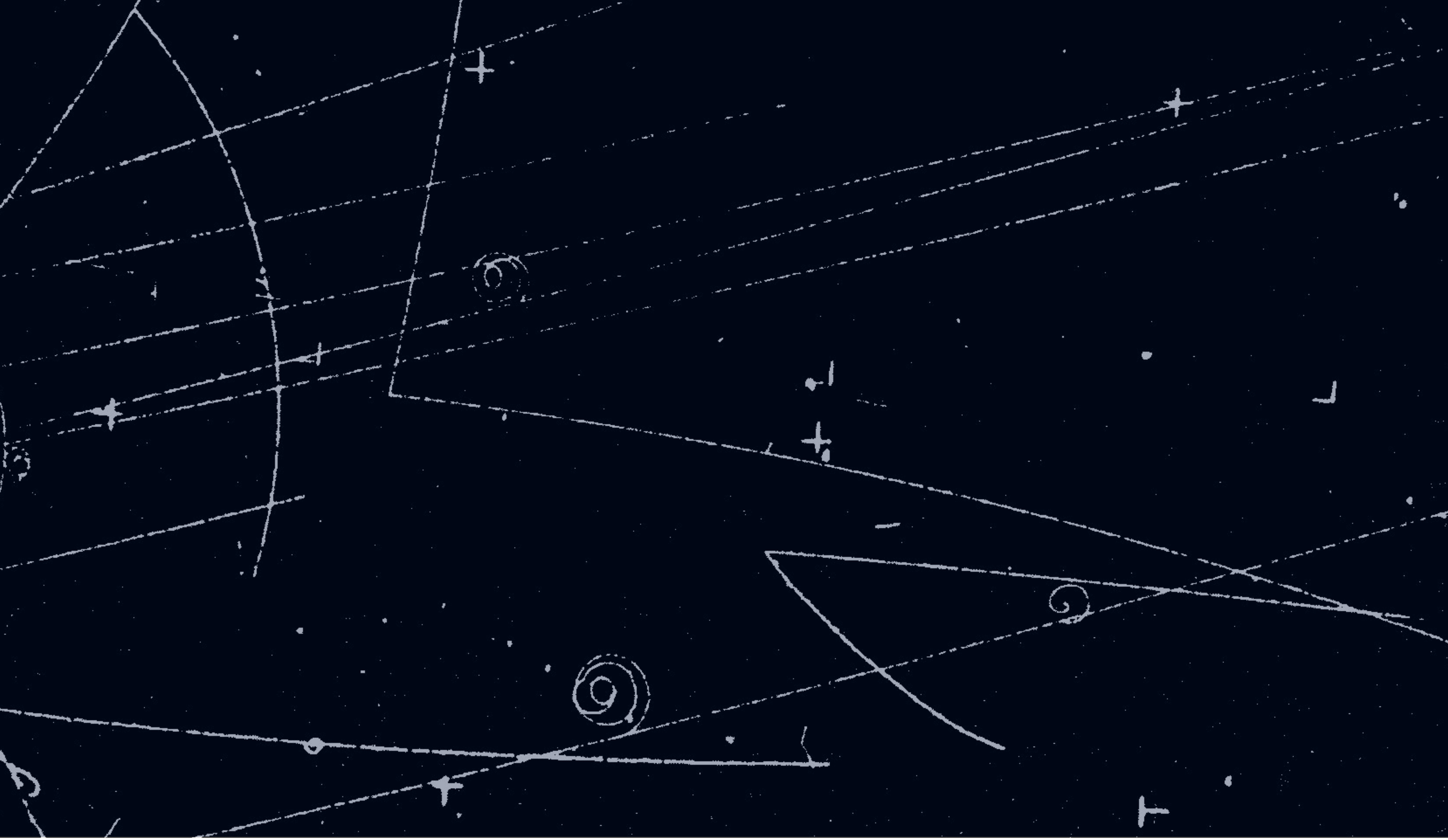
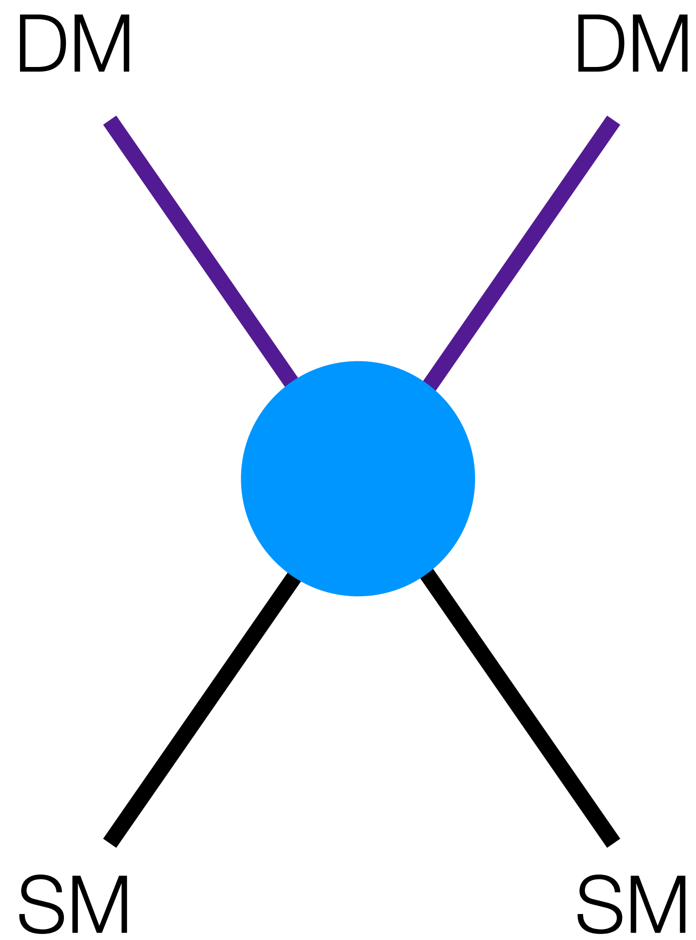


Hunting for new particles at TRIUMF with the DarkLight@ARIEL experiment

Kate Pachal
TRIUMF

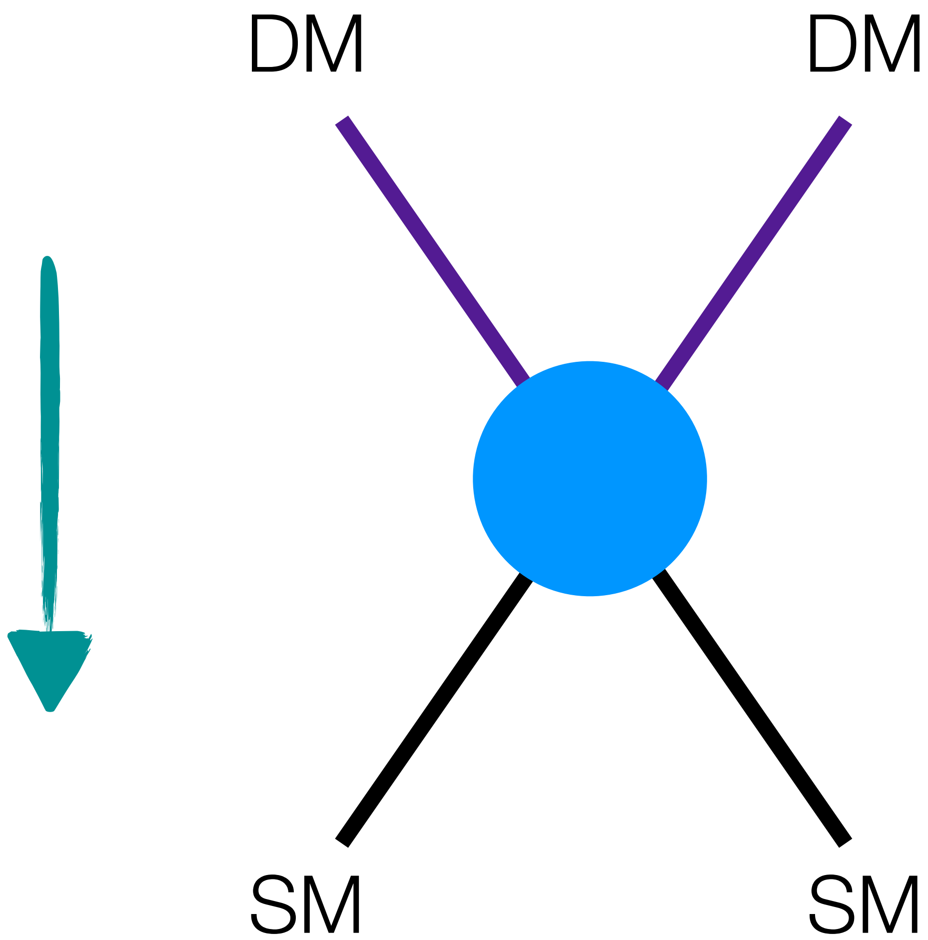
Looking for dark matter with experiments



Looking for dark matter with experiments

Indirect detection

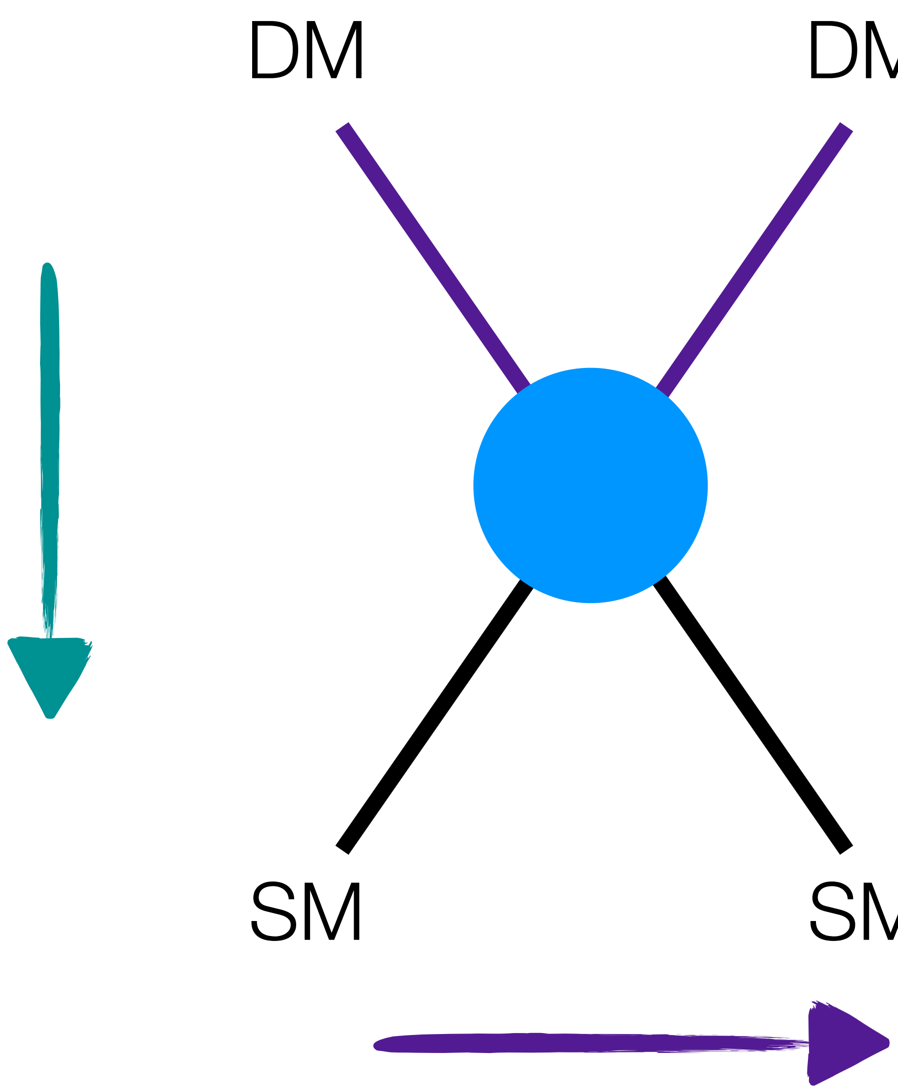
IceCube, Super-K, …



Looking for dark matter with experiments

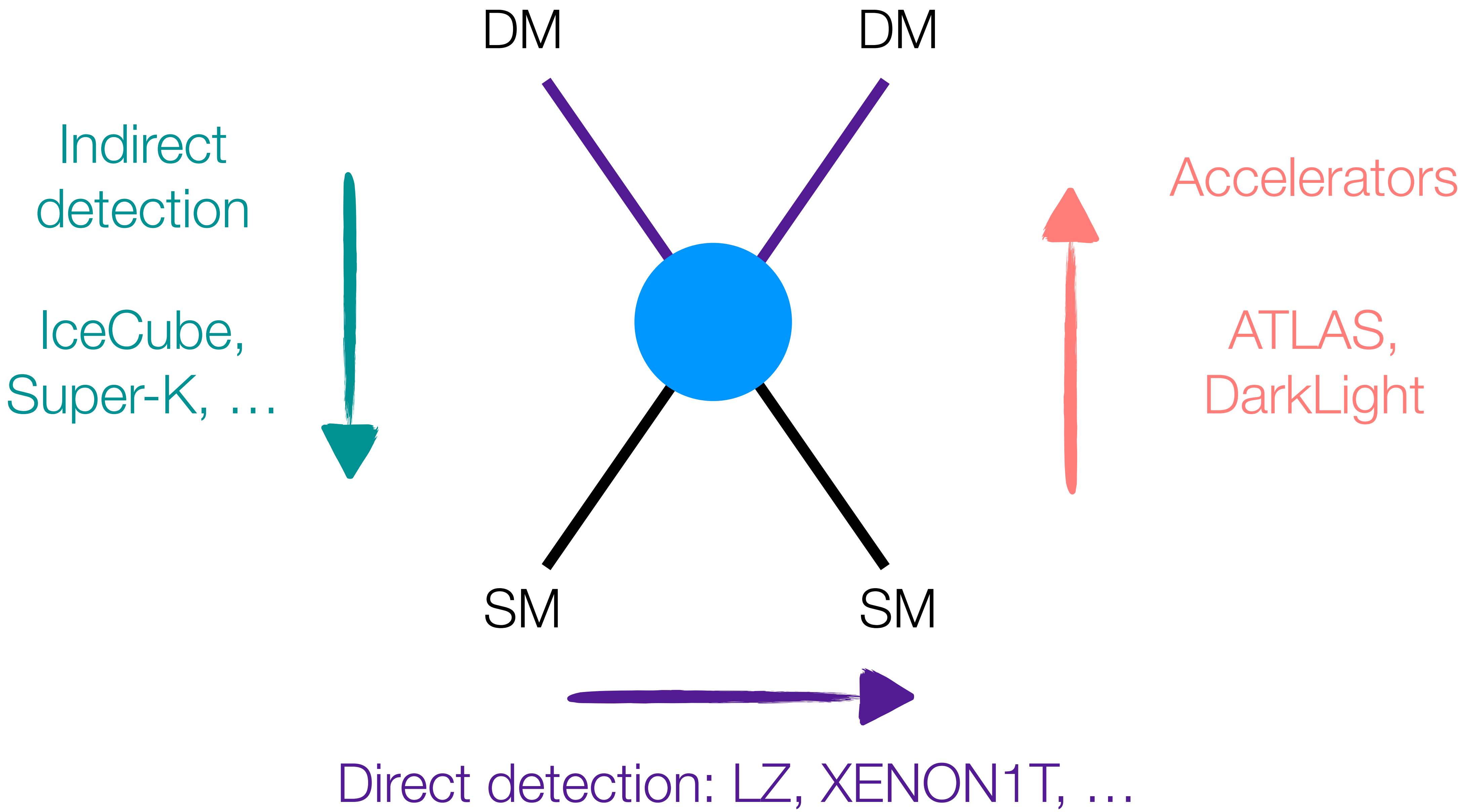
Indirect detection

IceCube, Super-K, …

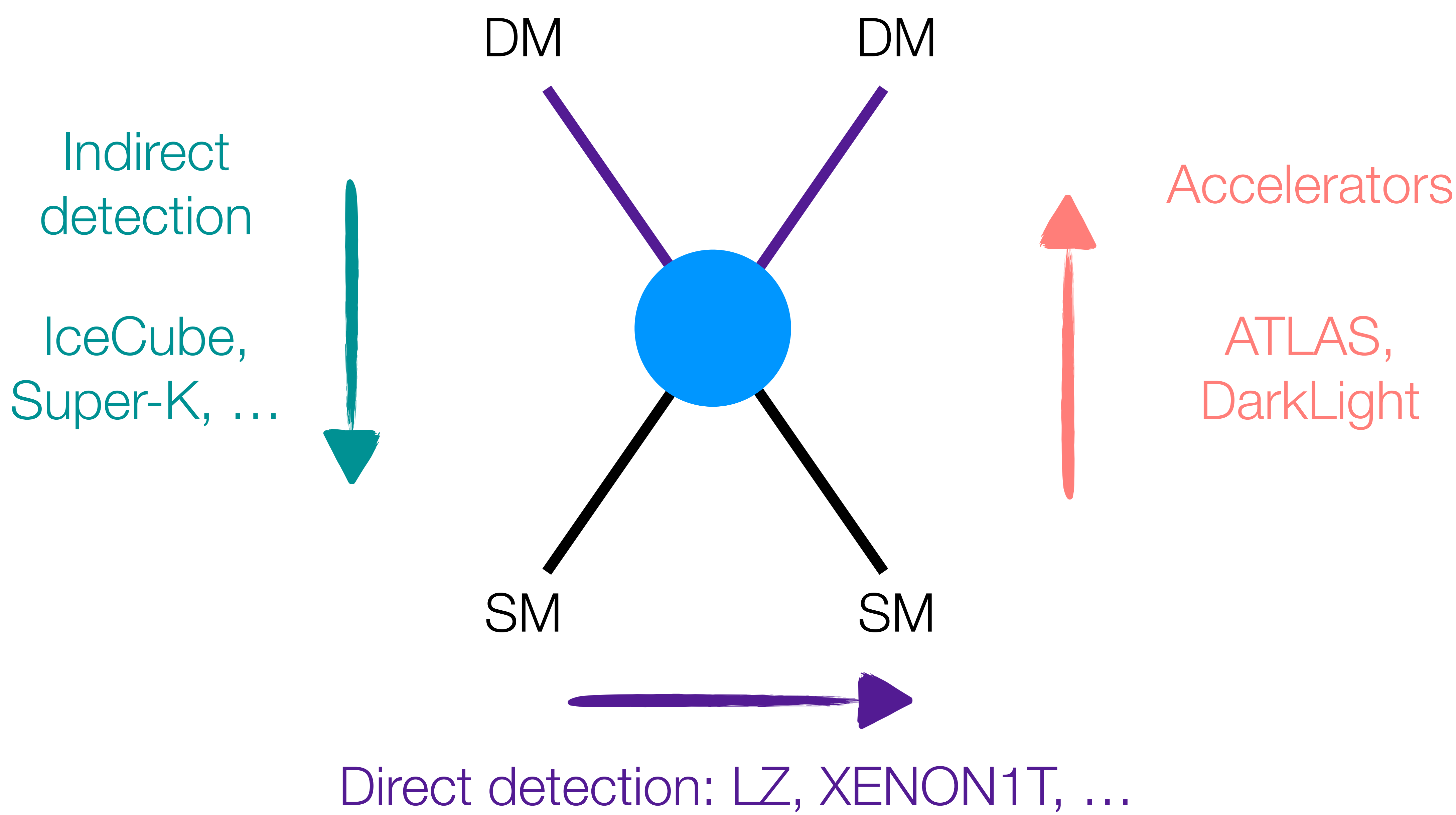


Direct detection: LZ, XENON1T, …

Looking for dark matter with experiments

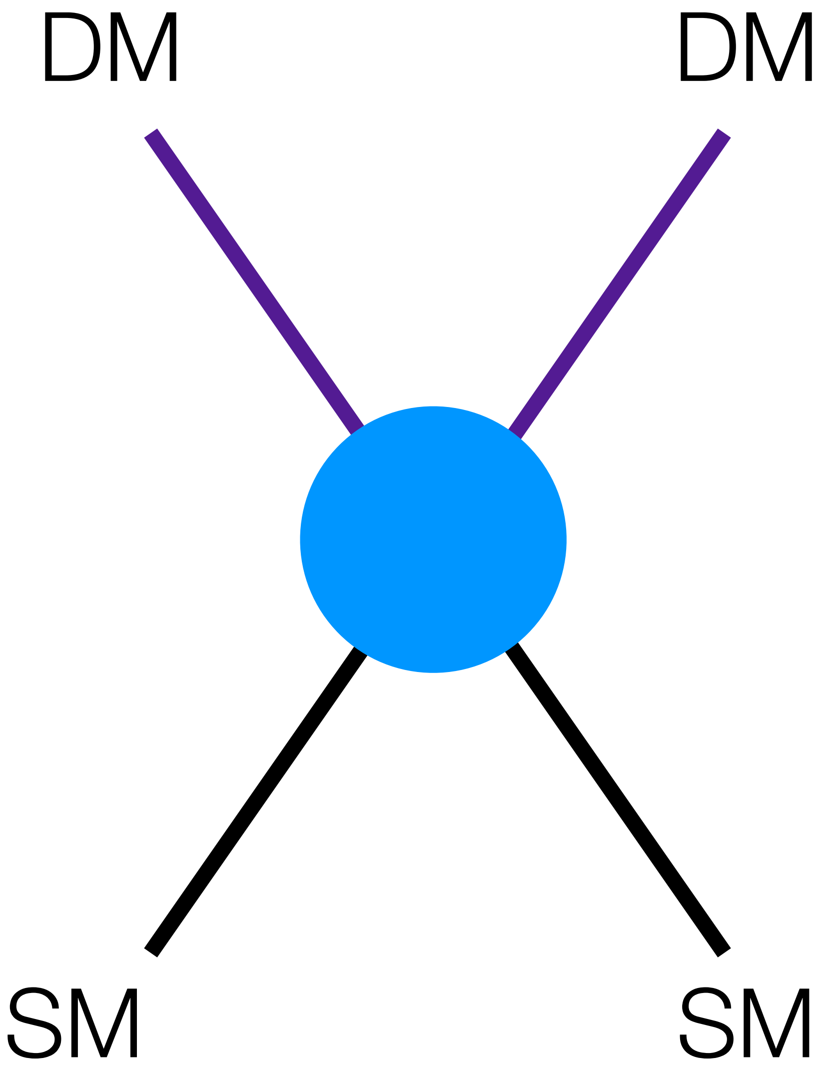


Looking for dark matter with experiments



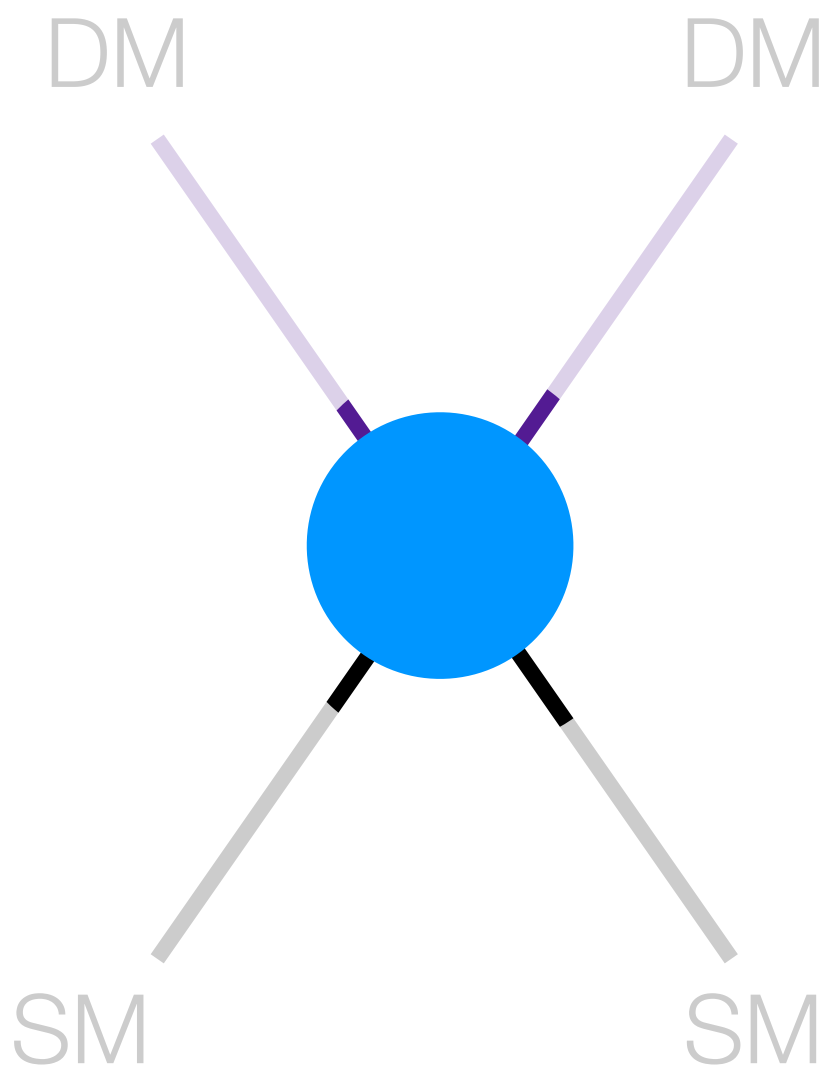
If there is some interaction with the Standard Model, and the energy scale isn't too high, → then we could we make it in the lab

Building a simplified model



Building a simplified model

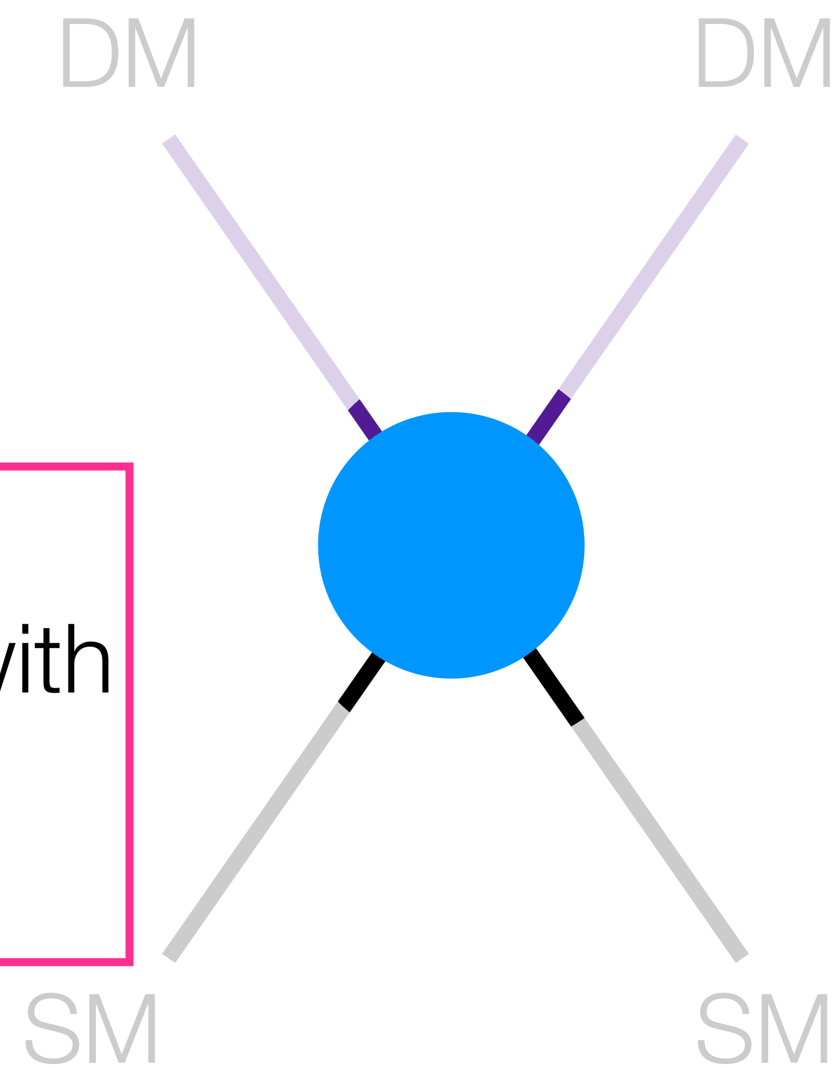
How should we interpret this?



Building a simplified model

How should we interpret this?

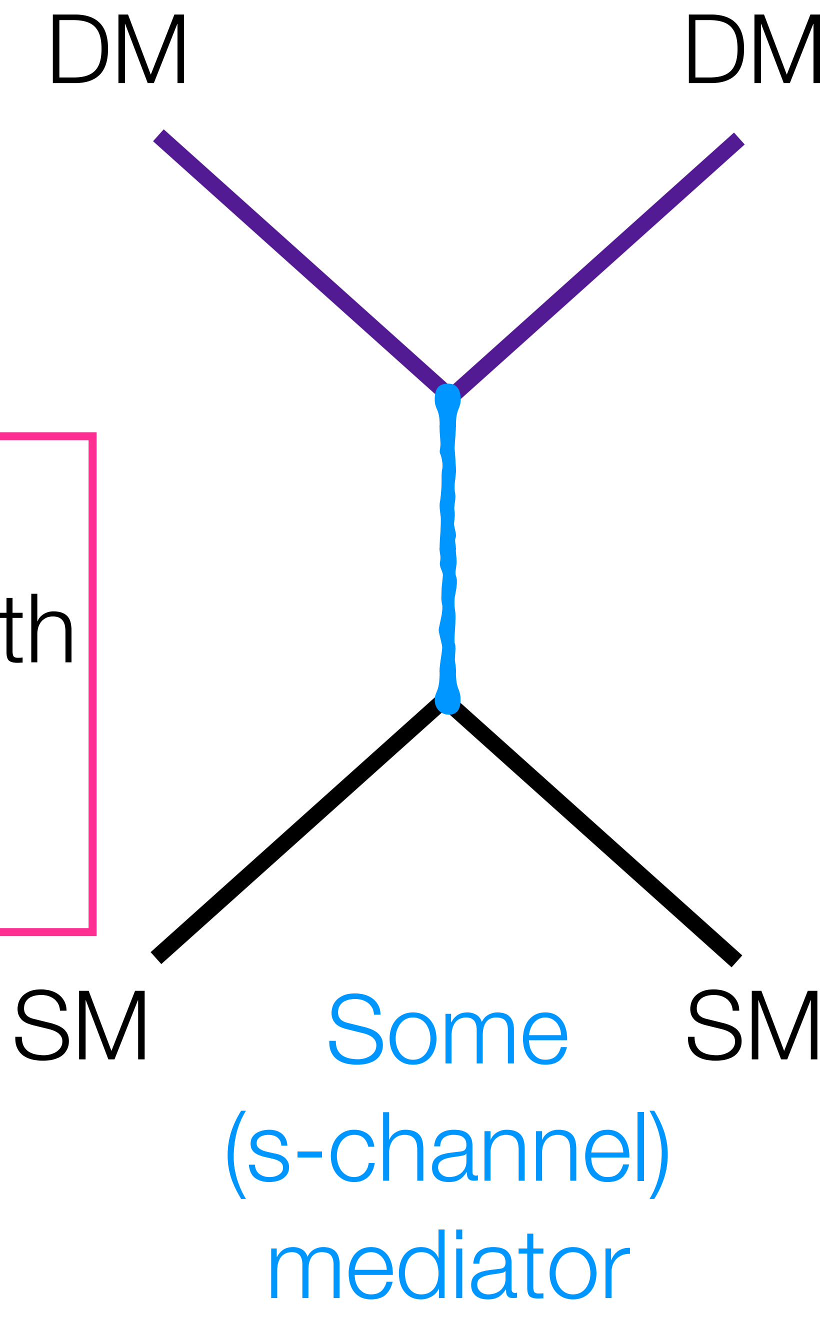
Let's make an s-channel mediator with SM boson like properties



Building a simplified model

How should we interpret this?

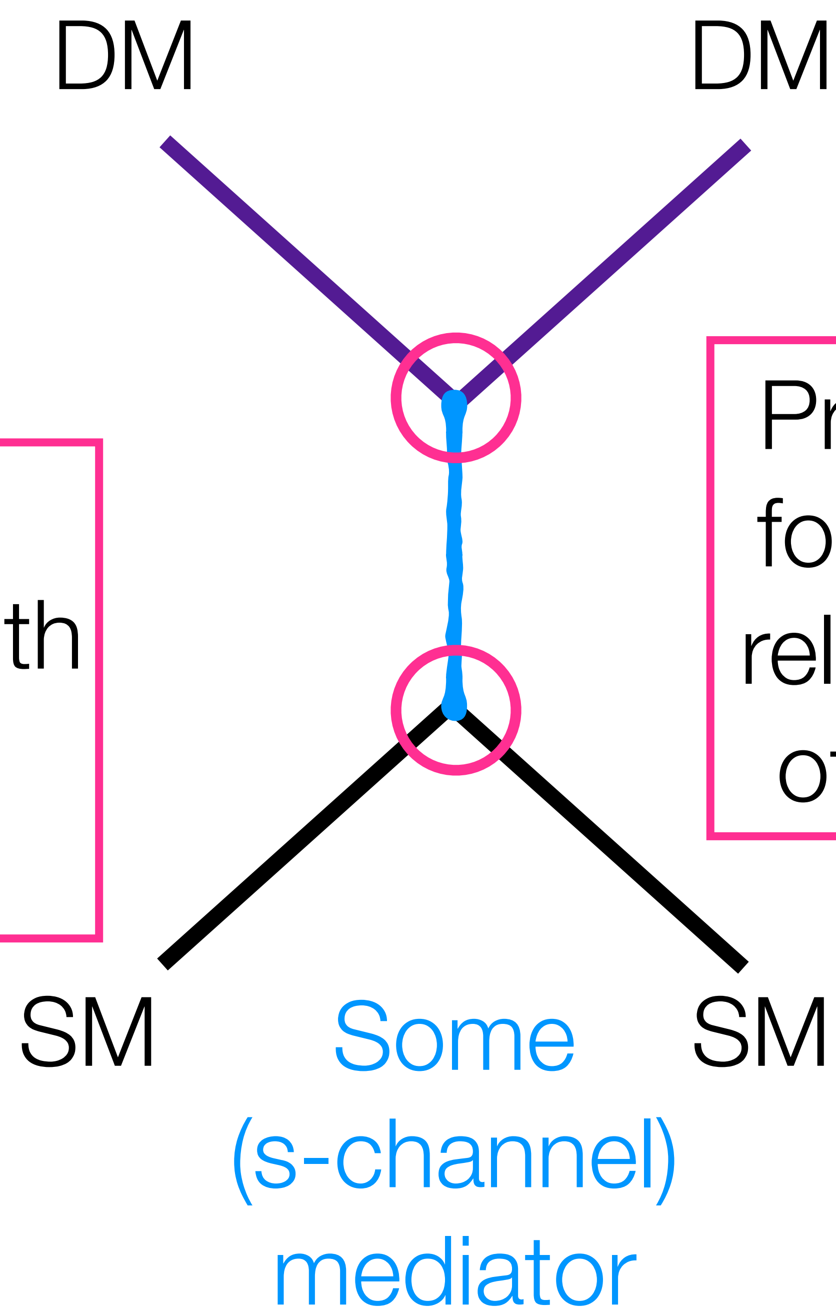
Let's make an s-channel mediator with SM boson like properties



Building a simplified model

How should we interpret this?

This mediator: *dark boson* (A')



Let's make an s-channel mediator with SM boson like properties

Practical consequences for model depending on relative masses, strength of couplings at vertices

Looking for dark bosons in practice

Experimentally: Can look for **signs of DM production**

Looking for dark bosons in practice

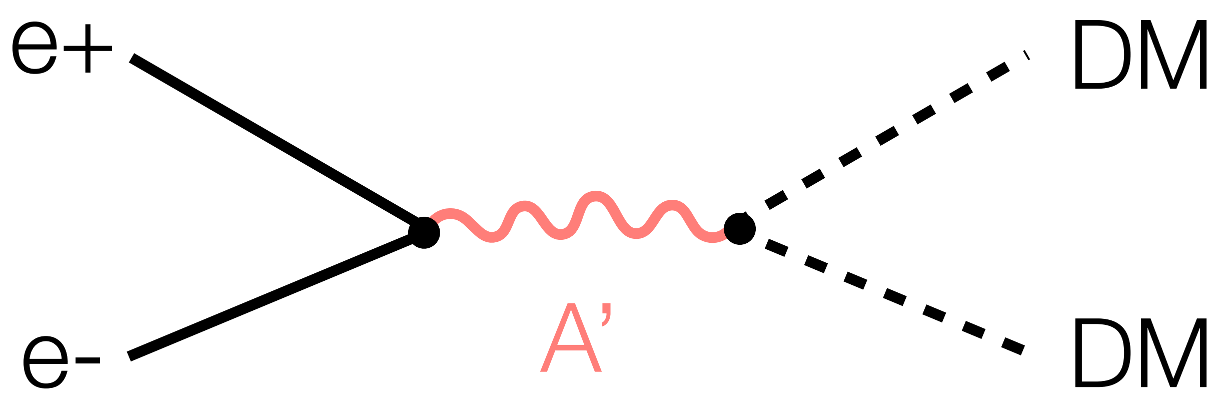
Experimentally: Can look for **signs of DM production**

Or look for the **mediator particle**

Looking for dark bosons in practice

Experimentally: Can look for **signs of DM production**

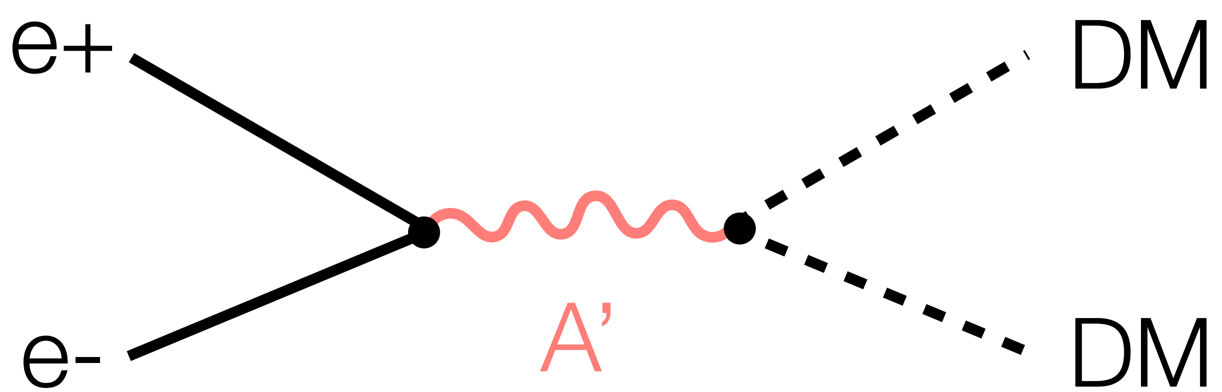
Or look for the **mediator particle**



Looking for dark bosons in practice

Experimentally: Can look for **signs of DM production**

Or look for the **mediator particle**

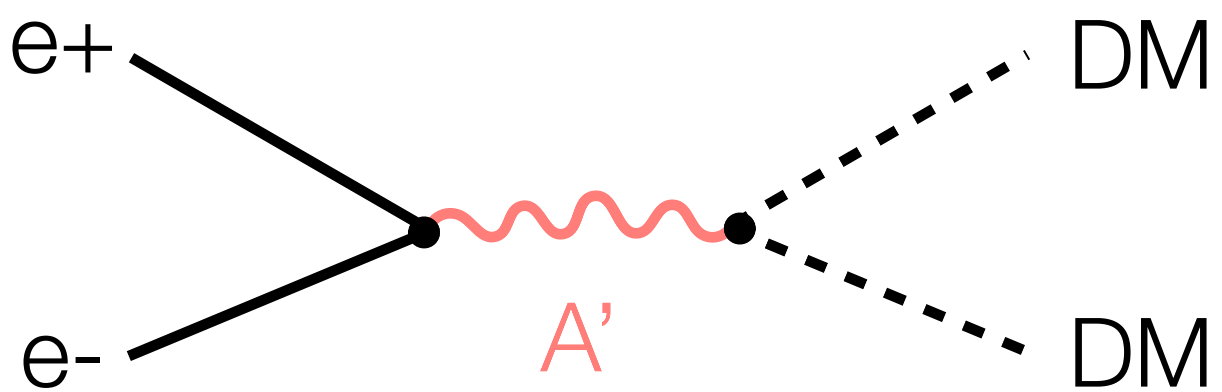


Requires $m_{A'} > 2\ m_{DM}$

Looking for dark bosons in practice

Experimentally: Can look for **signs of DM production**

Or look for the **mediator particle**



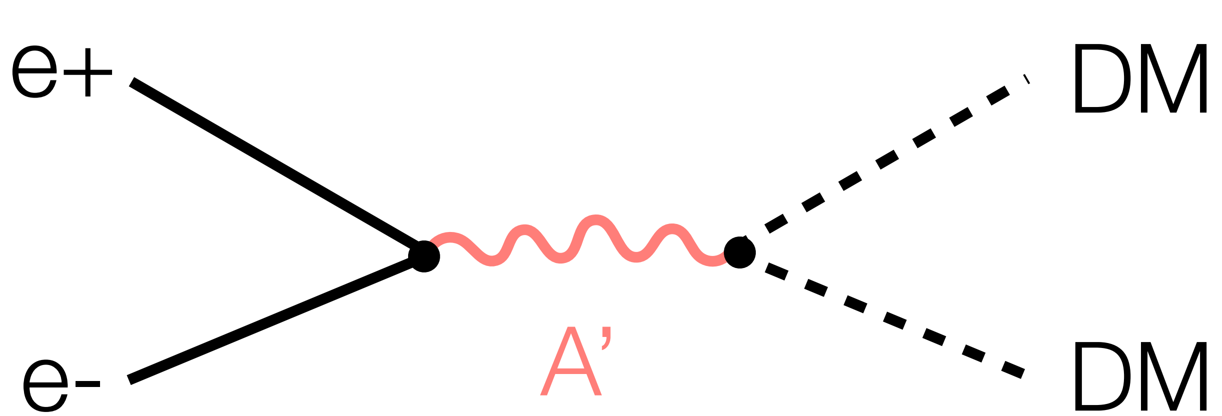
Requires $m_{A'} > 2\ m_{DM}$

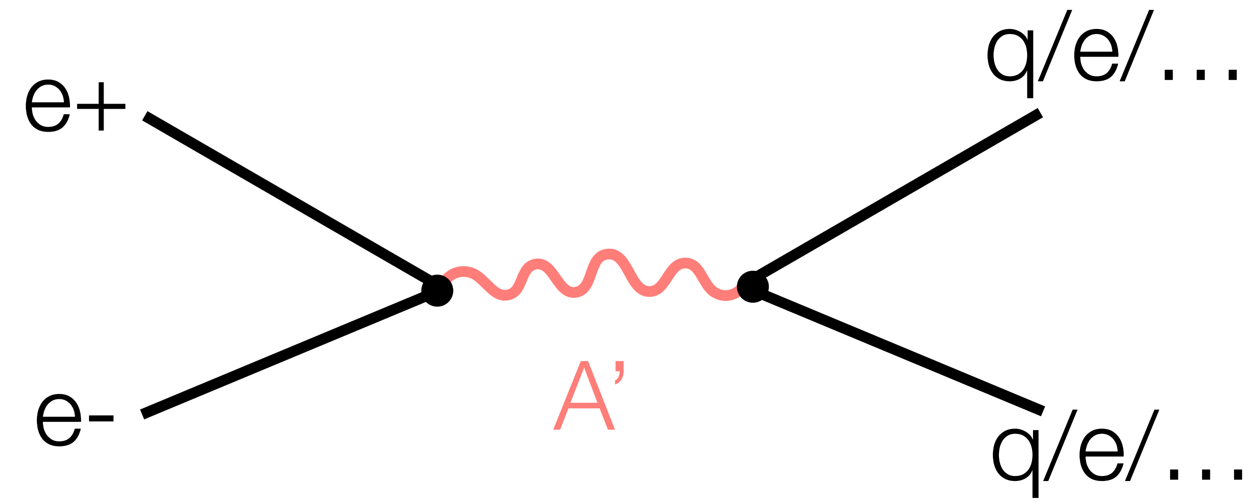
Signal is "missing energy": do not reconstruct the DM

Looking for dark bosons in practice

Experimentally: Can look for **signs of DM production**

Or look for the **mediator particle**





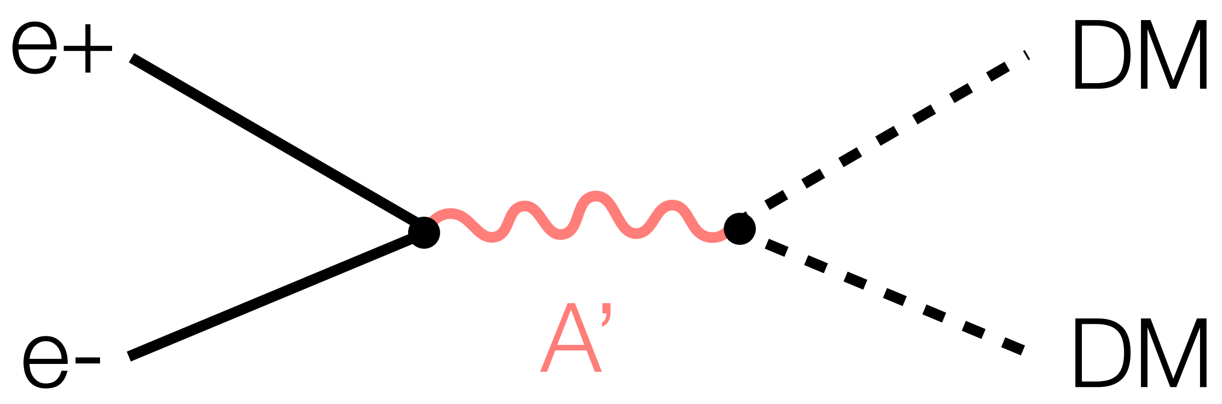
Requires $m_{A'} > 2\ m_{DM}$

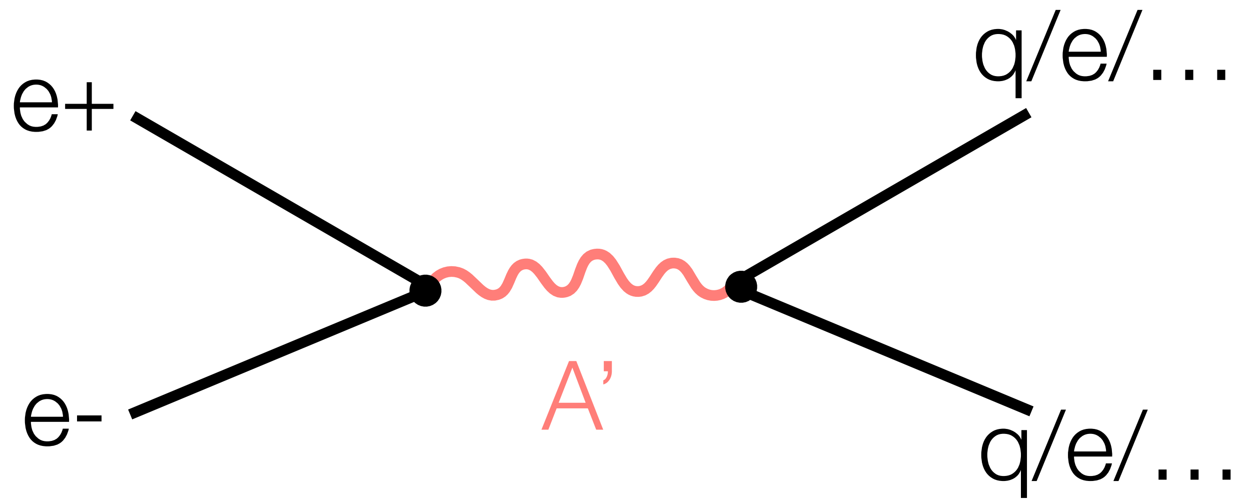
Signal is "missing energy": do not reconstruct the DM

Looking for dark bosons in practice

Experimentally: Can look for **signs of DM production**

Or look for the **mediator particle**



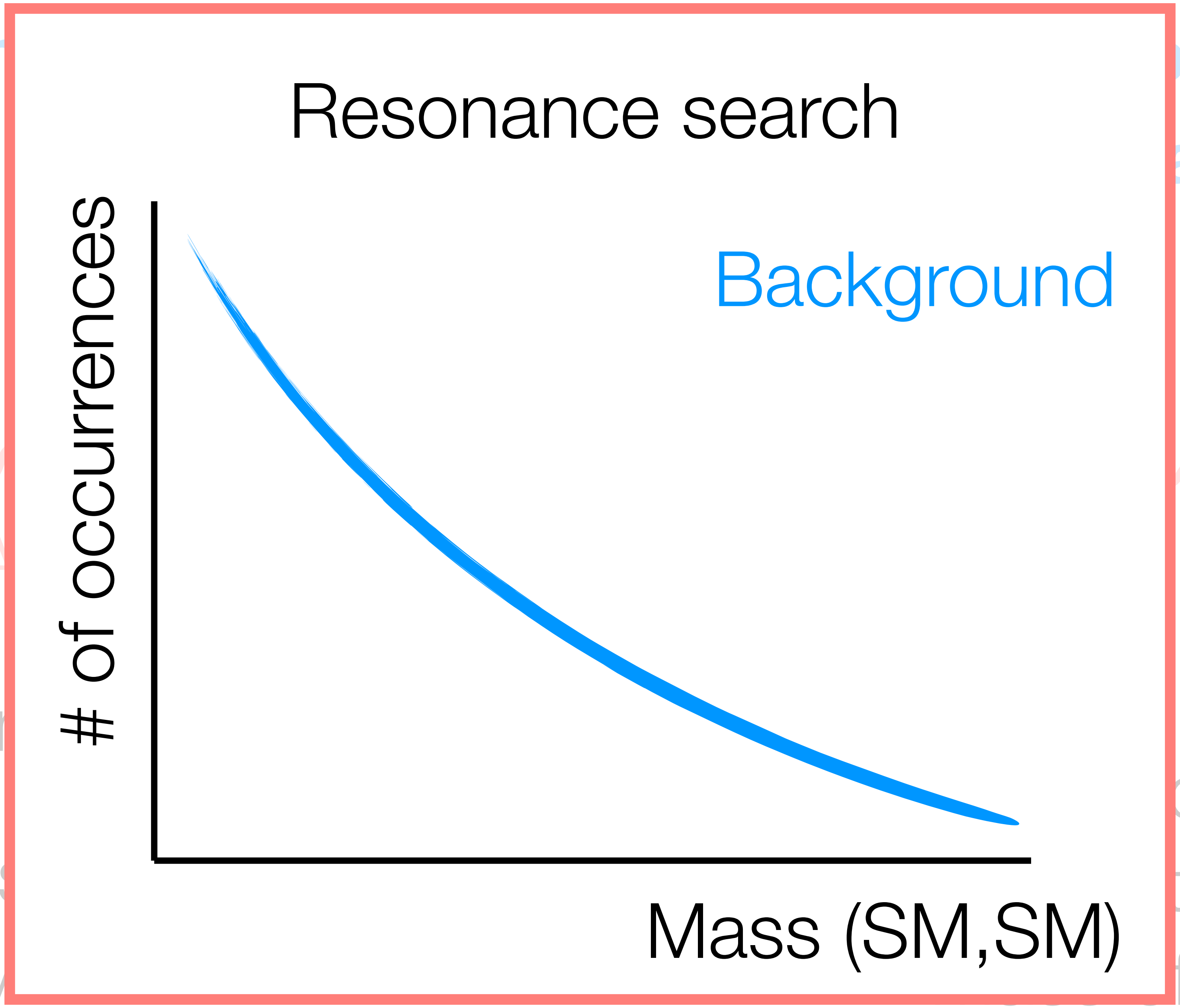


Requires $m_{A'} > 2\ m_{DM}$

Signal is “missing energy”: do not reconstruct the DM

Signal is “resonance”: pairs of particles at mass of A’

Looking for dark bosons in practice



Experim… …roduction …article

e+
e-
A…
q/e/…
q/e/…

Requires r…
Signal i… energy… reconstruct the DM

…onance”: …ticles at … of A’

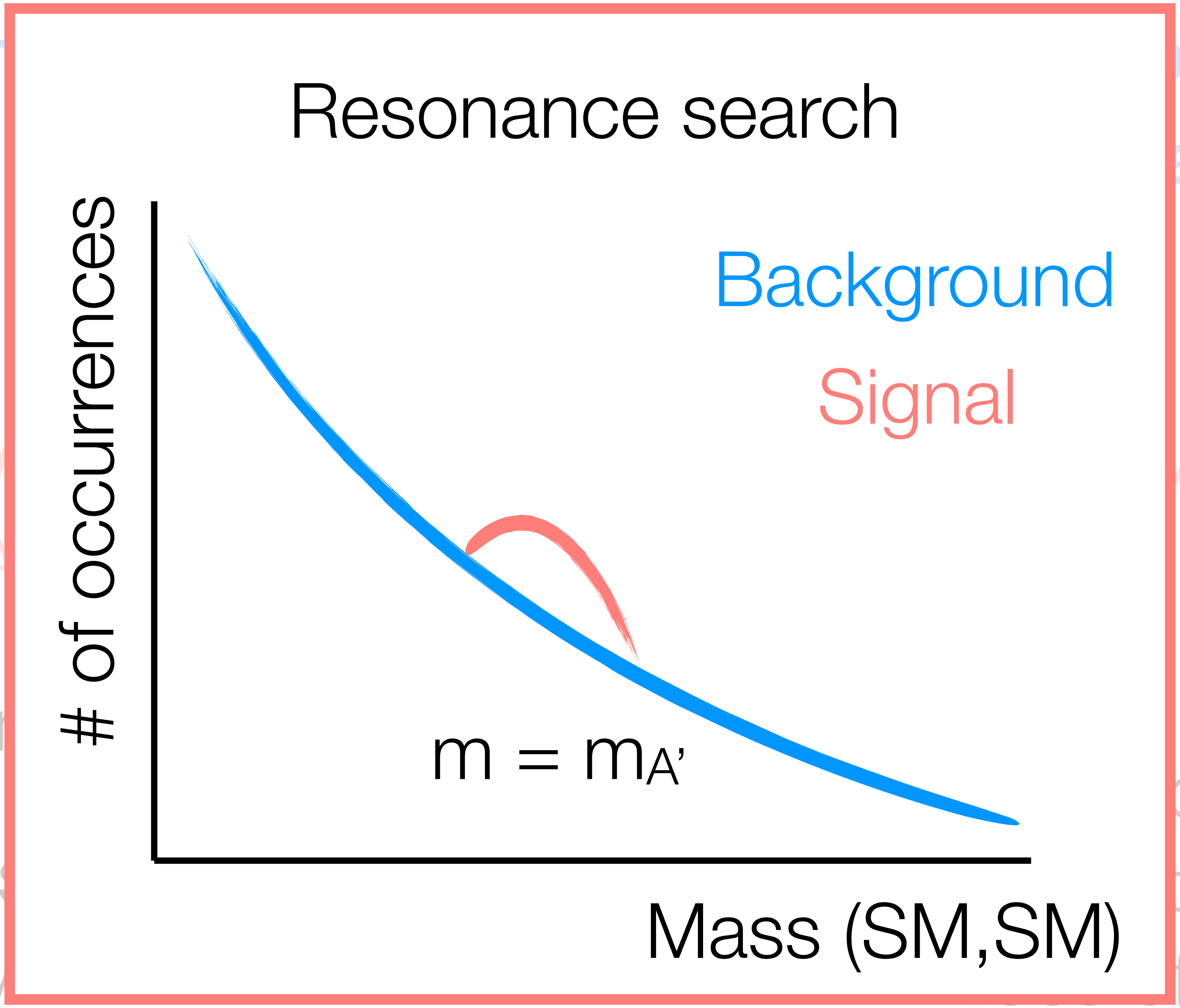
Looking for dark bosons in practice

Experim… …production

…article

e+ q/e/…

e- q/e/…



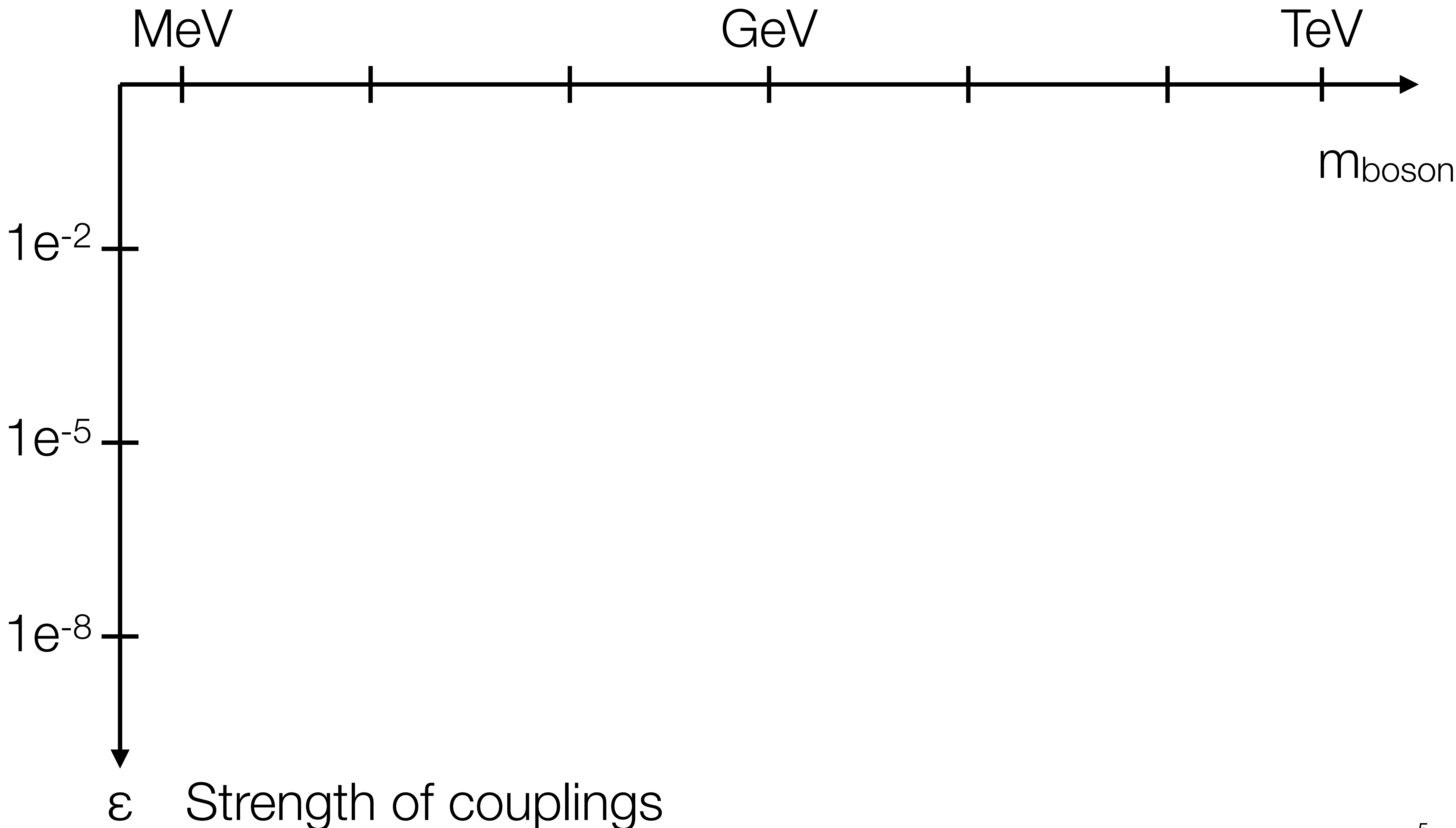
Requires … …onance”:

Signal i… …ticles at

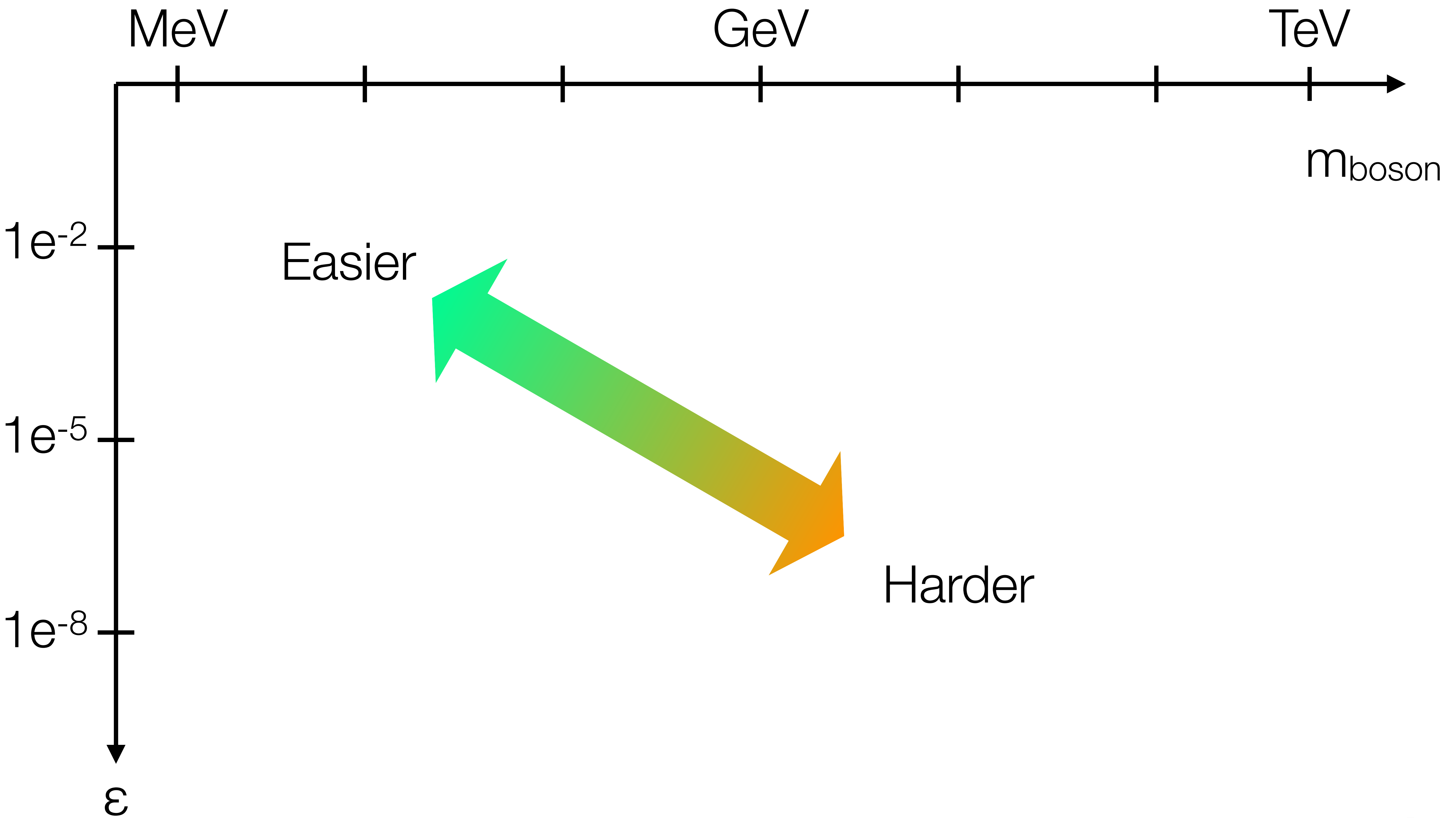
energy… …f A’

reconstruct the DM

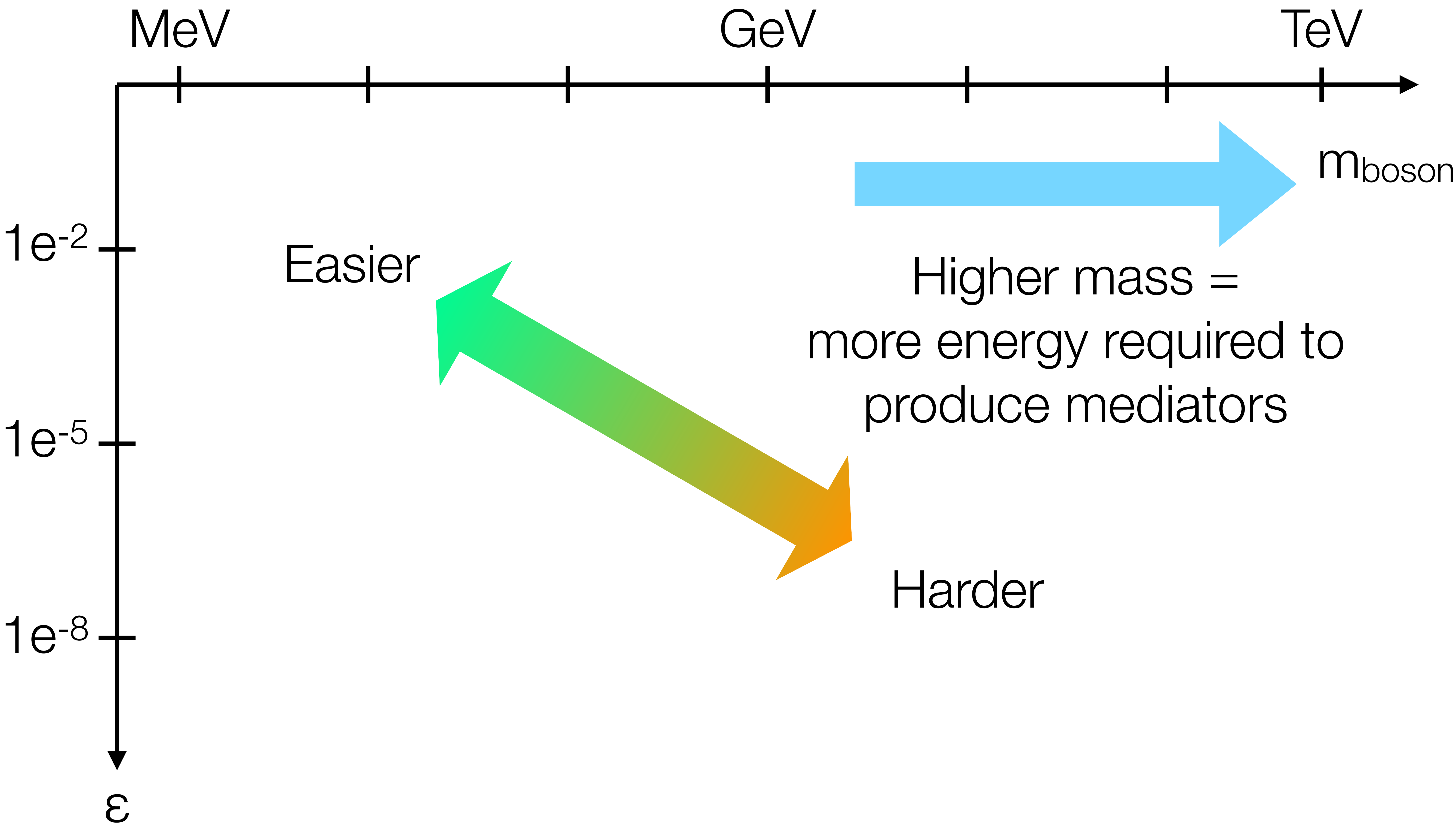
Where and how do we search for dark bosons?



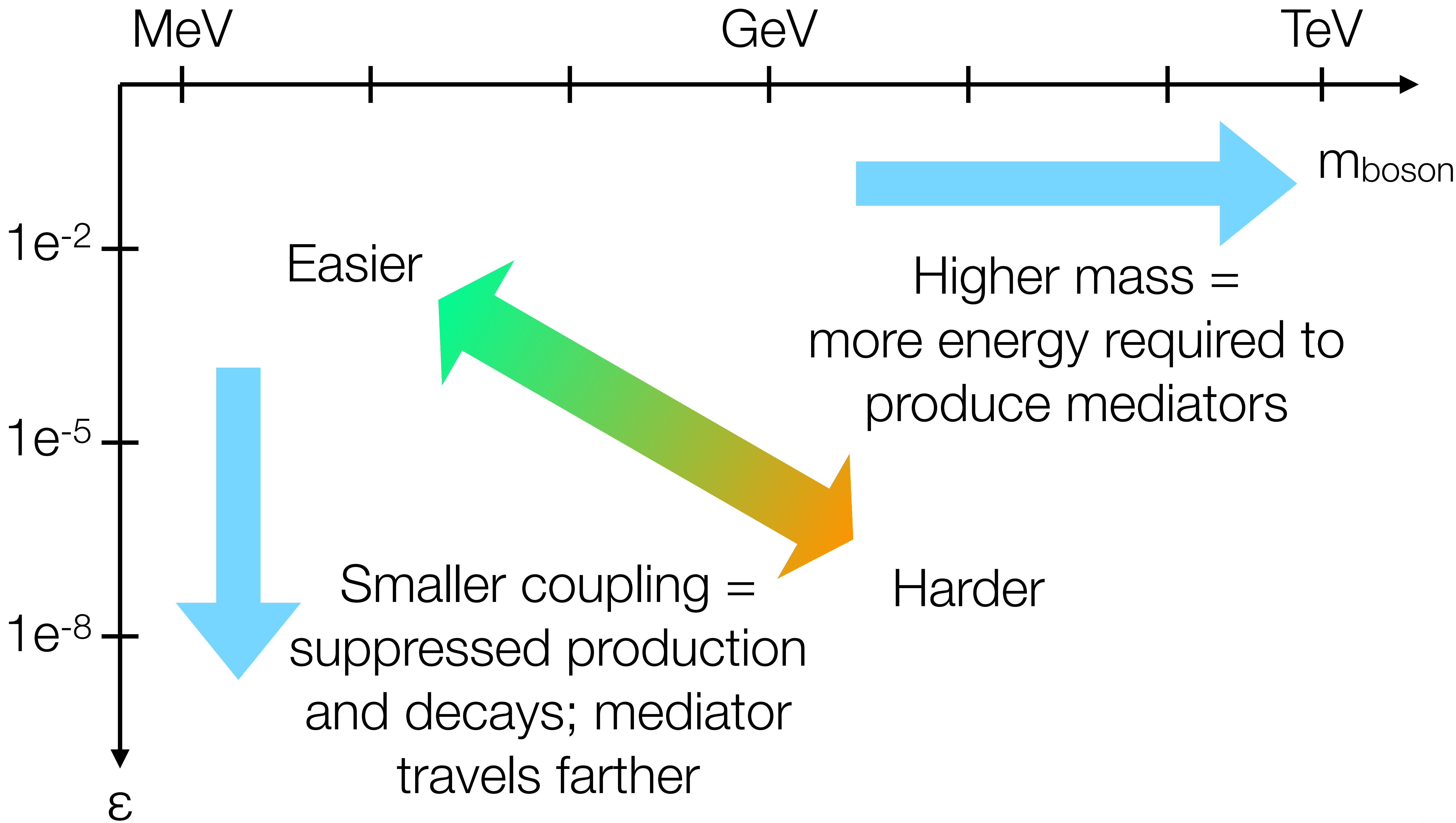
Where and how do we search for dark bosons?



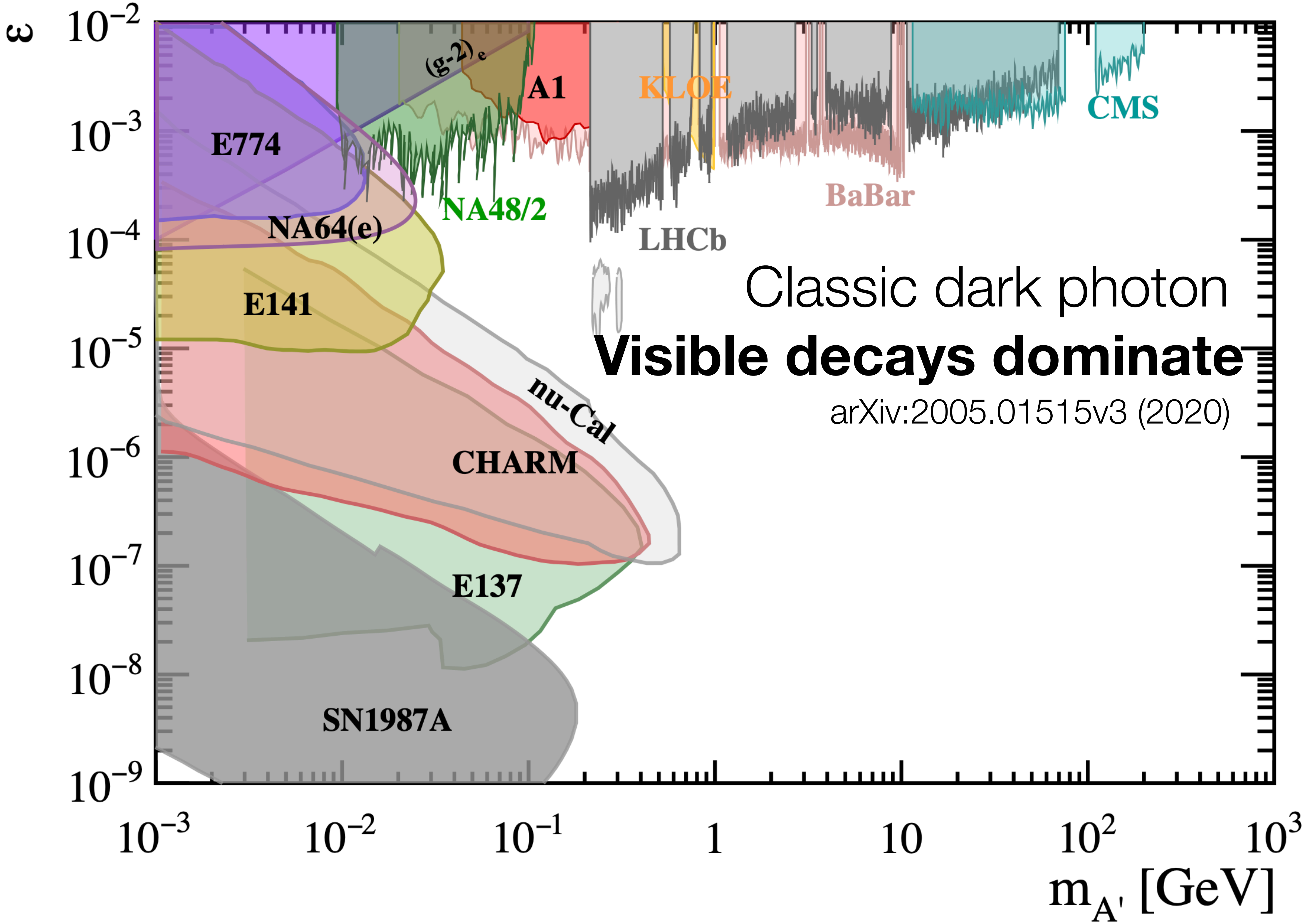
Where and how do we search for dark bosons?



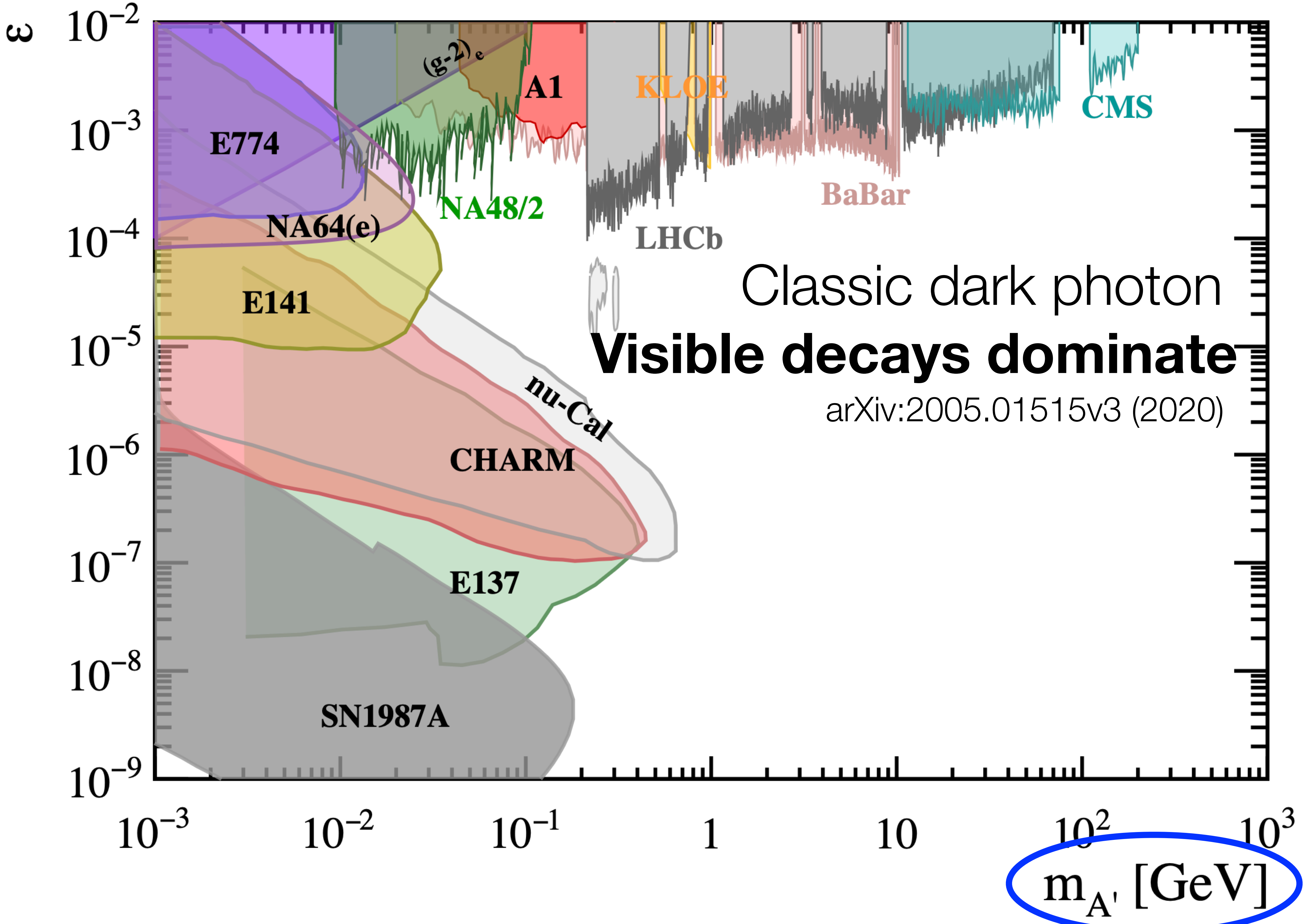
Where and how do we search for dark bosons?



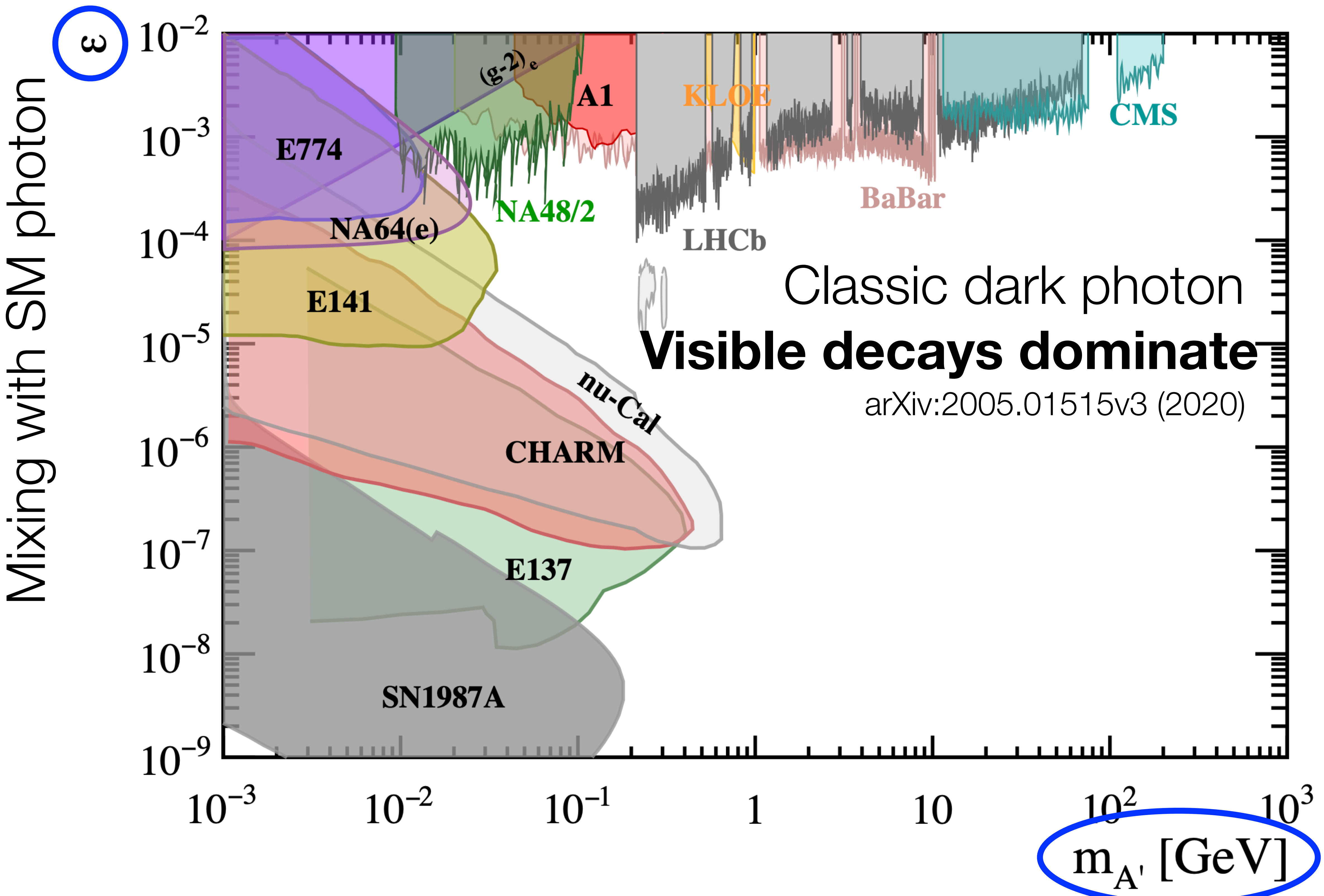
A real example: the dark photon



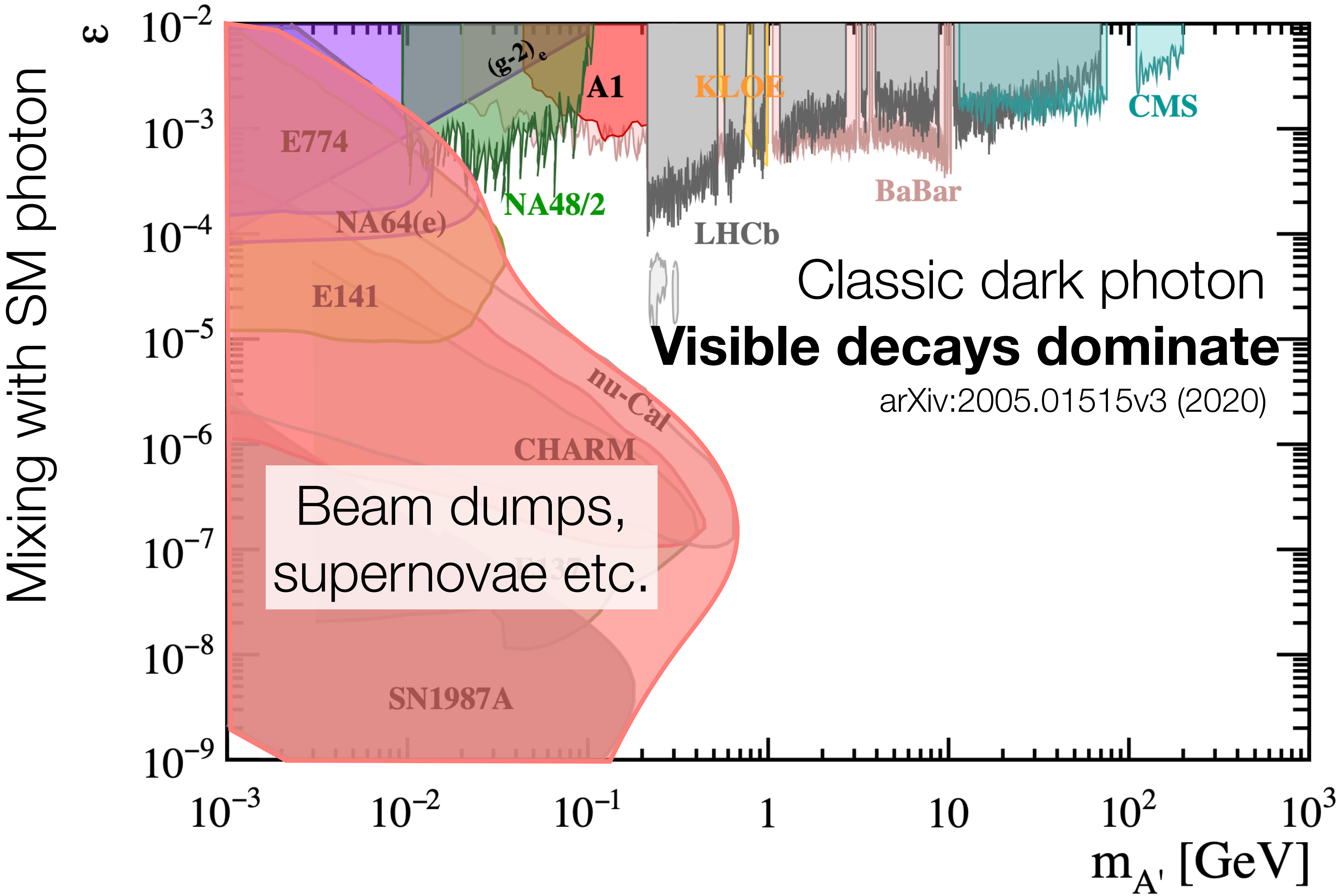
A real example: the dark photon



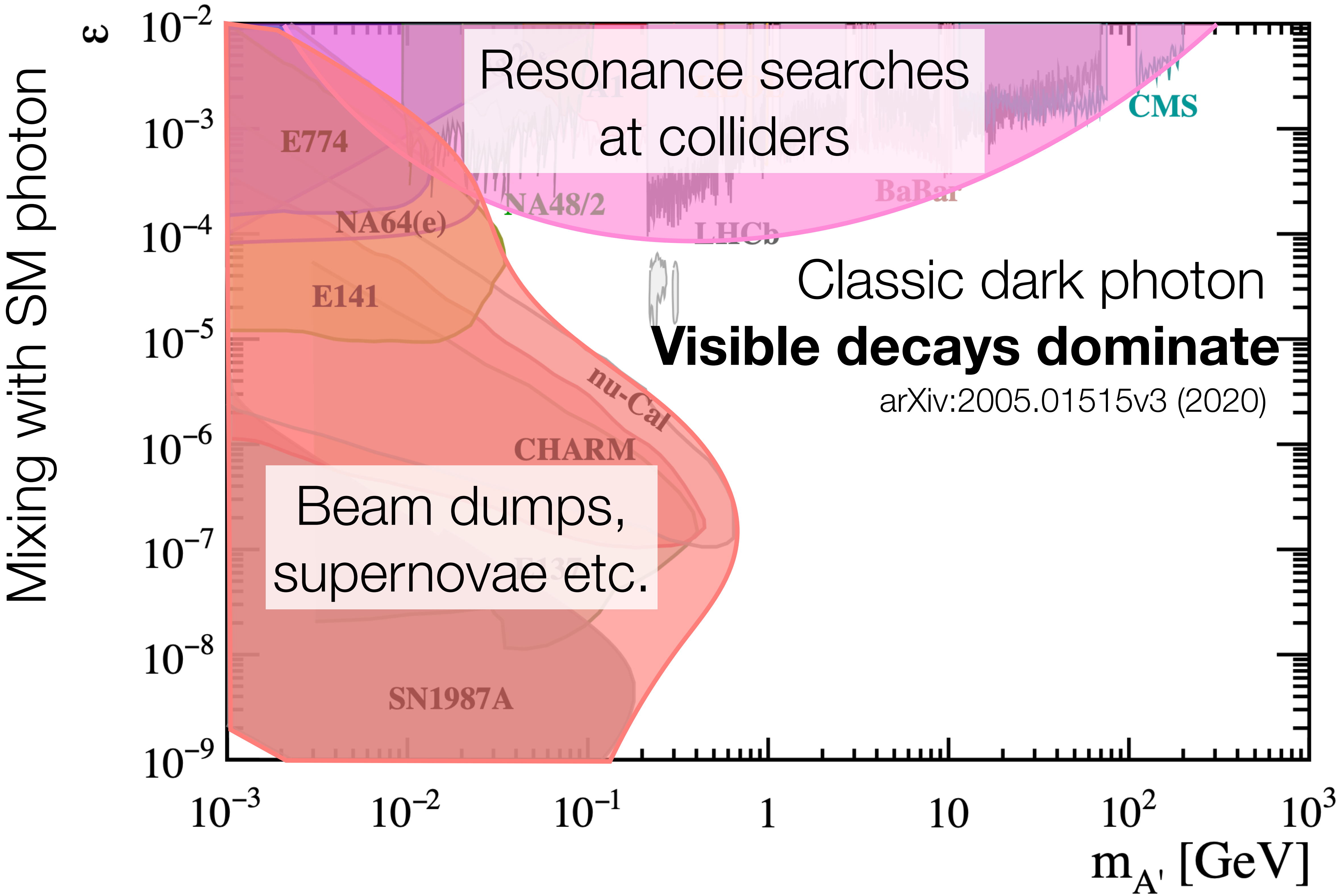
A real example: the dark photon



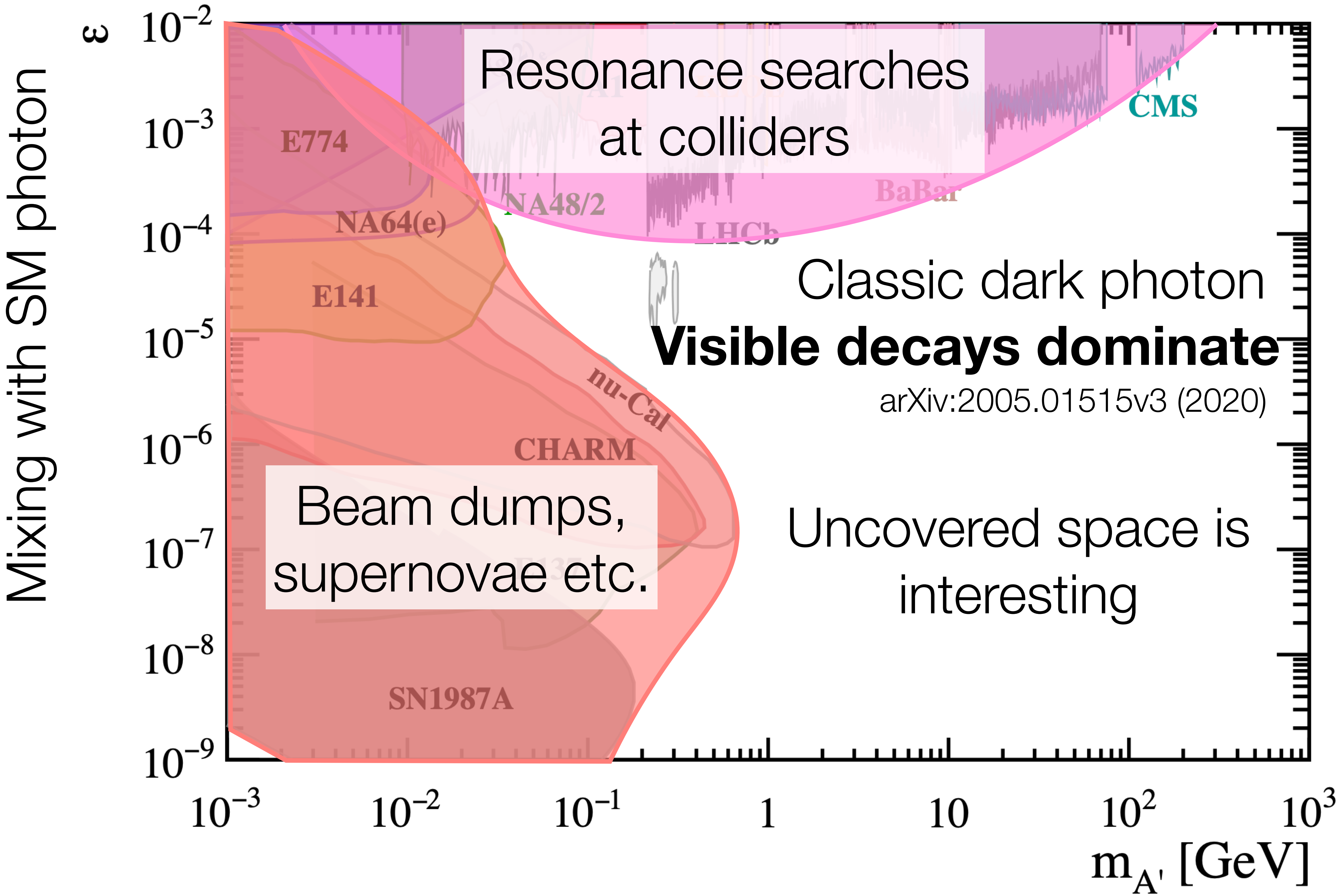
A real example: the dark photon



A real example: the dark photon

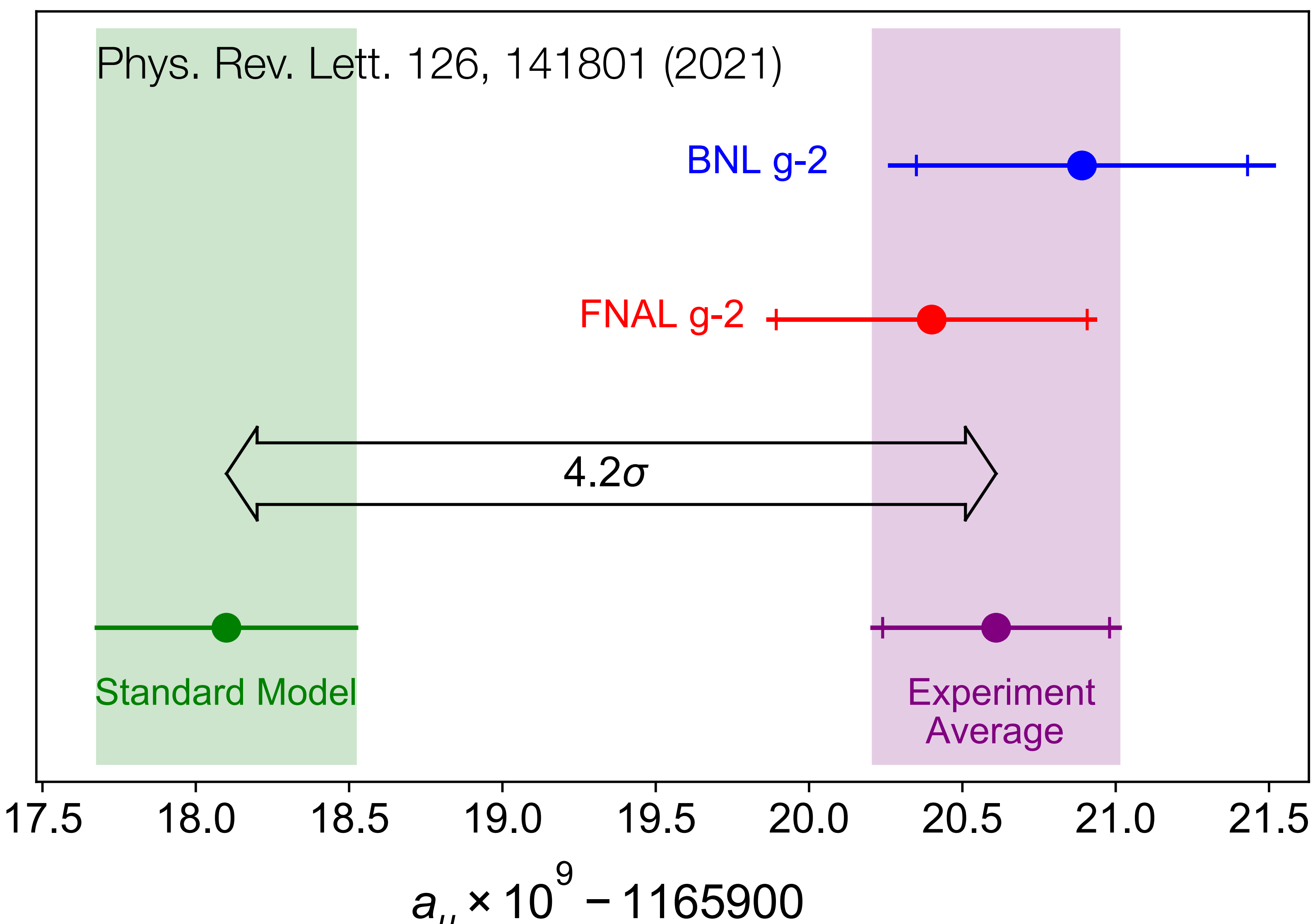


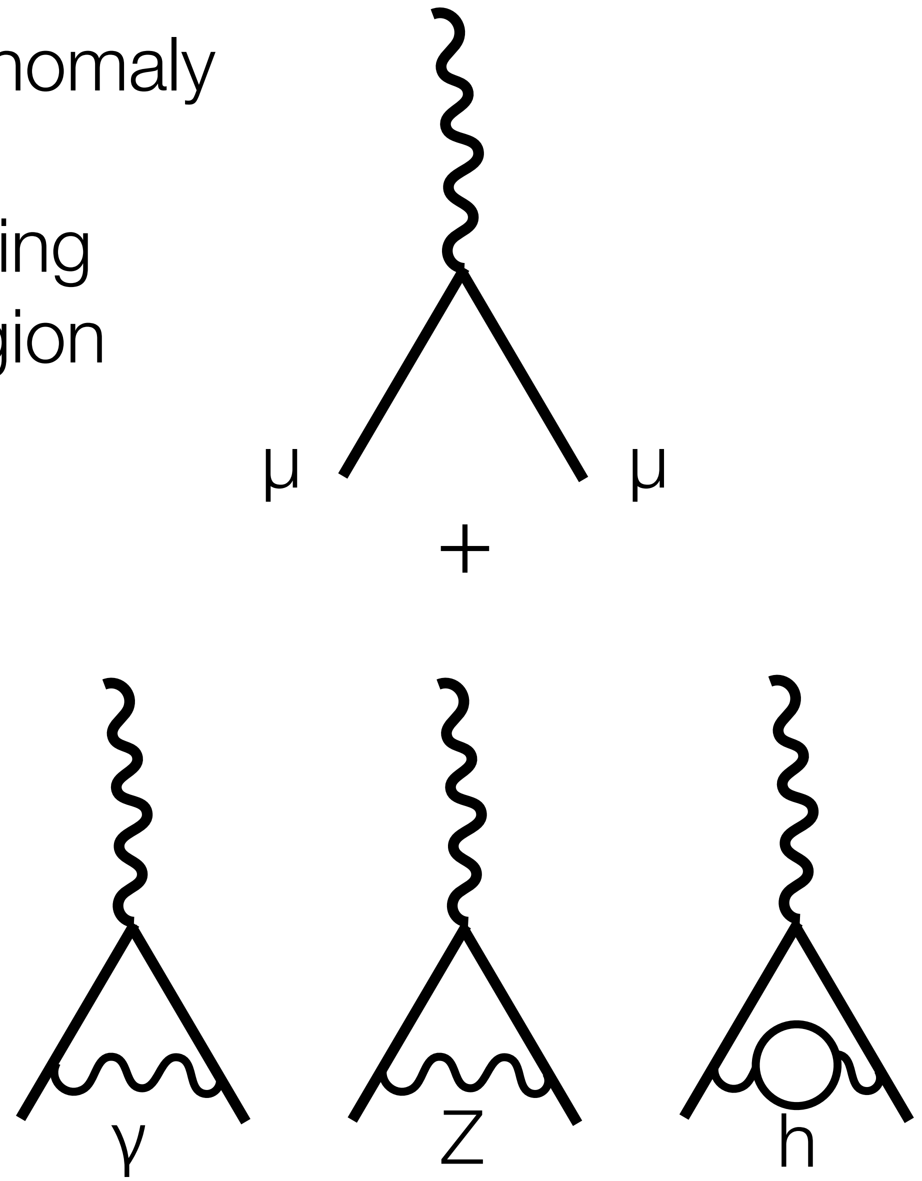
A real example: the dark photon



Light BSM boson: g-2 anomaly

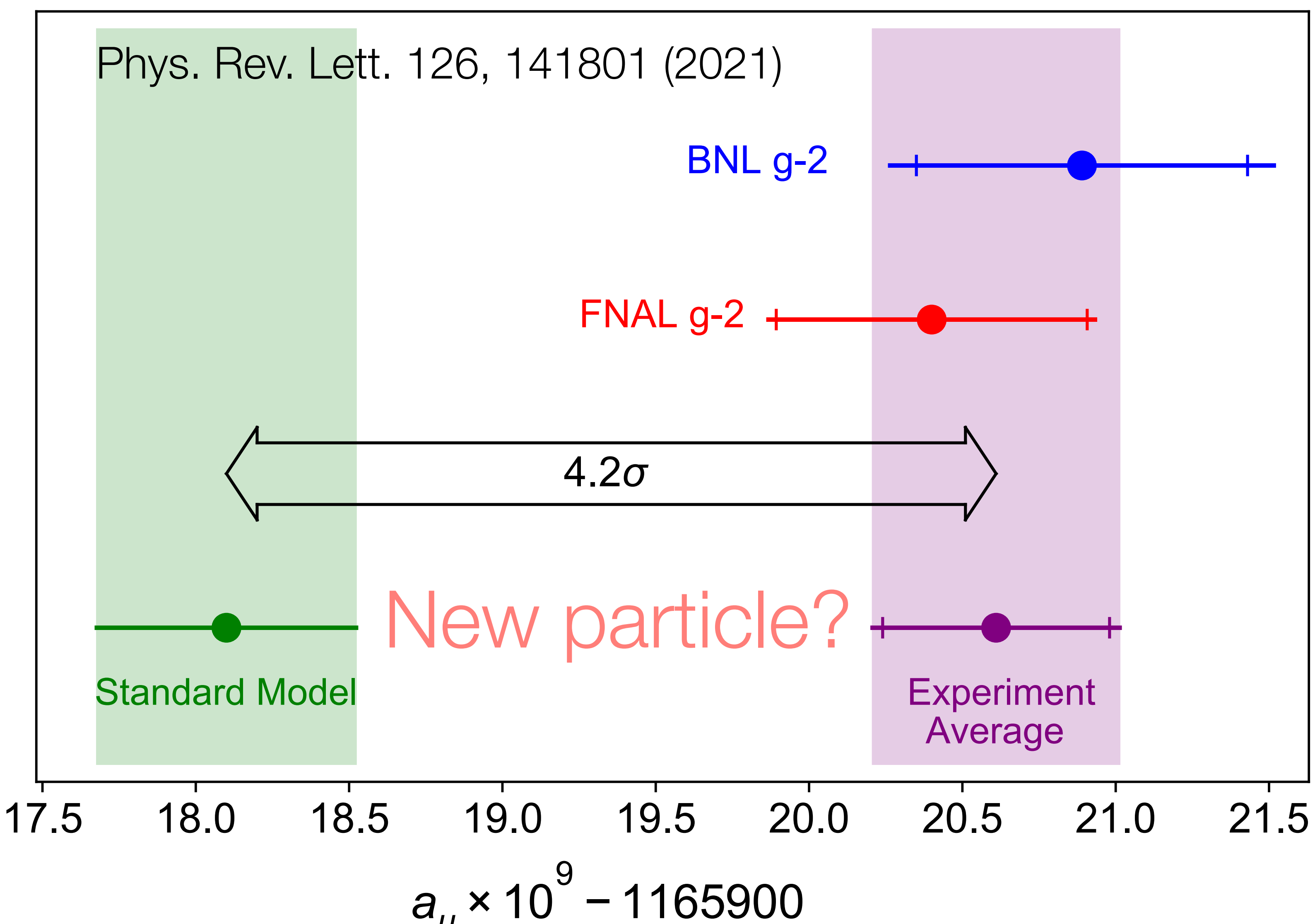
Many investigations into source of 4.2 σ muon g-2 anomaly
One possibility: new massive boson
Would be low mass, moderate coupling - kinetic mixing model disfavoured, but experimentally accessible region

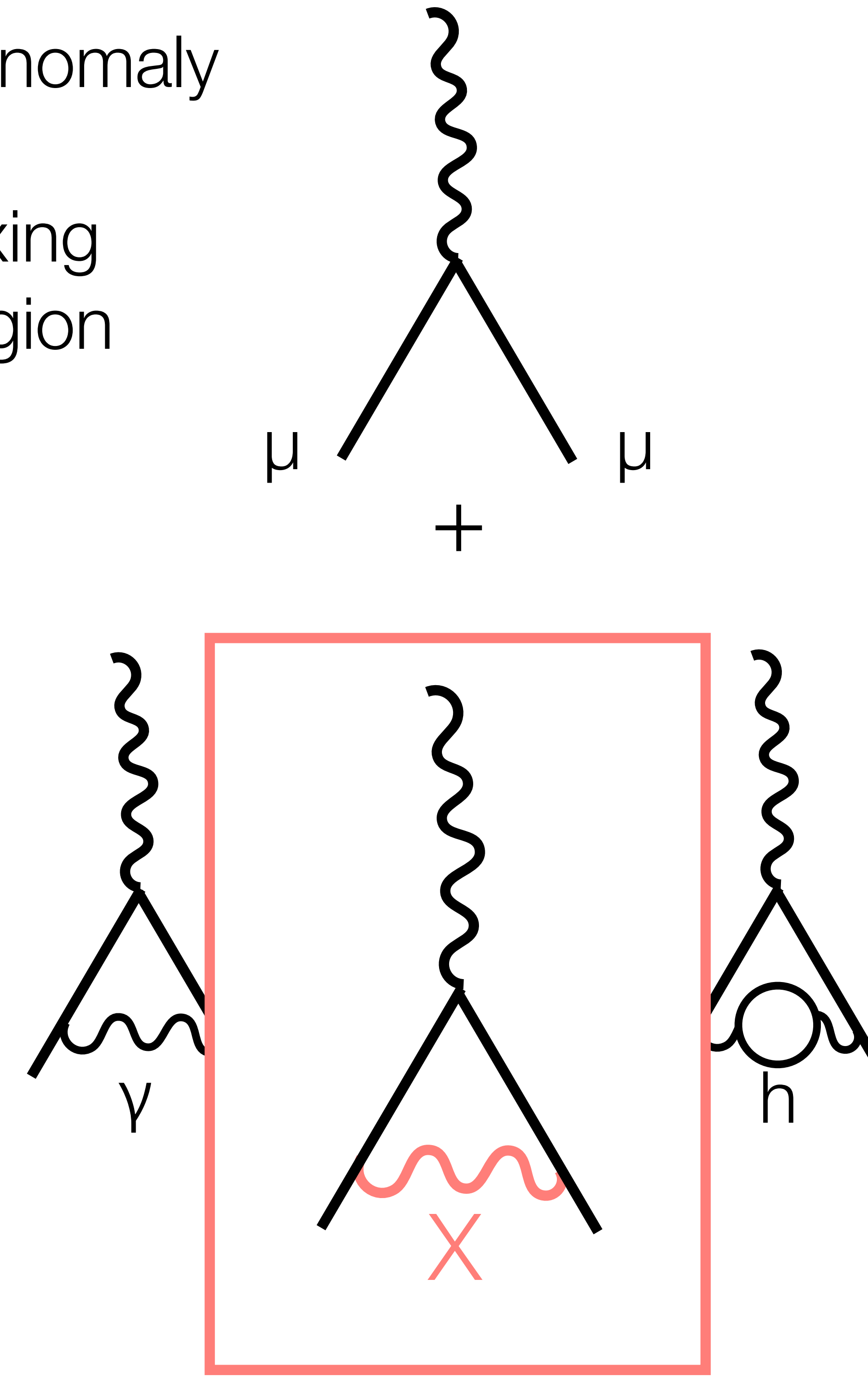




Light BSM boson: g-2 anomaly

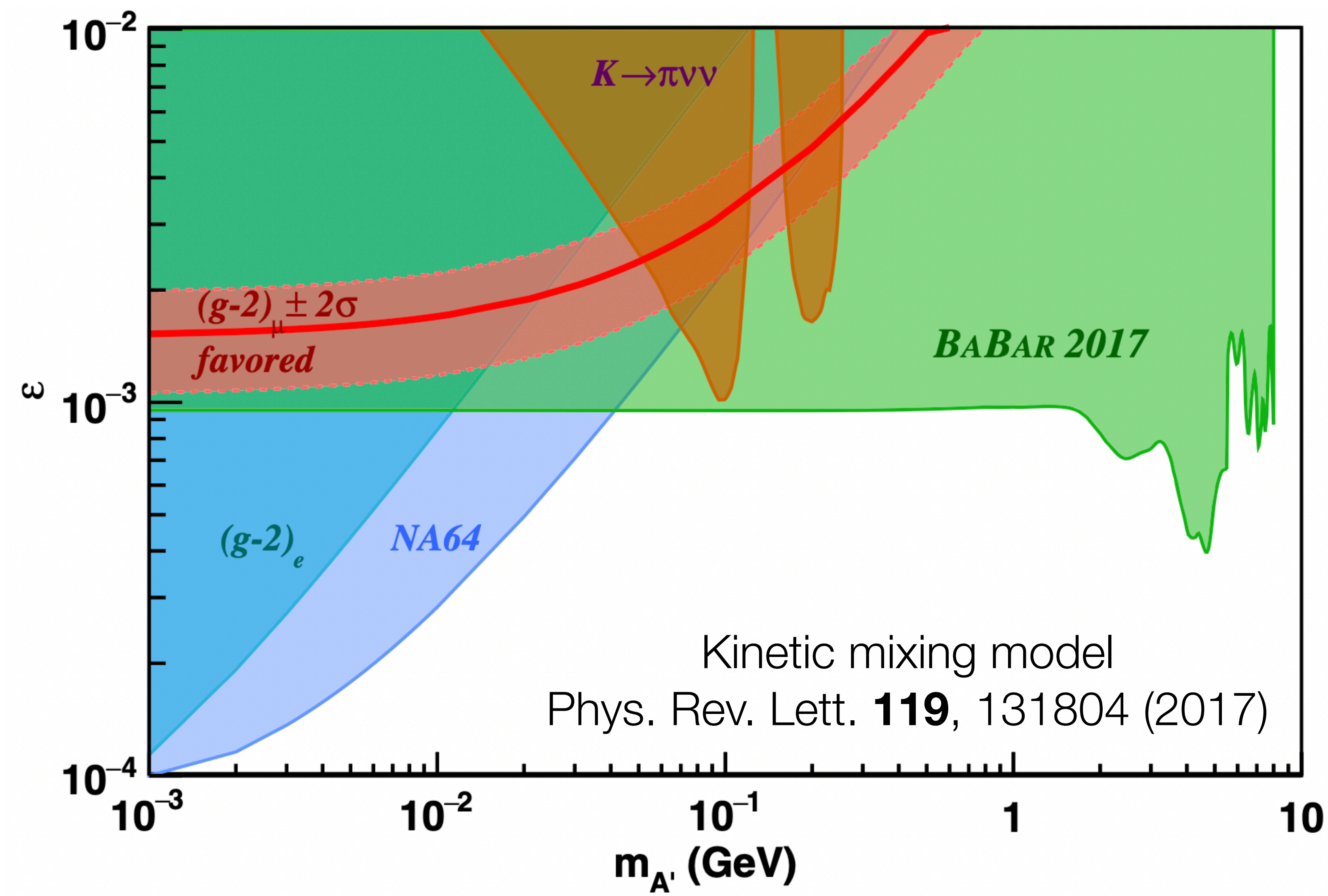
Many investigations into source of 4.2 σ muon g-2 anomaly
One possibility: new massive boson
Would be low mass, moderate coupling - kinetic mixing model disfavoured, but experimentally accessible region

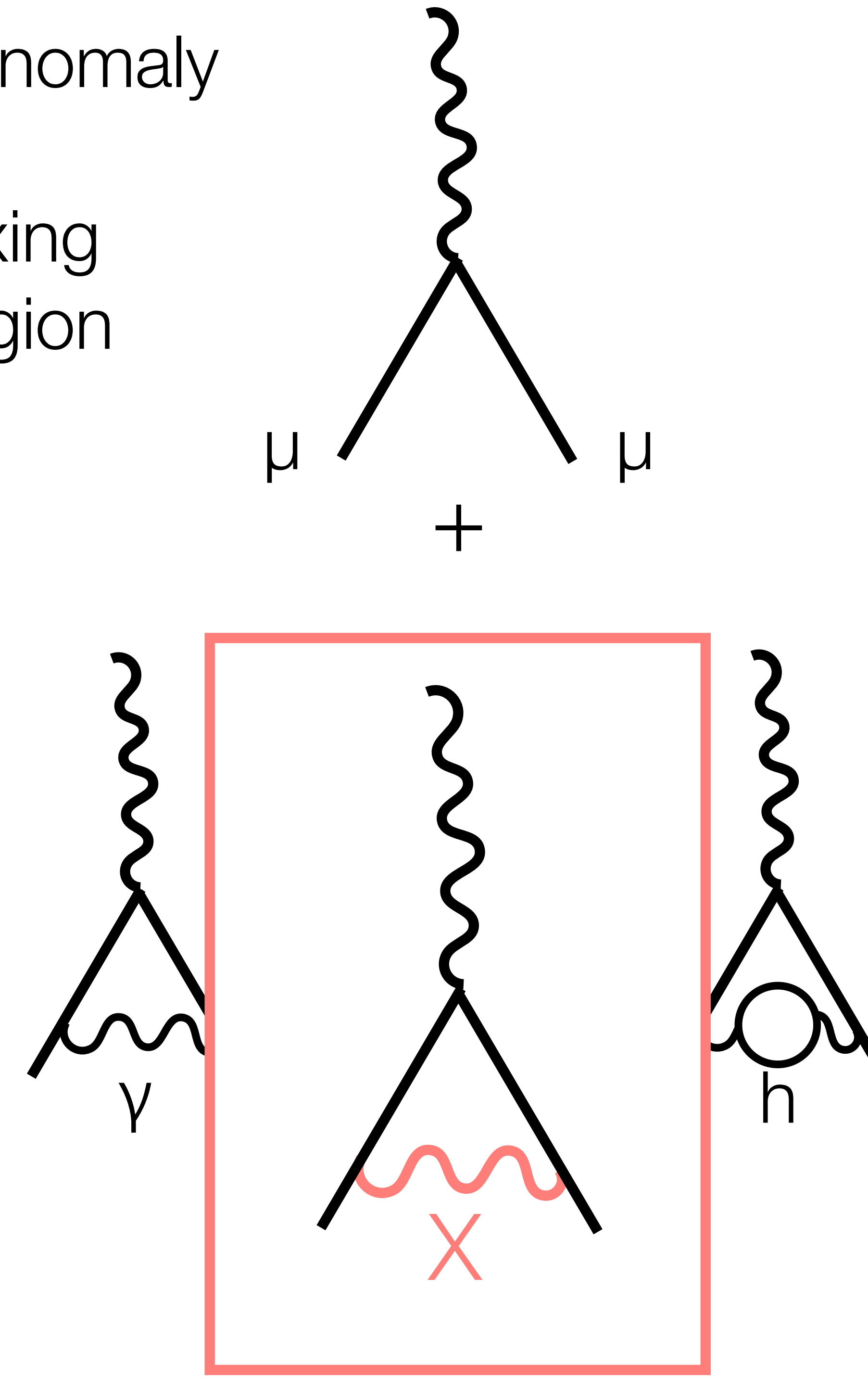




Light BSM boson: g-2 anomaly

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

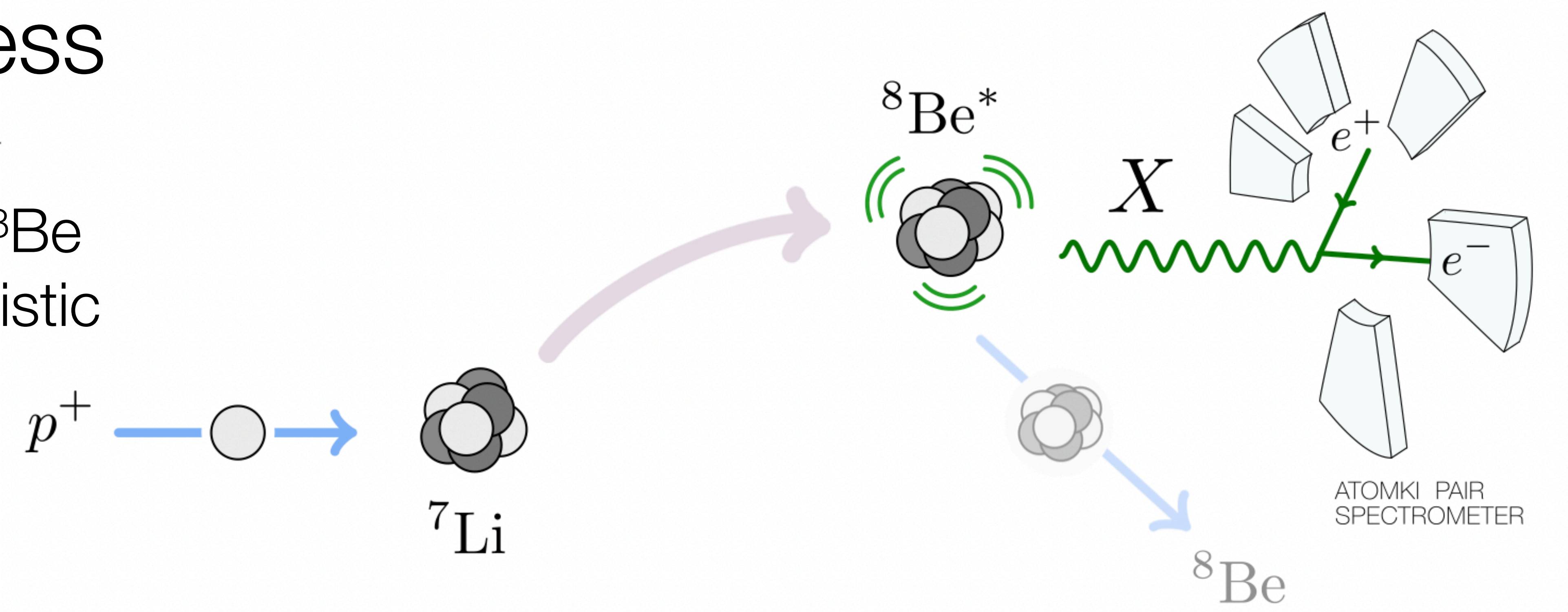




Light BSM boson: the X17 excess

Phys. Rev. D 95, 035017 (2017)

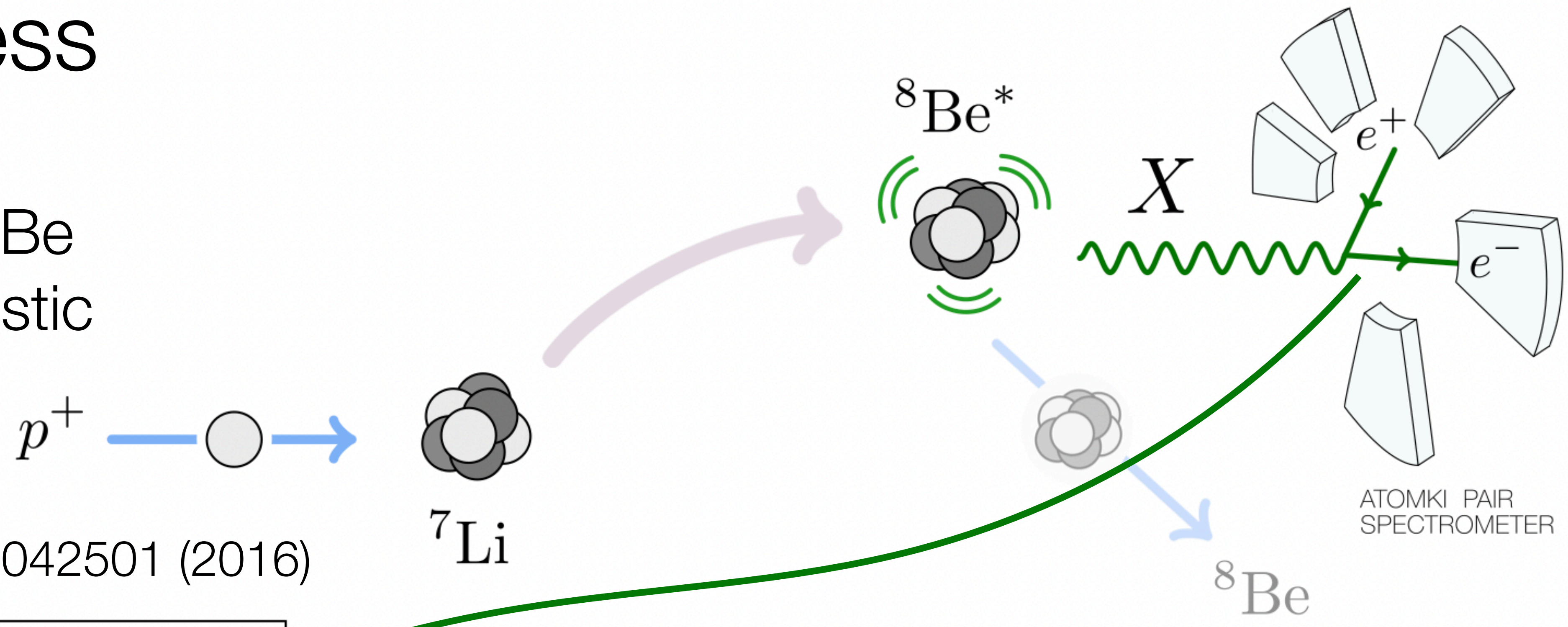
Decay of excited ^{8}Be through characteristic energy levels



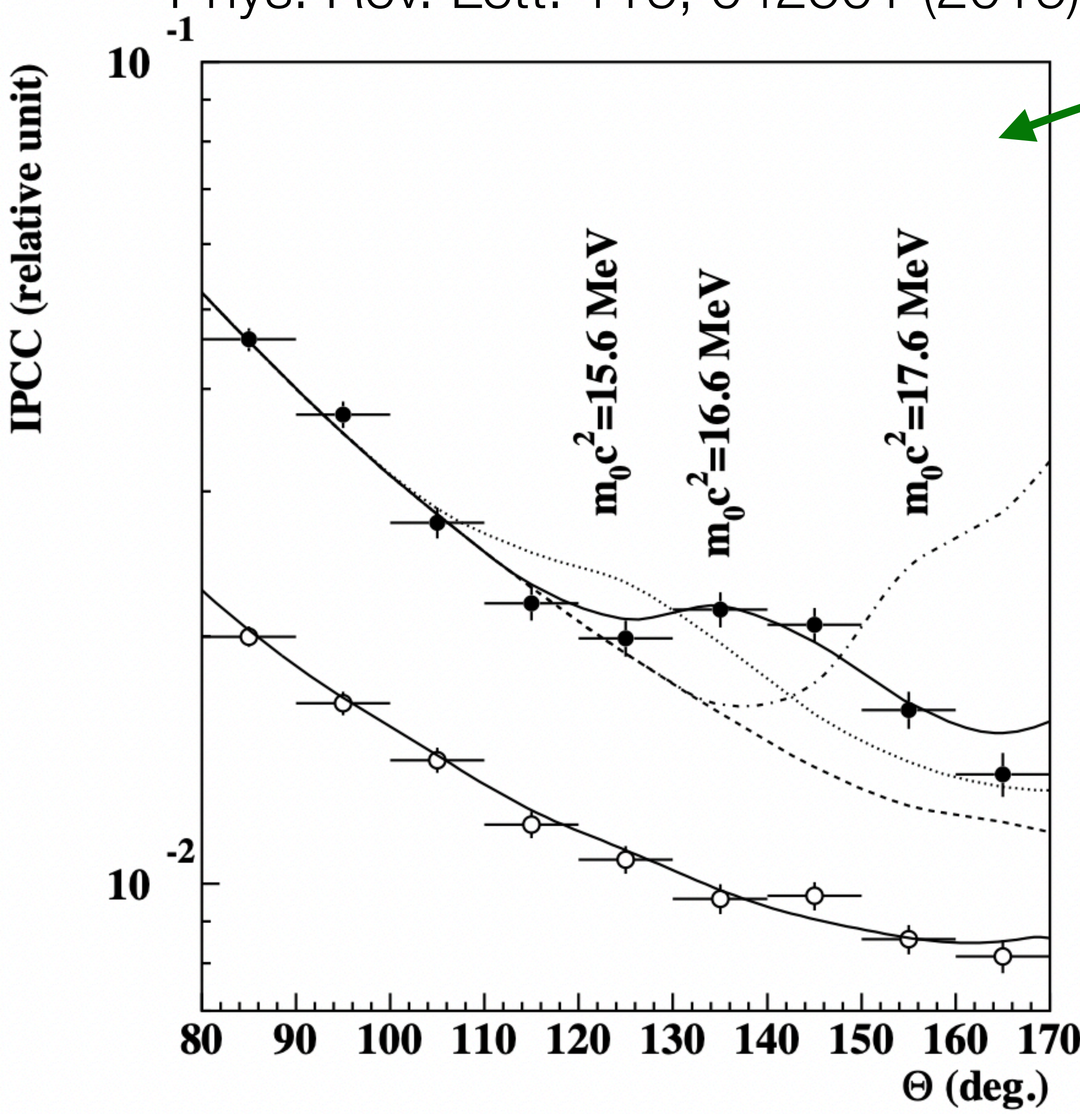
Light BSM boson: the X17 excess

Phys. Rev. D 95, 035017 (2017)

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



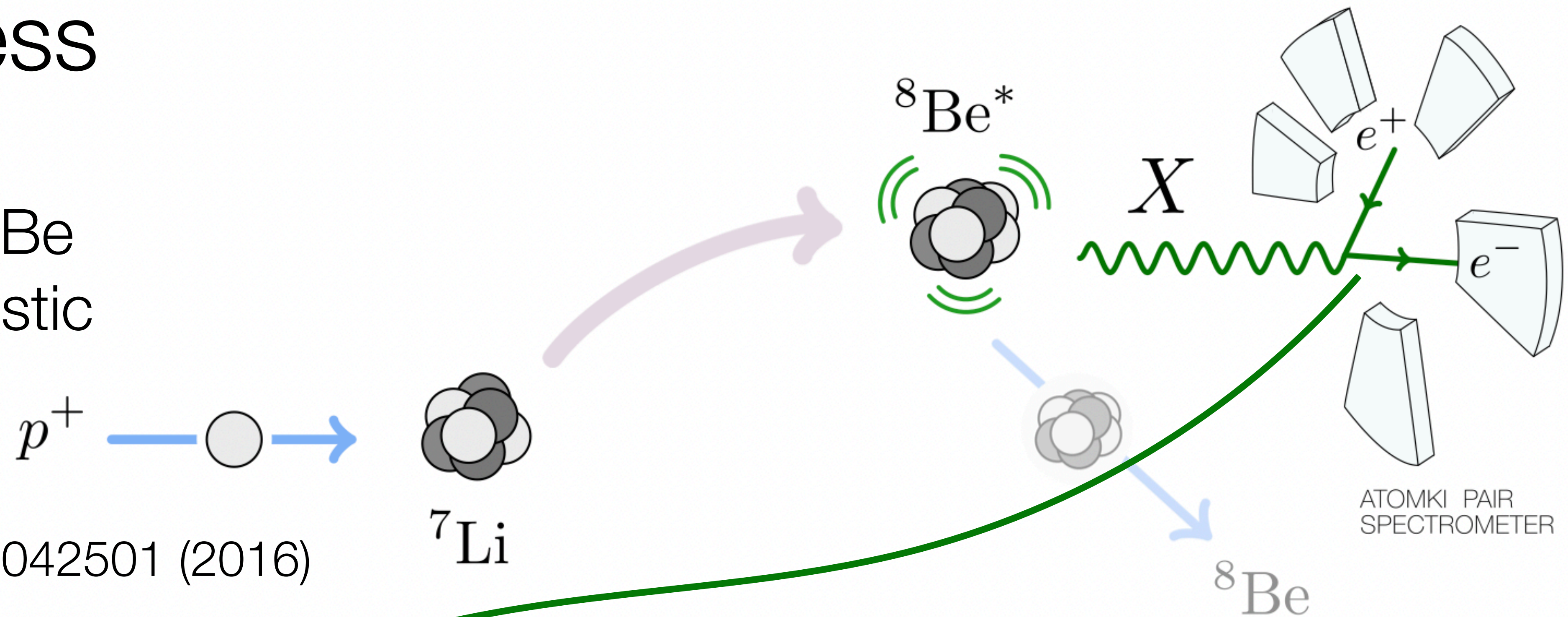
Phys. Rev. Lett. 116, 042501 (2016)



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

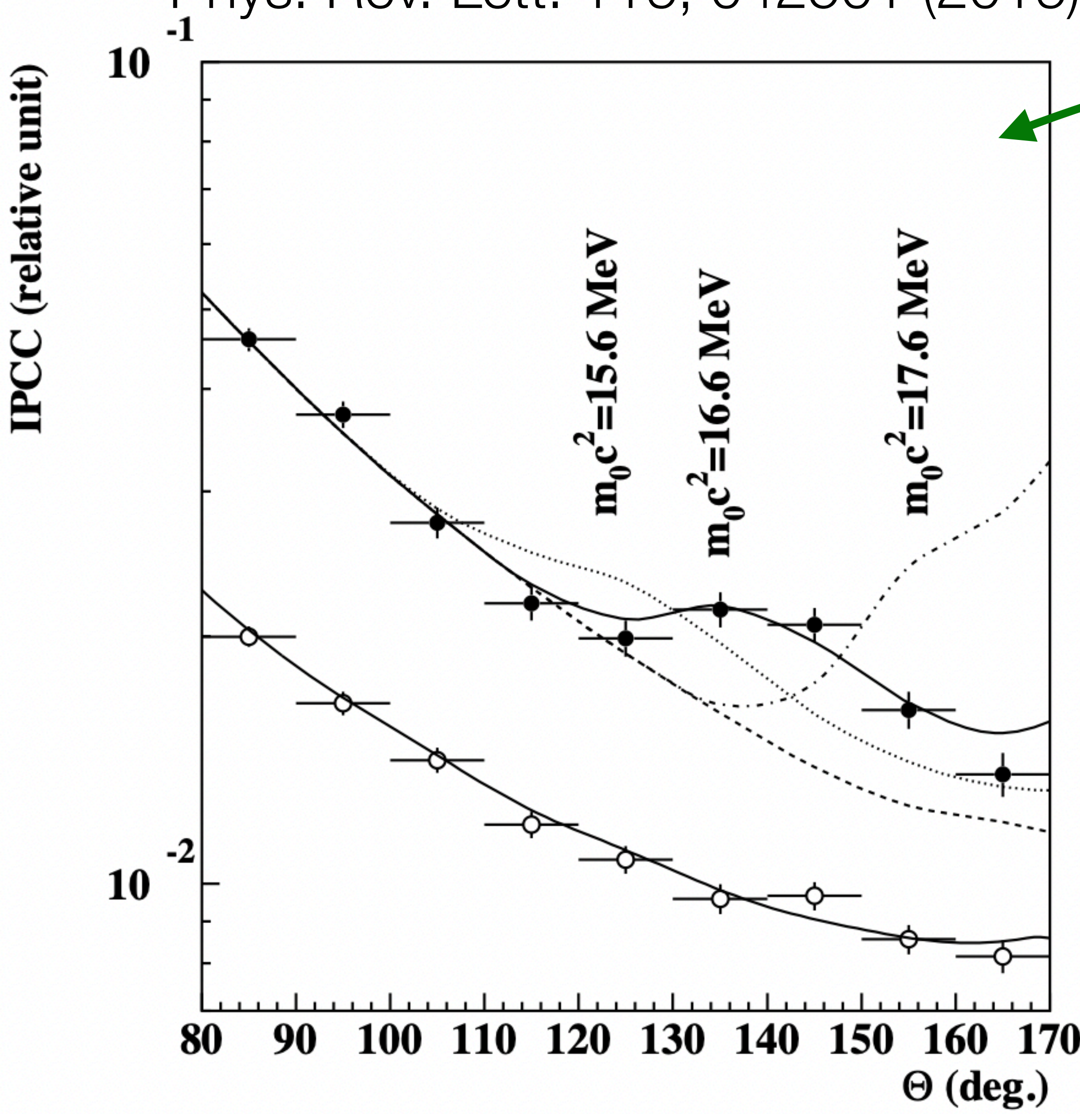
Light BSM boson: the X17 excess

Phys. Rev. D 95, 035017 (2017)



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

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



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

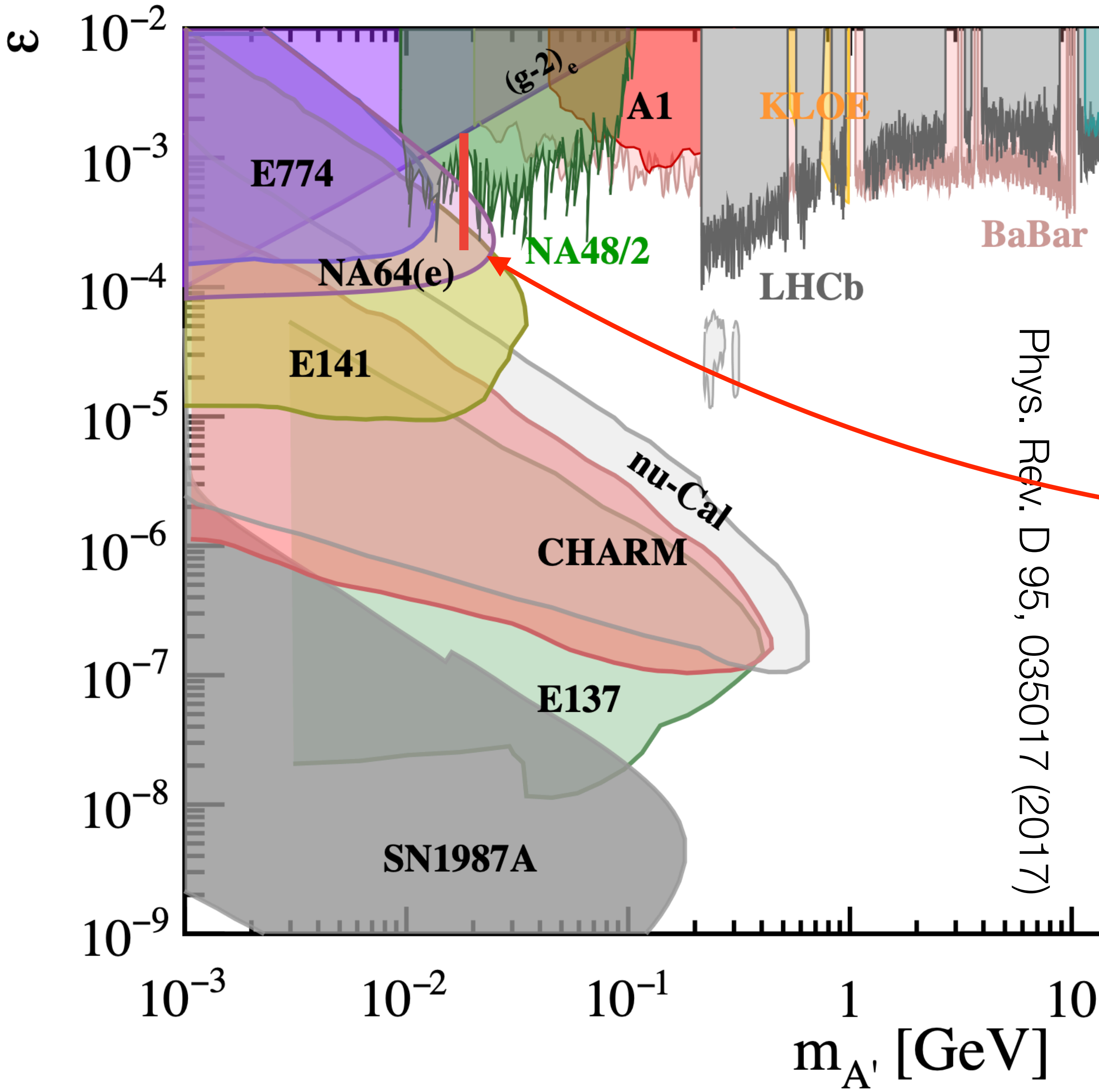
Not-yet-understood detector effect? Unexpected SM cause? Possibly!

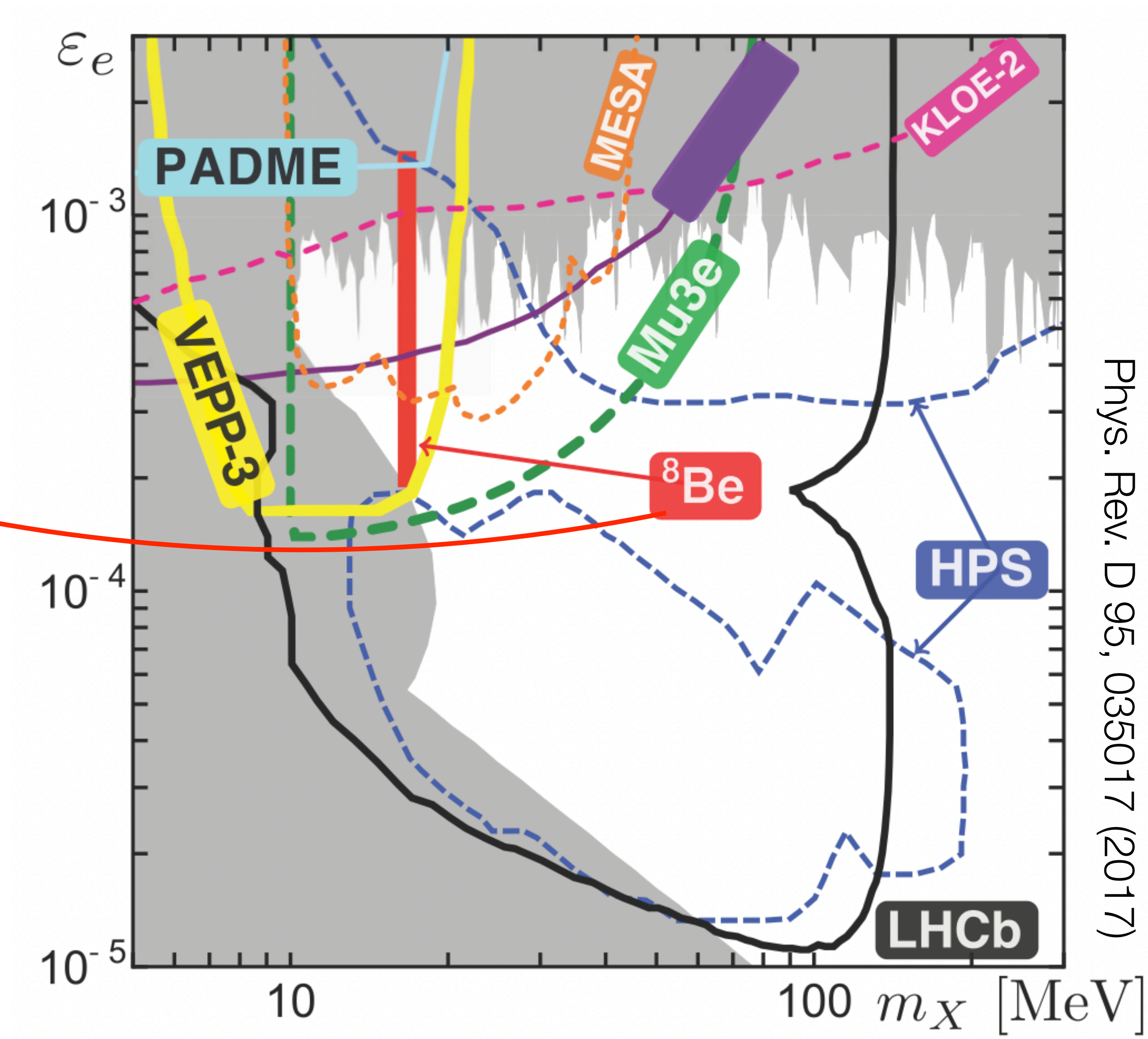
Or, compatible with new boson with mass ~ 17 MeV

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

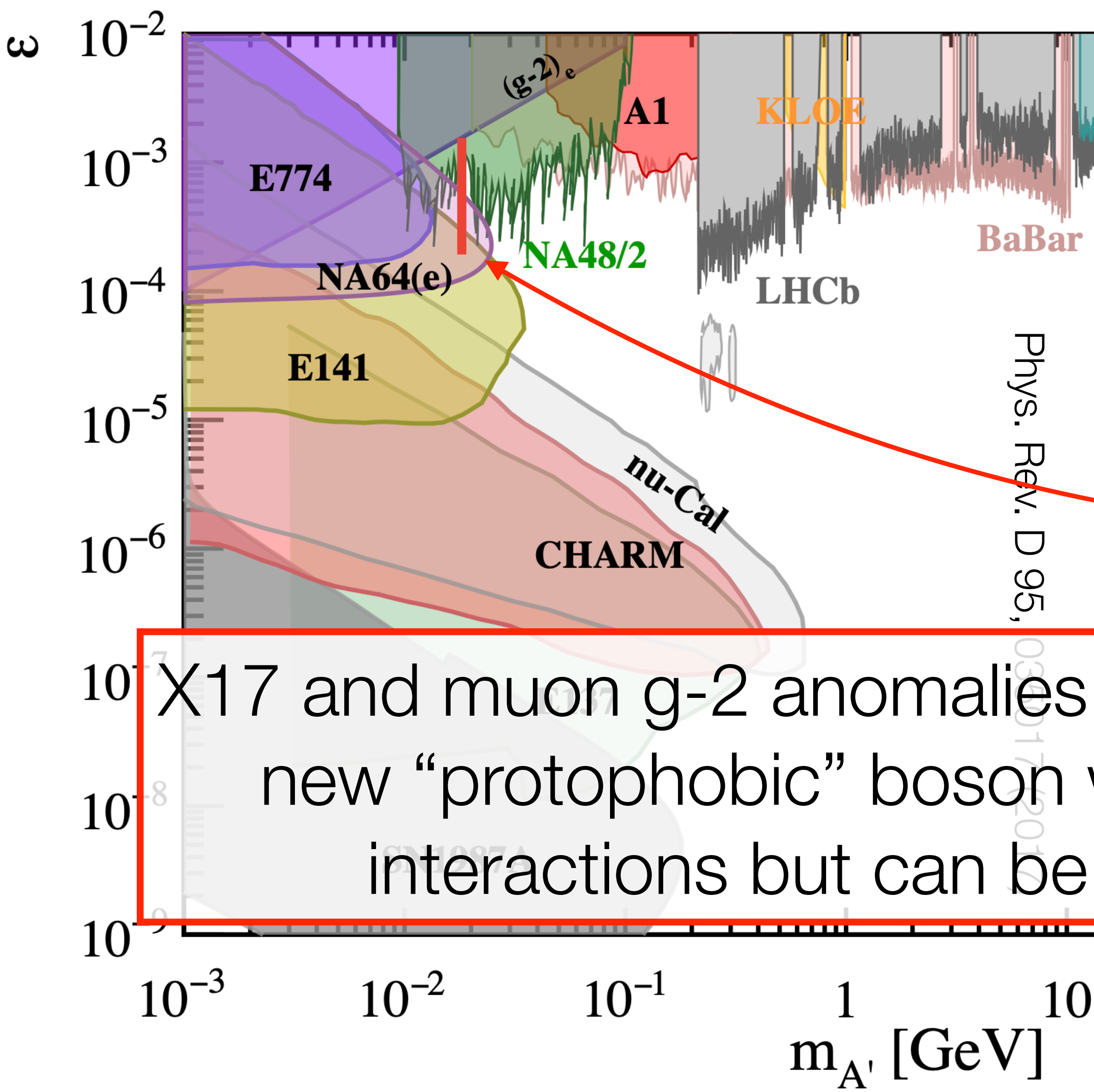


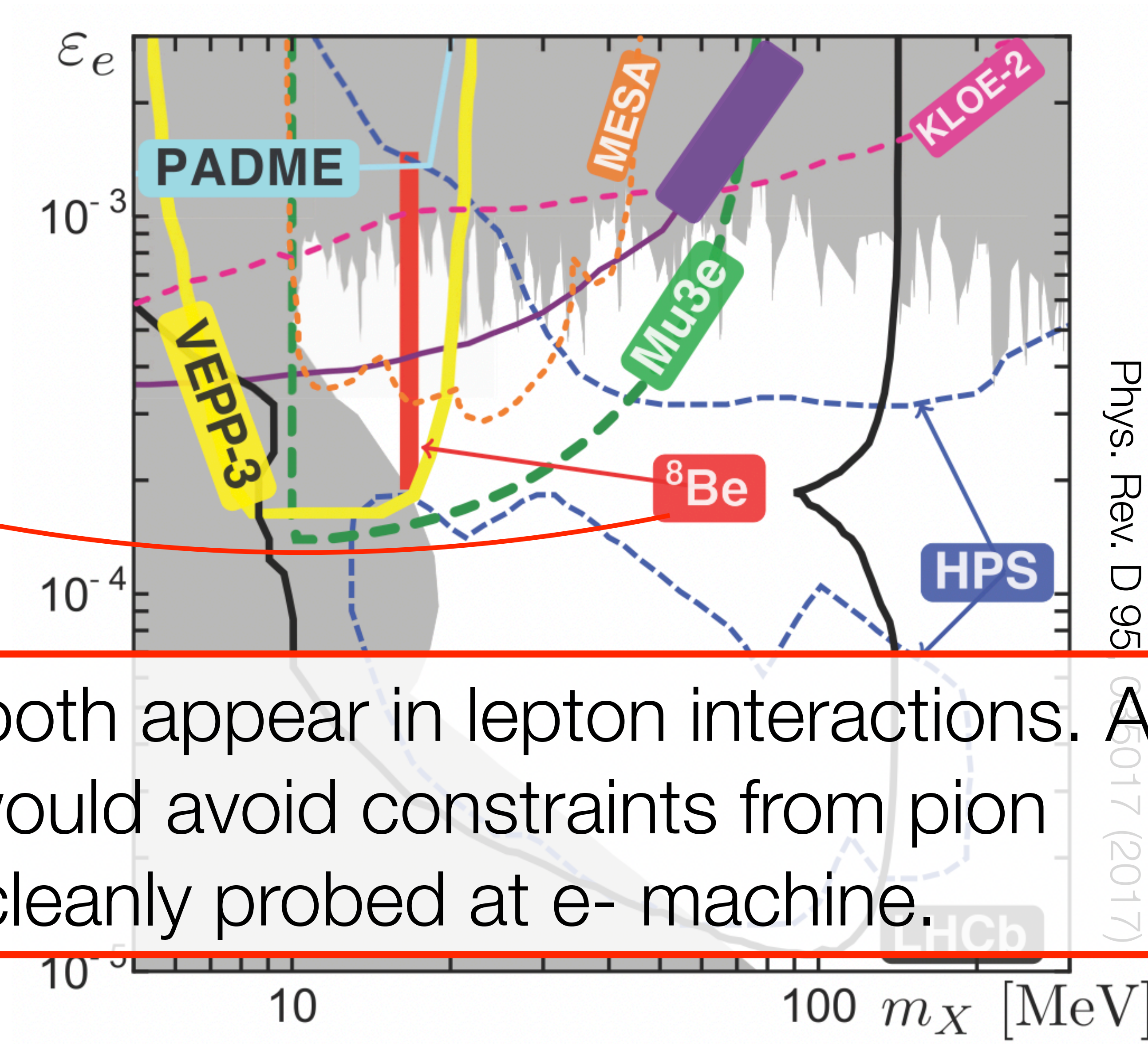


New boson experimental limits: very model dependent statements

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





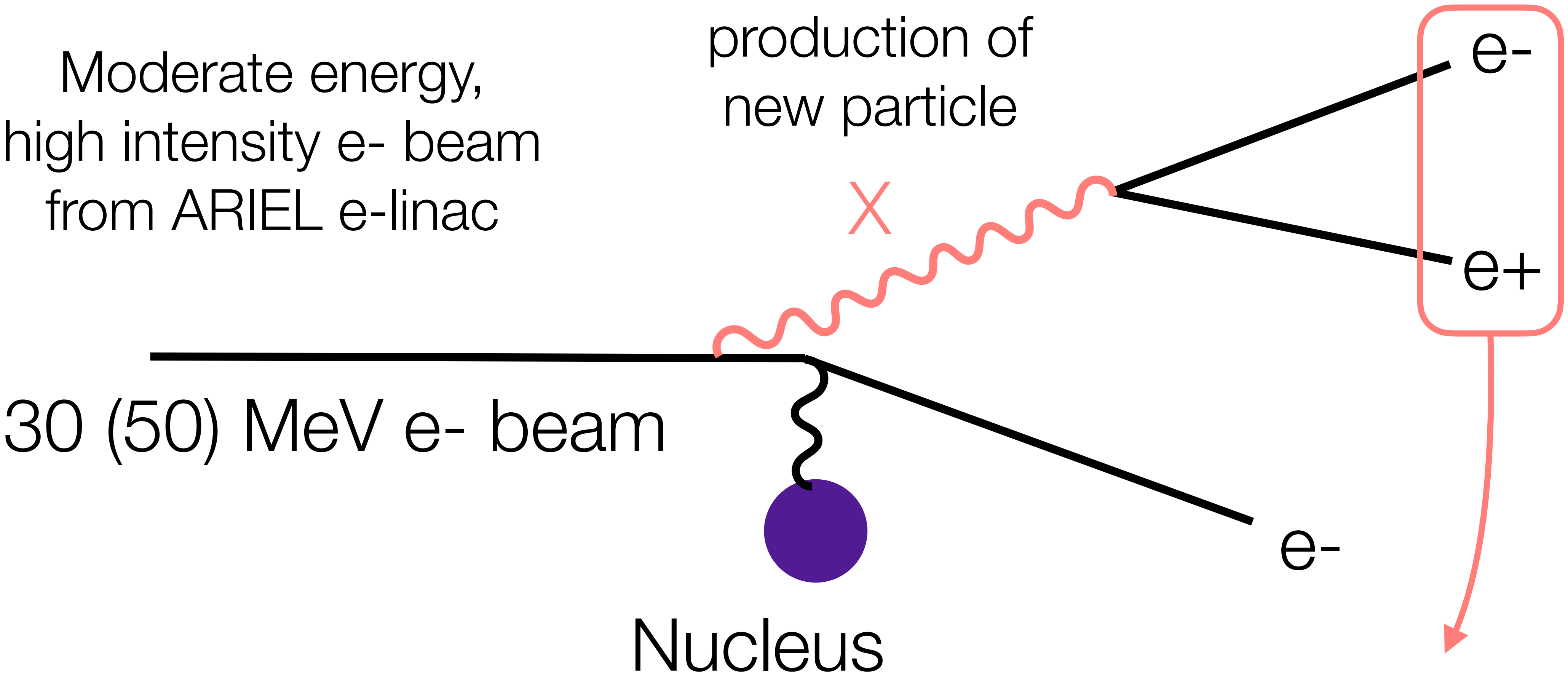
X17 and muon g-2 anomalies both appear in lepton interactions. A new "protophobic" boson would avoid constraints from pion interactions but can be cleanly probed at e- machine.

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

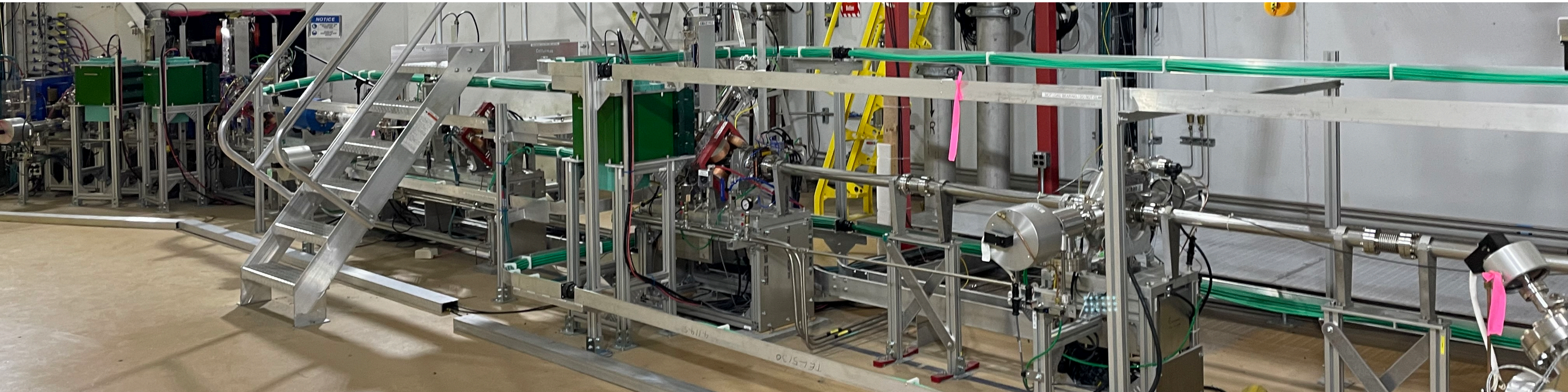


High-N target optimised for minimum multiple scattering: baseline target is 1 µm Tantalum foil

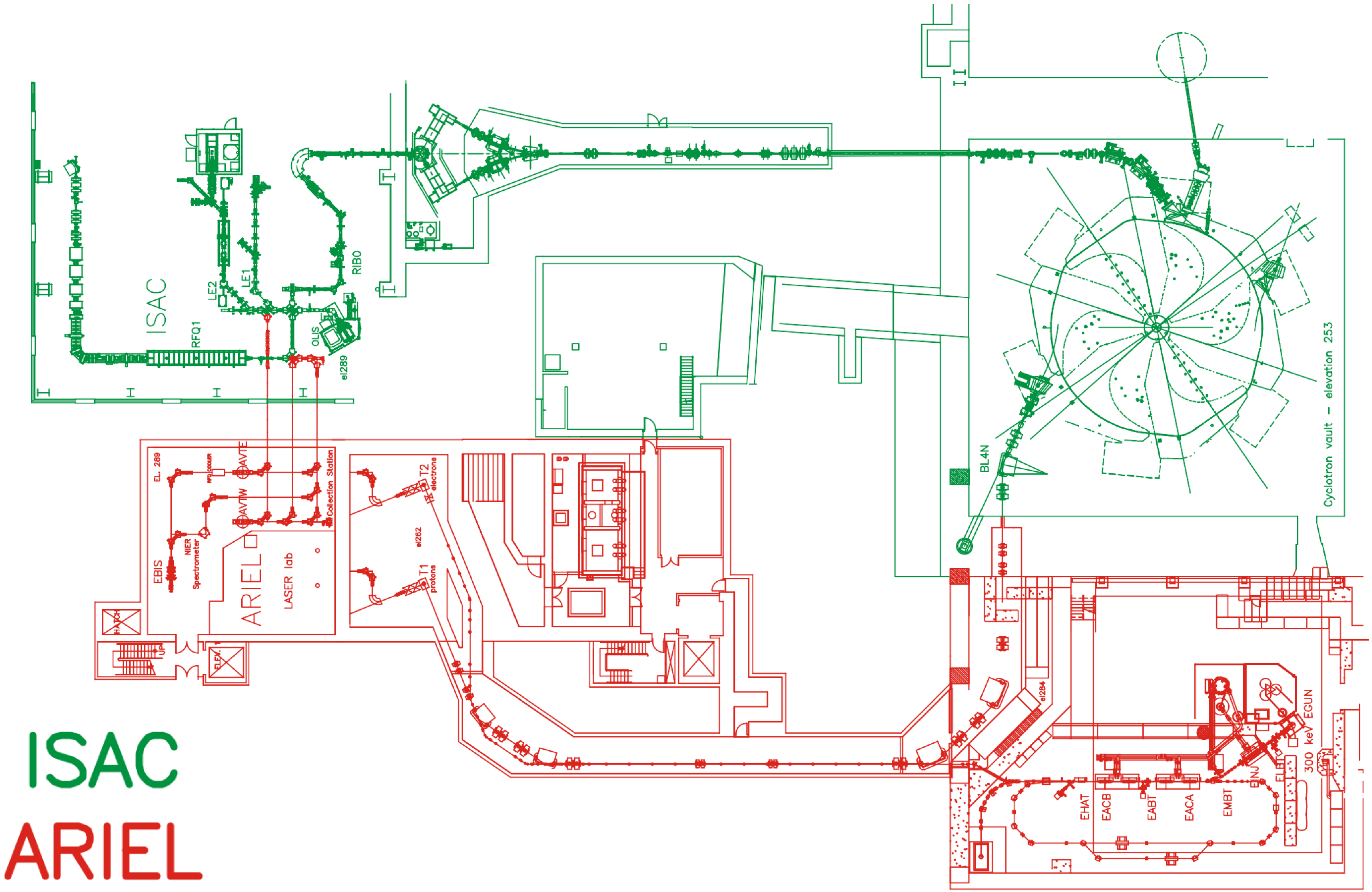
Reconstruct invariant mass of e+e- pair and search for resonant peak over smooth SM background

Collaboration

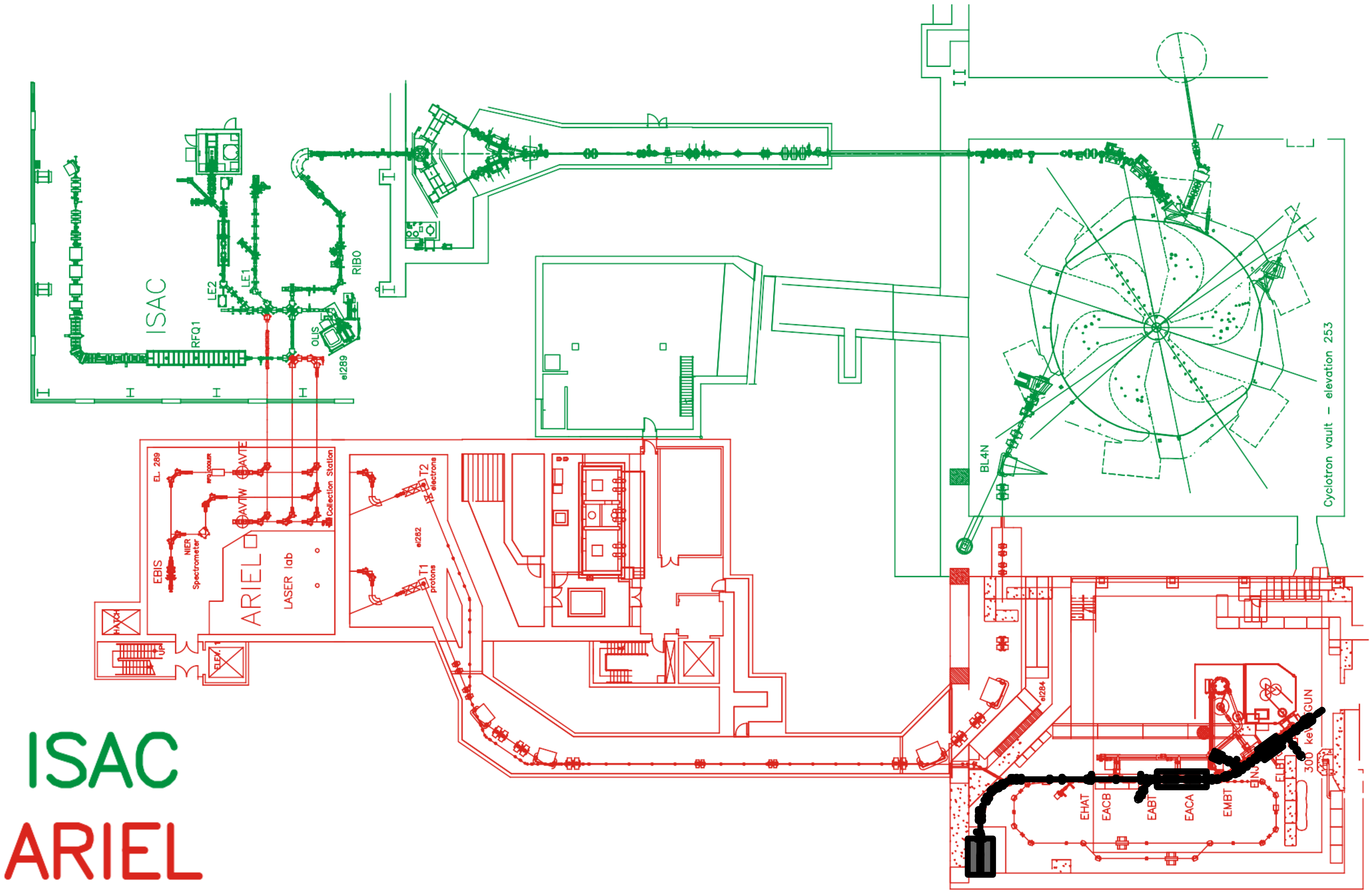
Arizona State University, Tempe, AZ, USA
University of British Columbia, Canada
Hampton University, Hampton, VA, USA
TJNAF, Newport News, VA, USA
Massachusetts Institute of Technology, Cambridge, MA, USA
St. Mary's University, Halifax, Nova Scotia, Canada
Stony Brook University, NY, USA
TRIUMF, Vancouver, British Columbia, Canada
University of Manitoba, Canada
University of Winnipeg, Manitoba, Canada



The accelerator

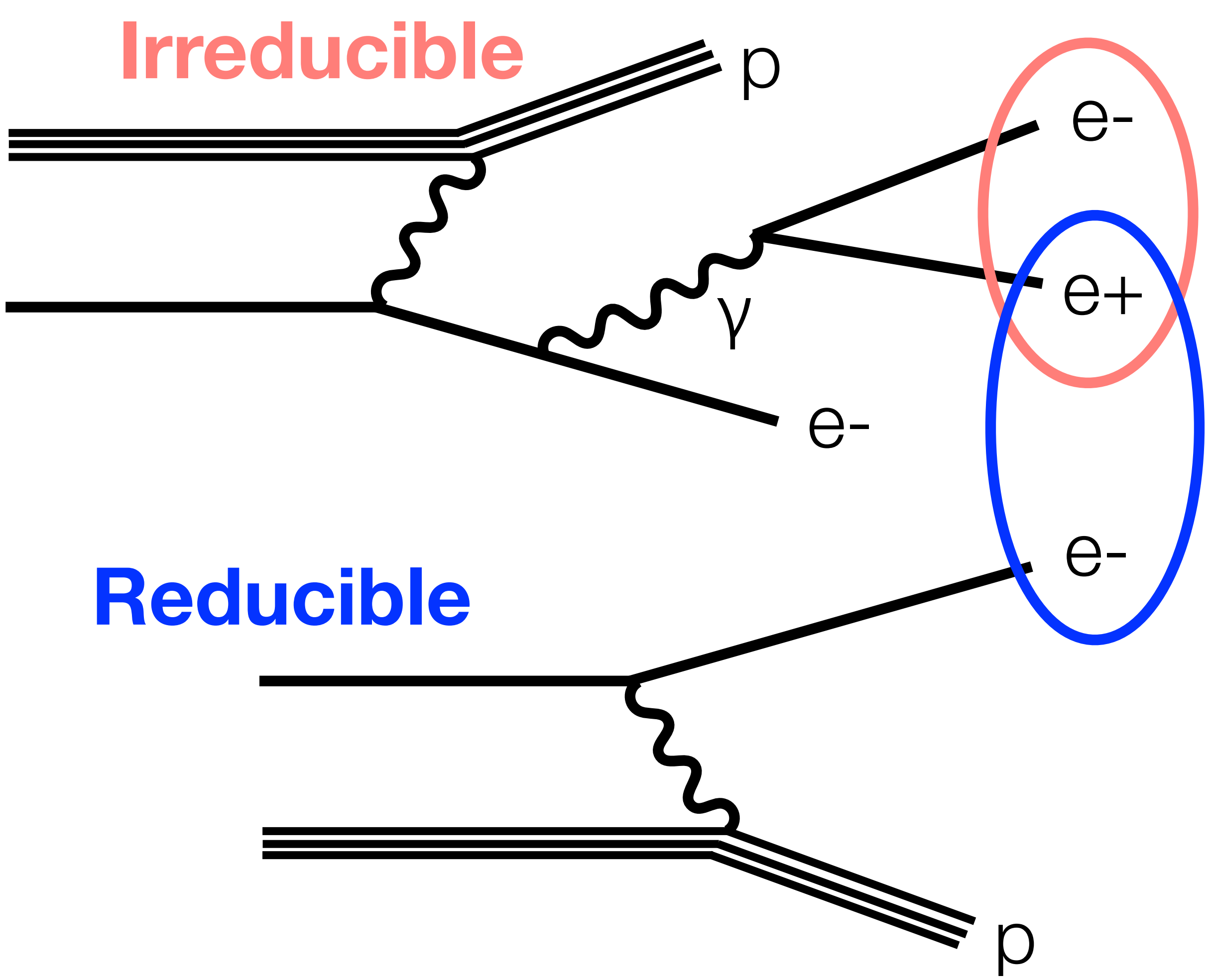


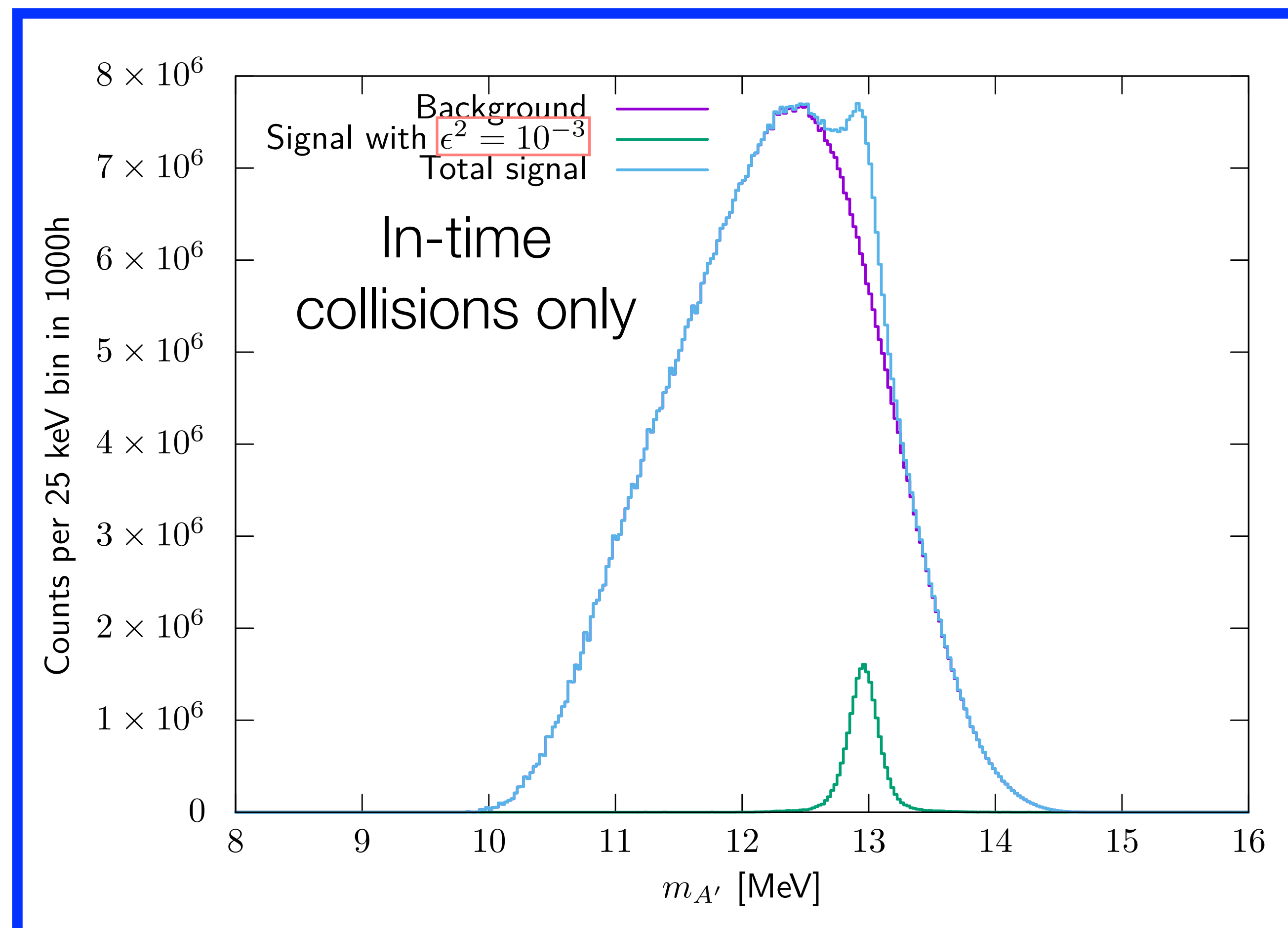
The accelerator



Background processes

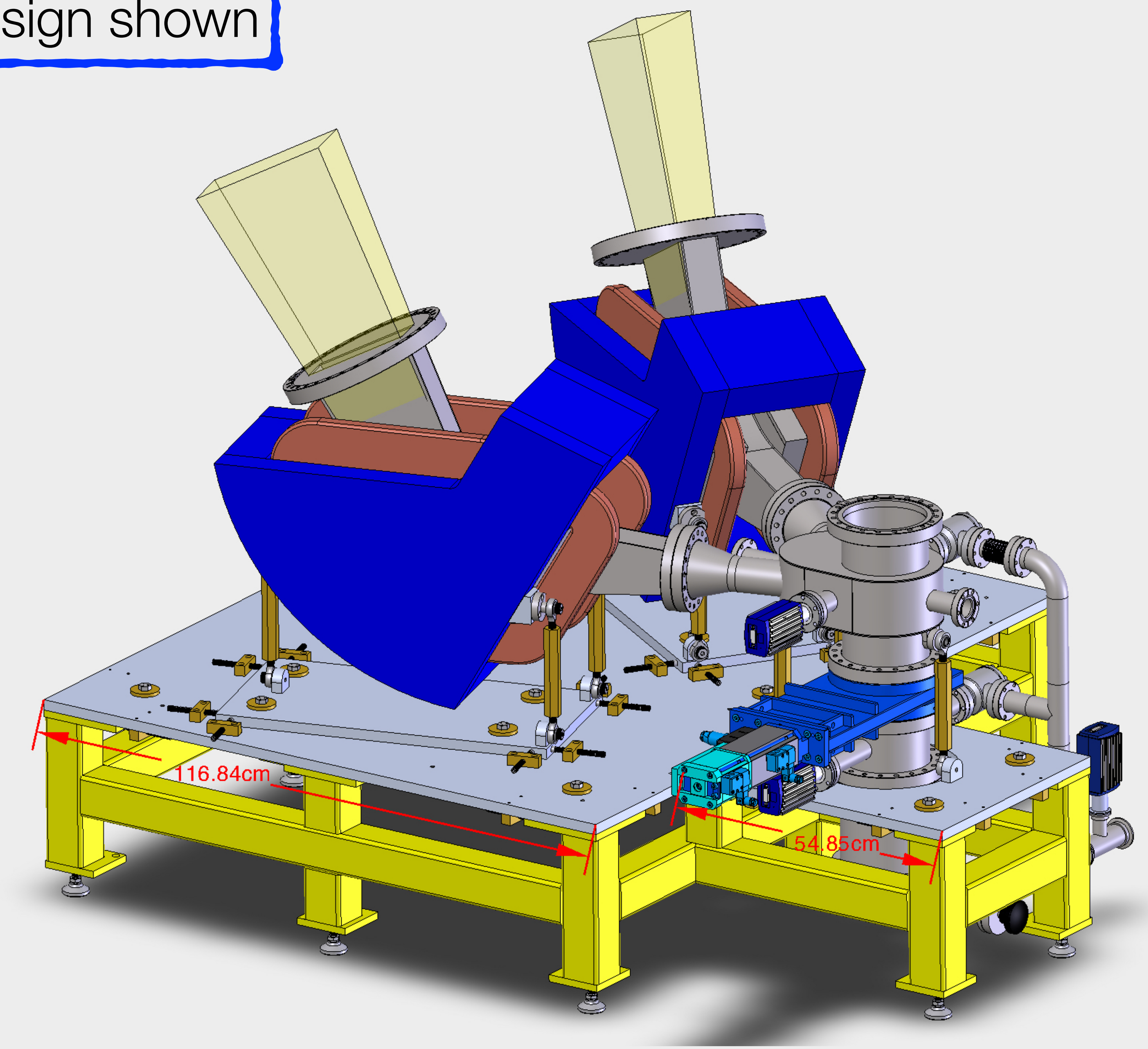
- Vastly dominant background is e+ from pair production combined with e- from simultaneous scattering event. **Coincidence**-based trigger is key
- Two ways to control rates: 1) angular position of detectors 2) timing resolution << bunch spacing (1.5 ns)





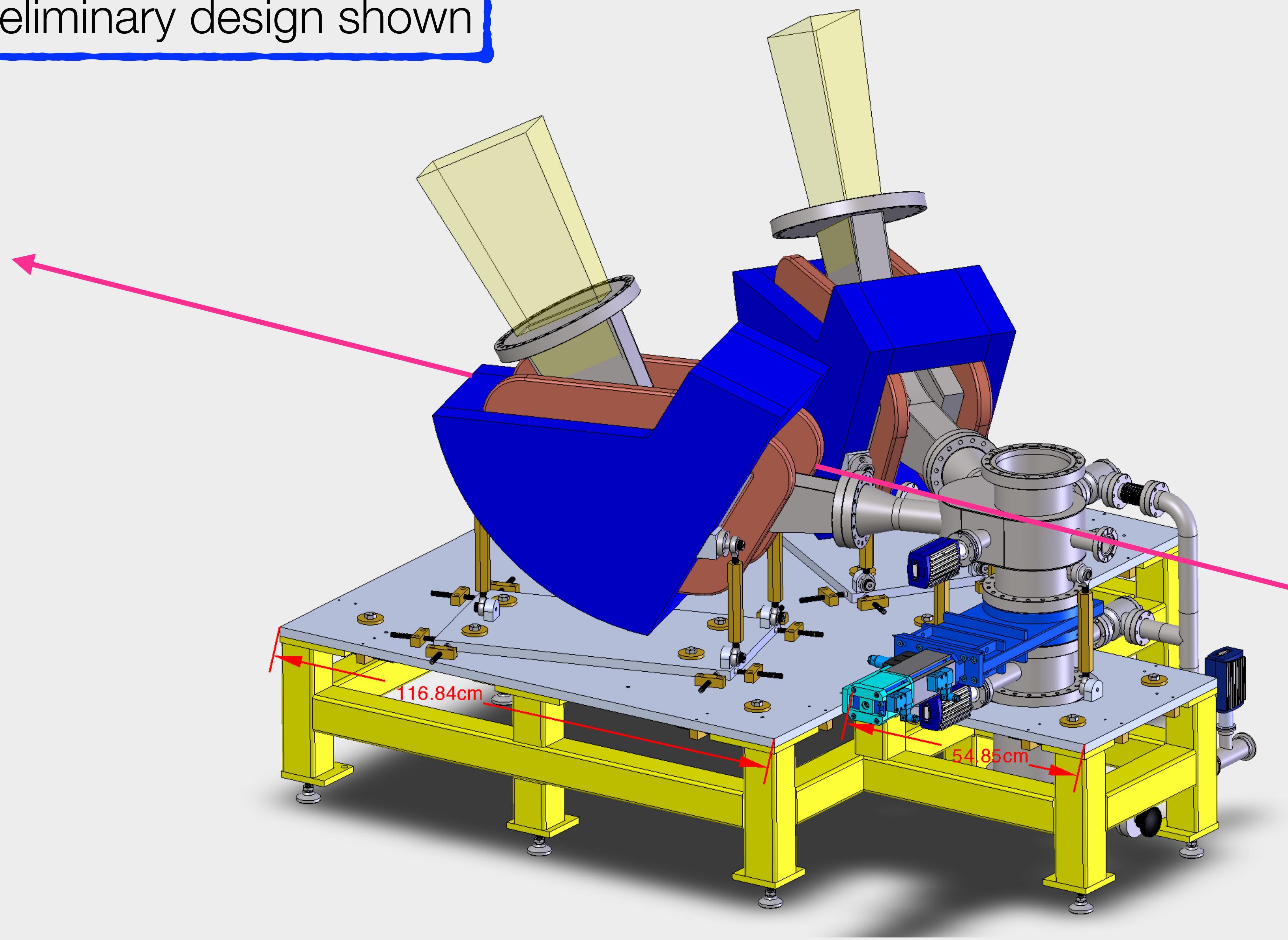
Experiment overview

Preliminary design shown



Experiment overview

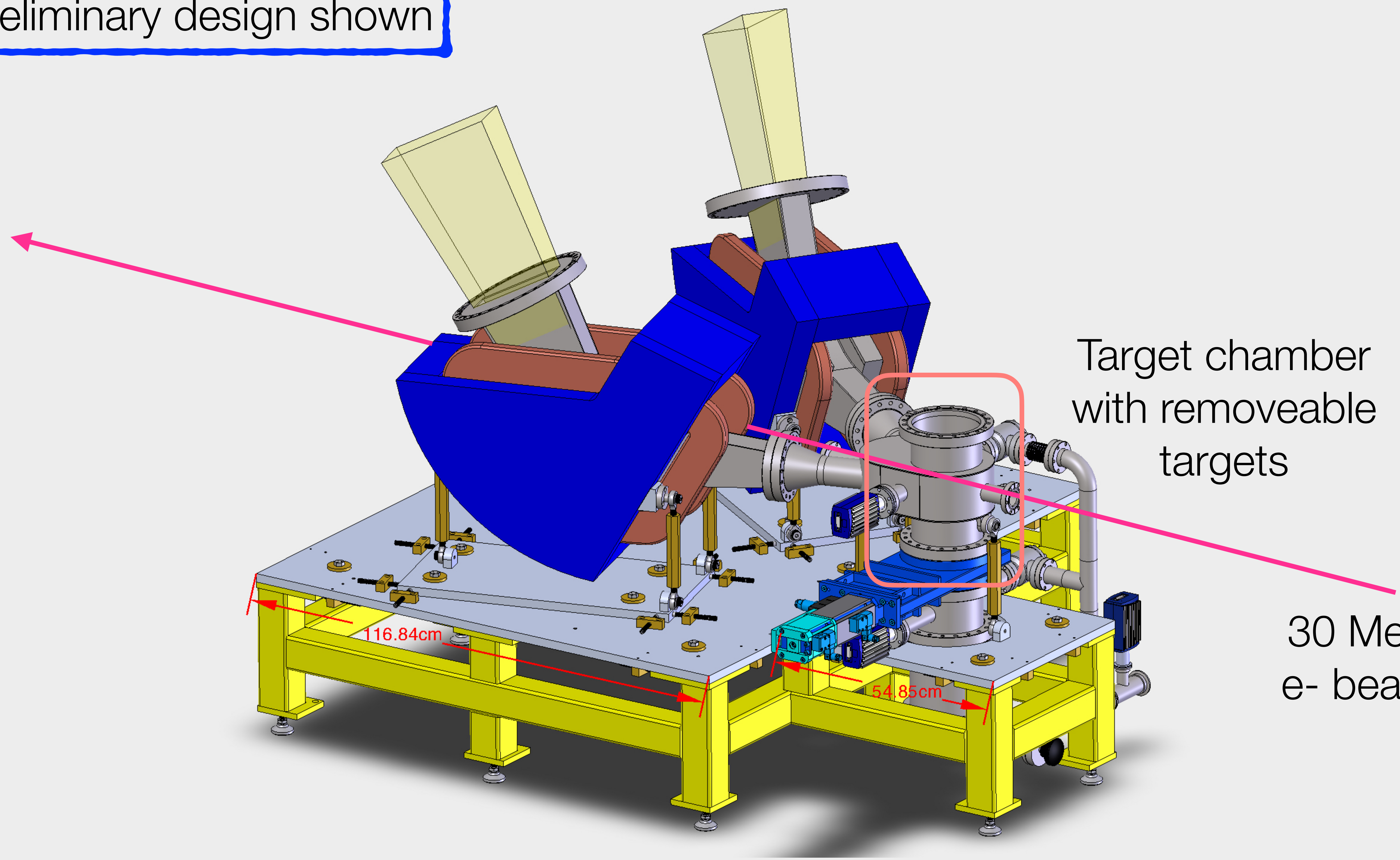
Preliminary design shown



30 MeV
e- beam

Experiment overview

Preliminary design shown

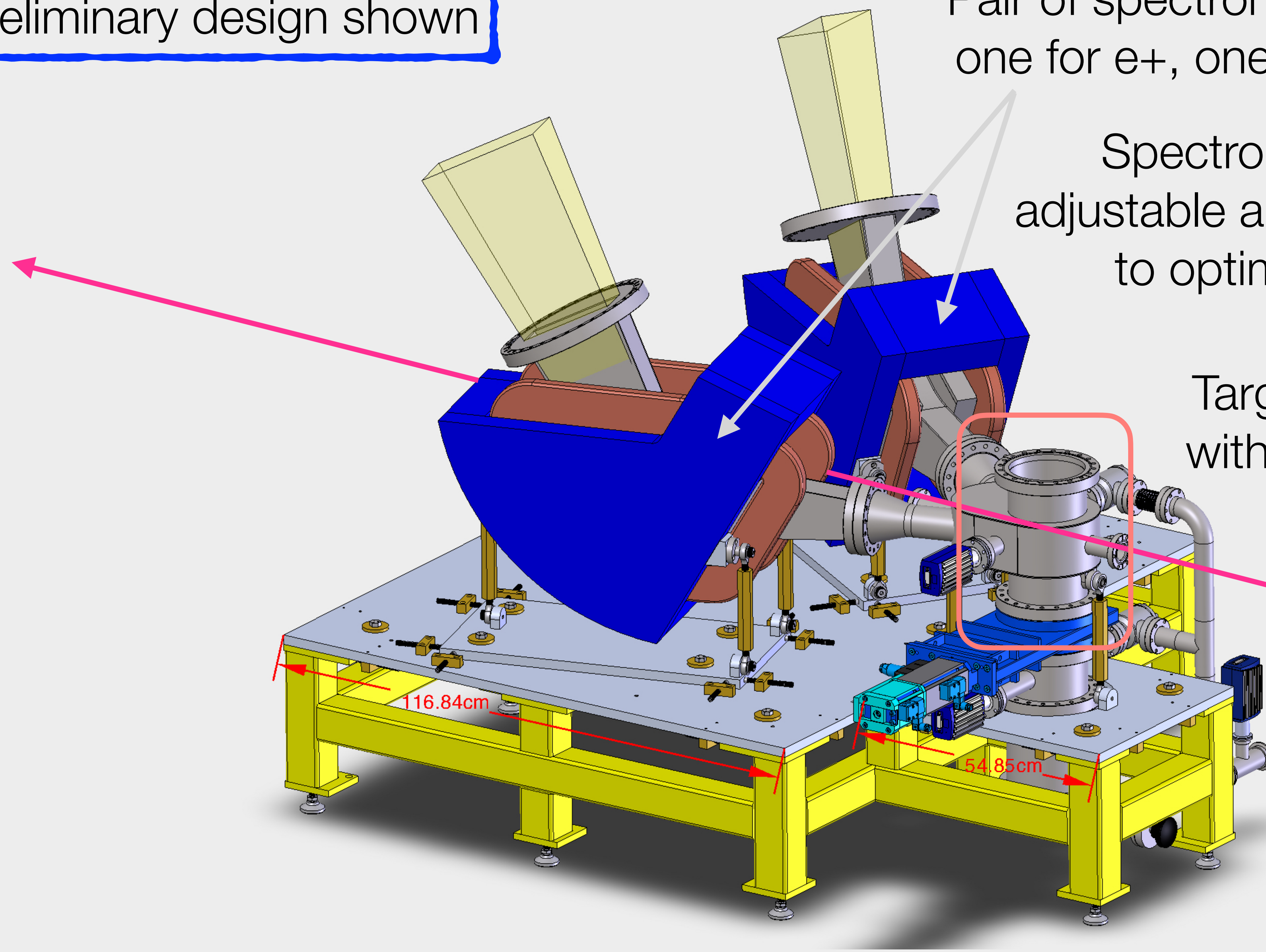


Target chamber with removeable targets

30 MeV e- beam

Experiment overview

Preliminary design shown



Pair of spectrometers: one for e+, one for e-

Spectrometer arms at adjustable angles: asymmetric to optimise selection

Target chamber with removeable targets

30 MeV e- beam

Experiment overview

Preliminary design shown

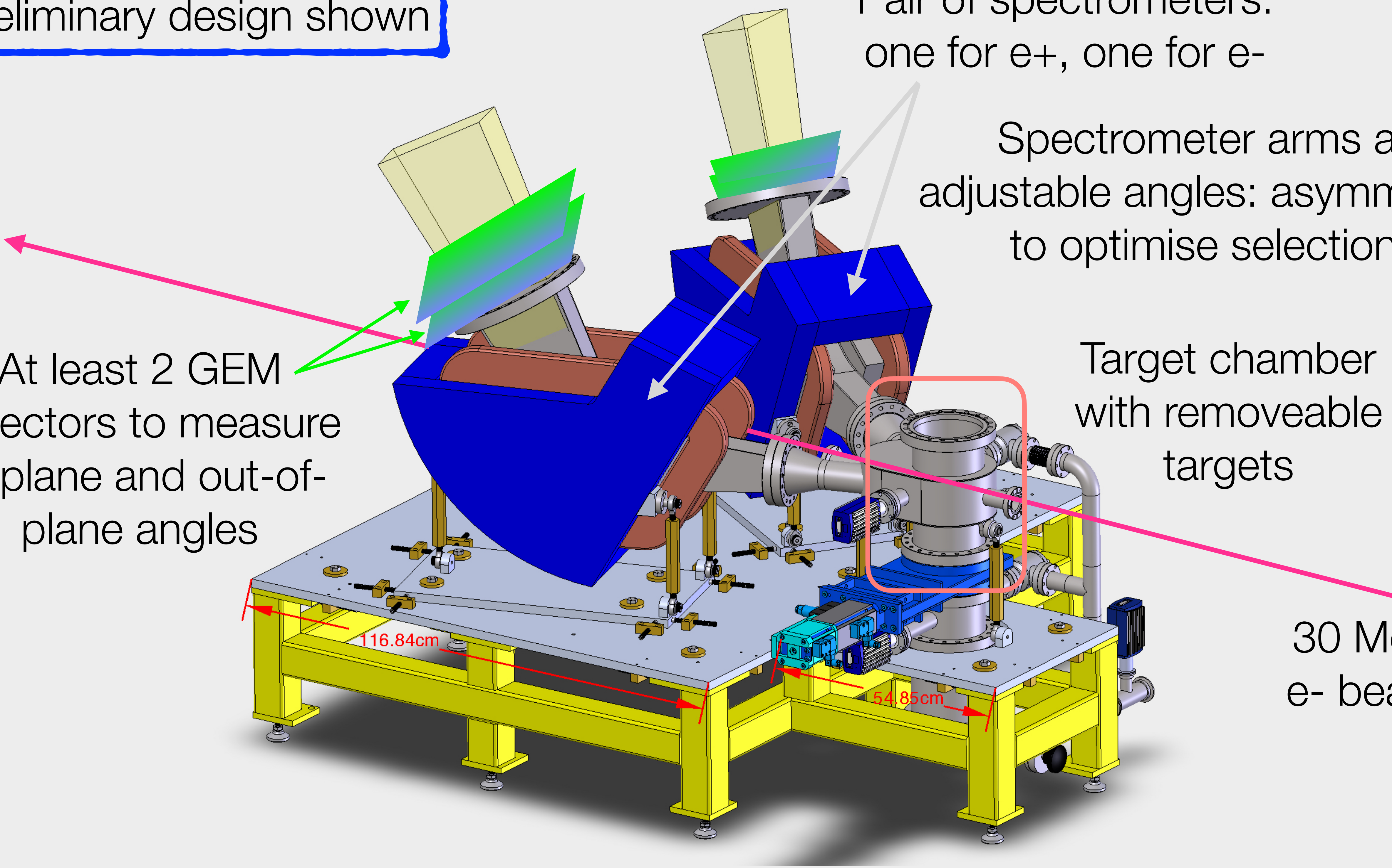
Pair of spectrometers:
one for e+, one for e-

Spectrometer arms at adjustable angles: asymmetric to optimise selection

At least 2 GEM detectors to measure in-plane and out-of-plane angles

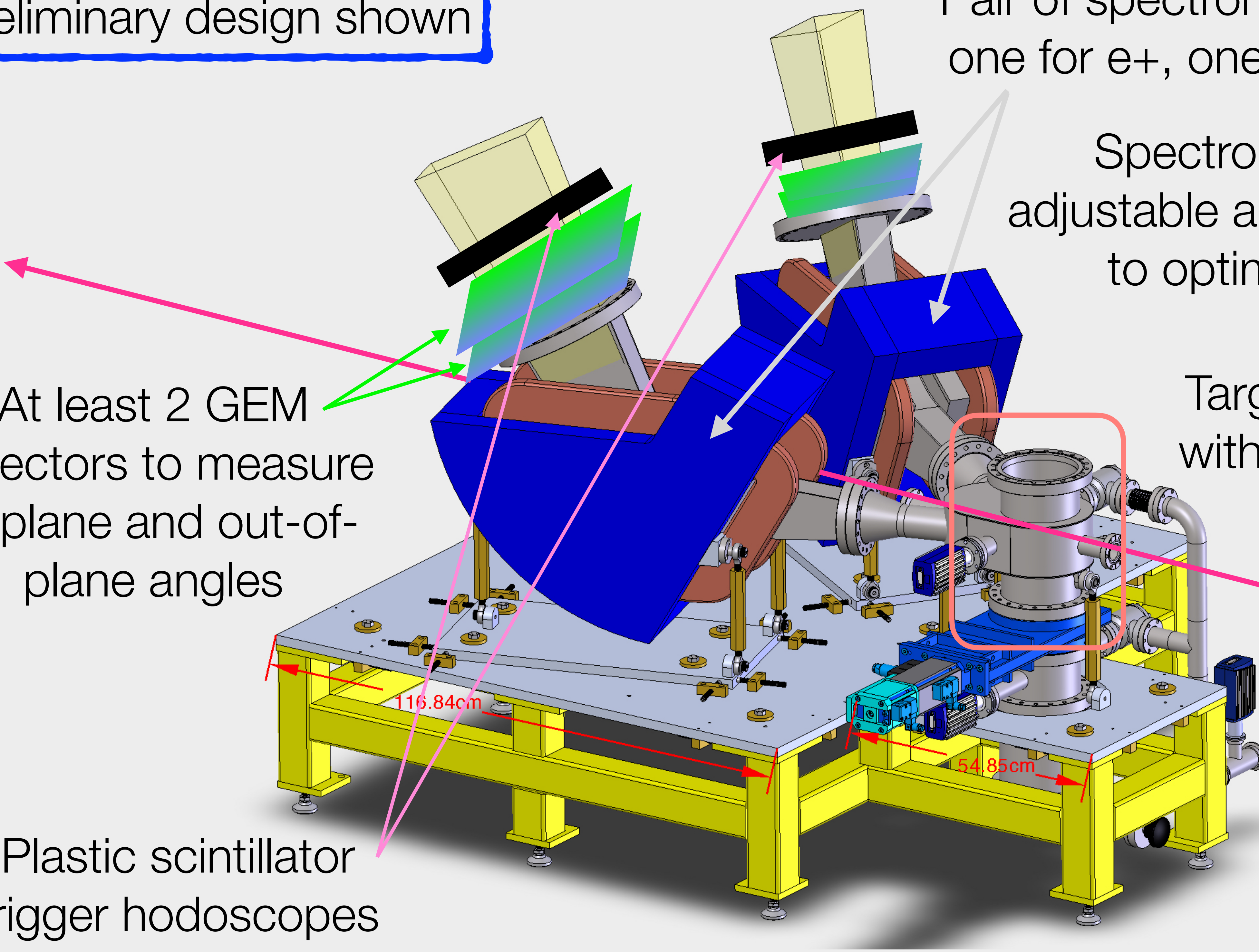
Target chamber with removeable targets

30 MeV
e- beam



Experiment overview

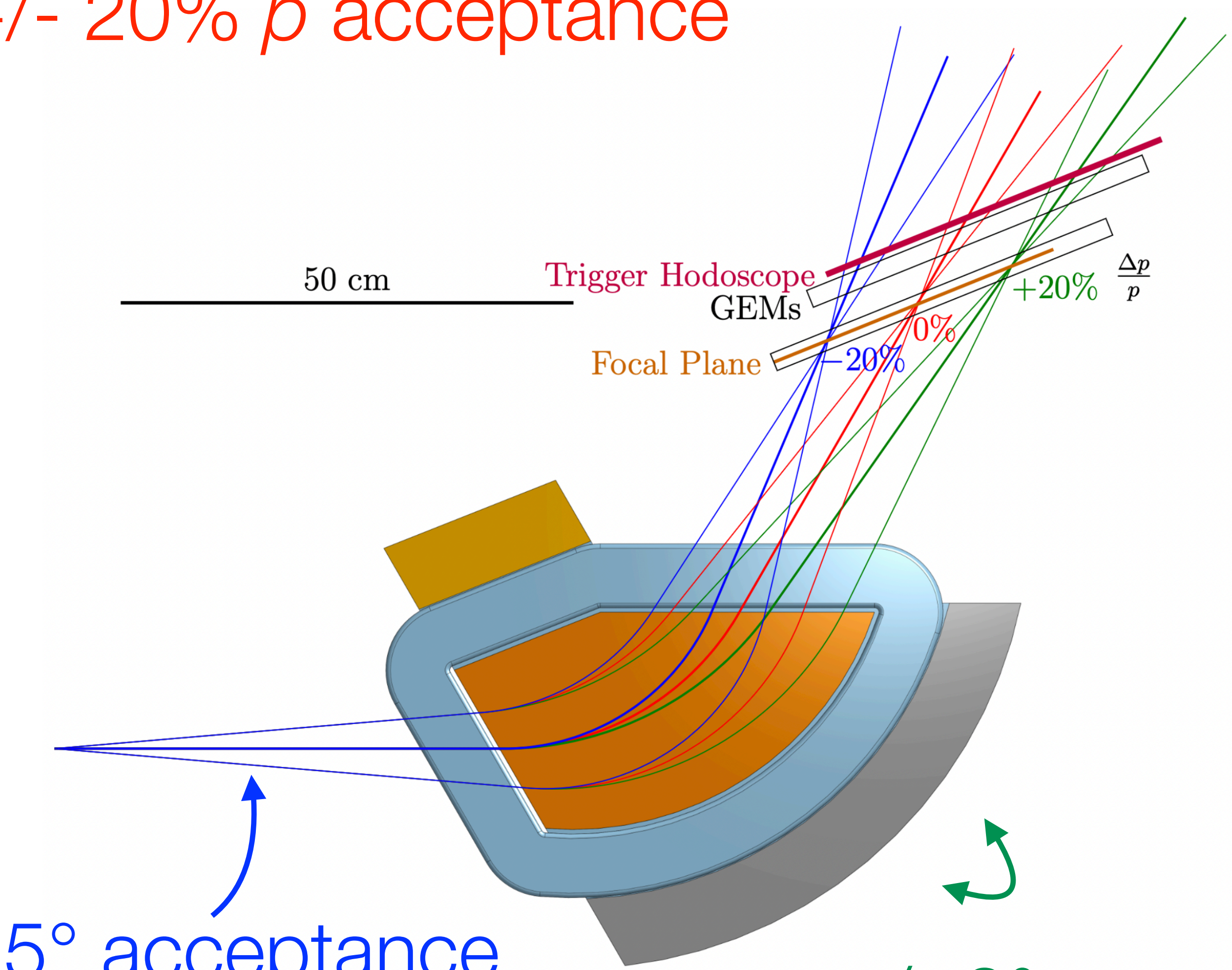
Preliminary design shown



Experiment status: spectrometers

- Two identical dipole spectrometers, 0.32 T
- Simulations ongoing to optimise mass resolution
- Main constraint: space
  - Size of magnet + beamline restrict possible angles for spectrometer

+/- 20% p acceptance

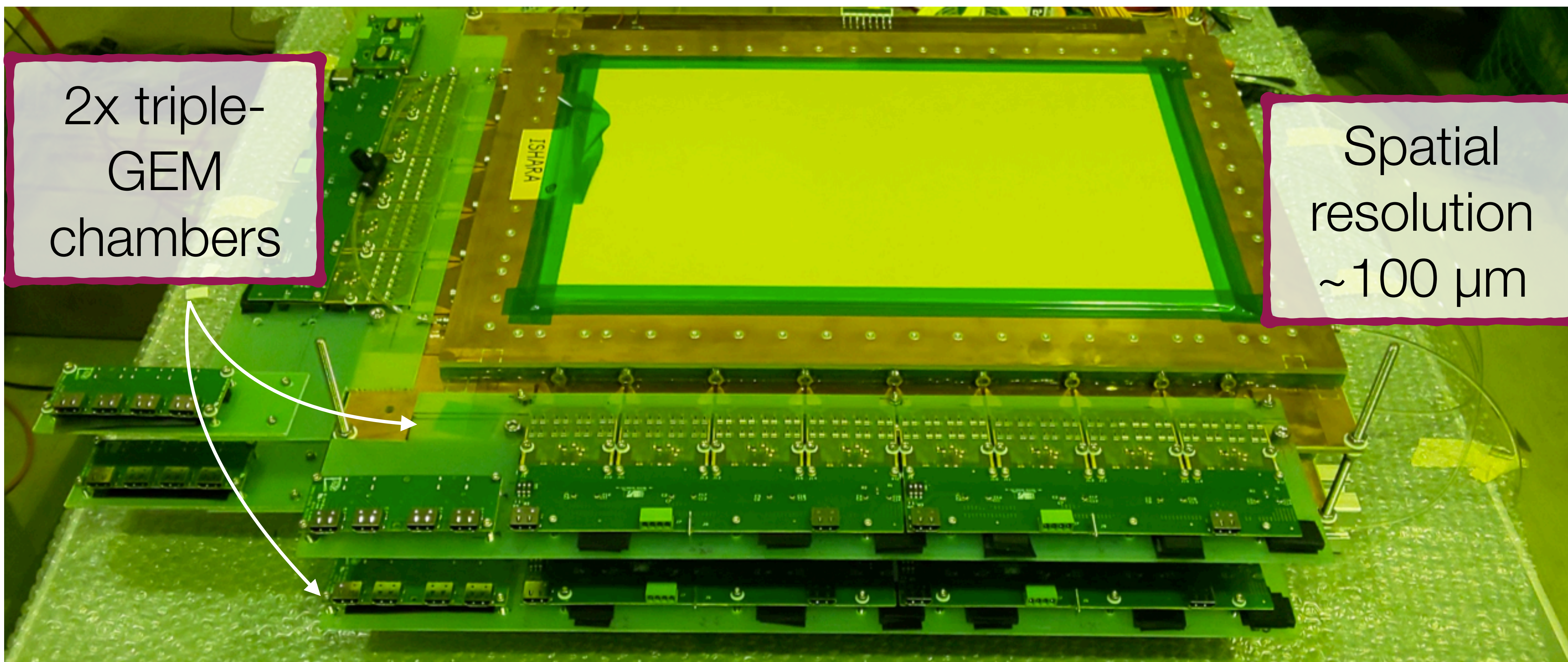


+/- 5° acceptance in this dimension

+/- 2° acceptance the other way

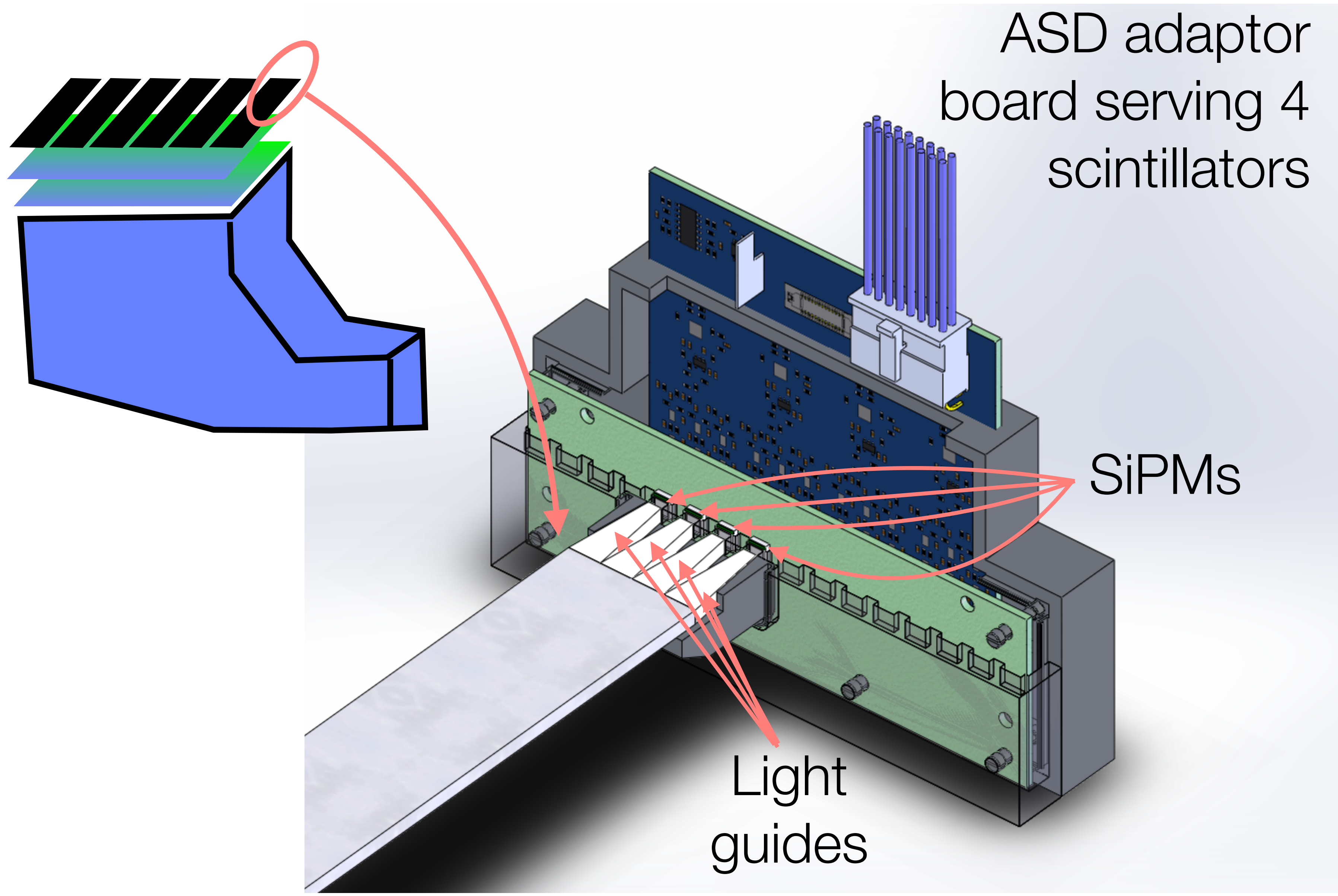
Experiment status: GEM detectors

- 25 x 40 cm triple-GEMs **already completed** by Hampton University collaborators
- Commissioning to be completed in next 6 to 9 months (JLab/ELPH)



Experiment status: trigger detectors

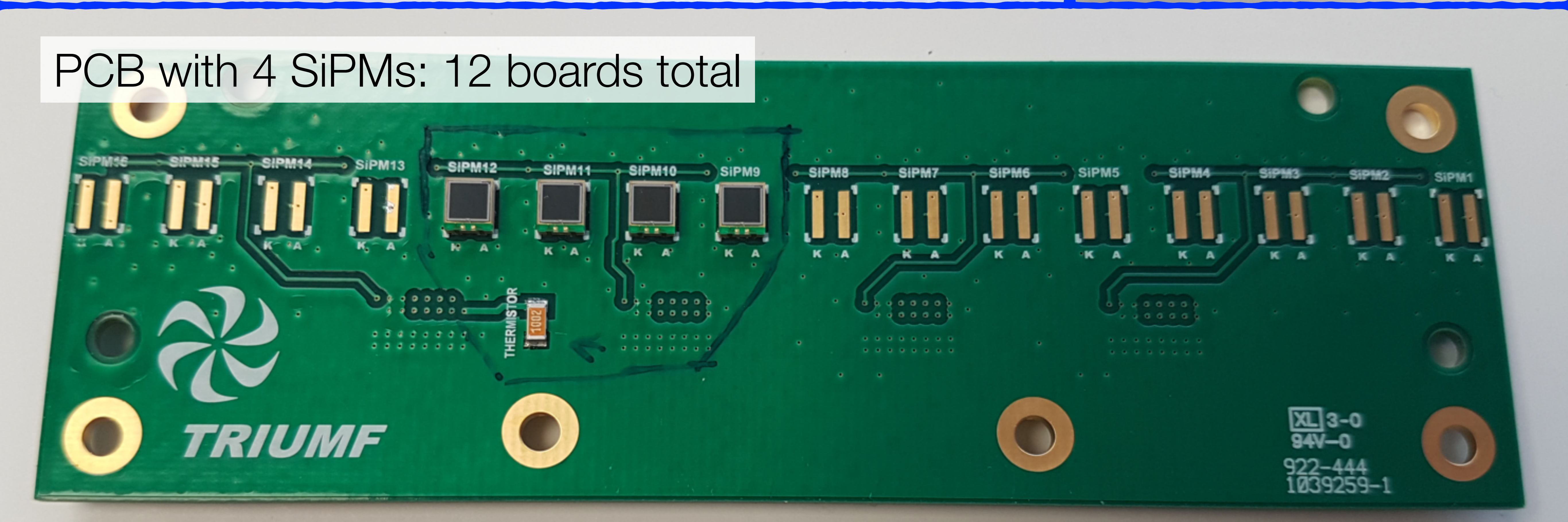
- Key performance metric: timing resolution ~200 ps
- 8 - 10 strips of fast plastic scintillator read out is via SiPMs, four per side per strip
- First prototypes being tested at TRIUMF now



Prototype scintillator dimensions:
150 mm x 30 mm x 3 mm

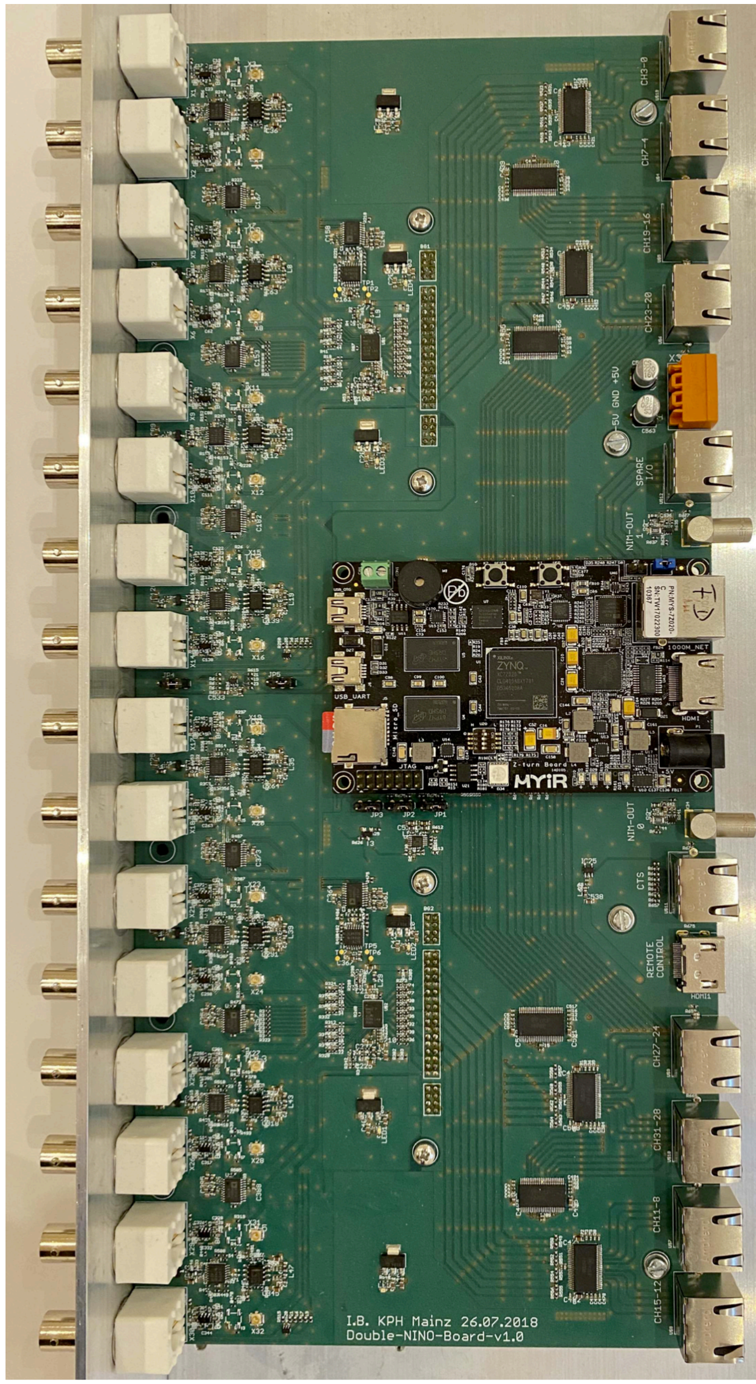

Scintillators mid-wrapping…


… and wrapped


PCB with 4 SiPMs: 12 boards total
SiPM12
SiPM11
SiPM10
SiPM9
SiPM8
SiPM7
SiPM6
SiPM5
SiPM4
SiPM3
SiPM2
SiPM1
THERMISTOR
TRIUMF
922-444
1039259-1

Experiment status: read-out and DAQ

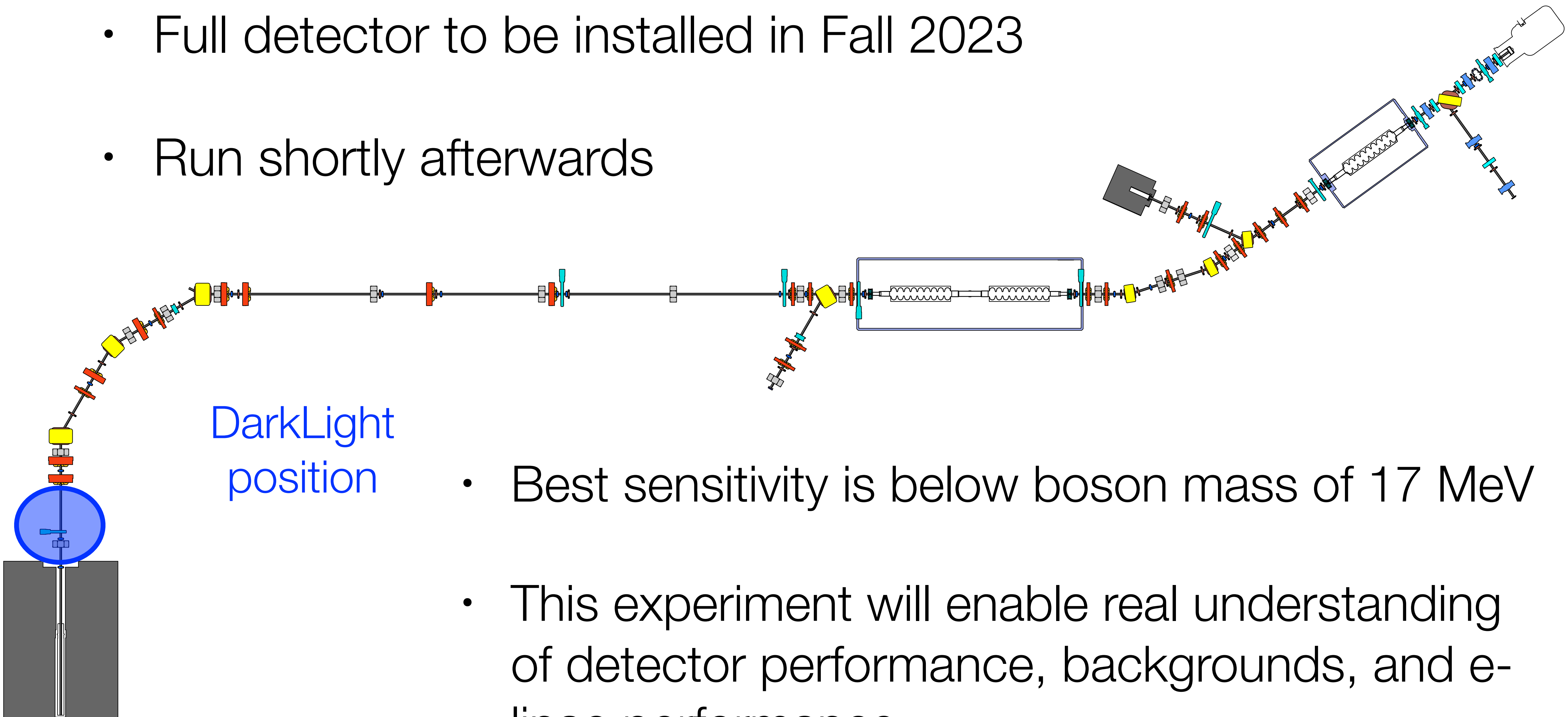
- GEM read-out electronics already in place: timing ~ 200 μs
- Trigger uses coincidence of scintillator outputs
    - Discrimination step, then FPGA will determine coincidence between individual scintillator strip pairs
- Investigated various existing systems
    - Likely to begin from trigger design of MAGIX experiment: similar timing resolution and a compact design
- DAQ software will be handled by Stony Brook + TRIUMF



MAGIX board with 32 inputs & FPGA
H. Merkel

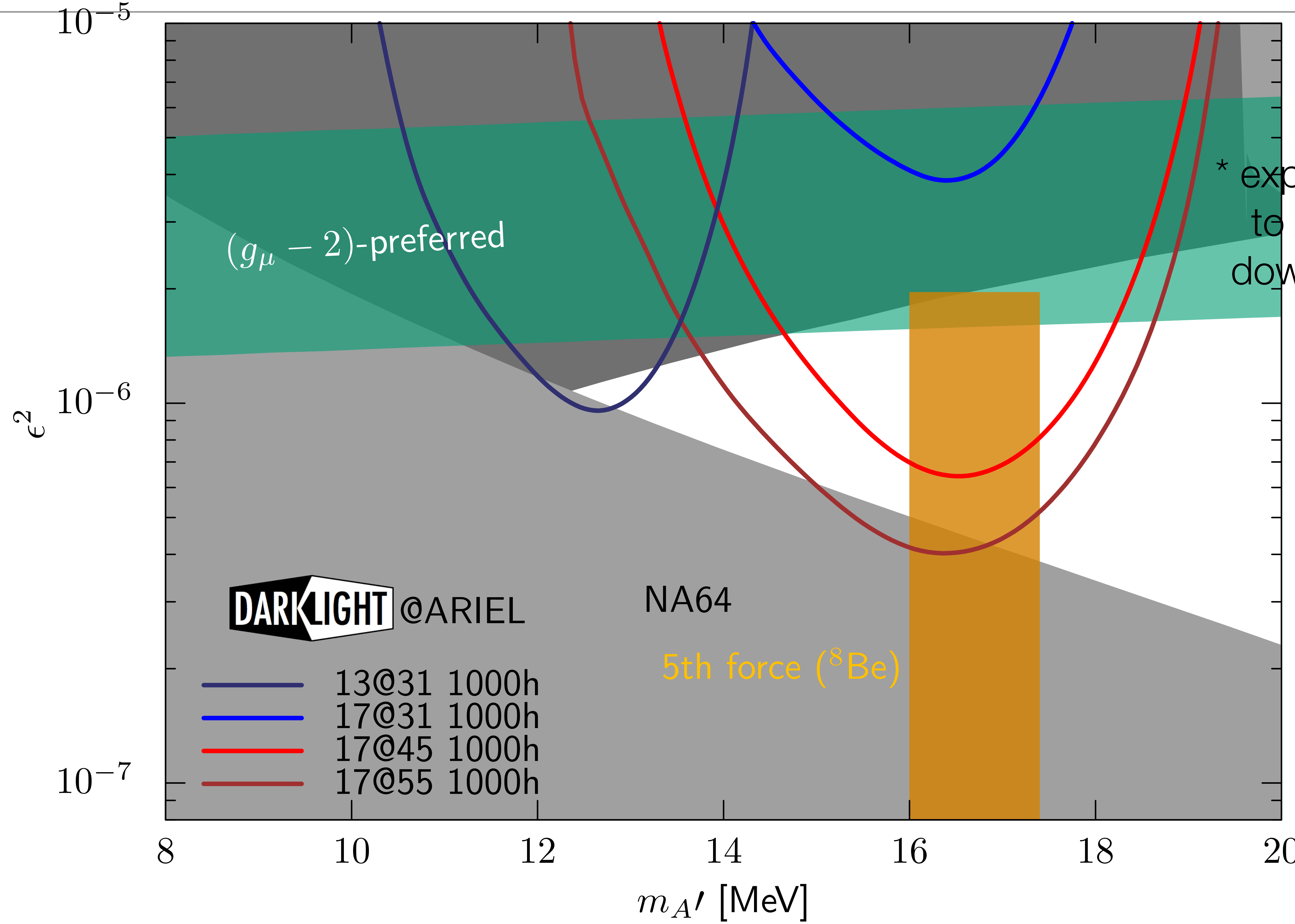
30 MeV running with current ARIEL e-linac

- First experimental stage is a full run (18 fb^{-1}) at 30 MeV
  - Full detector to be installed in Fall 2023
  - Run shortly afterwards



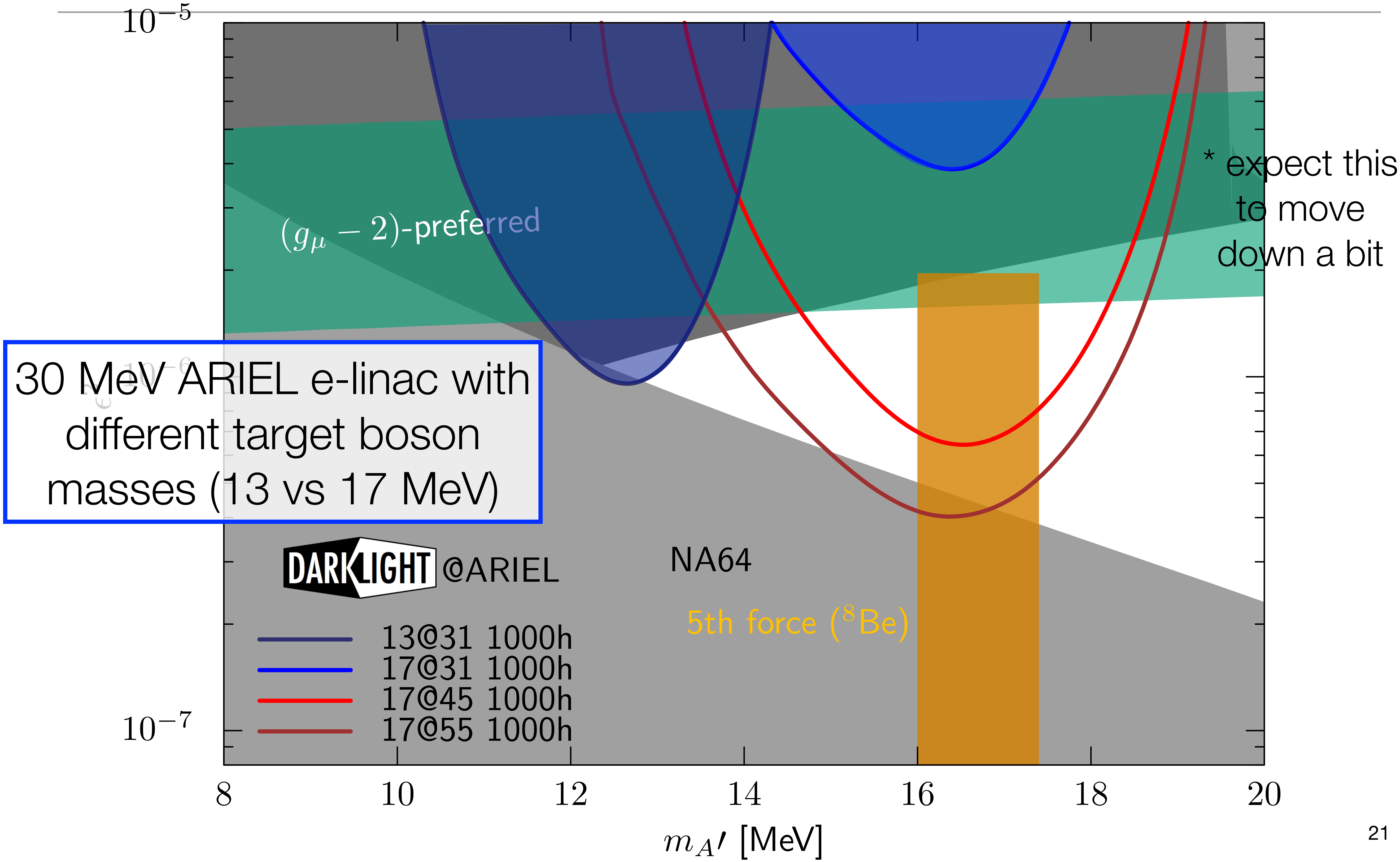
- Best sensitivity is below boson mass of 17 MeV
- This experiment will enable real understanding of detector performance, backgrounds, and e-linac performance

Sensitivity at 30 and 50 MeV accelerators



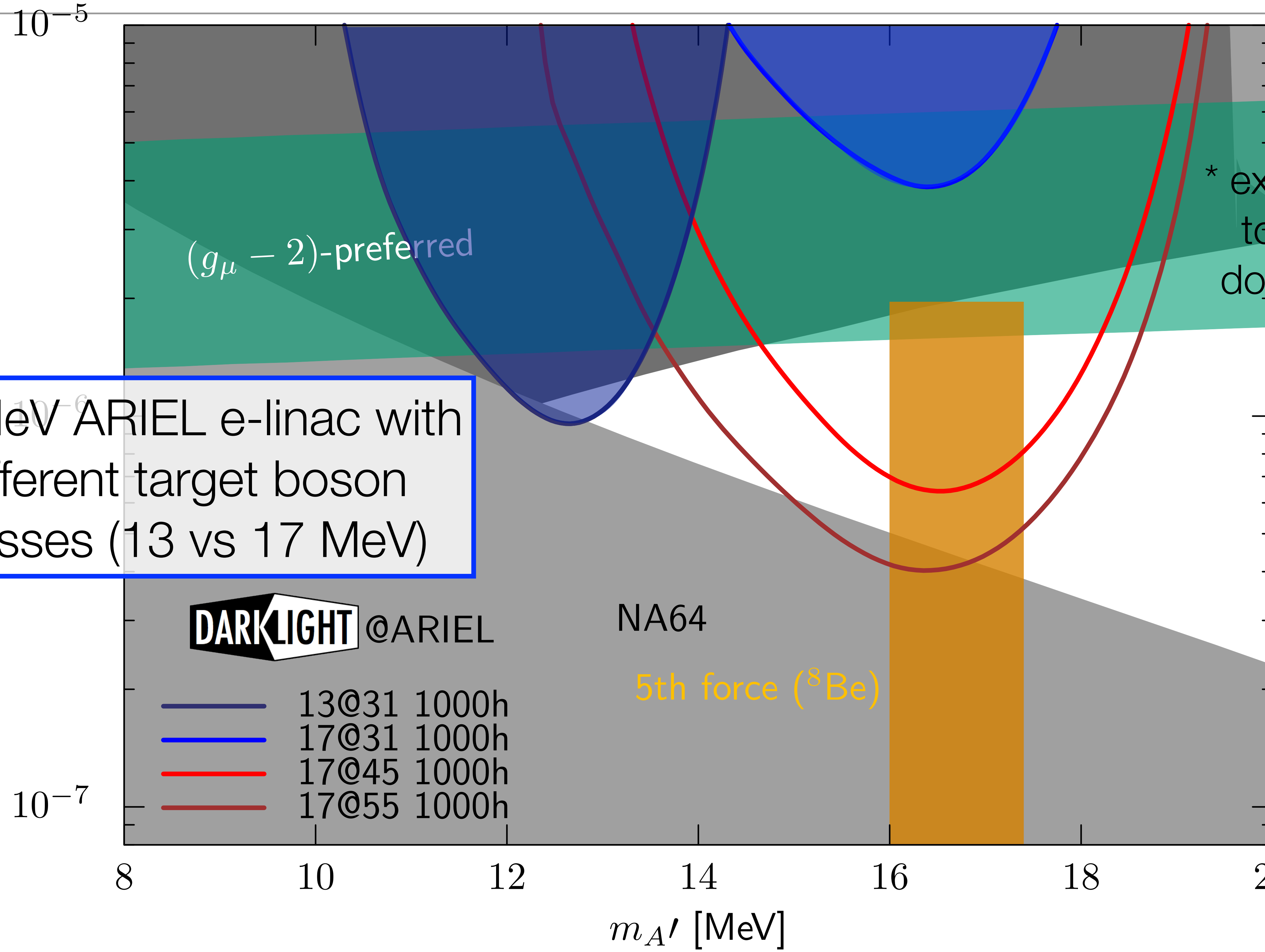
* expect this to move down a bit

Sensitivity at 30 and 50 MeV accelerators



Sensitivity at 30 and 50 MeV accelerators

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

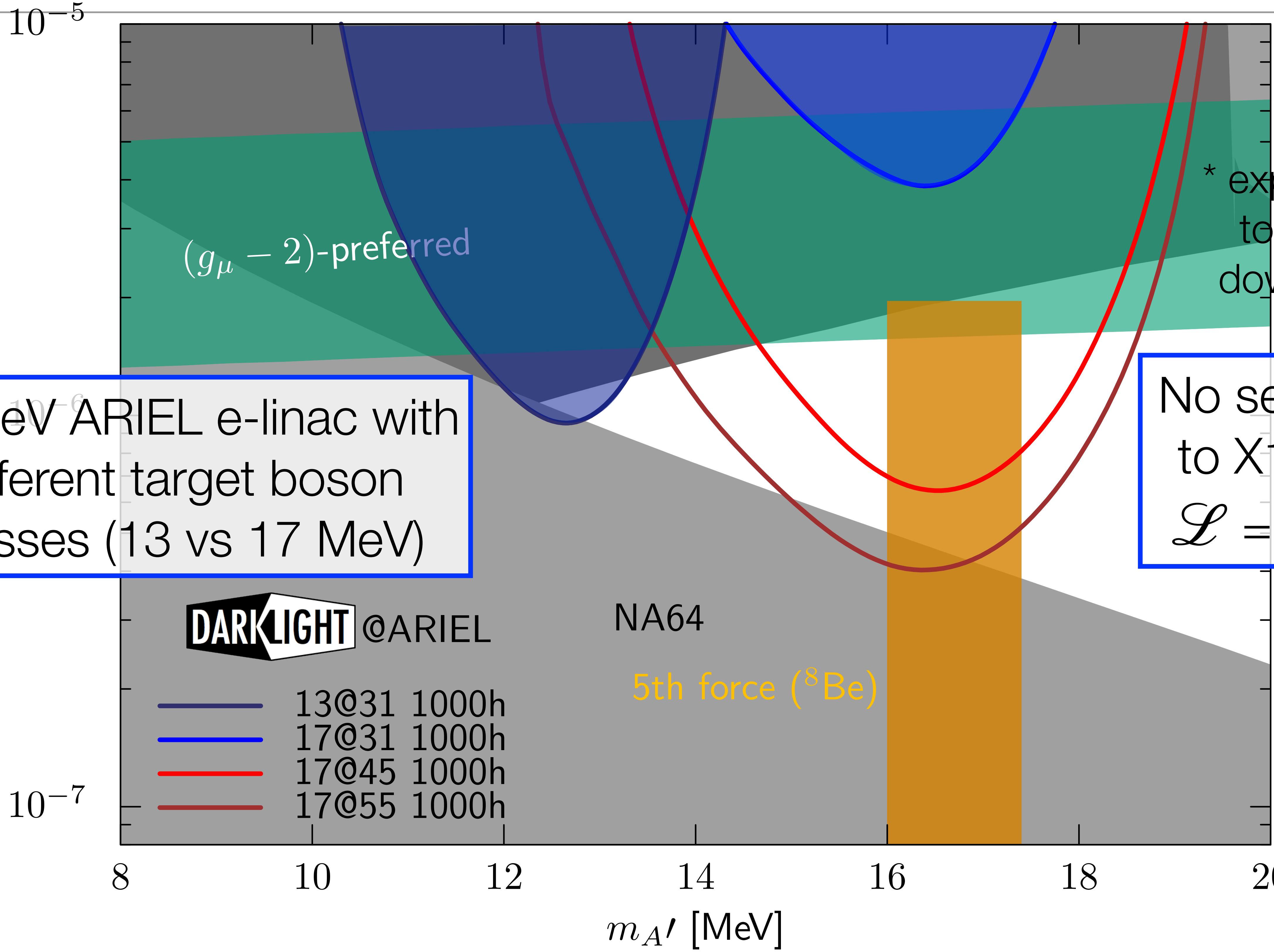


* expect this to move down a bit

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

Sensitivity at 30 and 50 MeV accelerators

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



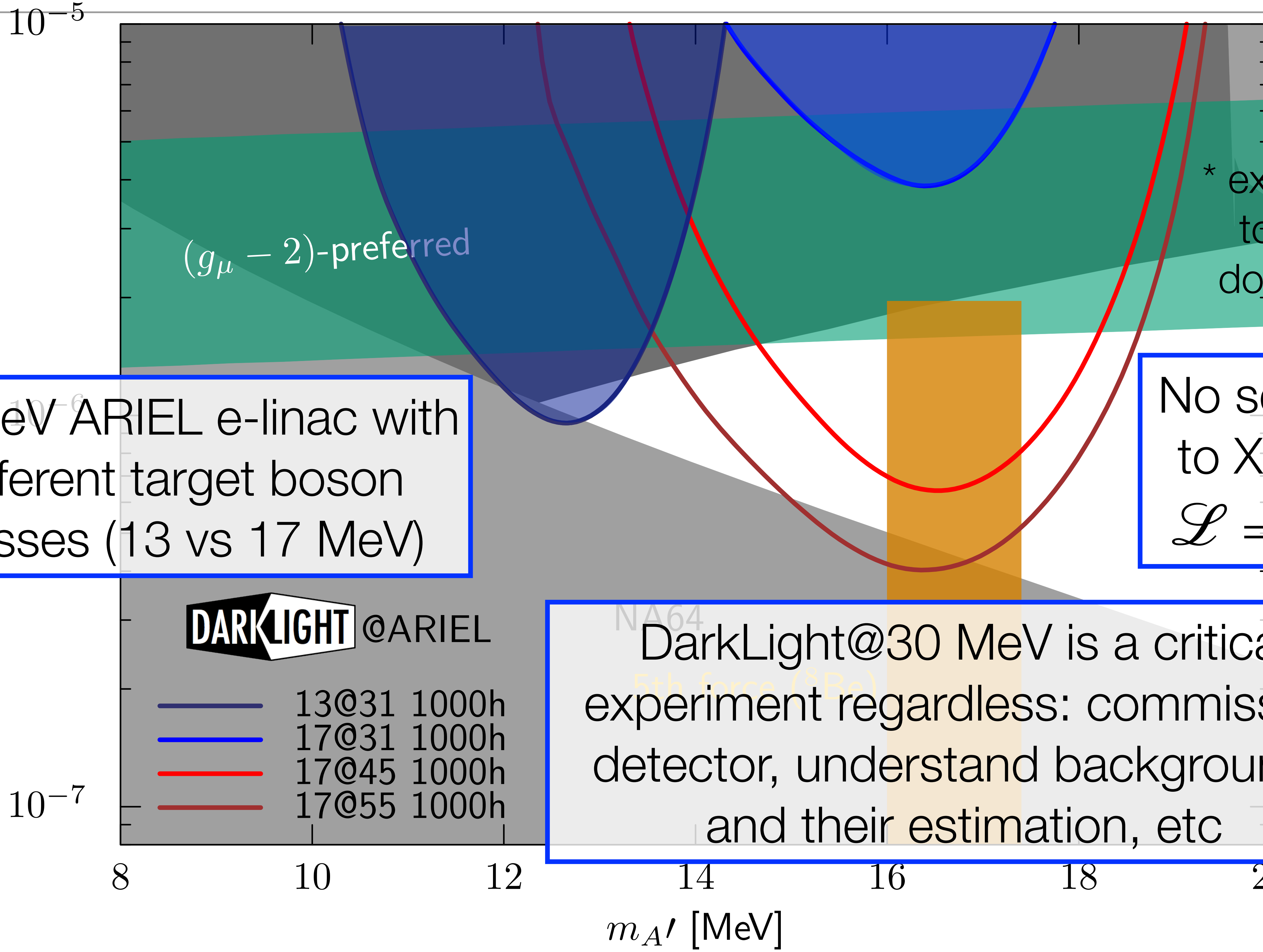
* expect this to move down a bit

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

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

Sensitivity at 30 and 50 MeV accelerators

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



* expect this to move down a bit

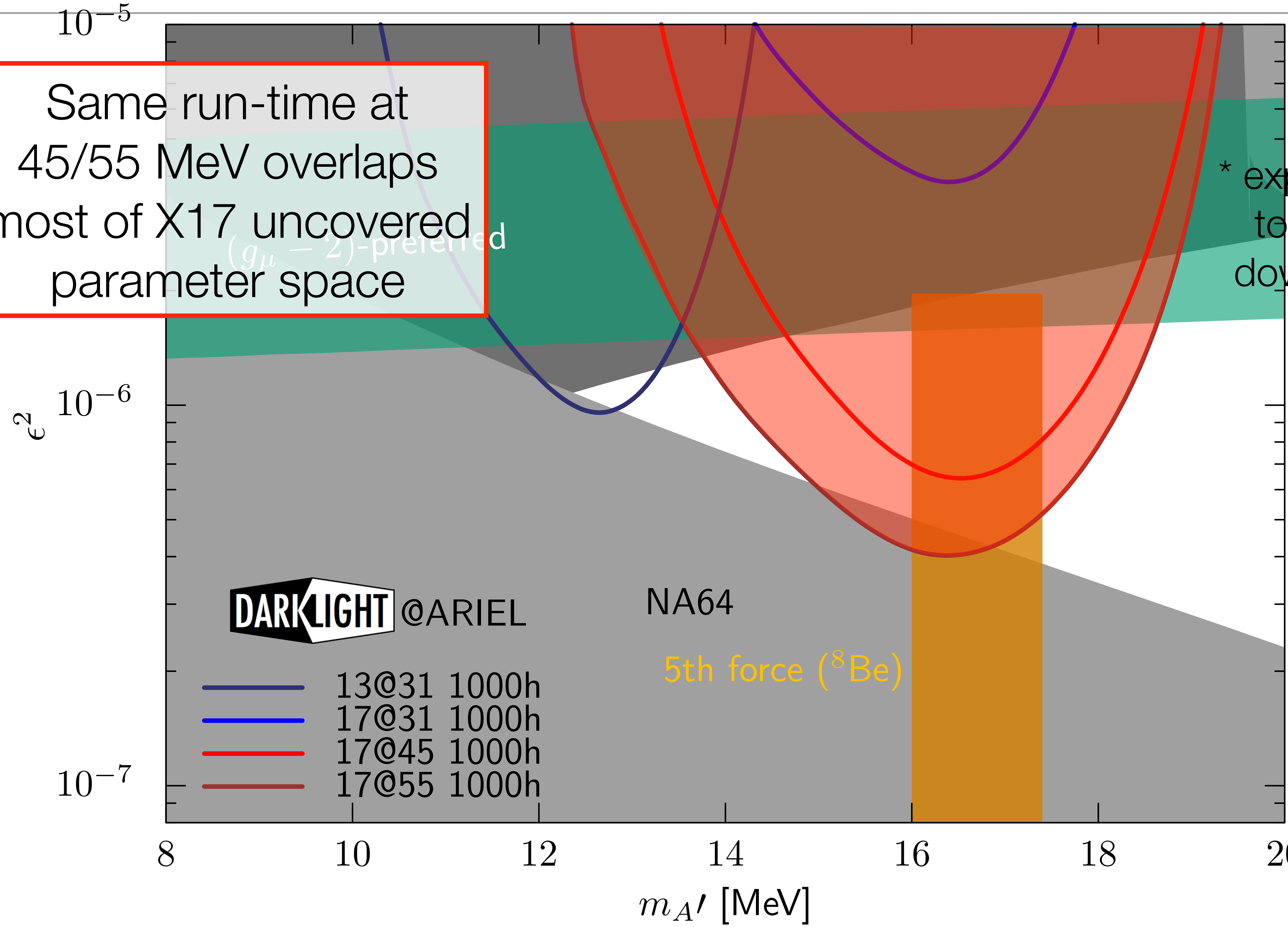
30 MeV ARIEL e-linac with different target boson masses (13 vs 17 MeV)

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

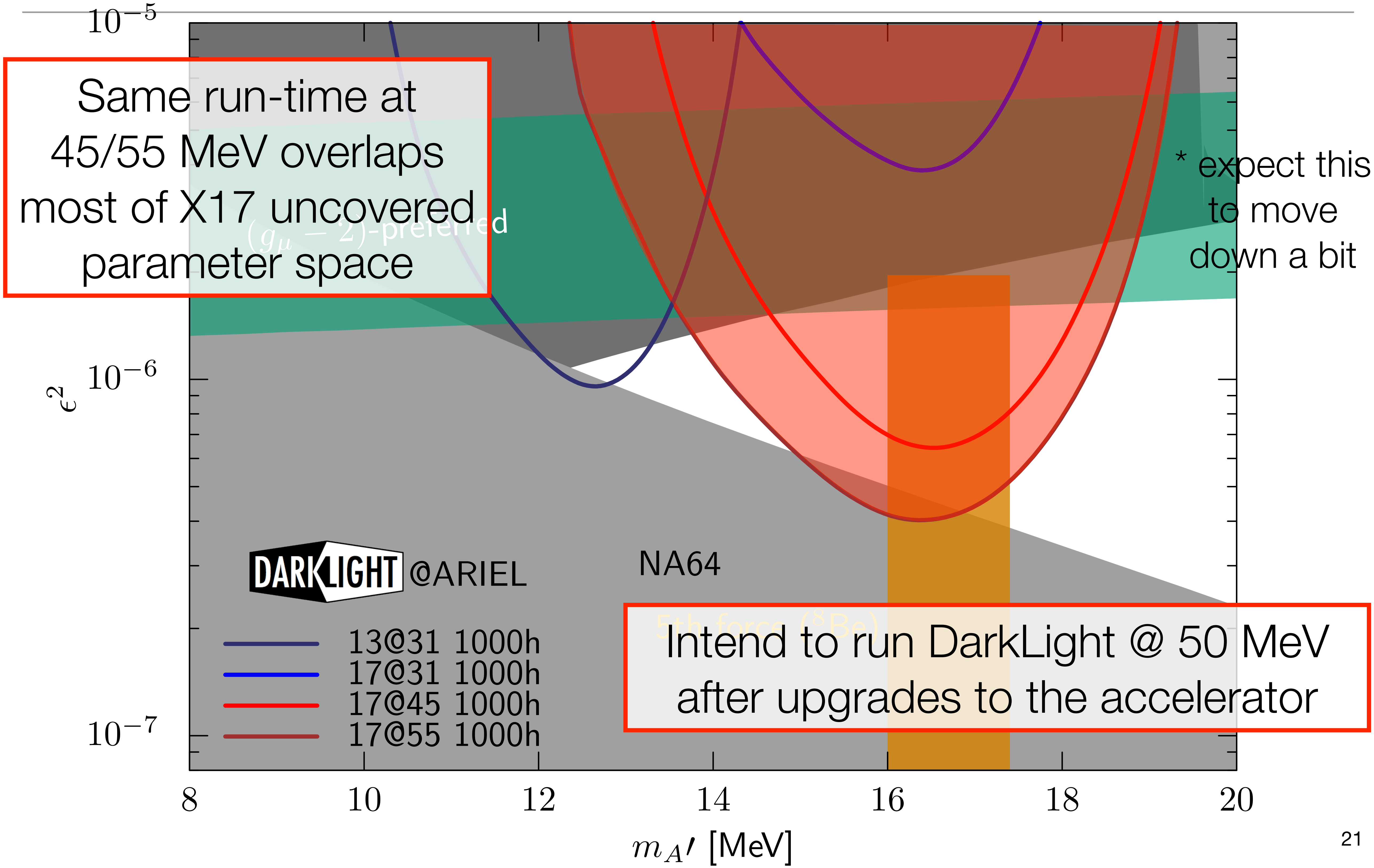
Sensitivity at 30 and 50 MeV accelerators

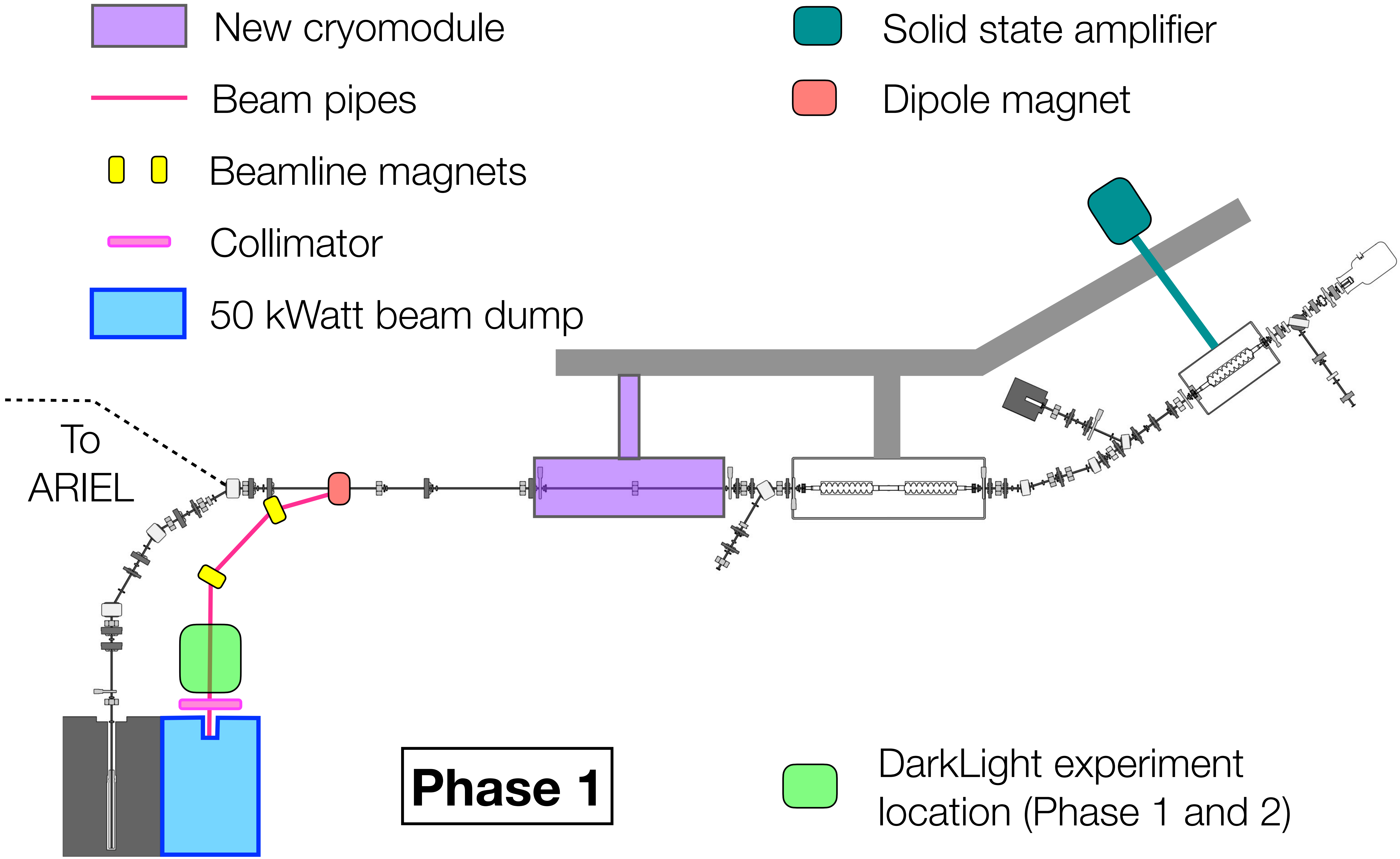
Same run-time at 45/55 MeV overlaps most of X17 uncovered parameter space

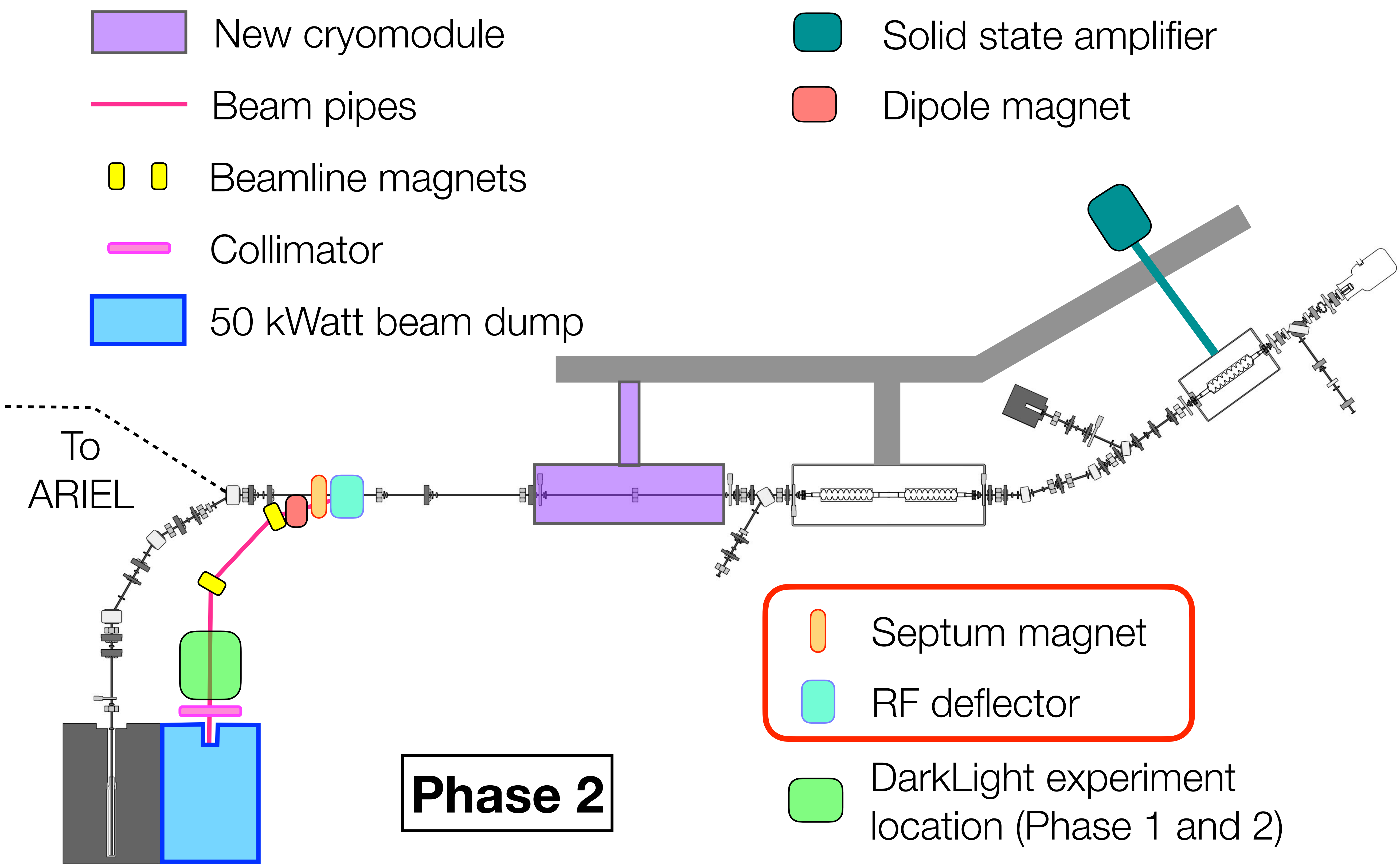


* expect this to move down a bit

Sensitivity at 30 and 50 MeV accelerators




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)


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

Timeline and milestones

Spring 2021: beam time approved @ TRIUMF

Dec 2021: test chamber installed in beamline

Feb 2022 CFI passed selection round at universities

Feb 2022: Passed TRIUMF Gate 1

April 2022: NSERC awarded

May 2022: workshop at TRIUMF, first collaboration meeting

Today

Rest of 2022: install existing spectrometer, initial test experiments

2023: CFI decision; install and run full experiment @ 30 MEV

2024/2025: install second cryomodule; first run @ 50 MeV

2025+: install infrastructure for parallel running with ARIEL

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!

Summary and conclusion

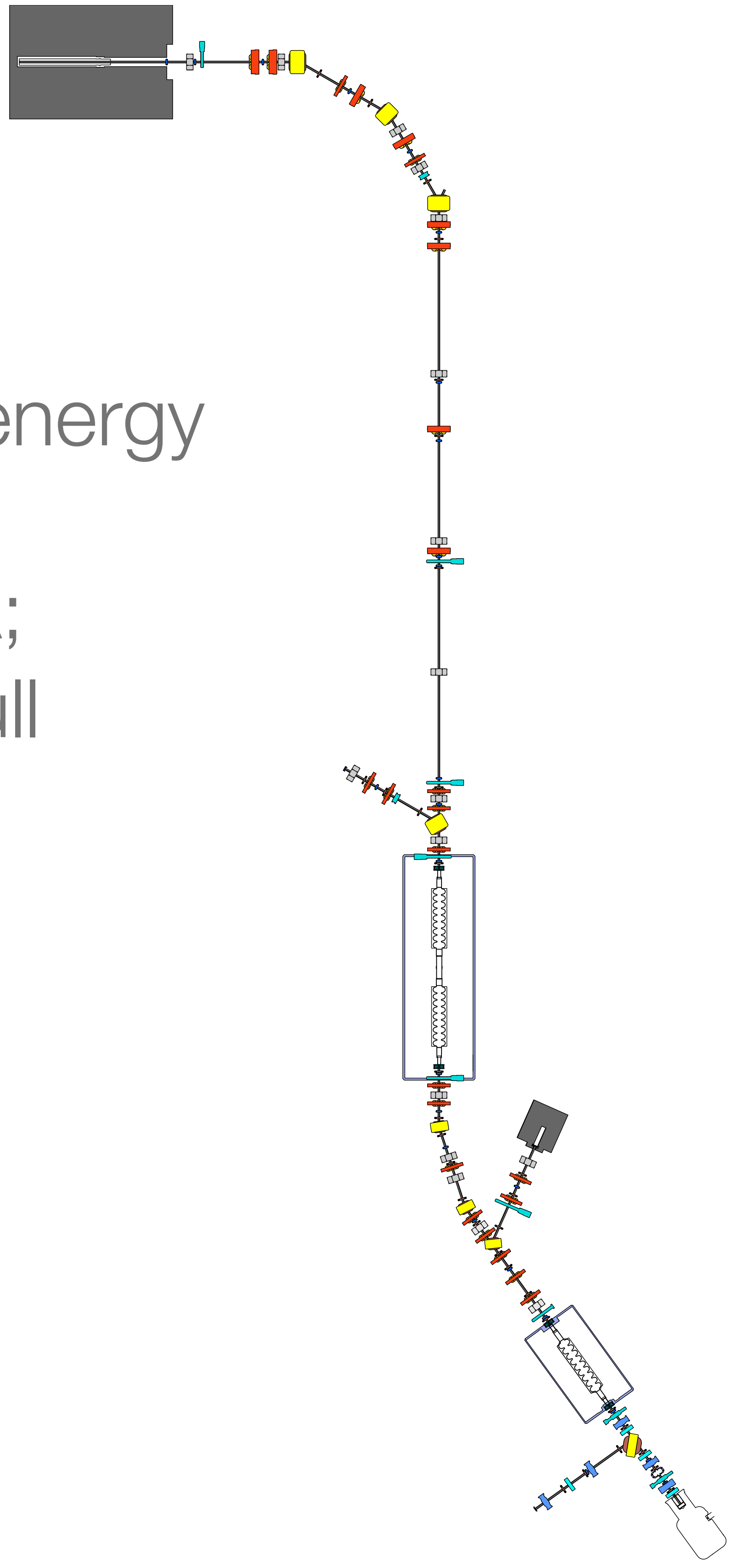
- DarkLight@ARIEL is a **new experiment** to be built **at TRIUMF** searching for low-mass e+e- resonances
    - **Compelling scientific motivation** and a strong international collaboration covering all relevant areas of expertise
- DarkLight will **add to continual progress** from many experiments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

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

Thank you!

Backup slides

ARIEL e-linac facility



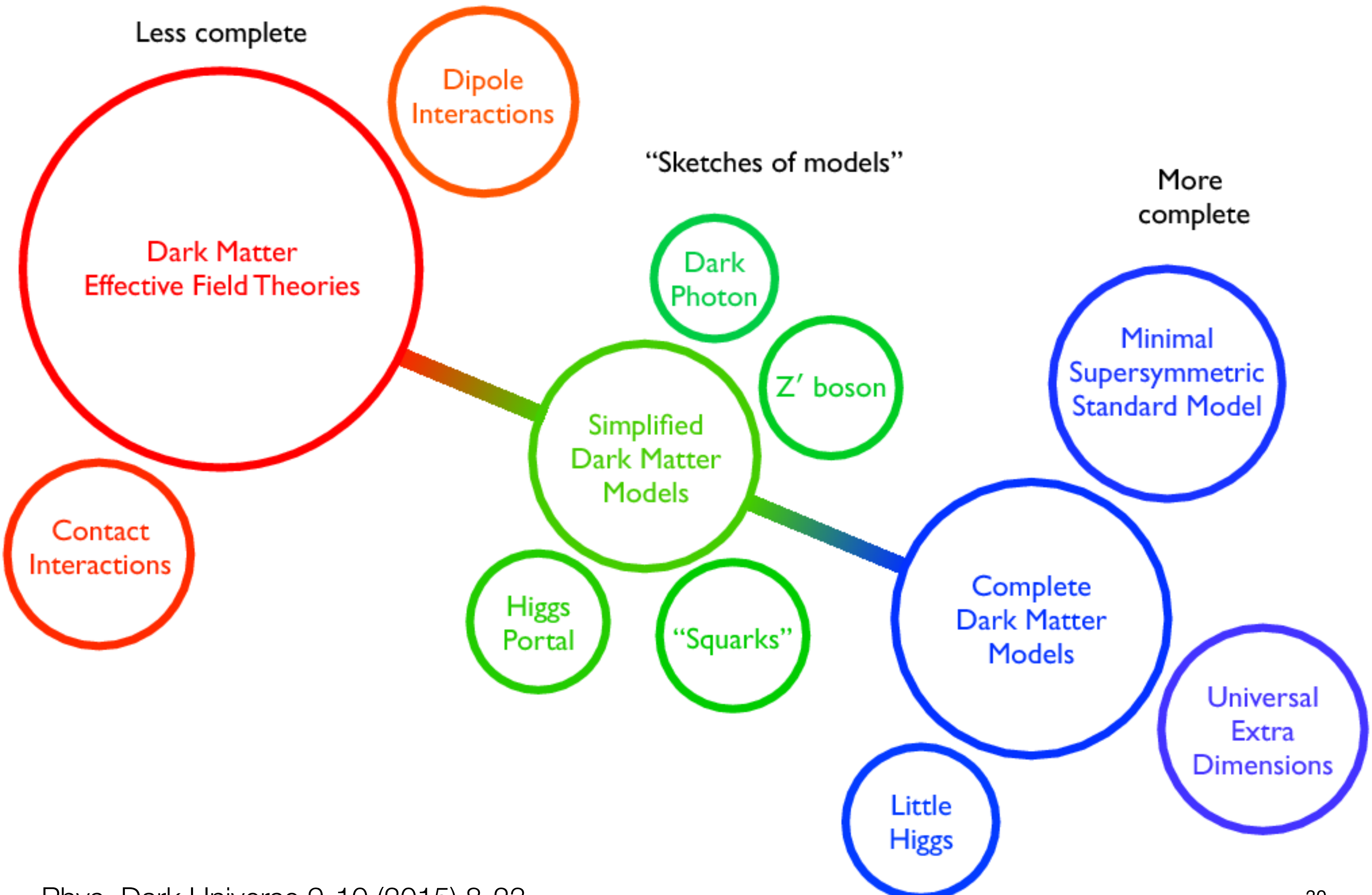
- 650 MHz frequency; currently 30 MeV energy
- Currents: Projections shown for 150 µA; considering designs that can support full design current of ~ a few mA
- Total design power ~ 100 kW
- Each bunch has ~ $9x10^6$ electrons

Why ARIEL?

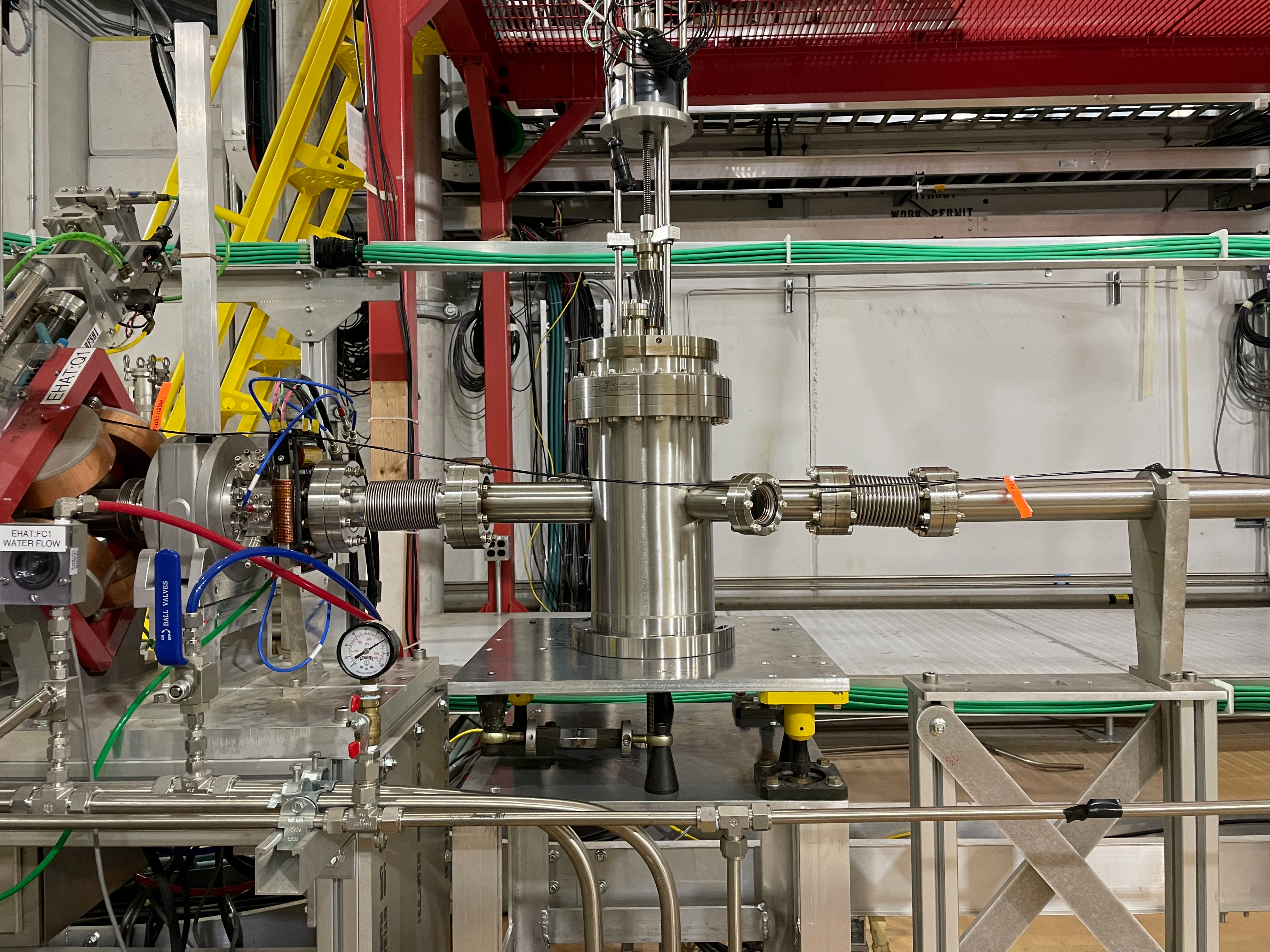
- Low energy, high intensity beam.
  - Energy not much above the production threshold is nice because it gives an opening angle that we can easily pick up with spectrometers
  - Peak intensity of 3 mA gives us plenty of instantaneous luminosity - don’t need to run forever
- Finally, because the e-linac 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
WORK PERMIT

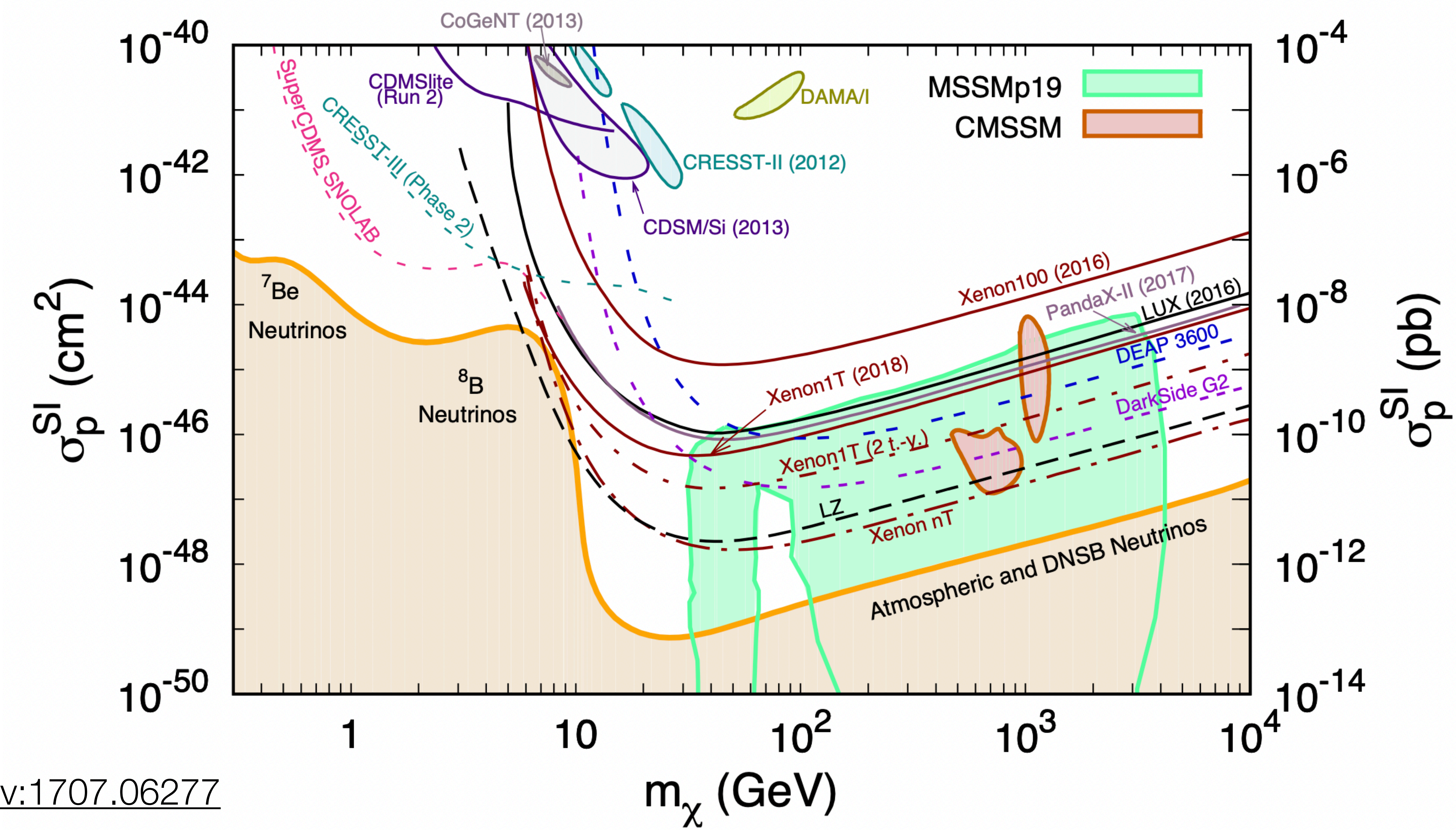
Complementary experiments

- 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.

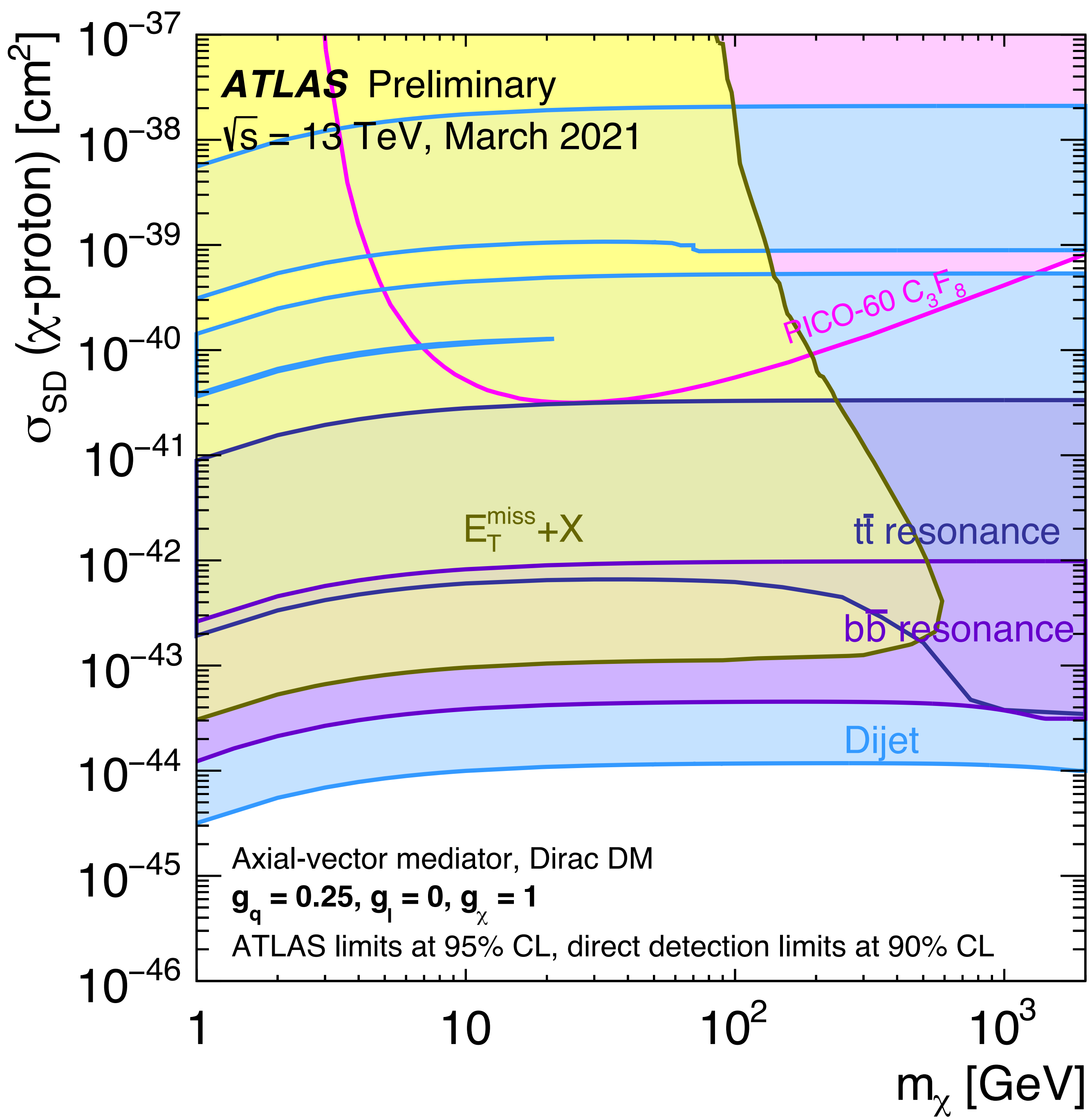


arXiv:1707.06277

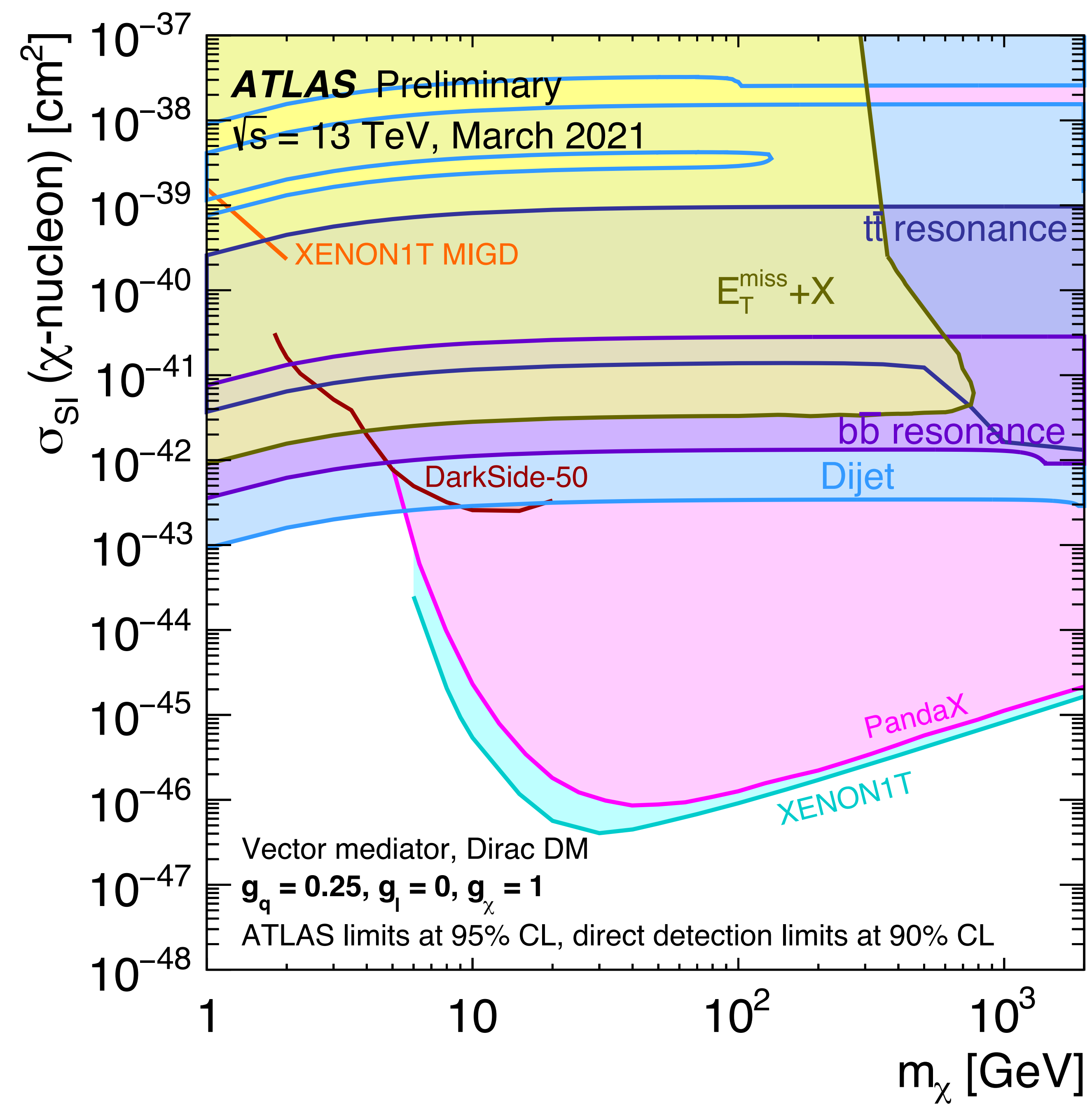
What does this plot tell us?

- 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…



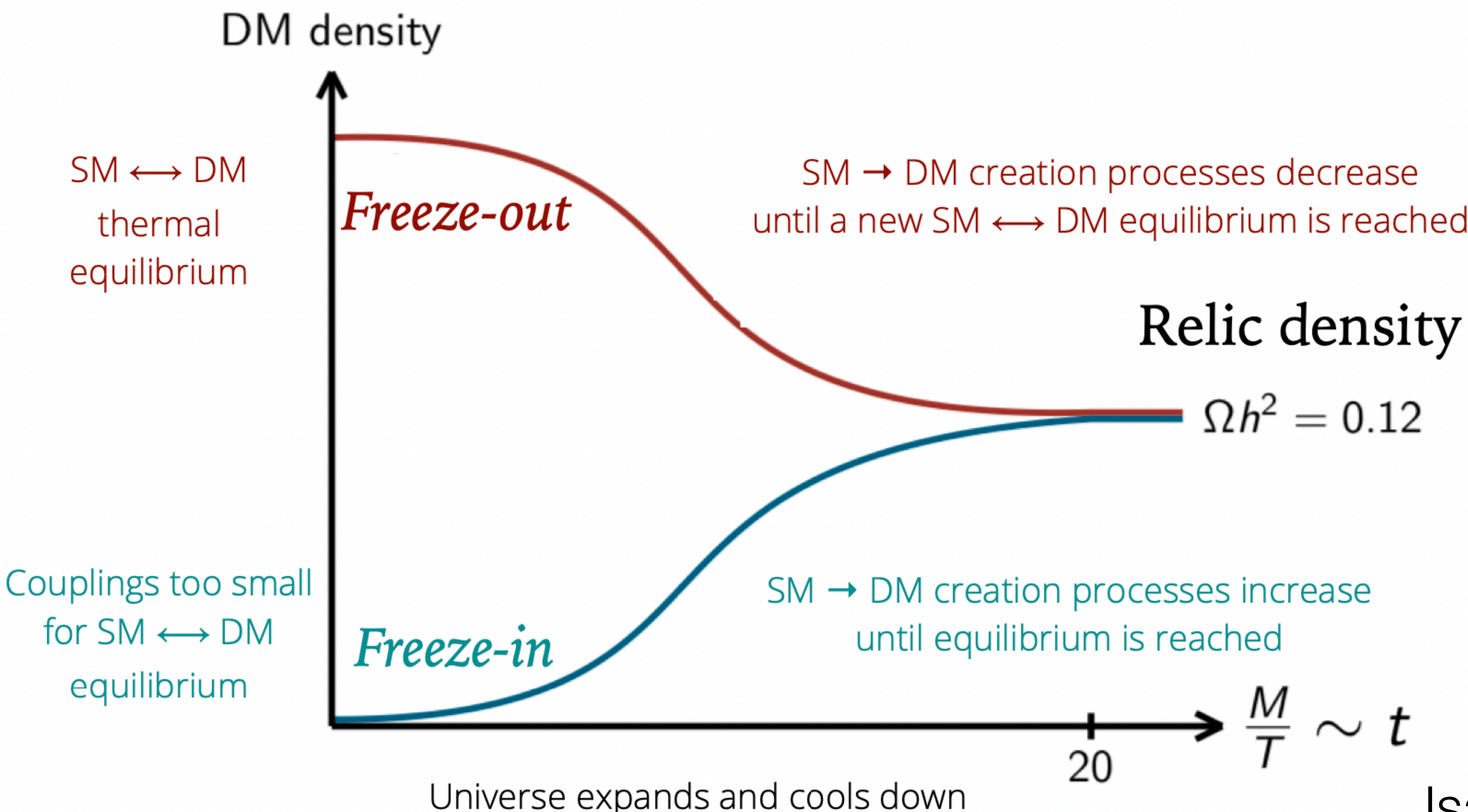
ATLAS Preliminary
√s = 13 TeV, March 2021
PICO-60 C3F8
E_T^miss+X
tt̄ resonance
bb̄ resonance
Dijet
Axial-vector mediator, Dirac DM
g_q = 0.25, g_l = 0, g_χ = 1
ATLAS limits at 95% CL, direct detection limits at 90% CL
σ_SD (χ-proton) [cm²]
m_χ [GeV]



ATLAS Preliminary
√s = 13 TeV, March 2021
tt̄ resonance
XENON1T MIGD
E_T^miss+X
bb̄ resonance
DarkSide-50
Dijet
PandaX
XENON1T
Vector mediator, Dirac DM
g_q = 0.25, g_l = 0, g_χ = 1
ATLAS limits at 95% CL, direct detection limits at 90% CL
σ_SI (χ-nucleon) [cm²]
m_χ [GeV]

Freeze-in and freeze-out

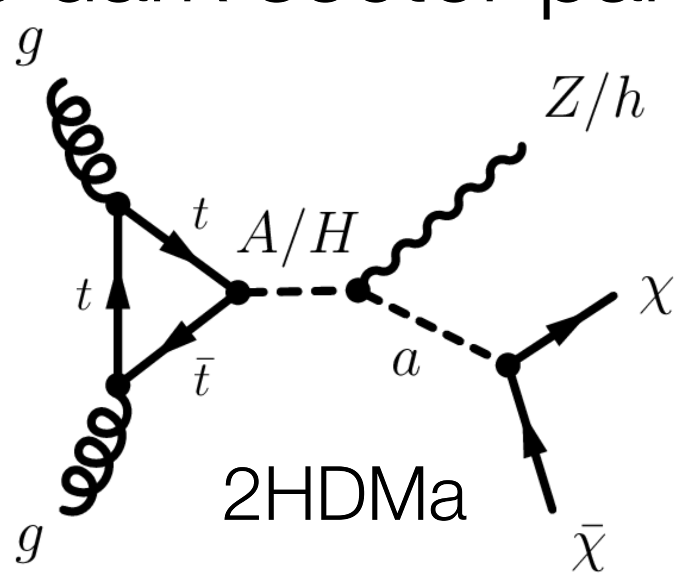
Usually think about freeze-in with WIMPs, but freeze-out and other interactions can give you exact same relic density with very different (smaller) couplings



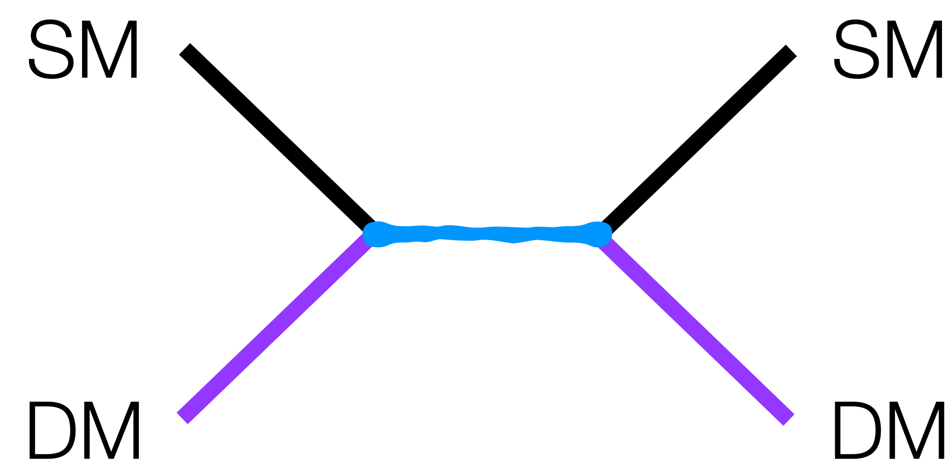
Isabelle John

When you said that model "really is simplified"…

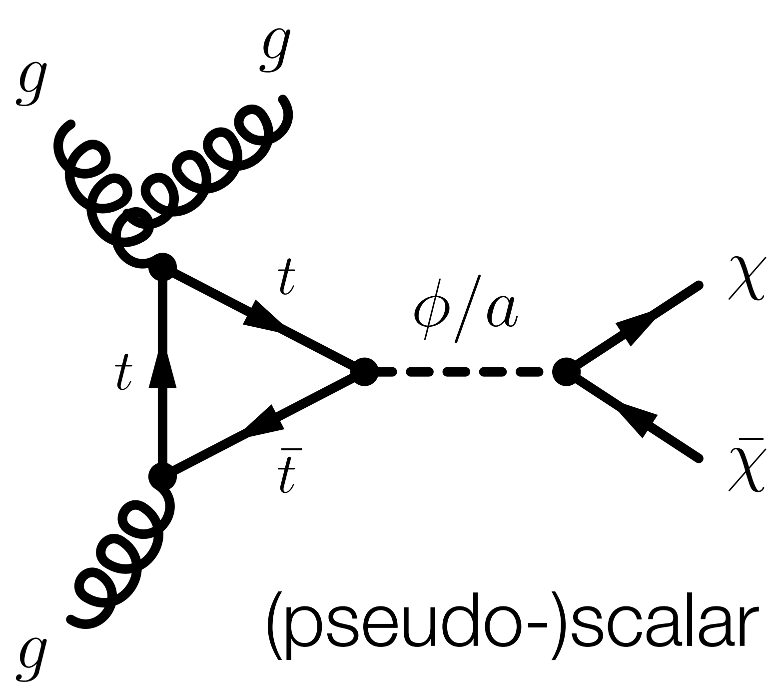
More dark sector particles



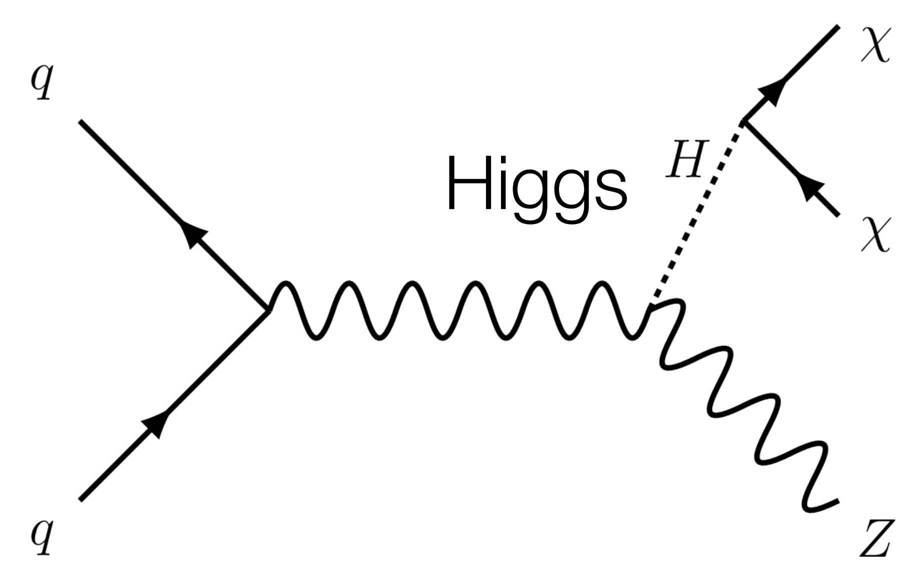
Not s-channel couplings



Not a vector mediator

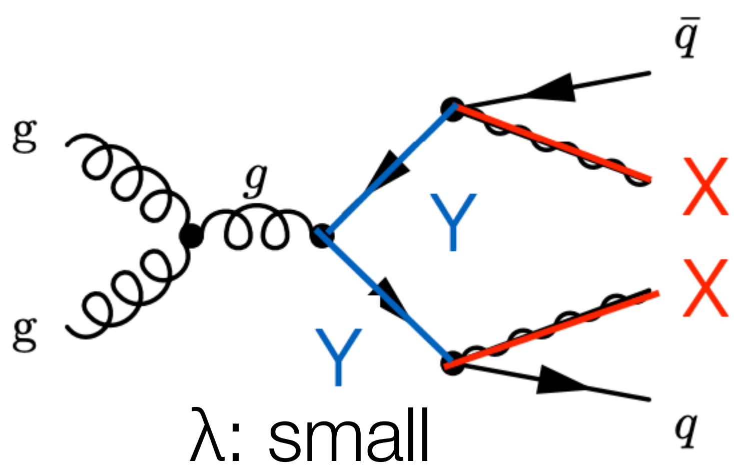


No BSM mediator



When you said that model “really is simplified”…

Not prompt



λ: small coupling

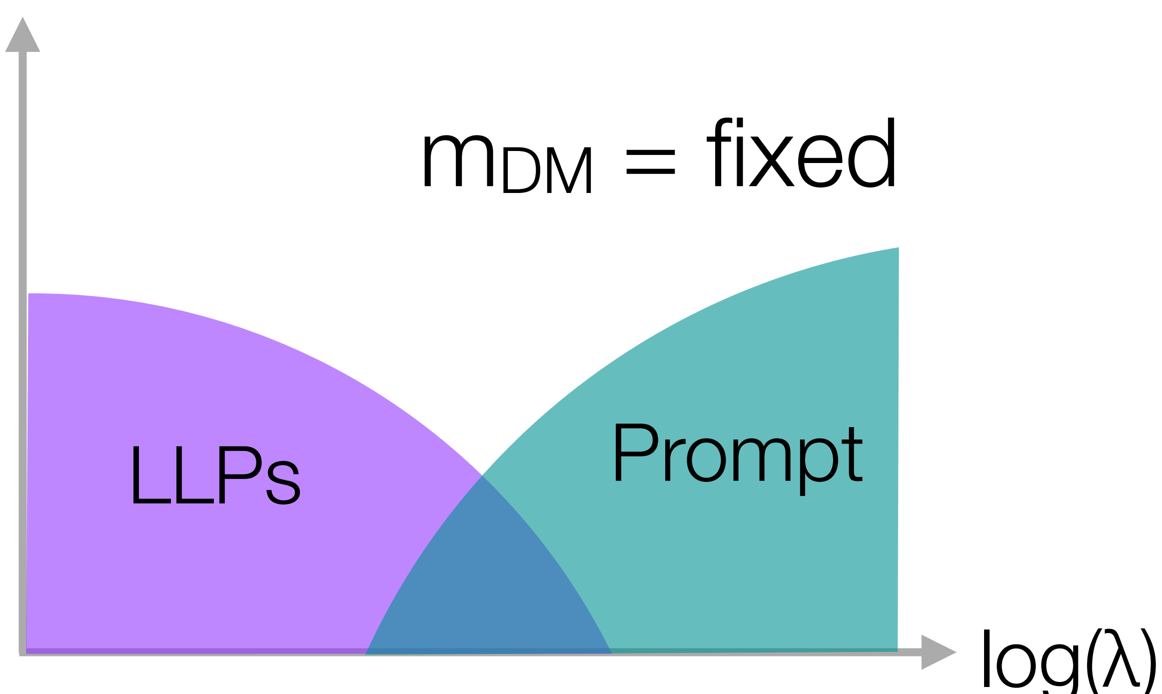


Diagram from C. Arina

Not a WIMP

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

(Not a particle)