DarkMESA –
Light Dark Matter Search
at the MESA Beam Dump

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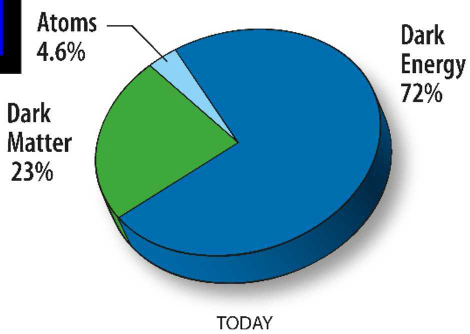
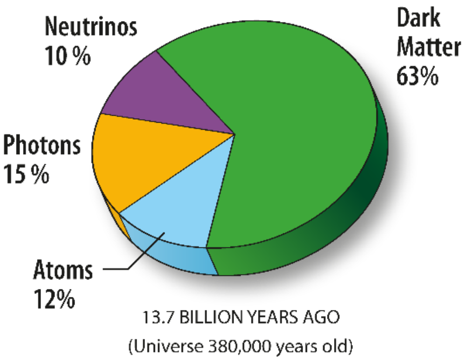
Dark Matter Properties





Matter content of the known Universe:

- Dark matter: ~23 %
- Dark energy: ~72 %
- Atomic matter: ~5 %
- Light neutrinos: ~0.1 %

Unknown DM properties:

- Weakly charged (WIMP) or not?
- E.-m. (milli?)-charged or not?
- Hidden sector existing or not?
- Portal existing or not?
- Darkly charged or not?
- Weak-scale mass or not?

Known DM properties:

- Gravitationally interacting
- Not short-lived
- Not hot
- Not baryonic

Early Universe Thermal DM Freeze-Out

(1) Assume a new heavy particle *X* is initially in thermal equilibrium:

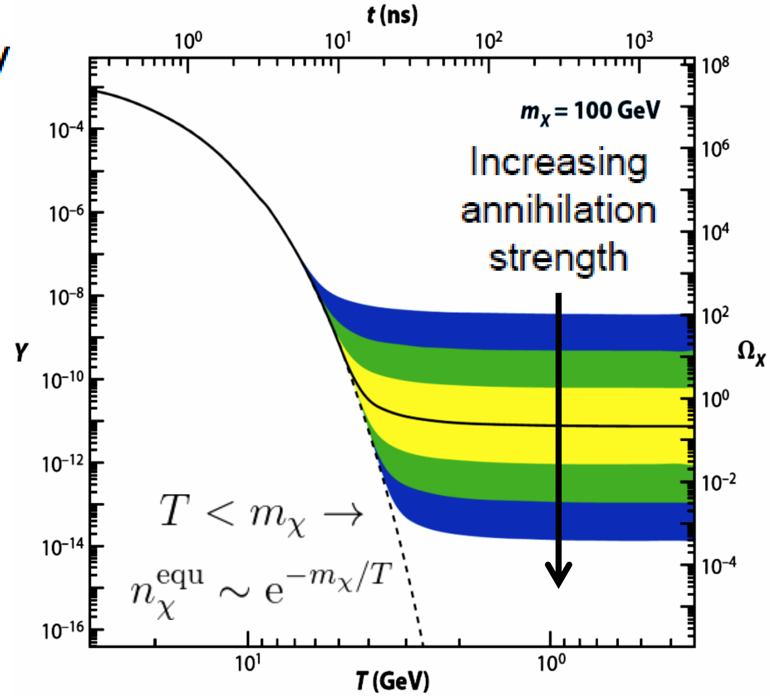
$$XX \leftrightarrow \bar{q}q$$

(2) Universe cools:

$$XX \;\substack{\rightarrow \\ \not\leftarrow}\; \bar{q}q$$

(3) Universe expands:

$$XX \;\substack{\not\rightarrow \\ \not\leftarrow}\; \bar{q}q$$



Freeze-out relation:
$\Omega_{\mathrm{DM}} \leftrightarrow$ annihilation rate

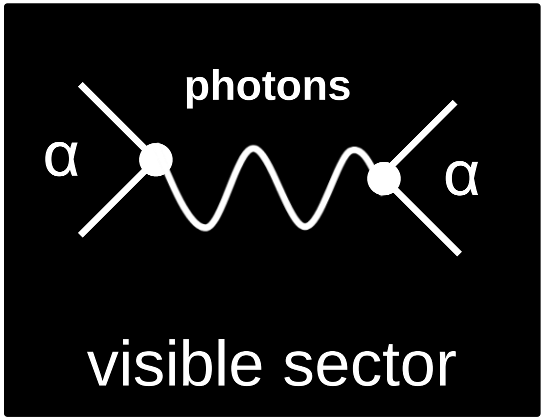
$$\Omega_{\mathrm{DM}} \approx \frac{2\times10^{-37}\mathrm{cm}^2}{\langle\sigma_{\mathrm{annih}} v\rangle} \approx 0.23$$

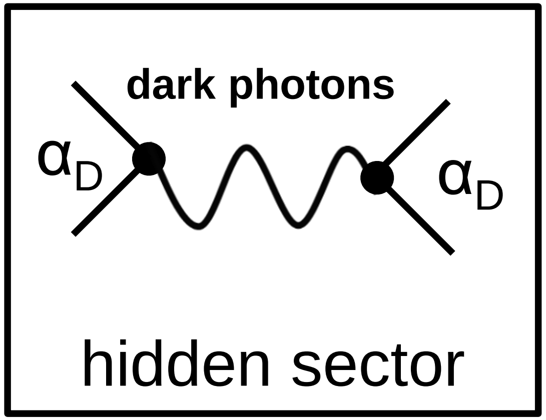
[Feng: Annu. Rev. Astron. Astrophys 48, 495 (2010)]

$$\langle\sigma_{\mathrm{annih}} v\rangle \sim \frac{g^4}{2\pi m^2} \simeq 6\times10^{-37}\mathrm{cm}^2 \left(\frac{g}{0.1}\right)^4 \left(\frac{m}{100\,\mathrm{GeV}}\right)^{-2}$$

WIMP Paradigm: If stable WIMPs exist, they are naturally produced with a relic density consistent with the one required of dark matter

Interactions in a Hidden Sector

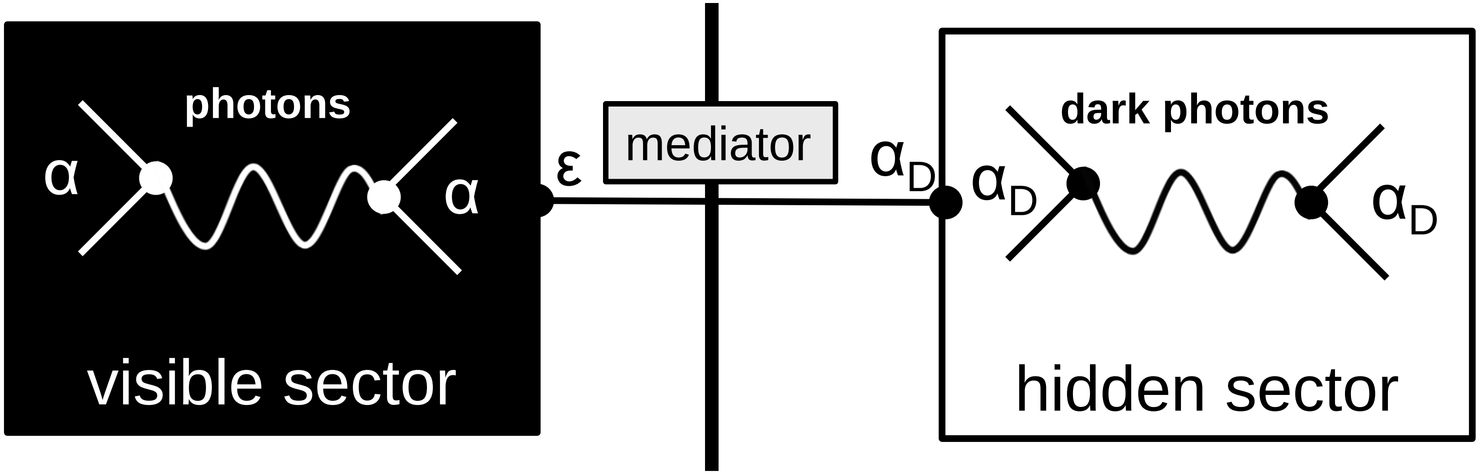




- Hidden sector composed of particles without SM interactions
- Many forms of hidden interactions seem conceivable
- The simplest form is an electromagnetism analogue
- Disclaimer: A dark sector with set of hidden interactions may seem an over-complicated solution to the dark matter problem

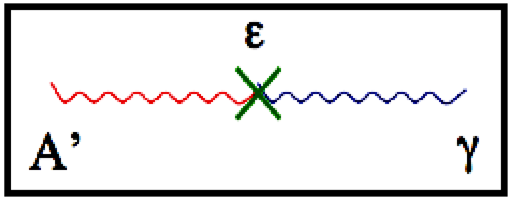
> *"Plurality must never be posited without necessity".*
> William of Ockham: *Sentences of Peter Lombard* (1495)

Mediators between Sectors

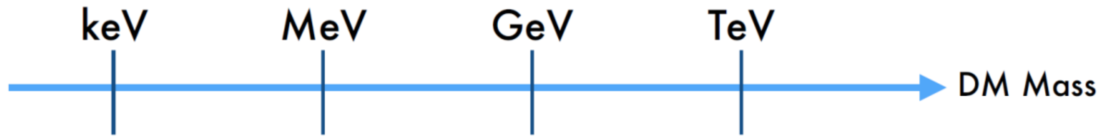


- Vector, Higgs, neutrino mediators in many BSM constructions
- Mediator typically is unstable (and not DM)
- Some aspects of this idea are testable and amenable to observations
- SM coupling via kinetic or mass mixing or with direct coupling

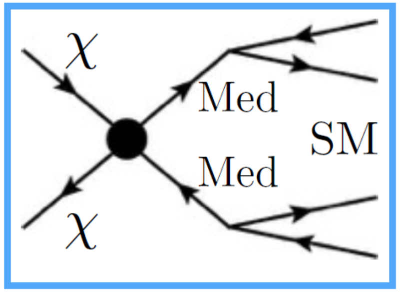
$$\mathcal{L}_{mix} = -\frac{\epsilon}{2} F^{QED}_{\mu\nu} F^{\mu\nu}_{dark}$$



Light Dark Matter Annihilation



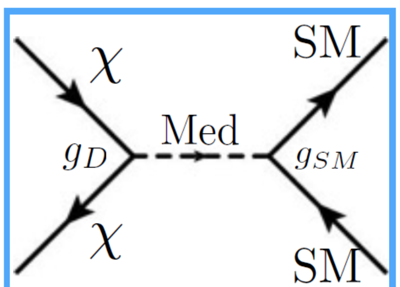
Secluded Annihilation



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

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

Direct Annihilation



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

There is a minimum SM coupling compatible with thermal history.

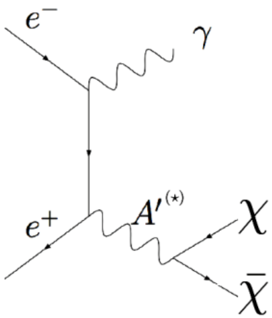
Experimentally testable target:

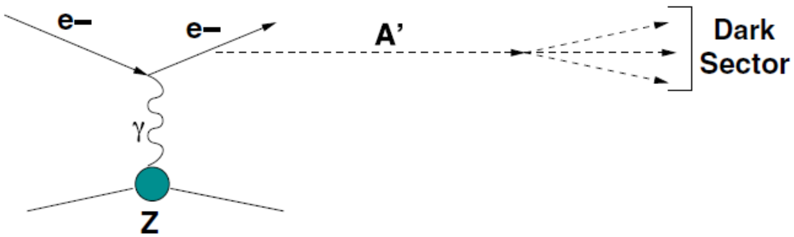
$$\boxed{y = \frac{g_D^2 g_{SM}^2}{4\pi} \left(\frac{m_\chi}{m_{Med}} \right)^4 \gtrsim m_\chi^2 \langle \sigma v \rangle_{Relic}}$$

The virtue of Dark Bremsstrahlung from Electrons

- *A′* carries away most of an electron’s energy in the first reaction
- *A′* emitted in a narrow forward cone
- Recoil electron is soft, *i.e.* large missing energy
- Recoil electron at large angles, *i.e.* large missing momentum

$$\sigma \propto \frac{\epsilon^2}{E_{\mathrm{cm}}^2} \ll \sigma \propto \frac{Z^2\epsilon^2}{m_{\mathrm{A'}}^2}$$





Dark Bremsstrahlung is a simple way to get large DM yield

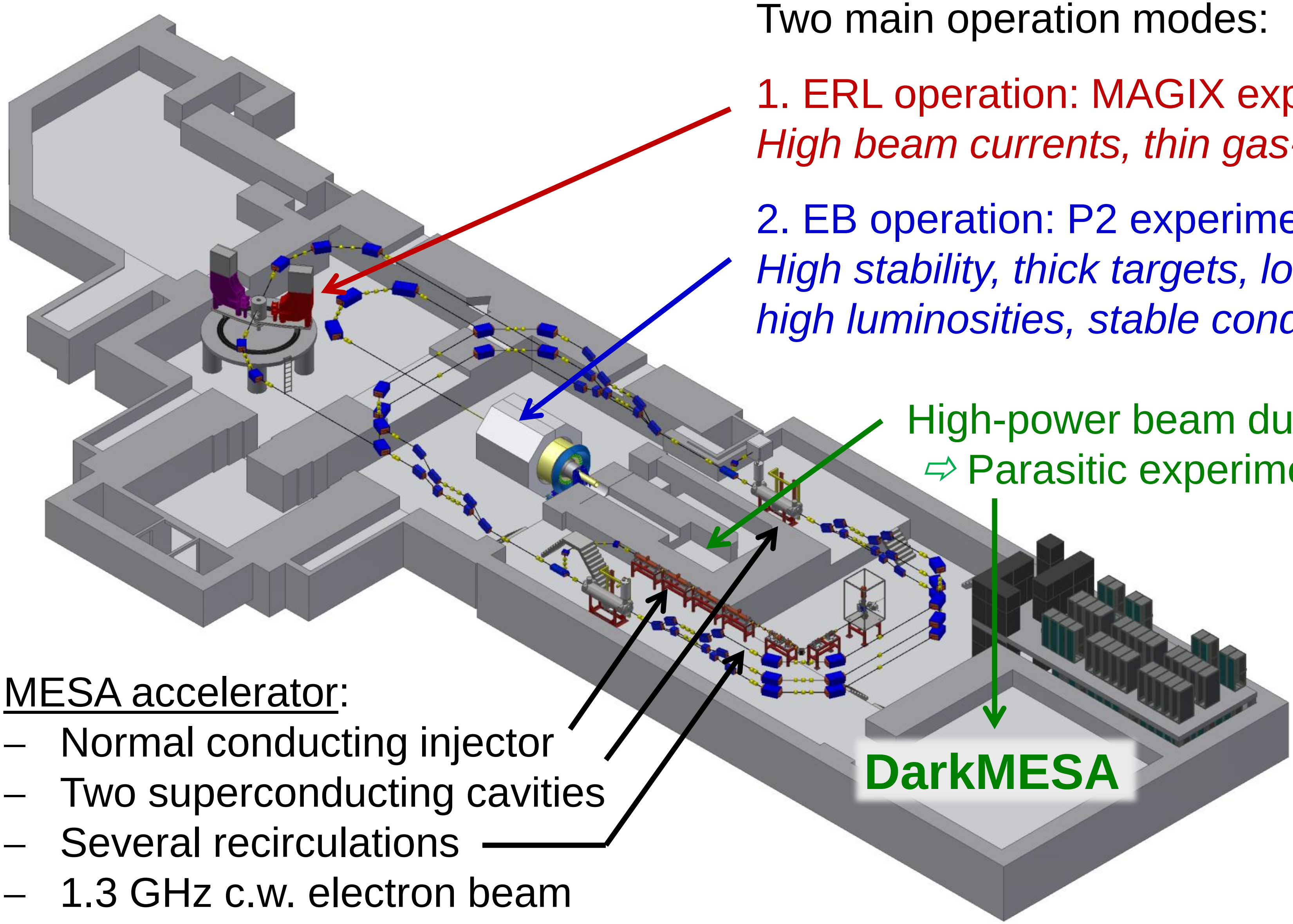
The MESA Accelerator in Mainz

Two main operation modes:

1. ERL operation: MAGIX experiment
High beam currents, thin gas-jet targets

2. EB operation: P2 experiment
High stability, thick targets, long runs, high luminosities, stable conditions

High-power beam dump
⇨ Parasitic experiments



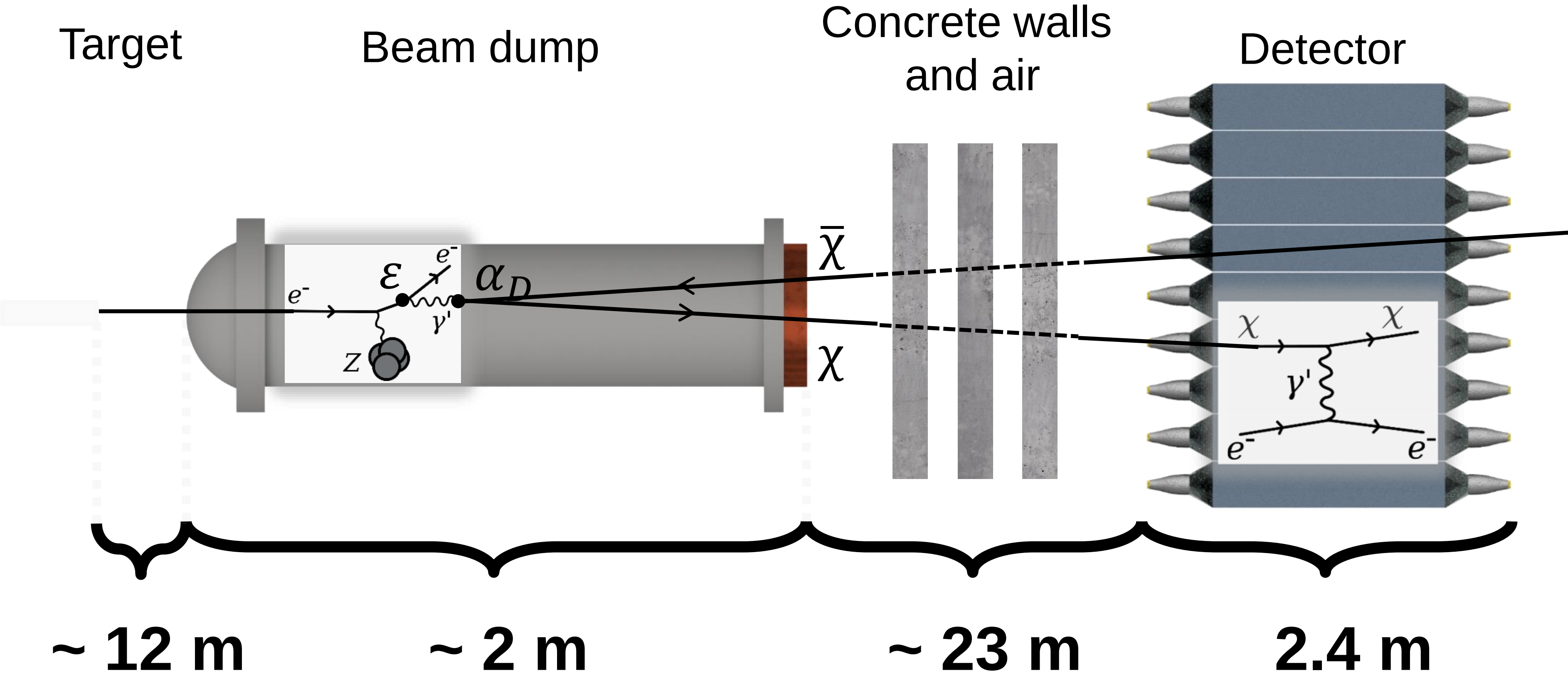
DarkMESA

MESA accelerator:
- Normal conducting injector
- Two superconducting cavities
- Several recirculations
- 1.3 GHz c.w. electron beam

The DarkMESA Concept

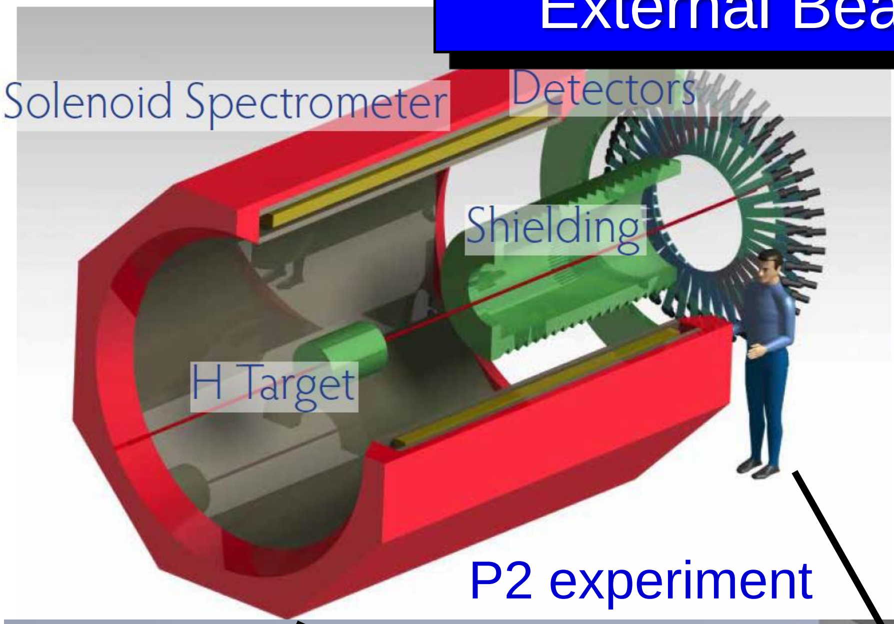
$$Y_{Prod} \sim \epsilon^2 / m_A^2$$

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



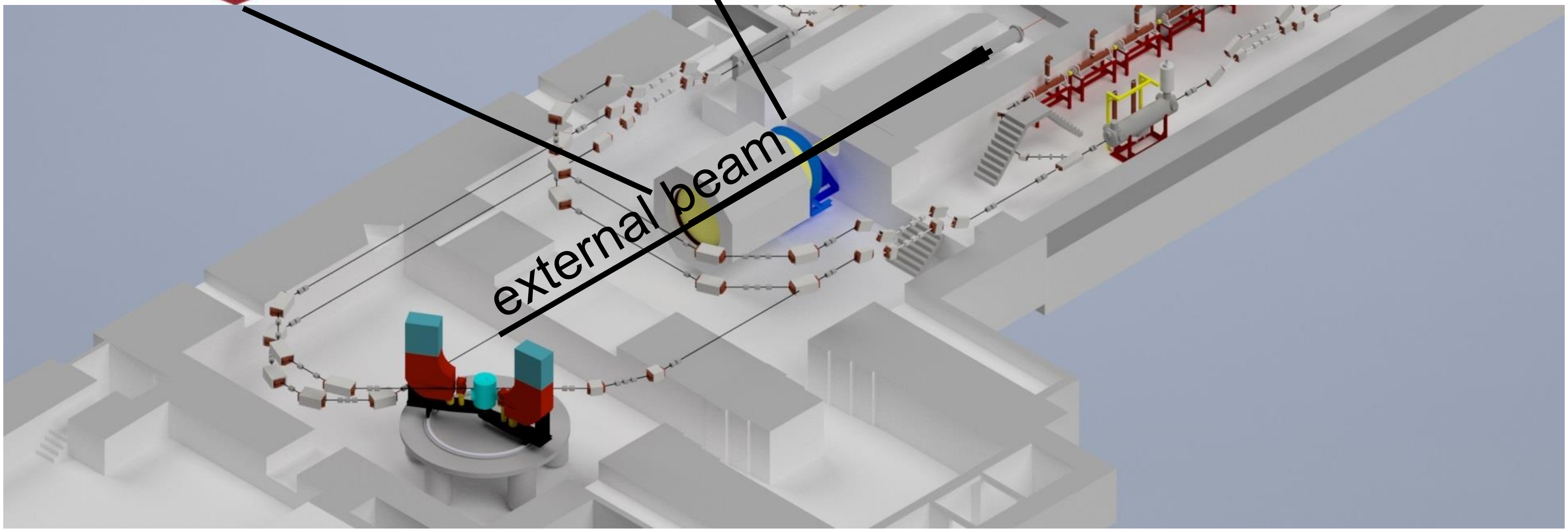
Total yield: $Y_{TOT} \sim \epsilon^4 \alpha_D / m_A^4$

External Beam Extraction



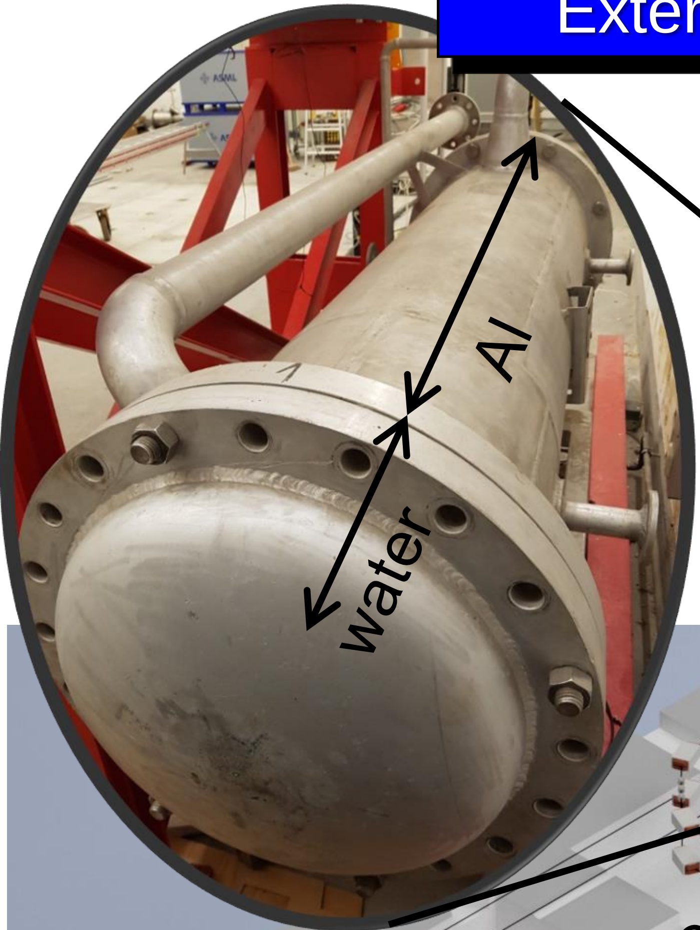
Beam energy ~ 147-155 MeV
Beam current ~ 150 μA
P2 target: 60 cm liquid hydrogen
- 3 kW beam power loss
- 17 MeV beam energy loss
- 2° multiple scattering angle
- e p → e n π^+ threshold at 152 MeV

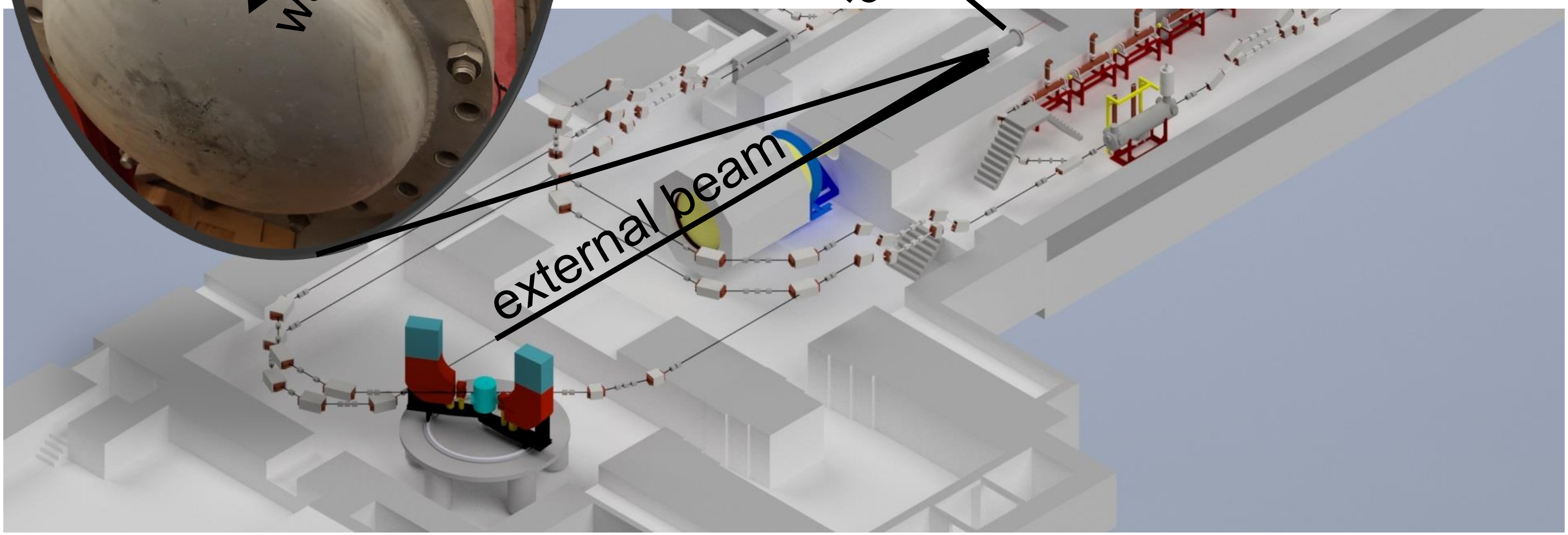
⇨ No pion/muon/neutrino production



External Beam Dumping

- Beam dumped after 12 m
- Beam energy ~ 130–138 MeV
- Beam power ~ 20 kW
- Lateral beam width ~ dump size
- Main absorber material: 20 X_o Al
- 10 000 h of operation:
  - ~ 3 x 10^{22} electrons
  - ~ 5400 C charge dumped

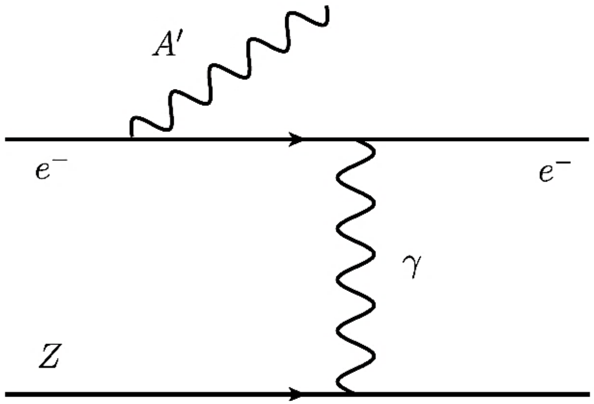




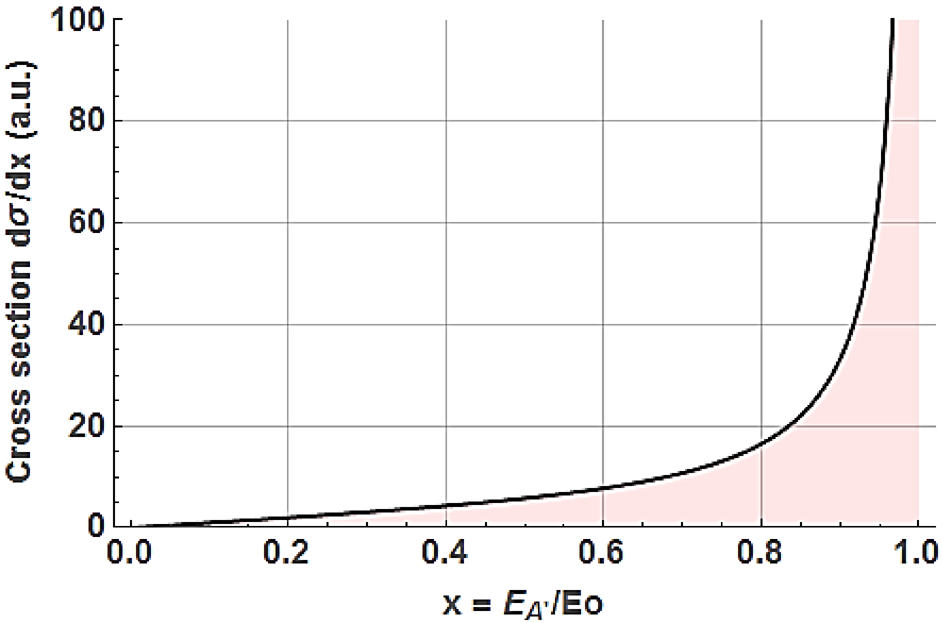
Model for A’ Bremsstrahlung

- Radiative production of (massive) dark photon A’ coupling with ε
- Subsequent decay to SM particle pairs with ε or dark matter pairs with α_D
- Assume dominant invisible decay channel $\Gamma(A' \to \bar{\chi}\chi)/\Gamma_{\rm total} \simeq 1$

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

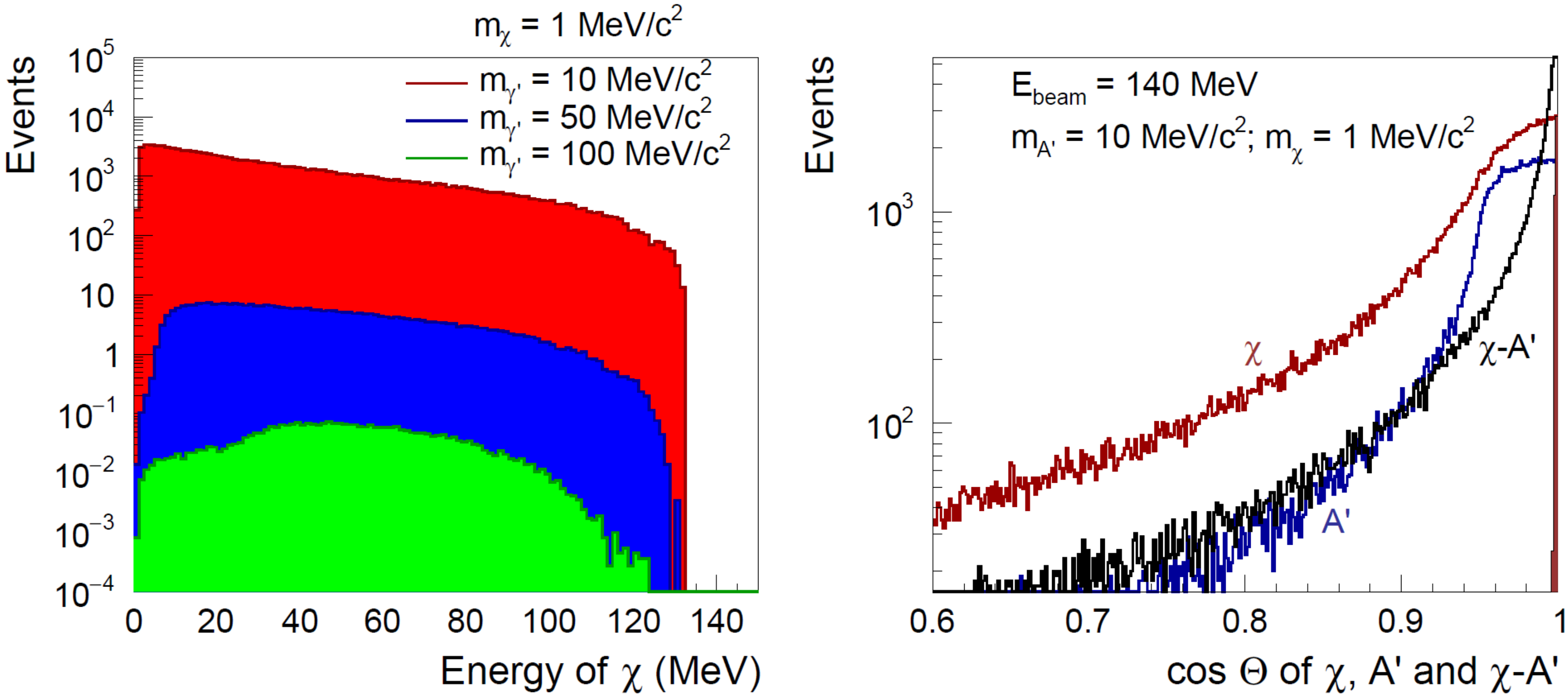


$$\frac{d\sigma}{dx} \approx \frac{8Z^2\alpha^3\epsilon^2 x}{m_{A'}^2}\left(1 + \frac{x^2}{3(1-x)}\right)\mathcal{L}og$$



Dark Matter Beam Properties

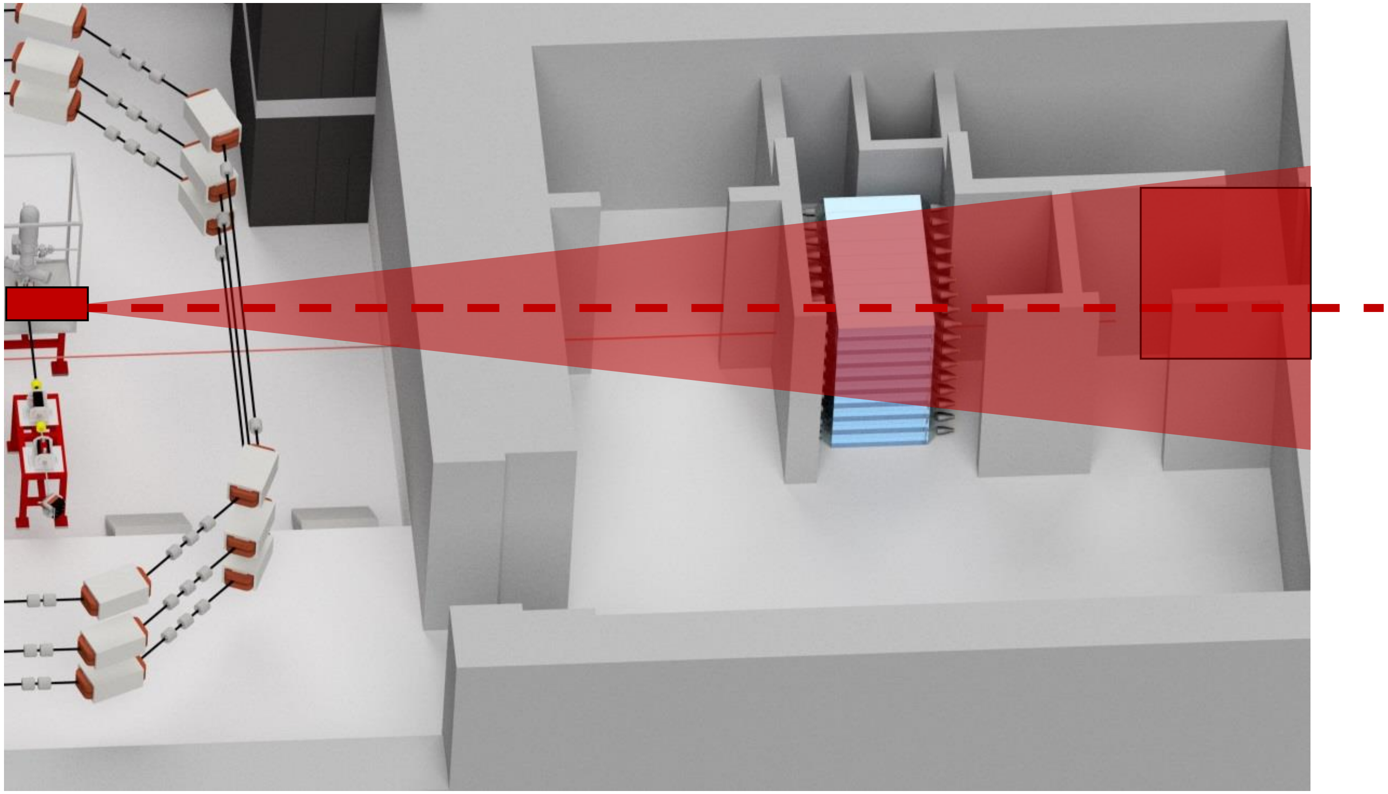
Example simulations for $m_{A'}$ = 10, 50 and 100 MeV/c^2



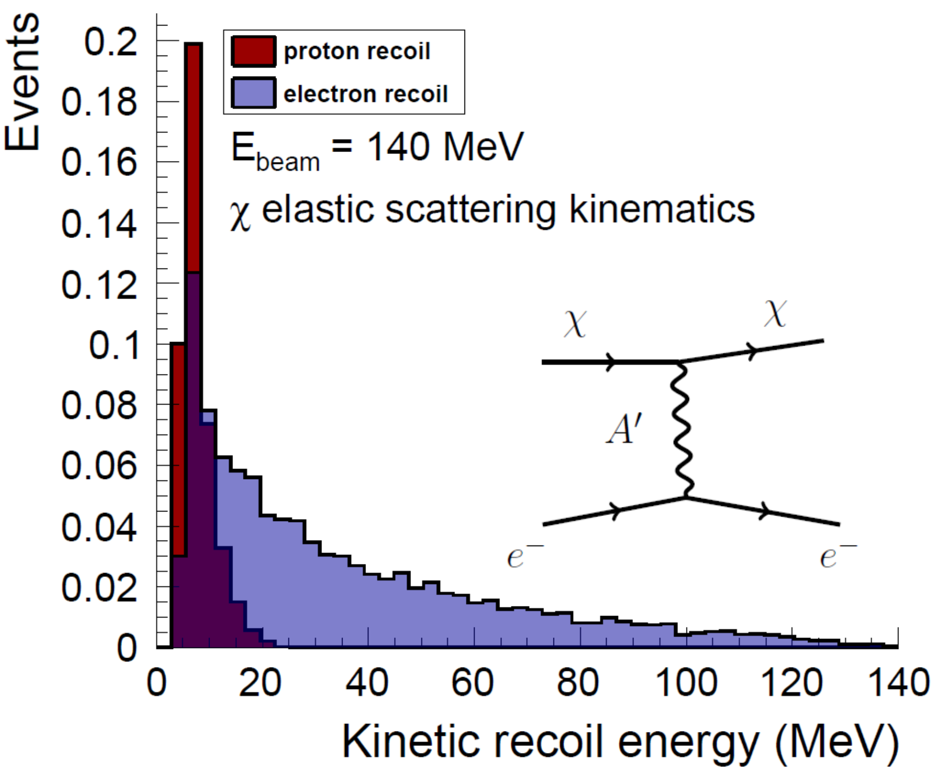
Testing ground for DM production with 20 MeV « $m_{A'}$ « 120 MeV

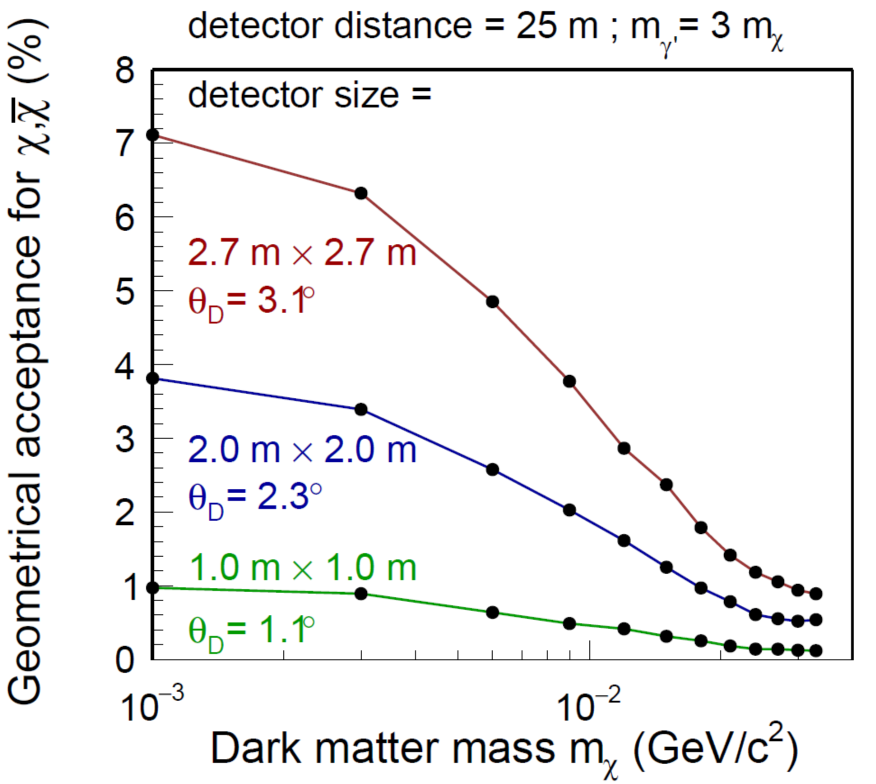
Dark Matter Beam-Line

- 20 X_o beam-dump, 70 X_o (~ 8 m) barite concrete
- Total length of 23 m including several shielding walls
- Practically free of beam-related background



Dark Matter Detection





Detector needs to be sensitive to small recoil energies

Detector acceptance: few % for small $m_{A'}$

Elements of Detector Design

Ideal Requirements:

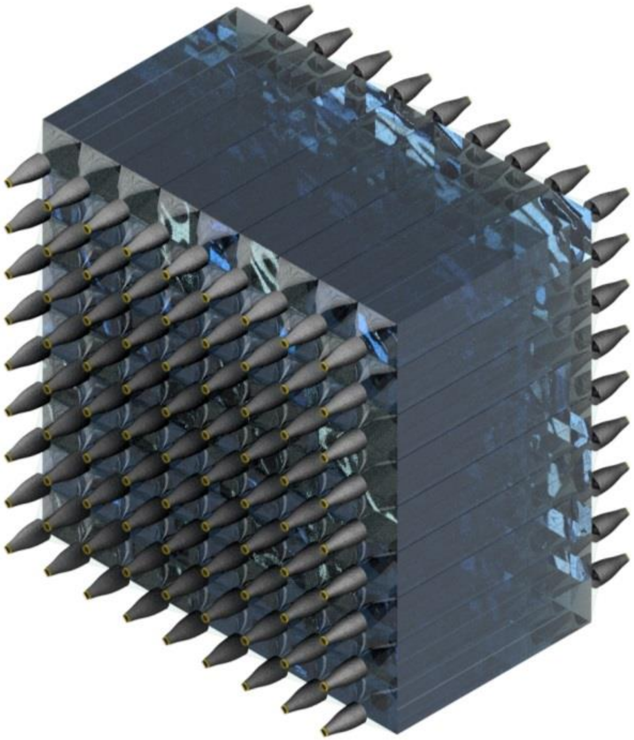
1. Large Surface (Acceptance)
2. Large thickness (Int. Prob.)
3. High density (Int. Prob.)
4. Reliability (long running time)
5. Background rejection
   - Cosmics
   - Natural Backgrounds
   - Beam Backgrounds
   - ...

Baseline Concept

Inorganic crystal calorimeter (high density)

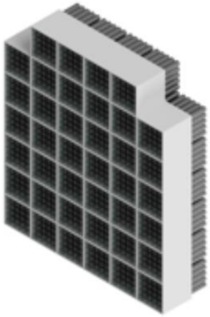
- Cherenkov (fast, no neutrons)
- Scintillator (higher light yield)

– 81 lead glass blocks
– 30 x 30 x 150 cm^3 = 11 m^3
– 274 x 274 cm^2 cross section
– Readout with 5 inch PMTs



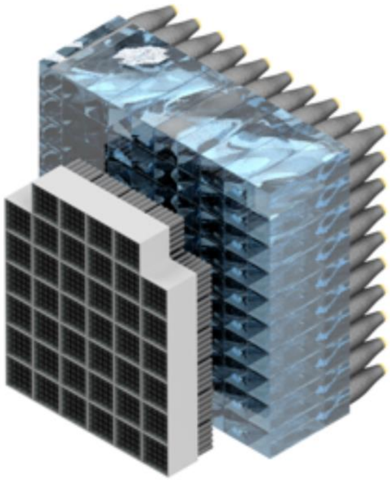
Phased Approach

Phase 1



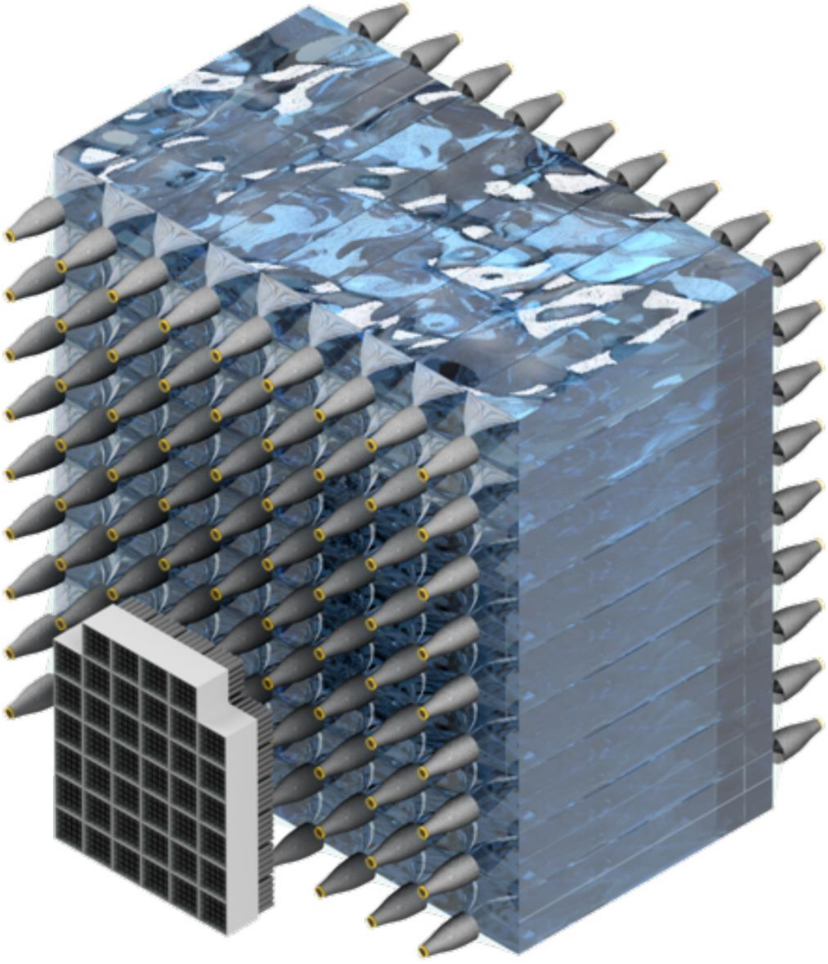
1000 (available!) PbF2 crys
Volume: 1x1x0.13 m^3
5x5 crystal sub-modules
1200 kg mass

Phase 2



Addition of Pb-Glass blocks
Volume: 1m^3
4100 kg mass

Phase 3



Reach maximum volume: O(10m^3)

A4 Calorimeter Recycling

- 1022 PbF_2 crystals
- Volume 0.15 m^3, 1.2 tons
- Density 7.77 g/cm^3

Status:

- A4 calorimeter disassembled
- Crystals and PMTs in laboratory

Phase 1 calorimeter of DarkMESA

Projected Exclusion Limits from DarkMESA

Full simulation of DarkMESA

Three detector stages:

- Stage A: existing PbF_2 crystals

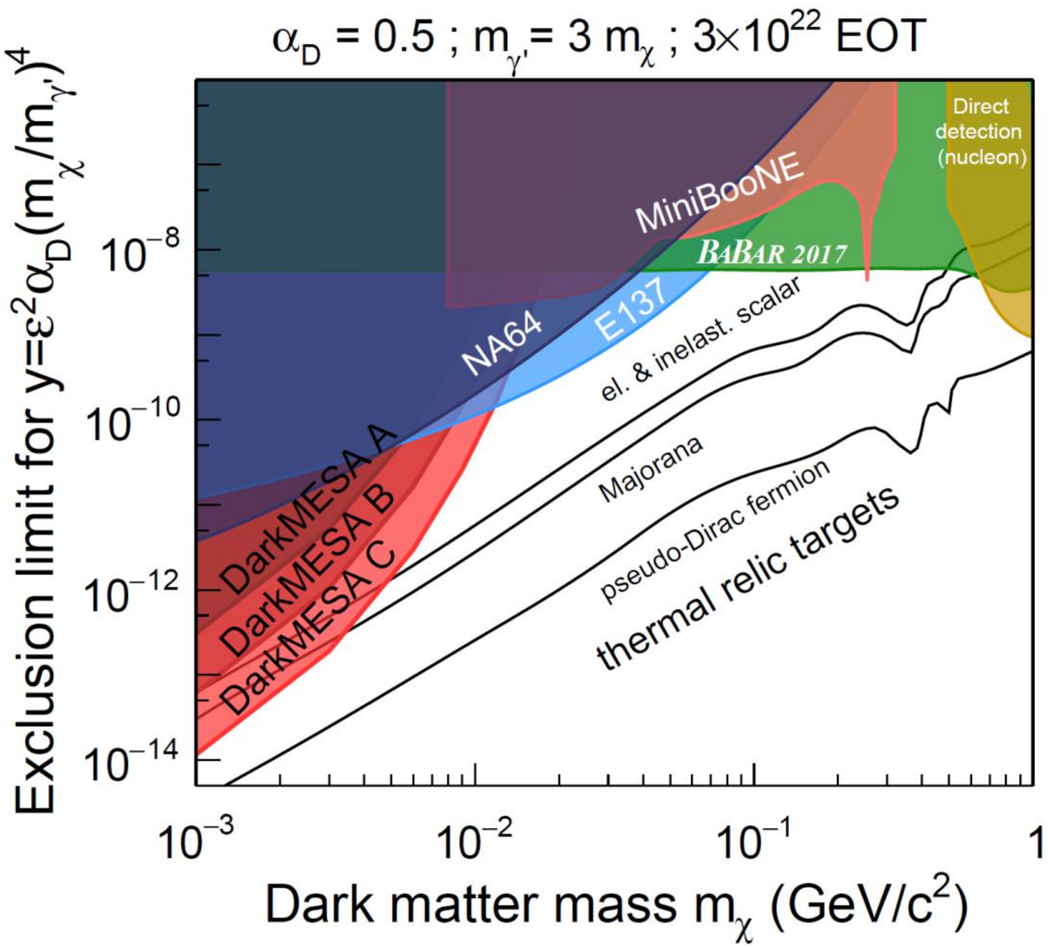
  (A4 - 0.13 m^3 volume)

- Stage B: lead glass calorimeter

  (1 m^3 volume)

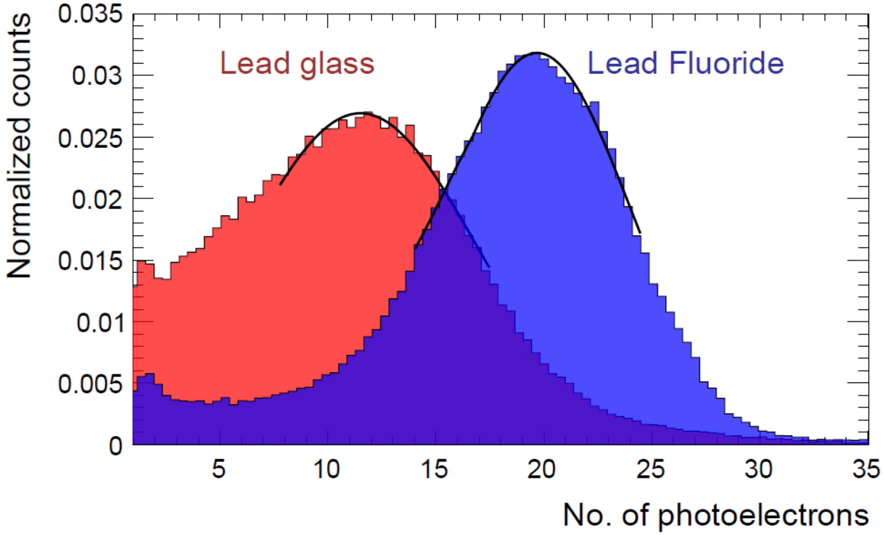
- Stage C: lead glass calorimeter

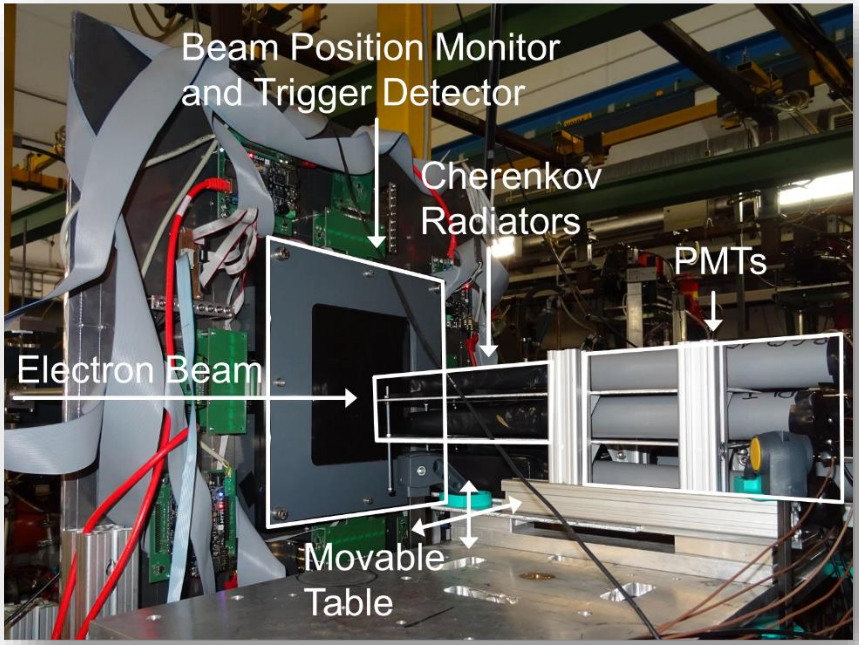
  (11 m^3 volume)



DarkMESA has the potential to touch the thermal relic targets!

Prototyping and Beam Tests





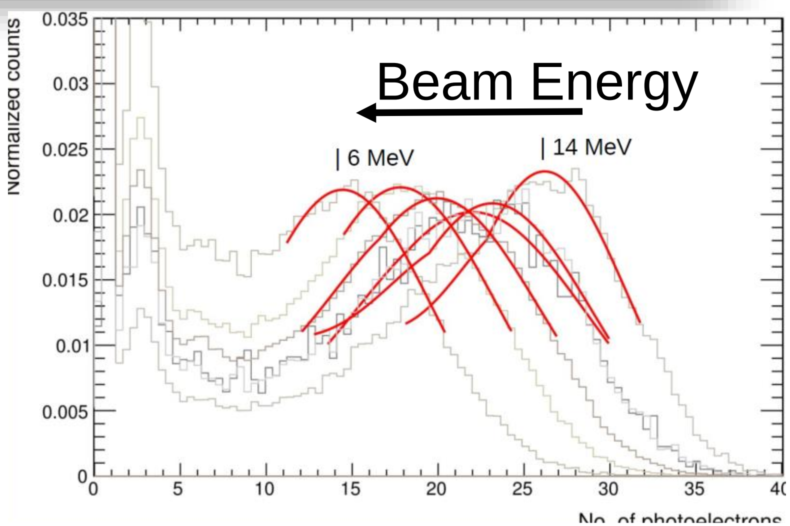
Measurements:

Light Yield
Position dependence
PMT voltage scan

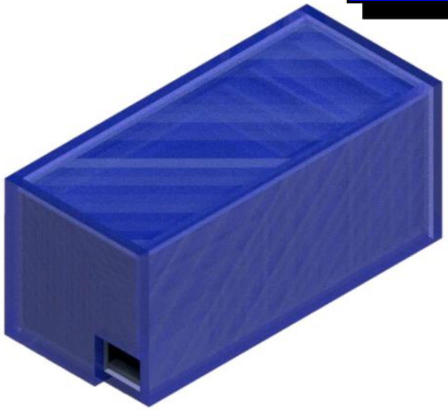
Input to Simulation

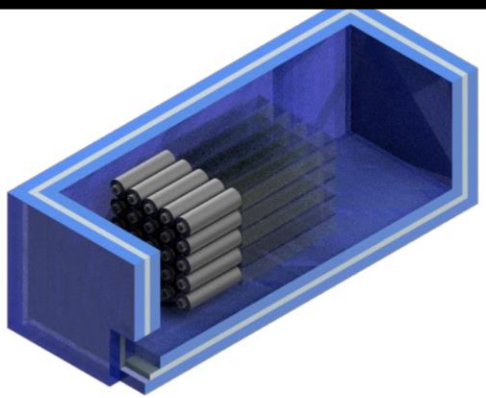
Investigated Crystals

SF5 (Pb-Glass, Schott AG)
SF6 (Pb-Glass, Schott AG)
SF57HTultra (Pb-Glass, Schott AG)
BGO (on loan from Frascati, L3-LEP)
PbF_2 (from A4)



Development of a Veto System





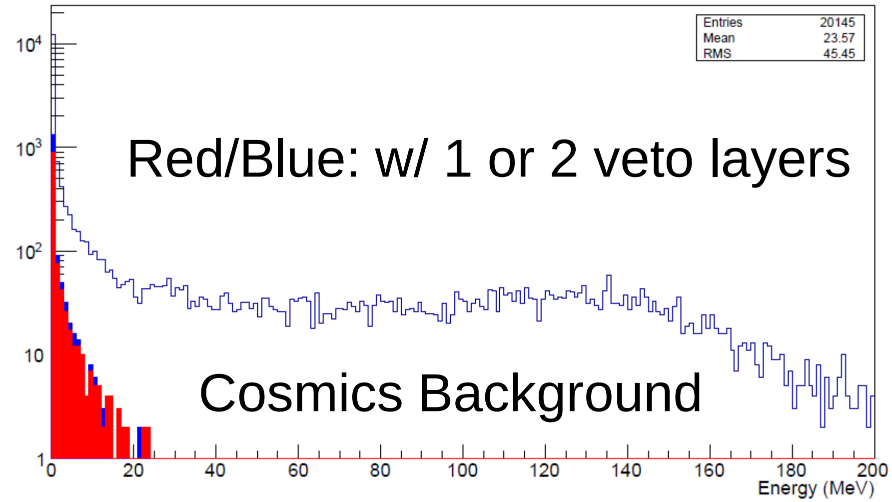
Comics Veto System
Multiple scintillator layers
Lead / Neutron shielding

Crystal Array
Available from A4:
- PbF_2 crystals
- PMTs

Key questions
- Signal properties
- Backgrounds

Background rejection:

– Use of beam on/off information:
  beam-time scheduling 50% / year
– Segmenting of detector read-out:
  coincidences eliminating noise
– Use of several layers of veto detectors

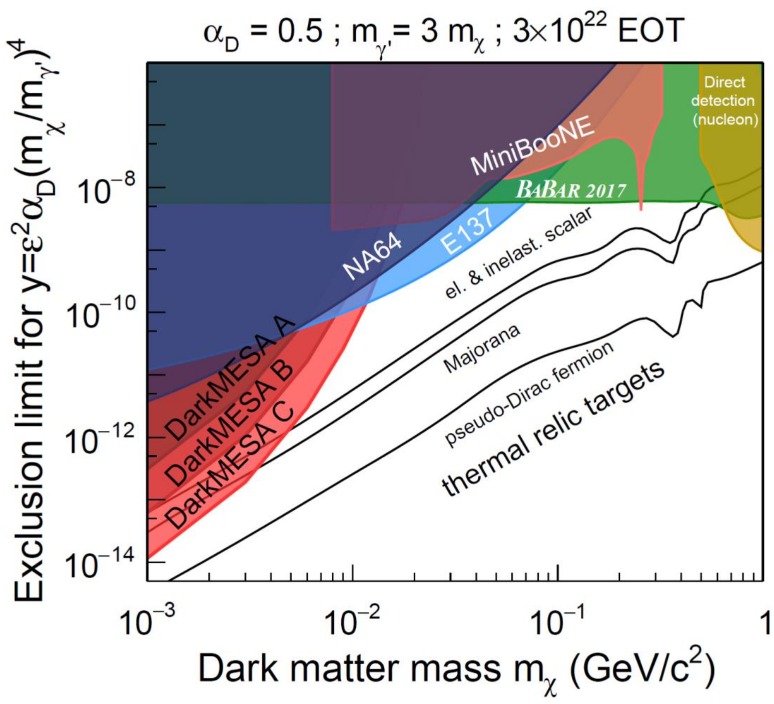


Conclusion

DarkMESA can contribute to DM searches

Ideal for *light* and *weakly coupled* particles:

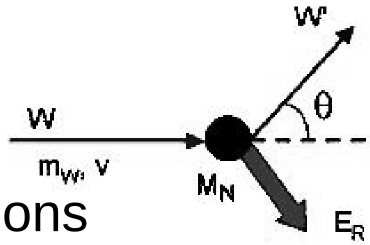
- Very large number of electron on target
- Extremely stable beam conditions
- Very low backgrounds
- New infrastructure
  with dedicated floor space for detector



Dark Photon thermal relic targets could be reached within a few years

Backup

Direct WIMP Searches

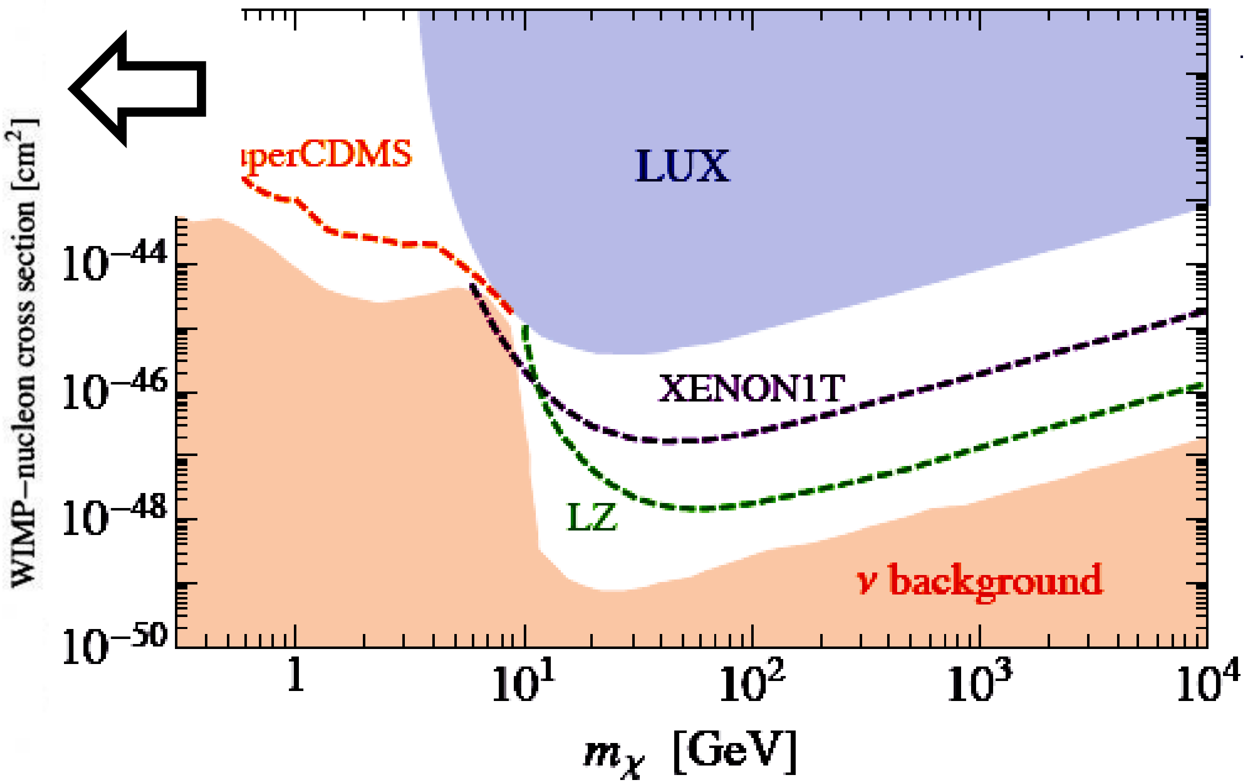


Assuming m_W ~ 100 GeV/c², v ~ $10^{-3}c$:

→ Ordinary matter recoiling with E ~ 1–100 keV from DM collisions

→ Typically ultra-sensitive detectors located deep underground

- WIMP hypothesis nowadays cornered
- Unexplored mass region < 1 GeV/c^2
- Small mass and small coupling can reproduce correct relic density if $m_\chi/g_\chi^2 \sim m_w/g_w^2$



Light Dark Matter with large self-interaction and small SM coupling possible

Dark Photon Couplings and Decays

- Photon-like couplings
- If 2 $m_X < m_{A'}$ and not too small α_D: invisible decays into DM pairs
- Else if kinematically allowed: visible decays to ee, μμ, ππ, …

• Dark Bremsstrahlung:	$eZ \rightarrow eZA'$	electron beam dump
• Annihilation:	$ee \rightarrow \gamma A'$	electron-positron collider
• Dark Bremsstrahlung:	$pZ \rightarrow pZA'$	proton beam dump
• Drell-Yan process:	$qq \rightarrow A'$	proton beam
• Meson decay:	$\pi \rightarrow \gamma A'$ etc.	proton beam

Searches with Collider and Beam Dump Experiments

<u>Colliders (visible/invisible decays)</u>

- B-Factories (BaBar/Belle II)
- LHC experiments
- Meson decays

<u>Beam dumps (invisible decays)</u>

- BDX@Jlab, DarkMESA
- Proton beam dumps, re-analyses

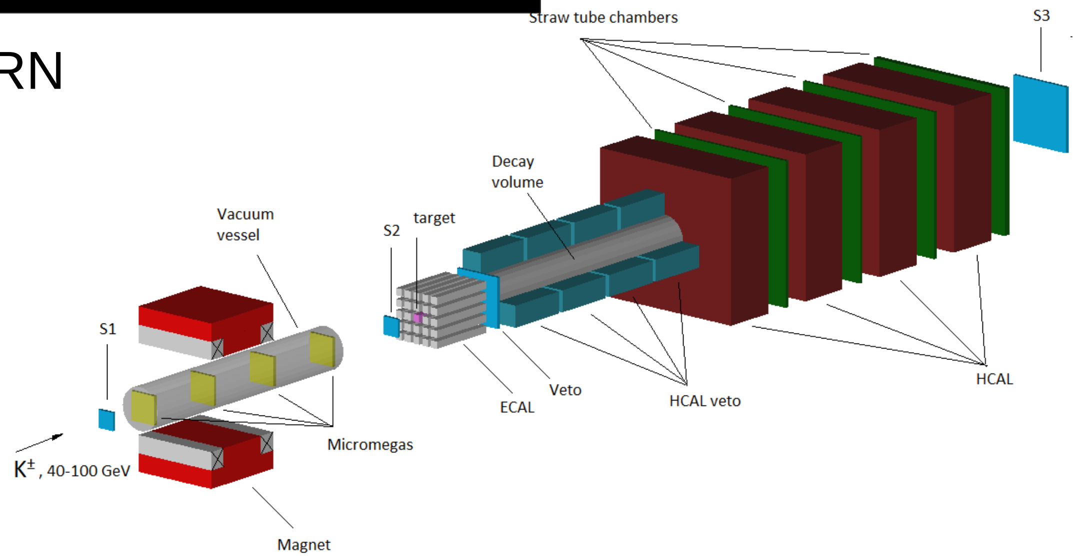
Recent Constraints from NA64

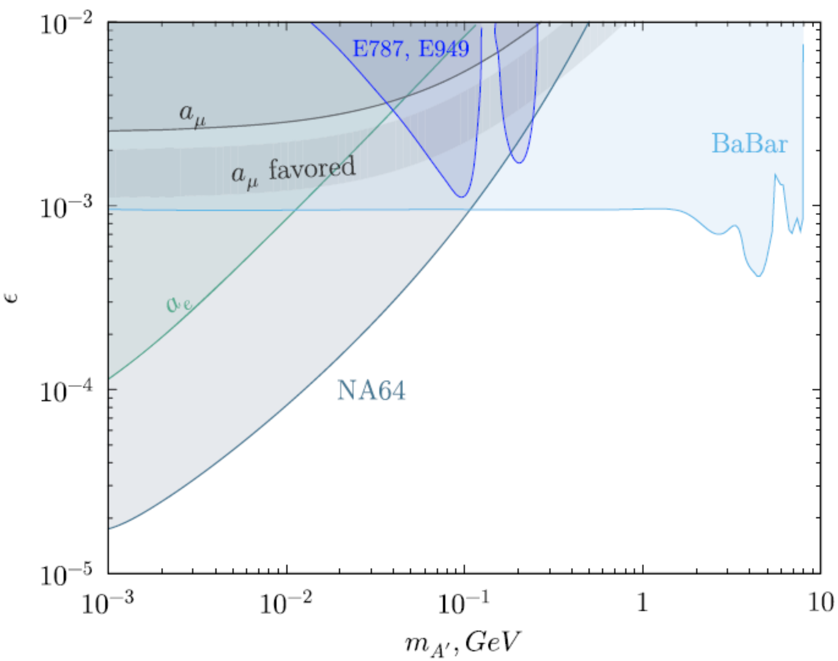
– 100 GeV electron beam at CERN

– Missing energy experiment

– 4.3 x 10^{10} electrons on target

[NA64, Phys. Rev. D 97 (2018)]



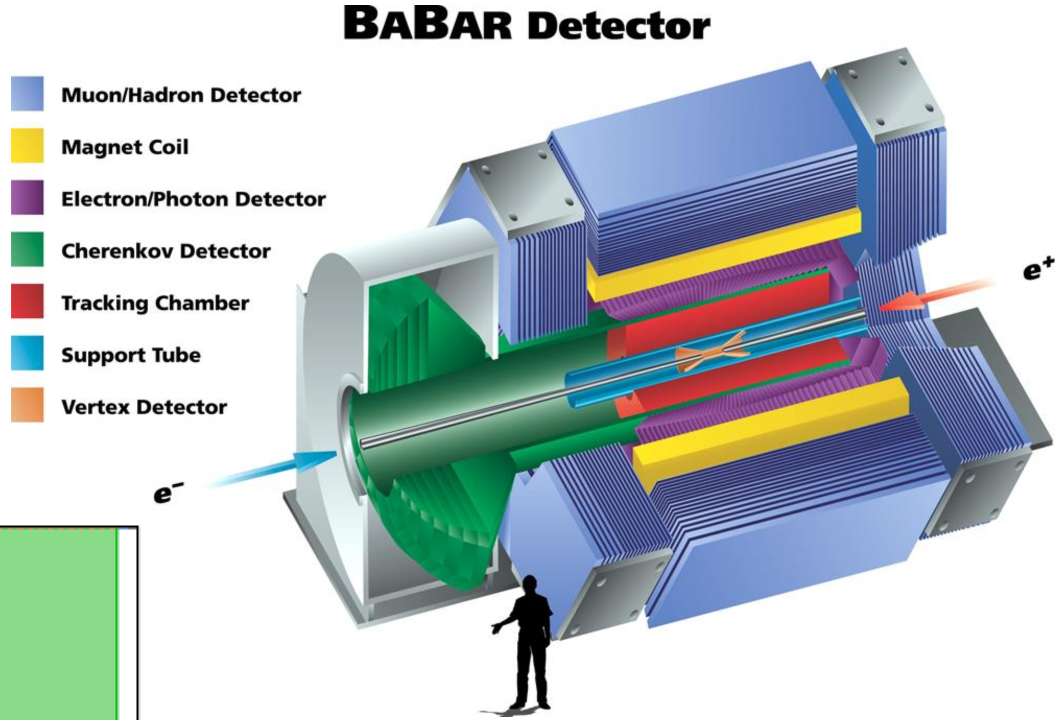


Invisible decay exclusion limits

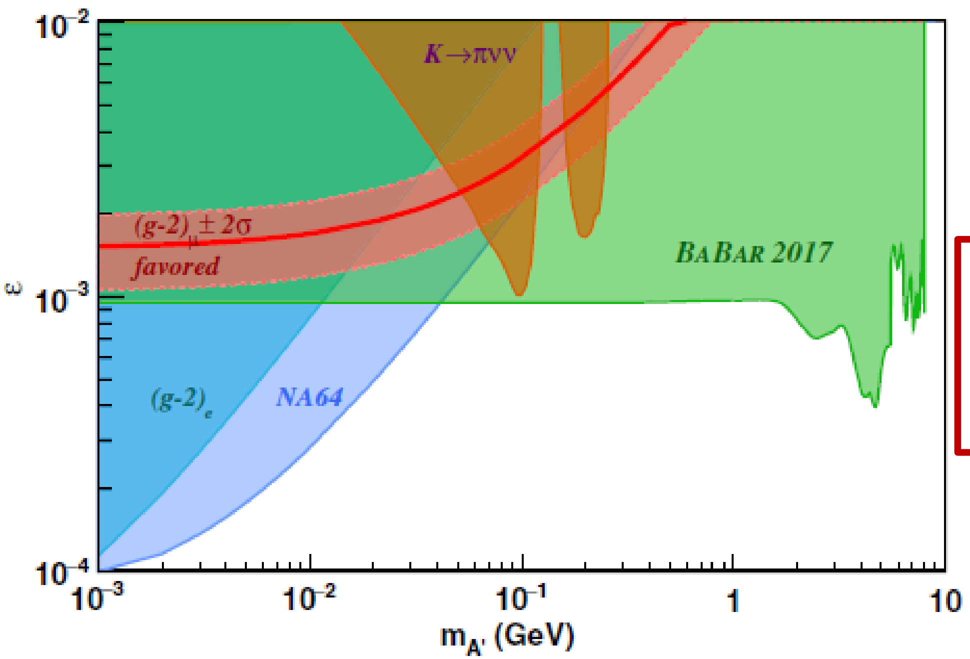
Extending to < 10^{-4} for masses of 10 MeV

Recent Constraints from *BaBar*

- e+e- collider at B-factory
- missing energy and missing momentum
- 53 fb^{-1} from $\Upsilon(nS)$



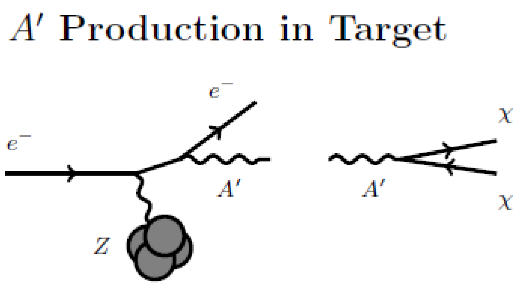
[PRL 119, 131804 (2017)]

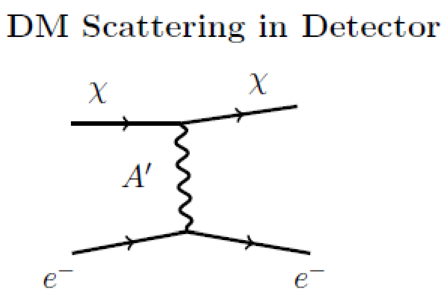


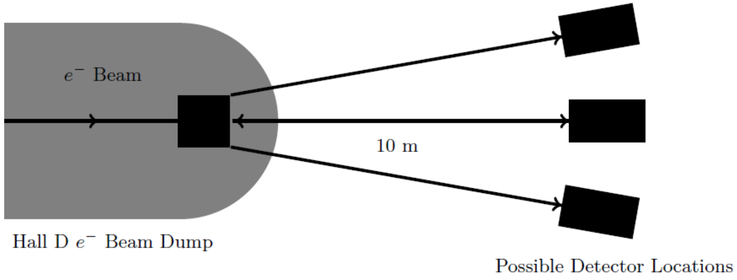
<u>Invisible decay exclusion limits</u>

Extending to 10^{-3} at masses < 1 GeV

Proposal for BDX@JLab



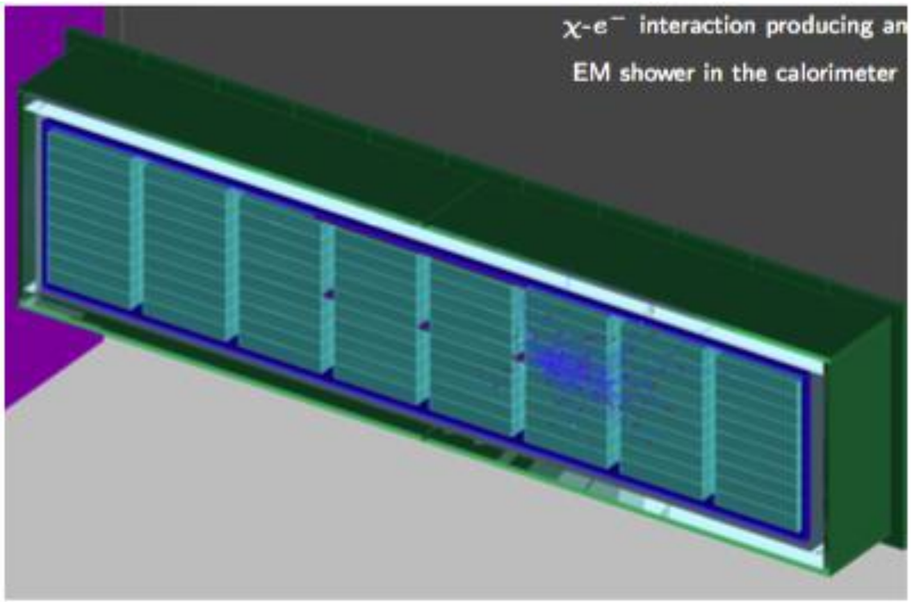




- 800 recycled *BaBar* crystals

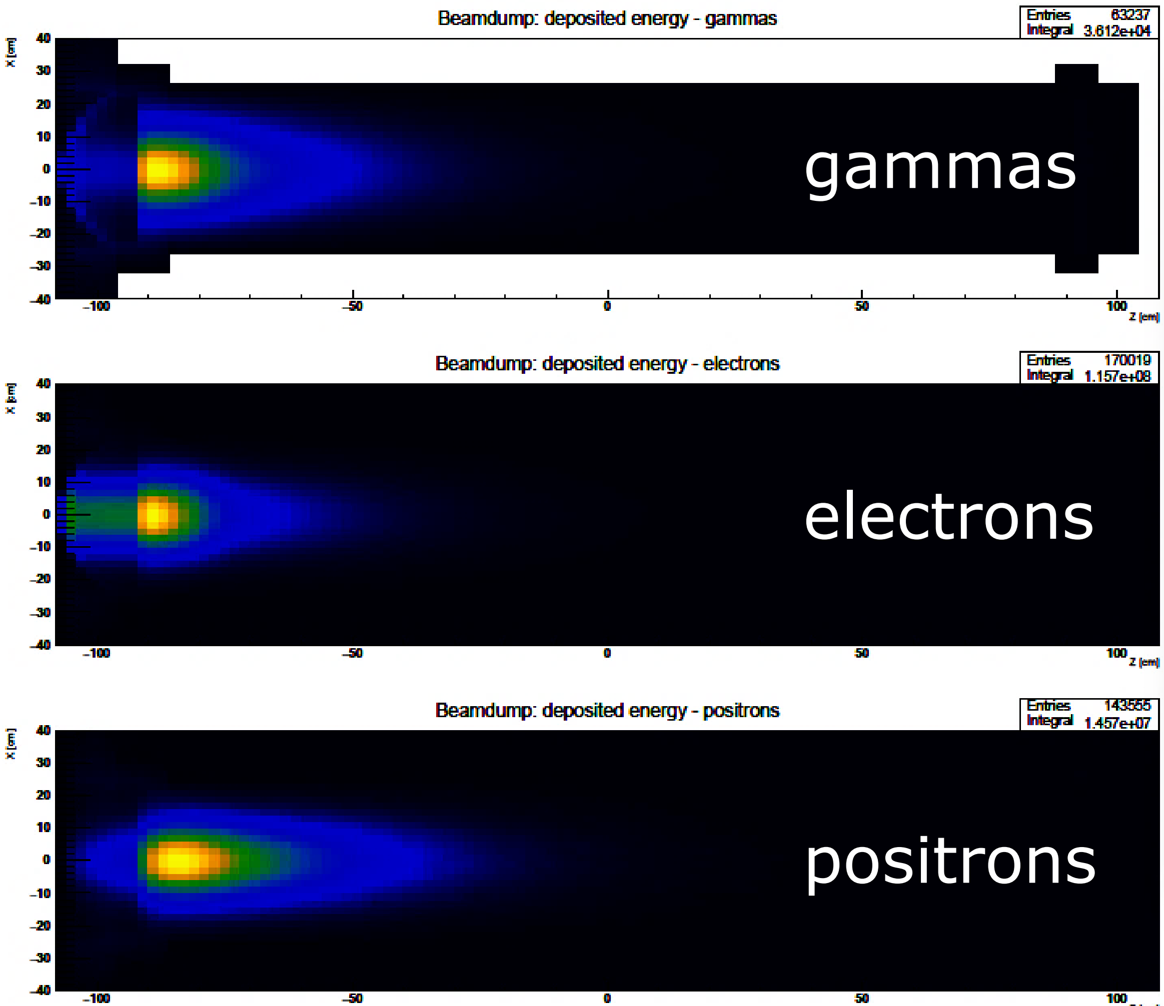
  Volume: ~ 0.5 m^3

  Signal: shower with E_{thr} ~ 300 MeV
- JLab PAC approval
- Funding & schedule unclear



spokesperson: Marco Battaglieri

Particle Production in Beam Dump

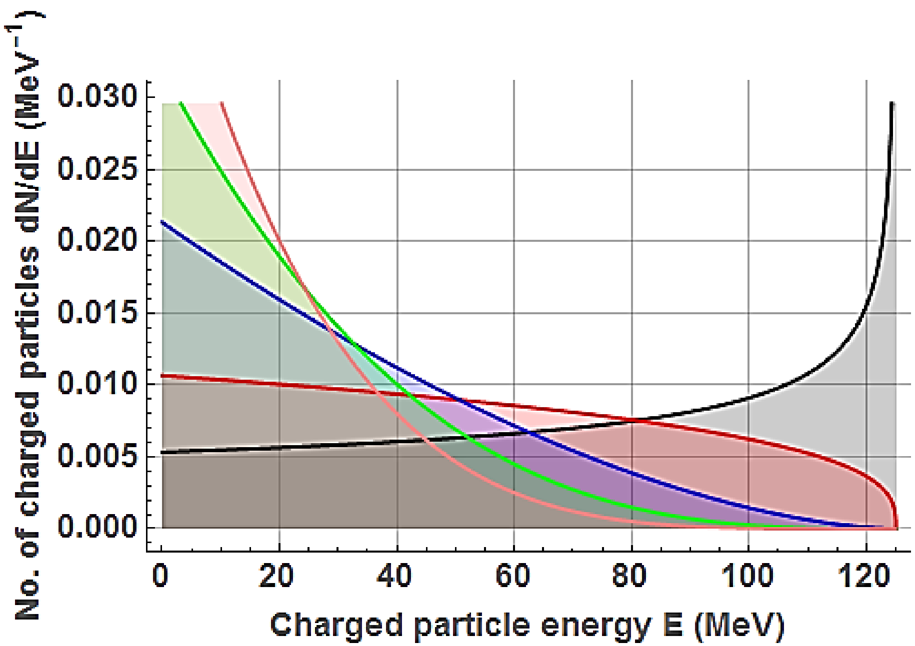


Geant4 simulation by Mirco Christmann

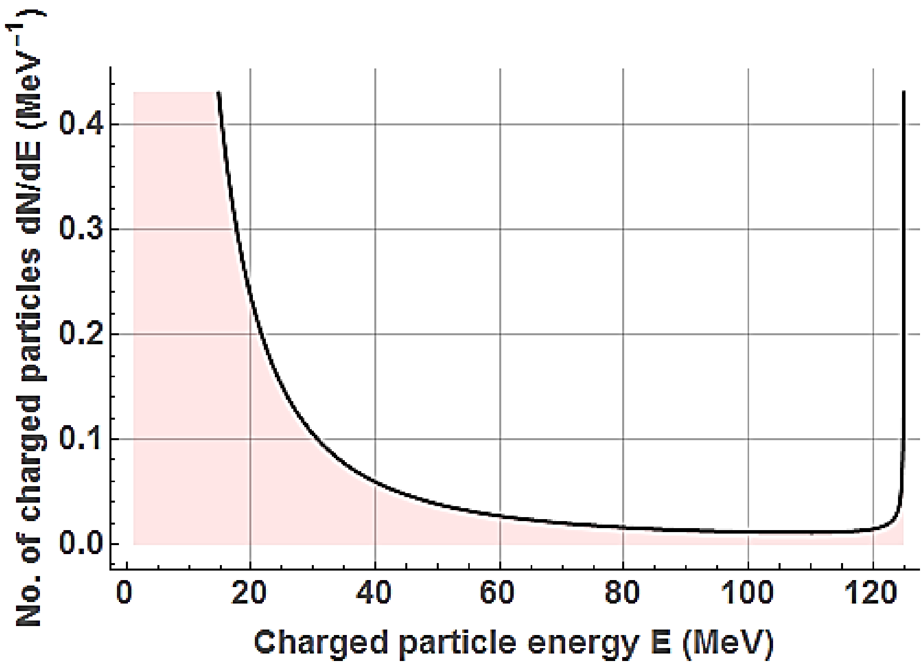
Hard photon flux relates to Dark Photons flux

Energies available for Dark Photon Bremsstrahlung

Energy distribution
at different shower depths:



Integral over complete shower:



- Shower maximum within first X_o
- On average only ~ 3 charged particles per beam electron
- On average only ~ 1 hard photon emission per beam electron

Complementary energies to all other beam dump experiments