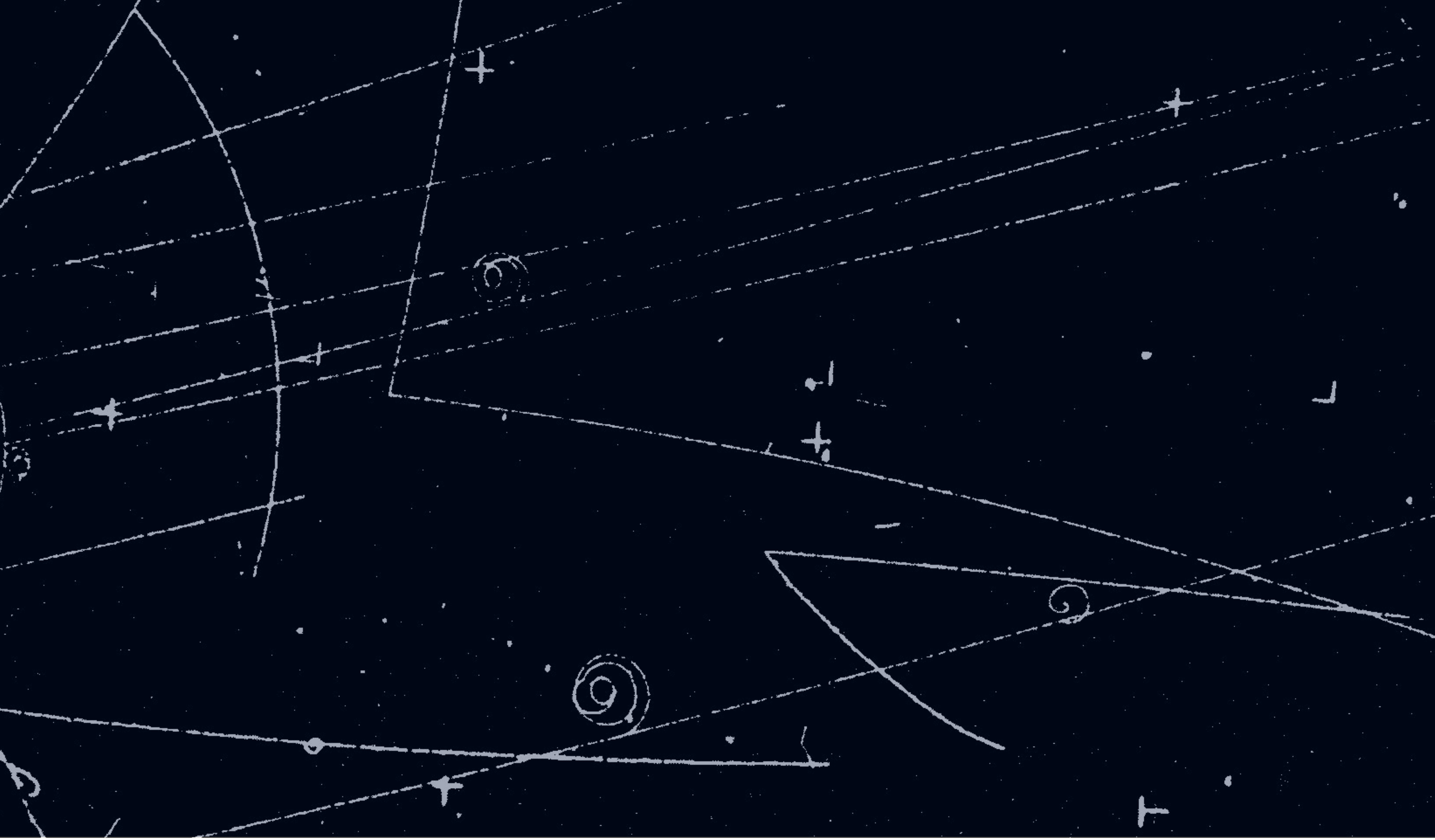
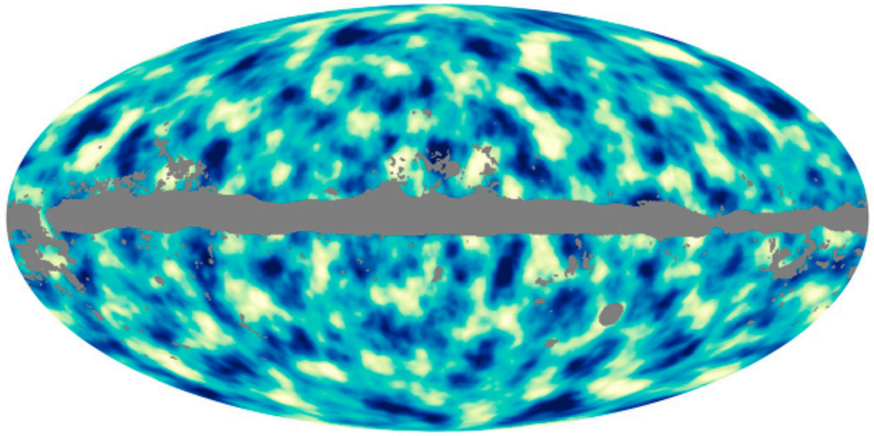


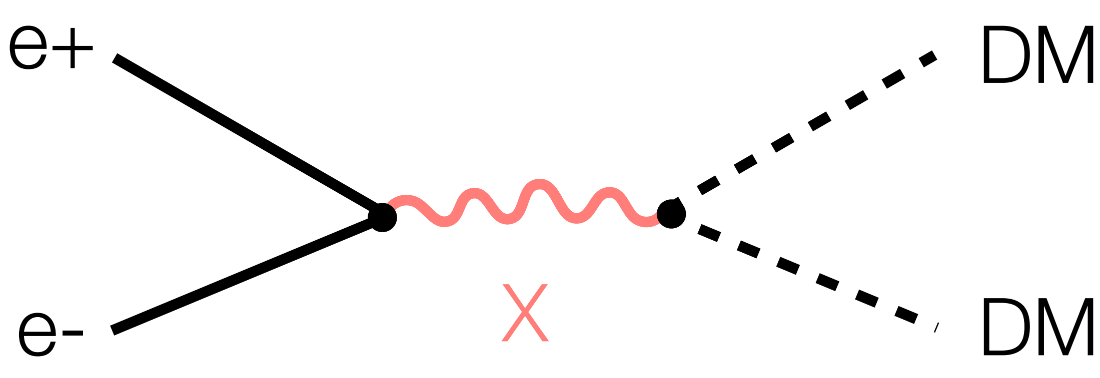
# Hunting for new particles at TRIUMF with the DarkLight@ARIEL experiment

Kate Pachal
TRIUMF
o.b.o the DarkLight collaboration

# Uniting dark matter with particle physics experimental anomalies

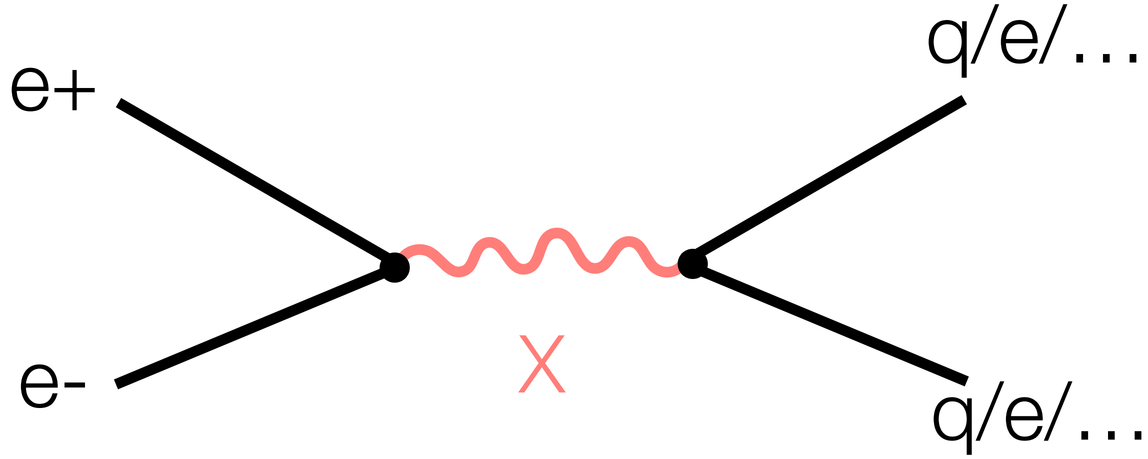
Dark matter remains one of the biggest unsolved mysteries of particle physics






Many many possibilities, but among them: s-channel boson could act as a mediator to dark sector

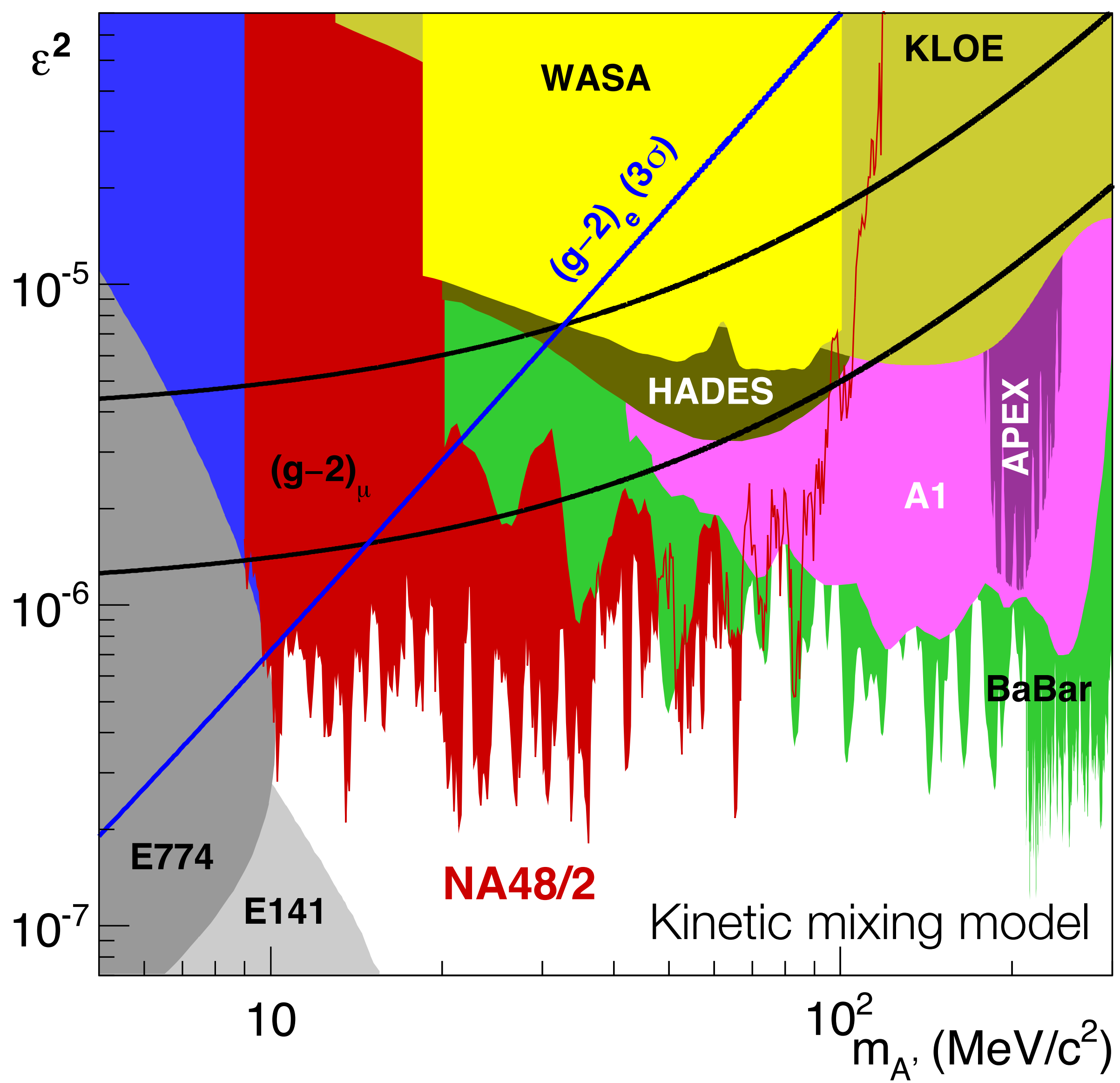
Depending on relative couplings and masses of SM versus dark sector particles, visible decays can dominate



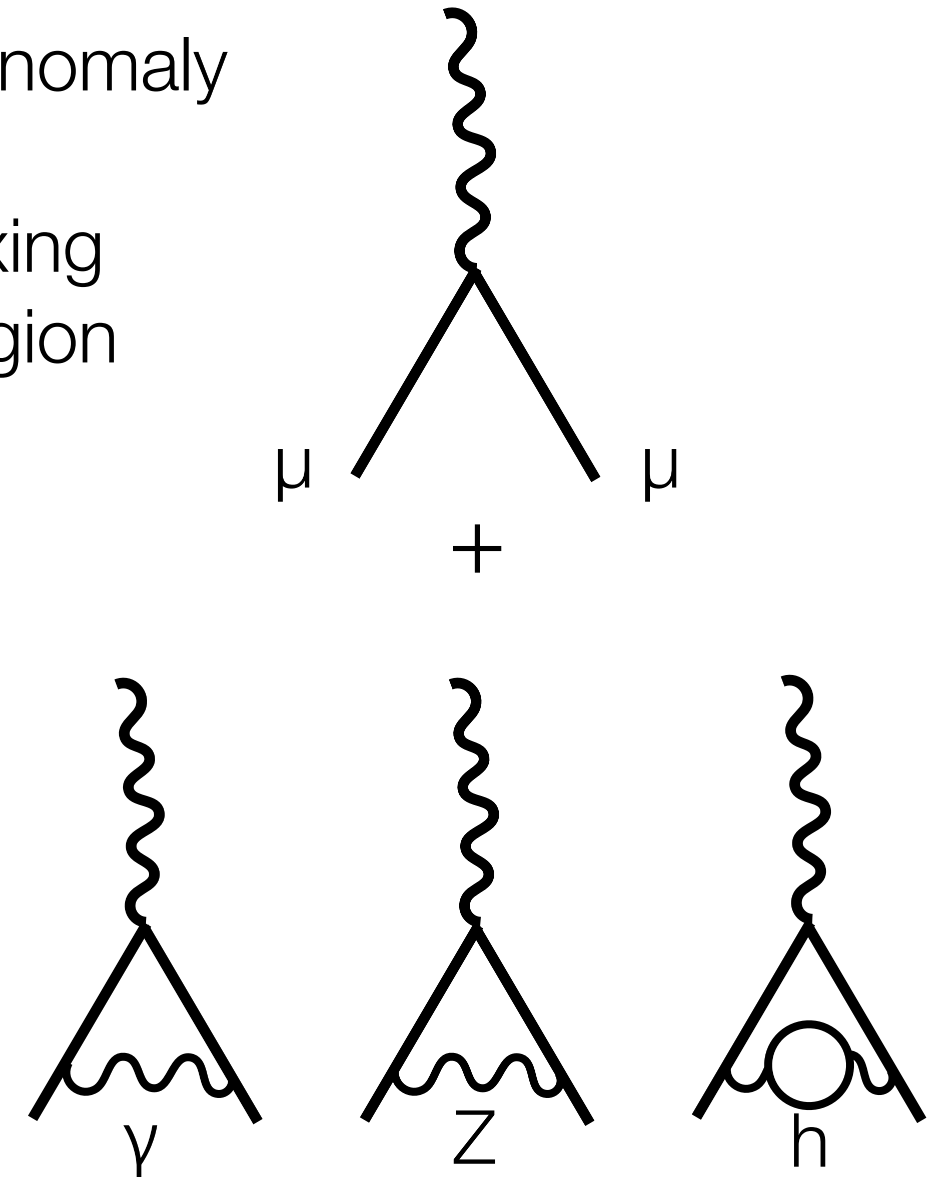

Where to look for such a particle?
Some experimental hints ….

# Light BSM boson: g-2 anomaly

Many investigations into source of 4.2 σ muon g-2 anomaly
One possibility: new massive boson
Would be low mass, moderate coupling - kinetic mixing model disfavoured, but experimentally accessible region




NA48 collaboration,
Phys.Lett. B746 (2015) 178-185



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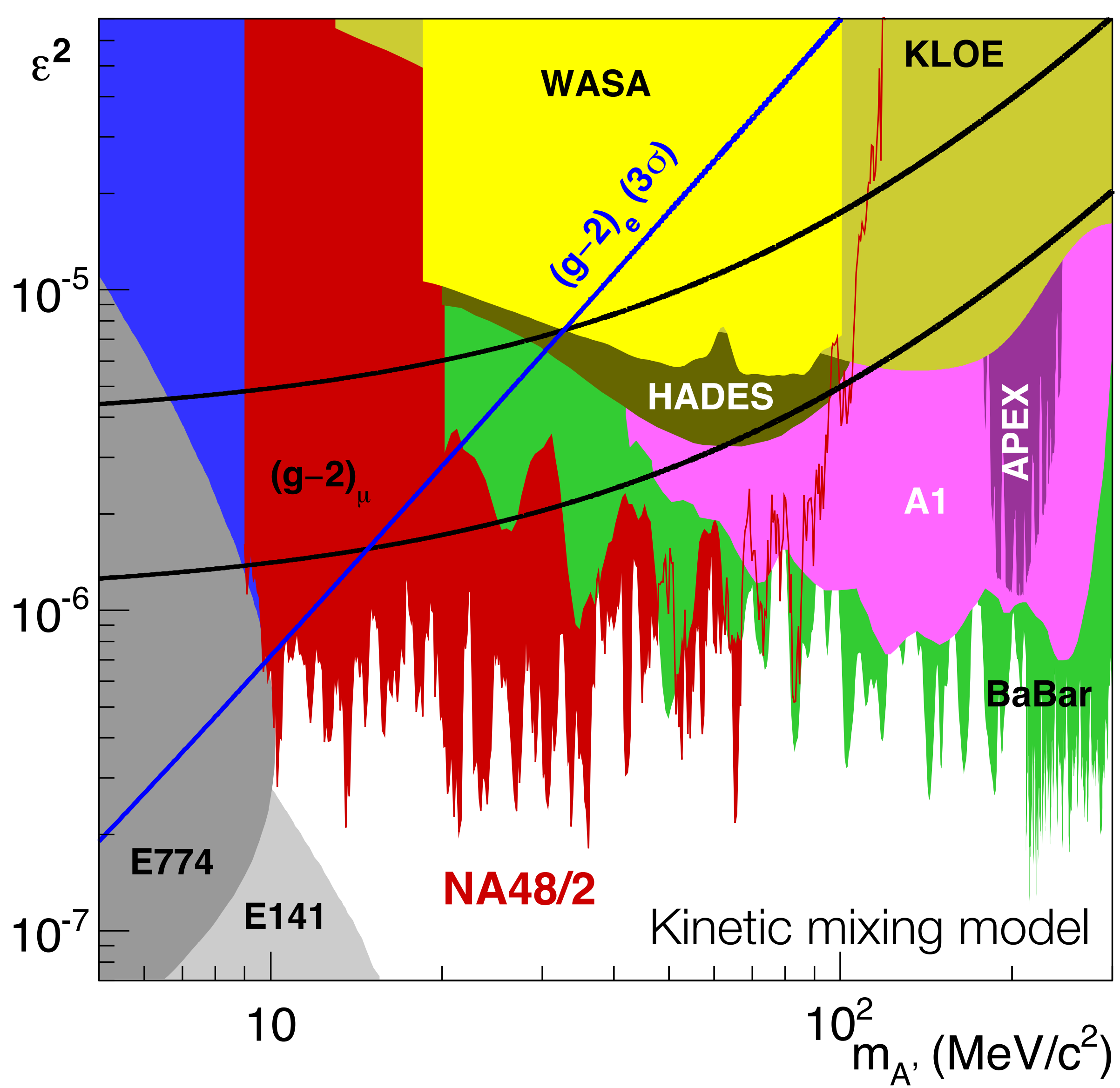


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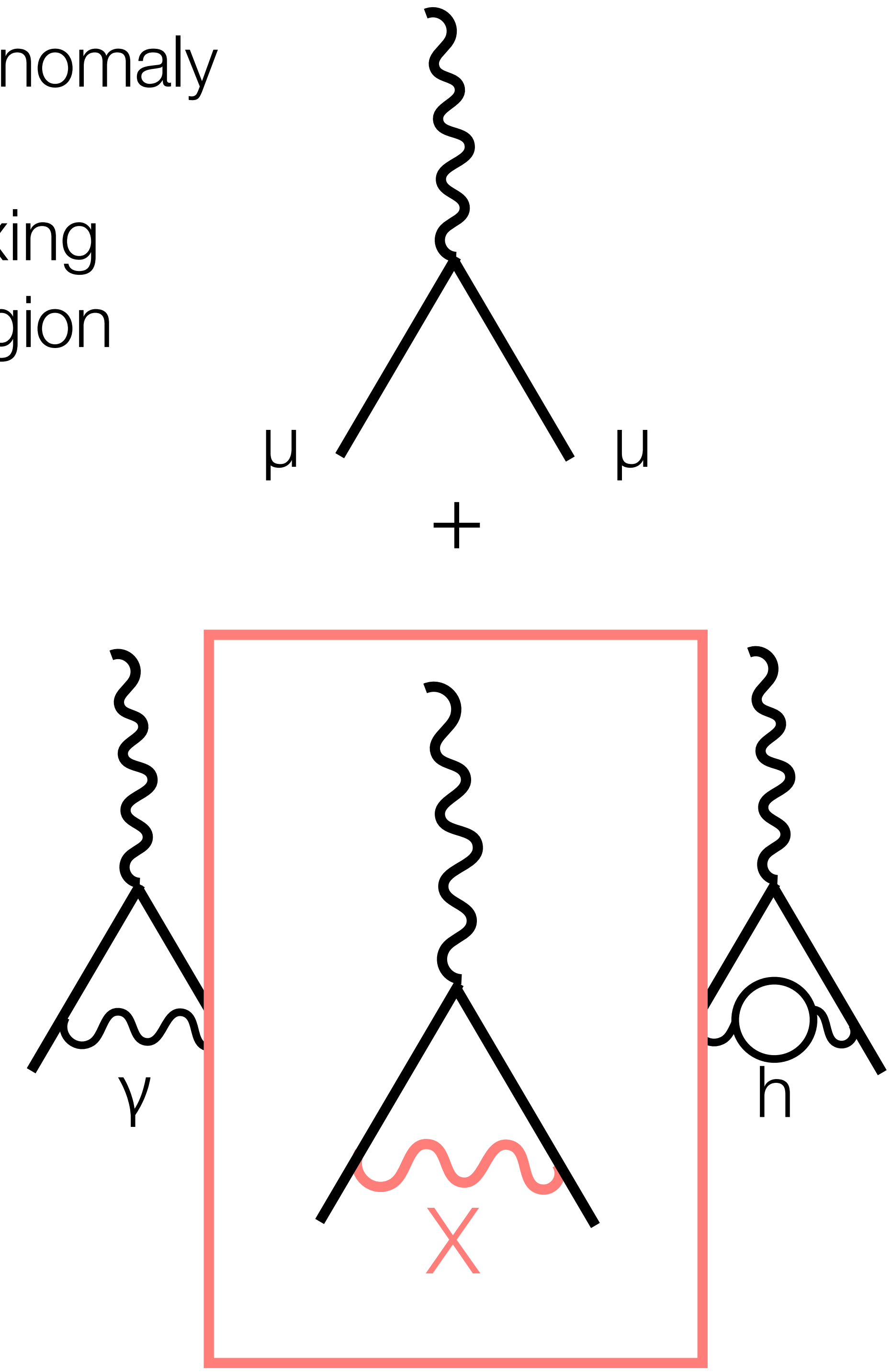
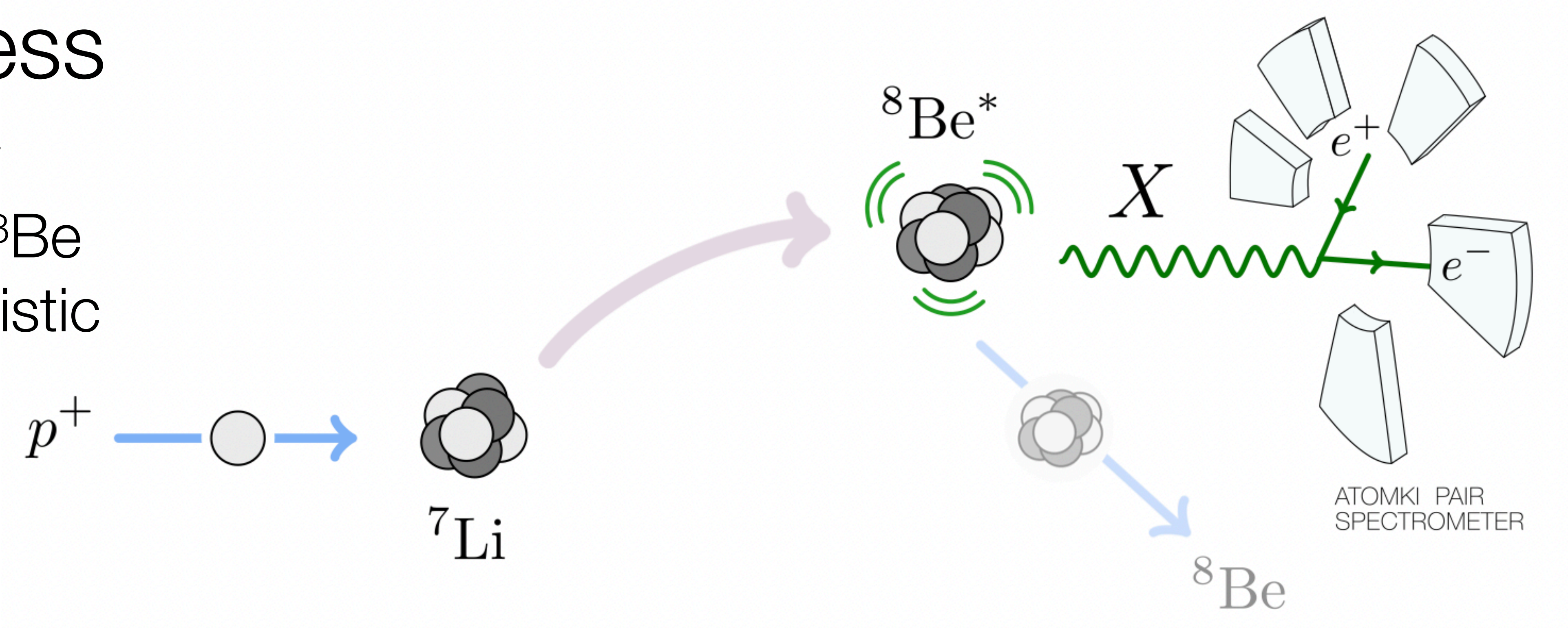


# Light BSM boson: the X17 excess

Phys. Rev. D 95, 035017 (2017)

Decay of excited $^8$Be through characteristic energy levels



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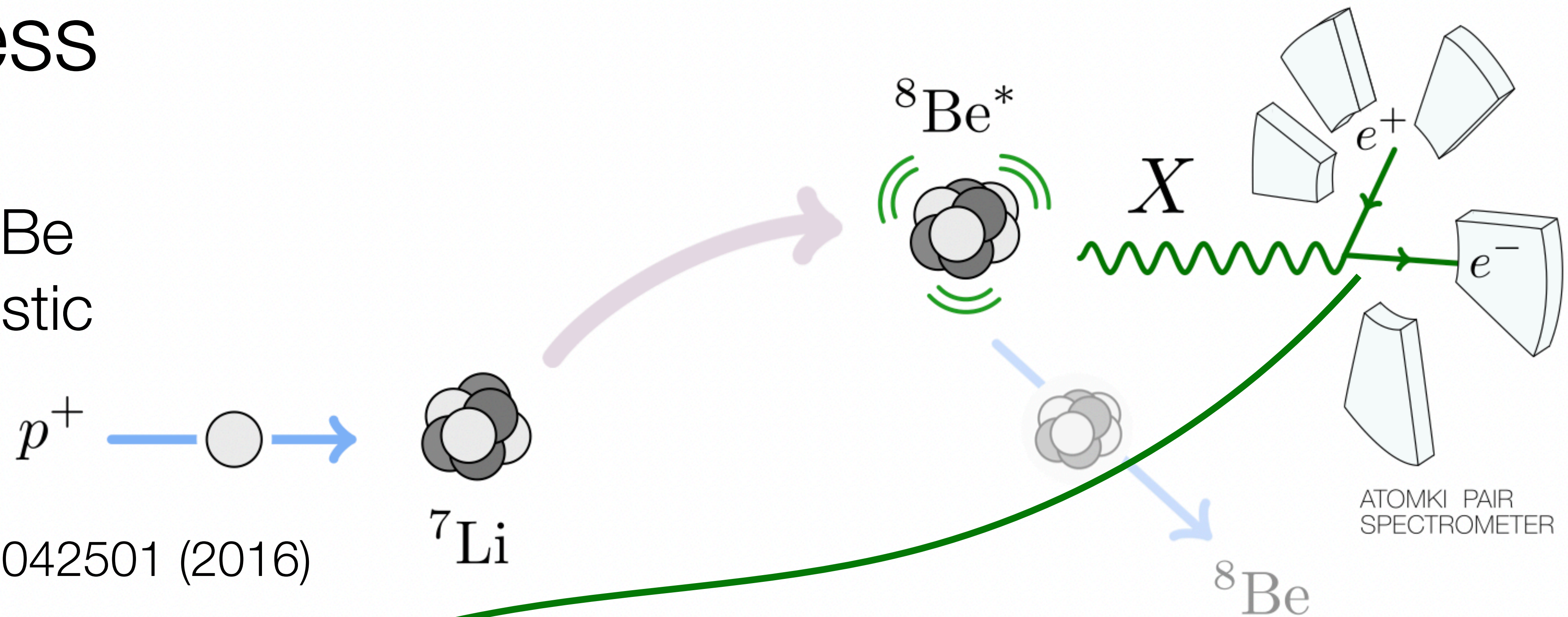
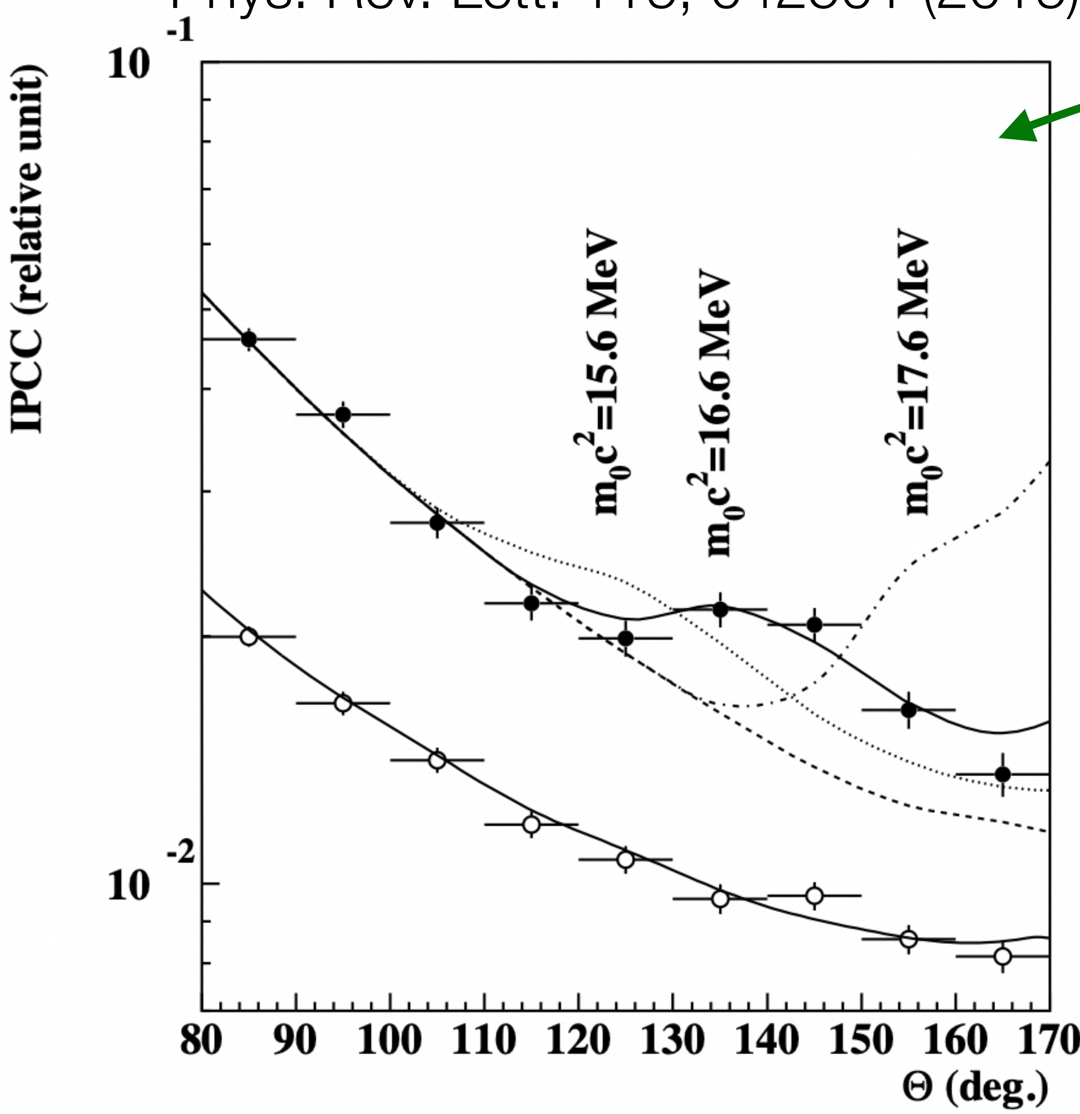



Phys. Rev. Lett. 116, 042501 (2016)




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

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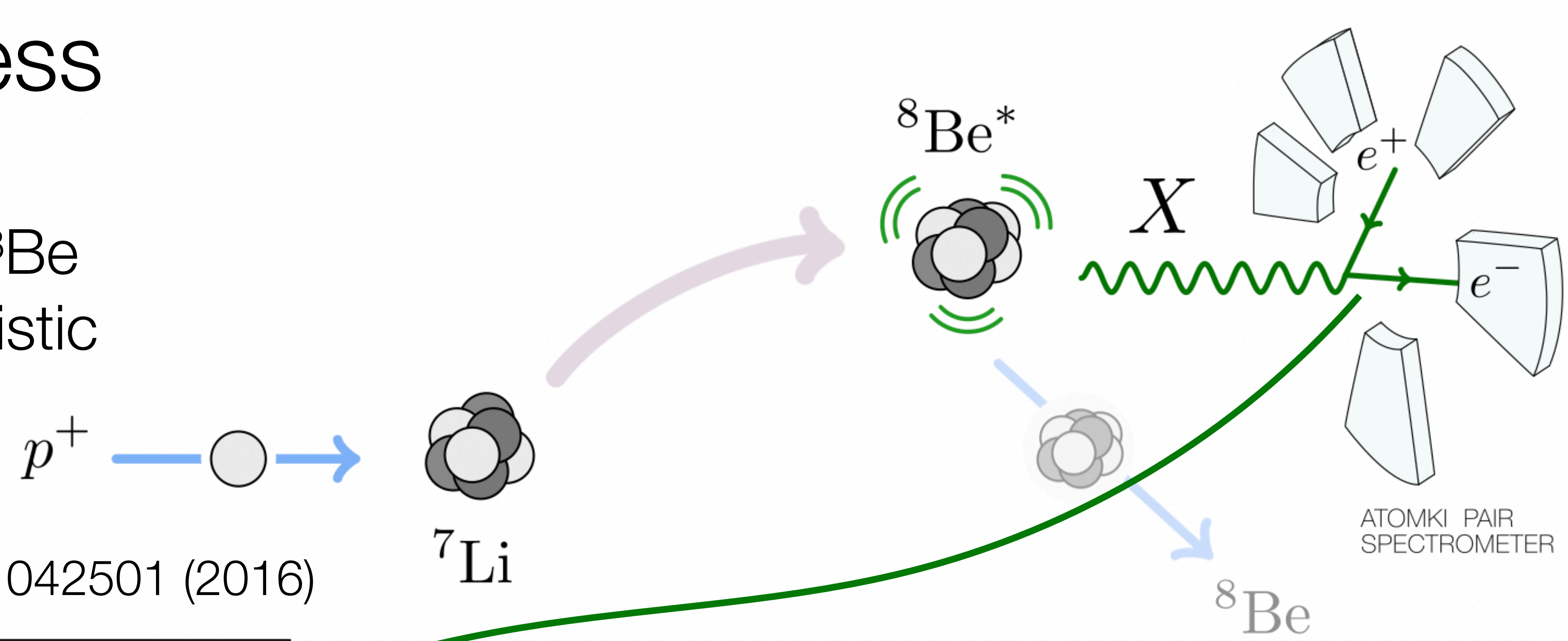


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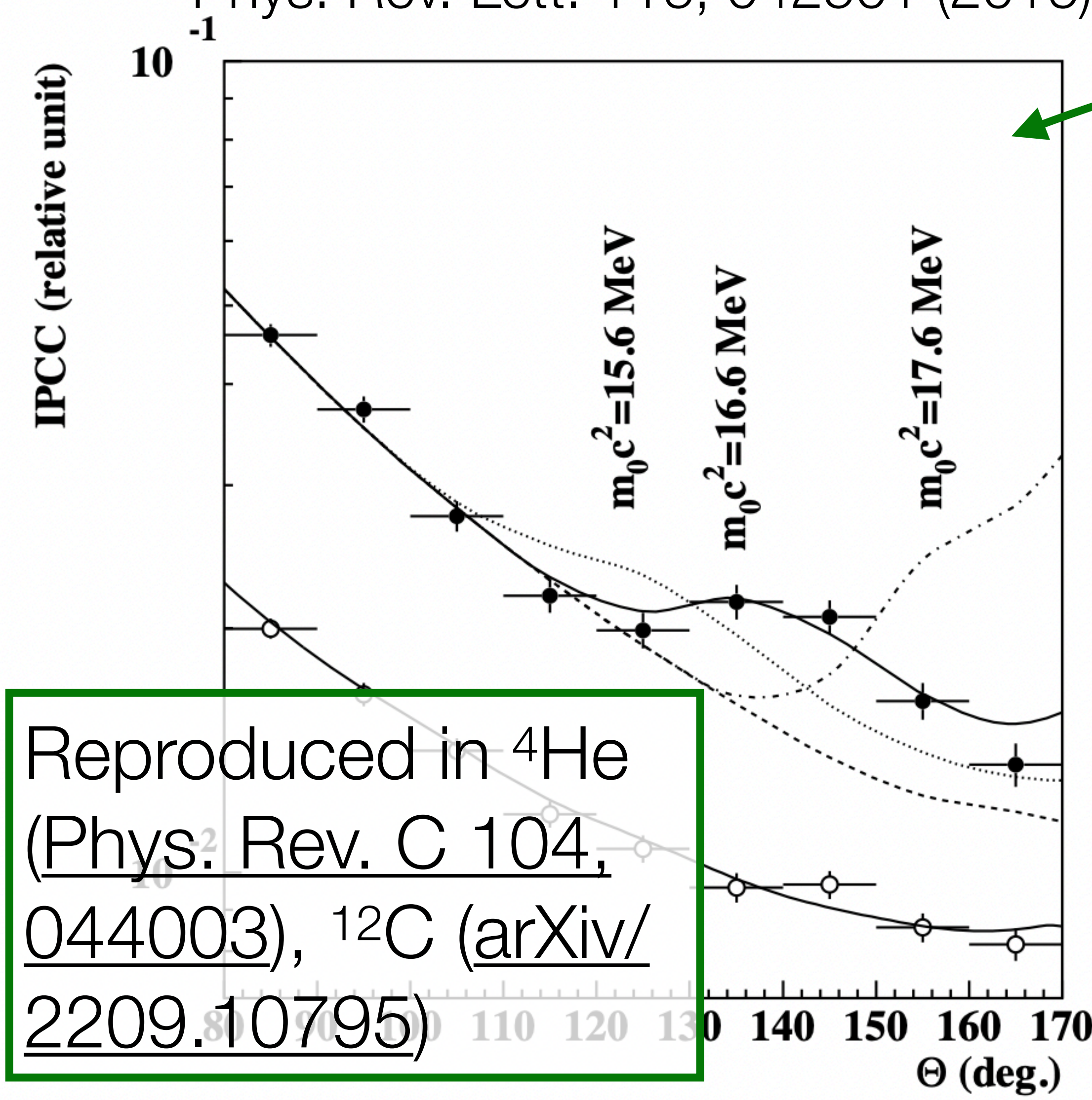


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Reproduced in $^4$He (Phys. Rev. C 104, 044003), $^{12}$C (arXiv/ 2209.10795)

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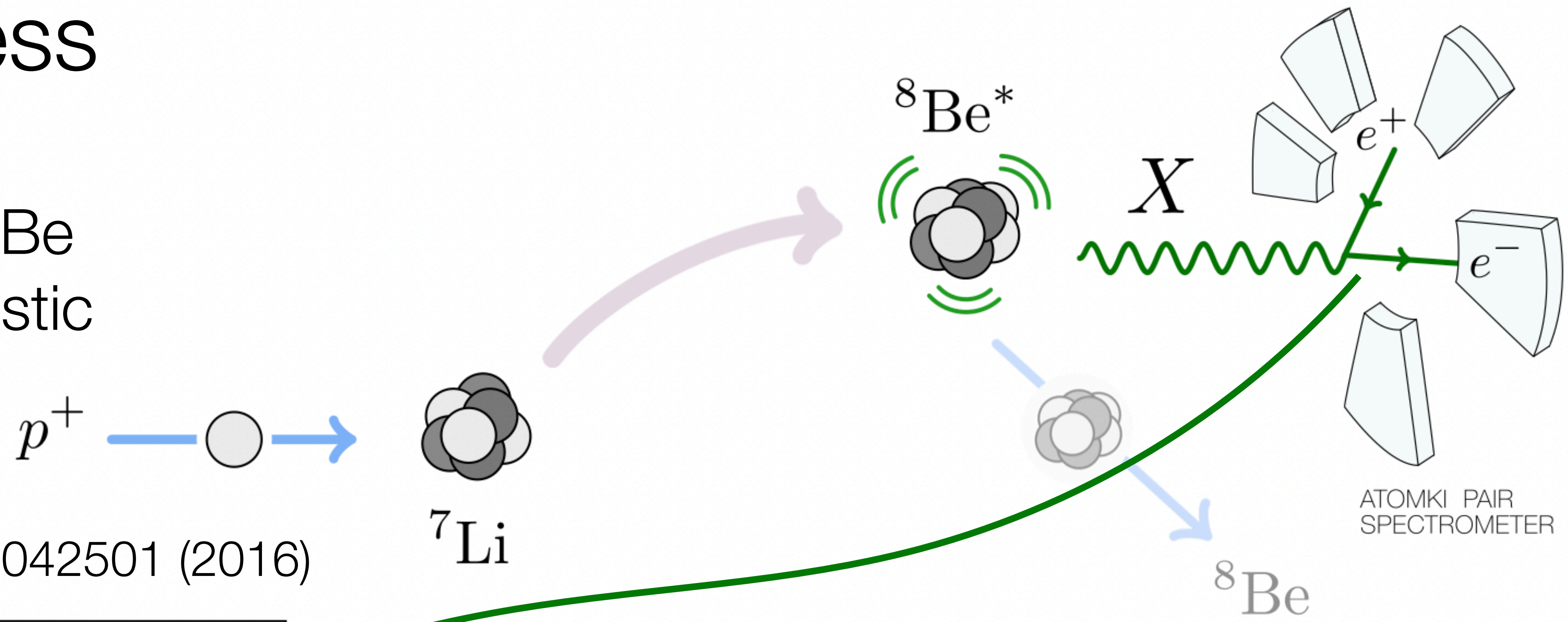


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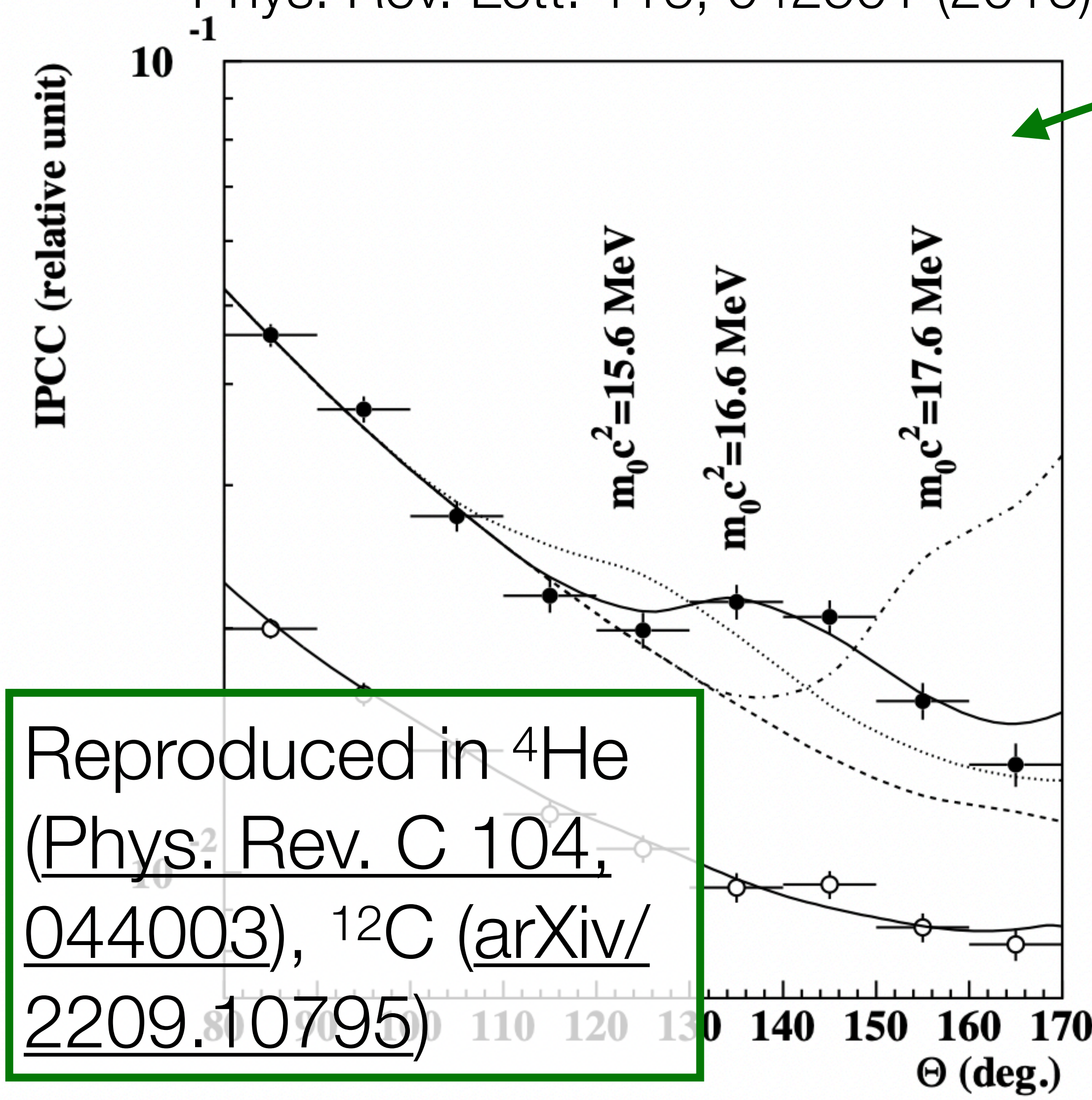


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Not-yet-understood detector effect? Unexpected SM cause? Possibly!

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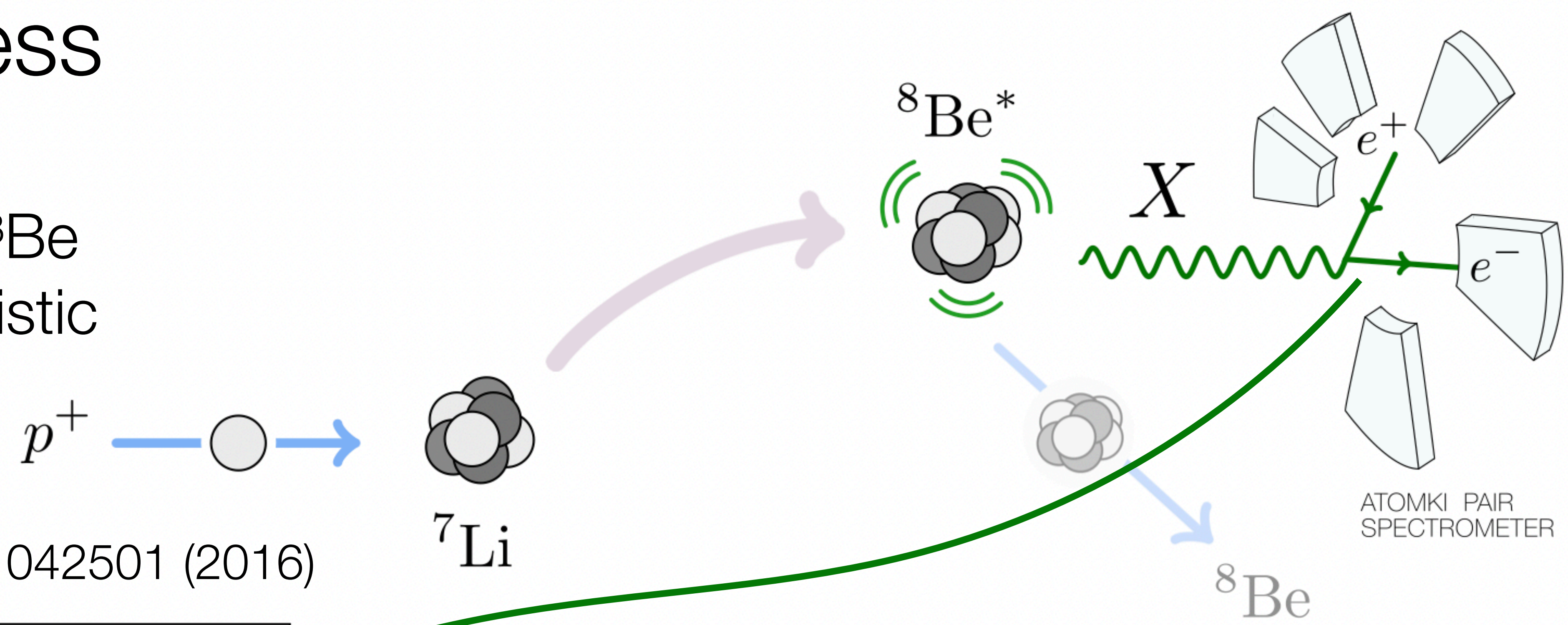


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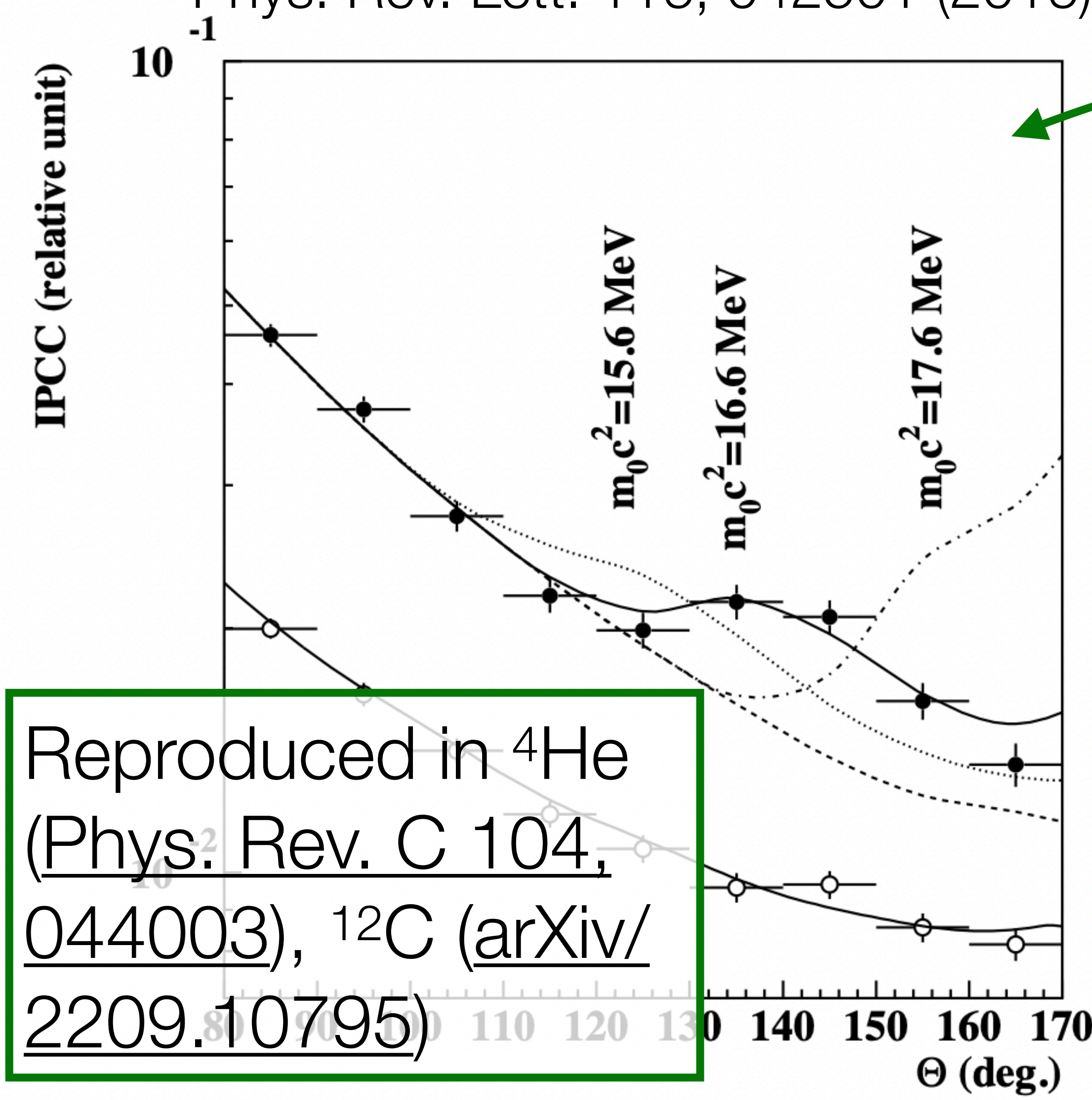


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Invariant mass and opening angle of e+e- pair show resonant signal

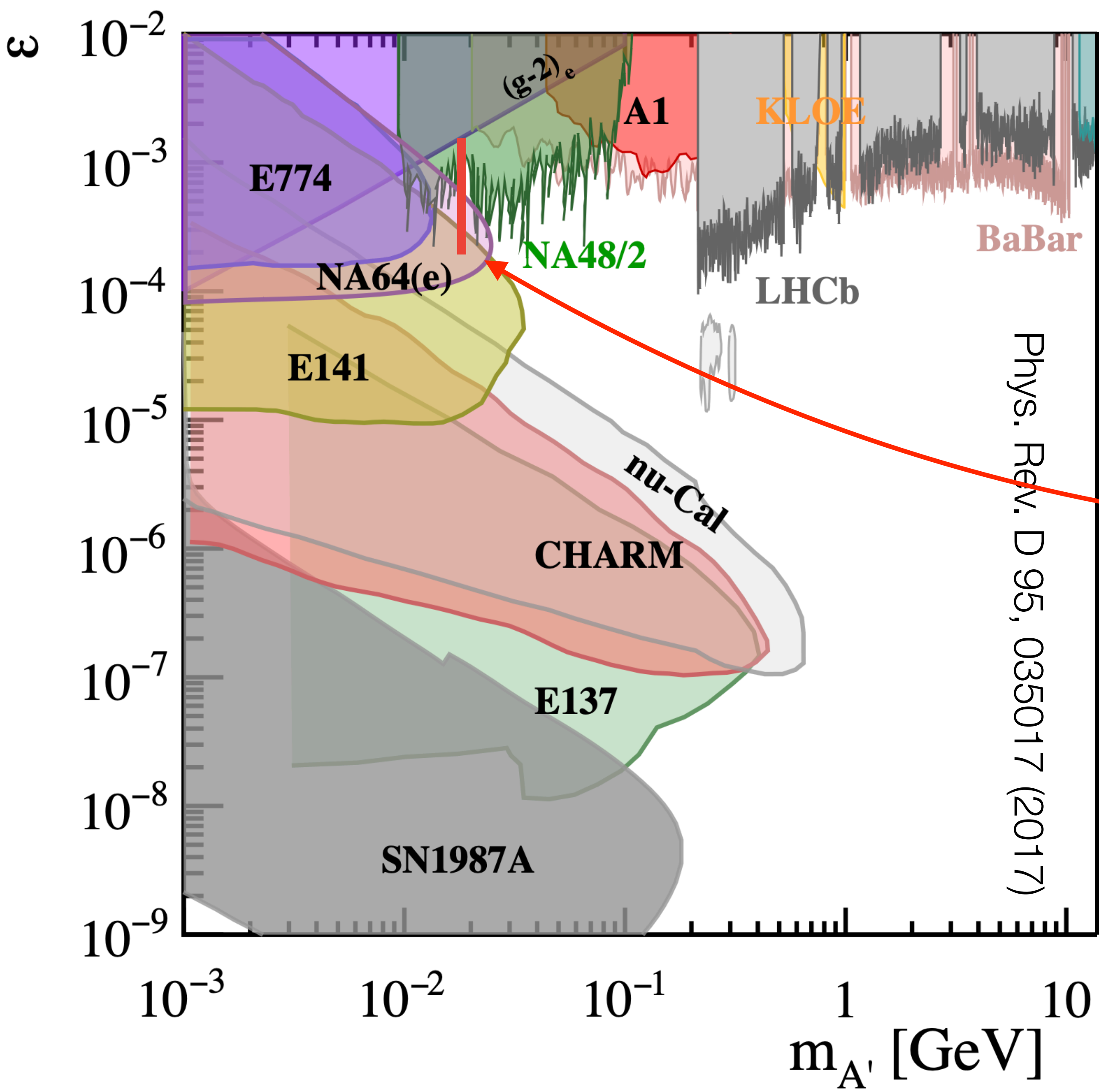
Not-yet-understood detector effect? Unexpected SM cause? Possibly!

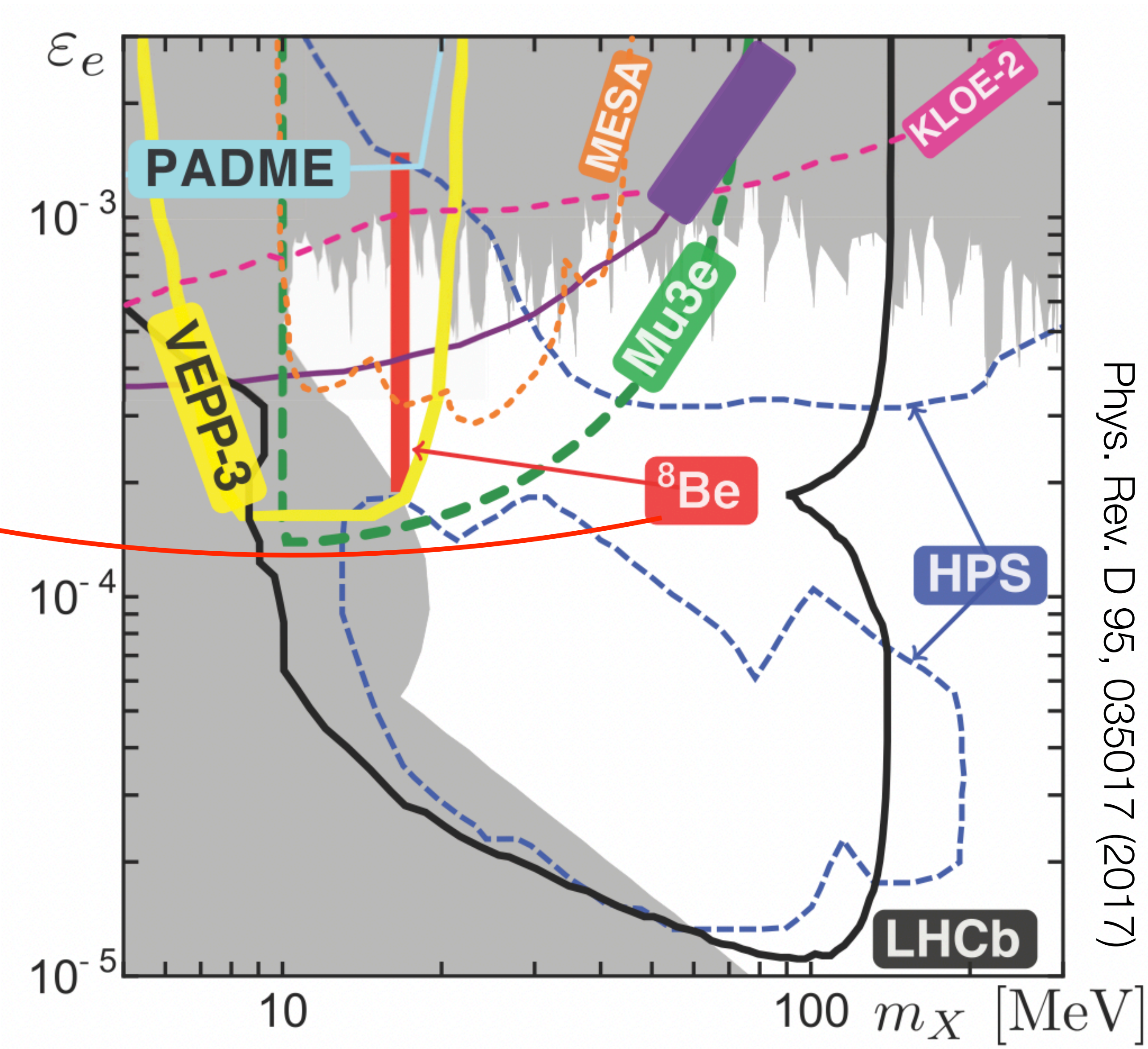
Or, compatible with new boson with mass ~ 17 MeV

# New boson experimental limits: very model dependent statements

Dark photon, visible decays: single universal coupling ε proportional to SM γ couplings

Massive boson with reduced coupling to protons. This plot: limits from e+e- interactions only



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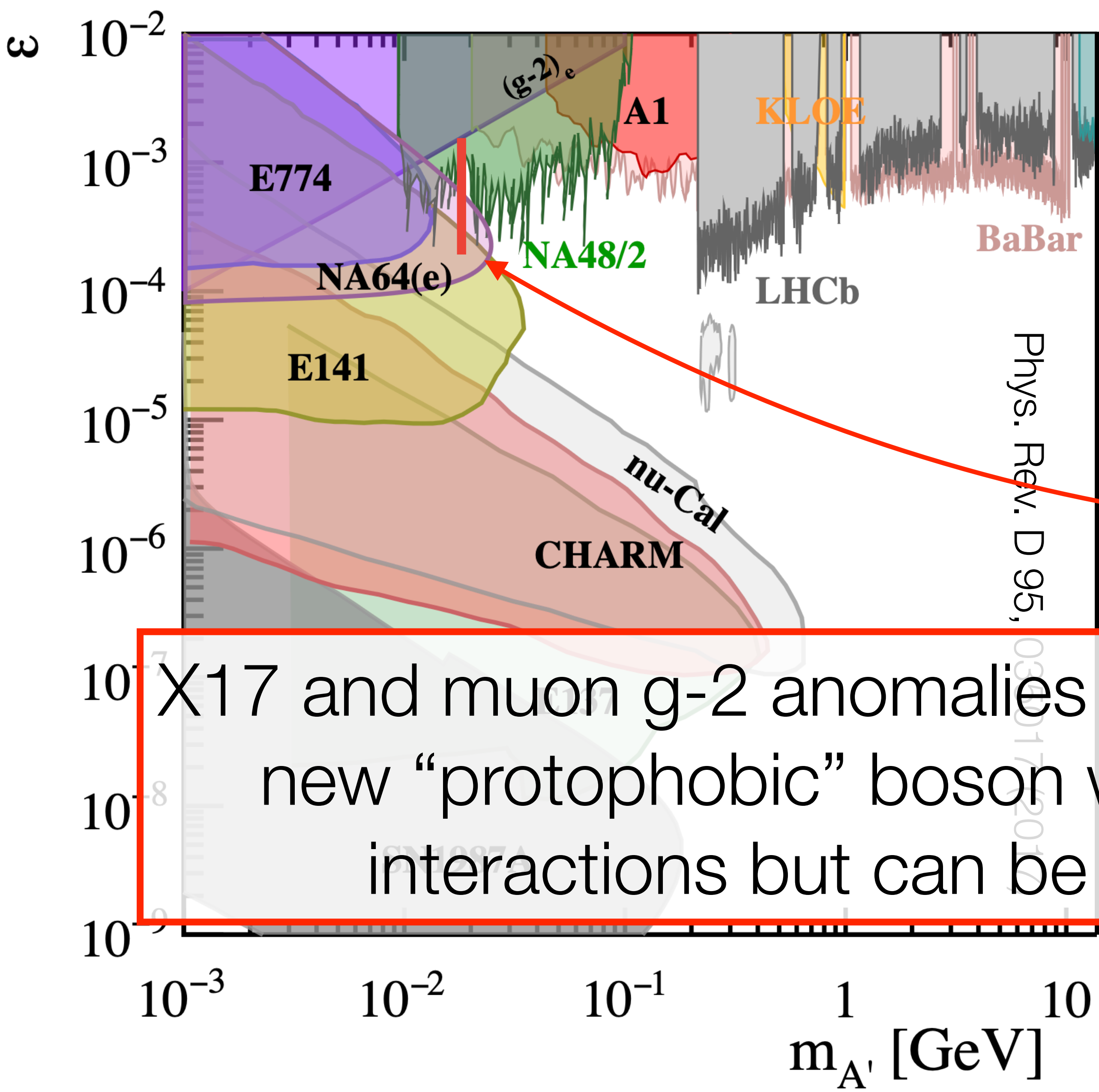
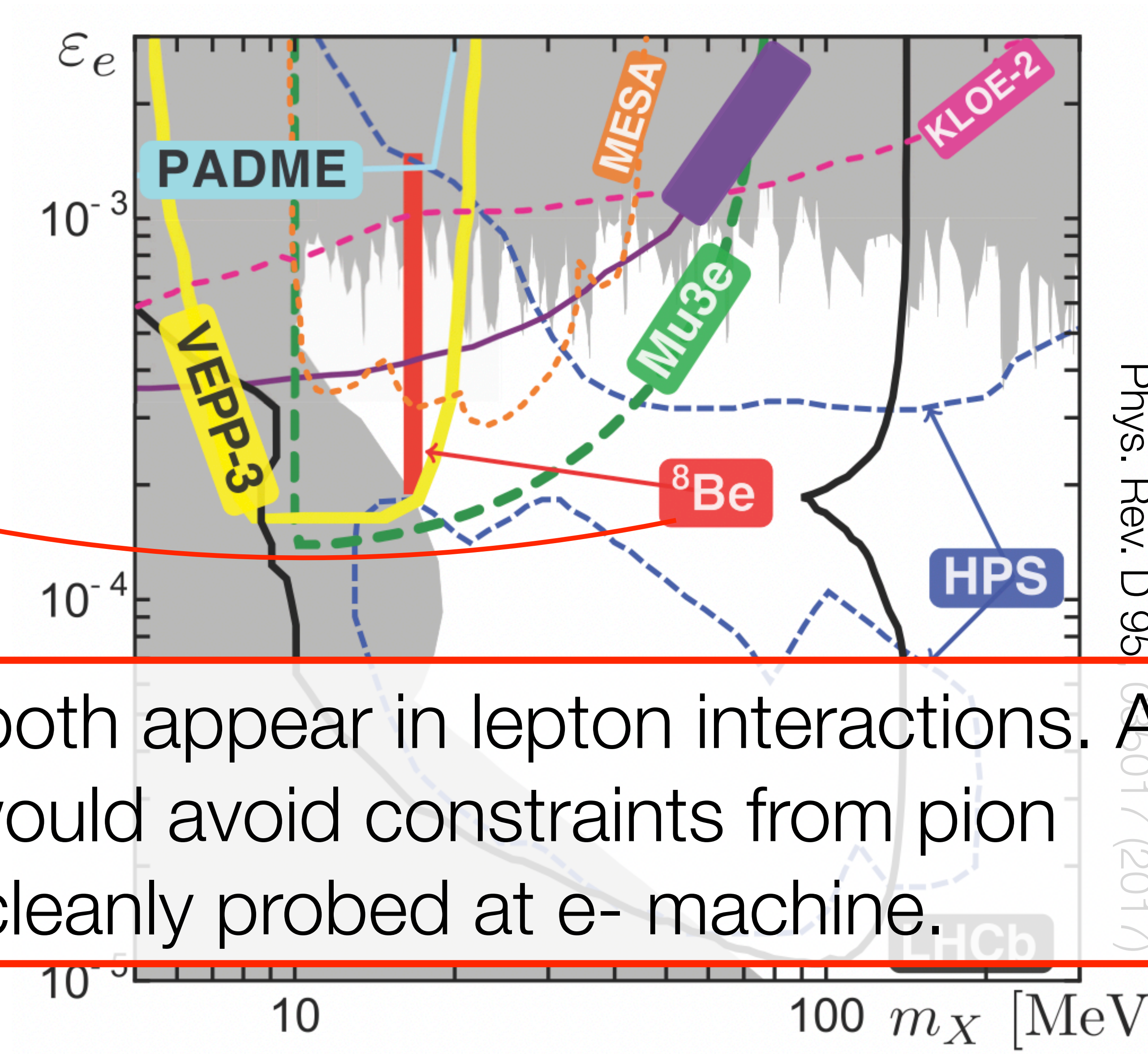


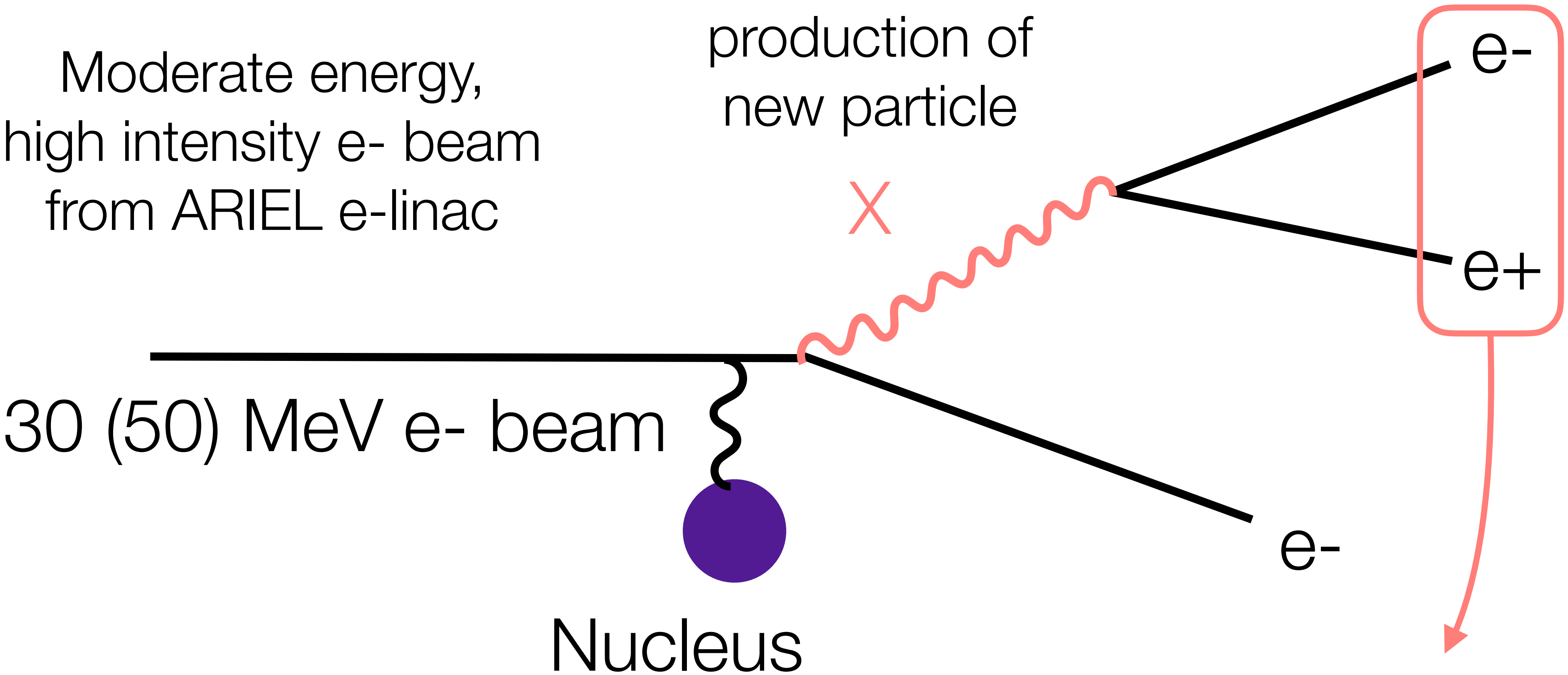

X17 and muon g-2 anomalies both appear in lepton interactions. A new “protophobic” boson would avoid constraints from pion interactions but can be cleanly probed at e- machine.

# The DarkLight @ ARIEL experiment

Moderate energy, high intensity e- beam from ARIEL e-linac

Radiative production of new particle

Broad opening angle: measure e+ and e- in spectrometers on opposite sides of beamline




High-N target optimised for minimum multiple scattering: baseline target is 1 µm Tantalum foil

Reconstruct invariant mass of e+e- pair and search for resonant peak over smooth SM background

# Collaboration

**Arizona State University, Tempe, AZ, USA**

**University of British Columbia, Canada**

**Hampton University, Hampton, VA, USA**

**TJNAF, Newport News, VA, USA**

**Massachusetts Institute of Technology, Cambridge, MA, USA**

**St. Mary's University, Halifax, Nova Scotia, Canada**

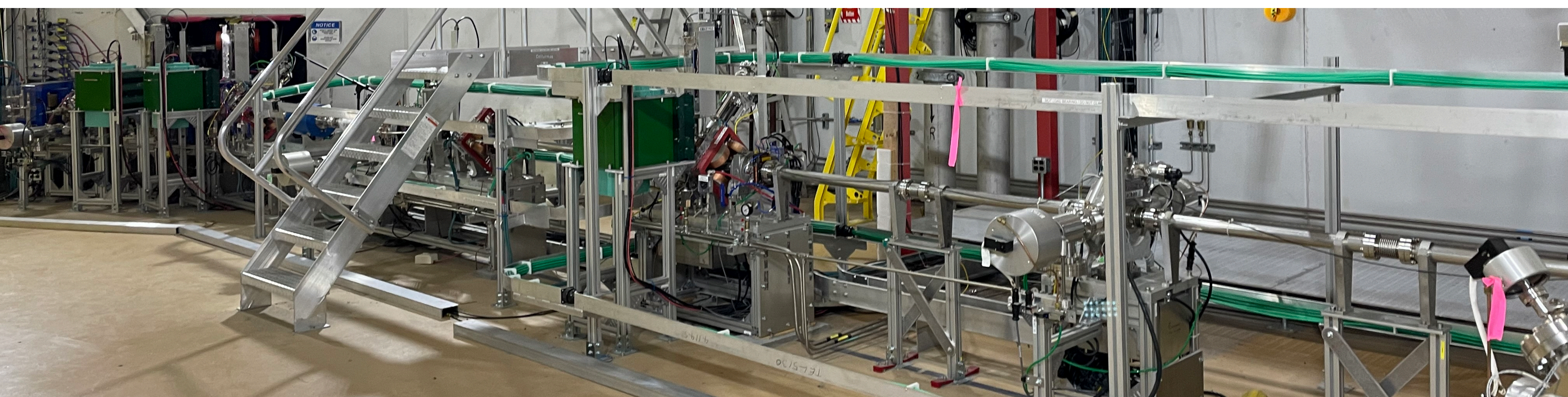
**Stony Brook University, NY, USA**

**TRIUMF, Vancouver, British Columbia, Canada**

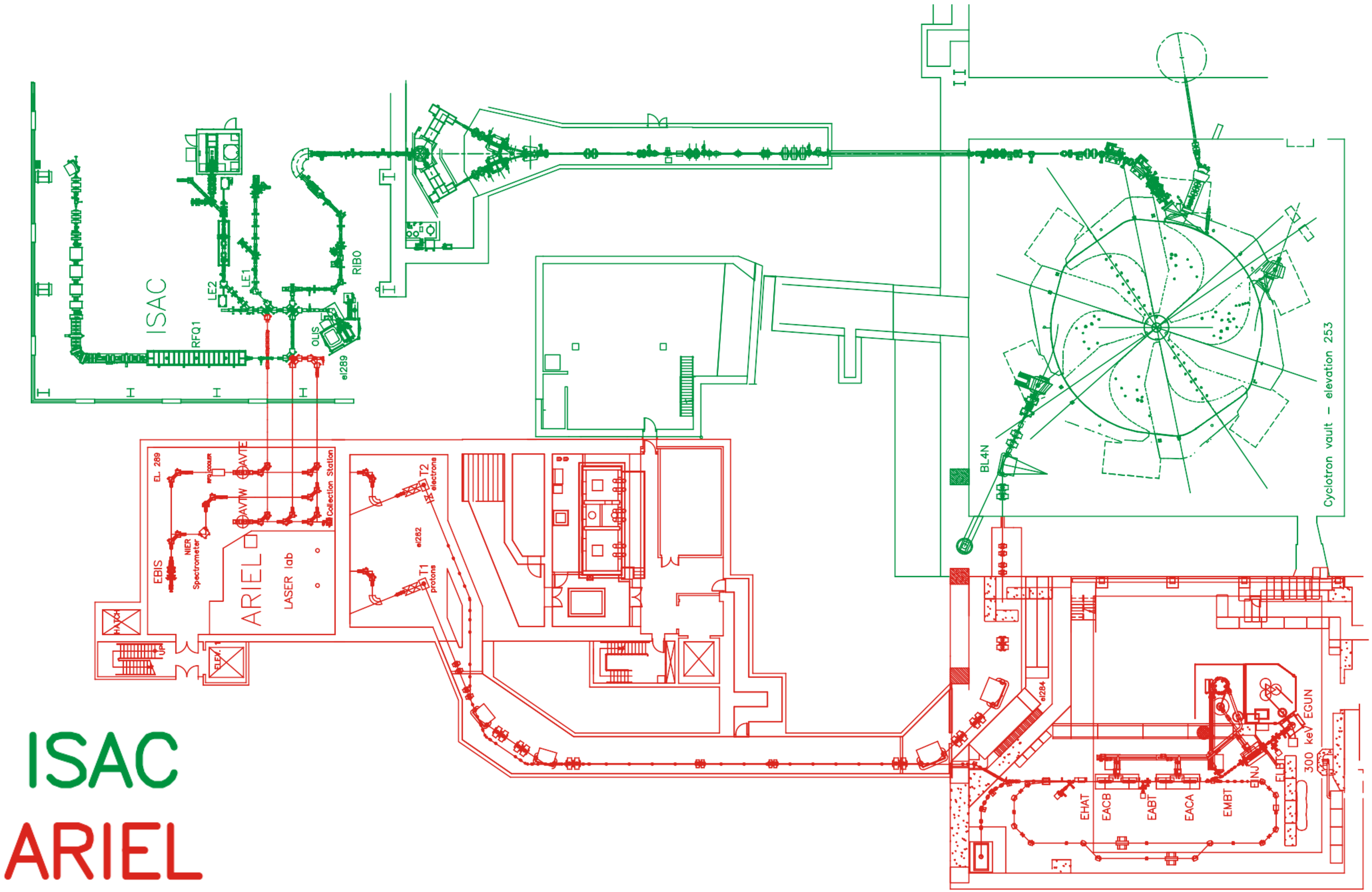
**University of Mainz, Germany**

**University of Manitoba, Canada**

**University of Winnipeg, Manitoba, Canada**



# The accelerator: TRIUMF ARIEL e-linac



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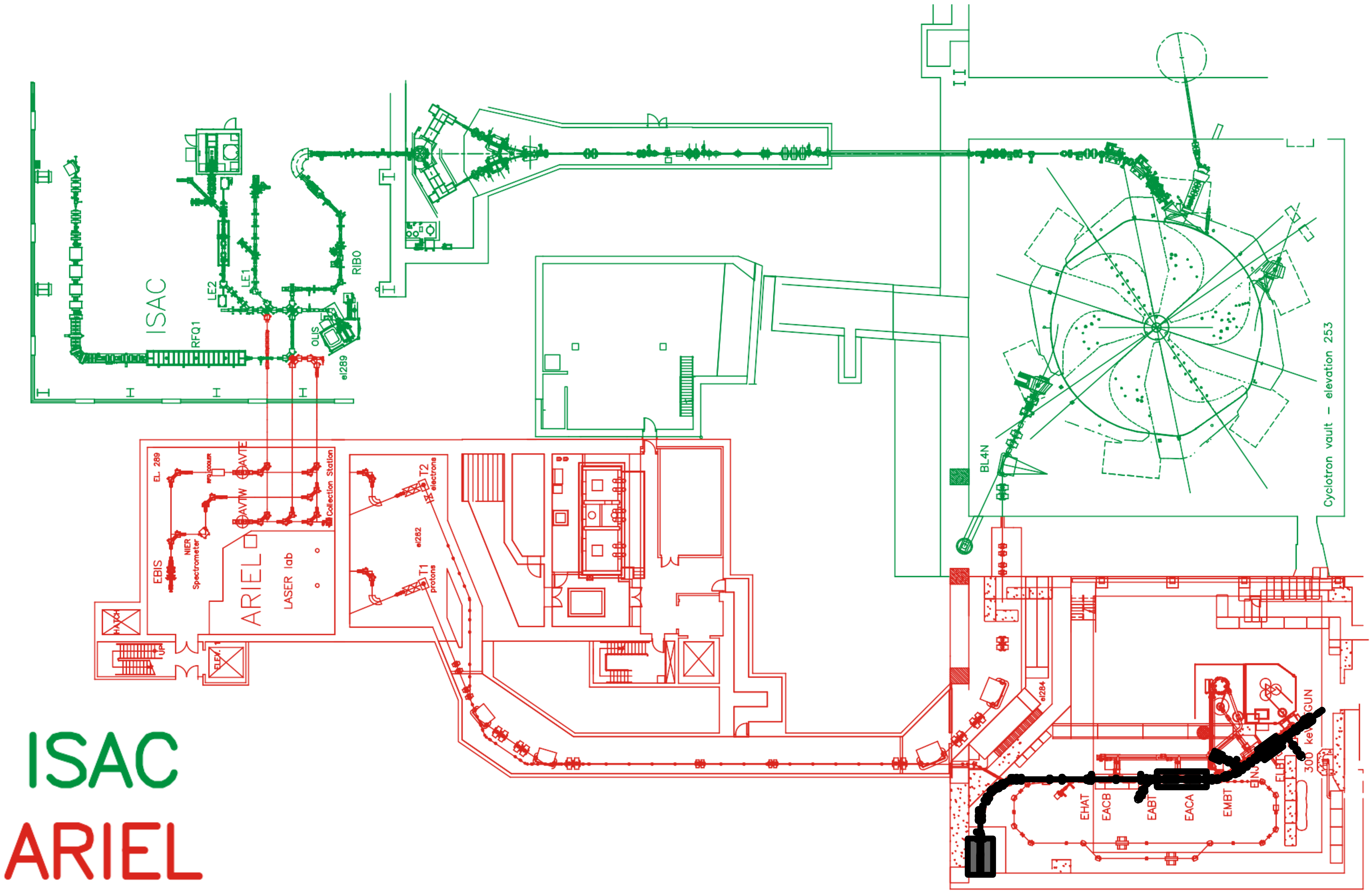
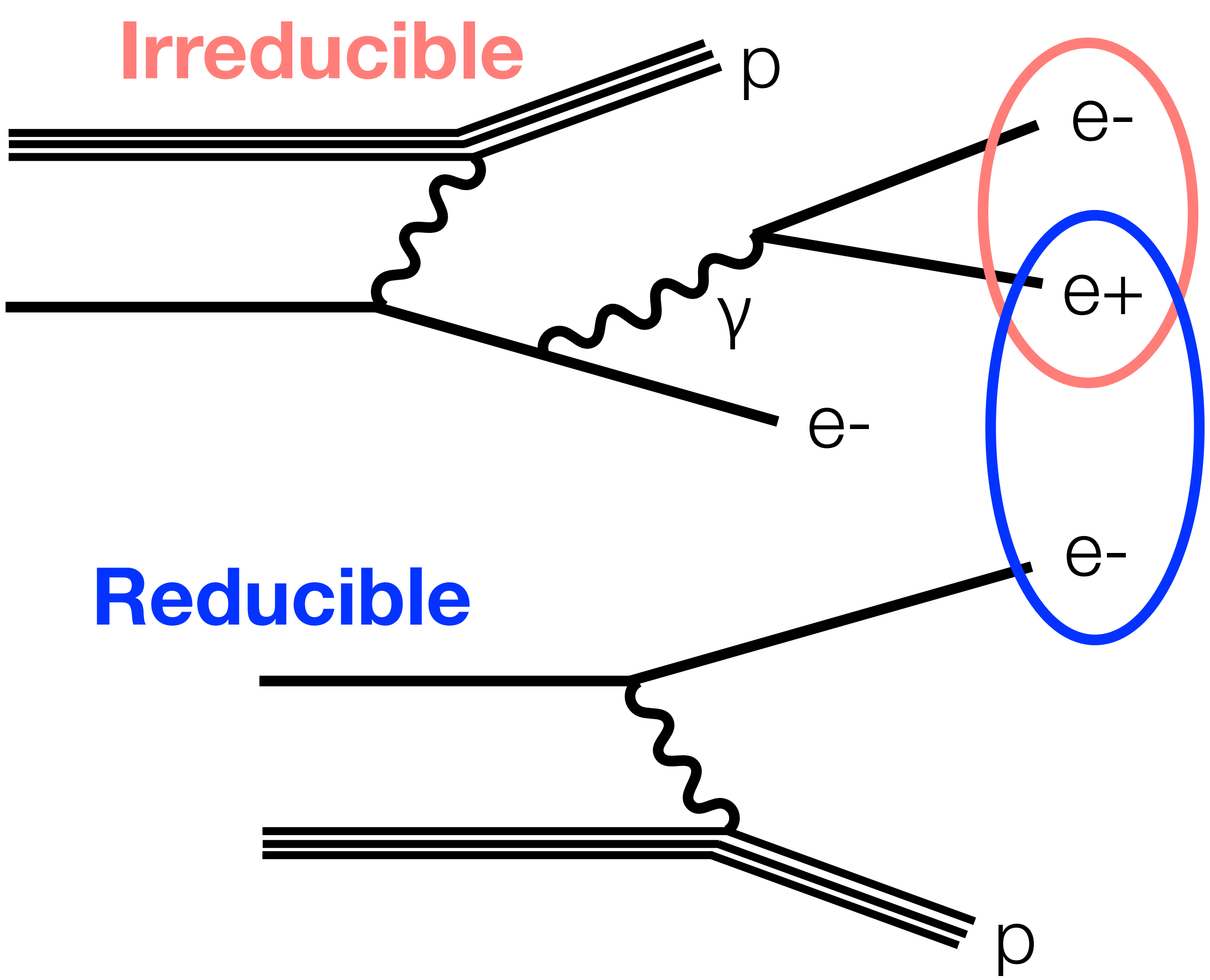
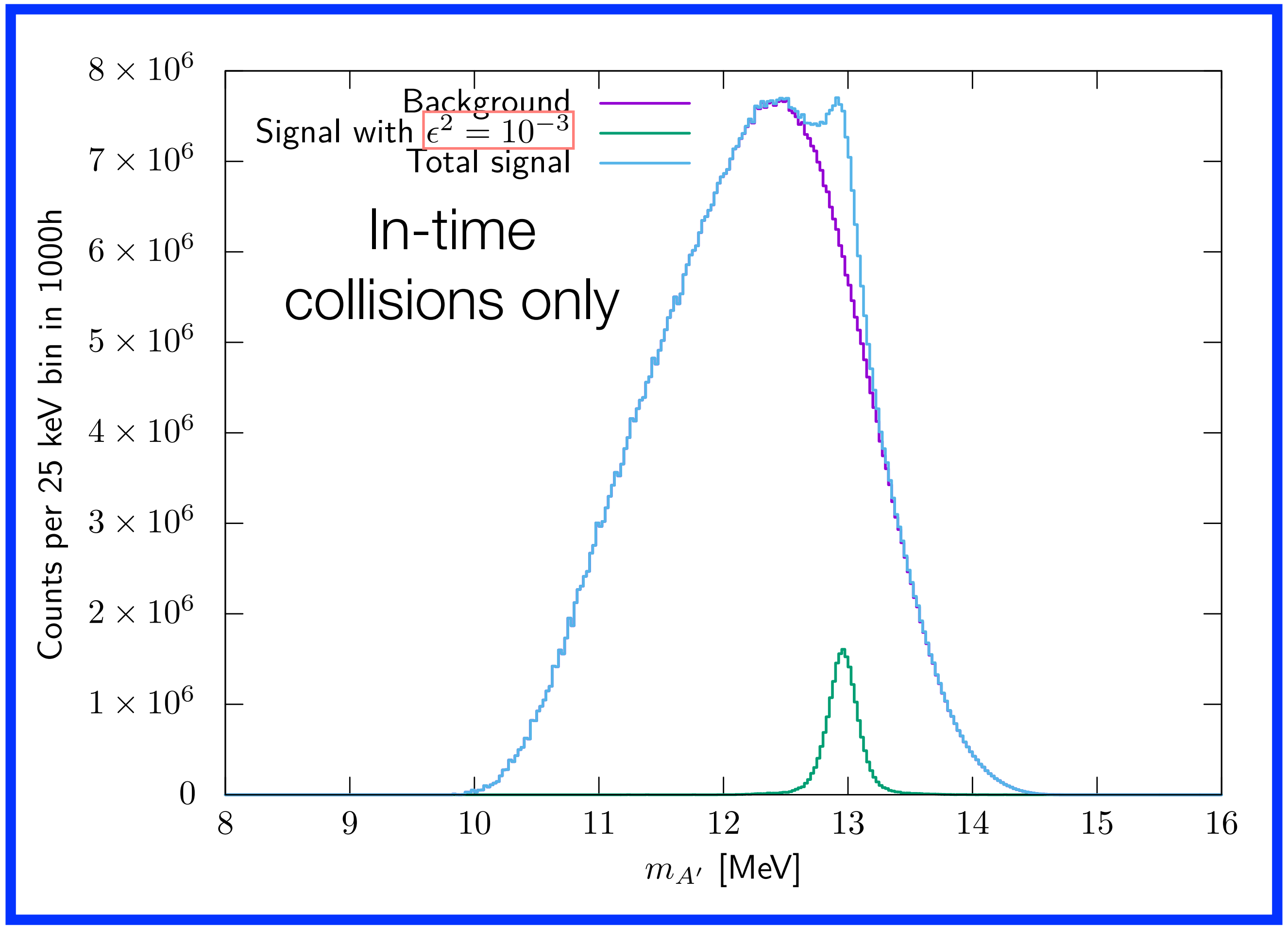


# Background processes

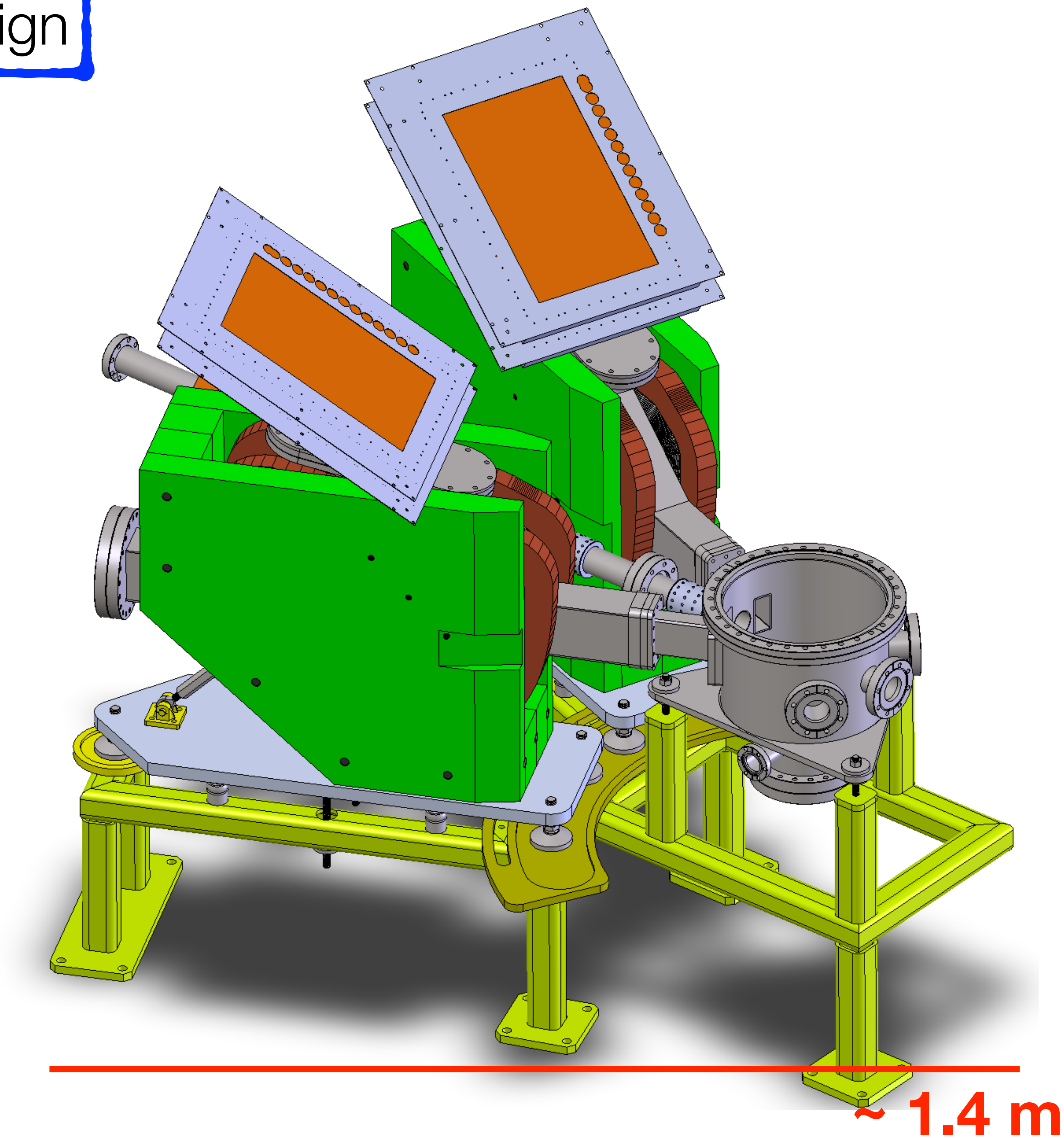
- Vastly dominant background is e+ from pair production combined with e- from simultaneous scattering event. **Coincidence** is key
- Two ways to control rates: 1) angular position of detectors 2) timing resolution << bunch spacing (1.5 ns)



# Experiment overview

Preliminary design



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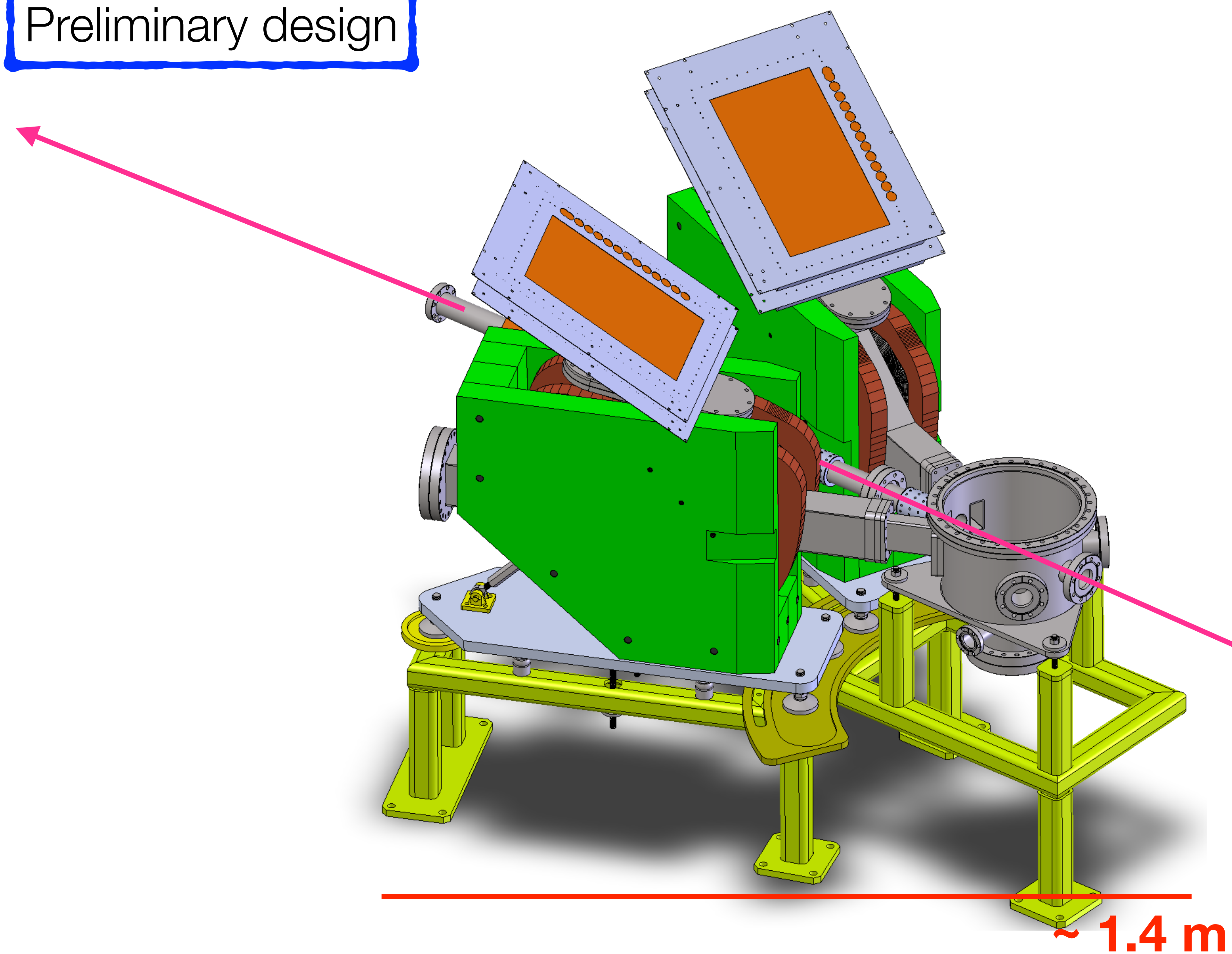

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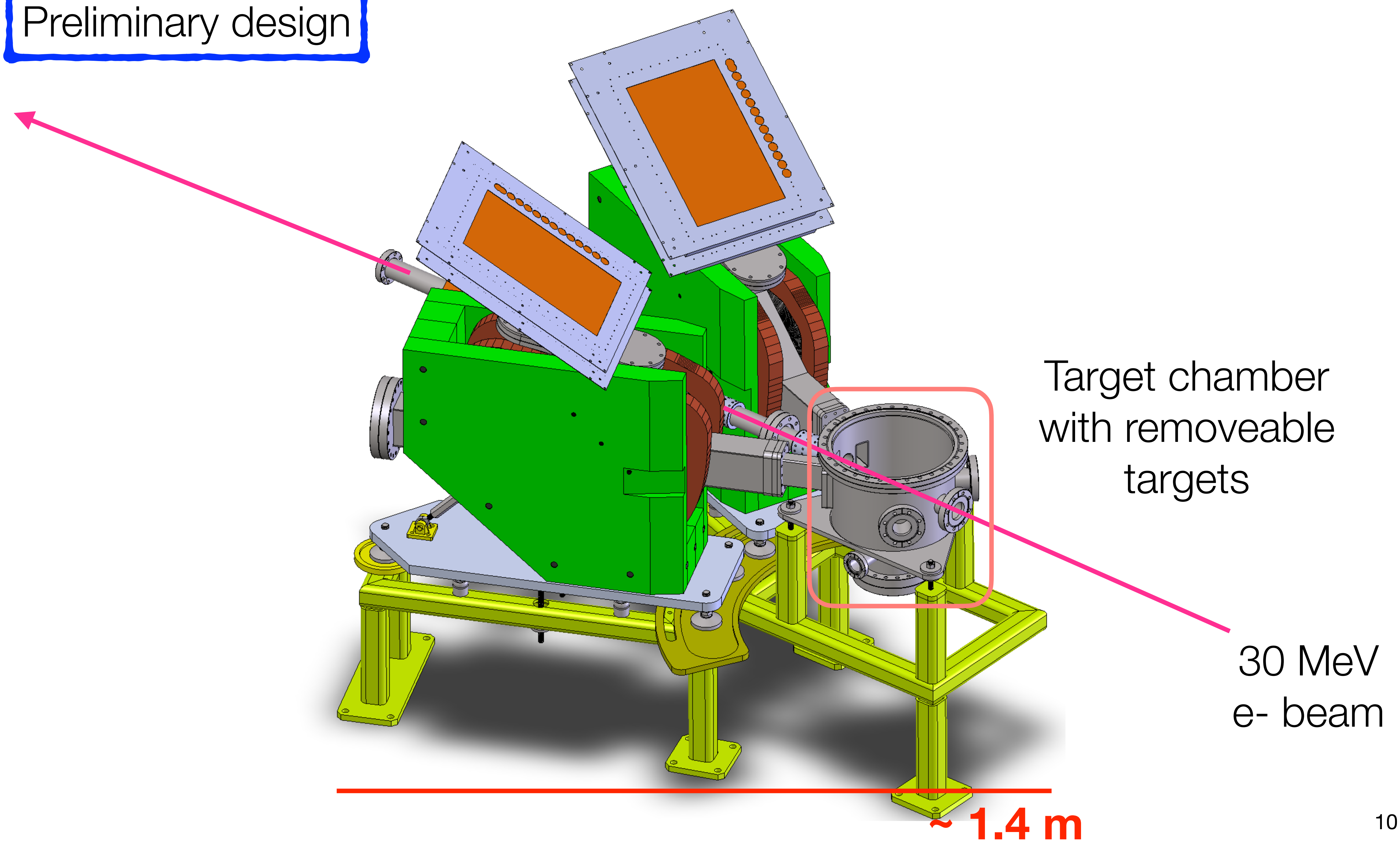

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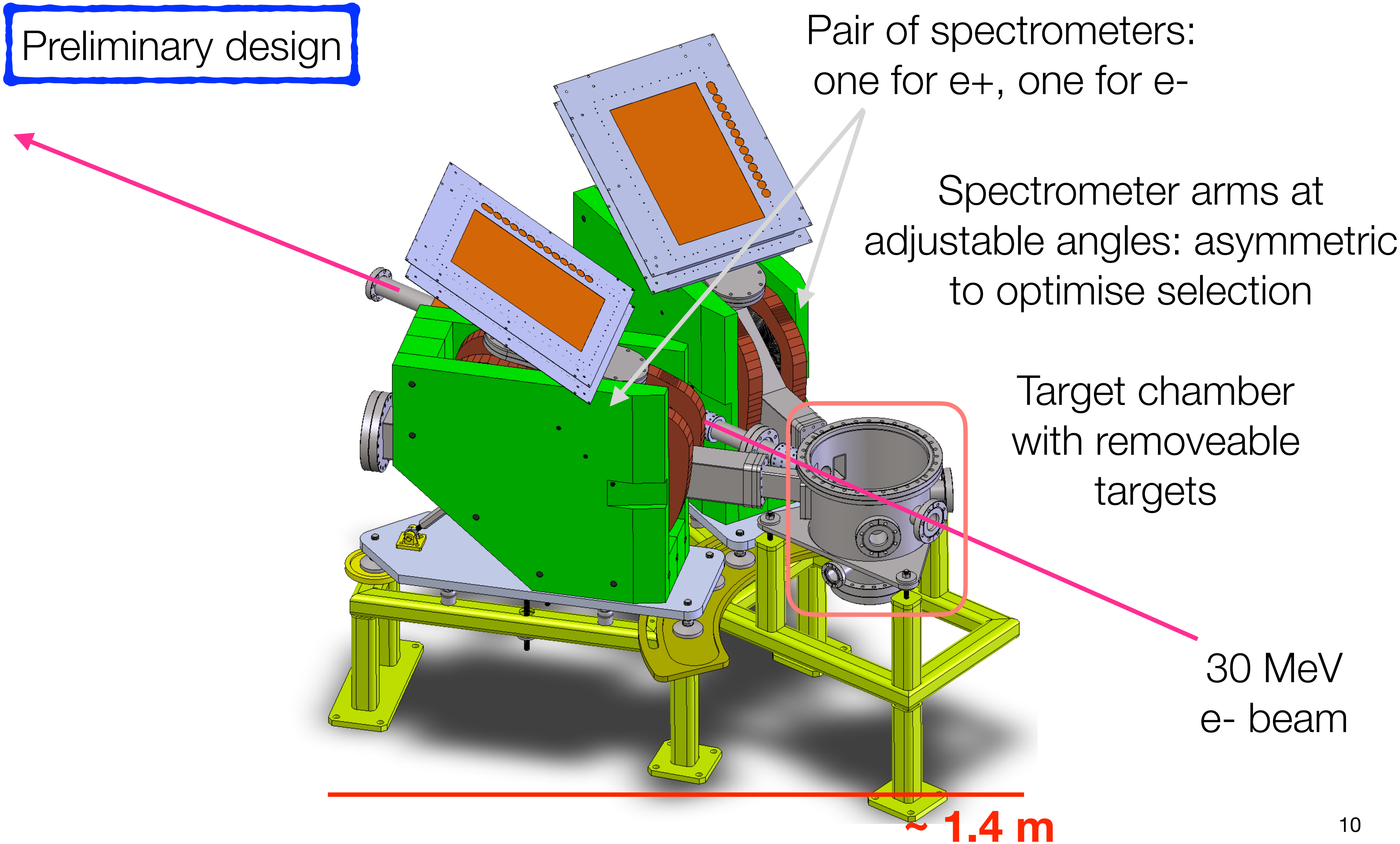

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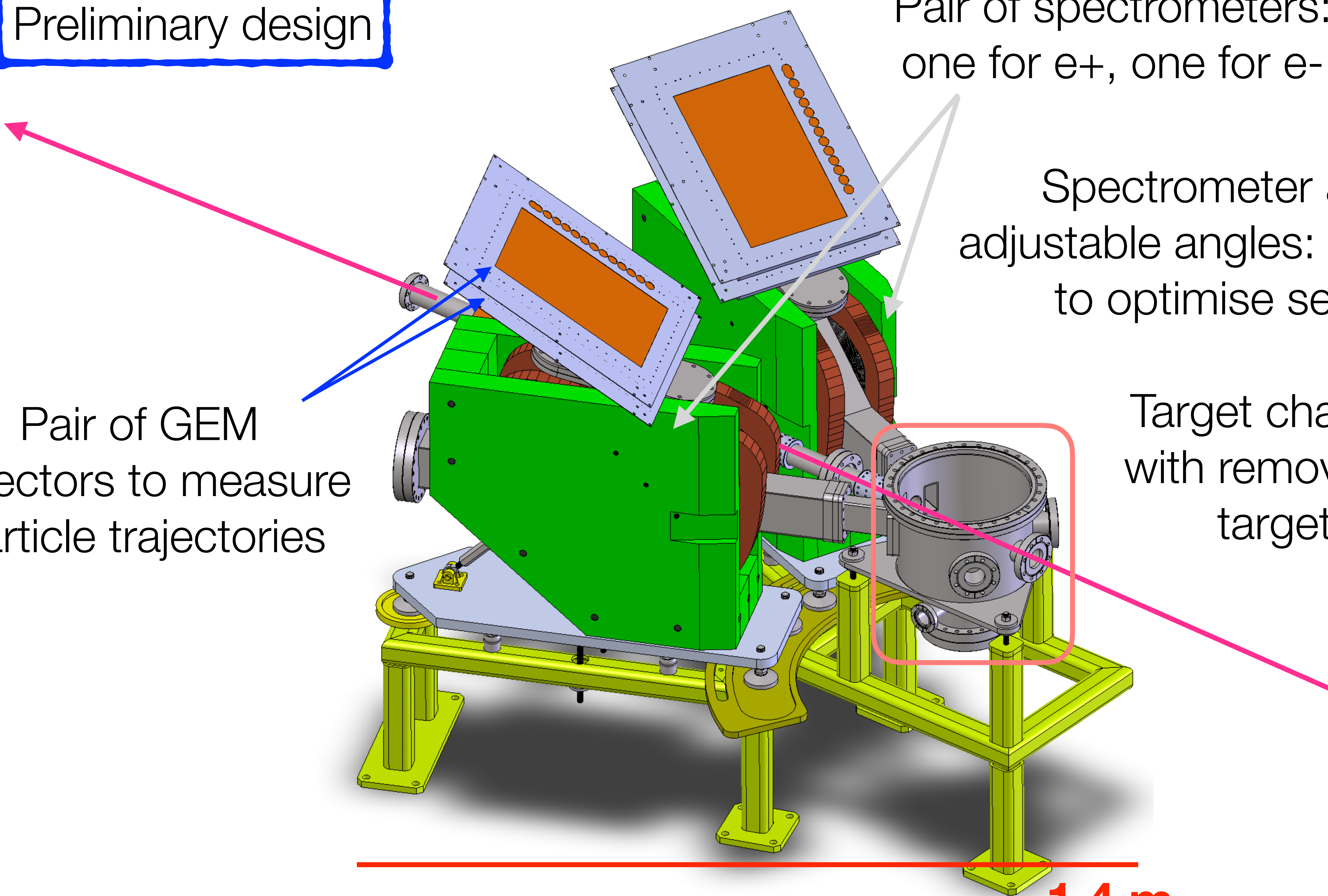

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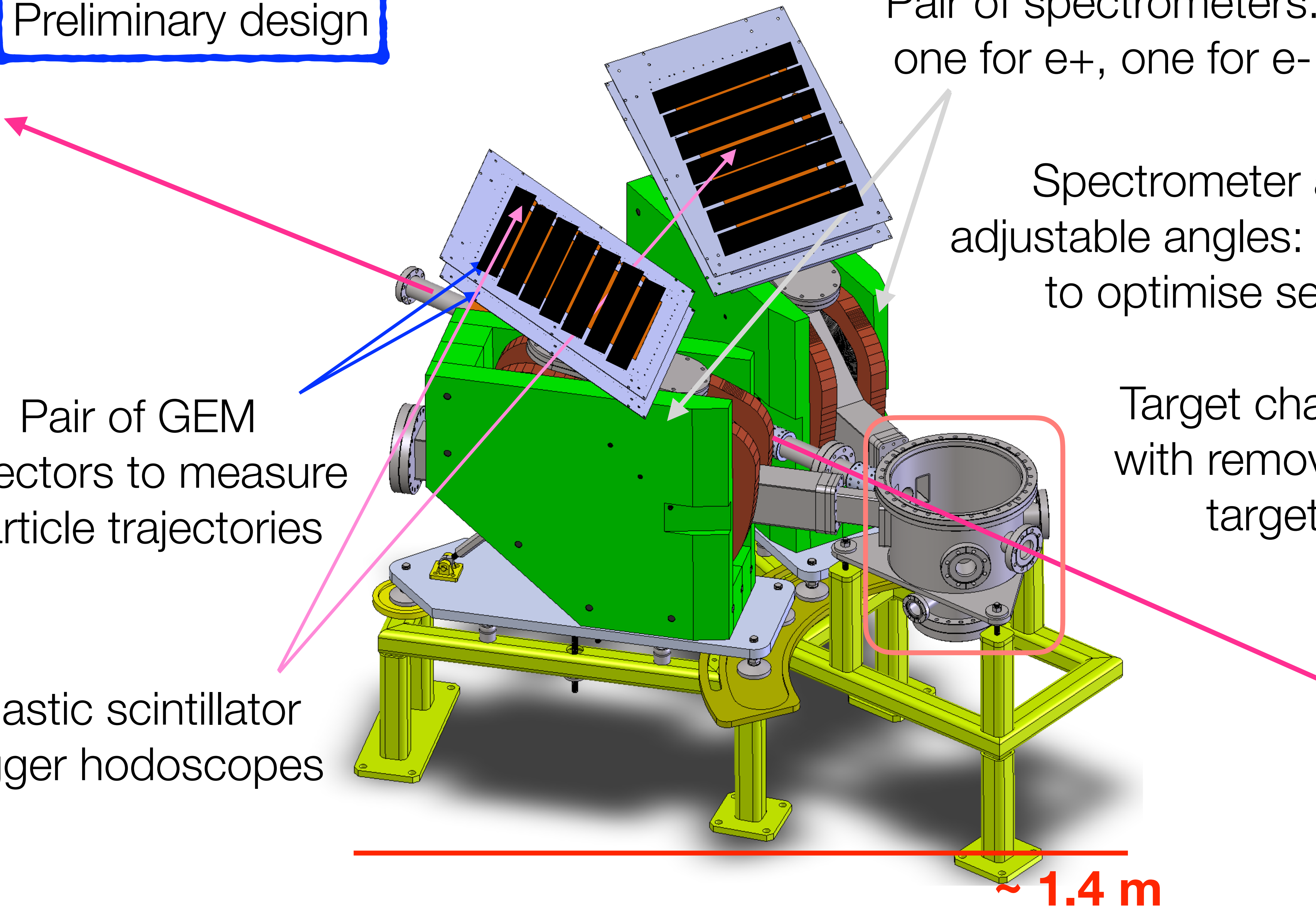
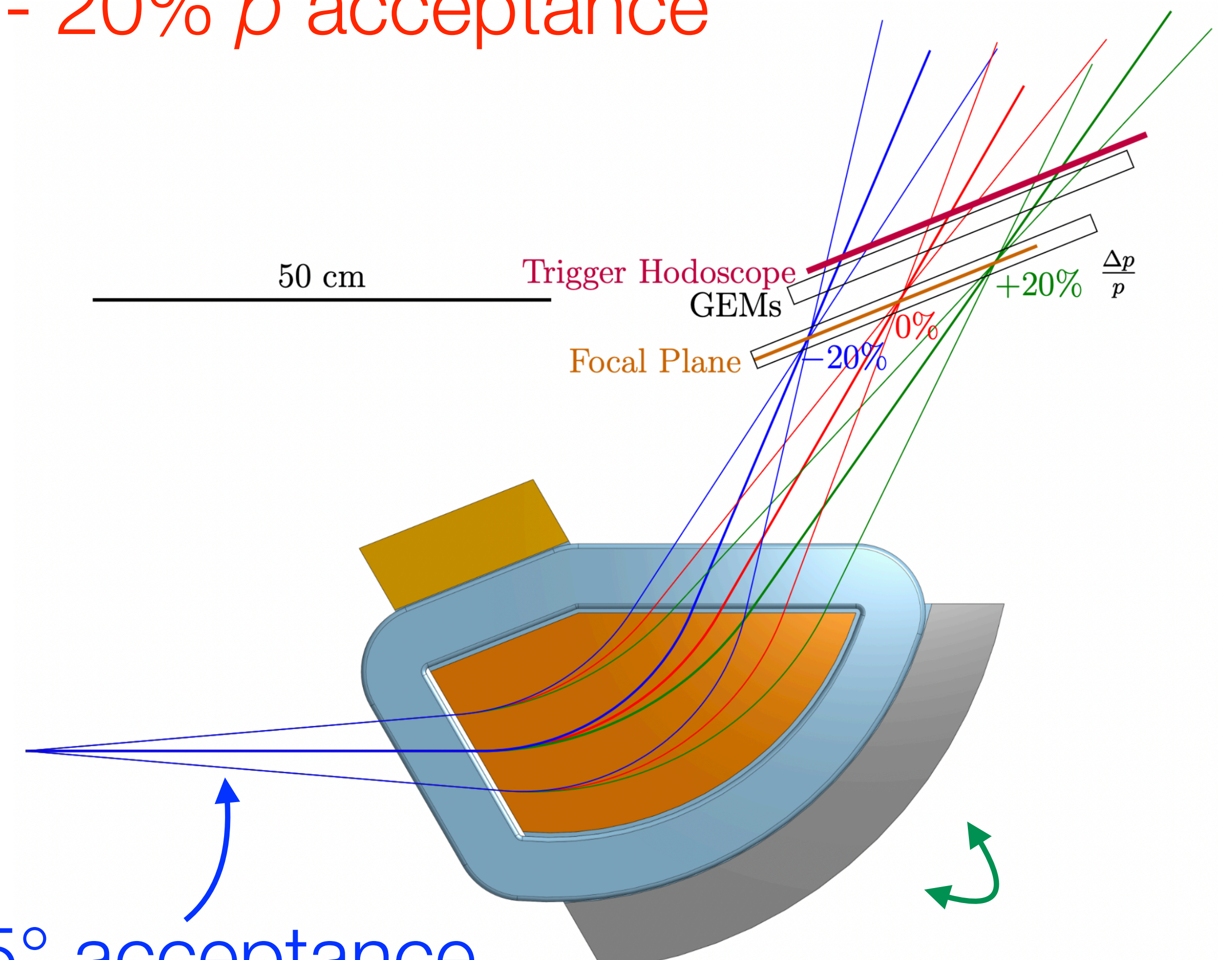


# Experiment components: spectrometers

- Two identical dipole spectrometers, 0.32 T
- Design nearing completion
- Try to maximise acceptance, minimise scattering of high-E electrons into detectors
- Metrics of success: low background and best possible mass resolution

+/- 20% *p* acceptance



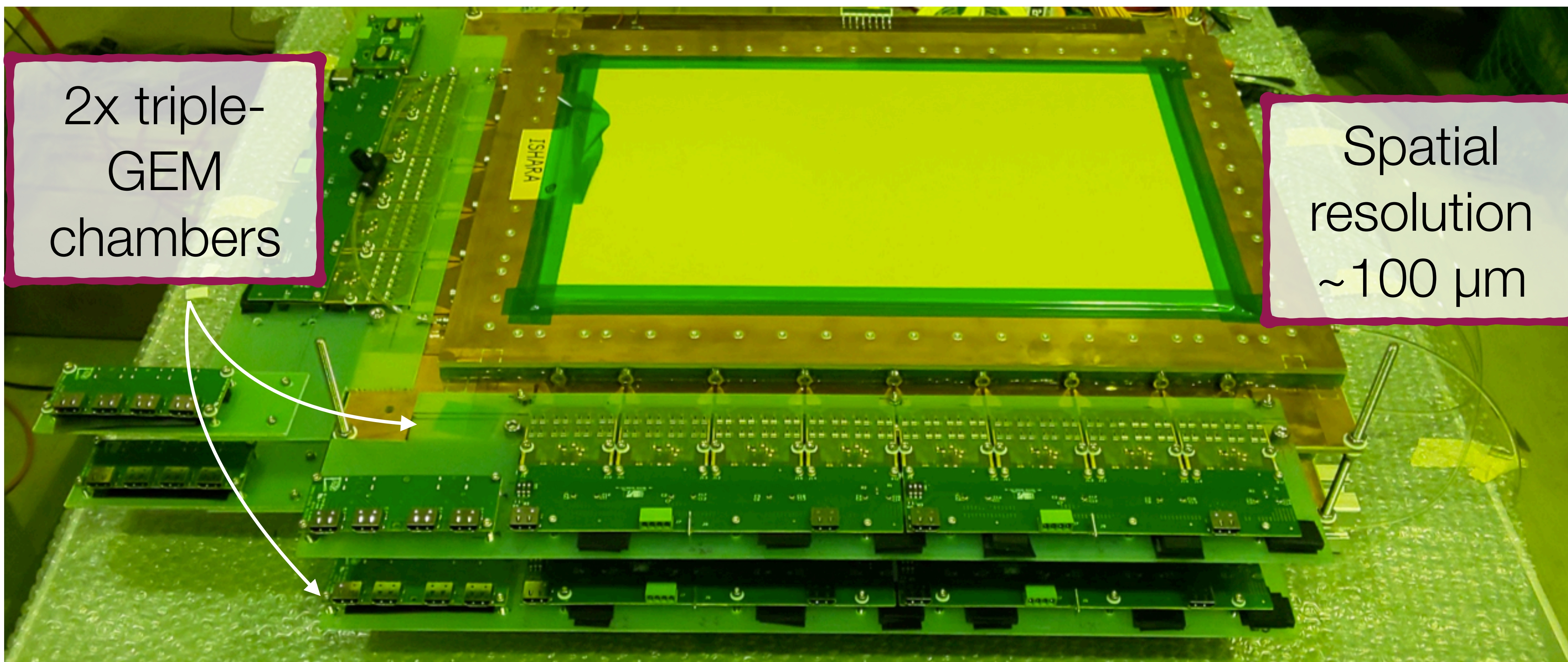

+/- 5° acceptance in this dimension

+/- ~1.6° acceptance the other way

# Experiment components: GEM detectors

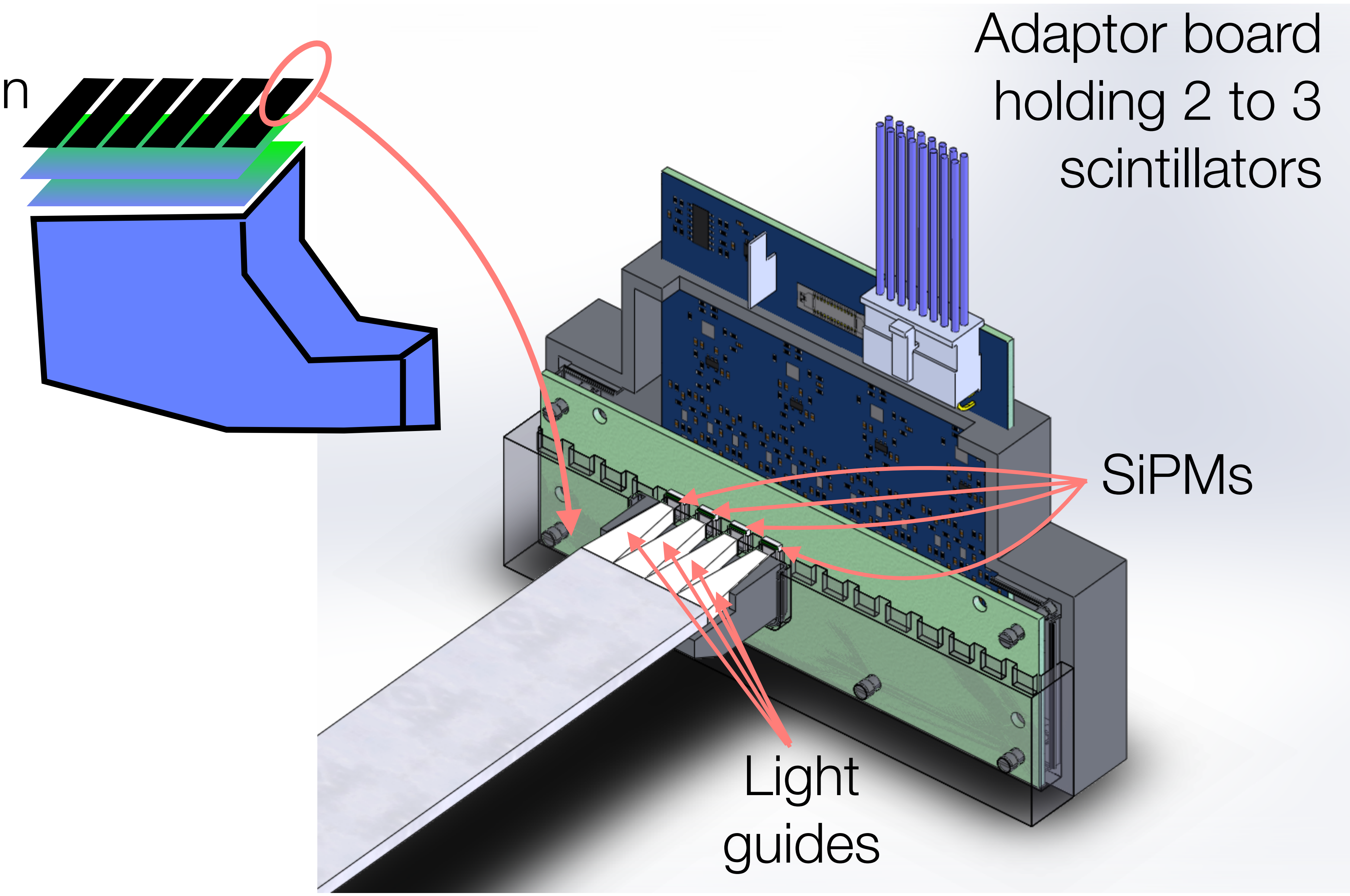
- 25 x 40 cm triple-GEMs **already completed** by Hampton University collaborators

- Commissioning in progress (JLab/ELPH)



# Experiment components: trigger detectors

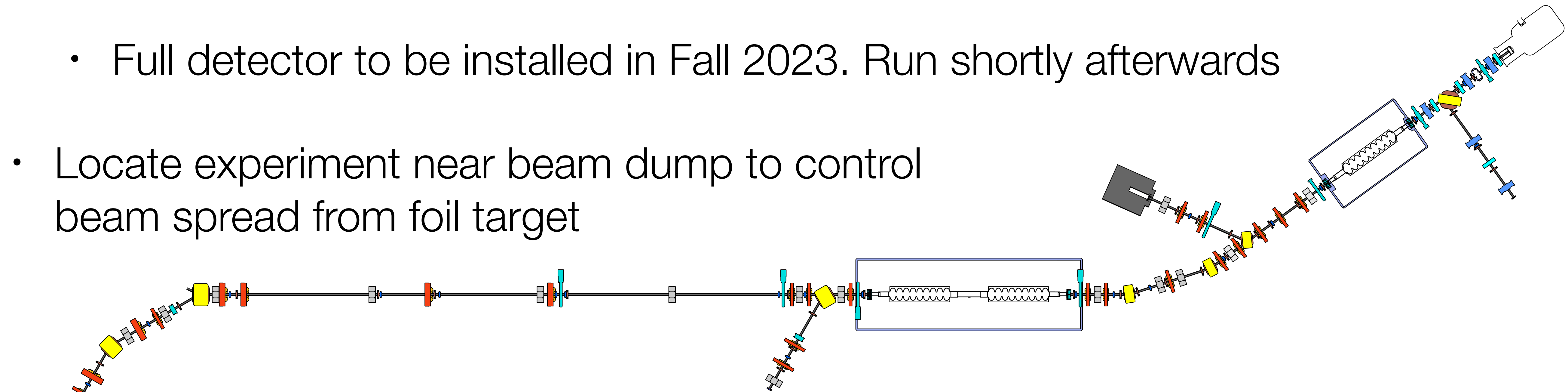
- Key performance metric: timing resolution ~200 ps
- 8 - 10 strips of fast plastic scintillator read out via SiPMs
    - Shielding will be important for longevity
- Prototype testing at TRIUMF under way
- DAQ design in progress

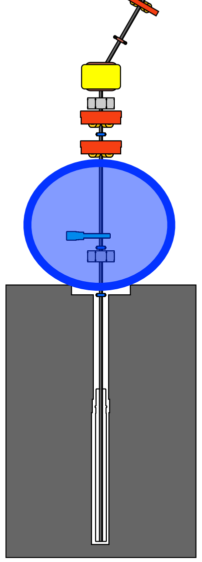



Exact dimensions and number of SiPMs remains open

# 30 MeV running with current ARIEL e-linac

- First experimental stage is a full run (18 $fb^{-1}$) at 30 MeV
  - Full detector to be installed in Fall 2023. Run shortly afterwards
- Locate experiment near beam dump to control beam spread from foil target



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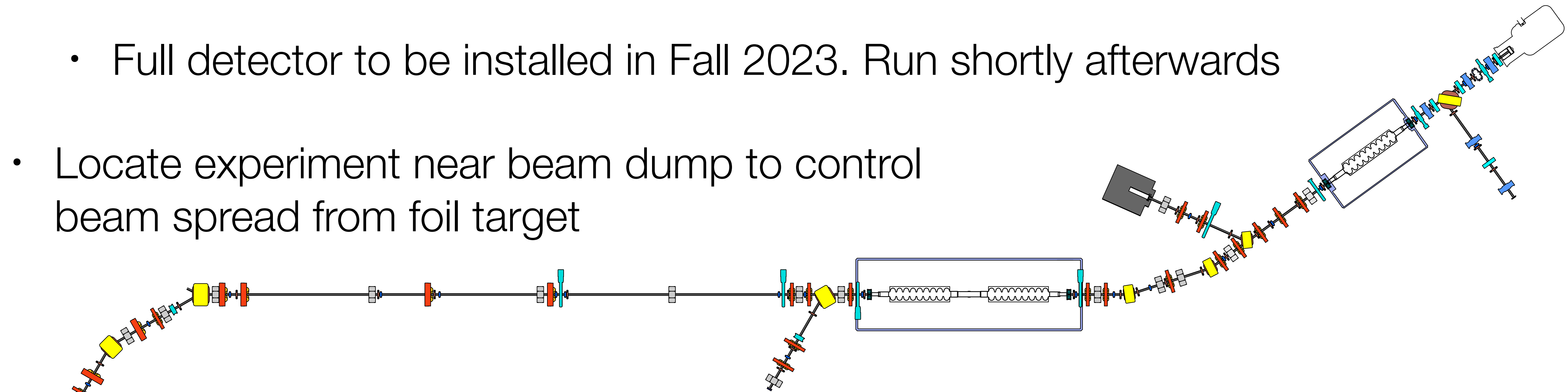
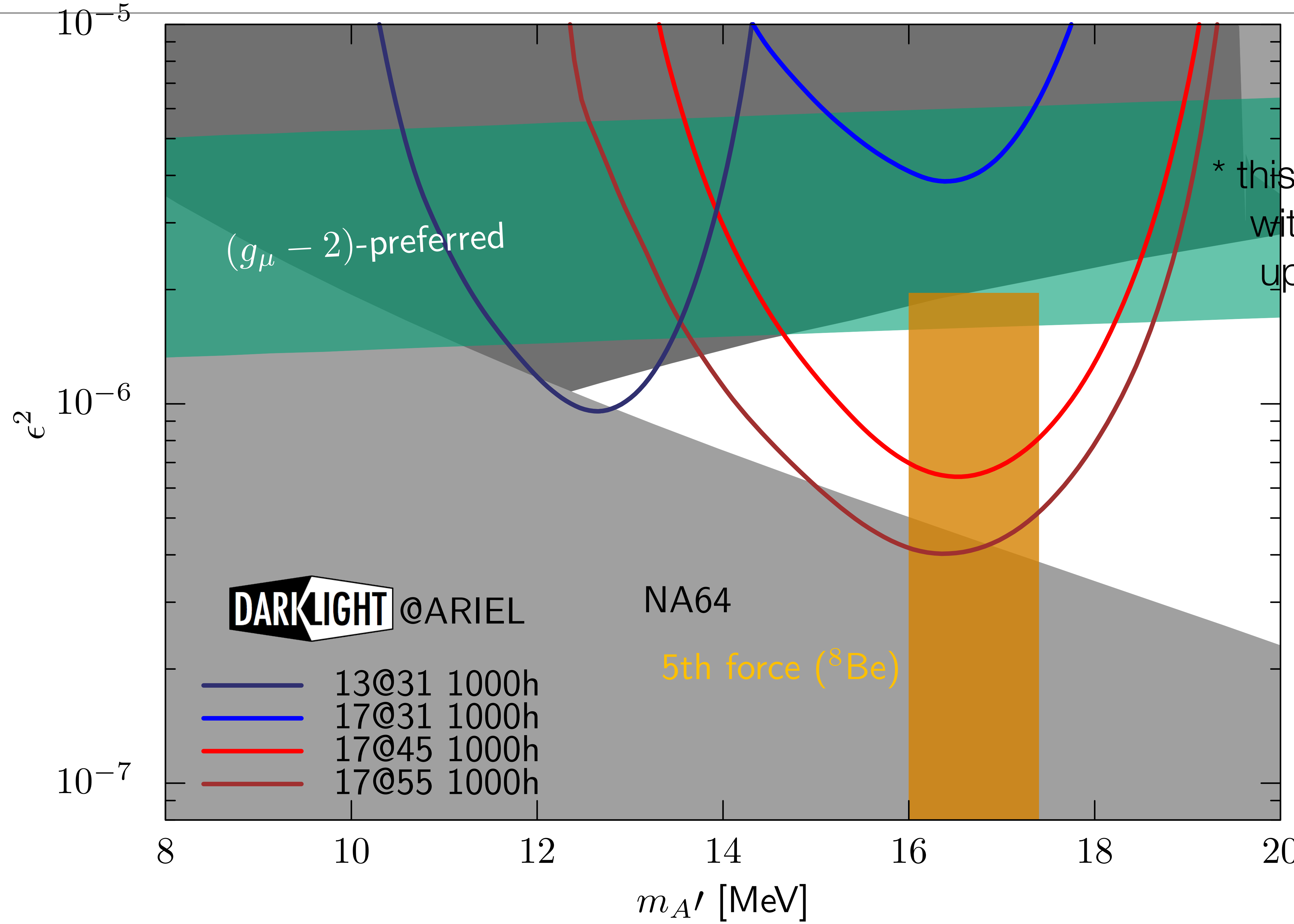



# Sensitivity at 30 and 50 MeV accelerators




* this shrinks with g-2 update

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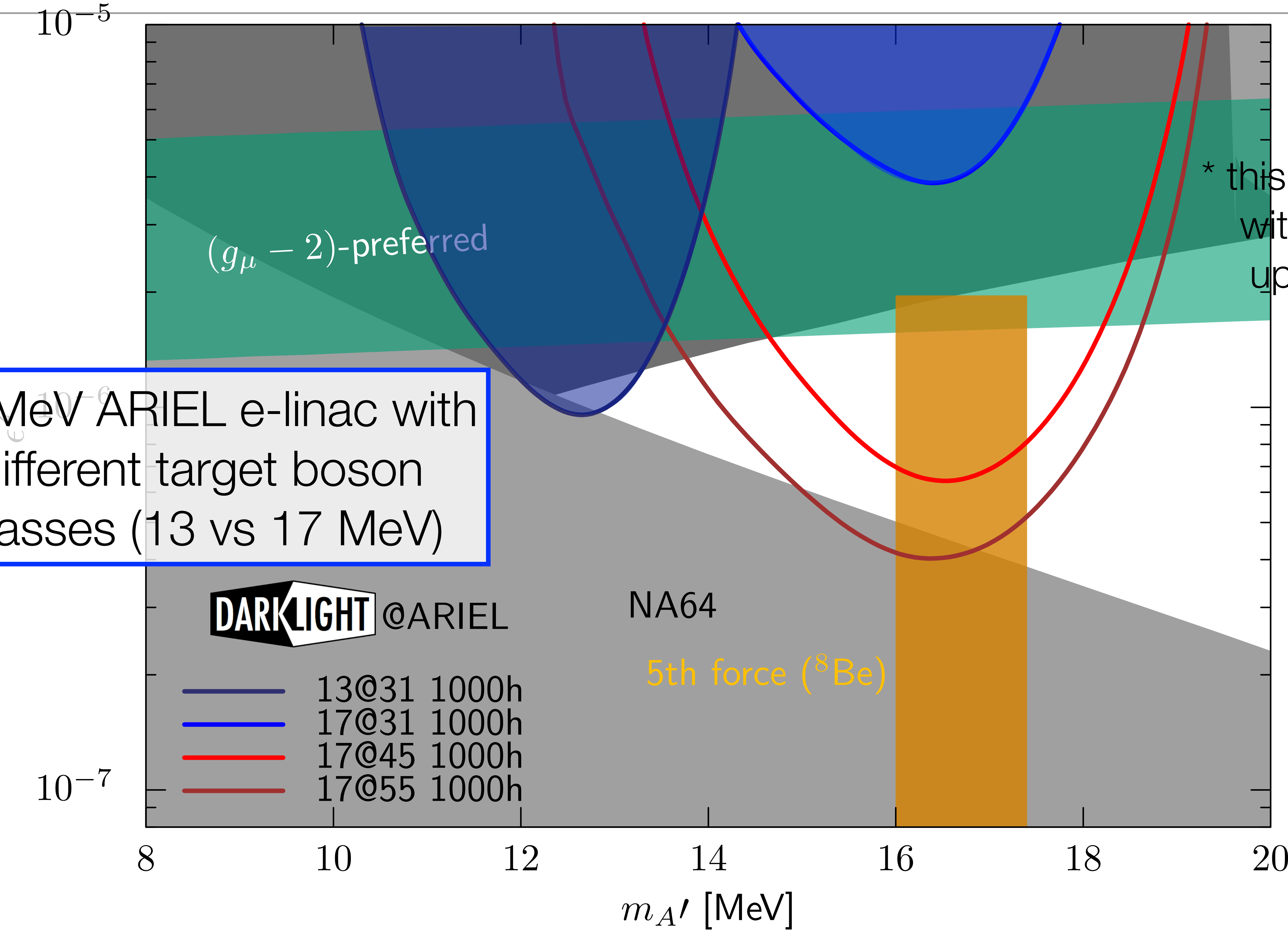


30 MeV ARIEL e-linac with different target boson masses (13 vs 17 MeV)

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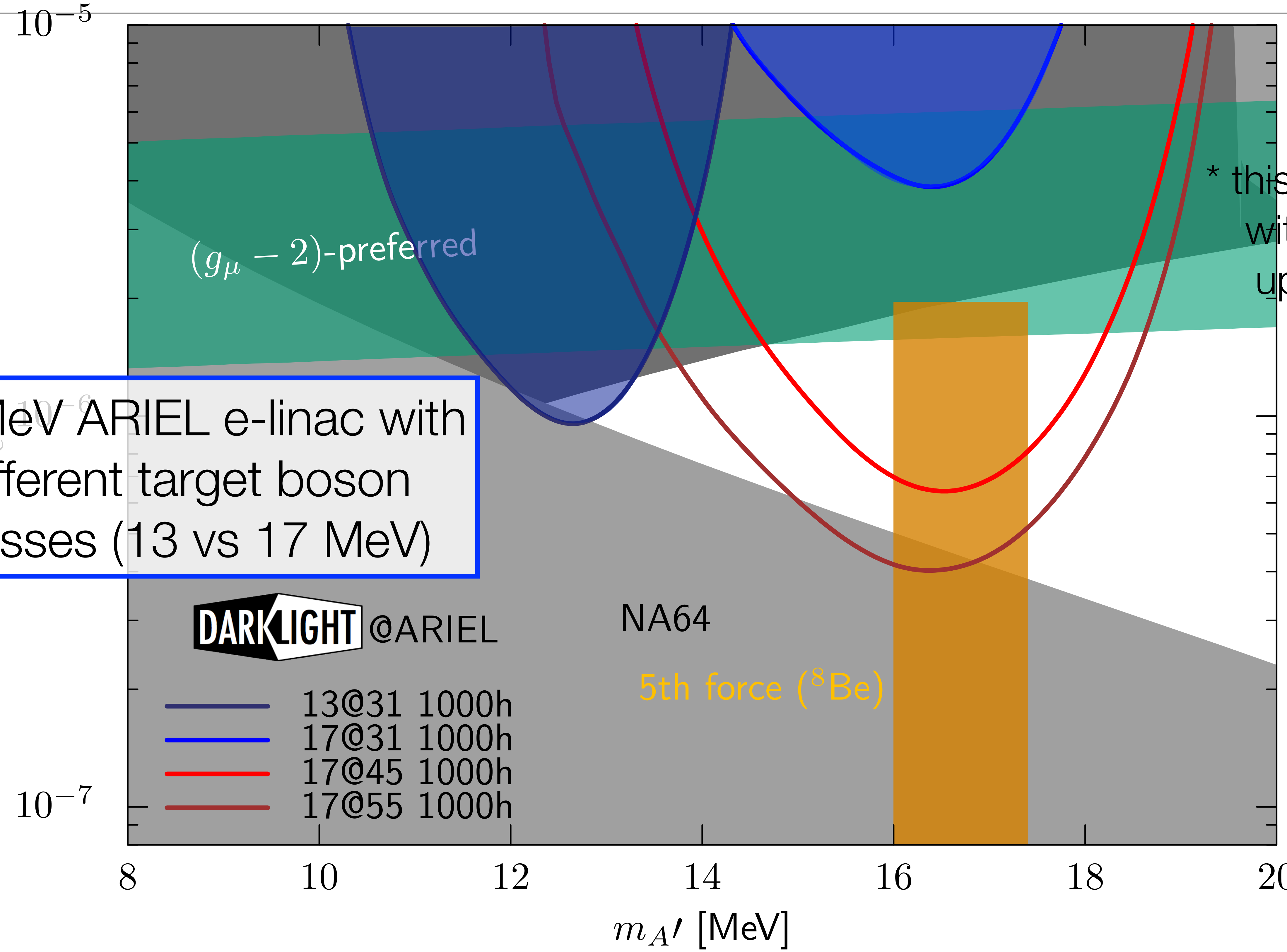
# Sensitivity at 30 and 50 MeV accelerators

Overlap with g-2 favoured region is only in already-excluded areas

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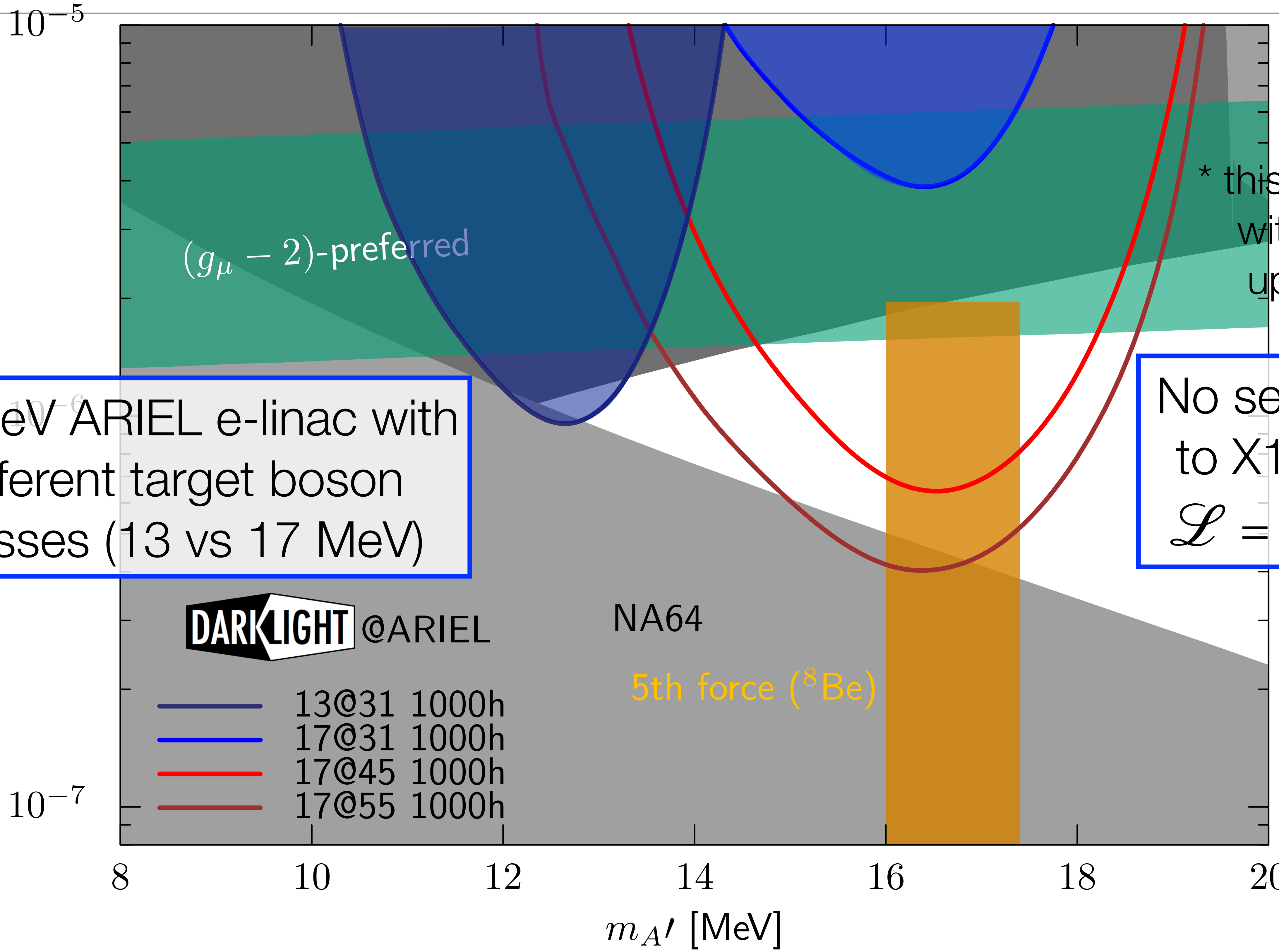


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No sensitivity to X17 with $\mathscr{L}$ = 18 fb$^{-1}$

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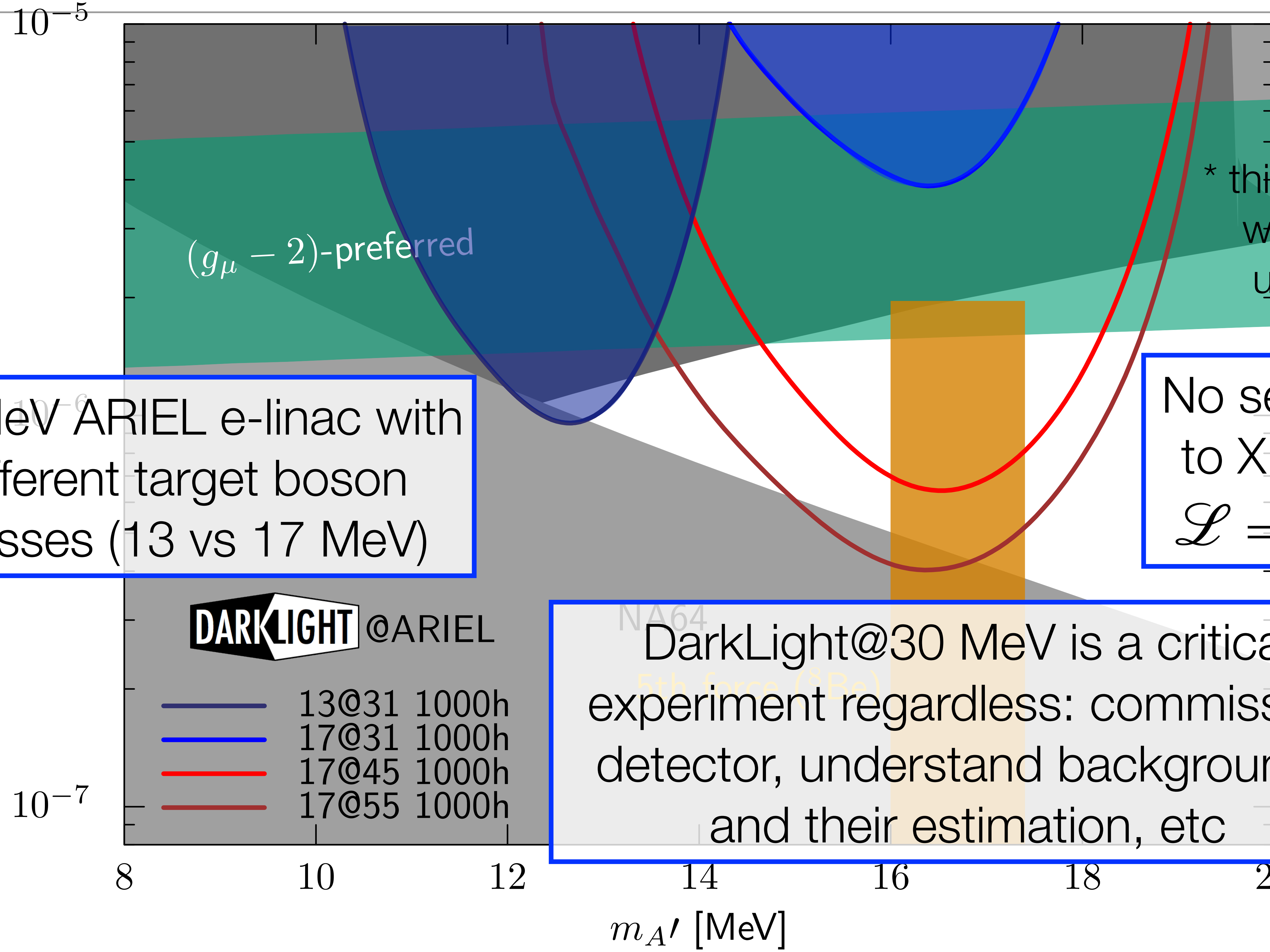


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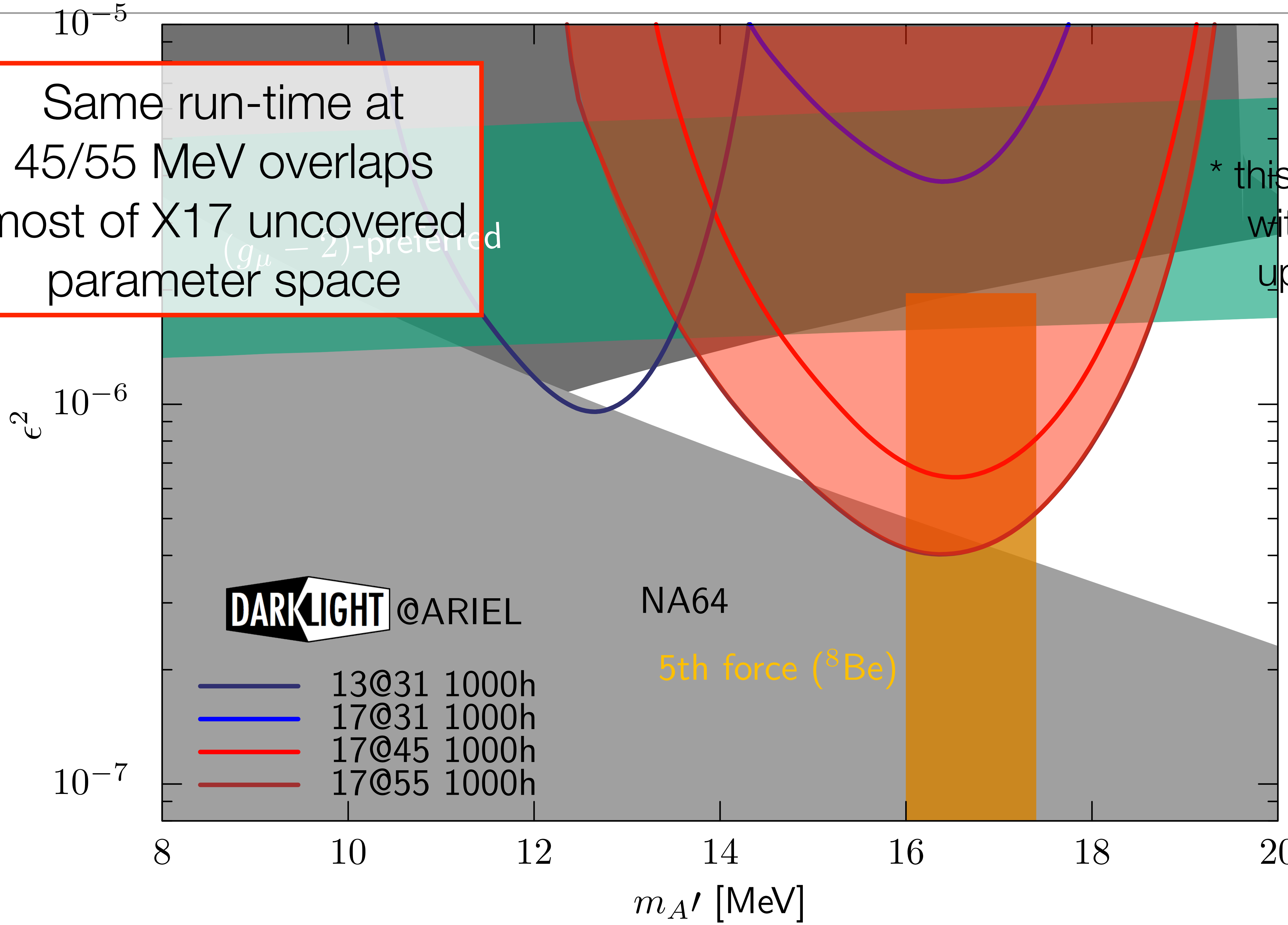
30 MeV ARIEL e-linac with different target boson masses (13 vs 17 MeV)

No sensitivity to X17 with $\mathscr{L}$ = 18 fb$^{-1}$

DarkLight@30 MeV is a critical experiment regardless: commission detector, understand backgrounds and their estimation, etc

# Sensitivity at 30 and 50 MeV accelerators

Same run-time at 45/55 MeV overlaps most of X17 uncovered parameter space

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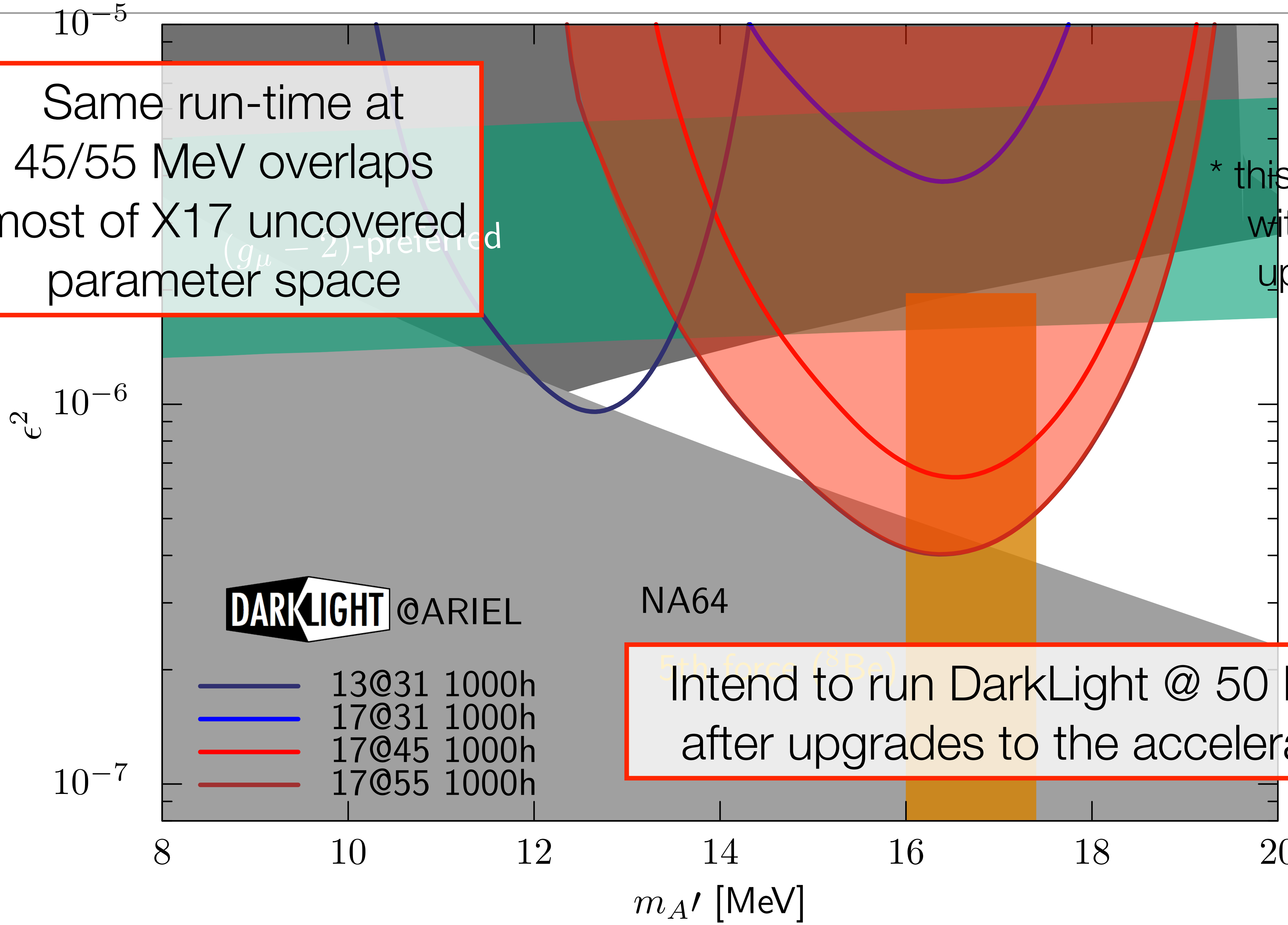


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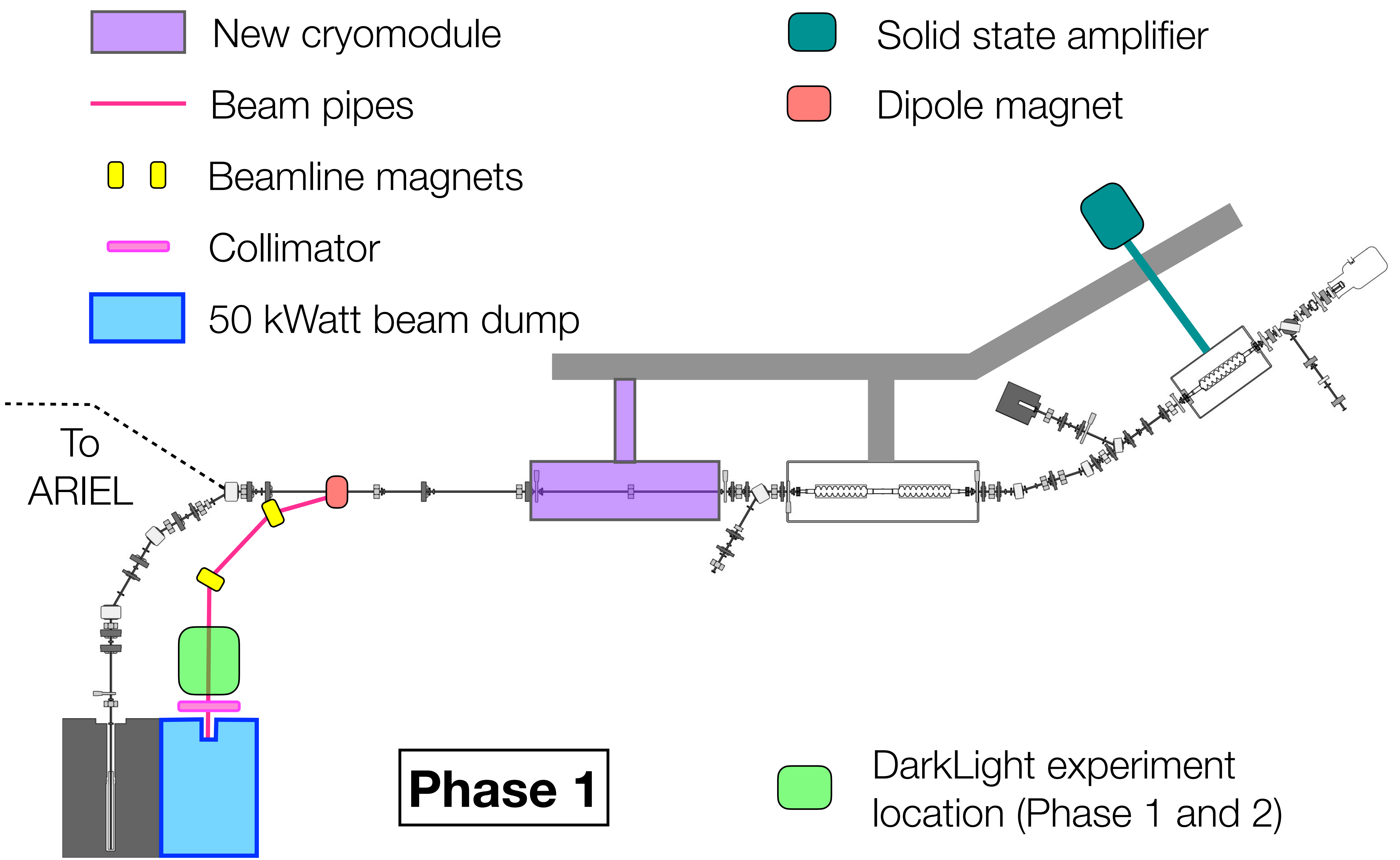
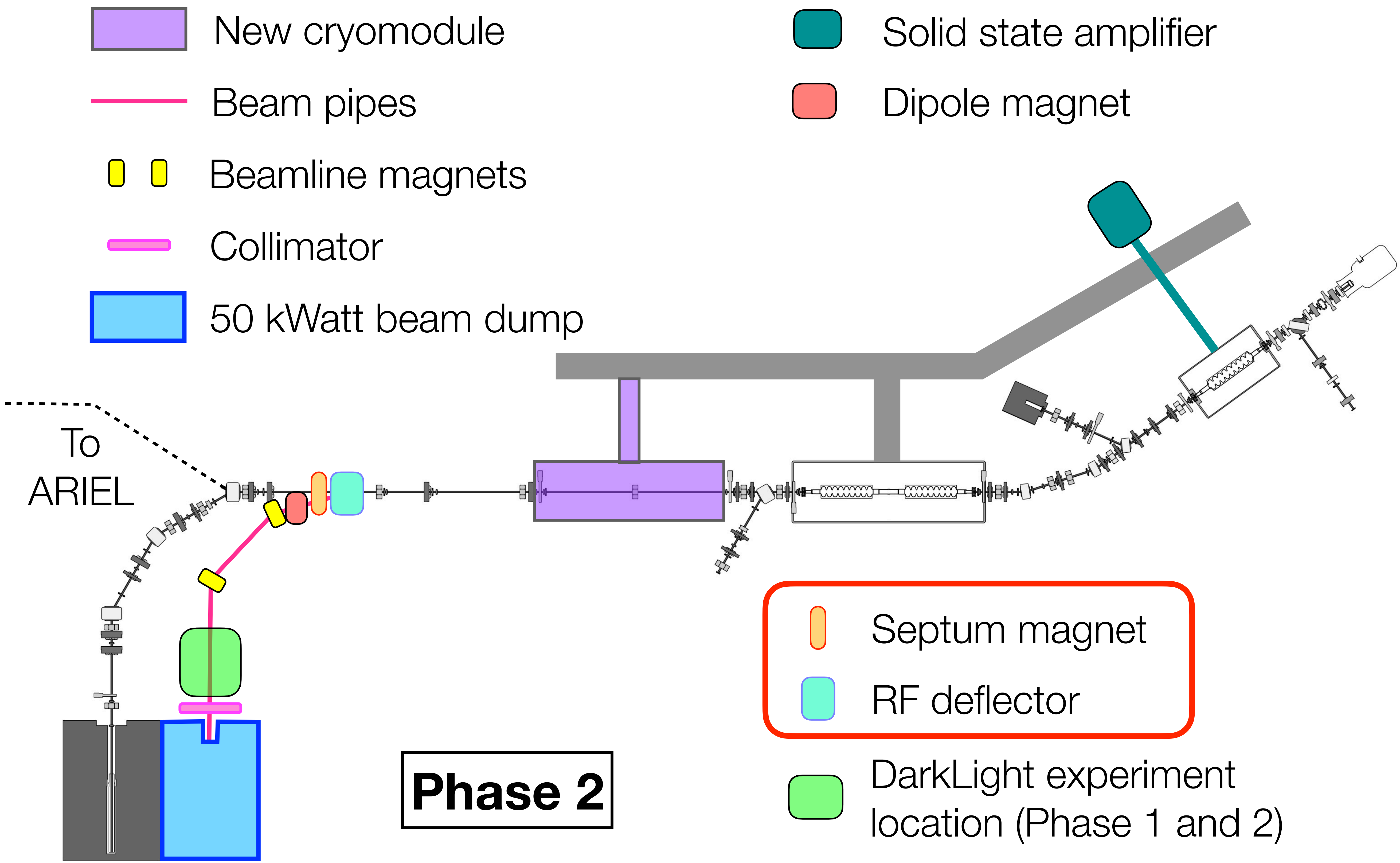
Intend to run DarkLight @ 50 MeV after upgrades to the accelerator


New cryomodule
Beam pipes
Beamline magnets
Collimator
50 kWatt beam dump
Solid state amplifier
Dipole magnet
To
ARIEL
Phase 1
DarkLight experiment
location (Phase 1 and 2)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Beamline magnets
Collimator
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Solid state amplifier
Dipole magnet
To
ARIEL
Septum magnet
RF deflector
DarkLight experiment
location (Phase 1 and 2)
Phase 2

# DarkLight timeline

- Spring 2021: beam time approved @ TRIUMF
- Dec 2021: test chamber installed in beamline
- May 2022: workshop at TRIUMF, first collaboration meeting
- August 2022: First beam on targets, background tests

Today

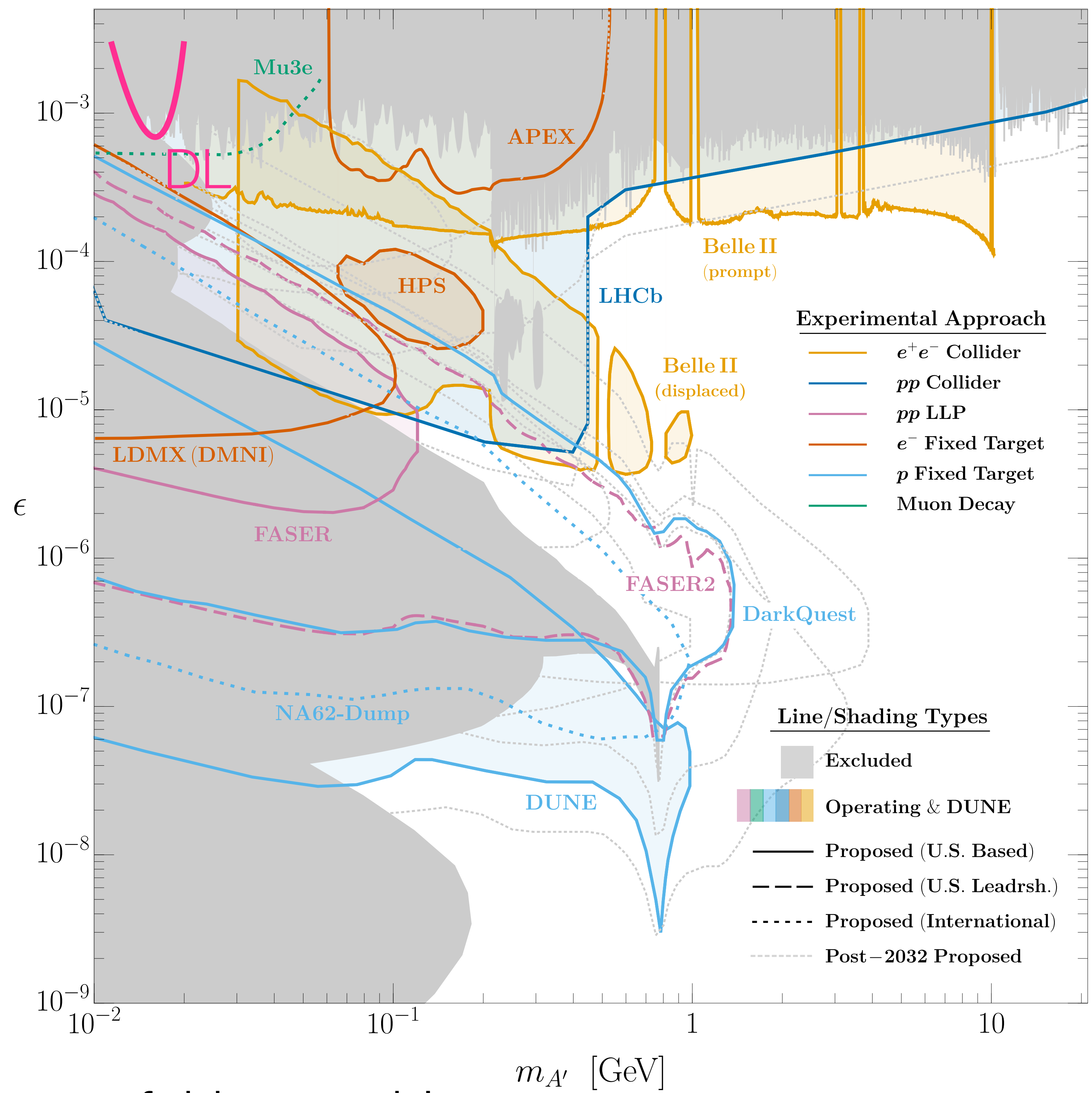
- Summer 2023: install experiment and begin background measurements
- Late 2023: Run full experiment @ 30 MEV
- 2024/2025: energy upgrade (TBC); first run @ 50 MeV
- 2025+: finish data taking, plan next experiments!

# The experimental landscape

This is an interesting and accessible region - lots of experiments planning to probe X17 in various different ways

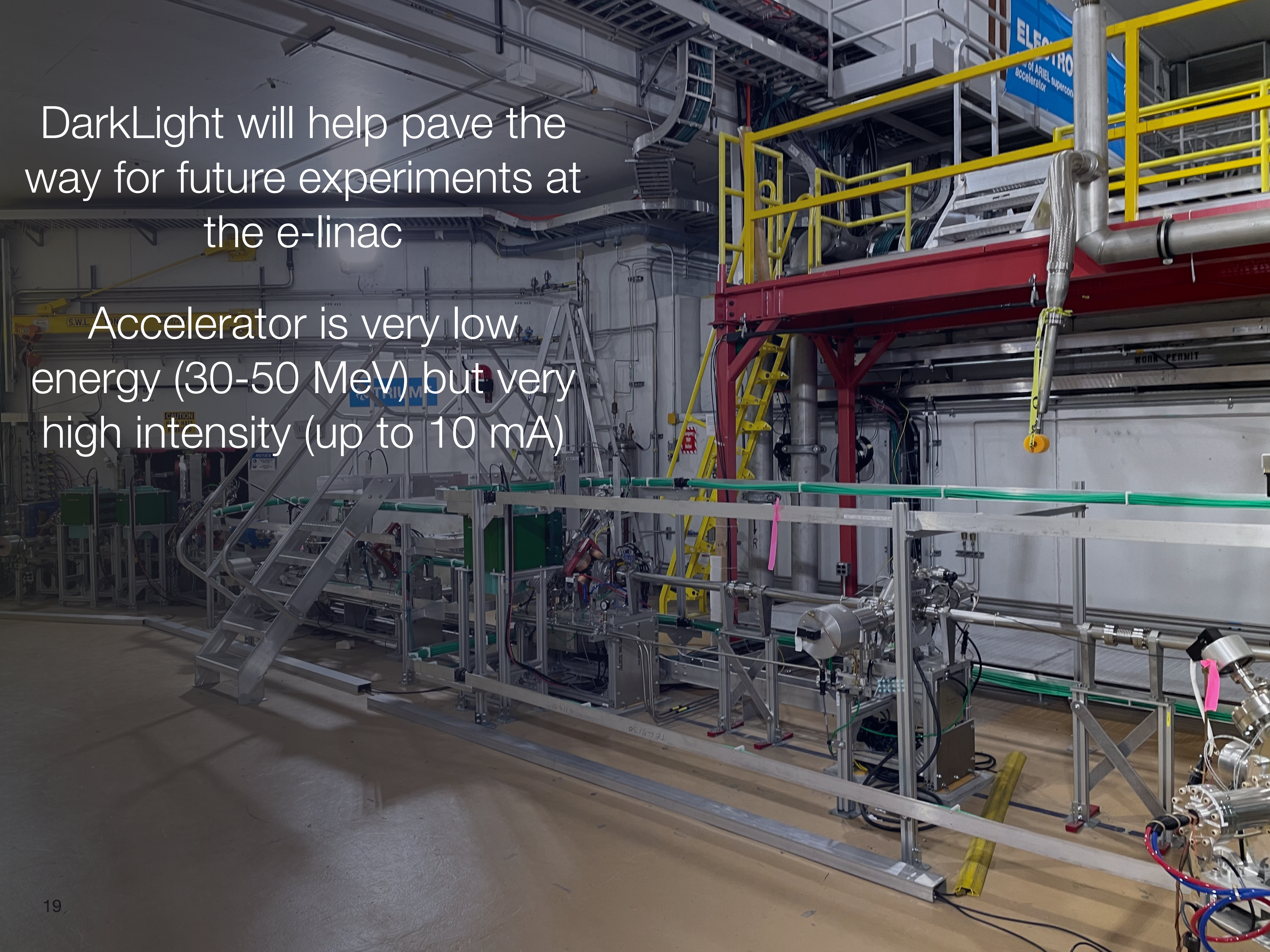
Some are reproducing ATOMKI experiment concept (Montreal, Notre Dame)

Others hope to access visible decays through meson decays (complementary to DL) or direct production (like DL)



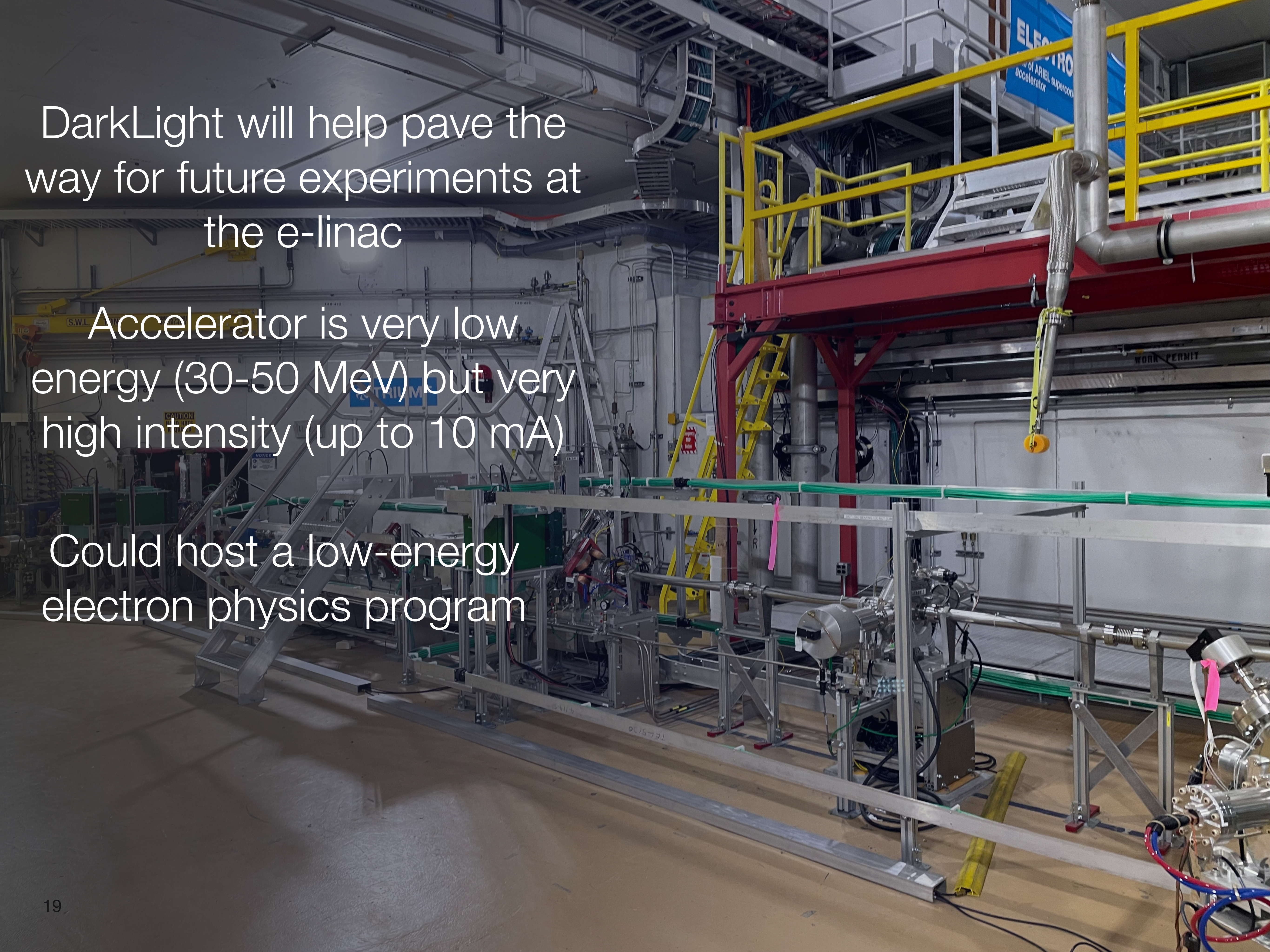

Exciting time to be part of this search!

DarkLight will help pave the way for future experiments at the e-linac



DarkLight will help pave the way for future experiments at the e-linac

Accelerator is very low energy (30-50 MeV) but very high intensity (up to 10 mA)



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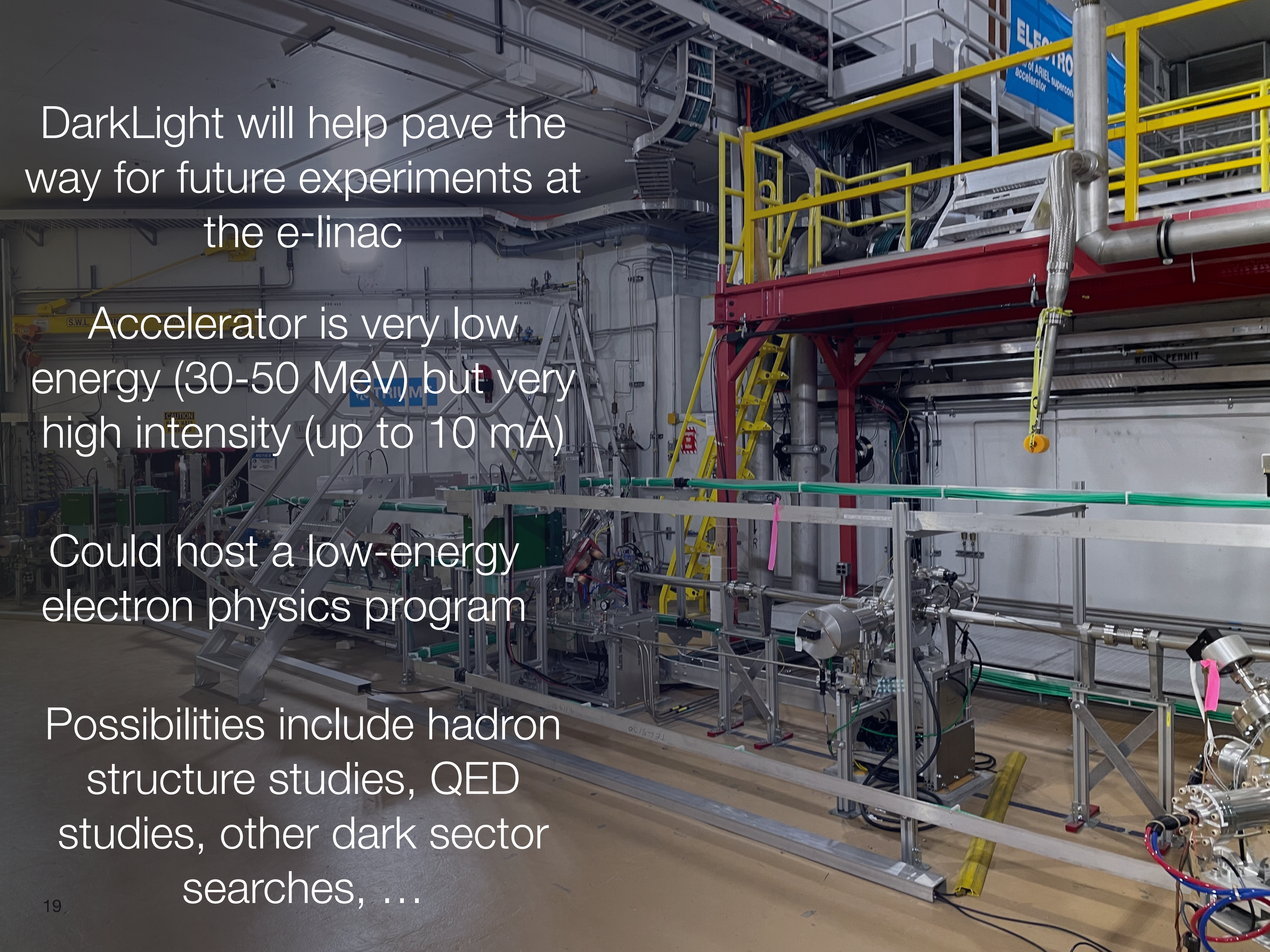
Accelerator is very low energy (30-50 MeV) but very high intensity (up to 10 mA)

Could host a low-energy electron physics program



DarkLight will help pave the way for future experiments at the e-linac

Accelerator is very low energy (30-50 MeV) but very high intensity (up to 10 mA)

Could host a low-energy electron physics program

Possibilities include hadron structure studies, QED studies, other dark sector searches, …

# Summary and conclusion

- DarkLight@ARIEL is a **new experiment** to be built **at TRIUMF** searching for low-mass e+e- resonances
    - **Compelling scientific motivation** and a strong international collaboration covering all relevant areas of expertise
- DarkLight will **add to continual progress** from many experiments searching for new bosons and dark matter at accelerators
- Exciting results to look forward to in the next years!

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- DarkLight@ARIEL is a **new experiment** to be built **at TRIUMF** searching for low-mass e+e- resonances
    - **Compelling scientific motivation** and a strong international collaboration covering all relevant areas of expertise
- DarkLight will **add to continual progress** from many experiments searching for new bosons and dark matter at accelerators
- Exciting results to look forward to in the next years!

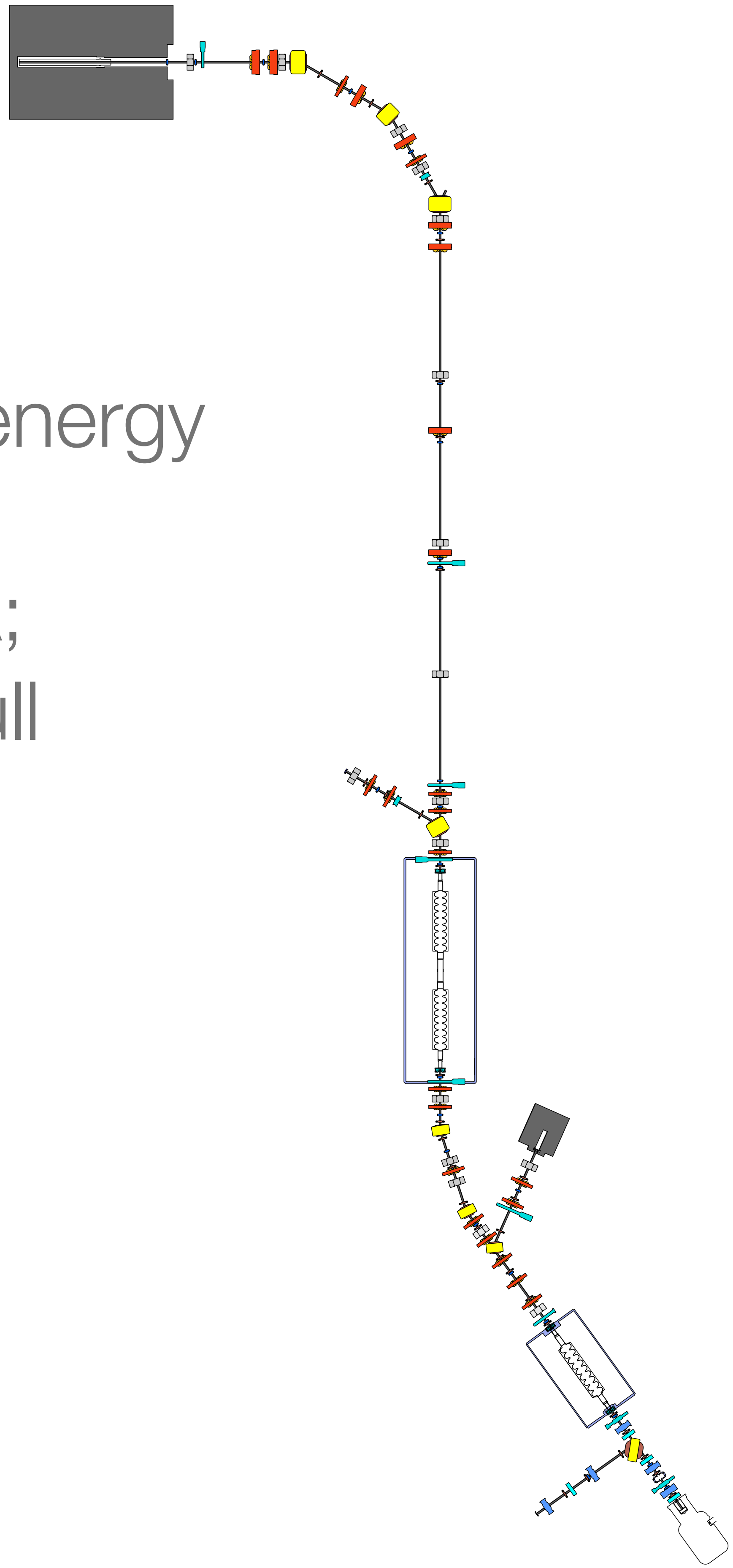
Currently looking for a postdoc - please get in touch if you are interested in working with us!

Thank you!

# Backup slides

# ARIEL e-linac facility

- 650 MHz frequency; currently 30 MeV energy
- Currents: Projections shown for 150 μA; considering designs that can support full design current of ~ a few mA
- Total design power ~ 100 kW
- Each bunch has ~ $9 \times 10^6$ electrons

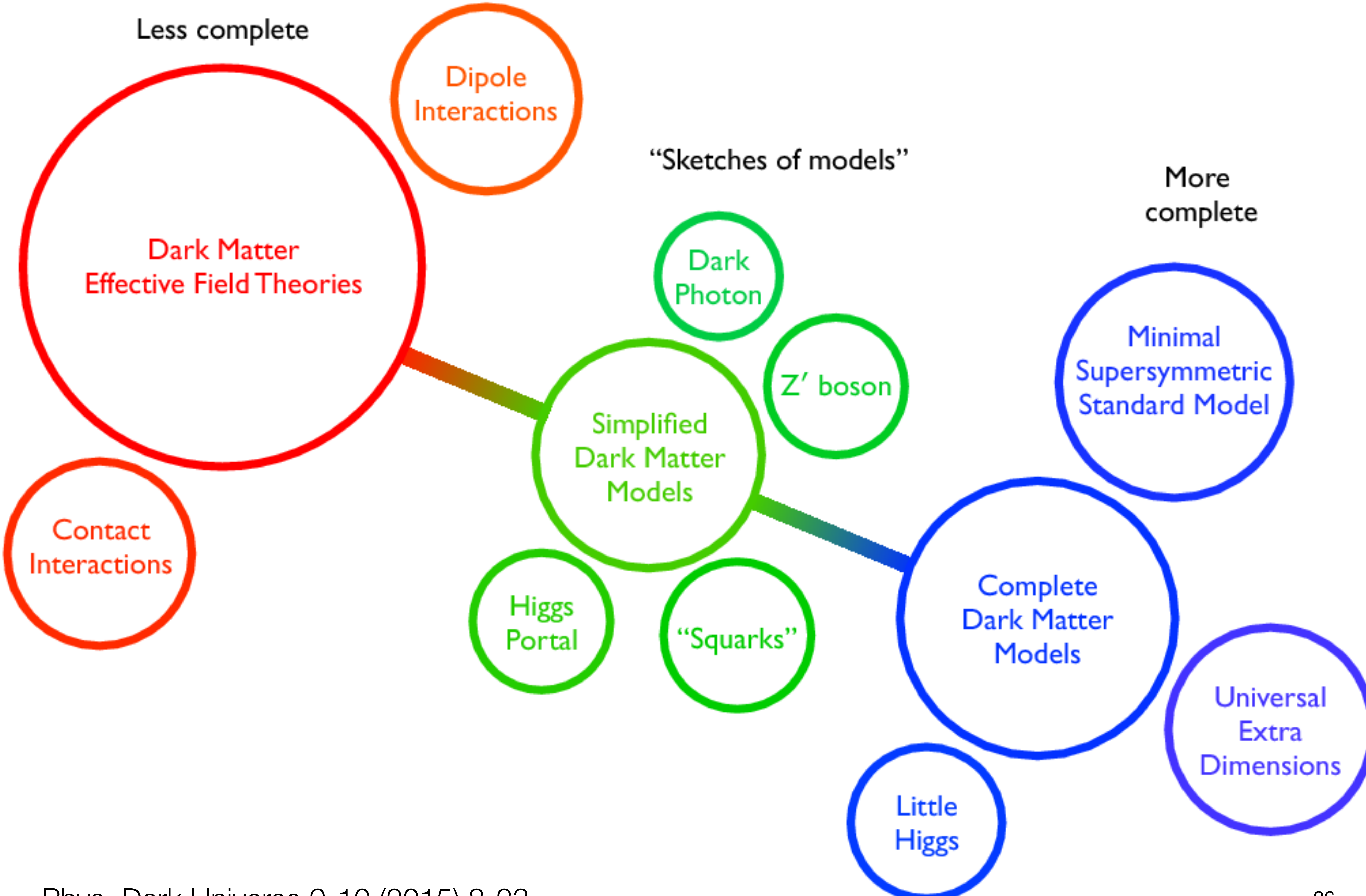


# Why ARIEL?

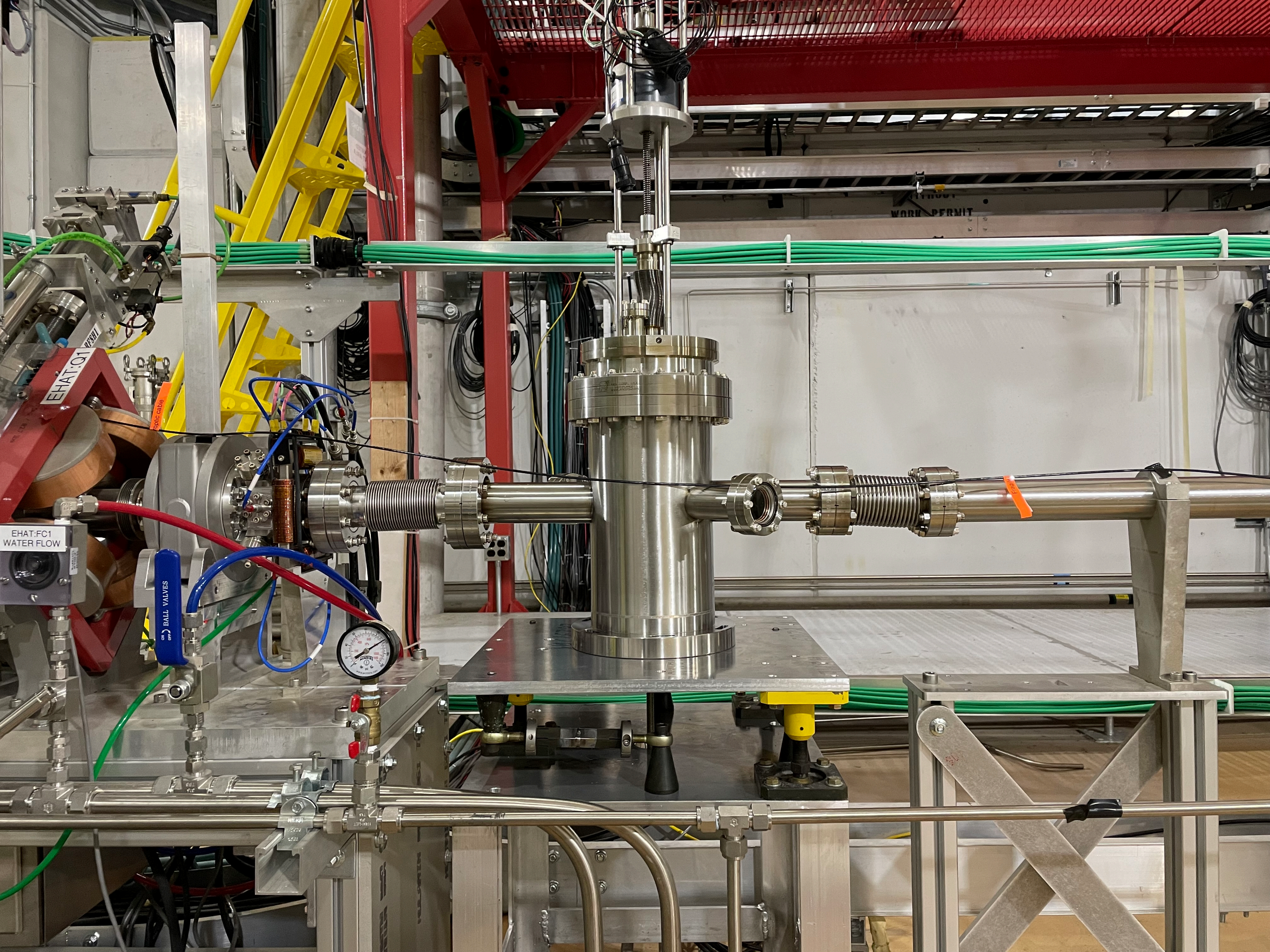
- Low energy, high intensity beam.
  - Energy not much above the production threshold is nice because it gives an opening angle that we can easily pick up with spectrometers
  - Peak intensity of 10 mA gives us plenty of instantaneous luminosity - don't need to run forever
- Finally, because the e-linac is available! No need to share beam time with any other targets until ~phase 2, at which point parasitic running will be an option

# Are we sensitive to anything else?

- Given the e+e- selection, we are sensitive only to resonances at masses relatively close to the selected target mass
- In general, lots of new physics models give resonances with this type of decay. E.g. doesn't have to be spin 1 like the target model discussed. But sensitivity != motivation: a more complete question would be "what might isn't yet excluded in this mass range that results in a dilepton final state." And I am not sure!
- What we do know: if we see something, there will be lots more study from a more complex detector required to determine what it actually is

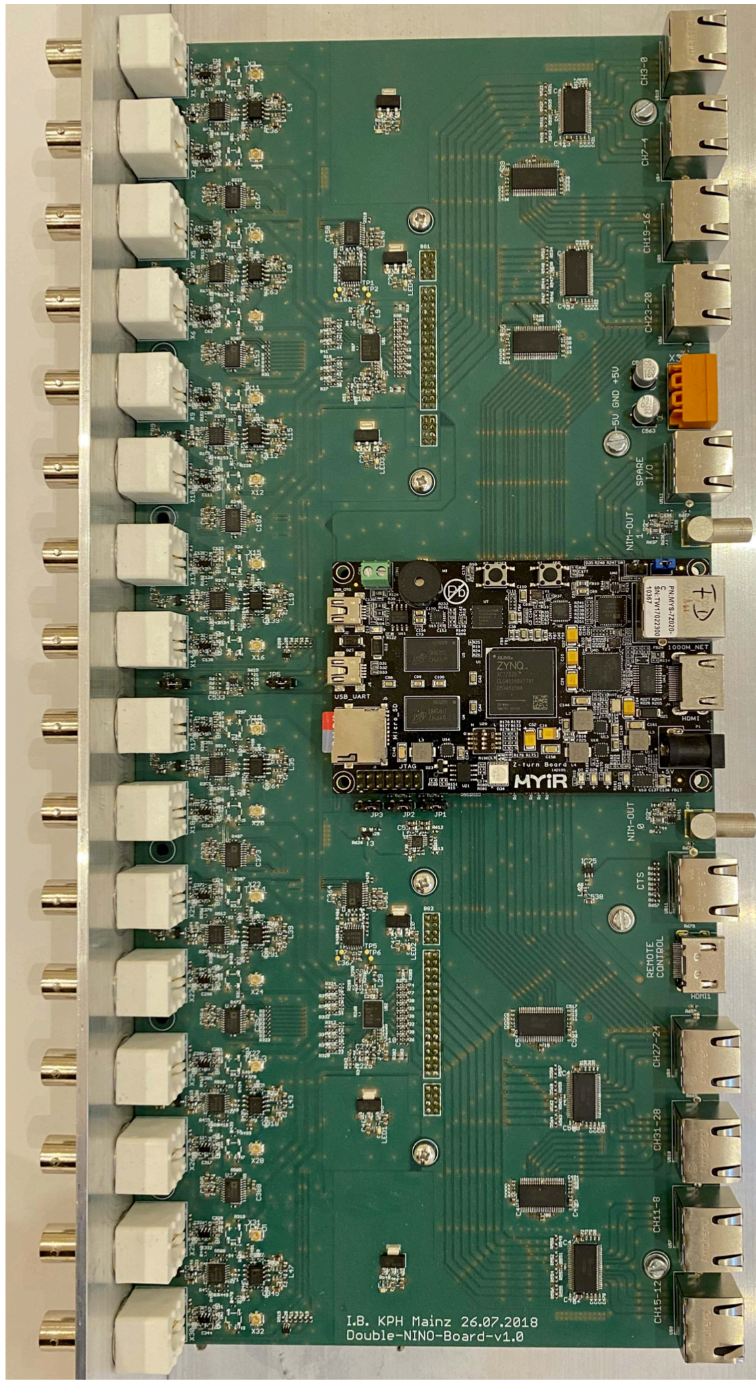



Phys. Dark Universe 9-10 (2015) 8-23


EHAT:Q1
EHAT:FC1
WATER FLOW
BALL VALVES

# Experiment status: read-out and DAQ

- GEM read-out electronics already in place: timing ~ 200 μs
- Trigger uses coincidence of scintillator outputs
  - Discrimination step, then FPGA will determine coincidence between individual scintillator strip pairs
- Investigated various existing systems
  - Likely to begin design from one of DarkSide or alpha-g DAQ boards also designed and manufactured at TRIUMF
  - Also investigating MAGIX experiment board




MAGIX board with 32 inputs & FPGA
H. Merkel

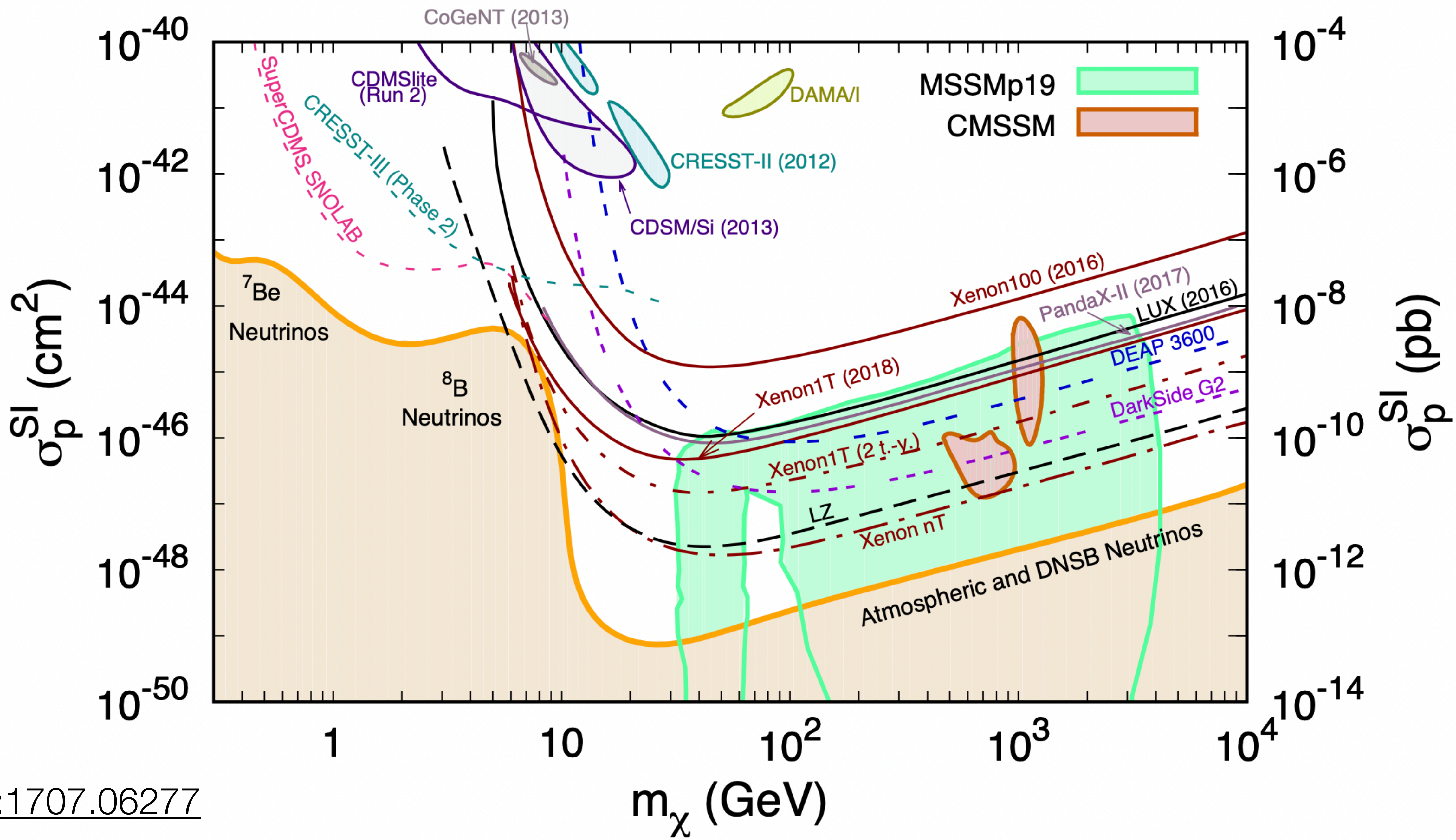
# Complementary experiments

- Type 1: ATOMKI-like; intending to reproduce and validate experiment
- Montreal, Notre Dame among groups working on this
- No conflict with collider/accelerator goals
- Type 2: mixed hadronic-leptonic
- Leading experiment LHCb: will cover all X17 space (even with protophobic assumptions) with full Run 3 data
- Complementary to DarkLight, which can probe electron coupling independently of hadronic couplings

- Type 3: pure leptonic production
- Lots of experiments covering invisible decay: LDMX, Na64, …
- A few experiments with similar visible final state sensitivity.
    - Na64 currently setting lower boundary. Future (2023+) runs with modified setup can probe higher ε
    - MAGIX very powerful here but on longer timeline (2025+)

# Aren't WIMPs basically excluded by direct detection?

- Reminder about WIMP models: make up relic density with a single particle, order GeV to TeV mass, couplings are order of weak scale.

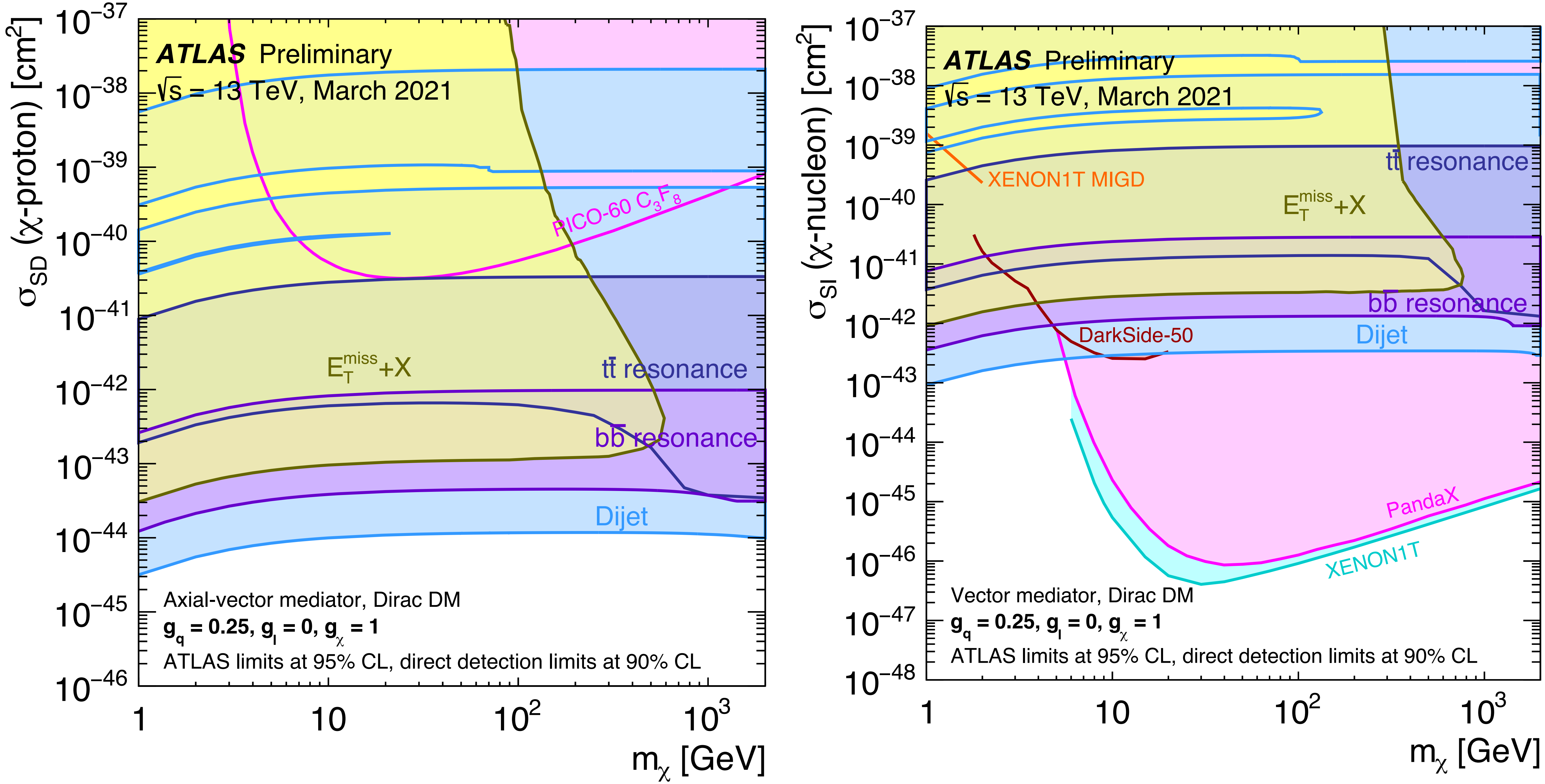



arXiv:1707.06277

# What does this plot tell us?

- Interpreted in a contact interaction (EFT) framework: applicable for these experiments but need to convert from other models to make a 1-to-1 equivalence
  - Different models have very different interactions (e.g. spin-dependent versus spin-independent)
- Freeze-in and other wimp paradigms can give very different probable coupling ranges
- Note that the neutrino floor is not a forbidden region, it's a hard to search region.

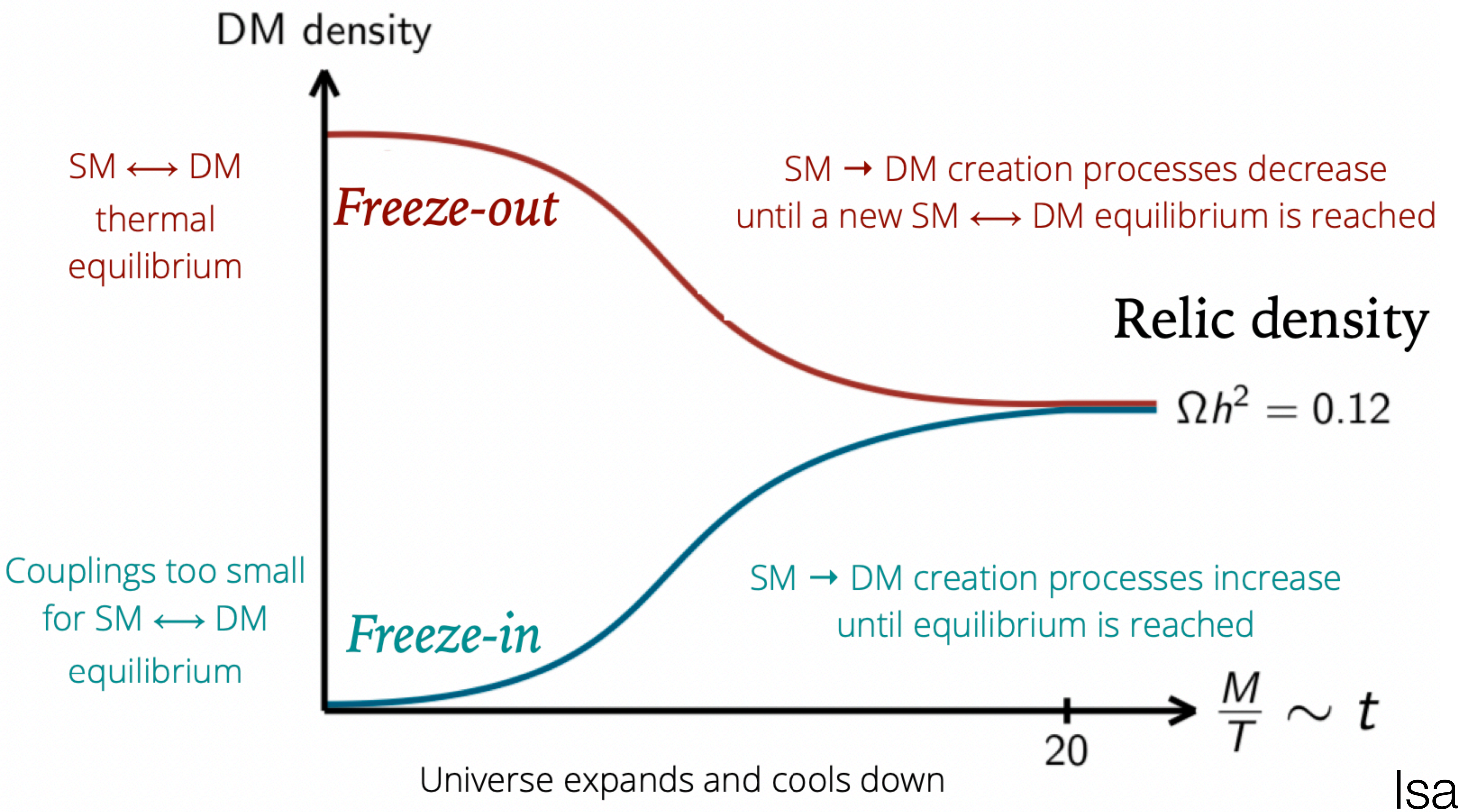
# Example…



ATLAS Preliminary
√s = 13 TeV, March 2021
σSD (χ-proton) [cm²]
PICO-60 C3F8
E_T^miss+X
tt̄ resonance
bb̄ resonance
Dijet
Axial-vector mediator, Dirac DM
gq = 0.25, gl = 0, gχ = 1
ATLAS limits at 95% CL, direct detection limits at 90% CL
mχ [GeV]
ATLAS Preliminary
√s = 13 TeV, March 2021
σSI (χ-nucleon) [cm²]
XENON1T MIGD
E_T^miss+X
tt̄ resonance
bb̄ resonance
DarkSide-50
Dijet
PandaX
XENON1T
Vector mediator, Dirac DM
gq = 0.25, gl = 0, gχ = 1
ATLAS limits at 95% CL, direct detection limits at 90% CL
mχ [GeV]

# Freeze-in and freeze-out

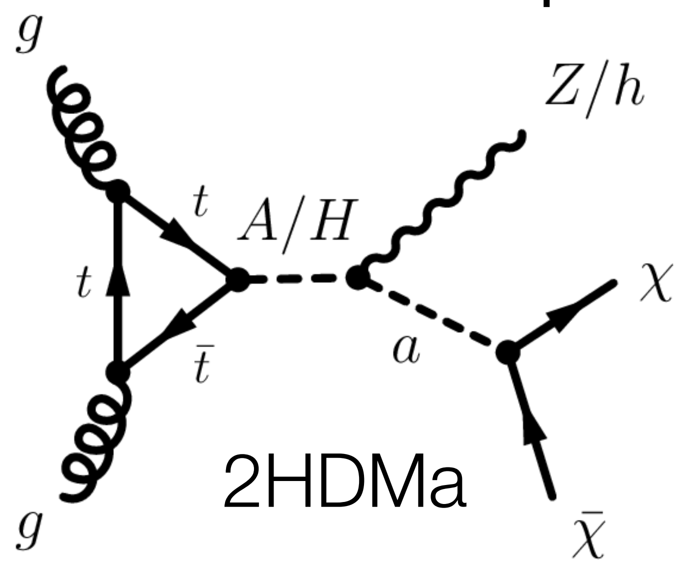
Usually think about freeze-in with WIMPs, but freeze-out and other interactions can give you exact same relic density with very different (smaller) couplings



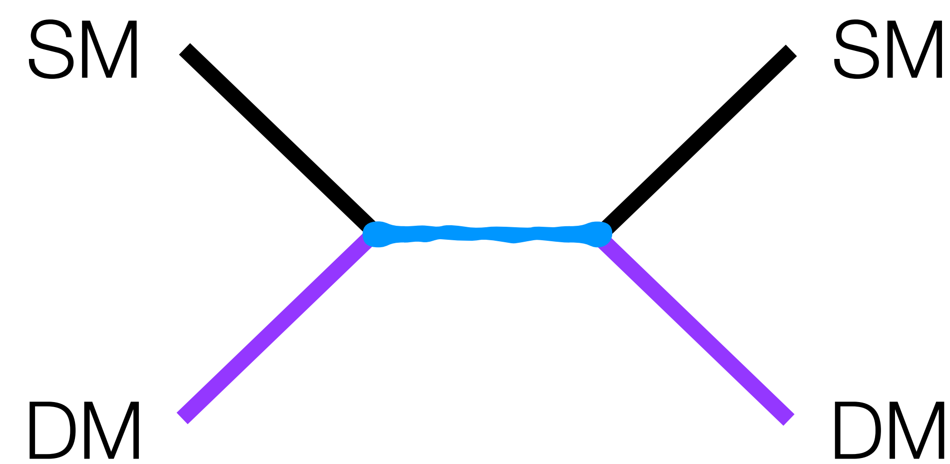

Isabelle John

# Variation in particle dark matter models

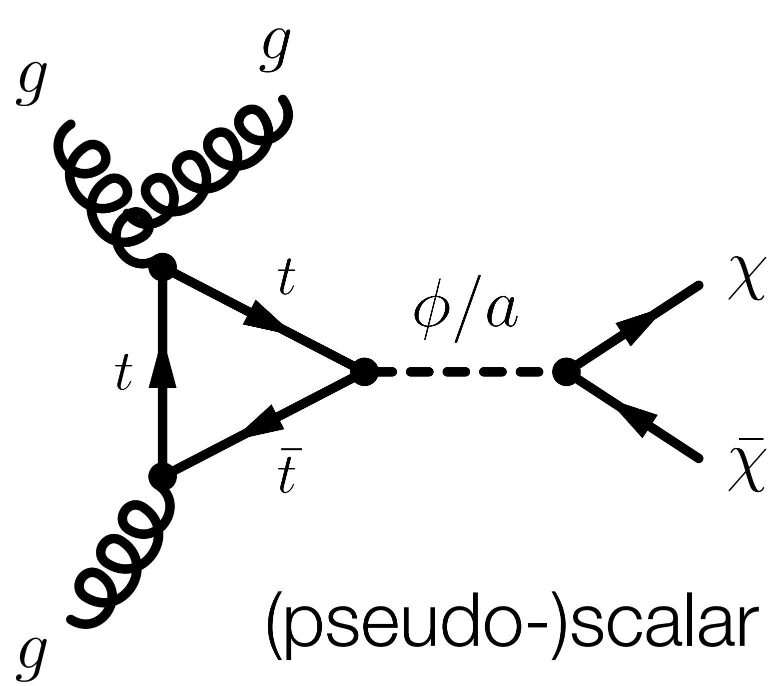
## More dark sector particles



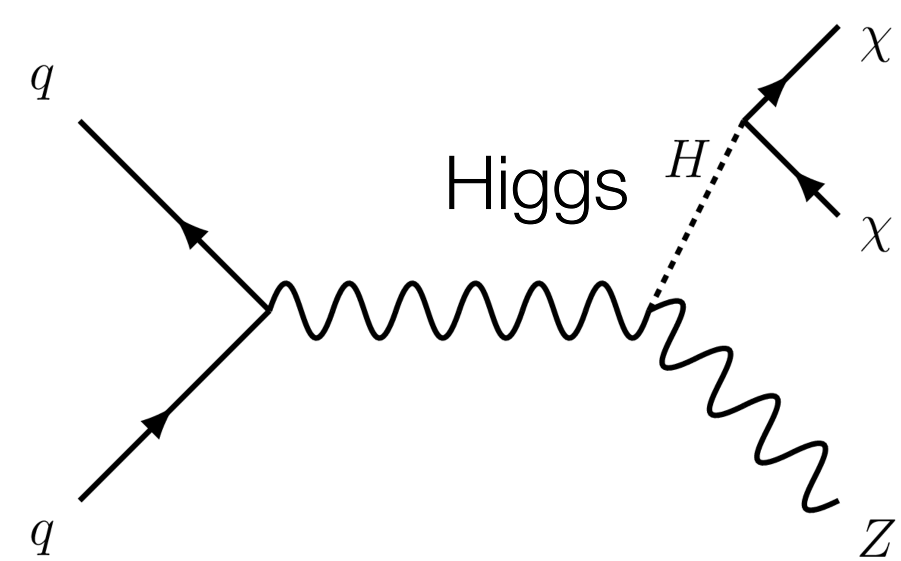

## Not s-channel couplings




## Not a vector mediator

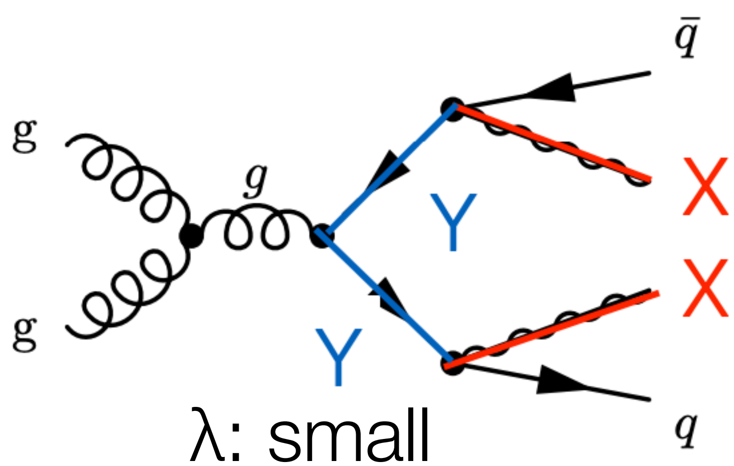



## No BSM mediator



# Variation in particle dark matter models

Not prompt




λ: small coupling

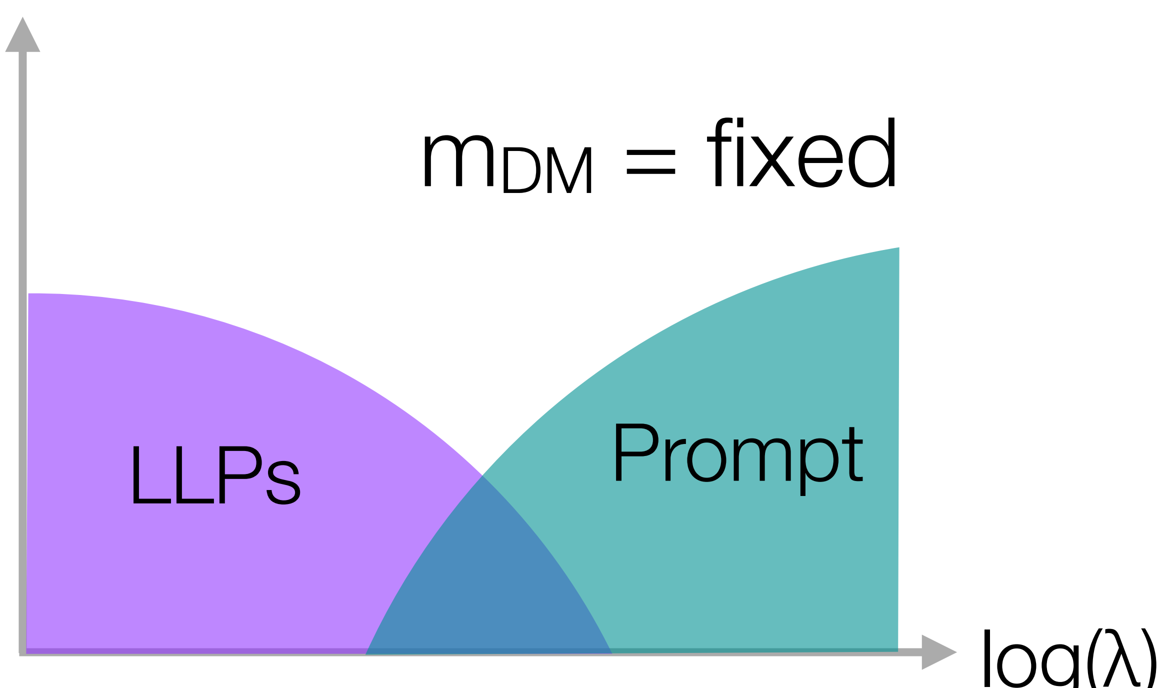



Diagram from C. Arina

Not a WIMP

Axions, asymmetric dark matter, sterile neutrinos, non-WIMP SUSY candidates

(Not a particle)