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מכון ויצמן למדע
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Dark matter (and relaxions) beams at proton fixed target experiments

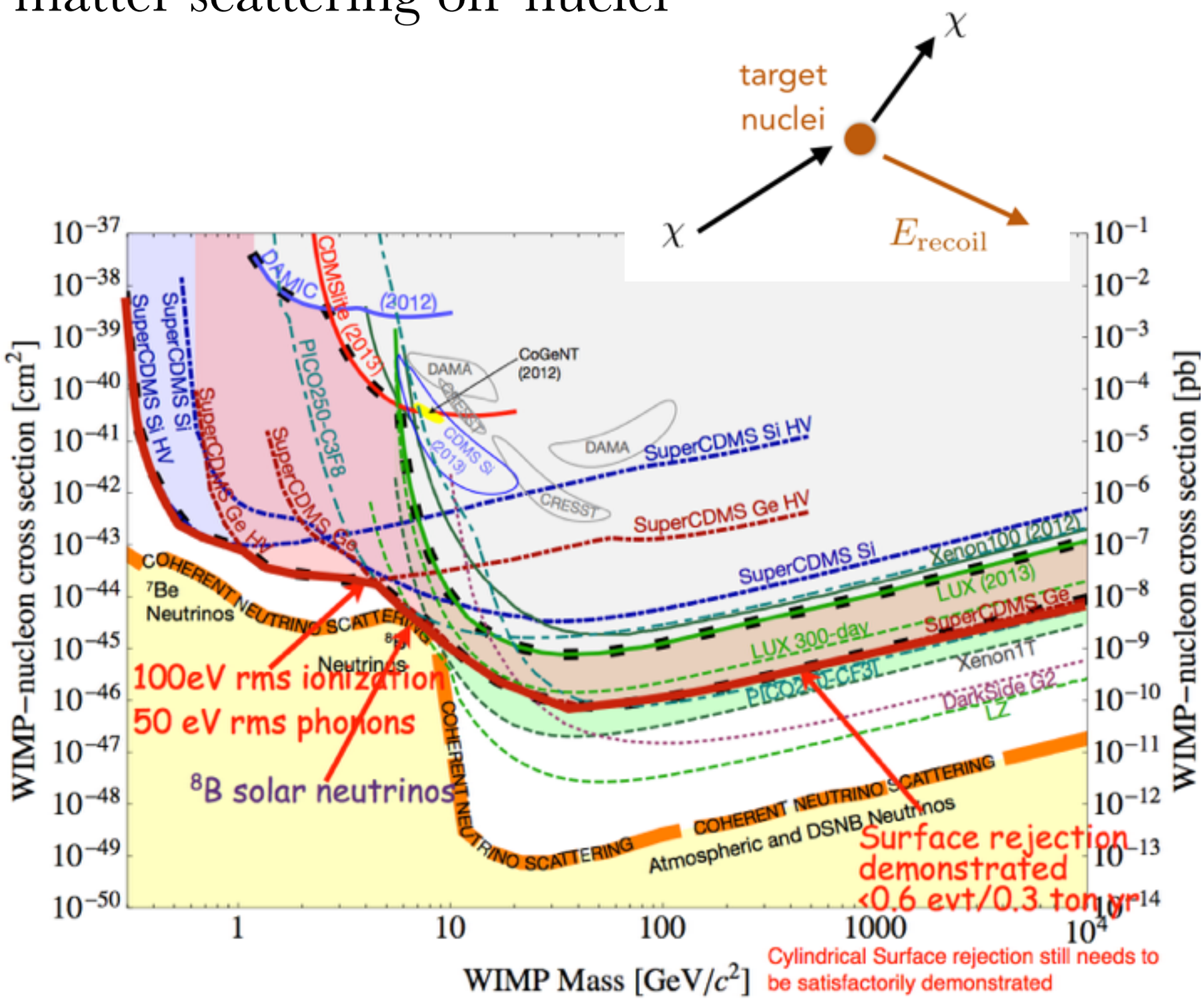
28 july 2016 CERN ‘ Charting the unknown’

Probing dark matter/nucleon coupling at neutrino facilities

in collaboration with B.Dobrescu, P.Coloma and R.Harnik

Dark matter direct detection

dark matter scattering off nuclei



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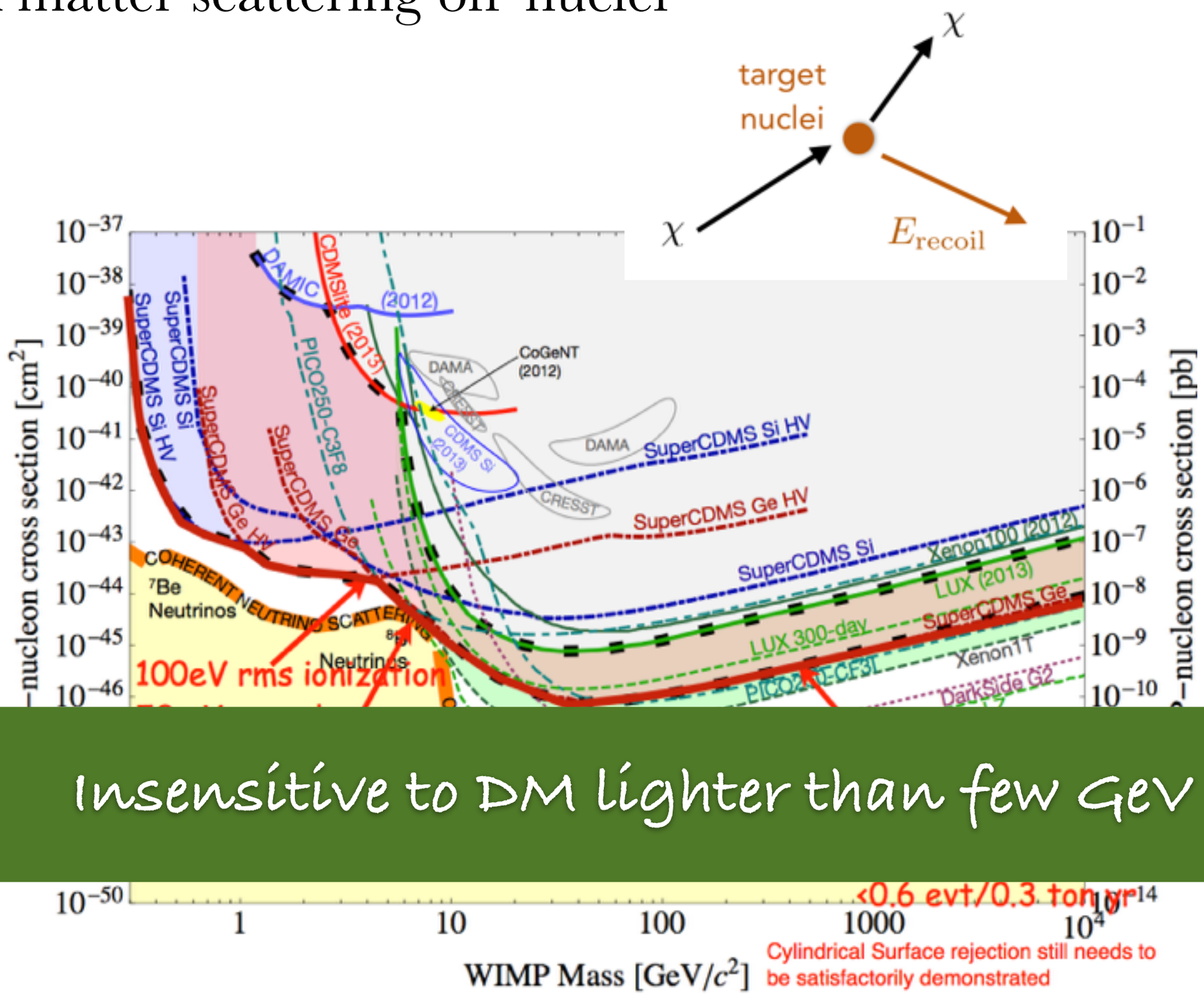


Insensitive to DM lighter than few GeV

What about LDM?

Recently a lot of effort has been put on filling this gap 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 measure nucleon dark matter coupling?

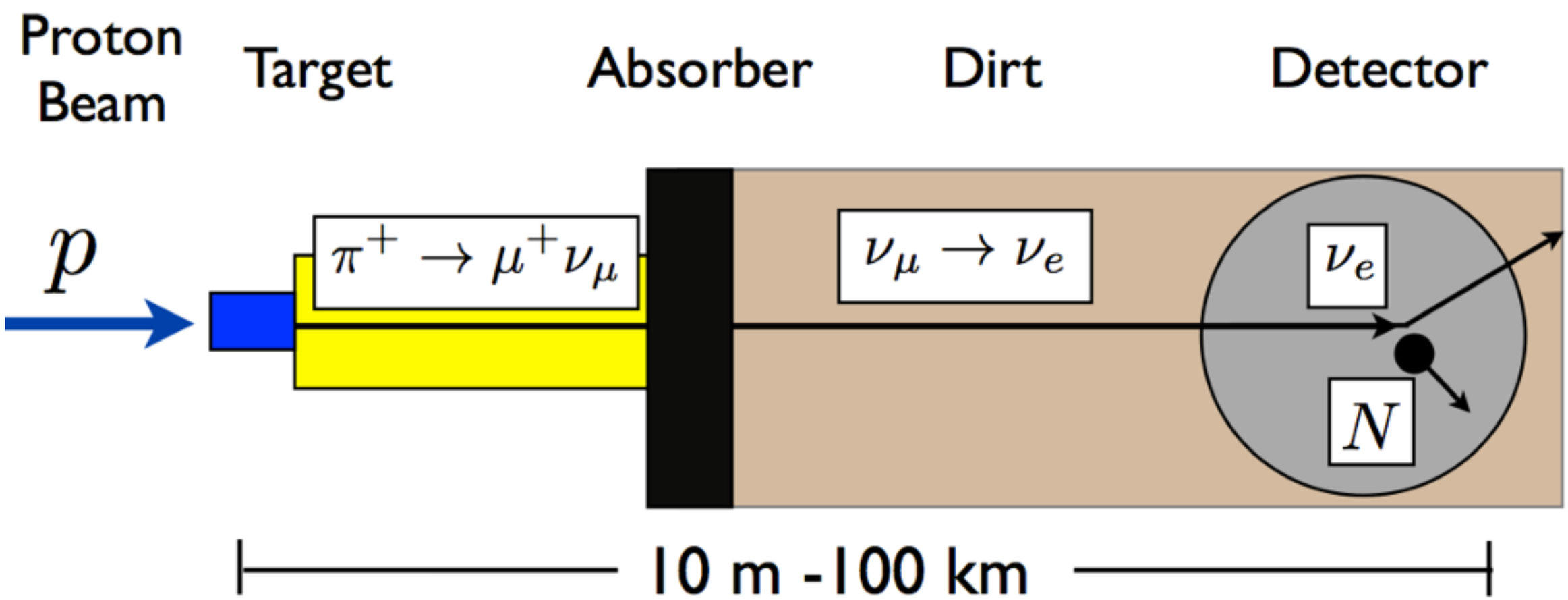
Yes at neutrino facilities

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

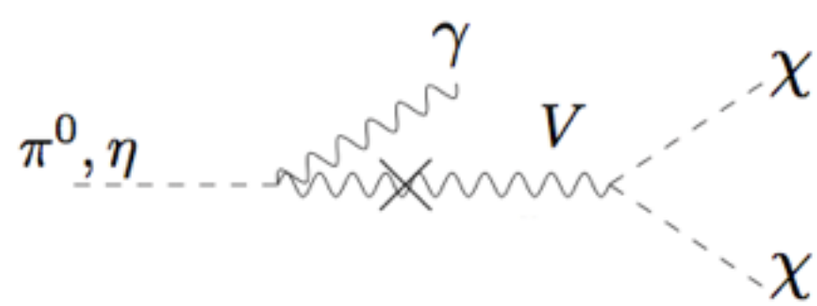


Quarks/dark sector portal

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

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

- indirect production, i.e. mesons decays

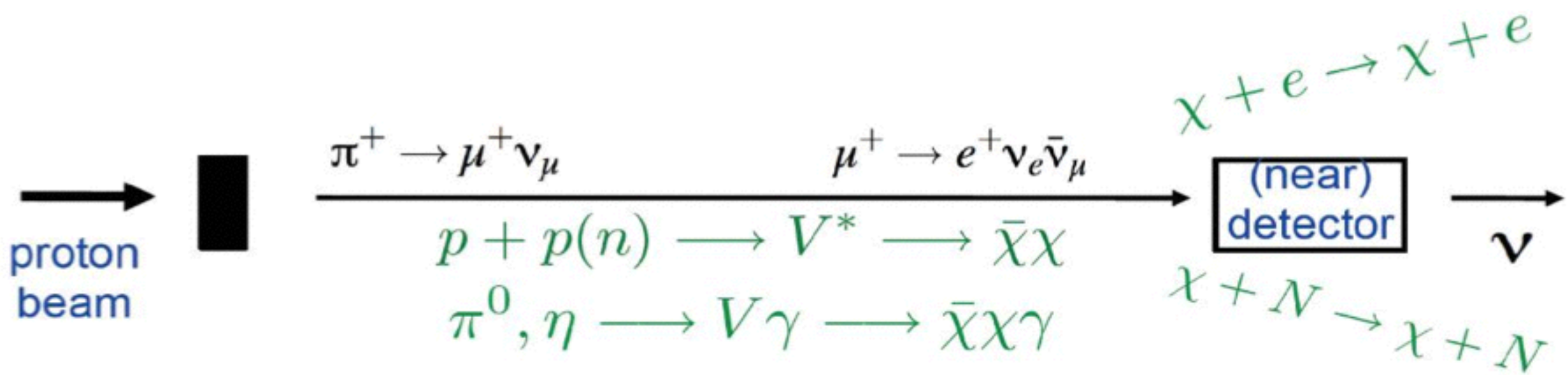


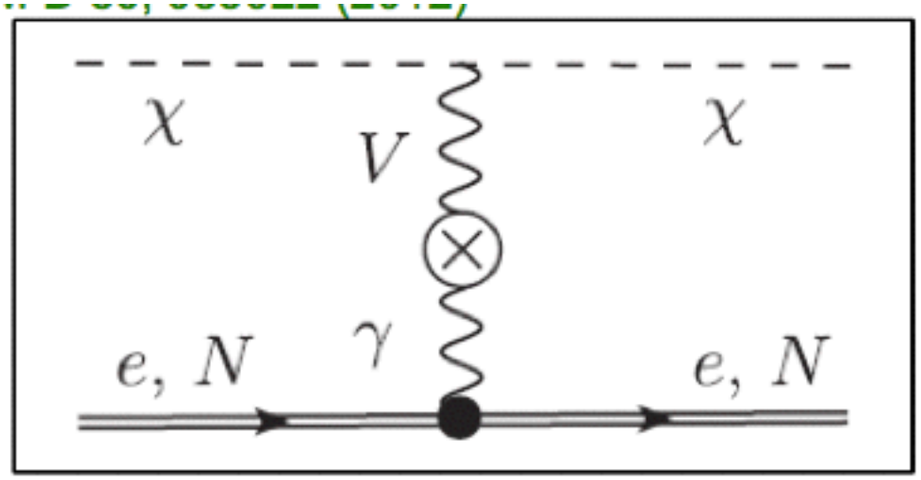
- direct production, i.e resonant Z′ production

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

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

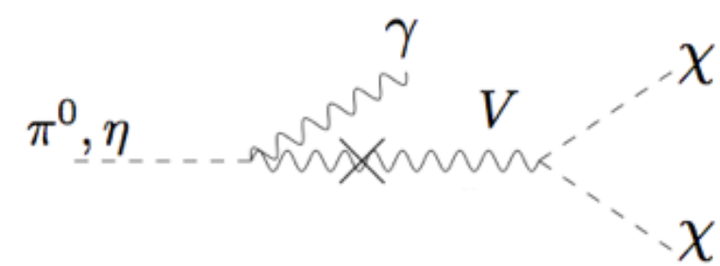
Very large number of events required

DM search @ Miniboone

Batell et al, 2013

★ 8 GeV proton on target -
reach up to 1 GeV in mV

★ DM is produced via meson decay

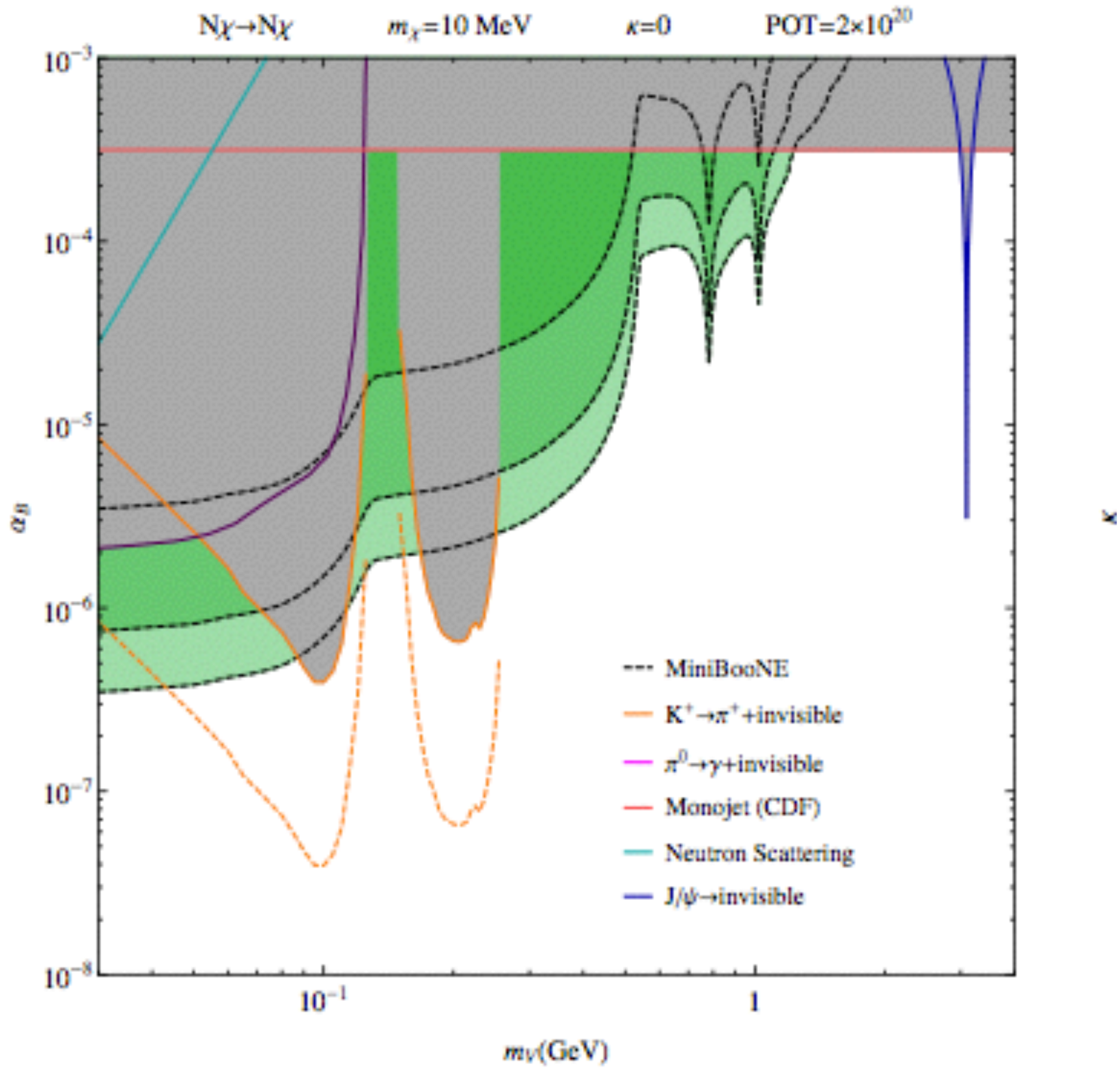


★ Signal process:
elastic DM nucleon scattering

How many signal events do we get?

DM search @ Miniboone

Batell et al, 2013



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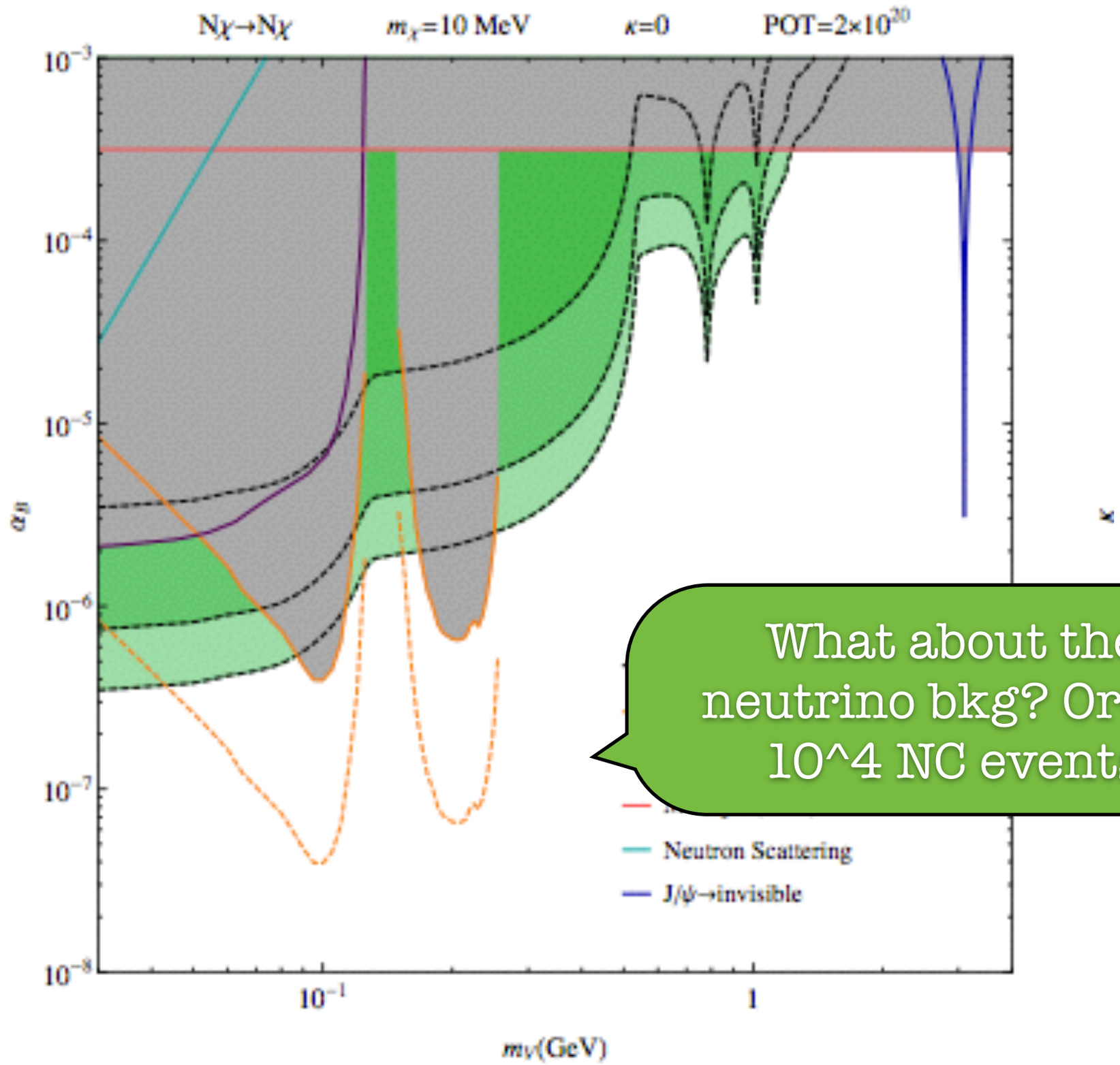
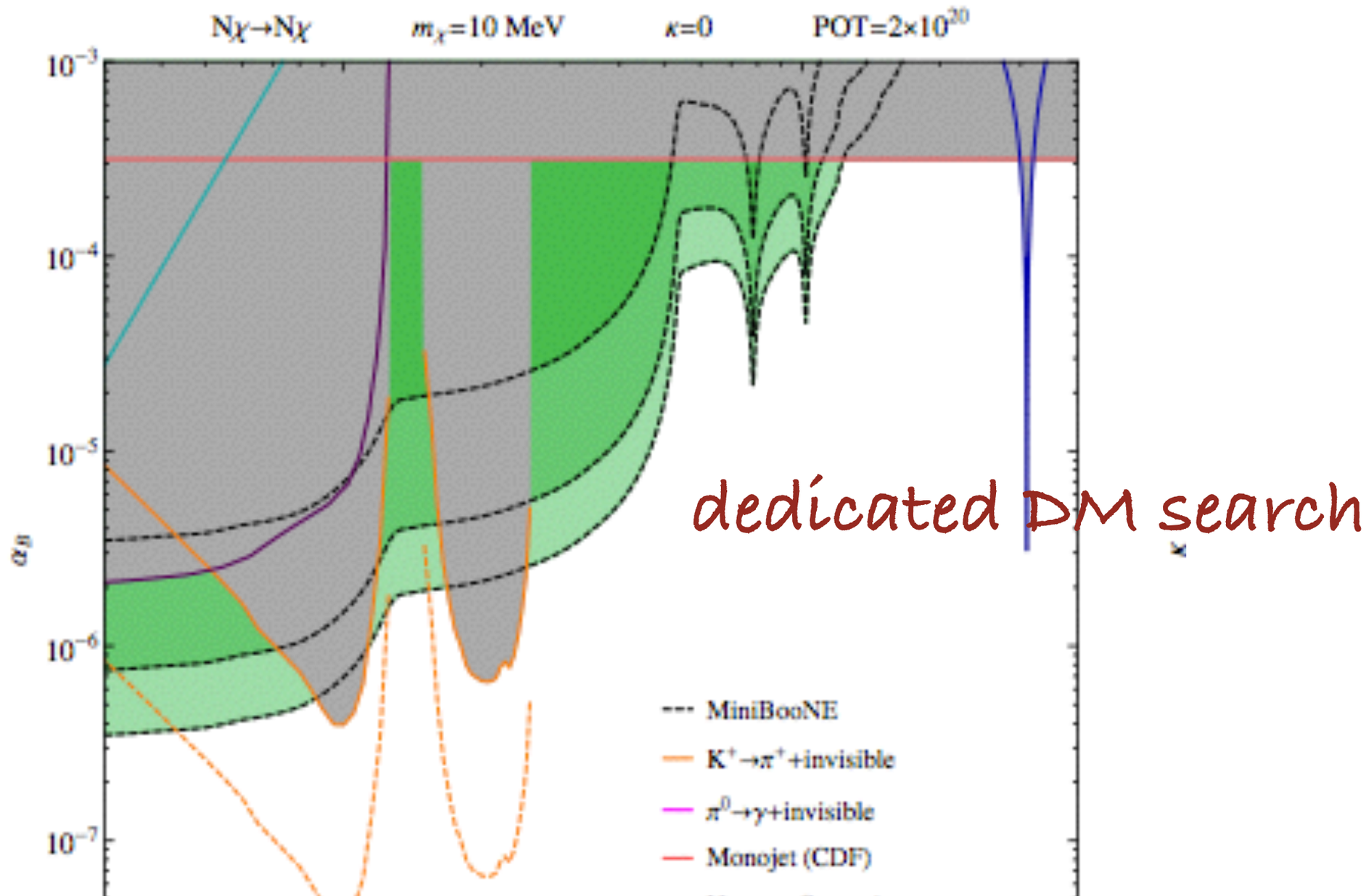


What about the neutrino bkg? Order 10^4 NC events

DM search @ Miniboone

Batell et al, 2013



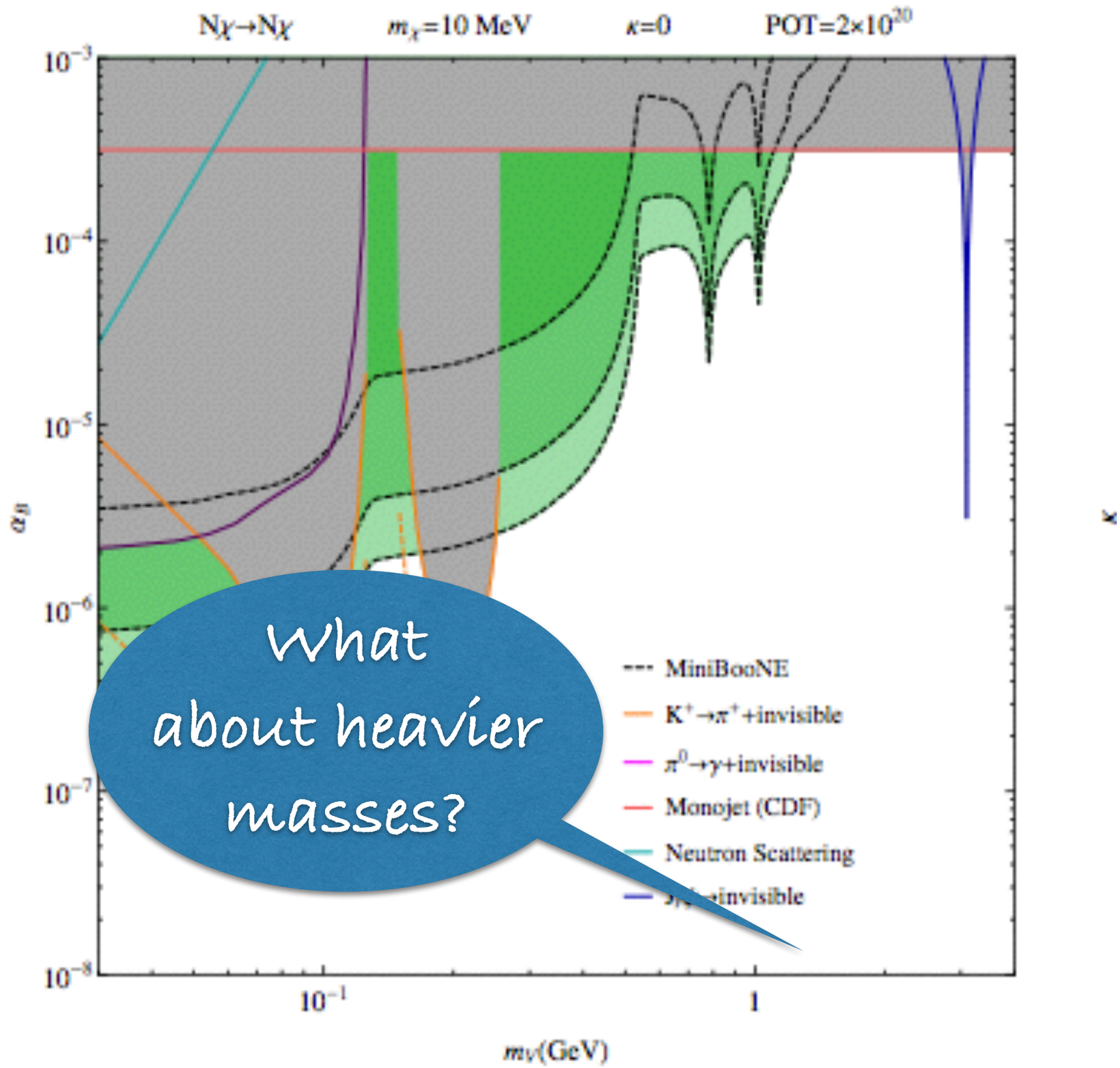
dedicated DM search

Neutrino bkg reduction

proton beam dump+time flight decay

DM search @ Miniboone

Batell et al, 2013



Dark matter beams at the Fermilab main injector

Dobrescu&CF 2014

- 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'!

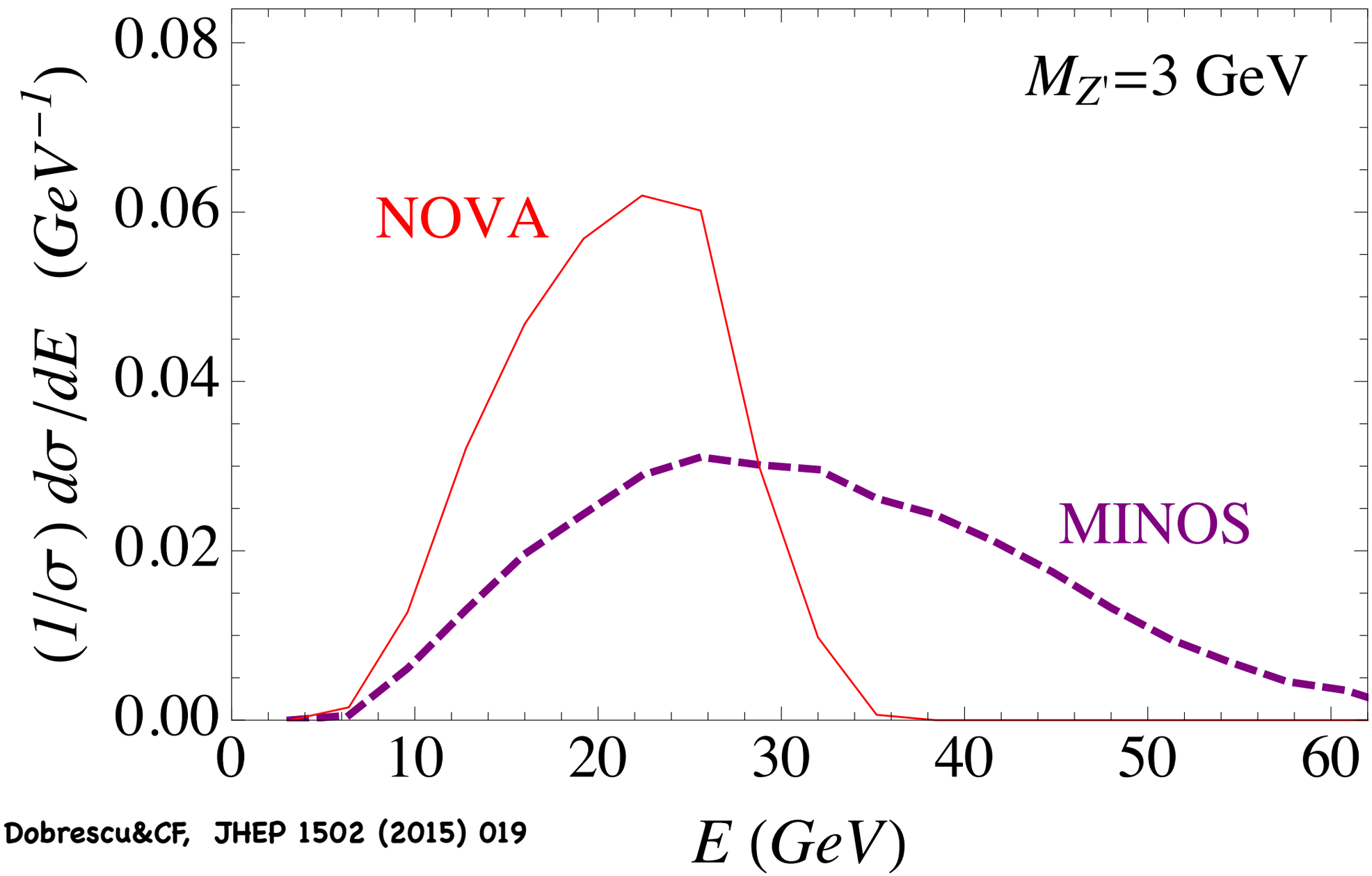
$$pp \to Z' \to \chi\chi$$

- Resonant Z' production

Several near detectors to consider

Minos, NOVA and Minerva

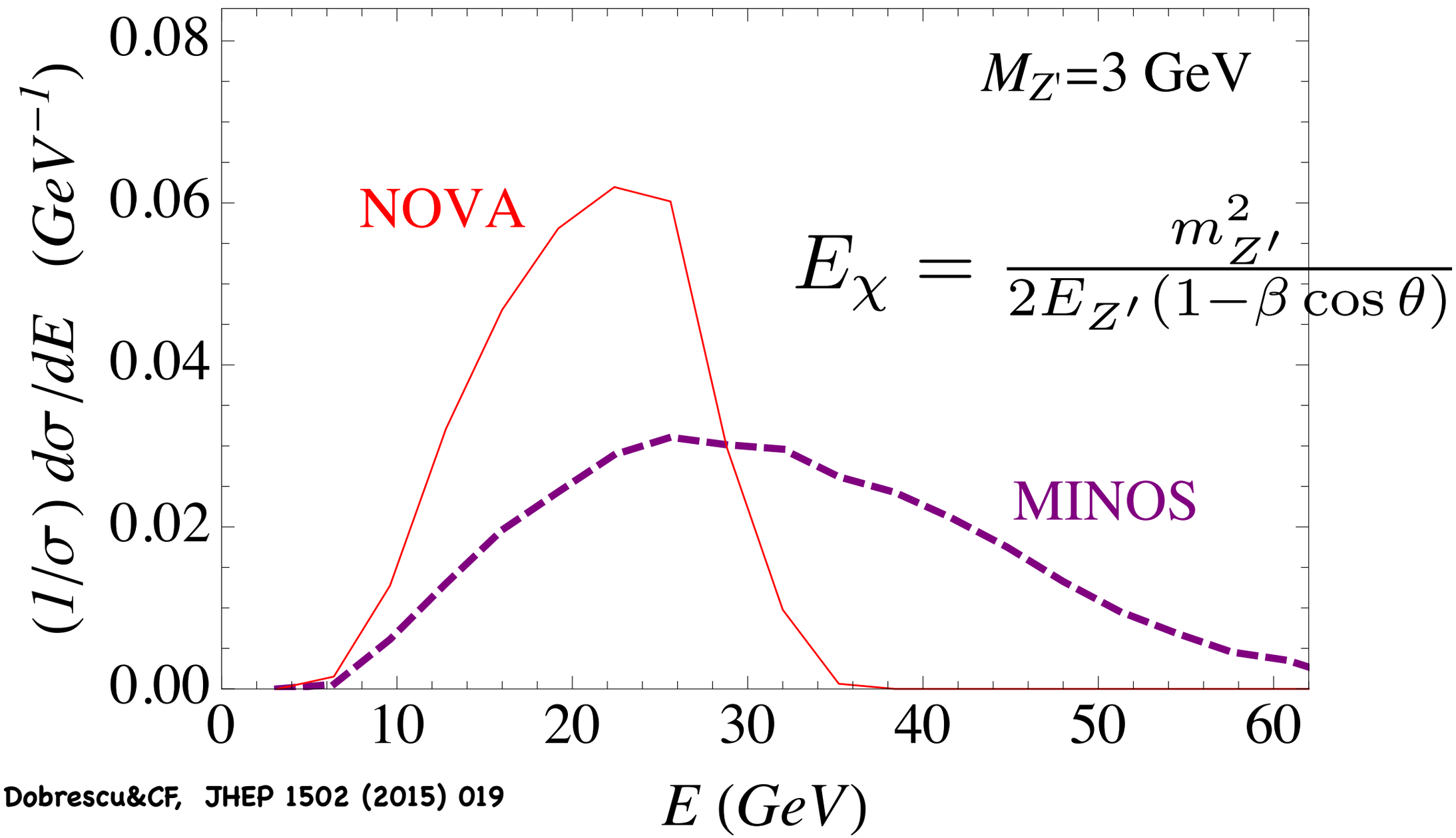
What is the DM signal inside these detectors?



Dobrescu&CF, JHEP 1502 (2015) 019

DM particles are fairly energetic

What is the DM signal inside these detectors?



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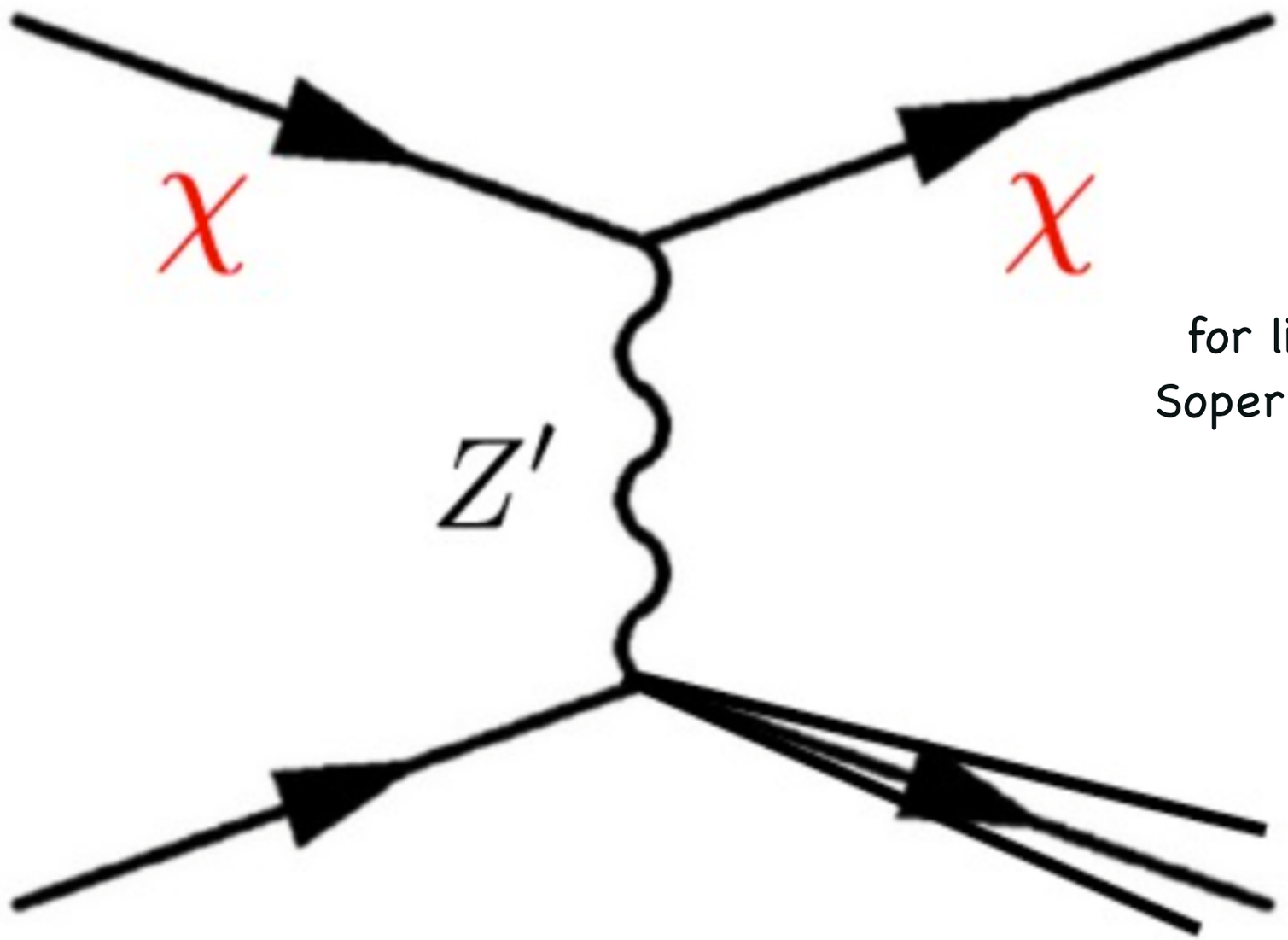
DM particles are fairly energetic

DM energy profile inside the detector

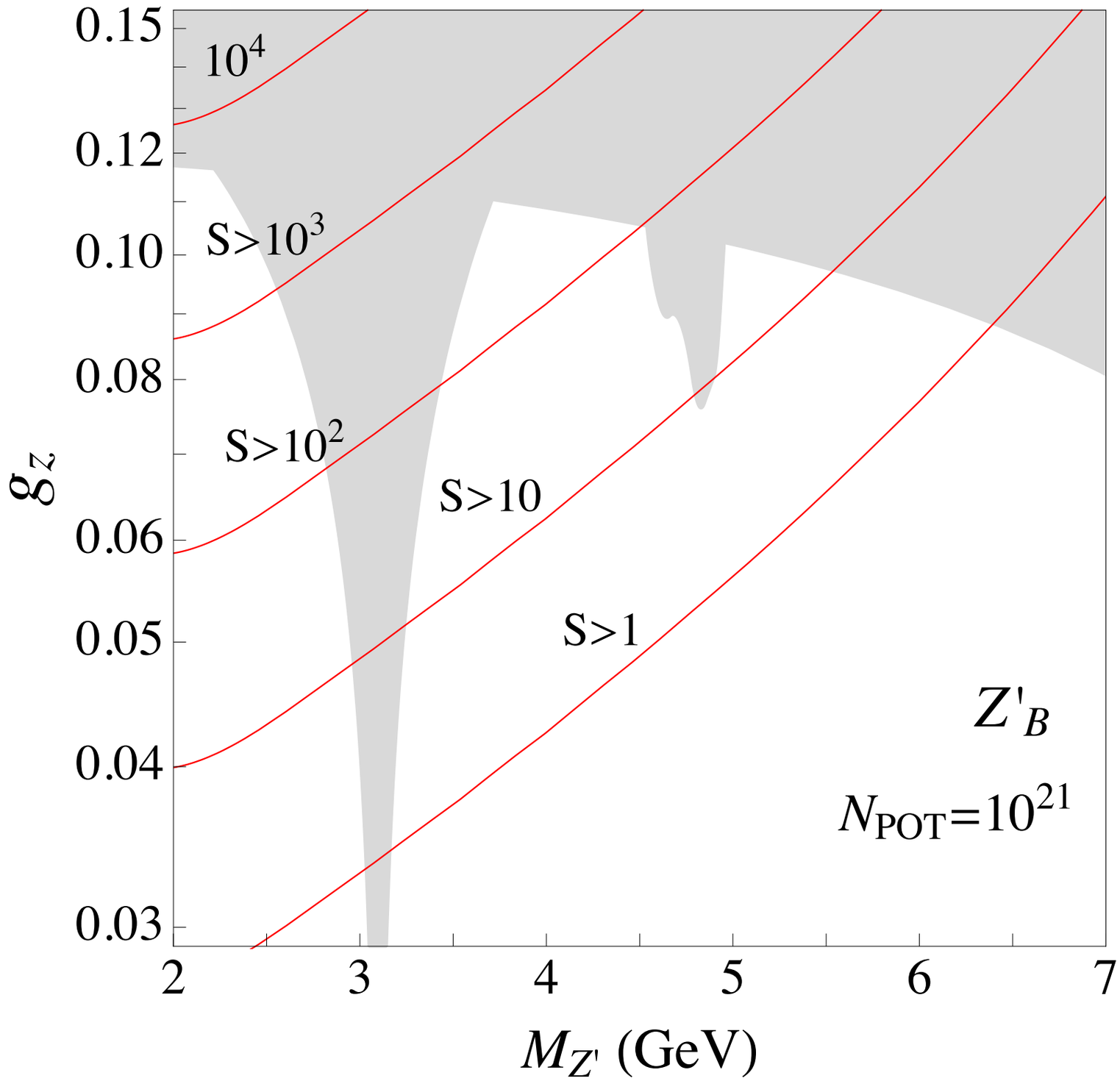
DM energetic - deeply inelastic events



for lighter DM
Soper et al. 2014

DM particles are fairly energetic

Number of DM DIS scattering events in NOVA



Dobrescu&CF 2014

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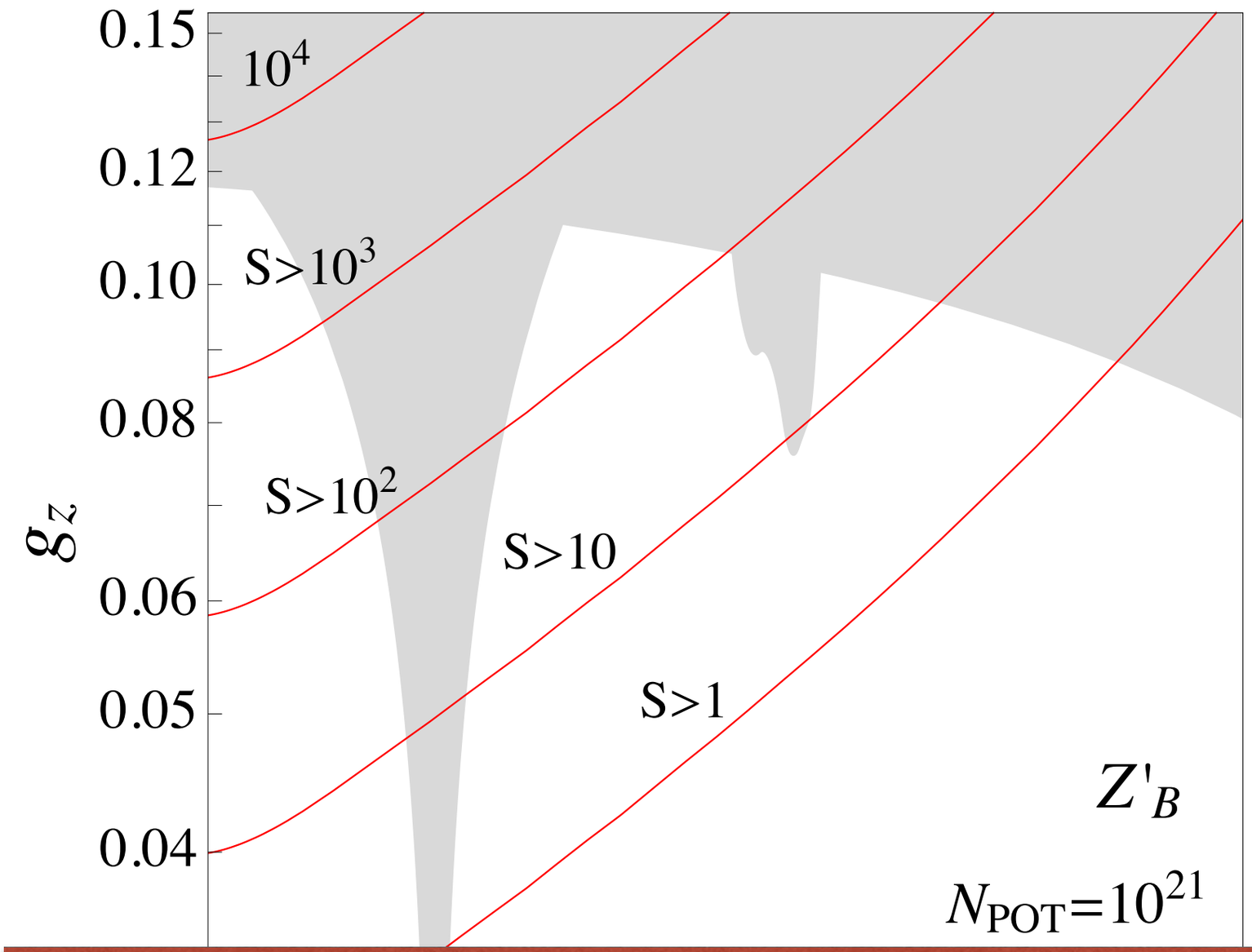
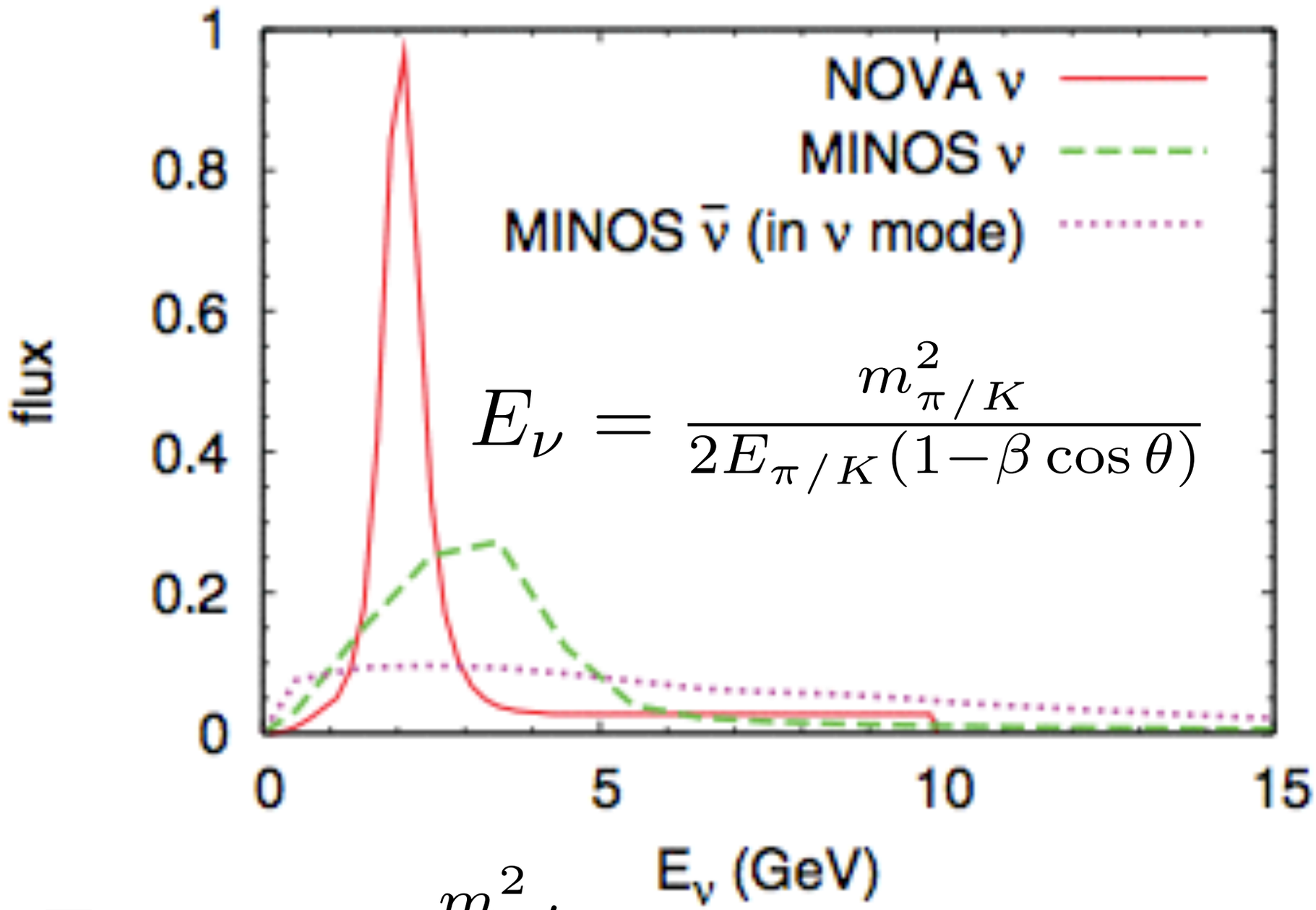


Dobrescu&CF 2014

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)

Neutrino energy profile peaked at a few GeV

Naive idea: in order to reduce neutrino bkg
we focus on the more energetic events

Deep inelastic scattering

Cut on hadronic energy $E_j > 2$ GeV

Neutrino energy profile peaked at a few GeV

Naive idea: in order to reduce neutrino bkg
we focus on the more energetic events

Deep inelastic scattering

Cut on hadronic energy $E_j > 2$ GeV

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

Neutrino energy profile peaked at a few GeV

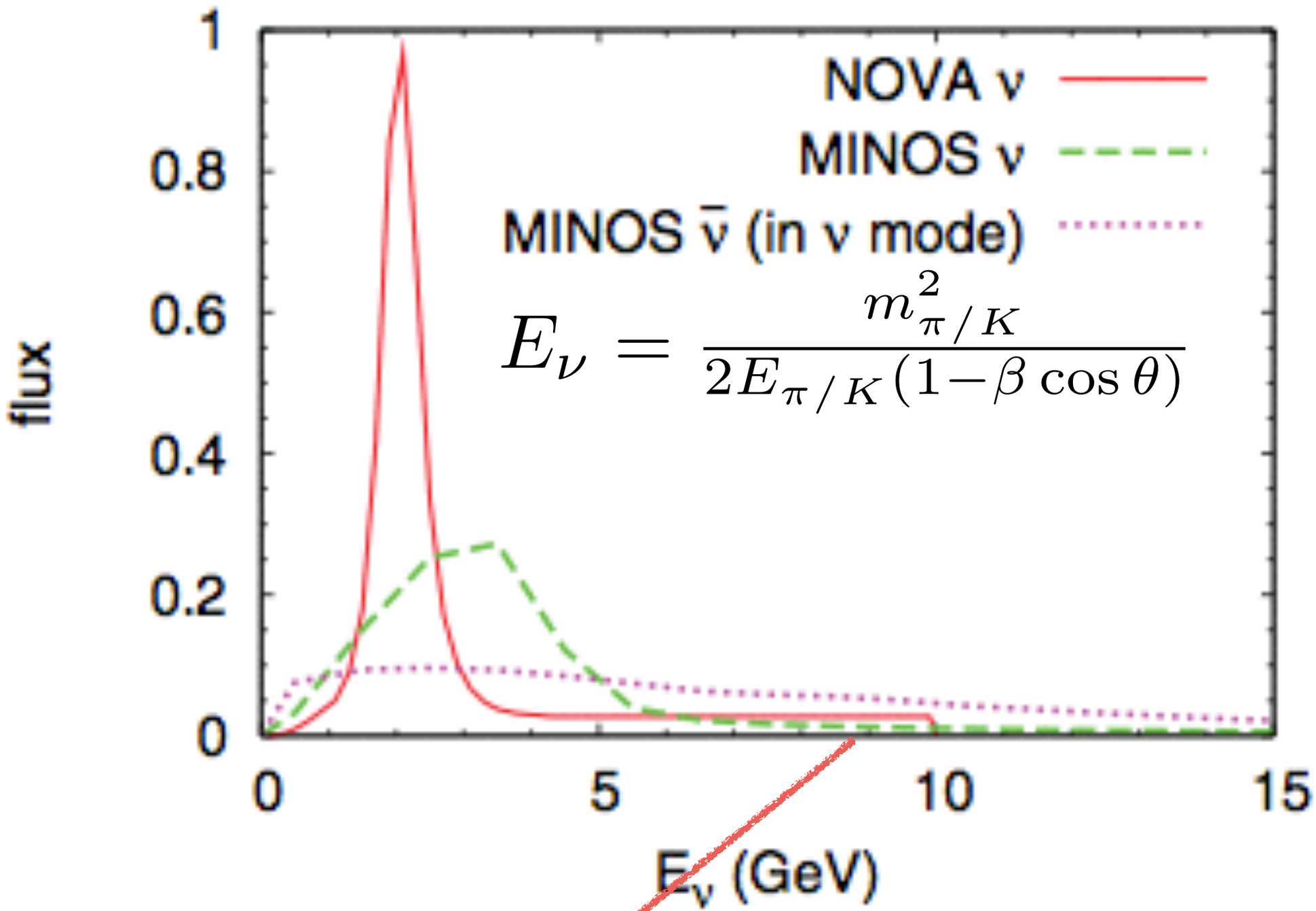
Naive idea: in order to reduce neutrino bkg
we focus on the more energetic events

Deep inelastic scattering

ut or

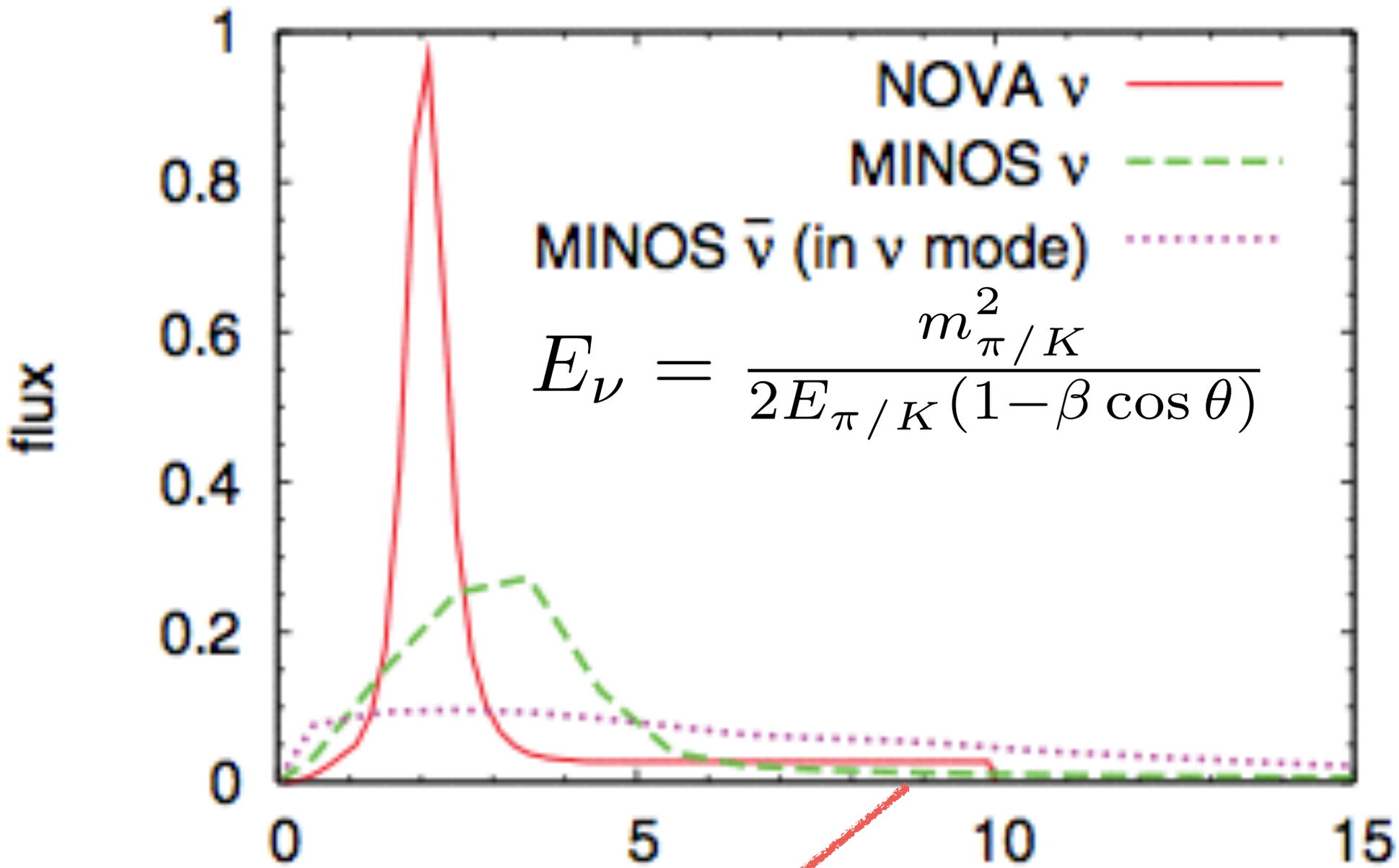
Can we kill the neutrino bkg more efficiently
or
shall we forget about these experiments?

Neutrinos energy profile



large tail of neutrinos coming from kaon decays

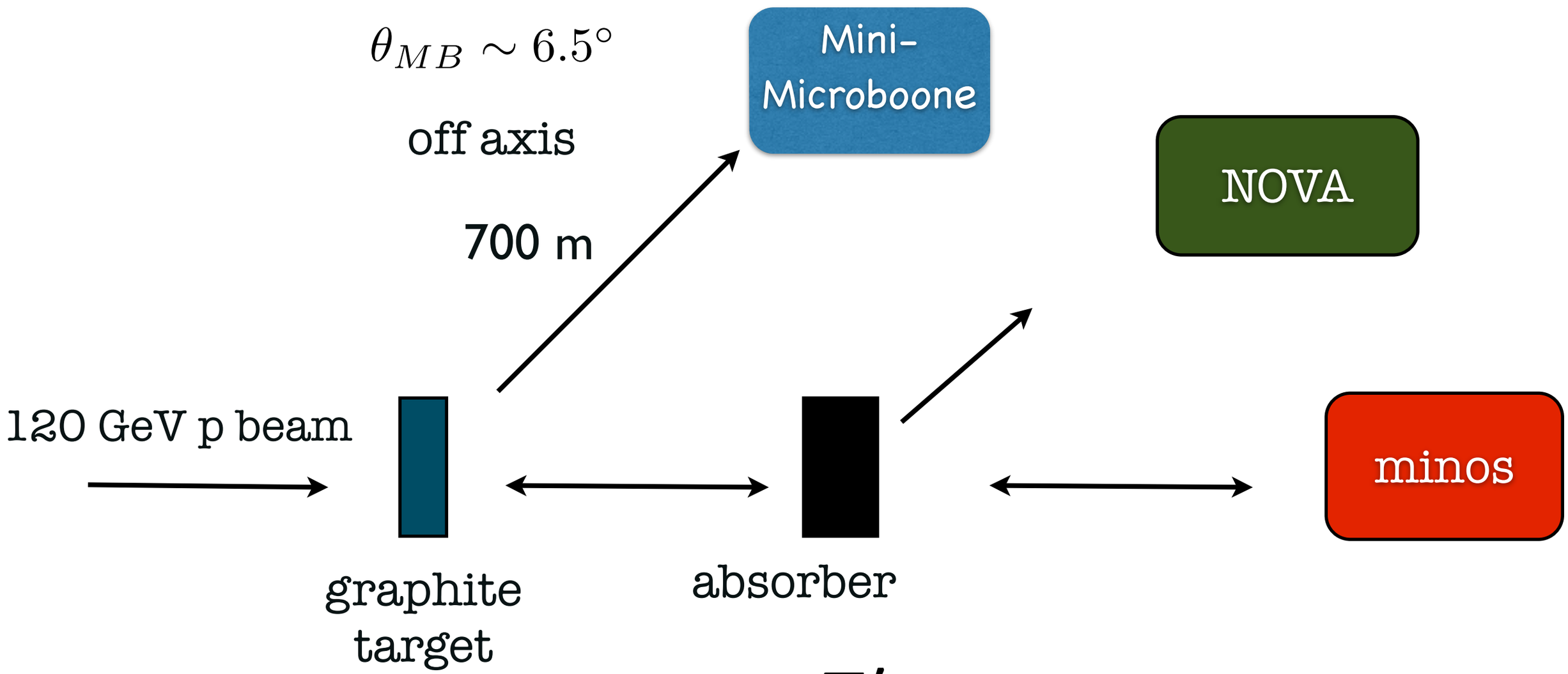
Neutrinos energy profile



off axis detectors to kill bkg!

large tail of neutrinos coming from kaon decays

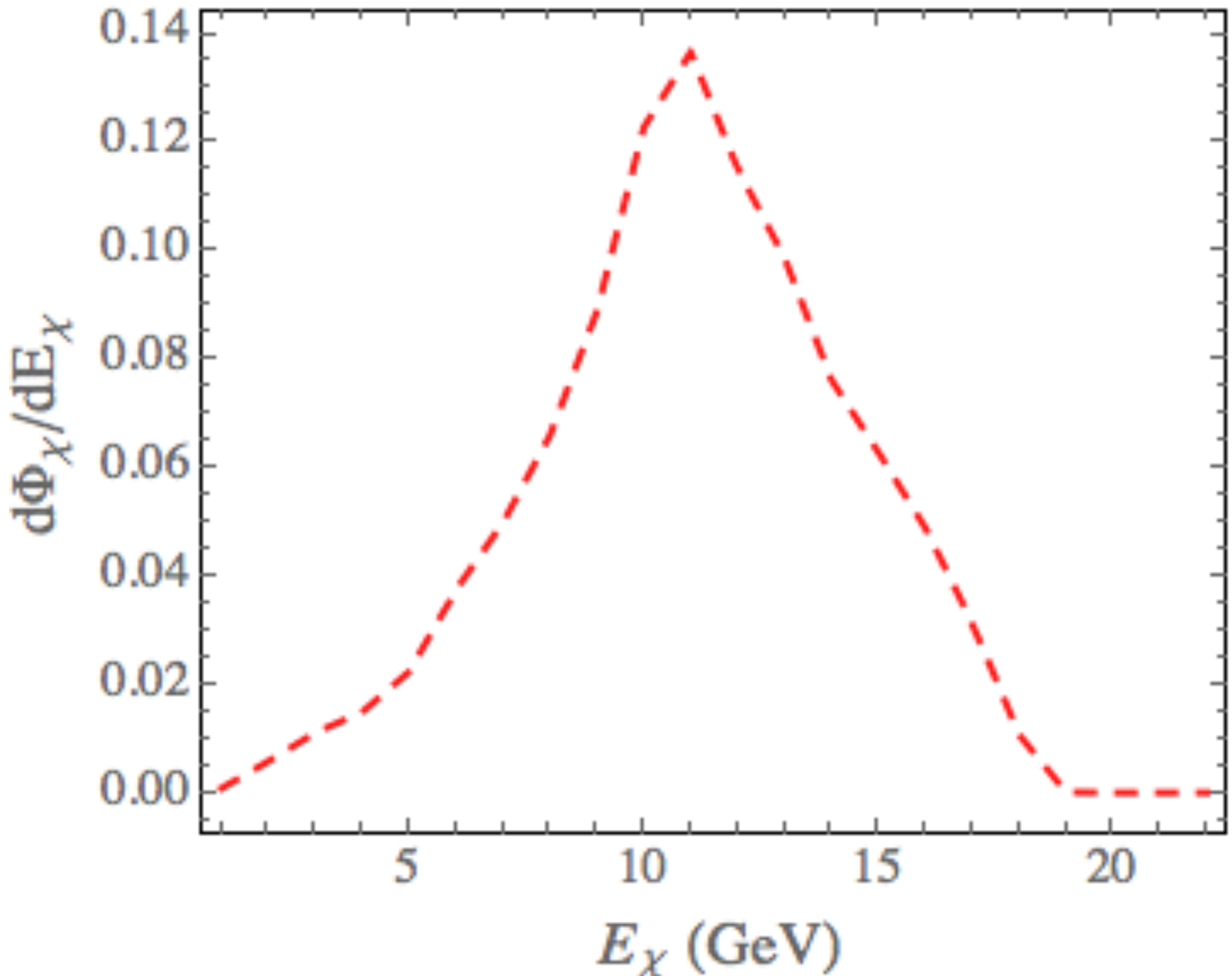
We have already an off axis detector!



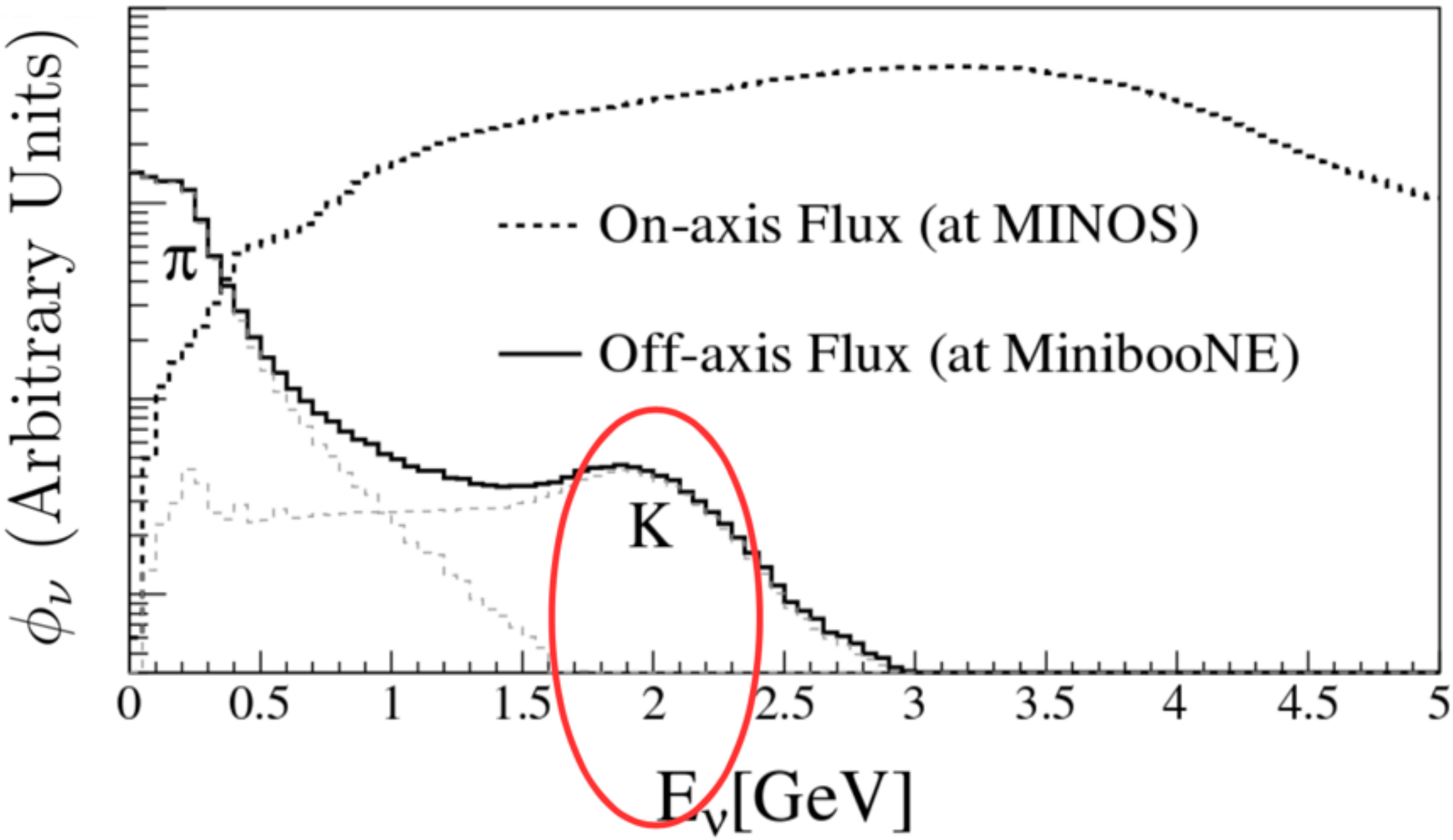
$$pp \to Z' \to \chi\chi$$

DM particle enter the near detector and scatter with nuclei

Dm energy inside Miniboone

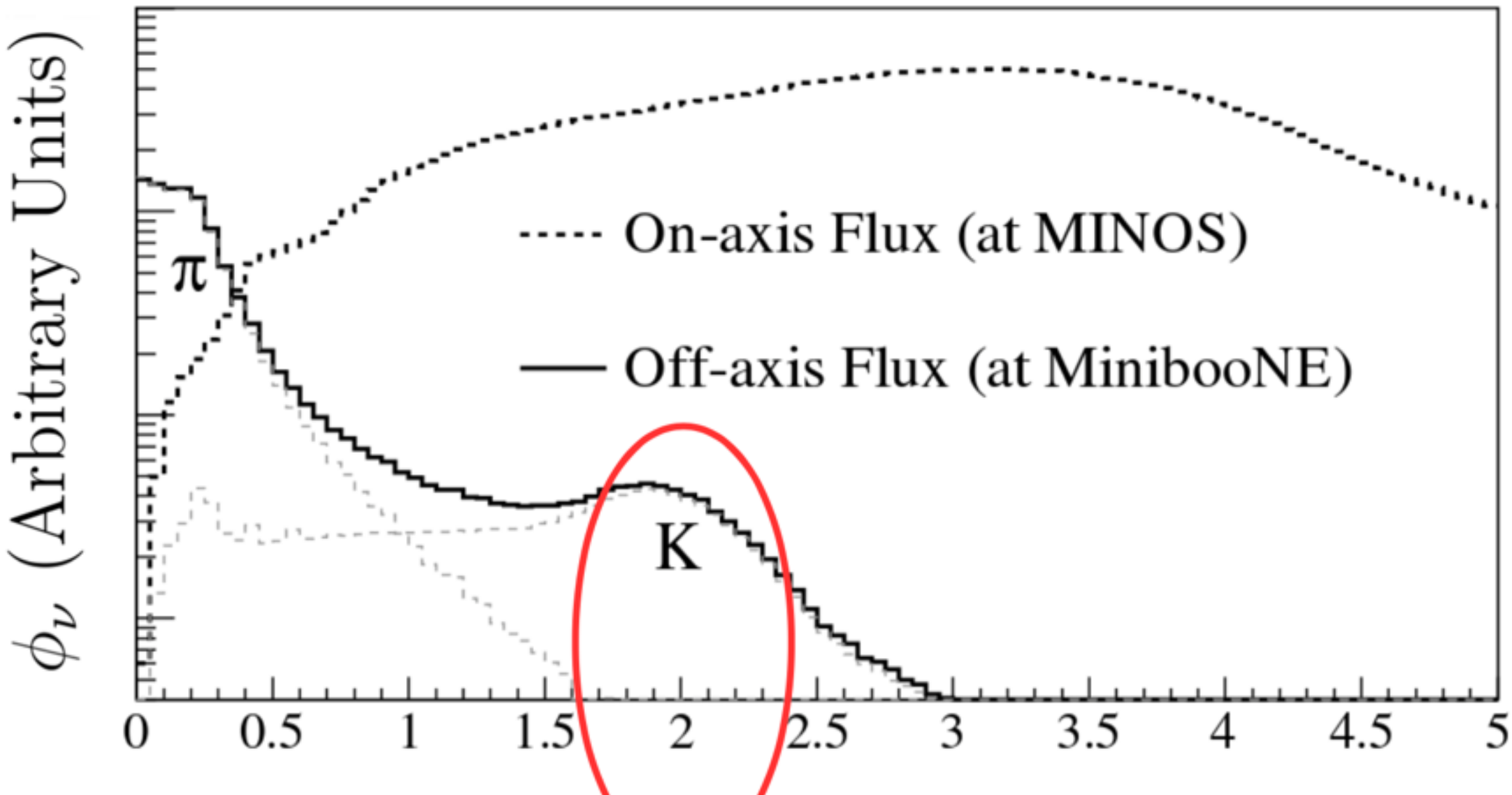


Off axis versus on axis bkg



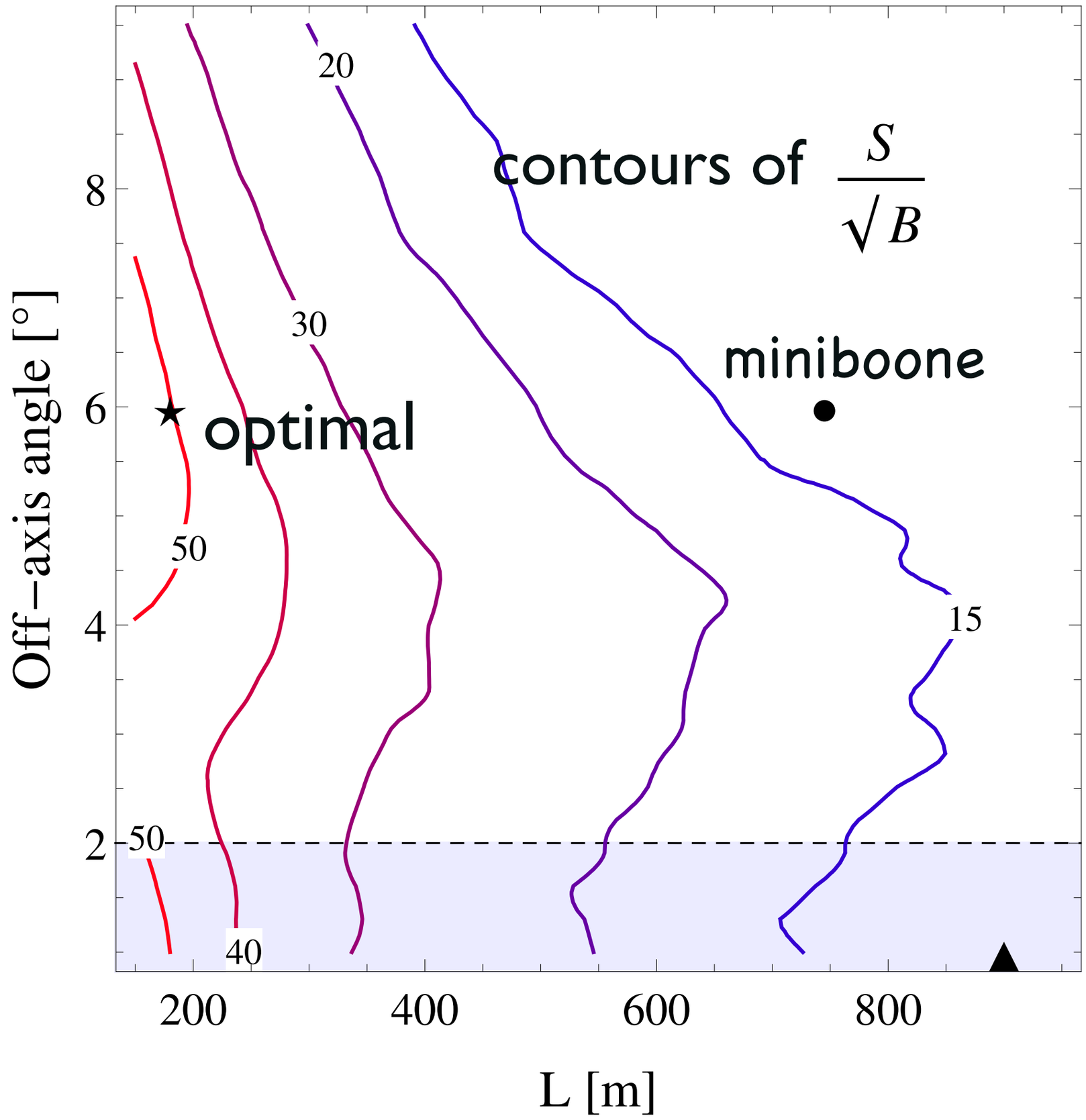
$$E_\nu = \frac{m^2_{\pi/K}}{2E_{\pi/K}(1-\beta\cos\theta)}$$

Off axis versus on axis bkg



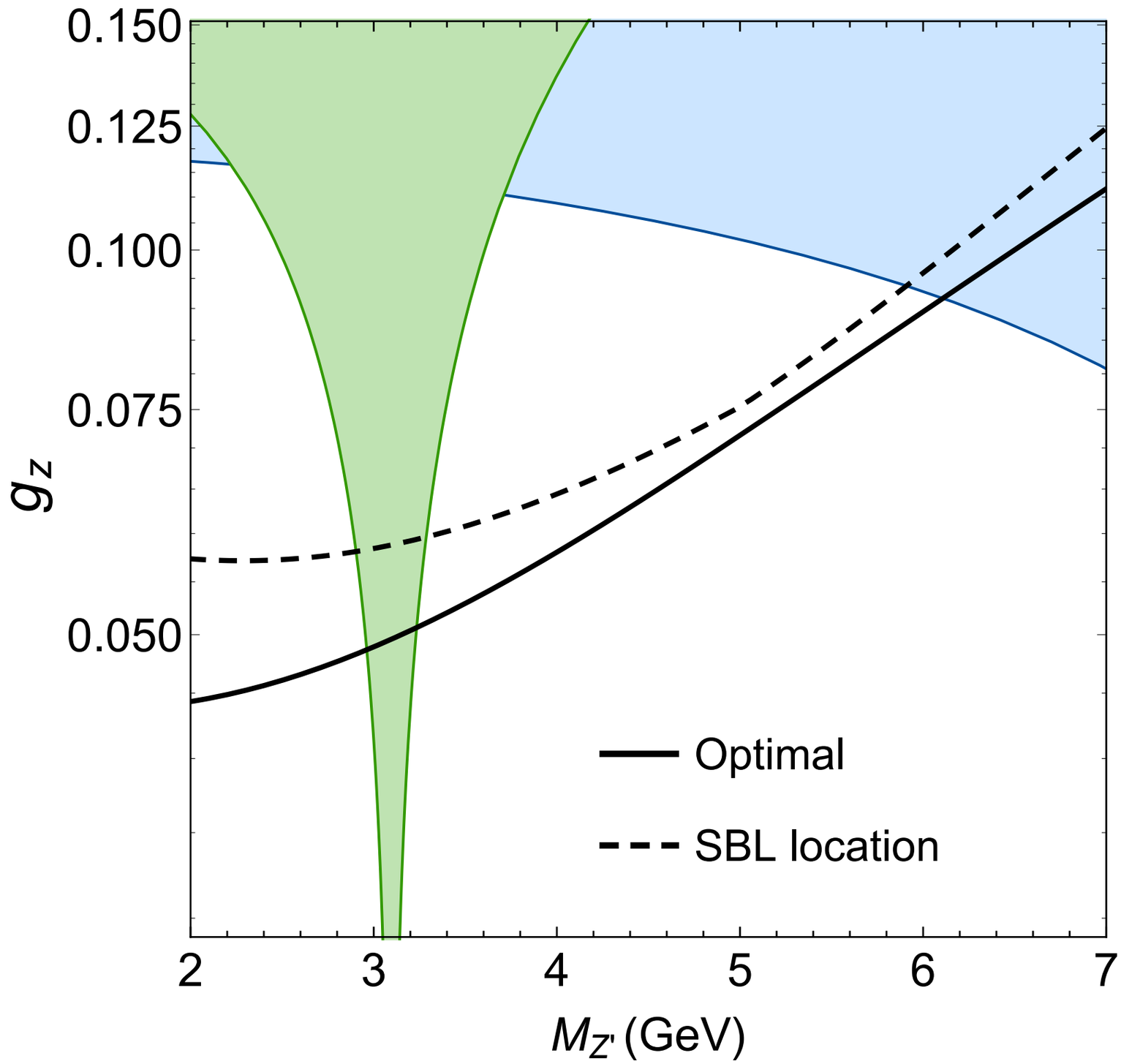
Going off axis we kill efficiently neutrino bkg- what would be an optimal location for a LBNF detector?

Ideal position for a future LBNF detector



$g_z = 0.1$

$\chi^2 contour$



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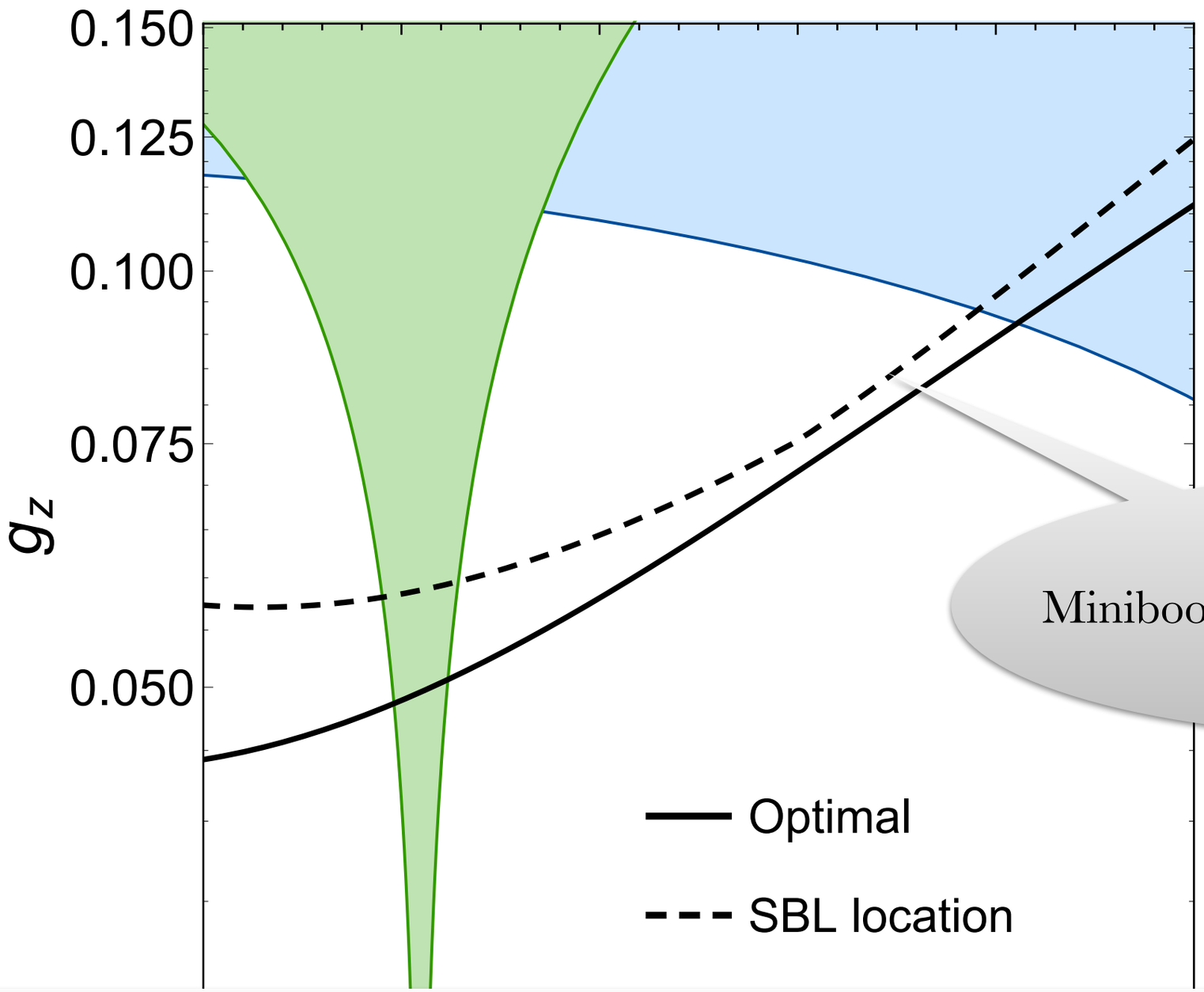
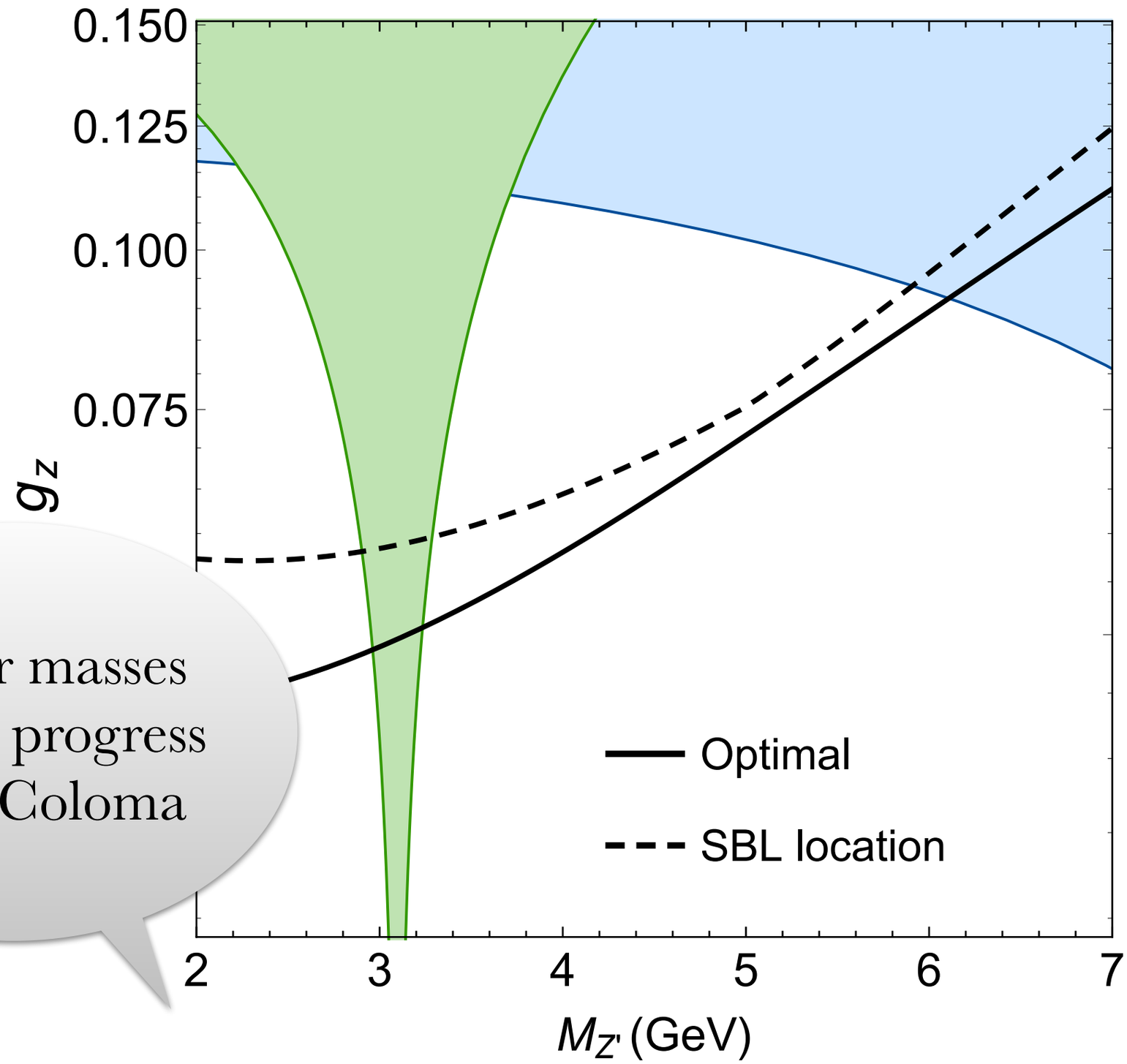


Miniboone location close to optimal!

Ideal detector for SHIP? New study of neutrino bkg needed (work in progress with P.Coloma)

$\chi^2 contour$



Lighter masses
work in progress
with P.Coloma

How do we probe the lighter mass region

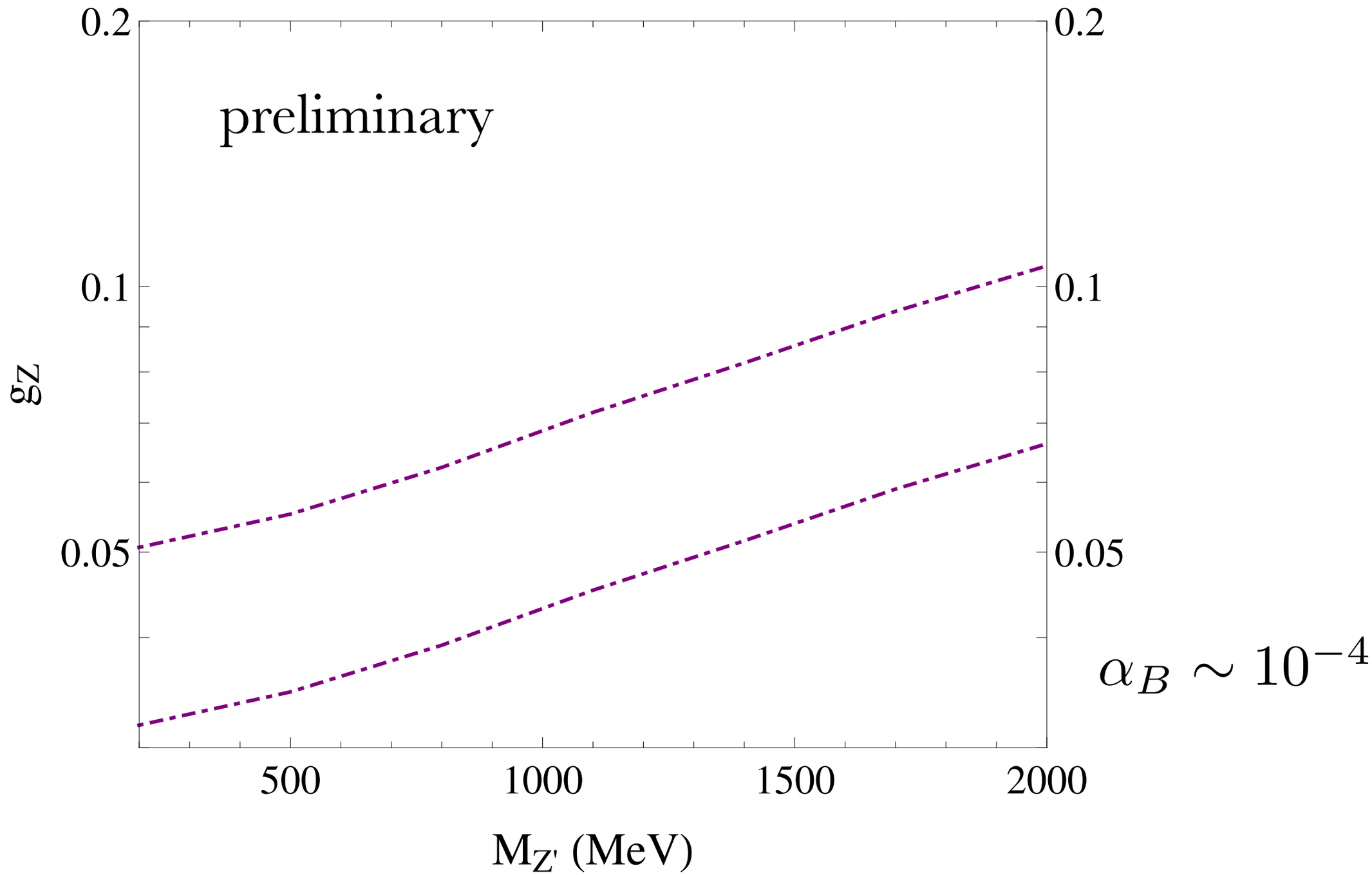
- Production via meson decay (Batell&co) good but need a special run in proton beam dump
- What about direct production?

pQCD requires partonic scale must be >1 GeV

$pp \to Z'$ below threshold

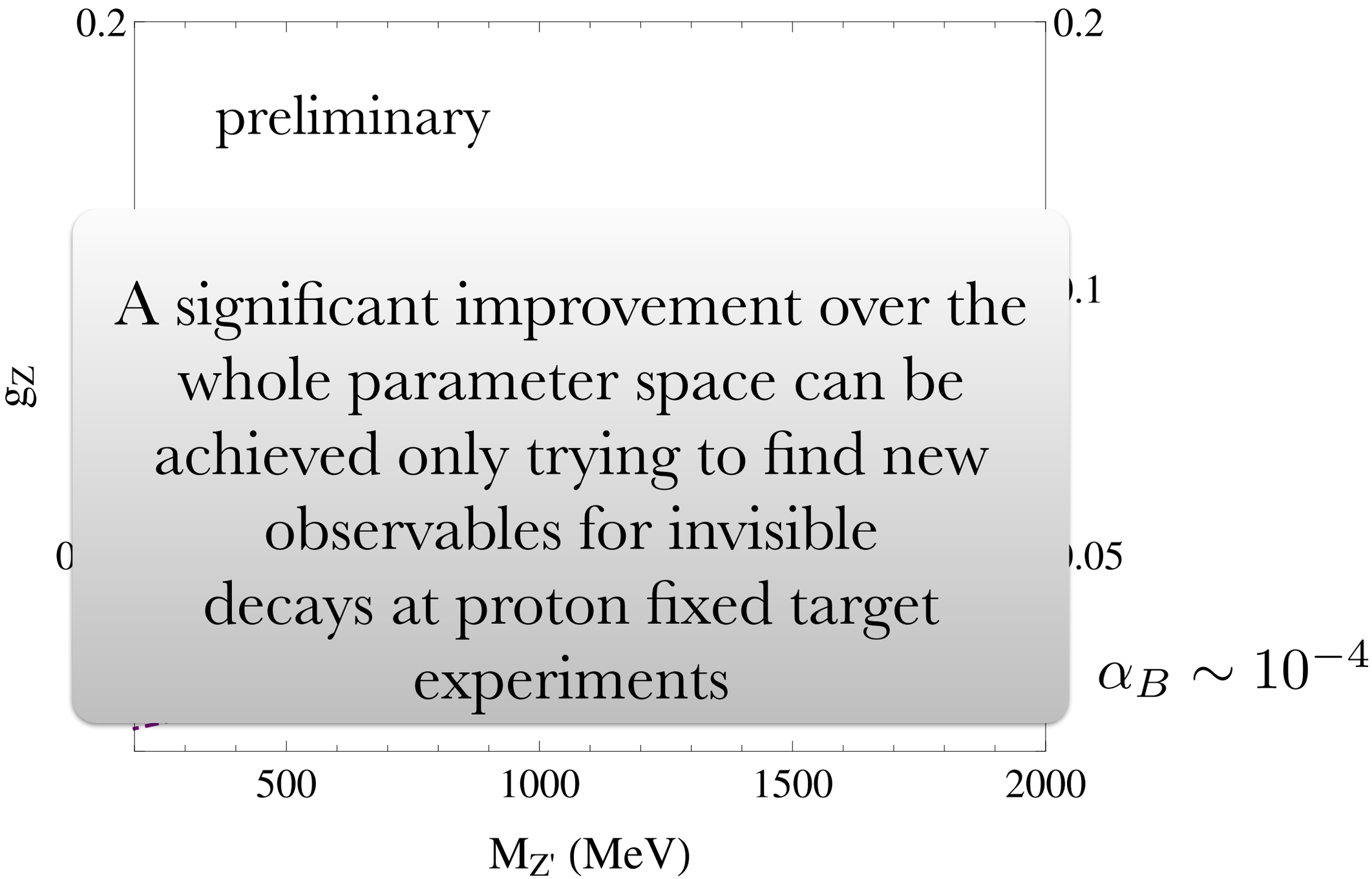
NLO process $pp \to Z' j$ $p_t > 1$ GeV

Limits



Strongest bounds on the market above kaon threshold

Limits



A significant improvement over the whole parameter space can be achieved only trying to find new observables for invisible decays at proton fixed target experiments

Strongest bounds on the market above kaon threshold

Outlook

- Neutrino facilities could offer the possibility to probe light DM/quarks couplings.
- Off axis near LBNF detector could set the strongest bounds available on few GeV leptophobic, but Miniboone/Microboone collaboration must look at their data!
- BSM physics program can be parasitic to LBNF neutrino program!
- Dark matter detector for SHIP
- Strong motivation to think about new observable at proton fixed target experiments to measure invisible decays

Other physics opportunities?

Relaxion beams at proton fixed target experiments

work in progress
with T.Flacke, E.Fuchs , R. Gupta and G.Perez

A dynamical solution to the hierarchy problem

Non QCD relaxion

$$V(H) = \mu^2(\phi) H^\dagger H + \lambda (H^\dagger H)^2$$

$$\mu^2(\phi) = -\Lambda^2 + g\Lambda\phi + ... \qquad \Lambda >> v$$

The initial value of the Higgs mass is positive and large

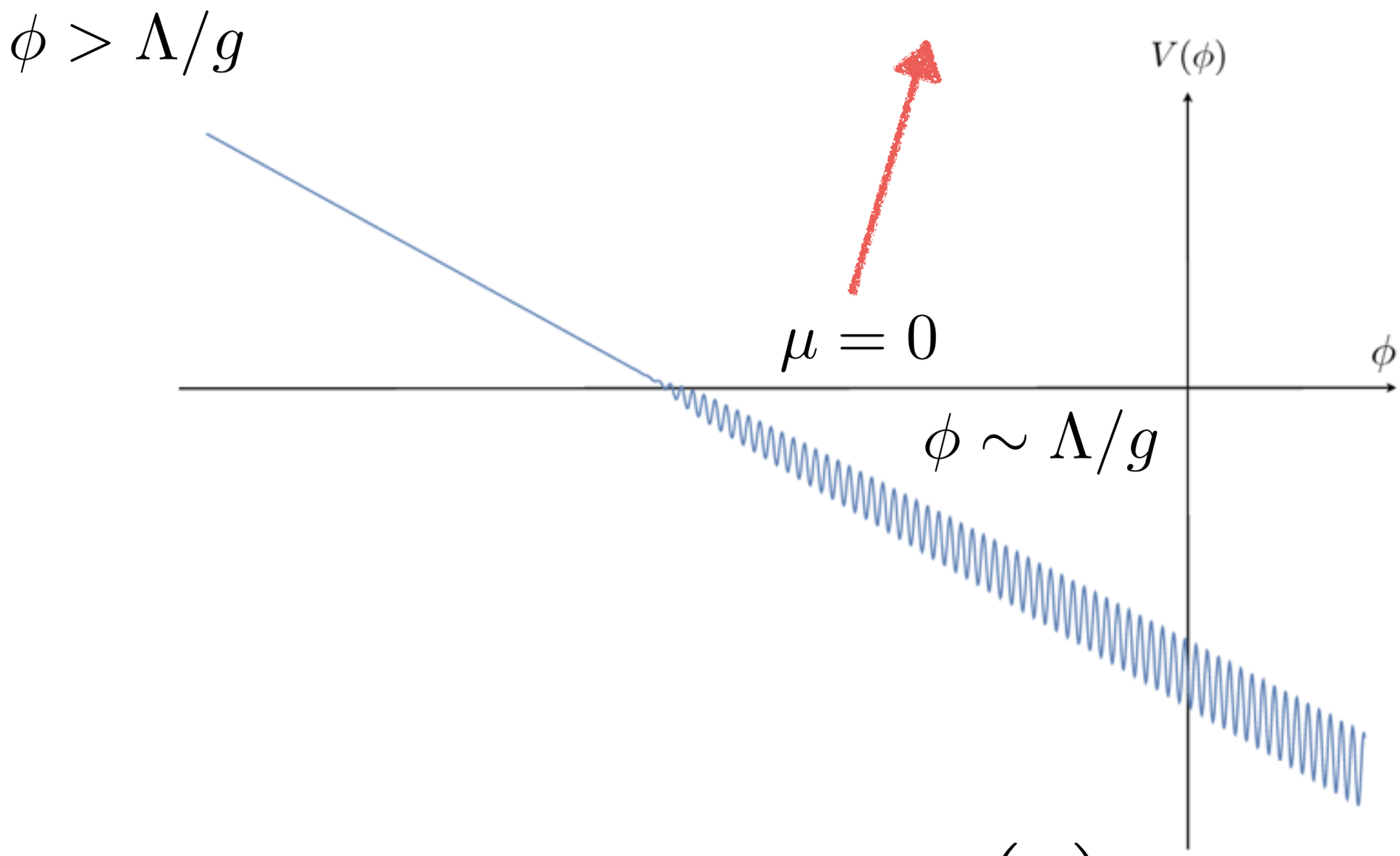
$$\phi > \Lambda/g$$

During inflation the relaxion slow roll and scan the mass of the Higgs

$$V(\phi, H) = g\Lambda^3\phi + ..$$

slow roll term

the quadratic term cross the zero so the Higgs gets a vev

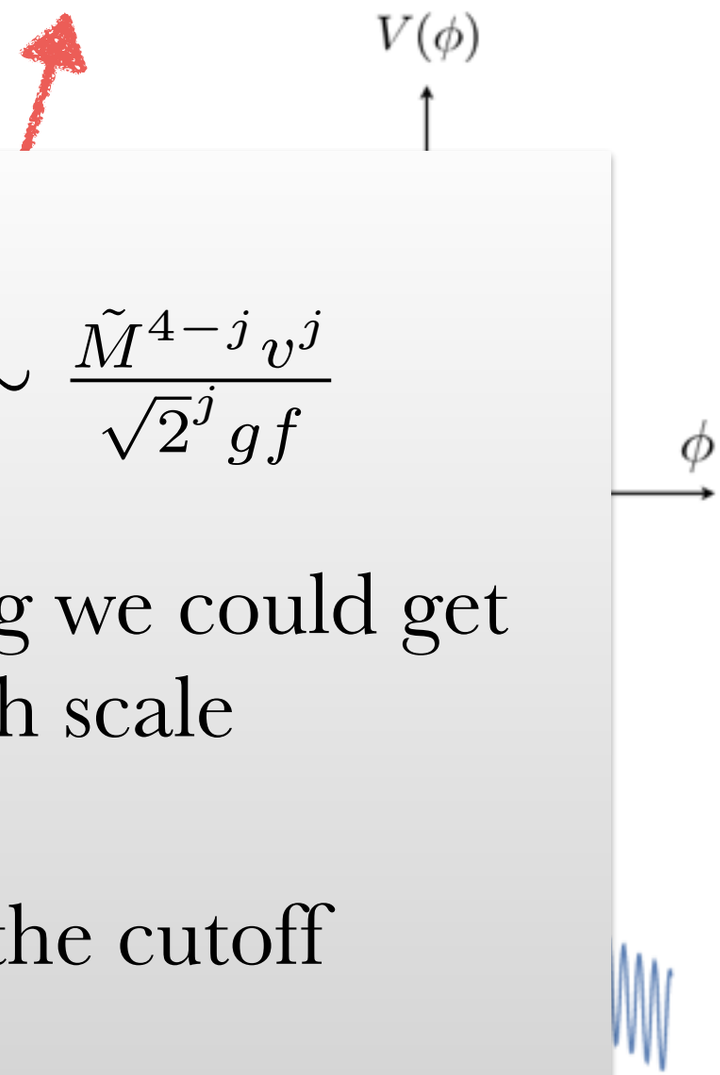


$$V(\phi, H) == rg\Lambda^3\phi + \tilde{M}^{4-j}\hat{h}^j \cos\left(\frac{\phi}{f}\right)$$

height of the barrier starts to grow and at some point stops the rolling of the relaxion

the quadratic term cross the zero so the Higgs gets a vev

$$\phi > \Lambda/g$$



The rolling stops when $\Lambda^3 \sim \frac{\tilde{M}^{4-j} v^j}{\sqrt{2}^j g f}$

so for small very small value of g we could get the EW scale from a high scale

cosmological upper bound on the cutoff

$$\Lambda \lesssim \left(\frac{\tilde{M}^{4-j} v^j}{f}\right)^{1/6} \sqrt{M_{Pl}}$$

not a solution to the full hierarchy problem

he ops the

rolling of the relaxion

How do we probe this scenario?

We might have some LHC signals, but very model dependent

Can we look for the relaxion ?

We generically expect the relaxion is a (very) weakly coupled light particle

→ Hierarchy problem at the low energy frontier!

What is its mass? How does it couple to the SM?

Which experiments can probe it?

Higgs/relaxion mixing

consider the following back reaction $\Delta V_{br} = \tilde{M}^2 H^2 \cos\left(\frac{\phi}{f}\right)$

$$m_\phi^2 \sim \frac{\tilde{M}^2 v^2}{2f^2}\left(1 - \frac{2\tilde{M}^2}{m_h^2}\right)$$

the relaxion mixes with the Higgs

$$\sin\theta \sim \frac{v}{f}\frac{\tilde{M}^2}{m_h^2}$$

Higgs portal model constraints apply!

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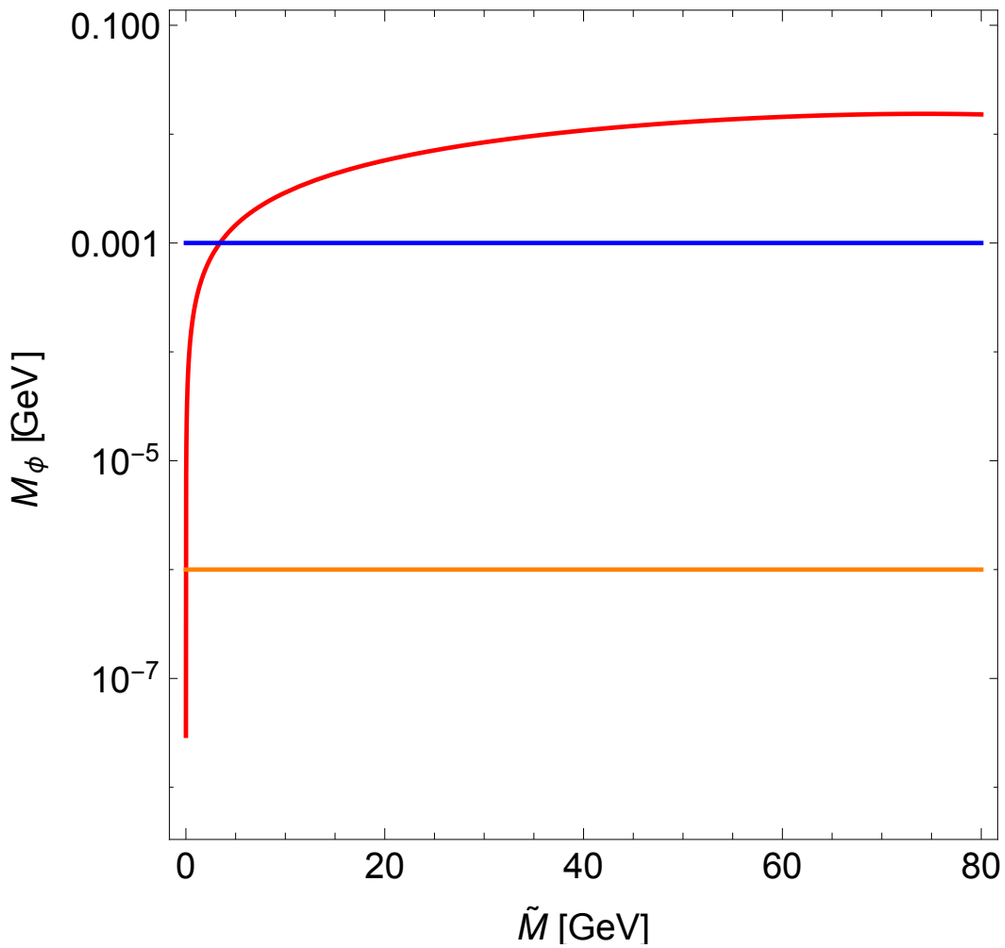


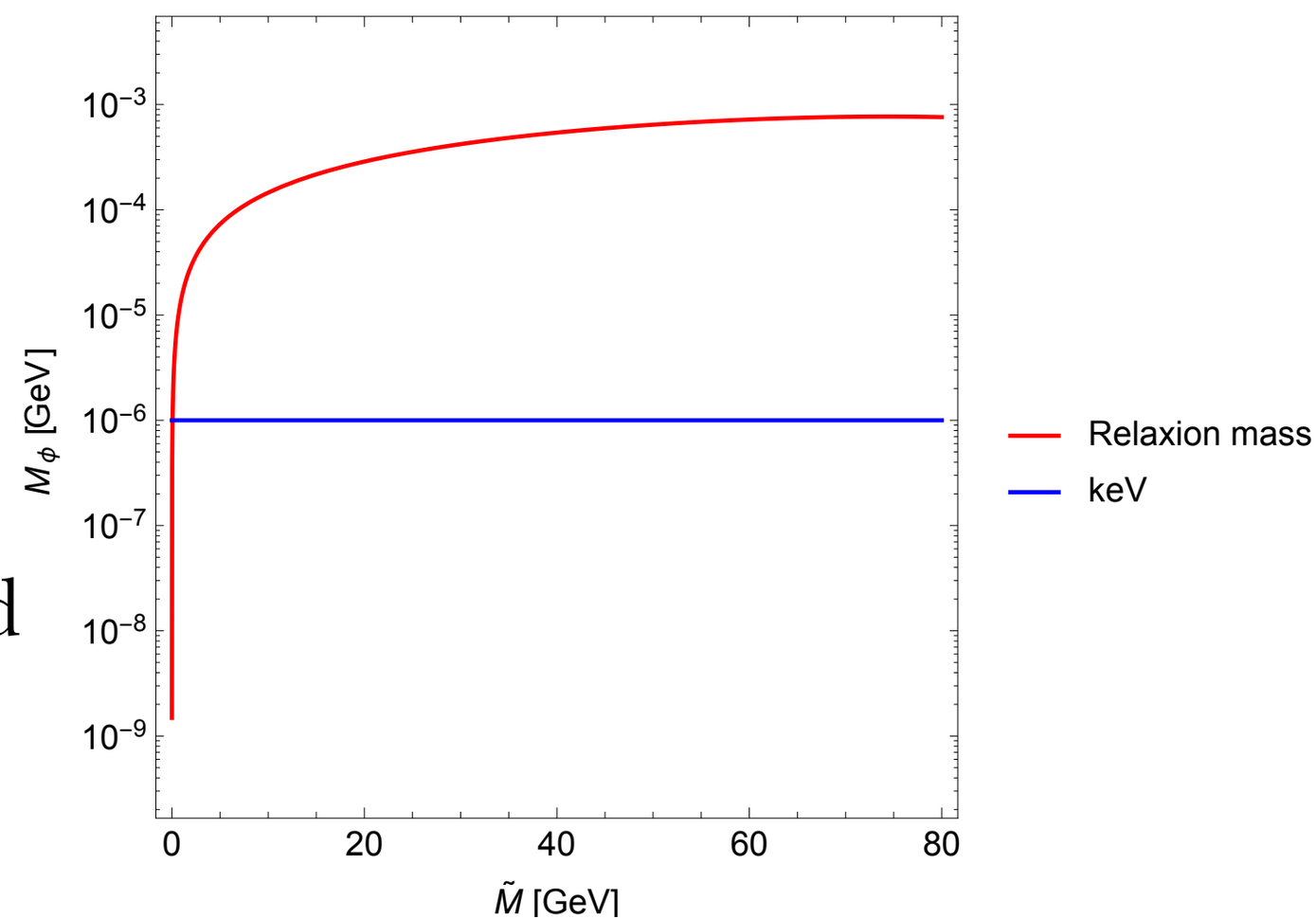
$$f \sim \Lambda \sim 50 \text{ TeV}$$

$$\sin\theta \sim 10^{-4} - 10^{-8}$$

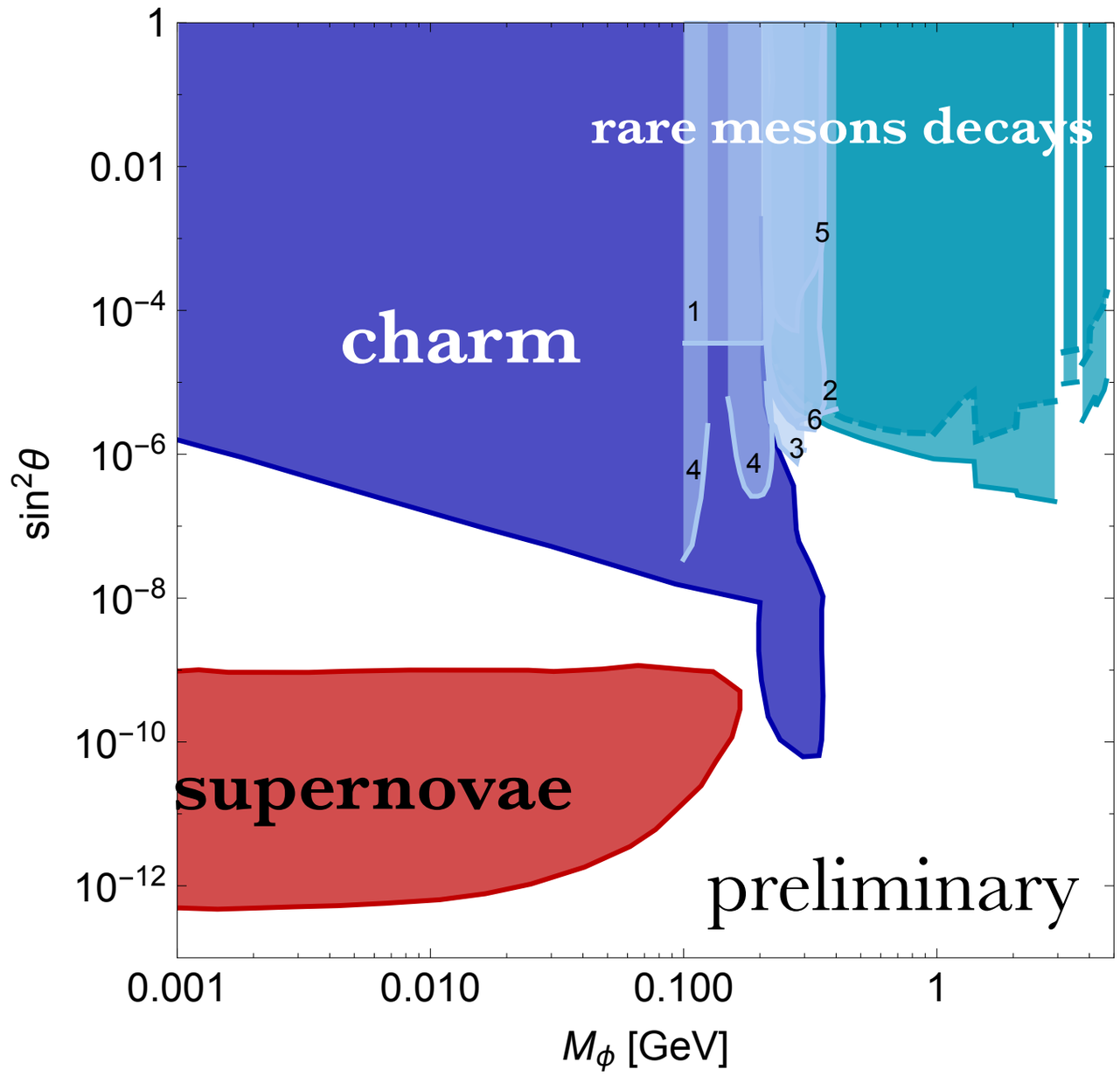
Relaxion mass
MeV
keV

$$f \sim \Lambda \sim 1000 \text{ TeV}$$

lighter relaxion
& more weakly coupled

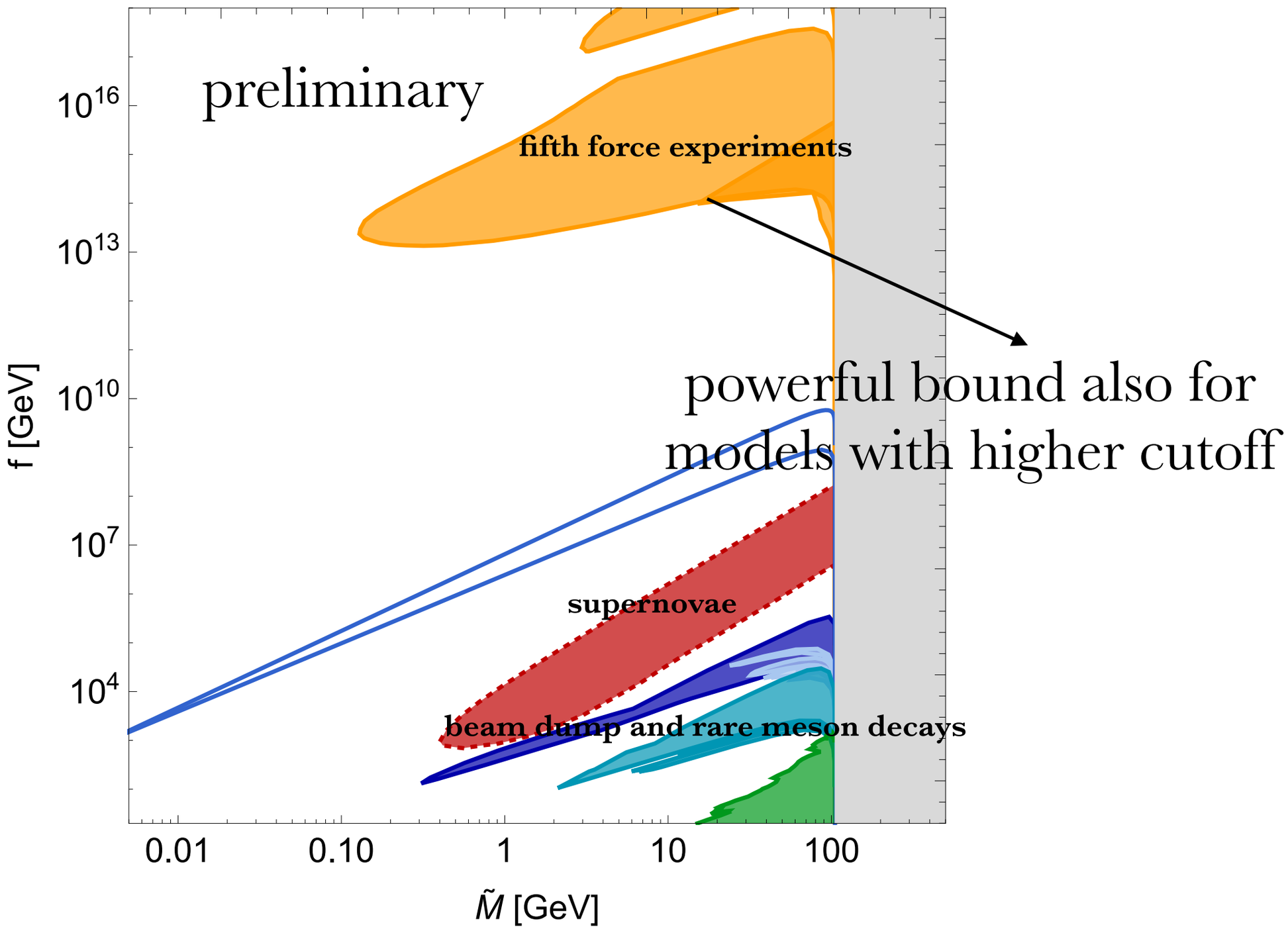


MeV region probes

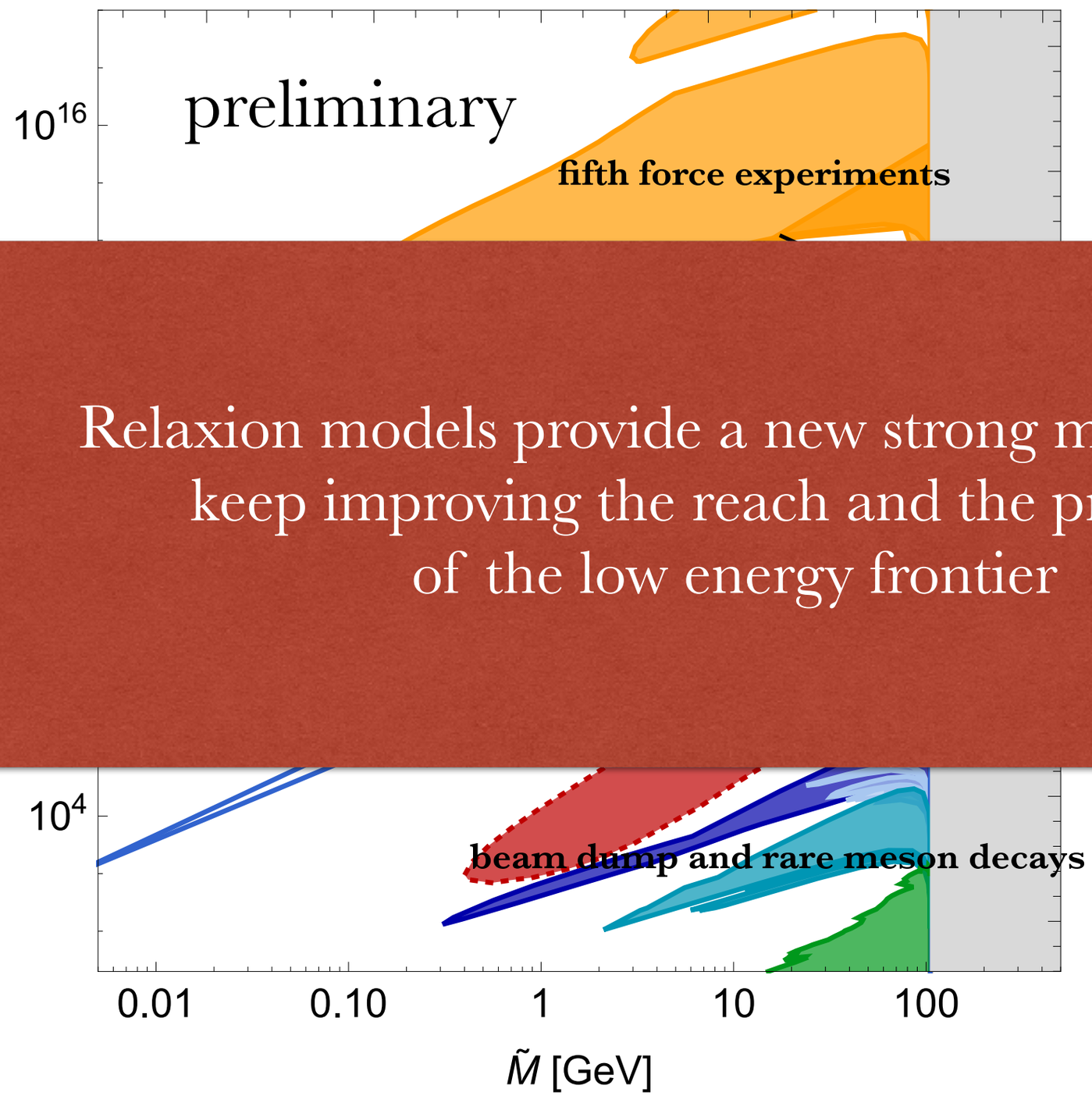


proton fixed target experiments
could probe the region of low cutoff for relaxion models

Low energy probes of the relaxion

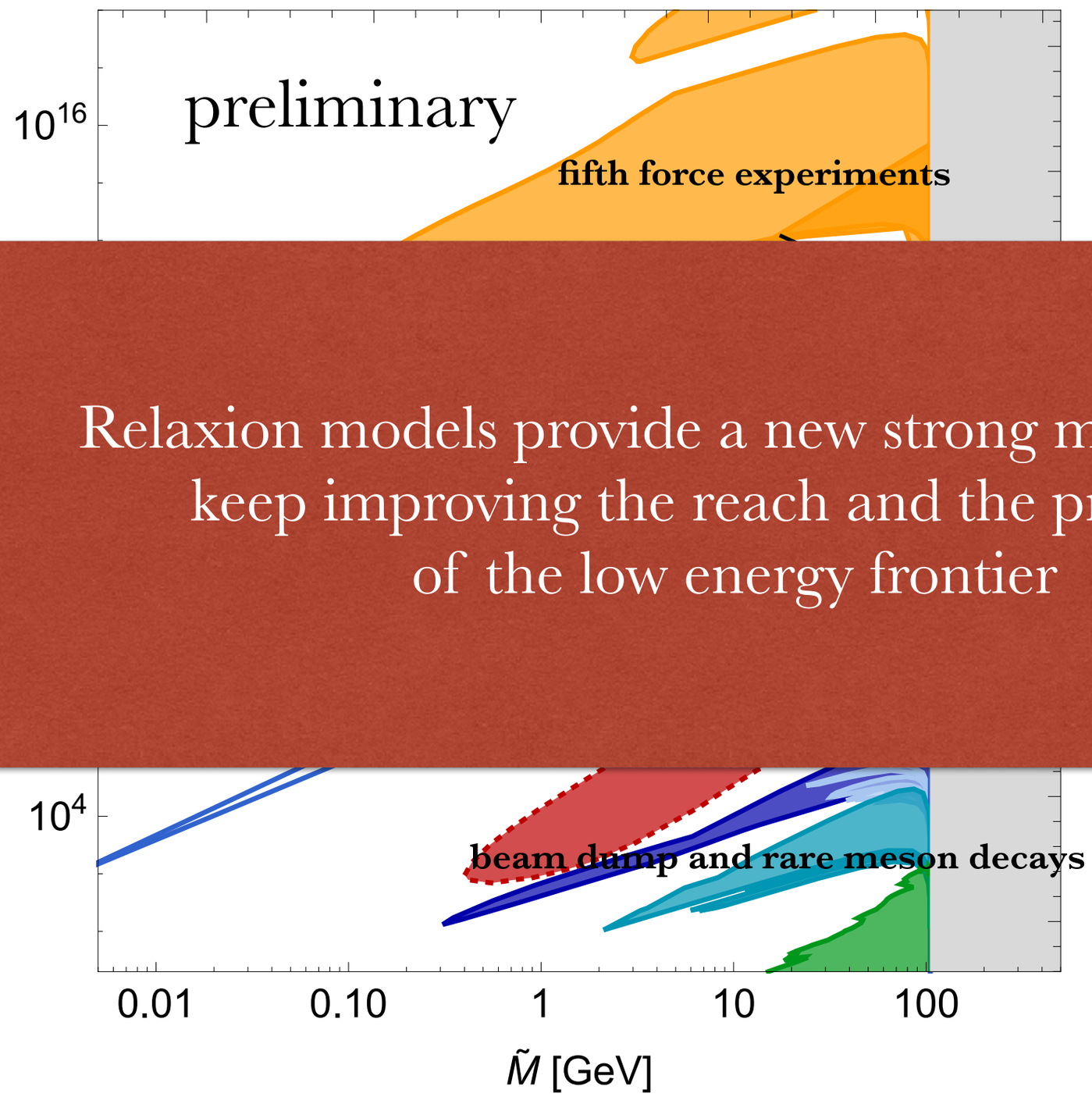


Low energy probes of the relaxion



Relaxion models provide a new strong motivation to keep improving the reach and the precision of the low energy frontier

Low energy probes of the relaxion



Relaxion models provide a new strong motivation to keep improving the reach and the precision of the low energy frontier

Thank you!