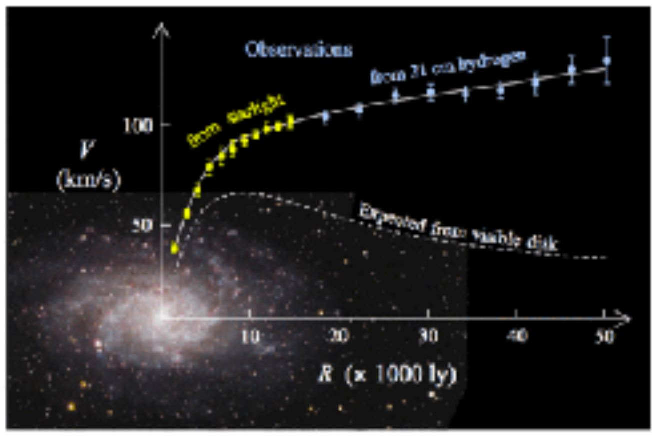
Dark Matter Production at High Intensity Facilities

Gordan Krnjaic

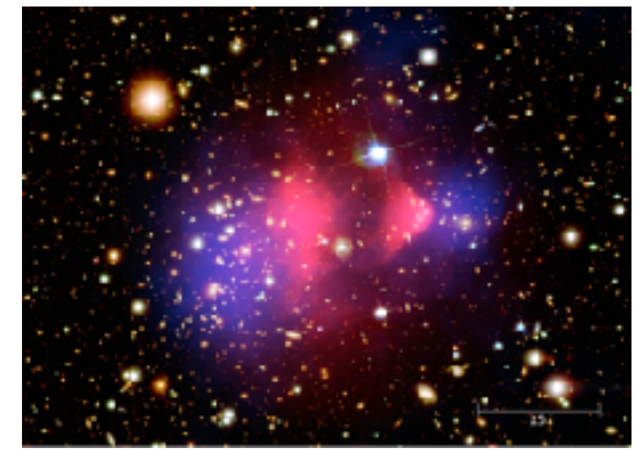
RF6 Kickoff Meeting, August 12, 2020

Remarkable Evidence for Dark Matter

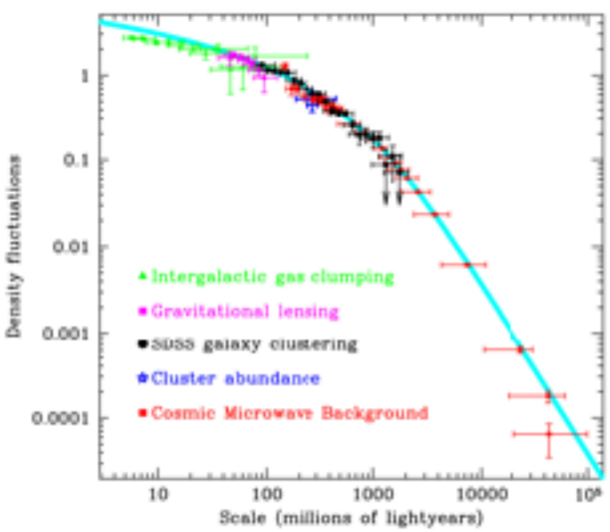


Rotation Curves

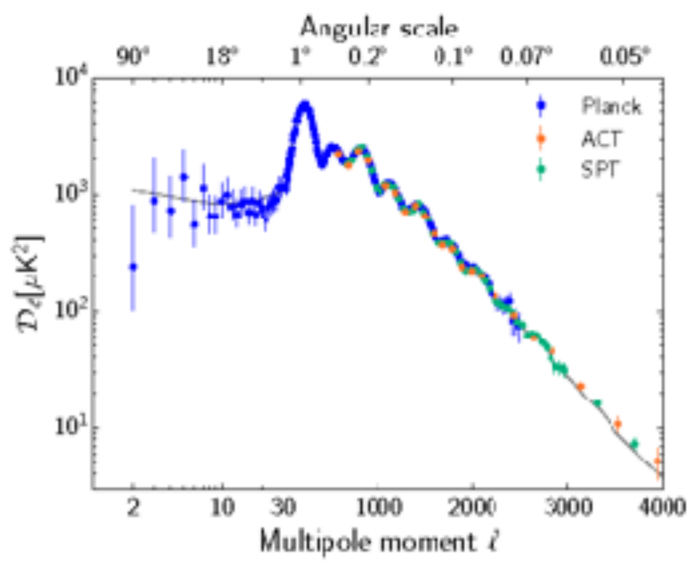
Gravitational Lensing



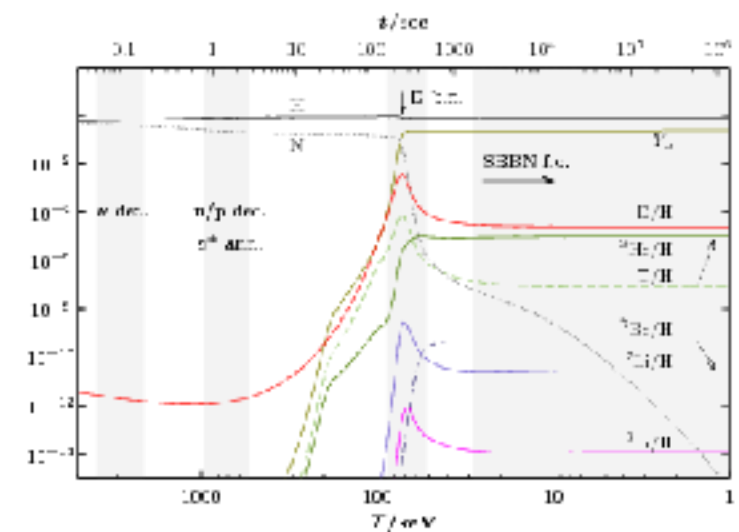
Cluster Collisions



Matter Power Spectrum



CMB Power Spectrum

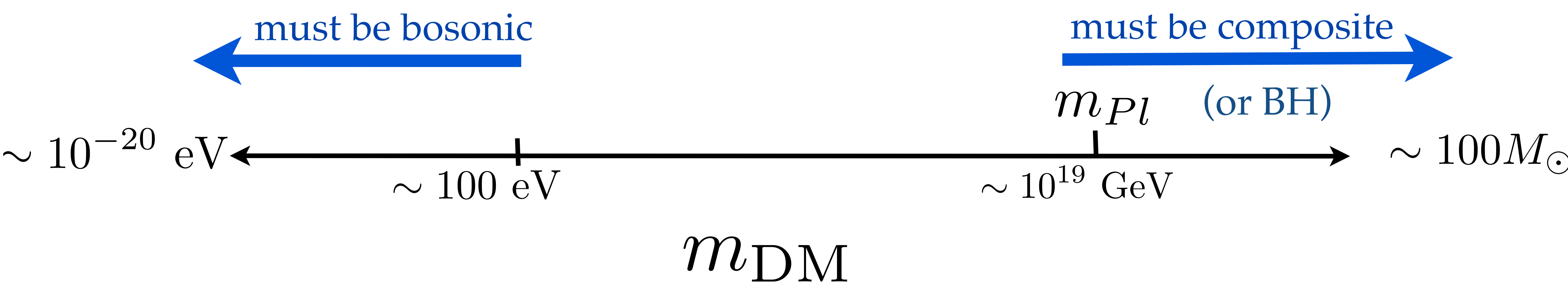


BBN Light Element Yields

Multiple independent, consistent observations
over **nearly** all of spacetime: kpc-Gpc, 13.7 Gyr ago-today

Holy Grail: extend our knowledge to terrestrial scales << kpc

What Clues Do We Have?



Huge space of allowed microscopic theories

Evidence only extends down to ~kpc (dwarf galaxy) scales

Theoretical guidance is essential

Need organizing principle for systematic progress

Overview

Preliminaries

B/K-Factories

Beam Dump Production

Missing Energy/Momentum

Overview

Preliminaries

B/K-Factories

Beam Dump Production

Missing Energy/Momentum

What kind of DM can we probe?

High intensity facilities: Ecm < few GeV

Kinematically produce sub-GeV DM

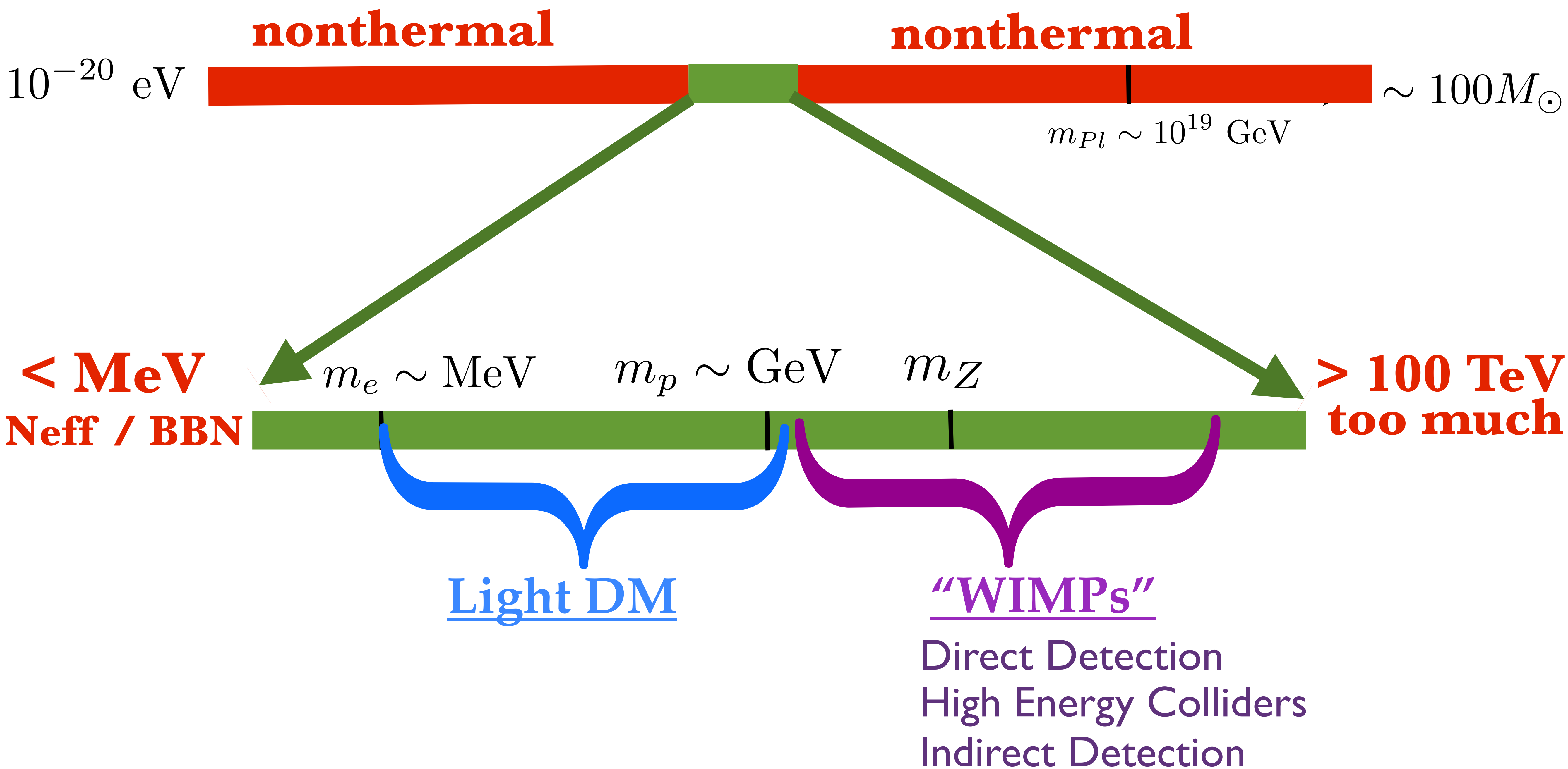
Need “large” couplings to visible matter

Accelerators sensitive to BSM couplings $g \gtrsim 10^{-4}$

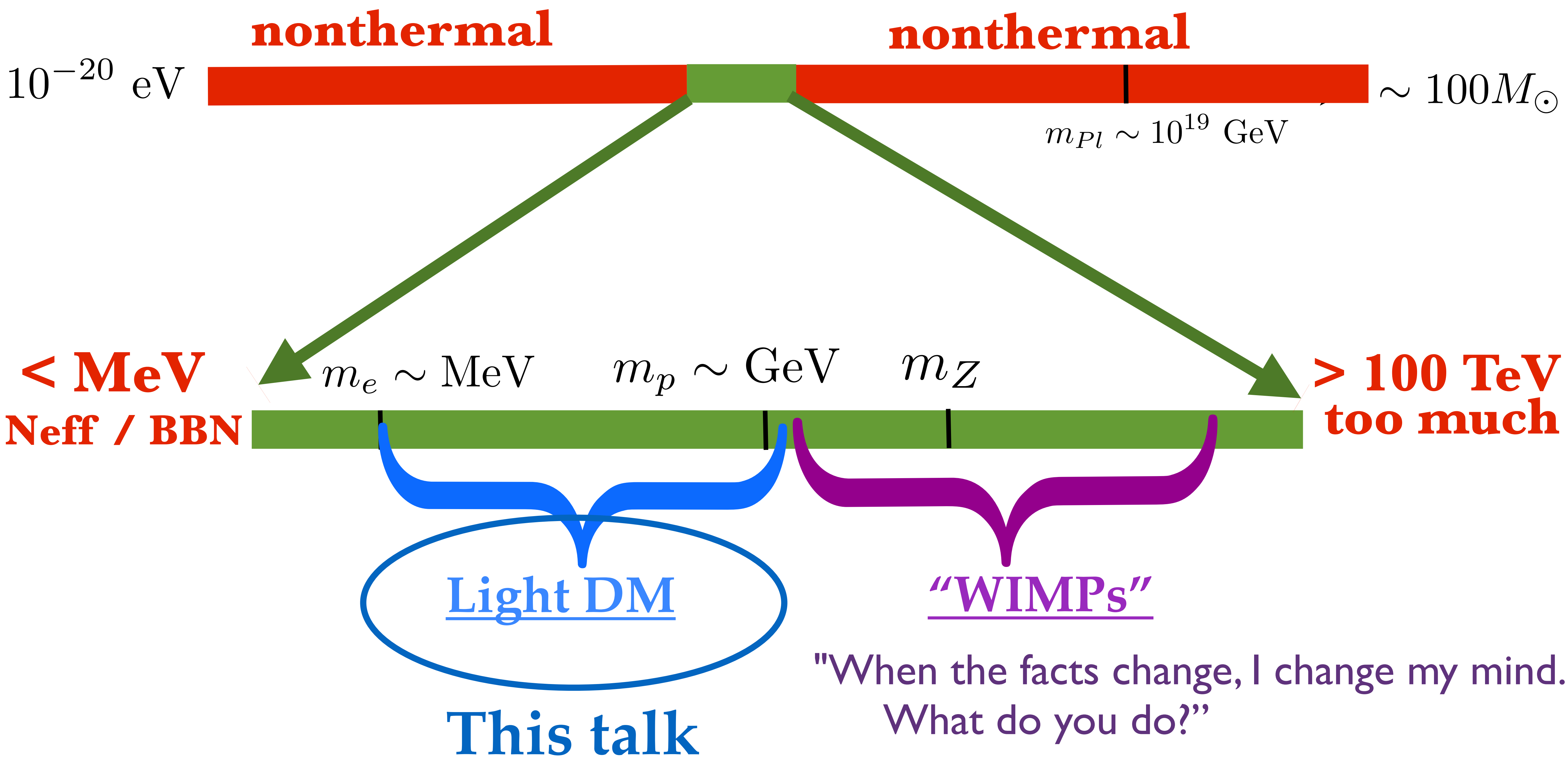
Therefore { Any* DM candidate that can be made in accelerators was in equilibrium with SM in the early universe $n_\chi \sim n_\gamma \sim T^3$

Model independent consequence

Equilibrium Narrows Mass Range!



Equilibrium Narrows Mass Range!



Light DM vs. WIMPs

Light DM must be SM neutral

Else would have been discovered (LEP, Tevatron…)

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Light DM requires light new force carriers "mediators"

Must annihilate away huge thermal density. Weak force too weak:

$$\sigma v \sim G_F^2 m_\chi^2 \sim 10^{-29}\,\mathrm{cm}^3\,\mathrm{s}^{-1}\left(\frac{m_\chi}{\mathrm{GeV}}\right)^2$$

need $\sigma v \sim 10^{-26}\mathrm{cm}^3\mathrm{s}^{-1}$ to avoid early universe overproduction

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need $\sigma v \sim 10^{-26}\mathrm{cm}^3\mathrm{s}^{-1}$ to avoid early universe overproduction

Annihilation through renormalizable "portal" interactions

Higher dimension operators have same problem as weak force

[See Adam Ritz's talk]

Light mediators are not optional!

Why Accelerators? Completeness

Traditional direct detection loses sensitivity

Nuclear recoils below ~ keV threshold $E_R = \frac{q^2}{2n_N} \sim \text{keV}\left(\frac{m_\chi}{\text{GeV}}\right)^2$

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Novel electron target direct detection

Promising for sub-GeV range, but hard to probe many scenarios
Rate suppressed for velocity dependent and inelastic models

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Novel electron target direct detection

Promising for sub-GeV range, but hard to probe many scenarios

Rate suppressed for velocity dependent and inelastic models

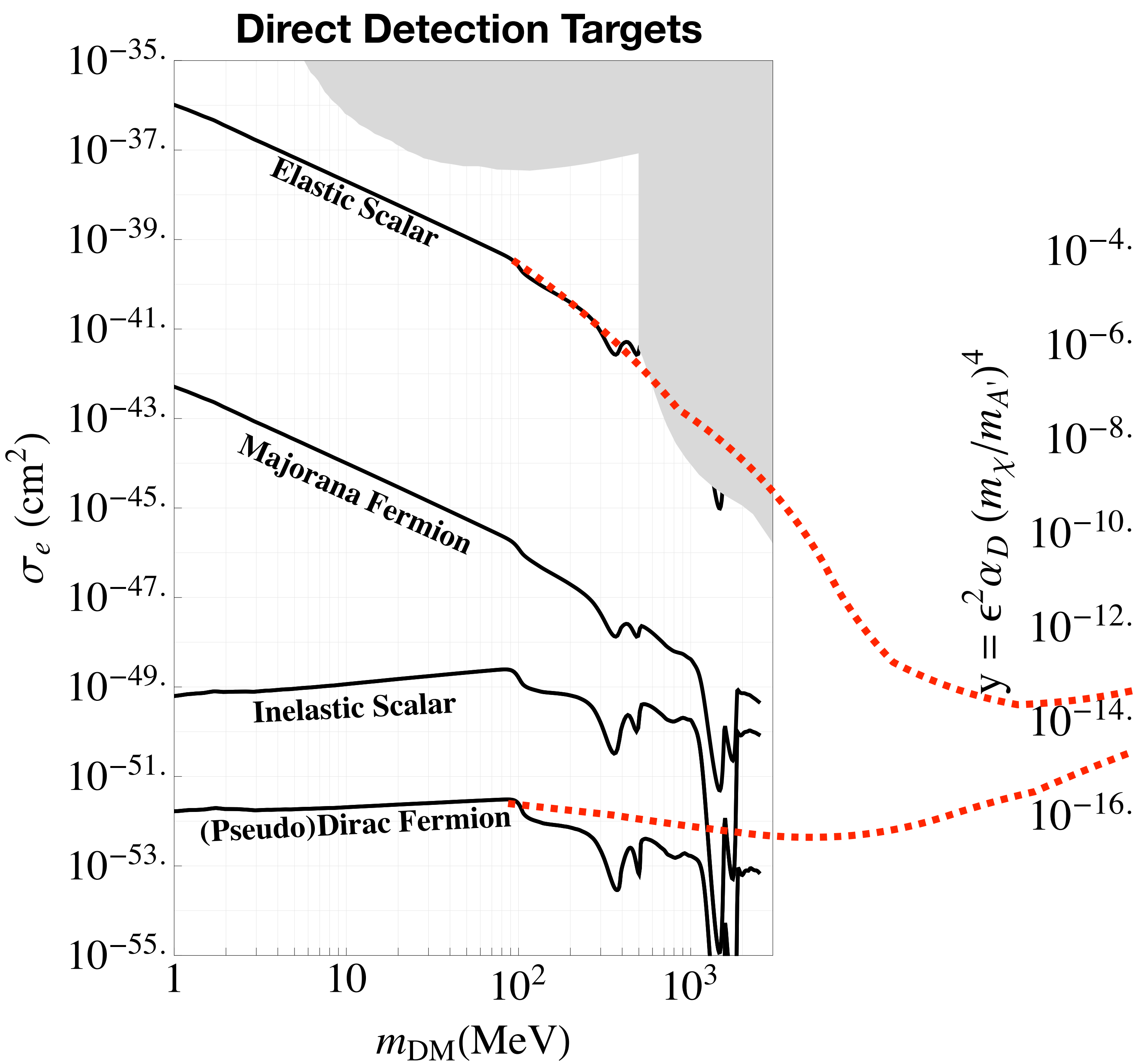
Indirect detection generically unavailable

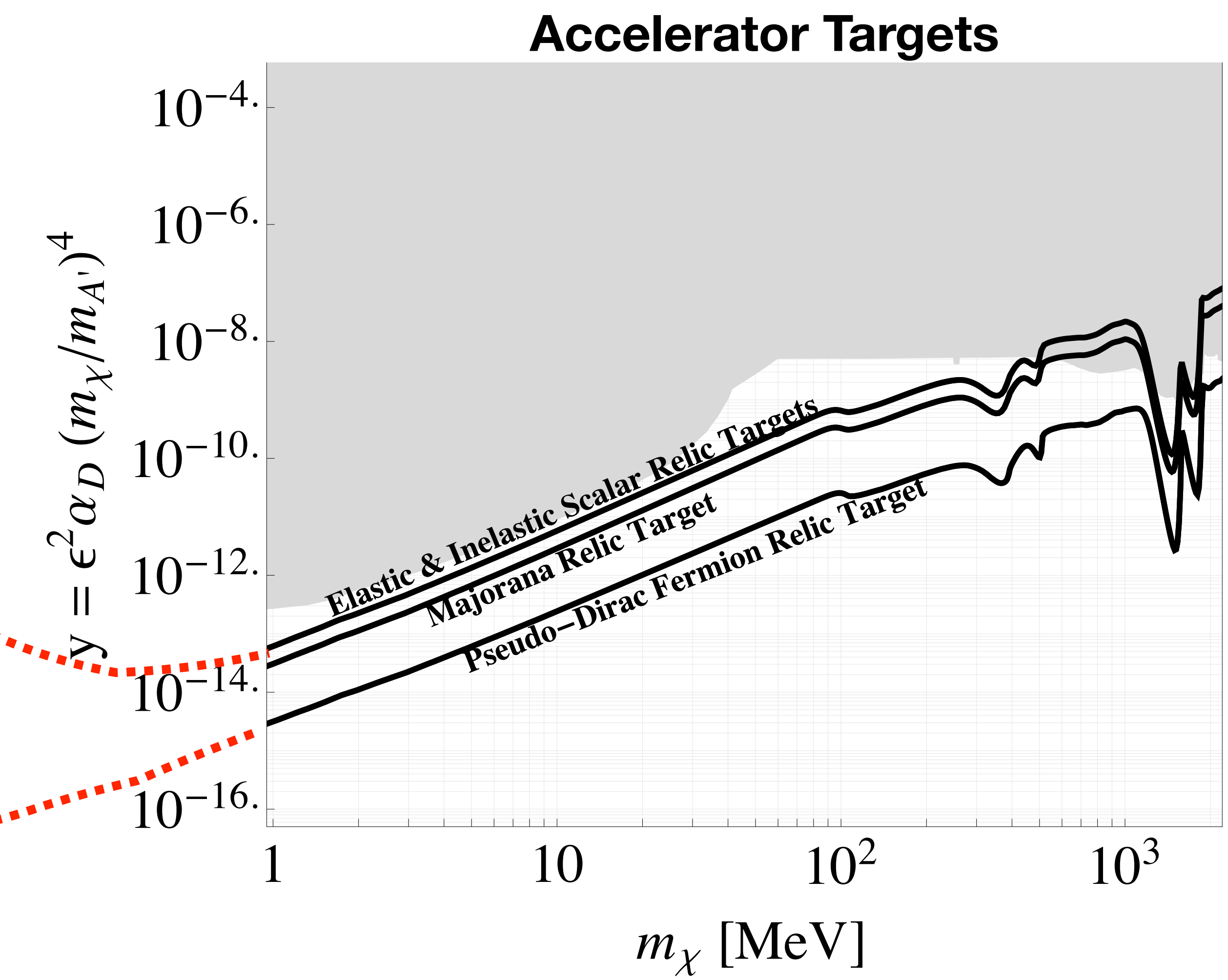
CMB bounds exclude relic annihilation for s-wave processes < 10 GeV

Need annihilation to end before recombination —> won't occur today

Accelerators are unaffected by these limitations

Why Accelerators? Accessible Thermal Targets





non-relativistic cross sections can be loop- or velocity- suppressed

Relativistic freeze-out kinematics

Calculable dark matter rate

No astrophysical uncertainties

All thermal targets within reach

Cosmic Visions Report https://arxiv.org/abs/1707.04591

Overview

Preliminaries

B/K-Factories

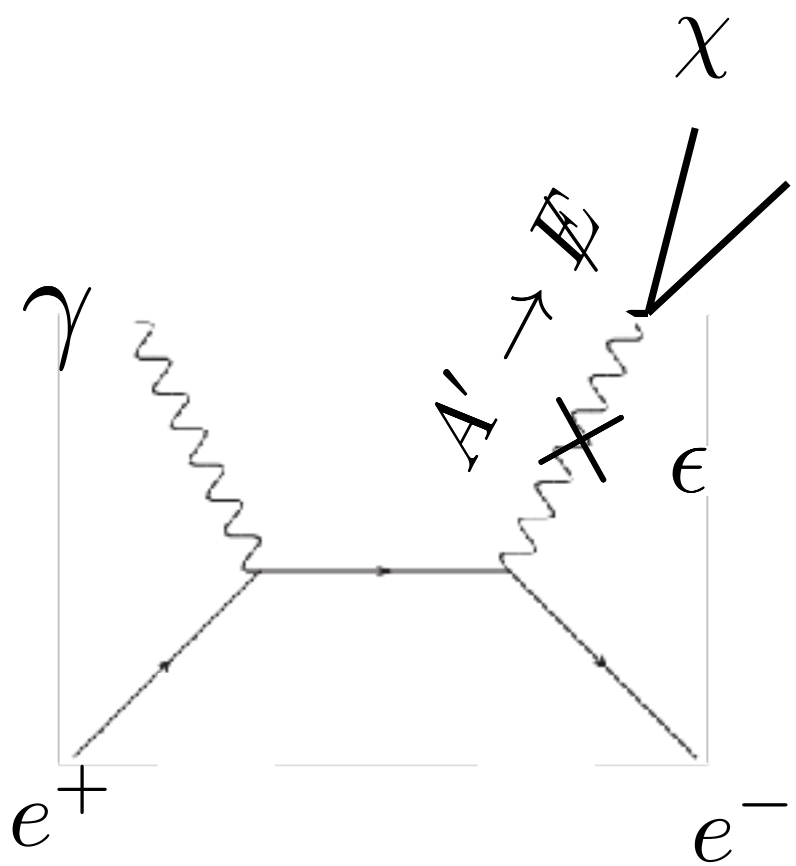
Observable: initial & final state four vectors

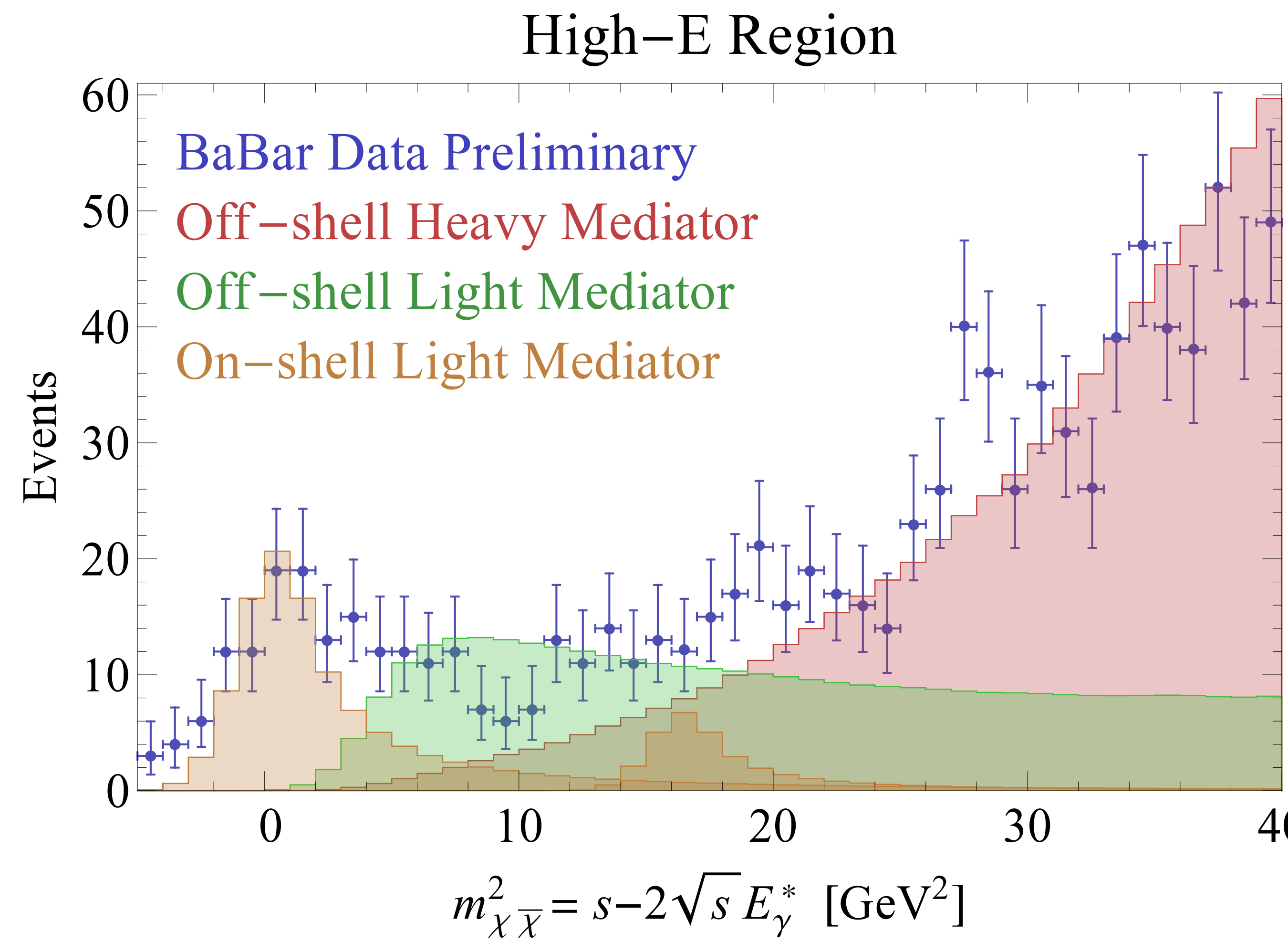
Beam Dump Production

Missing Energy/Momentum

B-Factories

"Traditional" mono-photon
+missing energy search





$$m^2_{\chi\chi} = (p_\gamma - p_{e^+} - p_{e^-})^2$$

$$E_{\rm cm} \approx 10\,\mathrm{GeV}$$

$$\mathcal{L} \sim \mathcal{O}(10)\,\mathrm{ab}^{-1}$$

BABAR, BELLE-II, BES-III

See Christopher Hearty's talk

Izaguirre, GK, Schuster, Toro 1307.6554
Essig, Mardon, Papucci, Volansky Zhong 1309.5084

B-Factories

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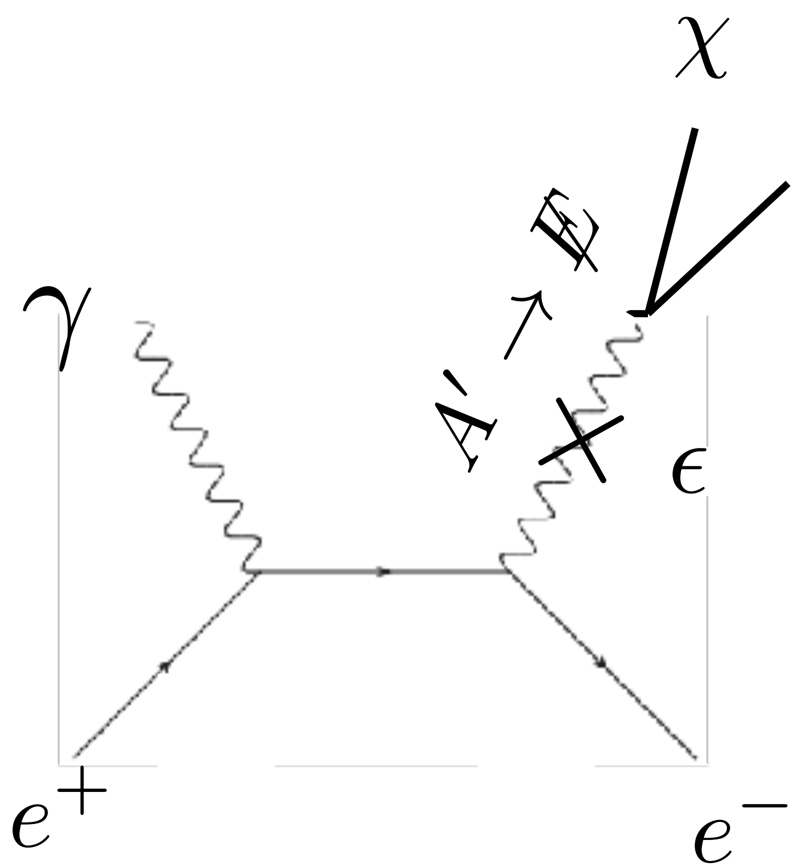
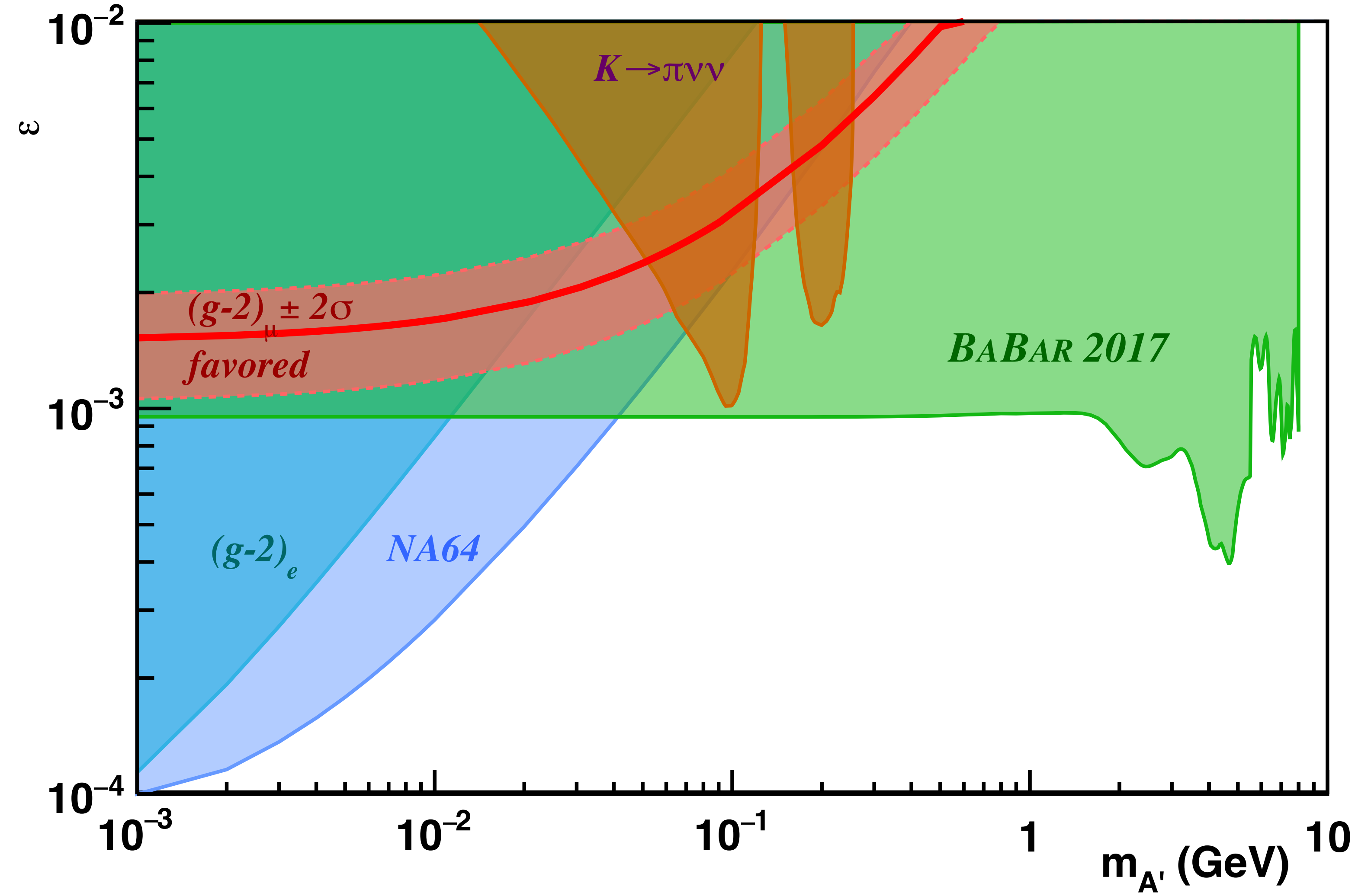


signal rate $\propto \epsilon^2$



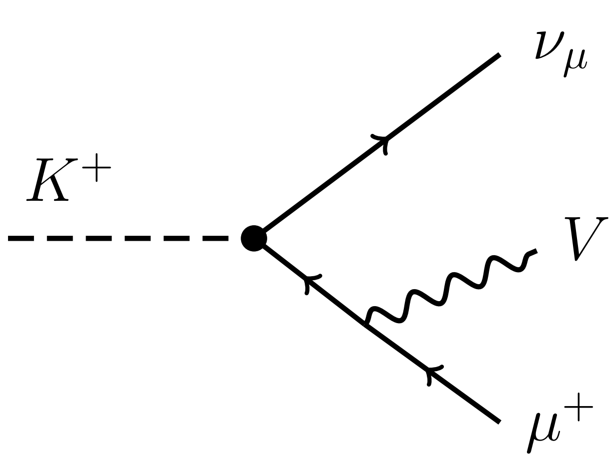
BaBar Collaboration 1702.03327

Izaguirre, GK, Schuster, Toro 1307.6554
Essig, Mardon, Papucci, Volansky Zhong 1309.5084

See Christopher Hearty's talk

Kaon Factories

Secondary kaon beam
Rare DM decays



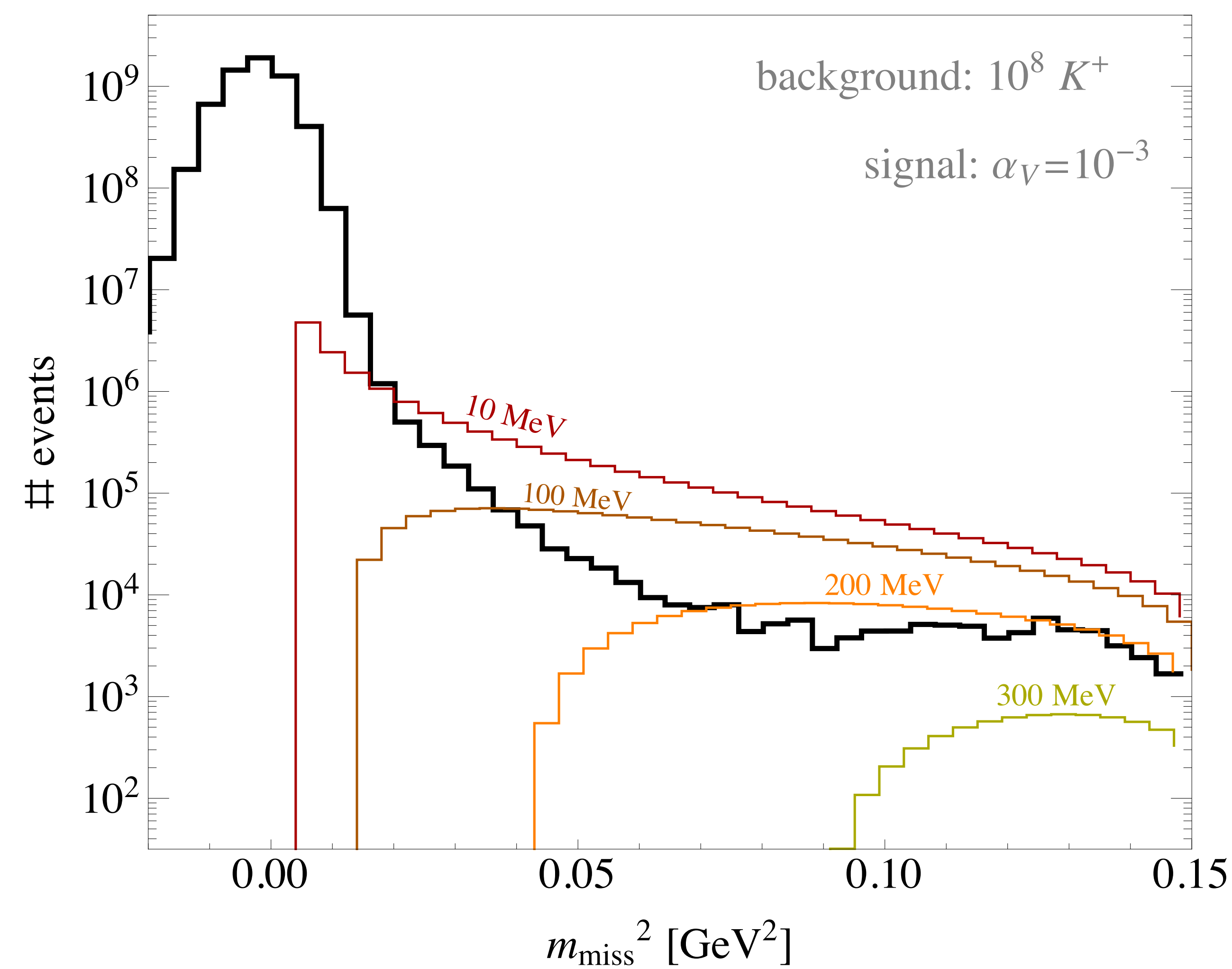
$$K^+ \to \mu^+ \nu_\mu V, \quad V \to \chi\chi$$

Kinematically distinct from main channel

Probe of muon, neutrino philic DM

Measure incident kaon, daughter muon

$$E_K \approx 75\,\text{GeV}, \quad N_K \sim 10^{13} \text{ proj.}$$



$$m^2_{\text{miss}} \equiv (p_K - p_\mu)^2$$

$$\text{signal rate} \propto \epsilon^2$$

GK, Marques-Tavares, Redigolo, Tobioka 1902.07715

See Diego Redigolo's talk

Kaon Factories

Secondary kaon beam
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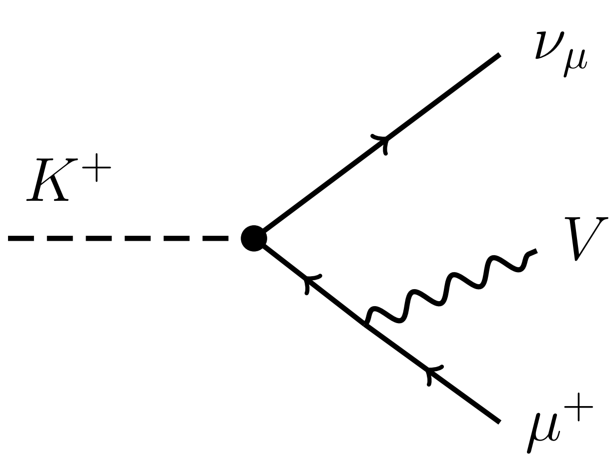

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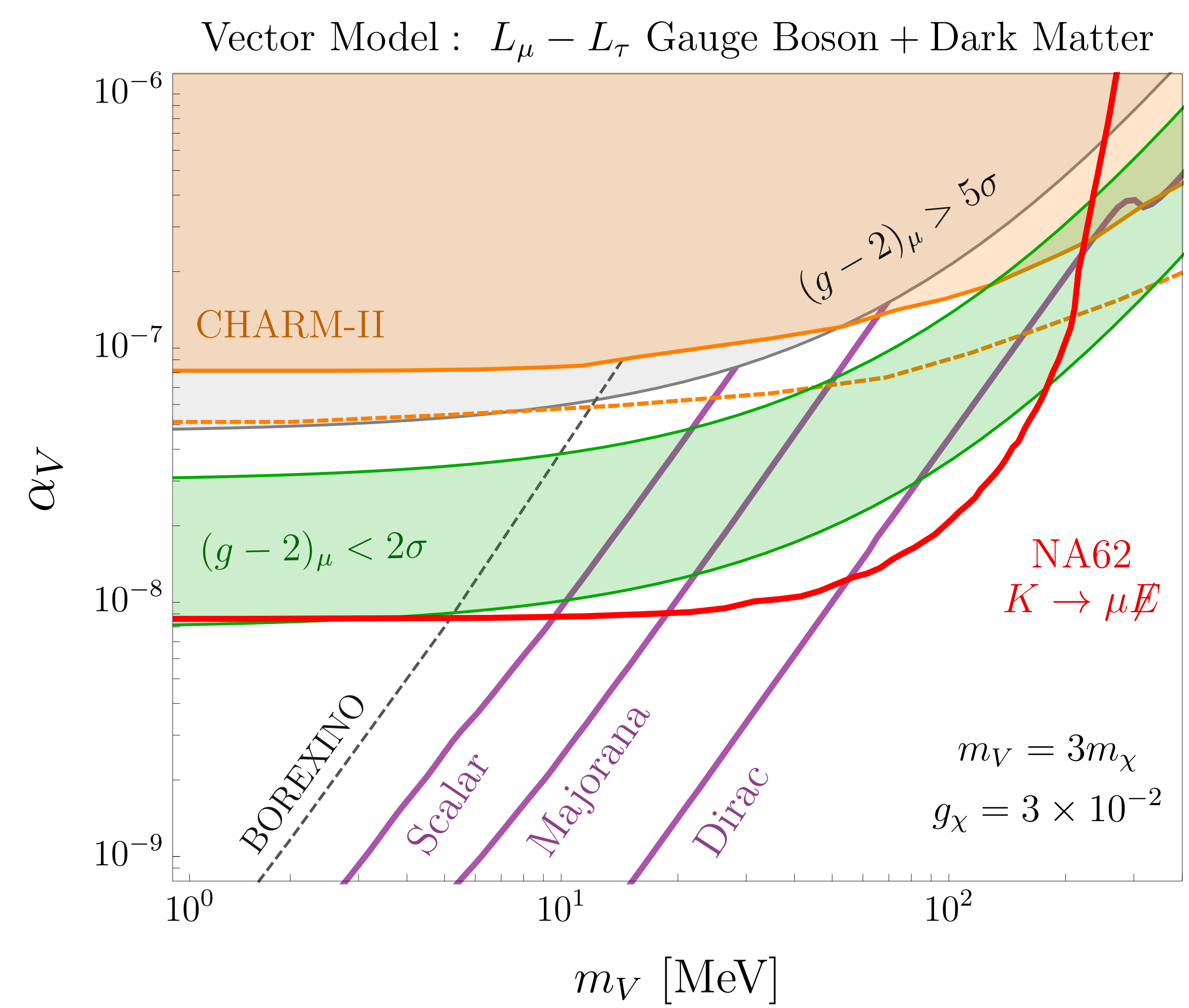
GK, Marques-Tavares, Redigolo, Tobioka 1902.07715



$$\text{signal rate} \propto \epsilon^2$$

See Diego Redigolo's talk

Overview

Preliminaries

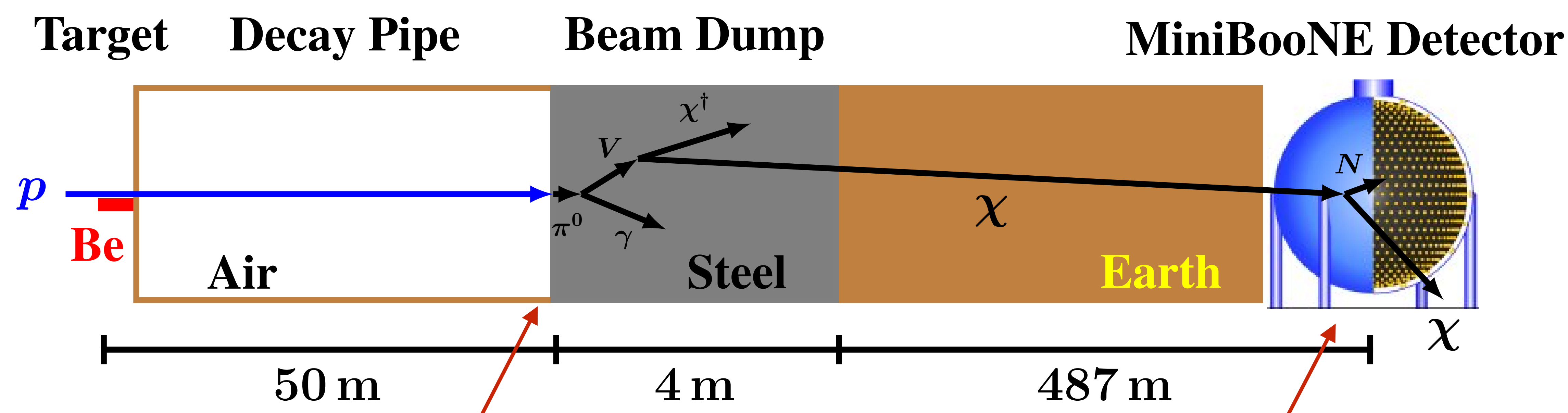
B/K-Factories

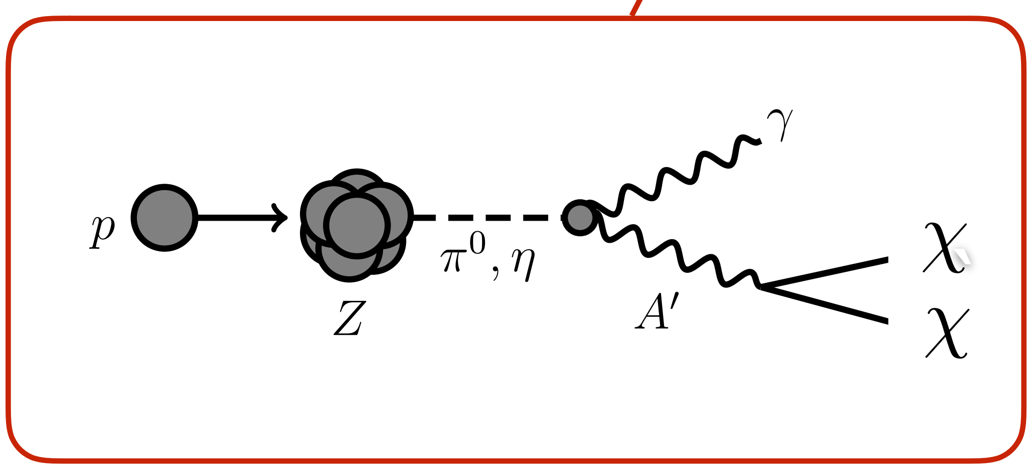
Beam Dump Production

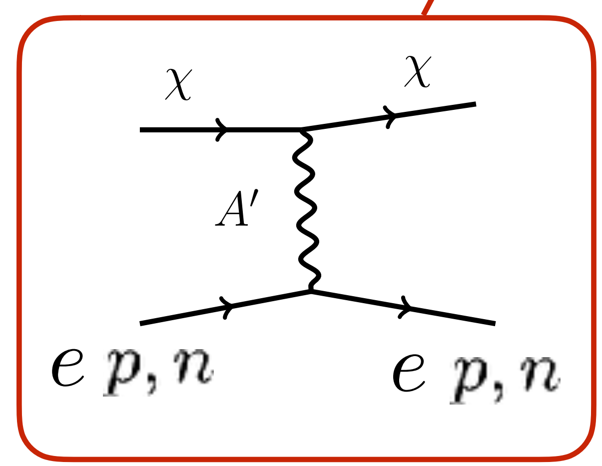
Observable: energy deposited in downstream detector

Missing Energy/Momentum

Proton Beam Dumps







Meson decay DIS
Proton bremsstrahlung

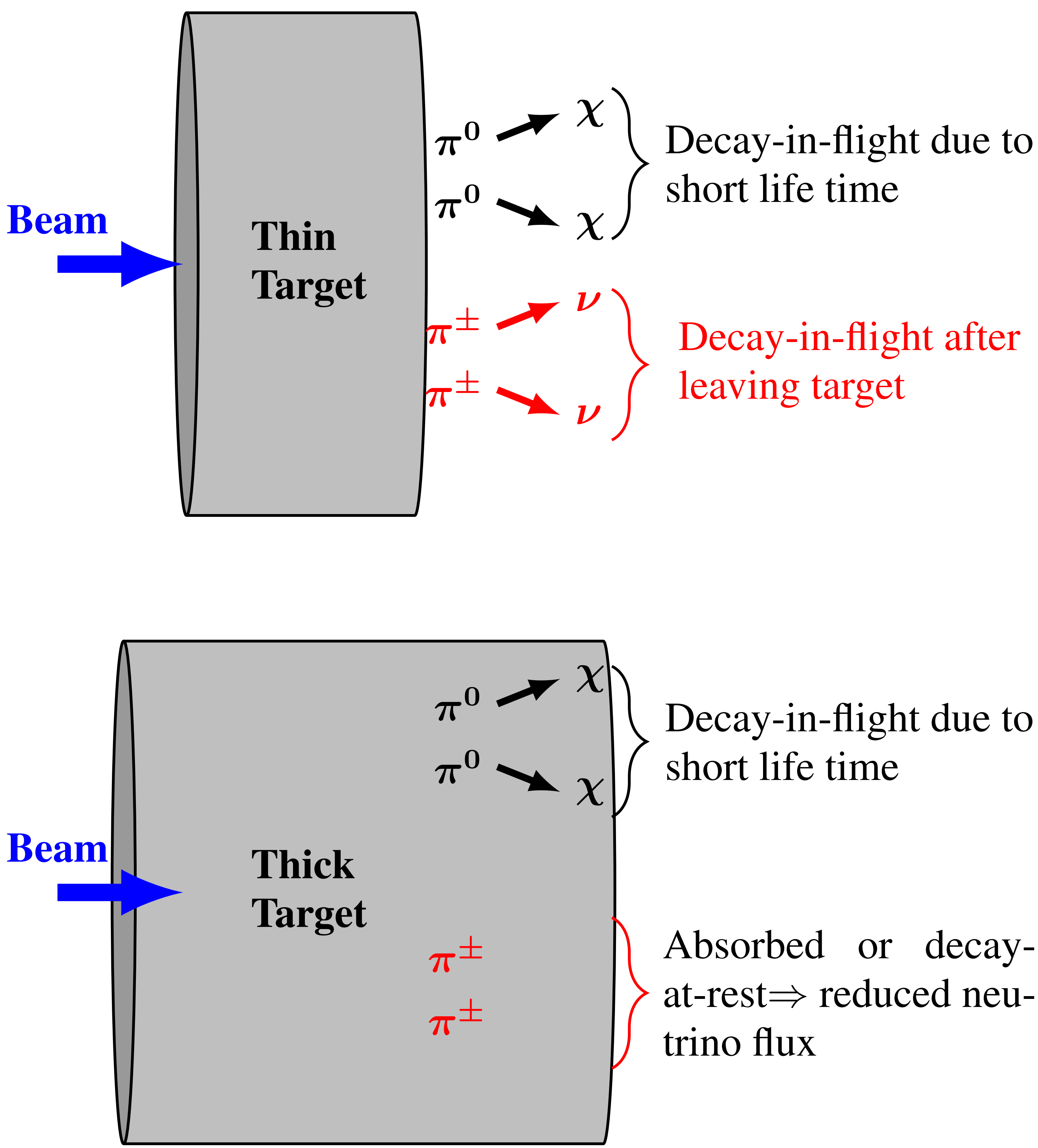
$$[\text{production}] \times [\text{detection}] \propto \epsilon^4$$

$E_p \sim 1 - 100\text{s GeV}$

$N_{\text{POT}}\ 10^{20} - 10^{24}$

Batell, Pospelov, Ritz 0903.0363
deNiverville, Pospelov, Ritz 1107.4580
Batell, deNiverville, McKeen, Pospelov, Ritz 1405.7049
Coloma, Dobrescu, Frugiuele, Harnik 1512.03852
Frugiuele 1701.05464

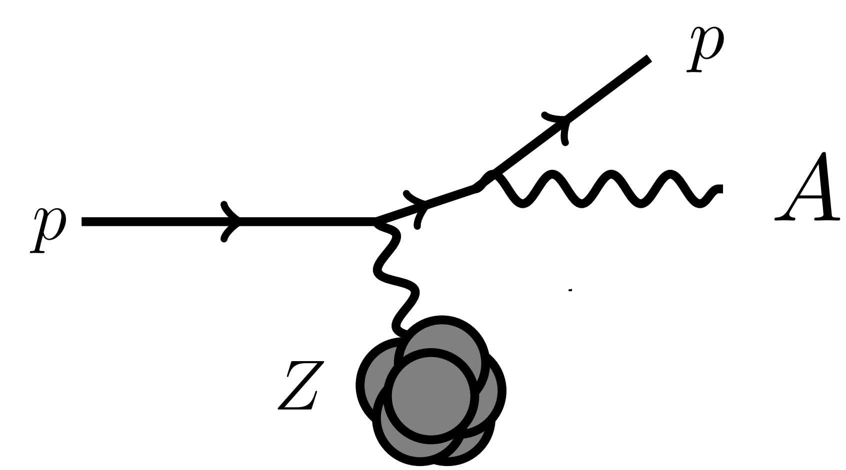
Neutrino Mode vs. Beam Dump Mode



MiniBooNE Collaboration arXiv1807.06137

Continuum production

Similar in both modes



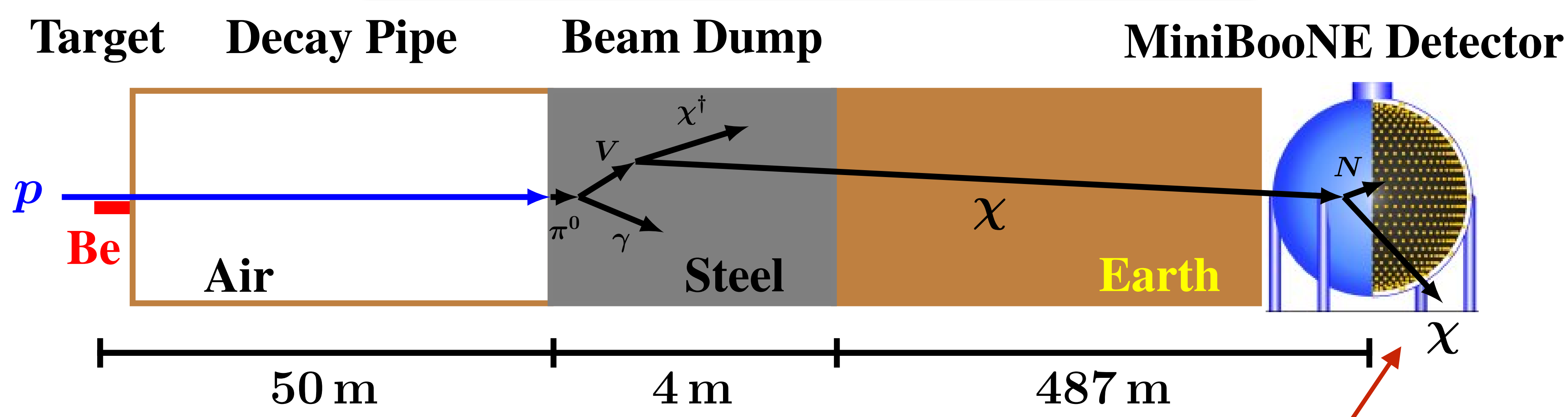
Uses full beam energy

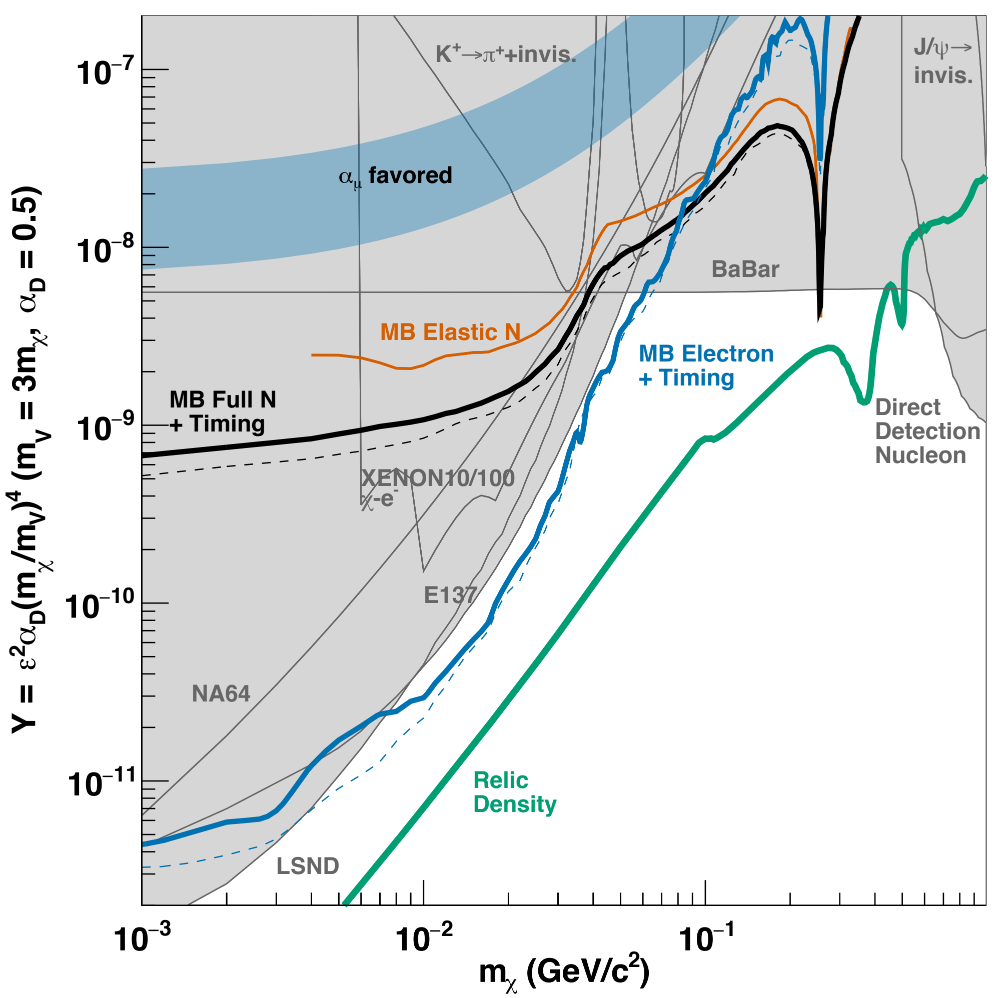
Important for heavy X

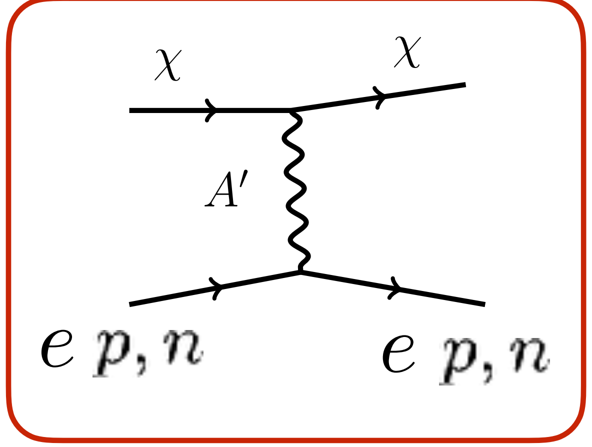
Thickness irrelevant

if greater than rad. length

Proton Beam Dumps





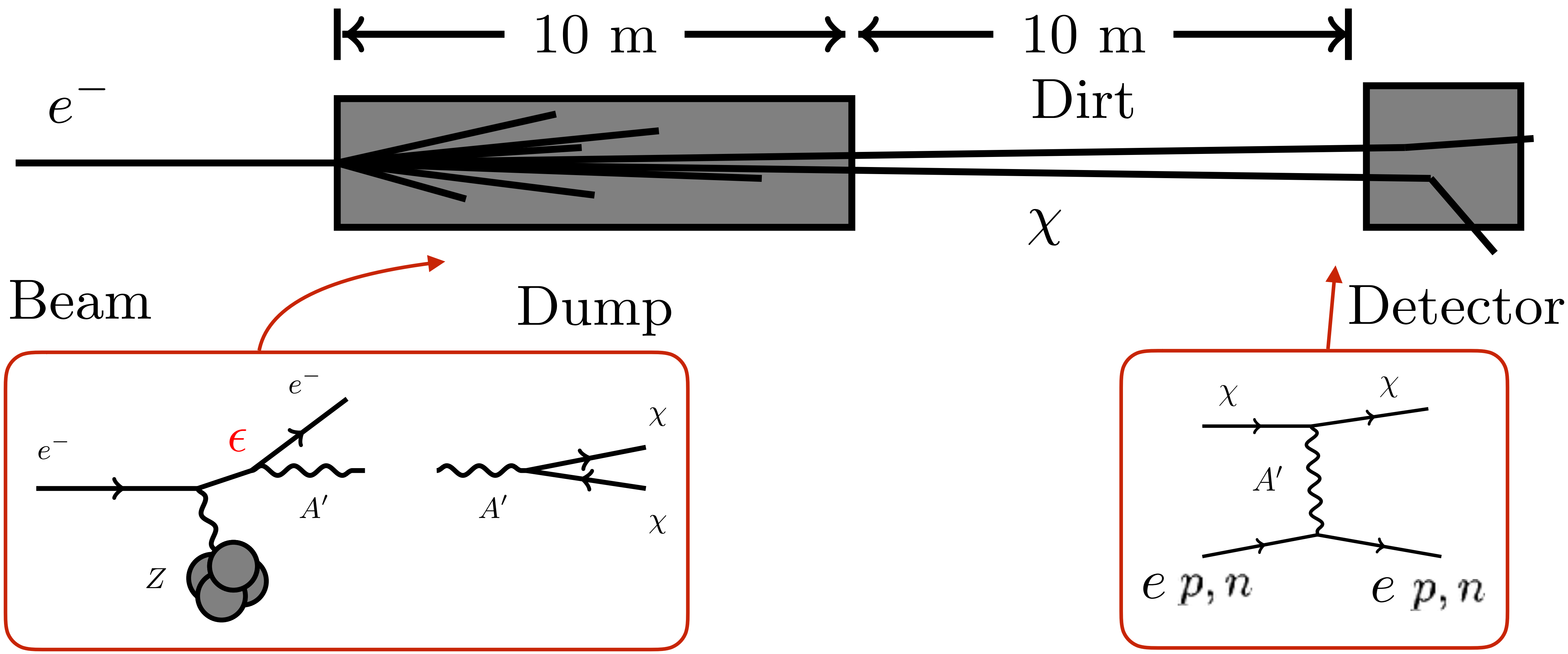


Also LSND, DUNE, SBND, CCM

See Brian Batell's talk

MiniBooNE, Phys. Rev. Lett. 118 (2017) and 1807.06137

Electron Beam Dumps



$E_{\rm beam} \sim 10\,{\rm GeV} \quad N_e \sim 10^{22}/{\rm yr} \qquad [{\rm production}] \times [{\rm detection}] \propto \epsilon^4$

All neutrino BG EW produced, lower than p-beams

Can run "parasitically" at existing facilities. Experiments: **E137, BDX**

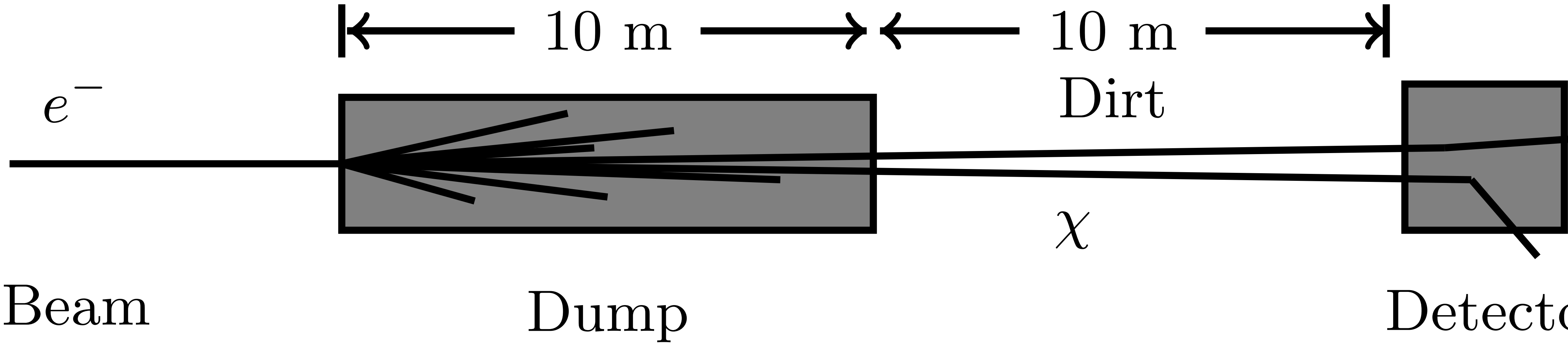
See Marco Battaglieri's talk

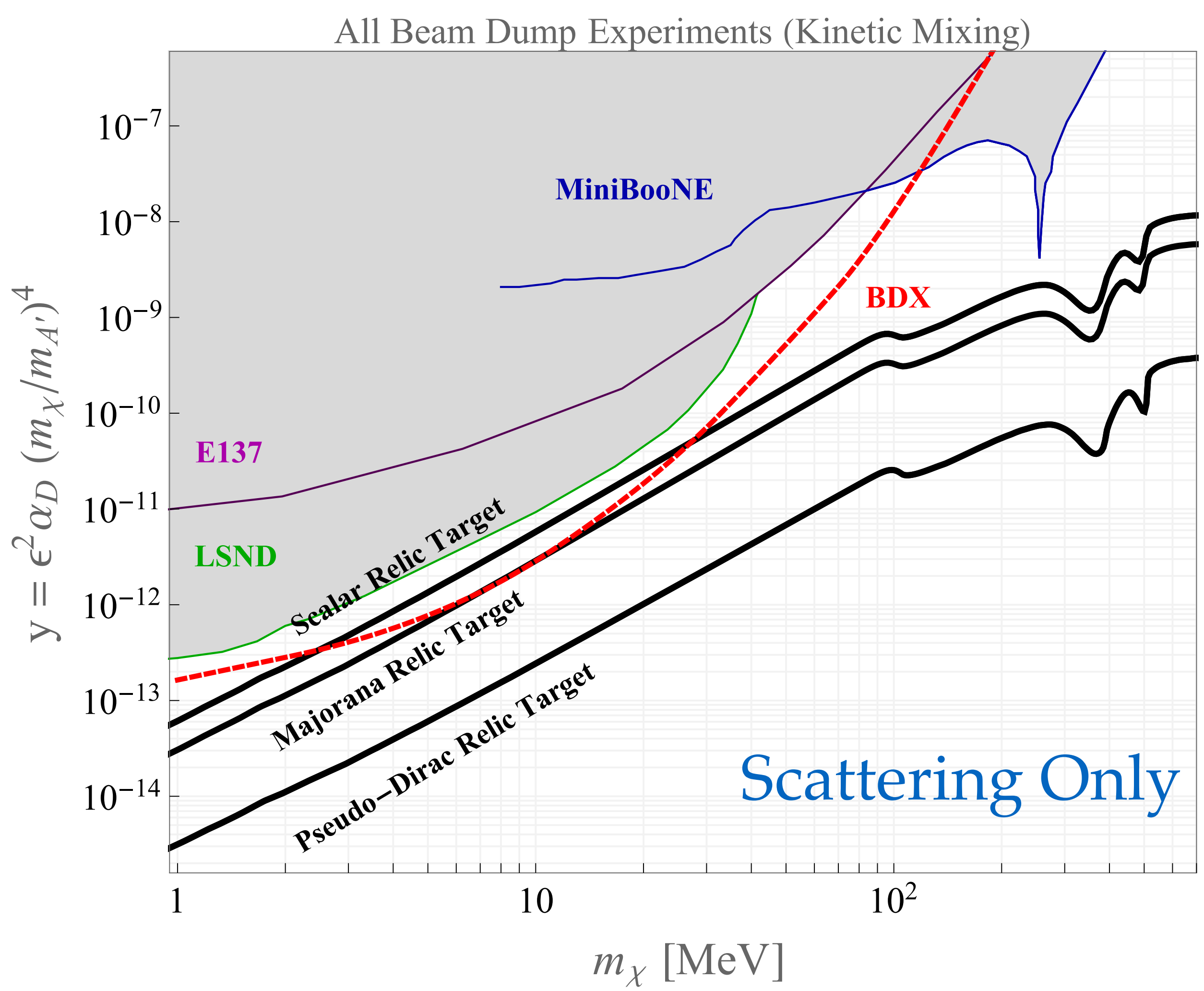
Izaguirre, GK, Schuster, Toro 1307.6554

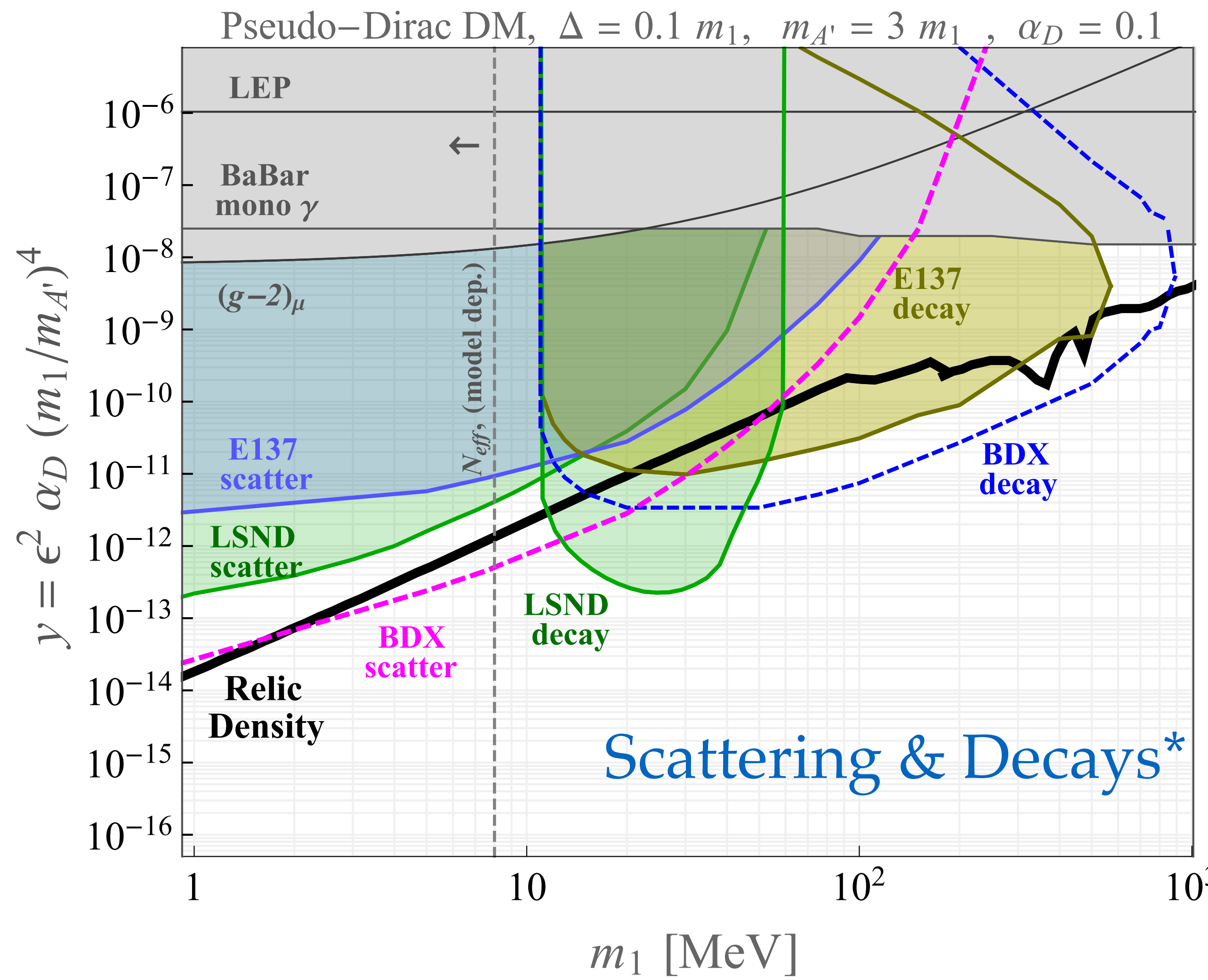
Batell, Essig, Surjuron 1406.2698

BDX Collaboration arXiv:1607.01390

Electron Beam Dumps





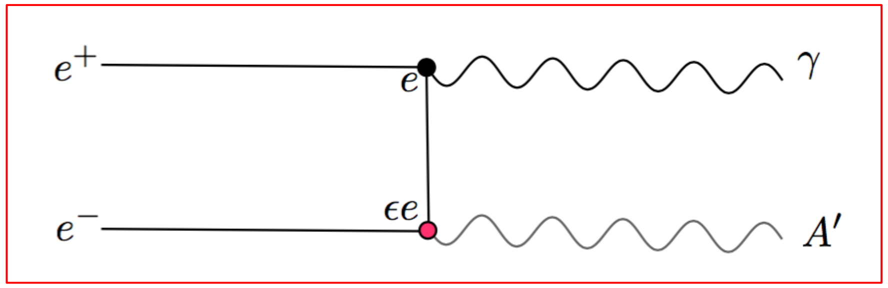


***See Asher Berlin's talk**

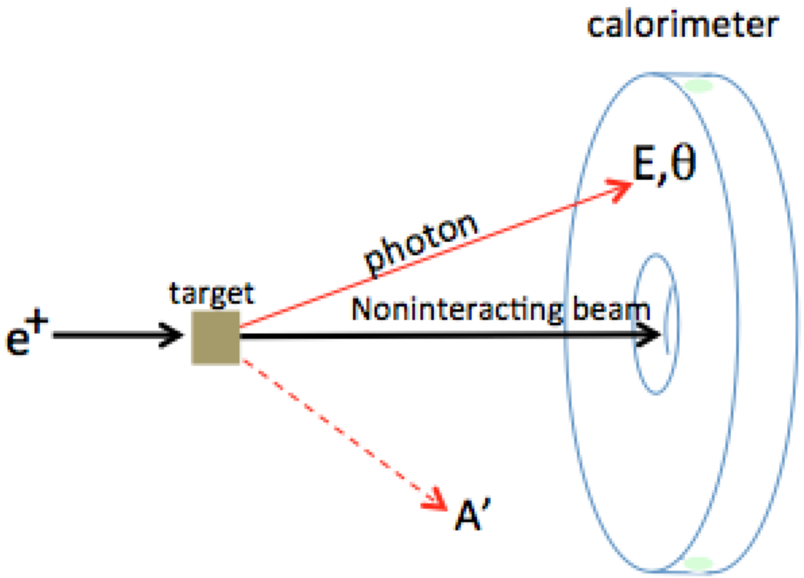
Izaguirre, Kahn, GK, Moschella 1703.06881

Positron Beam Dump

Process of interest:



Hardware:



- E_{beam} = 1.8 -- 5.3 GeV
- I_{beam} ~ 2.3 nA at target
- quasi-CW during ~millisecond spills @ 60H:
- pulse structure: 168ns

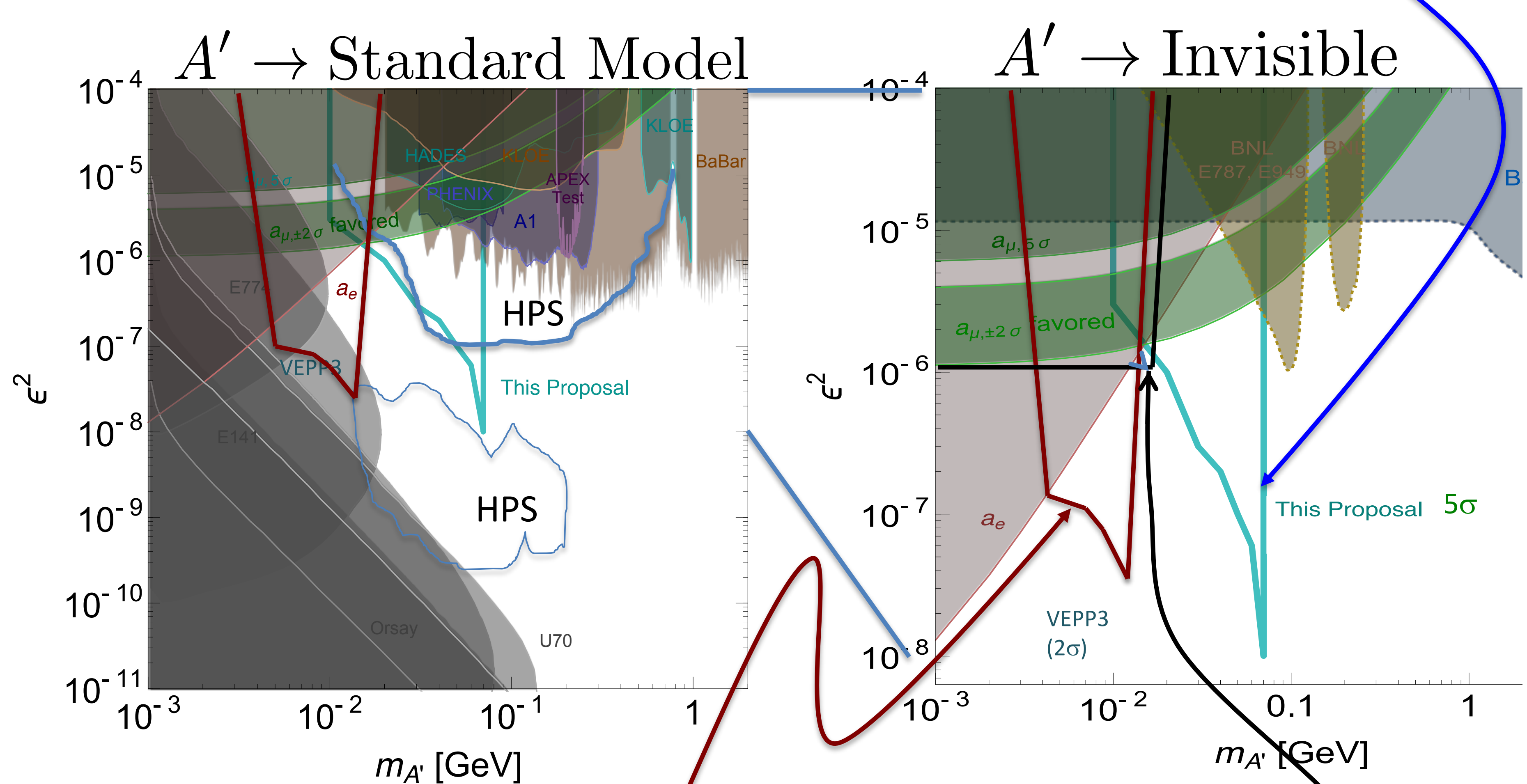
Fixed target, calorimeter 10m downstream.

Slide: Jim Alexander

Positron Beam Dump

Based on GEANT4 simulation with all bkgs and pileup included

E_{beam}=5.3GeV, I^{avg}_{beam}=2.3nA, Lumi = 1.0x10^{34}, T = 10^7sec, 5-sigma excl



Novosibirsk (proposed)

PADME @ Frascati (proposed)

Warning old plot

Source: Jim Alexander

Overview

Preliminaries

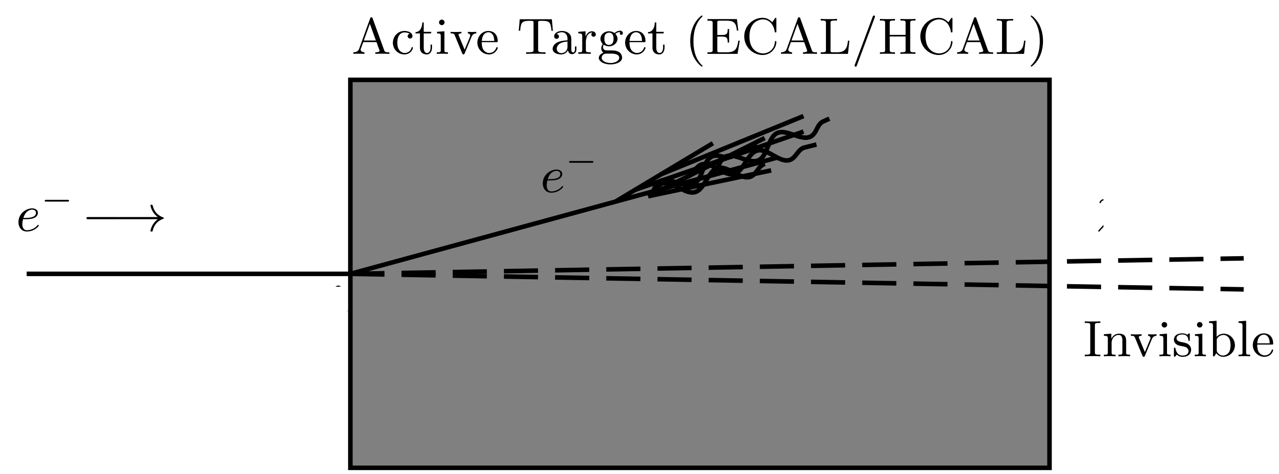
B-Factories (e+e- colliders)

Beam Dump Production

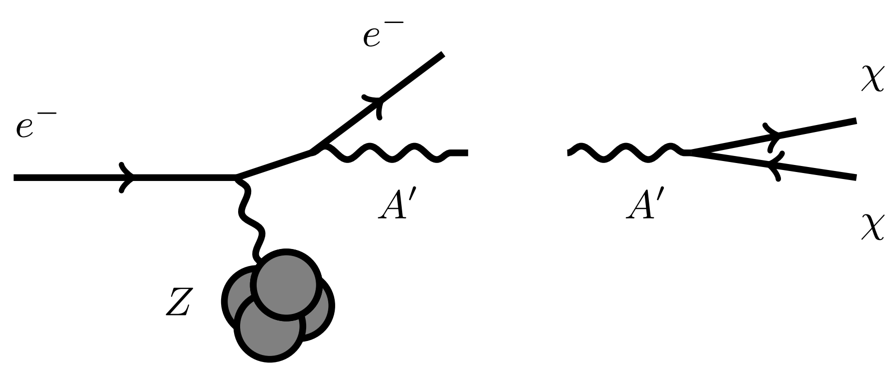
Missing Energy/Momentum

Observable: beam energy loss + no other SM activity

Electron / Muon Missing Energy



Deliver electron beam to thick (>> X0) ECAL target



$E_e \sim 100\,\mathrm{GeV}, N_e \sim 10^{12}$

1) Measure **each** e- energy in target

2) Trigger on 50% missing energy

3) Veto additional SM activity

Only measure electron beam — don't require DM to scatter

Signal $\propto \epsilon^2$

Andreas et. al. 1312.3309

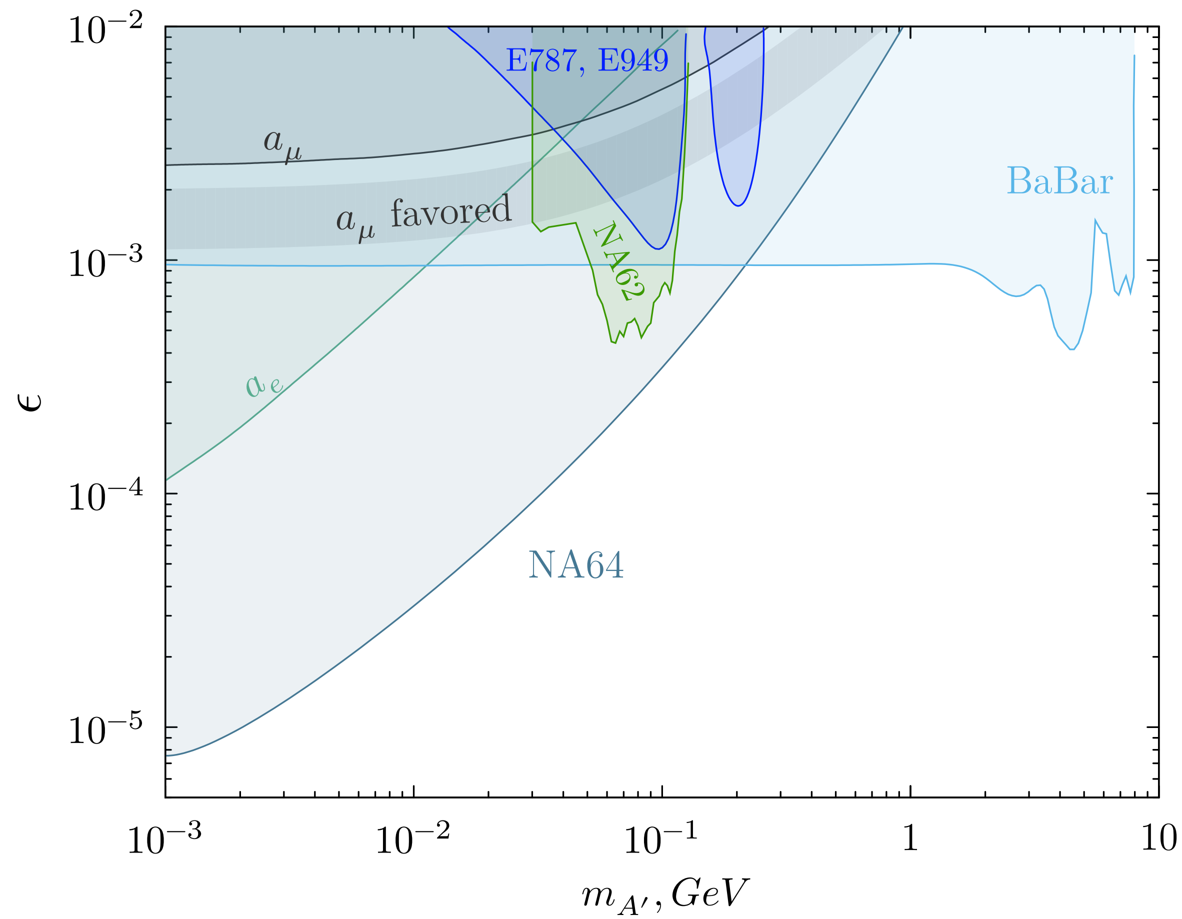
NA64 Collaboration 1906.00176

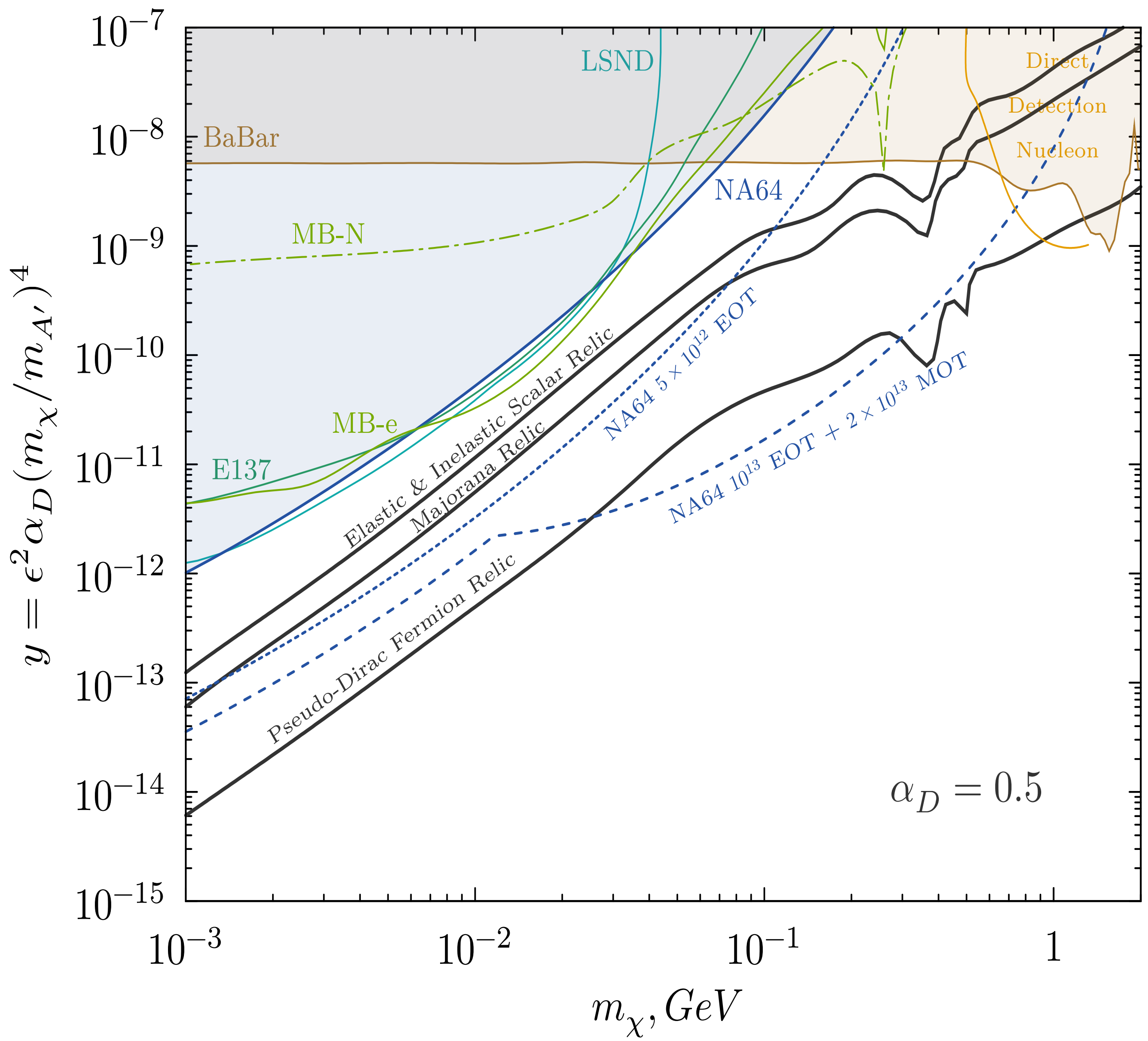
Gninenko, Krasnikov, Mateev 2003.07257

(see Tim Nelson's talk)

Electron / Muon Missing Energy

Thermal DM interpretation





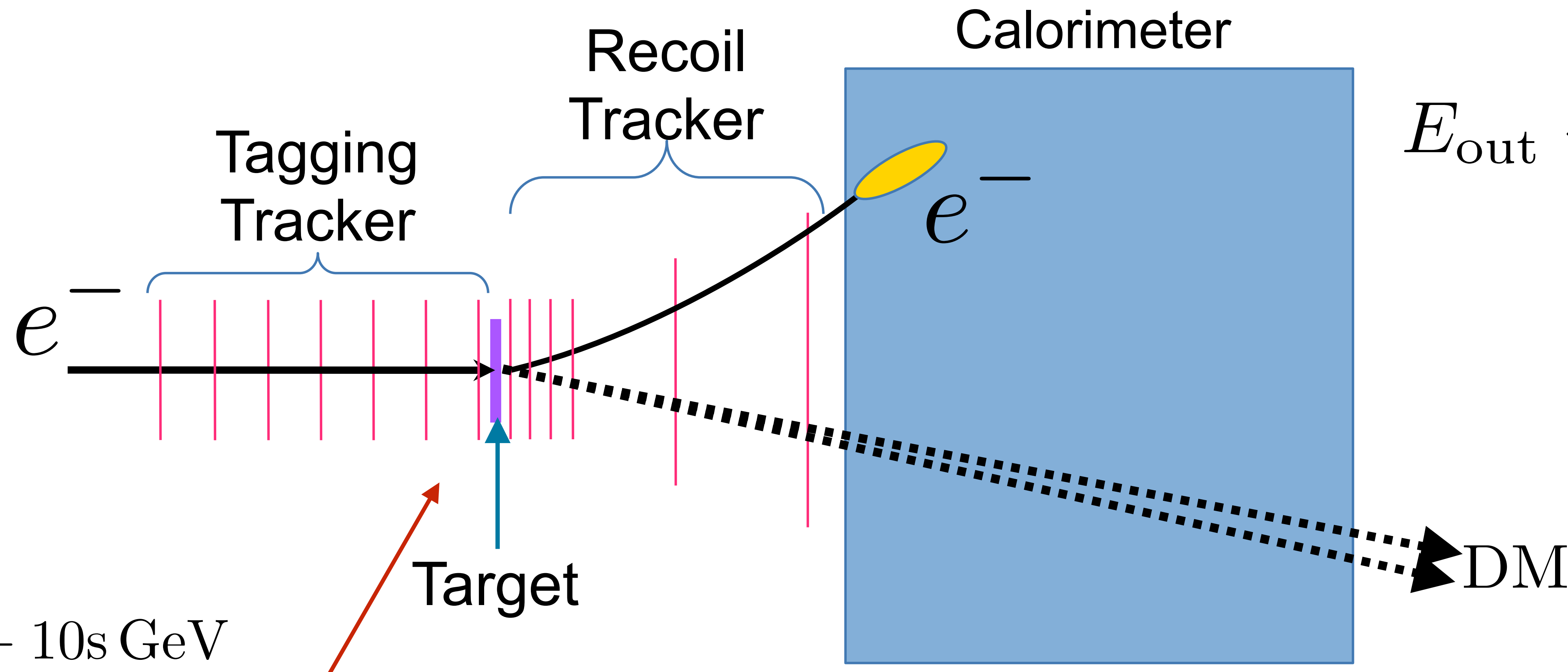
Invisibly decaying A'

NA64 currently running @ CERN

Andreas et. al. 1312.3309
NA64 Collaboration 1906.00176
Gninenko, Krasnikov, Mateev 2003.07257

(see Tim Nelson's talk)

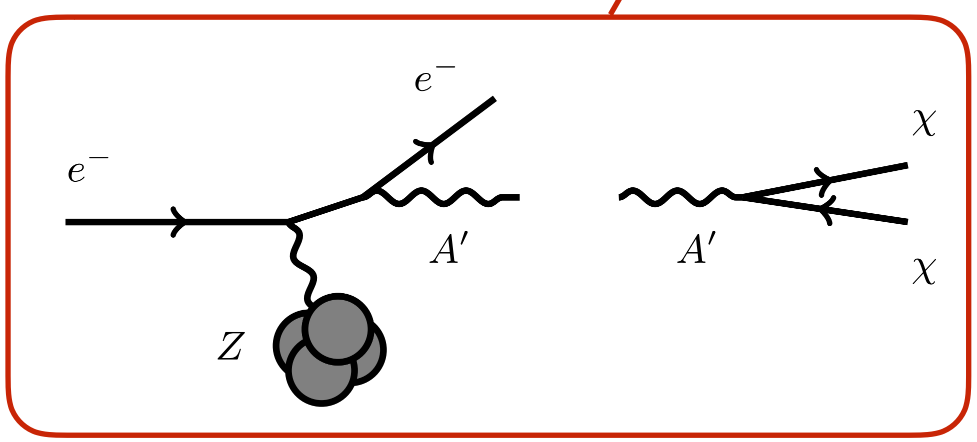
Electron Missing Momentum



$E_{\text{out}} \ll E_{\text{in}}$

$N_e \sim 10^{16}$

$E_e \sim \text{few} - 10\text{s GeV}$



1) Measure **each** e- energy in/out

2) Trigger on missing momentum

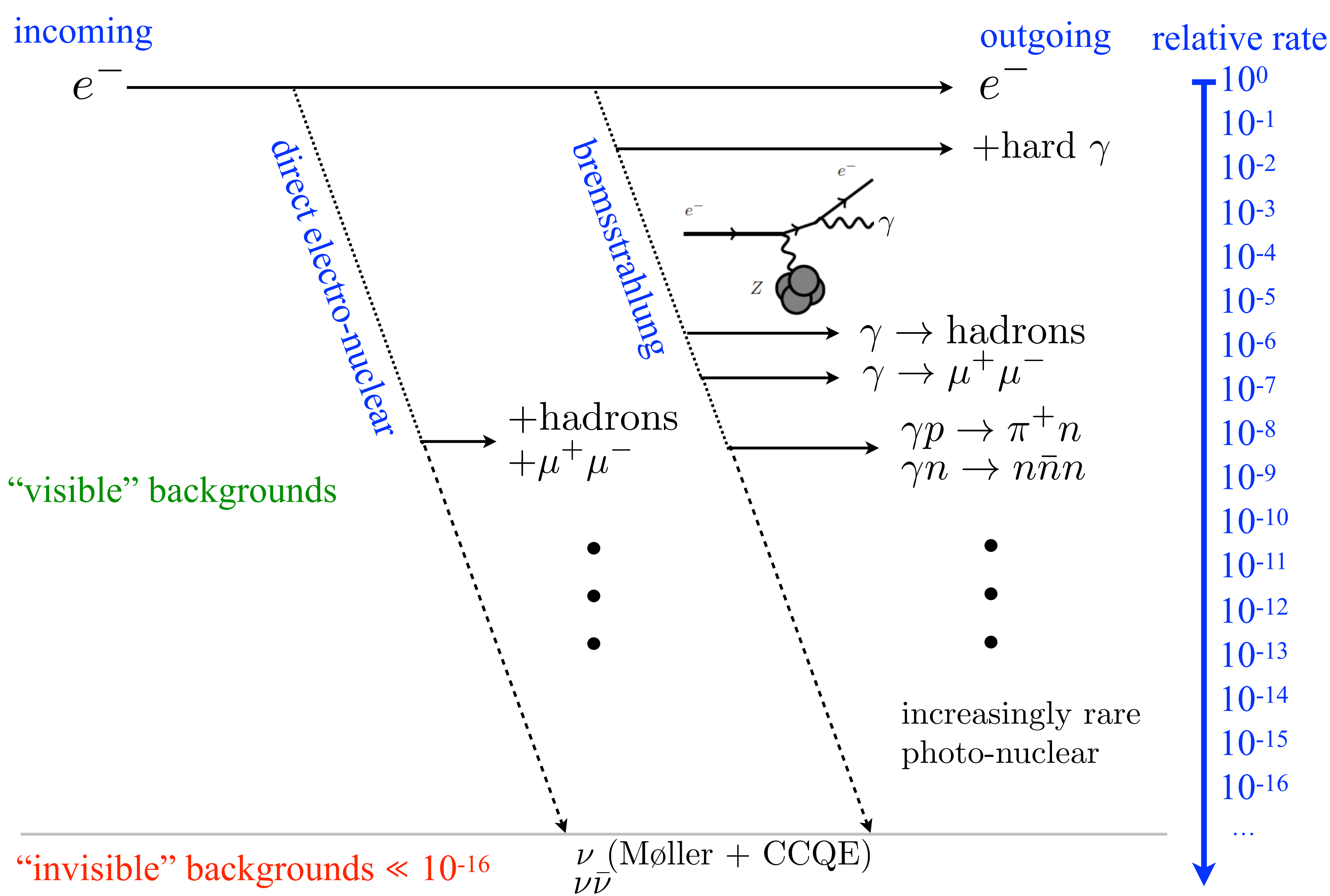
3) Veto additional SM activity

Only measure electron beam — don't require DM to scatter
Signal $\propto \epsilon^2$

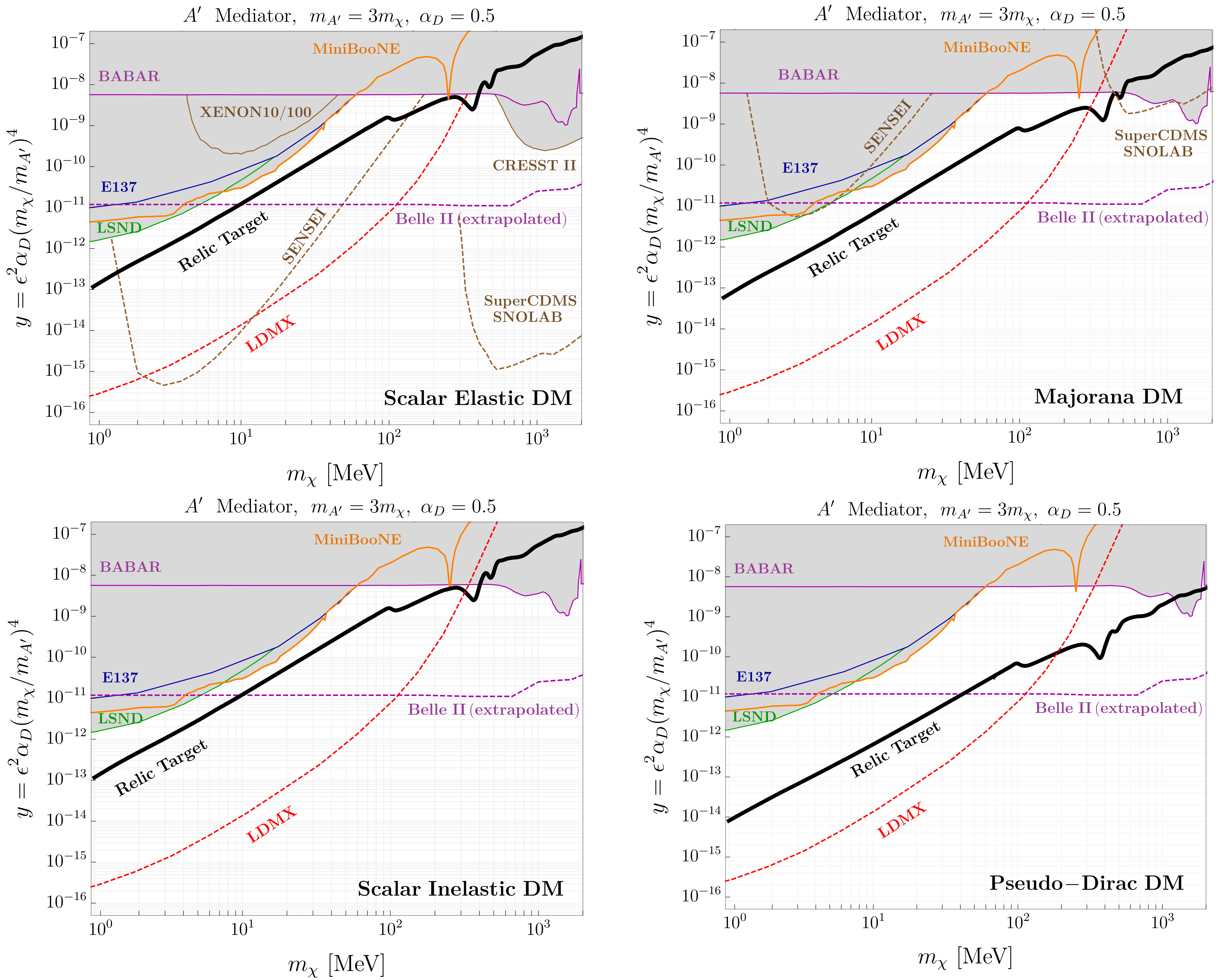
Izaguirre, GK, Schuster, Toro arXiv:1411.1404
LDMX Collaboration 1808.05219

(see Tim Nelson's talk)

Backgrounds per incident electron



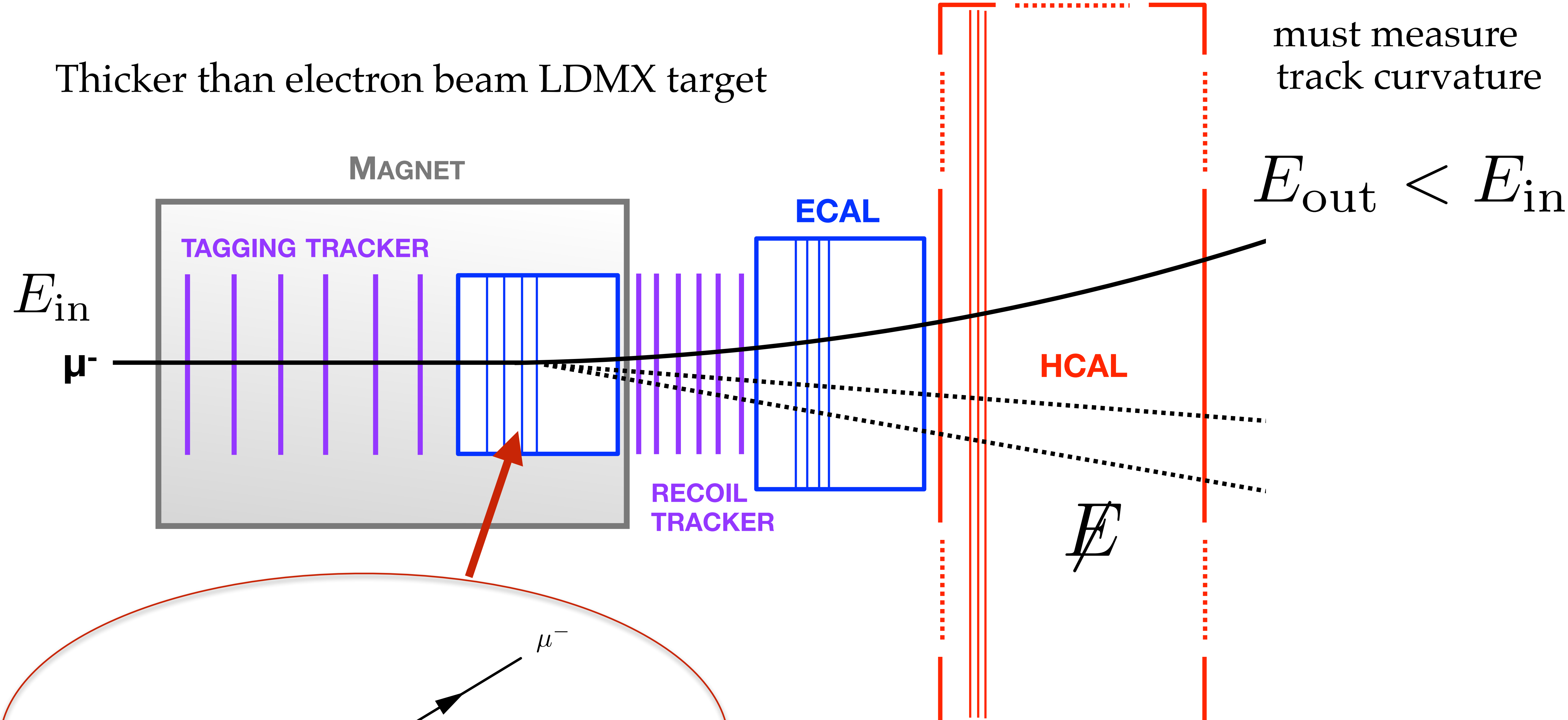
LDMX 1808.05219

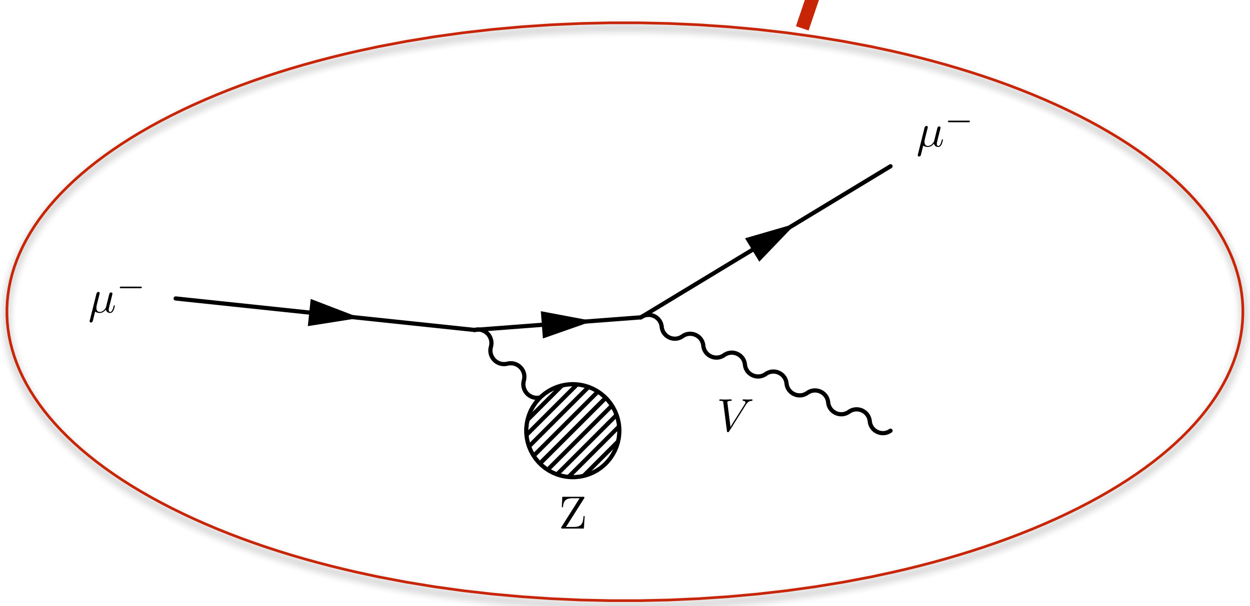


see Tim Nelson's talk

Berlin, Blinov GK, Schuster, Toro arXiv: 1807.01730

Muon Missing Momentum

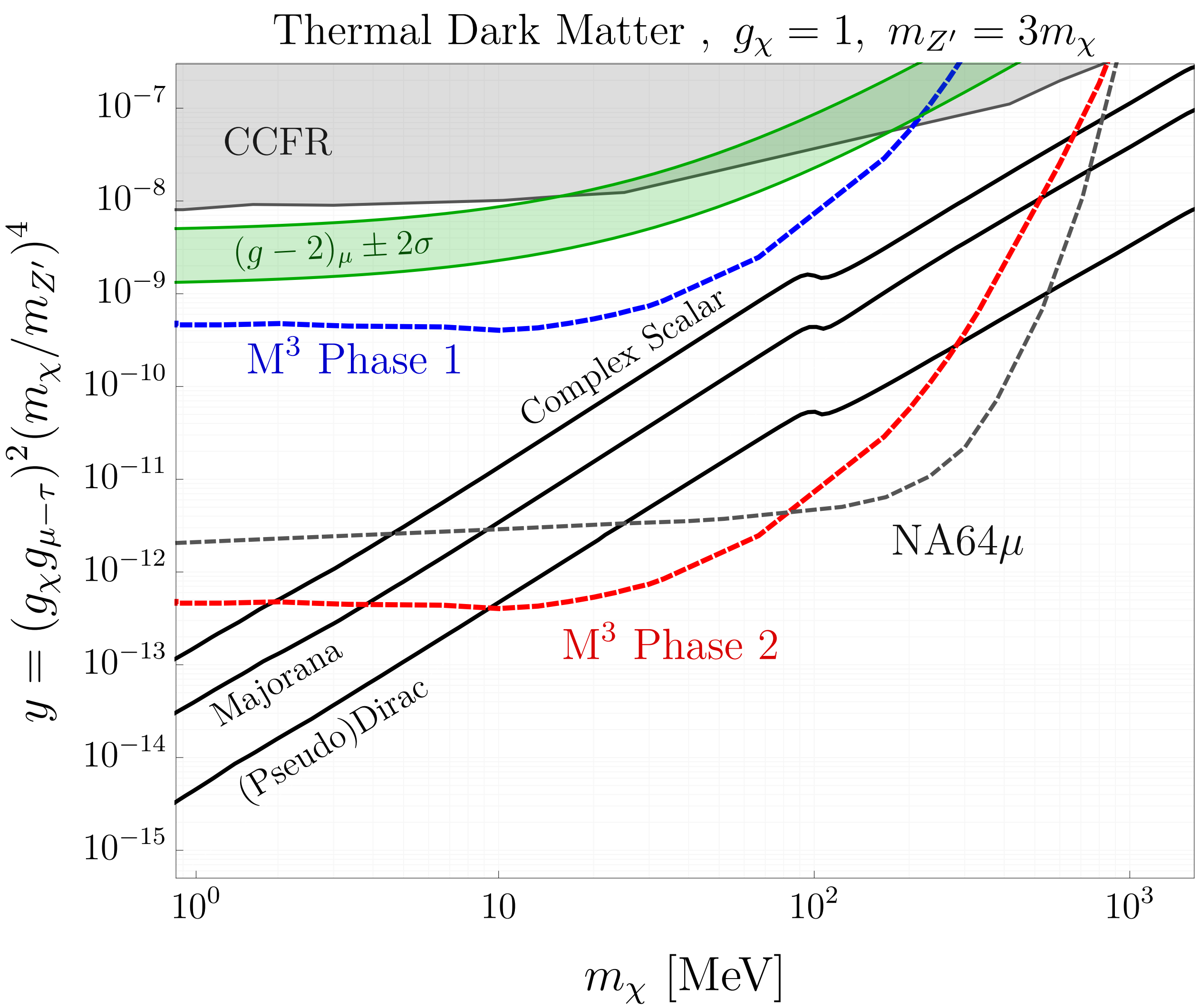


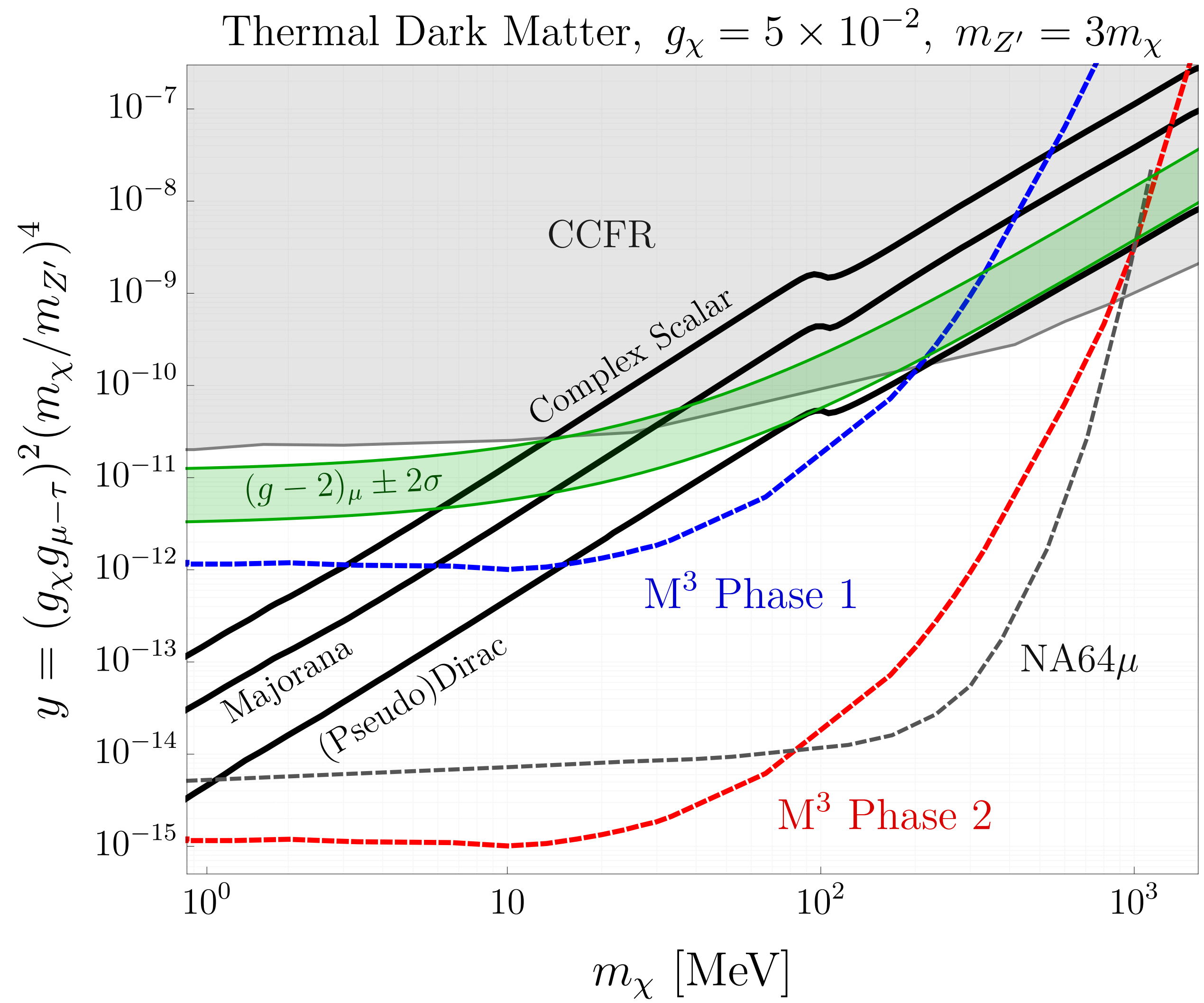


1) Measure E in/out with B field
2) Trigger on missing energy
3) Veto additional SM activity

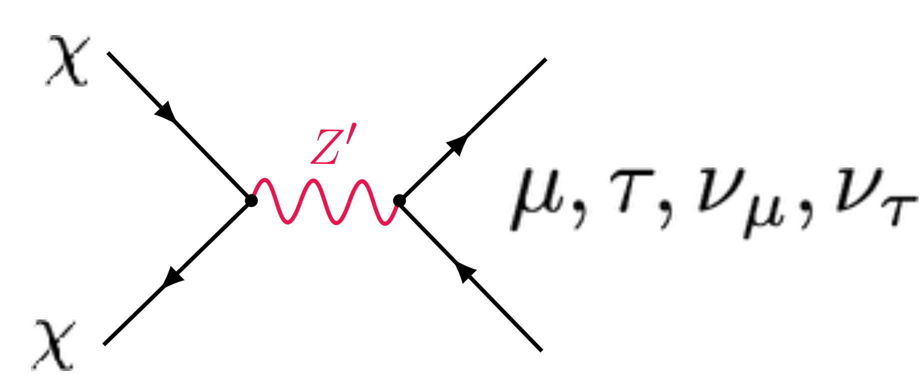
Kahn, GK, Tran, Whitbeck 1804.03144 (JHEP 2018)

Comparing Muon Beams: NA64μ and M^3





Gauged $L_\mu - L_\tau$ Interaction



Also resolve muon g-2 with light physics

Compatible parameter space for freeze-out

See Nhan Tran's talk

New Frontier of DM Searches: Accelerators

$\text{MeV} \sim m_e$	$\text{GeV} \sim m_p$	$m_{Z,h}$	$\sim 10\text{s TeV}$

LDM	**"WIMPs"**
B/K Factories	**Direct Detection**
Beam Dumps	**Indirect Detection**
Missing Energy/Momentum	**Collider Production**

Mature program of searches covers broad range of < GeV DM

Calculable, controllable no astro uncertainties

Replicates kinematics of hot early universe

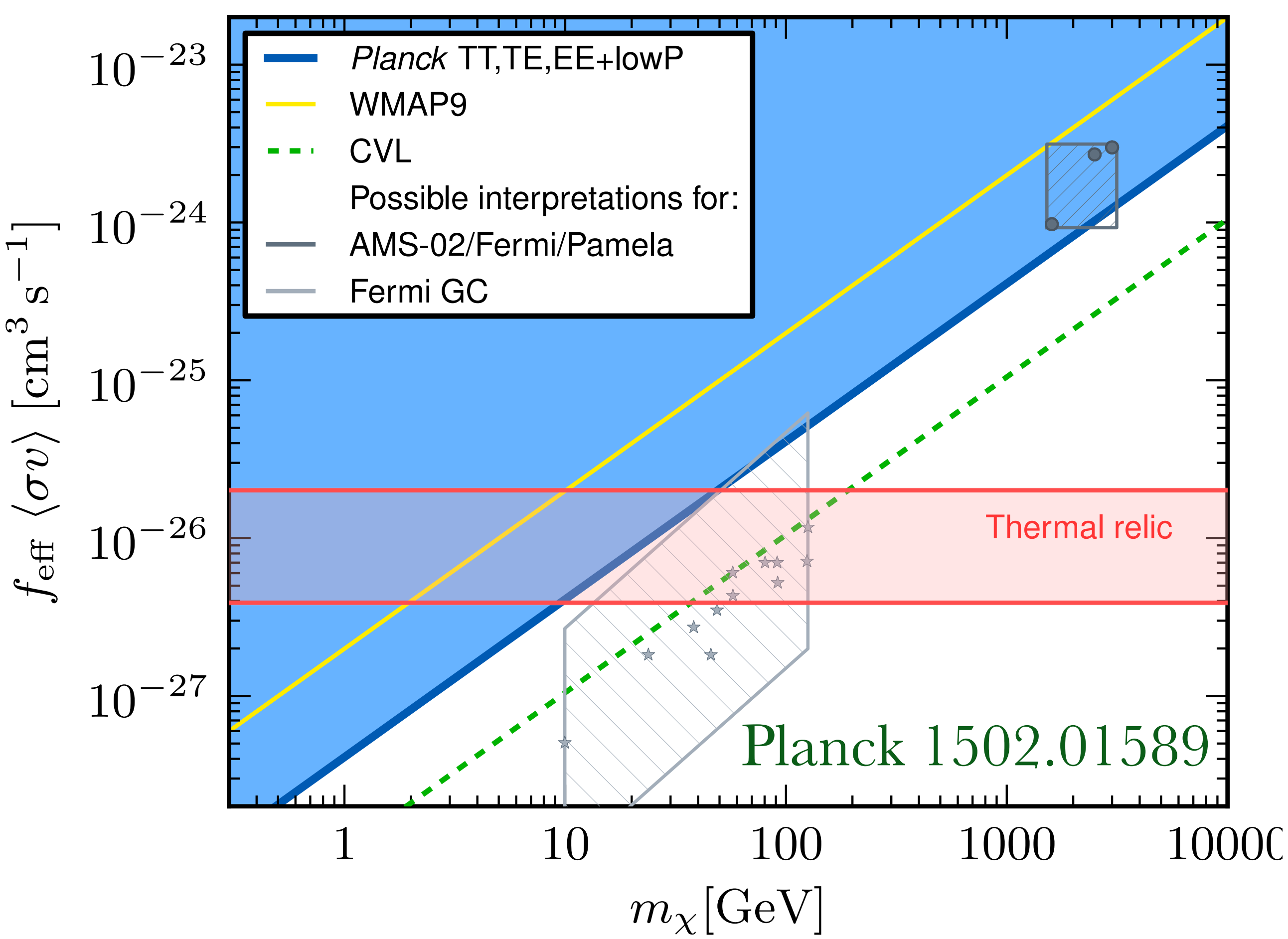
Test *nearly all* predictive DM models (density set by SM coupling)

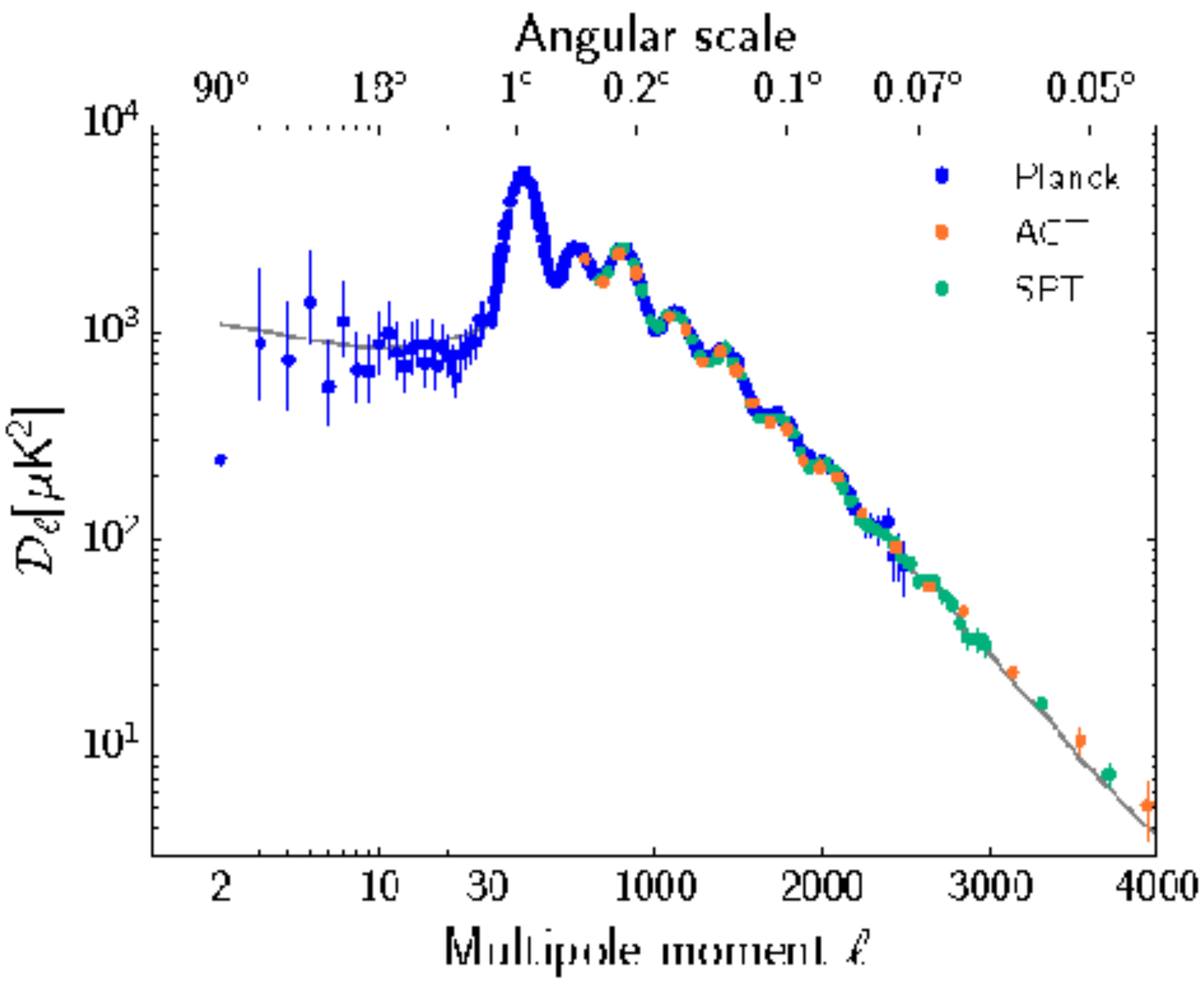
Also see 2019: DOE Basic Research Needs Report

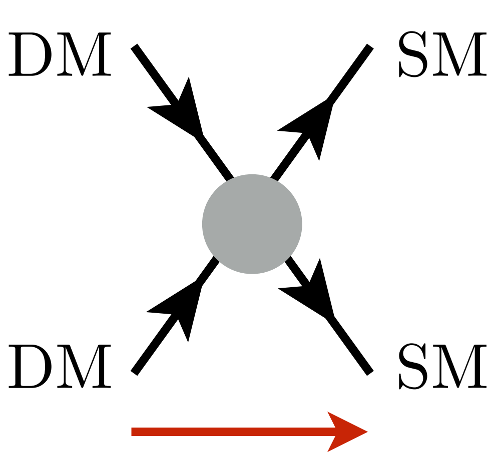
https://science.energy.gov/~/media/hep/pdf/Reports/201809_HEP-PI-BRN-Dark-Matter_New_Initiatives.pdf

Thanks!

What kind of DM? Use CMB to classify viable options







Rare out-of-equilibrium annihilation ionizes H (z=1100)

CMB photons pass through more plasma (modifies peaks)

Rules out s-wave relic cross section for DM < 10 GeV