RE-INVENTING FIXED-TARGET EXPERIMENTS TO PROBE LIGHT DARK MATTER

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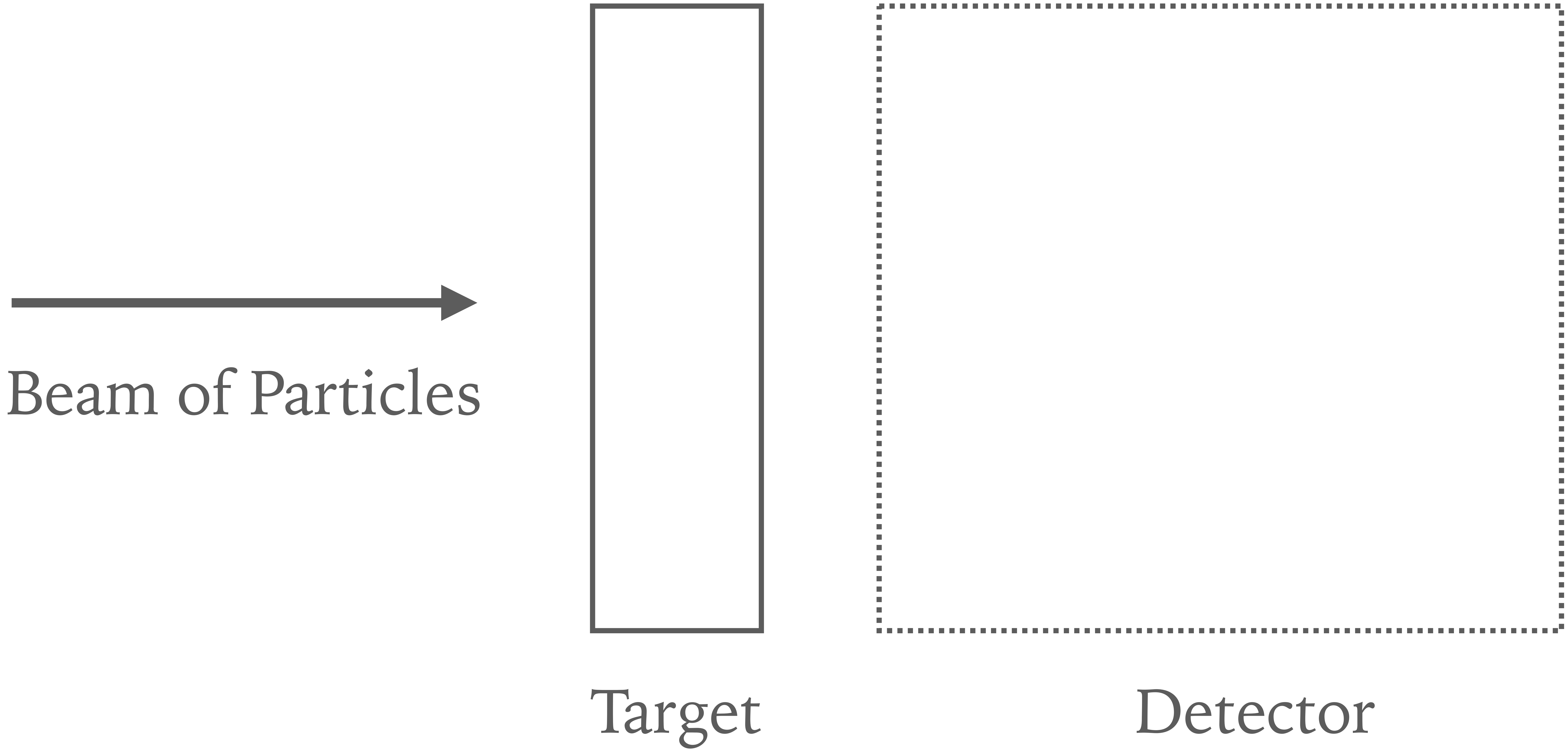
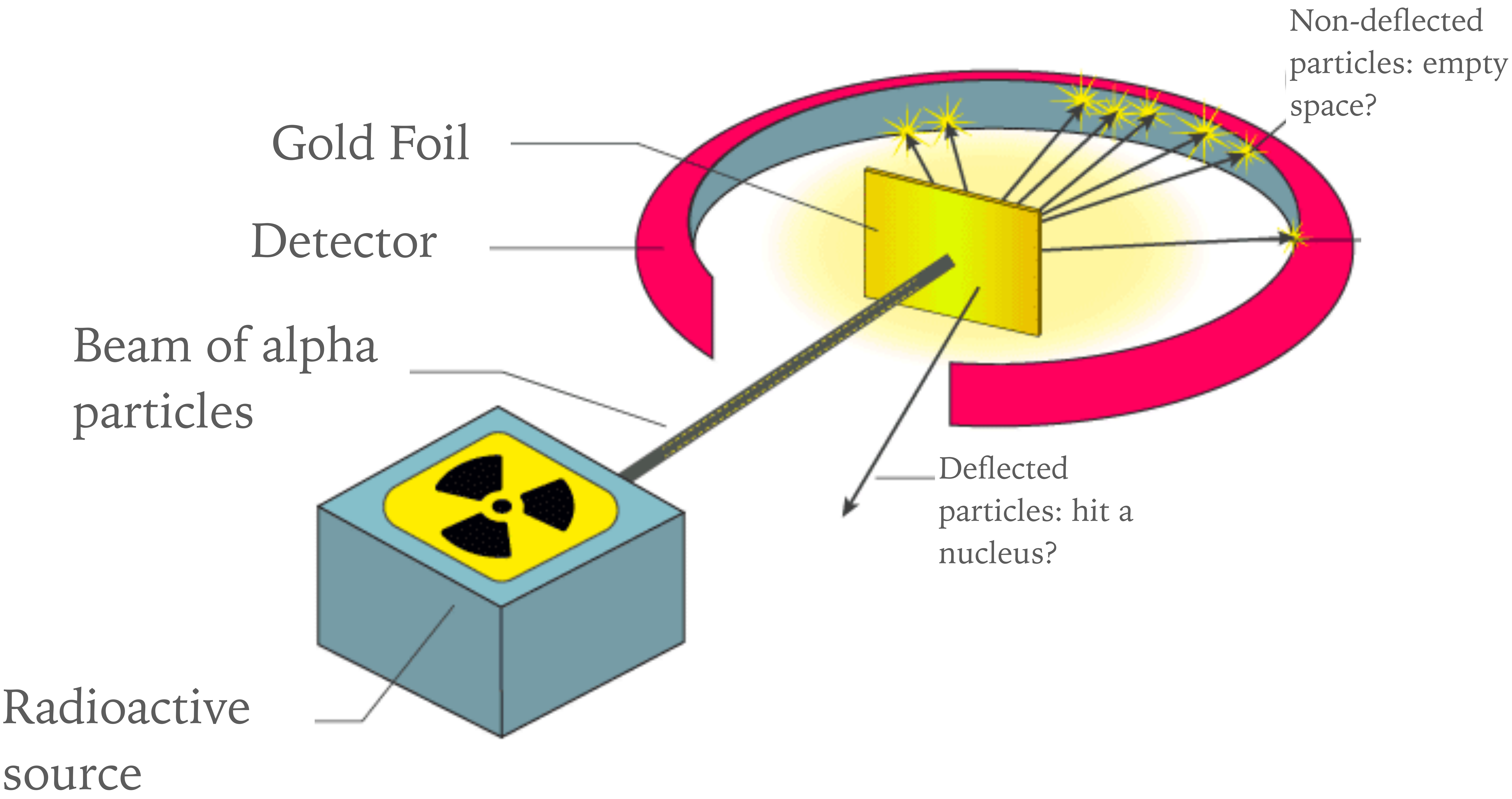
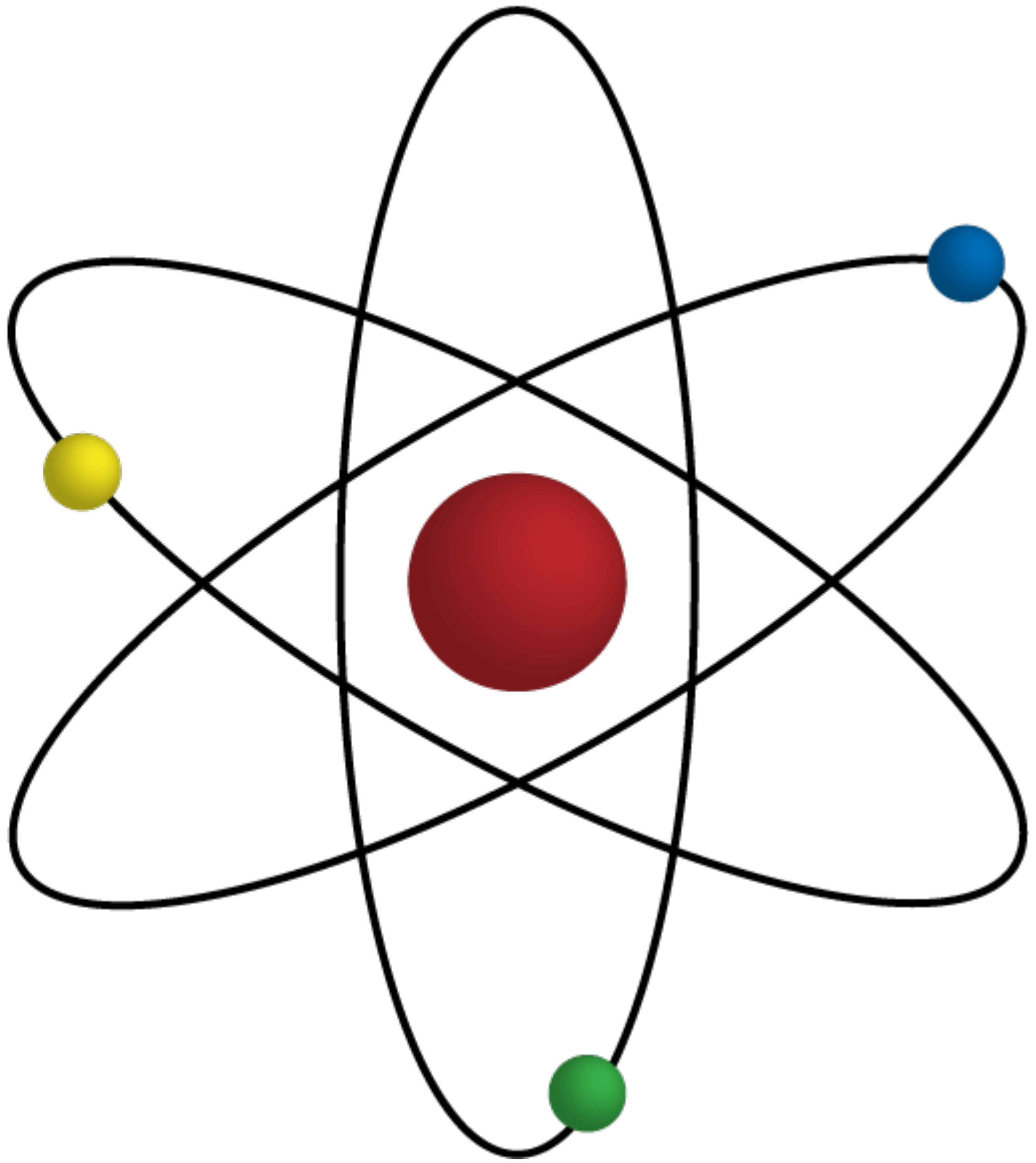
EPIC-2 school
October 12, 2022


Beam of Particles
Target
Detector

What was the first fixed-target experiment?


Non-deflected particles: empty space?
Gold Foil
Detector
Beam of alpha particles
Deflected particles: hit a nucleus?
Radioactive source



Electrons + Nucleus (p^+/n)

Quarks

Up	Charm	Top
Down	Strange	Bottom

Were any of these quarks discovered in a fixed-target experiment?

(A)	(B)	(C)
Charm	Bottom	Top
1974	1977	1995

Charm

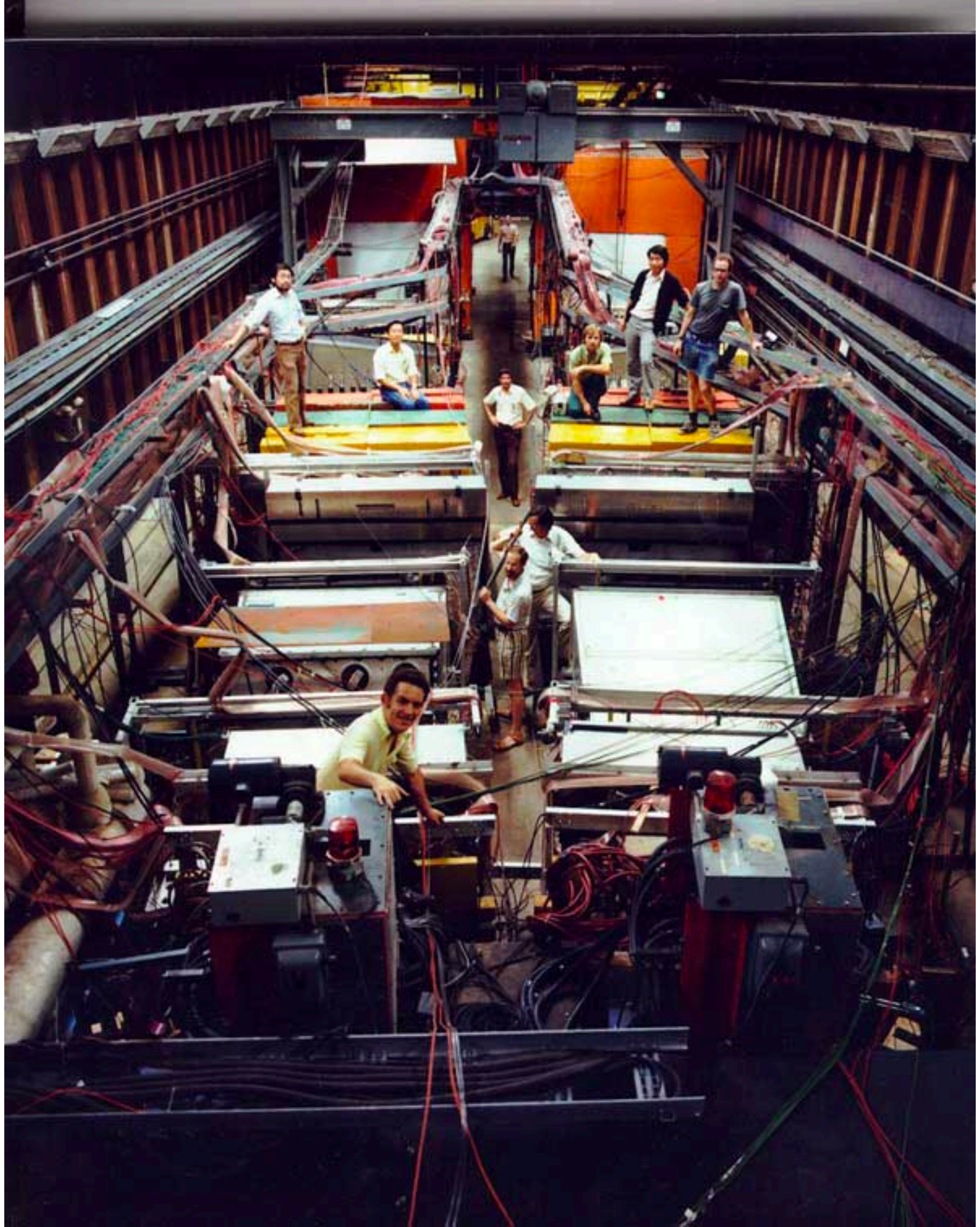
1974

Bottom

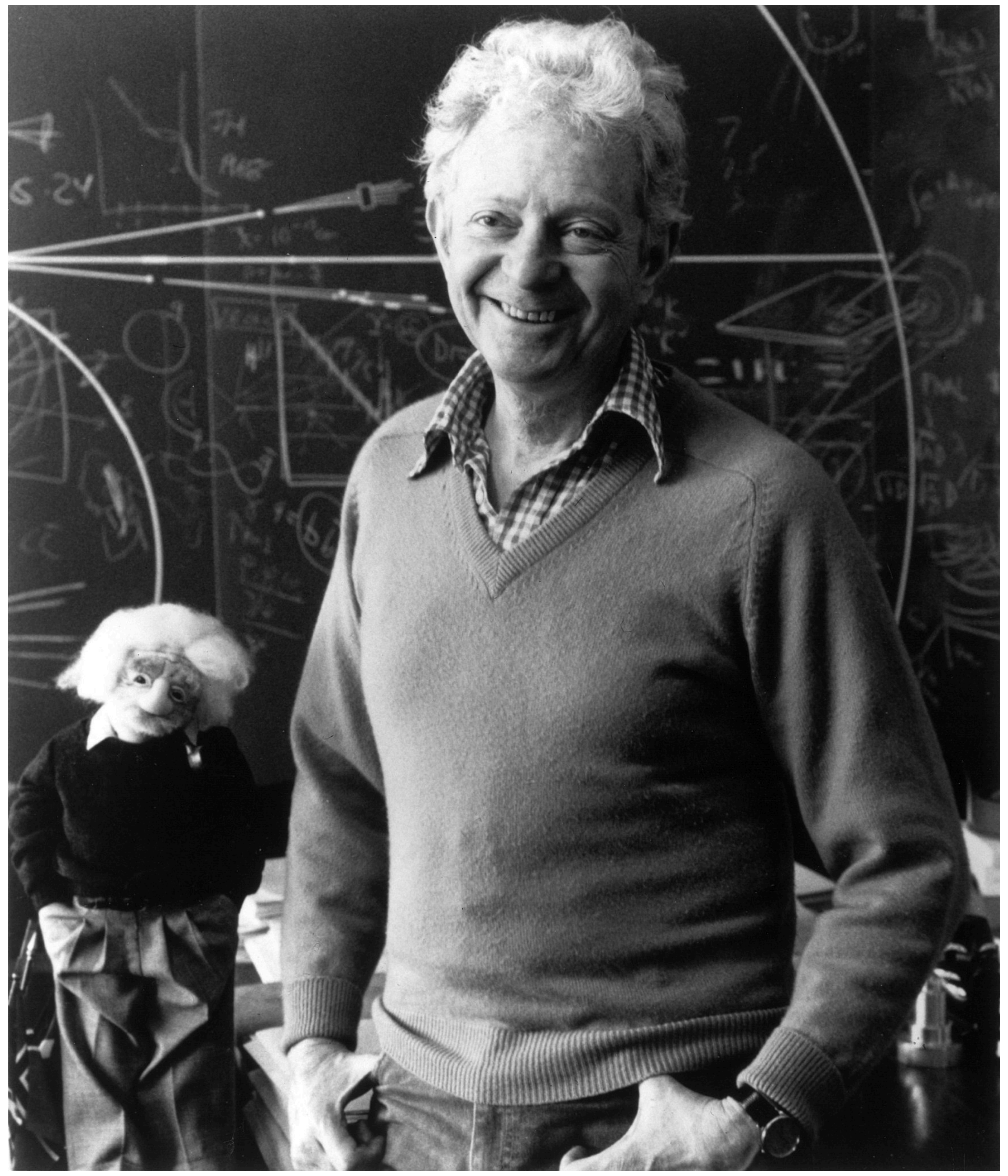
1977

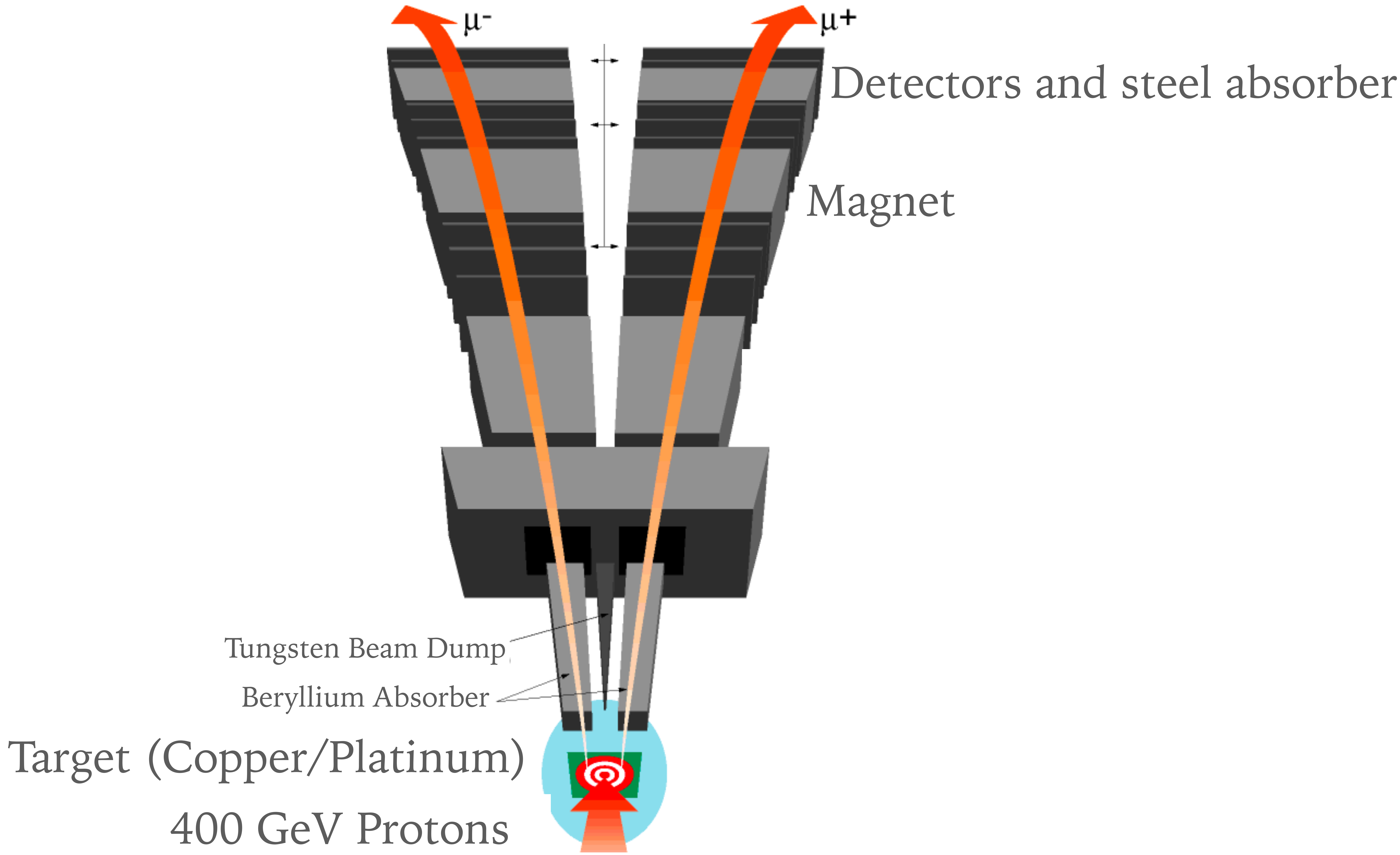
Top

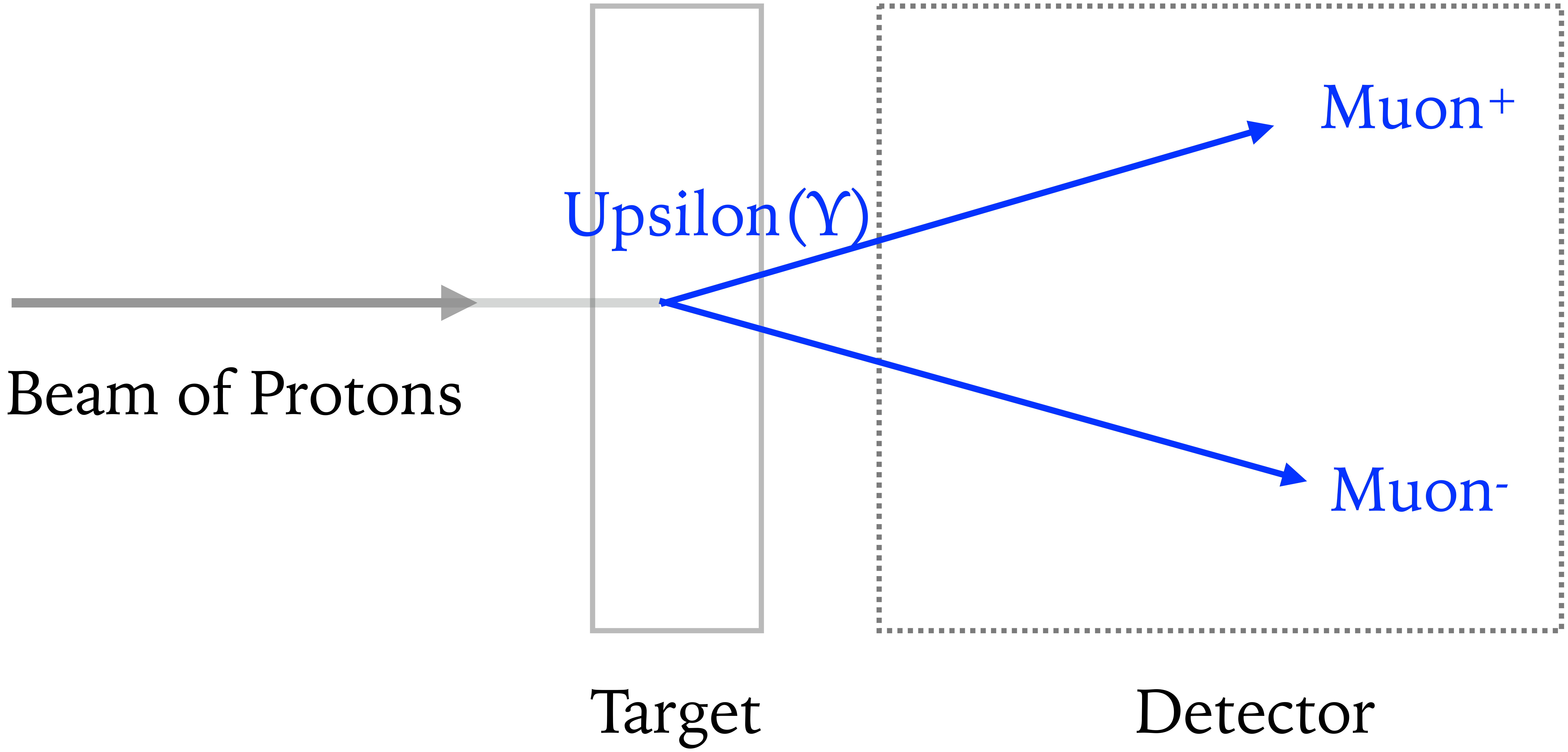
1995



The E288 Experiment Team led by Leon Lederman

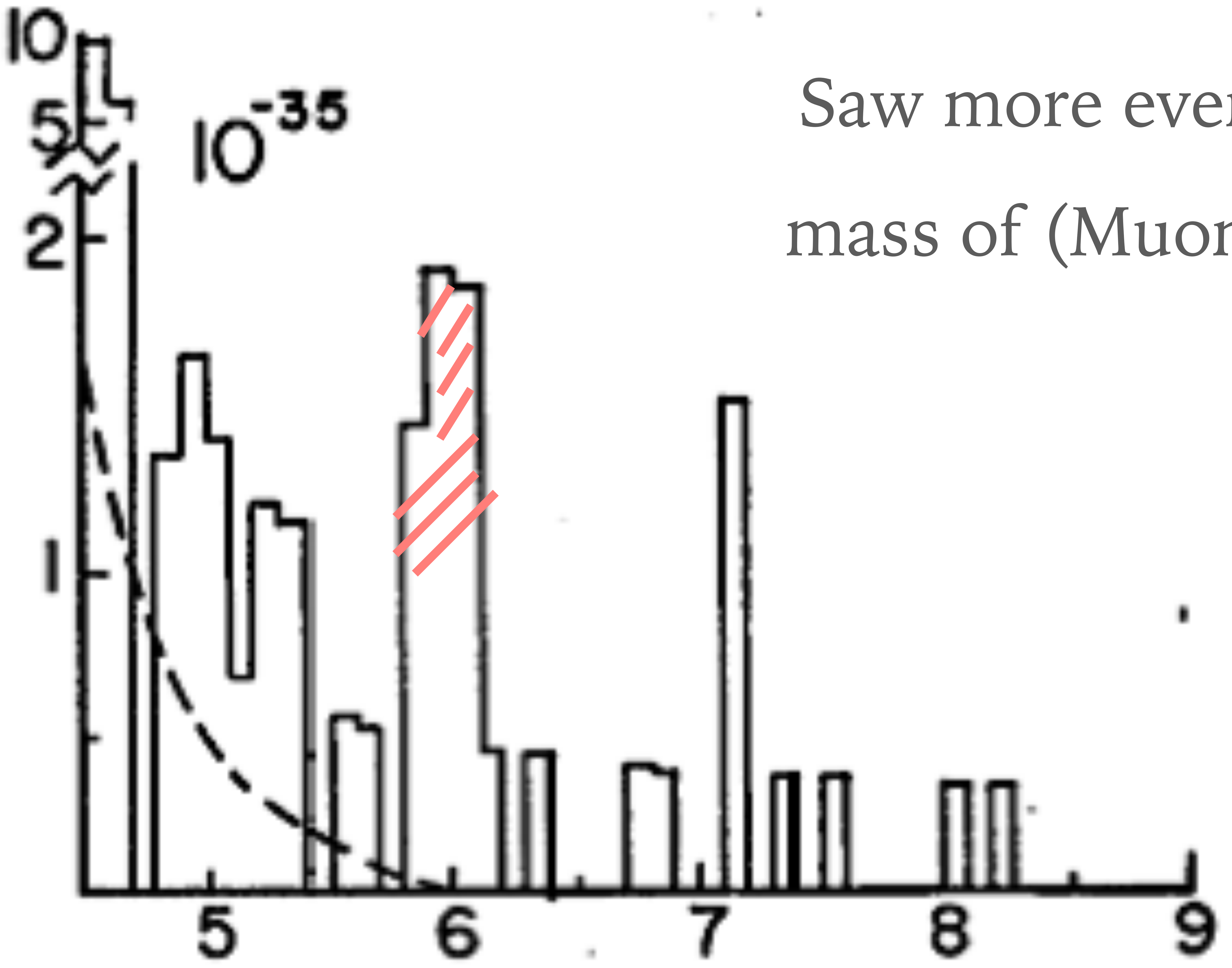



μ-
μ+
Detectors and steel absorber
Magnet
Tungsten Beam Dump
Beryllium Absorber
Target (Copper/Platinum)
400 GeV Protons



Υ is a bound state of two b quarks $(b\bar{b})$

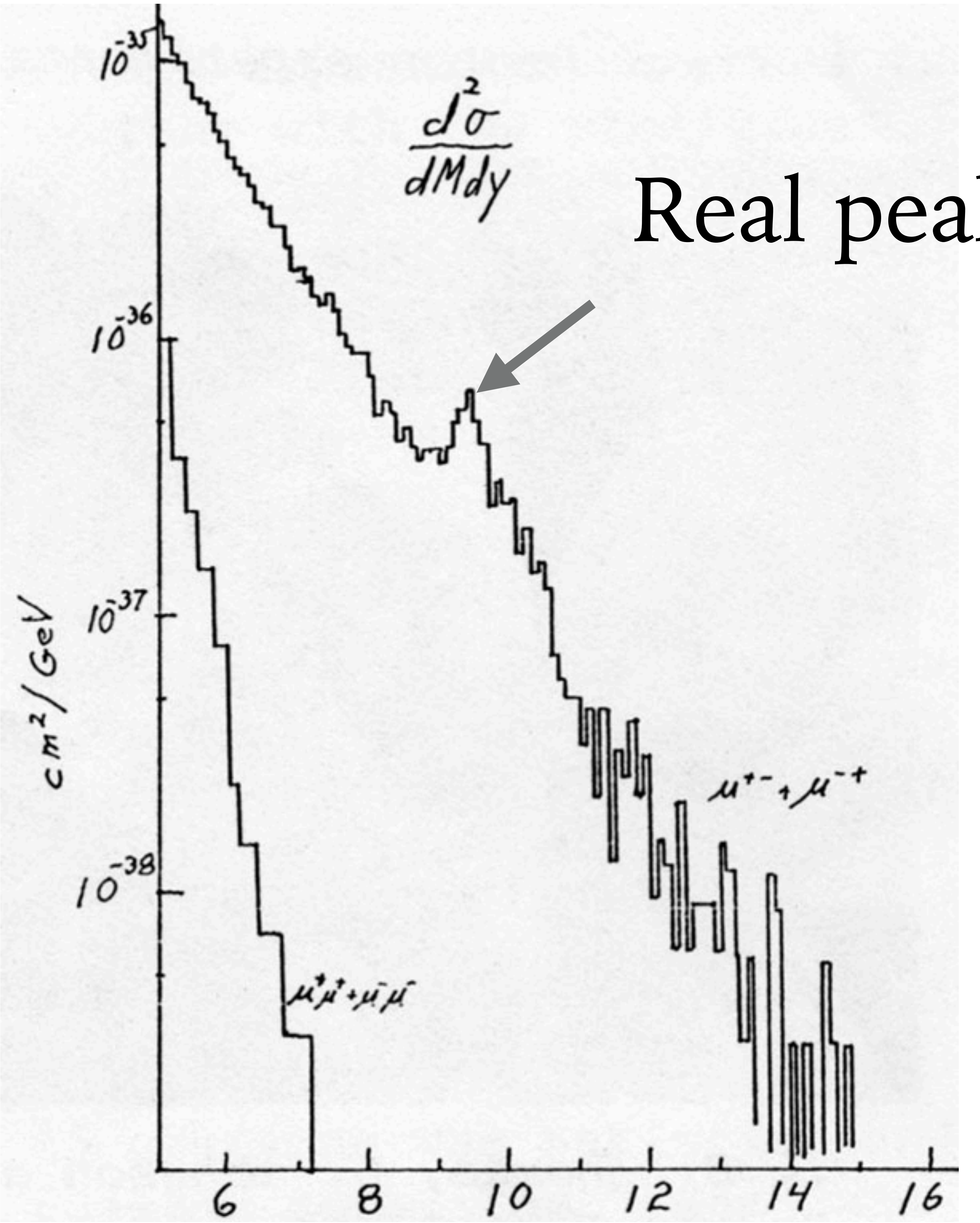
THE FIRST ROUND OF THE EXPERIMENT



Mass of two muons (GeV)

Saw more events than expected with mass of ($Muon^+$ + $Muon^-$) ~ 6 (GeV)

THE SECOND ROUND OF THE EXPERIMENT

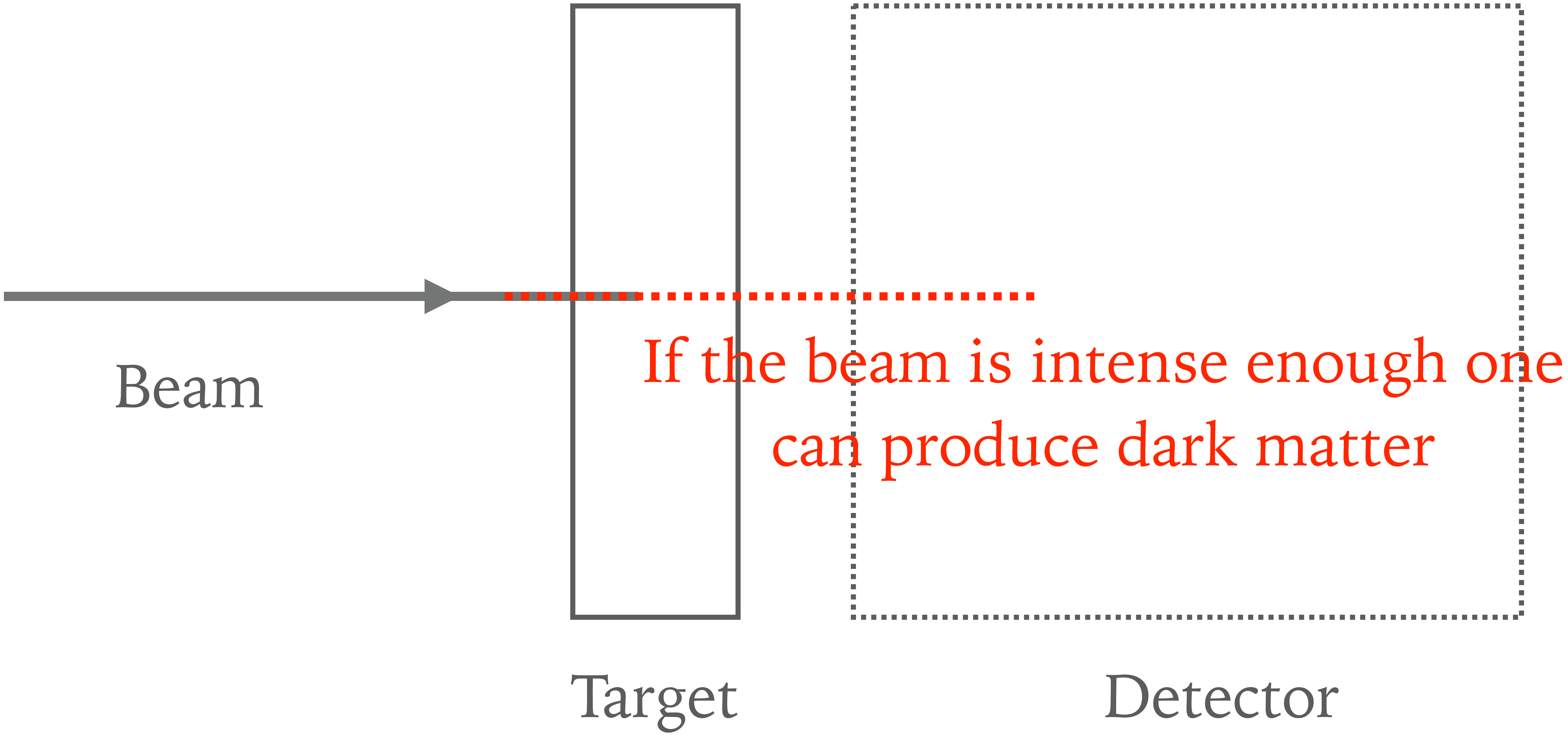


Real peak (Upsilon: pair of b-quarks)

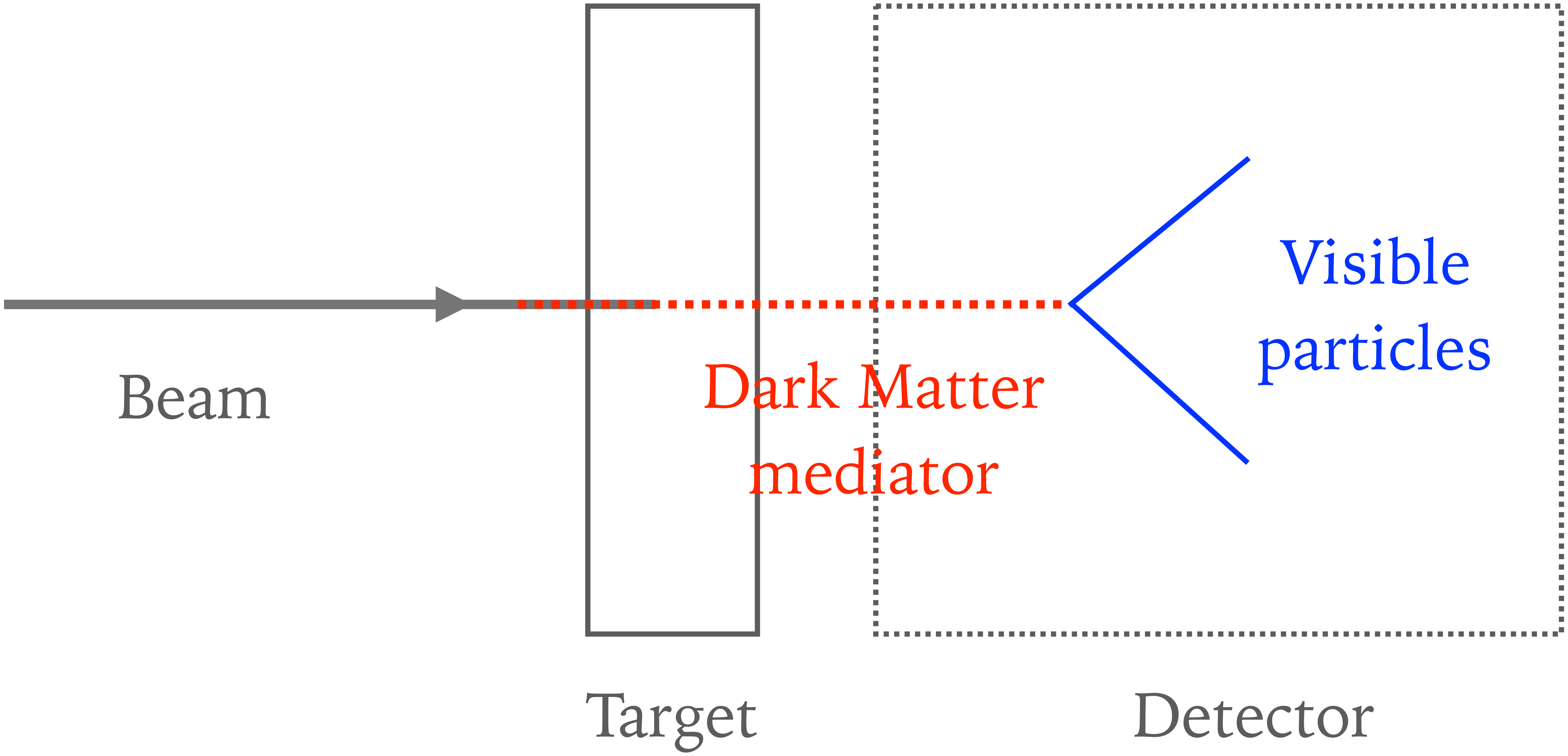
$\sim$ 10 GeV

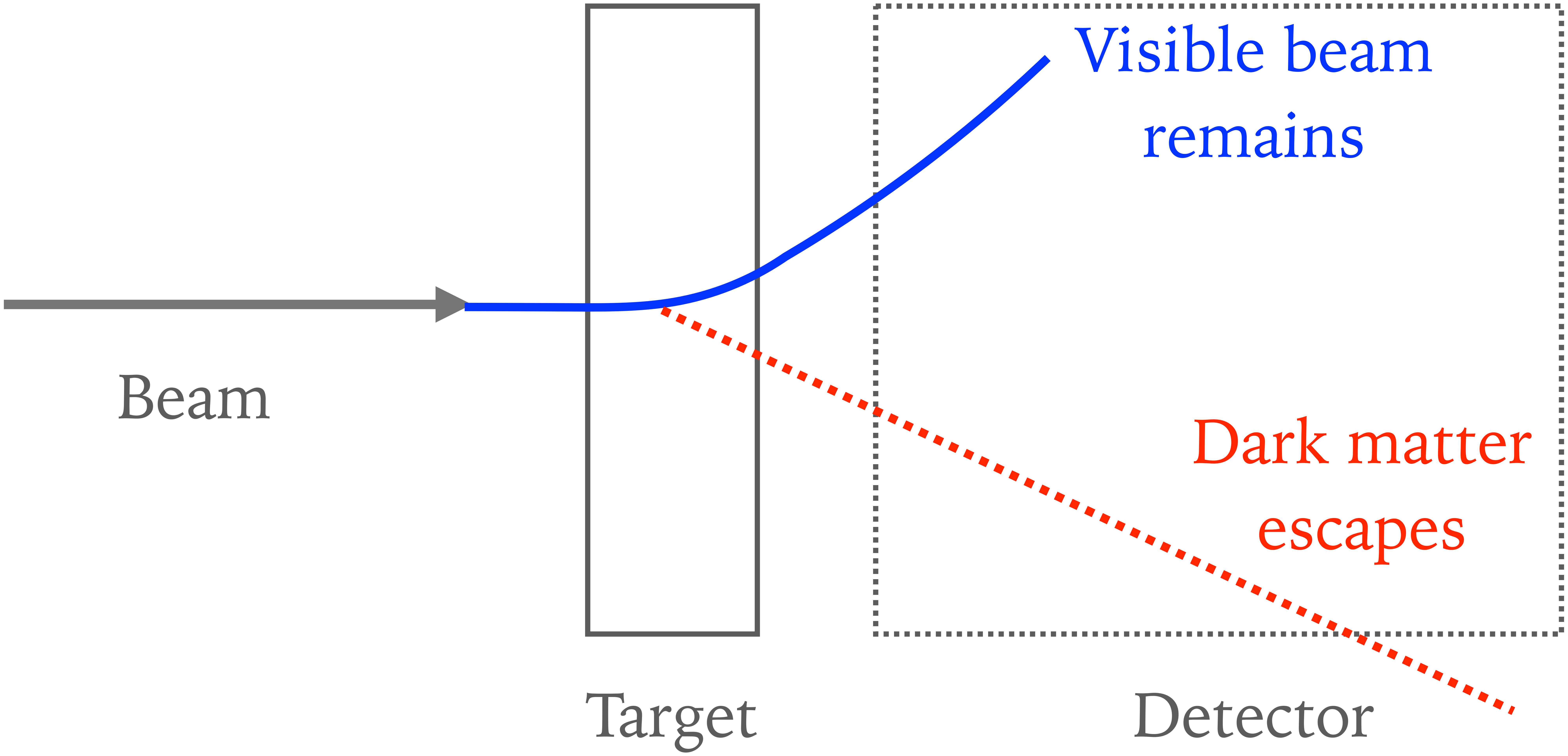
Mass of two leptons (GeV)

So, this is how the b-quark was discovered. How does this discovery relate to dark matter?



If the beam is intense enough one can produce dark matter


Visible
particles
Beam
Dark Matter
mediator
Target
Detector


Visible beam
remains
Beam
Dark matter
escapes
Target
Detector

IN THIS TALK I WILL SHOW THAT

- ➤Dark matter particles can be observably produced in fixed-target experiments.
- ➤These particles will be light because fixed-target experiments are low-energy. Exploring light dark matter is compelling and achievable.
- ➤One can take several approaches to search for dark matter in fixed-target experiments, it just requires a little bit of re-invention.

- Motivate the search for light dark matter and why fixed target experiments can probe it.
- Two forward experiments: DarkQuest and the Light Dark Matter Experiment (LDMX).

DARK MATTER IN THE INTENSITY FRONTIER

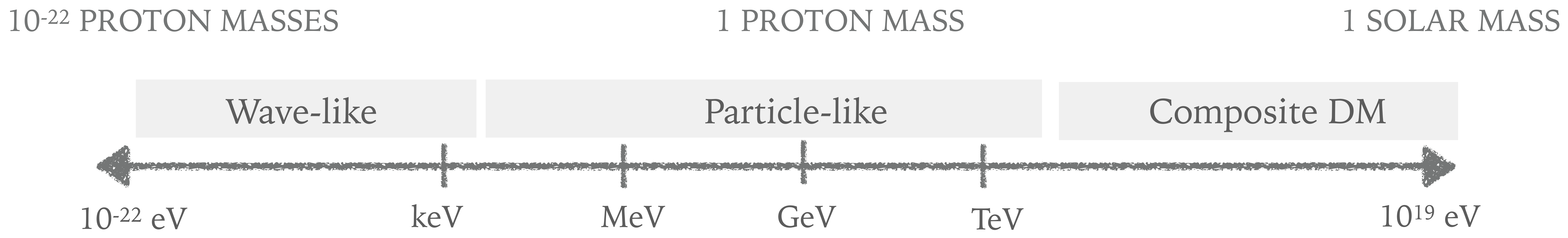
We know that dark matter exists.

WHAT ELSE DO WE KNOW (ABOUT DARK MATTER)?

- **Interacts gravitationally**: e.g. it bends light.
- **Dark**: does not radiate energy in the EM spectrum.
- **Old and Stable:** it is imprinted in the Cosmic Microwave Background and its lifetime $\sim$ 13 billion years.
- **Cold:** it moves slowly relative to the speed of light.
- **Abundant**: $\sim$ 5 times more abundant than ordinary matter.

But, we do not know its mass and how it interacts (beyond gravity).

THIS LEAVES A LOT OF ROOM FOR SPECULATION…



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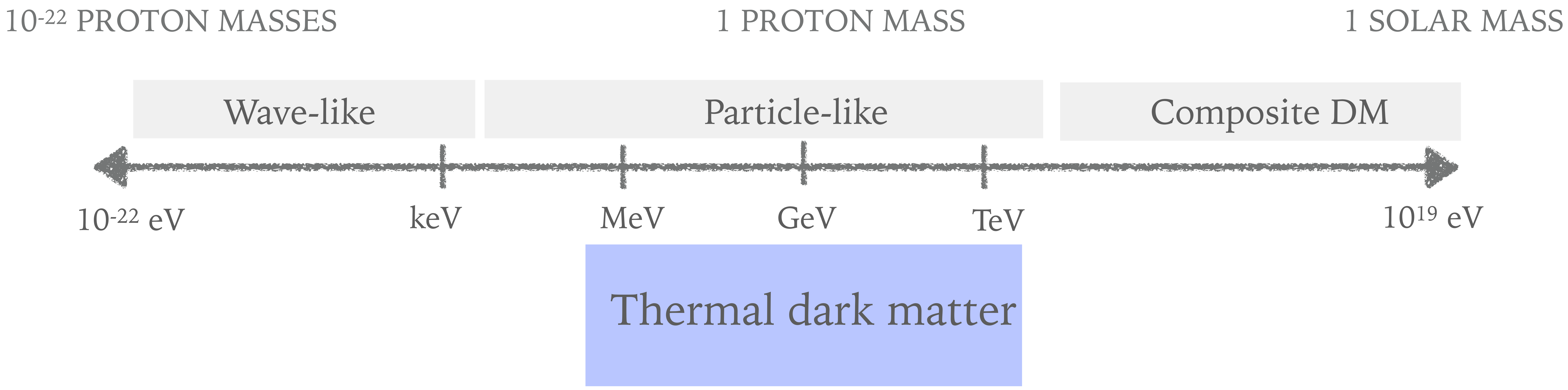
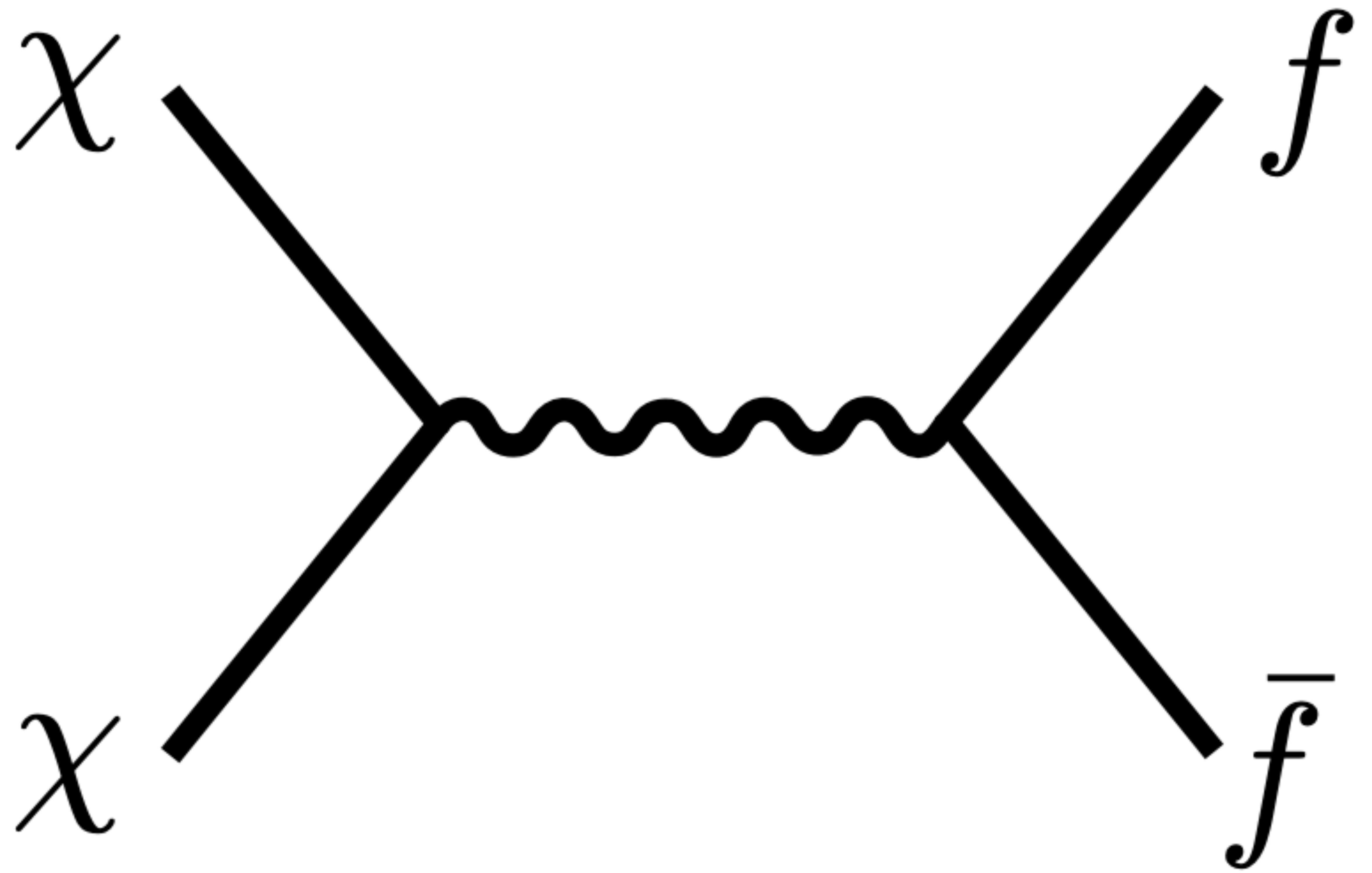
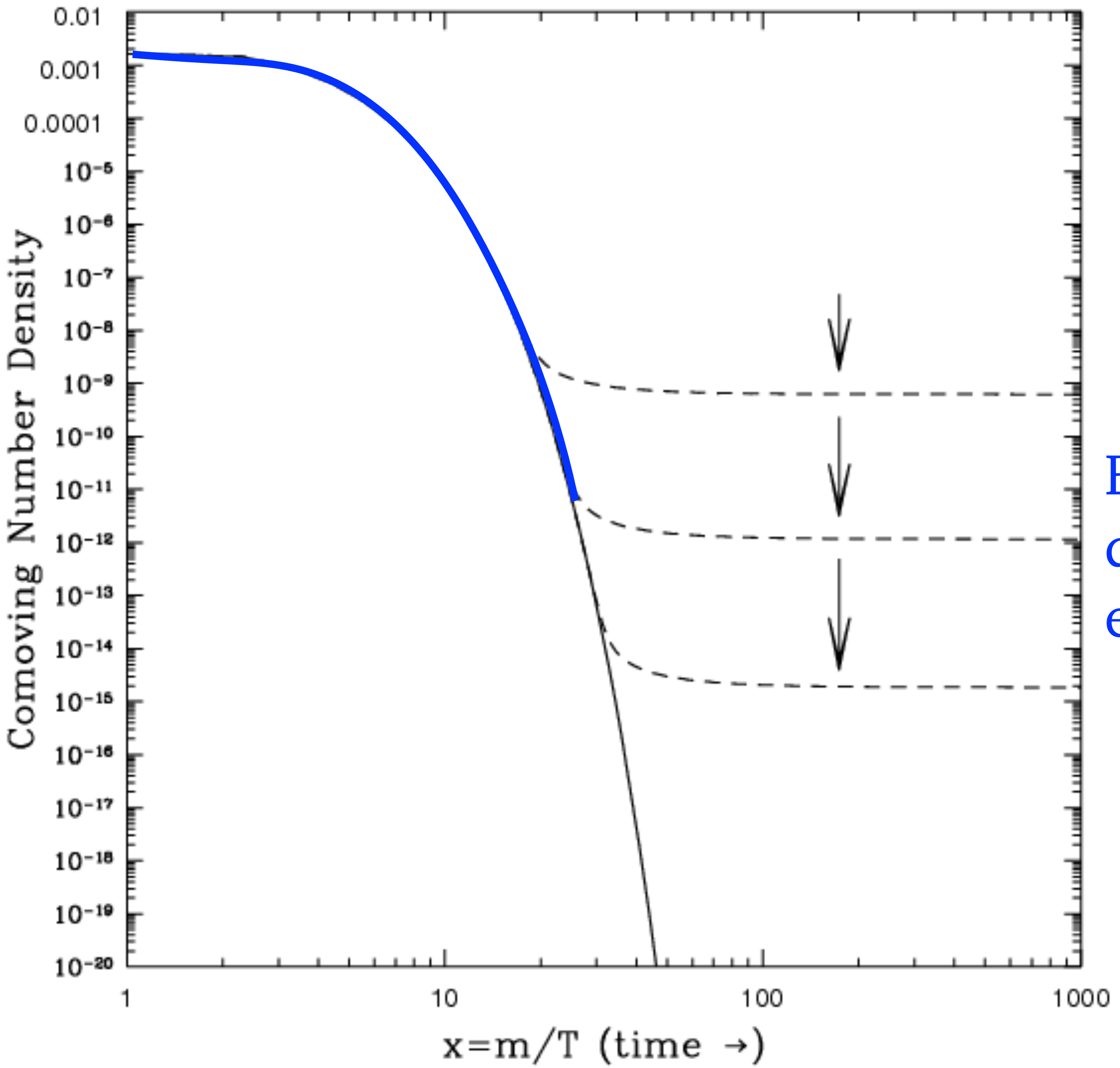


WHAT IF: DARK MATTER WAS IN A HOT-BATH WITH ORDINARY MATTER



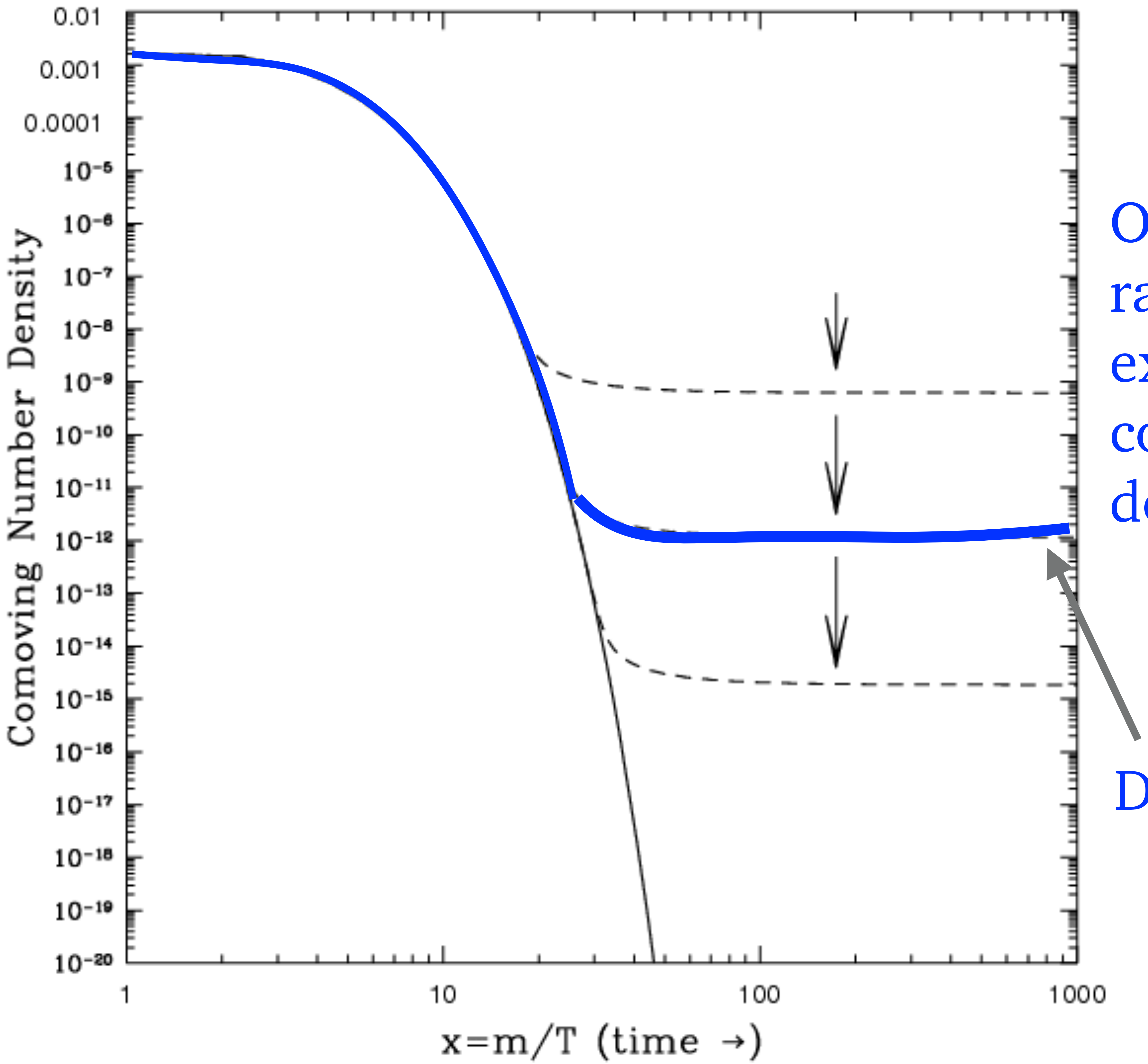
Thermal equilibrium is maintained by
DM particles (χ) annihilating into SM particles (f)

AS THE UNIVERSE COOLS DOWN, DM'S ABUNDANCE DECREASES



Below χ mass, DM density falls exponentially

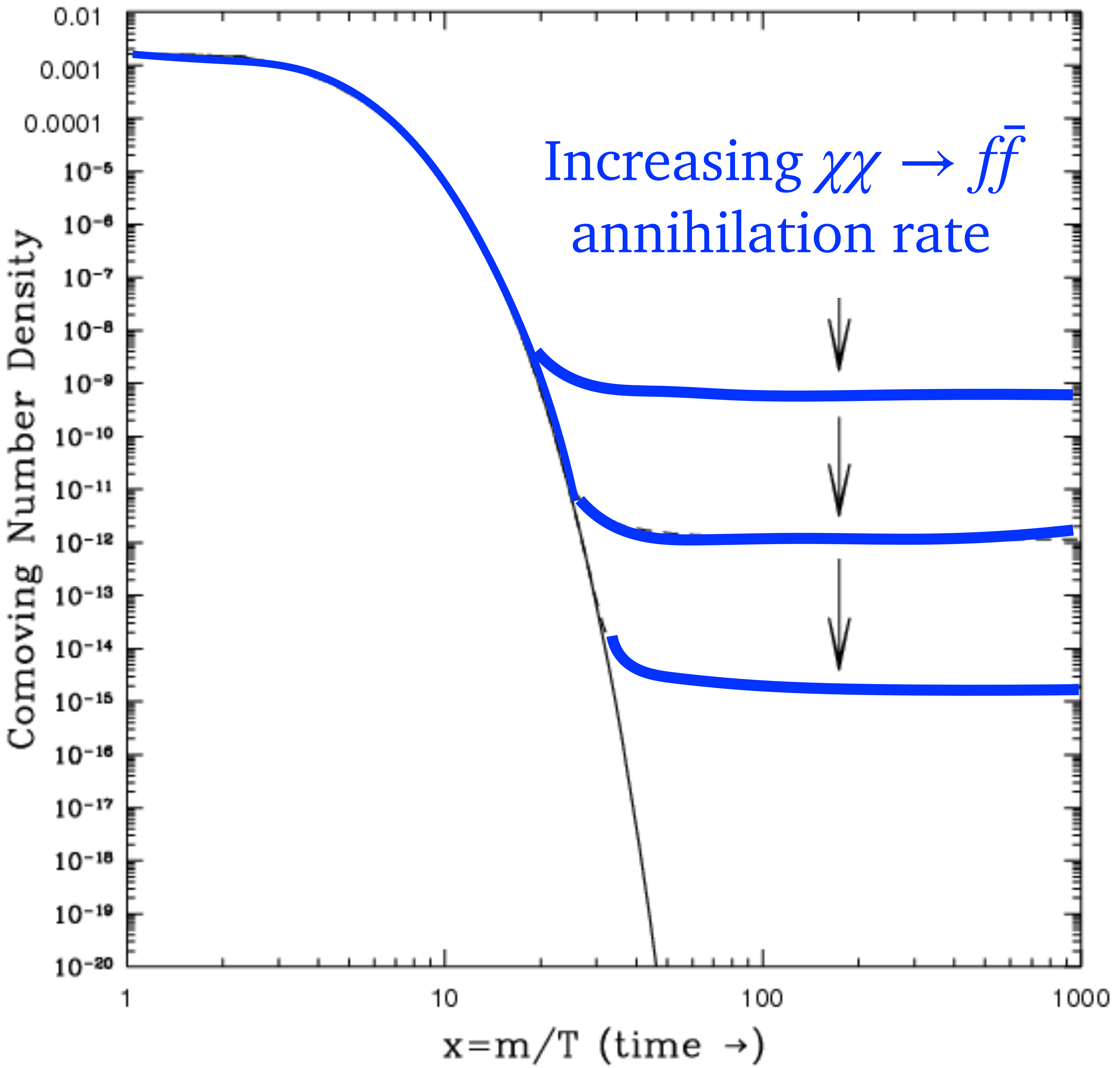
BUT THE ANNIHILATION RATE IS ALSO FALLING



Once the annihilation rate falls bellow the expansion rate: the DM comoving number density is fixed.

DM abundance now

THE ANNIHILATION RATE IS PROPORTIONAL TO THE DARK MATTER MASS



$\langle \sigma v \rangle \sim m_\chi^2$

Lighter dark matter

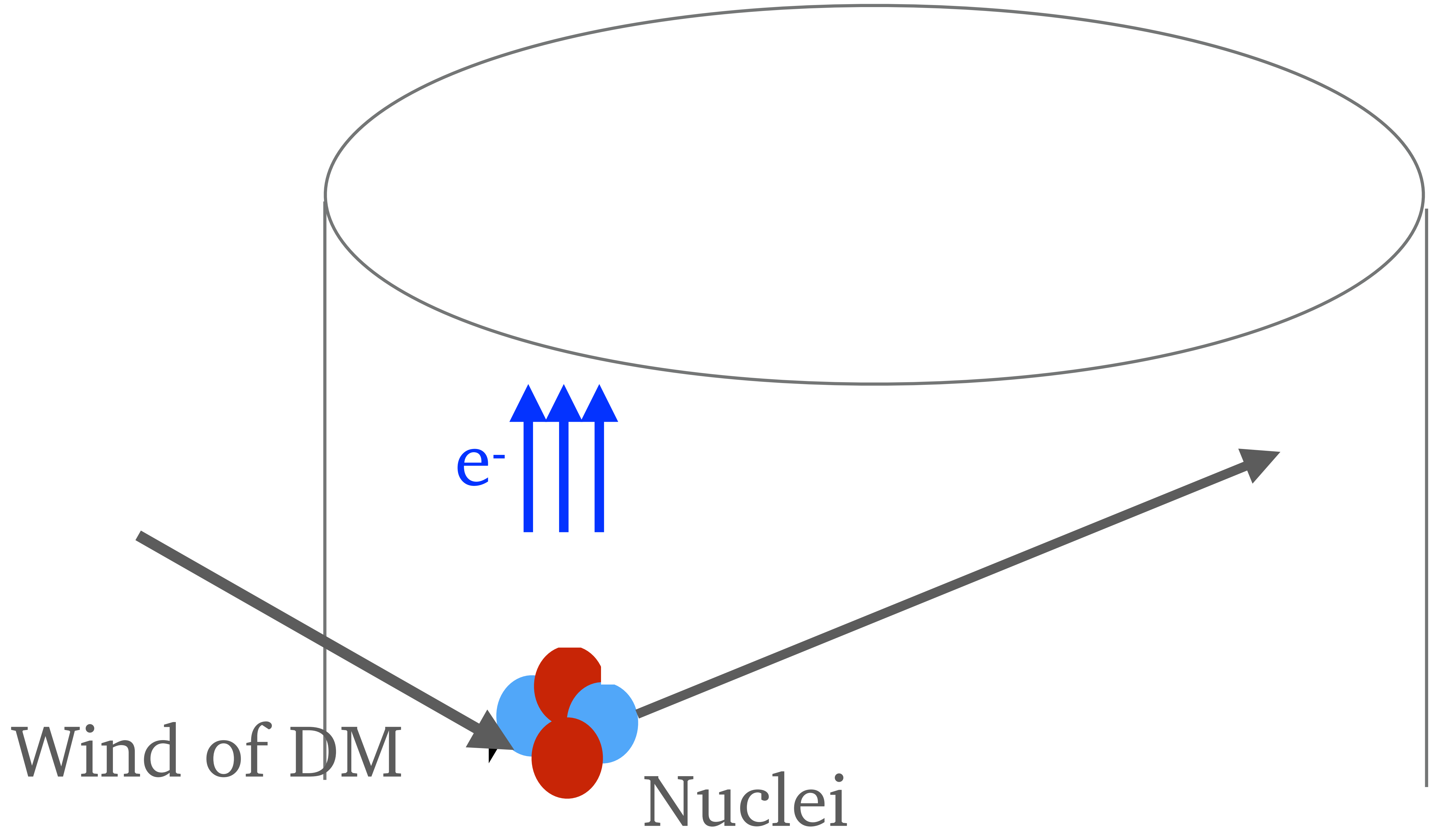
↓

Heavier dark matter

WHY THERMAL DARK MATTER?

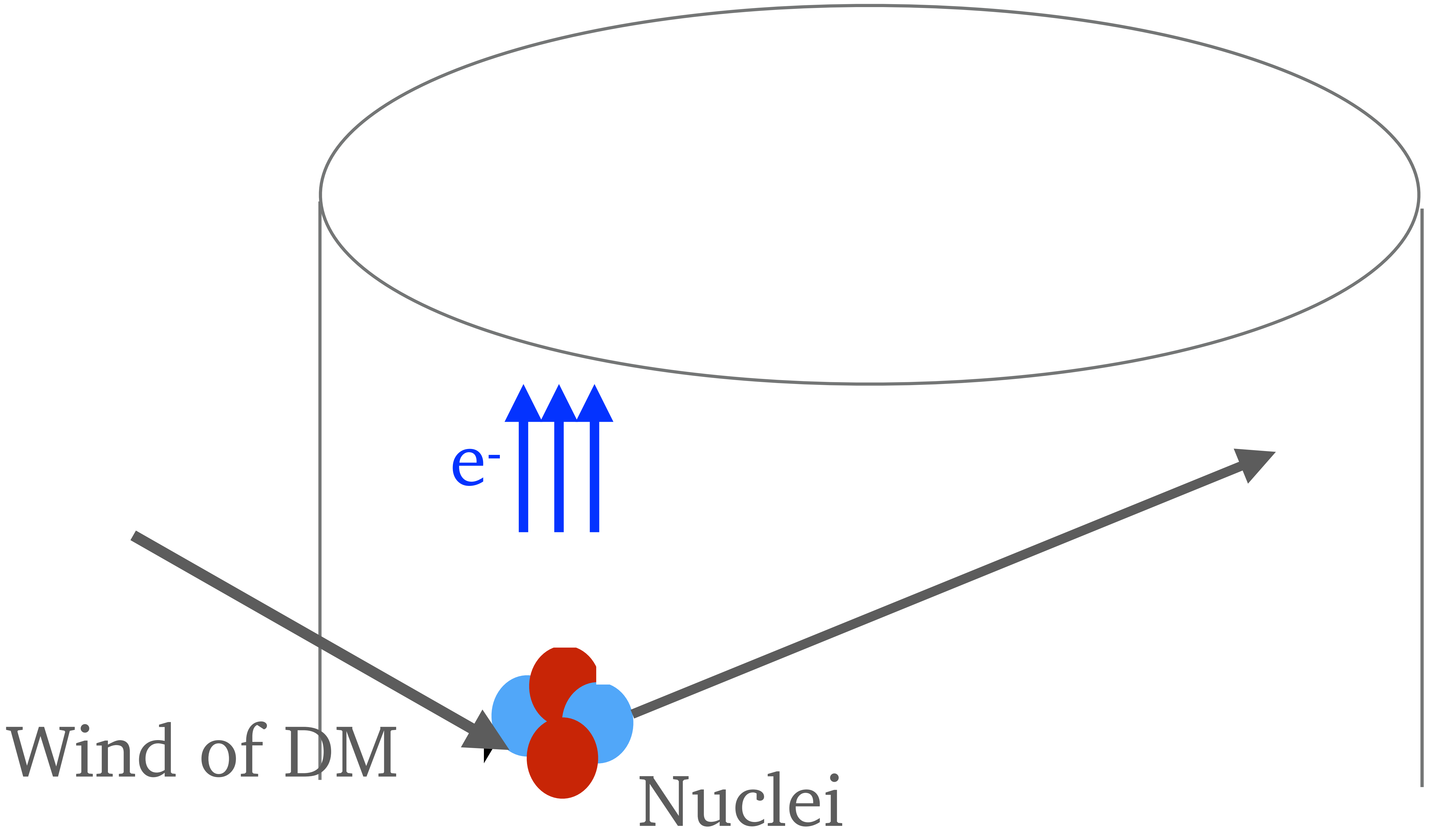
- **Generic**: assumes close and direct contact between dark matter and ordinary matter.
- **Predictive**: ballpark of a weak-scale mass yields the correct abundance.
- **Restrictive**: bounds mass range MeV-TeV.
- **Familiar**: mass regime is near range of known particles.

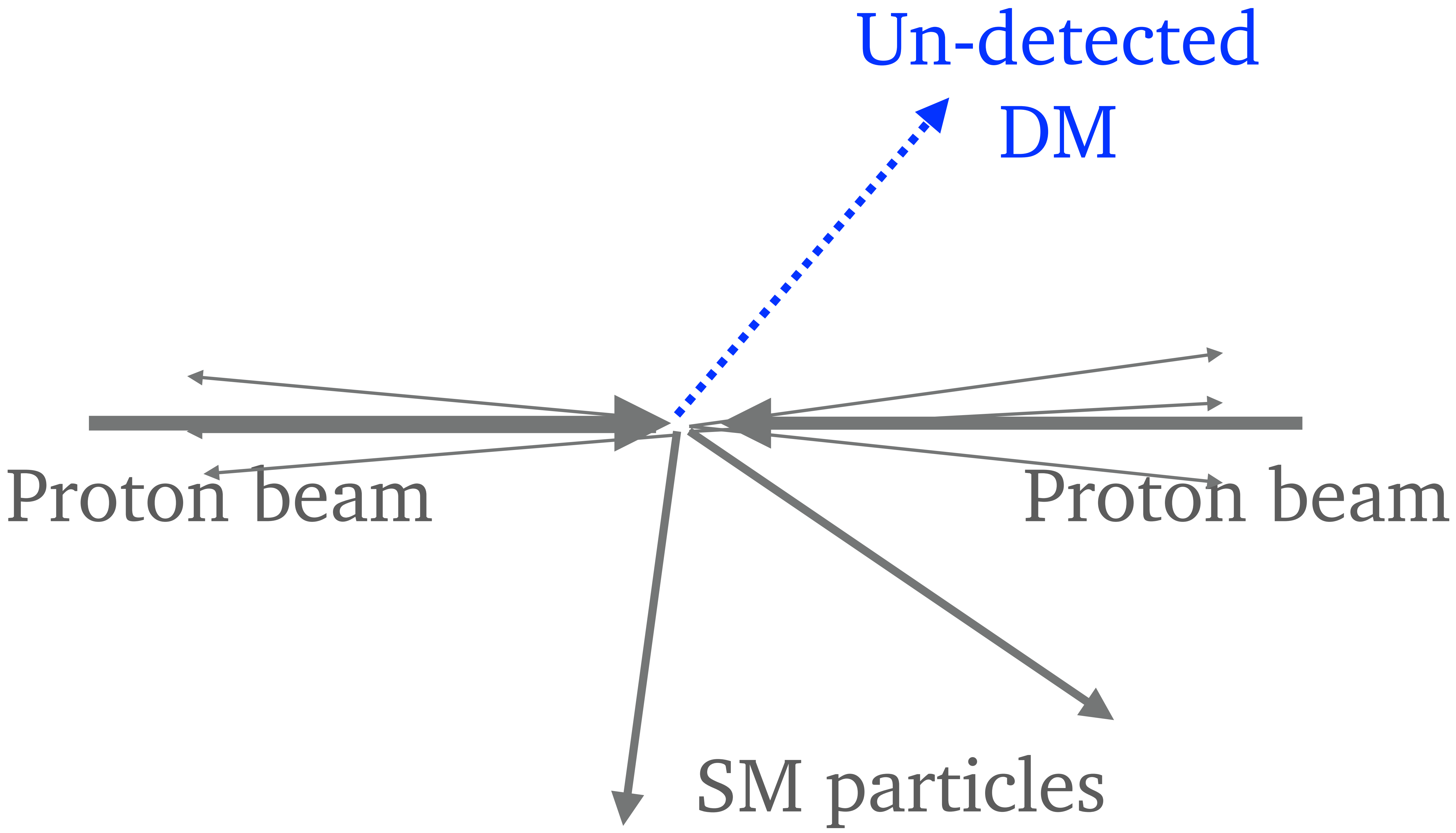
AREN'T EXPERIMENTS ALREADY LOOKING FOR THERMAL DARK MATTER?



DM recoil (ionization, scintillation ..)
in direct detection e.g. LUX/LZ

AREN'T EXPERIMENTS ALREADY LOOKING FOR THERMAL DARK MATTER?



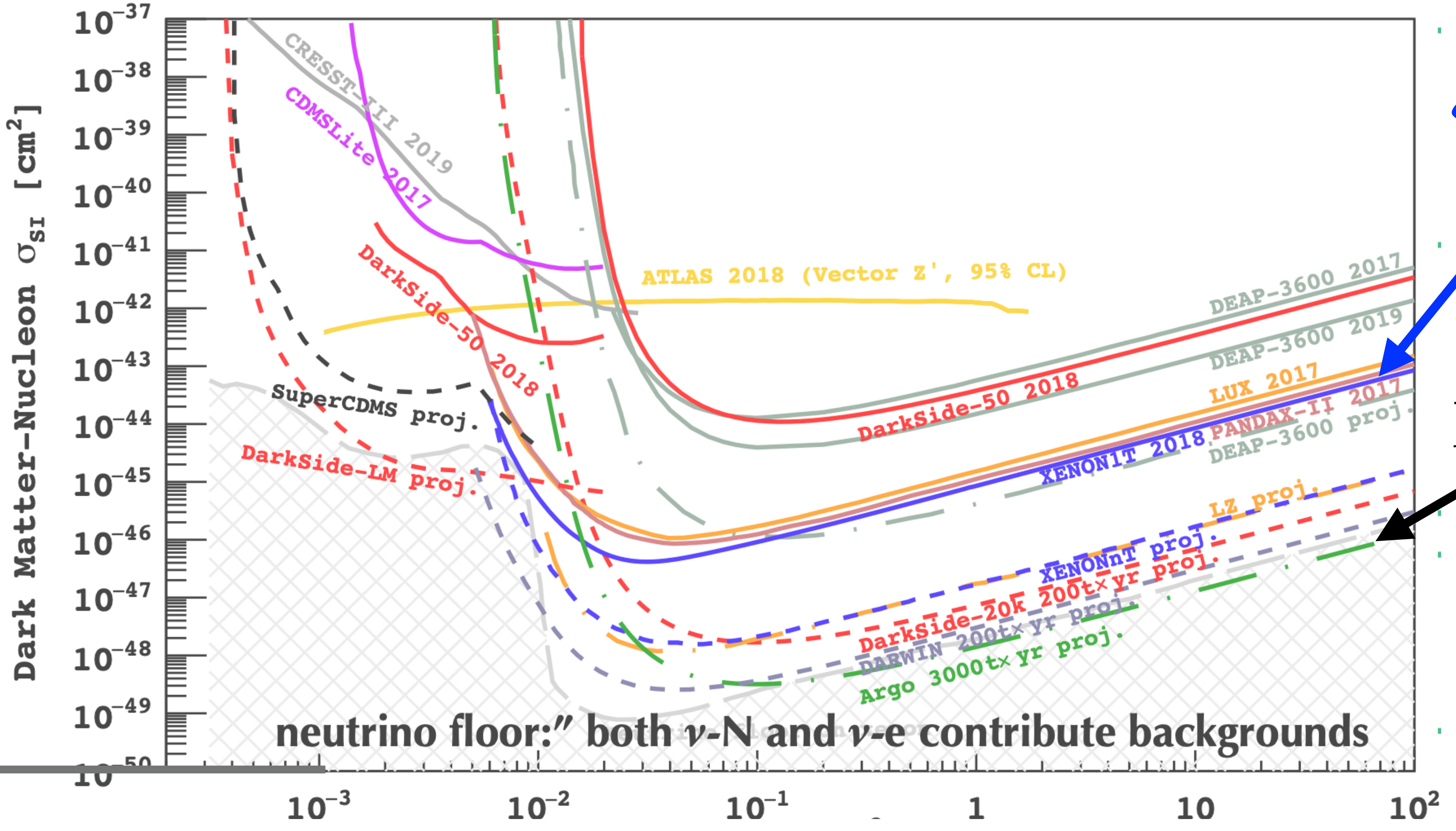


DM recoil (ionization, scintillation ..)
in direct detection e.g. LUX/LZ

DM production and escape
in colliders e.g. LHC

YES, WE ARE ALREADY LOOKING, BUT MASS > GEV

THE SEARCH FOR A PARTICLE IN THE WEAK SCALE



WHAT ABOUT THIS REGION?

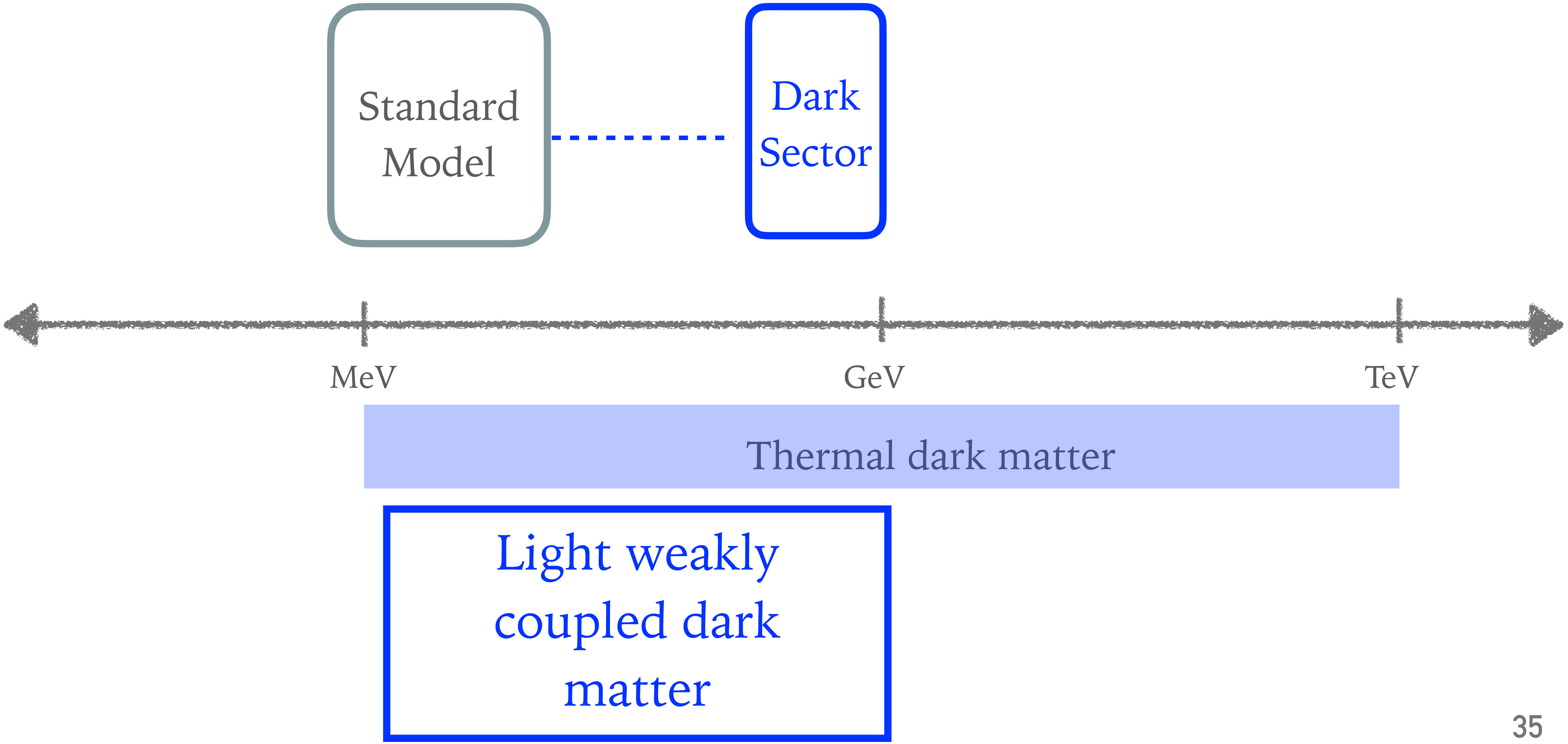
"Current" bounds

Projections

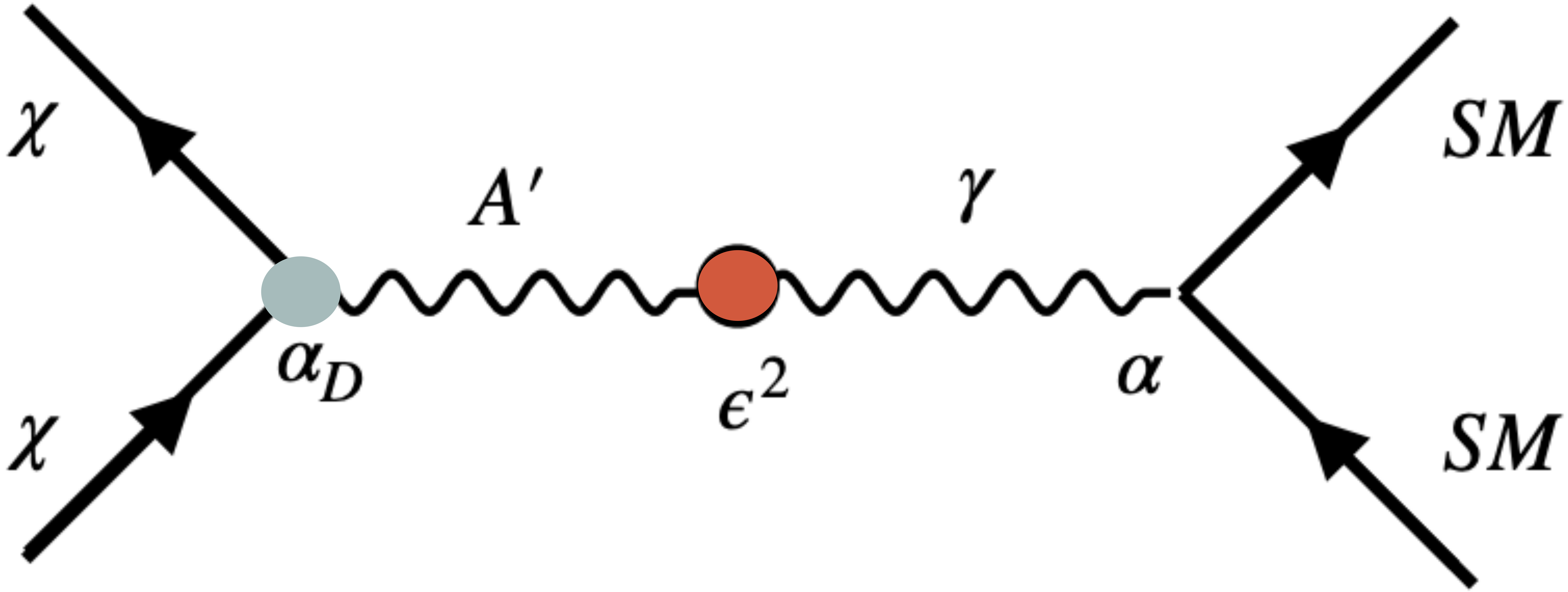
$1[MeV]$ $1[GeV]$ $M_\chi[TeV]$

We have been looking hard in the GeV-TeV regime, but we have not found any hints of DM. Let’s go to lower masses.

BELOW < GEV, THERMAL CONTACT IMPLIES NEW SECTOR OF PARTICLES



PORTALS MEDIATE INTERACTION BETWEEN DARK MATTER AND SM



New force e.g Dark Photon (A') weakly coupled to SM photon (γ)

WHY DARK SECTORS?

- Predict DM particle that is stable and dark.
- Still falls under thermal origin hypothesis because there is small “cross-talk” between SM and DM.

THE INGREDIENTS TO MAKE A DARK SECTOR

*FROM NHAN TRAN

Beam
(p, e, μ)

+

Lots of
particles
(dark sectors
have small
couplings)

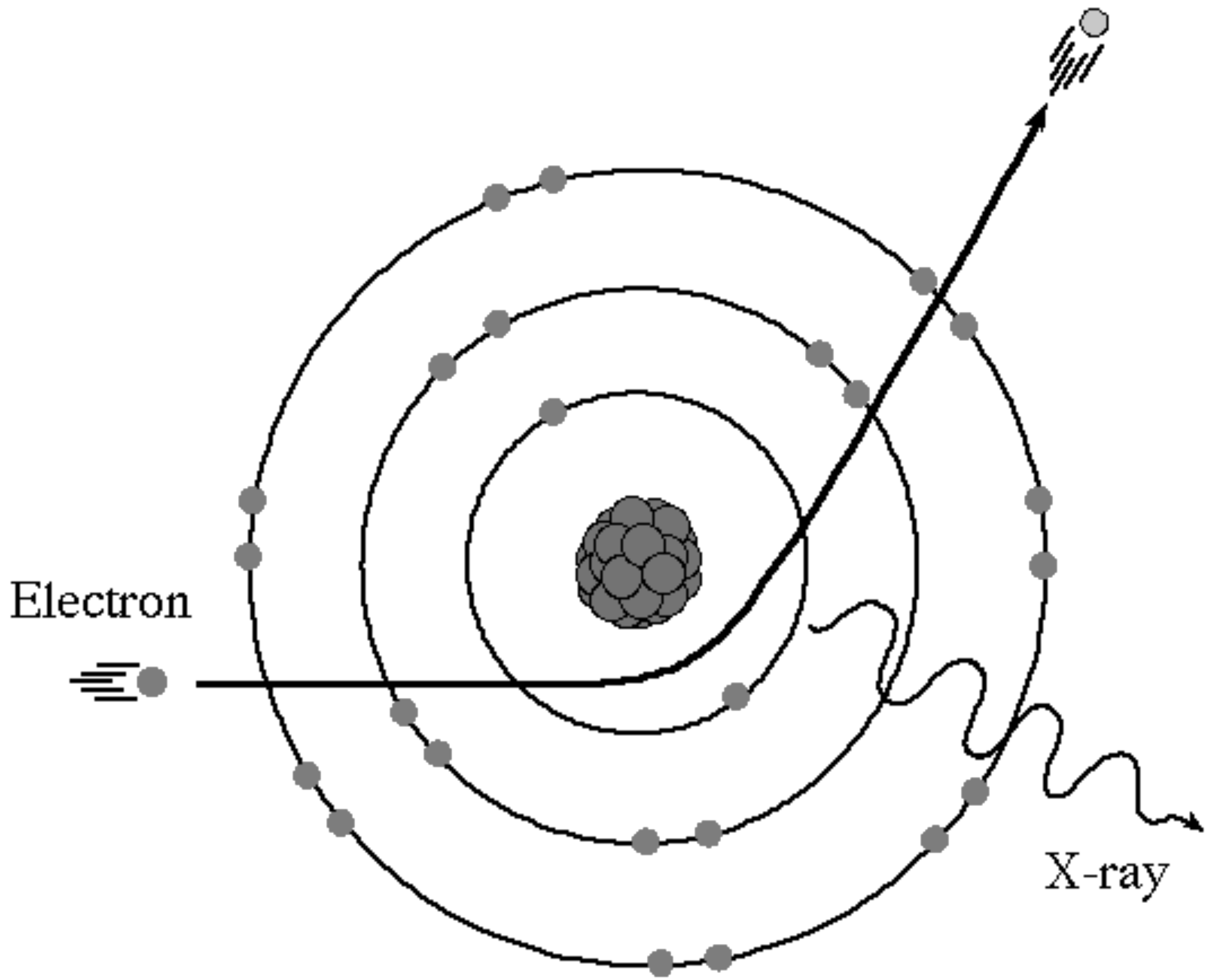
+

Collider

Beam dump

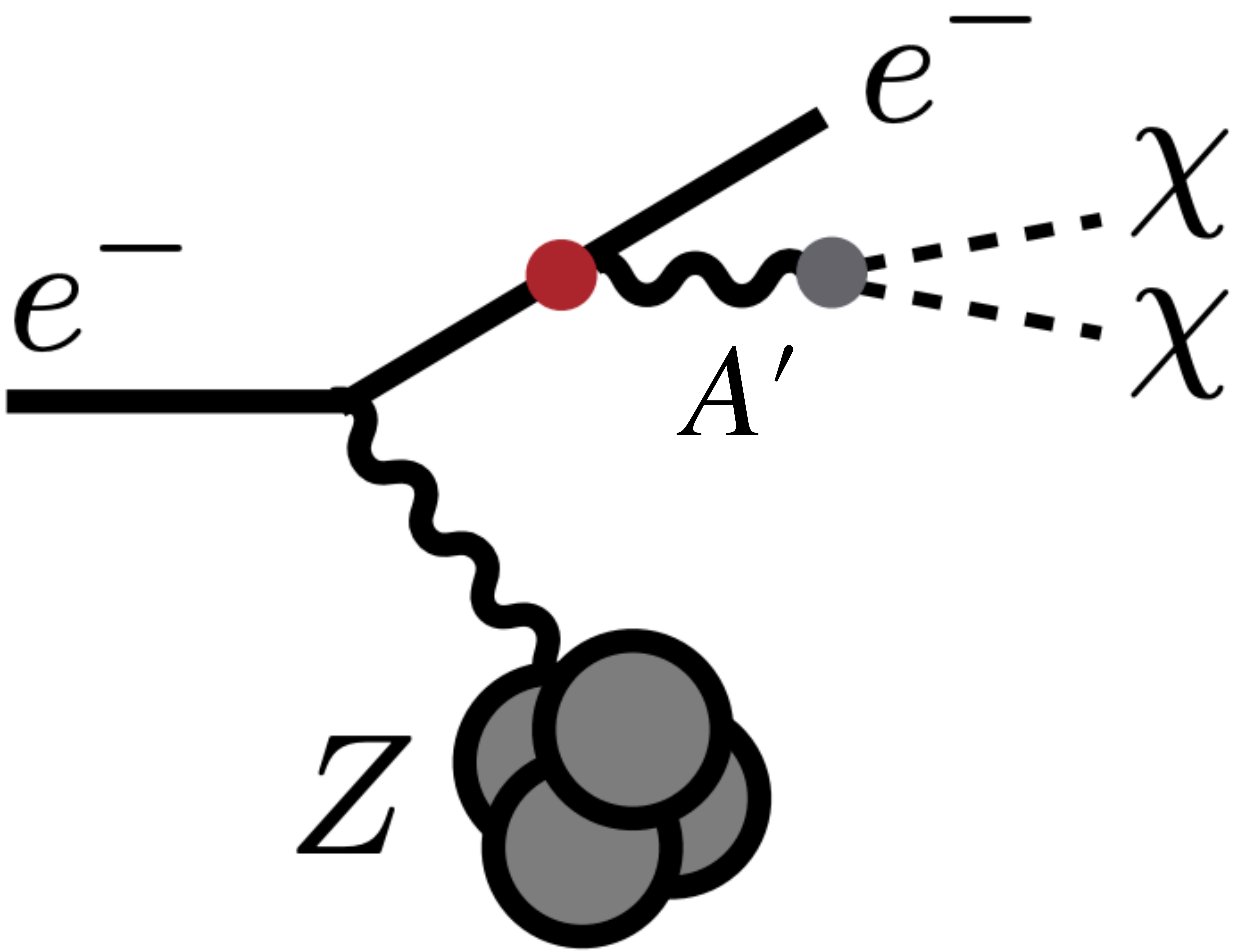
Fixed-target

HOW CAN YOU PRODUCE DARK SECTORS IN FIXED-TARGET EXP.?



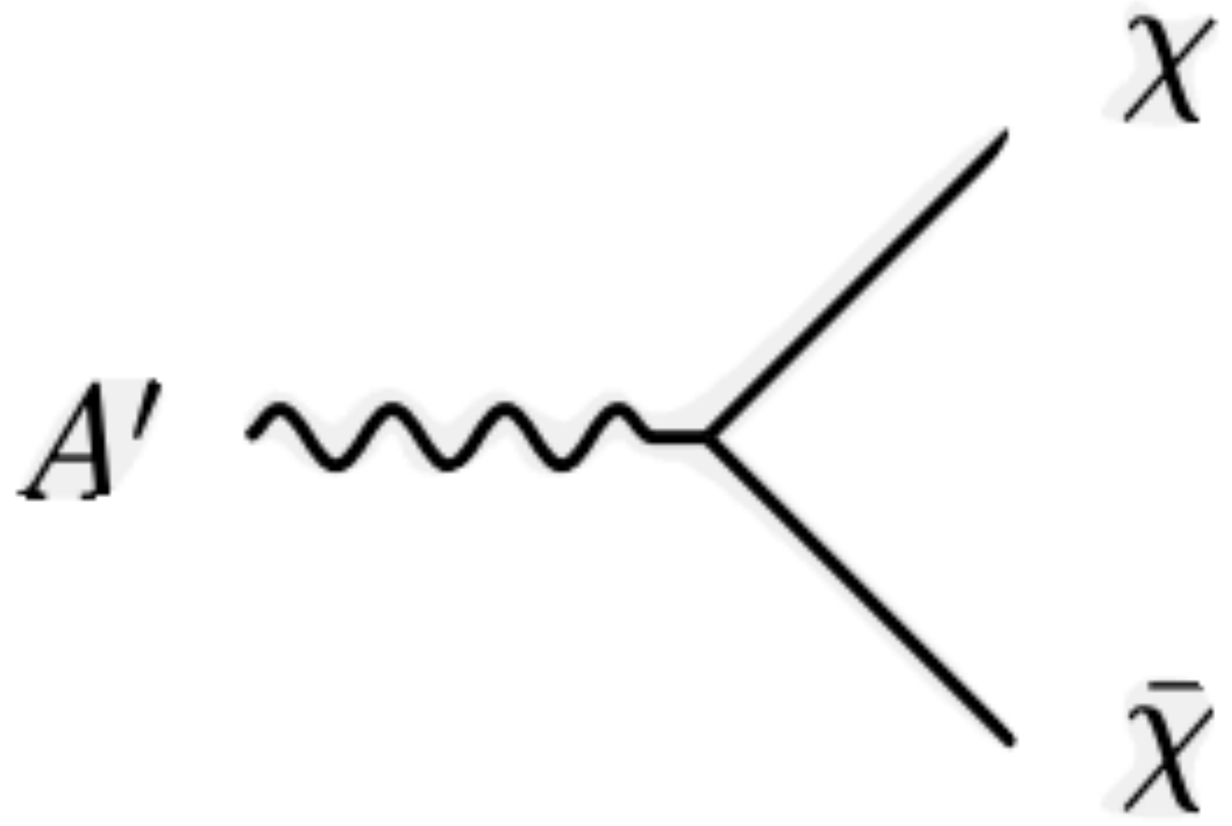
e.g. via beam Bremsthrahlung: “braking radiation”

HOW CAN YOU PRODUCE DARK SECTORS IN FIXED-TARGET EXP.?



e.g. via beam Bremsthrahlung: “braking radiation”

HOW CAN YOU DETECT DARK SECTORS?



Visible

$$2m_f < m_{A'} < 2m_x$$

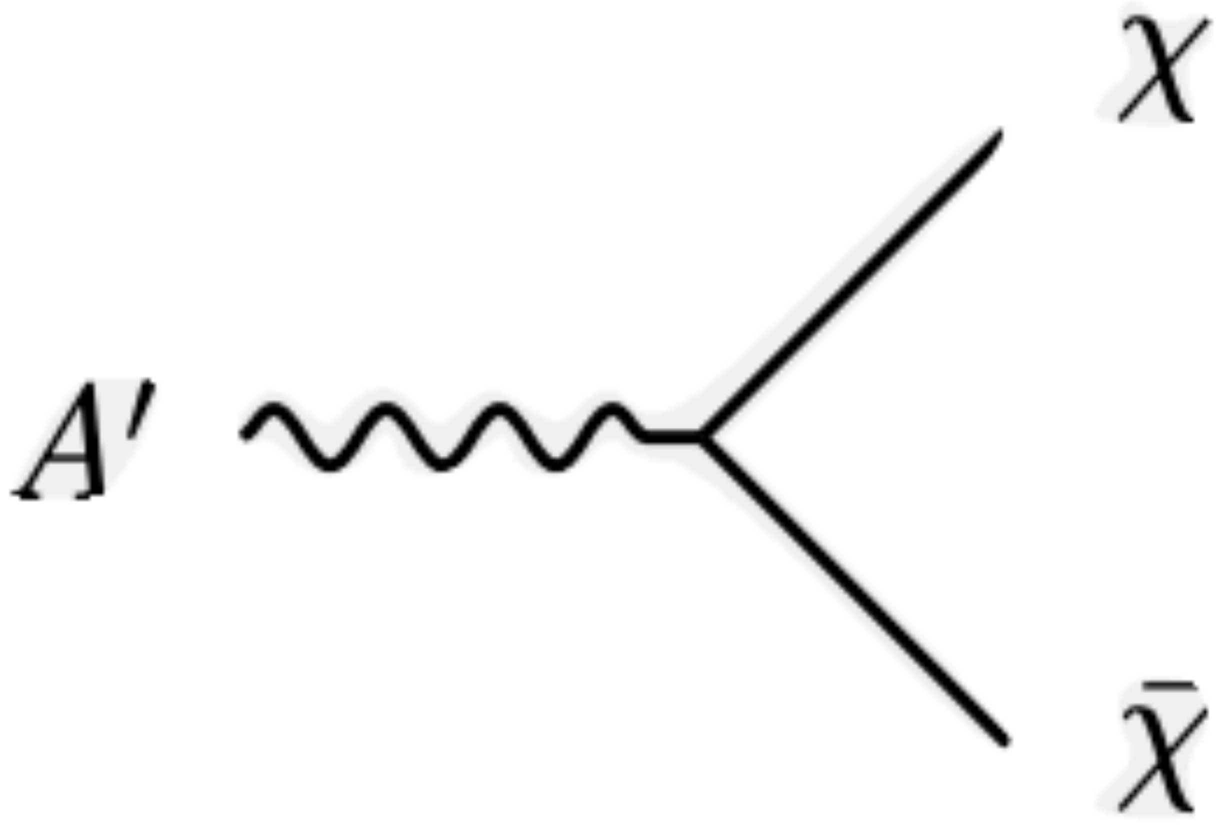
$$2m_\chi$$

Invisible

$$m_{A'} > 2m_x$$

WHICH METHOD YOU CHOOSE DEPENDS ON WHAT YOU WANT TO FIND*

*FROM NATALIA TORO



Produce mediators that decay to SM and study dark and minimal interactions

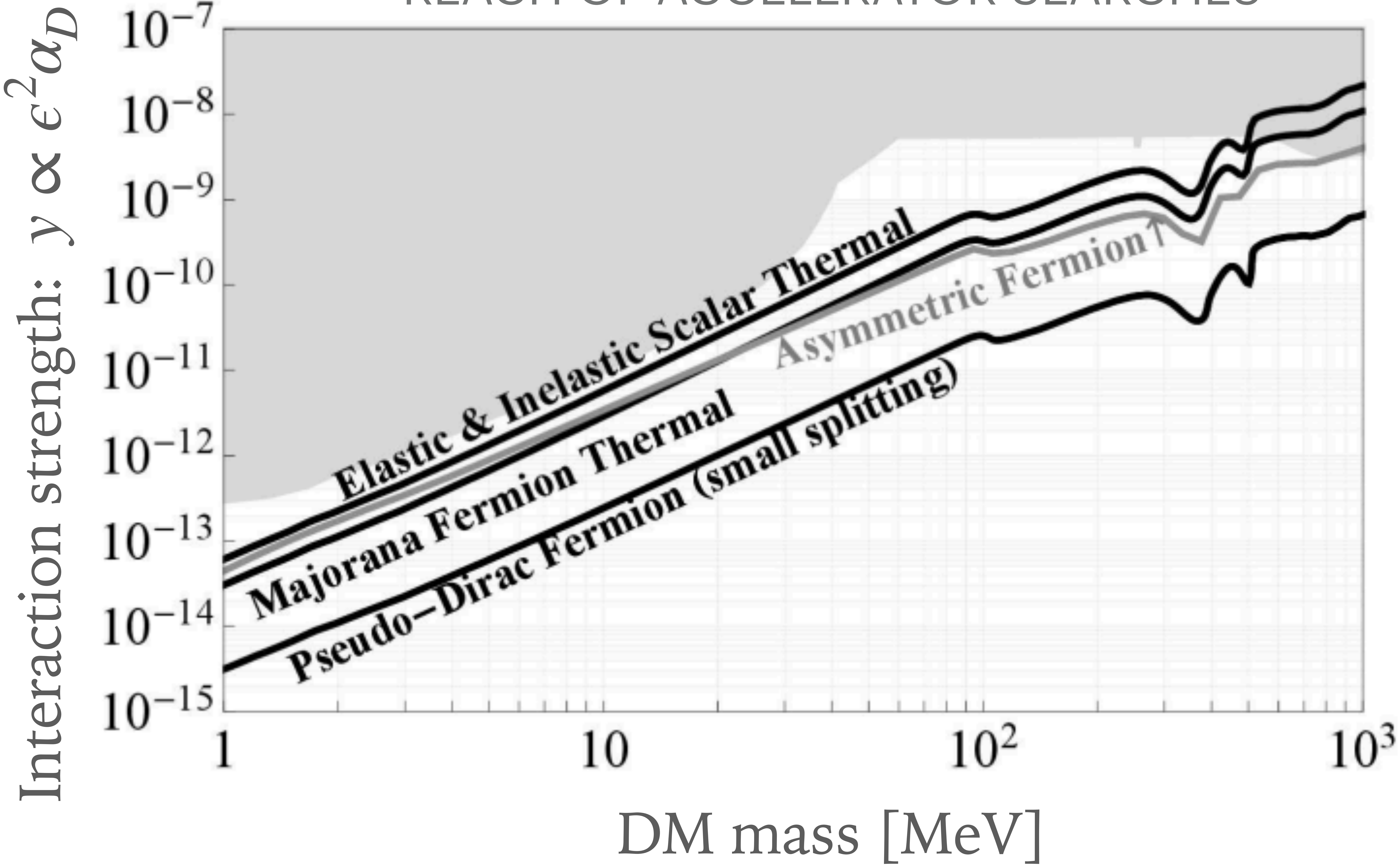
$$2m_{\chi}$$

Produce DM particles and explore predictive DM models

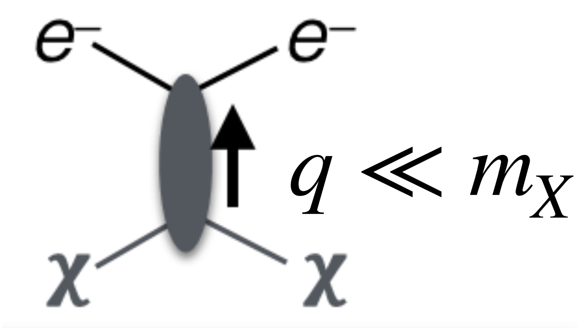
WHY ACCELERATORS?

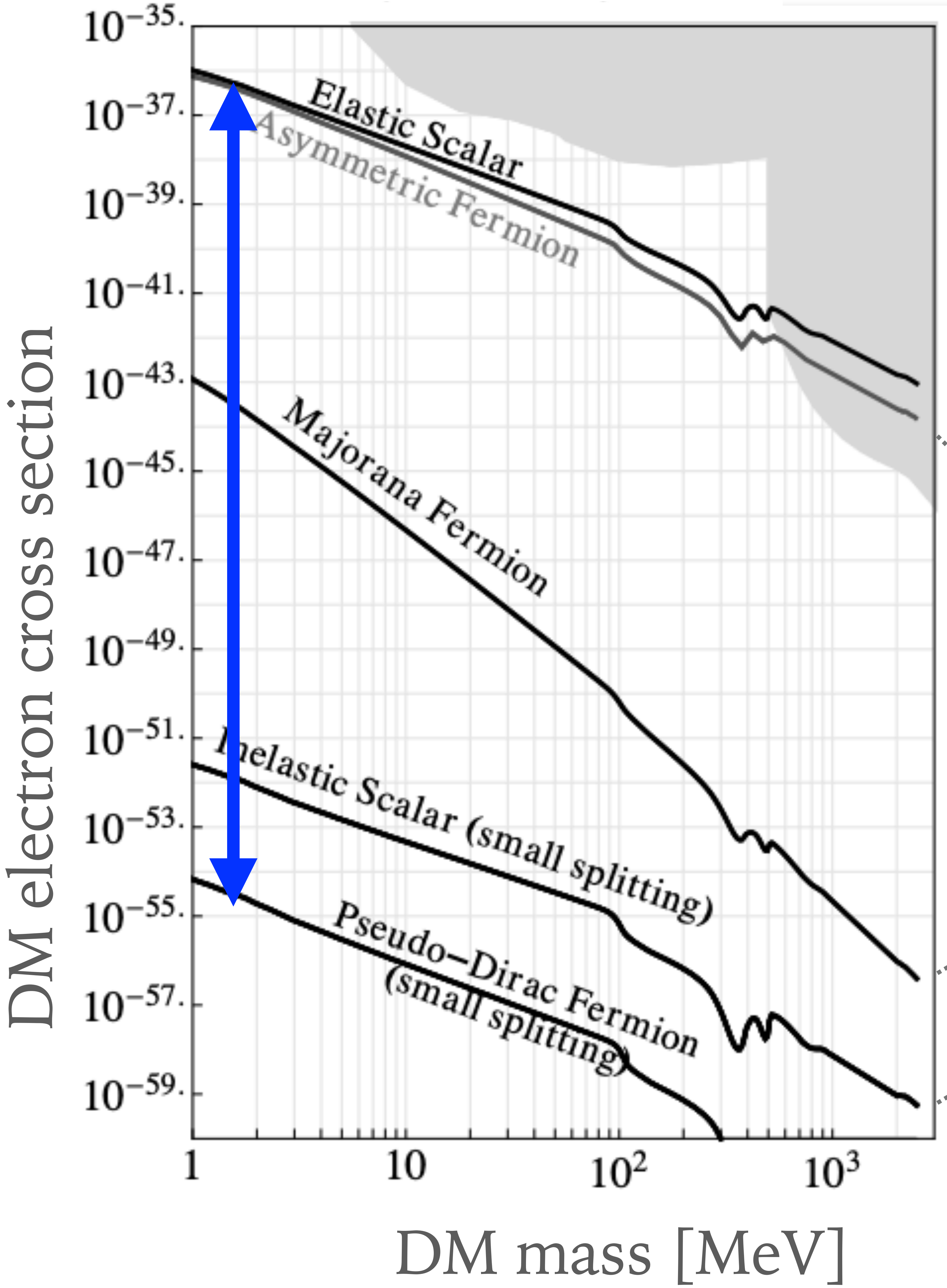
- Enough intensity to produce DM particles.
- Complimentary to direct detection:
  - Explores relativistic production of DM.
  - Explores whole dark sector of particles.
  - Explores couplings of dark matter w. different particles.
  - Still need direct detection to measure DM abundance or stability.

REACH OF ACCELERATOR SEARCHES

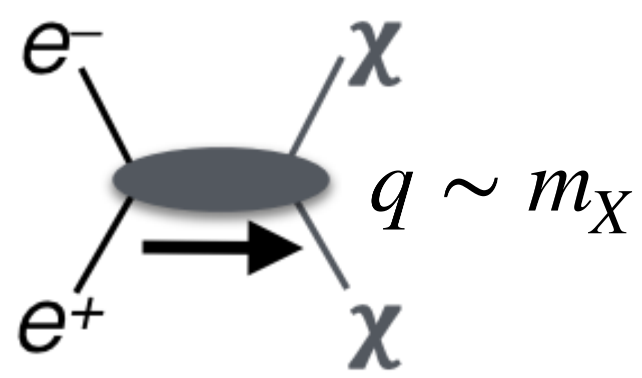


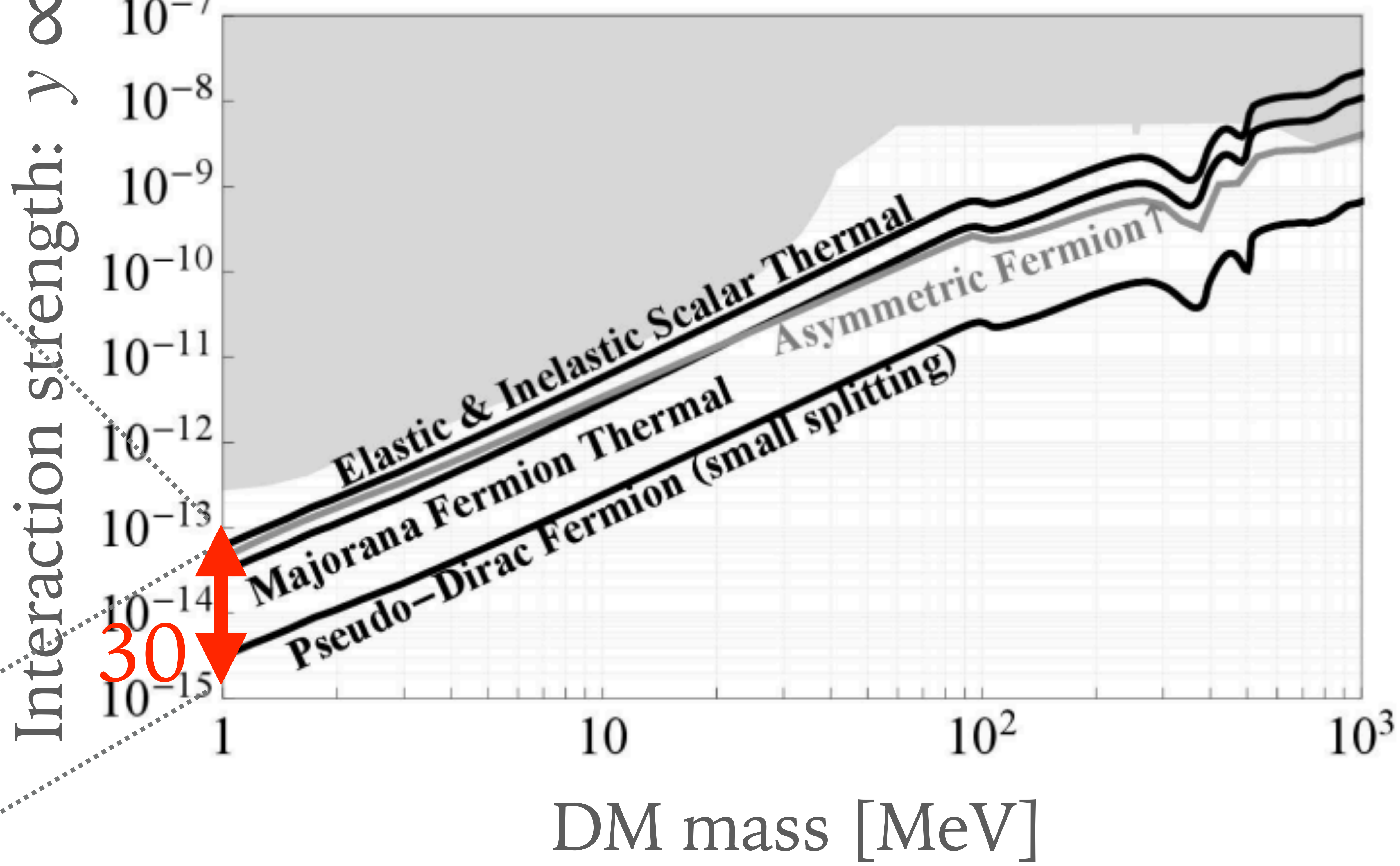
DM - e scattering





Accelerators

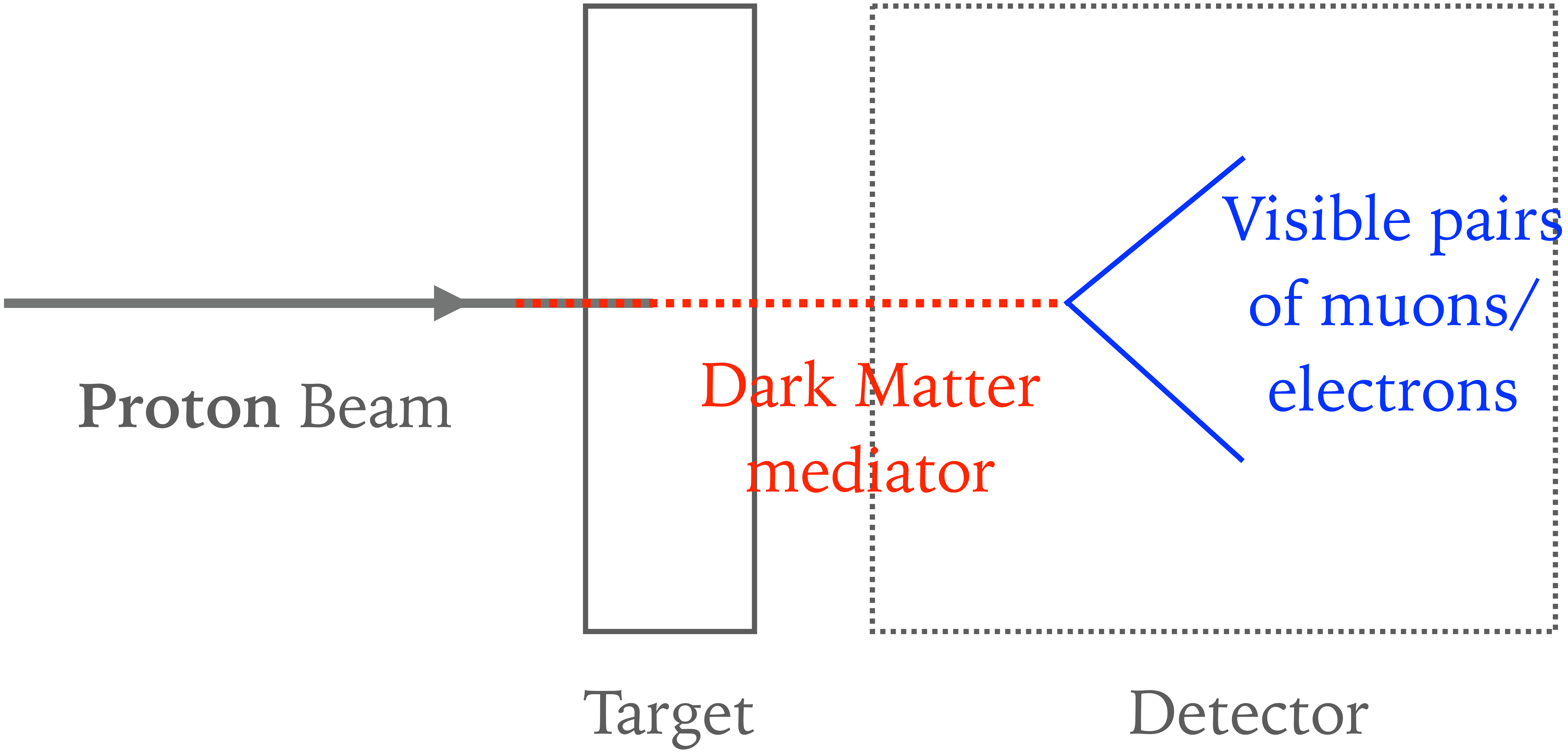




~ 4YEARS AGO: **DOE BASIC RESEARCH NEEDS** STUDY FOR SMALL DARK MATTER PROJECTS

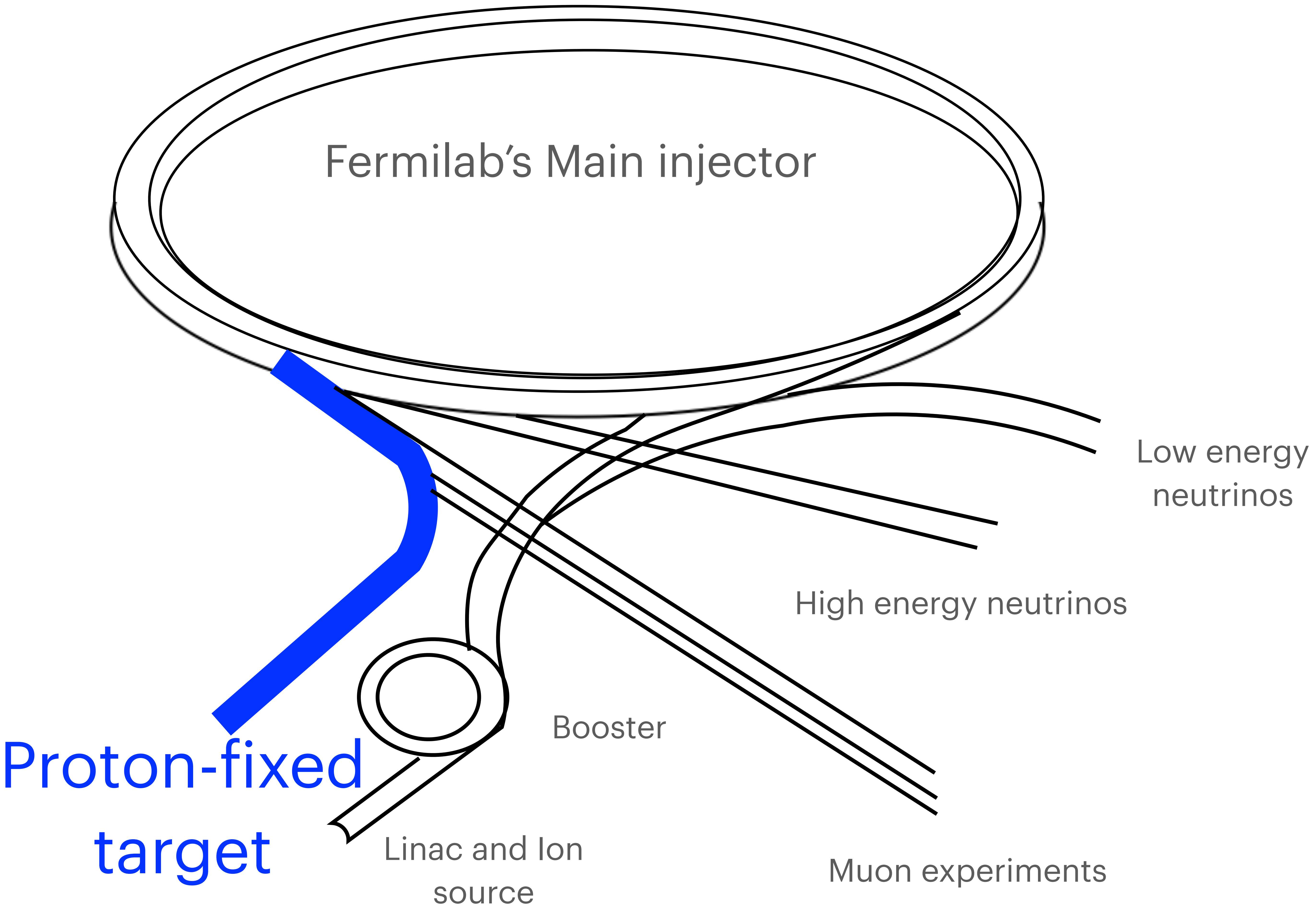
Accelerators can reach predictions of thermal light dark matter in a short time scale and they are "small" or "low-cost". We better build them.

DARKQUEST


Proton Beam
Target
Dark Matter mediator
Visible pairs of muons/ electrons
Detector

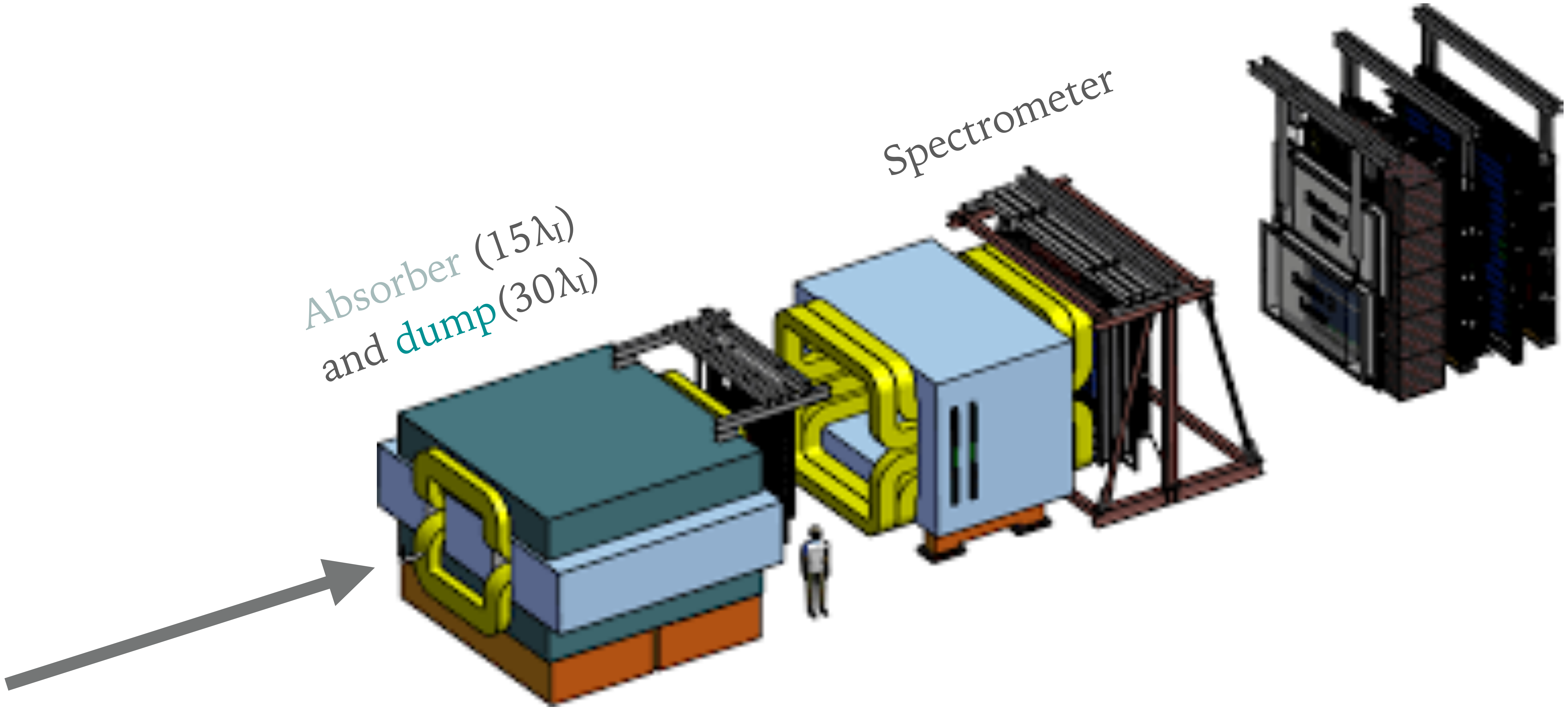
PROTON BEAM FIXED-TARGET SETUP AT FERMILAB

- 120 GeV proton beam.
- Number of protons: 10^{13} protons every 4s. spill - within 1ns: ~0-80000 protons.
- Total expected by 2025: 10^{18} Protons on Target.
- Fermilab's accelerator upgrade PIP-II by ~2026: 10^{20} Protons on Target.



A GENERATION OF EXPERIMENTS USING THE SAME SPECTROMETER

SeaQuest 2014-2017
SpinQuest 2022-2026
DarkQuest 2023-2026



Intense and **high energy** Proton Beam

BUT WITH DIFFERENT PURPOSES

SeaQuest
2014-2017

SpinQuest
2022-2026

DarkQuest
2023-2026

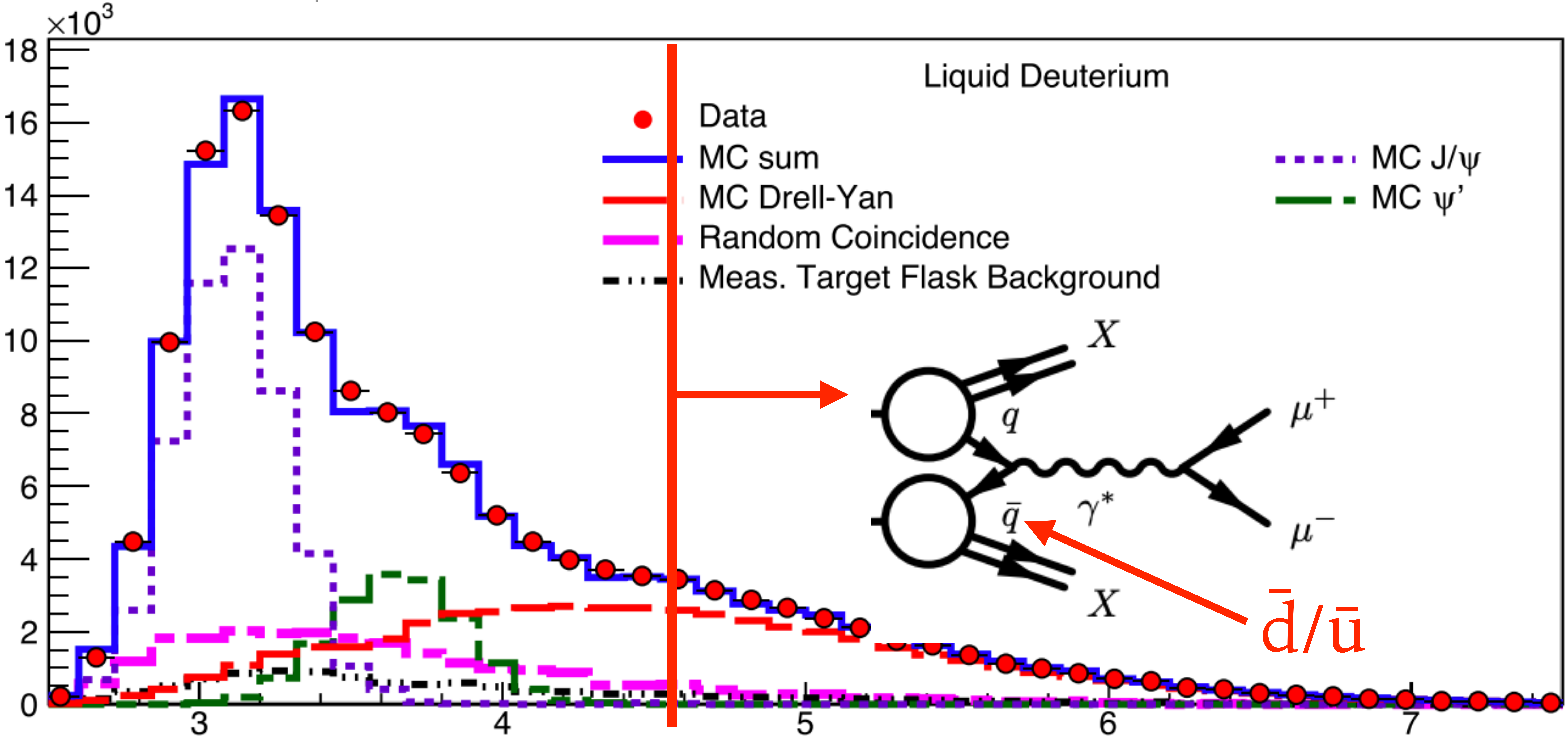
→ Detect muons to **probe the asymmetry of antimatter in the proton**

$\bar{d}/\bar{u} > 1$?

Article

SeaQuest results published in Nature 2020

The asymmetry of antimatter in the proton



Mass of two leptons (GeV)

BUT WITH DIFFERENT PURPOSES

SeaQuest
2014-2017

Detect muons to **probe the asymmetry of antimatter in the proton**

$\bar{d}/\bar{u} > 1?$

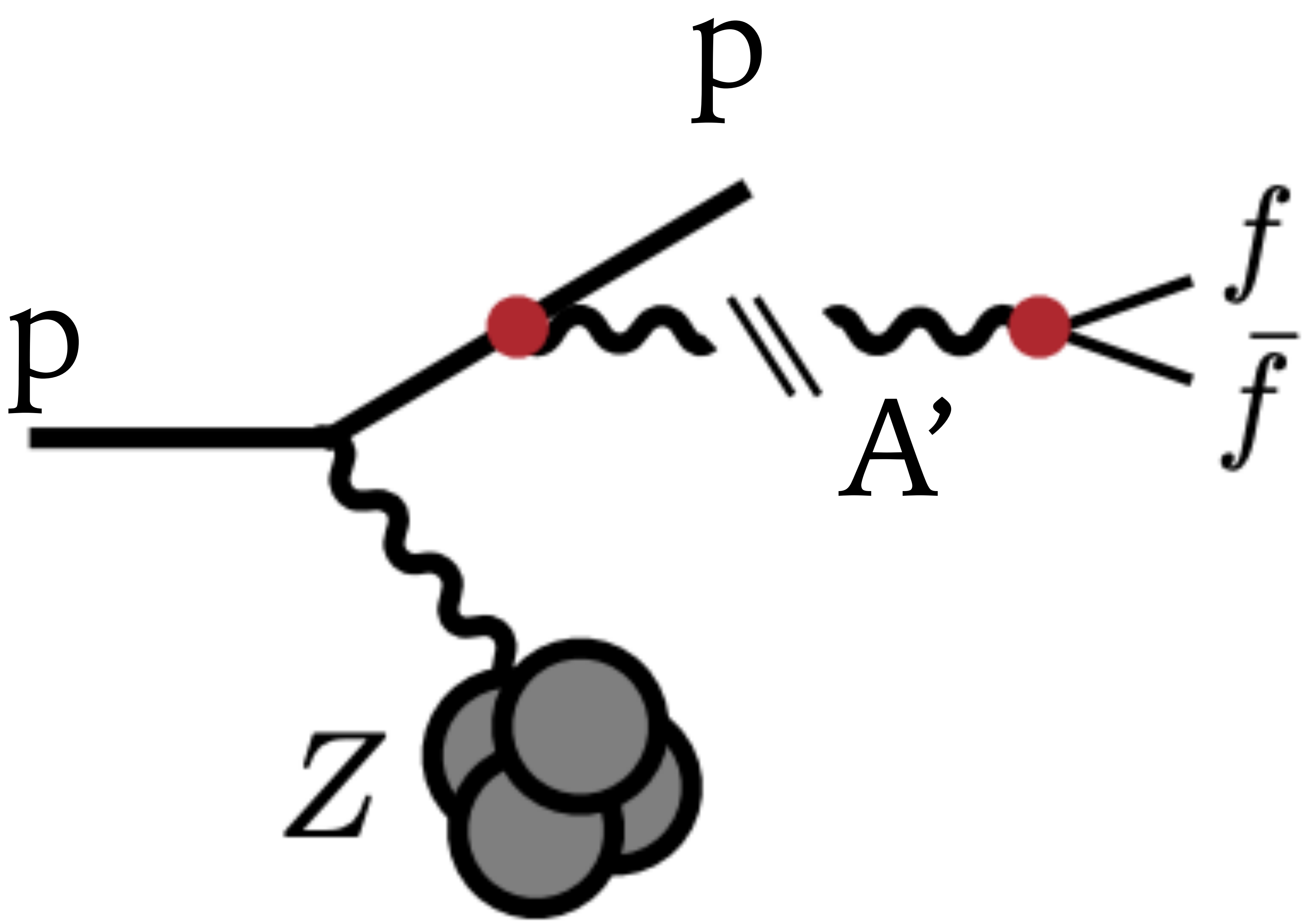
SpinQuest
2022-2026

Detect muons to **probe the sea quark's orbital momentum**

DarkQuest
2023-2026

Detect muons and electrons to **probe decays of light dark matter mediators**

$A' > \ell^+\ell^-?$



- DarkQuest produces dark matter mediators (e.g. A') with the proton beam.
- It looks for decays into a pair of muons or electrons.
- Because the interaction of the mediator w. leptons is very weak, the lifetime of the mediator is large.

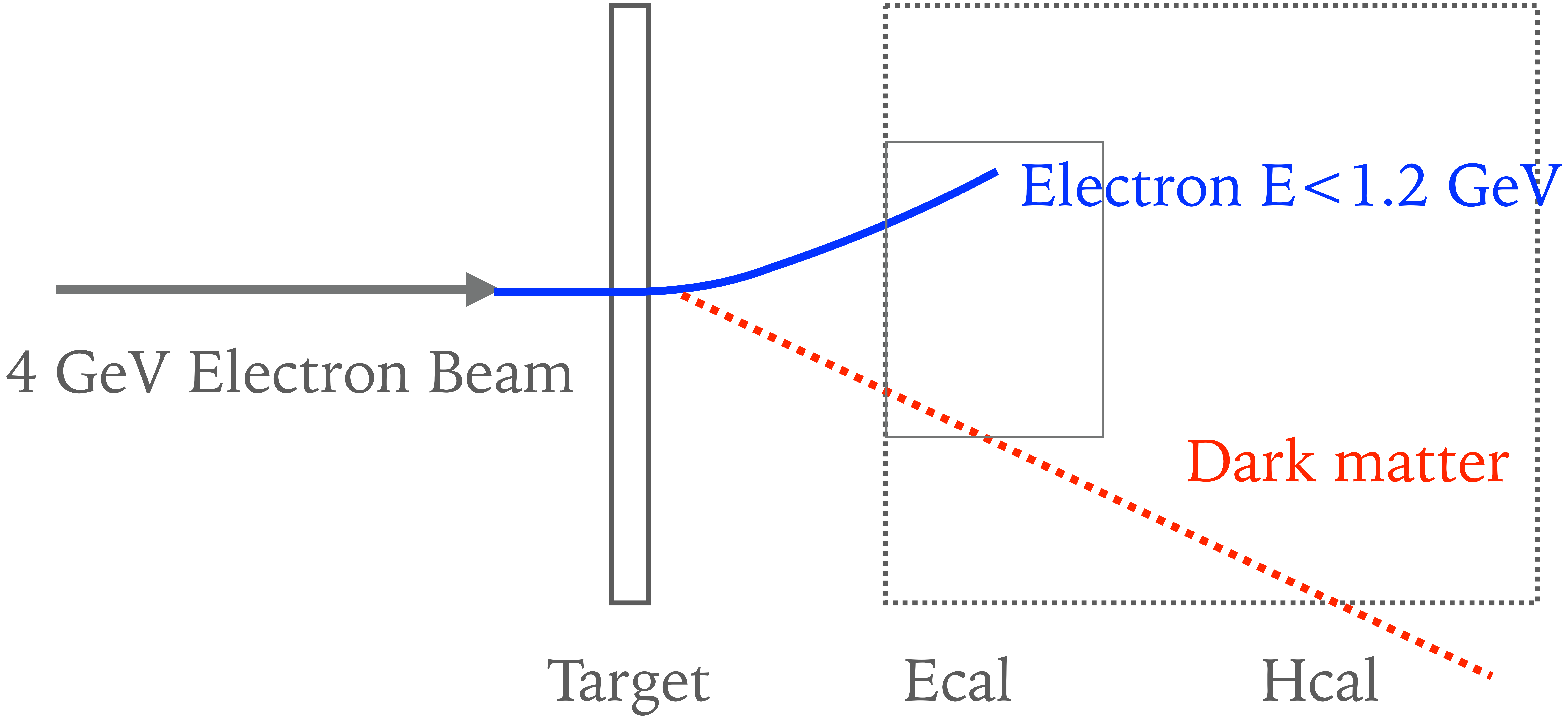

Spectrometer: Top view (Bend plane)
x[m]
z[m]
0
5
10
15
20
25
2
-2
X
Y
Z
p
Muon
Scalar
Dump
μ^+
ℓ^+
ℓ^-
Station components:
Drift chambers (6 planes)
Hodoscopes
Dark Photon Hodoscopes
Muon Prototubes
Extra tracking layer?
Trigger on displaced decays
EM Calorimeter

- DarkQuest is an opportunity: the muon spectrometer exists, an analysis of muon data can already be made and it only requires minimal (low cost) upgrades to be able to detect electrons.
- It is compelling because it uses the highest-energy proton beam in the US and it can be done in a short time-scale.
- It is currently looking for funding, a nuclear physics program is also planned to run in parallel.

LIGHT DARK MATTER EXPERIMENT

Caltech Fermilab Lunds Universitet University of Minnesota UCSB University of California Santa Barbara

SLAC National Accelerator Laboratory Stanford University Texas Tech University University of Virginia


Electron E<1.2 GeV
4 GeV Electron Beam
Dark matter
Target
Ecal
Hcal

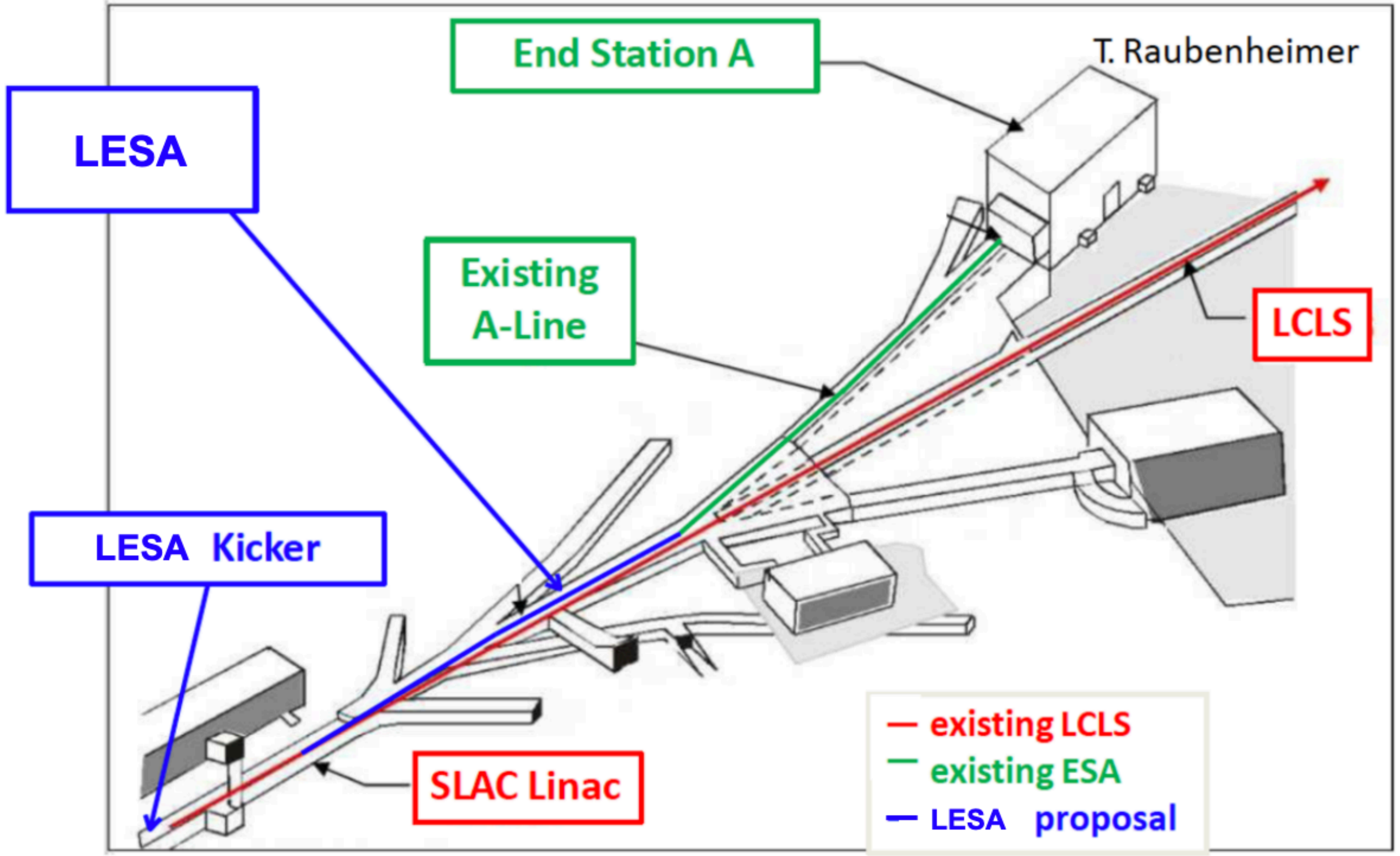
ELECTRON BEAM SETUP AT SLAC

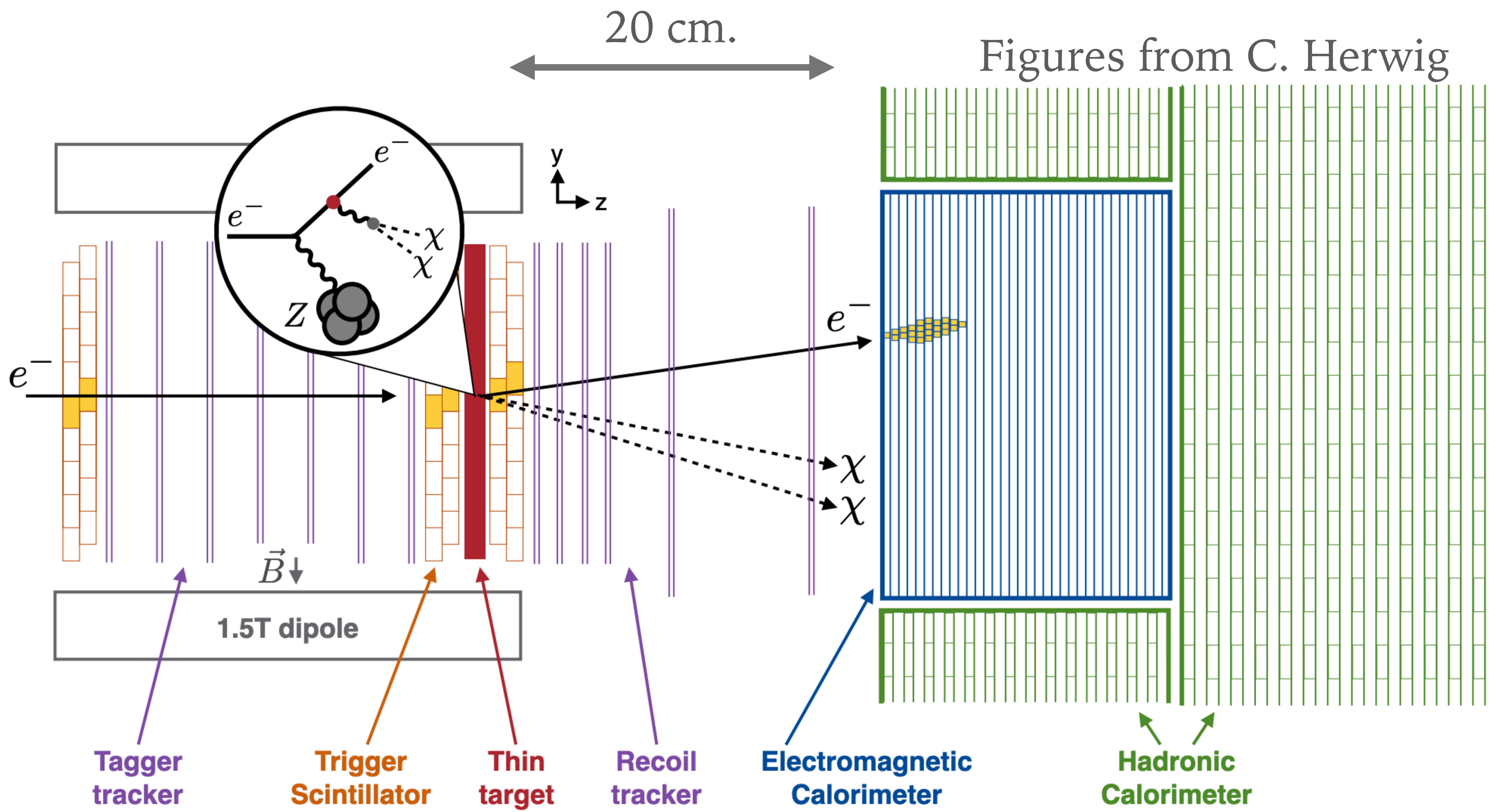
4 GeV electron beam delivered by SLAC (Linac to End-Station A)

High bunch repetition 37.2 MHz, 1e8 EOT/s

Expected luminosity: 4e14 Electrons on Target (EOT) in 1-2 years (2024-2026?)

Upgrade and ultimate target: 1e16 EOT (>2027, 8 GeV)




20 cm.
Figures from C. Herwig
y
z
e−
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χ
χ
Z
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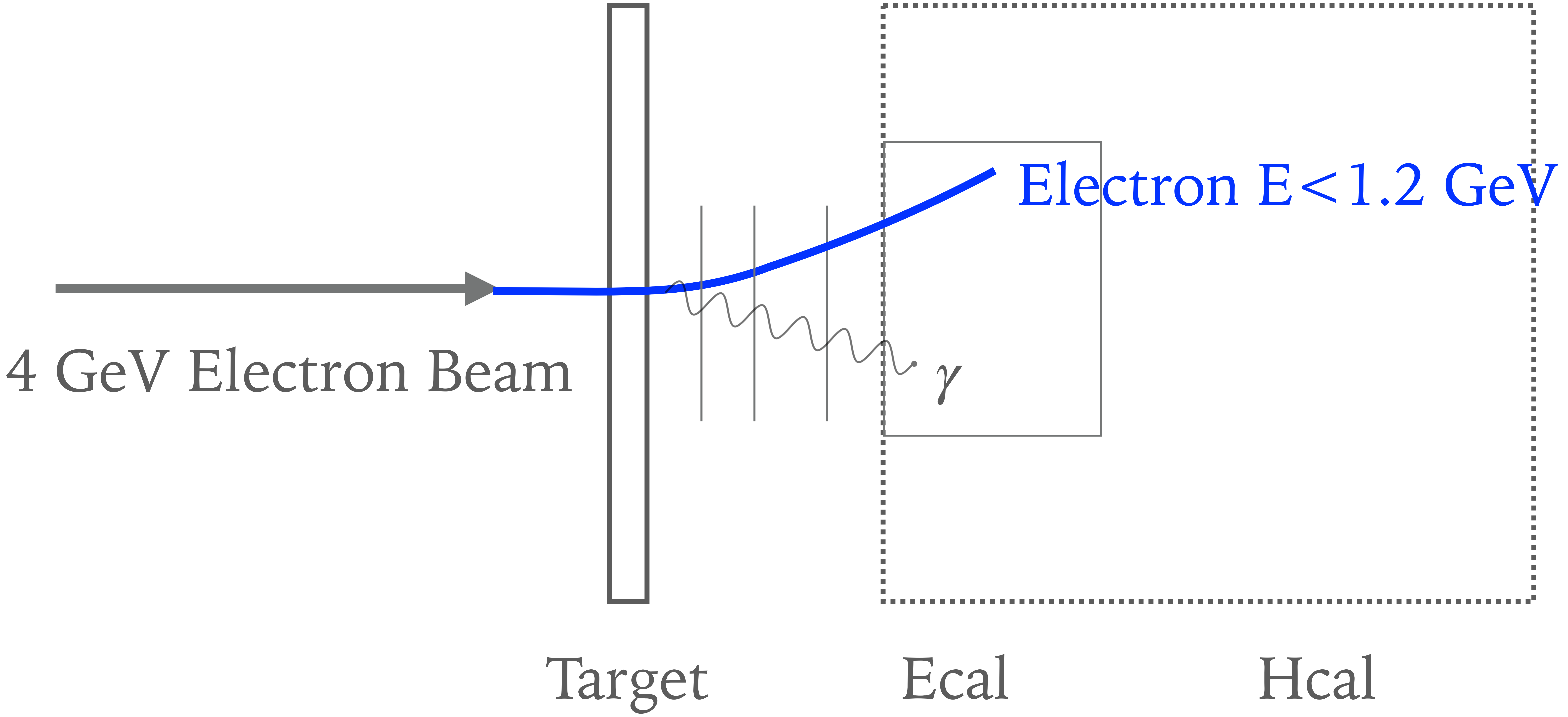
e−
χ
χ
B↓
1.5T dipole
Tagger tracker
Trigger Scintillator
Thin target
Recoil tracker
Electromagnetic Calorimeter
Hadronic Calorimeter

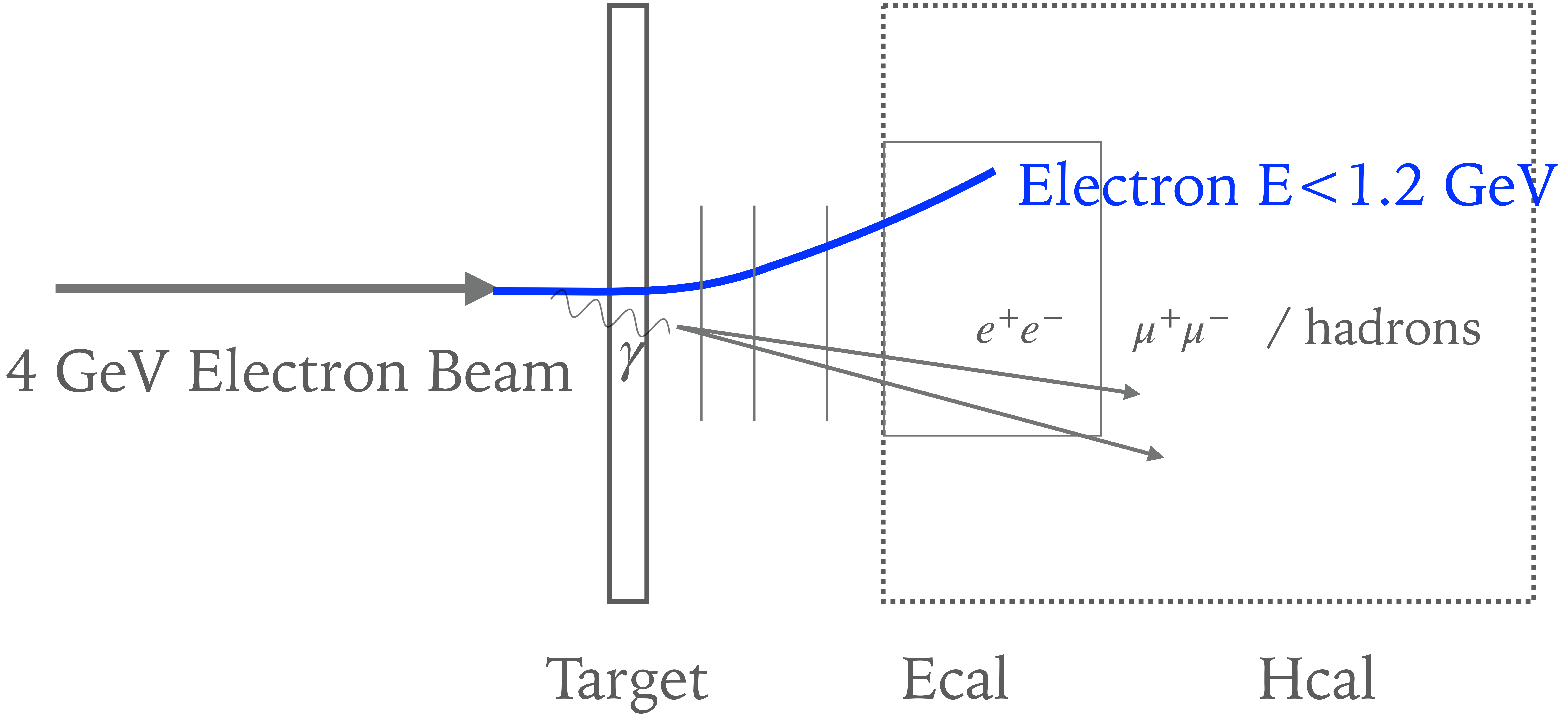
WHY IS LDMX CHALLENGING?

Identify each single incoming and outgoing electron	→	Need beam with minimal energy spread, high rate and low current.
Select only events with missing momentum	→	Make a decision (trigger) every ~25ns: LHC-like readout.
Operate with a high amount of electrons in a short period of time	→	Every detector (and electronics) needs to be radiation-hard.

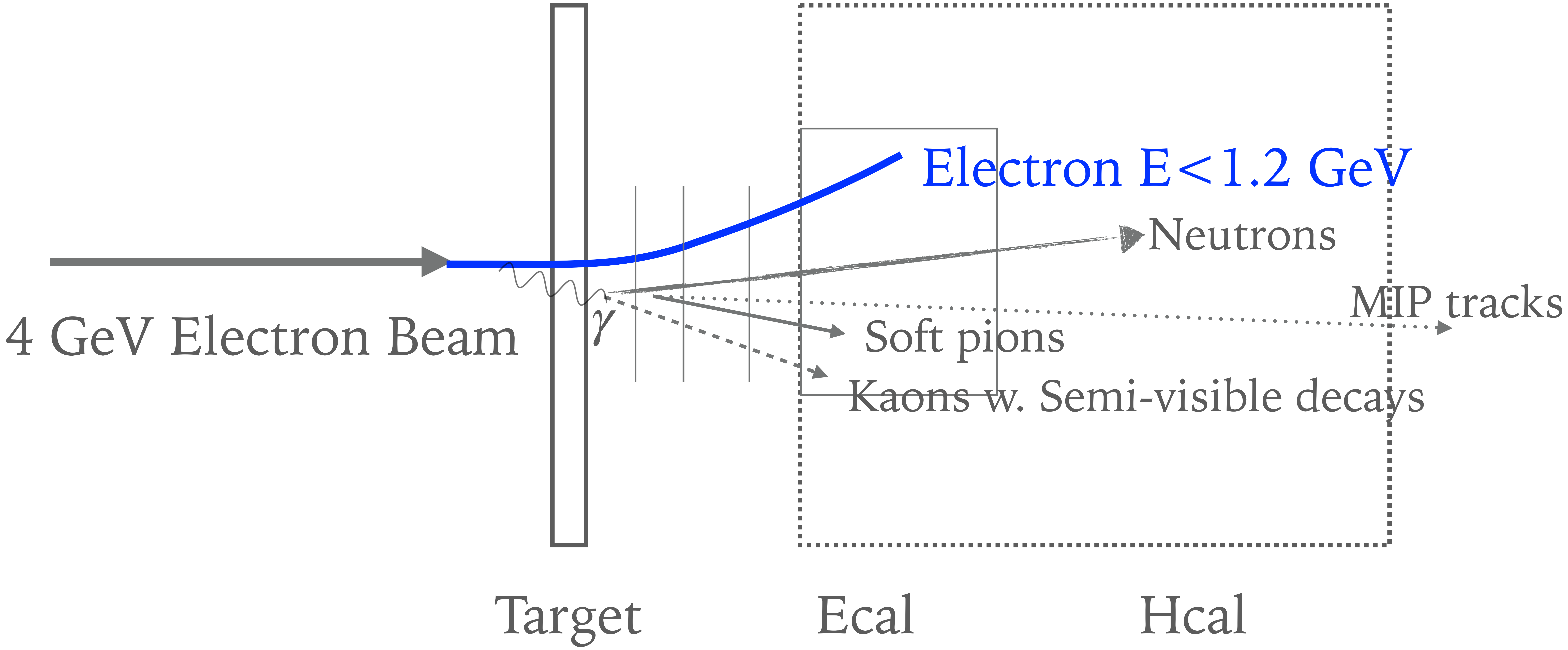
IDENTIFYING BACKGROUNDS: HARD BREMSSTRAHLUNG



IDENTIFYING BACKGROUNDS: TRIDENT AND PHOTO-NUCLEAR

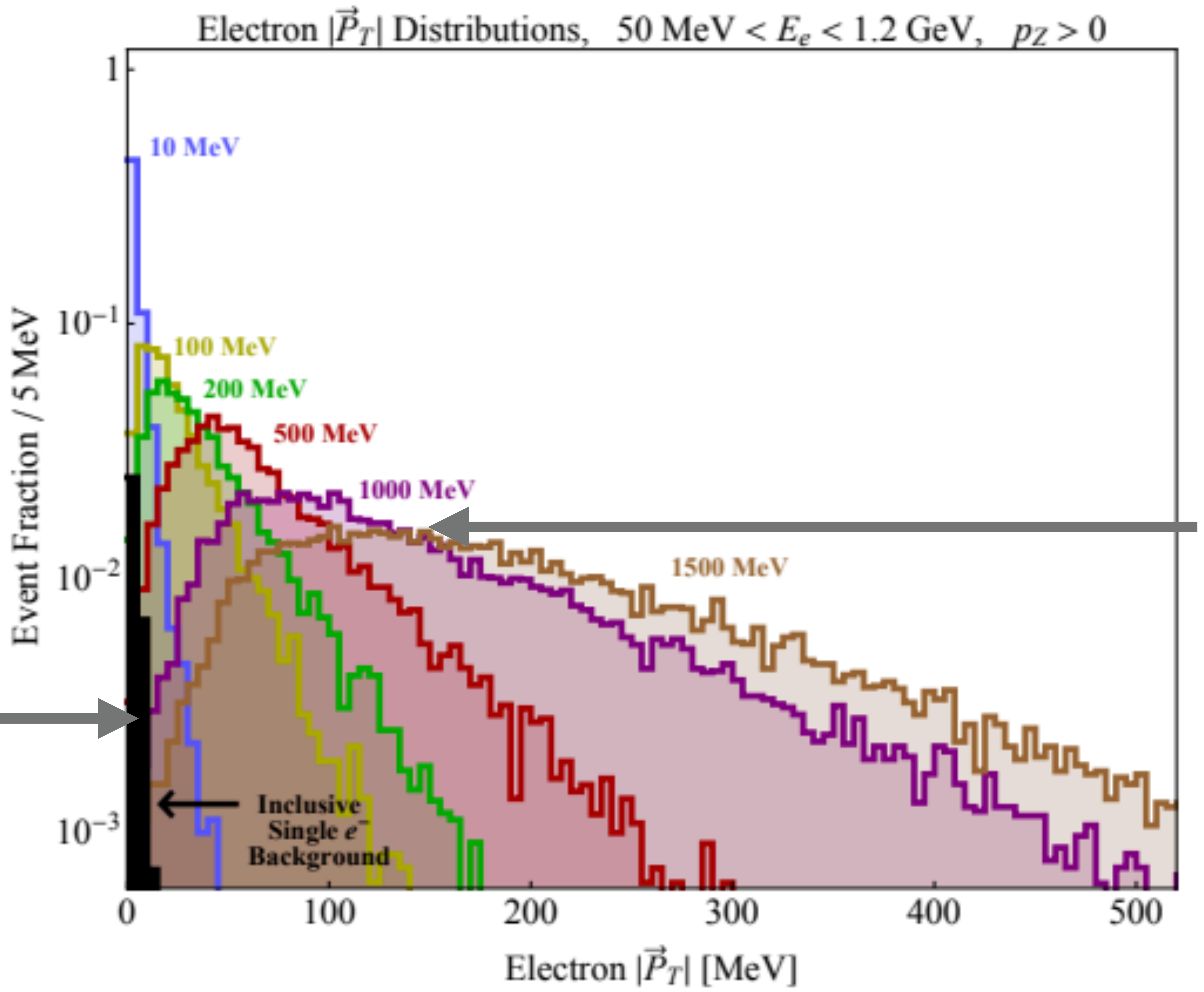


IDENTIFYING BACKGROUNDS: RARE SHOWER RECONSTRUCTION



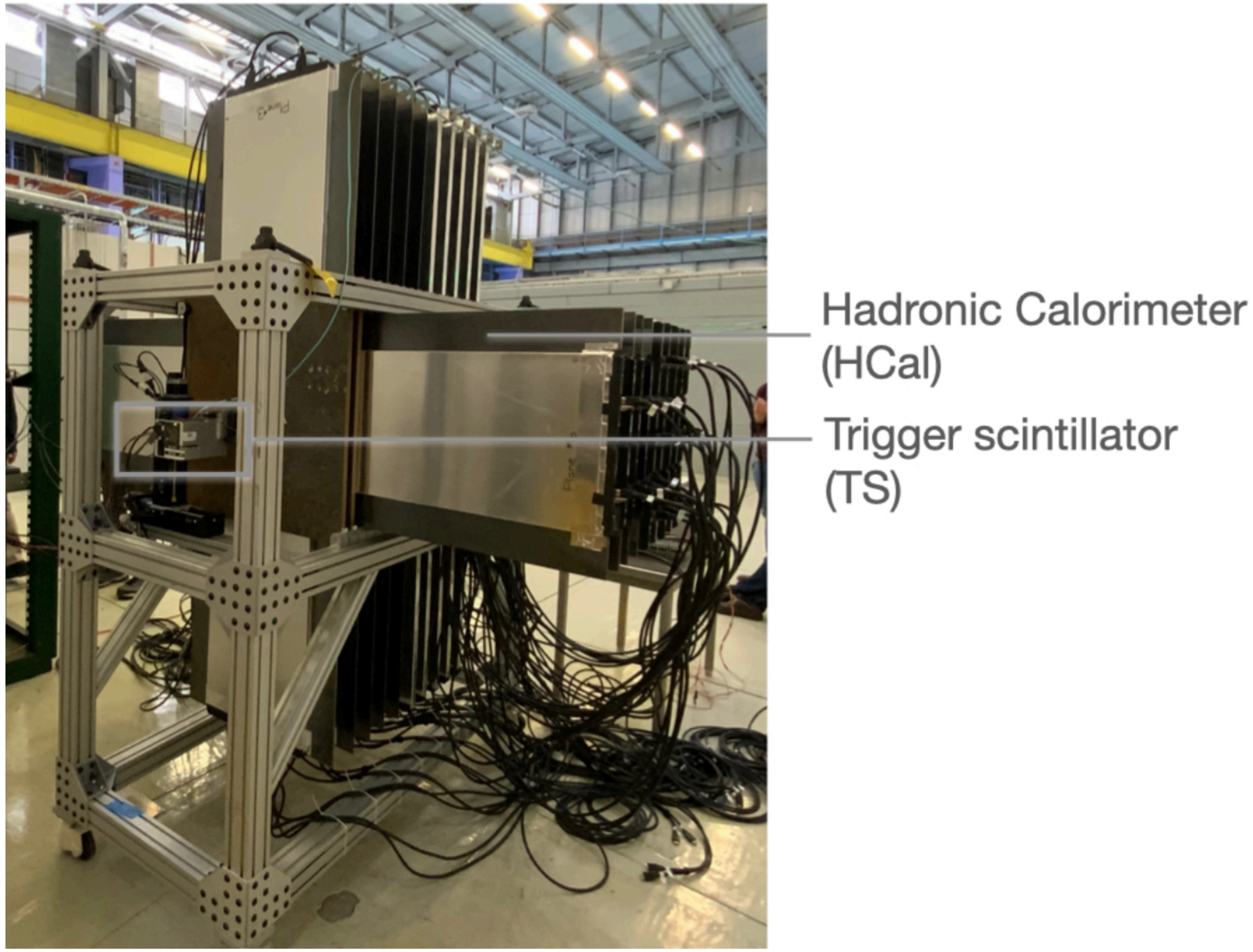
REJECT BACKGROUNDS, THEN IDENTIFY SIGNAL

Use Calorimetry detectors to reject **Bremsstrahlung and Photo-Nuclear** backgrounds to a level of < 1 background event.



Then use electron's transverse momentum to identify signals with different dark matter masses.

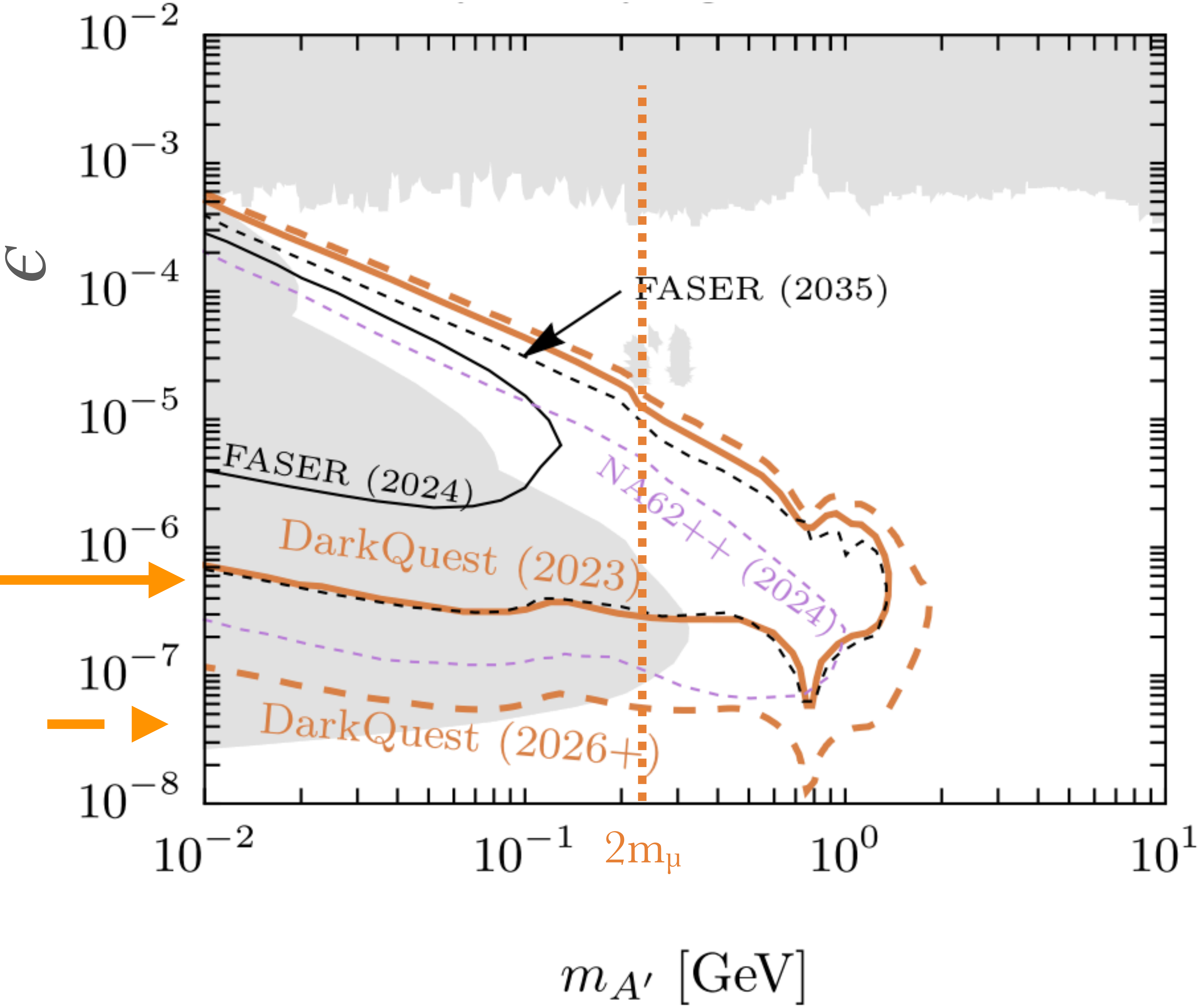
TESTING THE PROTOTYPE



- LDMX is a neat idea: electron recoils against dark matter, measure electron p_T.
- One of its main analysis challenges is to contain and measure any rare SM backgrounds.
- It's need for a clean and intense electron beam, and detectors that can sustain this beam, it is probably why it was not done before.
- But now we have the technology: we can build extremely fast and radiation hard readout electronics so we should build it.

Berlin, Gori, et. al. (2018)
and N. Blinov

PREDICTED BOUNDS ON VISIBLE A′ DECAYS

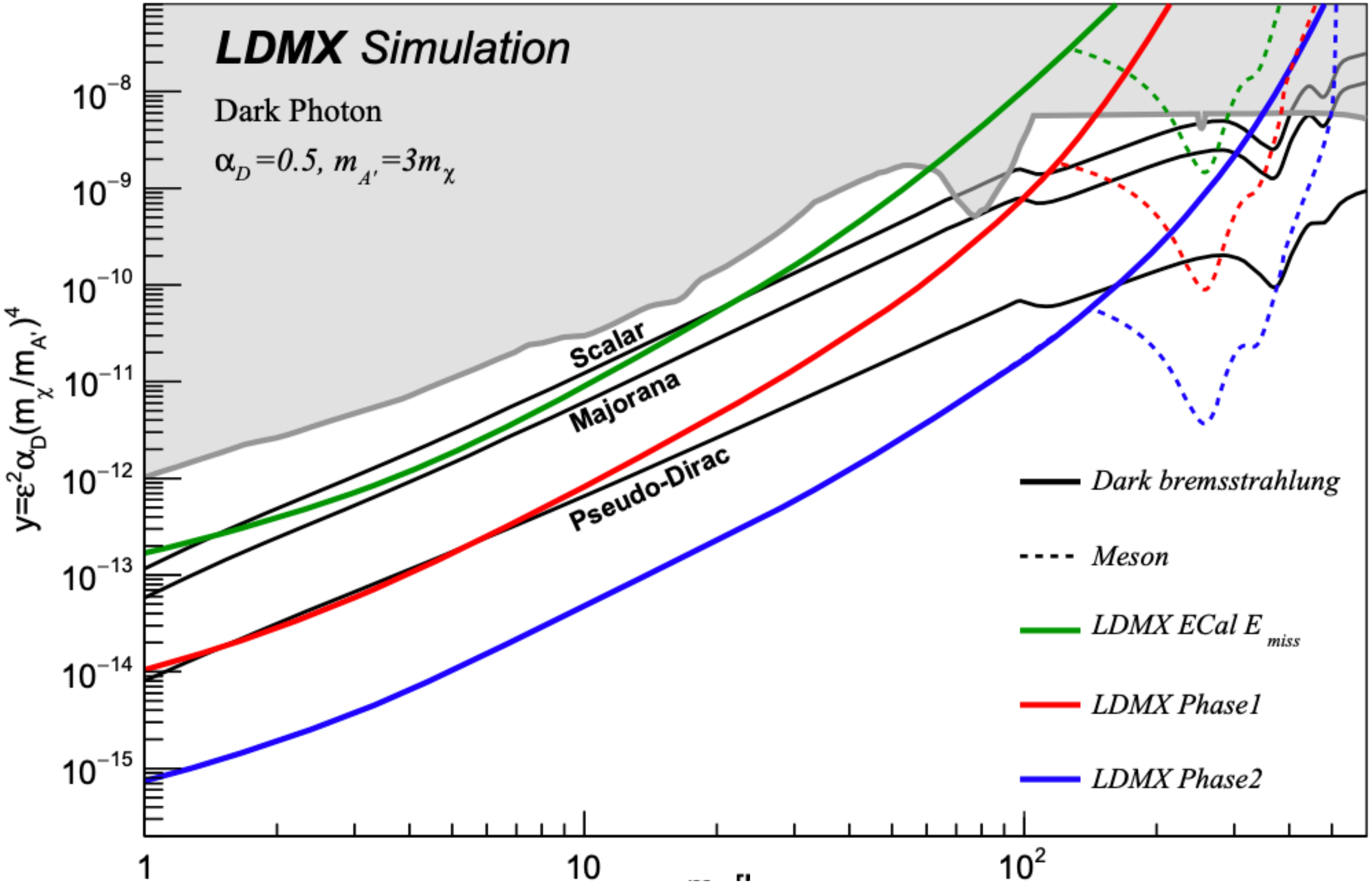


Preliminary luminosity

w. PIP-II upgrade

PREDICTED BOUNDS ON INVISIBLE A′ DECAYS

$$\sigma v \propto \epsilon^2 \alpha_D \frac{m_\chi^2}{m_{A'}^4} \equiv \frac{y}{m_\chi^2}$$



m_χ [GeV]

- ➤Fixed-target experiments have unique potential to probe sub-GeV dark matter.
- ➤DarkQuest and LDMX explore visible and invisible mediator decays and are complementary in the mediator/DM mass parameter space.
- ➤They have short-timescales, almost-ready-to-run beam lines, and they are low-cost.

THANKS!