

The MESA Science Program

Dark matter and more.

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New Scientific Opportunities at the TRIUMF ARIEL e-LINAC Workshop
May 2022, Vancouver, BC

Introduction

* The MESA facility

* Experiments

* Physics Program:

- Dark Matter
- Precision Electro-weak physics
- Hadron and Nuclear Physics

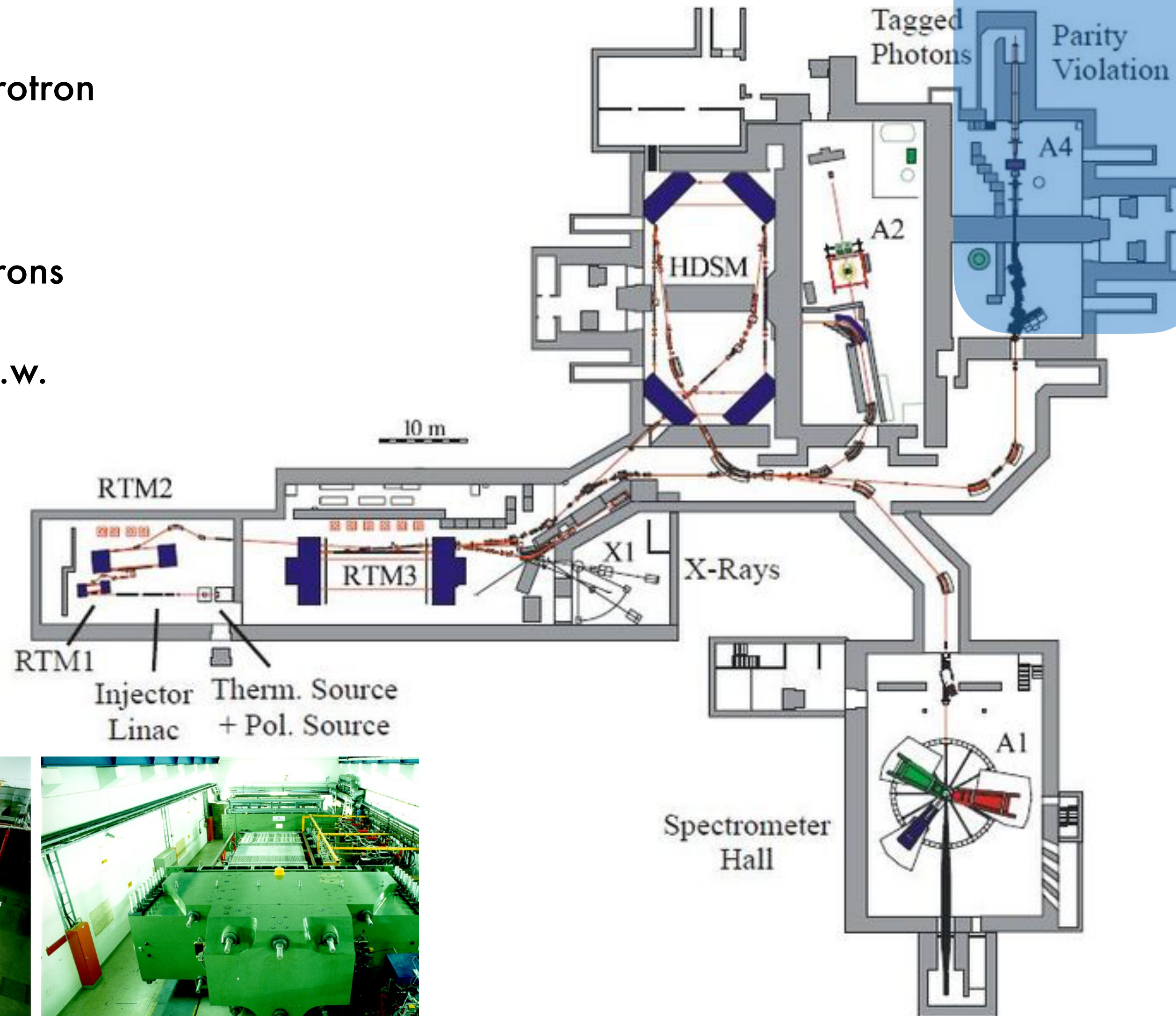
The MAMI and MESA Facilities

MAMI-C (since 2007)

Harmonic Double-sided Microtron
 $E = 1.5 \text{ GeV}$

MAMI-B

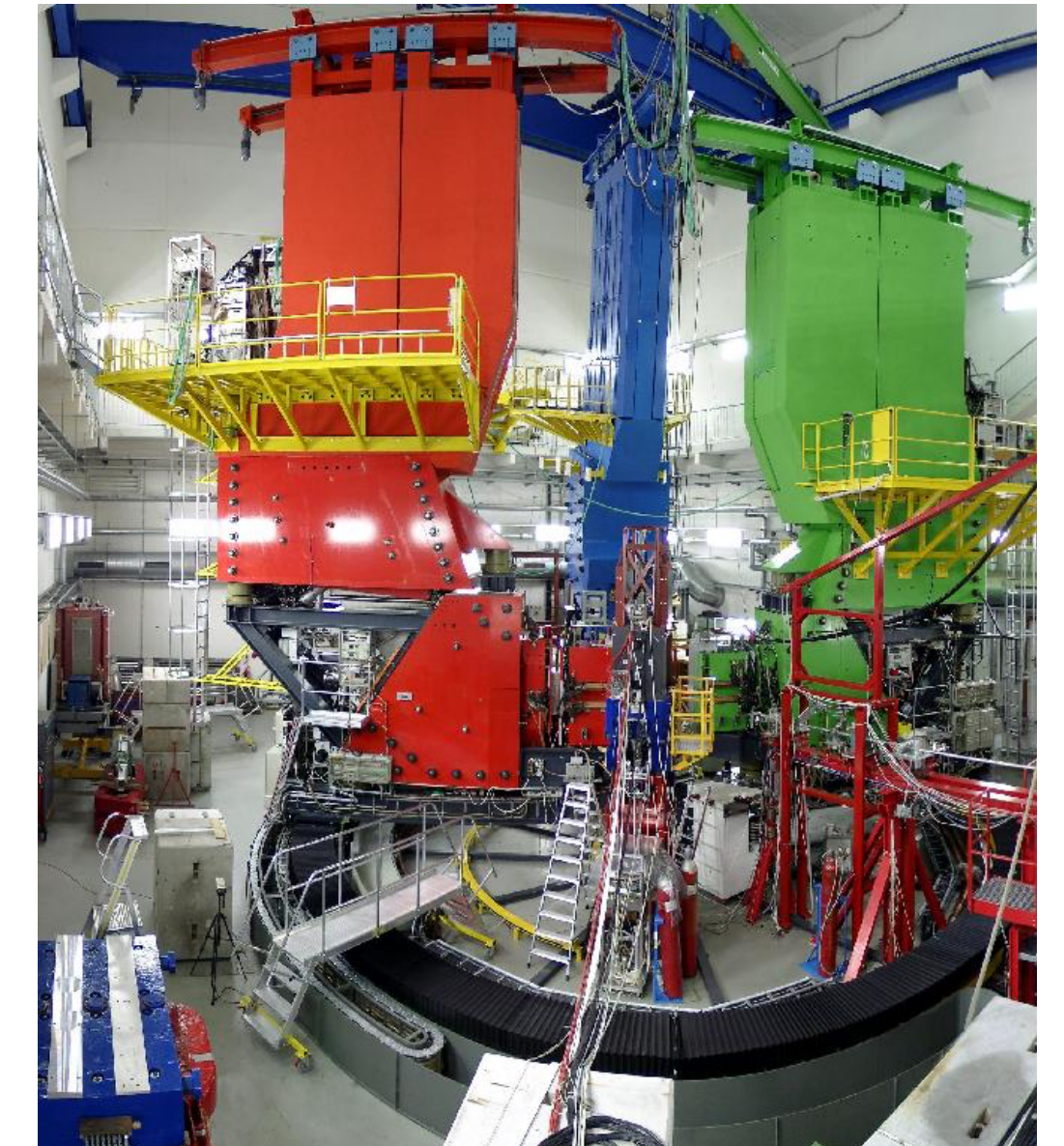
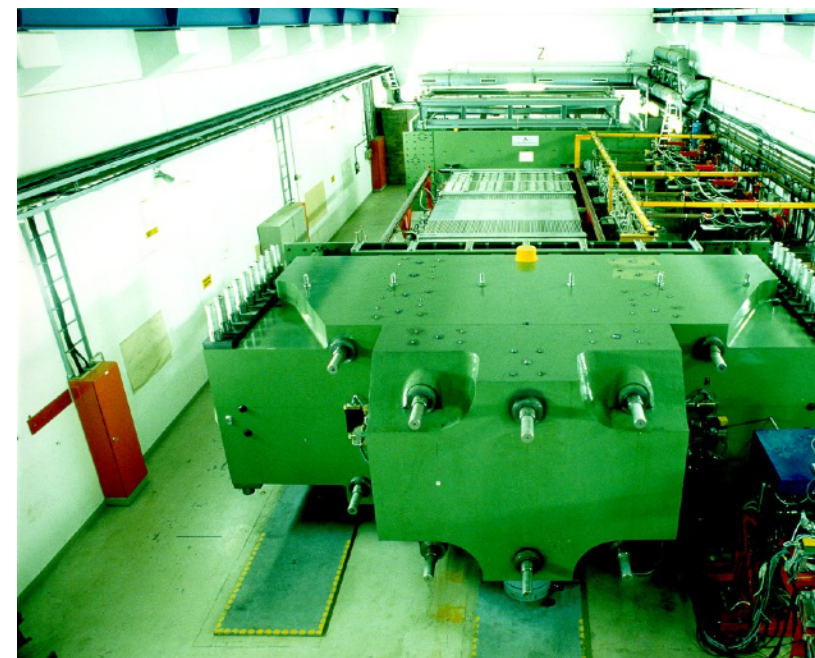
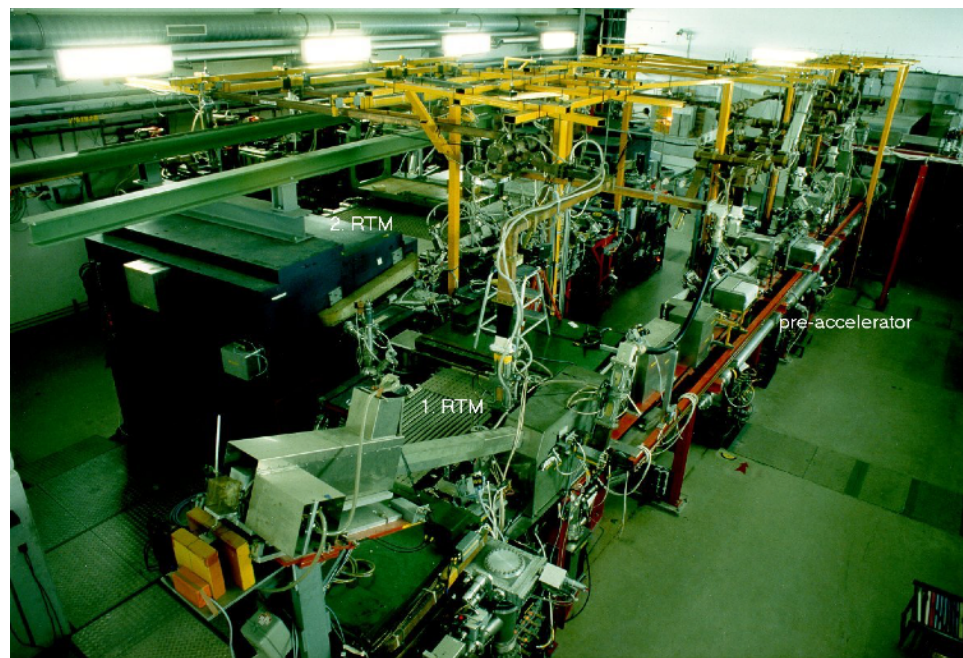
3 cascaded Racetrak Microtrons
 $E = 180\text{--}883 \text{ MeV}$
Max beam current $100 \text{ }\mu\text{A}$ c.w.



MESA

A1 Collaboration

3-spectrometer setup
Experiments with electrons

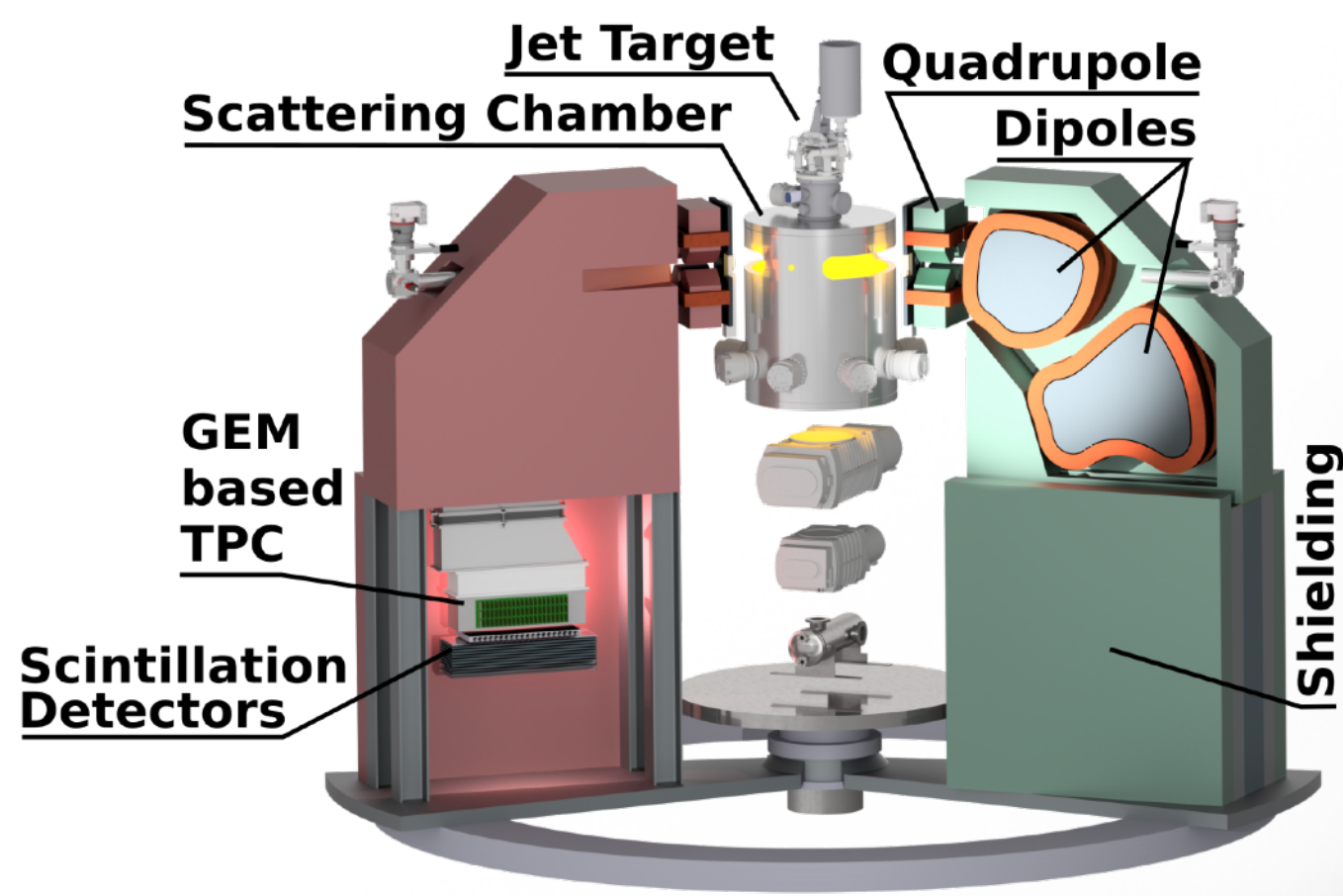


MESA

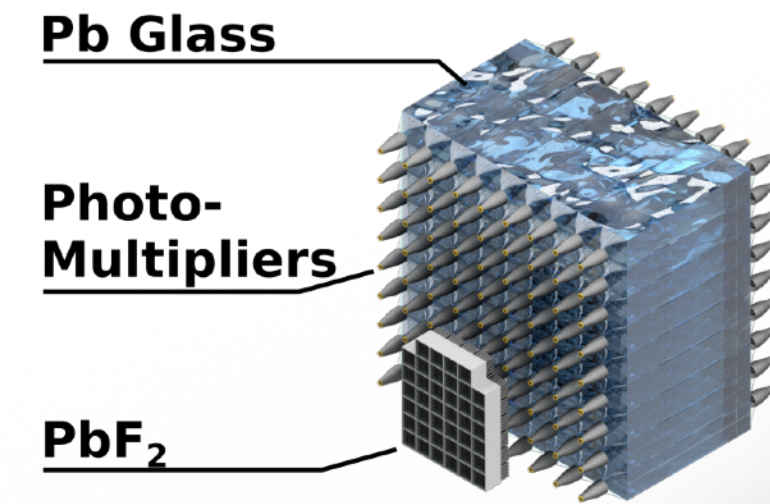
Two modes of operation:

- EB-operation (P2/BDX experiment):
polarized beam, 150 μ A @ 155 MeV
- ERL-operation (MAGIX):
(un)polarized beam,
up to 1 (10) mA @ 105 MeV

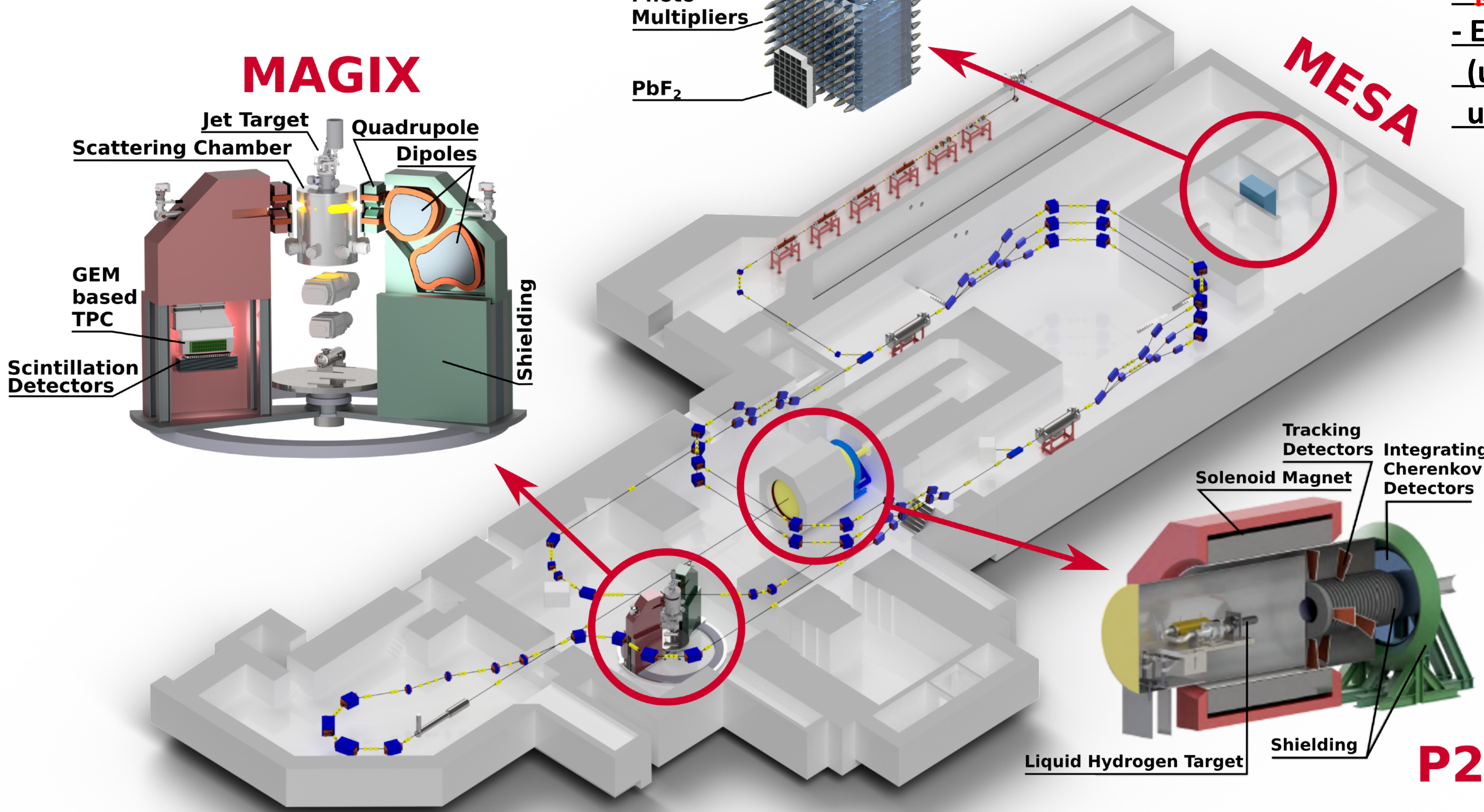
MAGIX



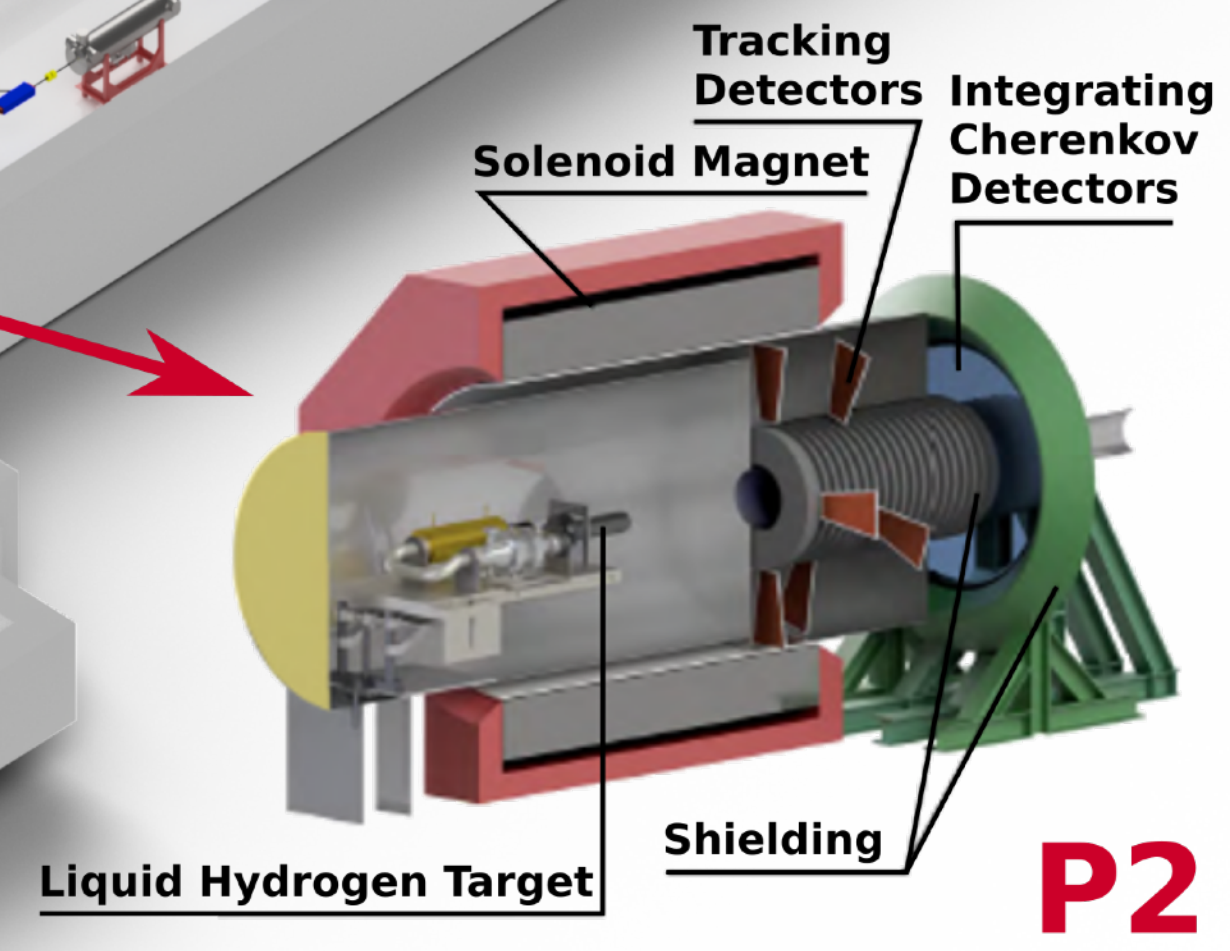
darkMESA



MESA



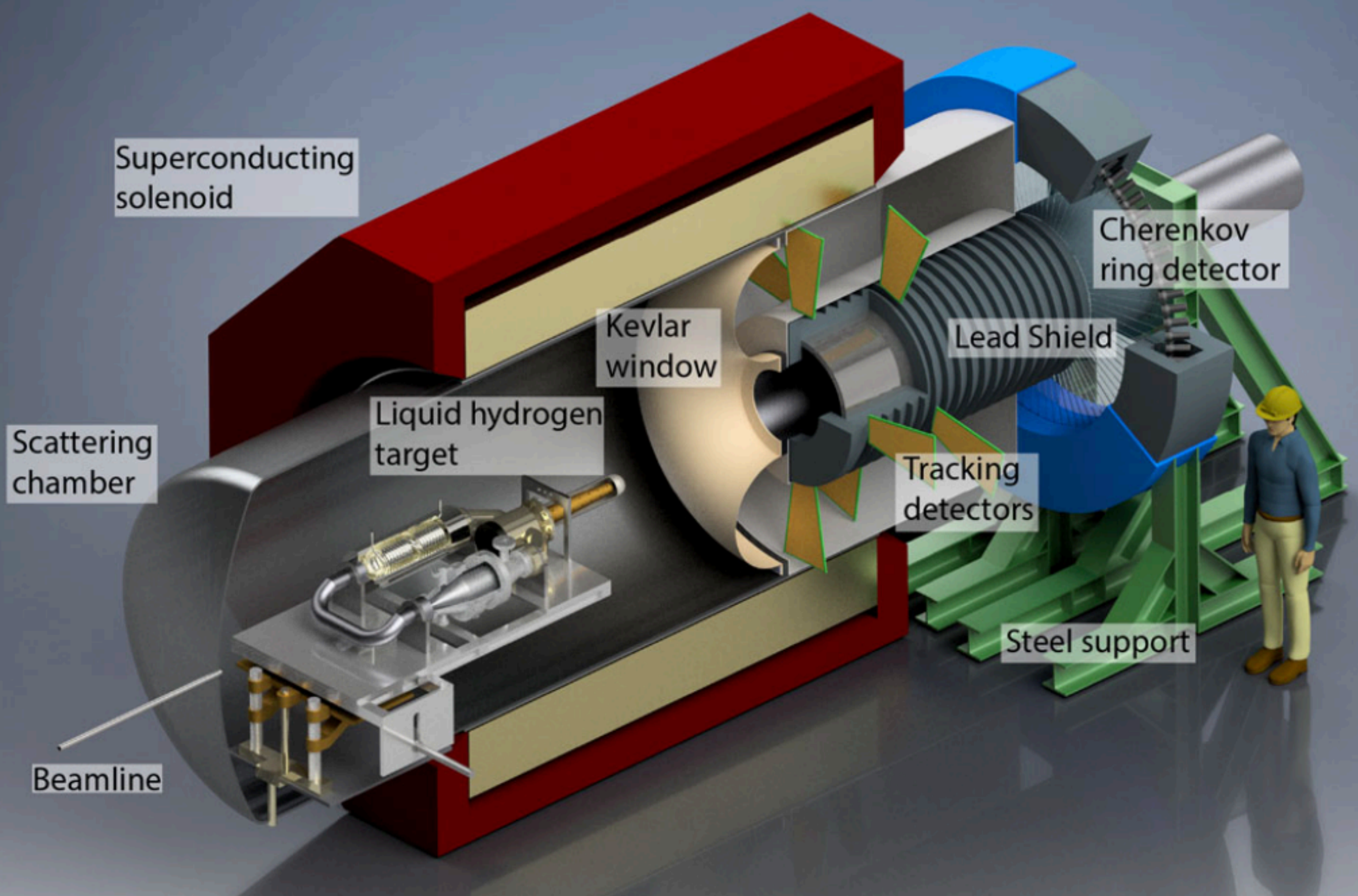
Superconducting Cavities:
9-cell ,1.3 GHz, CW operation
12.5 MeV gain
XFEL-TESLA type
Modified Rossendorf-type Modules



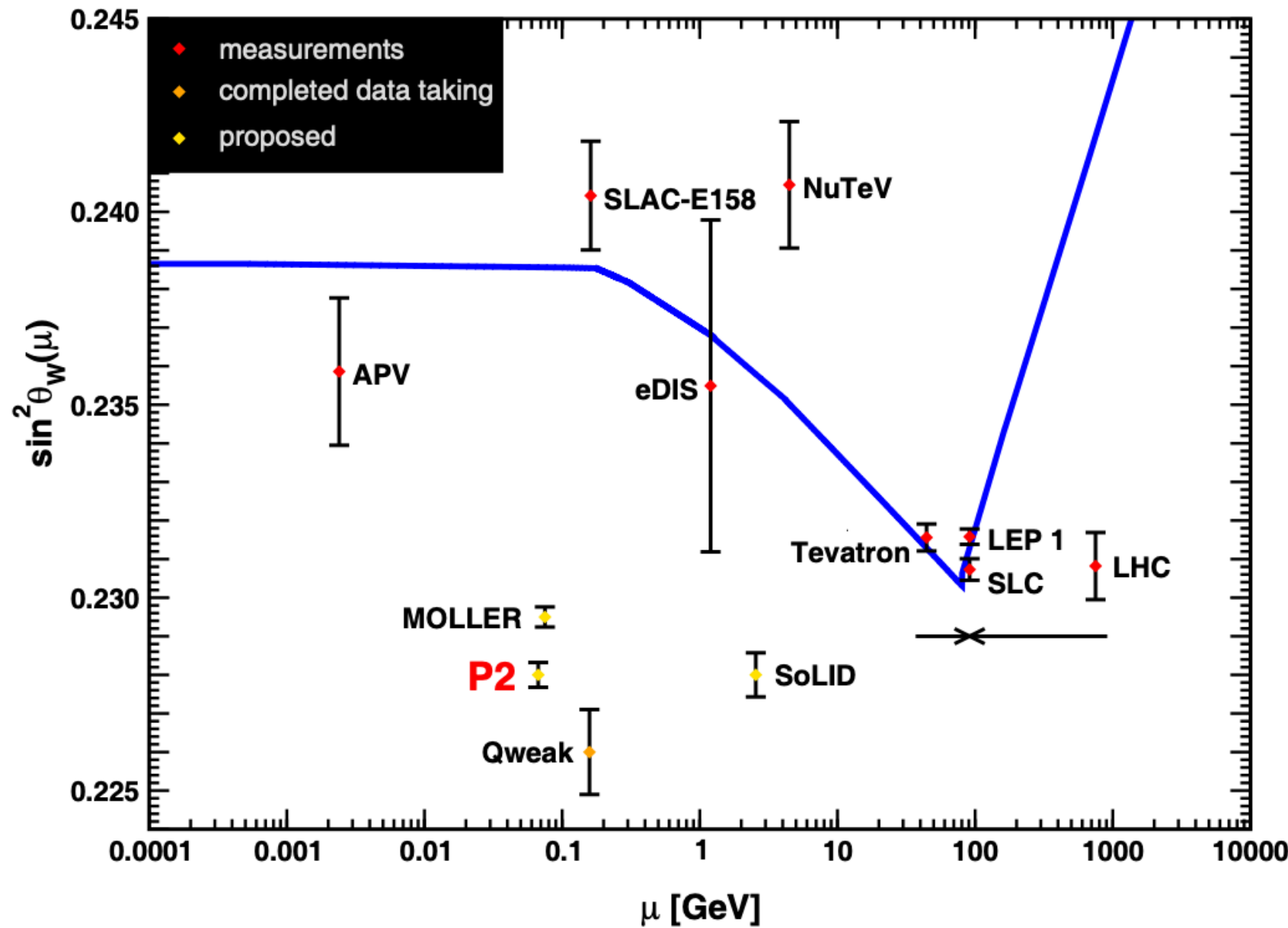
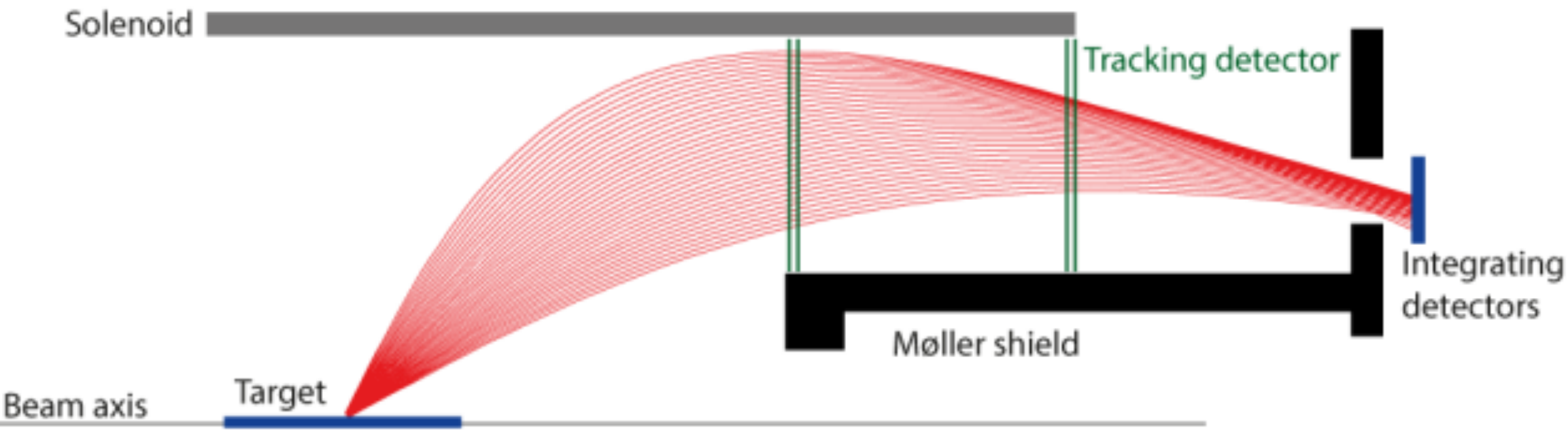
P2

P2

The P2 Experiment

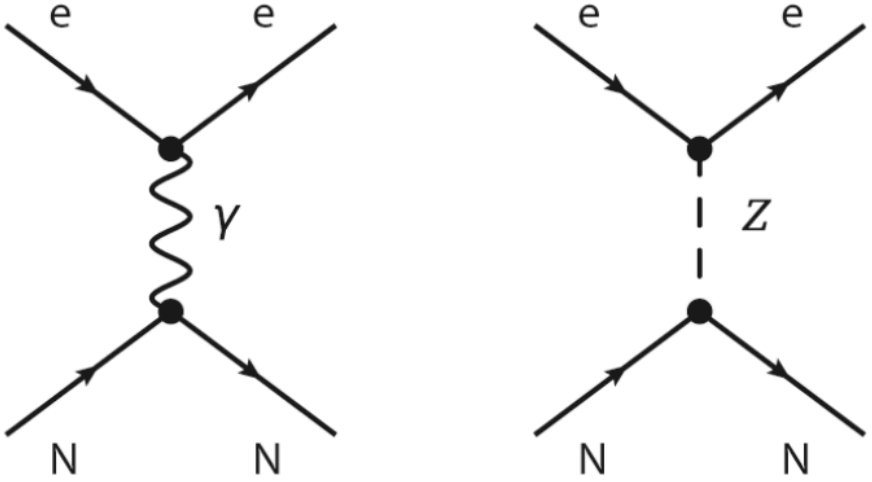


Becker et al, Eur. Phys. J. A (2018) 54: 208



$$A^{PV} = \frac{-G_F Q^2}{4\pi\alpha_{em}\sqrt{2}} [Q_W(p) - F(E_i, Q^2)]$$

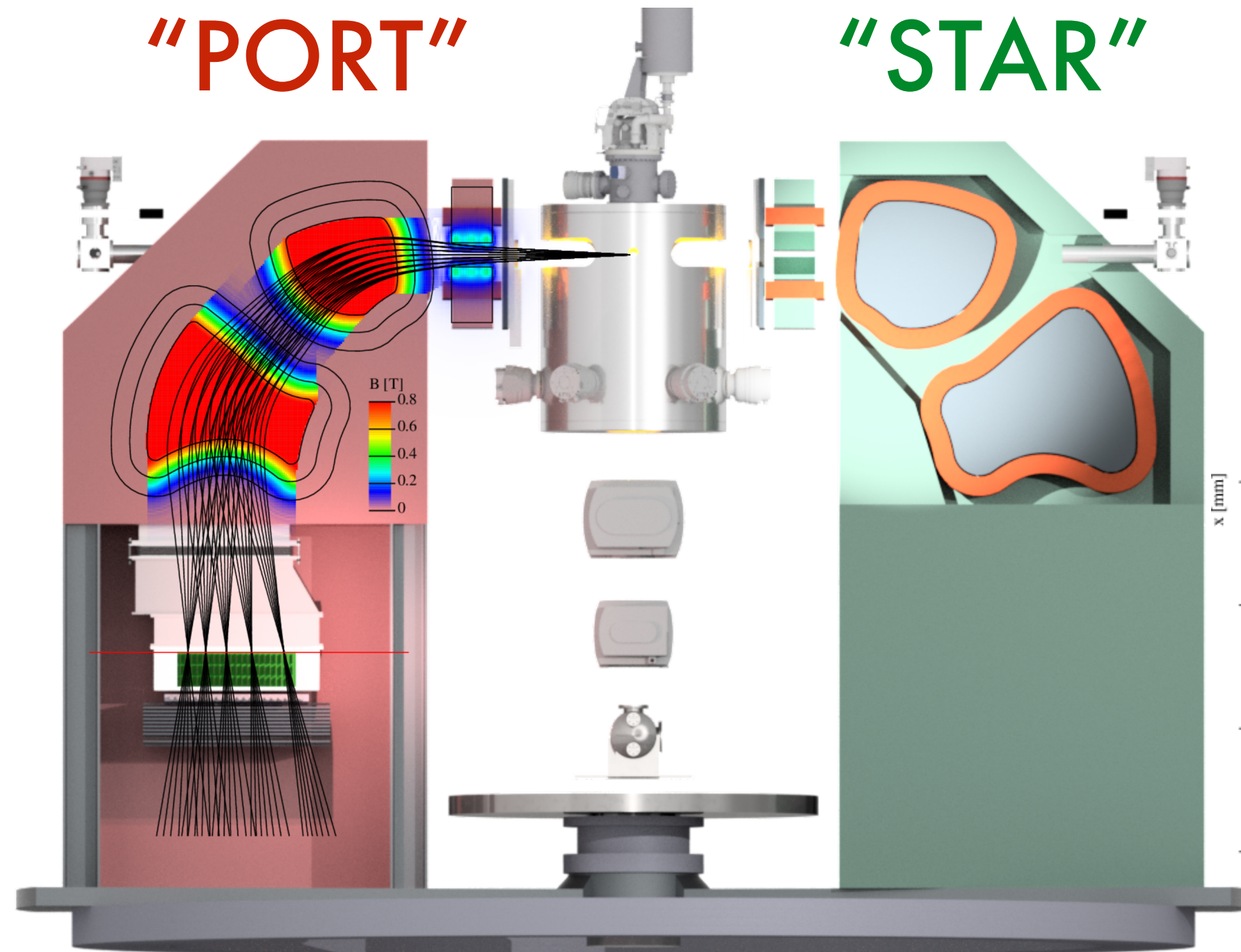
$$Q_W(p) = 1 - 4 \sin^2 \theta_W$$



- Precise measurement of the **Weinberg angle** at low energy
- PV elastic electron scattering
- Polarimetry: Mott+Hydro-Moller
- Feedback beam stabilisation
- High rate: integrating detectors.
- Silicon strip detectors tracking (HV-MAPS)

MAGIX

MAGIX



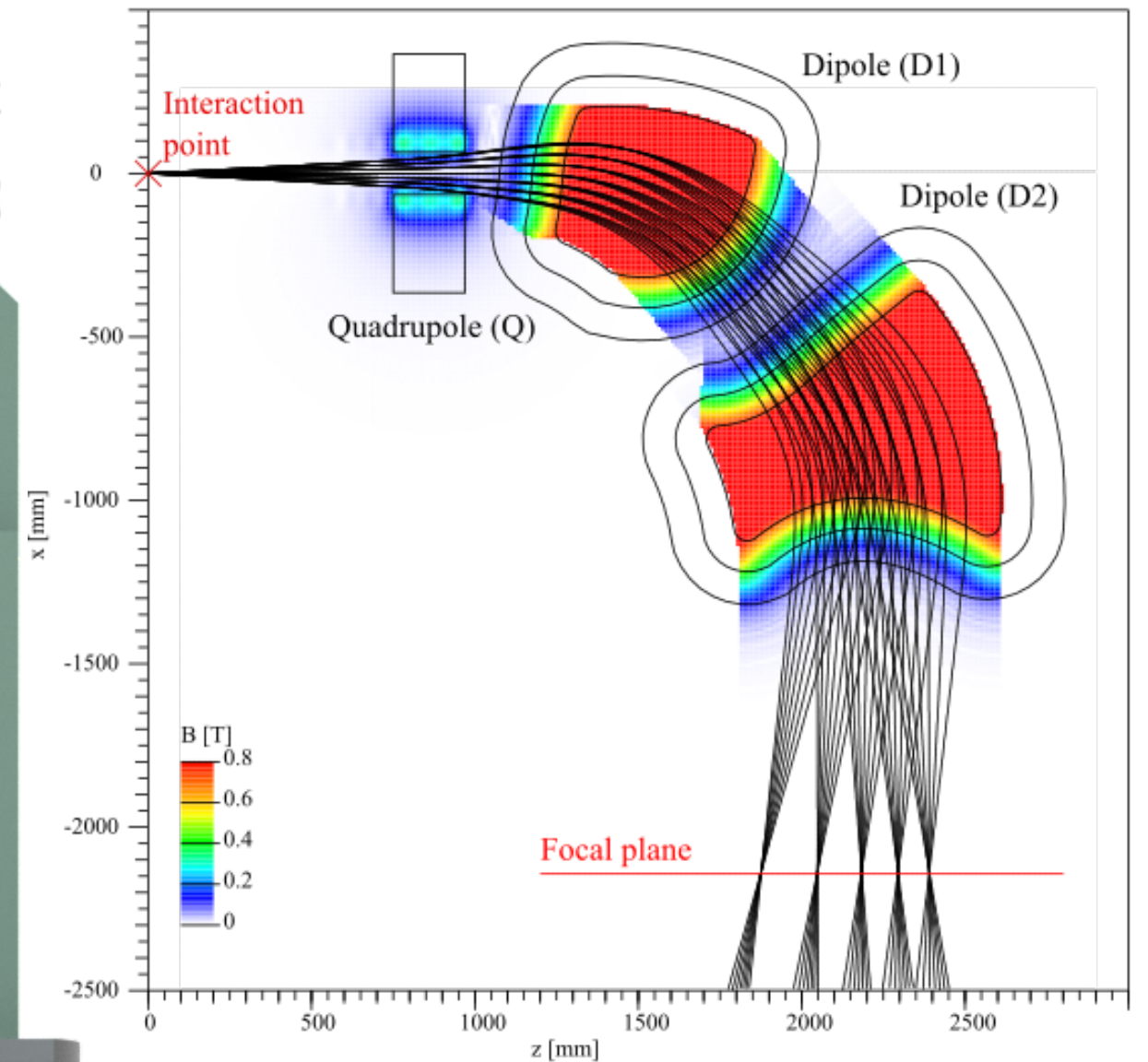
Rotation: 15°-165°

Timing

- TPC trigger: ~ 1 ns
- coincidence time **STAR** \leftrightarrow **PORT**: ~ 100 ps

Focal Plane resolutions (p -dependent etc)

- positions: ~ 100 μm angles: ~ 3.5 mrad

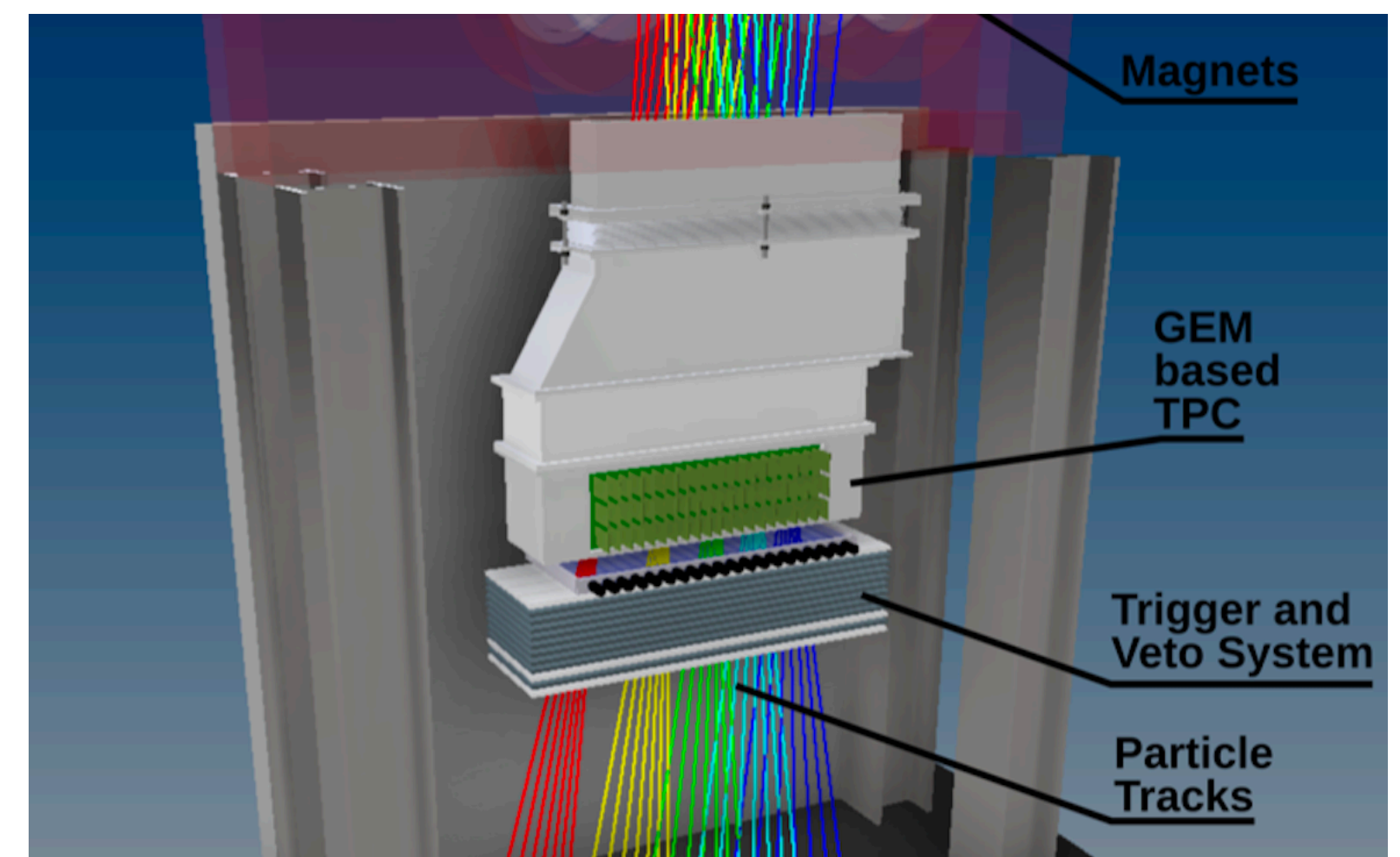
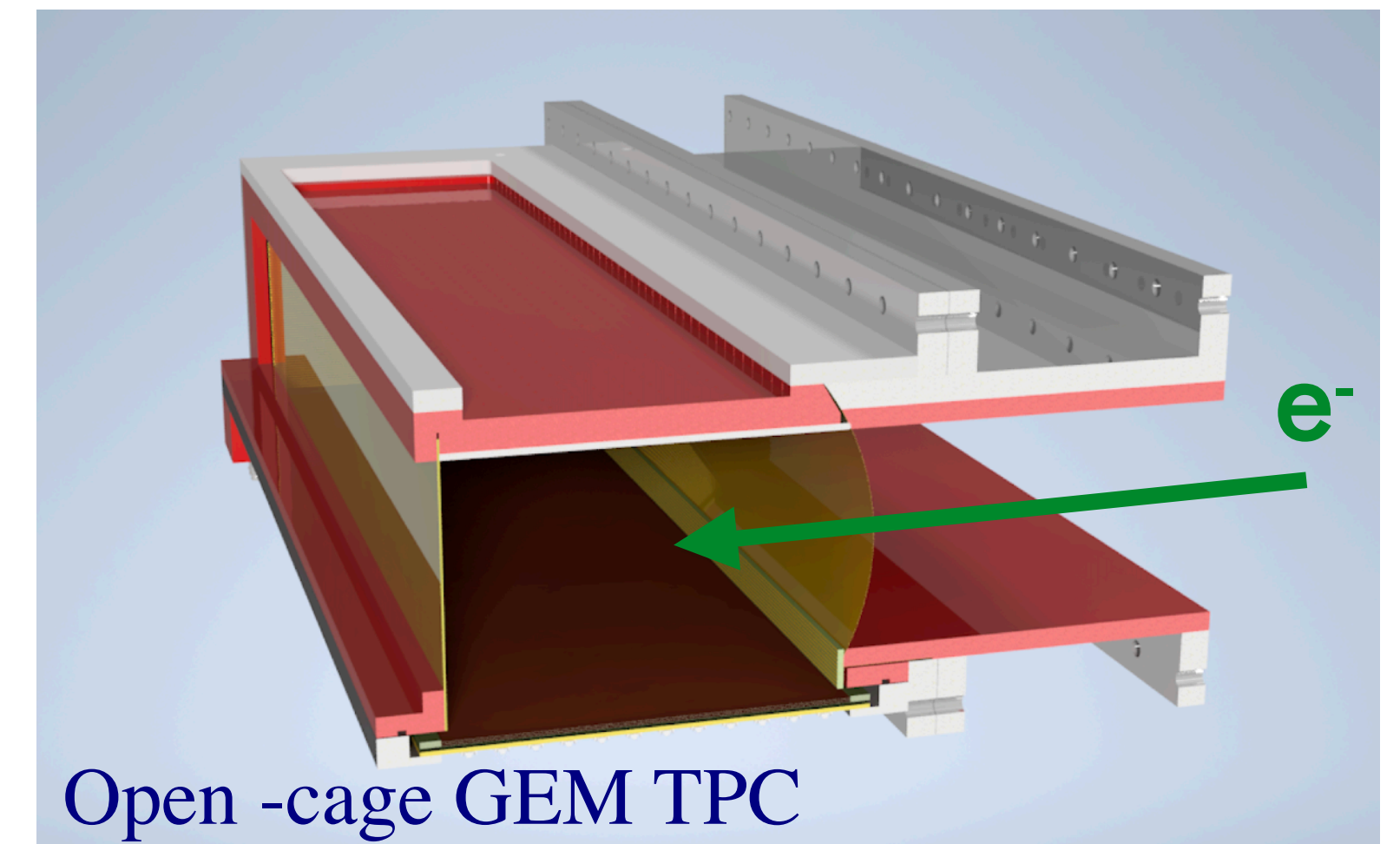


Target resolutions

- dp/p : 6×10^{-5}
- in-plane angle ϕ_0 : 6.5 mrad
- oop angle θ_0 : 1.6 mrad vertex y_0 : 60 μm

Acceptances

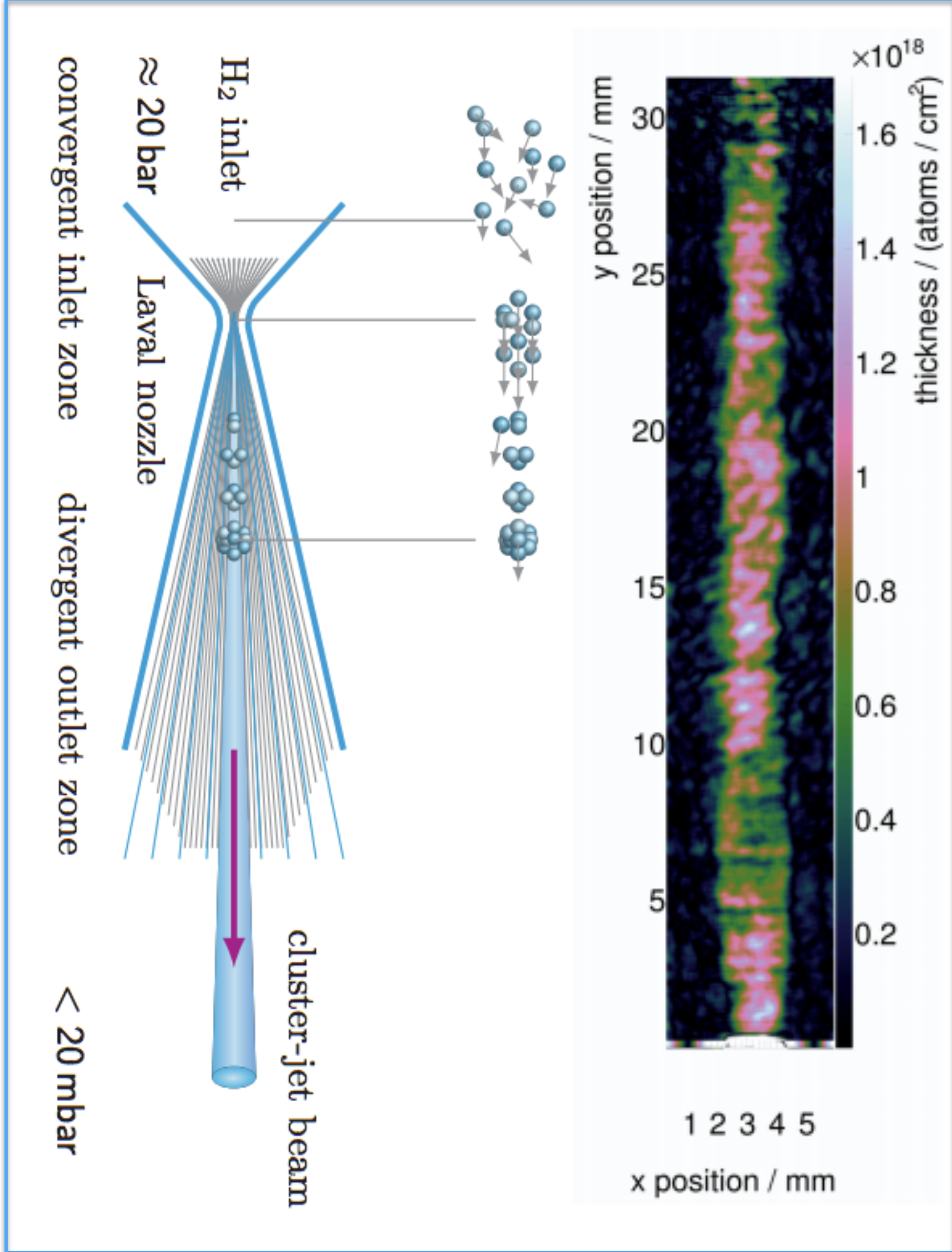
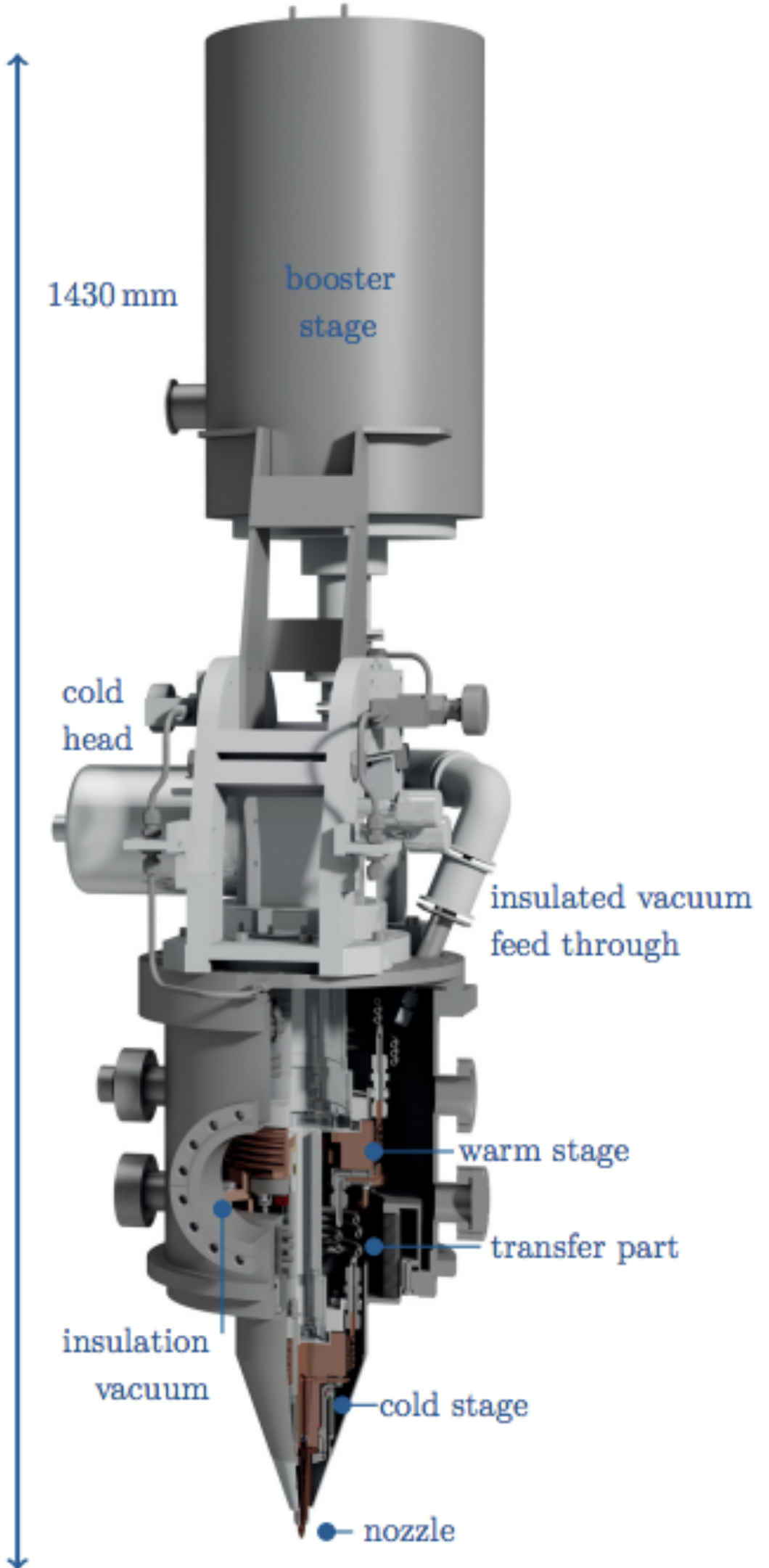
- momentum acceptance: ± 15 %
- solid angle: 18 msr



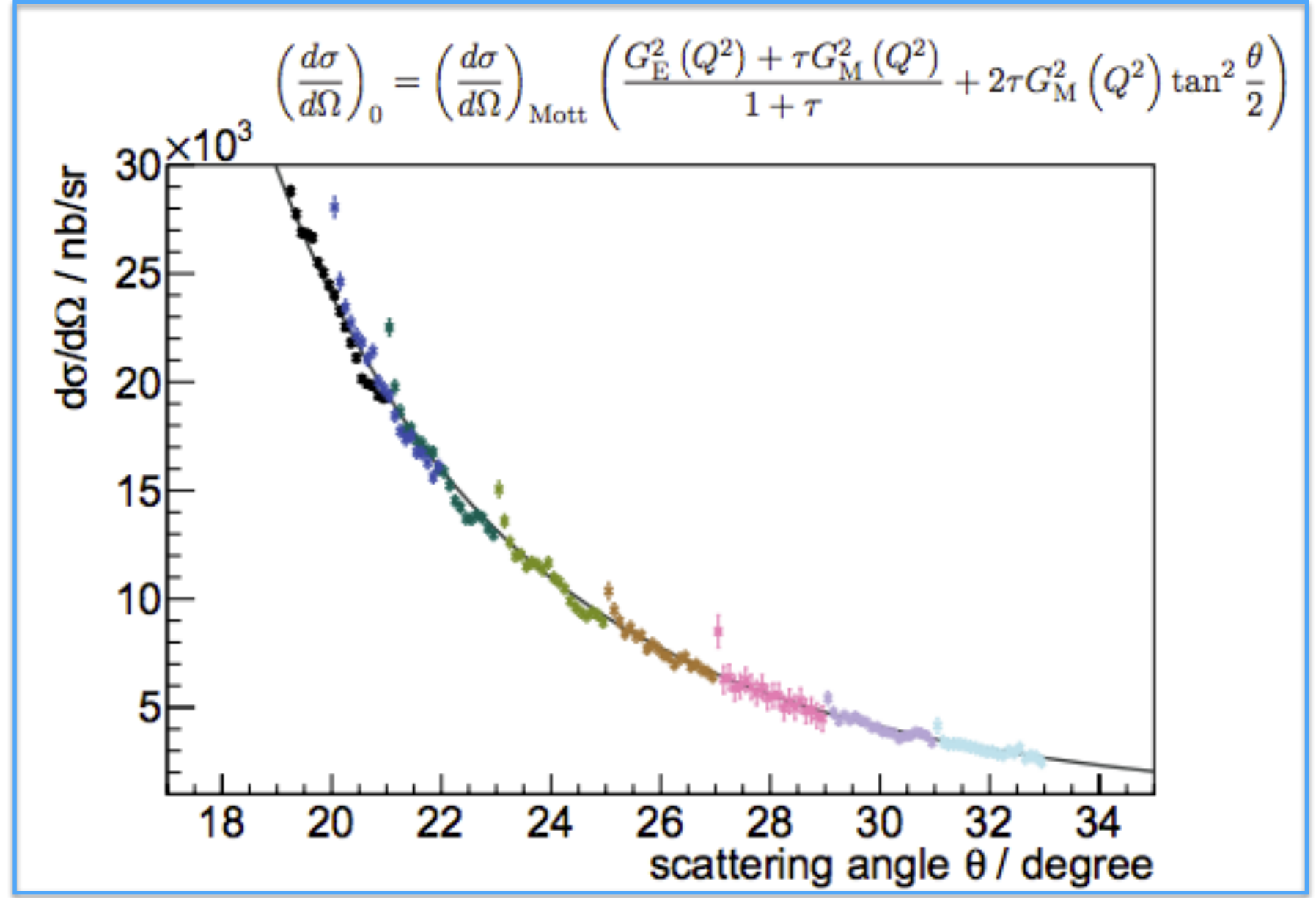
Focal Plane Dectectors

- Low-material open-cage GEM TPC
- Scintillator stack

The gas-jet Target



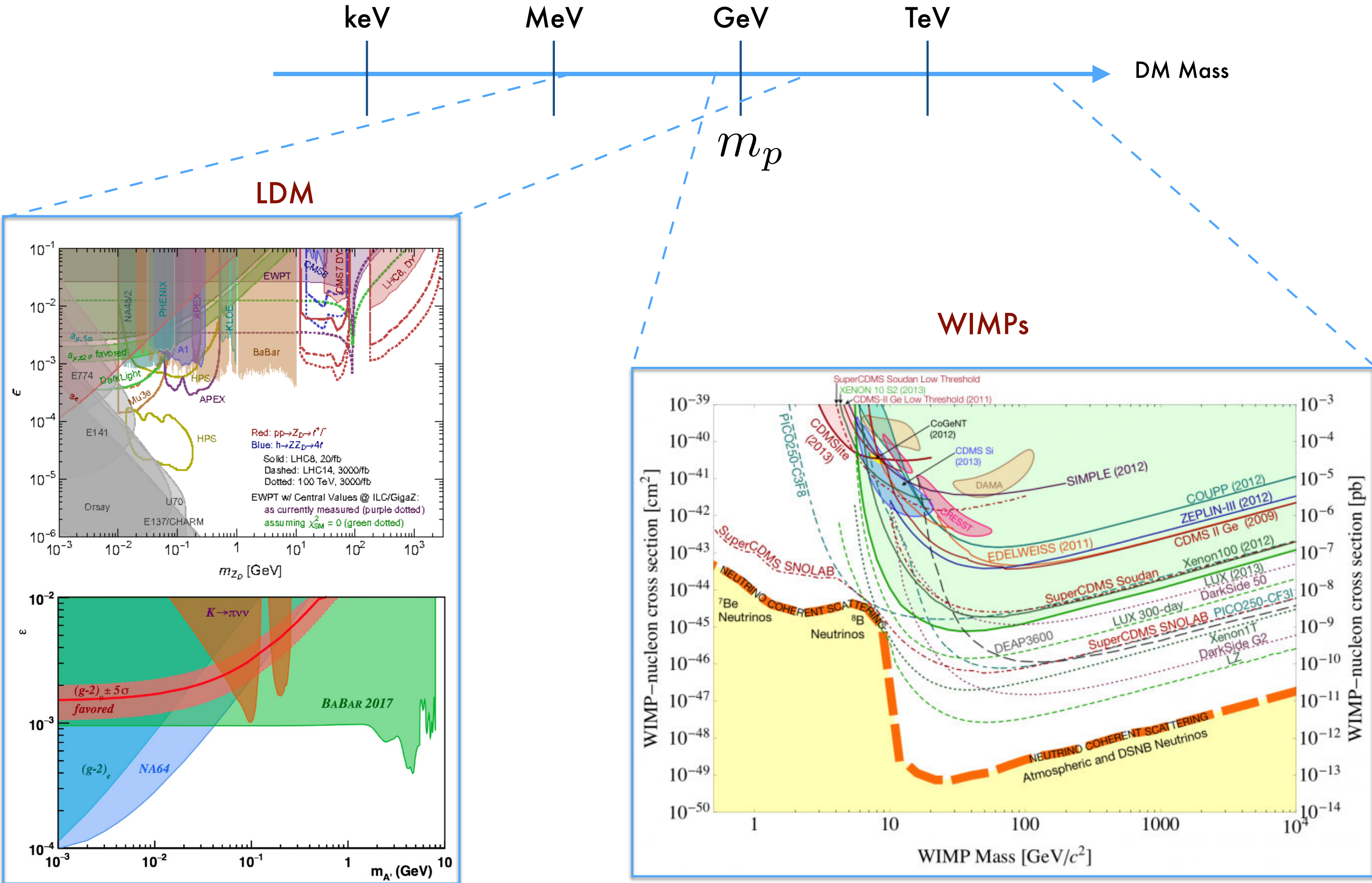
- *Supersonic gas flow from Laval nozzle
- *Supersonic shockwaves and clustering at cryogenic temperatures limit gas diffusion
- *mm-wide collimated gas stream



B.S. Schlimme et al., NIM A, 1013, 11, 165668 (2021)

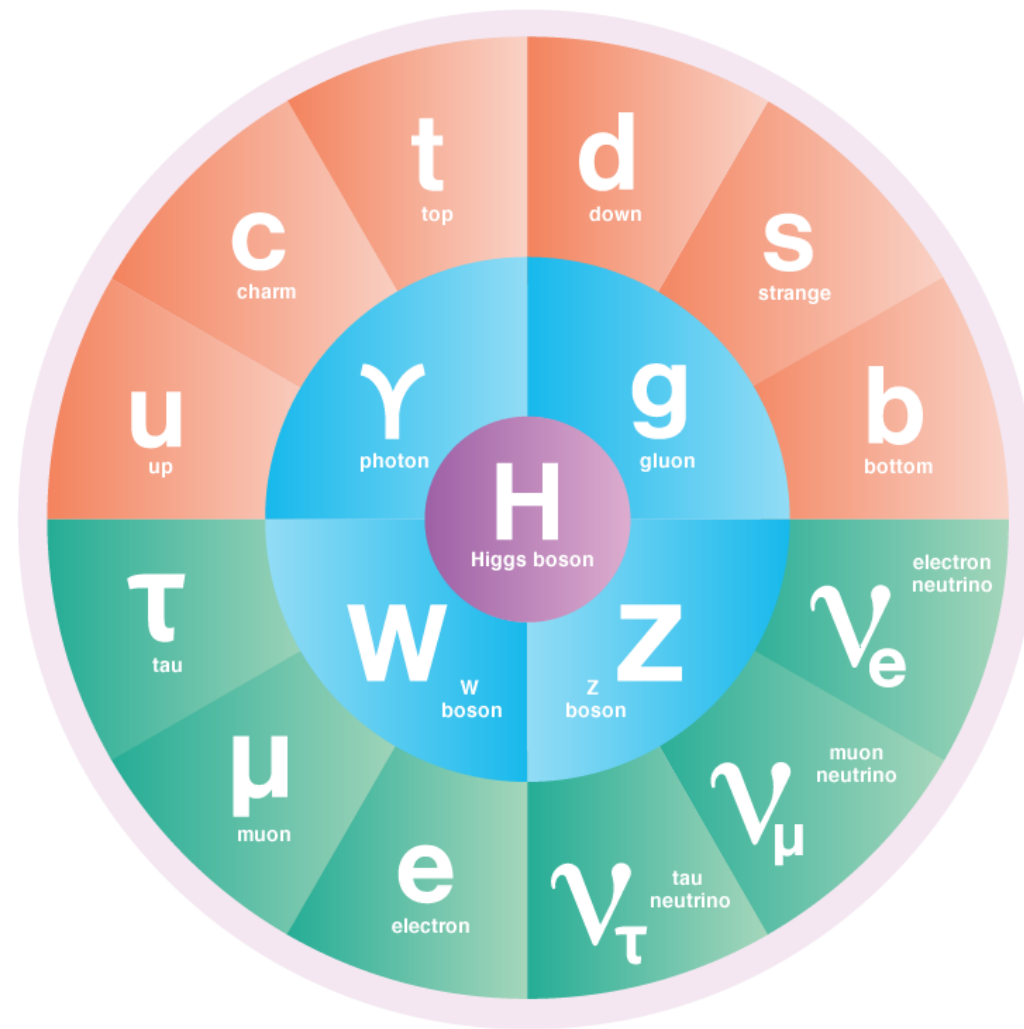
The MAGIX Science Program

Light Dark Matter

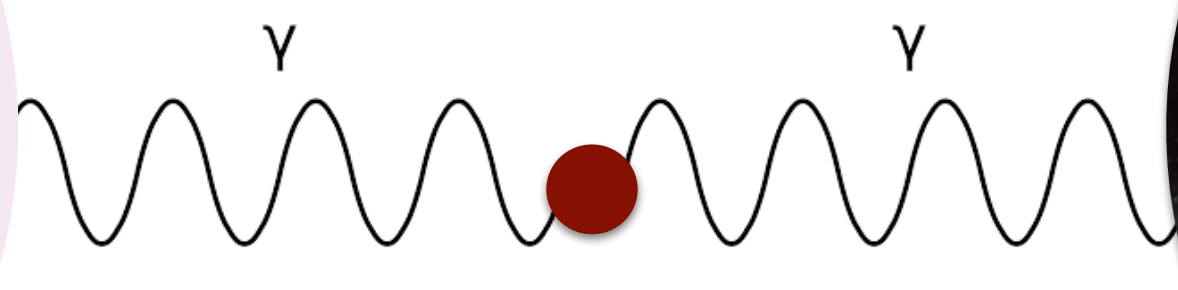


Dark Photon Models

Standard Model



Dark Sector



“Portals”

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

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

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

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

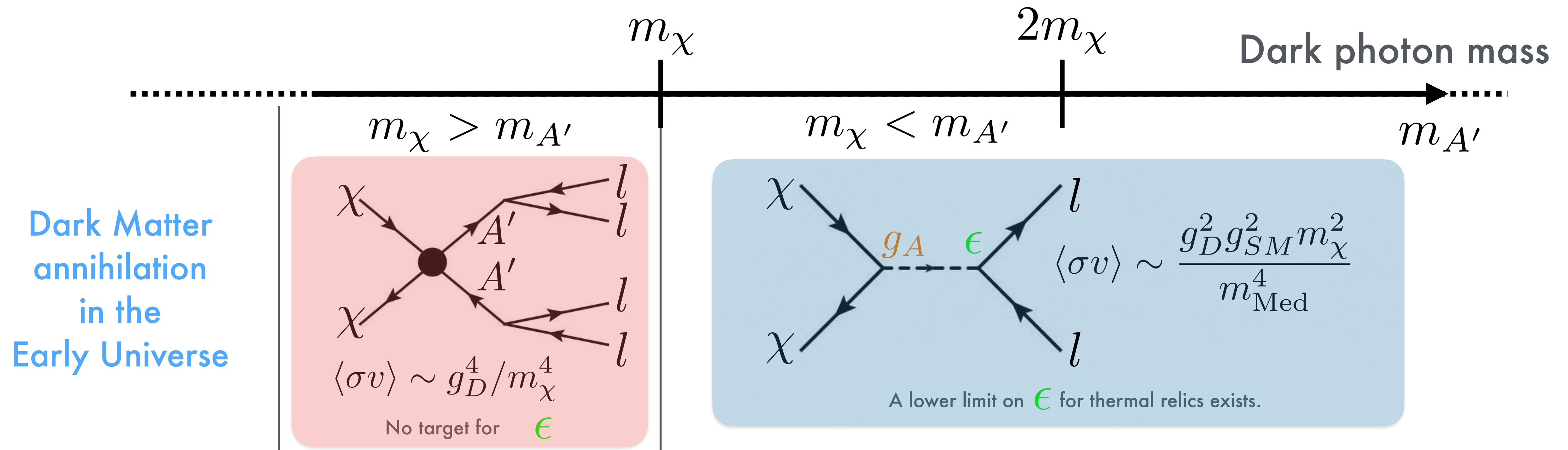
Minimal Dark Photon Model

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

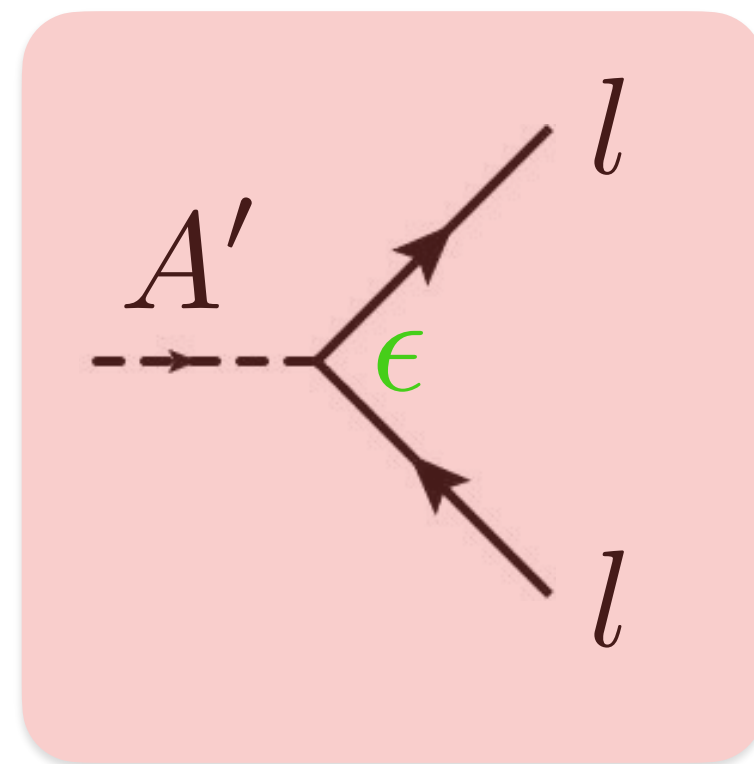
New U(1) massive gauge boson

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

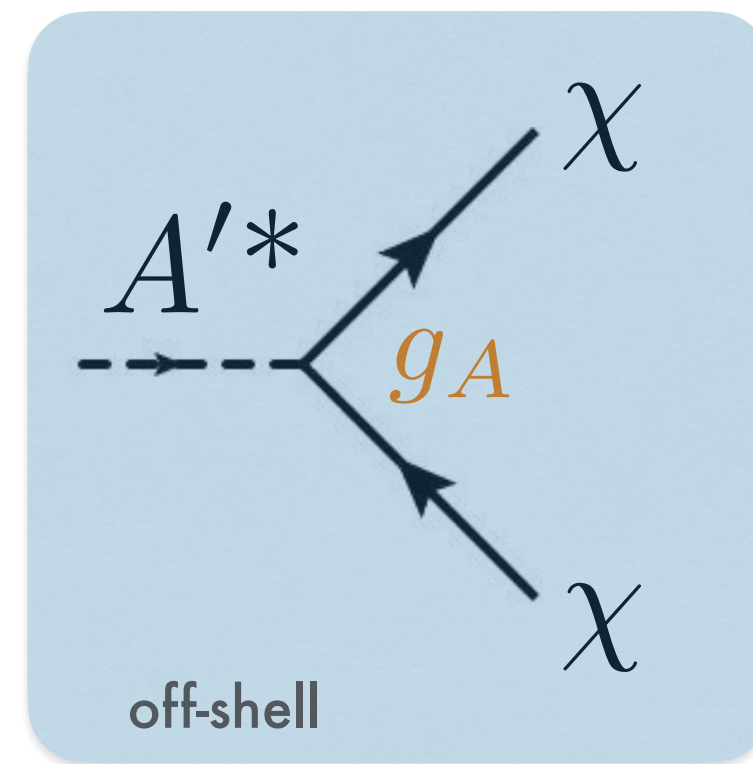
Dark Photon Models



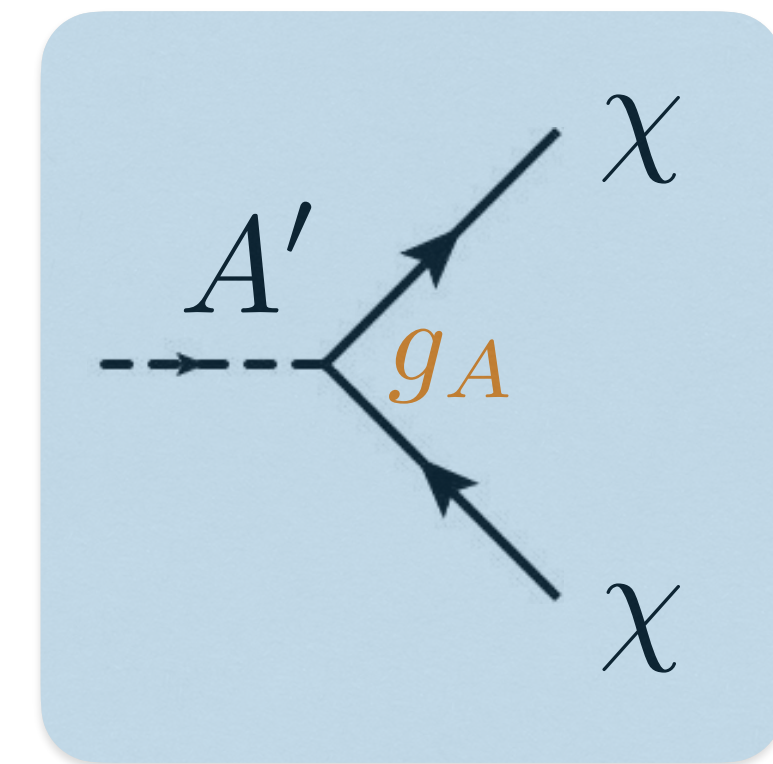
Process to search for



Decay to SM particles
Off-shell decay to DM



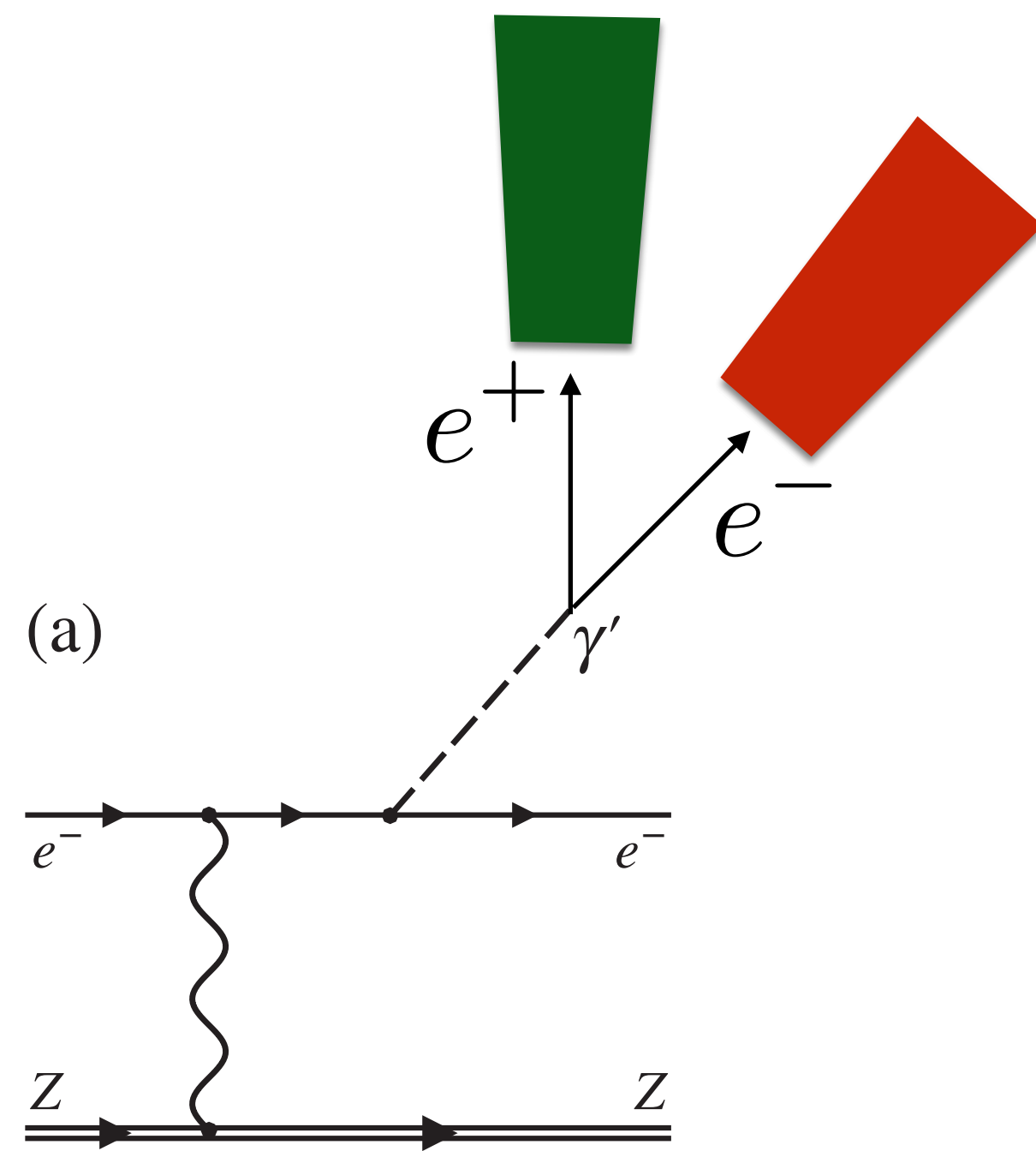
off-shell



On-shell decay to DM

Visible Dark Photon Decays

Visible decays

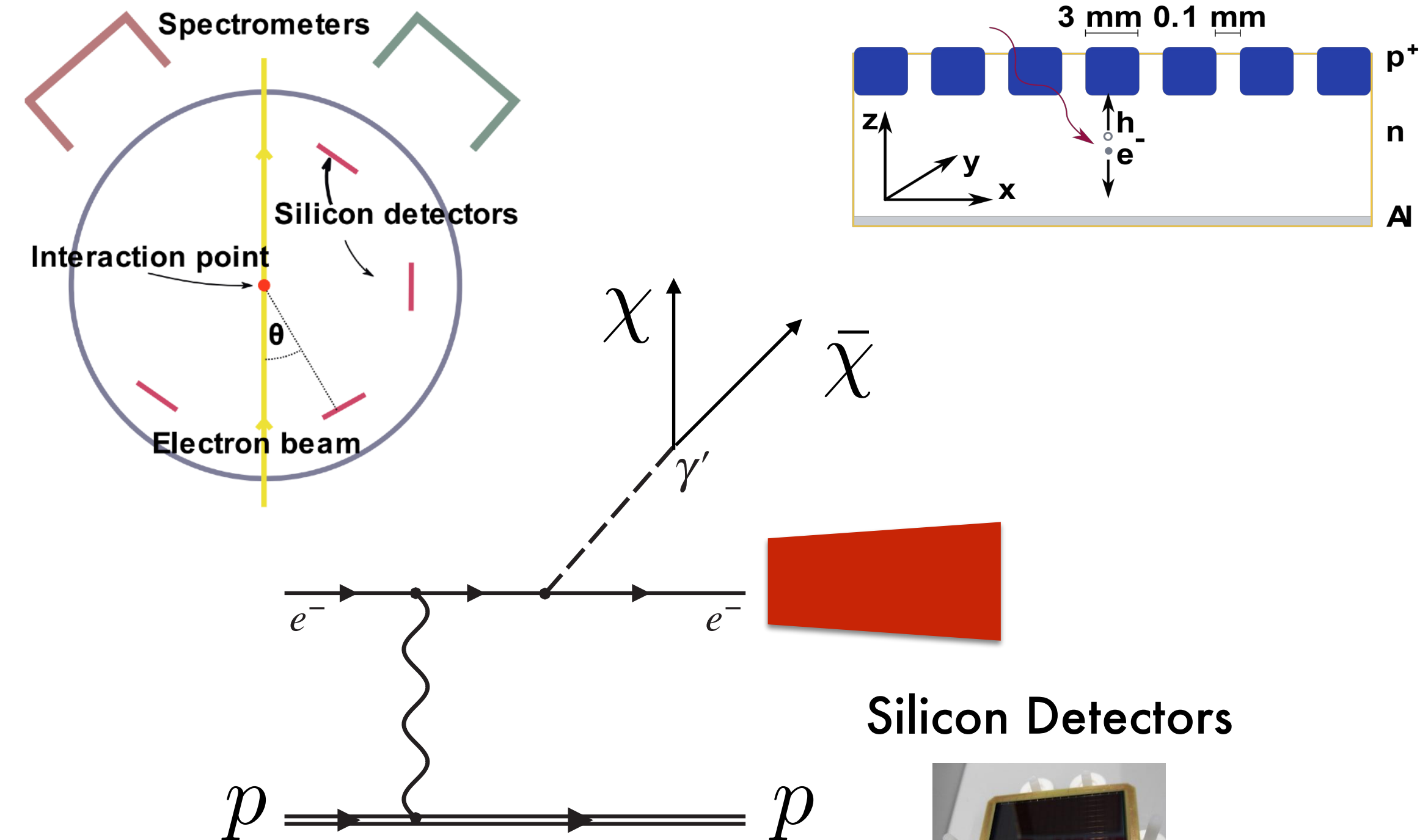


Coincidence detection of decay products
 Production on heavy nucleus (Ar, Xe, ..)
 Technique proved at A1

H Merkel et al. Phys. Rev. Lett. 106 (25), 251802 (2011)

H Merkel et al., Phys. Rev. Lett. 112 (22), 221802 (2014)

Invisible decays



Detect:

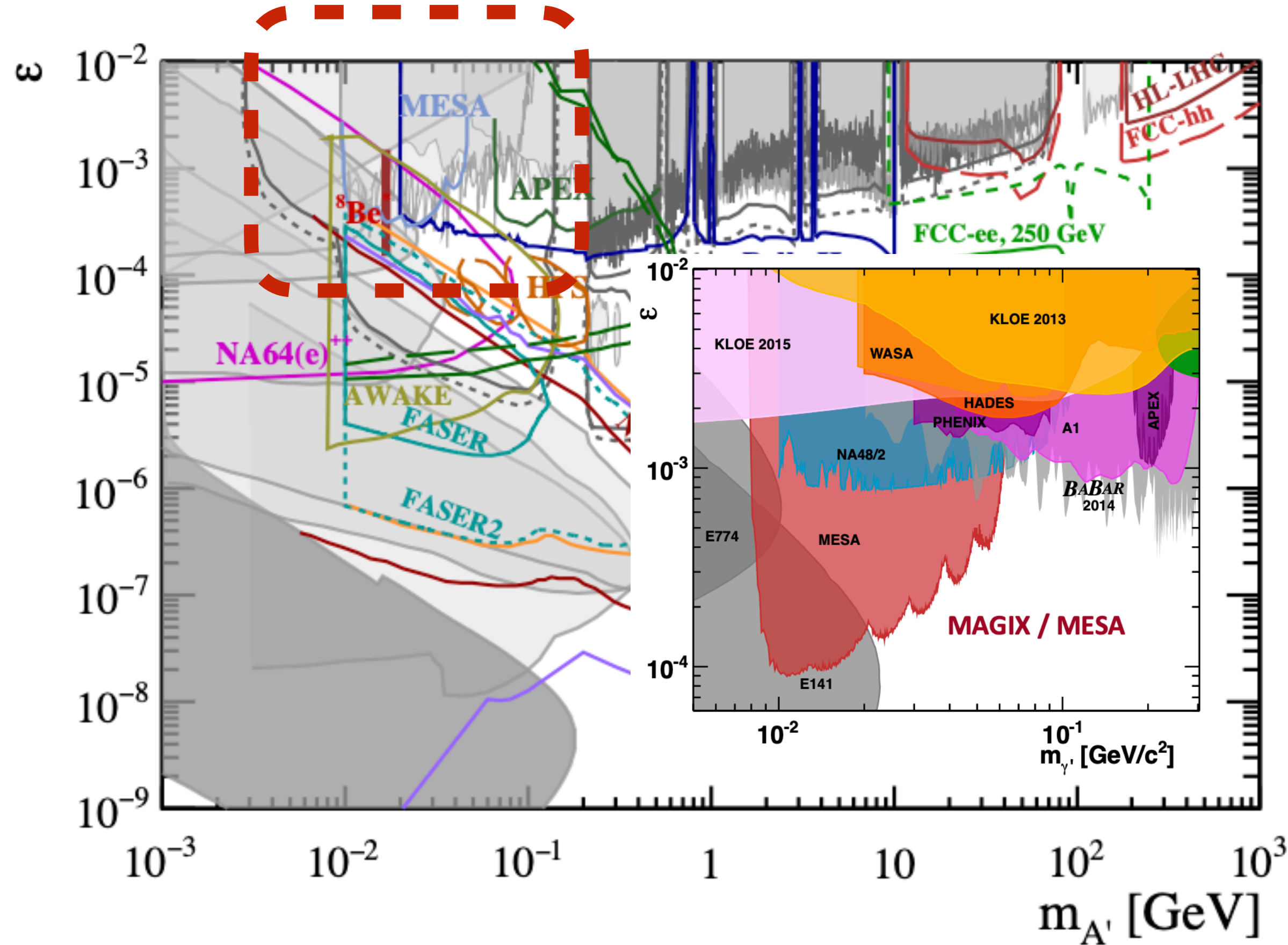
- Scattered electron
- Recoil proton

Search on missing mass spectrum

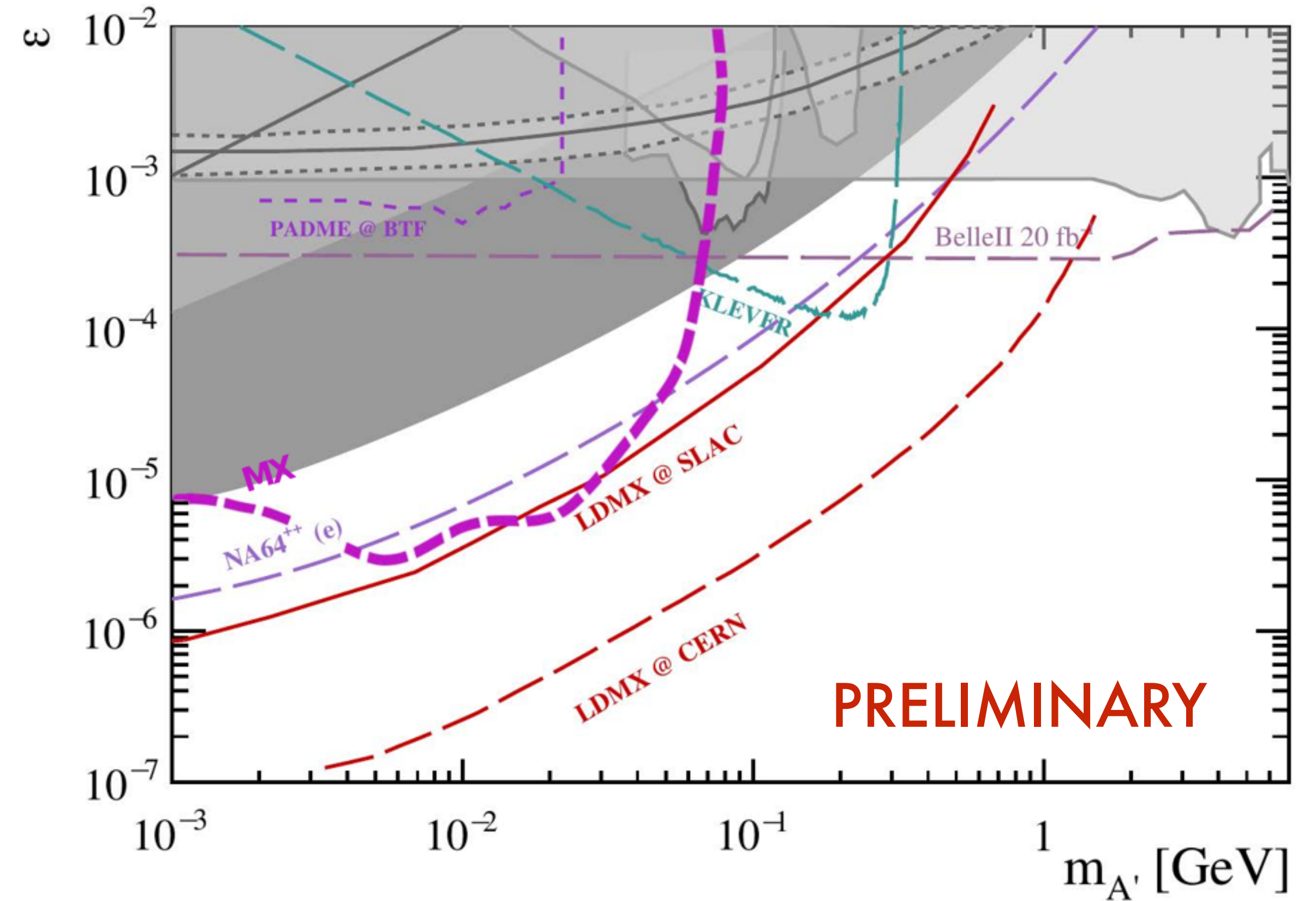
Dimension substrate	50 x 50 mm ²
Thickness substrate	995 μm
p-doped strips	16
Strip width	3 mm
Bias voltage	140 V

Dark Photons at MAGIX: Projections

Visible decays

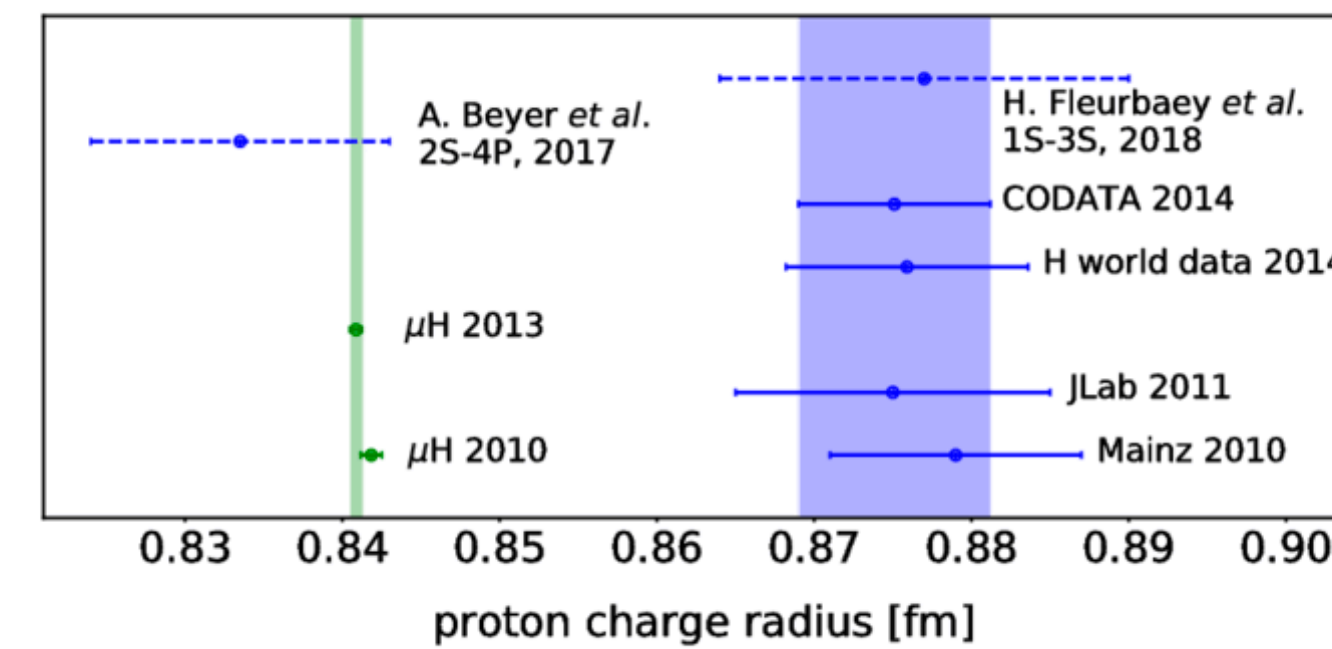
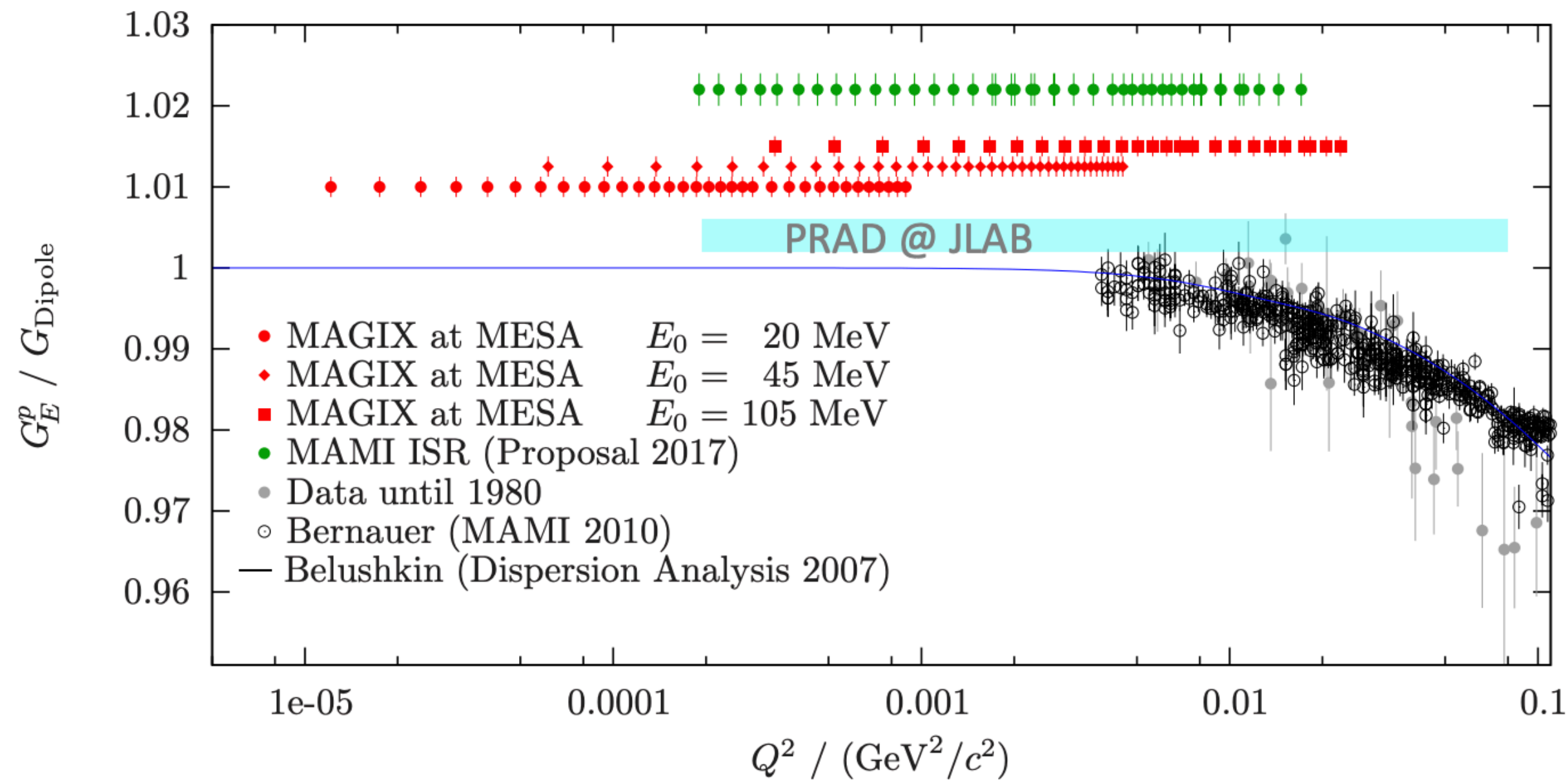


Invisible decays



More Physics Topics from MAGIX (1)

Nucleon Form Factor

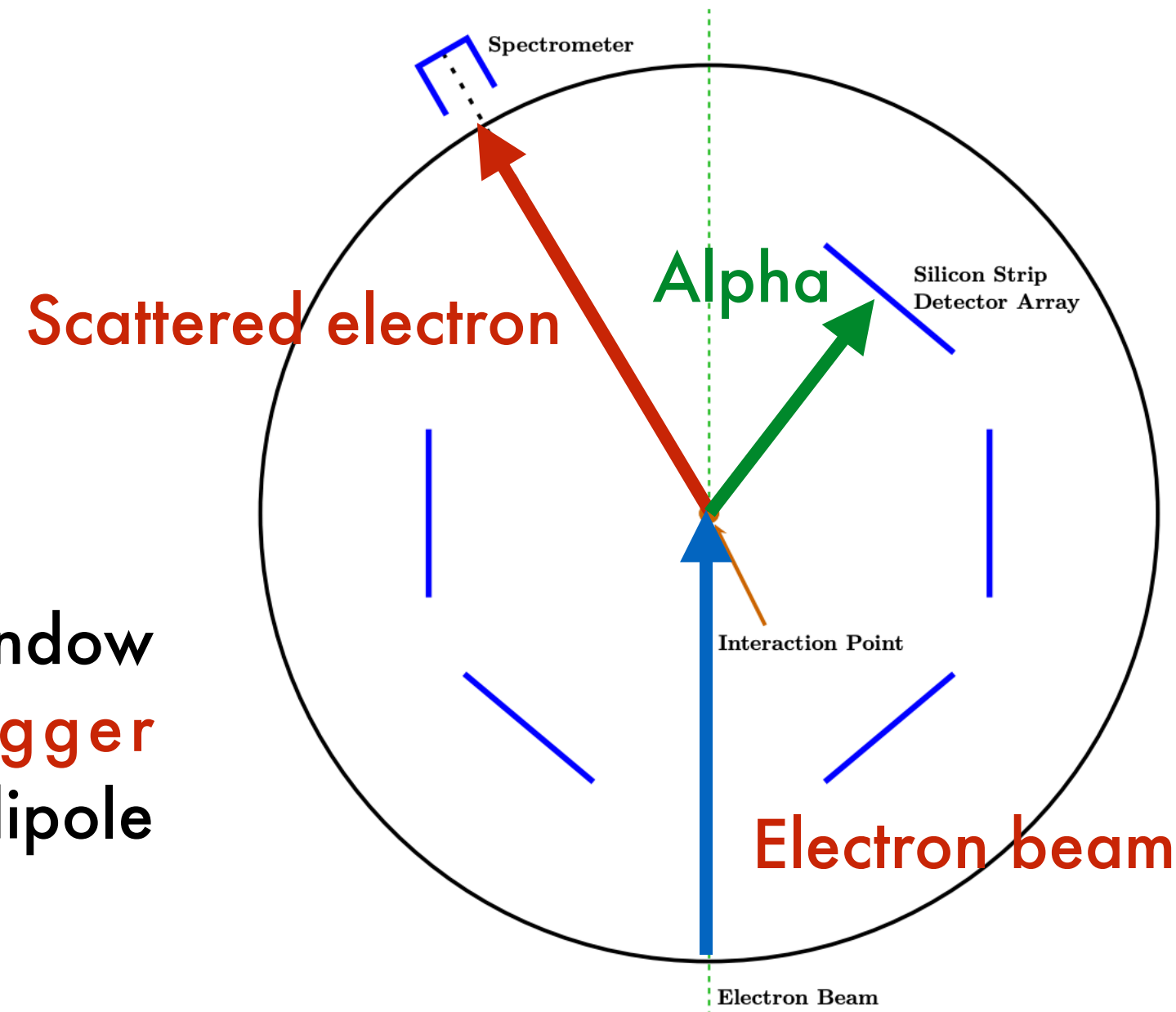
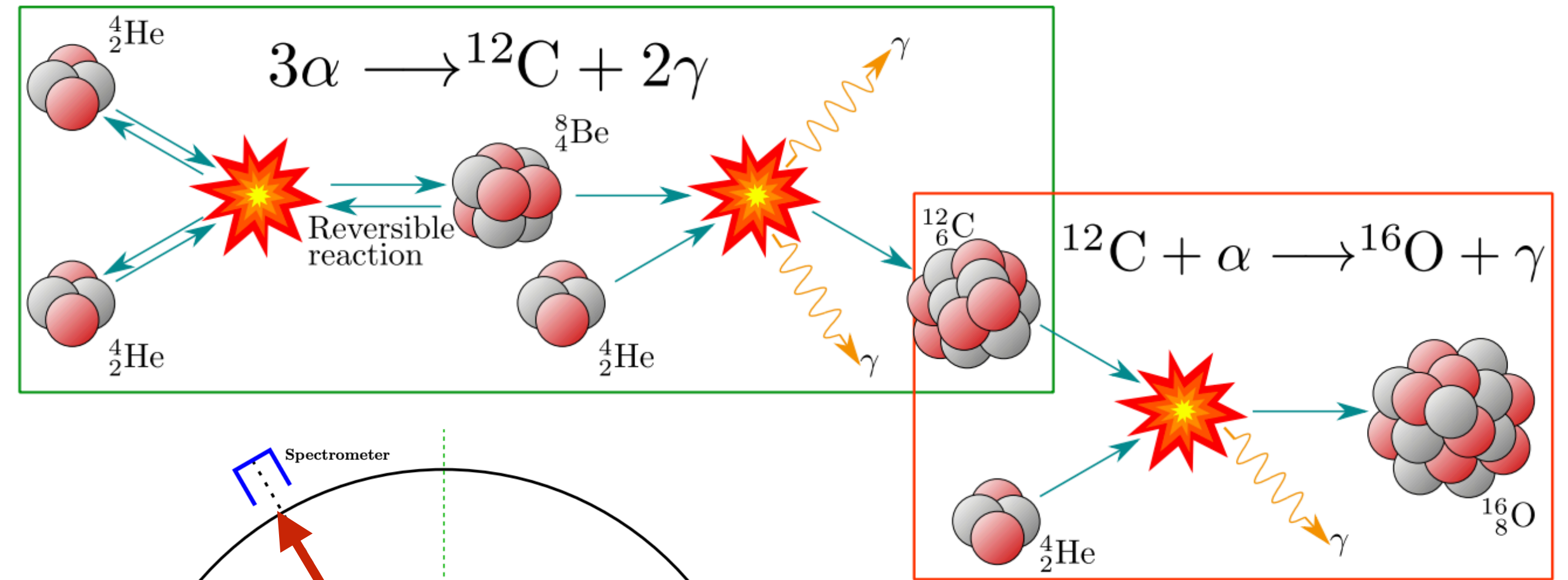
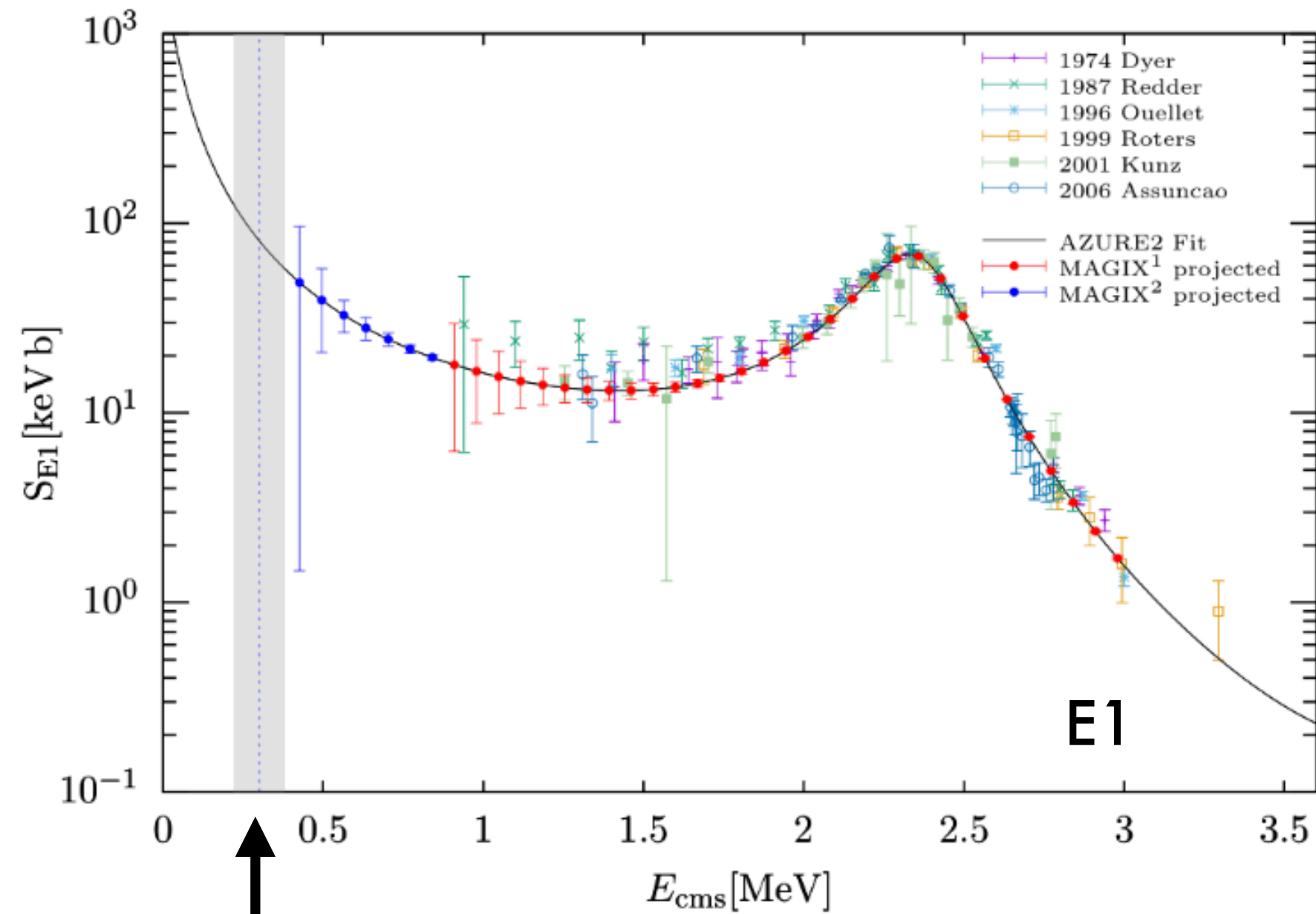


Perform precise elastic electron scattering experiments for the determination of the nucleon form factors for elucidating the discrepancy with spectroscopic measurements.

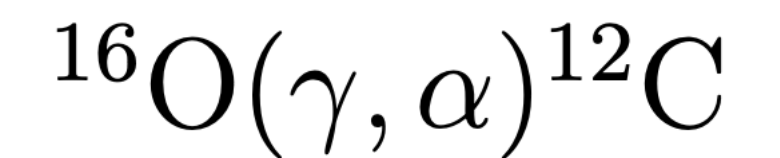
$$\left(\frac{d\sigma}{d\Omega}\right)_0 = \left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} \left[\frac{G_E^2(Q^2) + \tau G_M^2(Q^2)}{1 + \tau} + 2\tau G_M^2(Q^2) \tan^2 \frac{\theta}{2} \right]$$

More Physics Topics from MAGIX (2)

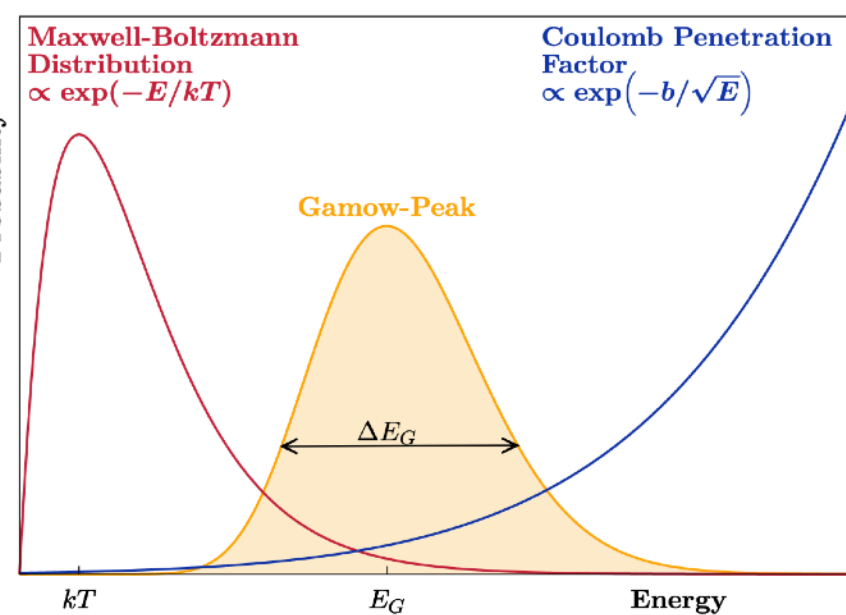
Astrophysical S-Factors $S(E) := \sigma(E) \cdot E \cdot e^{2\pi\eta}$



Measure astrophysical reactions in inverse kinematics with (virtual) photo disintegration



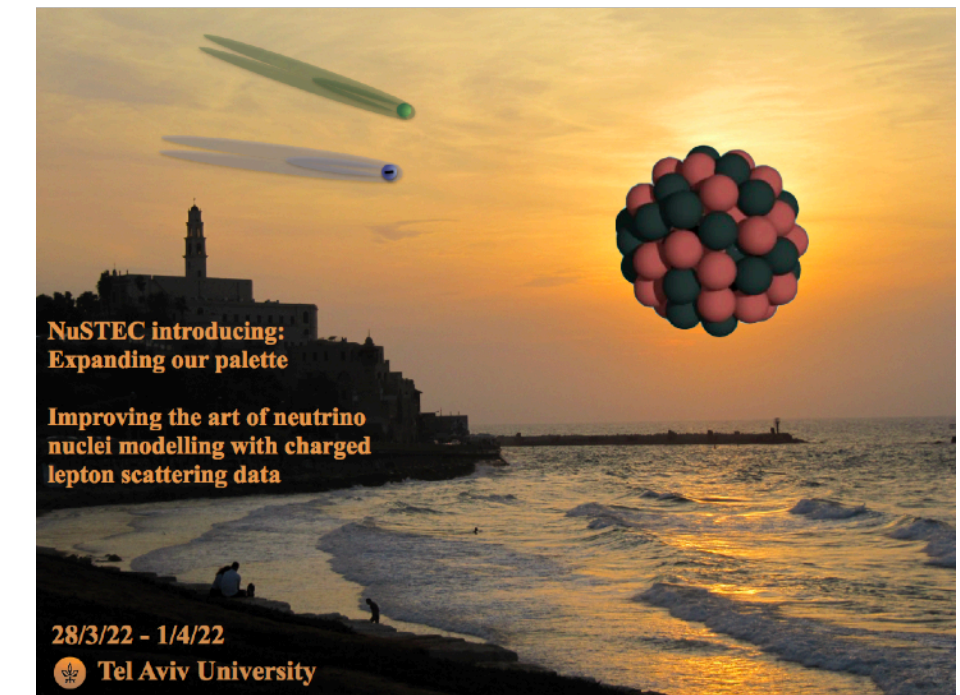
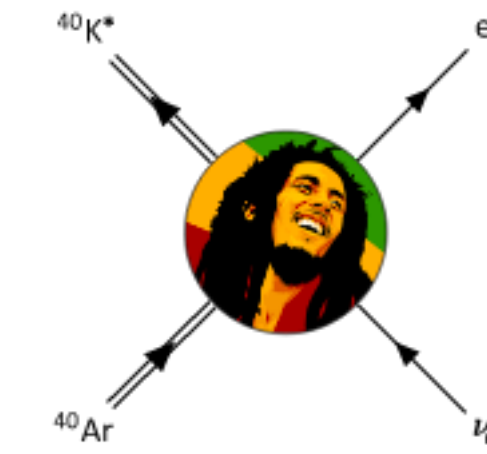
Plan: reach the Gamow window adding a **zero-degree tagger** exploiting one accelerator dipole downstream of the experiment.



More Physics Topics from MAGIX (3)

Neutrino Physics

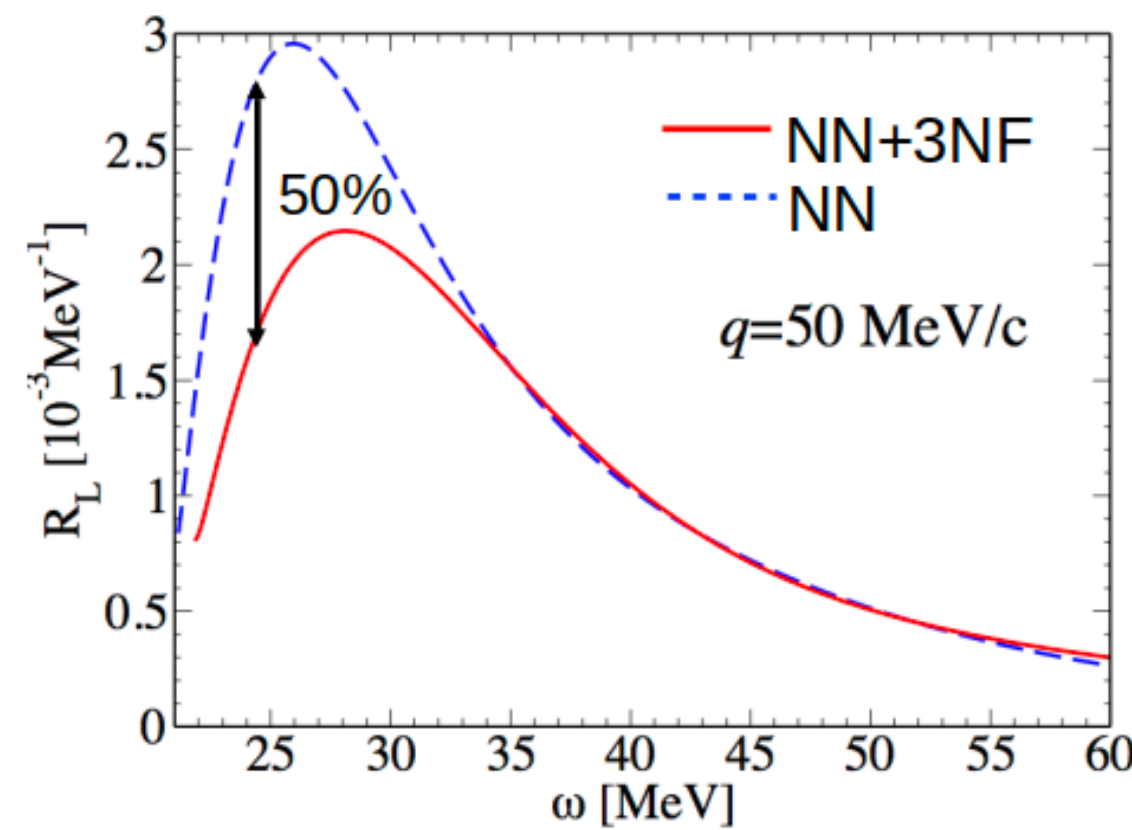
Exploit the similarity with neutrino scattering:
 measurement of low-energy nuclear cross sections for supernova neutrino detectors.
 Cross-check of neutrino generators (e.g. MARLEY [arXiv:2101.11867](https://arxiv.org/abs/2101.11867)).



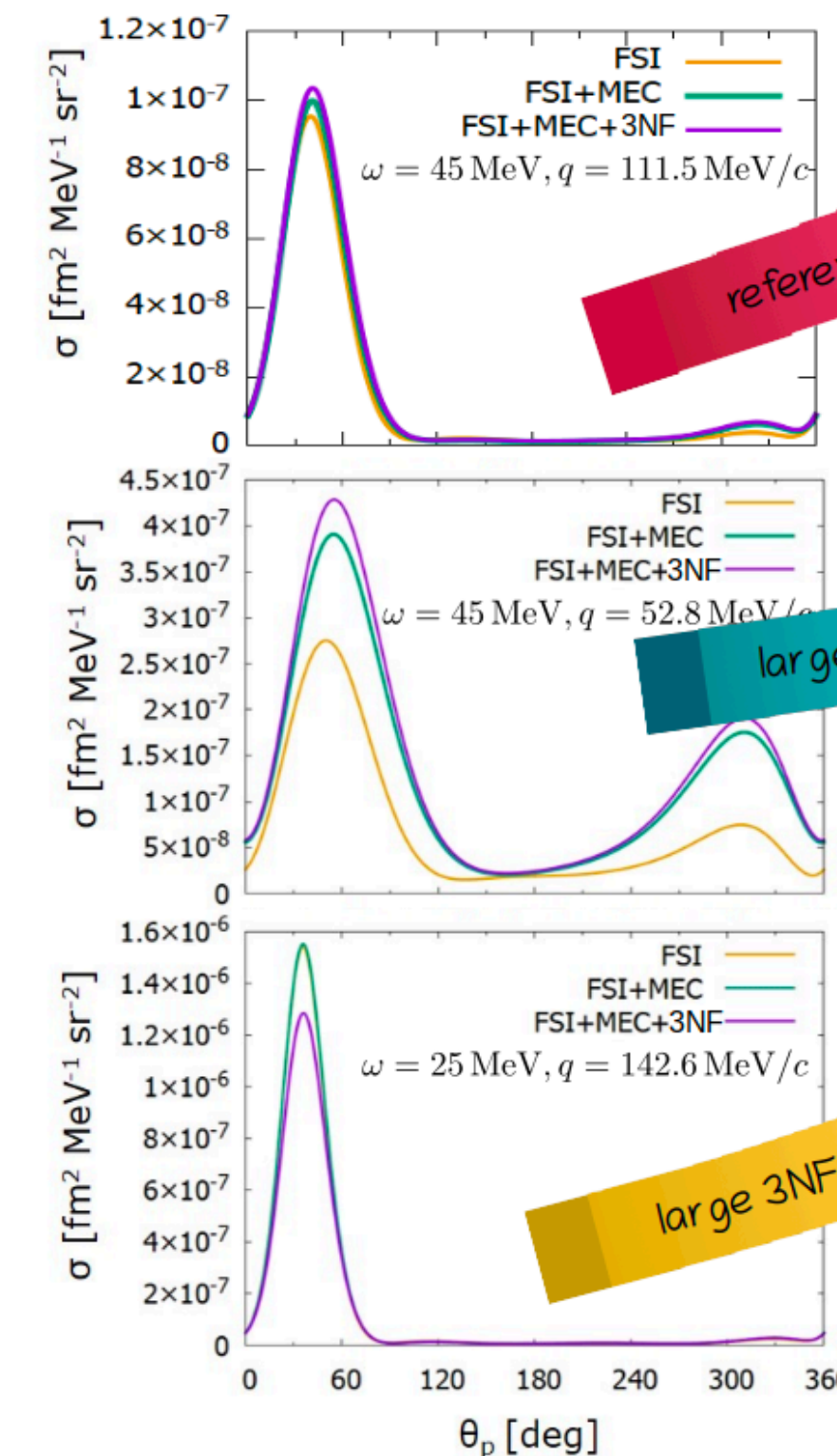
Few-Body Nuclear Physics

Perform inclusive and exclusive cross section measurements on few-body systems for precisely investigate the effect of MECs and test modern nuclear potential models (3-body forces).

inclusive measurements, ${}^4\text{He}(e,e')$



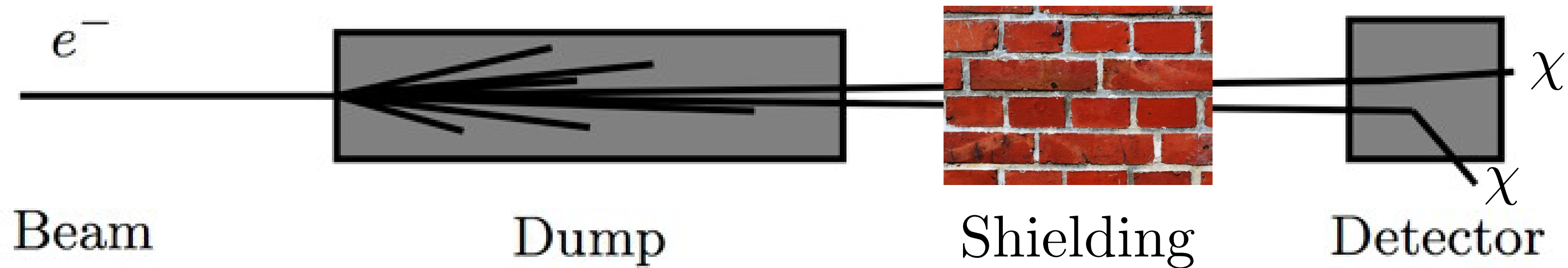
exclusive measurements, ${}^3\text{He}(e,e'p)d/{}^3\text{He}(e,e'd)p$



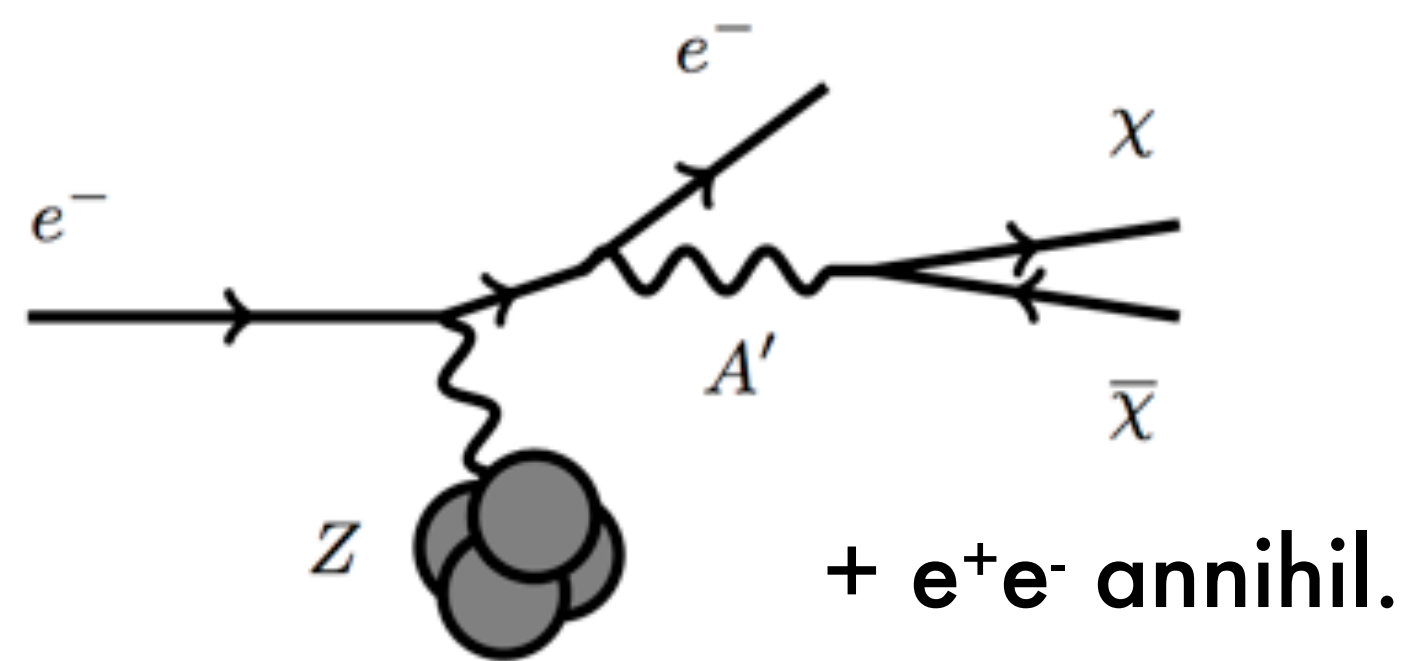
DarkMESA

DarkMESA

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



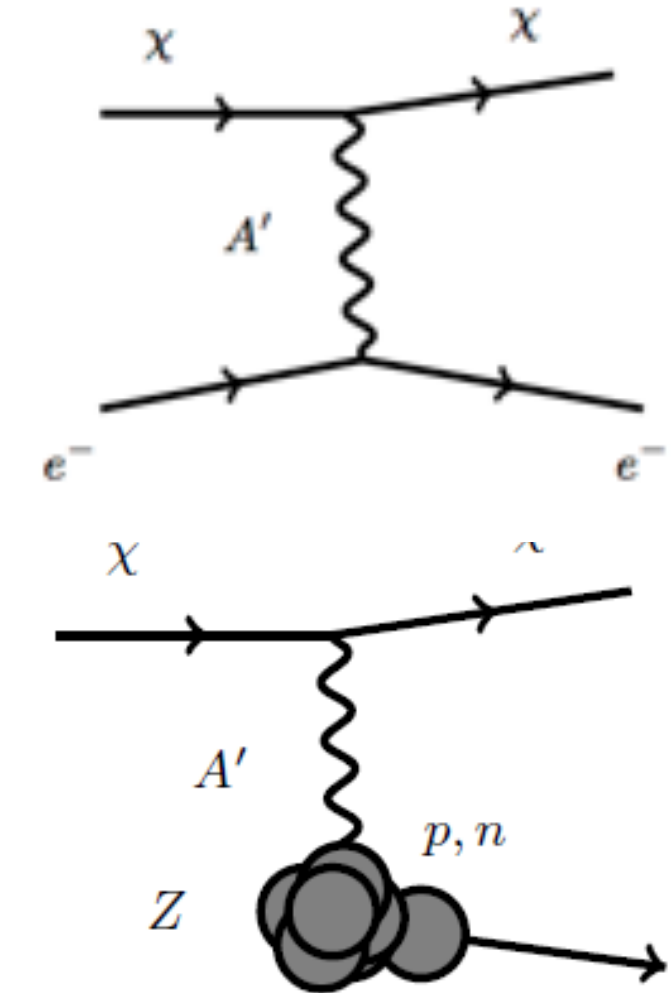
Production



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

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

Detection



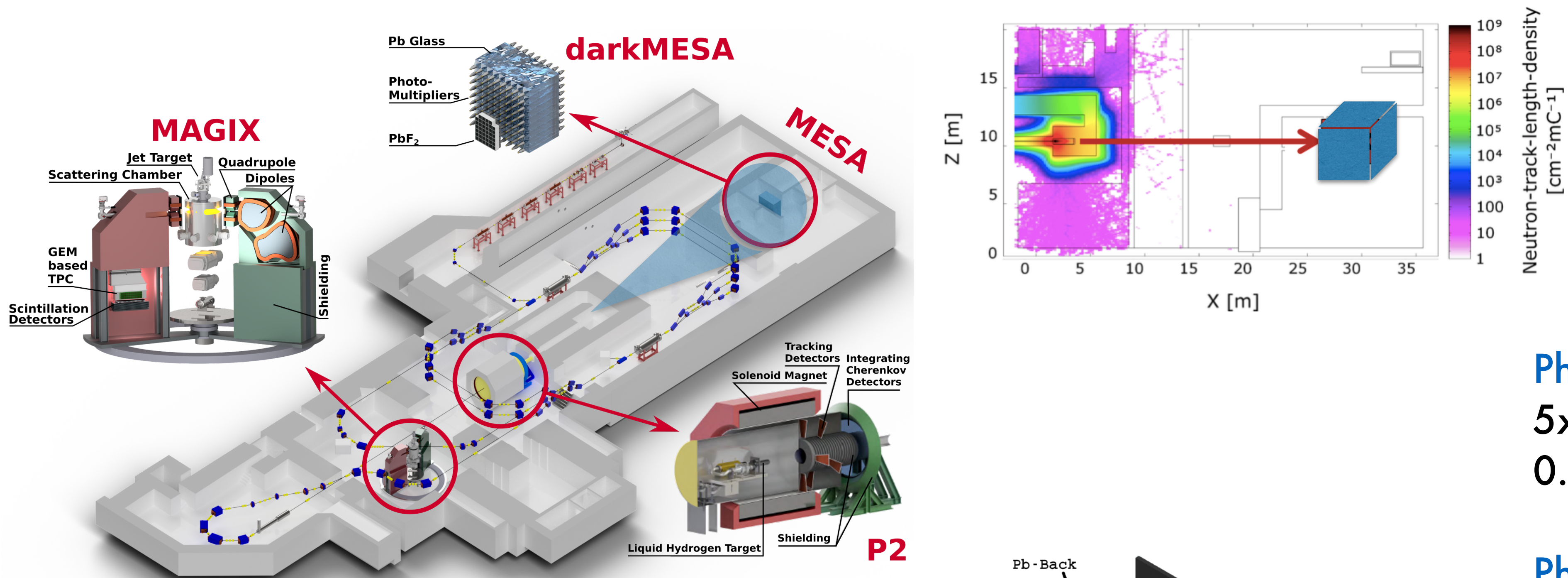
Total Yield

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

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

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

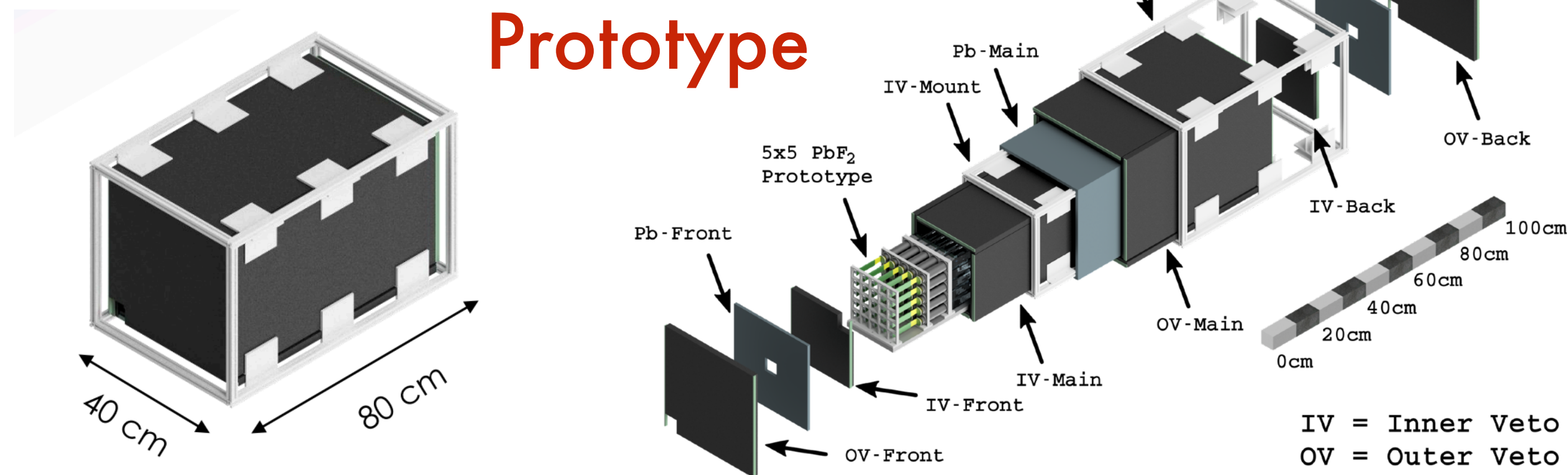
DarkMESA



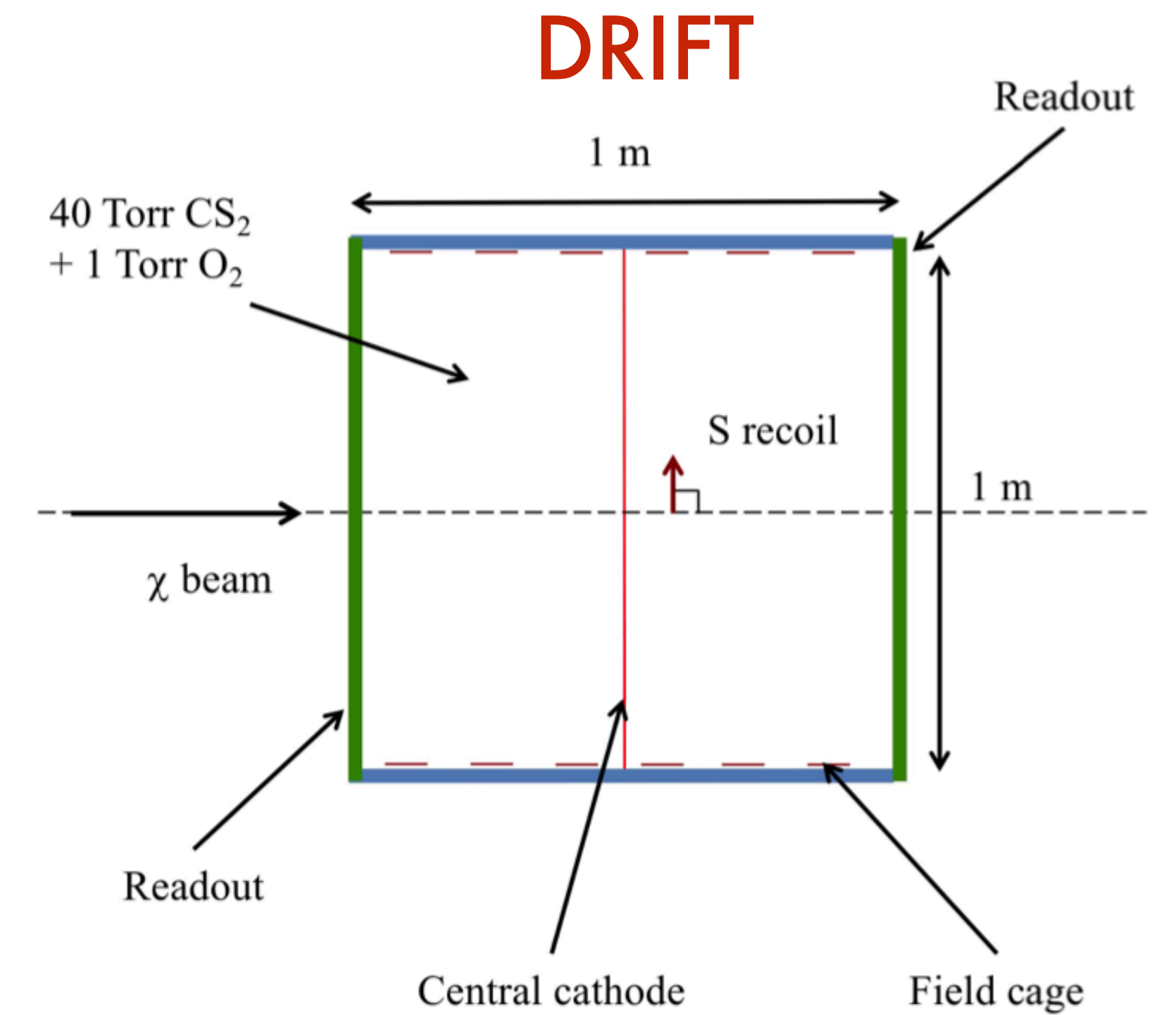
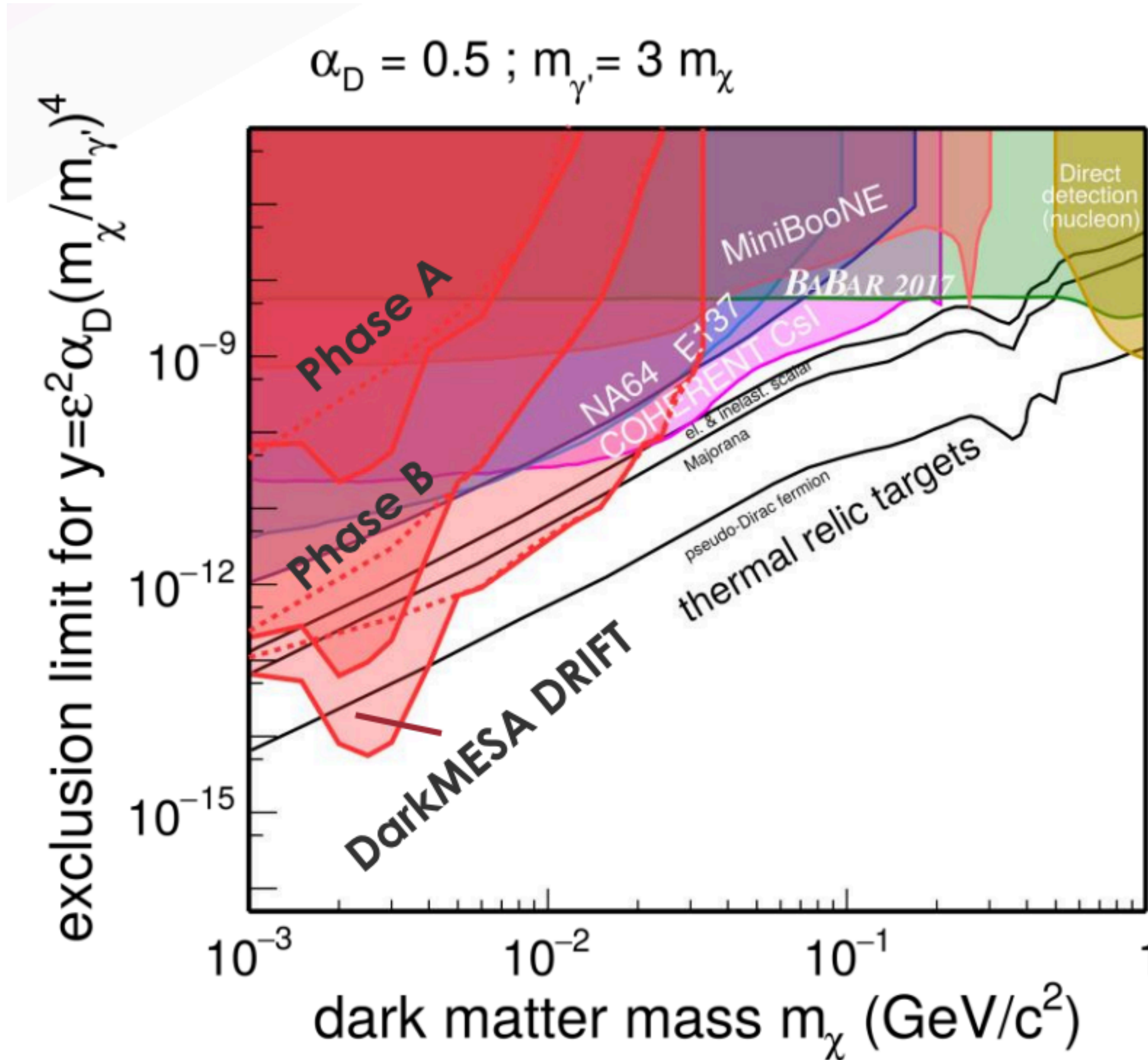
Phase A: Prototype
5x5 PbF₂ crystals
0.04 m³ volume

Phase B:
PbF₂ + SF₅ calorimeter
~1000 + ~1000 crystals
>1 m³ volume

Phase C: TBD..(DRIFT?)



Dark Photons at DarkMESA: Projections



- * Negative Ion TPC
- * 40 Torr $\text{CS}_2 + \text{O}_2$
- * ~ 20 keV threshold
- * Directionality

Snowden-Ifft et al., [arXiv:9904064](https://arxiv.org/abs/9904064)

Summary

- * **MESA: Superconducting energy recovery electron accelerator**
 - High current CW operation
 - 3 Experiments
- * **MAGIX:**
 - Very flexible setup
 - Rich experimental program
 - Unique: high current + jet target
- * **Contributions to DM searches, hadron, and nuclear (astro)physics**
- * **DarkMESA: opportunity detector, parasitic operation with P2.**

Thank you for your attention!

