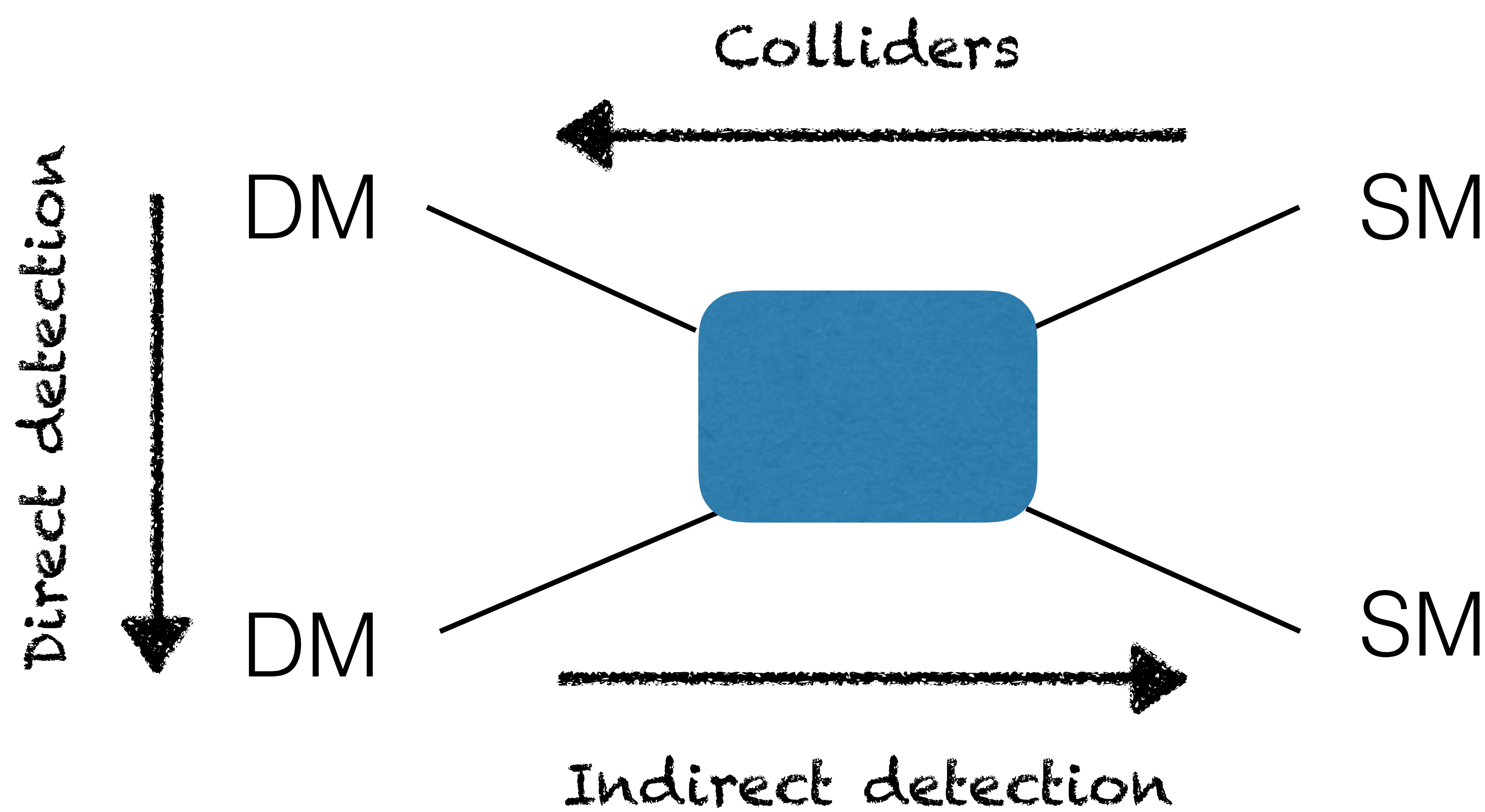
Dark matter collider:
cascade signals from inelastic boosted DM

Seodong Shin

arXiv: 1612.06867 with Doojin Kim, Jong-Chul Park

Contents

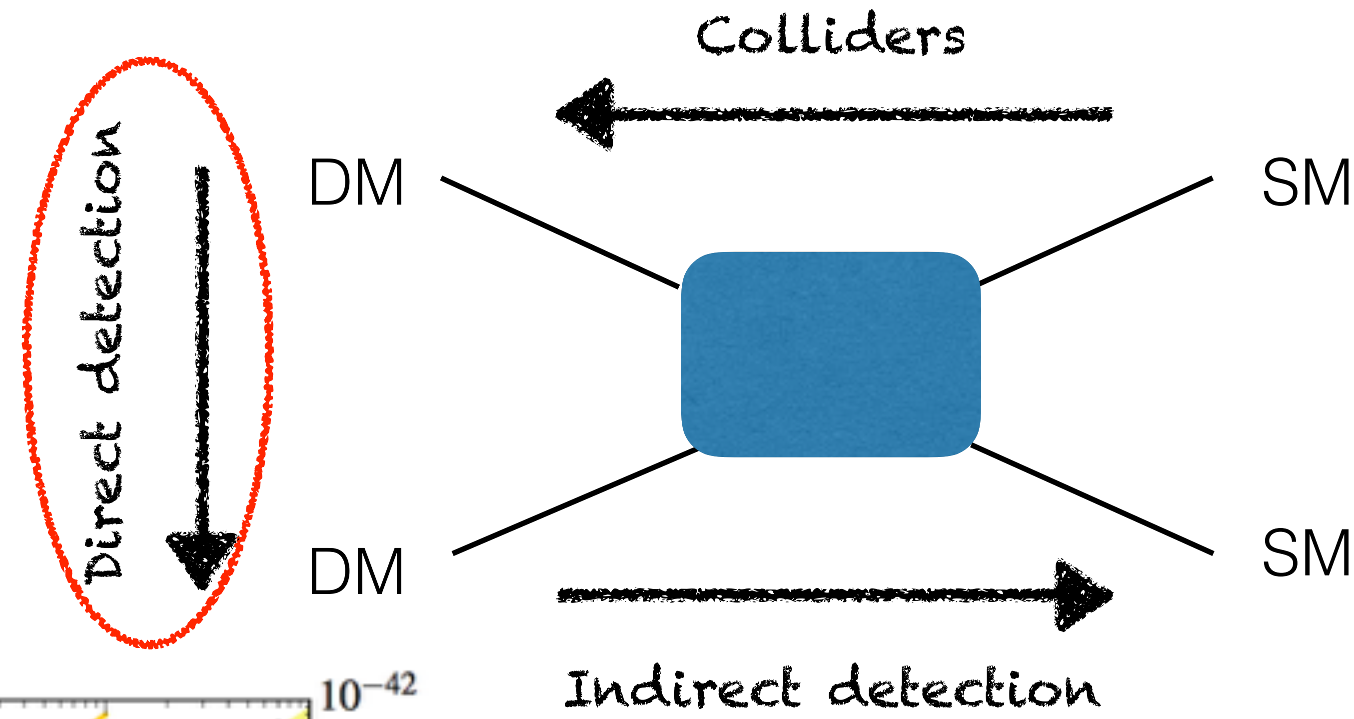
Search of Dark Matter

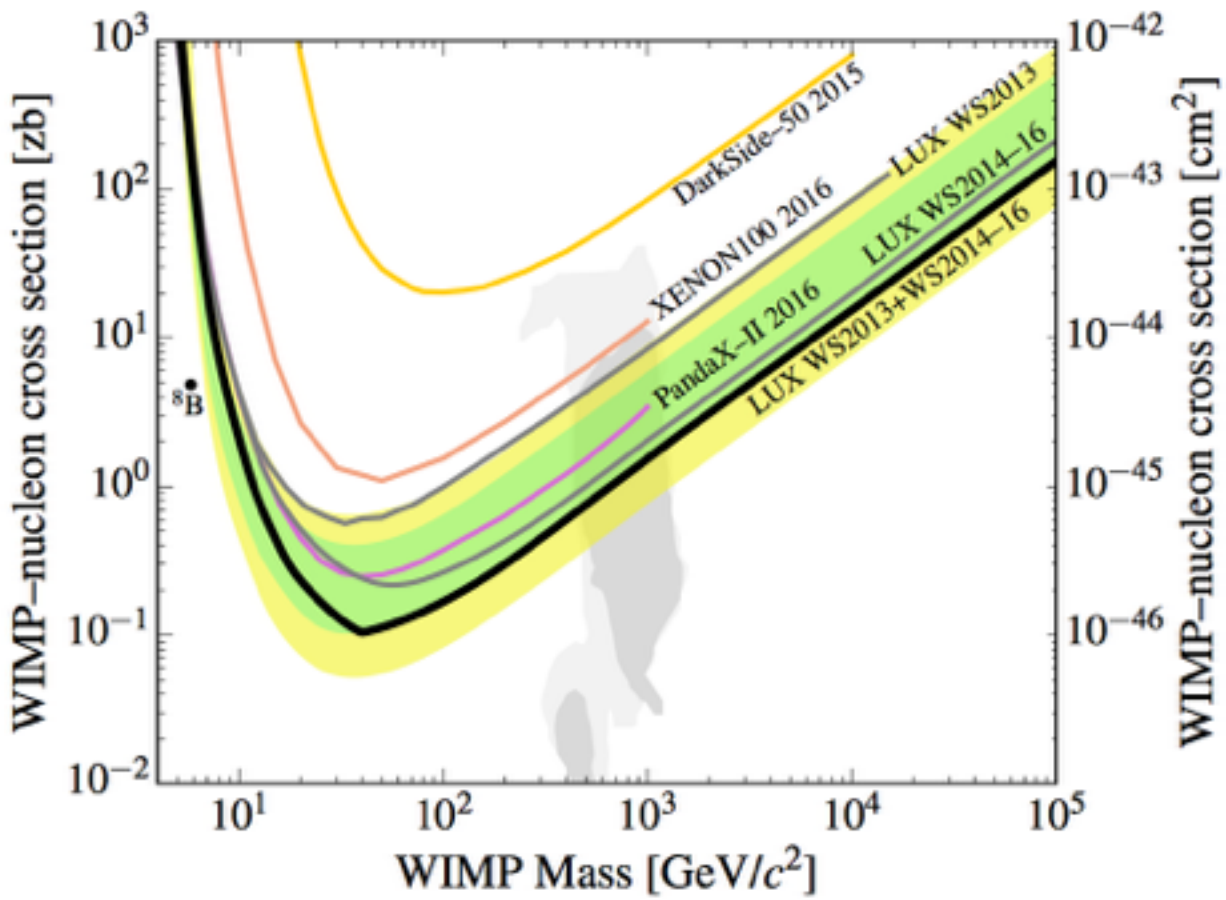


Popular diagram shown everywhere for the search of WIMP

Search of Dark Matter

Non-relativistic scattering of WIMP



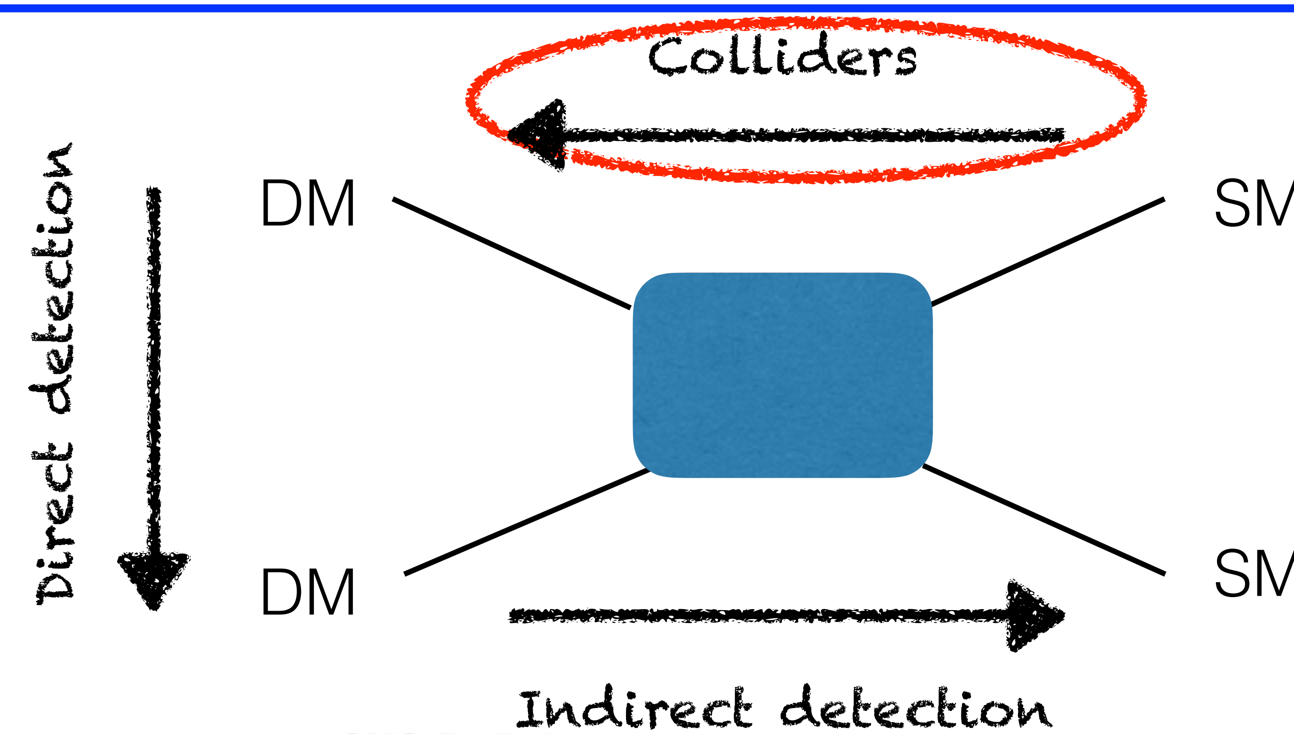


Touch down a part of neutrino floor soon!!!

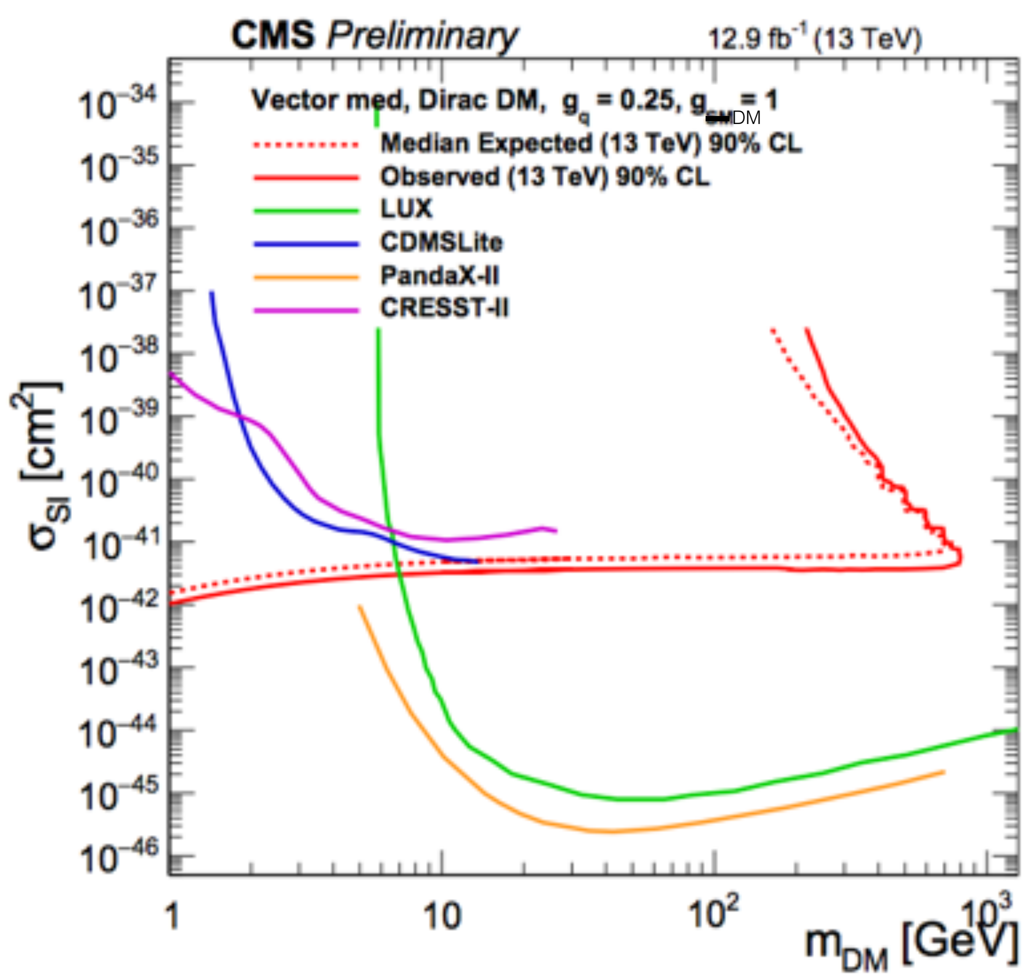
LUX 2016
1608.07648

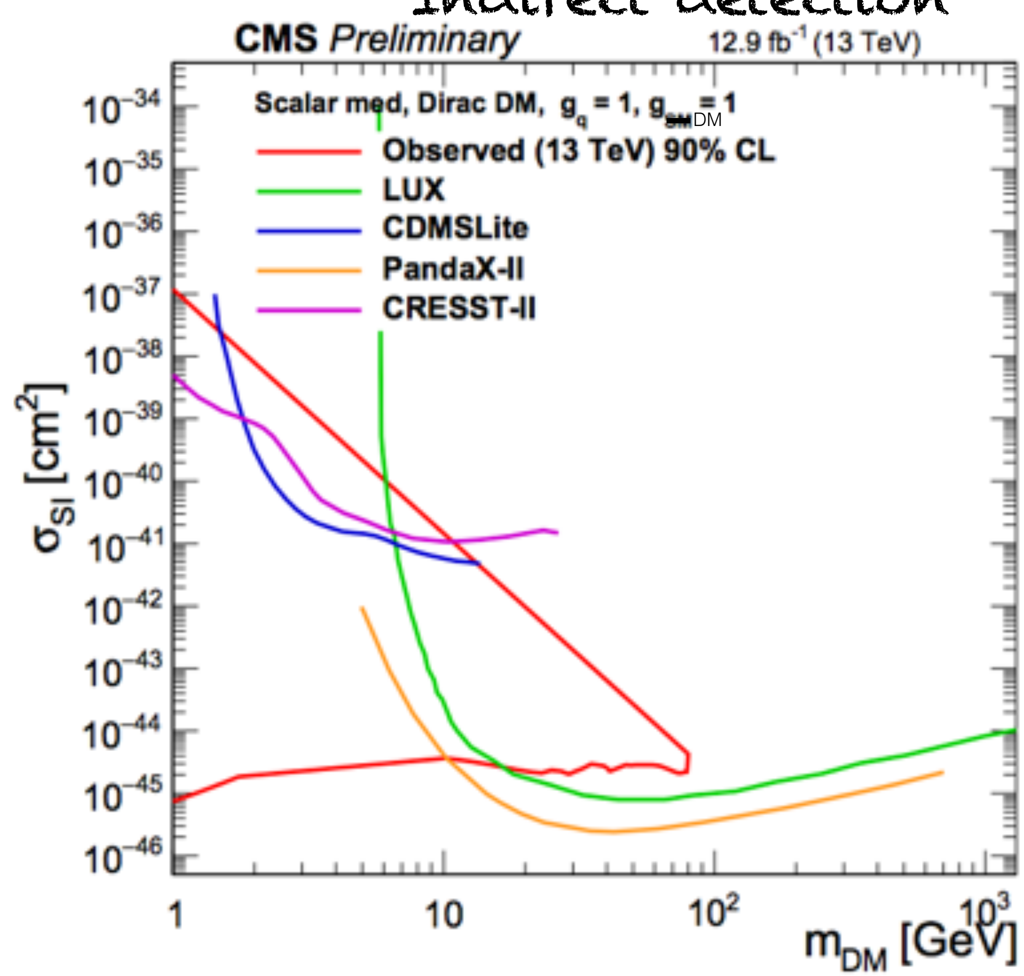
Search of Dark Matter

Strong bounds too
(mono-X)



CMS, EXO-16-037-pas

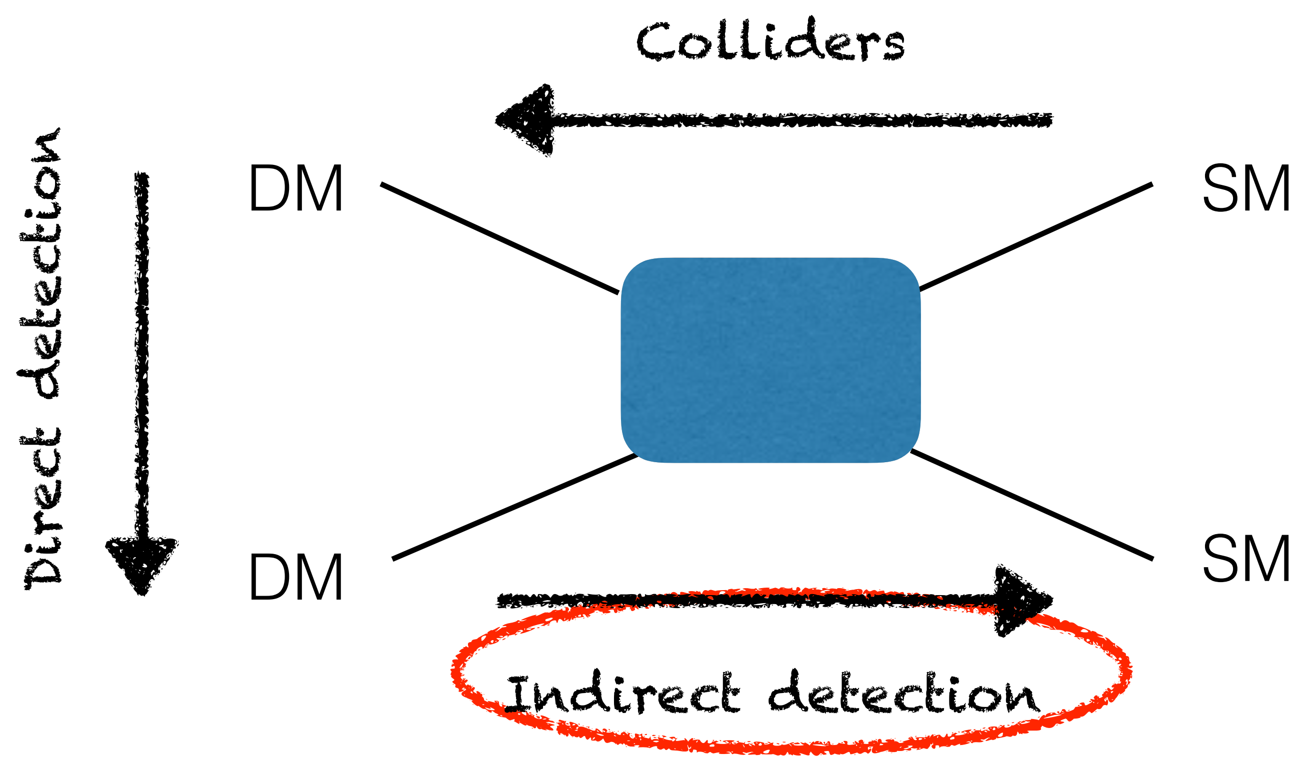




Search of Dark Matter

Some (strong) bounds

- γ-rays from dSphs
- Antiproton ratios



but some hints as well (although bkg. is not fully understood)

- γ-rays from the galactic center
- Positron ratio
- Neutrino signals

Search of Dark Matter

Some (strong) bounds

- γ-rays from dSphs
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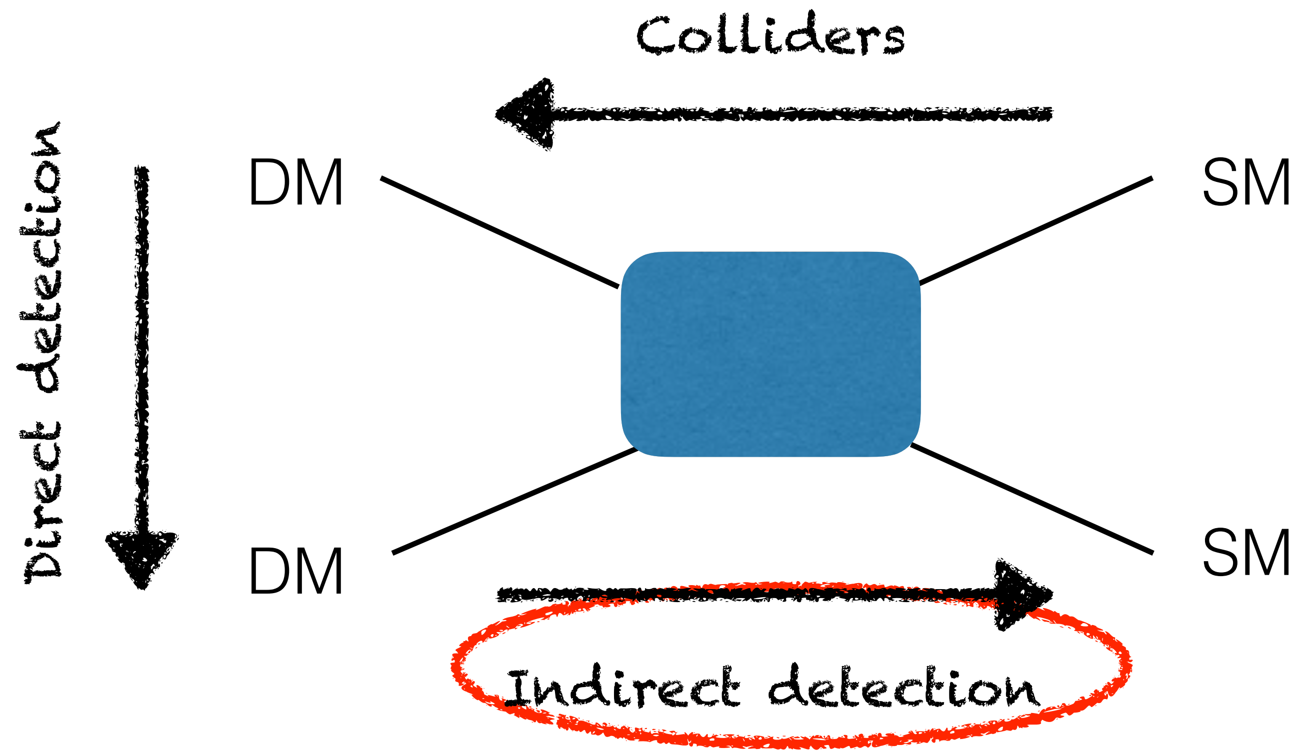


but some hints as well (although bkg. is not fully understood)

- γ-rays from the galactic center
- Positron ratio
- Neutrino signals

DM signal not sensitive to direct detection & colliders

Secluded Dark Matter?

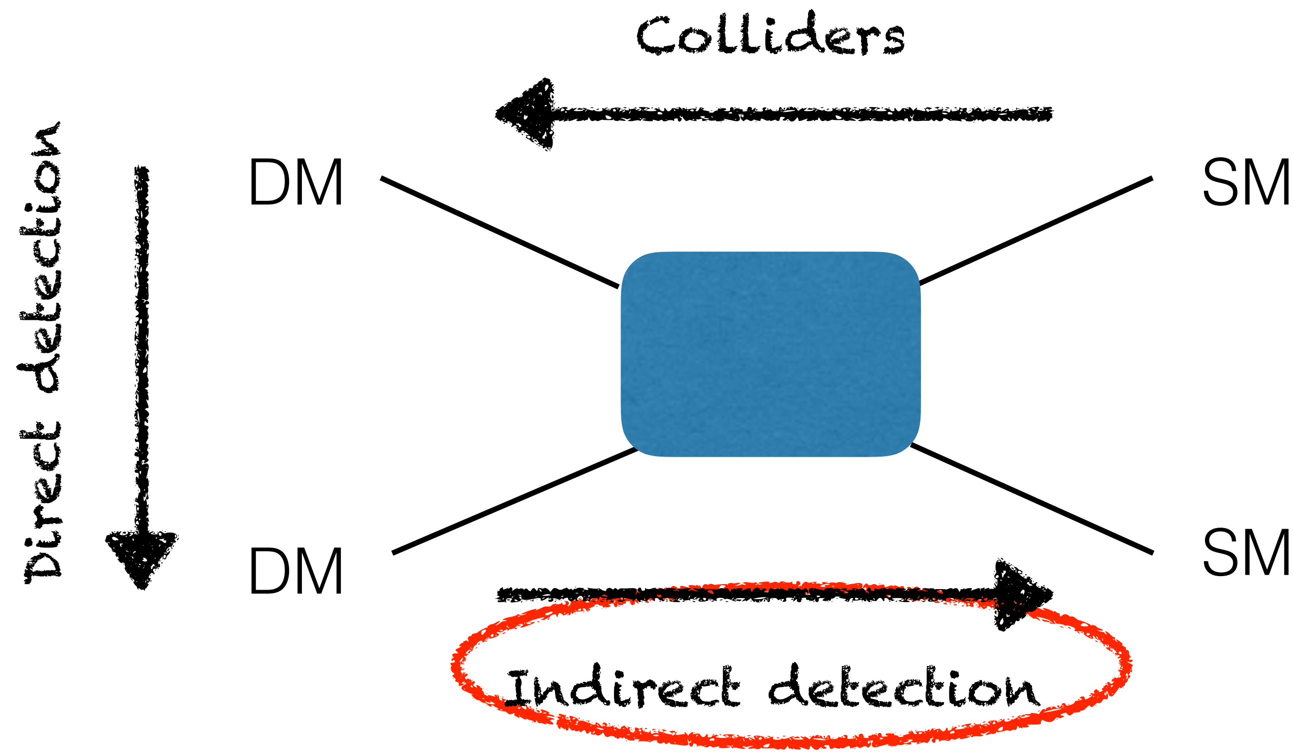
Secluded set-up

Huh, Kim, Park, Park, 0711.3528

Pospelov, Ritz, Voloshin, 0711.4866

Kim, **SS**, 0901.2609

& many others……

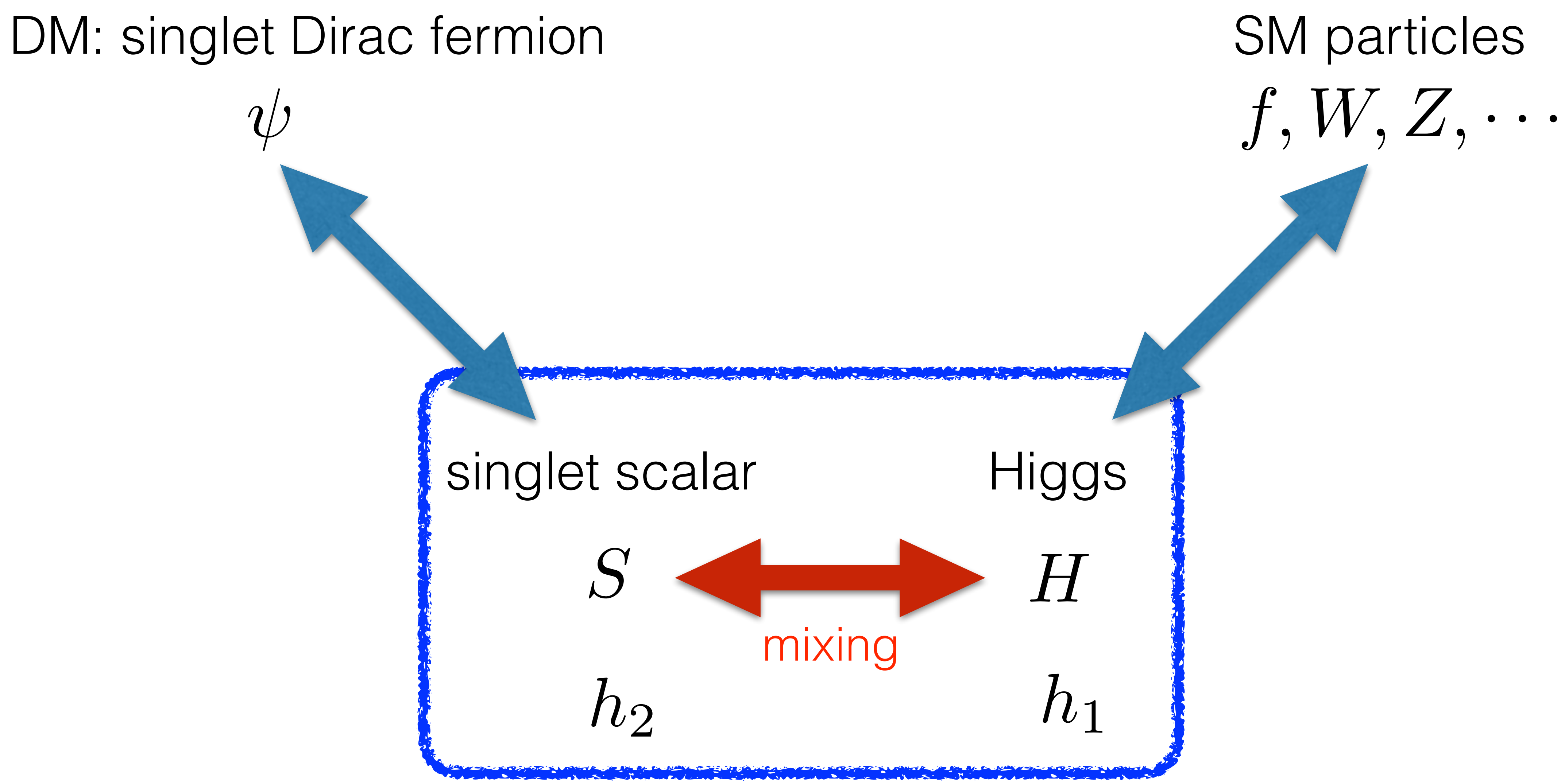


- Size of DM interaction with SM is small:
  avoid strong bounds from direct detection & colliders

- Processes for the relic/ID are separated from DD or collider:
  need more particles in the dark sector

Kim, **SS**, 0901.2609 Kim, Lee, **SS**, 0803.2932

Singlet Fermionic Dark Matter



Y.G. Kim, K.Y. Lee, **SS**, JHEP 0805, 100 [arXiv:0803.2932]

A renormalizable Higgs portal WIMP model

(induce bunch of phenomenological studies: exotic decay, …)

Search of Secluded Dark Matter

How do you search such a hidden DM?

- Indirect detection can be a key guide:
  provide reference parameters for the searches in colliders & DD

- Relativistic scattering of DM with a target

O(GeV) broad γ-ray excess from the galactic center

(Fermi-LAT)

Consistent parameters in famous WIMP models

Kim, Lee, Park, **SS**, 1601.05089

& many others……

Search of Secluded Dark Matter

How do you search such a hidden DM?

- Indirect detection can be a key guide:
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  Kim, Lee, Park, **SS**, 1601.05089
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Search of Secluded Dark Matter

How do you search such a hidden DM?

- Indirect detection can be a key guide:
  provide reference parameters for the searches in colliders & DD
  Kim, Lee, Park, **SS**, 1601.05089

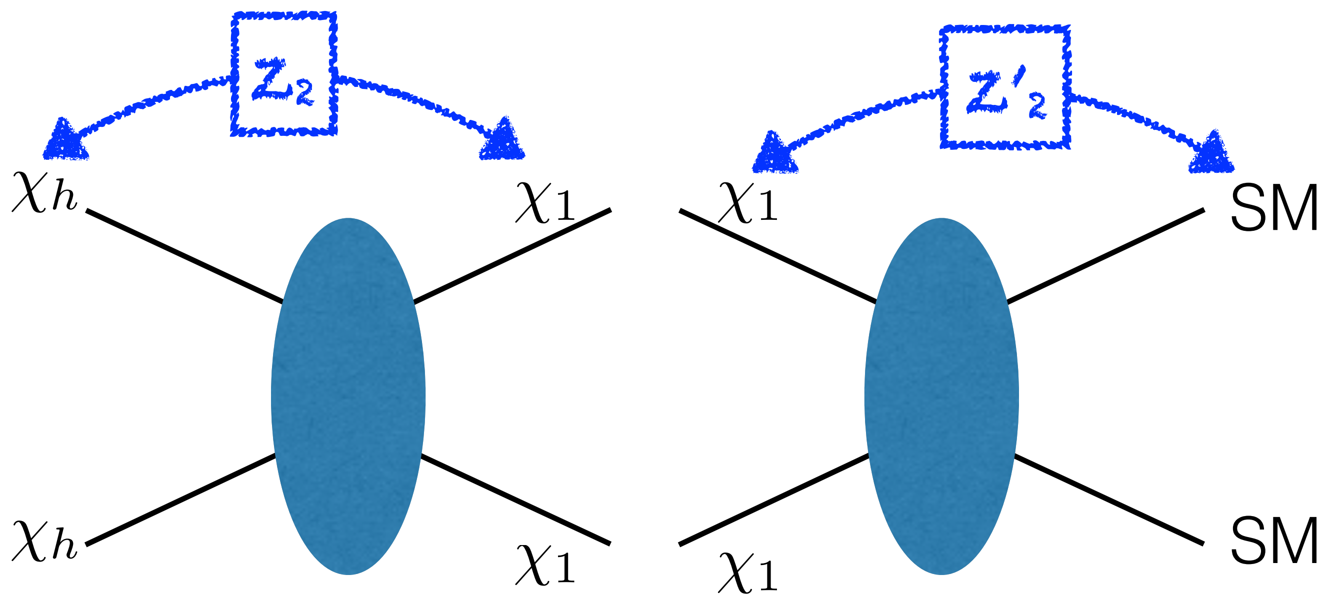
- Relativistic scattering of DM with a target

- Some components of DM are relativistic: boosted DM
  Agashe, Cui, Necib, Thaler, 1405.7370
  Kong, Mohlaberg, Park, 1411.6632

- (Light) DM is produced in fixed target experiments
  Bjorken, Essig, Schuster, Toro, 0906.0580
  Batell, Pospelov, Ritz, 0906.5614

Boosted DM

Minimal model example



Belanger, Park, 1112.4491

Agashe, Cui, Necib, Thaler, 1405.7370

Boosted DM

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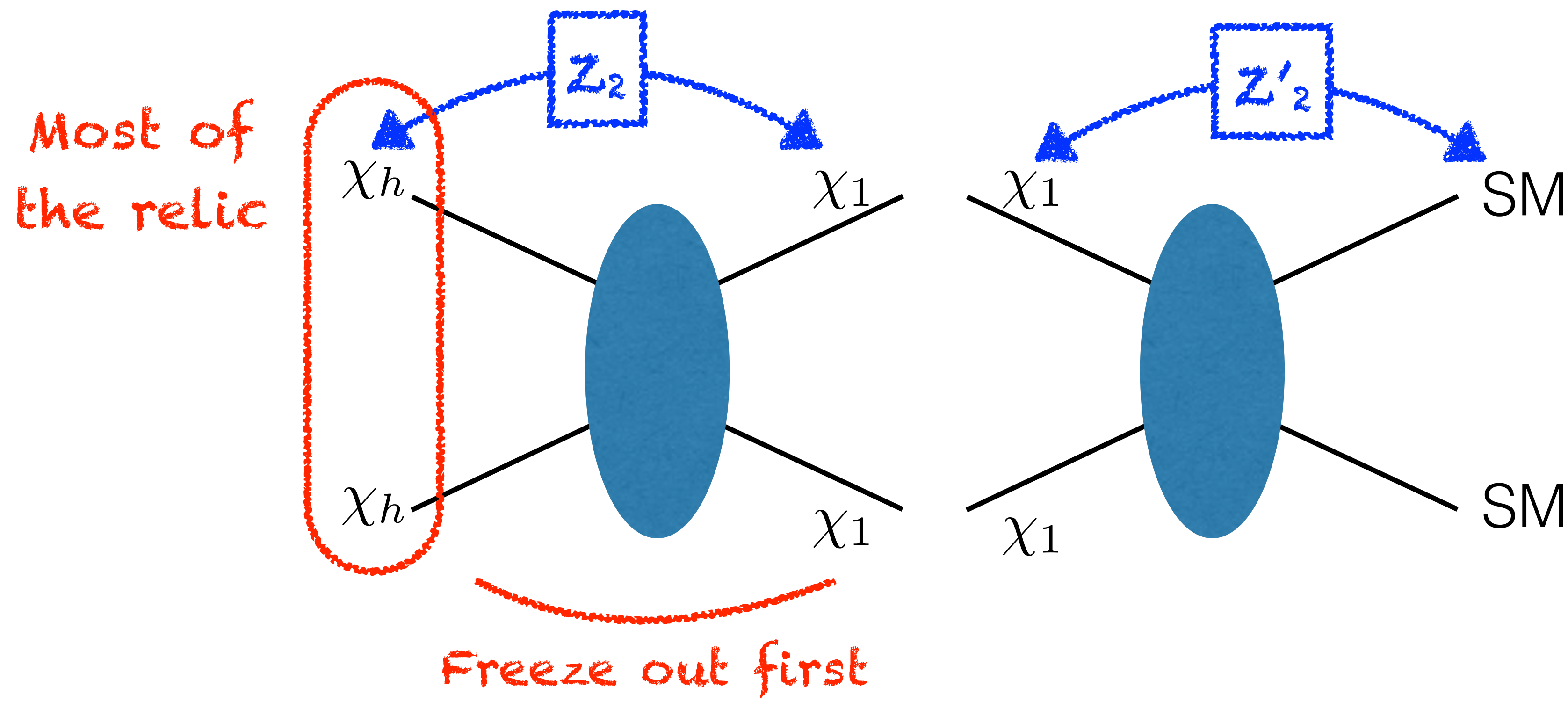

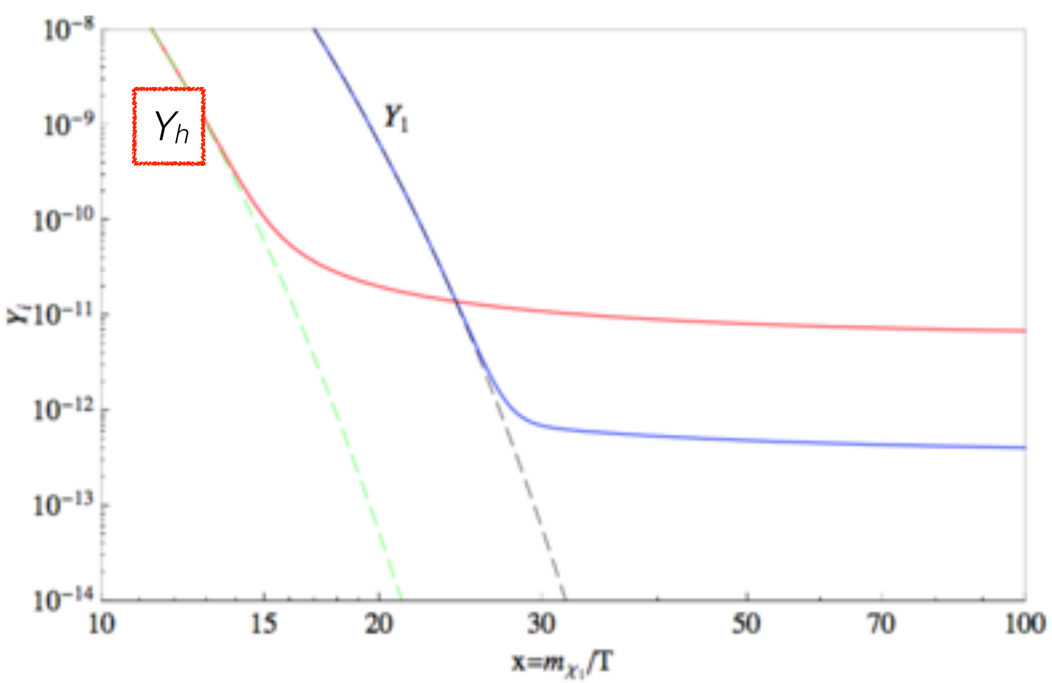

Belanger, Park, 1112.4491

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Boosted DM

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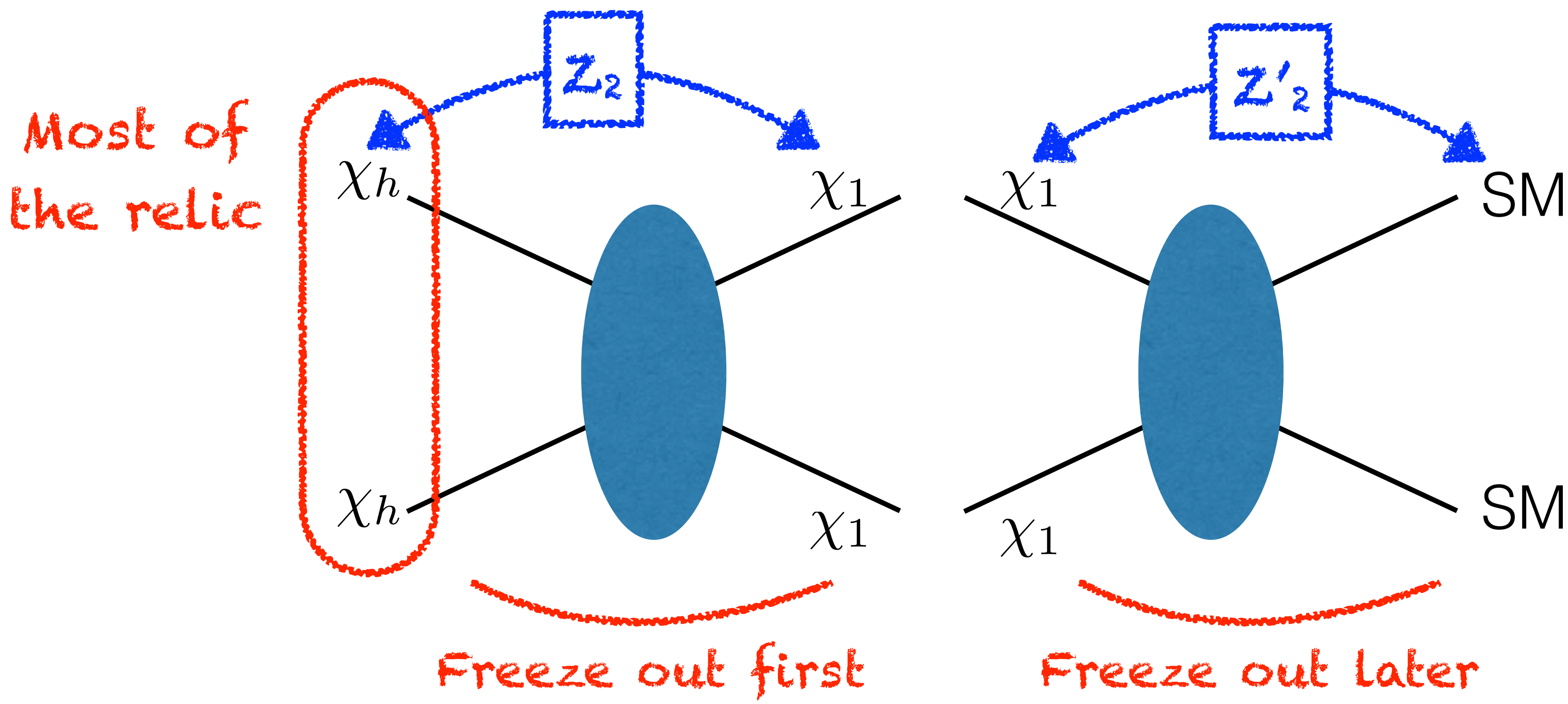
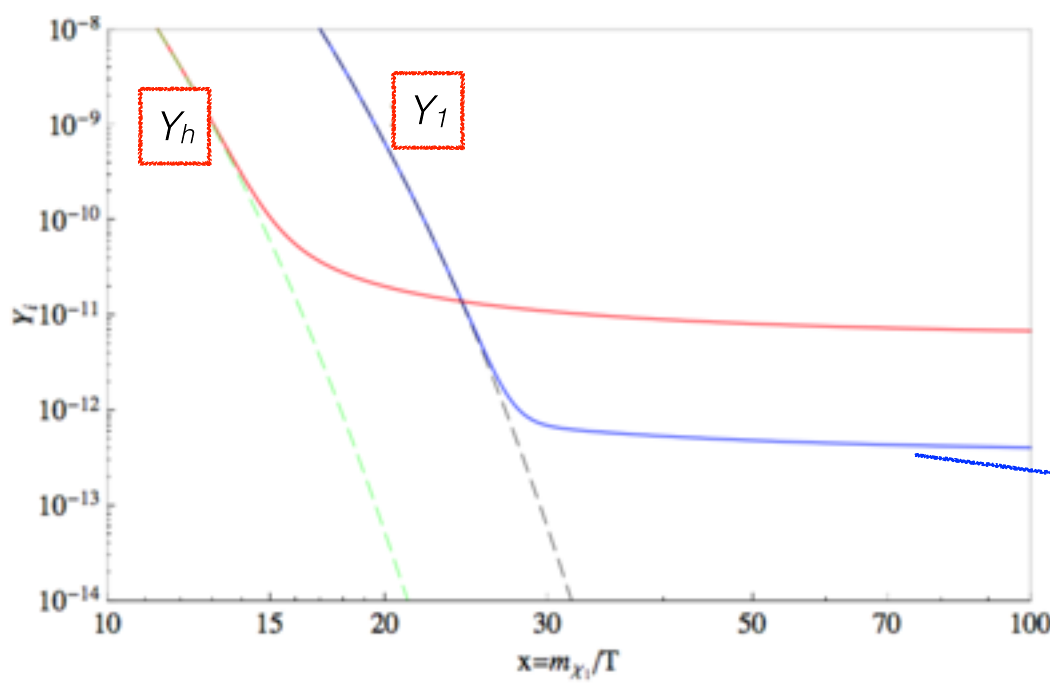




Belanger, Park, 1112.4491

Agashe, Cui, Necib, Thaler, 1405.7370

Talk by JC Park

Assisted freeze-out

(Flux of relic χ_1: small)

non-relativistic

Detection of boosted DM

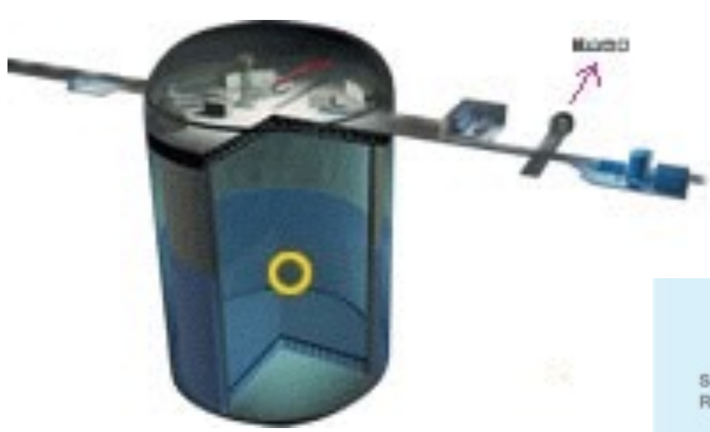
Dominant relic χ_h: but do not directly interact with SM

$\downarrow$

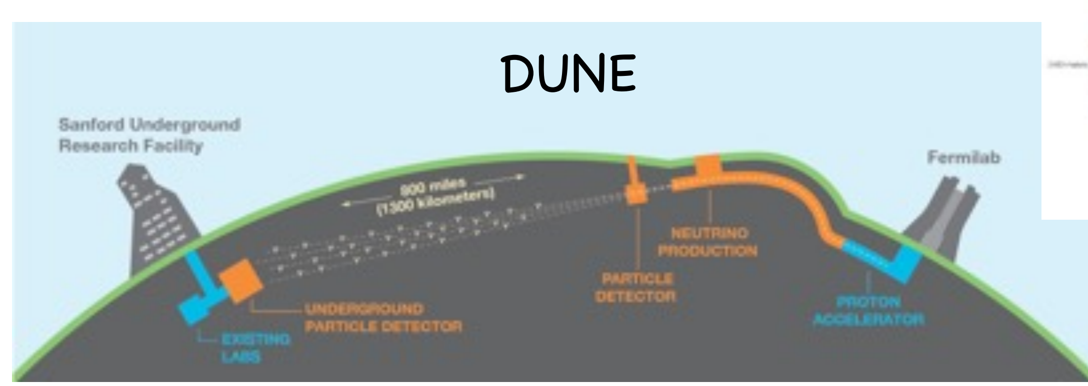
through χ_1

- $\chi_h \chi_h \to \chi_1 \chi_1$ (current universe) relativistic: need a huge detector $\because$ flux small

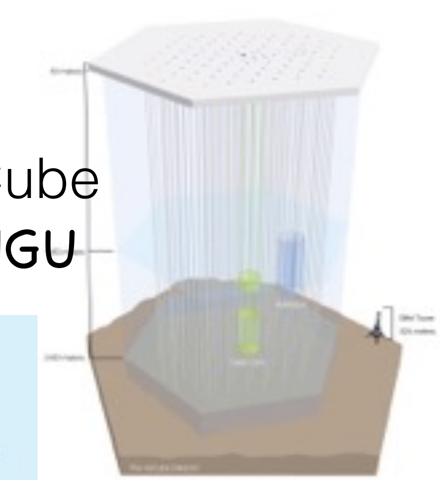
$$m_{\chi_h} \gtrsim \mathcal{O}(10\,\mathrm{GeV})$$



Super **(& Hyper)** Kamiokande



IceCube
PINGU



Detection of boosted DM

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↓

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Super-K	0.0224	0.01	1.07	3°	3°
Hyper-K	0.56	0.01	1.07	3°	3°
DUNE	0.04	0.03	0.05	1°	5°

even better

Detection of boosted DM

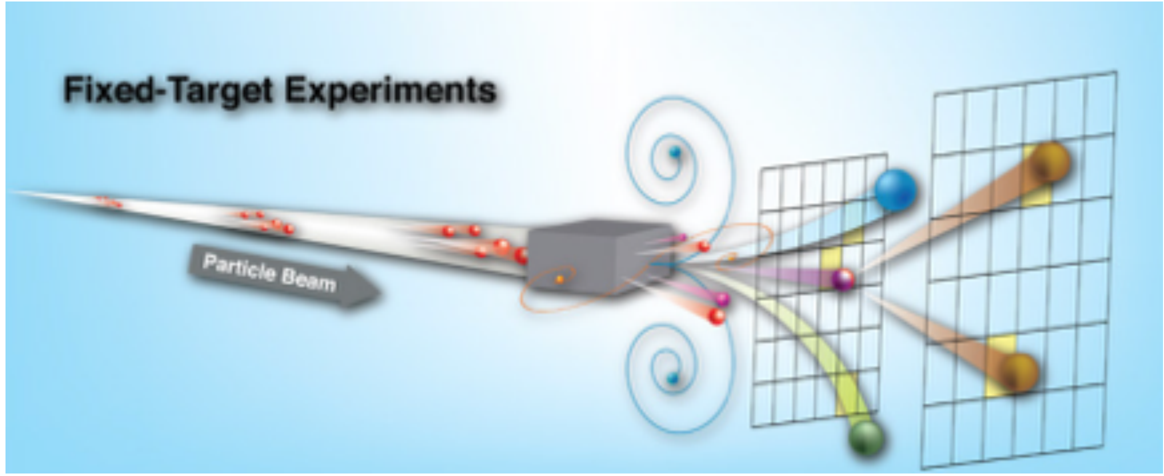
Dominant relic χ_h: but do not directly interact with SM

$\downarrow$

through χ_1

- $\chi_h \chi_h \to \chi_1 \chi_1$ (current universe) relativistic: need a huge detector $\because$ flux small

- Fixed target experiments relativistic: high intensity increases flux



Not have to be a BDM

Signal observations in both cases

Counting N_{events} over the expected background

neutrino

Super interesting but not easy
to confirm the signals over ν

Signal observations in both cases

Counting N_{events} over the expected background

neutrino

Super interesting but not easy
to confirm the signals over ν

Modification of minimal models make them promising

Talk by JC Park

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

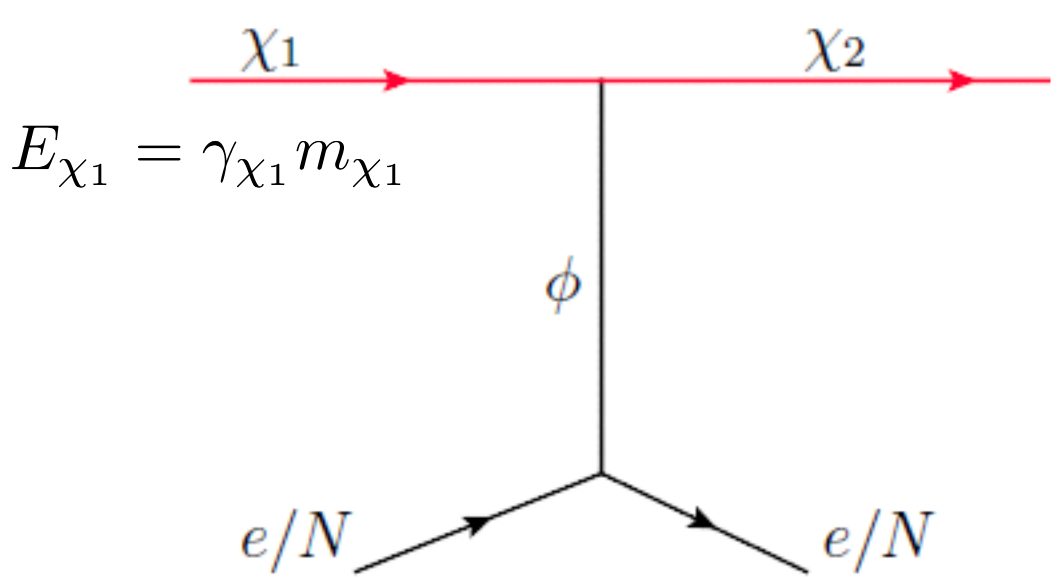
  Berger, Cui, Zhao, 1410.2246 Kong, Mohlaberg, Park, 1411.6632
  Alhazmi, Kong, Mohlaberg, Park, 1611.09866

- More complicated dark sector (just like SM?): extraordinary signal

  Kim, Park, **SS**, 1612.06867

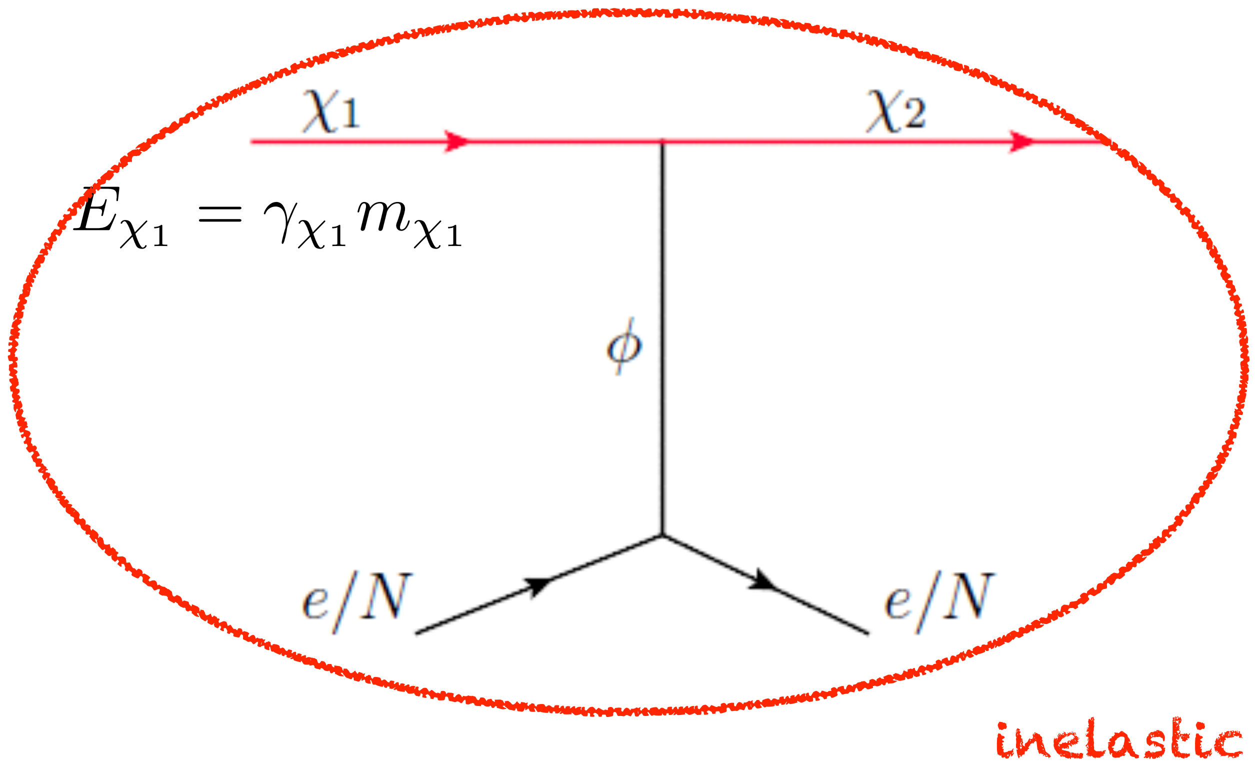
Cascade process in detection of DM

Cascade signal of relativistic DM



- Heavier (unstable) dark partner χ_2: $m_{\chi_2} > m_{\chi_1}$
- Mediator ϕ: not specified but assume either spin 0 or 1

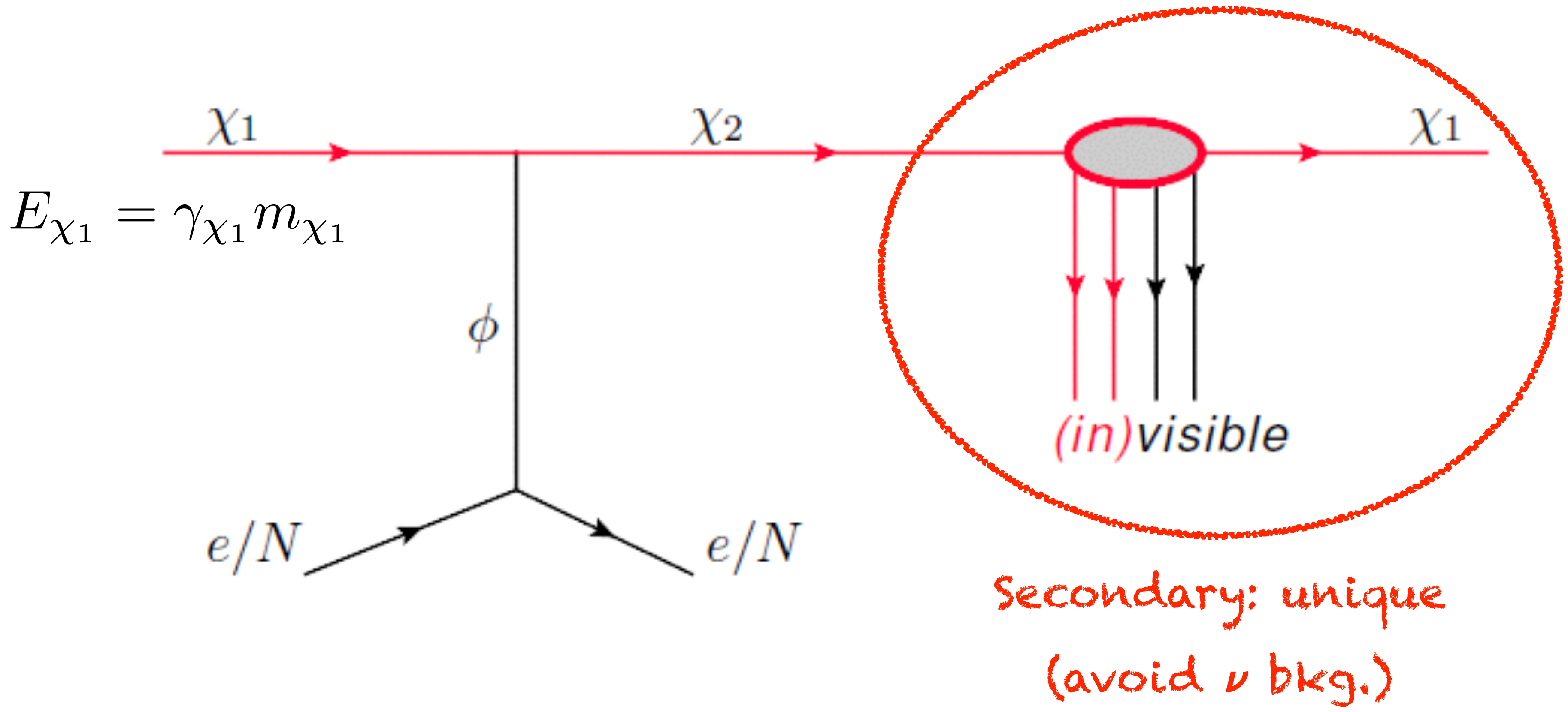
Cascade signal of relativistic DM



Inelastic Boosted DM
(but not has to be BDM)

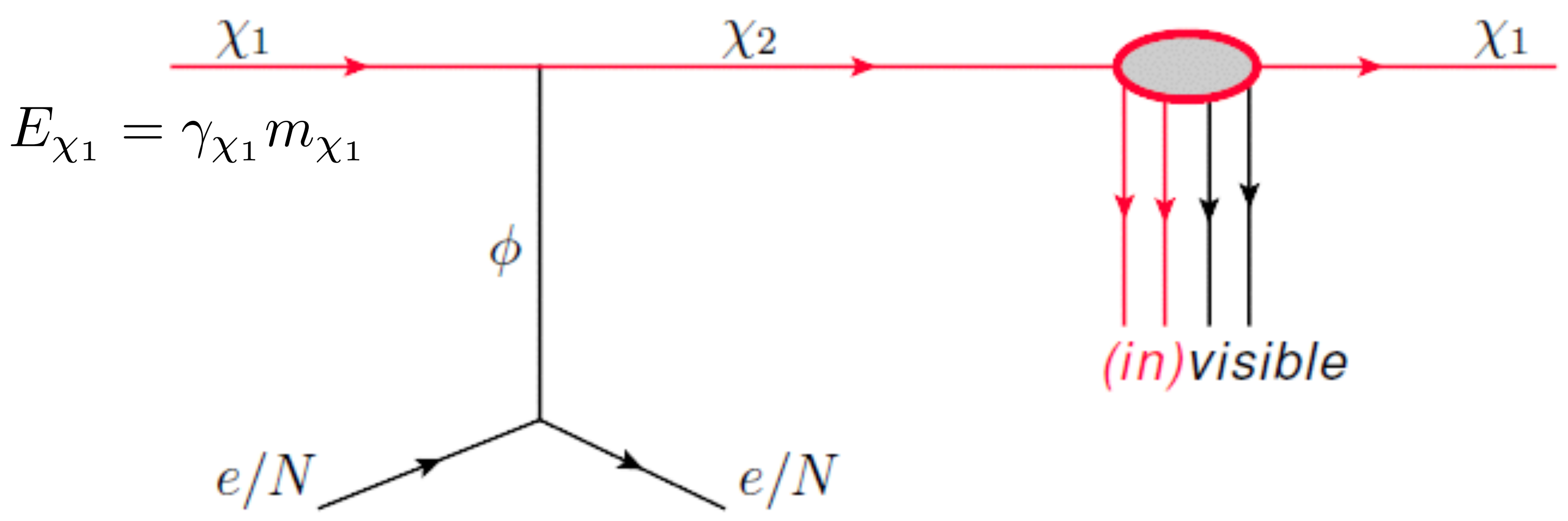
- Heavier (unstable) dark partner χ_2: $m_{\chi_2} > m_{\chi_1}$
- Mediator ϕ: not specified but assume either spin 0 or 1

Cascade signal of relativistic DM



- Heavier (unstable) dark partner χ_2: $m_{\chi_2} > m_{\chi_1}$
- Mediator ϕ: not specified but assume either spin 0 or 1
- Secondary (or more) process by χ_2: cascade signal (collider?)

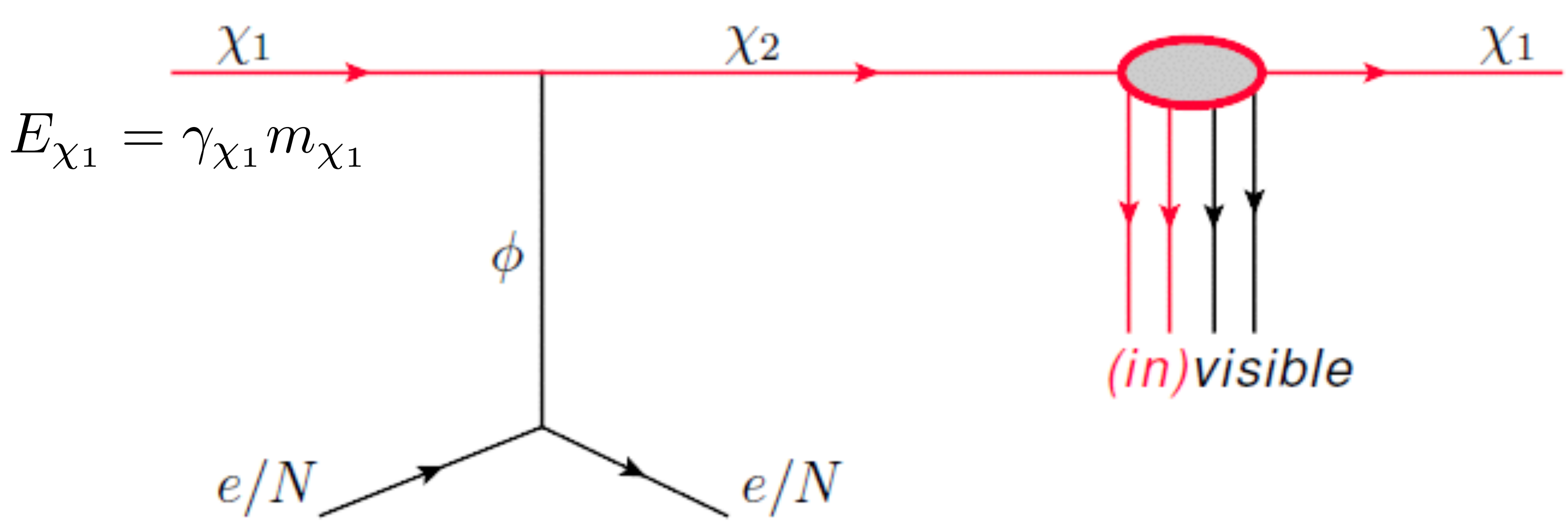
Cascade signal of relativistic DM



- Focus on the detection prospects in huge neutrino detectors in this talk
- Fixed target experiments: future work

Electron scattering

Energy spectrum

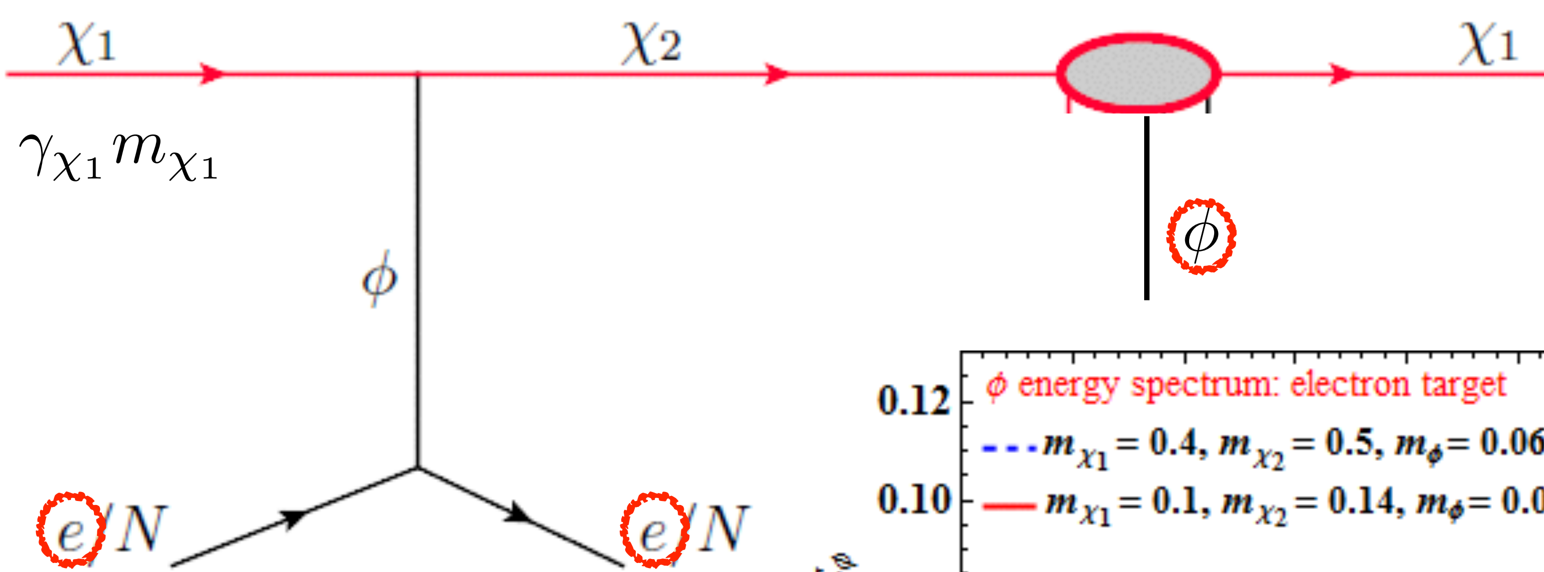


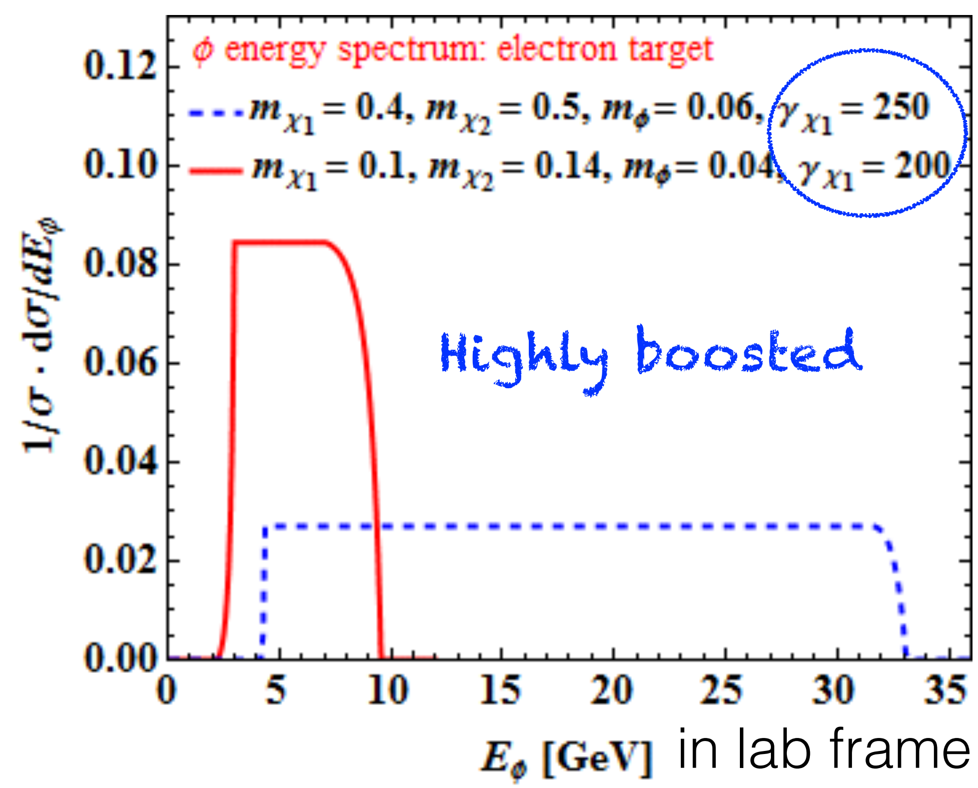
- Everything is relativistic: need large energy to have χ_2 (large γ_{χ_1})

- Electron scattering with one vector mediator: light DM with huge γ_{χ_1}

Energy spectrum: e-scattering

$$E_{\chi_1} = \gamma_{\chi_1} m_{\chi_1}$$





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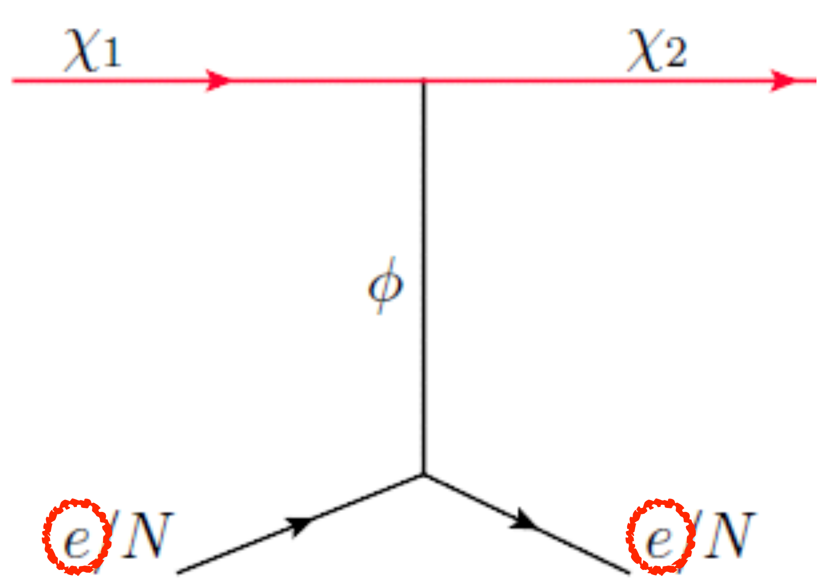
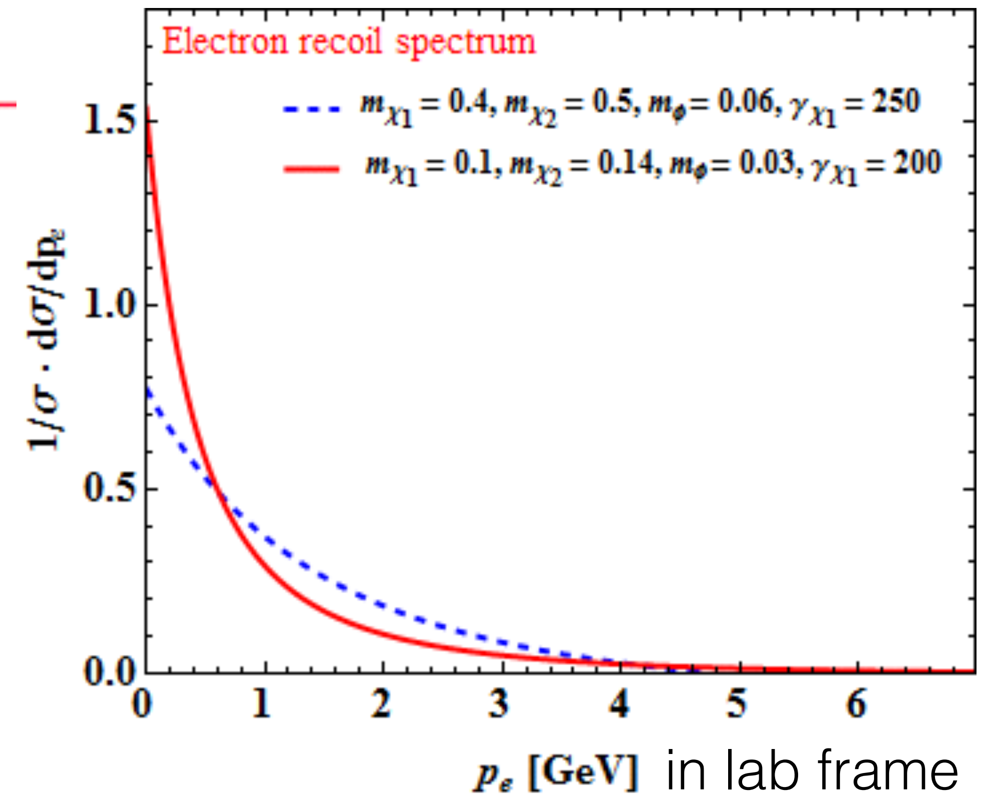


primary scattering

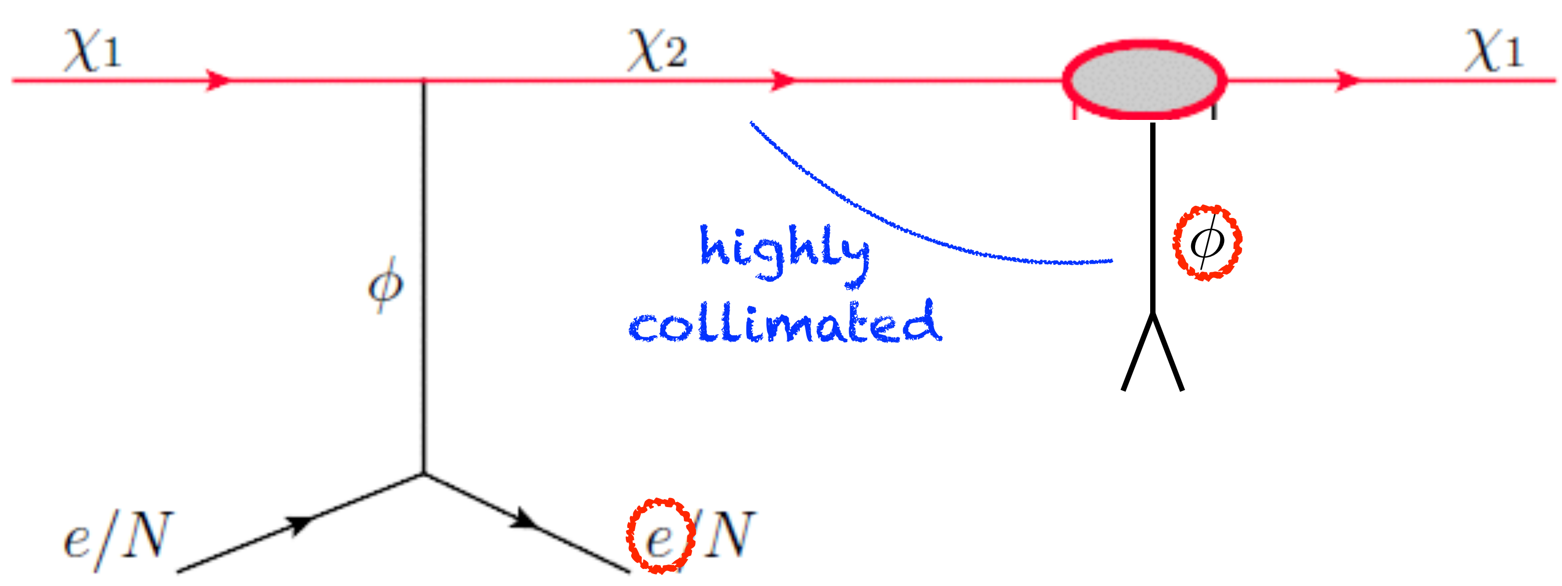


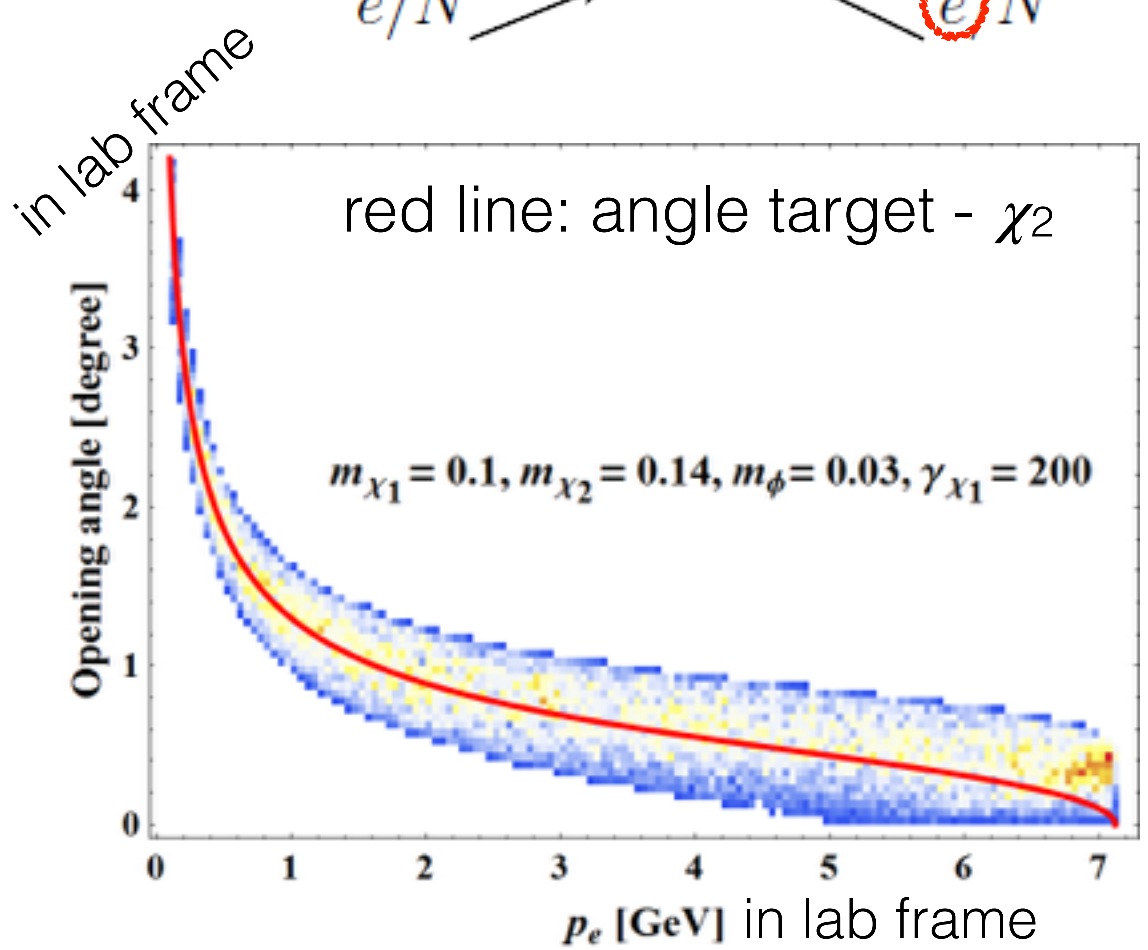
in lab frame

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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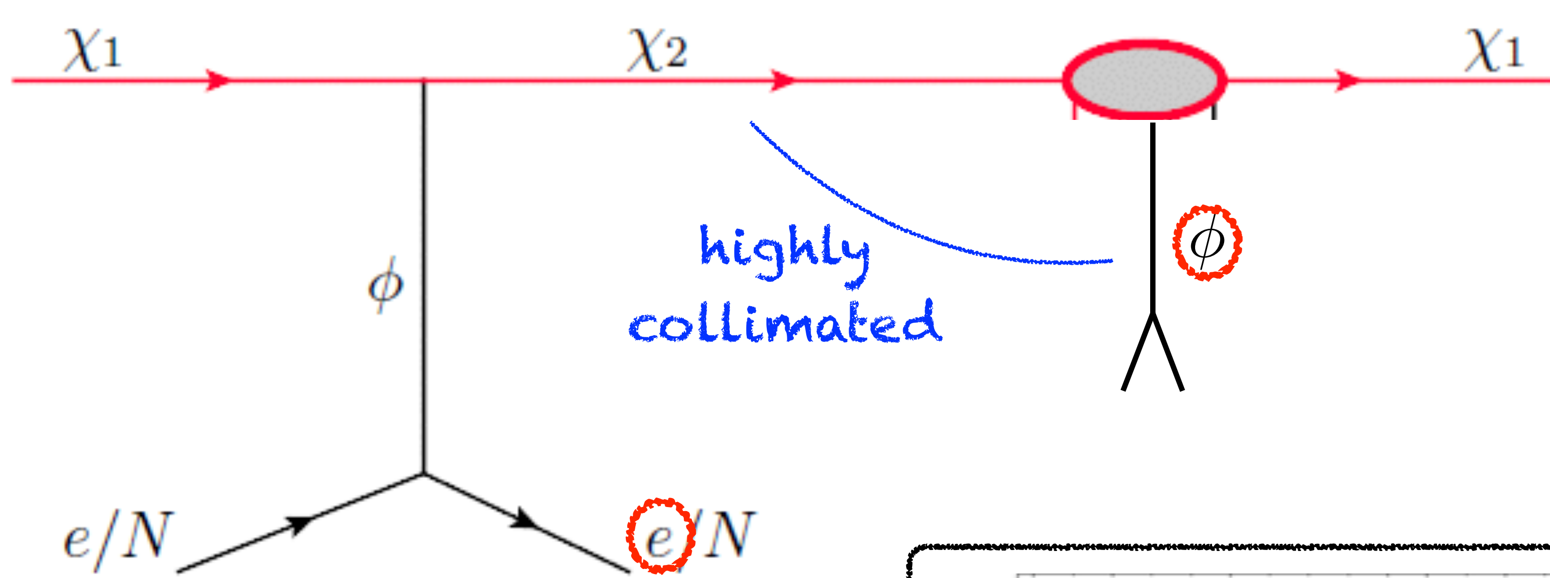
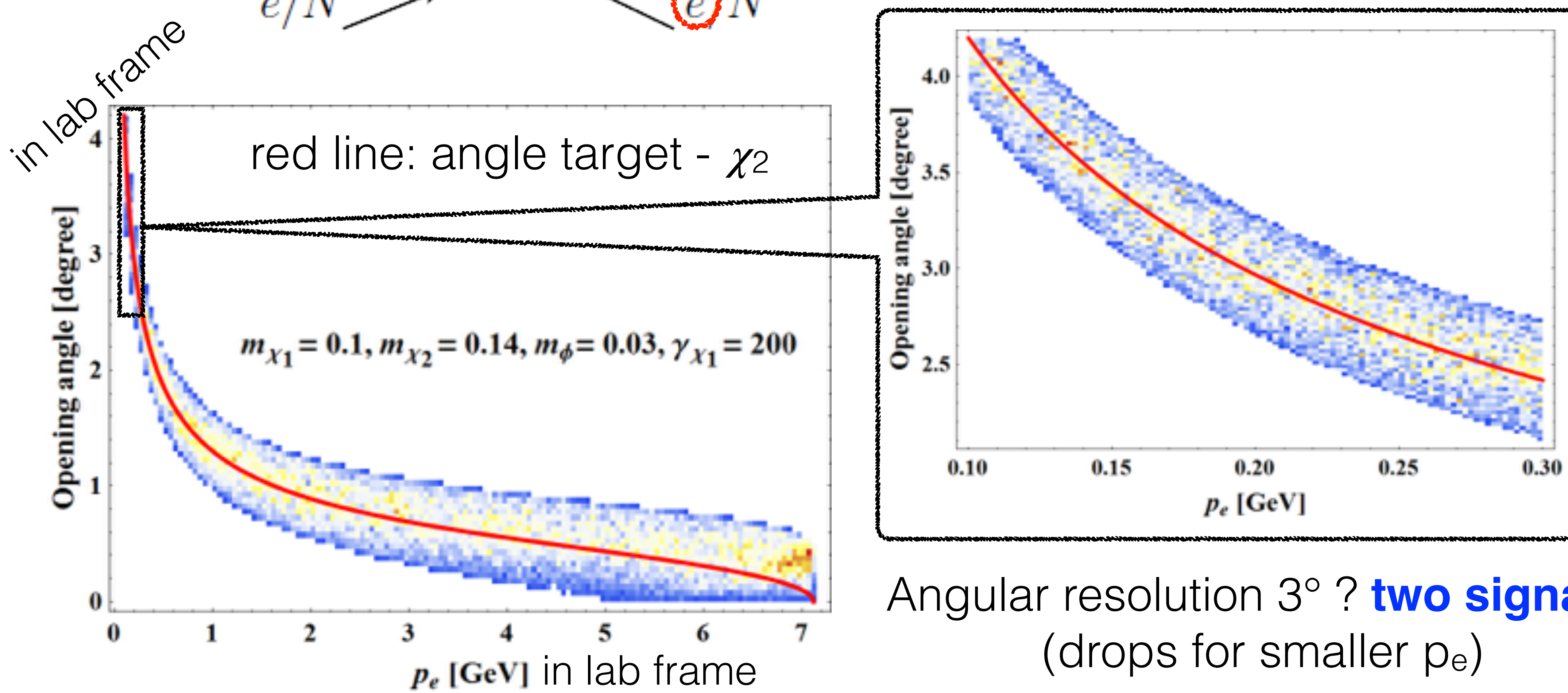
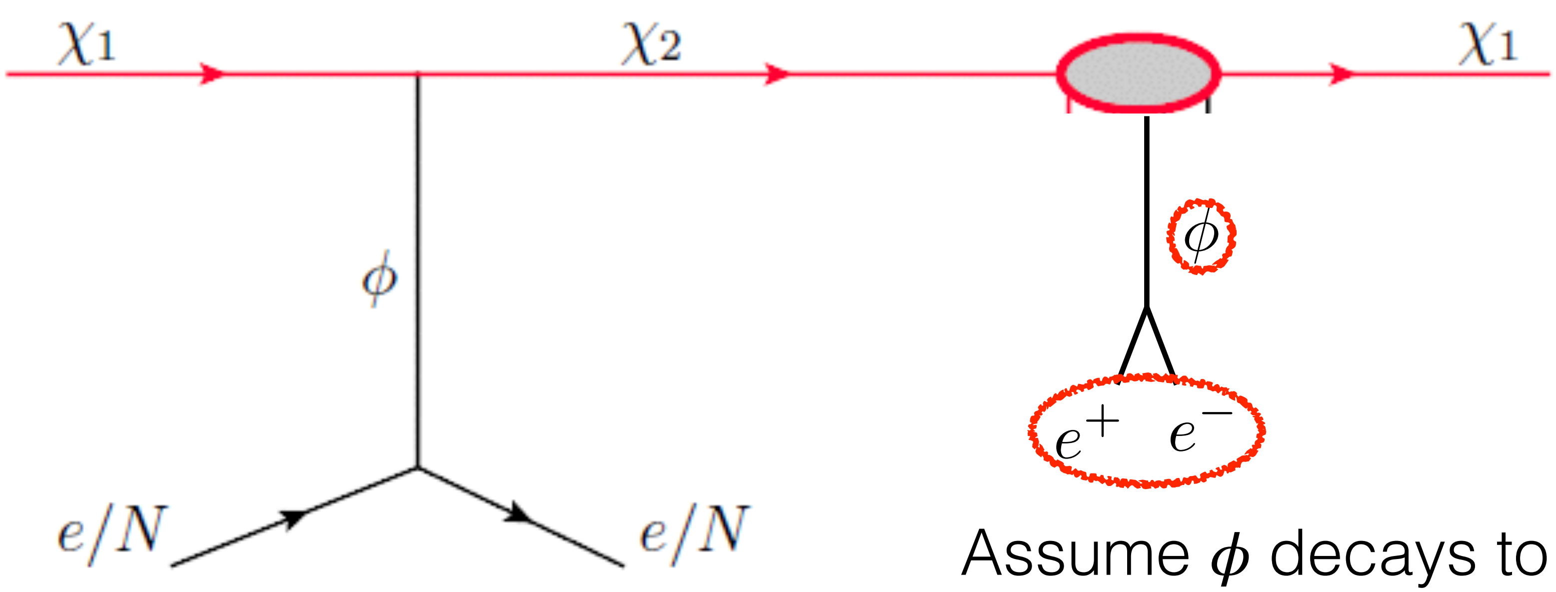




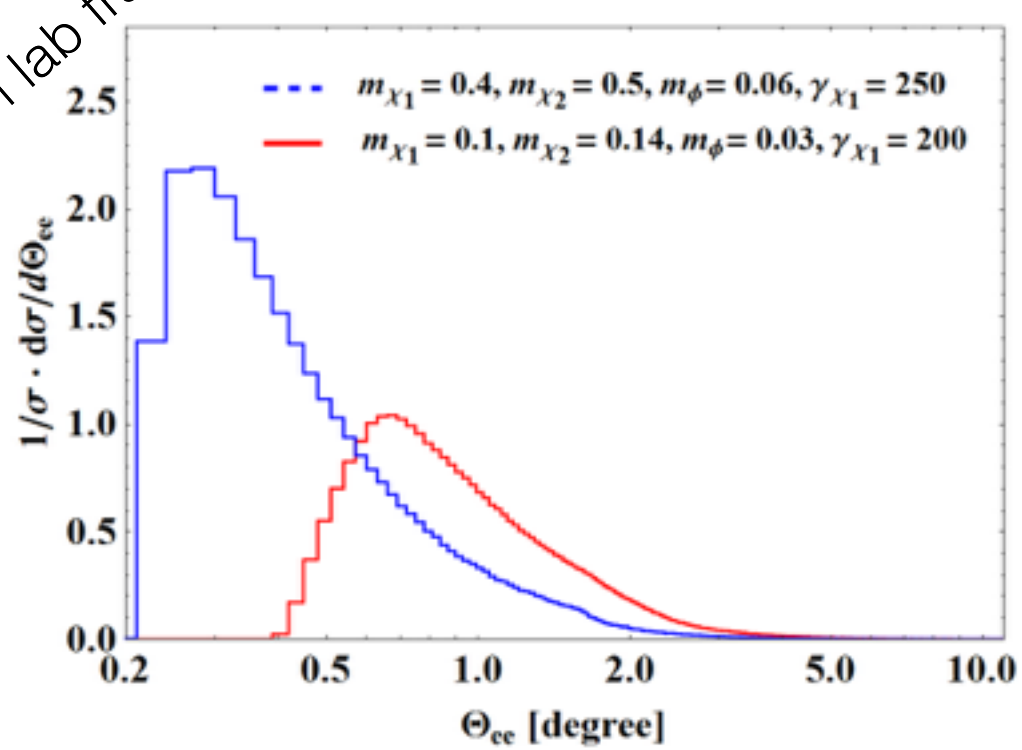
Angular resolution 3° ? **two signals!**
(drops for smaller p_e)

e-scattering: highly collimated



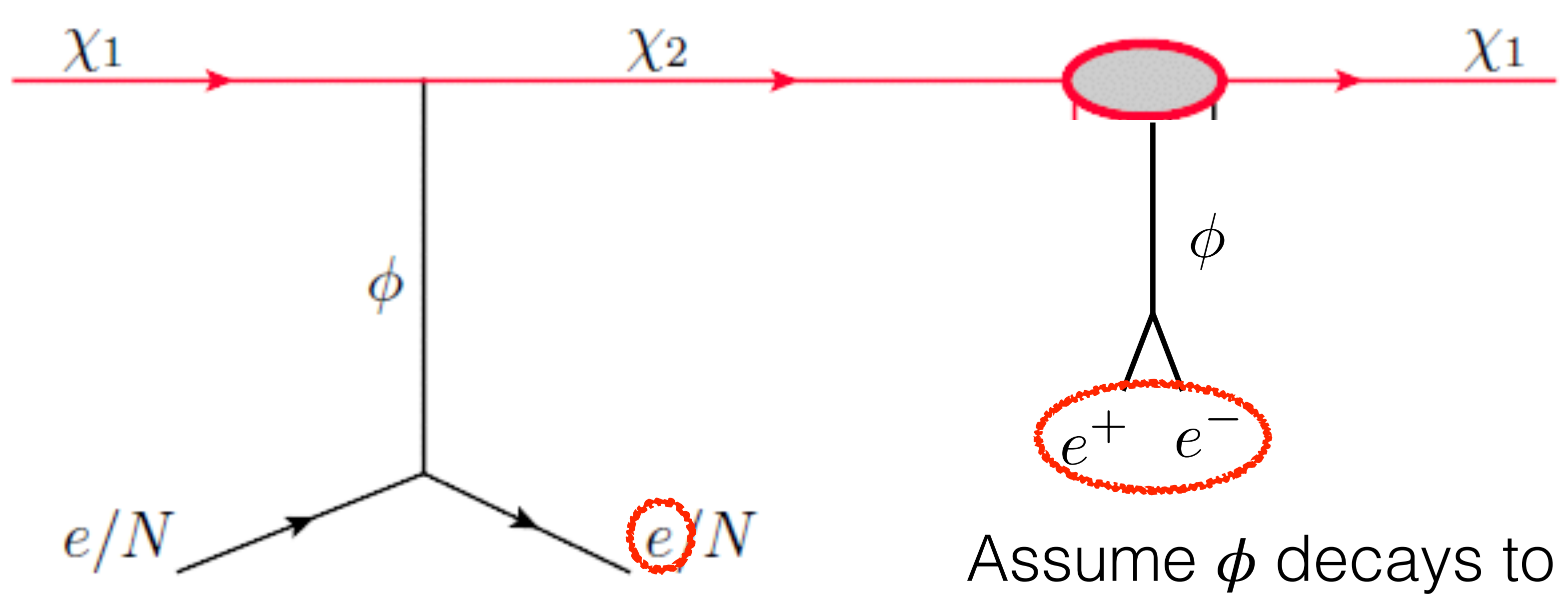
Assume ϕ decays to e^+e^-

in lab frame



Mostly < 1.5°

e-scattering: highly collimated



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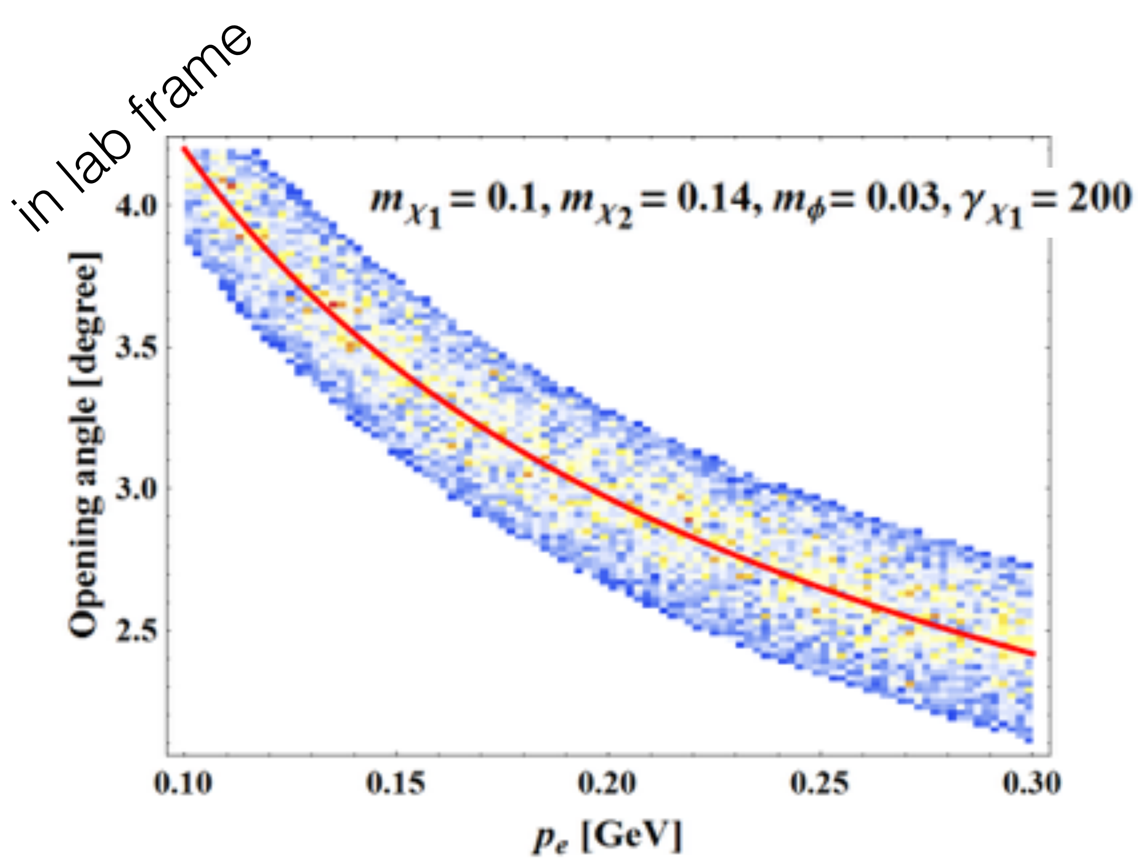
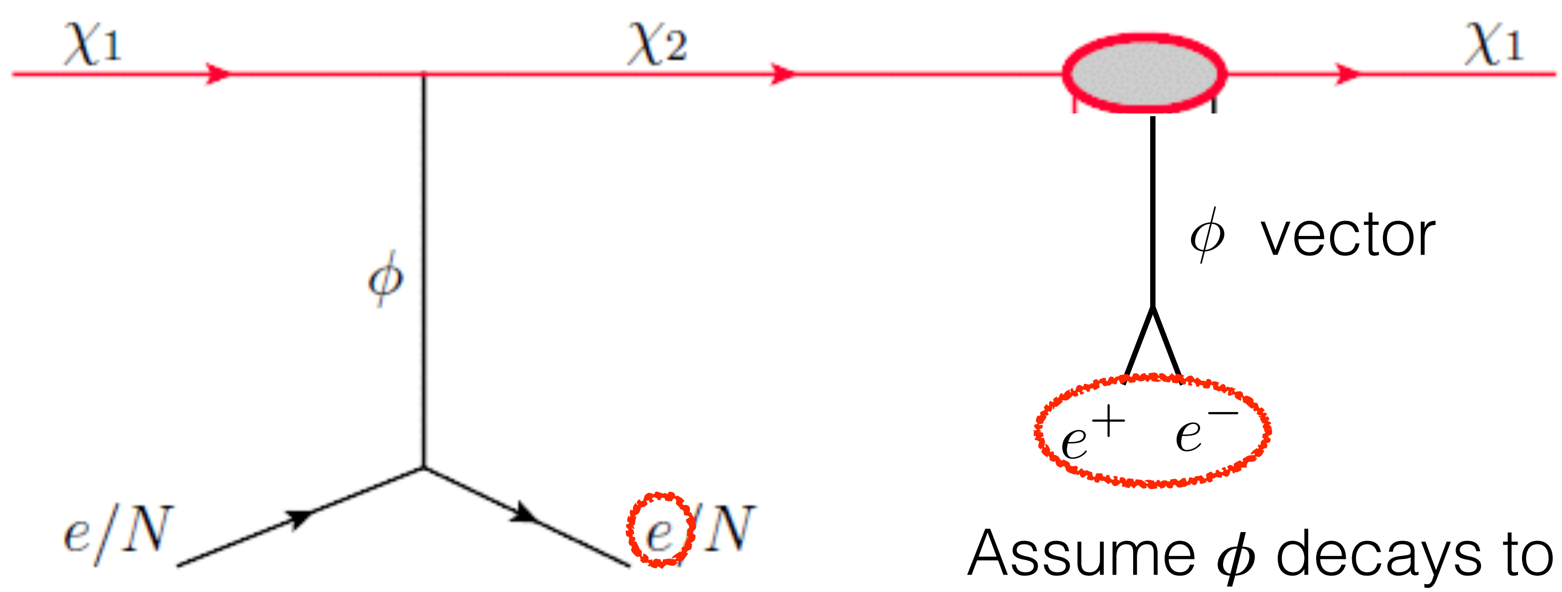


High chance to observe
two separate signals!!

in an experiment with
angular resolution 3°

e-scattering: detection prospects



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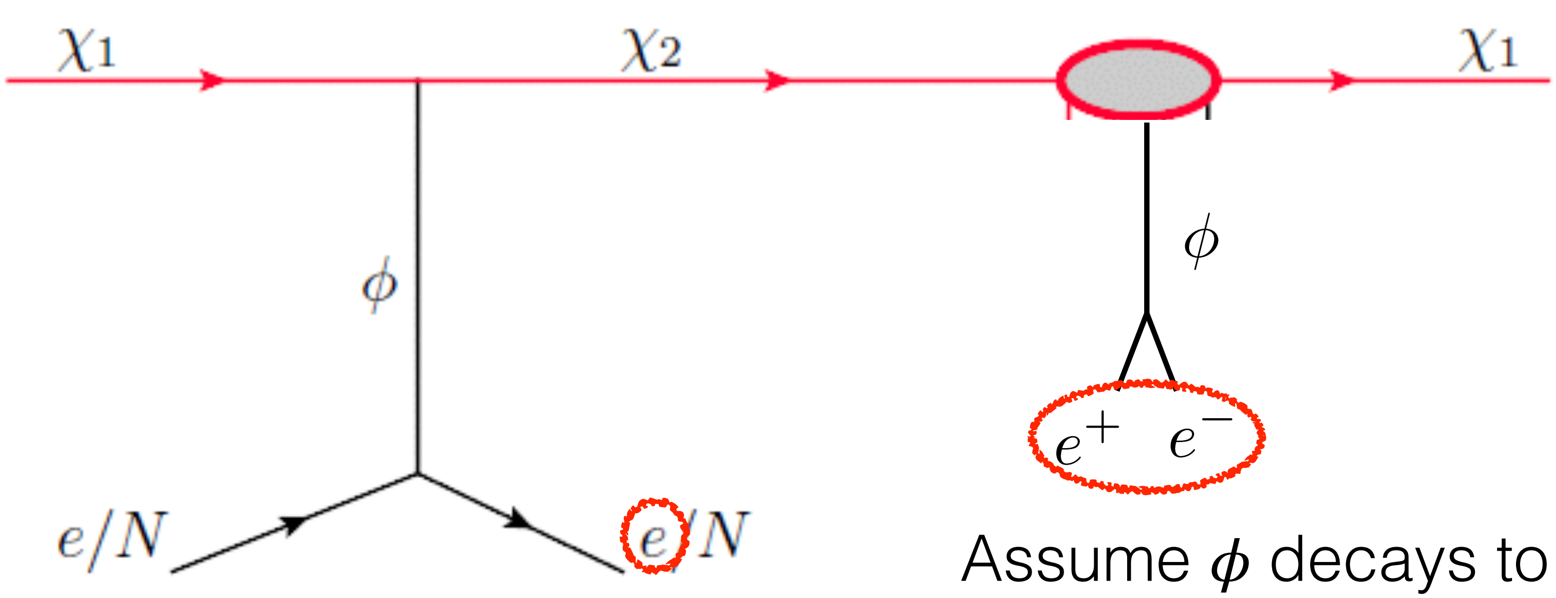
e-scattering: detection prospects



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effective for $E > E_{th}$

We need good res.

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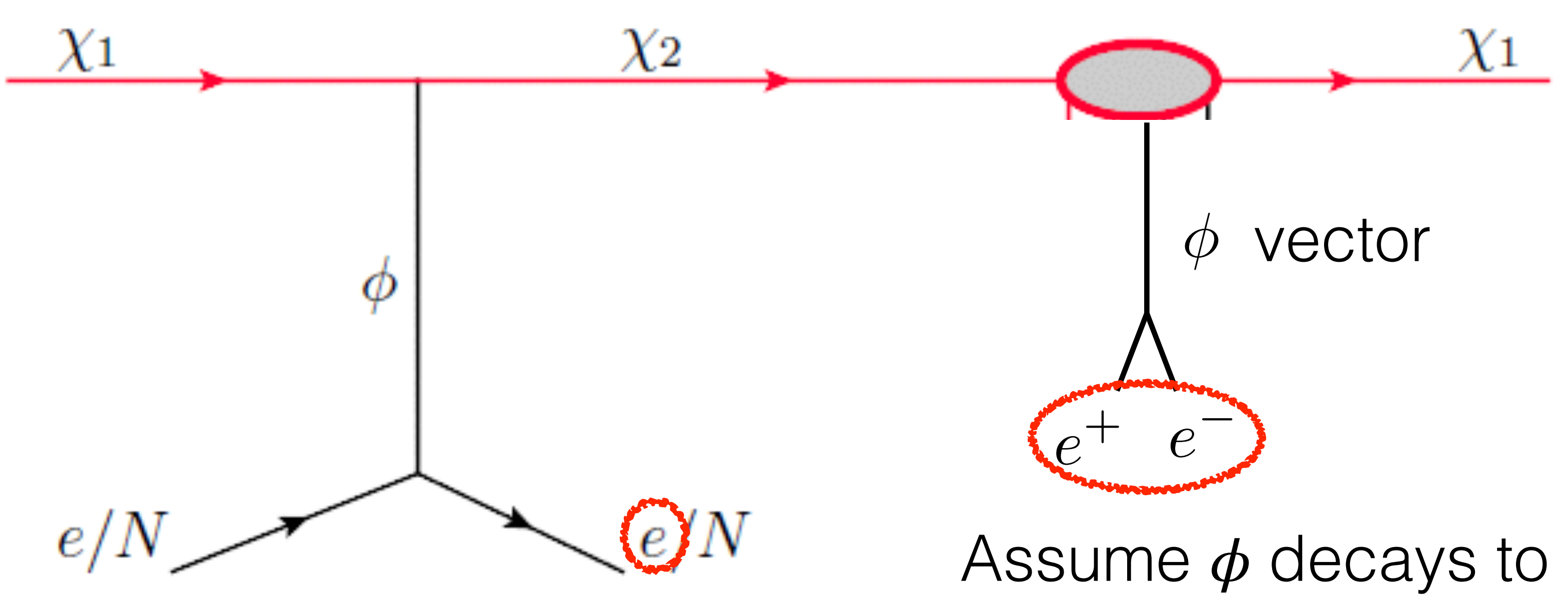
e-scattering: sensitivities on flux



Assume ϕ decays to e^+e^-

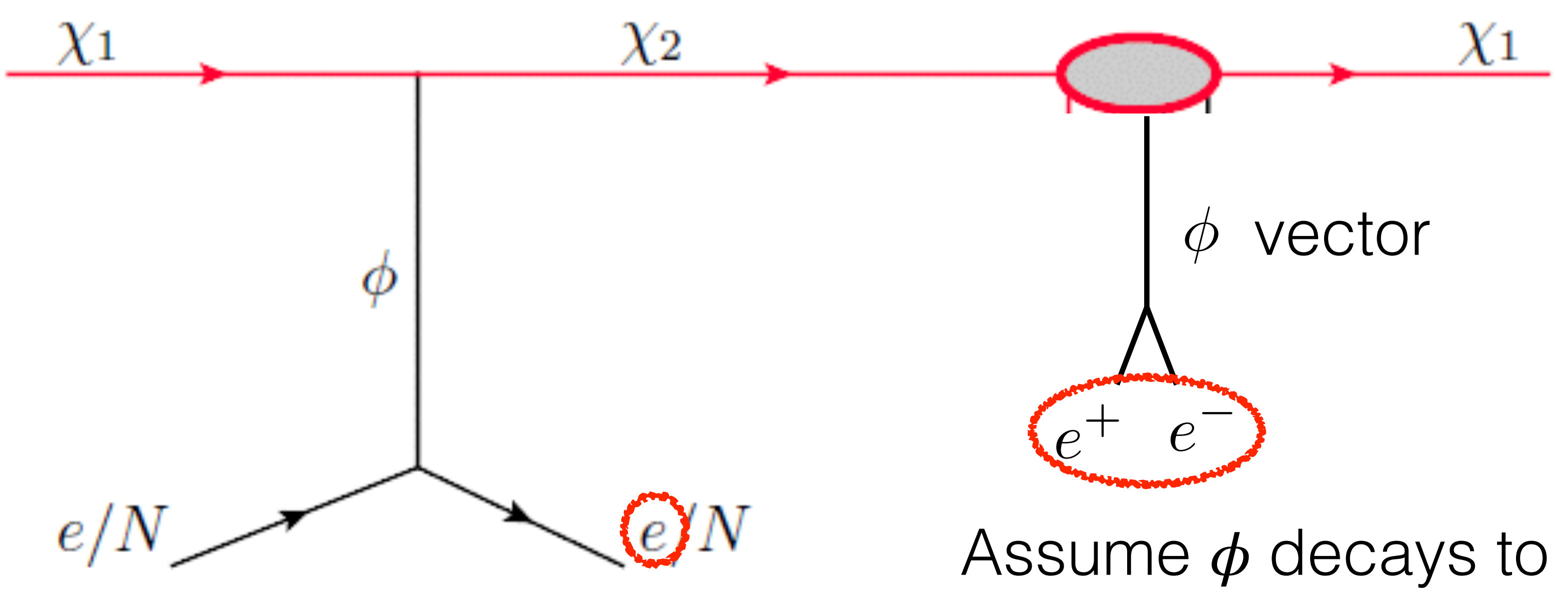
$m_{\chi_1} = 0.1, m_{\chi_2} = 0.14, m_\phi = 0.03, \gamma_{\chi_1} = 200$ $\quad g_{12} = 0.5,\ \epsilon = 0.0003$

toy model $\mathcal{L}_X \supset -\frac{\epsilon}{2} F_{\mu\nu} X^{\mu\nu} + g_{12} \bar{\chi}_2 \gamma^\mu \chi_1 X_\mu + h.c.$

Experiments	$\mathrm{cm}^{-2}\mathrm{s}^{-1}$
Super-K 4799 days	7.1×10^{-7}
Hyper-K 1 year	3.7×10^{-7}
Hyper-K 4799 days	2.8×10^{-8}
DUNE 1 year	9.0×10^{-7}
DUNE 4799 days	6.9×10^{-8}

Assume no bkg. 4799 days ≃13,6 yr

e-scattering: sensitivities on flux



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our process sensitive

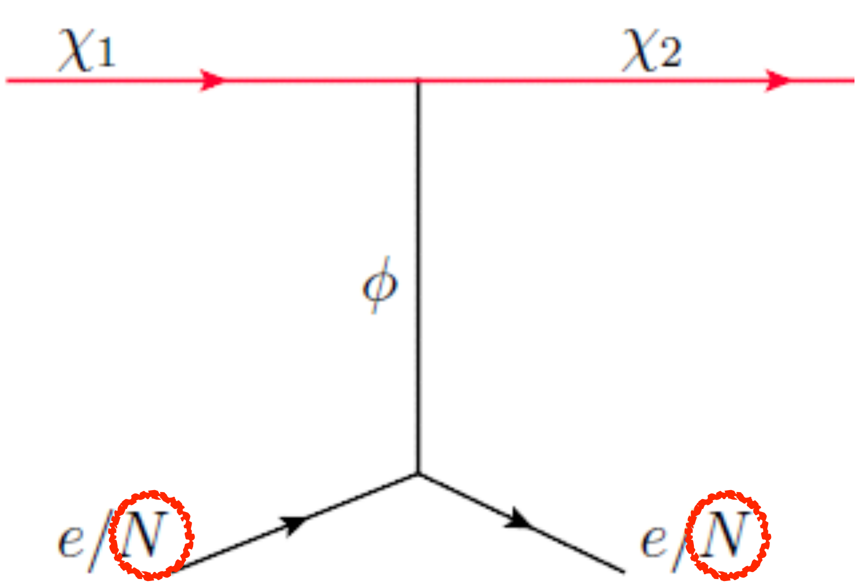
Assume no bkg. 4799 days ≃13,6 yr

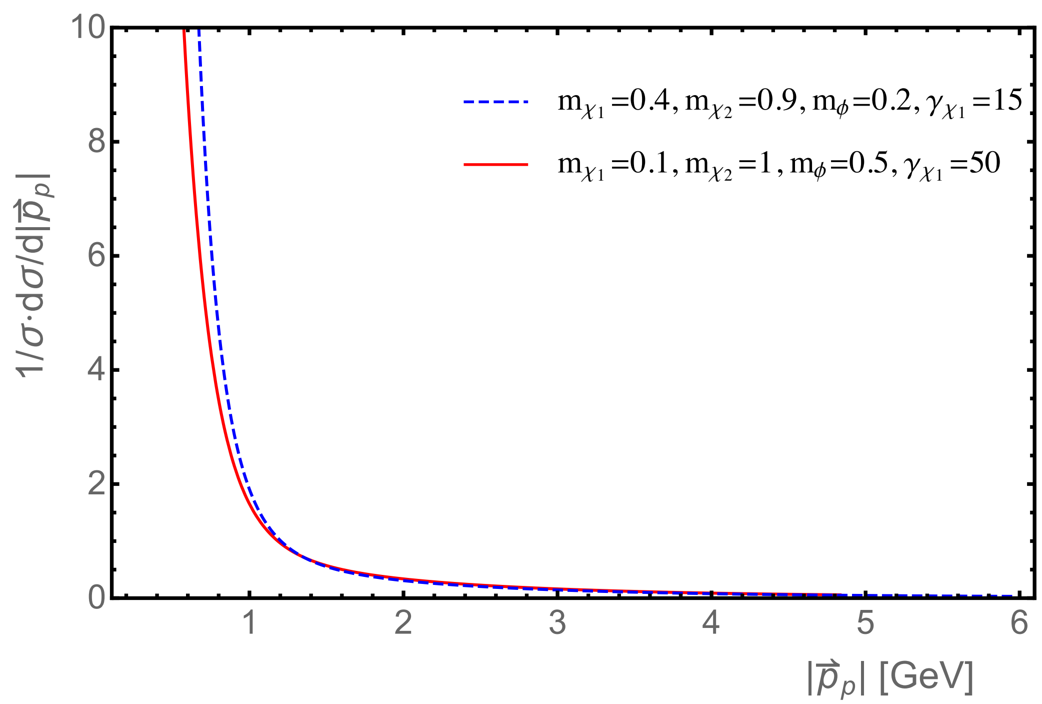
Remind, in a minimal BDM, flux over the whole sky $\mathcal{O}(10^{-7}\,\mathrm{cm}^{-2}\mathrm{s}^{-1})$

Promising example!

Proton scattering

p-scattering: energy spectrum

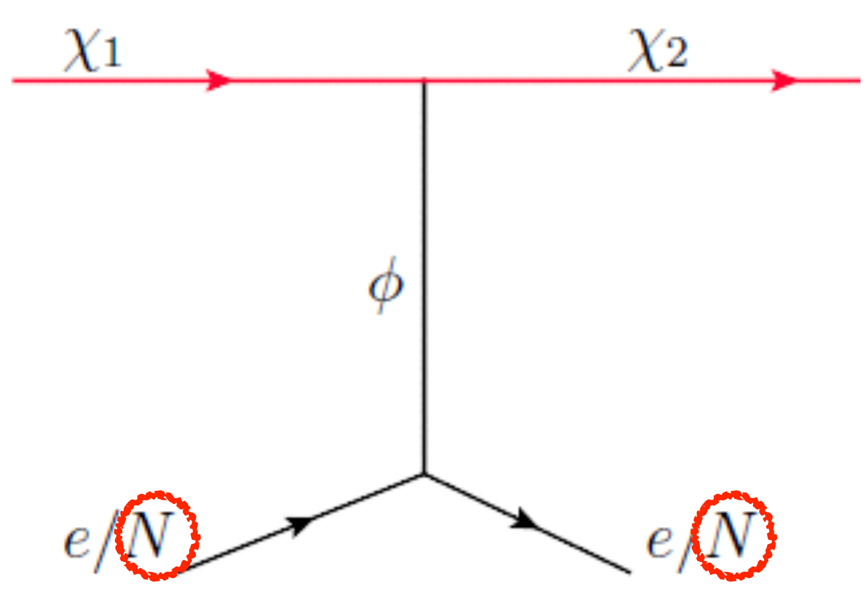


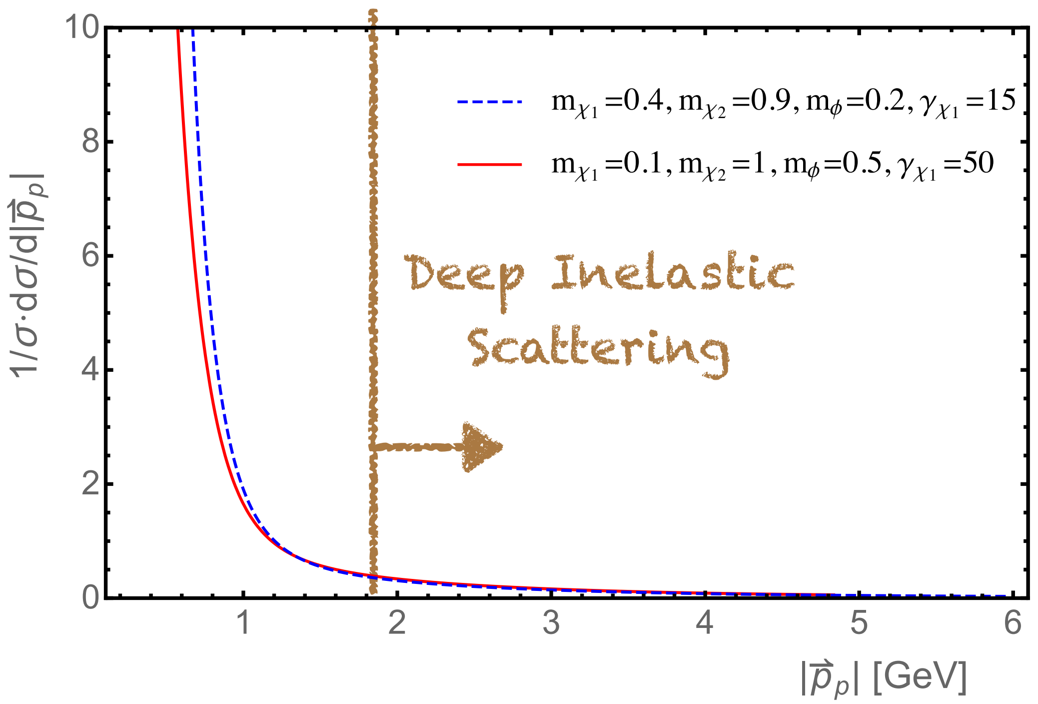


p-scattering NOT preferred over e-scattering (Cherenkov)

- 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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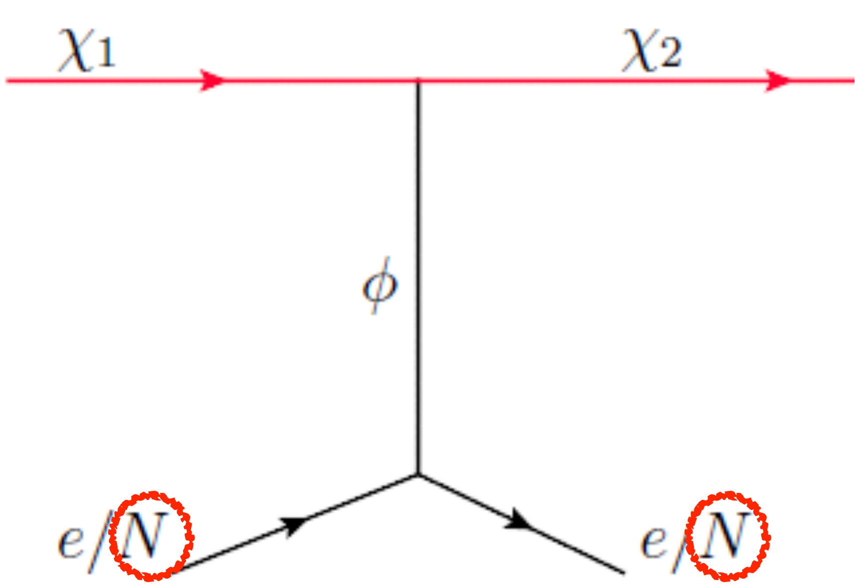
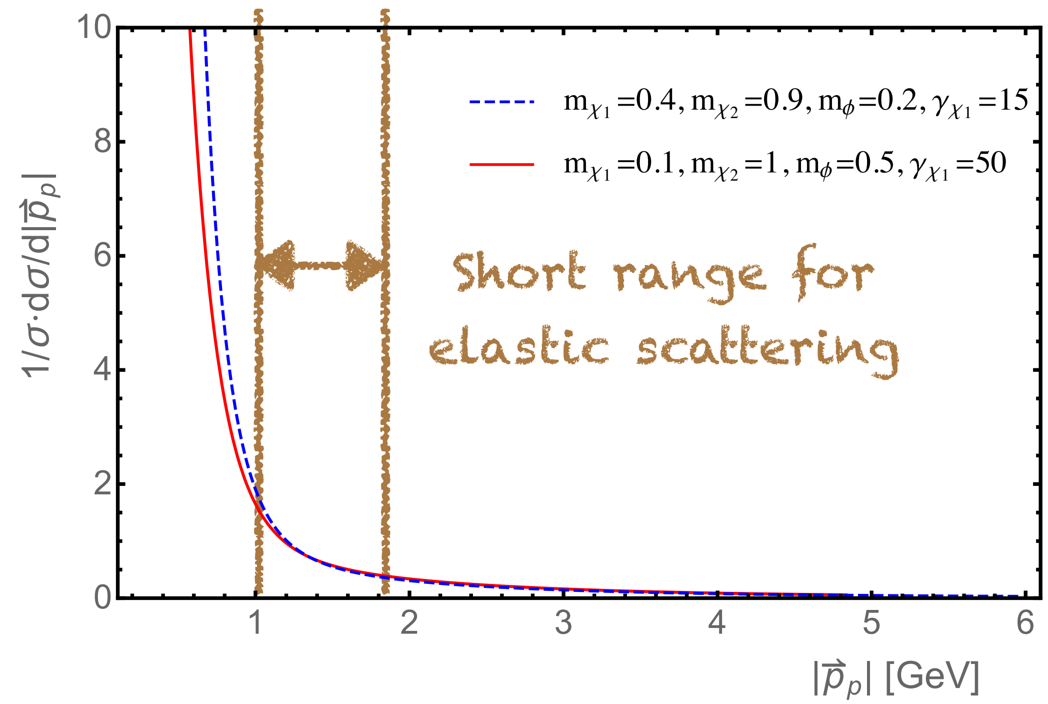
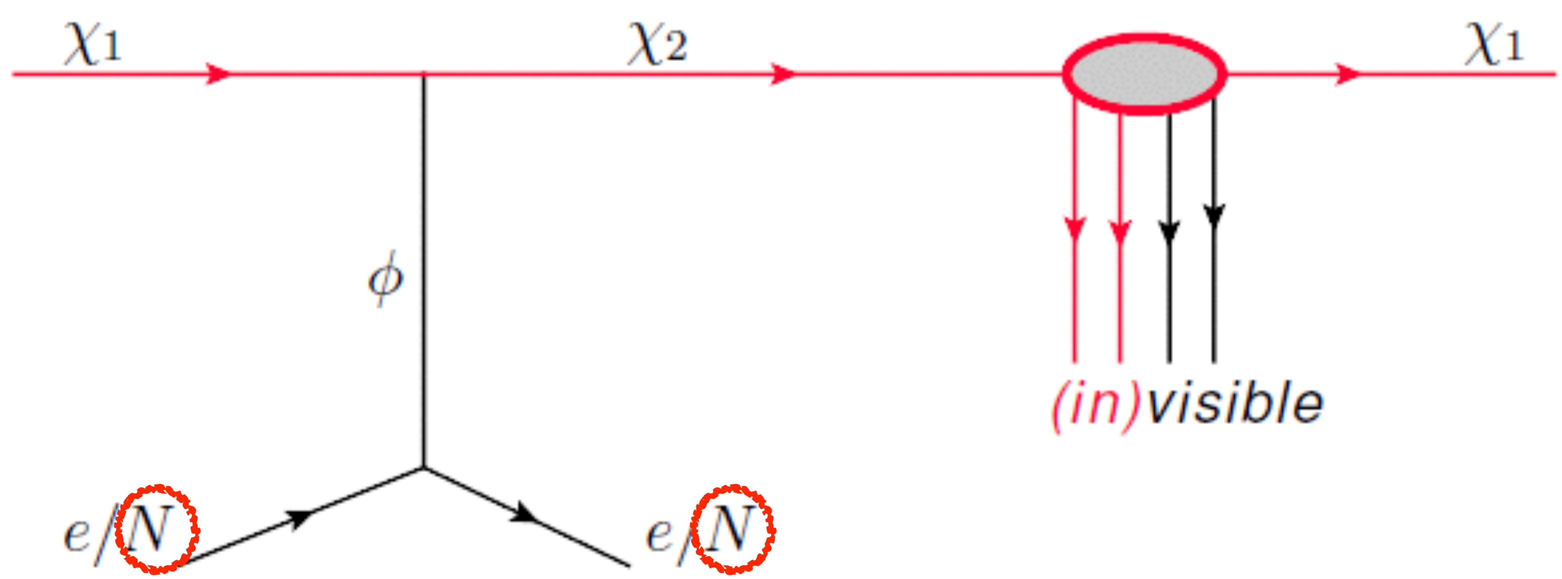




p-scattering NOT preferred over e-scattering (Cherenkov)

- Primary scattering cross section large when <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>

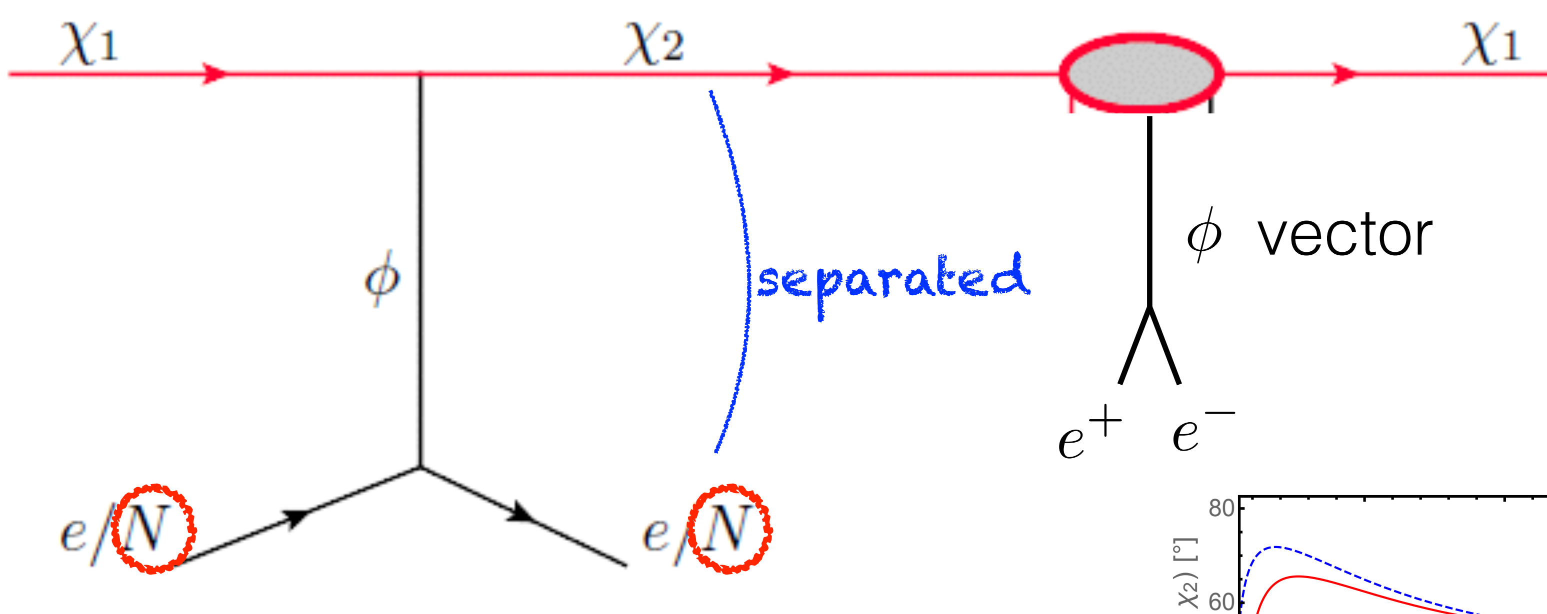
p-scattering: energy spectrum



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



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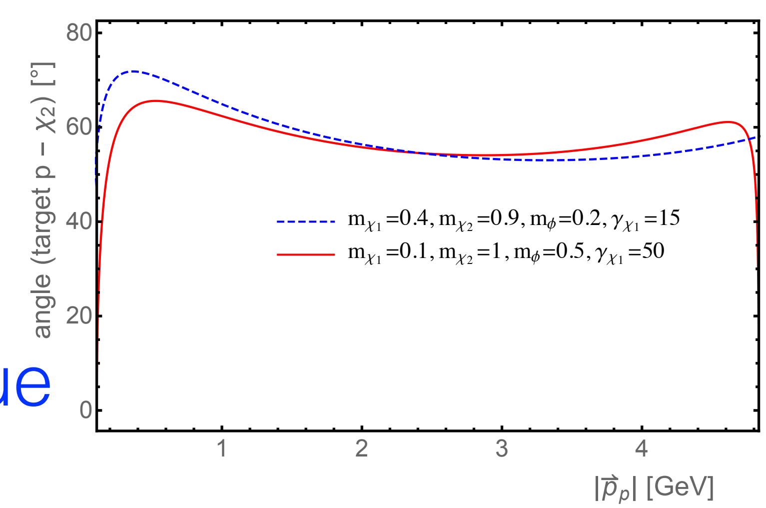
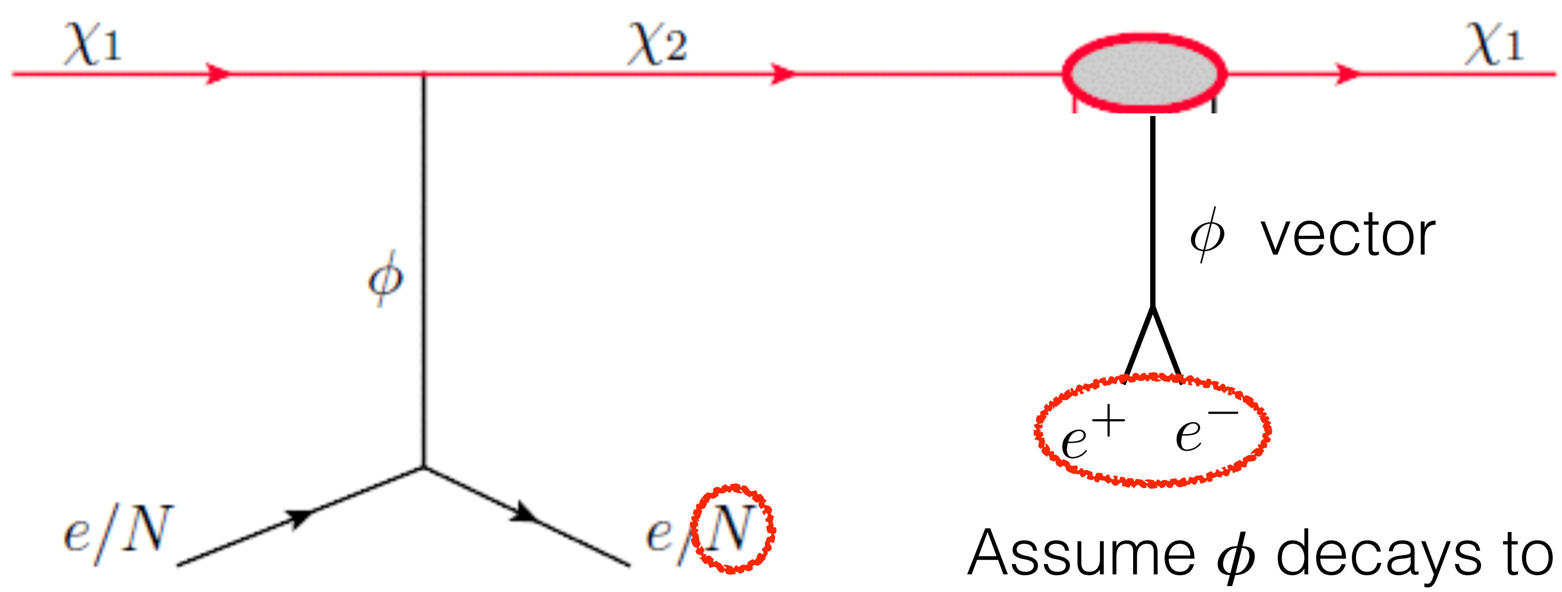


- E_{th} low for proton scattering for liquid Ar detectors (DUNE: E_{th} 50 MeV)
- Separation of two signals super good & **3 visible objects**

p-scattering: sensitivities on flux



Assume ϕ decays to e^+e^-

Flux can be higher in non-minimal BDM model
or fixed target experiments

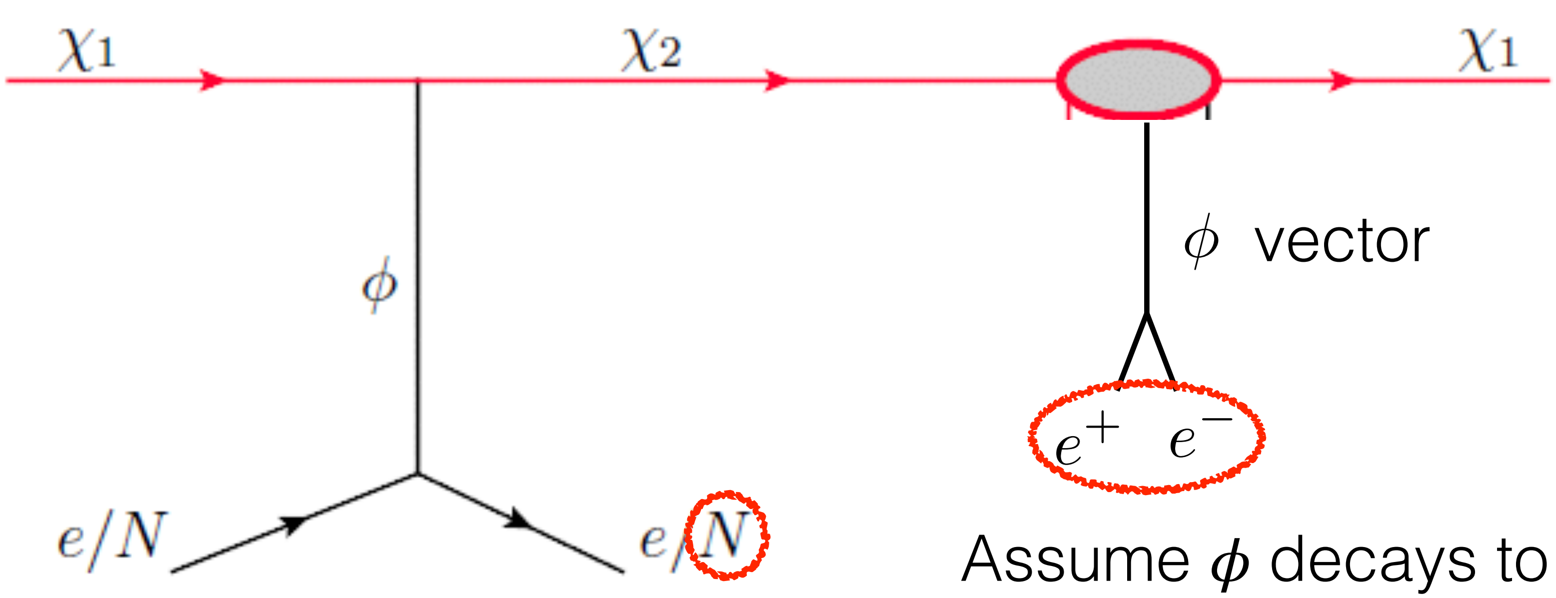
$g_{12} = 0.5,\ \epsilon = 0.0003$

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

less sensitive than e

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

p-scattering: sensitivities on flux



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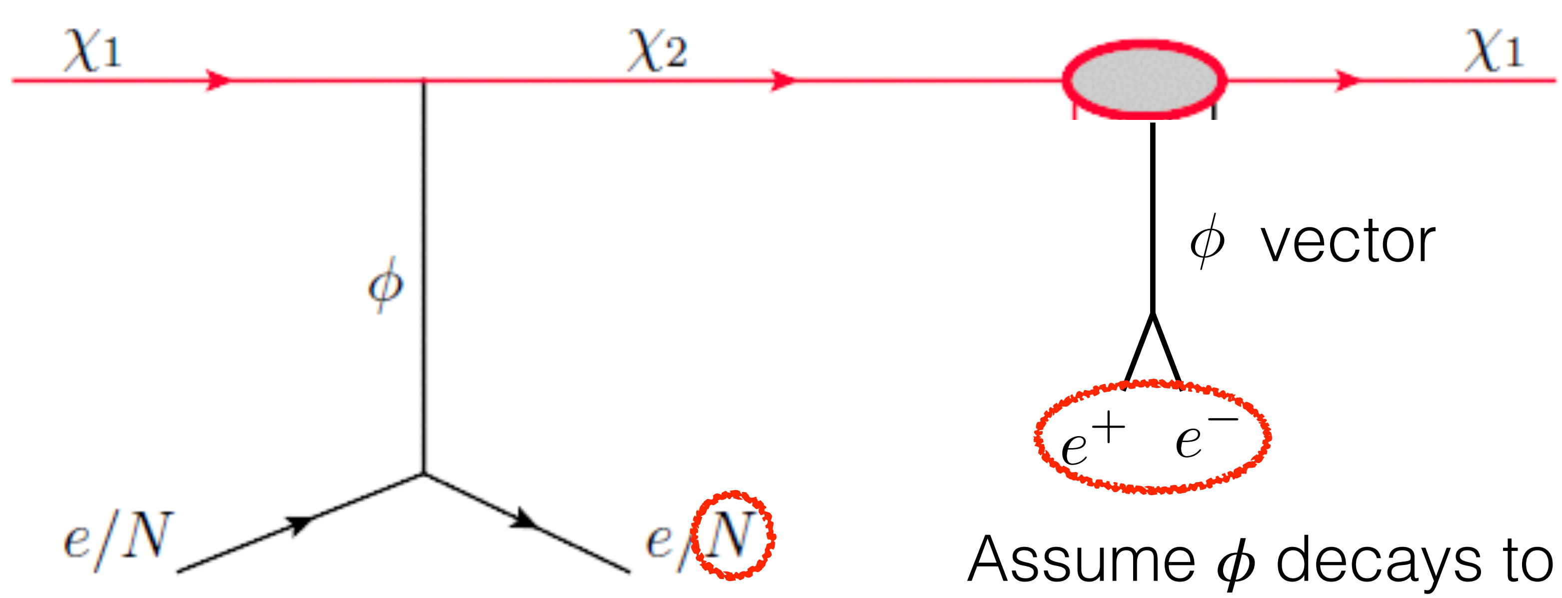
unit: $10^{-7}\mathrm{cm}^{-2}\mathrm{s}^{-1}$

13.6 yr of HK improves
the sensitivity

p-scattering: sensitivities on flux



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

Remarkable
improvement
in DUNE!!!

Promising
(3 simultaneous signals)

Conclusions

- Complicated dark sector (χ_2): cascade process

- Analyzed in current & future huge ν detectors:

  Super-K, Hyper-K, DUNE

e-scattering

- E_{th} low in Cherenkov light detectors (high σ)
- Sensitive with small flux
- Separation of two signals not easy (good for low p_e)

p-scattering

- E_{th} high in Cherenkov light detectors (low σ)
- Need large flux
- Separation of two signals & 3 visible objects: promising

Conclusions

- Complicated dark sector (χ_2): cascade process

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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
Separation of two signals not easy (good for low p_e)	Separation of two signals & 3 visible objects: promising

DUNE

Conclusions

- Complicated dark sector (χ_2): cascade process

- Analyzed in current & future huge 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
	non-minimal BDM, fixed target exp.
• Separation of two signals not easy (good for low p_e)	• Separation of two signals & 3 visible objects: promising

DUNE

Discussion for future

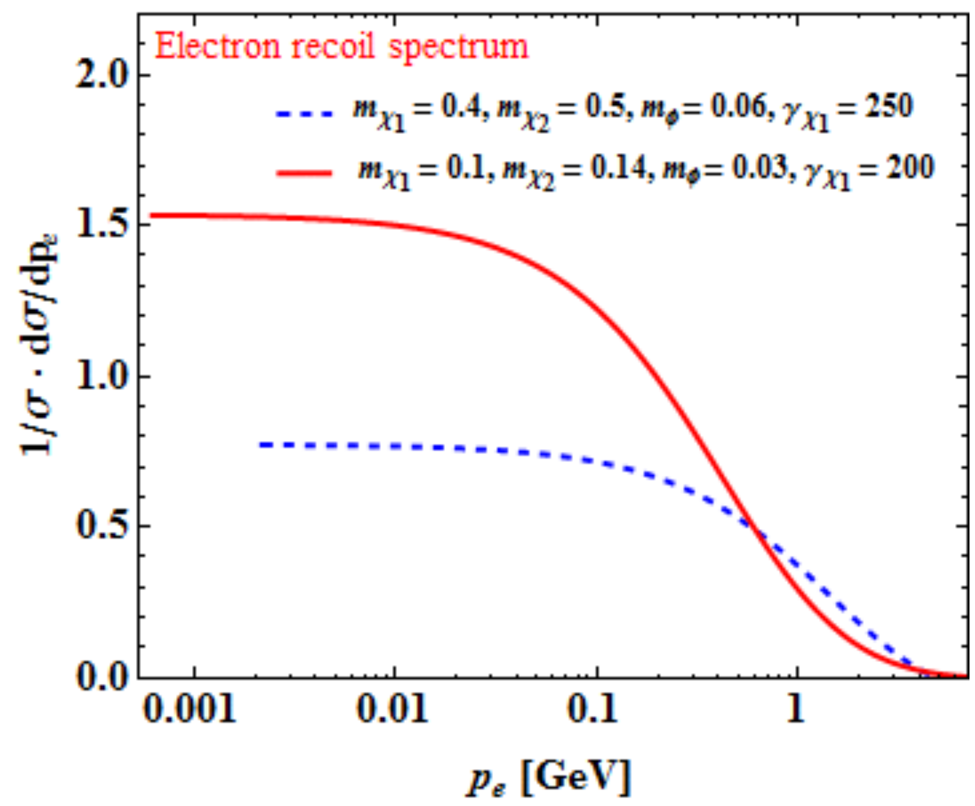
- Model building: χ_2 & mediator
- Analysis in fixed target experiments
- Background analysis
- Deep Inelastic Scattering region for proton scattering

Back up

Possible backgrounds

- 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

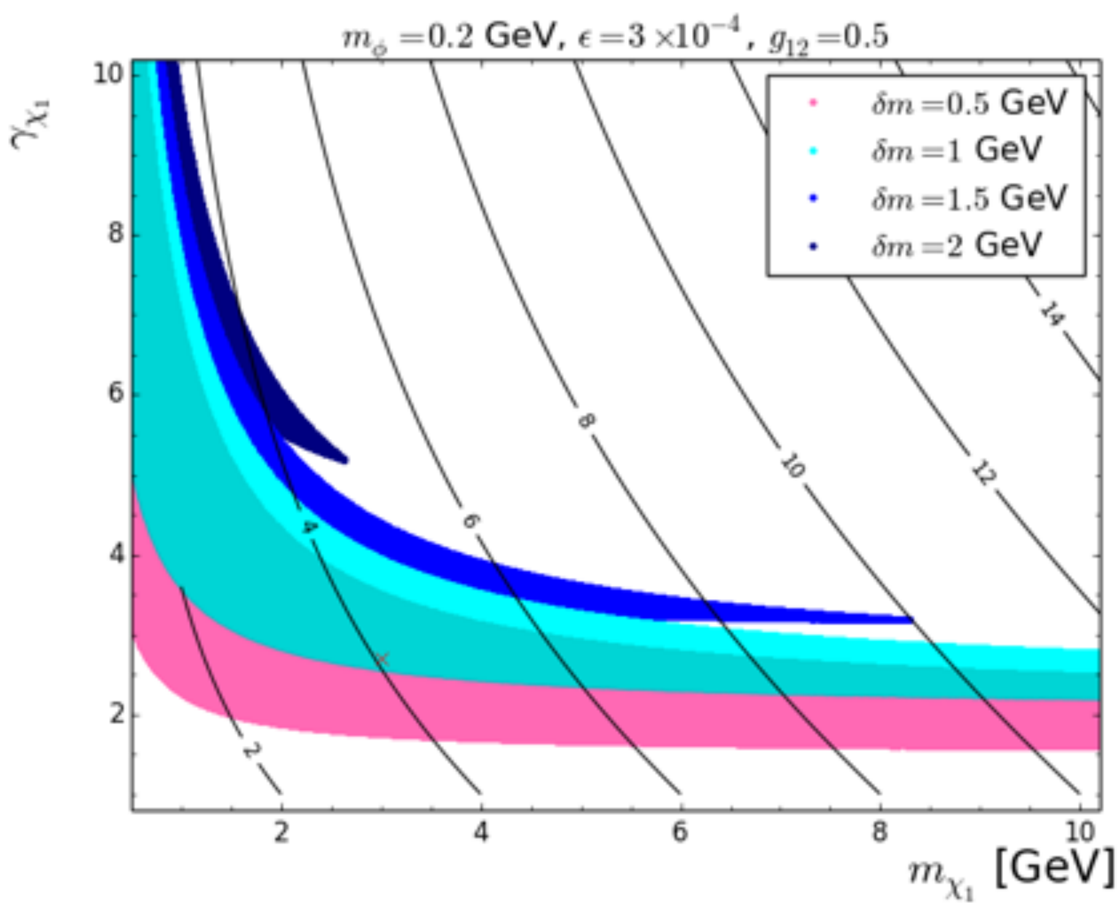
Back up



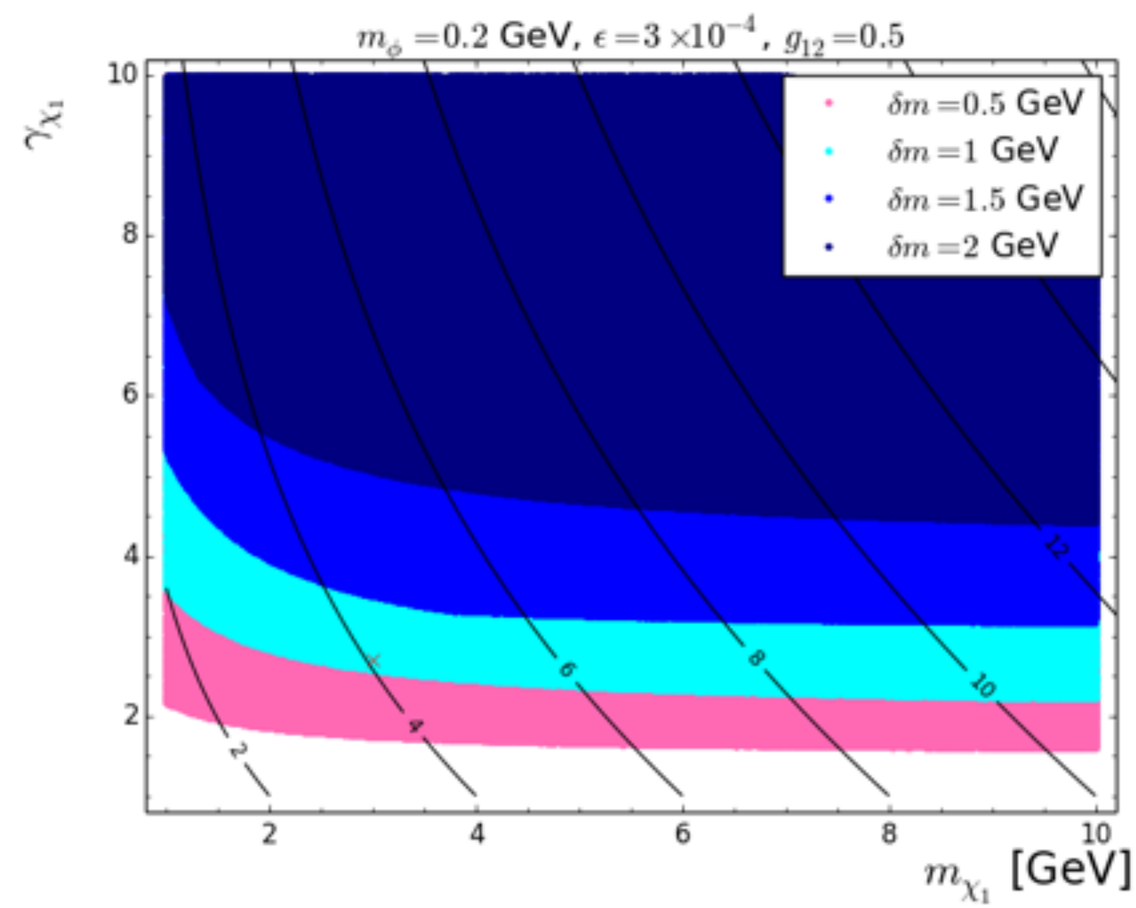
Electron recoil spectrum
$m_{\chi_1} = 0.4, m_{\chi_2} = 0.5, m_\phi = 0.06, \gamma_{\chi_1} = 250$
$m_{\chi_1} = 0.1, m_{\chi_2} = 0.14, m_\phi = 0.03, \gamma_{\chi_1} = 200$
$1/\sigma \cdot d\sigma/dp_e$
p_e [GeV]
2.0
1.5
1.0
0.5
0.0
0.001
0.01
0.1
1

p-scattering: possible search area

Region of elastic scattering p_p: [E_{th}, 1.8 GeV]

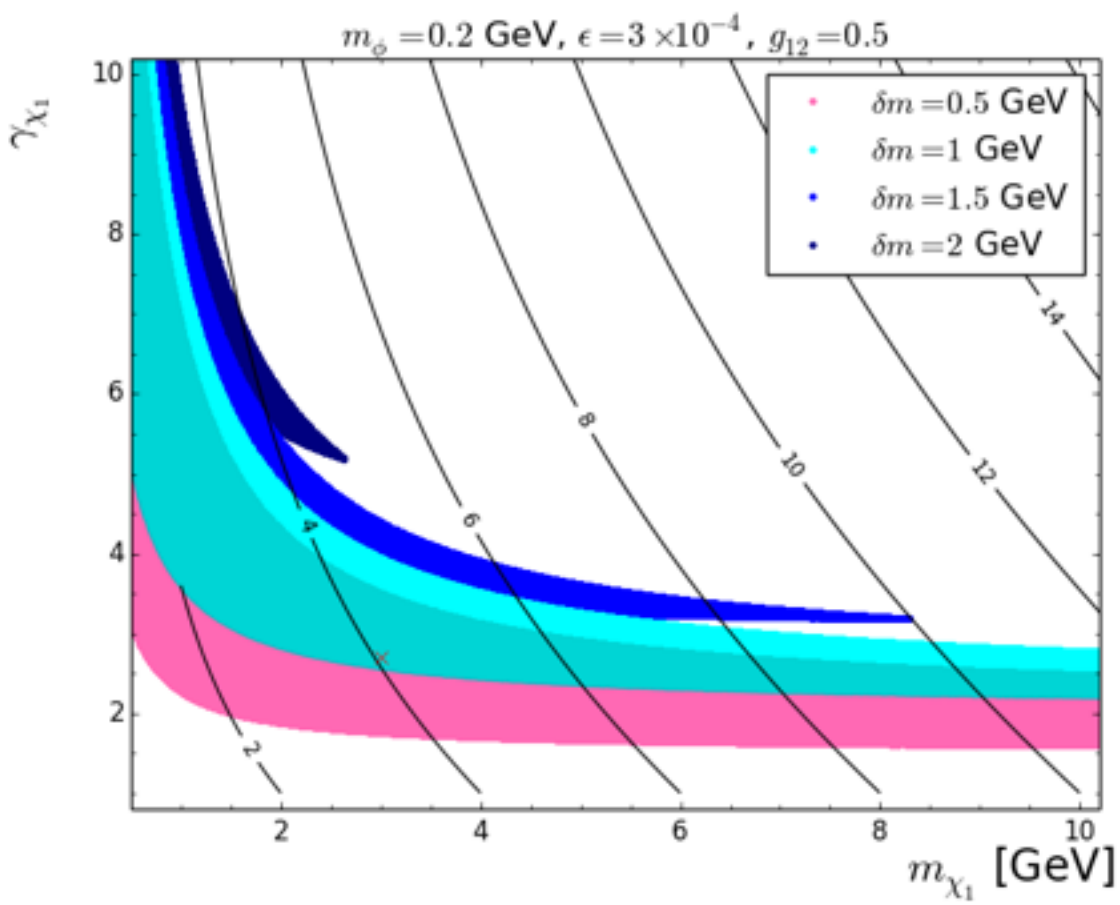


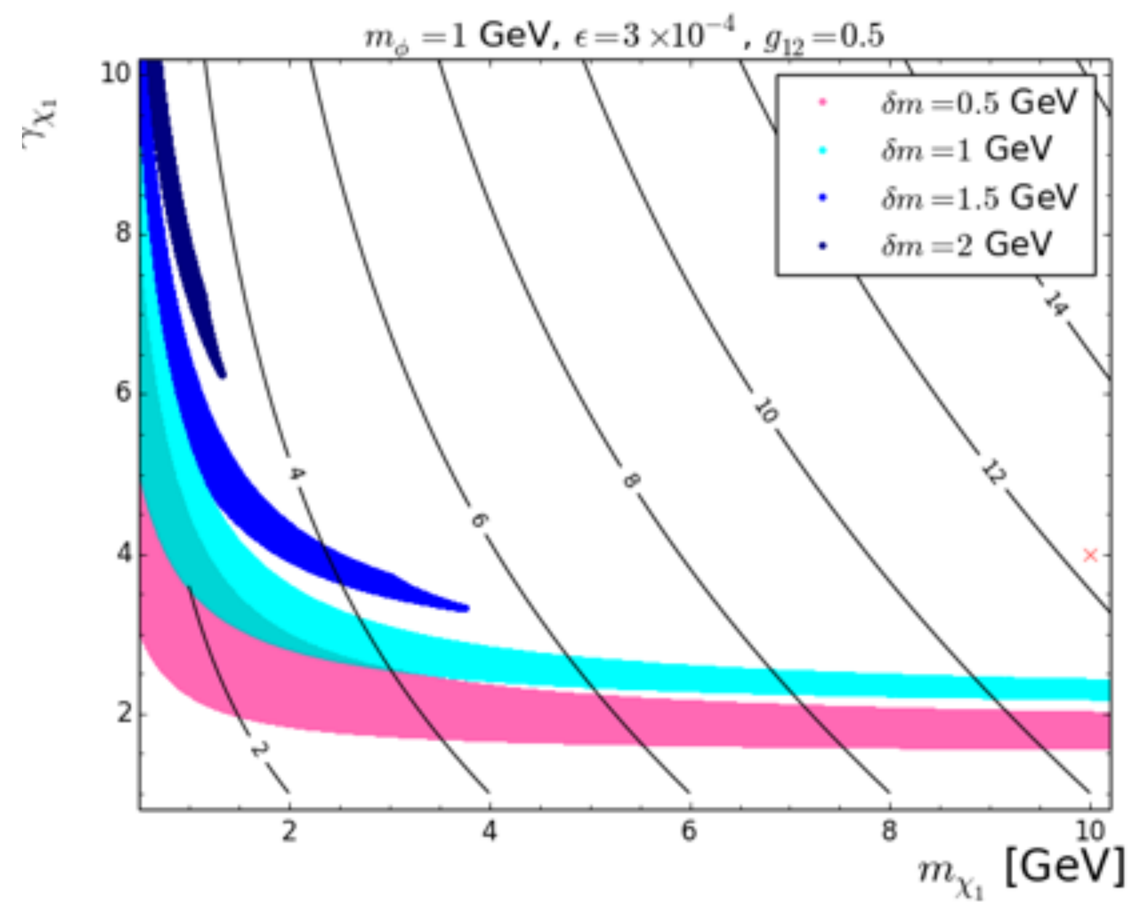
Kamiokande



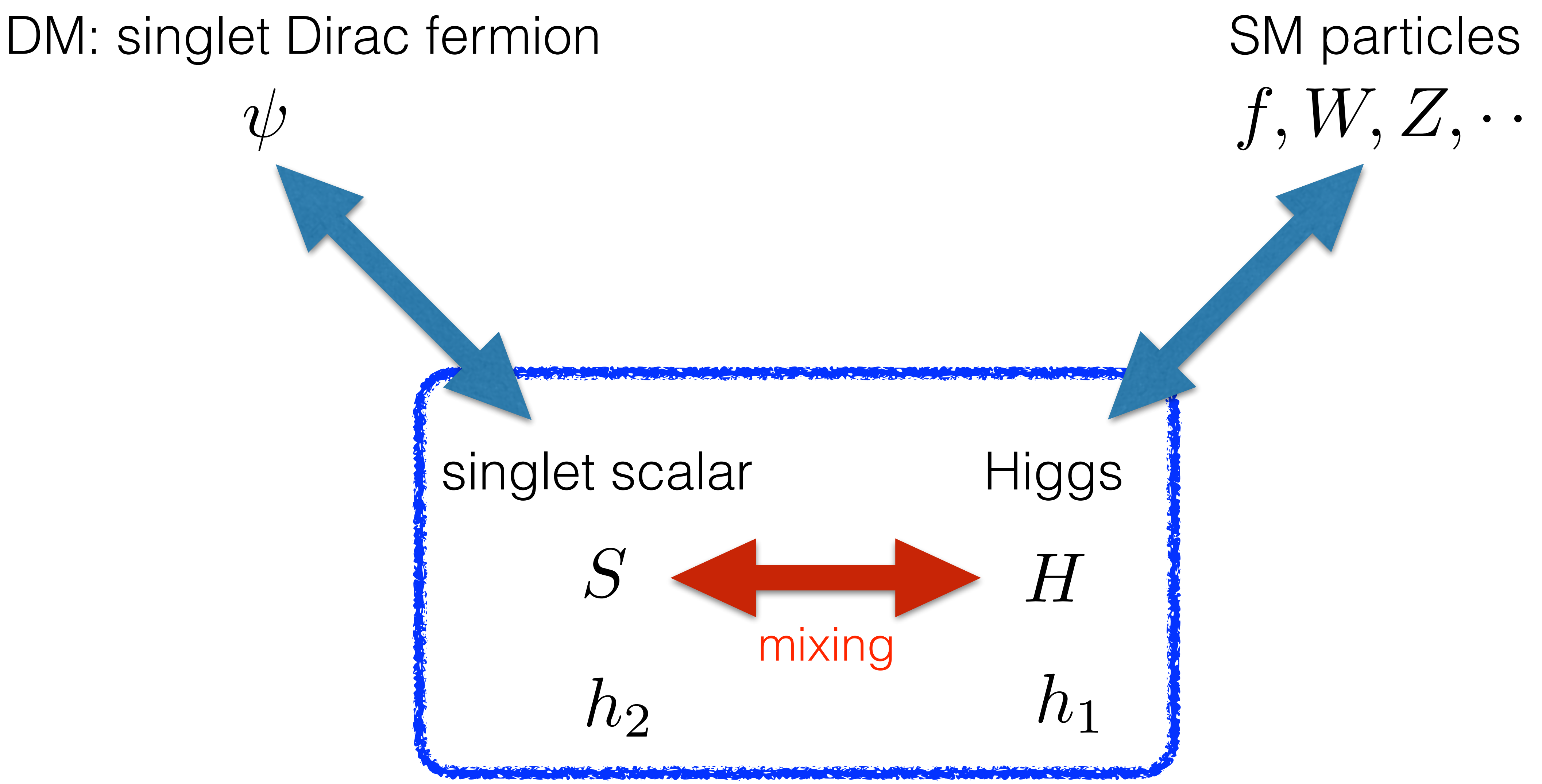
DUNE

Back up


$m_\phi = 0.2$ GeV, $\epsilon = 3 \times 10^{-4}$, $g_{12} = 0.5$
γ_{χ_1}
m_{χ_1} [GeV]
$\delta m = 0.5$ GeV
$\delta m = 1$ GeV
$\delta m = 1.5$ GeV
$\delta m = 2$ GeV


$m_\phi = 1$ GeV, $\epsilon = 3 \times 10^{-4}$, $g_{12} = 0.5$
γ_{χ_1}
m_{χ_1} [GeV]
$\delta m = 0.5$ GeV
$\delta m = 1$ GeV
$\delta m = 1.5$ GeV
$\delta m = 2$ GeV

Singlet Fermionic Dark Matter



Y.G. Kim, K.Y. Lee, **SS**, JHEP 0805, 100 [arXiv:0803.2932]

A renormalizable Higgs portal WIMP model

(induce bunch of phenomenological studies: exotic decay, …)

Secluded SFDM

Secluded set-up by Kim, Lee, Park, **SS**, 1601.05089

- Small mixing angle: Higgs measurements at the LHC
  & null results in direct detection

- Pseudoscalar int. in the dark sector: p-wave in t-channel WIMP-SM recoil
  s-wave in s-channel

Lopez-Honorez, Schwetz, Zupan, 1203.2064

Fedderke, Chen, Kolb, Wang, 1404.2283

$$\boxed{-\mathcal{L}_{\rm int}^{\rm dark} = g_S \cos\xi \, s\bar{\psi}\psi + g_S \sin\xi \, s\bar{\psi}i\gamma^5\psi,}$$

Secluded SFDM for the γ-ray excess

Our starting point

- DM annihilation (not denying other possibilities)
- Apply the result by Calore et al., 1409.0042, 1411.4647: syst. & stat. error
- Assume a generalized NFW profile allowing the uncertainties in the astrophysical factor $\bar{J}$ with scaling [0.17, 5.3] and $\gamma = 1.2$

Calore, Cholis, McCabe, Weniger, 1411.4647

$$\rho(r) = \rho_s \frac{(r/r_s)^{-\gamma}}{(1+r/r_s)^{3-\gamma}}$$

$$\frac{\mathrm{d}N}{\mathrm{d}E} = \frac{\bar{J}}{16\pi m_\chi^2} \sum_f \langle \sigma v \rangle_f \frac{\mathrm{d}N_\gamma^f}{\mathrm{d}E}$$

$$\bar{J} = \frac{1}{\Delta\Omega} \int_{\Delta\Omega} \int_{\mathrm{l.o.s}} \rho^2(r(s,\,\psi))\,\mathrm{d}s\,\mathrm{d}\Omega,$$

Secluded SFDM for the γ-ray excess

Analysis process

- Unavoidable bounds: Higgs measurements, $\bar{p}$ ratios, γ-rays from dSphs.
- GeV level excess is best-fitted by changing $\bar{J}$ while fixing the relic density as observed (how we avoid the astrophysical bounds)
- Check the pure (dark sector) pseudoscalar case first (sinξ=1). If not good, allow the scalar interaction.

Best-fitted for $\psi\bar{\psi} \to b\bar{b},\ h_i h_j$ as model independent searches expected

$i, j = 1, 2$

But some subtleties exist