Title: Accelerating our Understanding of Dark Matter

Date: May 06, 2015 02:00 PM

URL: http://pirsa.org/15050040

Abstract: <p>Most of the matter in the Universe is dark; determining the composition and interactions of this dark matter is among the defining challenges in particle physics today. I will briefly summarize the present status of dark matter searches and the case for exploration beyond the WIMP paradigm, particularly â€œlight dark matterâ€• close to but beneath the weak scale. I will define sharp milestones in sensitivity needed to decisively explore the best-motivated light dark matter scenarios, and describe experimental techniques to reach these milestones over the next several years.</p>

WHAT ARE WE MADE OF?

(The Standard Model)

Principled

+Relativity
+Quantum
Mechanics

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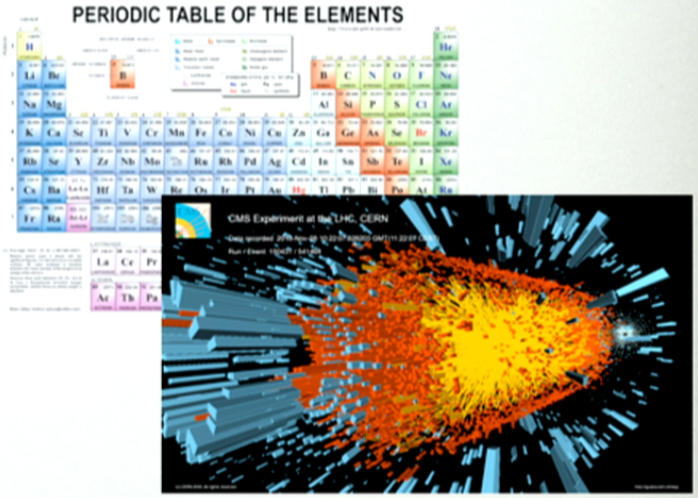
Predictive



WHAT ARE WE MADE OF?

(The Standard Model)

Principled

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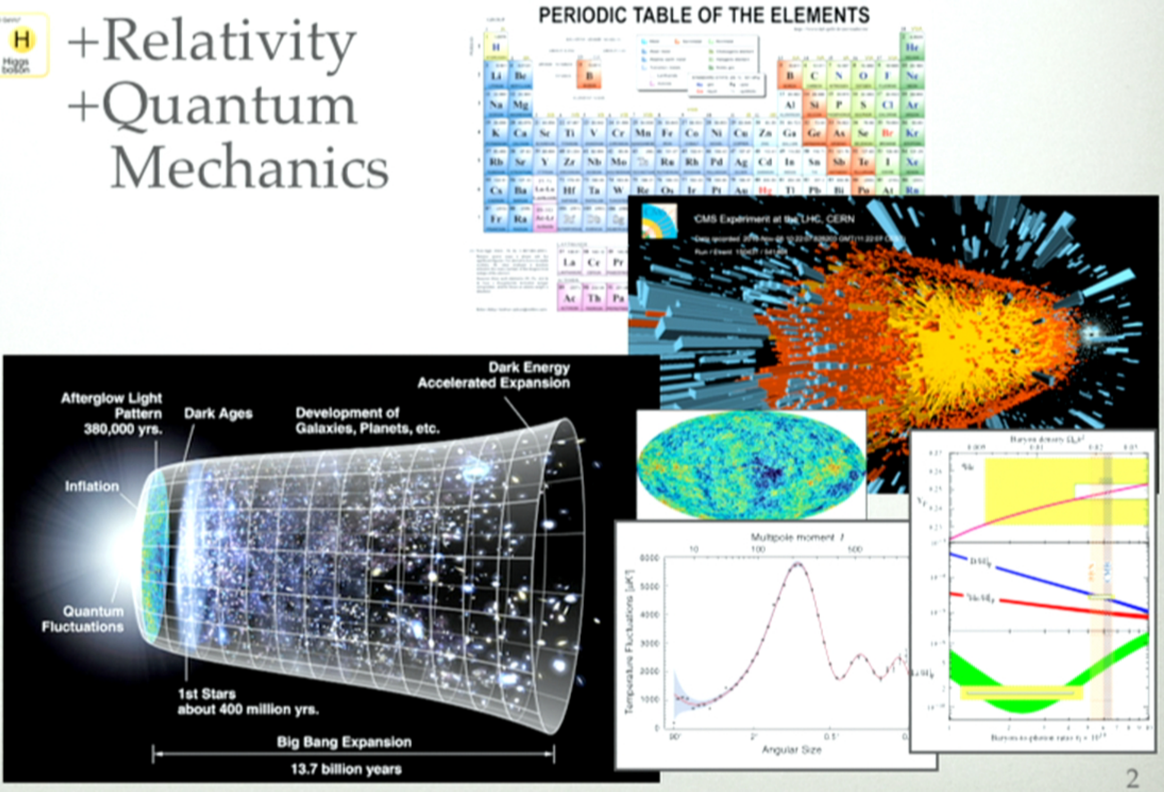
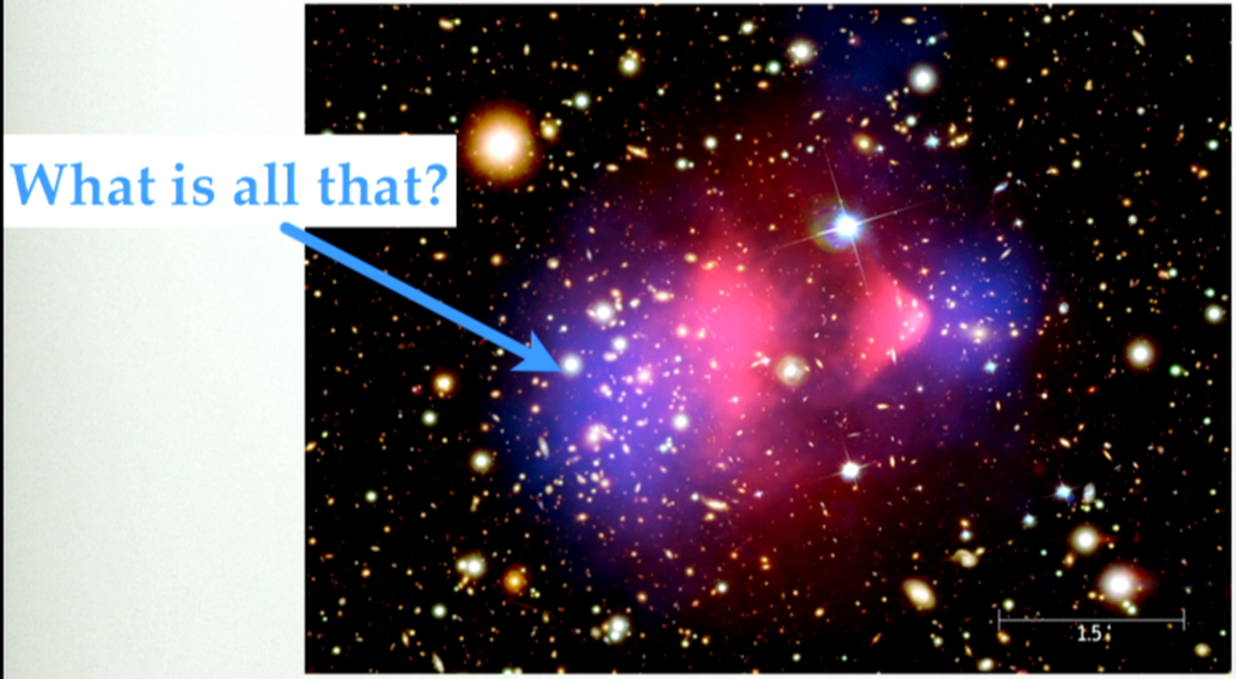
Powerful



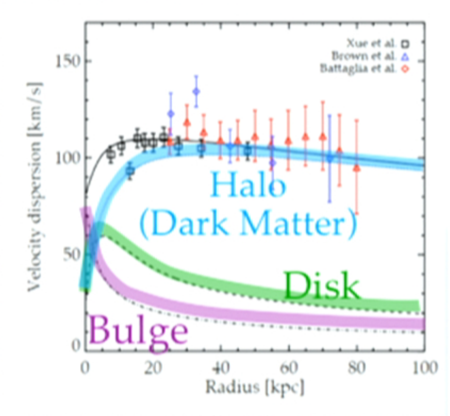
WHAT ARE WE MADE OF?



What is all that?

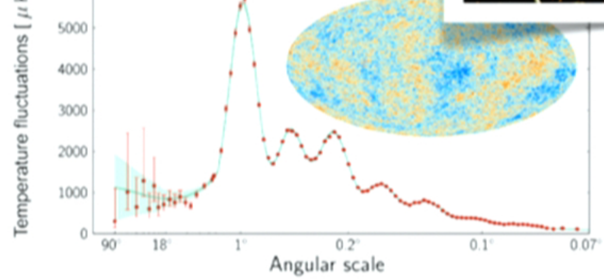
NATURE'S DARK SECTOR

Rotation Curves

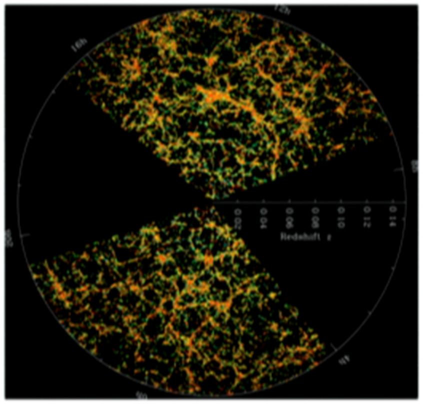


Cluster collisions

Gravitational lensing

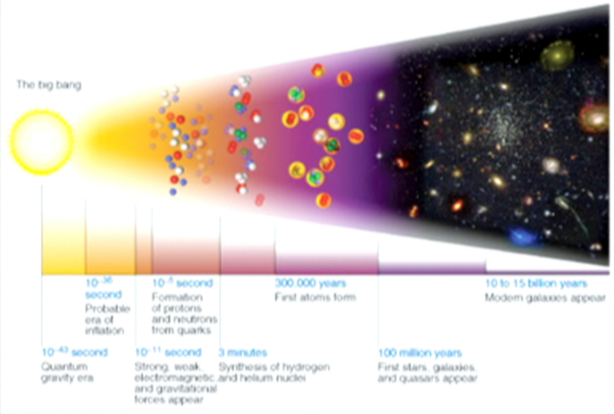


CMB Power Spectrum



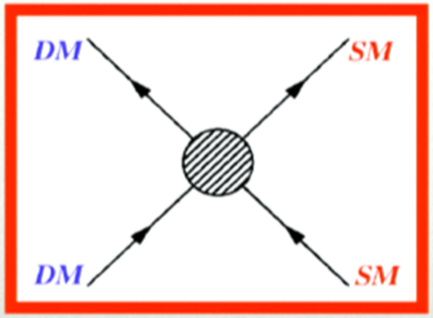
Large-scale Structure

A SUGGESTIVE HINT?

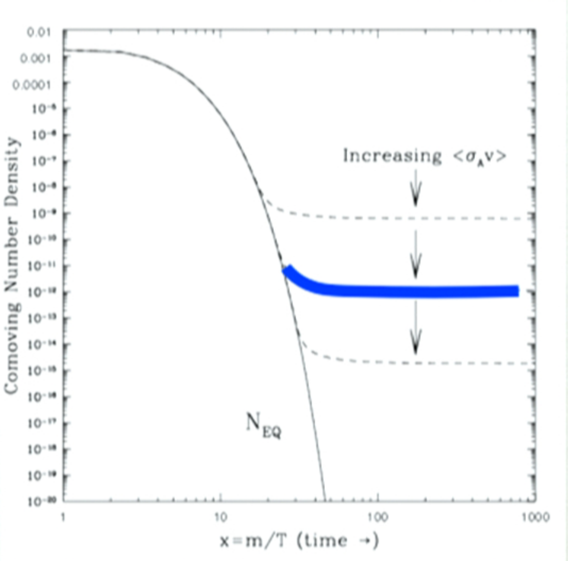


As Universe cools below DM mass, density decreases as $e^{-m/T}$

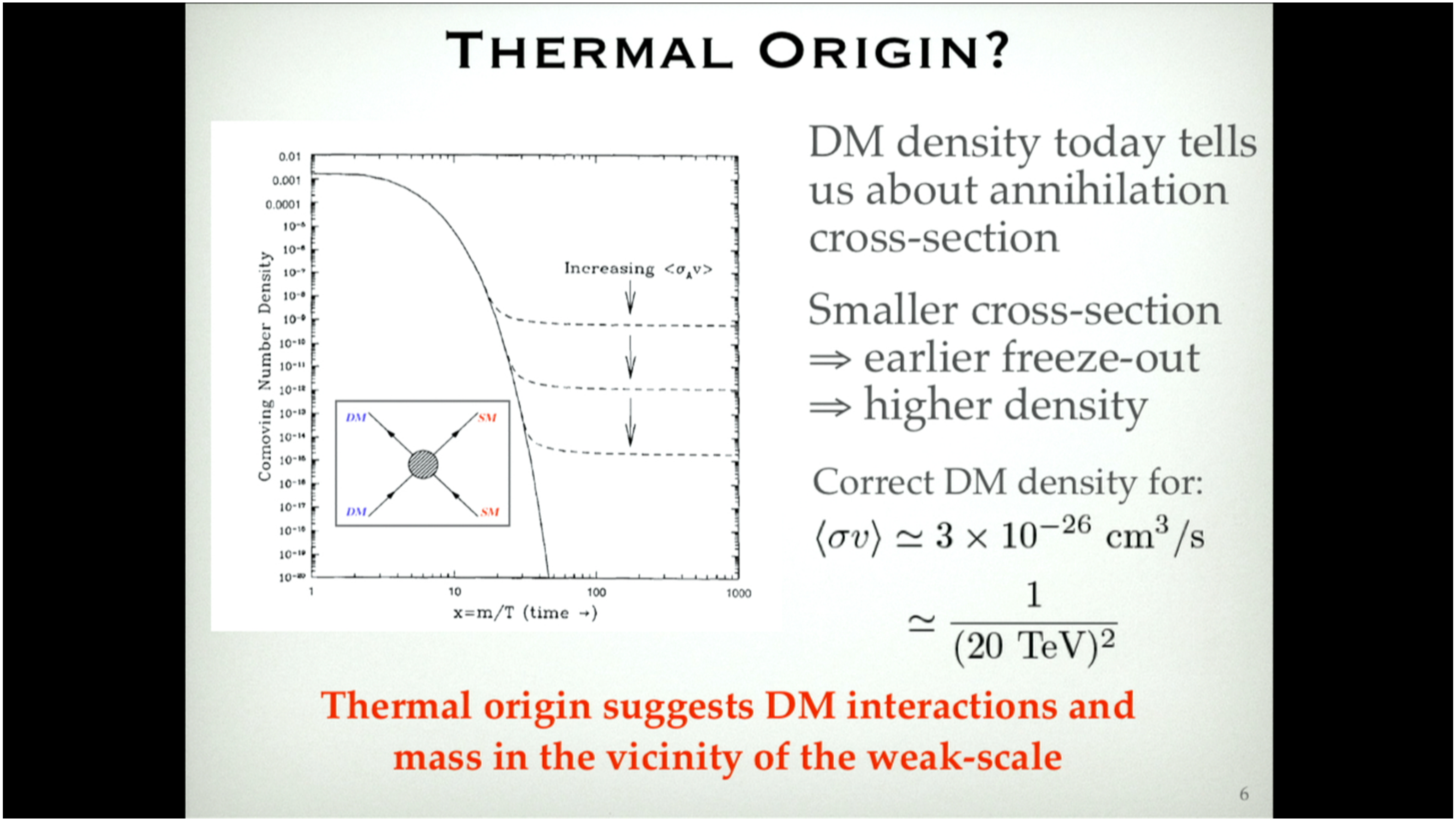
Dark Matter interacts with SM to stay in equilibrium…



Eventually dark matter particles can't find each other to annihilate



and a (minimal) DM abundance is left over to the present day



THERMAL ORIGIN?

DM density today tells us about annihilation cross-section

Smaller cross-section
⇒ earlier freeze-out
⇒ higher density

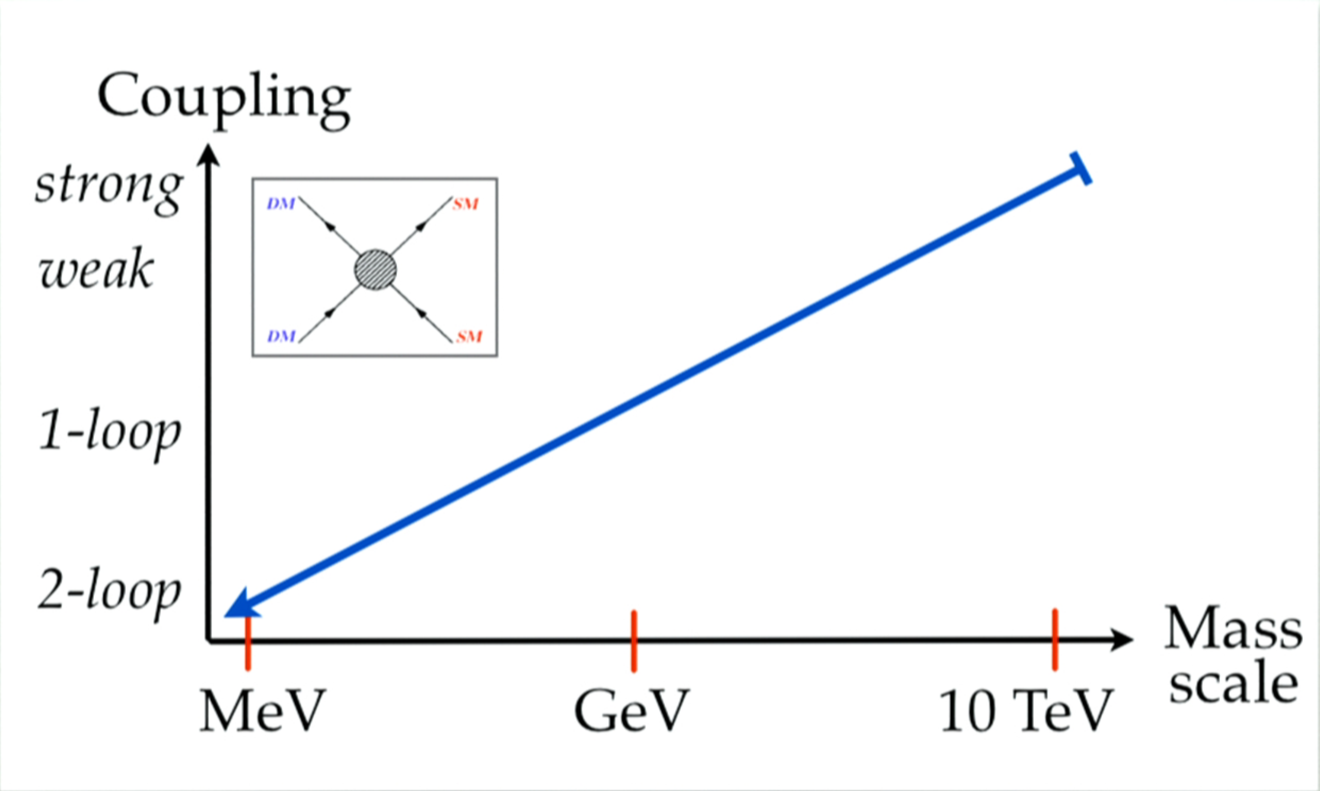
Correct DM density for:

$$\langle \sigma v \rangle \simeq 3 \times 10^{-26}\ \mathrm{cm}^3/\mathrm{s}$$

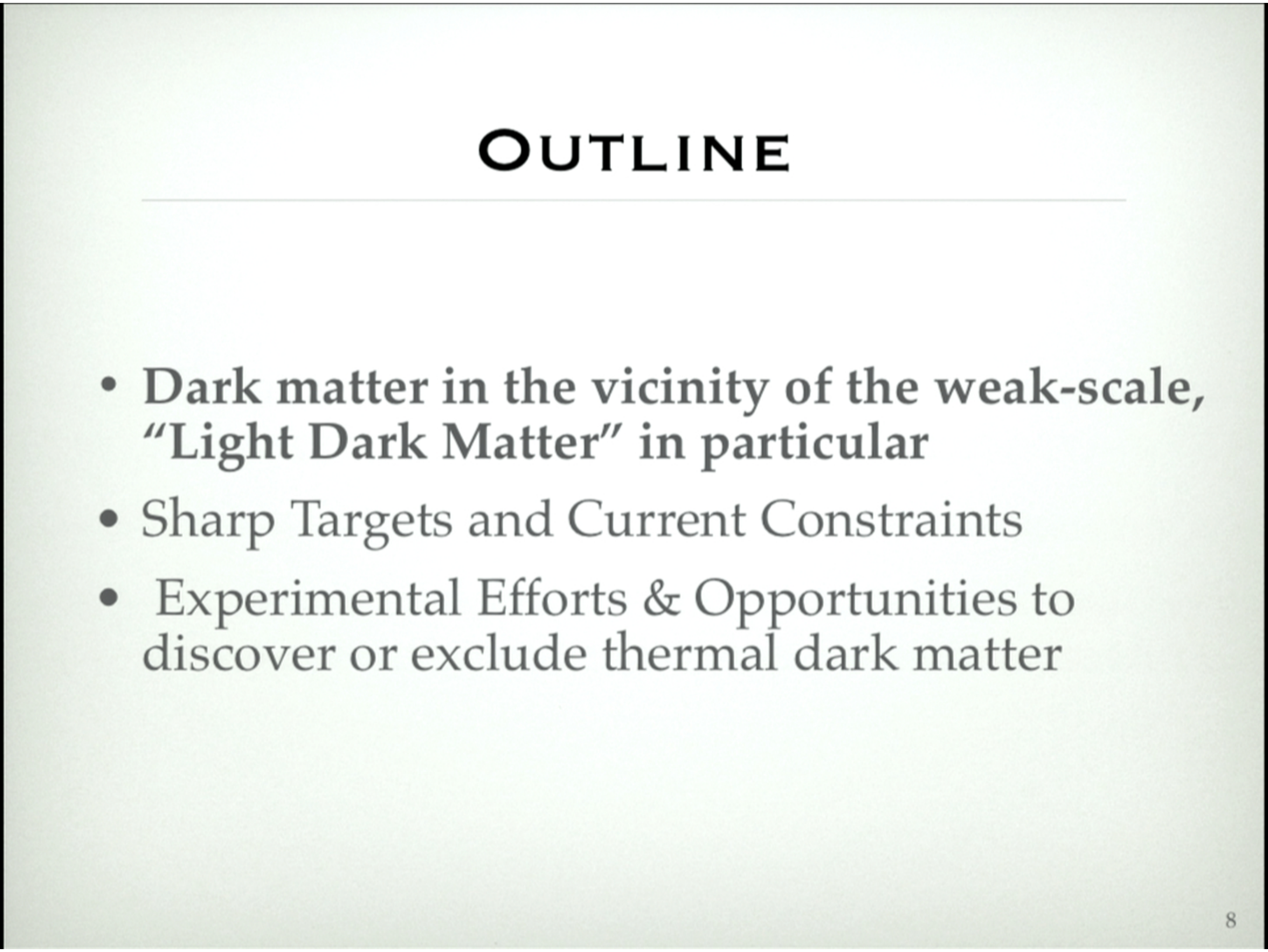
$$\simeq \frac{1}{(20\ \mathrm{TeV})^2}$$

Thermal origin suggests DM interactions and mass in the vicinity of the weak-scale

THERMAL ORIGIN AND INTERACTIONS



How do we test this idea broadly?



OUTLINE

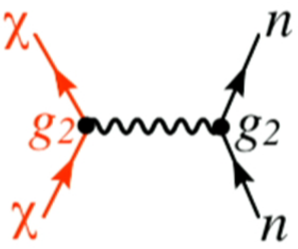
- **Dark matter in the vicinity of the weak-scale, "Light Dark Matter" in particular**
- Sharp Targets and Current Constraints
- Experimental Efforts & Opportunities to discover or exclude thermal dark matter

CANONICAL EXAMPLE: WIMP

(weakly interacting massive particle)

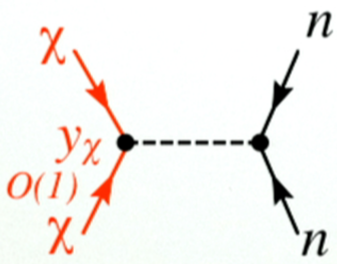
For ~100 GeV DM mass, weak-scale mediators provide reasonable annihilation rate and range of DM-scattering rates

e.g. Z-mediated:



$$\sigma_n \sim \frac{\alpha_2^2 \mu_n^2}{m_Z^4} \sim 10^{-38}\ \mathrm{cm}^2$$

higgs-mediated:

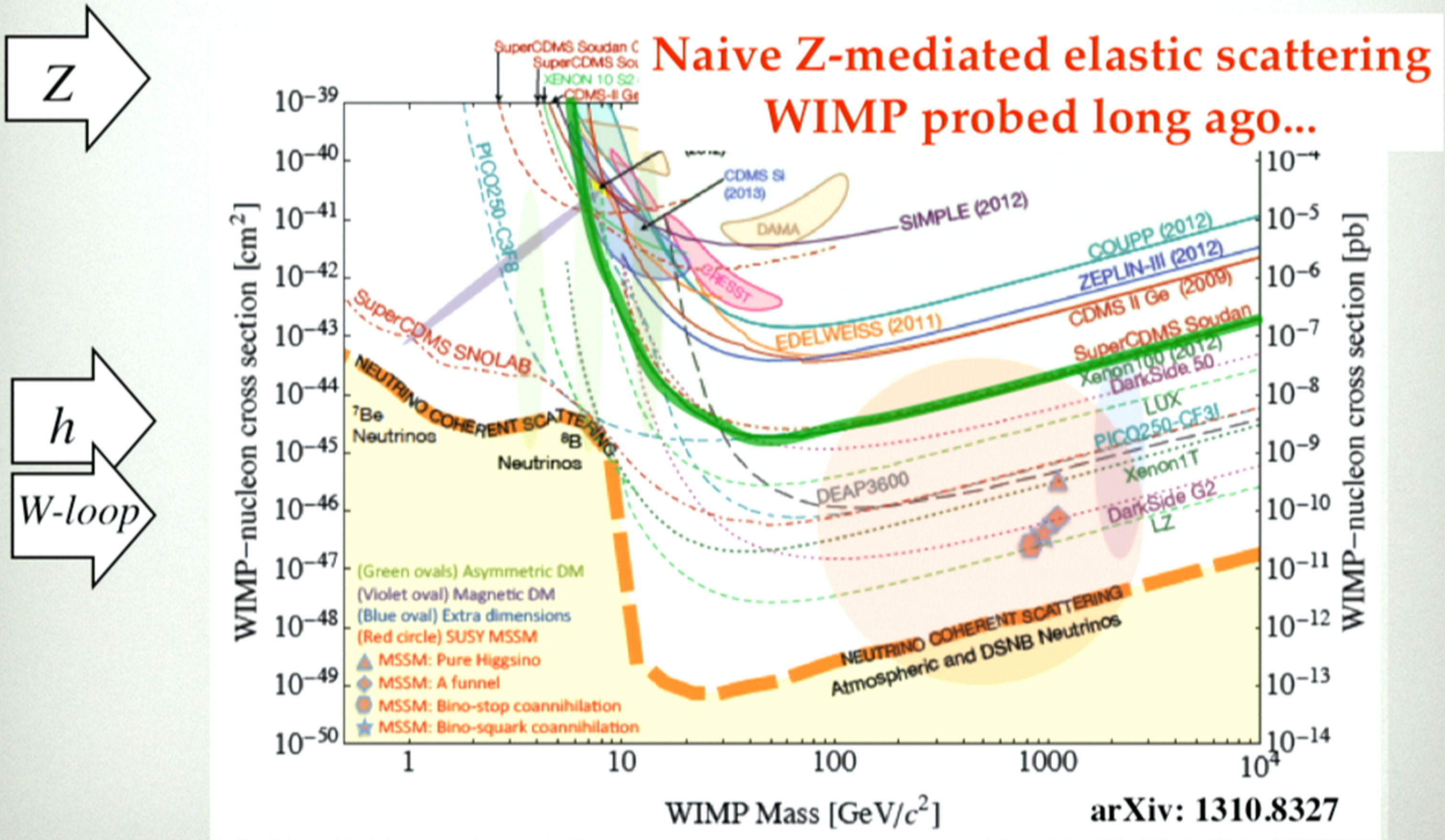


$$\sigma_n \lesssim 10^{-44}\ \mathrm{cm}^2$$

W-loop mediated a bit smaller than higgs-mediated

DIRECT DETECTION PROGRAM

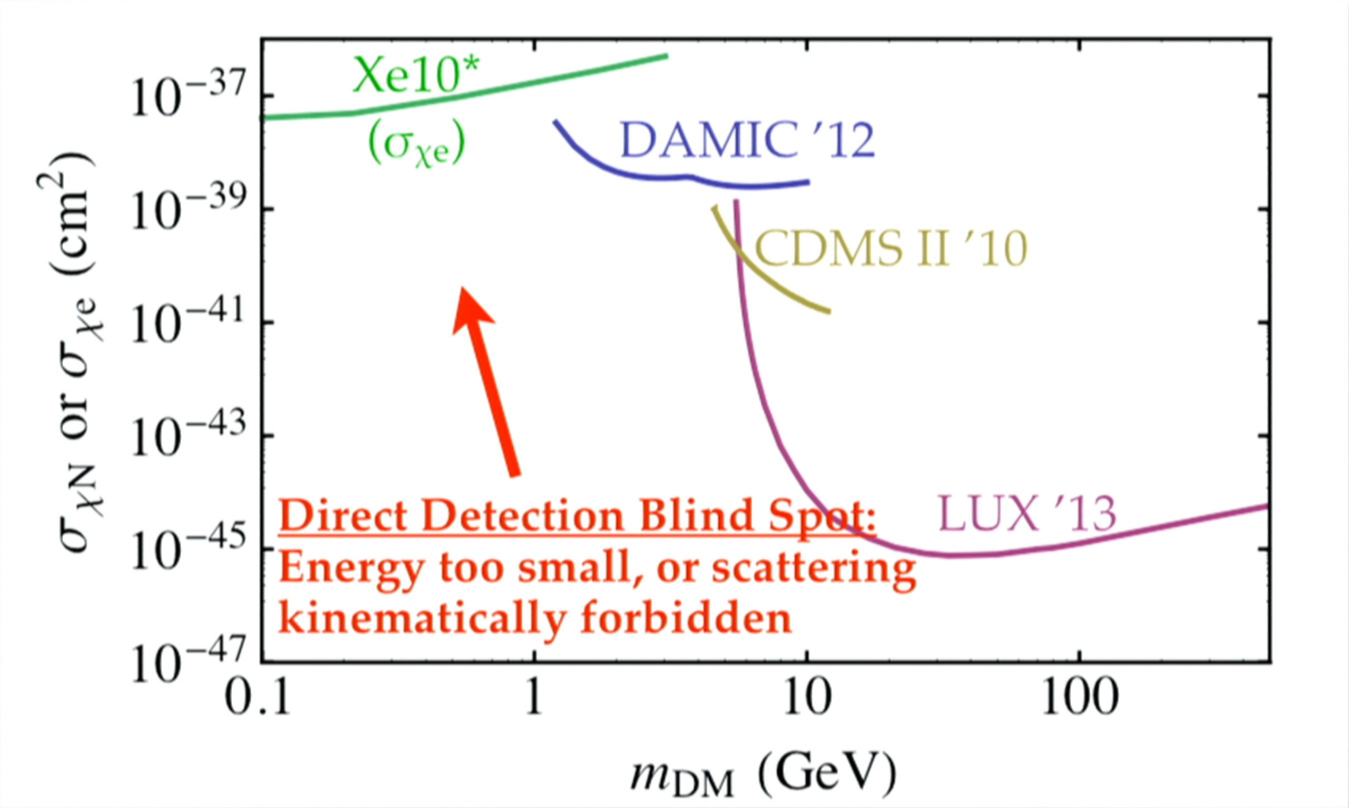
Dark matter searches target the WIMP paradigm



Naive Z-mediated elastic scattering WIMP probed long ago...

arXiv: 1310.8327

WHAT ARE WE MISSING?



Direct Detection Blind Spot:
Energy too small, or scattering kinematically forbidden

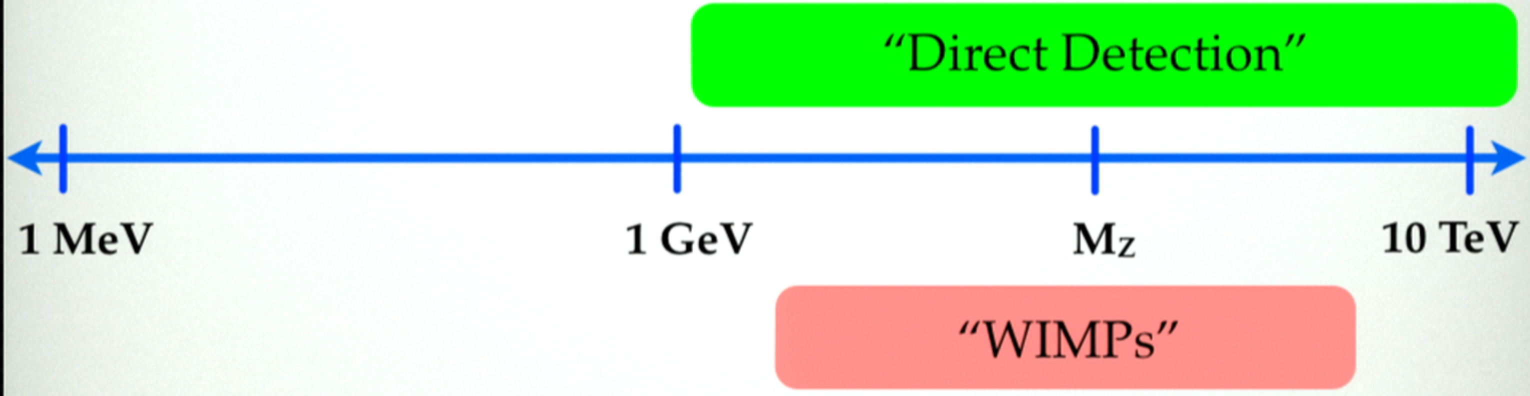
Big blind spots -- is this a problem for the science?

TESTING THERMAL DM

(an overly simplified view)

Laboratory probes that reach “milestone sensitivity”:

(will discuss colliders momentarily)



Nod bad if we only care about testing WIMPs...

TESTING THERMAL DM

(an overly simplified view)

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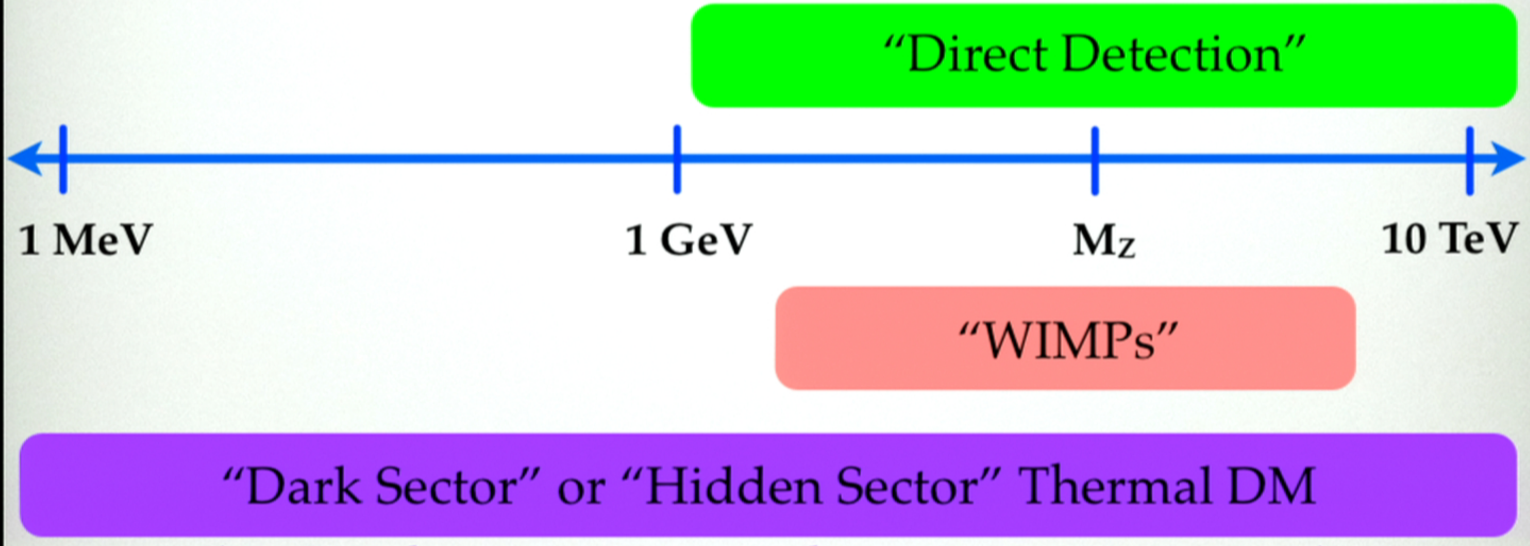


"Direct Detection"

1 MeV

1 GeV

M_Z

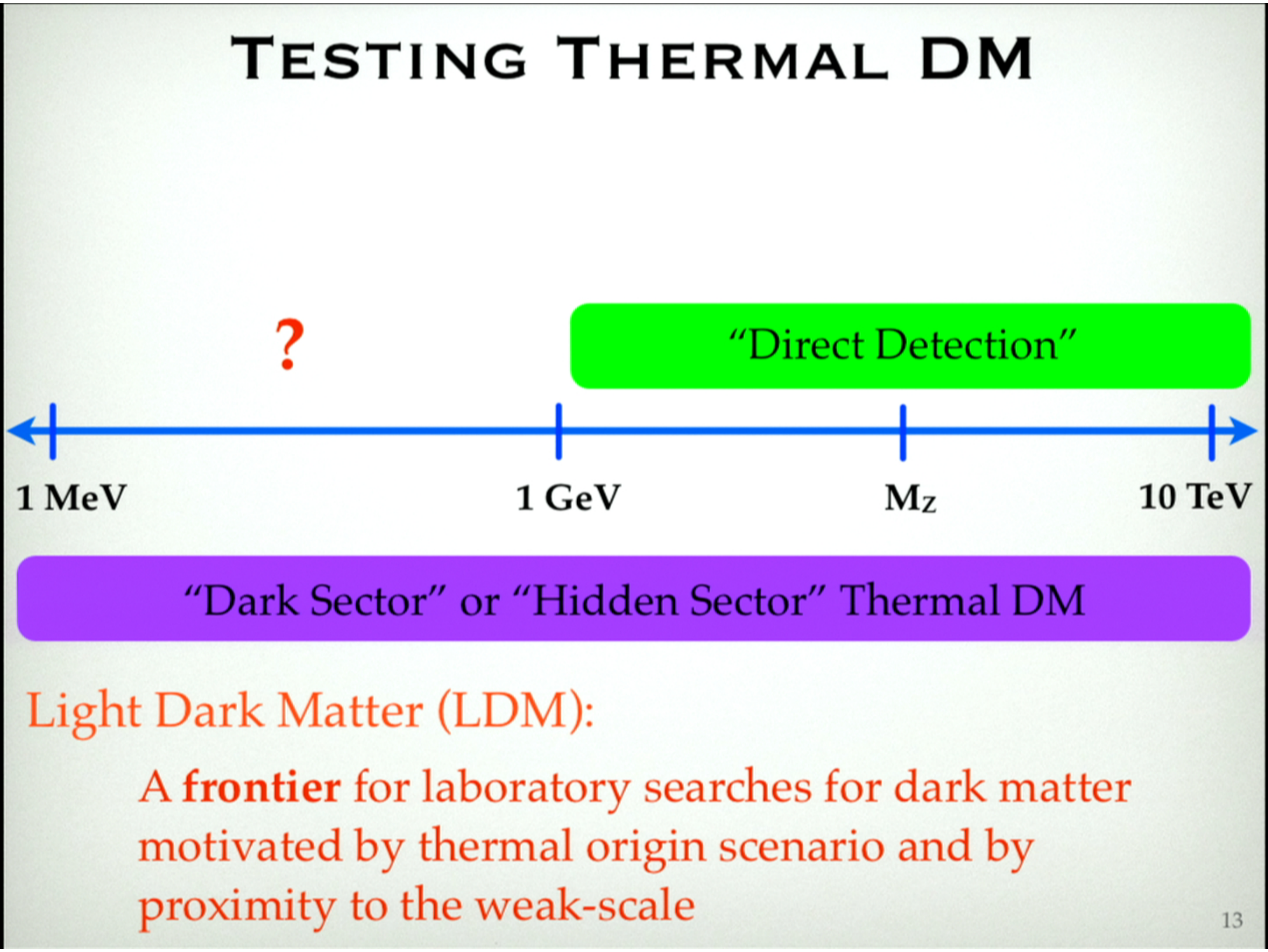
10 TeV

"WIMPs"

"Dark Sector" or "Hidden Sector" Thermal DM

(i.e. DM that is not directly charged under SM forces)

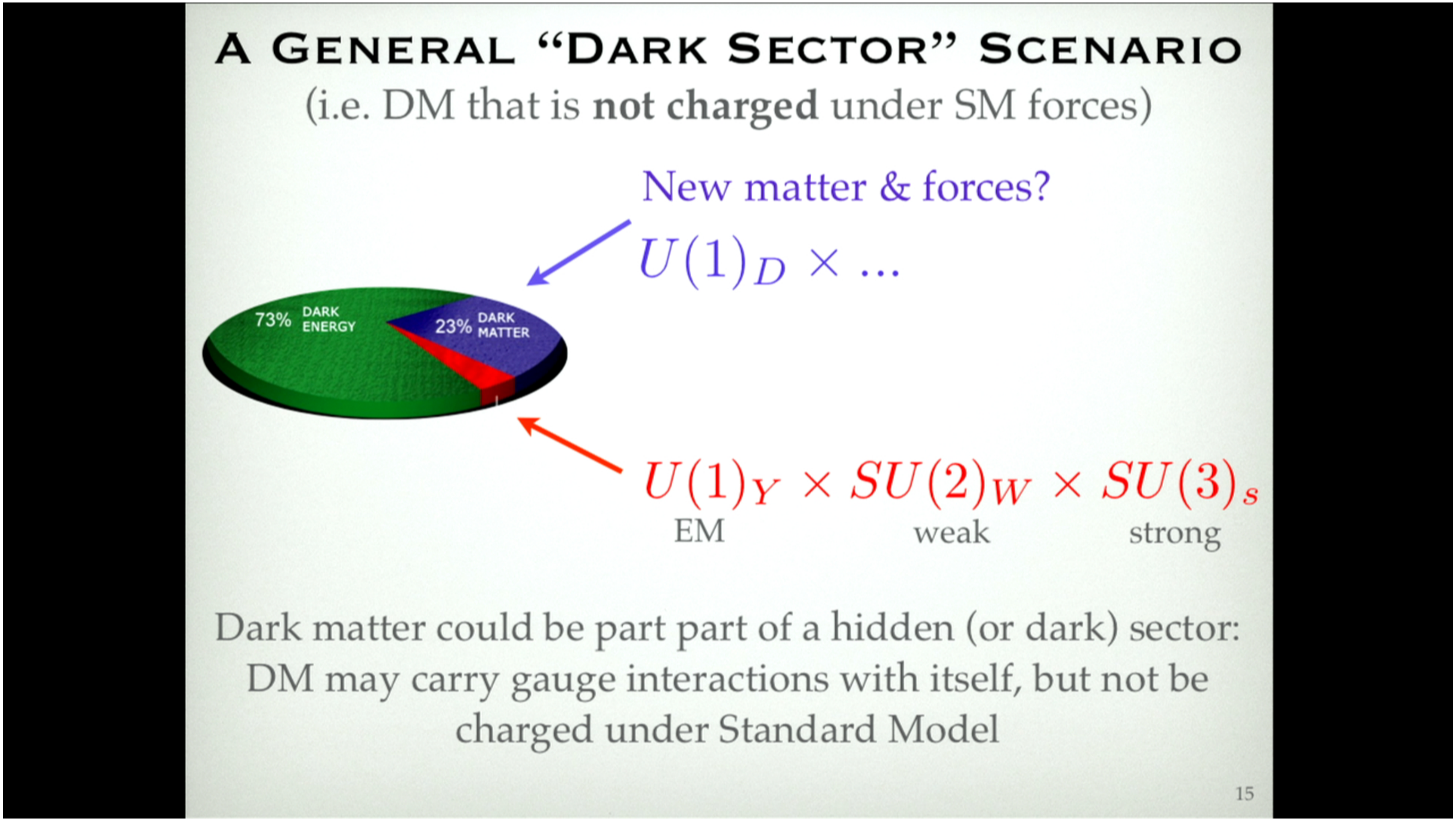
We are failing to test the thermal origin idea!



TESTING THERMAL DM

Light Dark Matter (LDM):

A **frontier** for laboratory searches for dark matter motivated by thermal origin scenario and by proximity to the weak-scale



A GENERAL "DARK SECTOR" SCENARIO

(i.e. DM that is **not charged** under SM forces)

New matter & forces?

$$U(1)_D \times \ldots$$

$$U(1)_Y \times SU(2)_W \times SU(3)_s$$

EM weak strong

Dark matter could be part part of a hidden (or dark) sector: DM may carry gauge interactions with itself, but not be charged under Standard Model

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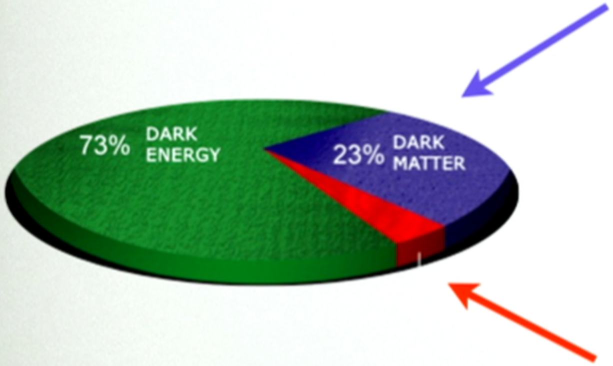


$U(1)_D \times \ldots$

$U(1)_Y \times SU(2)_W \times SU(3)_s$

EM weak strong

How do we test this possibility?

DARK SECTORS & THE “PORTALS”

Small number of interactions allowed by Standard Model symmetries with dimensionless couplings

this means they can be sizeable irrespective of “where” they come from

Vector Portal	$\frac{1}{2}\epsilon_Y\, F^Y_{\mu\nu} F'^{\mu\nu}$	kinetic mixing?
Higgs Portal	$\epsilon_h\, \lvert h\rvert^2 \lvert\phi\rvert^2$	exotic rare Higgs decays?
Neutrino Portal	$\epsilon_\nu\, (hL)\psi$	not-so-sterile neutrinos?

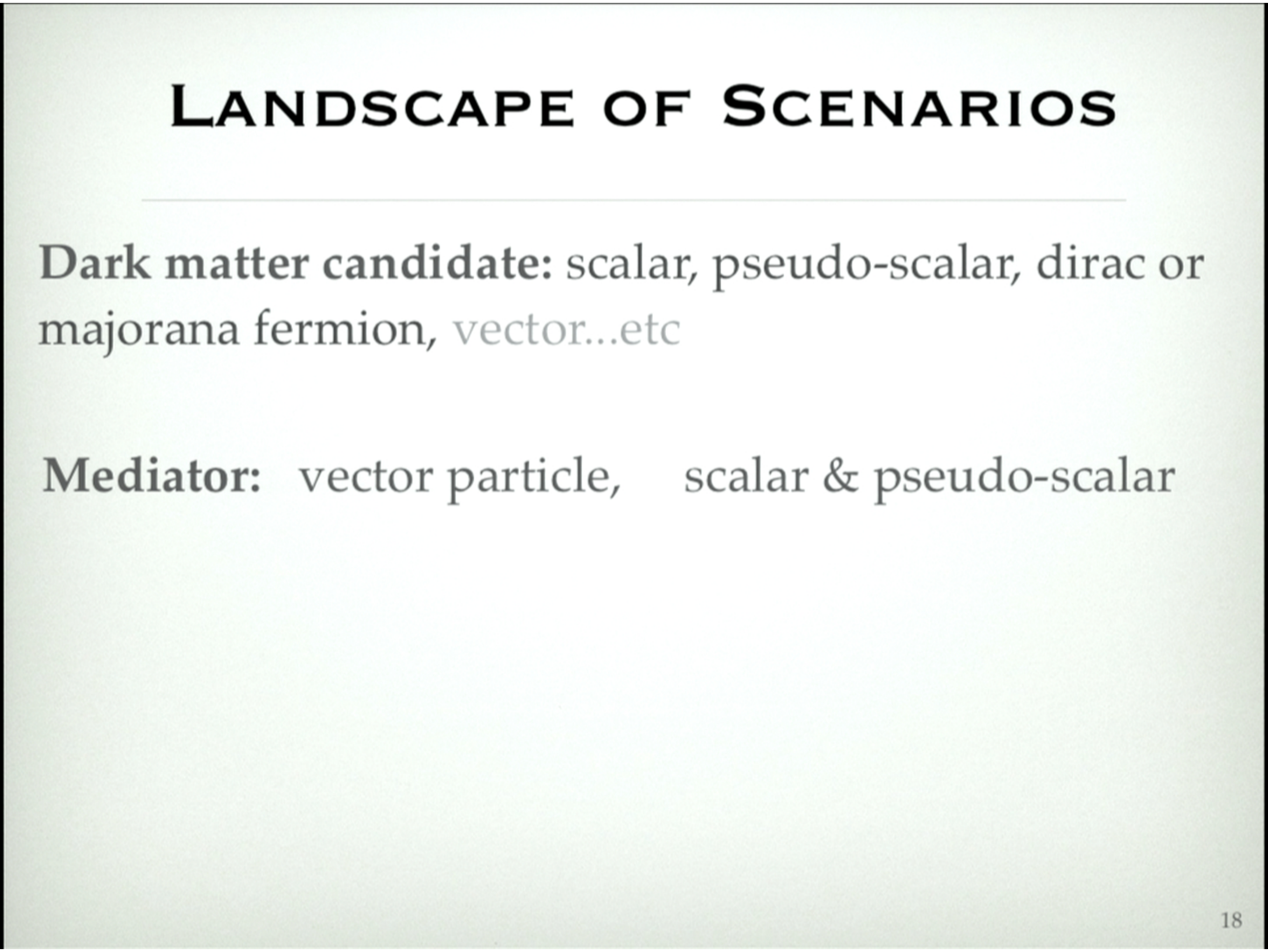
DARK SECTORS & THE "PORTALS"

Small number of interactions allowed by Standard Model symmetries with dimensionless couplings

this means they can be sizeable irrespective of "where" they come from

Organizing principle: focus on interaction type & search for salient signatures of each one

→ **tremendous simplification!**



LANDSCAPE OF SCENARIOS

Dark matter candidate: scalar, pseudo-scalar, dirac or majorana fermion, vector...etc

Mediator: vector particle, scalar & pseudo-scalar

LANDSCAPE OF SCENARIOS

Dark matter candidate: scalar, pseudo-scalar, dirac or majorana fermion, vector...etc

Mediator: vector particle, scalar & pseudo-scalar

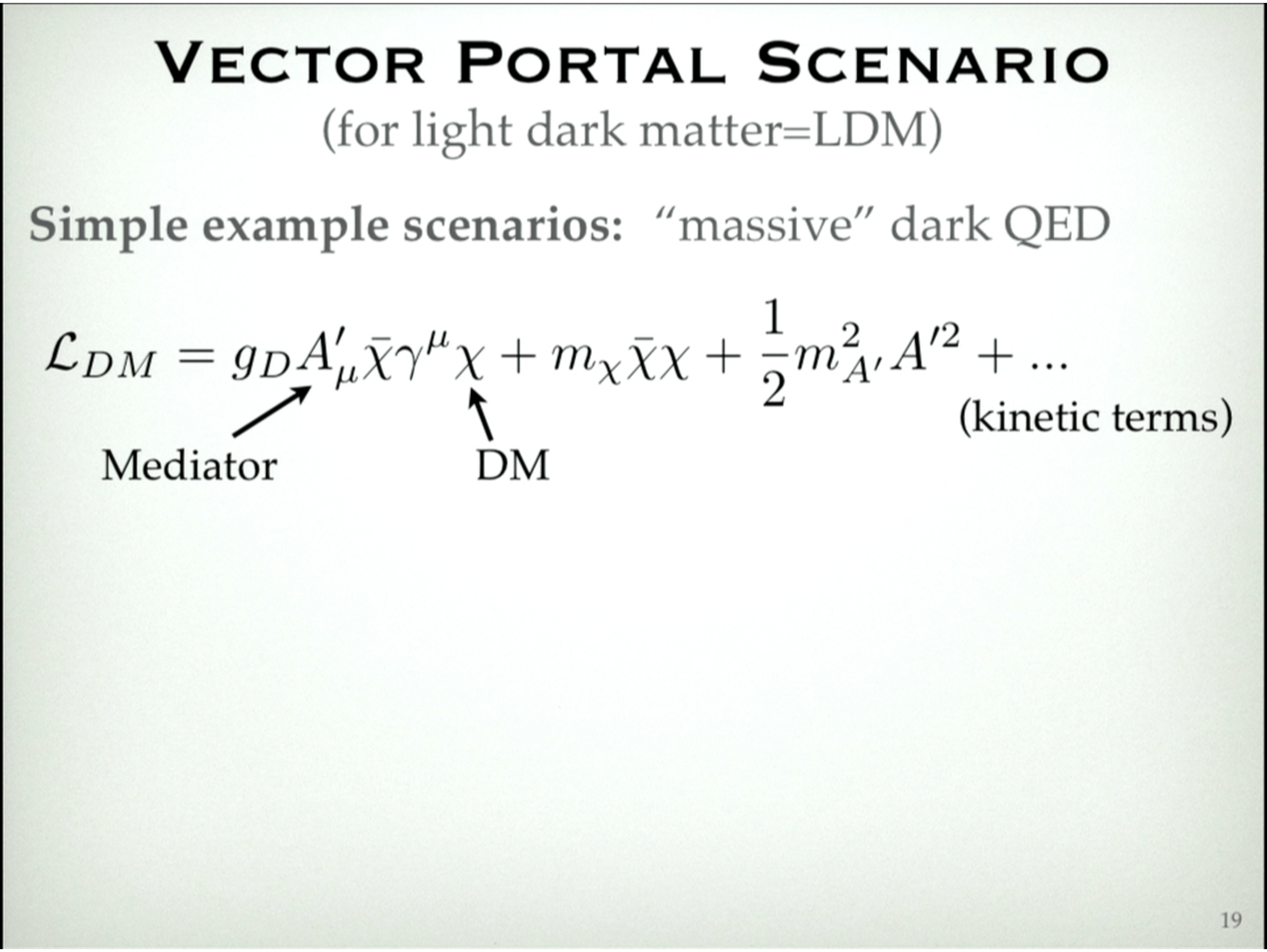
Can be traditional Z′(near weak-scale).

We will focus on kinetic mixing (“vector portal”)

works over large range of mass

Tightly constrained by rare meson decays (and other data), topic of another talk...

[work to appear]



VECTOR PORTAL SCENARIO

(for light dark matter=LDM)

Simple example scenarios: "massive" dark QED

$$\mathcal{L}_{DM} = g_D A'_\mu \bar{\chi}\gamma^\mu \chi + m_\chi \bar{\chi}\chi + \frac{1}{2} m_{A'}^2 A'^2 + \ldots$$

(kinetic terms)

Mediator

DM

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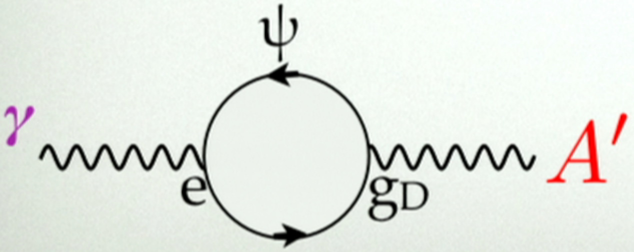
(kinetic terms)

Mediator

DM

Vector portal: $\mathcal{L}_{int} = \frac{1}{2}\epsilon_Y \, F^Y_{\mu\nu} F'^{\mu\nu}$

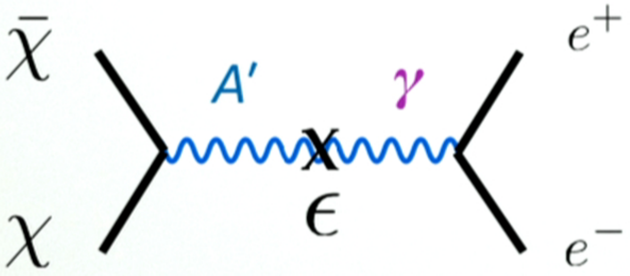


$$\epsilon \sim \frac{e\, g_D}{16\pi^2} \log \frac{m_\psi}{M_*} \sim 10^{-2} - 10^{-4}$$

VECTOR PORTAL SCENARIO

(for light dark matter=LDM)

Small interaction between dark sector and Standard Model:



+ other modes

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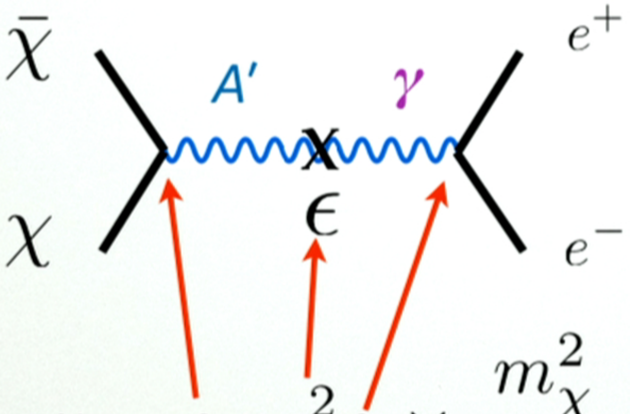
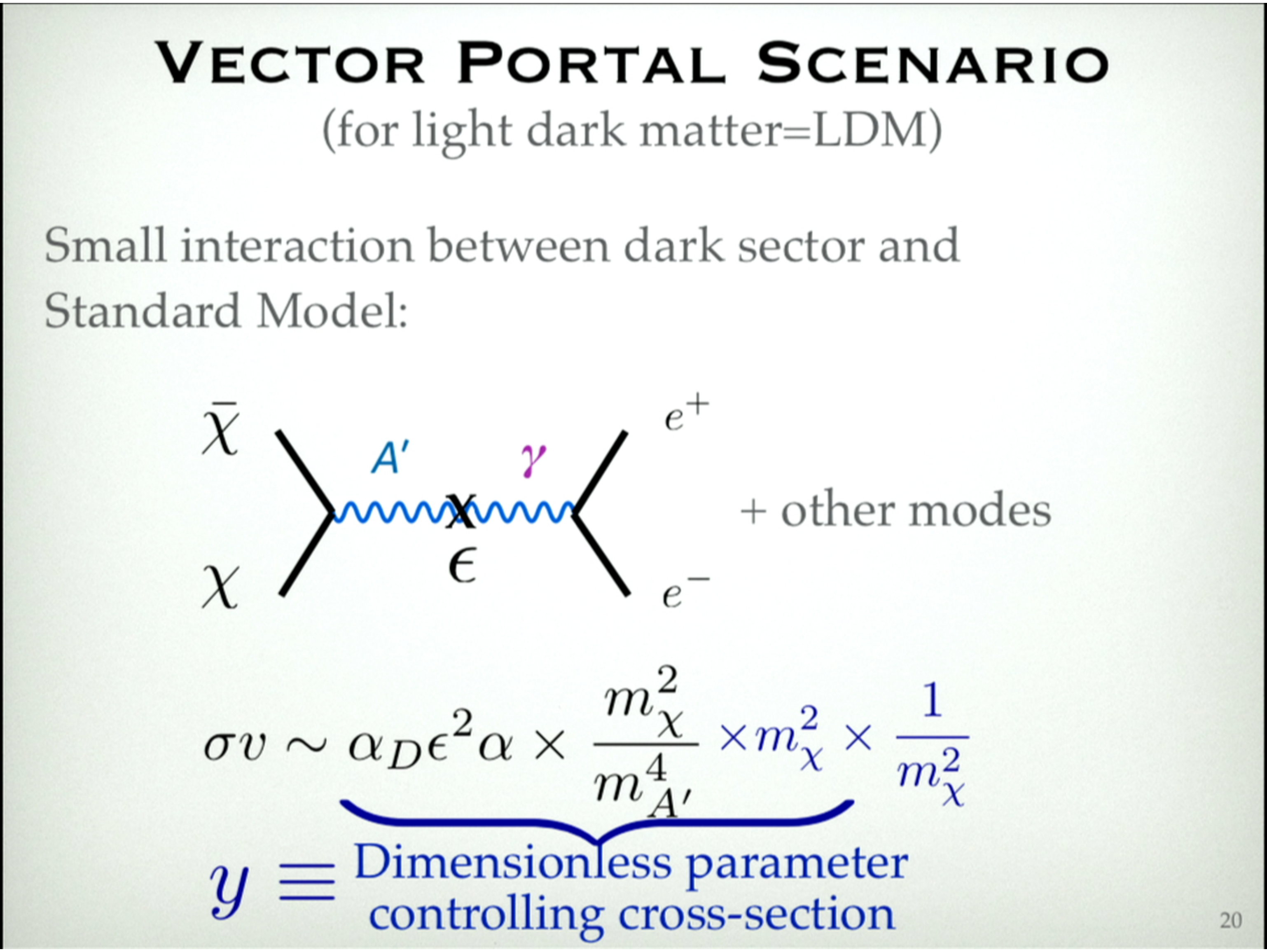


+ other modes

$$\sigma v \sim \alpha_D \epsilon^2 \alpha \times \frac{m_\chi^2}{m_{A'}^4}$$

kinematics



VECTOR PORTAL SCENARIO

(for light dark matter=LDM)

Small interaction between dark sector and Standard Model:

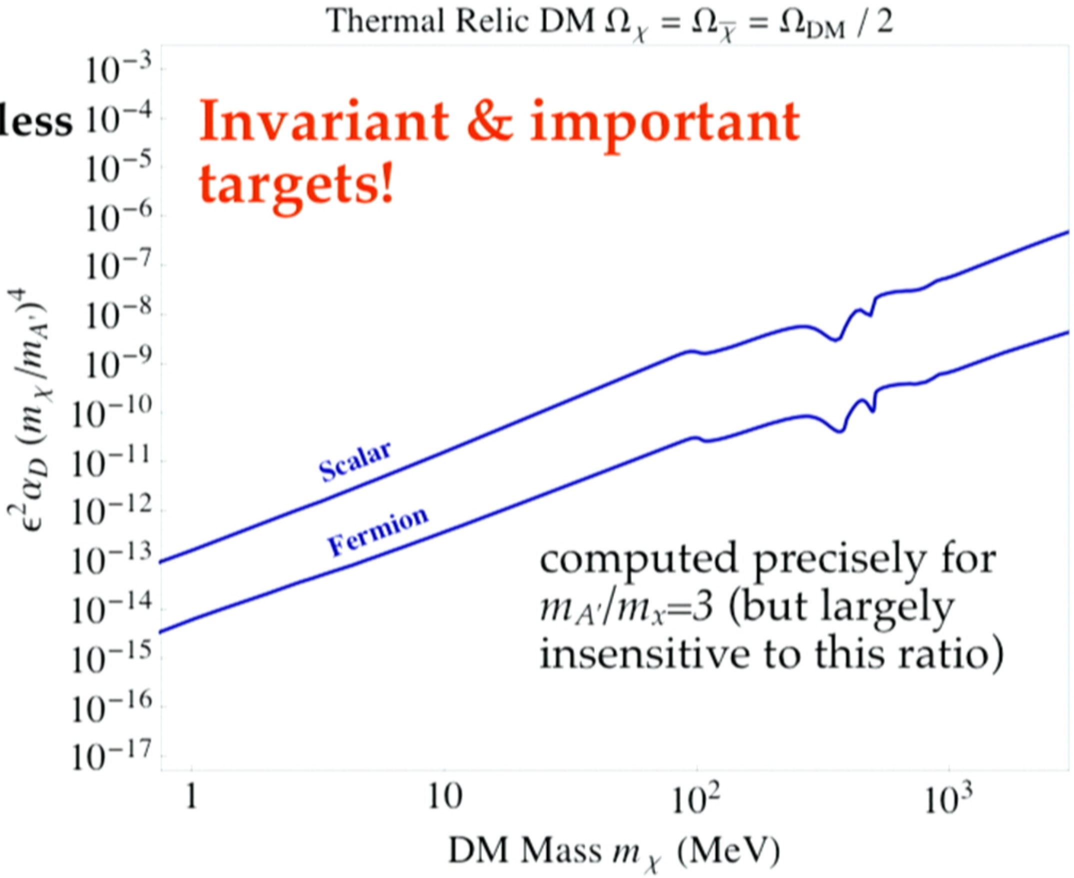
+ other modes

$$\sigma v \sim \underbrace{\alpha_D \epsilon^2 \alpha \times \frac{m_\chi^2}{m_{A'}^4}}_{y\,\equiv\,\text{Dimensionless parameter controlling cross-section}} \times m_\chi^2 \times \frac{1}{m_\chi^2}$$

THE THERMAL ORIGIN TARGET

(for vector portal)

Natural dimensionless interaction strength


Thermal Relic DM $\Omega_\chi = \Omega_{\overline{\chi}} = \Omega_{DM} / 2$

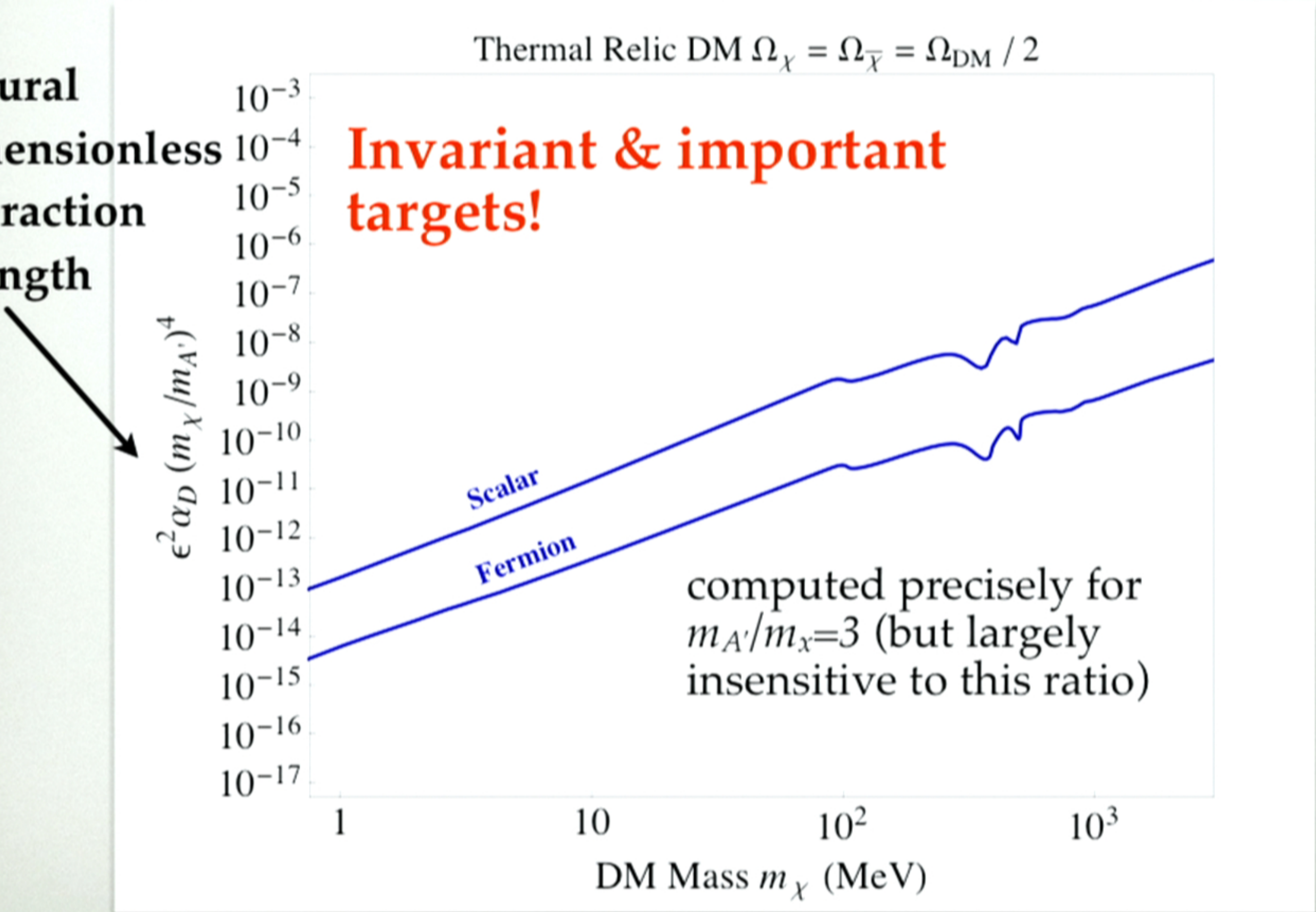
Invariant & important targets!

computed precisely for $m_{A'}/m_\chi$=3 (but largely insensitive to this ratio)

THE THERMAL ORIGIN TARGET

(for vector portal)

Natural dimensionless interaction strength



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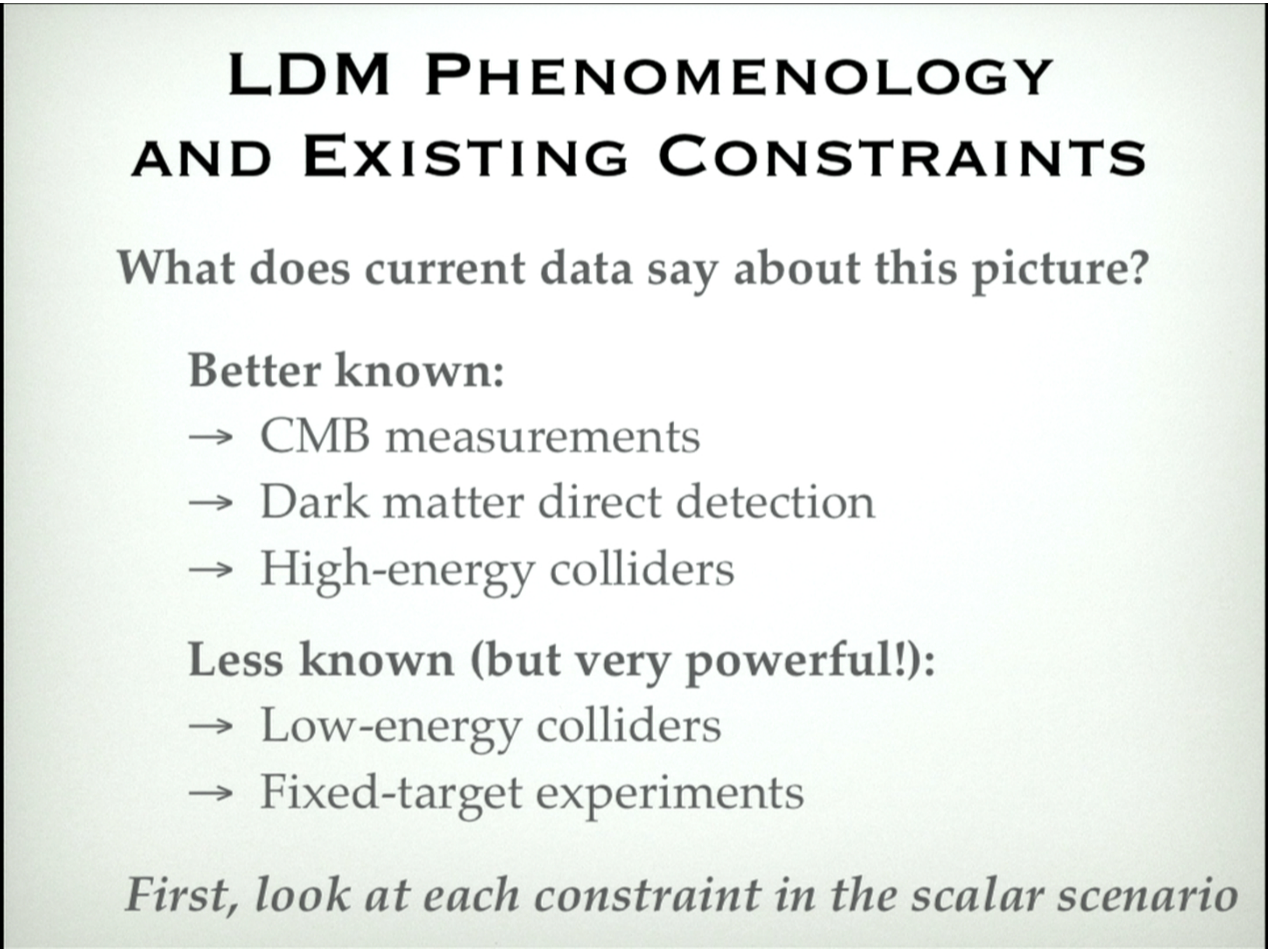


LDM PHENOMENOLOGY AND EXISTING CONSTRAINTS

What does current data say about this picture?

Better known:

→ CMB measurements

→ Dark matter direct detection

→ High-energy colliders

Less known (but very powerful!):

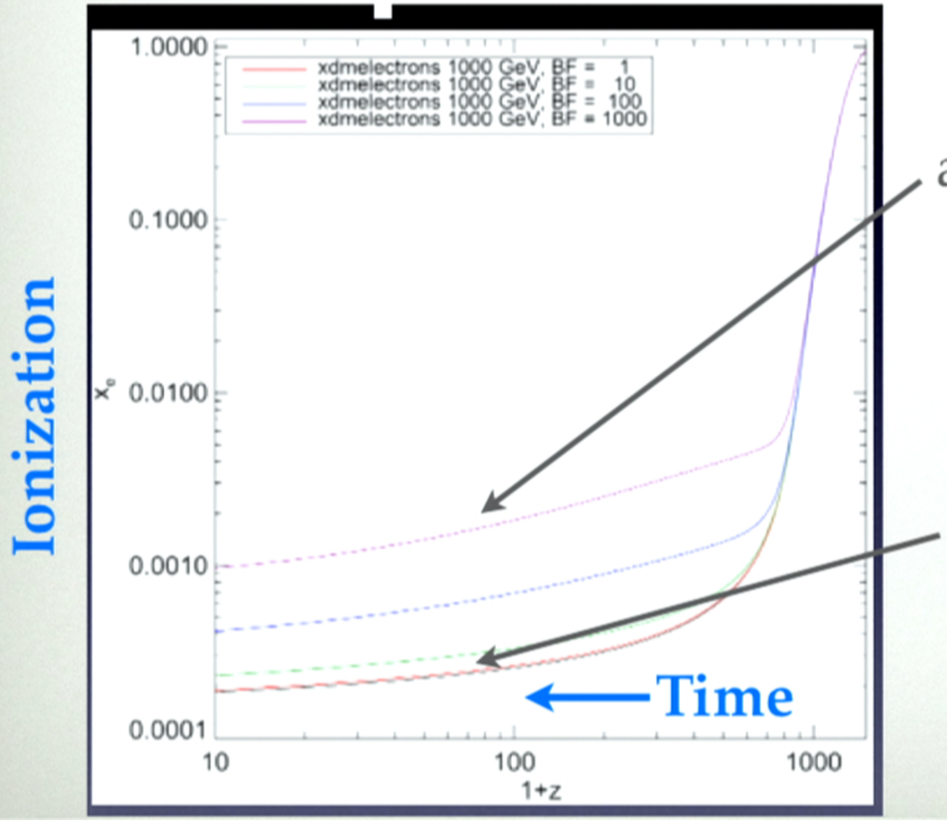
→ Low-energy colliders

→ Fixed-target experiments

First, look at each constraint in the scalar scenario

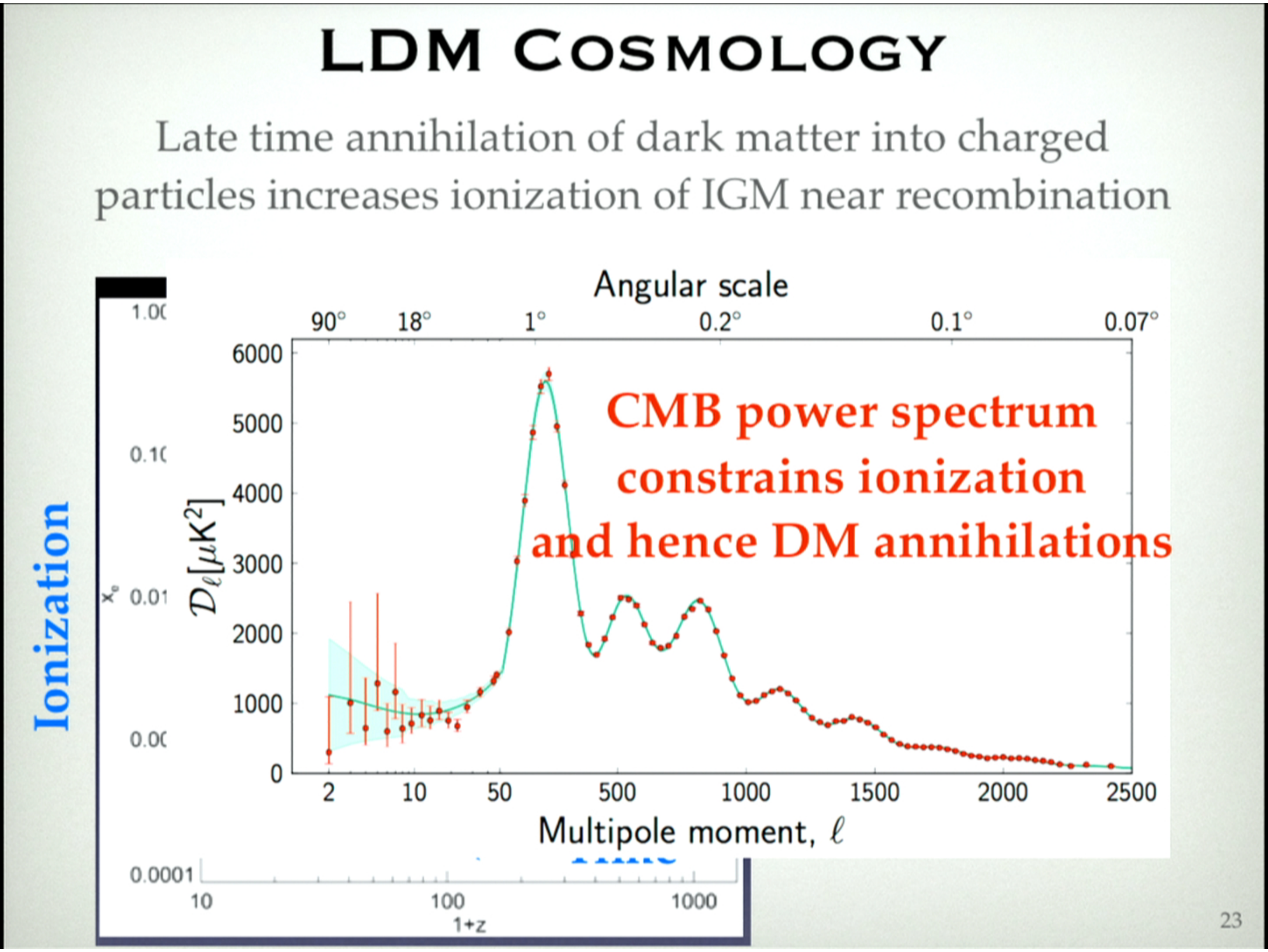
LDM COSMOLOGY

Late time annihilation of dark matter into charged particles increases ionization of IGM near recombination



More DM annihilation into charged matter

Less DM annihilation



LDM COSMOLOGY

Late time annihilation of dark matter into charged particles increases ionization of IGM near recombination

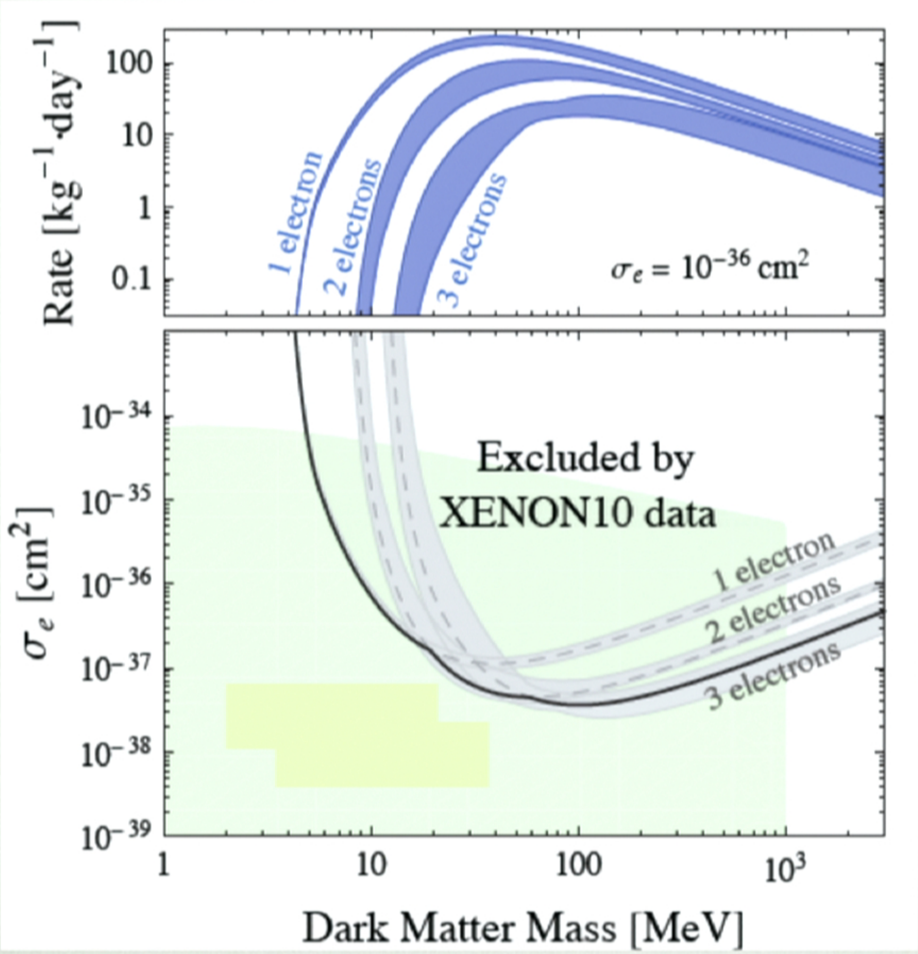
CMB power spectrum constrains ionization and hence DM annihilations

LDM Direct Detection

At low mass, dark matter scattering deposits too little energy on a heavy nuclear target
→ Not enough scintillation, ionization, or phonons

Can use much lighter **electron** as a target
→ dark matter scattering yields more energy

LDM DIRECT DETECTION

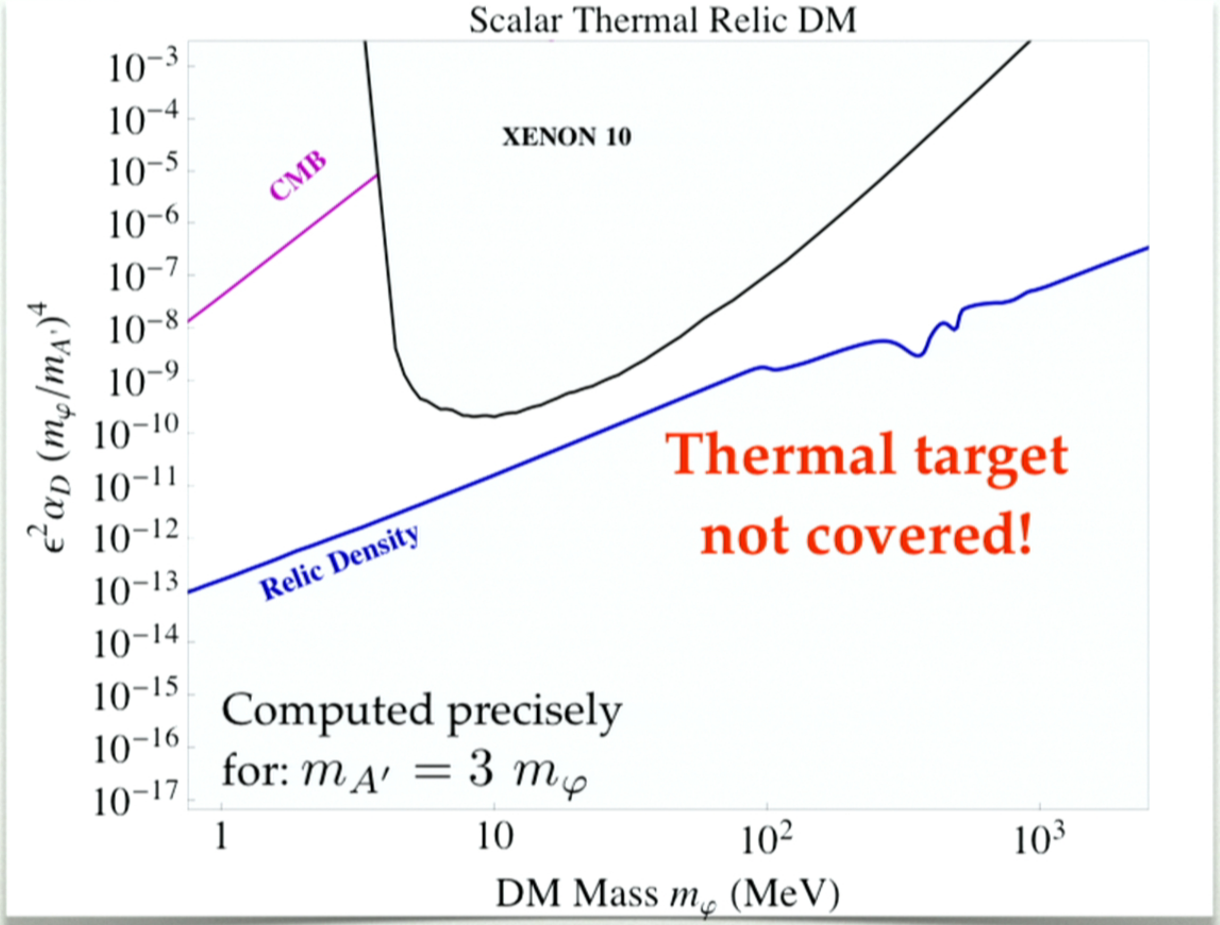


1206.2644

~10 eV threshold for DM-electron scattering to ionize electron(s)

CMB & DIRECT DETECTION

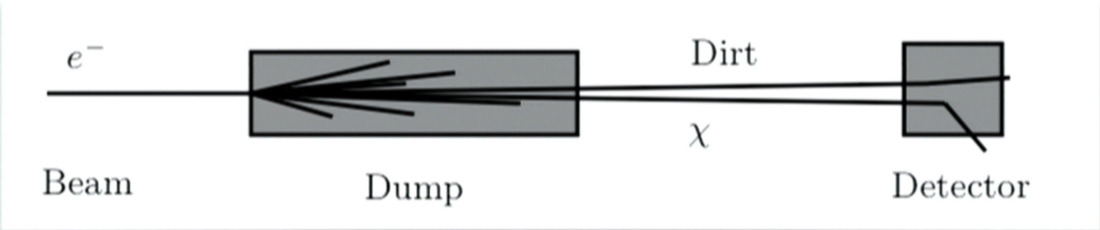
Scenario: Scalar DM



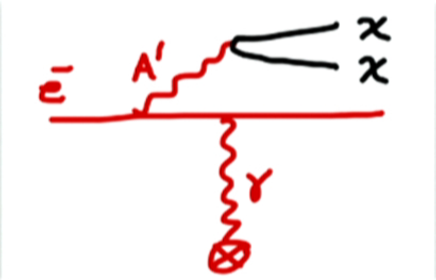
Thermal target not covered!

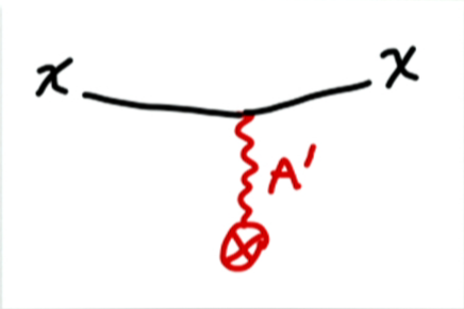
Computed precisely for: $m_{A'} = 3\ m_\varphi$

LDM & BEAM DUMPS



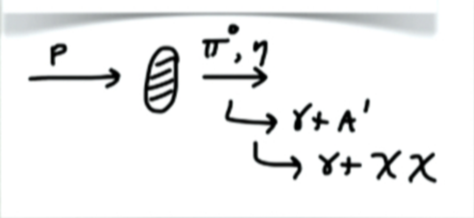
Izaguirre, Krnjaic, PS & Toro
PRD.88.114015 and
PRD.90.014052





nuclear dissociation; nucleon, nucleus, or electron recoil

0906.5614,
1107.4580,1205.3499
Batell,DeNiverville,
McKeen, Pospelov, Ritz

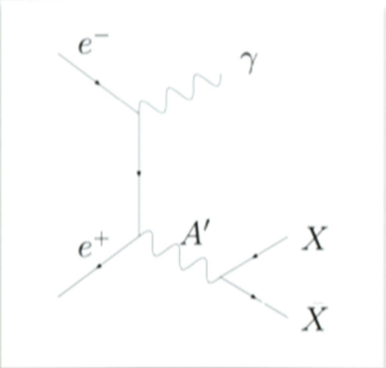


Excellent existing sensitivity to LDM from LSND (proton beam + electron scattering)

QUANTIFYING COLLIDERS

Recall: $y \equiv \alpha_D \epsilon^2 \left(\frac{m_\chi}{m_{A'}}\right)^4$

For direct DM production (on-shell mediator):



$$\sigma \sim \epsilon^2 \frac{1}{E_{CM}^2}$$

$$\sim y \times \underbrace{\frac{1}{\alpha_D}\left(\frac{m_{A'}}{m_\chi}\right)^4}_{}$$

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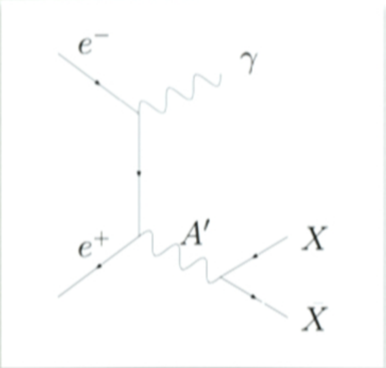


$$\sigma \sim \epsilon^2 \frac{1}{E_{CM}^2}$$

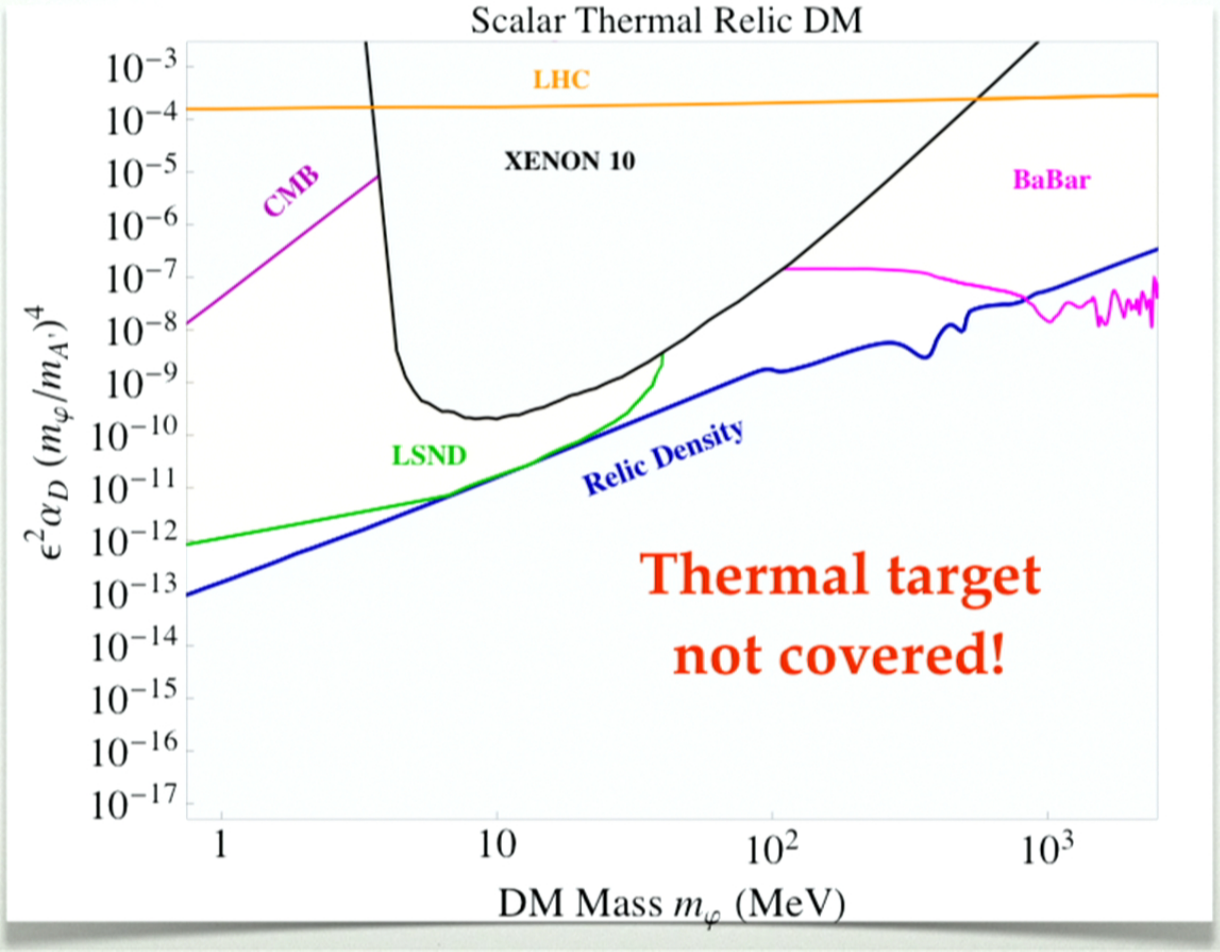
$$\sim y \times \underbrace{\frac{1}{\alpha_D}\left(\frac{m_{A'}}{m_\chi}\right)^4}$$

In this scenario $\begin{bmatrix} \alpha_D \leq 0.1 - \boxed{1} \\ m_{A'} \geq (2 - \boxed{3}) m_\chi \end{bmatrix} \Rightarrow$ combination >100

Saturate inequalities to show worst-case sensitivity

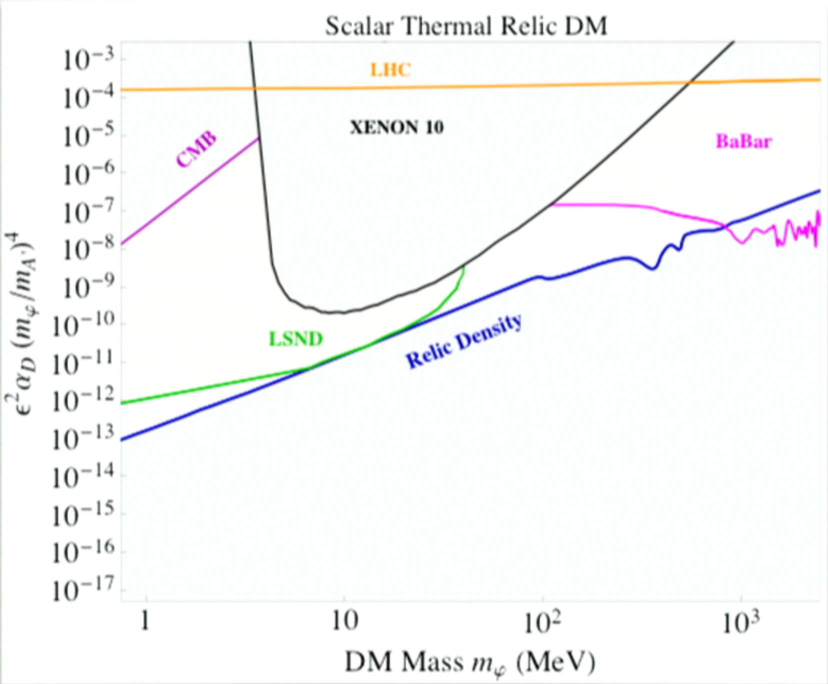
SUMMARY OF ALL CONSTRAINTS

Scenario: Scalar DM



Thermal target not covered!

SUMMARY SO FAR

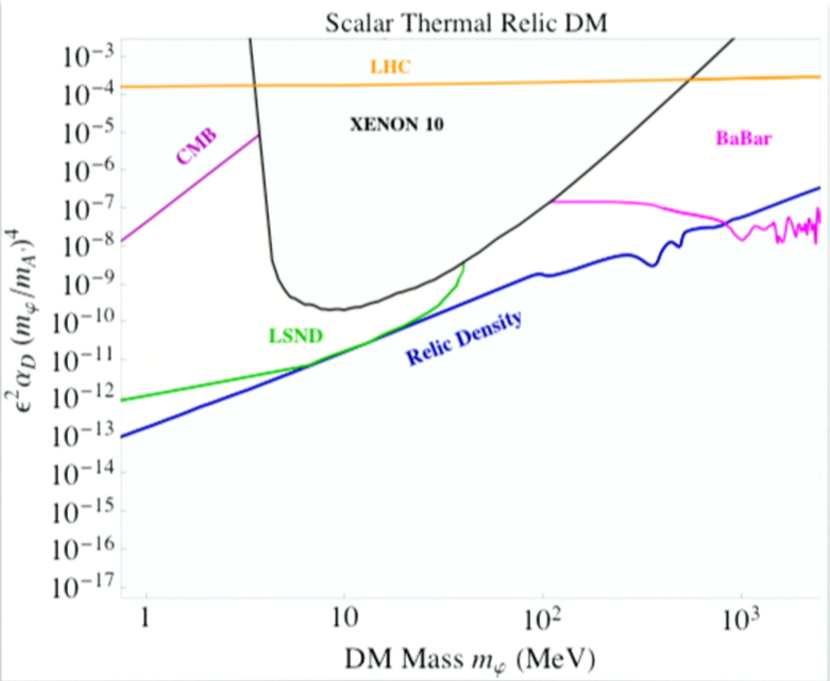


Several constraints on scalar LDM, but thermal target has not been covered!

Relic density ⇒ *minimum* expected yield in accelerator-based experiments

Need 1–3 orders of magnitude improvement for 1–1000 MeV DM to *decisively* test this scenario

Summary so Far



Several constraints on scalar LDM, but no decisive tests of this scenario.

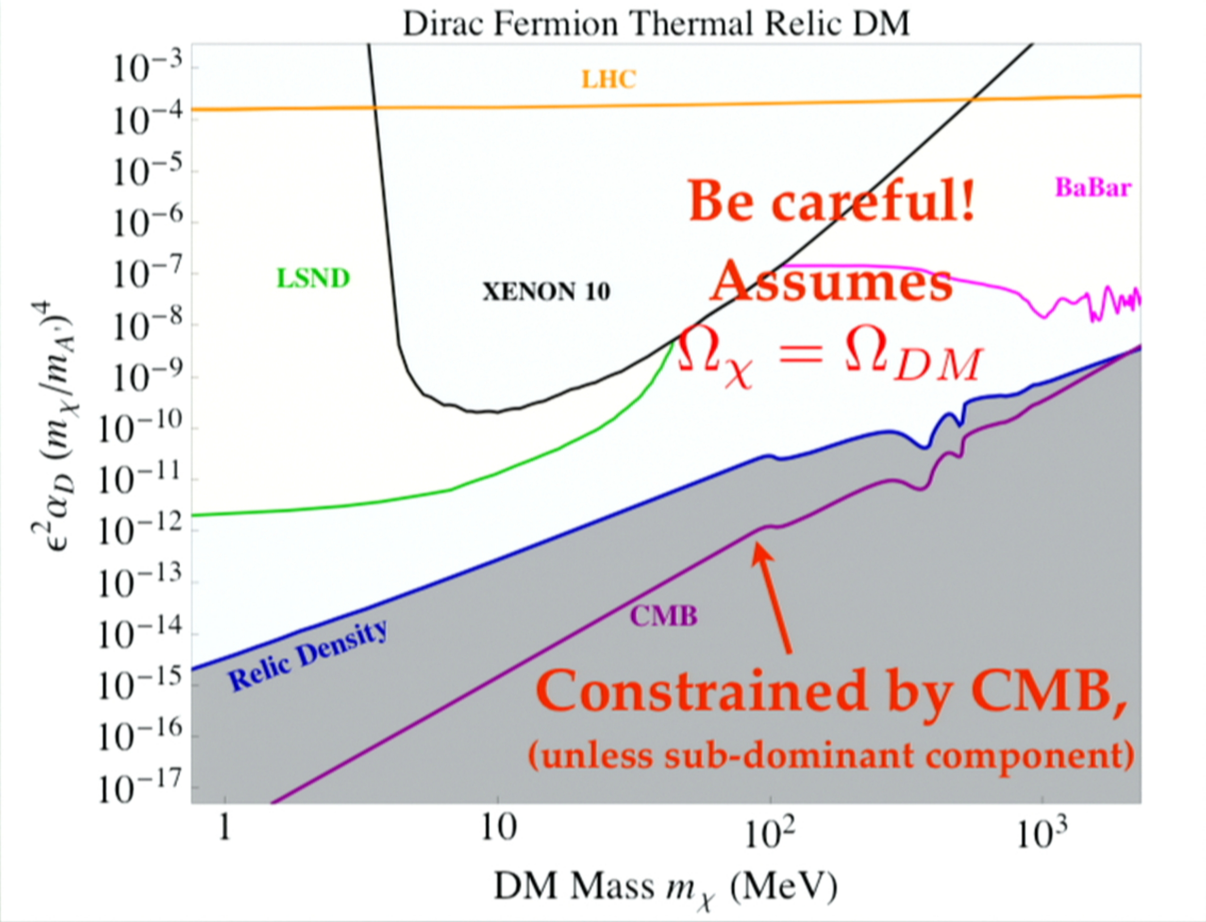
Next: 2 equally "minimal" scenarios

- Dirac fermion
- Majorana (inelastic) fermion/scalar

+additional scenarios (for another day)

SUMMARY OF ALL CONSTRAINTS

Scenario: Dirac (or elastic scattering) Fermion DM



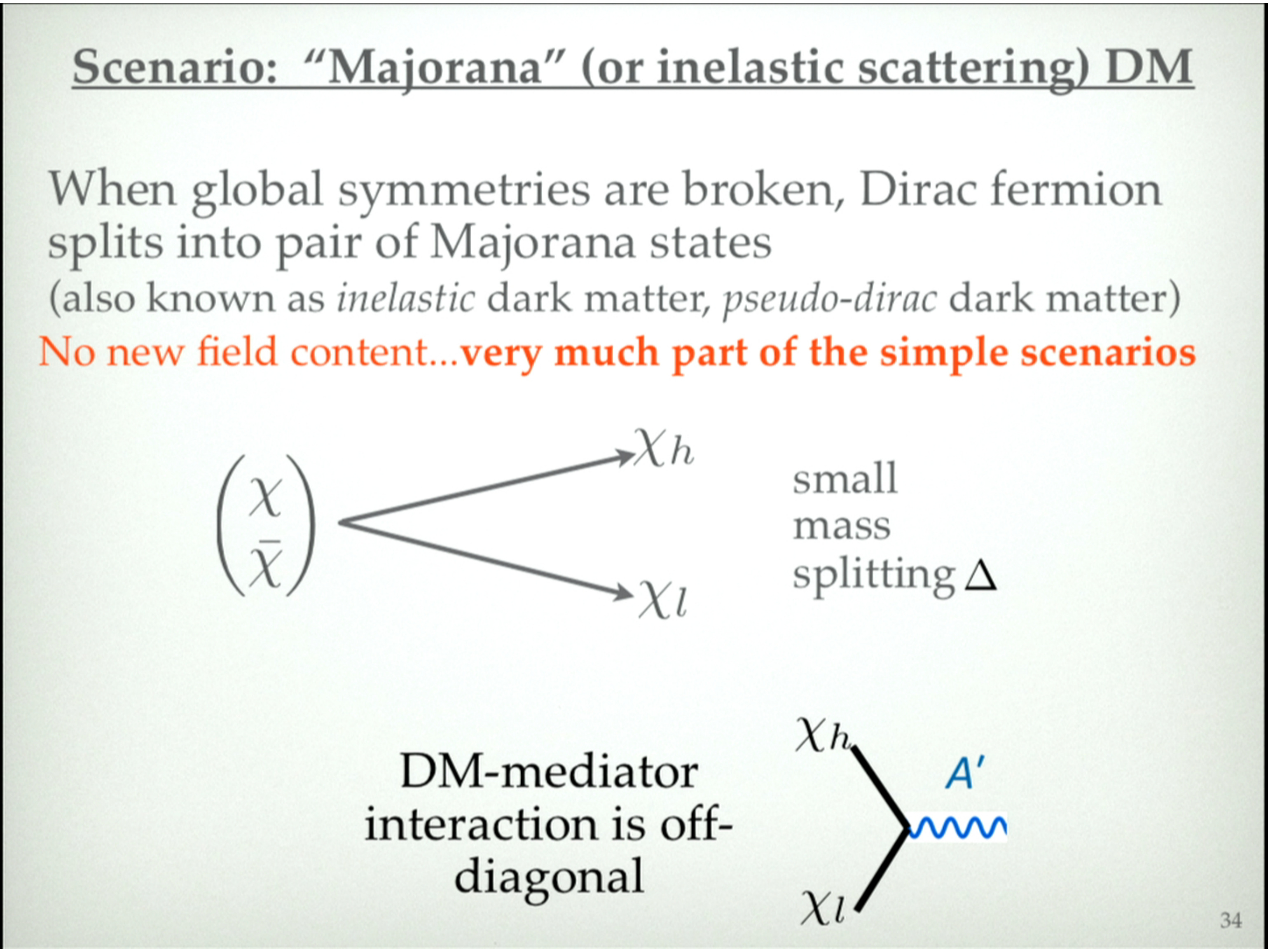
Dirac Fermion Thermal Relic DM

Be careful!

Assumes $\Omega_\chi = \Omega_{DM}$

Constrained by CMB,

(unless sub-dominant component)



Scenario: "Majorana" (or inelastic scattering) DM

When global symmetries are broken, Dirac fermion splits into pair of Majorana states

(also known as *inelastic* dark matter, *pseudo-dirac* dark matter)

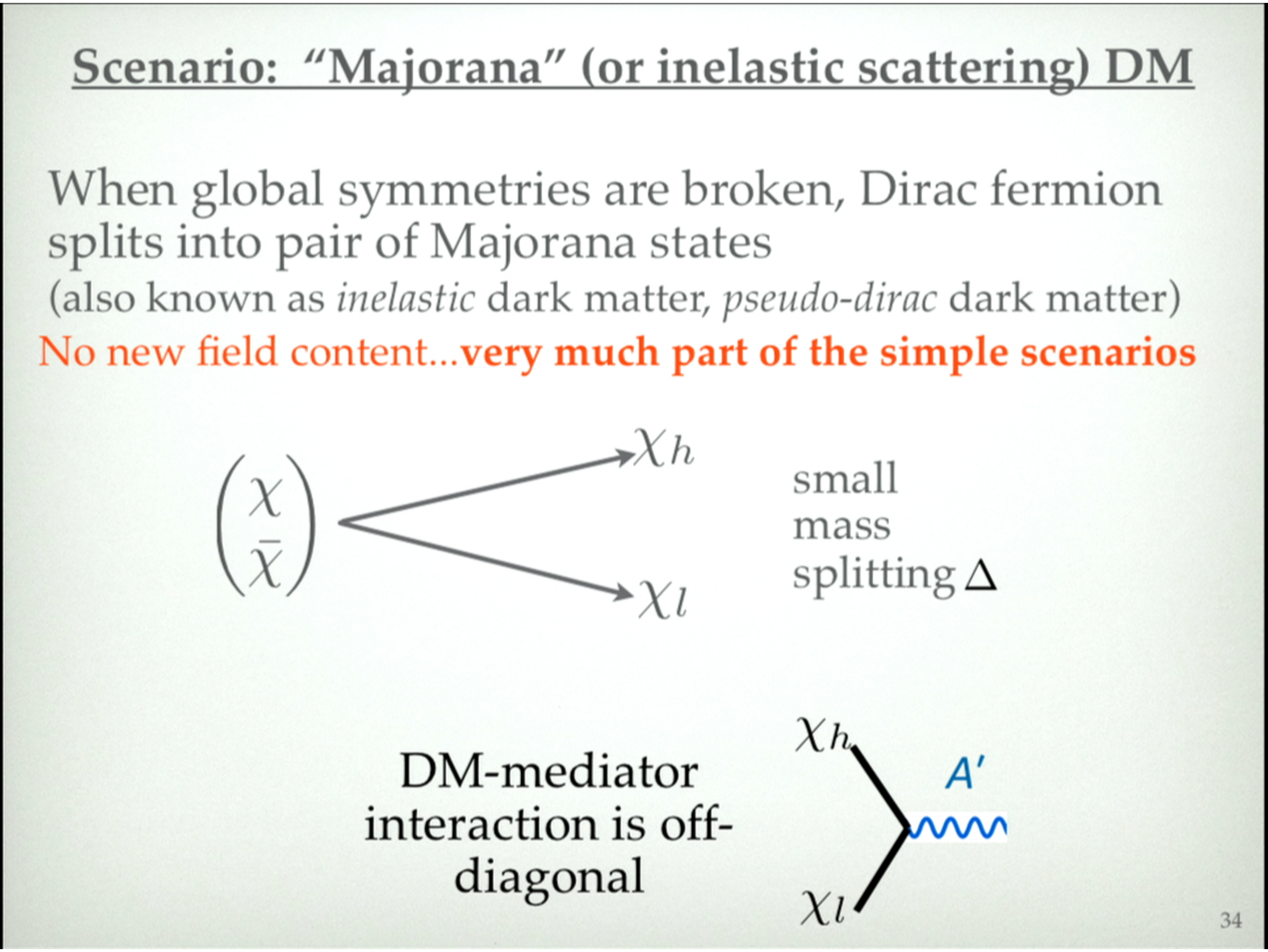
No new field content...**very much part of the simple scenarios**

$\begin{pmatrix} \chi \\ \bar{\chi} \end{pmatrix} \to \chi_h$, χ_l

small
mass
splitting Δ

DM-mediator interaction is off-diagonal

χ_h, χ_l, A'



Scenario: "Majorana" (or inelastic scattering) DM

When global symmetries are broken, Dirac fermion splits into pair of Majorana states

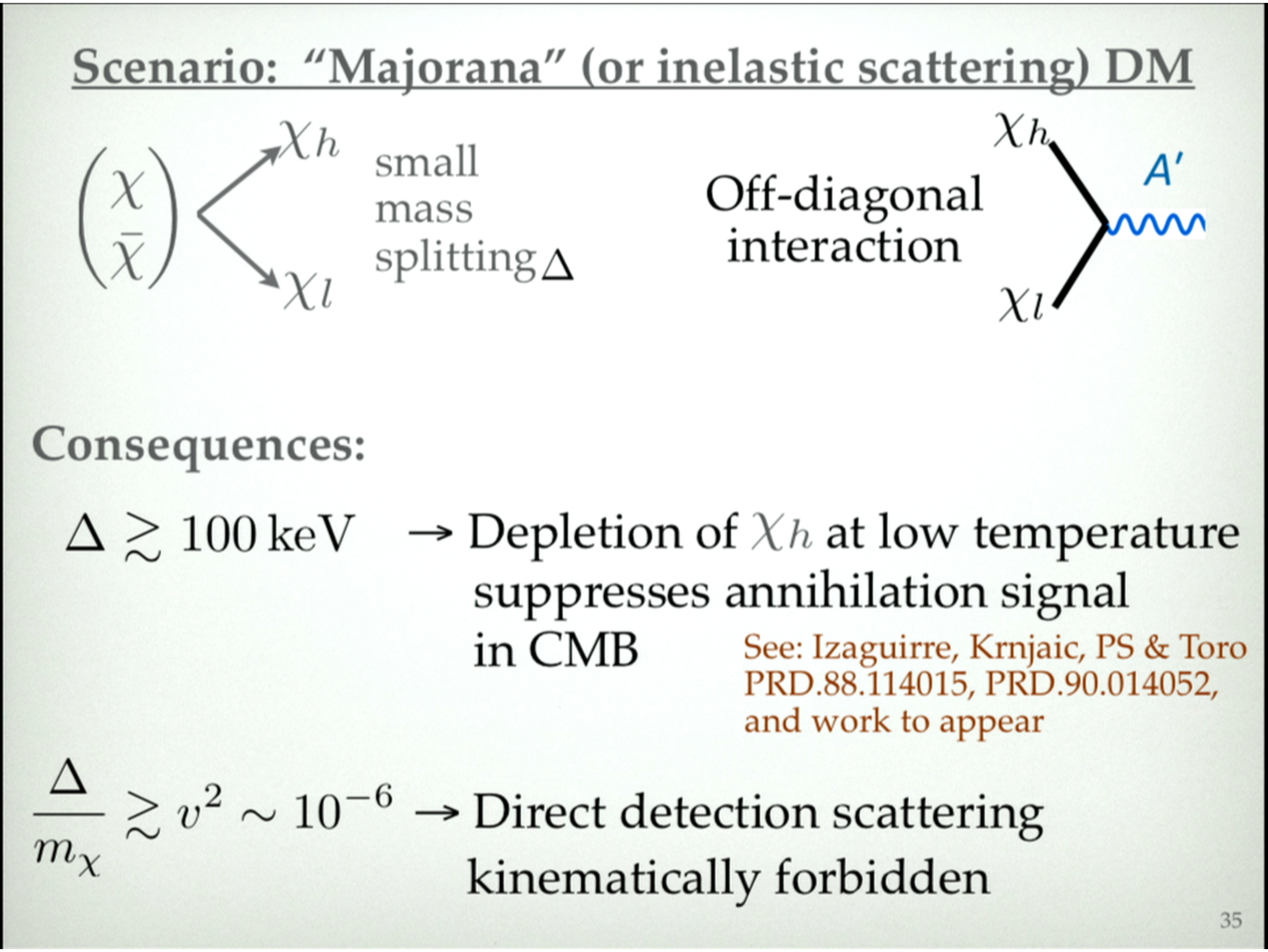
(also known as *inelastic* dark matter, *pseudo-dirac* dark matter)

No new field content...**very much part of the simple scenarios**

$\begin{pmatrix} \chi \\ \bar{\chi} \end{pmatrix}$ → χ_h, χ_l

small
mass
splitting Δ

DM-mediator interaction is off-diagonal



Scenario: "Majorana" (or inelastic scattering) DM

$\begin{pmatrix}\chi \\ \bar{\chi}\end{pmatrix} \begin{matrix}\nearrow \chi_h \\ \searrow \chi_l\end{matrix}$ small mass splitting Δ

Off-diagonal interaction

Consequences:

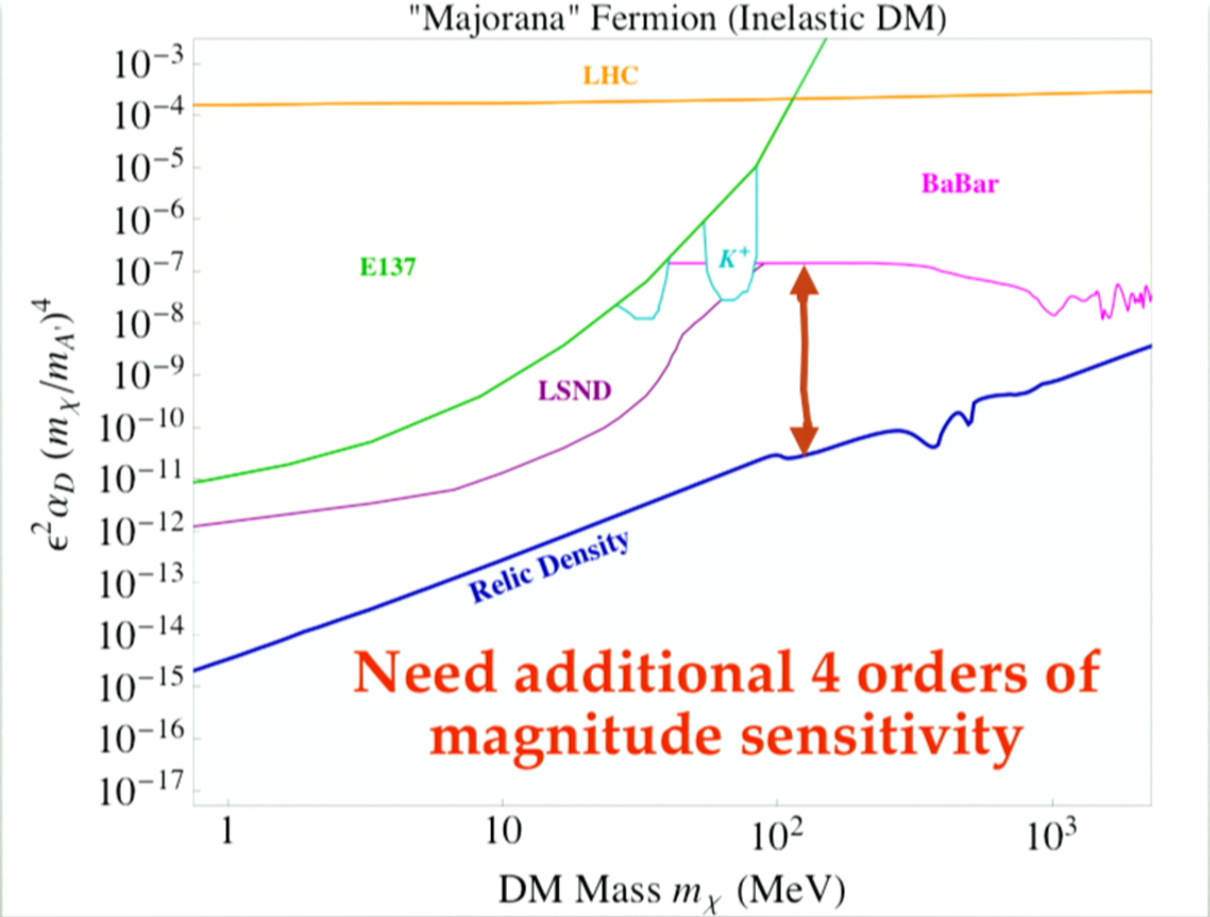
$\Delta \gtrsim 100\,\mathrm{keV}$ → Depletion of χ_h at low temperature suppresses annihilation signal in CMB

See: Izaguirre, Krnjaic, PS & Toro
PRD.88.114015, PRD.90.014052,
and work to appear

$\frac{\Delta}{m_\chi} \gtrsim v^2 \sim 10^{-6}$ → Direct detection scattering kinematically forbidden

SUMMARY OF ALL CONSTRAINTS

Scenario: “Majorana” (or inelastic scattering) DM

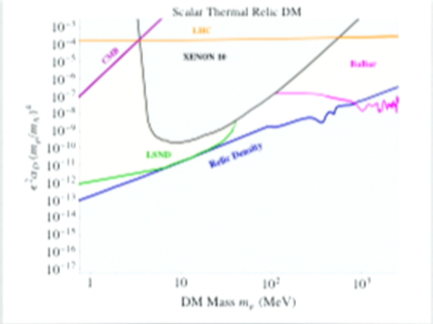


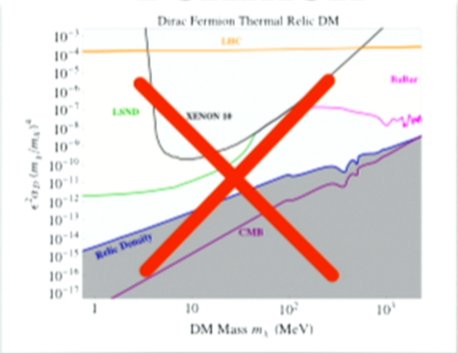
Need additional 4 orders of magnitude sensitivity

SUMMARY OF SCENARIOS

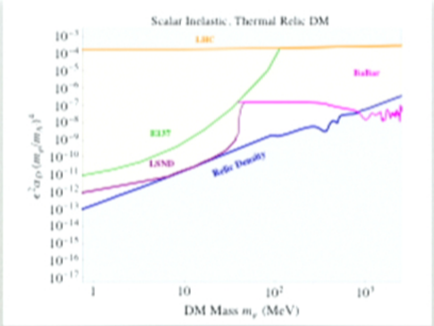
Scalar **Fermion**

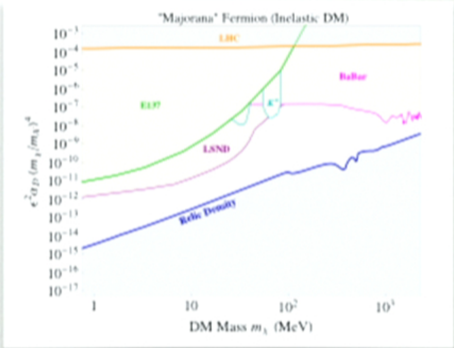
Thermal Elastic





Thermal Inelastic

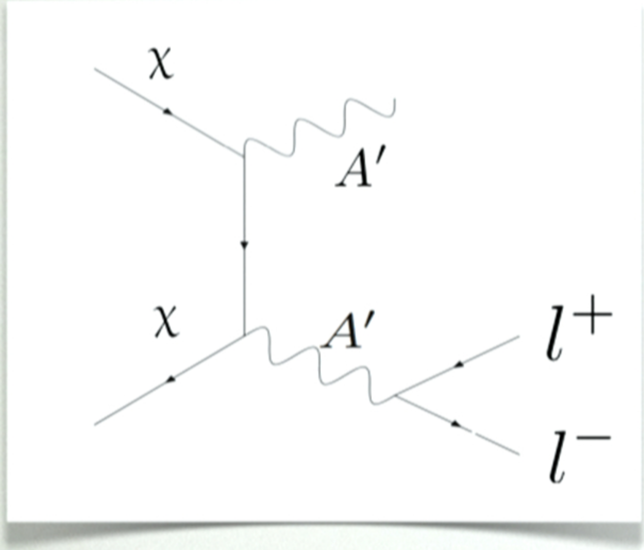




+ additional scenarios not discussed...

MORE GENERAL KINEMATICS

Off-shell: $m_{A'} < m_\chi$



→ Thermal annihilation, $\chi\chi \to A'A'$ dominates.

→ **CMB largely constrains thermal scalar and fermion cases.**

Asymmetric scenarios are not constrained in this regime...

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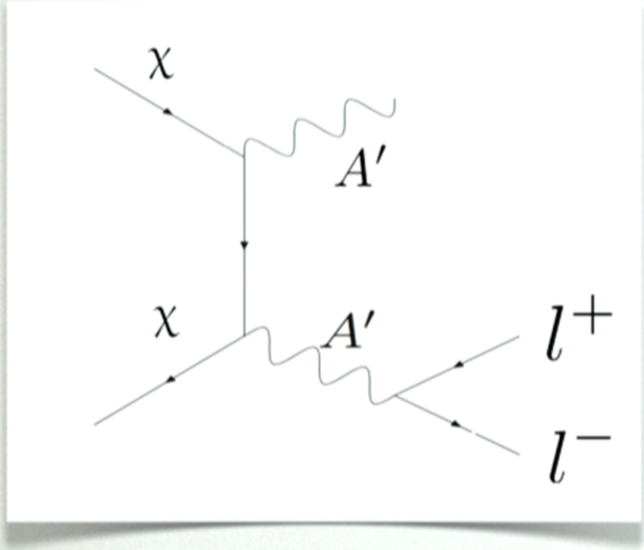

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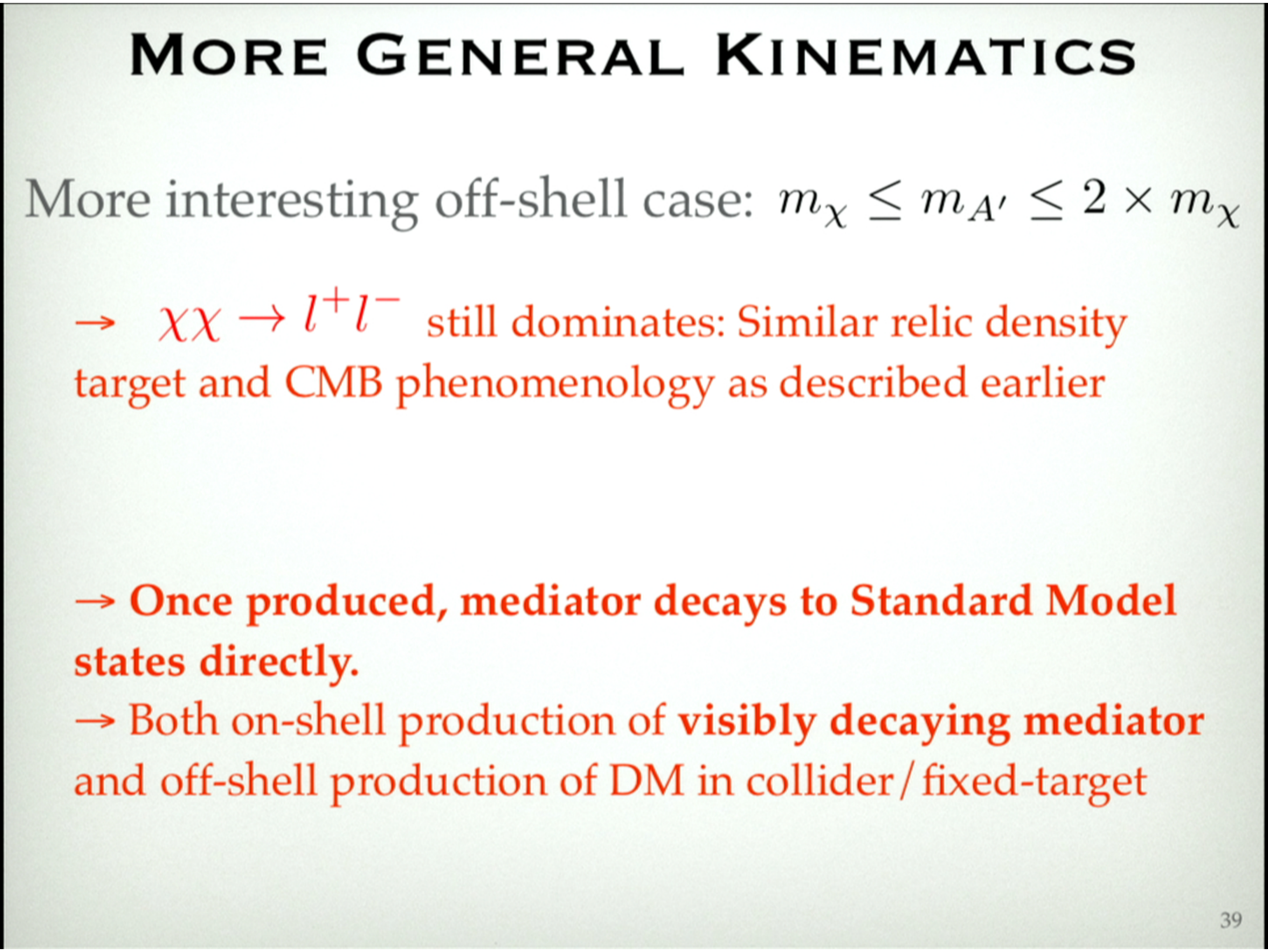


MORE GENERAL KINEMATICS

More interesting off-shell case: $m_\chi \leq m_{A'} \leq 2 \times m_\chi$

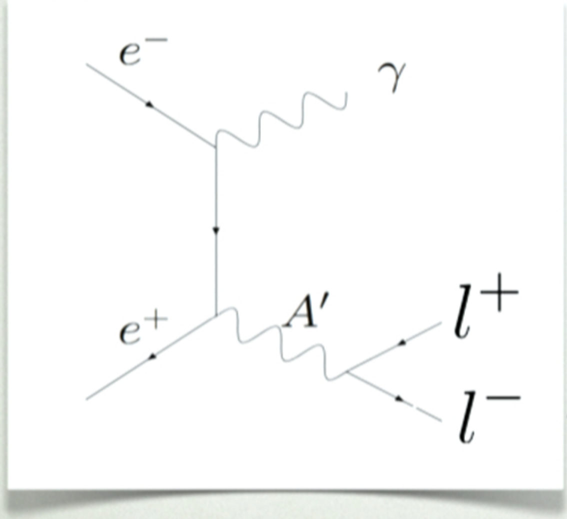
→ $\chi\chi \to l^+l^-$ still dominates: Similar relic density target and CMB phenomenology as described earlier

→ **Once produced, mediator decays to Standard Model states directly.**

→ Both on-shell production of **visibly decaying mediator** and off-shell production of DM in collider/fixed-target

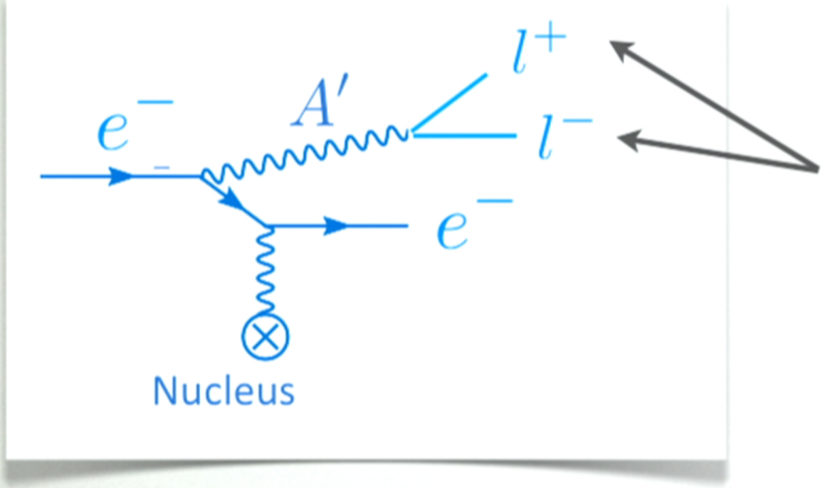
DIRECT MEDIATOR SEARCHES

High *intensity* colliders



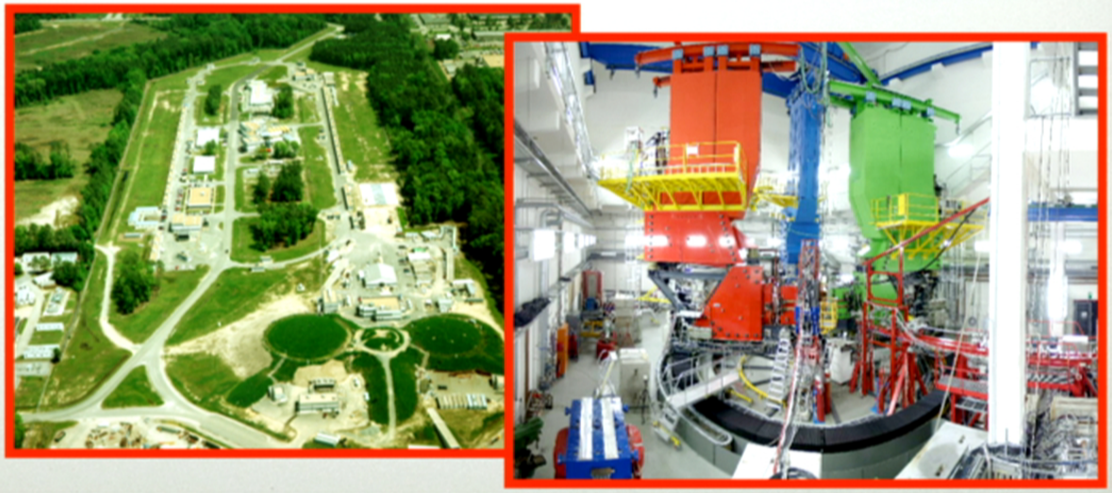
Search for a narrow resonance in electron-positron collisions

DIRECT MEDIATOR SEARCHES



Search for a narrow resonance in electron-nucleus collisions

Fixed Target



MORE GENERAL KINEMATICS

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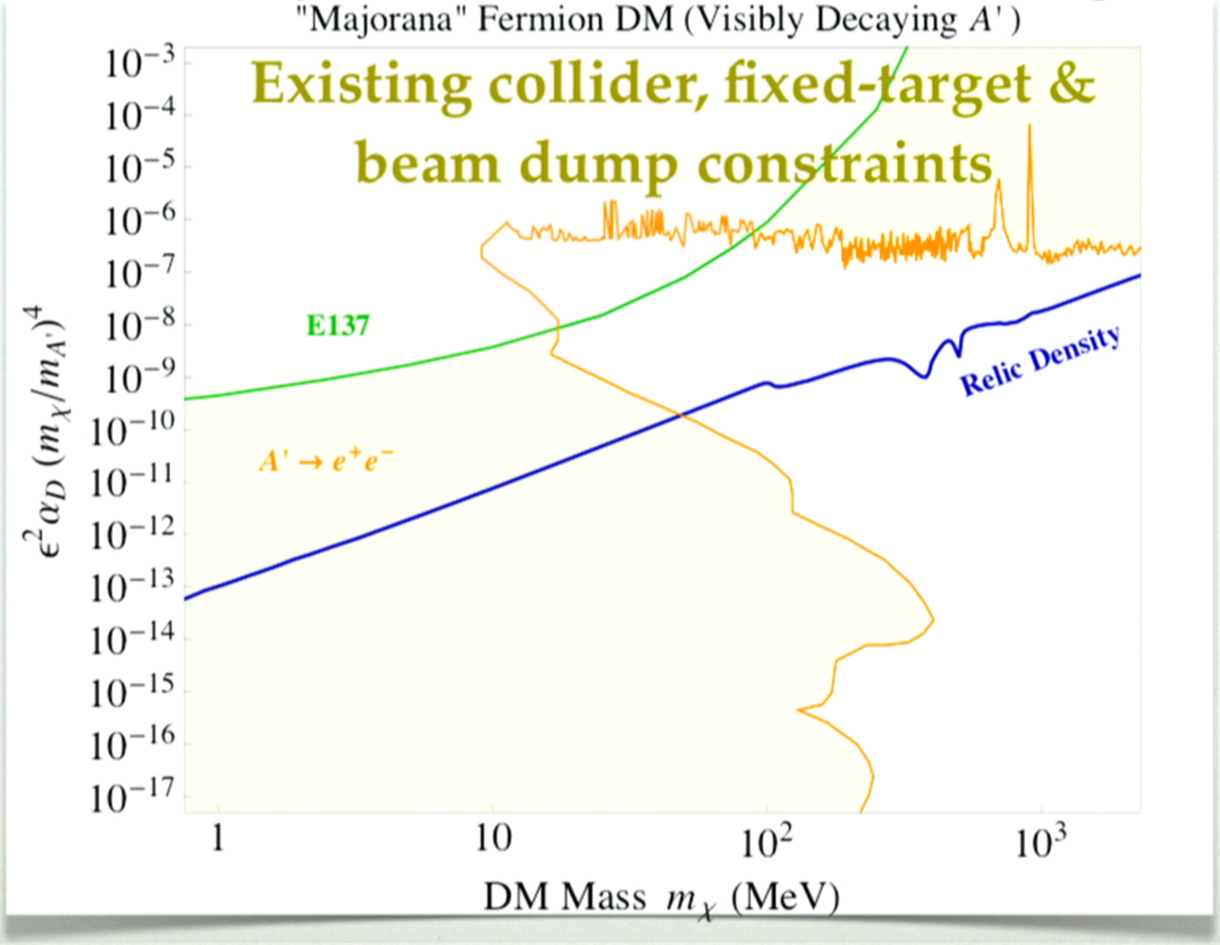
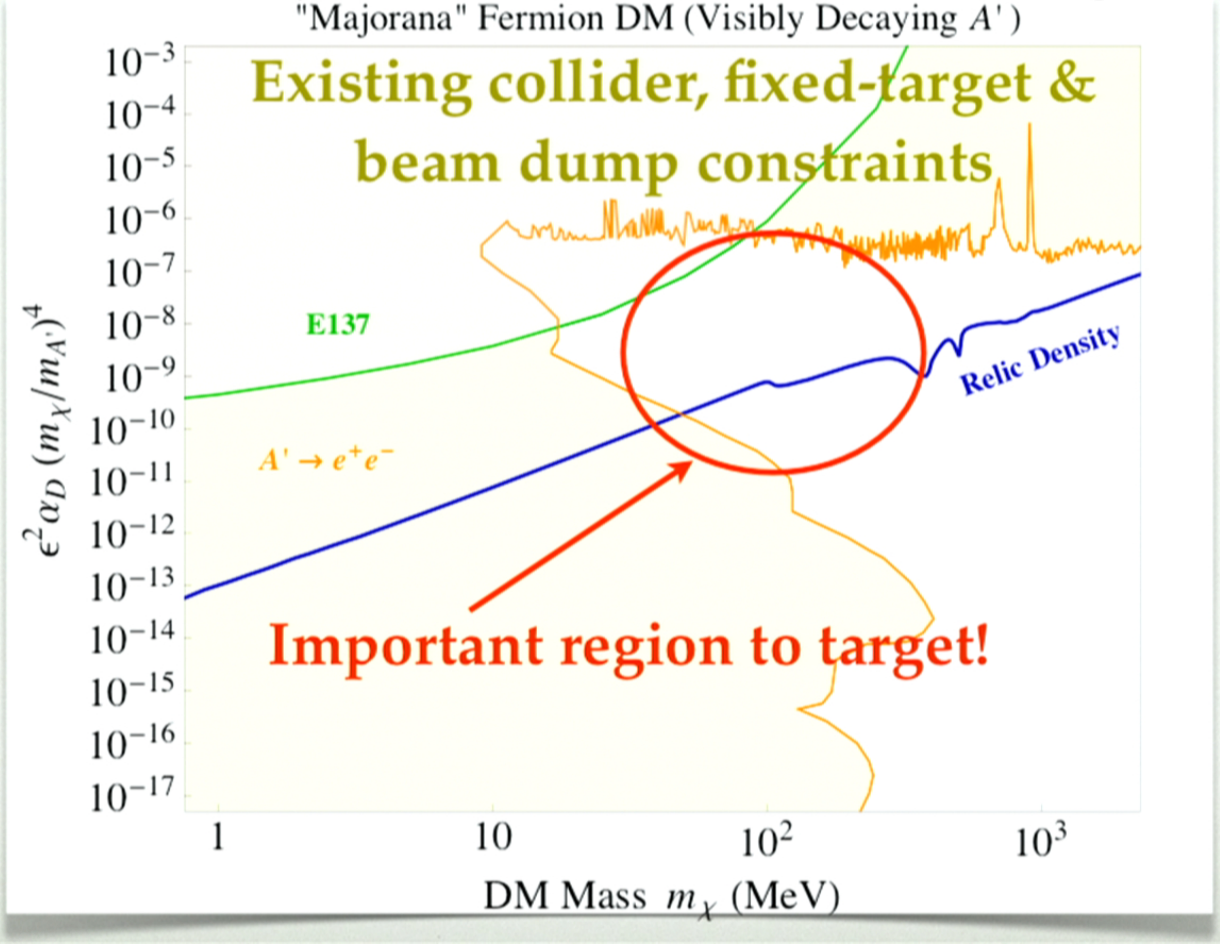


MORE GENERAL KINEMATICS

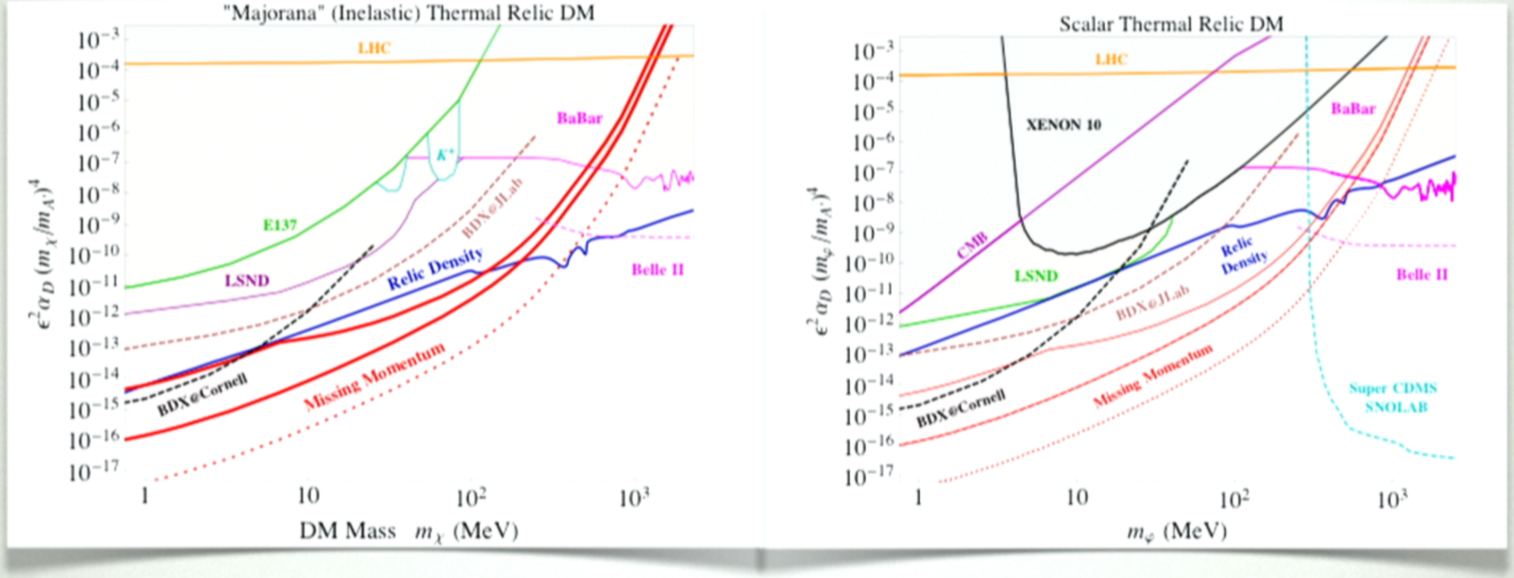
Scenario: "Majorana" (or inelastic scattering) DM



OUTLINE

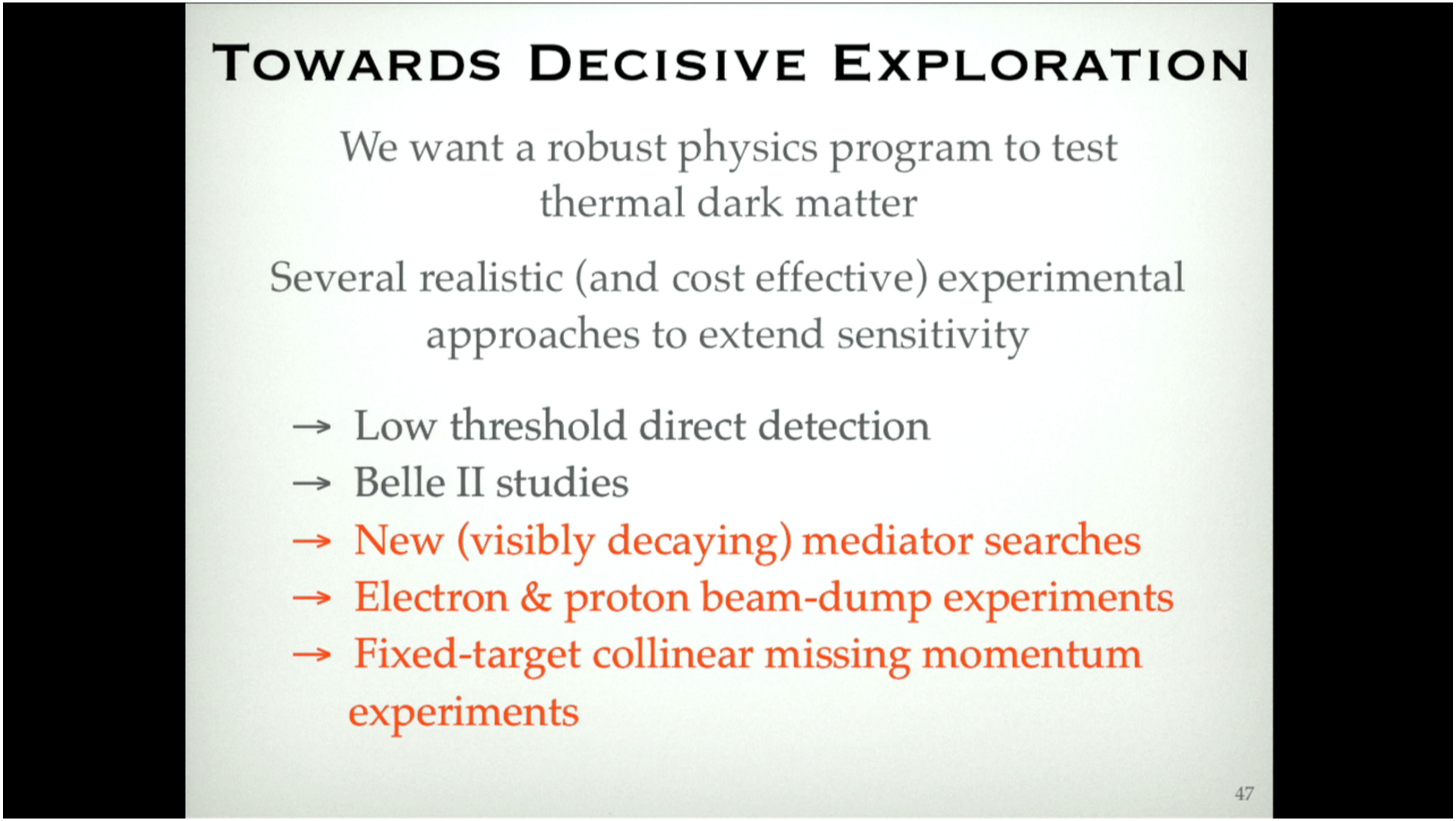
- “Light Dark Matter” in the vicinity of the weak-scale
- Sharp Targets for and Current Constraints
- **Experimental Efforts & Opportunities to discover or exclude thermal dark matter**

TOWARDS DECISIVE EXPLORATION



New opportunities to explore dark matter interactions with a decisive level of sensitivity!

We will return to these plots momentarily...



TOWARDS DECISIVE EXPLORATION

We want a robust physics program to test thermal dark matter

Several realistic (and cost effective) experimental approaches to extend sensitivity

- → Low threshold direct detection
- → Belle II studies
- → New (visibly decaying) mediator searches
- → Electron & proton beam-dump experiments
- → Fixed-target collinear missing momentum experiments

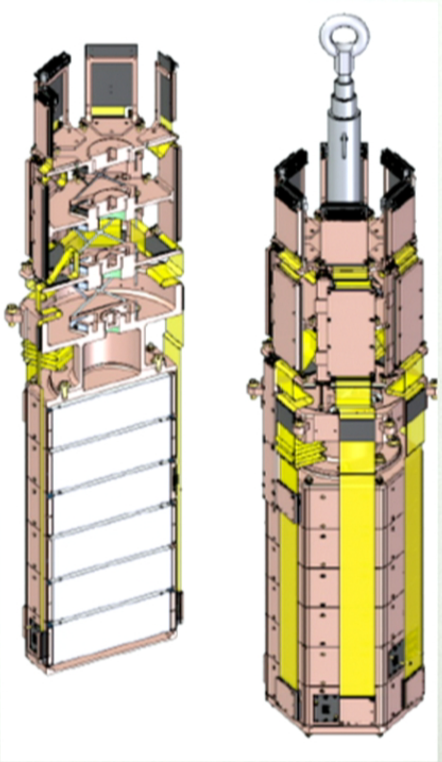
EXTENDING DIRECT DETECTION

SuperCDMS @ SNOLAB

- Lower energy thresholds
- Clean environment and low backgrounds
- Large exposure

Big sensitivity gains may be possible

Pictures from SuperCDMS talk by P. Di Stefano (Patras 2014); See also: http://cdms.berkeley.edu/



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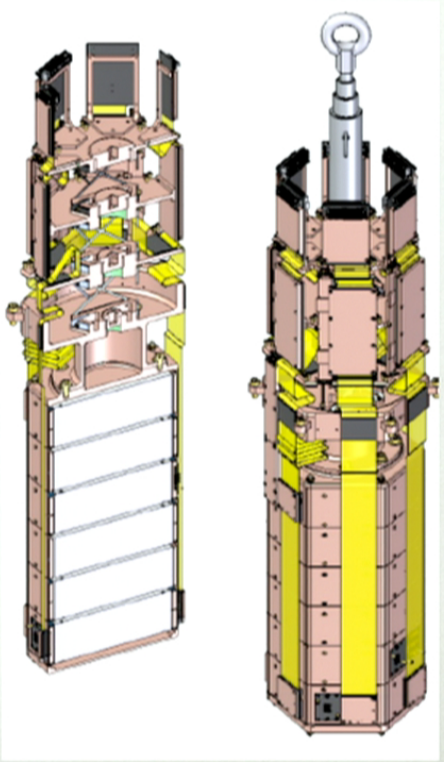

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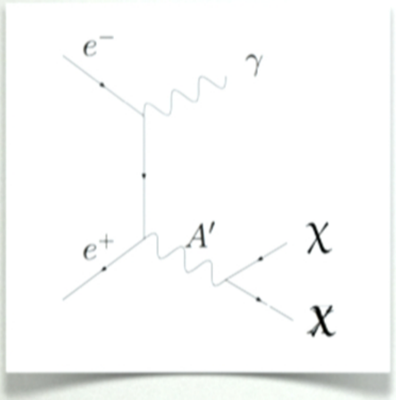
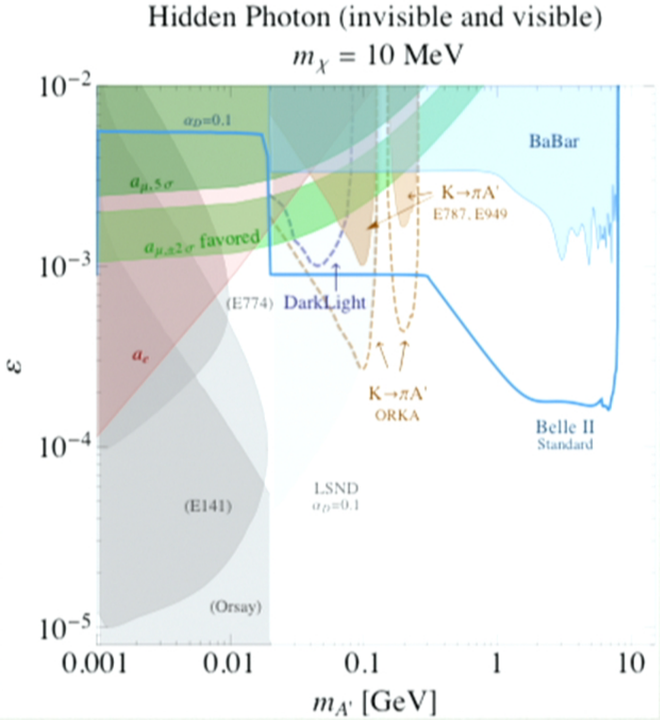
FUTURE LOW-ENERGY COLLIDERS

Belle II might dramatically extend coverage



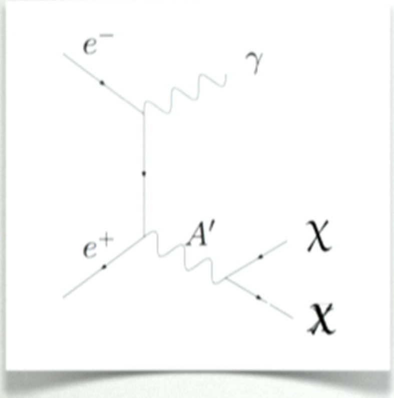


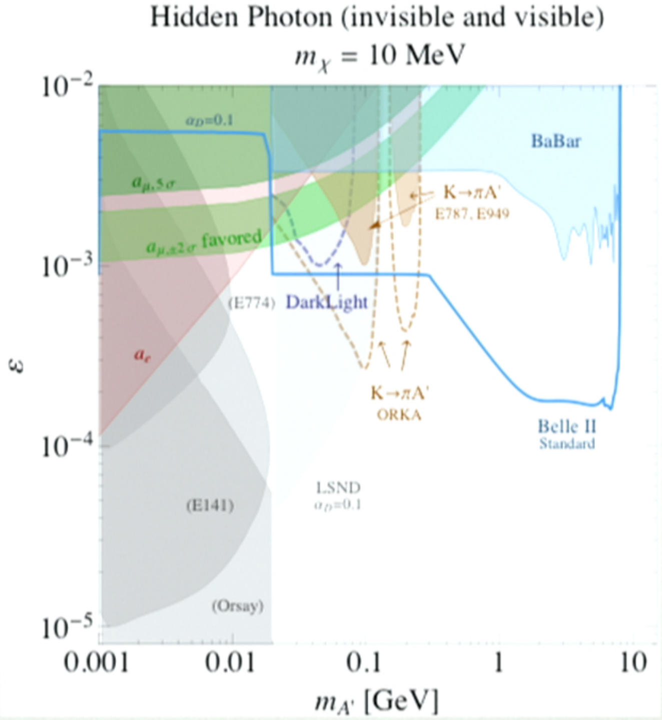
See arXiv: 1309.5084

New (non-standard) photon-MET trigger needed!

FUTURE LOW-ENERGY COLLIDERS

Belle II might dramatically extend coverage





See arXiv:
1309.5084

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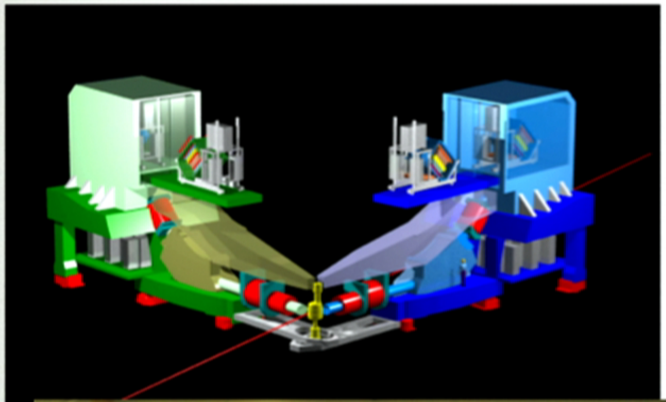
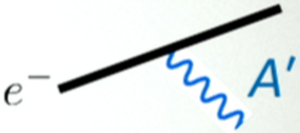
APEX

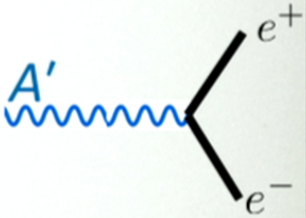
Powerful search for new forces via resonances



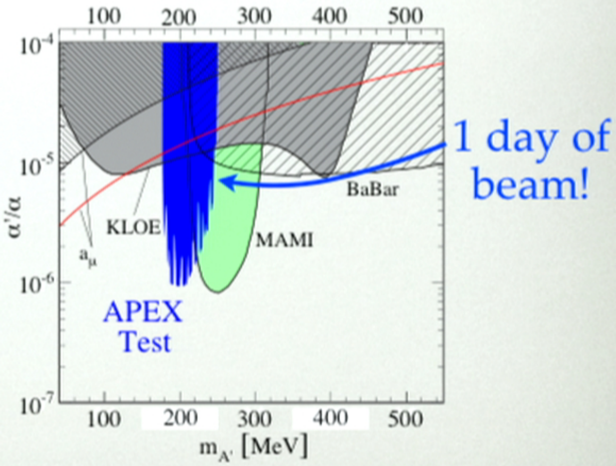
Production:



Decay:



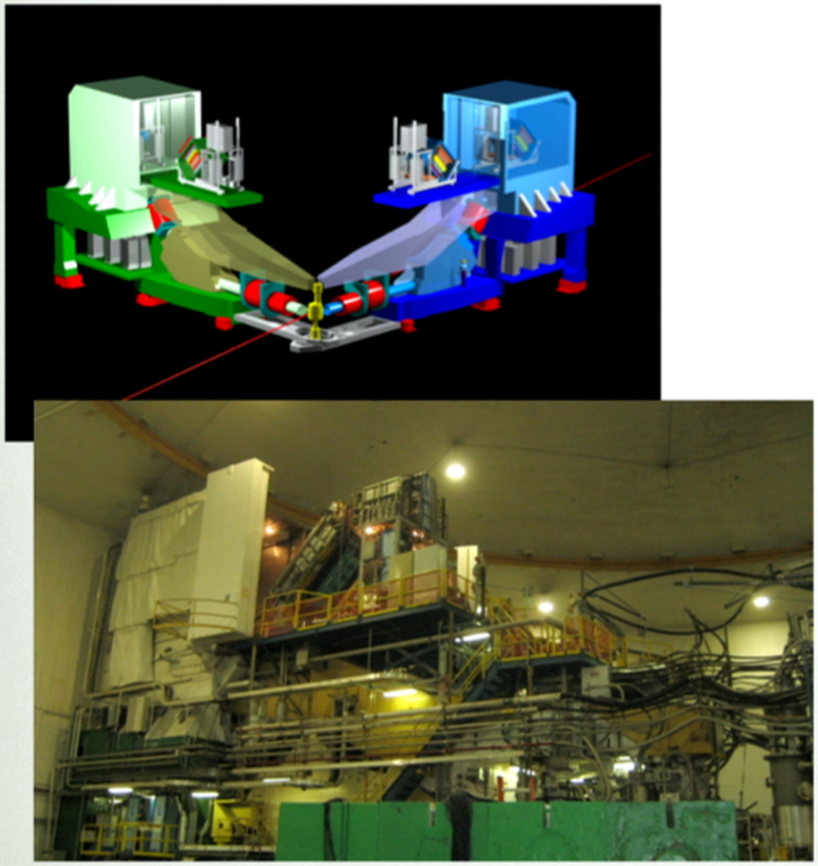
Test run PRL 2011



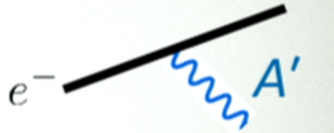
…full run ~2016/17

APEX

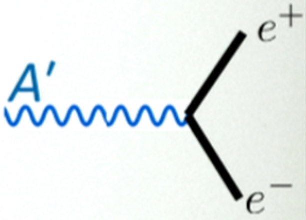
Powerful search for new forces via resonances



Production:



Decay:



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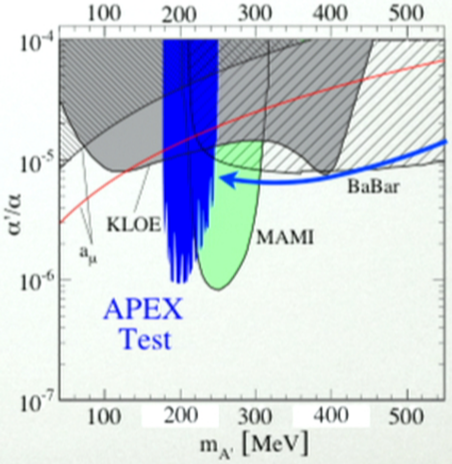
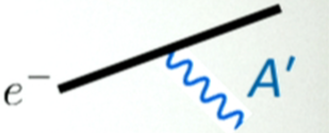


1 day of beam!

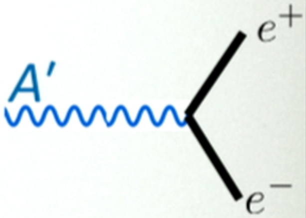
…full run ~2016/17

Powerful search for new forces via resonances

Production:



Decay:



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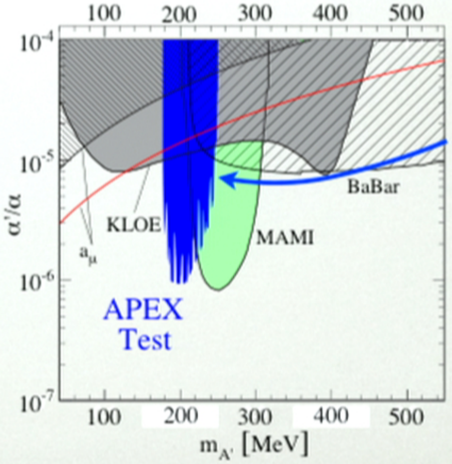
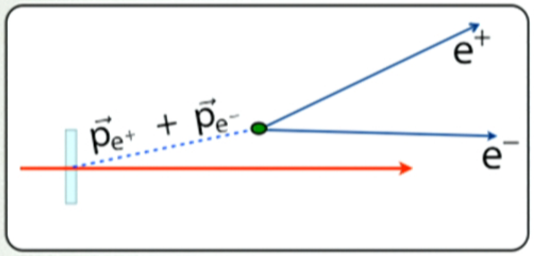


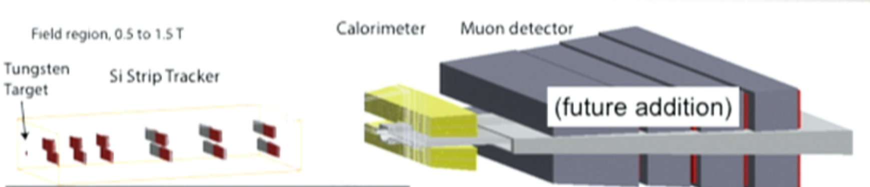
1 day of beam!

…full run ~2016/17

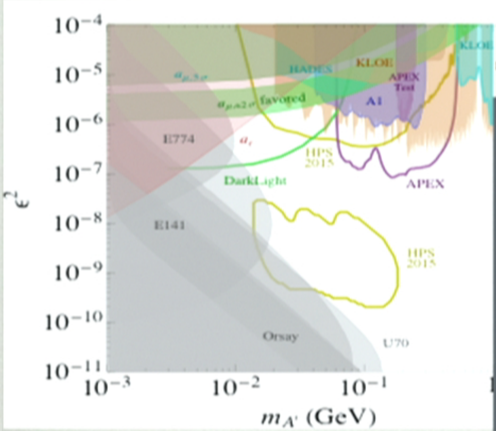
…full run ~2016/17

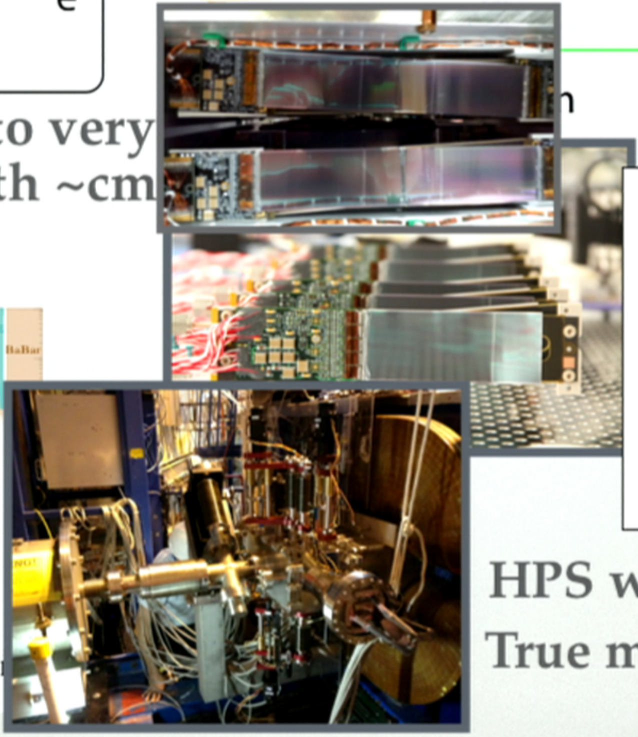
HPS: RESONANCE + VERTEX SEARCHES

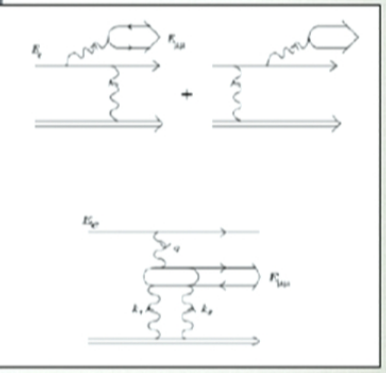




Allows sensitivity to very weak couplings with ~cm decay vertex







HPS will also discover True muonium (ortho)!

A. Banburski, PS; PRD.86.093007

First science run underway this spring!

https://confluence.slac.stanford.edu/display/hpsg/Heavy+Photon+Search+Experiment

EARCHES

10

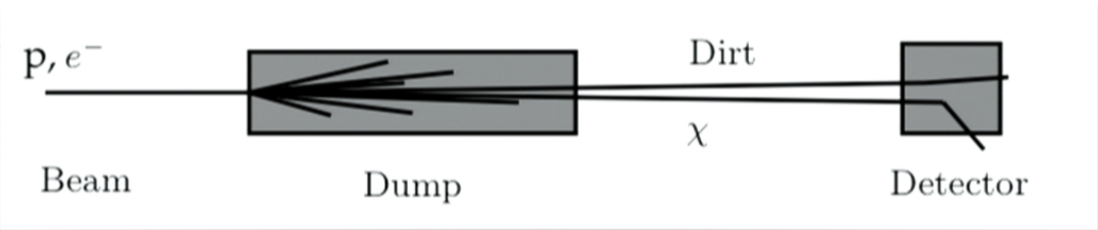
10

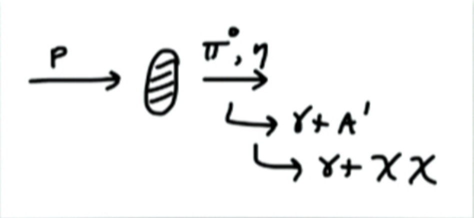
First science run underway this spring!

PRD.86.093007

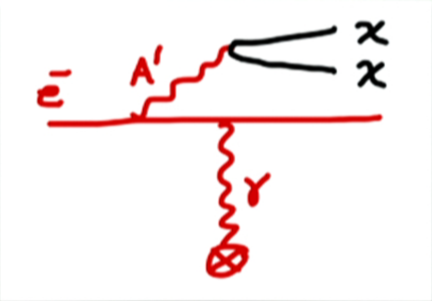
https://confluence.slac.stanford.edu/display/hpsg/Heavy+Photon+Search+Experiment

“BEAM DUMP” OPPORTUNITIES



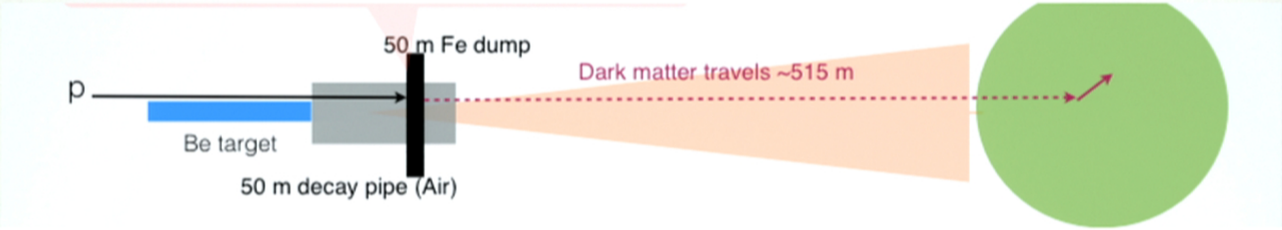


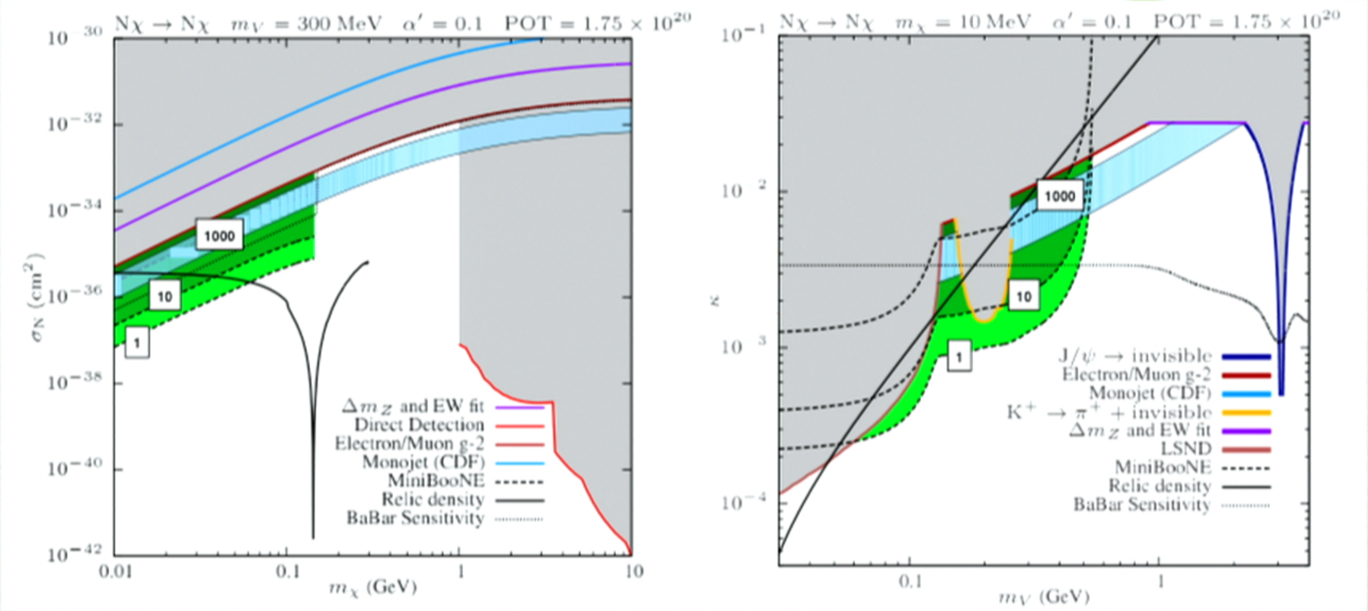
Proton beams:
Reaching beam related neutrino background limits. Future advances still possible



Electron beams:
Negligible beam related neutrino background → big gains possible from high-luminosity beams

NEW RUN FROM MINIBOONE





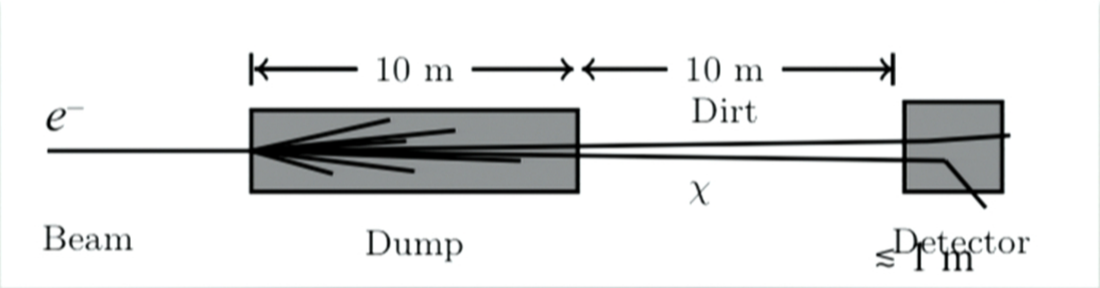
R. Dharmapalan and P. de Niverville

Run completed September 2014!

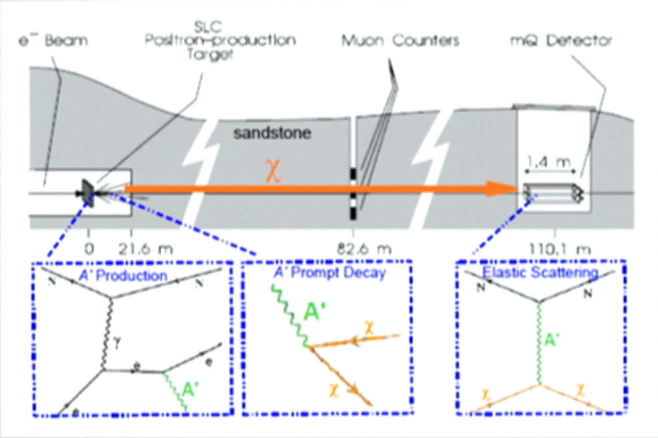
ELECTRON BEAM OPPORTUNITY

Izaguirre, Krnjaic, PS & Toro
PRD.88.114015 and PRD.90.014052

Layout for 12 GeV electron beam concept:



Low beam bkg. & forward A′ production ⇒ small detector suffices!



Past Experience:

SLAC mQ experiment sensitive to coherent nuclear recoil

M. Diamond, PS Phys.Rev.Lett. 111 (2013) 22, 221803

SLAC E137 sensitive to electron scattering.

See: Phys.Rev.Lett. 113 (2014) 17, 171802

THE BDX EXPERIMENT

V1.8
June 3, 2014

Letter of Intent to PAC 42

Dark matter search in a Beam-Dump eXperiment (BDX) at Jefferson Lab

The BDX Collaboration

M. Battaglieri[*†], A. Bersani, A. Celentano[†], R. De Vita[†], E. Fanchini, S. Fegan, P. Musico,
M. Osipenko, M. Ripani, E. Santopinto, M. Taiuti
Istituto Nazionale di Fisica Nucleare, Sezione di Genova
e Dipartimento di Fisica dell'Università, 16146 Genova, Italy

E. Izaguirre[†], G. Krnjaic[†], P. Schuster, N. Toro
Perimeter Institute for Theoretical Physics, Waterloo, Ontario, Canada, N2L 2Y5

M. Dalton, A. Freyberger, F.-X. Girod, V. Kubarovsky, E. Smith[†], S. Stepanyan[†], M. Ungaro
Jefferson Lab, Newport News, VA 23606, USA

G. De Cataldo, R. De Leo, D. Di Bari, L. Lagamba, E. Nappi, R. Perrino
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M. Carpinelli, V. Sipala
Università di Sassari e Istituto Nazionale di Fisica Nucleare, 07100 Sassari, Italy

S. Aiello, V. Bellini, M. De Napoli, A. Giusa, F. Mammoliti, E. Leonora, F. Noto, N. Randazzo,
G. Russo, M. Sperduto, C. Sutera, C. Ventura
Istituto Nazionale di Fisica Nucleare, Sezione di Catania, Catania, Italy

L. Barion, G. Ciullo, M. Contalbrigo, P. Lenisa, A. Movsisyan, F. Spizzo, M. Turisini
Istituto Nazionale di Fisica Nucleare, Sezione di Ferrara e Dipartimento di Fisica dell'Università, Ferrara, Italy

F. De Persio, E. Cisbani, C. Fanelli, F. Garibaldi, F. Meddi, G. M. Urciuoli
Istituto Nazionale di Fisica Nucleare, Sezione di Roma e Gruppo Collegato Sanità, e Università La Sapienza, Italy

S. Anefalos Pereira, E. De Sanctis, D. Hasch, V. Lucherini, M. Mirazita, R. Montgomery,
S. Pisano
Istituto Nazionale di Fisica Nucleare, Laboratori Nazionali di Frascati, P.O. 13, 00044 Frascati, Italy

G. Simi
Istituto Nazionale di Fisica Nucleare, Sezione di Padova, Padova, Italy

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[*] Contact Person, email: Marco.Battaglieri@ge.infn.it

[†] Spokesperson

Positive and supportive review of LOI by JLab PAC 42.

THE BDX EXPERIMENT

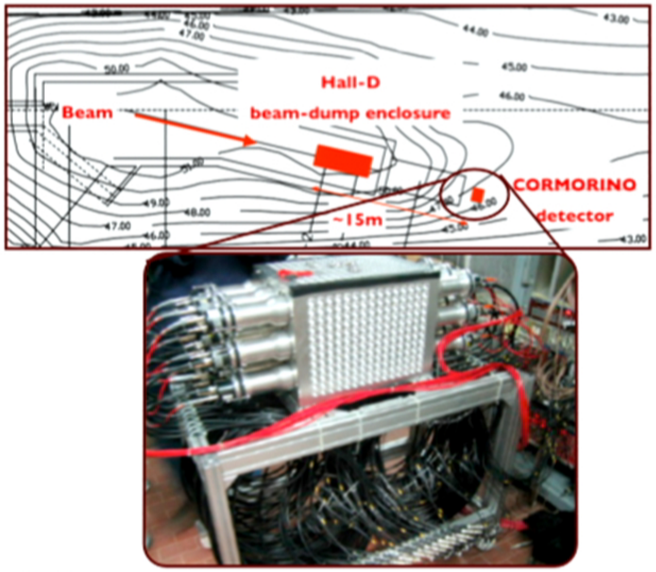
V1.a
June 5, 2014

Letter of Intent to PAC 42

Dark matter search in a Beam-Dump eXperiment (BDX) at Jefferson Lab

The BDX Collaboration

BDX test layout & detector



Positive and supportive review of LOI by JLab PAC 42.

PI postdoc co-spokespeople

Full proposal development underway

First phase at Frascati (Italy) followed by second phase at JLab is current focus

THE BDX EXPERIMENT

BDX will go here

tive

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way

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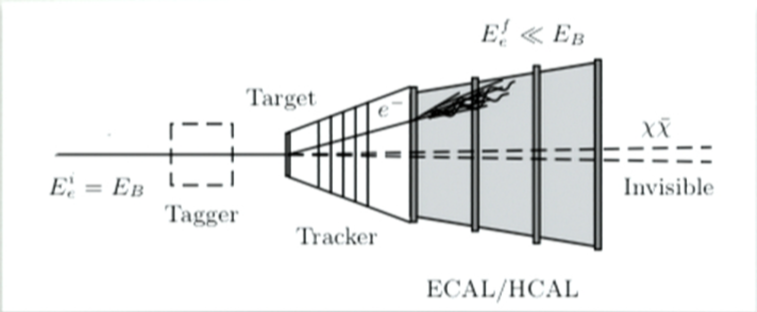
cond

ent

focus

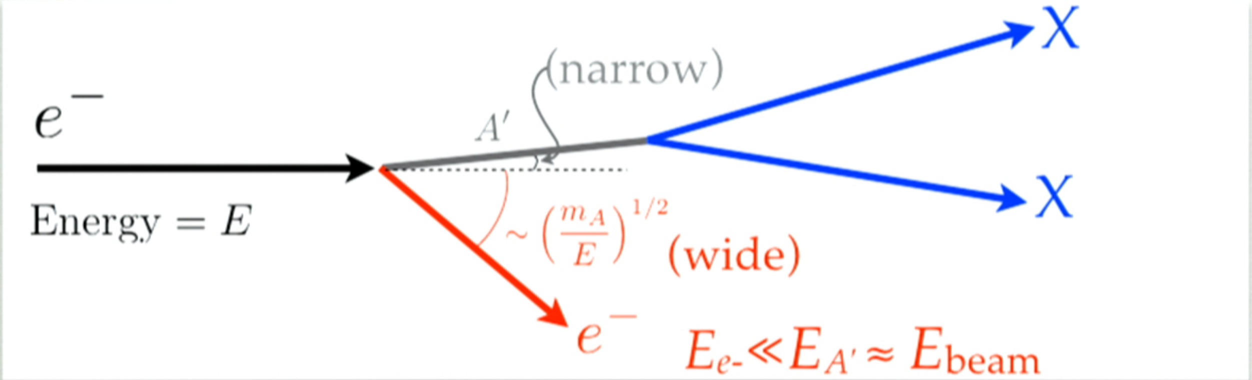
FIXED-TARGET MISSING MOMENTUM



Exploit distinctive kinematics of fixed-target DM production

See: Izaguirre, Krnjaic, PS & Toro; 1411.1404

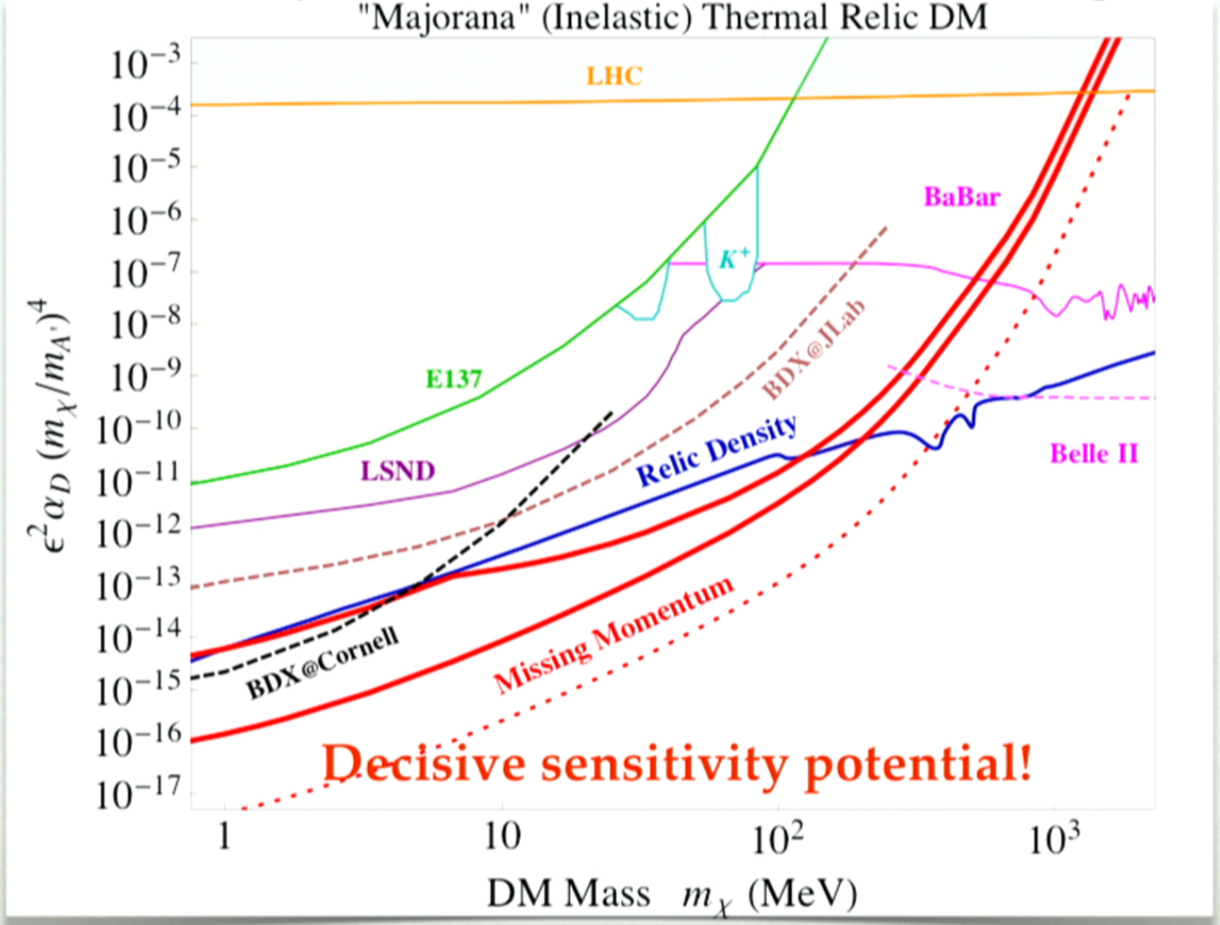
Tag events with ~90-95% missing collinear momentum



Only needs production, not re-scattering → Big advantage!
More on this momentarily...

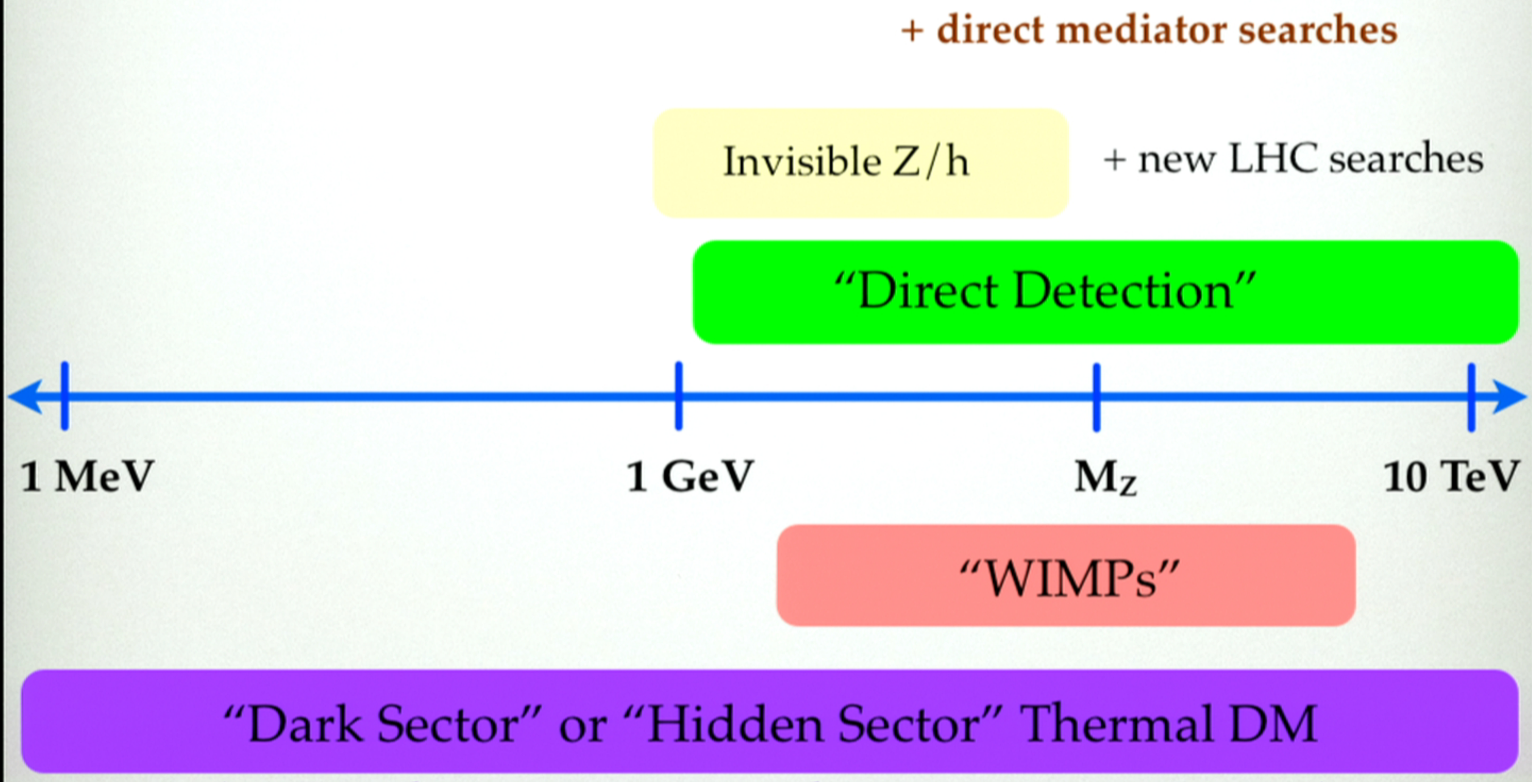
TESTING LDM

Scenario: “Majorana” (or inelastic scattering) DM



Decisive sensitivity potential!

TESTING THERMAL DM



+ direct mediator searches

Invisible Z/h

+ new LHC searches

"Direct Detection"

1 MeV

1 GeV

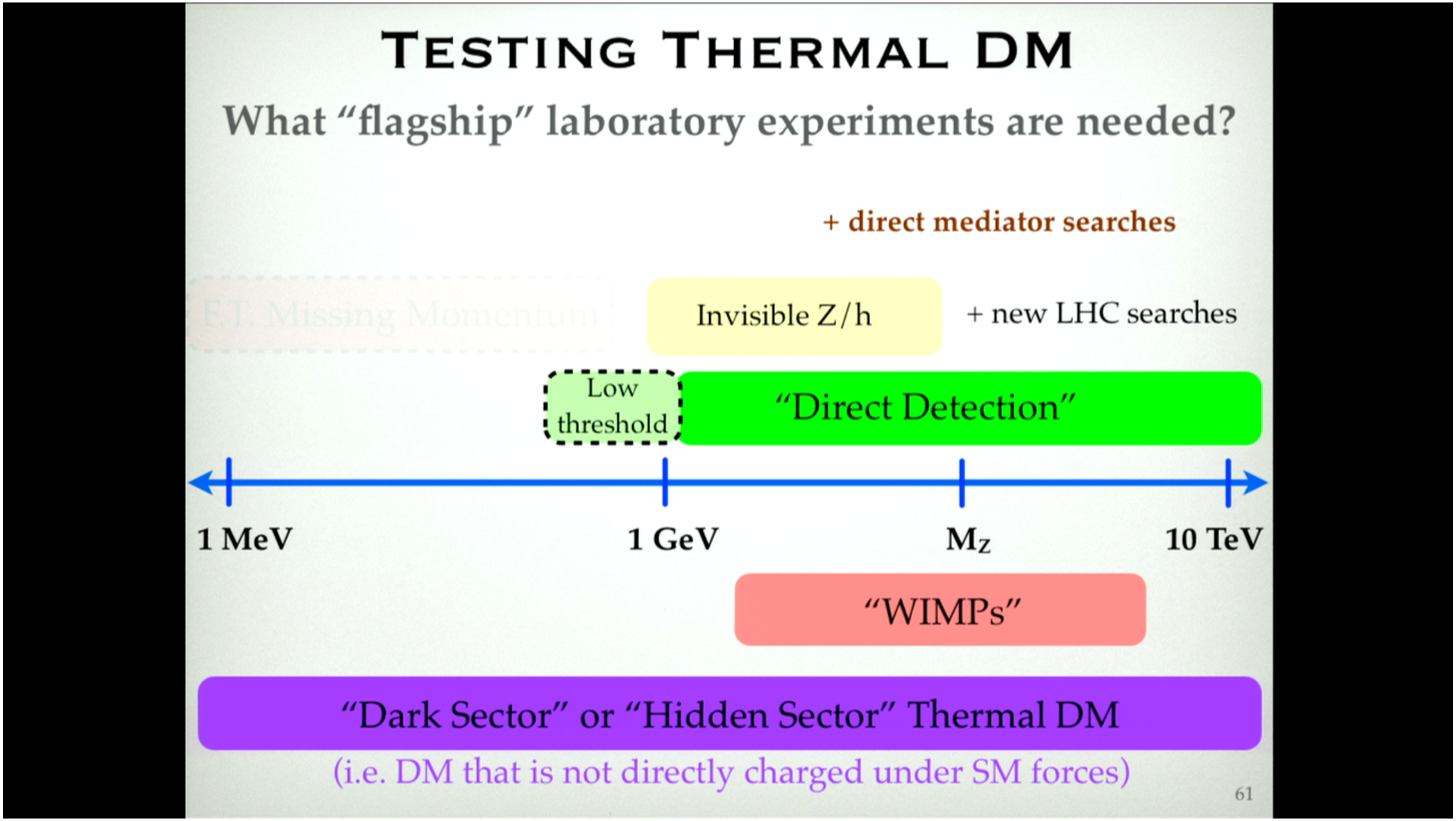
M_Z

10 TeV

"WIMPs"

"Dark Sector" or "Hidden Sector" Thermal DM

(i.e. DM that is not directly charged under SM forces)



TESTING THERMAL DM

What "flagship" laboratory experiments are needed?

+ direct mediator searches

F.T. Missing Momentum

Invisible Z/h

+ new LHC searches

Low threshold

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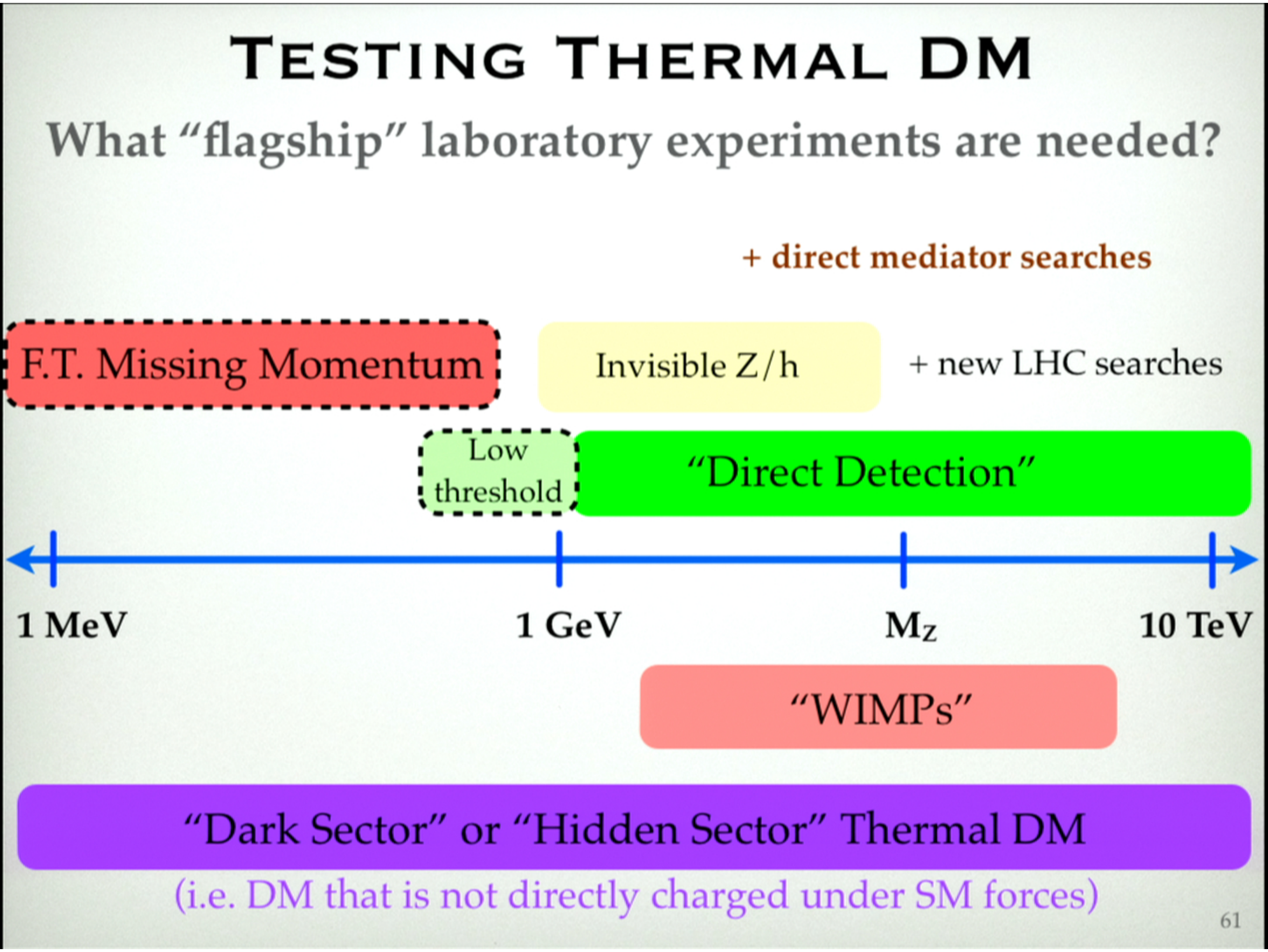

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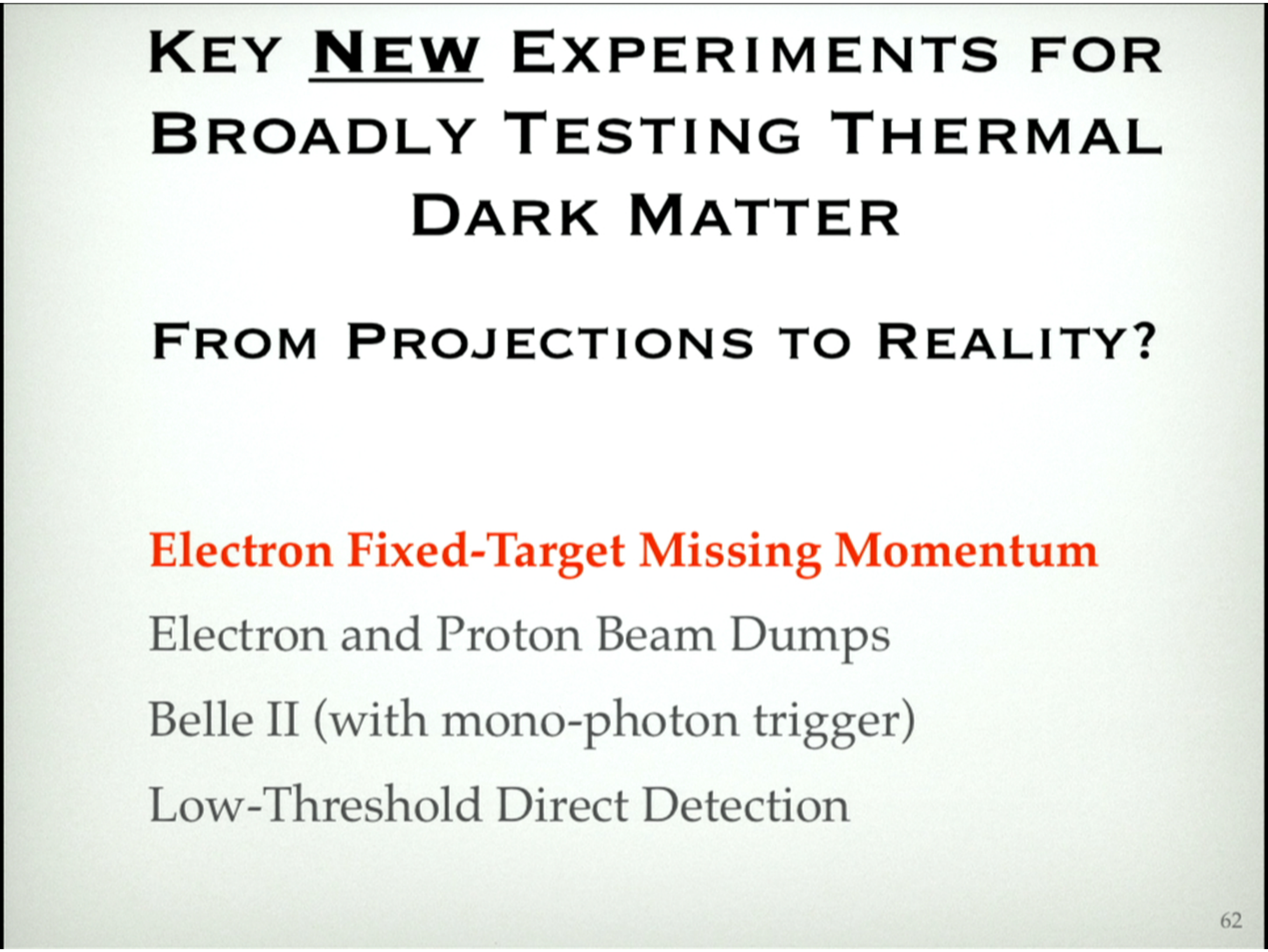


KEY <u>NEW</u> EXPERIMENTS FOR BROADLY TESTING THERMAL DARK MATTER

FROM PROJECTIONS TO REALITY?

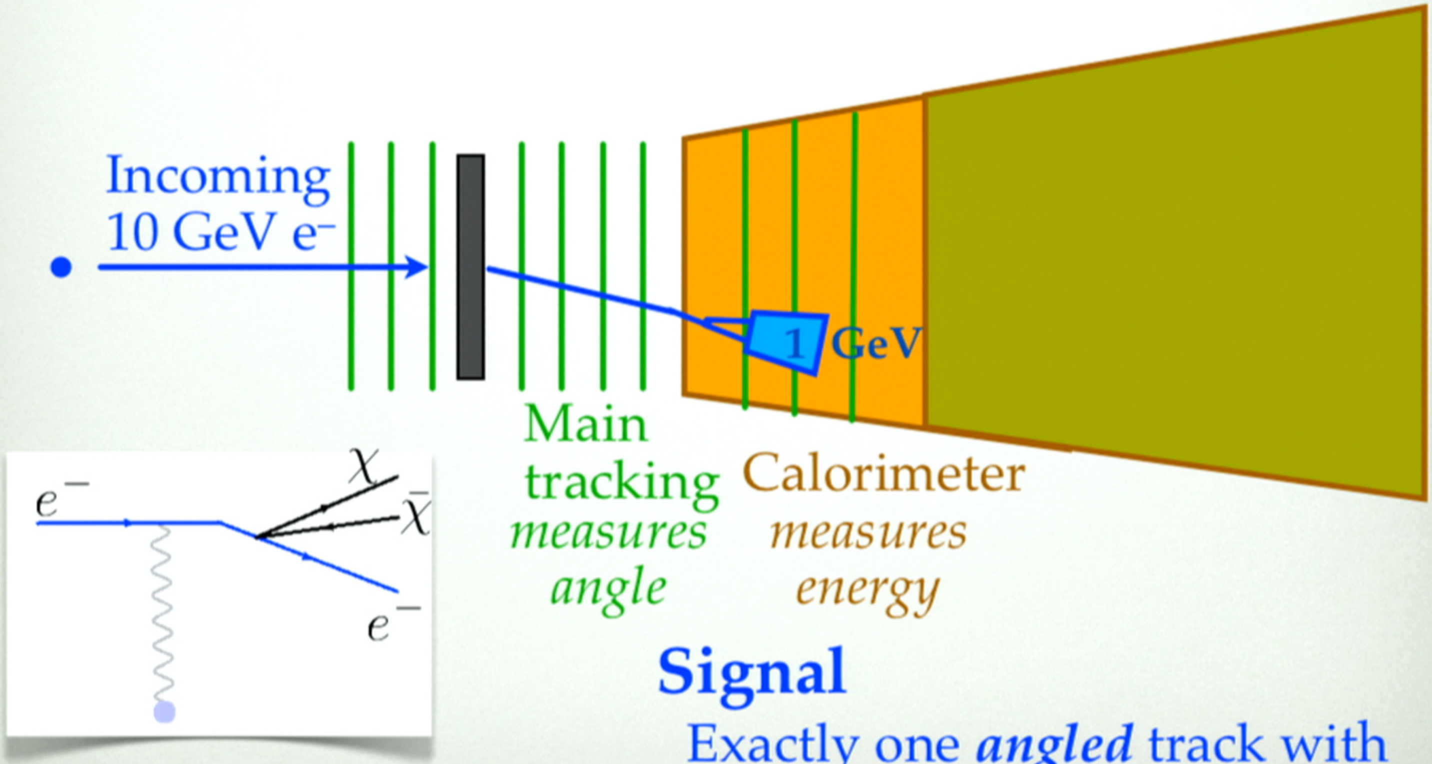
Electron Fixed-Target Missing Momentum

Electron and Proton Beam Dumps

Belle II (with mono-photon trigger)

Low-Threshold Direct Detection

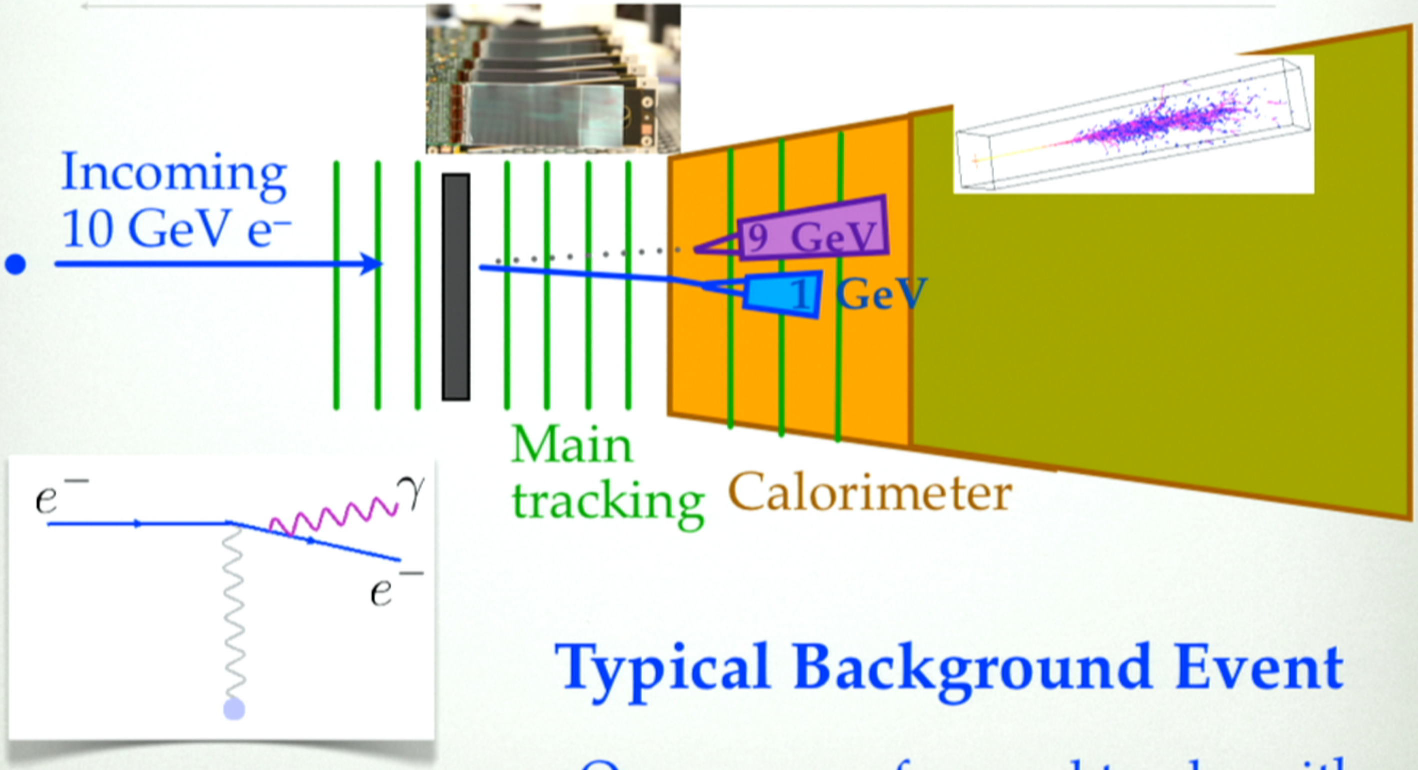
FIXED-TARGET MISSING MOMENTUM: AN INTRODUCTION



Signal

Exactly one ***angled*** track with EM shower energy 0.5-3 GeV

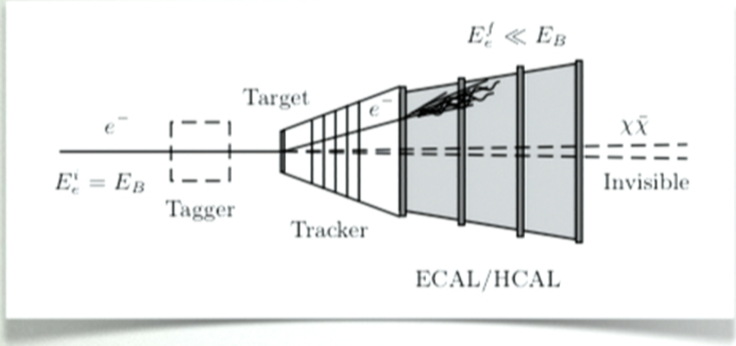
FIXED-TARGET MISSING MOMENTUM: AN INTRODUCTION



Typical Background Event

One or more forward tracks with
EM shower total energy ~10 GeV

ROBUST AND POWERFUL



Electron Fixed-Target Missing Momentum

Very simple (and old) idea, but never used this way

Why?

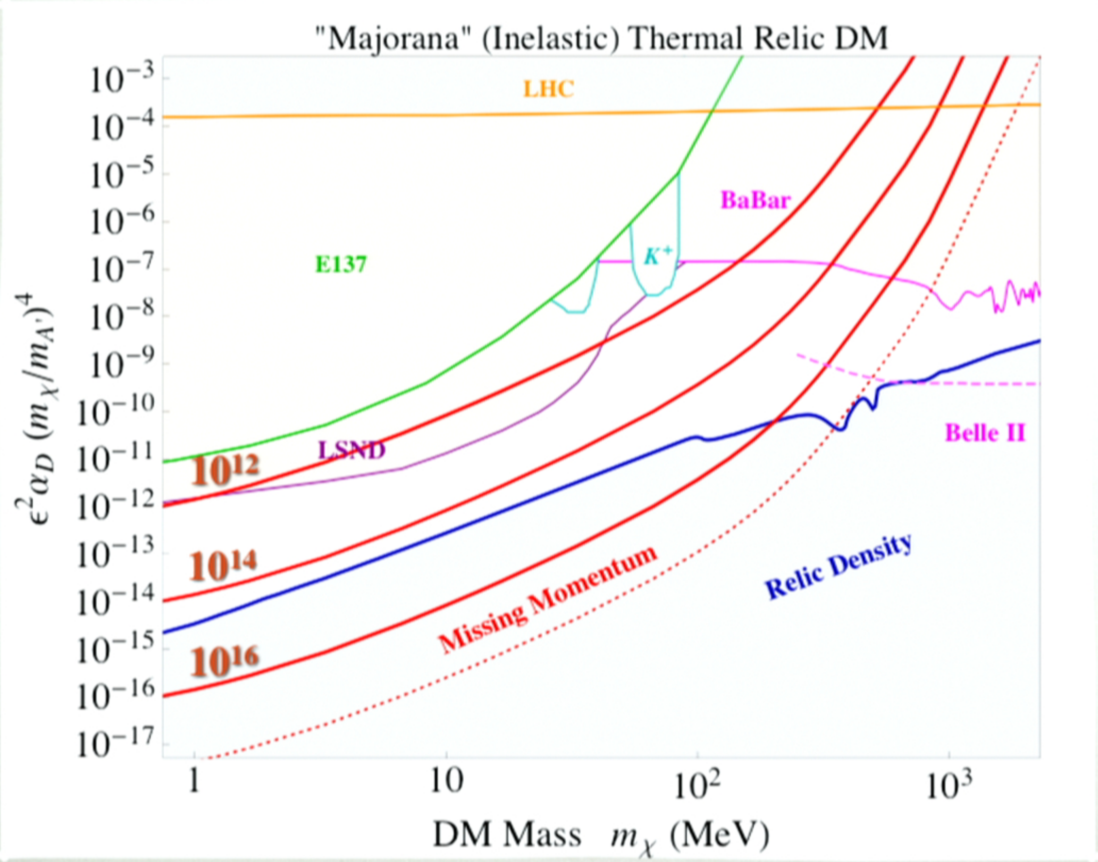
→ Unusual **beam requirements**

→ Strategy for mitigating **backgrounds**

→ Distinctive dark matter kinematics overlooked

See: Izaguirre, Krnjaic, PS & Toro;
1411.1404 and 1515.00011

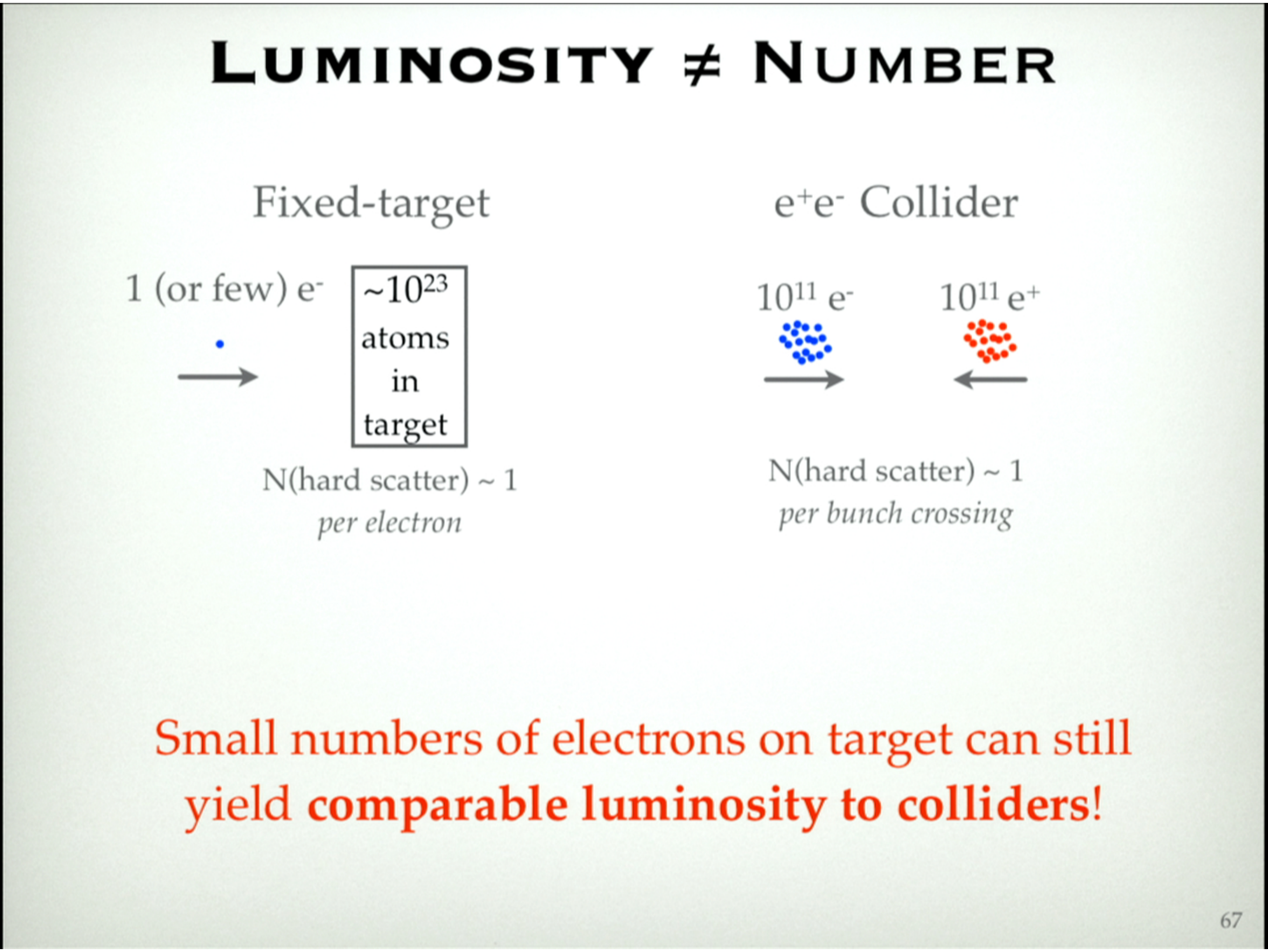
LUMINOSITY & DECISIVE SENSITIVITY



Red curves:
Rate-limited sensitivity for various # of e⁻ on a 30% X_0 target, 10 GeV beam, W target

~10^{14} electrons on target probes considerable new territory

~10^{15} electrons on target is needed for an excellent experiment



LUMINOSITY ≠ NUMBER

Fixed-target

1 (or few) e^-

~10^{23} atoms in target

N(hard scatter) ~ 1
per electron

e^+e^- Collider

10^{11} e^-

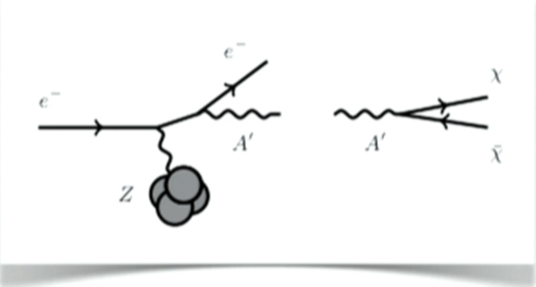
10^{11} e^+

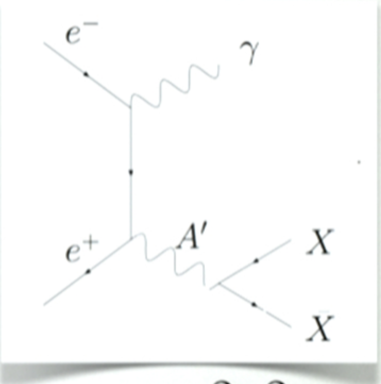
N(hard scatter) ~ 1
per bunch crossing

Small numbers of electrons on target can still yield **comparable luminosity to colliders**!

FIXED-TARGET CROSS-SECTION ADVANTAGE

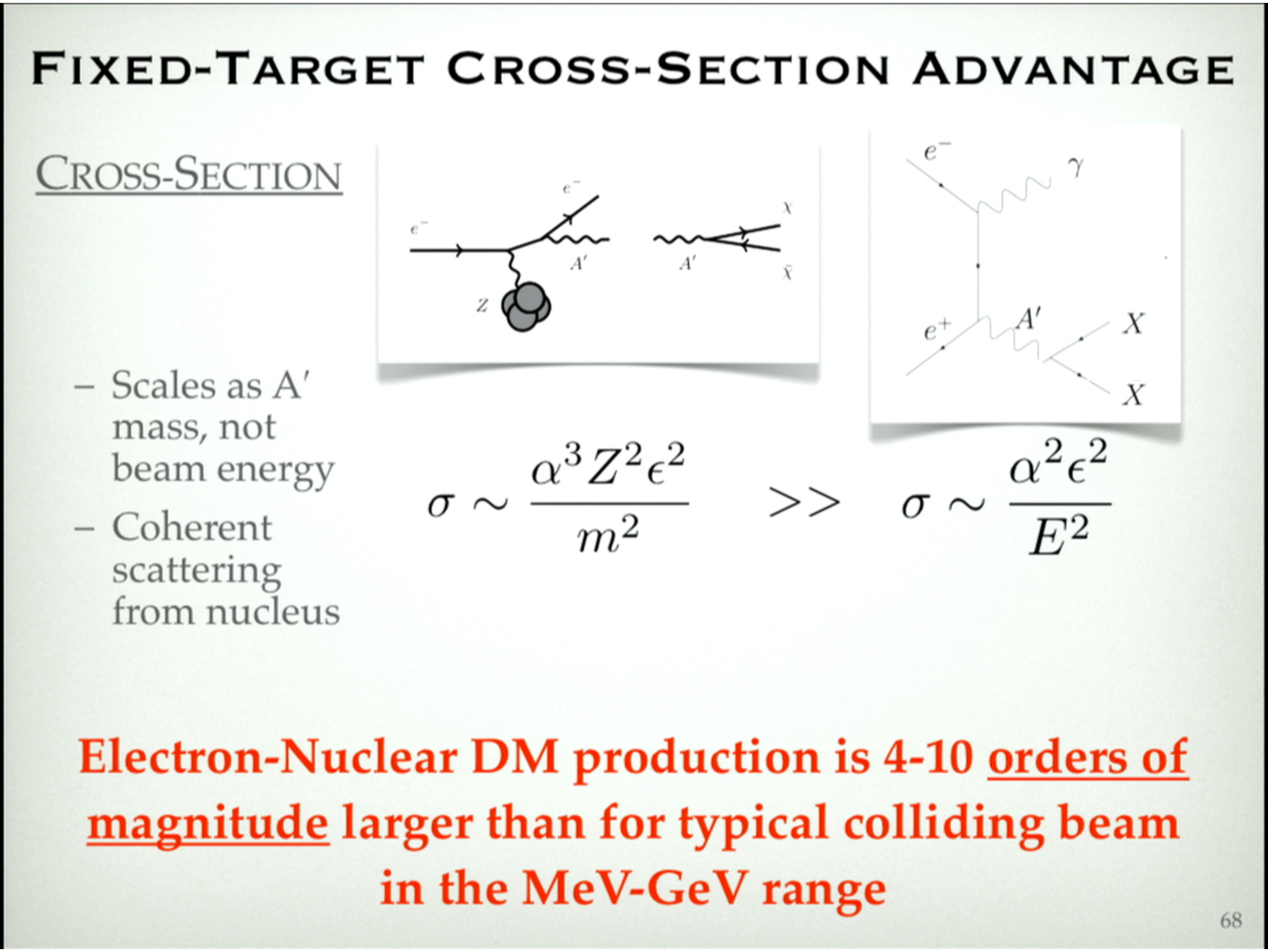
CROSS-SECTION





- Scales as A′ mass, not beam energy
- Coherent scattering from nucleus

$$\sigma \sim \frac{\alpha^3 Z^2 \epsilon^2}{m^2} \quad >> \quad \sigma \sim \frac{\alpha^2 \epsilon^2}{E^2}$$



FIXED-TARGET CROSS-SECTION ADVANTAGE

CROSS-SECTION

- Scales as A′ mass, not beam energy
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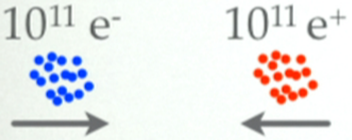
$$\sigma \sim \frac{\alpha^3 Z^2 \epsilon^2}{m^2} \quad >> \quad \sigma \sim \frac{\alpha^2 \epsilon^2}{E^2}$$

Electron-Nuclear DM production is 4-10 orders of magnitude larger than for typical colliding beam in the MeV-GeV range

NUMBER VS. TIME

Accelerator beams have time structure

e^+e^- Collider



Old SLAC Linac

Typical electron beam repetition rate is ~100 Hz

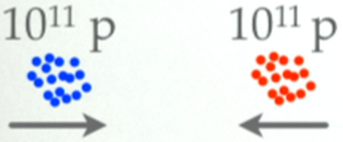
In a year, expect maybe 10^9 packets of particles to cross

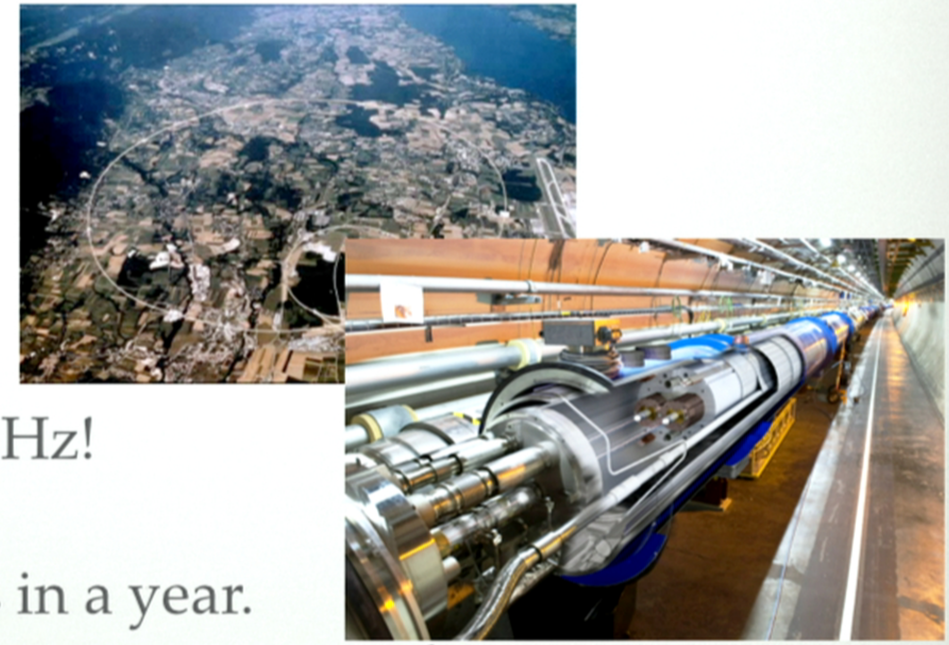
→ way too few if we only have one electron per packet

NUMBER VS. TIME

Accelerator beams have time structure

Proton Colliders



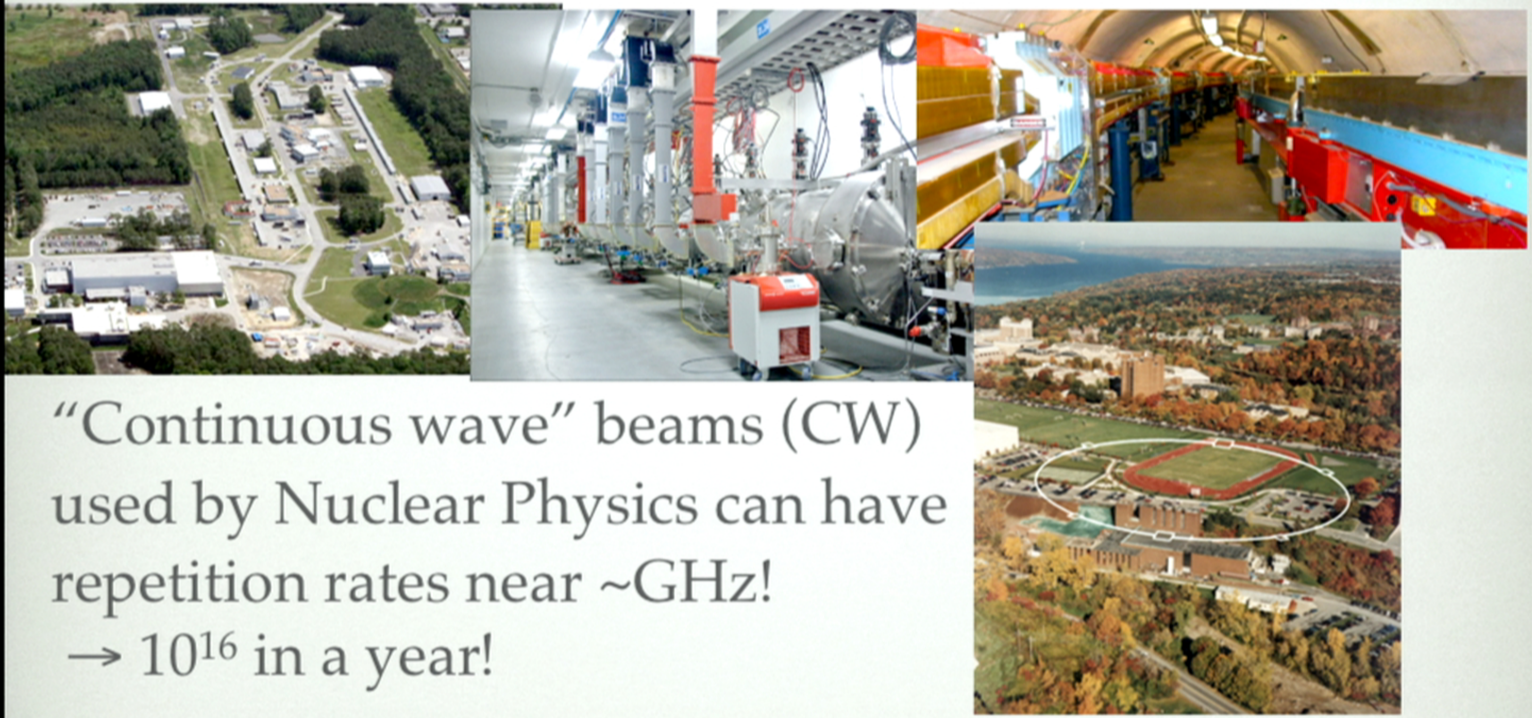


The LHC is ~40 MHz!

~4 x 10^{14} crossings in a year.
Interesting, but still not fast enough
(even if it were electrons)!

NUMBER VS. TIME

Accelerator beams have time structure

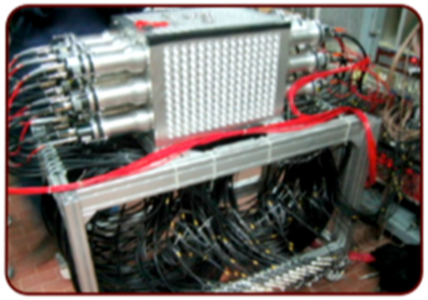


"Continuous wave" beams (CW) used by Nuclear Physics can have repetition rates near ~GHz!
→ 10^{16} in a year!

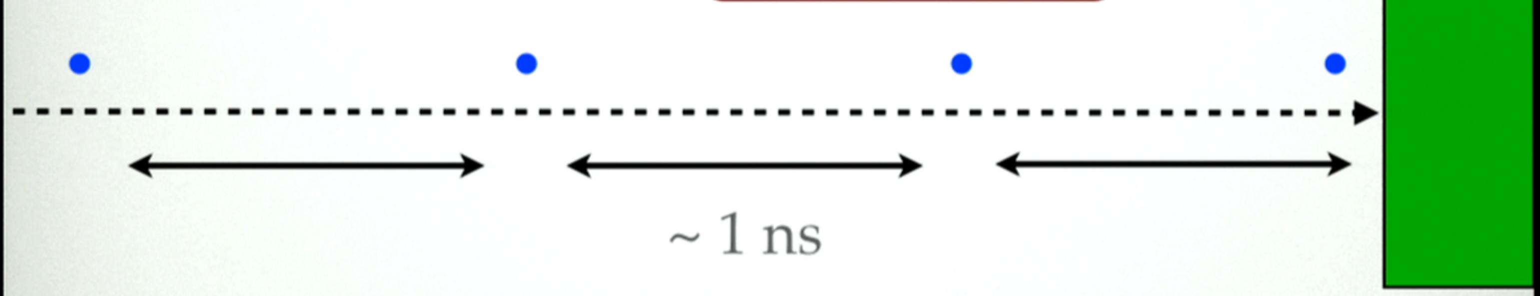
Storage rings can also hold packets with a total circulation rate of ~100 MHz

TOO FAST?

Simple
calorimeter



Detector Face



Can we actually detect reactions this quickly?

Too Fast?

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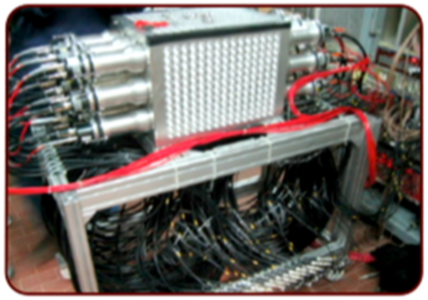
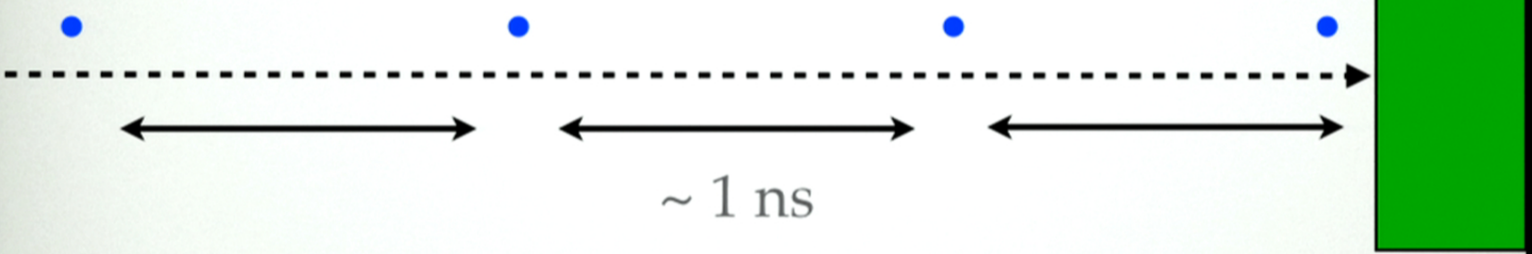


Detector Face

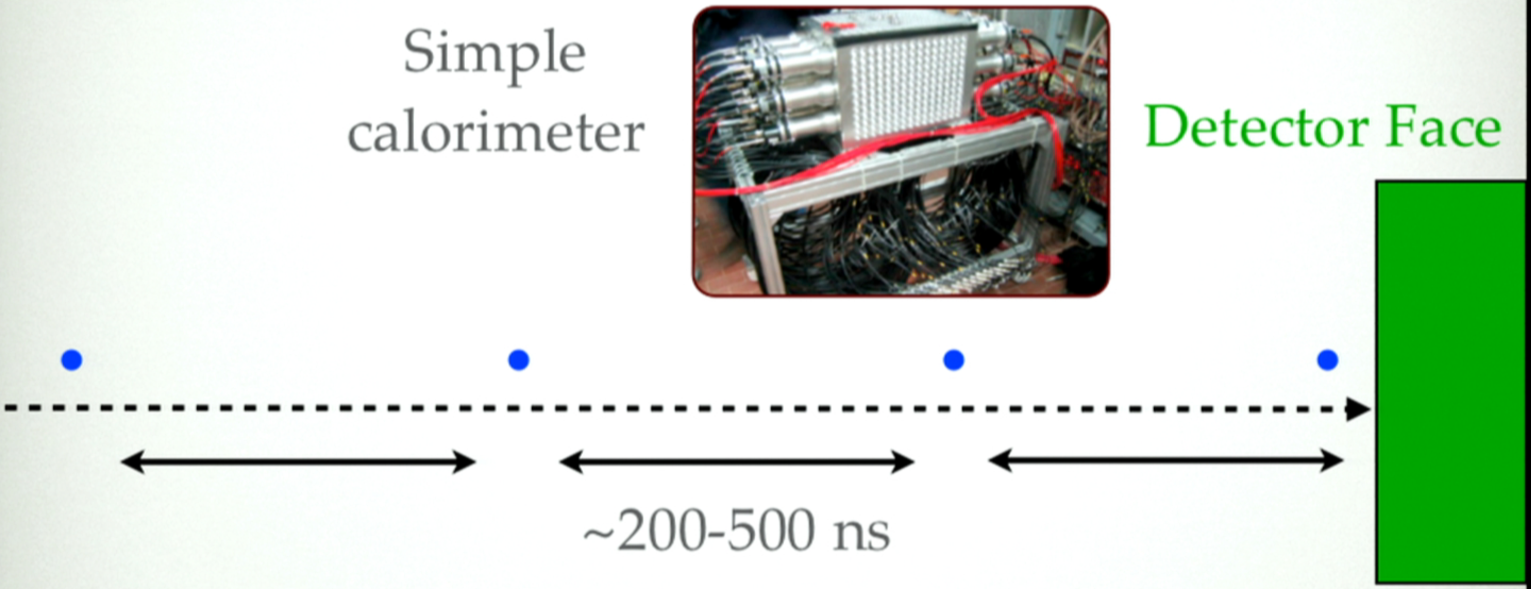


~ 1 ns

Can we actually detect reactions this quickly?

No, not readily...

READILY ACHIEVABLE


Simple calorimeter

Detector Face

~200-500 ns

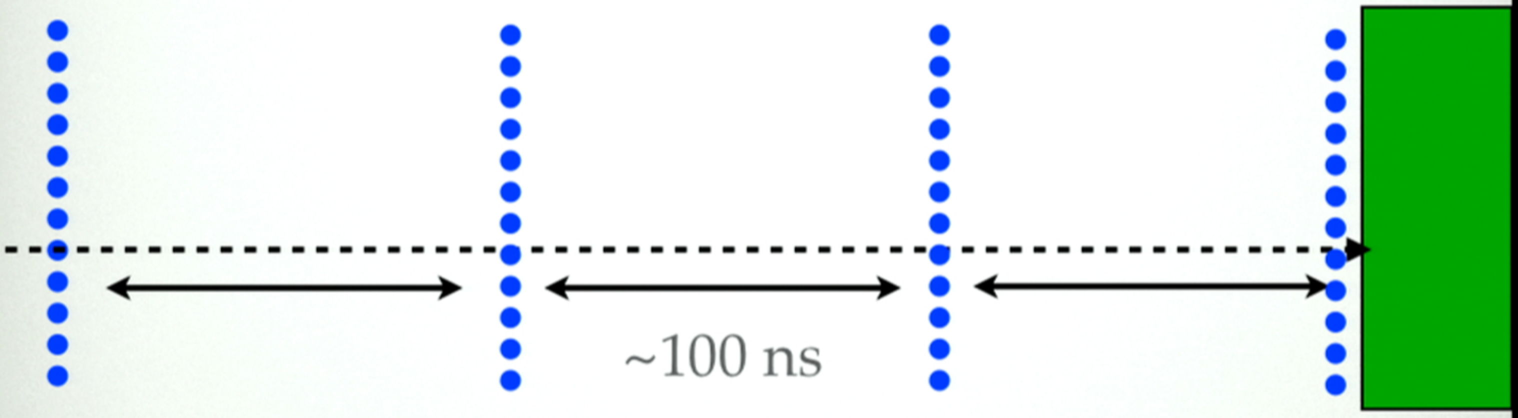
1 electron per bunch, 2-5 MHz for 10^7 s

→ **few x 10^{13} electrons on target (EOT)**

Definitely achievable with existing detectors and readout

PUSHING THE ENVELOPE

Use spoiling foils or defocusing quadrupole magnets



~10-30 electrons per bunch at 3 MHz for 10^7 s

→ **10^{15} electrons on target (EOT)**

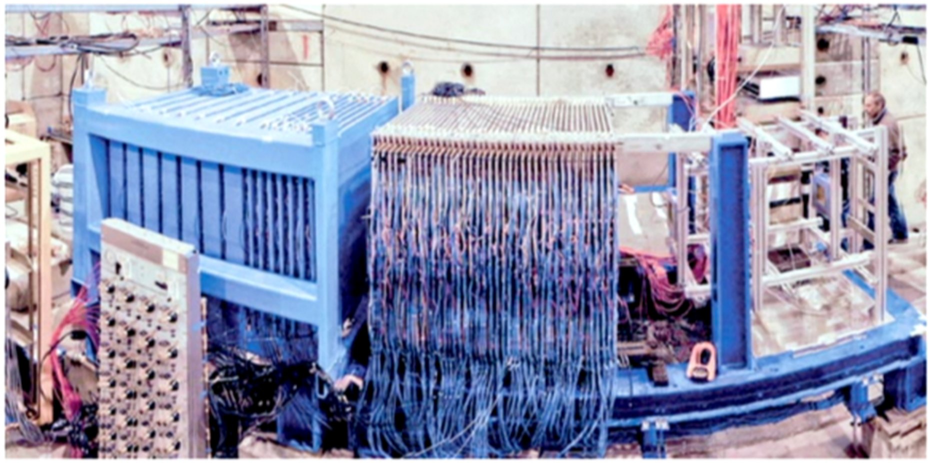
~100 electrons per bunch at 10 MHz for 10^7 s

→ **10^{16} electrons on target (EOT)**

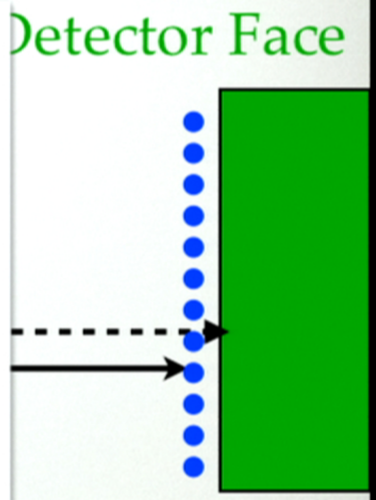
PUSHING THE ENVELOPE

Use spoiling foils or defocusing

Example: CALICE prototype



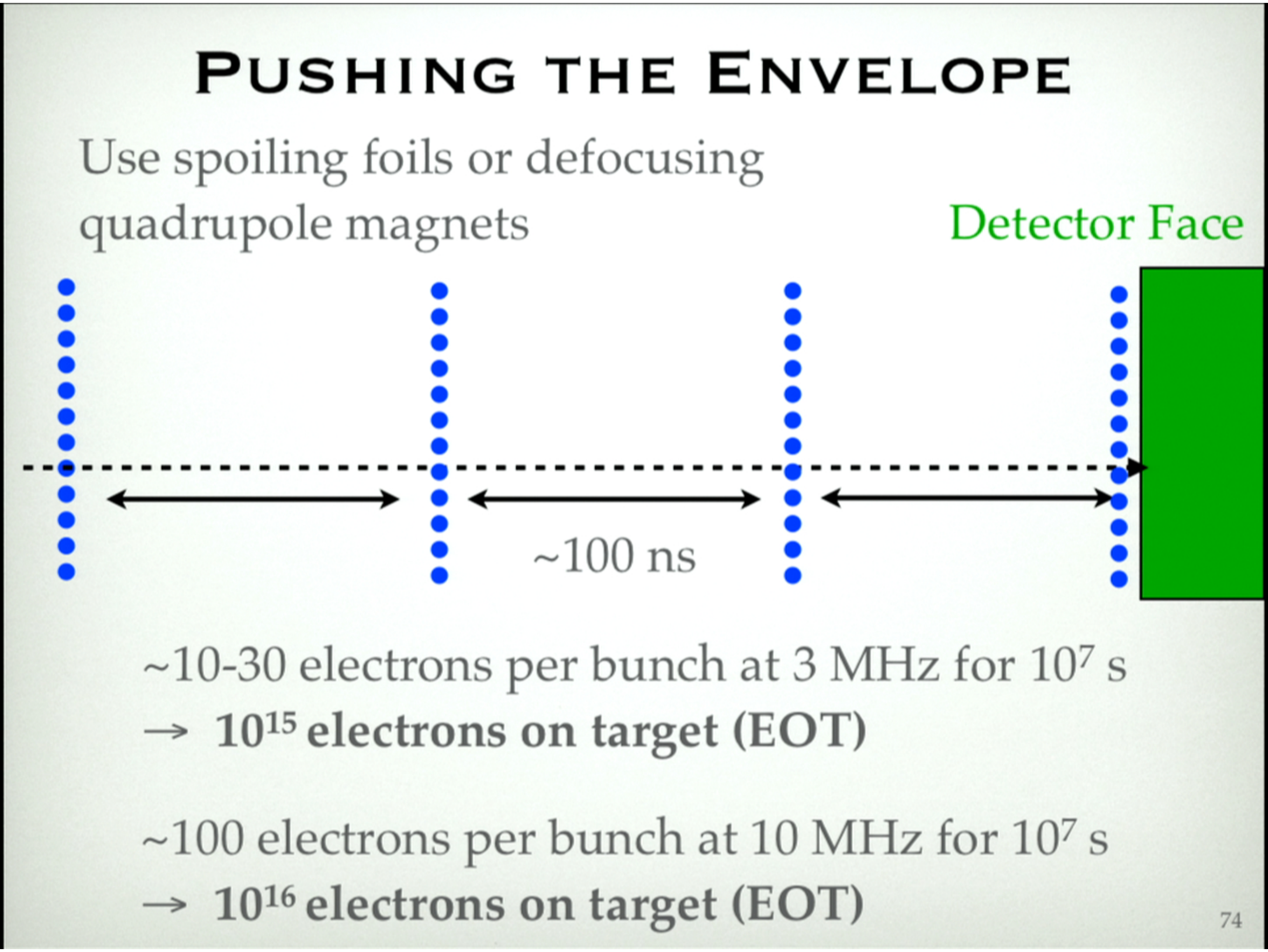
Highly granular & high-speed detectors needed, i.e. silicon/tungsten calorimeters designed for HL-LHC or ILC



or 10^7 s

r 10^7 s

→ **10^{16} electrons on target (EOT)**



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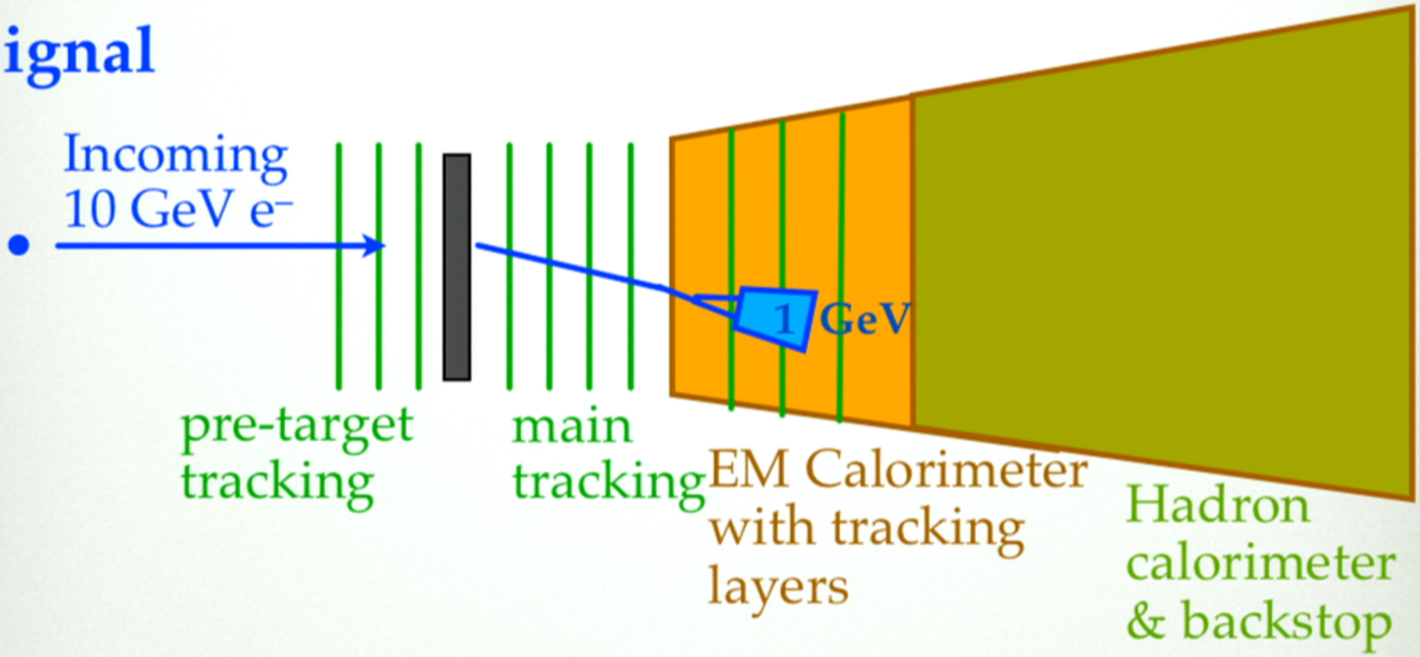
SIGNAL VS. BACKGROUND

Signal



Exactly one *angled* track with
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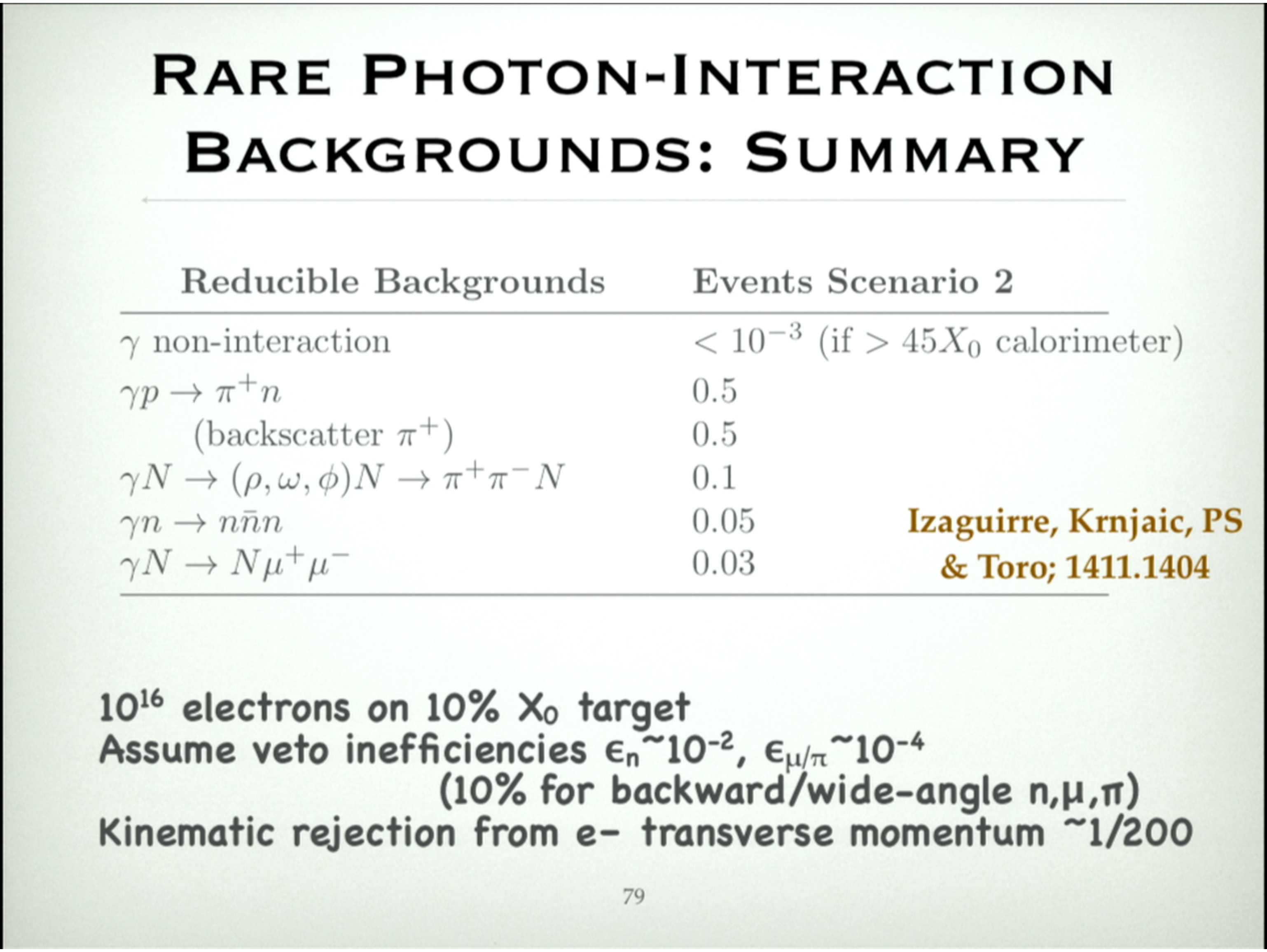
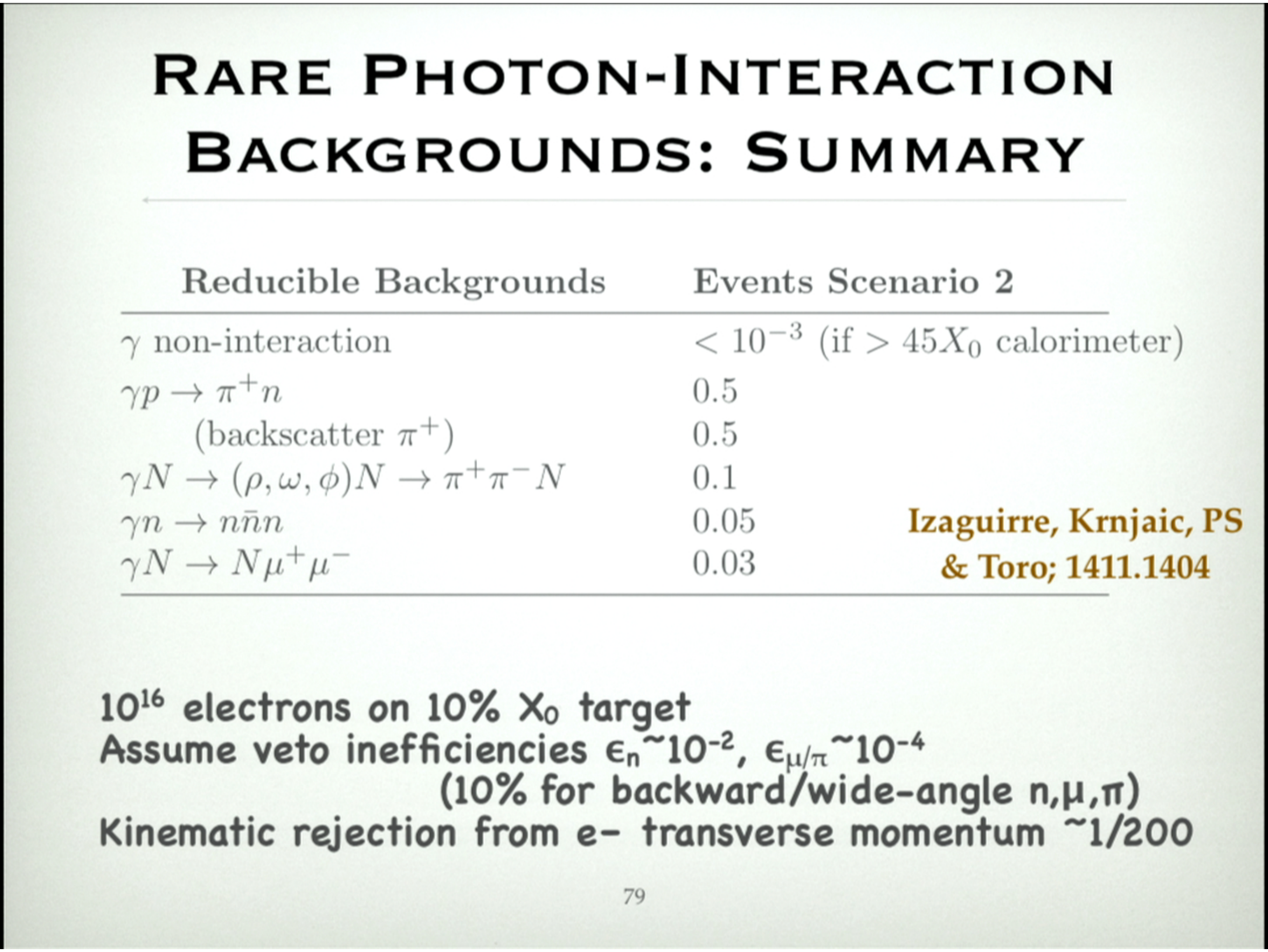


RARE PHOTON-INTERACTION BACKGROUNDS: SUMMARY

Reducible Backgrounds	Events Scenario 2
γ non-interaction	$< 10^{-3}$ (if $> 45X_0$ calorimeter)
$\gamma p \to \pi^+ n$	0.5
(backscatter π^+)	0.5
$\gamma N \to (\rho, \omega, \phi)N \to \pi^+\pi^- N$	0.1
$\gamma n \to n\bar{n}n$	0.05
$\gamma N \to N\mu^+\mu^-$	0.03

Izaguirre, Krnjaic, PS & Toro; 1411.1404

10^{16} electrons on 10% X_0 target
Assume veto inefficiencies ϵ_n~10^{-2}, $\epsilon_{\mu/\pi}$~10^{-4}
(10% for backward/wide-angle n,μ,π)
Kinematic rejection from e- transverse momentum ~1/200



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STRIKING DM KINEMATICS

Izaguirre, Krnjaic, PS
& Toro; 1411.1404

Electron kinematics:

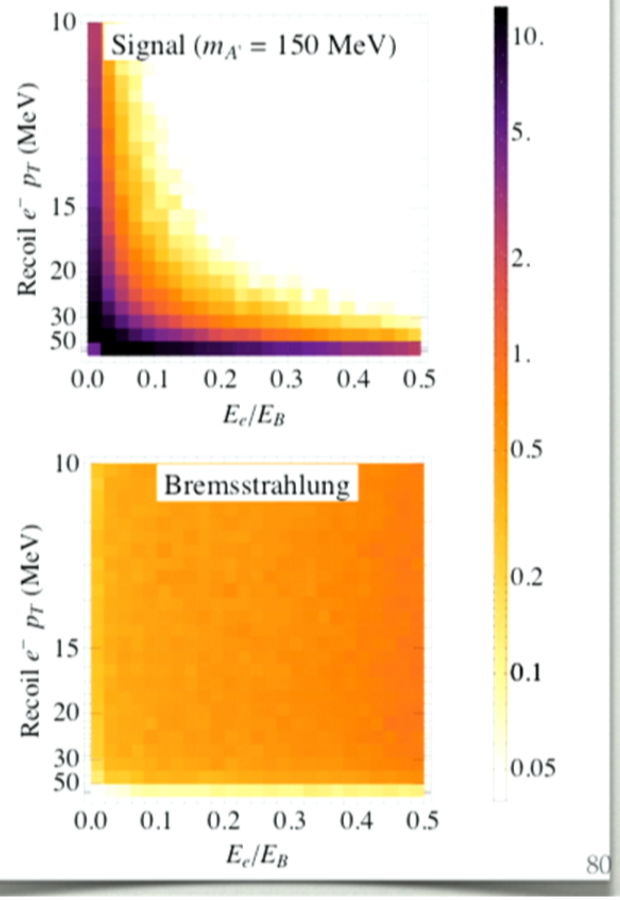
- → energy fraction
- → transverse momentum

Signal Events:

Characteristic low E_e, broad spread in p_T

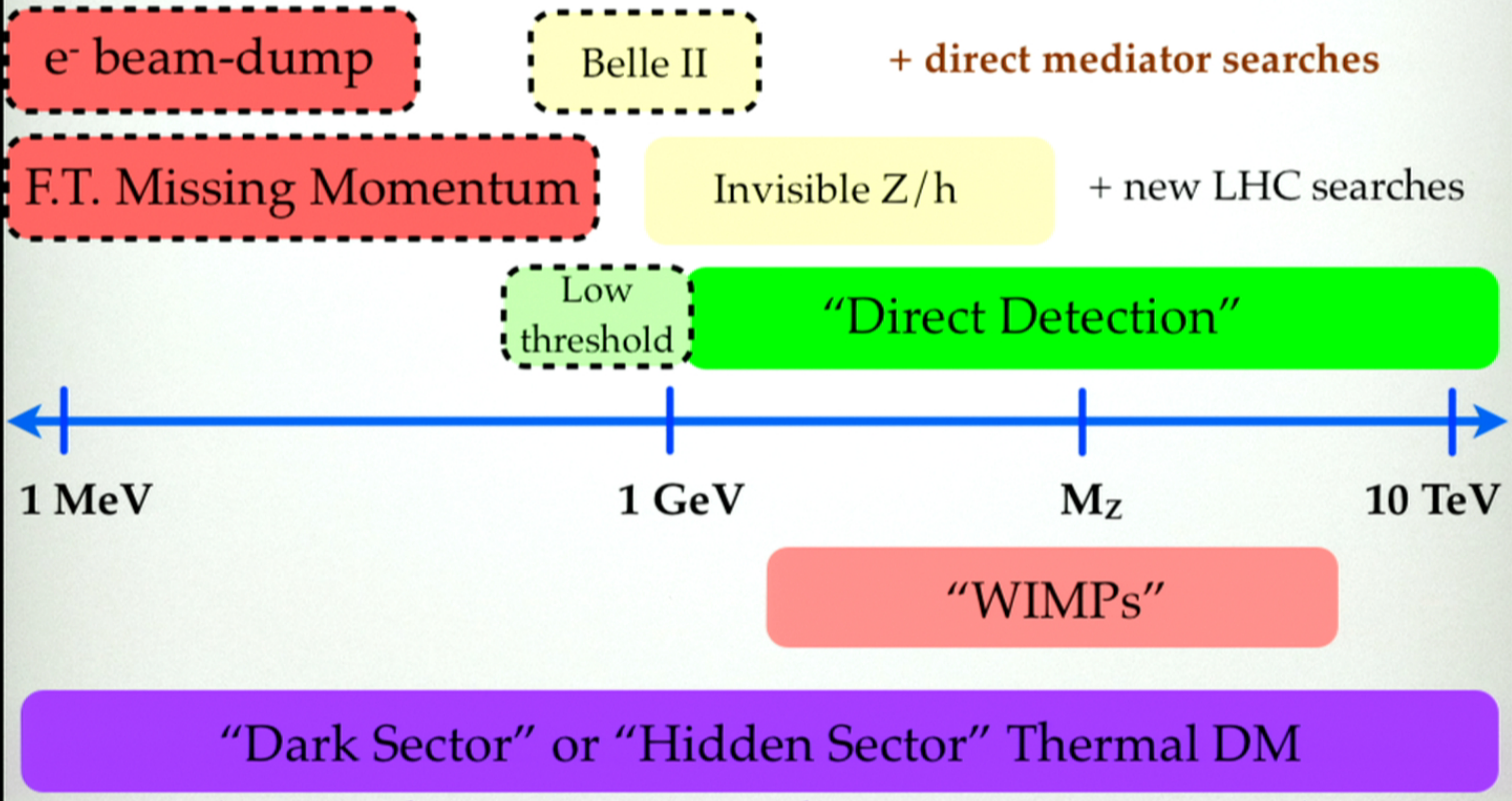
Simple cuts can reduce background by 2-4 orders of magnitude

Kinematics can be used to measure background veto performance!



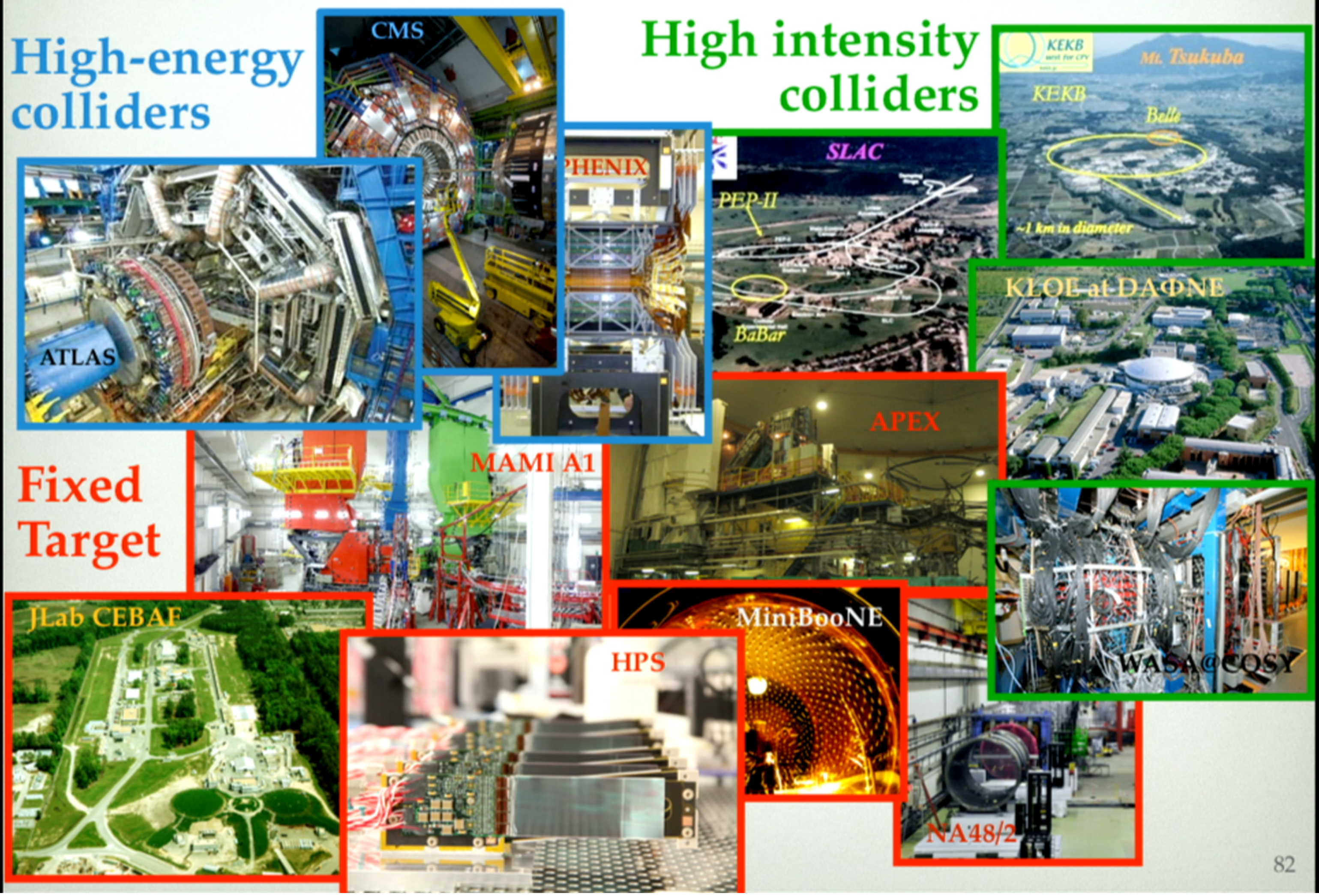
TESTING THERMAL DM

Broad physics program required!



(i.e. DM that is not directly charged under SM forces)

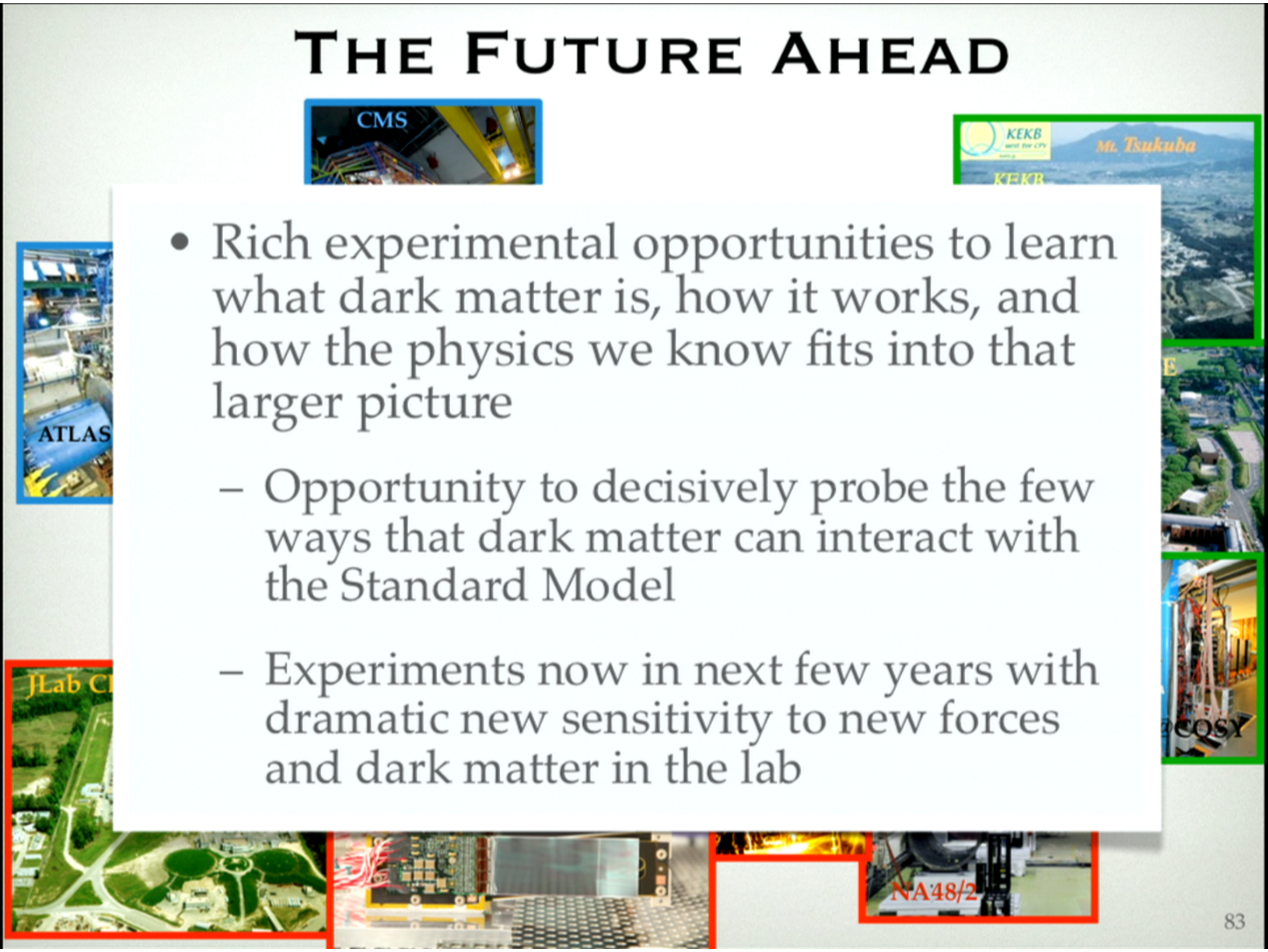
AN EXPERIMENTAL RENAISSANCE



High-energy colliders

High intensity colliders

Fixed Target



THE FUTURE AHEAD

- Rich experimental opportunities to learn what dark matter is, how it works, and how the physics we know fits into that larger picture
  - Opportunity to decisively probe the few ways that dark matter can interact with the Standard Model
  - Experiments now in next few years with dramatic new sensitivity to new forces and dark matter in the lab