Light Hidden-sector Particle Searches at Dark Matter "Colliders"

Doojin Kim

New Physics at the Intensity Frontier

CERN-EPFL-Korea Theory Institute, CERN, Geneva, Switzerland, February 24th, 2017

DK, Jong-Chul Park, and Seodong Shin, arXiv: 1612. 06867

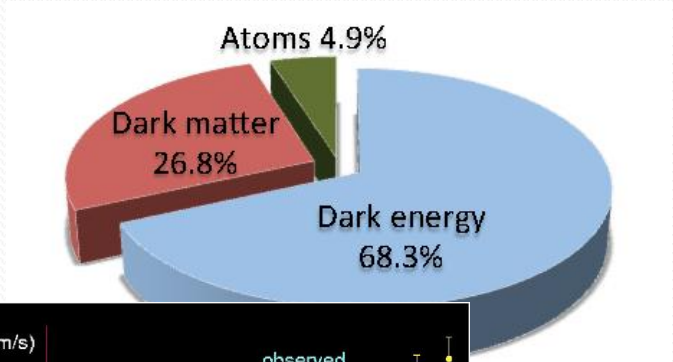
Dark Matter

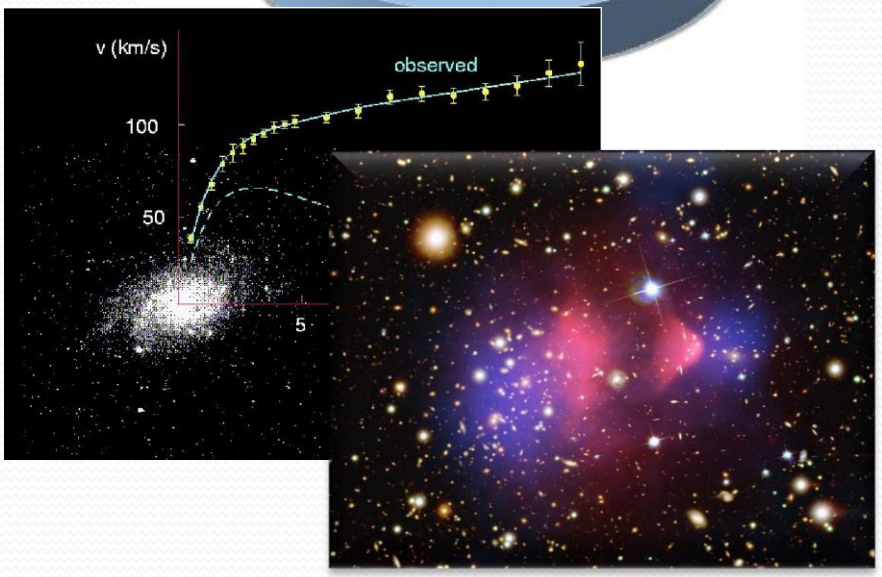
Existence of dark matter

- Dark Matter (DM): ~25% of our universe

- Evidence
  - ✓ Rotation curve
  - ✓ Gravitational lensing
  - ✓ CMB
  - ✓ Many more …

- **Compelling paradigm**

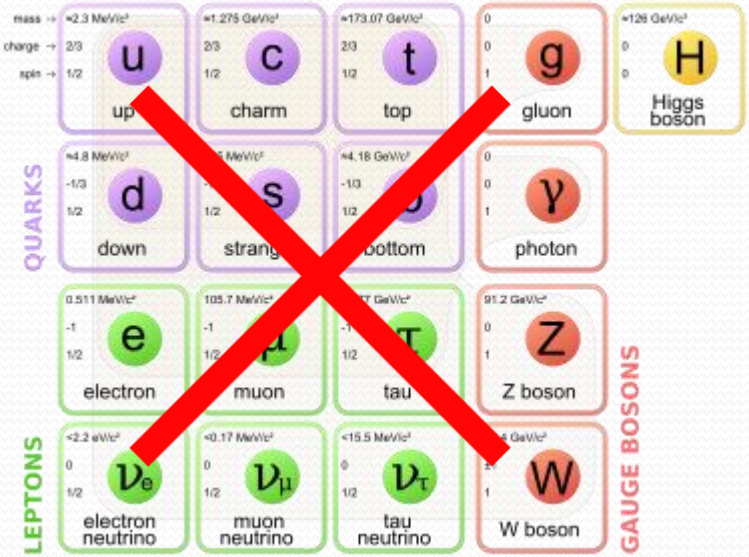




Dark Matter

Known DM properties

1) Gravitationally interacting: since having mass, dark matter can couple to gravity… but the strength small..
2) Not short-lived: i.e., stable to survive for a long time, otherwise, wouldn't be observed
3) Not hot: non-relativistic
4) Not baryonic: i.e., not made of ordinary matter, protons, electrons and atoms
5) Neutral: otherwise, would be already detected

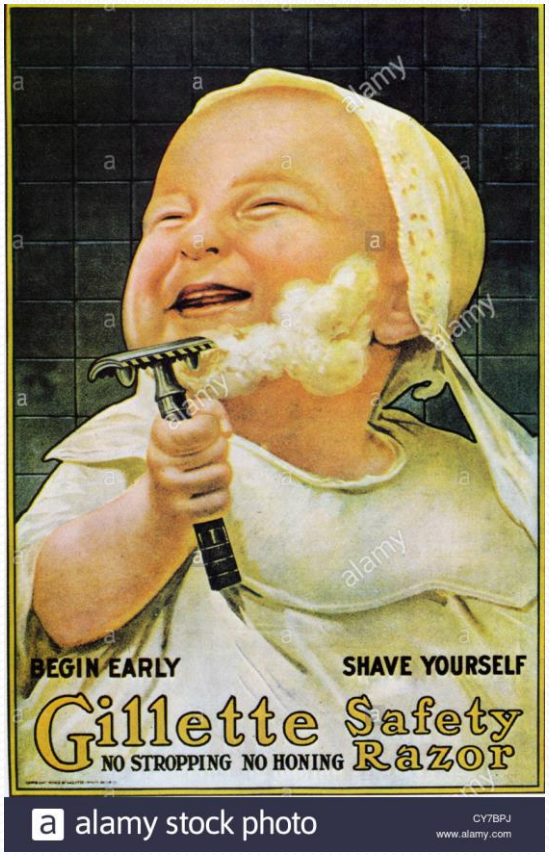


Need for new particles!!

“Minimal” Dark Sector

- Occam's razor(?)

  - Positing single dark matter species (forget other dark sector particles)



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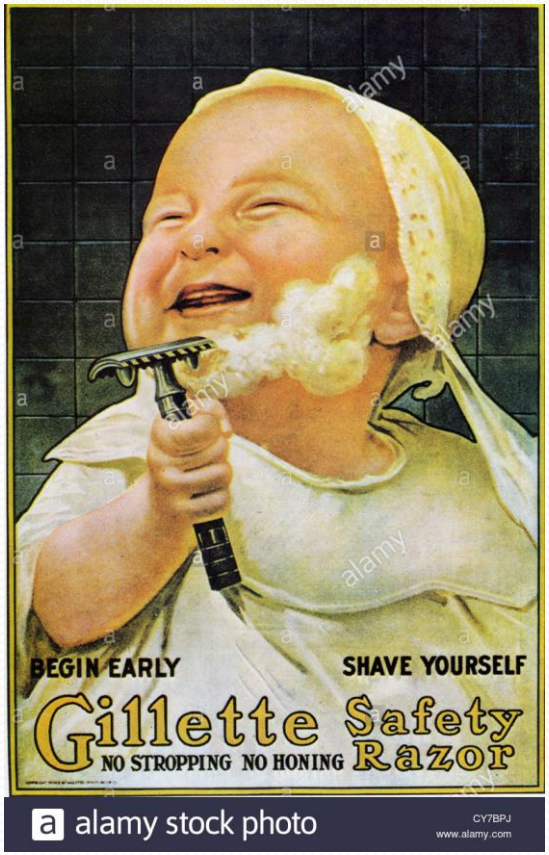
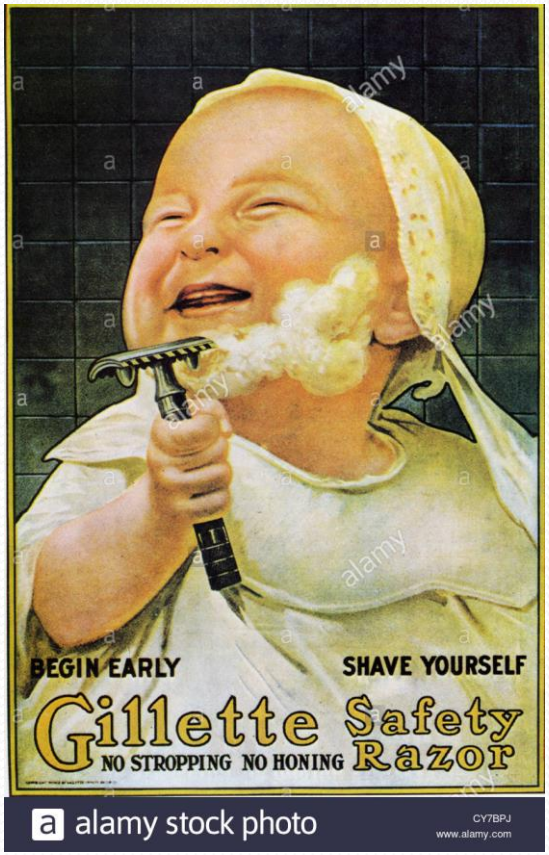


“Minimal” Dark Sector

Occam's razor(?)

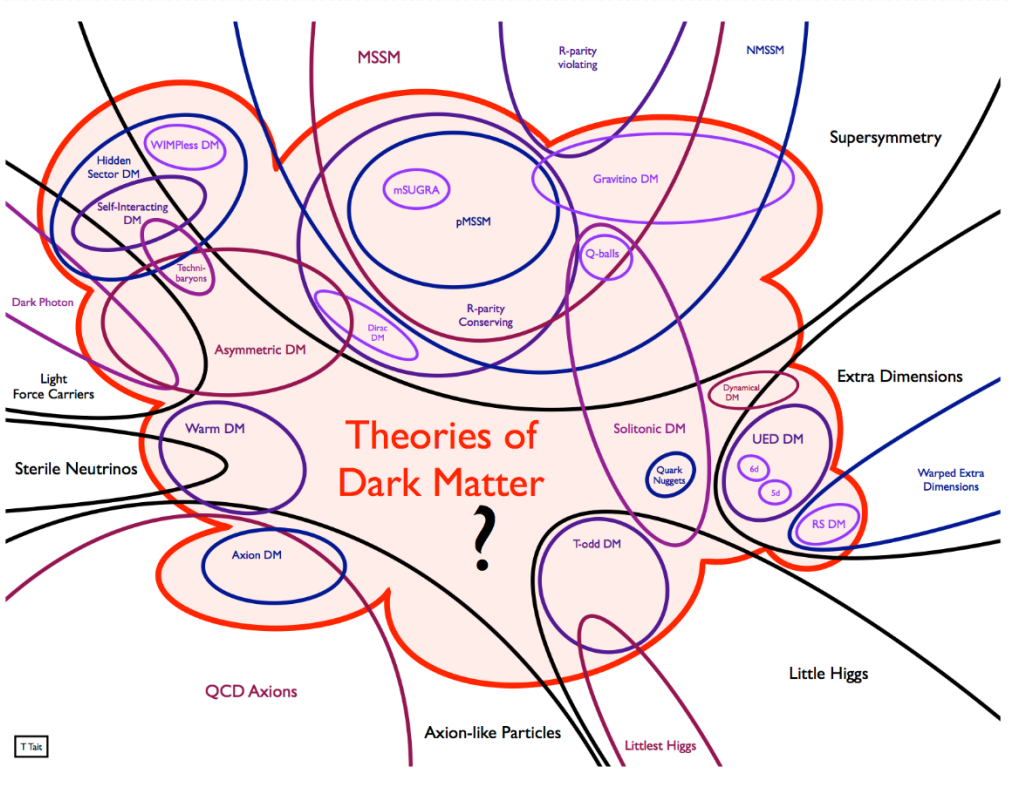
- Positing single dark matter species (forget other dark sector particles)
- The simpler, the better? (not always the case… but can be a good and economical approach toward the truth in the earlier stage!)
- Focusing on dark matter itself and relevant phenomenological implications



"Minimal" Dark Sector

Various DM models

- Many dark matter simplified models/new physics models including a dark matter candidate proposed
- Most of models assume the "minimal" dark sector (single type of dark matter)



from the talk by Tim Tait

"Minimal" Dark Sector

- "Minimal" phenomenological implications

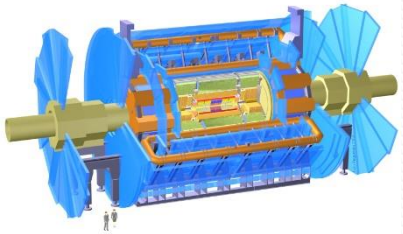
$\langle\sigma v\rangle \sim 10^{-26}\ \mathrm{cm}^3/\mathrm{s}$

DM

DM

SM

SM



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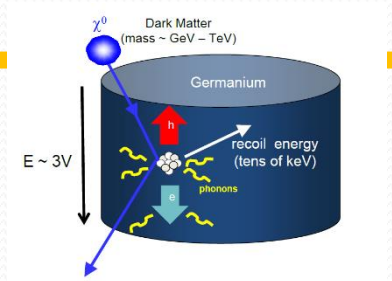
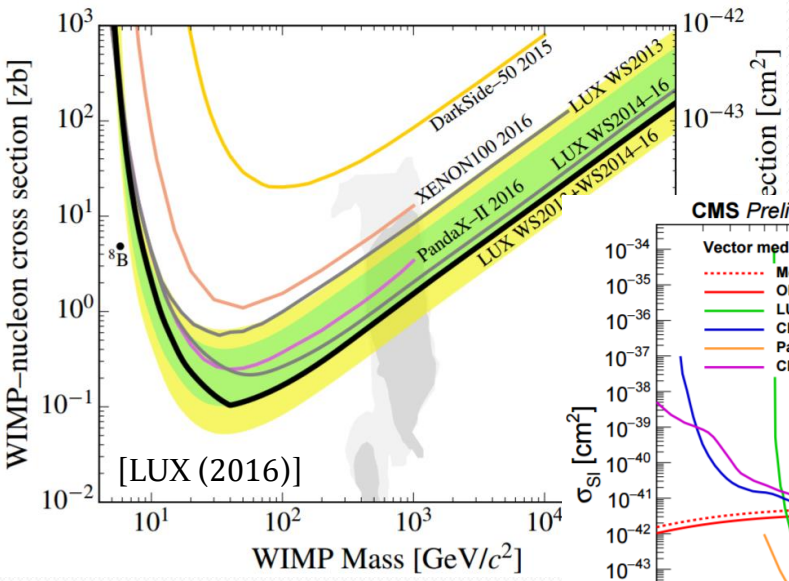


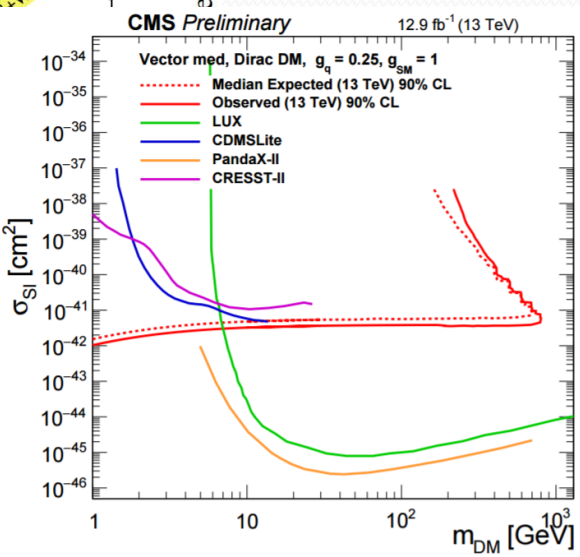
Recoil energy $\sim 1 - 100$ keV

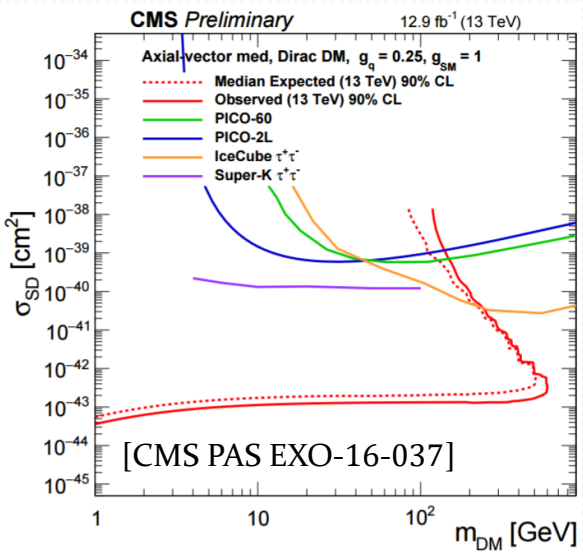
"Non-minimal" Dark Sector

Why non-minimal?

- No "unambiguous" observation of the existence of DM via non-gravitational interactions







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Why non-minimal?

❑ No "unambiguous" observation of the existence of DM via non-gravitational interactions

❑ Various particles in the SM sector

- ✓ Multiple stable particles (proton, electron, photon, neutrinos) → **interesting physics** from other stable components which are **not difficult to detect** although not dominant
- ✓ Many heavier states (top quark, massive gauge bosons, higgs, etc.) → **interesting signatures** from their decays

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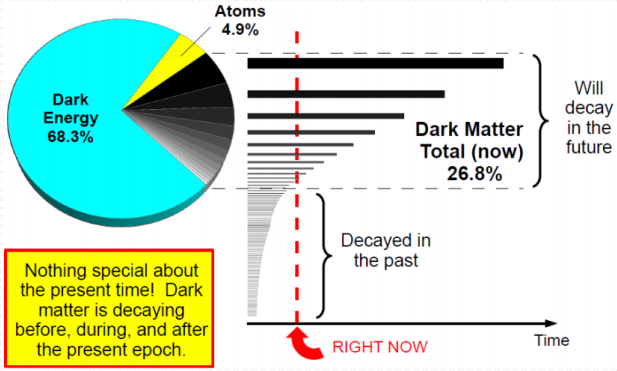
- Theoretically interesting *per se*

"Non-minimal" Dark Sector

- **In what sense?**

❑ **More members** in the dark sector

- ✓ More dark matter species (e.g., dynamical dark matter models, [K. Dienes and B. Thomas, (2011)])
- ✓ Unstable members



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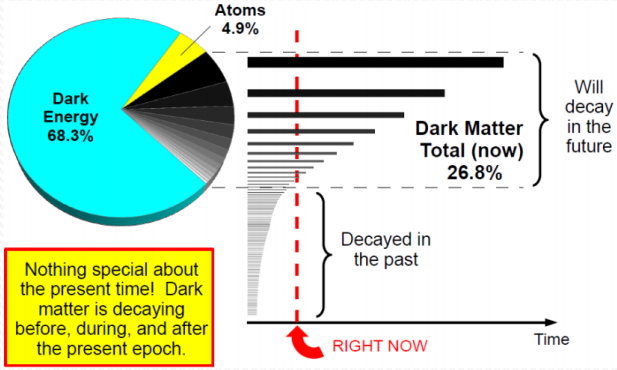
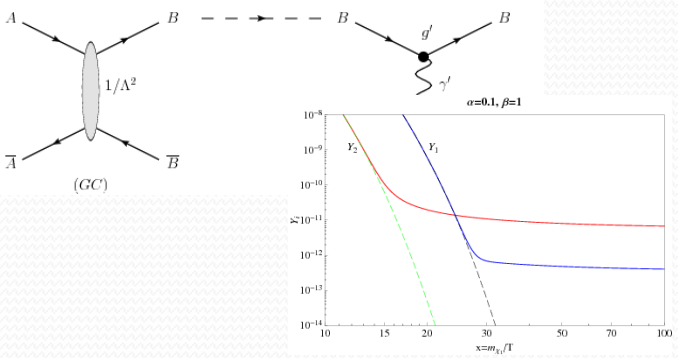


Rising interest

- Boosted dark matter scenarios [K. Agashe et al., (2014); K. Kong, G. Mohlabeng, J.-C. Park (2014)]
- Assisted freeze-out mechanism [G. Belanger and J.-C. Park (2011)]



"Non-minimal" Dark Sector

Question

- Existence of more members in the dark sector

  → are there any **non-trivial/non-conventional implications not available in the minimal setup**?

"Non-minimal" Dark Sector

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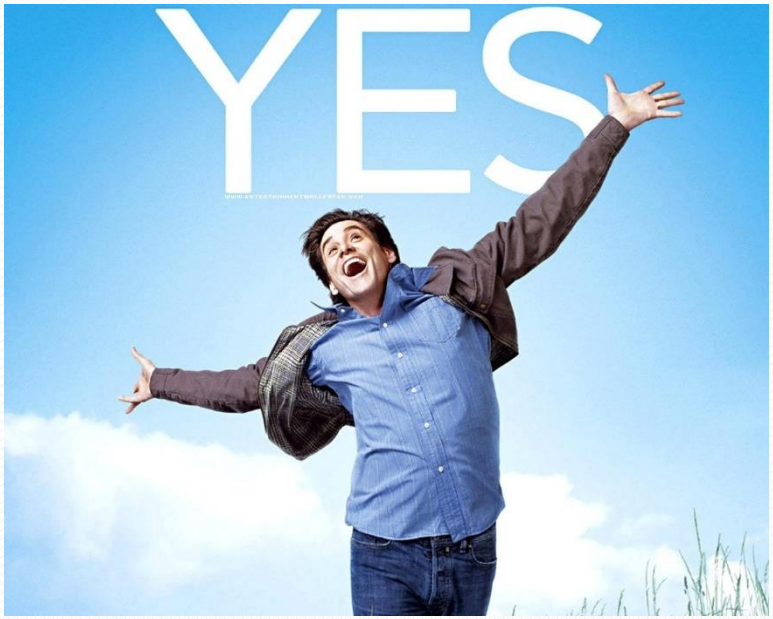

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  → are there any **non-trivial/non-conventional implications not available in the minimal setup**?

  - ✓ **New dark matter search strategies: dark matter "colliders" (also at intensity frontiers)**

Basic Setup

- **Dark matter "collider"** [DK, J.-C. Park, S. Shin, 1612.06867]

  - We are imaging the situation where

    χ_B: **boosted** DM
    (boosted DM, beam-dump,
    collider., etc.)

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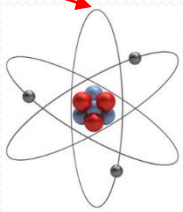
Fixed target (electron proton, etc.)



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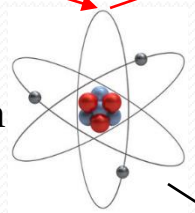
X: **heavier** dark sector state (**unstable**)



Fixed target (electron proton, etc.)

Target recoiling (**visible**)

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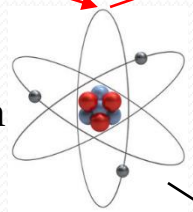
X: **heavier** dark sector state (**unstable**)

χ_B: escaping undetected



Secondary signatures (some are **visible**)

Fixed target (electron proton, etc.)

Target recoiling (**visible**)

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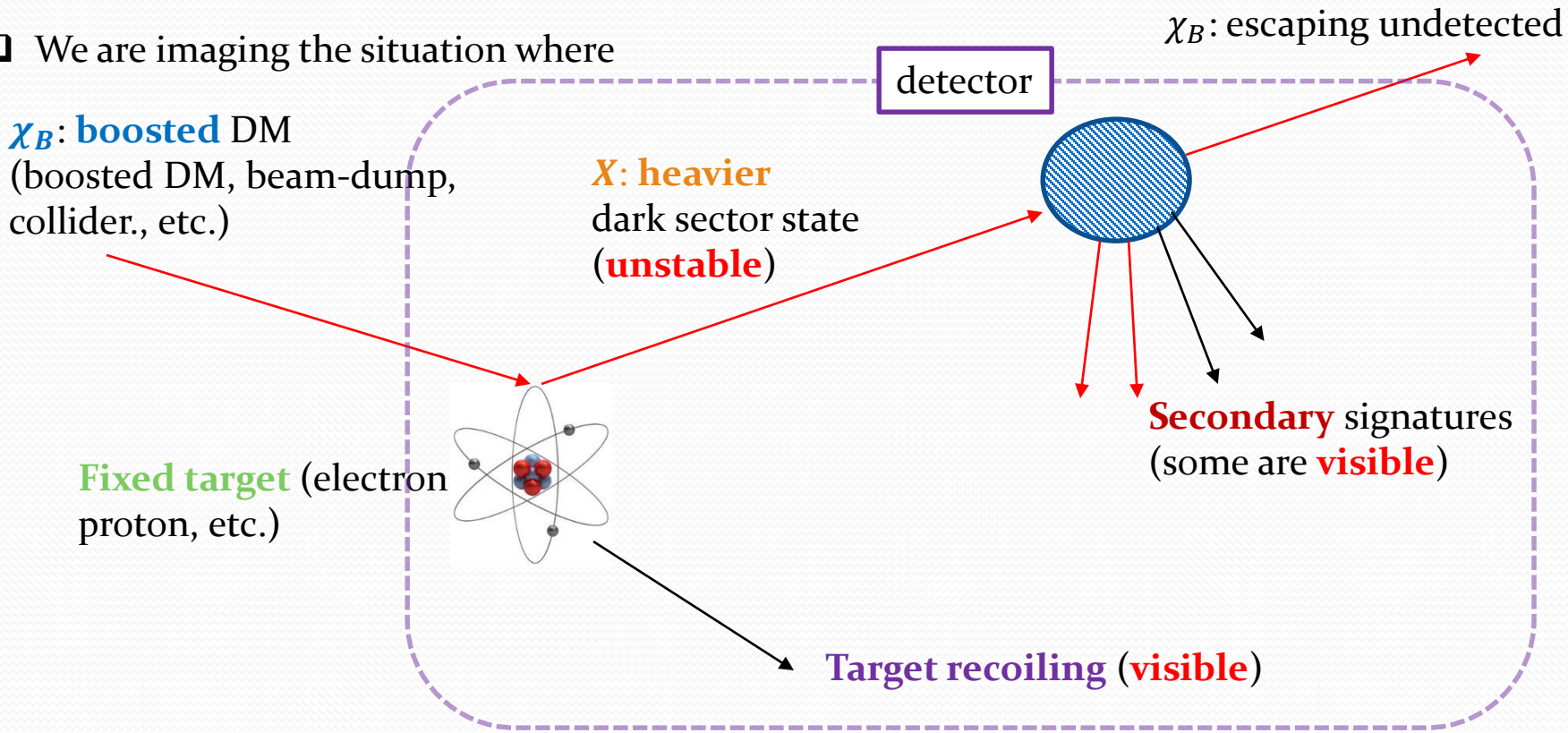

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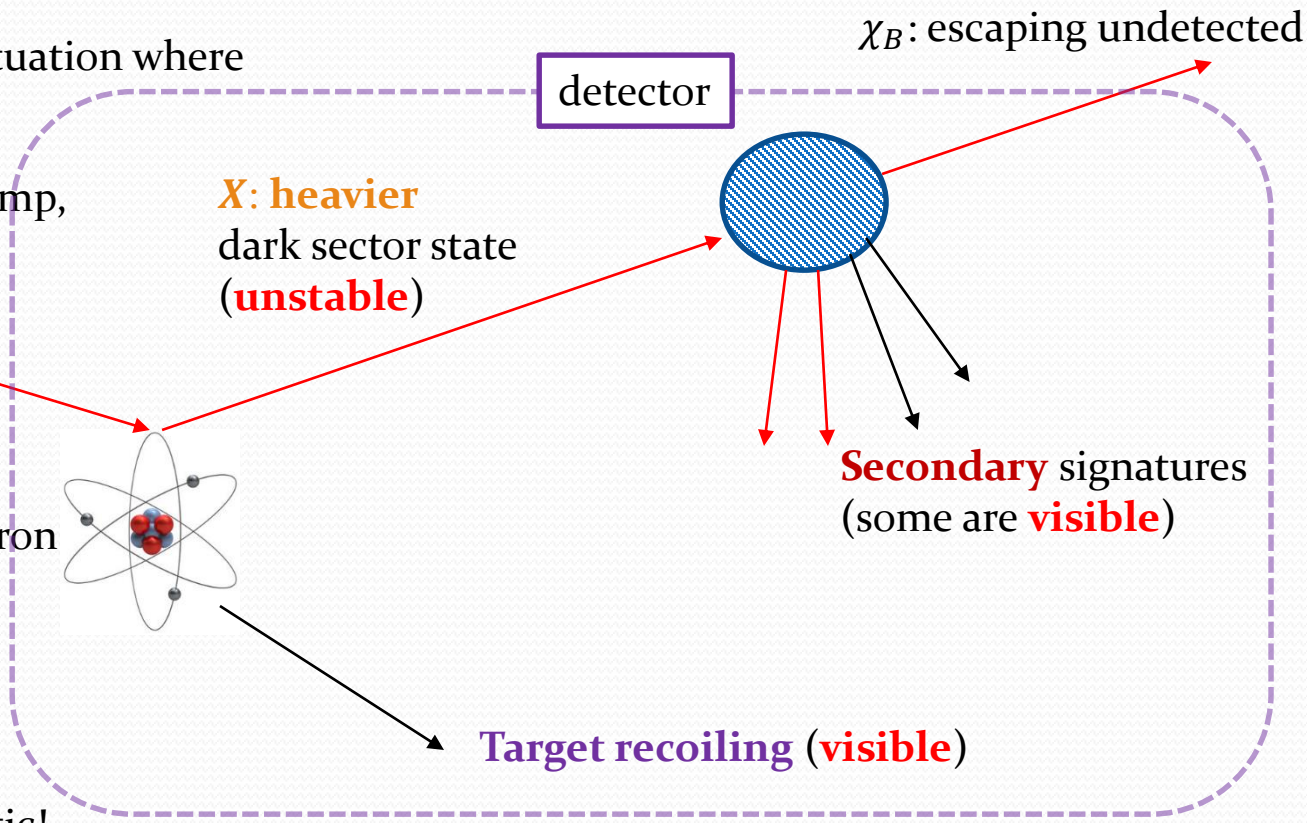
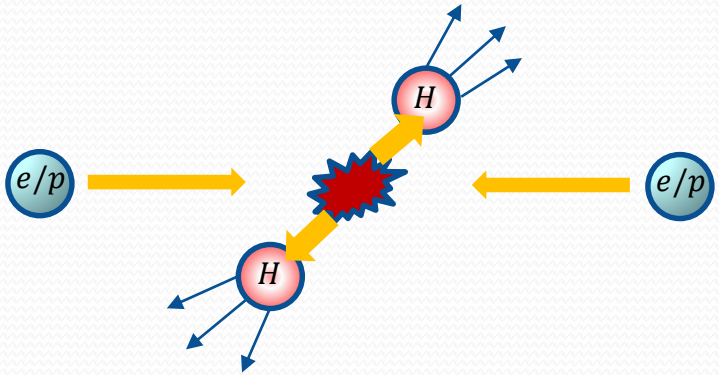


❑ Everything is relativistic!

Dark Matter "Collider"

- **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

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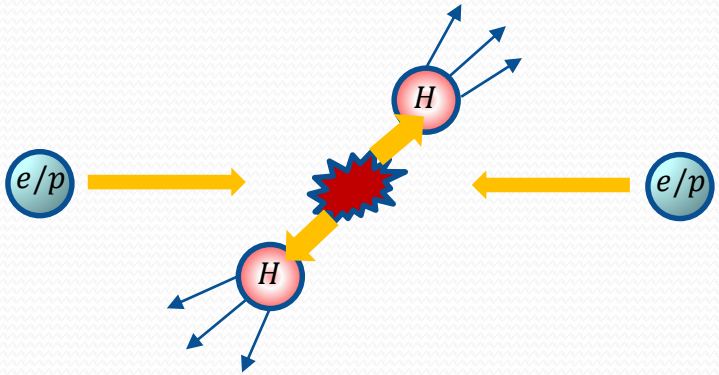
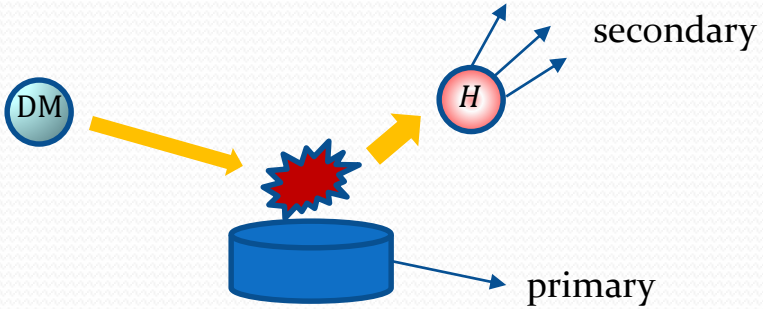




Conventional colliders

- ❑ 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

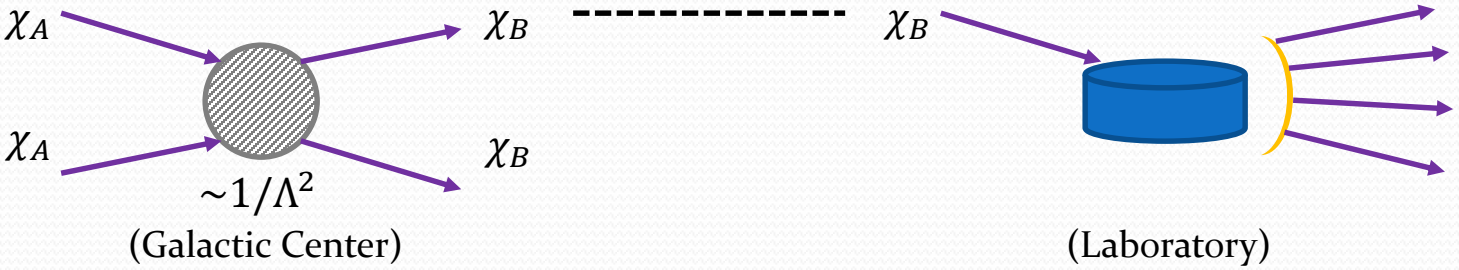
Benchmark Scenario

Boosted DM source

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

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

$\Phi \sim 10^{-7}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ for $\mathcal{O}(10-100)$ GeV χ_A



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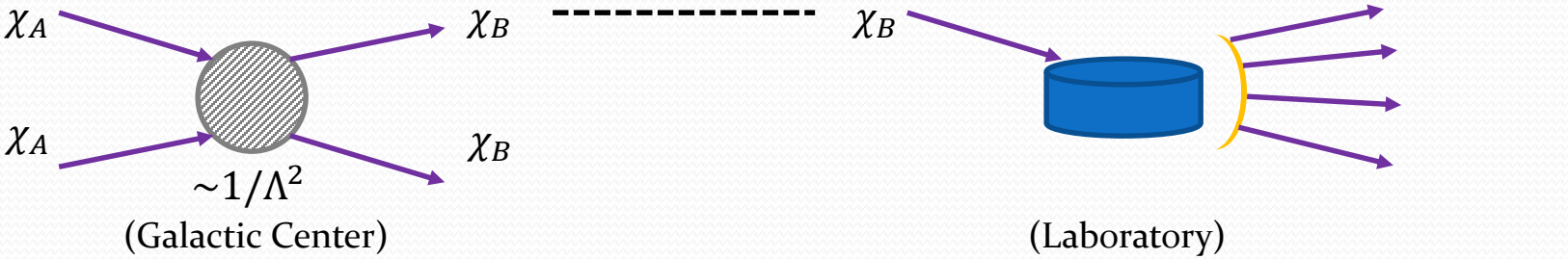

(Galactic Center) (Laboratory)

- χ_A: heavier DM, dominant relic, non-relativistic, **not directly** communicating with SM
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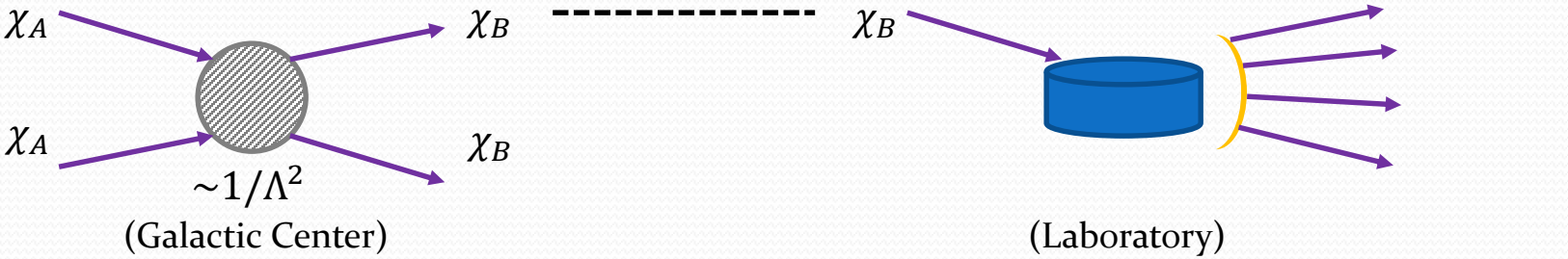

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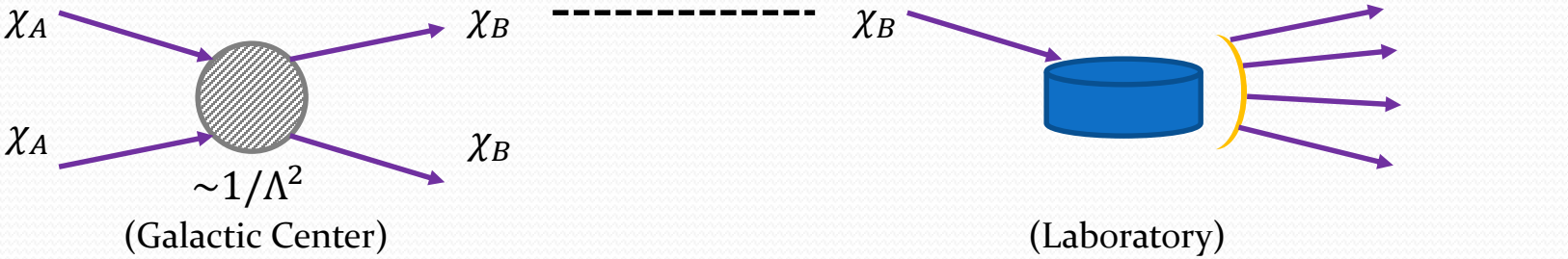

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- (**NOT the only way** of having boosted DM particles)

Benchmark Scenario

- **Dark sector model**

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

- Vector portal [Holdom (1986)] (see also Feng's and Lee's talks)

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

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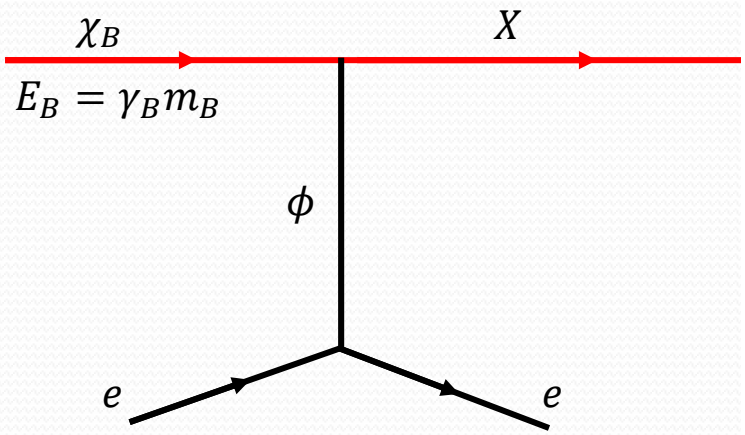
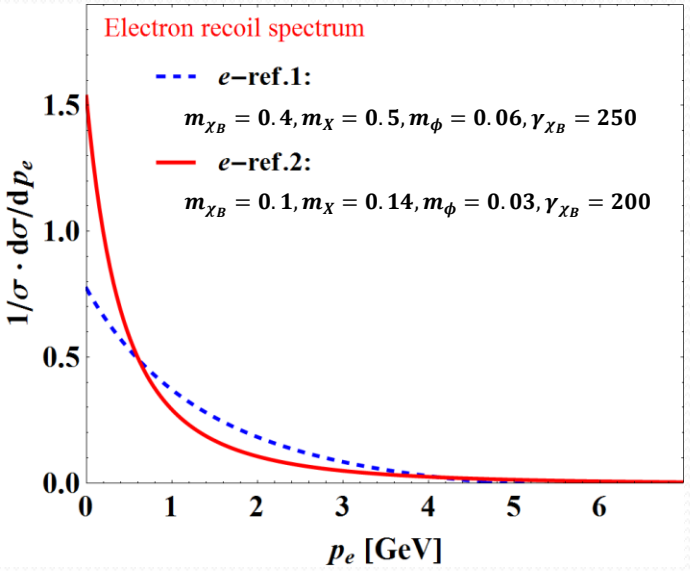
- (**NOT restricted** to vector portal scenarios)

Electron Scattering

Energy spectrum

- Electron scattering of highly-boosted incident DM with a vector mediator





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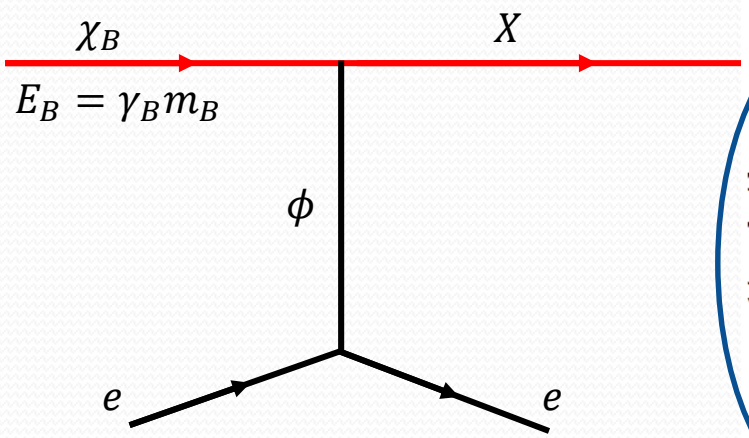

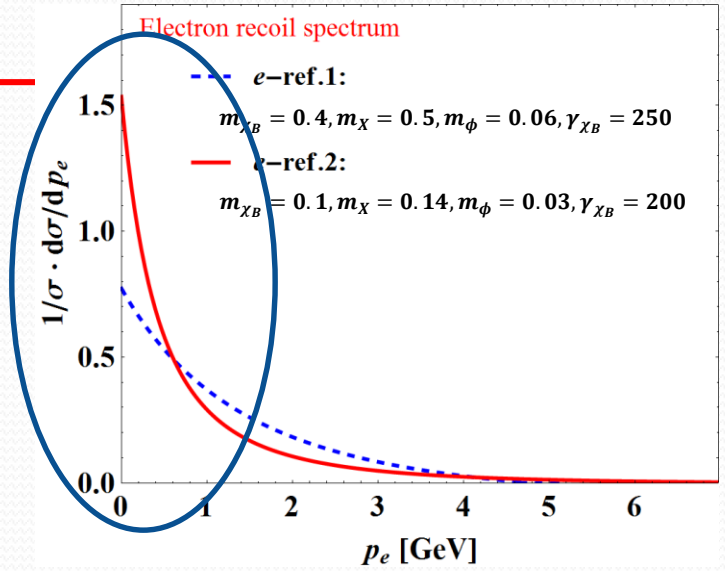

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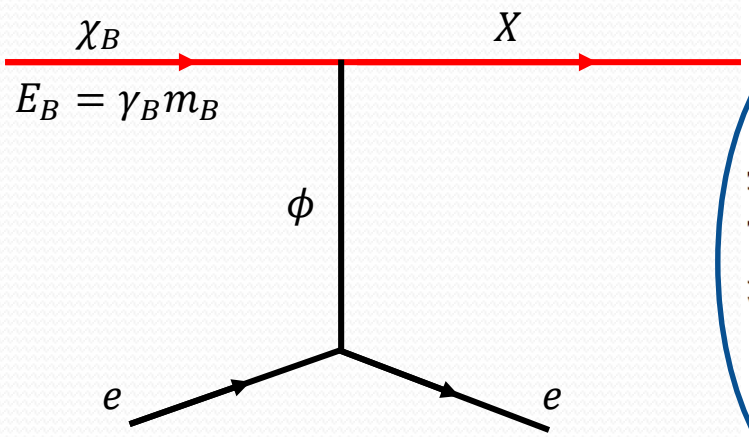

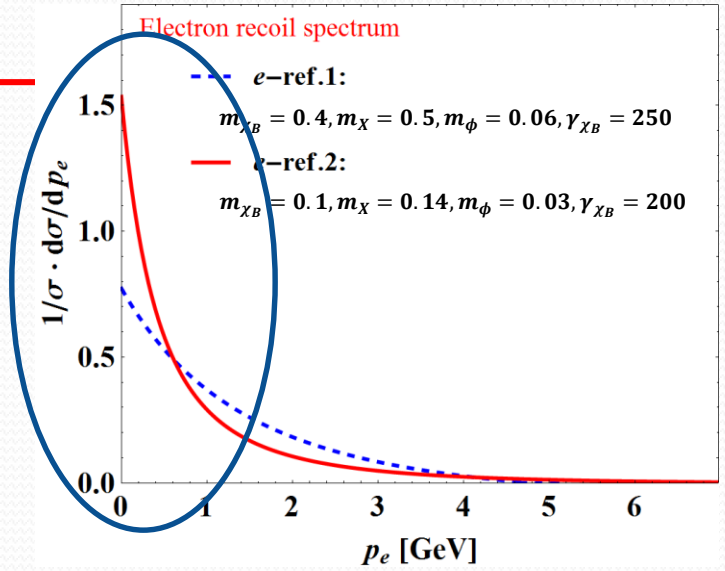

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  - ✓ **Low threshold** energy for e-scattering but high for p-scattering (Cherenkov detectors)

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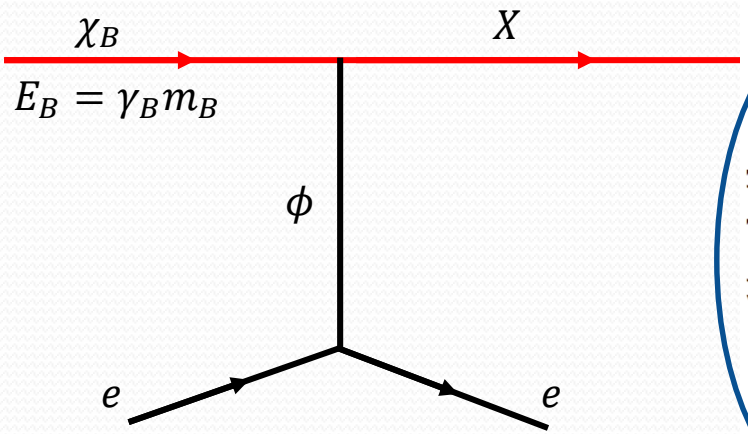

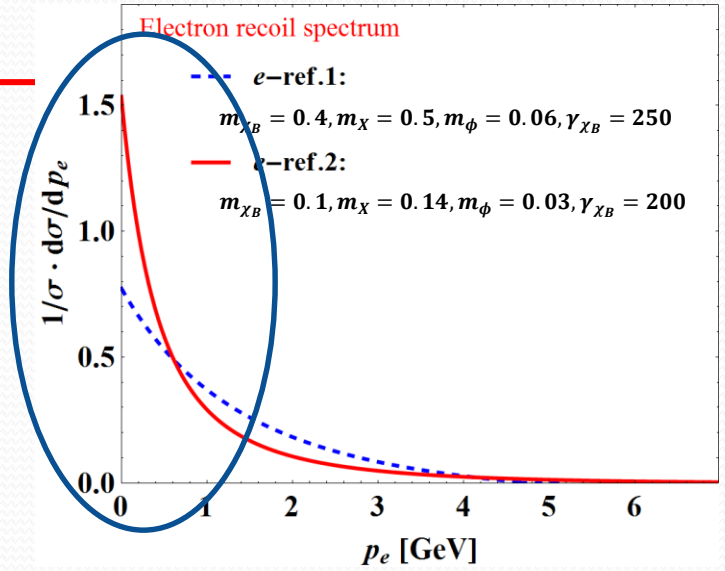

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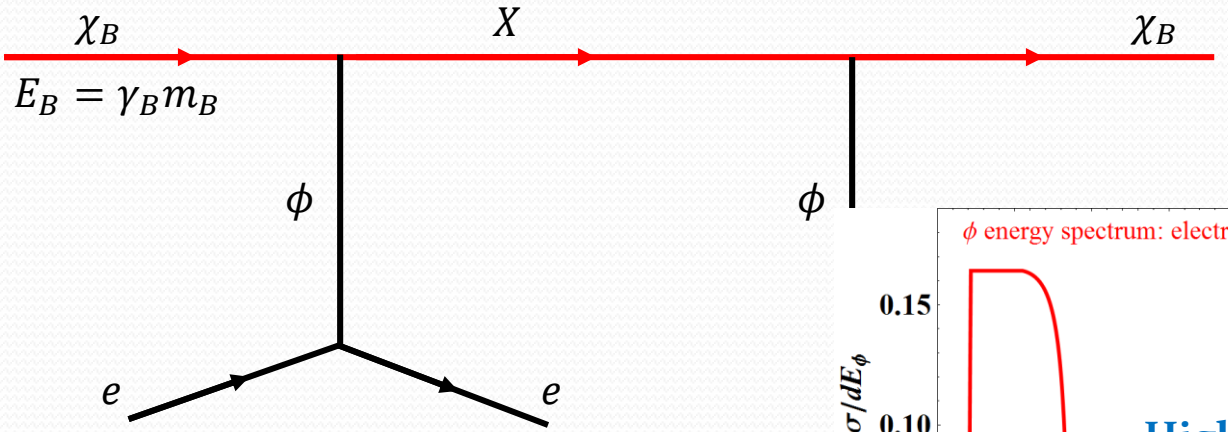
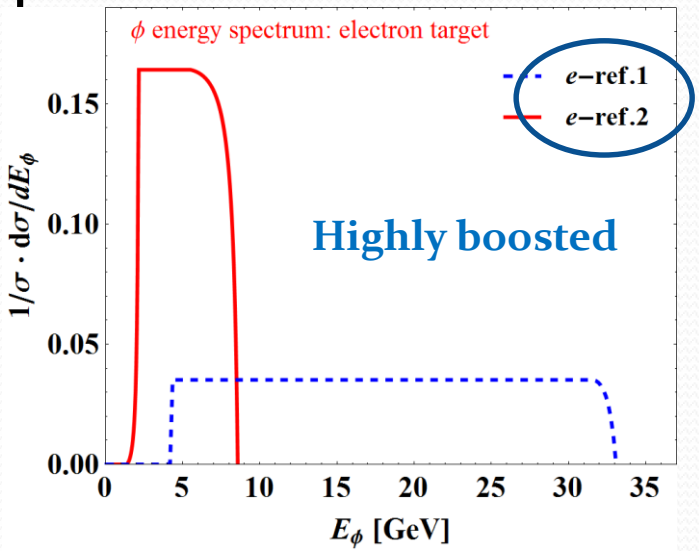
  - ✓ Primary scattering cross-X large when **momentum transfer small**
  - ✓ **Low threshold** energy for e-scattering but high for p-scattering (Cherenkov detectors)
  - ✓ p-scattering suppressed by the atomic form factor

Electron Scattering

Energy spectrum

- Simple scenario where ***X* decays back into χ_B and ϕ**

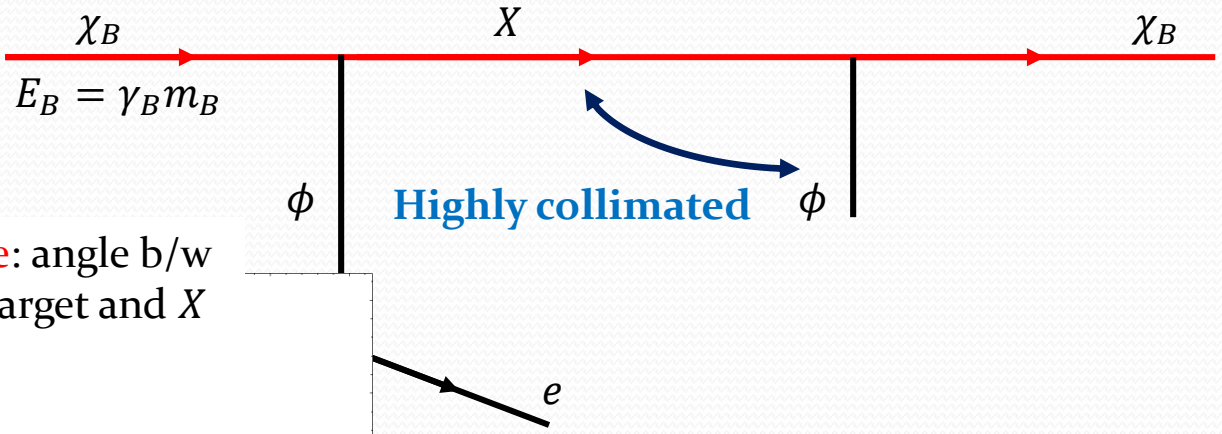


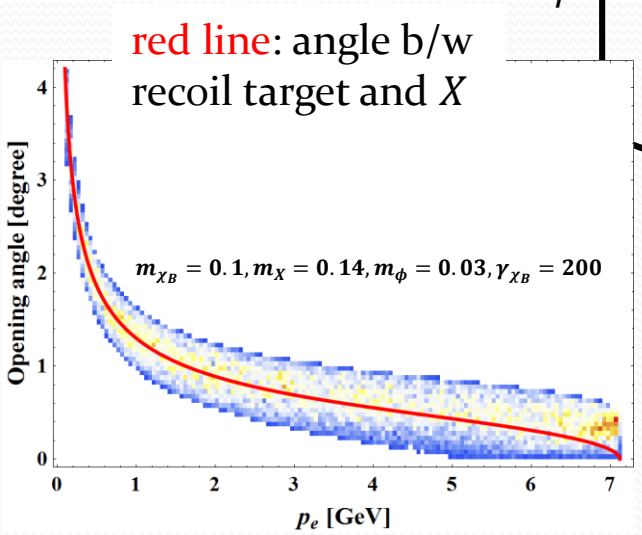


Electron Scattering

Highly collimated objects

- All final state objects are highly collimated.





Electron Scattering

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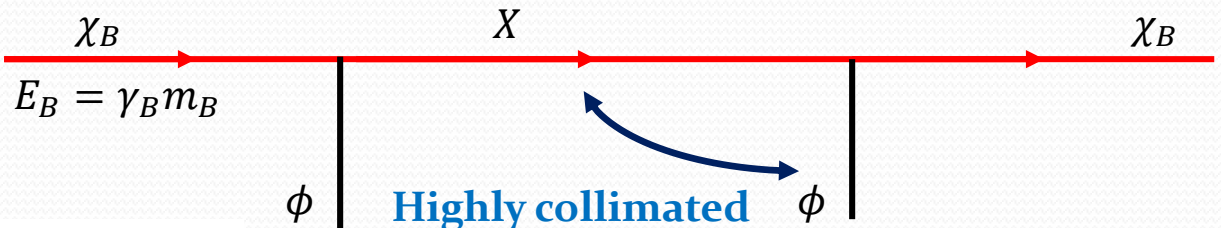
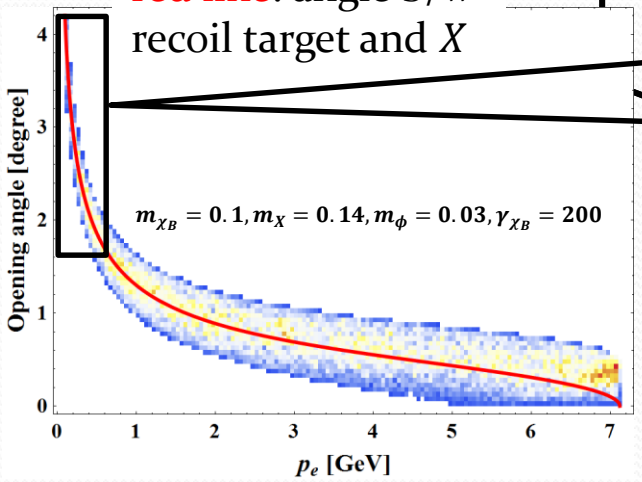
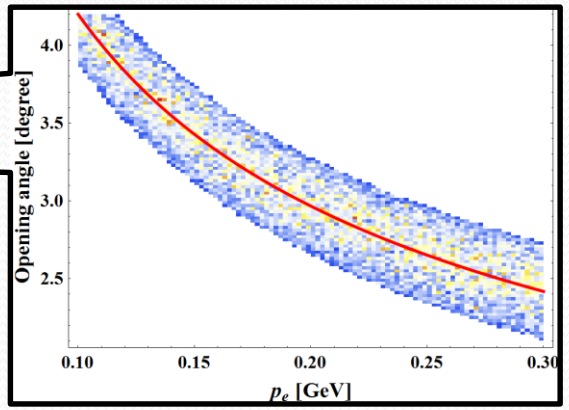


red line: angle b/w recoil target and X



e



Angular resolution of 3° (explain in a couple of slides)

→ "**two**" final state objects

Electron Scattering

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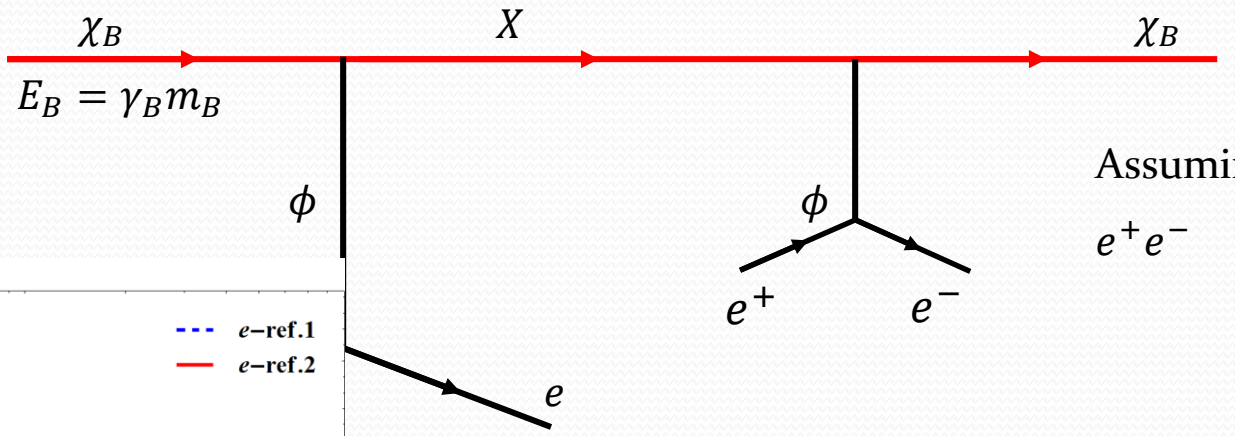
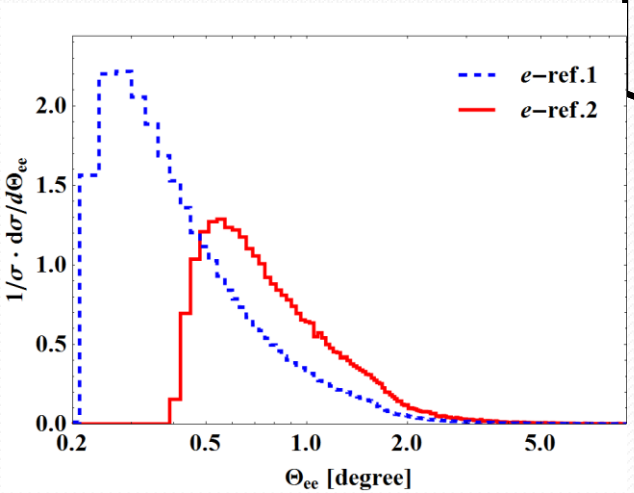


Assuming ϕ decays to e^+e^-



Angle between e^+e^- mostly $< 1.5°$

Electron Scattering

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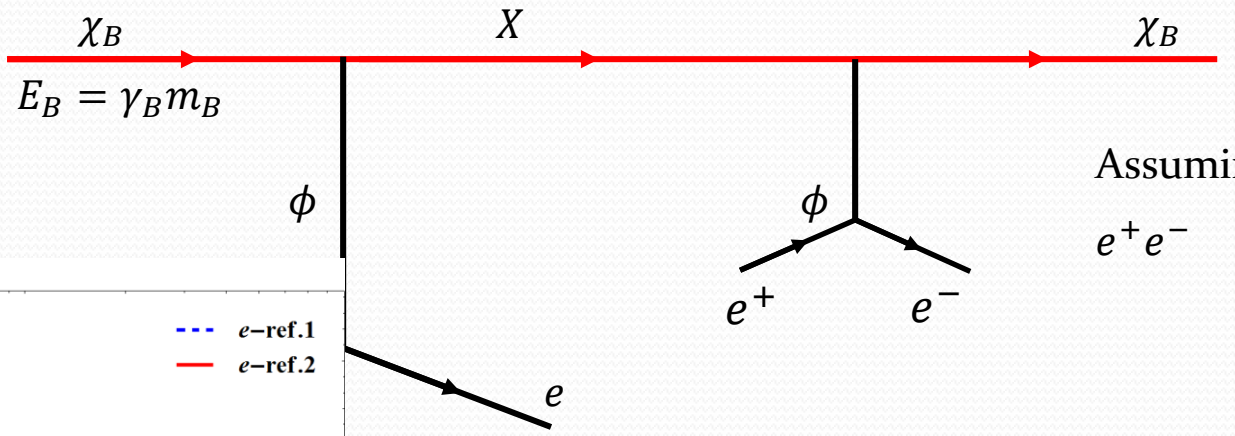

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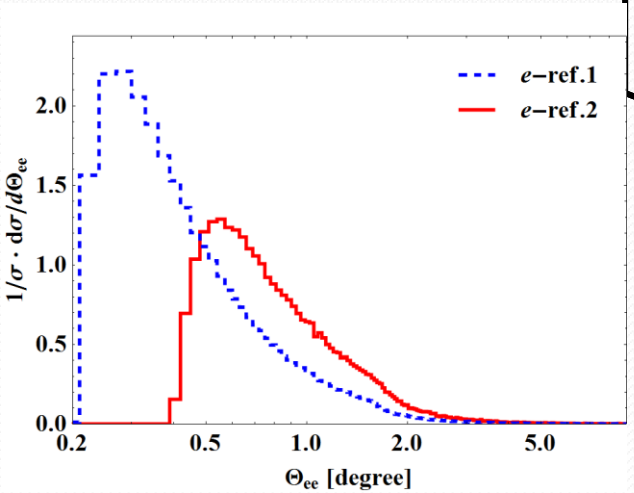


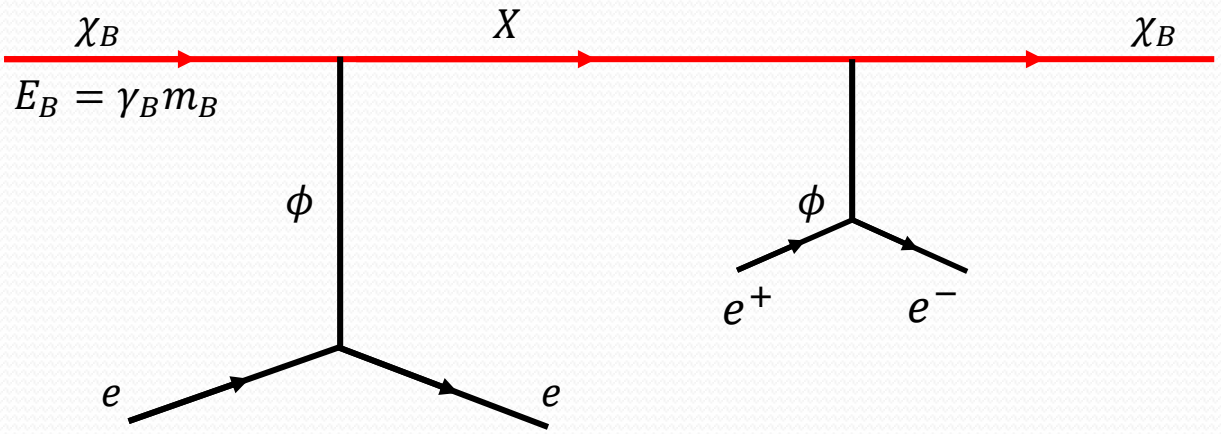
Angle between e^+e^- mostly $< 1.5°$

→ **High chance to observe two separate objects** in an experiment with an angular resolution of 3°

Discovery at Neutrino Detectors

Detection prospects

- Discovery opportunity at neutrino detectors



Exp.	Volume [Mt]	E_e^{thres} [GeV]	E_p^{thres} [GeV]	θ_e^{res}	θ_p^{res}
Super-K [24]	0.0224	0.01	1.07	3°	3°
Hyper-K [25]	0.56	0.01	1.07	3°	3°
DUNE [26]	0.04	0.03	0.05	1°	5°

Discovery at Neutrino Detectors

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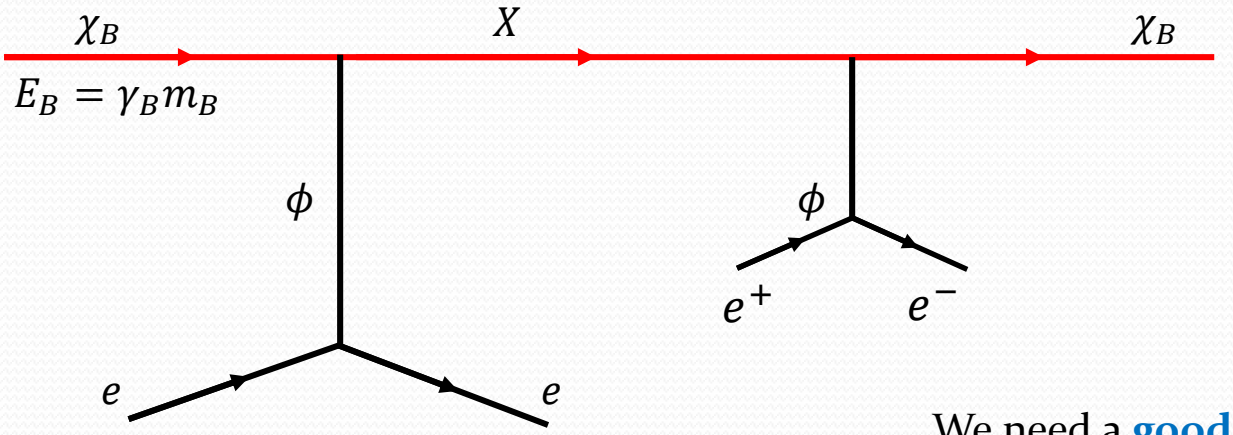


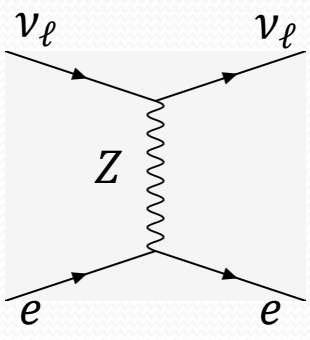
We need a **good resolution.**

Exp.	Volume [Mt]	E_e [GeV]	E_p^{thres} [GeV]	θ_e^{res}	θ_p^{res}
Super-K [24]	0.0224	**0.1**	1.07	3°	3°
Hyper-K [25]	0.56		1.07	3°	3°
DUNE [26]	0.04	0.03	0.05	1°	5°

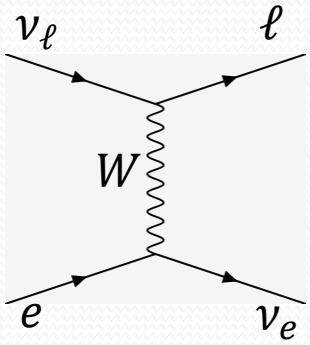
Background Considerations

Potential sources (work in progress)

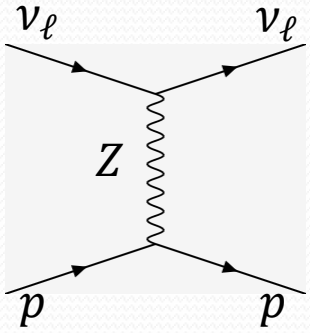
- Cherenkov radiation (CR) by electron/muon is distinguished from that by proton.
- Electron-preferred scenarios:



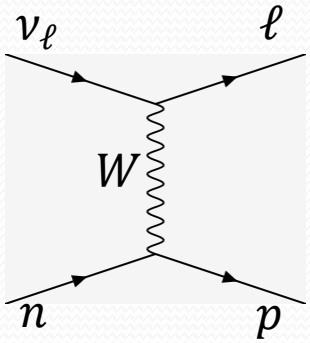
: CR by an N.C. electron



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



: CR by an N.C. proton unless broken



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

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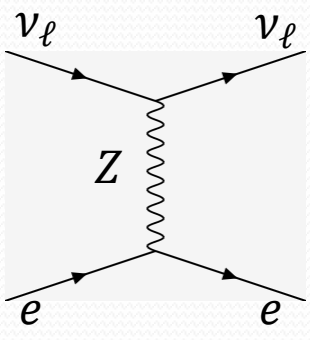
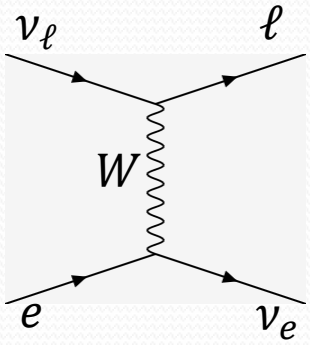
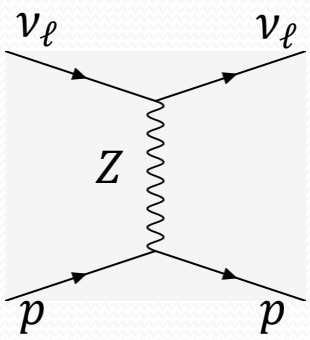


: CR by an N.C. electron



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



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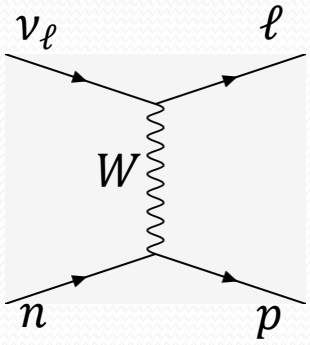
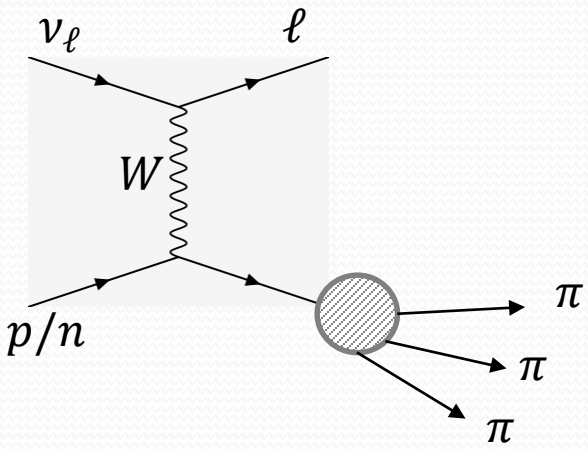


: CR by at least, a C.C. proton unless broken

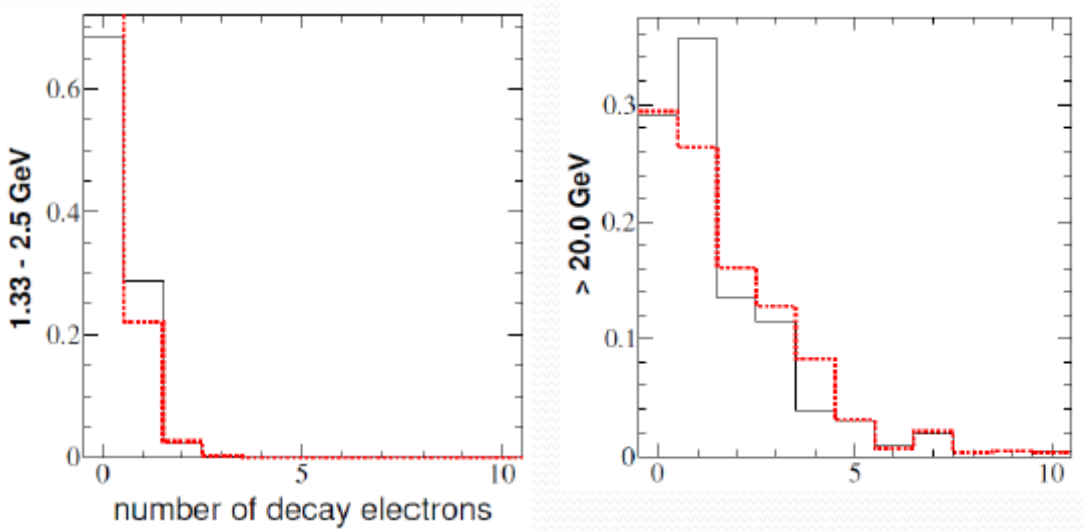
- Proton-preferred scenarios (discussed later): opening angles among recoil proton, decayed electrons are large enough to resolve

Background Considerations

- More challenging cases: broken nuclei



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



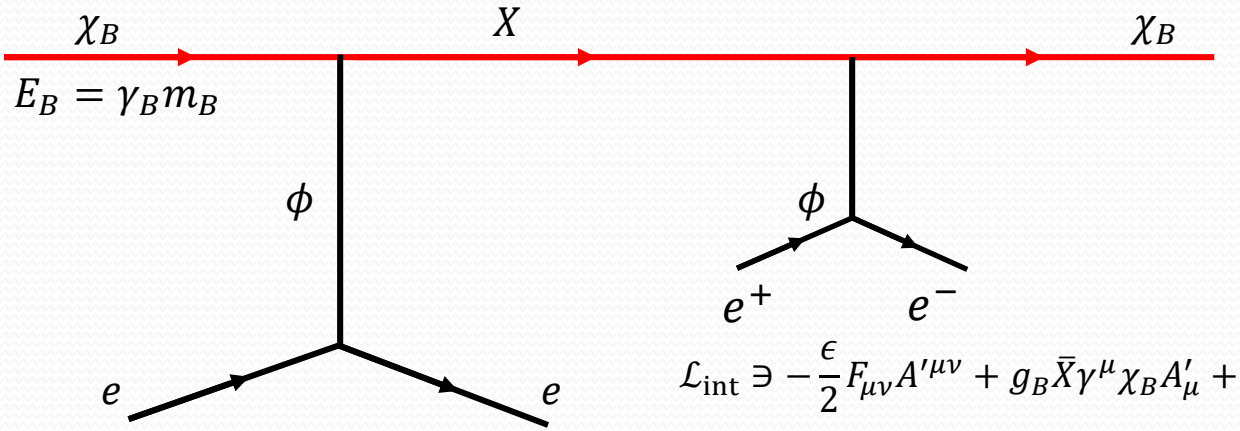
Super-K (2012)

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

Discovery Potential with *e*-Scattering

Required flux for discovery

- Expected experimental sensitivity defined by **three signal events** ("no bkg." assumed)



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

Exp.	e-ref1	e-ref2
Super-K 13.6 years	170	7.1
Hyper-K 1 year	88	3.7
Hyper-K 13.6 years	6.7	2.8
DUNE 1 year	190	9.0
DUNE 13.6 years	14	6.9

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

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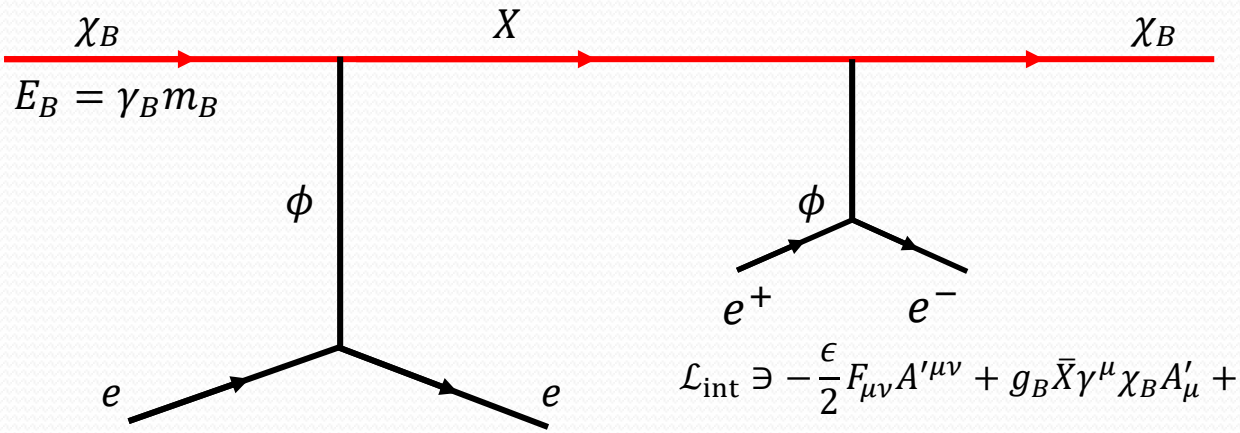

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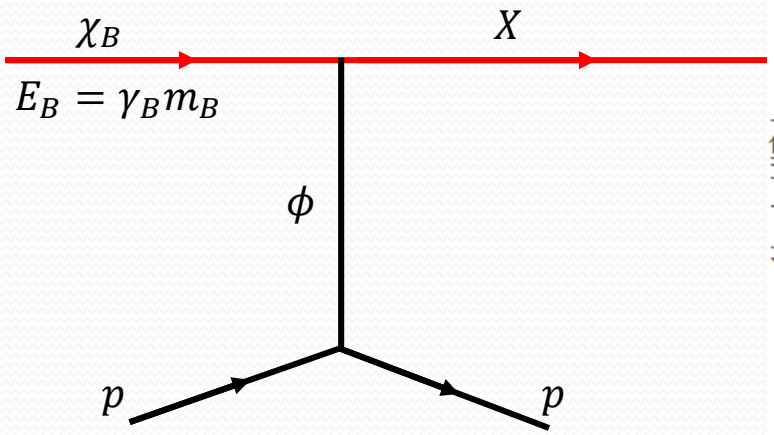
$(10^{-7}\mathrm{cm}^{-2}\mathrm{s}^{-1})$

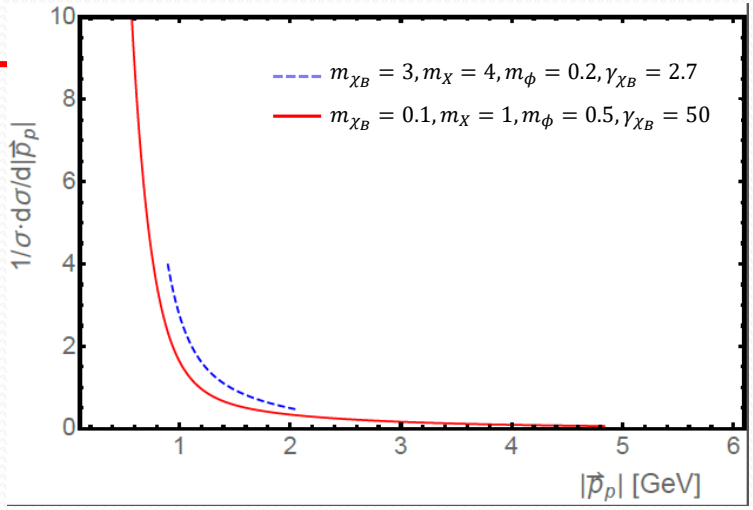
Remind, in a minimal boosted DM scenario, if flux over the whole sky is $\mathcal{O}(10^{-7})$ $\mathrm{cm}^{-2}\mathrm{s}^{-1}$, it is promising and achievable!

Proton Scattering

Energy spectrum

- Proton scattering of highly-boosted incident DM with a vector mediator





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  - ✓ Primary scattering cross-X large when **momentum transfer small**

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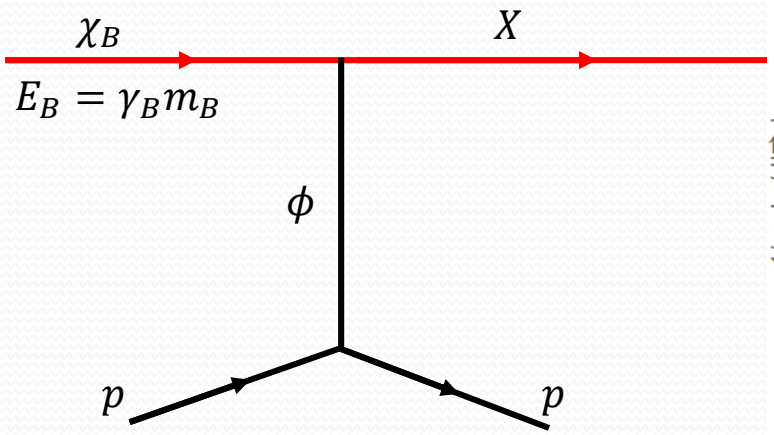

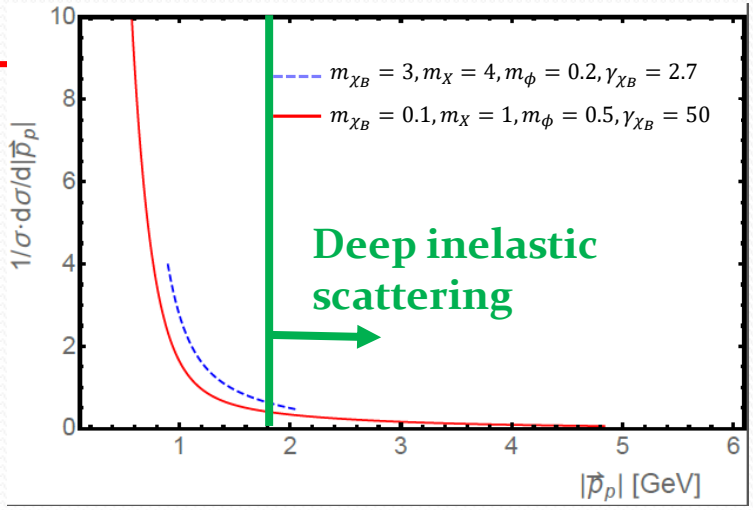

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Energy spectrum

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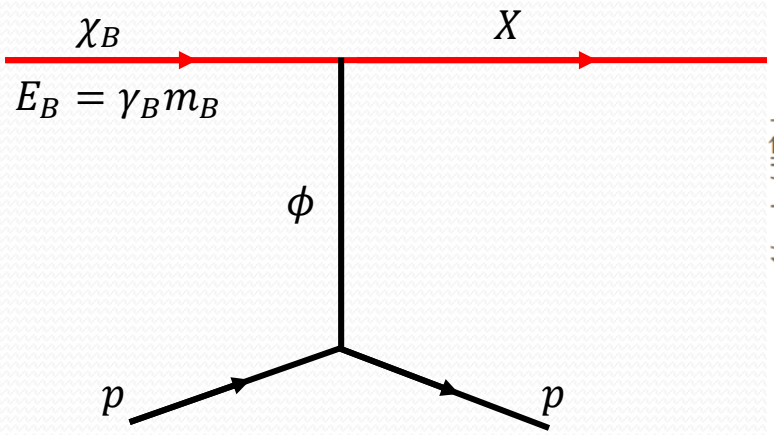

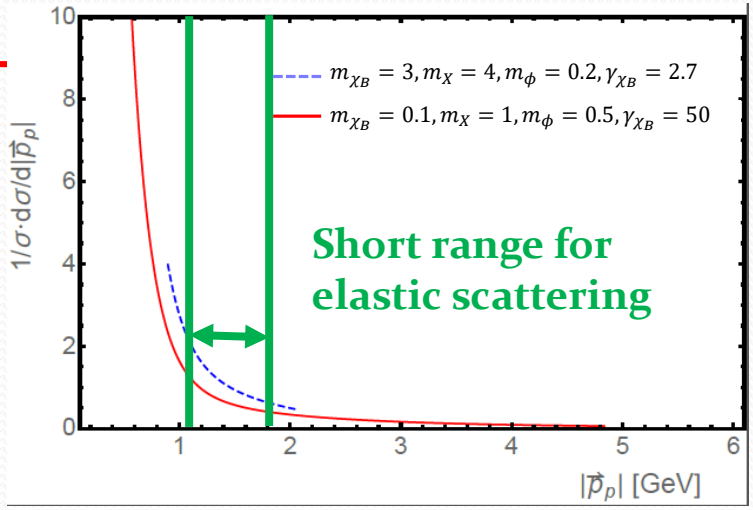

- p-scattering NOT preferred over e-scattering
  - ✓ Primary scattering cross-X large when **momentum transfer small**
  - ✓ p-scattering suppressed by the atomic form factor
  - ✓ **High threshold** energy for p-scattering (Cherenkov detectors)

Proton Scattering

Energy spectrum

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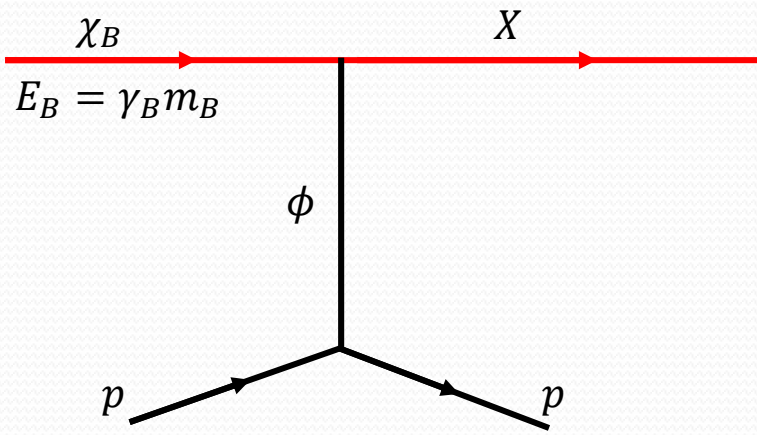

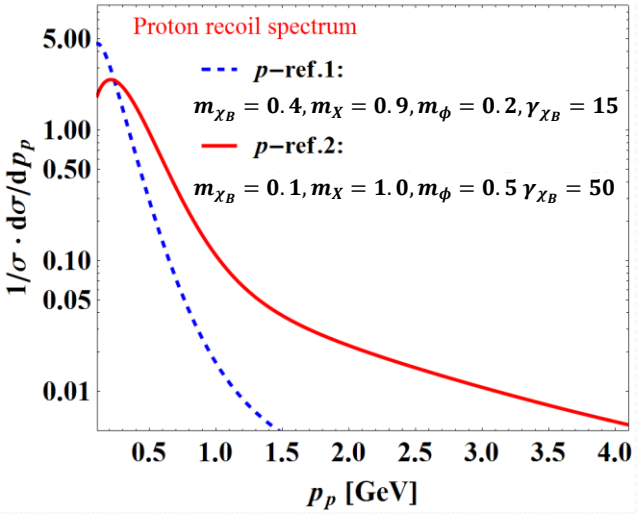

- However, the **cascade process is unique**!

Proton Scattering

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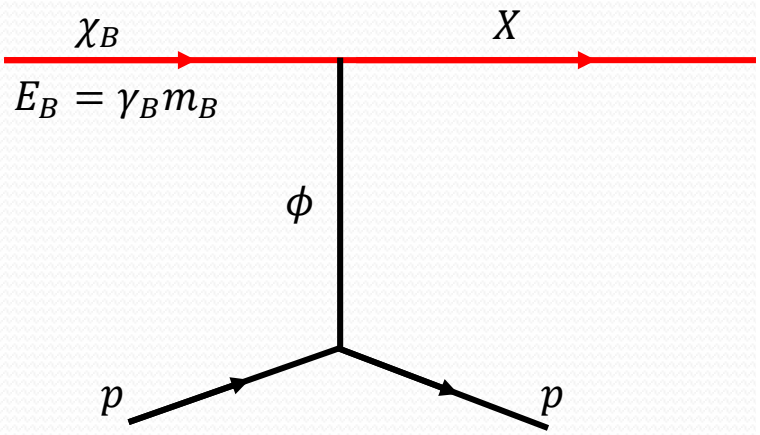

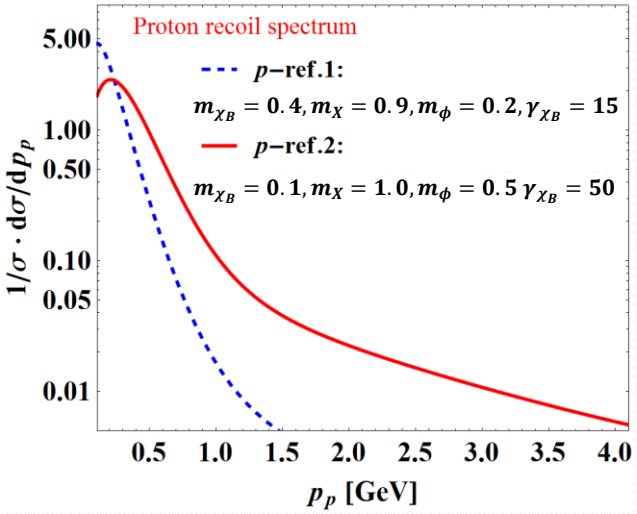

- However, the **cascade process is unique**!
- **Low threshold** for p-scattering for liquid Ar detectors

  (e.g., DUNE: $E_{th} = 50$ MeV)

Proton Scattering

Energy spectrum

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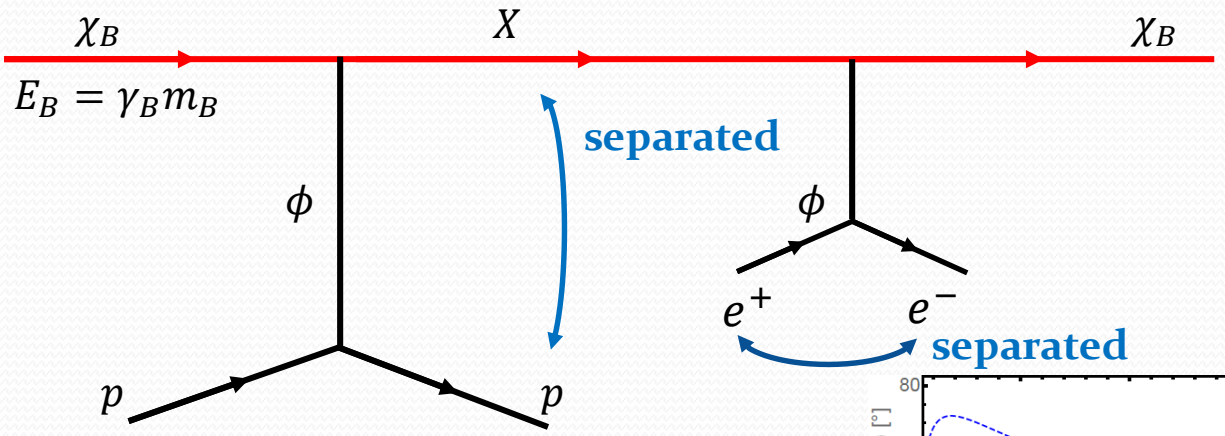

- However, the **cascade process is unique**!
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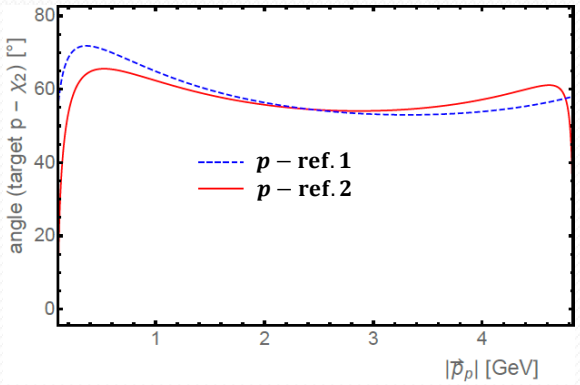
- **3 separated visible objects**



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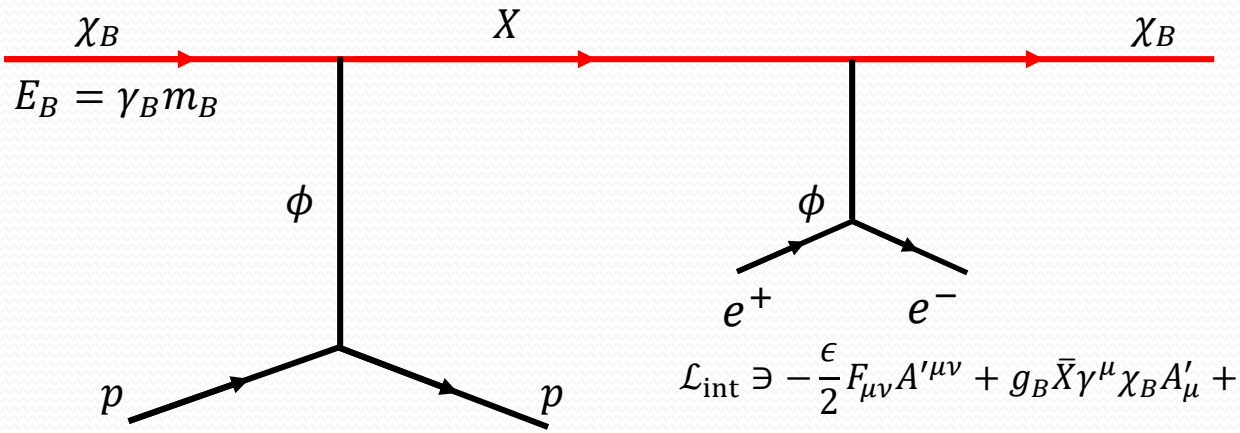

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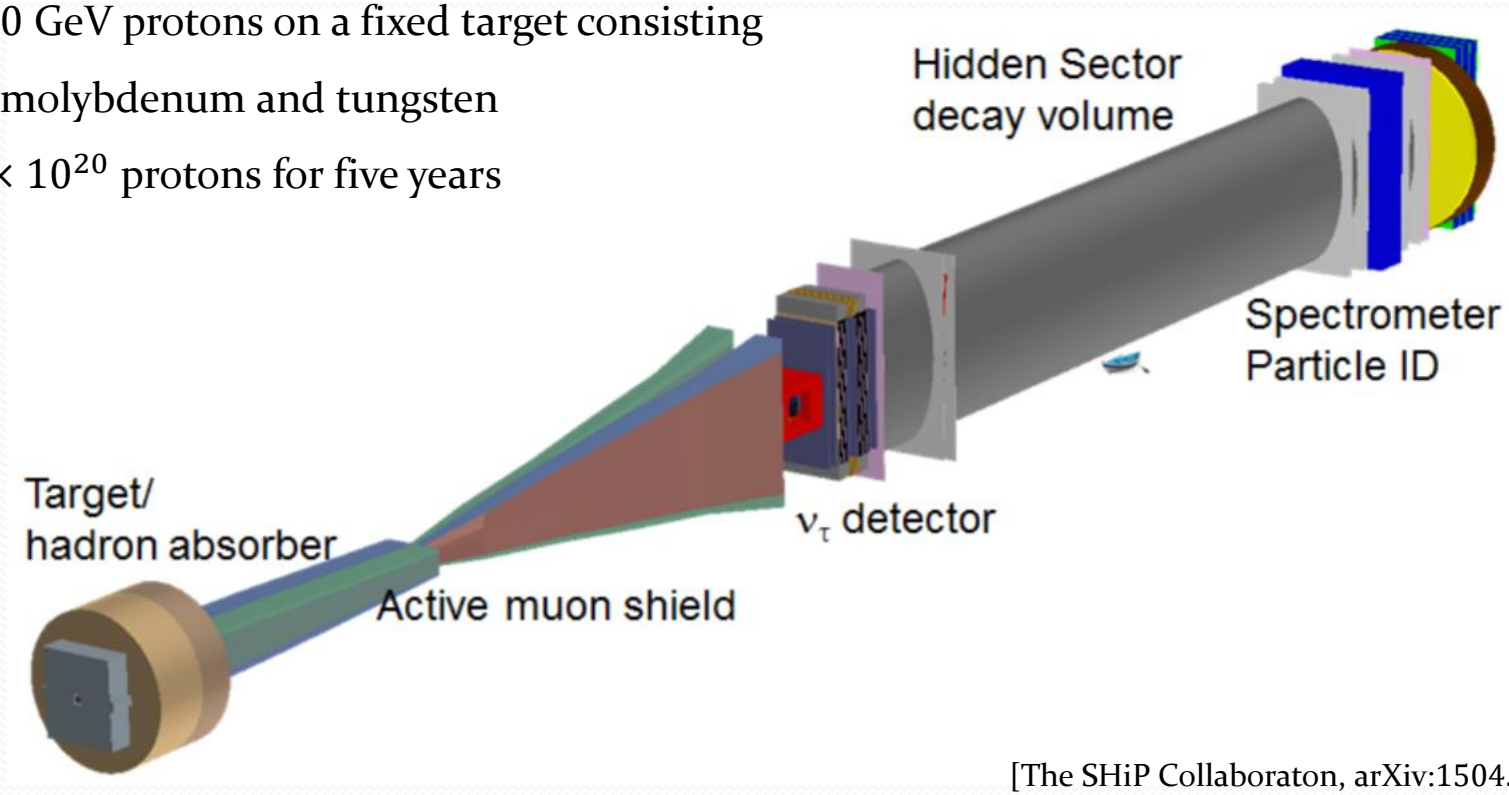
Exp.	p-ref1	p-ref2
Super-K 13.6 years	3500	5200
Hyper-K 1 year	1900	2800
Hyper-K 13.6 years	140	210
DUNE 1 year	150	1600
DUNE 13.6 years	11	120

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

SHiP as a Hidden Sector Detector

Overview of the SHiP facility

- 400 GeV protons on a fixed target consisting of molybdenum and tungsten
- 2×10^{20} protons for five years

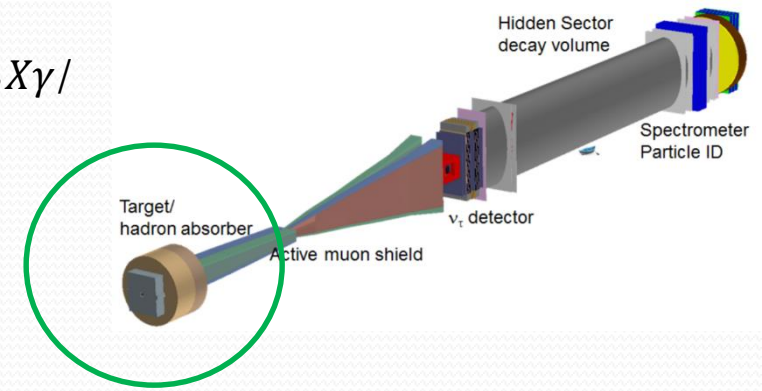


[The SHiP Collaboraton, arXiv:1504.04956]

SHiP as a Hidden Sector Detector

Production

- $pp \rightarrow B + \text{others}, B \rightarrow A'^{*}\gamma \rightarrow \chi_B\chi_B\gamma / B \rightarrow A'^{*}\gamma \rightarrow \chi_B X\gamma /$
  $B \rightarrow A'^{*}\gamma \rightarrow XX\gamma$
- $pp \rightarrow A'^{*} \rightarrow \chi_B\chi_B, \chi_B X, XX$
- Etc.



SHiP as a Hidden Sector Detector

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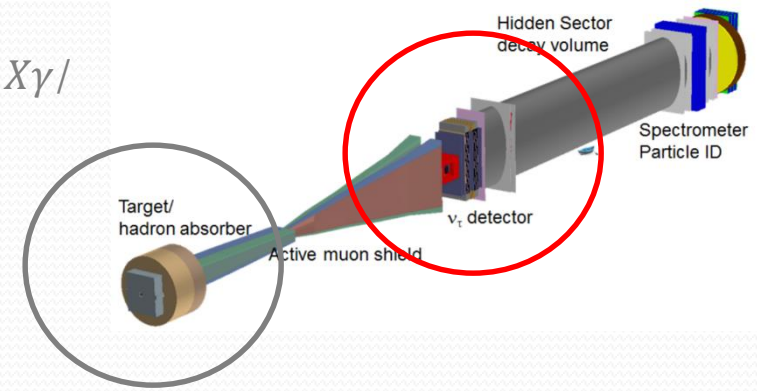
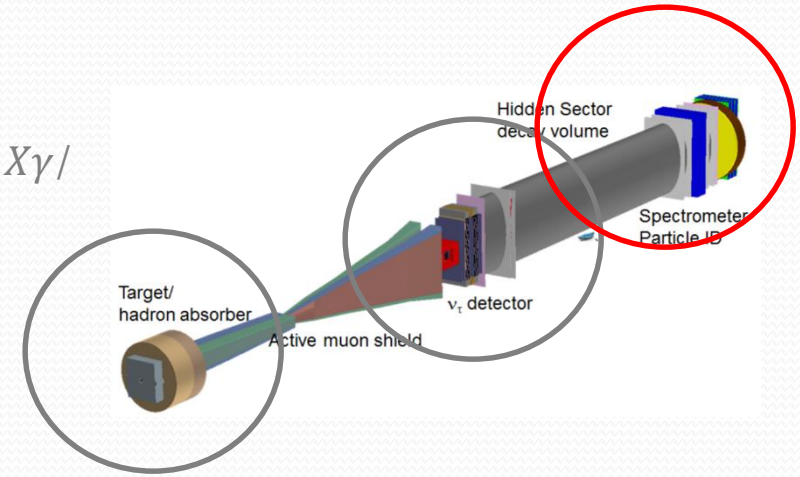


- $\chi_B + \nu_\tau$ detector $\rightarrow X +$ recoil e/p
  - Prompt scenario: $X \rightarrow \chi_B A', A' \rightarrow e^+e^-$ at ν_τ detector, **3 (hopefully) resolvable** objects

SHiP as a Hidden Sector Detector

Detection

- $pp \rightarrow B +$ others, $B \rightarrow A'^{*}\gamma \rightarrow \chi_B\chi_B\gamma / B \rightarrow A'^{*}\gamma \rightarrow \chi_B X\gamma /$ $B \rightarrow A'^{*}\gamma \rightarrow XX\gamma$
- $pp \rightarrow A'^{*} \rightarrow \chi_B\chi_B, \chi_B X, XX$
- Etc.



- $\chi_B + \nu_\tau$ detector $\rightarrow X +$ recoil e/p
  - Prompt scenario: $X \rightarrow \chi_B A', A' \rightarrow e^+e^-$ at ν_τ detector, **3 (hopefully) resolvable** objects
  - "Long-lived" scenario: 1) $X \rightarrow \chi_B A'^{*} \rightarrow \chi_B e^+e^-$ 2) $X \rightarrow \chi_B A', \ldots\ldots, A' \rightarrow e^+e^-$, detection of electron/positron at the calorimeter complex → **3 resolvable** objects

Conclusions

Summary and outlook

- The more, the messier? The more, the merrier!

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Conclusions

Summary and outlook

- The more, the messier? The more, the merrier!
- ***Orthogonal***: (Relatively) **background-free** due to secondary signatures → **new direct DM search paradigm**!
- ***Inexpensive***: Exclusion limit/detection prospects at existing/future experiments such as Super-K, Hyper-K, DUNE, SHiP, etc. → **worth further investigation**

Conclusions

Summary and outlook

- The more, the messier? The more, the merrier!
- ***Orthogonal***: (Relatively) **background-free** due to secondary signatures → **new direct DM search paradigm**!
- ***Inexpensive***: Exclusion limit/detection prospects at existing/future experiments such as Super-K, Hyper-K, DUNE, SHiP, etc. → **worth further investigation**
- ***Complementary***: constraining parameters for various DM scenarios/models

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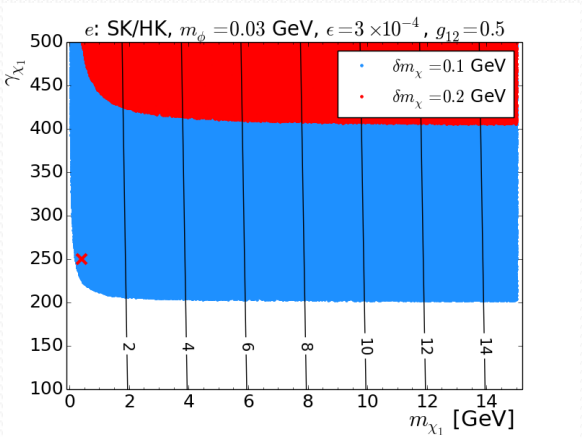
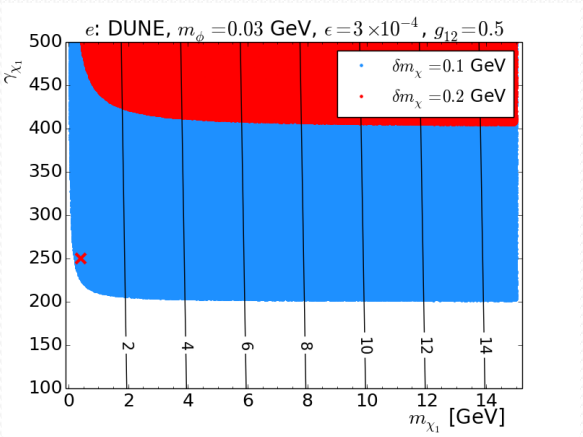
- ***Complementary***: constraining parameters for various DM scenarios/models
- ***Interdisciplinary***: If this scenario is the truth, **many ideas in collider phenomenology directly apply**!

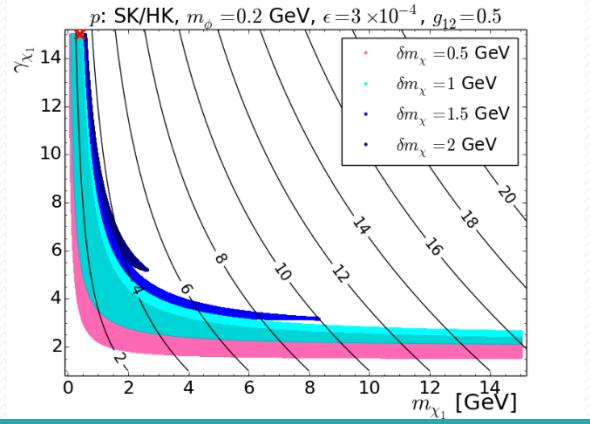
Thank you!

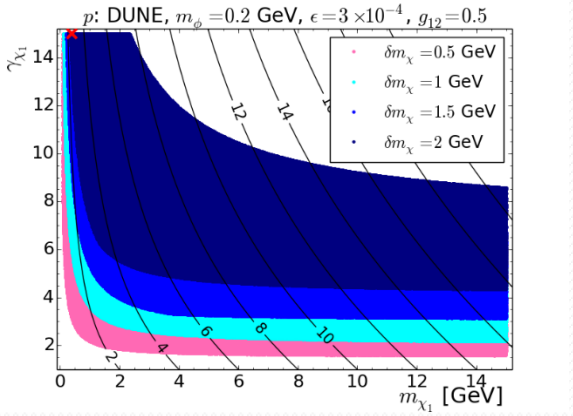
Back-up

- Parameter scanning





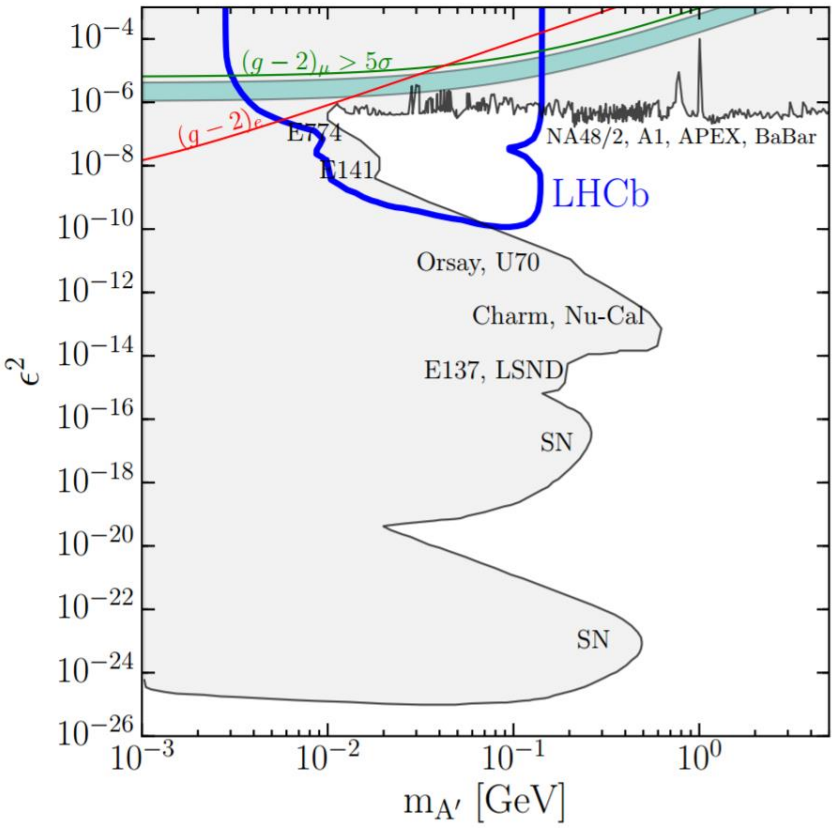


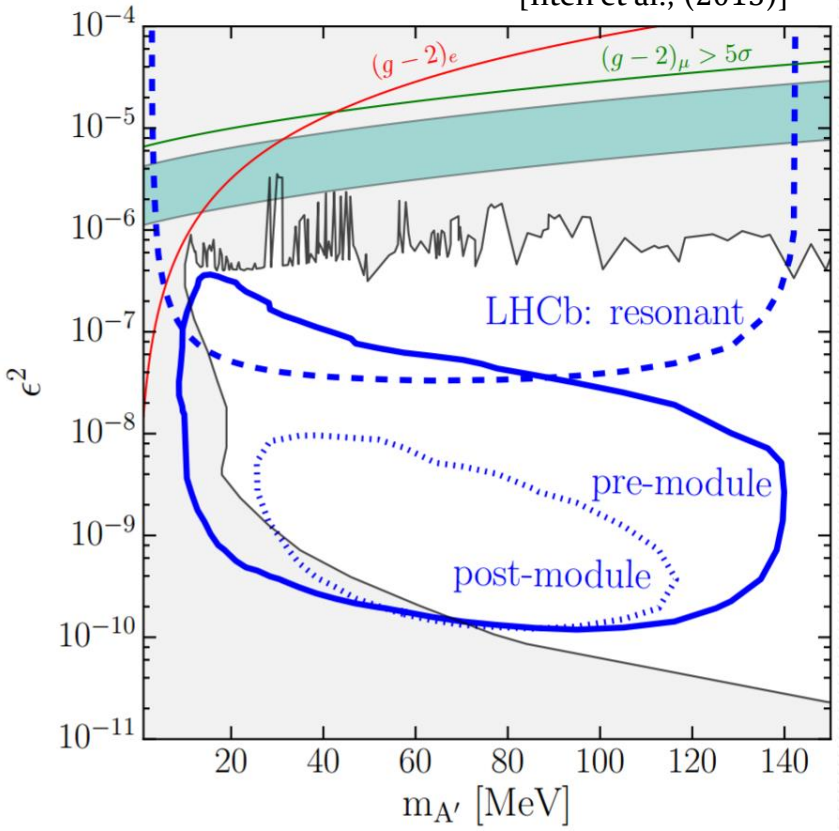


Back-up

- Kinetic mixing parameter choice

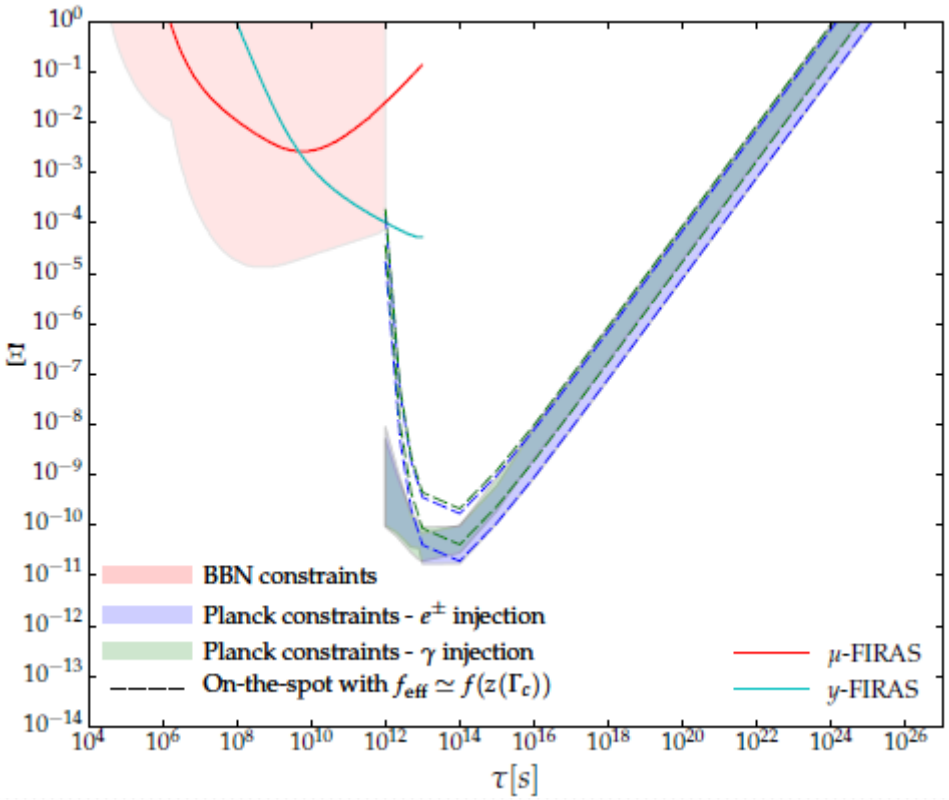
[Ilten et al., (2015)]





Back-up

- BBN/CMB constraints



[Poulin et al., (2016)]