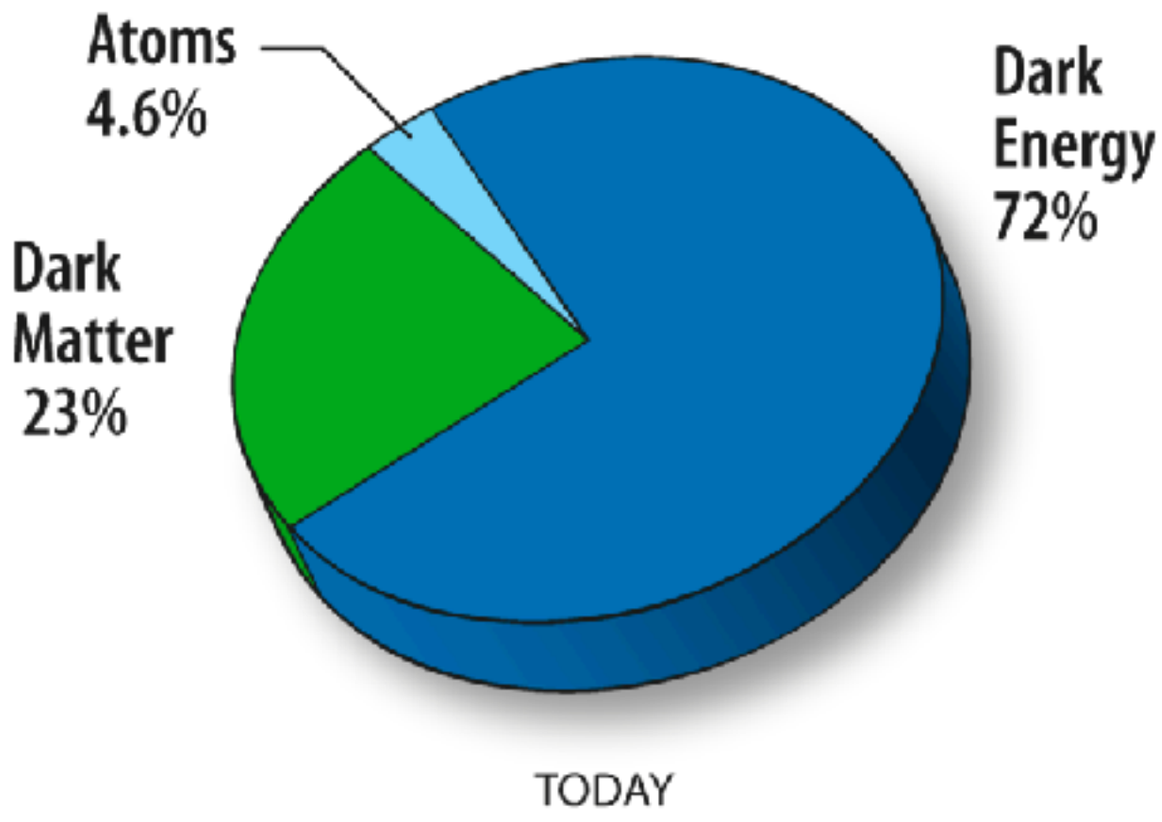
Dark Matter "Big Ideas"

Gordan Krnjaic

ACE Workshop, Fermilab, June 15, 2023

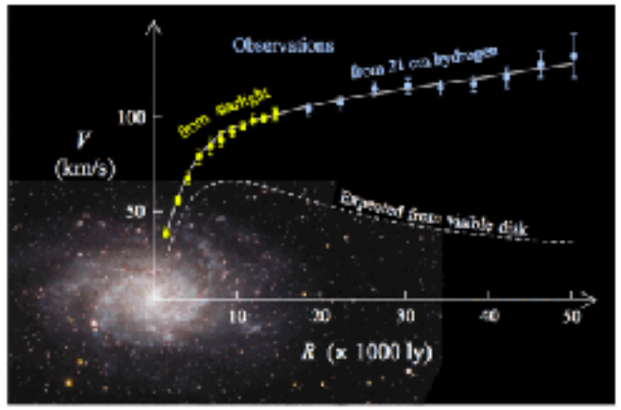
The Cosmic Inventory



What is **dark matter** and does it have **friends**?

*new forces, radiation, additional structure etc…

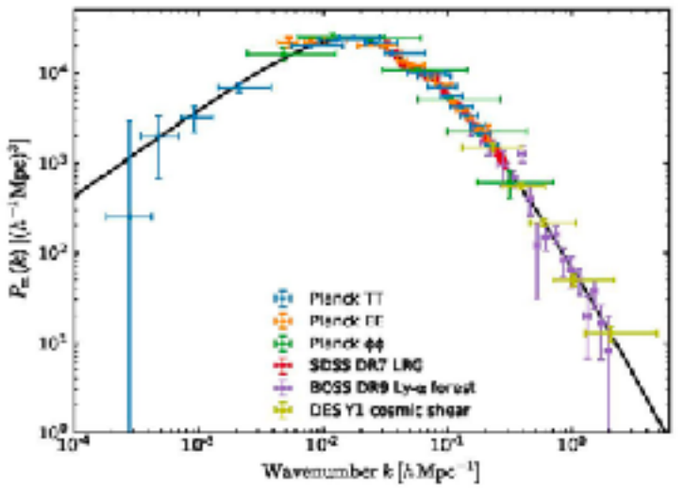
Remarkable Evidence for Dark Matter



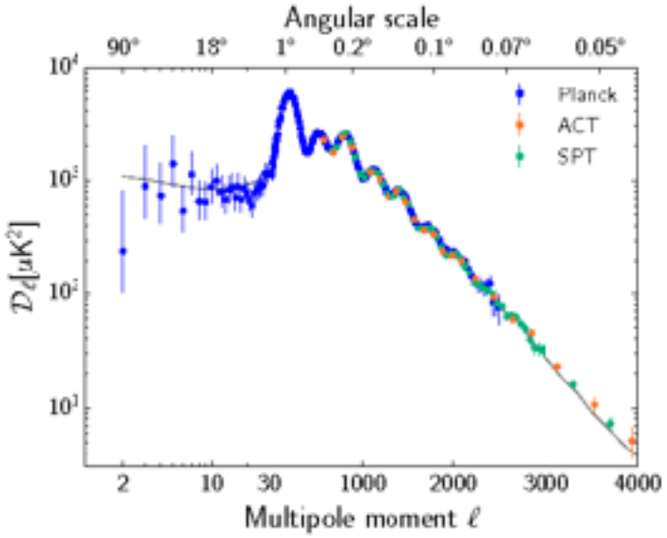
Rotation Curves

Gravitational Lensing

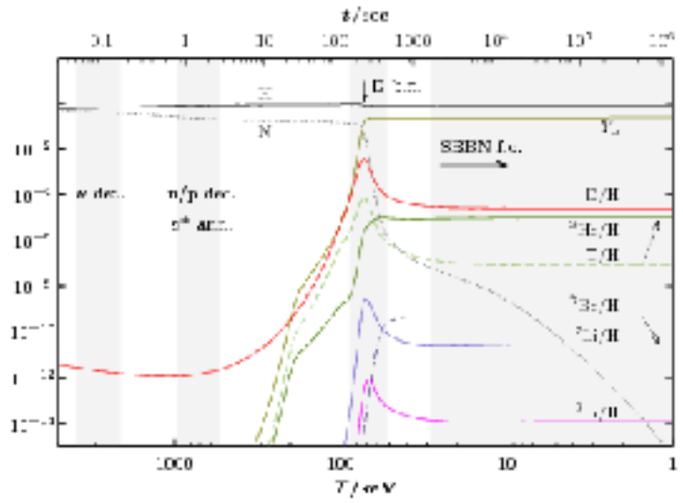
Cluster Collisions



Matter Power Spectrum



CMB Power Spectrum



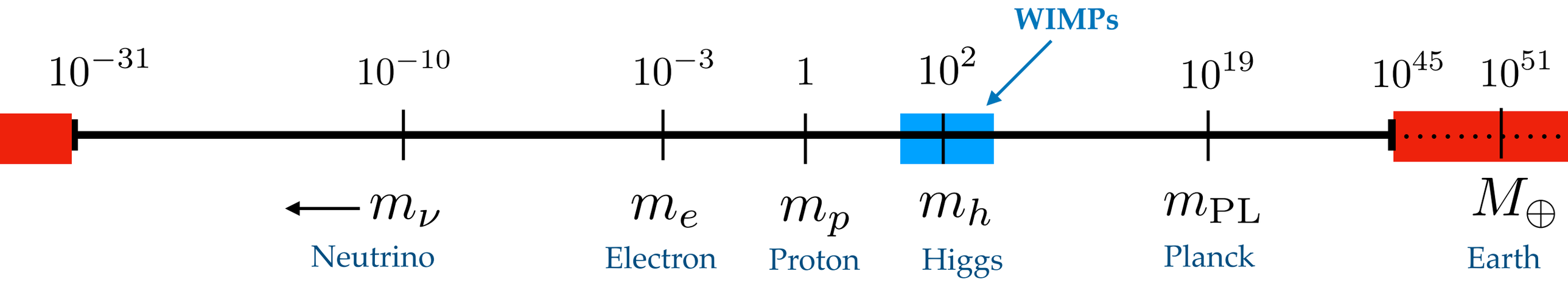
BBN Light Element Yields

Independent, consistent observations spanning nearly all of space and time

kpc-Gpc scales and redshifts $z \sim 3400 \to 0$

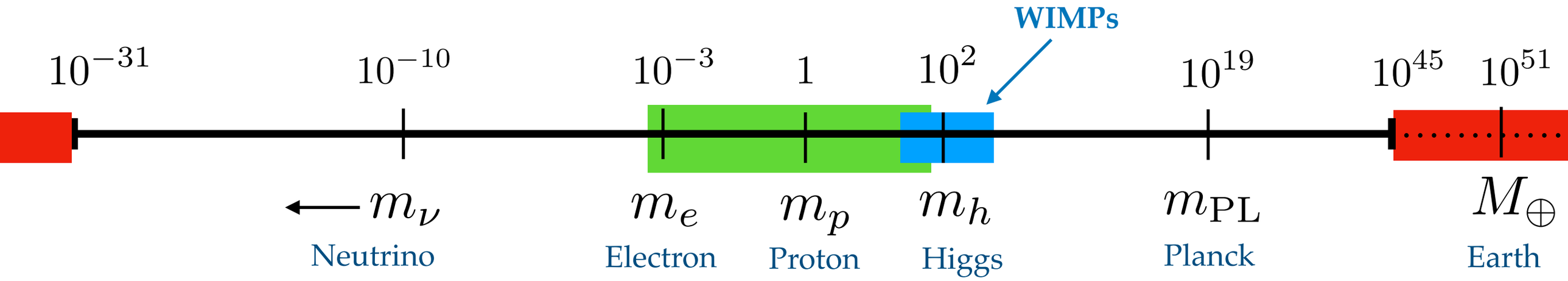
Holy Grail: extend knowledge to laboratory scales

Huge Range of Possible DM Masses



Traditional DM searches for WIMPs near the weak scale

Huge Range of Possible DM Masses



Traditional DM searches for WIMPs near the weak scale

Updated priors null results from LHC & WIMP direct-detection

Key priorities going forward

Identify theoretical milestones

Propose new experimental searches

Which theories make sense and how do we test them?

Light DM vs. WIMPs : General Issues

LDM must be neutral under SM

Else would have been discovered @ LEP/Tevatron/LHC…

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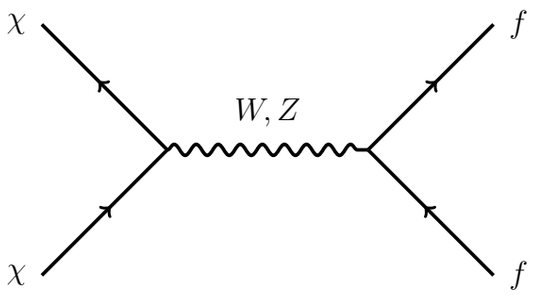
LDM requires light new mediators

Overproduced without additional light, neutral "mediators"



$$\sigma v \sim \frac{\alpha^2 m_\chi^2}{m_Z^4} \sim 10^{-29}\mathrm{cm}^3\mathrm{s}^{-1}\left(\frac{m_\chi}{\mathrm{GeV}}\right)^2$$

Lee/Weinberg '79

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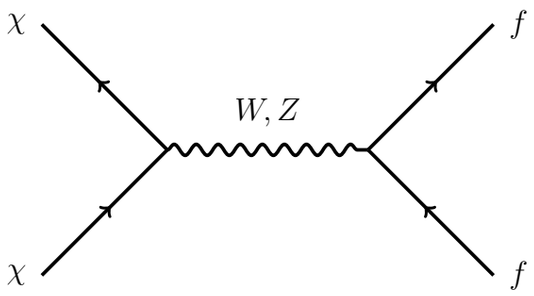

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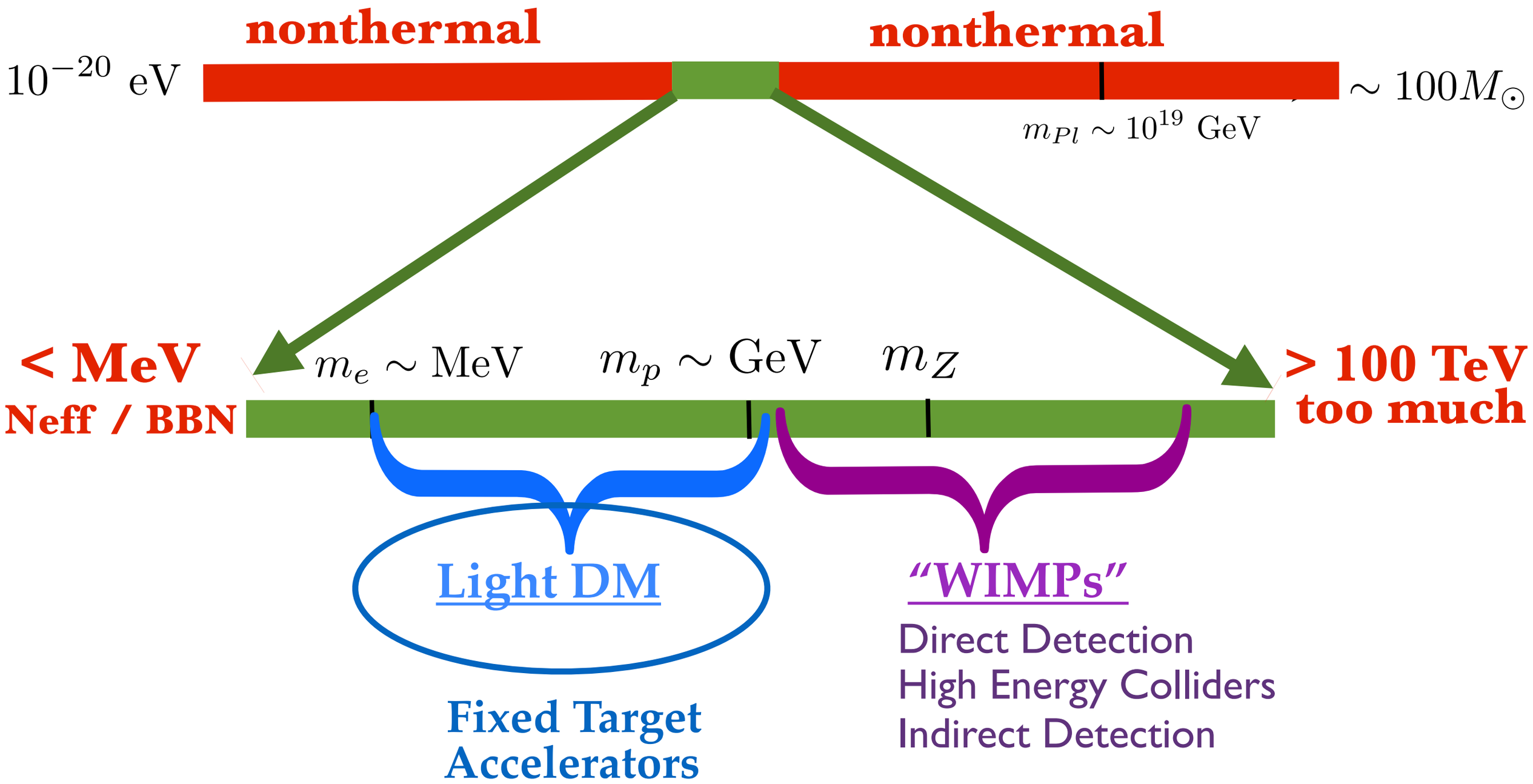
Lee/Weinberg '79

LDM interactions renormalizable at accelerator energies

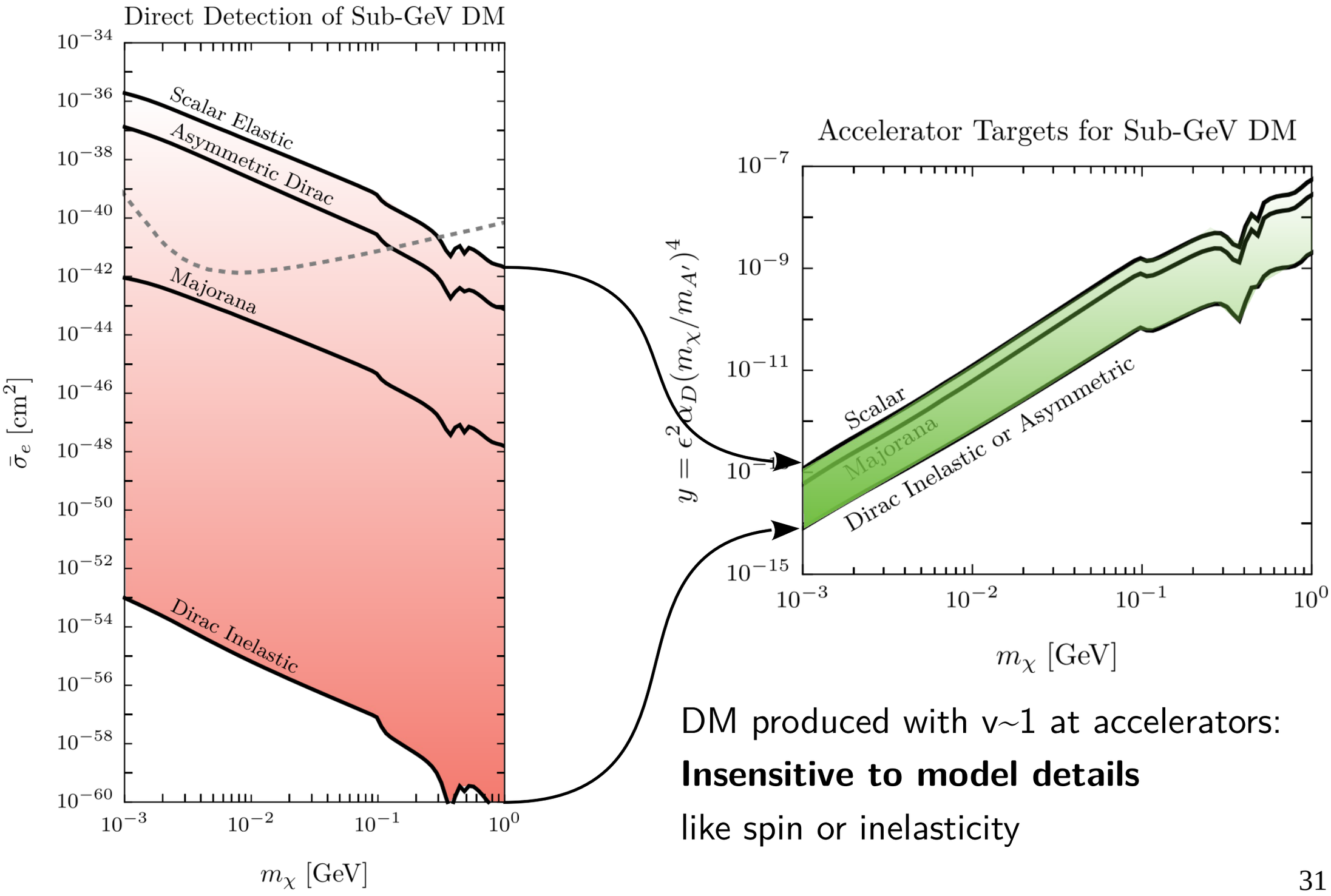
Else rate too small — greatly simplifies space of possible theories

See Maxim's talk

Equilibrium Narrows Mass Range!



Advantages of Accelerator Searches



DM produced with v~1 at accelerators:

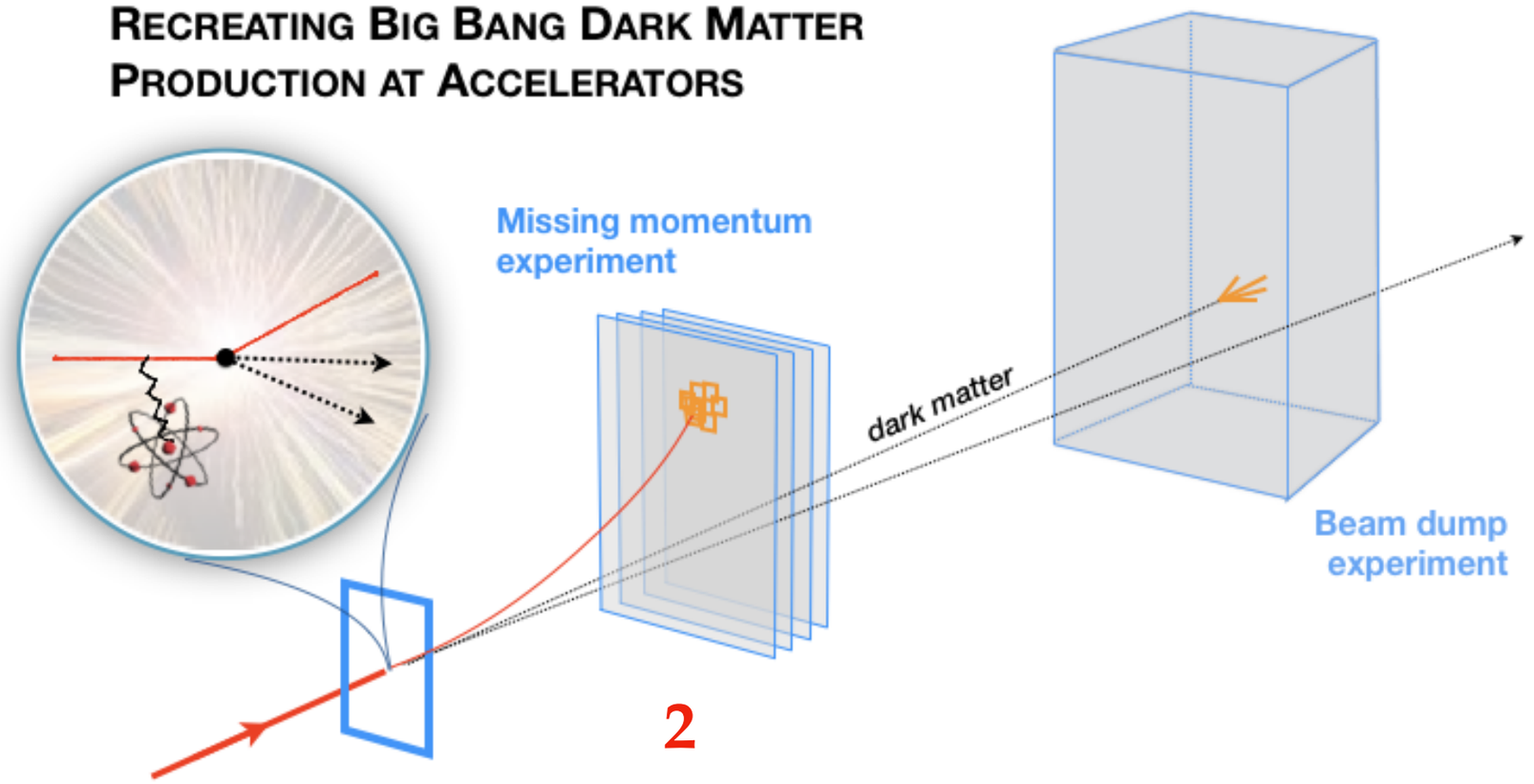
Insensitive to model details

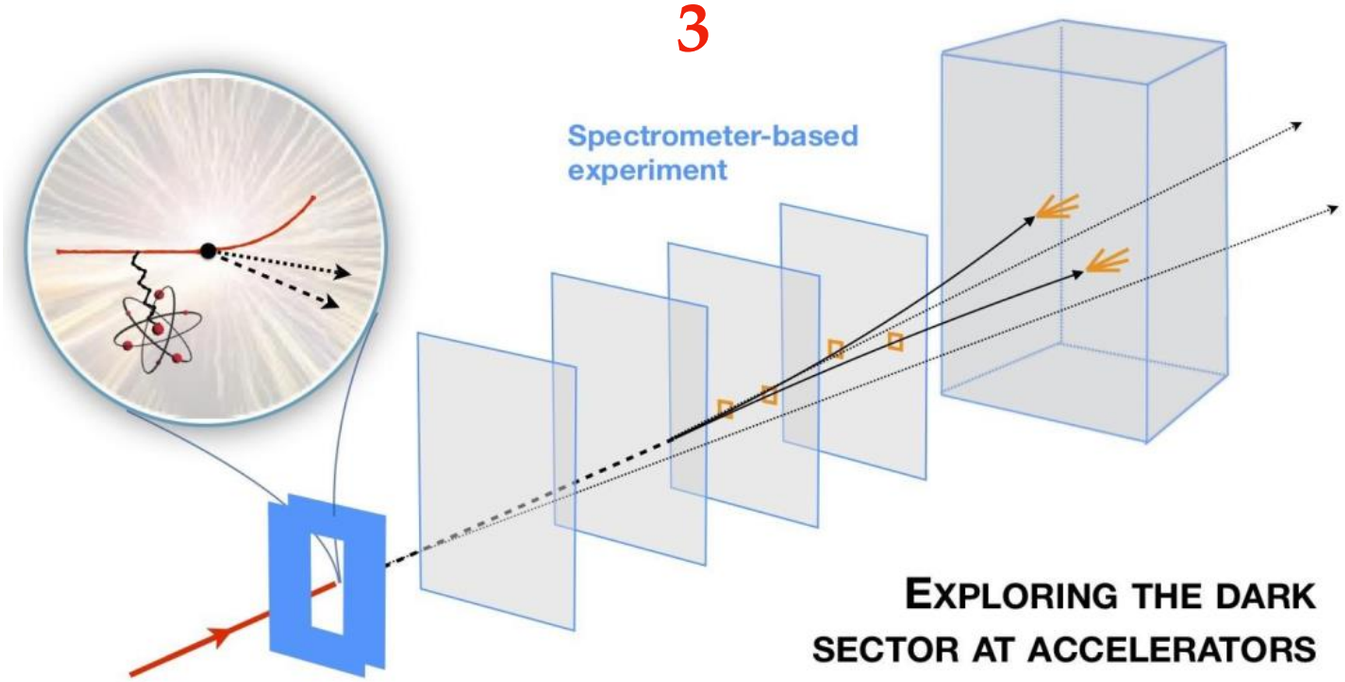
like spin or inelasticity

Izaguirre, GK, Schuster, Toro 1505.00011 PRL

Slide: Nikita Blinov

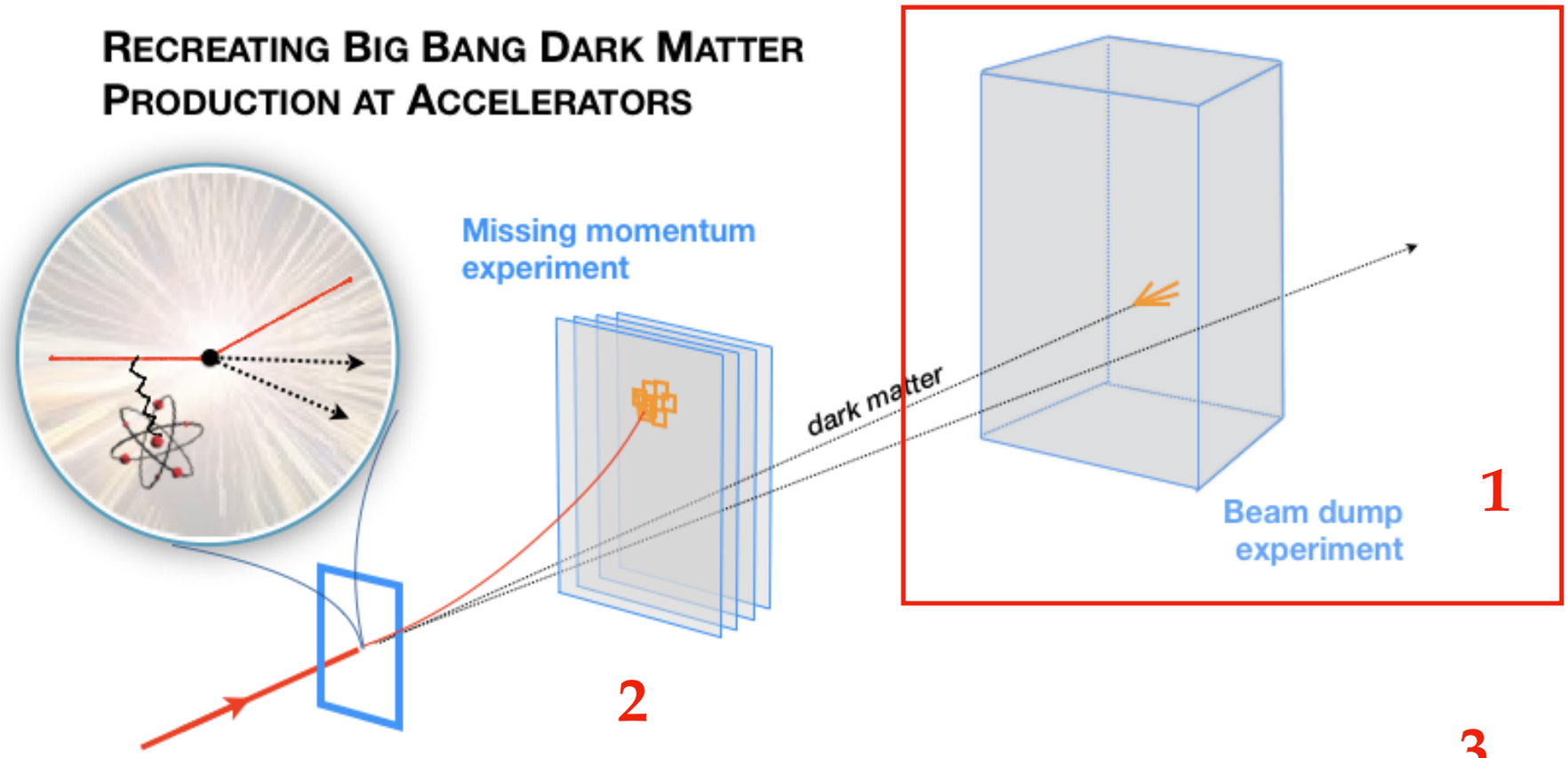
Three “Big Ideas”



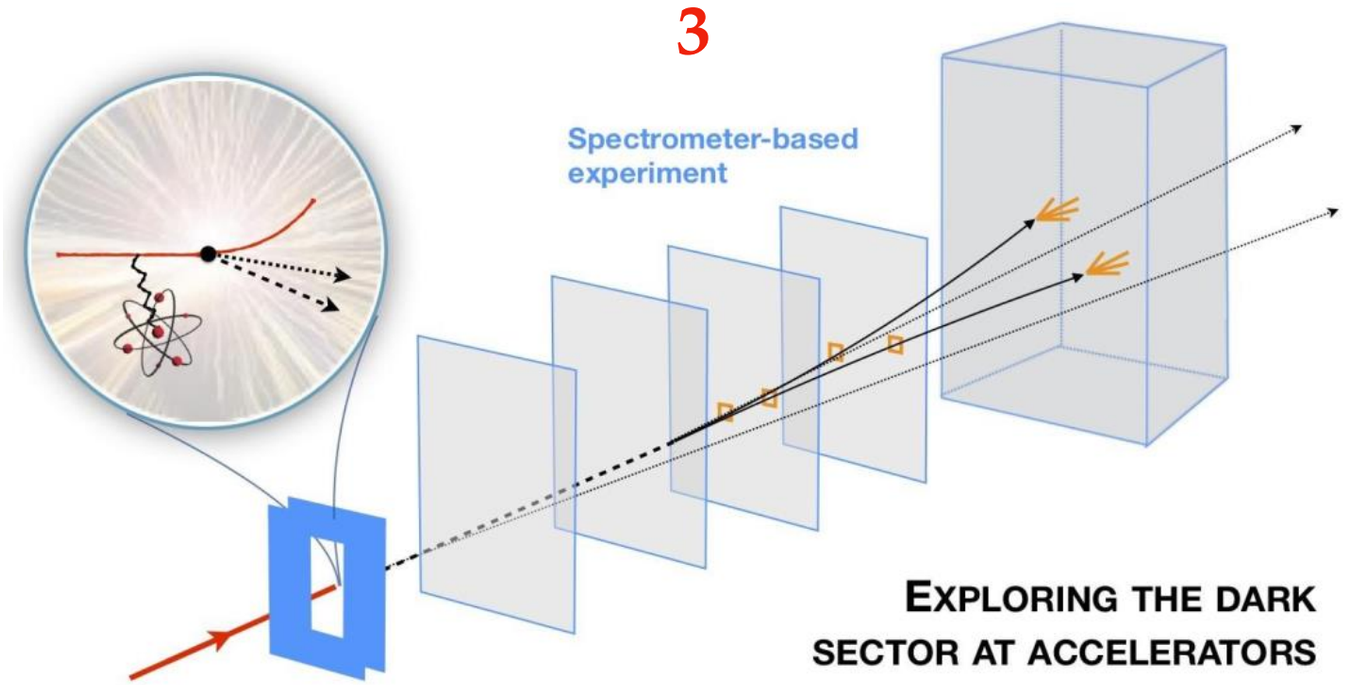


DM New Initiatives BRN Report (Kolb++)
https://www.osti.gov/servlets/purl/1659757

Three “Big Ideas”



Look for DM Scattering Downstream



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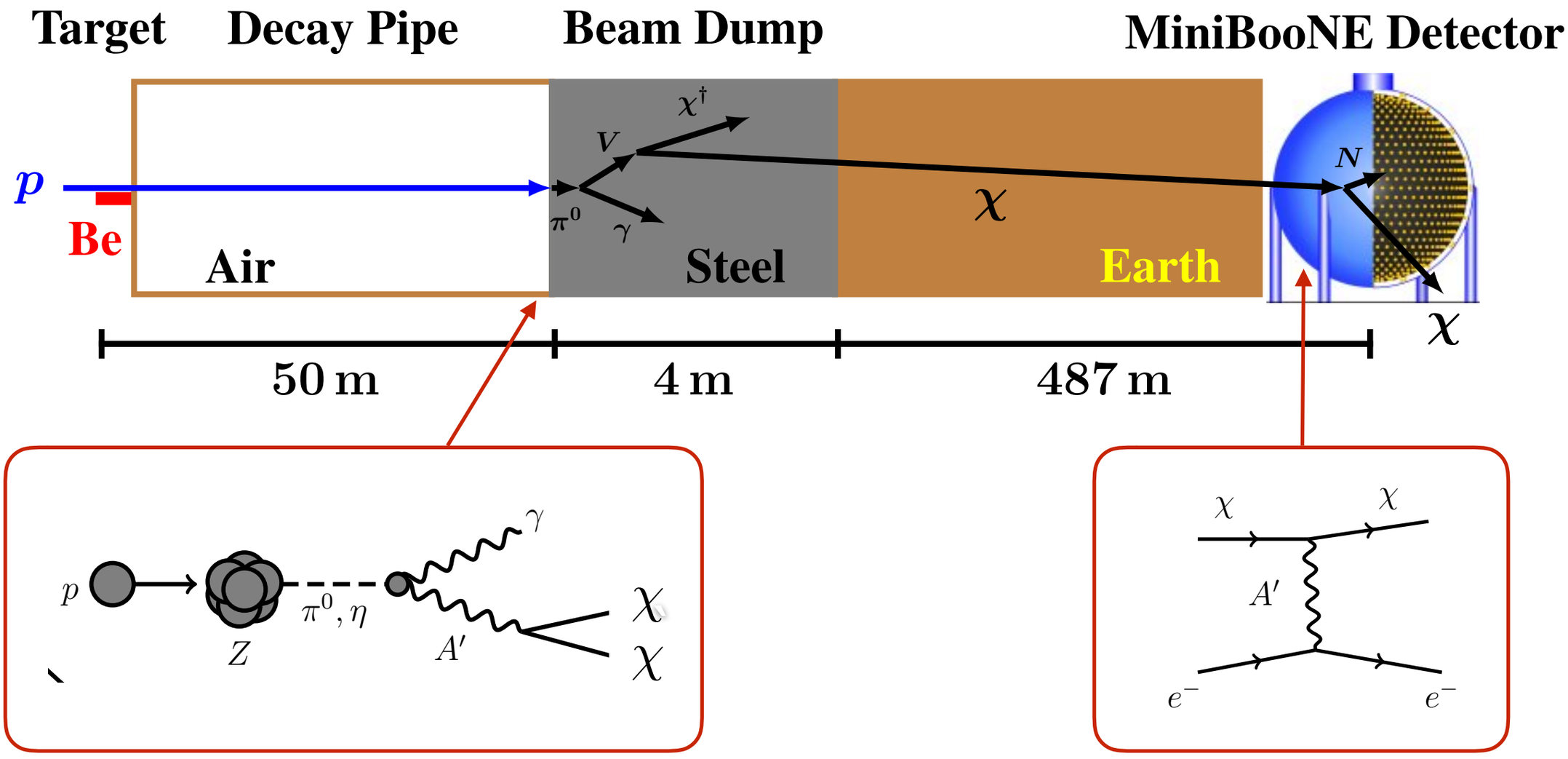
DM Production at proton beam facilities

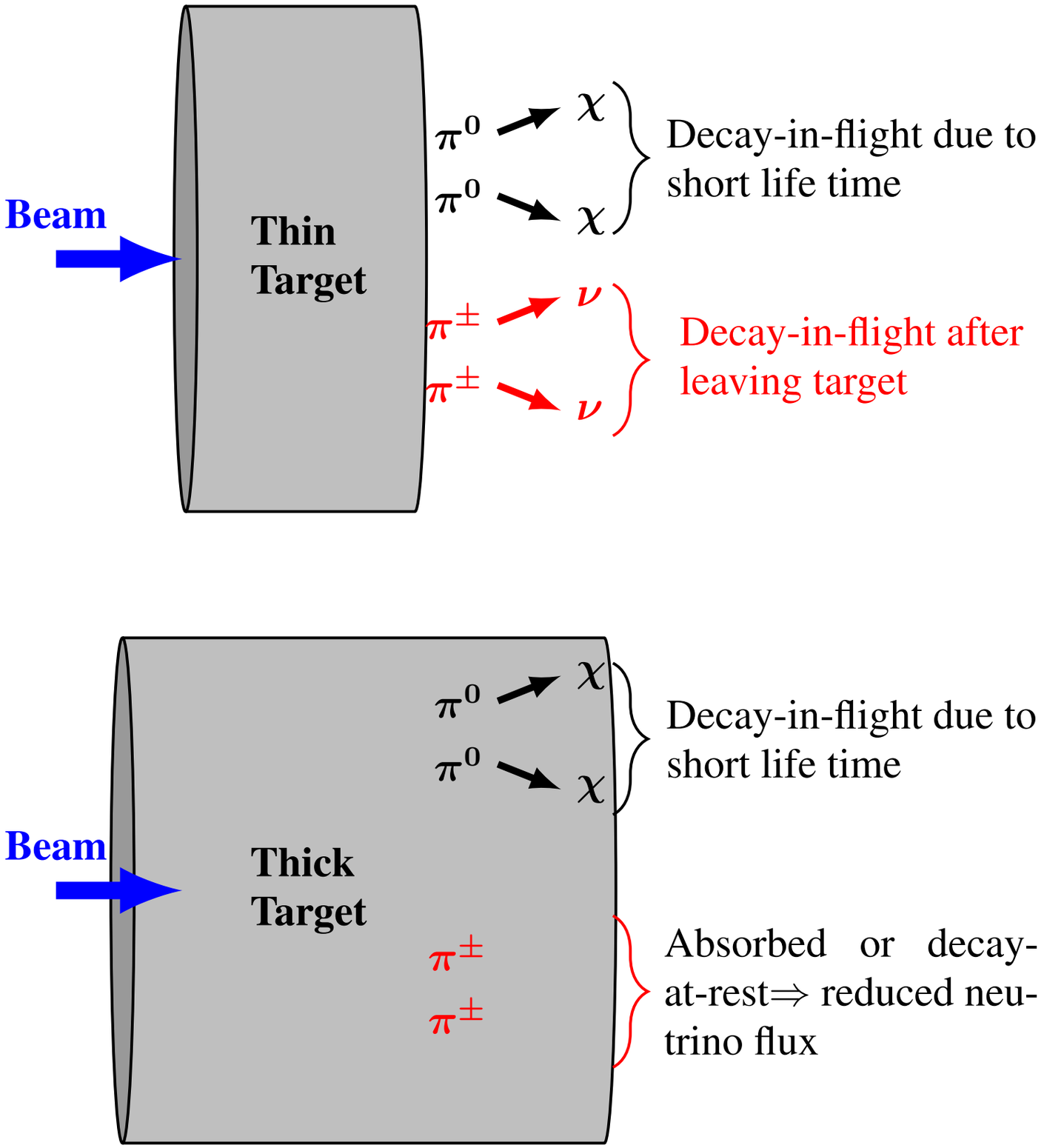


Batell, Pospelov, Ritz 0903.0363

Produce DM at in proton fixed target setup. DM resetters downstream

Dobrescu, Friuguele 1410.1566
Kahn, GK, Thaler, Toups 1411.1055
Izaguirre, Kahn, Krnjaic, Moschella 1703.06881
De Gouvea, Fox, Harnik, Kelly, Zhang 1809.06388
Berlin, Kling 1810.01879
De Niverville, Tsai, Liu 1908.07525

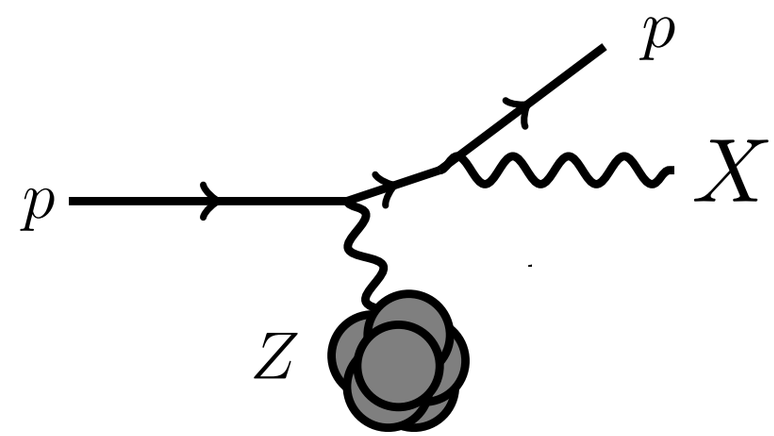
Neutrino Mode vs. Beam Dump Mode



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

MiniBooNE-DM

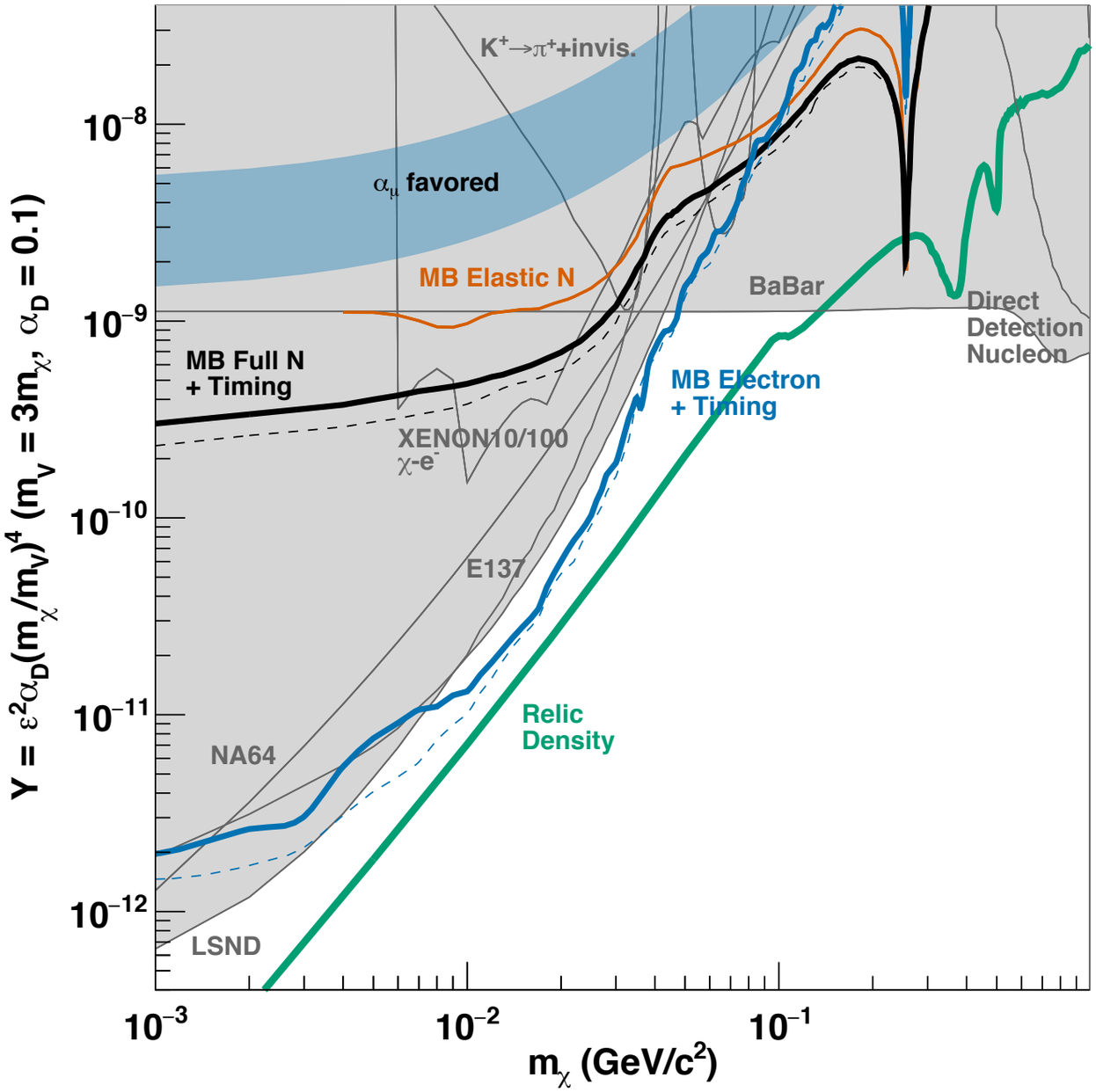
First ever dedicated accelerator search for light DM scattering

8 GeV proton beam, 2e20 POT
Uses timing to reduce NC-BG

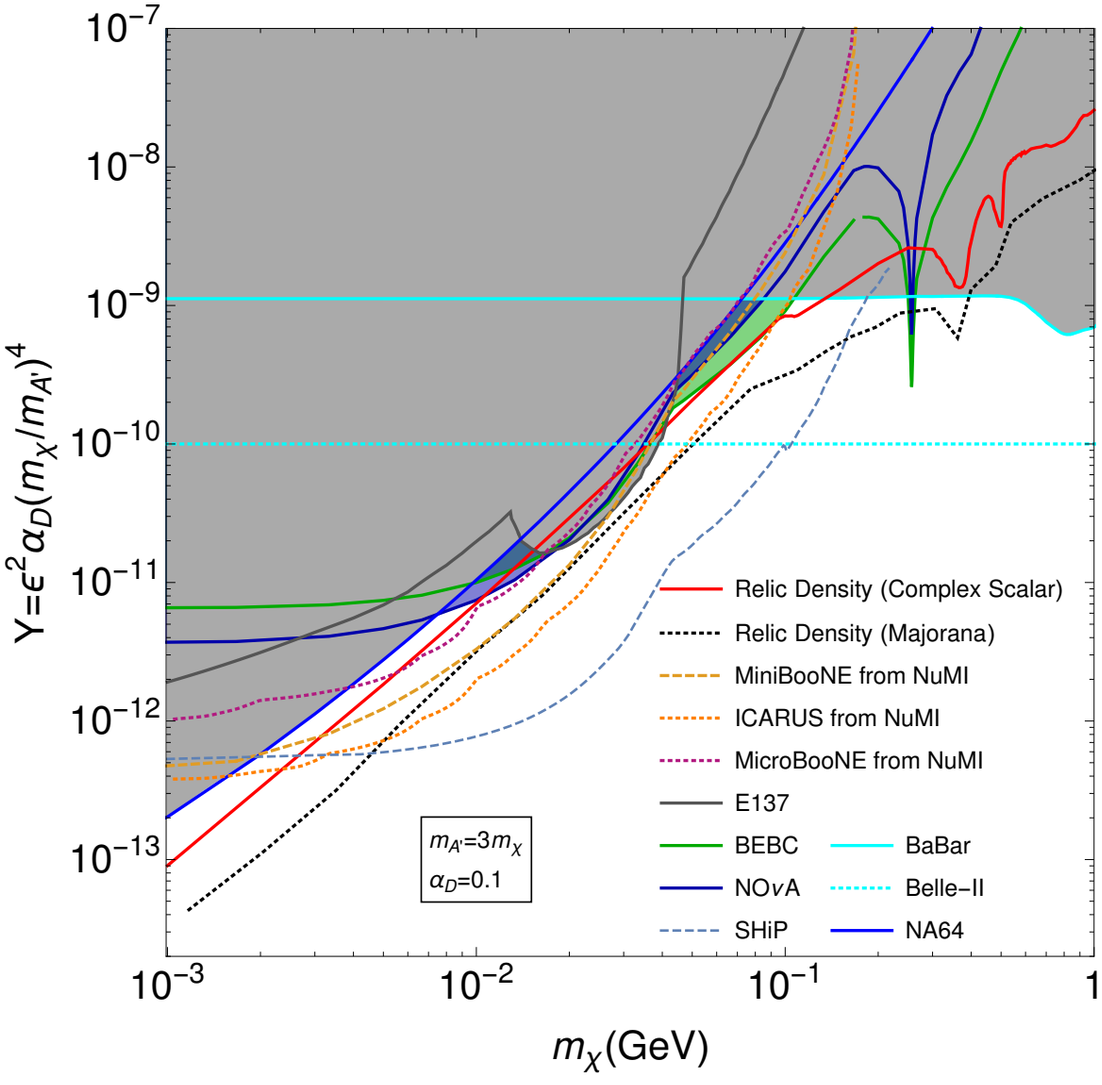
Beats 20+ year limits from theorist Reinterpretations of E137/LSND

Approaching key thermal DM production milestones

MiniBooNE-DM Collaboration 1807.06137

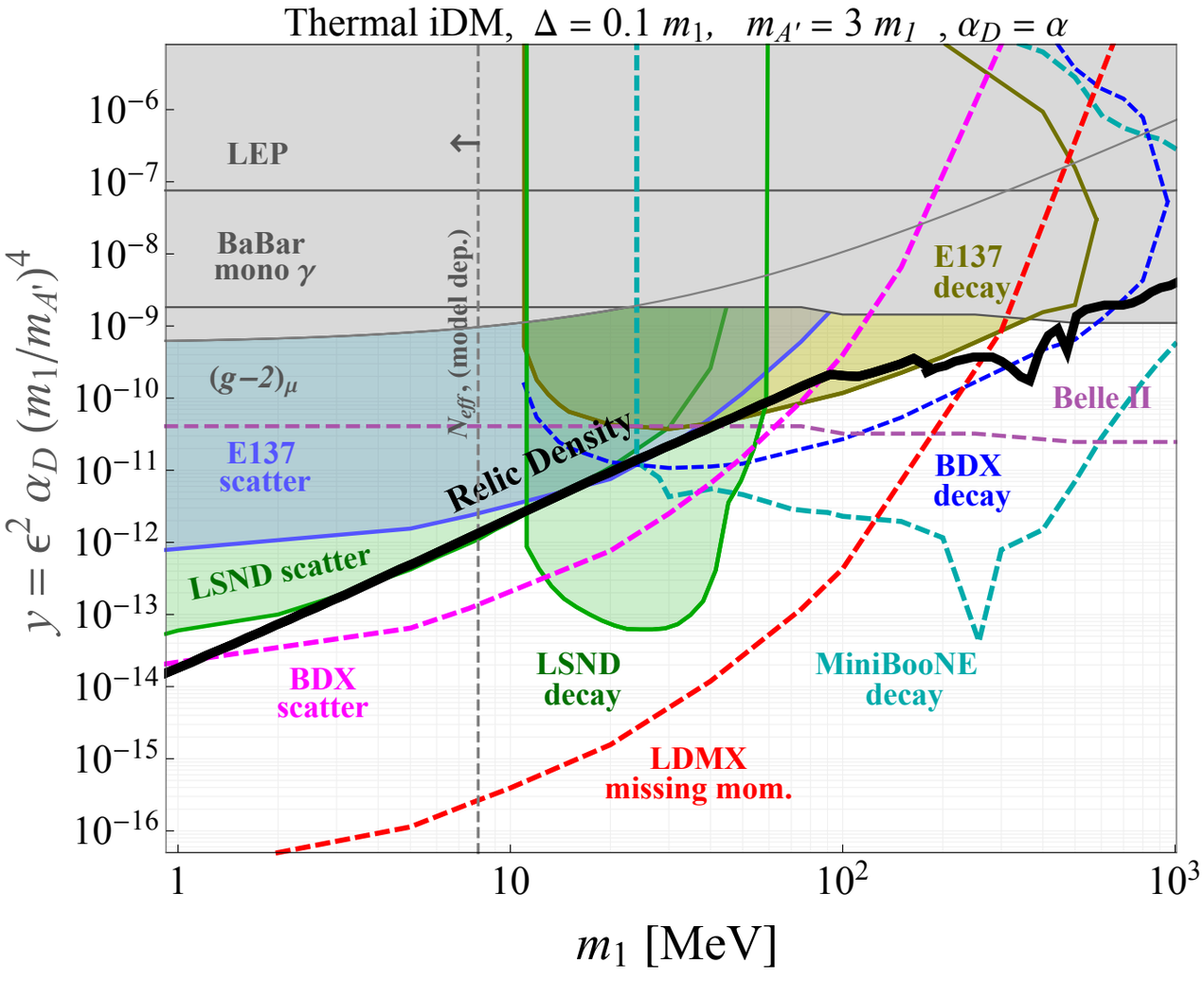


Future DM Reach @ FNAL Neutrino Experiments

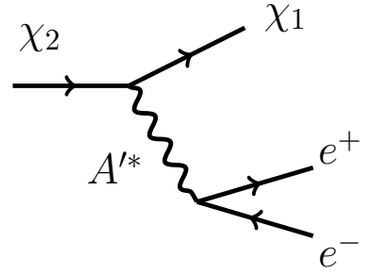


Future DM scatter reach for @ FNAL neutrino experiments

Buonocore, Frugiuele, deNiverville 1912.09346

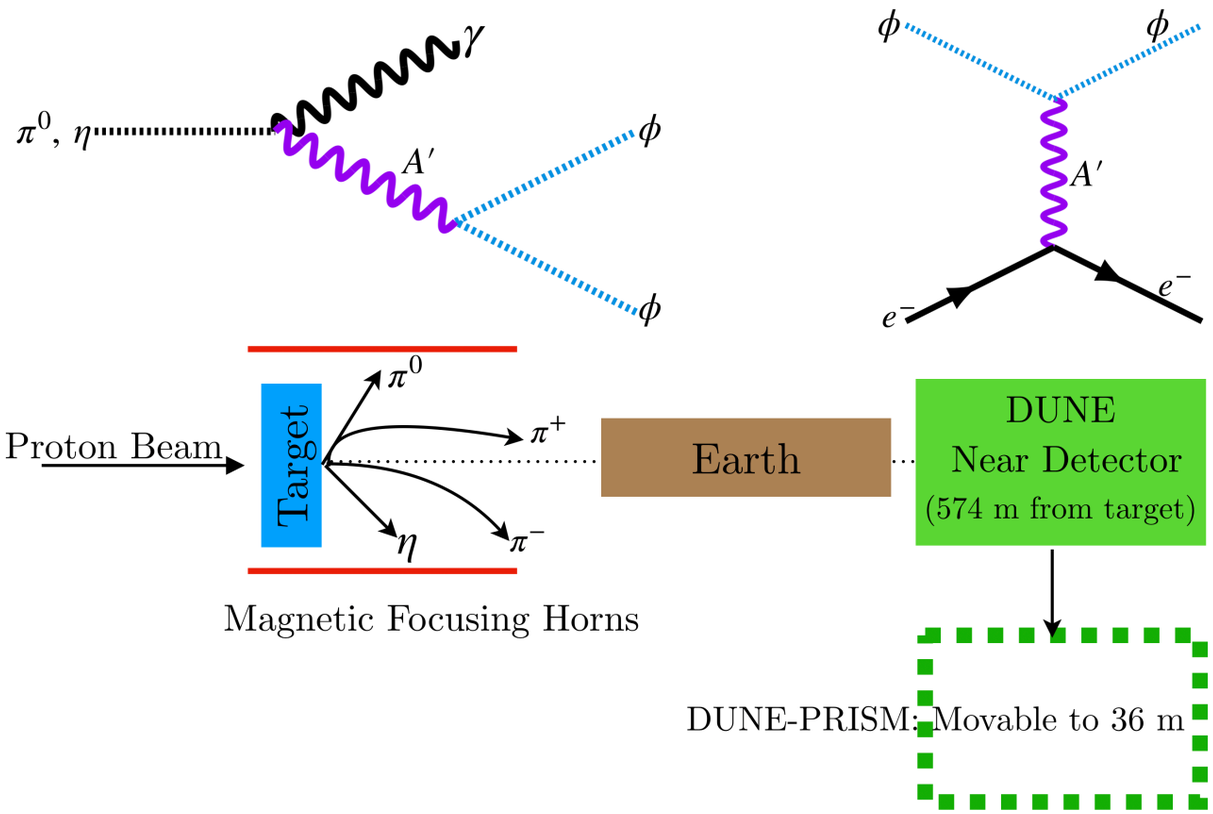


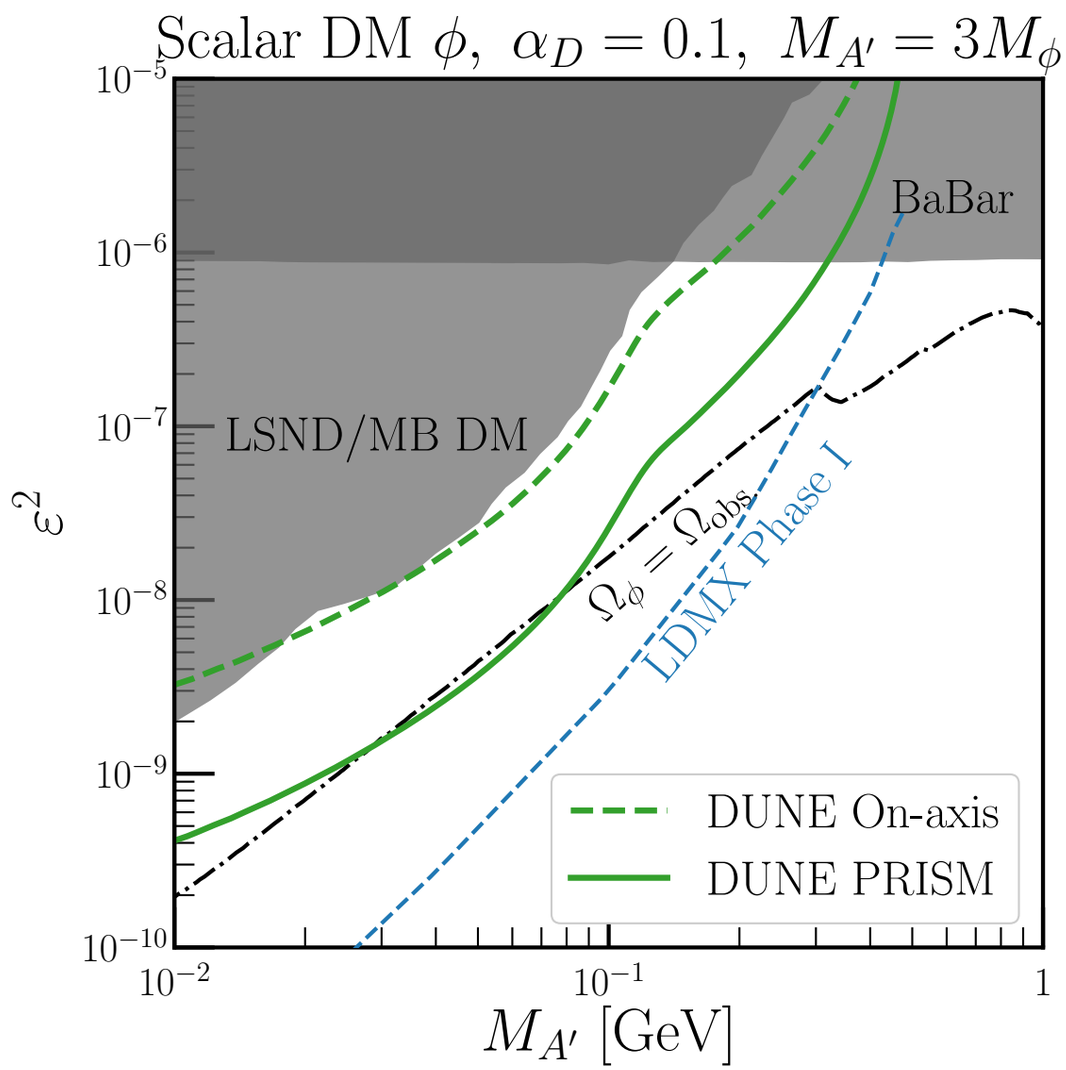
Same strategy probes Inelastic DM decays



Izaguirre, Kahn, GK, Moschella 1703.06881
Batell, Berger, Darme, Frugiuele, 2106.04584

DM @ DUNE/PRISM





DUNE near detector (on-axis) and PRISM (off axis) sensitive to thermally produced DM in early universe

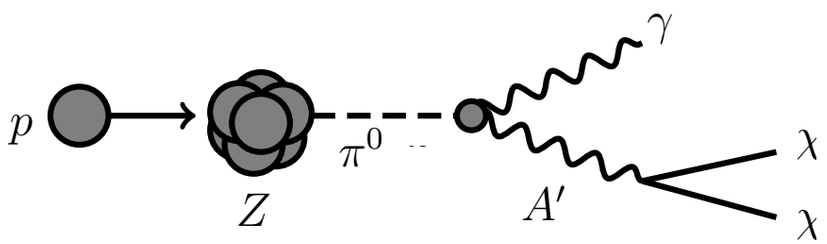
DM production through meson decay — favorable S/B 36 m off axis

De Romeri, Kelly, Machado 1903.10505

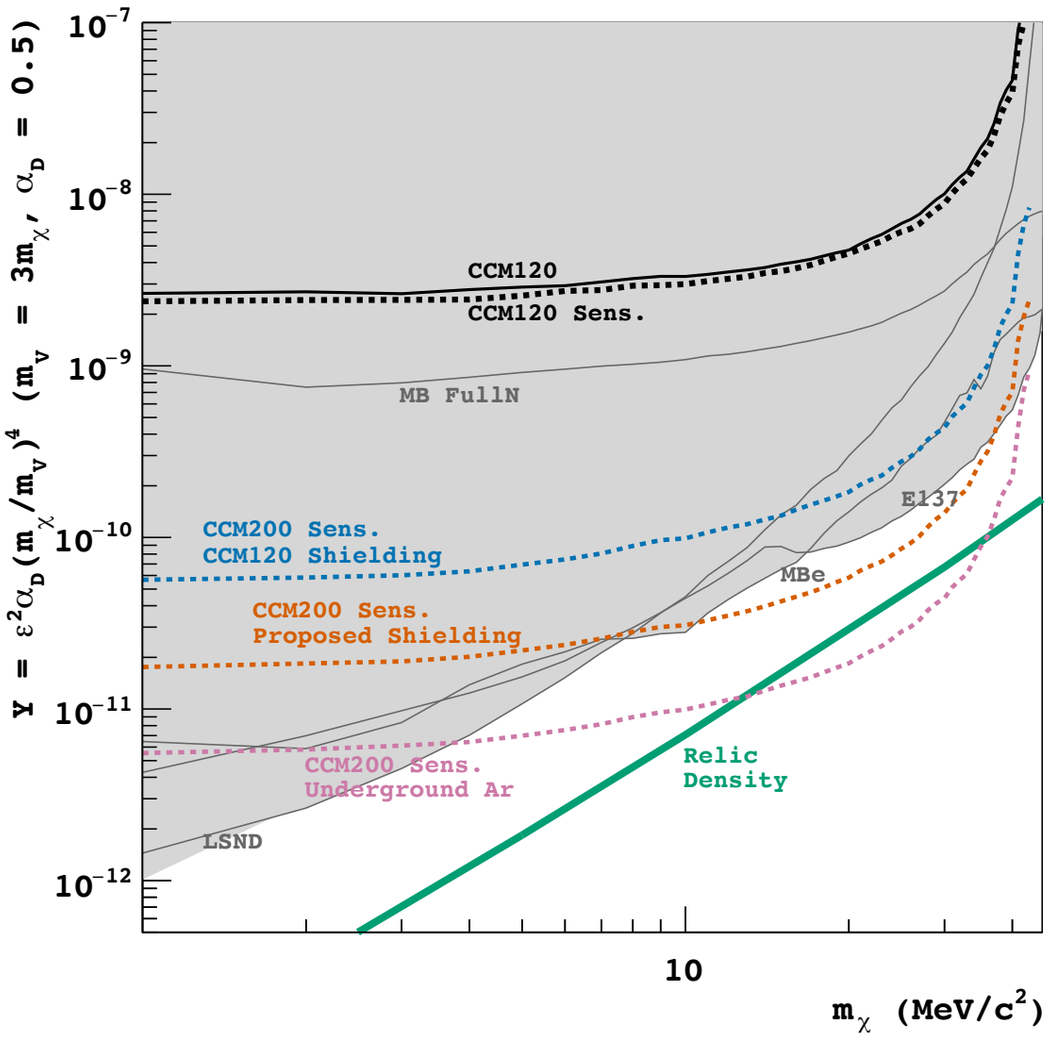
DM @ Coherent Captain Mills (LANL)

800 MeV proton beam
~ 1e22 POT luminosity

DM production from neutral pion decay



DM rescattering downstream in
10 ton LAr scintillating detector

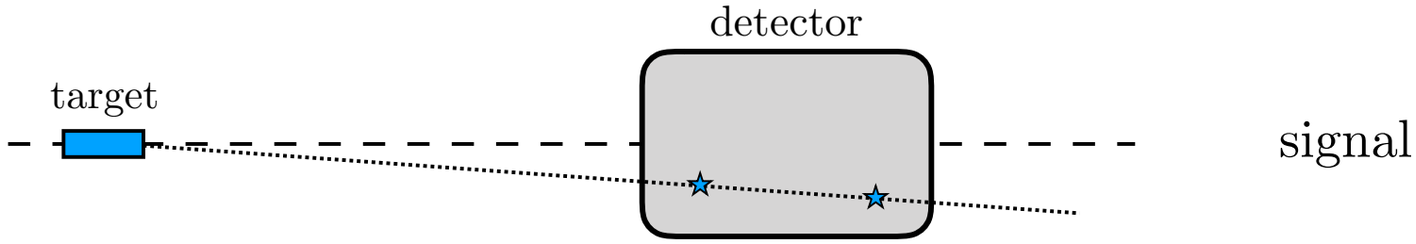


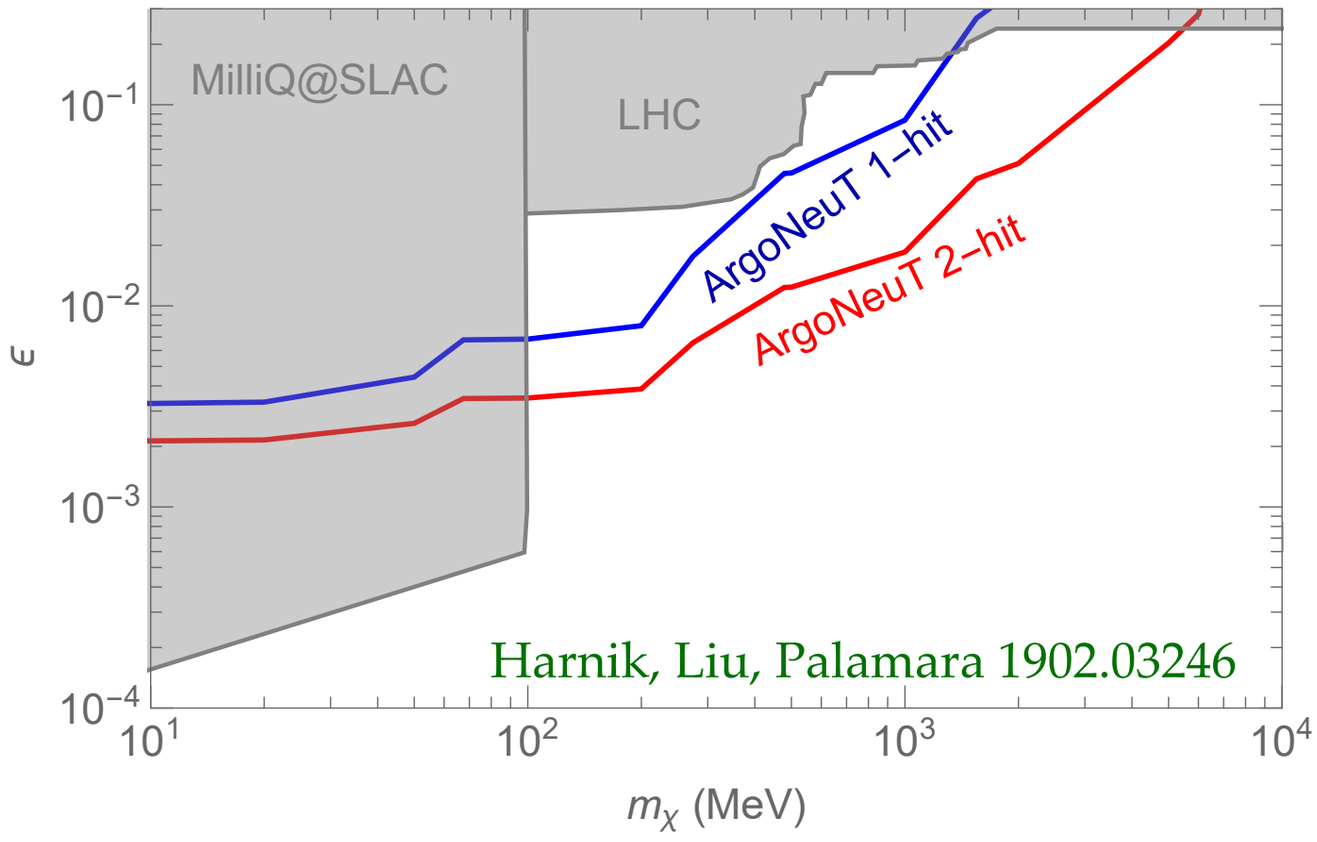
DM search complements CEvENs program

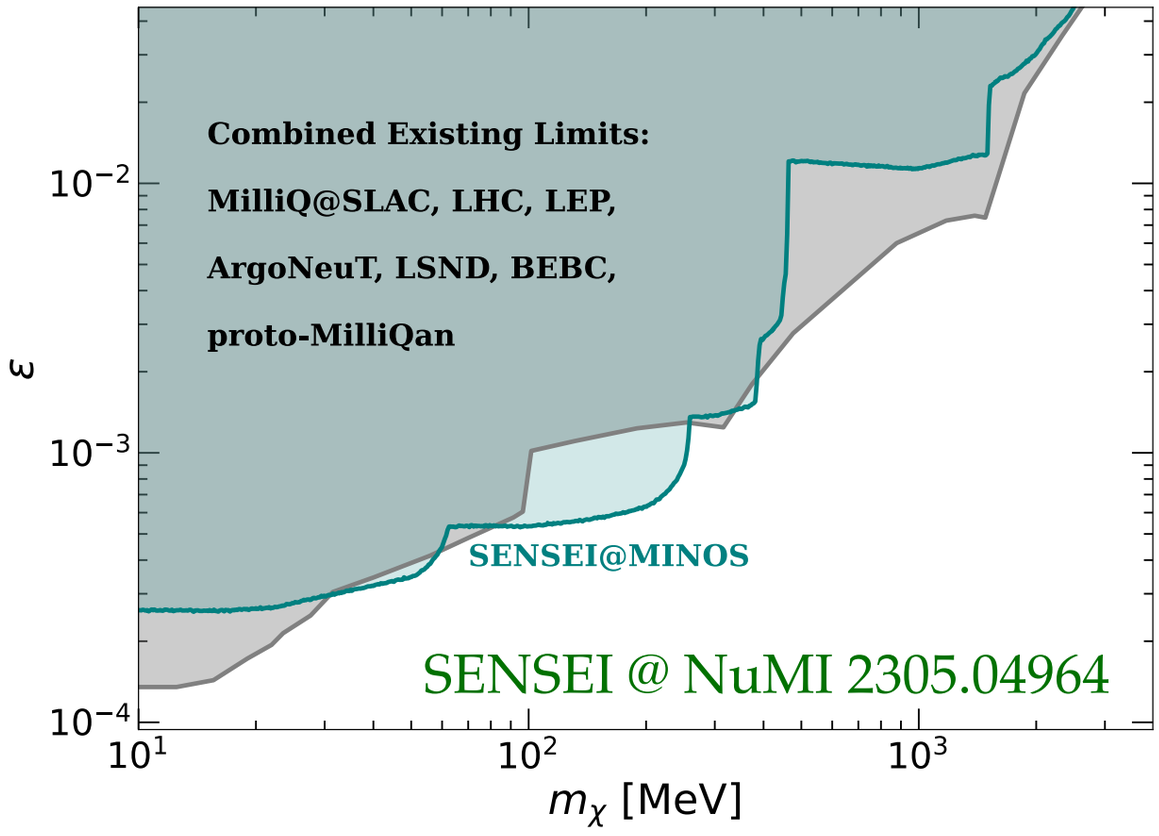
DMNI funded, first round

Aguilar-Arevalo et. al. 2105.14020

Millicharged particles: ArgoNeuT+SENSEI

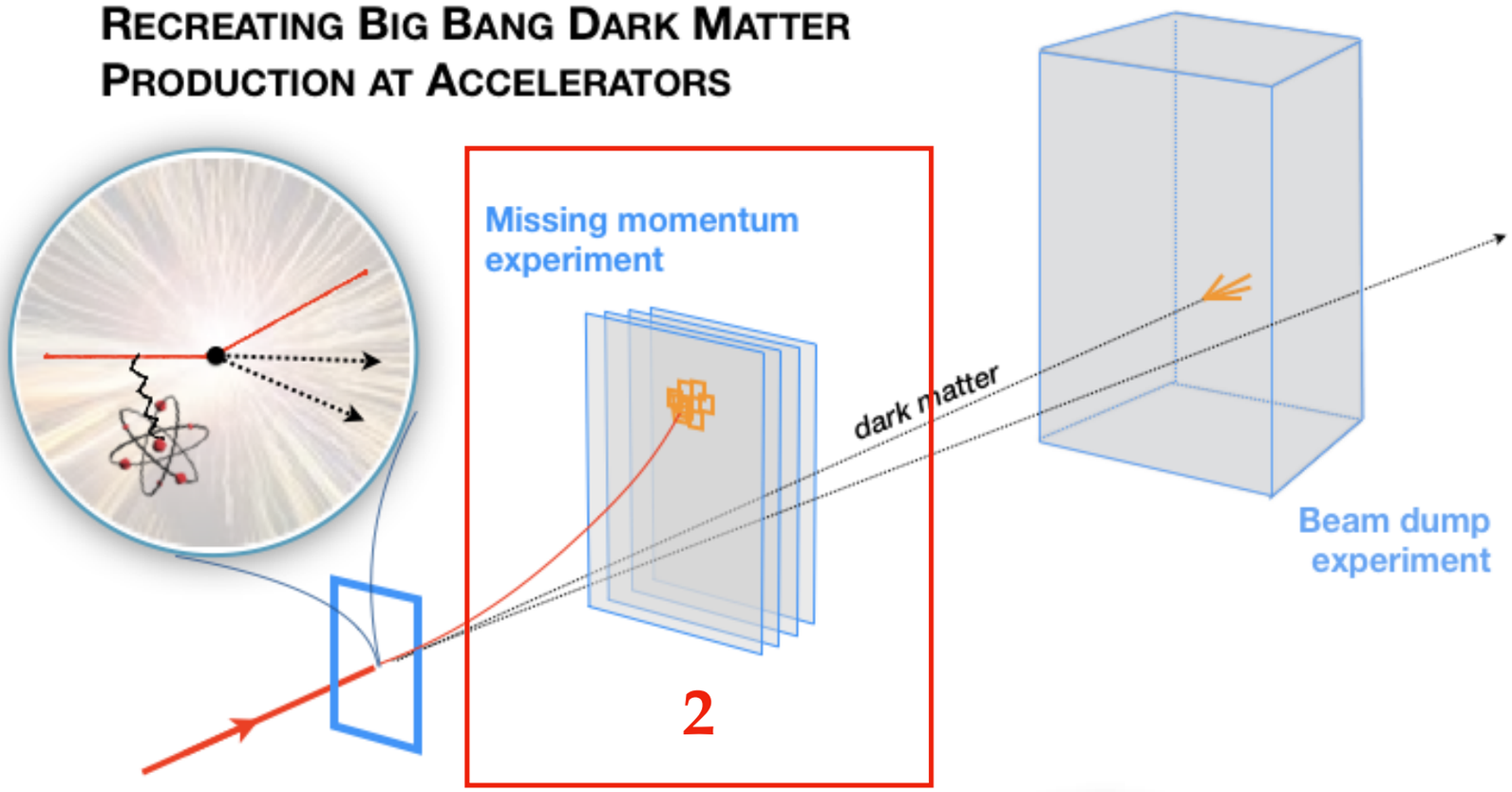






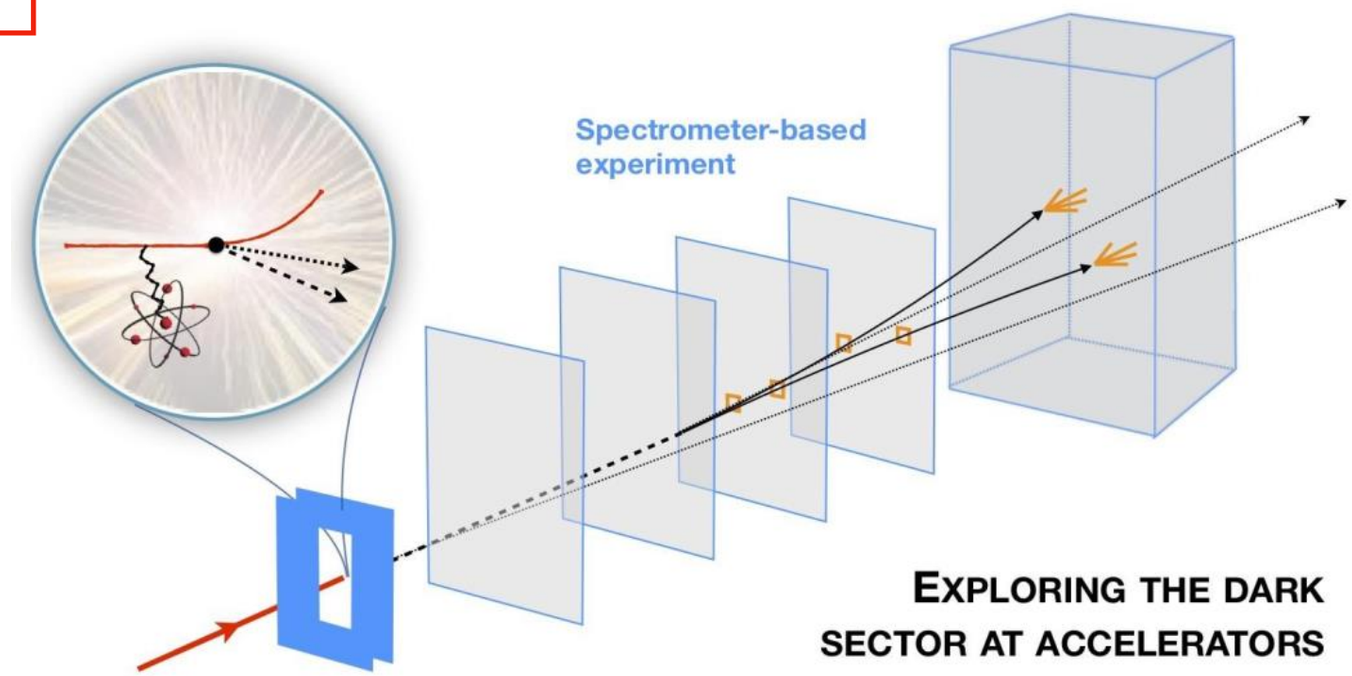
QED interactions in beam dump can produce millicharged particles which can be detected with LAr detector(ArgoNeuT) or skipper CCD (SENSEI) downstream

Three “Big Ideas”



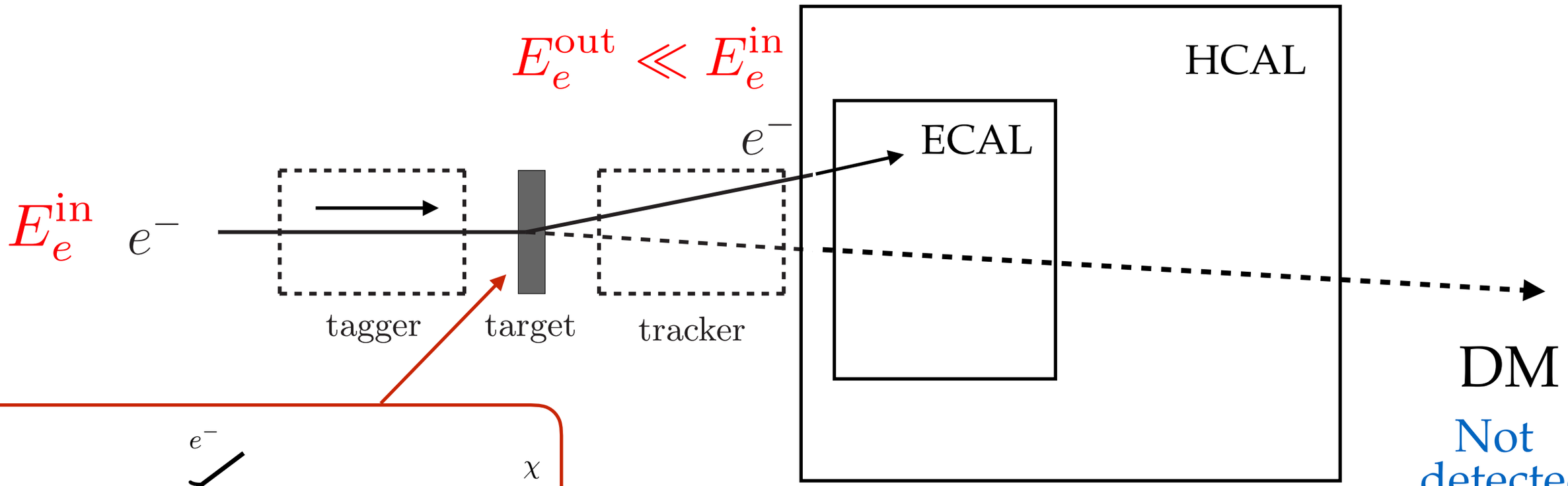
Infer DM Production with beam kinematics

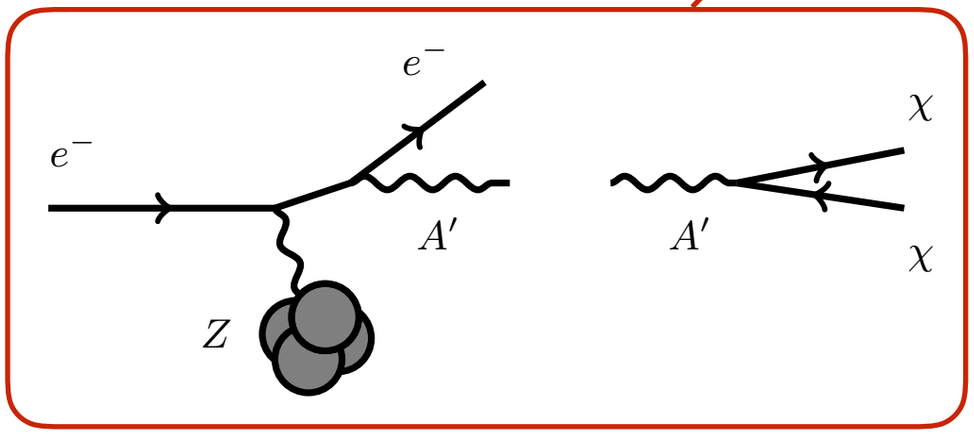
The beam itself is the signal



DM New Initiatives BRN Report (Kolb++)
https://www.osti.gov/servlets/purl/1659757

Missing Energy / Momentum Strategy





Monitor e-beam for signal

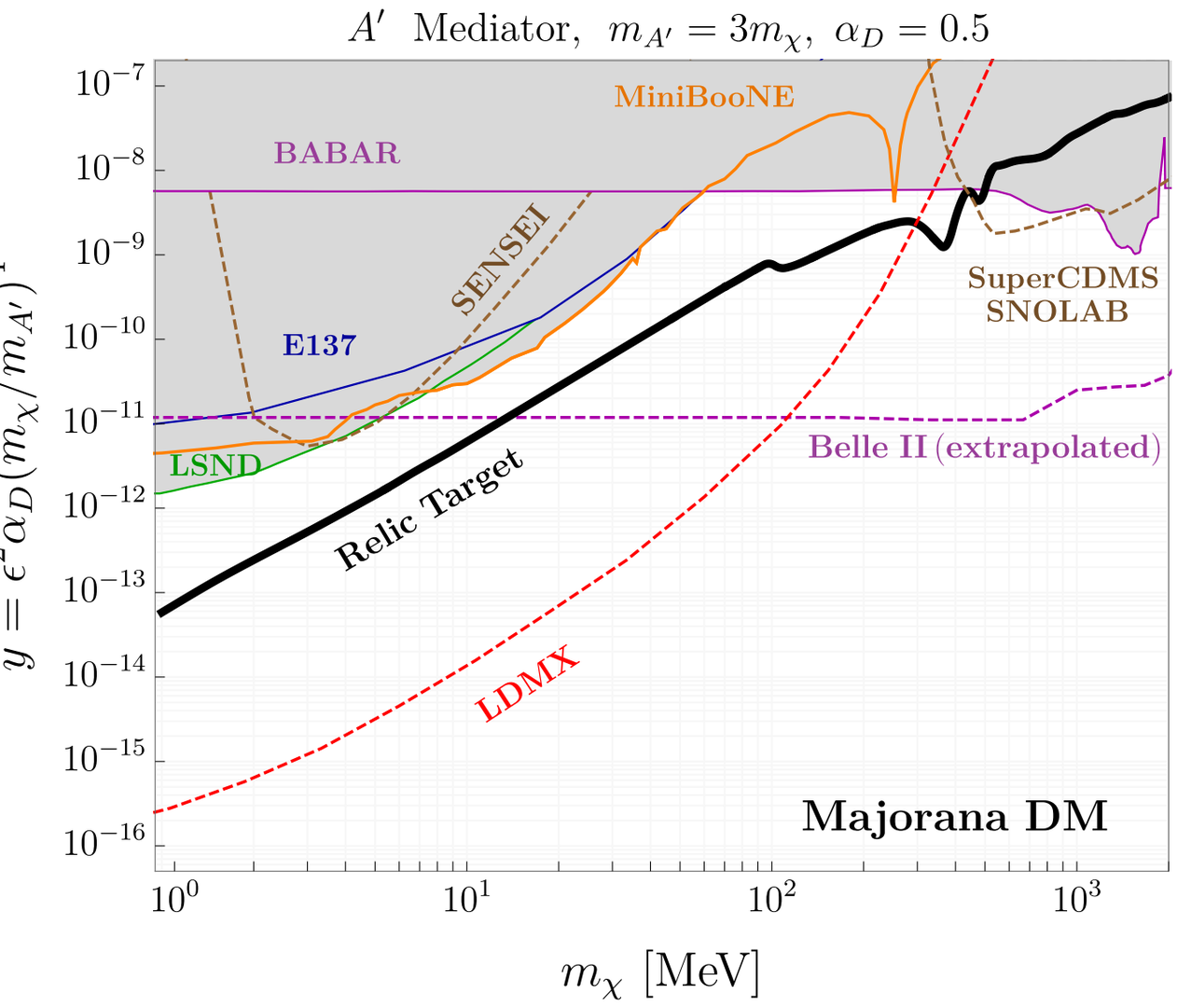
Low current, track individual *e-*

DMNI funded, first round

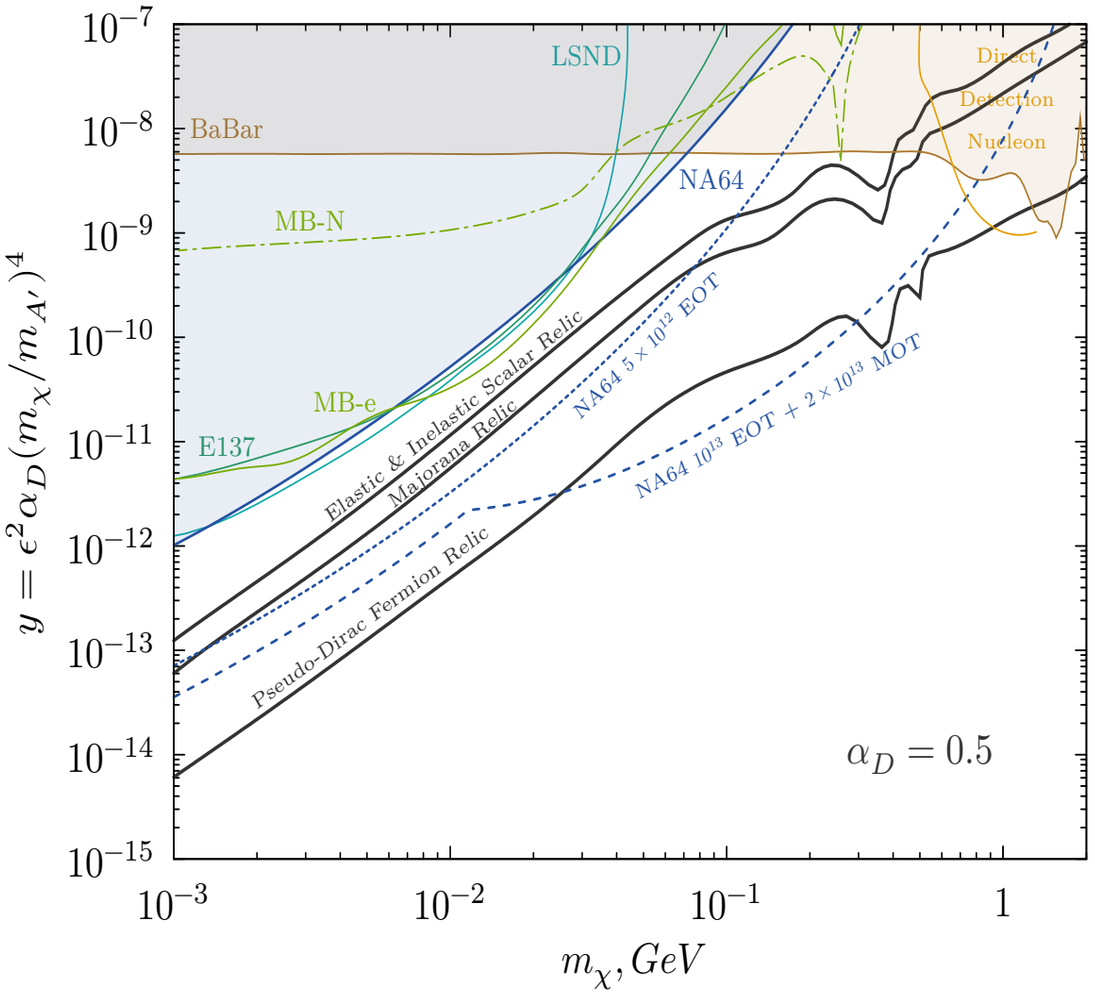
1) Measure E in/out
2) Trigger on missing P
3) Veto additional SM activity
4) Repeat ~1e16 times

Izaguirre, GK, Schuster, Toro arXiv:1411.1404

Missing Energy / Momentum Strategy



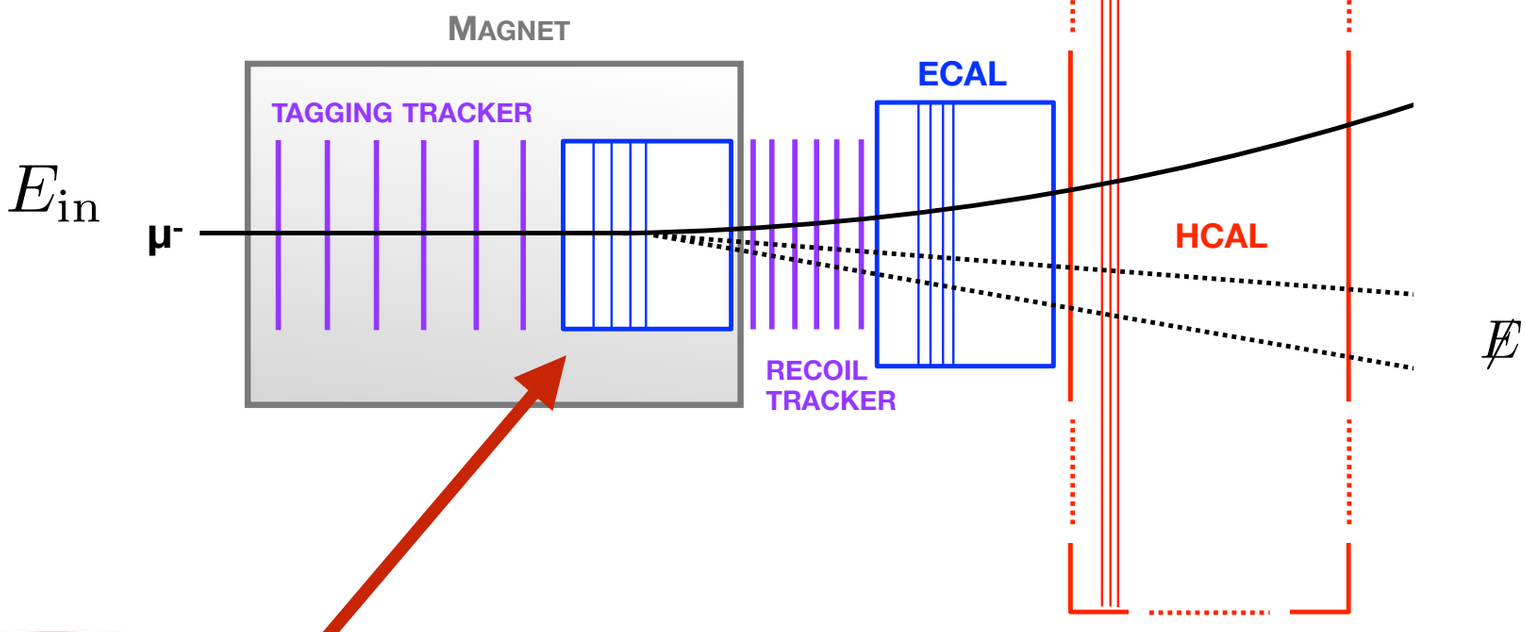
Berlin, Blinov, GK, Schuster, Toro arXiv: 1807.01730

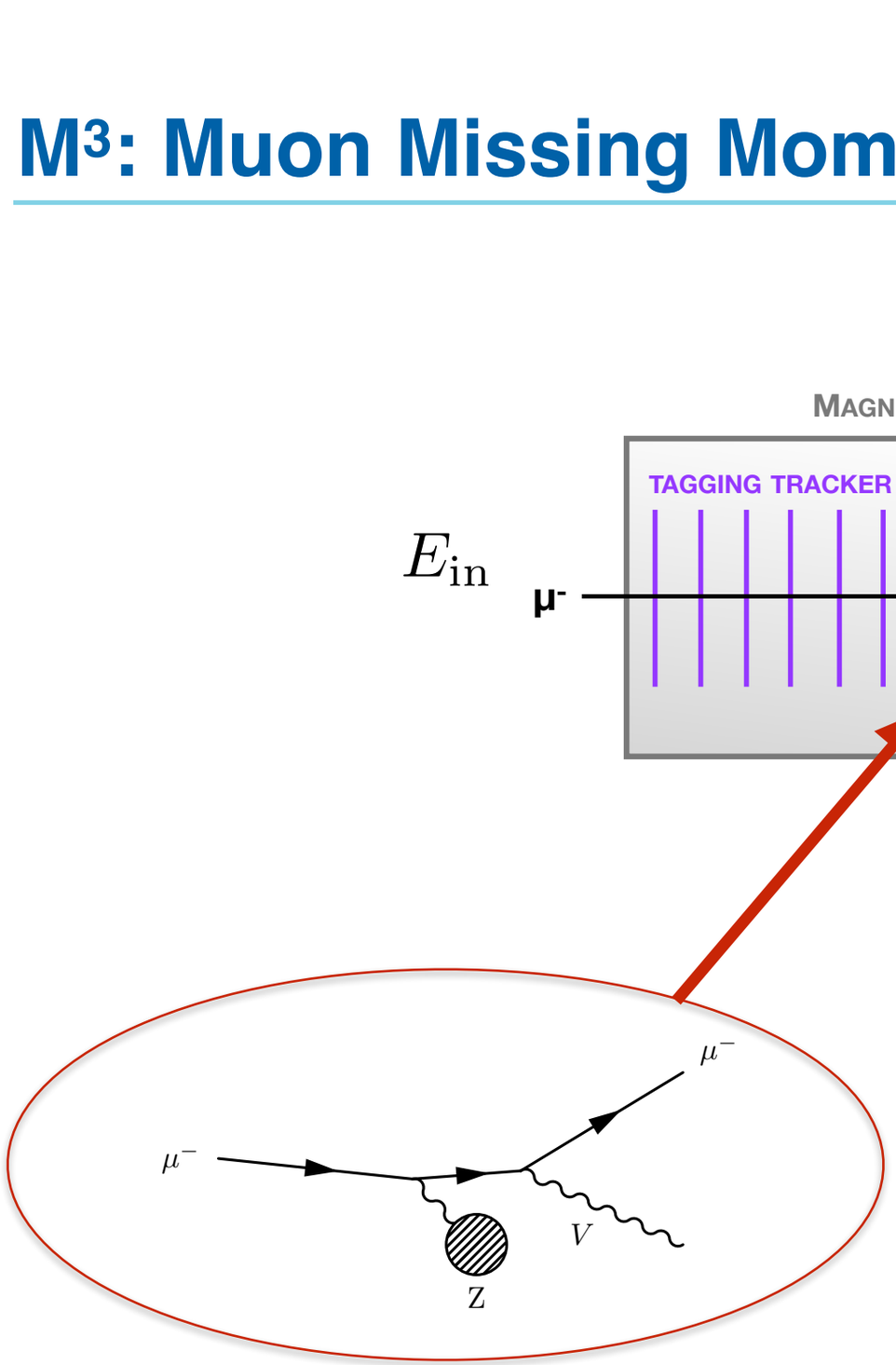


Andreas et. al. 1312.3309
NA64 Collaboration 1906.00176
Gninenko, Krasnikov, Mateev 2003.07257

NA64 currently running @ CERN

M³: Muon Missing Momentum @ FNAL



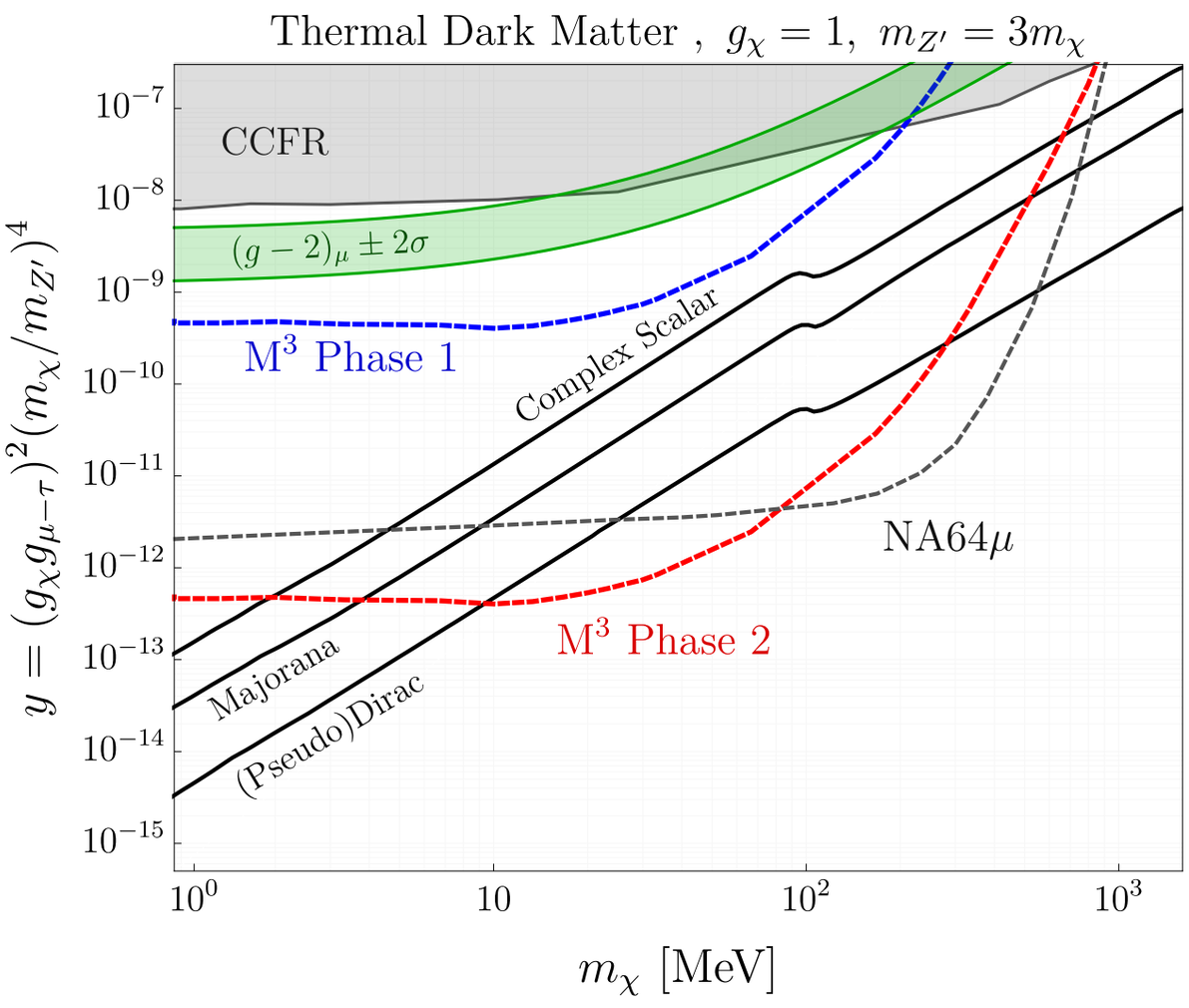


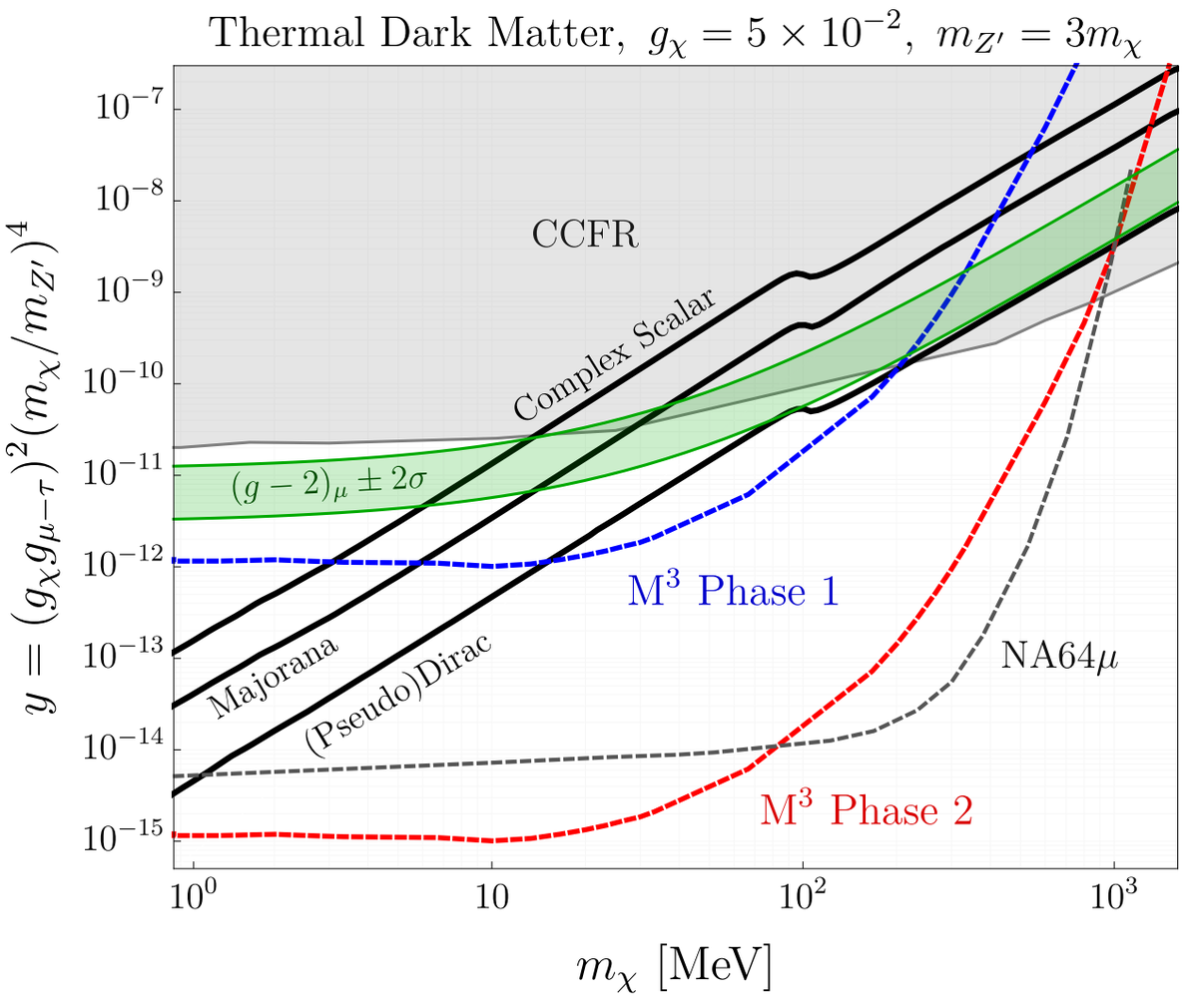
1) Measure E in/out with B field
2) Trigger on missing P
3) Veto additional SM activity
4) Repeat ~ 1e14 times

Fermilab

Kahn, GK, Tran, Whitbeck 1804.03144, LDRD supported

M³: Muon Missing Momentum @ FNAL





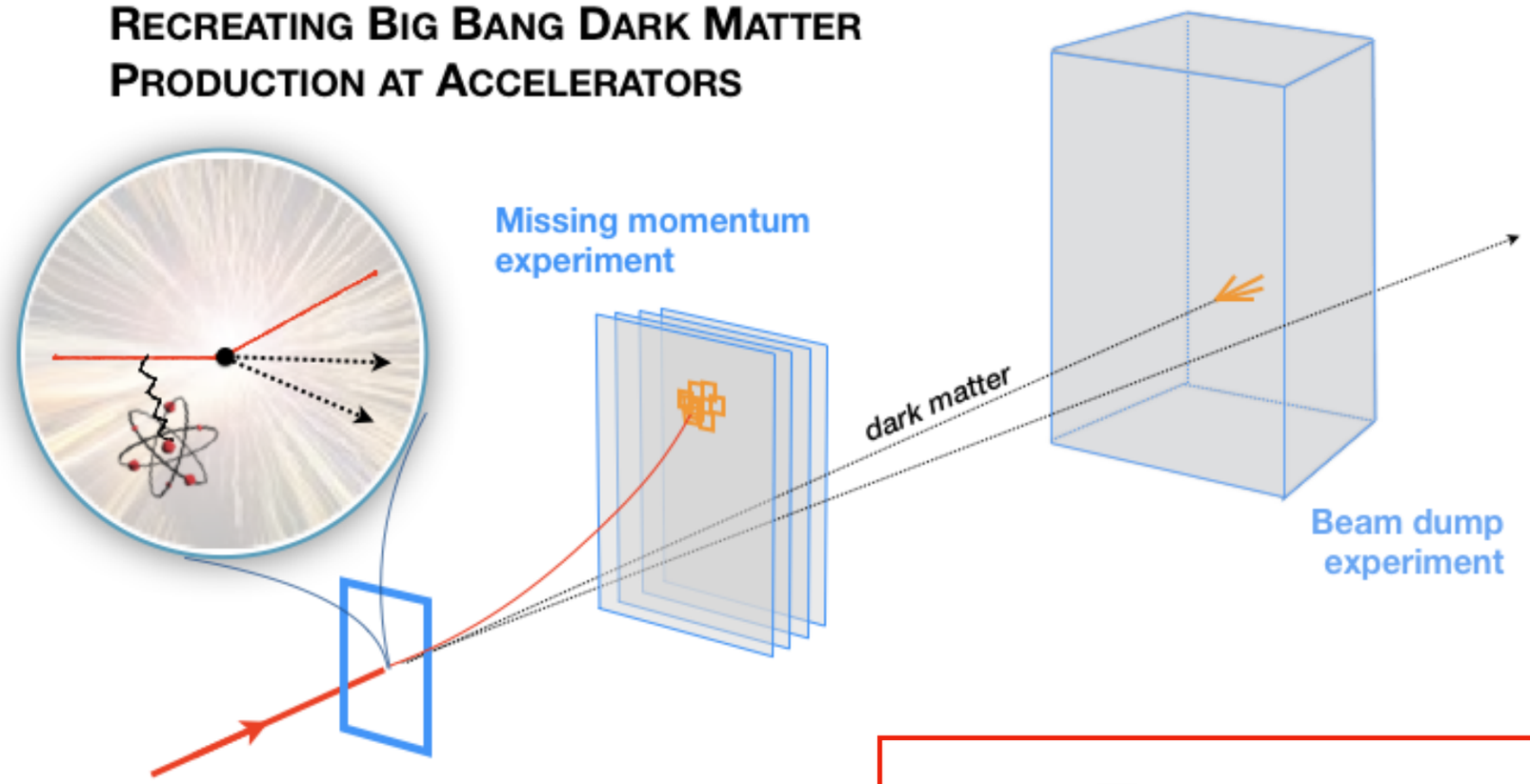
Covers predictive thermal production targets for muon-philic DM. Including models that also explain g-2 anomaly

Holst, Hooper, GK 2107.09067 PRL

Fermilab

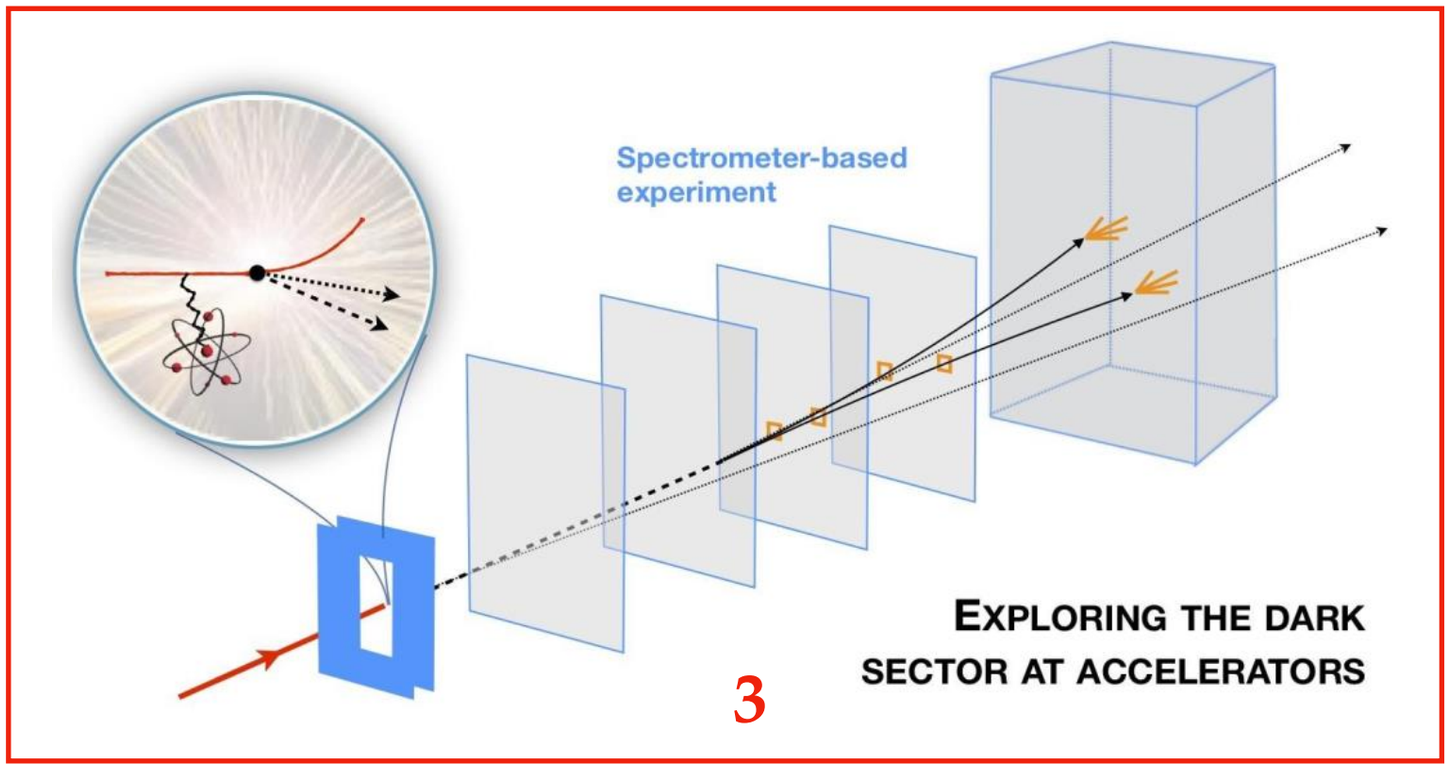
Kahn, GK, Tran, Whitbeck 1804.03144, LDRD supported

Three “Big Ideas”



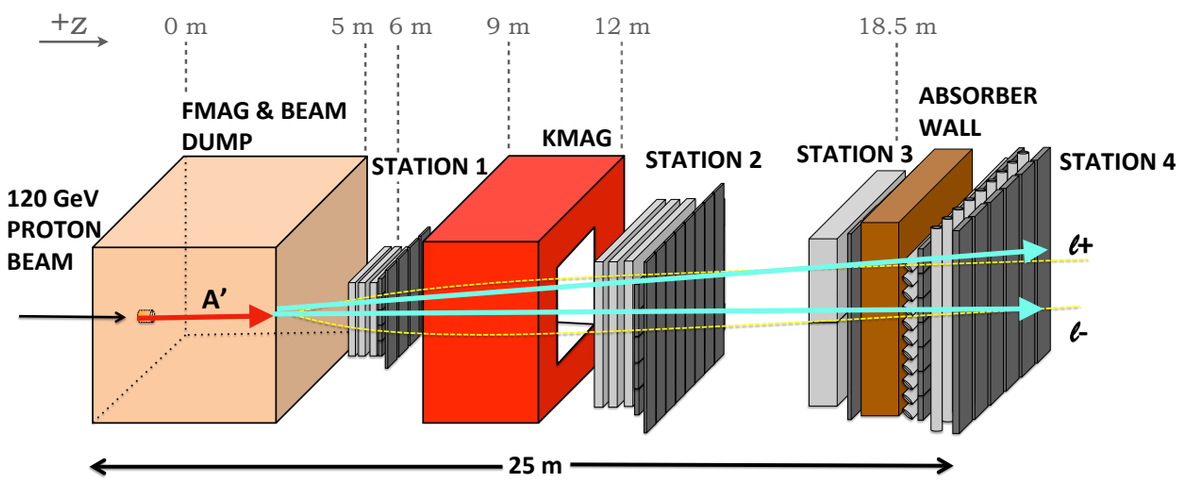
Probe DM’s “friends” w/ (semi) visible decays

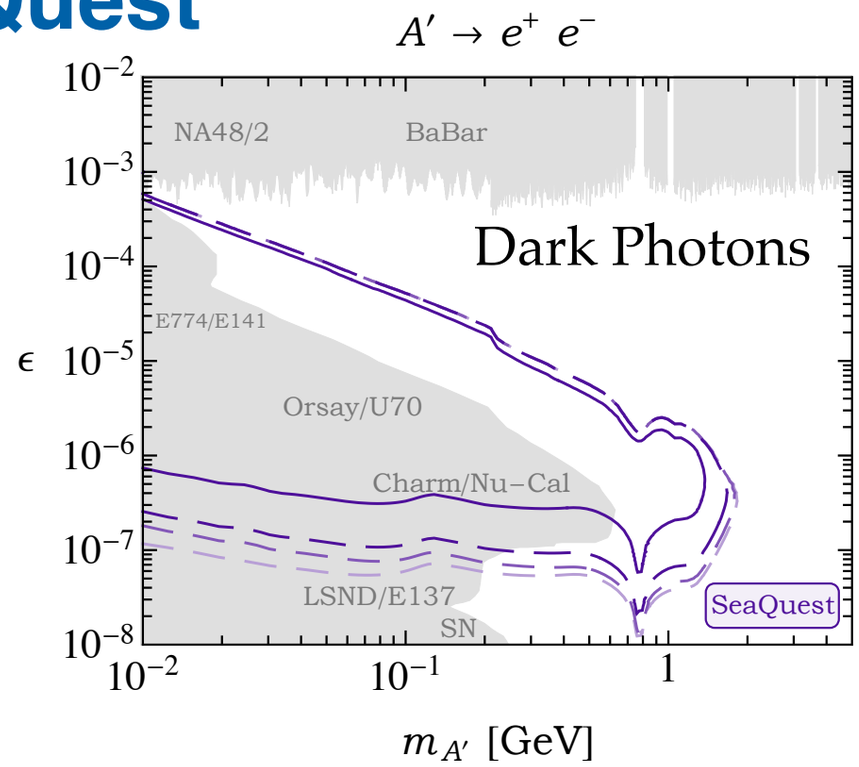
[+see Cari & Maxim’s talks]



DM New Initiatives BRN Report (Kolb++)
https://www.osti.gov/servlets/purl/1659757

Rich Dark Sectors @ FNAL Sea/SpinQuest

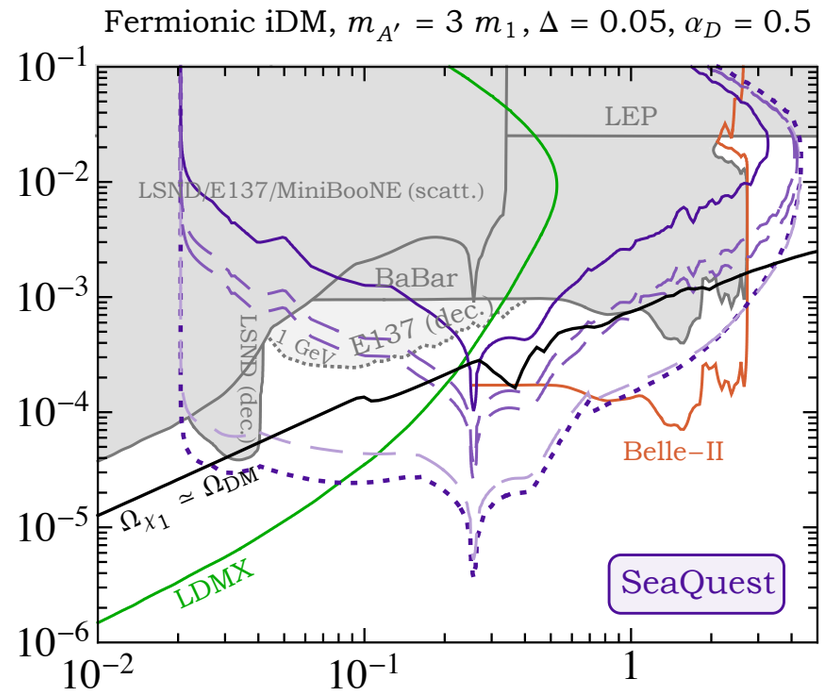




Proton spectrometer 120 GeV Main Injector
Designed to study muon Drell-Yan production

~1e20 POT w/ proposed installation of downstream ECAL

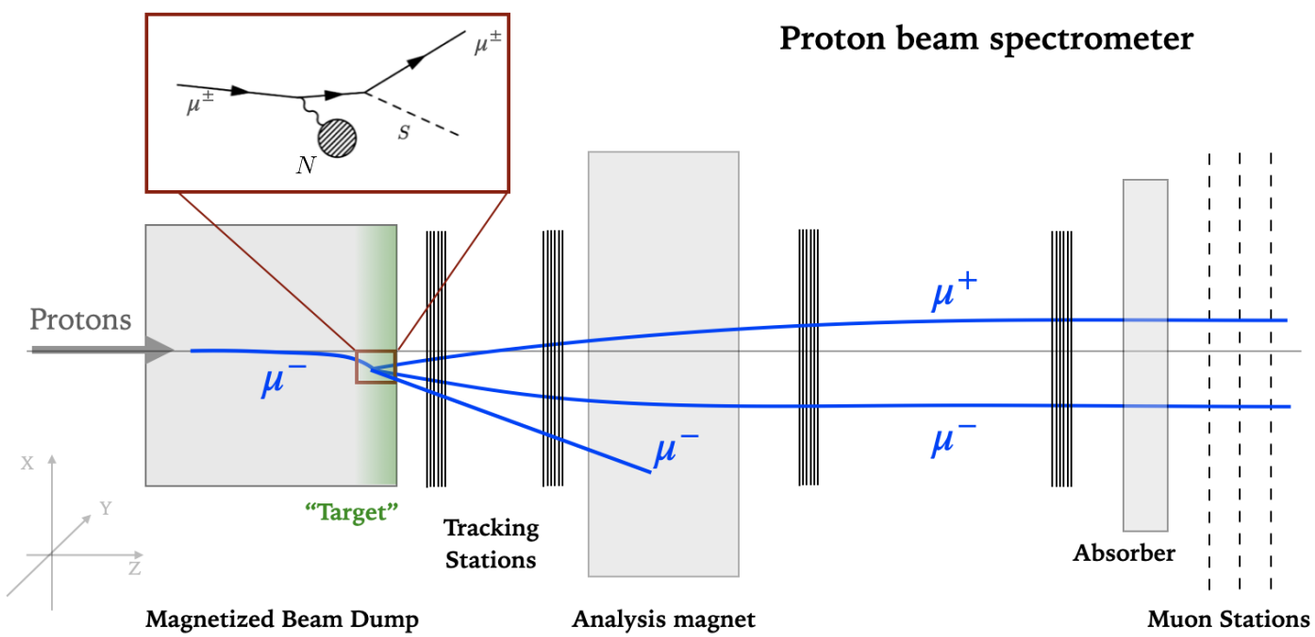
Sensitivity to rich dark sectors with ~ meter scale decays: dark photons, axion-like particles, inelastic DM

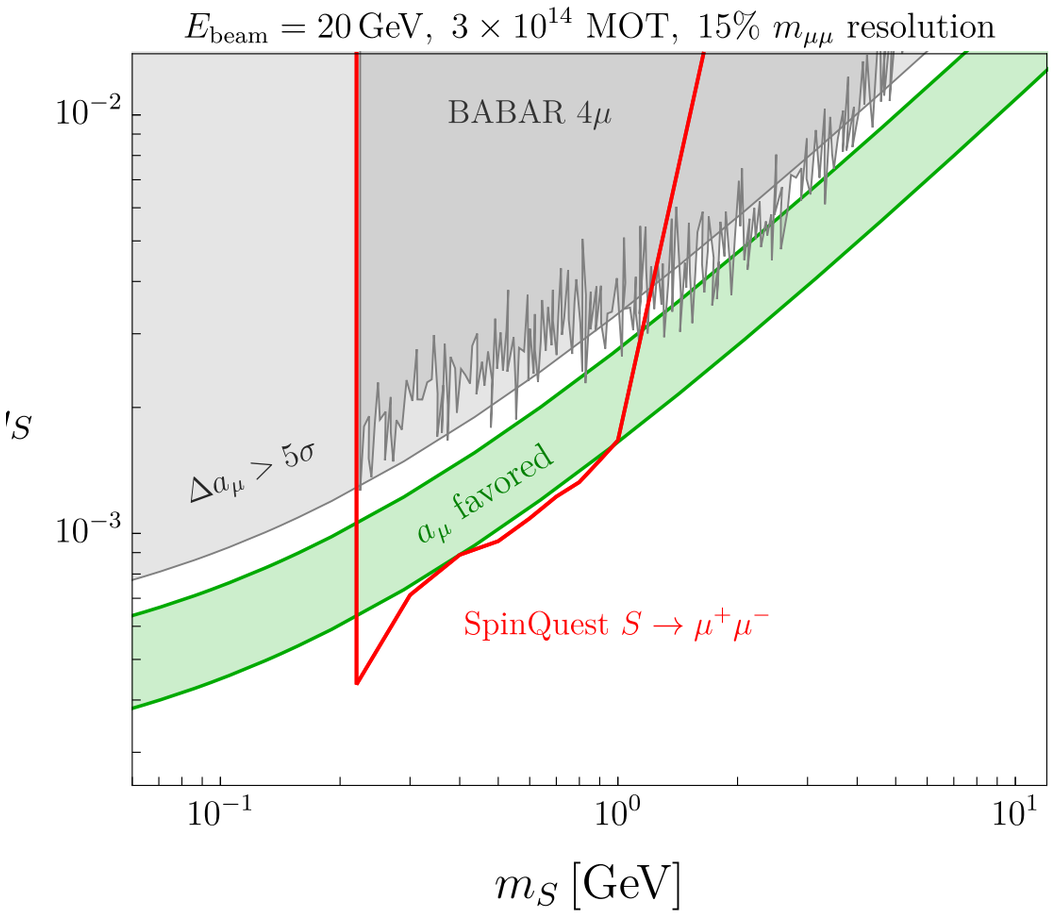


Inelastic DM decays

Berlin, Gori, Schuster, Toro 1804.00661

Muonic Forces & g-2 @ FNAL SpinQuest





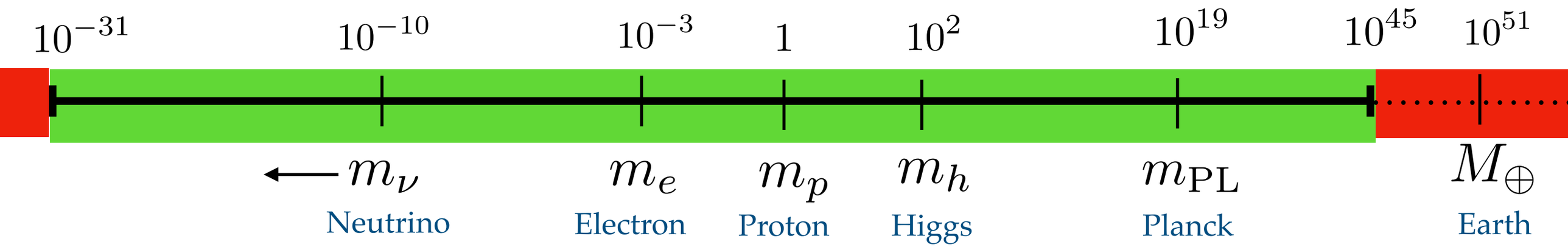
Proposed bump search for BSM dimuon decays at proton spectrometer

Parasitic on existing SpinQuest @ FNAL experiment

Coverage of low-mass BSM solutions to muon g-2

Forbes, Herwig, Kahn, GK, Suarez, Tran, Whitbeck 2212.00033

Concluding Remarks



DM search effort has vastly expanded in scope

Broader priors motivate wider mass range

"Big Ideas" for DM searches @ fixed targets

1) Beam Dumps (DM re-scatters in downstream detector)
2) Missing Energy / Momentum
3) Proton beam spectrometers

DMNI funding has kicked off new generation of fixed target searches

First round funding for LDMX (R&D) and
Coherent Captain Mills (currently running)

Concluding Remarks

Experiment	Facility	Beam Config	Beam Energy	Det Signature	Timeline	Refs.
US-based						
HPS	CEBAF @ JLab	electron FT	1-6 GeV	LLP	running	section 3.15, [16]
COHERENT	SNS @ ORNL	proton FT	1 GeV	rescattering	running	section 4.5, [17]
CCM	LANSE @ LANL	proton FT	0.8 GeV	rescattering	running	[18]
SpinQuest/DarkQuest	MI @ FNAL	proton FT	120 GeV	LLP	construction, proposed upgrade	section 3.5, [19]
LDMX	LESA @ SLAC	electron FT	4-8 GeV	Missing X	R&D funding, 2024	section 3.17, [20]
BDX	CEBAF @ JLab	electron BD	11 GeV	rescattering, Millicharged	proposed	section 3.1, [21]
JPOS	CEBAF @ JLab	positron FT	11 GeV	Missing X	proposed	section 3.16, [22]
PIP-II BD	PIP-II @ FNAL	proton FT	1 GeV	rescattering, LLP	proposed (2029)	section 3.23, [23]
SBN-BD	Booster @ FNAL	proton BD	8 GeV	rescattering	proposed (2029)	[24]
REDTOP	TBD	proton FT	1-5 GeV	Missing X, LLP, Prompt	proposed	section 3.25, [25]
M^3	MI @ FNAL	muon FT	15 GeV muons	Missing X	proposed	[26]
FNAL-μ	muon campus @ FNAL	muon FT	3 GeV	LLP	proposed	section 3.13, [27]
International						
Belle-II	SuperKEKB @ KEK	e+e- collider	150 MeV	Missing X, LLP, Prompt	running	section 3.2, [28]
CODEX-β	LHC @ CERN	pp collider	6.5-7 TeV	LLP	construction (2023)	section 3.4, [29]
CODEX-b	LHC @ CERN	pp collider	6.5-7 TeV	LLP	proposed (2026)	section 3.3, [30]
LHCb	LHC @ CERN	pp collider	6.5-7 TeV	LLP, Prompt	running, future upgrade planned	section 3.18, [31]
NA62	SPS-H4 @ CERN	proton BD	400 GeV	LLP	dedicated running planned	[32]
FASERnu	LHC @ CERN	pp collider	6.5-7 TeV	rescattering	running	section 3.9, [33]
milliQAN	LHC @ CERN	pp collider	6.5-7 TeV	Millicharged	running	section 3.19, [34]
DarkMESA	MESA @ Mainz	Electron FT	150 MeV	rescattering, LLP	construction (2023)	section 3.6
NA64-e	SPS-H4 @ CERN	electron FT	100-150 GeV	Missing X, Prompt	running	section 3.20, [35]
NA64-mu	SPS-M2 @ CERN	muon FT	100-160 GeV	Missing X	commissioning	section 3.21
NA64/POKER	SPS-H4 @ CERN	positron FT	100 GeV	Missing X	planned (2024)	section 3.24, [35]
PIONEER	πE5 @ PSI	proton FT	10-20 MeV pions	Prompt	planned (2028)	section 3.22, [36]
FASER2	FPF @ CERN	pp collider	6.5-7 TeV	LLP	proposed (2029)	section 3.8 [37]
FORMOSA	FPF @ CERN	pp collider	6.5-7 TeV	Millicharged	proposed (2029)	section 3.14, [38]
FASERnu2	FPF @ CERN	pp collider	6.5-7 TeV	rescattering	proposed (2029)	section 3.10, [33]
FLArE	FPF @ CERN	pp collider	6.5-7 TeV	rescattering	proposed (2029)	section 3.12, [39]
SND@LHC	LHC @ CERN	pp collider	6.5-7 TeV	rescattering	running	section 3.27, [40]
Advanced SND@LHC	FPF	pp collider	6.5-7 TeV	rescattering	proposed (2029)	section 3.27, [40]

Many new existing/proposed experiments!

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