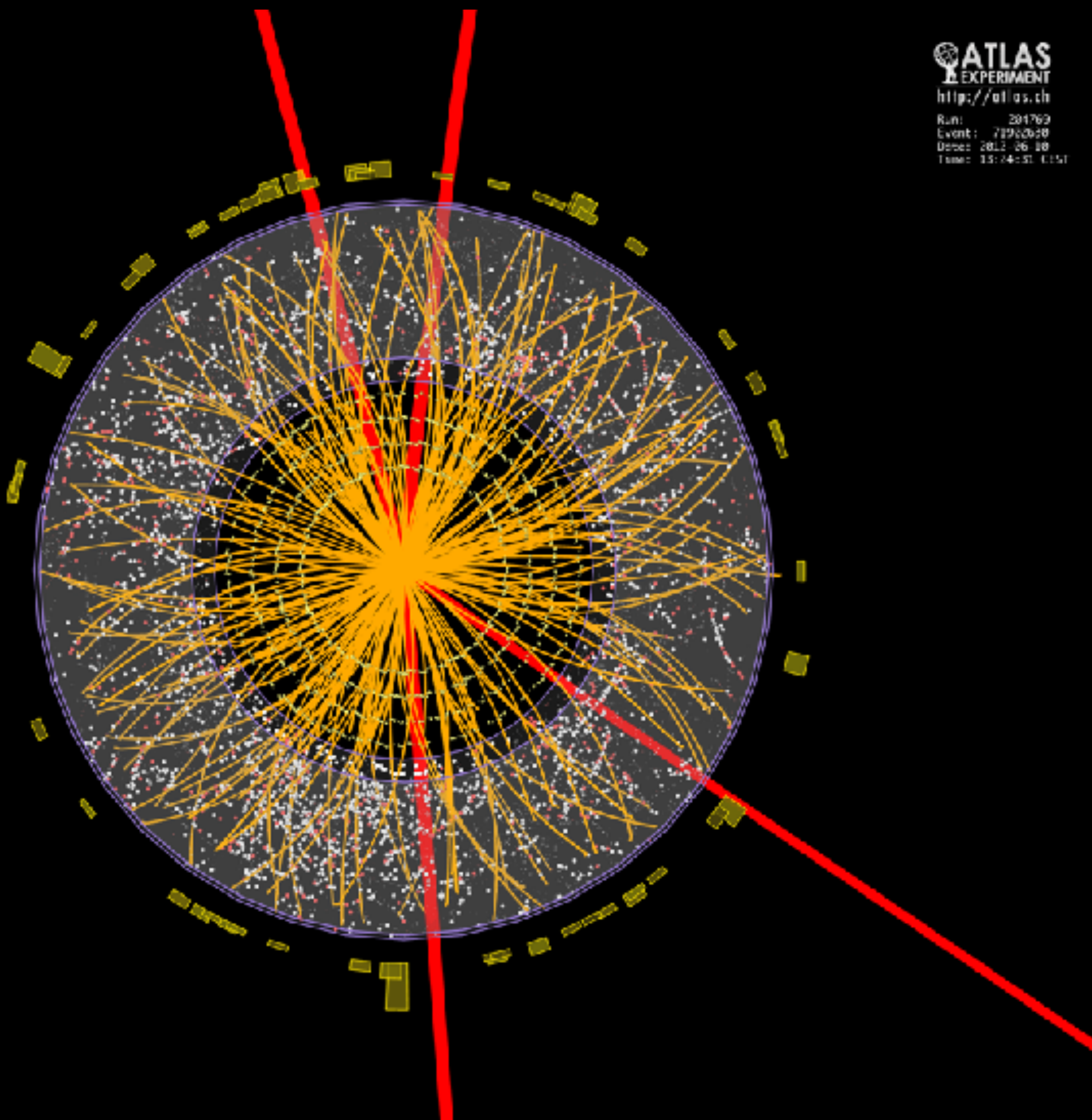
Searching for whispers from beyond the Standard Model

@ University of Oxford
02/07/2019

Simon Knapen
Institute for Advanced Study

A once in a lifetime discovery…



ATLAS candidate higgs → 4μ event

15 million Higgs bosons produced in ATLAS + CMS so far

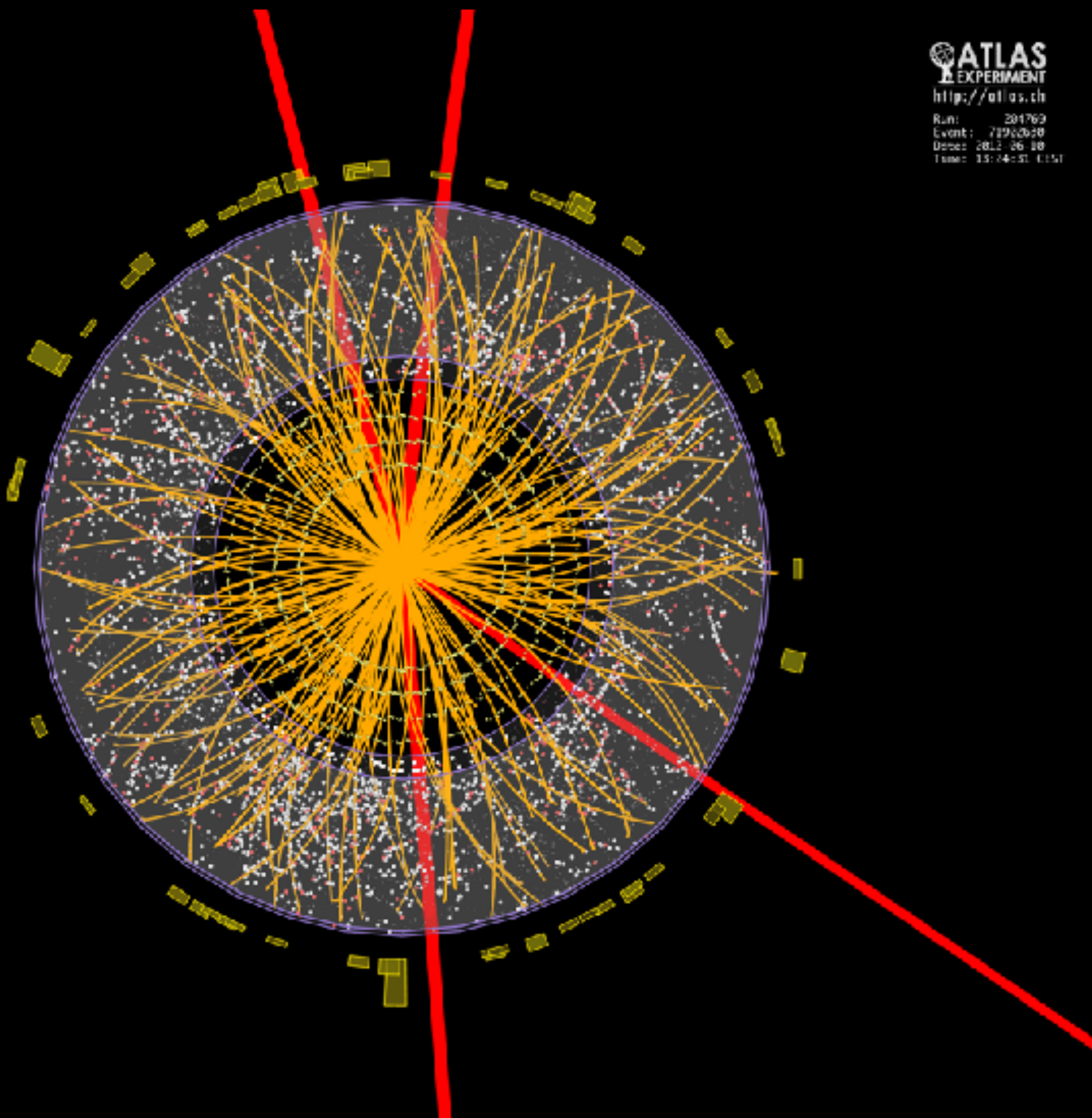
- 9 million decayed to b-quarks
- 3 x 10^4 decayed to photons
- 500 decayed to 4 muons

~ 1.5 million Higgs bosons could have decayed through an exotic channel

↓

Top priority for the high-luminosity LHC

… but many mysteries remain



ATLAS candidate higgs → 4μ event

Hierarchy problem

Dark Matter

Baryon/anti-baryon asymmetry

The origin of flavor

CP violation

We need to expand our set of probes

A turning point

LHC

Entering luminosity driven phase

Searches for “conventional” models already extremely sophisticated

(WIMP) dark matter direct detection

Next generation experiments will push to the neutrino floor

Searching for soft/subtle signatures by

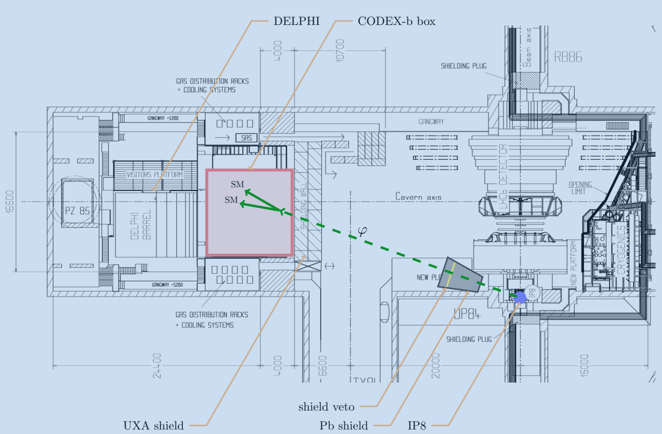
- Using existing infrastructure in new ways (“Leave no stone unturned”)
- Considering the next generation of experiments (5-10 years timescale)

This talk

Outline

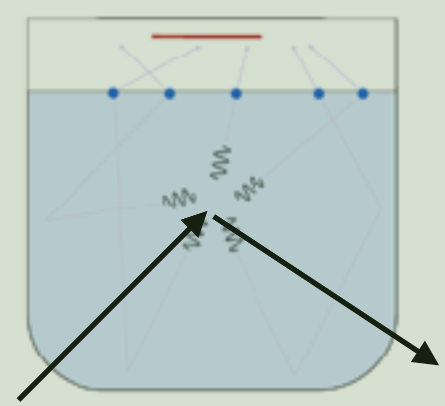
Three experimental proposals

LHC

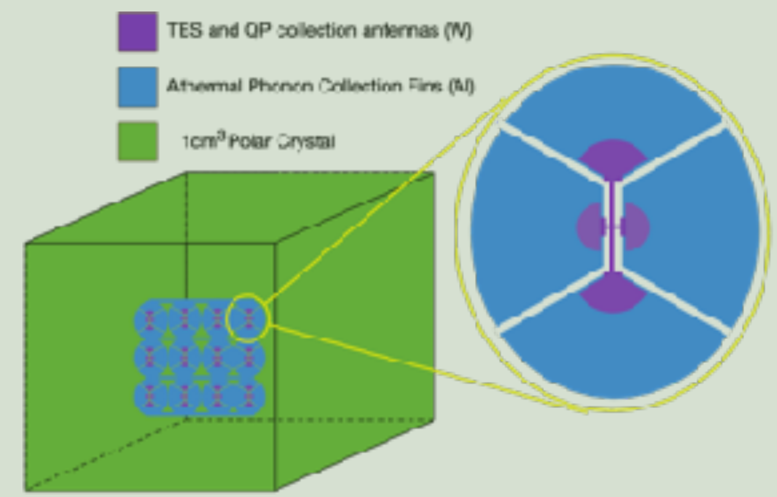


CODEX-b detector

Dark matter direct detection



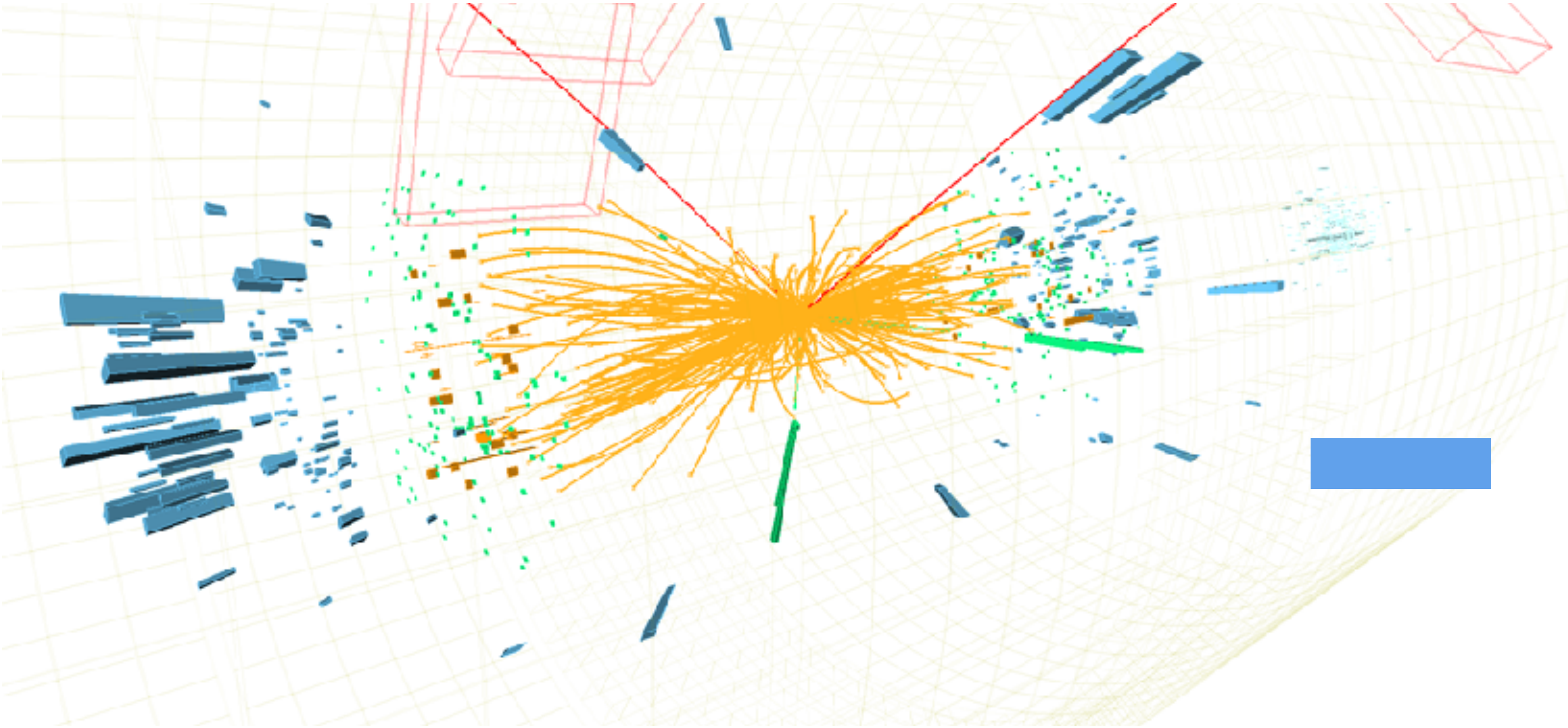
superfluid helium detector



polar material detector

↓

Need a multidisciplinary approach



The soft frontier at LHC

Long-lived particles are generic

In the Standard Model

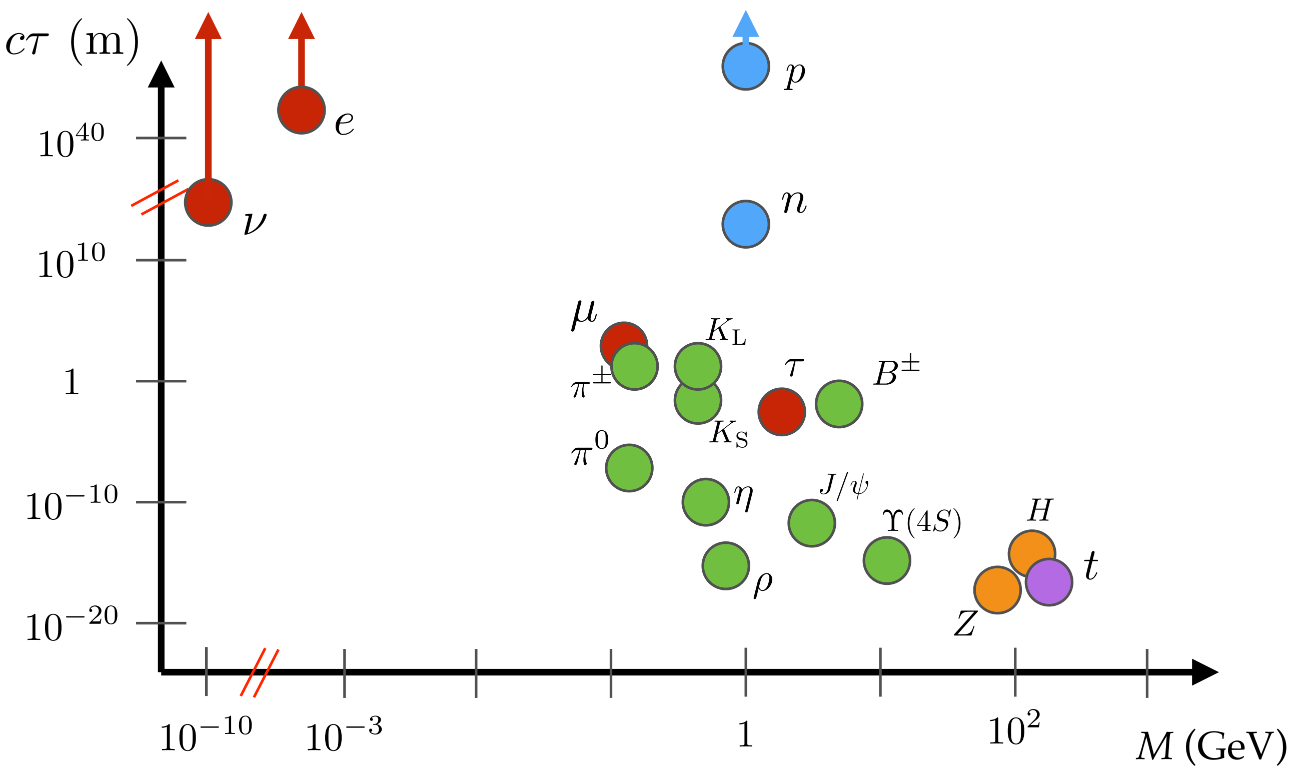


Image by B. Shuve

Beyond the Standard Model

- Supersymmetry
- Dark matter
- Neutrino masses
- Baryogenesis
- …

Long-lived particles when there is a
separation of scales and / or a weakly broken symmetry

Finding Long-Lived Particles

ATLAS and CMS are great for high mass LLPs…

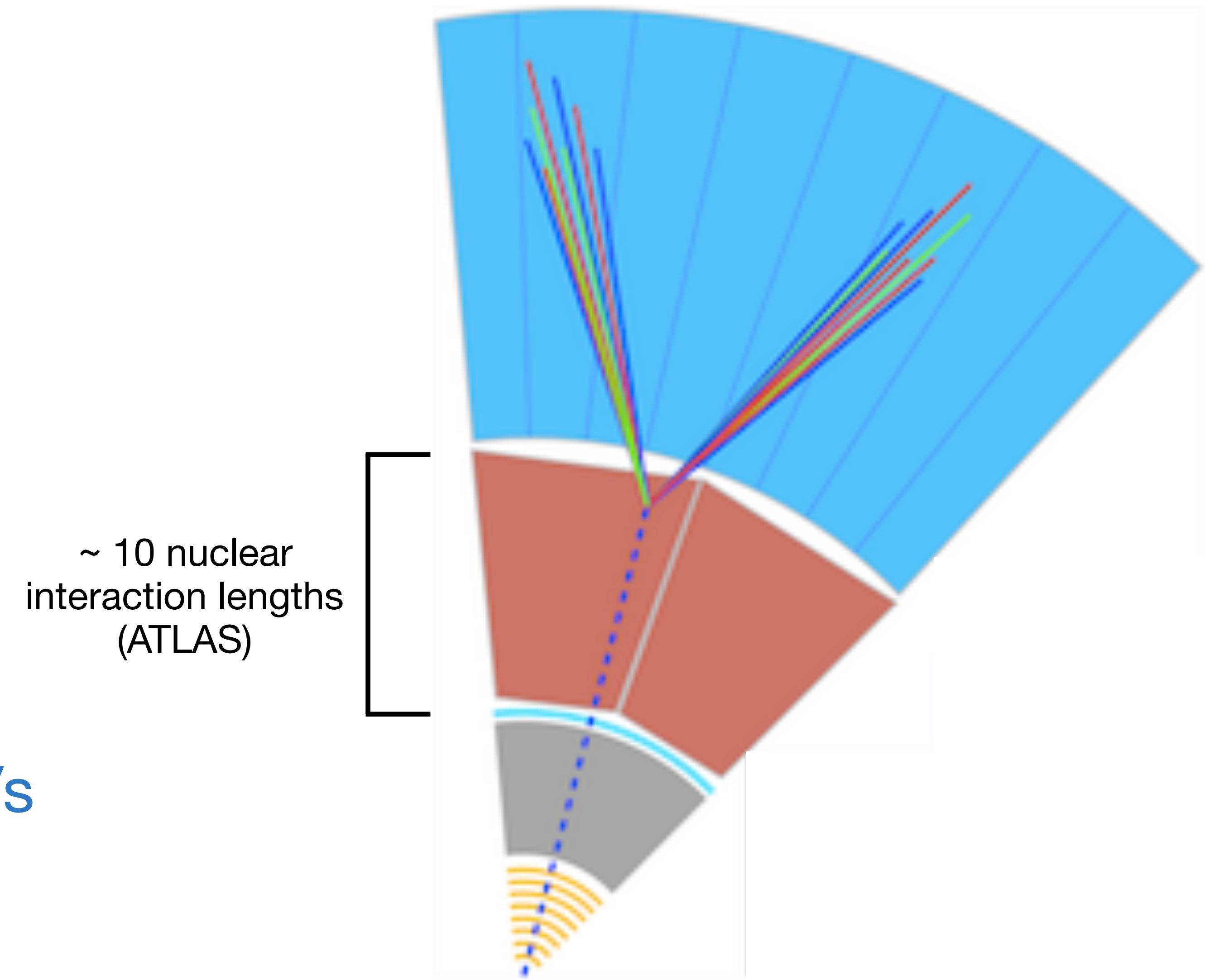
… but for low masses they suffer from:

1. Tight trigger requirements
2. Backgrounds

A typical hadron has a chance of

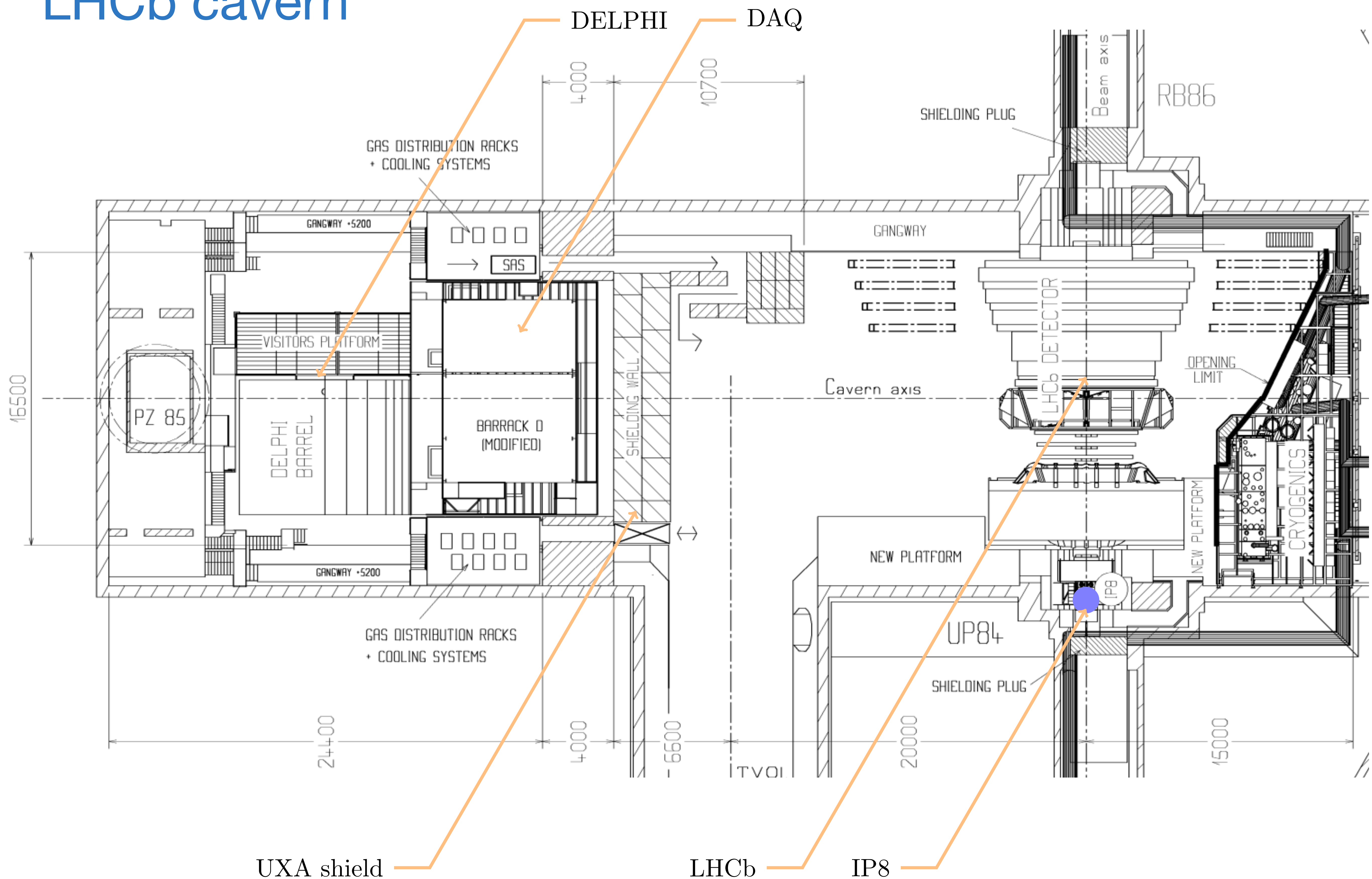
~ 10^{-5} to punch through calorimeter…

…but the LHC makes ~ 10^9 K_L mesons/s



Solution:
Dedicated detector with ~ 3 times more shielding

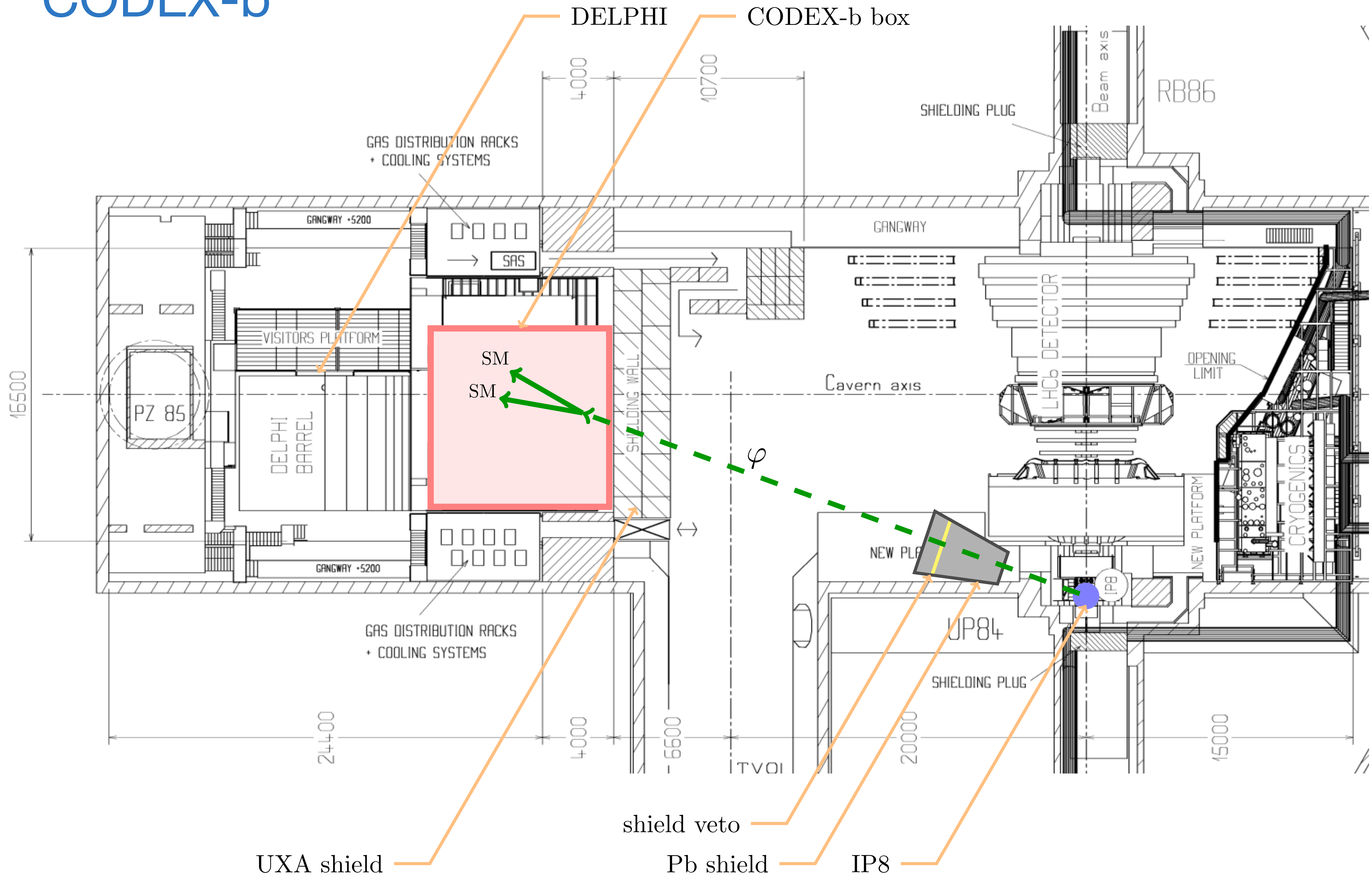
LHCb cavern



Data acquisition will be moved to surface for run 3

CODEX-b

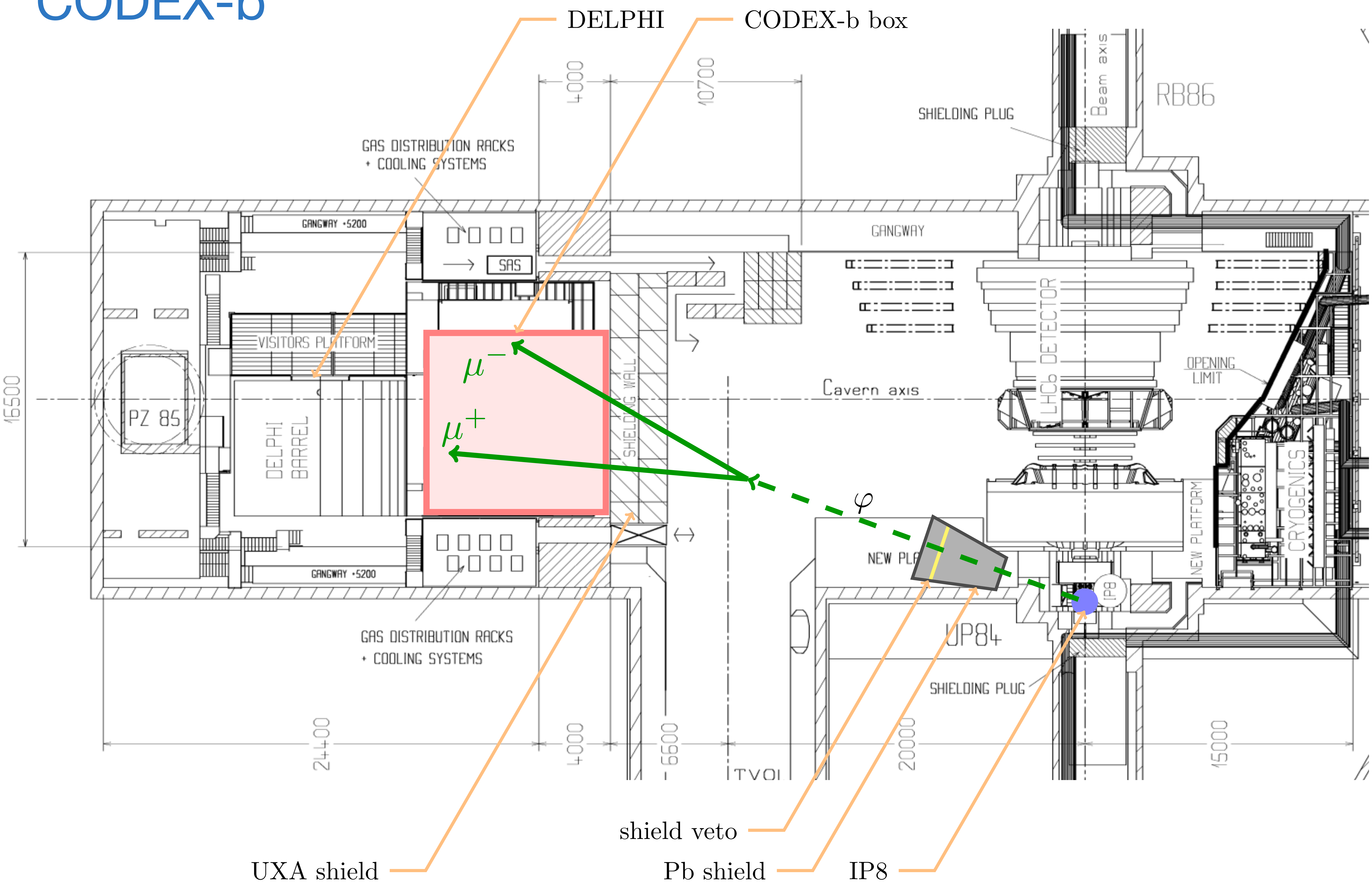
V. Gligorov, SK, M. Papucci, D. Robinson: 1708.02243



With ~ 4 meters of shielding, background free

CODEX-b

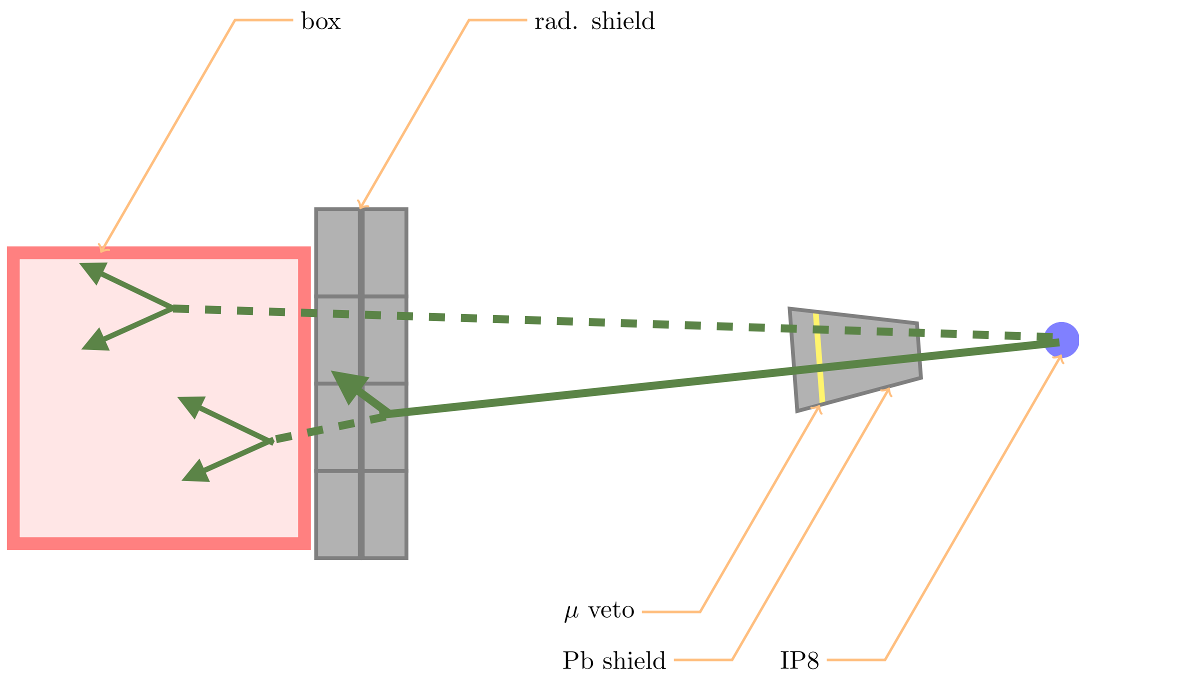
V. Gligorov, SK, M. Papucci, D. Robinson: 1708.02243



Possibly extra reach for muonic channels

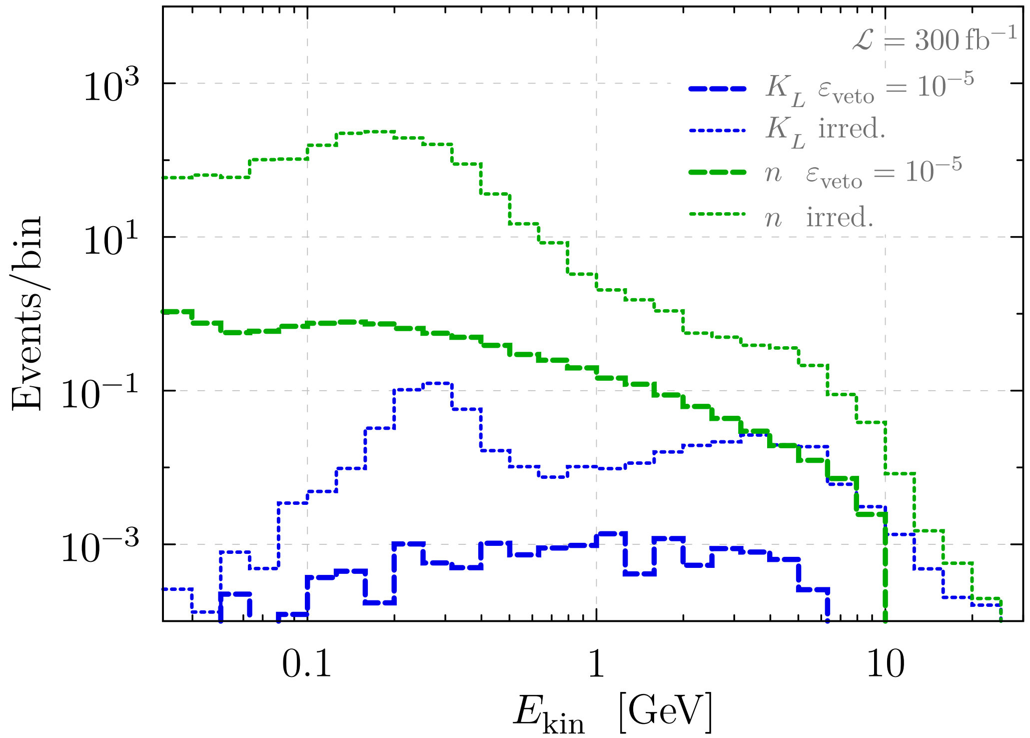
Backgrounds

- Absorb neutral hadrons in shield
  (irreducible background)
- Veto muon-induced backgrounds
  with muon veto + front face of the detector (reducible background)



BG species	Particle yields: irreducible by shield veto	Particle yields: reducible by shield veto	Baseline Cuts
$n + \bar{n}$	7	$5 \cdot 10^4$	$E_{\rm kin} > 1\,\rm GeV$
K_L^0	0.2	870	$E_{\rm kin} > 0.5\,\rm GeV$
$\pi^\pm + K^\pm$	0.5	$3 \cdot 10^4$	$E_{\rm kin} > 0.5\,\rm GeV$
$\nu + \bar{\nu}$	0.5	$2 \cdot 10^6$	$E > 0.5\,\rm GeV$

Simulation: pythia 8 + GEANT 4
4.5m Pb + 3m concrete



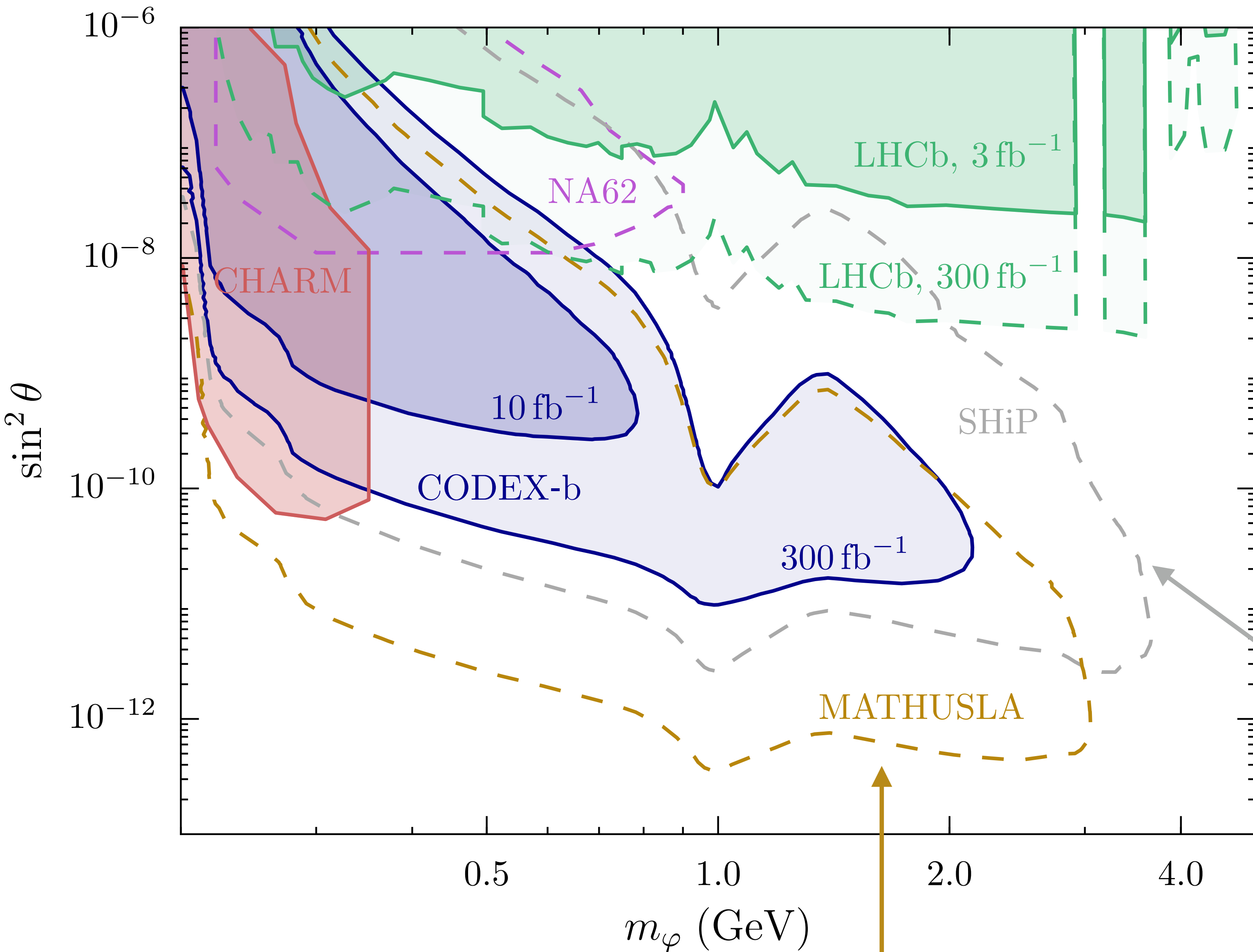
Dominant background: neutron on air ~ 0.3 events

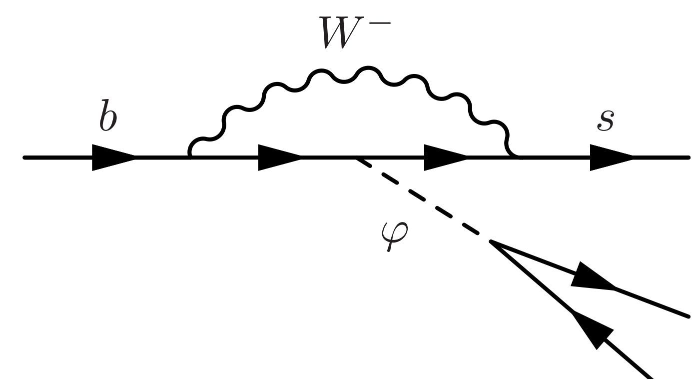
V. Gligorov, SK, M. Papucci, D. Robinson: 1708.02243

Higgs portal

Model: $\mathcal{L} \supset \mu\,\varphi H^\dagger H + \frac{\lambda}{2}\varphi^2 H^\dagger H$

With $\lambda = 0$



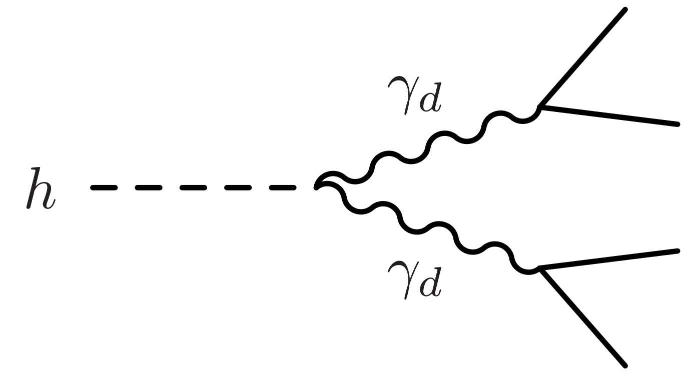


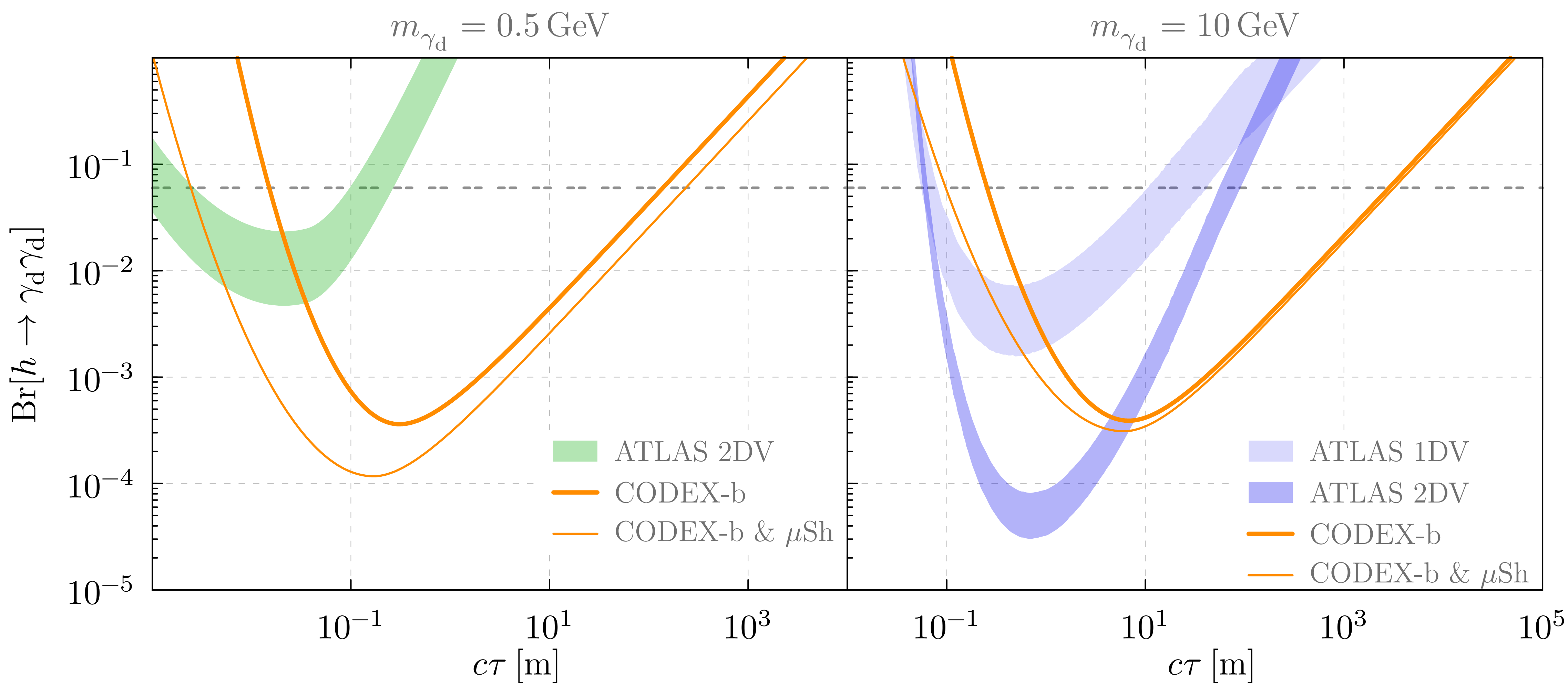
Proposed ~ 150 m long beam dump at CERN SPS accelerator

Proposed 200 m x 200 m detector on the surface above CMS

V. Gligorov, SK, M. Papucci, D. Robinson: 1708.02243

Exotic Higgs decays





For low masses, ATLAS/CMS are background limited, CODEX-b has an edge

V. Gligorov, SK, M. Papucci, D. Robinson: 1708.02243

ATLAS reach rescaled from: 1811.07370

Moving forward

We are part of the “Physics Beyond Colliders” effort at CERN

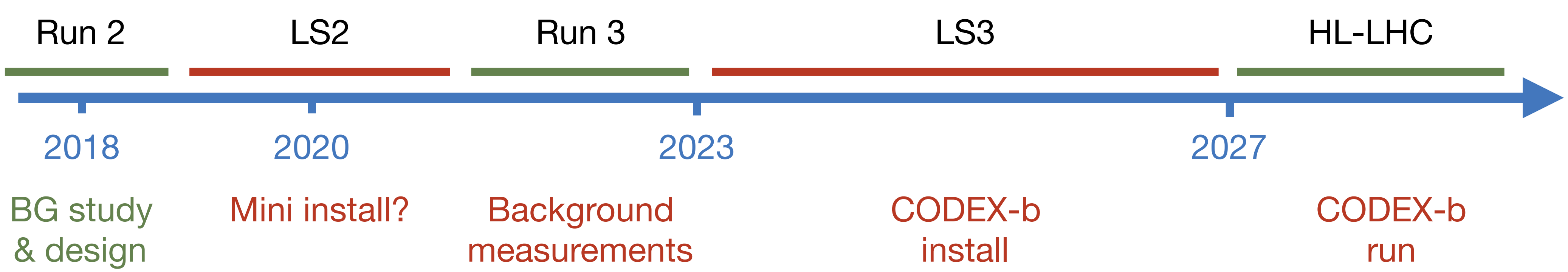
(See 1901.09966 for many more signal benchmarks)

Muon tagger in UX85A cavern

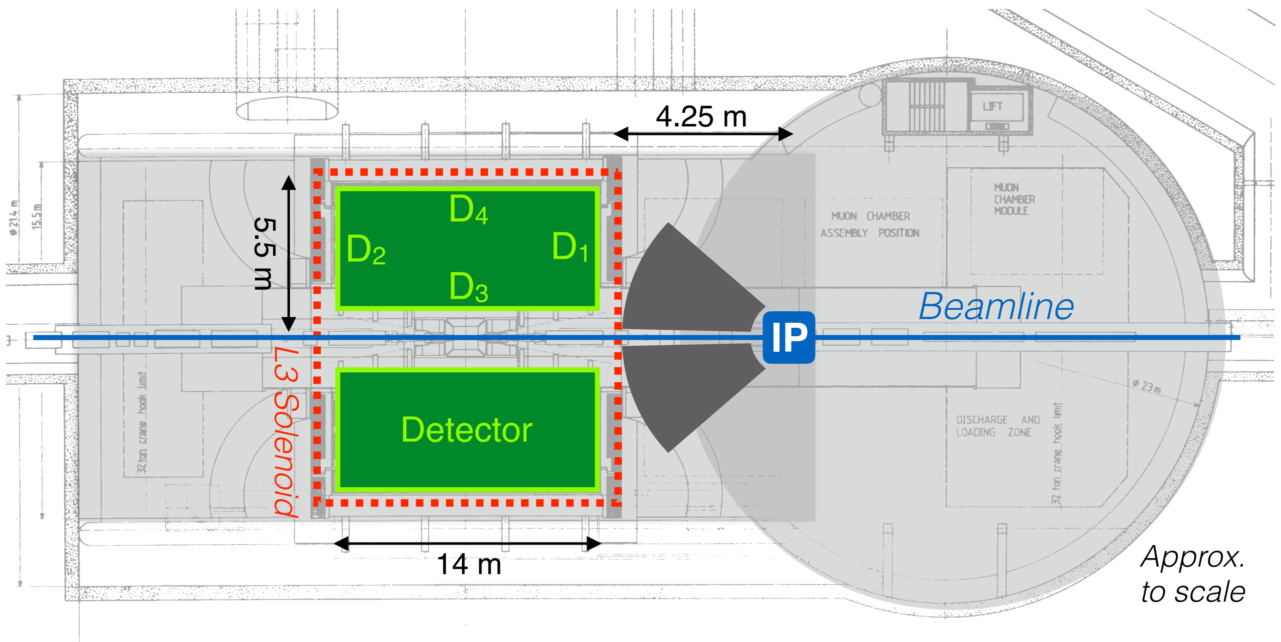
Ongoing work on the LHCb side

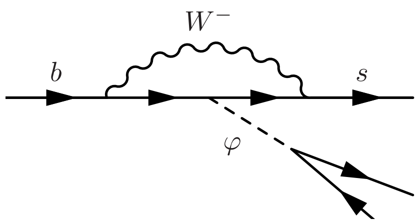
- Background data analysis
- Detector design and simulation
- 1^{th} collaboration meeting in June 2019 at CERN

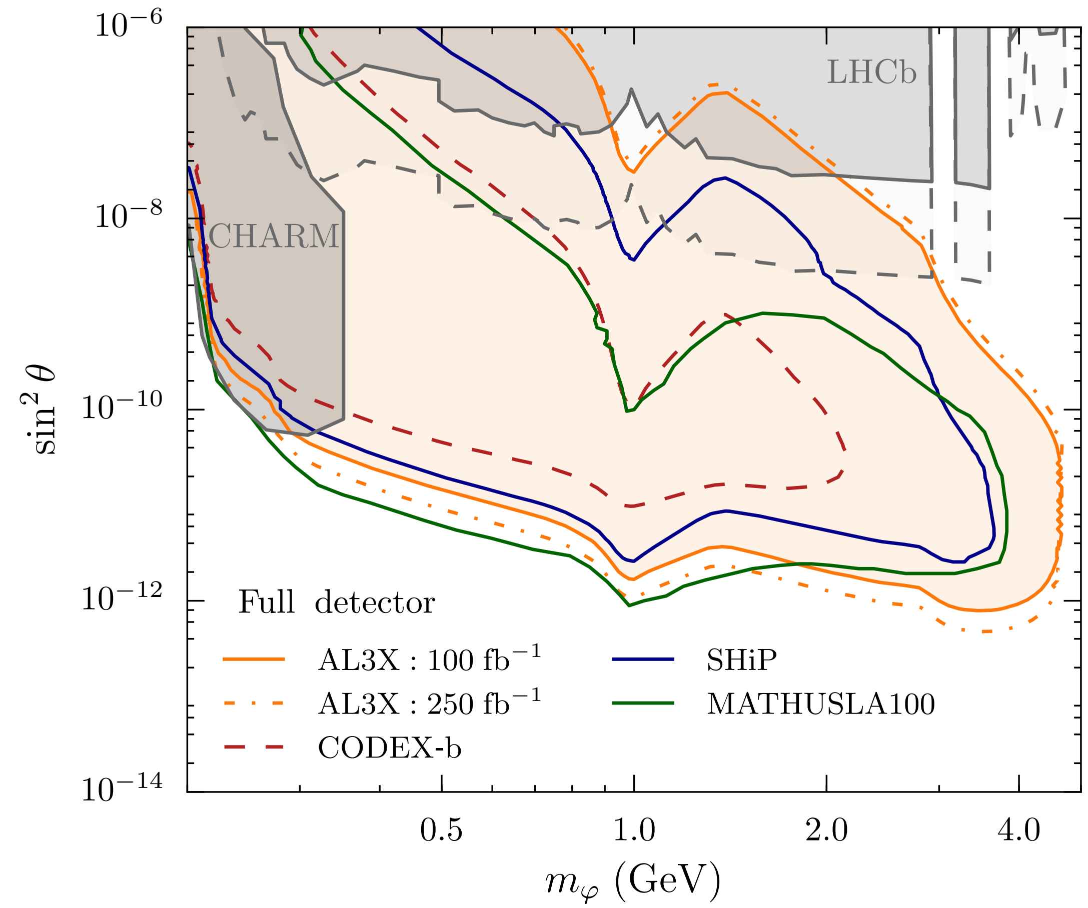
→ On track for a full proposal by late 2019



A more ambitious version



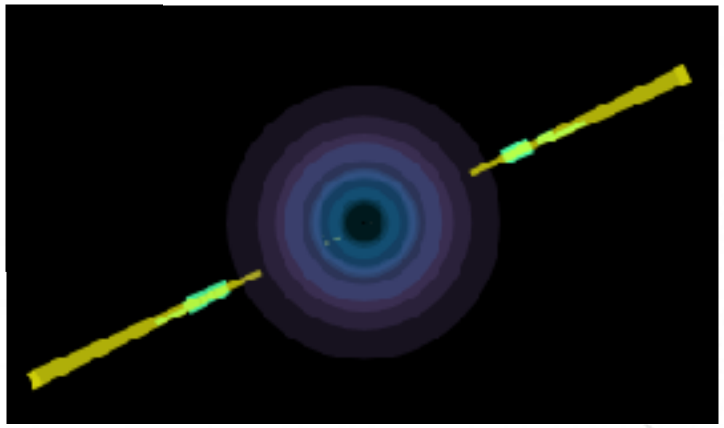




- Reuse L3 magnet and ALICE TPC (excellent momentum measurement!)

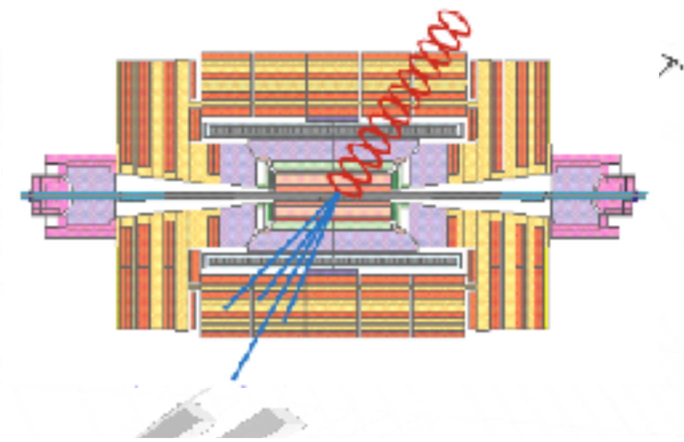
V. Gligorov, SK, B. Nachman, M. Papucci, D. Robinson: 1810.03636

Soft signatures with existing detectors



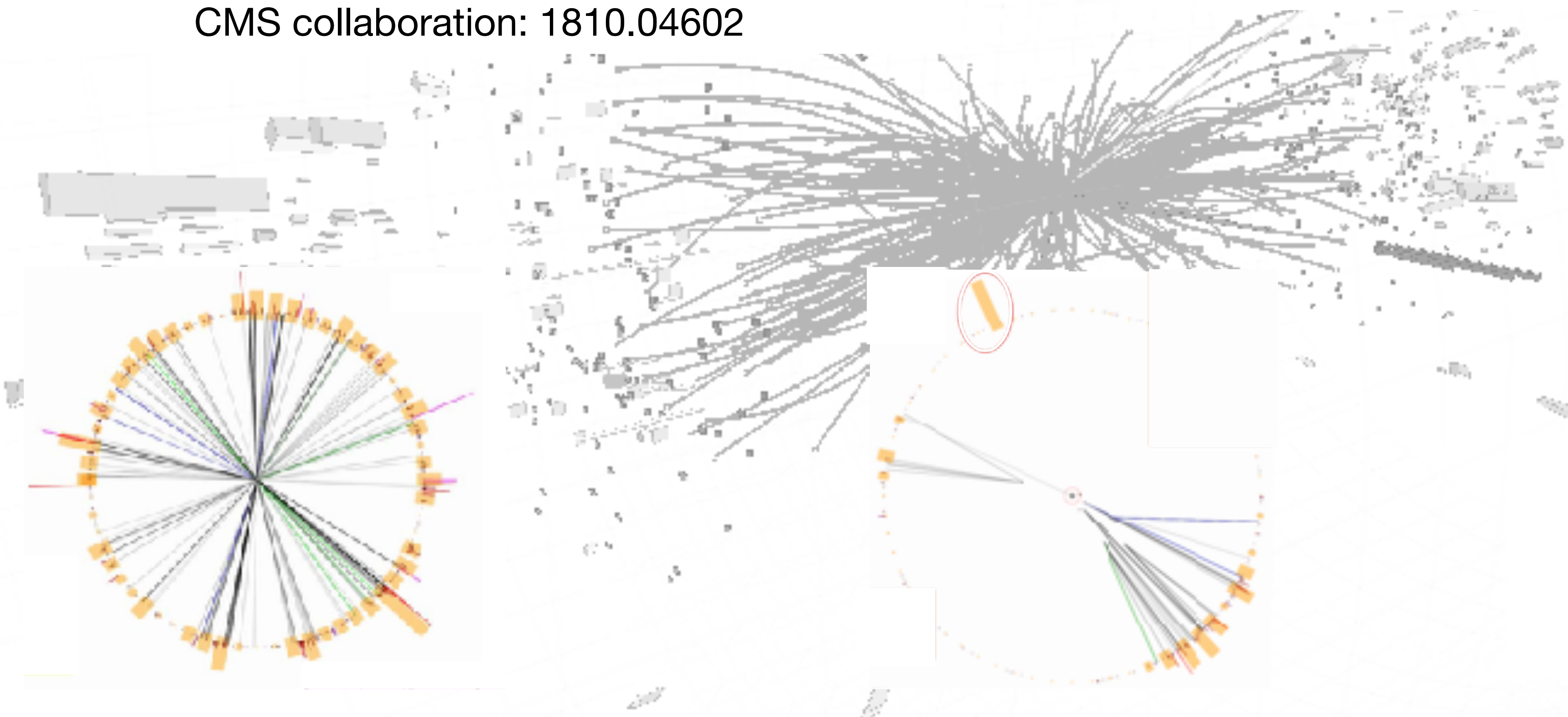
ALPs in heavy ion collisions

SK, T. Lin, H. Lou, T. Melia: 1607.06083 ,1709.07110
CMS collaboration: 1810.04602



Tracking for Quirks

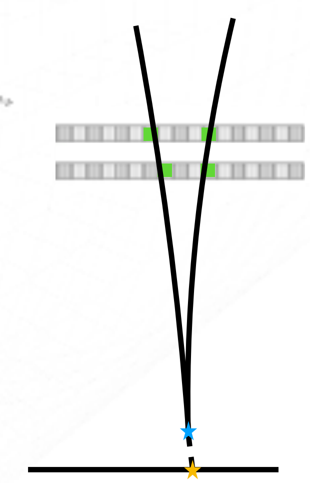
SK, H. Lou, M. Papucci, J. Setford: 1708.02243



Triggers for dark showers

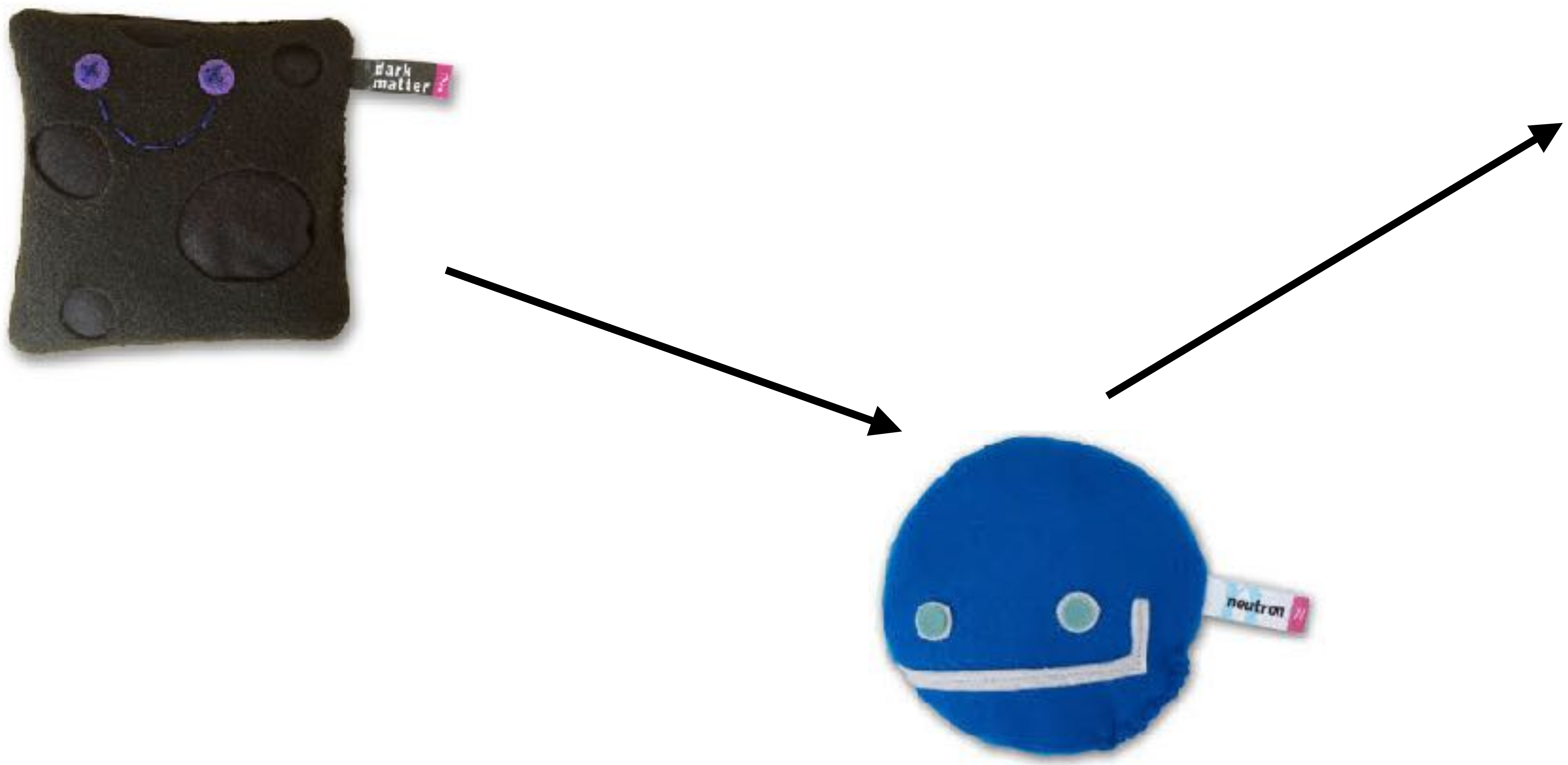
SK, et. al. : 1612.00850
with ATLAS collaboration: in progress

J. Shelton, SK, D. Xu: in progress



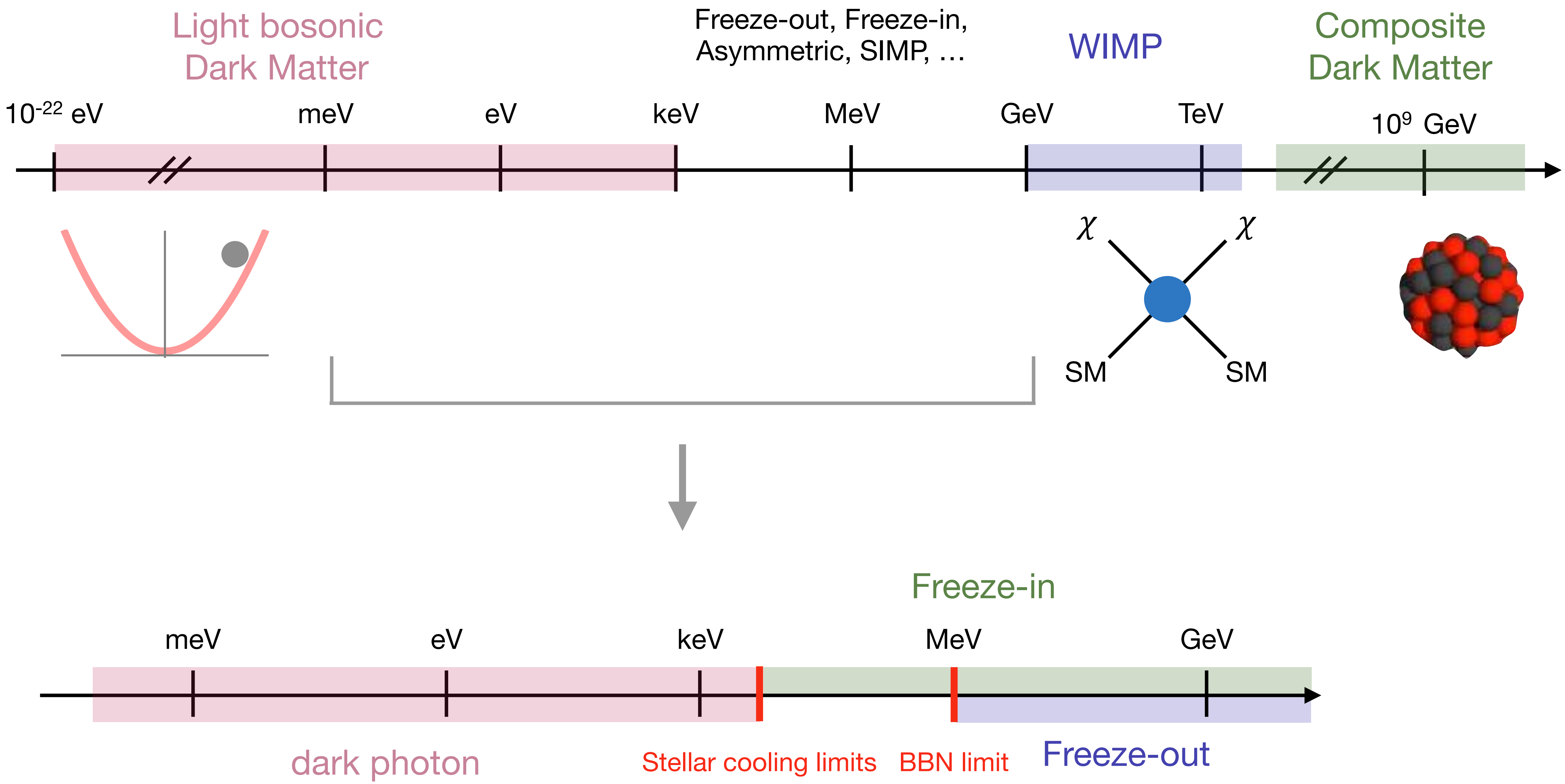
CMS vertex trigger

Y. Gershtein, SK: in progress



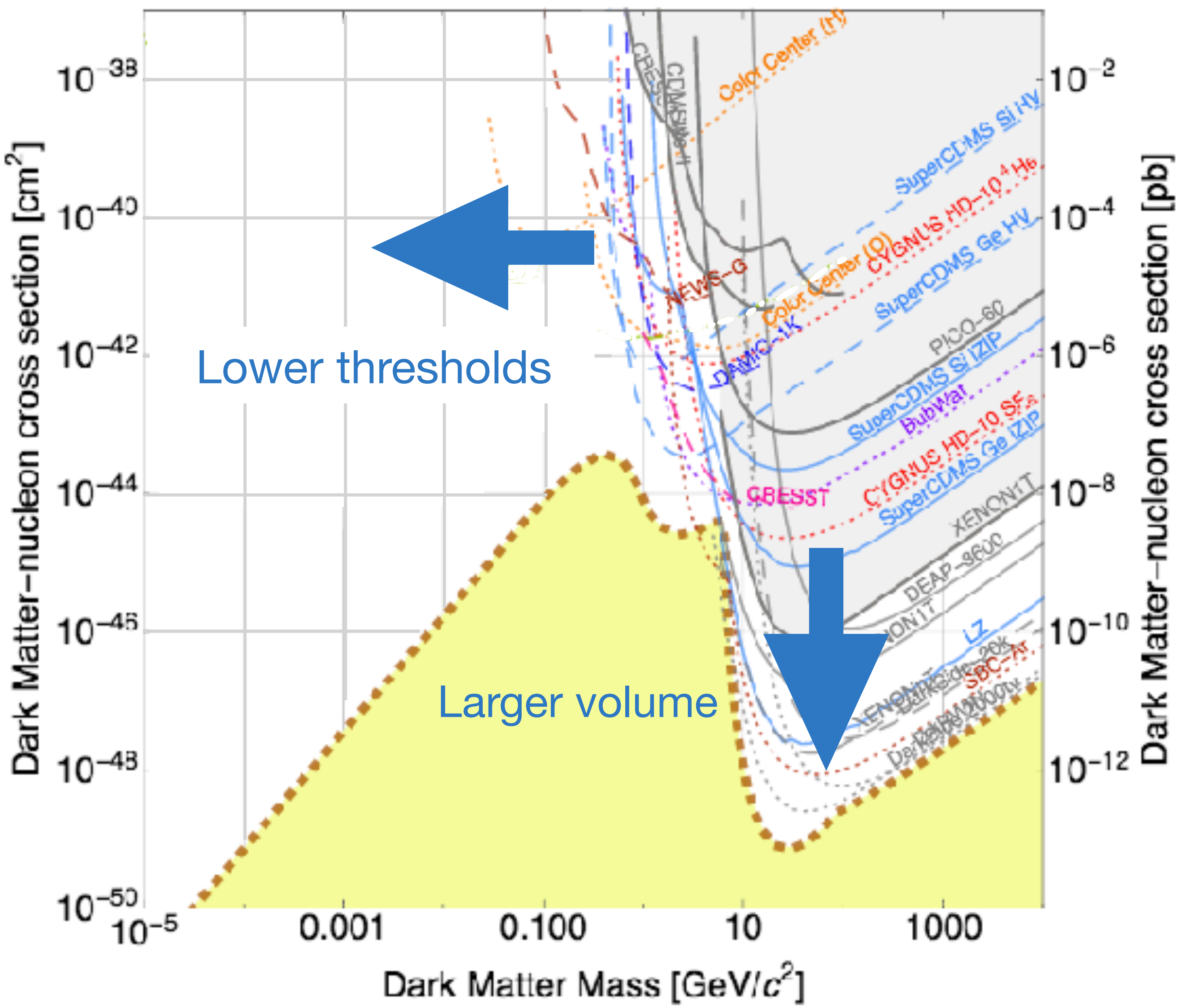
The soft frontier in dark matter detection

Models of Dark Matter



Freeze-out: Dark Matter drops out of equilibrium with Standard Model (e.g. WIMP's)
Freeze-in: Dark Matter is never in equilibrium; Standard Model "leaks" into the dark sector

Dark matter direct detection



Cosmic visions report 2017: 1707.04591

What do we need?

Experiment:

1. Low target mass materials:

$$q < 2 m_\chi v_\chi, \qquad v_\chi \approx 10^{-3}$$

$$E_R = \frac{q^2}{2 m_N} < 10^{-6} \times \frac{m_\chi^2}{m_N}$$

2. Ultra-sensitive calorimeters with low dark counts

Theory:

1. The mediator is important, independent set of constraints

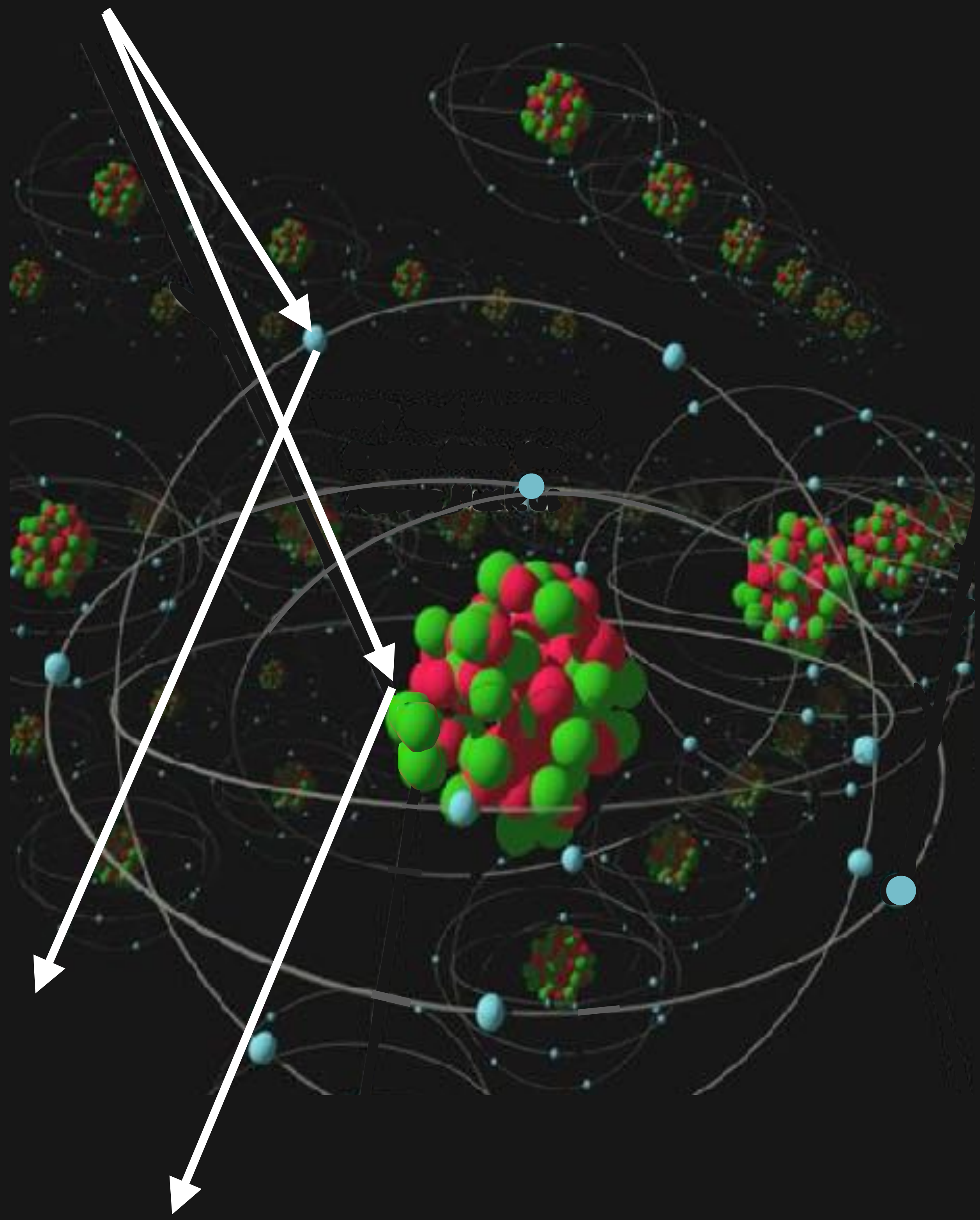
   SK, T. Lin, K. Zurek: 1709.07882

2. Beyond “billiard ball” scattering: structure effects are critical!

Structure effects

Attempt to “match” target mass with dark matter mass

- $m_\chi > 1$ GeV
  → nuclear recoils
- 1 MeV $< m_\chi <$ 1 GeV
  → electron recoils
- $m_\chi < 1$ MeV
  → $q \approx m_\chi v_\chi < \text{keV} \sim \text{nm}^{-1}$



Structure effects

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- $m_\chi > 1$ GeV
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- 1 MeV < m_χ < 1 GeV
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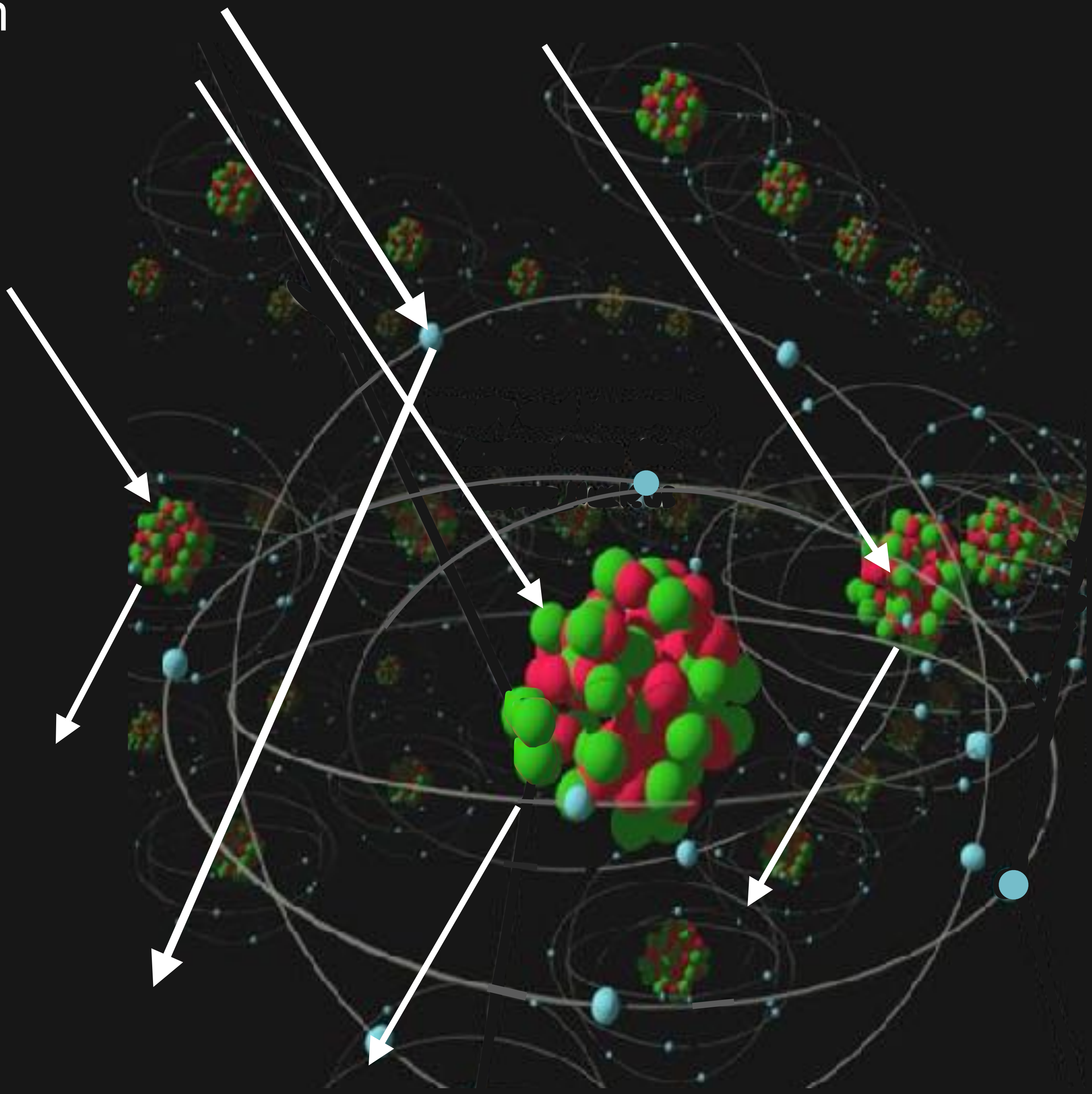
- $m_\chi < 1$ MeV
  → $q \approx m_\chi v_\chi < \text{keV} \sim \text{nm}^{-1}$

↓

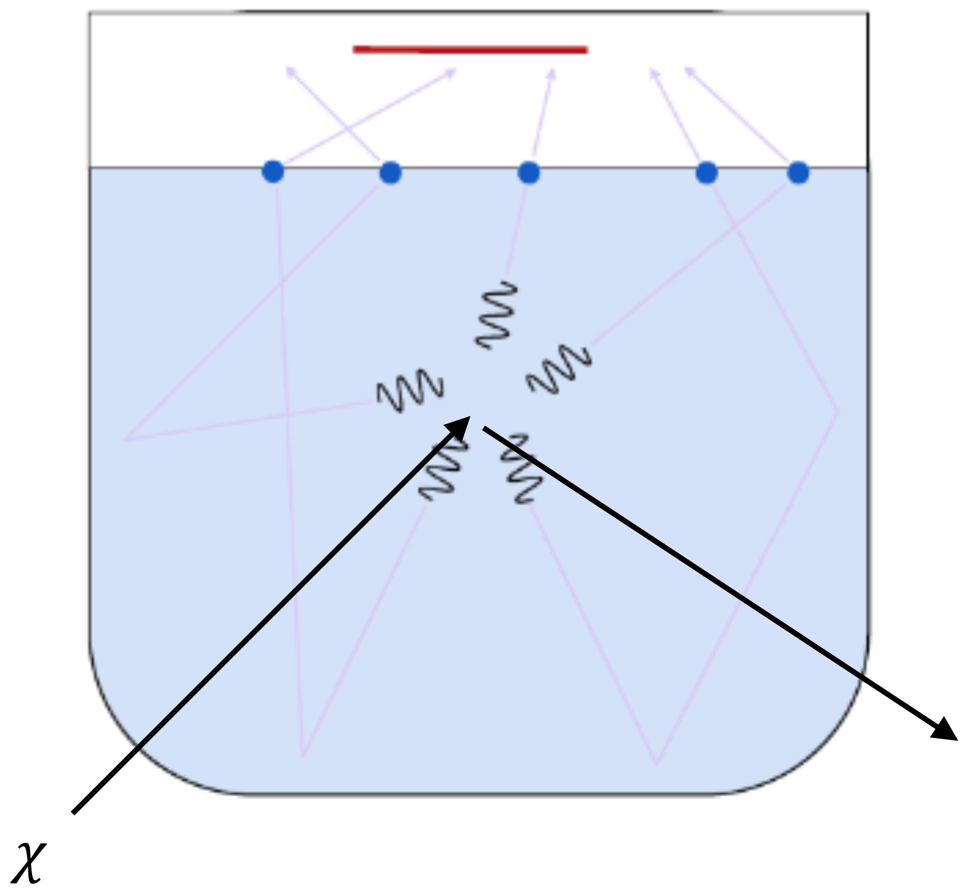
Scatter of collective excitations

(e.g. phonons)



Proposed Detectors

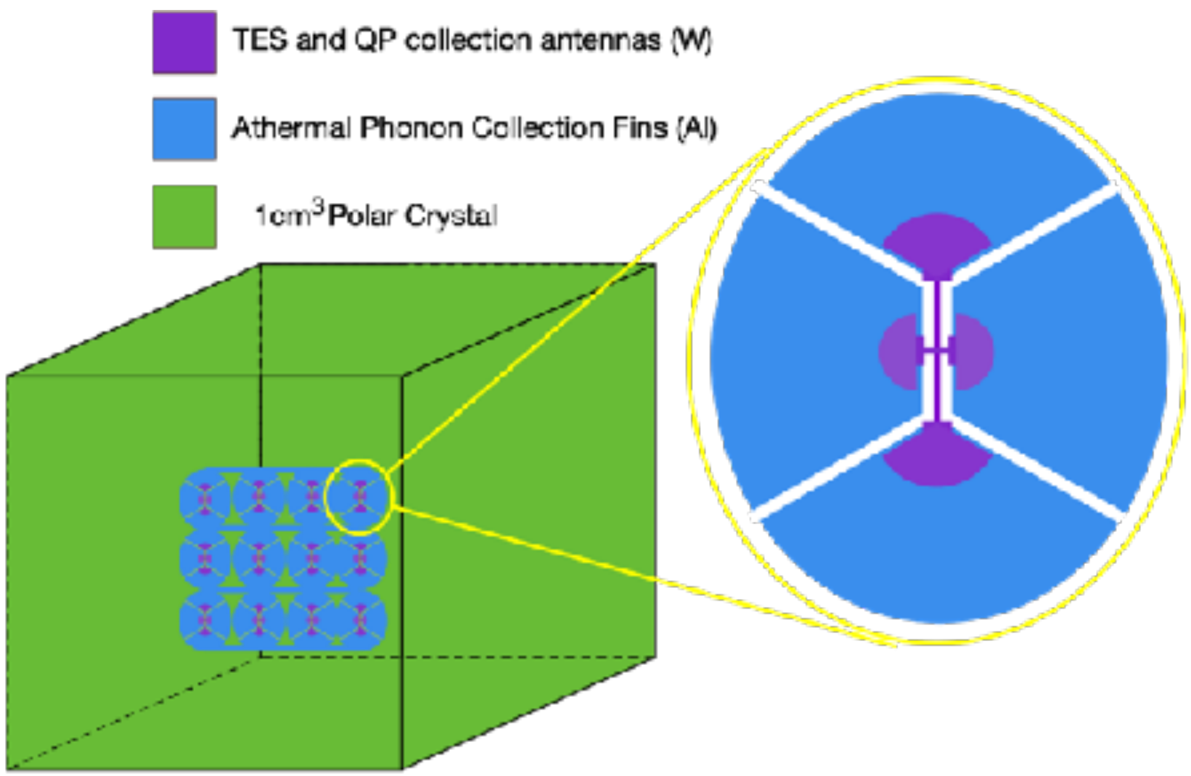
Superfluid helium detector



Detector concept: W. Guo, D. McKinsey: 1302.0534
SK, T. Lin, K. Zurek: 1611.06228

Scalar mediator only

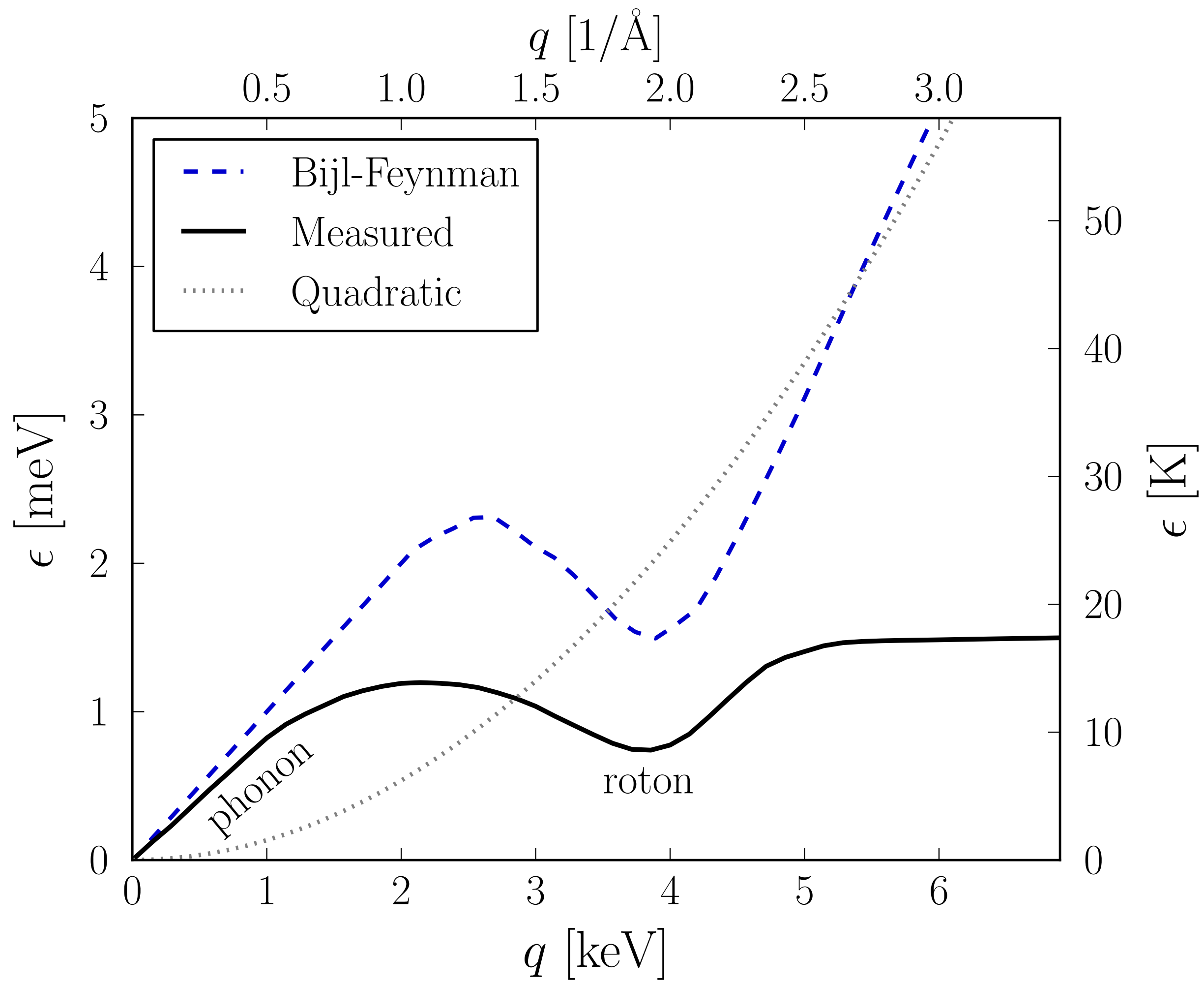
Polar material detector



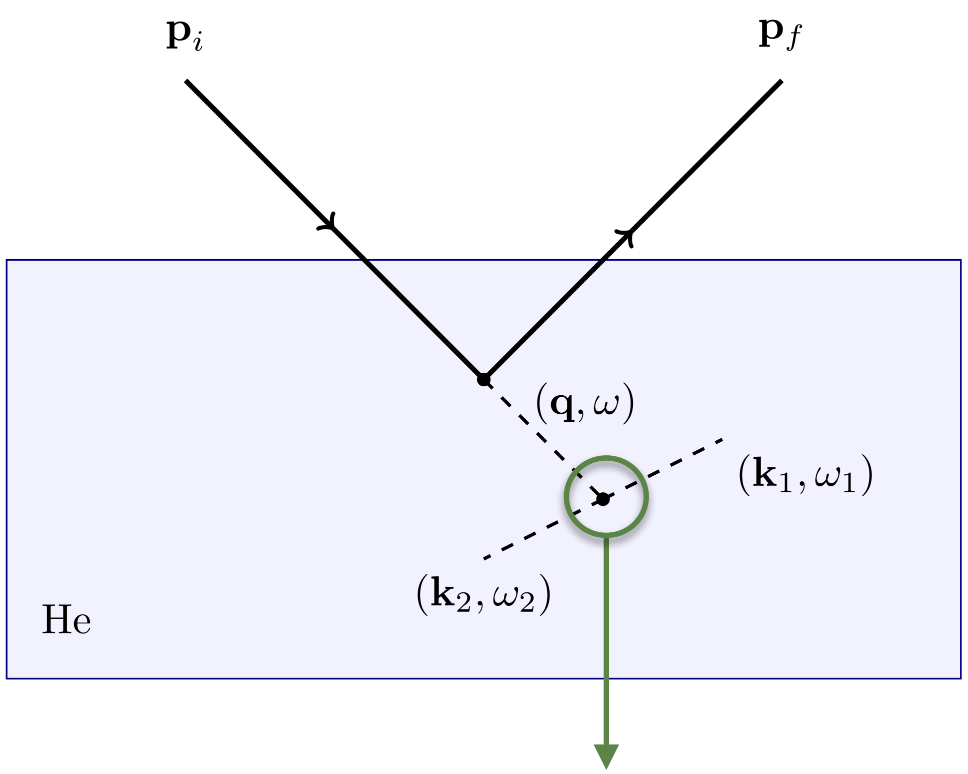
SK, T. Lin, M. Pyle, K. Zurek: 1712.06598
S. Griffin, SK, T. Lin, M. Pyle, K. Zurek: 1807.10291

Scalar mediator &
dark photon mediator

Phonons & rotons in superfluid He



Final state: two hard, back-to-back phonons



Issue: speed of Dark Matter >> speed of sound

↓

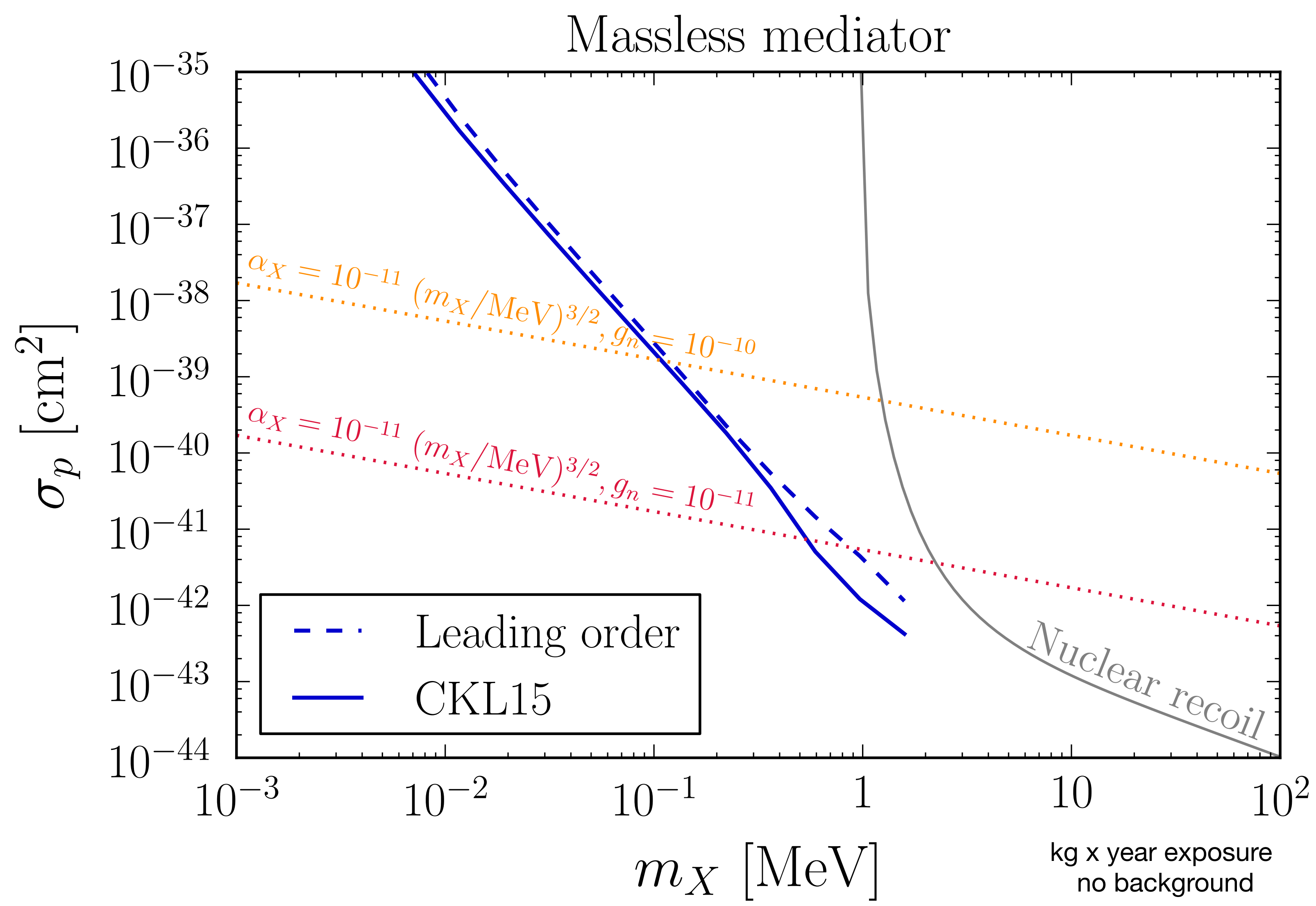
Cannot scatter against single, on shell excitation

Calculate the 3-excitation matrix element

R. Feynman, 1954
H. W. Jackson, E. Feenberg, 1962
E. Feenberg, 1969
M. J. Stephen, 1969

SK, T. Lin, K. Zurek: 1611.06228

Comparison with simulation



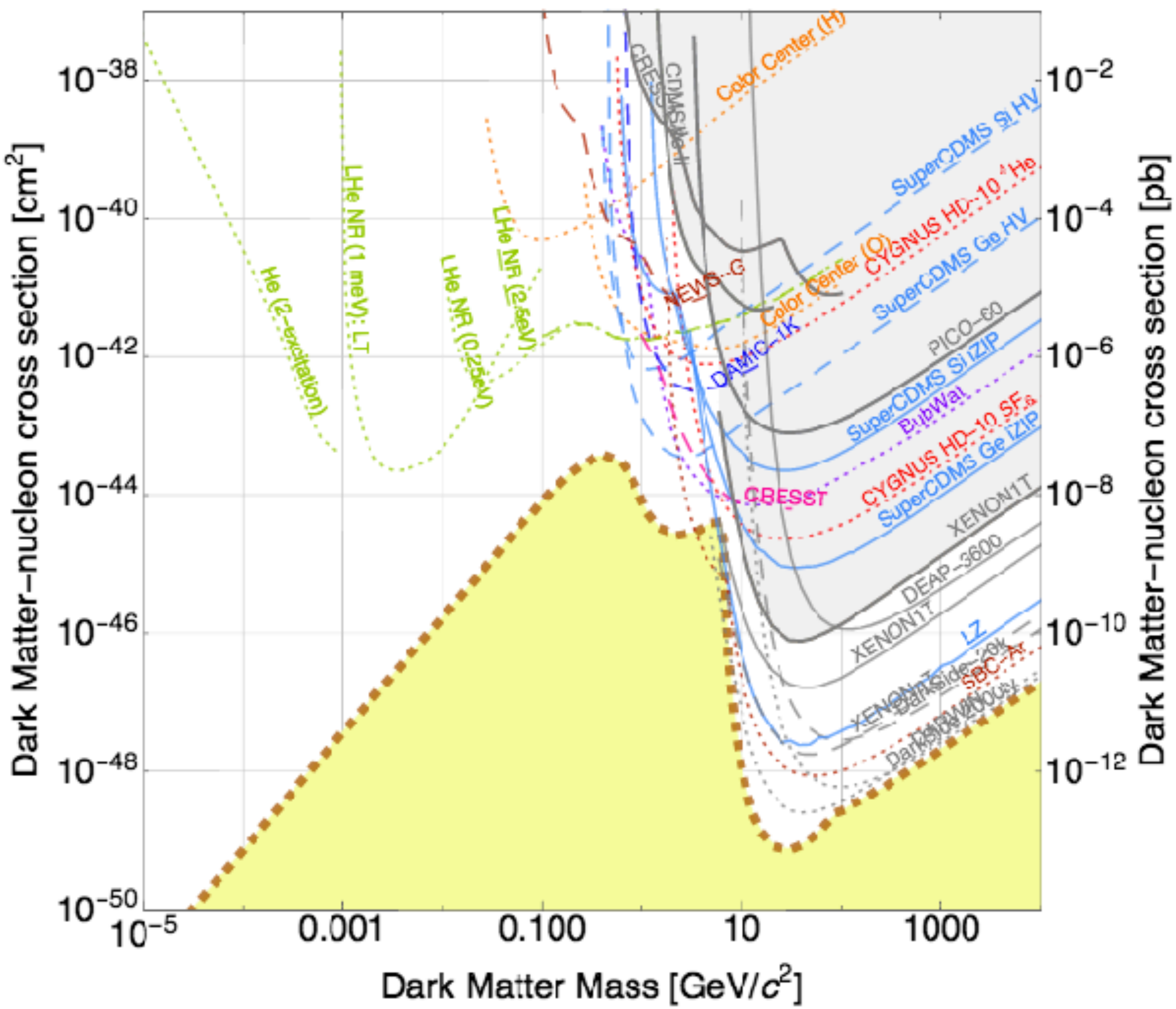
kg x year exposure
no background

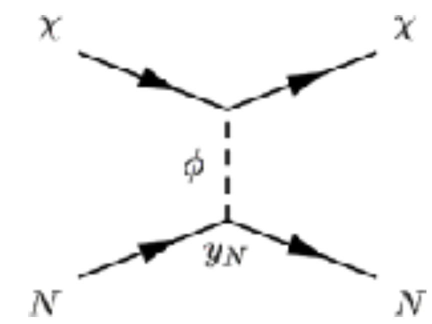
Reach agrees within a factor of ~ 2 with extrapolated simulation data*

* Campbell, Krotscheck and Lichtenegger (2015)

SK, T. Lin, K. Zurek: 1611.06228

Reach

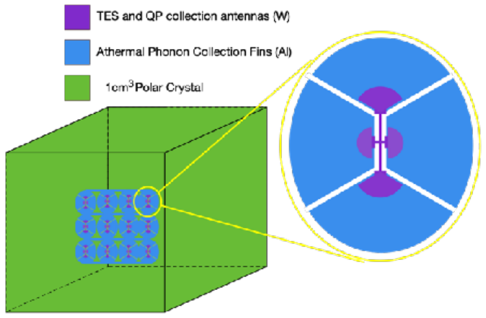




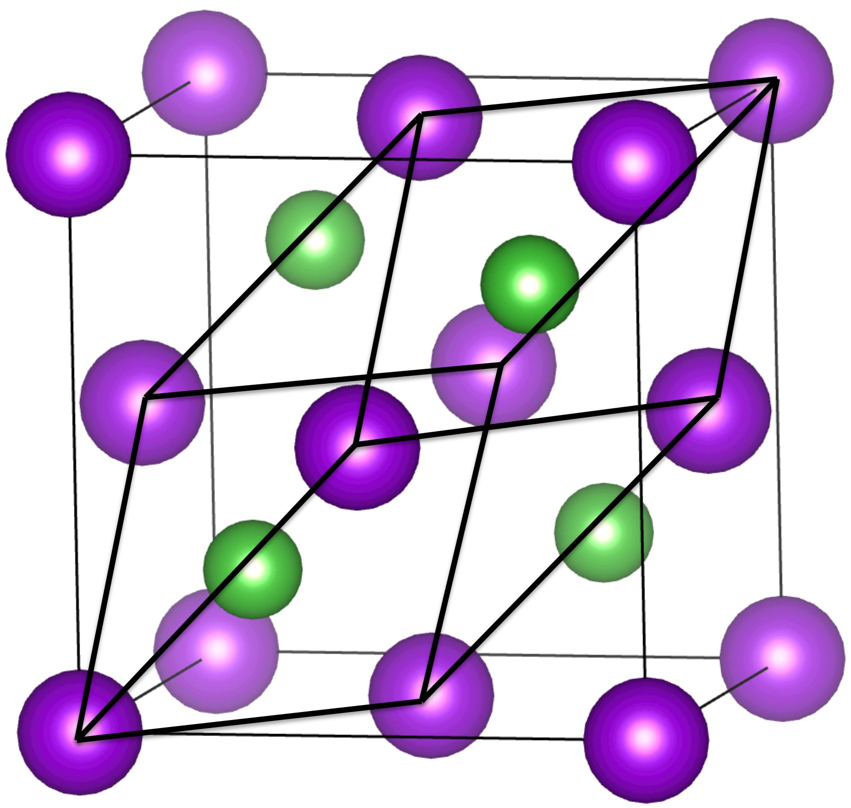
Superfluid helium can be sensitive down to m_χ ~ 10 keV

Cosmic visions report 2017: 1707.04591

Polar Materials

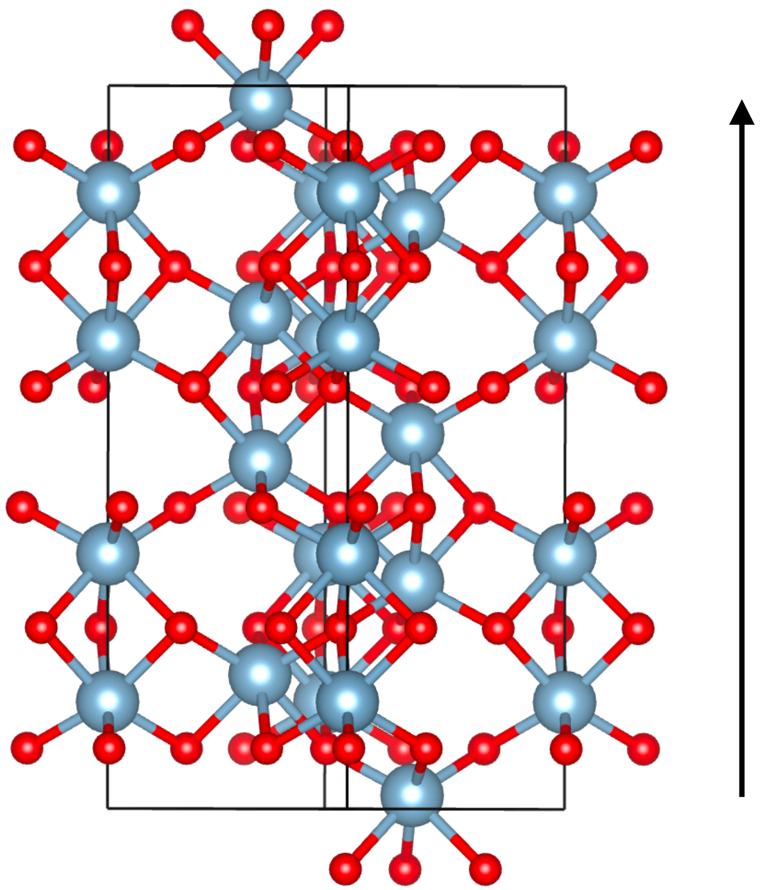


GaAs



2 atoms in primitive cell

Al_2O_3 (Sapphire)



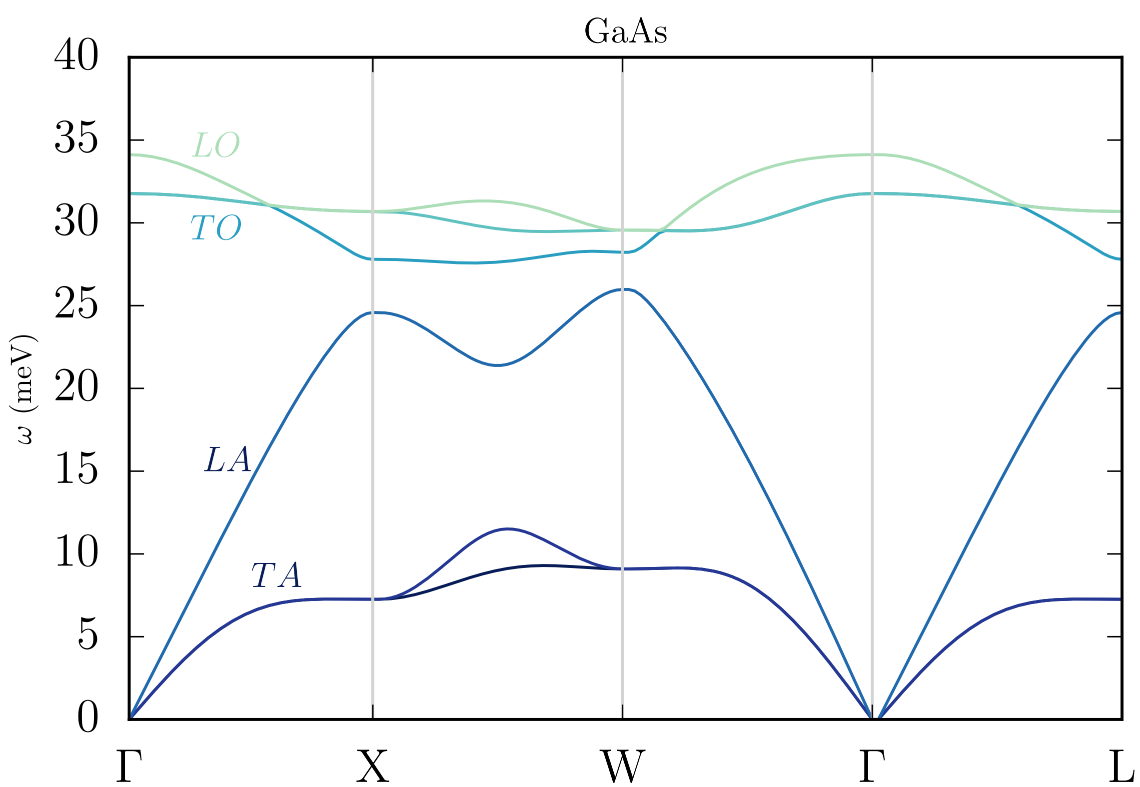
Primary crystal axis

10 atoms in primitive cell

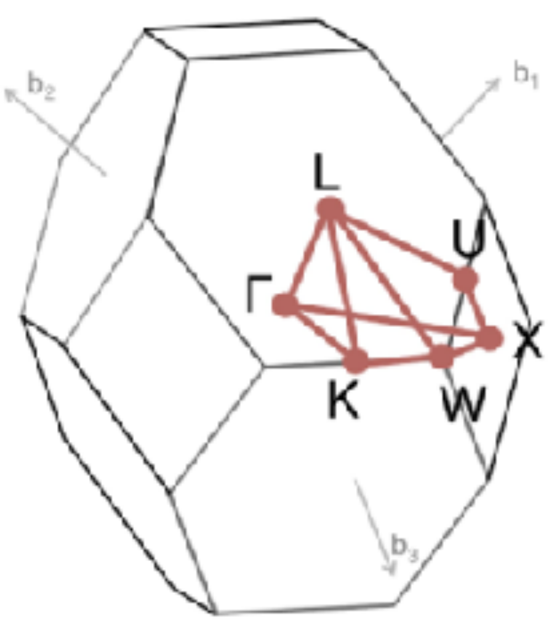
At least two *different* atoms in the unit cell

Why polar materials?

1. Optical phonons for kinematic matching



GaAs Brillouin zone



3. Semi-conductors or insulators: screening is small

4. Crystal axis allows for directional detection (daily modulation!)

5. Readily available now

SK, T. Lin, M. Pyle, K. Zurek: 1712.06598

Frölich Hamiltonian

H. Frölich, 1954
C. Verdi, F. Giustino, Phys. Rev. Lett. 115, 176401 (2015)

Electric dipole interacting with test charge: $$H \sim i\,e \sum_{\mathbf{q}} \frac{\mathbf{q}\cdot\mathbf{P}}{|\mathbf{q}|^2} e^{i\mathbf{q}\cdot\mathbf{r}}$$

Born effective charge tensor for each atom

phonon eigenvectors (atomic displacements)

$$H = i\frac{\kappa e^2}{V} \sum_{j,\nu,\mathbf{q}} \sum_{\mathbf{G}\neq\mathbf{q}} \frac{1}{\sqrt{2N m_j \omega_{\nu,\mathbf{q}}}} \frac{(\mathbf{q}+\mathbf{G})\cdot\mathbf{Z}_j\cdot\mathbf{e}_{j,\nu}(\mathbf{q})}{(\mathbf{q}+\mathbf{G})\cdot\boldsymbol{\epsilon}_\infty\cdot(\mathbf{q}+\mathbf{G})} e^{i(\mathbf{q}+\mathbf{G})\cdot(\mathbf{r}+\boldsymbol{\tau}_j)}$$

Sum over:

- j atoms in unit cell
- ν phonon modes
- **q** 1st Brillouin zone
- **G** reciprocal lattice

phonon energy

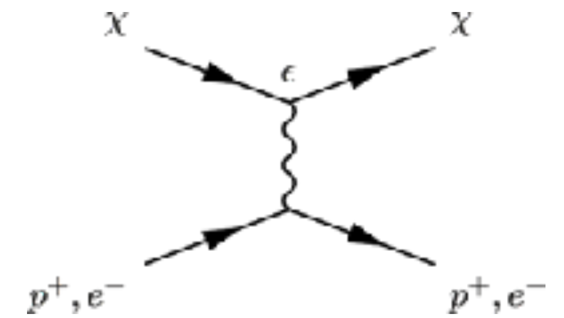
high frequency dielectric tensor

Calculation overview:

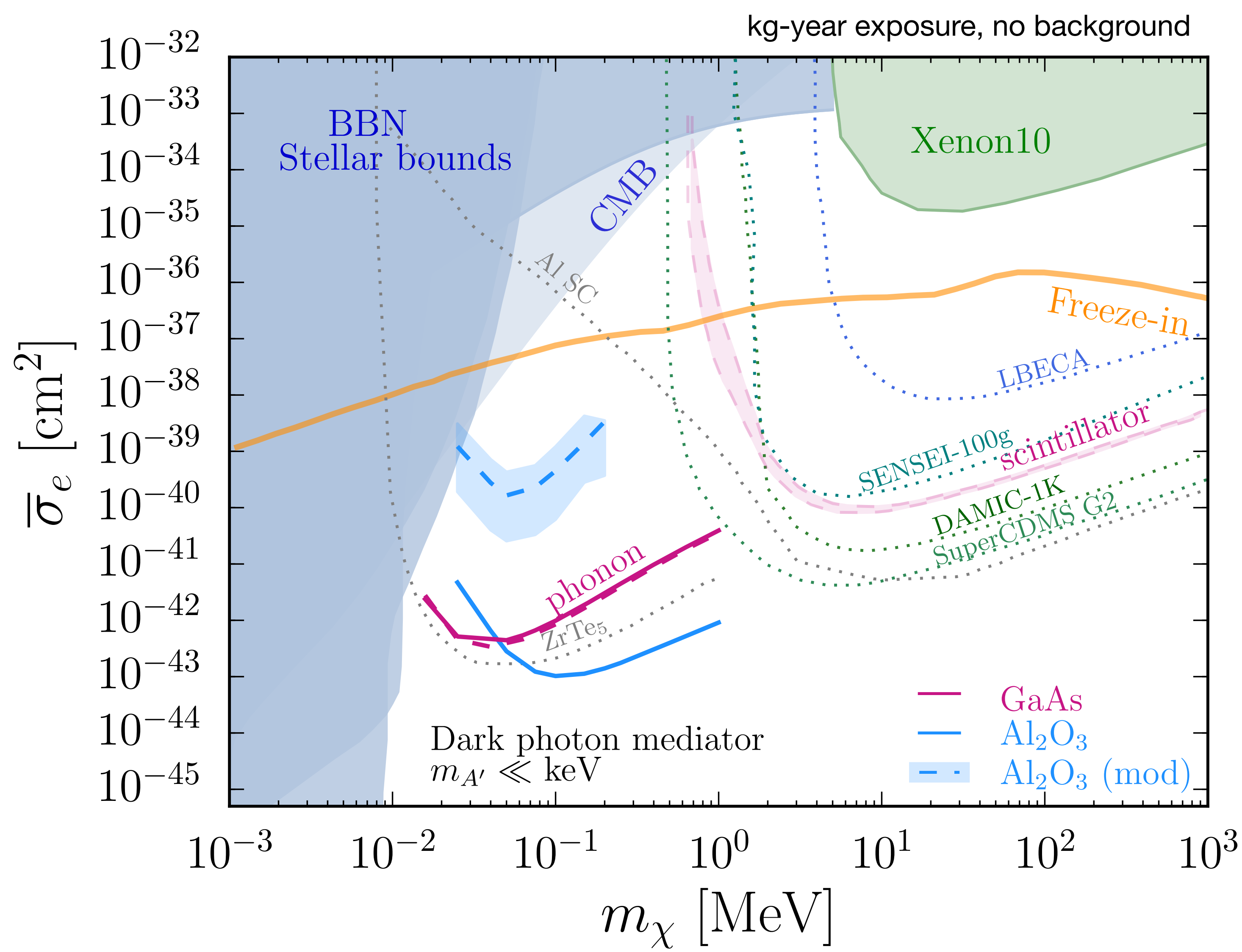
Crystal structure → **VASP** (DFT calculation) → Force constants, Born effective charges → **phonopy** (diagonalize force matrix) → Phonon energies & eigenvectors

S. Griffin, SK, T. Lin, M. Pyle, K. Zurek: 1807.10291

Reach



Both GaAs and Sapphire probe Dark Matter masses as low as 10 keV
("milicharged" dark matter)

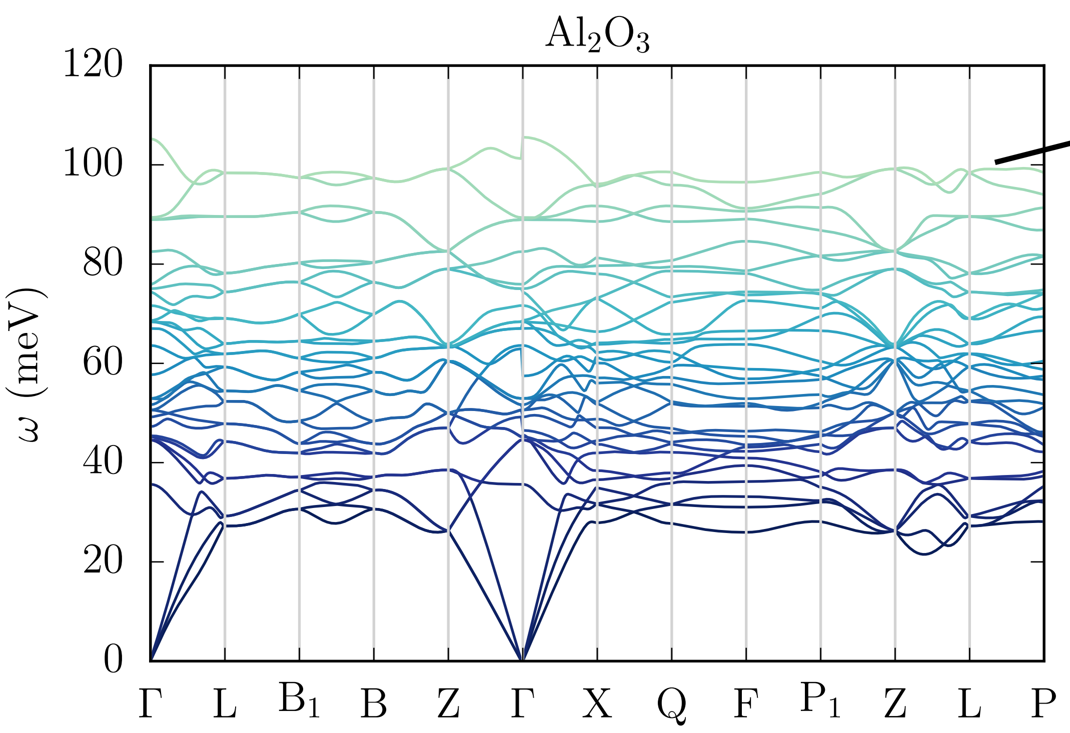


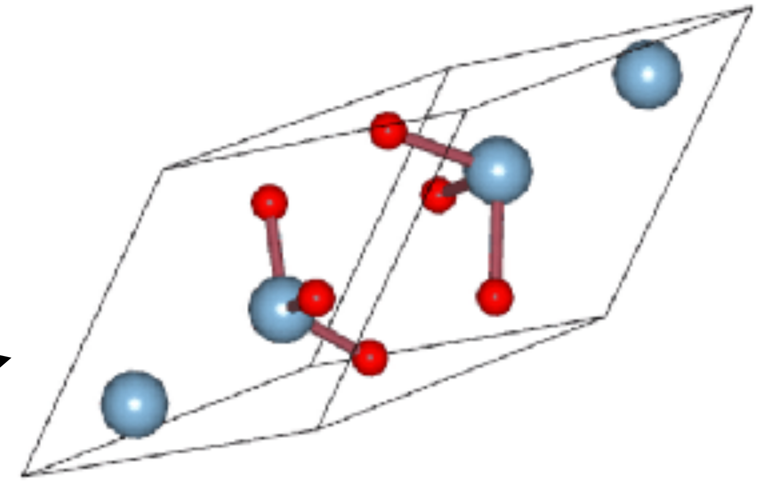
Probe the new parameter space with milligram-day exposure

SK, T. Lin, M. Pyle, K. Zurek: 1712.06598
S. Griffin, SK, T. Lin, M. Pyle, K. Zurek: 1807.10291

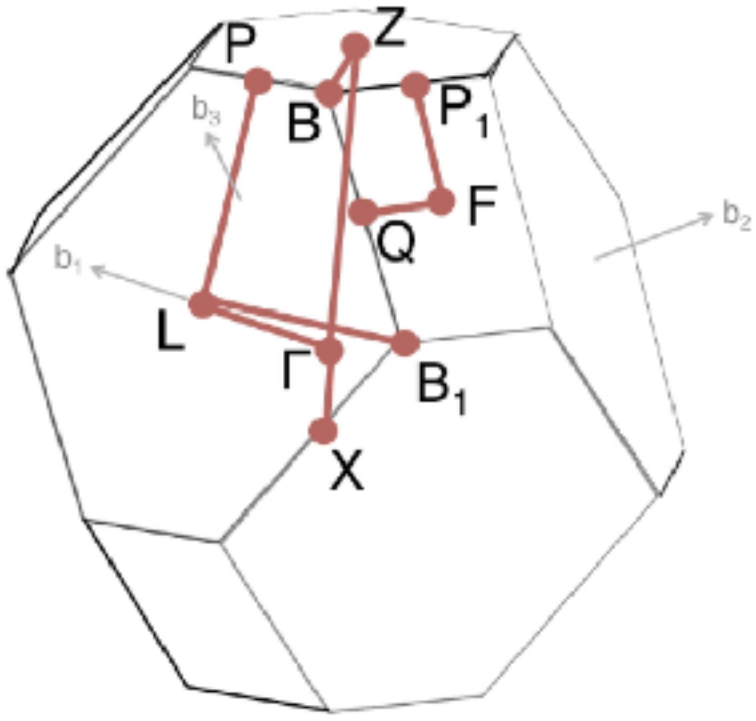
Most important mode

Most energetic mode dominates





Al₂O₃ Brillouin zone



Aluminum atoms move in phase

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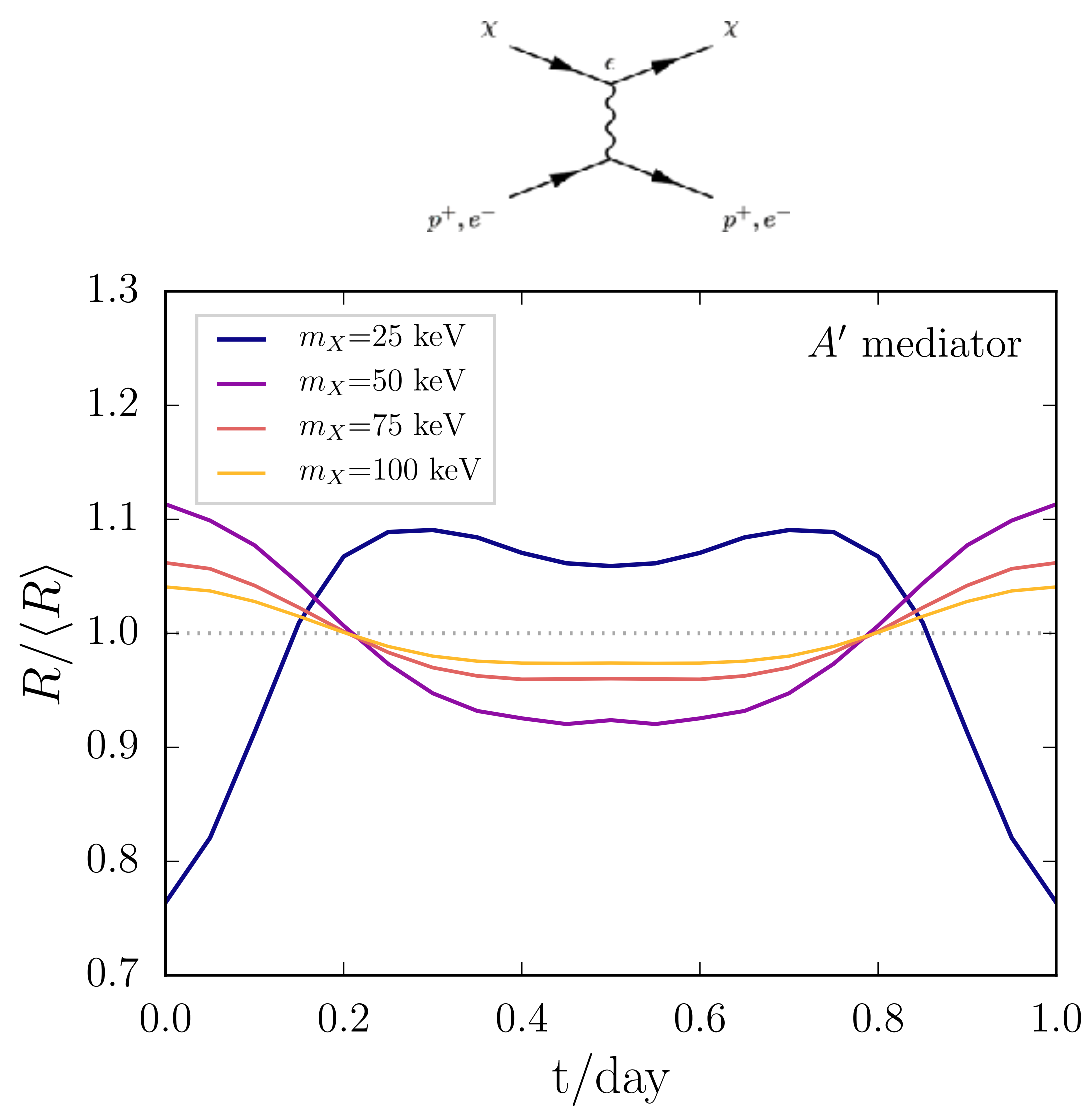
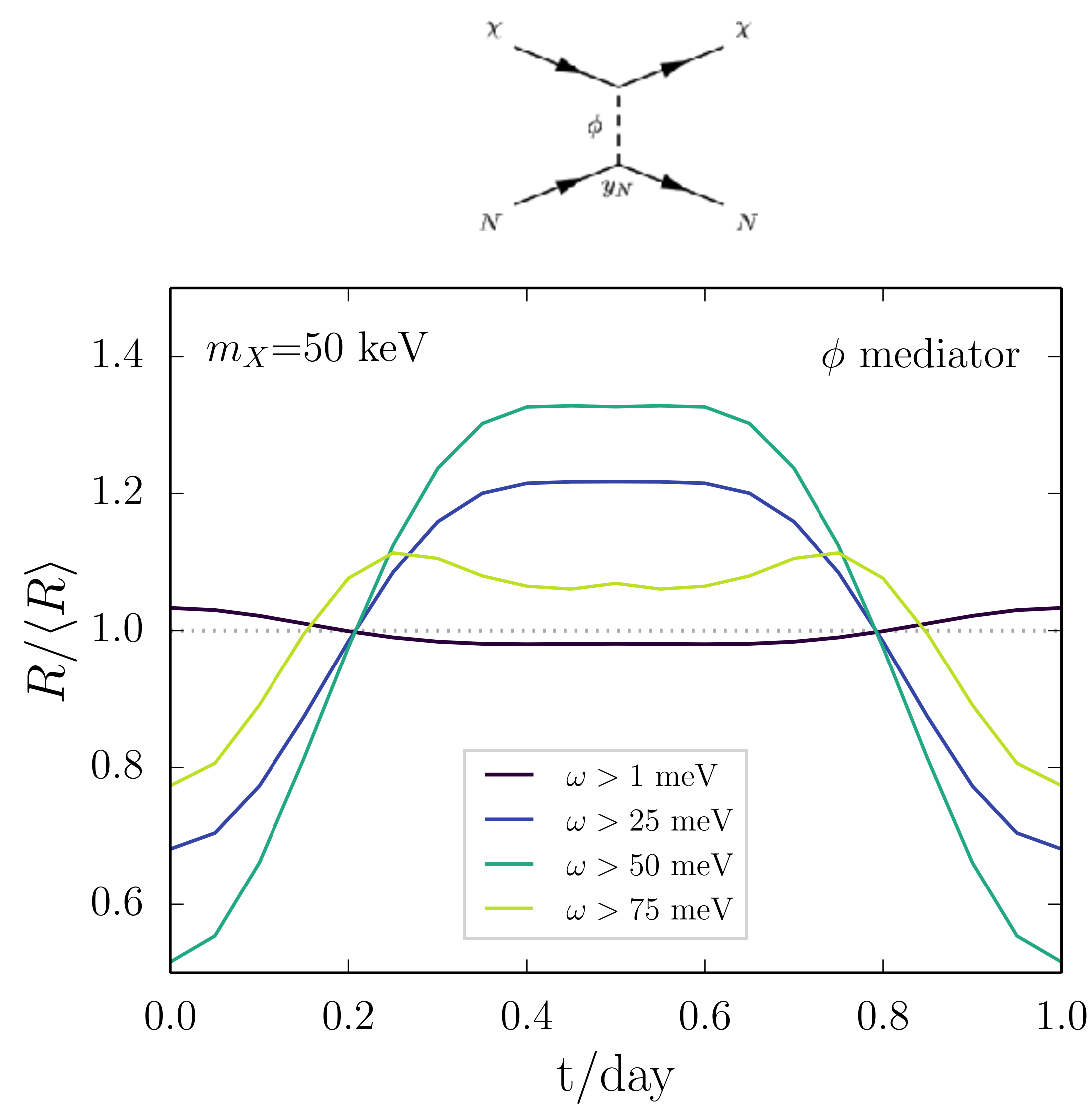
Large dipole

S. Griffin, SK, T. Lin, M. Pyle, K. Zurek: 1807.10291

Daily modulation





Daily modulation depends on dark matter mass, type of mediator type and threshold

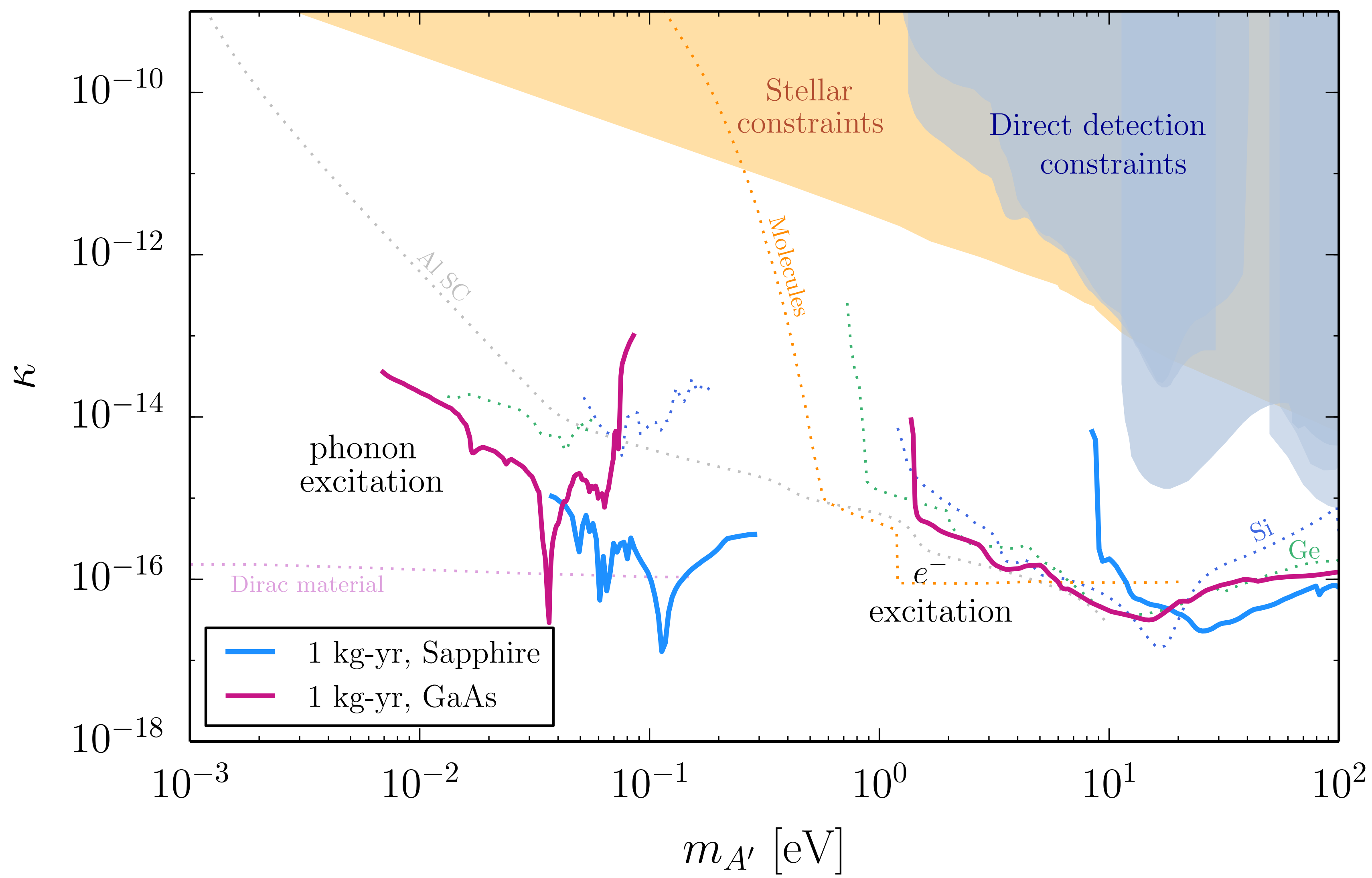
↓

Potential to measure the dark matter *mass* and *mediator type* using the daily modulation!

S. Griffin, SK, T. Lin, M. Pyle, K. Zurek: 1807.10291

Dark photon absorption

Dark photon dark matter: $\mathcal{L} \supset -\frac{\kappa}{2} F'_{\mu\nu} F^{\mu\nu}$



Extracted from the measured index of refraction

S. Griffin, SK, T. Lin, M. Pyle, K. Zurek: 1807.10291
(for a model see e.g. A. Long, L. Wang: 1901.03312)

Looking ahead

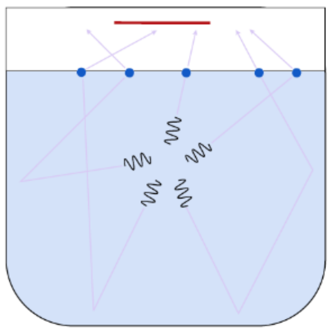
Experiment:

- 100 μm x 400 μm TES with 50 meV resolution achieve by Matt Pyle's group in Berkeley
- Next steps:
    - Scale & cool down TES further → 1 meV resolution
    - Build and optimize collector interface
    - Fabricate sensor on crystal (Si and GaAs first, sapphire later)

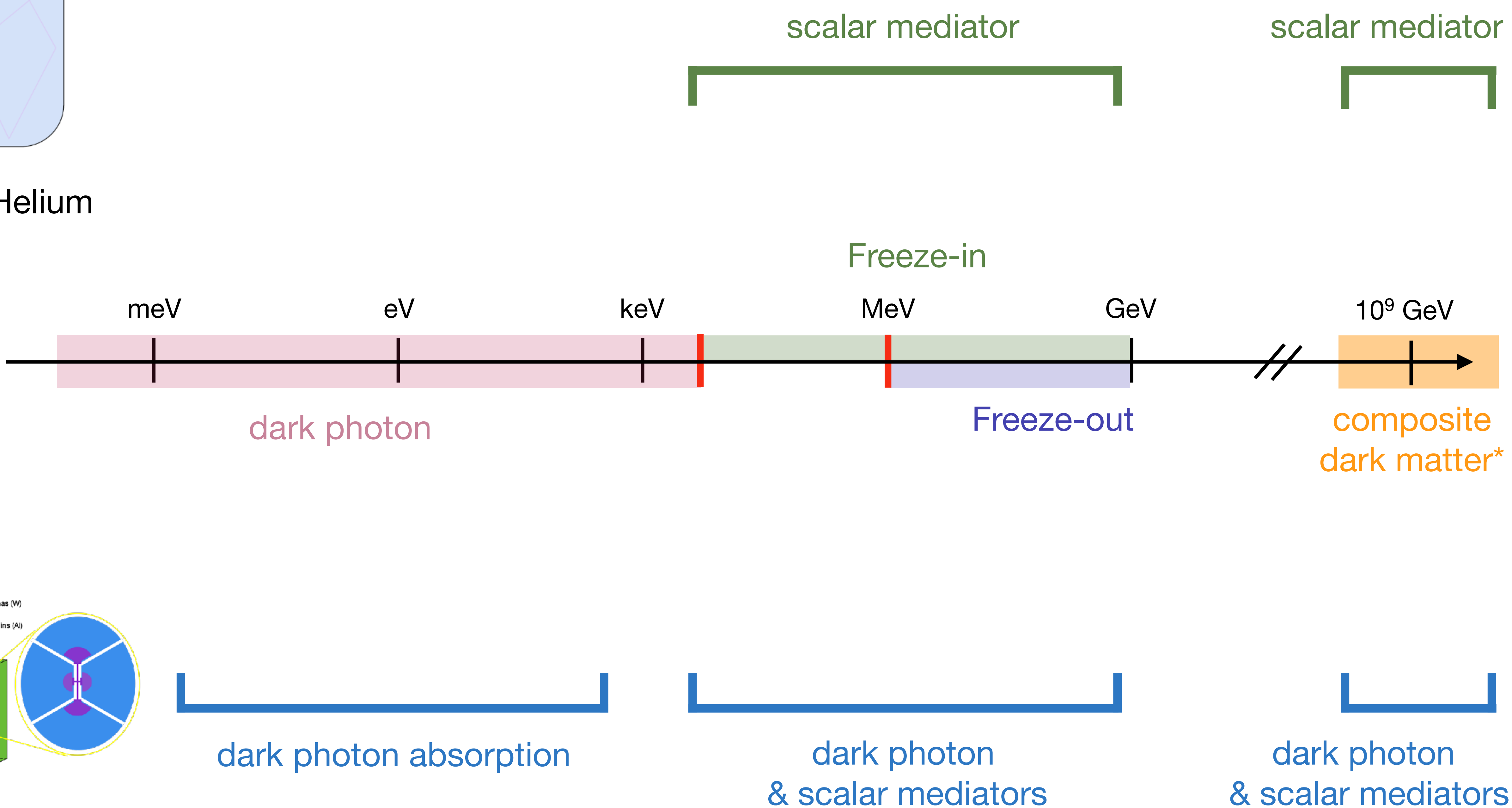
Theory:

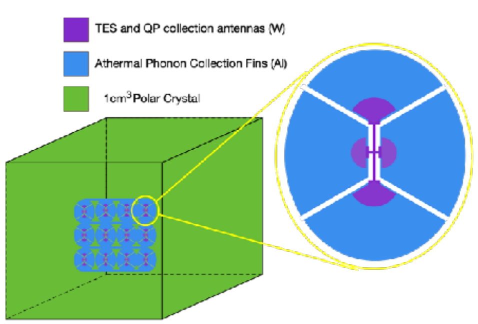
- Extend the calculation beyond first Brillouin zone (heavier dark matter, neutrinos)
- Multi-phonon production (similar to superfluid He)
- Generalize to different materials (e.g. PbS, SiC, …)

Dark Matter Summary



Superfluid Helium





Polar materials

* A. Coskuner, D. Grabowska, SK, K. Zurek: 1812.07573

Conclusion

The LHC will run for another ~ 15 years

- Higgs couplings / exotic decays
- Searches for new physics

↳ No free lunch: diminishing returns unless we keep innovating!

The search for cracks in the Standard Model is also diversifying rapidly

New (renewed) attention for:

- light dark matter
- axion-like dark matter
- gravitational wave detectors
- "smaller" accelerators experiments (Seaquest, NA62, COMPASS, Belle II ...)
- (neutron) stars
- neutrino experiments
- ....

US Cosmic Visions: New Ideas in Dark Matter 2017 : Community Report

Marco Battaglieri (SAC co-chair),[1] Alberto Belloni (Coordinator),[2] Aaron Chou (WG2 Convener),[3] Priscilla Cushman (Coordinator),[4] Bertrand Echenard (WG3 Convener),[5] Rouven Essig (WG1 Convener),[6] Juan Estrada (WG1 Convener),[3] Jonathan L. Feng

SK + few hundred others

Crucial input from

- Nuclear physics
- Condensed matter physics
- Astrophysics / cosmology

Particle physics is evolving to a more multidisciplinary field


Thank you!