Search for Light Dark Matter
(and other new phenomena)
using a primary electron beam

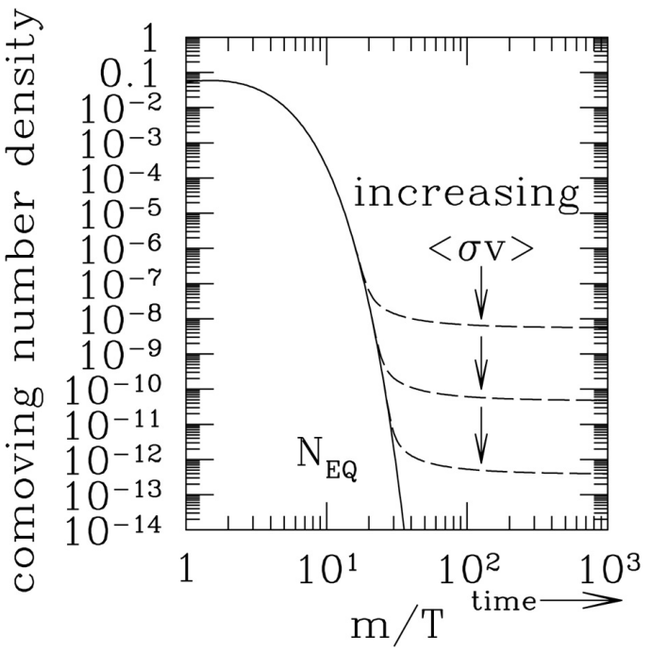
Particle Physics Strategy Discussion, Uppsala

Torsten Åkesson, Caterina Doglioni, **Ruth Pöttgen**

13 March 2018

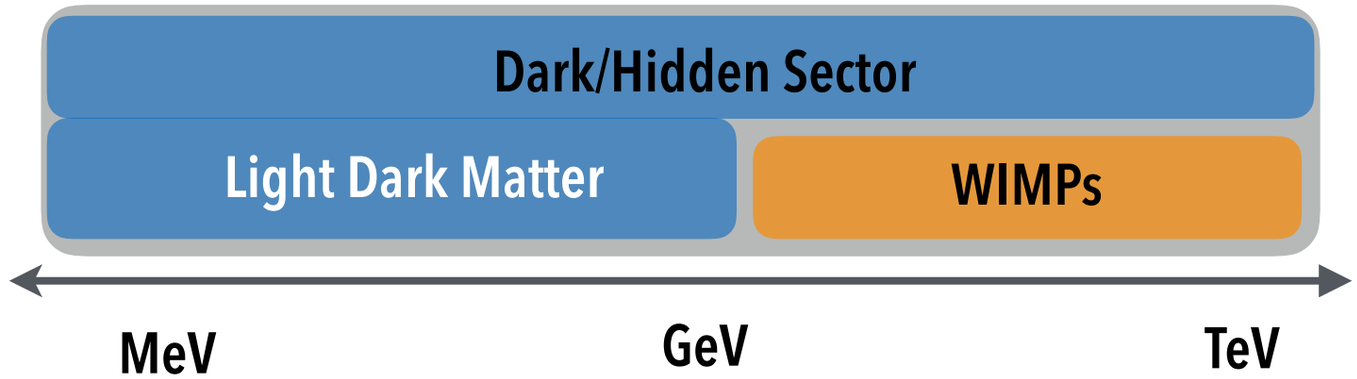
Light Dark Matter

thermal relic DM

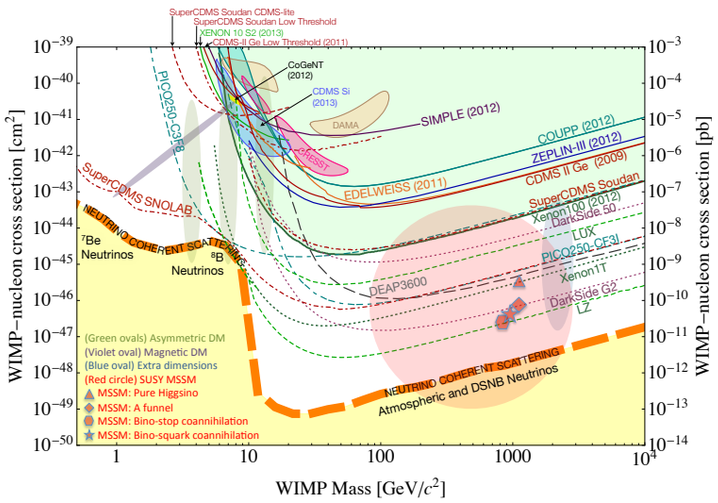


=>

- viable mass range:



- **hole** in experimental coverage
  - we have to look here!

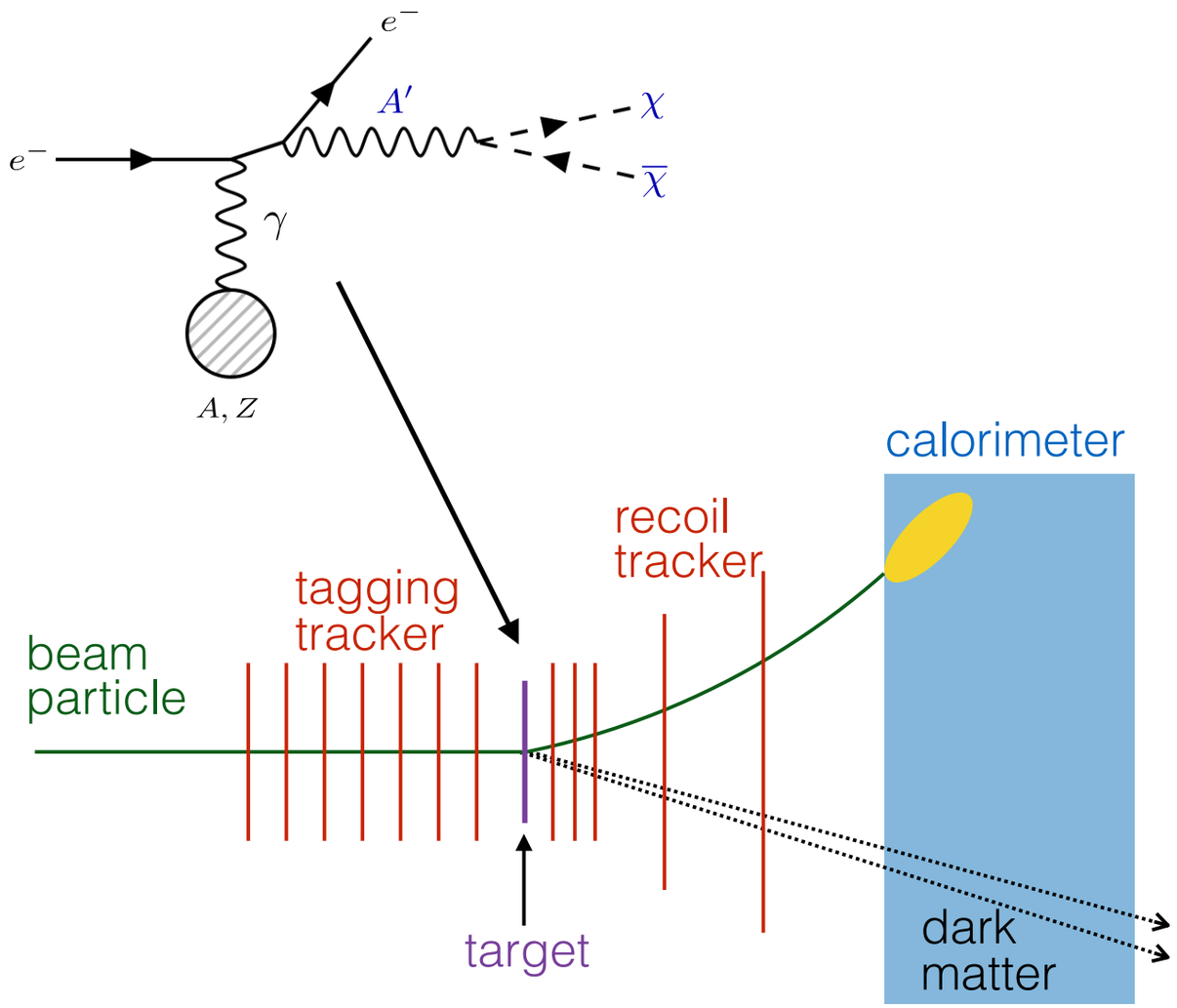


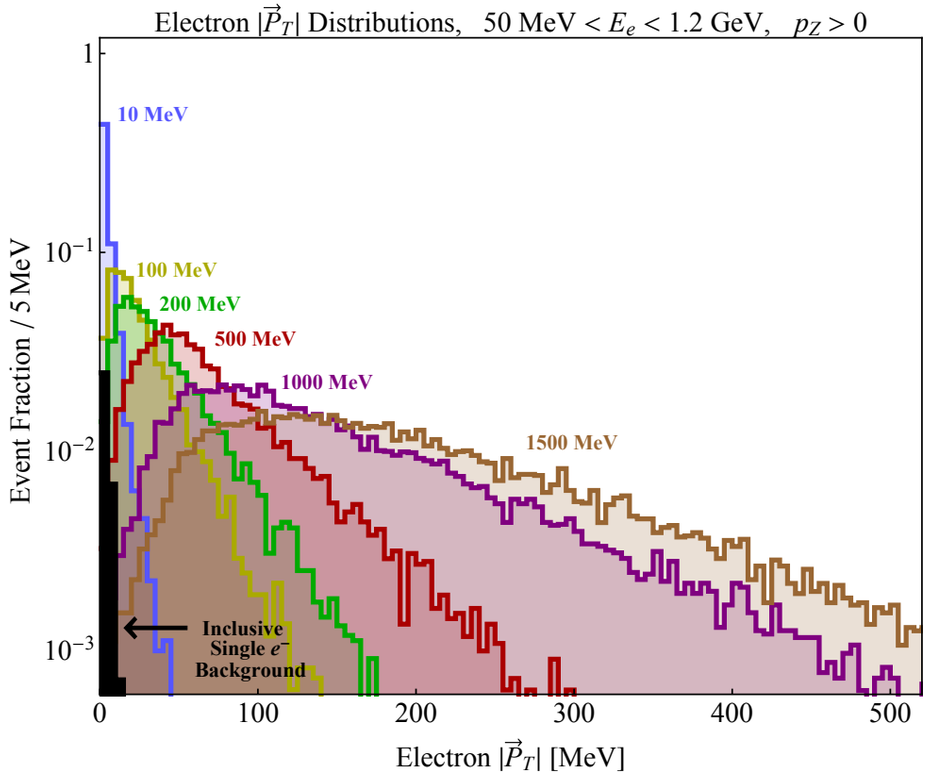
- minimal, yet representative model: Dark Photon (A')
  - many dedicated searches for visible decay, but not *invisible* into DM

- highly relevant for decision on **future directions** of particle physics (dark sector studies, **intensity** rather than energy frontier)

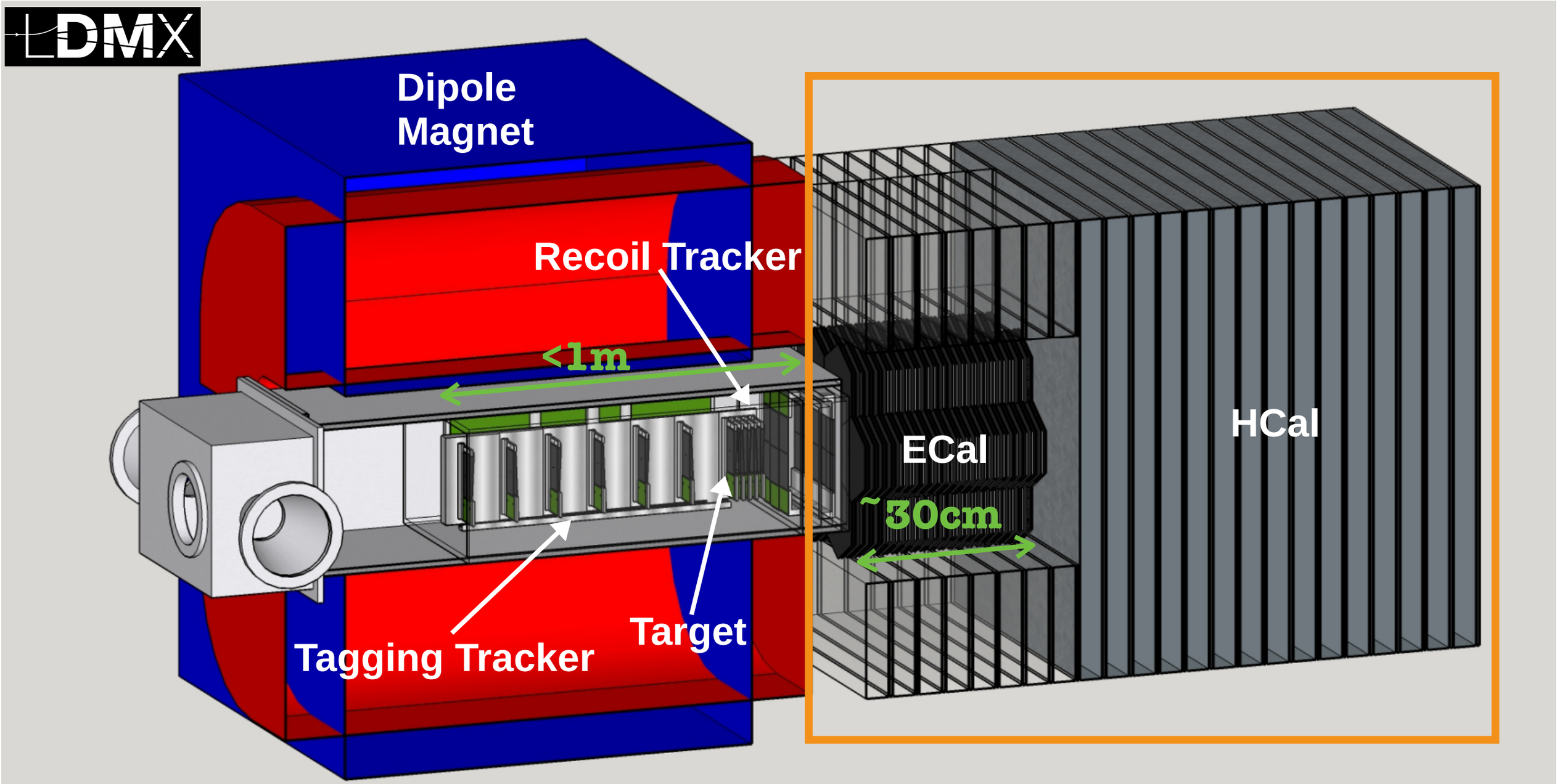
Kinematics & Experimental Layout

- highest sensitivity: **fixed-target, missing momentum** experiment @ **e-beam**
  - **bremsstrahlung** of massive dark photon
    —> kinematics distinctly different from SM





Light Dark Matter eXperiment

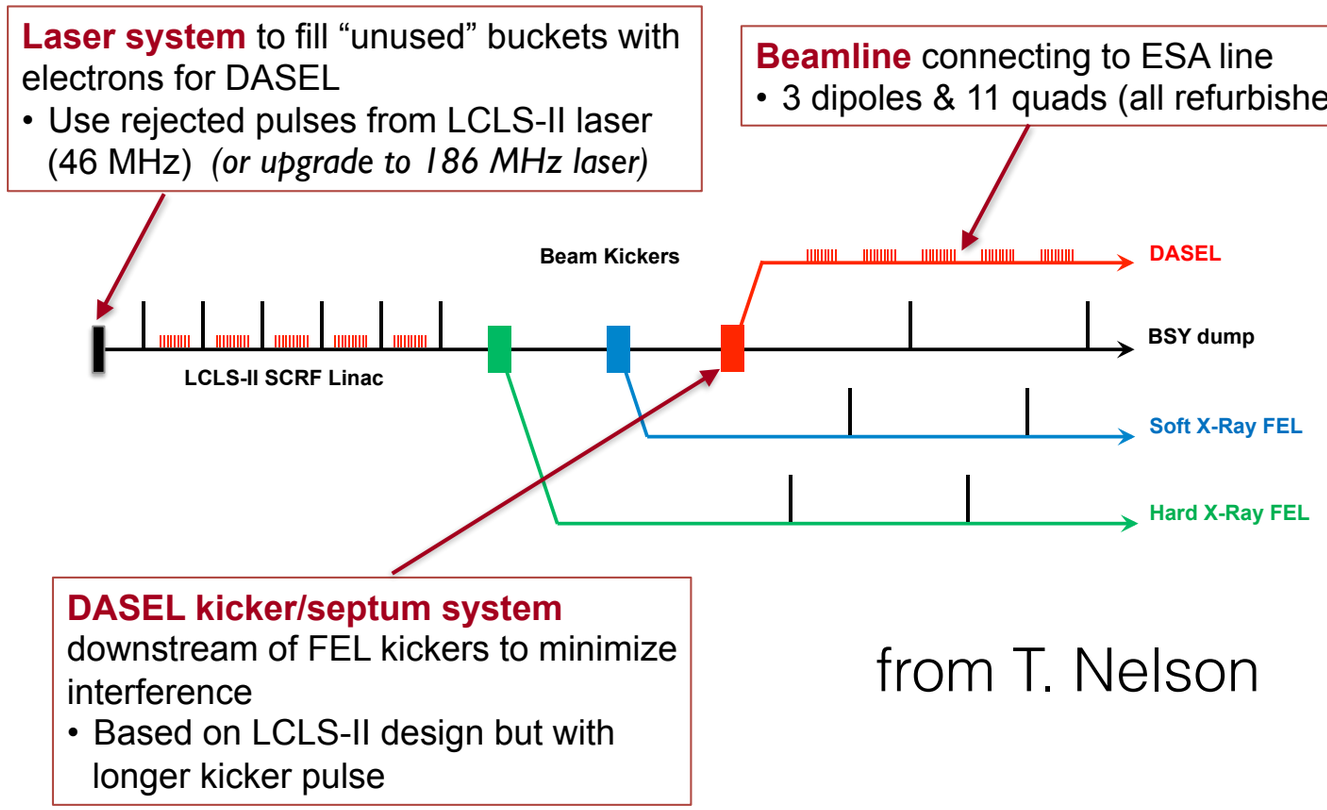


Caltech Fermilab SLAC NATIONAL ACCELERATOR LABORATORY UCSB UNIVERSITY OF CALIFORNIA SANTA BARBARA UNIVERSITY OF MINNESOTA UNIVERSITY OF CALIFORNIA SANTA CRUZ LUNDS UNIVERSITET

Setup at SLAC

- detector leveraging existing concepts/technologies
  - tracking à la HPS (Heavy Photon Search @ JLab)
  - ECAL module design close to CMS forward calorimeter upgrade
- HCAL being optimised for veto power of rare backgrounds

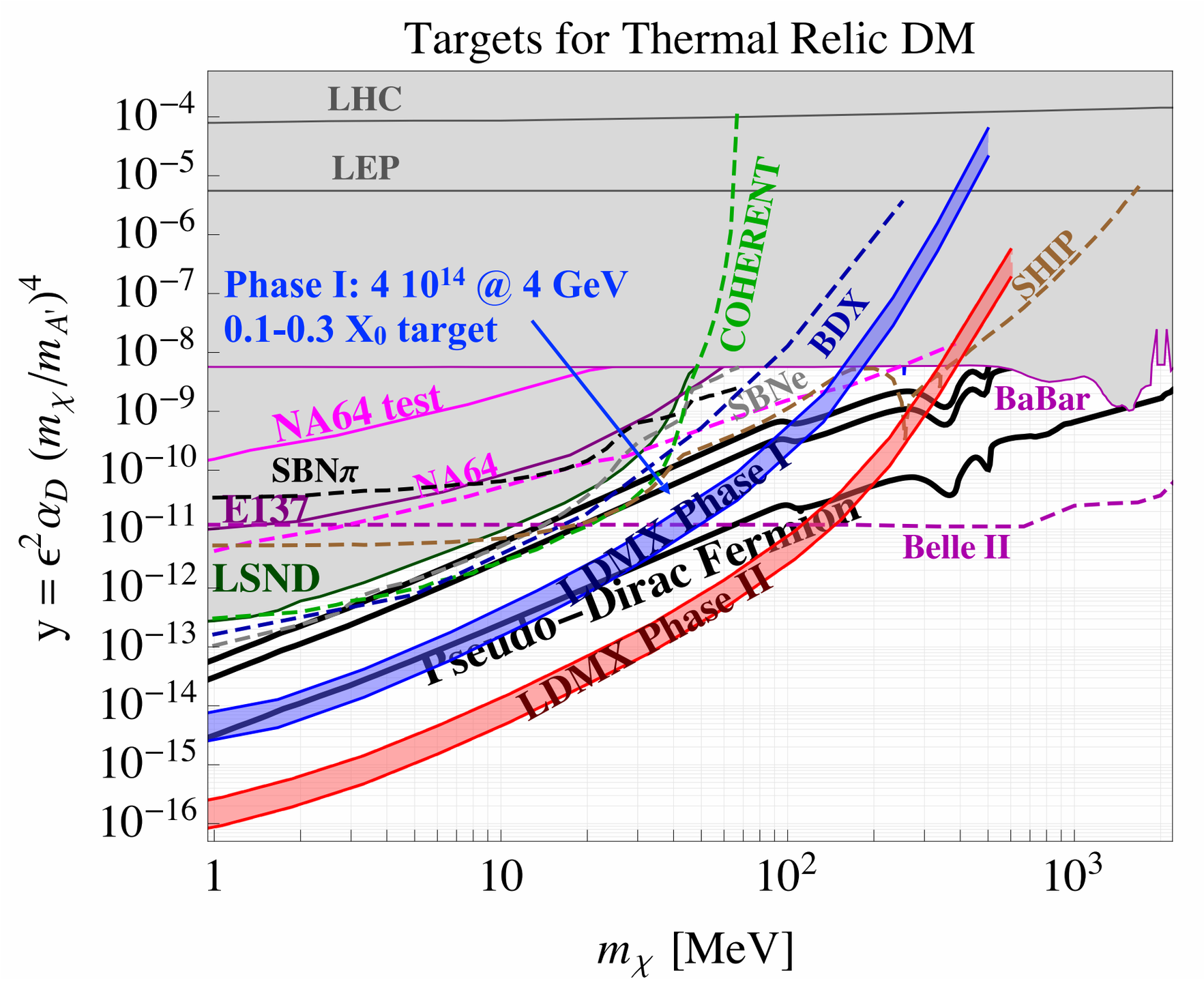
- beam requirements:
  - **multi-GeV**
    higher energy —> better S/B
  - **high rate**
    need 10^{14}-10^{16} electrons on target
  - **low current**
    “not too many” electrons per bunch



from T. Nelson

- DASEL@SLAC:
  - phase-I: 4 GeV, 46 MHz, O(1) e/bunch
  - phase-II: 8 GeV, 186 MHz, O(5) e/bunch

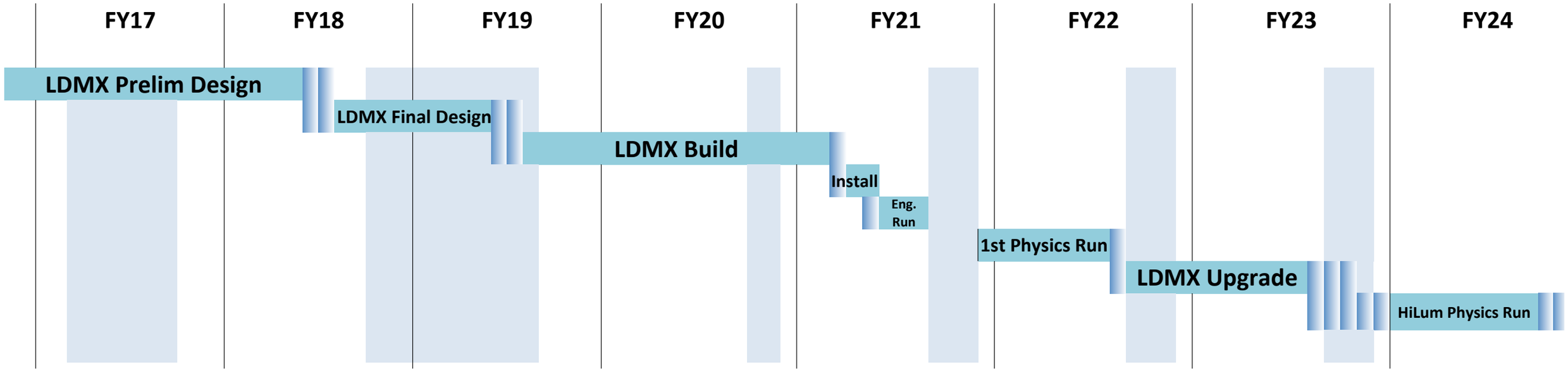
Sensitivity



- α_D = 0.5, $m_{A'}/m_\chi$ =3 (conservative, weakest bounds)
- unprecedented sensitivity and ability to test all thermal targets over most of the MeV - GeV range

Status and Plans

- from T. Nelson at **US Cosmics Vision Workshop**

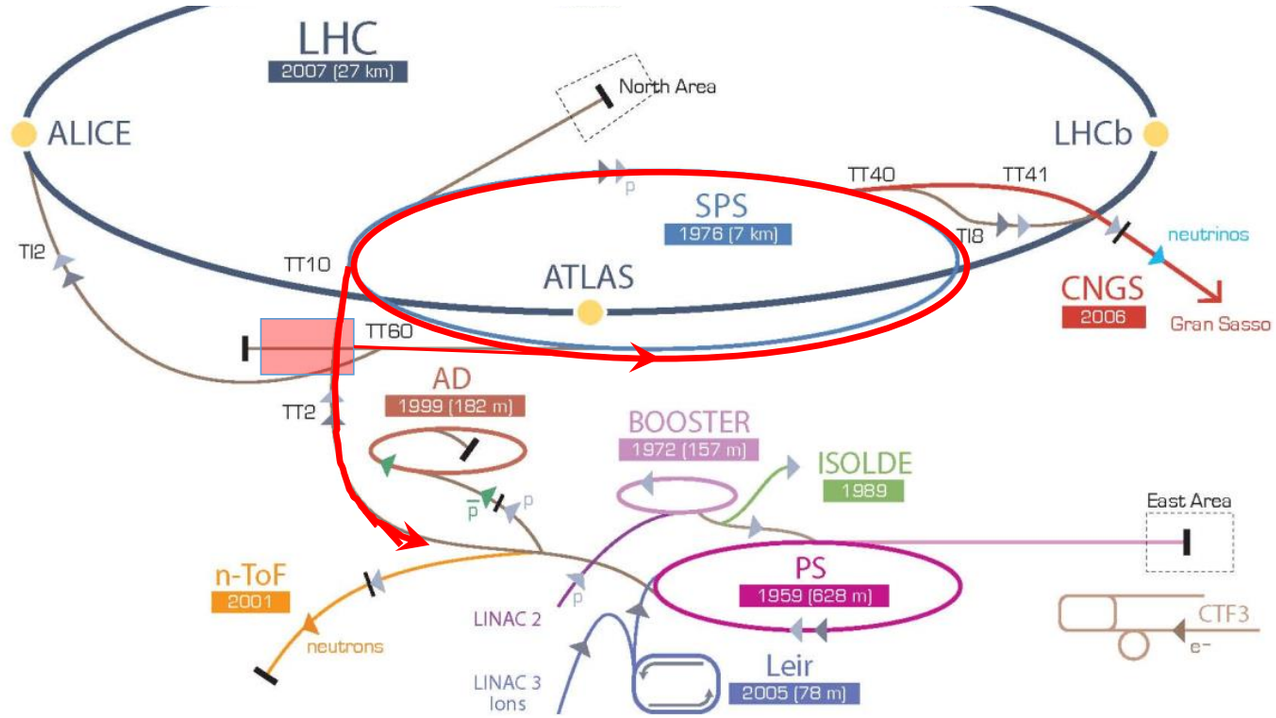


- collaboration meeting in May — finalise White Paper with updated design studies
- very positive feedback from SLAC particle physics
  - not approved yet, no major funding source secured yet

Other options?

- CEBAF@JLab (≤12 GeV)
- **CERN!**
  - initiative started by Torsten in fall, involving several of the CERN accelerator people
  - has been included in PBC group, P. Schuster representing LDMX in BSM WG
  - quite some momentum generated by now

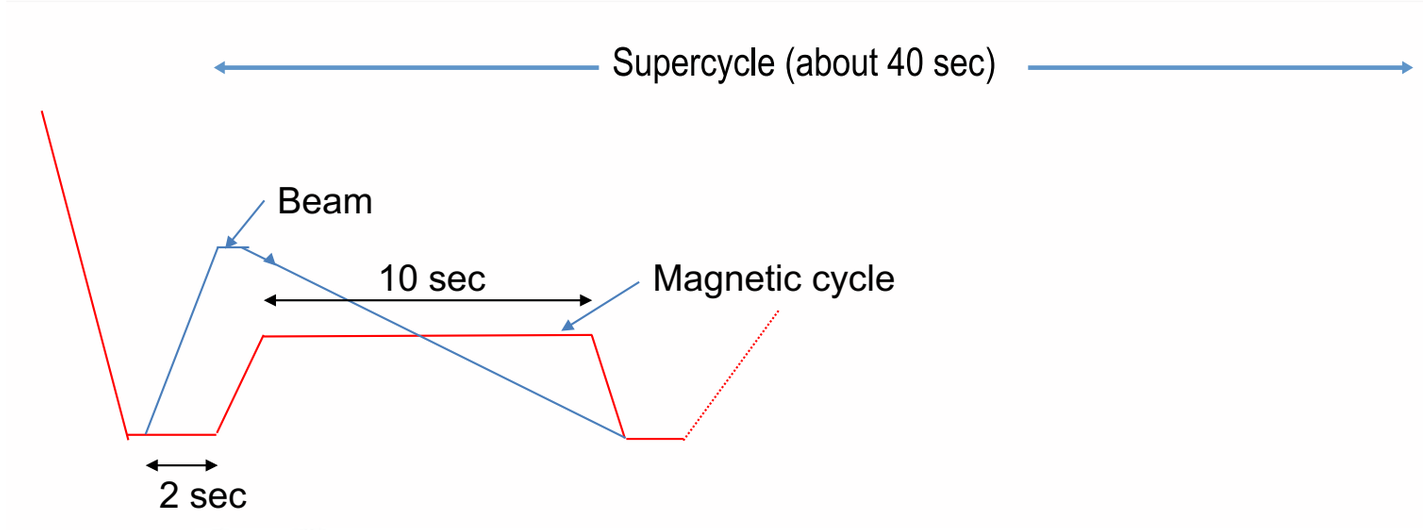
- current scenario:
  - LINAC as injector to SPS
  - fill SPS in ~2s every ~40s
  - accelerate to up to **16 GeV** in SPS
  - slow extraction (10s) to experiment(s)
    - 70 M CHF (w/o experiments)



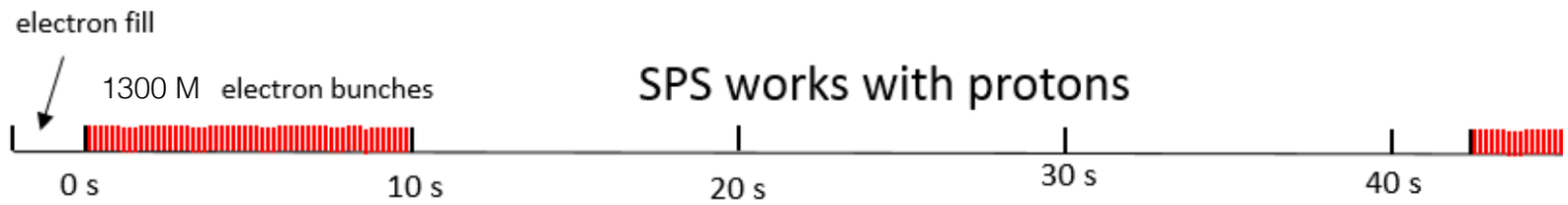
Current CERN Scenario

- 40 x 75 = 3000 bunches
  (5 ns spacing, 100 ns gap),
  n electrons/bunch

- ~40s SPS supercycle,
  10s for extraction of electrons



- SPS revolution frequency: 43 kHz
  - 43000*3000*n = 1.3e9*n electrons in 10s
  - (3600/40)*1.3e9*n electrons in 1h



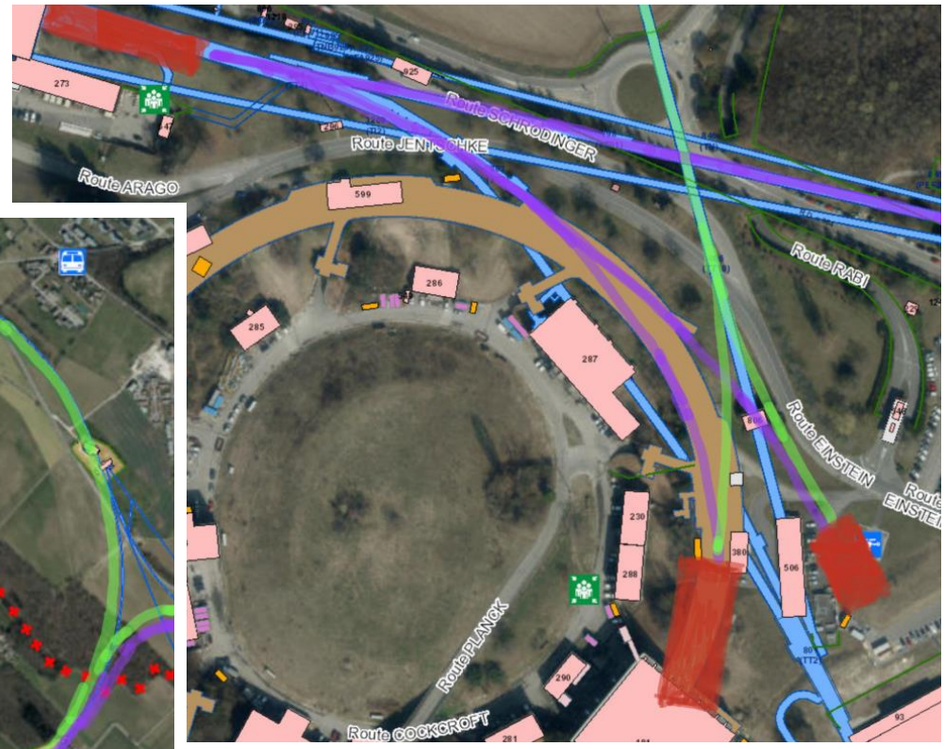
- assume 3000 h/y, 80% efficiency => EOT/y = 2.8e14 * n

  for 10^{16} EOT per year => n=36 => initial bunch intensity of 1.5e7

- n = 36 poses different challenges for experiment, spacing can be increased

Possible Beam Lines

- **LINAC** in TT5,TT4 (60 m, 3.5 GeV)
- acceleration in **SPS** to 16 GeV
- several other use cases for LINAC and SPS beams for R&D

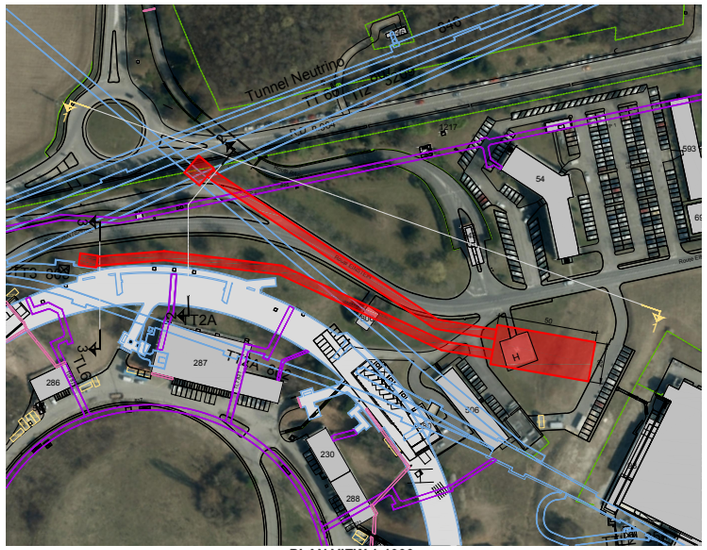


- extract beam to experiment(s) on Meyrin site (via TT10)

- timeline: could be ready 2023-2025

Possible Experiment Locations

OPTION 1

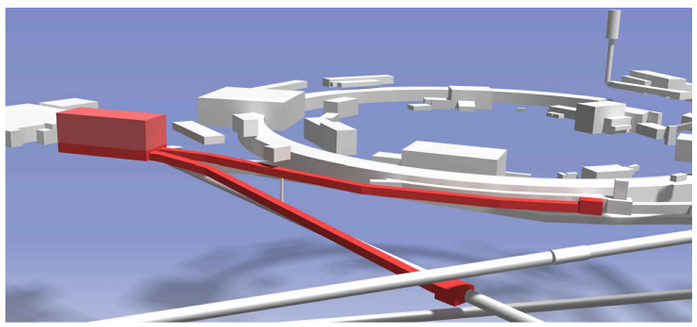


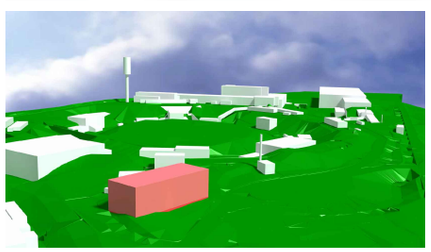
PLAN VIEW 1:1000

SECTION 1-1 1:1000

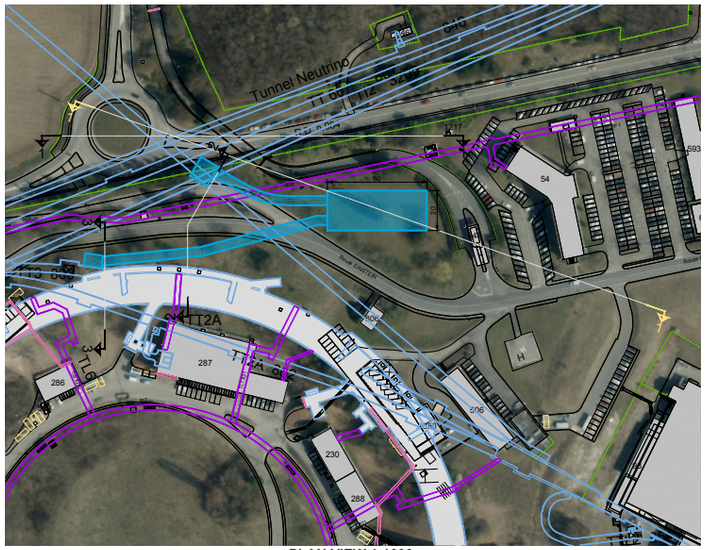
SECTION 2-2 1:500

SECTION 3-3 1:500





OPTION 2



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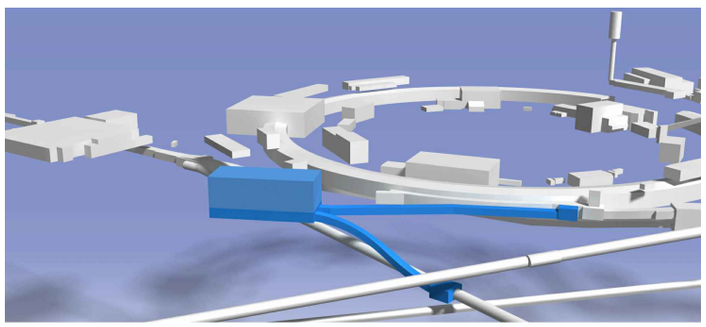
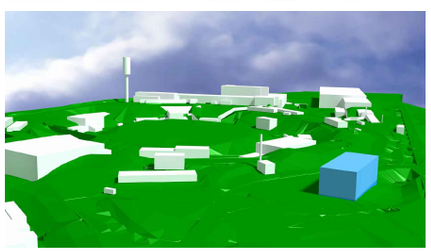
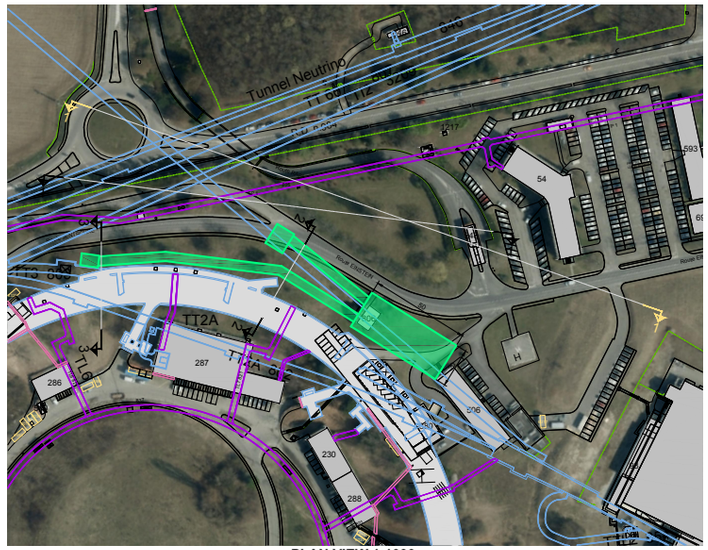




OPTION 3



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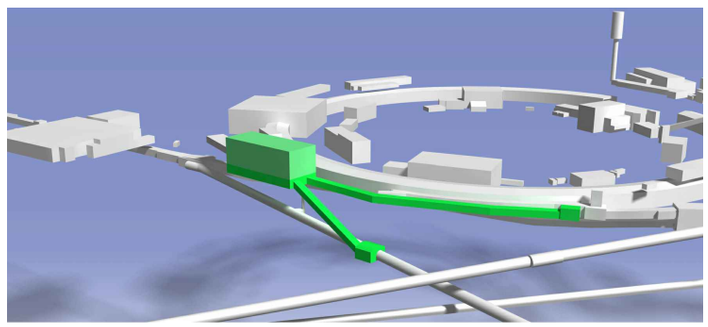
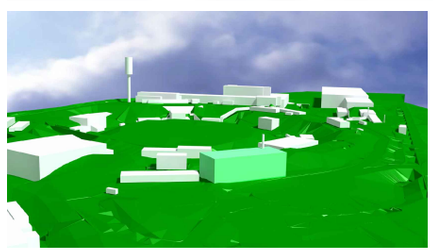




NOTE
Drawing for discussion: geometries and dimensions are provided as a guideline only.

e-SPS
DESIGN STUDY
23/02/2018 - DRAFT
Angel Navascues SMB-SE-DOP
SC: as indicated V0 - *23/02/2017*

Particle Physics Strategy

- DM aspects in strategy document so far mostly energy frontier/WIMPs

- should accelerator-based light dark matter searches (intensity frontier) be included as well?
  - we think yes

- electron beam at CERN will likely enter via PBC (activities picking up there)

Summary

- light, thermal relic Dark Matter well motivated
- fixed-target, missing-momentum approach provides best sensitivity
- LDMX the only such experiment on the horizon
  - start of data-taking in early 2020s

- great opportunity at CERN for very interesting electron beam programme
  - accelerator R&D
  - LDMX + other experiments addressing important physics questions
  - "too good to be missed"

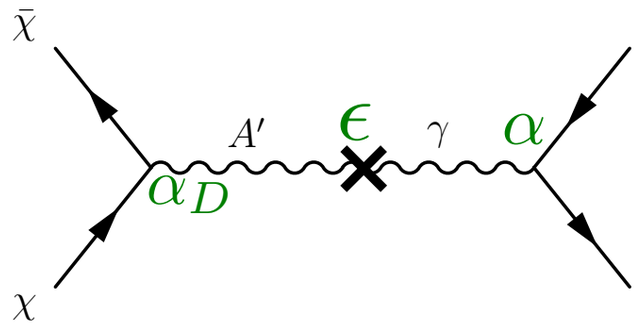
Additional Material

The Model

- thermal relic —> mass constraint & minimum annihilation cross section
  - WIMP too light —> annihilation inefficient —> overproduction of DM
    - Lee-Weinberg bound: m_χ > some GeV

- new, light mediator —> additional annihilation channels
  - widely-used minimal but representative model:

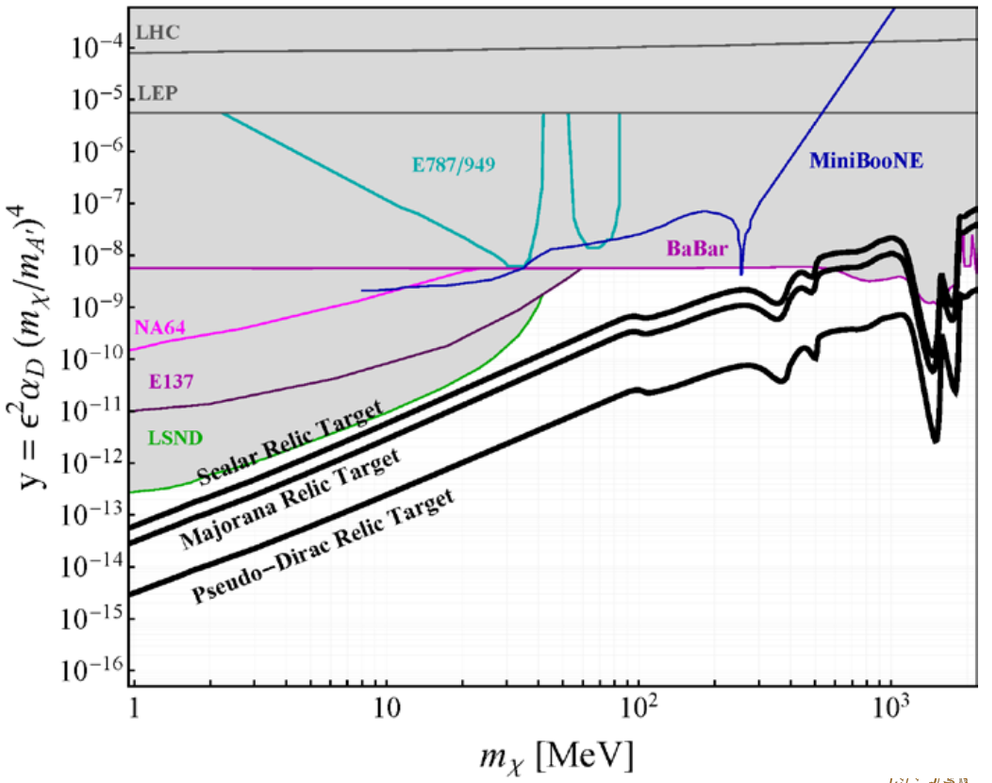
    Dark Photon, A' (vector mediator)



  - kinetic mixing with SM photon (ε)
  - $m_{A'} > 2m_\chi$: **invisible** decay into DM
  - annihilation cross section ~ y * m_χ^{-2}

$$y = \varepsilon^2 \alpha_D (m_\chi / m_{A'})^4$$

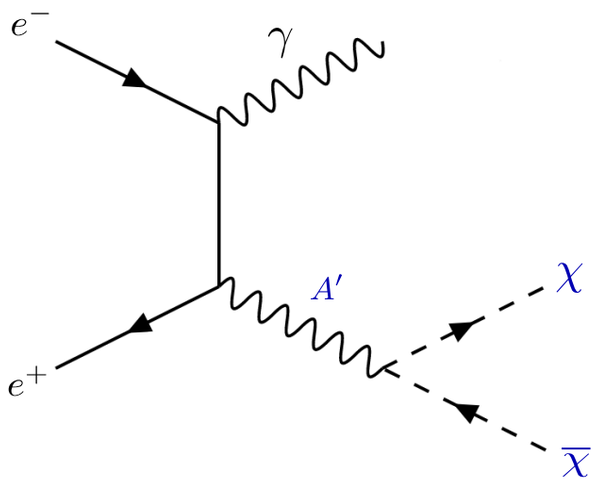
  - clear *'thermal targets'* in y-mass-plane



Why fixed-target?

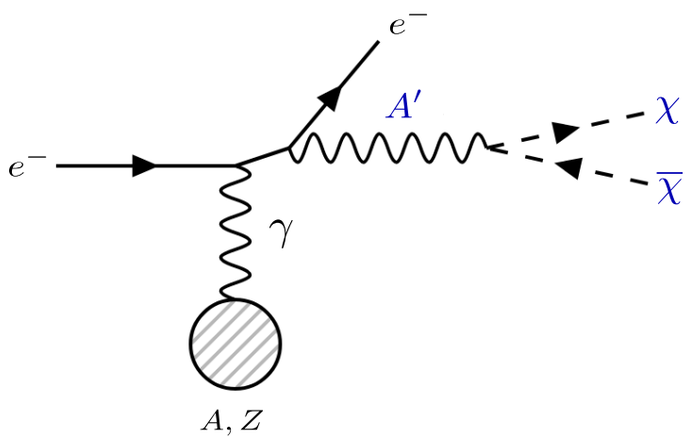
- maximise DM yield (**production** & detection **efficiency**)

- collider
  ($m_{A'} << E_{cm}$)

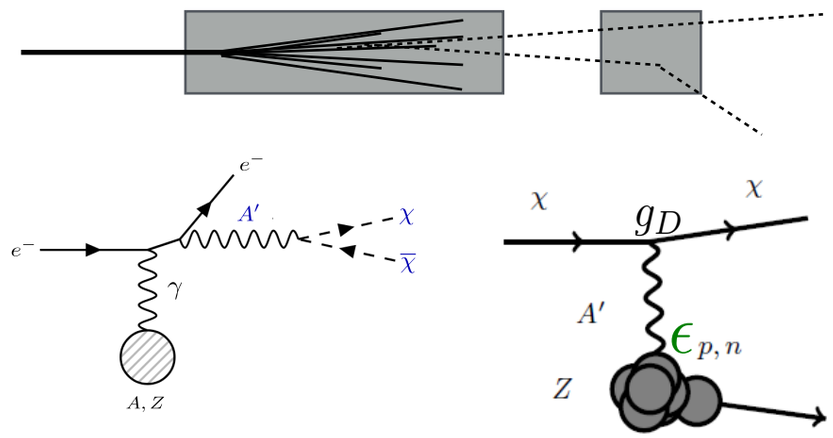


- fixed target

dark bremsstrahlung



- beam-dump



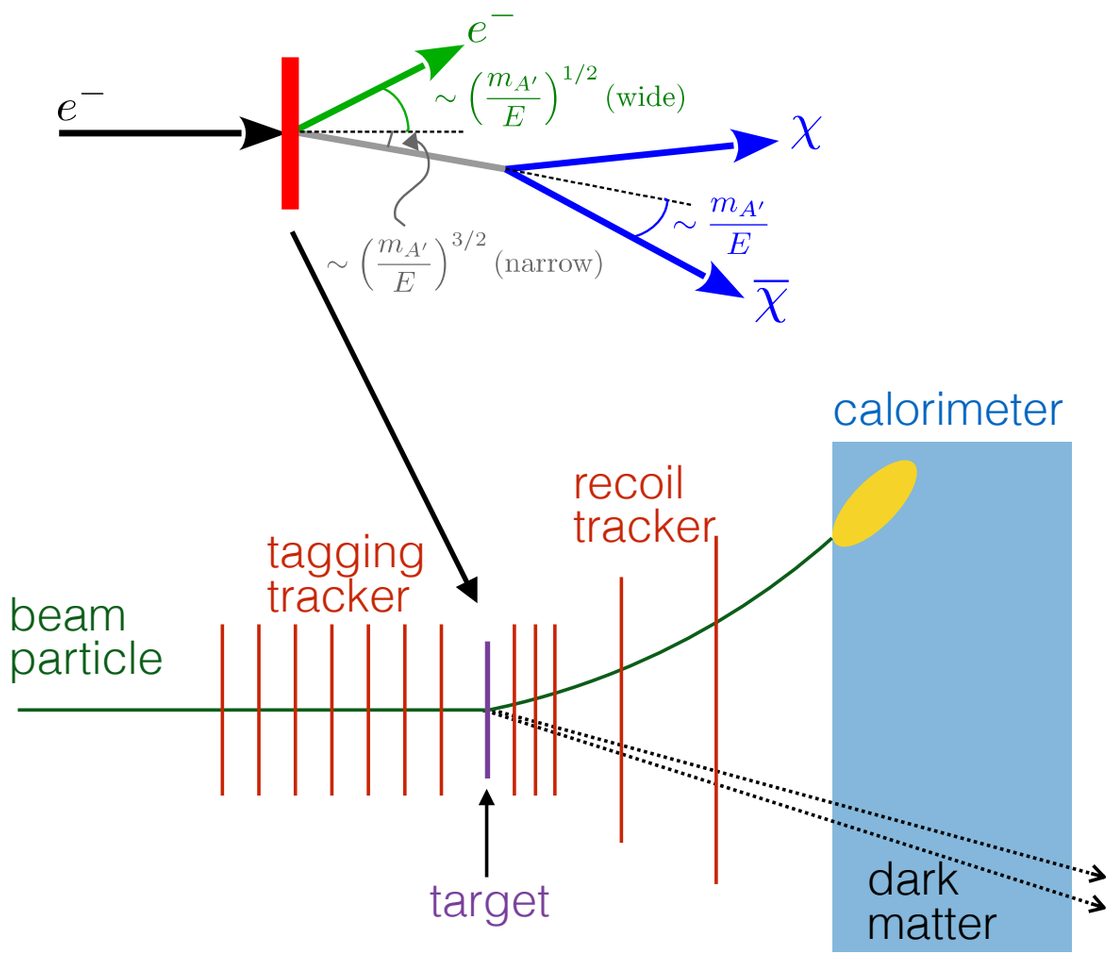
$$\sigma_{\text{coll}} \propto \frac{\varepsilon^2}{E_{\text{cm}}^2} \quad \ll \quad \sigma_{\text{FT}} \propto \frac{Z^2\varepsilon^2}{m_{\text{A'}}^2}$$

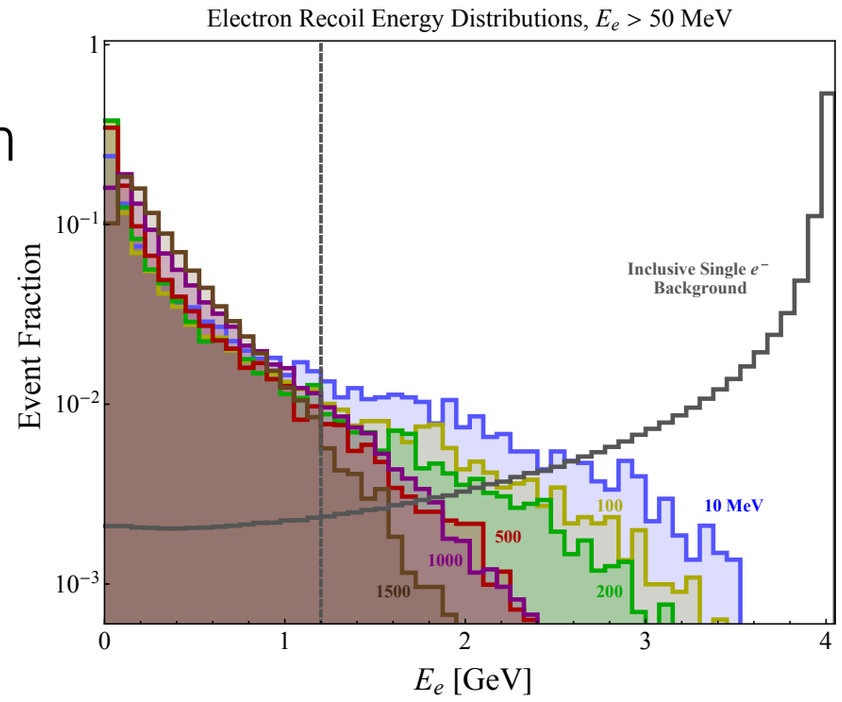
$$\frac{\sigma_{\text{FT}}}{\sigma_{\text{coll}}} \propto Z^2\left(\frac{E_{\text{cm}}}{m_{\text{A'}}}\right)^2 \quad >> 1$$

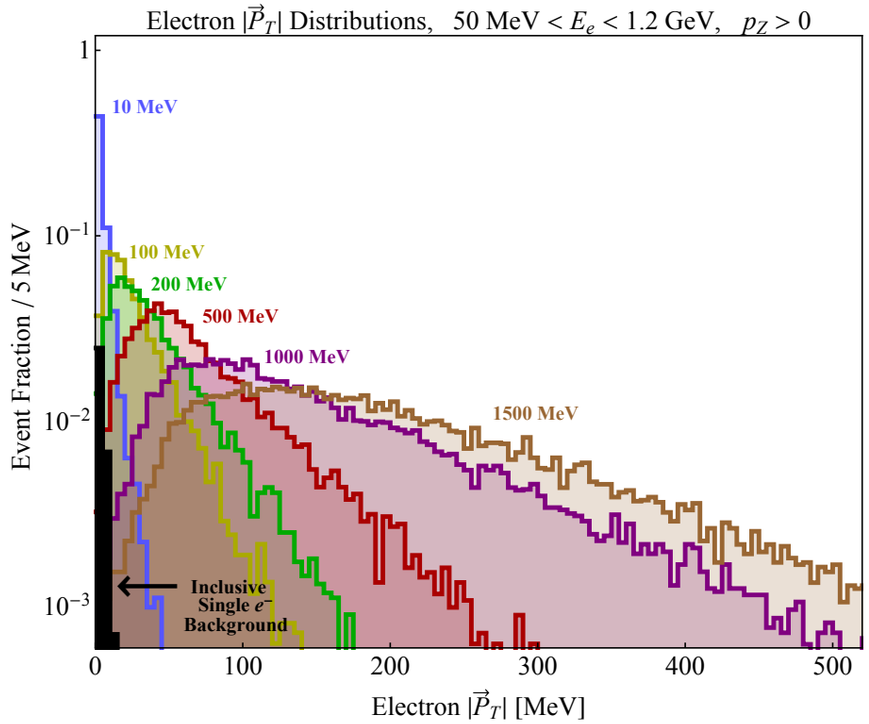
$$N \propto \varepsilon^2(1-\varepsilon^2) \approx \varepsilon^2 \quad \gg \quad N \propto \varepsilon^4$$

Kinematics & Experimental Layout

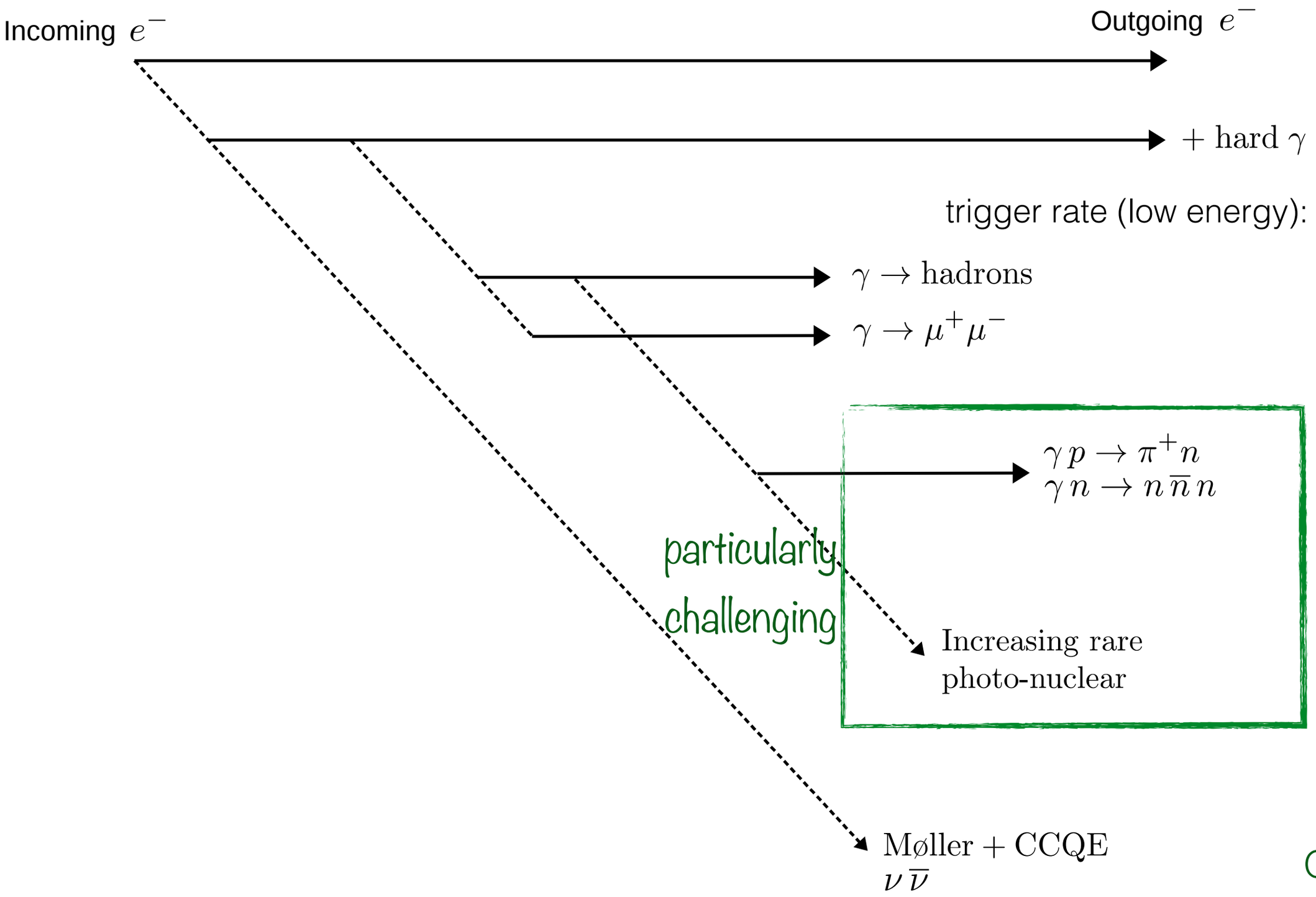
- due to mass of mediator, kinematics distinctly different from SM bremsstrahlung
  - mediator carries most of the energy
    —> soft recoil electron, large missing momentum
  - recoil electron gets transverse ‘kick’
    —> large missing transverse momentum







Background Challenges



40 MHz

MHz

10 kHz

O(100) Hz

O(few/hour)

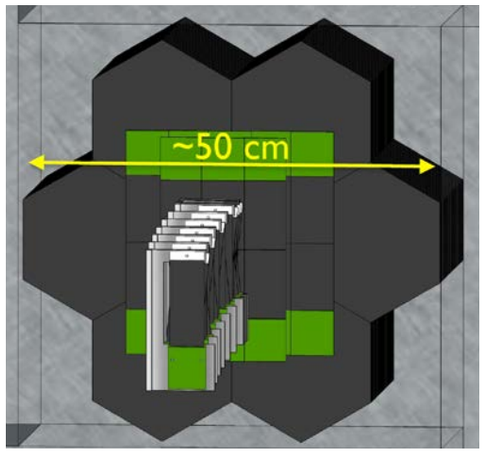
O(1/many years)

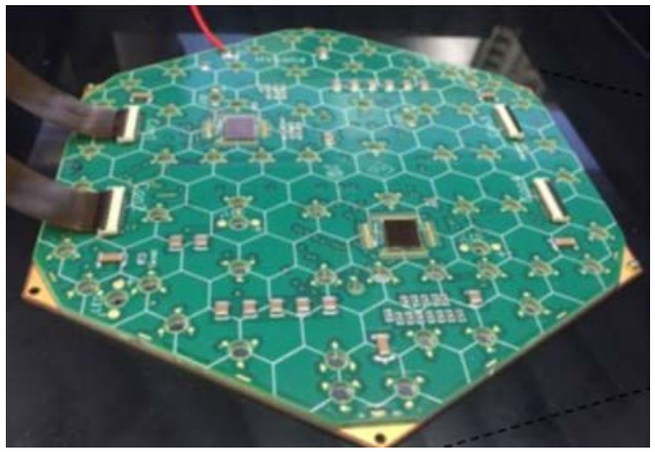
Electromagnetic Calorimeter (ECal)

- to achieve large number of electrons on target (10^{14}-10^{16}): **high-rate beam** (1e/few ns)
  - candidates: DASEL at SLAC (4/8 GeV), CEBAF @ JLab (≤12 GeV)

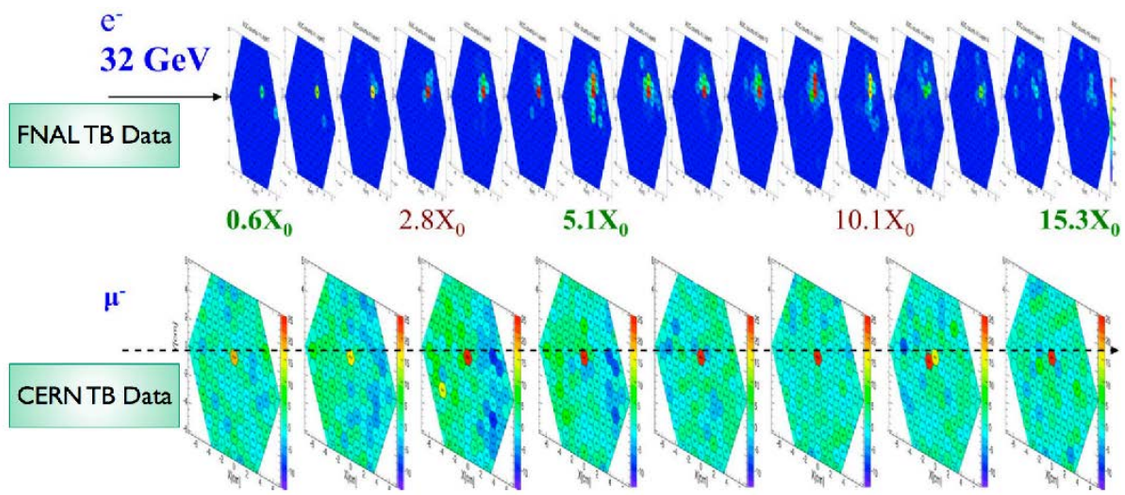
- ECal shopping list:
  - fast
  - radiation hard
  - dense
  - high-granularity
  - deep (containment)

very similar to forward SiW sampling calorimeter for CMS@HL-LHC → design based on this





- in LDMX:
  - 40 radiation lengths deep
  - 30 layers, 7 modules each
  - central modules with higher granularity (up to 1000 channels)
    - PCBs to be designed in Lund
  - high granularity allows MIP 'tracking' —> important tool in background suppression



Hadronic Calorimeter (HCal)

- essential **veto** instrument
- goal: catch ~everything that makes it out of the ECal
  - in particular: photo-nuclear reactions that produce only neutral particles
    - e.g. $\gamma n \rightarrow nn\bar{n}$
- surround ECal as much as possible
- be as efficient as possible for both low- and high-energy neutrons
  - baseline: **plastic scintillator + absorber** (steel)
  - design optimisation studies ongoing
    - materials
    - geometry
    - dimensions (largest piece of the experiment)
    - configurations of scintillator/sampling
- develop **in-situ verification** of veto power

Further Potential

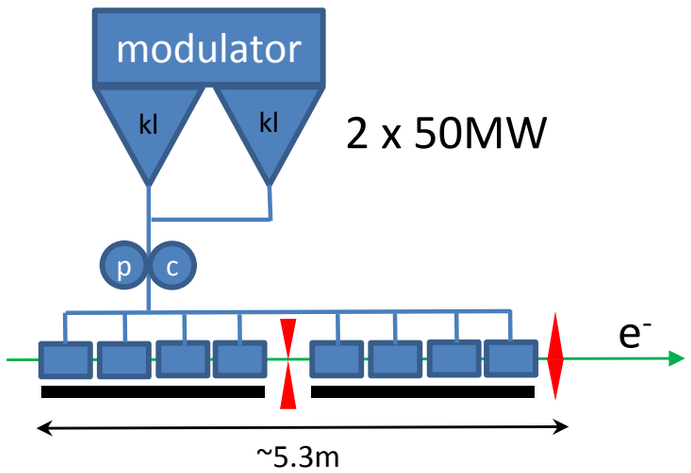
- also sensitive to
  - DM with quasi-thermal origin (asymmetric DM, SIMP/ELDER scenarios)
  - new invisibly decaying mediators in general, improve sensitivity for Dark Photon
  - displaced vertex signatures from DM co-annihilation or SIMP model
  - milli-charged particles

- plus measurement of photo- and electro-nuclear processes (for future neutrino experiments)

- from Steinar Stapnes

X-band linac layout

Make use of study recently made for LNF ~1.0 GeV X-band linac
"CLIC-like" RF unit: 2*(klystron+modulator) + pulse compressor + 8 accelerating structures



2 x 50MW

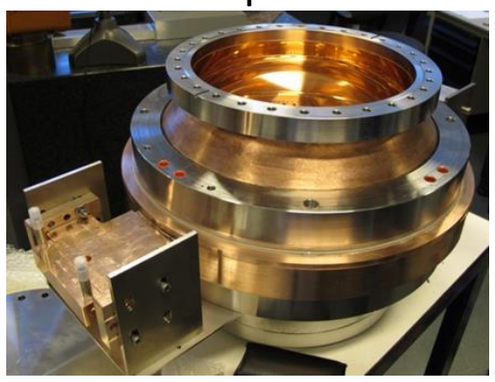
Klystron

+

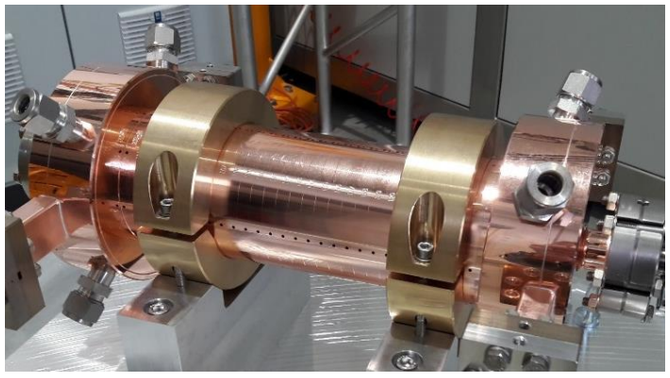
Modulator

- One "CLIC-like" type RF unit accelerates 200ns bunch train up to 264 MeV*
- 11 RF units to get to 2.9 GeV in ~60 m

Pulse compressor



Accelerating structure

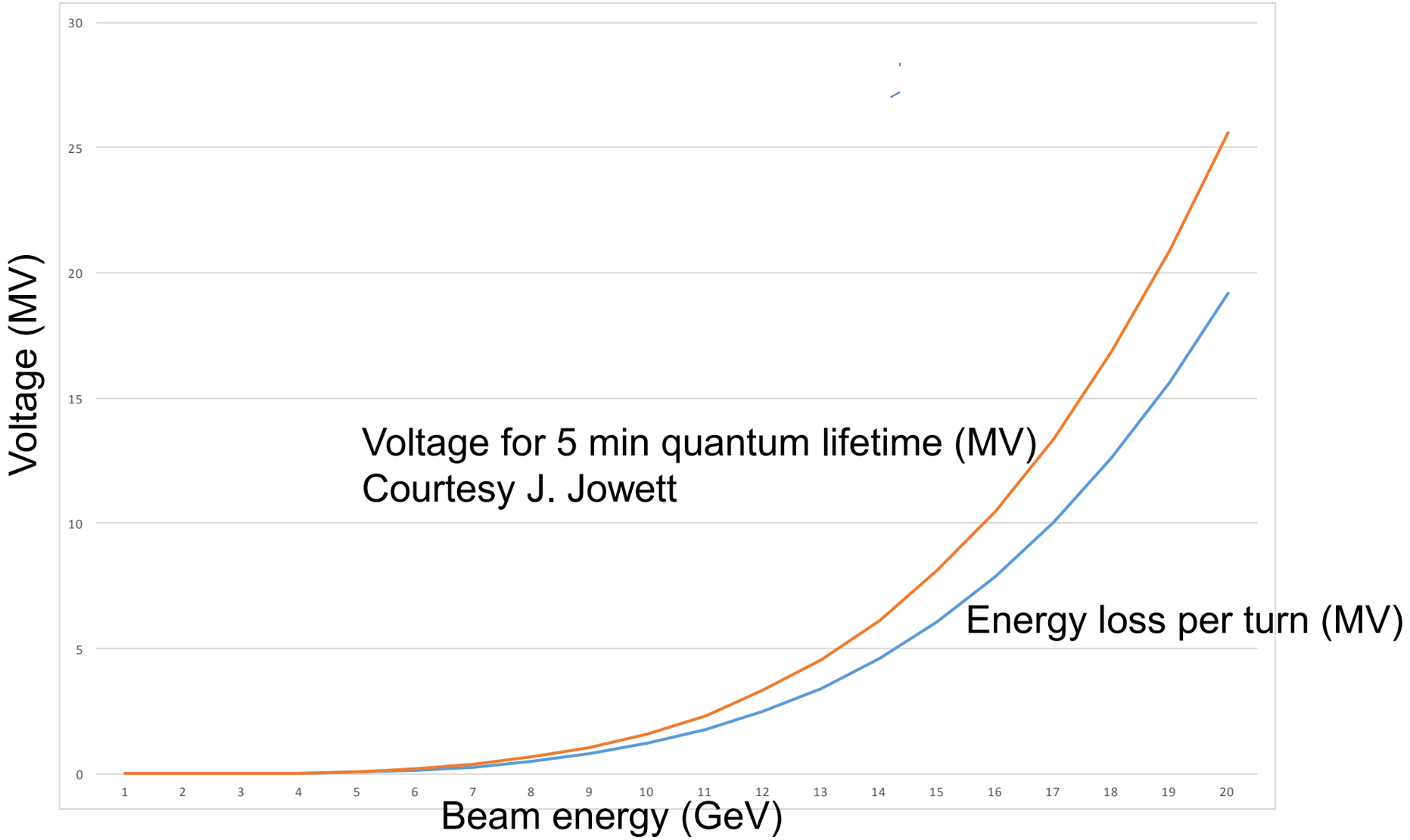


* (lower than for Frascati single bunch operation: 336 MeV/unit)

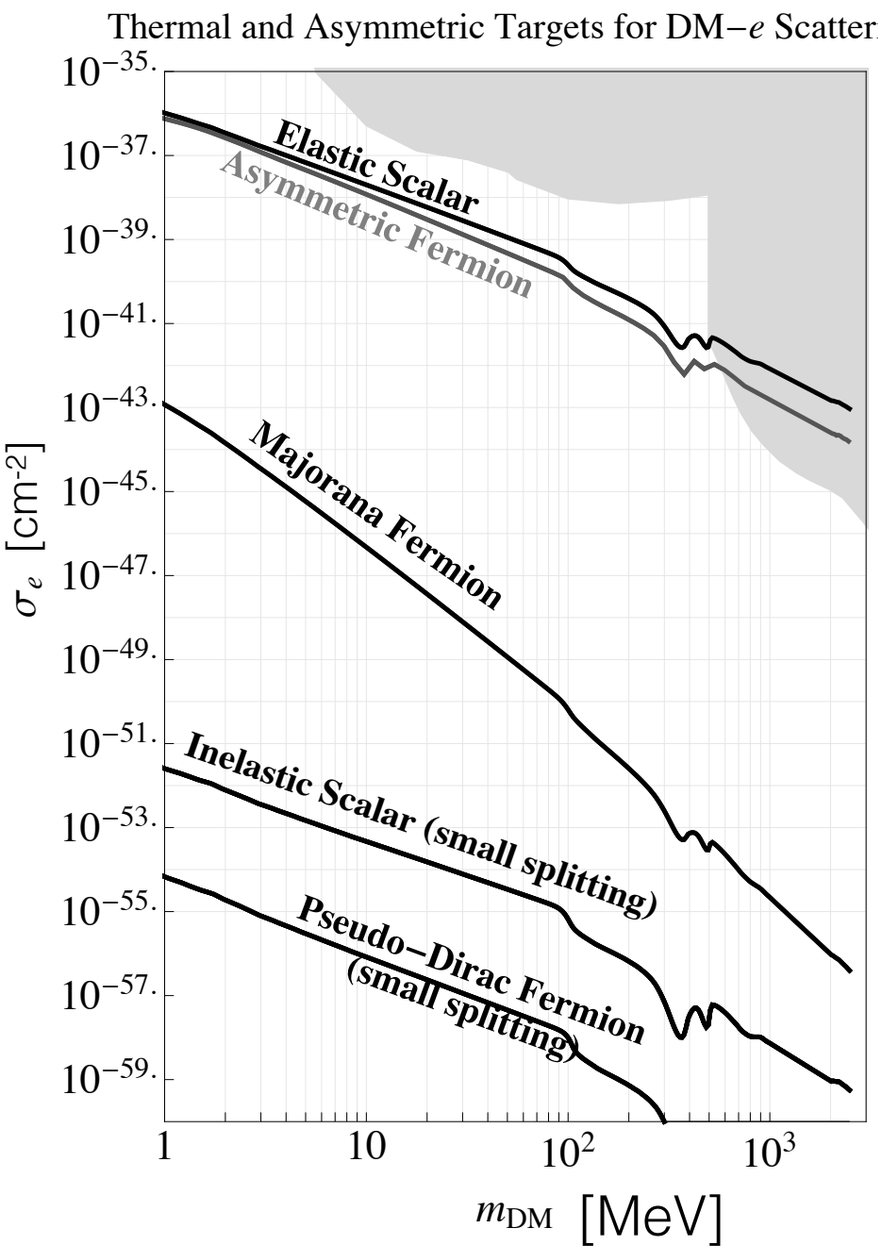
Energy

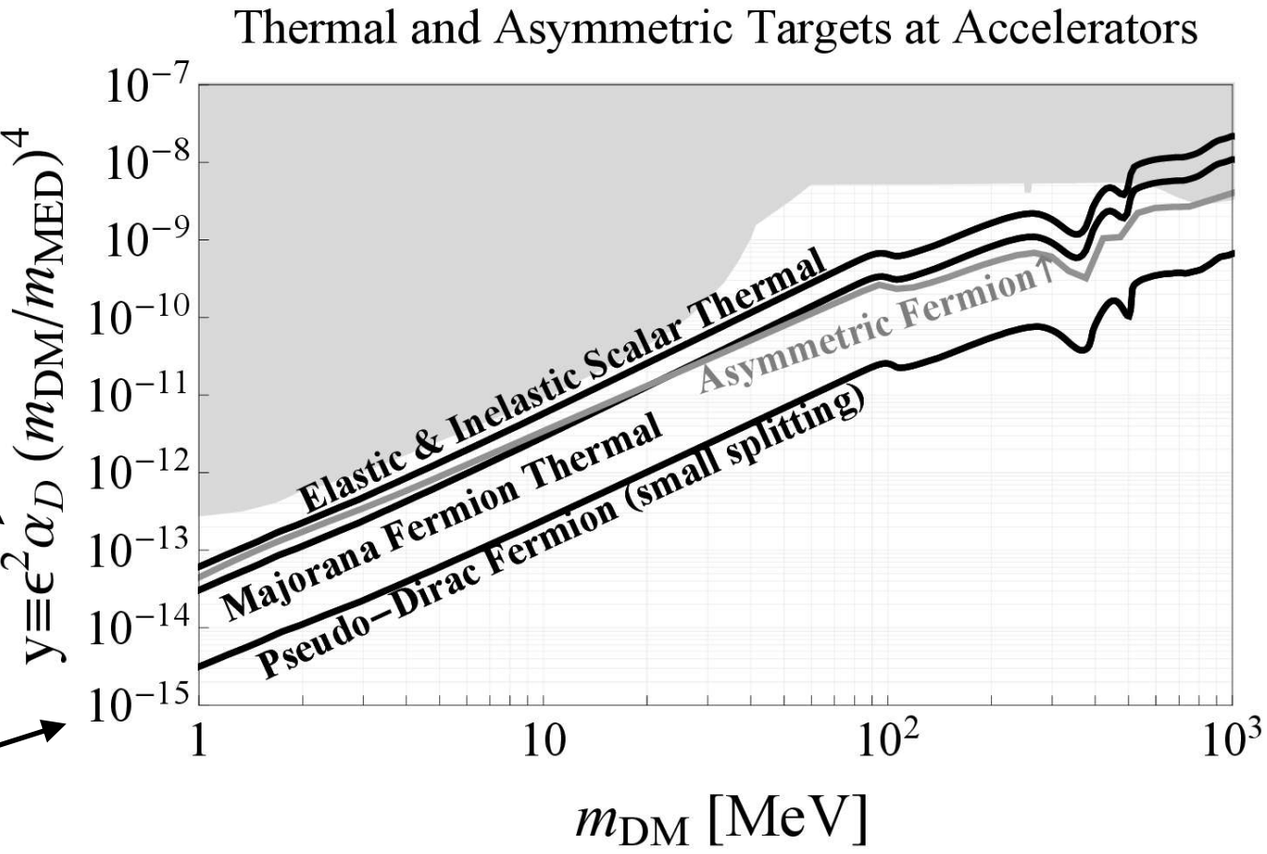
- from Steinar Stapnes

RF voltage in the SPS



Direct Detection and Accelerators

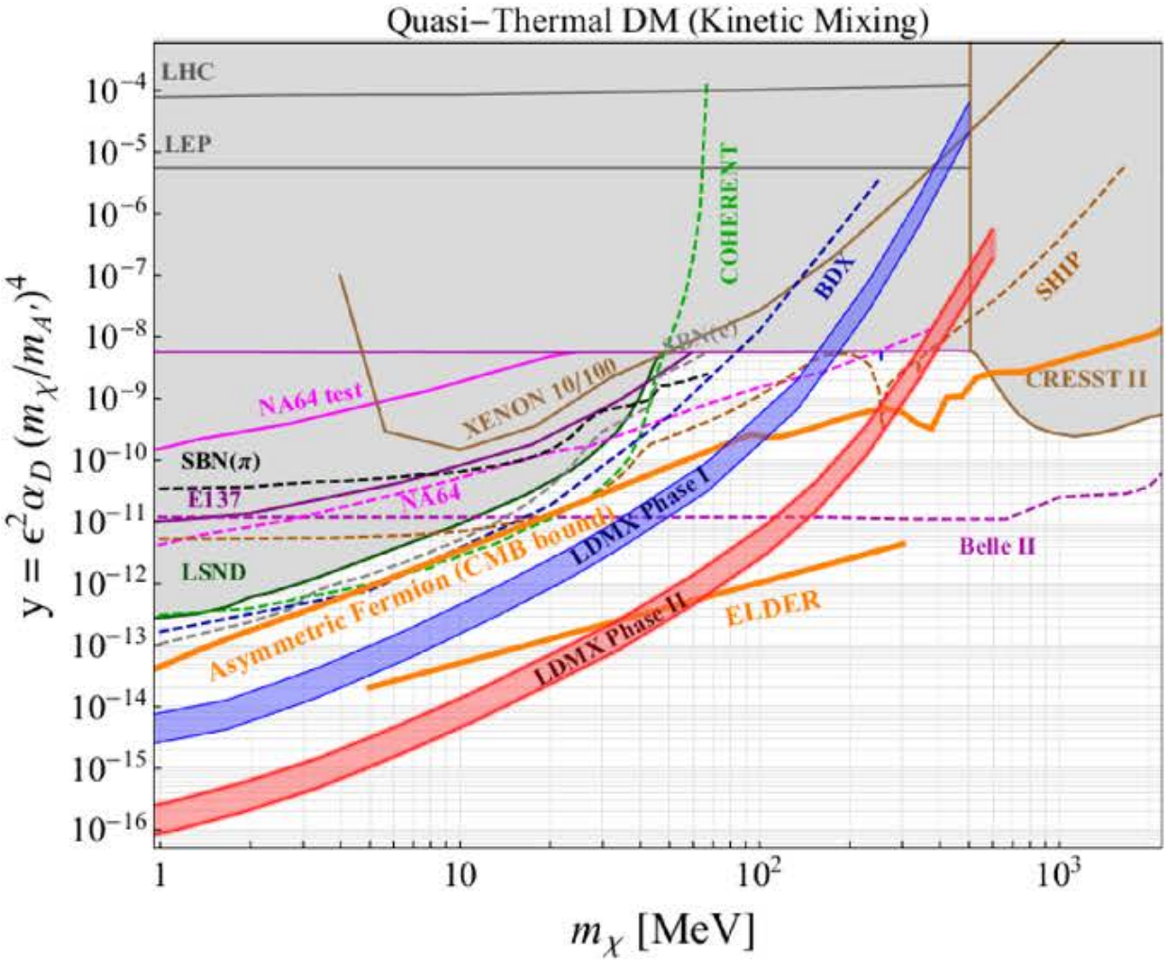




- at accelerators: relativistic production
  —> much smaller velocity/spin dependence
  - thermal targets are all in reach!

Further Potential

- explore DM with quasi-thermal origin (asymmetric DM, SIMP/ELDER scenarios)



- improve sensitivity for invisibly decaying Dark Photon