Dark matter at the GeV scale and searches at low-energy experiments

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Anomalies and Precision in the Belle II Era

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Including results from **arXiv:1907.04346, arXiv:1911.03176, arXiv:2010.14522, arXiv:2011.06604** and **ongoing work**
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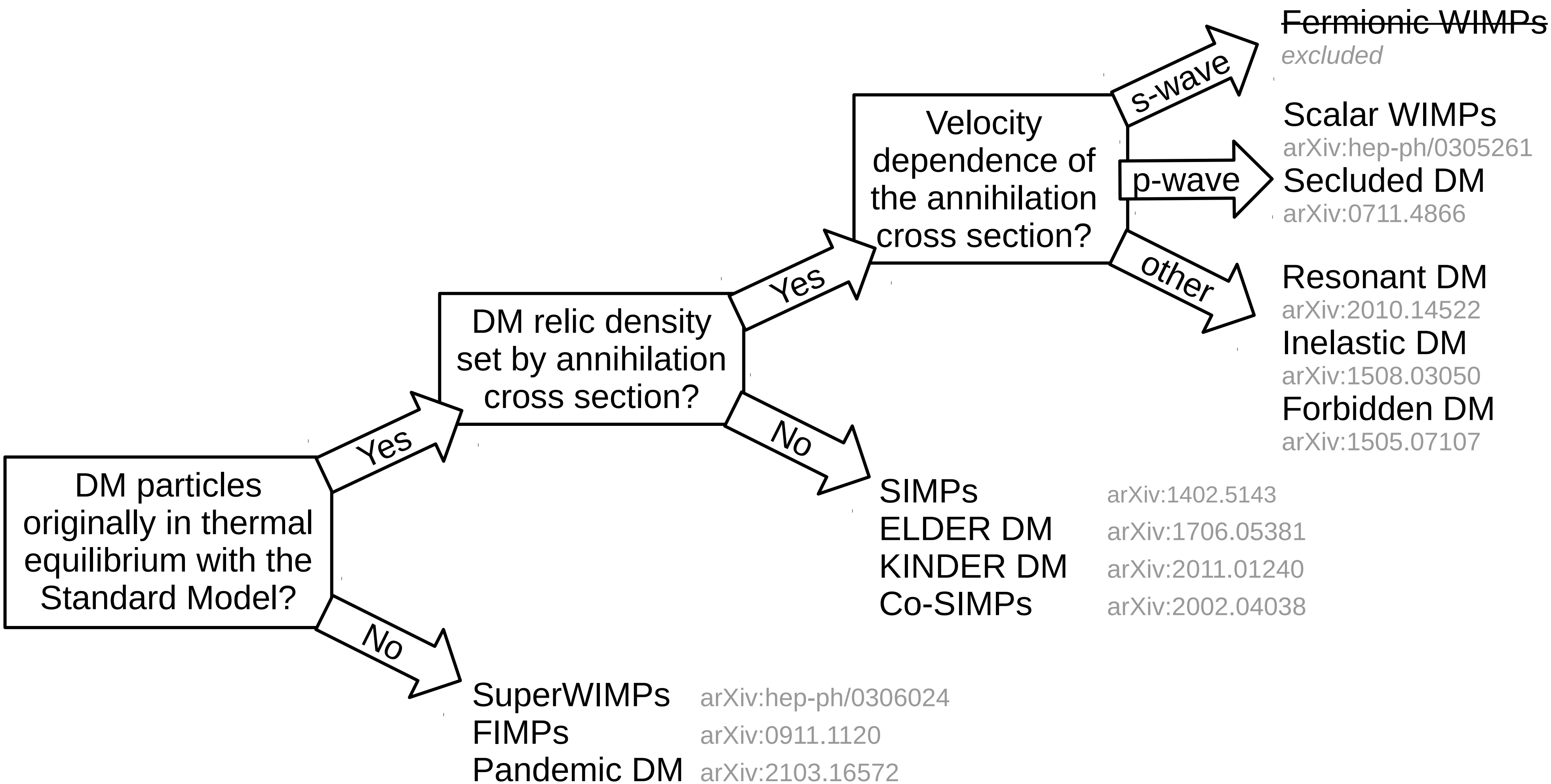
Models for GeV-scale dark matter: Overview



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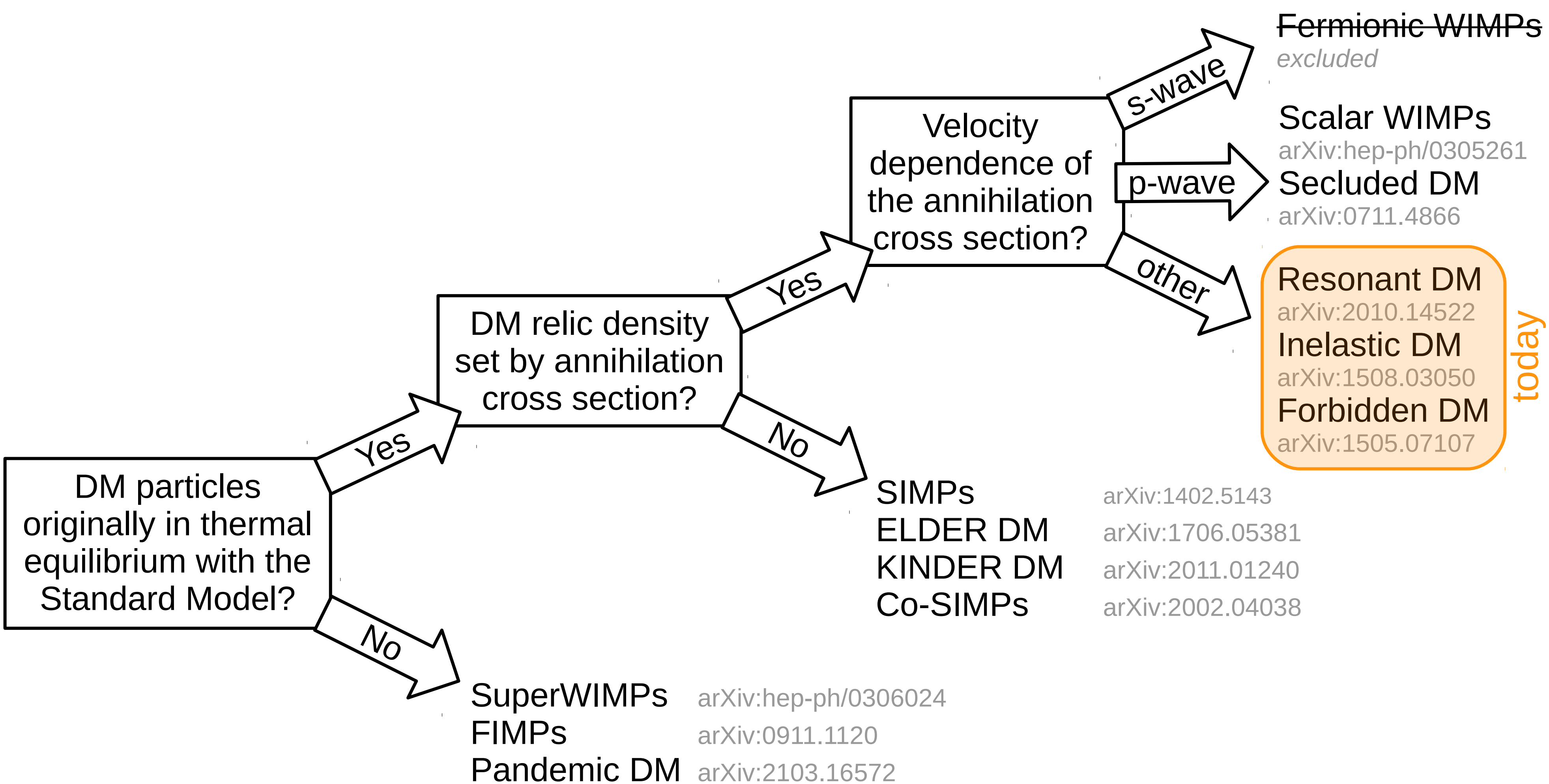
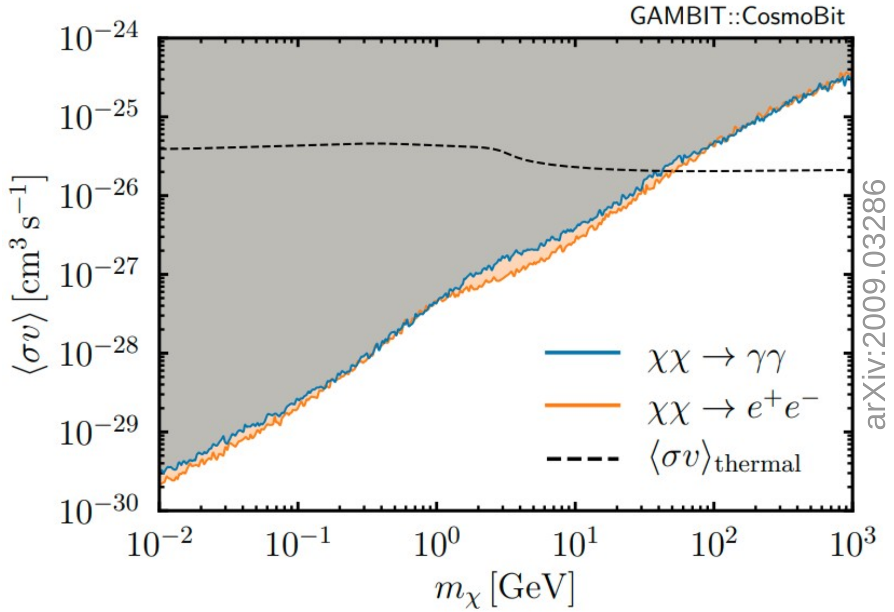


Velocity dependence of DM annihilations

- Thermal freeze-out requires annihilation cross section $\sigma v \sim 10^{-26}$ cm^3/s
- If σv is velocity independent, DM annihilations are still ongoing during recombination and in the present universe
  - → Strong constraints on GeV-scale DM from CMB observations and indirect detection experiments



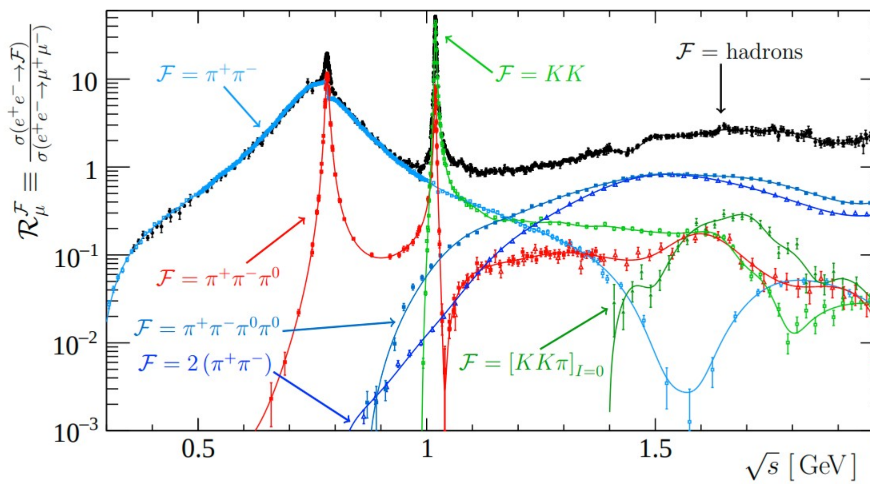
- To evade these constraints, it is necessary to suppress the annihilation cross section at small velocities
- Three main avenues:
  - Suppression of co-annihilation partners → Inelastic dark matter
  - Strongly energy-dependent matrix element → Resonant dark matter
  - Strongly energy-dependent phase space → Forbidden dark matter

Quick interlude: Portal interactions

- Mechanisms discussed in this talk largely independent of how the dark sector couples to the Standard Model
- For simplicity, consider a dark photon mediator with kinetic mixing
  → Couplings proportional to electric charge
- Many other interesting options:
  - Gauged baryon-minus-lepton number (B-L)
  - Gauged baryon number (B)
  - Axial or chiral couplings
  - (Pseudo-)scalar mediators

  → Determines experimental signatures
  - Final-state leptons?
  - Missing energy (neutrinos)?
  - Photonic decays?
- Ideally all of these possibilities should be explored!

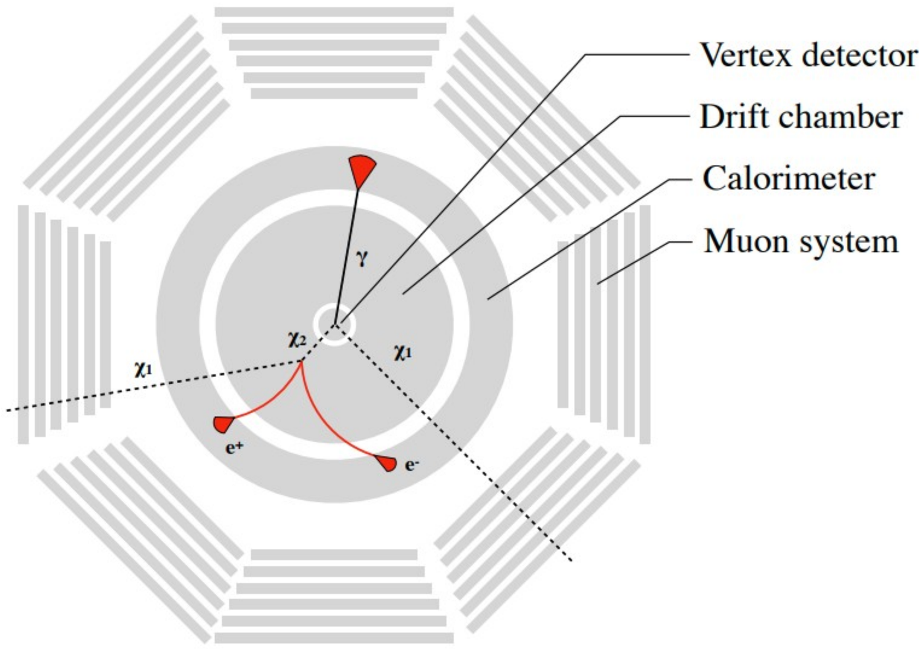
arXiv:1801.04847



Inelastic dark matter

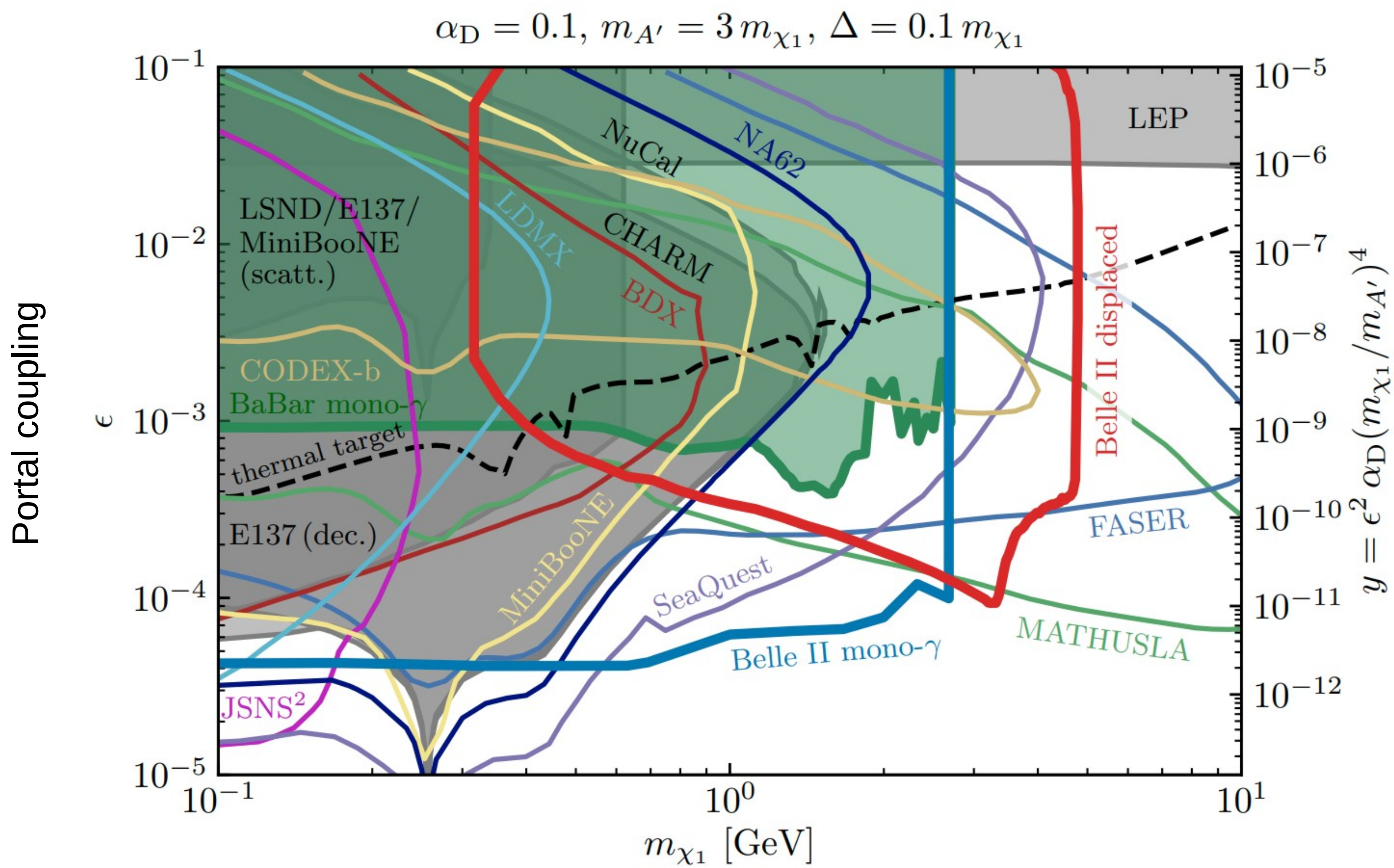
- Mass splitting Δ between ground state x_1 and excited state x_2
- Relative abundance of excited state scales ~ exp(-Δ/T) in the early universe
- All interactions involve one ground state and one excited state
  → Annihilation rate becomes suppressed for T < Δ
- Also: Strong suppression of scattering in direct detection experiments

- Key prediction: Long-lived excited state
  - Decay length may be in mm-cm range
  - Interesting decay mode: $x_2 \rightarrow x_1 e^+ e^-$
- Possible search at Belle II:
  - ISR photon allows for triggering (three isolated clusters)
  - Even better prospects with dedicated displaced vertex trigger
  - Complementary constraints from single-photon search



Inelastic dark matter: Results

Additional model parameters



Dark matter mass

arXiv:1911.03176

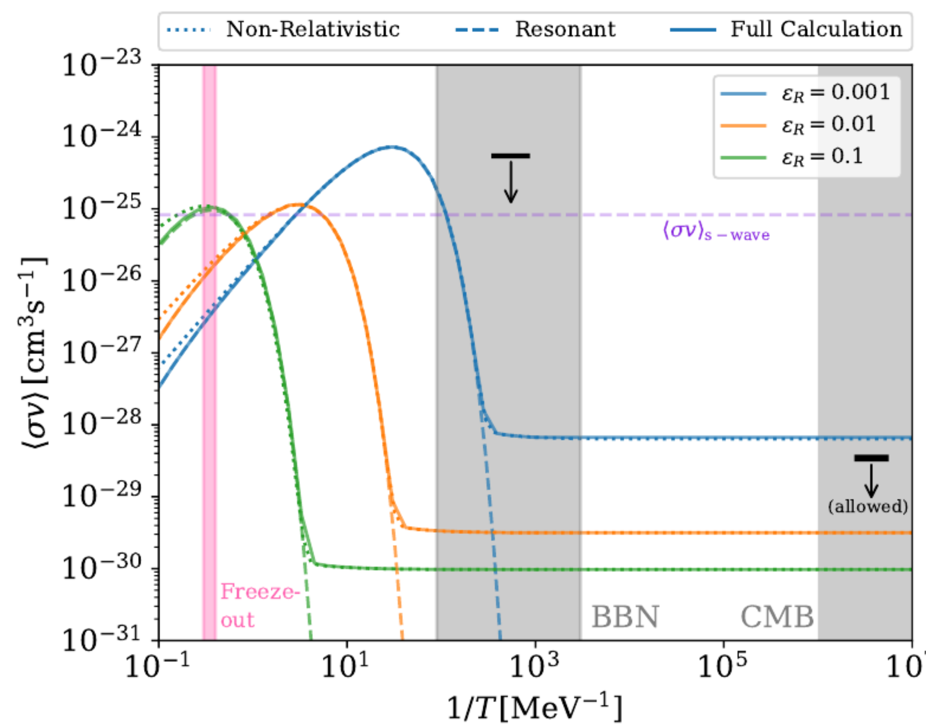
Resonant dark matter

- If the DM mass is close to twice the mediator mass, annihilations receive a resonant enhancement

$$\sigma v_{\rm lab} = F(\epsilon)\frac{m_{A'}\Gamma_{A'}}{(s - m_{A'}^2)^2 + m_{A'}^2\Gamma_{A'}^2}$$

→ No strong constraints from CMB and indirect detection

→ Relic density requirement can be satisfied even for tiny couplings



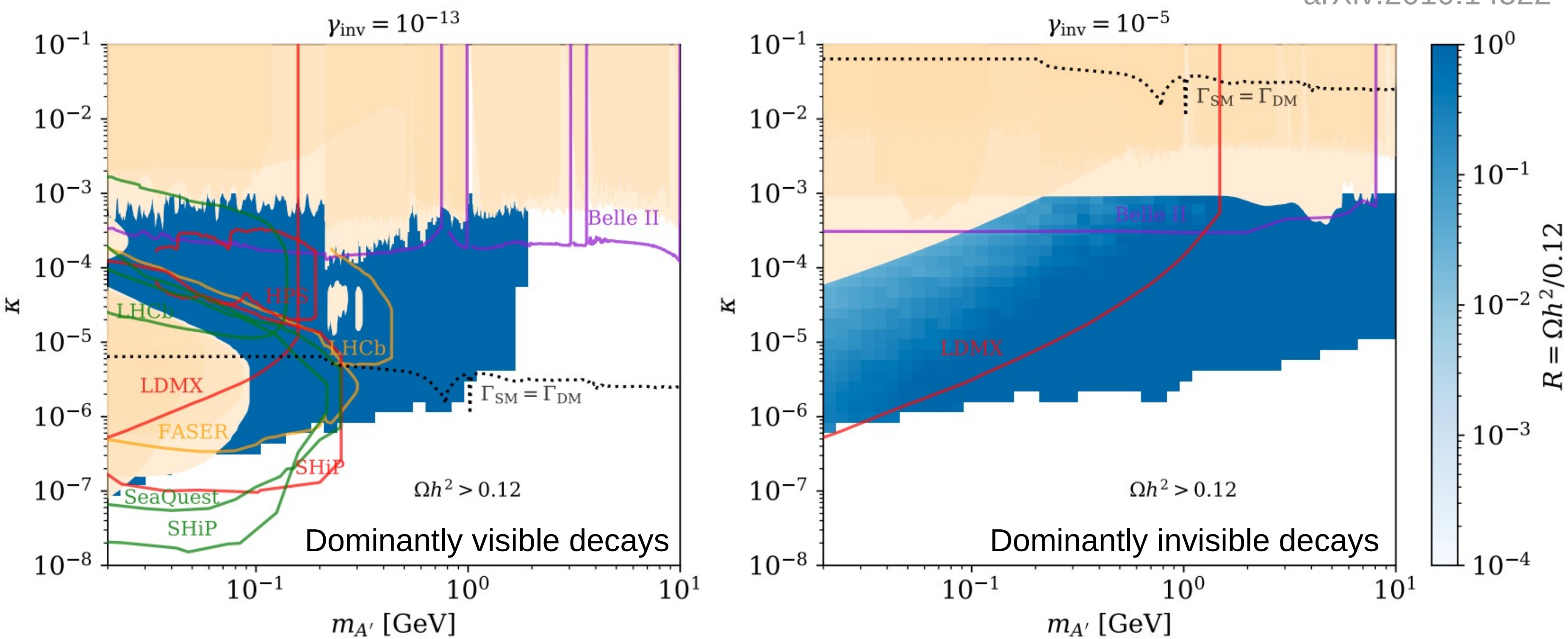
arXiv:2010.14522

- Dark sector characterised by two quantities
  - Resonance parameter: $$\epsilon_R = \frac{m_{A'}^2 - 4m_\chi^2}{4m_\chi^2}$$
  - Reduced invisible width: $$\gamma_{\rm inv} \equiv \frac{\Gamma_{\rm DM}}{m'_A} = \frac{g_\chi^2}{12\pi}\left(1 - \frac{1}{1+\epsilon_R}\right)^{1/2}\left(1 + \frac{1}{2(1+\epsilon_R)}\right)$$

Resonant dark matter: Results

- Blue shading: Viable parameter space (light blue: viable only for DM sub-component)
- Orange shading: Existing constraints

arXiv:2010.14522



- Comprehensive exploration requires combination of searches for visible and invisible final states

Forbidden dark matter

- Dark matter freeze-out proceeds via annihilation into dark sector states: $\chi\,\chi \rightarrow A'\,A'$
  - Assumption: A' unstable with $m_{A'} < 2\,m_\chi$

    → Any A' produced decays into SM states
  - Additional assumption: $m_{A'} > m_\chi$

    → Annihilations are kinematically allowed only at finite temperature/energy

    → Exponential suppression of annihilations at late times

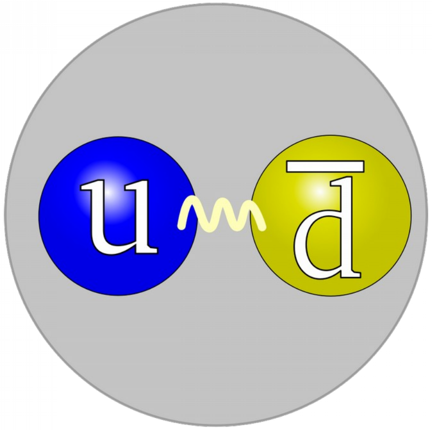
arXiv:1505.07107

- Original idea: A' is a dark photon that couples to SM particles via kinetic mixing

  → Similarity of $m_{A'}$ and m_χ largely accidental

- Alternative perspective: χ and A' both arise as bound states from a strongly-interacting dark sector that resembles QCD
  - Dark matter particles ↔ pseudoscalar mesons (dark pions)
  - Annihilation partners ↔ vector mesons (dark rho mesons)

  → Underlying motivation for $m_\chi < m_{A'} < 2\,m_\chi$



arXiv:1907.04346

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Strongly-interacting dark sectors: Example

- Consider SU(N) gauge group with N = 3 (like QCD)
- Focus on the case of two light quarks with equal mass

- Assume that the two quarks couple to a dark photon with opposite charge
  - → Confinement gives rise to three light pions (π^+, π^-, π^0)
  - → All three pions may be stable and suitable dark matter candidates

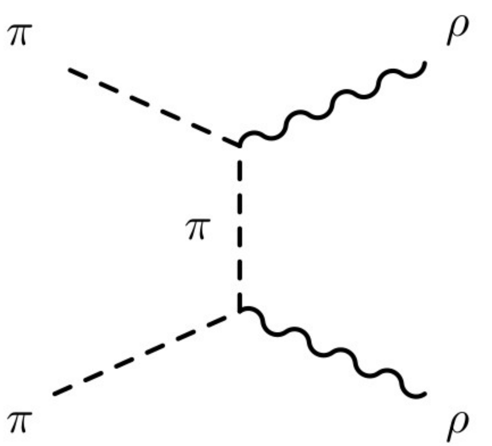
arXiv:1801.05805

- The neutral vector meson (ρ^0) mixes with both the dark and the SM photon
  - → Long-lived particle that decays into SM final states

- No 3→2 processes (as required for the SIMP mechanism)

- Relic density set by the forbidden annihilations $\pi\,\pi \to \rho^0\,\rho^0$

arXiv:1907.04346



Strongly-interacting dark sectors at Belle II

- No preferred energy scale for the confinement of the dark sector
- Confinement scales < 50 MeV are in conflict with bounds on DM self-interactions

  → Interesting to think about dark sectors in the 100 MeV – 1 GeV range

- Dark photon could be significantly heavier

  → Interactions between dark quarks and SM described by effective operator

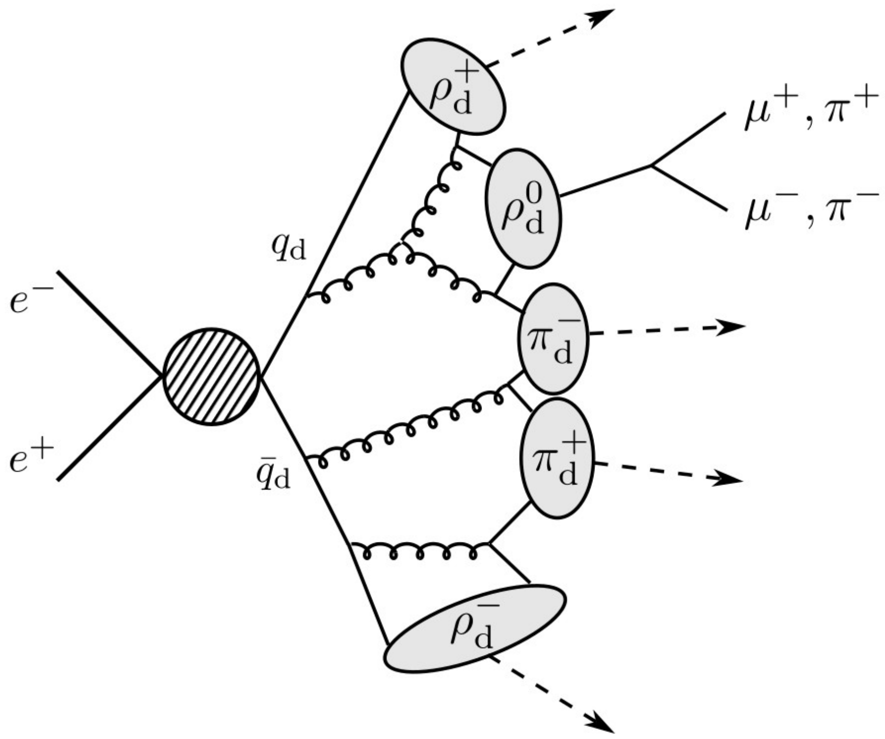
$$\mathscr{L}_{\mathrm{eff}} \supset \frac{1}{\Lambda^2} \sum_f q_f \bar{f} \gamma^\mu f \bar{q}_{\mathrm{d}} \gamma_\mu q_{\mathrm{d}}$$

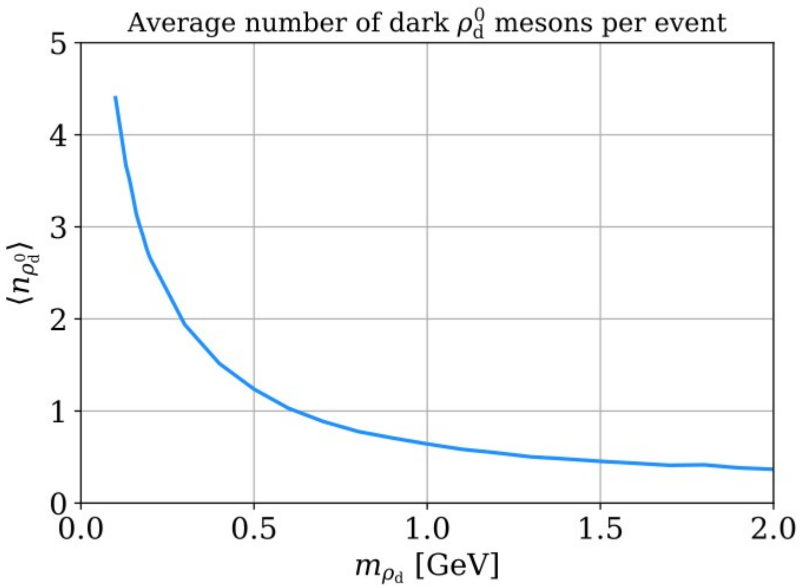
  → For $\Lambda \sim$ TeV the dark rho meson has detector-size decay length

- Highly interesting scenario for electron-positron colliders!

Dark showers at Belle II

- Dark quarks produced in e^+e^- collisions will hadronise and create a dark shower
- Multiplicity (and boost) of long-lived dark rho mesons depends on mass scale

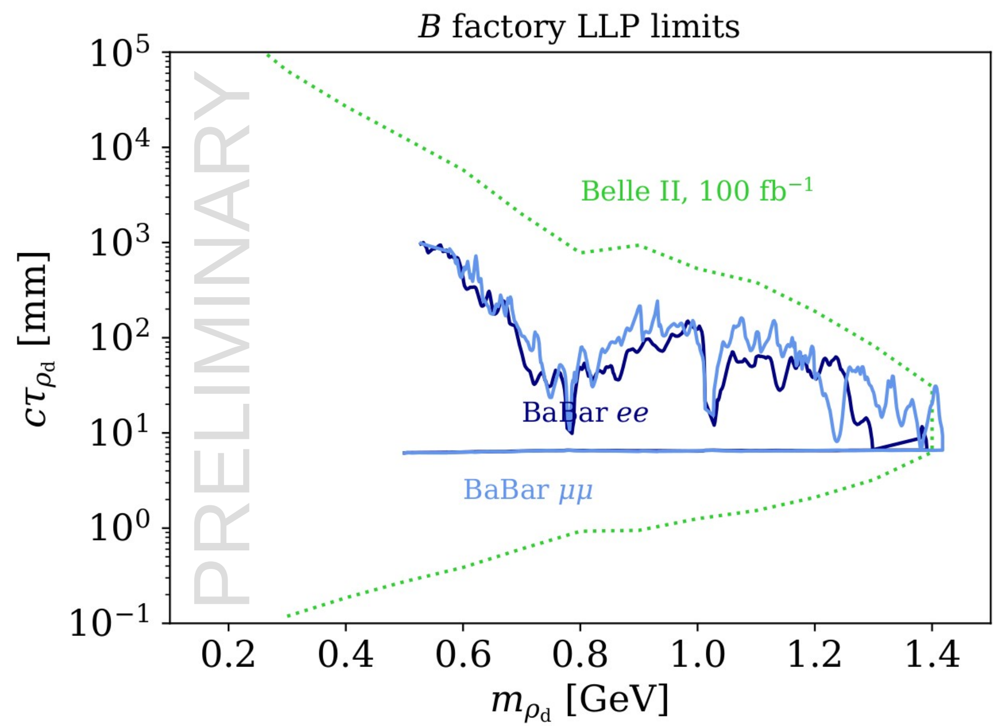




- Possible strategy: Search for events with a muon pair from a displaced vertex

Existing exclusion limits and projections

- Existing BaBar limit from model-independent search for LLPs
  arXiv:1502.02580
- Belle II projection based on similar assumptions as for inelastic DM
  arXiv:2012.08595
- Interesting parameter regions compatible with other constraints (EWPT, Z boson invisible width, …)



- Not shown: Additional exclusion limits from searches for displaced di-muon resonances in LHCb
  → Comparison cannot be done in EFT approach (dark photon produced on-shell)

Conclusions

- Huge variety of models for GeV-scale dark sectors
- Dark matter particles may reproduce observed relic abundance via freeze-out
- Constraints require annihilation rate with non-standard velocity dependence

- **Inelastic dark matter**
  → Excited state has three-body decay with macroscopic decay length

- **Resonant dark matter**
  → Tiny couplings viable for both visible and invisible decays

- **Forbidden dark matter**
  → Well-motivated annihilation partners from strongly-interacting dark sectors
  → Prediction: Dark showers at e^+e^- collisions
  → Evaluation of existing constraints and projected sensitivities ongoing