Light Dark Matter searches at MAGIX

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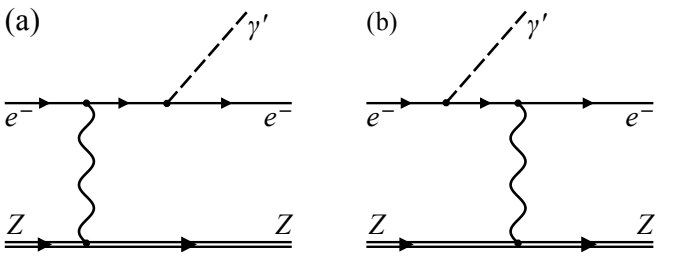
Light Dark Matter at Accelerators 2025
Genova, April 9th, 2025

- Motivation
  - Resolution rules!
- The MESA Accelerator
  - New low energy machine
  - Energy Recovery Linac
- The MAGIX Setup
  - High-resolution spectrometers
  - Internal gas-jet target
- LDM possibilities at MAGIX
  - Visible decay
  - Invisible decay
  - Displaced vertex

History (2015): LDM search with Magnetic Spectrometers

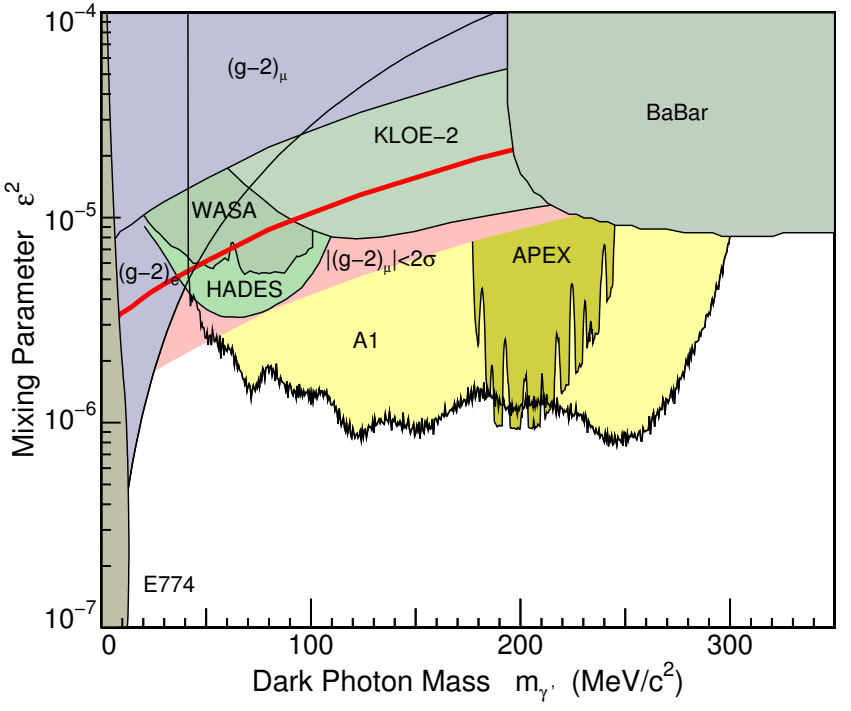
- Search for a radiative produced dark photon



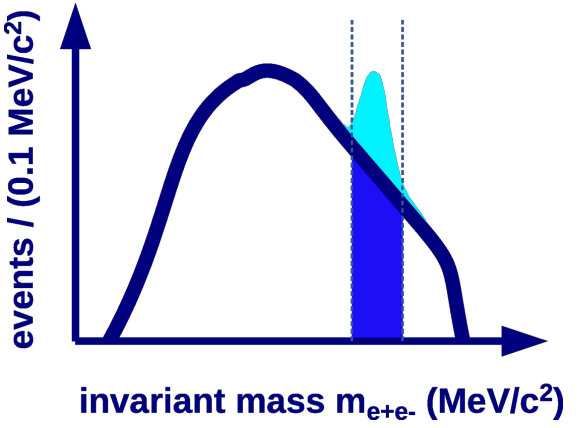
- Signature: Radiative decay

$$e + Z \rightarrow e + Z + \gamma' \hookrightarrow e^+ + e^-$$

- Search for a peak in e^+e^- mass spectrum:



Bump Hunt: looking for a peak



Statistical Significance:

- Width of decay negligible (small coupling!)
- Background well known (QED)
- Bin width $\sim$ mass resolution $\sigma_{m(e^+e^-)}$

$$\frac{\sigma(\text{Signal})}{\text{Background}} \sim \frac{\sigma_{m(e^+e^-)}}{\sqrt{L \cdot t \cdot \Delta\Omega}}$$

- Resolution dominates over luminosity, run time, acceptance

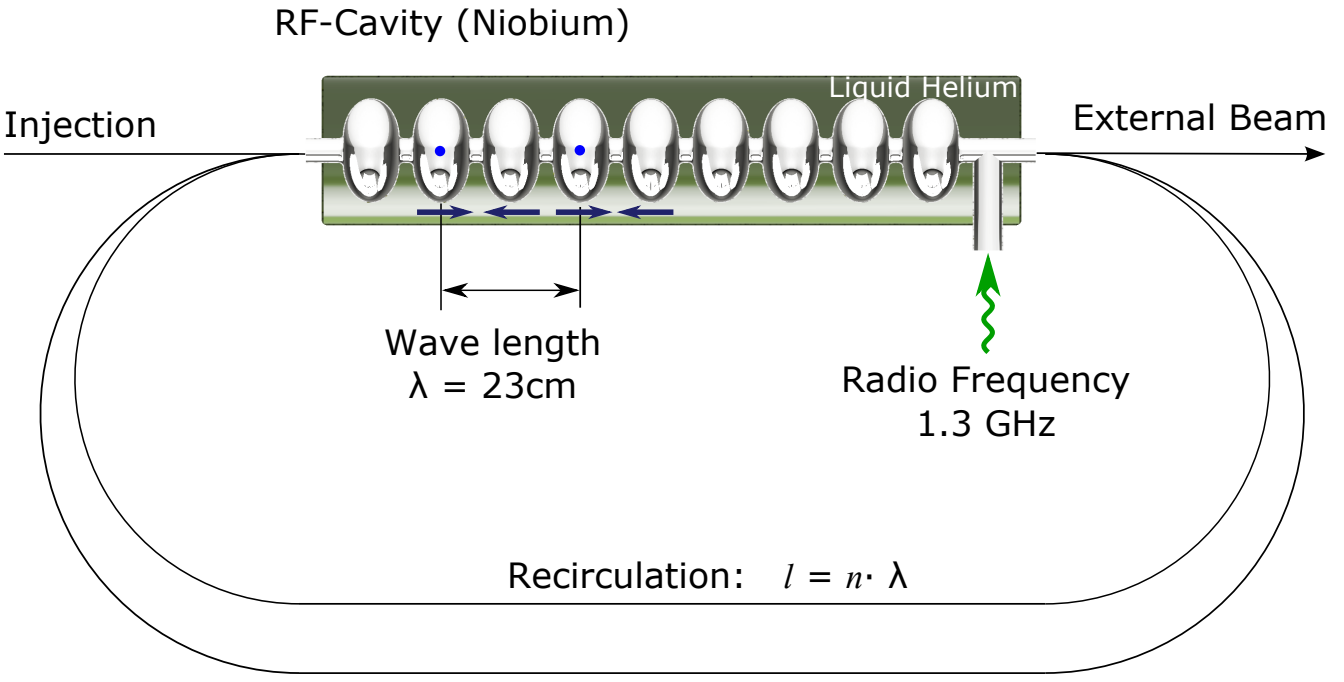
Spectrometer: $\frac{\delta p}{p} = 10^{-4}$

4π-Detector: $\frac{\delta p}{p} = 10^{-2}$

(Caveat: mass resolution $\neq$ momentum resolution!)

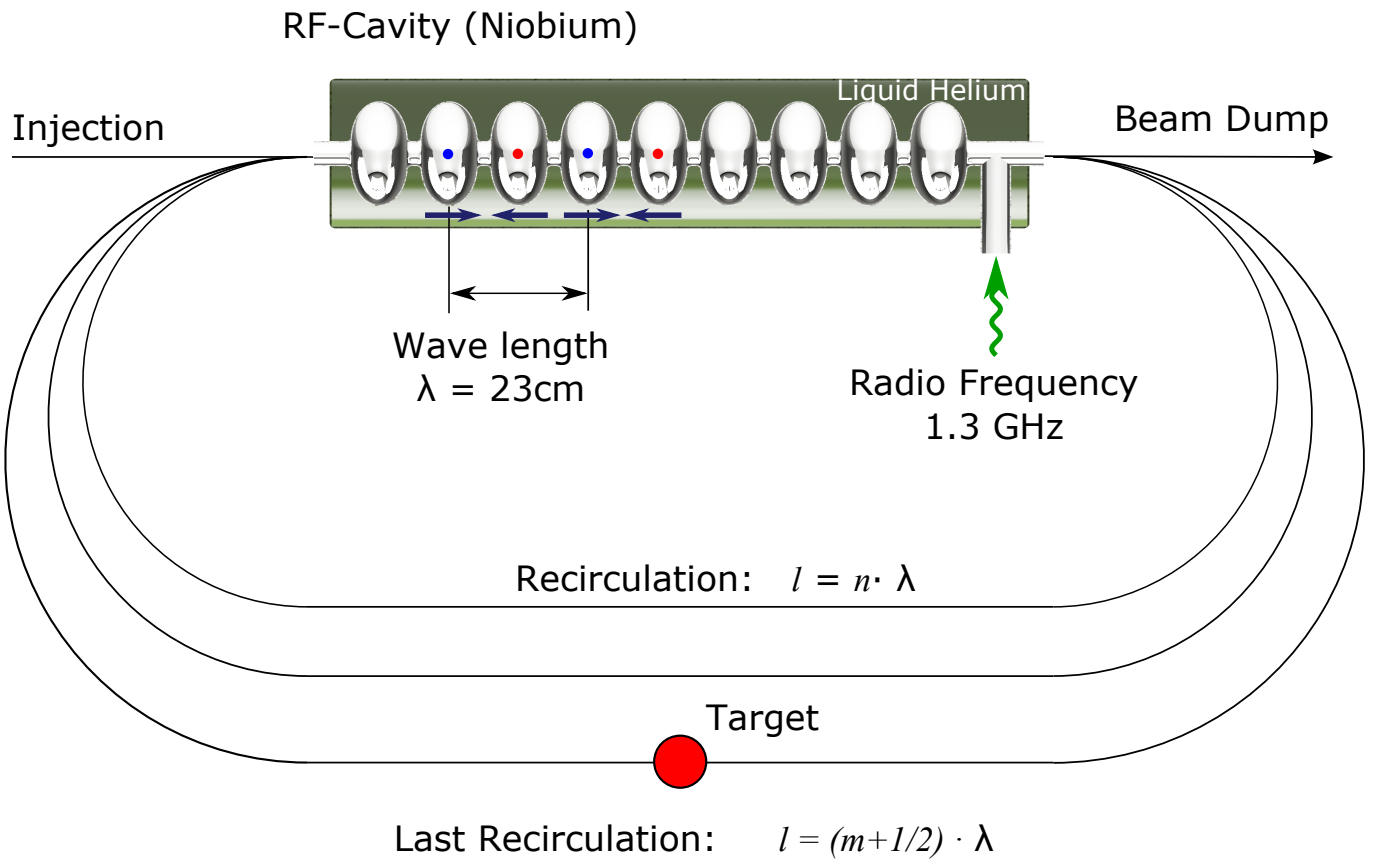
- But for **Light**DMA: **high resolution is difficult at low energies!**

Energy Recovery Linac - Idea



- Recirculating Linear Accelerator $\rightarrow$ increase beam *energy*

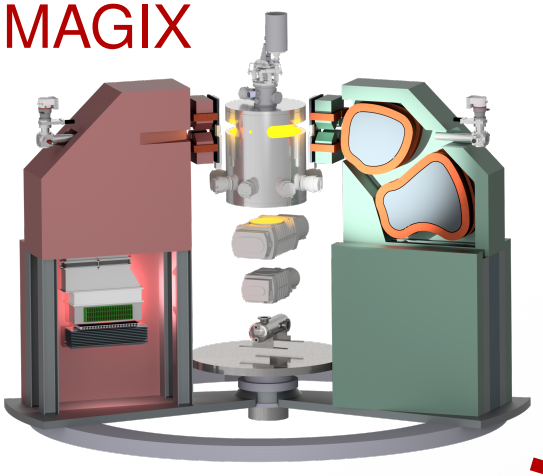
Energy Recovery Linac - Idea

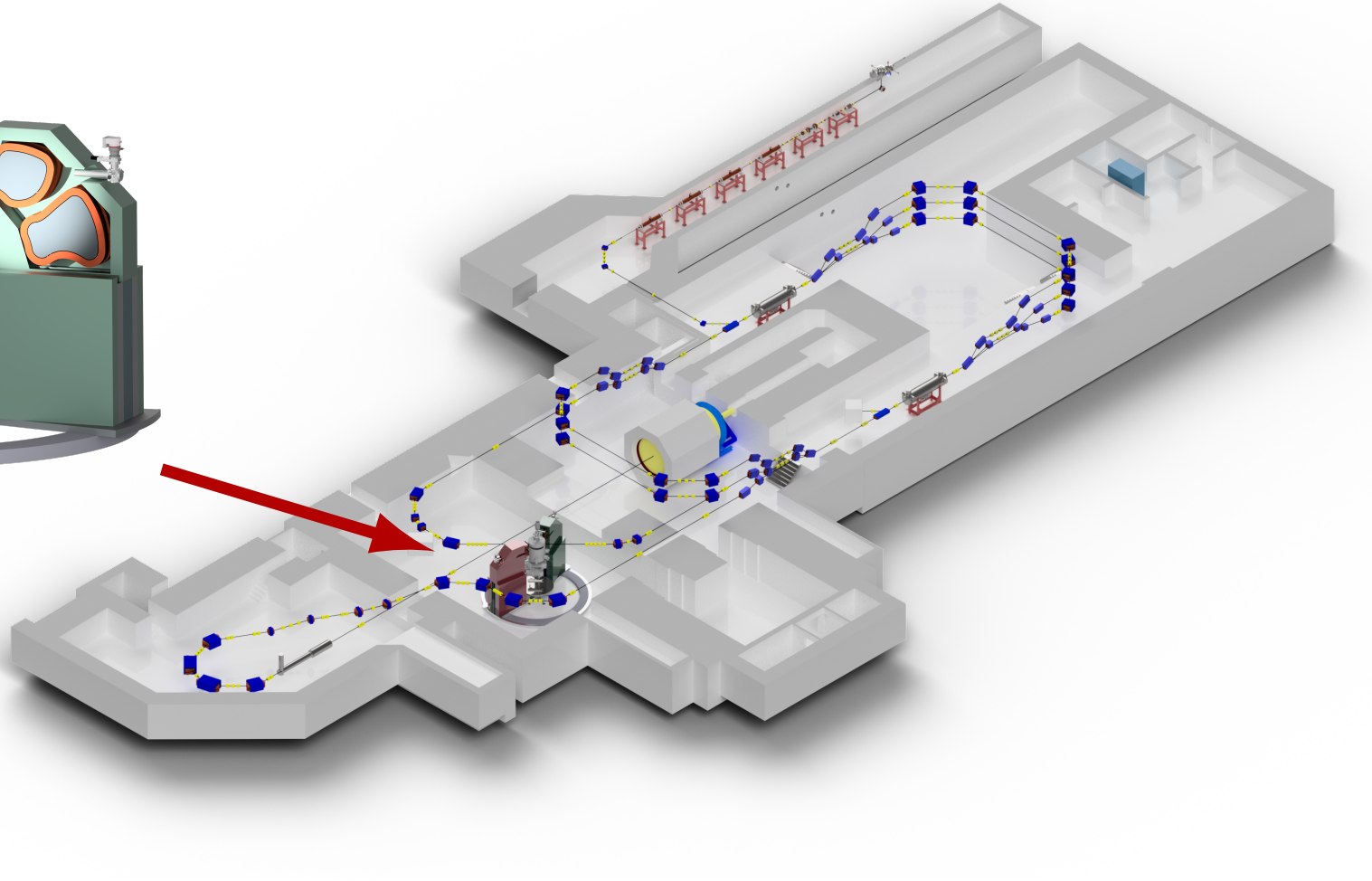


- Recirculating Linear Accelerator $\rightarrow$ increase beam *energy*
- Last return path: $l = (m + \frac{1}{2})\lambda \rightarrow 180^\circ$ Phase shift
- Energy feed back to cavities $\rightarrow$ increase beam *current*

MESA - Mainz Energy Recovery Superconducing Acclerator

MAGIX





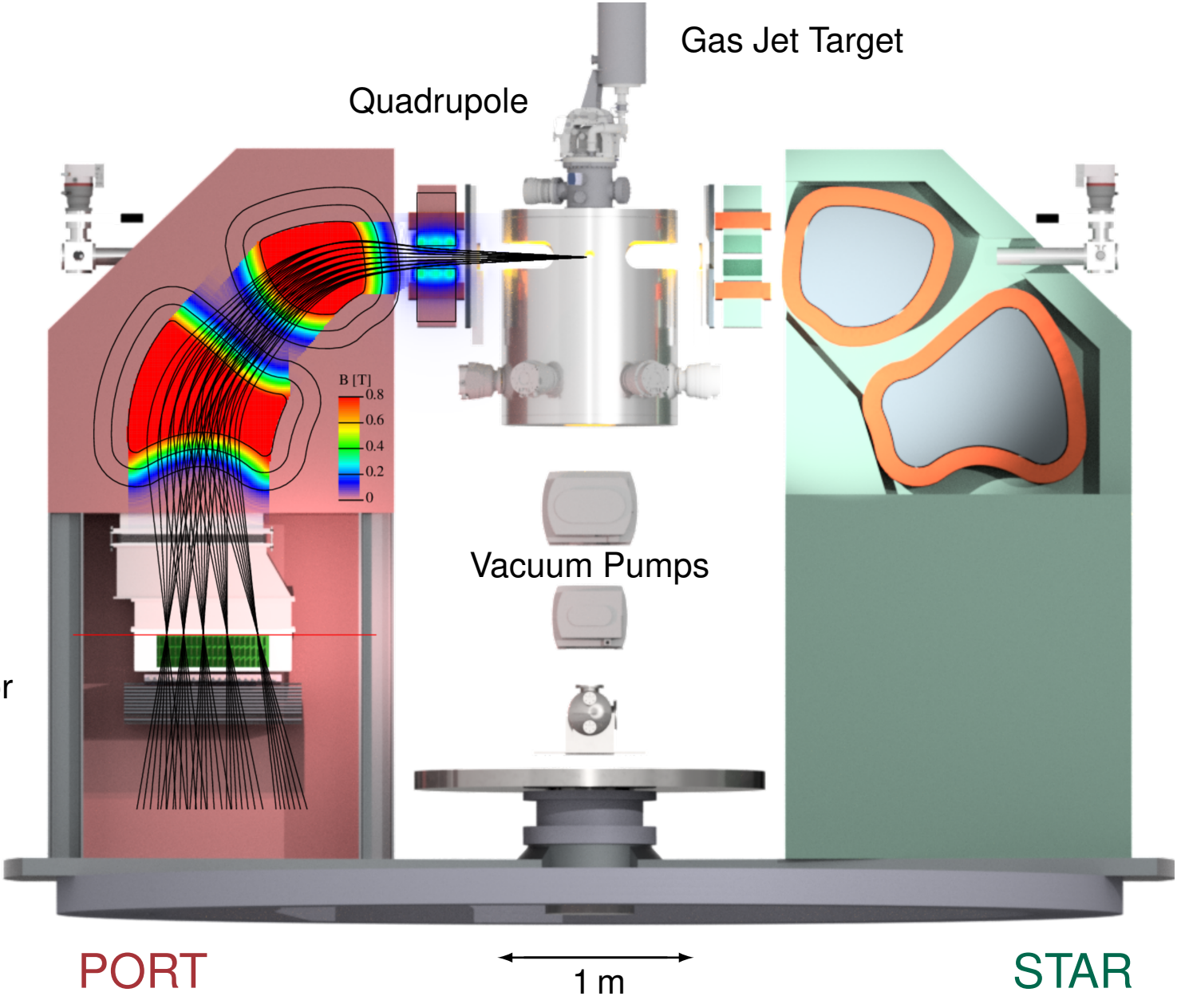
- Super-conducting, recirculating LINAC in ENERGY RECOVERY MODE
  - Energy of up to 105 MeV
  - High beam current (up to 10 mA)
  - Large fraction of the beam can be used for an INTERNAL target

MAGIX - MAinz Gas Injection Target EXperiment

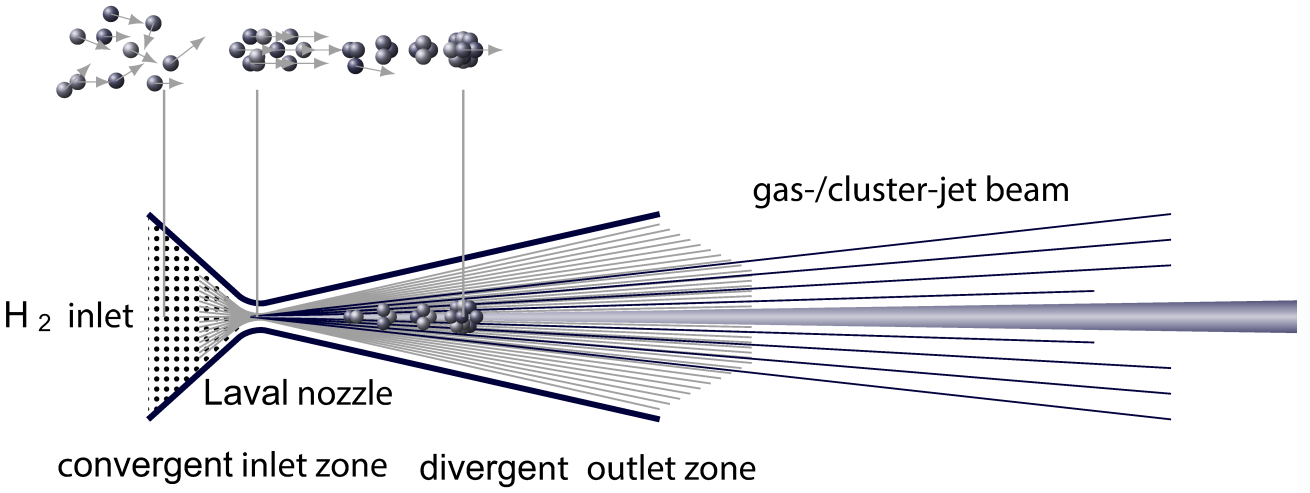
2× Dipole
90° Bending

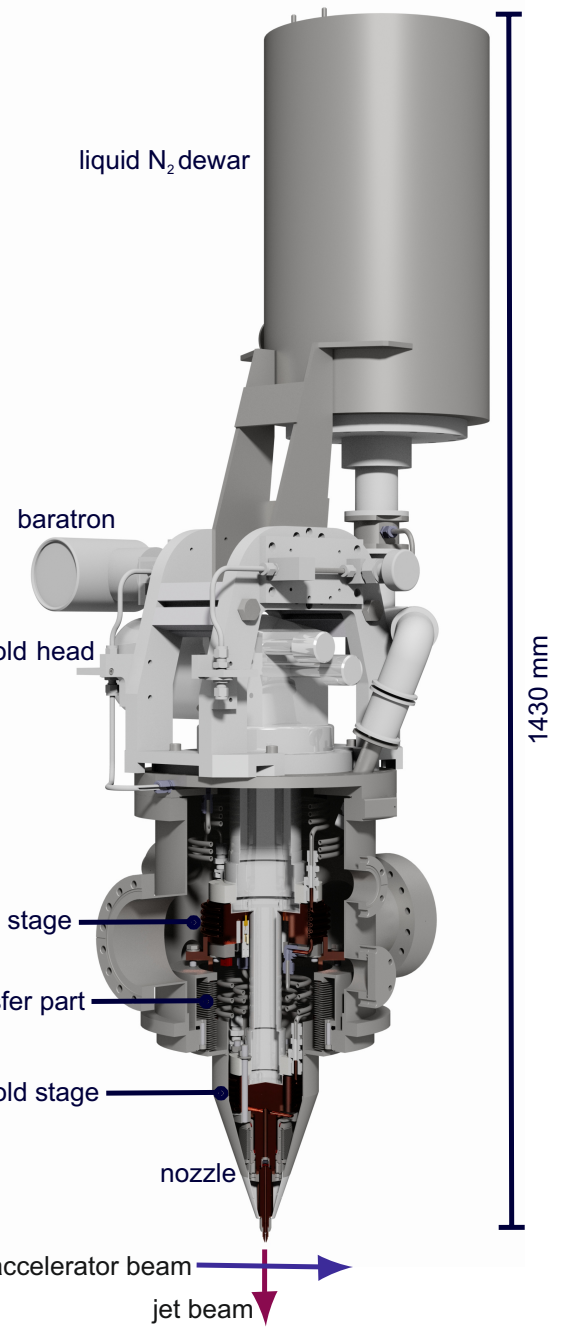
$$\frac{\delta p}{p} < 10^{-4}$$

GEM based TPC
Scintillator Detector
Muon Veto



Supersonic Gas-Jet Target

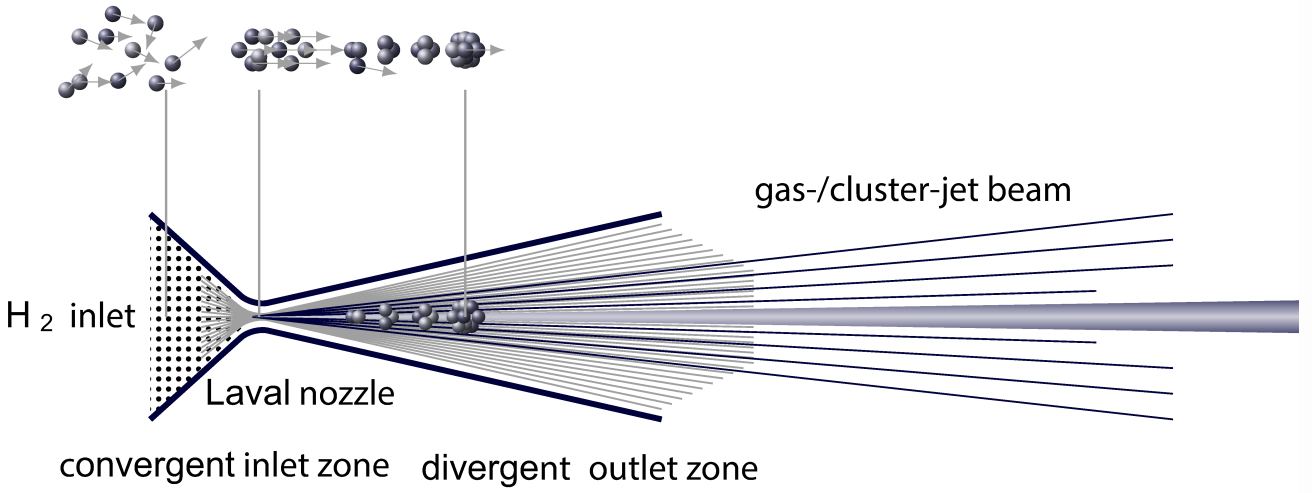


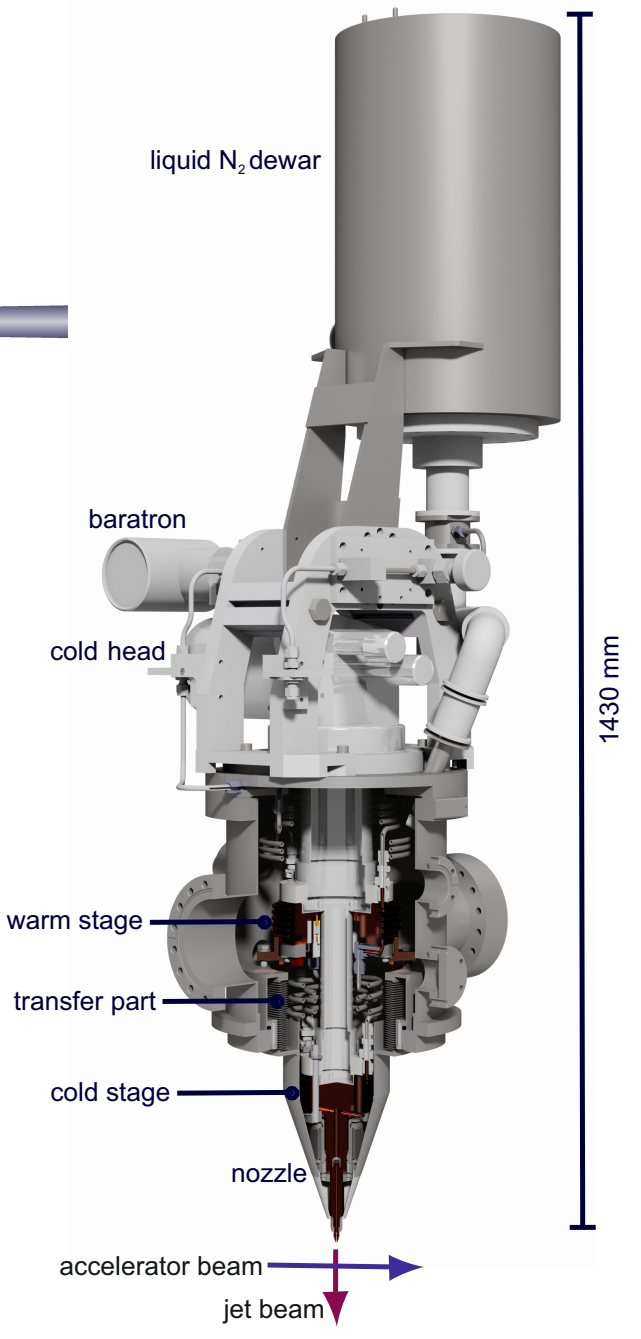


- Laval Nozzle
- Supersonic Gas-Jet
- Temperature drops below freezing point
- Massive Clusters ($\approx$ 10000 atoms)
- 10^{18}Particles/cm^2
- Windowless, pointlike target, negligible Multiple Scattering

AG A. Khoukaz (Univ. Münster)
S. Grieser *et al.*, NIM A 906 (2018) 120

Supersonic Gas-Jet Target





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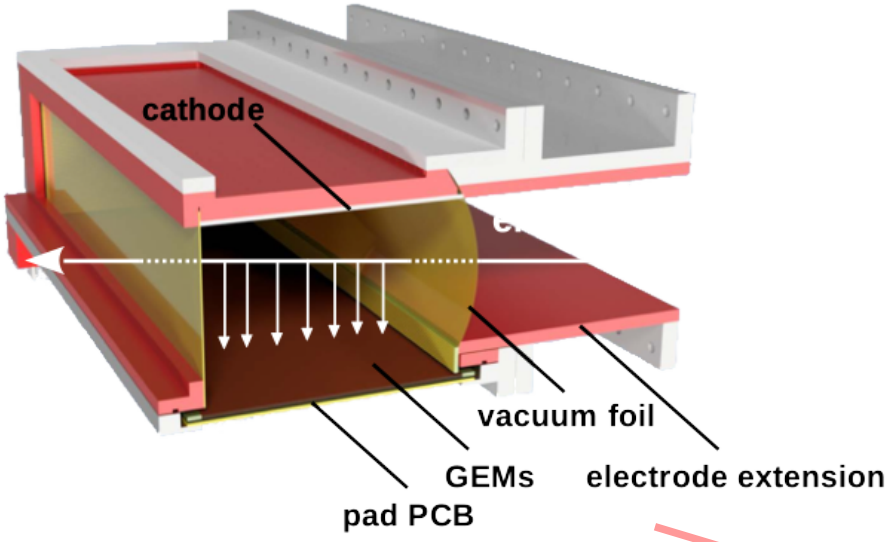
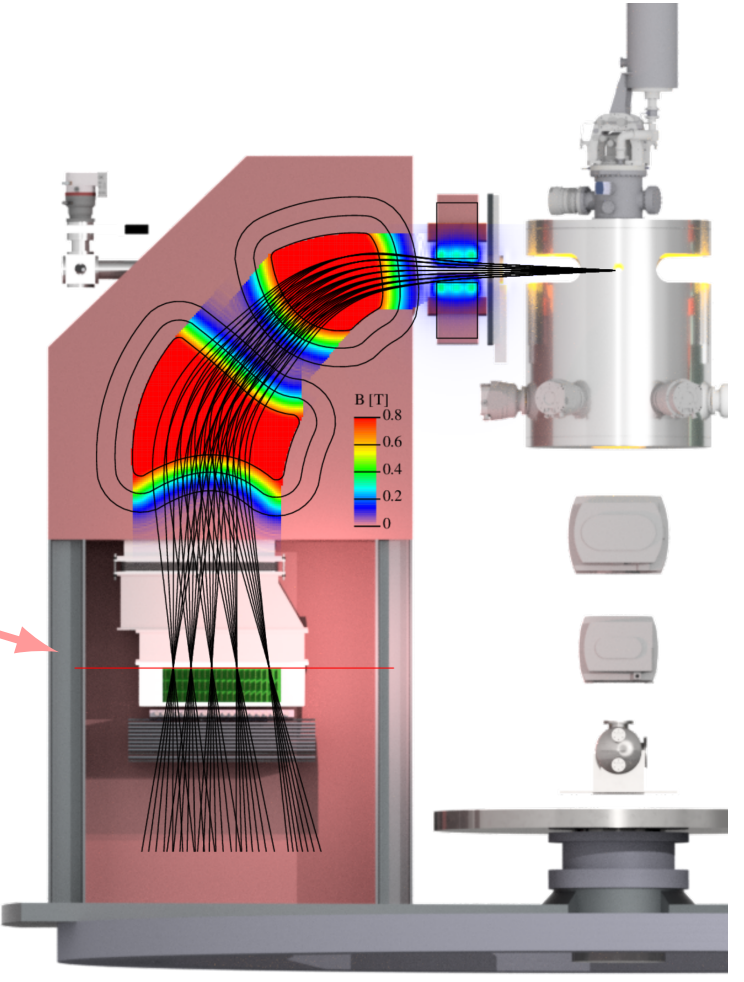
Minimal Material Budget

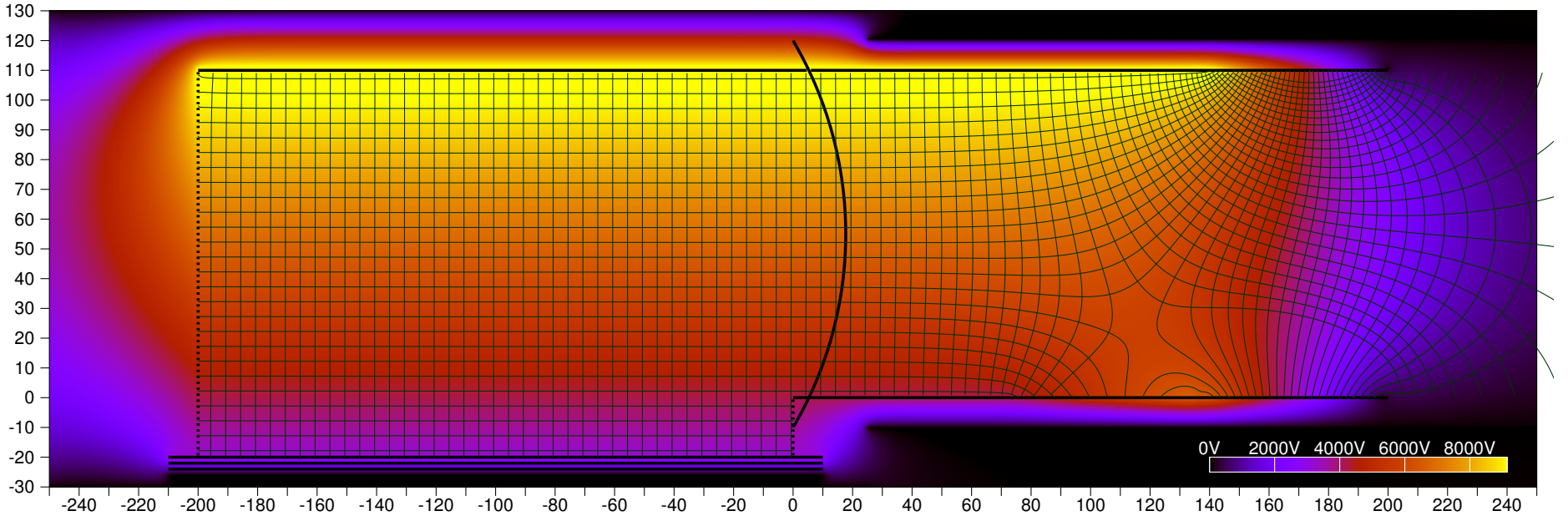




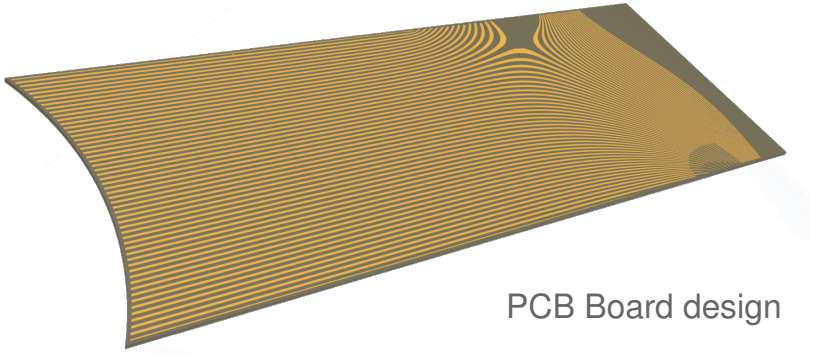
Focal plane tracking detector:

- Time projection chamber
- GEM readout plane
- Vacuum down to focal plane
- Total material budget: 75 μm Kapton (0.26% X_0)
- Open field cage

Open Field Cage



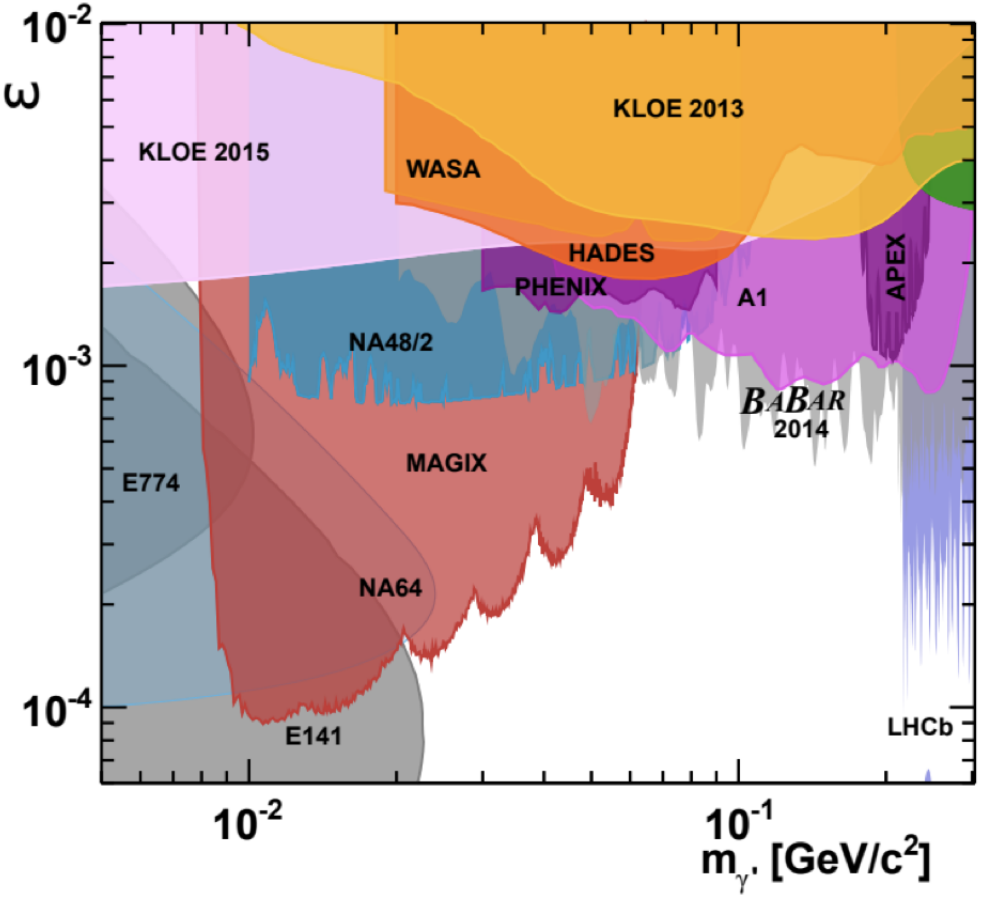
- Vacuum Exit-foil defines Multiple Scattering
- Argon - CO_2 Sensitive Volume
- No field forming wires for entering particle tracks
  - Extension of field into vacuum box
  - Controlled reduction to ground level
  - Numerical optimized field to homogenize active volume
  - Field-shaping PCBs
- **Count rates up to MHz!**



PCB Board design

Expected Limits for dark Photons

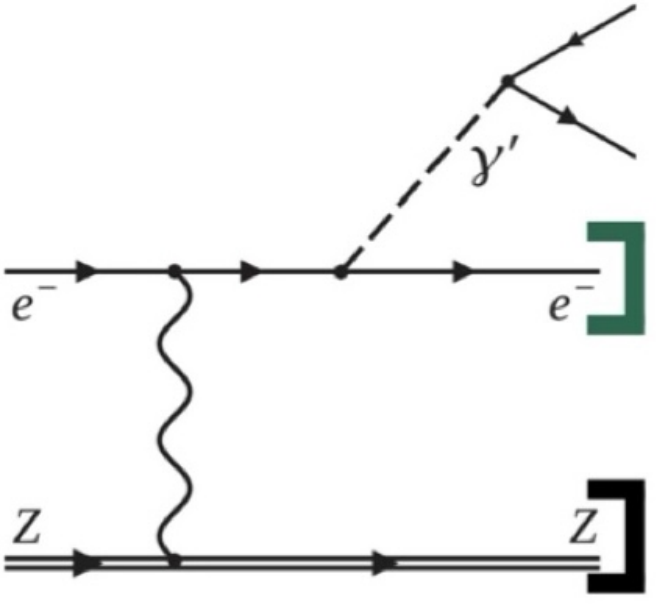
- Simultion with full QED background

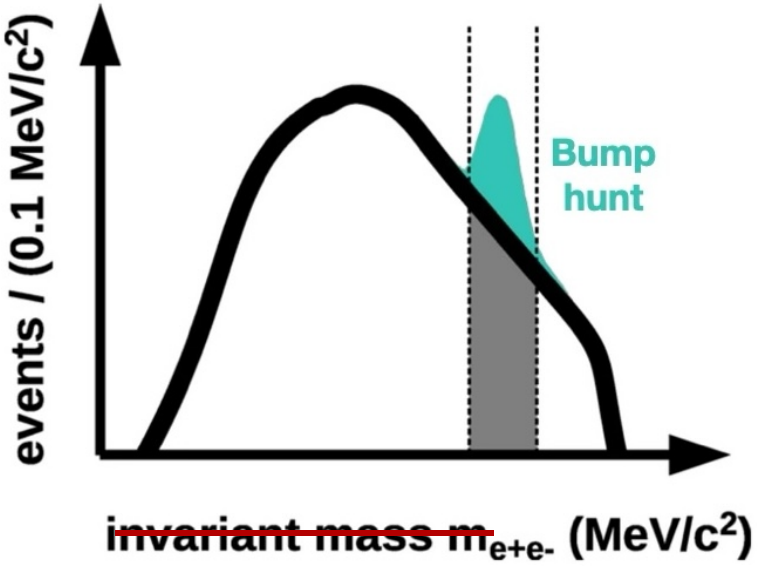


- Order of magnitude more sensitivity at low masses
- One of the first experiments at MAGIX!

Invisible Decay

Mass of DM particles $< m_{\gamma}/2$ $\Rightarrow$ Invisible Decay into DM particles



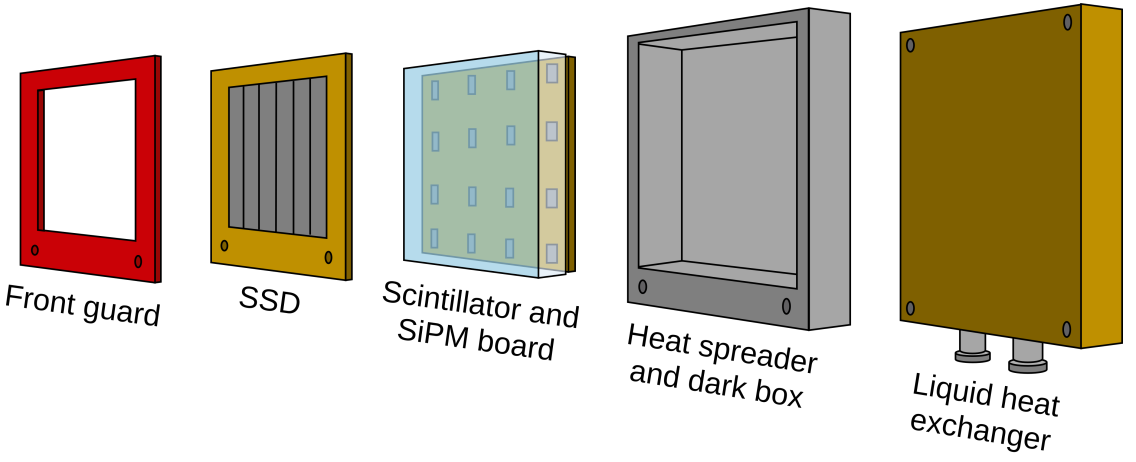


Missing Mass

- Detection of electron and **recoil particle**
- Peak in Missing Mass $m(e + m_{\text{target}} - e' - p_{\text{recoil}})$
- E.g. proton target
- At this energy: only electrons can be detected with high resolution in spectrometers

$\Rightarrow$ Additional recoil detector neccessary

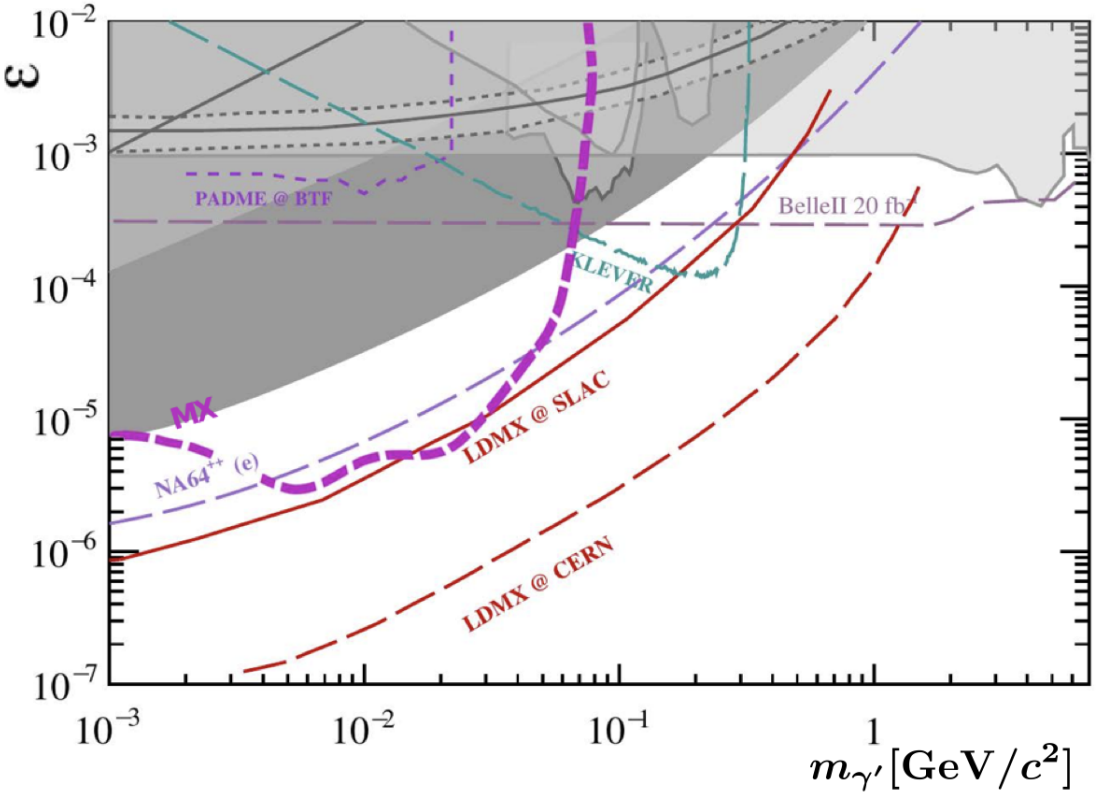
Silicon Strip Detectors

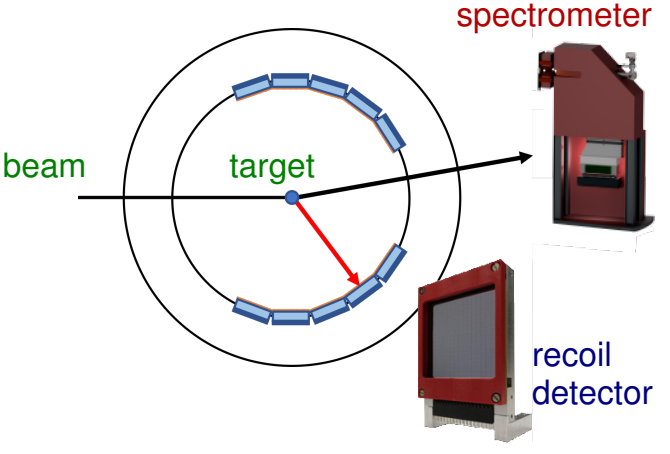


→

- Silicon strip detectors 5 cm × 5 cm
- NO material beween reaction vertex and detection volume
- Horizontal resolution by stripes, vertical by two-sided readout
- Cooled, stack with scintillator
- High angular resolution ⇒ high missing mass resolution
- Streaming readout ⇒ high count rate close to target
- Radiation: will die after a few weeks, but still affordable...

Invisible Decay



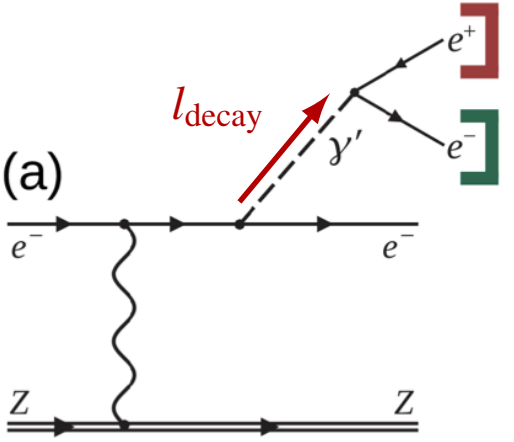


- Full QED Simulation of signal, QED-Background
- Proton (H) or Helium gas jet target
- Array of Silicon recoil detectors
- Background: Radiative tail, virtual Compton Scattering *etc.*

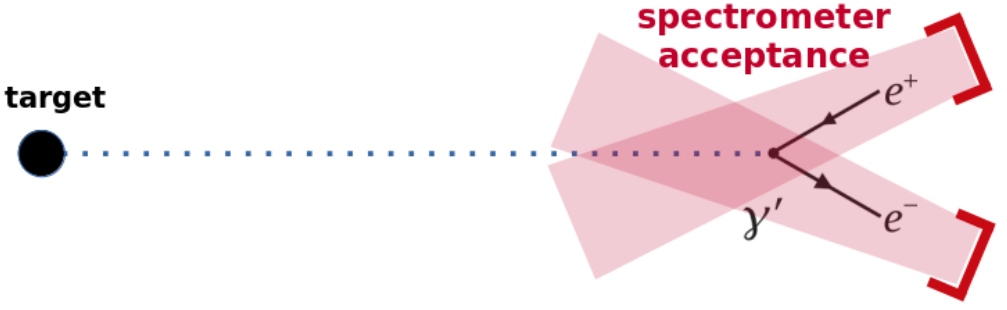
Displaced Vertex

Decay Length:

$$l_{\text{decay}} \approx 1.5\,\text{mm} \left(\frac{E_{\text{beam}}}{55\,\text{MeV}}\right) \cdot \left(\frac{10^{-4}}{\varepsilon}\right)^2 \cdot \left(\frac{17\,\text{MeV}/c^2}{m_{\gamma'}}\right)^2$$



Vertex resolution of MAGIX $\approx 0.1\,\text{mm}$



- Target length acceptance $\approx 10\,\text{mm}/\sin\theta$
- Low mass $\Rightarrow$ large angles
- Target upstream, outside of acceptance, $\approx 8\,\text{mm}$
- Fixed high Z target foil (no gas background, resolution is target-independent!)
- Background conditions will define the limit

Summary

- MESA: a new accelerator for precision physics
  - Energy recovery mode for MAGIX
  - High internal current
  - Enables low density targets
- MAGIX
  - High resolution spectrometers
  - Optimized for low energy measurements
  - High count rate capability
- LDM possibilities at MAGIX
  - Visible decay at low masses: *High resolution at low energies*
  - Invisible decay: *Recoil detector with high missing mass resolution*
  - Displaced Vertex: *Spectrometer optics gives spacial resolution*

MAGIX – What else...

Hadron Structure

Topic	Reaction	Jet	Observables
p Formfactor	$H(e,e')p$	H	$G_E(Q^2)$, $G_M(Q^2)$, r_E, r_M
d Formfactor	$D(e,e')d$	D	$A(Q^2)$, $B(Q^2)$, r_d
^{3}He Formfactor	$^3\mathrm{He}(e,e')^3\mathrm{He}$	^{3}He	r_E
^{4}He Formfactor	$^4\mathrm{He}(e,e')^4\mathrm{He}$	^{4}He	r_E

Few-Body Systems

d Breakup	$D(e,e'p)$	D	$\mathrm{d}\sigma/\mathrm{d}\Omega$, polarizabilities
^{3}He inclusive	$^3\mathrm{He}(e,e')$	^{3}He	Structure functions, R_L
^{4}He inclusive	$^4\mathrm{He}(e,e')$	^{4}He	Structure functions, R_L
^{4}He monopole	$^4\mathrm{He}(e,e')^4\mathrm{He}^*$	^{4}He	Transition Formfactors $E(^4\mathrm{He}^*)$, $\Gamma(^4\mathrm{He}^*)$
^{16}O inclusive	$^{16}\mathrm{O}(e,e')$	^{16}O	Structure functions, R_L
^{40}Ar inclusive	$^{40}\mathrm{Ar}(e,e')$	^{40}Ar	Structure functions, R_L
^{3}He exclusive	$^3\mathrm{He}(e,e'p/d)d/p$	^{3}He	$\mathrm{d}\sigma/\mathrm{d}\Omega$
^{4}He exclusive	$^4\mathrm{He}(e,e'p/d)$	^{4}He	$\mathrm{d}\sigma/\mathrm{d}\Omega$

Dark Sector

Leptonic Decay	$Ar(e,A' \rightarrow e^+e^-)$	^{40}Ar, Xe	Lepton pair mass $m_{A'}$ peak search
Invisible Decay	$p(e,e'p)A'$	H	Missing mass $m_{A'}$ peak search

Astrophysical Reactions

S-Factor Phase 1	$^{16}\mathrm{O}(e,e'\alpha)^{12}\mathrm{C}$	^{16}O	$S_{E1}(E)$, $S_{E2}(E)$
S-Factor Phase 2	$^{16}\mathrm{O}(e,e'\alpha)^{12}\mathrm{C}$	^{16}O	$S_{E1}(E)$, $S_{E2}(E)$


CIAT
The central idea behind the MAGIX experiment

Thank you for your attention!