Dark Sectors at Low Energy Colliders.

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Torben Ferber (torben.ferber@desy.de)

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

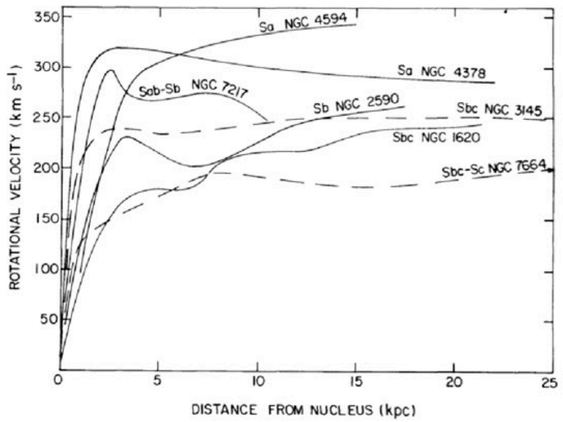
CLUSTER OF EXCELLENCE QUANTUM UNIVERSE

Belle II

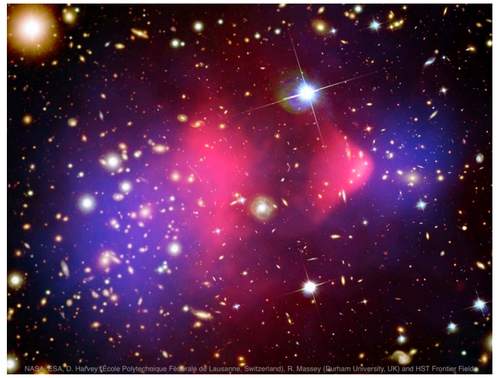
UH Universität Hamburg DER FORSCHUNG | DER LEHRE | DER BILDUNG

DESY.

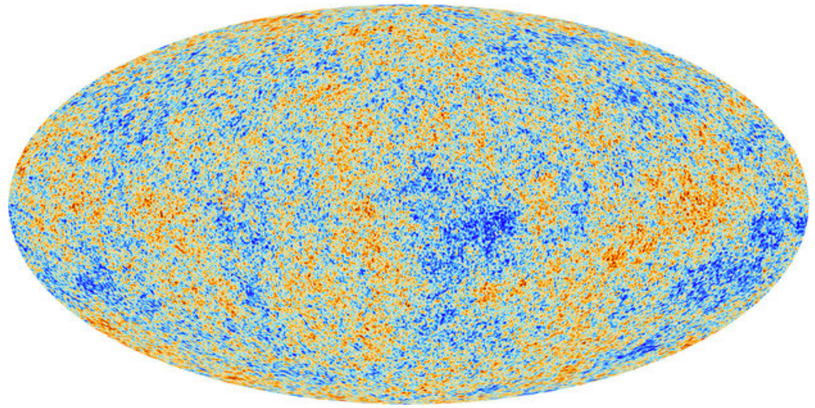
Dark Matter Evidence



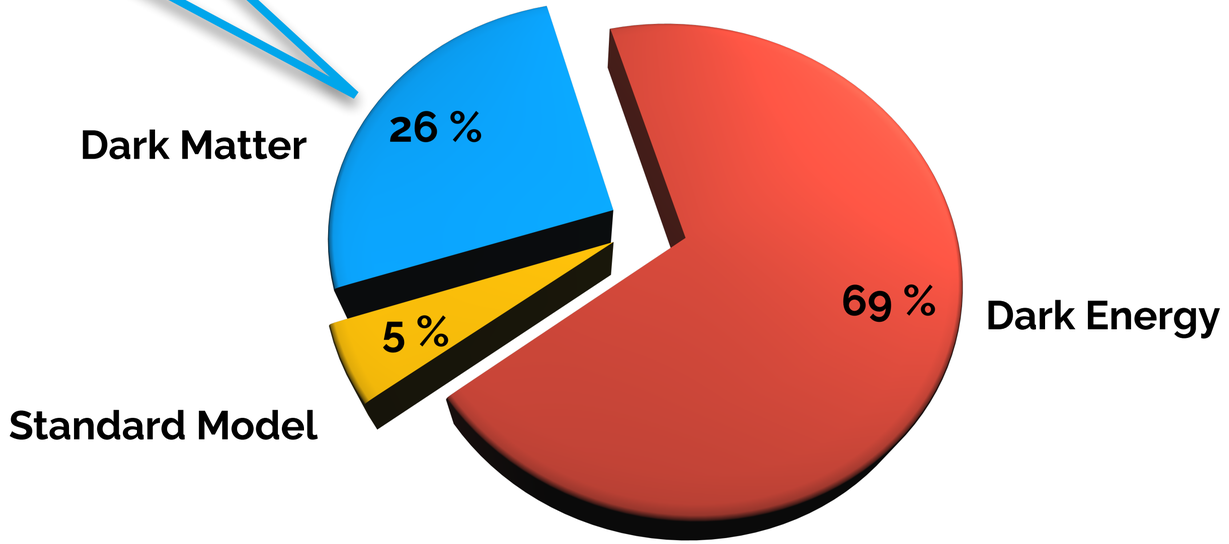
Galactic Rotation Curves



Gravitational Lensing



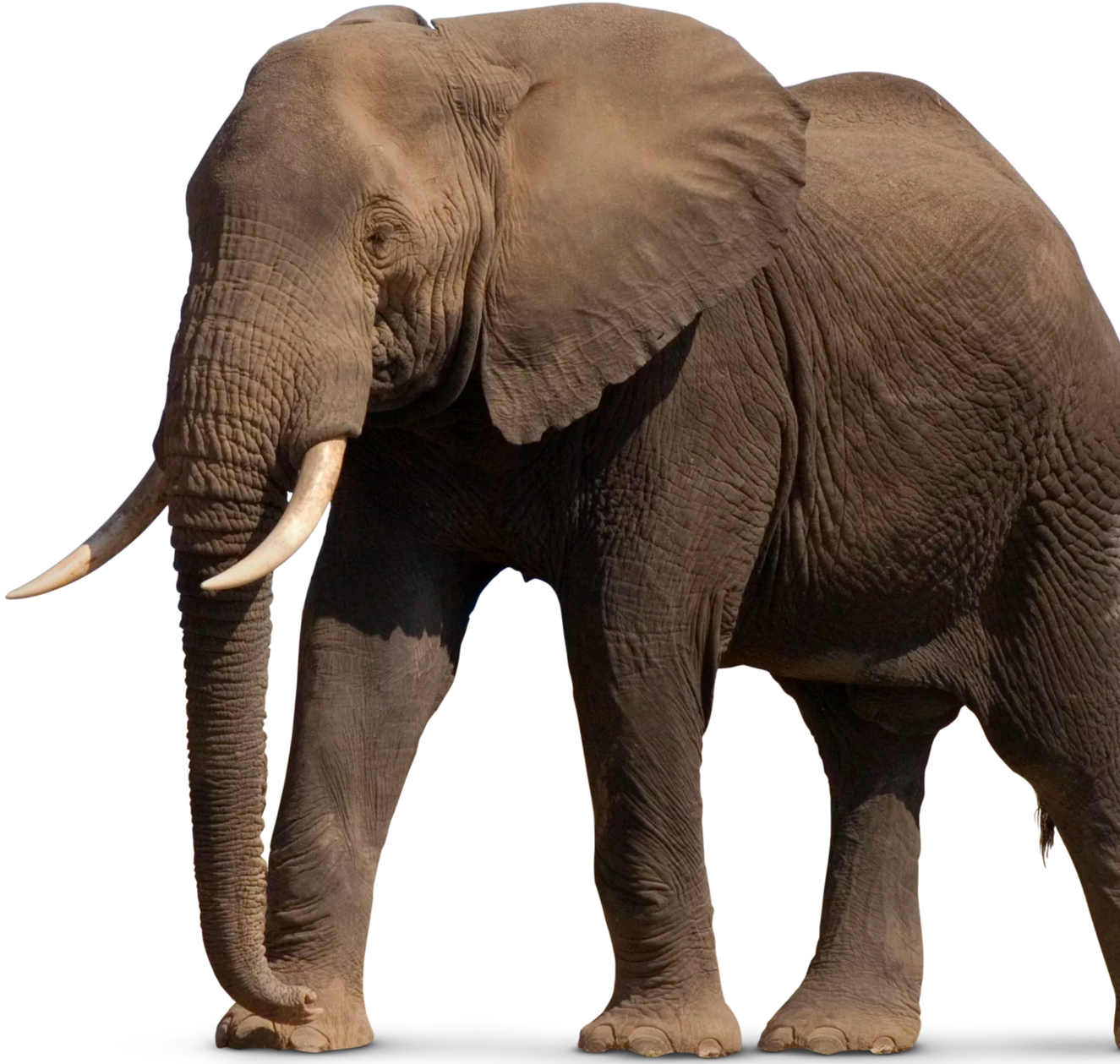
Cosmic Microwave Background



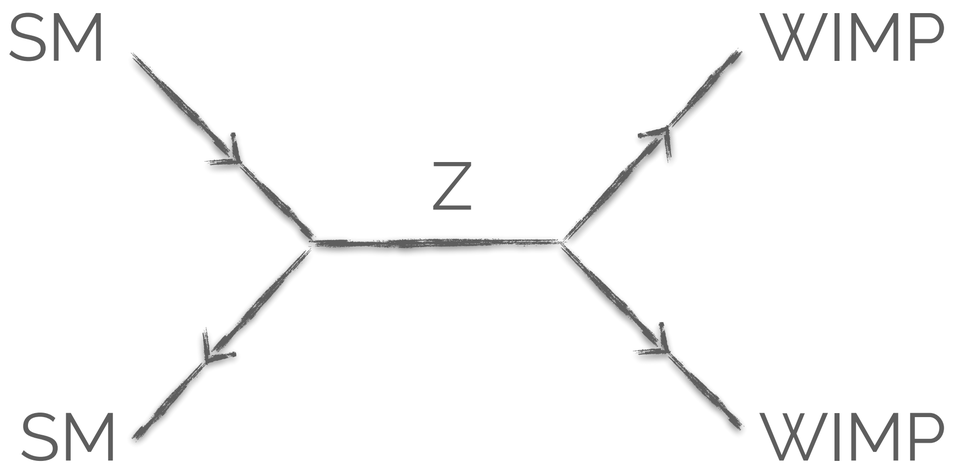
Dark Matter Properties

- We are rather **sure**:
  - Does interact **gravitationally**.
  - Does **not** strongly interact via **electromagnetic** or **strong** force.
  - Is **non-relativistic** (or cold).
  - Local density: $\rho_{local} \approx 0.4$ GeV/cm$^3 \approx$ 1 proton mass per 5 M&Ms

- We are **not so sure**:
  - **Collision-less** (assumed in ΛCDM)?
  - Does it interact with the **weak force** and via the **Higgs** mechanism?



Weakly Interacting Massive Particles: WIMPs



- WIMP: Weakly Interacting Massive Particles
  - Weak scale mass (GeV-TeV)
  - Weak scale cross section
  - Perfect candidate: Lightest SUSY Particle

→ correct present relict DM density

$$\Omega h^2 \simeq 0.1\ \text{pb}\ c\ /\ \langle \sigma v \rangle$$

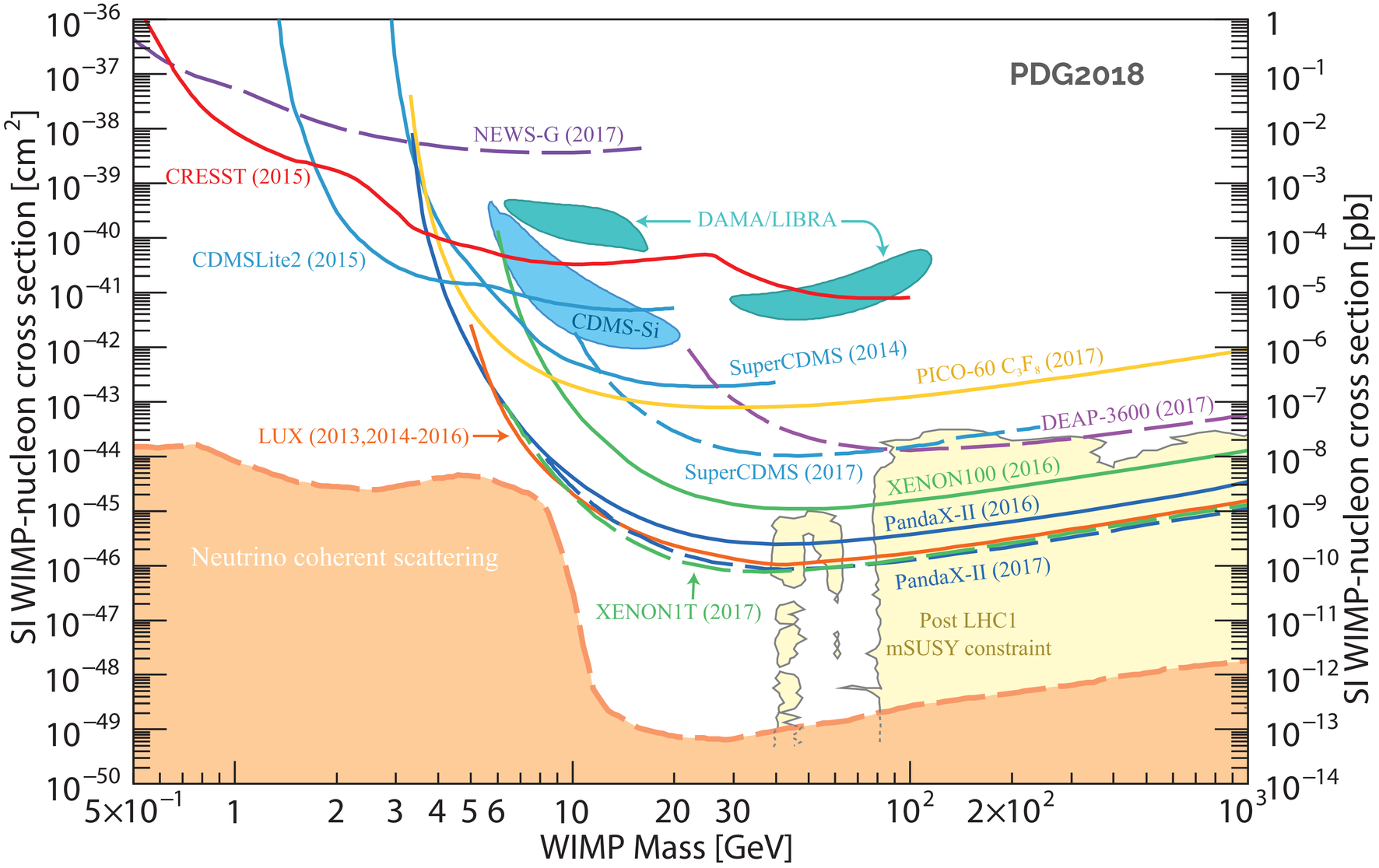
Hubble expansion rate of the universe

Thermal averaging

Relative velocity in DM CMS

Annihilation cross section into SM particles

Weakly Interacting Massive Particles: WIMPs

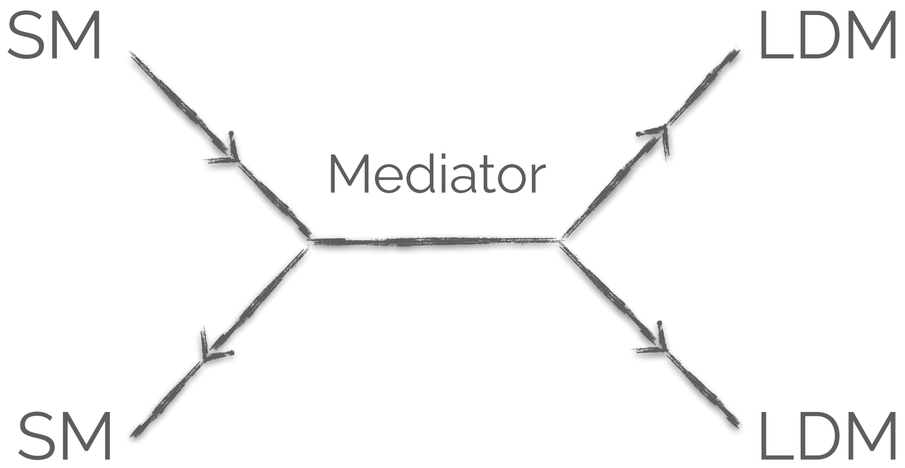


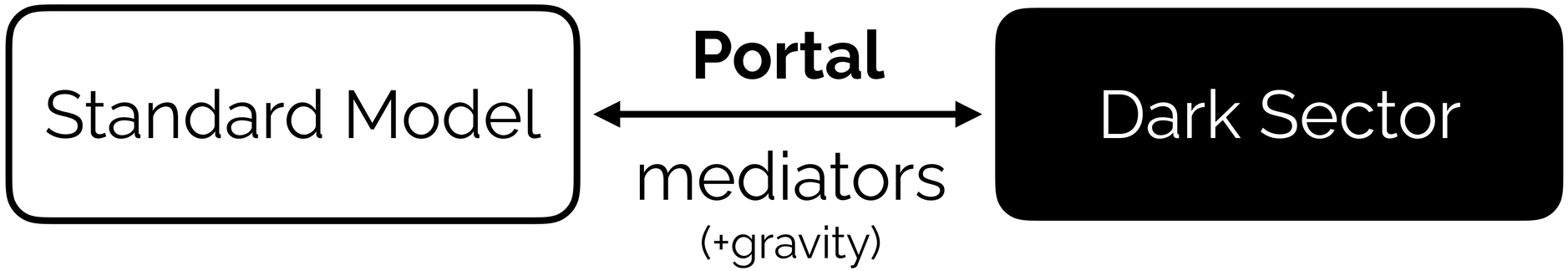
From WIMPs to LDM

- Since $\sigma_{annihilation} \sim m_{DM}^2/m_{med}^4$:

  Need new mediator between SM and Dark Sector if $m_{DM} \lesssim 2$ GeV:

  Light Dark Matter (LDM)





New mediators

Only **three sizeable interactions (or portals) to a Dark Sector**, unsuppressed by the (possibly large) NP scale Λ.

$$\mathcal{L} = \sum_{n=k+l-4} \frac{c_n}{\Lambda^n} \mathcal{O}_k^{(\mathrm{SM})} \mathcal{O}_l^{(\mathrm{med})} = \mathcal{L}_{\mathrm{portals}} + \mathcal{O}\left(\frac{1}{\Lambda}\right)$$

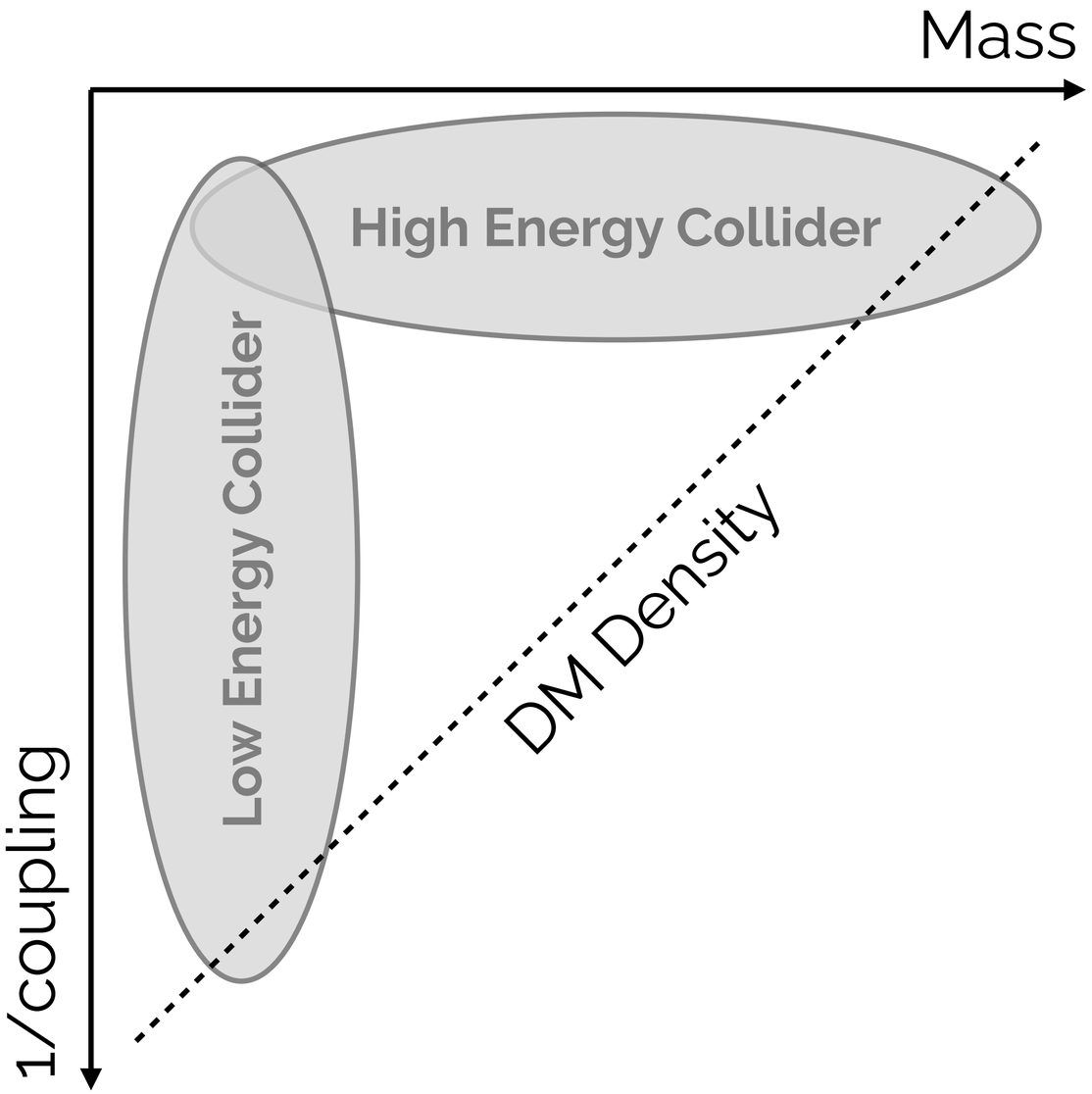
$$= \boxed{-\frac{\epsilon}{2} B^{\mu\nu} A'_{\mu\nu}} - \boxed{H^\dagger H (AS + \lambda S^2)} - \boxed{Y_N^{ij} \bar{L}_i H N_j} + \boxed{\mathcal{O}\left(\frac{1}{\Lambda}\right)}$$

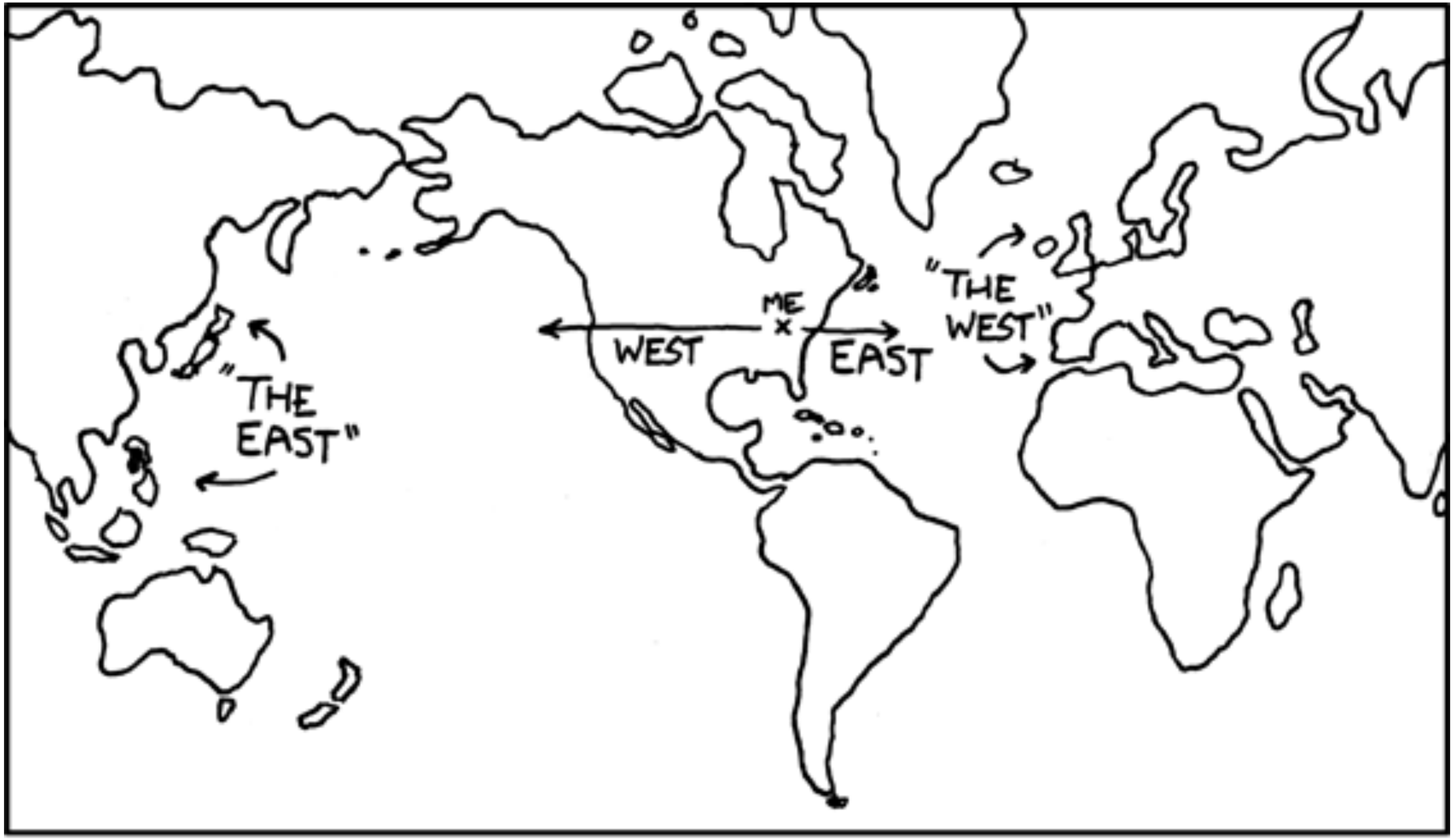
Vector Portal: Massive A' mixes with SM γ via strength parameter ε.

Scalar (Dark Higgs) and Neutrino (Sterile Neutrinos) Portals.

Axion Portal: Massive ALP couples to SM bosons.

Intensity vs Energy

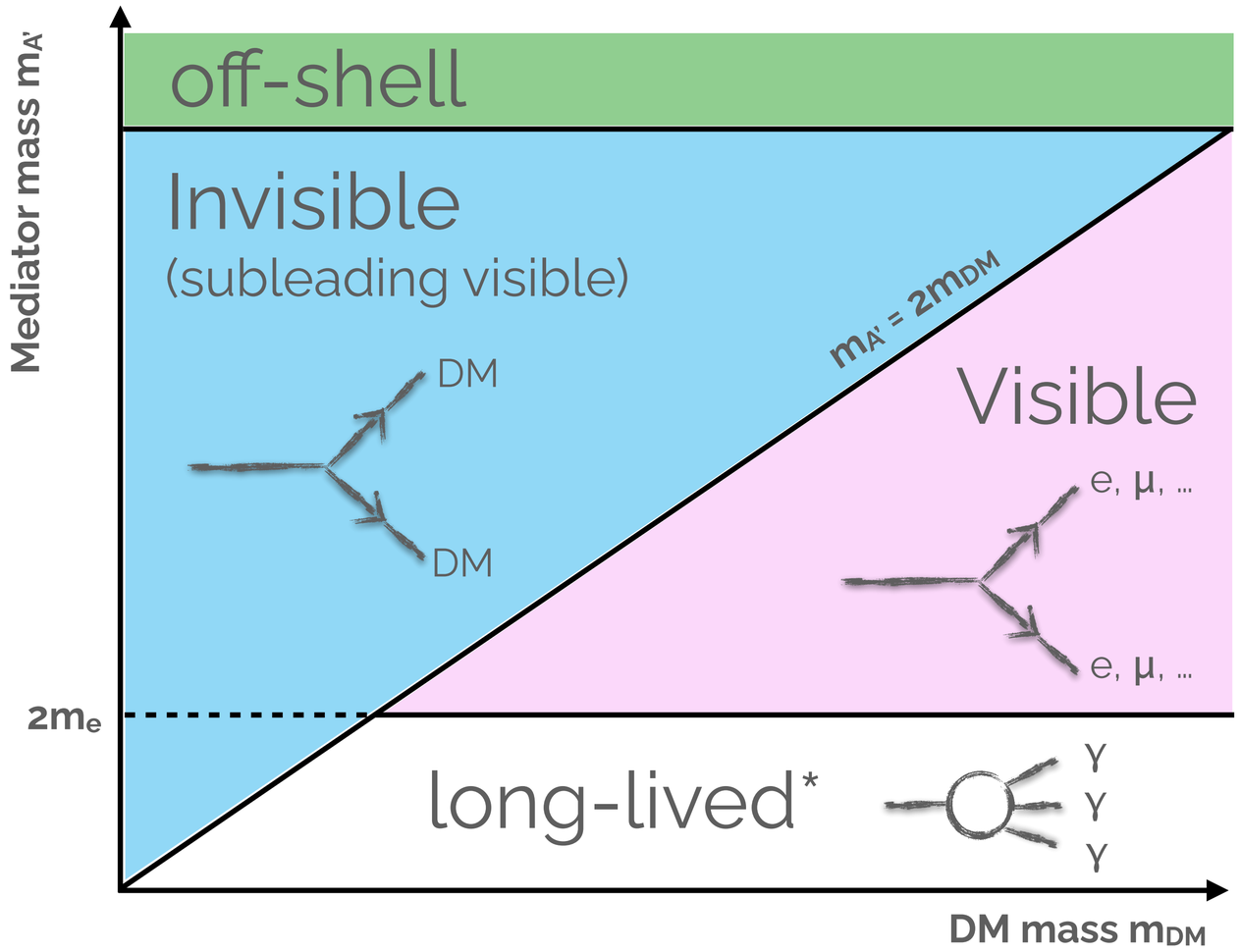



"THE EAST"
WEST
ME
EAST
"THE WEST"
THIS ALWAYS BUGGED ME.

Dark Terminology

- Different terms for (basically) the same things
- I will use:
  - Hidden Sector = Secluded Sector = Dark Sector
  - Dark Photon = Hidden Photon = Heavy Photon = U-Boson = $\gamma_D = \gamma' = \mathbf{A'}$, couples via kinetic mixing $\alpha'/\alpha = \boldsymbol{\varepsilon}$, sometimes ε^2 or $y(\varepsilon) = \varepsilon^2 \alpha_D (m_\chi/m_A)^4$
  - Relic Dark Matter = $\chi = \chi_1$ generally is the lightest DM particle
  - Dark coupling $\alpha_D = g_D^2 / (4\pi)$

Mediator decays

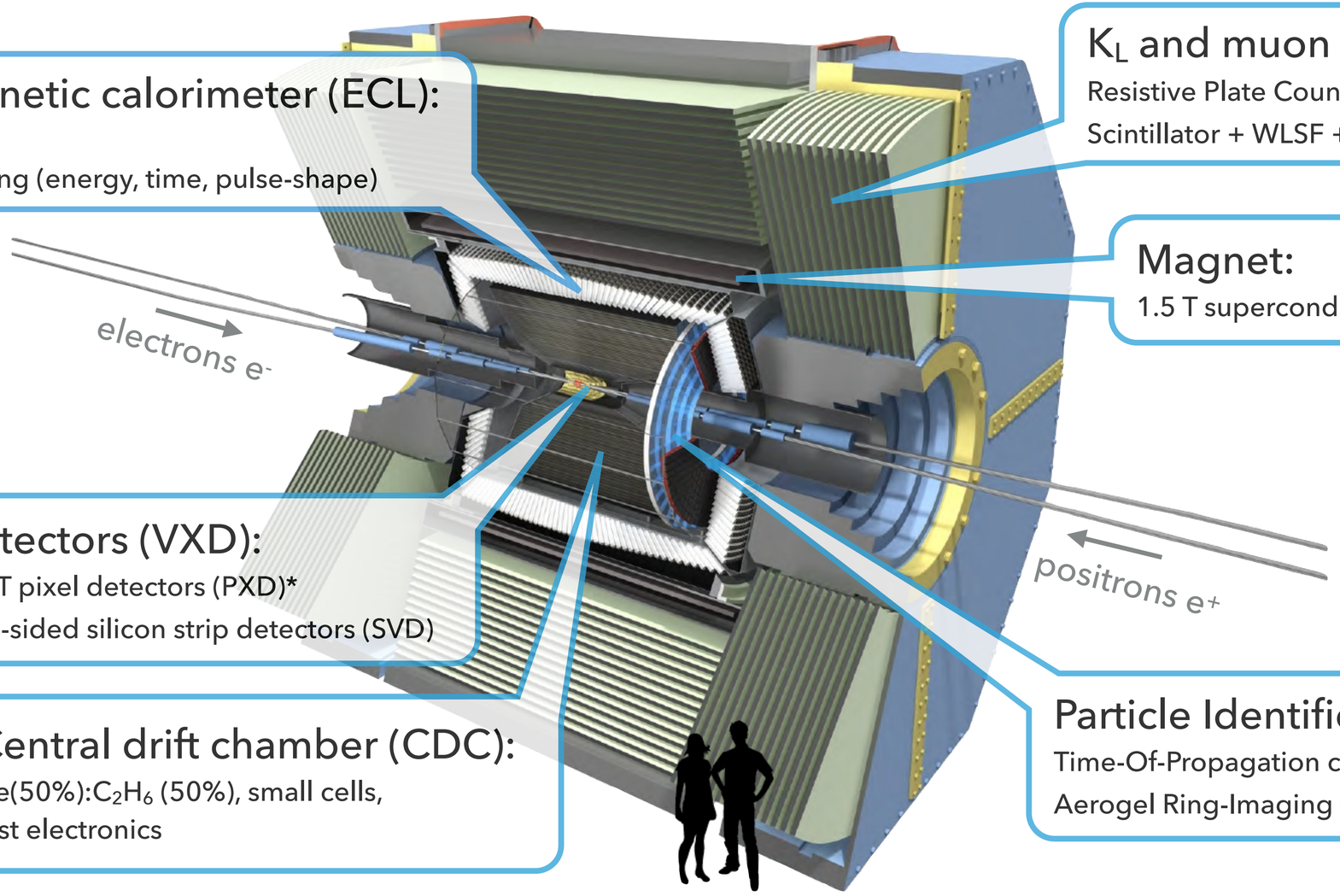


The e^+e^- collider flagship: Belle II

Electromagnetic calorimeter (ECL):
CsI(Tl) crystals
waveform sampling (energy, time, pulse-shape)

K_L and muon detector (KLM):
Resistive Plate Counters (RPC) (outer barrel)
Scintillator + WLSF + MPPC (endcaps, inner barrel)

Magnet:
1.5 T superconducting



Trigger*:
Hardware: < 30 kHz
Software: < 10 kHz

Vertex detectors (VXD):
2 layer DEPFET pixel detectors (PXD)*
4 layer double-sided silicon strip detectors (SVD)

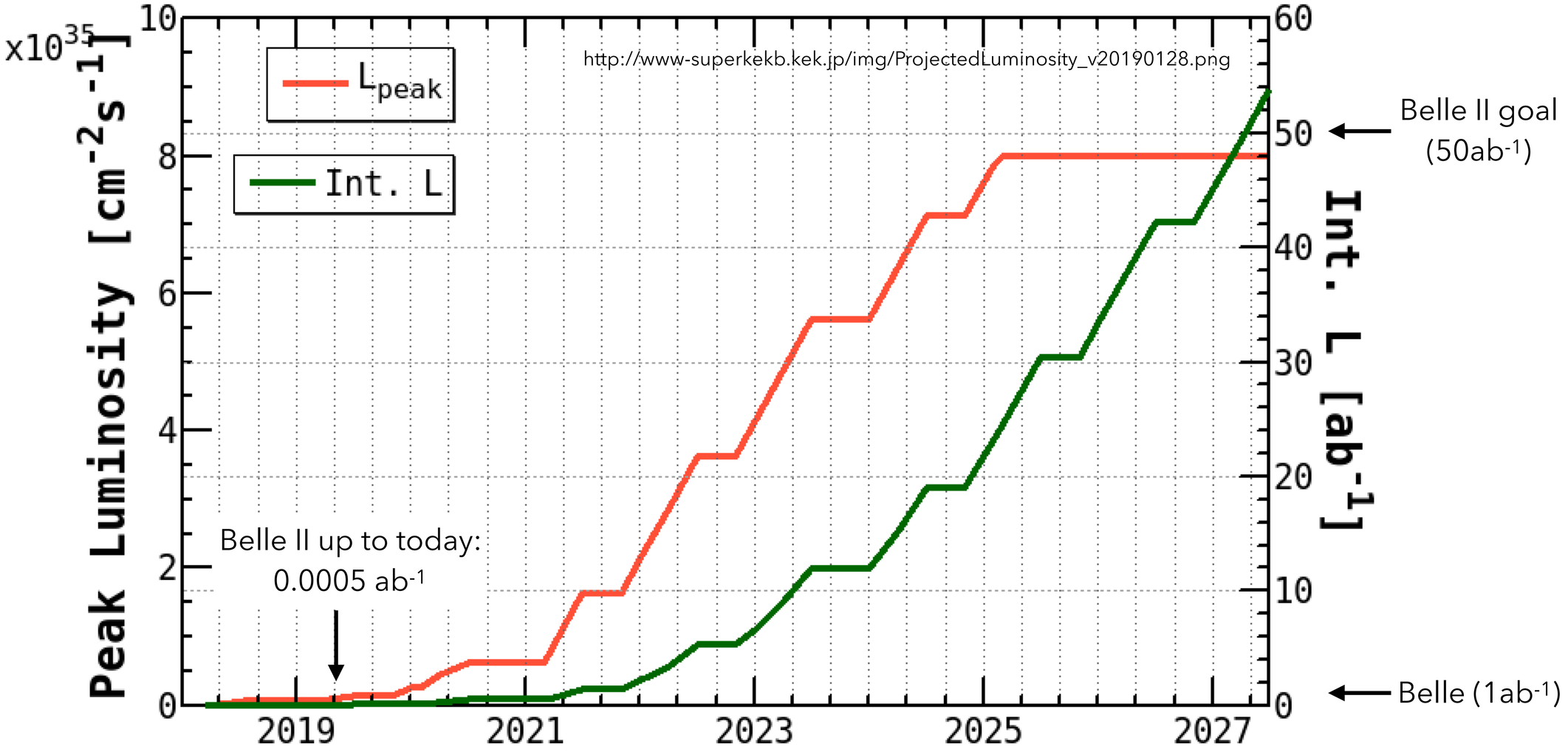
Central drift chamber (CDC):
He(50%):C_2H_6 (50%), small cells,
fast electronics

Particle Identification (PID):
Time-Of-Propagation counter (TOP) (barrel)
Aerogel Ring-Imaging Cherenkov Counter (ARICH) (FWD)

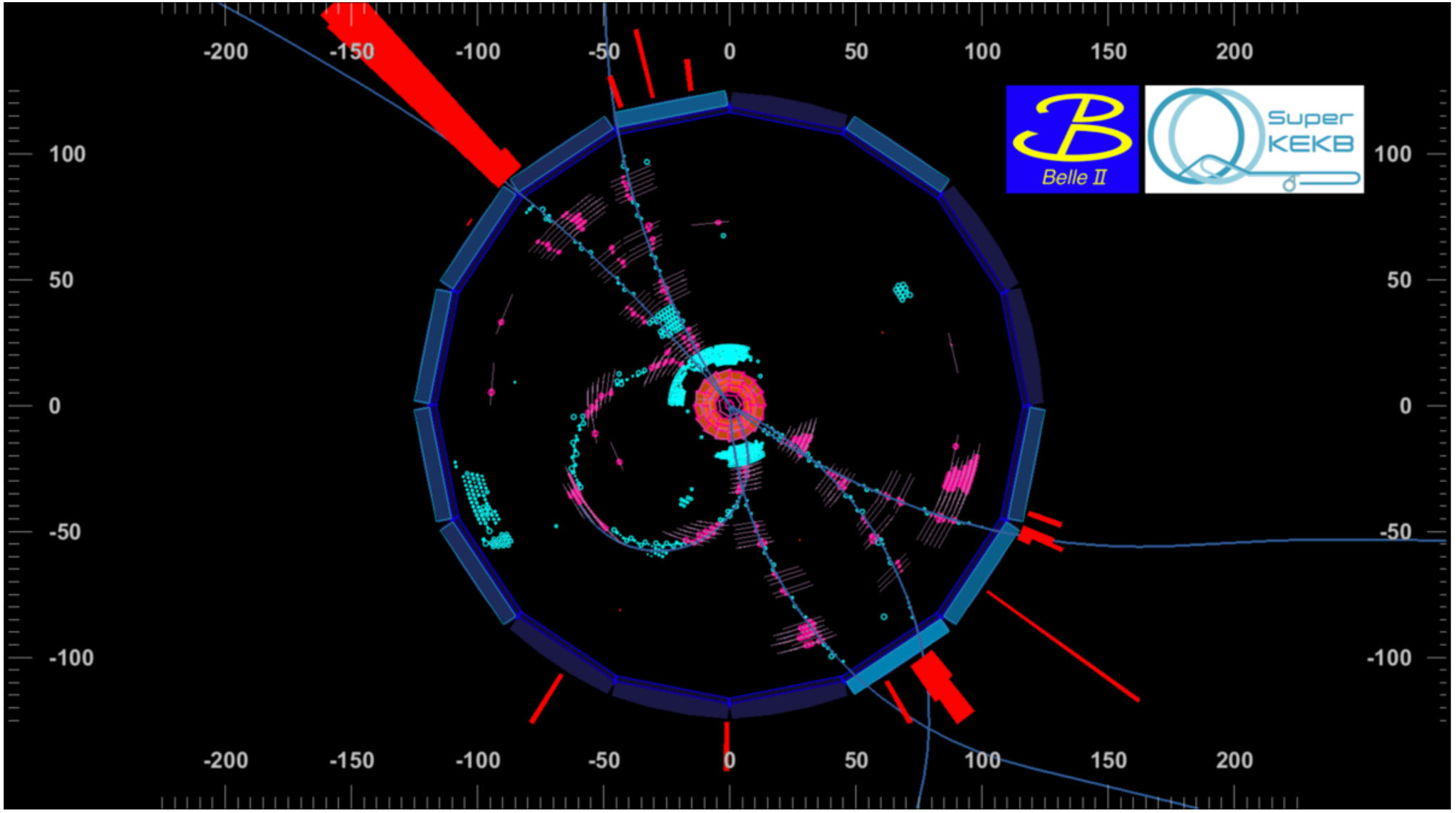
DEPFET: depleted p-channel field-effect transistor
WLSF: wavelength-shifting fiber
MPPC: multi-pixel photon counter

* Some modifications for early data taking

The e^+e^- collider flagship: Belle II expected luminosity

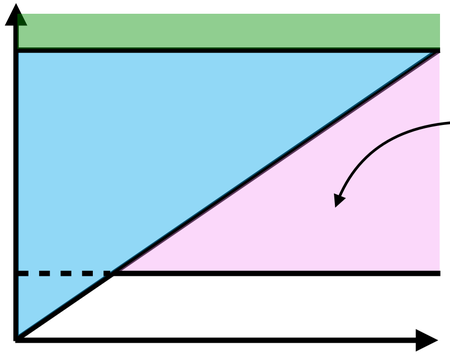


The e^+e^- collider flagship: First 2019 events in Belle II



Golden modes of Dark Mediator decays

A

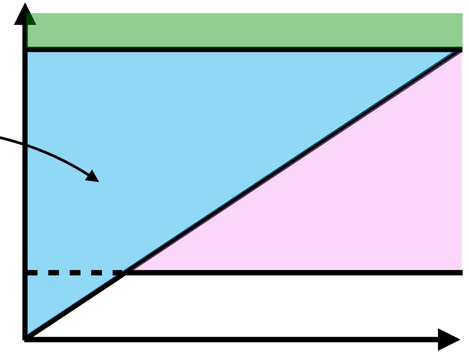


Visible Dark Photon Searches:
$A' \rightarrow \ell^+\ell^-$

Belle II needs ~5 years data for leading sensitivity

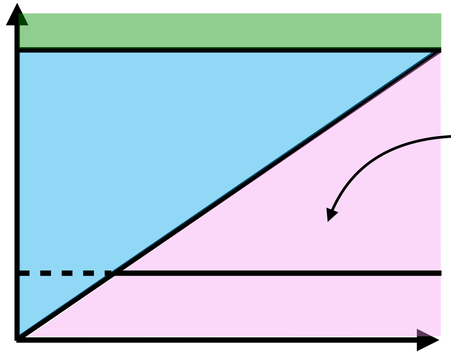
Existing Belle II data is leading (Z')
or needs 1 year data (invisible A', invisible ALPs)

Invisible Dark Photon, ALP, and Z' Searches*:
B: $A' \rightarrow$ xx, a→xx, C: Z'→xx



B, C

D



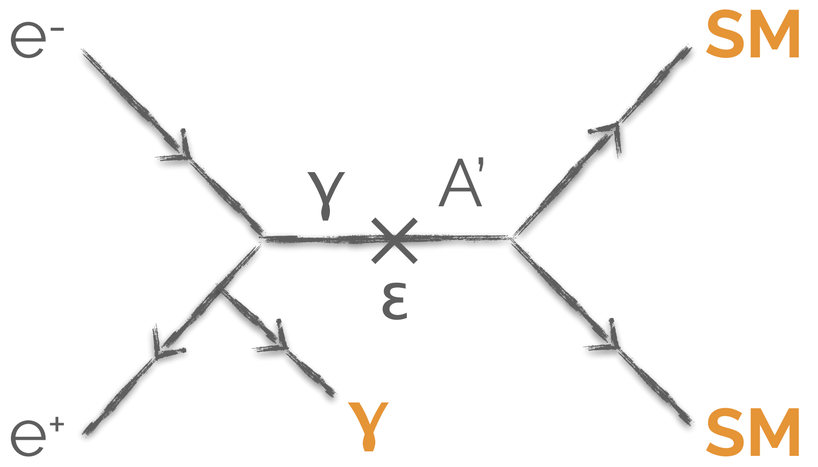
Visible ALP Searches:
$a \rightarrow \gamma\gamma$

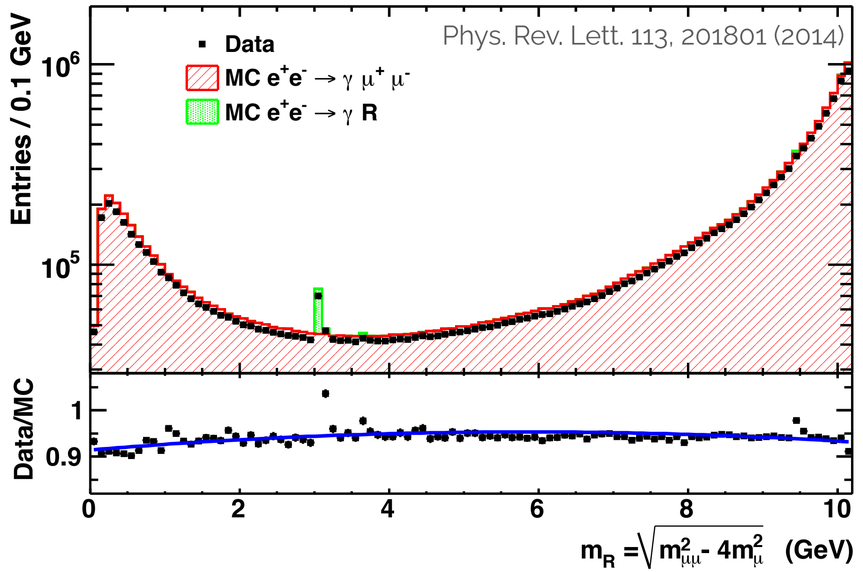
Existing Belle II data is world leading

*not a minimal model

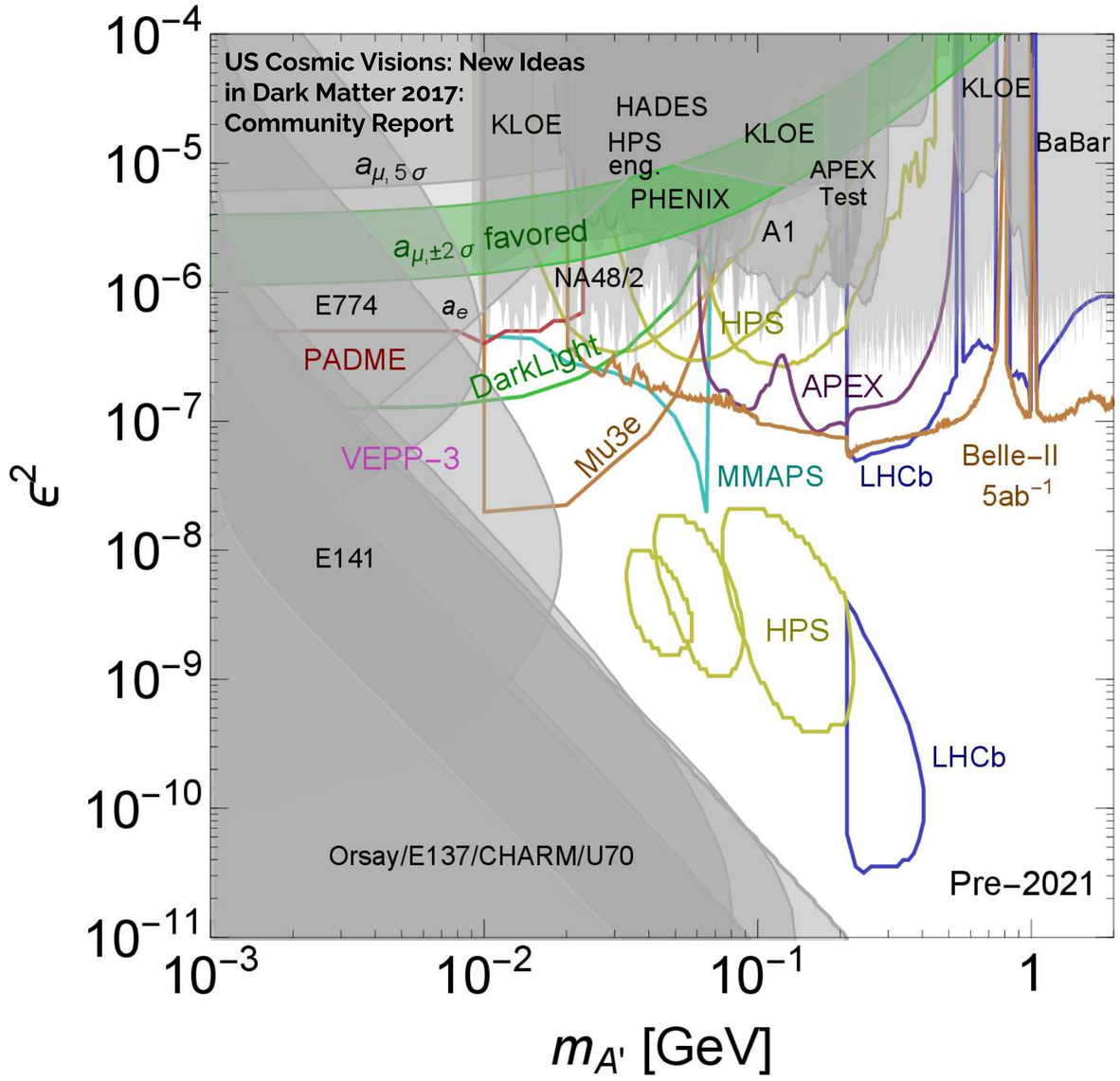
A: Visible Dark Photon searches

- Bump hunt for ee and μμ over smooth, but large SM backgrounds, avoid SM resonances.
- Hadronic final states are more challenging, analysed at KLOE
- ττ channels have not been analysed yet (missing energy from neutrinos)
- So far all searches at low energy colliders hunt prompt A' decays: $\tau_{A'} \sim 1/(\varepsilon^2 m_{A'})$





A: Visible Dark Photon searches

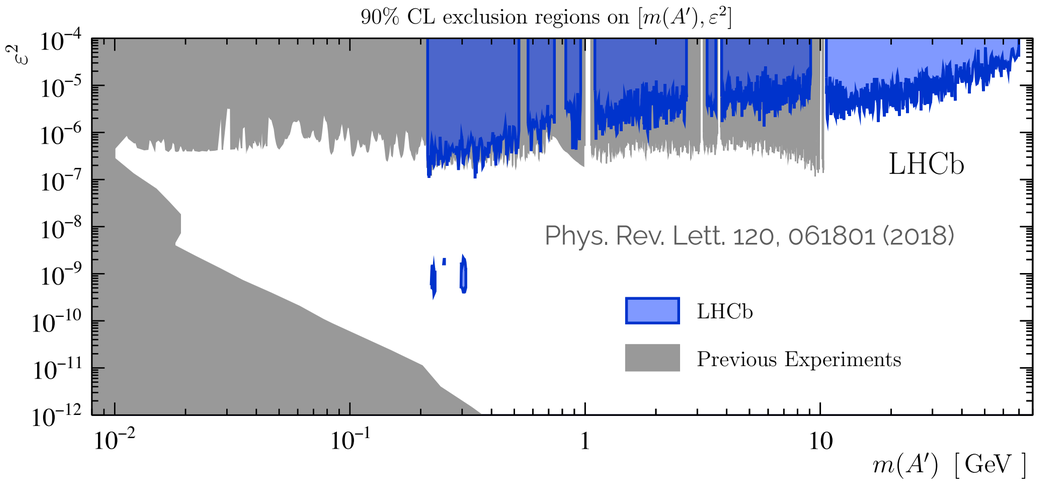


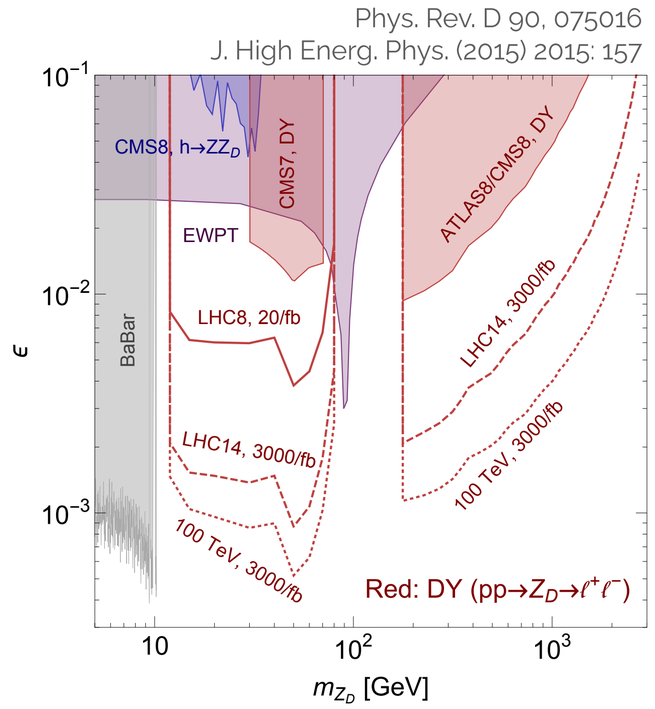
beyond 2021:

- NA62, SHiP, SeaQuest, …
- Belle II 50 ab^{-1}
- LHCb e^+e^-

Dark Photons at the LHC?

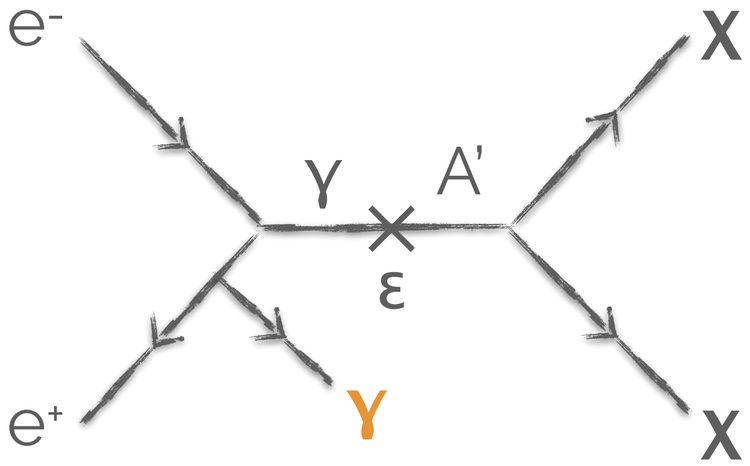
- Drell-Yan production pp→A'→μμ (some mild model-dep. near Z peak)
  - Dedicated LHCb analysis of 13TeV data (incl. meson decays). A future analysis of A'→ee from D* is a potential game-changer.
- h→Z*Z_D (kinetic mixing) is complementary but not very sensitive.
- EW global fits.



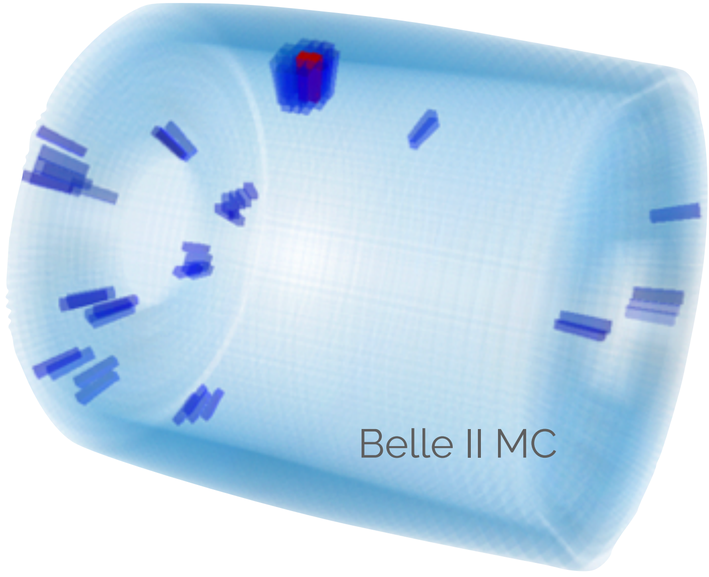


B: Invisible Dark Photon searches

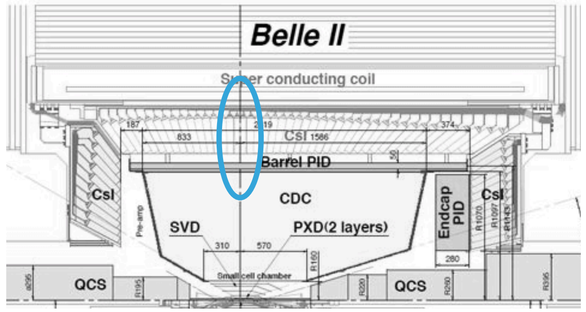
$$E_\gamma = ((2E_{Beam})^2 - M_{A'}^2) \,/\, (2\,E_{Beam})$$



- Requirement:
  - Single photon trigger ($E_{th} \approx 1$ GeV for $E_{Beam} = 5.3$ GeV)
  - Large solid angle coverage of calorimeter
  - Efficient outer detectors to veto calorimeter gaps
- SM backgrounds if one misses all but one γ:
  - Low mass A' (= high energy single γ): ee→γγ and ee→γγγ
  - High mass A' (= low energy single γ): ee→ eeγ

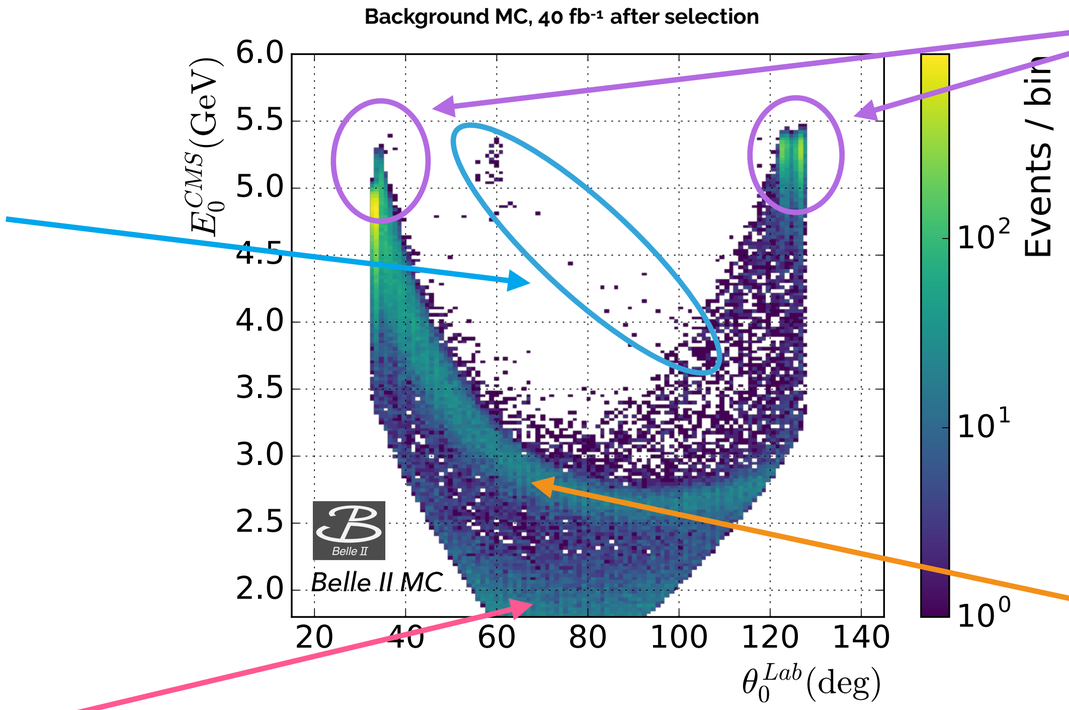


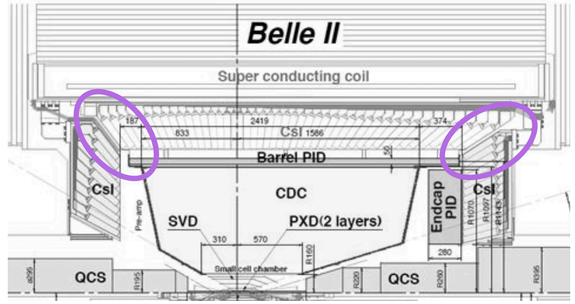
B: Invisible Dark Photon searches



ee→2γ and 3γ
1γ in ECL 90° gap
1γ out of ECL acceptance

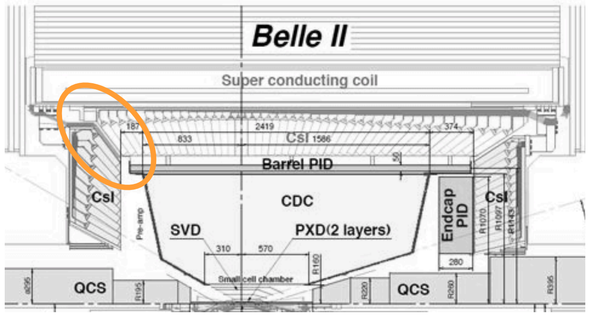
$$E_\gamma = \frac{s - M_{A'}^2}{2\sqrt{s}}$$





ee→2γ
1γ in ECL BWD or FWD gap

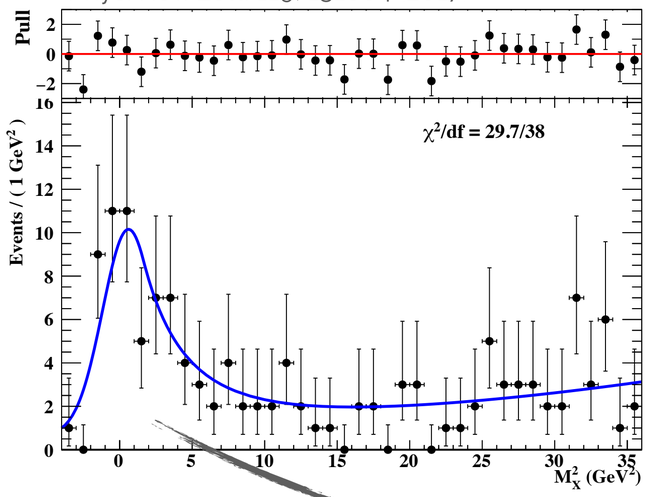
ee→eeγ
both electrons
out of tracking acceptance



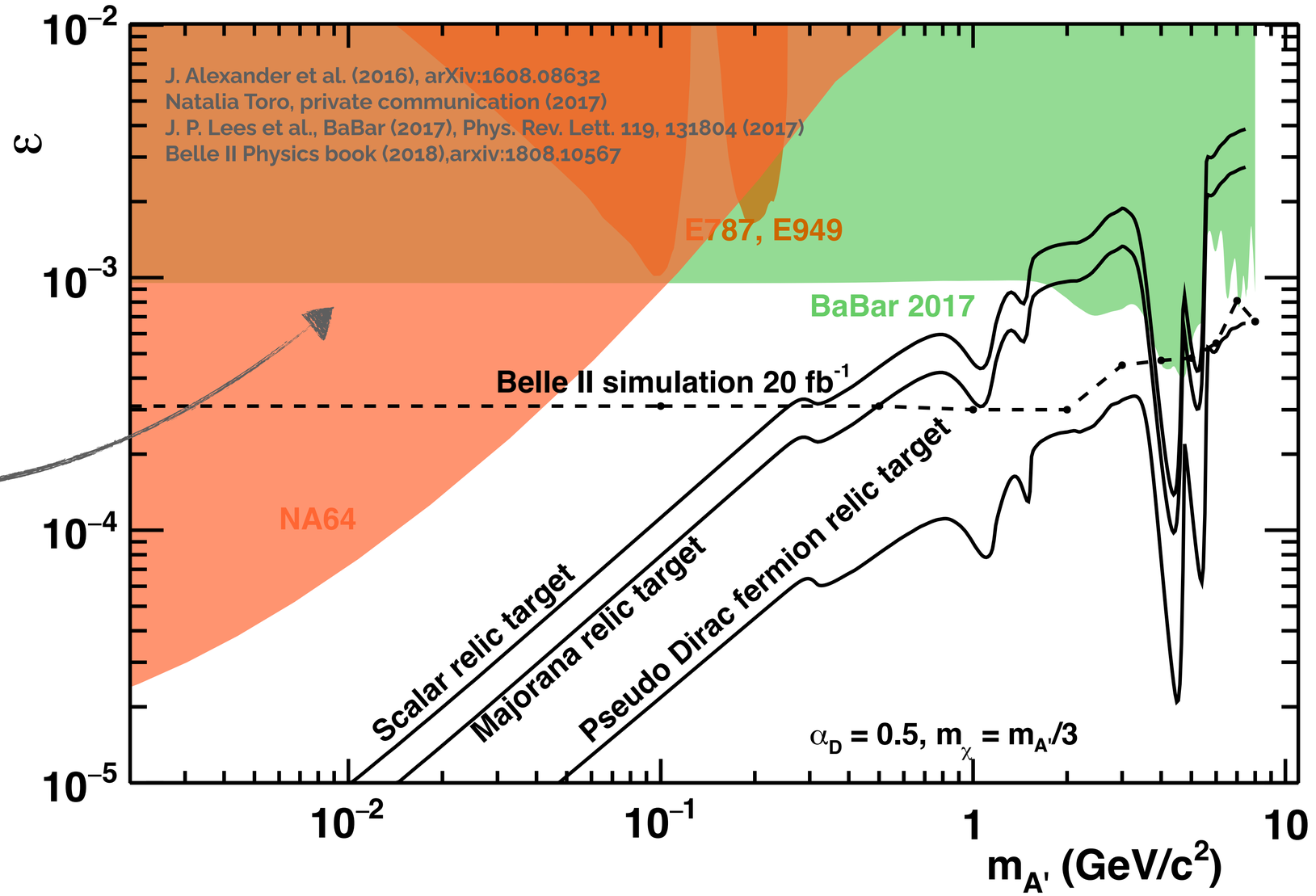
ee→3γ
1γ in ECL BWD gap
1γ out of ECL acceptance

B: Invisible Dark Photon searches

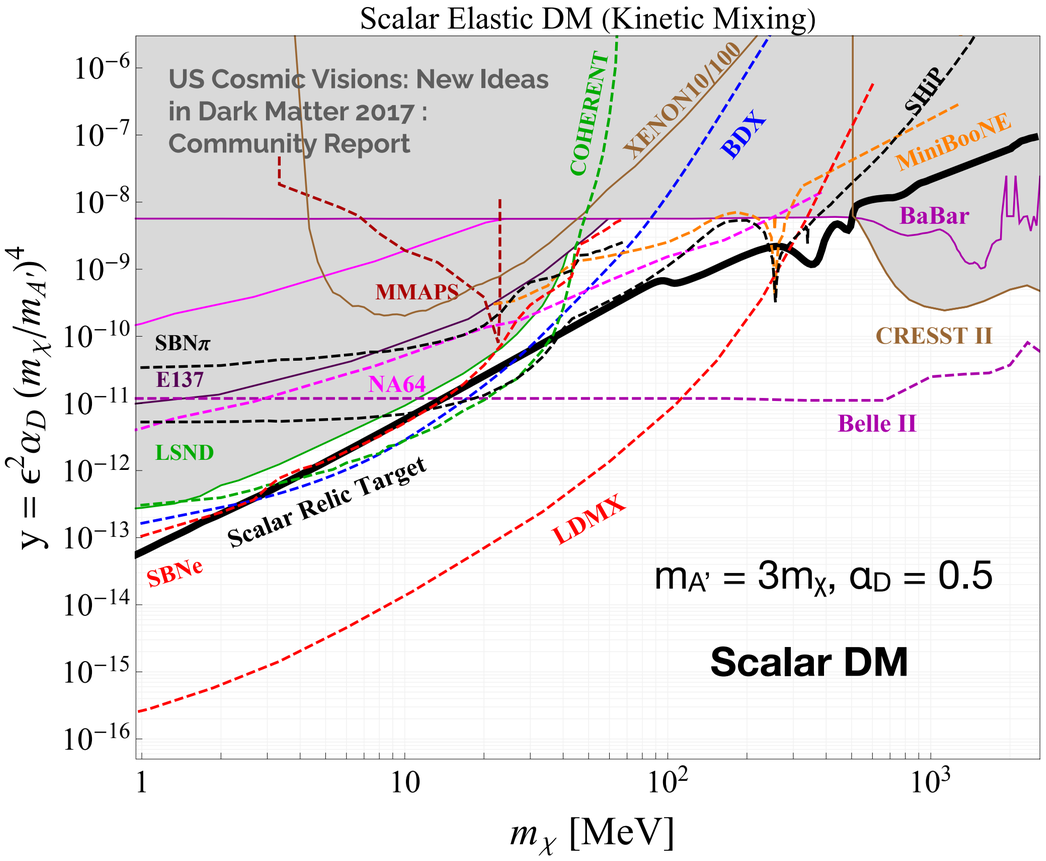
Phys. Rev. Lett. 119, 131804 (2017)

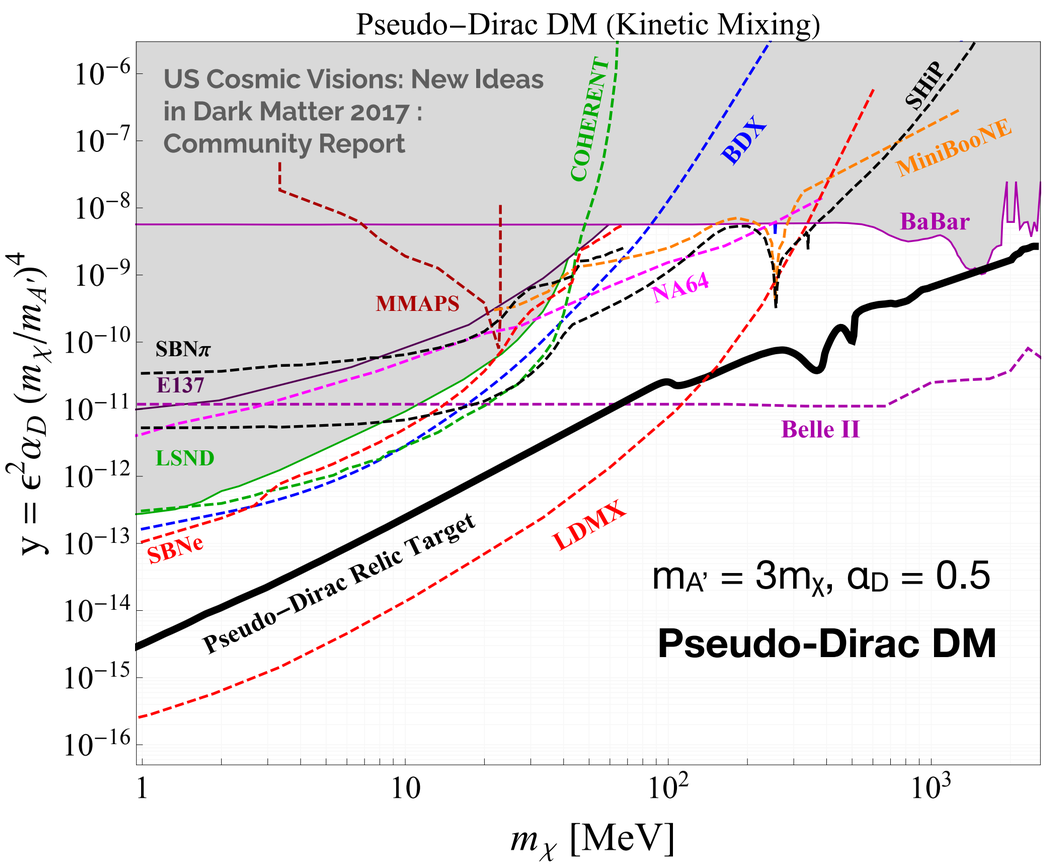


Projective gaps in BaBar's ECAL:
Peaking Background from ee→γγ
that is not present in Belle II



B: Invisible Dark Photon searches

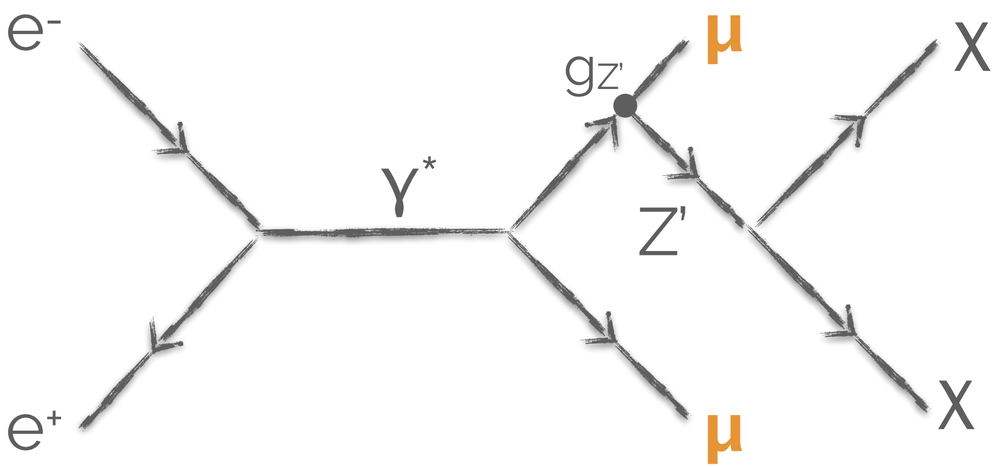


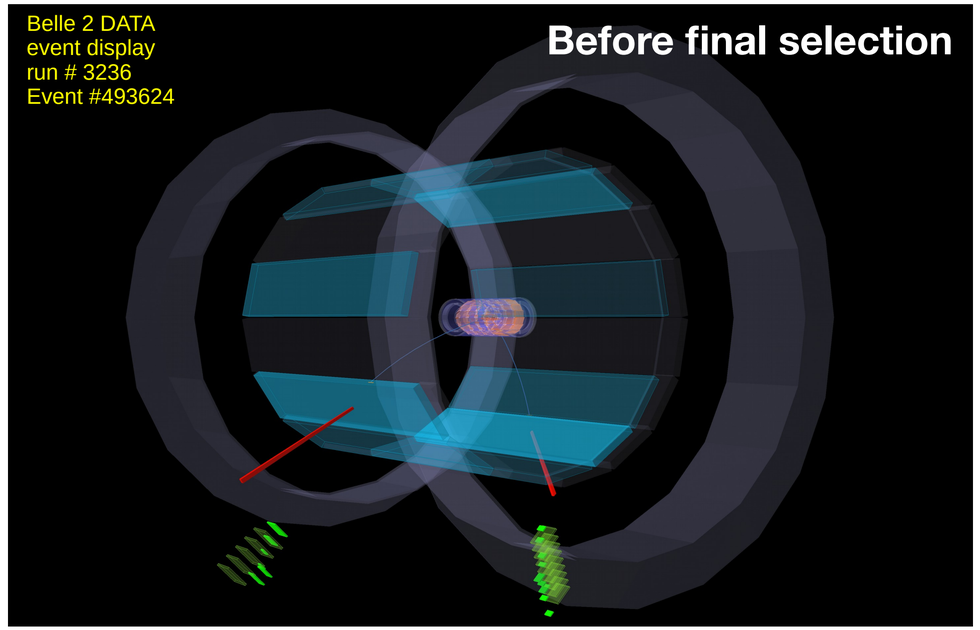


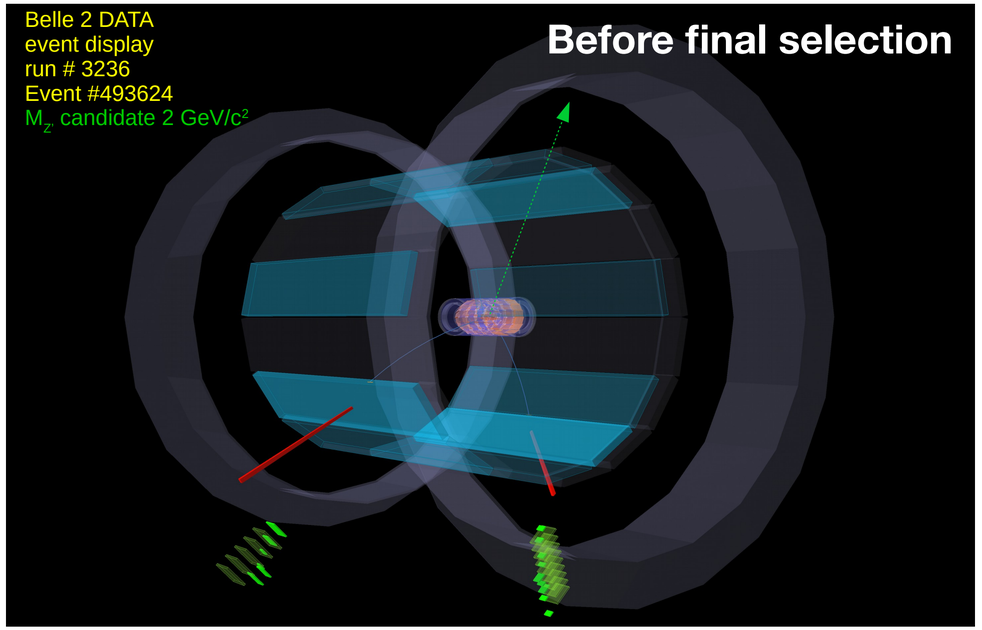
BDX and **LDMX** have different beam option with different sensitivity.
Plot for BDX@CEBAF(A), JLab and LDMX@DASEL, SLAC.
not in the plots: BESIII (low energy e+e- near charm threshold) has (some) data with single photon triggers.

C: Invisible Z' searches

- Non-minimal vector portal:
  - Mediator Z' that couples to muons and taus but not to electrons (L_μ-L_τ)



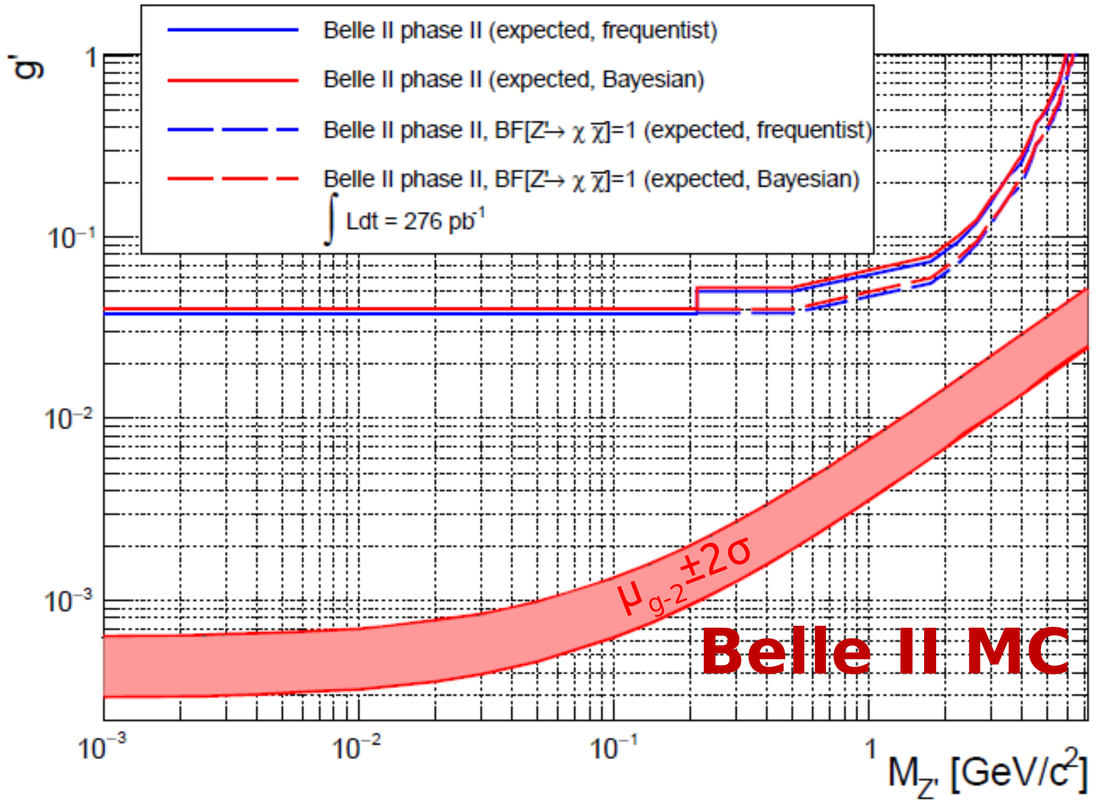




C: Invisible Z' searches

Track-triggers required

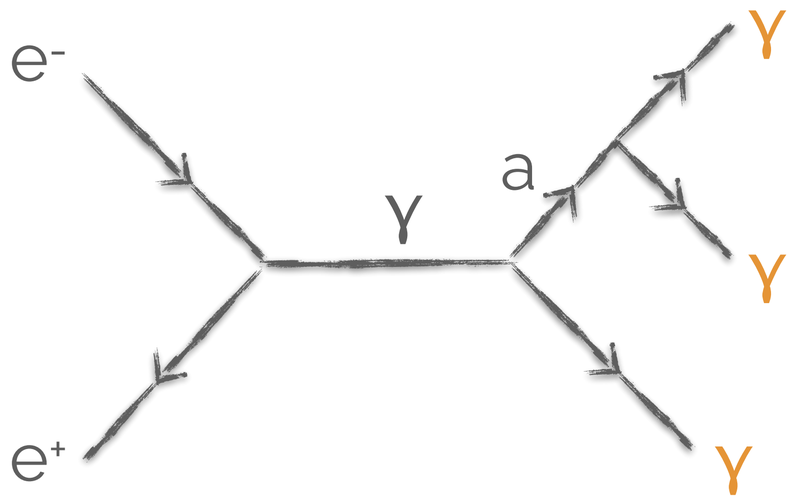
Belle II expected sensitivity for the 2018 dataset (276pb^{-1})

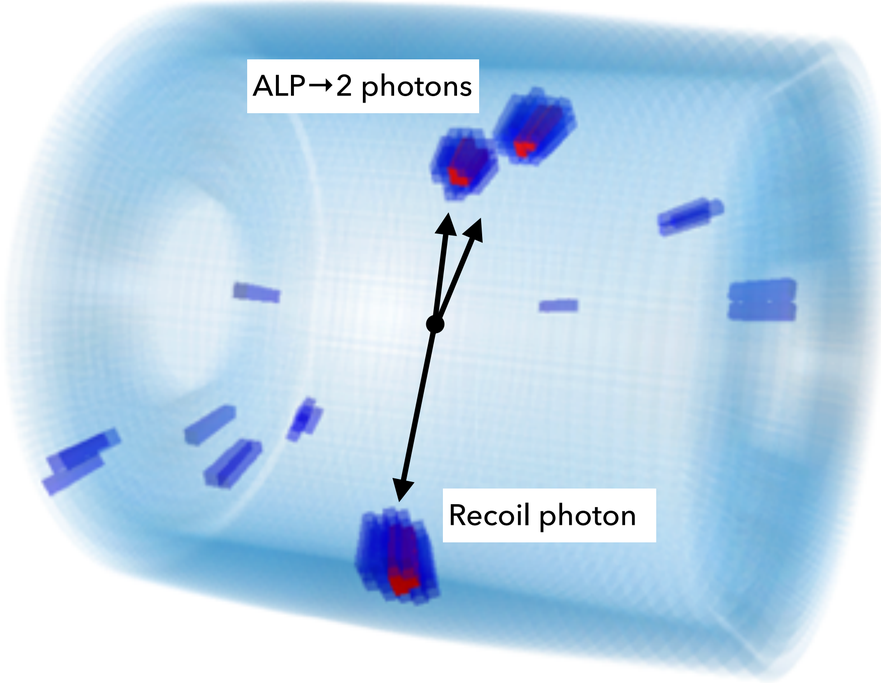


Systematic effects:
- trigger + tracking + PID + mass resolution systematics included (~10%)
- possible additional systematics on background estimate not included (0-30 %)
- analysis optimisation still undergoing -> details might change
- other systematic effects expected to be negligible

D: Visible ALP searches

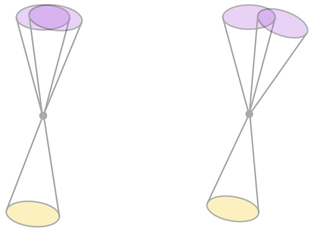
- Axion-like particles (ALPs) are pseudo-scalars and couple to bosons. Unlike QCD Axions, ALPs have no relation between mass and coupling.
- Focus on coupling to photons ($g_{a\gamma\gamma}$)
- B-decays give access to coupling to charged bosons (need rather large datasets $\gg 1 ab^{-1}$ to improve).
- No Belle or BaBar analysis yet.

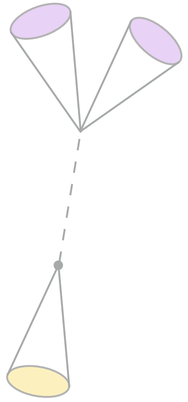




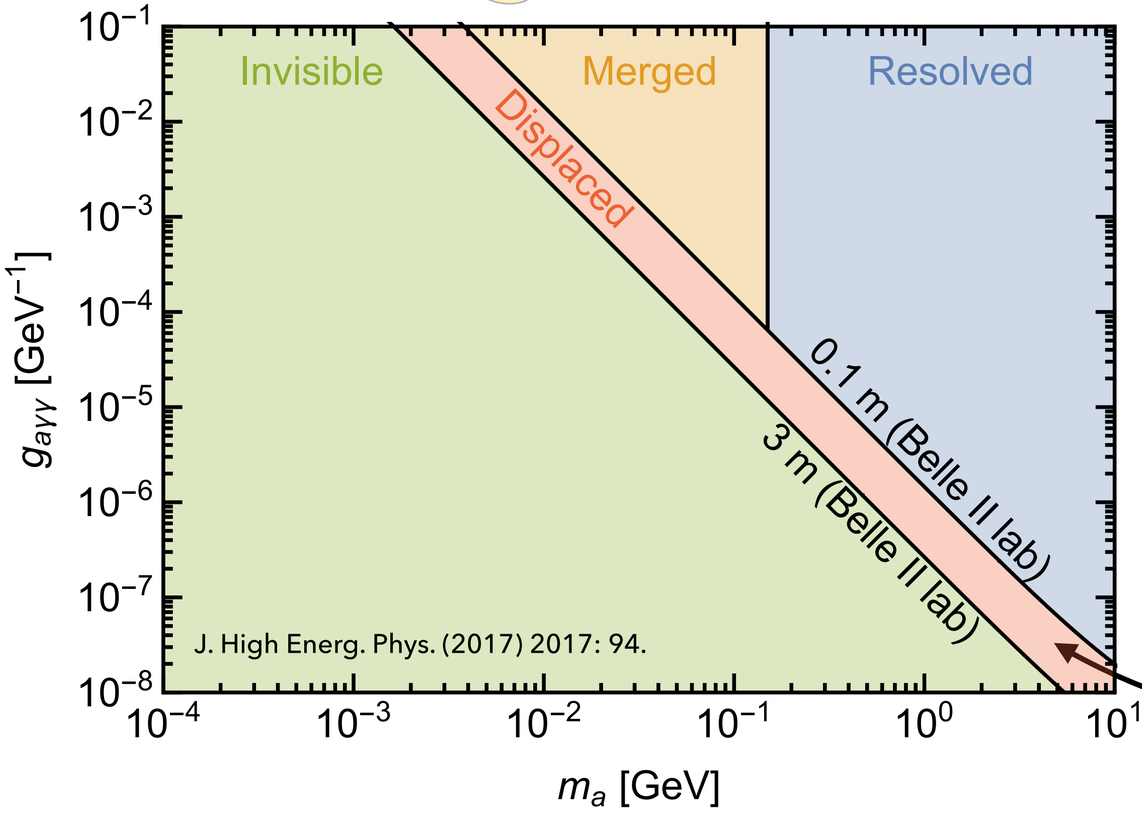
D: Visible ALP searches

Two of the photons overlap or **merge**.

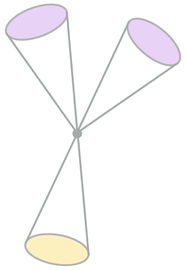




ALP decays outside of the detector or decays into **invisible** particles: Single photon final state.



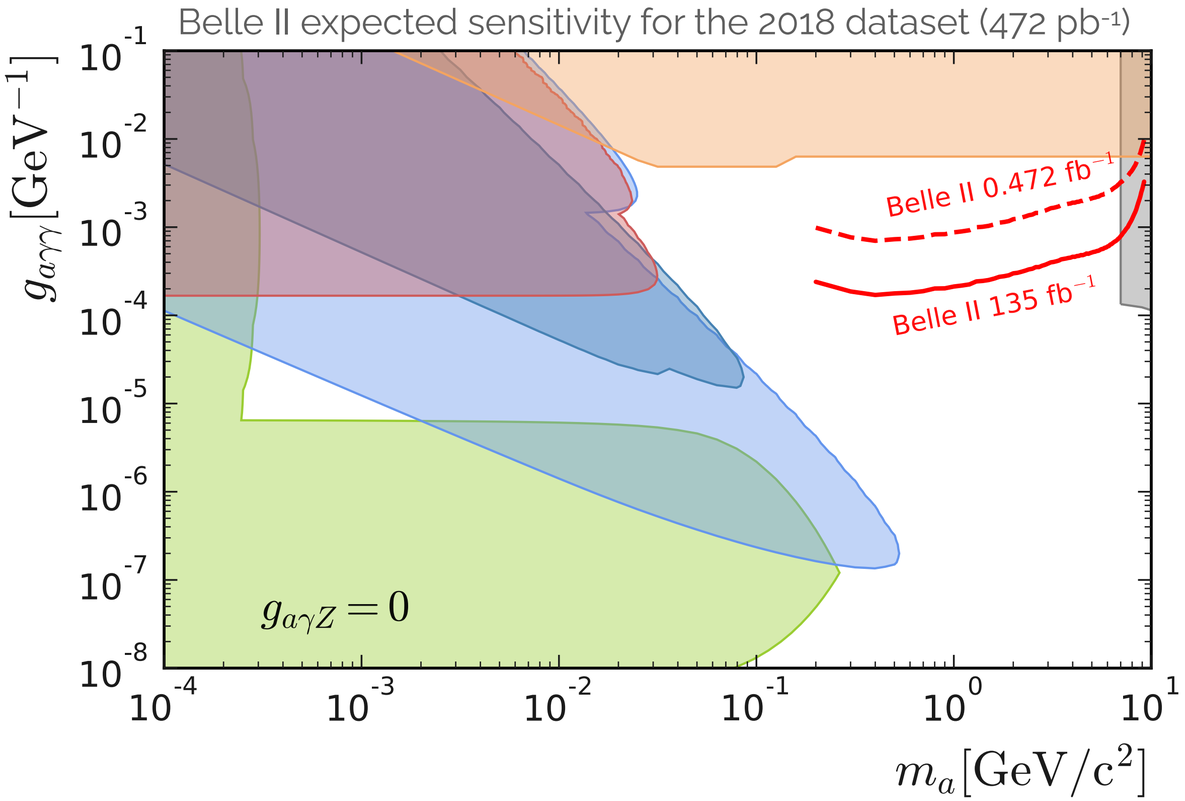
Three **resolved**, high energetic photons.



The searches for invisible and visible ALP decays veto this region.

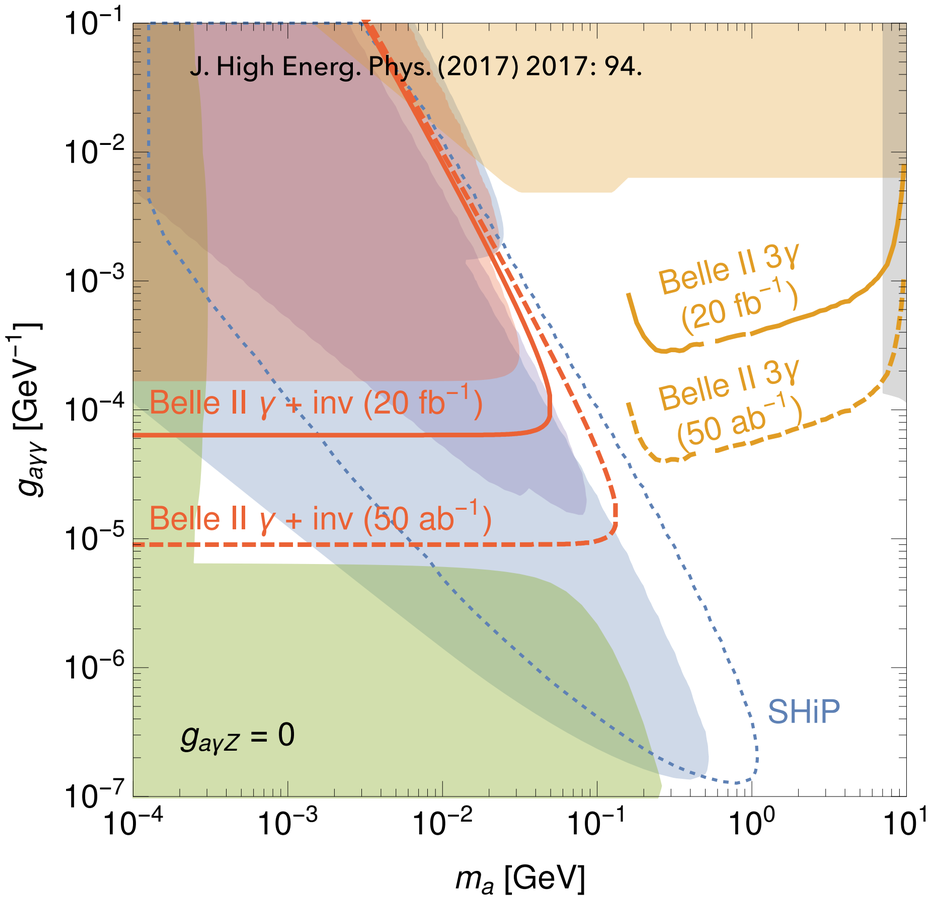
D: Visible ALP searches

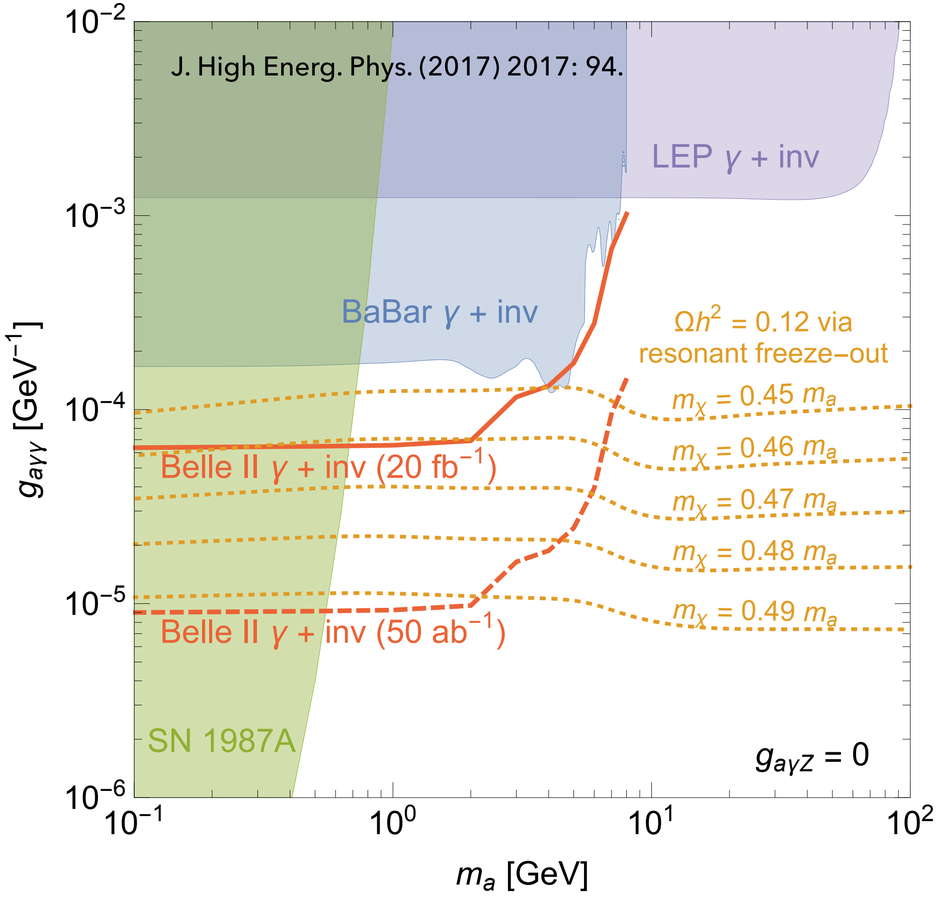
- Background from SM is large and partially peaking:
  - ee→γγγ
  - ee→eeγ (early Belle II tracking was rather inefficient)
  - ee→π⁰/η/η'γ (Form factors help)
  - ee→ωγ, ω→π⁰γ

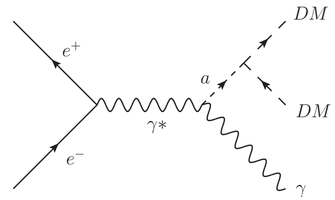


- No systematics
- Only dominant ee→γγγ background included
- 135fb-1 assumes no γγ trigger veto in the barrel

D: Visible and invisible ALP searches







Relic Dark Matter Density

What is next?

Belle II: We just started. Ultimately much better triggers, better detector, much higher statistics, and higher beam backgrounds.

Belle and BaBar: *Still ongoing analyses.*

Not covered today:

- Transition-tagged Υ(2S, 3S) decays (Dark Higgs)
- DM or new mediators in B decays
- Displaced vertices
- Missing energy cascades
- τ and hadronic final states
- …

Summary

- Low energy colliders (Belle, BaBar,Belle II, …) have a **very broad and active DM program** well beyond B physics

- Access to Dark Photons, Z', ALPs, light Higgs in simple and complex models (You have ideas/theories? Let's talk!)

- Orthogonal to direct searches. Not only sensitive to scalar DM.

- Belle II started physics data taking April 2019, first calibration run in 2018

- First publications with Belle II data planned for summer 2019 (using 2018 data)

Contact

DESY.

Deutsches Elektronen Synchrotron
www.desy.de

Torben Ferber
torben.ferber@desy.de
ORCID: 0000-0002-6849-0427