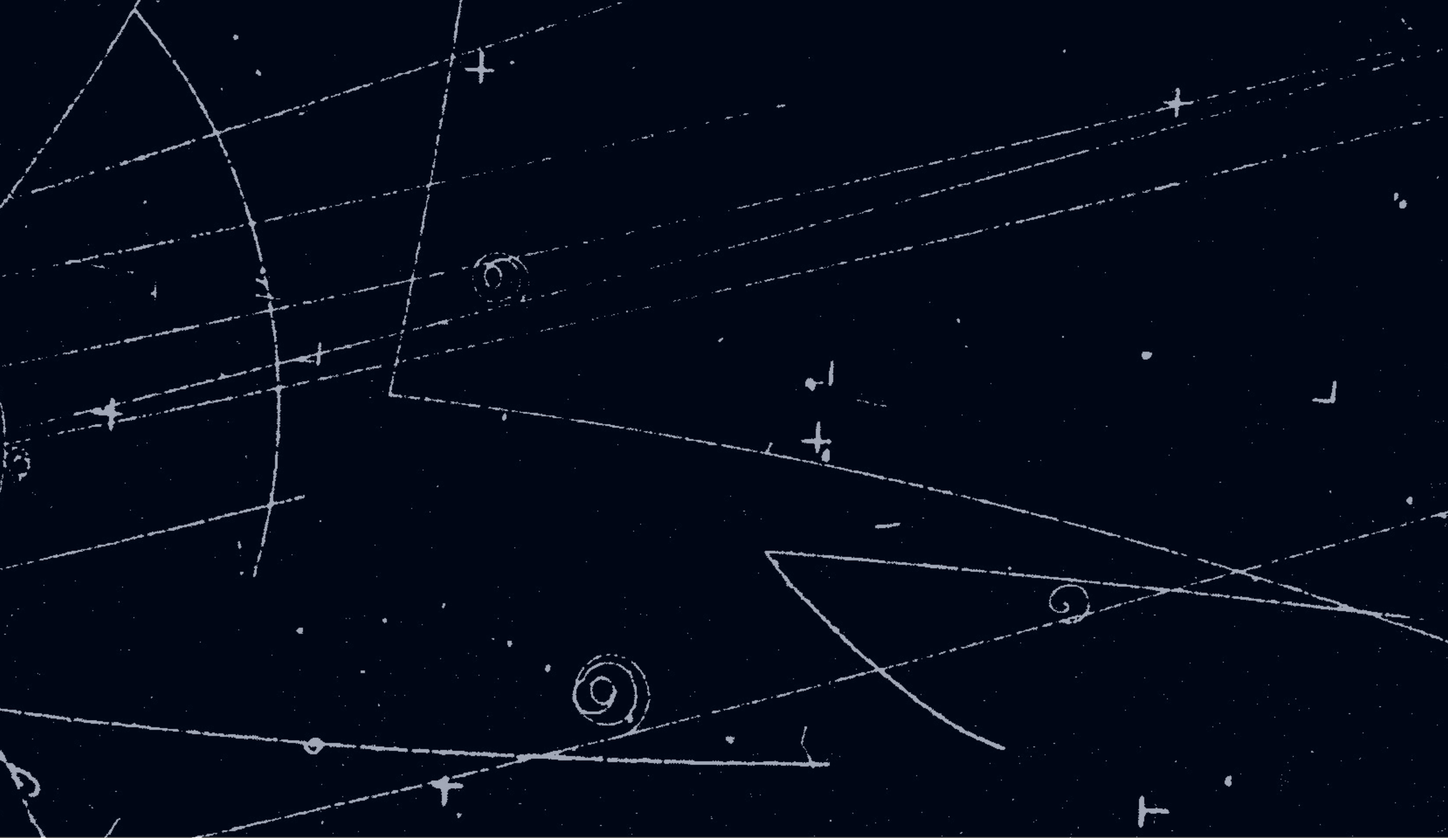
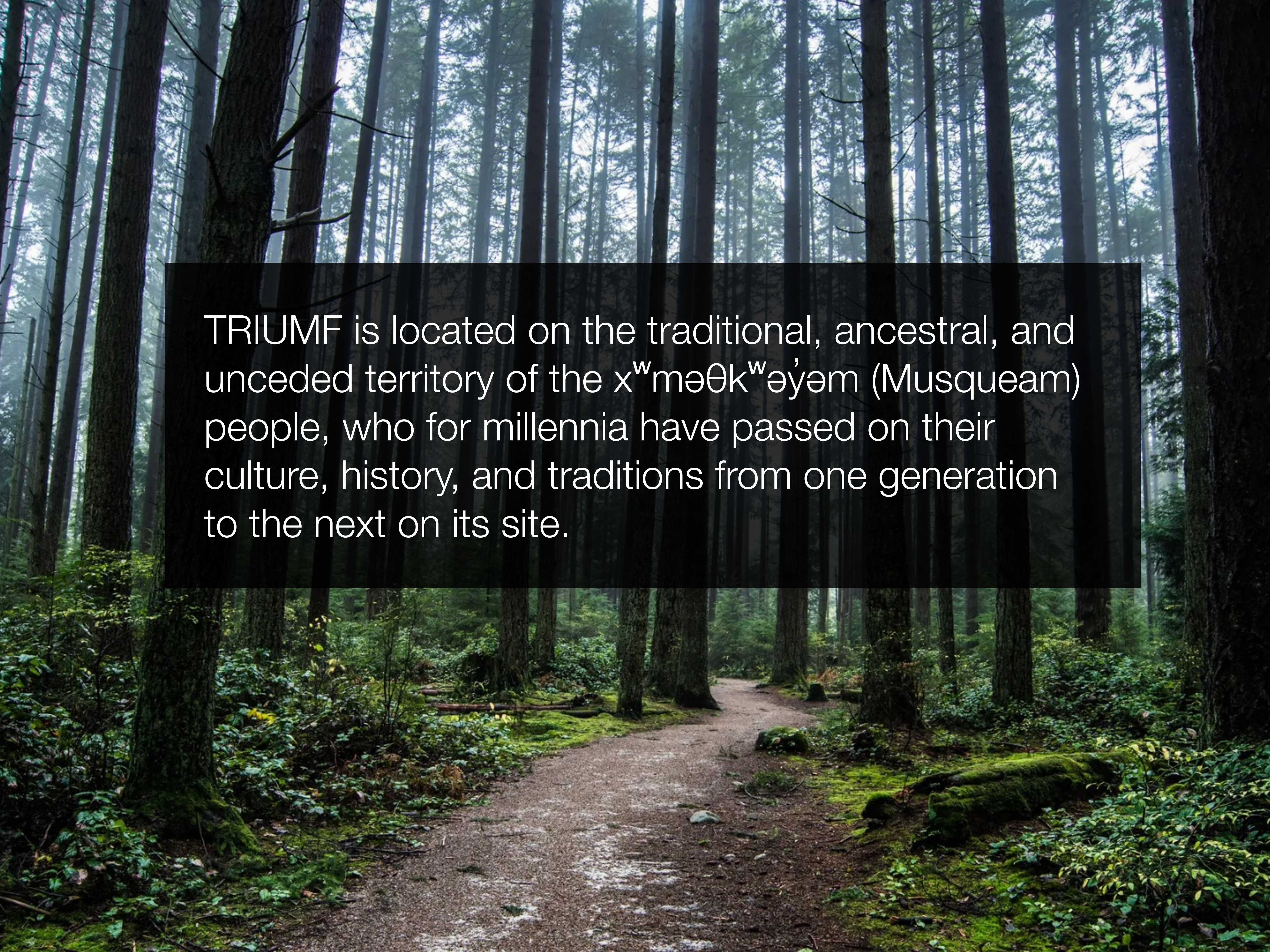


Searching for Dark Photons at TRIUMF

Leveraging Canadian facilities to advance fundamental science

Kate Pachal
TRIUMF
& the DarkLight collaboration



TRIUMF is located on the traditional, ancestral, and unceded territory of the xʷməθkʷəy̓əm (Musqueam) people, who for millennia have passed on their culture, history, and traditions from one generation to the next on its site.

Introduction

I'm going to use DarkLight, a small experiment at TRIUMF, as the basis for a range of topics:

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What is the experiment and why are we doing it?

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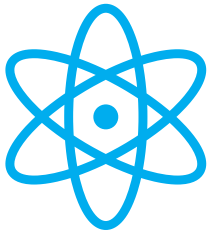

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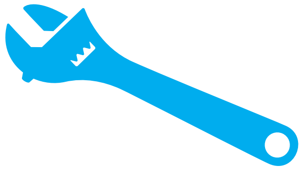

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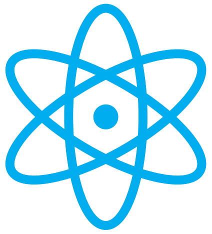

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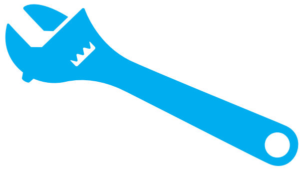

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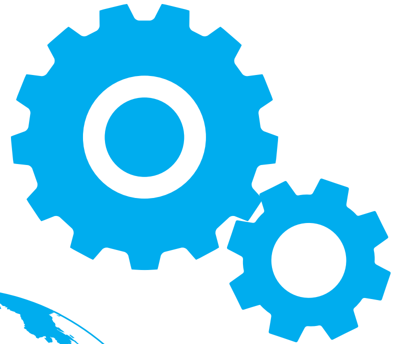

Considerations of detector technology for subatomic experiments more broadly

How TRIUMF fits into detector development ecosystem and Canadian physics landscape

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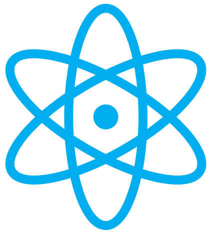

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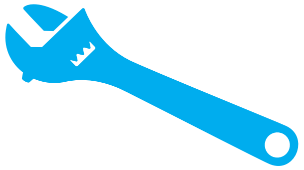

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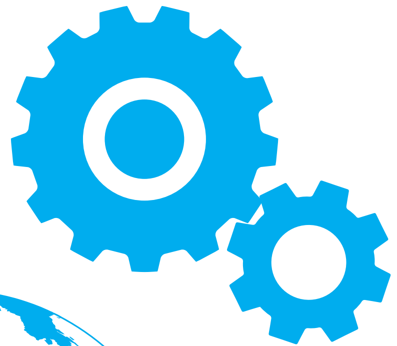

Considerations of detector technology for subatomic experiments more broadly

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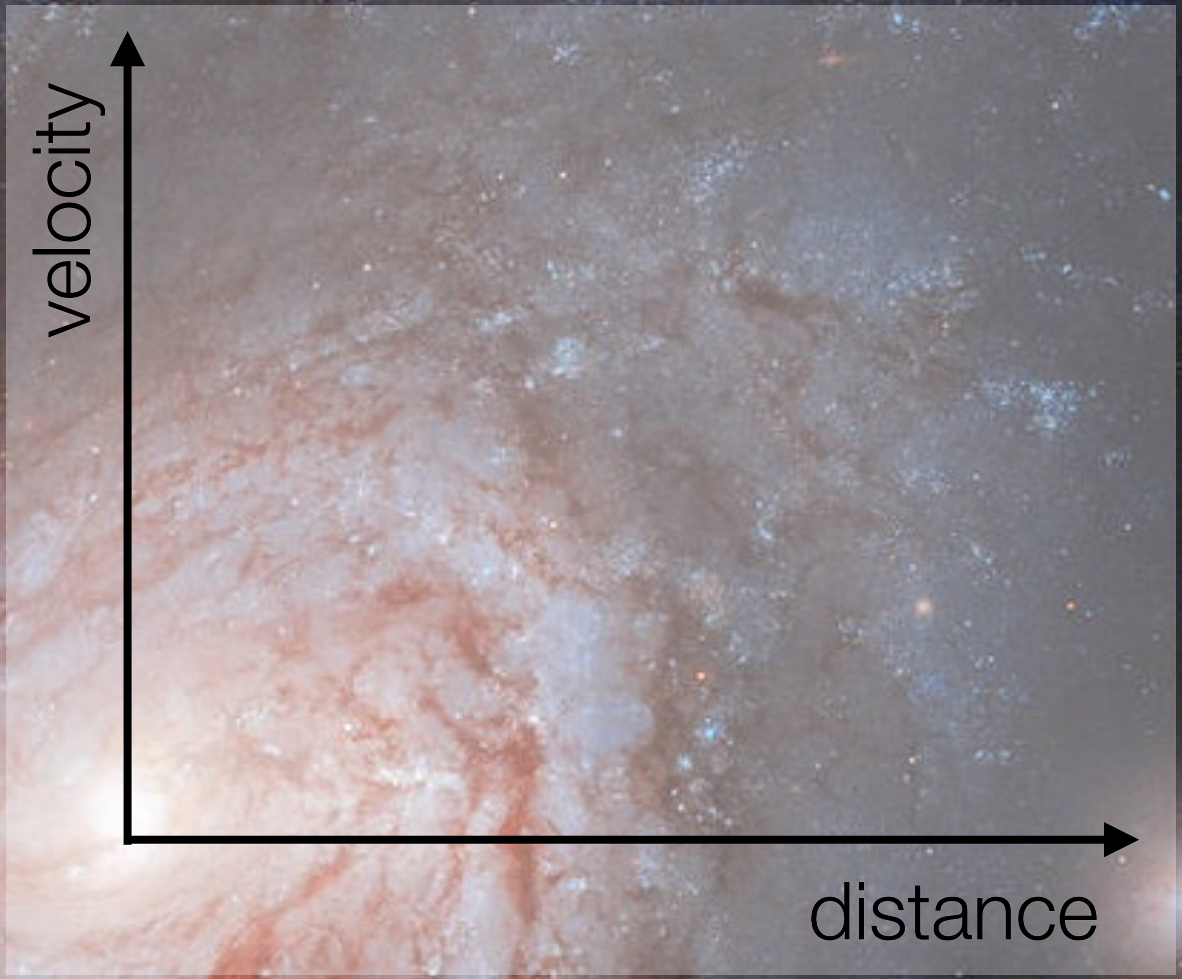
Let's discuss!

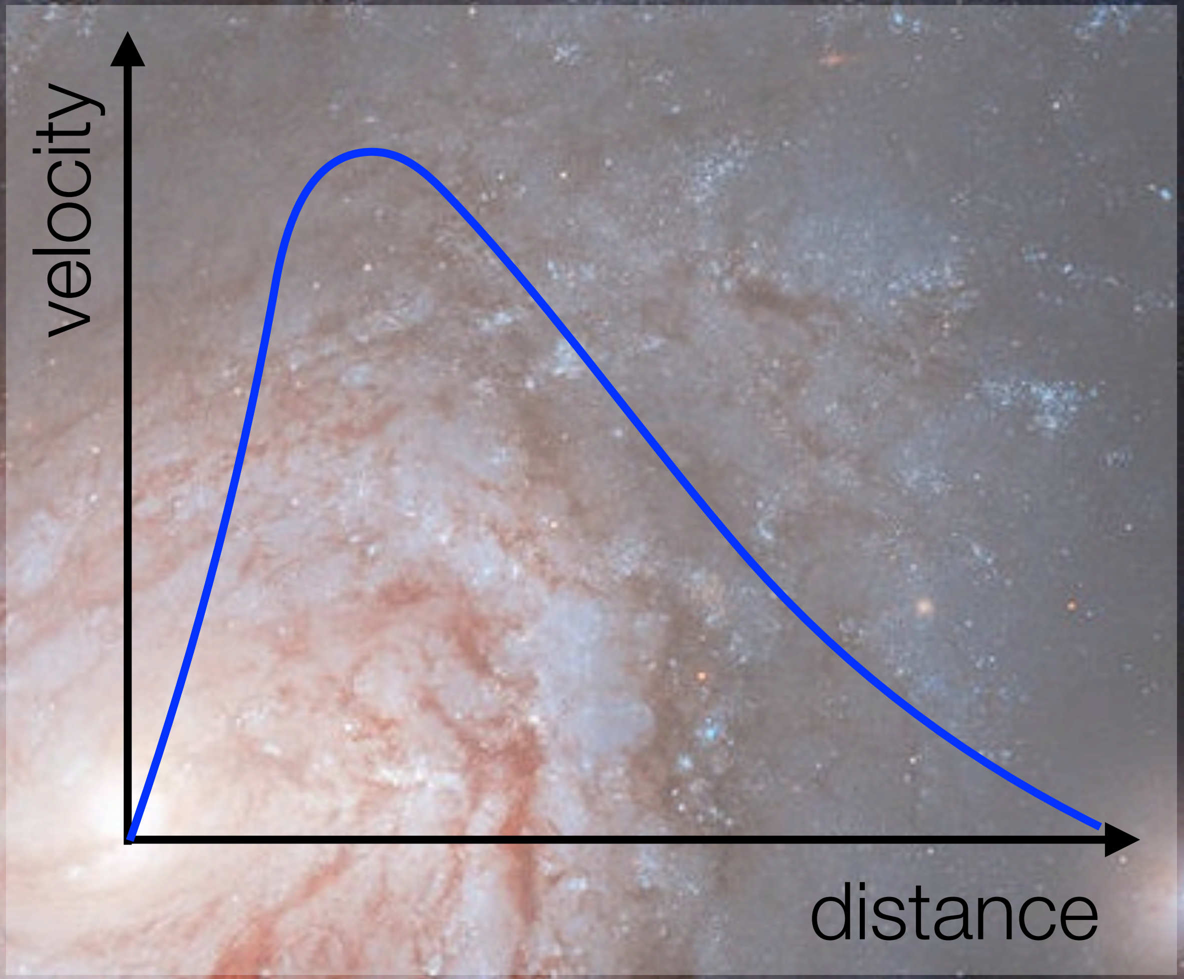
What we know about the universe



ESA/Hubble

What we know about the universe

If stars were the only matter, velocity would follow this curve



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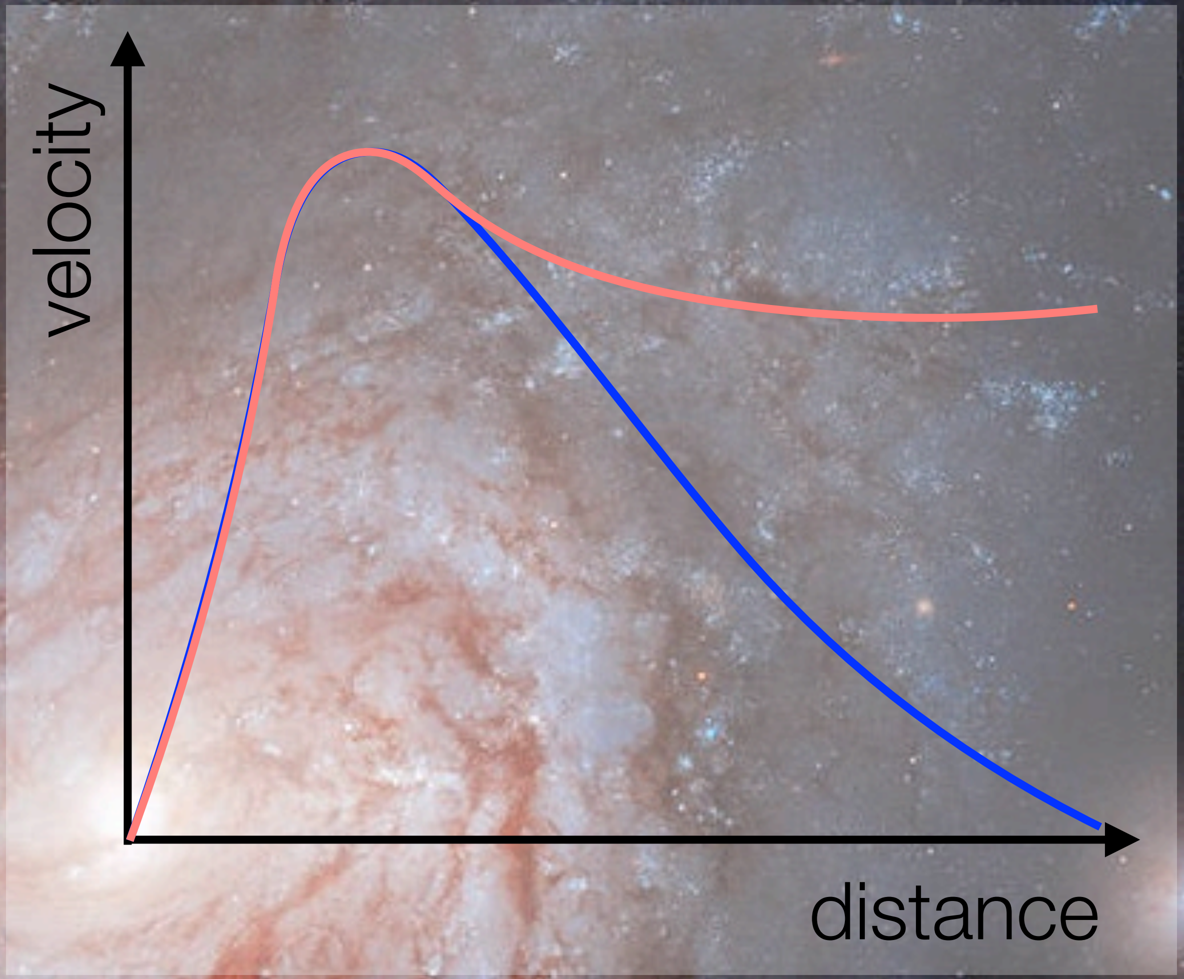

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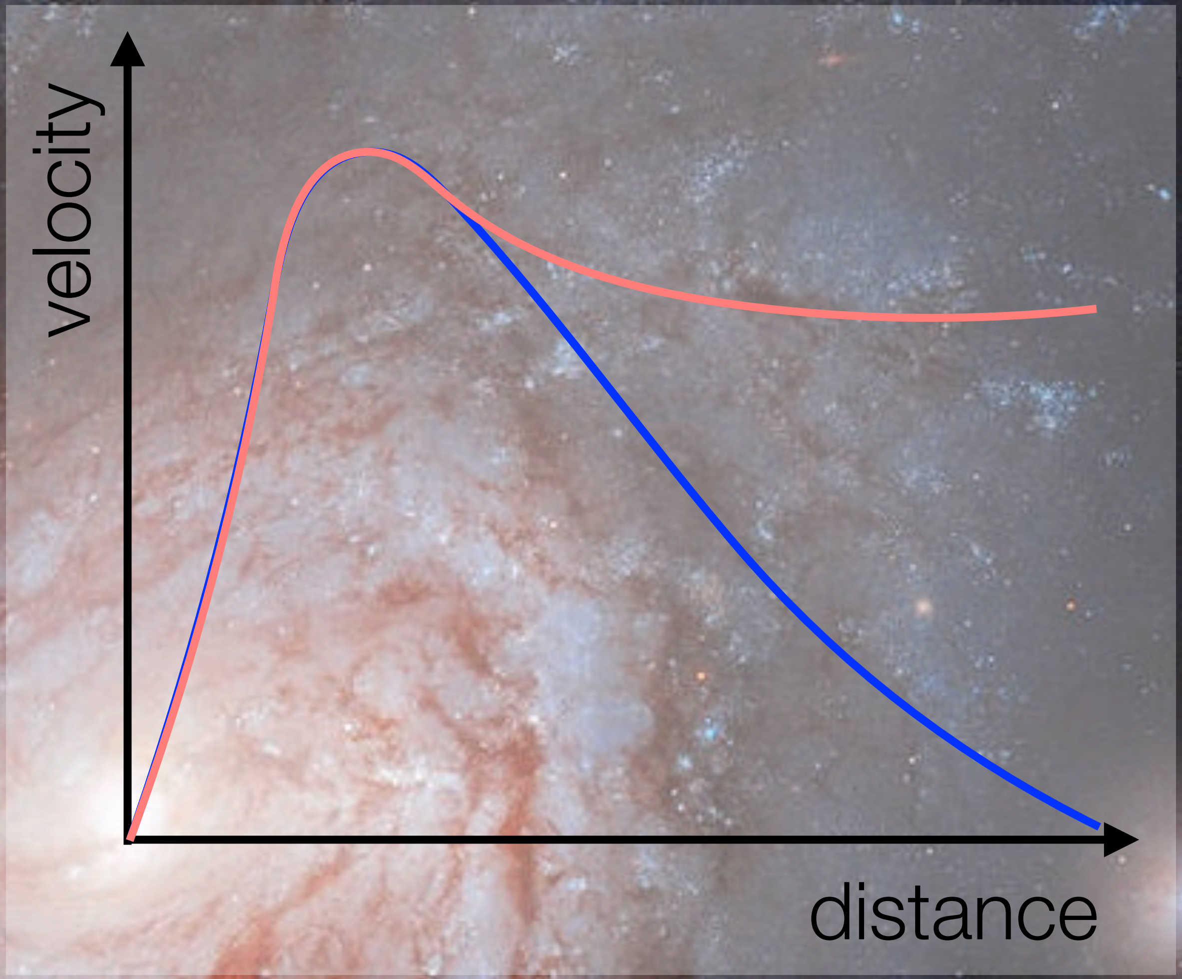
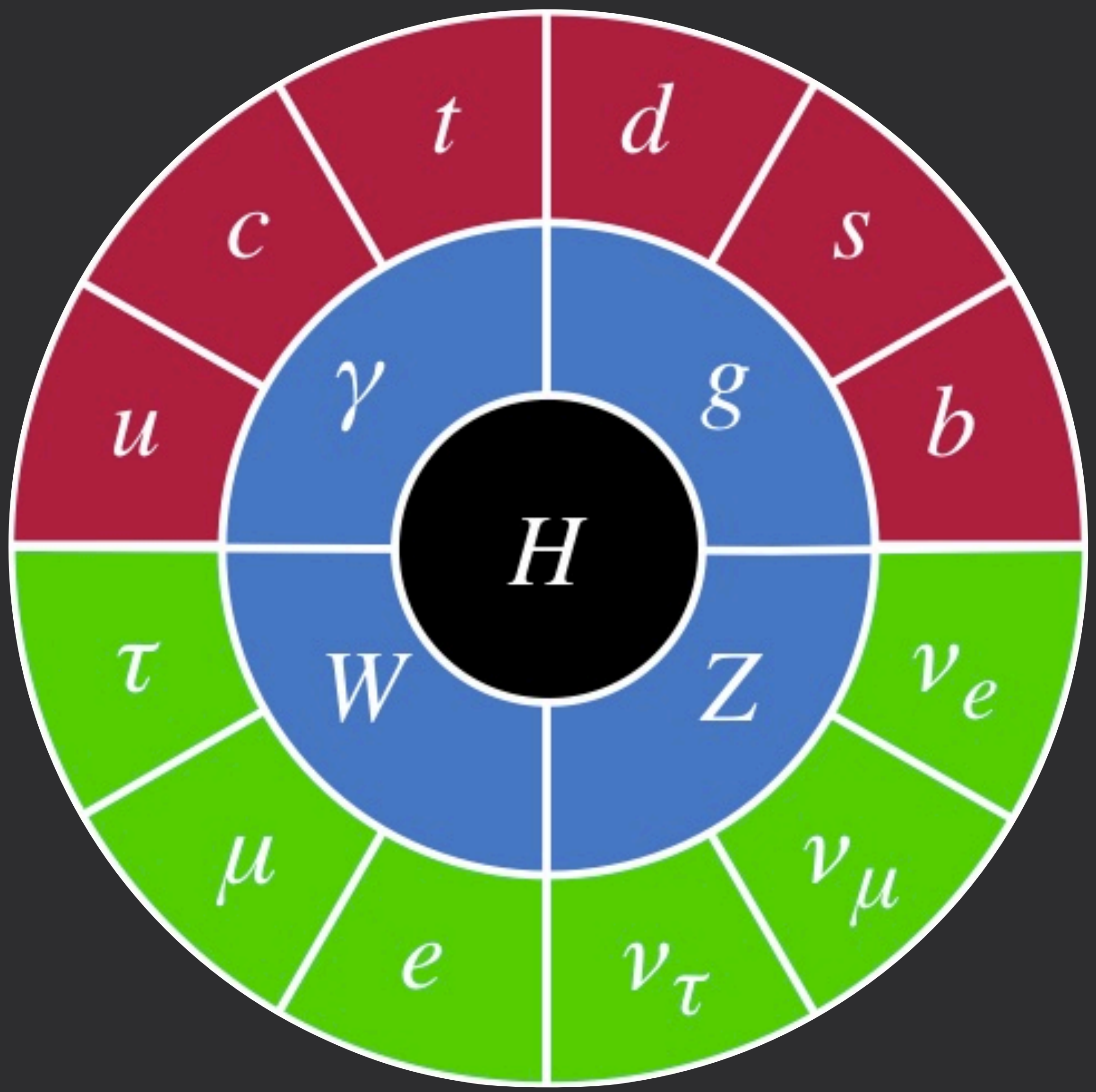


Instead it follows this one

Requires additional, invisible mass:
Dark matter!

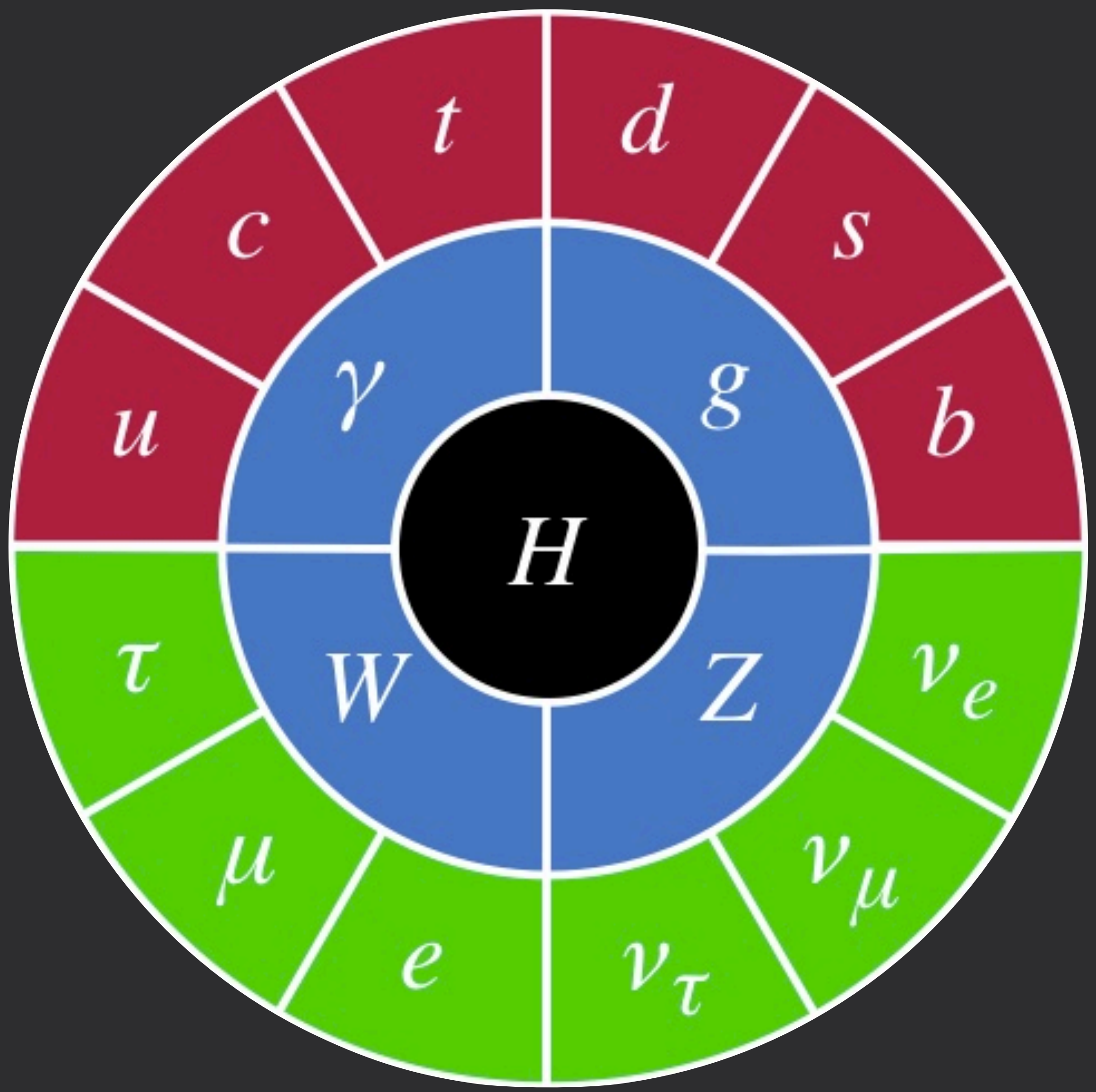
ESA/Hubble

Dark matter and particle physics



Known particles of the Standard Model (SM)

Dark matter and particle physics



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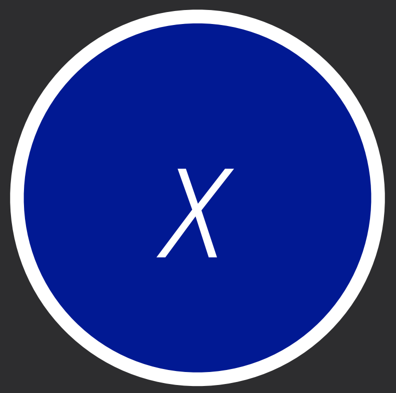

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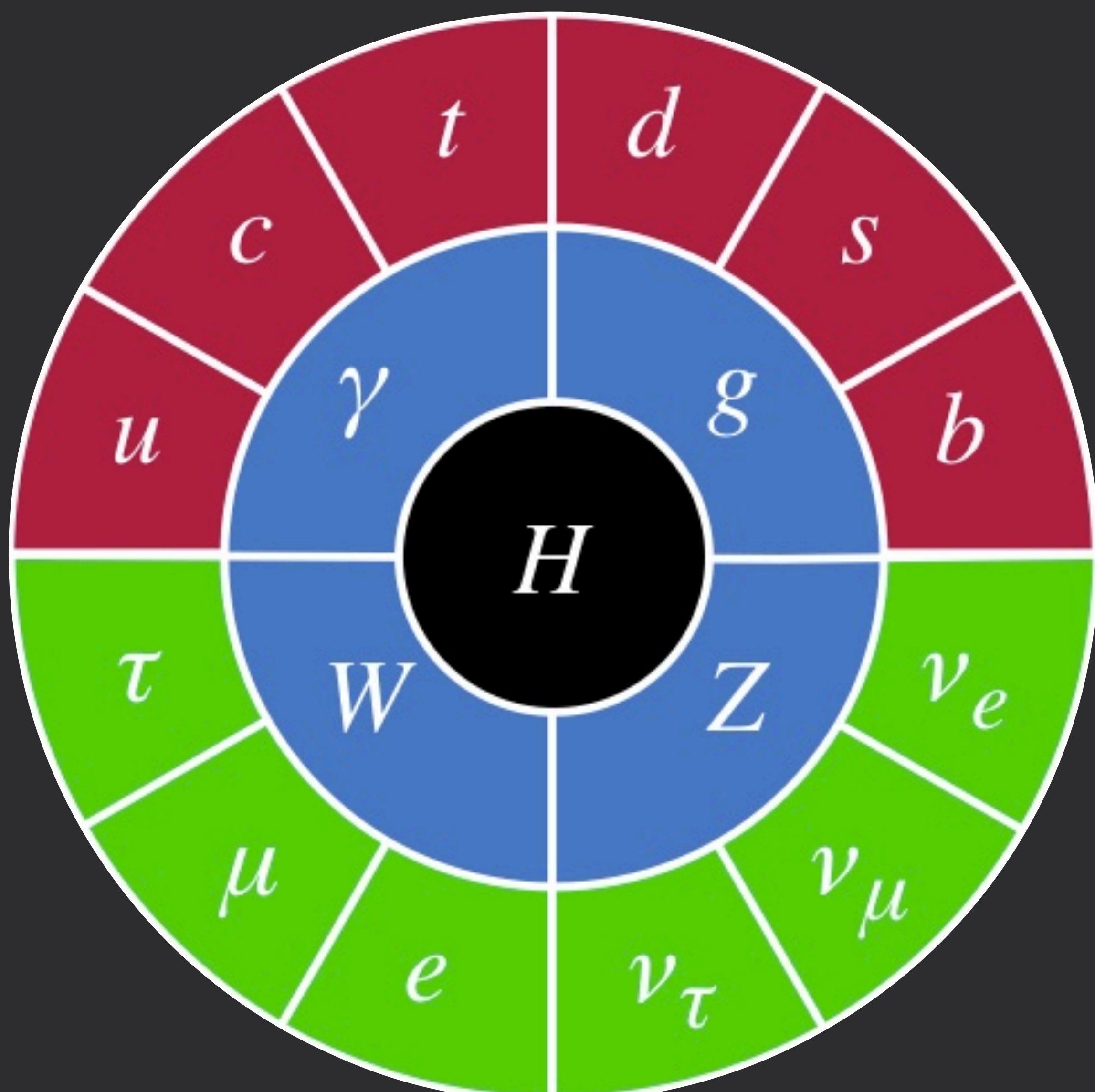

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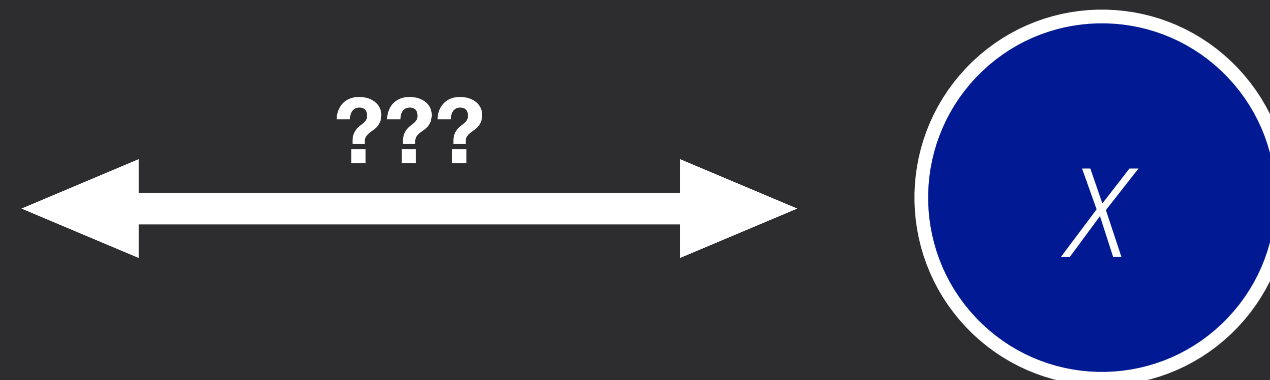

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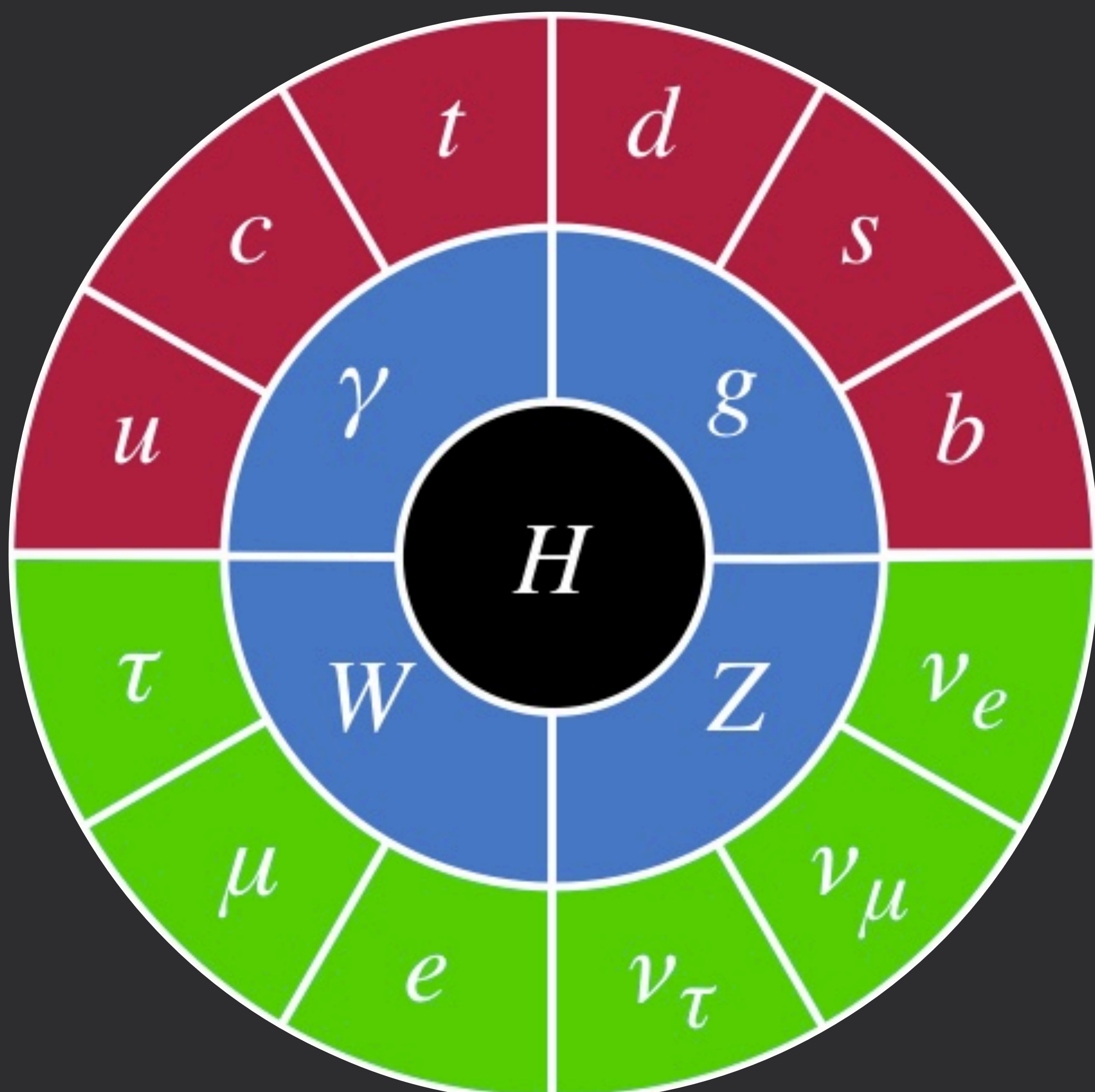

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Dark photon?

Dark matter particles

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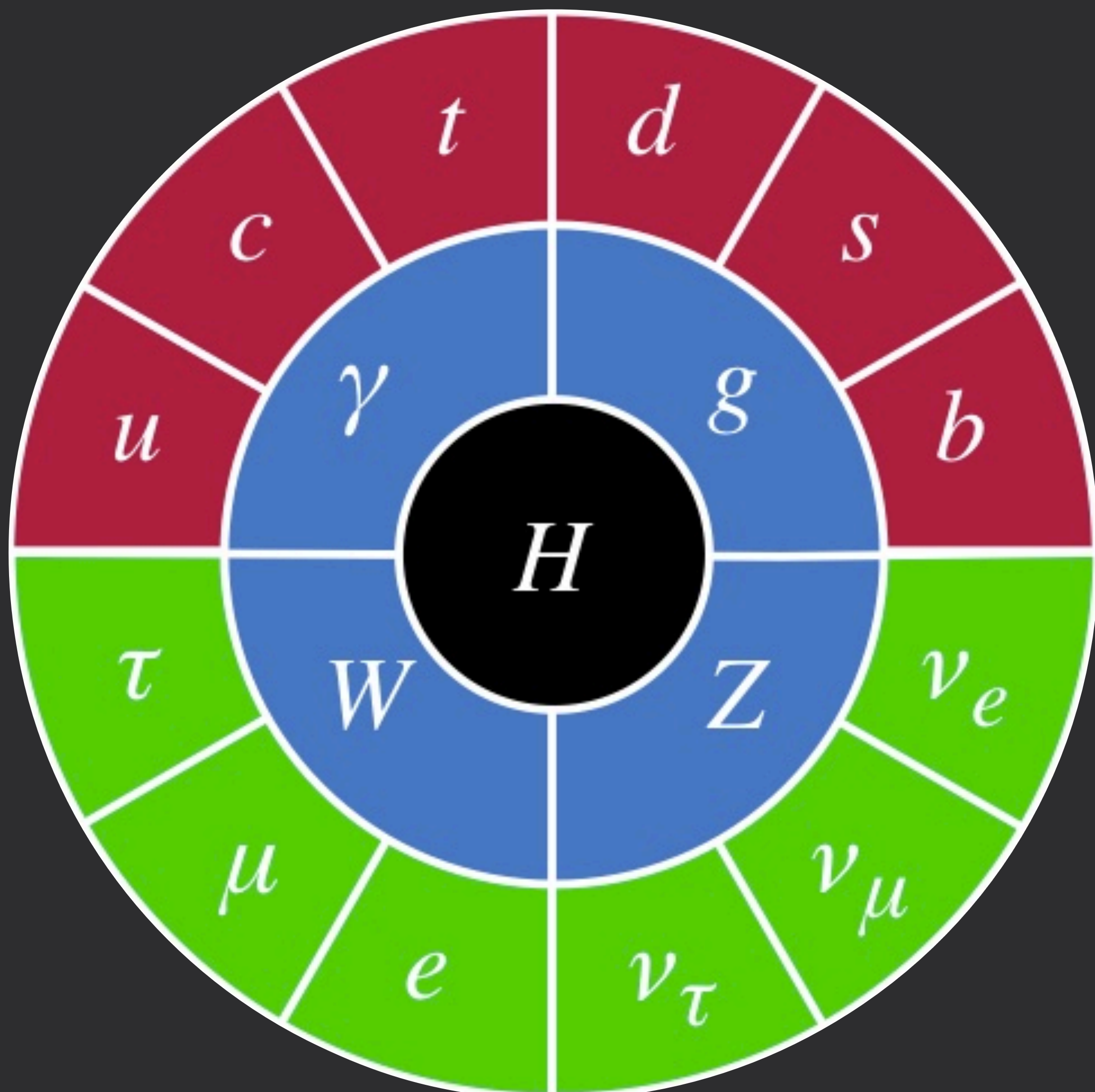
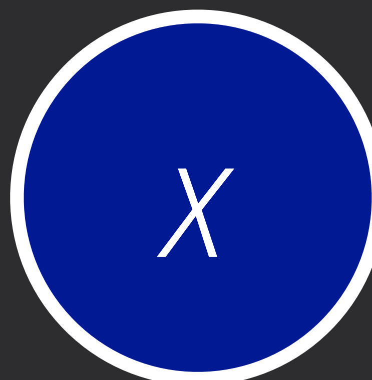


Known particles of the Standard Model (SM)

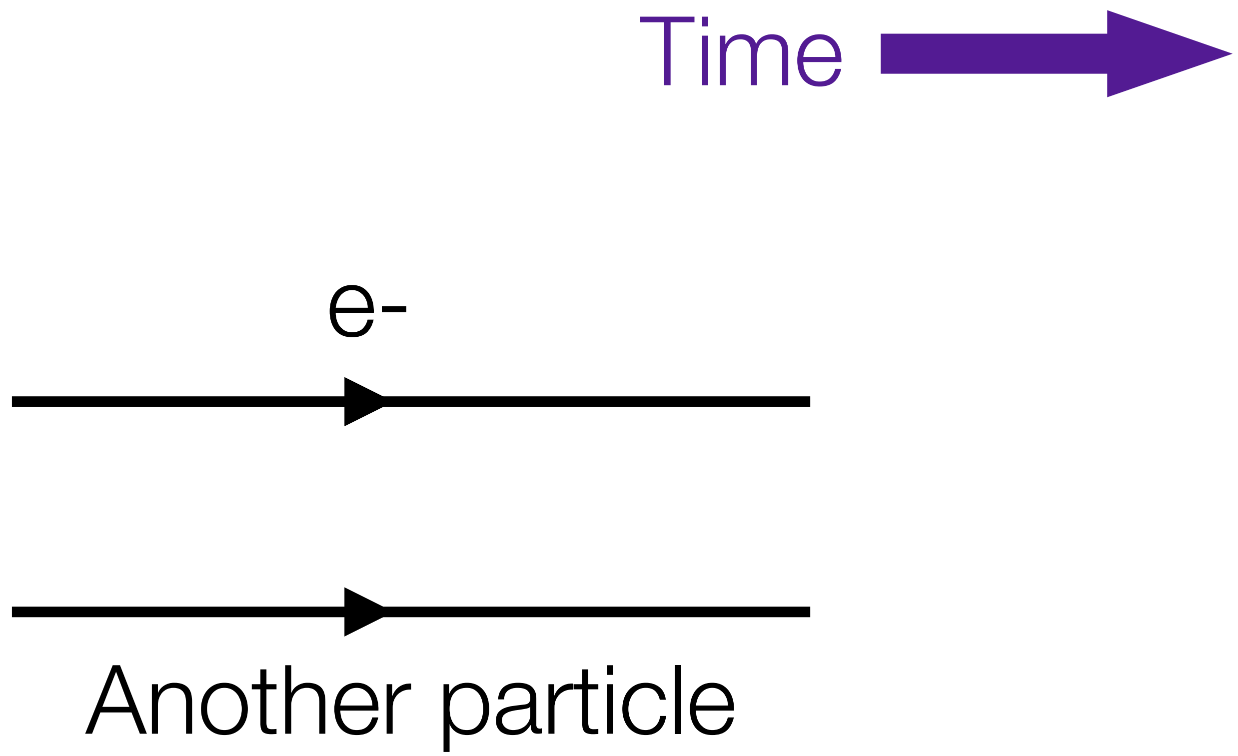
Dark photon?

- New particle
- Not dark matter itself
- Has mass
- Couples to SM and χ



Dark matter particles

Making dark photons at accelerators



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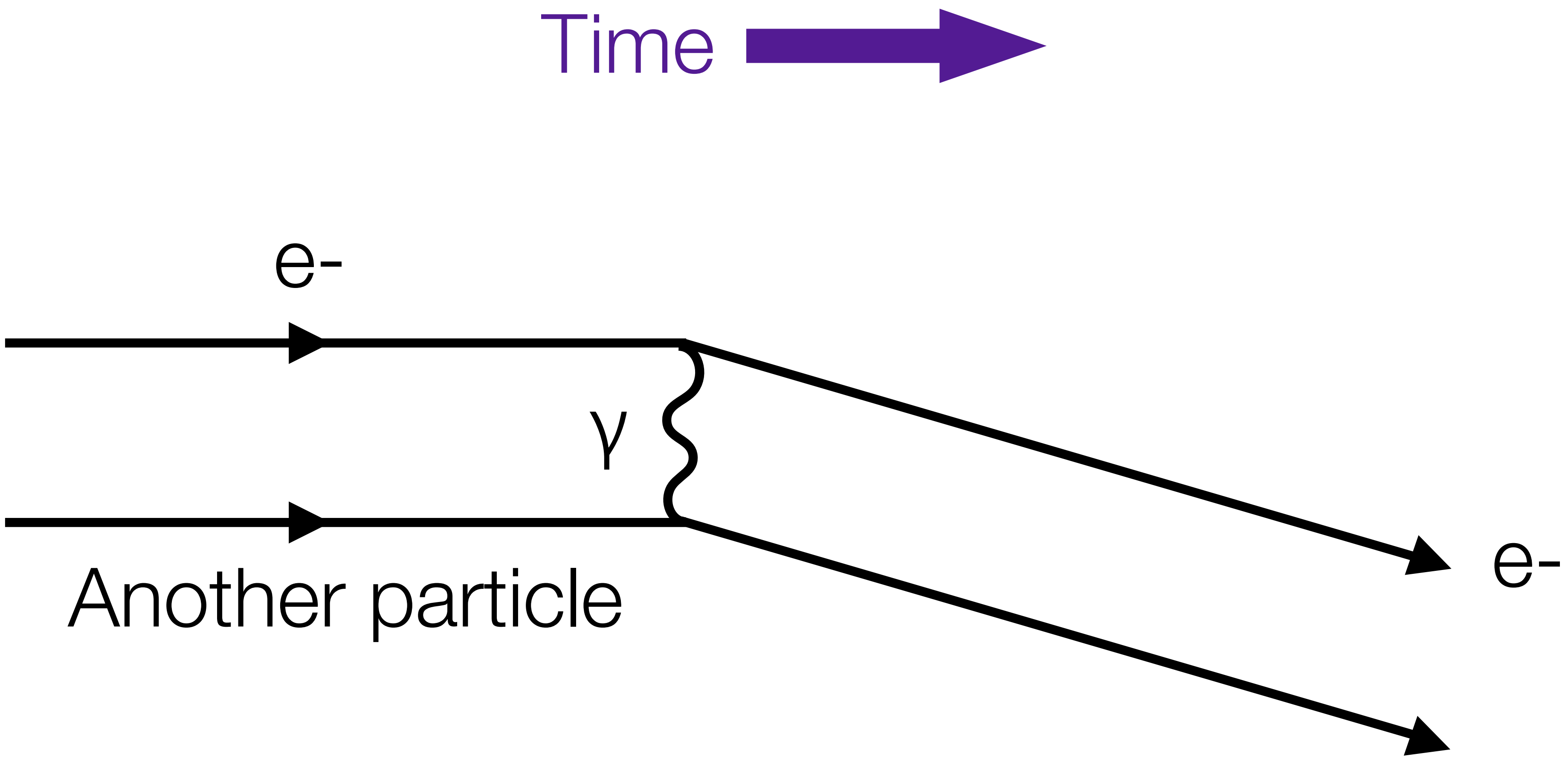

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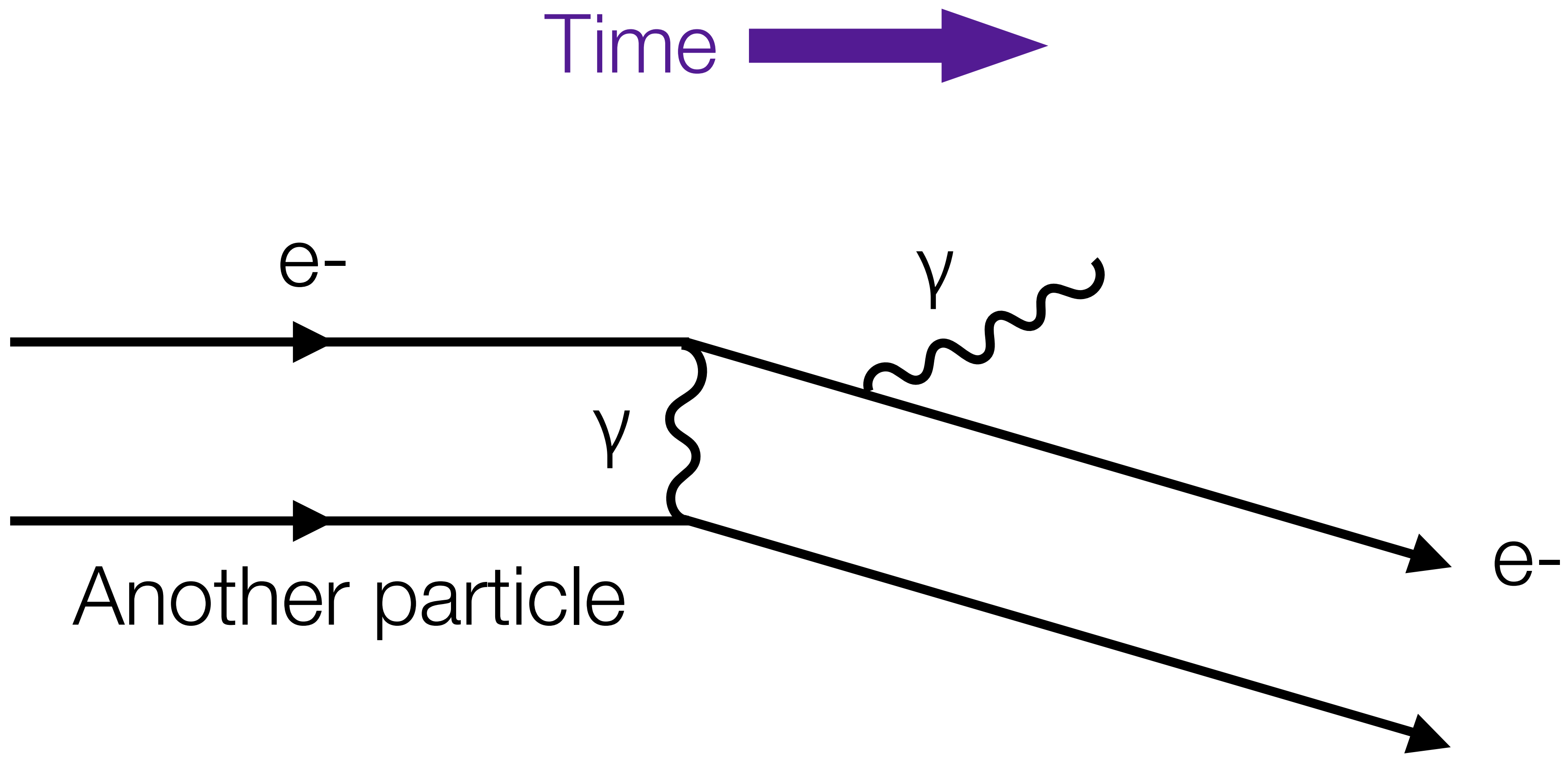

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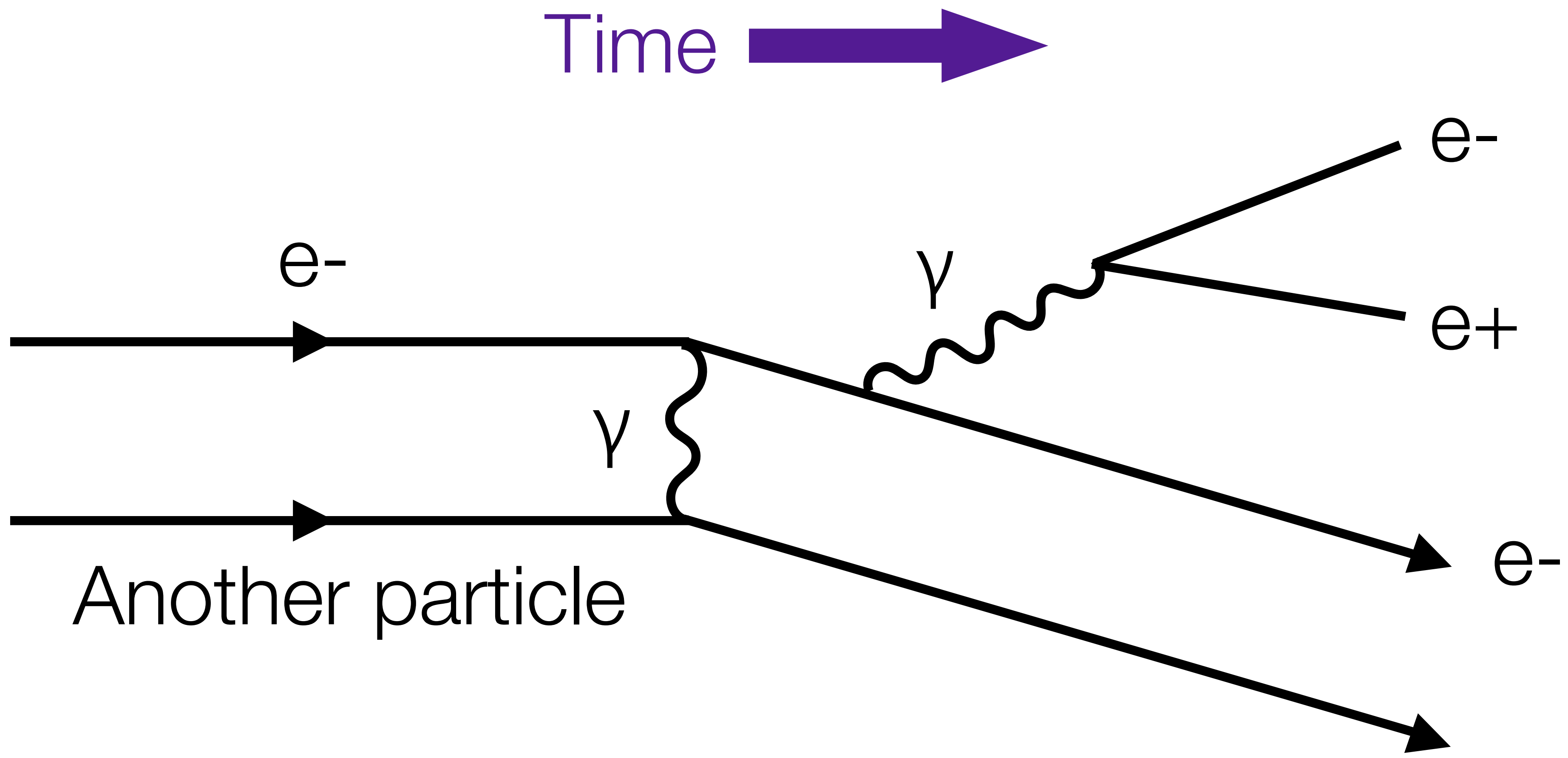

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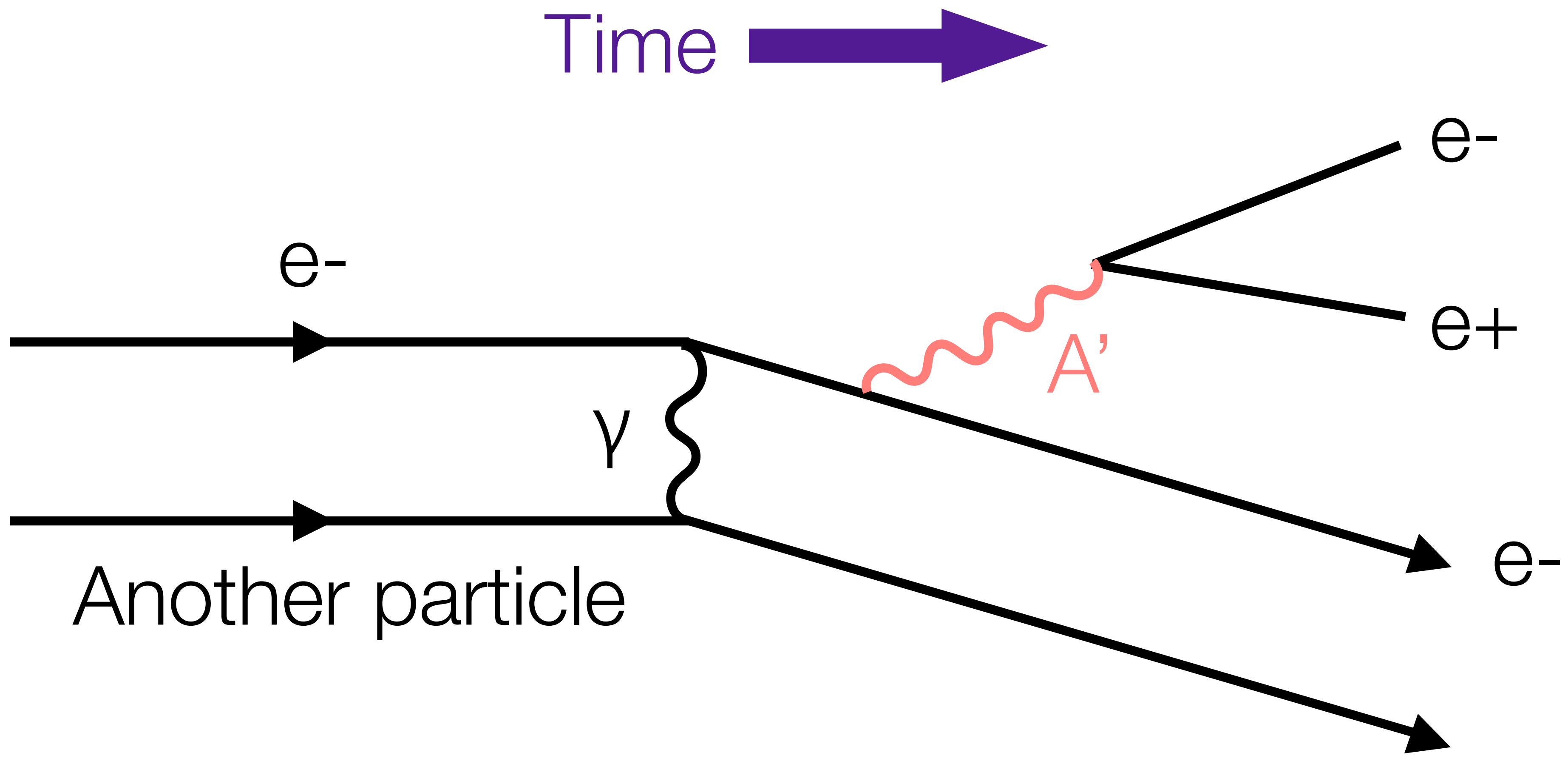

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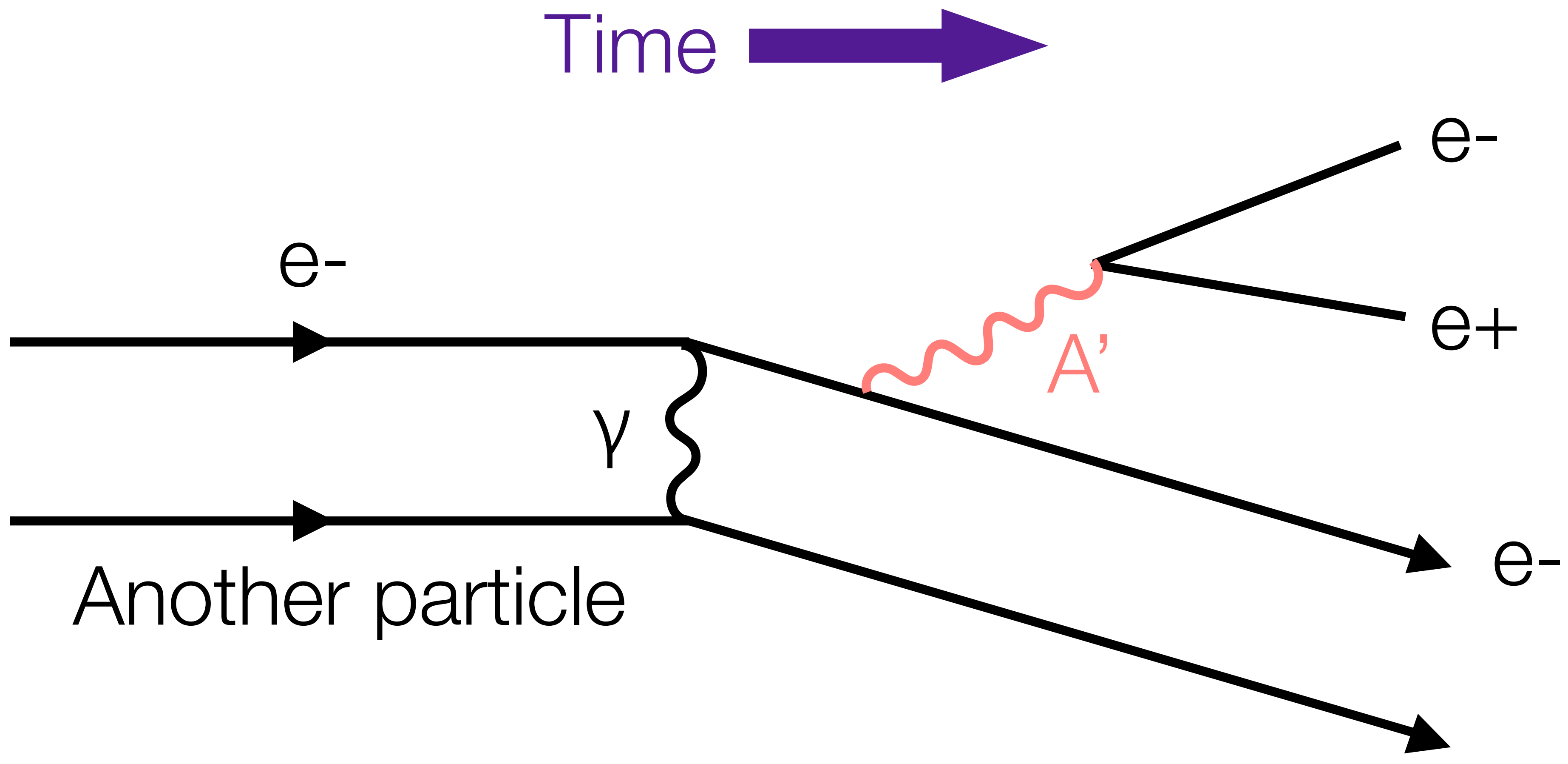
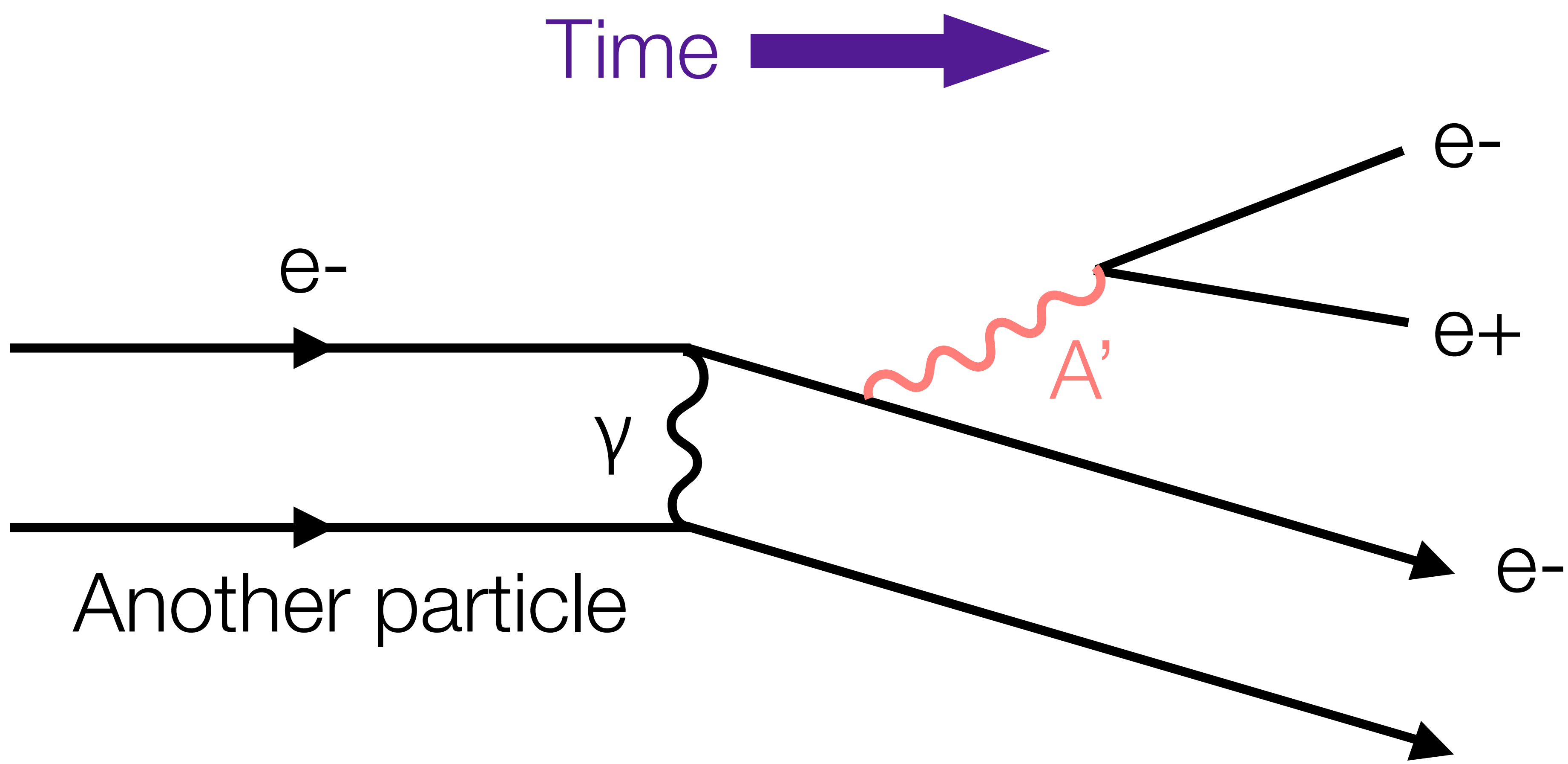


How to tell this apart?

See next slide …

Making dark photons at accelerators



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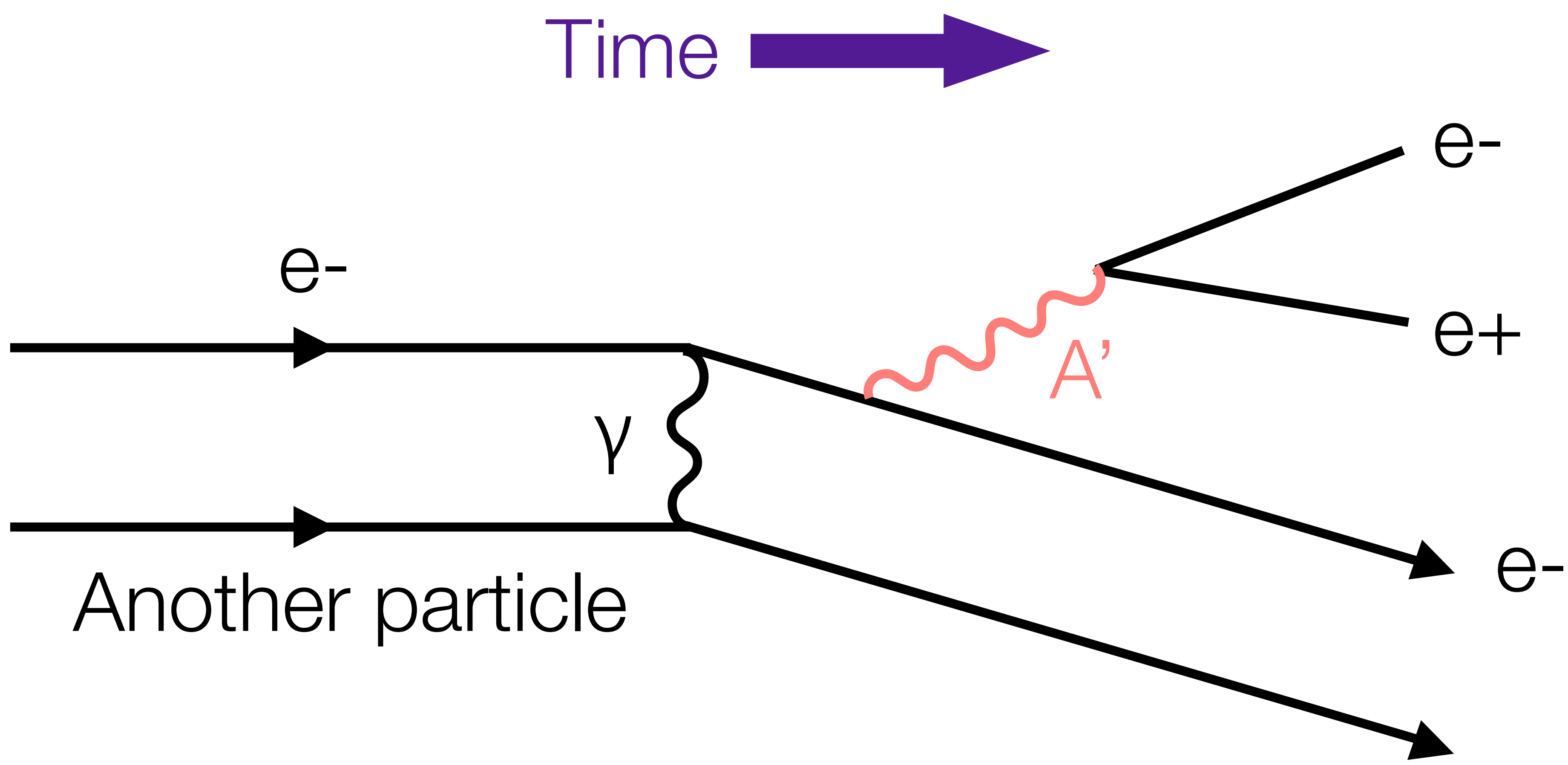
Making dark photons at accelerators



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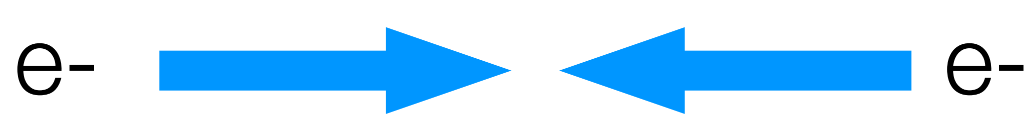

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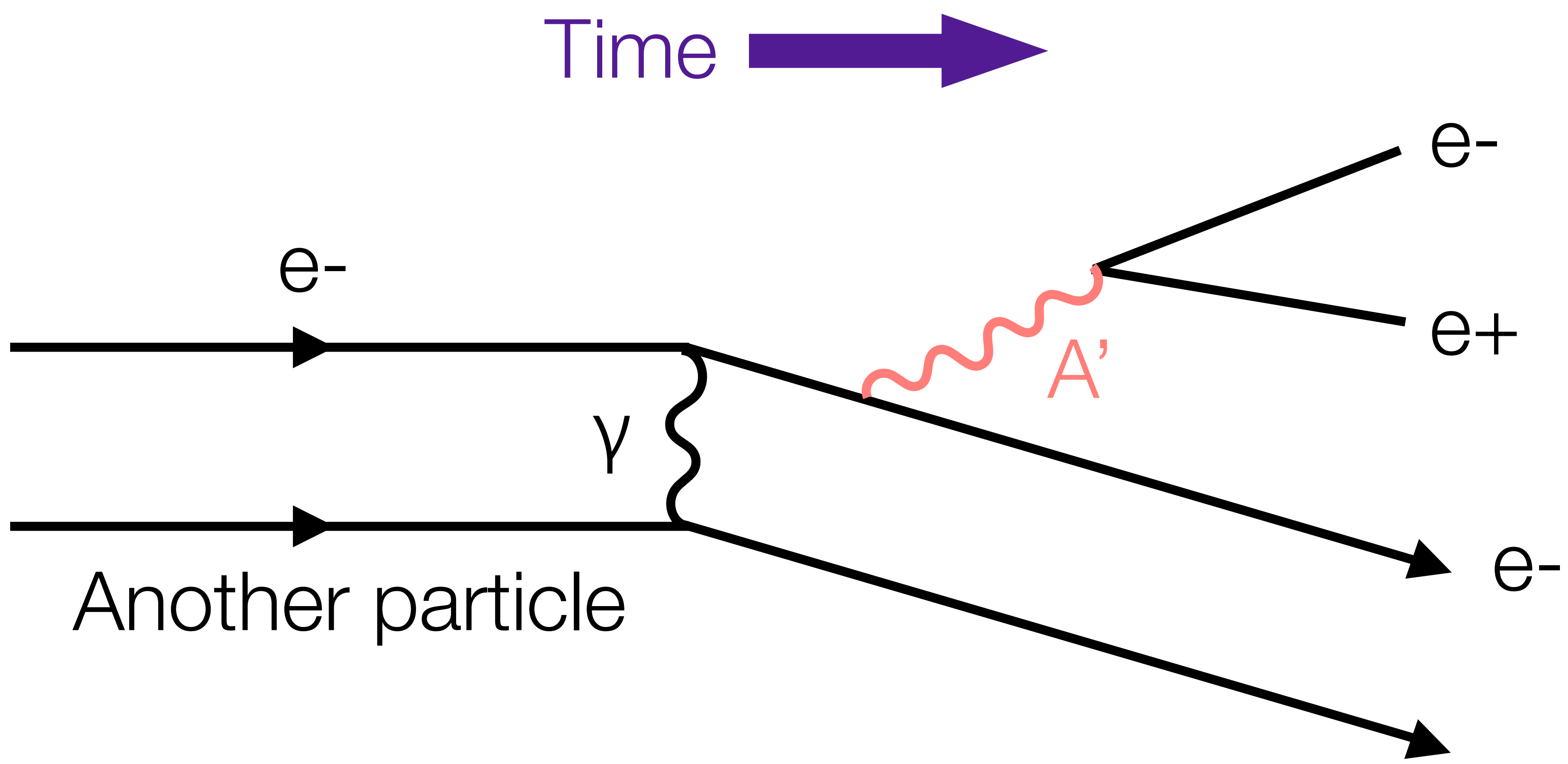

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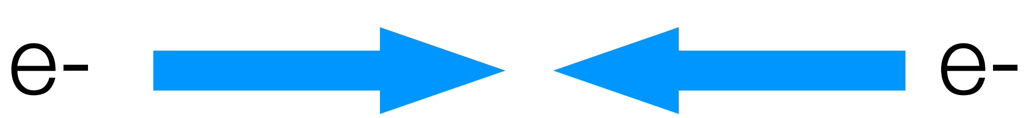
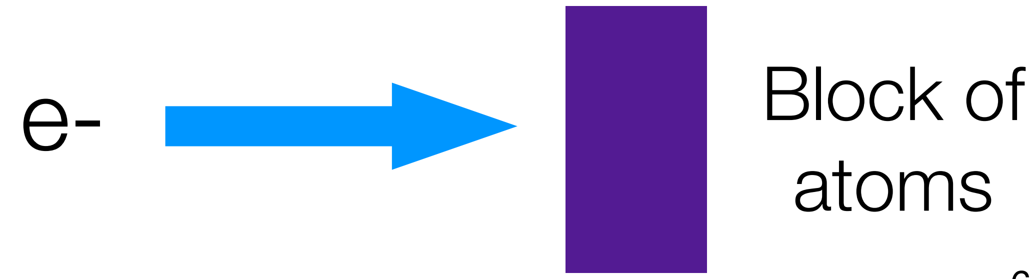
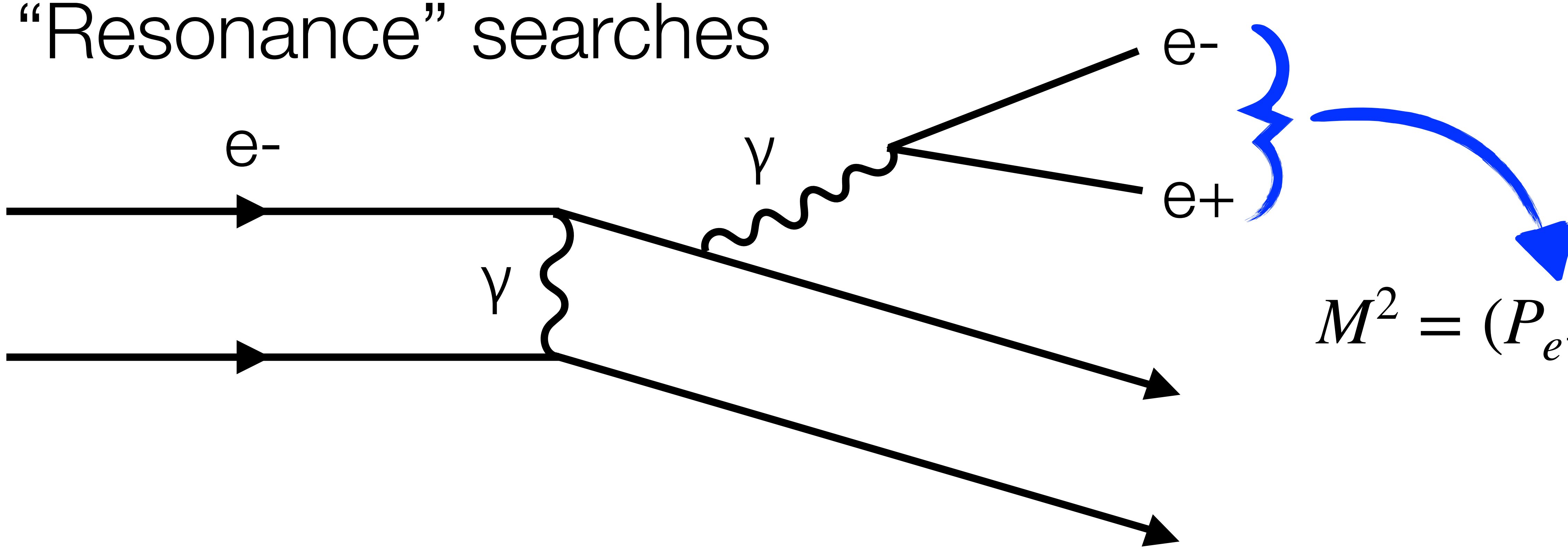


High interaction rate:



“Resonance” searches



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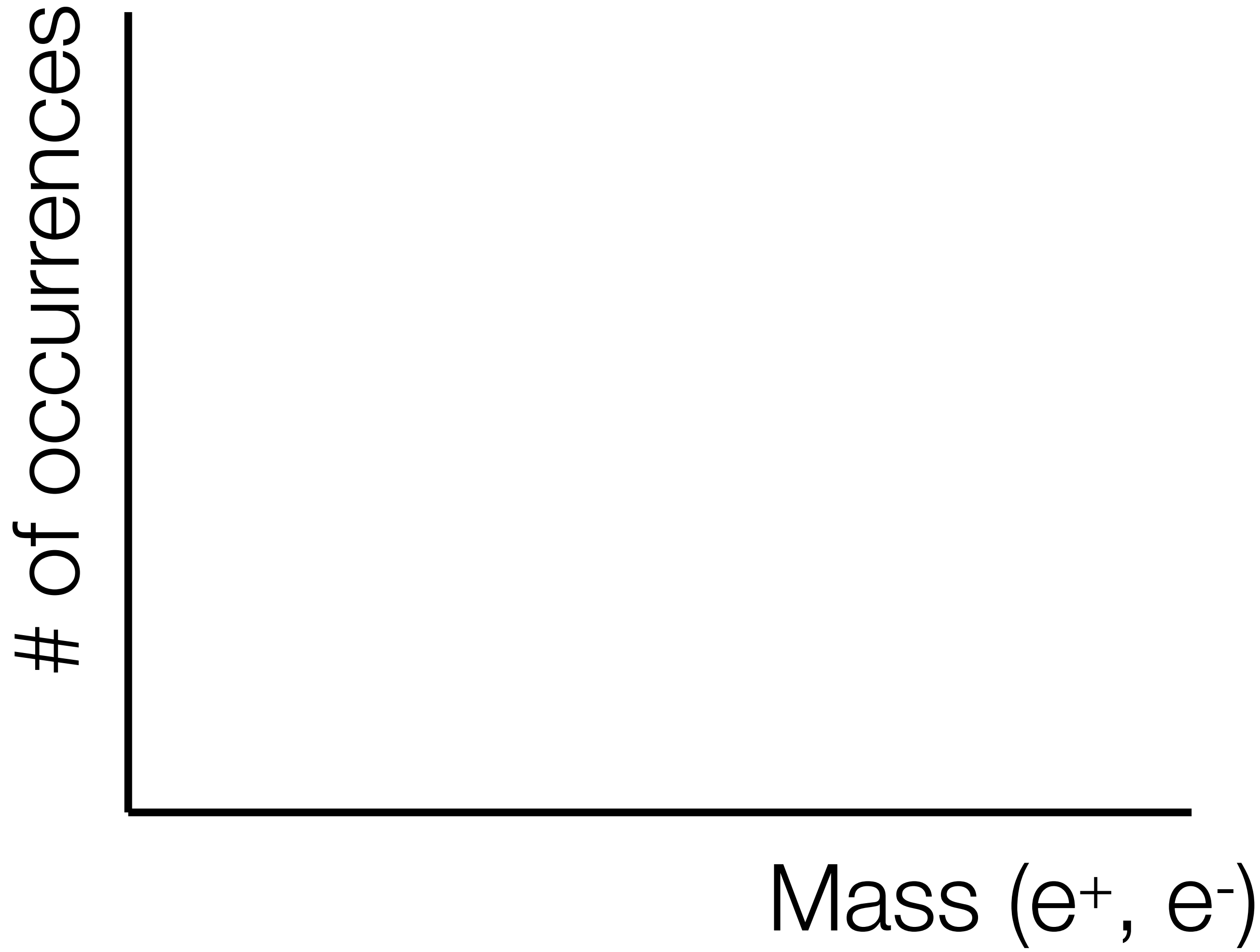

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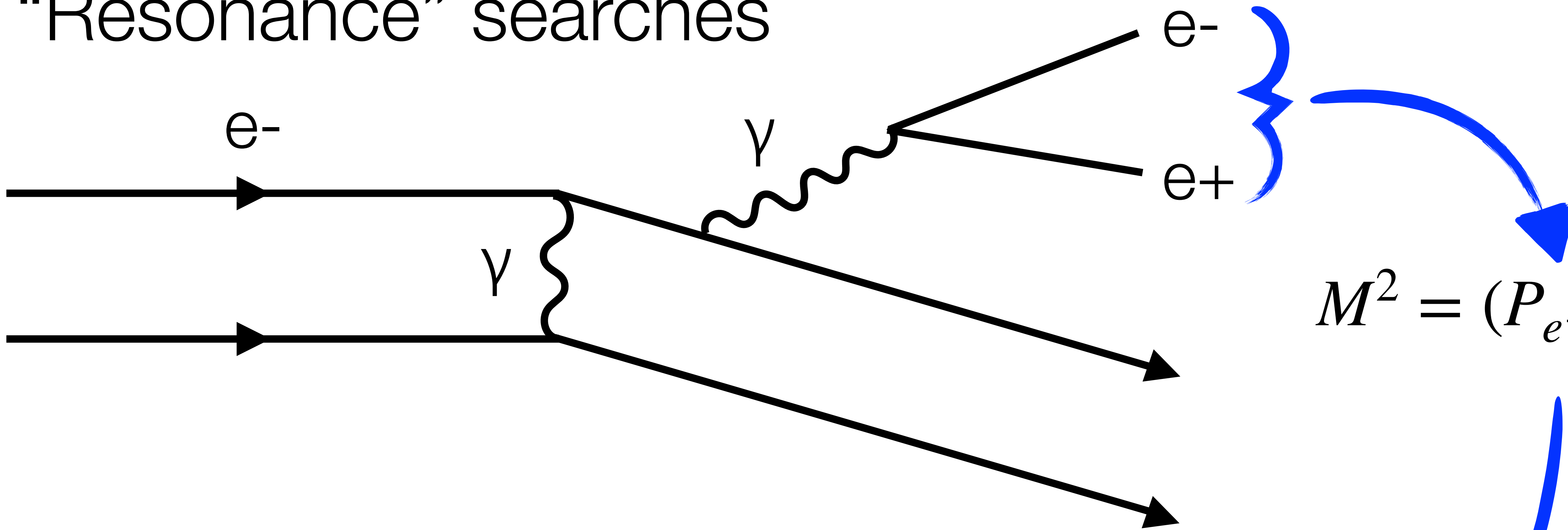

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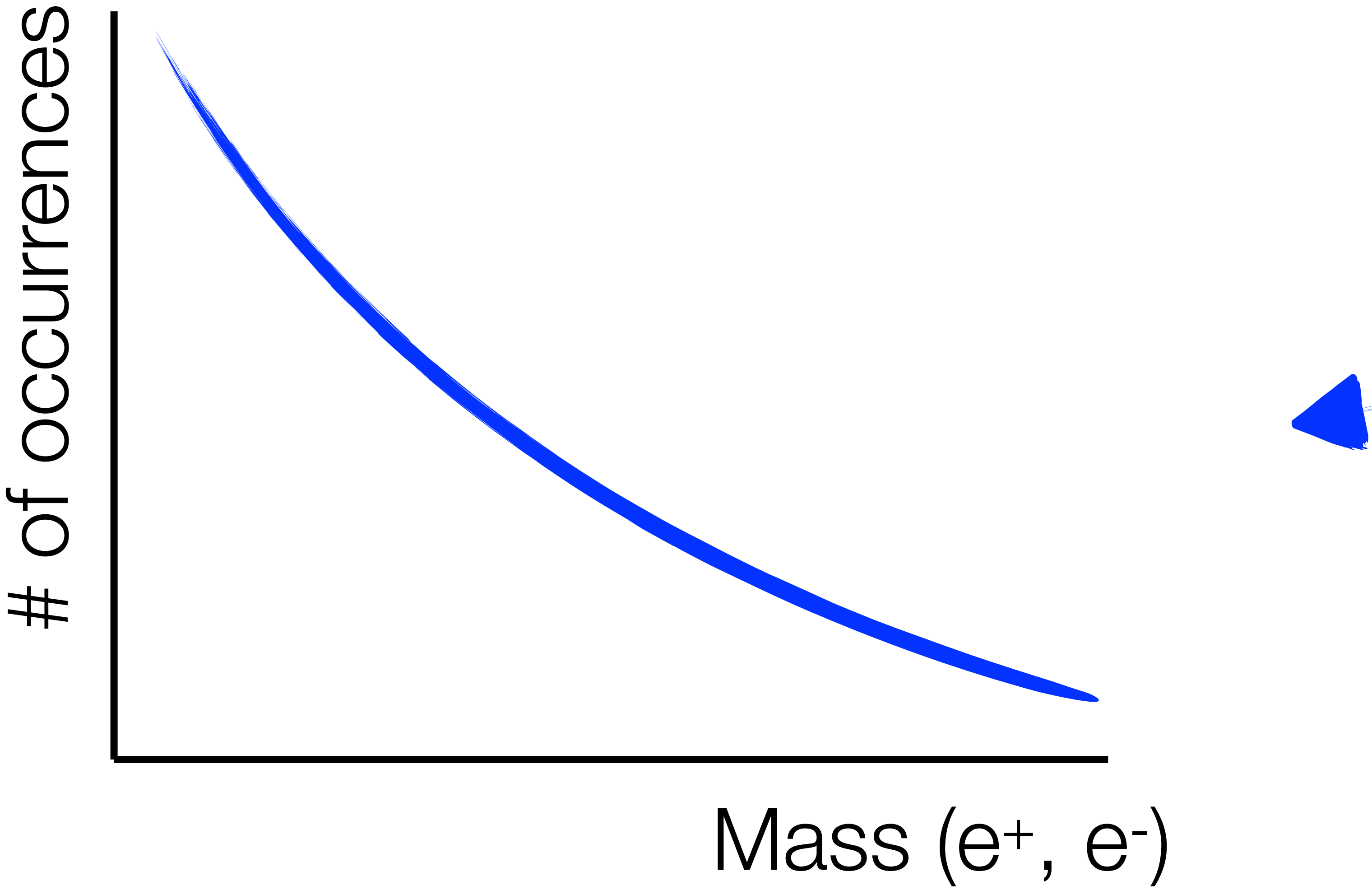

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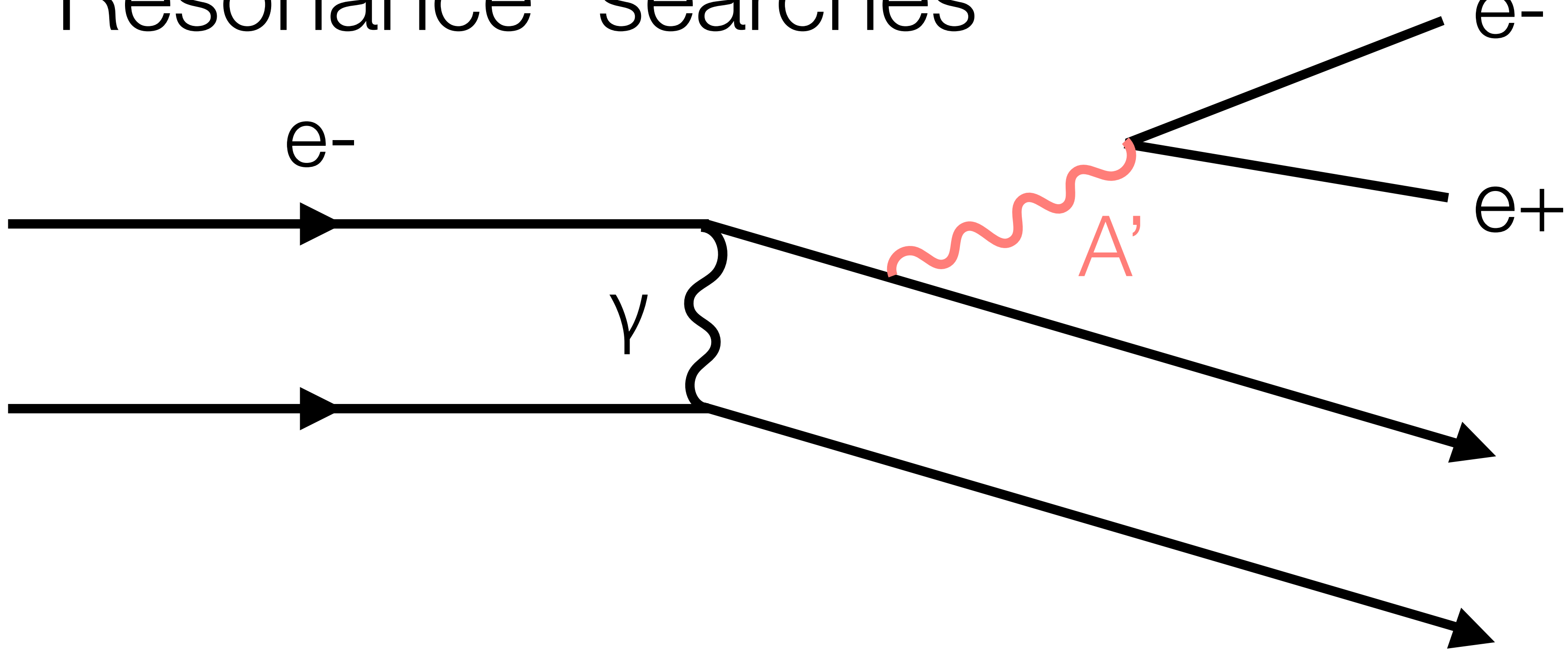

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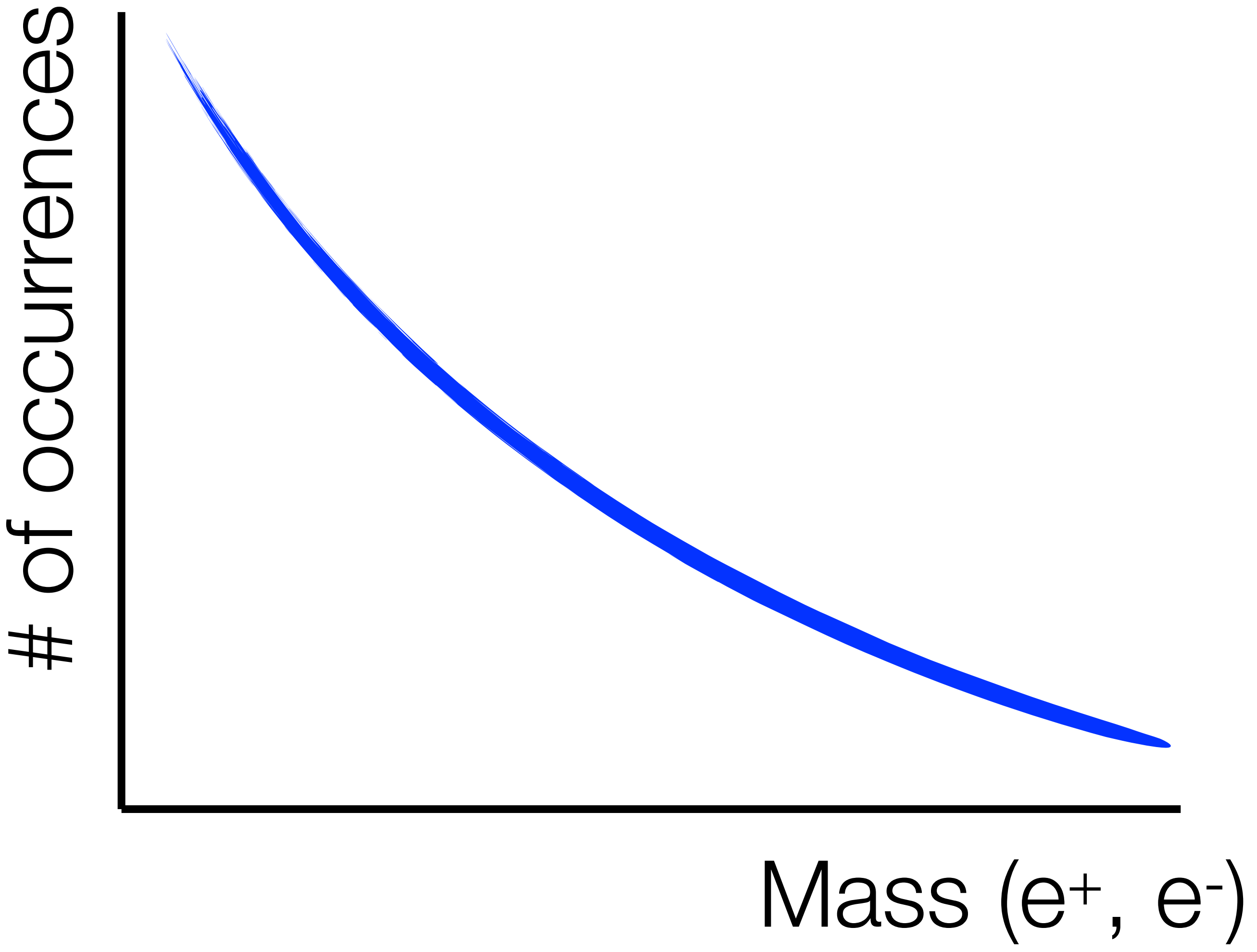

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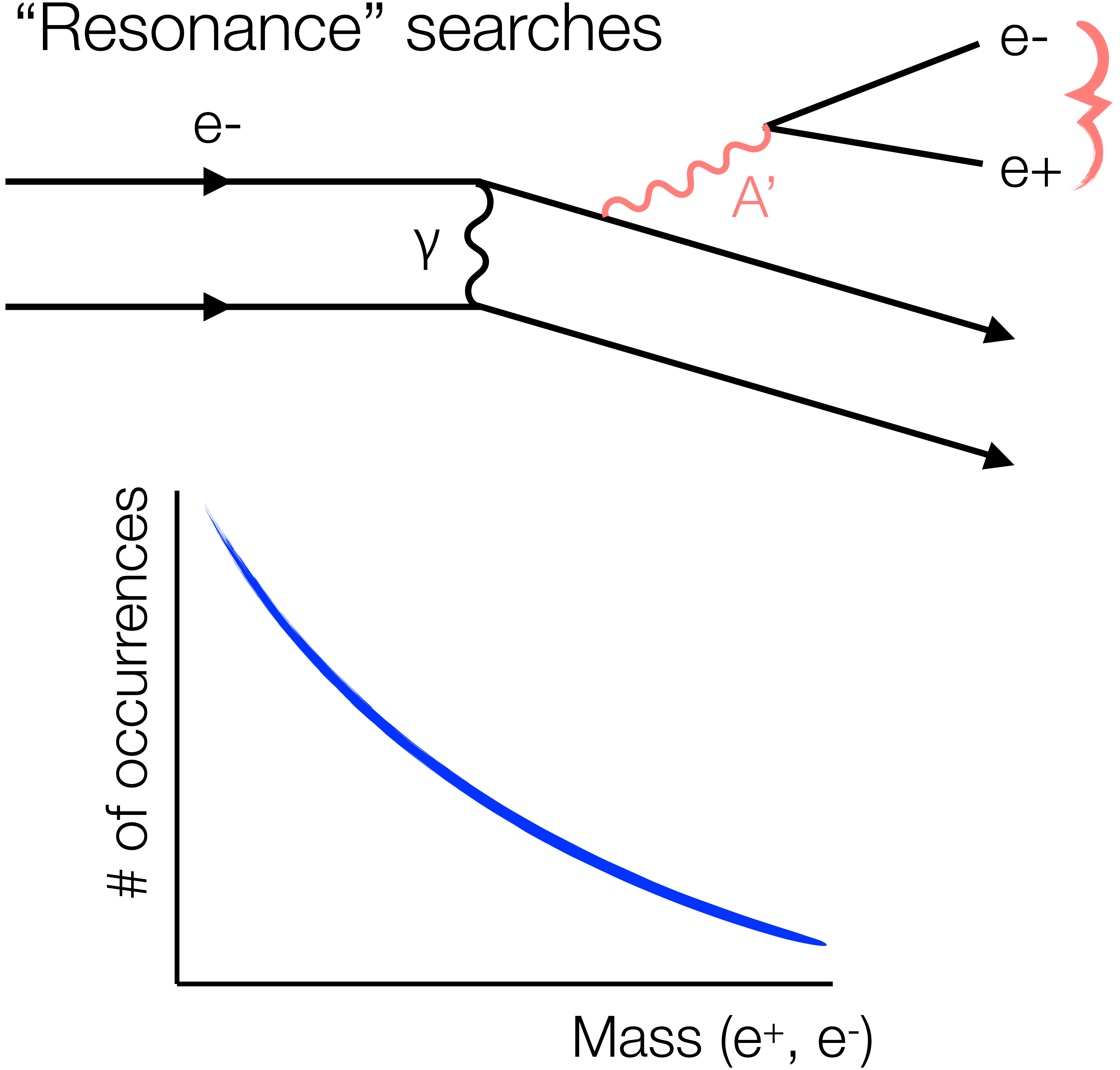

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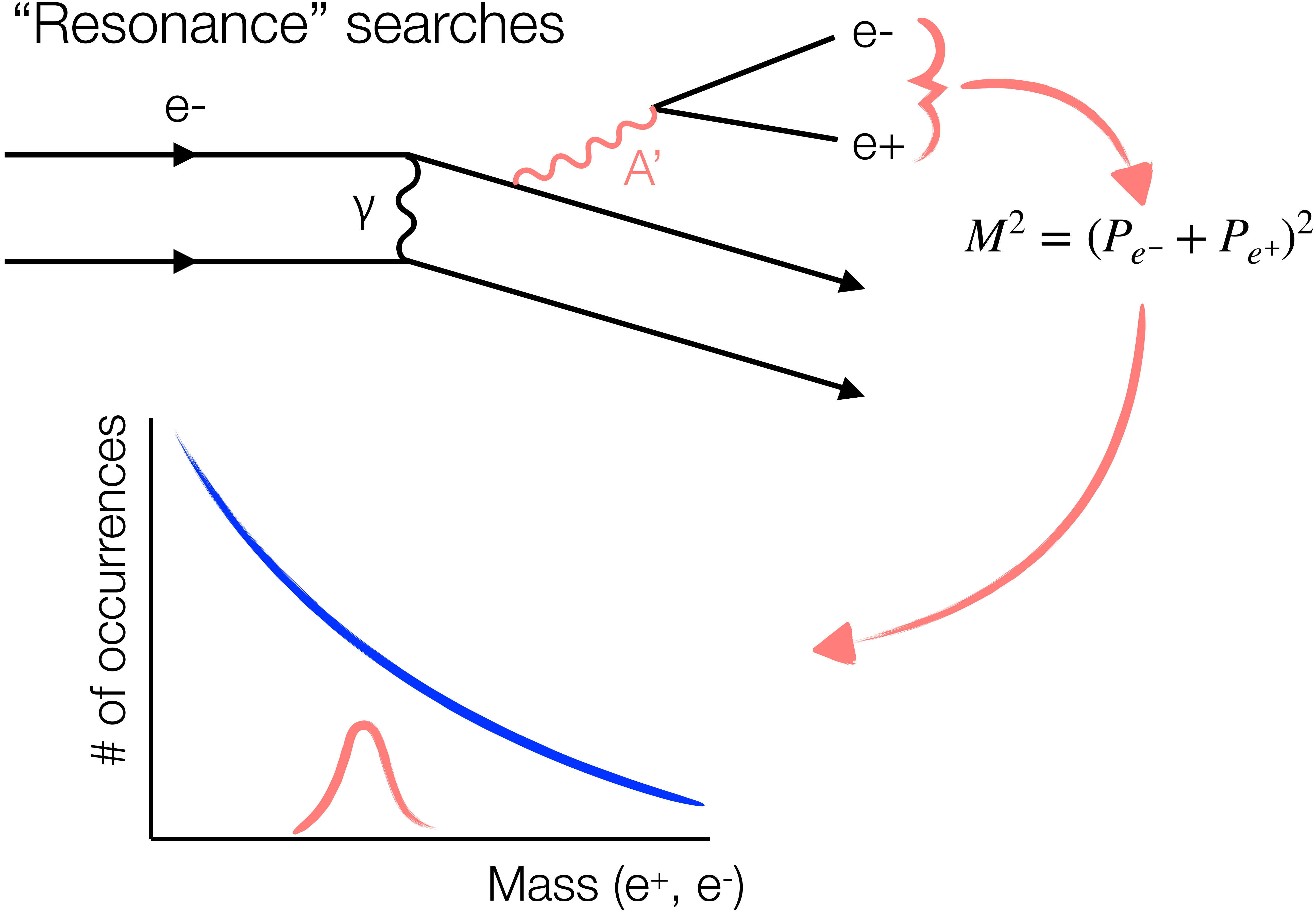

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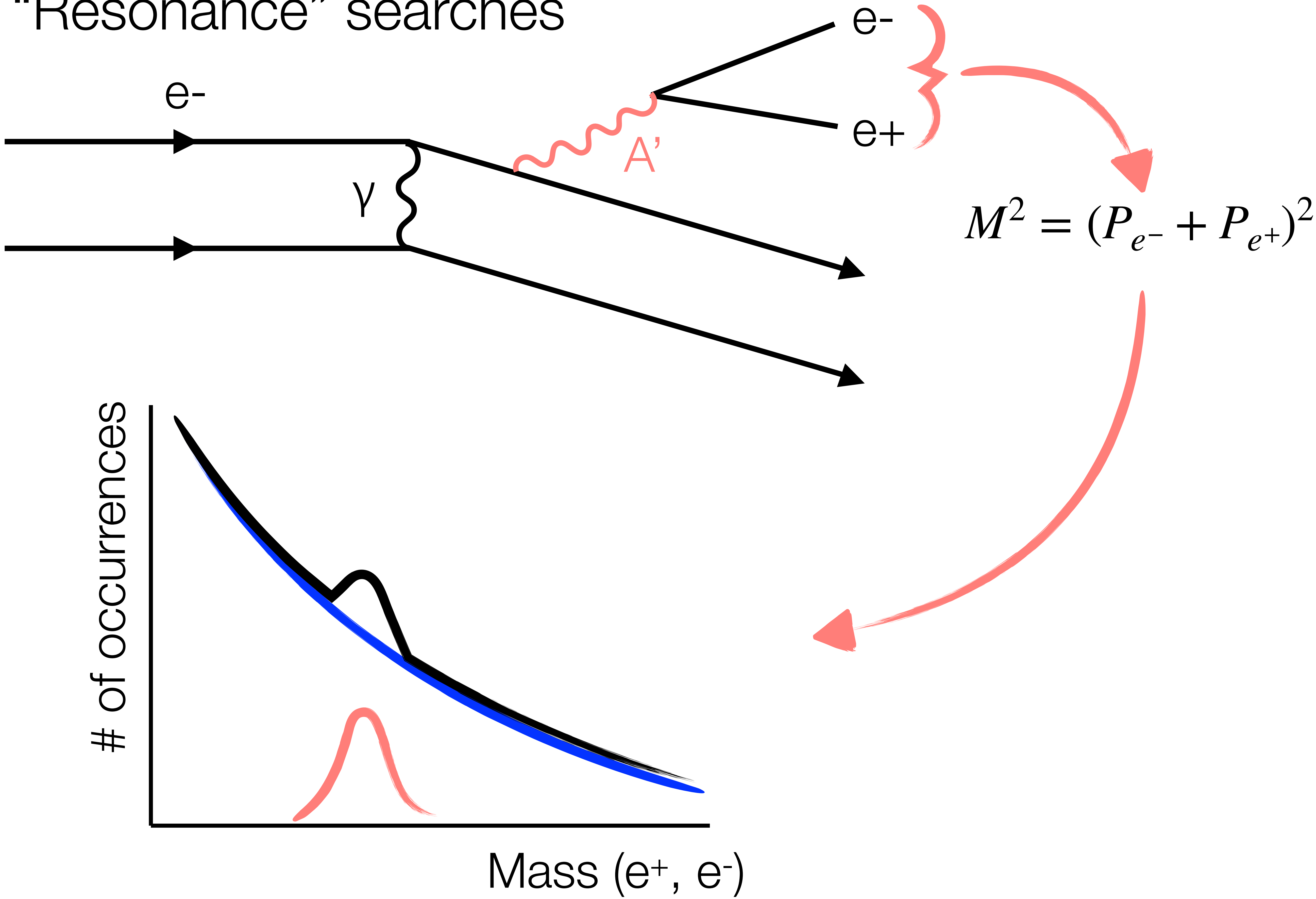

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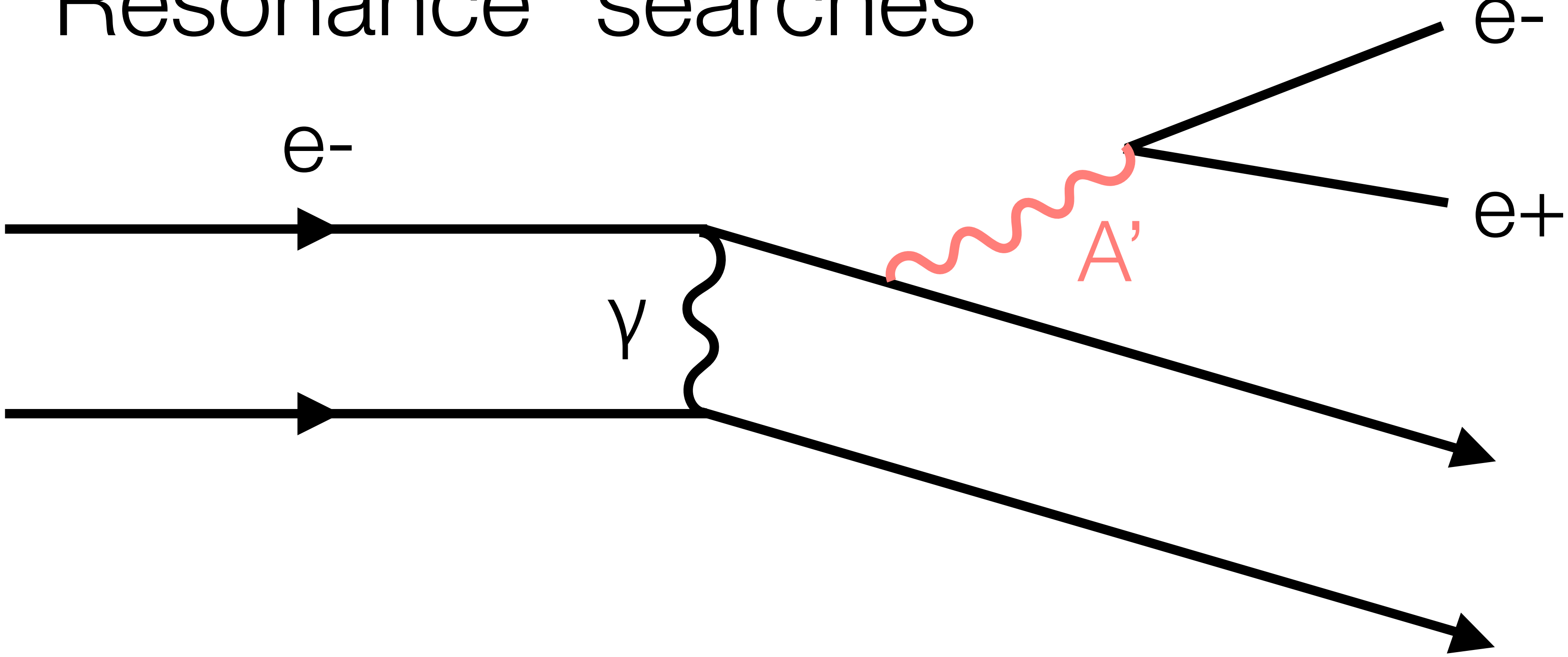

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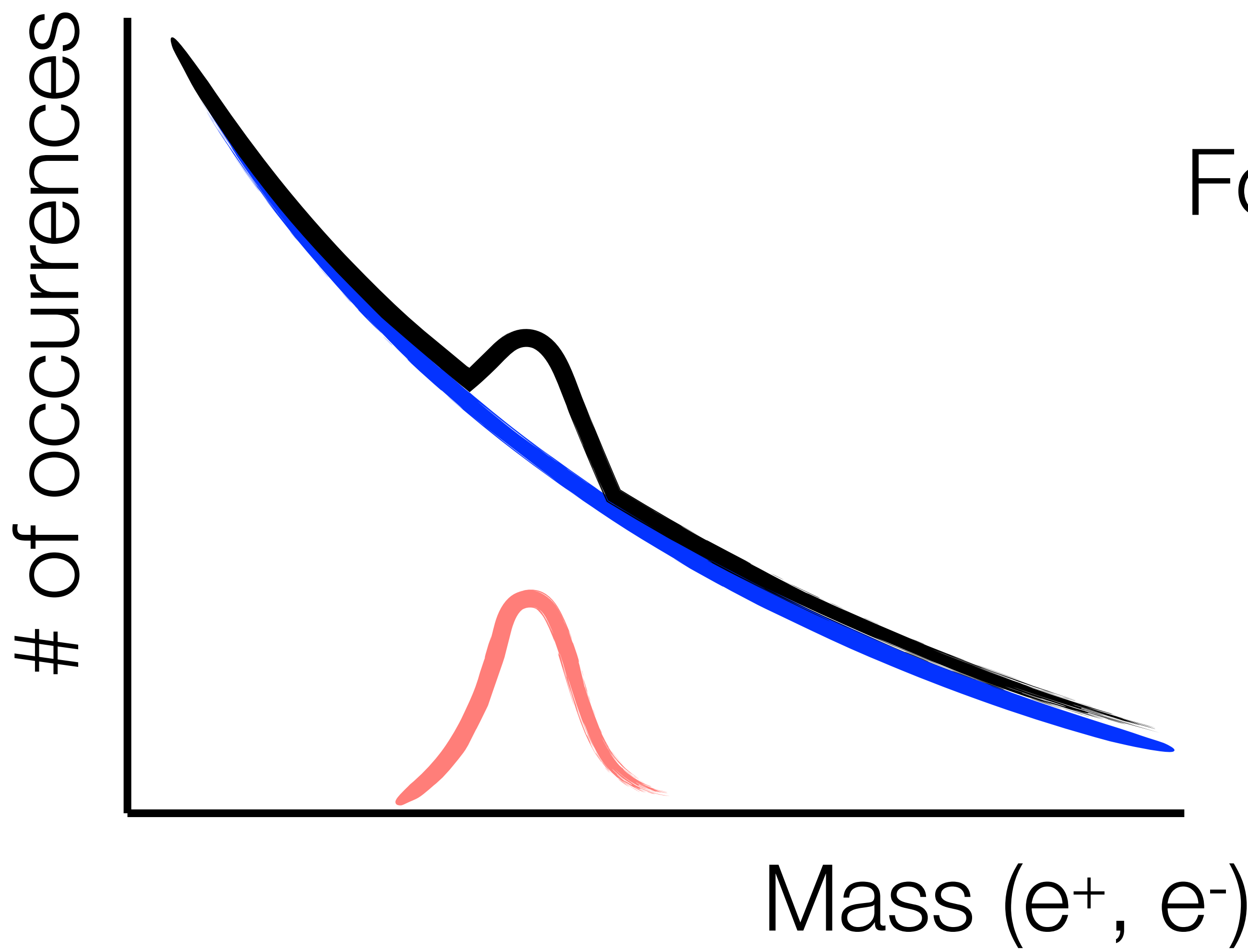
For any given event, **no way to tell** if we made γ or A’



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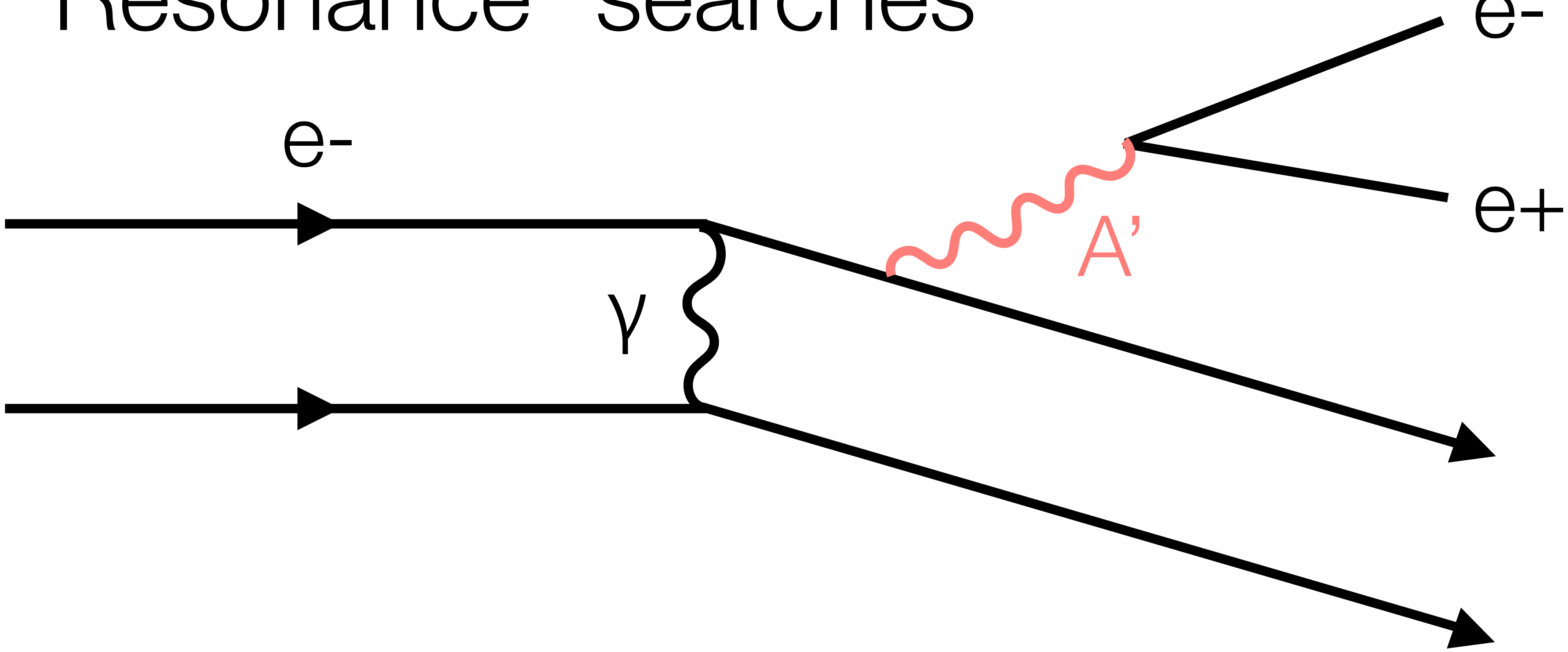

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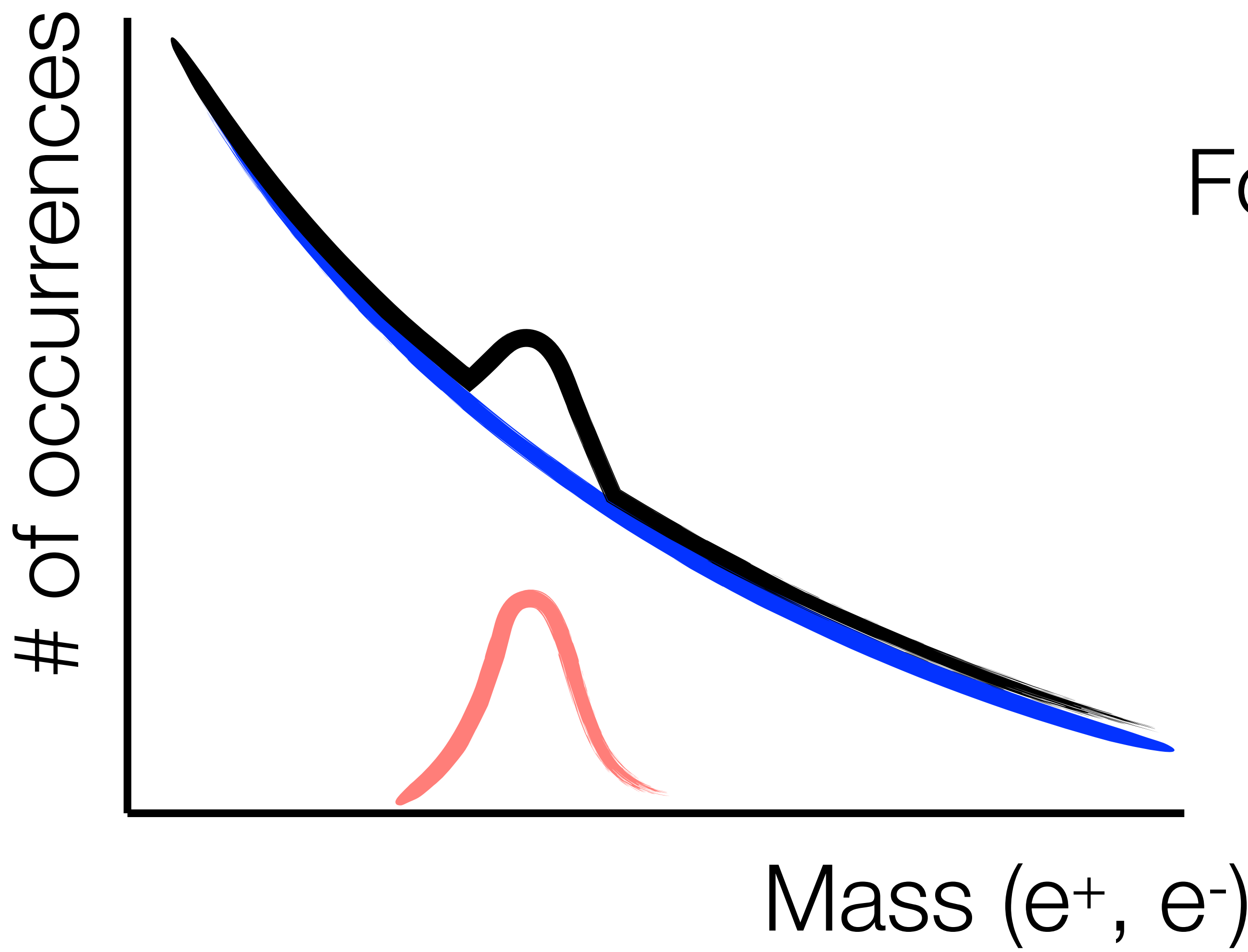
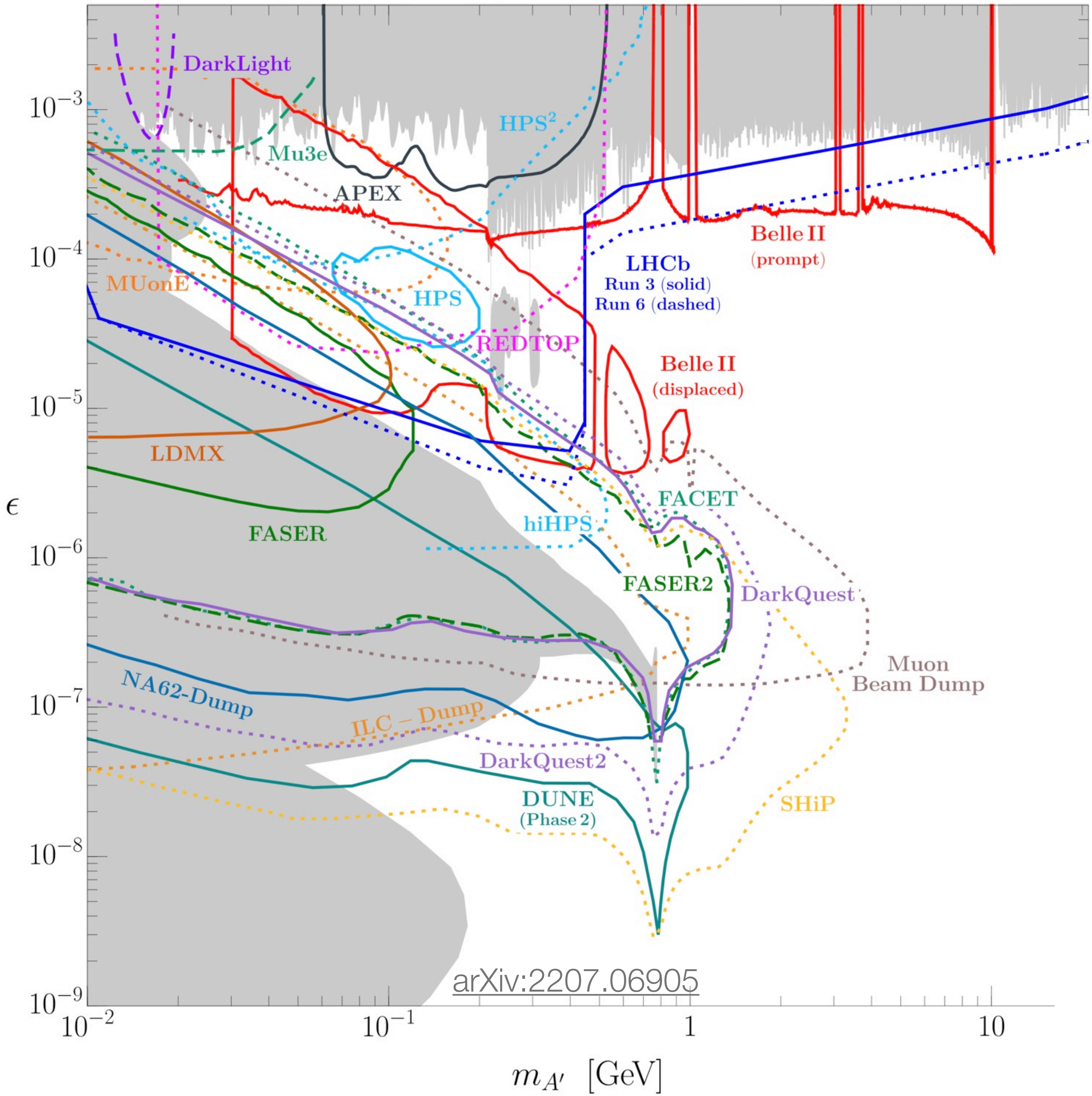


For any given event, **no way to tell** if we made γ or A’

But with enough data, statistics can show something interesting!



DarkLight
Mu3e
APEX
HPS^2
Belle II
(prompt)
LHCb
Run 3 (solid)
Run 6 (dashed)
MUonE
HPS
REDTOP
Belle II
(displaced)
LDMX
FACET
FASER
hiHPS
FASER2
DarkQuest
Muon
Beam Dump
NA62-Dump
ILC – Dump
DarkQuest2
DUNE
(Phase 2)
SHiP
arXiv:2207.06905
ϵ
$m_{A'}$ [GeV]
10^{-3}
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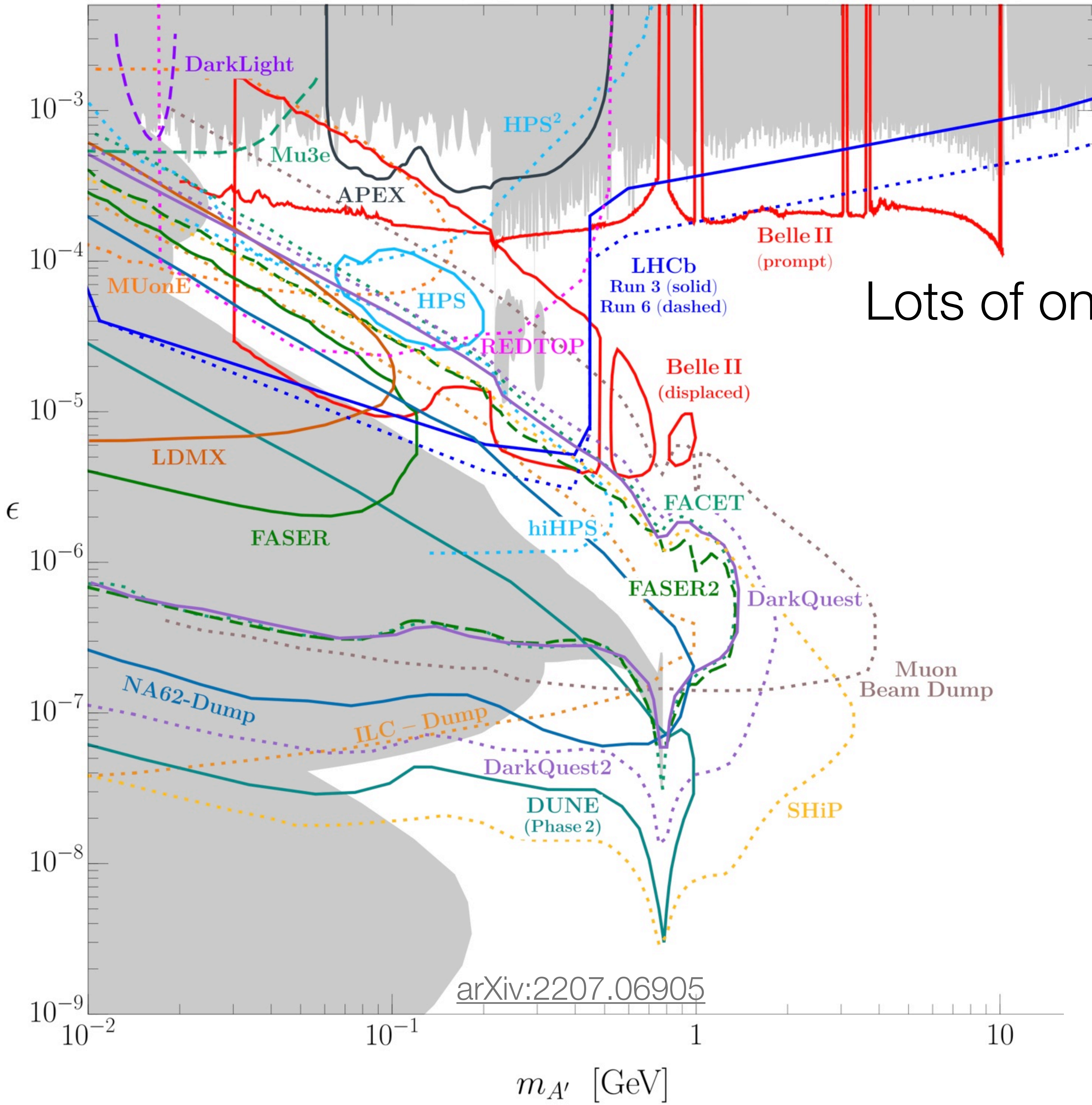
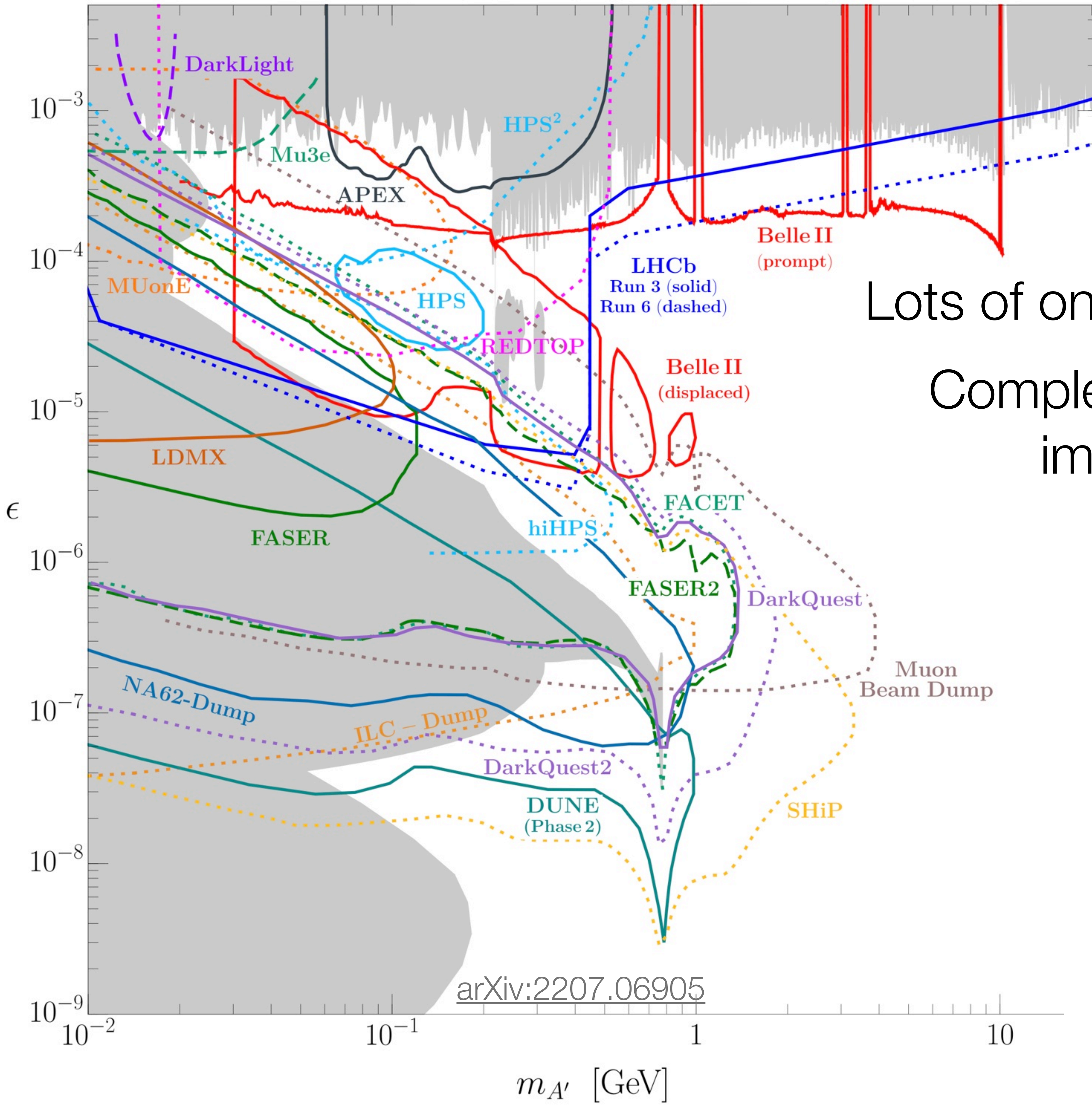
10^{-1}
1
10



Lots of ongoing projects!



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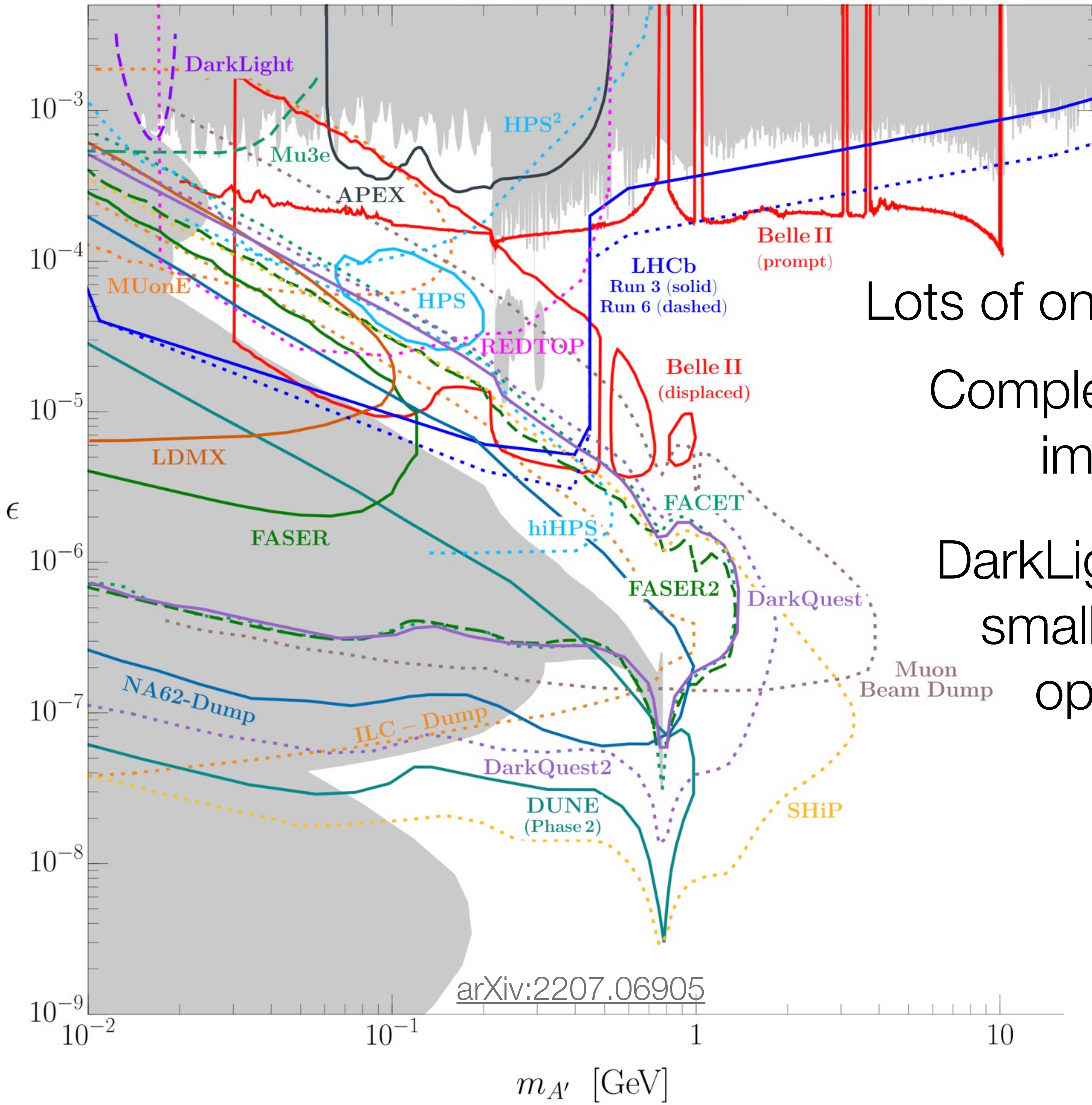
Complementarity is important



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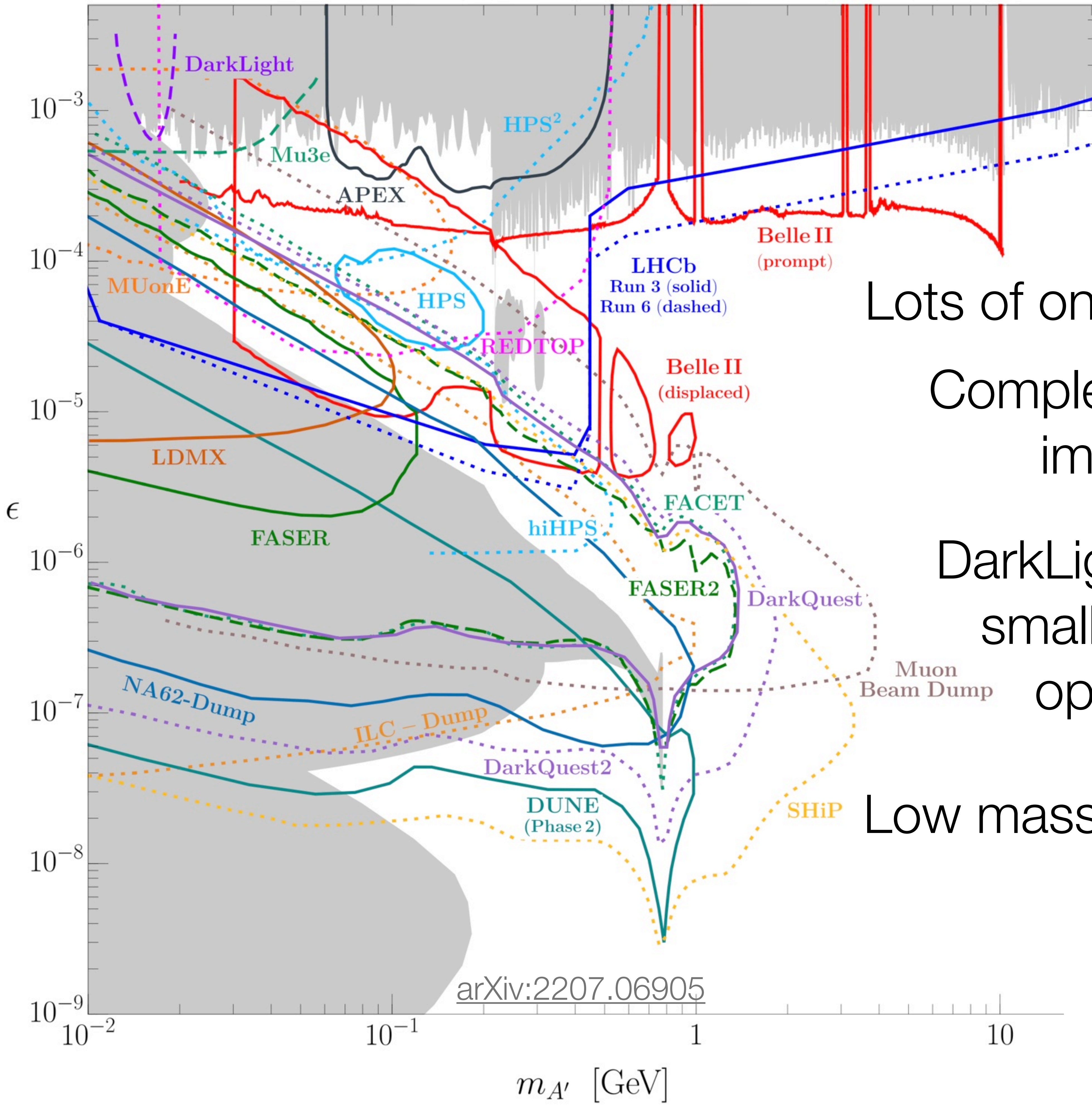
Complementarity is important

DarkLight looking at small window of opportunity



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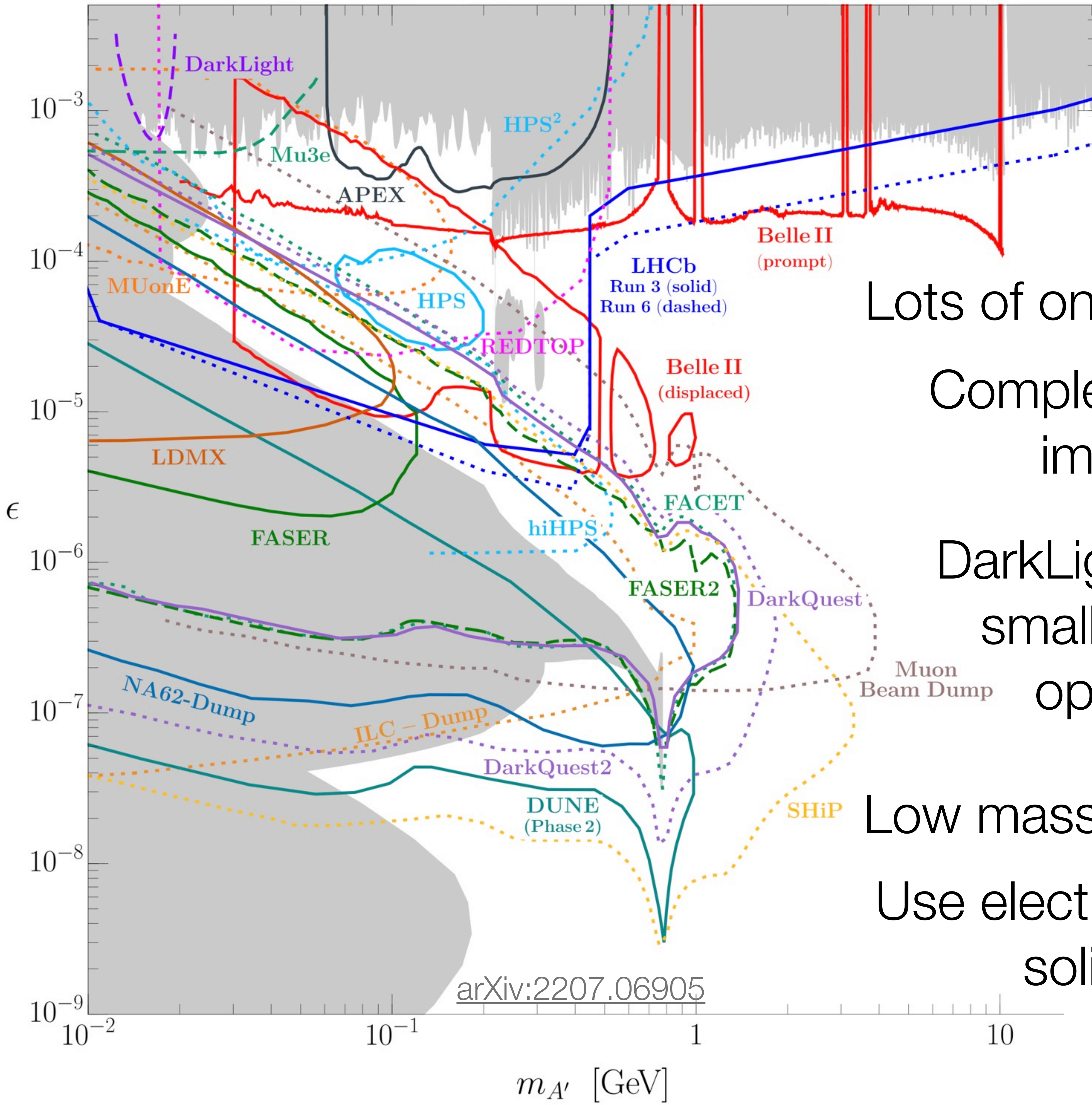

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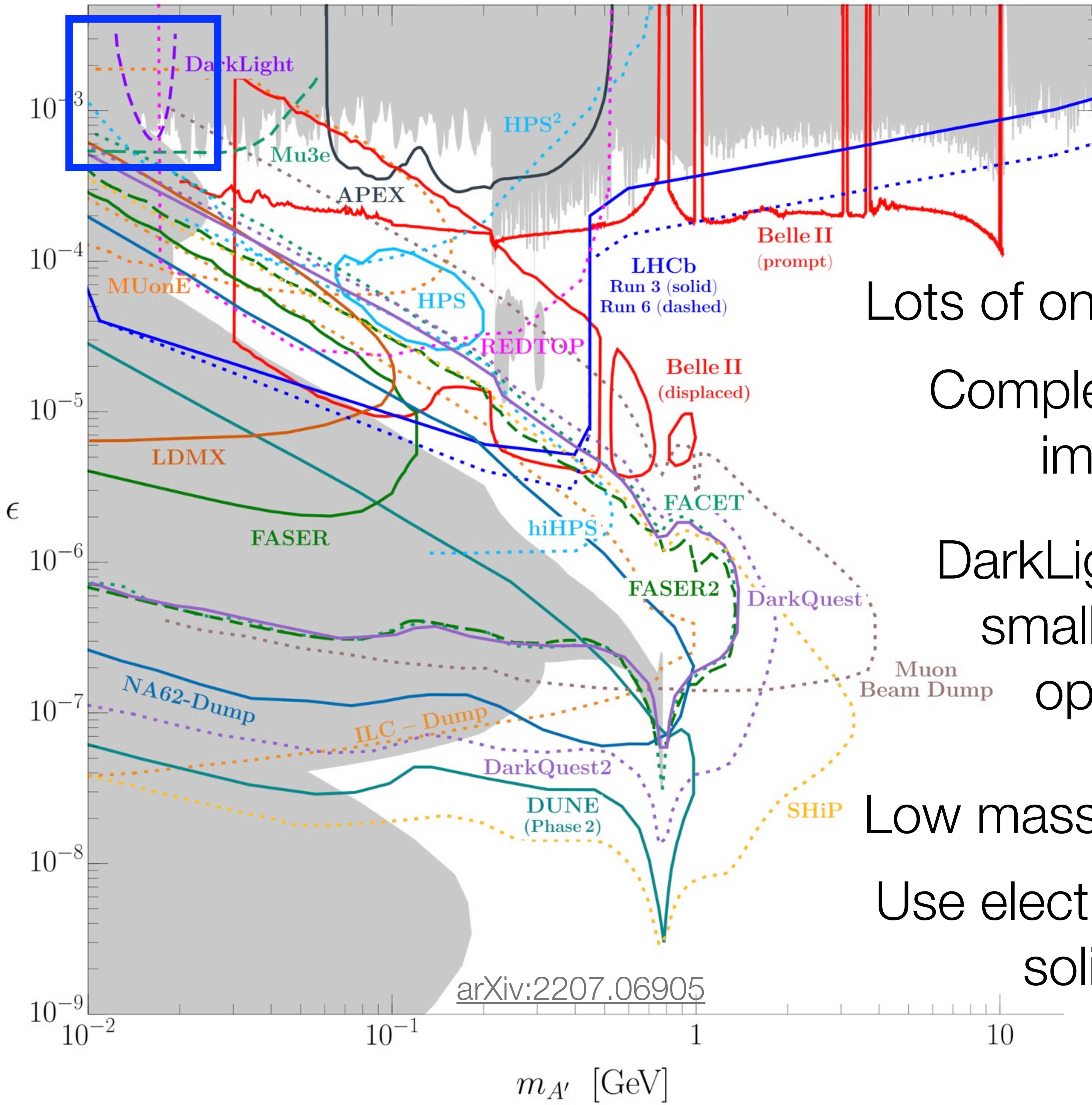
Use electron beam on a solid target



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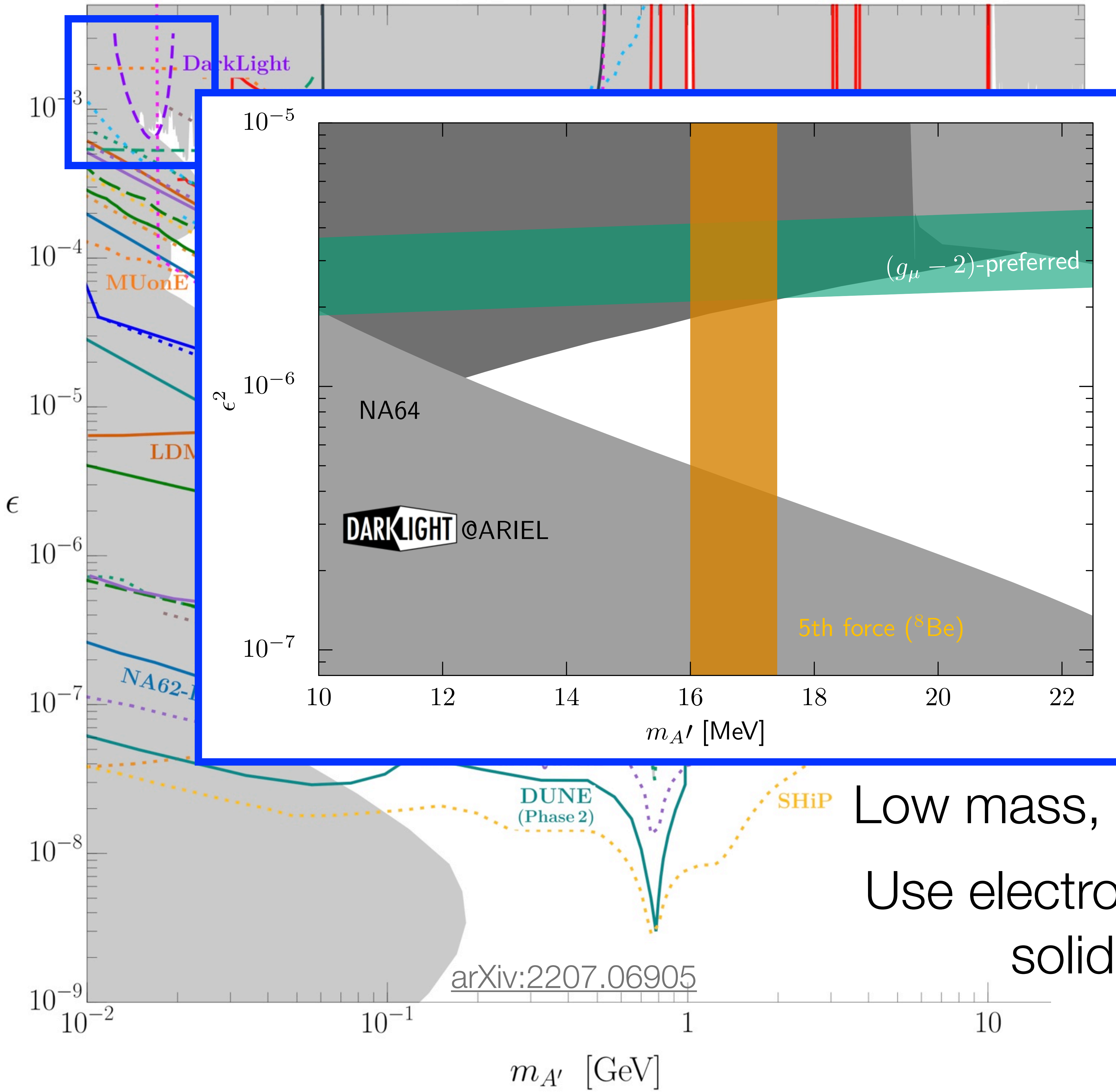

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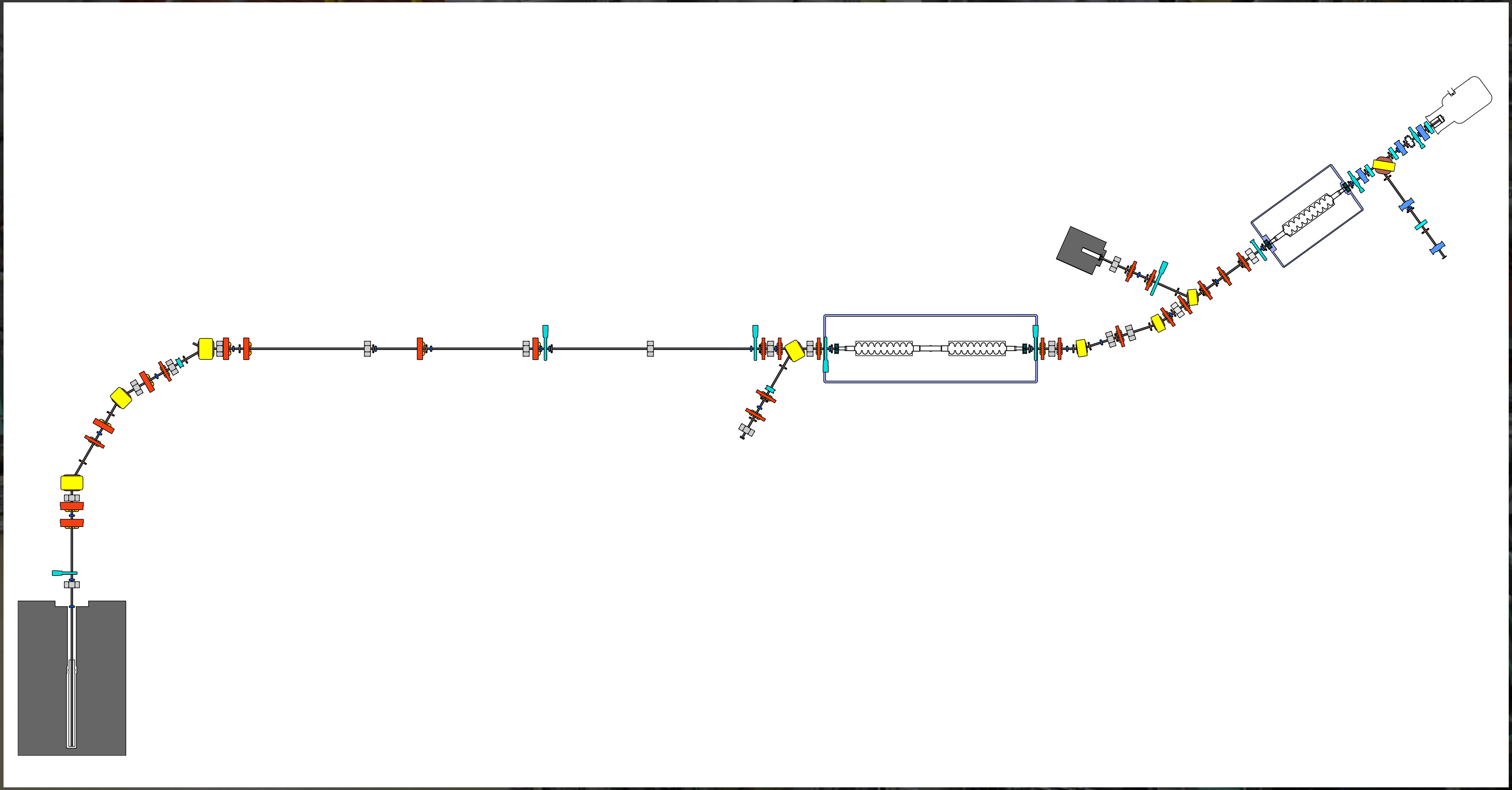
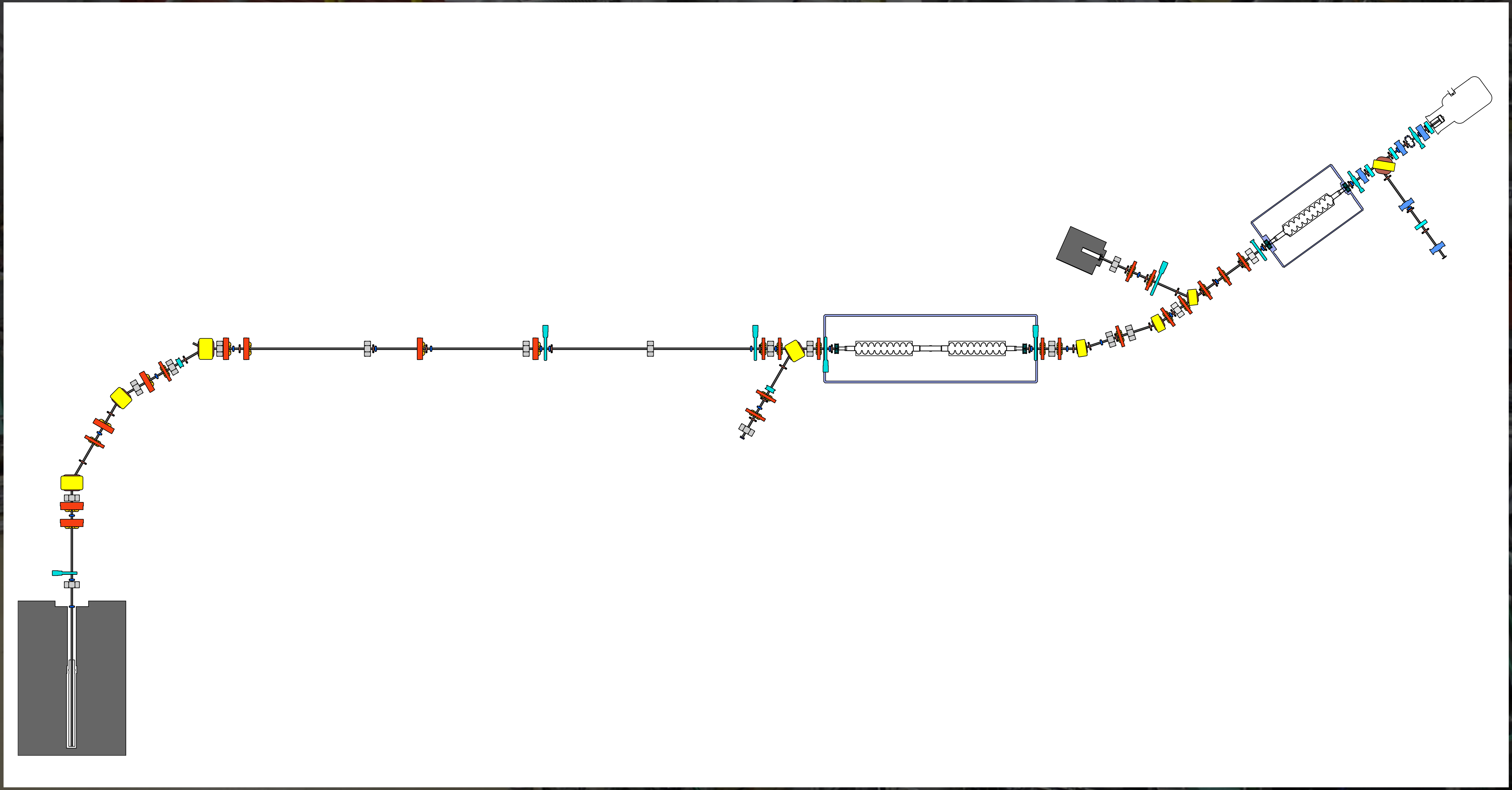
The TRIUMF electron linear accelerator



The TRIUMF electron linear accelerator

Abbreviated “LINAC"



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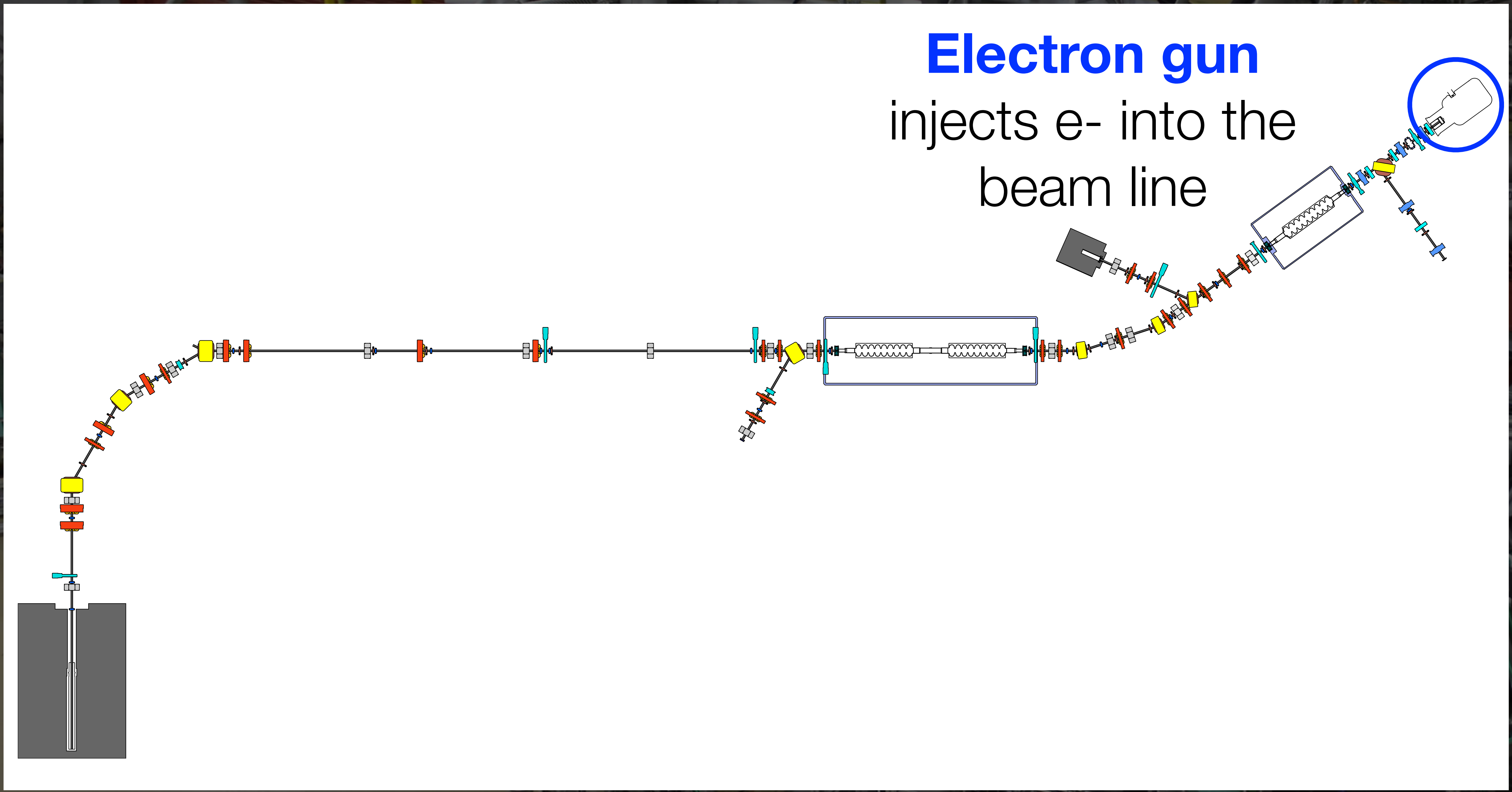

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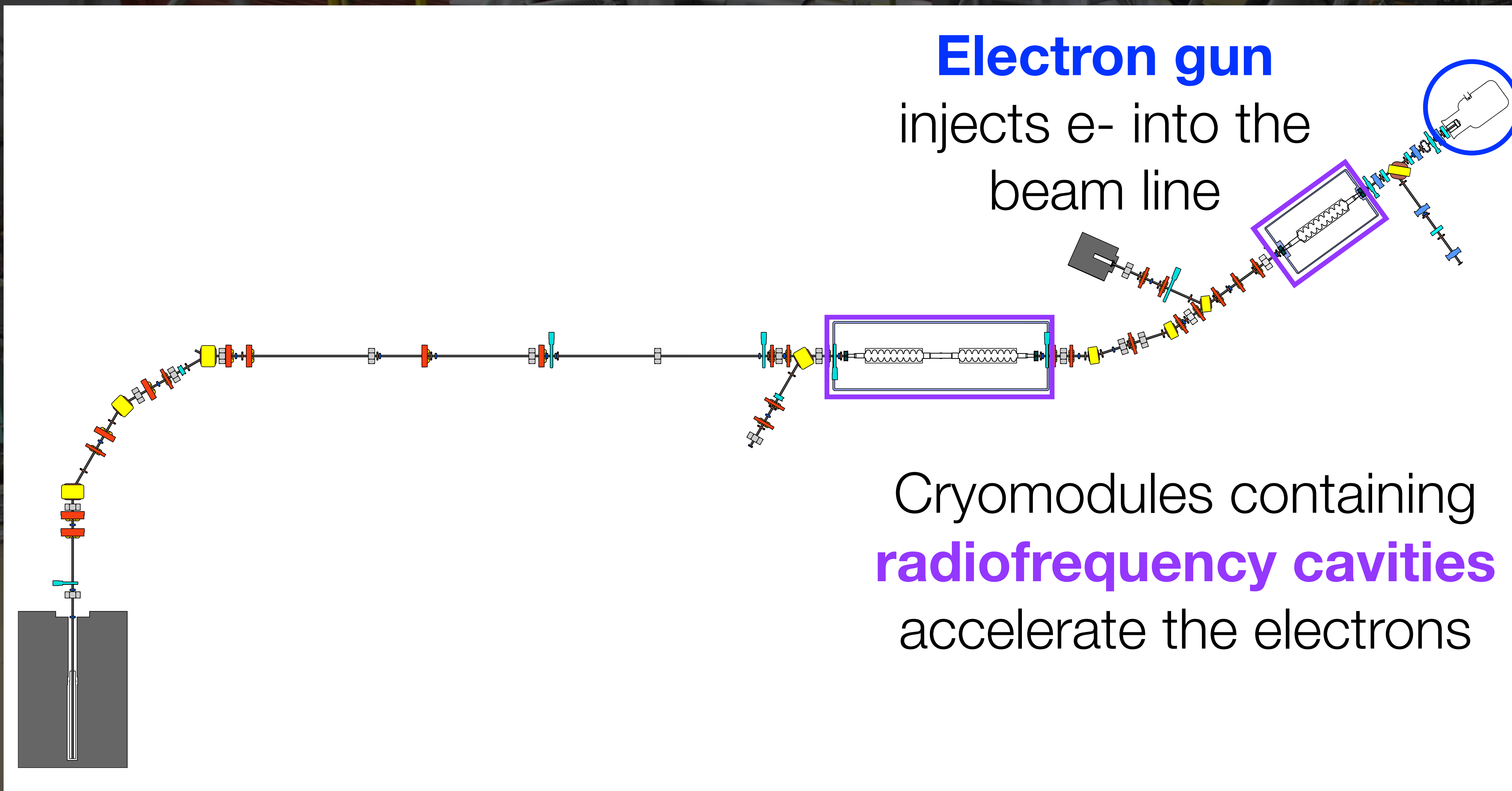

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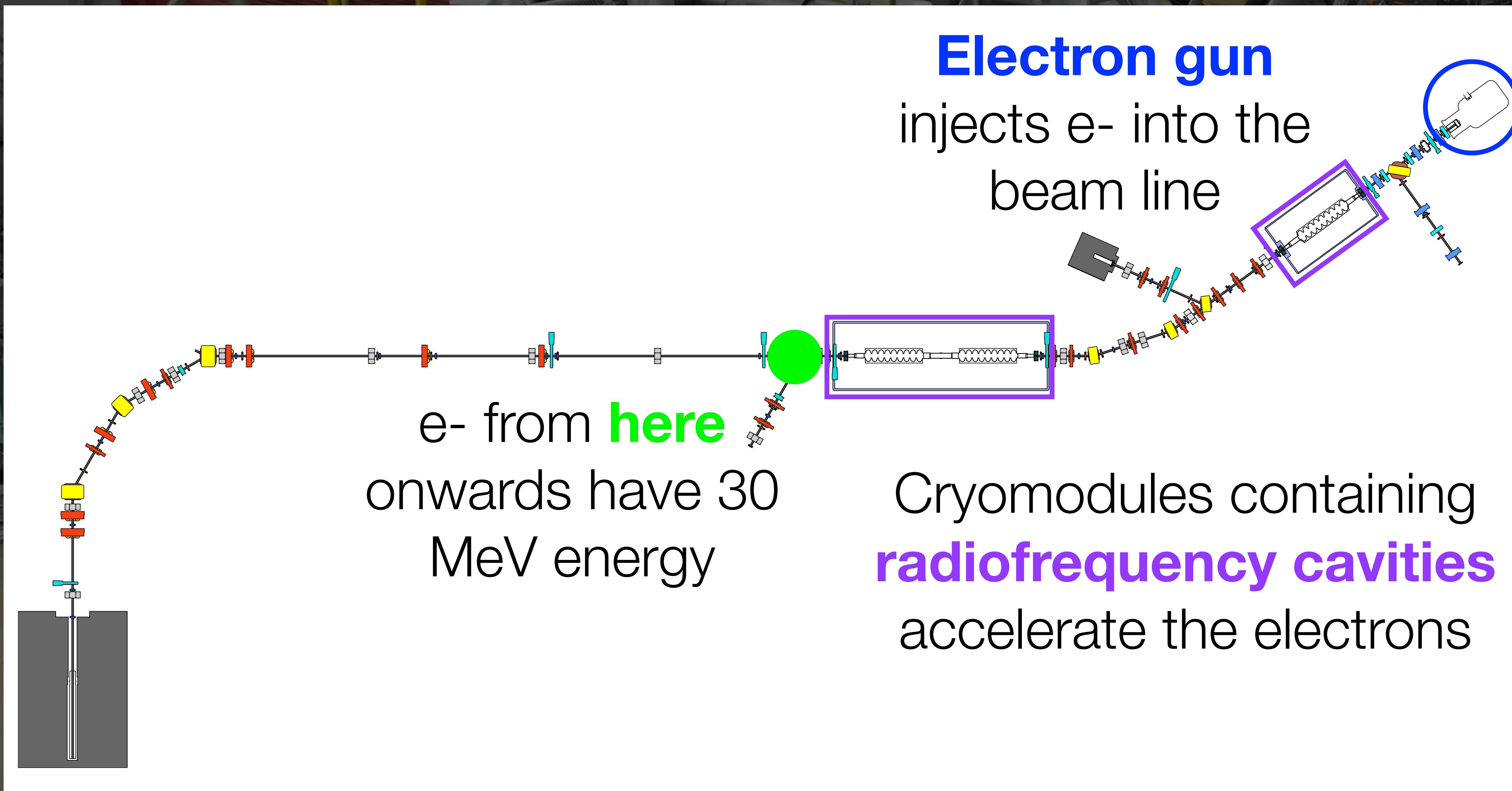

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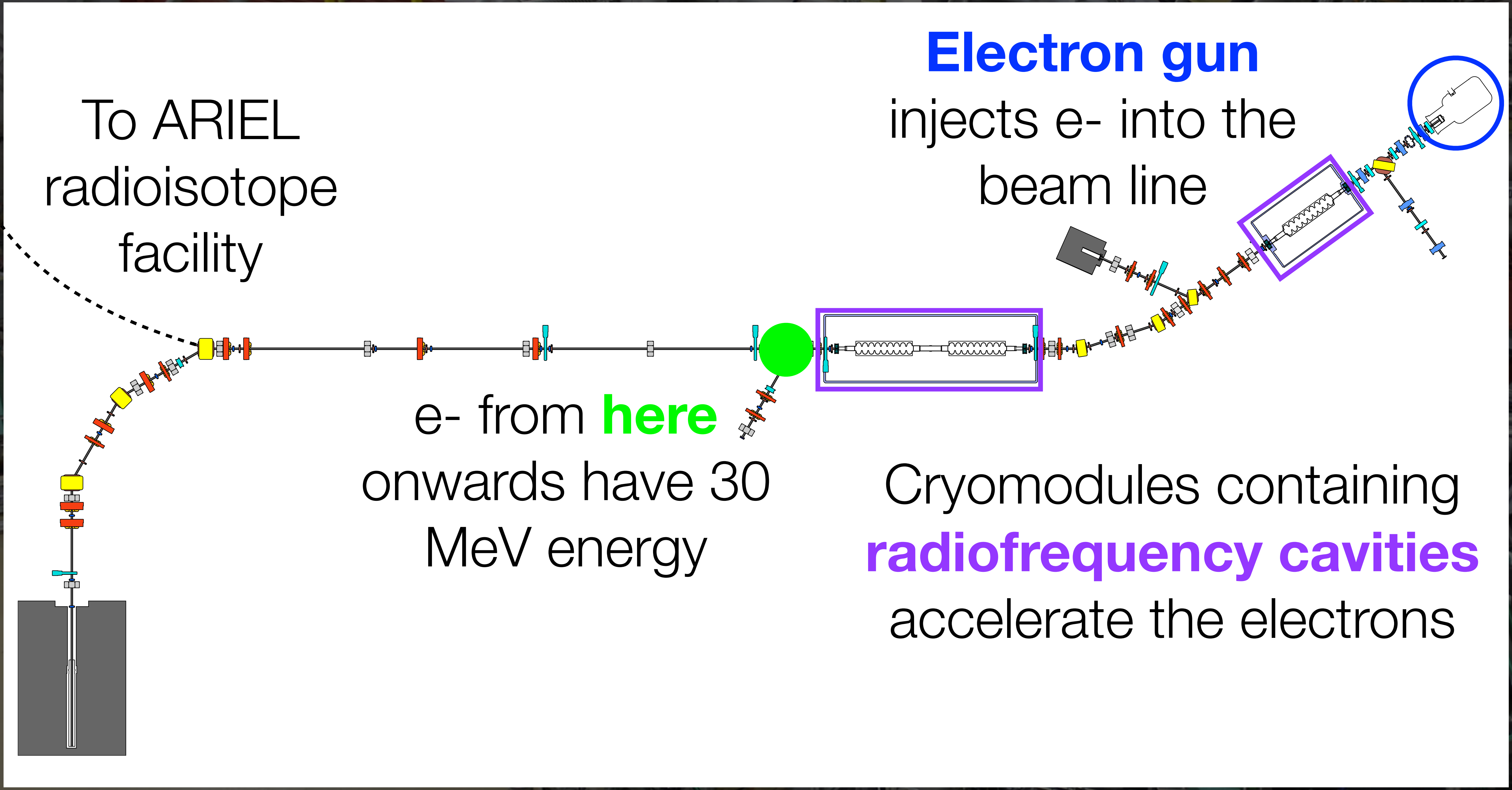
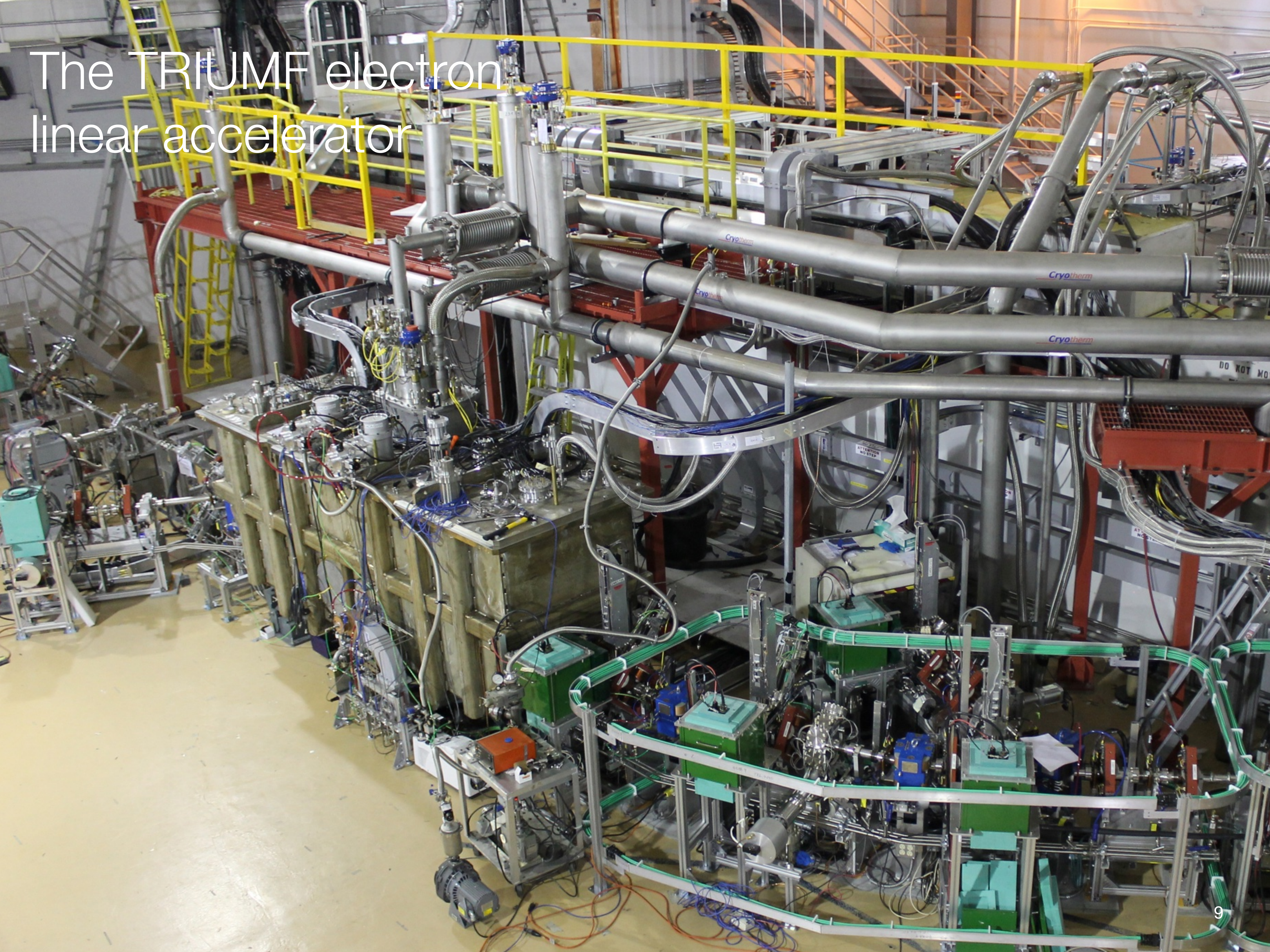


The TRIUMF electron linear accelerator



The e-linac as an experiment site

High power

E-linac designed to produce a 100 kW e- beam

- Enough power to run a restaurant!

We'll operate at 10 kW

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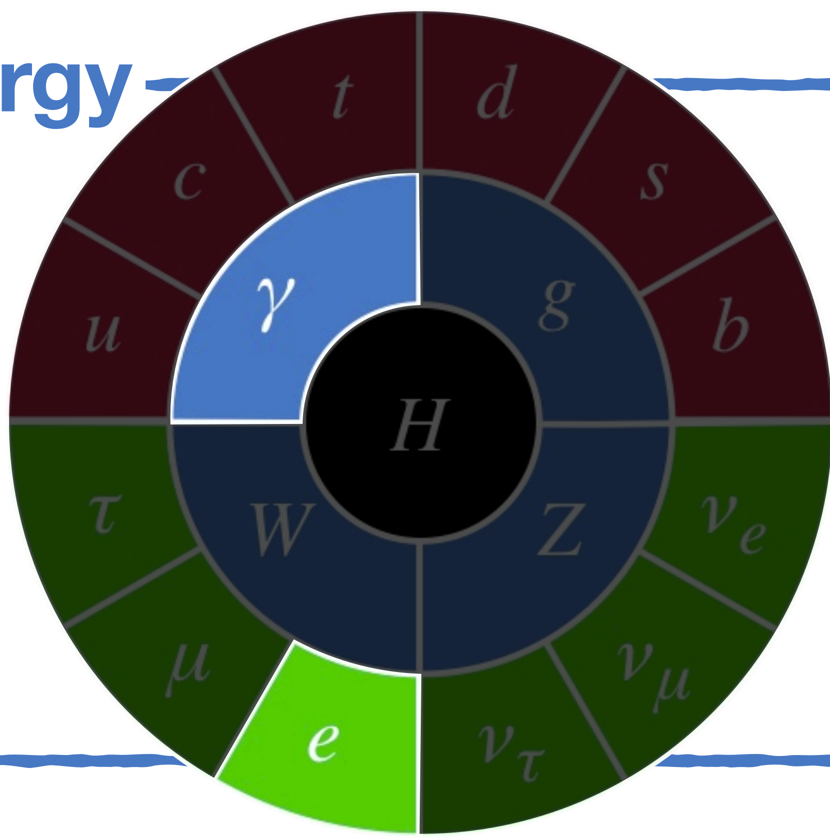
Modest energy

Accelerated e- energy is 30 (50) MeV

Only e, γ, n are relevant



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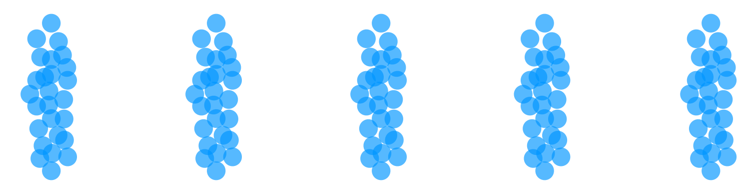
Electrons arrive in *bunches* only 1.5 ns apart



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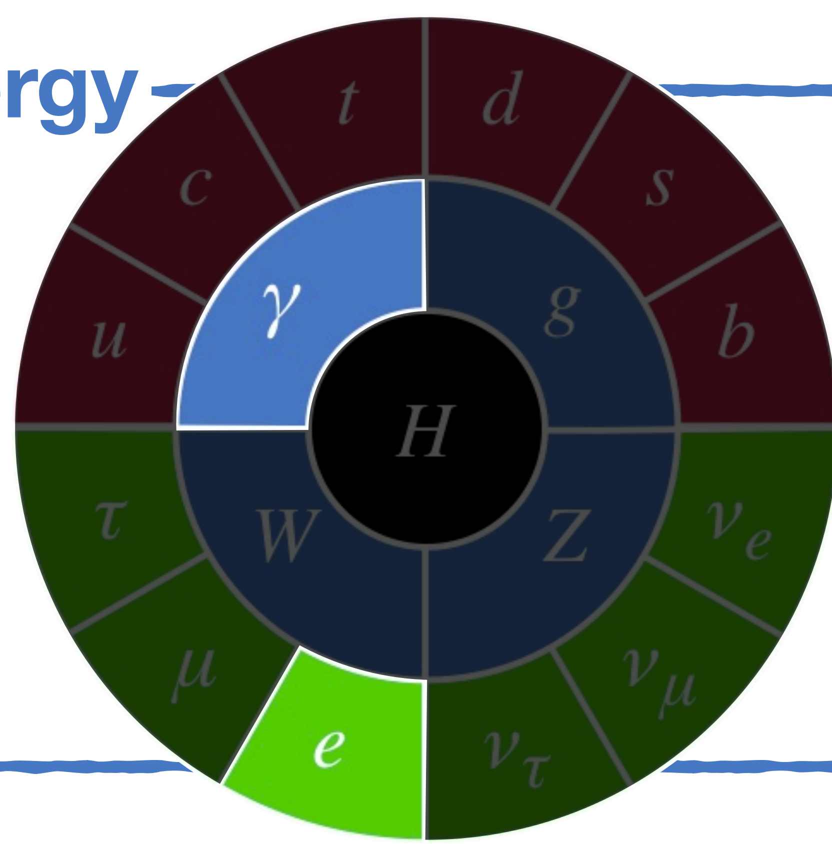

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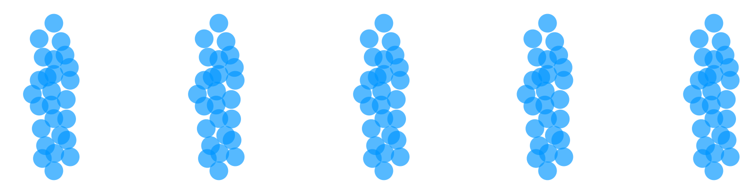

At 10 kW, each bunch contains > 2 million electrons

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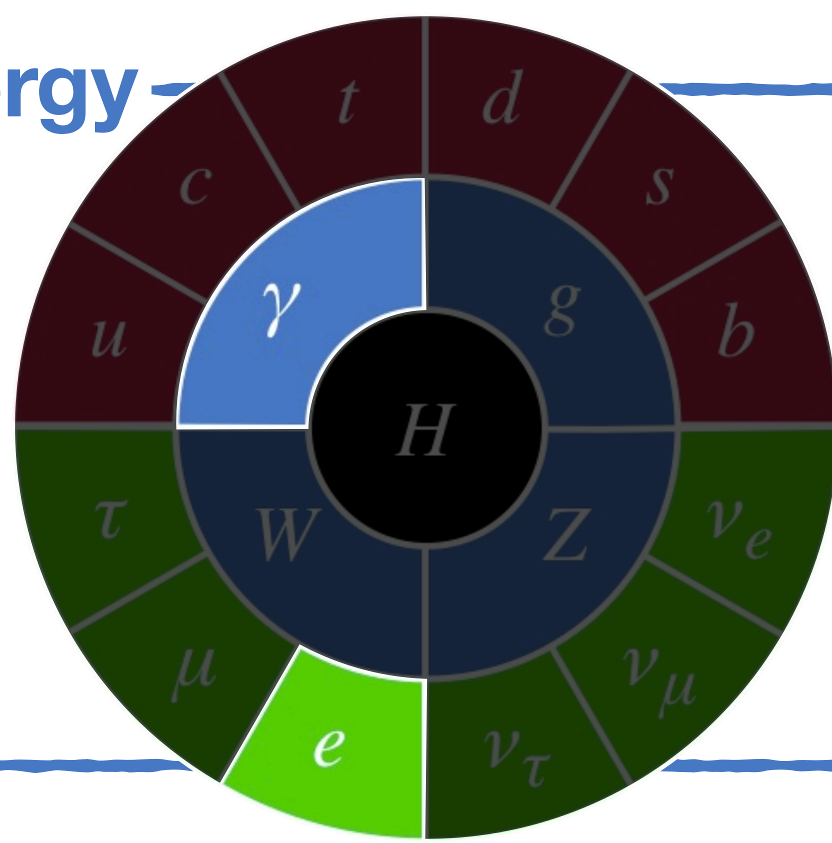

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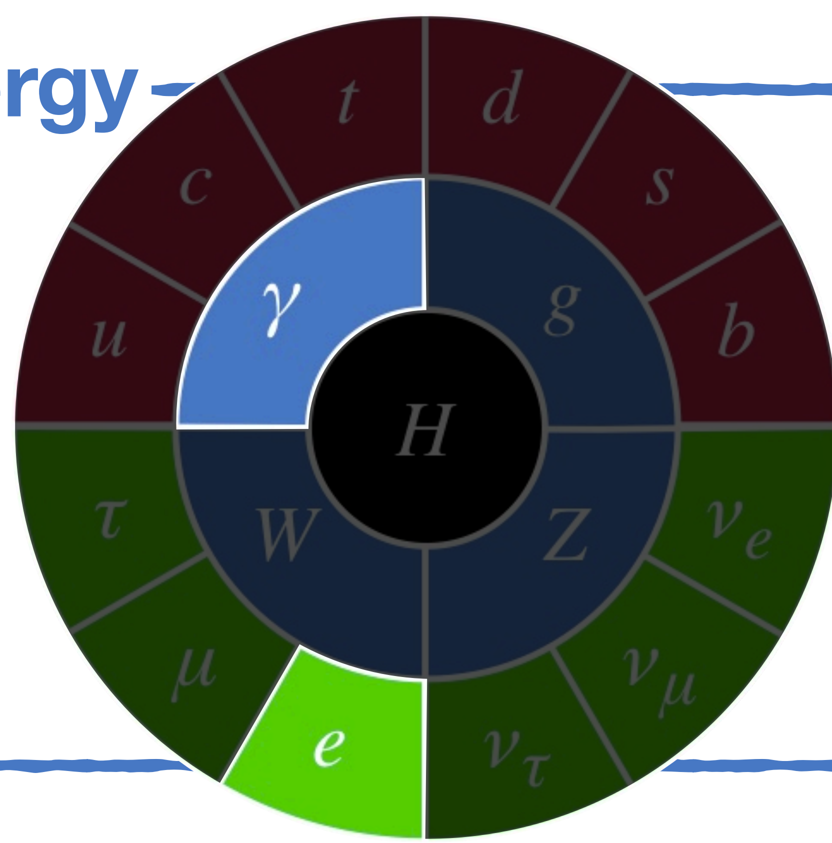

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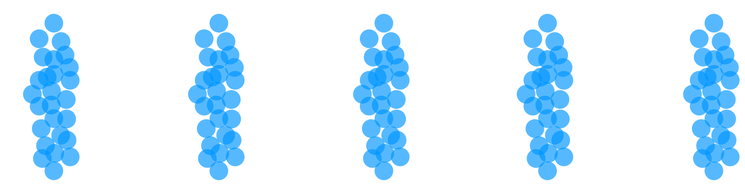

At 10 kW, each bunch contains > 2 million electrons

→ Challenge 1: backgrounds. Additional activity in detectors will come from extra e- interacting in target

→ Challenge 2: radiation. Scattered e- and radiated photons can damage sensors and electronics

What are the resulting experiment requirements?

Track resolution

Accurate momentum means good mass resolution → high sensitivity to signals

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Experiment has to be small to fit in available space

Affordable

Small collaboration with limited funds!

The DarkLight collaboration

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

JG|U JOHANNES GUTENBERG UNIVERSITÄT MAINZ

UBC

STONY BROOK STATE UNIVERSITY OF NEW YORK

Saint Mary's University

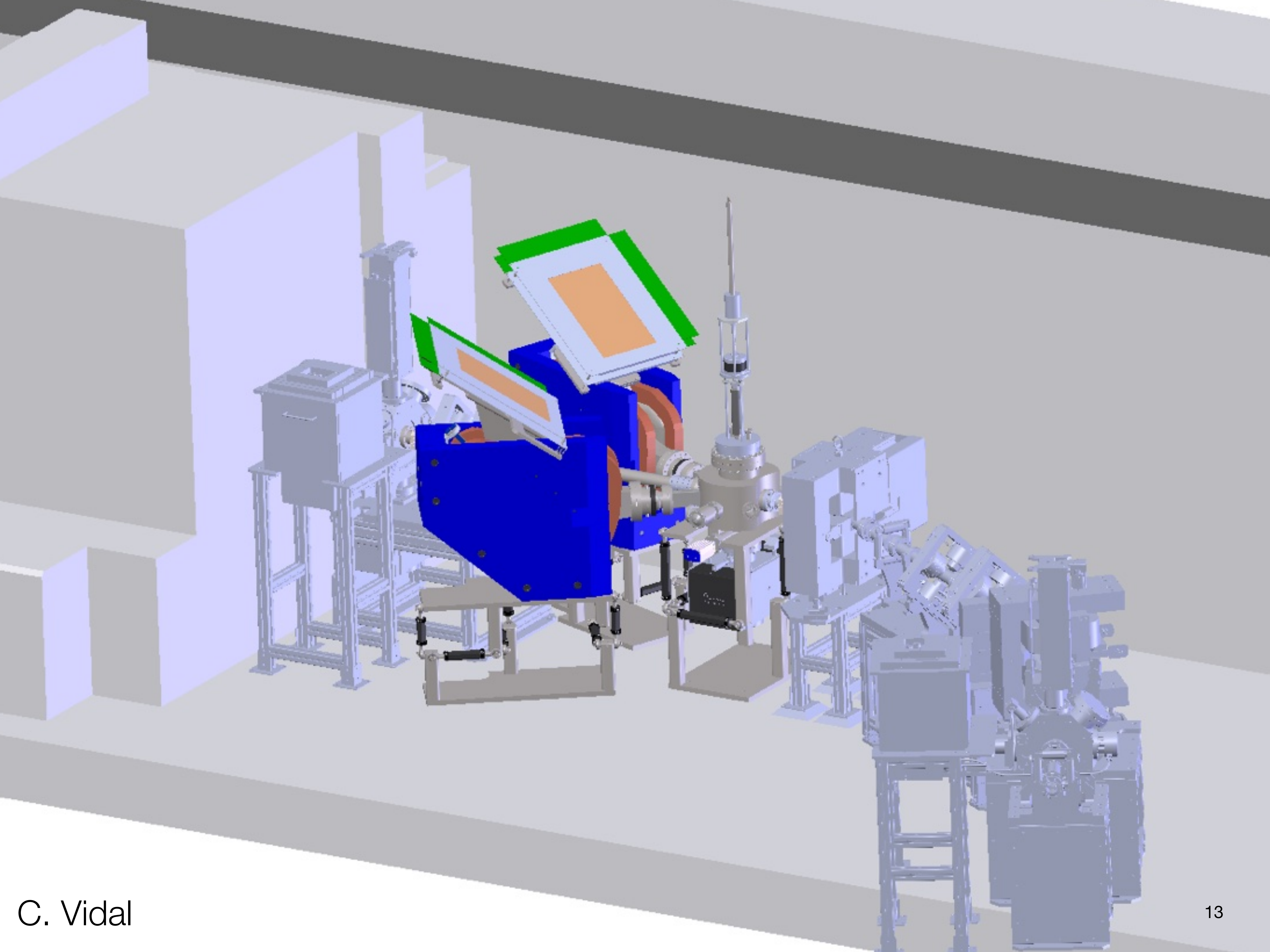
HAMPTON UNIVERSITY

University of Manitoba

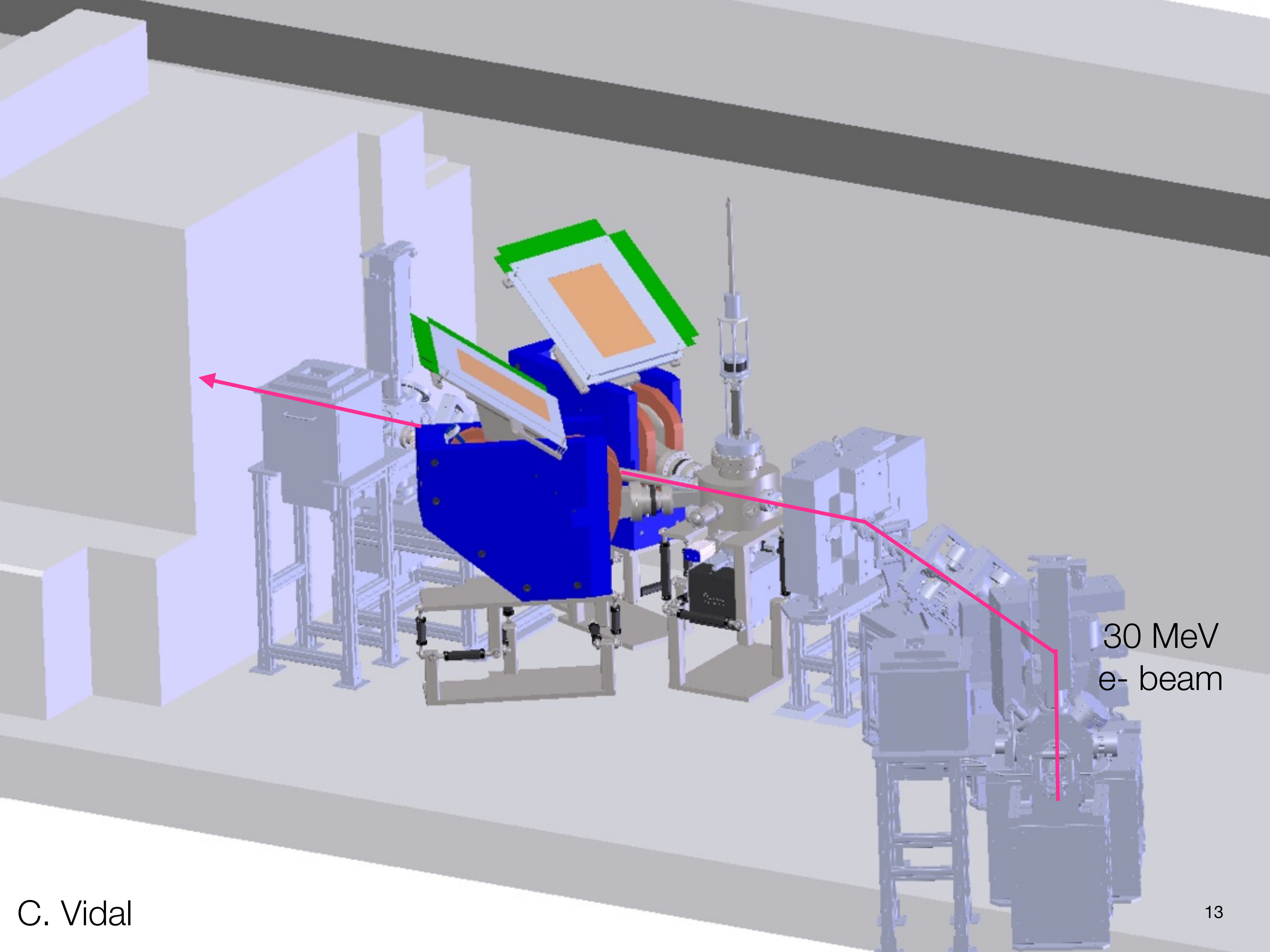
THE UNIVERSITY OF WINNIPEG

Jefferson Lab

ARIZONA STATE UNIVERSITY



C. Vidal



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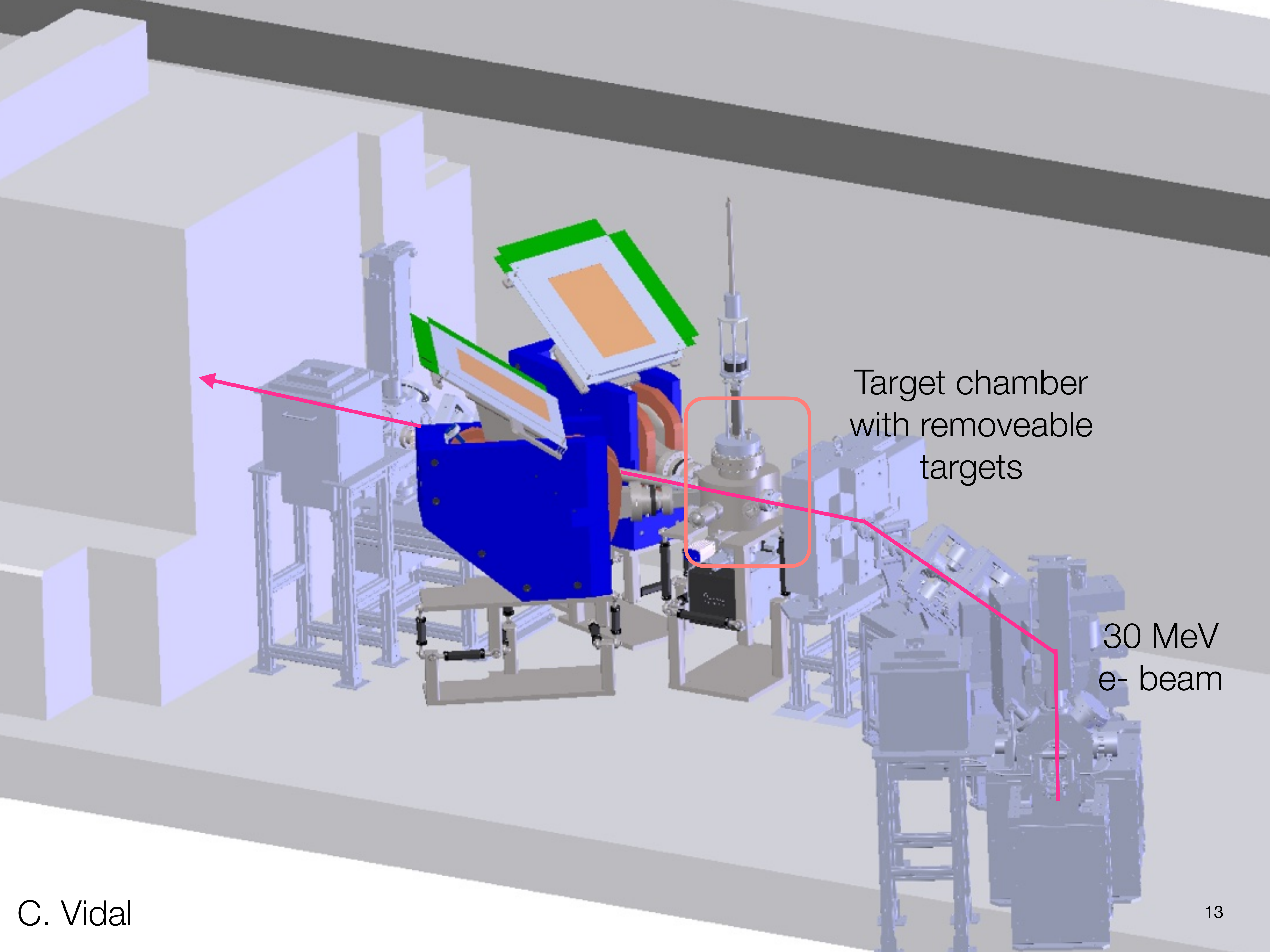

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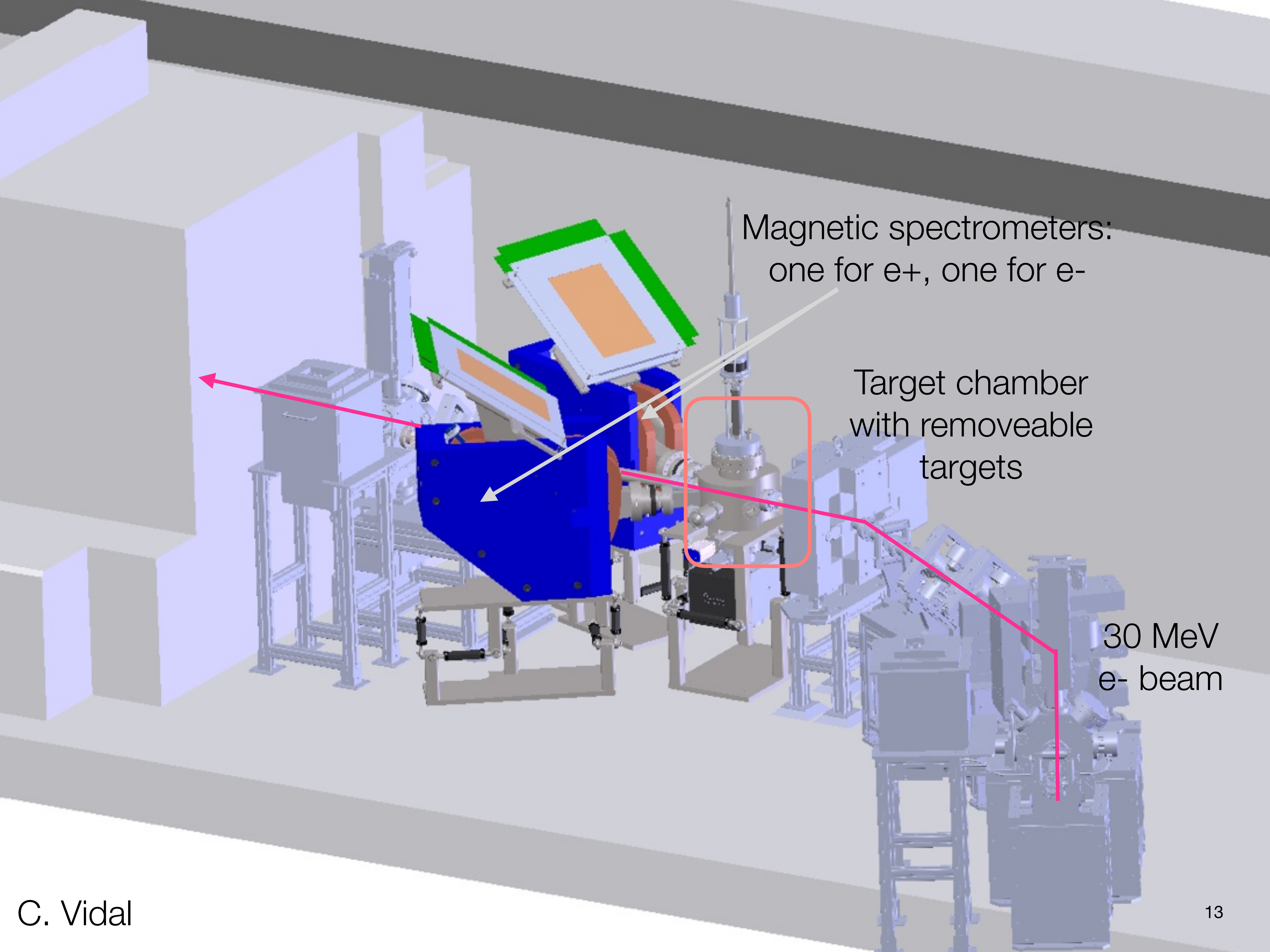
Magnetic spectrometers:
one for e+, one for e-
Target chamber
with removeable
targets
30 MeV
e- beam

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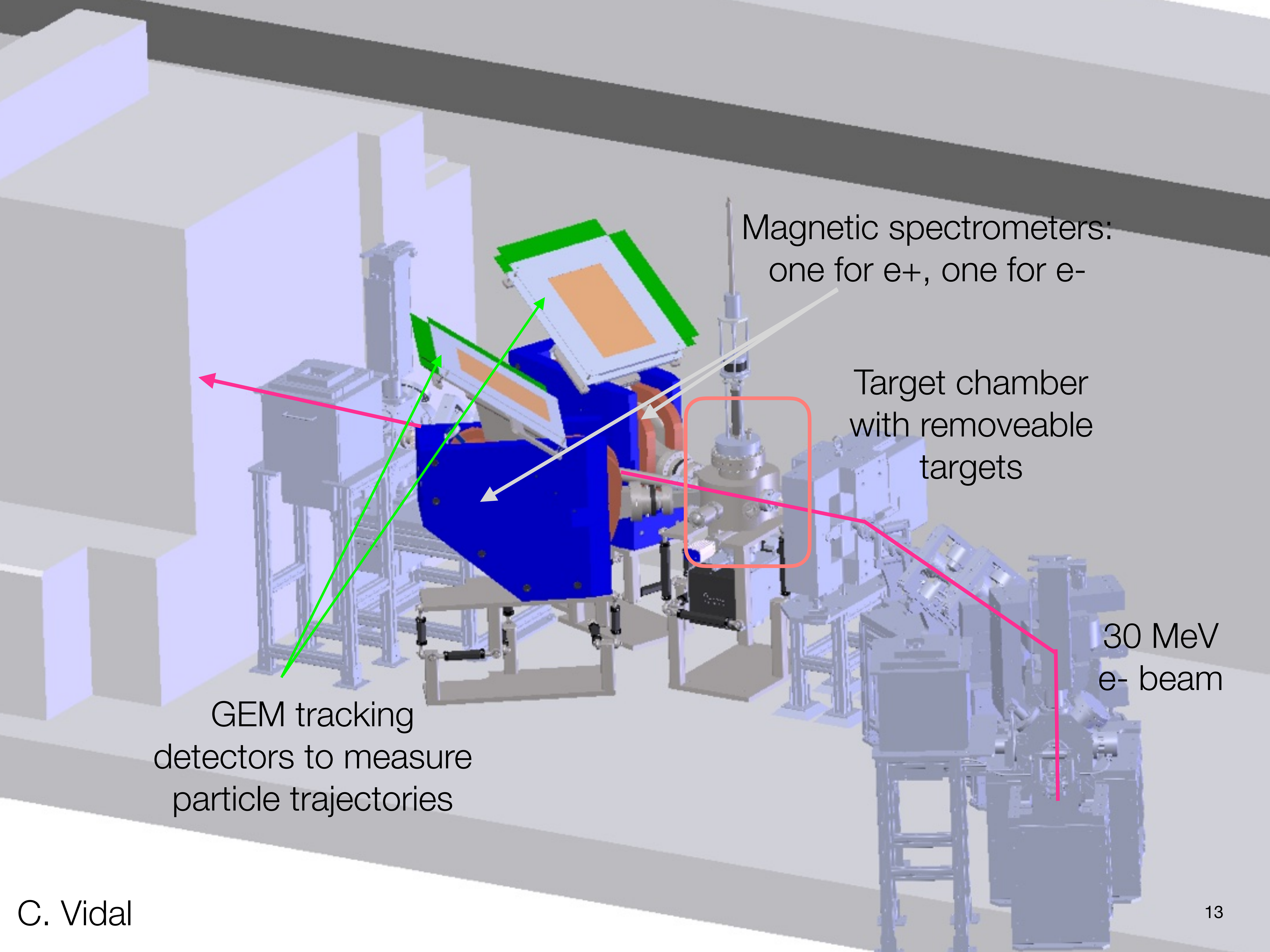
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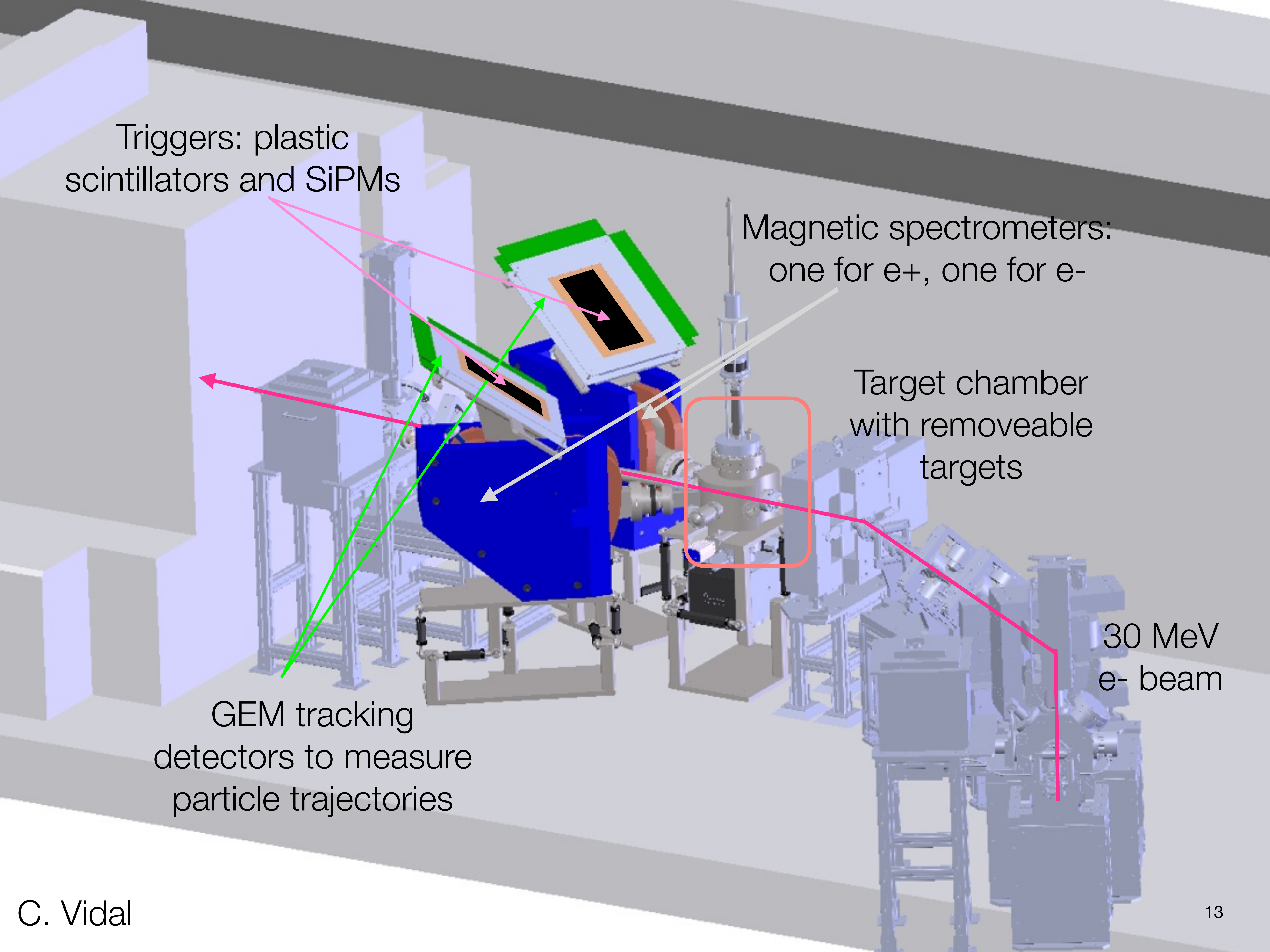
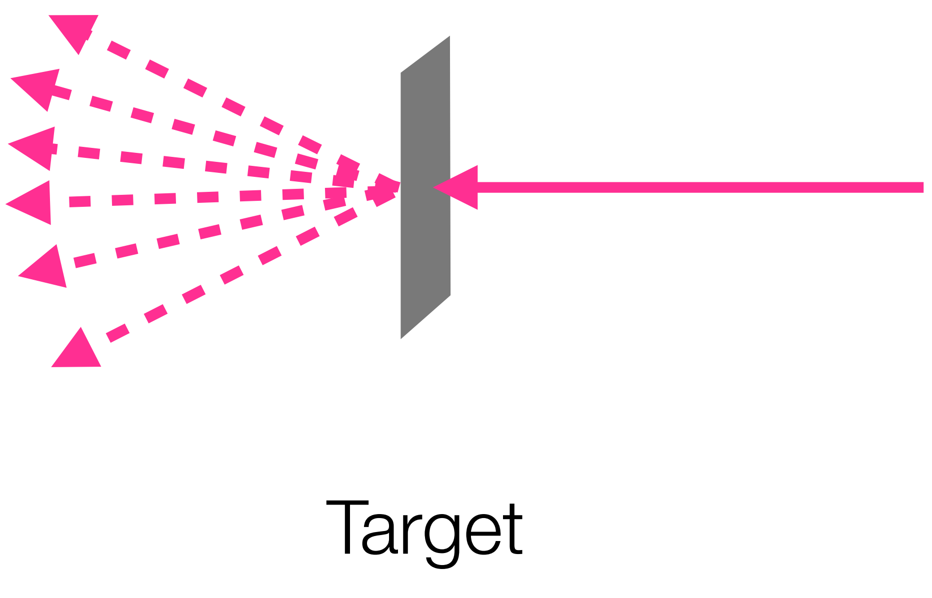
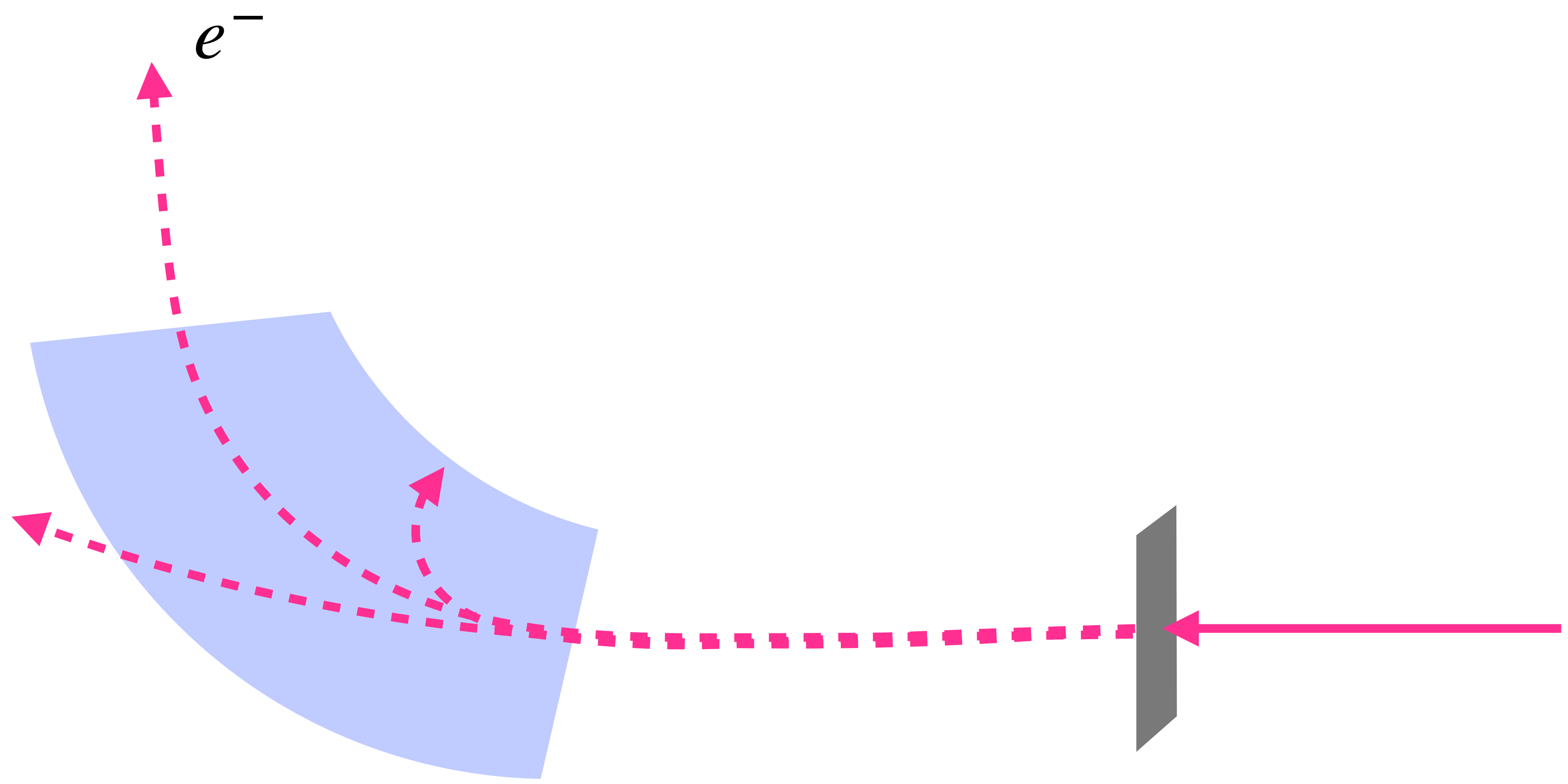


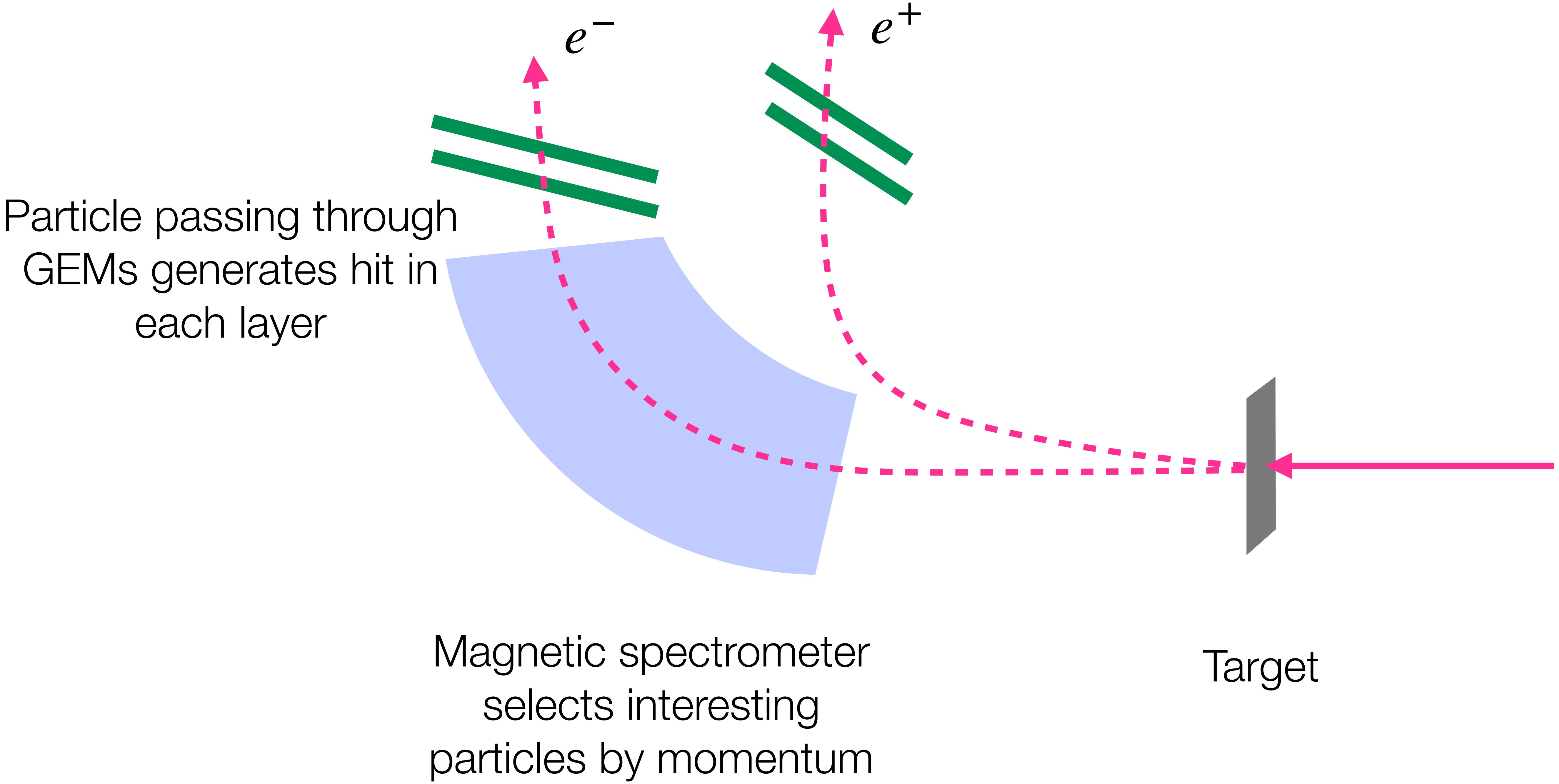
Triggers: plastic scintillators and SiPMs
Magnetic spectrometers: one for e+, one for e-
Target chamber with removeable targets
30 MeV e- beam
GEM tracking detectors to measure particle trajectories
C. Vidal


Target



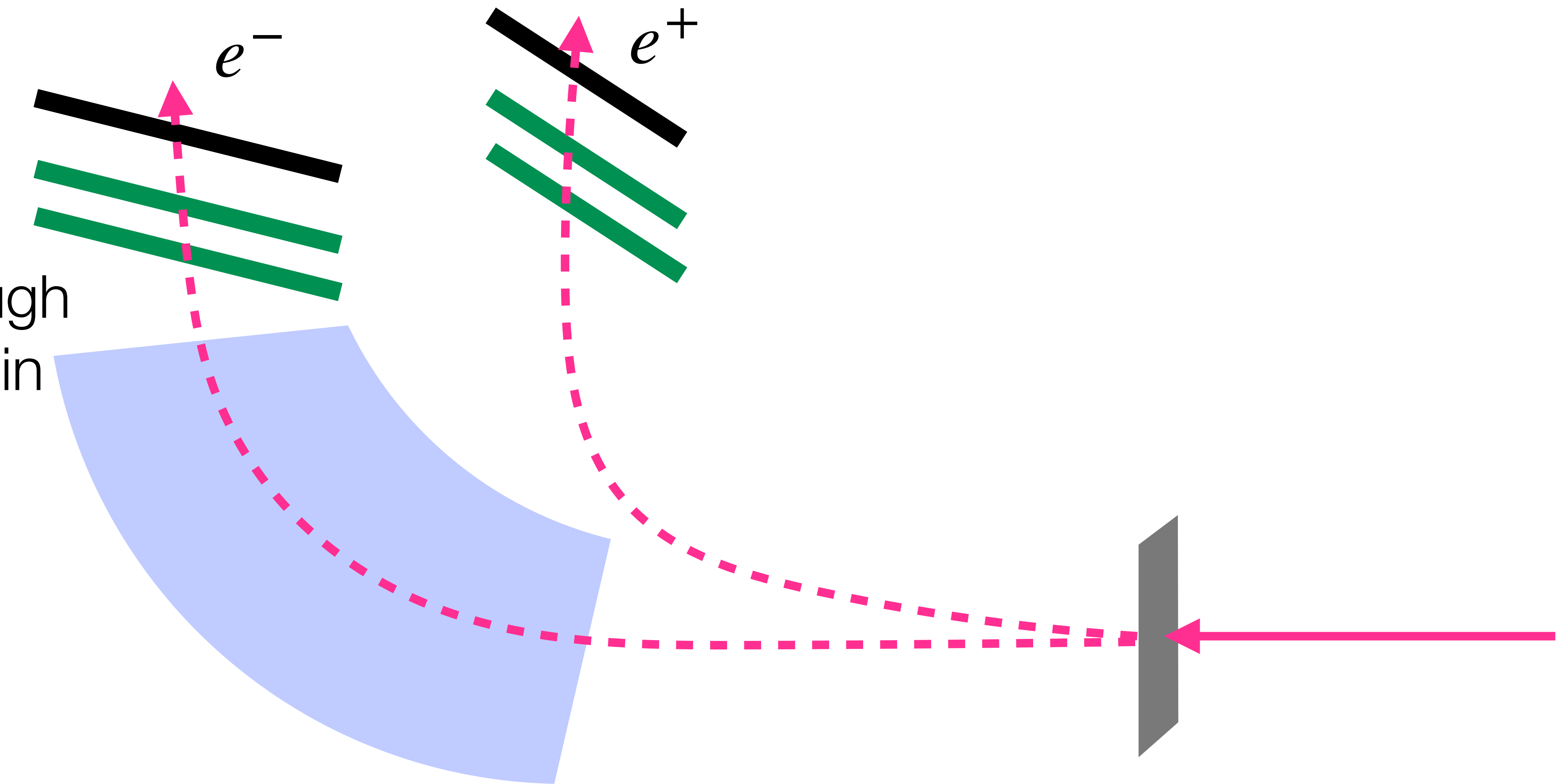
Magnetic spectrometer
selects interesting
particles by momentum

Target


e^-
e^+
Particle passing through GEMs generates hit in each layer
Magnetic spectrometer selects interesting particles by momentum
Target

Fast trigger detector looks for coincidence in both spectrometers

Particle passing through GEMs generates hit in each layer



Magnetic spectrometer selects interesting particles by momentum

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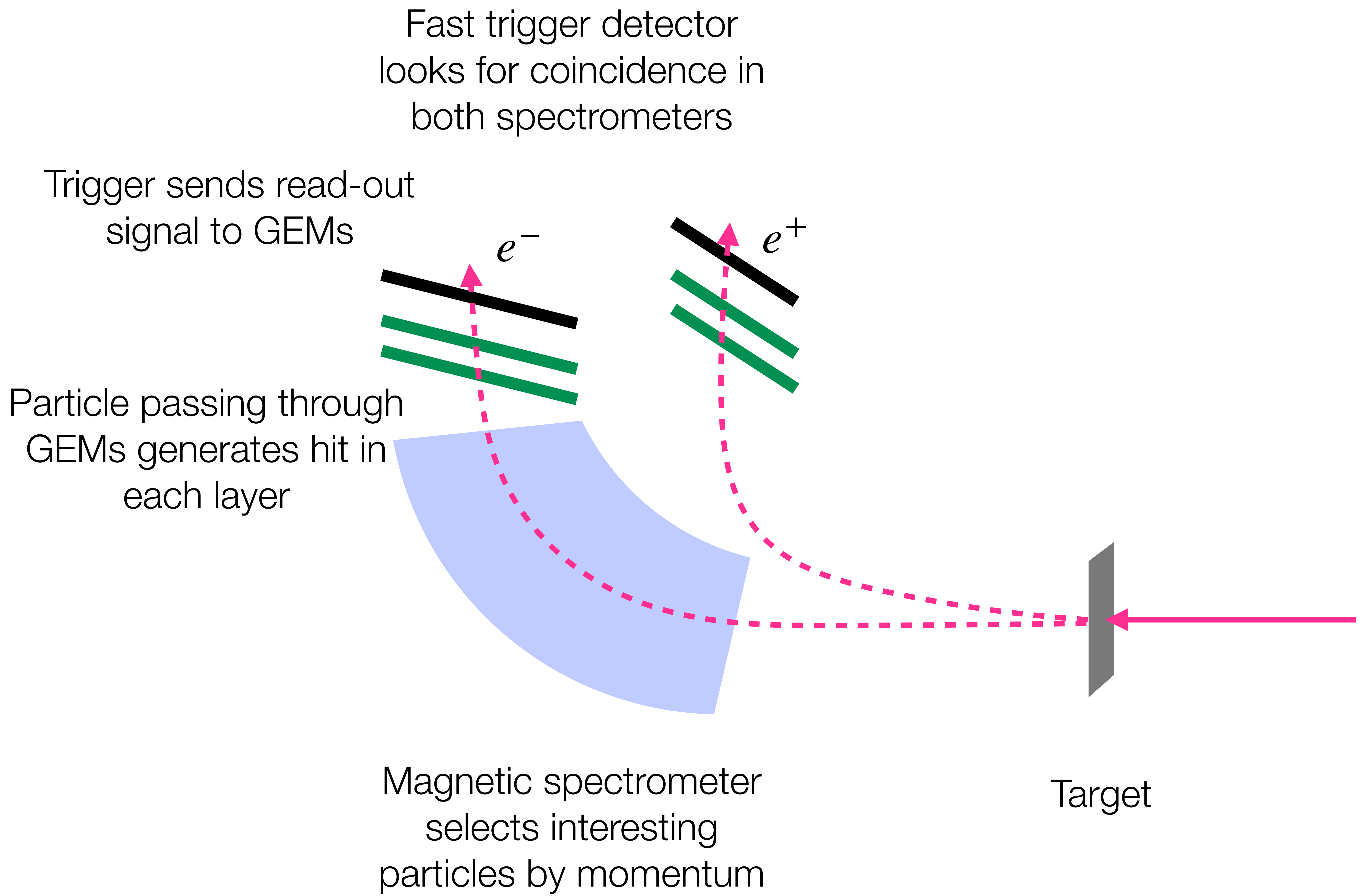
Fast trigger detector looks for coincidence in both spectrometers
Trigger sends read-out signal to GEMs
e^-
e^+
Particle passing through GEMs generates hit in each layer
Magnetic spectrometer selects interesting particles by momentum
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Fast trigger detector looks for coincidence in both spectrometers

Two hits on each side define a track, with x coordinate proportional to momentum

Trigger sends read-out signal to GEMs

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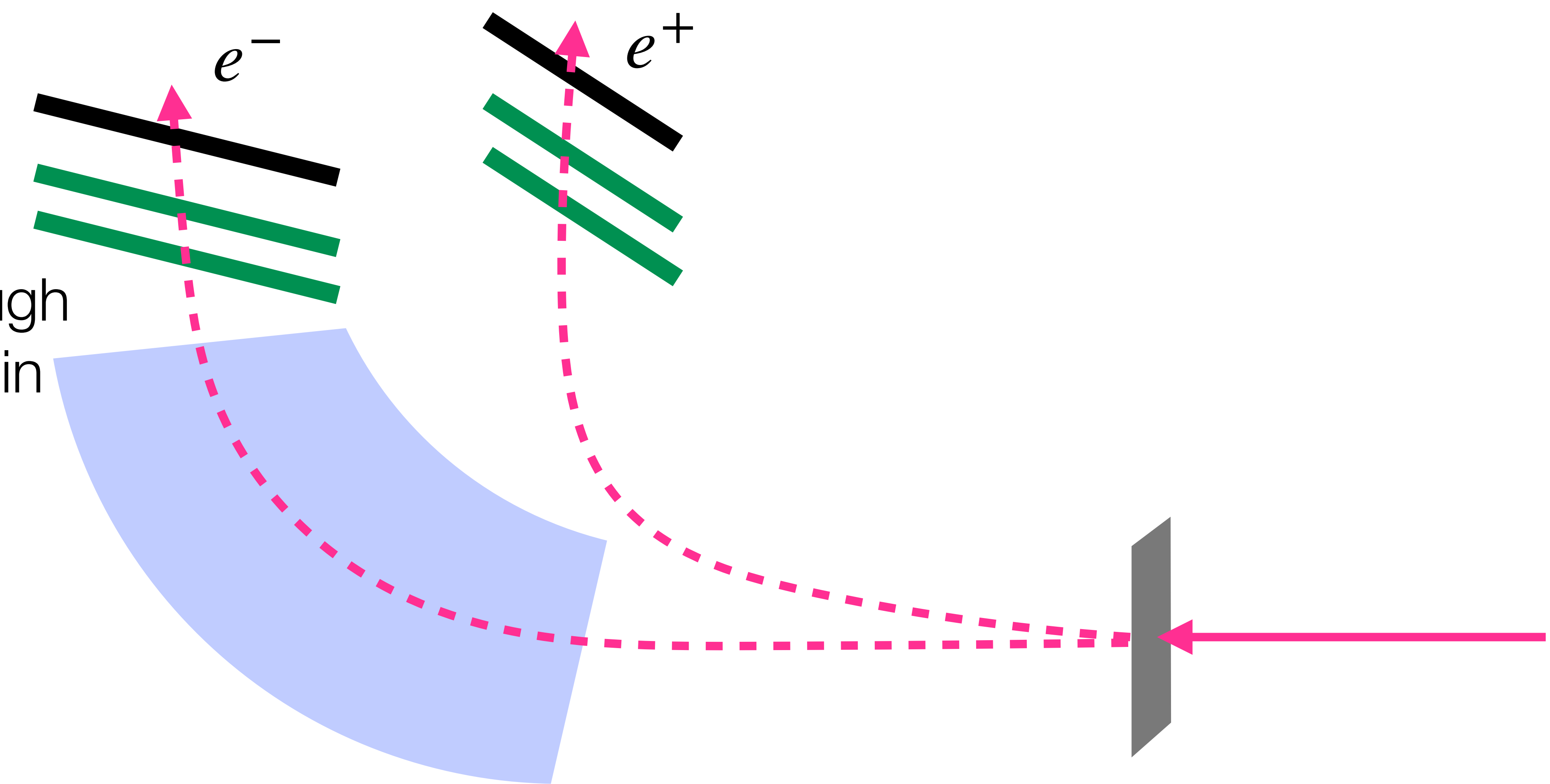

Magnetic spectrometer selects interesting particles by momentum

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Fast trigger detector looks for coincidence in both spectrometers

Two hits on each side define a track, with x coordinate proportional to momentum

$$M^2 = (P_{e^-} + P_{e^+})^2$$

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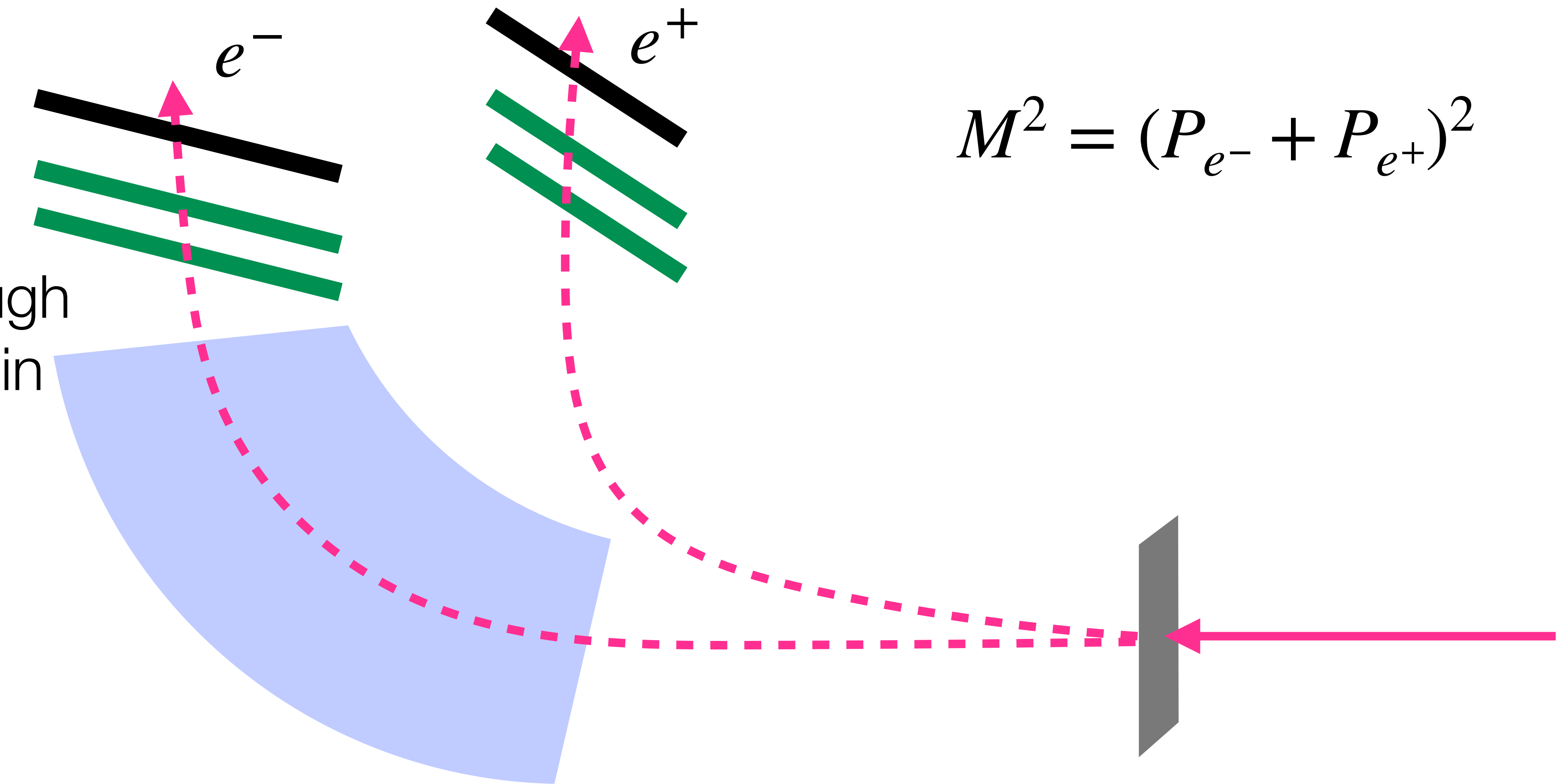
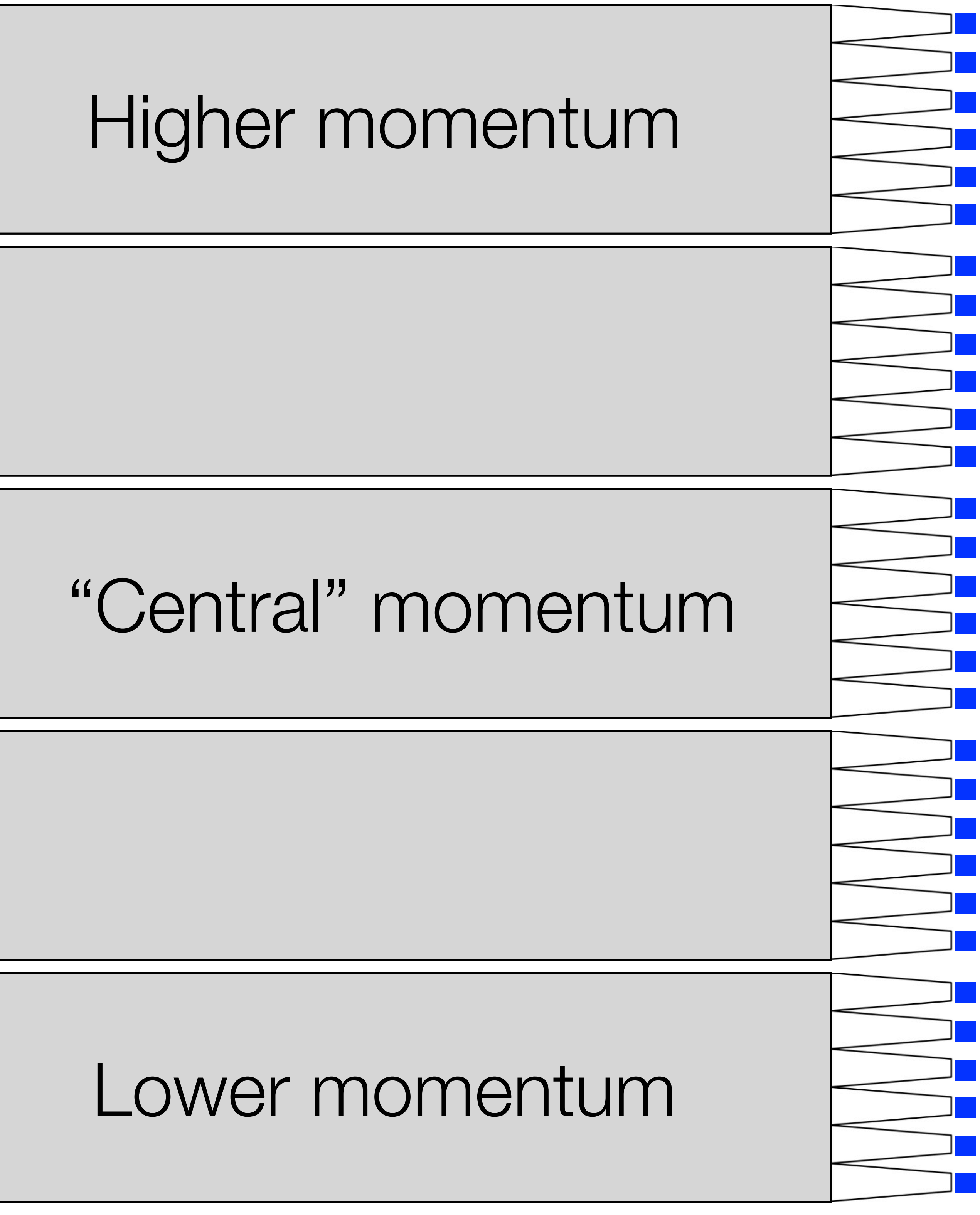


Magnetic spectrometer selects interesting particles by momentum

Target

Trigger hardware

Split plane up into eight slices



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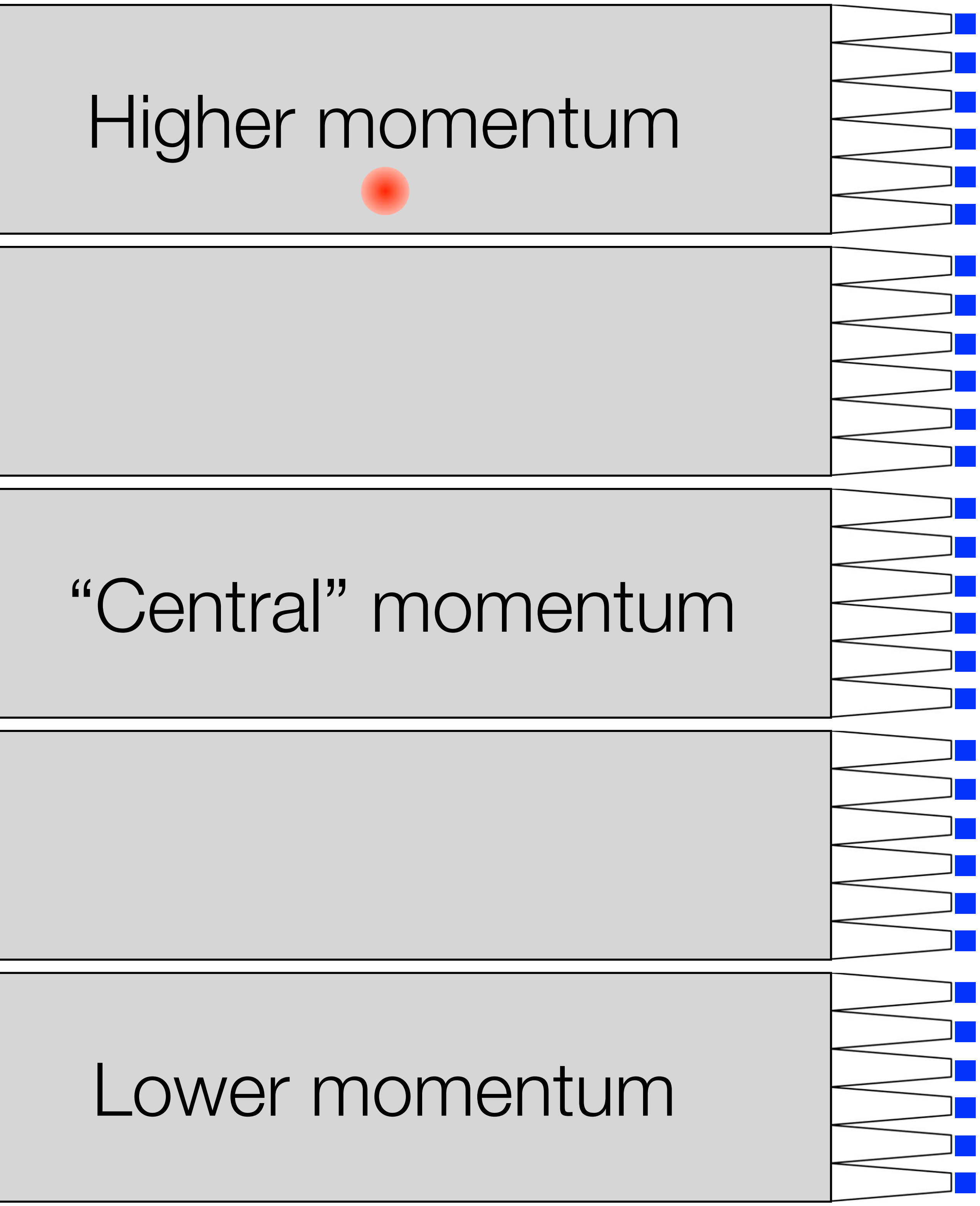

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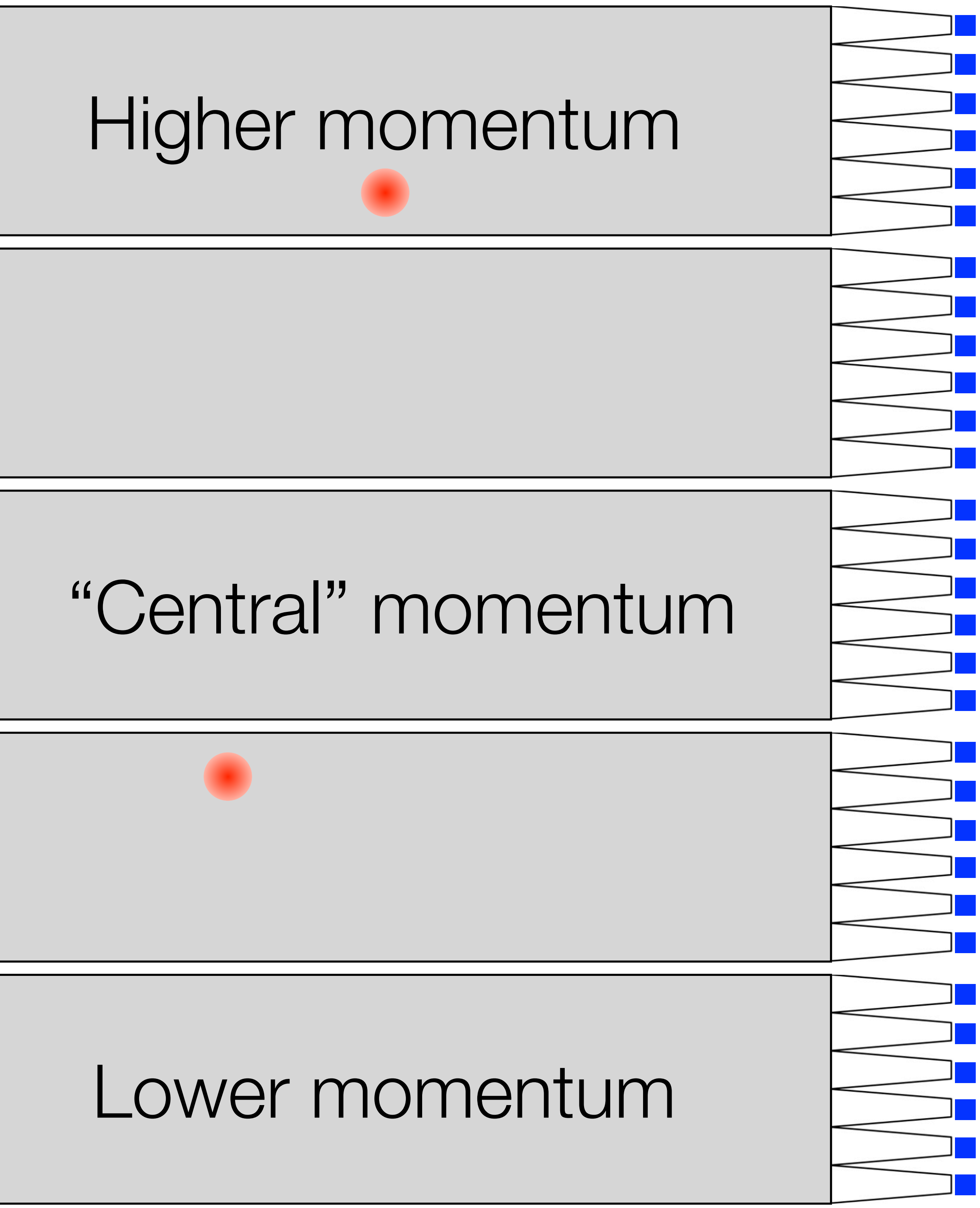

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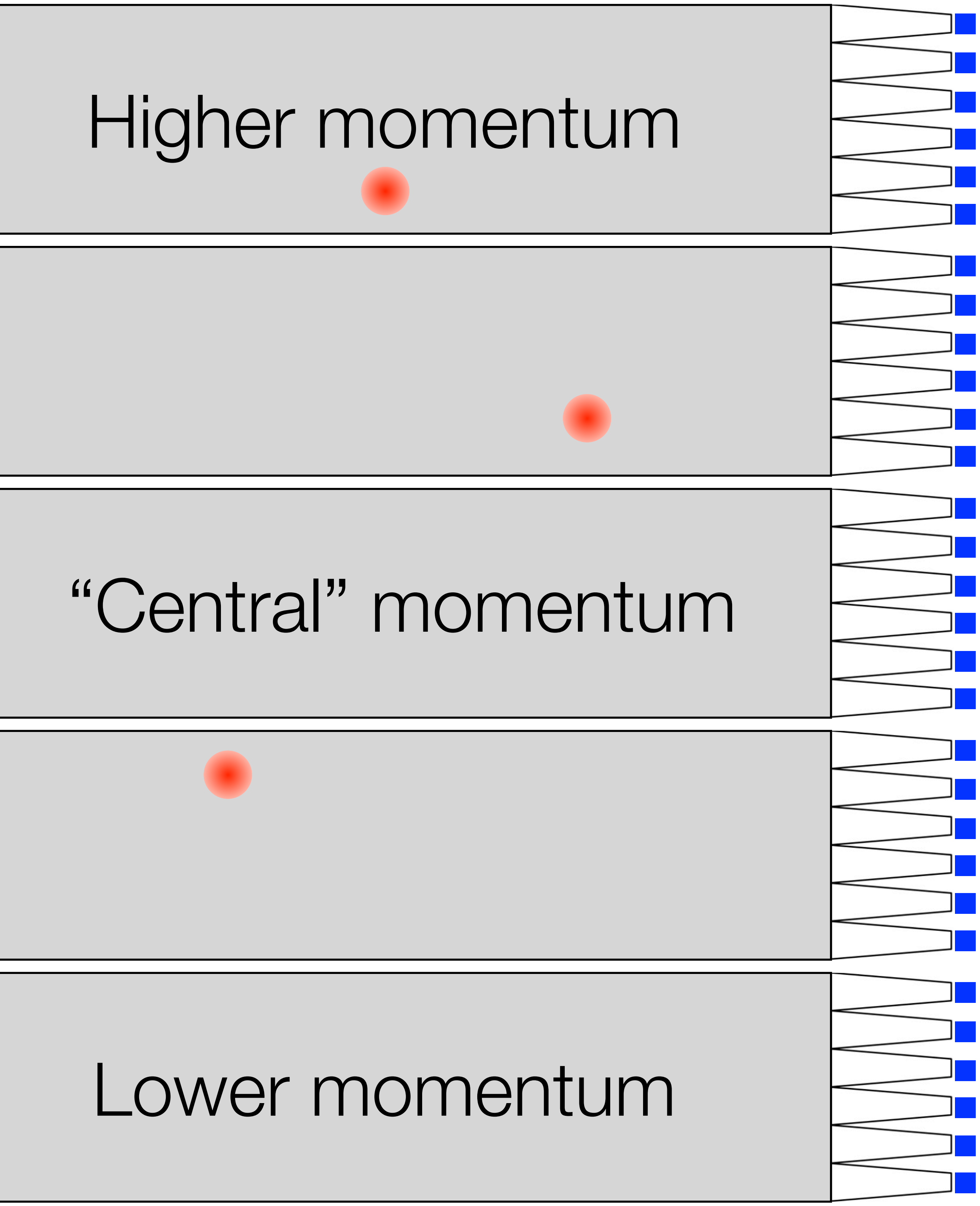

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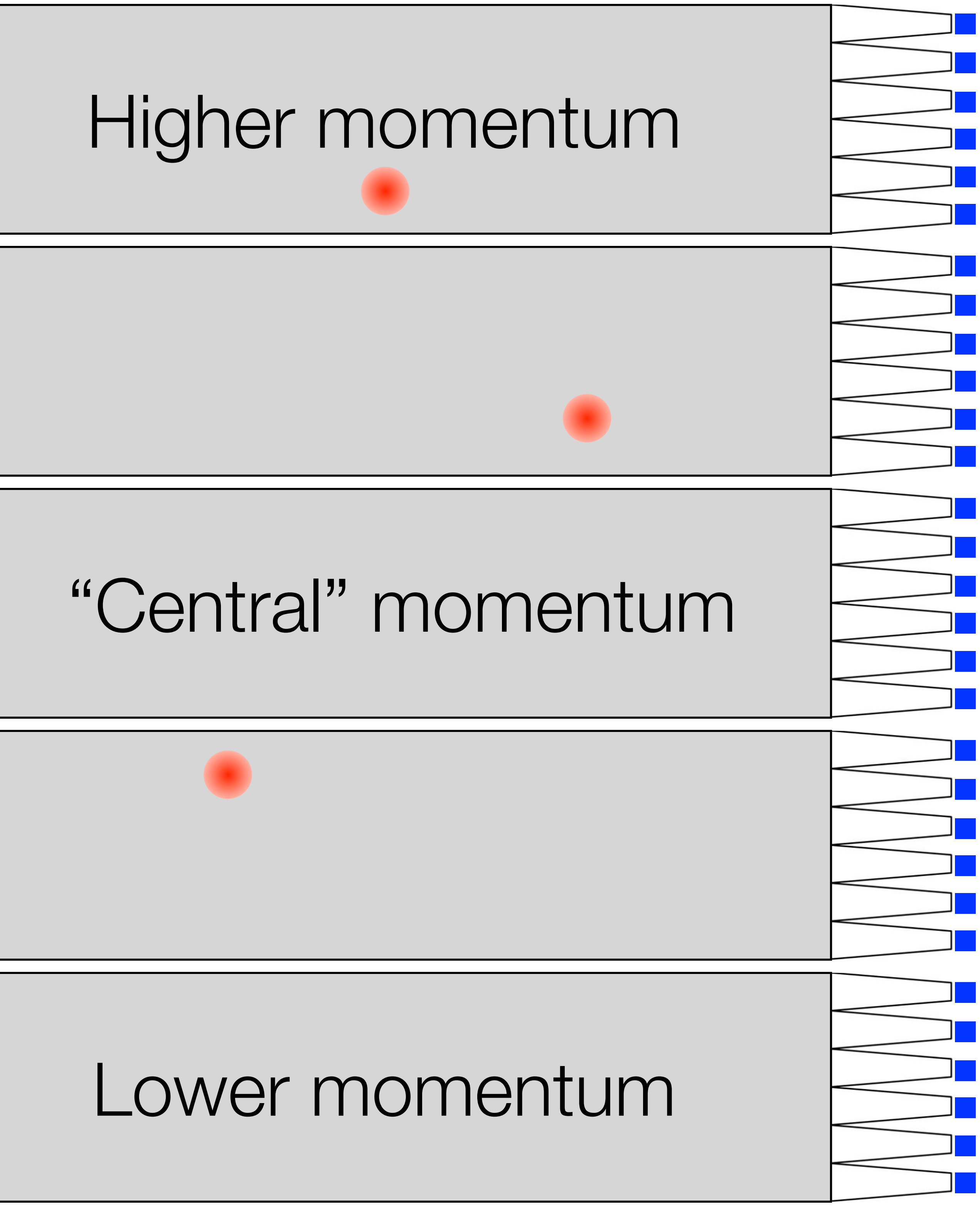
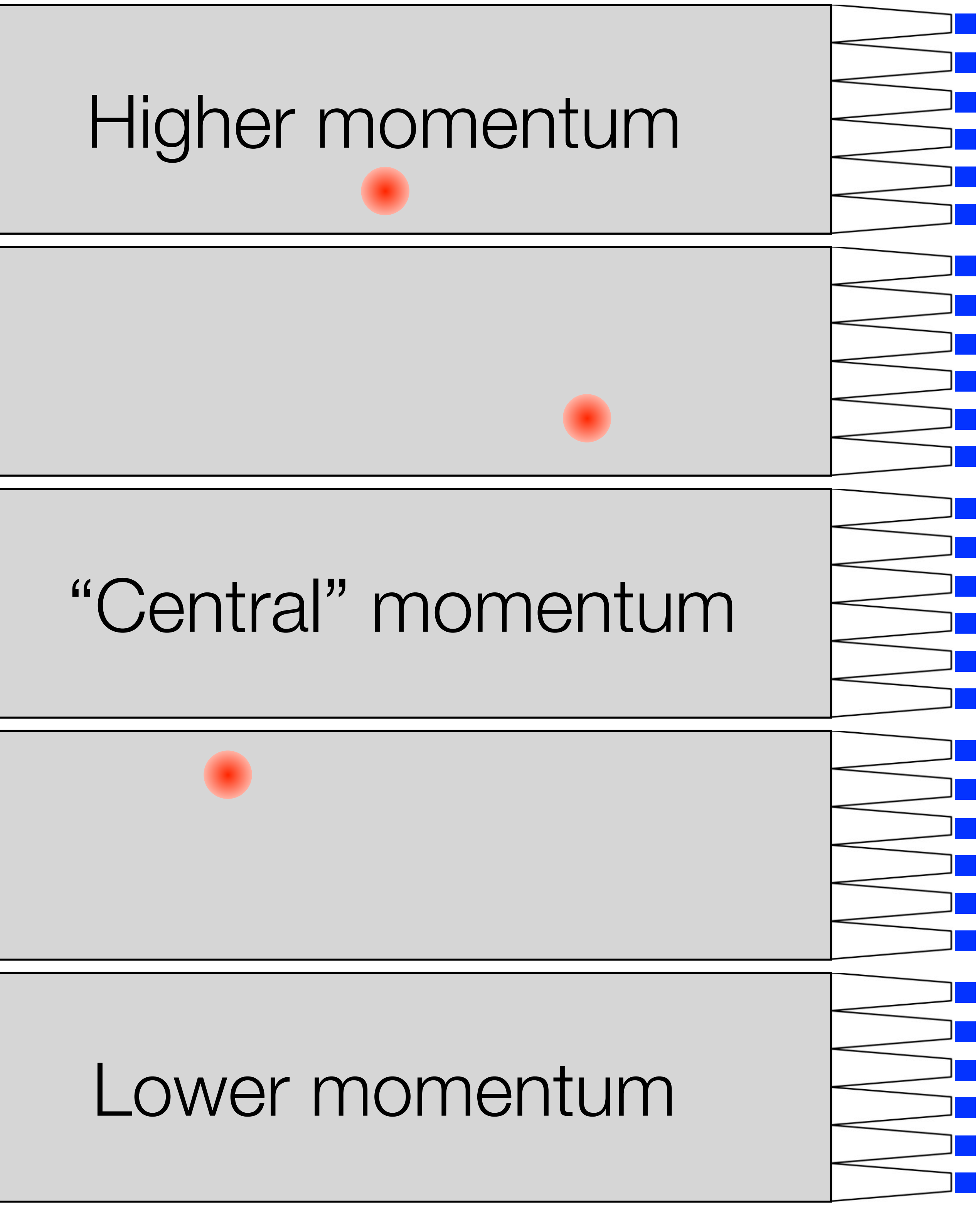


Split plane up into eight slices

3 mm fast plastic scintillator read out via 6 SiPMs, summed on read out board

Trigger hardware



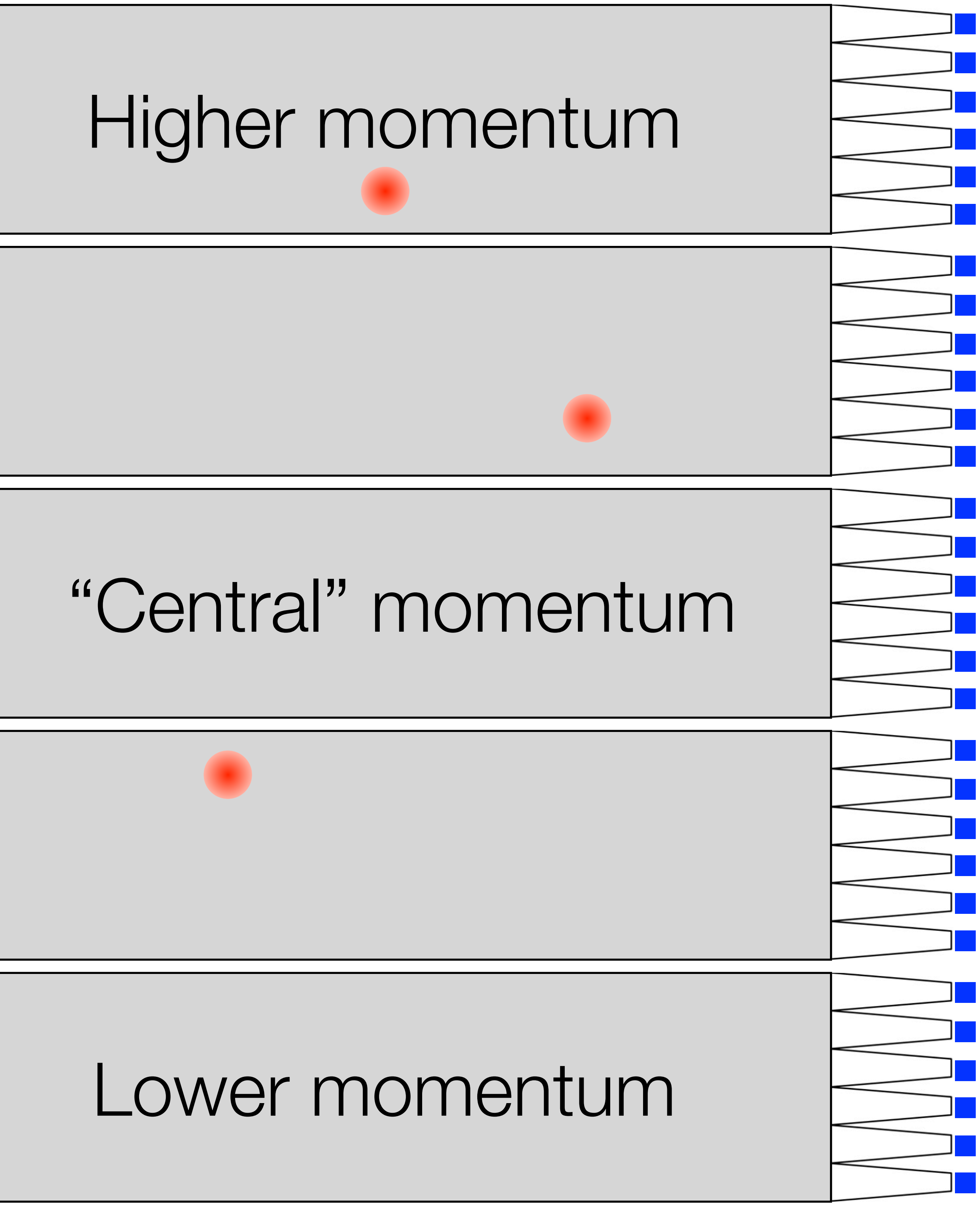
Split plane up into eight slices

3 mm fast plastic scintillator read out via 6 SiPMs, summed on read out board

Timing resolution ~ 300 ps

→ Comparison point: 1.5 ns bunch spacing

Trigger hardware



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3 mm fast plastic scintillator read out via 6 SiPMs, summed on read out board

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Recharging time ~ 50 ns

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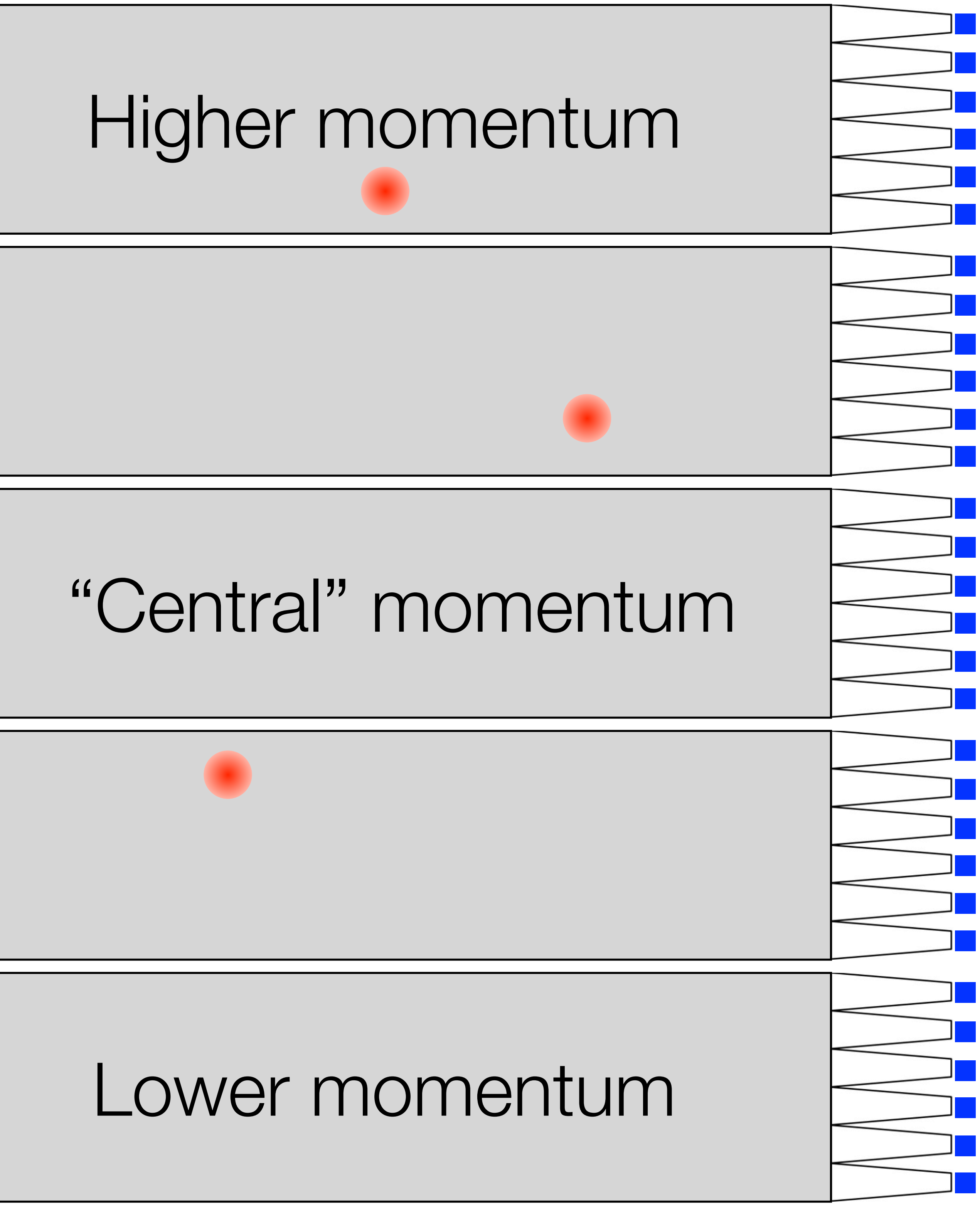

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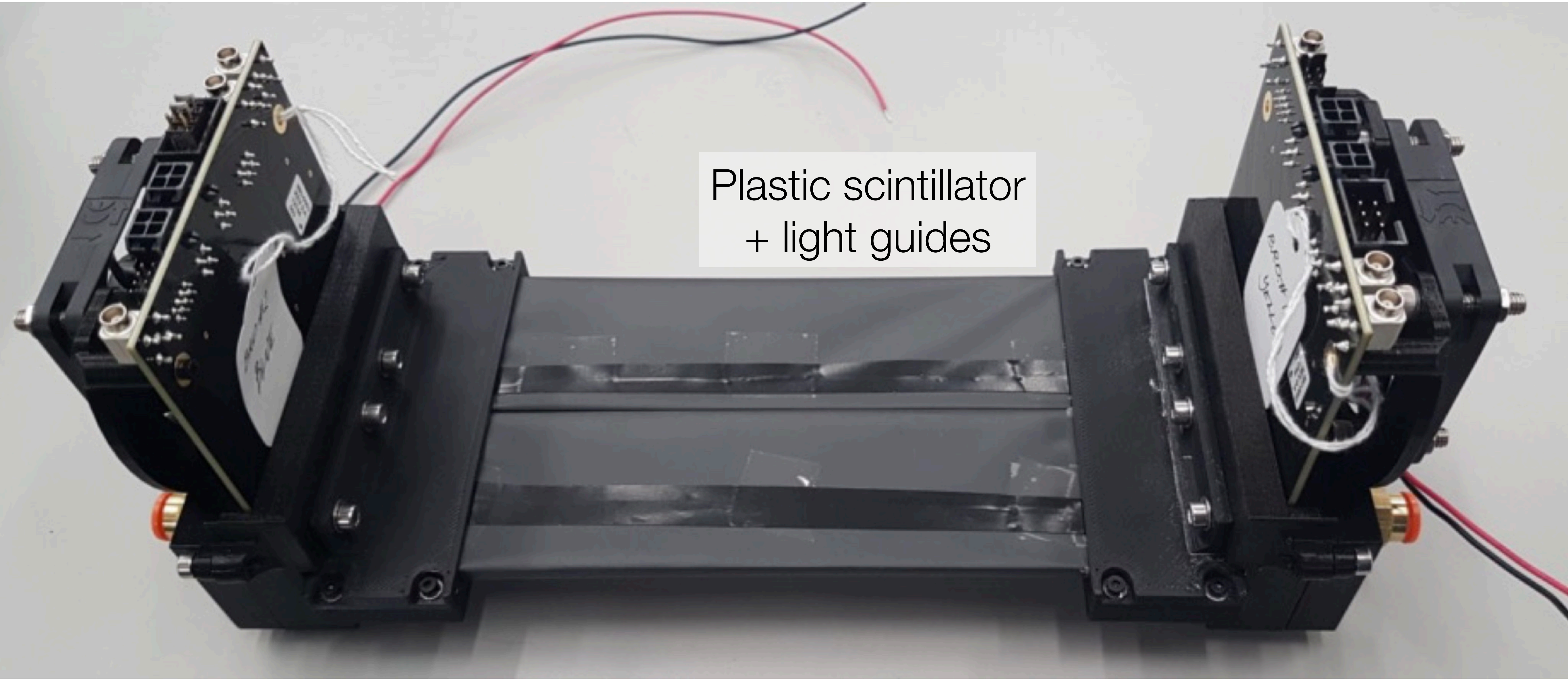
3 mm fast plastic scintillator read out via 6 SiPMs, summed on read out board

Timing resolution ~ 300 ps

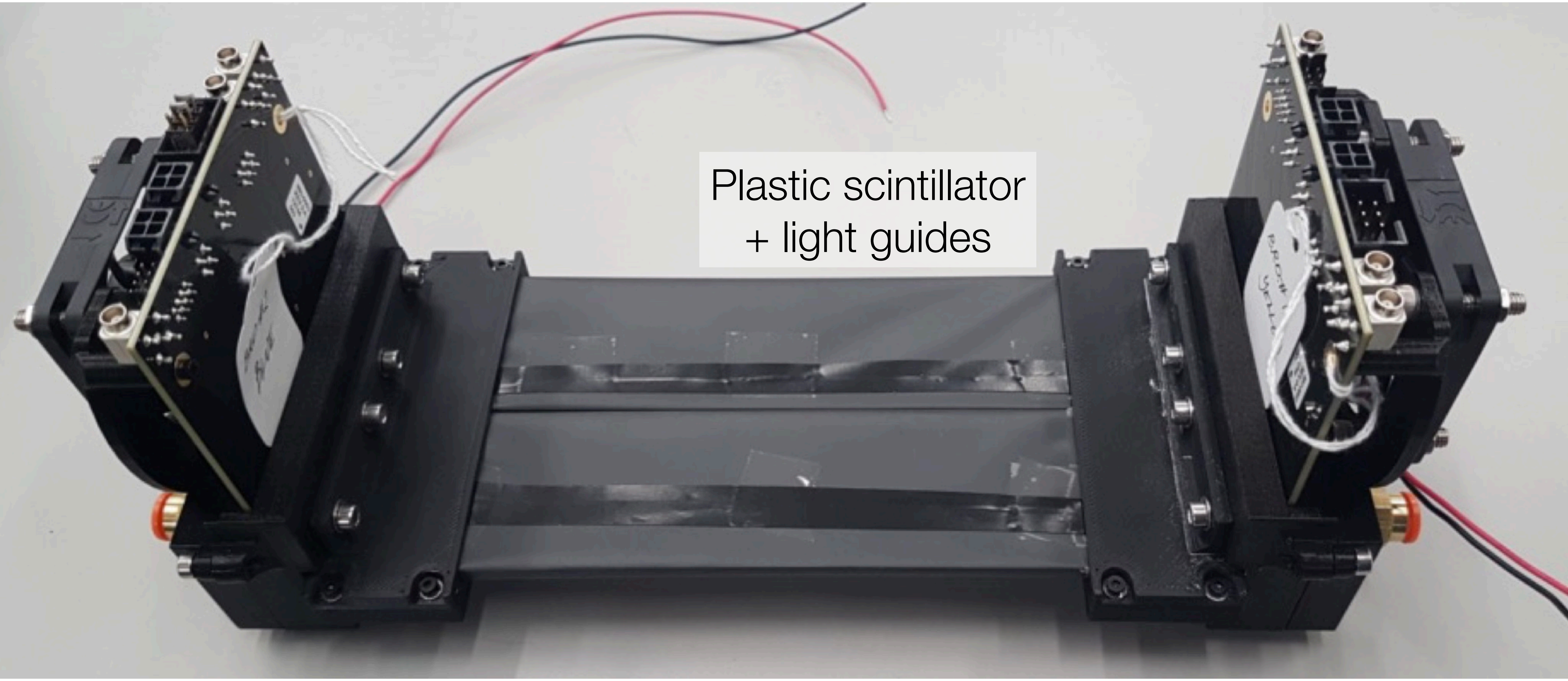
→ Comparison point: 1.5 ns bunch spacing

Recharging time ~ 50 ns

→ Comparison point: ~ 1 μs average time between hits


Plastic scintillator
+ light guides

4x each of these units
per spectrometer arm



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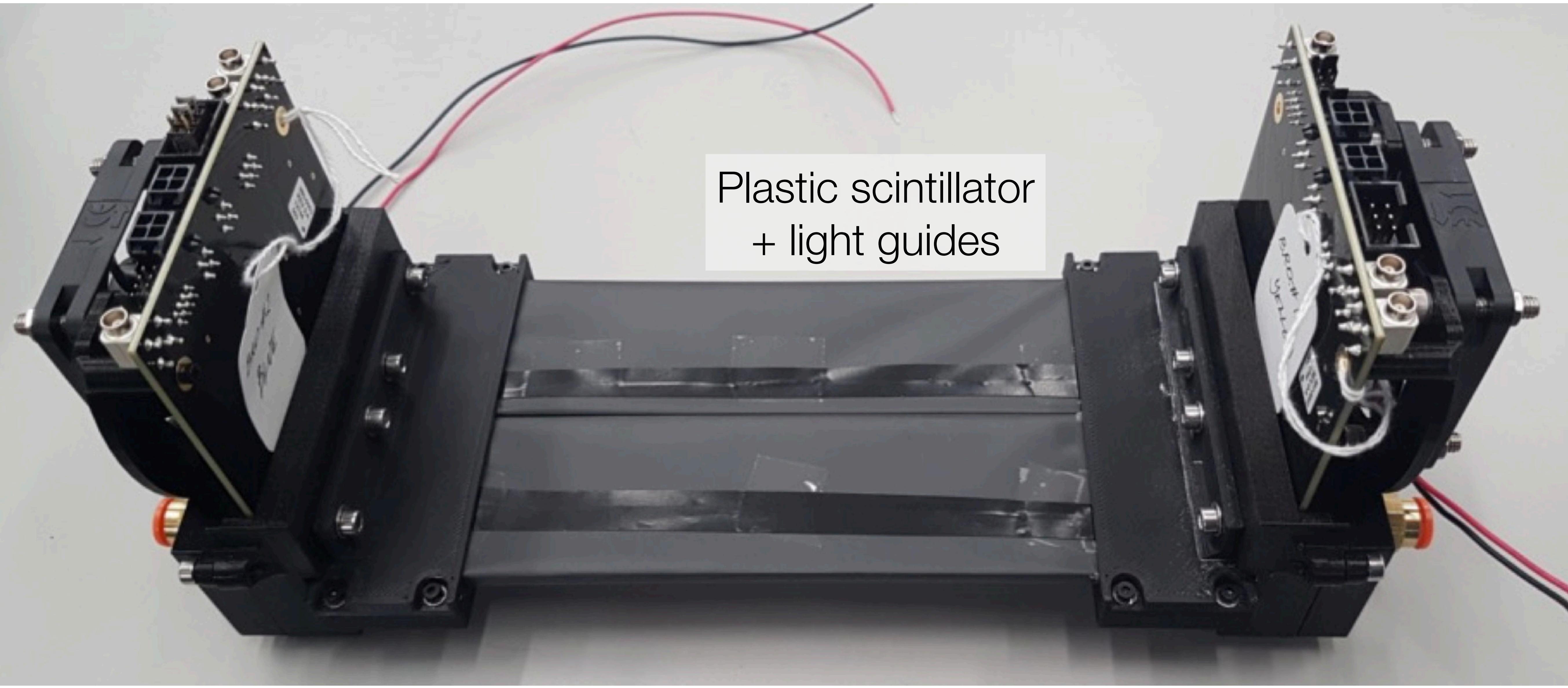
Read out signal is time over threshold **only**: no signal shape



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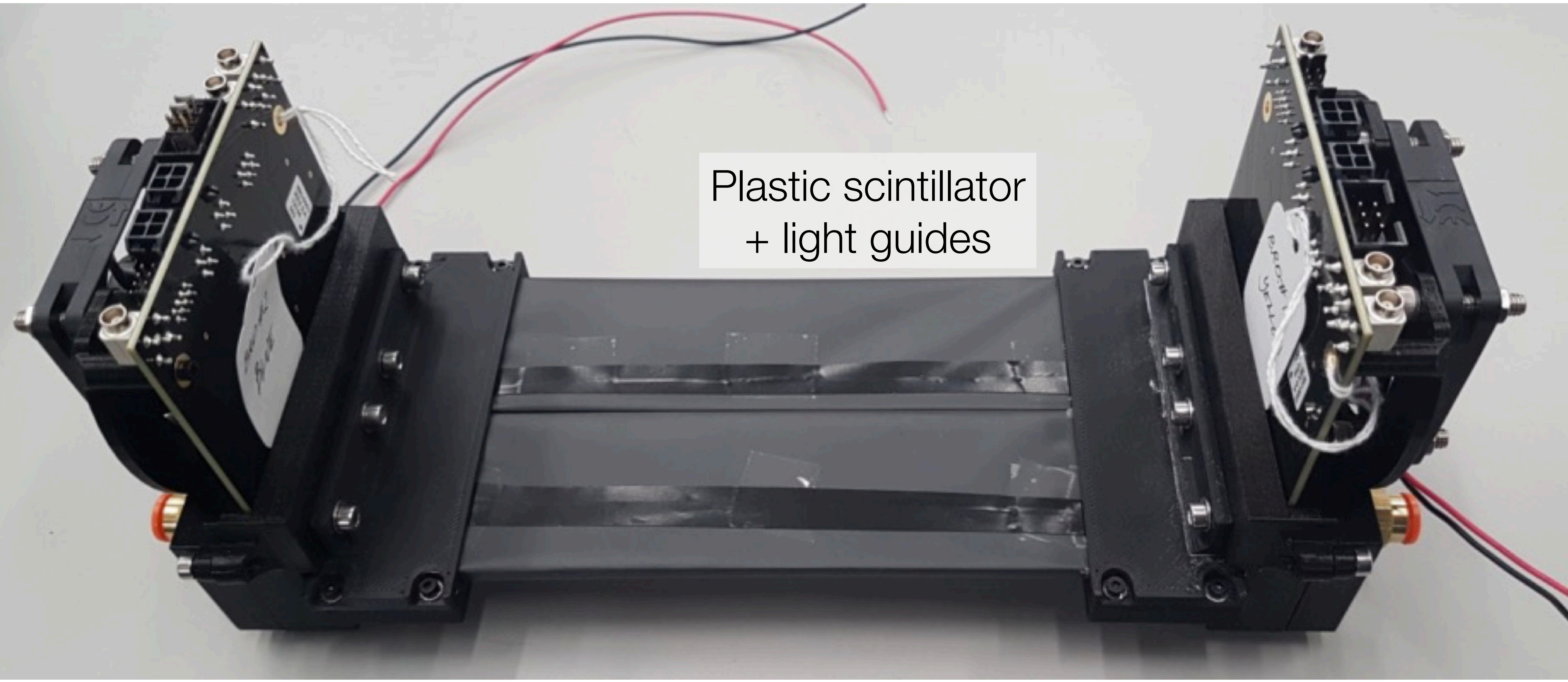

Fans and compressed air to keep SiPMs cool

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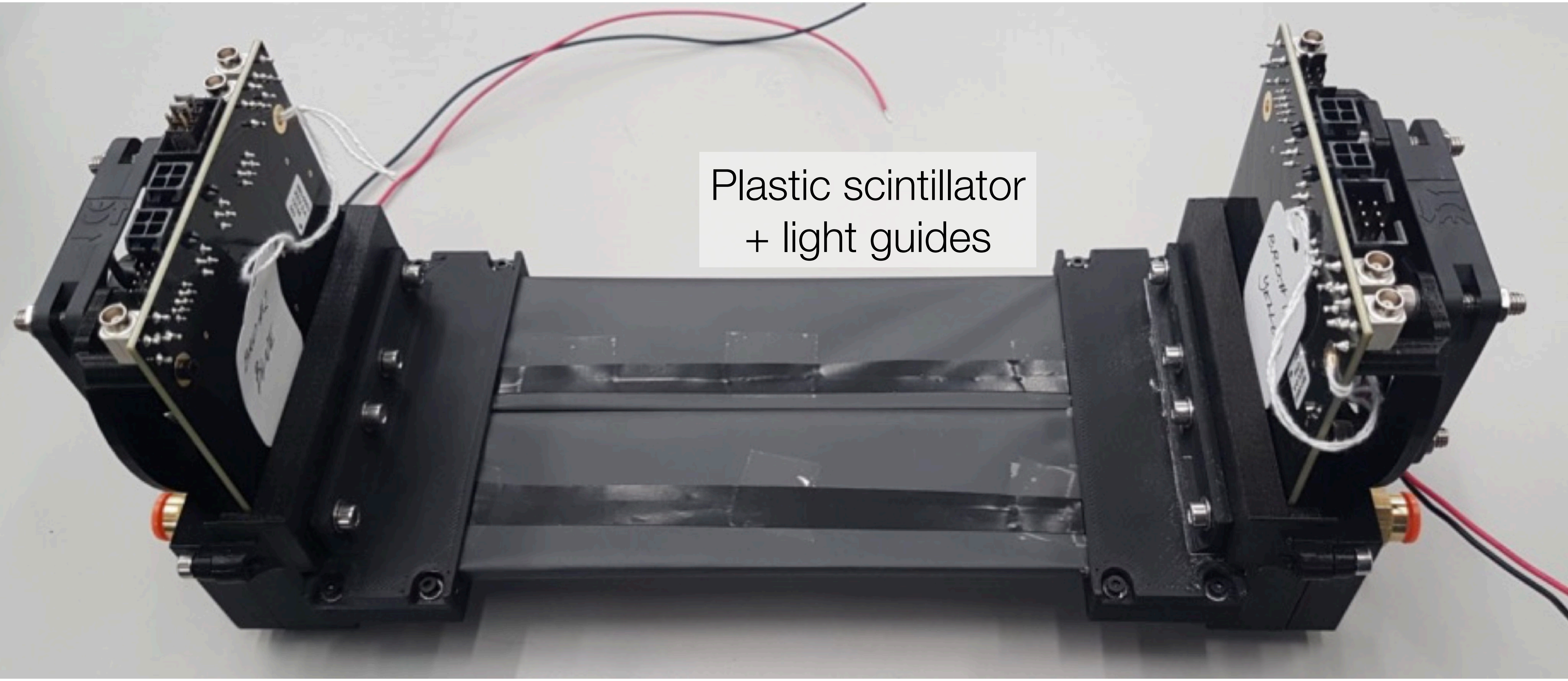
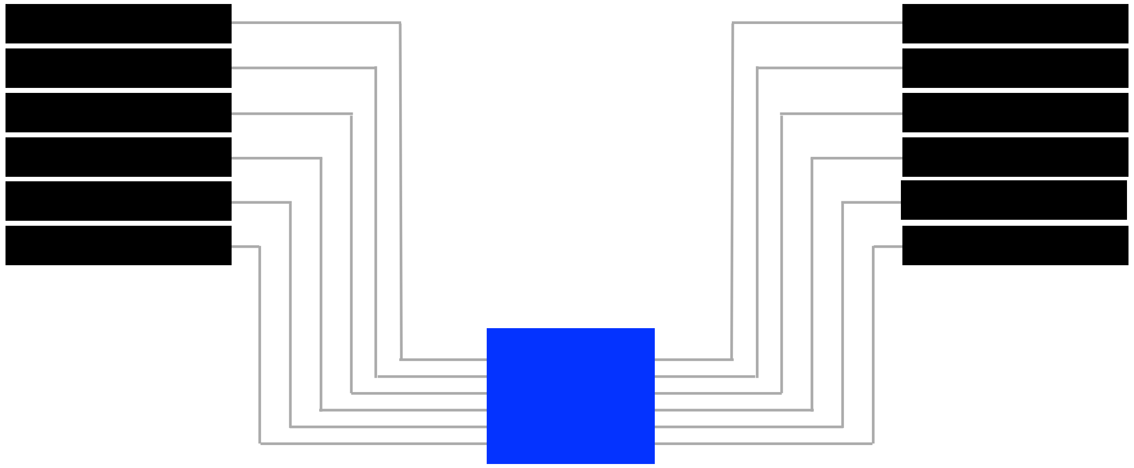


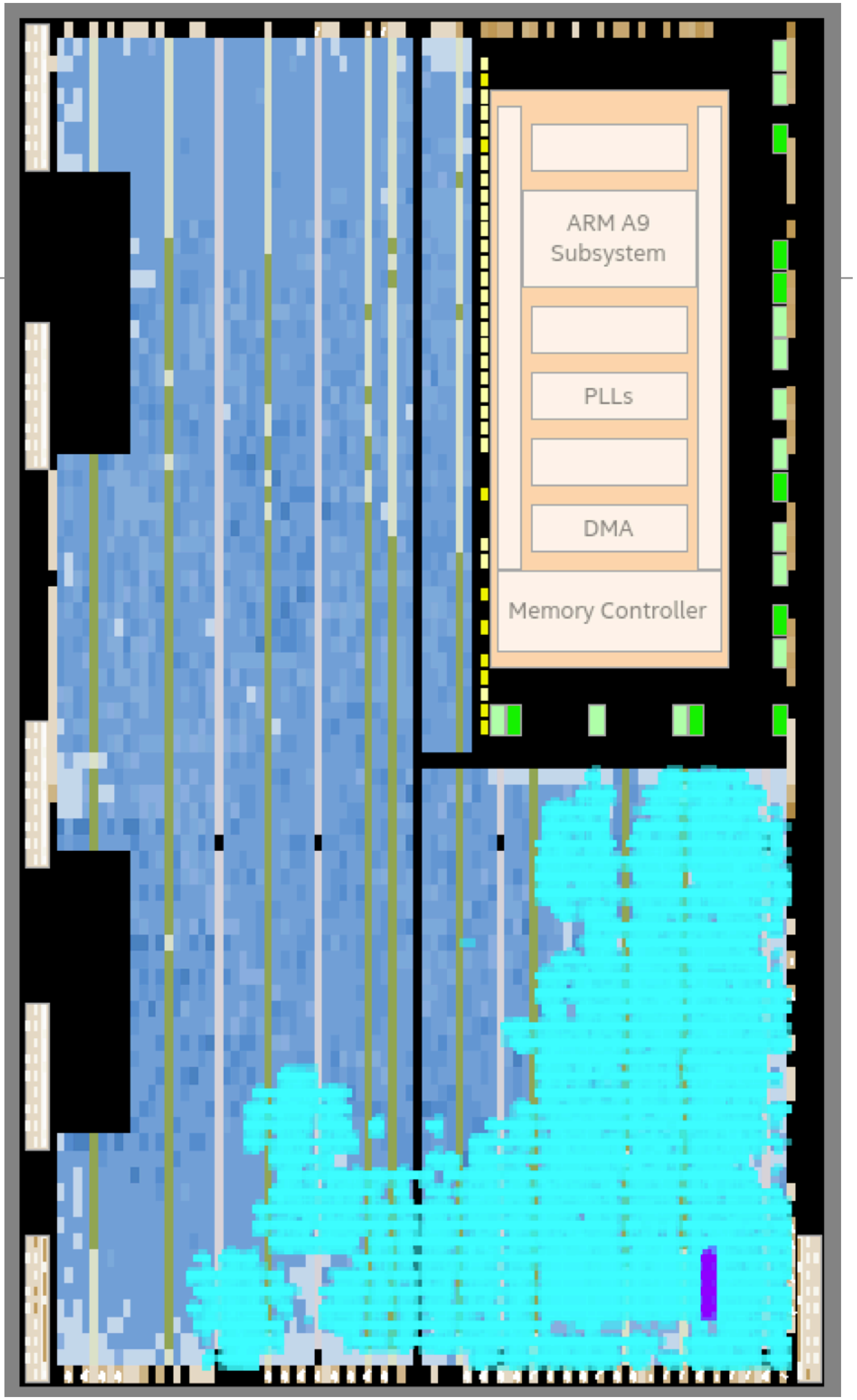
Fans and compressed air to keep SiPMs cool

Entire detector system will sit inside shielding box to protect SiPMs from radiation

Trigger data acquisition

TDCs and coincidence trigger logic being implemented on single Cyclone V FPGA





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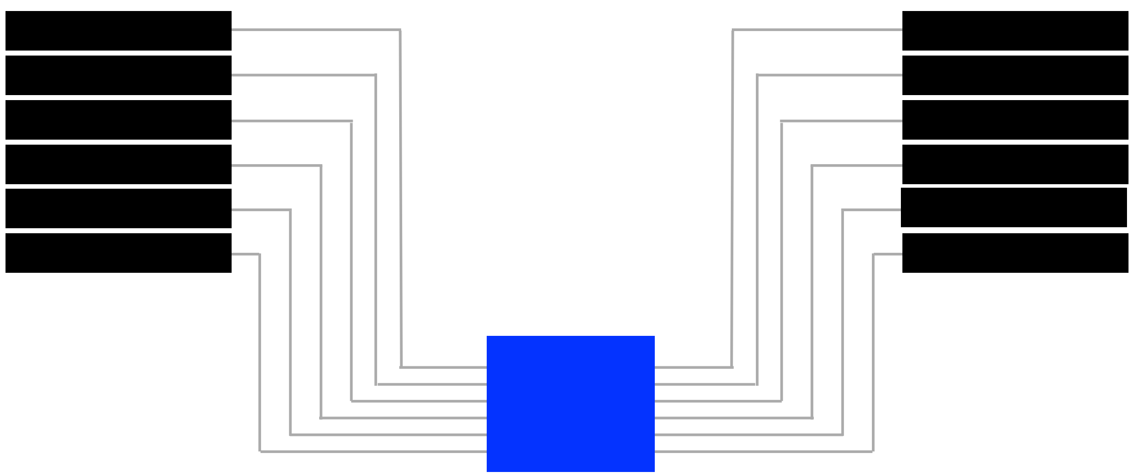
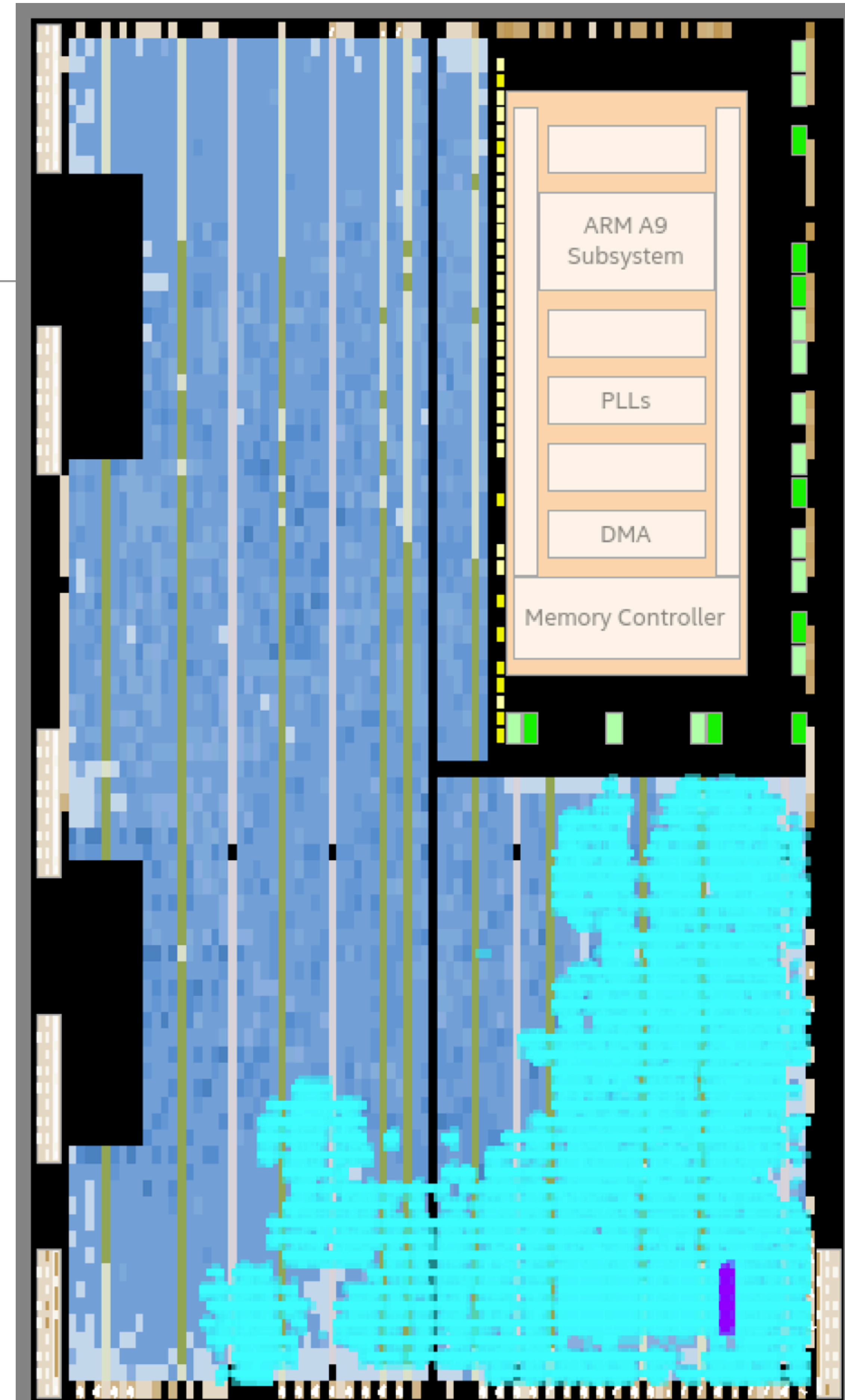


Time in each potential scintillator pair individually based on difference in track path lengths



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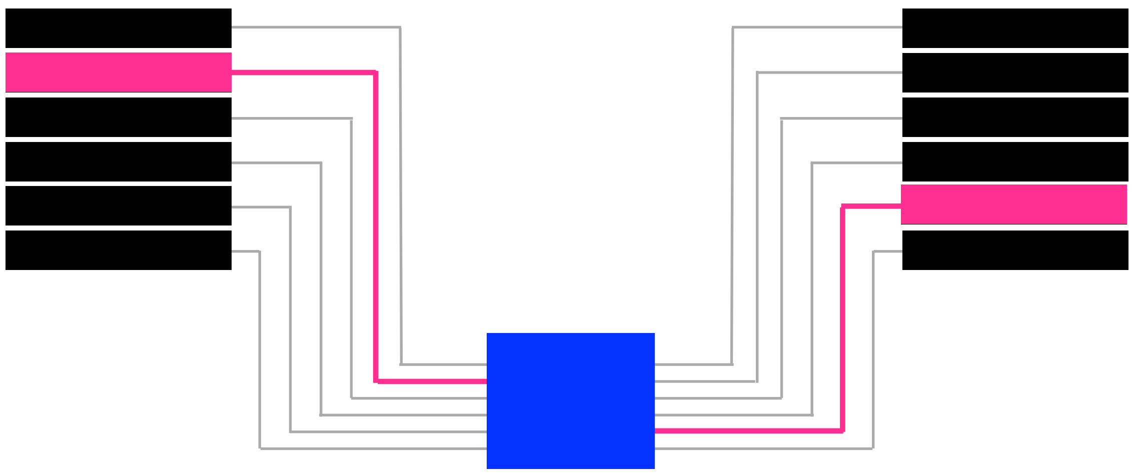

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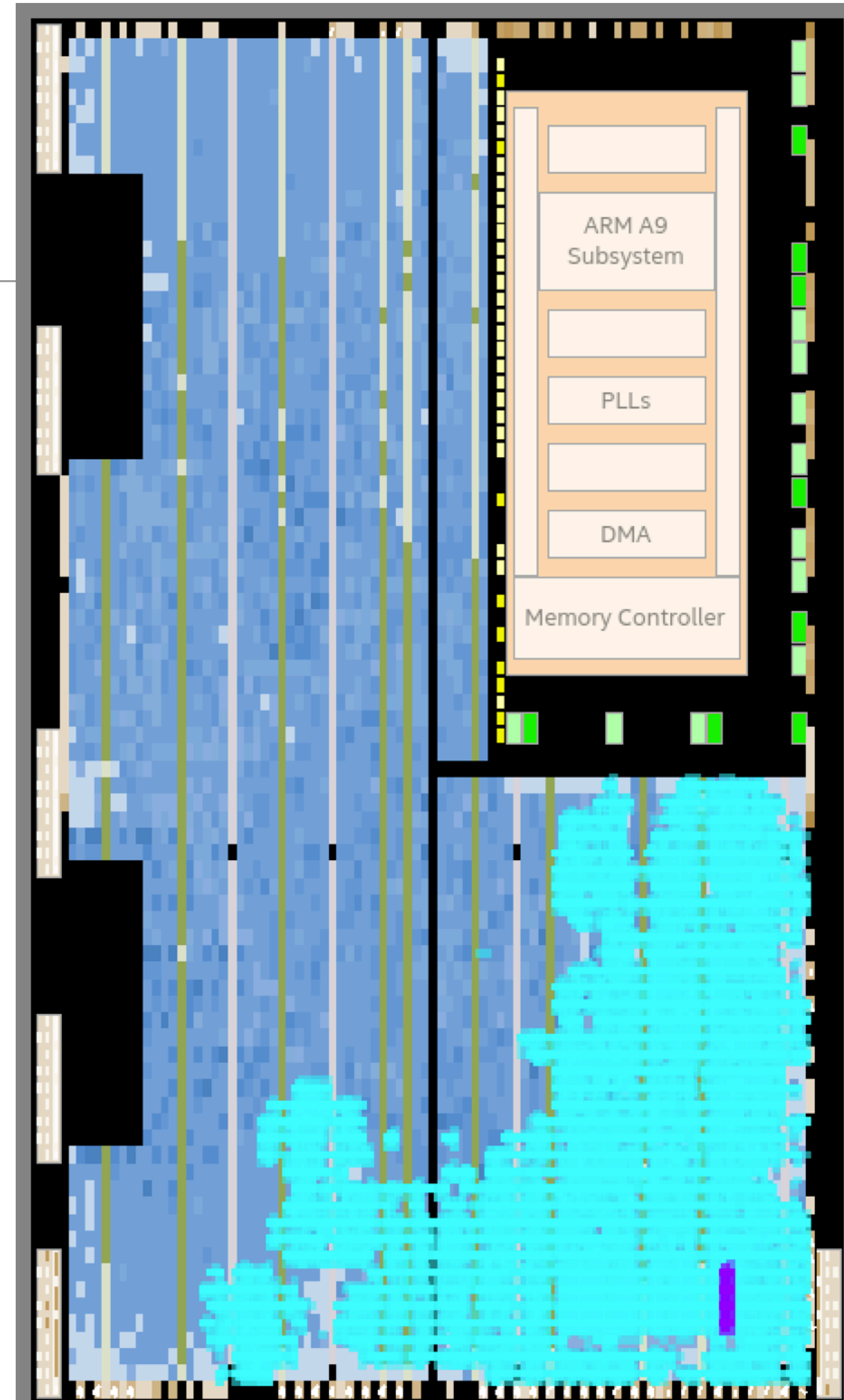

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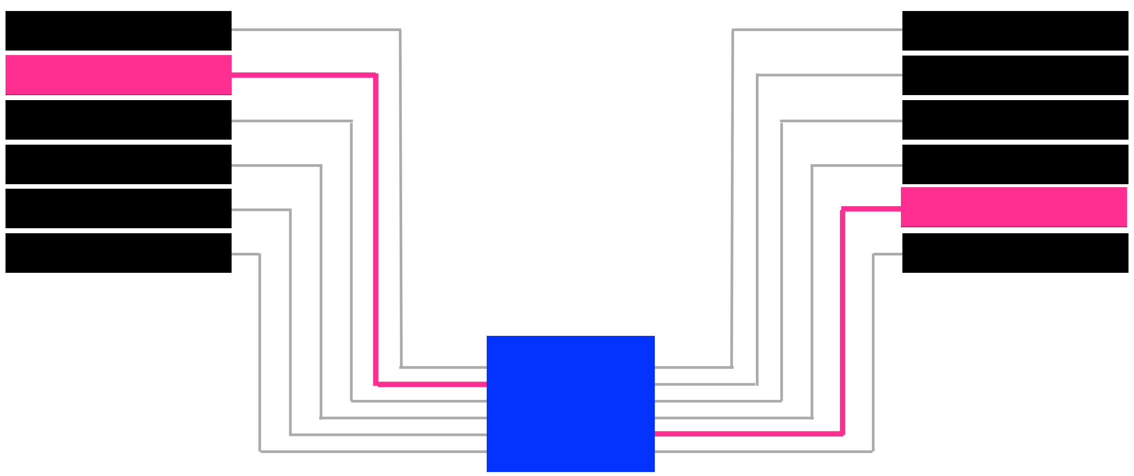
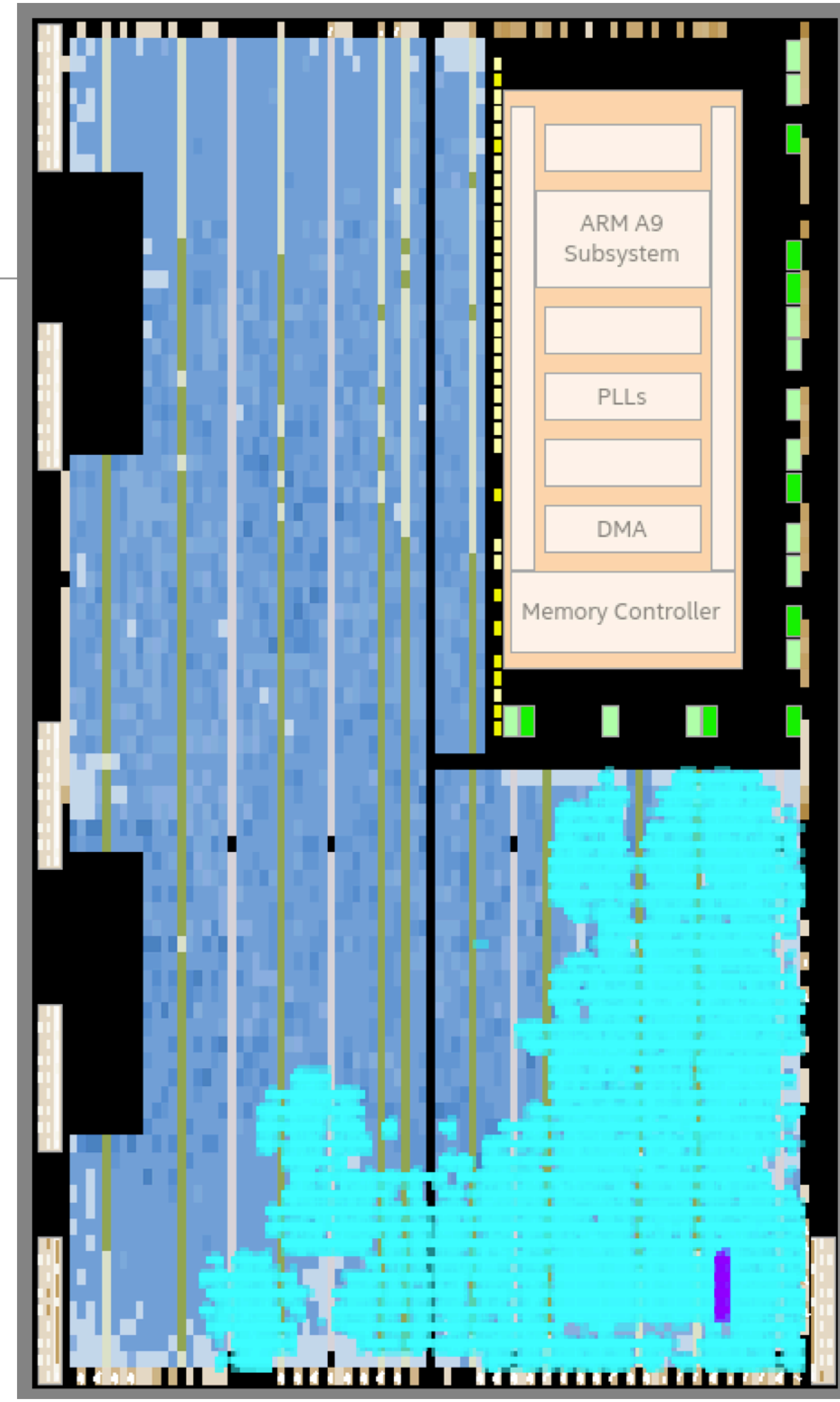


Time in each potential scintillator pair individually based on difference in track path lengths

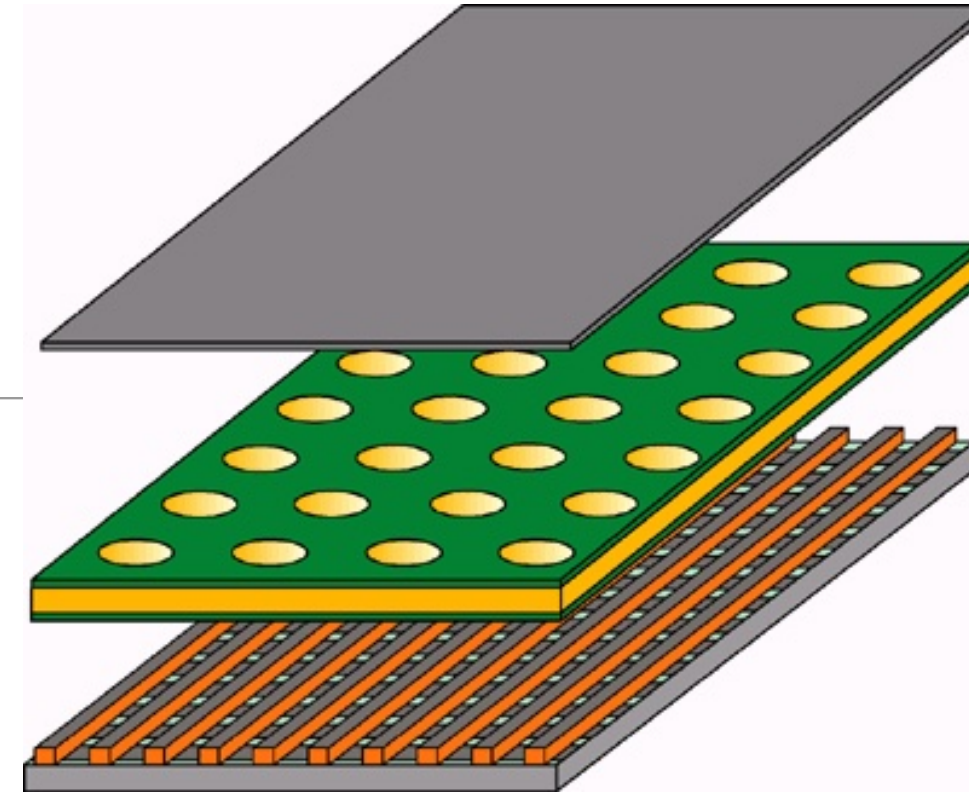
Trigger signal sent when hits observed in each arm compatible with same bunch crossing



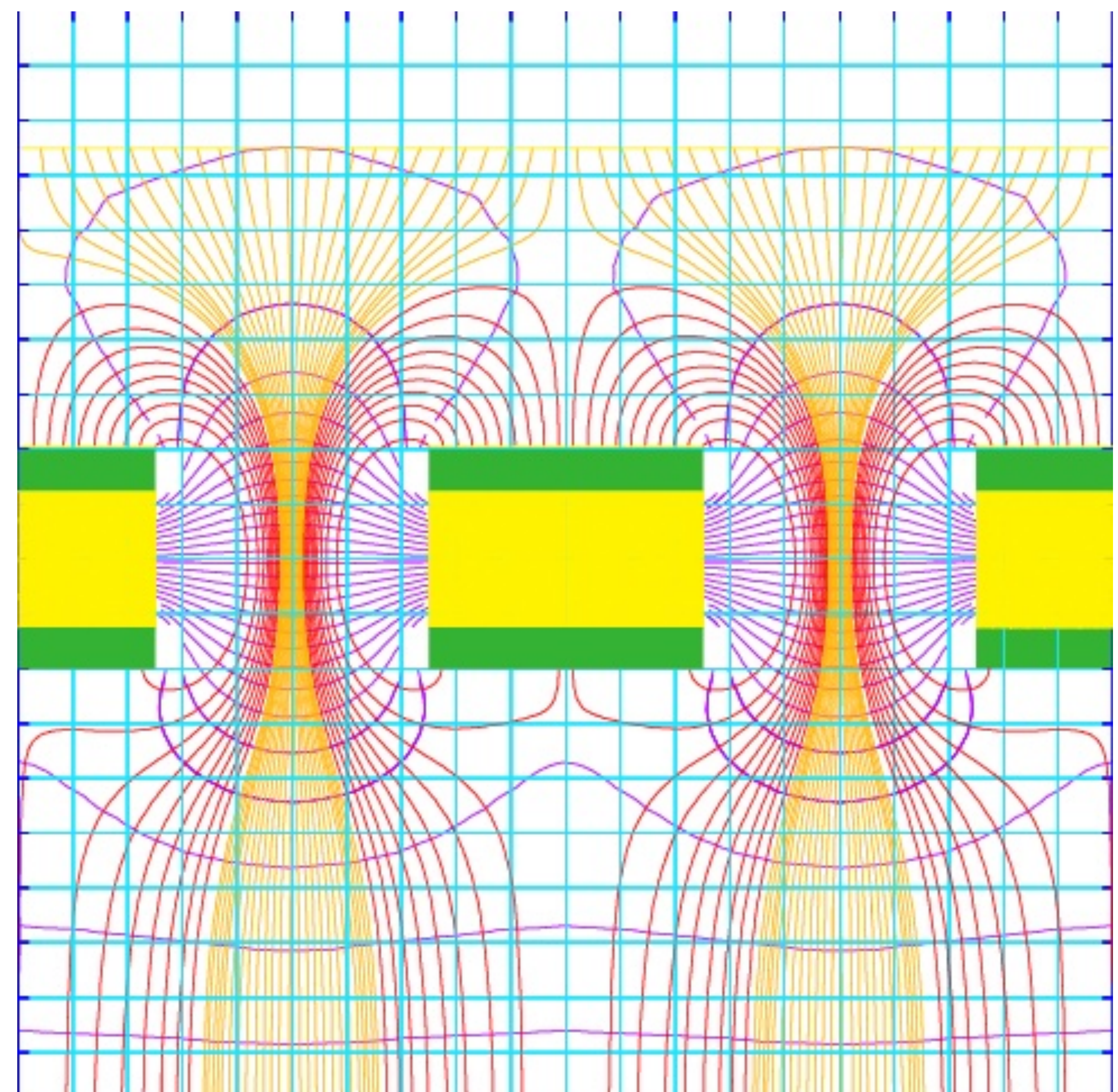
Charged particle tracking detectors

Technology choice for DarkLight:
Gas Electron Multipliers (GEMs)

DarkLight uses two triple-GEMs per spectrometer arm



https://cerncourier.com/a/a-gem-of-a-detector/



CMS NOTE 1999/036

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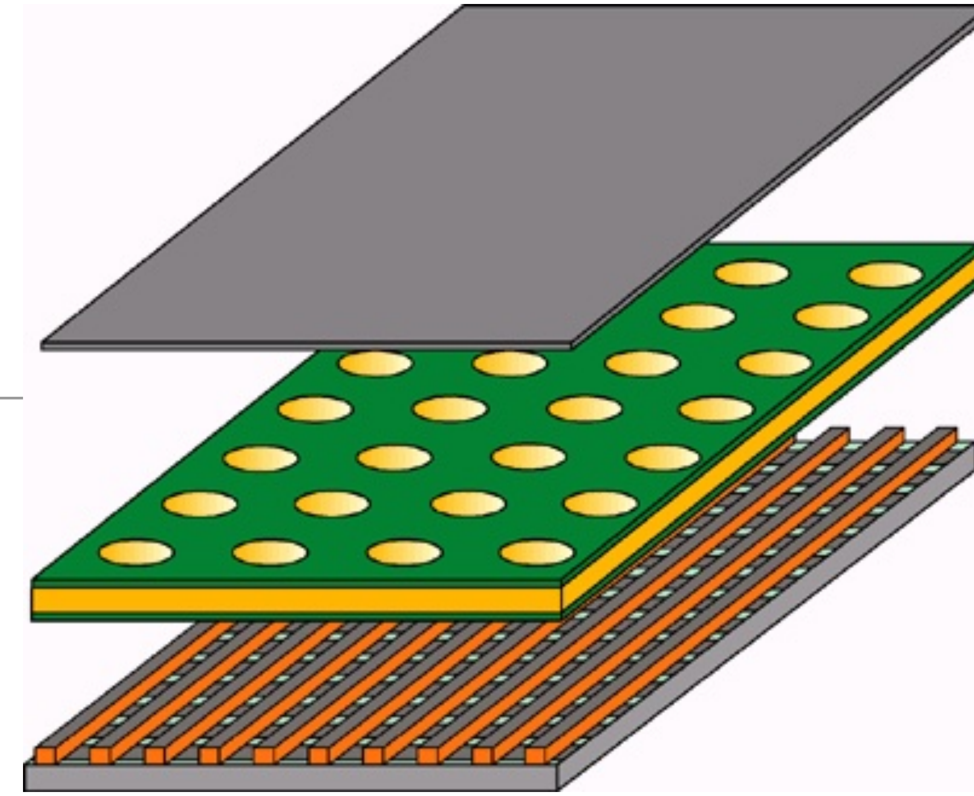

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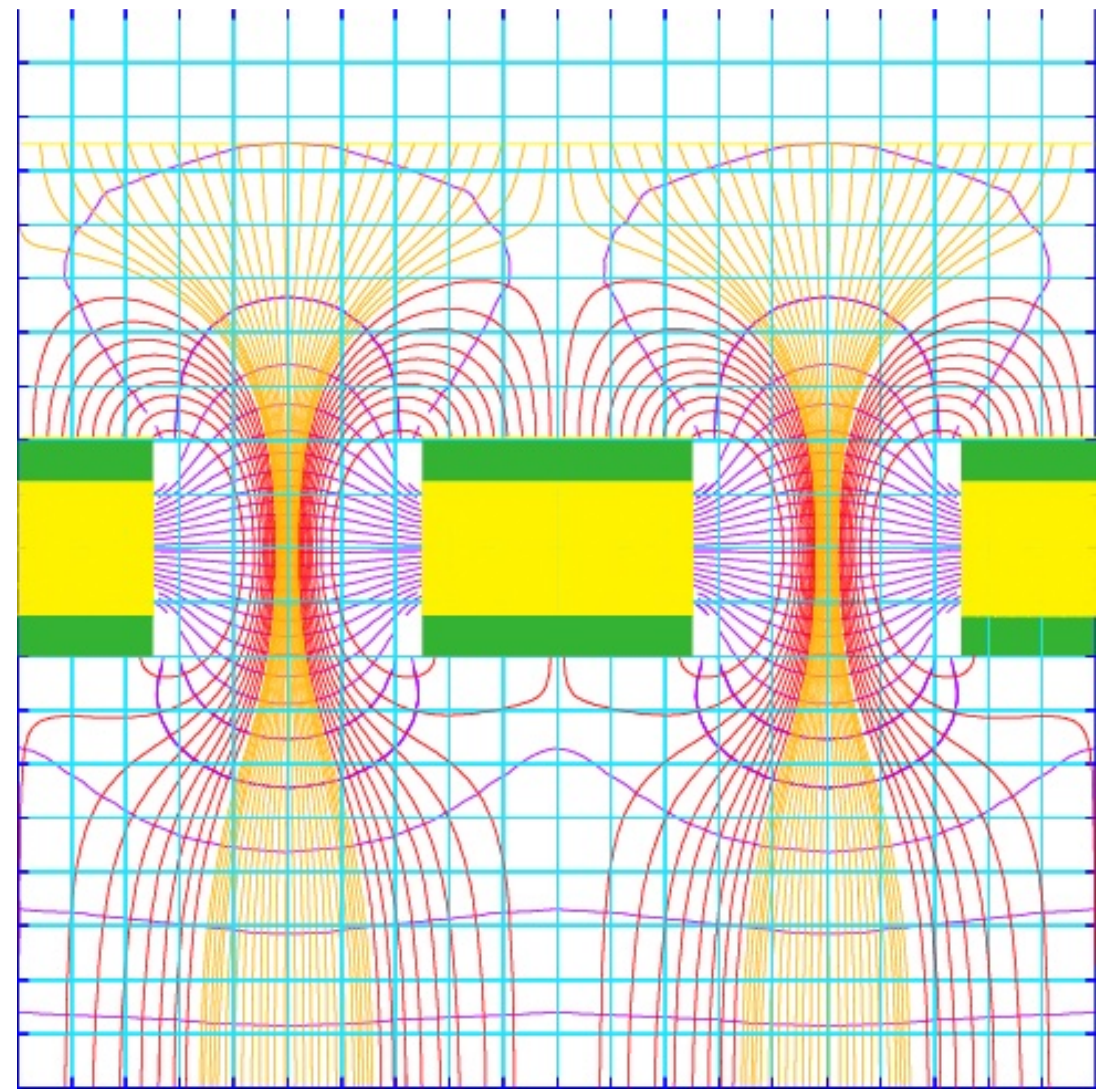

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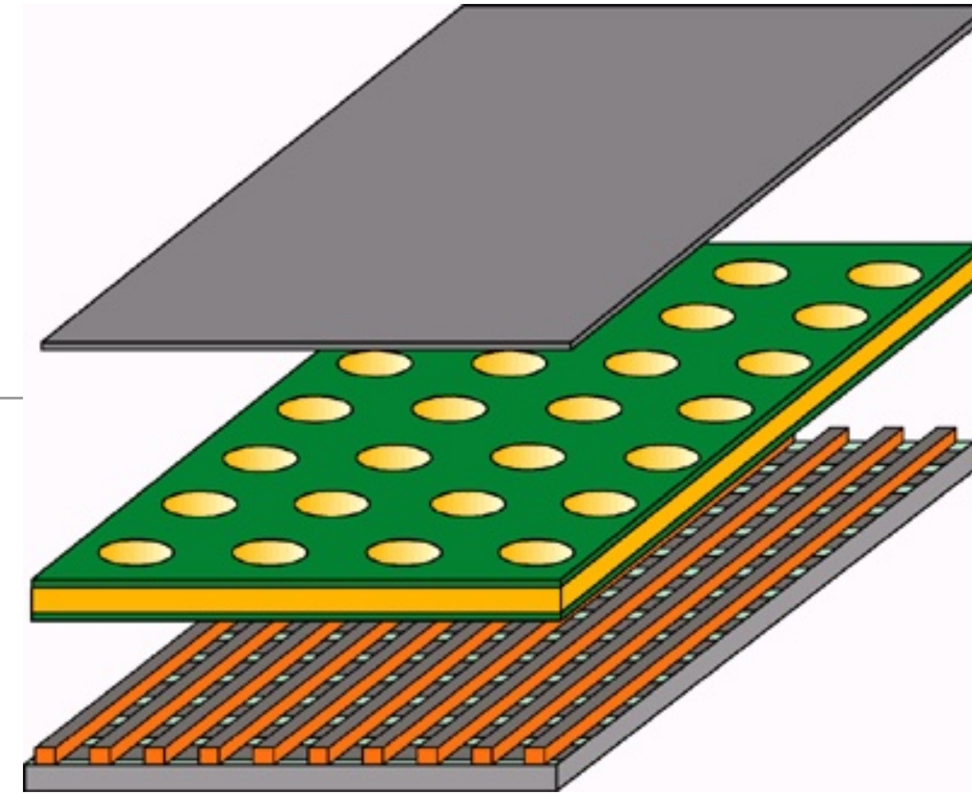

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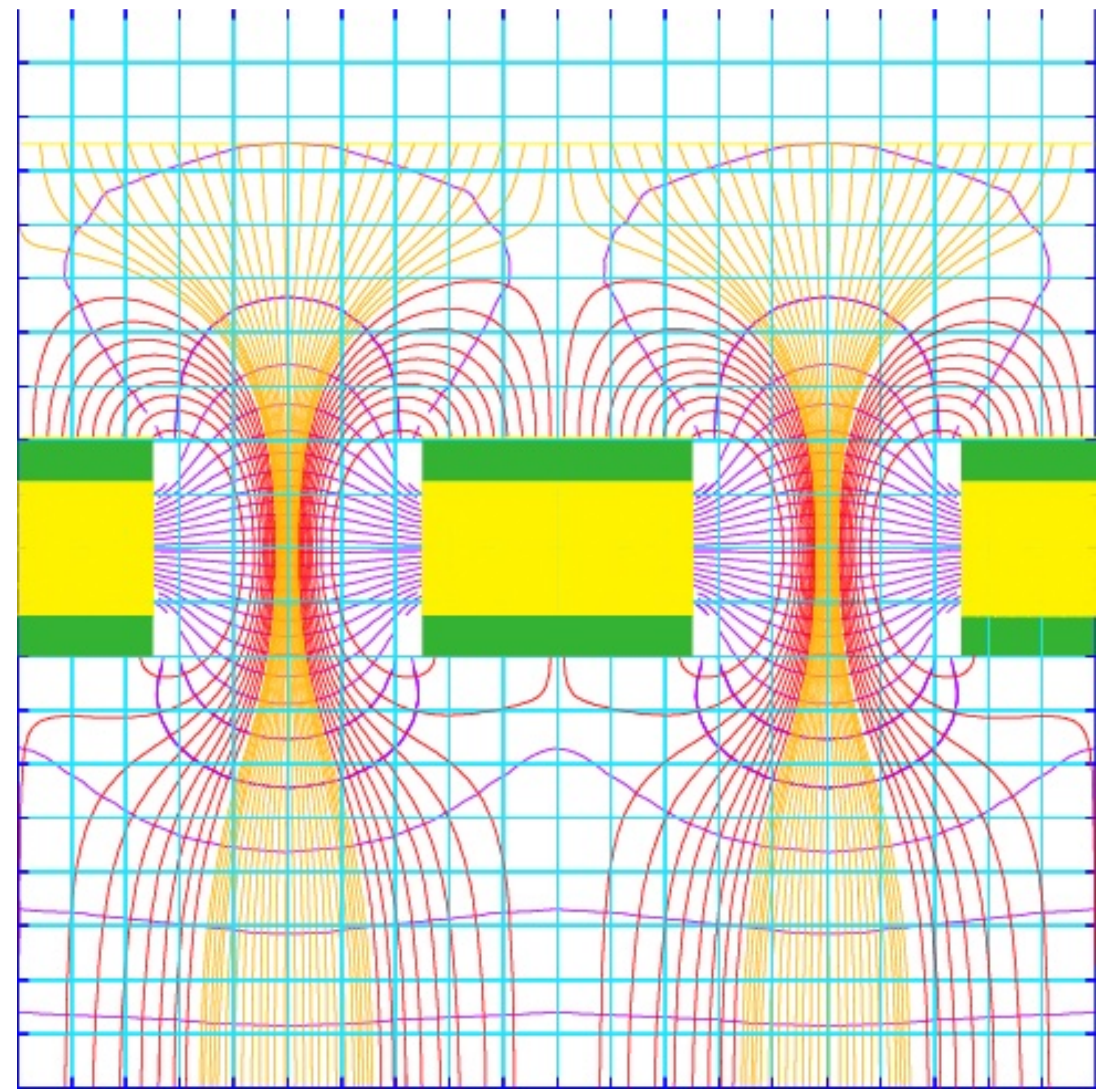

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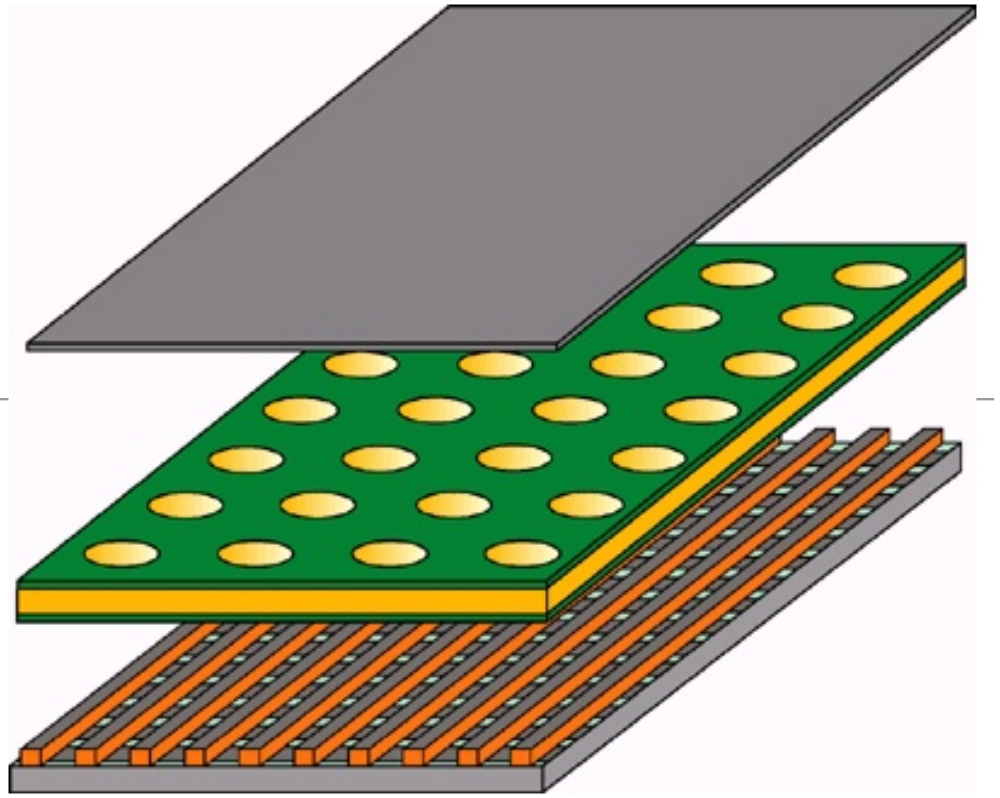

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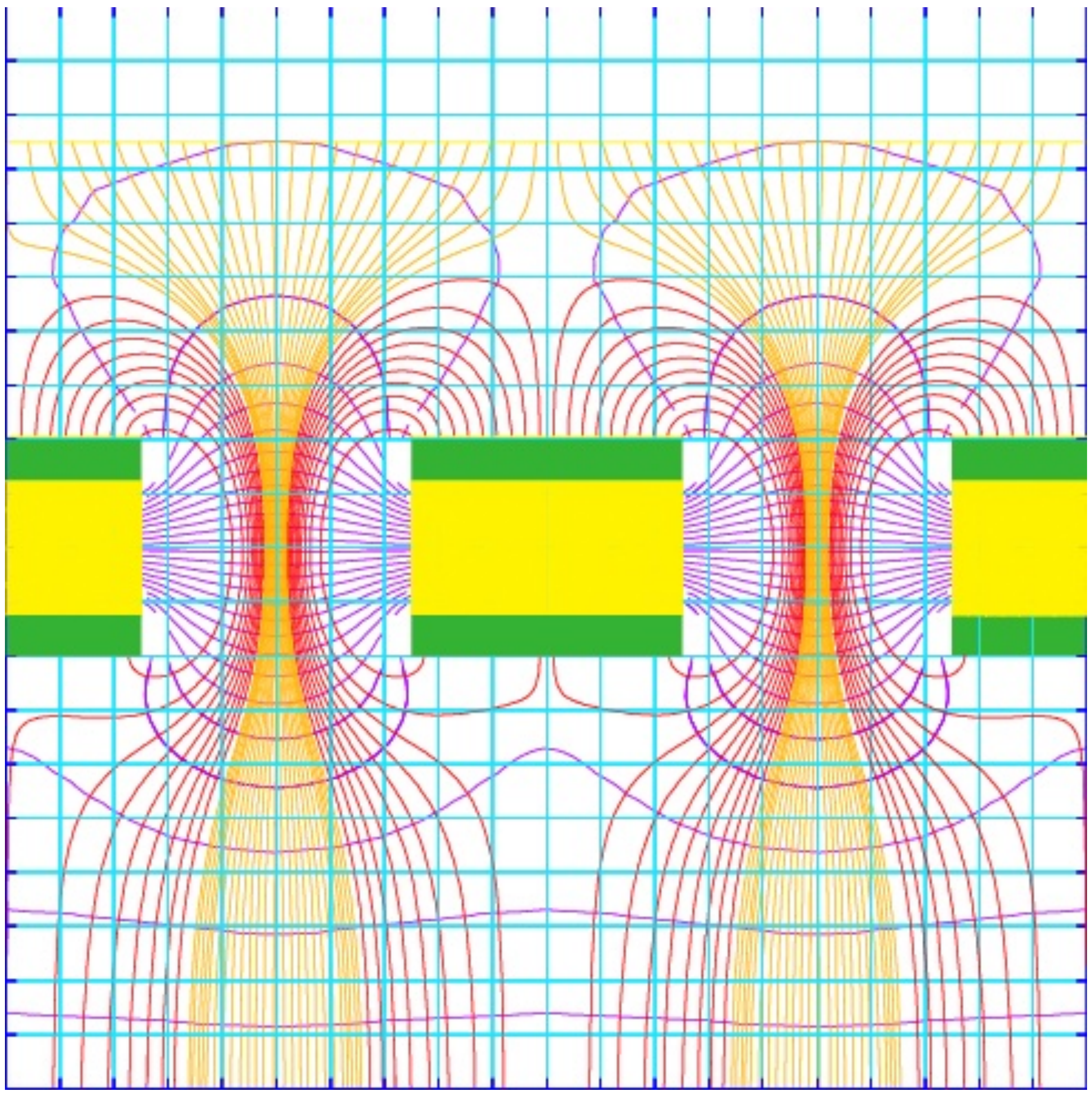

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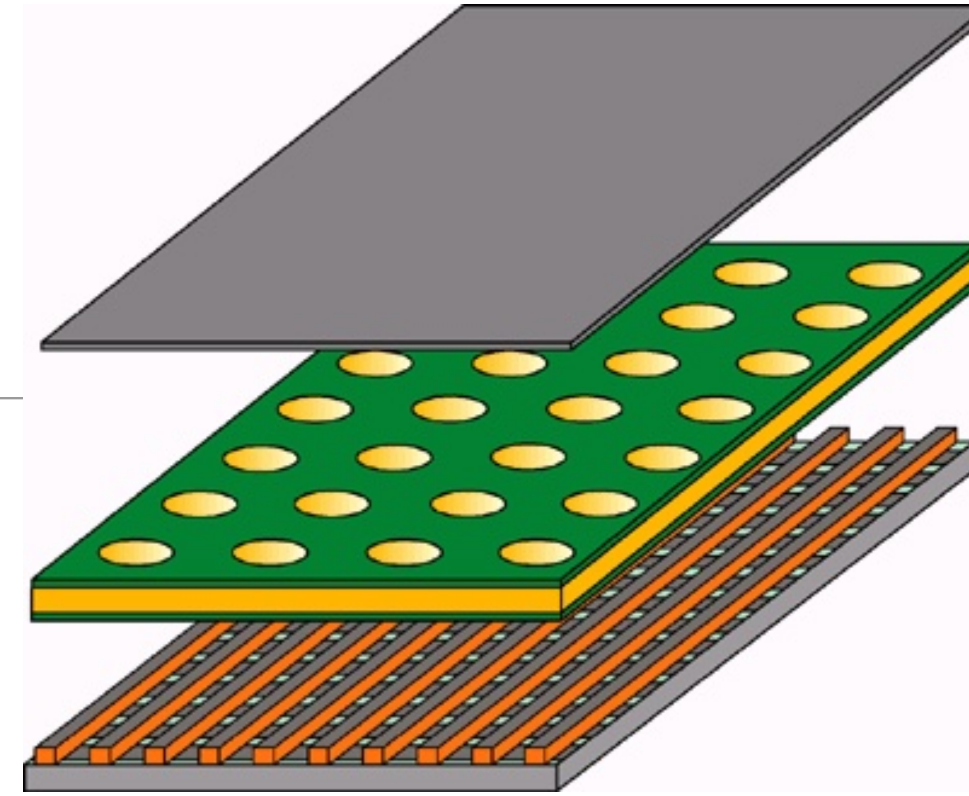

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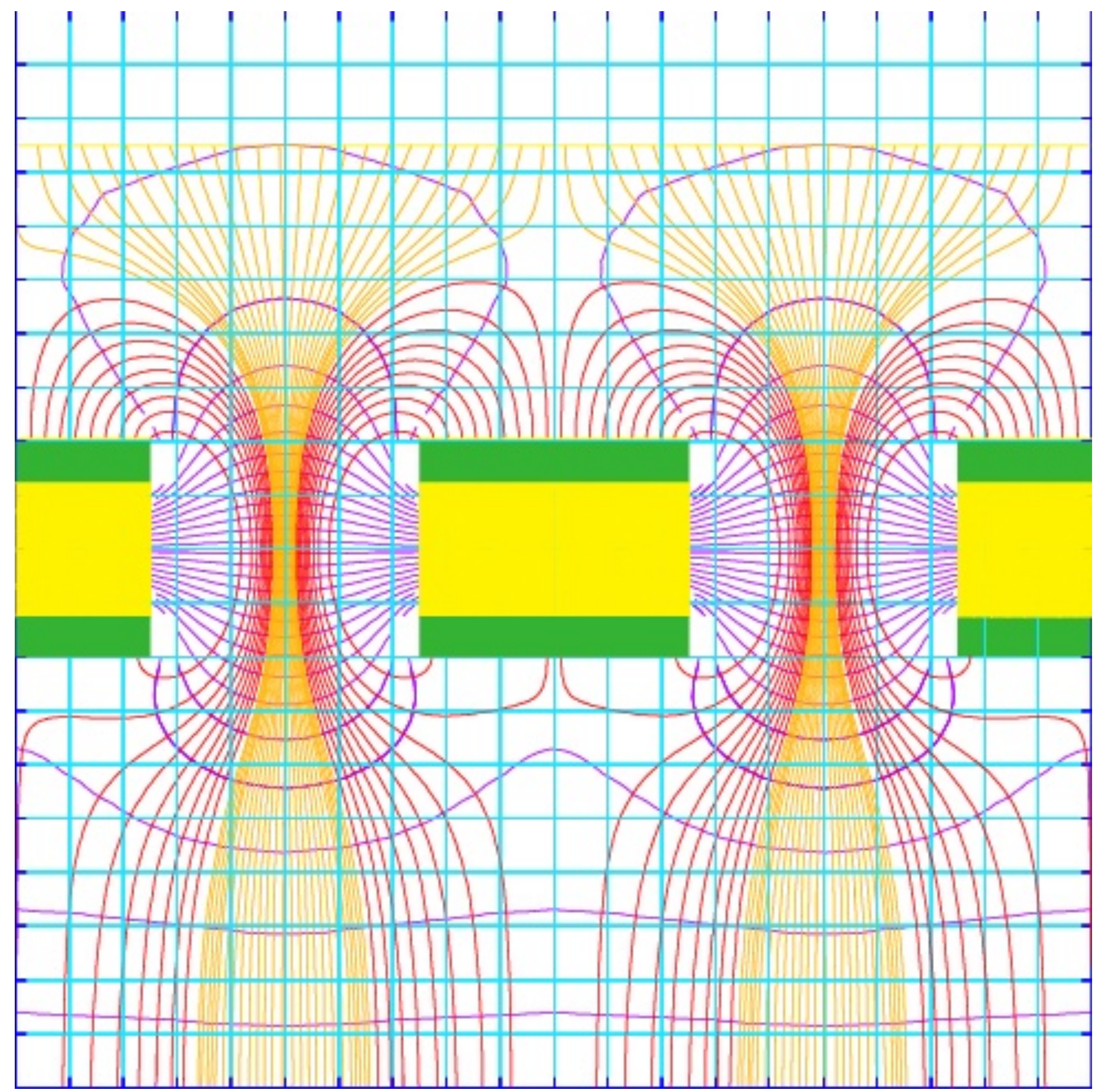

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Technology choice for DarkLight:
Gas Electron Multipliers (GEMs)

DarkLight uses two triple-GEMs per spectrometer arm

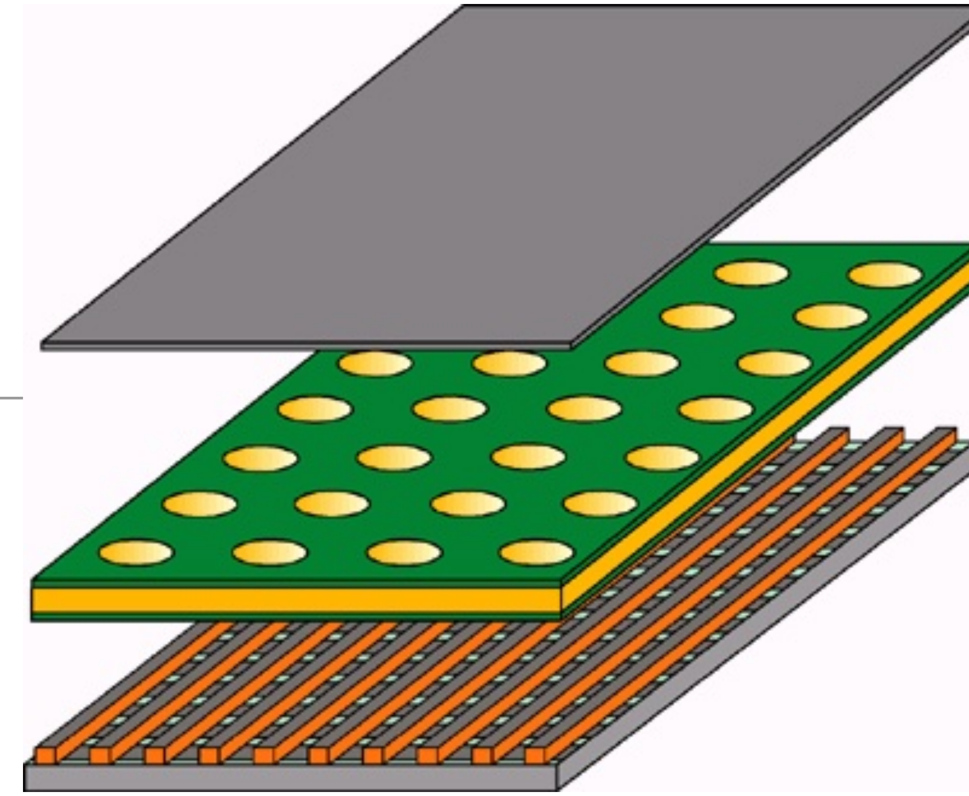
Why GEMs?

Good spatial resolution:
σ~0.1 mm on hit locations

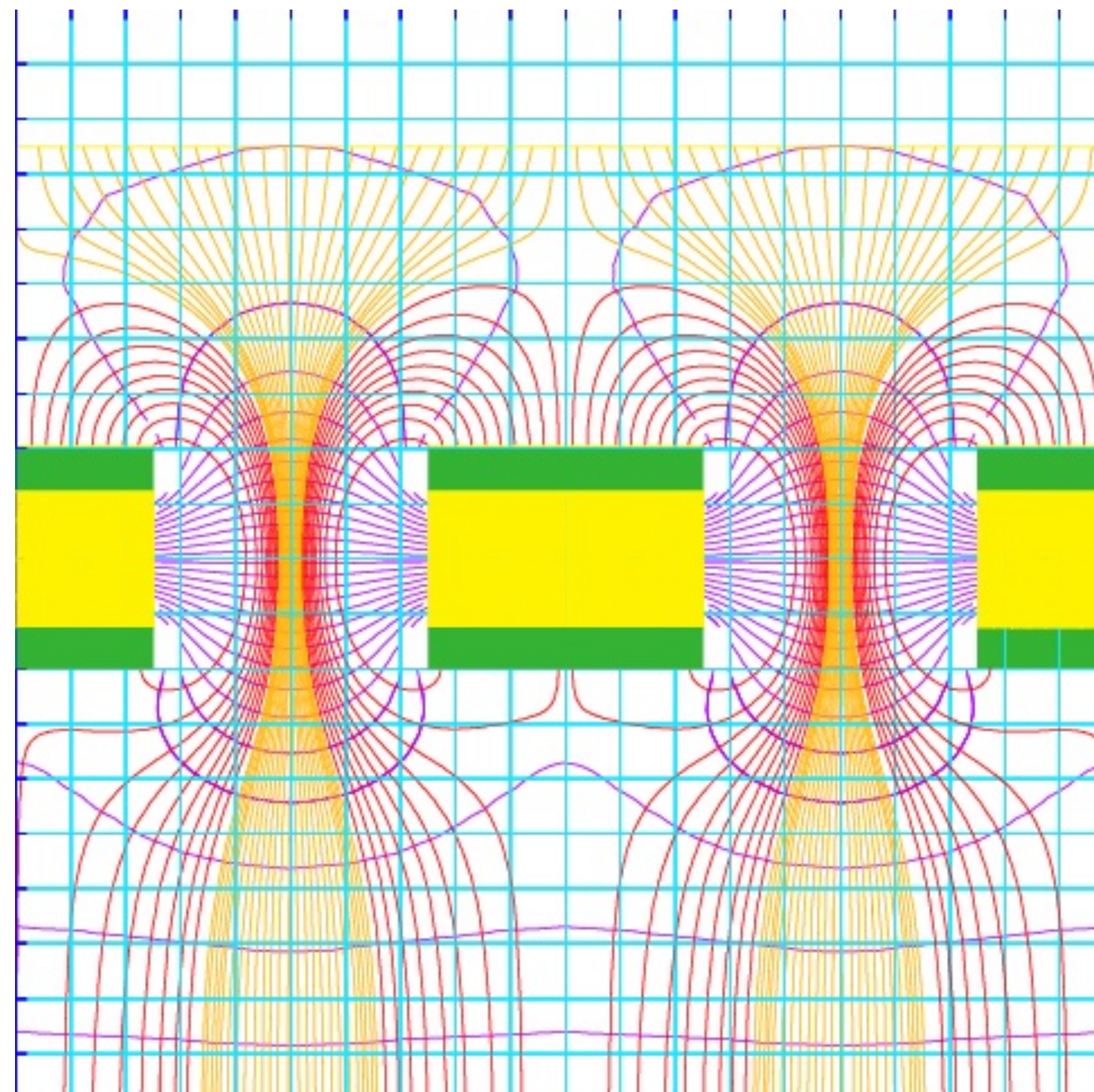
Can sustain high hit rates

Low material density

Affordable/available

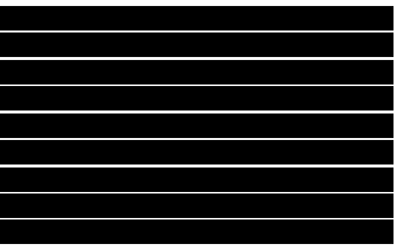


https://cerncourier.com/a/a-gem-of-a-detector/

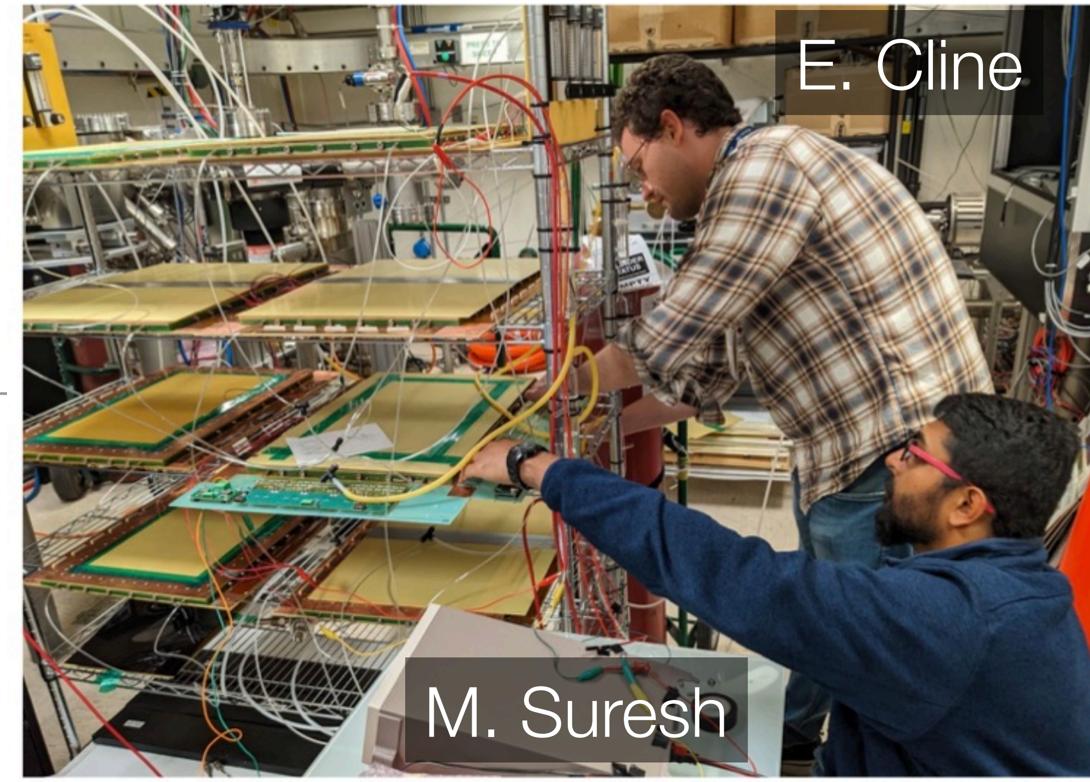


CMS NOTE 1999/036

GEM support and DAQ



GEM
strips



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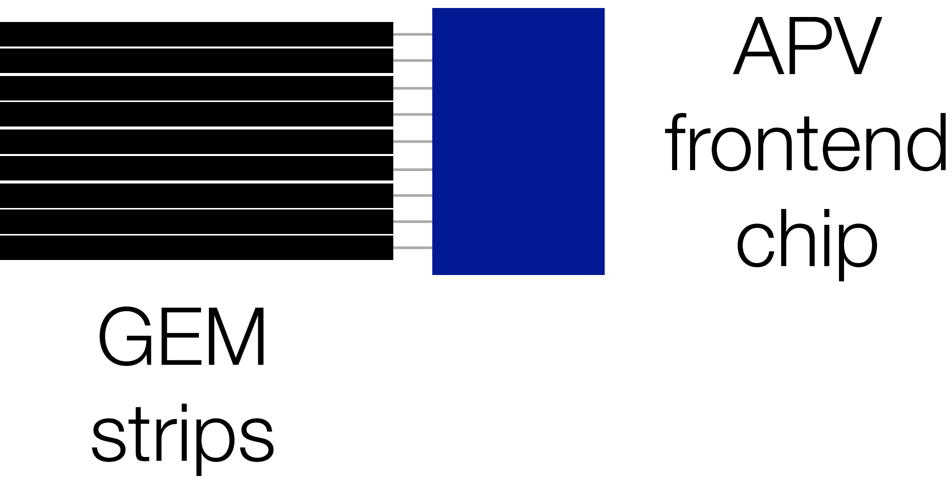

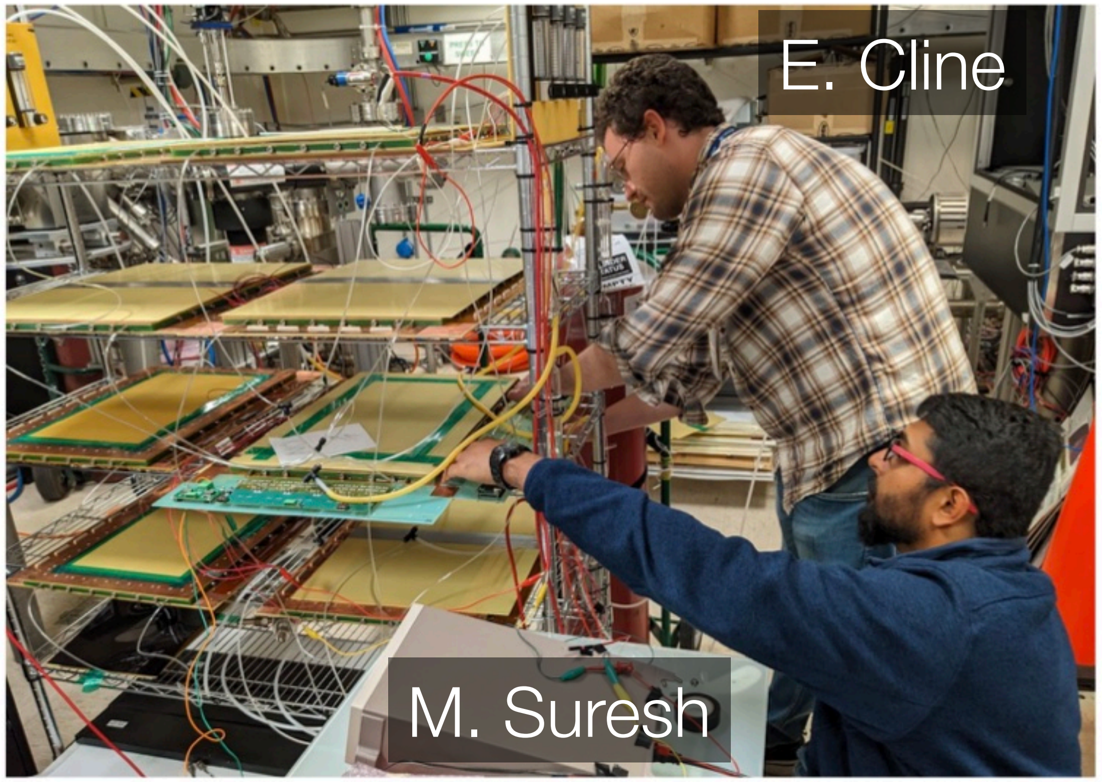

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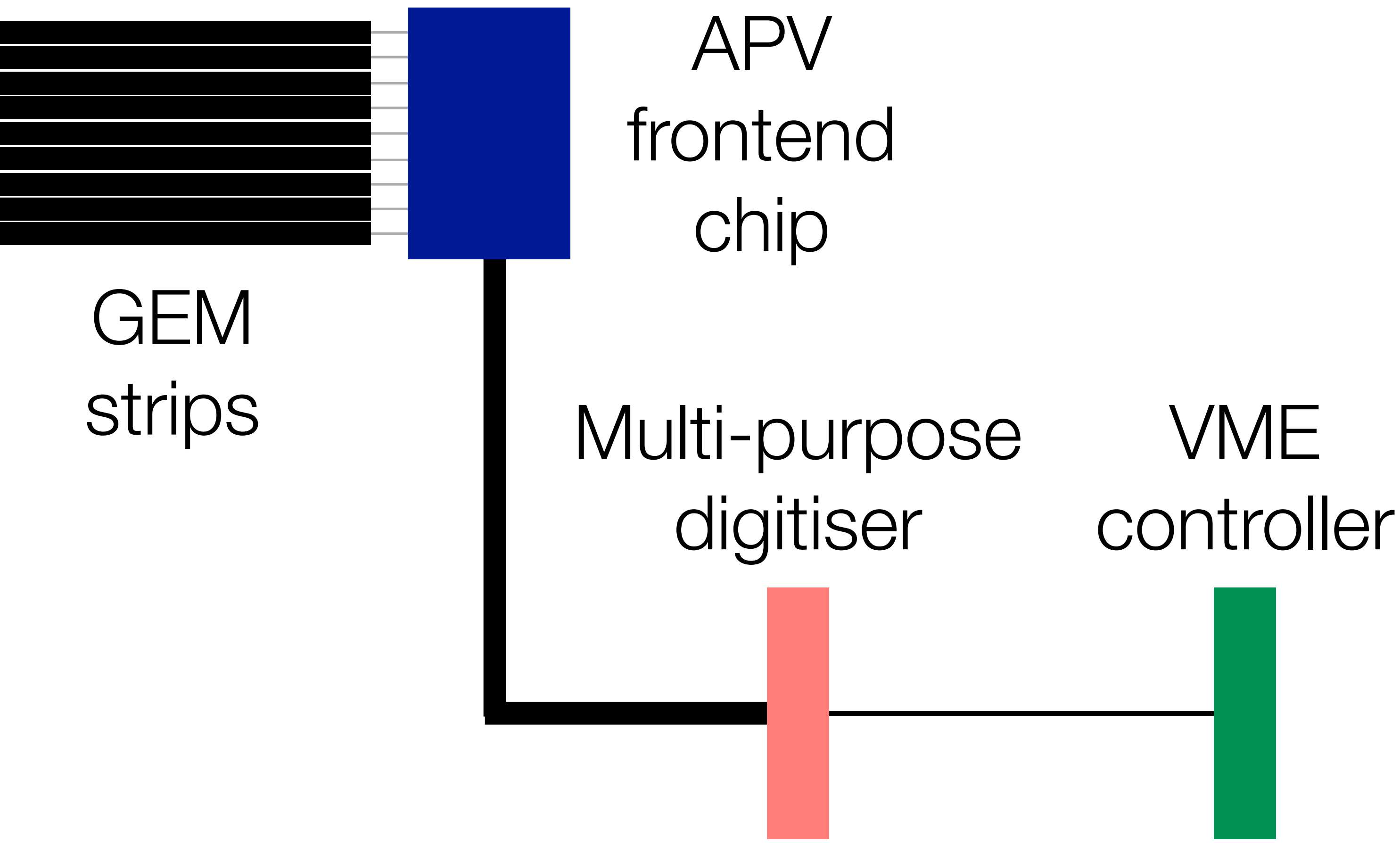

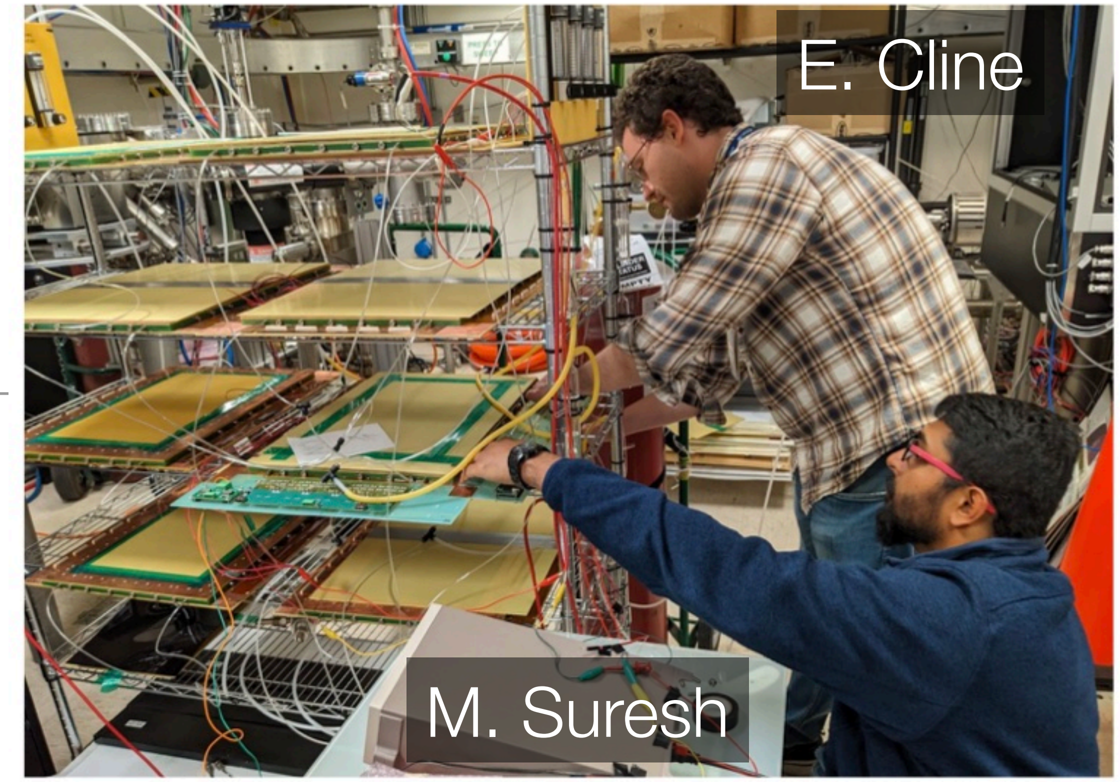

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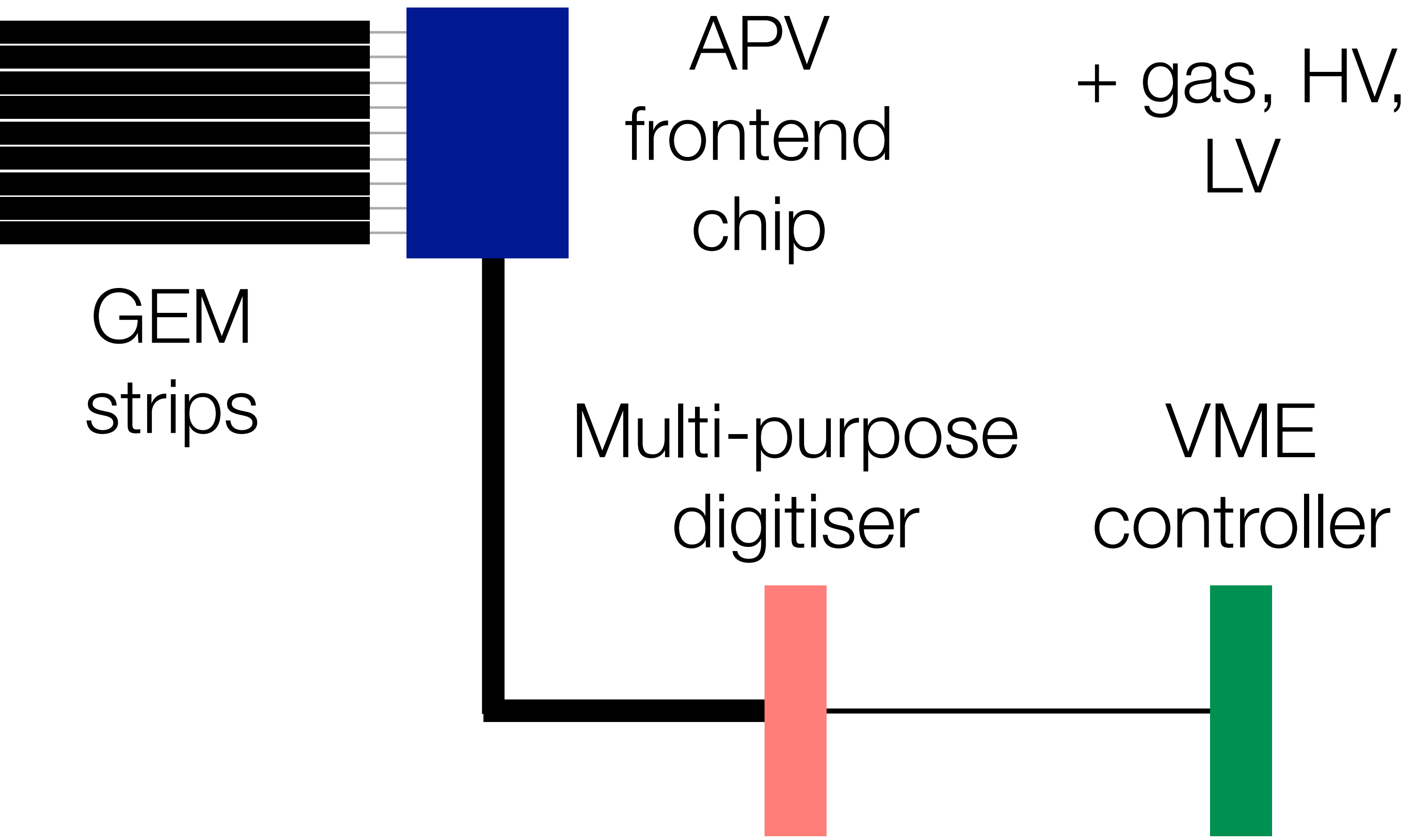

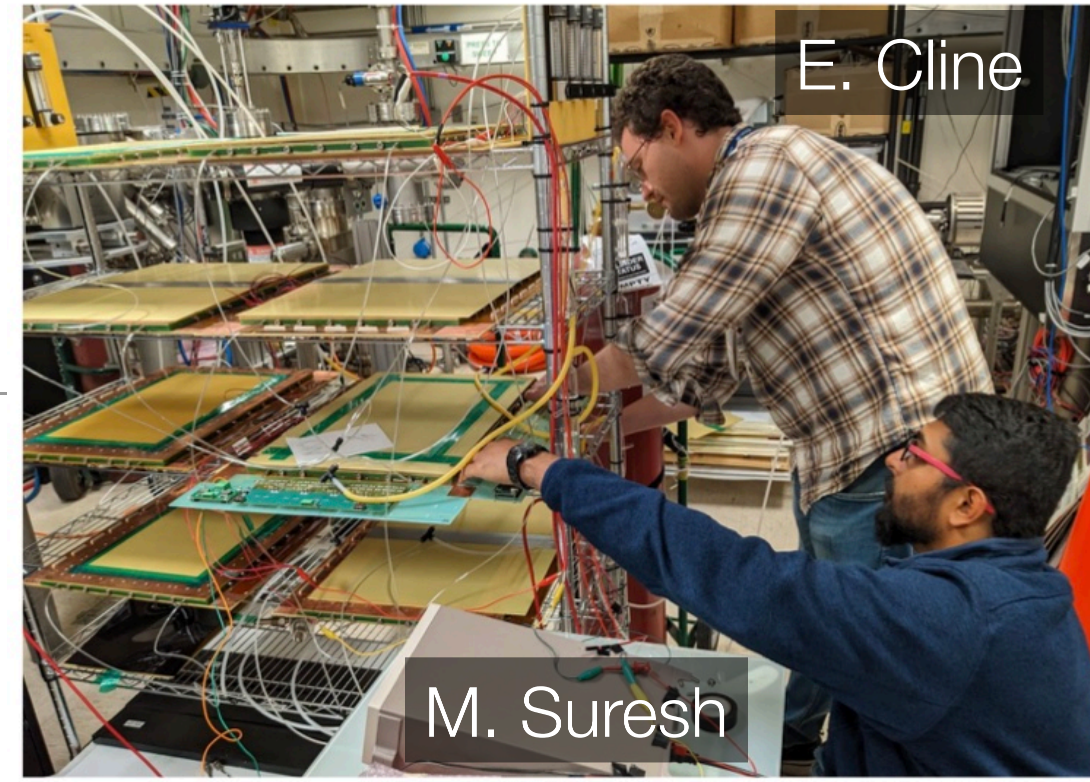

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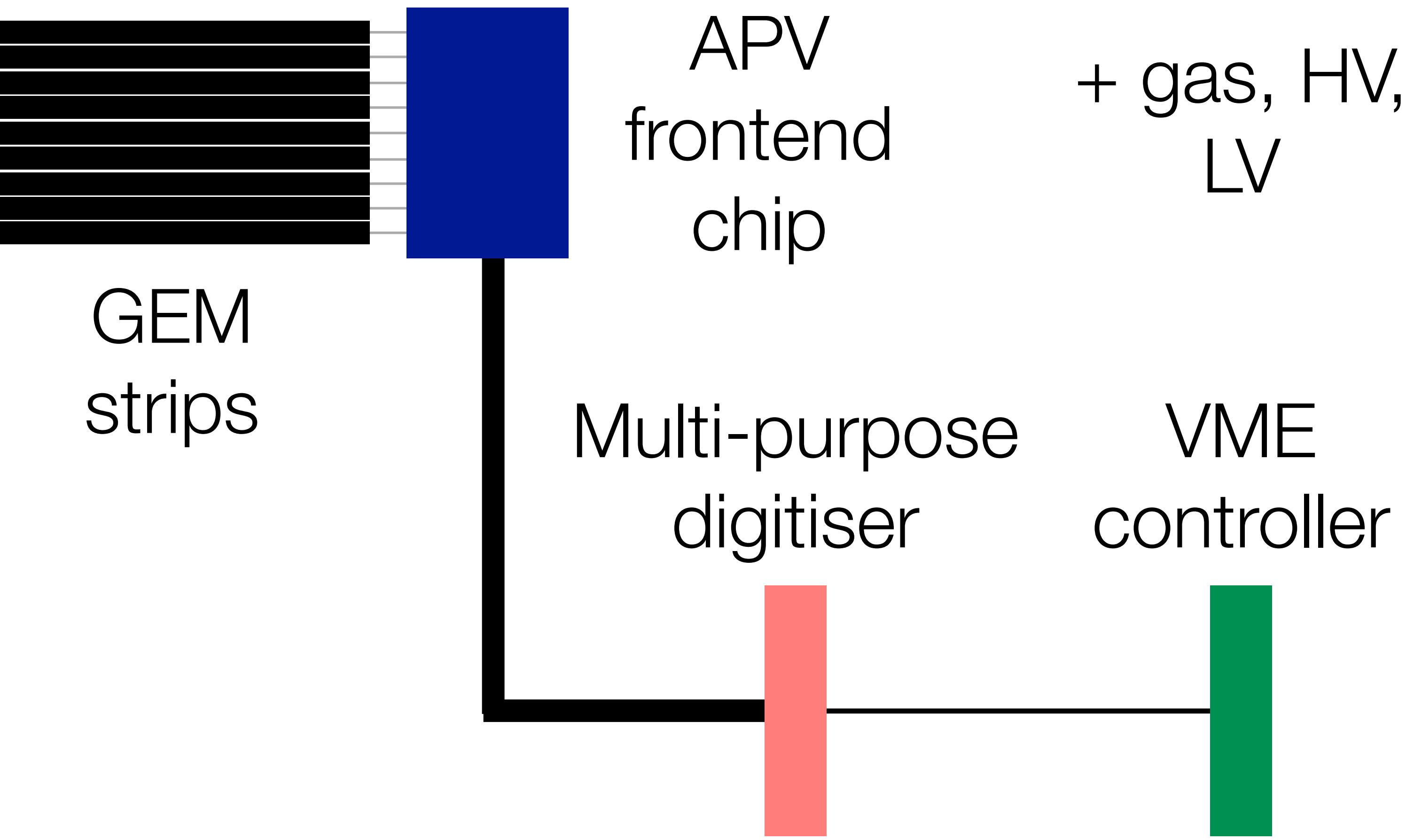
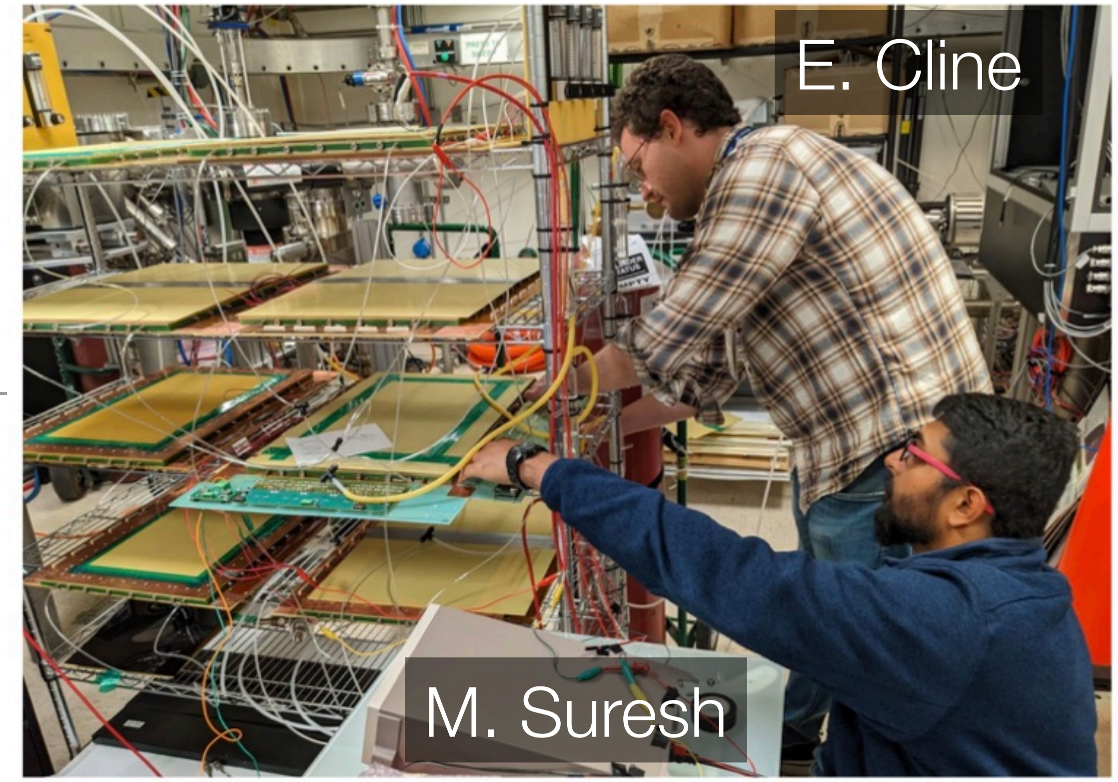
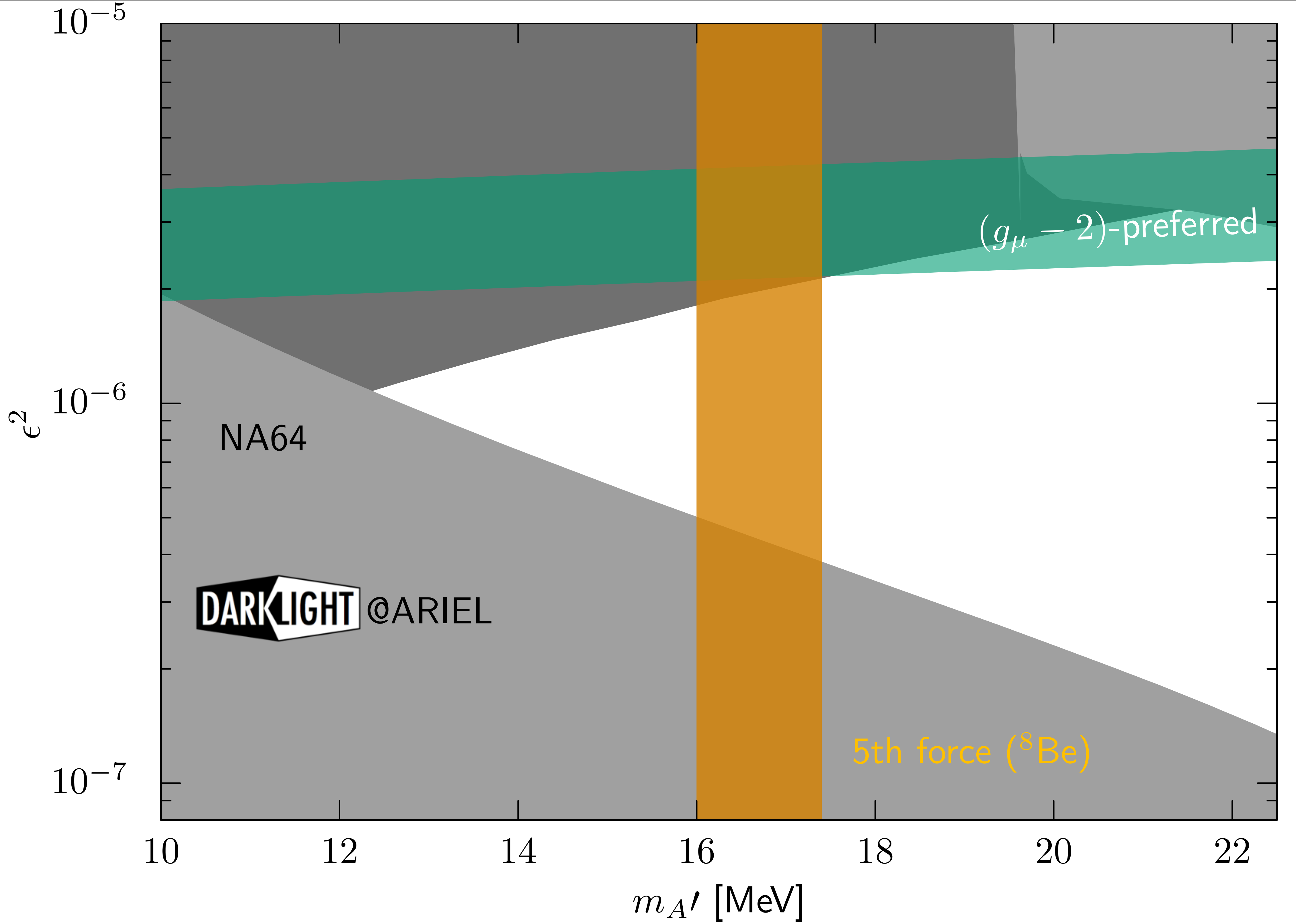




GEMs radiation tolerant, but electronics are sensitive

House power supplies and VME crate in shielded hut in e-linac hall

Projected sensitivity



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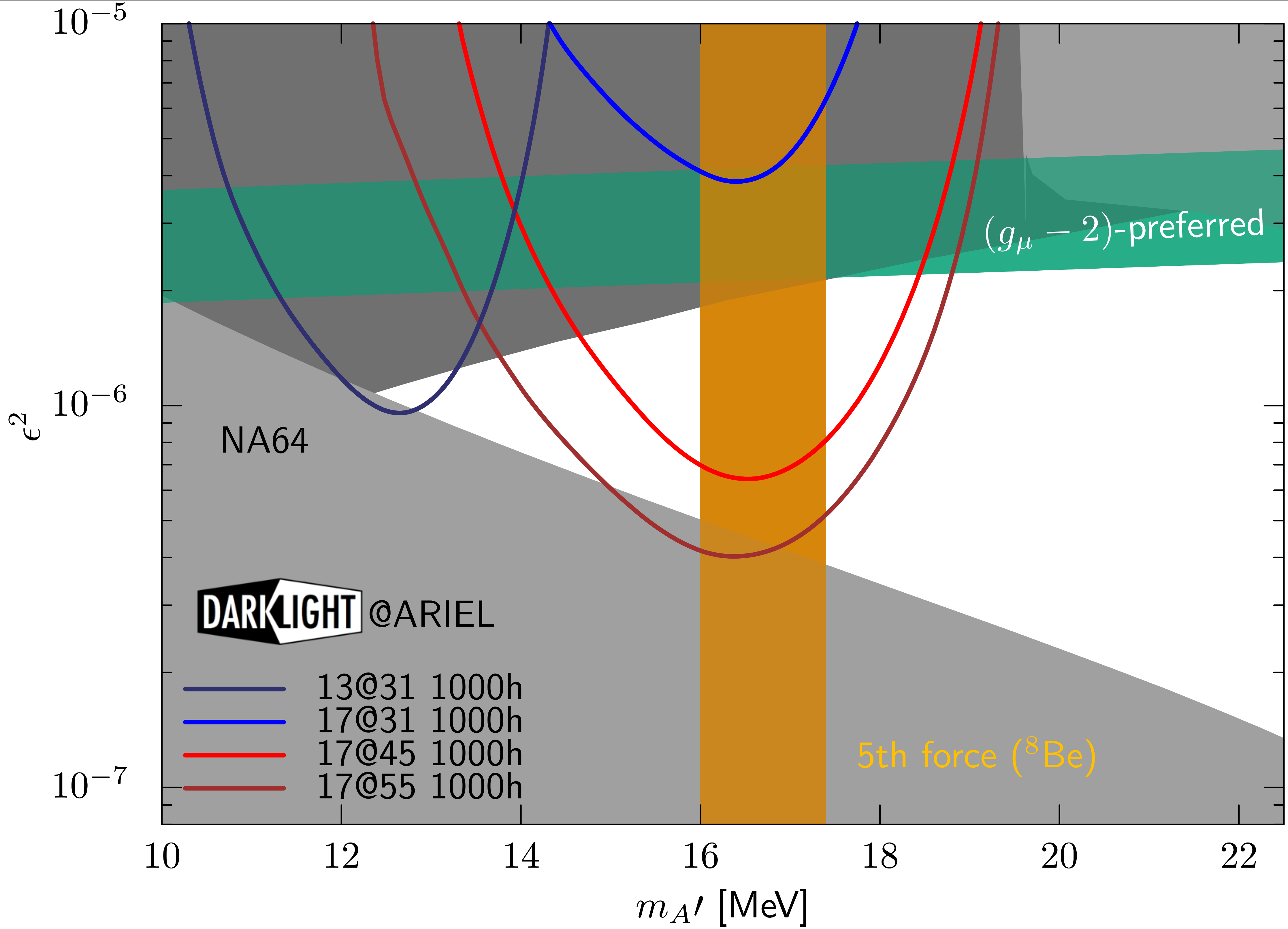

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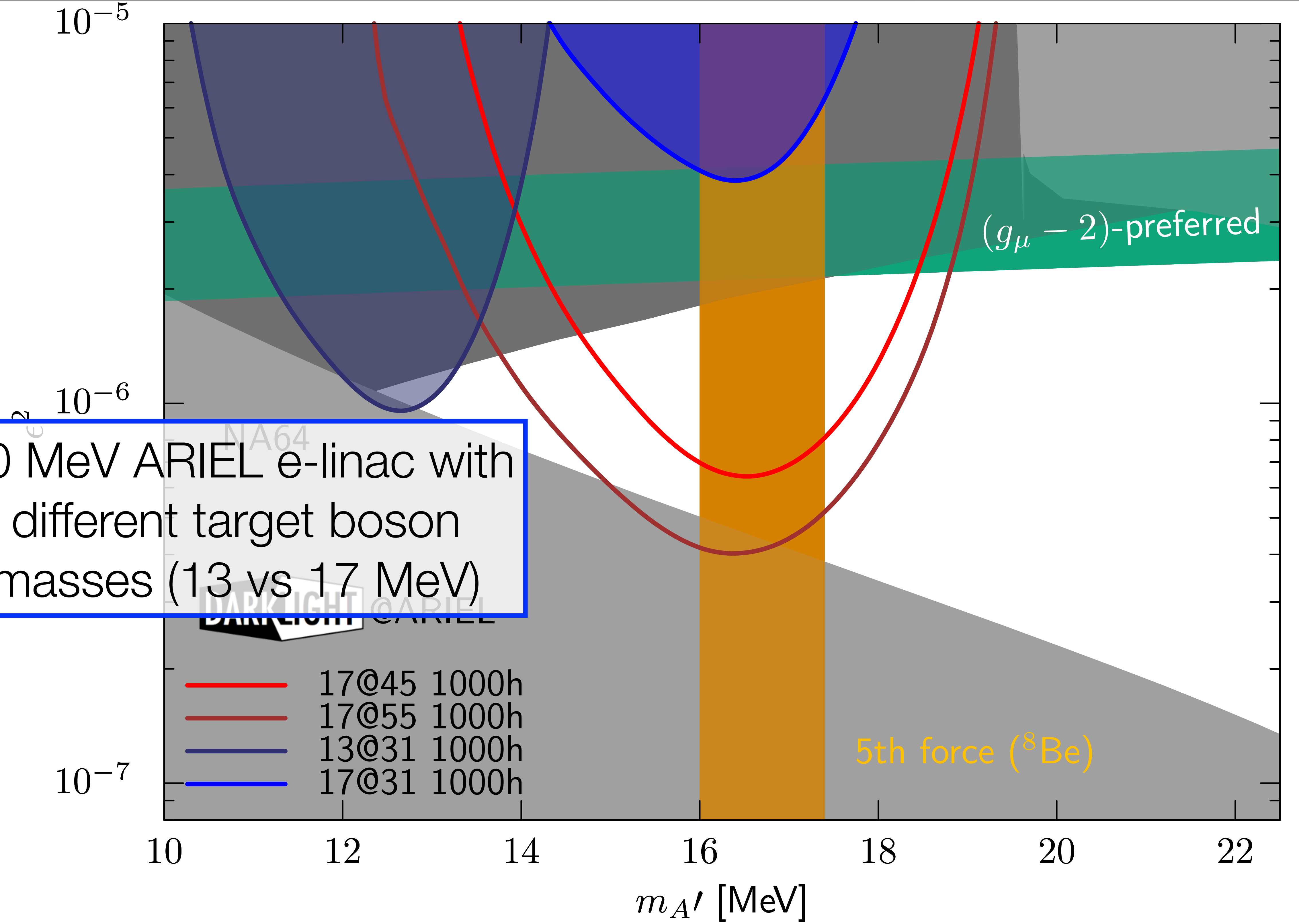
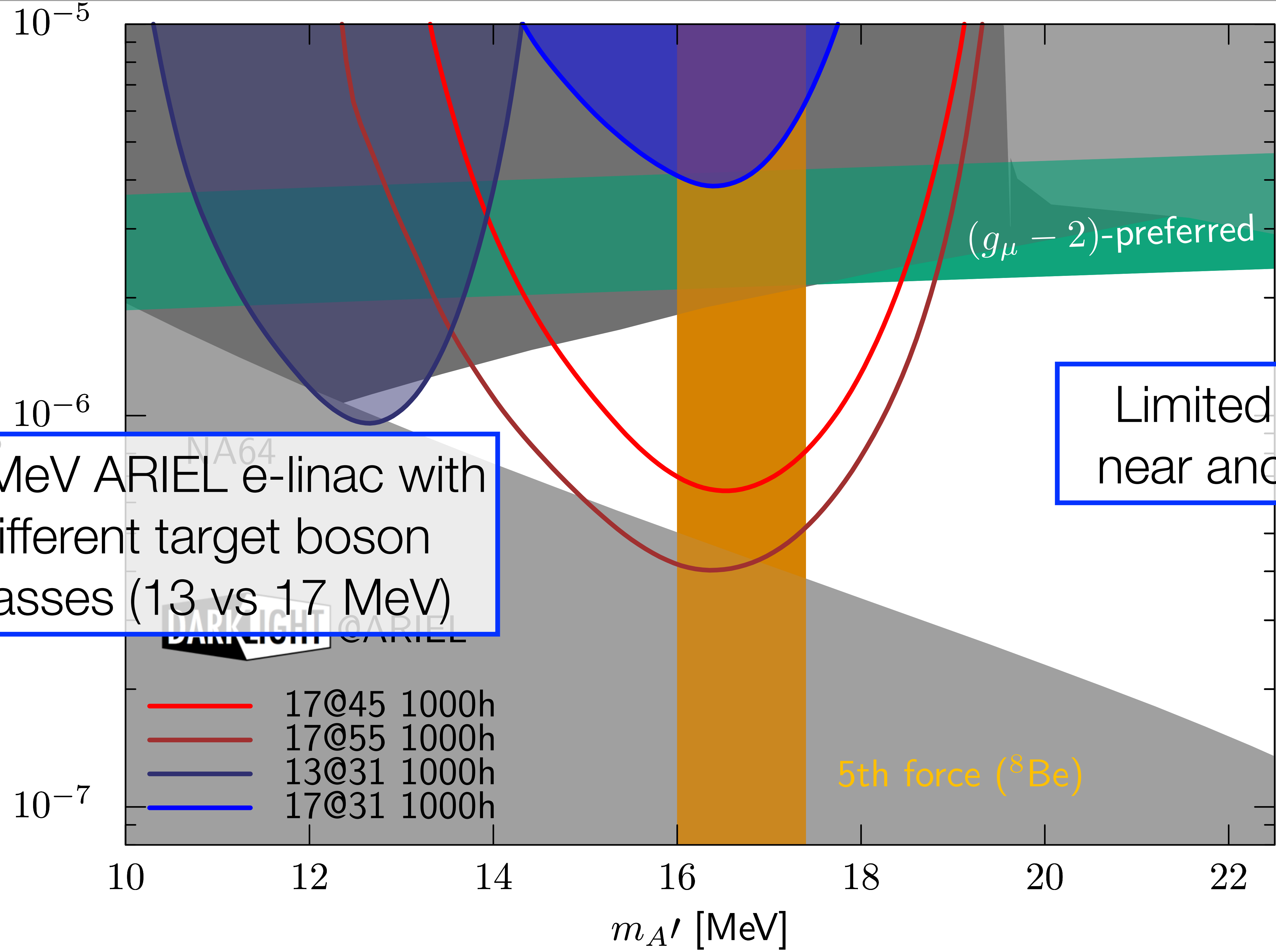


30 MeV ARIEL e-linac with different target boson masses (13 vs 17 MeV)

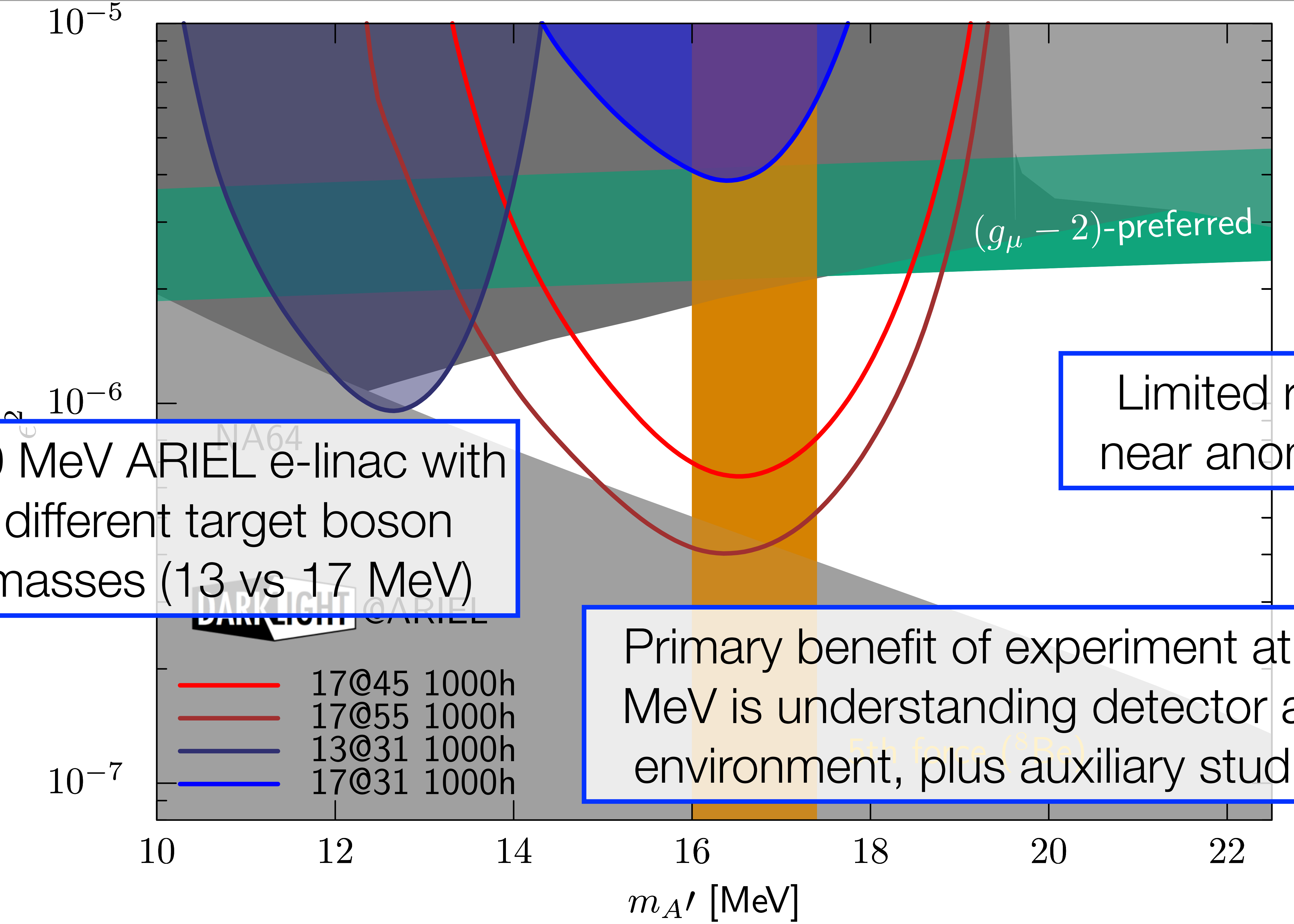
Projected sensitivity



30 MeV ARIEL e-linac with different target boson masses (13 vs 17 MeV)

Limited reach near anomalies

Projected sensitivity

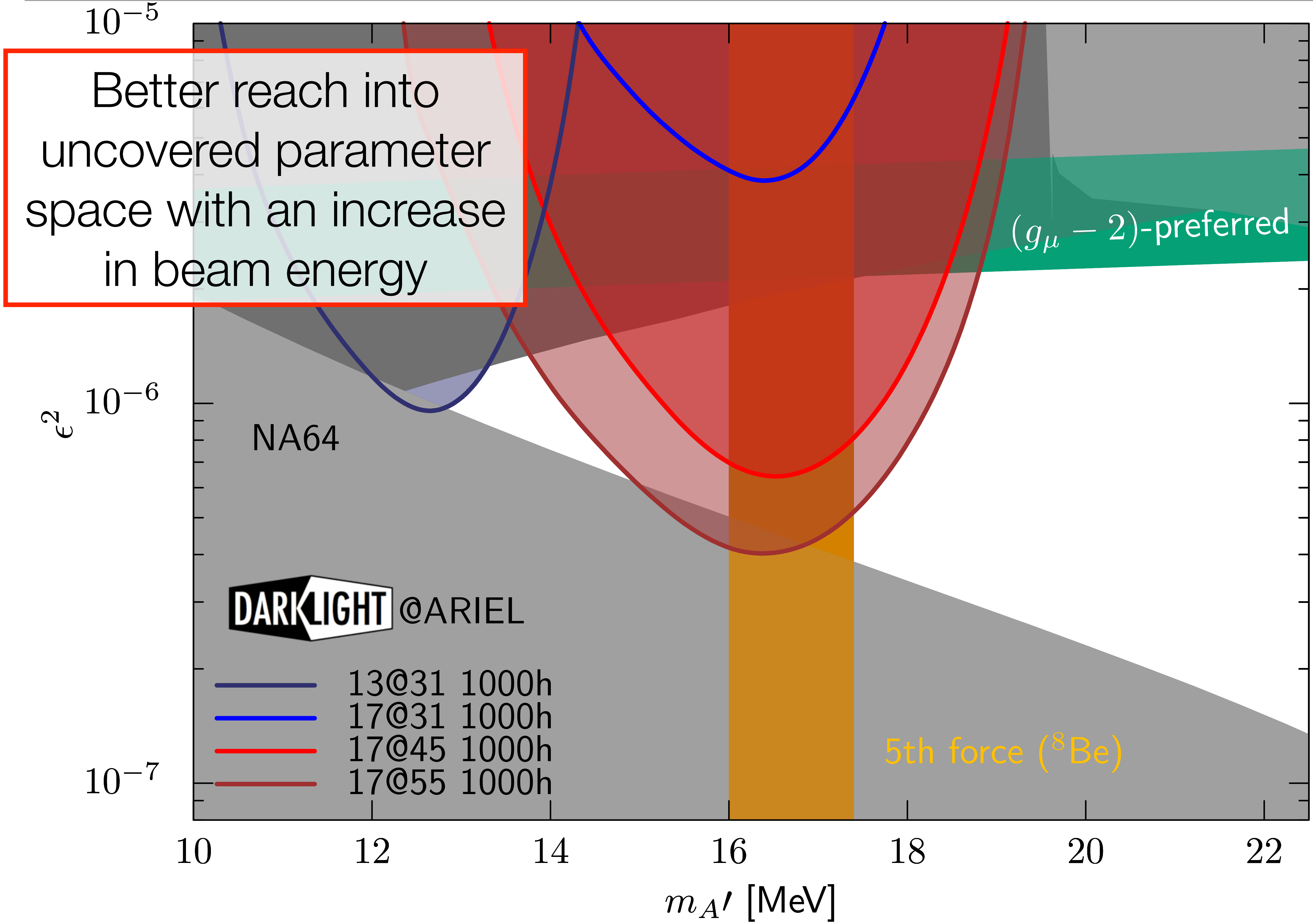


30 MeV ARIEL e-linac with different target boson masses (13 vs 17 MeV)

Limited reach near anomalies

Primary benefit of experiment at 30 MeV is understanding detector and environment, plus auxiliary studies

Projected sensitivity



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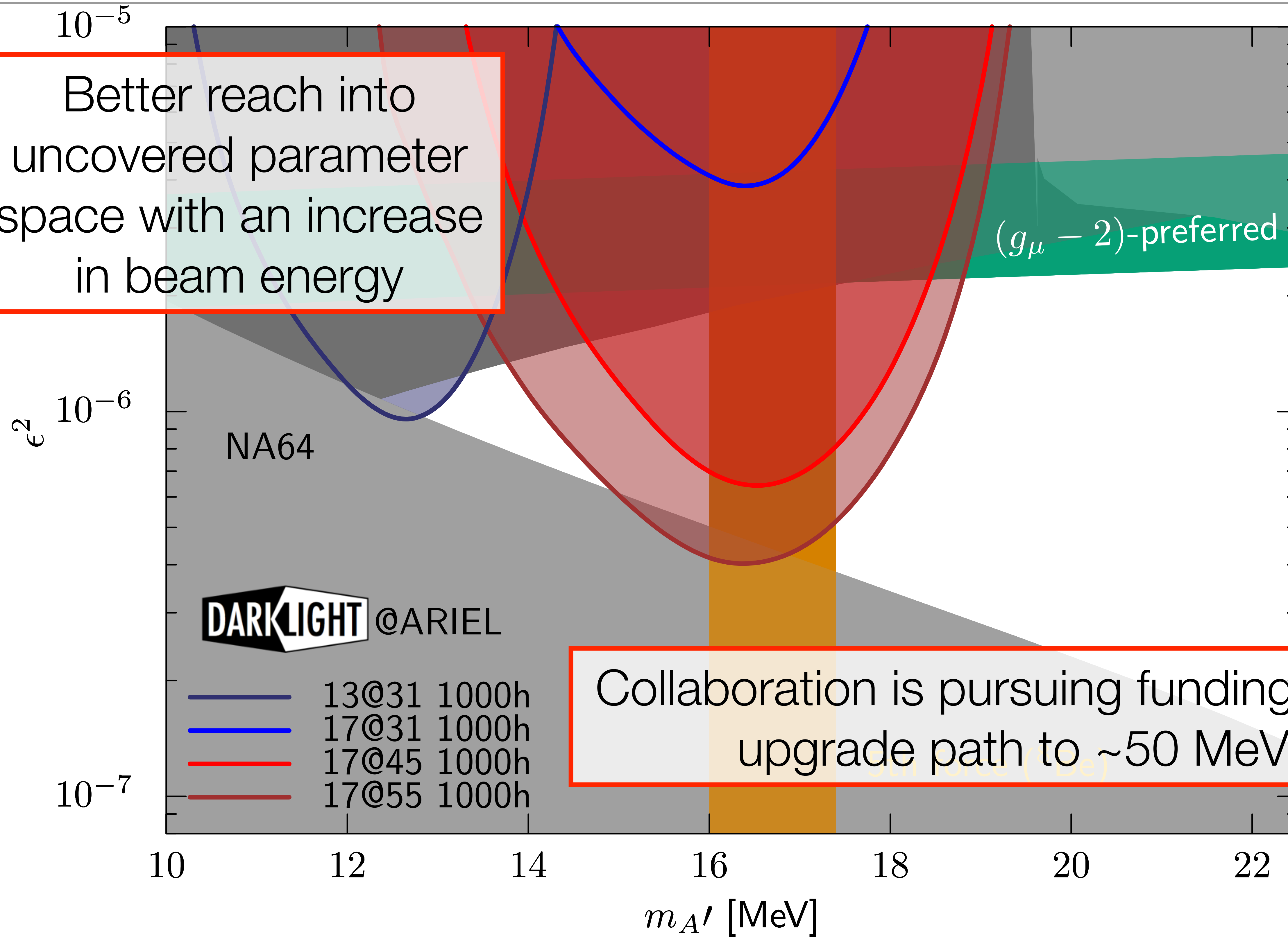
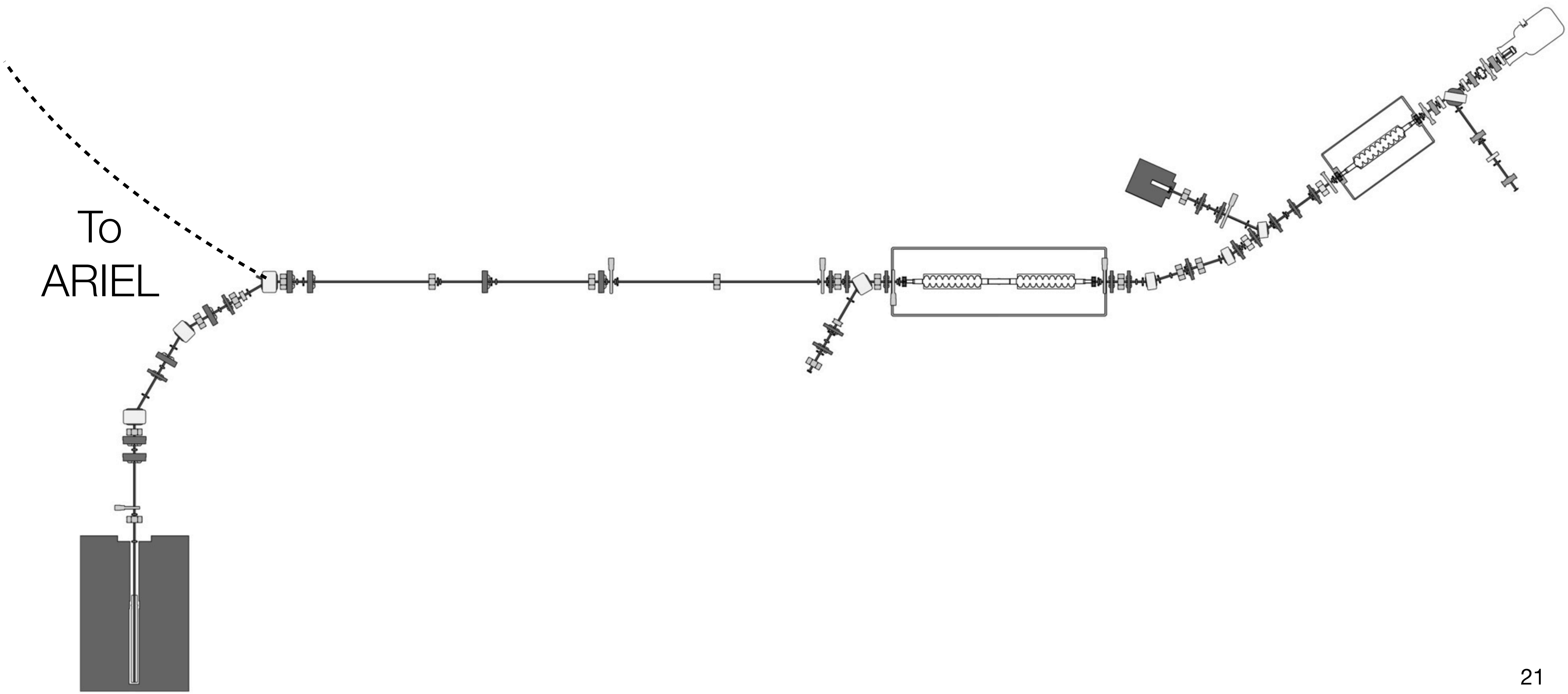


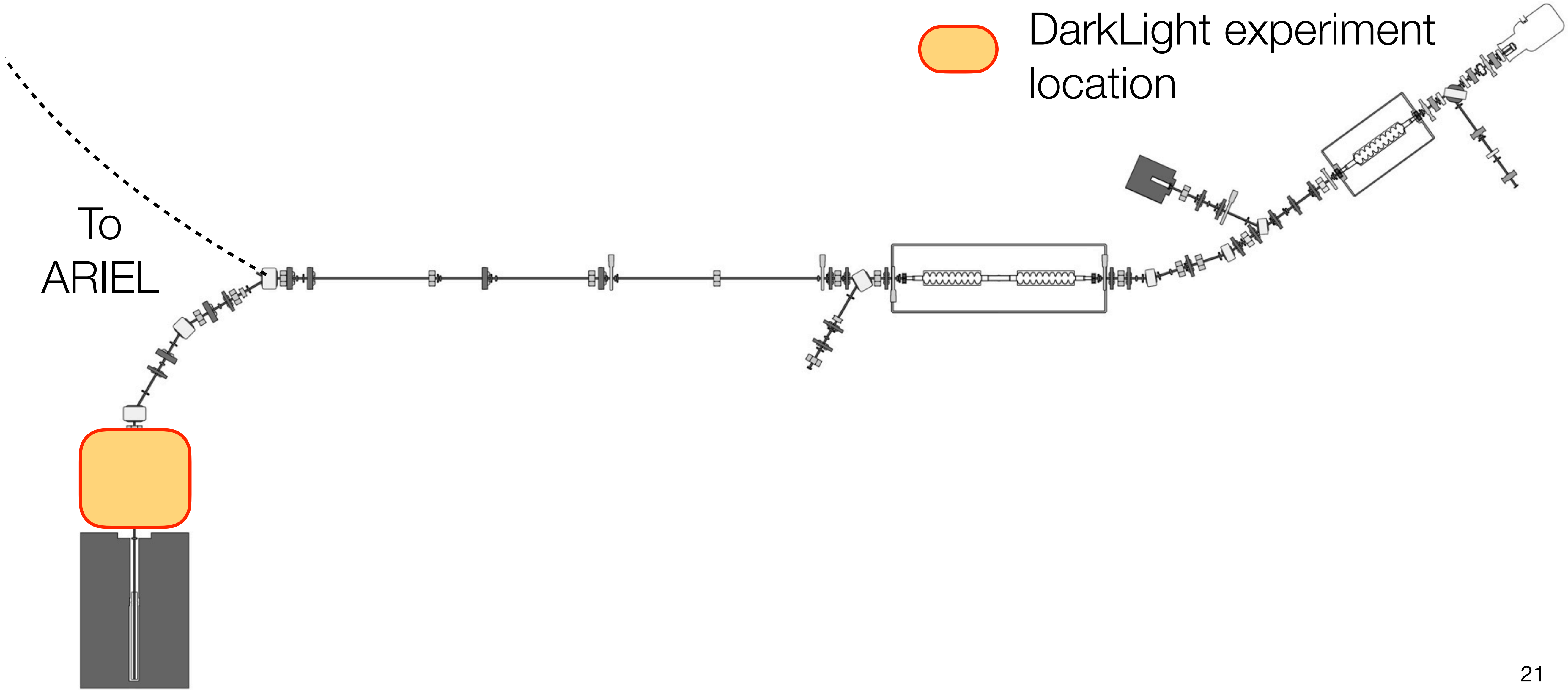
Better reach into uncovered parameter space with an increase in beam energy

Collaboration is pursuing funding for an upgrade path to ~50 MeV

Ongoing work: energy upgrade



Ongoing work: energy upgrade



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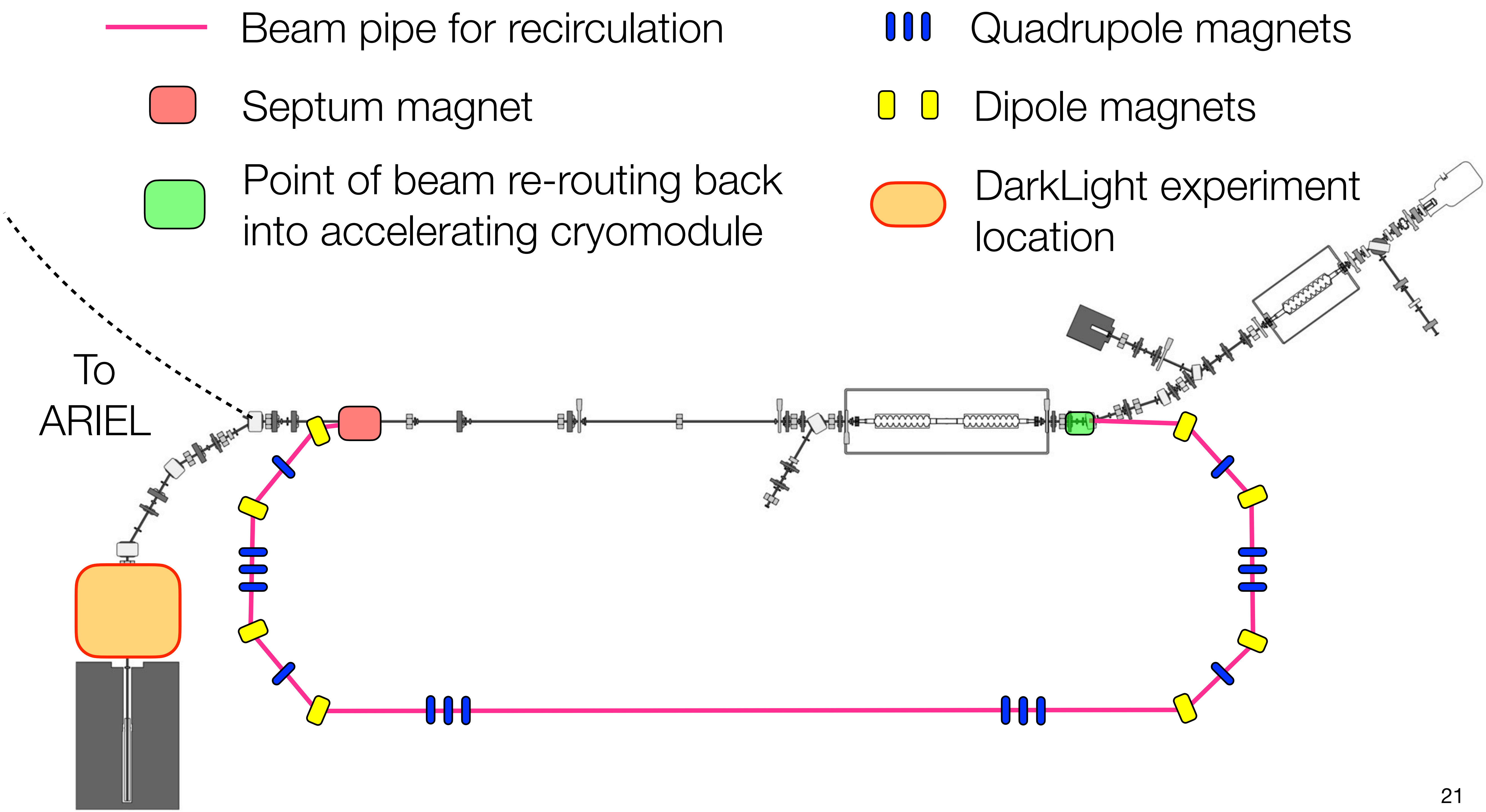

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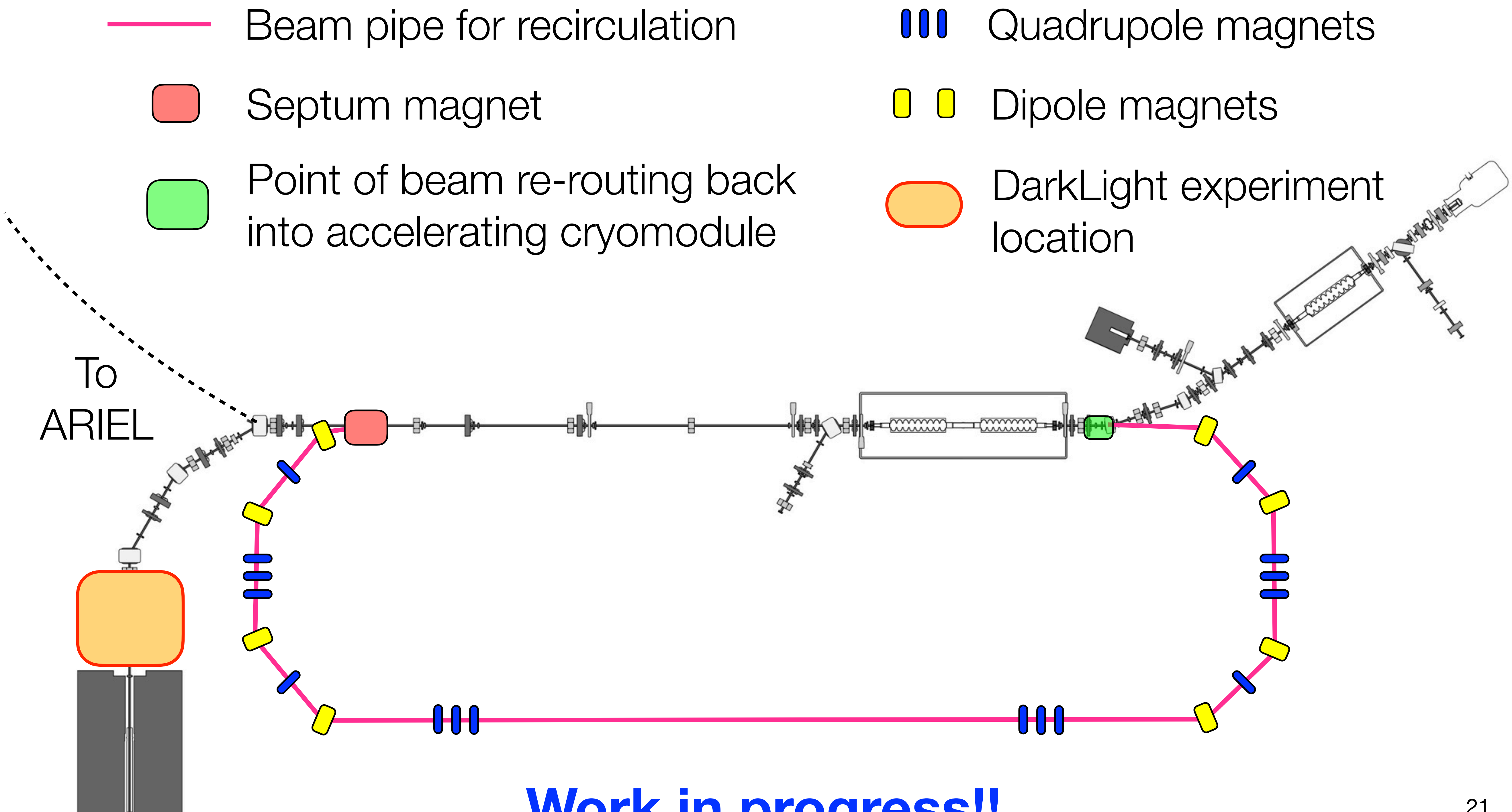

Work in progress!!

TRIUMF is:

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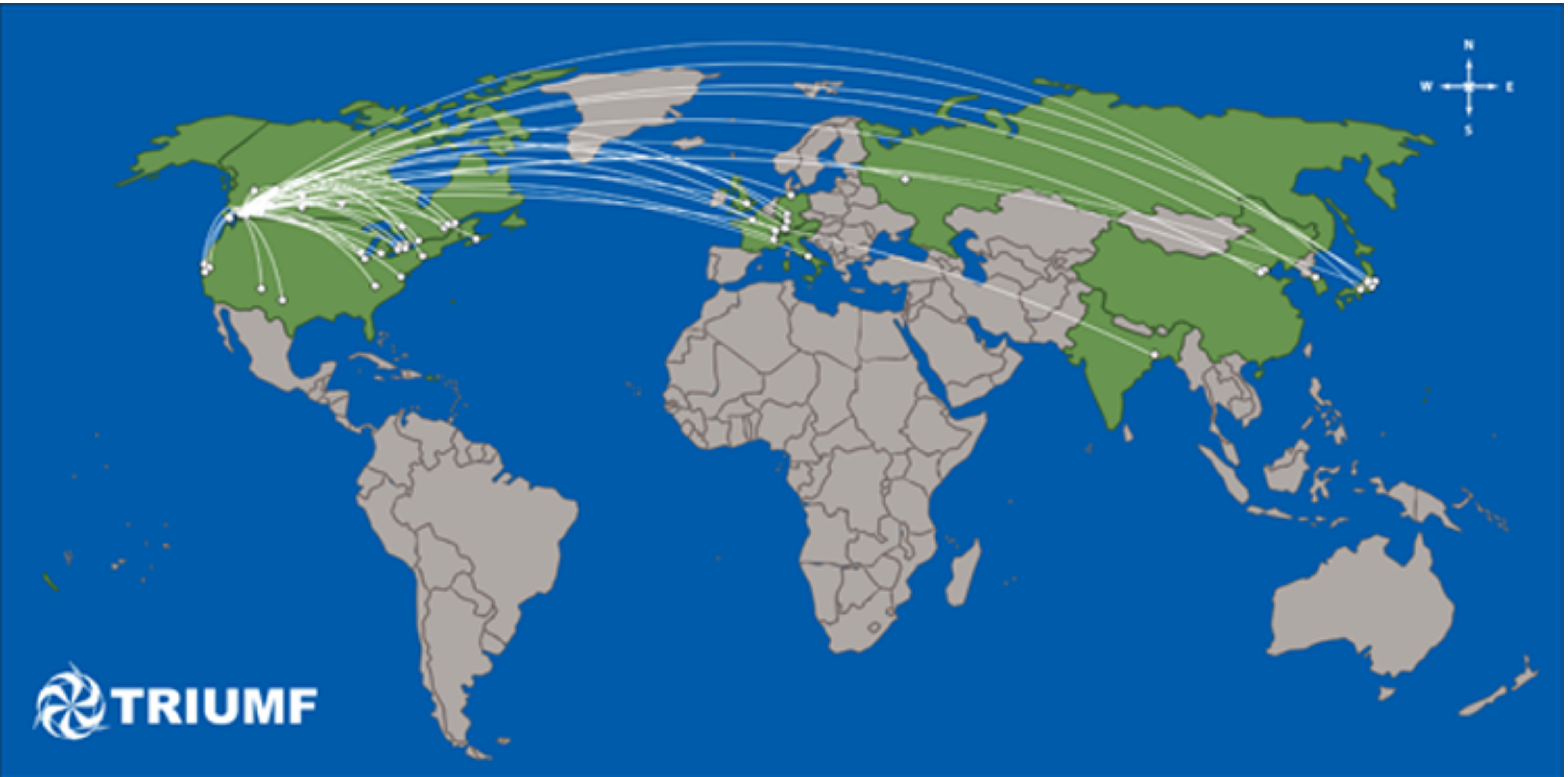

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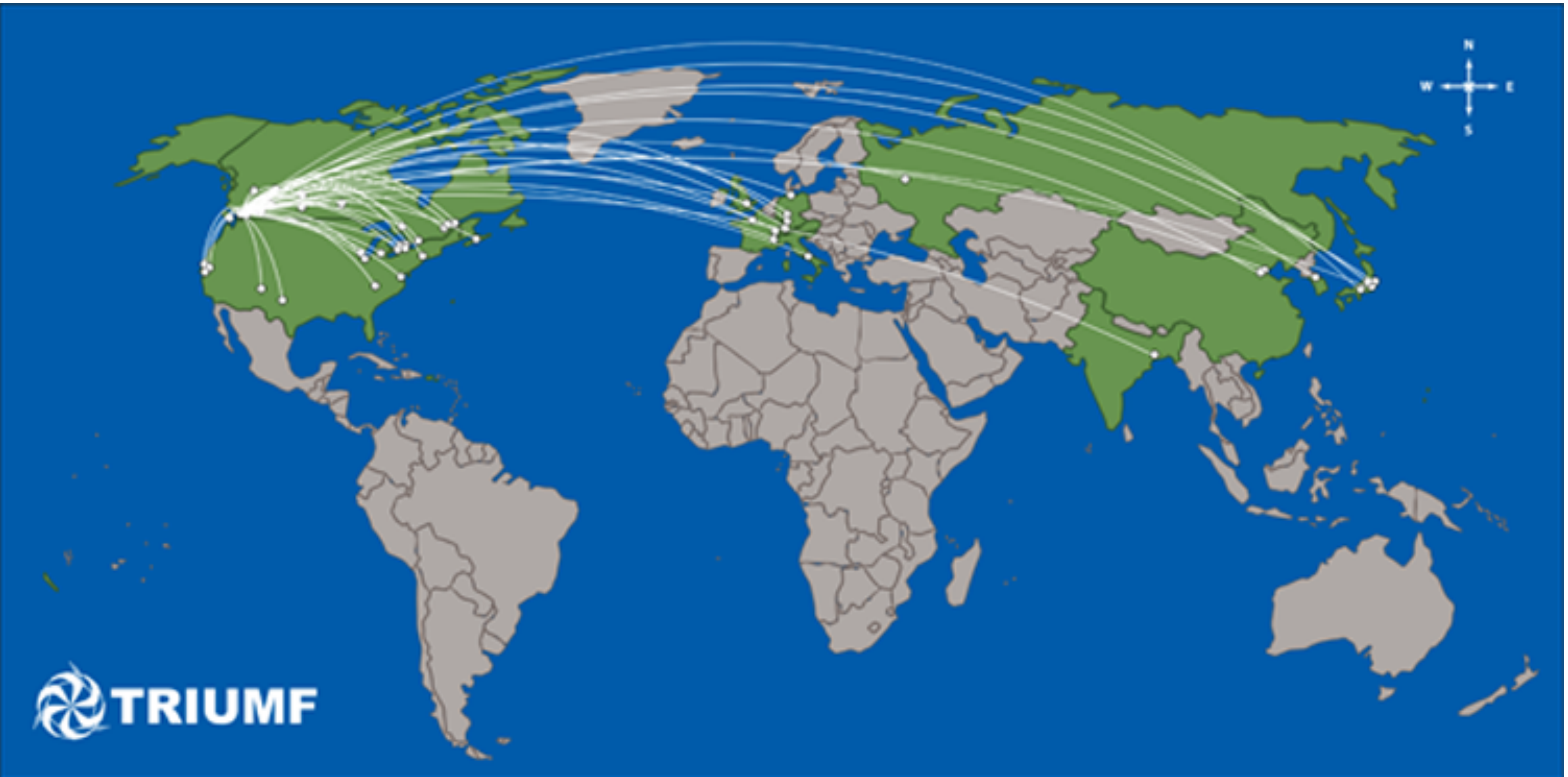
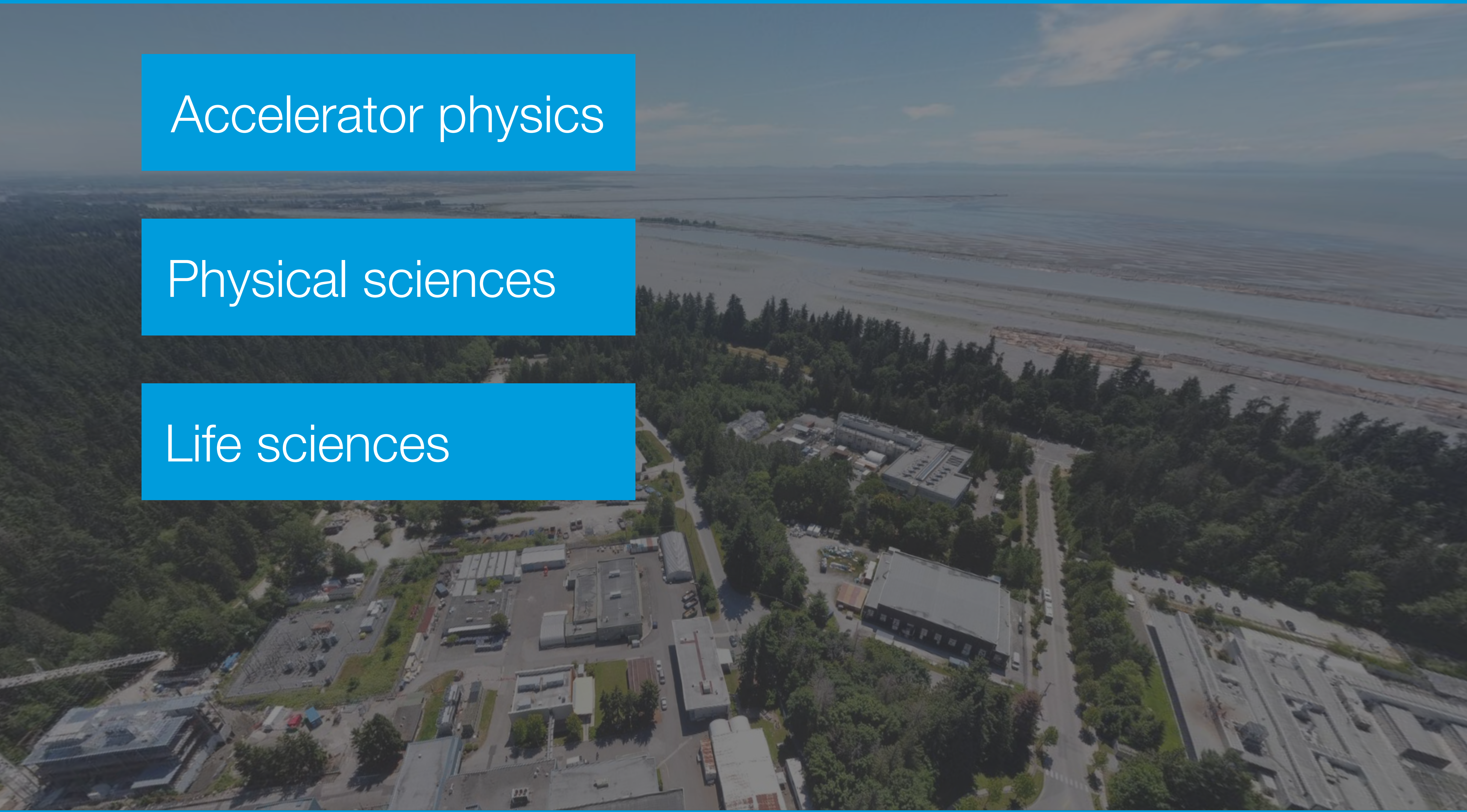


Directly contributing hardware to projects at Snolab, CERN, KEK, Gran Sasso, …

TRIUMF

TRIUMF

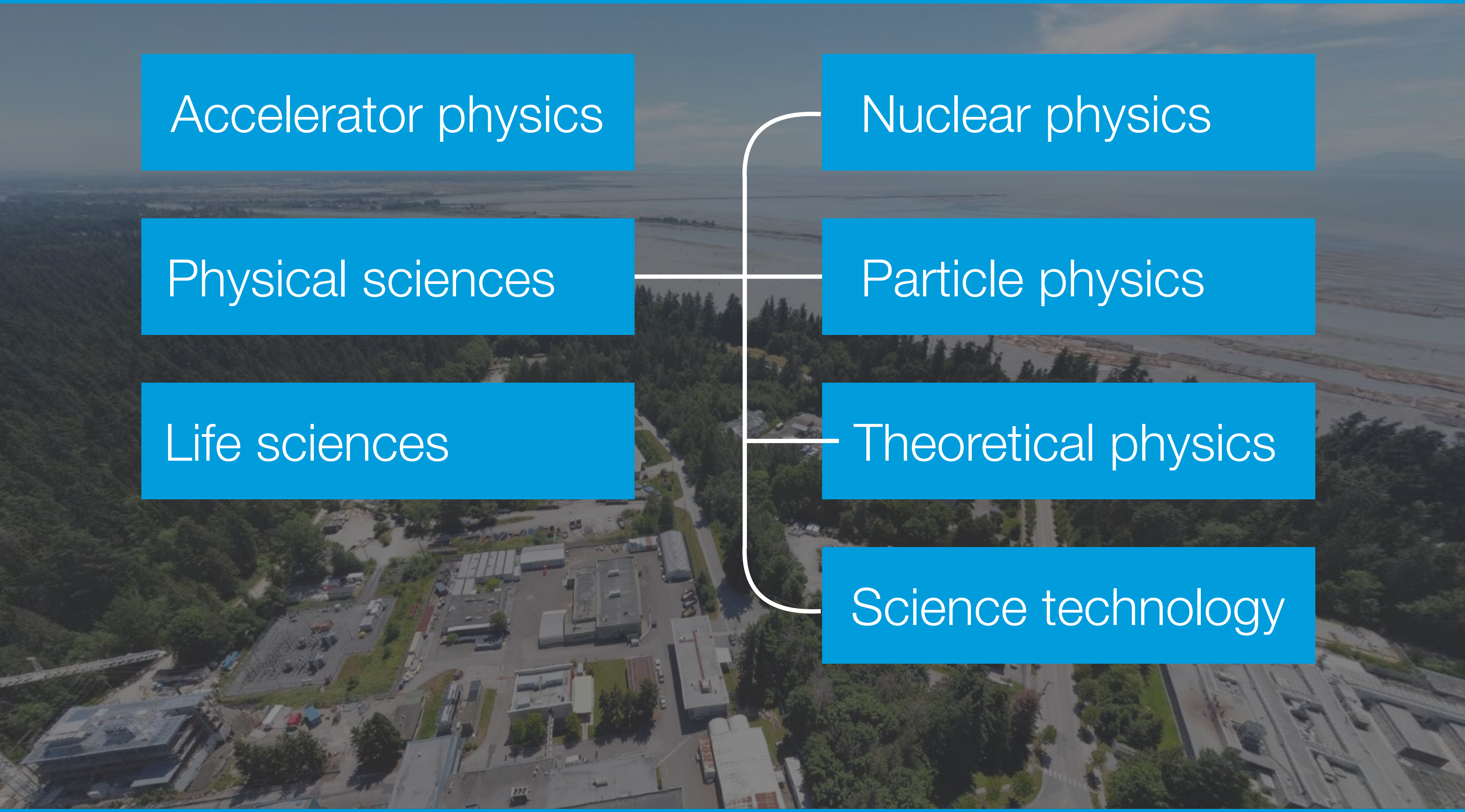


Accelerator physics

Physical sciences

Life sciences

TRIUMF



Accelerator physics

Physical sciences

Life sciences

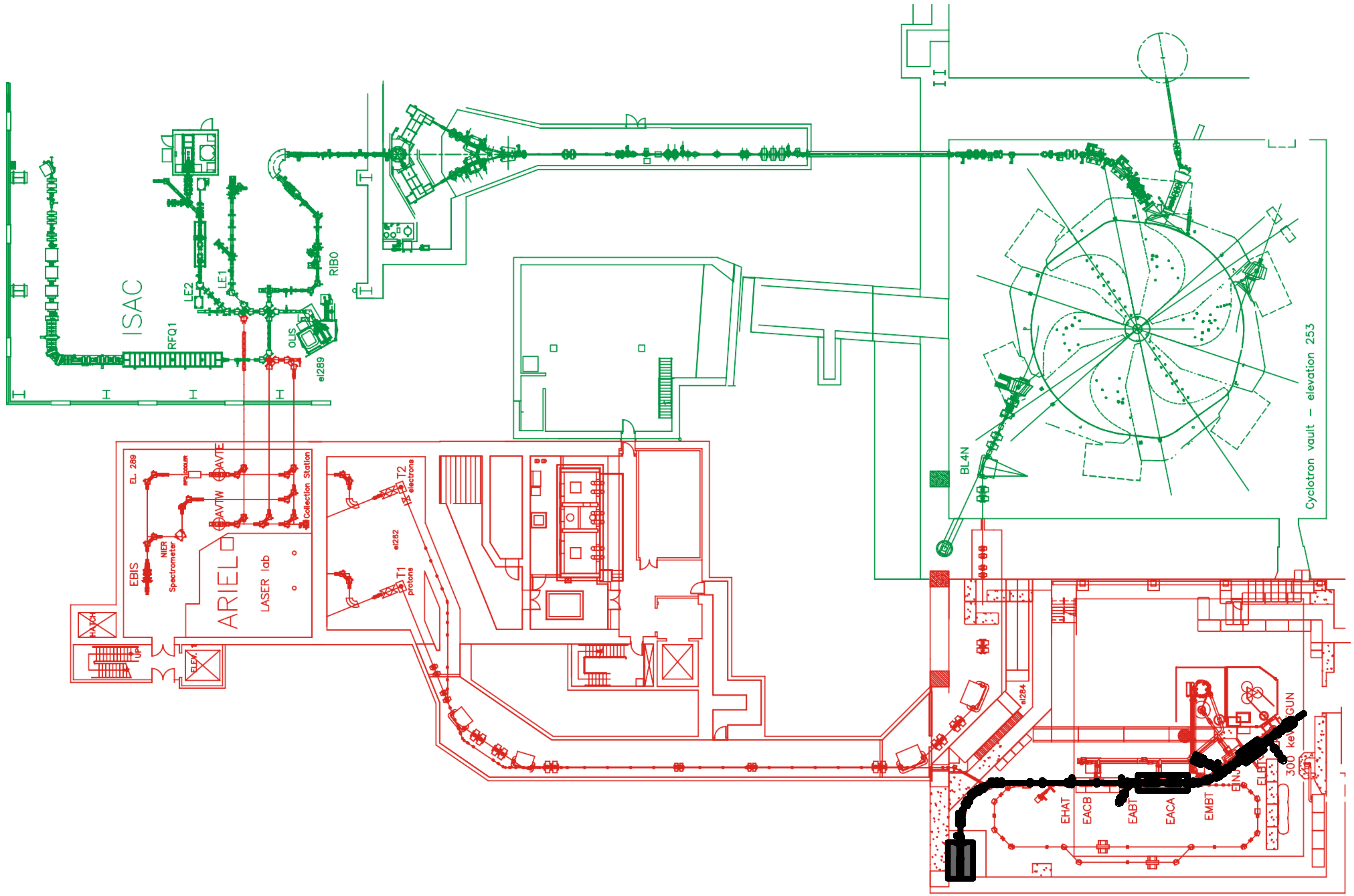
Nuclear physics

Particle physics

Theoretical physics

Science technology

TRIUMF accelerator complex



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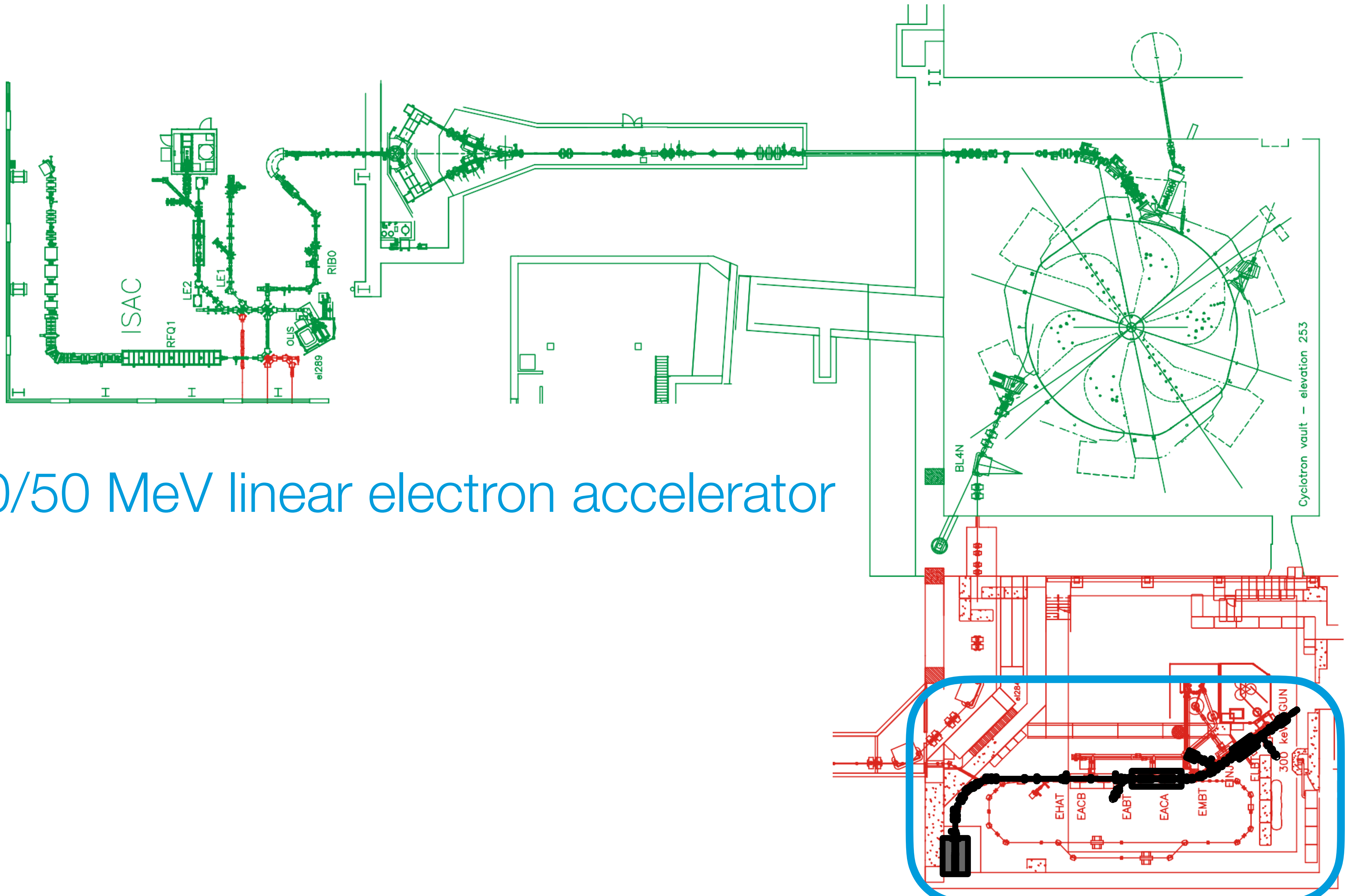
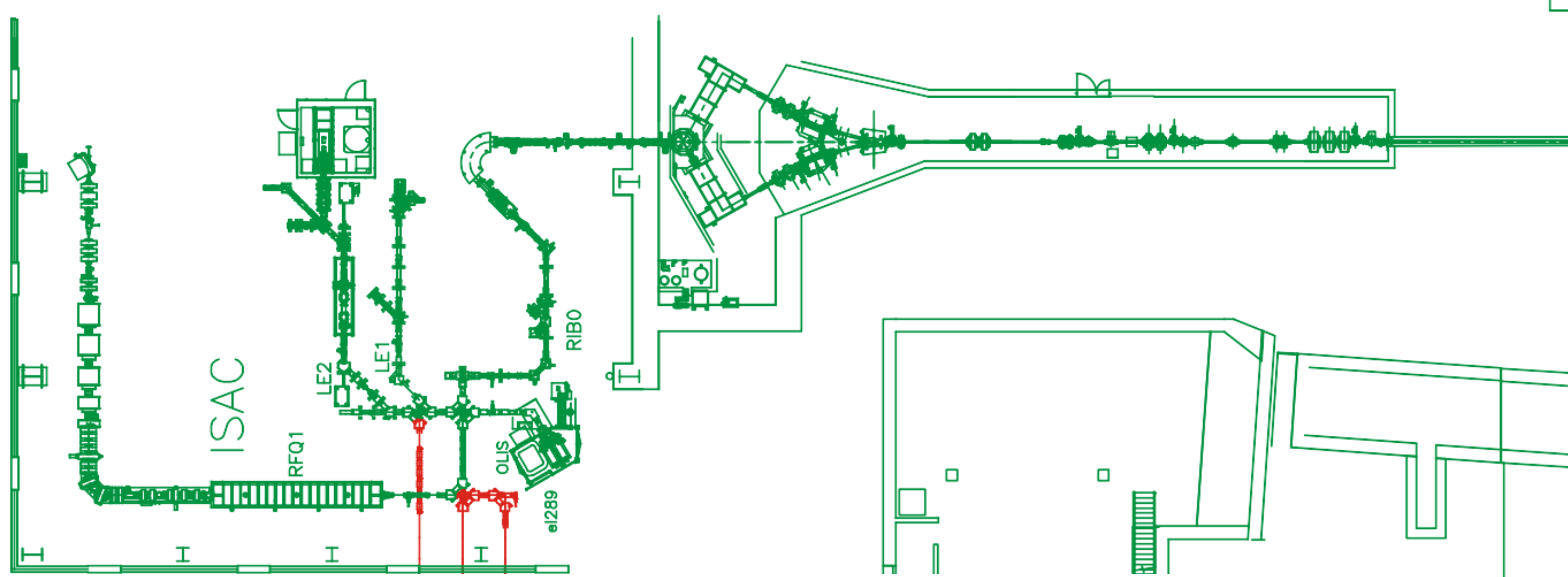


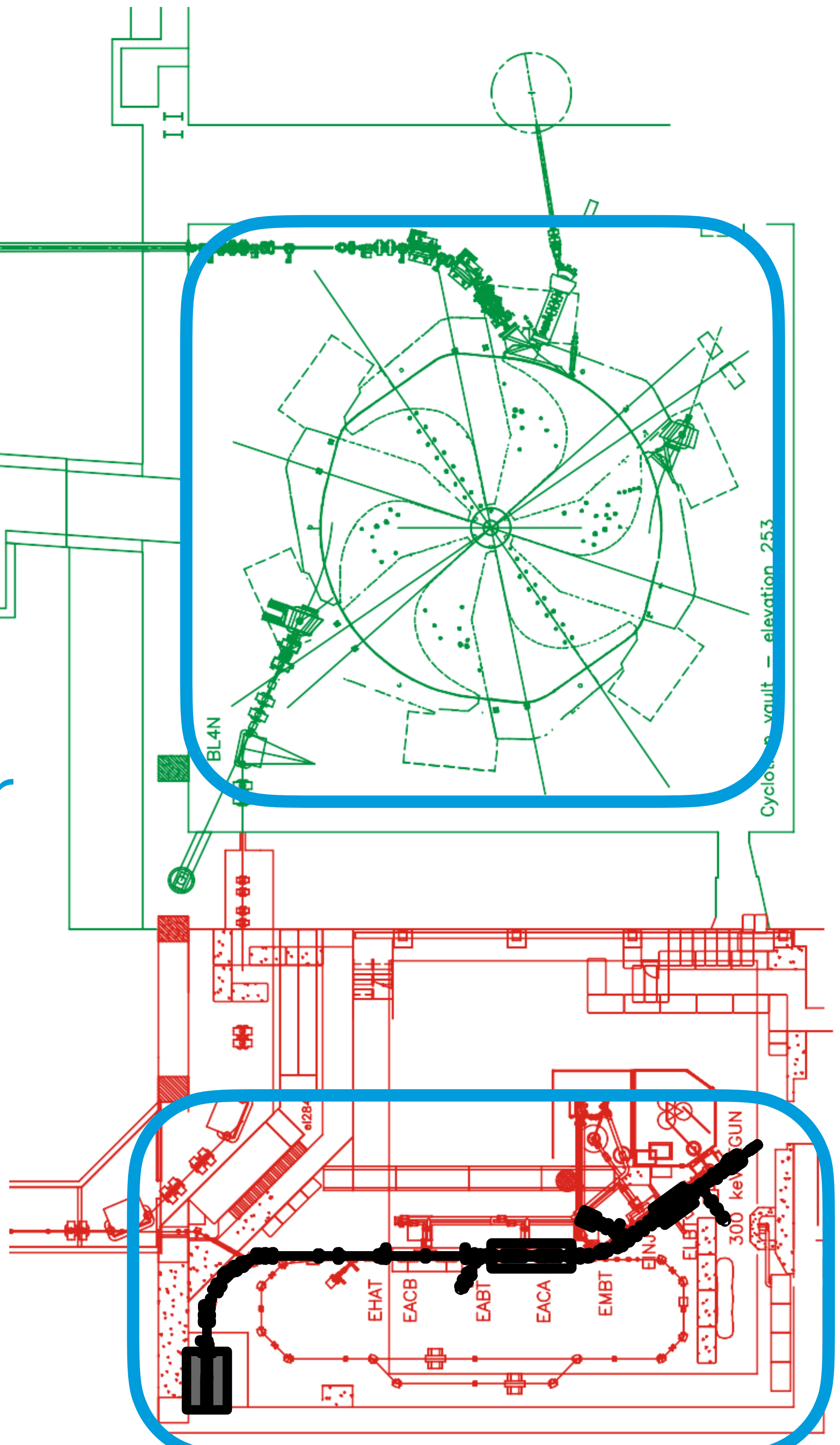
30/50 MeV linear electron accelerator

TRIUMF accelerator complex



30/50 MeV linear electron accelerator

520 MeV proton circular accelerator



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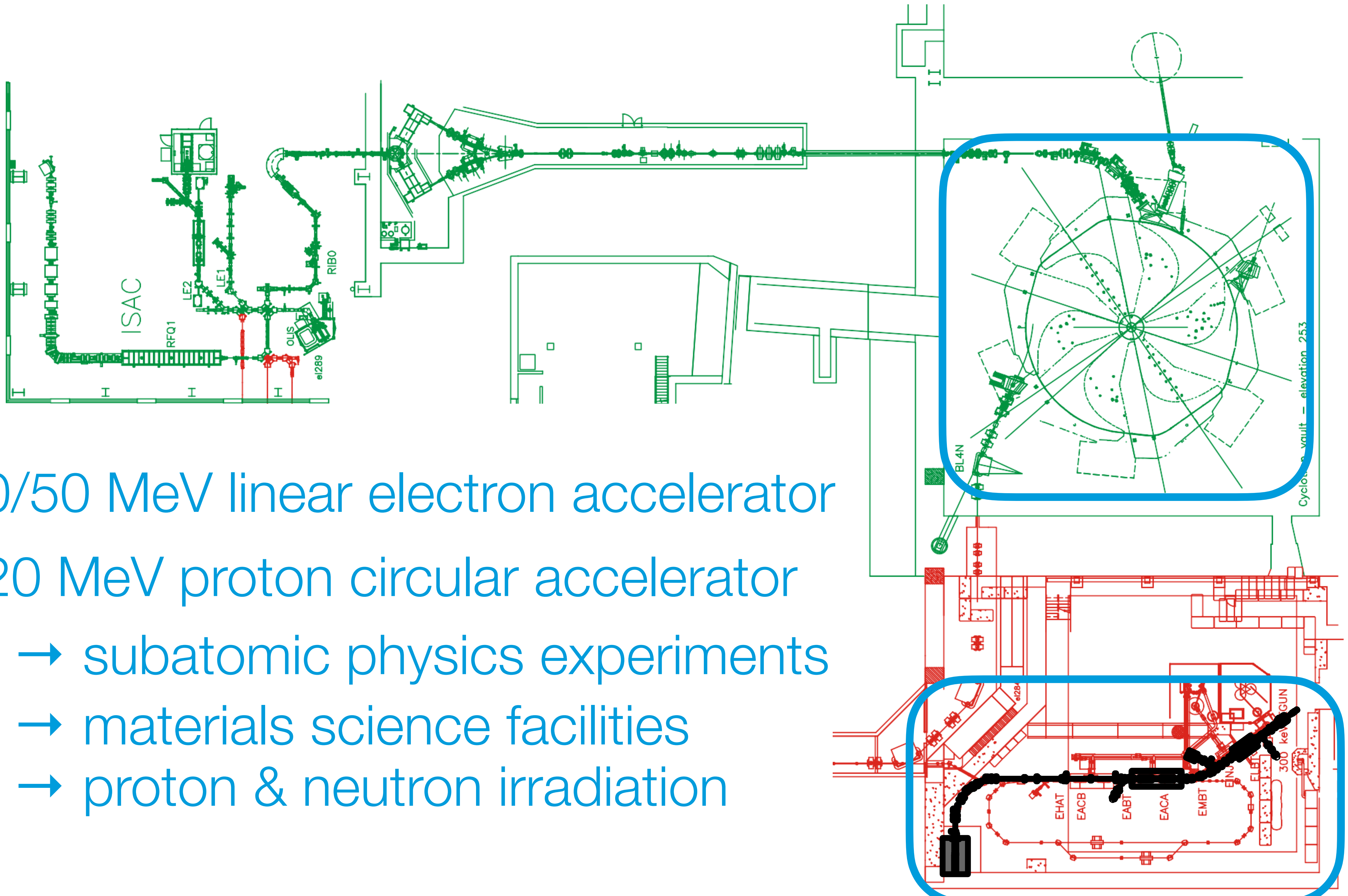


30/50 MeV linear electron accelerator

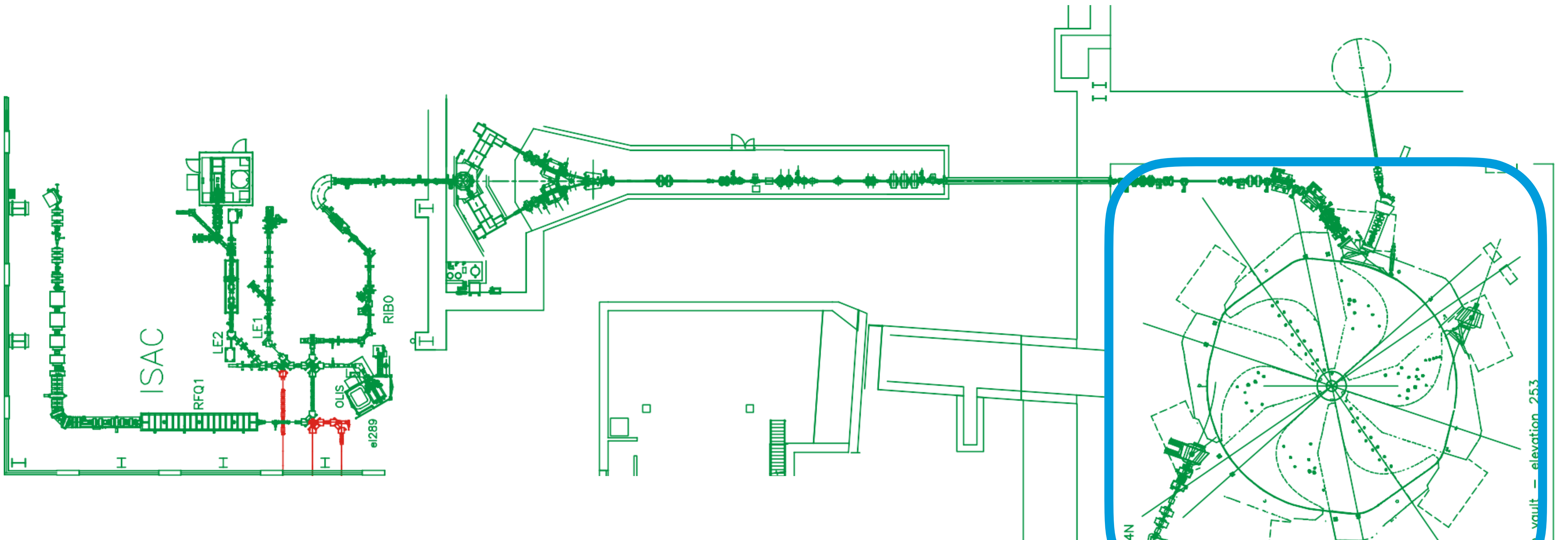
520 MeV proton circular accelerator

→ subatomic physics experiments

→ materials science facilities

→ proton & neutron irradiation

TRIUMF accelerator complex



30/50 MeV linear electron accelerator

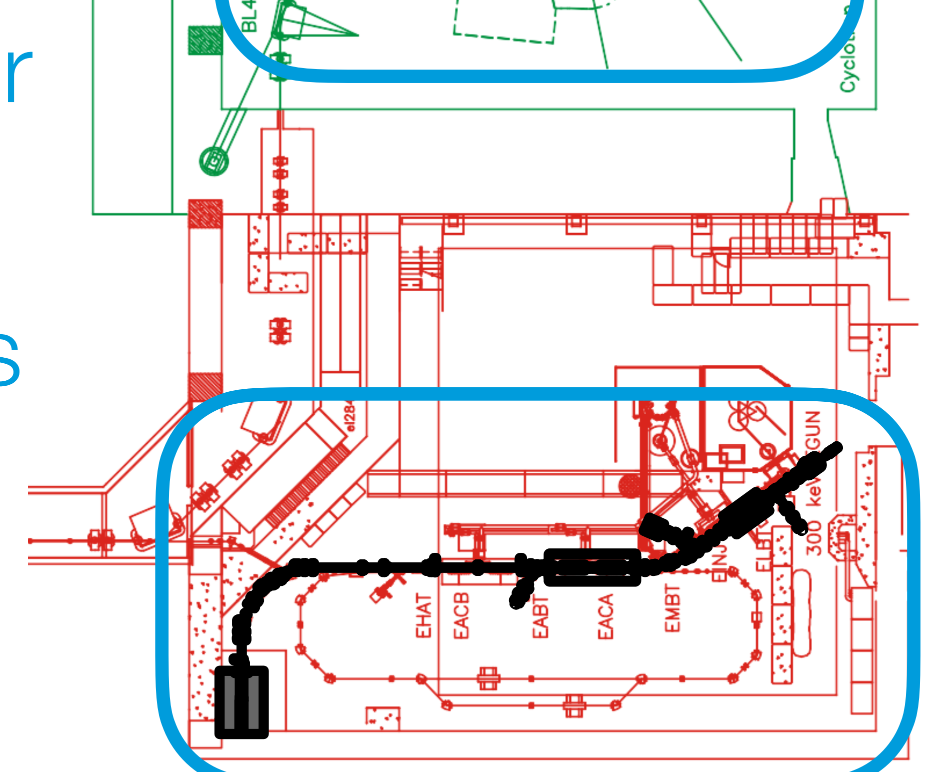
520 MeV proton circular accelerator

→ subatomic physics experiments

→ materials science facilities

→ proton & neutron irradiation

+ various small cyclotrons



Particle physics at TRIUMF

TRIUMF makes impacts through a
"focus project" strategy

Particle physics at TRIUMF

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Critical mass, meaningful leadership, and investment from start to finish:

Detector design/construction, operation, data analysis

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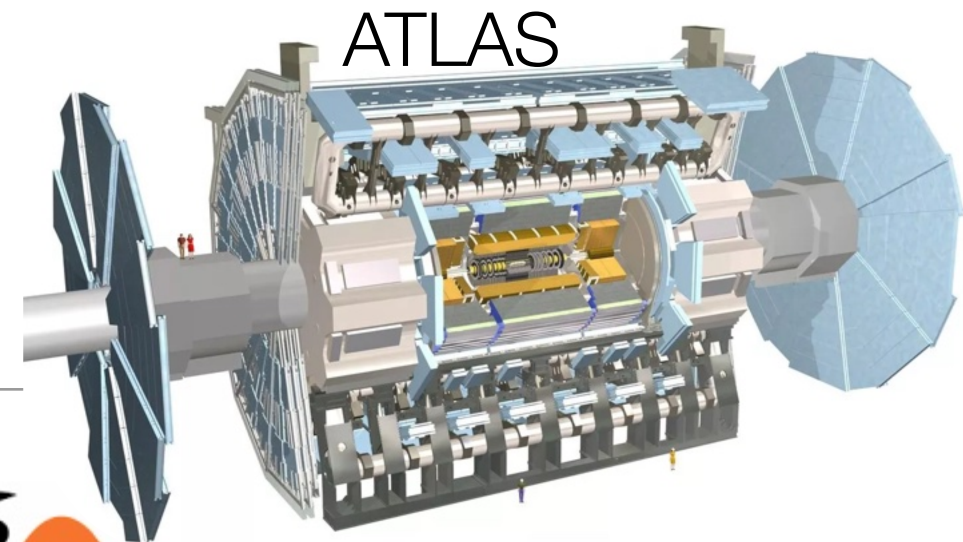
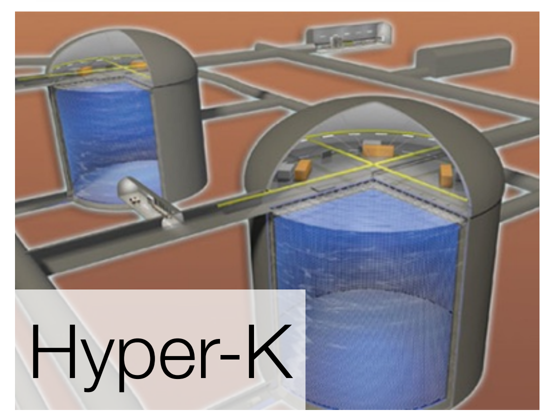
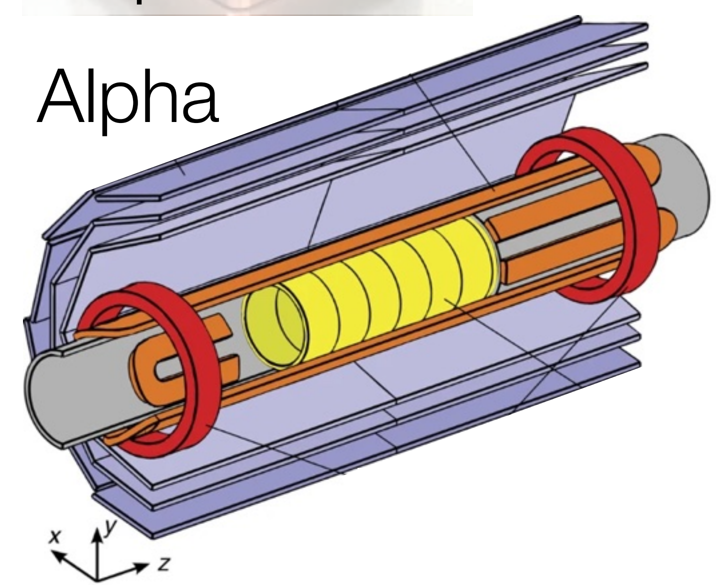


TUCAN
Collaboration





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Critical mass, meaningful leadership, and investment from start to finish:

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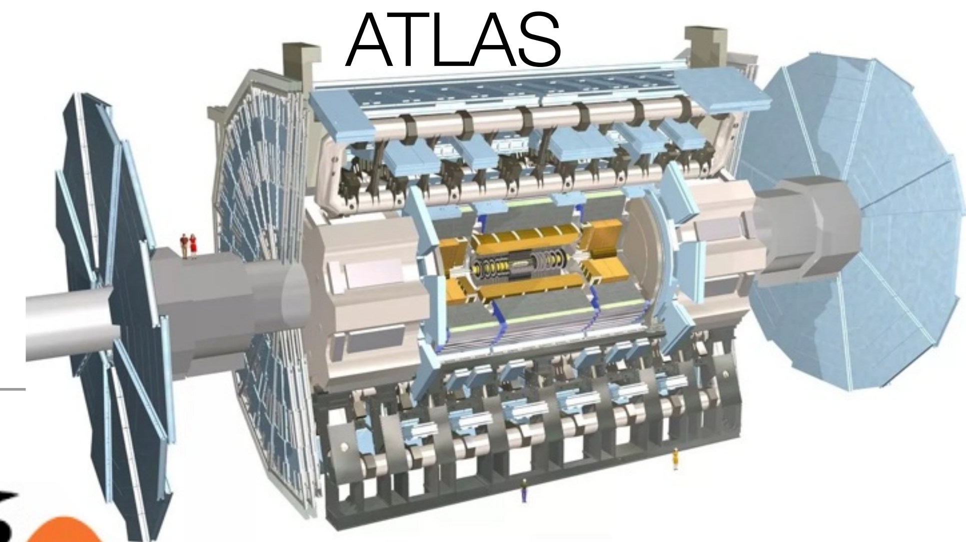
Future-looking: DarkLight, nEXO, PIONEER, HAICU



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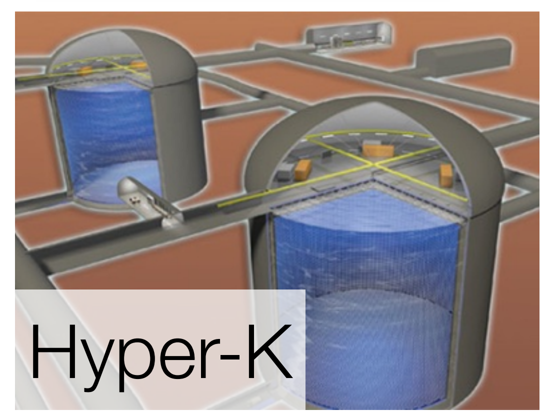

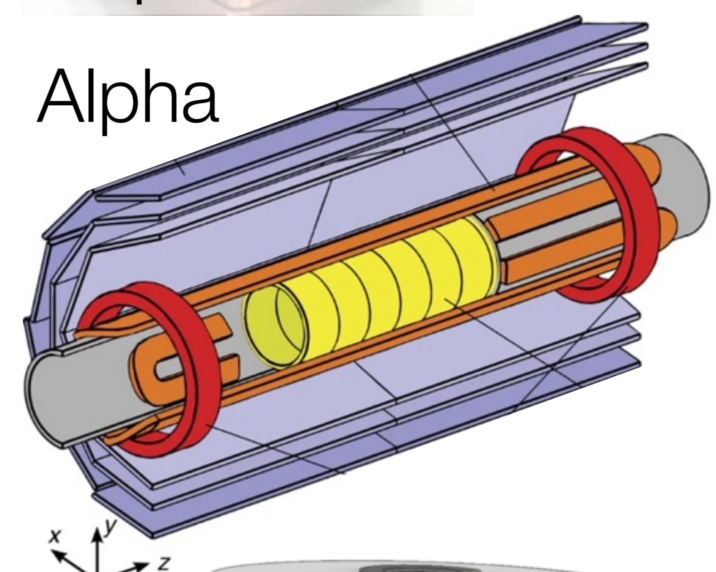

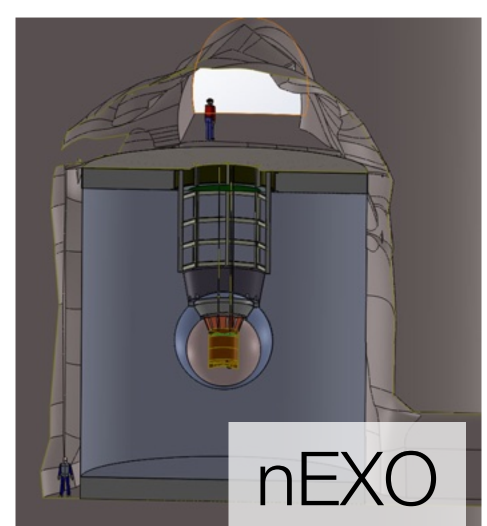

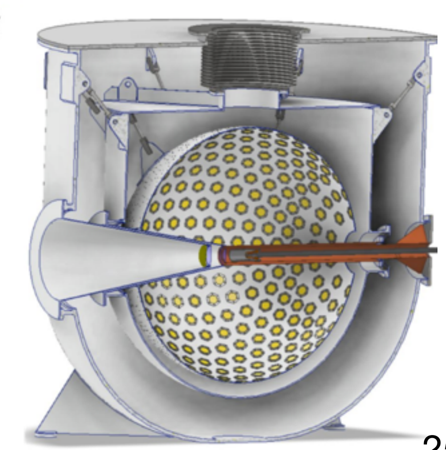

PIONEER

The Science Technology department

The Science Technology department

- Physics technology
- Detectors
- Electronics
- Data acquisition

The Science Technology department

Physics technology

Detectors

Electronics

Data acquisition

Simulation,
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Building detectors!
Testing, construction,
& implementation

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The Science Technology department

Physics technology | **Detectors** | **Electronics** | **Data acquisition**

Simulation, conceptual design, detector R&D

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Firmware, software, ongoing experiment support

SciTech delivers systems from idea to finished product

So what **else** could improve the experiment?

In a context like this conference, we can ask
fun hypotheticals:

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What instrumentation changes would improve our performance, while working within our constraints?

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Better timing resolution in FPGA electronics

Shorter integration time, faster read-out for GEMs

… Additional tracking layers, maybe?

Answers can look very different for others …

What’s important to DarkLight boils down to:
good timing resolution, affordable, robust

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Dark matter direct detection: extremely low noise
& low radioactivity

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LHC experiment trackers: extremely high radiation tolerance

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Precision particle physics **experiments**: excellent energy resolution

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Dark matter direct detection: extremely low noise
& low radioactivity

LHC experiment trackers: extremely high radiation tolerance

Precision particle physics **experiments**: excellent energy resolution

Developments should look in all directions

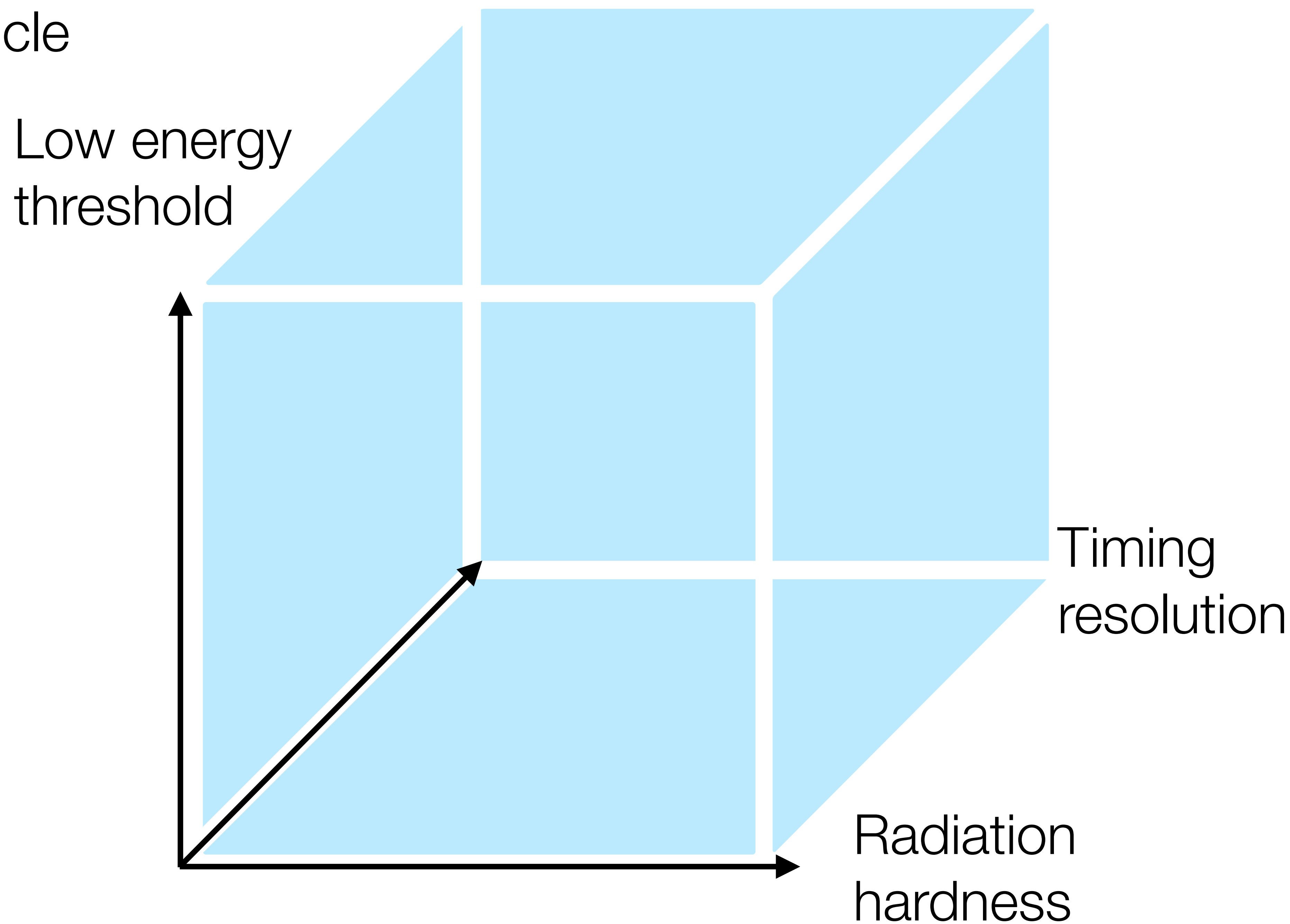
Micropattern gas tracking detectors in particle physics

Future uses for muon systems, TPCs, particle ID, tracking, …

Micropattern gas tracking detectors in particle physics

ECFA R&D roadmap

Future uses for muon systems, TPCs, particle ID, tracking, …

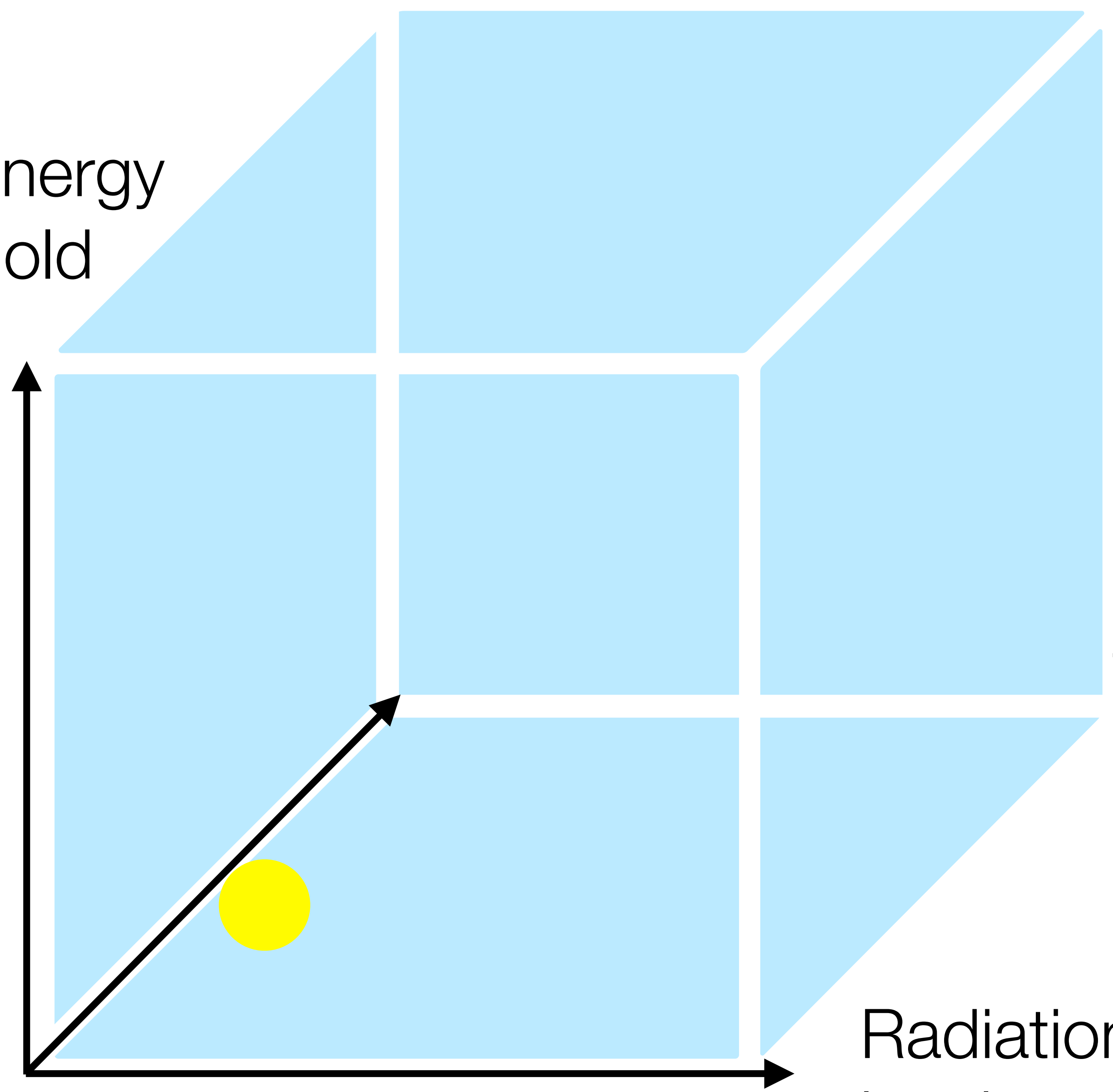


Micropattern gas tracking detectors in particle physics

ECFA R&D roadmap

Future uses for muon systems, TPCs, particle ID, tracking, …

DarkLight



Micropattern gas tracking detectors in particle physics

ECFA R&D roadmap

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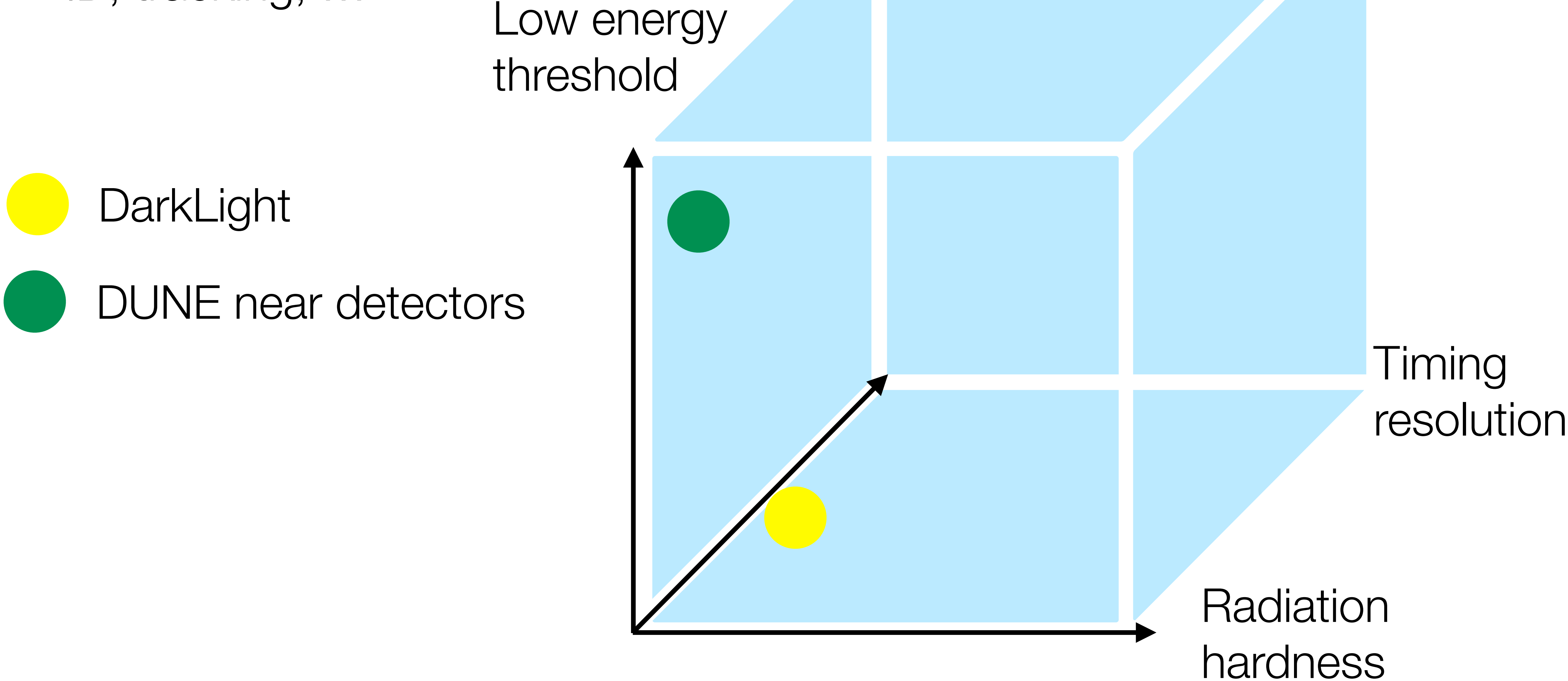
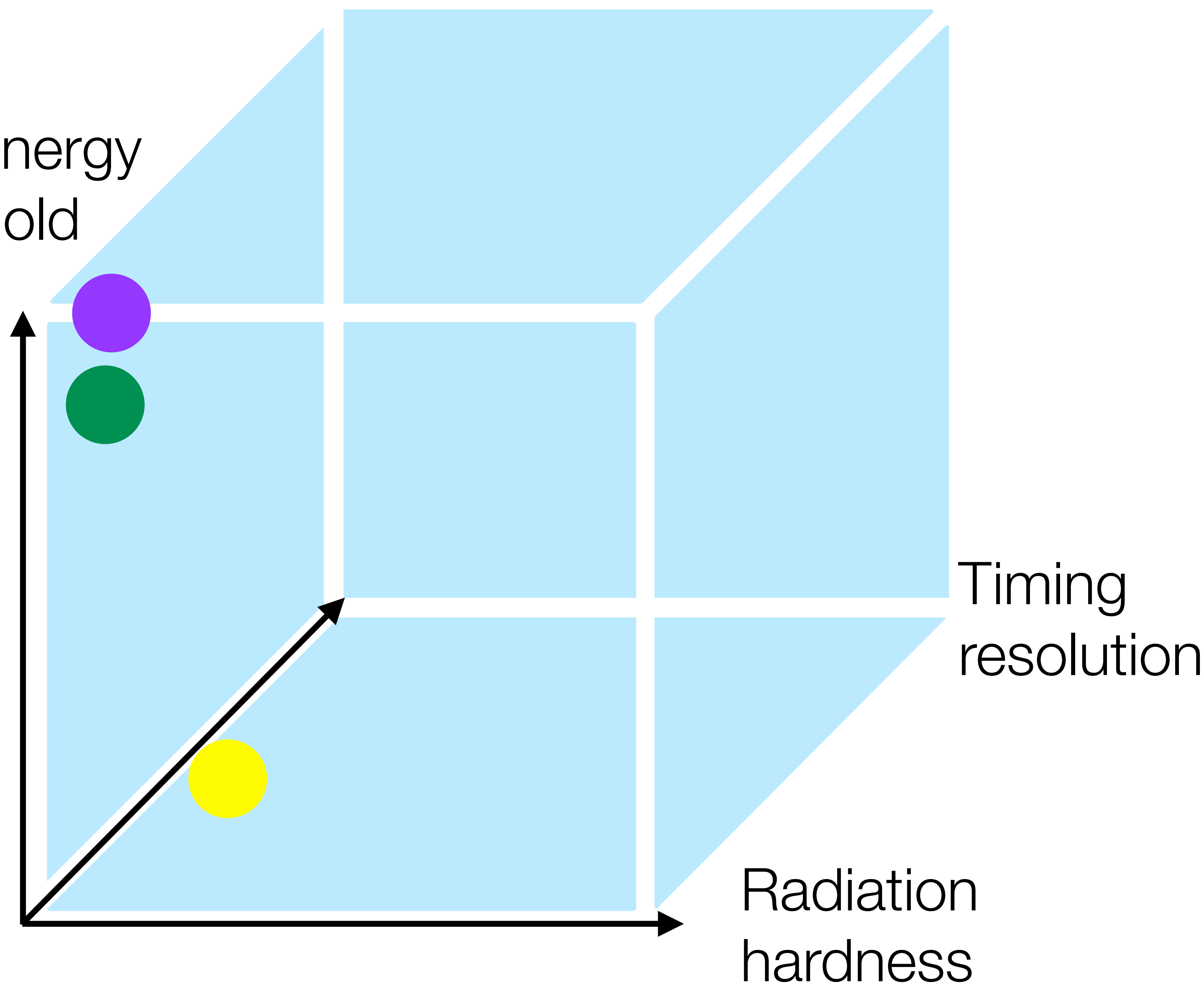


Micropattern gas tracking detectors in particle physics

ECFA R&D roadmap

Future uses for muon systems, TPCs, particle ID, tracking, …

- DarkLight
- DUNE near detectors
- Light dark matter



Micropattern gas tracking detectors in particle physics

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Future uses for muon systems, TPCs, particle ID, tracking, …

- DarkLight
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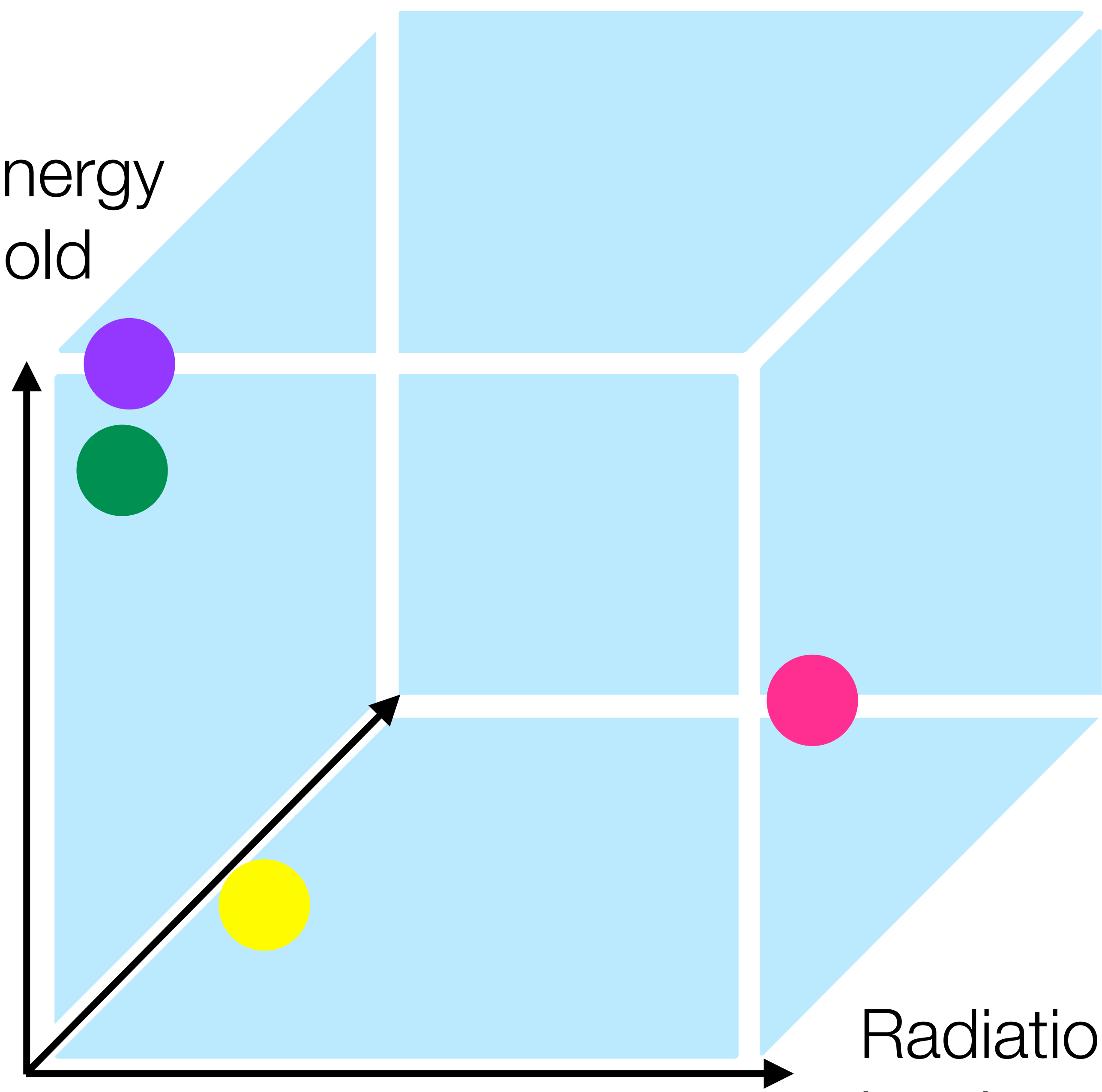
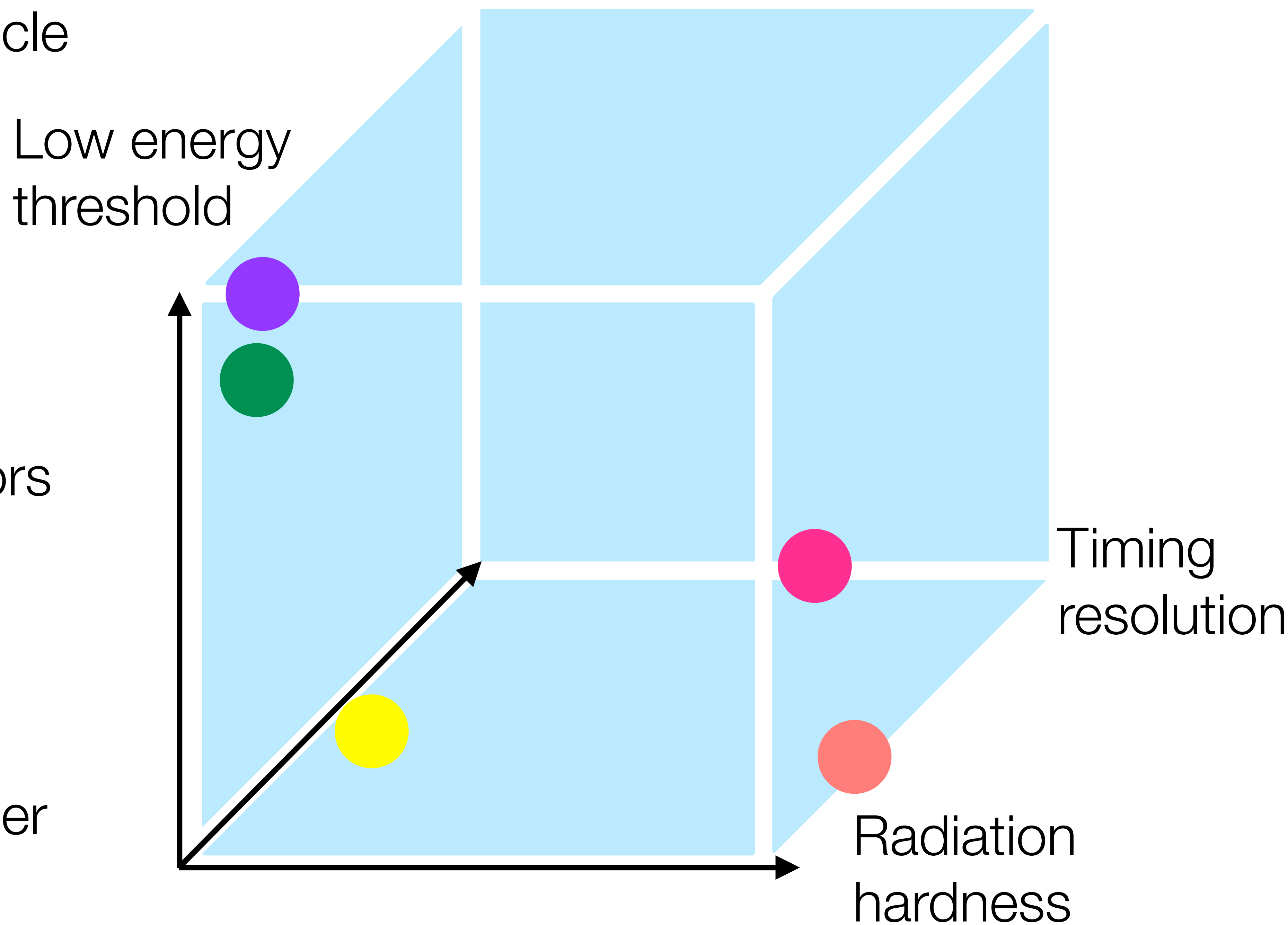
- FAIR & EIC



Micropattern gas tracking detectors in particle physics

[ECFA R&D roadmap]

Future uses for muon systems, TPCs, particle ID, tracking, …



- DarkLight
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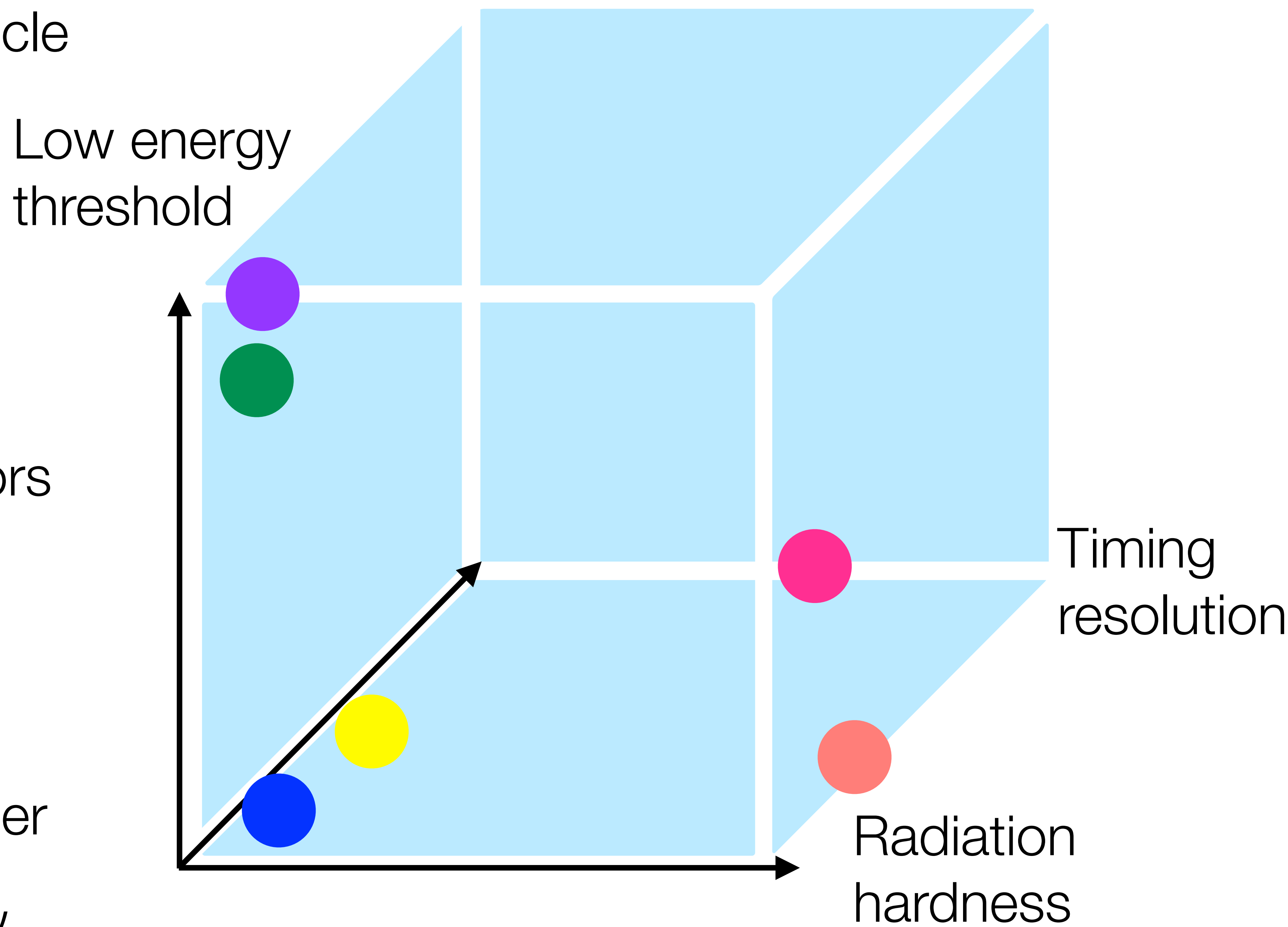
Micropattern gas tracking detectors in particle physics

ECFA R&D roadmap

Future uses for muon systems, TPCs, particle ID, tracking, …

- DarkLight
- DUNE near detectors
- Light dark matter
- FAIR & EIC
- Future energy frontier
- Large-volume DM/v



SiPMs and silicon sensors in particle physics

Other needs: cryogenic operation, low power, position precision, large wafers …

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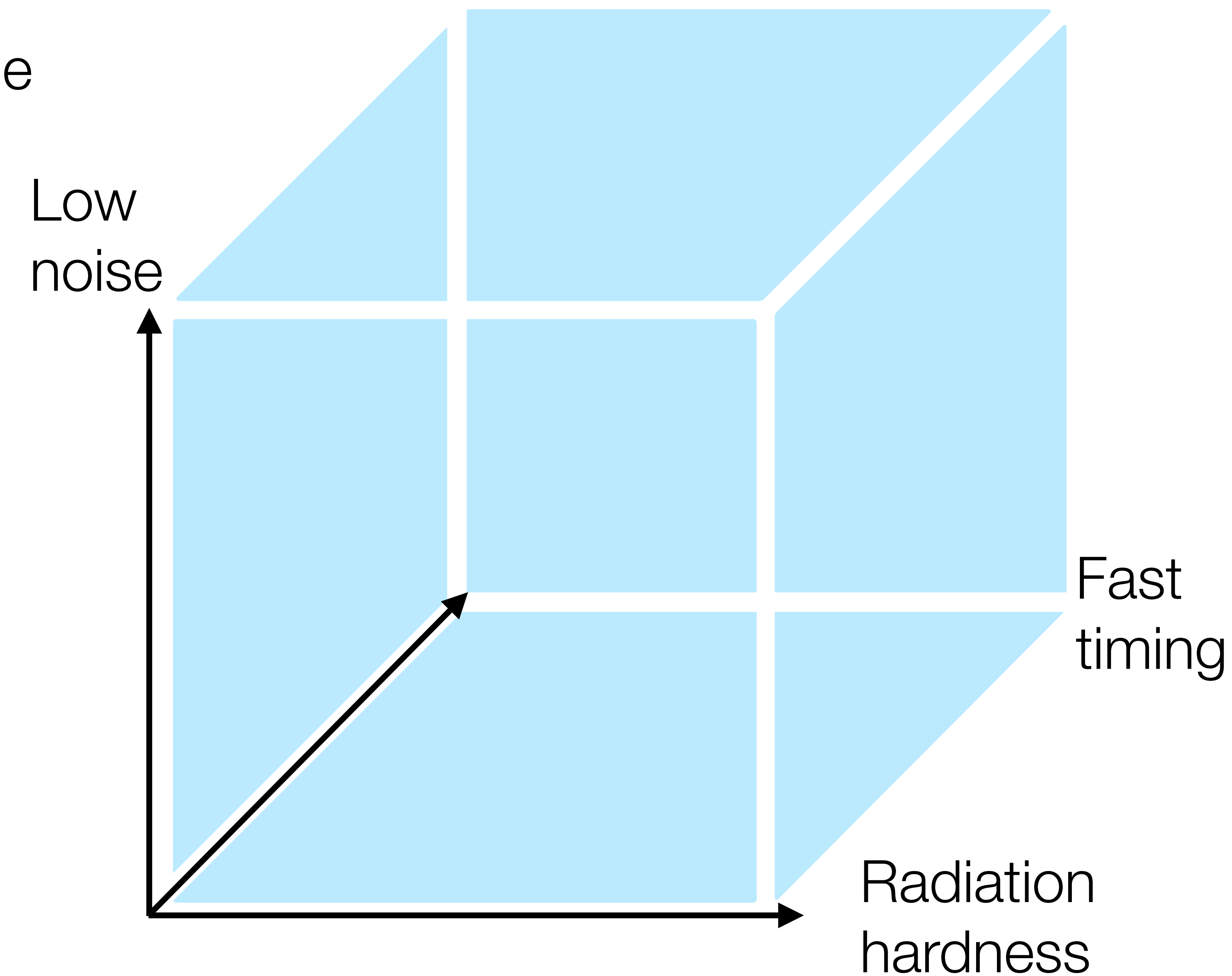

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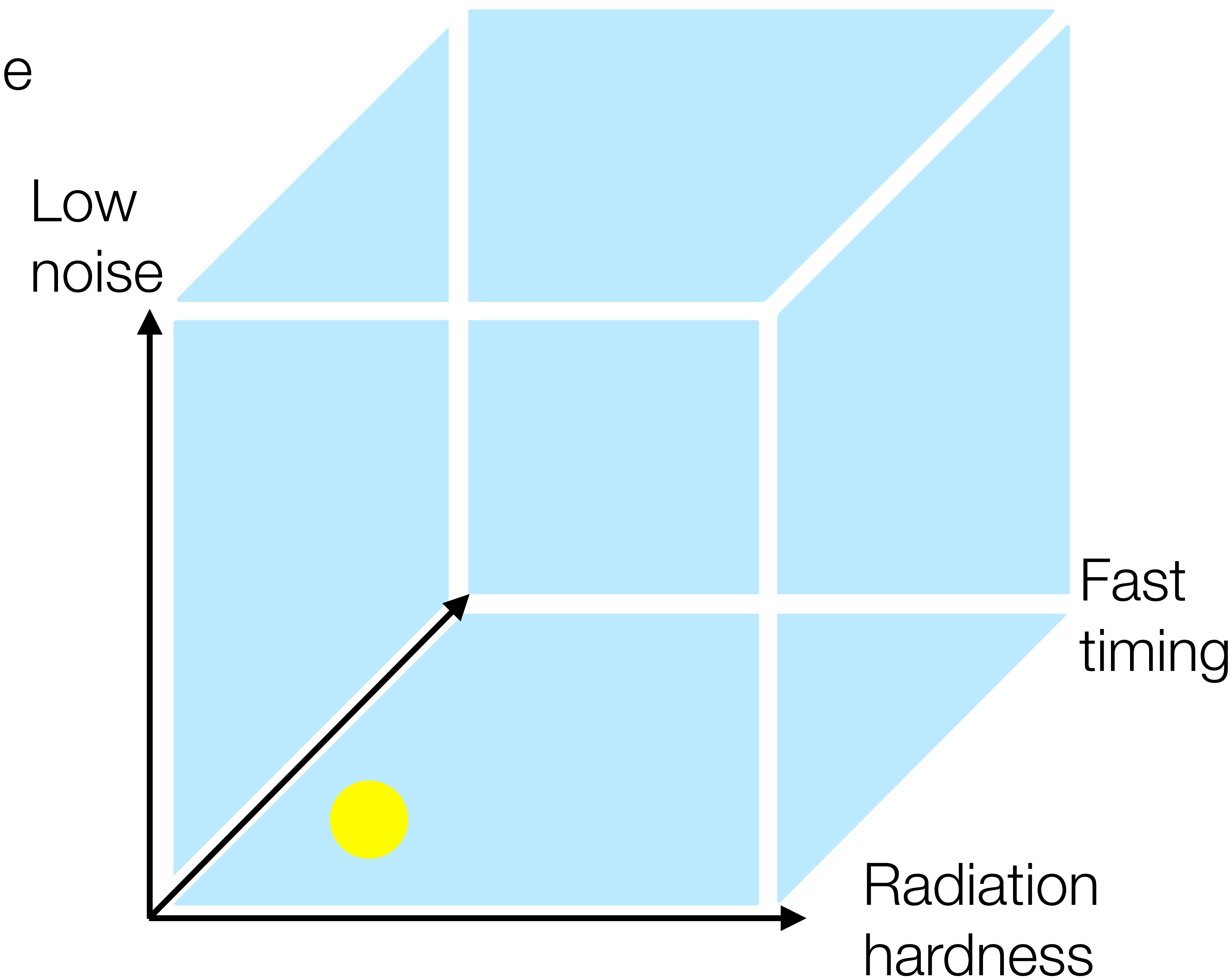
DarkLight (SiPMs)



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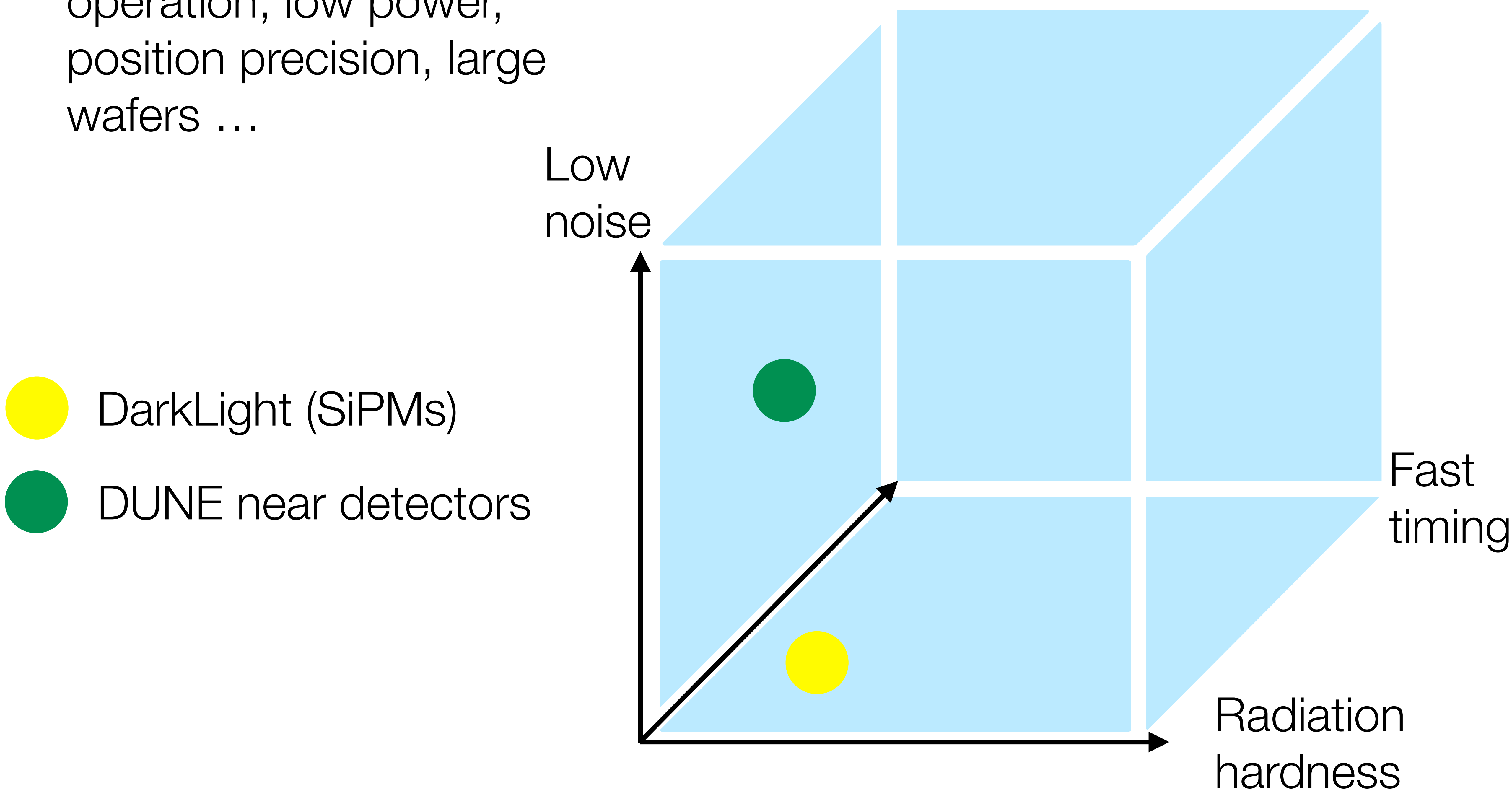

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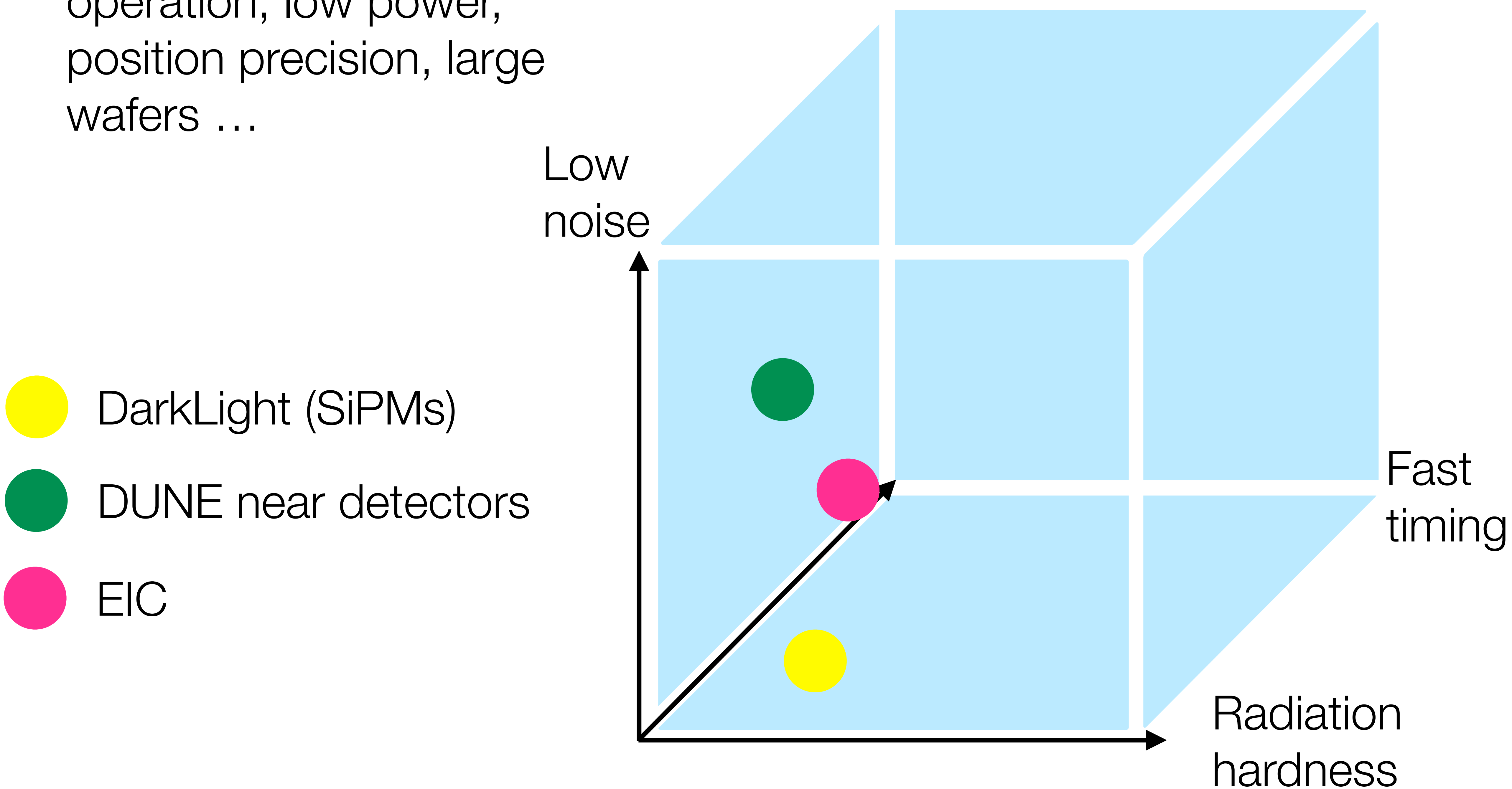

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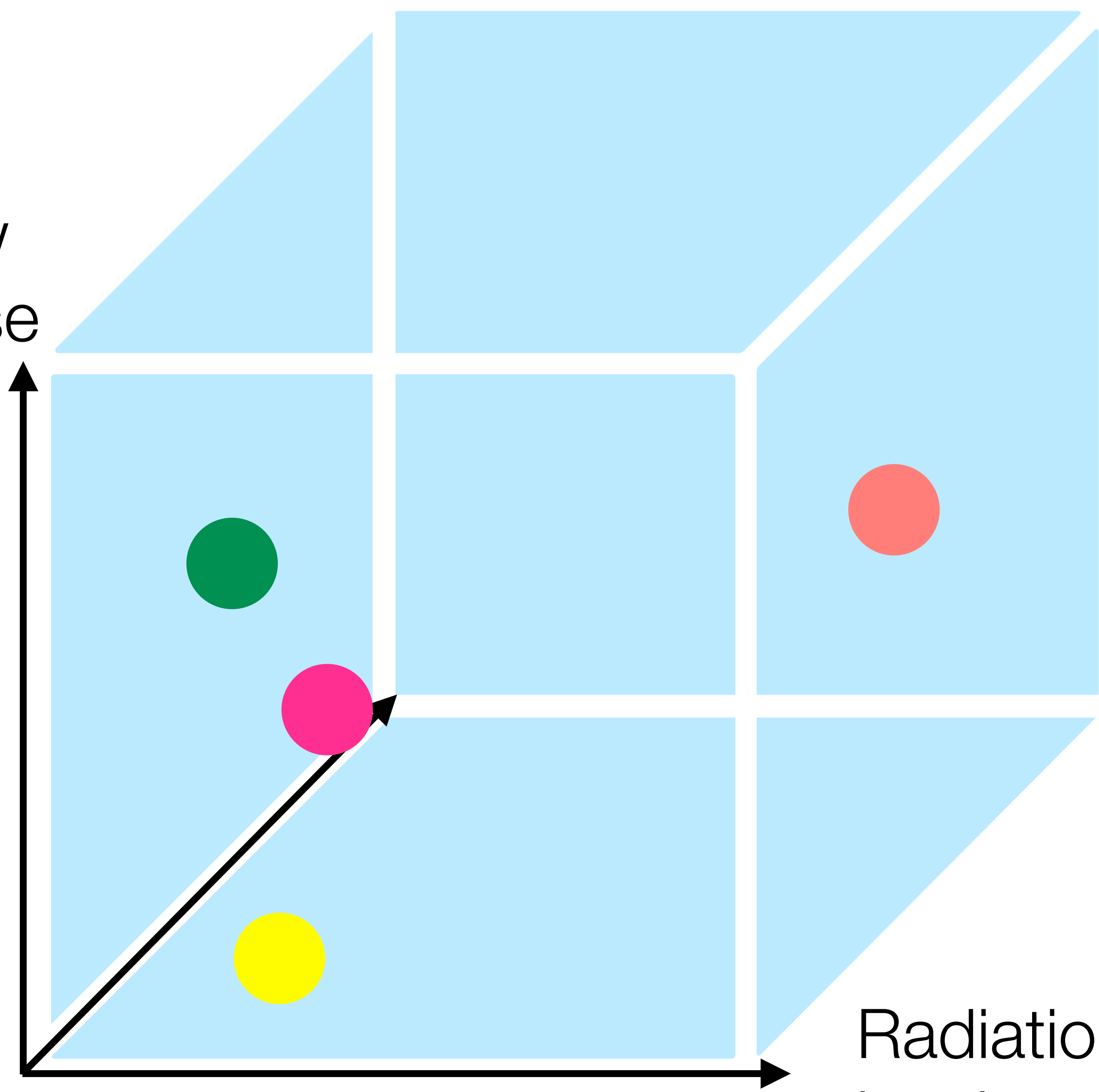

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- DUNE near detectors
- EIC
- Future energy frontier

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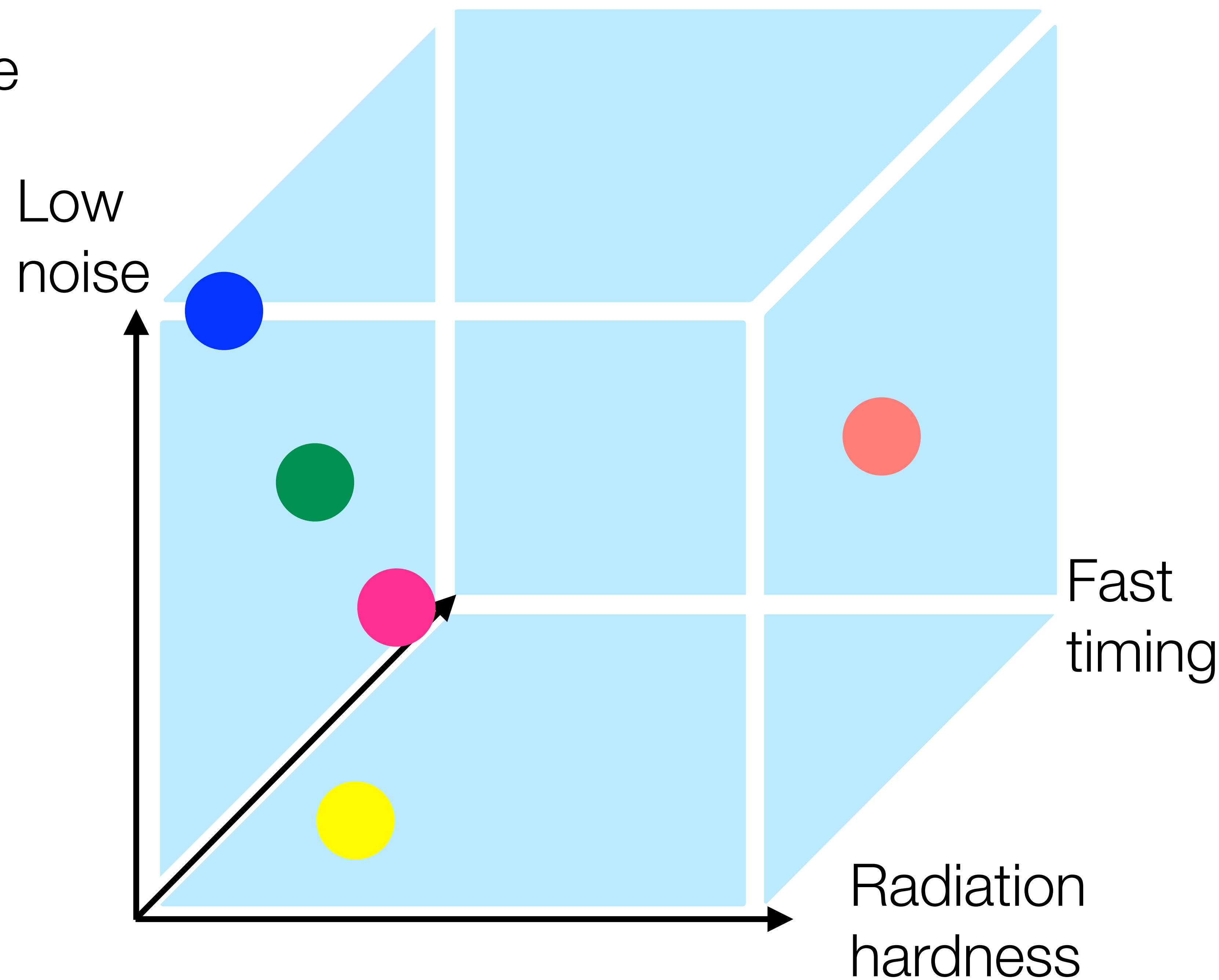

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TRIUMF & similar institutions provide training in addition to service

Scientific computing

- What DarkLight needs:
    - Close to real-time processing of GEM tracking data
- DarkLight's demands relatively lightweight relative to other experiments, but computing demands as a whole projected to grow dramatically in HEP
- Combine with electronics/DAQ: smart readout and on-detector data reduction will contribute
- TRIUMF hosted major ATLAS computing cluster; scientific computing department working on ML and quantum applications

Detector development at TRIUMF

Wide range of projects - just a few recent related examples here

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Gas detectors

ATLAS New Small Wheels

Alpha-g TPC

* N31-04, N31-05, N11-022, N07-01, N01-045

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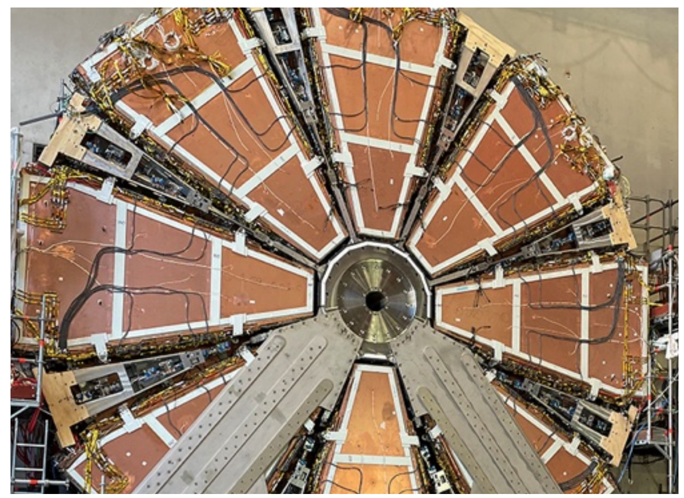

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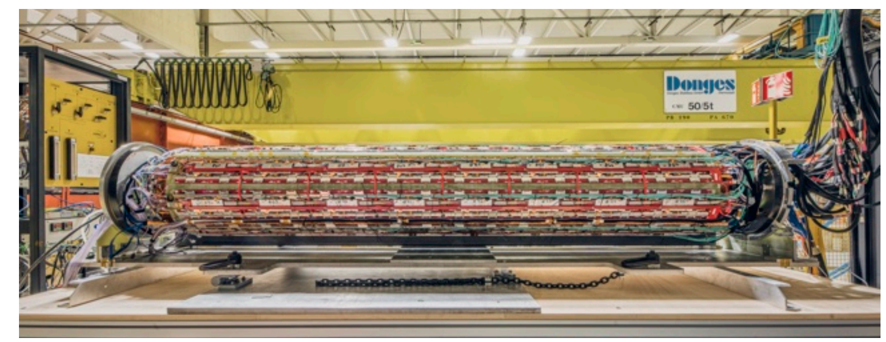
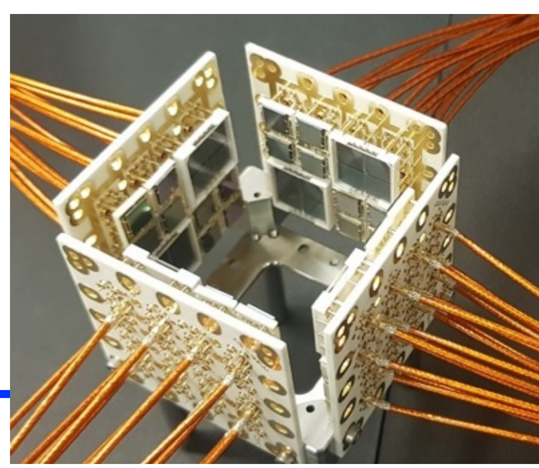


SiPMs & SPADs

LoLX



See talks and posters! (*)

* N11-092,
N26-06, JS01

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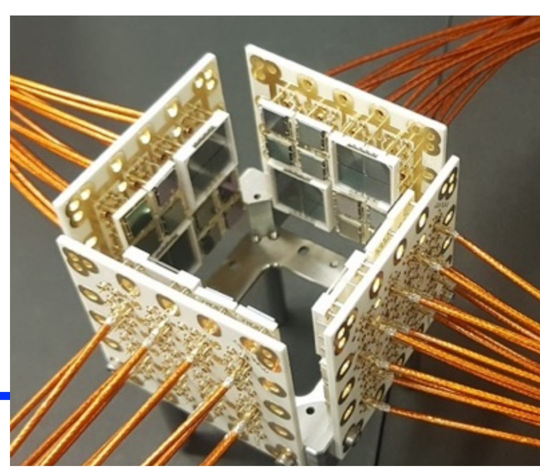

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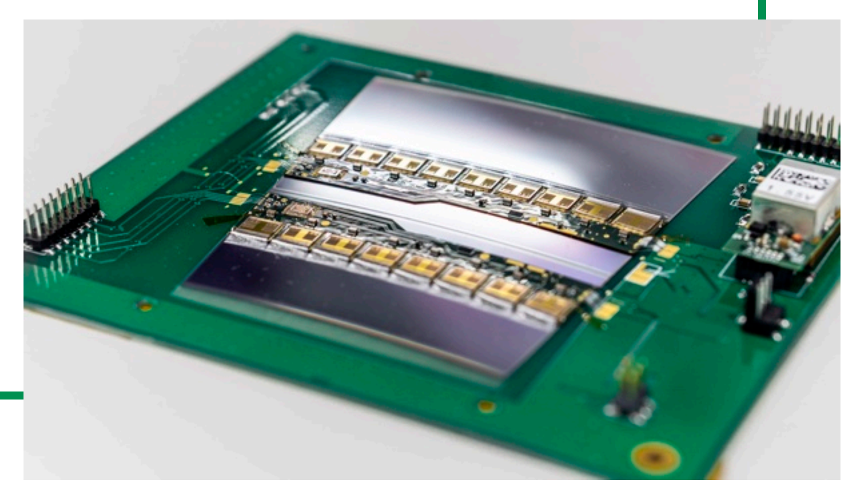

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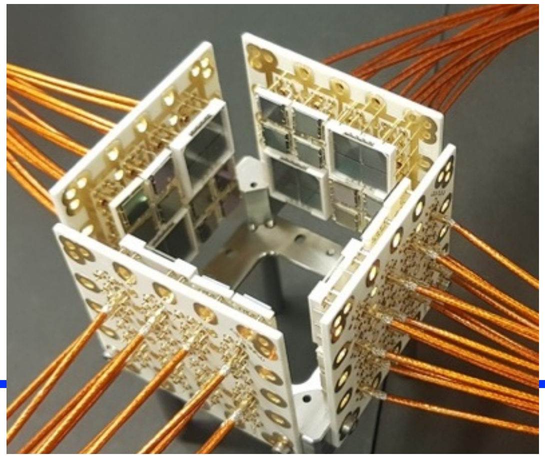

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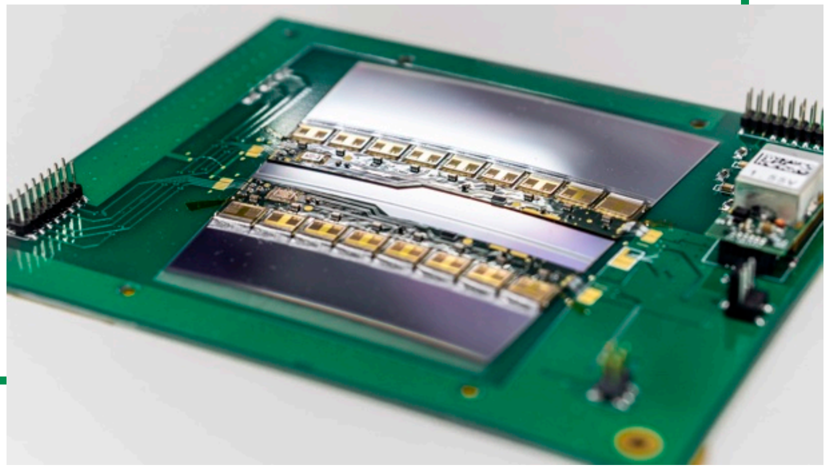

TRIUMF provides key support for Canadian and international experiments

Future detector R&D initiatives

Silicon sensors: leverage existing infrastructure at TRIUMF and across Canada (ITk, nEXO)

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Ultimate TRIUMF goal is a new **Detector Center:**

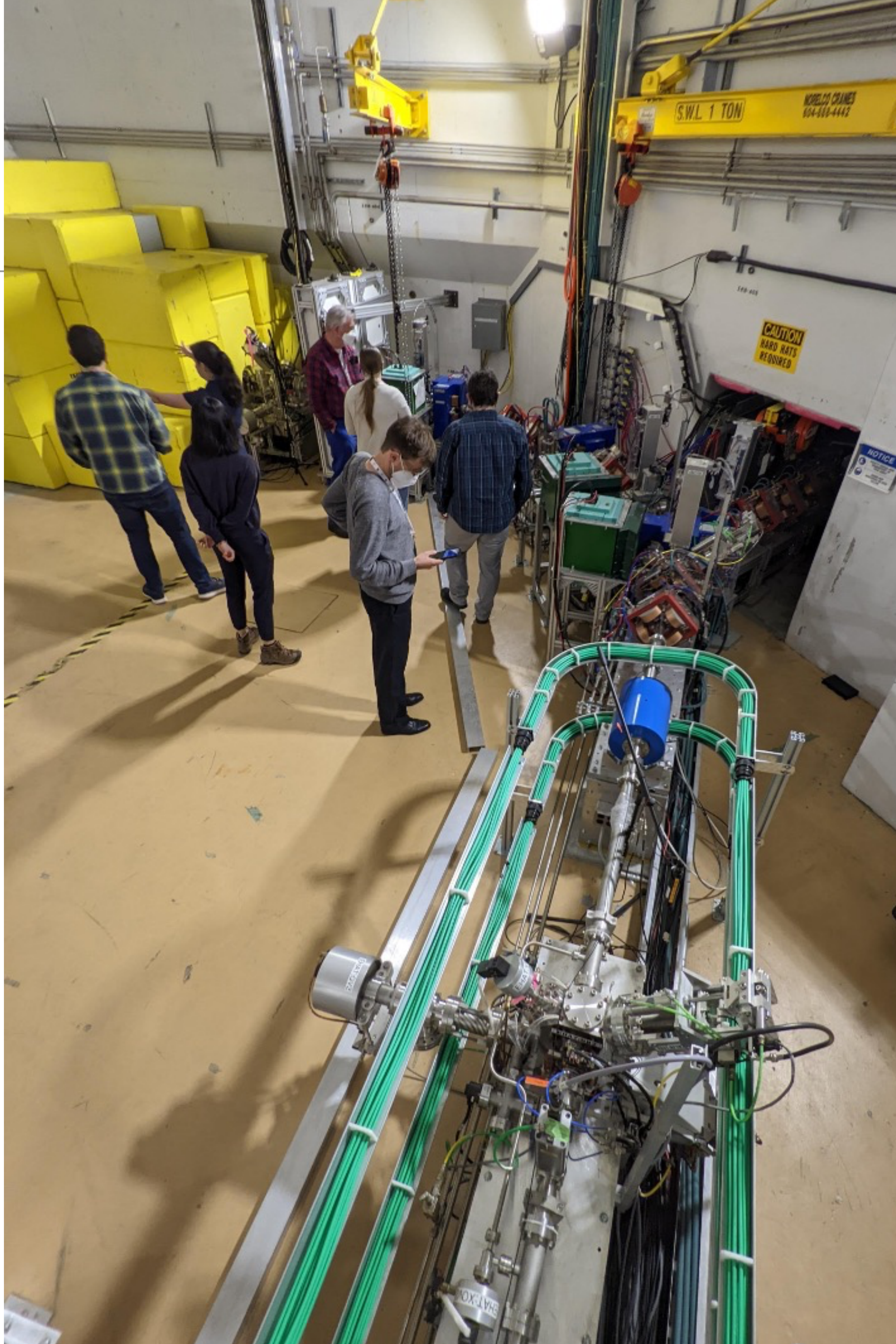
- Build on existing institutional knowledge and provide training for continuity of key expertise
- Focus on integrated detector technology, introducing climate applications
- Check out the 5 year plan for more

* N20-02, WS-SPAD-I

** N16-01, N28-04

The future of DarkLight

Start installation in the spring



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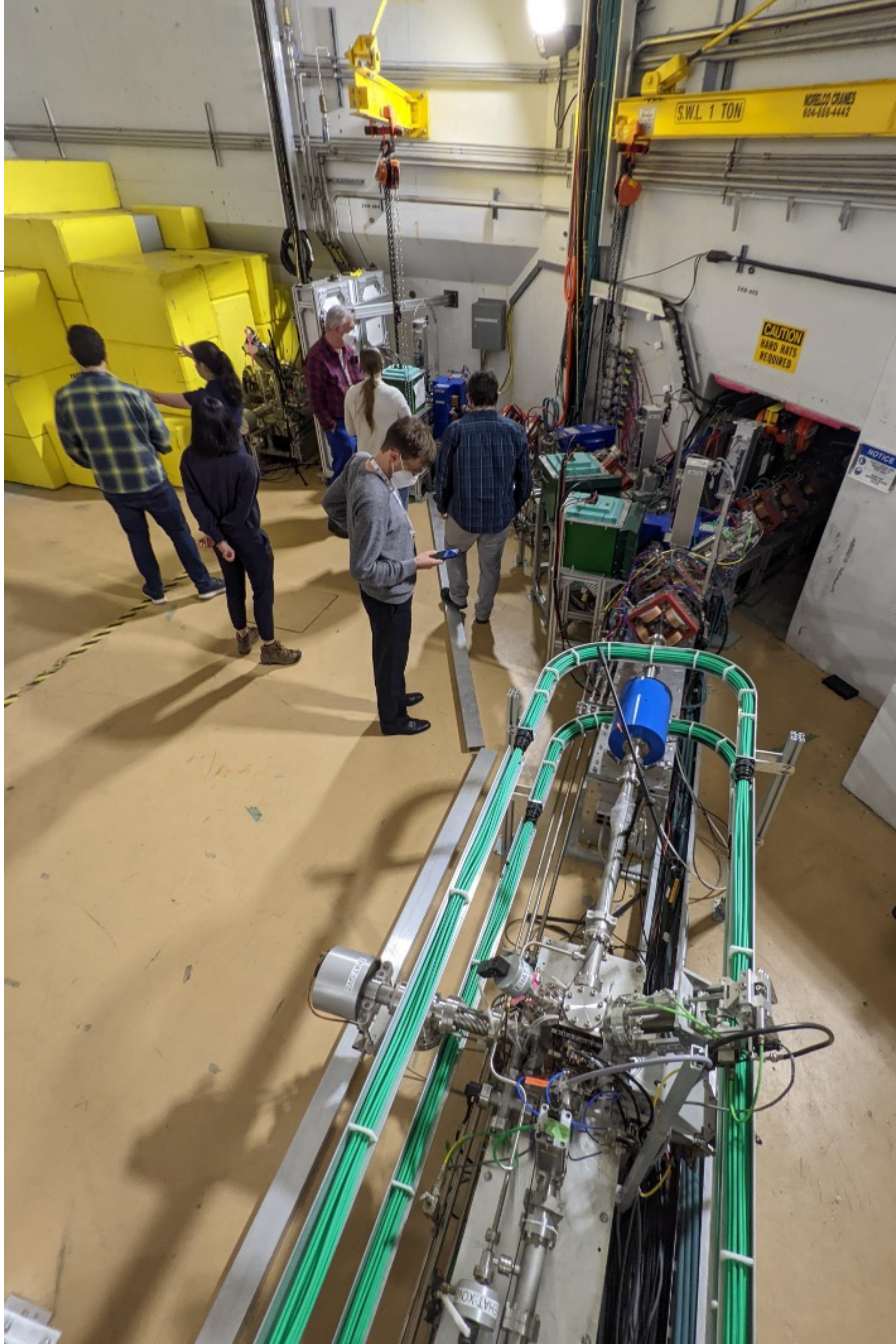

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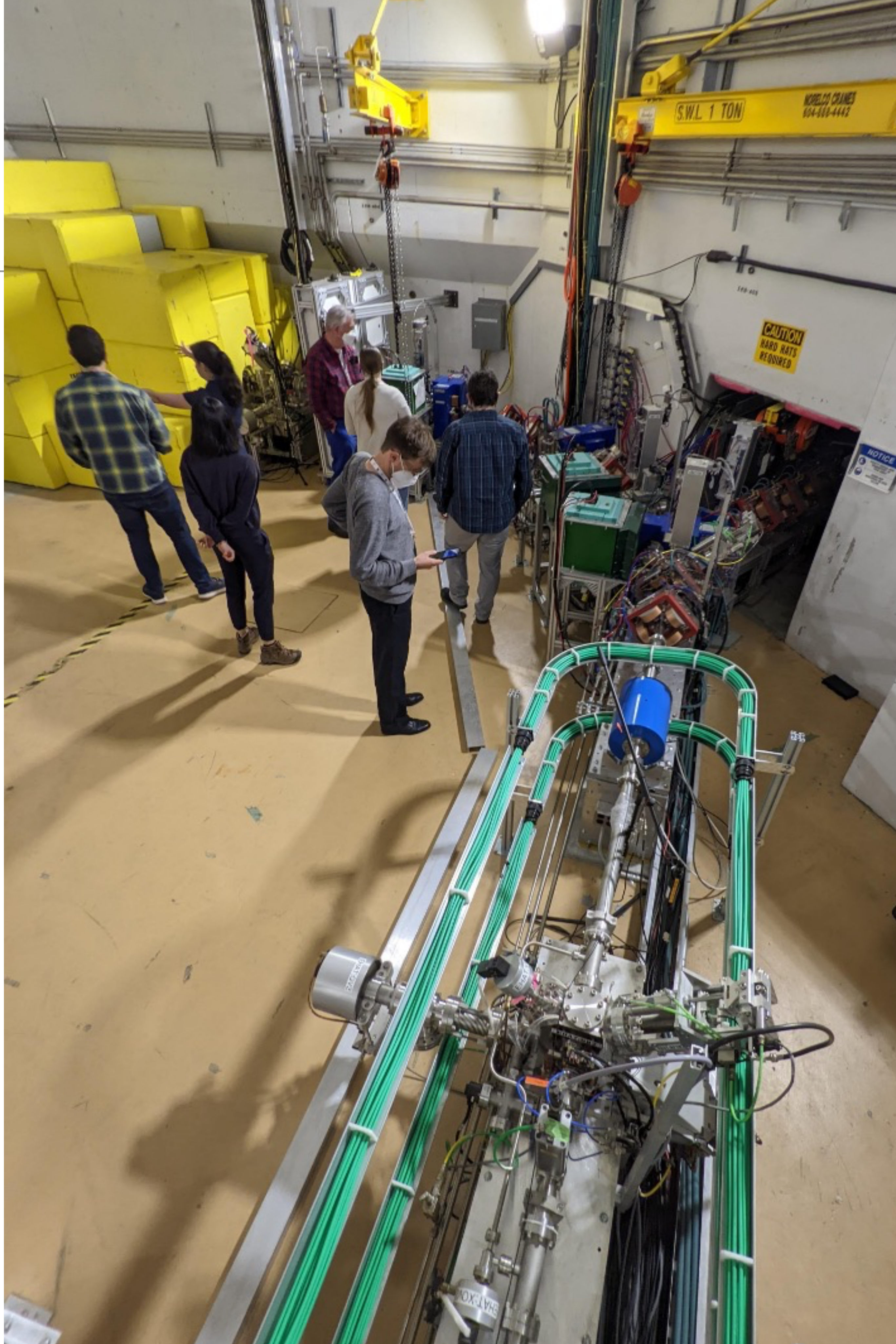

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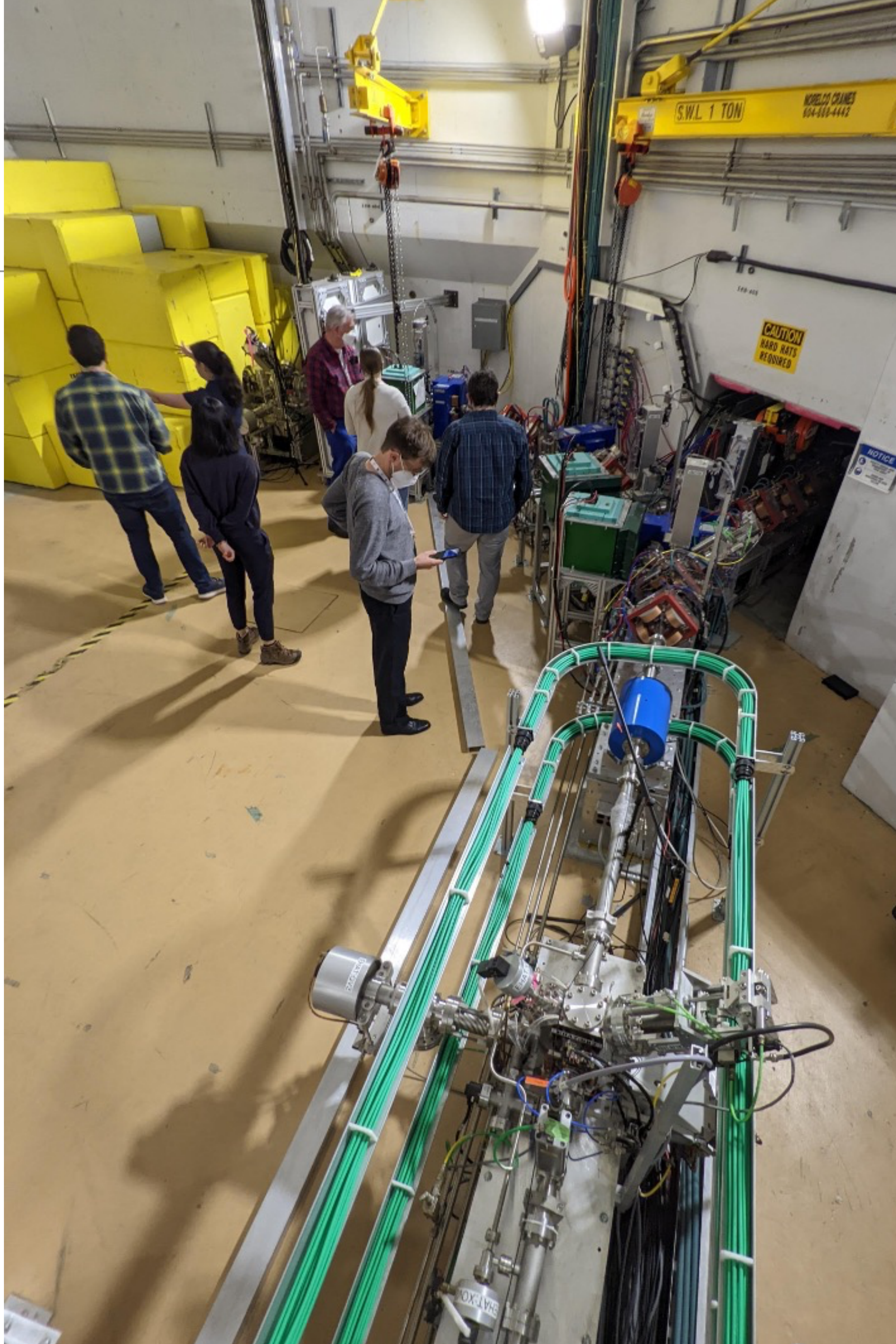

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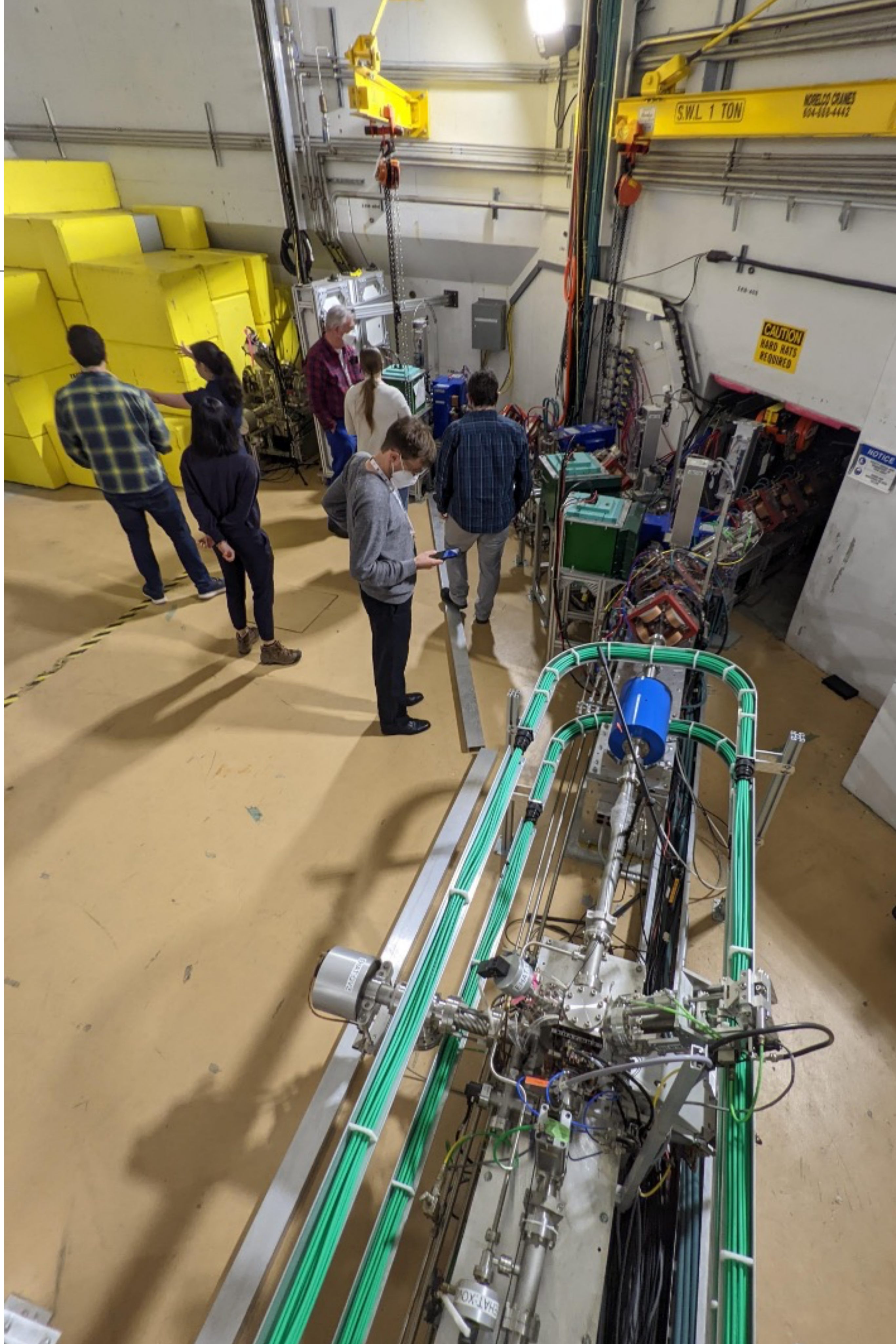
Potential to grow a low energy electron scattering program?



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Higgs factory next top priority

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EIC example of growing scale of nuclear facilities

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EIC example of growing scale of nuclear facilities

Accelerator

Advance power and scale efficiency (gradient)

High power targets

Stronger magnets

Theory, modelling

The future of particle physics instrumentation

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You are the people who will make this happen!

Conclusions

Subatomic physics experiments have wide range of instrumentation requirements

As a global community, we must keep pushing all R&D axes to serve future needs

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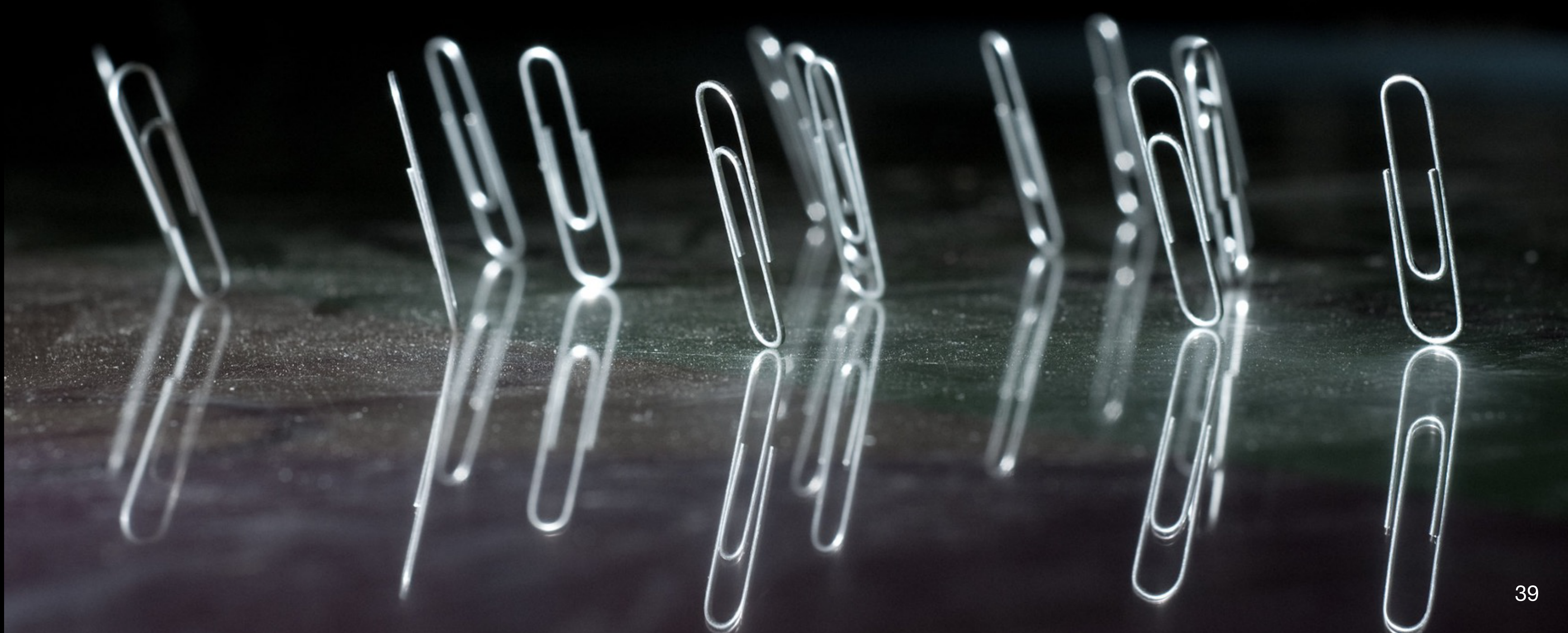
Come see us at the lab!! Public tours on Tuesdays (https://www.triumf.ca/public-tours) or come talk to me if you have any questions

Thanks for listening!

Questions?



Backup

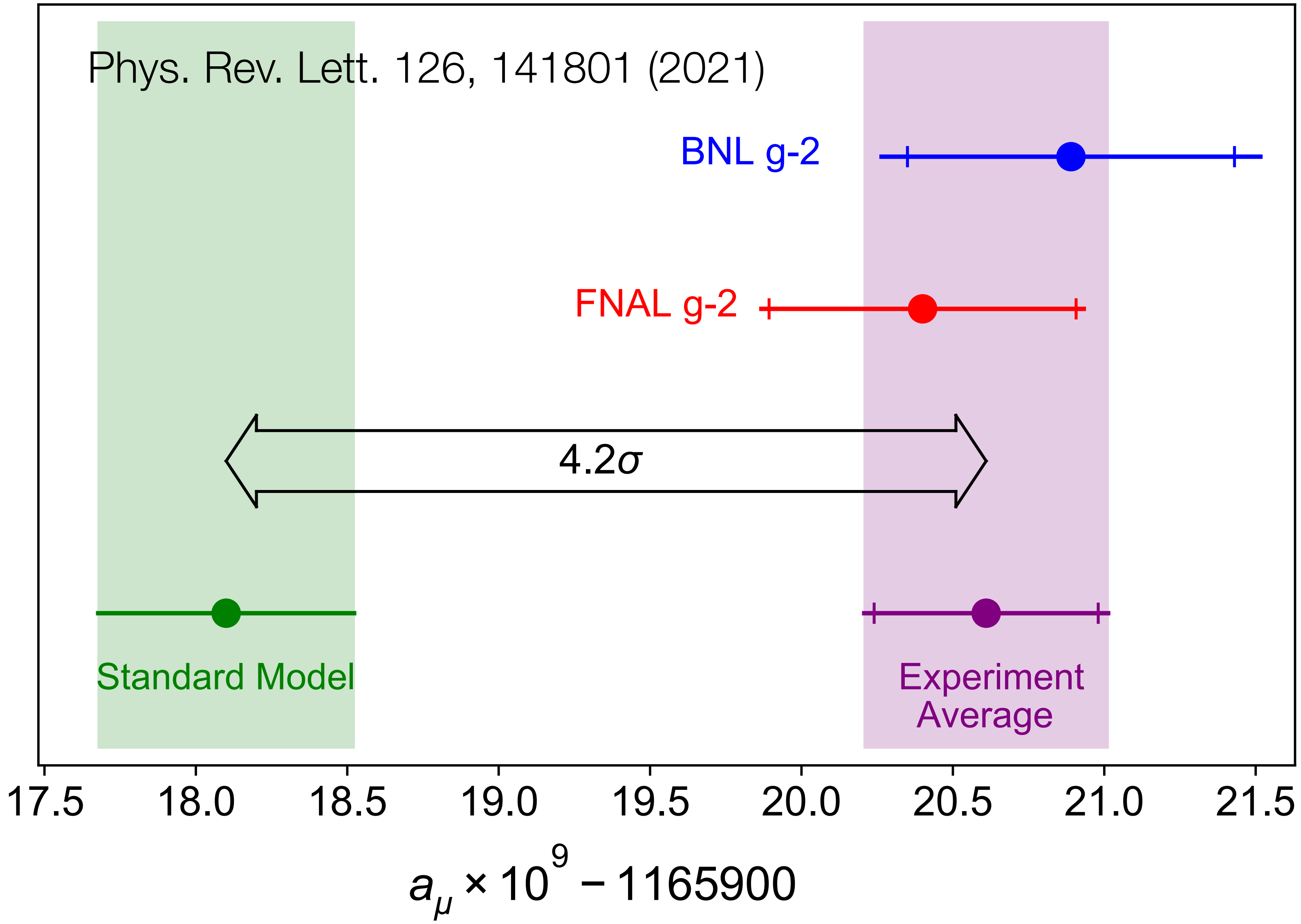
SiPMs history at TRIUMF and relevant talks

- T2K Fine Grained Detectors completed in 2009. 8,448 Hamamatsu MPPCs
- Contributed to SiPM readout for PET-MR (UBC+Manitoba), 2011-2016
- TREK experiment
- High timing resolution spectrometer for muon spin rotation experiments. SensL. 2013-now
- ALPHAg barrel veto. SensL with custom electronics. 2017-2020
- nEXO, SiPM (FBK++Hamamatsu) in liquid Xenon - 2015-now. Two talks, K. Raymond (SFU, N31-04) and S. Bron (TRIUMF, N31-05) and a poster (N11-022) at the conference!
- DarkLight
- Single Photon Air Analyser for early forest fire detection. 2021-now
- High rate (>100MHz) neutron detector for General Fusion. Broadcom SiPM, 2022-now. See a talk (N07-01 by Alison Radich) and a poster (N01-045) here.
- Beyond SiPMs to integrated detectors: see talks N28-04 and N16-01

Muon g-2

"Spin" of a muon in a magnetic field **very precisely predicted**

Measured value is significantly different



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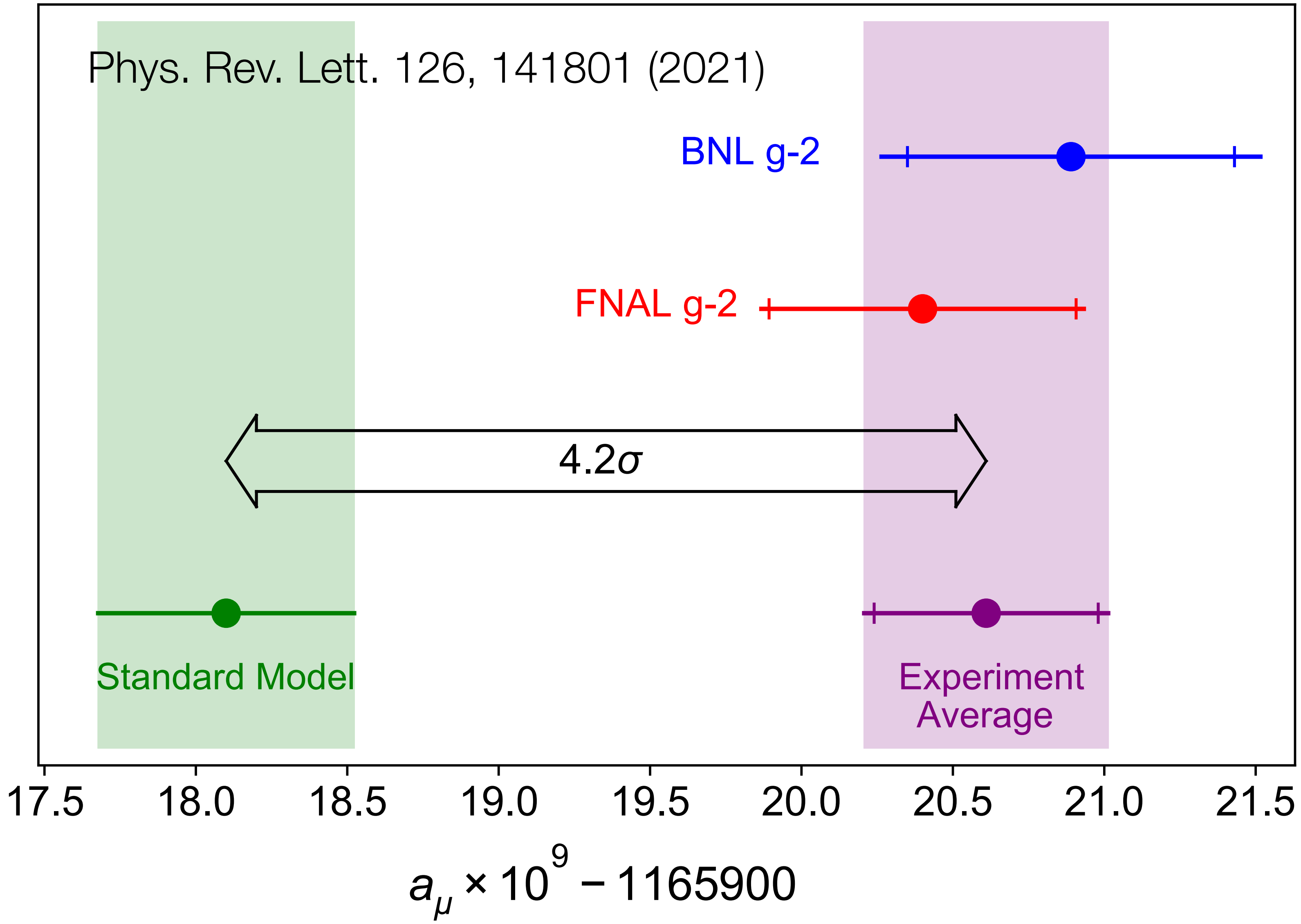
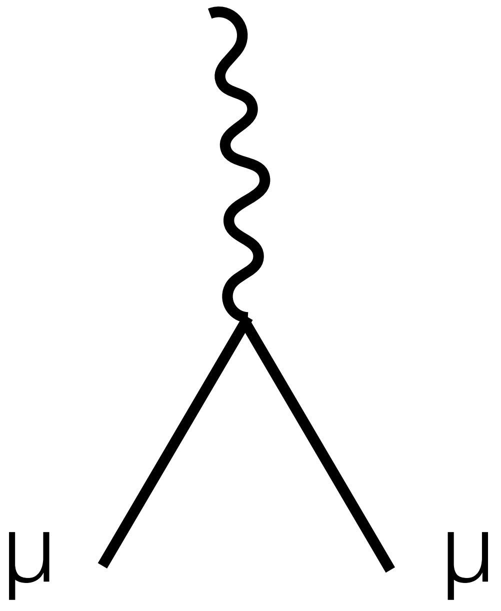


(magnetic field)



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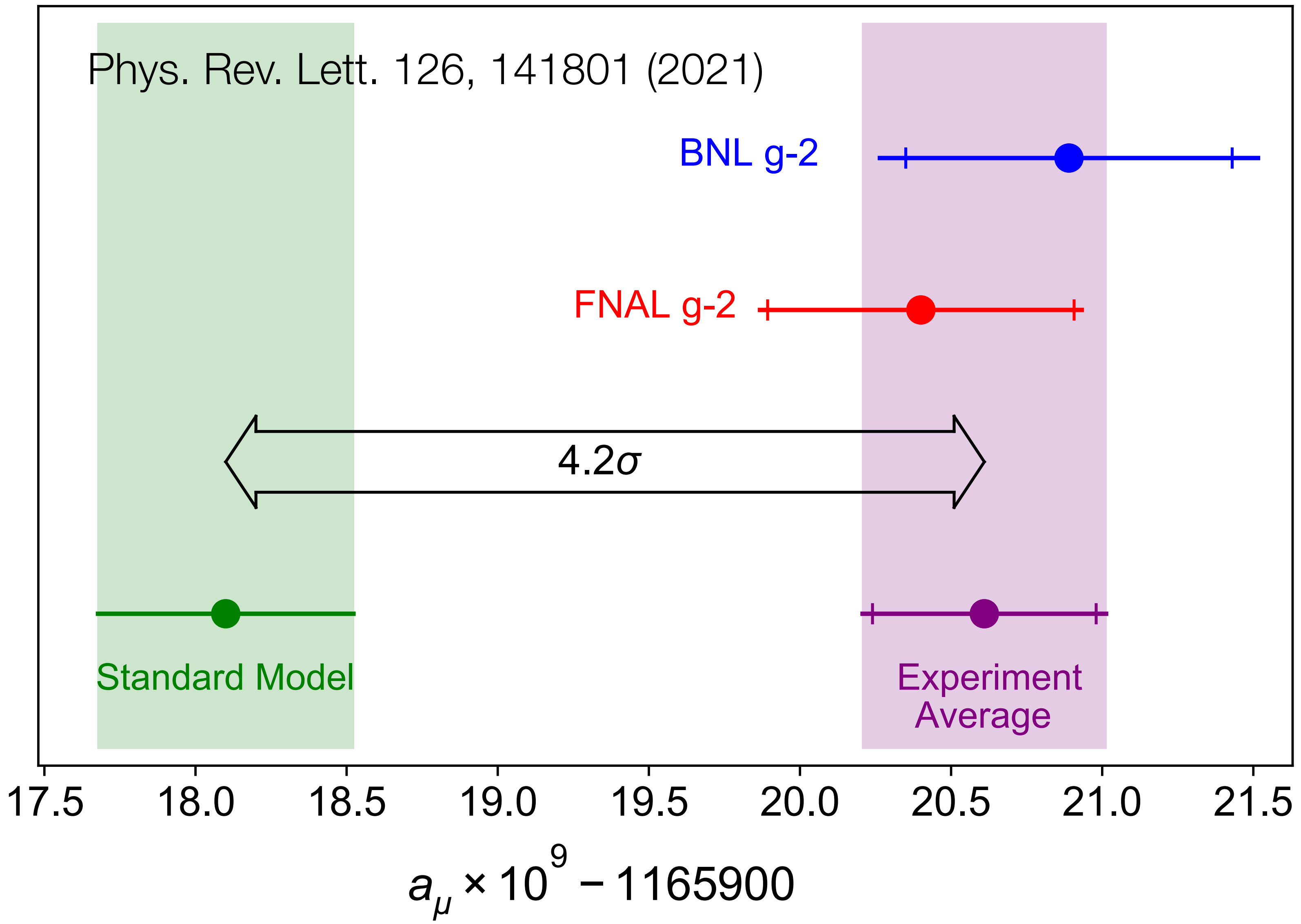

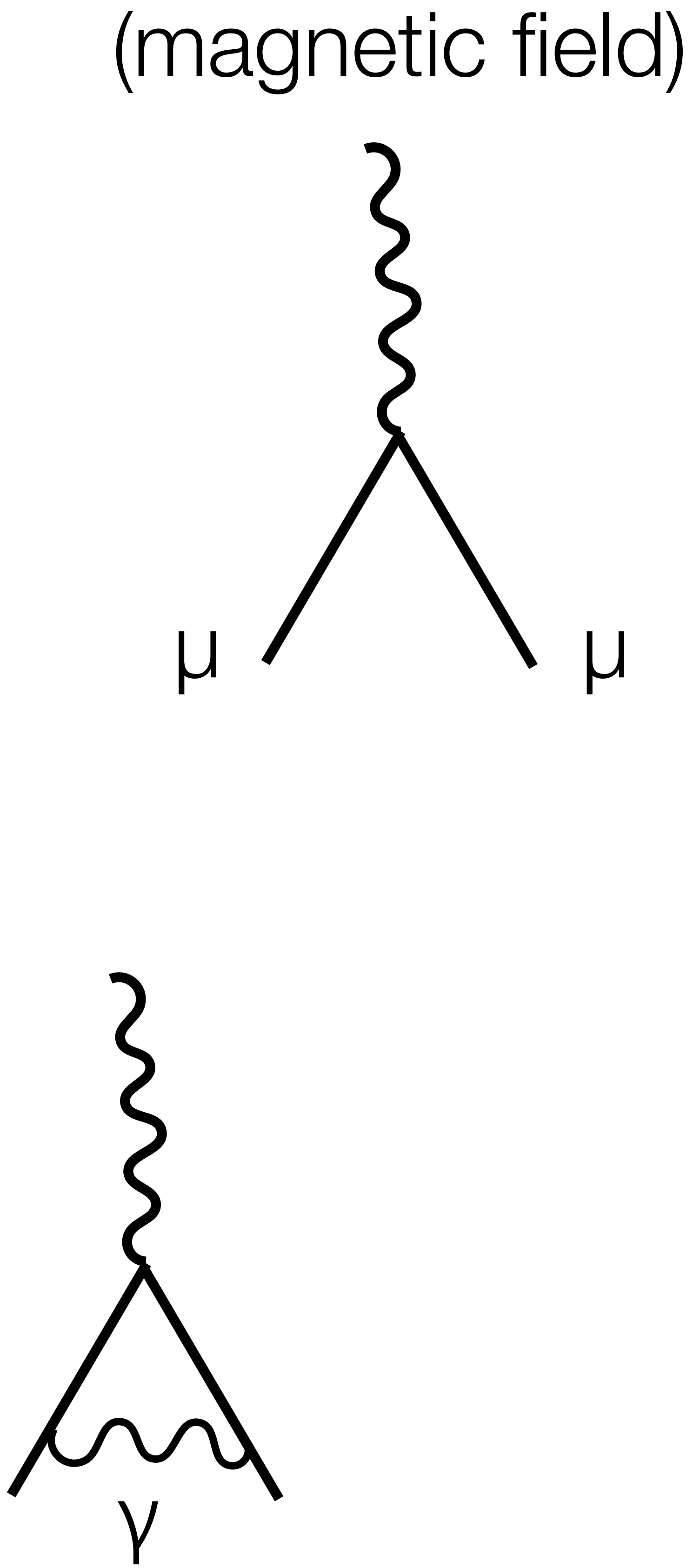

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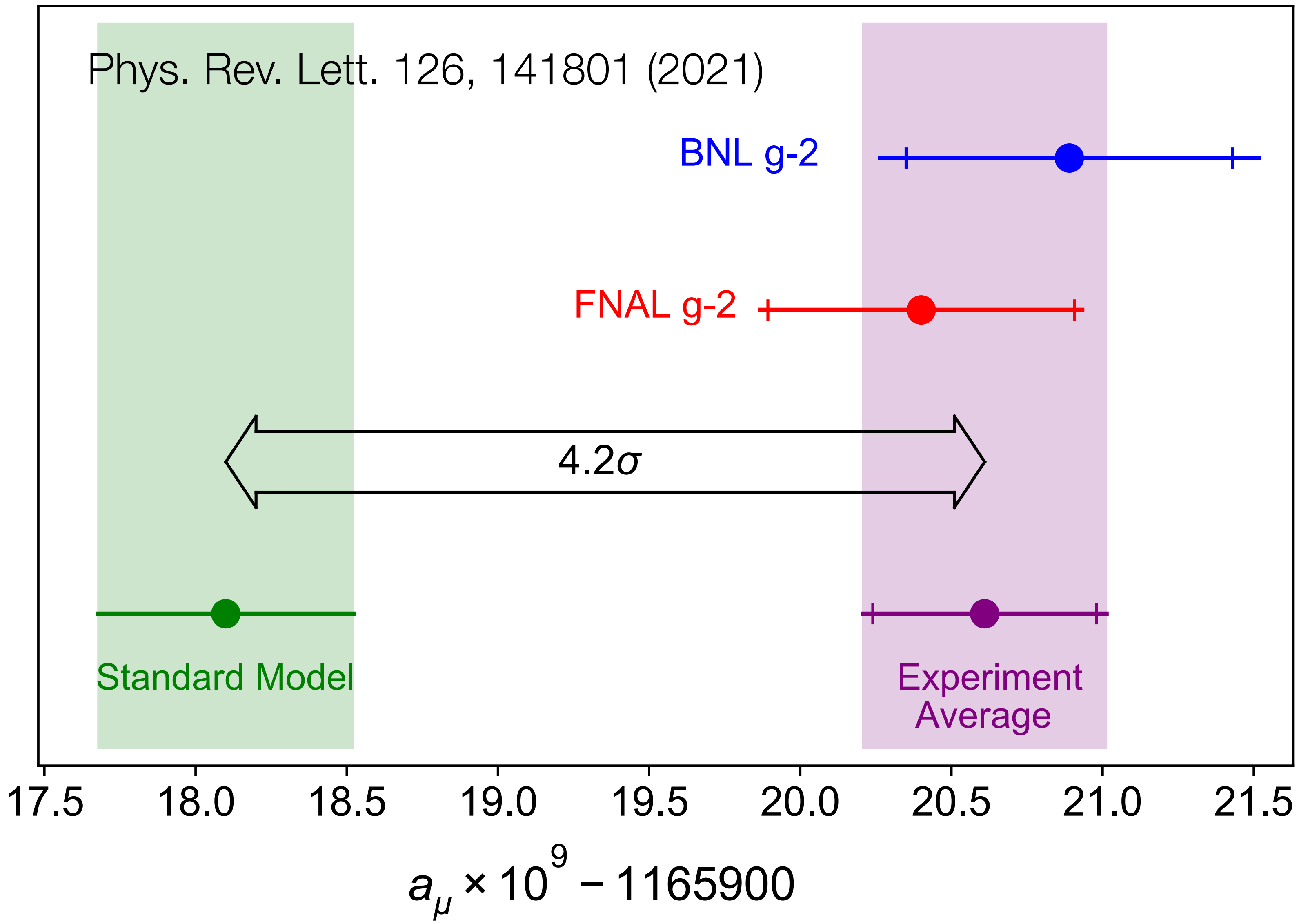

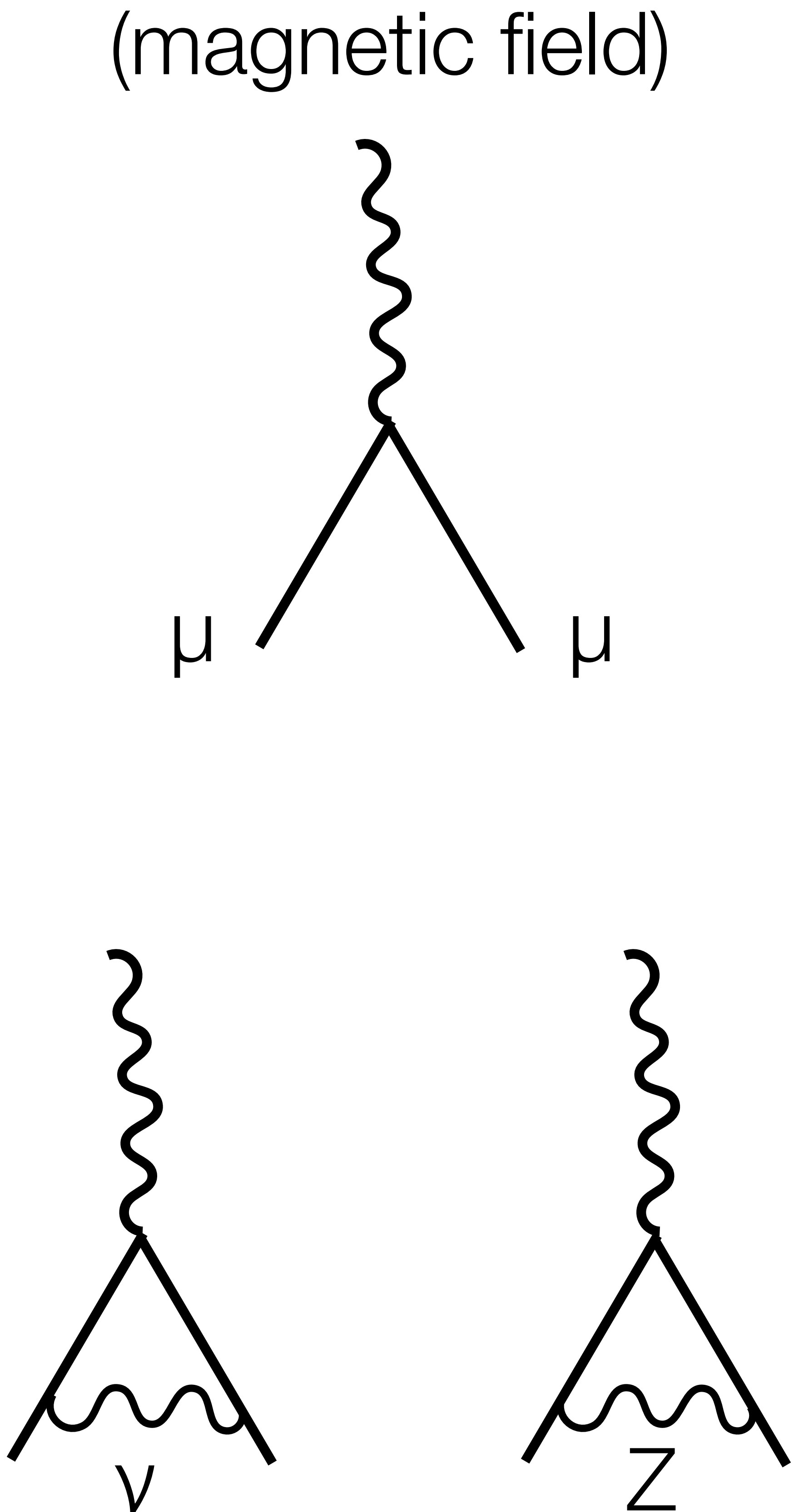

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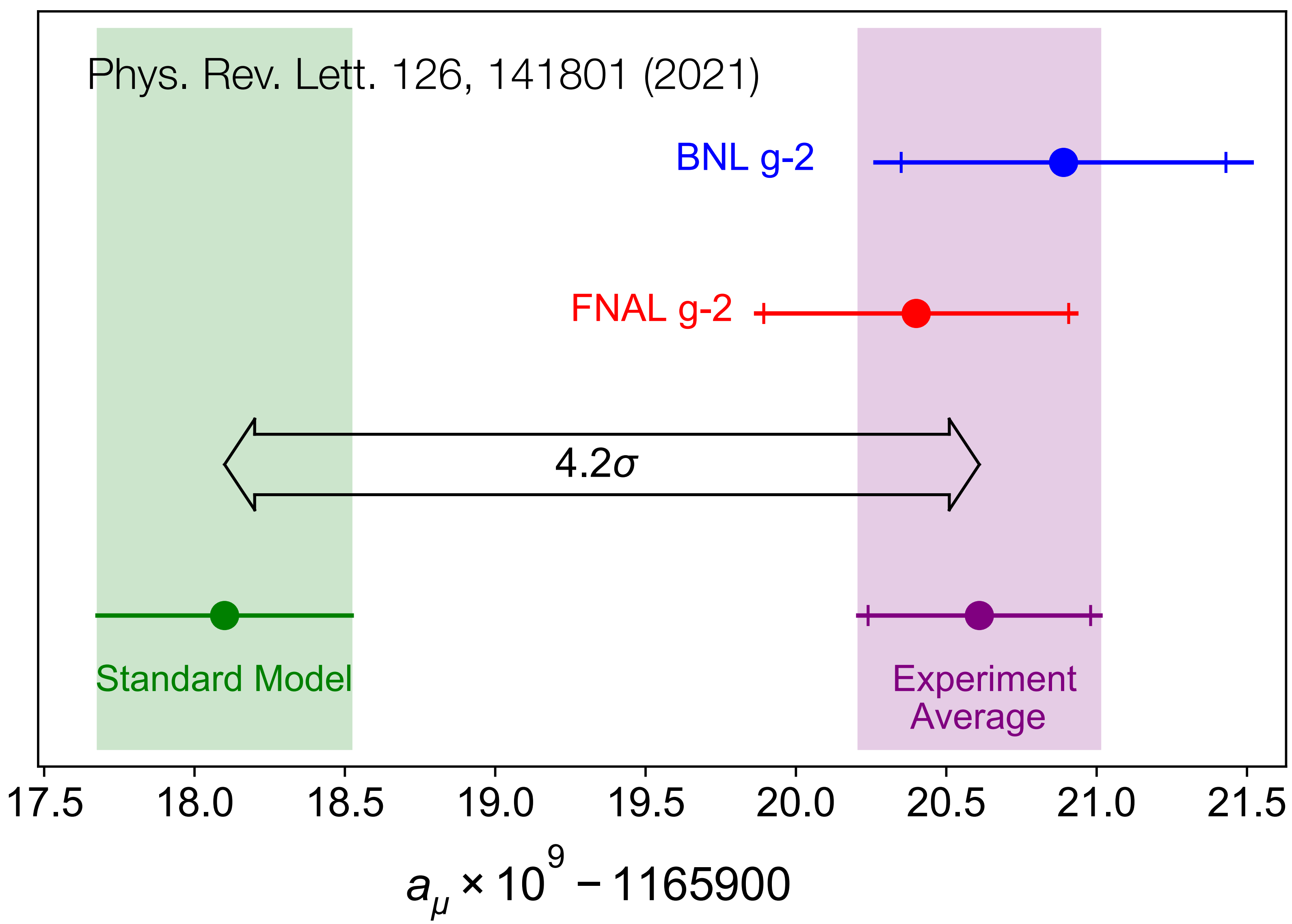

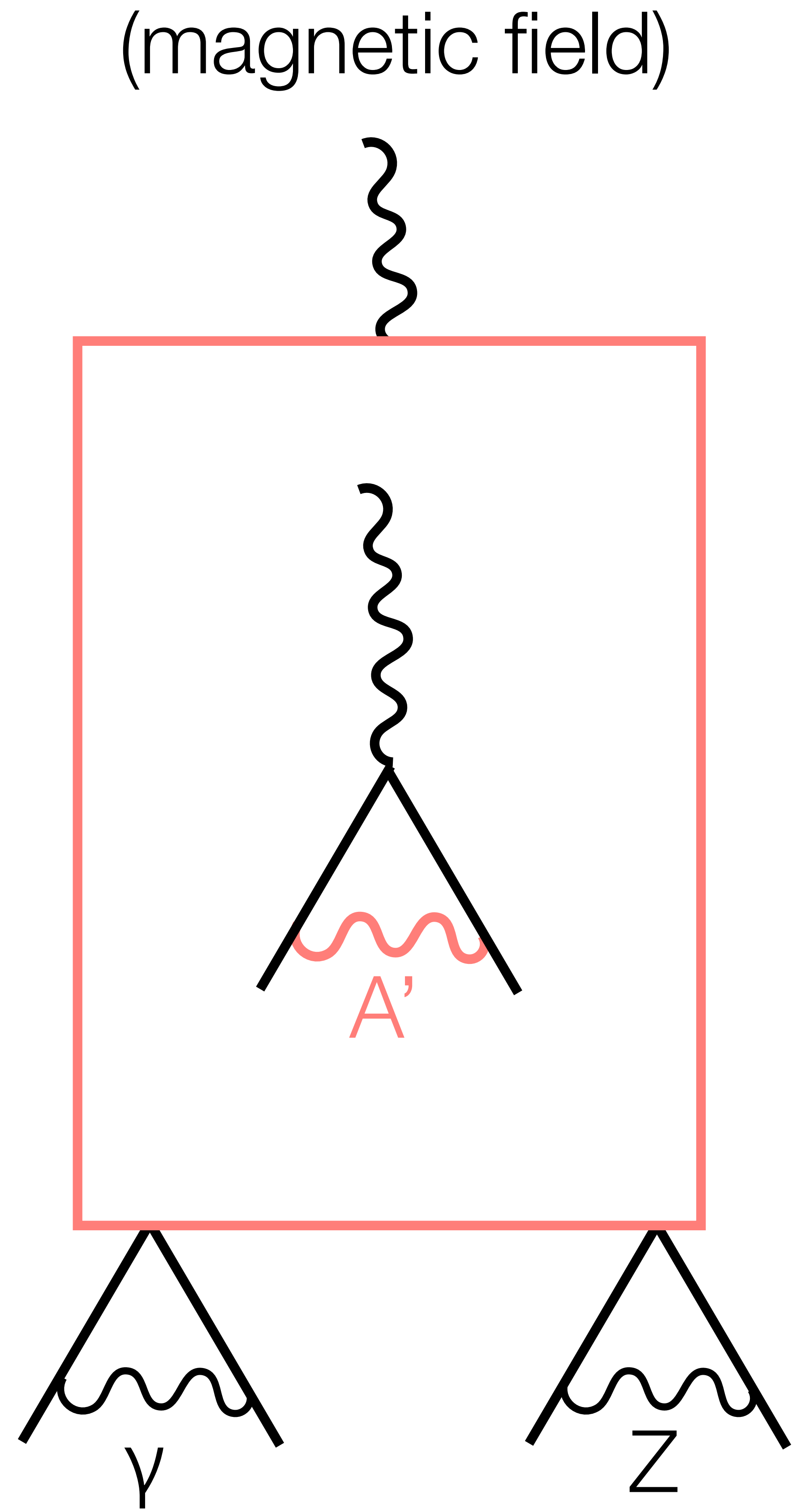

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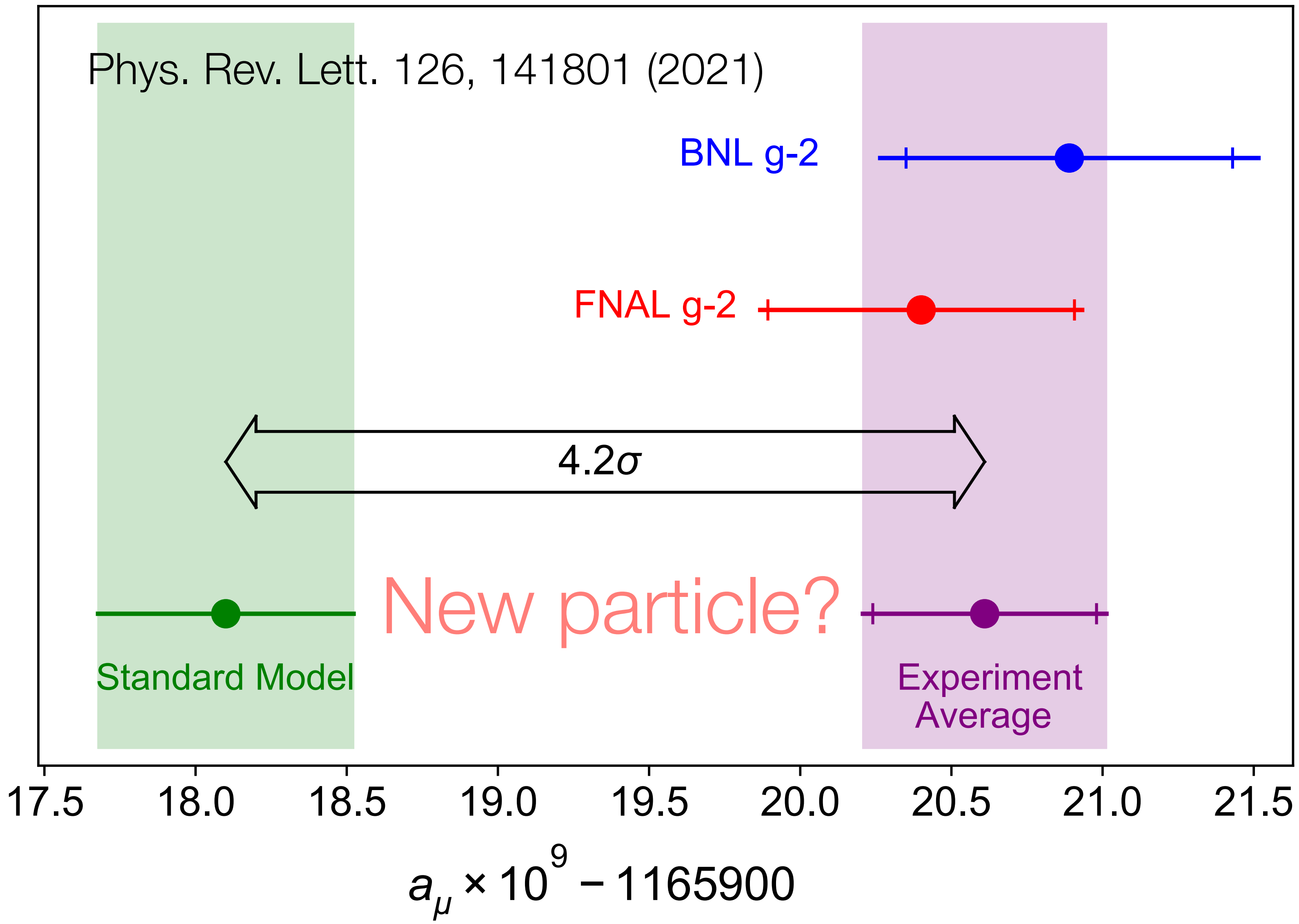
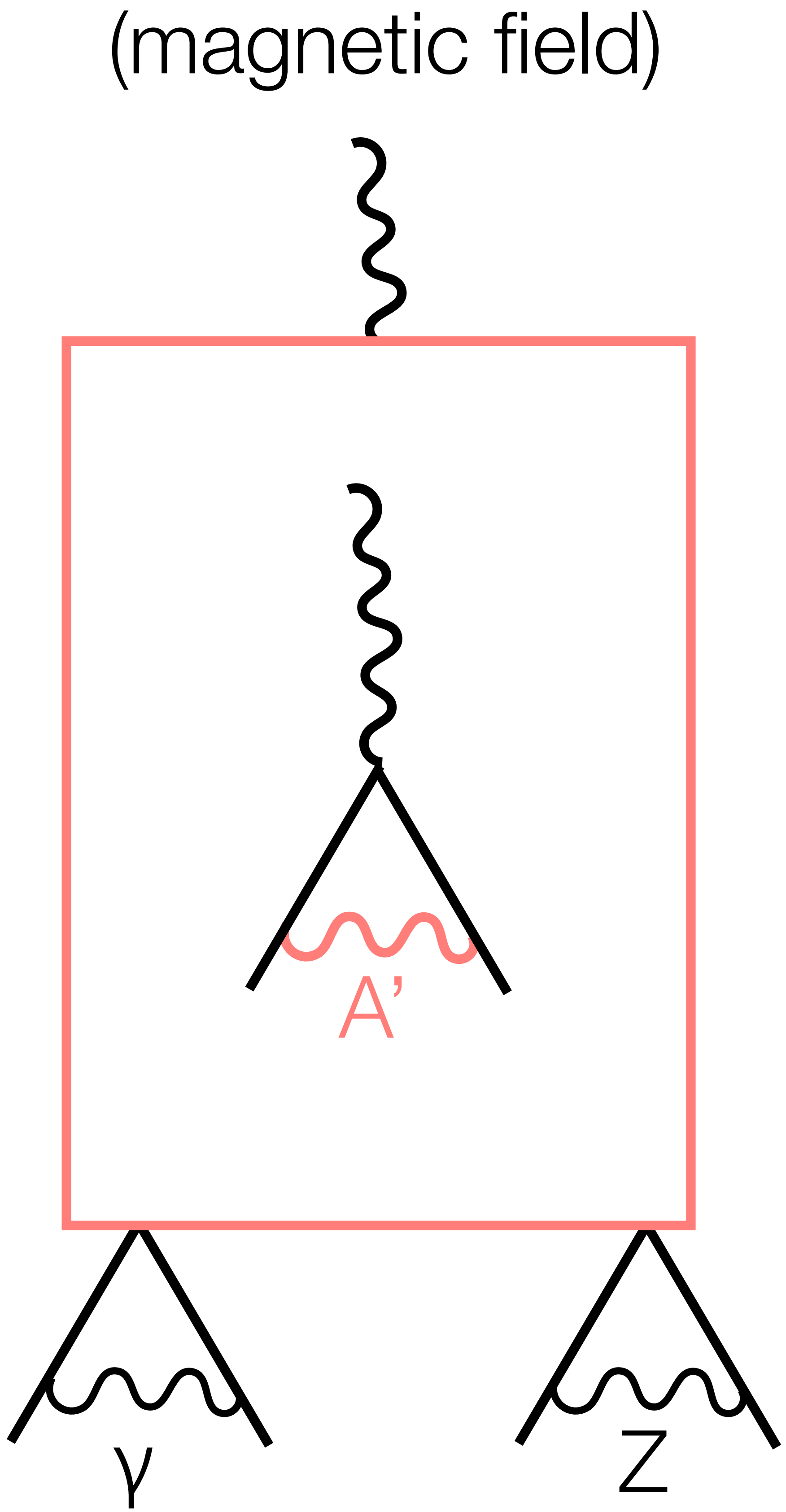
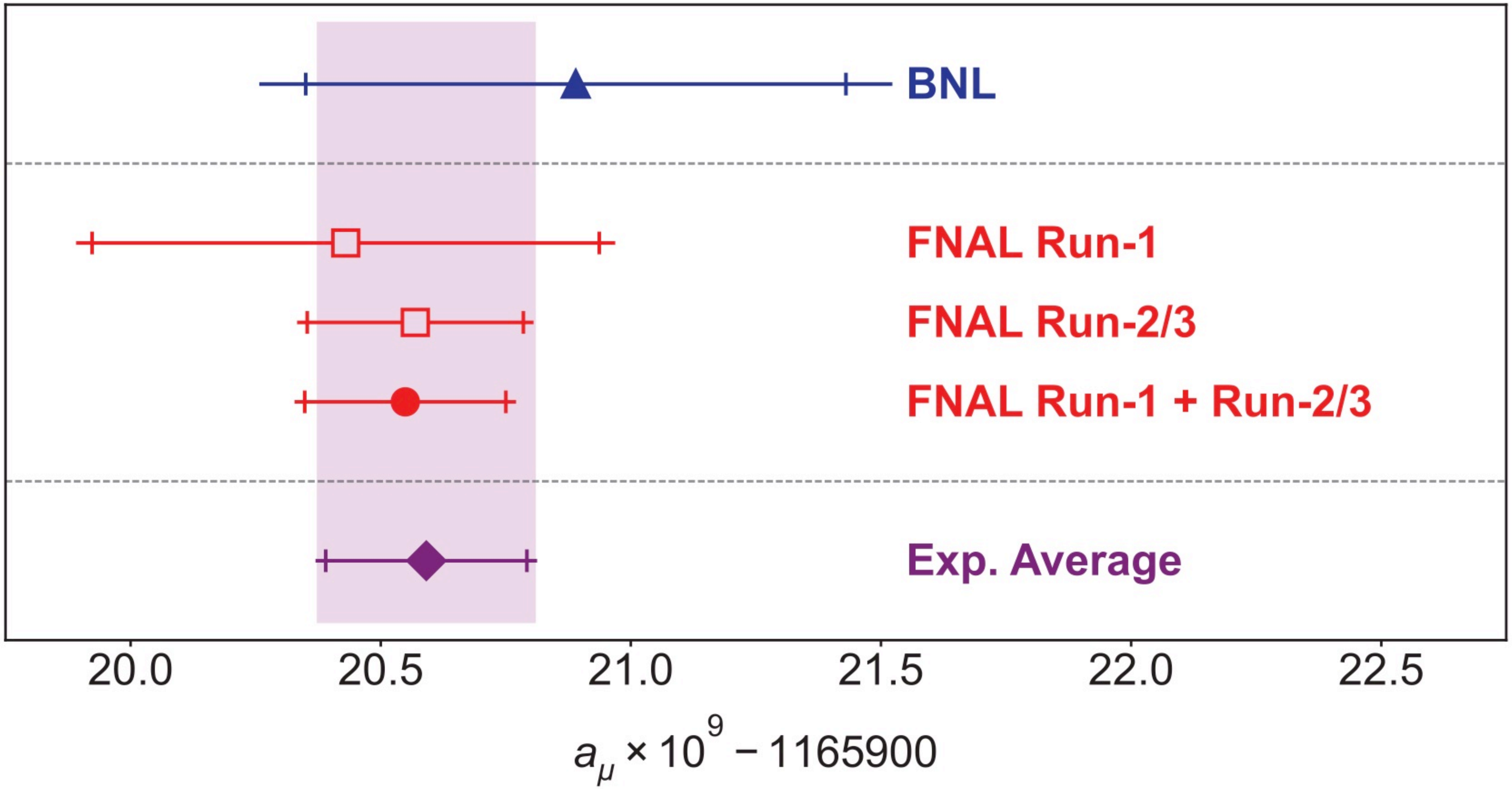




Muon g-2 update

Phys. Rev. Lett. 131, 161802

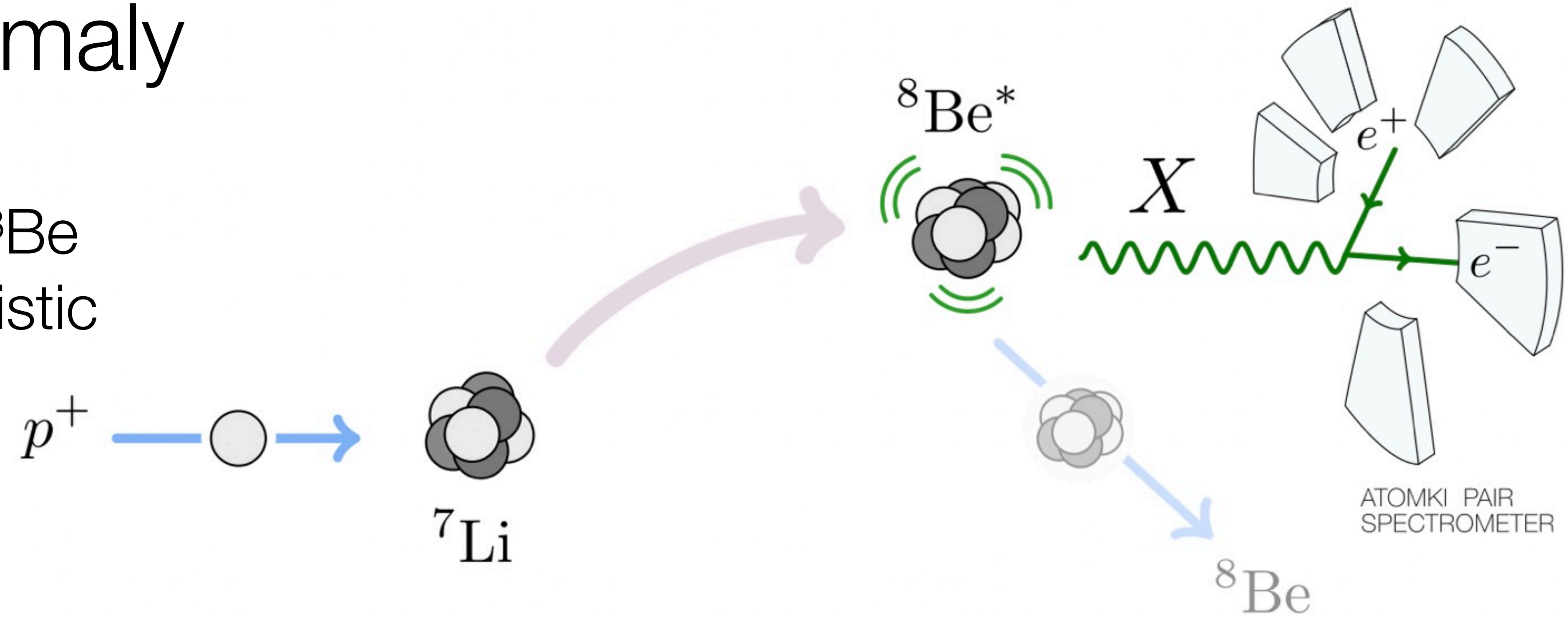


SM results in tension with lattice QCD: next steps are in the hands of theory community

Phys. Rev. D 95, 035017 (2017)

The X17 anomaly

Decay of excited ^{8}Be through characteristic energy levels



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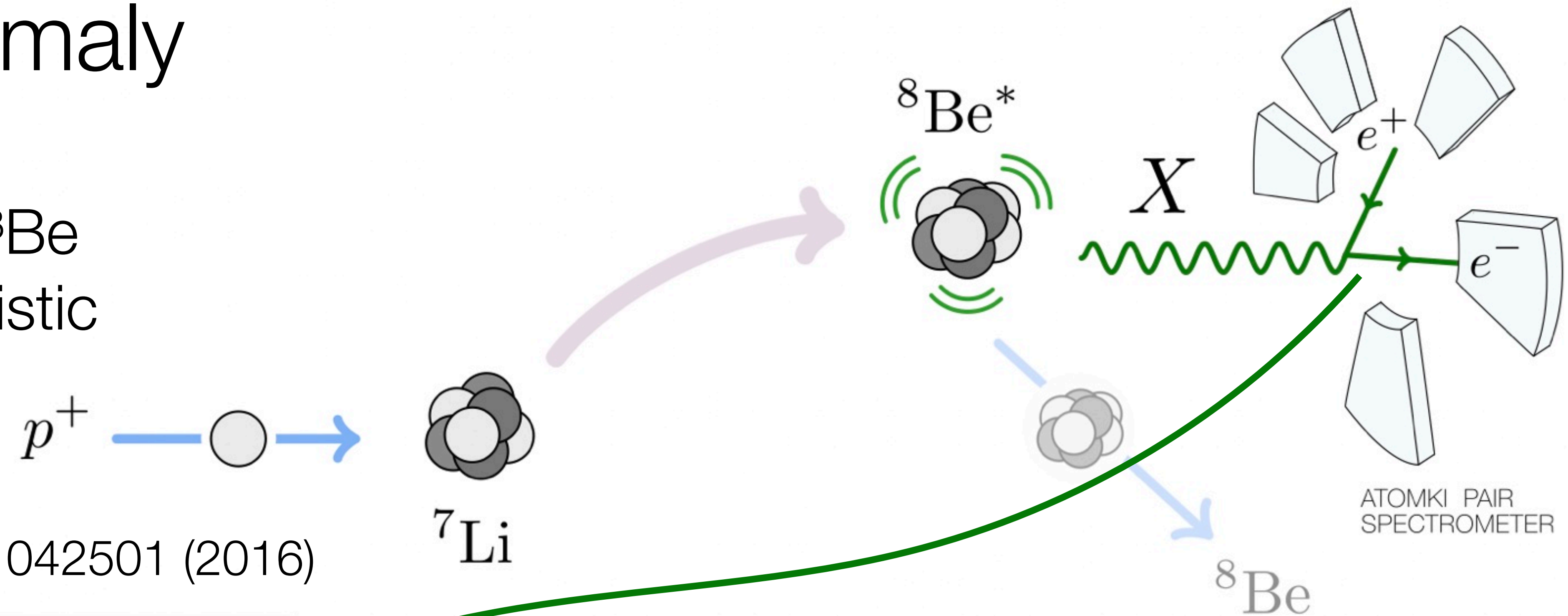

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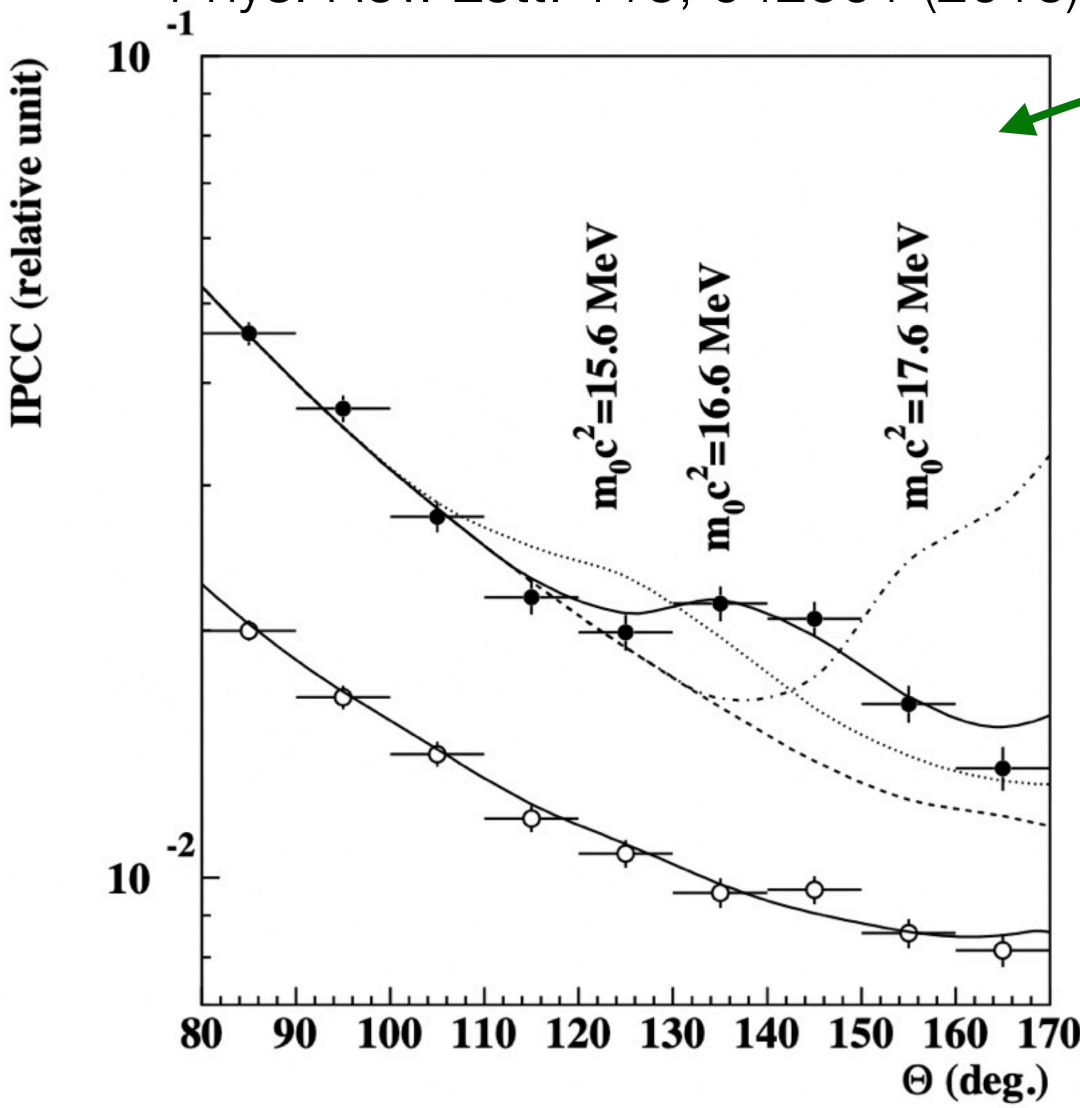

Invariant mass and opening angle of e+e- pair show resonant signal

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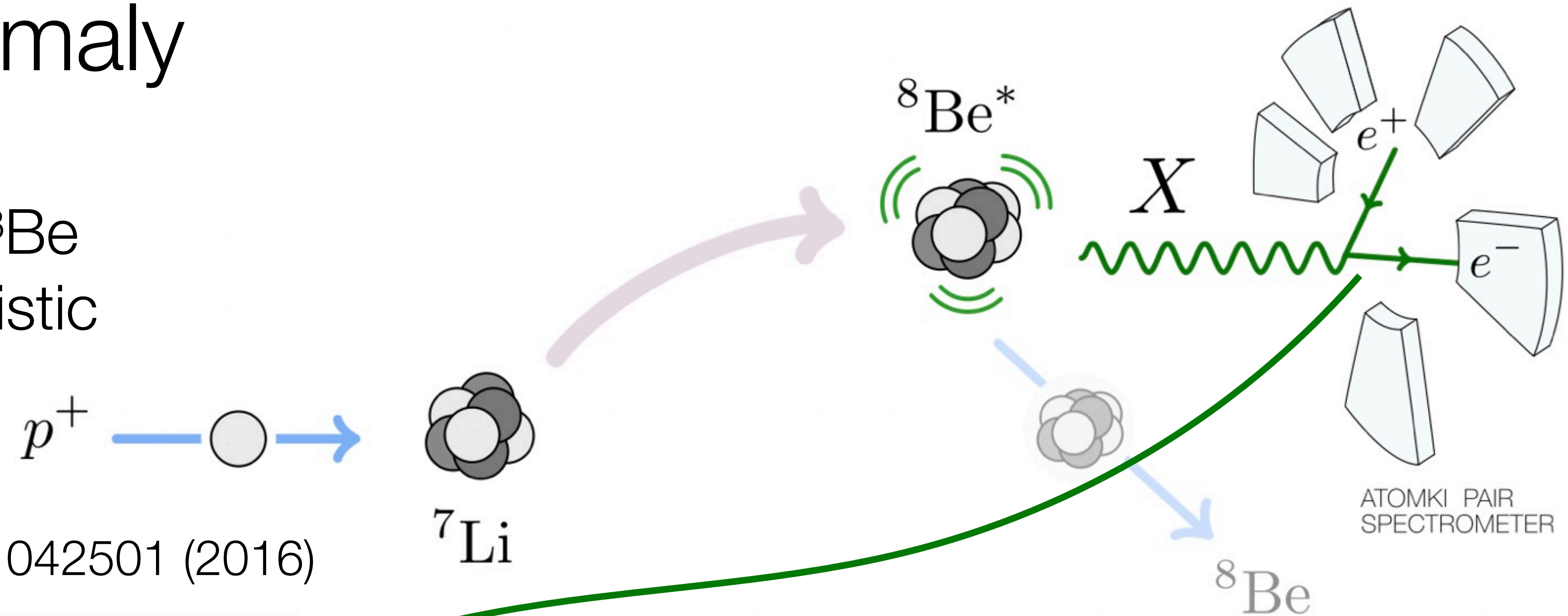

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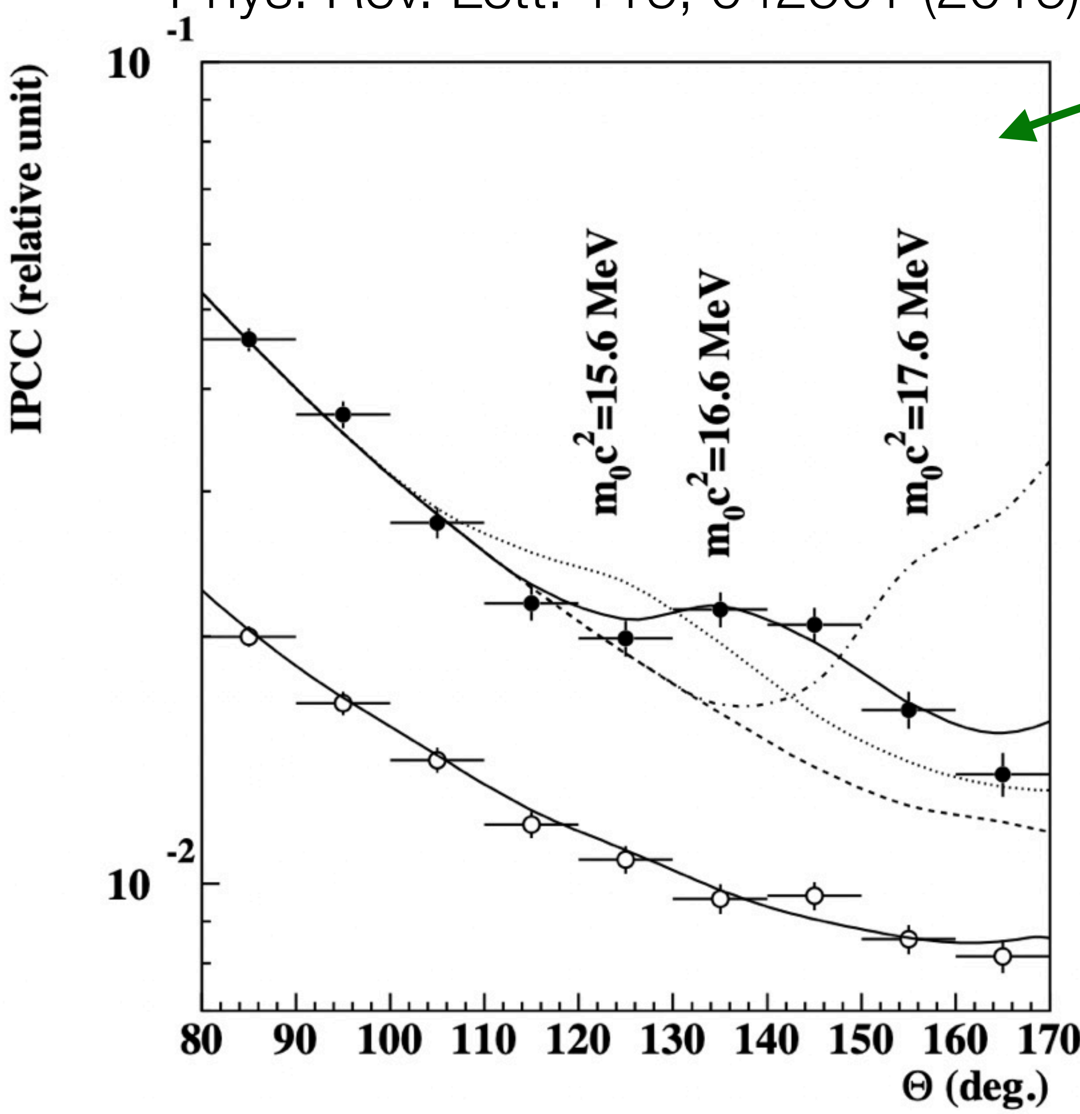

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Not-yet-understood detector effect?
Unexpected SM cause? Possibly!

(For SM see: arXiv:2201.09764 arXiv:2102.01127)

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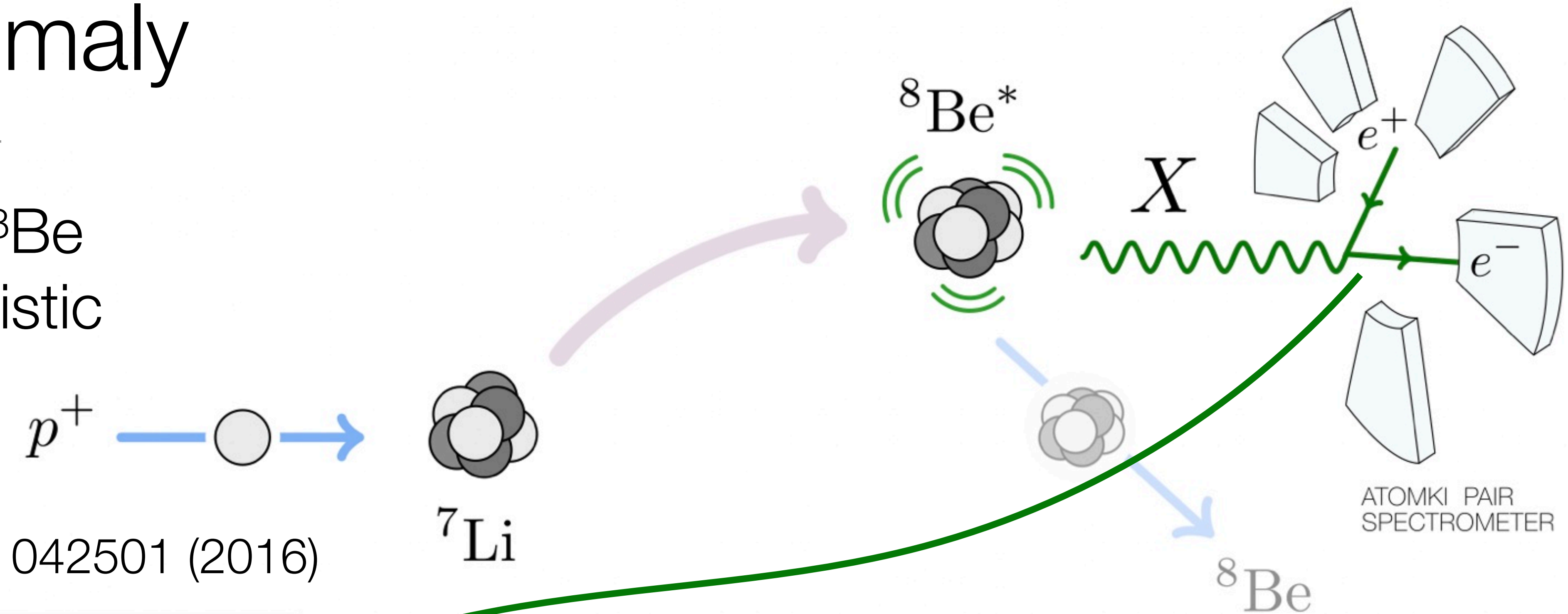

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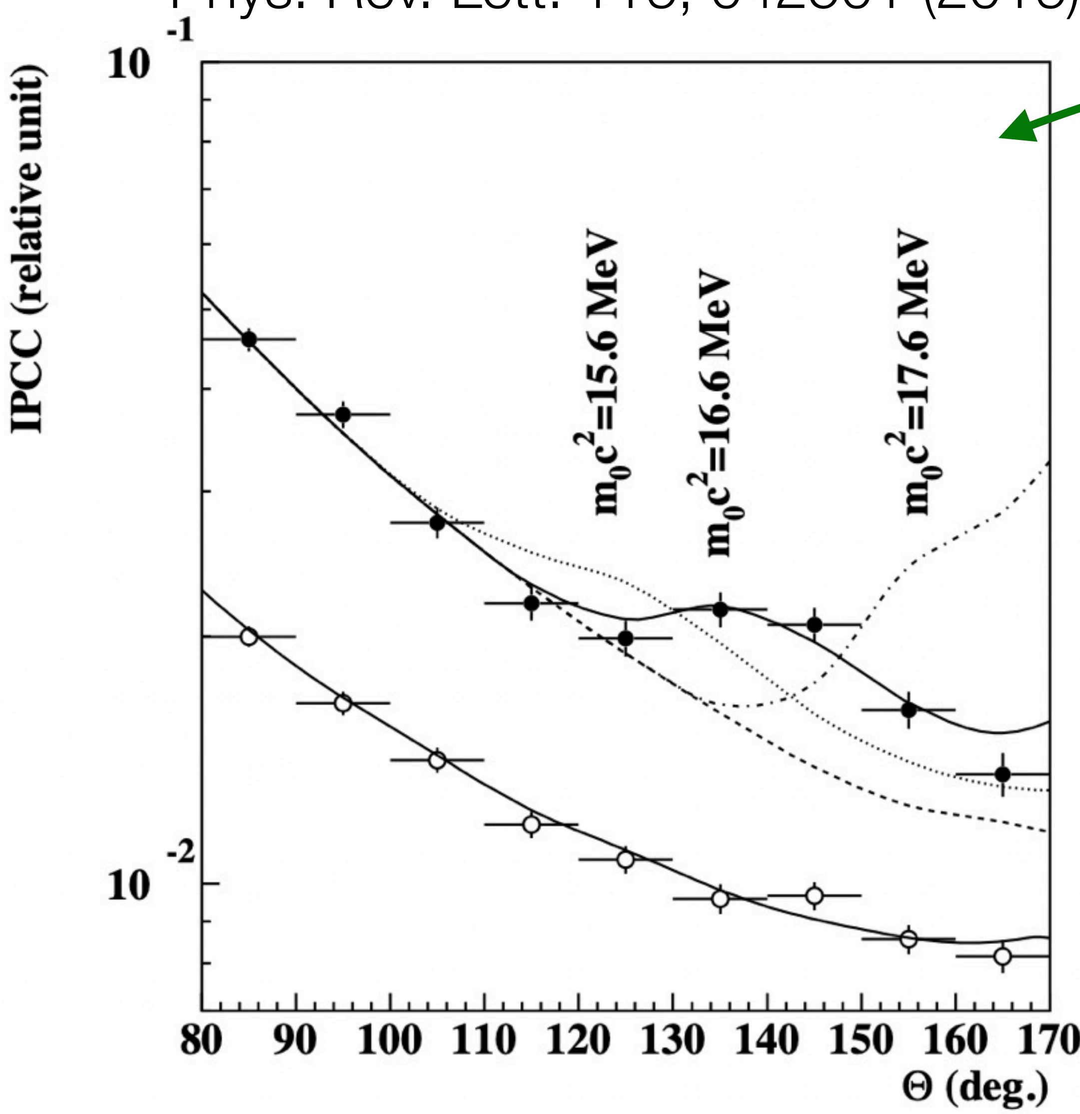

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Or, compatible with new boson with mass ~ 17 MeV

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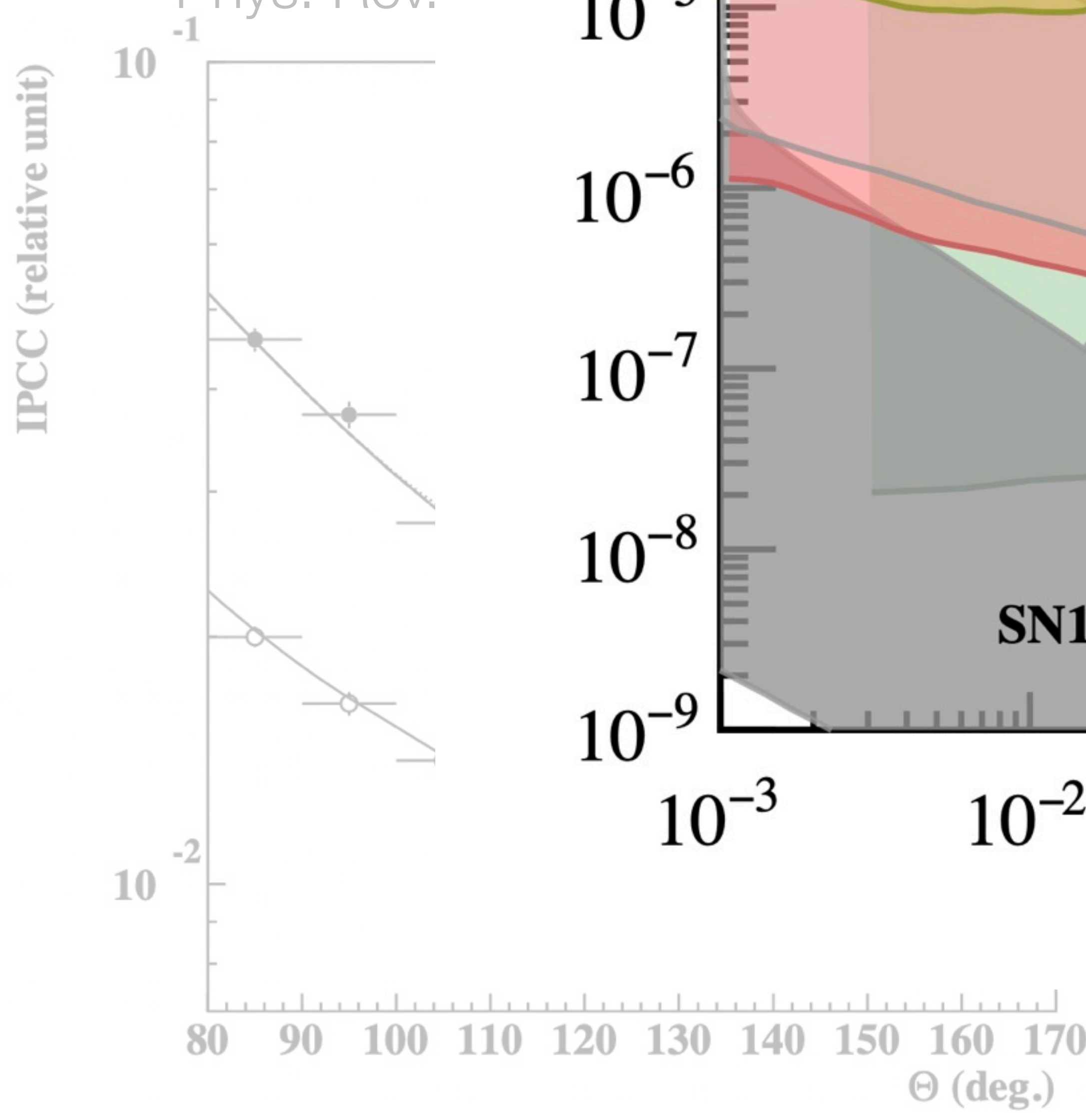
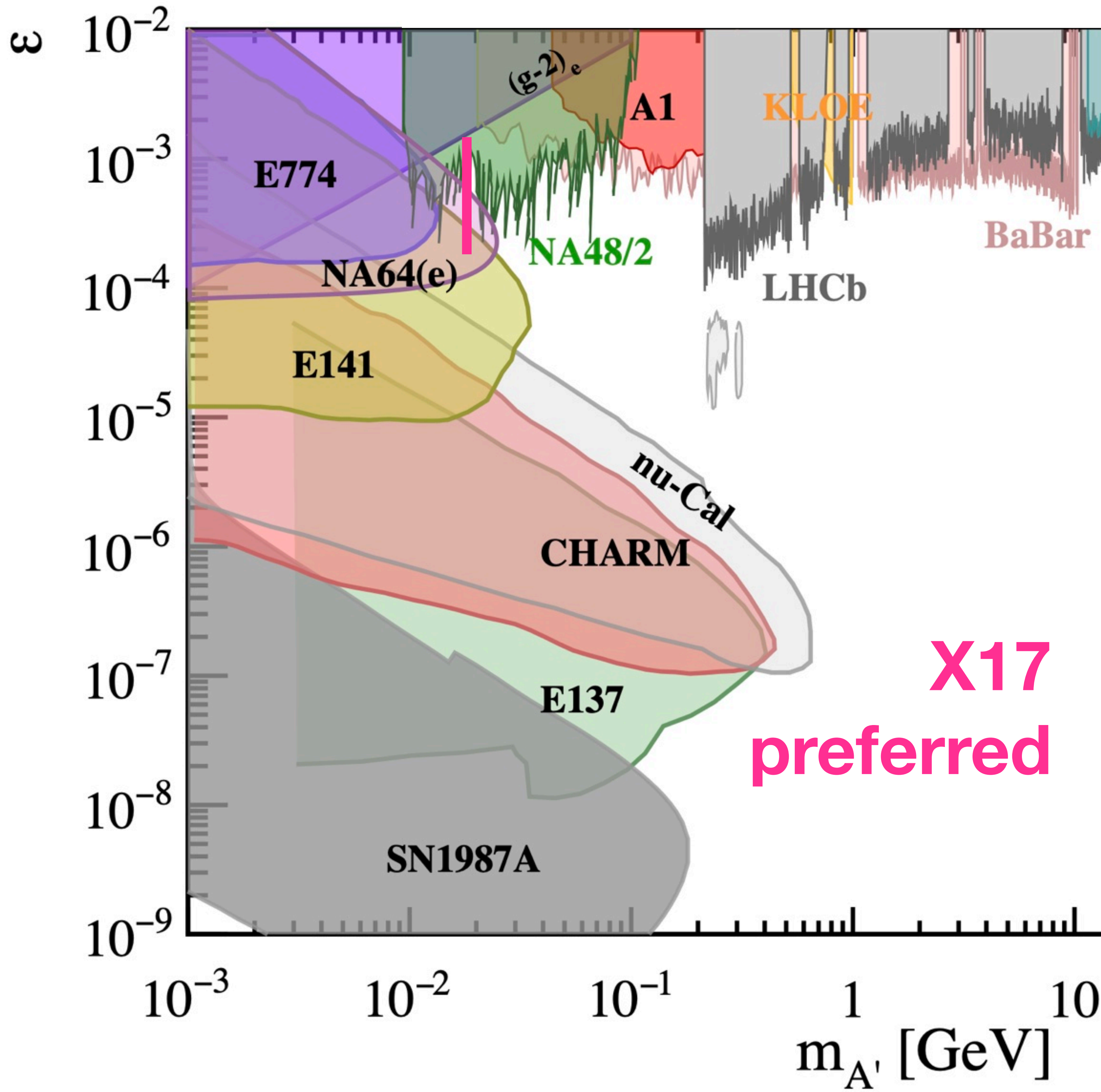
arXiv:2005.01515v3 (2020)

Decay of
through c
energy lev

Phys. Rev.





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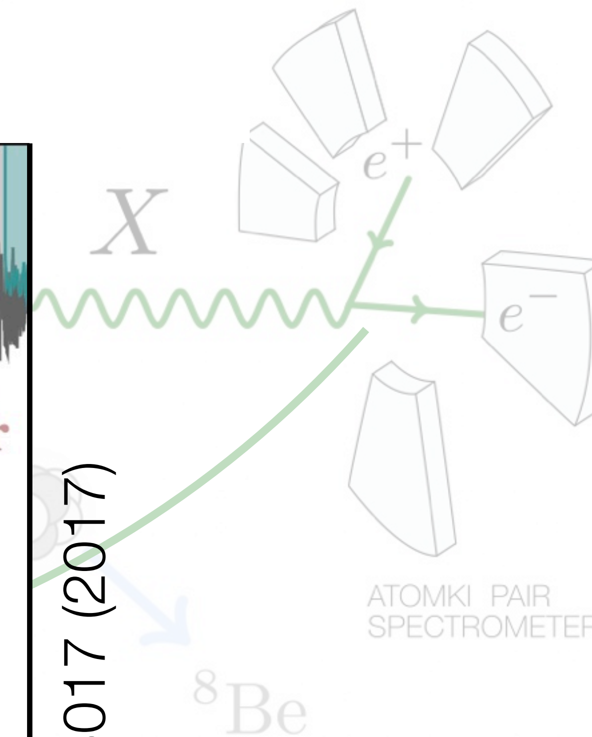

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ignal

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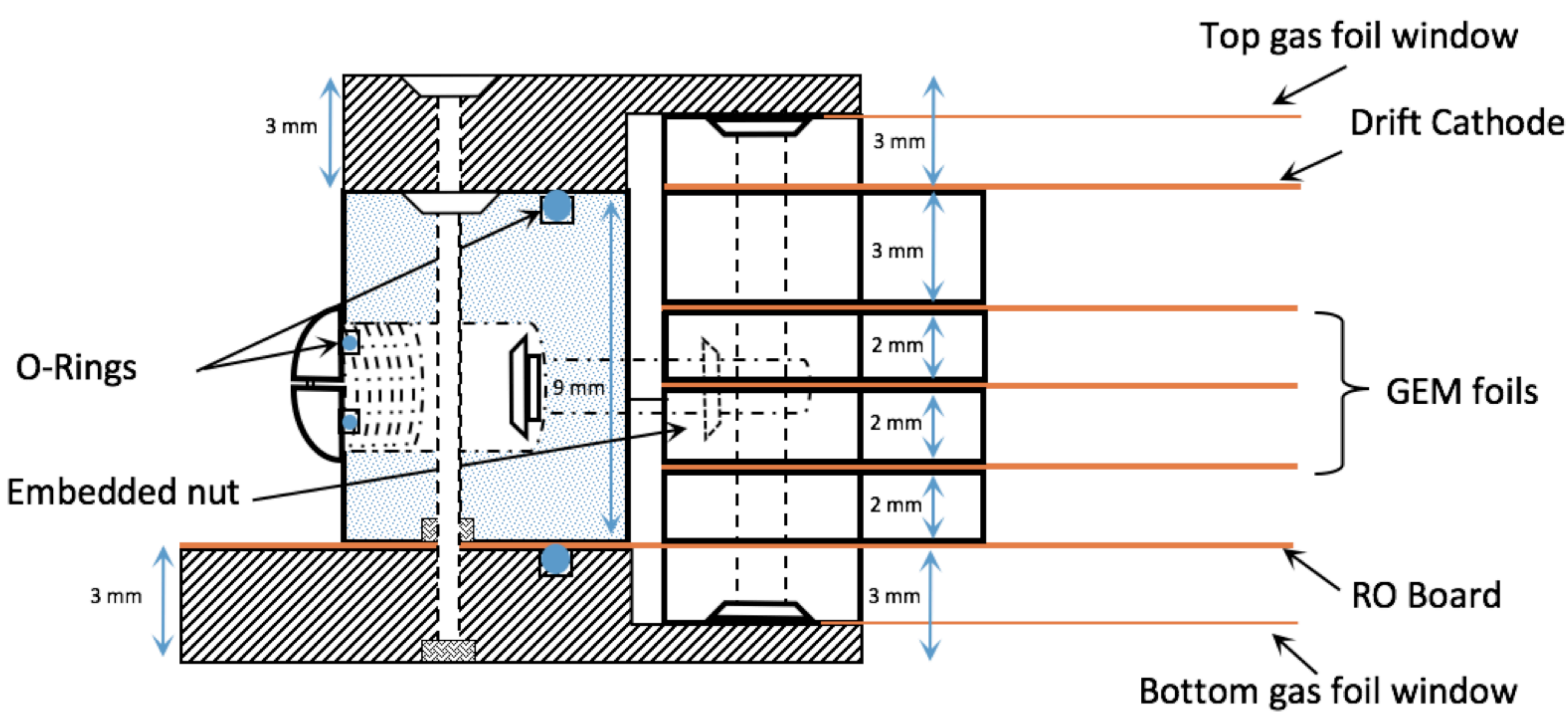
Xiv:2201.09764
Xiv:2102.01127

oson with
mass ~ 17 MeV

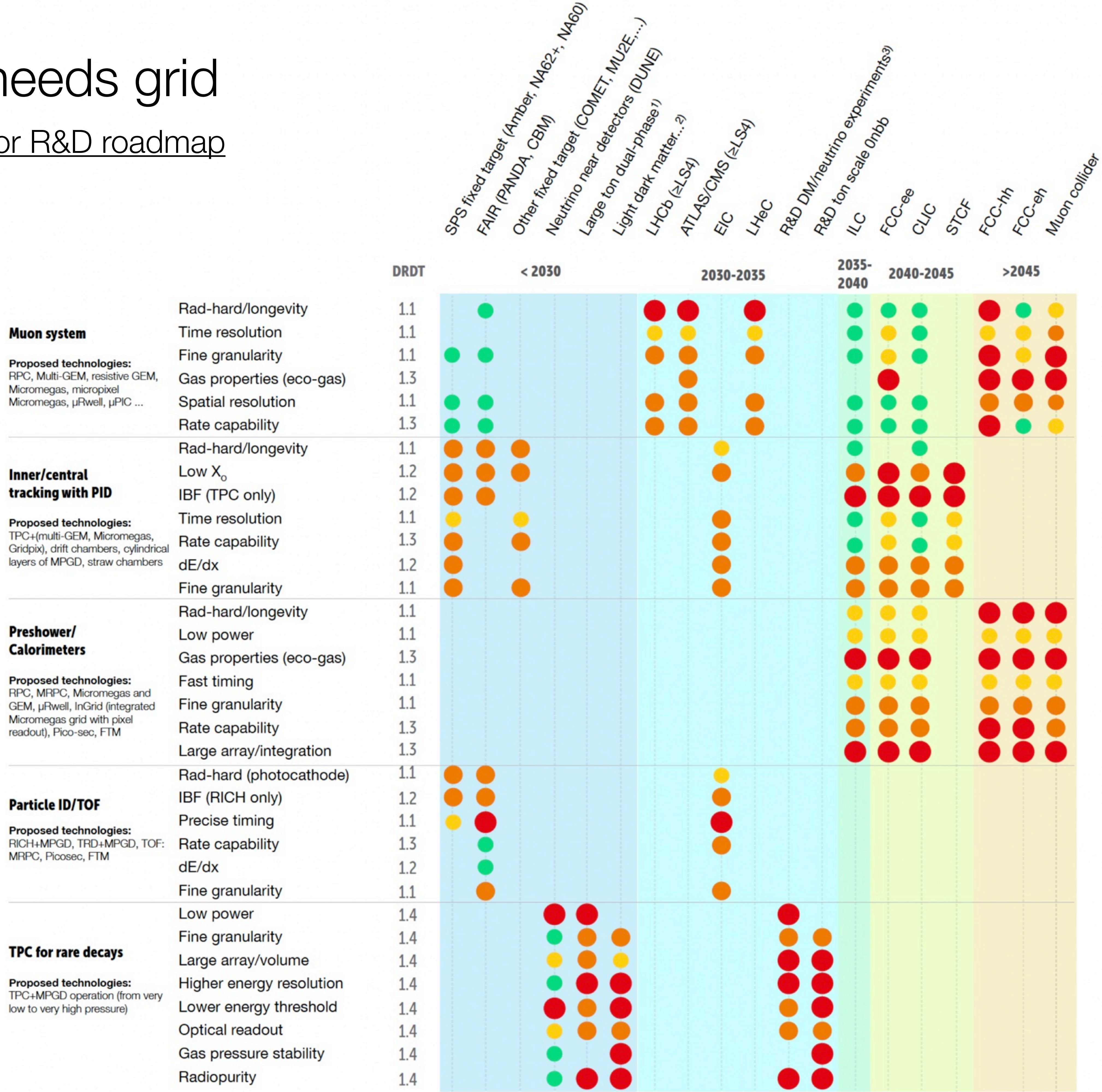
GEM details

- Top and bottom have chromium coated Kapton windows
- GEM foils are copper on Kapton, operating at 400 V across each foil, to readout at ground. Holes are ~50 μm
- Total active area 25 x 40 cm, 400 μm strip pitch, ~13k readout channels.



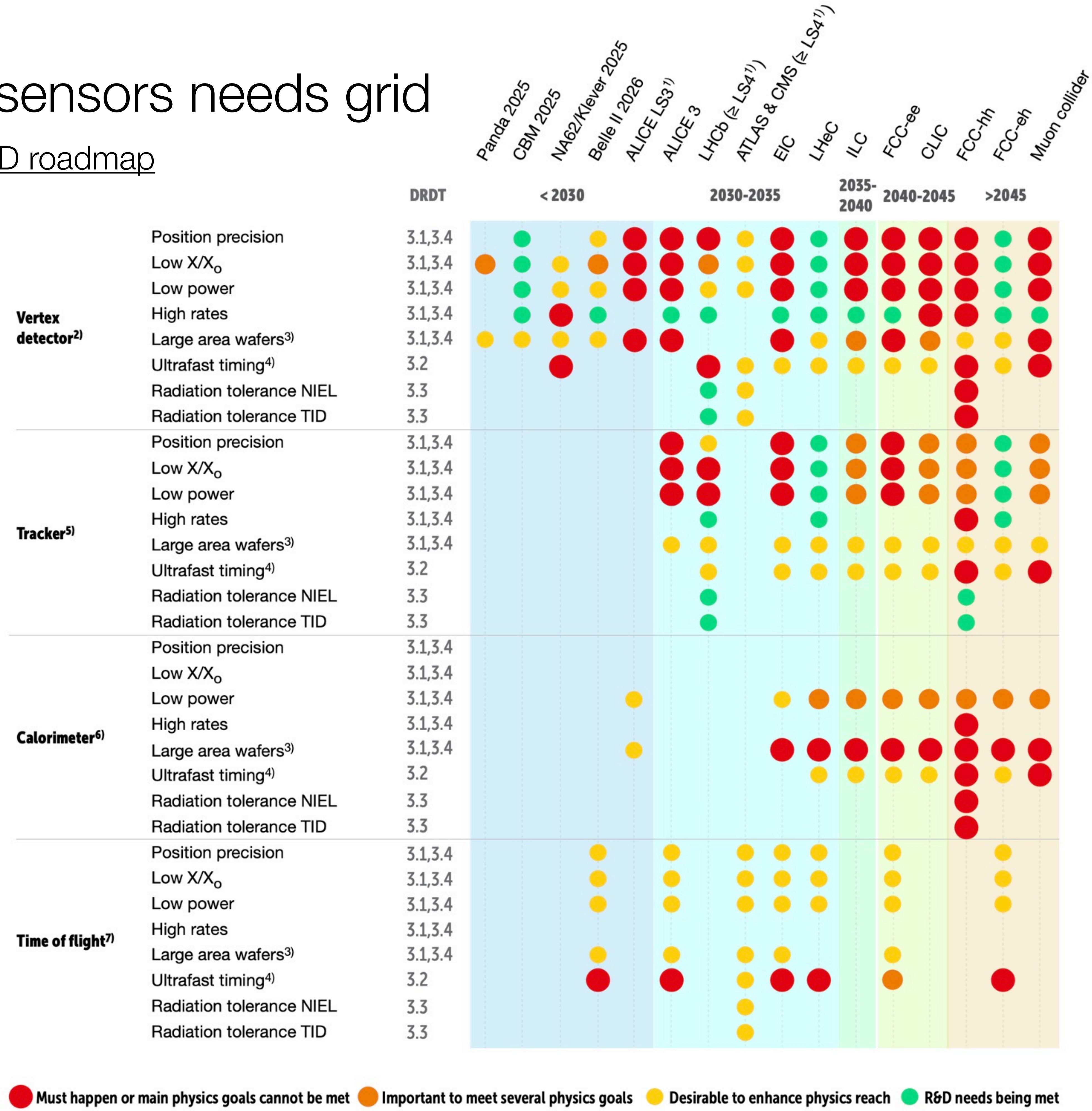
MPGD needs grid

ECFA detector R&D roadmap



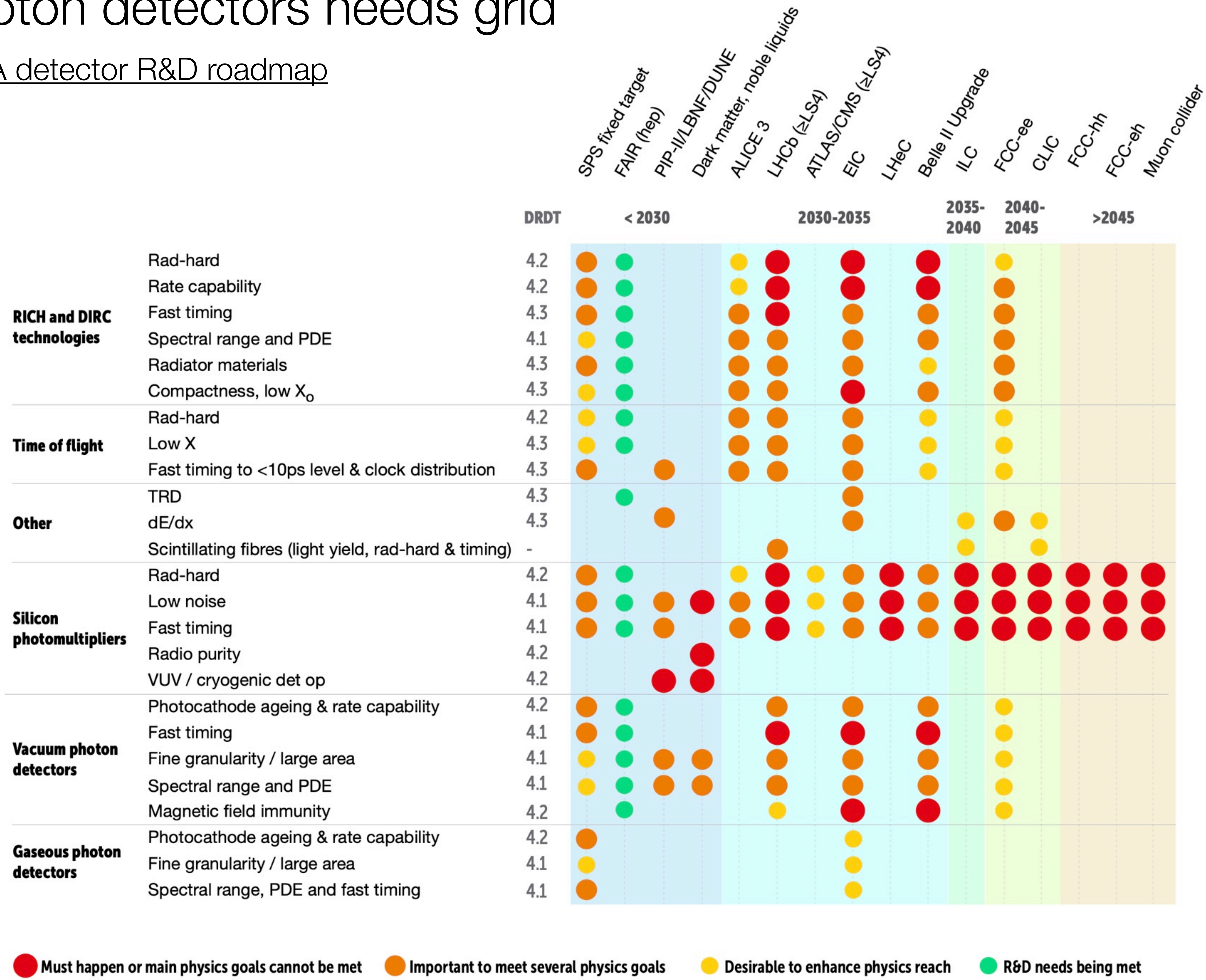
Solid state sensors needs grid

ECFA detector R&D roadmap



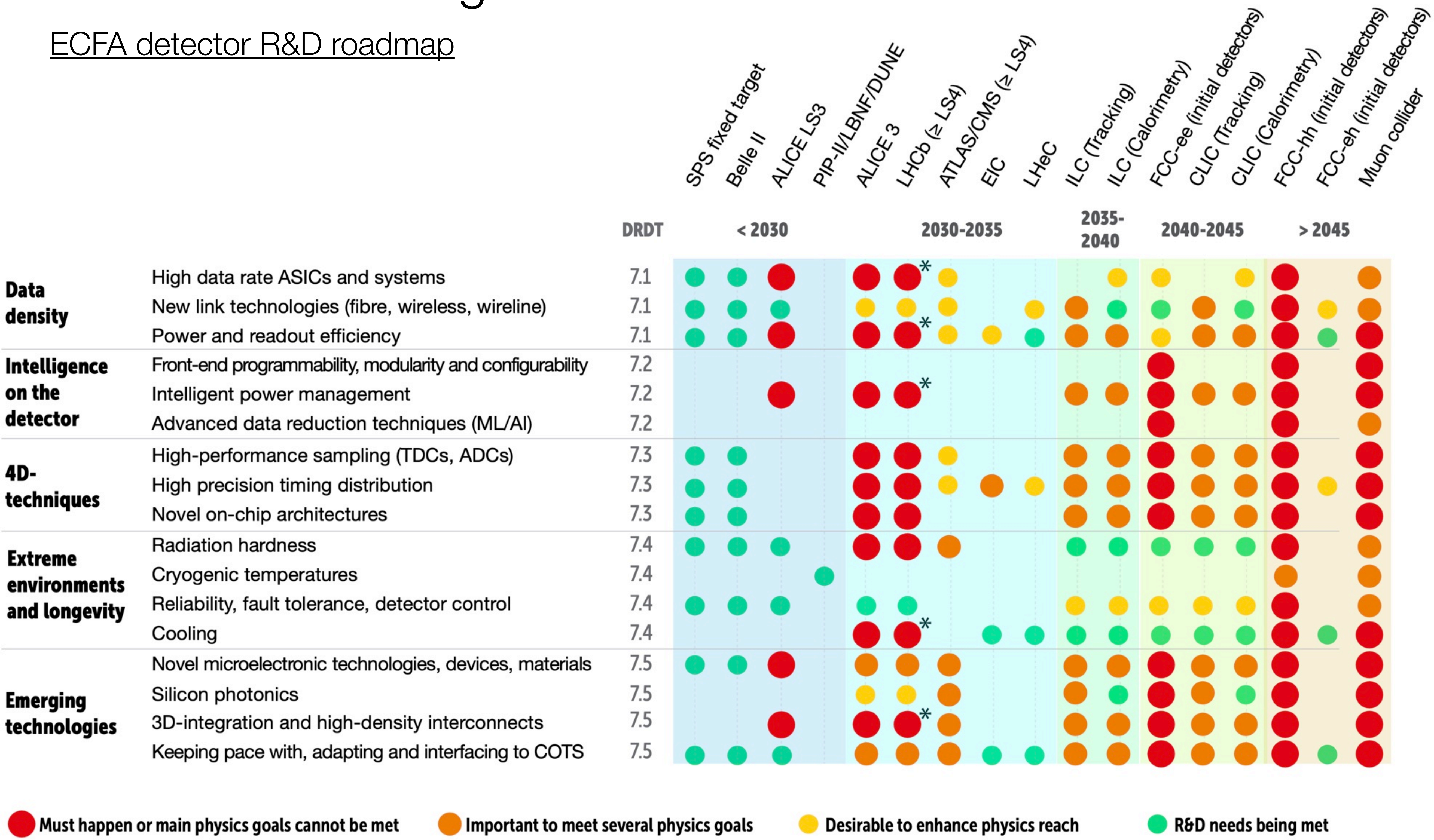
Photon detectors needs grid

ECFA detector R&D roadmap



Electronics needs grid

ECFA detector R&D roadmap



Evolutionary R&D within
collaborations

Cross-project R&D benefitting
multiple experiments

Long-term, high risk R&D projects
with revolutionary potential

A balanced portfolio supporting
all of the above

SciTech projects

Ongoing / Finished	In development	Foreseen
▪ TWIST (Completed)	▪ ARIEL	▪ nEXO (Snolab, Ontario, Canada)
▪ PIENU (Completed)	▪ TIGRESS	▪ HYPER-K (Kamiokande, Japan)
▪ MUSR (Running)	▪ GRIFFIN	▪ IWCD
▪ DEAP-3600 (Running)	▪ uSR 3T (Devel)	▪ SiP
▪ IRIS (Running)	▪ SuperCDMS	
▪ ALPHA (Completed)	▪ ATLAS LAr electronics	
▪ ALPHA-II (Running)	▪ ATLAS-ITK	
▪ ALPHA-G (Running)	▪ UCN/nEDM	
▪ T2K (Running)	▪ Moller	
▪ TREK (Completed)	▪ Ac-225 Processing Capabilities	
▪ MVM (Completed)	▪ Flash Radiotherapy	
▪ Tunneling Electron Microscope (UBC)	▪ DarkSide-20K	

Key sources

- Rare & precision report https://arxiv.org/pdf/2209.14111.pdf
- Energy frontier report: https://arxiv.org/pdf/2211.11084.pdf
- Accelerator frontier report: https://arxiv.org/pdf/2209.14136.pdf
- Instrumentation frontier report: https://arxiv.org/pdf/2210.04765.pdf
- ECFA detector R&D roadmap: https://cds.cern.ch/record/2784893?ln=en
- Canadian subatomic physics long range plan: https://subatomicphysics.ca/