Dark Sector Searches at MESA

Luca Doria
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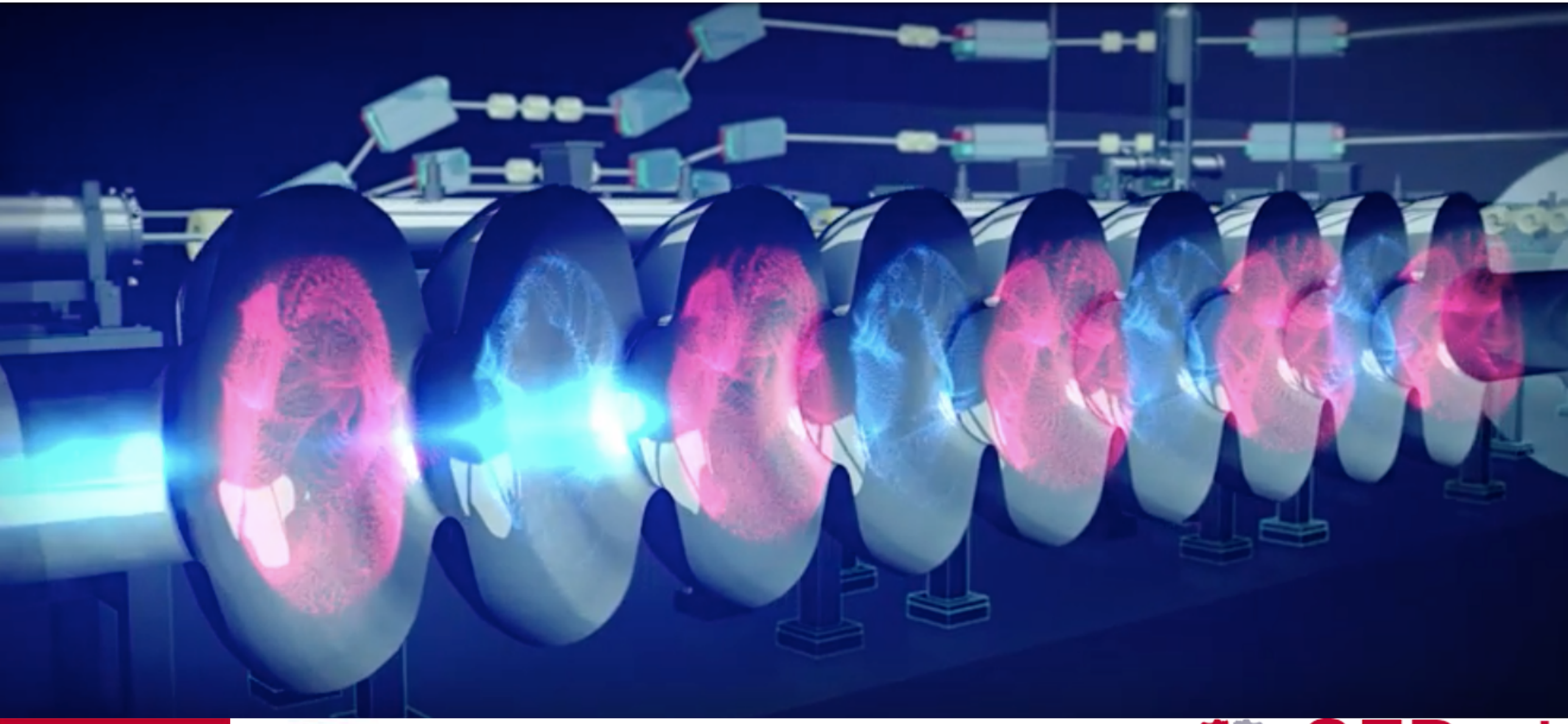


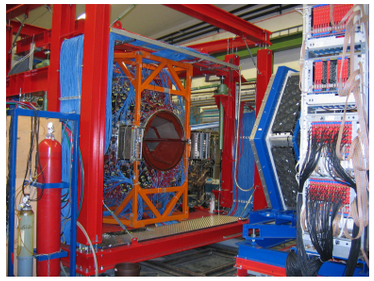
JG|U

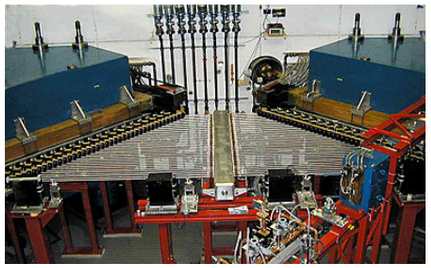
PRISMA | Cluster of Excellence
Precision Physics, Fundamental Interactions and Structure of Matter

SFB 1044
THE LOW-ENERGY FRONTIER OF THE STANDARD MODEL

Introduction

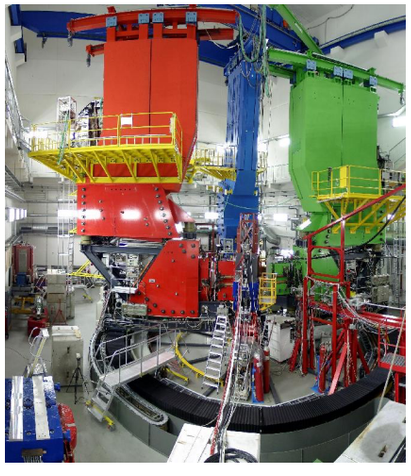
[A2 Collaboration]
Experiments with real photons





[MAMI-C (since 2007)]
Harmonic Double-sided Microtron
E= 1.5 GeV

[MAMI-B]
3 cascaded Racetrak Microtrons
E=180-883 MeV
Max beam current 100 uA c.w.



[A1 Collaboration]
3-spectrometer setup
Experiments with electrons

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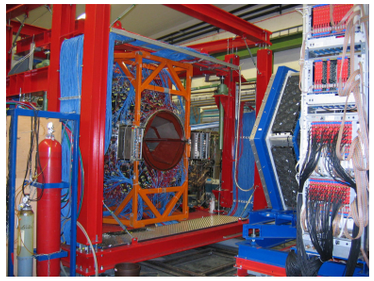

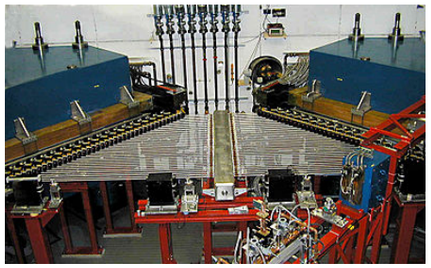

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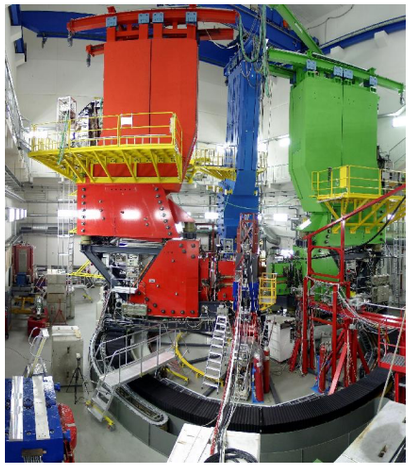

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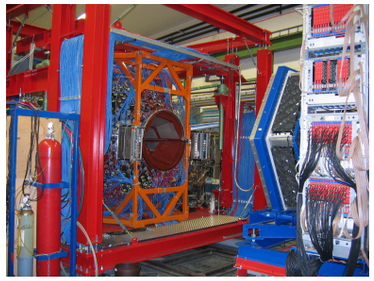

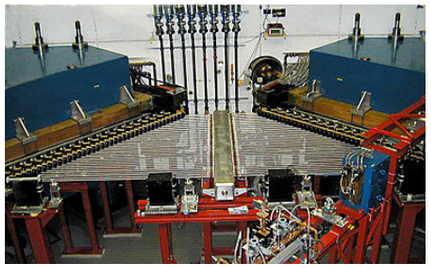

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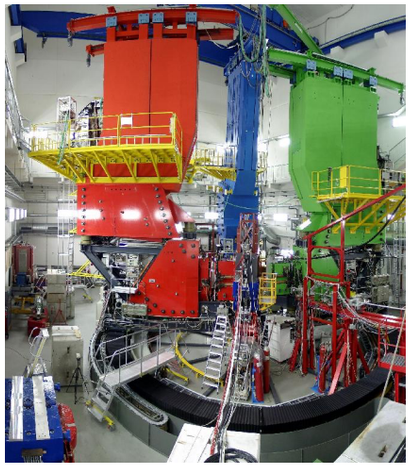

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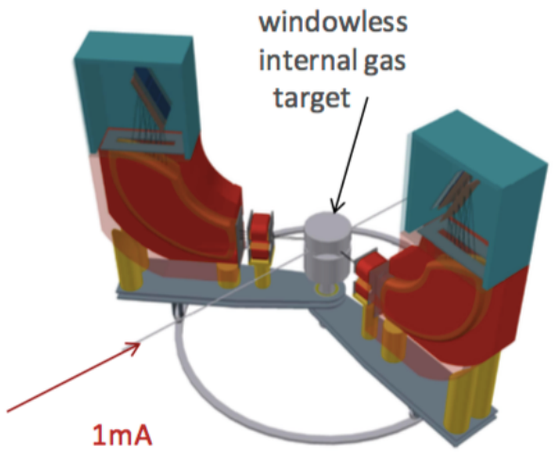
Mainz Energy-Recovering Superconducting Accelerator

MAGIX



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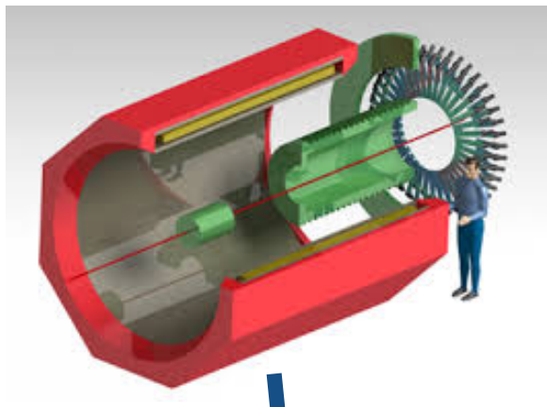


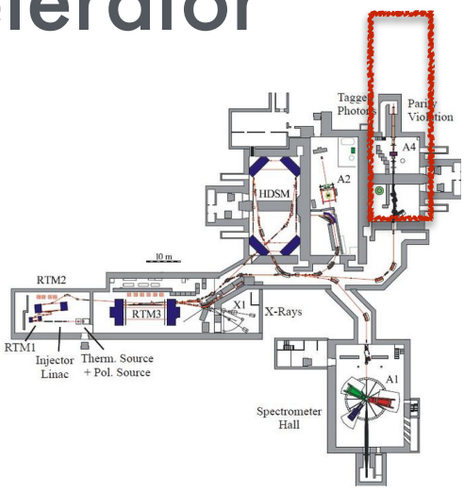
<u>Superconducting Cavities:</u>

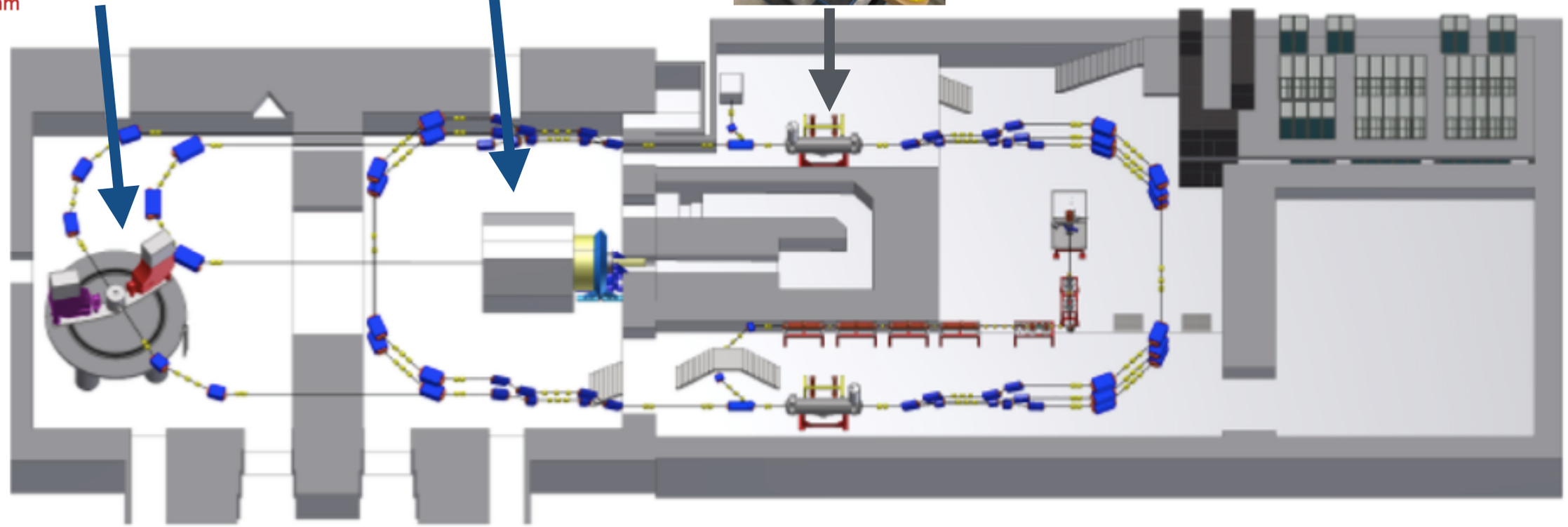
9-cell ,1.3 GHz

12.5 MeV/m gain

XFEL-TESLA type

Modified Rossendorf-type Modules





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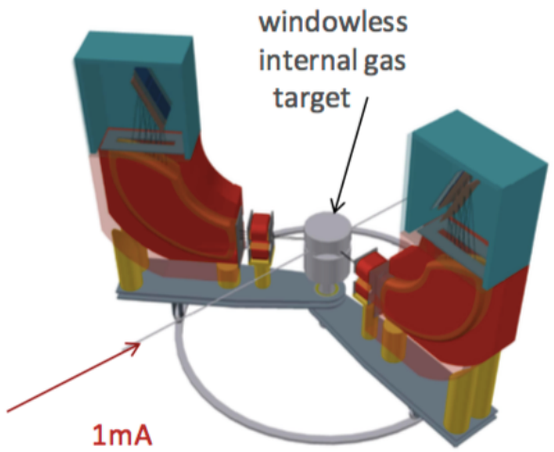

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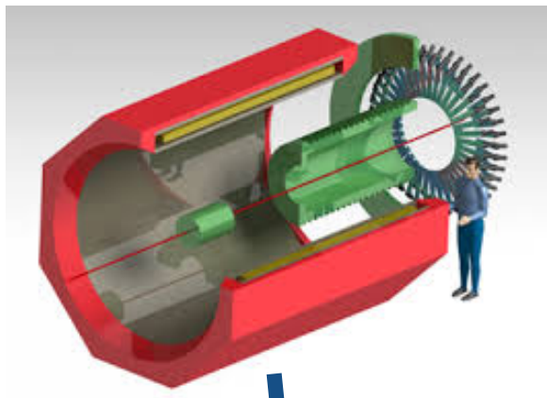

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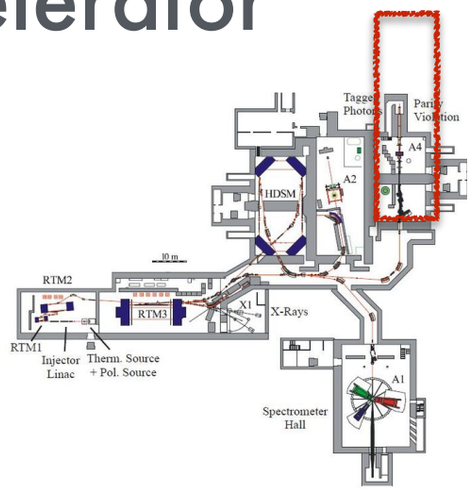
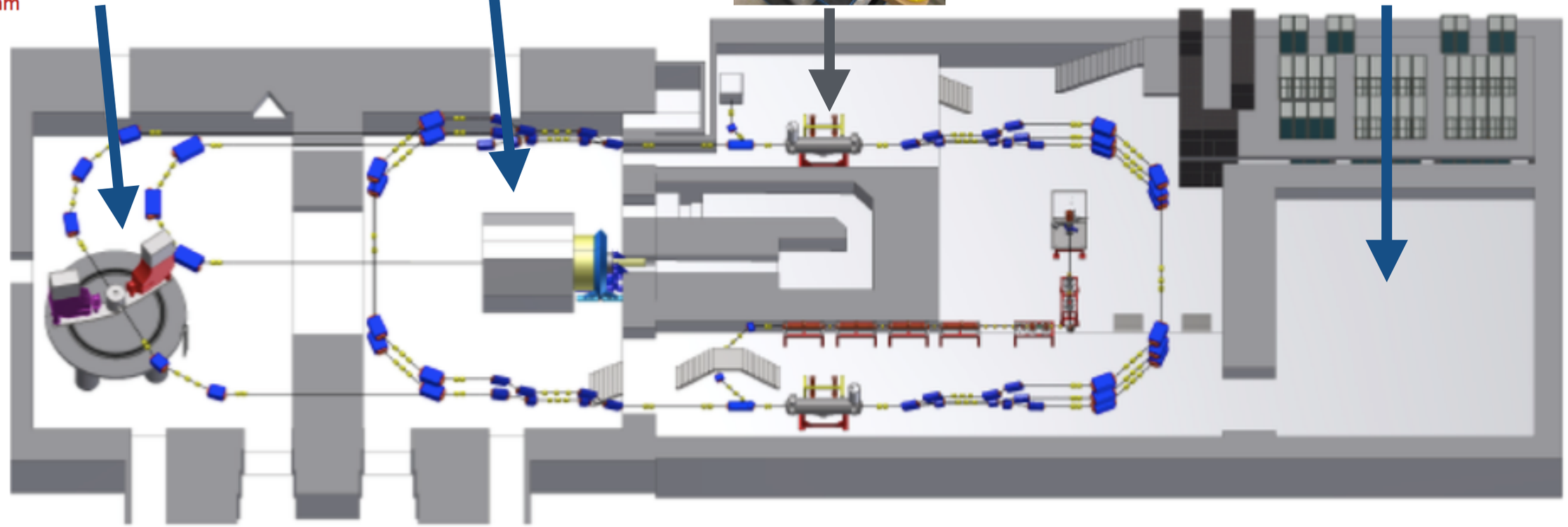
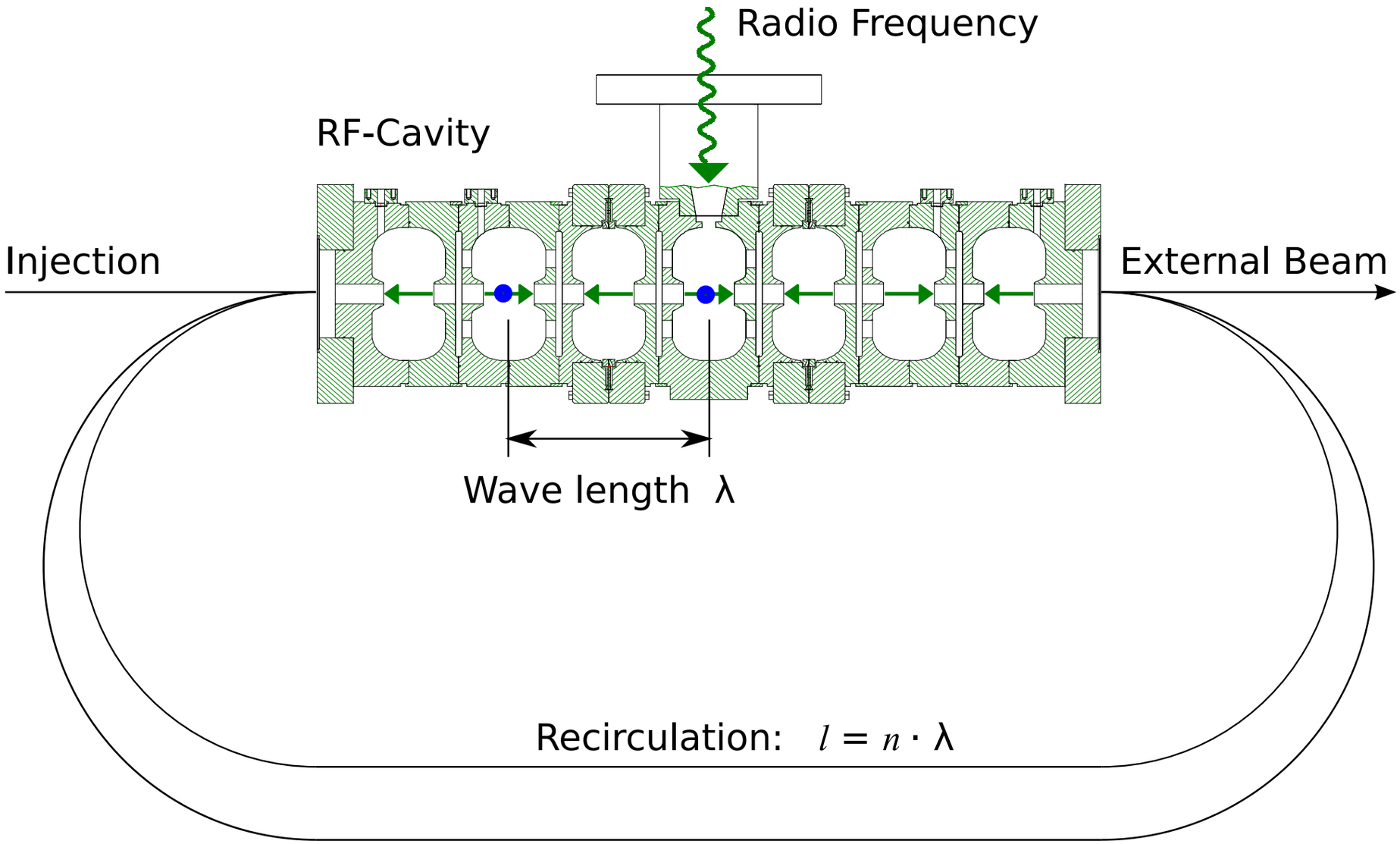


Available Space for an additional experiment



Energy Recovery Linac



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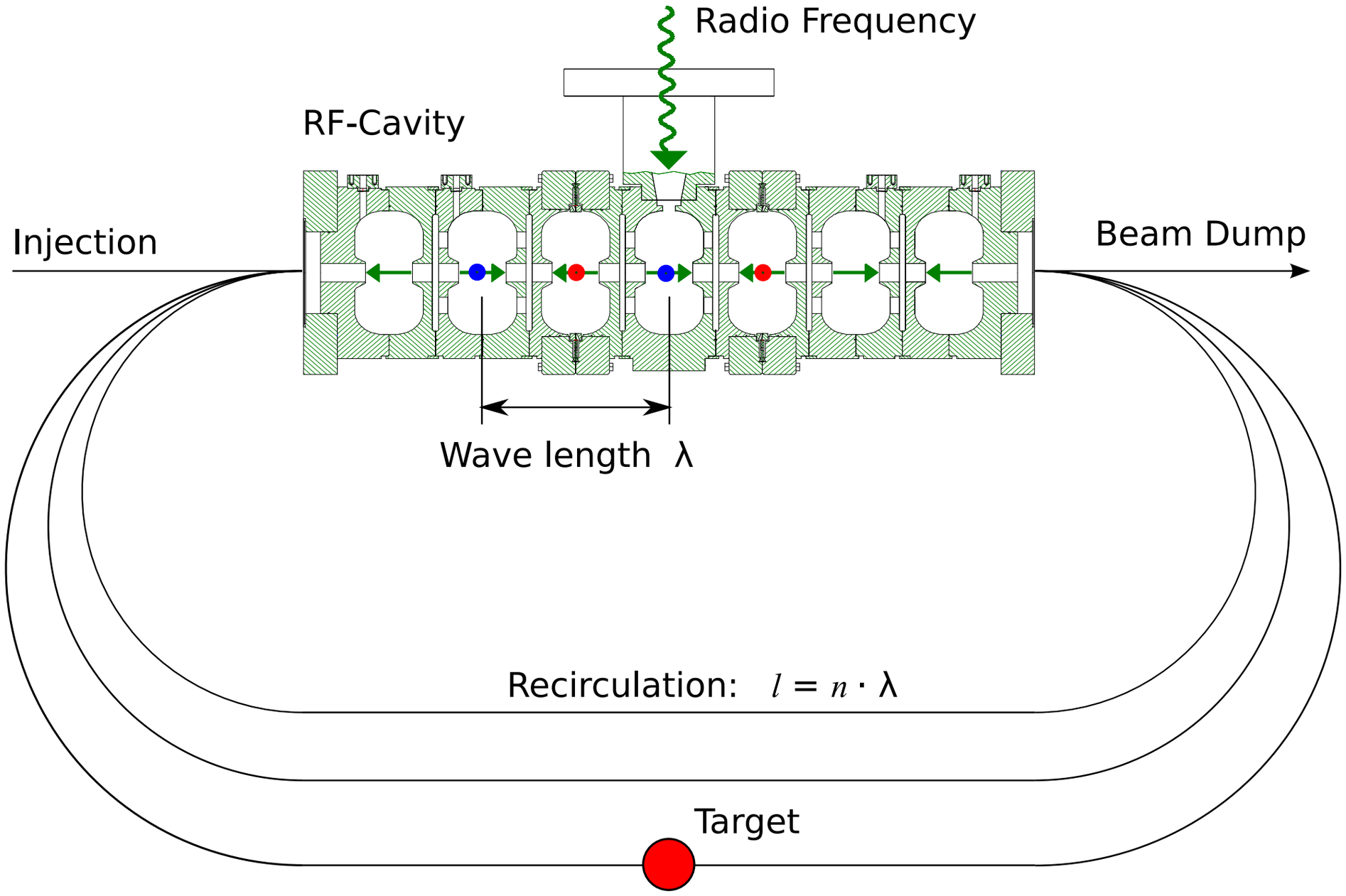
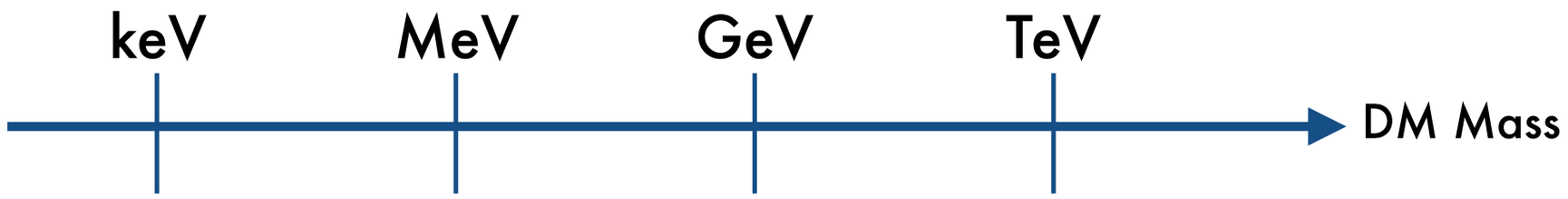


Last Recirculation: $l = (m + 1/2) \cdot \lambda$

Light Dark Matter

(Light) Dark Matter



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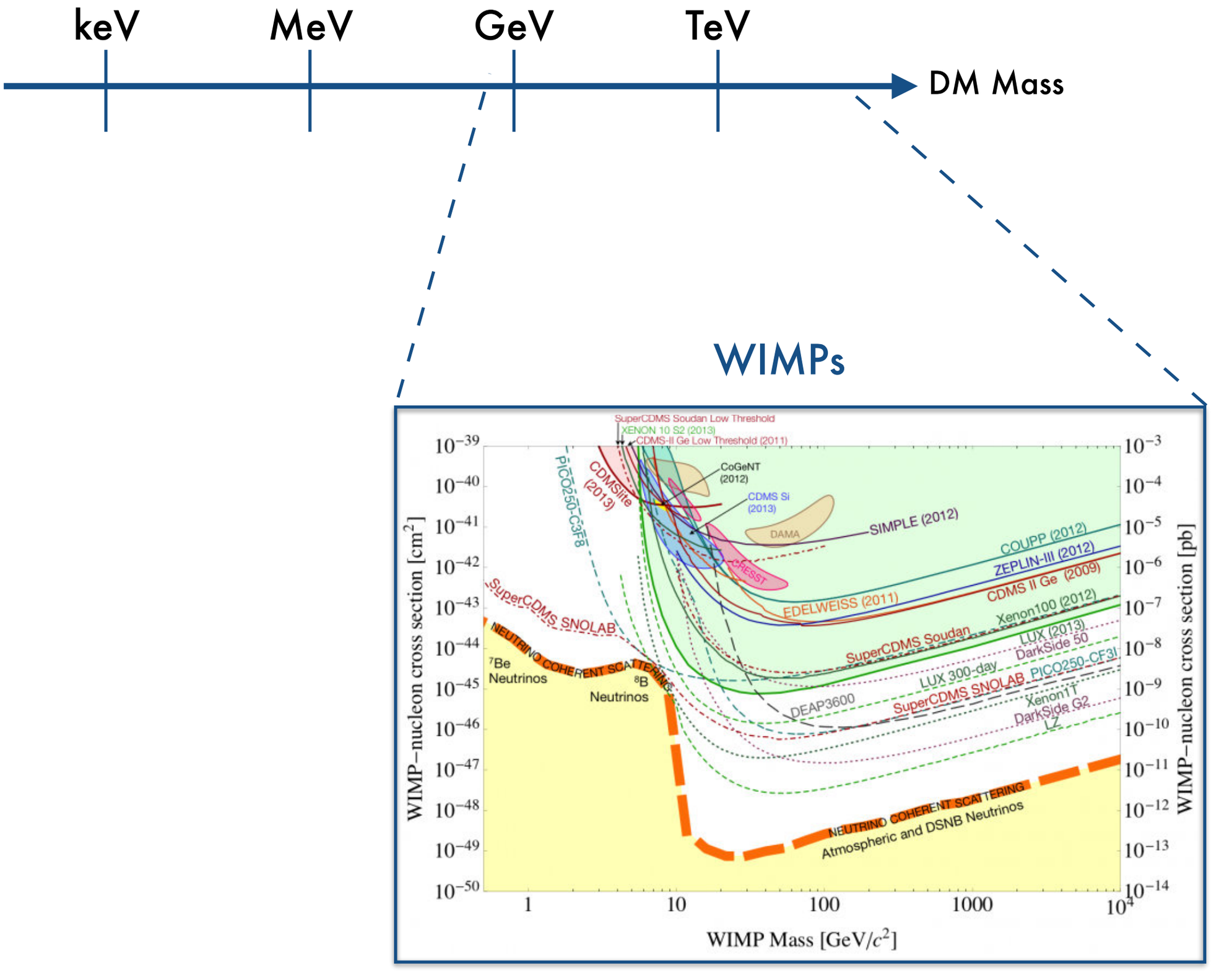
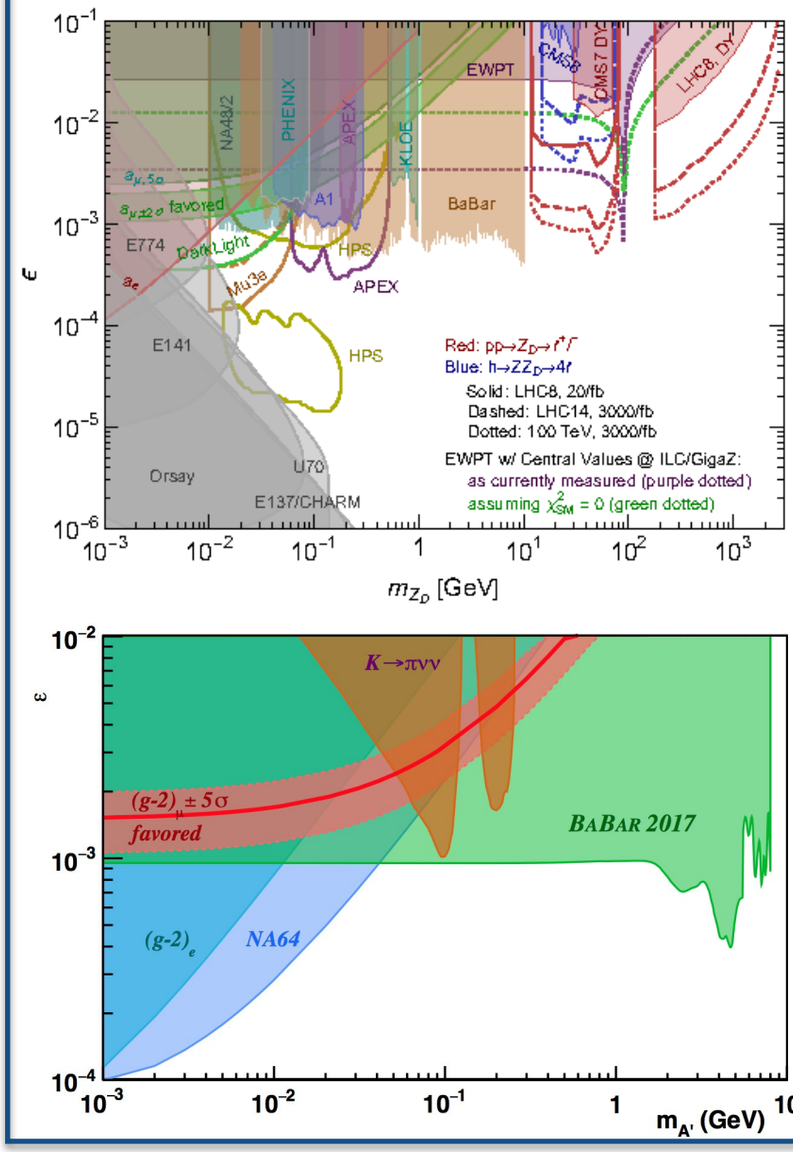


(Light) Dark Matter

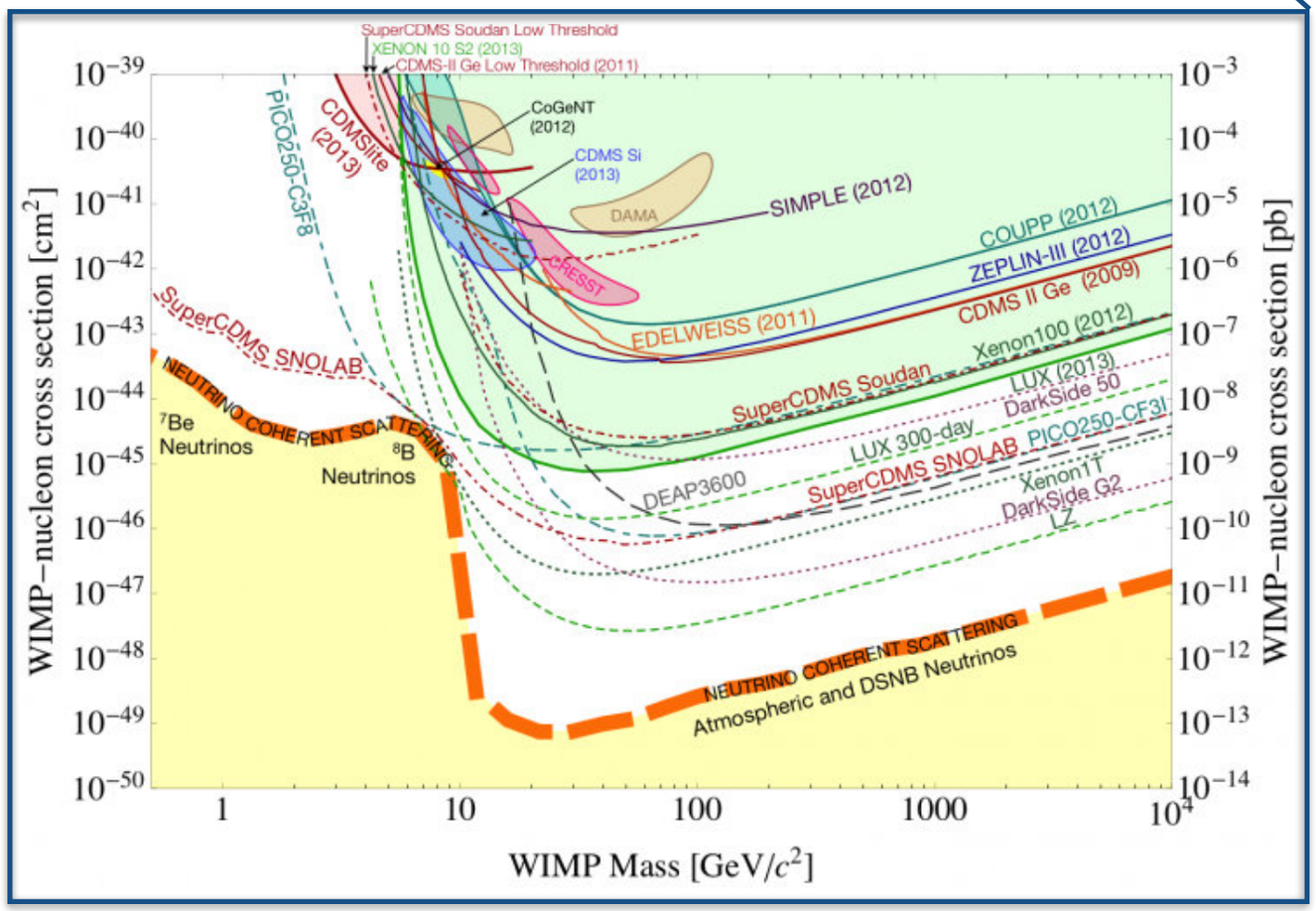
keV MeV GeV TeV

DM Mass

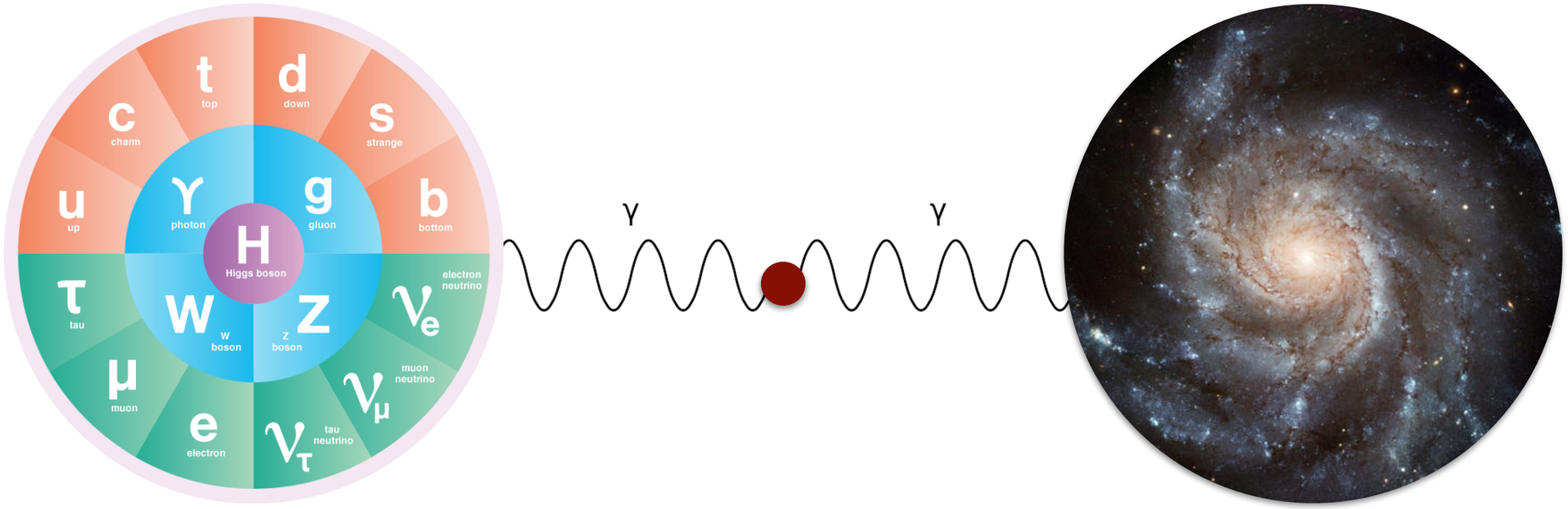
LDM



WIMPs



Dark Sector



"Portals"

Vector Portal $\frac{1}{2}\epsilon_Y F_{\mu\nu} F^{'\mu\nu}$

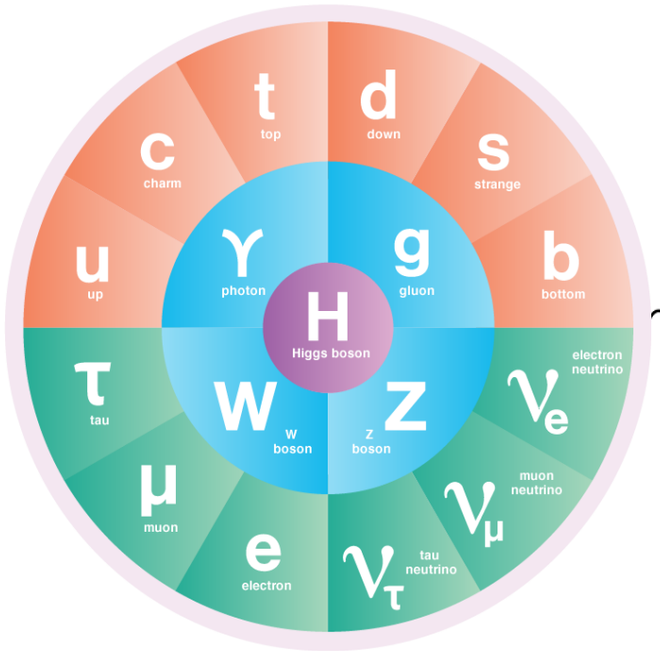
Higgs Portal $\epsilon_h |h|^2 |\phi|^2$ Precision Higgs Physics

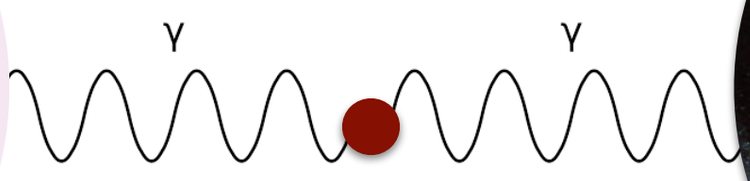
Neutrino Portal $\epsilon_\nu h L \psi$ New Neutrino States

Axion Portal $\frac{G_{a\gamma\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu}$

Dark Sector

Standard Model





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Minimal Dark Photon Model

$$\mathcal{L} \sim \bar{\chi}(i\not{D} - m_\chi)\chi + \frac{1}{2}\epsilon_Y F^{'}_{\mu\nu} B_{\mu\nu} + \frac{1}{2} m^2_{A'} A^{'}_\mu A^{'\mu}$$

$D_\mu = \partial_\mu + i g_D A^{'}_\mu$ New U(1) massive gauge boson

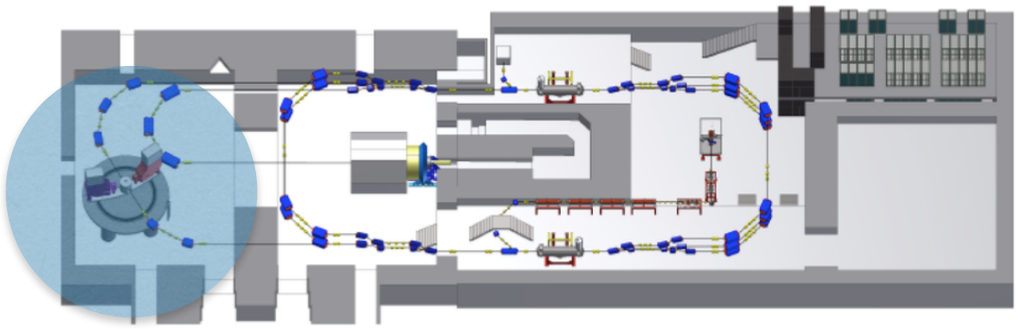
After EW Symmetry Breaking:

$$\epsilon = \epsilon_Y \cos\theta_W \ll 1 \qquad \frac{1}{2}\epsilon F^{'}_{\mu\nu} F_{\mu\nu}$$

4 parameters: $m_{A'}$ $\alpha_D = \frac{g^2_D}{4\pi}$ m_χ ϵ_Y

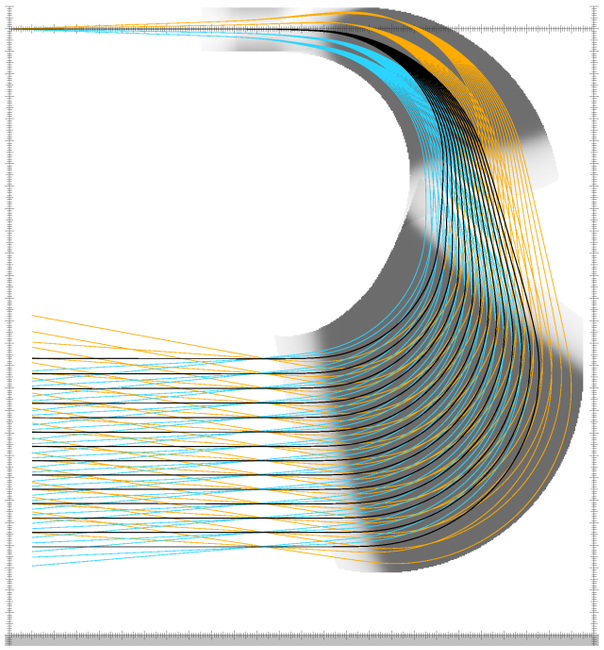
The MAGIX Experiment

The MAGIX Experiment

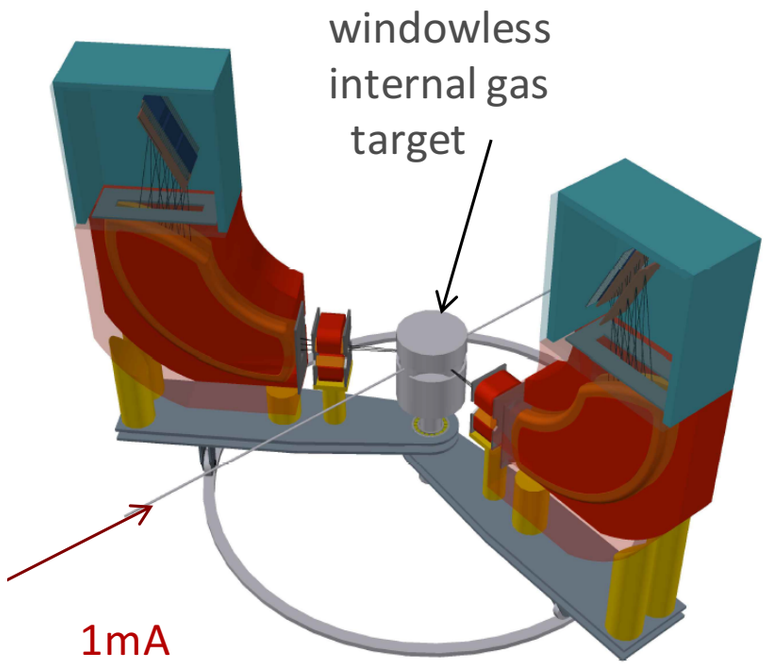


- New technique in low-energy part/nucl phys experiments
- Competitive luminosity (mA beam current)
- Double arm spectrometer (ns time coincidence)
- High-resolution tracking at low energies dp/p = 10^{-4}
- Acceptance +/- 50mr
- Focal plane detectors current design options:
  - low material budget GEMs
  - Time Projection Chamber with GEM readout

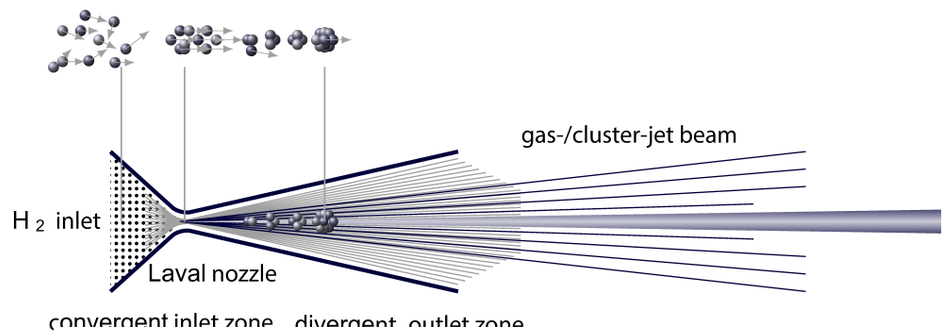
Magnetic optics studies

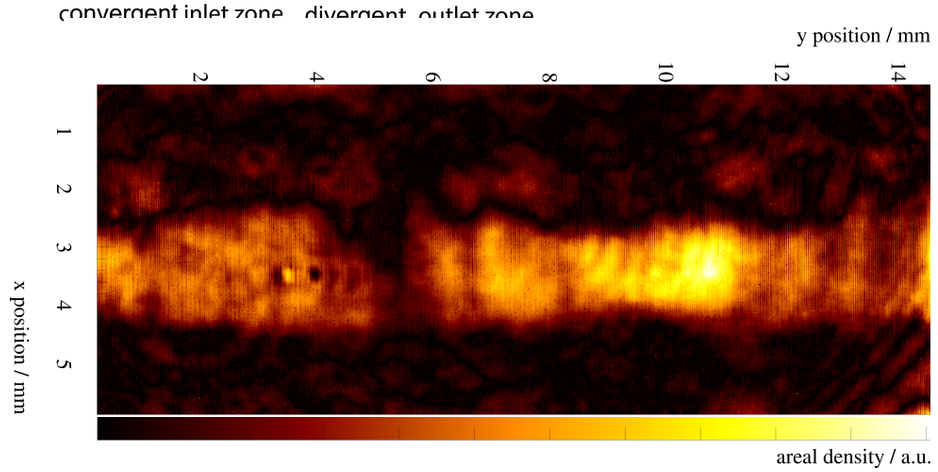


Experimental Setup



Gas-Jet Target



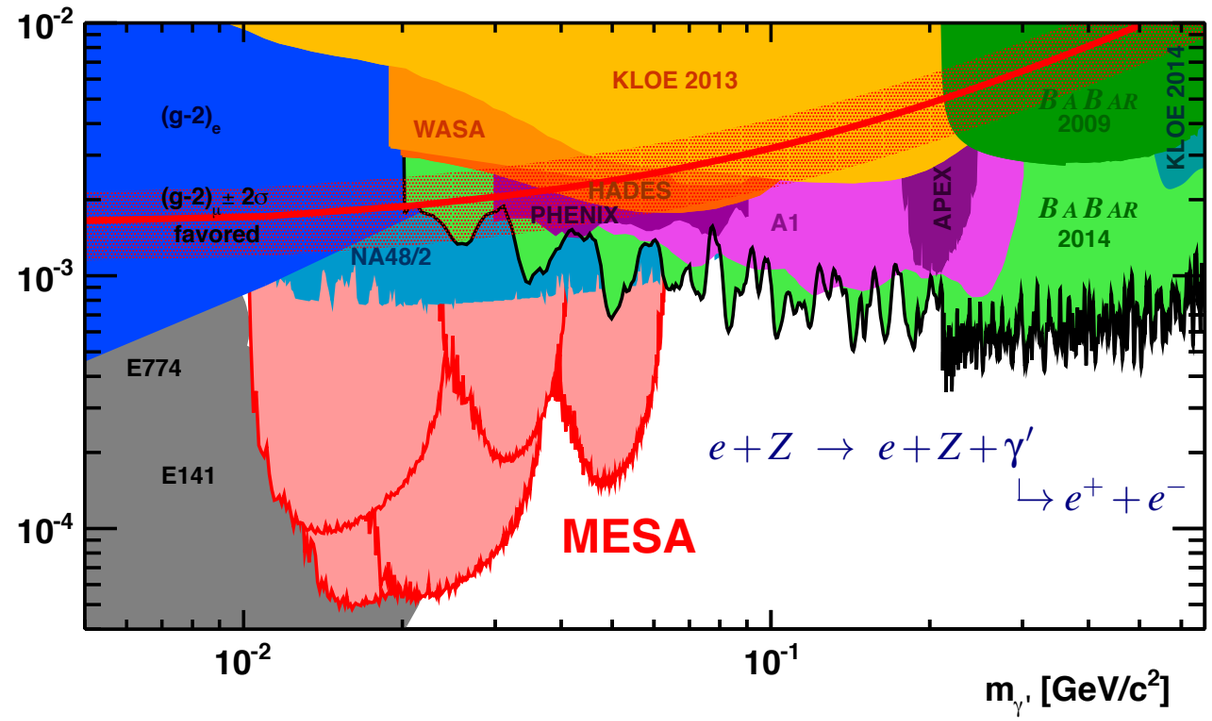


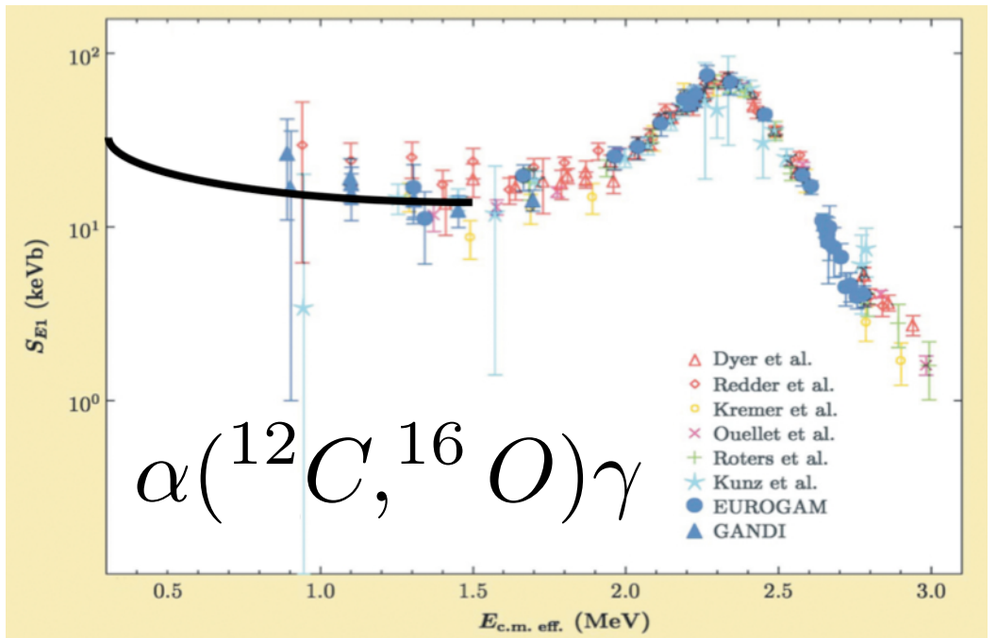
MAGIX Physics Program

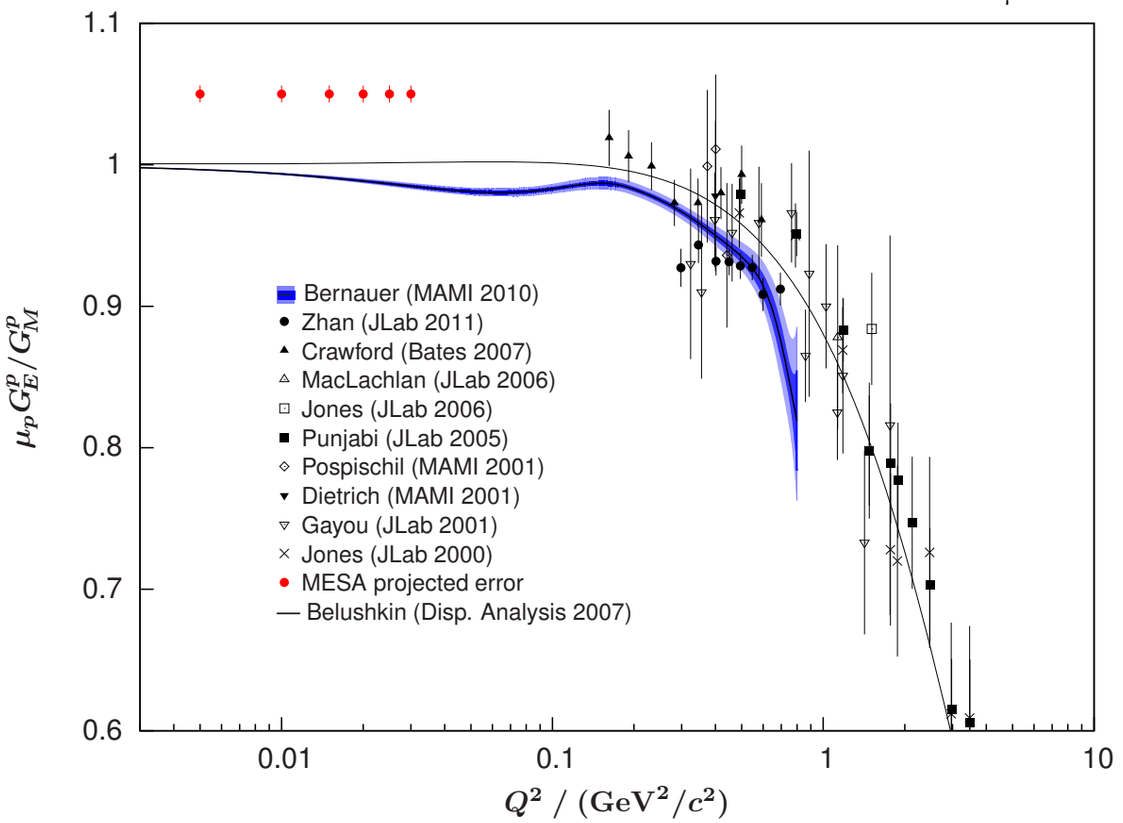
Physics:

- Nucleon Form factors (proton radius puzzle)
- Dark photon (visible and invisible decays)
- Nuclear Astrophysics

Other possibilities
- Nuclear physics (3-body forces)
- Nucleon polarizabilities
- …



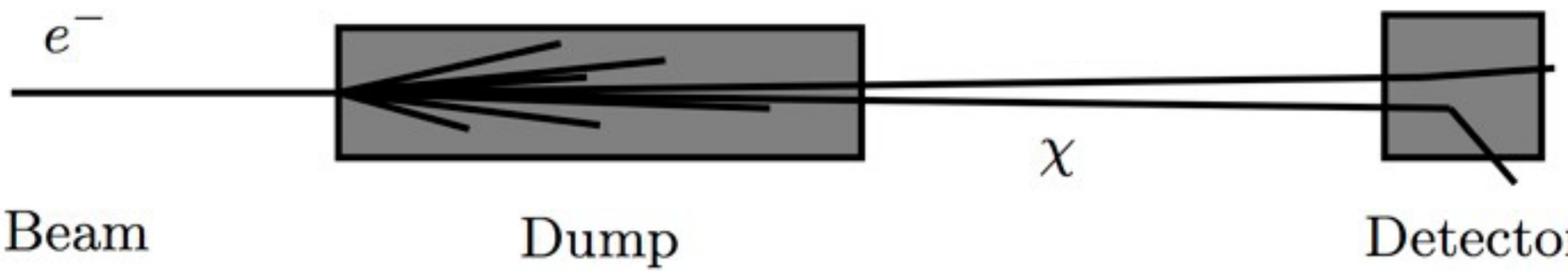




BDX@MESA

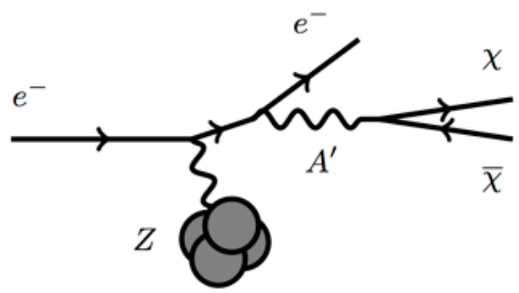
A Beam-Dump Experiment at MESA

Bjorken et al., Phys. Rev. D80, 075018 (2009)

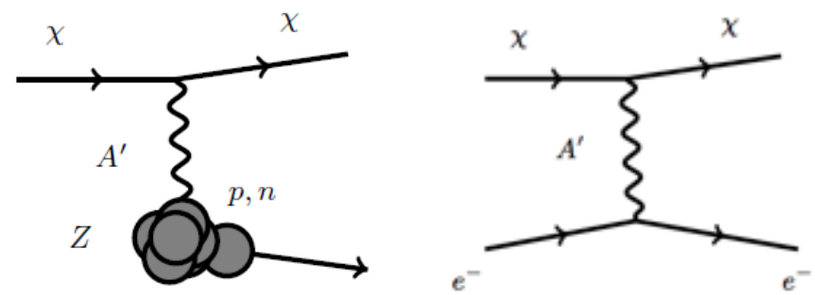


$$\frac{d\sigma}{dx} \approx \frac{8Z^2\alpha^3\epsilon^2 x}{m_{A'}^2}\left(1+\frac{x^2}{3(1-x)}\right)\mathcal{L}og$$

$$\theta_{A'\,\mathrm{max}} \sim \max\left(\frac{\sqrt{m_{A'}m_e}}{E_0}, \frac{m_{A'}^{3/2}}{E_0^{3/2}}\right)$$

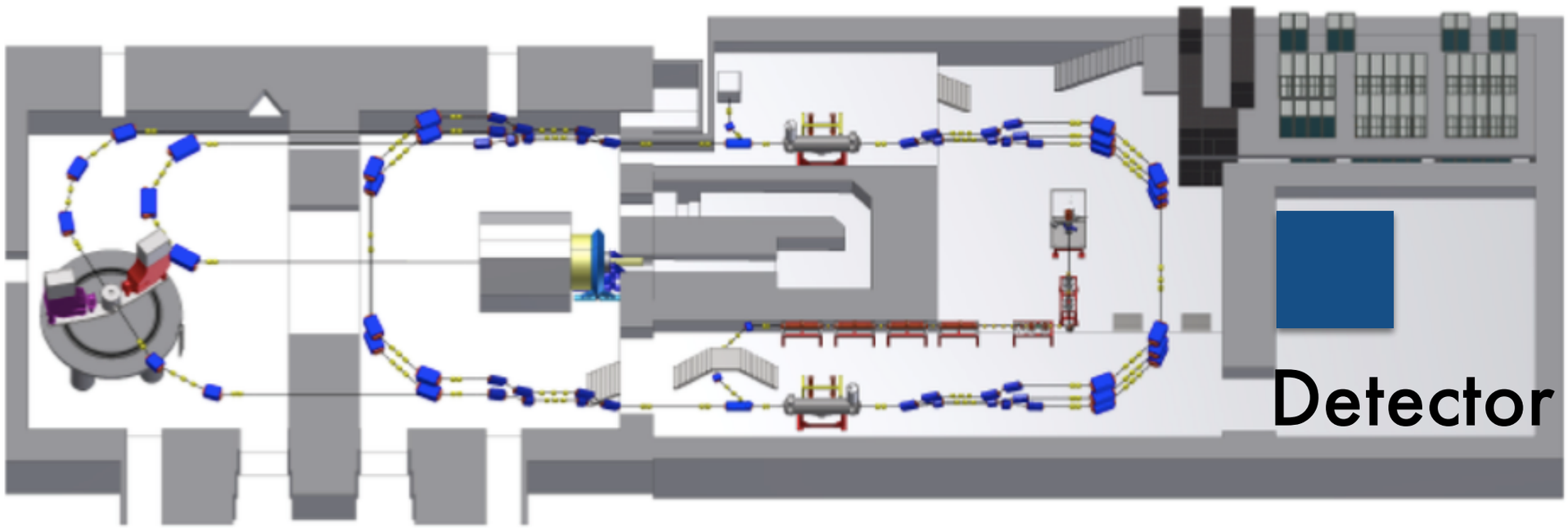


$Y_{Prod} \sim \epsilon^2/m_A^2$



$Y_{Det} \sim \epsilon^2\alpha_D/m_A^2$

Total Yield $Y_{TOT} \sim \epsilon^4\alpha_D/m_A^4$



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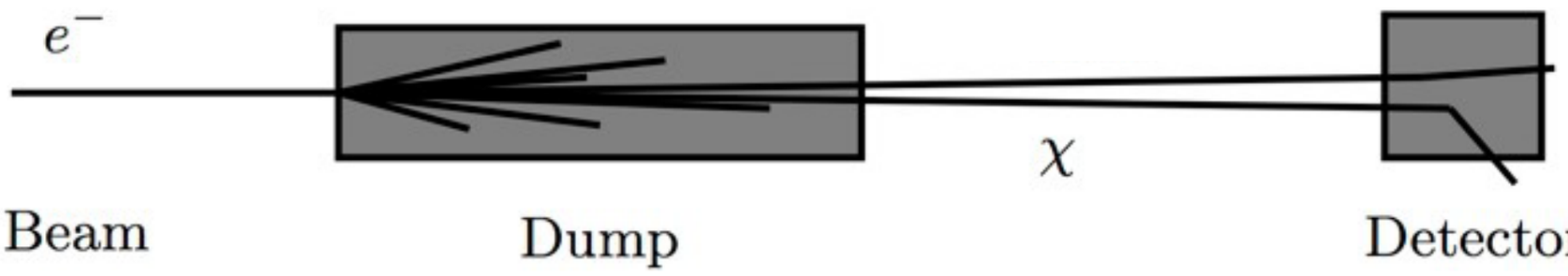

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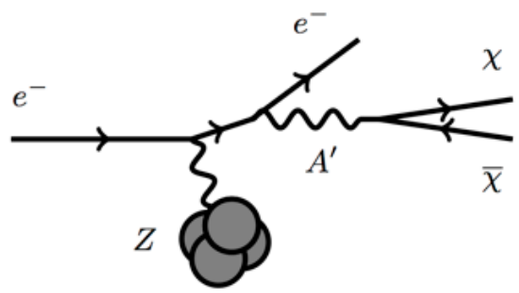

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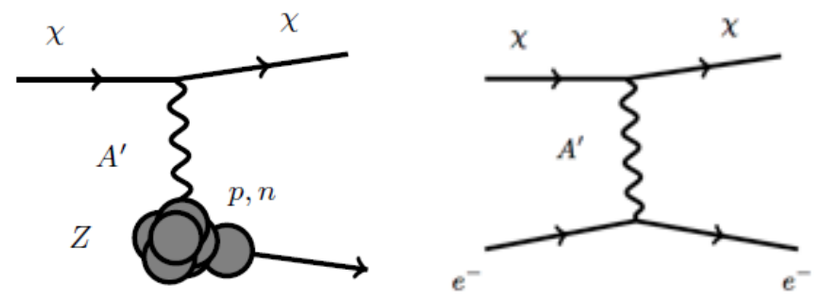

$Y_{Det} \sim \epsilon^2\alpha_D/m_A^2$

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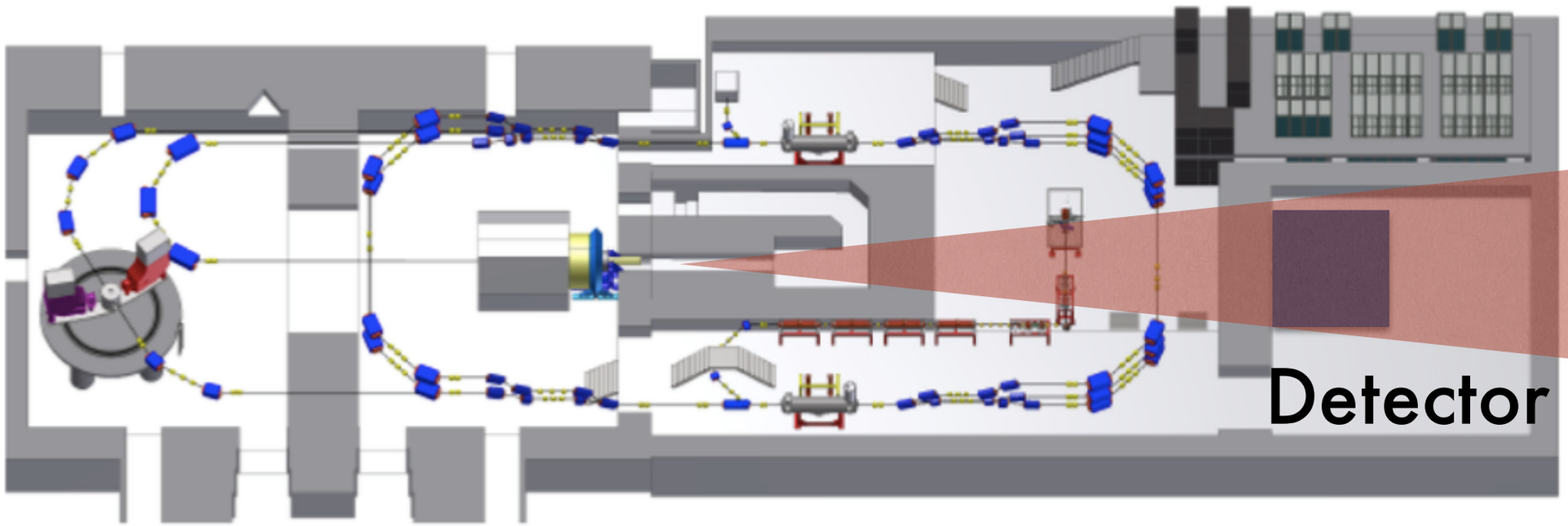


$$\theta_{RMS} \sim \frac{m_{A'}}{E_{beam}}$$

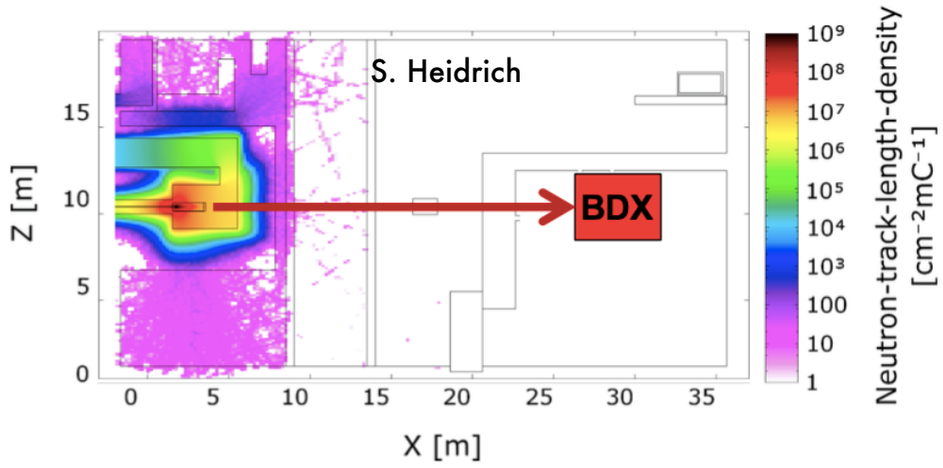
Opportunity: A BD Experiment at MESA

Beam Dump

- 20 X_0 Beam Dump
- Material: Aluminum (+ Water)
- Addition of a W plate?
- Energy on Dump: ~135 MeV
- 10^4 h of operation; 10^{22} EOT

Experimental Area

- 70 X_0 (~8m) barite concrete
- ~ no neutrons at detector position
- no beam dump backgrounds
- No neutrinos



Detector:

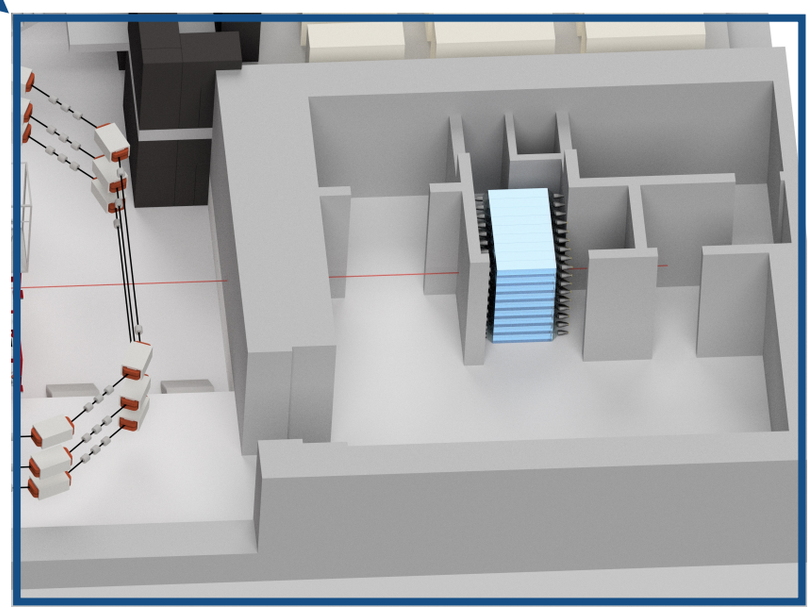
- Maximize active volume
- Maximize Density
- Directionality

Detector Concept:

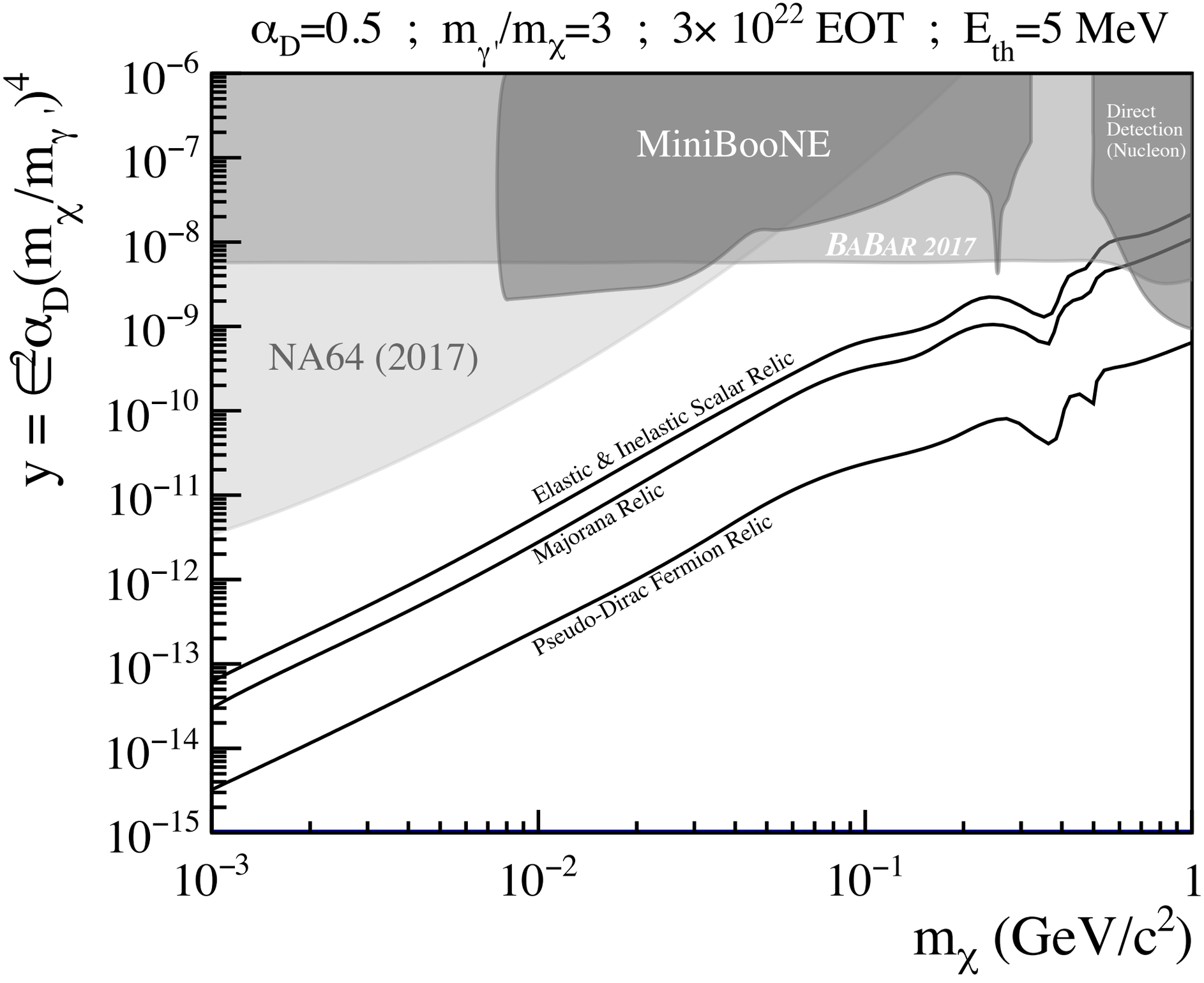
- 81 lead glass blocks
- 30x30x150cm each
- 5'' PMTs or SiPM readout
- Other crystals under study

Background Rejection

- Beam on/off
- Comics Veto
- Segmentation



Predicted Limits



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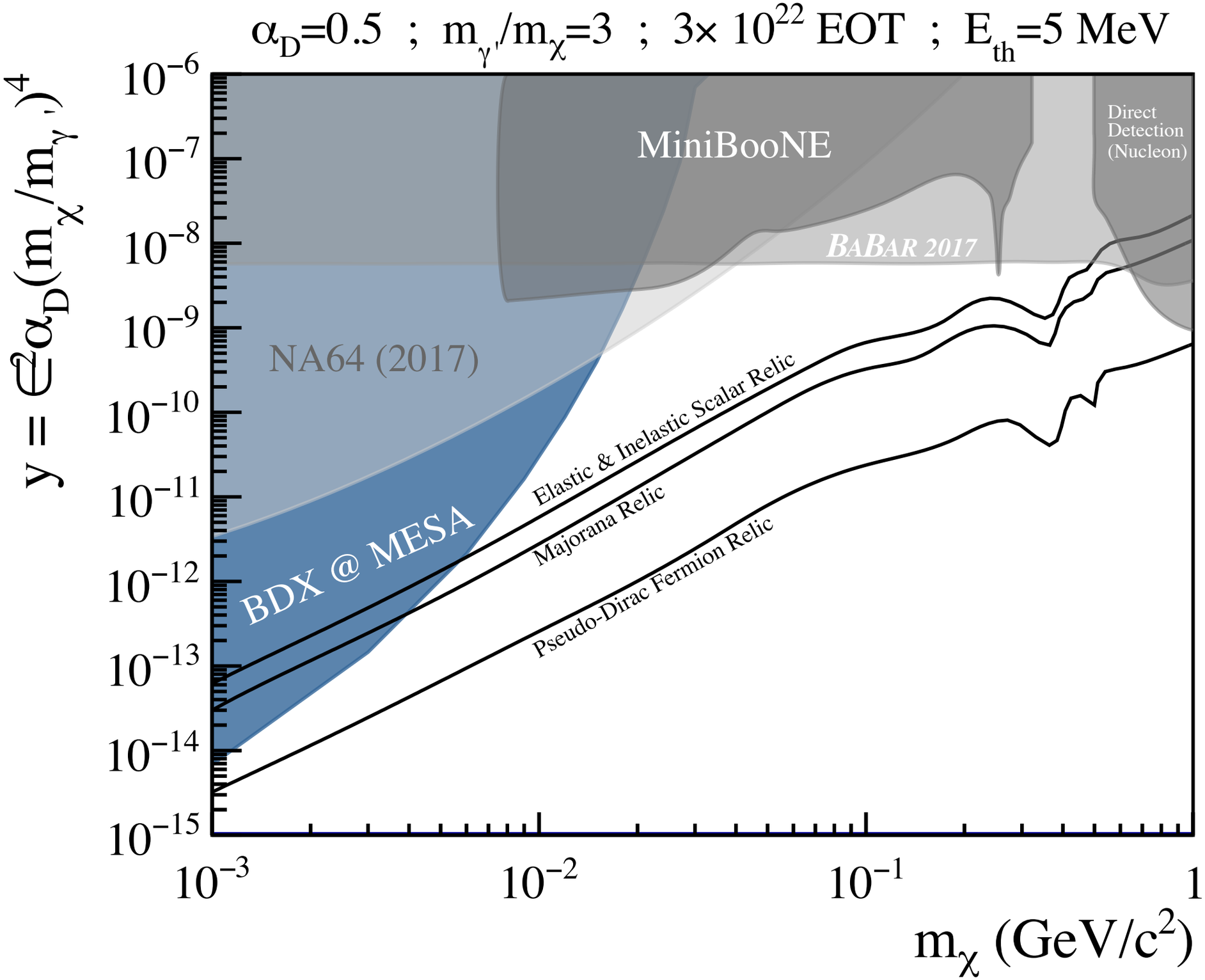


Summary

Potential for significant contributions to LDM searches:

- Visible Decays: expand current limits in new territory (MAGIX)
- Invisible Decays: still large parameter space to explore (MAGIX + BDX@MESA)
- Unique test for both DM production and interaction.
- High sensitivity: potential to “hit” the thermal target

Beam at MESA ideal:

- Very large luminosity, CW beam, and excellent stability
- Recirculation for MAGIX and parasitic operation + beam-off for BDX@MESA
- Low backgrounds (below pion threshold: no neutrinos/muons)

Near-Future Directions:

- MAGIX: Magnetic optics and detector R&D ongoing (GEMs, TPC)
- BDX@MESA: Extend G4 Simulation+MadGraph , Calorimeter R&D started
    - many possibilities to investigate (Cherenkov/Scintillation crystals)

Many Experiments running or planned:

NA62, HPS, SeaQuest, MiniBoone,DarkLight, APEX,
B-Factories, PADME, LDMX, SHiP,

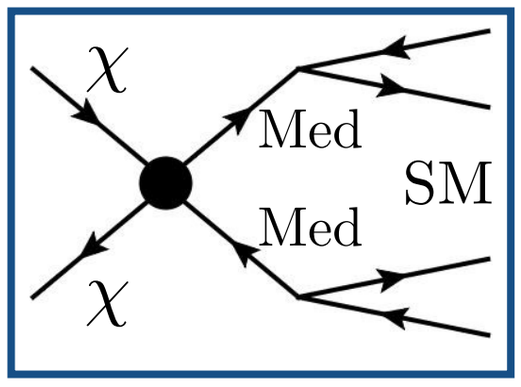
MESA and Dark Sector Experiments could start by >2020 !

Thank You!

Backup

Thermal Relic Target

Secluded Annihilation

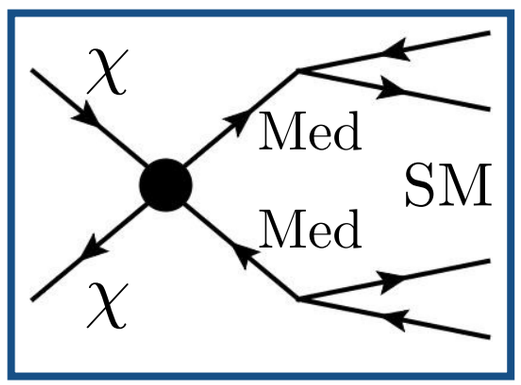


$$m_\chi > m_{Med} \qquad \langle \sigma v \rangle \sim g_D^4 / m_\chi^4$$

No SM coupling dependence:
arbitrary coupling possible.
Hard to test experimentally.

Thermal Relic Target

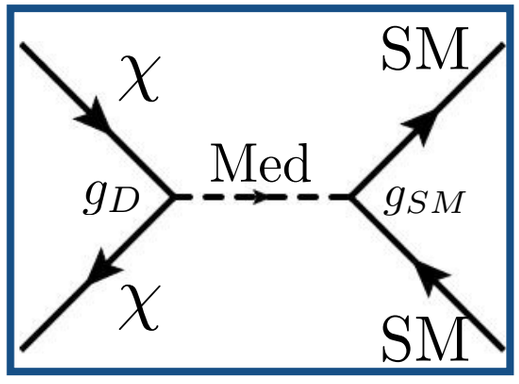
Secluded Annihilation



$$m_\chi > m_{Med} \qquad \langle \sigma v \rangle \sim g_D^4 / m_\chi^4$$

No SM coupling dependence: arbitrary coupling possible. Hard to test experimentally.

Direct Annihilation

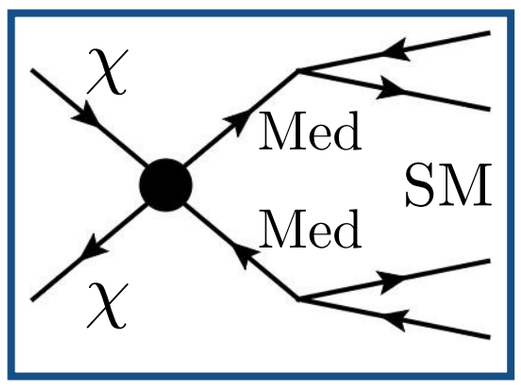


$$m_\chi < m_{Med} \qquad \langle \sigma v \rangle \sim \frac{g_D^2 g_{SM}^2 m_\chi^2}{m_{\mathrm{Med}}^4}$$

There is a minimum SM coupling compatible with thermal history.

Thermal Relic Target

Secluded Annihilation



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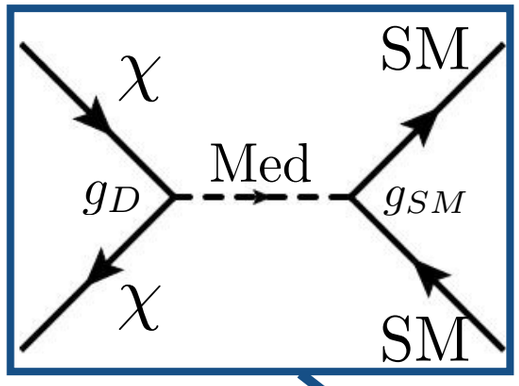
Direct Annihilation



$$m_\chi < m_{Med} \qquad \langle \sigma v \rangle \sim \frac{g_D^2 g_{SM}^2 m_\chi^2}{m_{\mathrm{Med}}^4}$$

There is a minimum SM coupling compatible with thermal history.

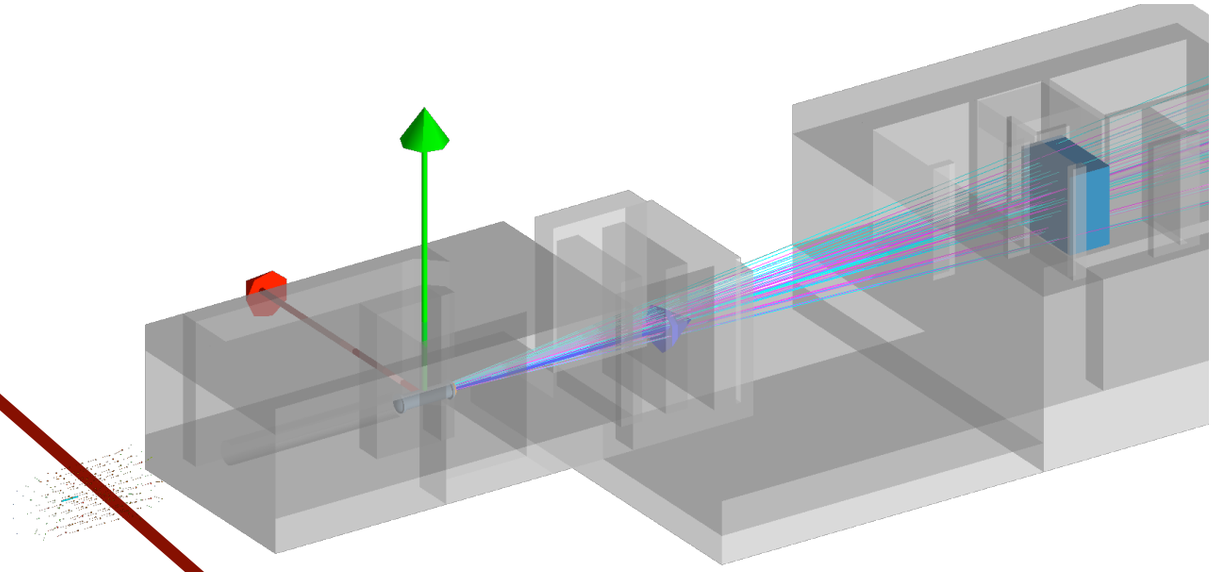
Experimentally testable target:

$$y = \frac{g_D^2 g_{SM}^2}{4\pi} \left(\frac{m_\chi}{m_{Med}} \right)^4 \gtrsim m_\chi^2 \langle \sigma v \rangle_{Relic}$$

Simulation

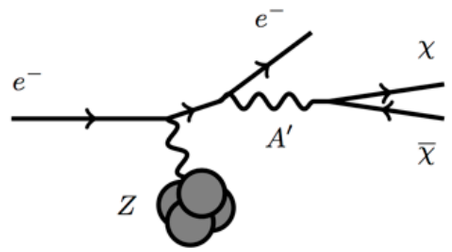
Geant4 Simulation

P2 Target, Magn. Field
Beam Dump, Exp. Halls

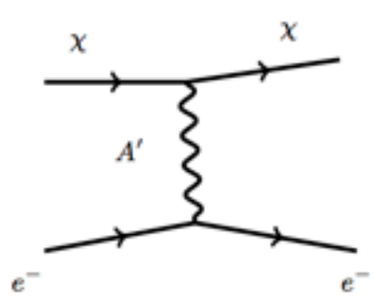


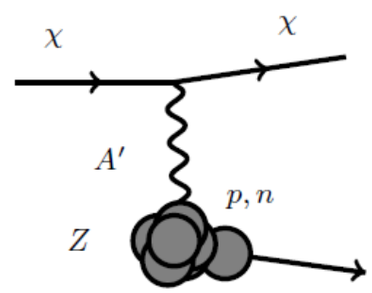
MadGraph

M. Battaglieri
A. Celentano
(INFN Genova)



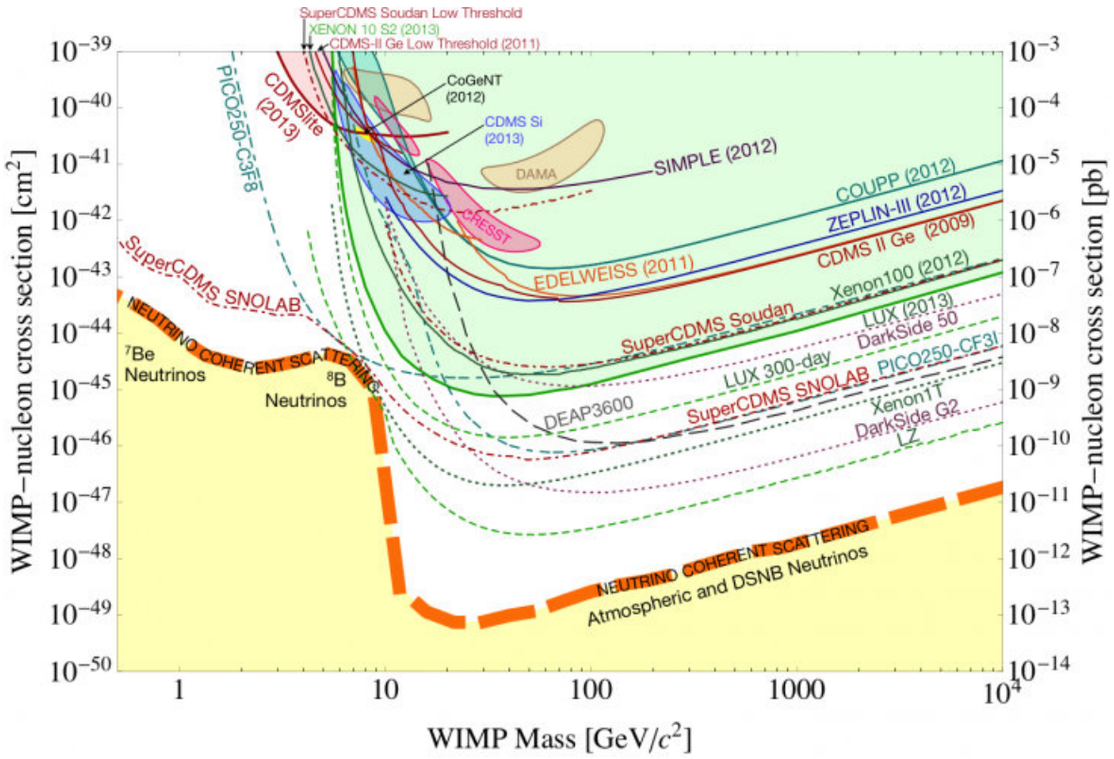
e/N DM Scattering





Detector Response

(WIMP) Direct Dark Matter Searchs



Light Dark Matter

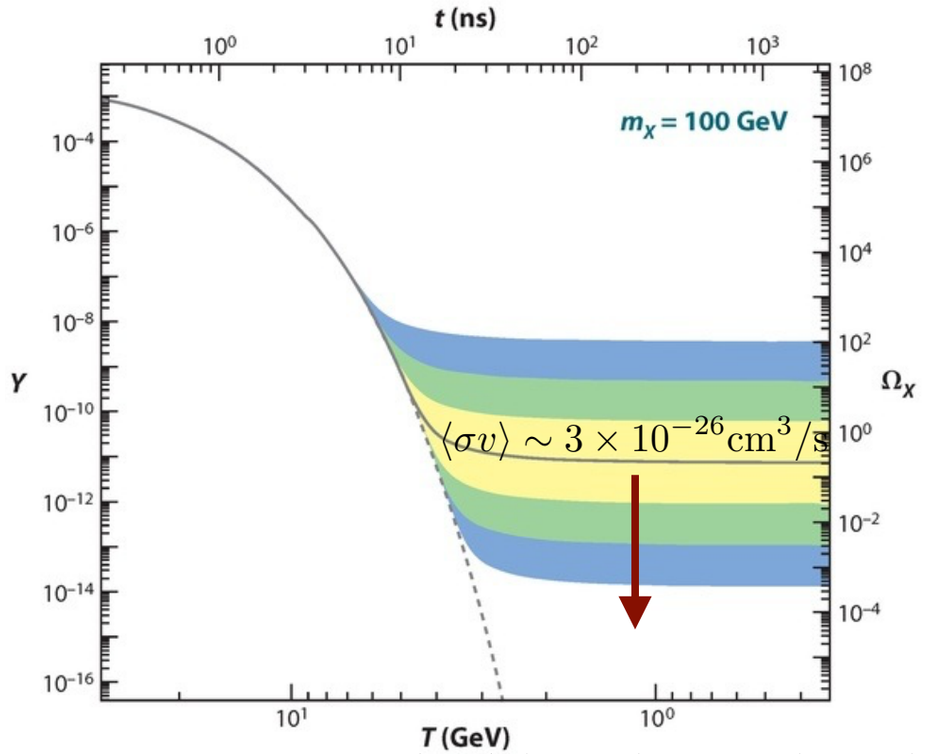
- If light, smaller annihilation CS
- DM overabundance
- “Overclosed" Universe

The way out:

- postulate a new interaction
- annihilation via a new force carrier

If coupling small enough, DM can be light!

Thermal Relic Paradigm



Freeze out: $n\langle\sigma v\rangle(T_{FO}) \sim H(T_{FO})$

WIMP “miracle”:

$$\left.\begin{aligned} &m/T \gg 1 \\ &\sigma_{EW} \sim G_F^2 T_{FO} \sim 10^{-8}\mathrm{GeV}^2 \end{aligned}\right\} \Rightarrow \Omega_{DM} \sim 0.2$$

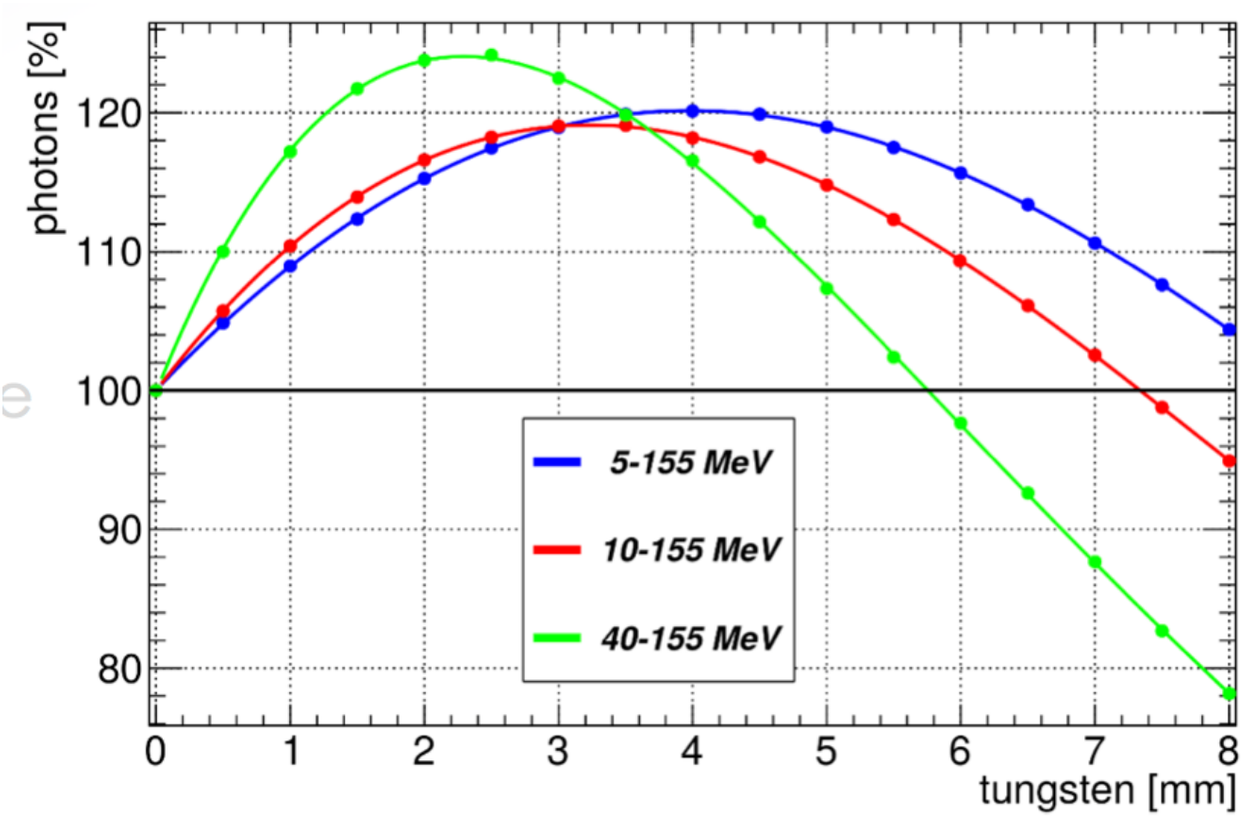
But:

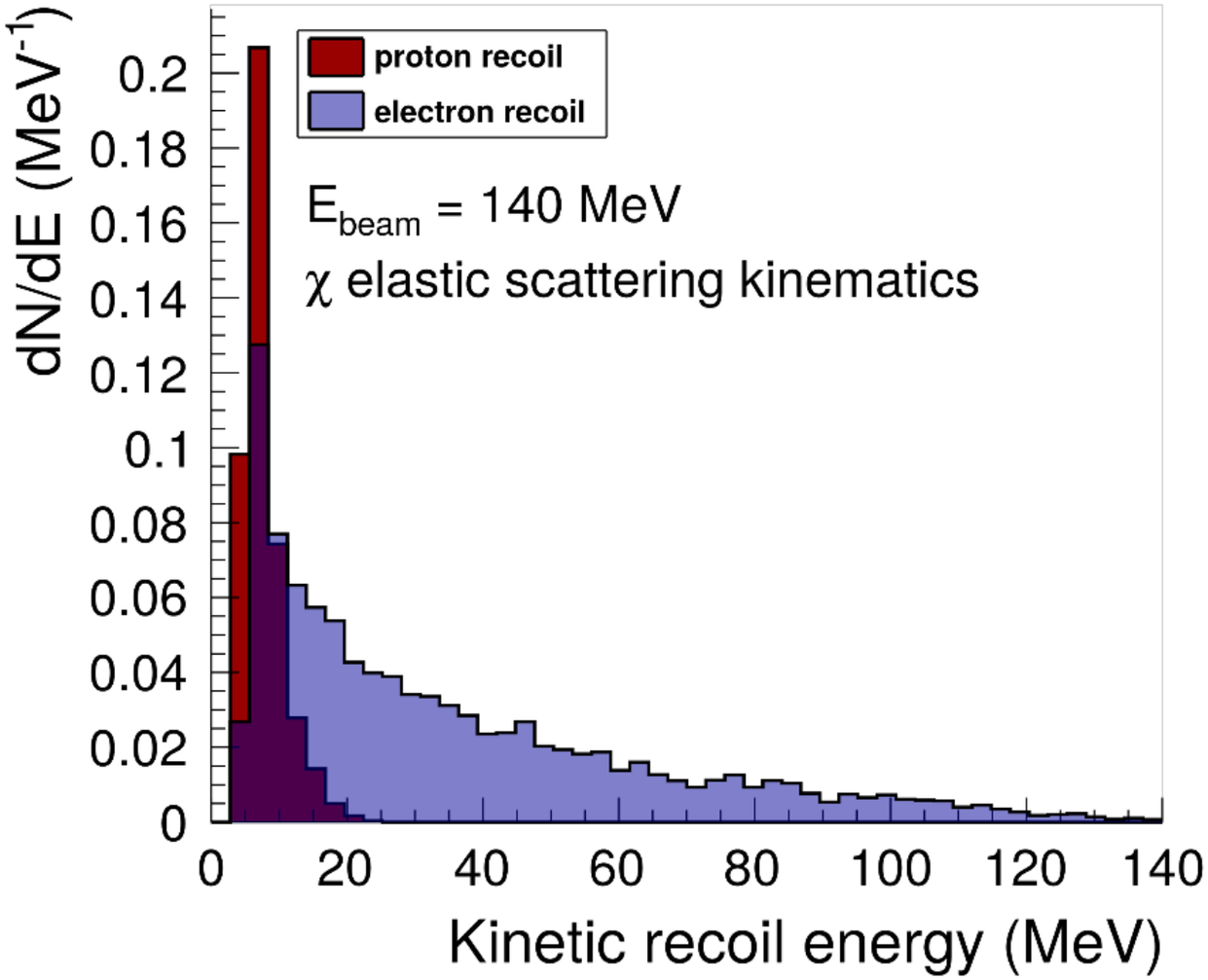
$$\sigma \sim g^4/m_{DM}^2 \Rightarrow m_{DM} \gg 0.1\mathrm{eV}$$

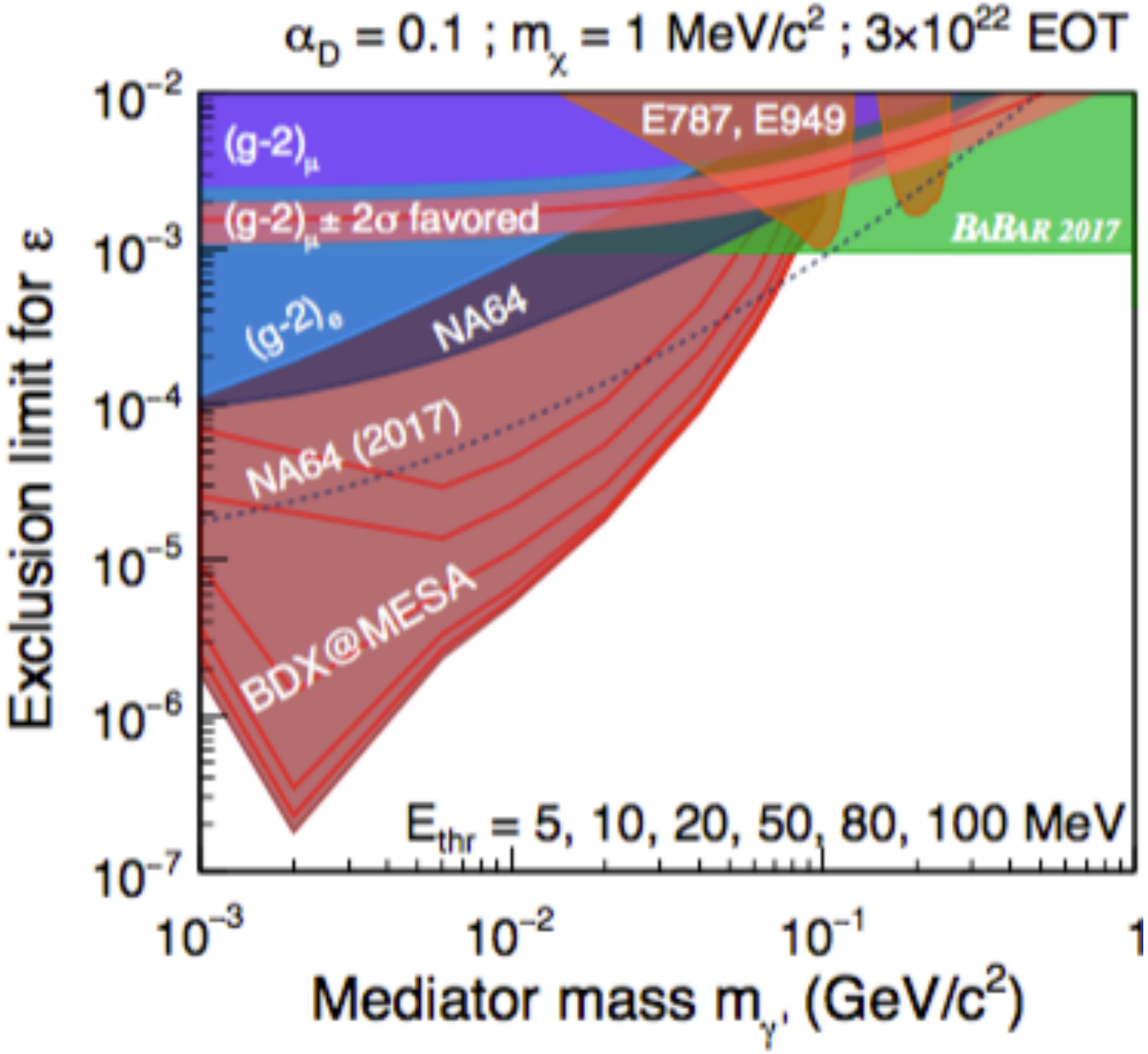
And in general:

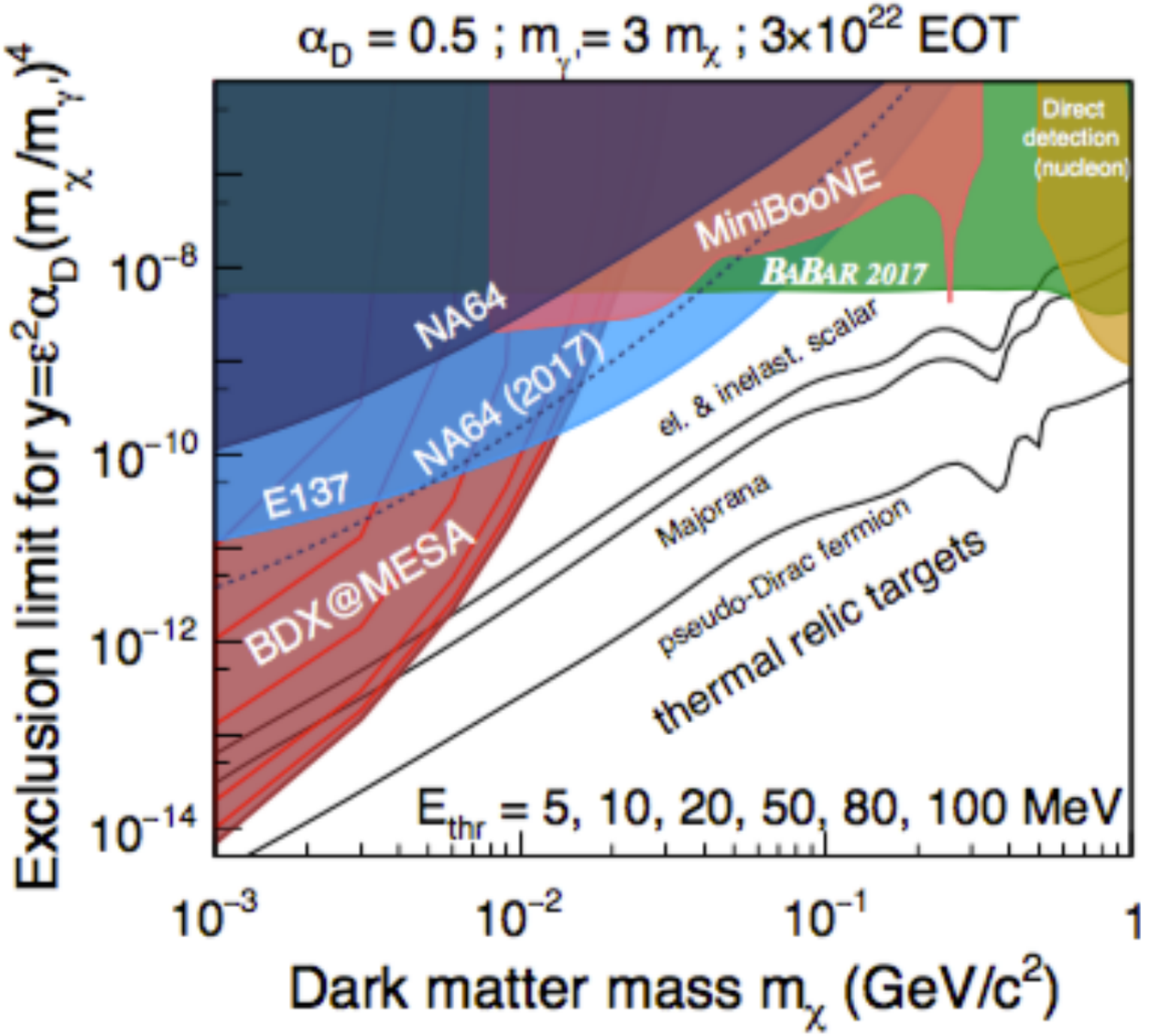
$$10\ \mathrm{GeV} < m_{DM} < 120\ \mathrm{TeV}$$

Lee-Weinberg — Unitarity Limit


photons [%]
120
110
100
90
80
0
1
2
3
4
5
6
7
8
tungsten [mm]
5-155 MeV
10-155 MeV
40-155 MeV


dN/dE (MeV⁻¹)
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0
20
40
60
80
100
120
140
Kinetic recoil energy (MeV)
proton recoil
electron recoil
E_beam = 140 MeV
χ elastic scattering kinematics


$\alpha_D = 0.1$; $m_\chi = 1$ MeV/c^2 ; 3×10^{22} EOT
$(g\text{-}2)_\mu$
$(g\text{-}2)_\mu \pm 2\sigma$ favored
$(g\text{-}2)_e$
E787, E949
BABAR 2017
NA64
NA64 (2017)
BDX@MESA
E_{thr} = 5, 10, 20, 50, 80, 100 MeV
Exclusion limit for ε
Mediator mass $m_{\gamma'}$ (GeV/c^2)


$\alpha_D = 0.5$; $m_{\gamma'} = 3\, m_\chi$; 3×10^{22} EOT
Direct detection (nucleon)
MiniBooNE
BABAR 2017
NA64
NA64 (2017)
el. & inelast. scalar
E137
Majorana
pseudo-Dirac fermion
BDX@MESA
thermal relic targets
E_{thr} = 5, 10, 20, 50, 80, 100 MeV
Exclusion limit for $y=\varepsilon^2\alpha_D(m_\chi/m_{\gamma'})^4$
Dark matter mass m_χ (GeV/c^2)