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מכון ויצמן למדע

WEIZMANN INSTITUTE OF SCIENCE

Off-axis detectors for light dark matter @ proton fixed target experiments

CERN-EPFL-Korea Institute:
"New physics at the intensity frontier"

With P.Coloma, B. Dobrescu and R. Harnik JHEP 1604 (2016) 047

CF hep ph 1701.05464 With B. Dobrescu JHEP 1502 (2015) 019

Outline

Probing sub-GeV dark matter/nucleon couplings at proton fixed target experiments

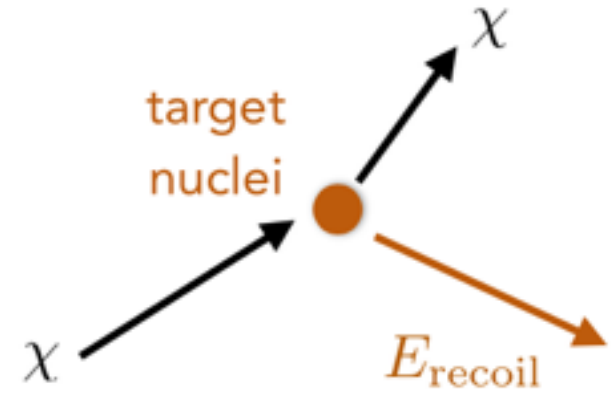
Maxim talk last week

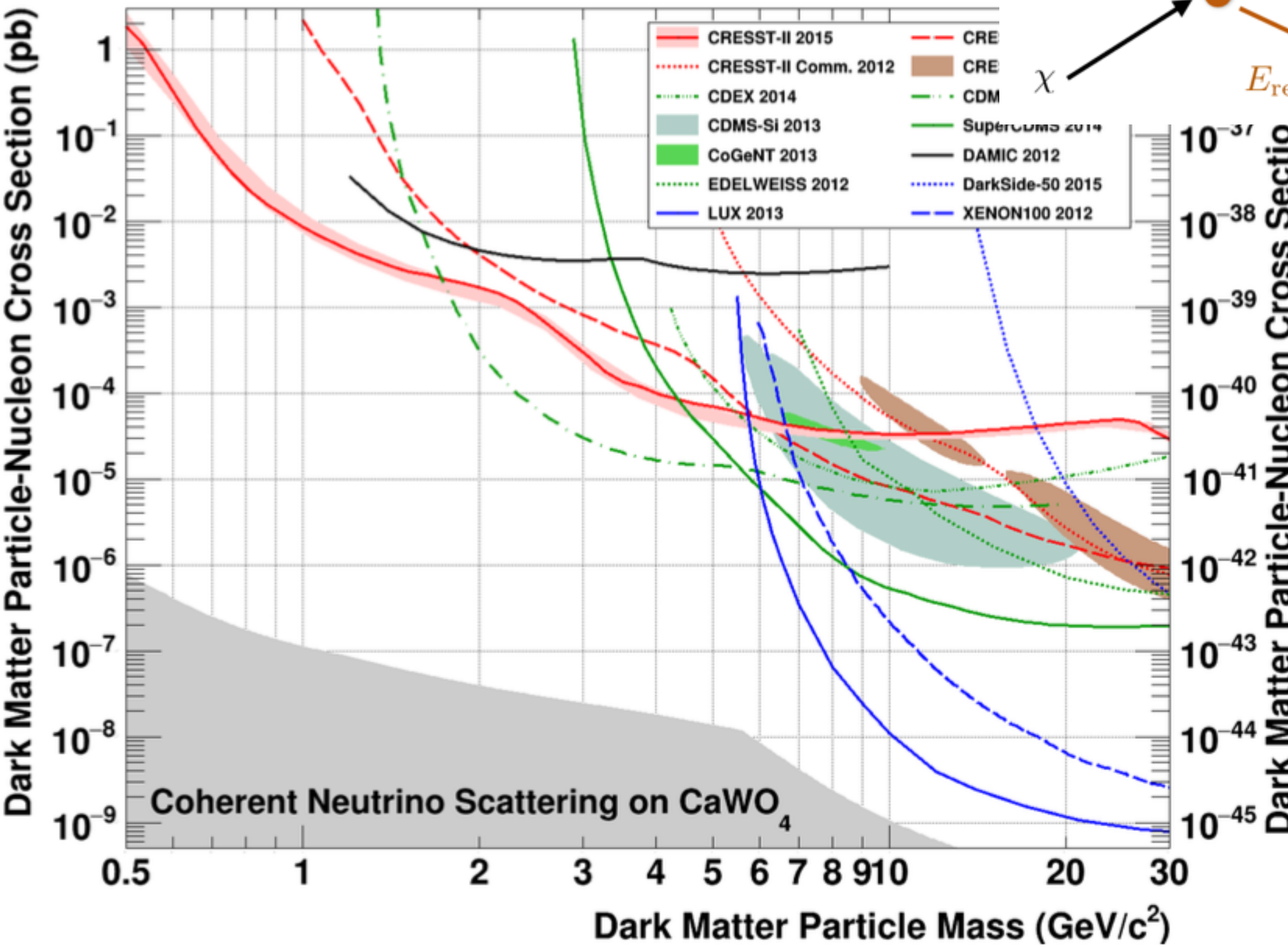
★ Focus on Fermilab based experiments: NOVA, MINOS, MiniBoone/MicroBoone and future LBNF/DUNE

Prospects for SHIP?

Dark matter direct detection

dark matter scattering off nuclei





Dark matter direct detection

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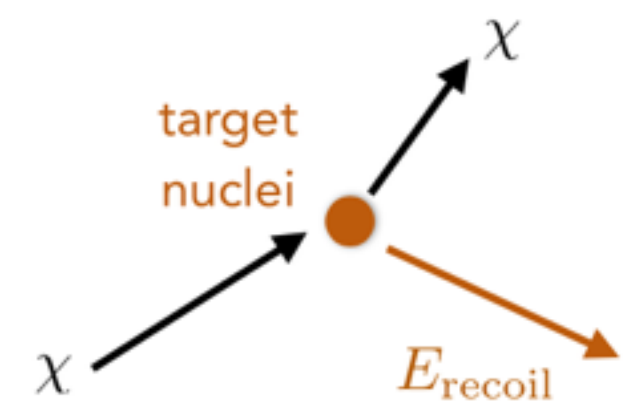
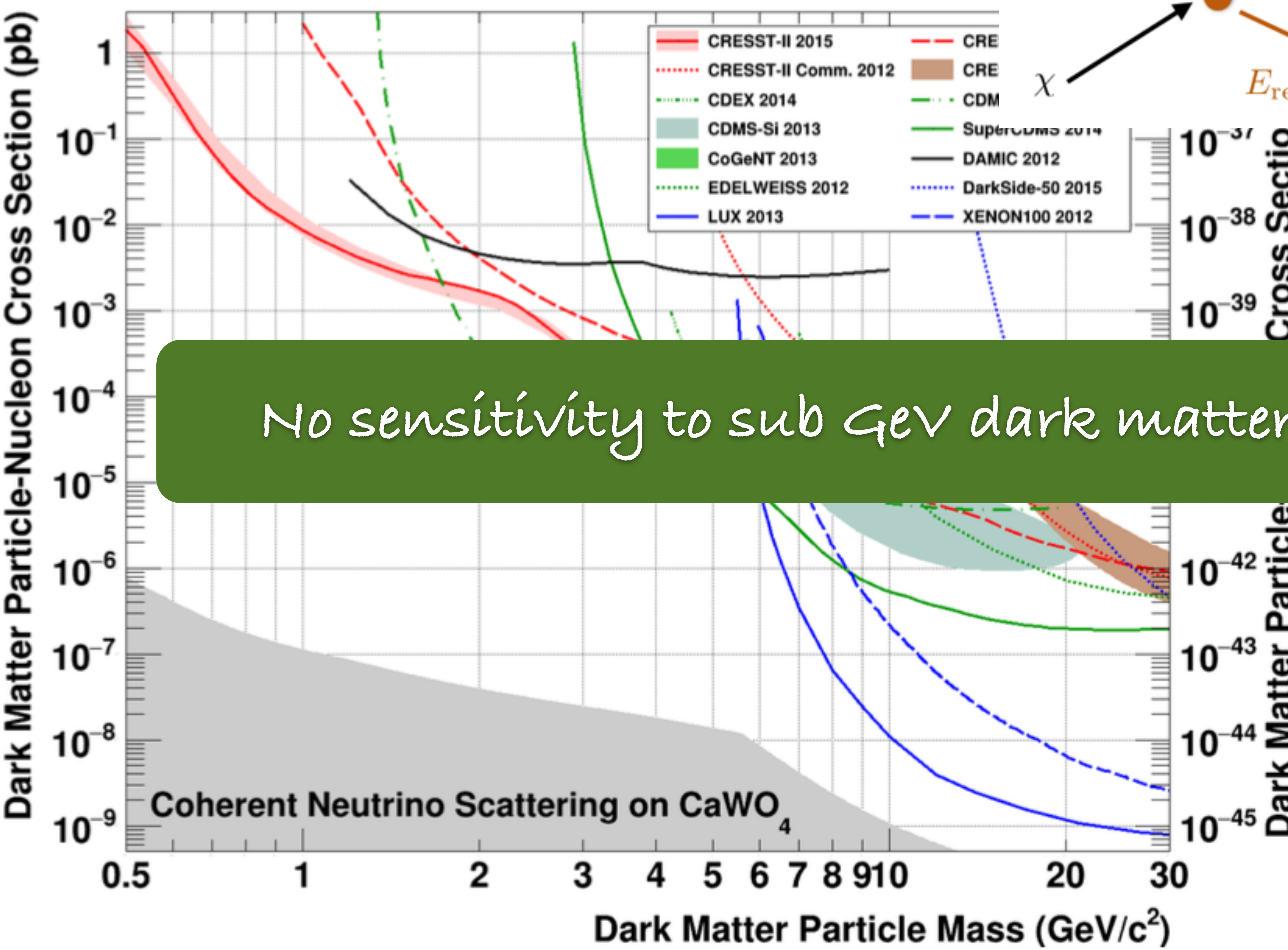




No sensitivity to sub GeV dark matter

What about light (sub-GeV) dark matter?

Recently a lot of effort has been put on filling this loophole by the theory community

★ Direct detection:
electron-DM interaction more promising direction

Essig, Mardon, Volansky 2011   Essig et al 2015 Zurek et al. 2015

★ Can we probe nucleon dark matter coupling?

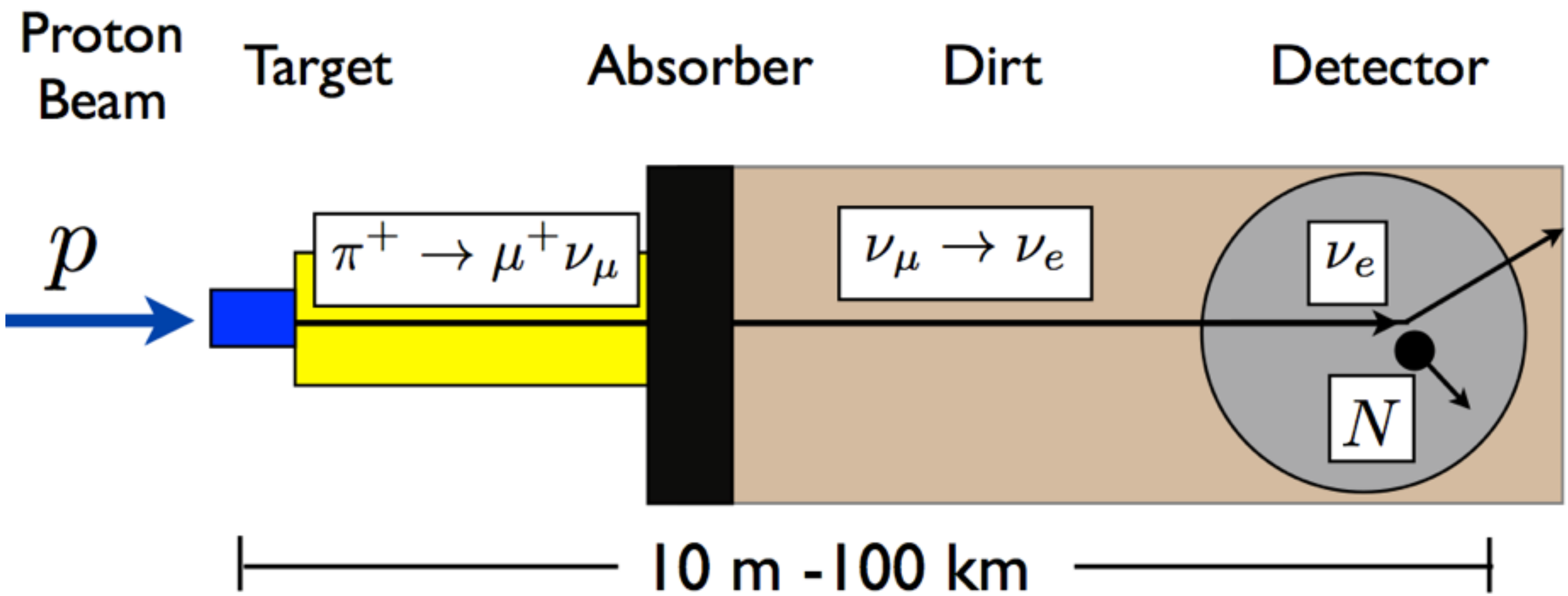
Yes at neutrino facilities

we can produce relativistic DM beams

Batell, Pospelov and Ritz 2009

Looking for light dark matter @ neutrino short baseline experiments

Batell, Pospelov and Ritz 2009

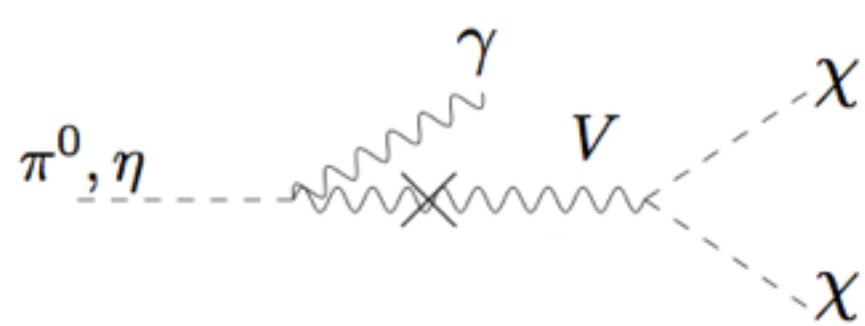


Quarks/DM vector portal

$$\frac{g_z}{2} Z'^{\mu} \frac{1}{3} \sum_q \bar{q}\gamma_\mu q \qquad \frac{g_z}{2} Z'^{\mu} z_\chi \bar{\chi}\chi$$

it could the DM particle or a particle of a more complex dark sector

- Production via meson decay

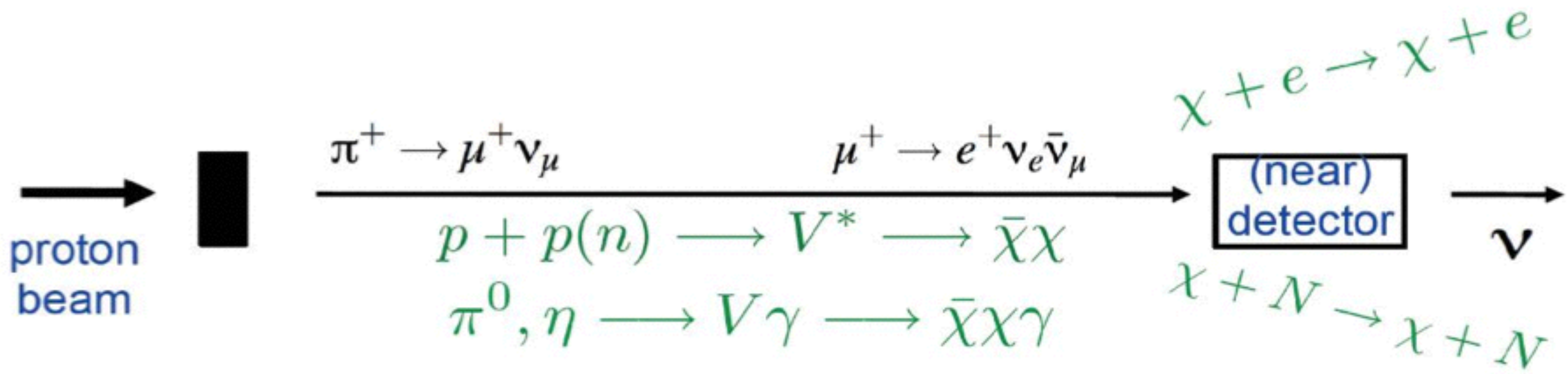


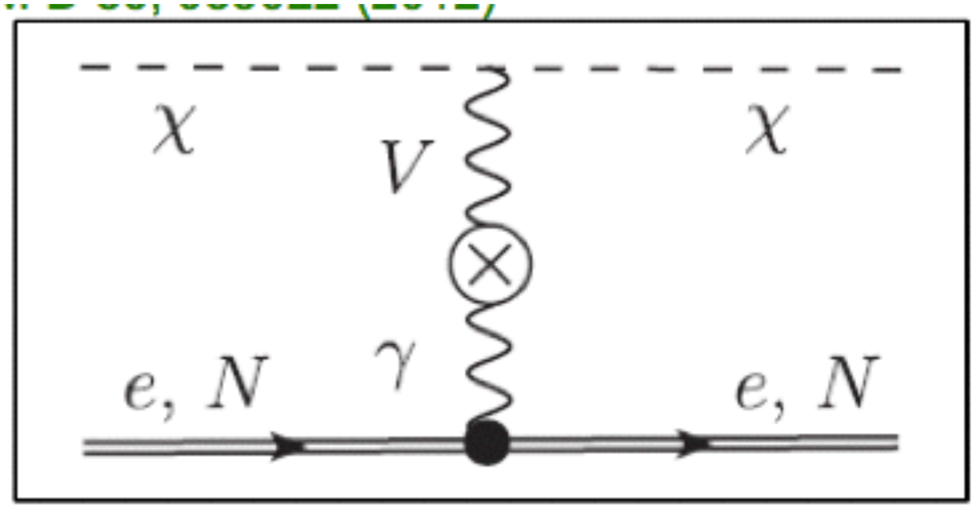
- Direct production

$$pp \to Z' \to \chi\chi \qquad pp \to Z'j \to \chi\chi j$$

We produce a dark matter beam!

Basic idea: we produce a DM beam





and we look for DM-nuclei scattering inside the near detector

Weak point: neutrino background irreducible bkg

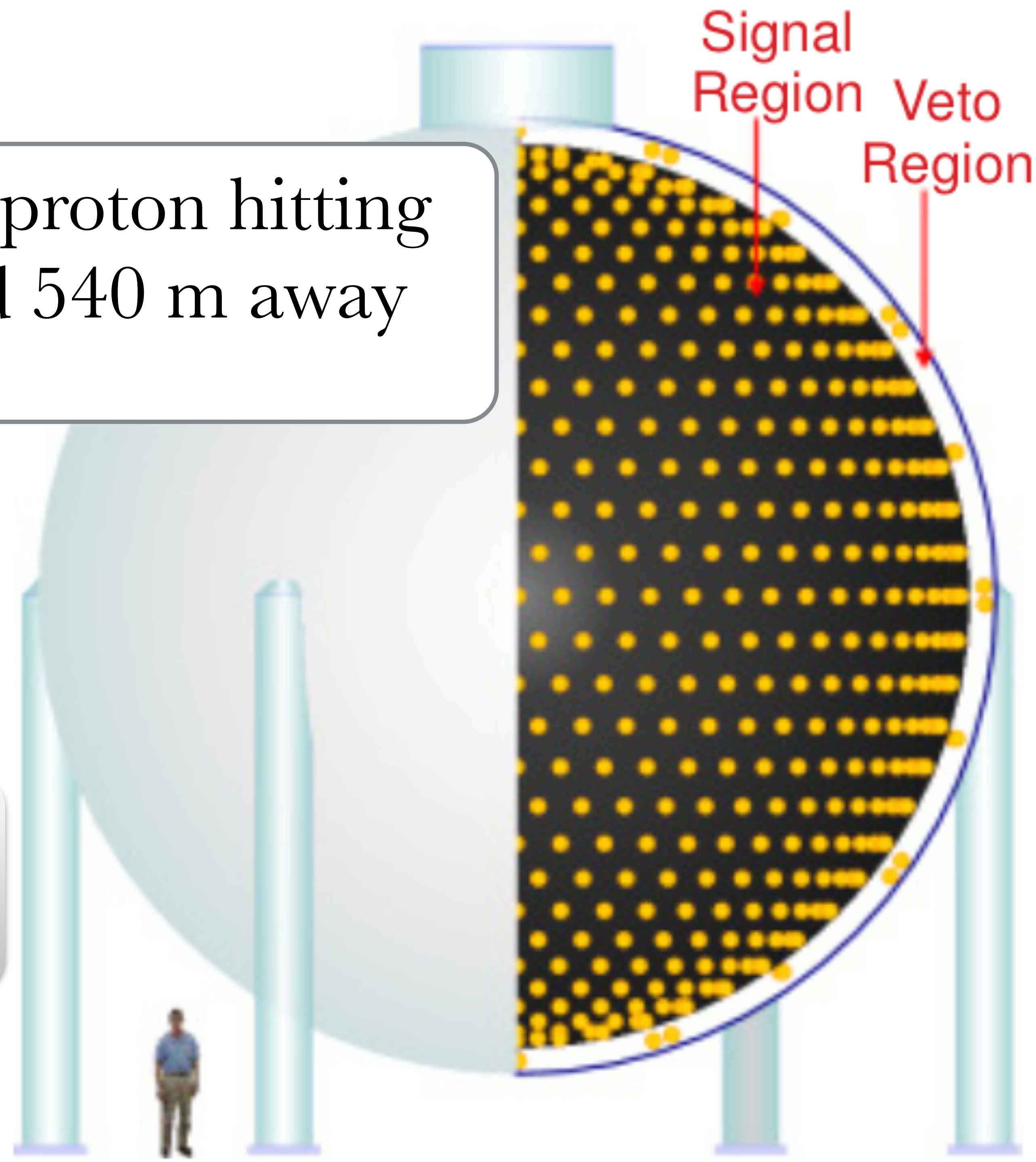
Main challenge: its suppression

Light DM @ MiniBOOne

B. Batell,P. deNiverville, D.McKeen, M.Pospelov, A.Ritz

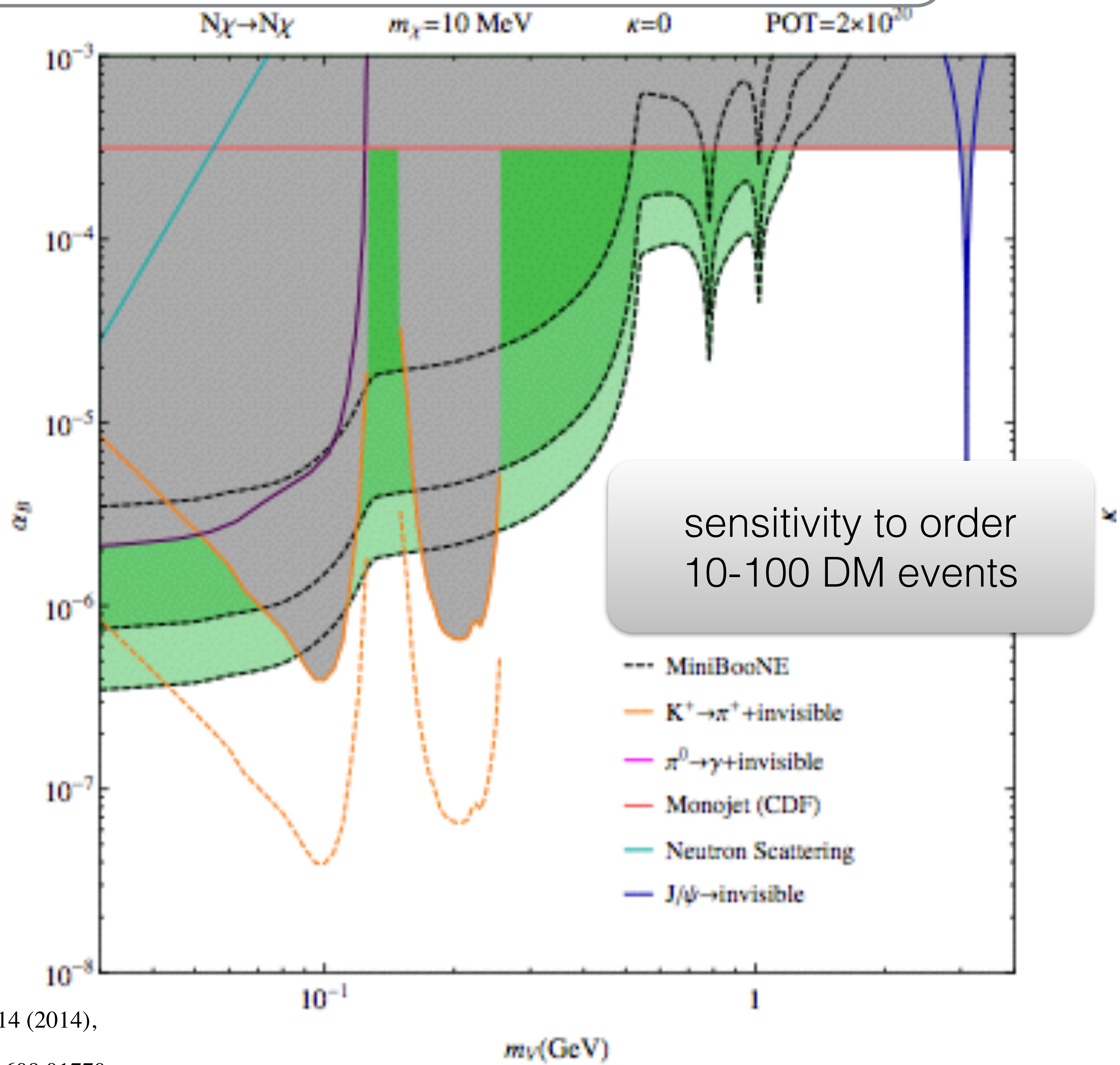
800 tons filled with mineral oil

On-axis detector for 8 GeV proton hitting a beryllium target . Located 540 m away



We can use it as DM detector looking at nucleon DM elastic events!

How many DM events?

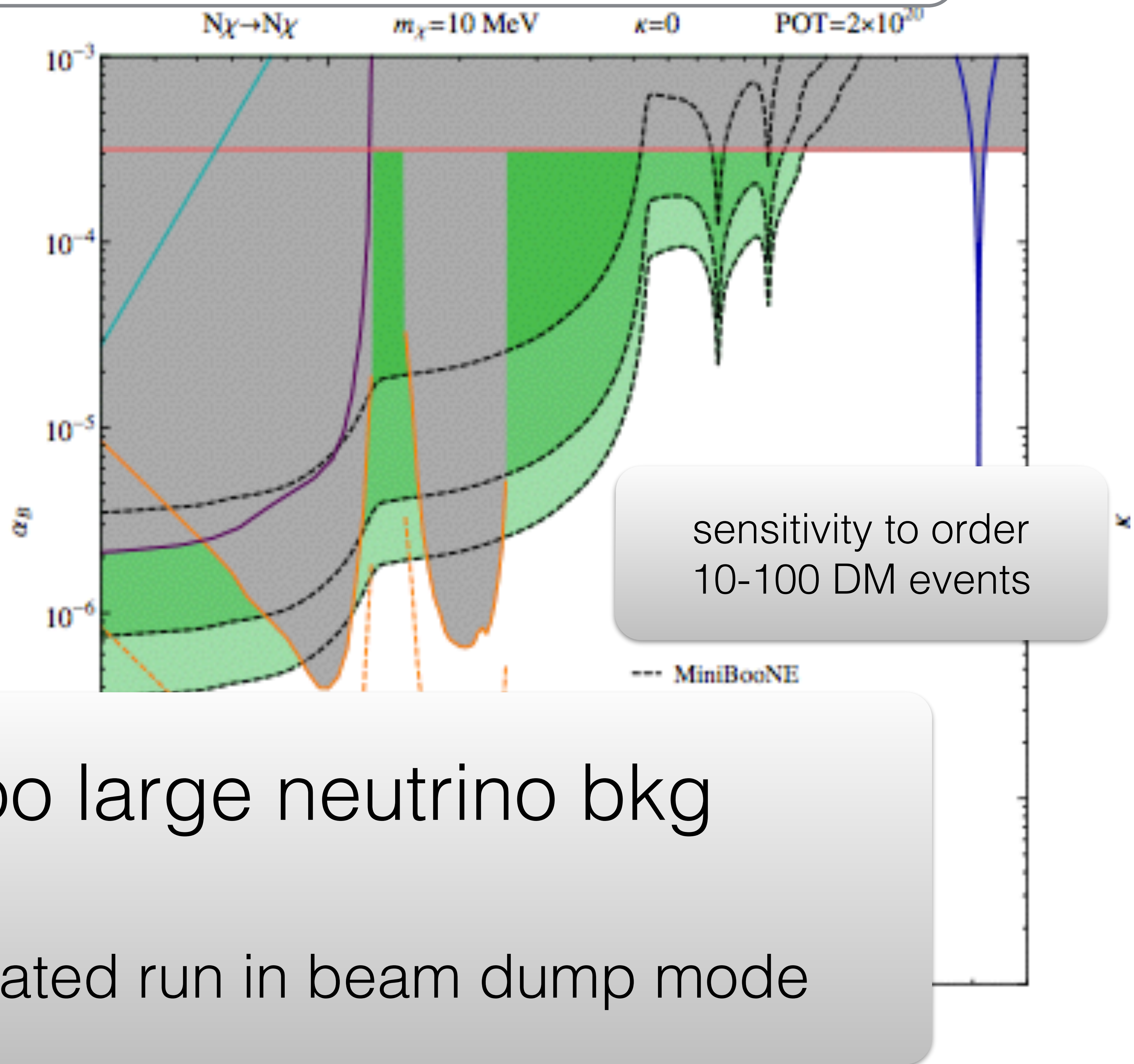


sensitivity to order
10-100 DM events

B. Batell et al., Phys. Rev. **D90**, 115014 (2014),

P. deNiverville et al., (2016), hep ph 1609.01770

How many DM events?



sensitivity to order 10-100 DM events

Too large neutrino bkg

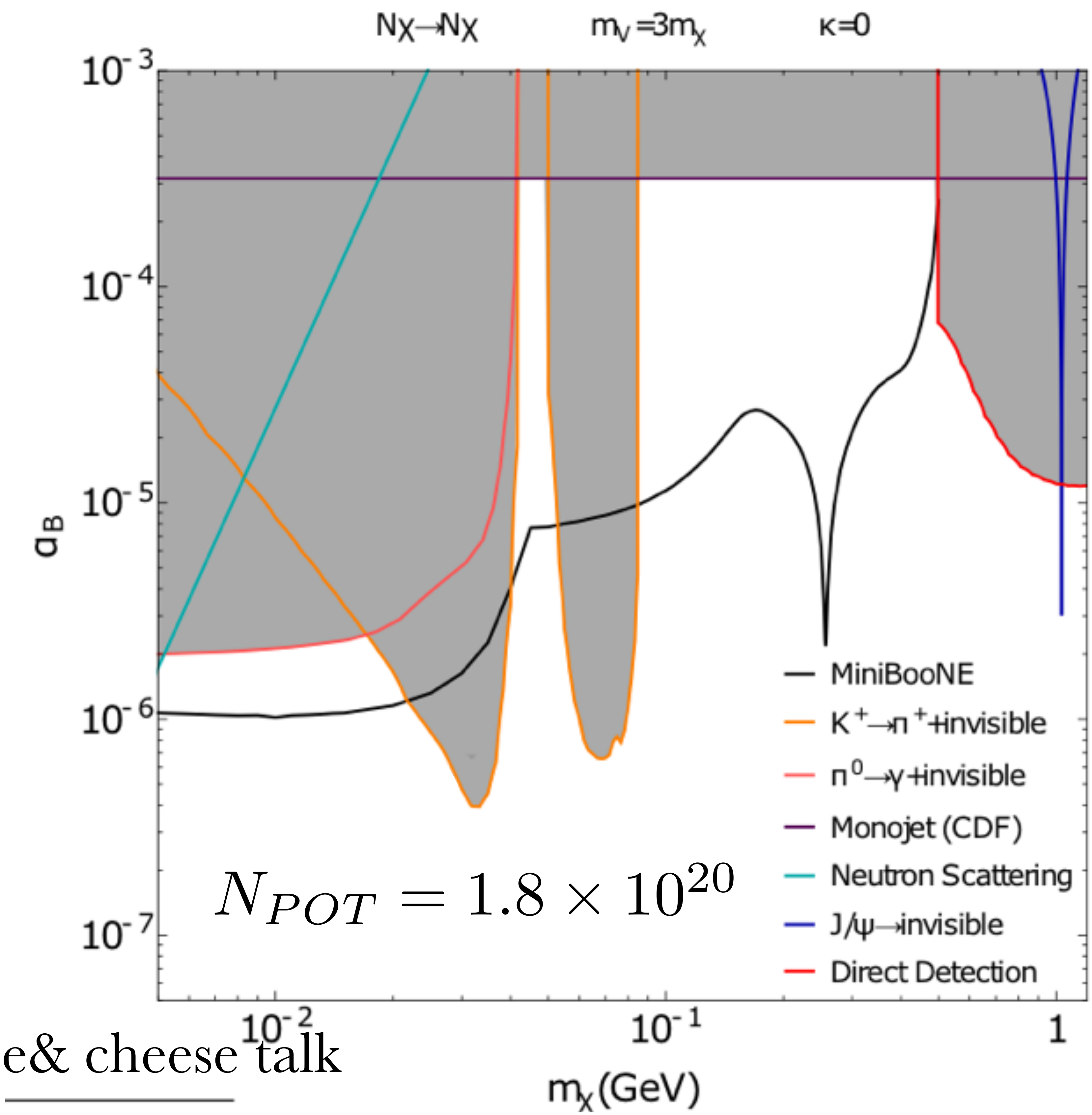
Dedicated run in beam dump mode

B. Batel

P. deNiverville et al., (2016), hep ph 1609.01770

Light DM @ MiniBOOne

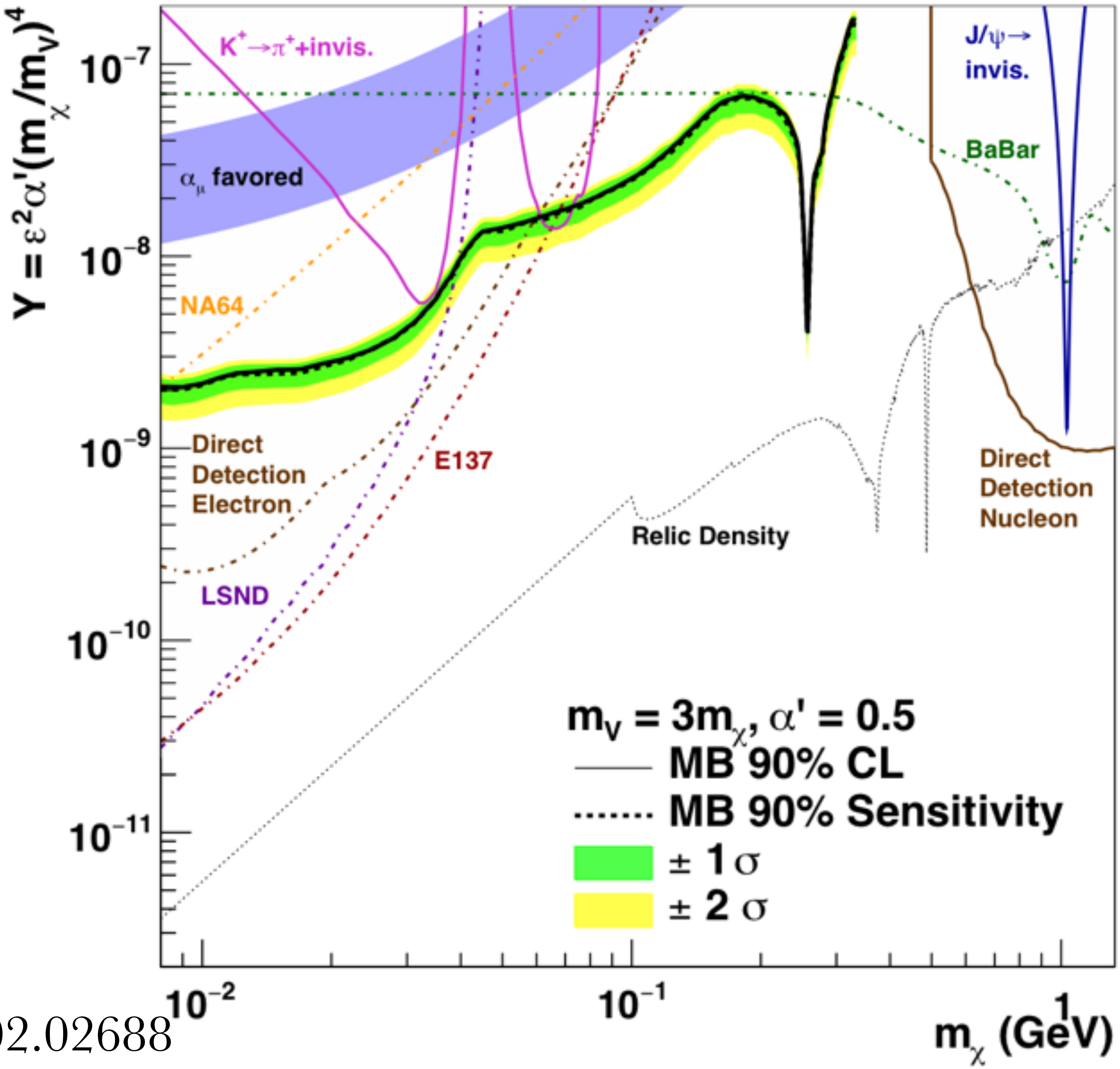
Signal: neutral current elastic DM/nucleon scattering (NCE)



Fermilab wine& cheese talk

Light DM @ MiniBOOne

Signal: neutral current elastic DM/nucleon scattering (NCE)



solid line: quark/DM probe

dashed line: electron/DM probe

hep ex 1702.02688

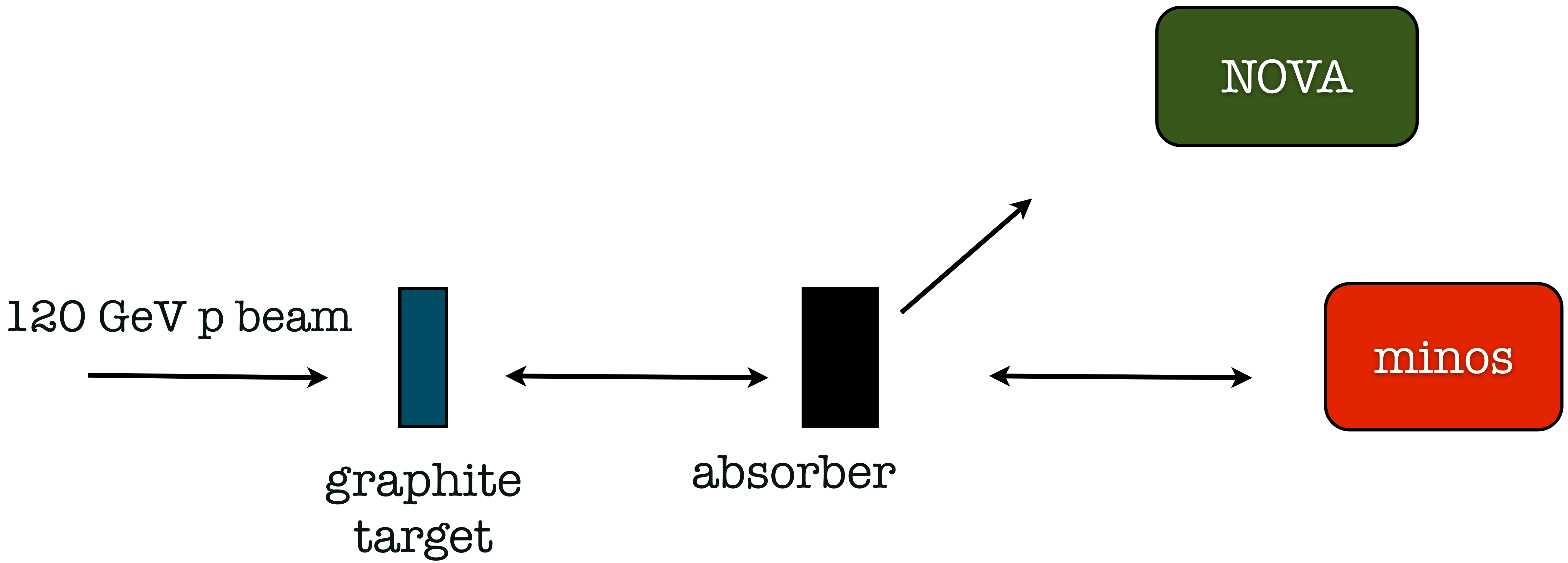
What about other neutrino facilities?

In particular high energy proton fixed target experiments such as CERN SPS and FNAL Main Injector facilties

- ★ We can extend the mass reach to few GeV mediators mass
- ★ How their reach compare to the MB BD run for lighter masses?
- ★ Can the DM program be symbiotic to the neutrino program?

Main injector facility

Several detectors (MINOS, NOVA and MINERVA) potentially good for DM detection



Dark matter beams at the Fermilab main injector

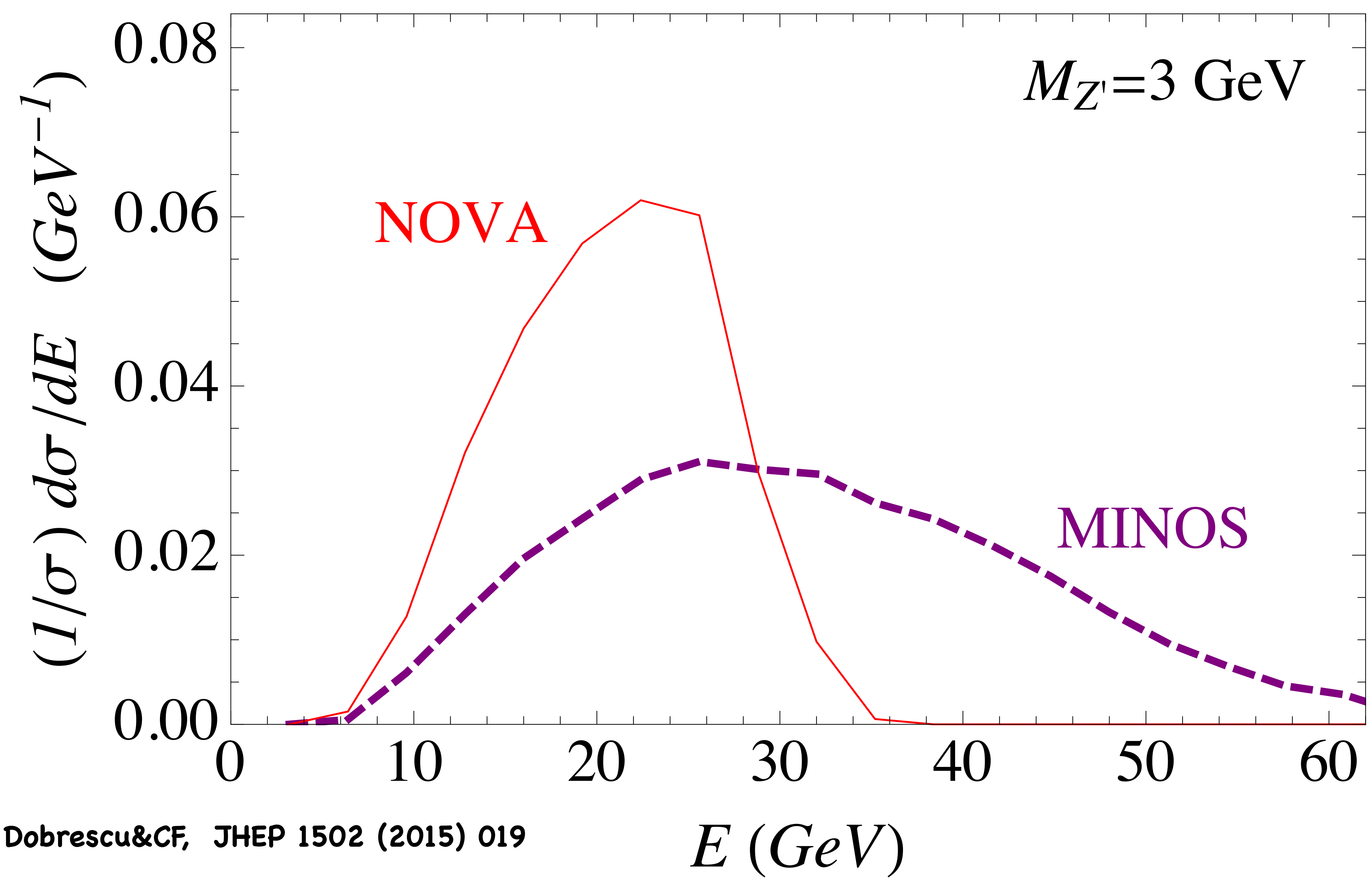
- 120 GeV (14 GeV CME) protons from Main Injector at Fermilab hitting a carbon target

it can extend the reach of MiniBoone towards heavier DM and Z'!

- Resonant direct Z' production

$$pp \to Z' \to \chi\chi$$

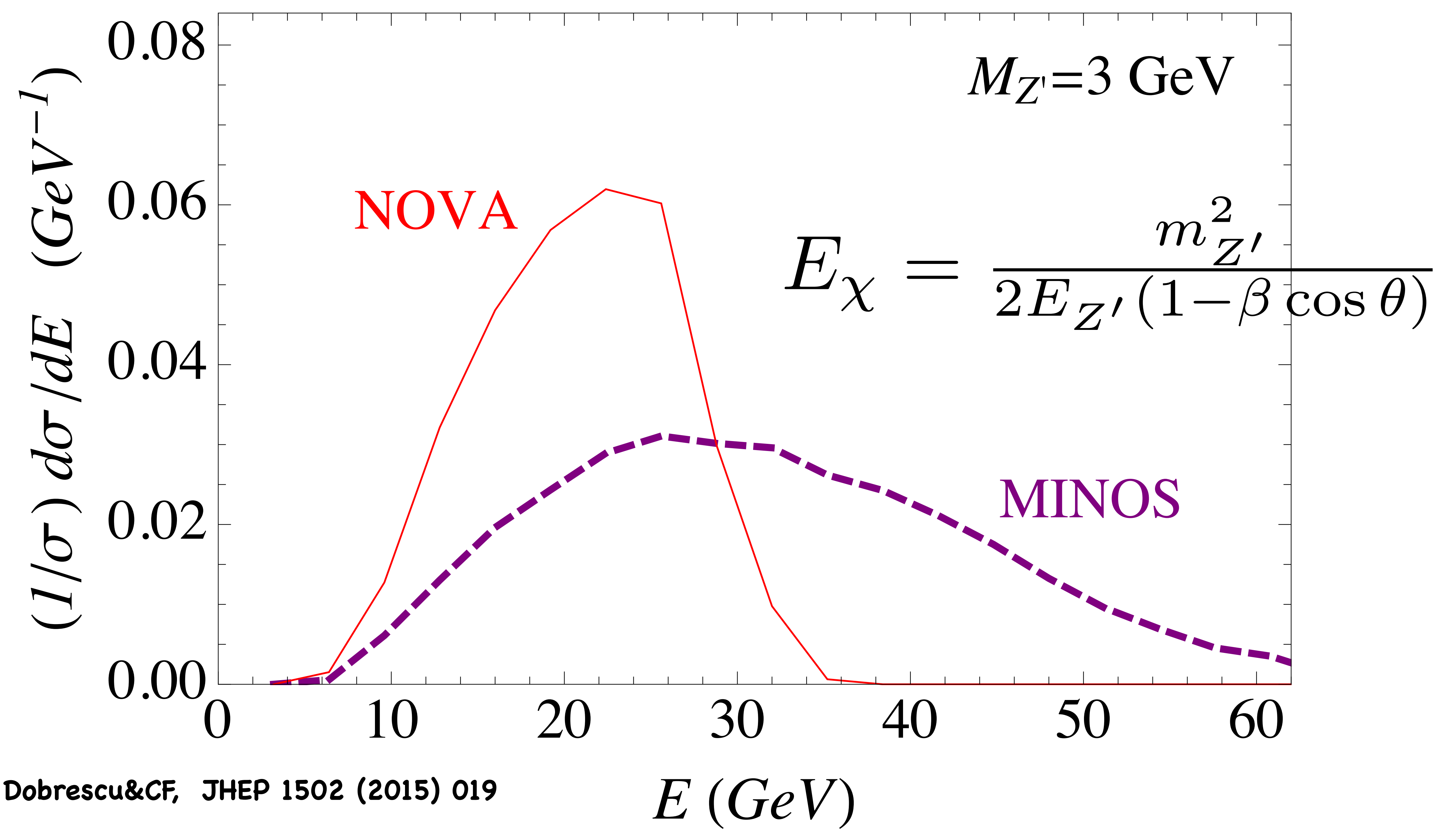
What is the DM signal inside these detectors?



Dobrescu&CF, JHEP 1502 (2015) 019

DM particles are fairly energetic

What is the DM signal inside these detectors?

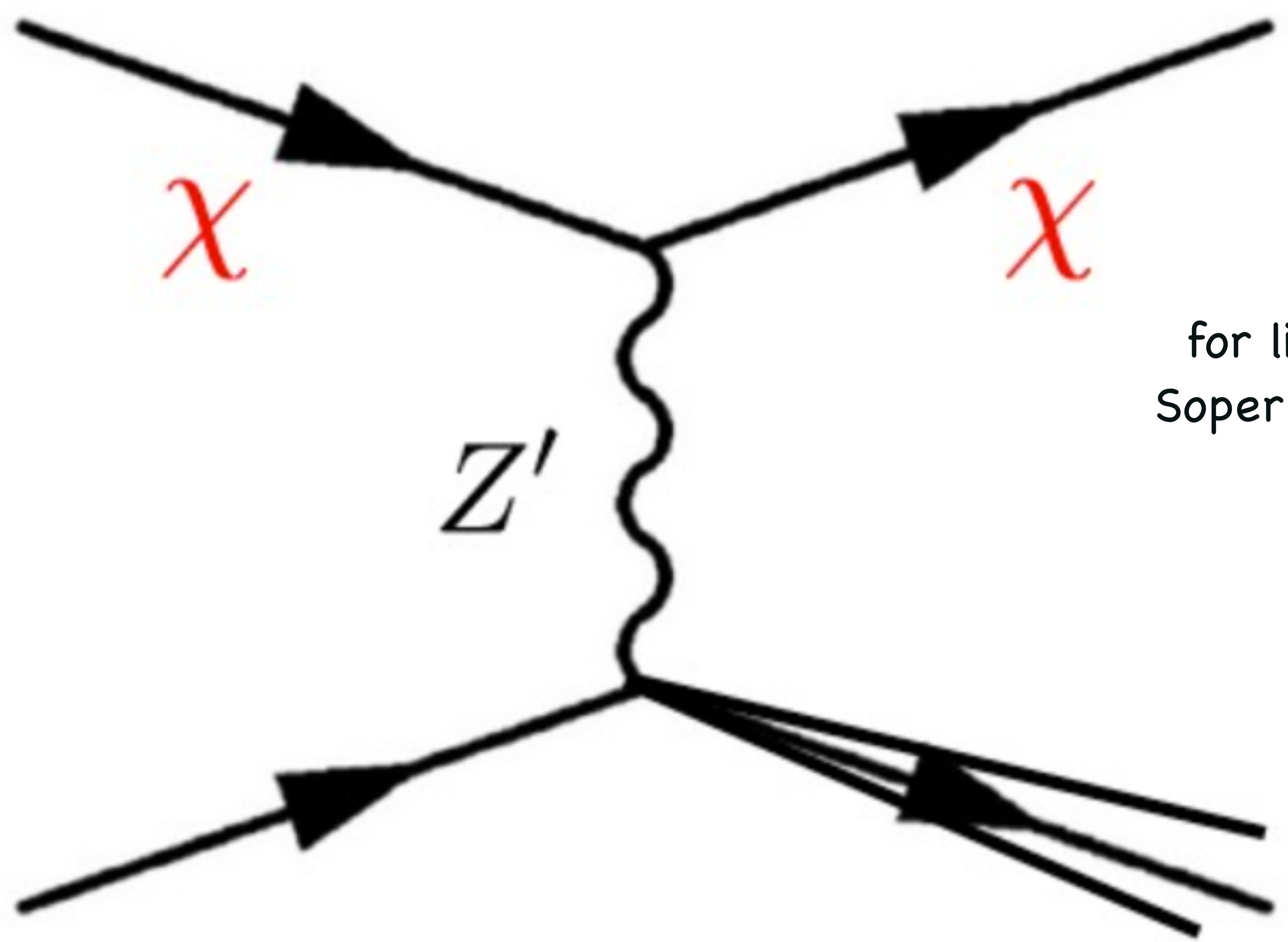


Dobrescu&CF, JHEP 1502 (2015) 019

→ DM particles are fairly energetic

DM energy profile inside the detector

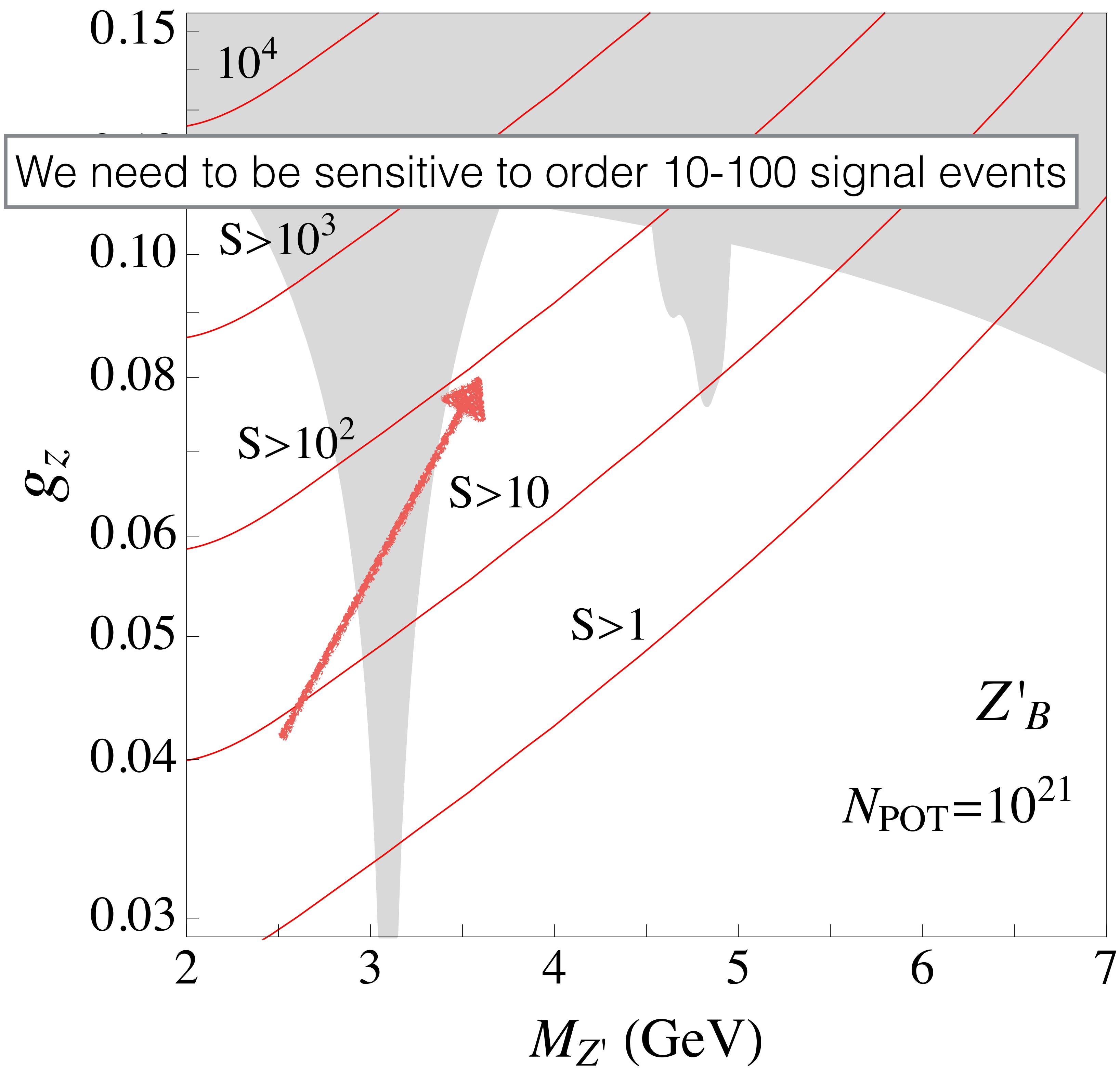
DM energetic - deeply inelastic events



for lighter DM
Soper et al. 2014

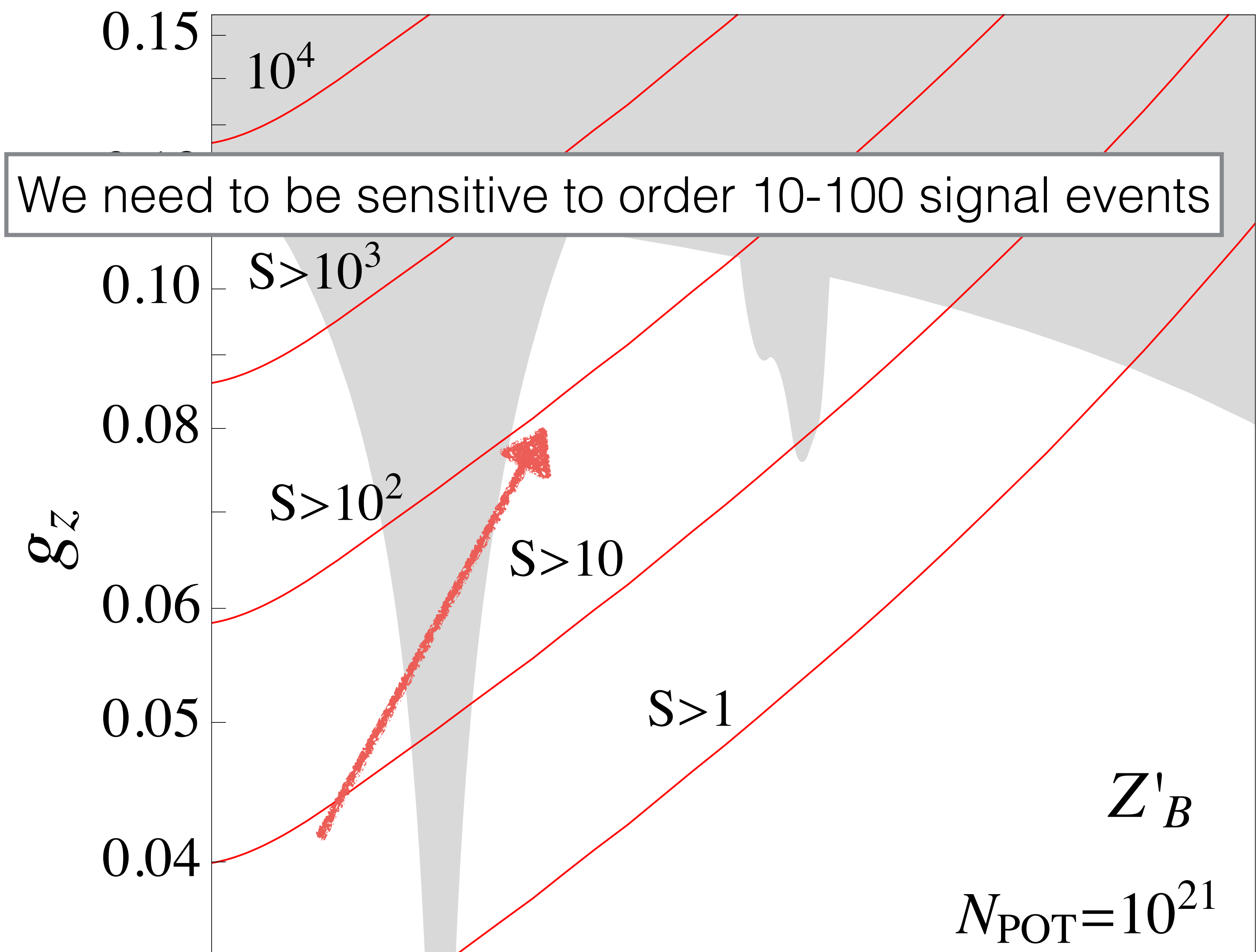
→ DM particles are fairly energetic

Number of DM DIS scattering events in NOVA



Dobrescu&CF 2014

Number of DM DIS scattering events in NOVA

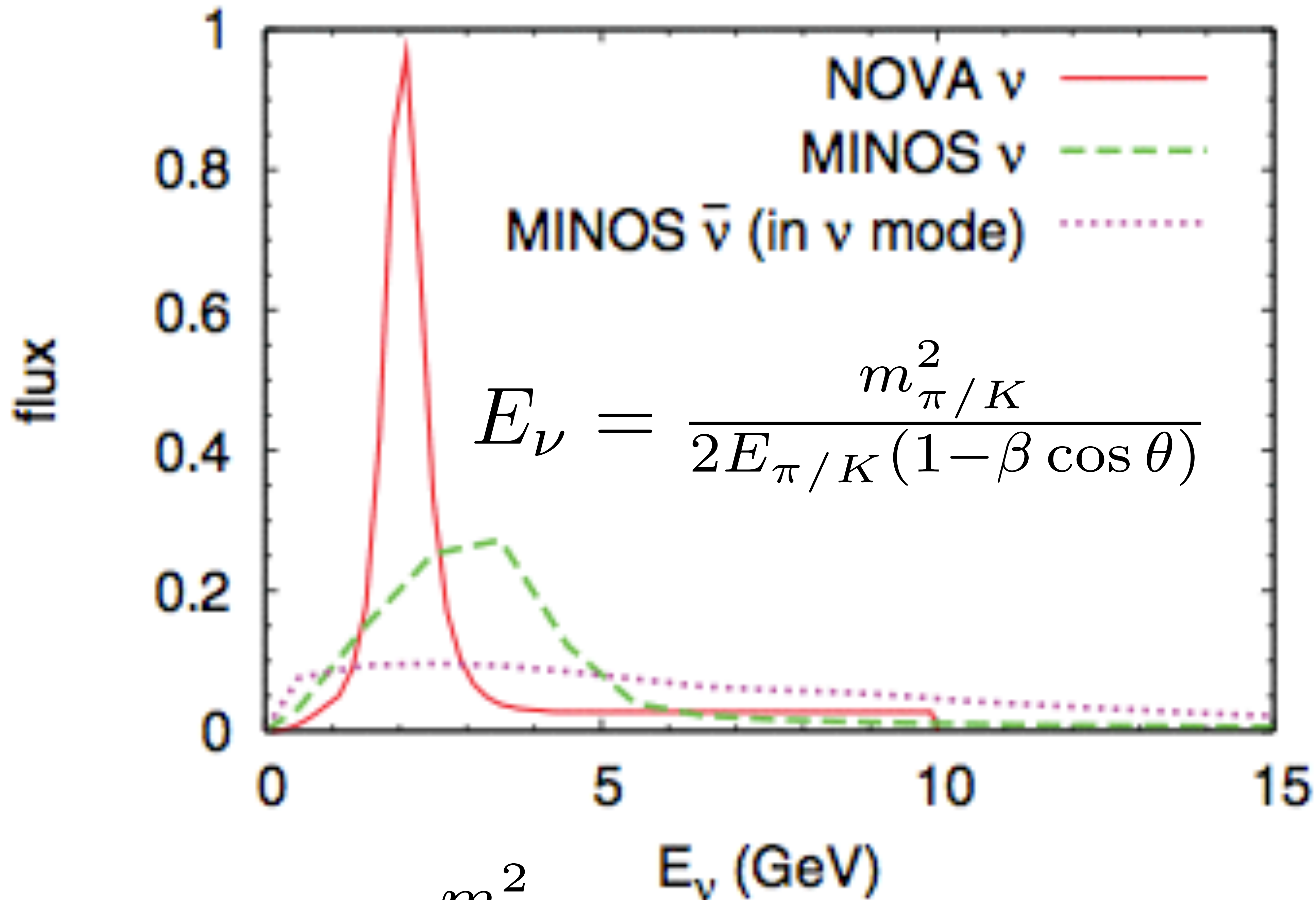


We need to be sensitive to order 10-100 signal events

Dobrescu&CF 2014

what about neutrinos?

Neutrinos energy profile

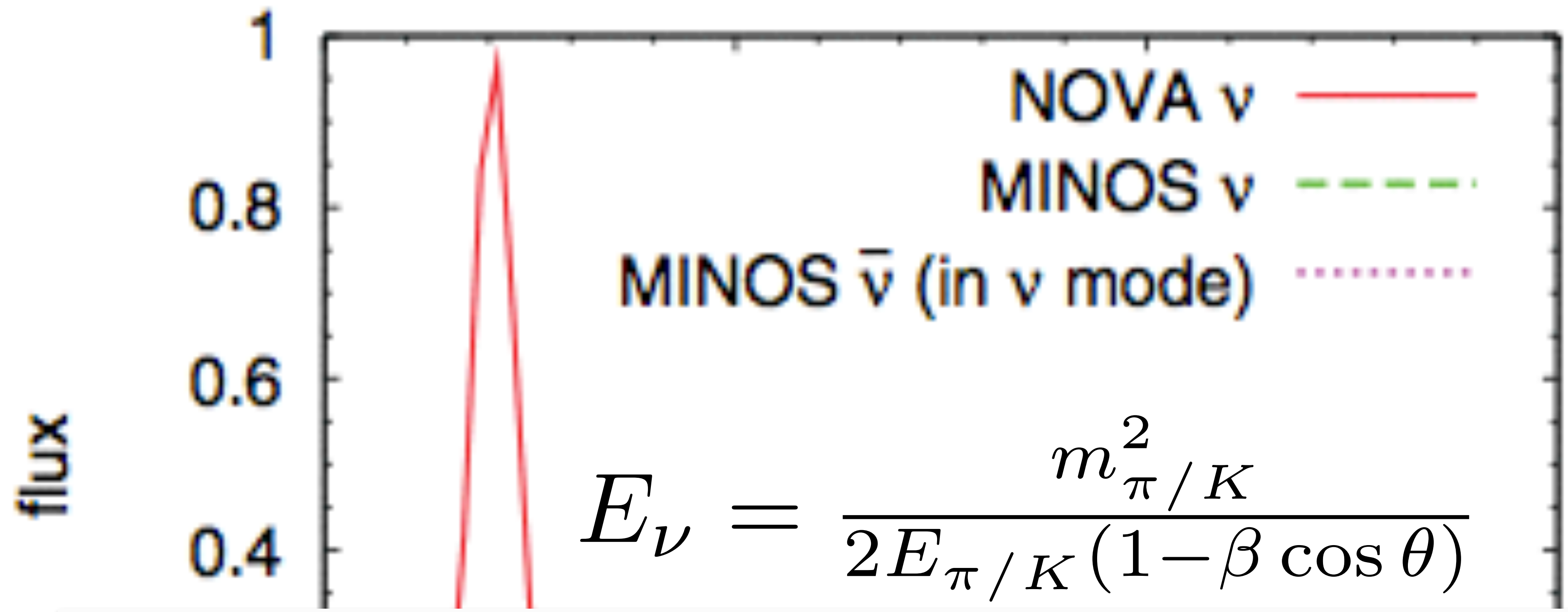


$$E_\nu = \frac{m^2_{\pi/K}}{2E_{\pi/K}(1-\beta\cos\theta)}$$

$$E_\chi = \frac{m^2_{Z'}}{2E_{Z'}(1-\beta\cos\theta)}$$

Dark matter more energetic
(peak around 20-30 GeV)

Neutrinos energy profile



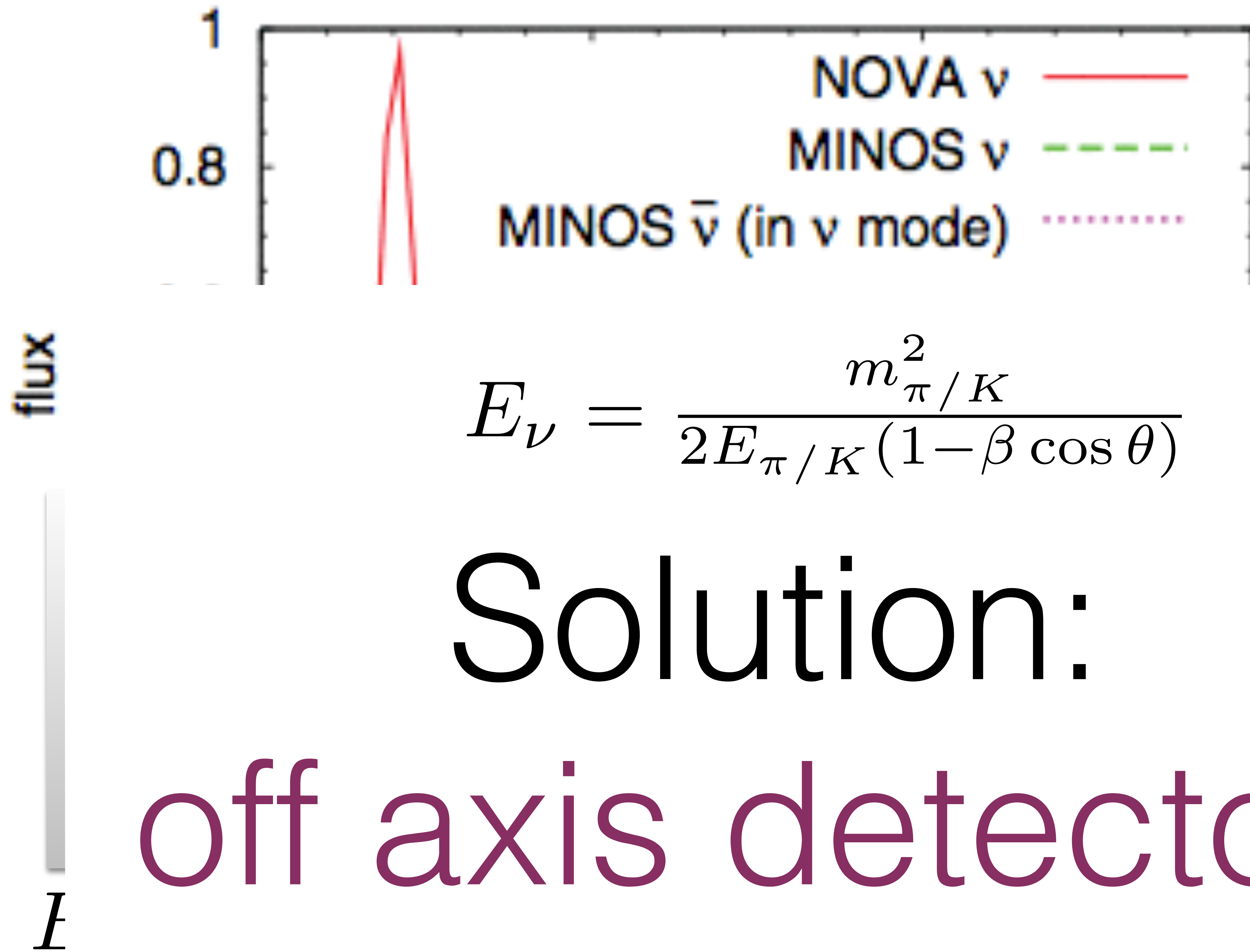
$$E_\nu = \frac{m^2_{\pi/K}}{2E_{\pi/K}(1-\beta\cos\theta)}$$

still a big neutrino tail!
10^6 bkg NC DIS events-
not enough to have sensitivity!

$$E_\chi = \frac{m^2_{Z'}}{2E_{Z'}(1-\beta\cos\theta)}$$

Dark matter more energetic
(peak around 20-30 GeV)

Neutrinos energy profile



$$E_\nu = \frac{m^2_{\pi/K}}{2E_{\pi/K}(1-\beta\cos\theta)}$$

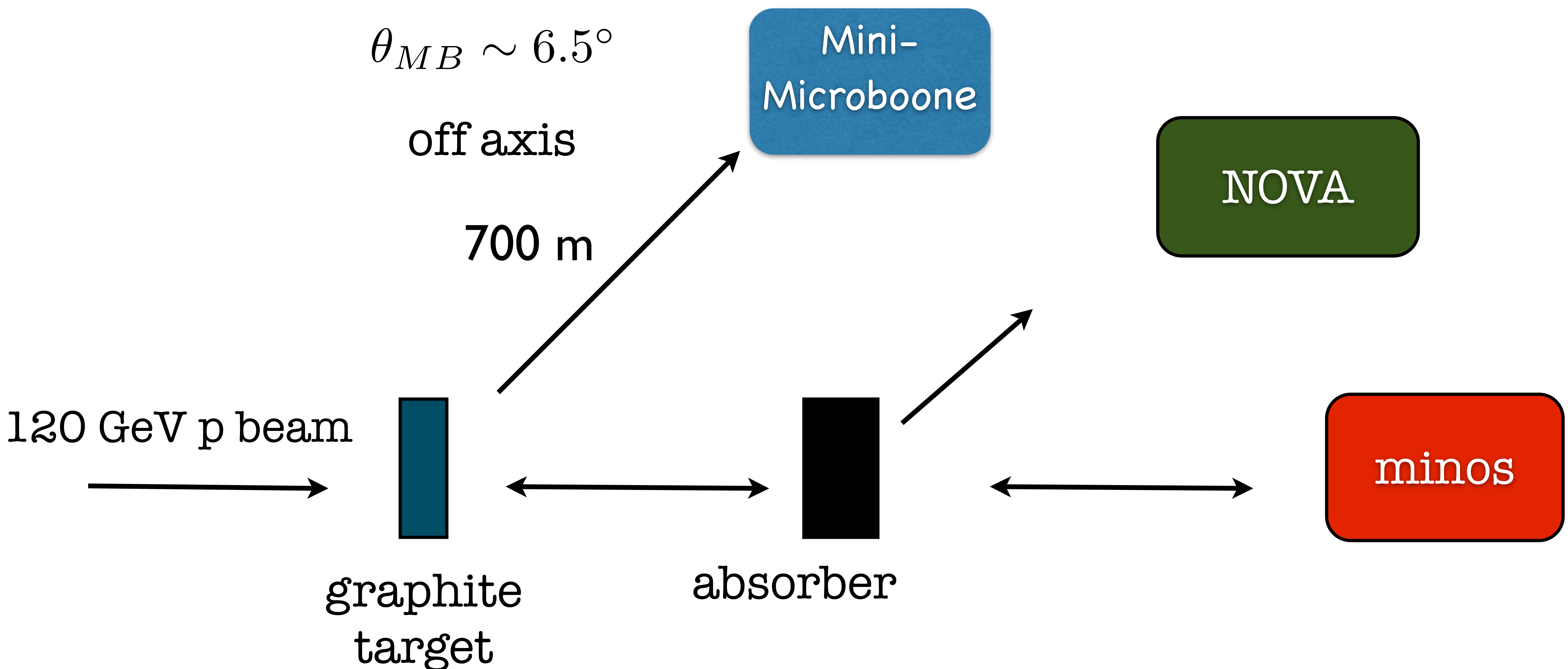
Solution:

off axis detector!

etic

eV)

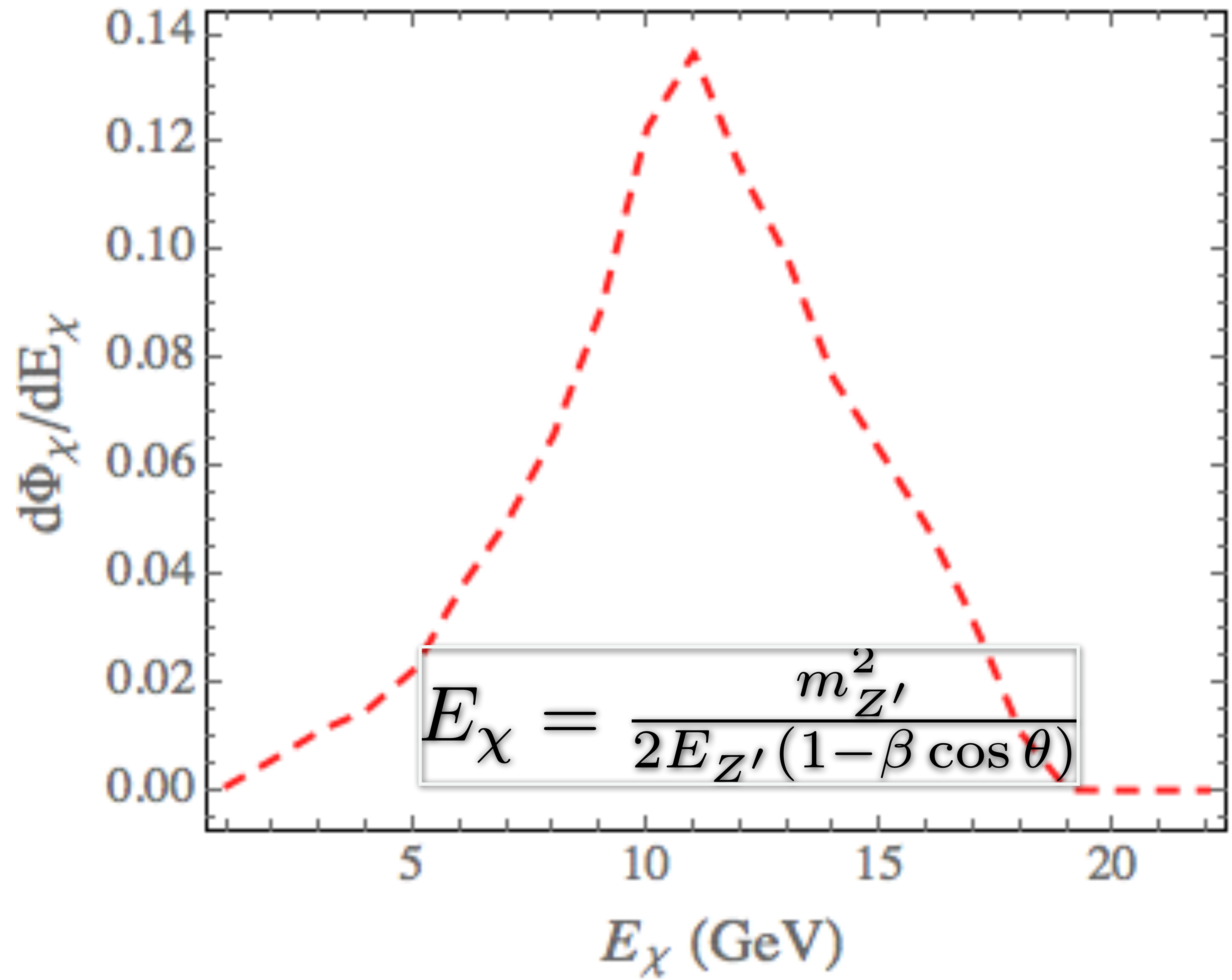
We have already an off axis detector!



$$pp \to Z' \to \chi\chi$$

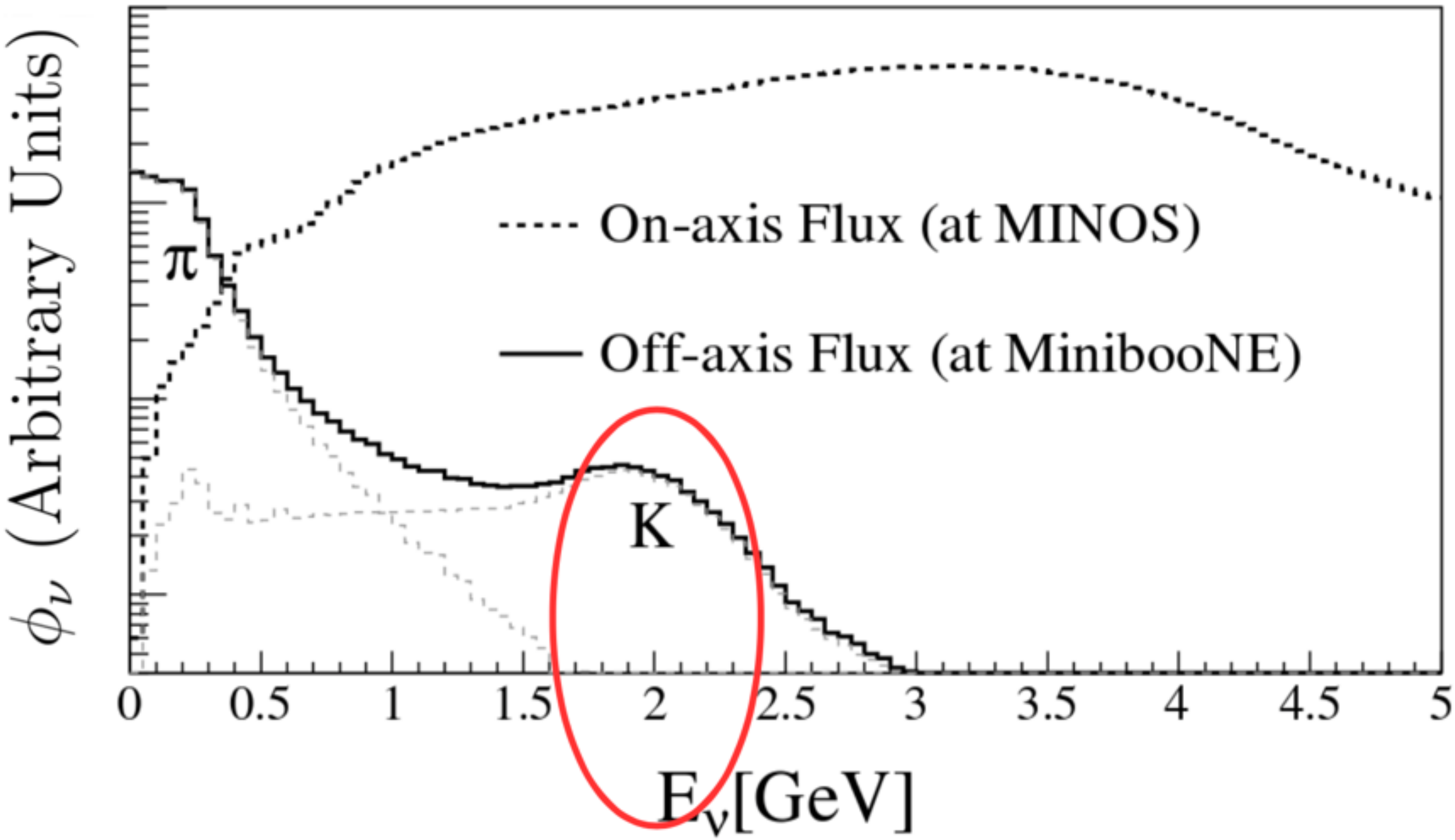
DM particle enter the near detector and scatter with nuclei

Dm energy inside MinibooNE



$$E_\chi = \frac{m_{Z'}^2}{2E_{Z'}(1-\beta\cos\theta)}$$

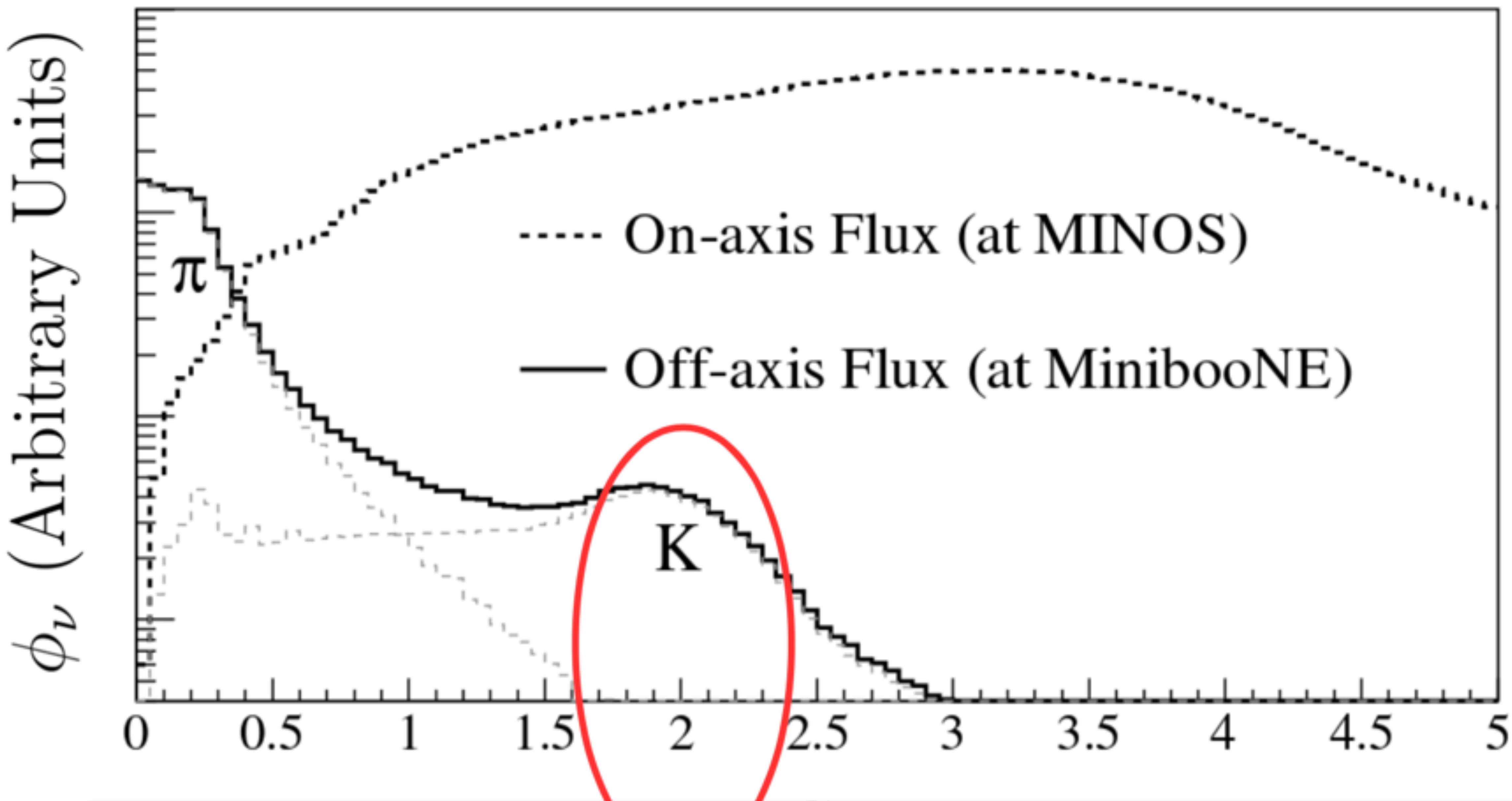
Off axis versus on axis bkg



0.25 GeV pion average energy

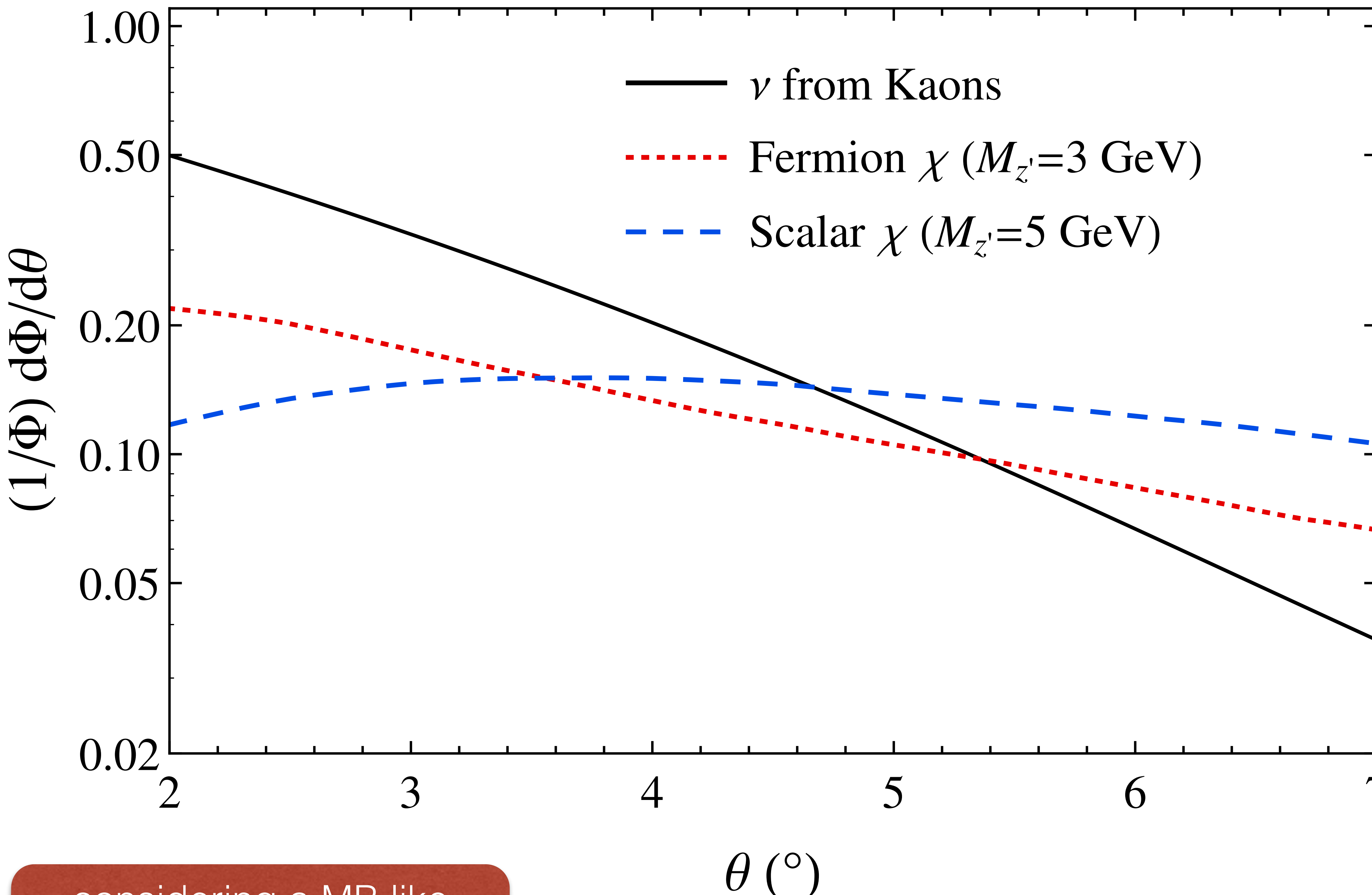
$$E_\nu = \frac{m^2_{\pi/K}}{2E_{\pi/K}(1-\beta\cos\theta)}$$

Off axis versus on axis bkg



Going off axis we kill efficiently neutrino bkg-
10^6 DIS events in MINOS/NOVa reduced
to 10^3 in MinibooNE!

The signal stays almost constant!



considering a MB like detector

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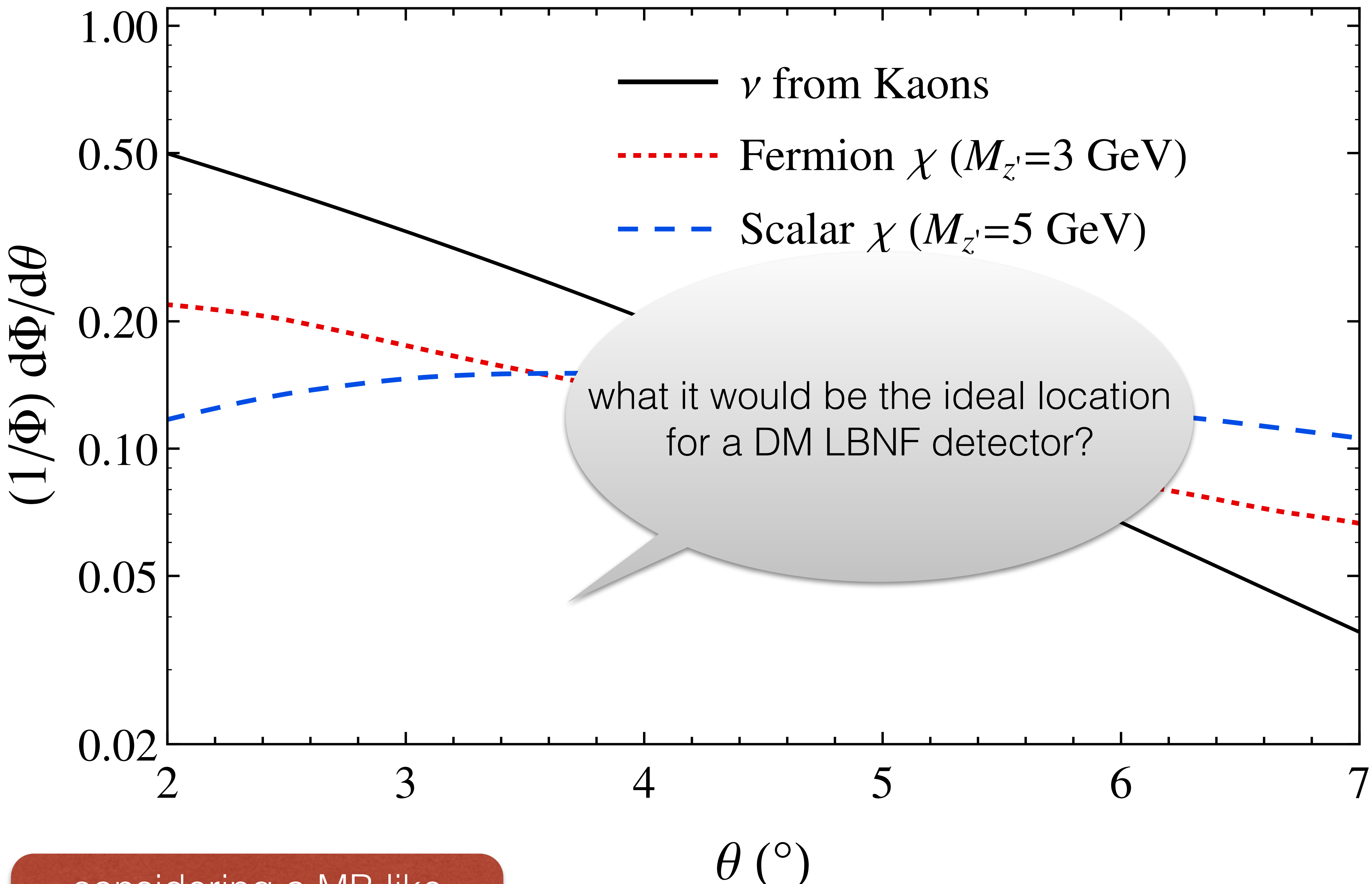
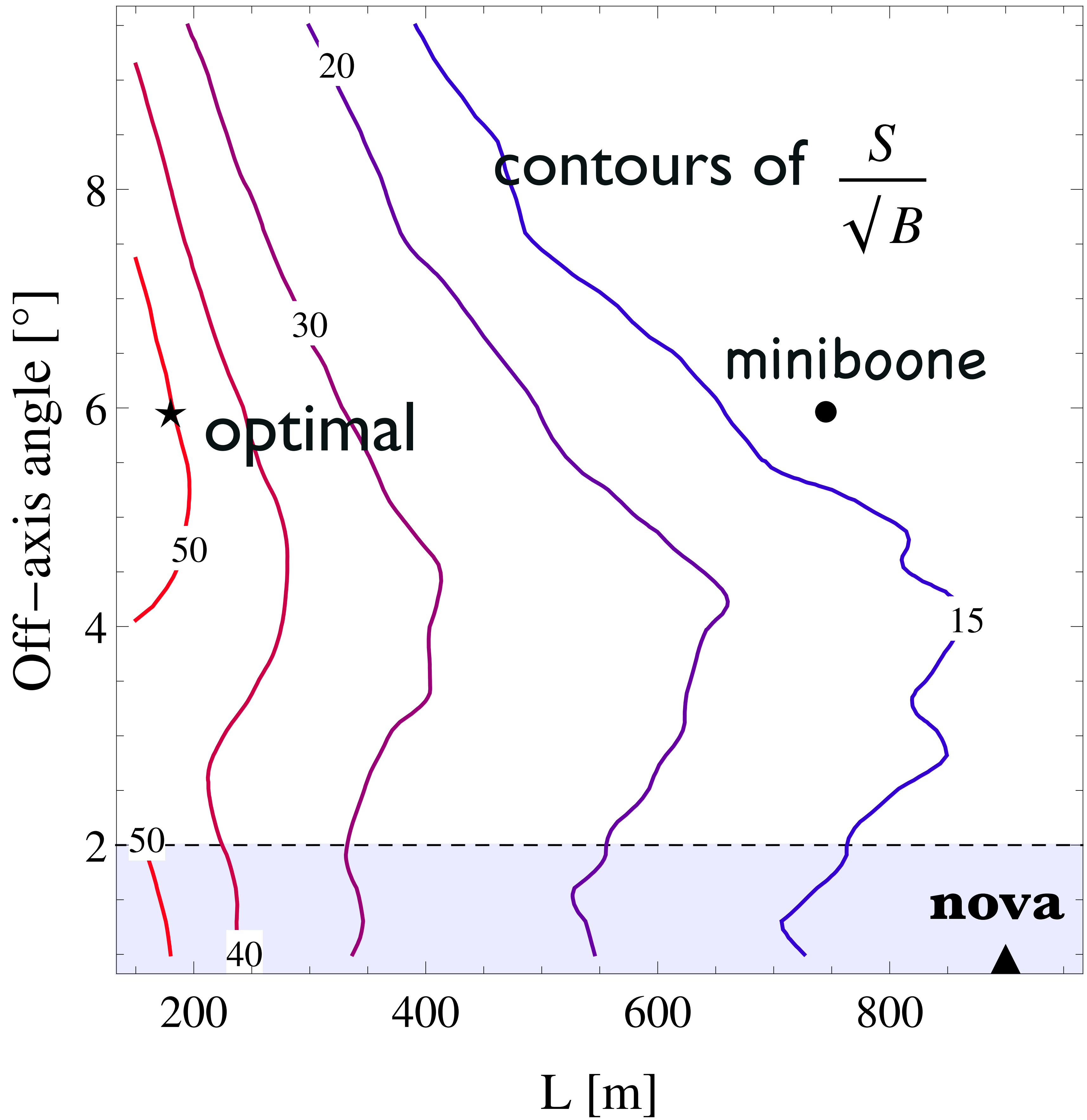


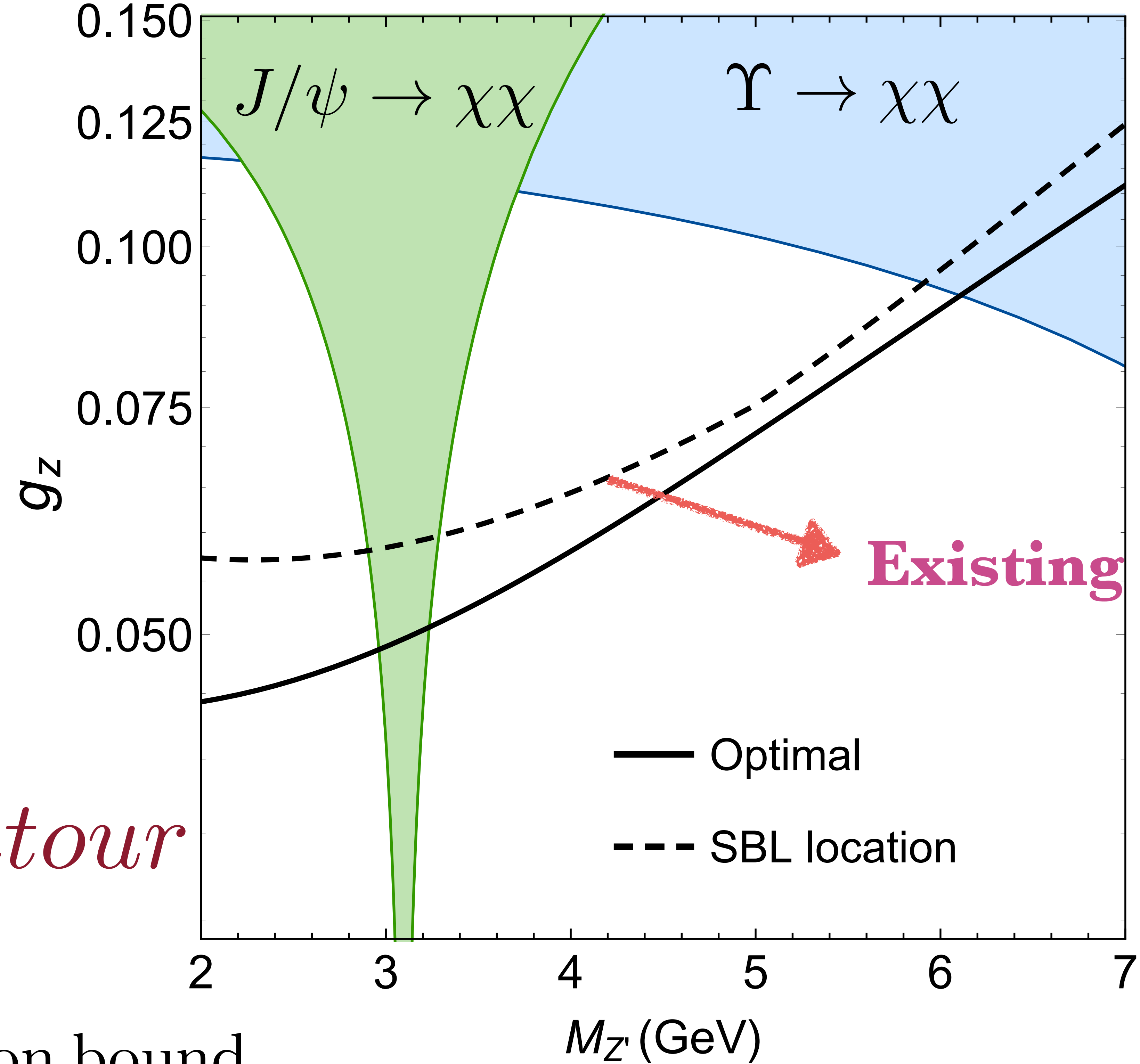
considering a MB like detector

Ideal position for a future LBNF detector



$g_z = 0.1$

Projected sensitivity



Existing data!

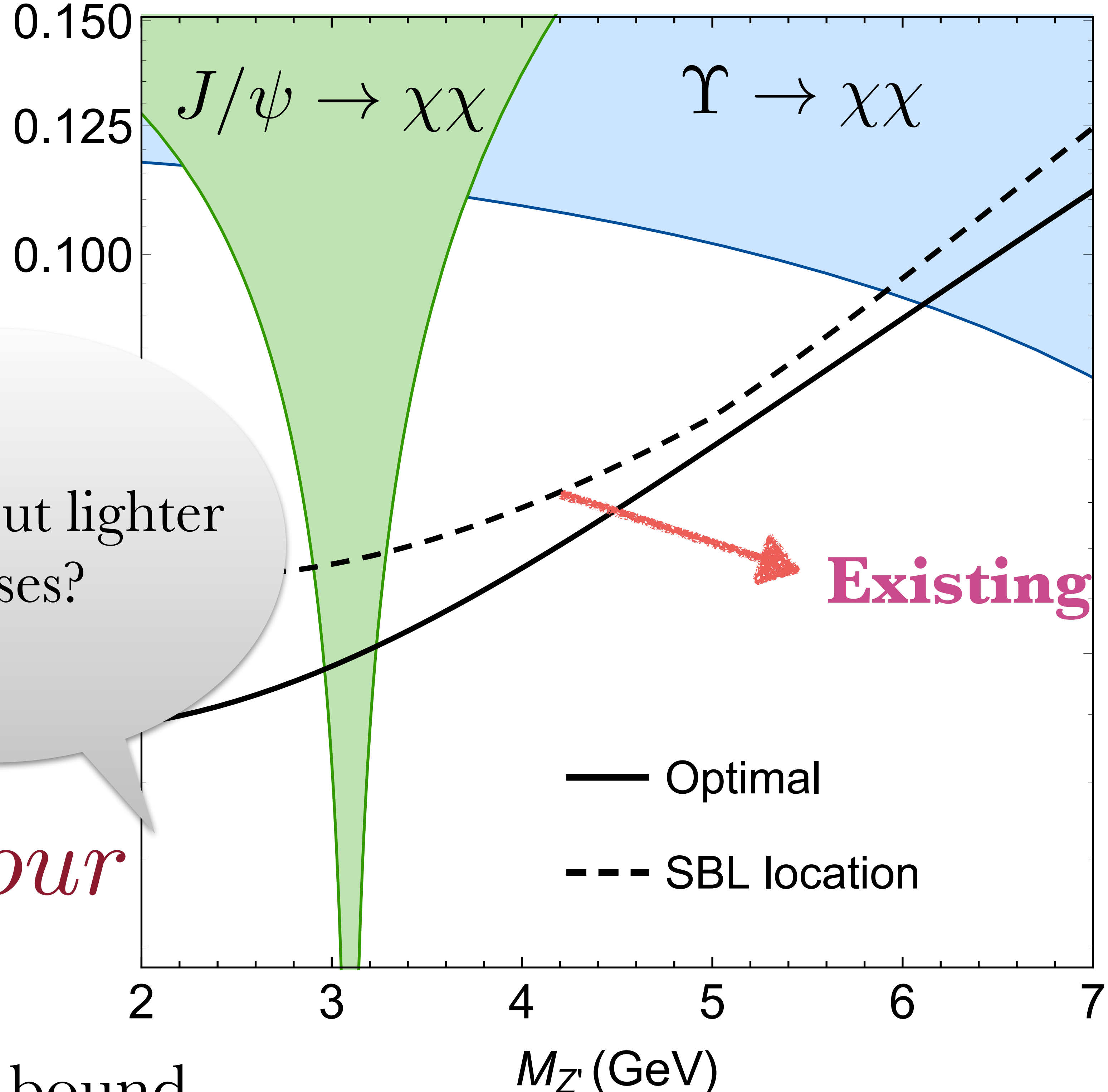
$\chi^2 contour$

Dark photon bound

$\epsilon \sim 10^{-2}$

Weaker than the Babar bound

Projected sensitivity



What about lighter masses?

Existing data!

$\chi^2 contour$

Dark photon bound

$\epsilon \sim 10^{-2}$

Weaker than the Babar bound

Can we constraint sub-GeV Z' mass with an off-axis detector?

CF hep ph 1701.05464

For lighter Z' in principle signal
and background are not distinguishable!

$$E_\chi = \frac{m_{Z'}^2}{2E_{Z'}(1-\beta\cos\theta)}$$

similar to Kaon and Pion masses

We expect a very soft spectrum of DM particles
inside an off axis detector!

However, this is a problem ONLY if DM is emitted
by a collimated
Z' beam parallel to the beam line

→ uncollimated part of the beam!

Can we constraint sub-GeV Z' mass with an off-axis detector?

For lighter Z' in principle signal
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similar to Kaon and Pion masses

We expect a very soft spectrum of DM particles
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However, this is a problem ONLY if DM is emitted
by a collimated
Z' beam parallel to the b

how do we
produce it?

→ uncollimated part of the beam!

Can we constraint sub-GeV Z’ mass with an off-axis detector?

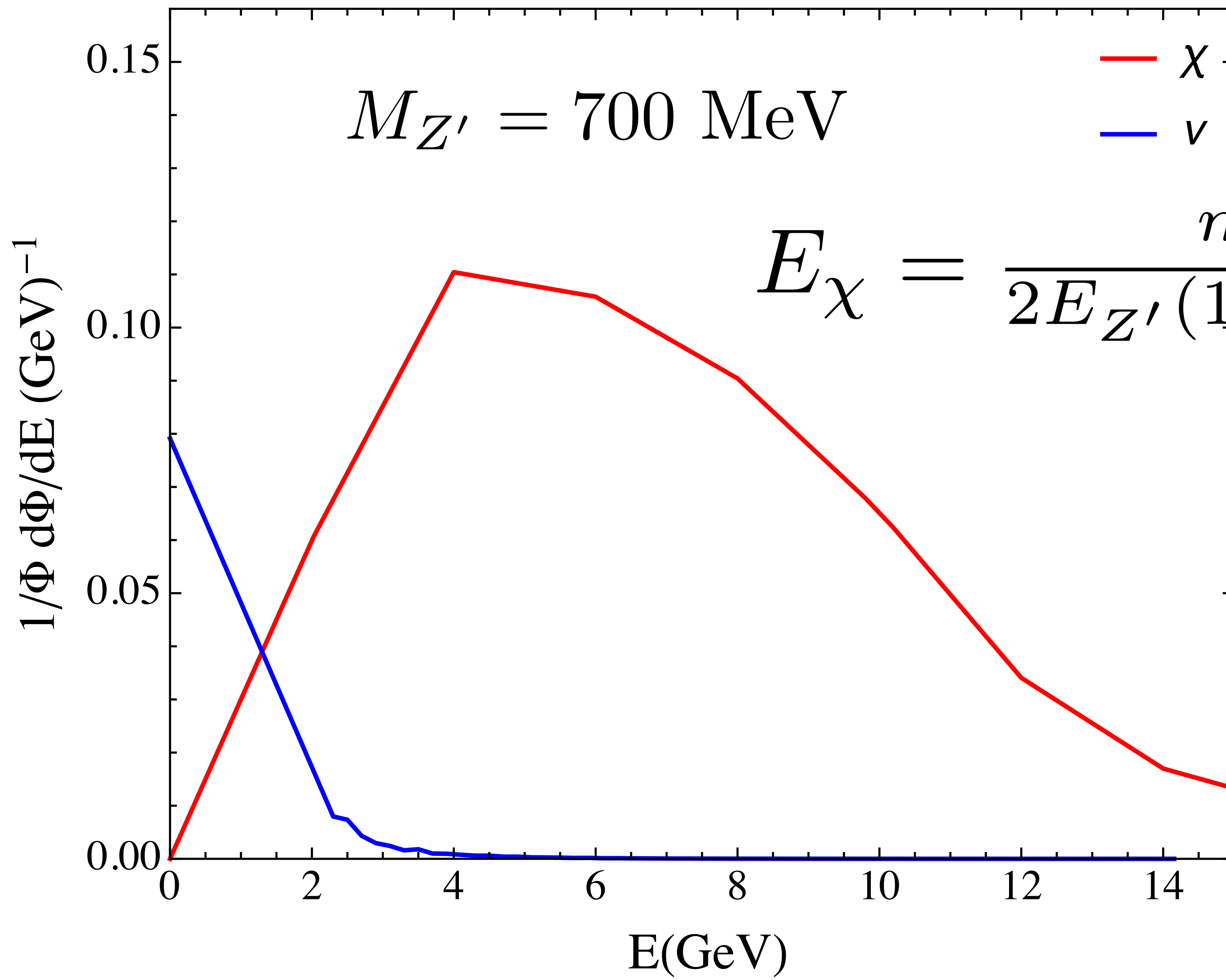
For lighter Z’ in principle signal
and background are not distinguishable!

NLO process

$$pp \to Z' j \qquad p_t > 1 \text{ GeV}$$

uncollimated part of the beam!

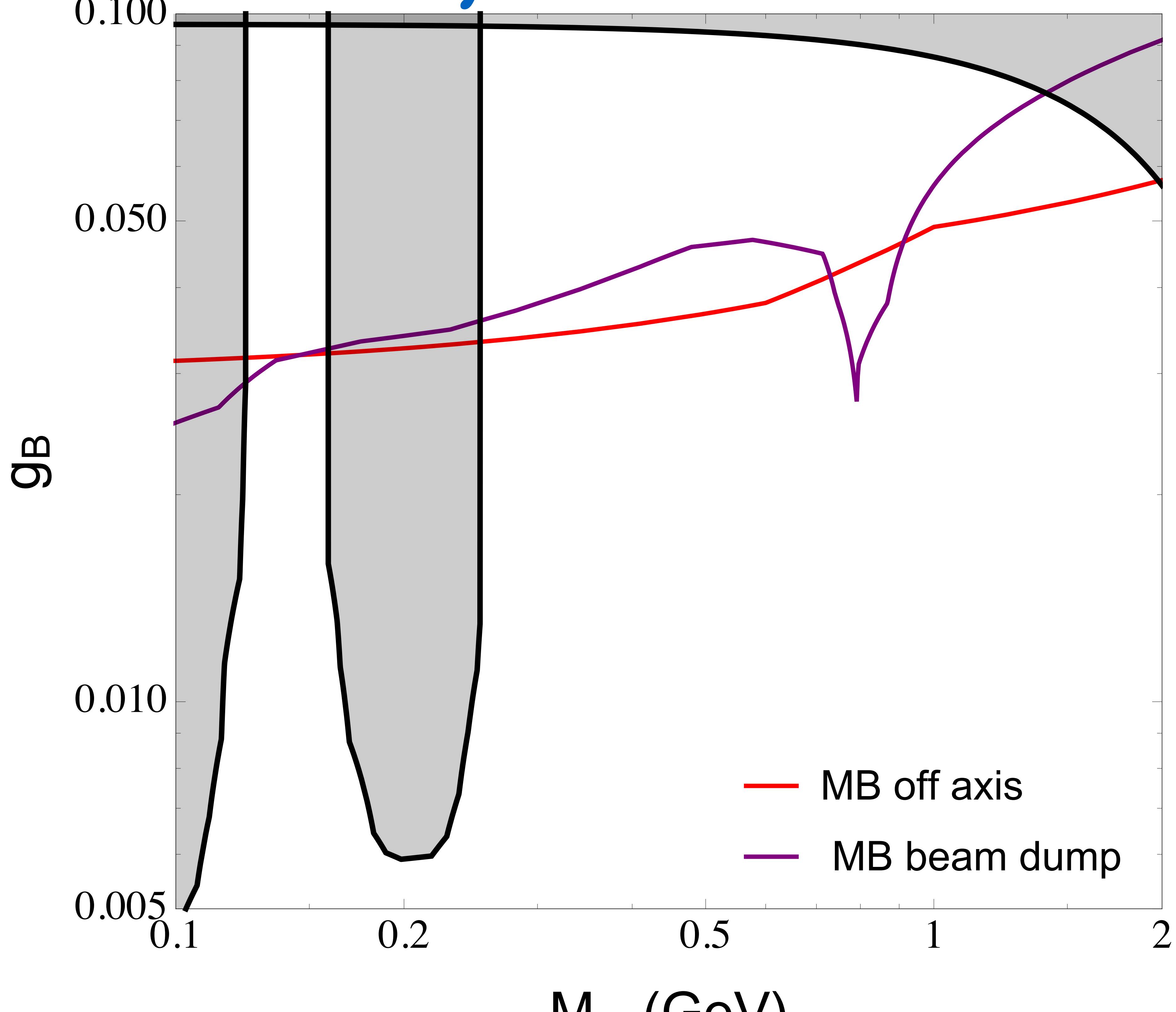
DM energy profile inside MiniBoone



$$E_\chi = \frac{m_{Z'}^2}{2E_{Z'}(1-\beta\cos\theta)}$$

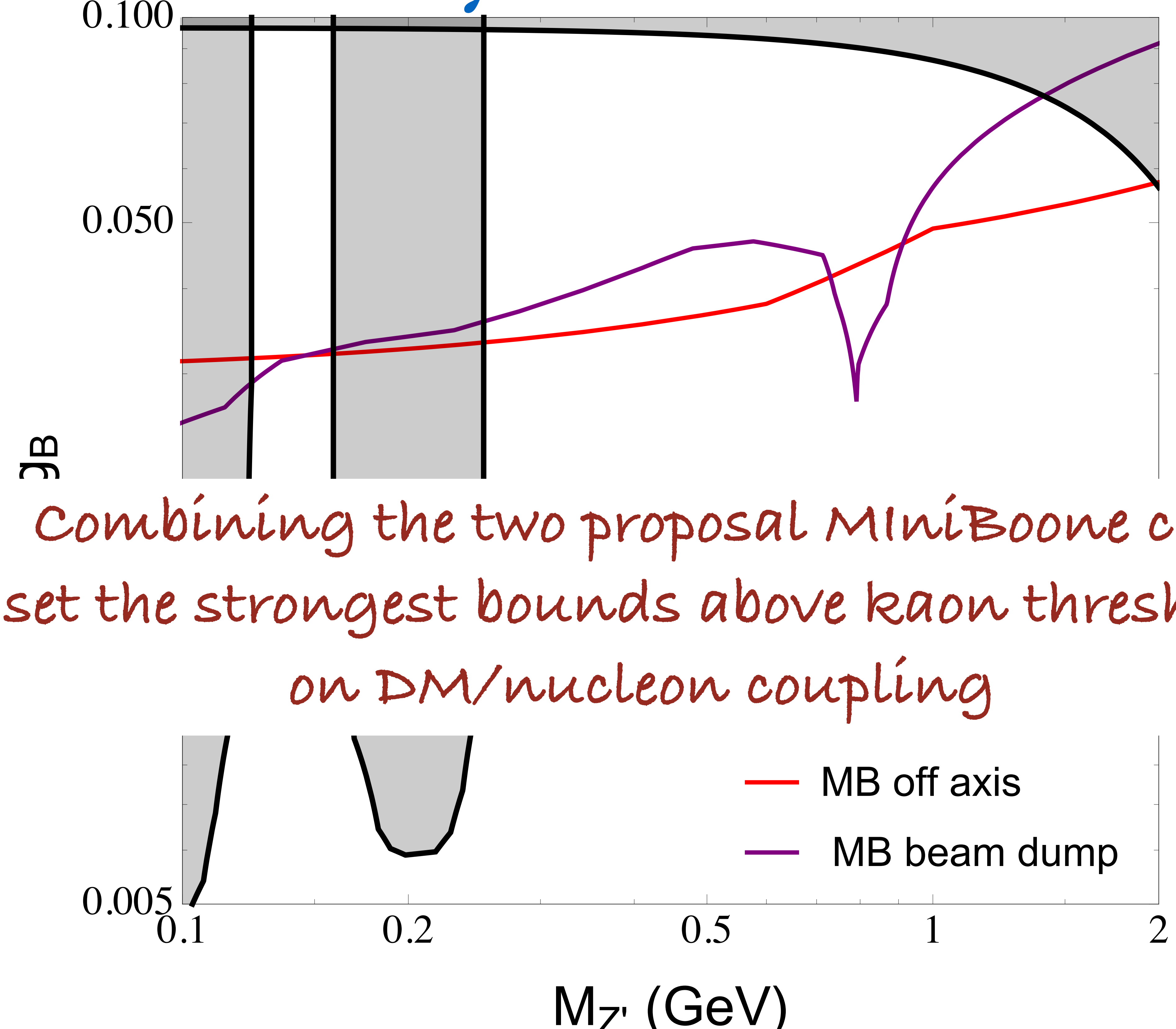
DIS scattering cross section enlarged by very light Z' mass!

Sensitivity to sub-GeV Z'



$N_{POT} = 2 \times 10^{20}$ existing data!

Sensitivity to sub-GeV Z'



Combining the two proposal MiniBoone can set the strongest bounds above kaon threshold on DM/nucleon coupling

$N_{POT} = 2 \times 10^{20}$ existing data!

Conclusions

- Neutrino facilities could offer the possibility to probe light DM/quarks couplings.
- Off axis LBNF detector for DM could set the strongest bounds, but Miniboone/ Microboone collaborations must look at their data!
- BSM physics program can be parasitic to the neutrino program!

Outlook

- Is this at all relevant for SHIP?
- SHIP is not a neutrino facility. It is not necessary to go all way to 6.5 degrees to reduce the background
- What is the ideal location for a DM dector?
- Can this be symbiotic to the neutrino program?

work in progress
with A. Dery