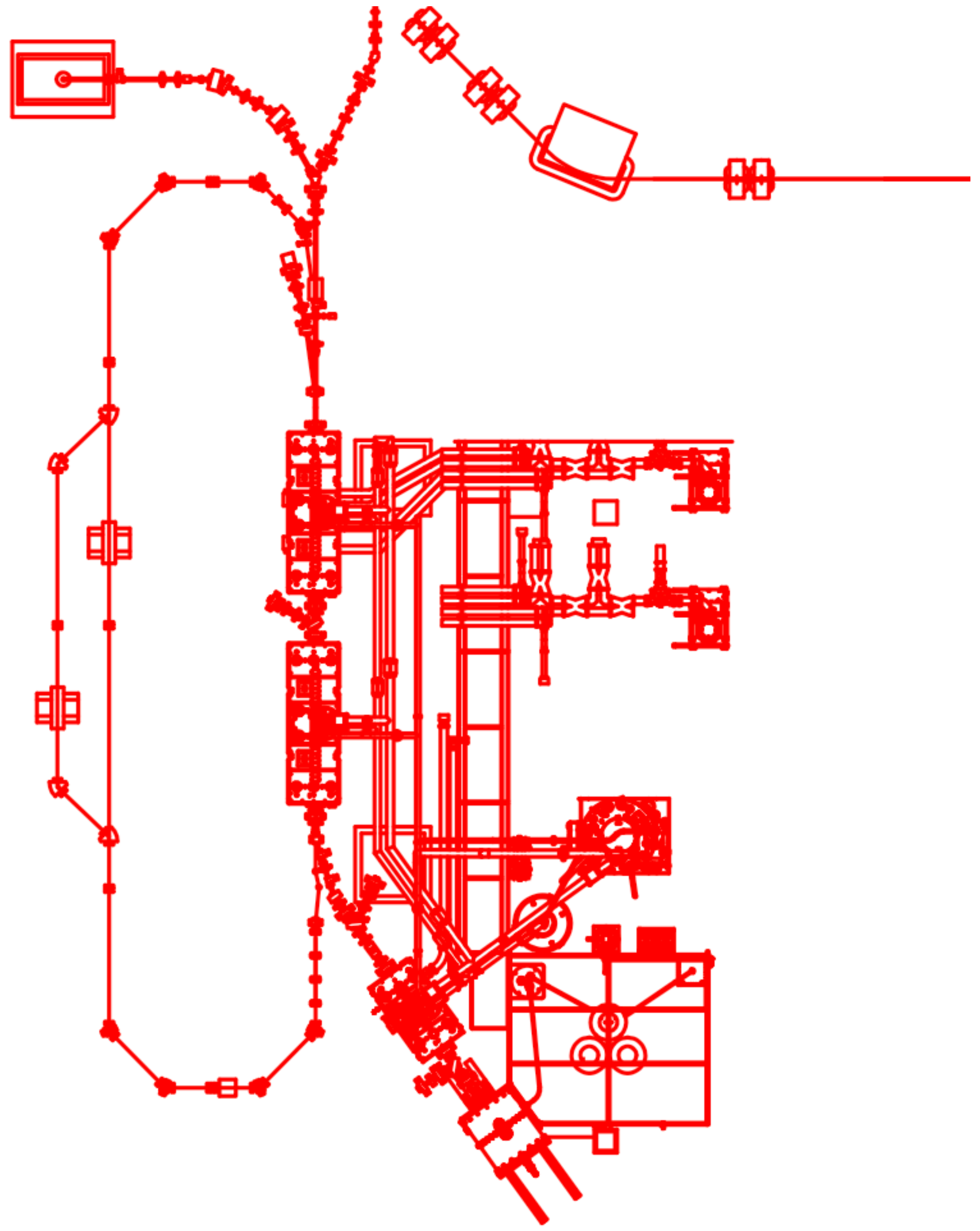
Opportunities with the ARIEL e-linac WG summary



ELECTRON HALL

Print | Full screen | Filter

14:00	**Electron beams and new physics**	*Brian BATELL*	*https://ca01web.zoom.us/j/69998354433 (password: 972986)*	14:00 - 14:30
	Electron beam dump experiments	*Dr. Luca DORIA*	*https://ca01web.zoom.us/j/69998354433 (password: 972986)*	14:30 - 15:00
15:00	**Discussion**		*https://ca01web.zoom.us/j/69998354433 (password: 972986)*	15:00 - 15:30
	Break		*https://ca01web.zoom.us/j/69998354433 (password: 972986)*	15:30 - 16:00
16:00	**The DarkLight experiment**	*Jan BERNAUER*	*https://ca01web.zoom.us/j/69998354433 (password: 972986)*	16:00 - 16:30
	Electron beams and missing momentum	*Nikita BLINOV*	*https://ca01web.zoom.us/j/69998354433 (password: 972986)*	16:30 - 17:00
17:00	**Discussion**		*https://ca01web.zoom.us/j/69998354433 (password: 972986)*	17:00 - 17:30

See also plenary talks by O. Kester & J. Dilling

David McKeen

DND2020 Nov 6 2020

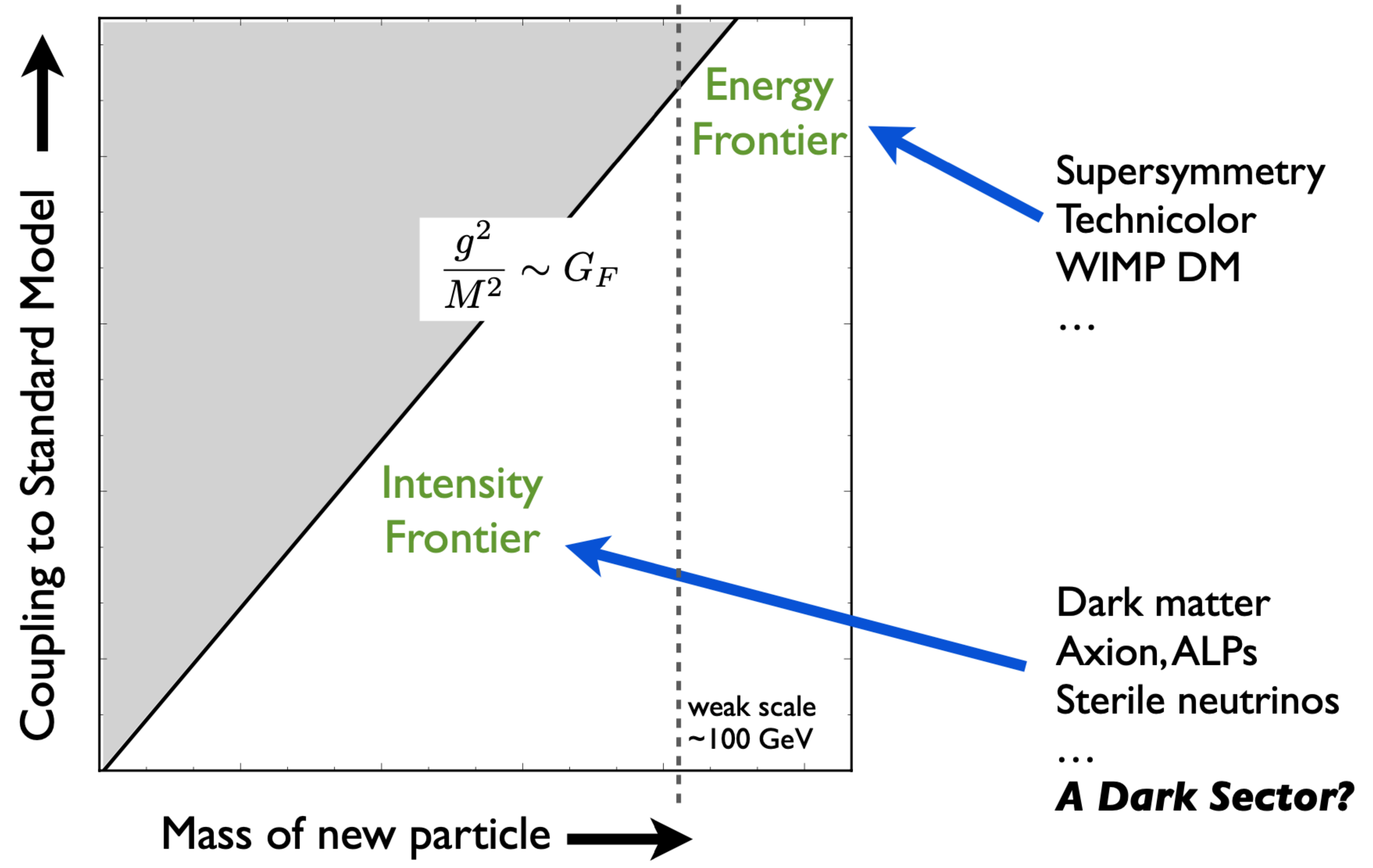
Electron Beams and New Physics

Brian Batell
University of Pittsburgh

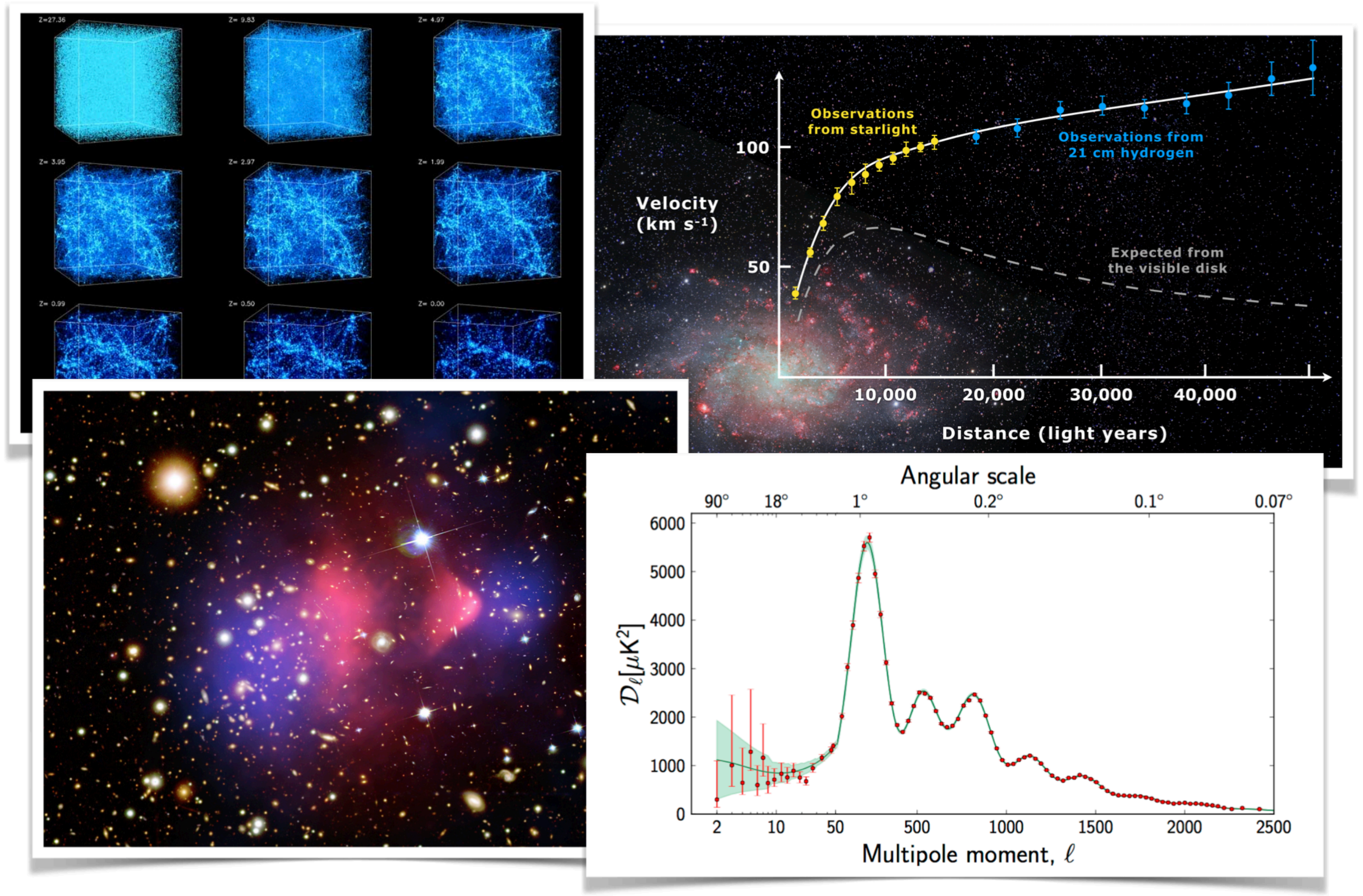
$$M_{\rm Pl} \sim 10^{19}\,{\rm GeV}$$
$$M_{\rm GUT} = ?$$
$$M_N = ?$$
$$M_{\rm Flavor} = ?$$
$$M_{\rm SUSY} = ?$$
$$v_{\rm EW} \sim 100\,{\rm GeV}$$
$$\Lambda_{\rm QCD} \sim 1\,{\rm GeV}$$
$$\rho_{\rm vac}^{1/4} \sim 10^{-3}\,{\rm eV}$$

See also plenary talks by Rajendran & Baryakhtar

Where is the New Physics?



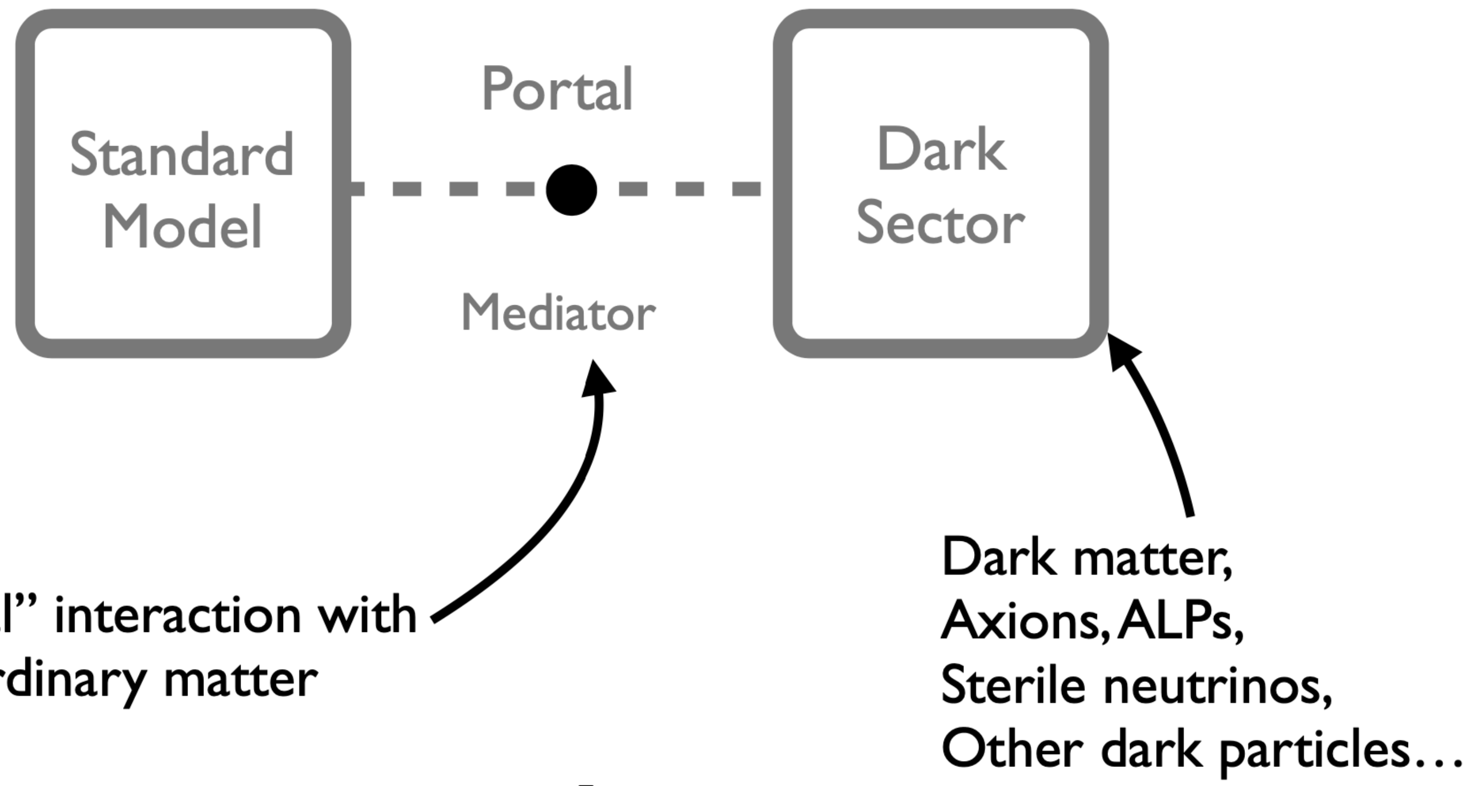
Dark Matter



DM in thermal contact at early times has interesting implications

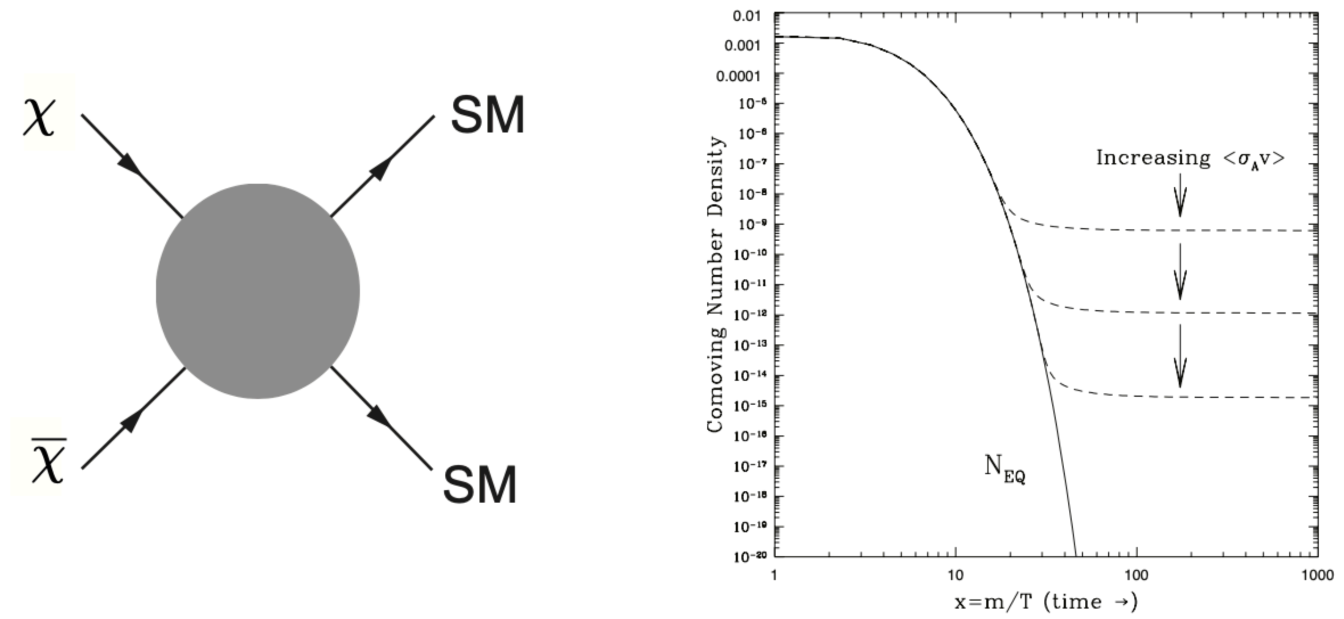
Light DM needs new interactions for this to be viable⇒portals &dark sectors

The Dark Sector Paradigm

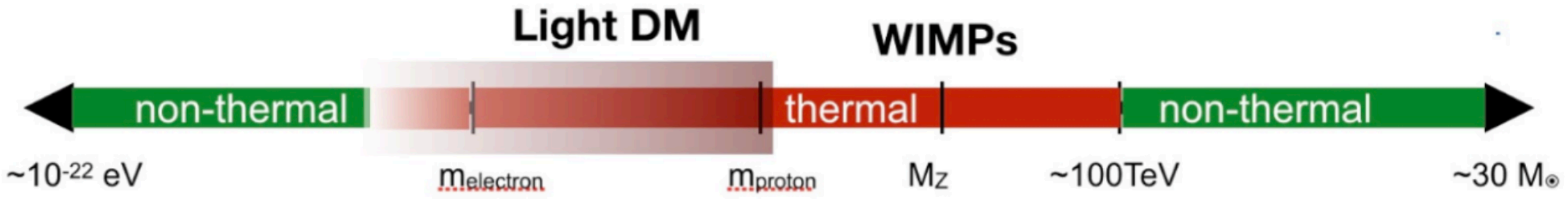


Thermal Freezeout

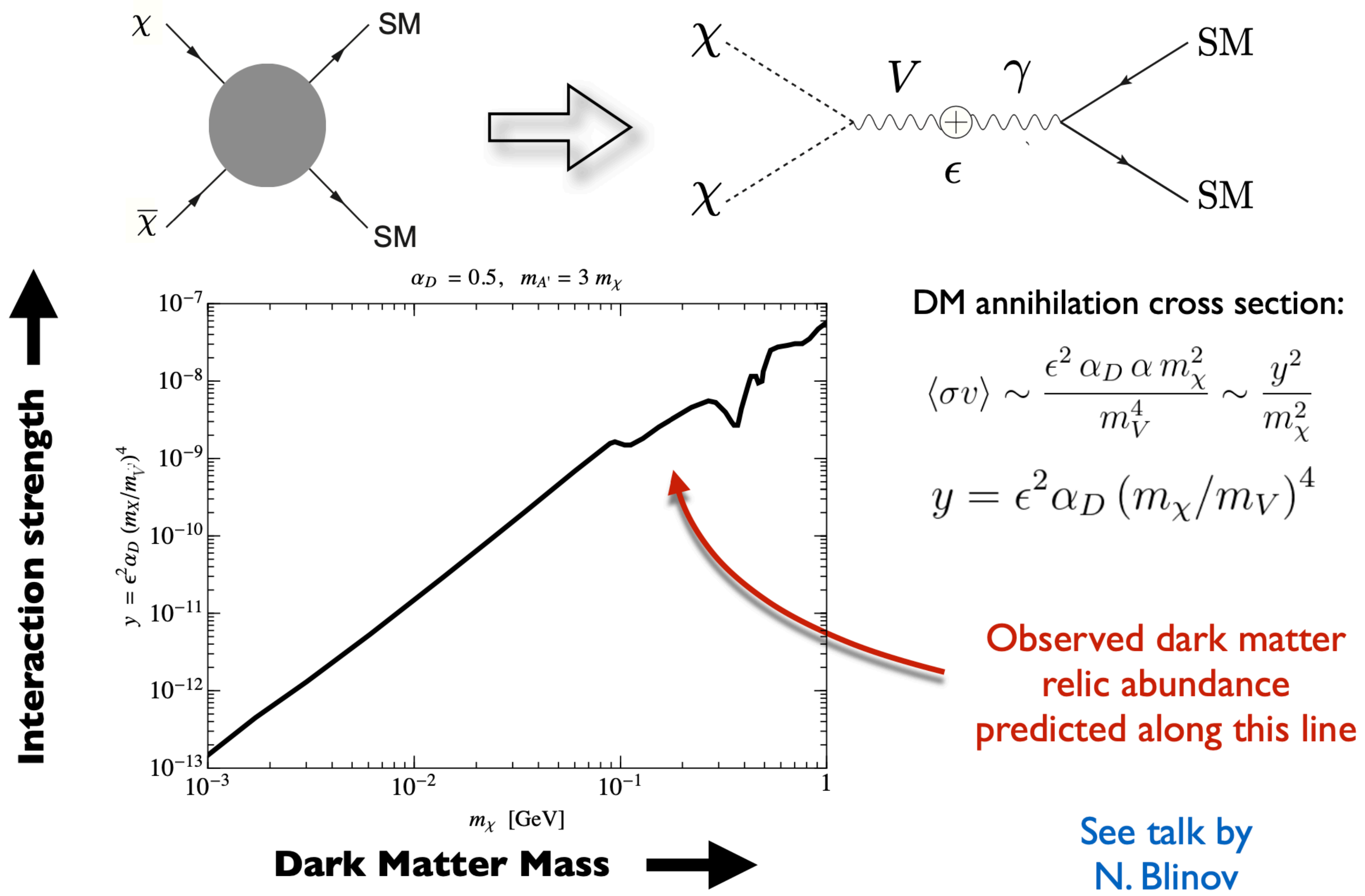
- Dark matter produced from reactions in the plasma during the Big Bang
- Requires *non-gravitational* dark matter interactions



- Viable mass range between MeV - 100 TeV in simplest scenarios



Relic Abundance of Vector Portal Dark Matter



DM annihilation cross section:

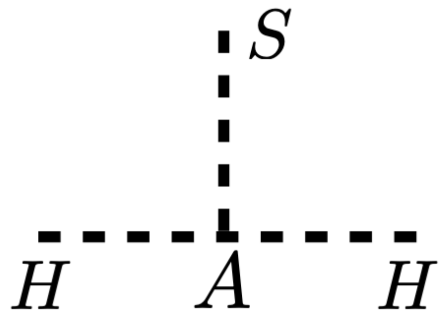
$$\langle\sigma v\rangle \sim \frac{\epsilon^2\,\alpha_D\,\alpha\,m_\chi^2}{m_V^4} \sim \frac{y^2}{m_\chi^2}$$

$$y = \epsilon^2\alpha_D\,(m_\chi/m_V)^4$$

See talk by N. Blinov

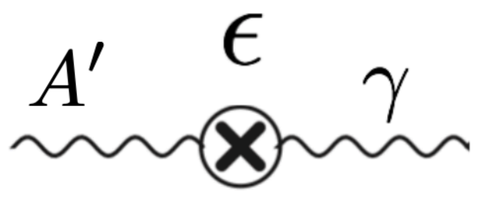
Renormalizable Portals

$AH^\dagger HS$



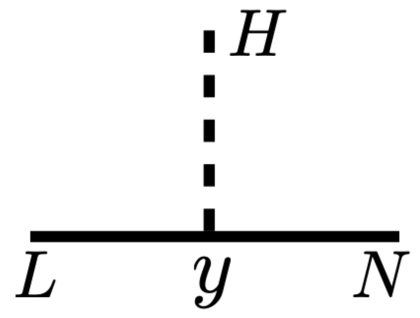
Higgs Portal

$\frac{\epsilon}{2}F_{\mu\nu}F'^{\mu\nu}$



Vector Portal

$yLHN$

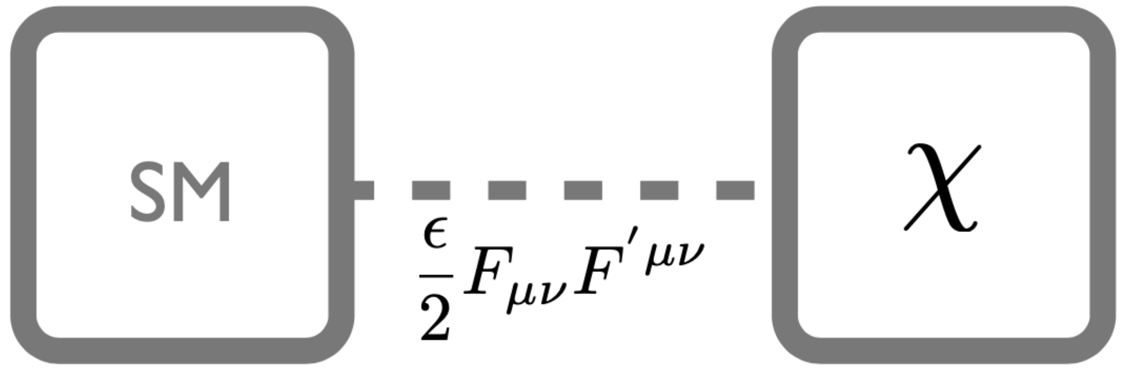


Neutrino portal

Vector portal ("dark photon") is a very nice benchmark⇒

⇐Lots of interest in a handful of "portals"

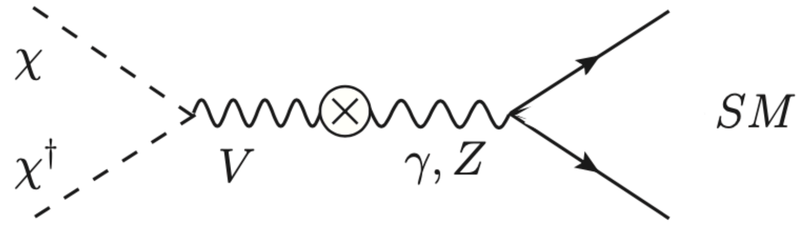
Benchmark Model: Vector Portal Dark Matter



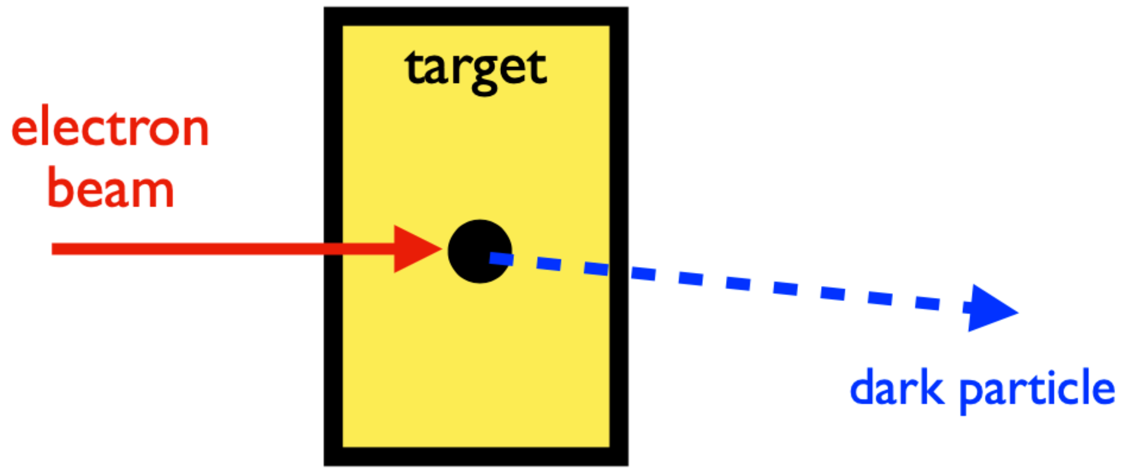
[Holdom]
[Pospelov, Ritz, Voloshin]
[Hooper, Zurek]
[Arkani-Hamed, et al]
...

$$\mathcal{L} \supset |D_\mu\chi|^2 - m_\chi^2|\chi|^2 - \frac{1}{4}(F'_{\mu\nu})^2 + \frac{1}{2}m_{A'}^2(A'_\mu)^2 - \frac{\epsilon}{2}F'_{\mu\nu}F^{\mu\nu} + \ldots$$

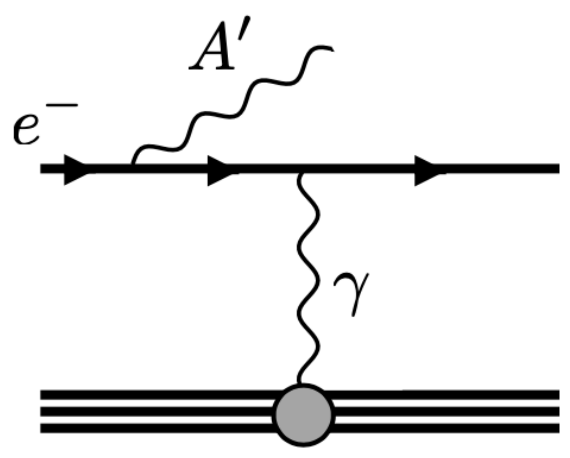
- Dark photon mediates interaction between DM and SM
- 4 new parameters: $m_\chi, m_{A'}, \alpha_D, \epsilon$
- Can obtain correct relic abundance
- CMB bounds evaded due to p-wave annihilation
- Variations in cosmology and phenomenology obtained by changing mediator, or dark matter properties - important to explore all options



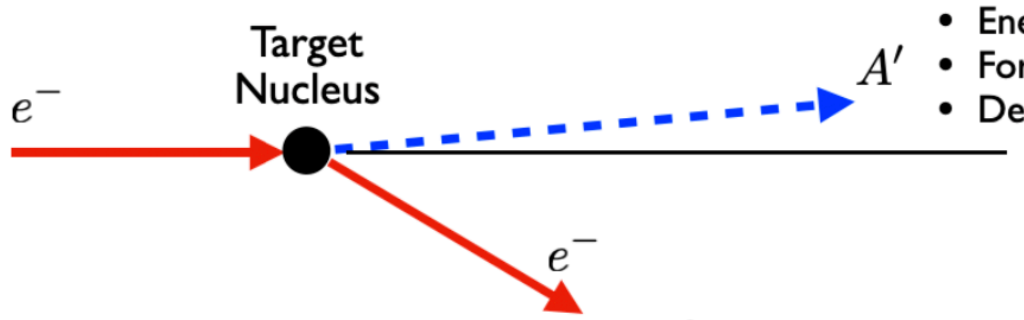
Dark Particle Production in Electron Fixed Target Experiments



Advantages:
- high collision luminosity
- forward kinematics
- large production rates
- clean experimental environment



Dark Photon Production
via Bremsstrahlung



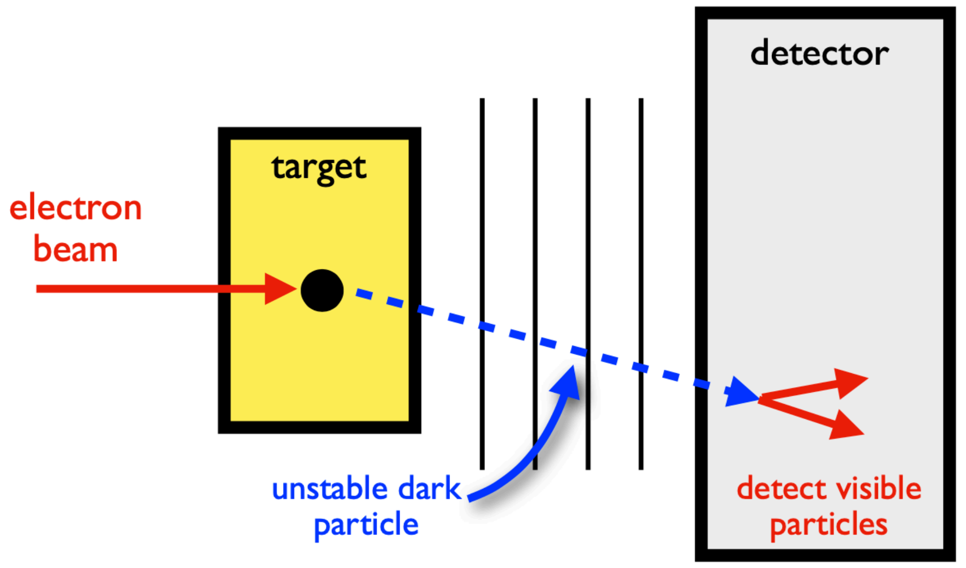
- Energetic
- Forward
- Decay products collimated

- soft
- wide-angle

Electron beams typically useful for new vectors

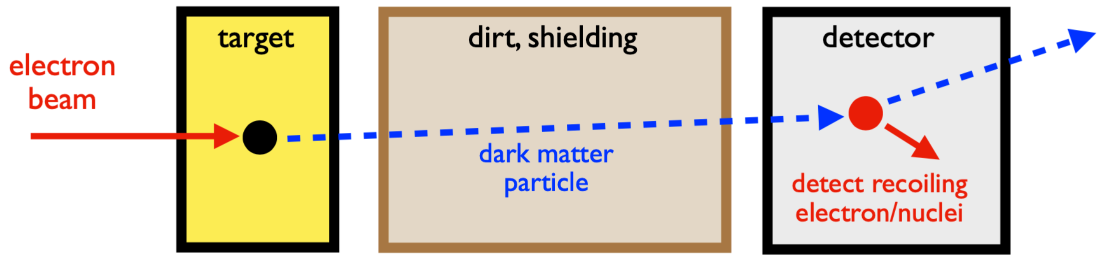
Visible Decays

$$m_{A'} < 2m_\chi$$



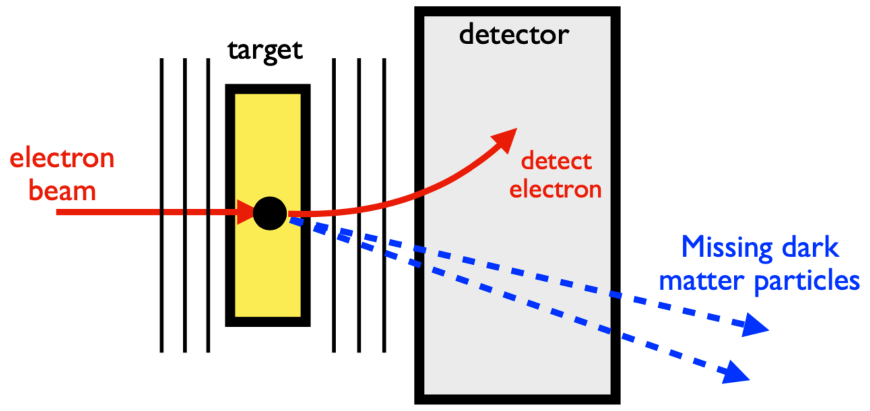
Dark matter scattering

$$m_{A'} > 2m_\chi$$



Missing energy / momentum

$$m_{A'} > 2m_\chi$$

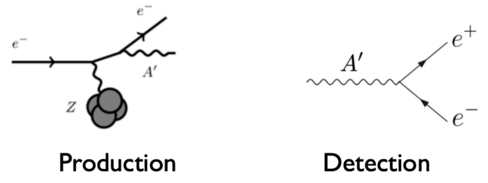


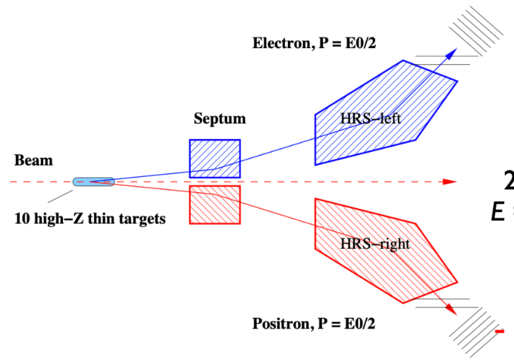
See talk by
N. Blinov

[Andreas. et al]
[Izaguirre, Krnjaic, Schuster, Toro]

APEX@JLAB

- Multi-GeV electron beam;
- High Z thin target
- High resolution spectrometer
- Search for prompt di-electron pair





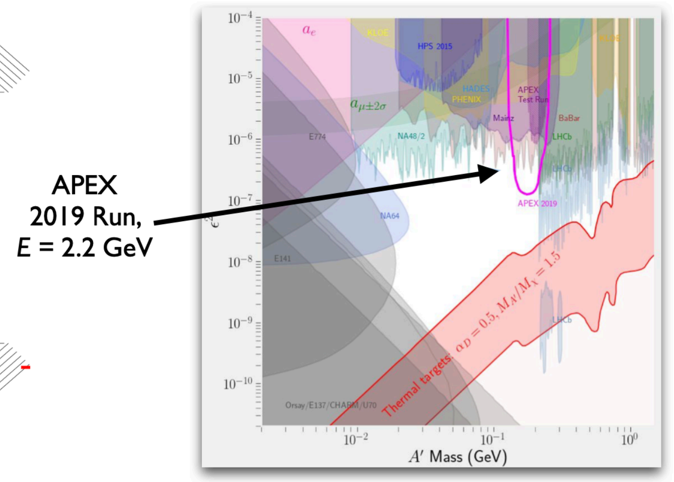
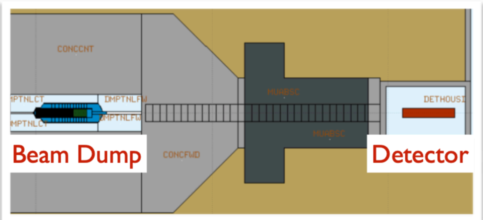
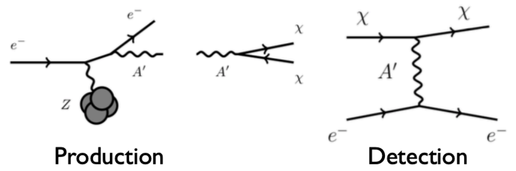


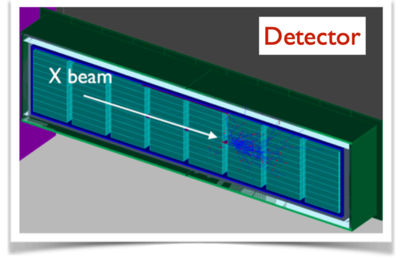
Fig. from O. Moreno, talk at LDMA 2019

BDX @ JLAB

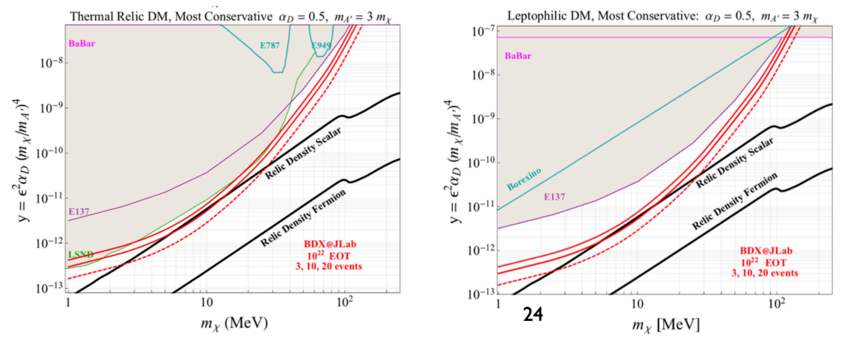
- 11 GeV electron beam on Water-Aluminum dump
- ECAL detector located 20m downstream







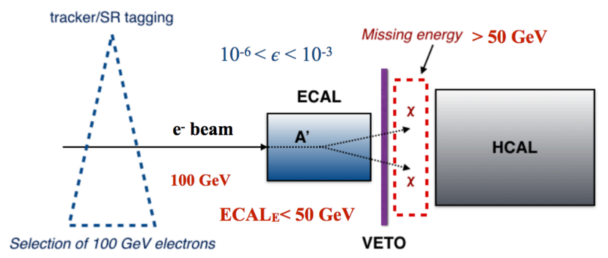
- Approved by JLAB PAC for 10^{22} EOT run

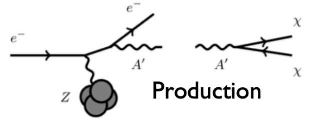


BDX proposal
1607.01390

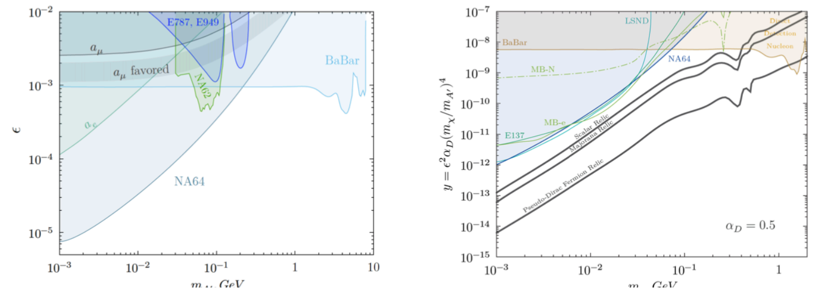
NA64 @ CERN

- 100 GeV electron beam incident on ECAL
- Dark matter produced in ECAL and carries most of the beam energy





- Large missing energy signature (small energy deposition in ECAL, no energy deposition in HCAL)
- 2.84 x 10^{11} EOT - best limits on invisibly decaying dark photon below 300 MeV



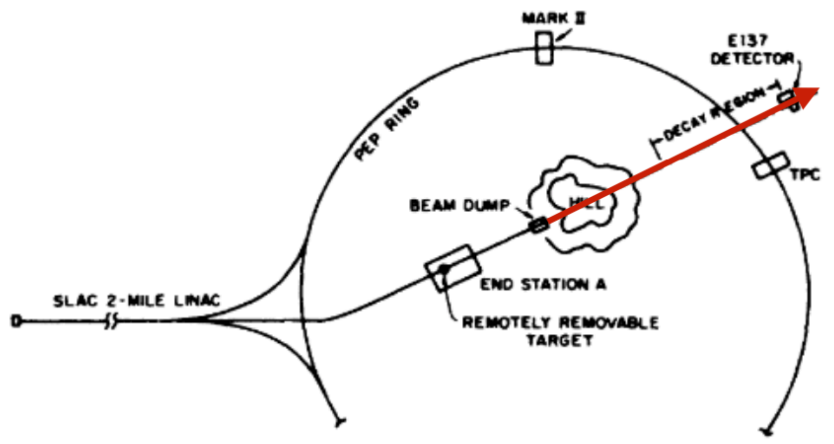
Experimental Perspectives on Electron Beam Dumps

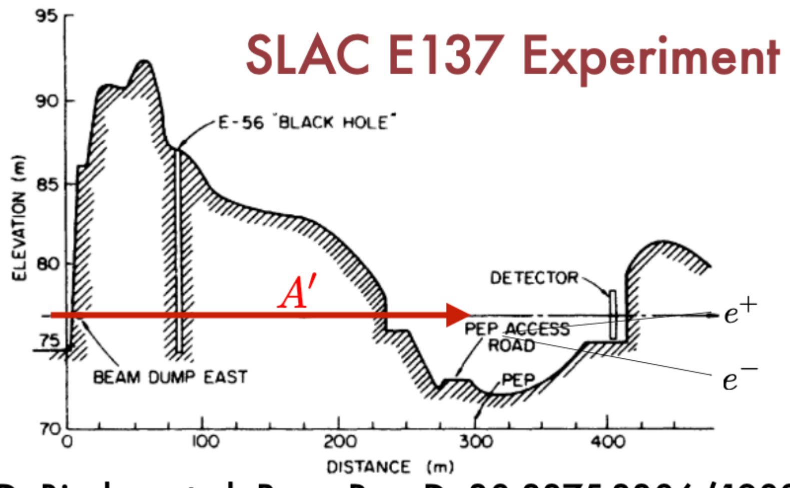
DND2020 Workshop

Luca Doria (doria@uni-mainz.de)

PRISMA Cluster of Excellence and Institut für Kernphysik
Johannes-Gutenberg Universität Mainz

Prehistory of electron BD experiments

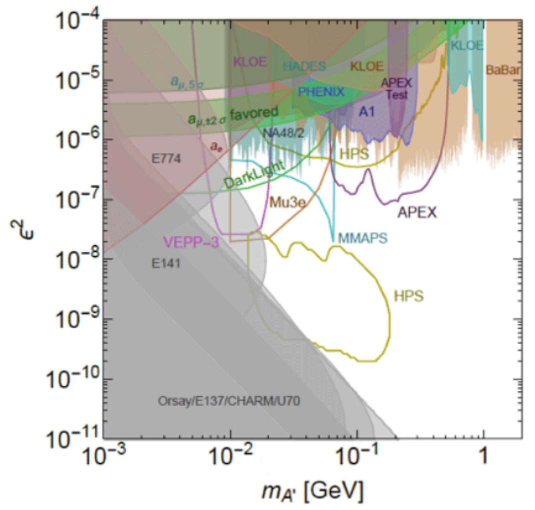




J.D. Bjorken et al. Pays. Rev. D, 38:3375-3386 (1988)

*Beam: 20GeV electrons on Al target
*~200m decay length (mostly earth shielding)
*Detector: scintillators + wire chambers

*Other experiments (originally for axion searches):
- SLAC E141: 9 GeV electrons on W
  E. M. Riordan et al., Phys. Rev. Lett. 59, 755 (1987).
- Fermilab E774: 275 GeV electrons on W
  A. Bross et al., Phys. Rev. Lett. 67, 2942 (1991).



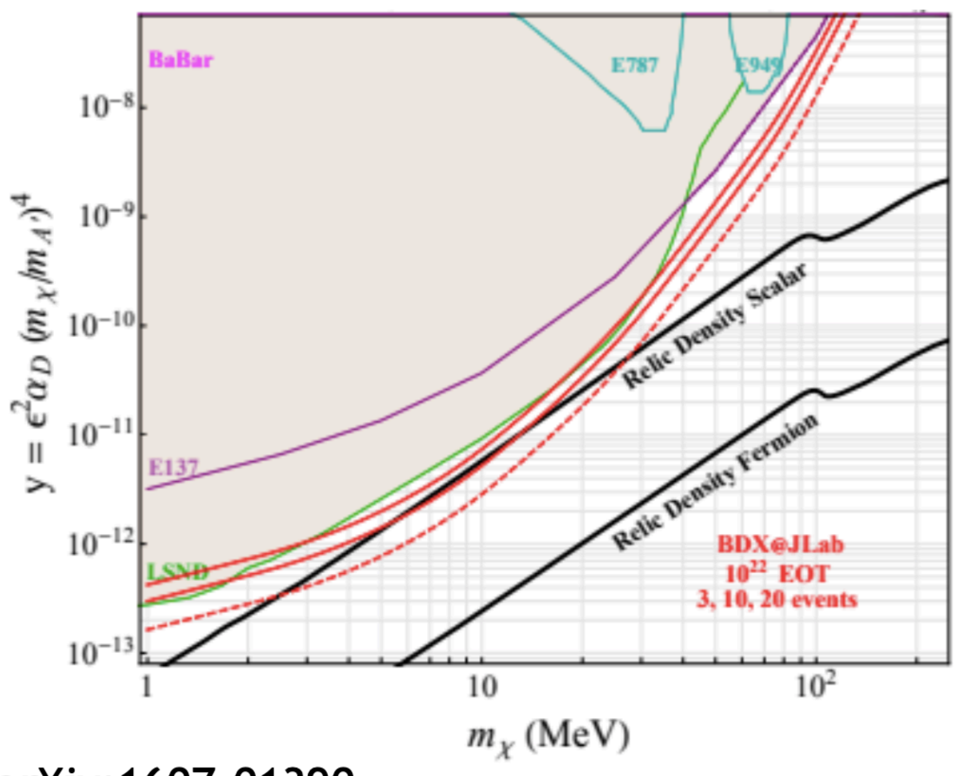
Data reinterpreted theoretically by: Bjorken et al. Phys.Rev.D80:075018 (2009)

Electron Beam Dump Experiments

- Availability of high-current, CW accelerators
- Parasitic operation
- Complementarity wrt proton beam dumps (meson decays)
- Lower neutrino background
- Theoretically simpler signal (similar to QED processes)
- Double test: DM production (in the BD) AND interaction (in the detector)

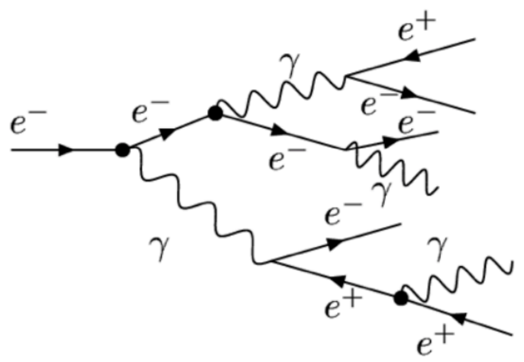
BDX at JLab

90% Upper limits



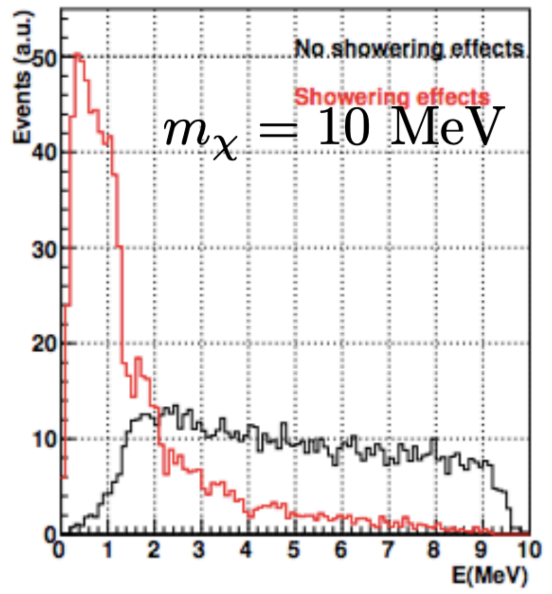
arXiv:1607.01390

https://www.jlab.org/accel/ops/ops_liaison/BDX/BDX.html

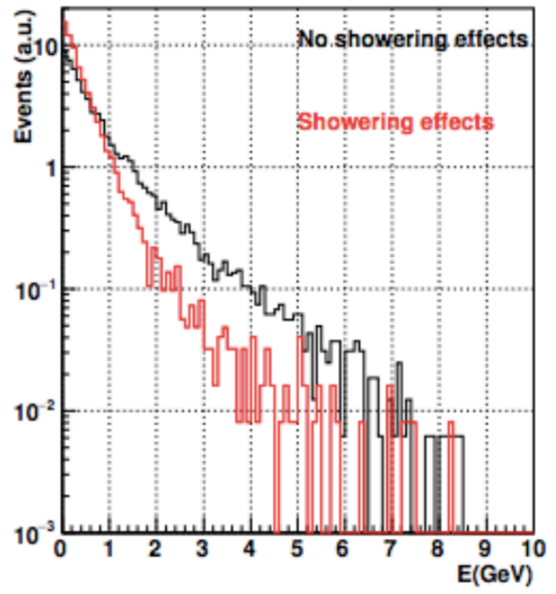


Simulation of showering effects in the beam dump mandatory for assessing the experimental reach.

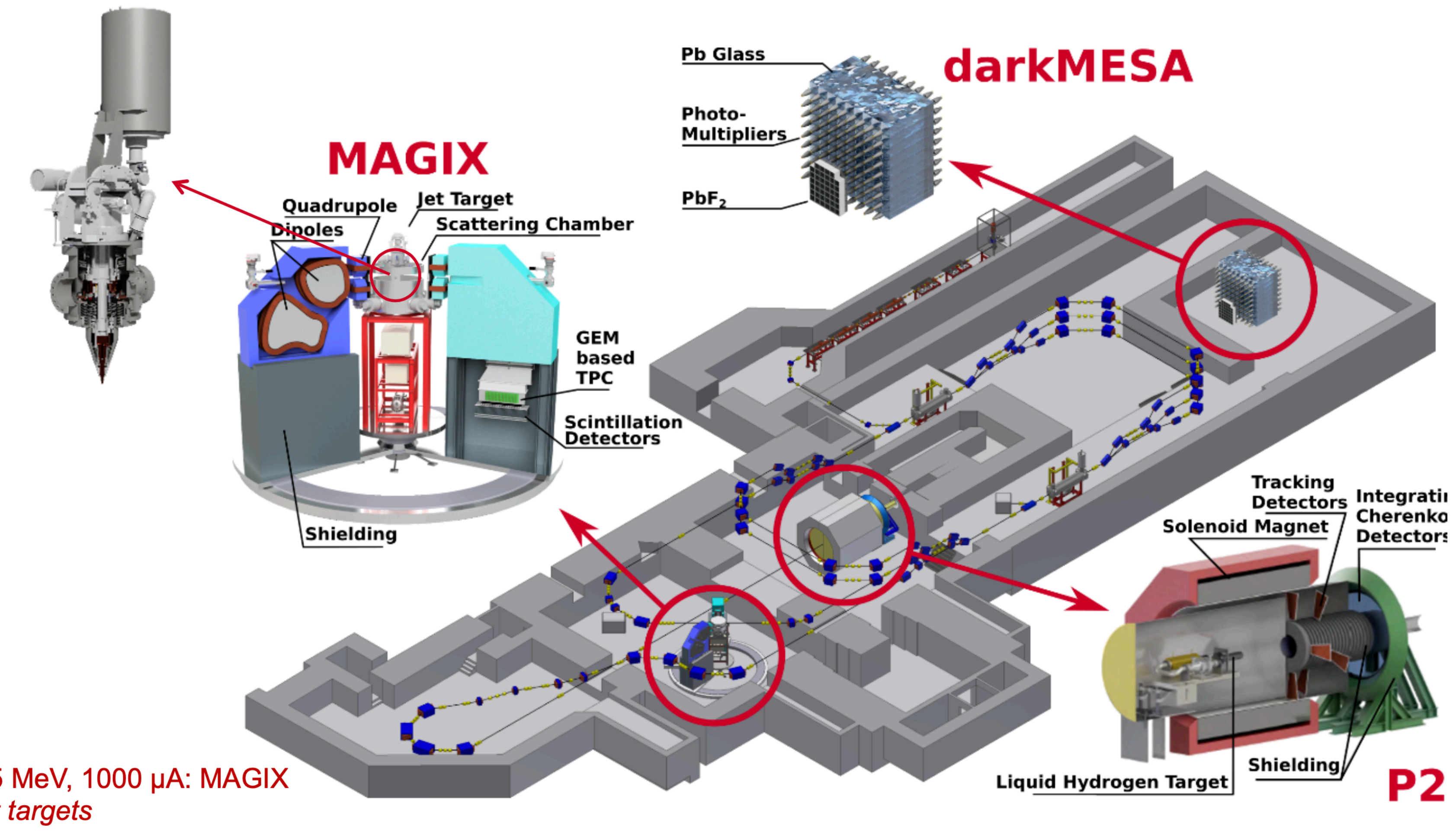
DM energy



Recoil Electron energy



MESA



MESA accelerator
1.3 GHz c.w. beam
Normal conducting injector
2 superconducting cavities
Several recirculations

Two main operation modes

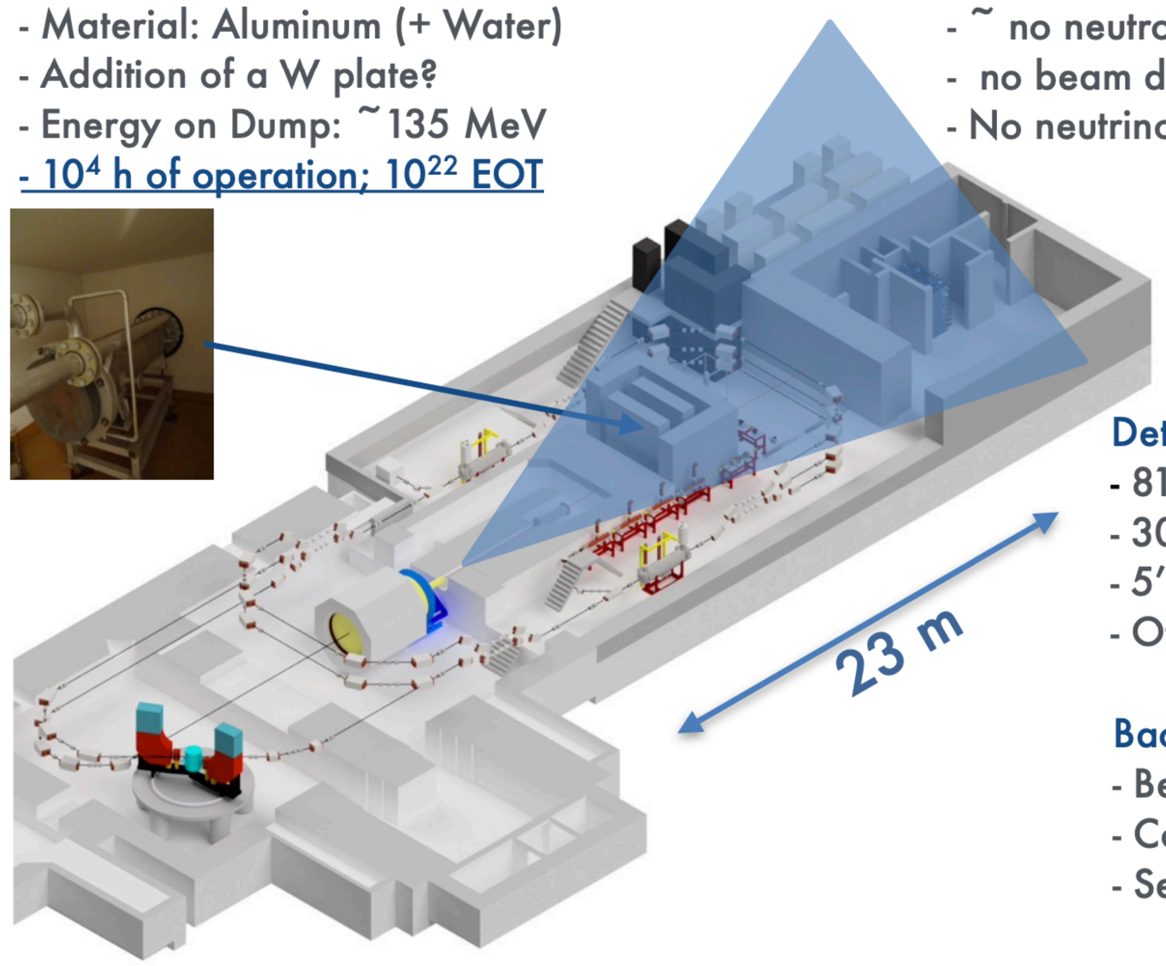
1. ERL mode, polarized, 30–105 MeV, 1000 μA: MAGIX
High beam currents, thin gas-jet targets

2. EB mode, (un-)polarized, 155 MeV, 150 μA: P2
High stability, thick targets, long runs, high luminosities

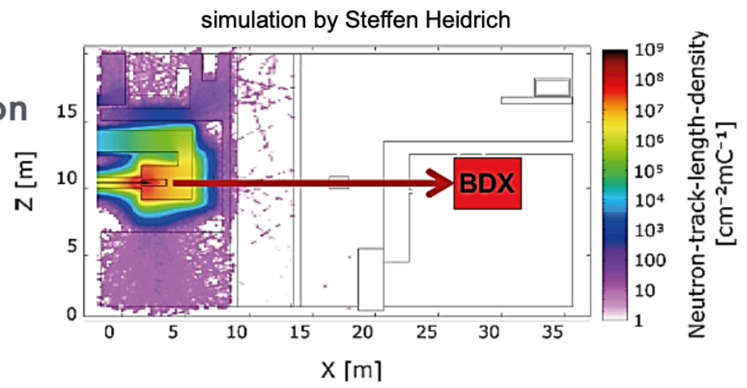
(2.) MX-EB mode: (un-)polarized, 30–105 MeV, 10 μA: MAGIX
Early MAGIX measurements, short runs

DarkMESA

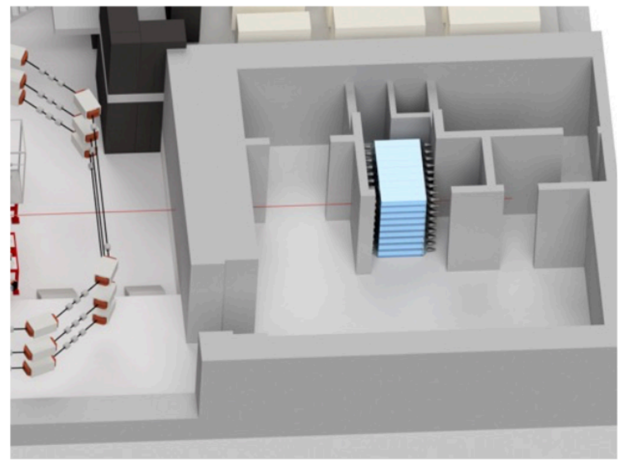
Beam Dump
- 20 X_0 Beam Dump
- Material: Aluminum (+ Water)
- Addition of a W plate?
- Energy on Dump: ~135 MeV
- 10^4 h of operation; 10^{22} EOT



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



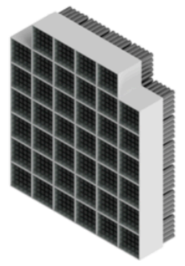
Detector Concept:
- 81 lead glass blocks
- 30x30x150cm each
- 5'' PMTs or SiPM readout
- Other crystals under study



Background Rejection
- Beam on/off
- Comics Veto
- Segmentation

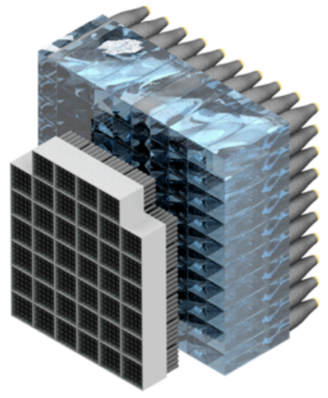
DarkMESA

Phase 1



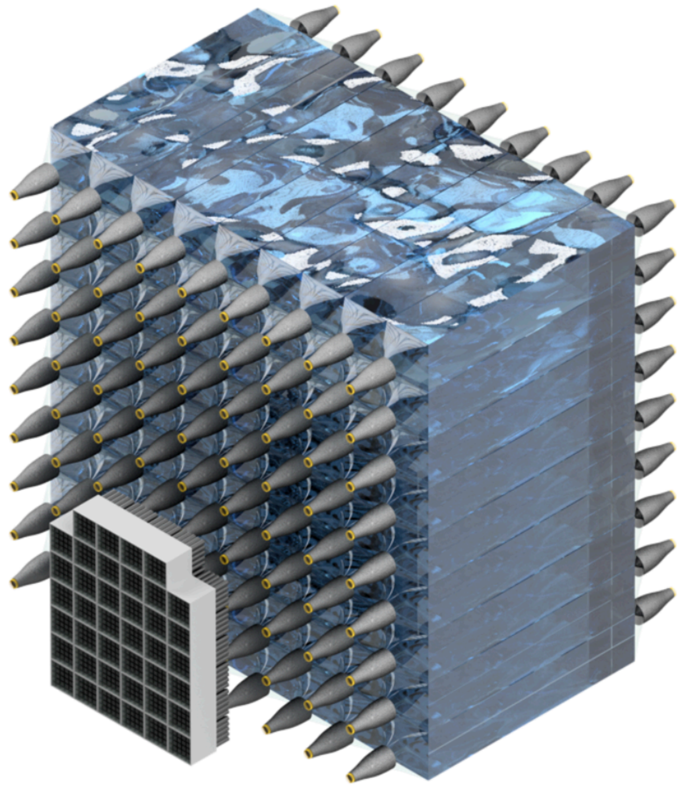
1000 (available!) PbF2 crystals
Volume: 1x1x0.13 m^3
5x5 crystal sub-modules
1200 kg mass

Phase 2



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

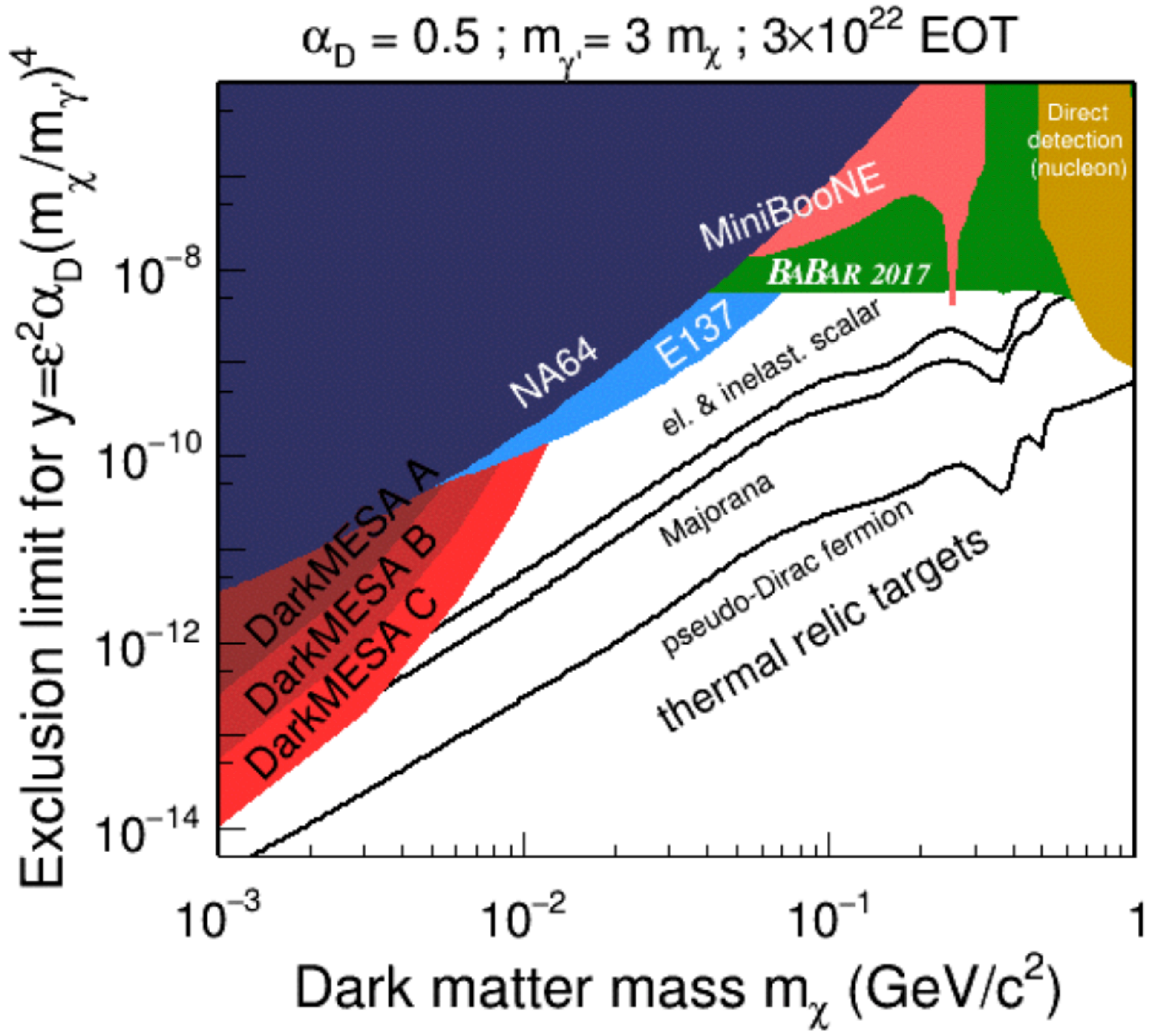
Phase 3



Reach maximum volume: O(10m^3)

⇐Staged detector design

DarkMESA



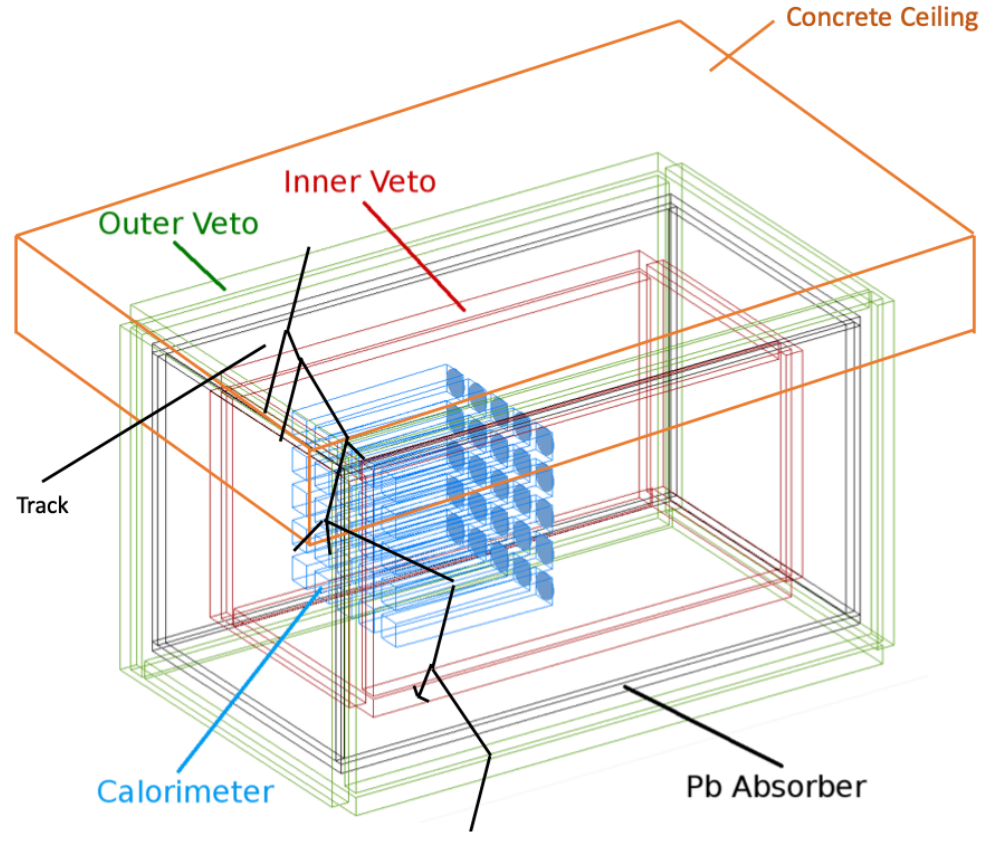
Simulation

- GEANT4
  - Experimental Halls
  - Beam Dump
  - Detector
  - DM/e DM/p interaction
- MadGraph-4
  - Dark Photon Production
  - Input to GEANT4

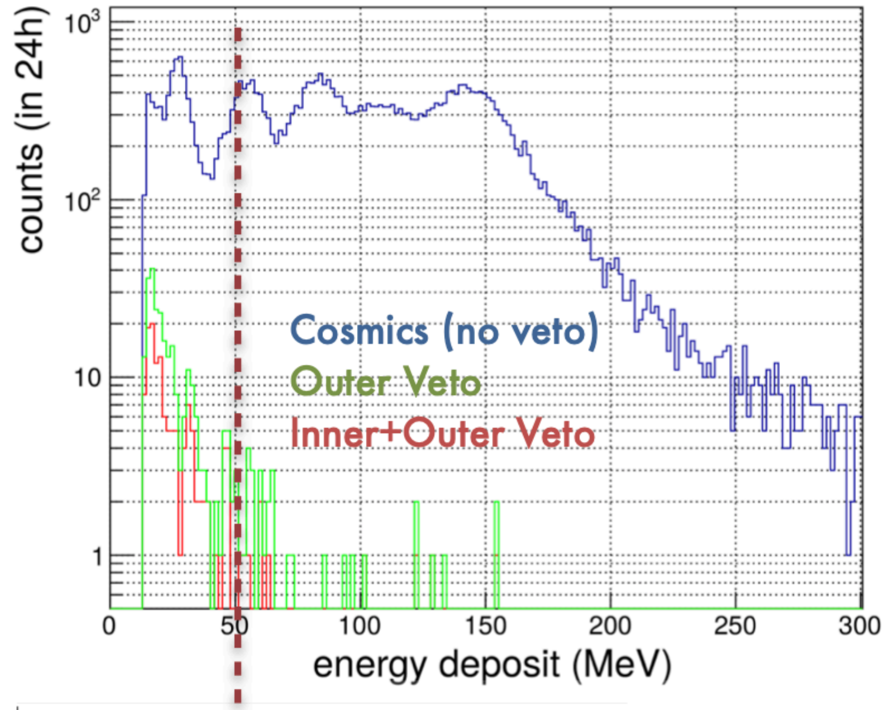
⇐Estimated reach for dark photon DM is interesting

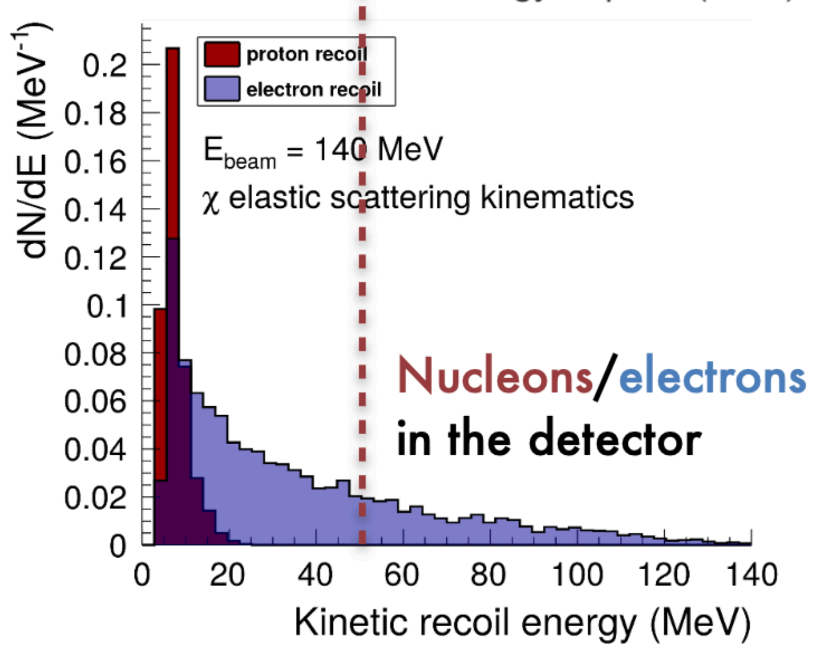
Experience with DarkMESA

Full simulation of the prototype



Simulation by M. Christmann

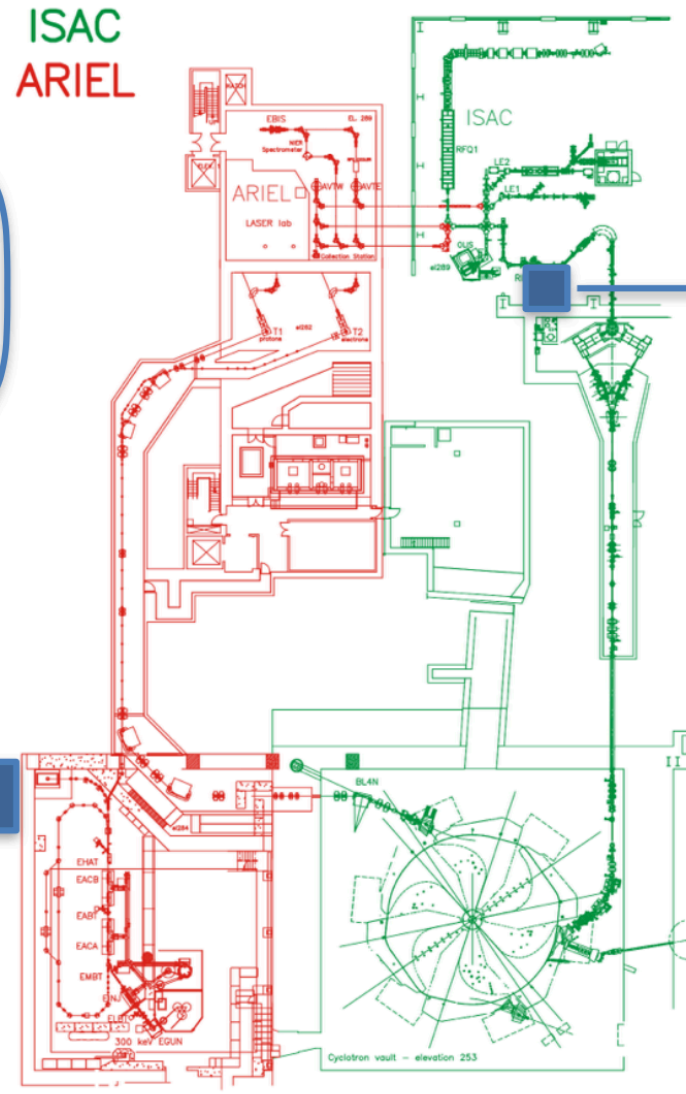




Nucleons/electrons in the detector

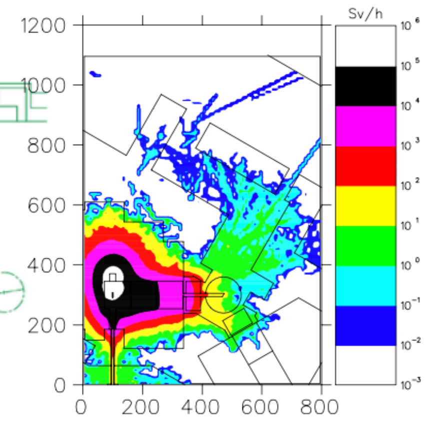
Cosmic background sets a lower limit on threshold⇒

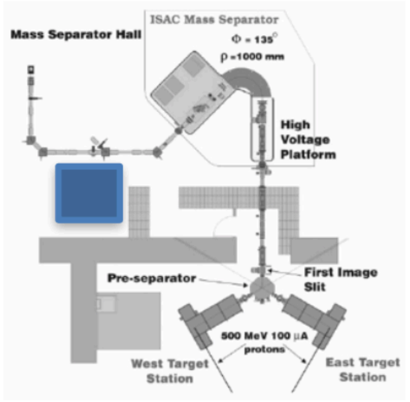
The ARIEL Case



Option 2
- Beam-dump in ARIEL Hall
- Distance: ~3m

Option 1
- ARIEL targets + Separator room.
- Parasitic operation possible.
- Backgrounds from ISAC targets?
- Enough space?
- Distance ~ 20m

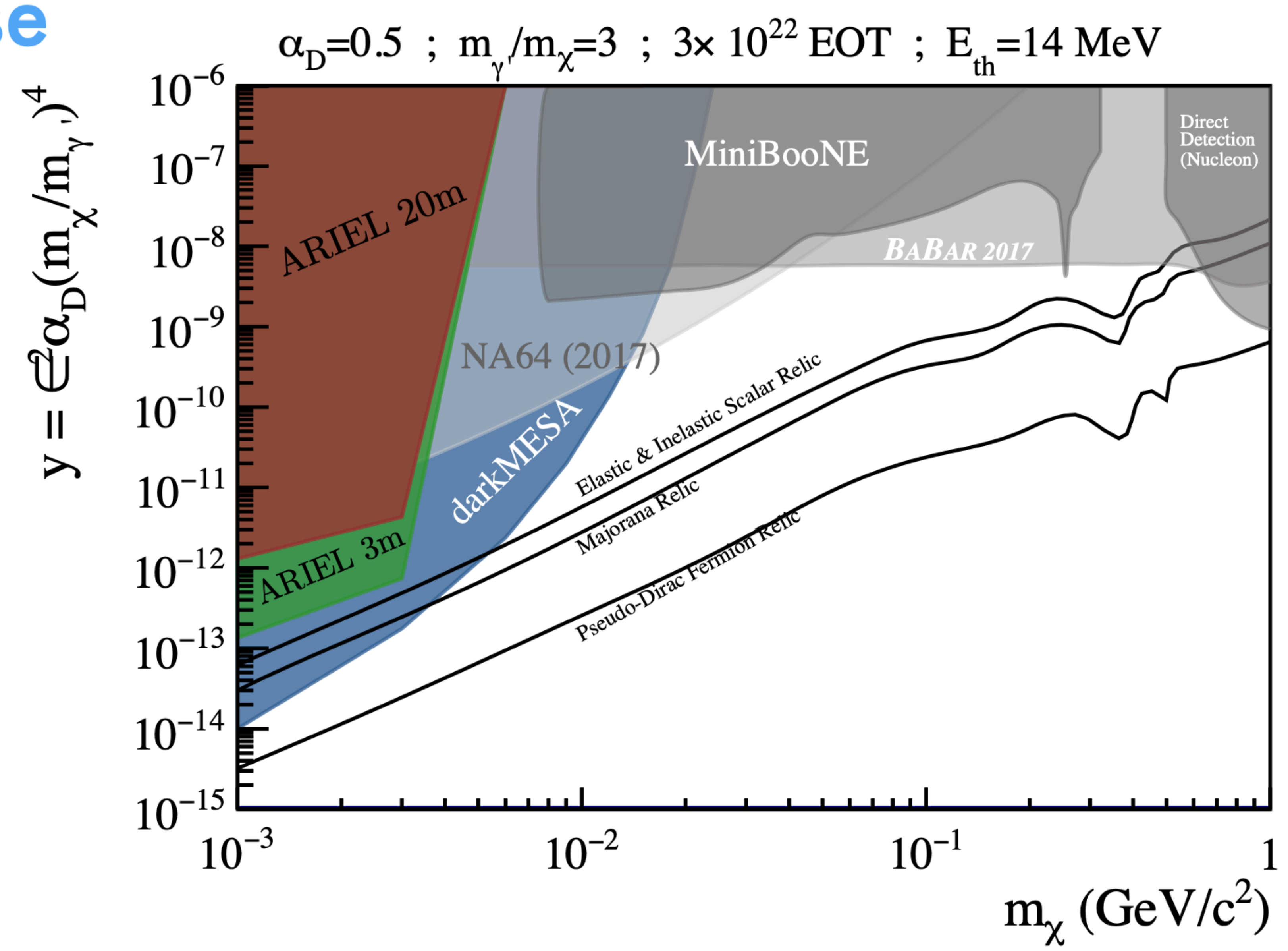




The ARIEL Case

Beam
- E= 30MeV
- 10000 h/year
- 3x10^23 EOT

Detector
- 3x3x3 m
- 3m OR 20m distance
- 14 MeV threshold



Summary of Strengths and Challenges

Beam Properties:

High power BD (~100kW expected, more w/o ISOL target..500kW?) , bremsstrahlung on Au (+Al)
Low beam energy (30 MeV —> 50 MeV?)
Have to stay close to BD for good acceptance -> backgrounds?
Advantage: no muon/neutrino background

Detector:

Calorimeter / Noble liquid detector / Gas TPC … ?
Low DM masses —> Low threshold -> BKGs again (environment, BD, low-E neutrals)
Veto system: cosmics, low energy neutrons and photons
Timing? Challenging with CW beam (need sub-ns resolution) —> dedicated bunched beam?

Further studies:

Complex logistics: where to place the detector (separator room, new cave, new beamline, …)?
Enough space in the separator room?
Radiation levels low enough?

Summary

- LDM is a quite generic possibility. Many models on the market: experiments needed!

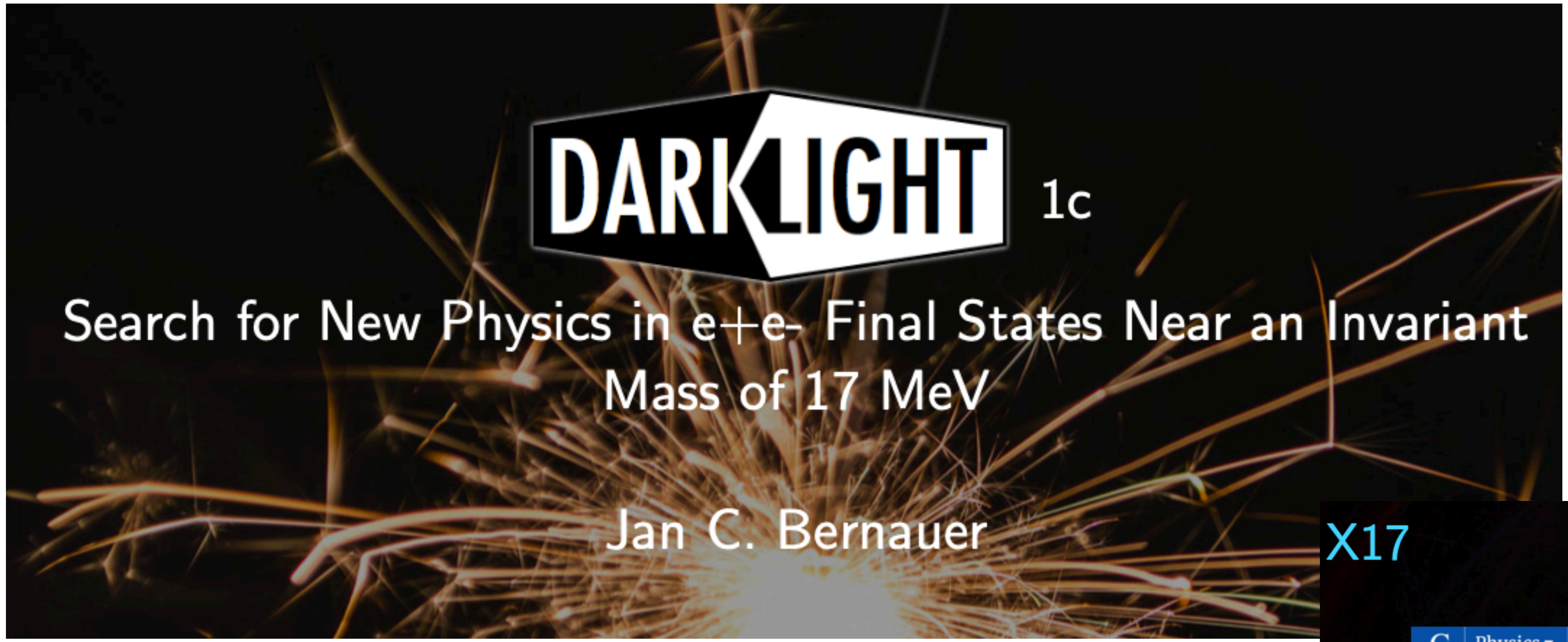
- With a rapidly “heavy” DM window closing, “light” DM searches are gaining a lot of interest.

- Dark sector experiments discussed at major labs equipped with electron machines: SLAC, Cornell, DESY, ELSA, MAMI/MESA, Frascati, KEK, … Lot of competition.

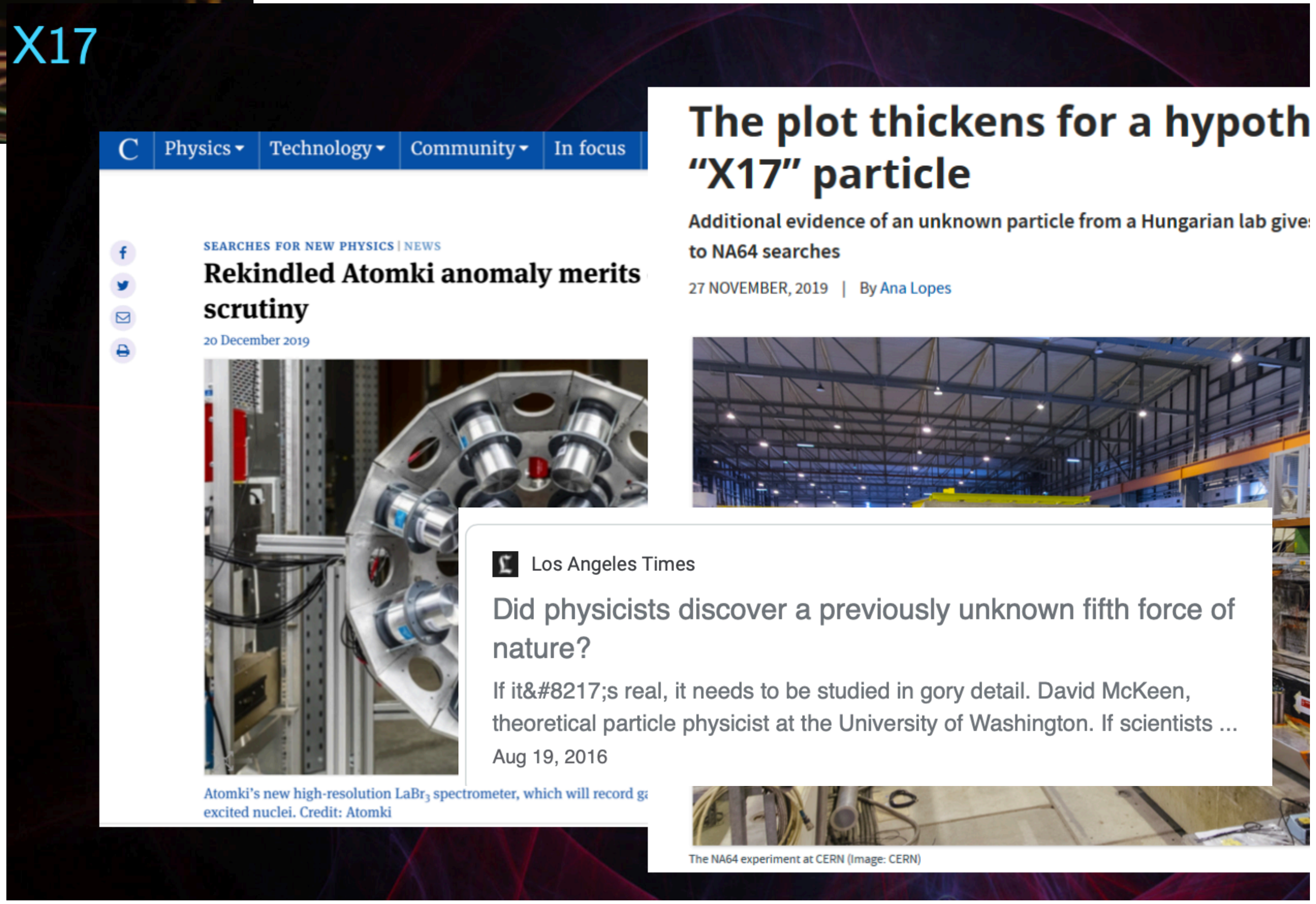
- BD-type experiments have the potential to explore unique parameter regions at low masses.

- An opportunity for the TRIUMF beams (protons could also be an option…?)

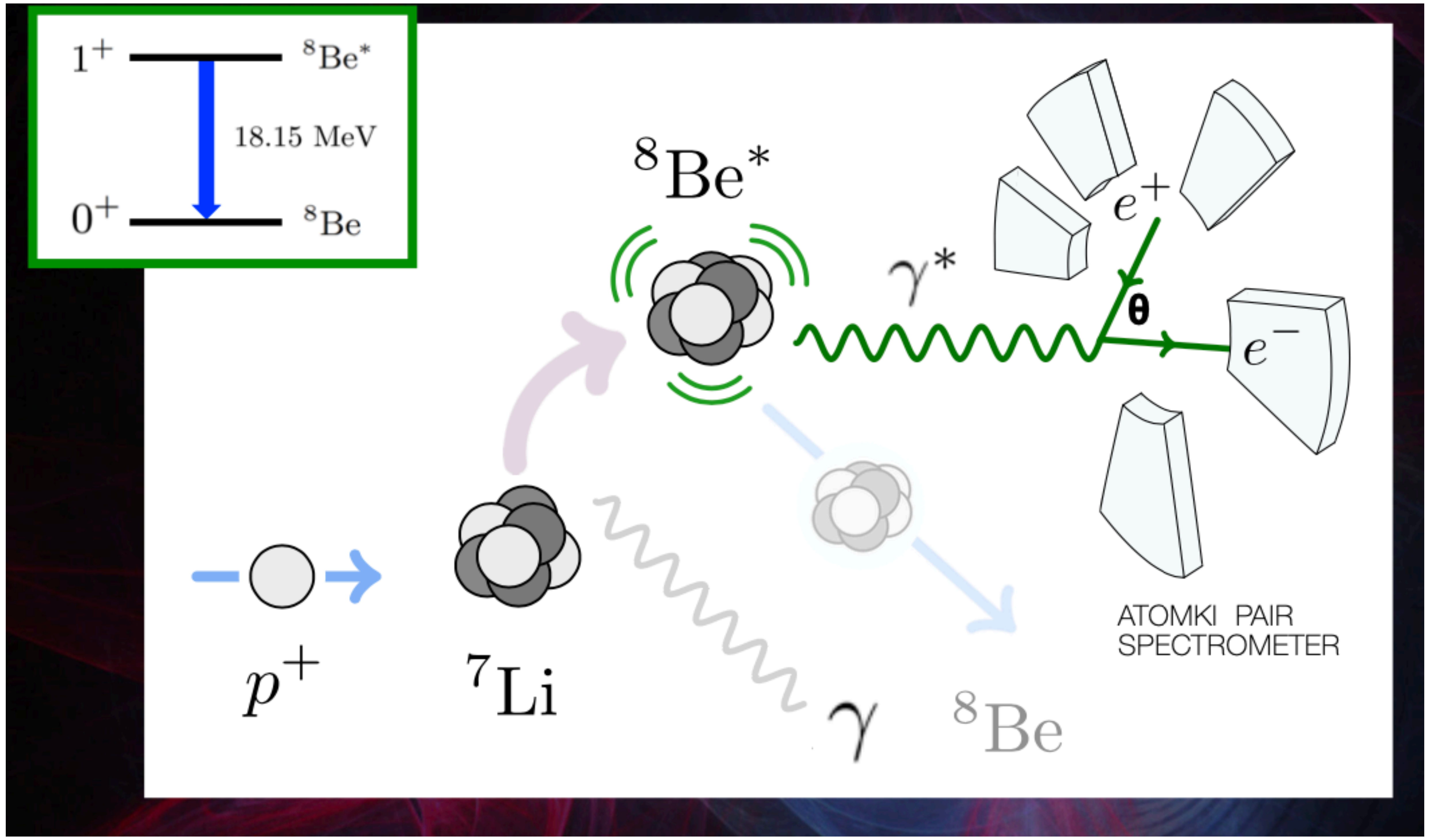
- Realistic full simulation study needed: beam dump + detector technology



There has been a lot of attention on experiment at ATOMKI⇒

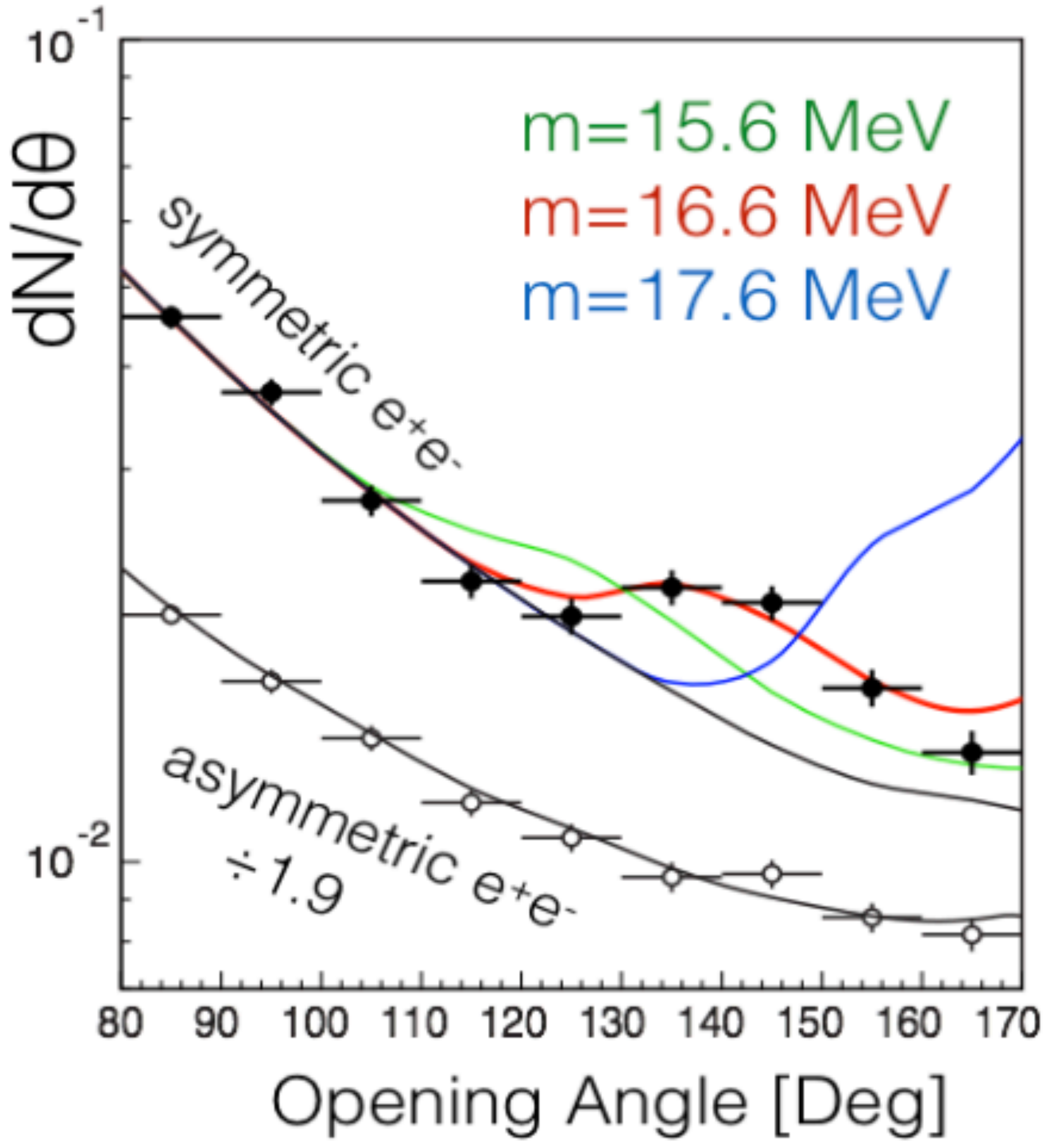


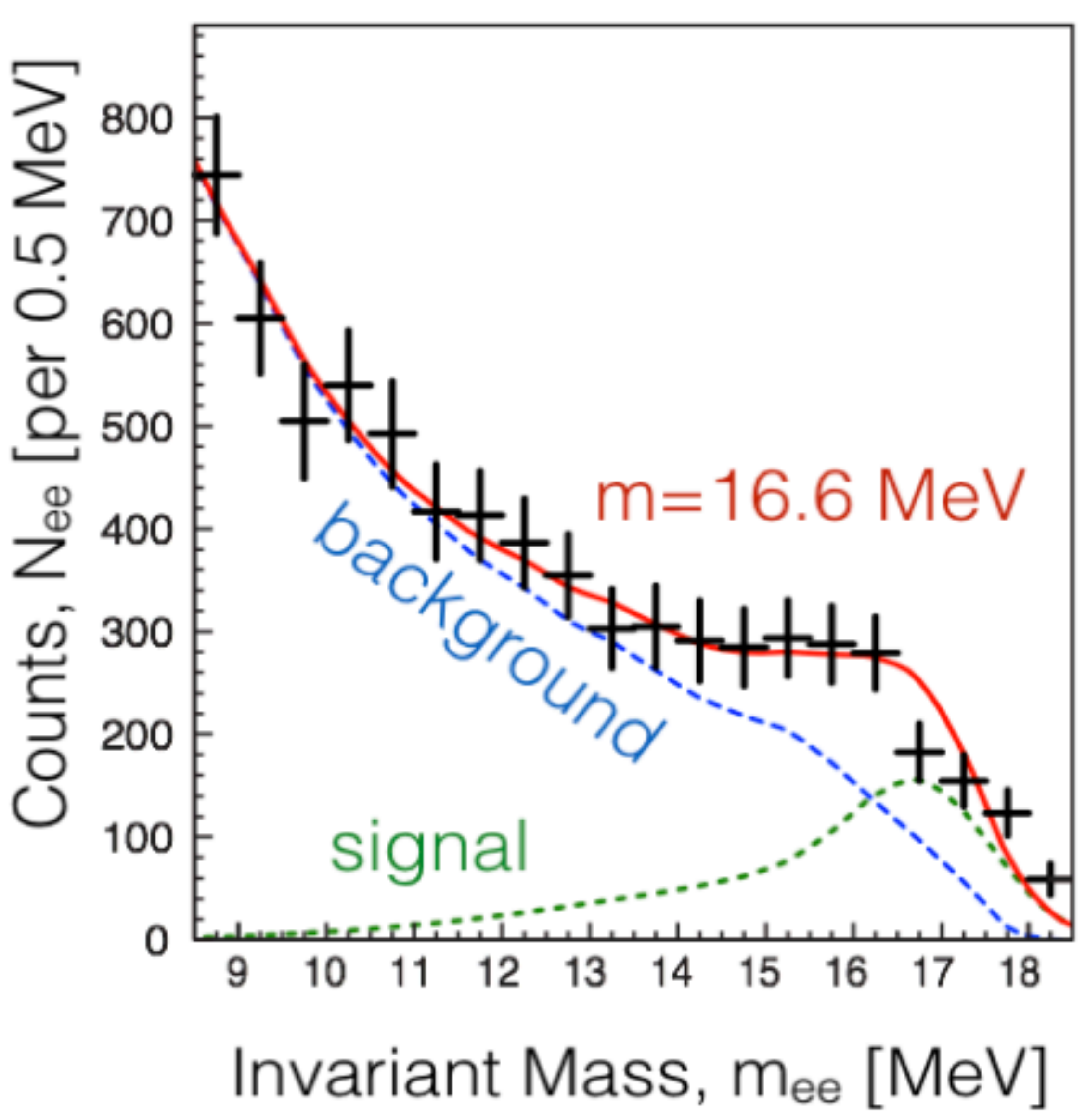
The experiment at ATOMKI⇒

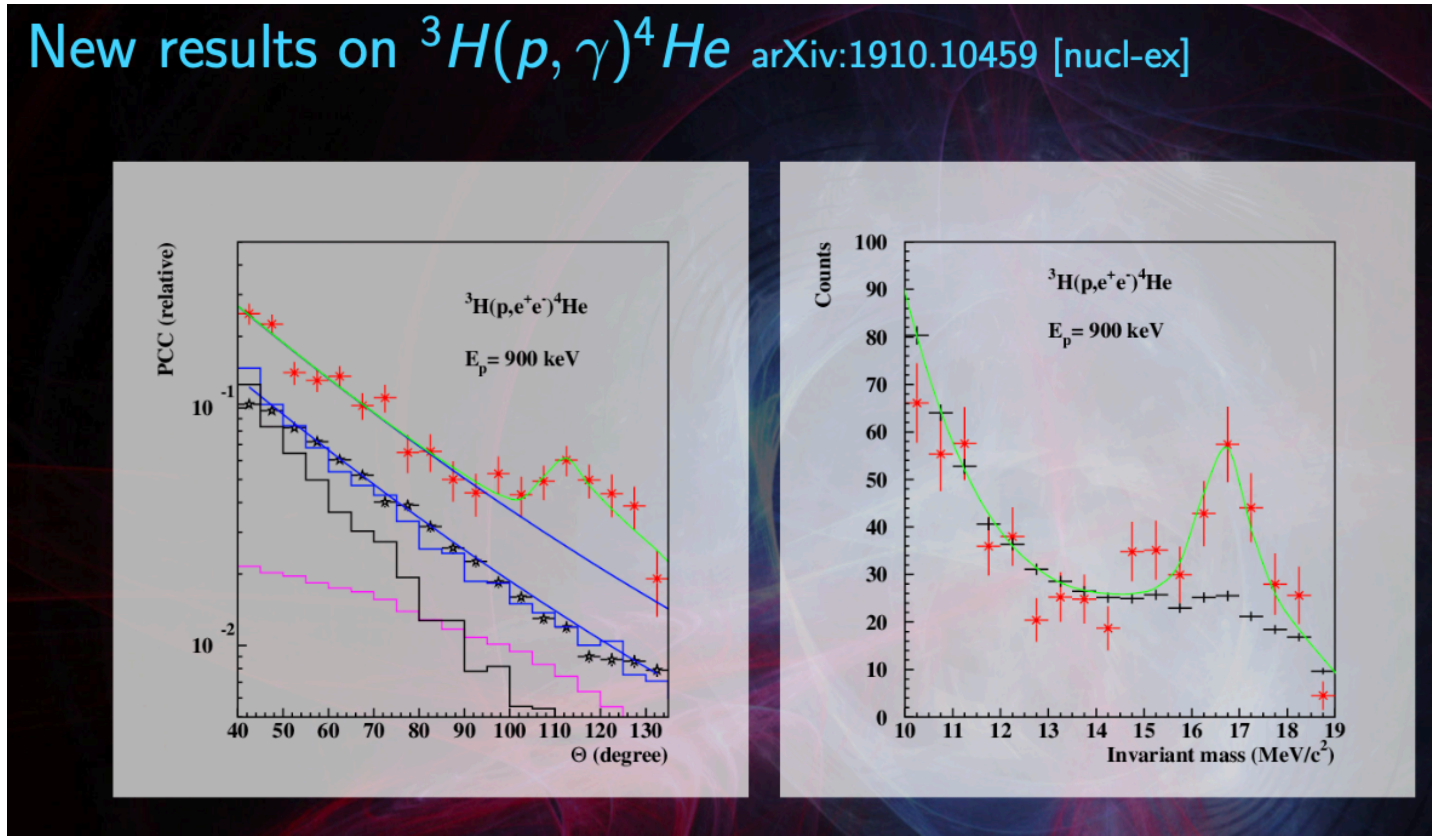


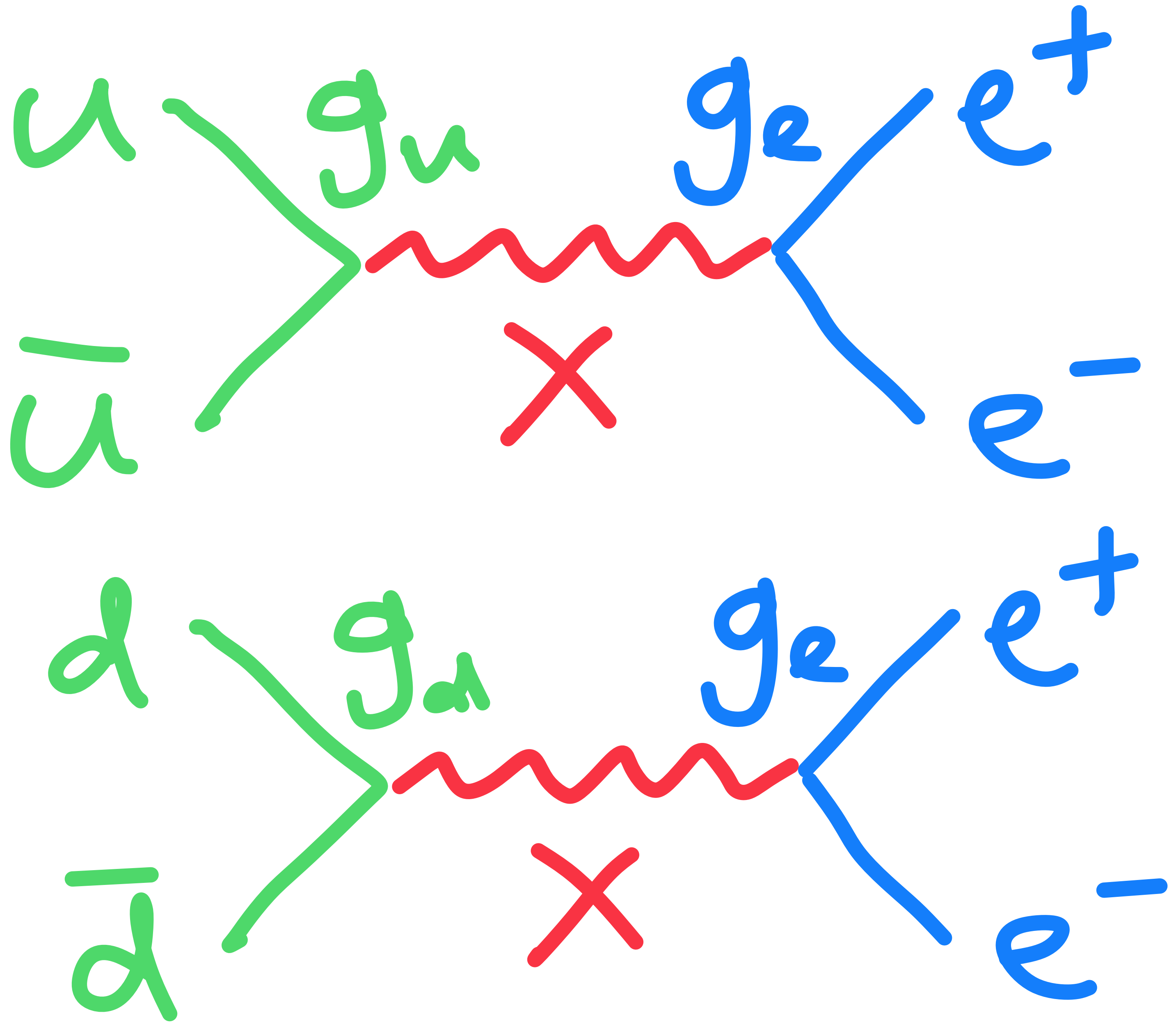
What's seen

⇓








u
ū
g_u
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X
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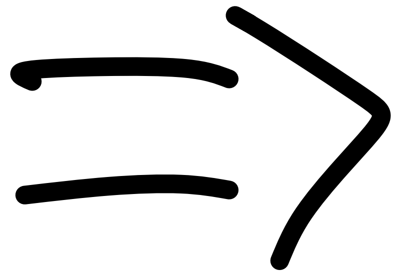
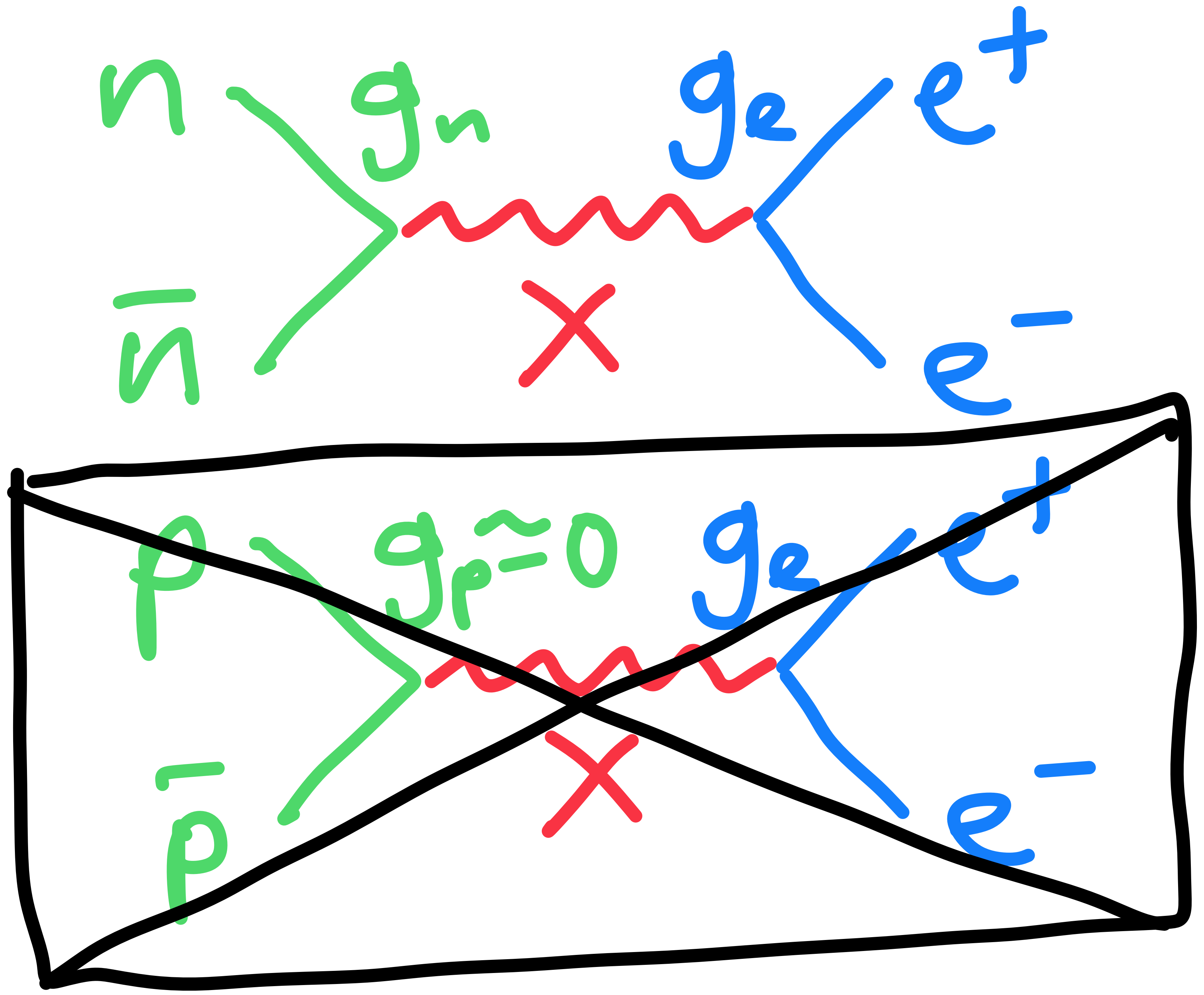
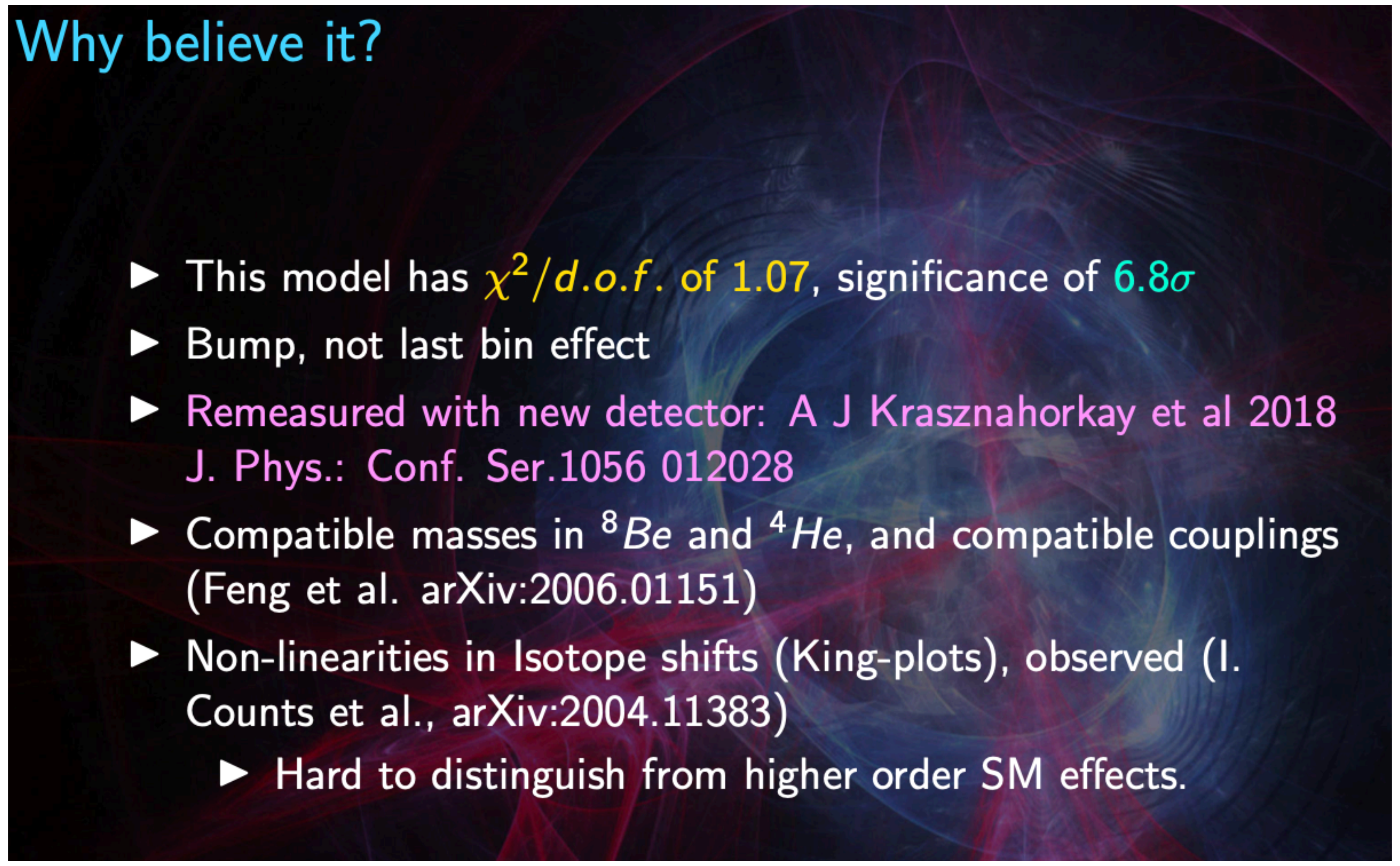
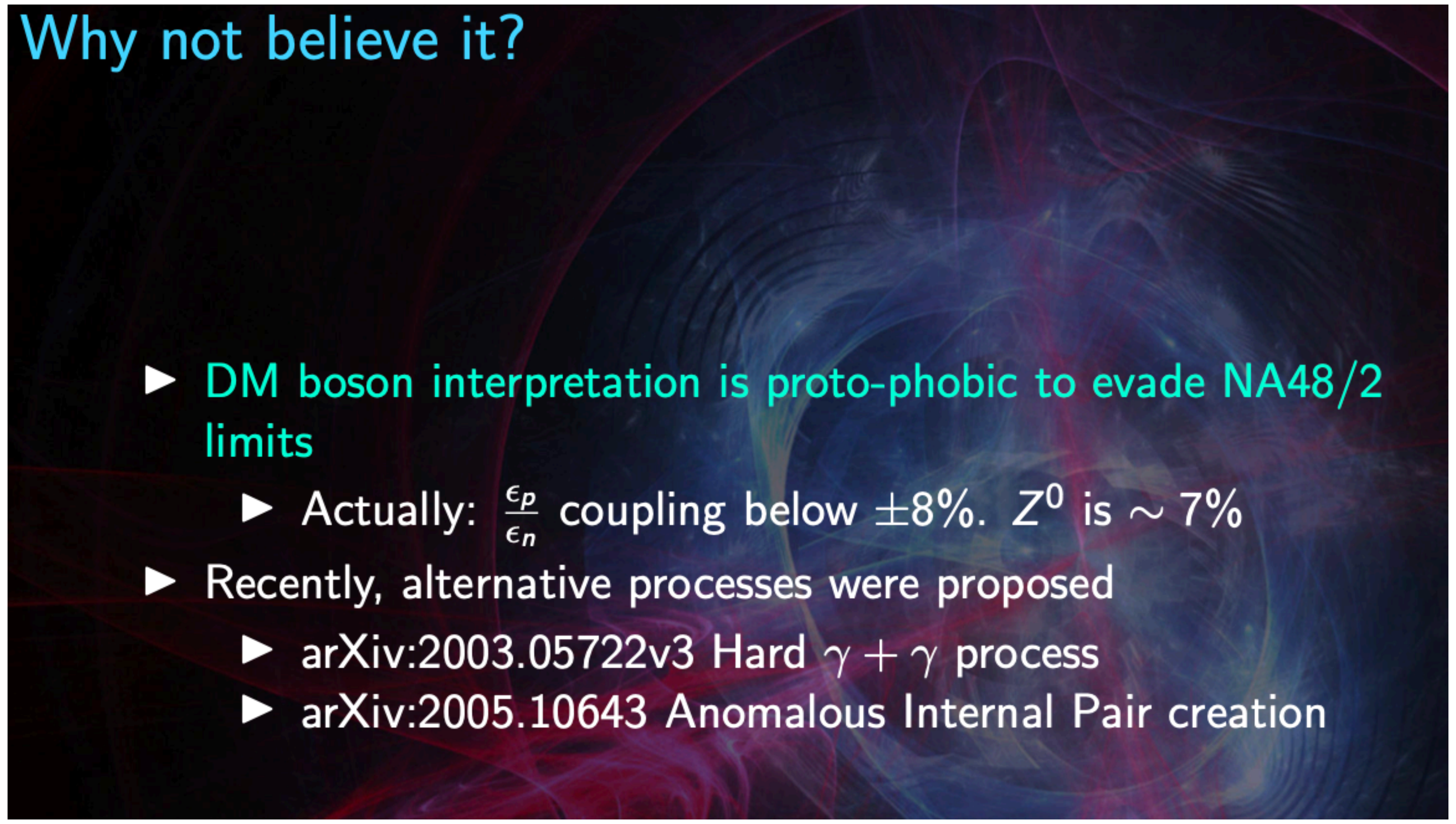
g_d
g_e
e^+
e^-
X




n
n̄
g_n
g_e
e^+
e^-
X
p
p̄
$g_p \simeq 0$
g_e
e^+
e^-
X


Why believe it?
This model has $\chi^2/d.o.f.$ of 1.07, significance of 6.8σ
Bump, not last bin effect
Remeasured with new detector: A J Krasznahorkay et al 2018 J. Phys.: Conf. Ser.1056 012028
Compatible masses in ^8Be and ^4He, and compatible couplings (Feng et al. arXiv:2006.01151)
Non-linearities in Isotope shifts (King-plots), observed (I. Counts et al., arXiv:2004.11383)
Hard to distinguish from higher order SM effects.


Why not believe it?
DM boson interpretation is proto-phobic to evade NA48/2 limits
Actually: $\frac{\epsilon_p}{\epsilon_n}$ coupling below ±8%. Z^0 is $\sim 7\%$
Recently, alternative processes were proposed
arXiv:2003.05722v3 Hard $\gamma + \gamma$ process
arXiv:2005.10643 Anomalous Internal Pair creation

How can we measure it at an electron accelerator?

- This particle can be produced via Bremsstrahlung, predominantly ISR off the electron.
- Measure

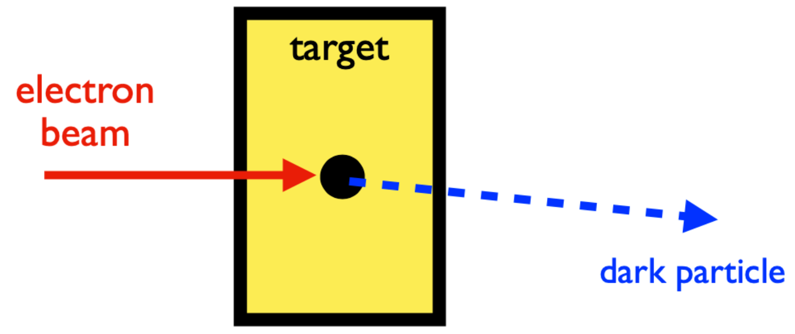
$$e^- Ta \to e^- Ta X \text{ followed by } X \to (e^- e^+)$$

- Irreducible background:

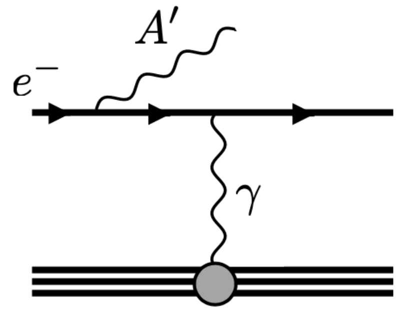
$$e^- Ta \to e^- Ta \gamma^* \to e^- Ta e^+ e^-$$

- two spectrometers, measure e^+ and e^- in coincidence
- Best kinematics:
  - highest production rate if X takes all electron energy. Rise in CS beats all.
  - with limited and same out-of-plane acceptance, symmetric angle optimal.

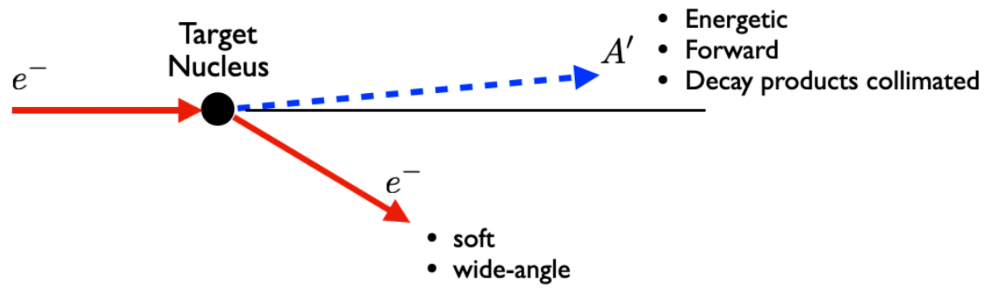
Dark Particle Production in Electron Fixed Target Experiments



Advantages:
- high collision luminosity
- forward kinematics
- large production rates
- clean experimental environment



Dark Photon Production via Bremsstrahlung



Possible setup

- 45 MeV beam, 150 μA on 10 μm tantalum foil $\longrightarrow$about 52 inv. nb/s
- Two spectrometers
  - $\pm 2°$ in-plane, $\pm 5°$ out-of-plane
  - Positron spectrometer at 16°, 28 MeV
  - Electron spectrometer at 33.5°, 15 MeV

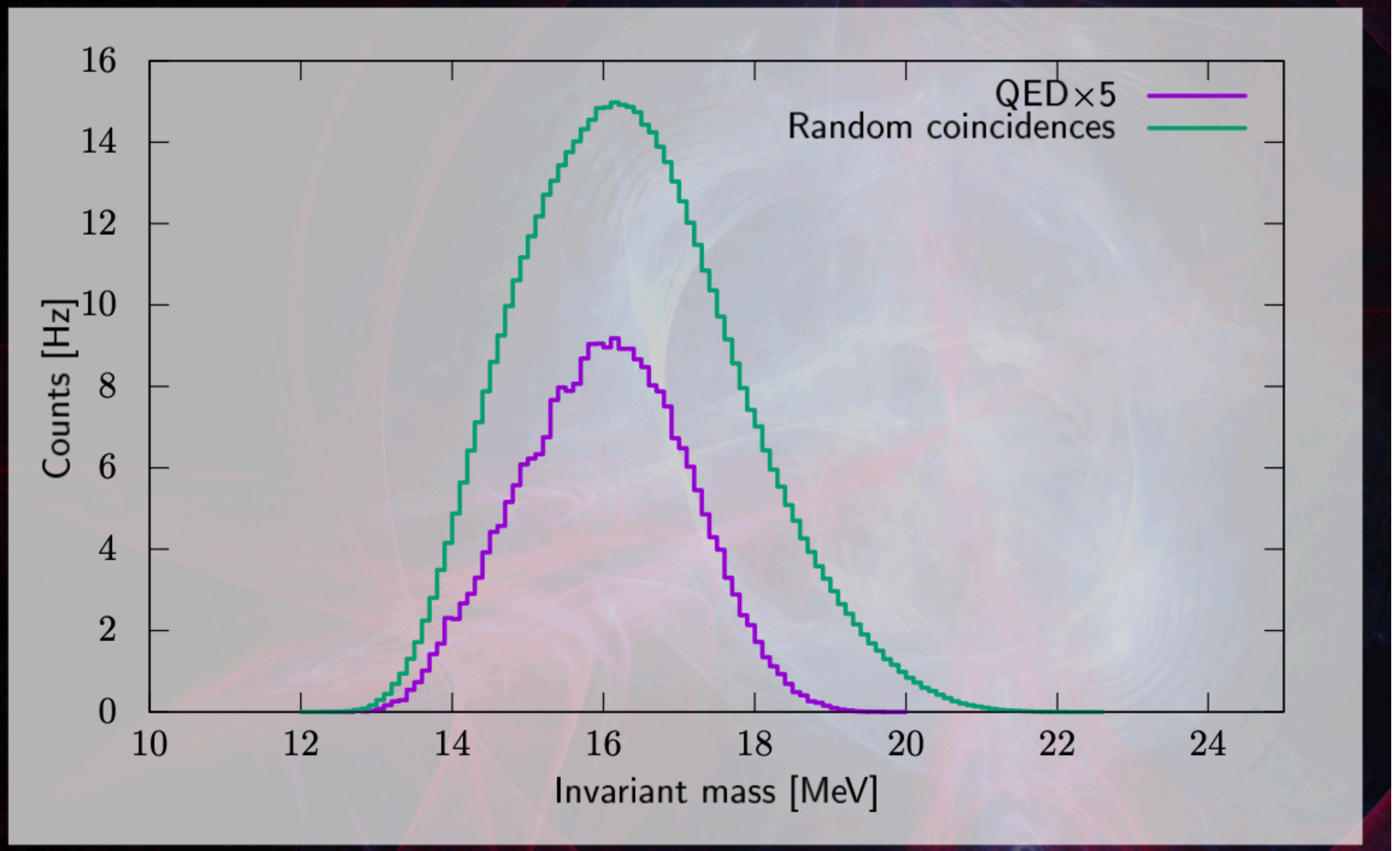
Background

- Main background is NOT the irreducible one. Random coincidences between
  - radiative elastic electrons
  - positrons from (virtual) photon pair-production where e^- is missed
- Can optimize by moving electron arm backward.

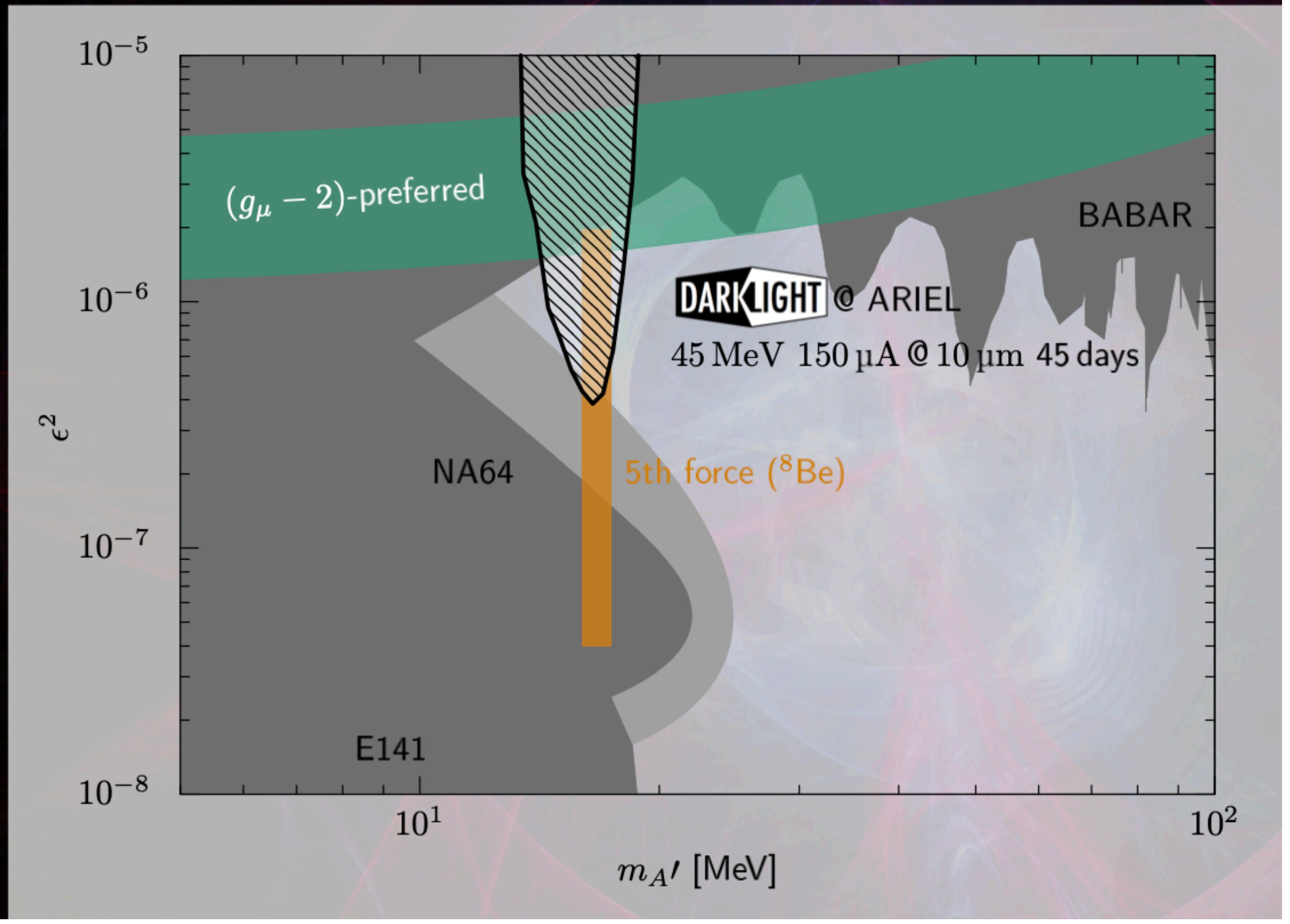
Dominated by accidental background

- Random coincidences dominate
- Scaling with instantaneous luminosity:
  - Signal $S \sim \mathcal{L}$
  - QED background $Q \sim \mathcal{L}$
  - Accidental background $A \sim \mathcal{L}^2$
  - Sensitivity $\frac{S}{\sqrt{Q+A}} \propto 1$ for $A \gg Q$
- Sensitivity almost independent of luminosity. Scale is set by bunch-clock / time resolution
- Out-of-time "coincidences" give accurate measure of acceptance including efficiency.

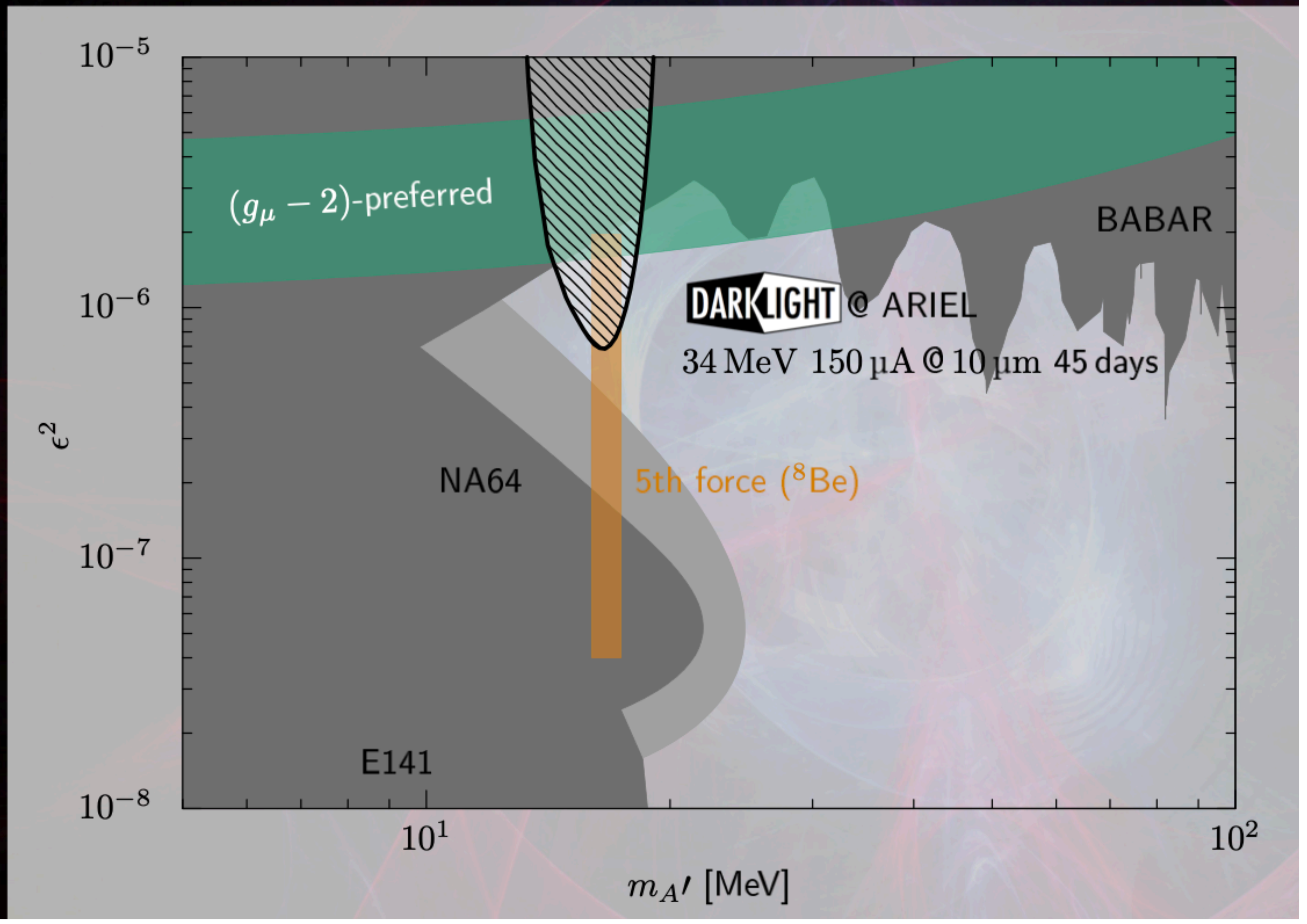
Counting rates: Backgrounds



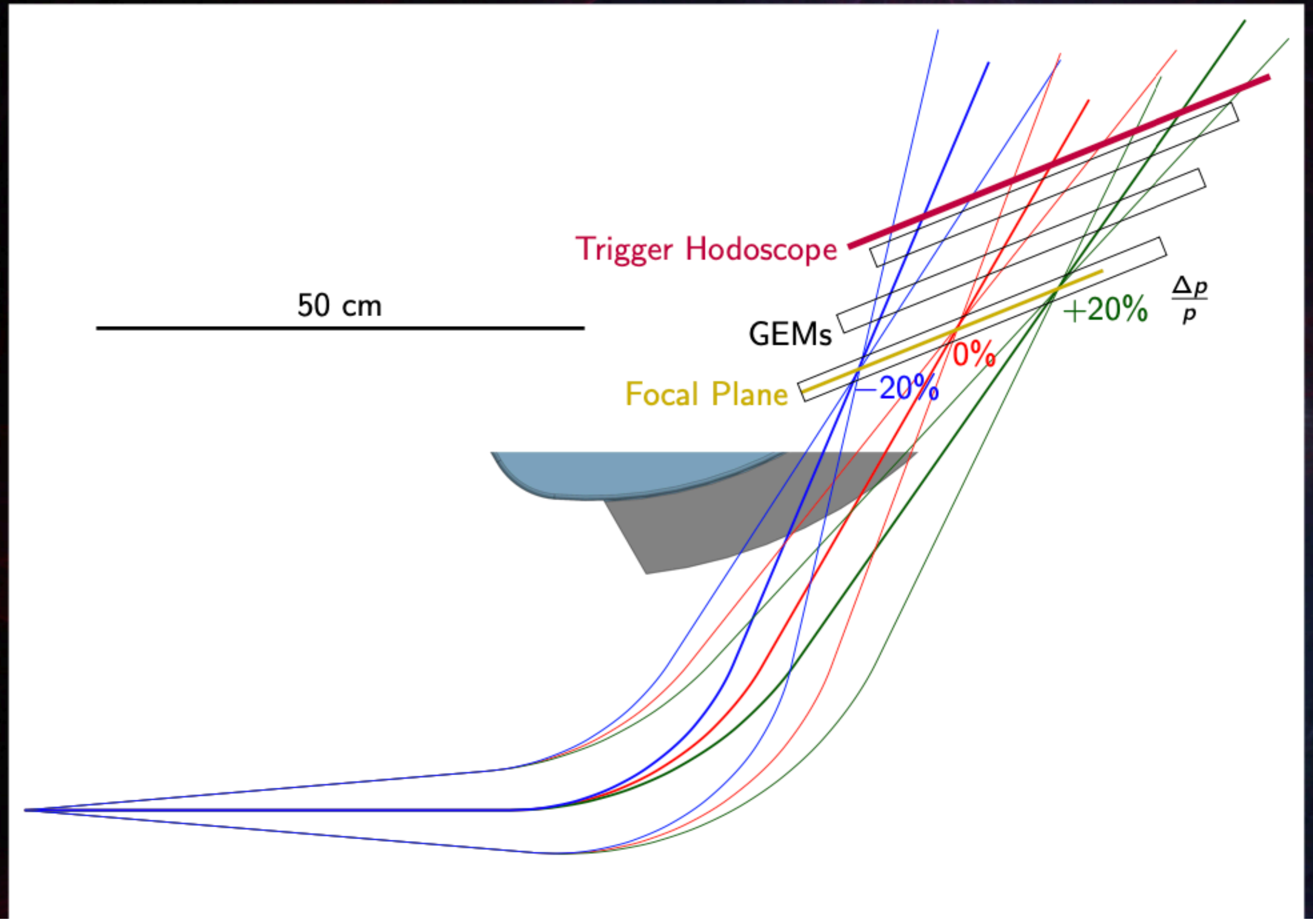
Reach at 45 MeV



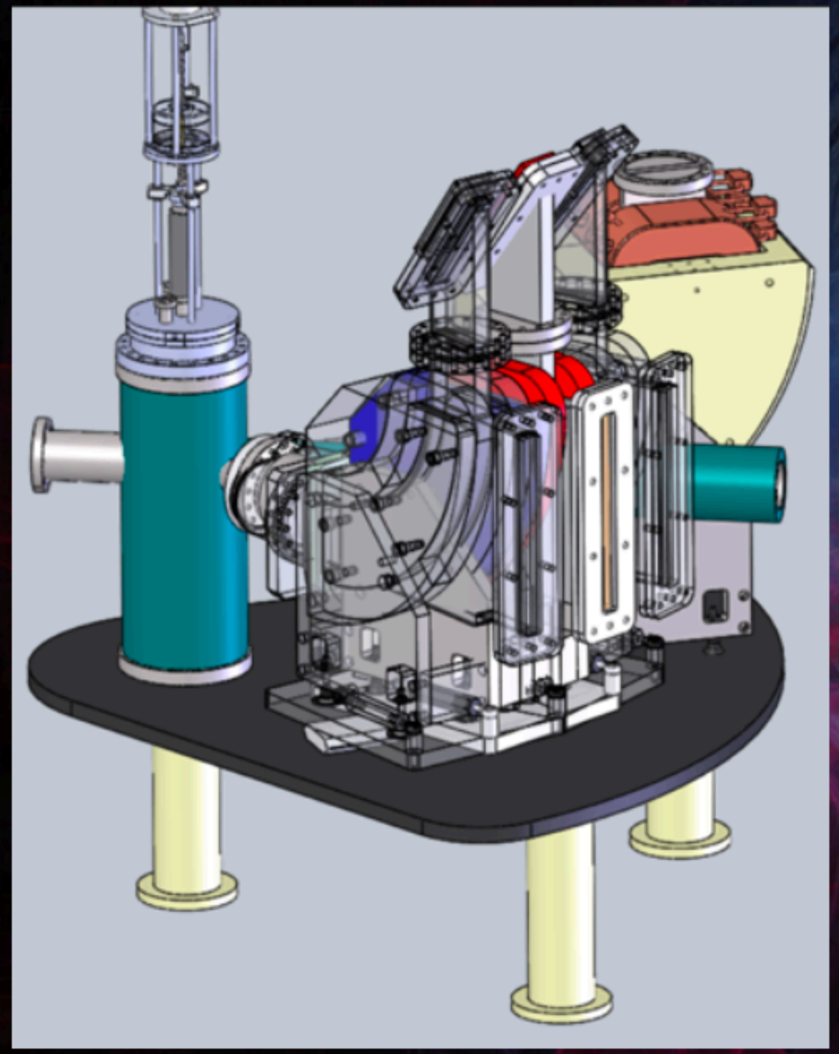
Reach at 34 MeV

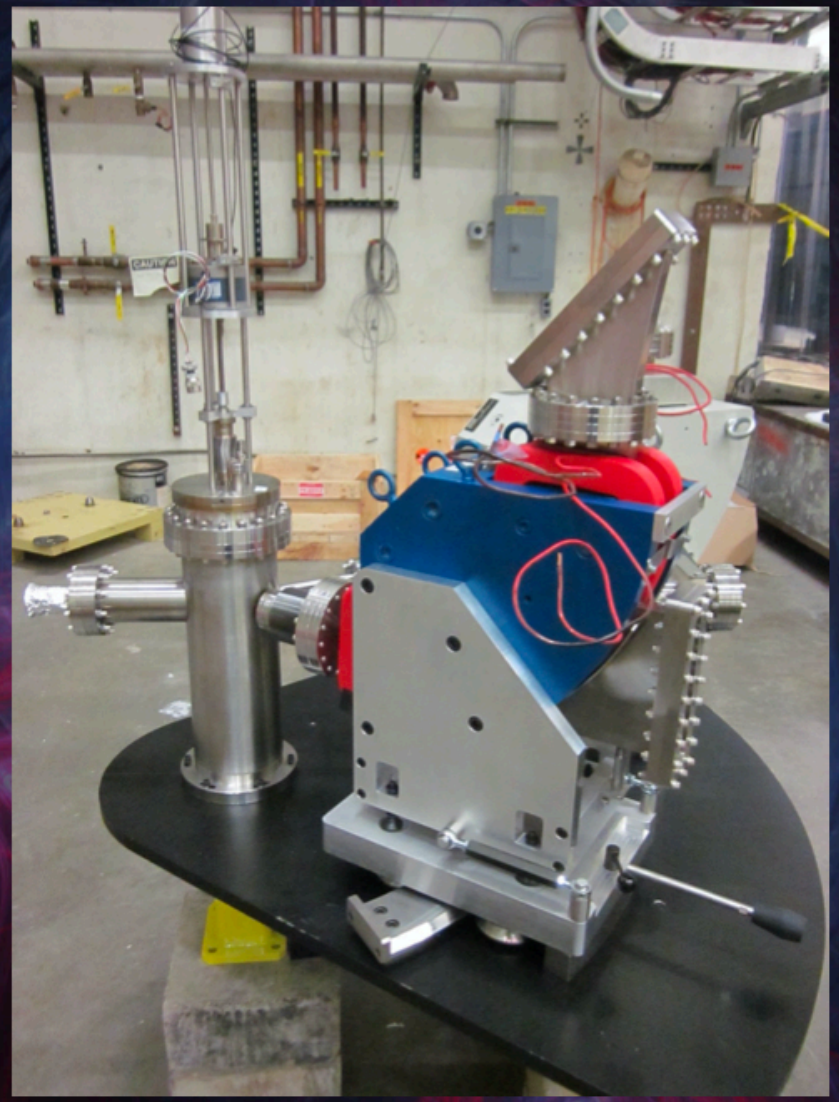


Spectrometers



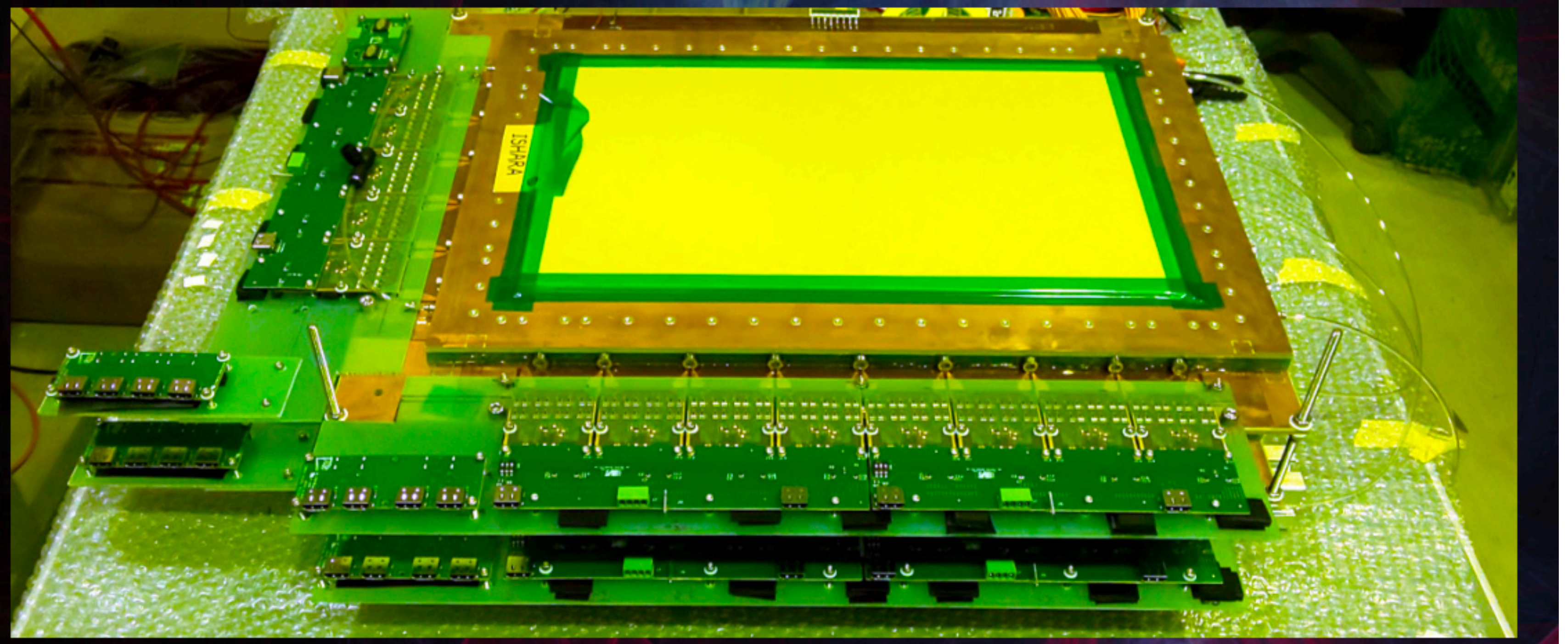
Experience: Møller at MIT HVRL





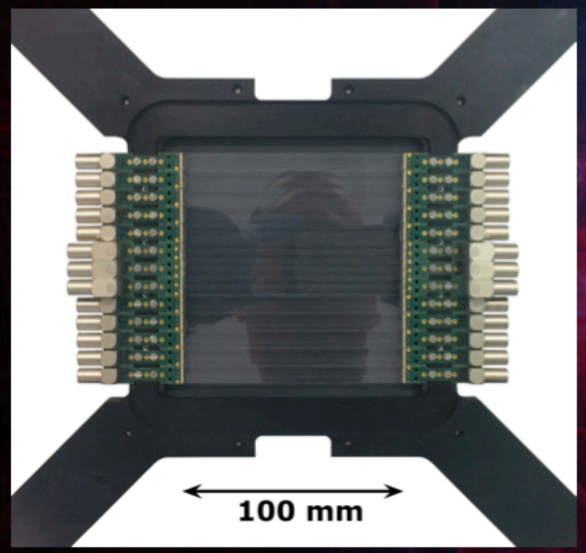
Tracking detectors

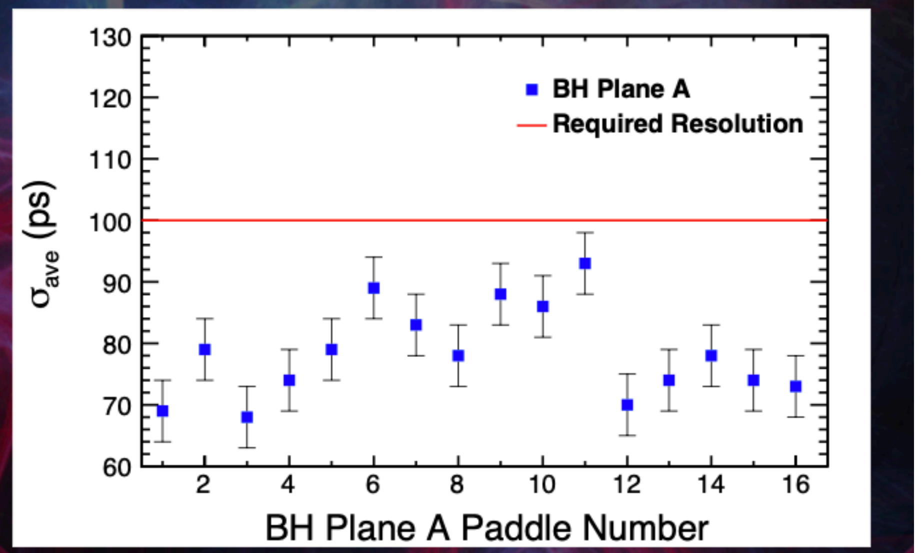
- Stack of three tGEMs, 25x40 cm, modified CERN design
- Readout via APVs and MPD4 (Same as SBS and PREX)
- Hampton group has built eight.



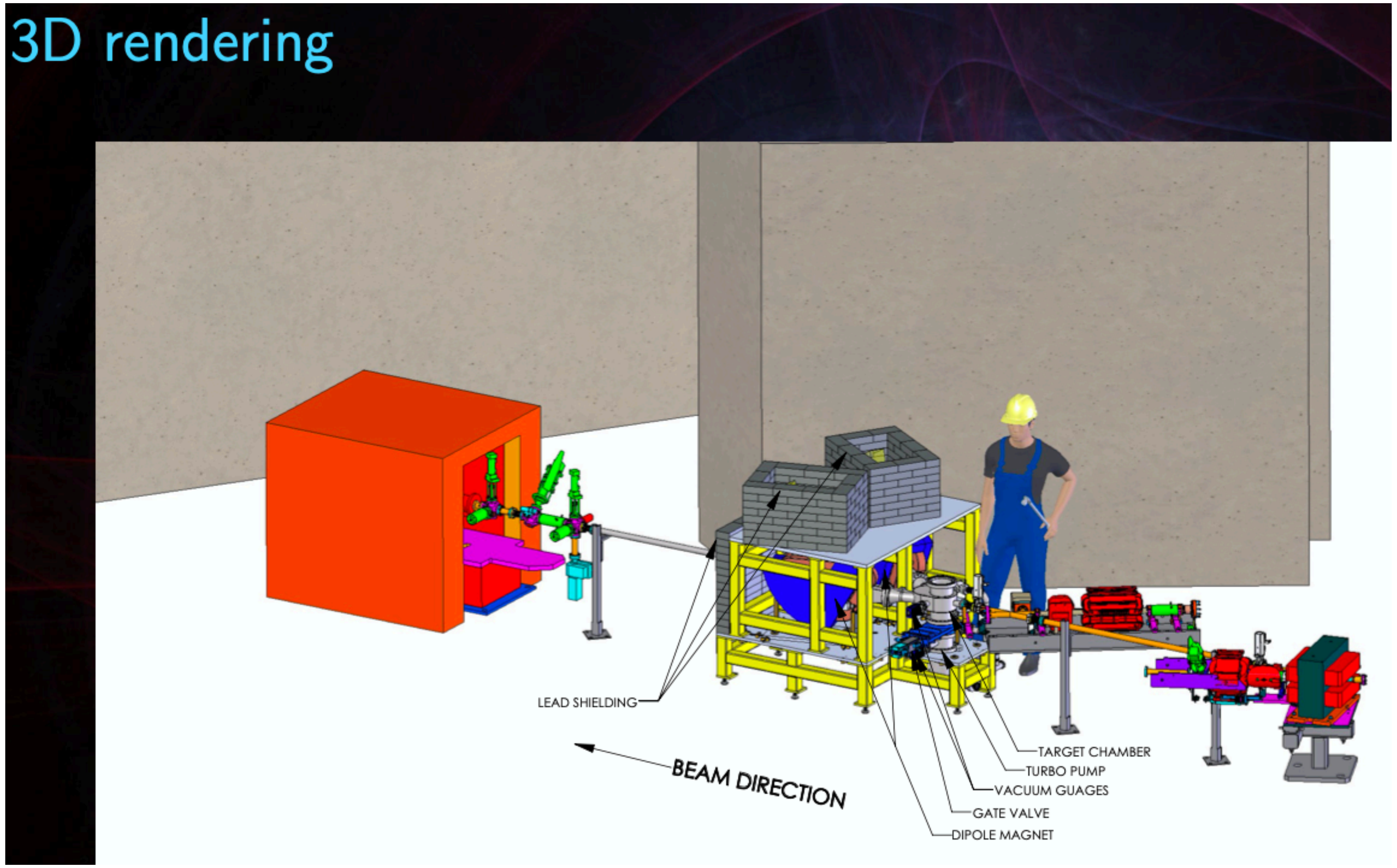
Trigger detectors

- Scintillator Hodoscope, 10 segments/spectrometer
- Needs timing resolution of < 500 ps
- MUSE beam hodoscope: 2 mm thick scintillator, SiPM readout: < 100 ps
  - Tested up to 8mm wide, 15 cm long.



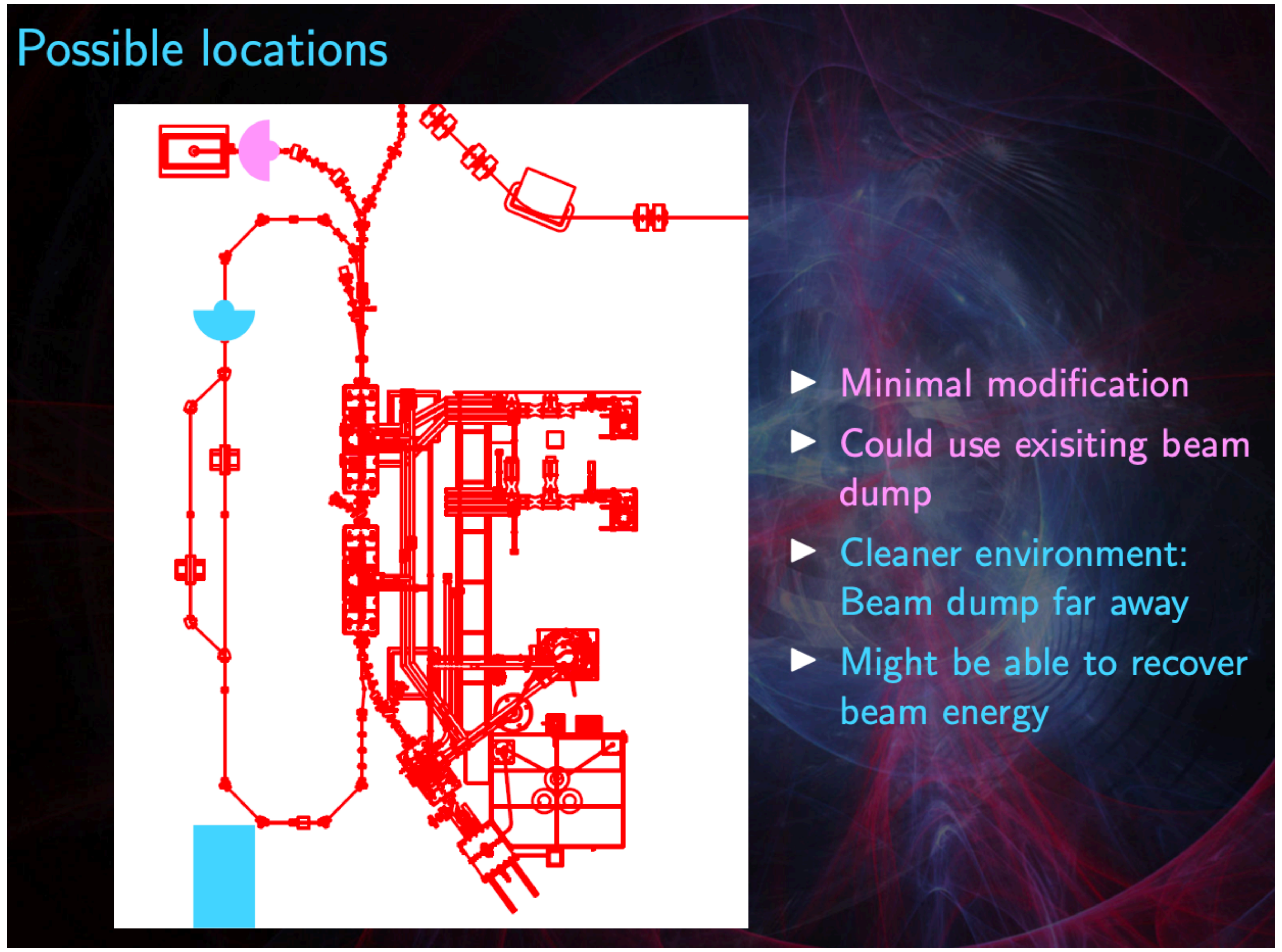


(T. Rostomyan et al., NIMA 986 164801)



⇐ What the experiment would look like

Where it could be sited ⇒



Opportunities for Missing Momentum Experiments

Nikita Blinov

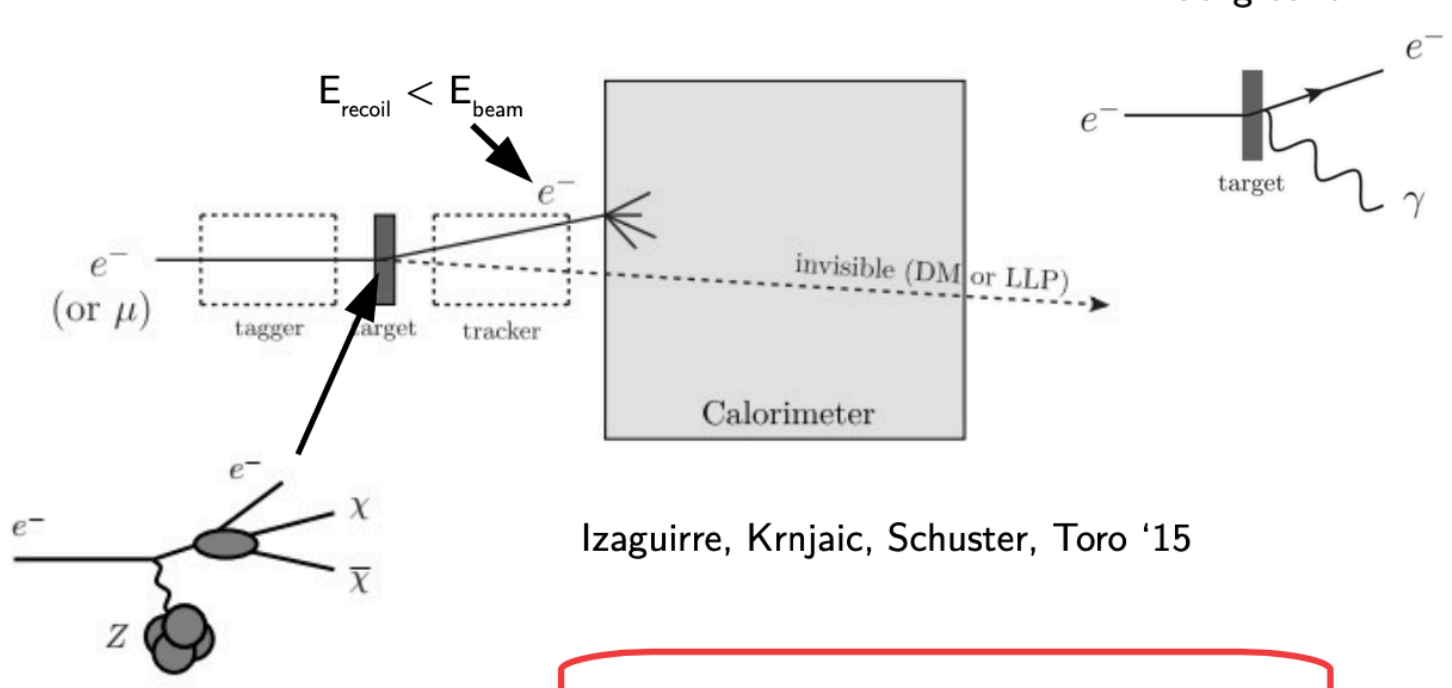
November 5, 2020

DND 2020, TRIUMF

Fermilab KICP

Missing Energy/Momentum

Detect DM indirectly by observing recoiling SM particle.



Izaguirre, Krnjaic, Schuster, Toro '15

production $\propto y$

$\text{Signal Yield} \sim y \times N_{\text{EOT}}$

Every Mediator/DM particle produced is detected!

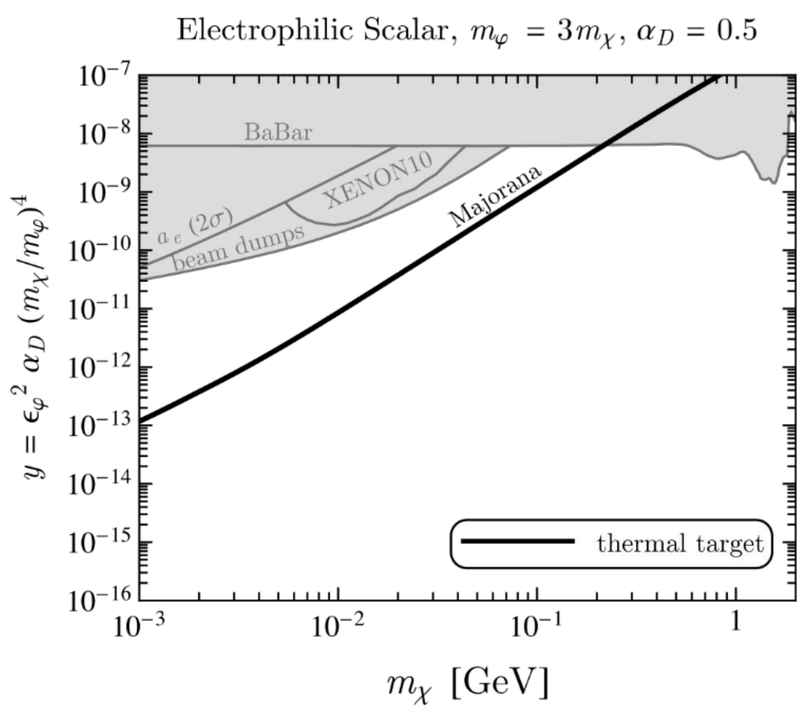
Variations on a Theme

- Other DM options:

  Scalar, Majorana or Dirac
  Asymmetric, inelastic, SIMPs,..

- Other mediators

  B-L, L_e-L_{mu},...
  Scalar, pseudoscalar, ...



Berlin, NB, Gori, Schuster & Toro '18
Berlin, NB, Krnjaic, Schuster & Toro '19

Qualitatively similar targets in a wide variety of other models

Beam Requirements

1) Need to track each incident beam particle

   low current

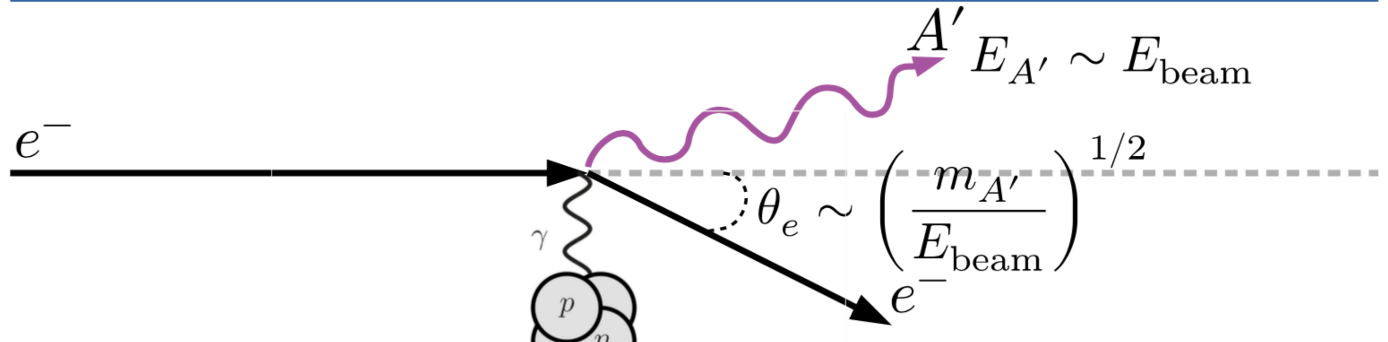
2) High statistics on a ~year time scale ($>10^{14}$ EOT)

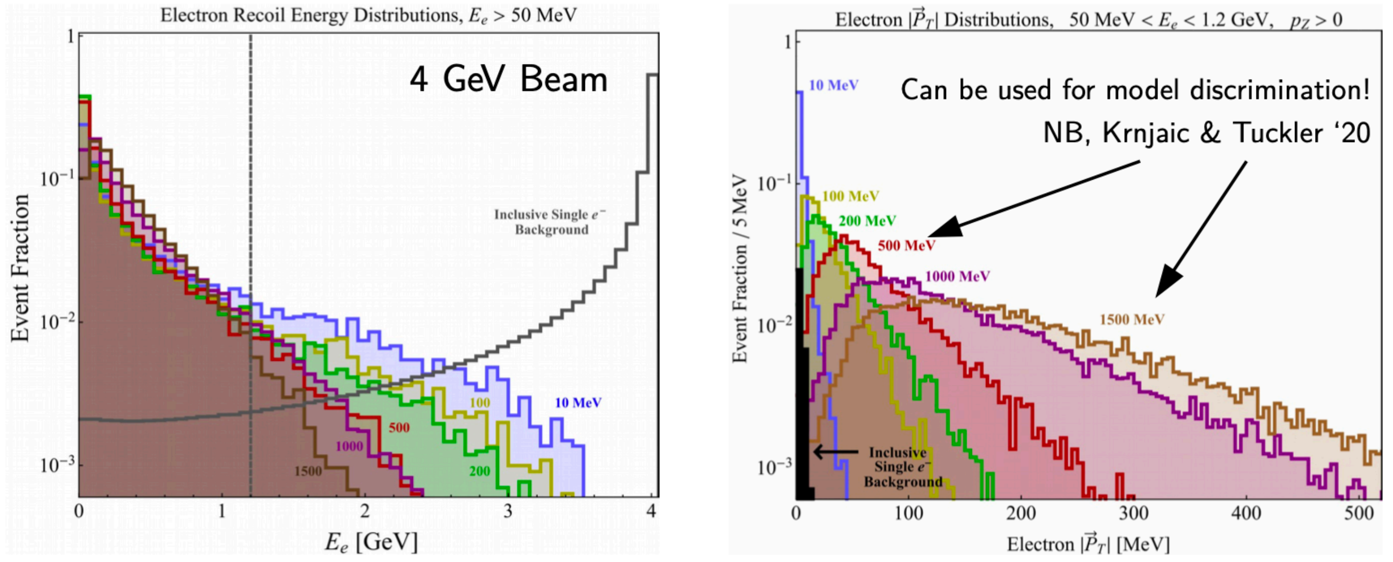
   single/few electrons @ > 30 MHz repetition rate

Candidate beams:

- S30XL@SLAC - SLAC-R-1147; must be parasitic to free-electron laser program
- CEBAF@JLAB – primarily a nuclear physics facility
- eSPS@CERN - CERN-SPSC-2018-023 - hypothetical

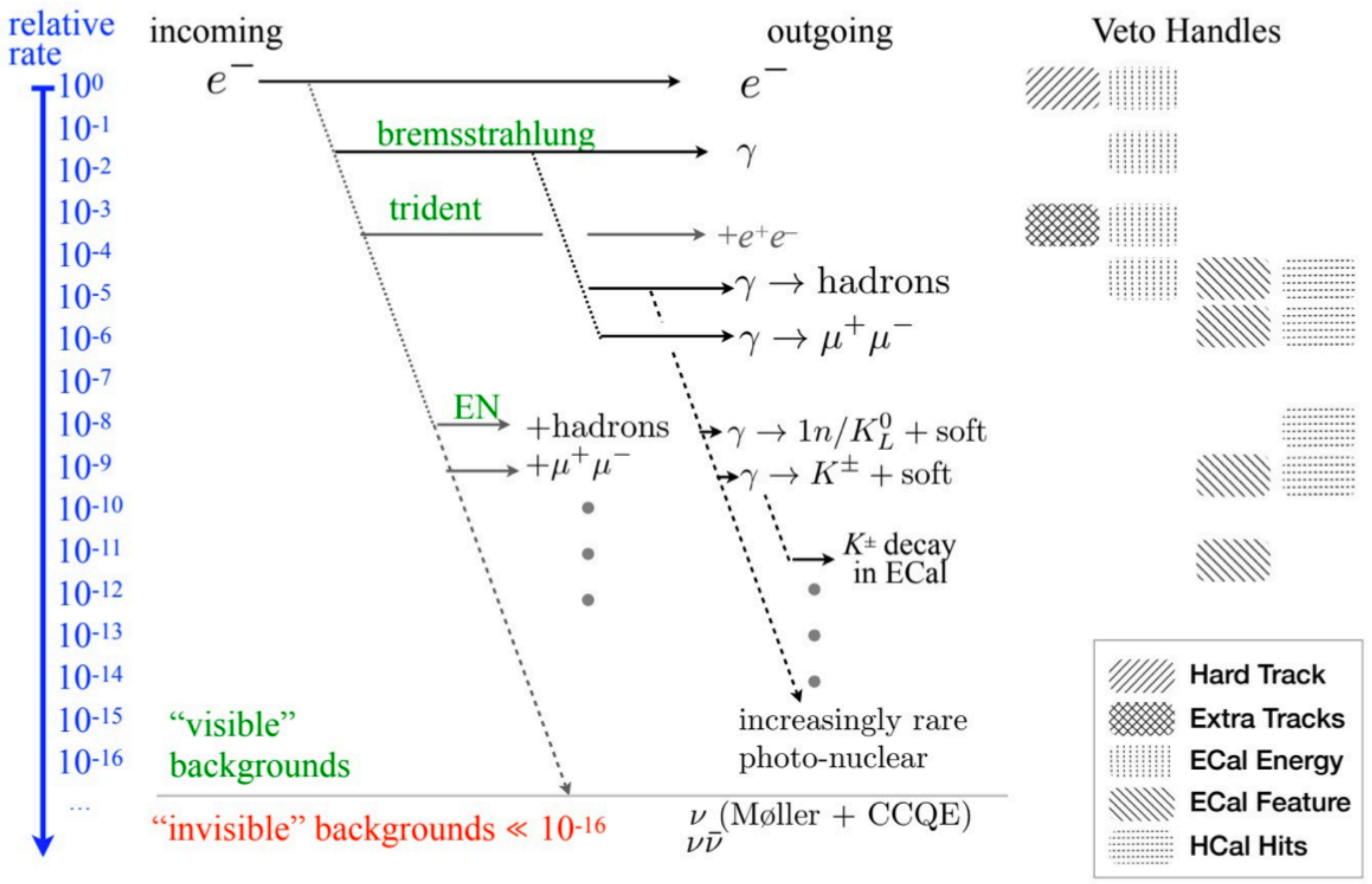
Signal Kinematics





LDMX Collaboration (1808.05219) '18

Backgrounds



Visible energy deposition in ECAL/HCAL

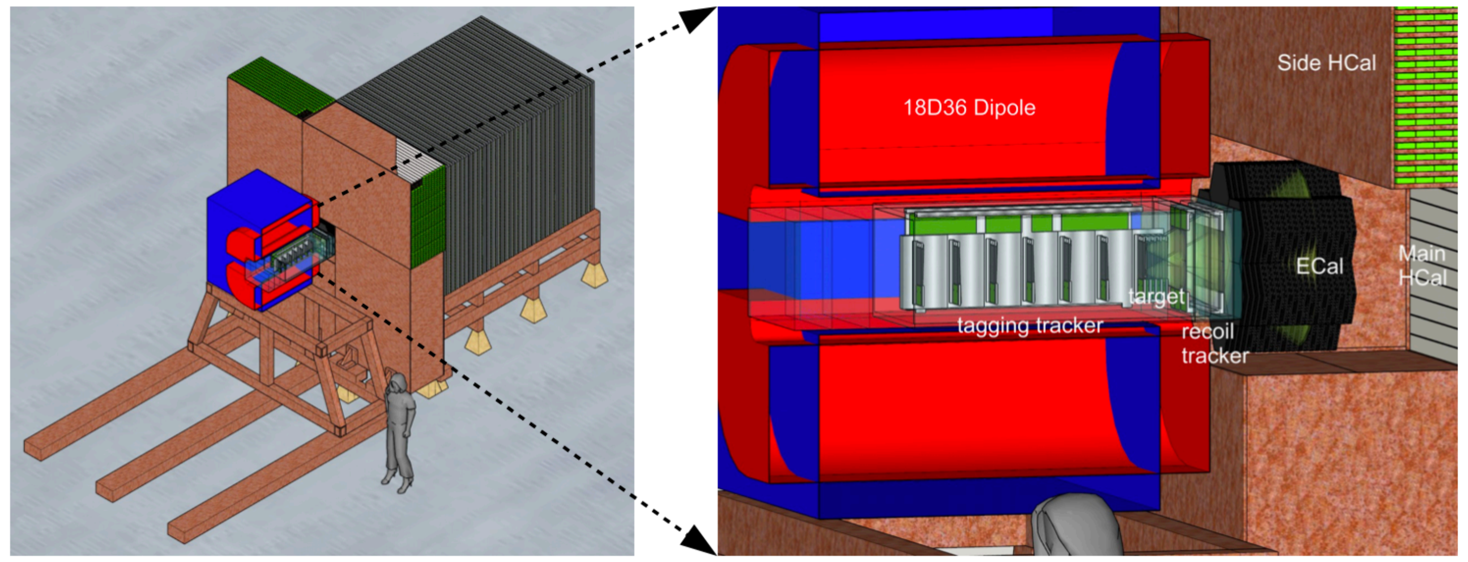
LDMX Collaboration '19

Light Dark Matter eXperiment LDMX

- Detector design developed by the LDMX collaboration, using technology from CMS, Mu2e and HPS experiments

  LDMX Collaboration (1808.05219) '18

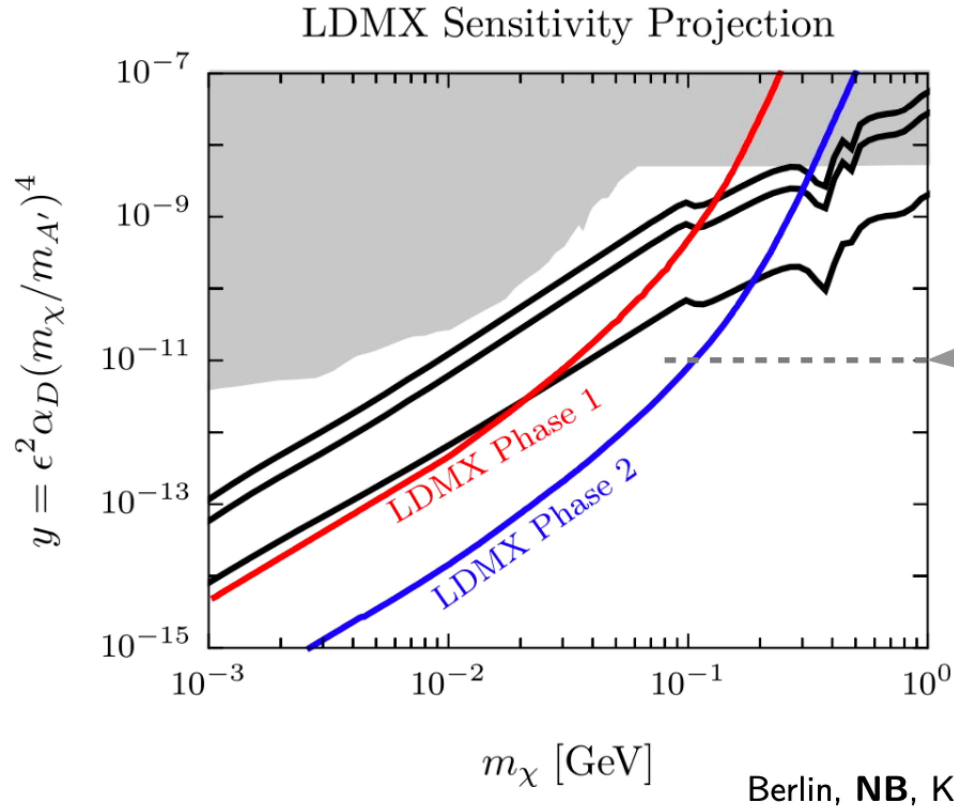
- Background studies using realistic detector simulation show the design achieves the necessary background rejection for 10^{14} EOT LDMX Collaboration (1912.05535) '19

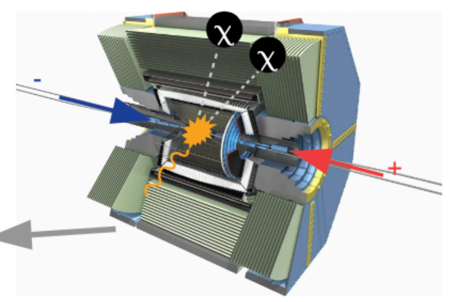


Fermilab SLAC UCSB University of Minnesota Caltech Lund University University of Virginia

27

LDMX Projections





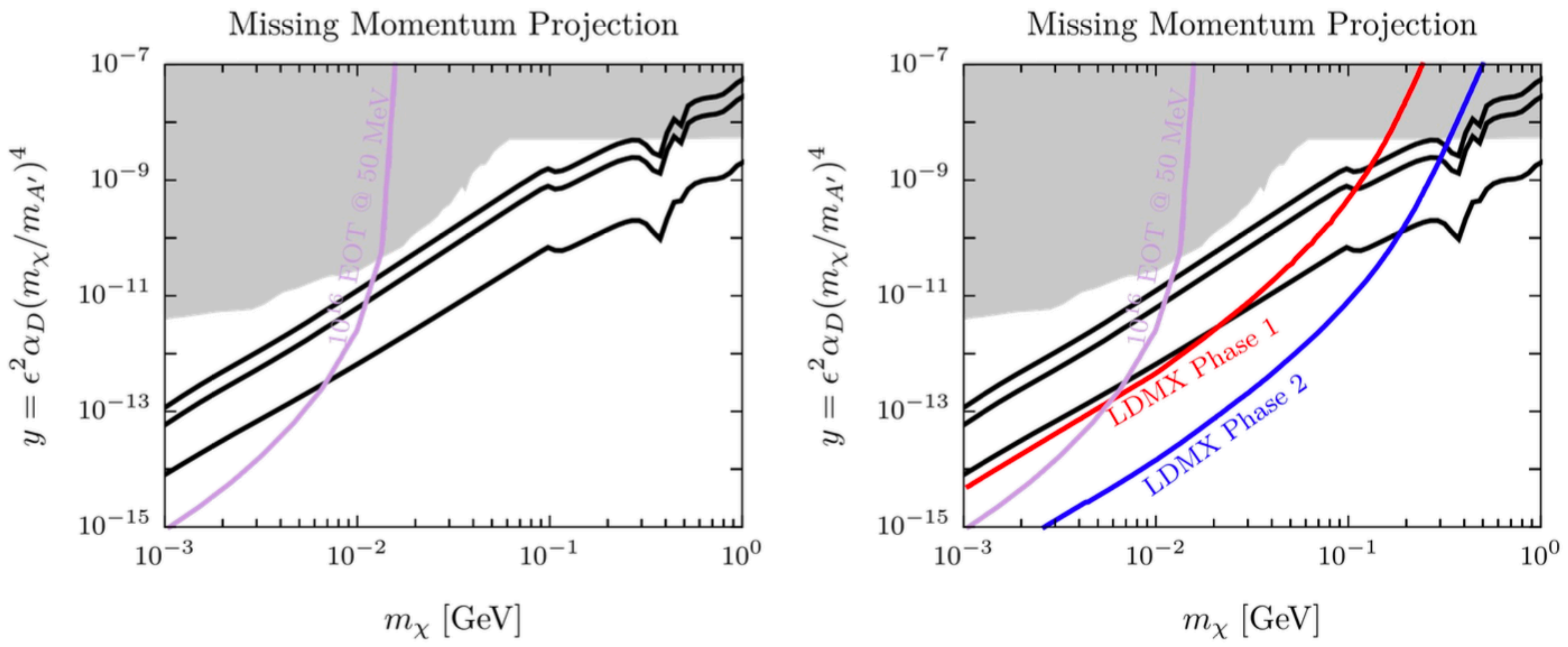
Berlin, **NB**, Krnjaic, Schuster, Toro '19

Phase 1: ~10^{14} EOT, 4 GeV e Beam
Phase 2: ~10^{16} EOT, 8 GeV e Beam

LDMX+Belle II can decisively test thermal DM below a GeV!

Possible Reach

50 MeV electron beam, 10^{16} EOT on $0.1X_0$ Tungsten

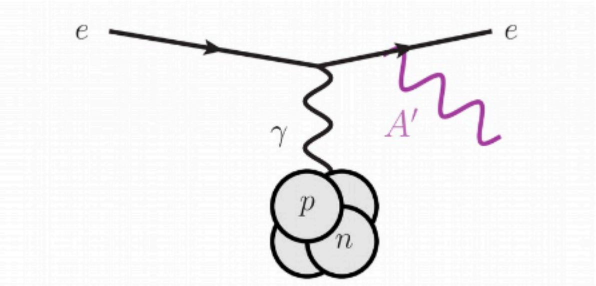


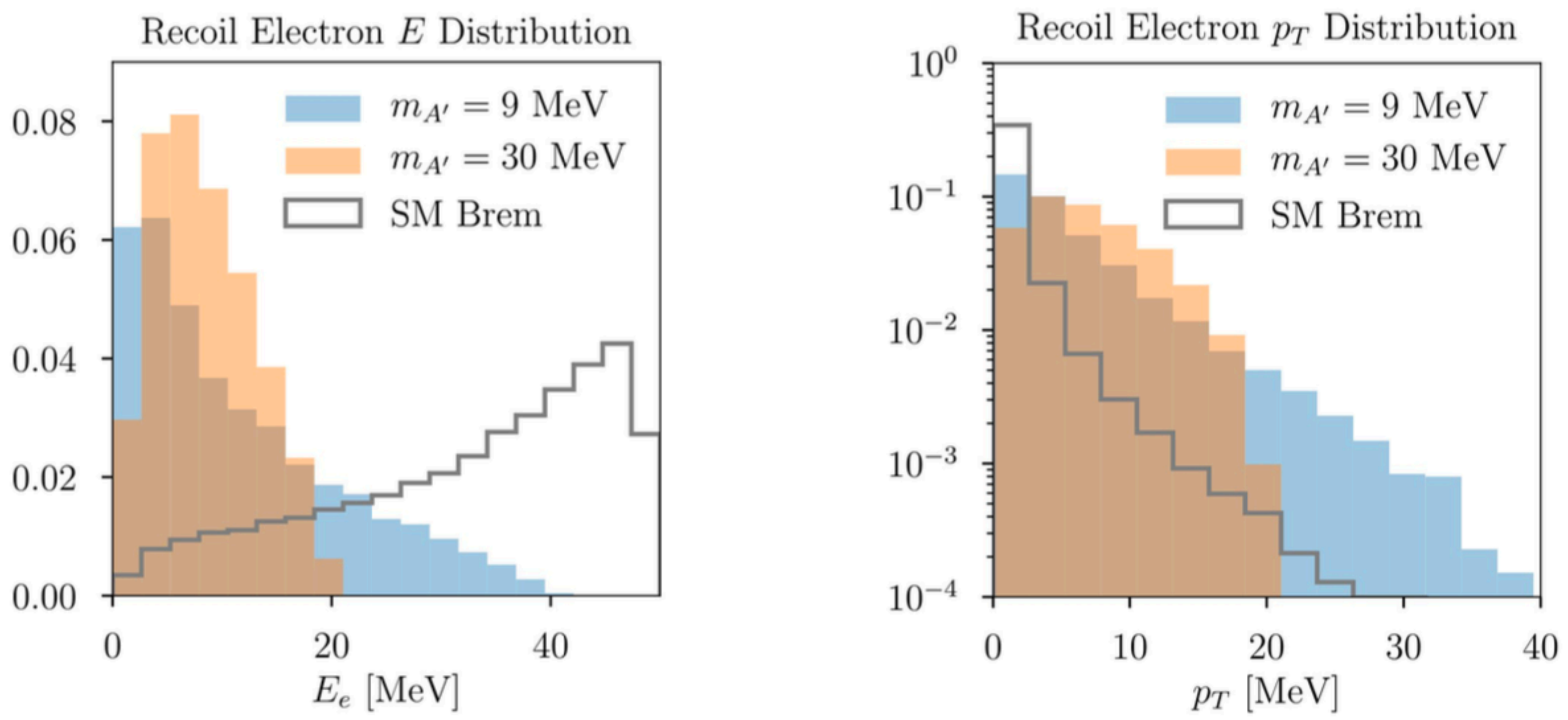
Challenge 1: nominal ARIEL current probably too high (pileup)
Challenge 2: lower energy, more wide-angle/lost emissions (background)?

Nikita Blinov performed quick ARIEL beam study for LDMX-type setup!

ARIEL Beam

- Much of previous discussion translates to ~50 MeV electron beam

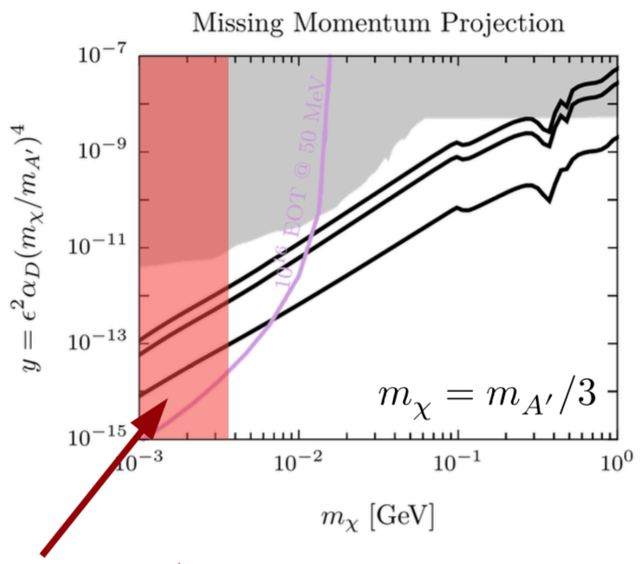




Viable Parameter Space

- **Challenge 3: Large range of accessible parameter space in tension with cosmology**

Nontrivial reach but some area in tension with cosmology⇒



In conflict with BBN/CMB

Prompts from the Organizing Team

What ideas could (or could not) be turned into **actual experiments** at TRIUMF/CENPA?

What **homework** do we need to do to figure this out?

Should we form a **working group** to answer such questions? Who are key people to target for this working group?

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The DarkLight concept looks really exciting. Beam dump also interesting. What about other beams, e.g. p?
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Absolutely! DarkLight collaborators & theorists (and others?)