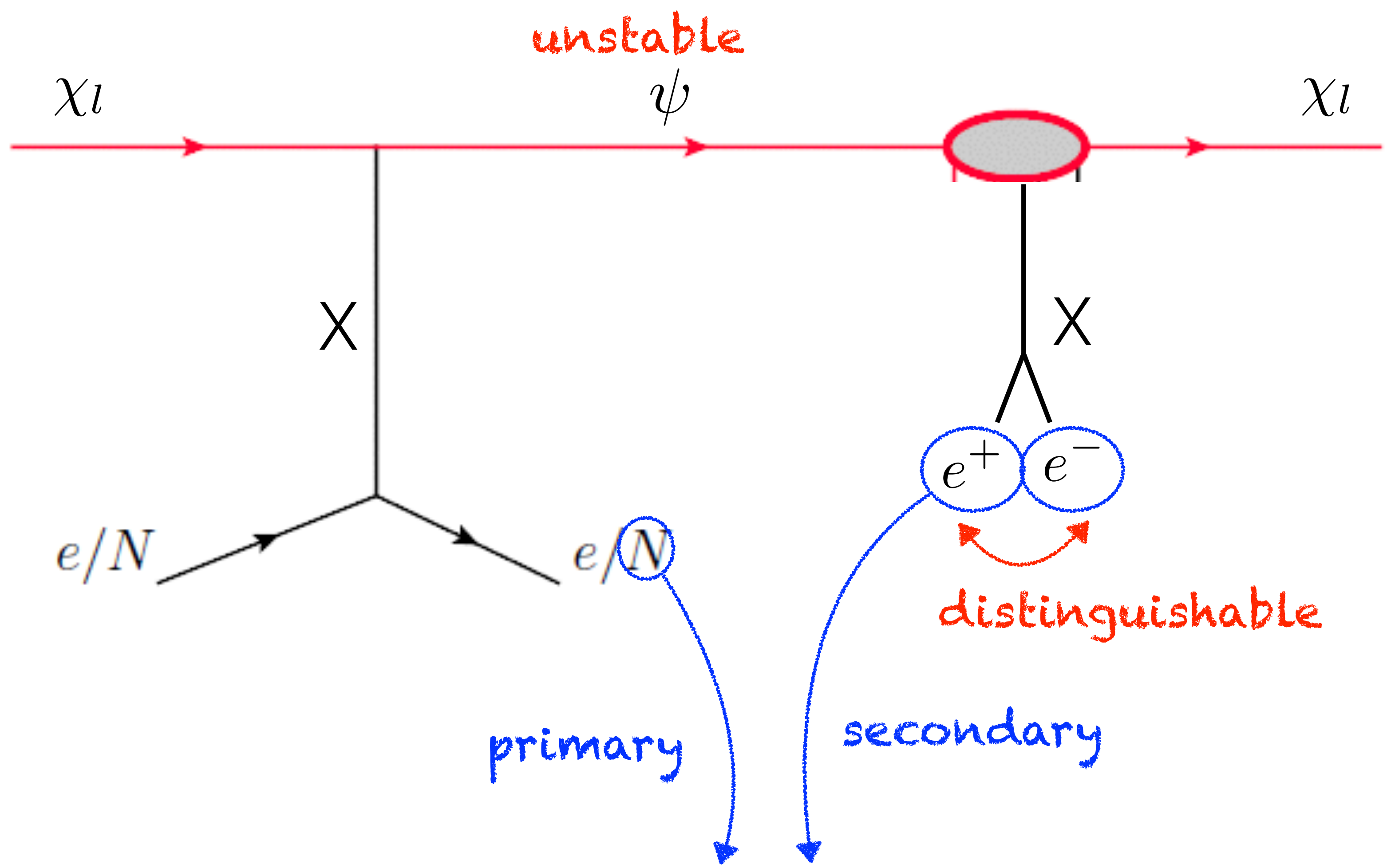
smaller volume

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

passive & active active

Moderate recoil E

p-scattering: less boosted

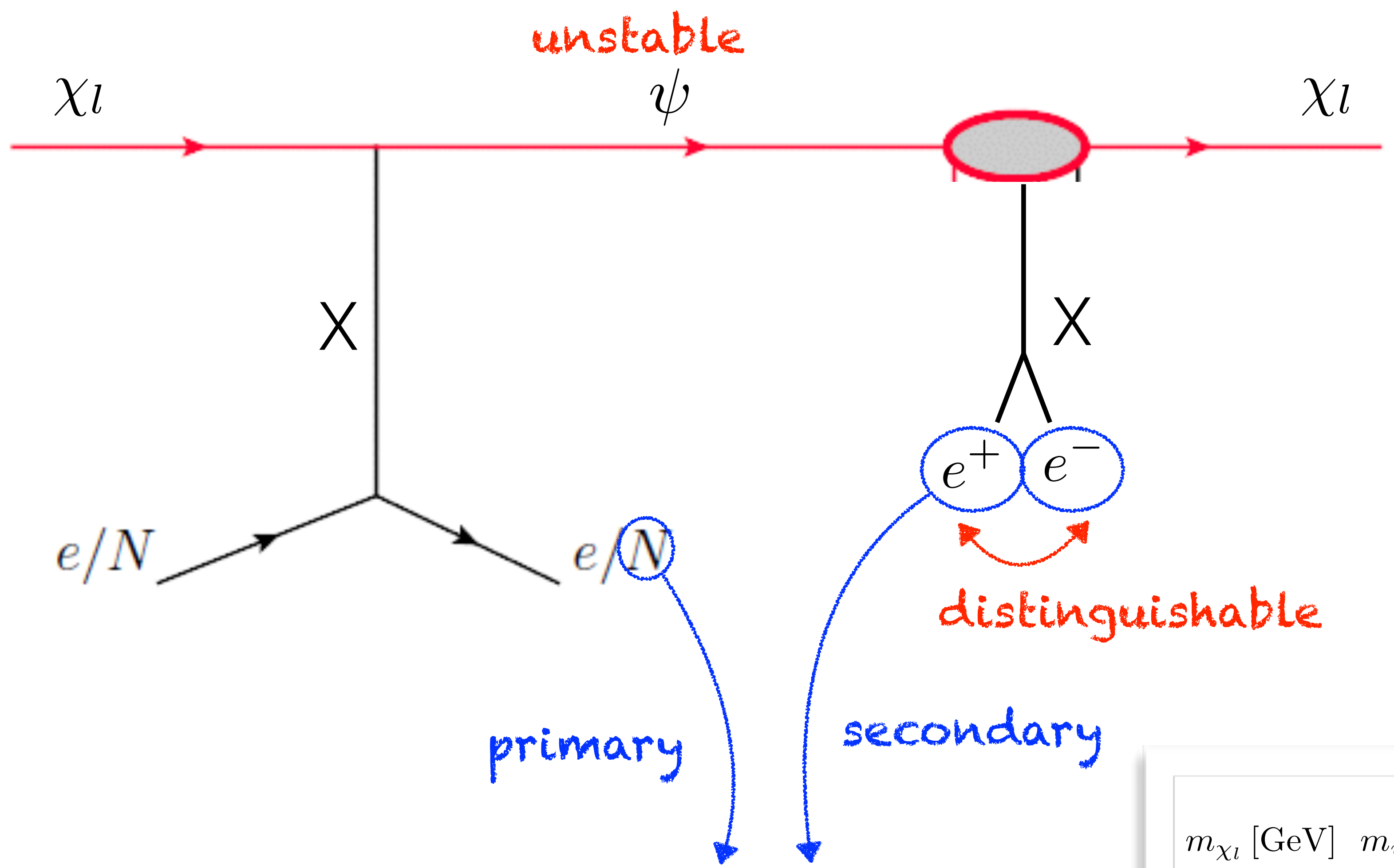


High chance to observe
three separate signals!!

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)

p-scattering: less boosted



High chance to observe
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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)

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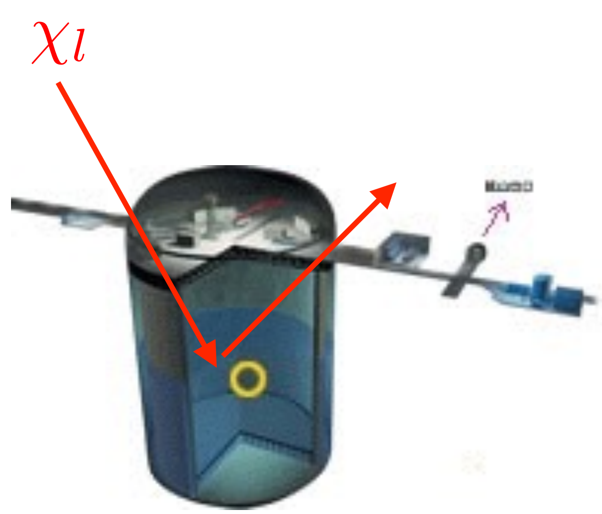
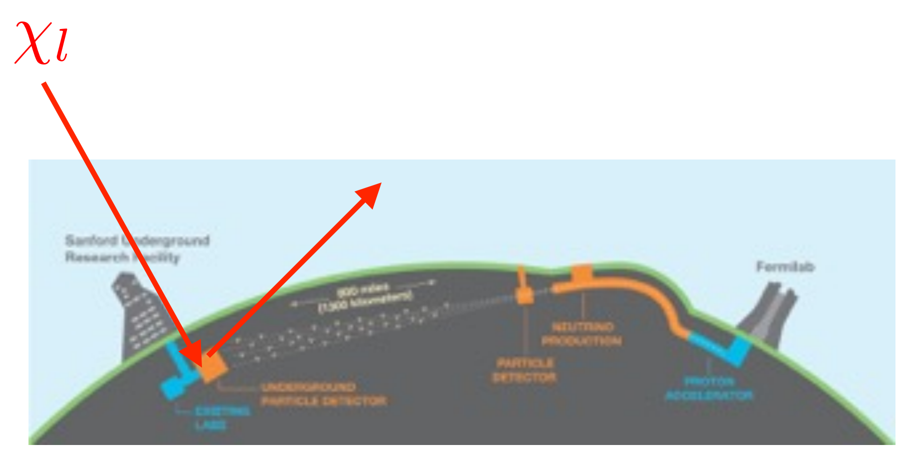
Passive search of relativistic DM scattering

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





toy model: dark gauge boson X

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

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

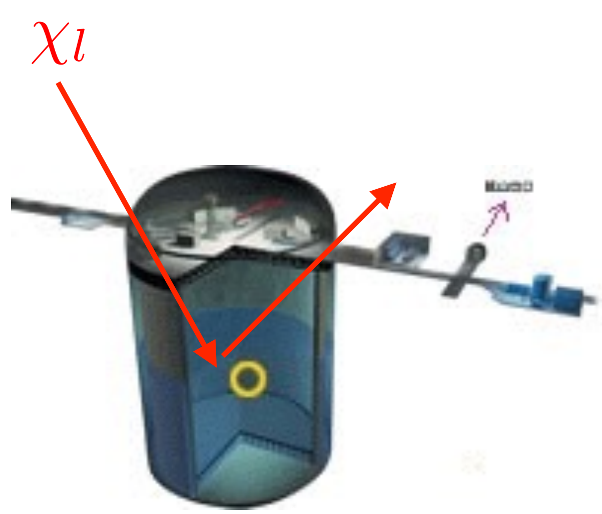
$\mathcal{O}(10^{-7}\,\mathrm{cm}^{-2}\mathrm{s}^{-1})$

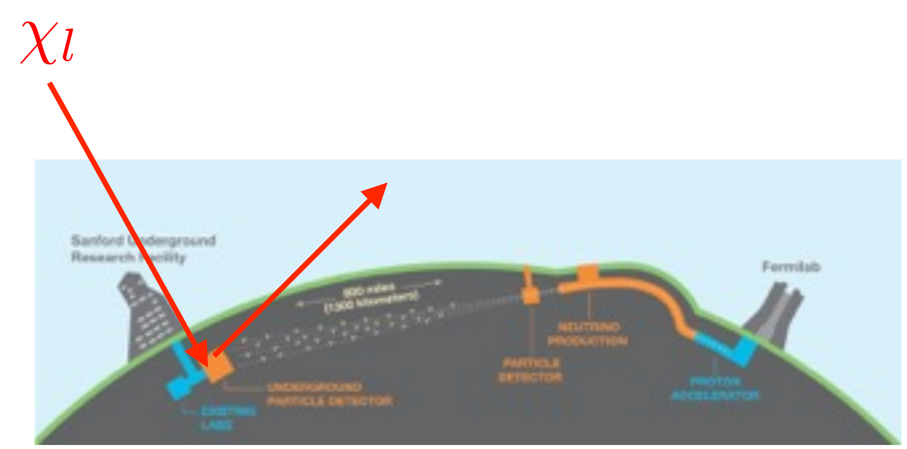
$m_{\chi_h} \sim O(10\ \mathrm{GeV})$

Promising example!

Passive search of relativistic DM scattering

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





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less sensitive than e

Assume no bkg.

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Passive search of relativistic DM scattering

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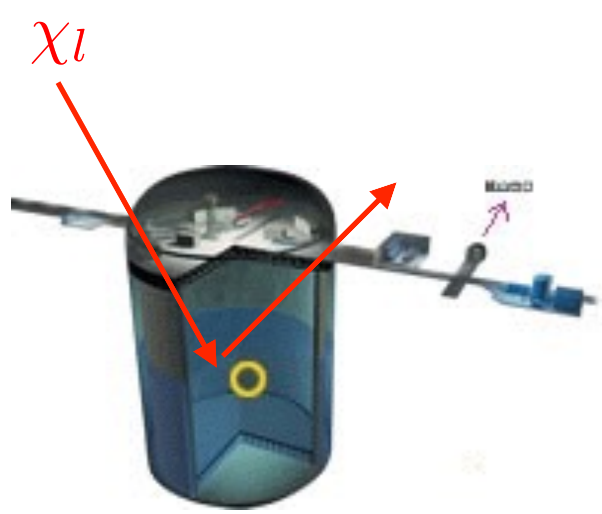

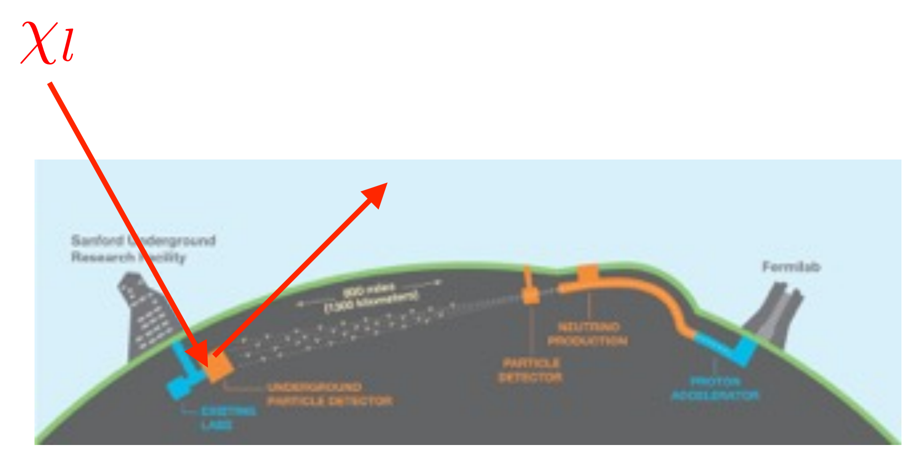

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13.6 yr of HK improves the sensitivity

Assume no bkg.

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Passive search of relativistic DM scattering

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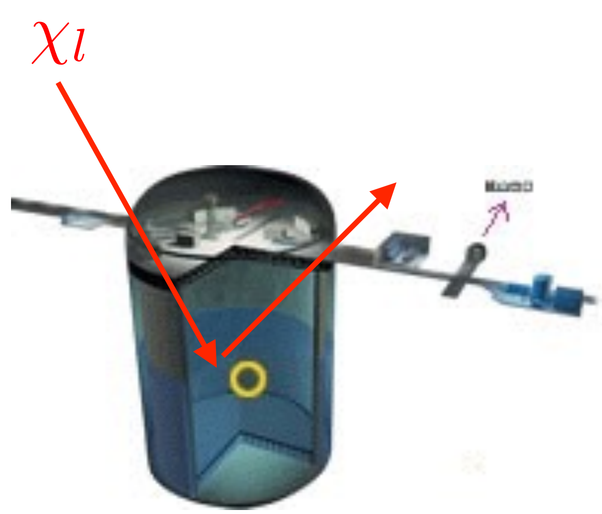

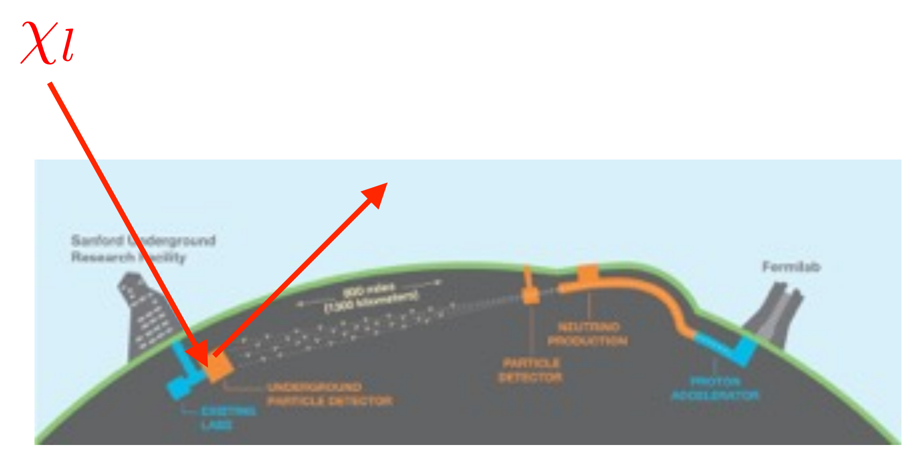

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unit: $10^{-7}\text{cm}^{-2}\text{s}^{-1}$

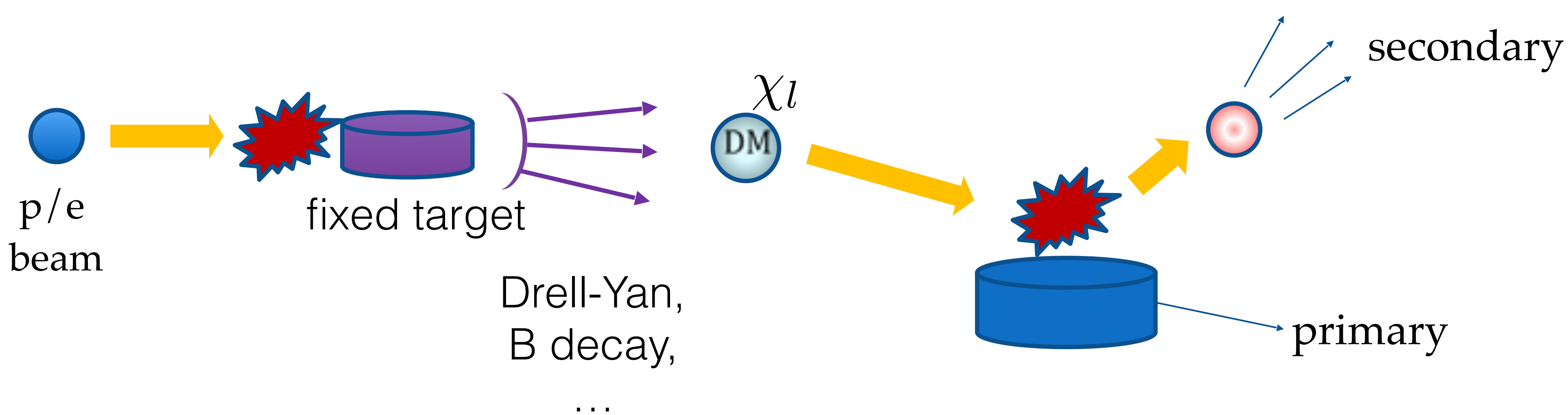
Remarkable improvement in DUNE!!!

Promising (3 simultaneous signals)

Active search of relativistic DM scattering

Intensity frontier: increase fluxes of incoming χ_l

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



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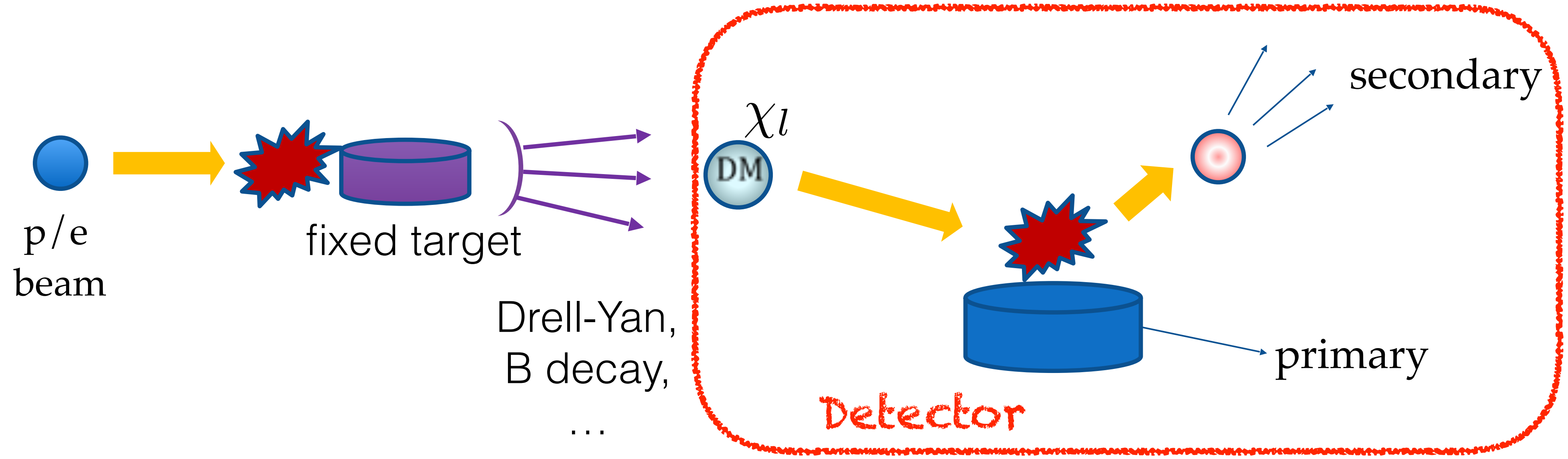
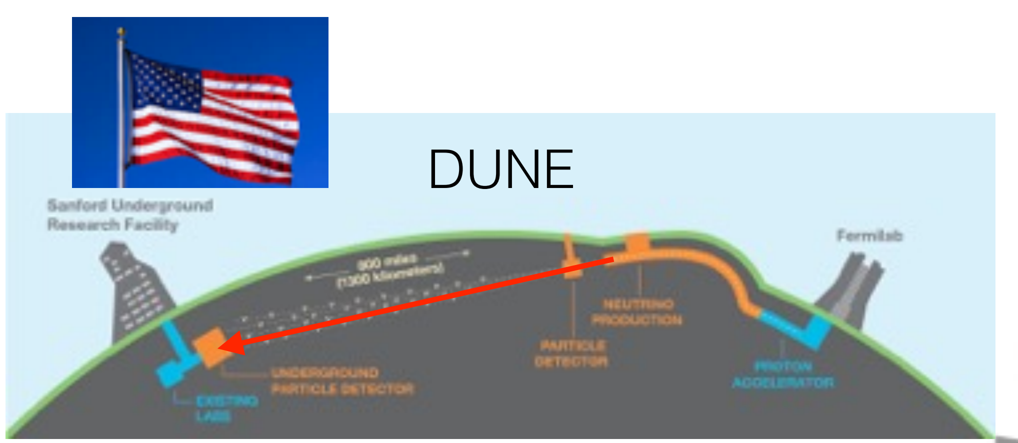
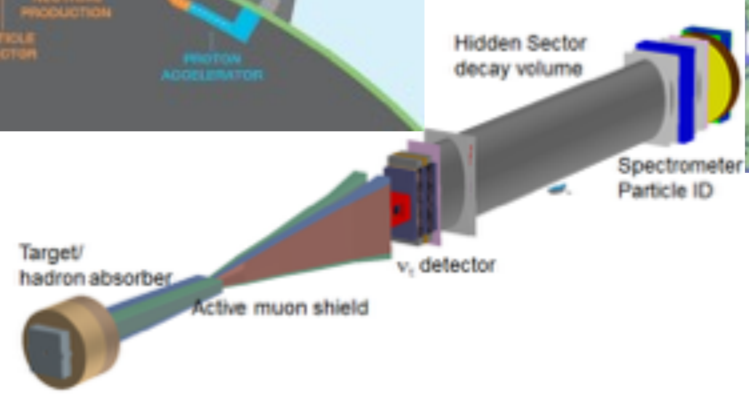




DUNE

SHiP



T2HK or T2HKK

Conclusions

- Non-minimal/flavorful dark sector (χ_I): cascade process

- Analyzed in current & future huge 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

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DUNE
SHiP

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e-scattering

(pros)
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DUNE
SHiP

(cons)
- Separation of two signals not easy (good for low p_e)

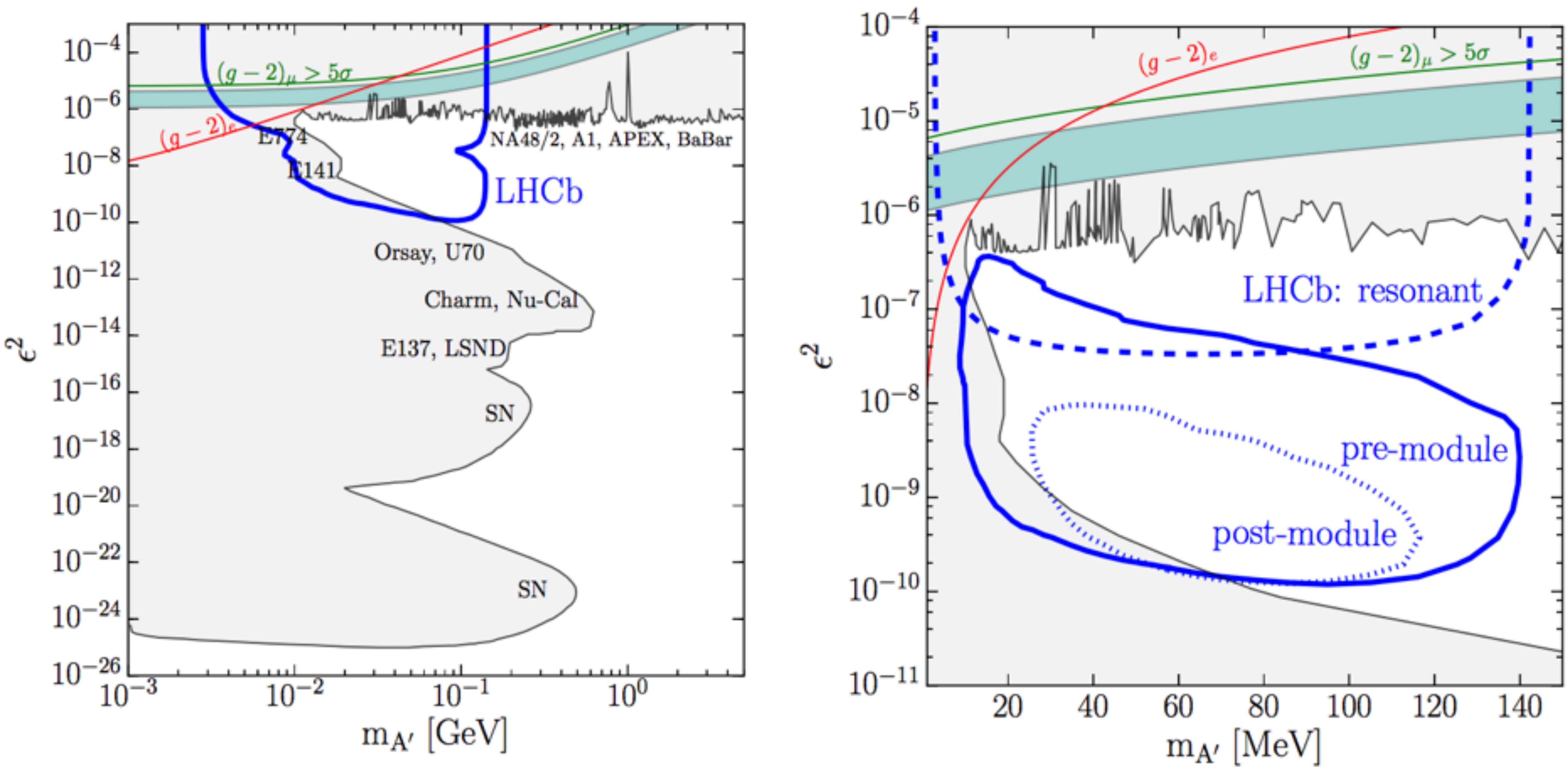
p-scattering

(cons)
- E_{th} high in Cherenkov light detectors (low σ)
- Need large flux

fixed target exp.

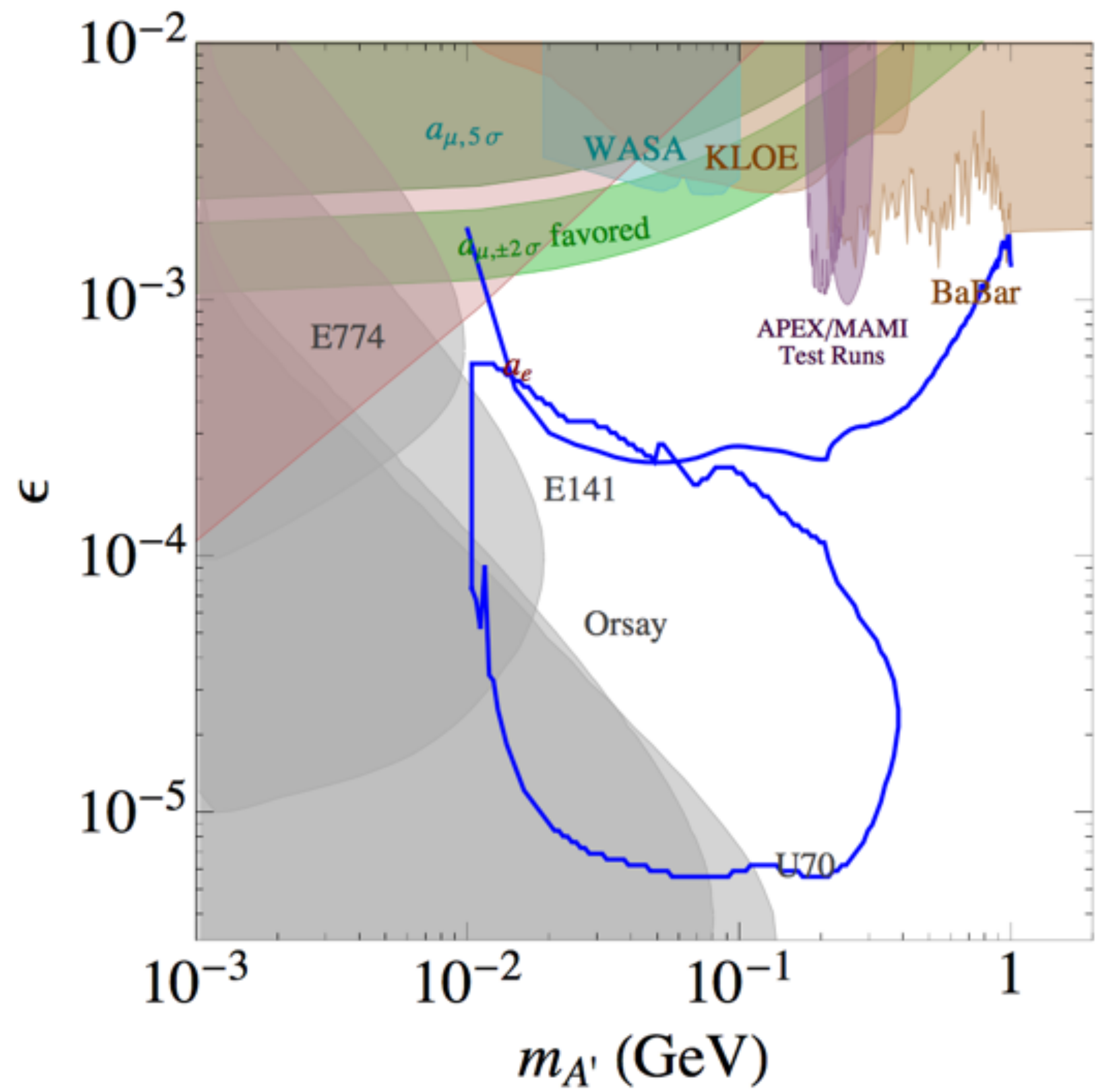
(pros)
- Separation of two signals & 3 visible objects: promising

Back up



Ilten, Thaler, Williams, Xue, 1509.06765

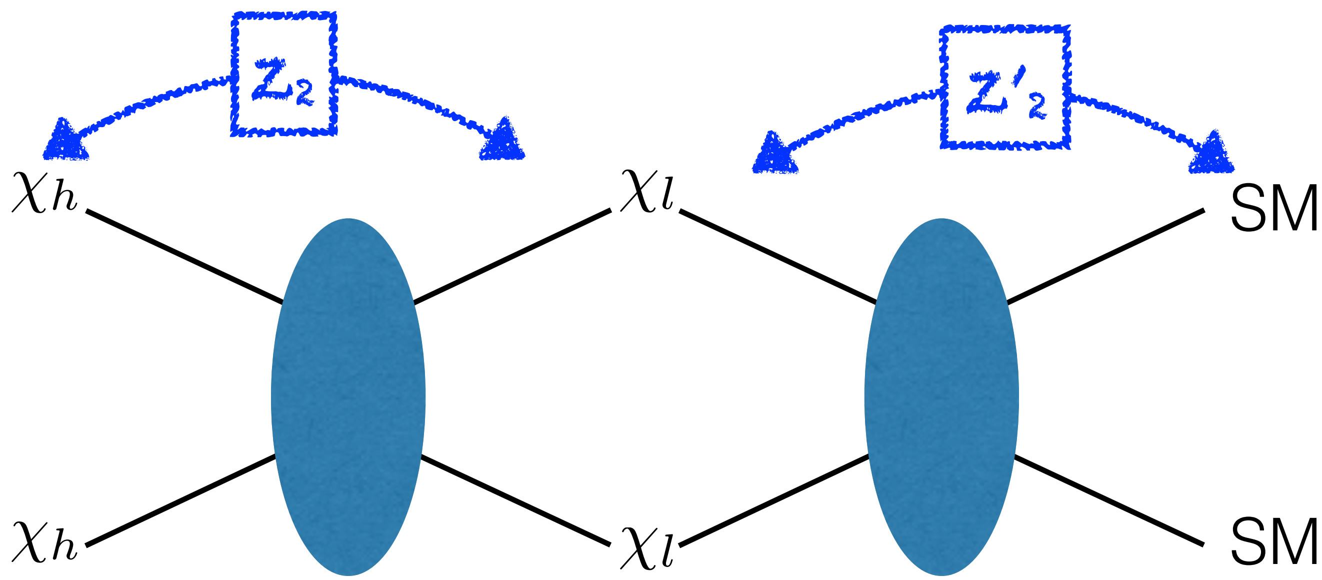
Back up



Essig et al., 1311.0029

Boosted DM

Minimal model example



Belanger, Park, 1112.4491

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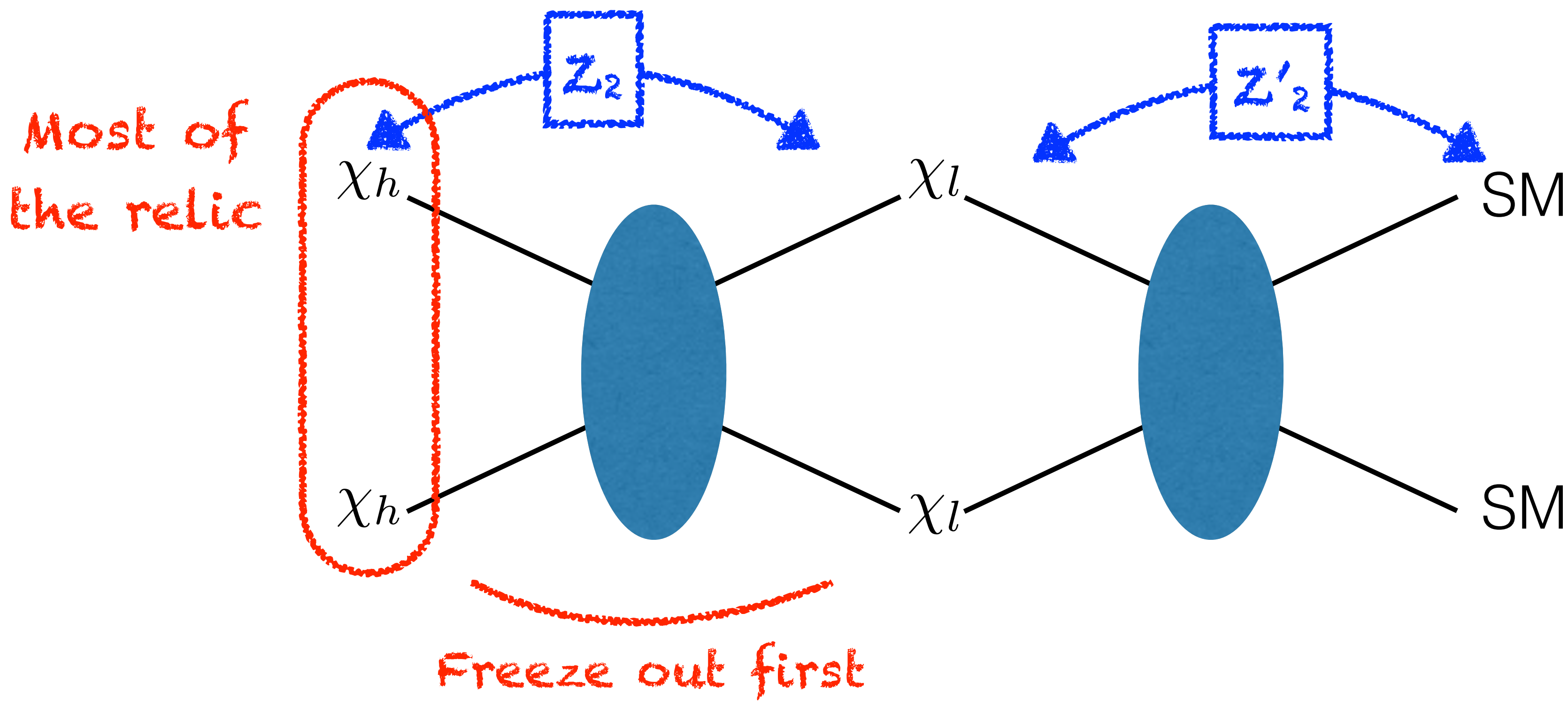

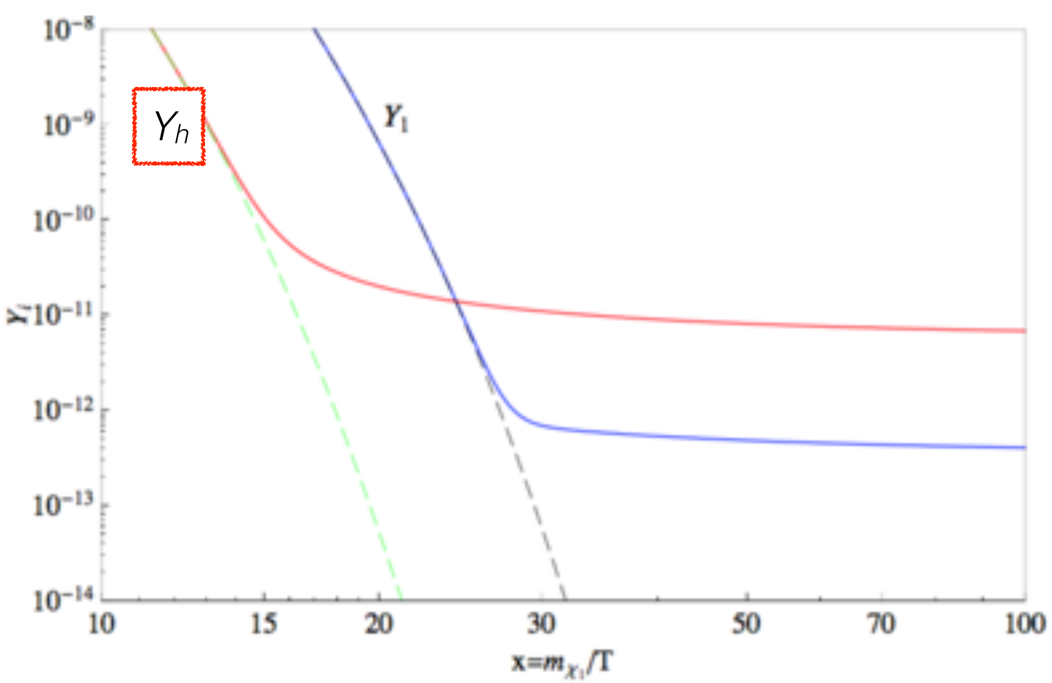

Belanger, Park, 1112.4491

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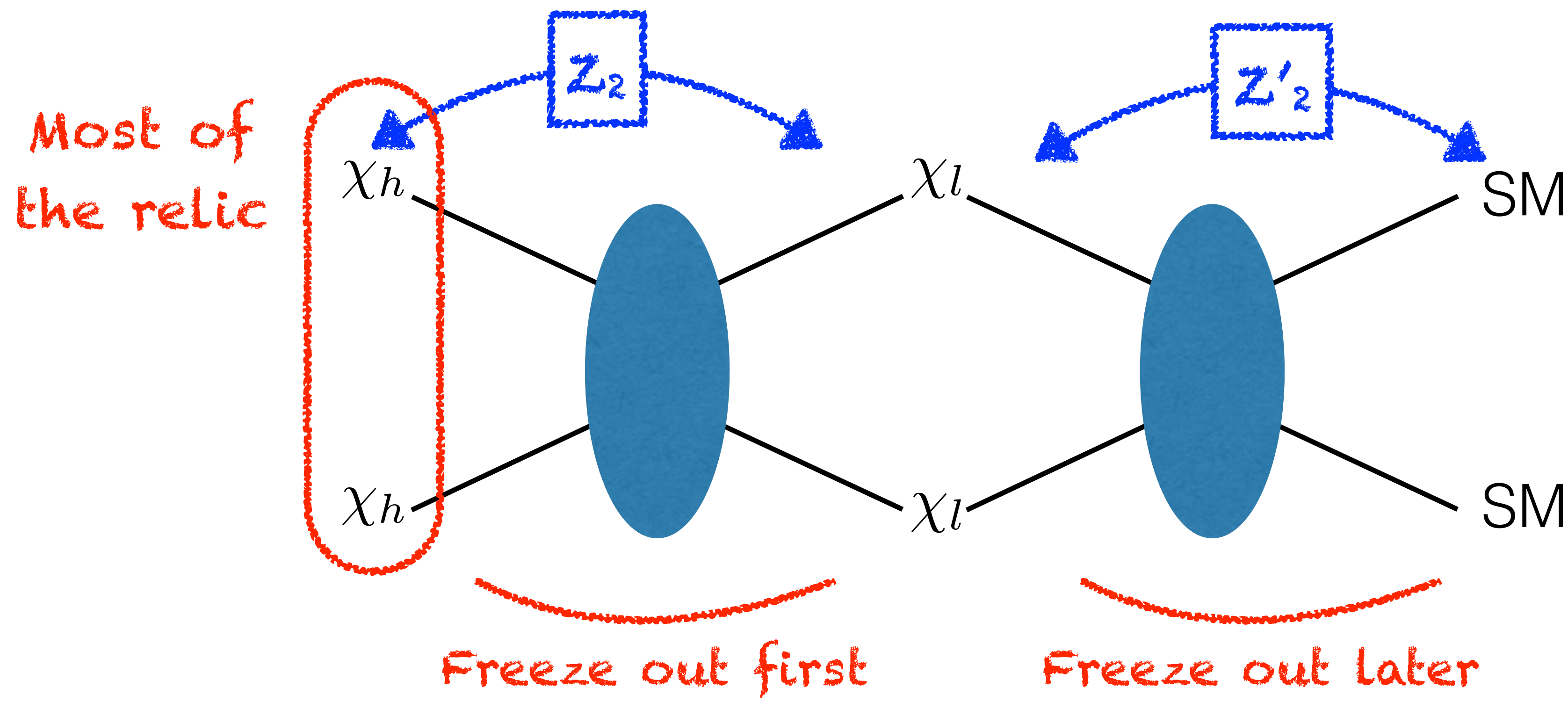
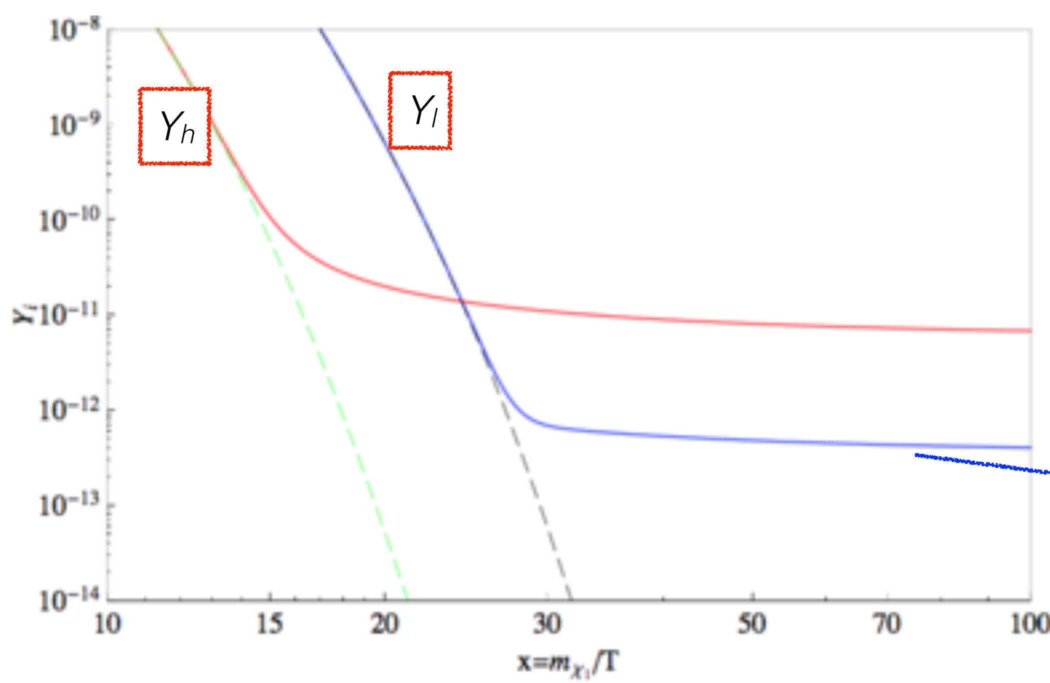




Belanger, Park, 1112.4491

Agashe, Cui, Necib, Thaler, 1405.7370

Assisted freeze-out

(Flux of relic χ_1: small)

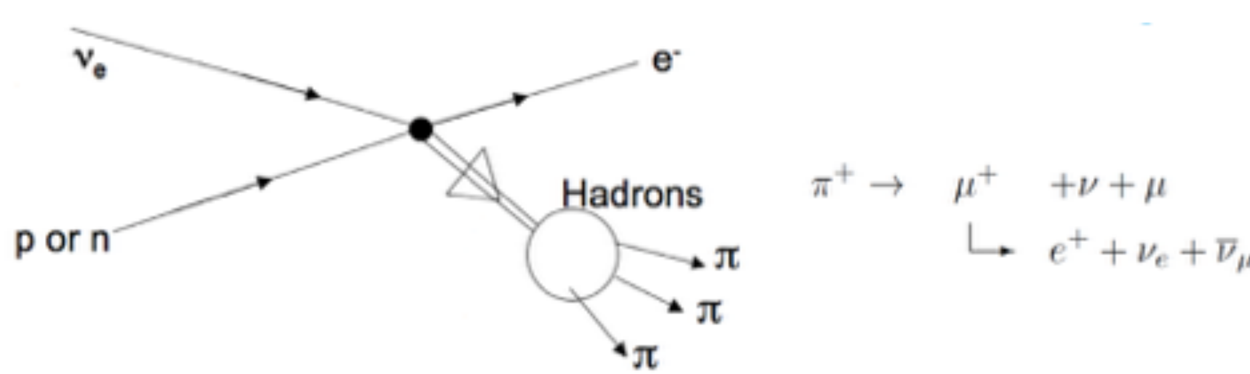
non-relativistic

Really background free?

Background may be negligible (dedicated analysis needed)

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

- Not energetic muon $\mu \to e \nu_e \nu_\mu$ ($e + \ell$): 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



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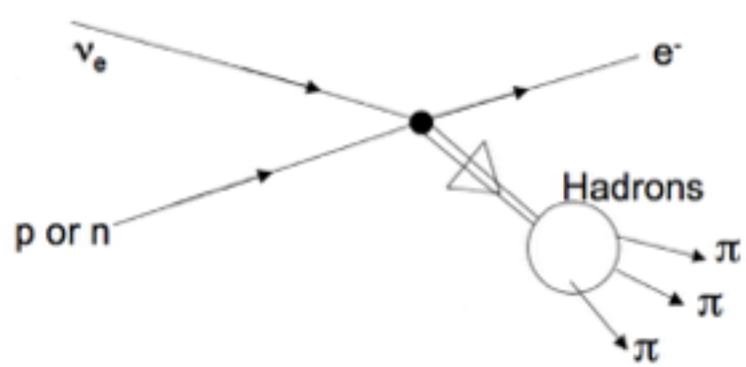

$$\pi^+ \rightarrow \mu^+ + \nu + \mu$$
$$\hookrightarrow e^+ + \nu_e + \overline{\nu}_\mu$$

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Cherenkov light detectors (Kamiokande)

- Not energetic muon $\mu \to e \nu_e \nu_\mu$ (e + ℓ): cut out by requiring E > 0.1 GeV
- $n\nu_\tau \to p\tau \to p\ell\nu_\ell \nu_\tau$ (p + ℓ): 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 + directionality (GC)?

Really background free?

Background may be negligible (dedicated analysis needed)

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

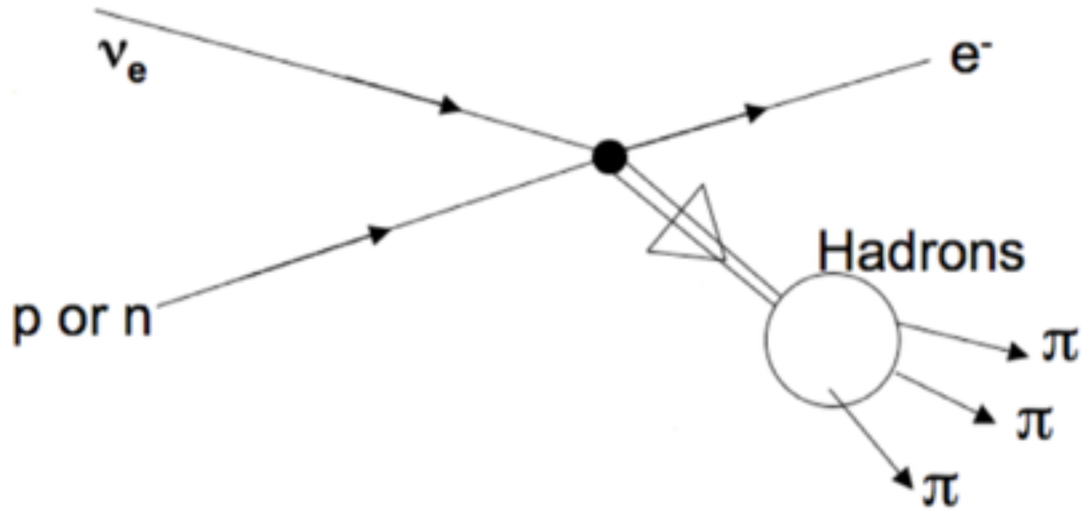
Ionization from the charged track (DUNE)

- 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

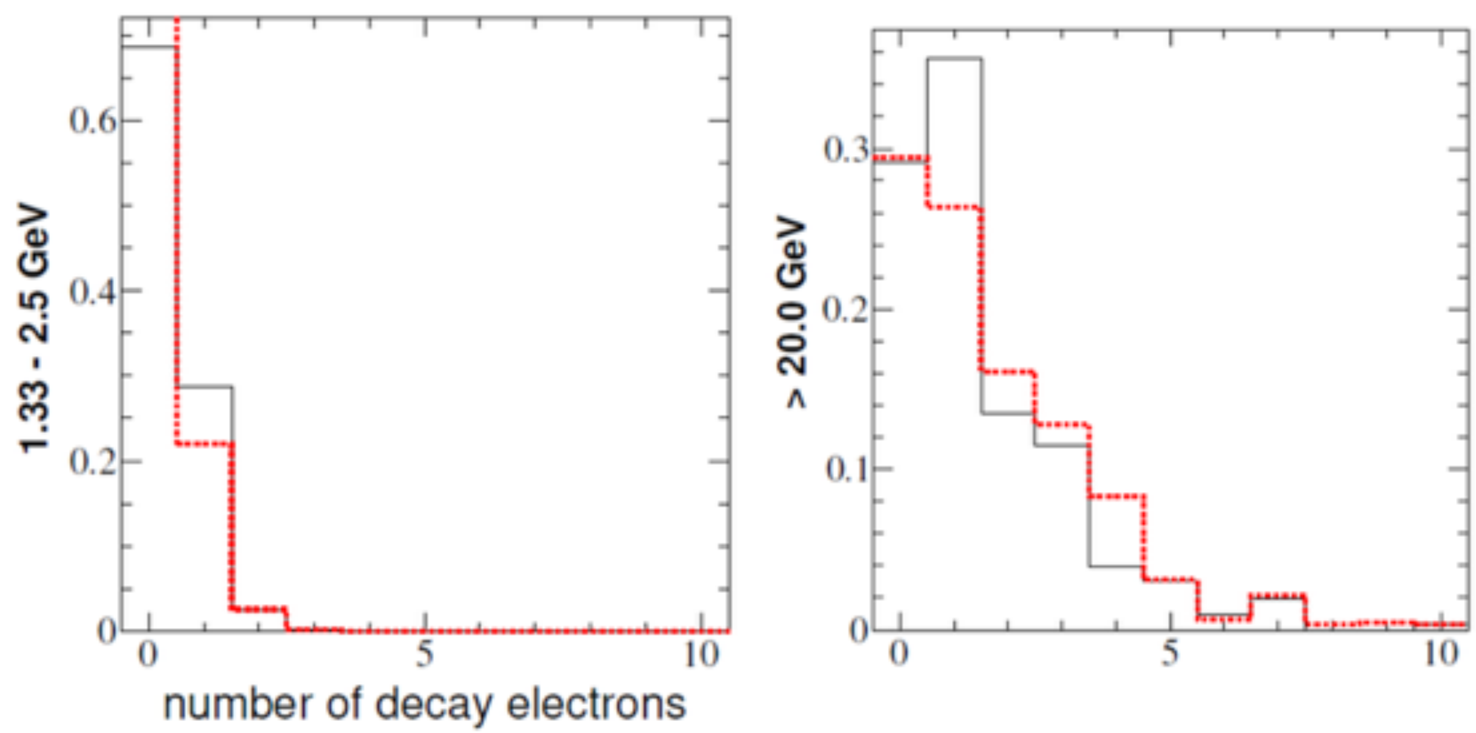
Maybe DUNE can separate all possible backgrounds

Back up

Super-K (2012)

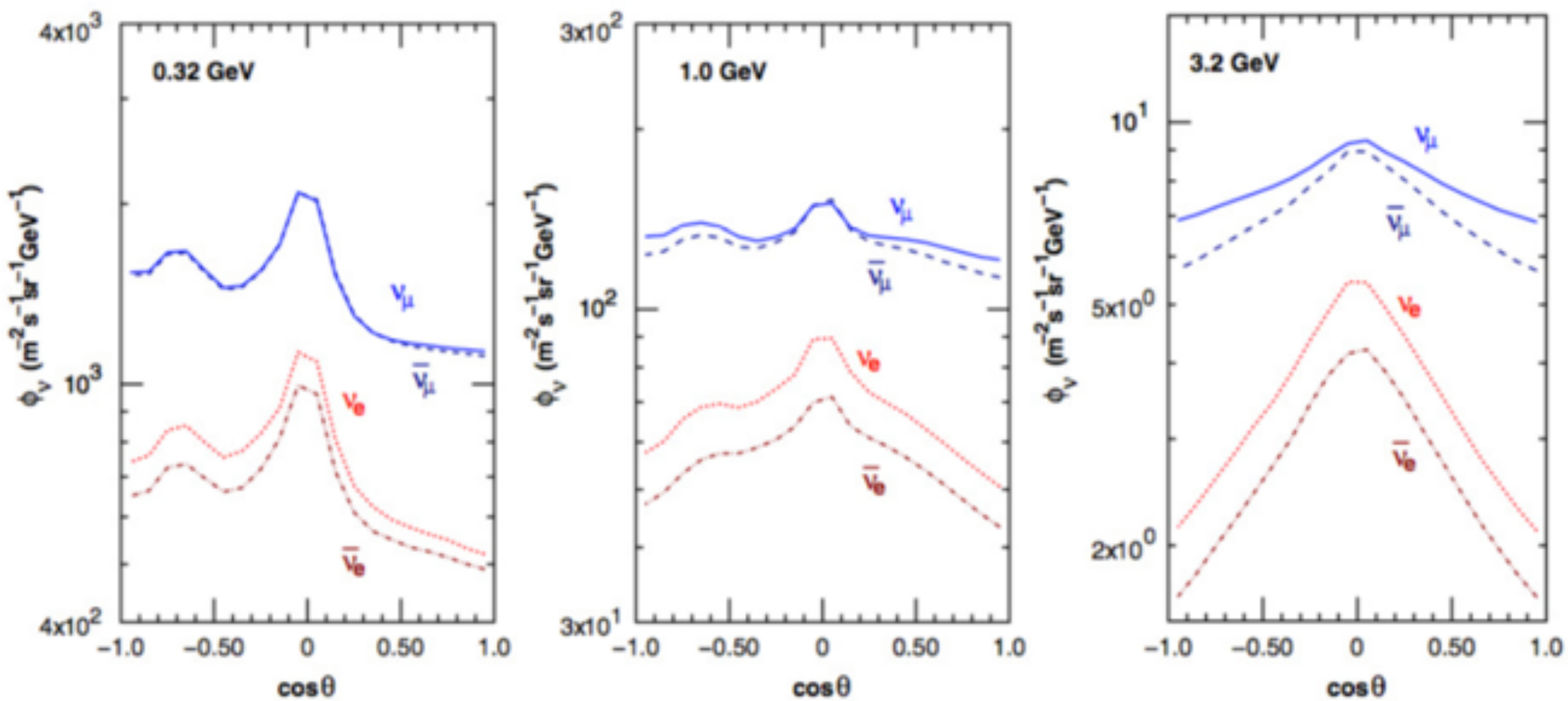


$$\pi^+ \rightarrow \mu^+ + \nu + \mu$$
$$\quad\quad \hookrightarrow e^+ + \nu_e + \overline{\nu}_\mu$$



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	ν_eCC	ν_μCC	NC
			Livetime (days)					
FC and PC	1489	799	518	1993	4799			
UPMU	1646	828	636	1993	5103			
			Number of Events			Interaction [%]		
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

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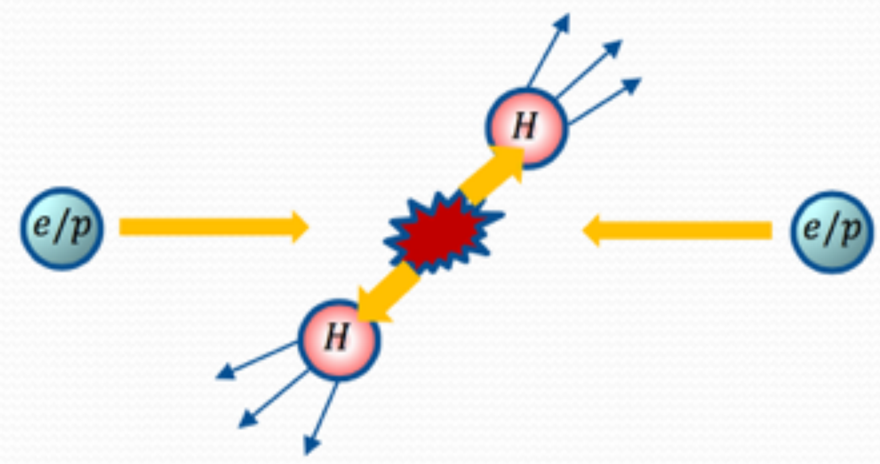
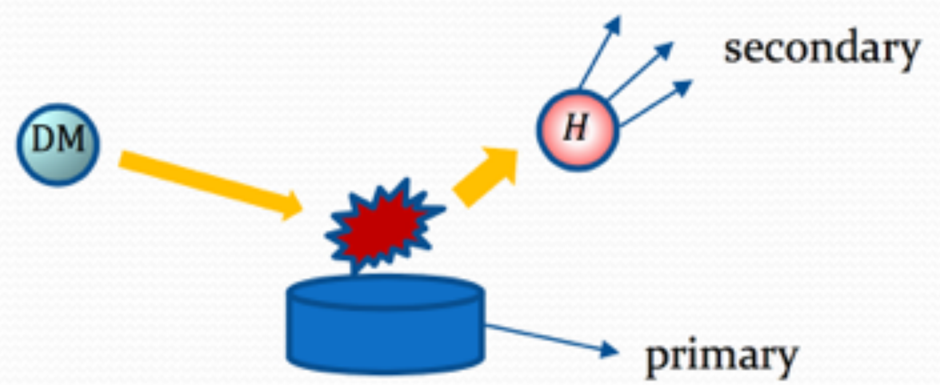
Back up

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

Active search of relativistic DM scattering

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	(700 – 1,000) 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	48×10^{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

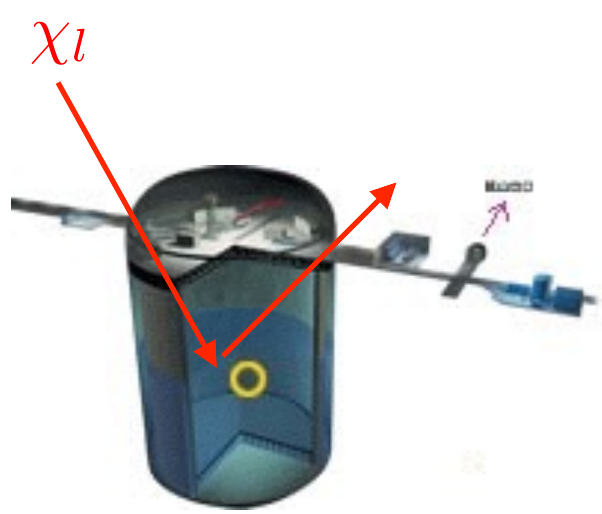
Main signatures
at far detector

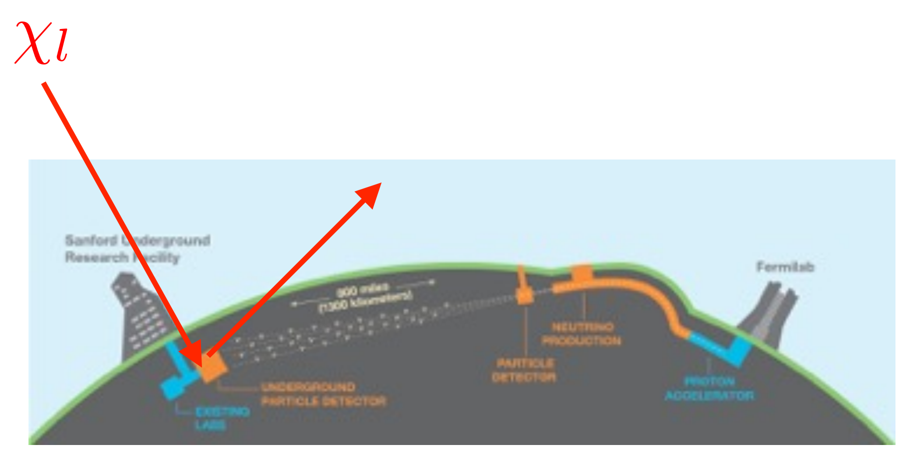
or at near detector,
if lucky

T2HKK?
Main signatures
at both Kamioka
and korea?

Passive search of relativistic DM scattering

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

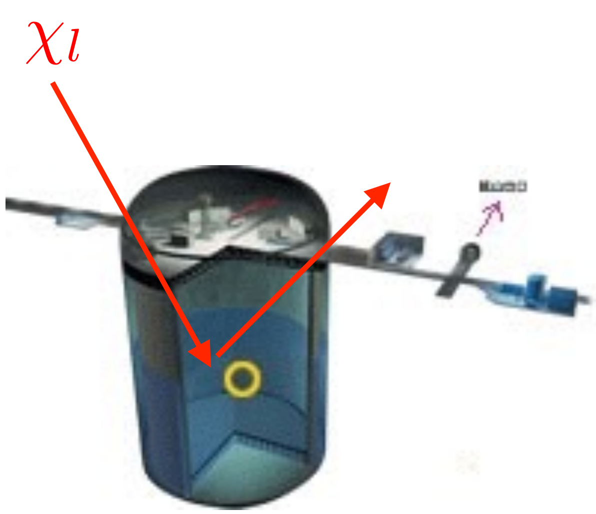


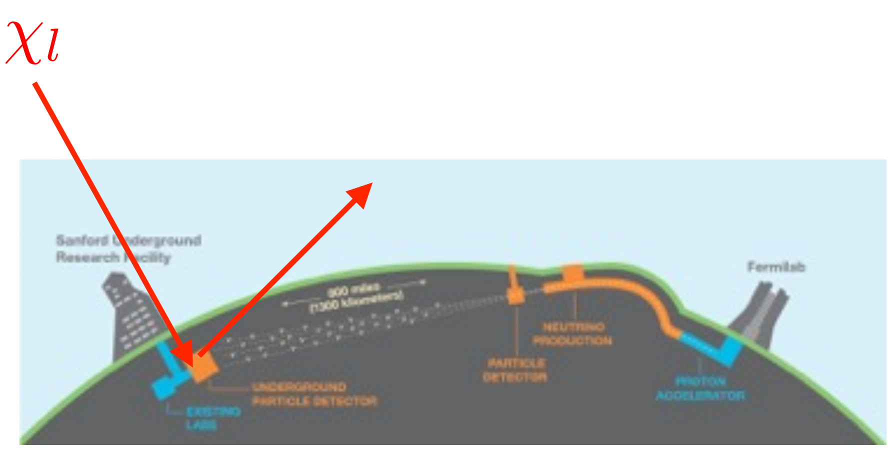


Identify the signals by simple counting N_{obs} over the expected bkg.

Passive search of relativistic DM scattering

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





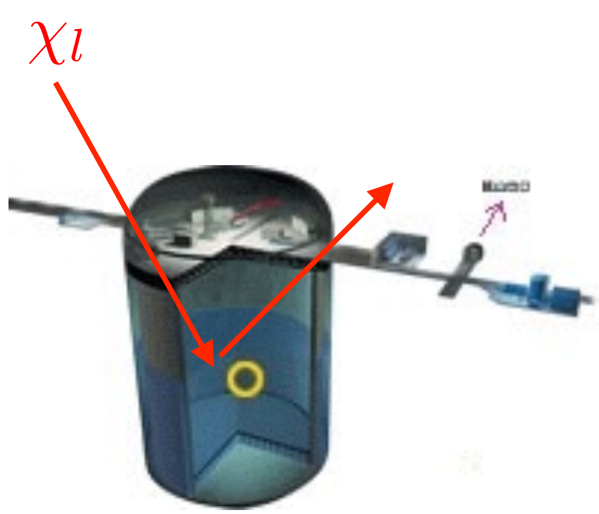
Identify the signals by simple counting N_{obs} over the expected bkg.

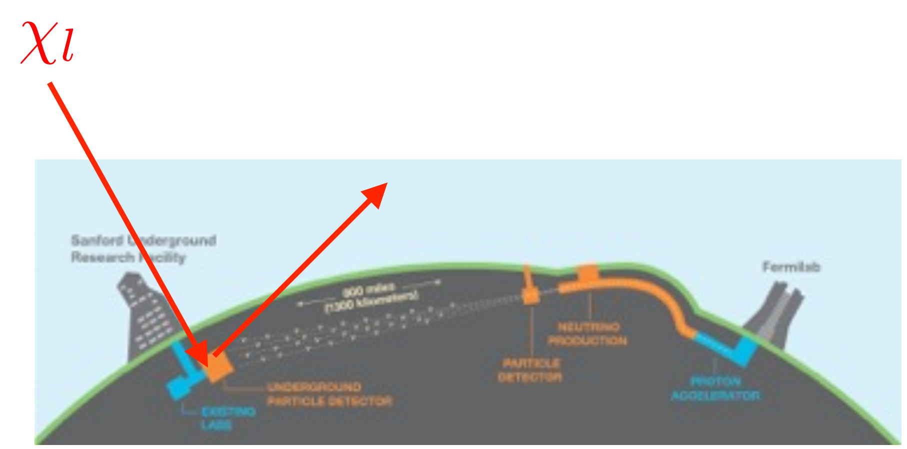
neutrino

Interesting but not easy
to confirm the signals over ν

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*

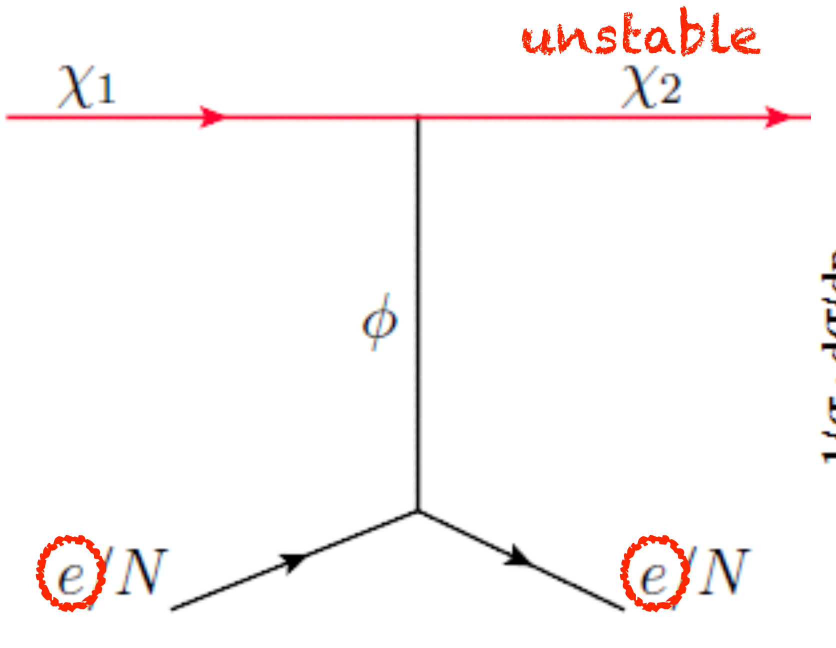
- From Sun: a small coupling of χ_h - SM or self-interaction of χ_h

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

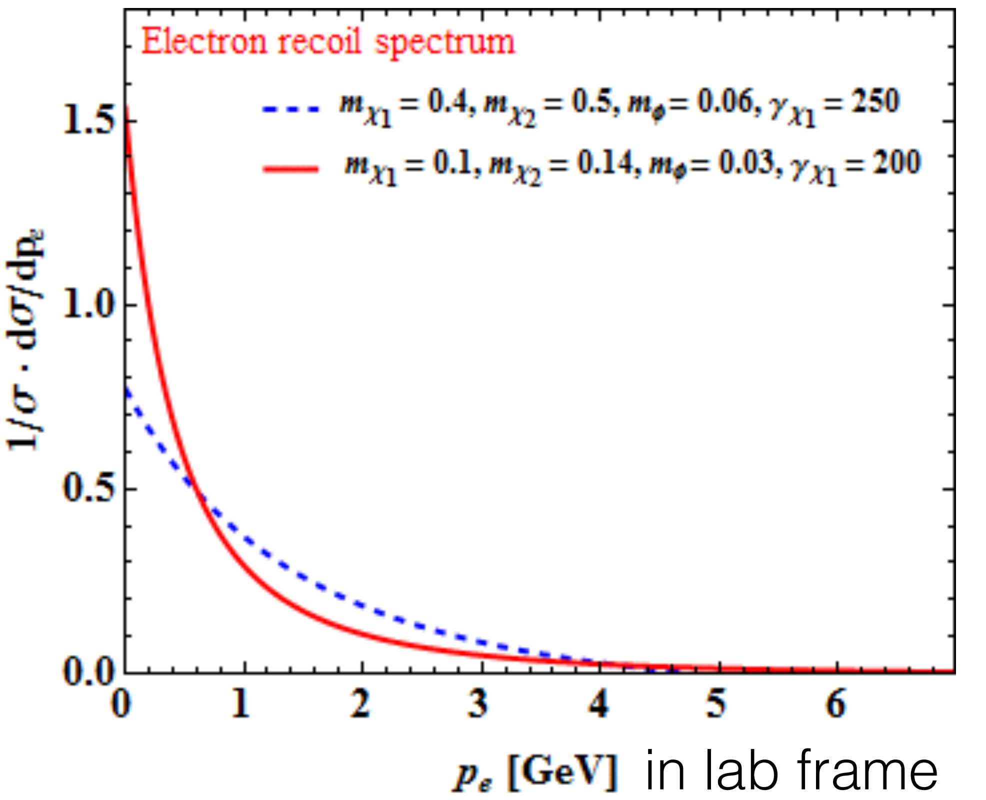
- Non-minimal dark sector (just like SM?): extraordinary signal

  Kim, Park, **SS**, 1612.06867

Energy spectrum: e-scattering



primary scattering

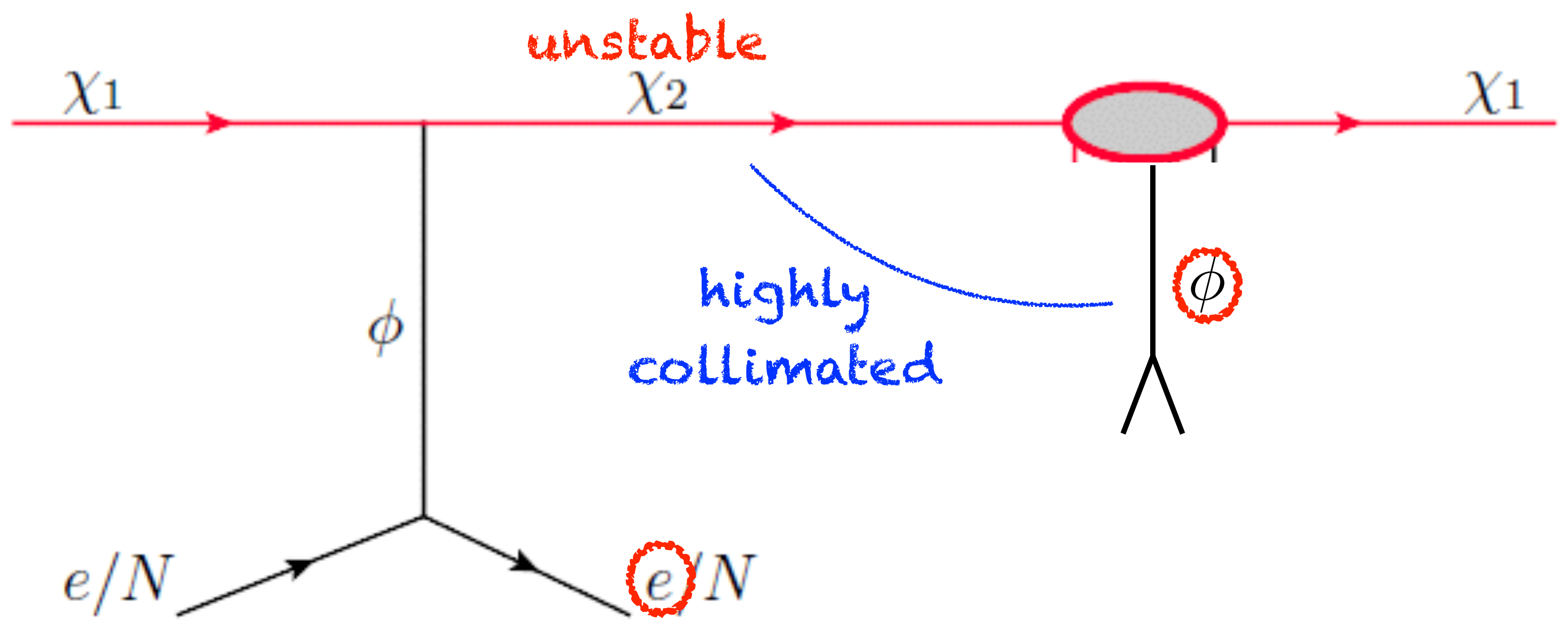


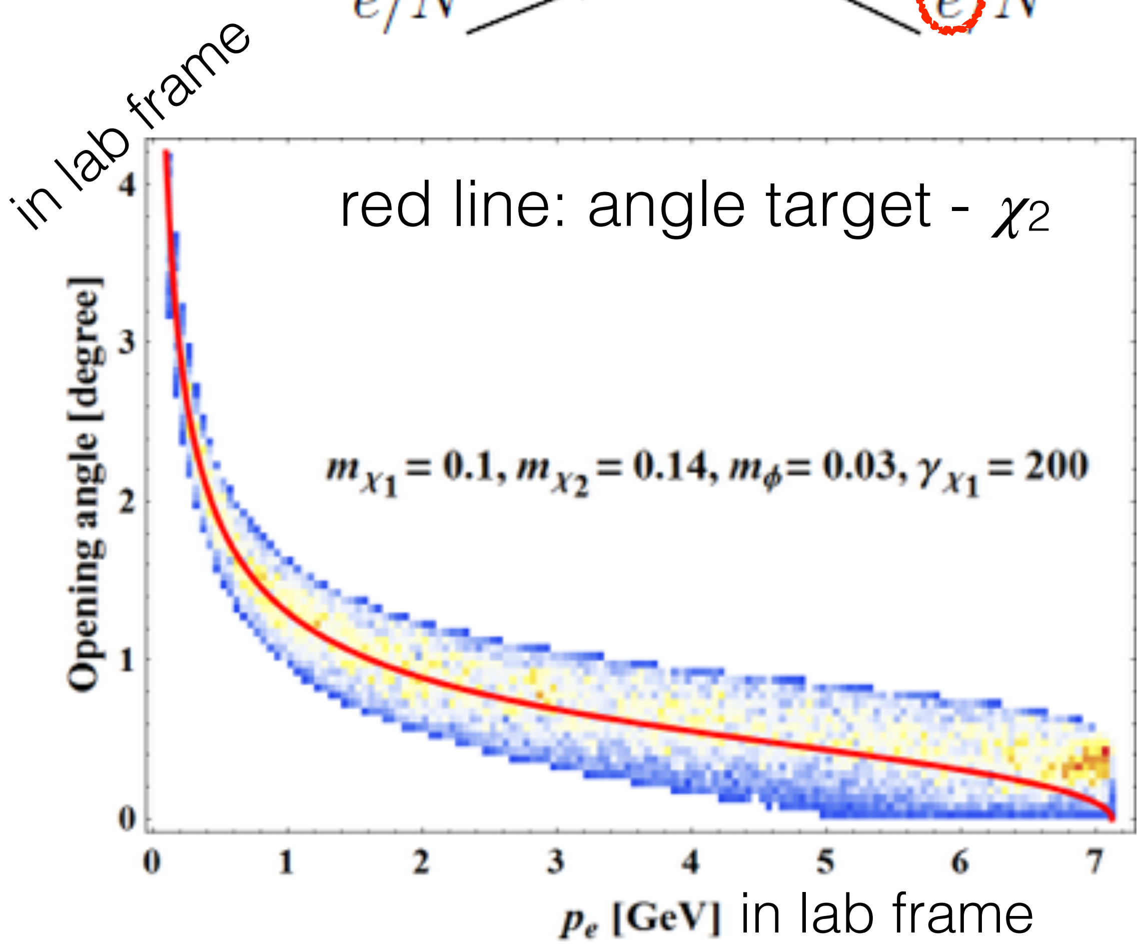
in lab frame

e-scattering preferred over p-scattering

- Primary scattering cross section large when momentum transfer small
- E_{th} low 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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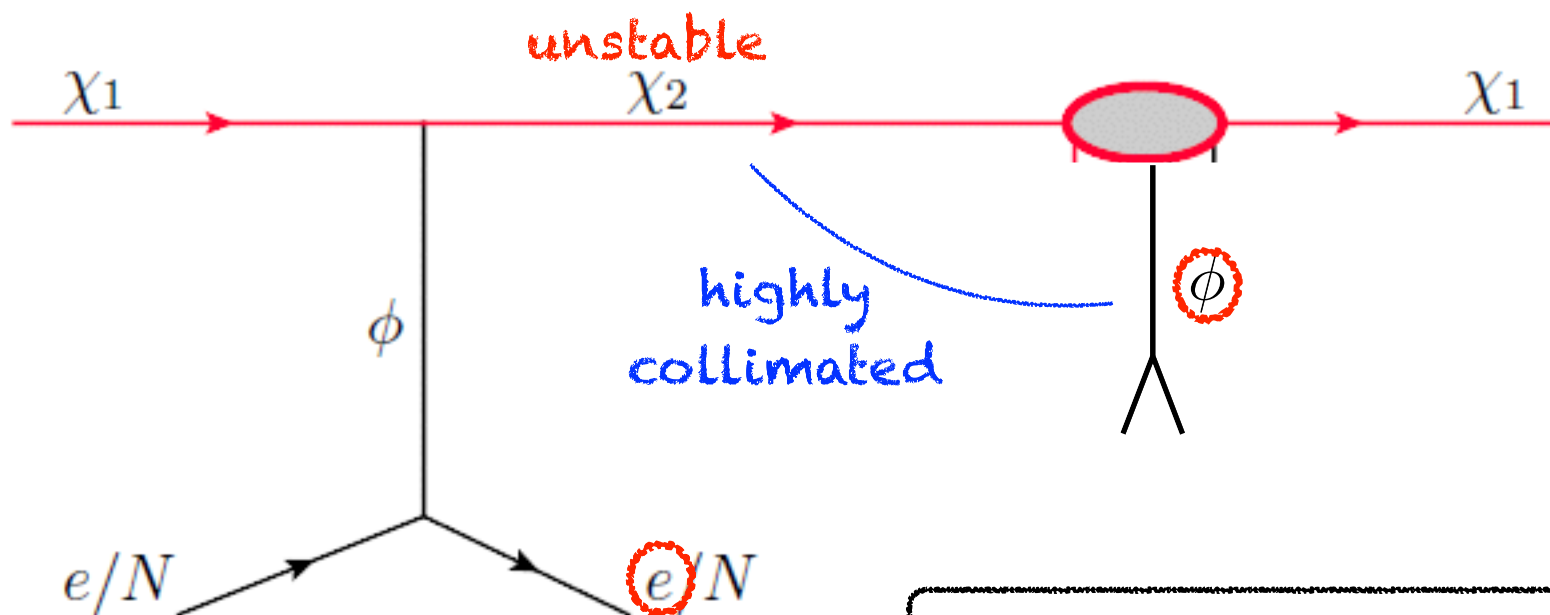
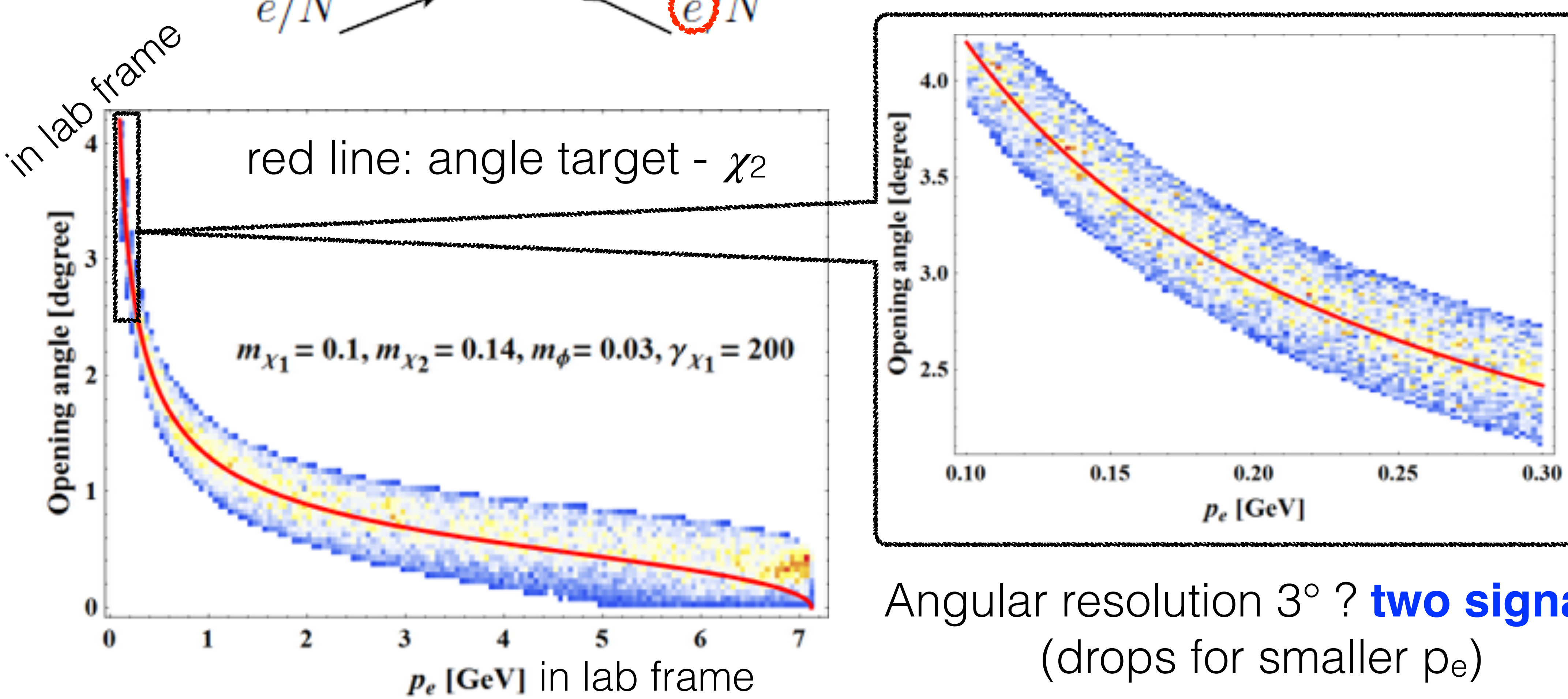
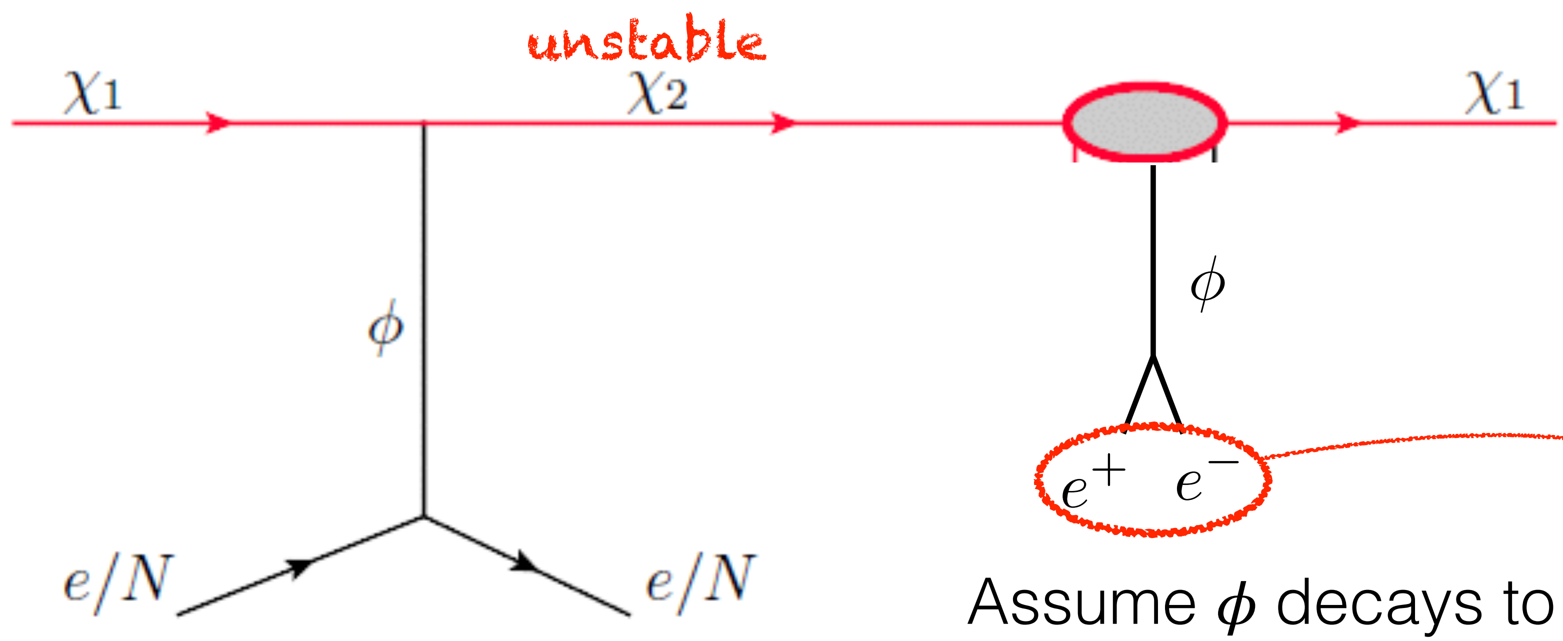




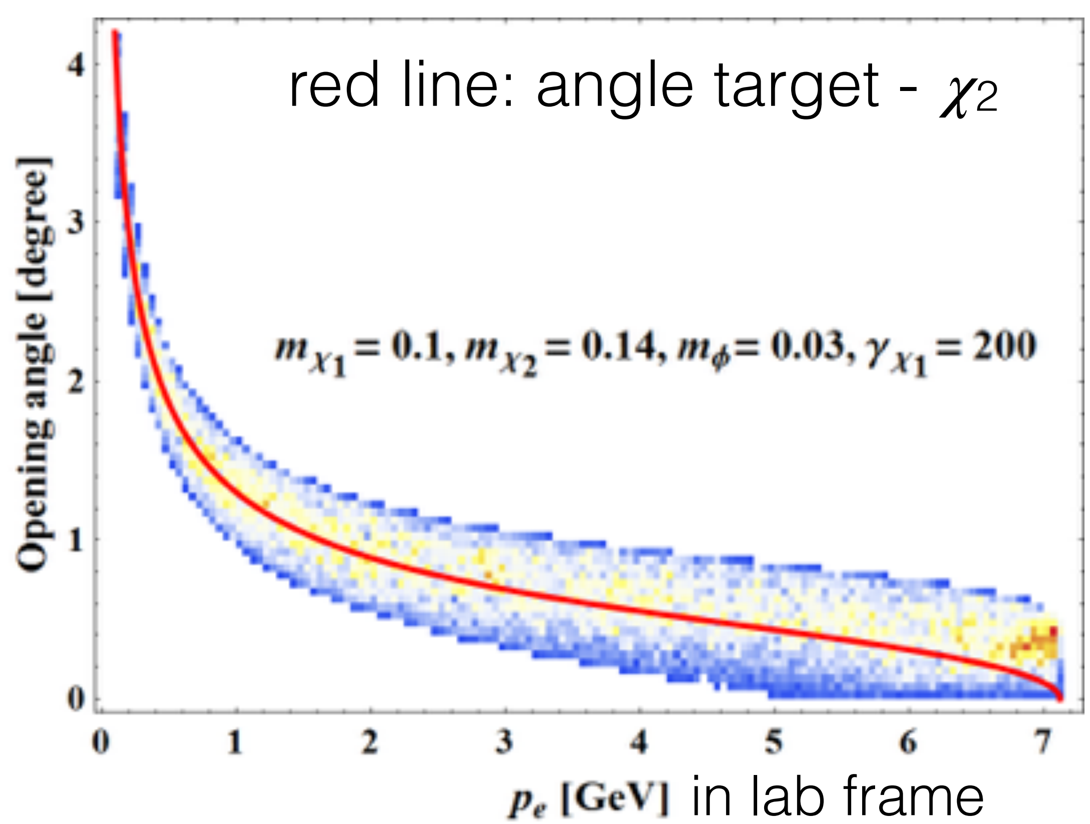
Angular resolution 3° ? **two signals!**

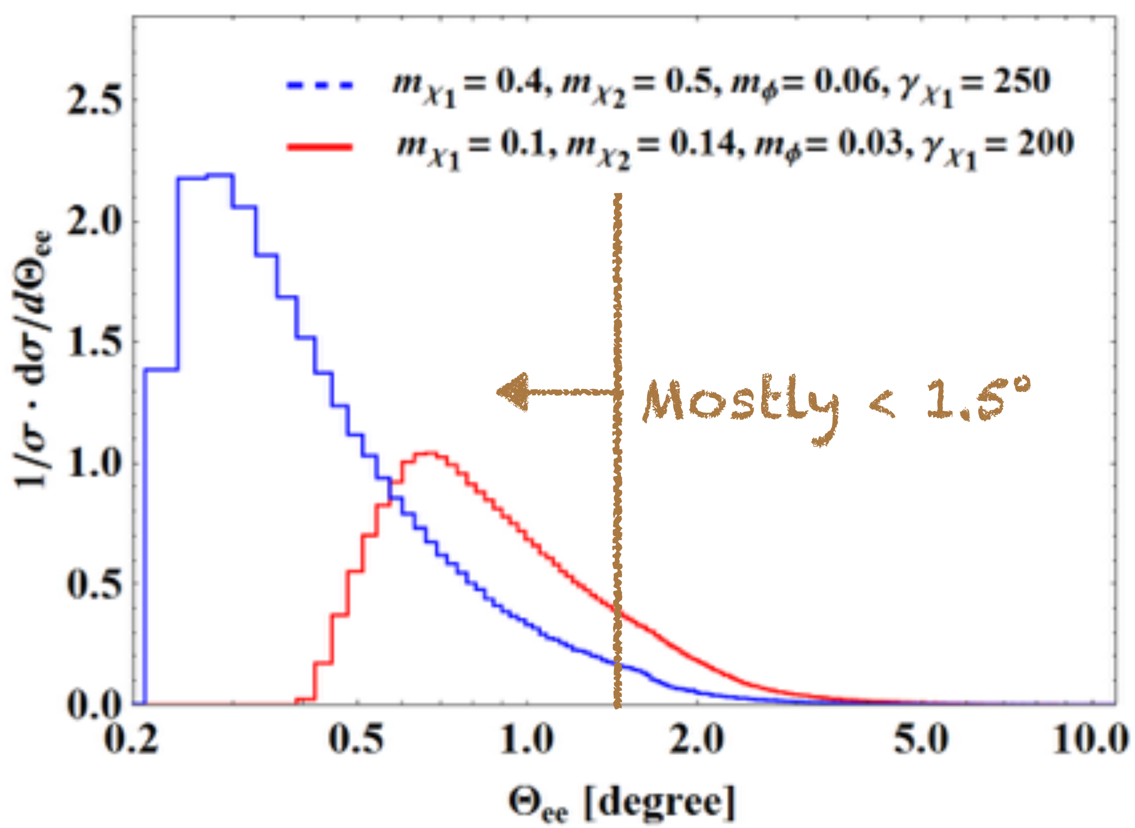
(drops for smaller p_e)

e-scattering: highly collimated

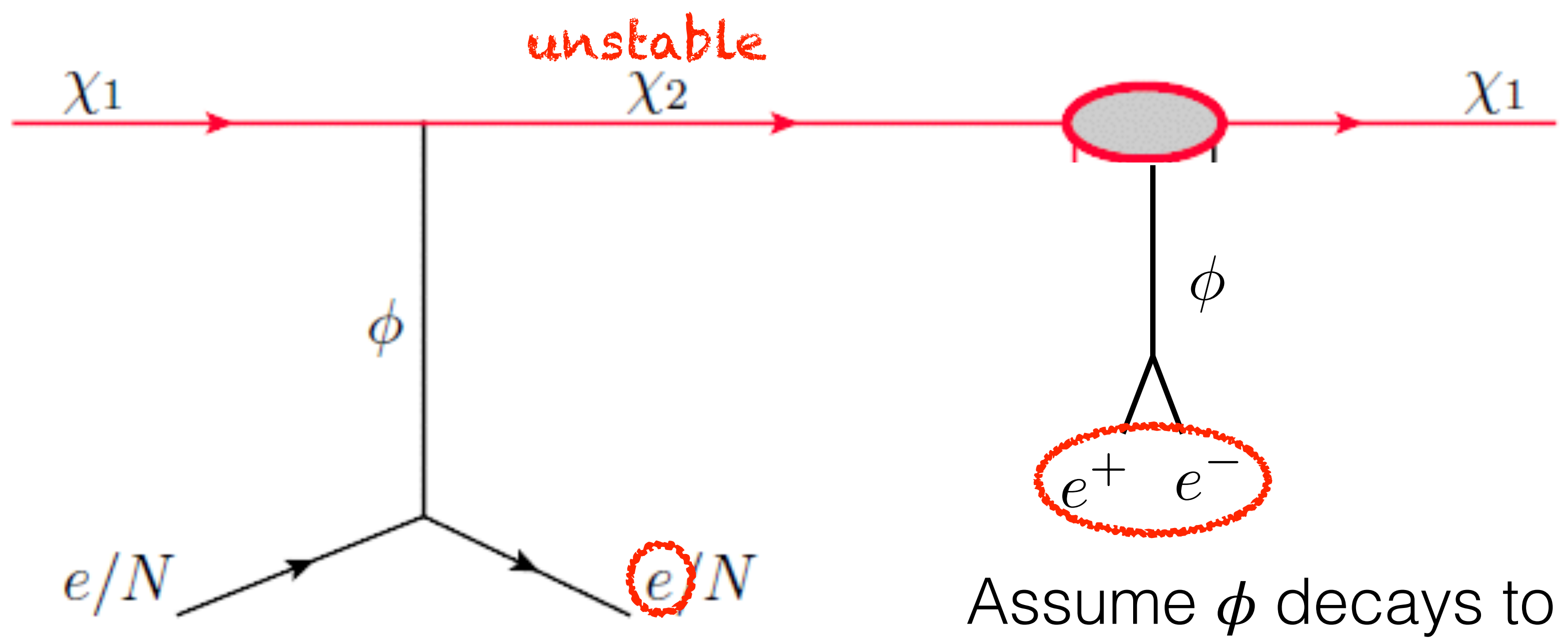


Assume ϕ decays to e^+e^-





e-scattering: detection prospects



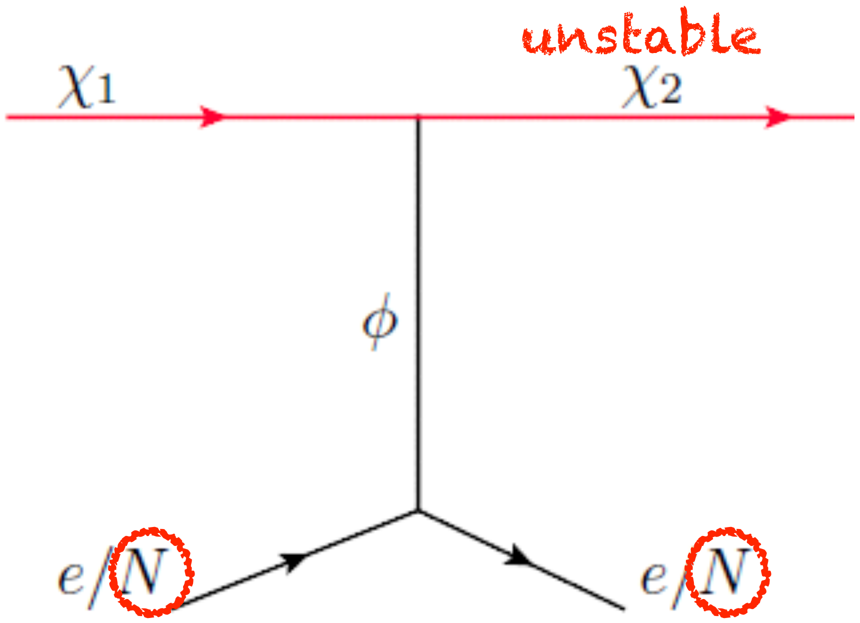
Assume ϕ decays to e^+e^-

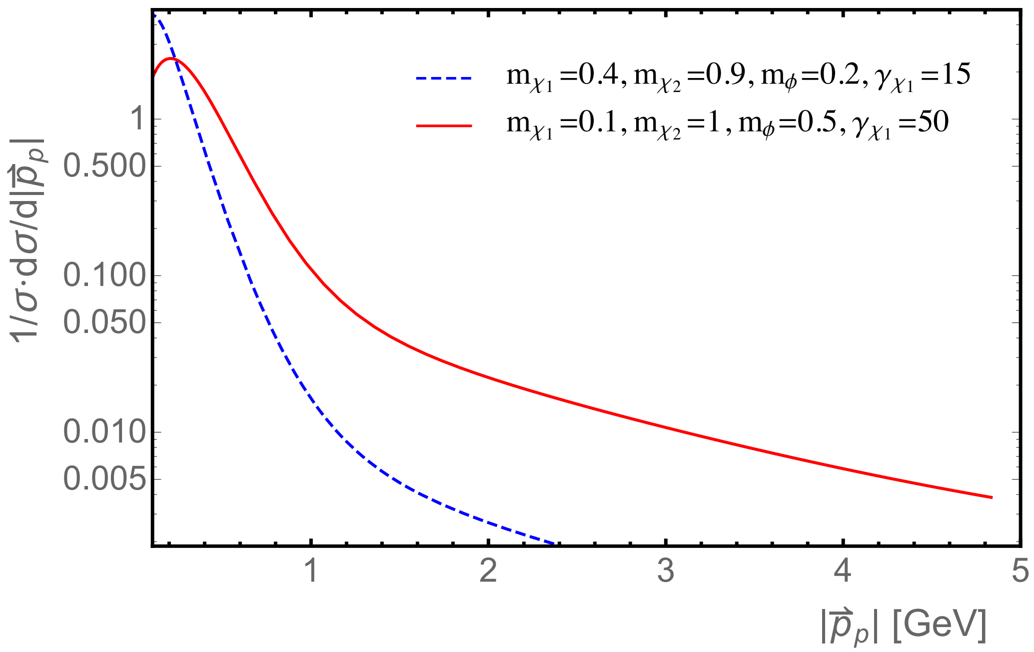
effective for $E > E_{th}$

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

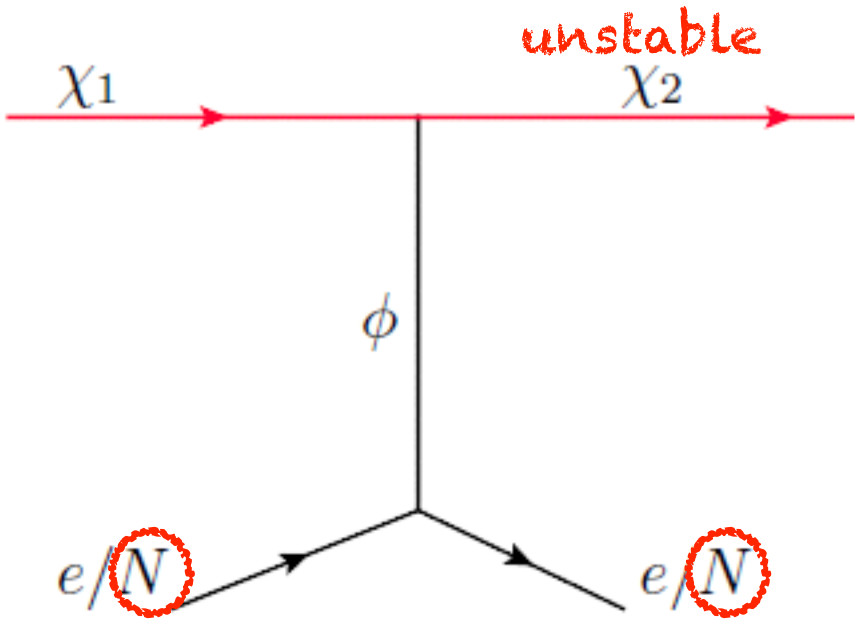


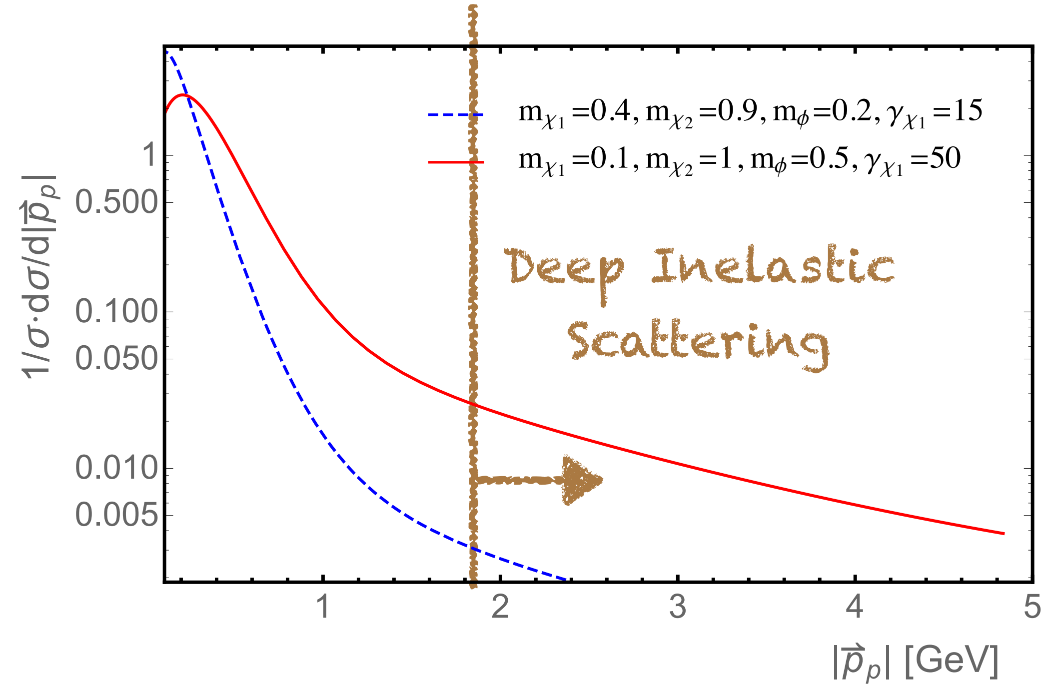


p-scattering NOT preferred over e-scattering (Cherenkov)

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

p-scattering: energy spectrum





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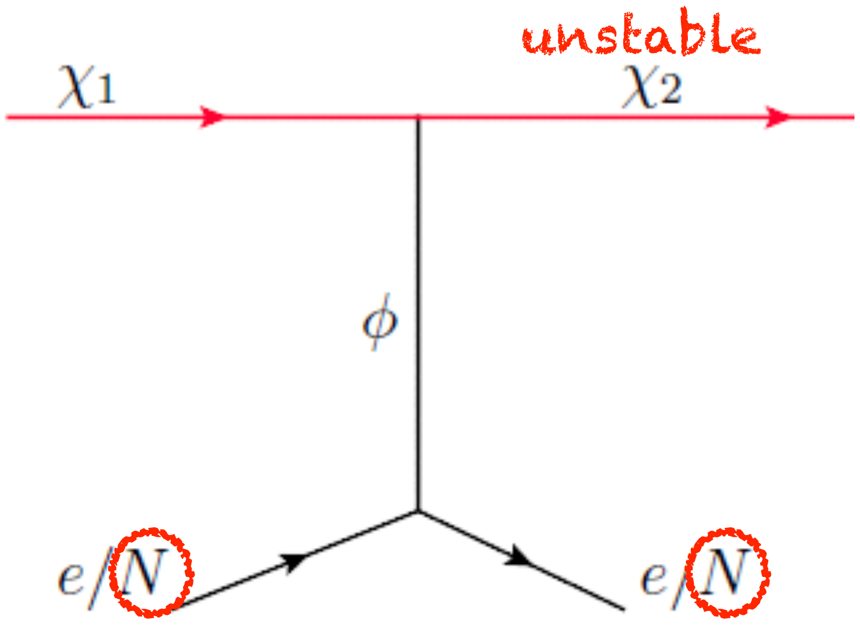
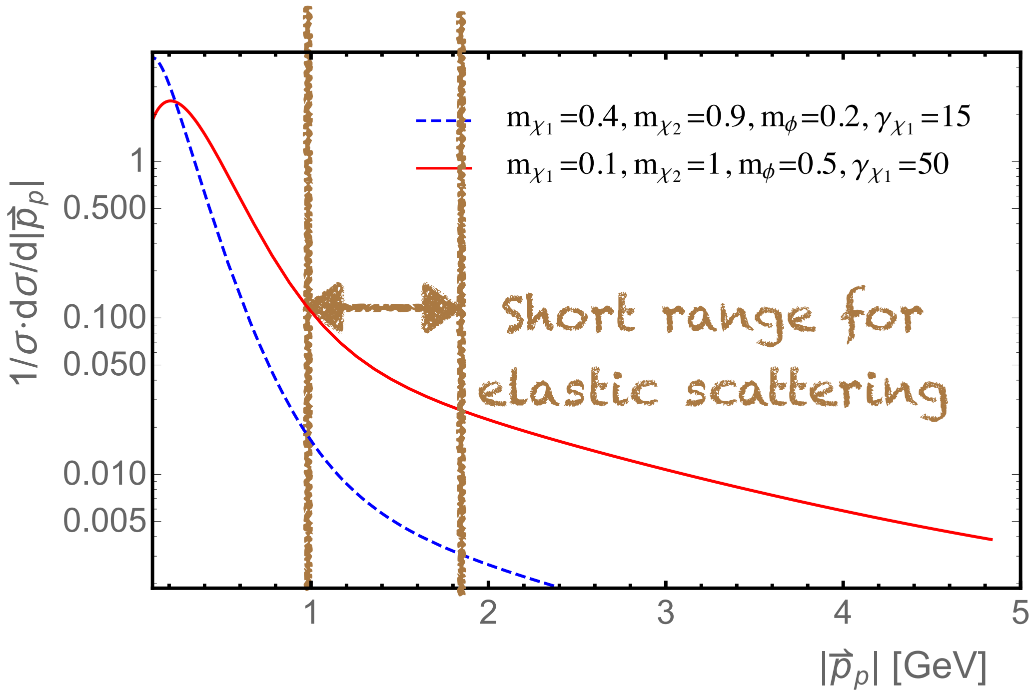
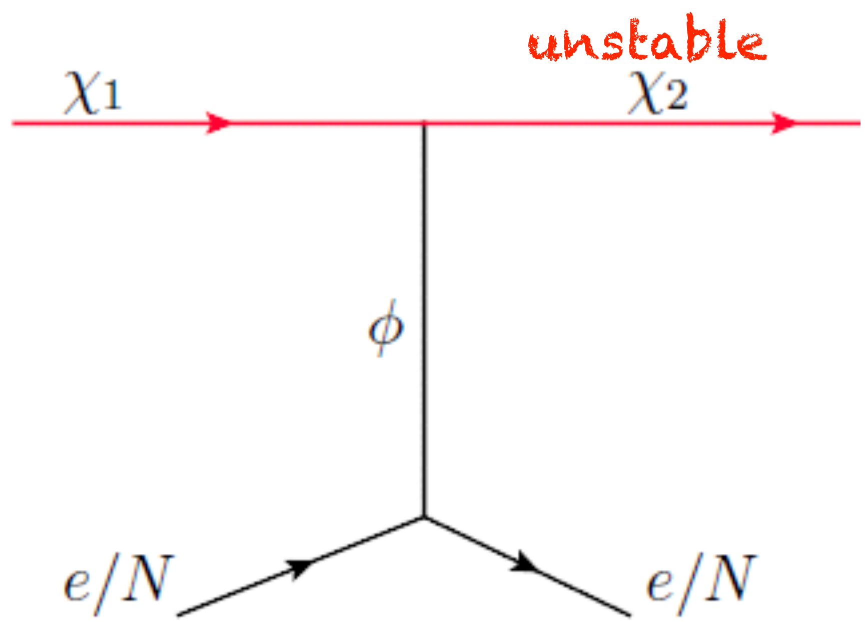


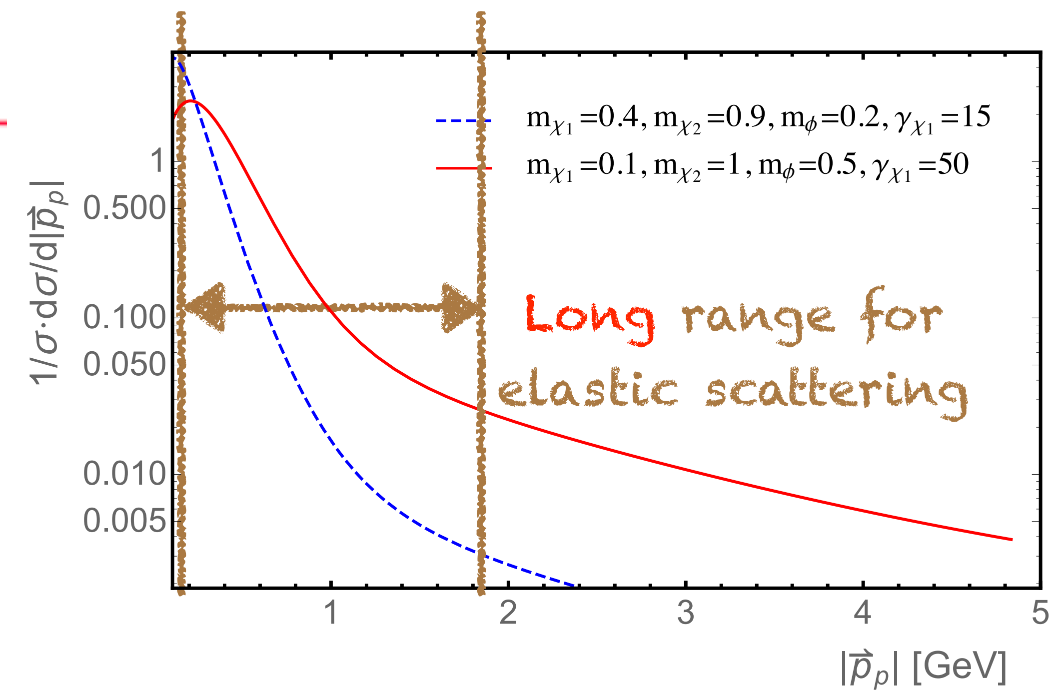


p-scattering NOT preferred over e-scattering (Cherenkov)

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

p-scattering: energy spectrum

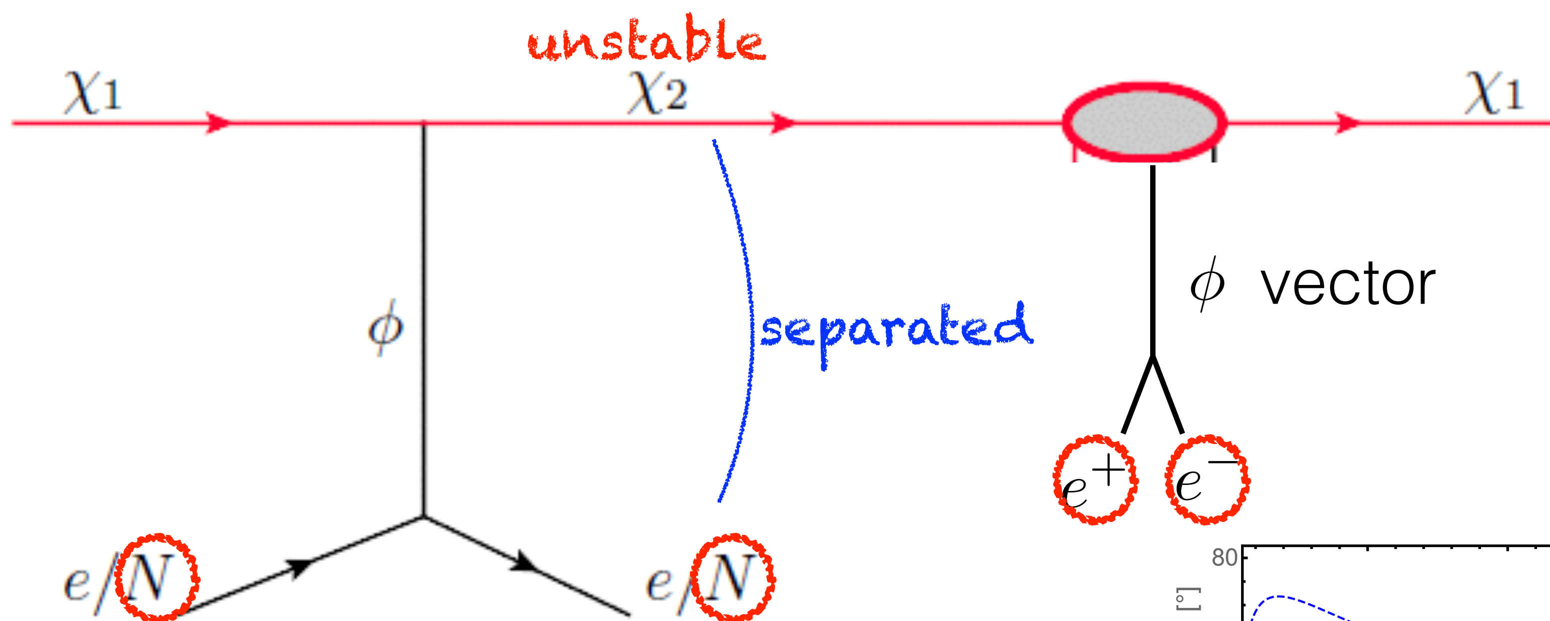


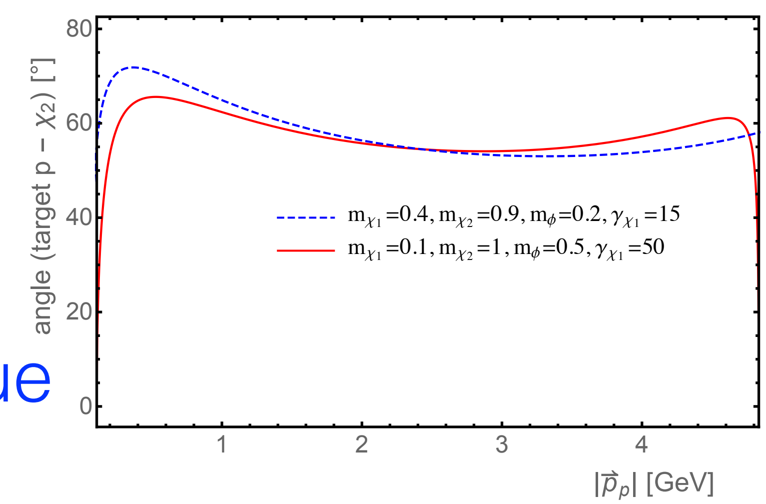


However, the cascade process is still unique

- 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