Dark matter beyond the WIMP paradigm

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Chalmers Göteborg
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Including results from **arXiv:1907.04346, arXiv:1911.03176, arXiv:2010.14522** and **ongoing work** in collaboration with Kai Böse, Elias Bernreuther, Timon Emken, Torben Ferber, Jonas Frerick, Chris Hearty, Saniya Heeba, Michael Krämer, Alessandro Morandini and Kai Schmidt-Hoberg

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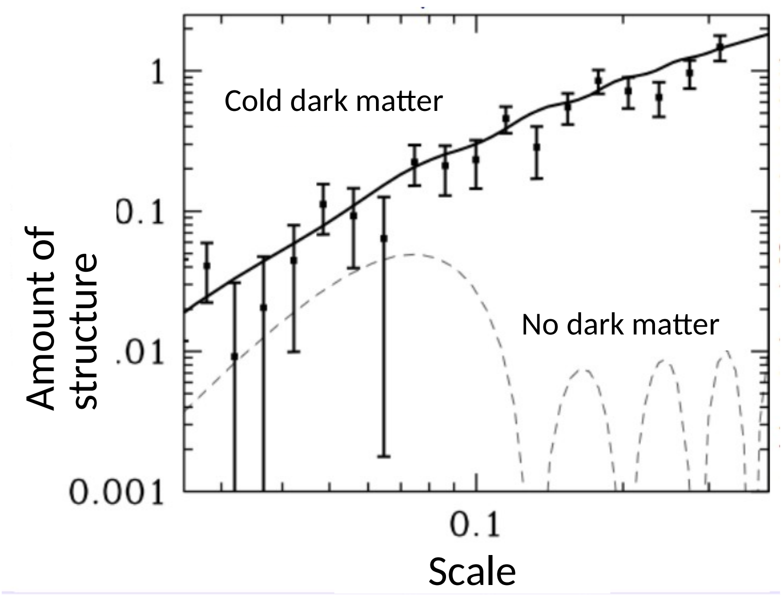
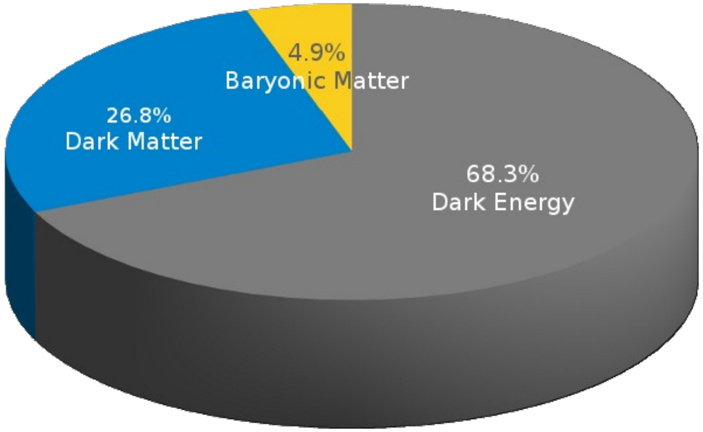
Why dark matter?

- Dark matter (DM) is an **essential ingredient** to describe Early Universe cosmology
  - Acts as the early seed for **structure formation**
  - Creates the **potential wells** for stars and galaxies
  - **Explains** the amount and distribution of structure that we observe today





- A wealth of **successful predictions** from a very simple model
- Only draw-back: We understand only **5%** of the Universe!

What is dark matter?

- Observations clearly **confirm the existence** of dark matter (DM) in the Universe, but they give **almost no indications** concerning its nature
- No known particle (within the Standard Model of particle physics) has the **required properties** to be DM
- Need to postulate the **existence of a new particle** with unknown properties
- The only thing we know about it is **its abundance** in the Universe:

$$\Omega h^2 = 0.1199 \pm 0.0027$$

- Any model of dark matter must provide a mechanism to **explain this number**

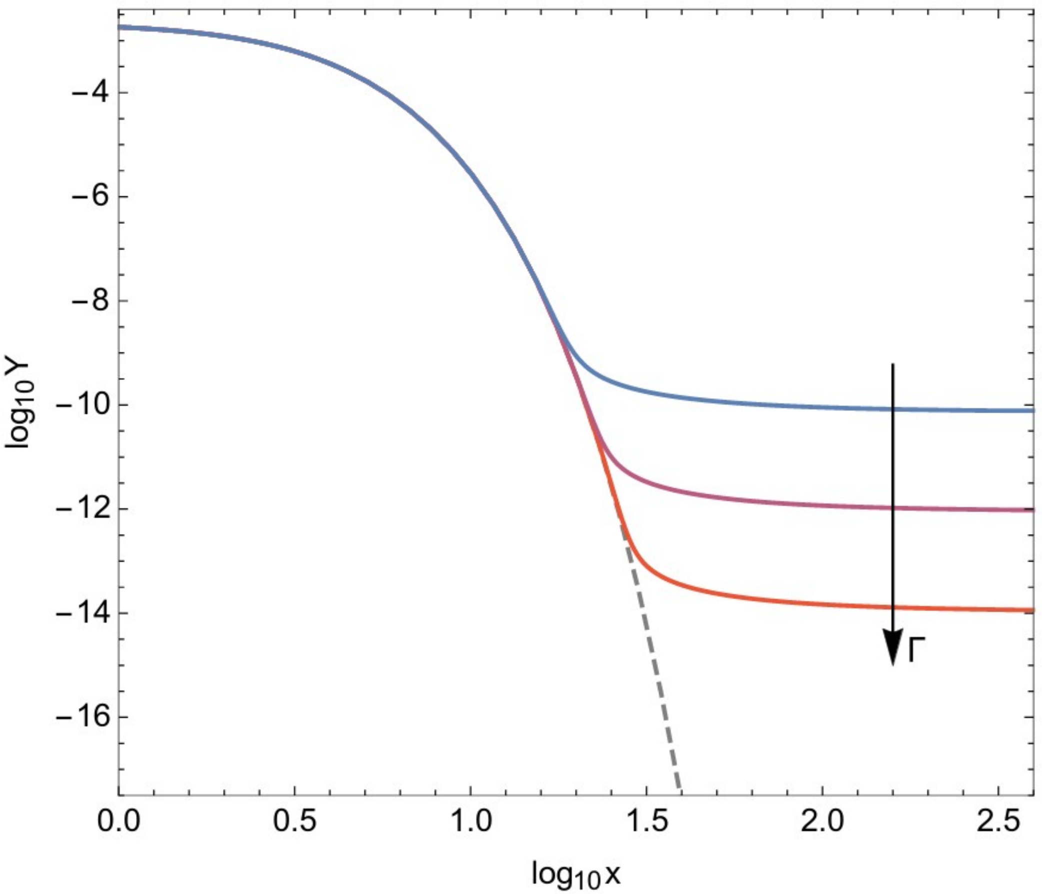
by Saniya Heeba

The thermal freeze-out paradigm

- **High temperatures** ($T >> m_{DM}$)
  - DM **annihilation and production** processes are in equilibrium

- **Low temperatures** ($T << m_{DM}$)
  - **DM particles decouple** from equilibrium

Bernal et al.: arXiv:1706.07442



Qualitative solution: Stronger interactions ↔ smaller abundance

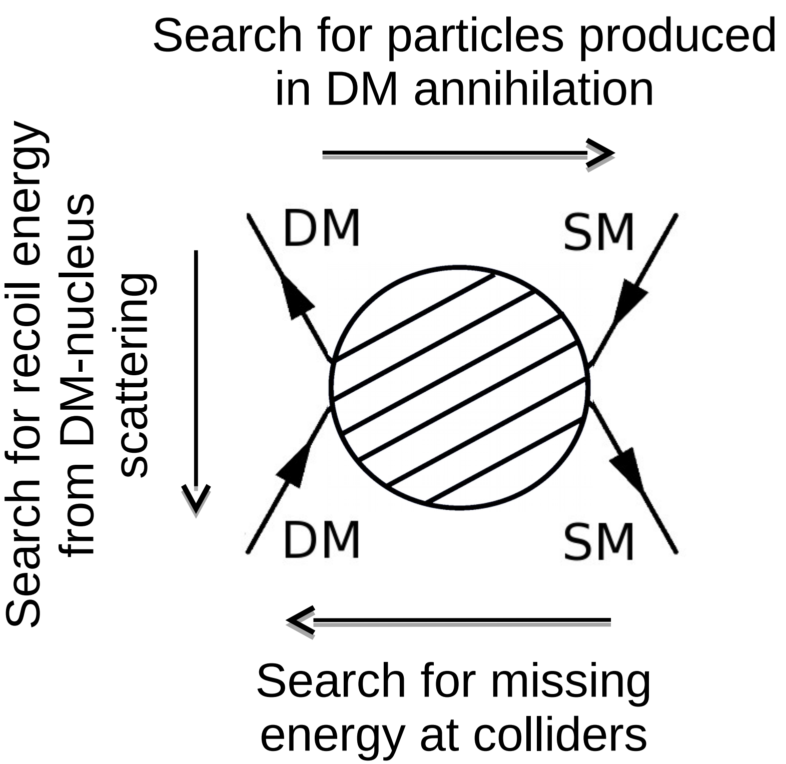
Weakly Interacting Massive Particles (WIMPs)

- Particles that obtain their relic abundance through **thermal freeze-out** are called WIMPs

- If these particles have similar interactions as known particles but are slightly heavier, thermal freeze-out leads to the **correct relic density**

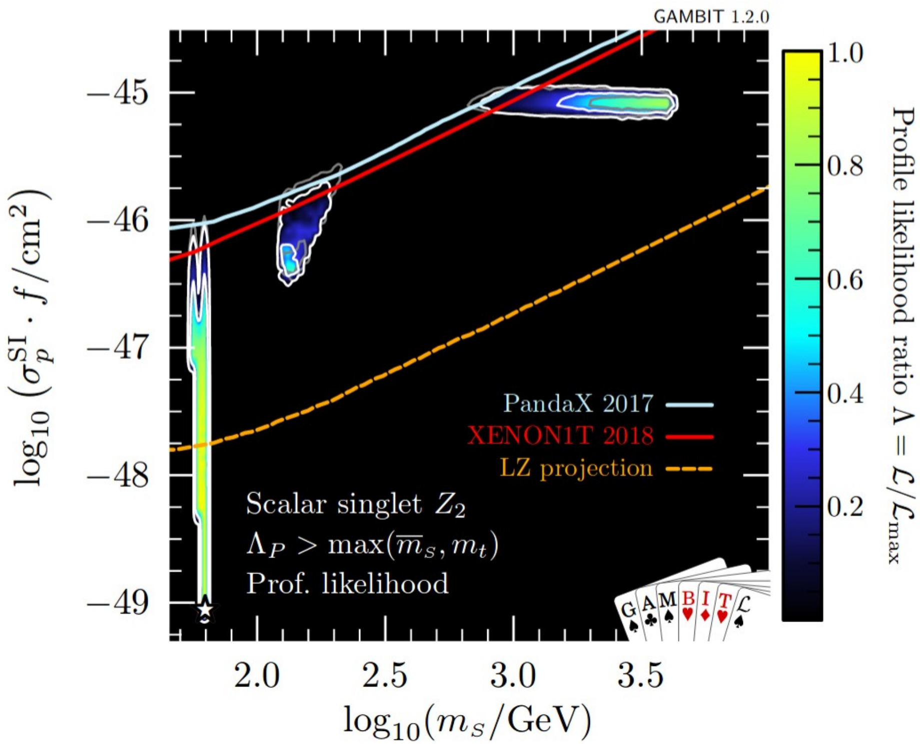
- The corresponding cross sections for WIMP-SM interactions are sizeable

- We can **hope to observe WIMPs** in the laboratory!



See talk by Eleni Skorda earlier today

Where Is My Particle?



- **Parameter space for WIMPs is getting tight!**

Athron, FK et al., arXiv:1806.11281

by Saniya Heeba

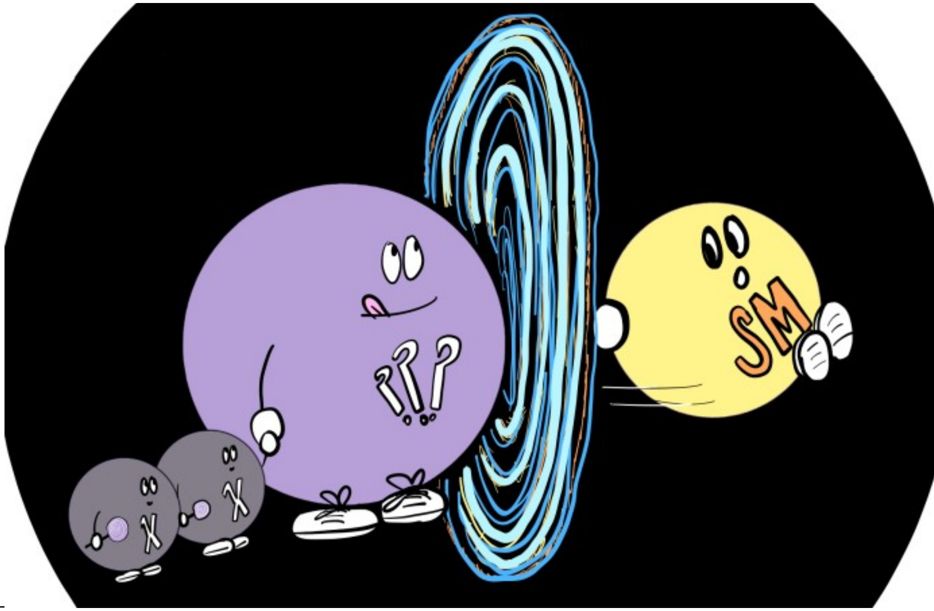
- **Most WIMP models are still viable**, but the non-observation of dark matter signals mounts **substantial pressure** on the WIMP idea
- Well-motivated to **question underlying assumptions** and consider alternative DM models

The future is light

- Direct detection experiments become insensitive to DM-nucleus scattering for DM masses below a few GeV
  - → Large unexplored parameter regions for sub-GeV DM masses

- **Main obstacle:** Lee-Weinberg bound
  - Particles interacting via the weak force have $\sigma v \sim G_F^2\, m^2 \quad \rightarrow \quad \Omega h^2 \sim m^{-2}$
  - For small DM masses we end up with too much DM!

- Sub-GeV DM particles cannot interact only via the known forces of the SM
  - → Require new types of interactions for thermal freeze-out to work
  - → Mediator of new interaction must be light (compared to weak scale)



Light mediators

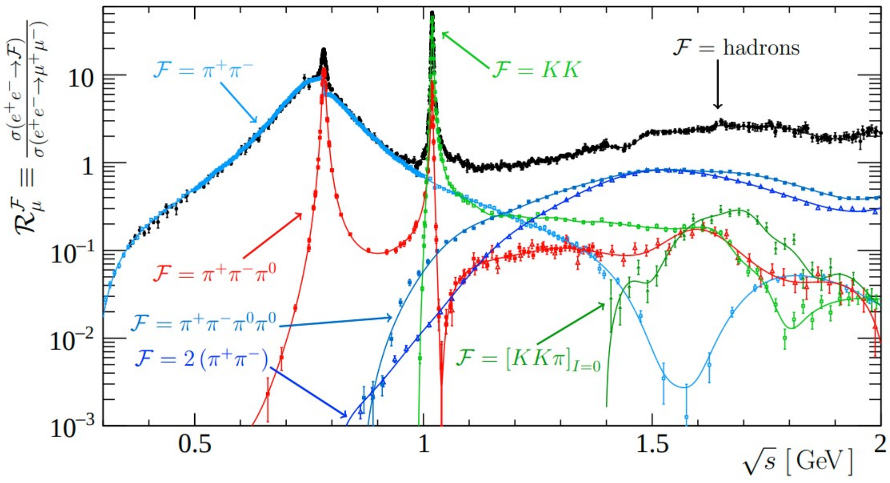
- There are **many different ways** how sub-GeV DM particles can couple to SM states
  - New gauge bosons (vector mediators)
  - New Higgs bosons (scalar mediators)
  - Axion-like particles (pseudoscalar mediators)
  - ...
- Mechanisms discussed in this talk **largely independent** of the detailed interactions
- For concreteness, consider a **dark photon vector mediator** with mass $m_{A'}$ and kinetic mixing with electromagnetism:

$$\mathcal{L} \supset -\frac{1}{4} X^{\mu\nu} X_{\mu\nu} + \frac{1}{2} m_{A'}^2 A'_\mu A'^\mu - \frac{\epsilon}{2} F^{\mu\nu} X_{\mu\nu}$$

→ Couplings proportional to electric charge

→ Total width and branching ratios correspond to decay modes of off-shell photons

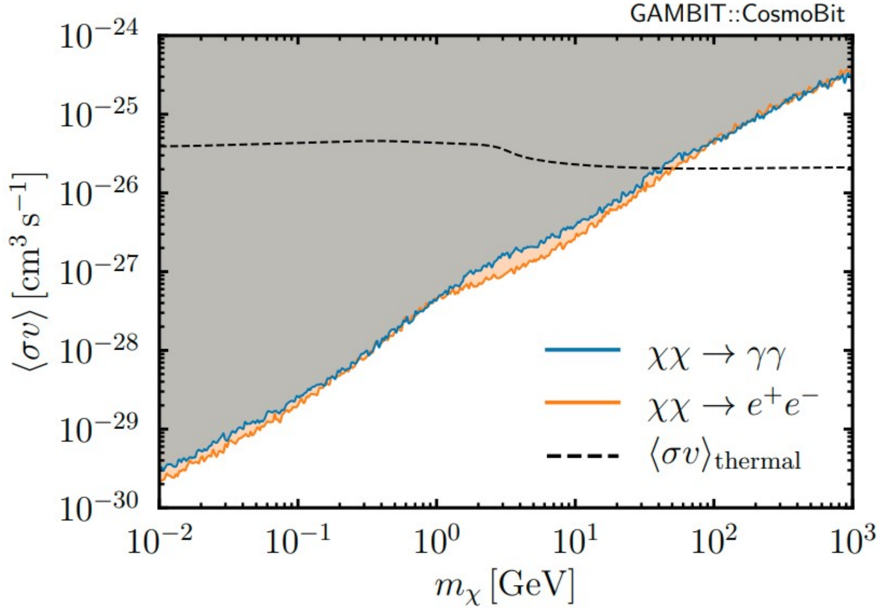
arXiv:1801.04847



Key problem: Late-time annihilations

- Thermal freeze-out requires annihilation cross section $\sigma v \sim 10^{-26}$ cm^3/s
- A small fraction of DM particles will continue to annihilate even after the end of freeze-out
- The energy injected by these annihilations into the electron-photon plasma modifies reionisation

Renk, FK et al., arXiv:2009.03286



→ Strong constraints on GeV-scale DM with velocity-independent annihilation cross section from observations of the Cosmic Microwave Background

- To evade these constraints, it is necessary to suppress the annihilation cross section at small velocities

Three possible avenues

Minimal solution:

- s-wave annihilation forbidden
- Dominant contribution from p-wave
- Velocity suppression: $\sigma v \sim v^2$
- Examples:
  - Complex scalar DM annihilating via off-shell vector mediator

    arXiv:hep-ph/0305261
  - Fermionic DM annihilating into two on-shell scalar mediators

    arXiv:0711.4866

Radical solution:

- DM relic density not determined by freeze-out mechanism
- Examples:
  - Particle-antiparticle asymmetry

    arXiv:0901.4117
  - No thermal equilibrium

    arXiv:0911.1120
  - Relic density not determined by annihilations

    arXiv:1402.5143

Creative solution:

- DM relic density set by thermal freeze-out but via a non-standard annihilation process

Non-standard annihilation processes

To evade the strong CMB constraints on sub-GeV DM, we can modify any of the three main contributions to the DM annihilation rate:

Rate = |Matrix element|^2 * (Phase space) * (Number density)

Consider strongly energy-dependent matrix element

→ Resonant DM

Bernreuther, Heeba & FK, arXiv:2010.14522

Consider strongly energy-dependent phase space

→ Forbidden DM

arXiv:1505.07107

Consider suppression of co-annihilation partners

→ Inelastic DM

arXiv:1508.03050

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Resonant dark matter

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

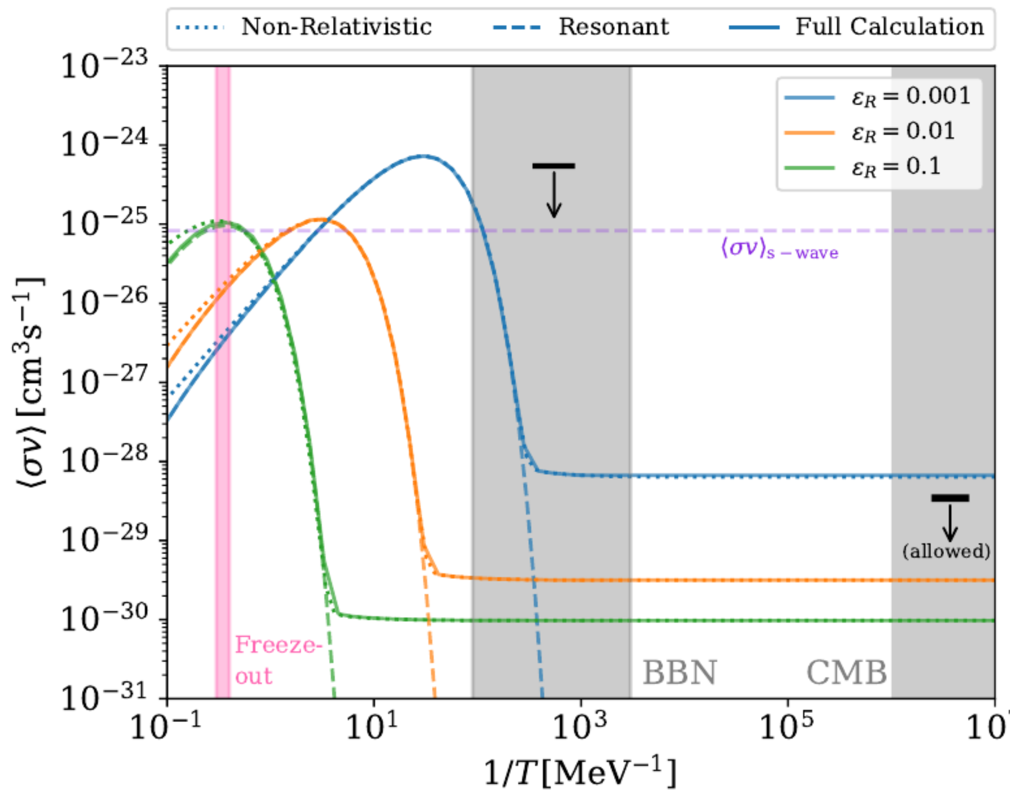
$$\sigma v_{\rm lab} = F(\epsilon) \frac{m_{A'}\Gamma_{A'}}{(s - m_{A'}^2)^2 + m_{A'}^2 \Gamma_{A'}^2}$$

- Enhancement is largest if DM velocity squared is close to the resonance parameter

$$\epsilon_R = \frac{m_{A'}^2 - 4m_\chi^2}{4m_\chi^2}$$

Freeze-out: $v^2 \sim 10^{-1} - 10^{-2}$

Recombination: $v^2 < 10^{-14}$



arXiv:2010.14522

→ CMB constraint can be evaded for wide range of ε_R

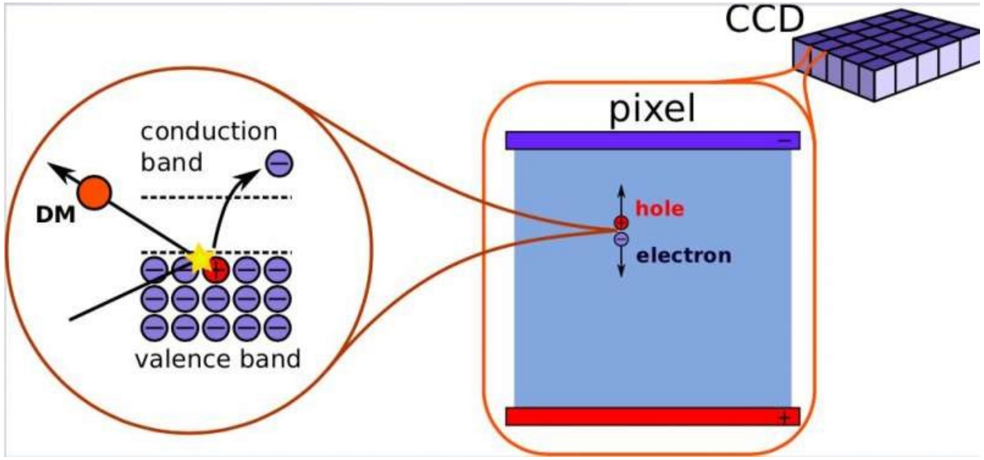
→ Due to the enhancement relic density can be reproduced even for tiny couplings

Resonant dark matter: Direct detection

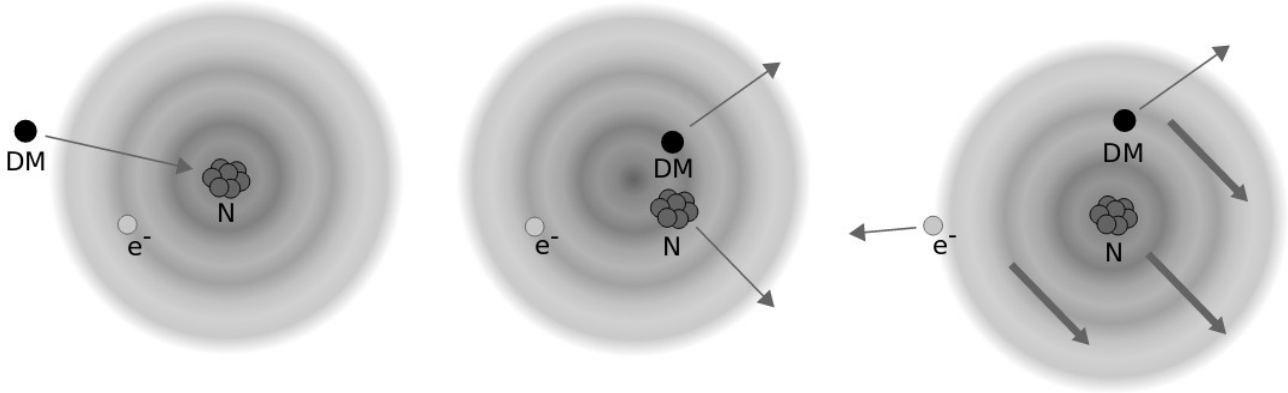
- For sub-GeV DM the nuclear recoil energy is unobservably small
- **Instead:** Search for electron recoils from DM-electron scattering
- Previously studied only as background
- **Exciting opportunity** for DM searches

See talk by Einar Urdshals tomorrow

- Recent excess observed by XENON1T (more on this later)



- **Note:** nuclear recoil may also be converted to electron recoil via the Migdal effect

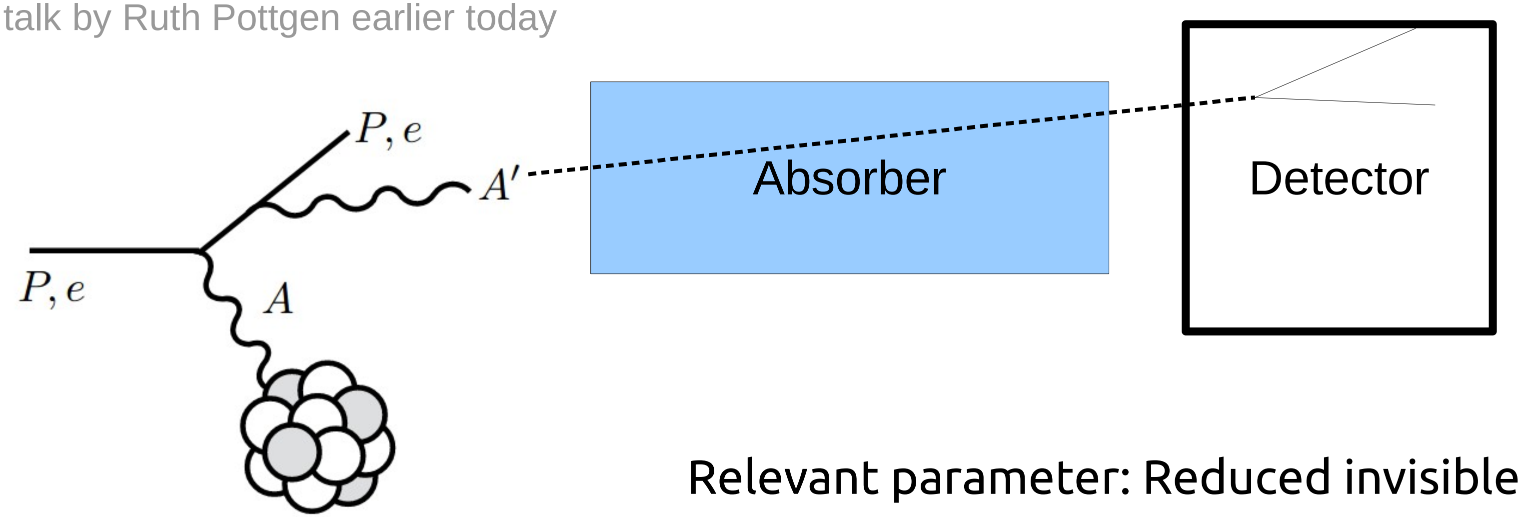


arXiv:1711.09906

Resonant dark matter: Accelerator searches

- **Basic idea:** Search for the mediator of the DM interactions (i.e. the dark photon)
- Dark photons are so weakly coupled that they **easily travel through matter**
- For $m_{A'} > 2\, m_e$ they are however **unstable** against the decay into two electrons
- **Example:** $m_{A'} \sim 10$ MeV and $g' \sim 10^{-6}$ → decay length ~ 1m
- We can search for dark photon decays in beam-dump experiments

See talk by Ruth Pottgen earlier today



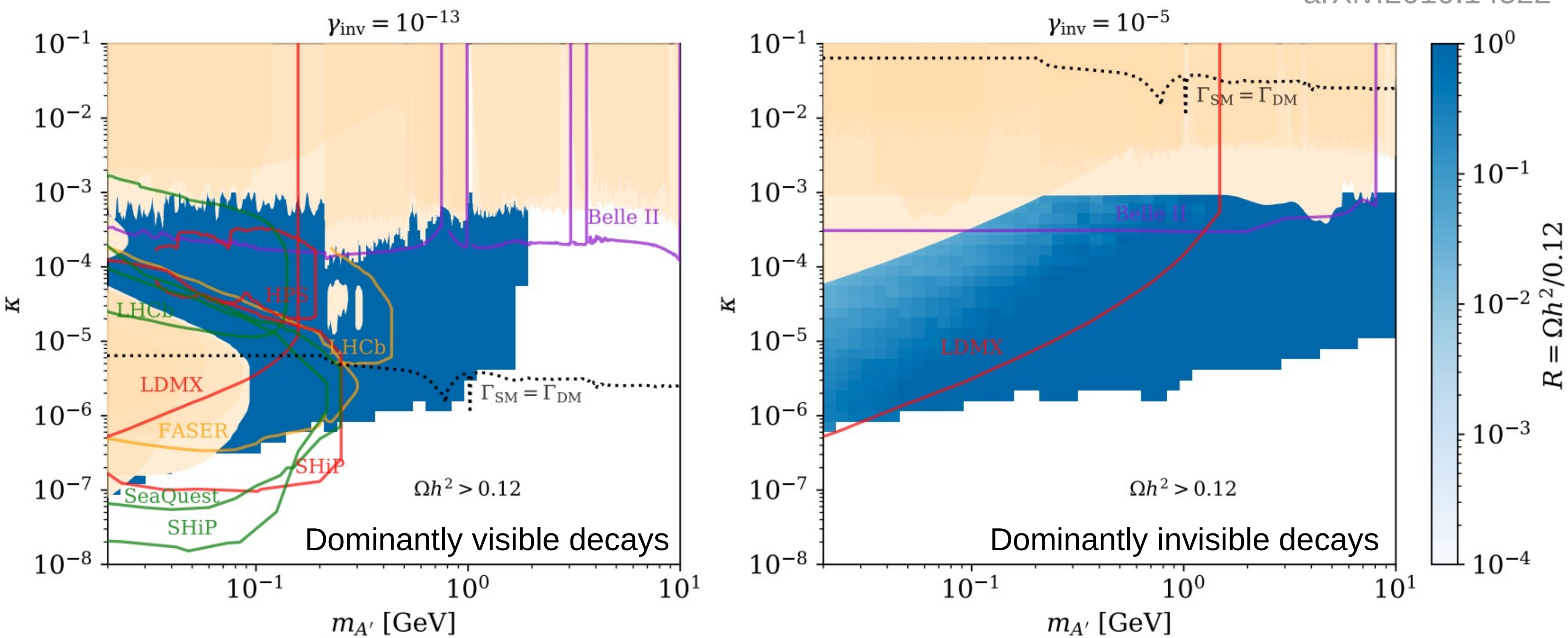
Relevant parameter: Reduced invisible width

$$\gamma_{\rm inv} \equiv \frac{\Gamma_{\rm DM}}{m'_A} = \frac{g_\chi^2}{12\pi}\left(1 - \frac{1}{1+\epsilon_R}\right)^{1/2}\left(1 + \frac{1}{2(1+\epsilon_R)}\right)$$

Resonant dark matter: Results

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

arXiv:2010.14522

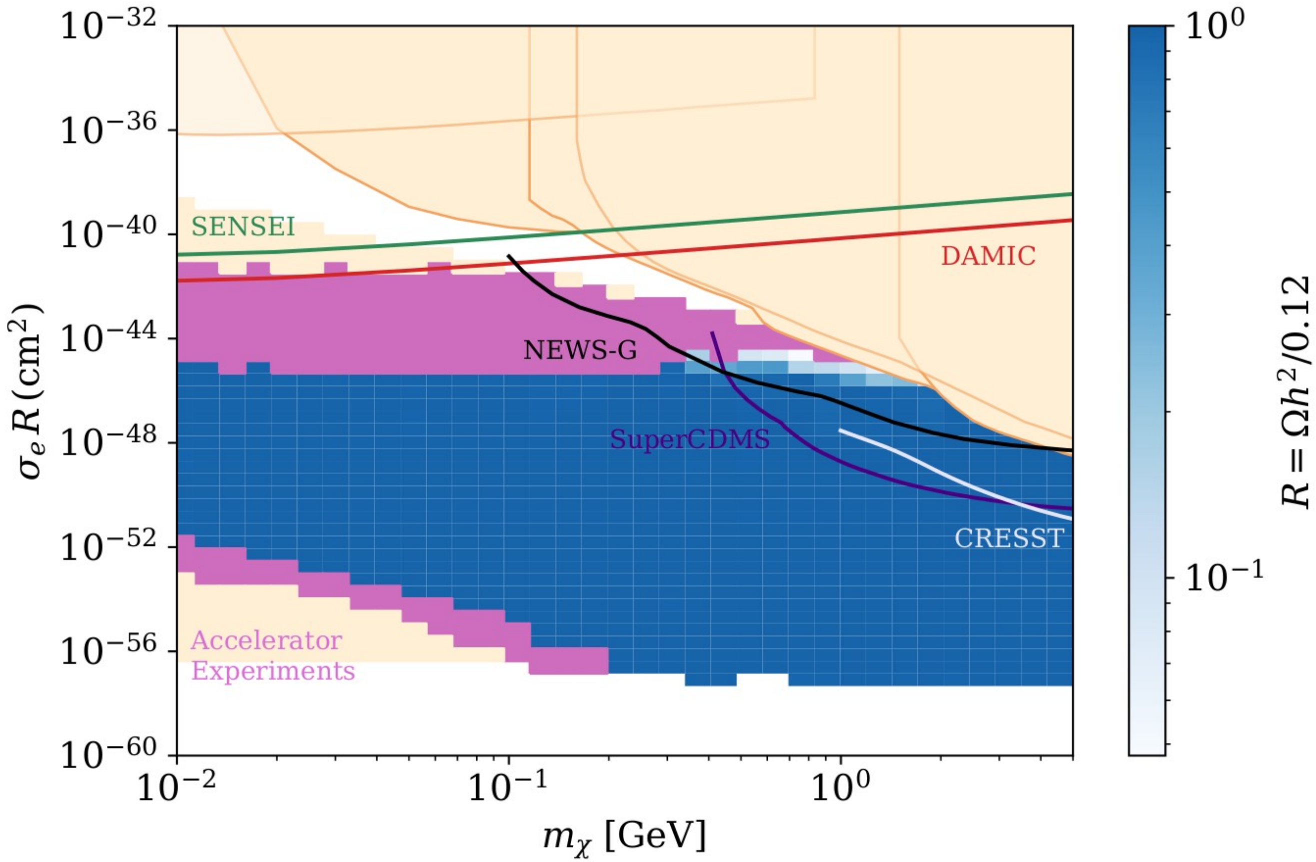


- Comprehensive exploration requires combination of searches for visible and invisible final states

Resonant dark matter: Global fit

- Scan over all four model parameters and eliminate all points excluded by existing experiments (orange shading)
- Plot the remaining points in the parameter plane relevant for direct detection
- Make the distiction:
  - Viable parameter point (blue)
  - Viable for DM sub-component (light blue)
  - Testable by future accelerator experiments (purple)
- The results can be compared to sensitivity projections for direct detection experiments

arXiv:2010.14522



Non-standard annihilation processes

To evade the strong CMB constraints on sub-GeV DM, we can modify any of the three main contributions to the DM annihilation rate:

Rate = |Matrix element|^2 * (Phase space) * (Number density)

Consider strongly energy-dependent matrix element

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Bernreuther, Heeba & FK, arXiv:2010.14522

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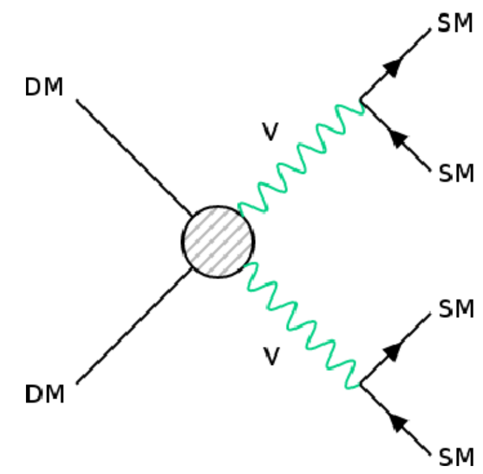
Forbidden dark matter



- **Basic idea:** Dark matter freeze-out proceeds via so-called cascade (or secluded) annihilations:

  $$\text{DM DM} \rightarrow \text{V V} \rightarrow 4\ \text{SM}$$

  where V is another dark sector state with mass $m_V < 2\, m_{DM}$

- In the case that $m_V > m_{DM}$, non-zero kinetic energy is required to open up the phase space

  → Exponential suppression of annihilation rate for small temperatures/velocities

- If m_V is too large, annihilations are strongly suppressed → too much DM

  → Require small mass splitting: $\Delta = (m_V - m_{DM})/m_{DM} \ll 1$

- Several new parameters and degrees of freedom! Too contrived?

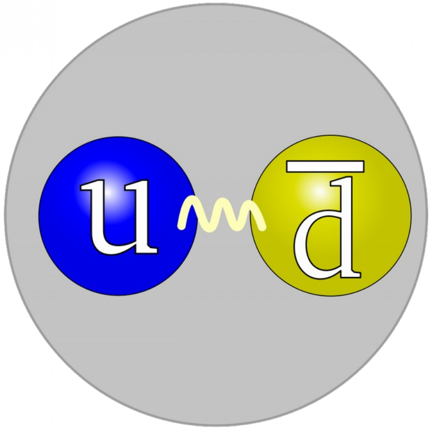
Strongly-interacting dark sectors

- Possible explanation for the existence of many dark sector states with similar mass:
  Dark sector particles arise as bound states from a non-Abelian gauge group

- High energies: Asymptotic freedom → dark sector described by free dark quarks and dark gluons
- Low energies: Confinement → dark sector described by dark mesons and dark baryons

- Attractive possibility:
  Dark matter particles ↔ pseudoscalar mesons (dark pions)
  Annihilation partners ↔ vector mesons (dark rho mesons)

  → Underlying motivation for $m_{DM} < m_V < 2\ m_{DM}$



Strongly-interacting dark sectors: Phenomenology

- 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 range 100 MeV – 1 GeV

- Dark photon could be significantly heavier
  - → Interactions between dark quarks and SM described by effective operator

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

  - → For Λ ~ TeV the dark rho meson has detector-size decay length

- Highly interesting scenario for electron-positron colliders!

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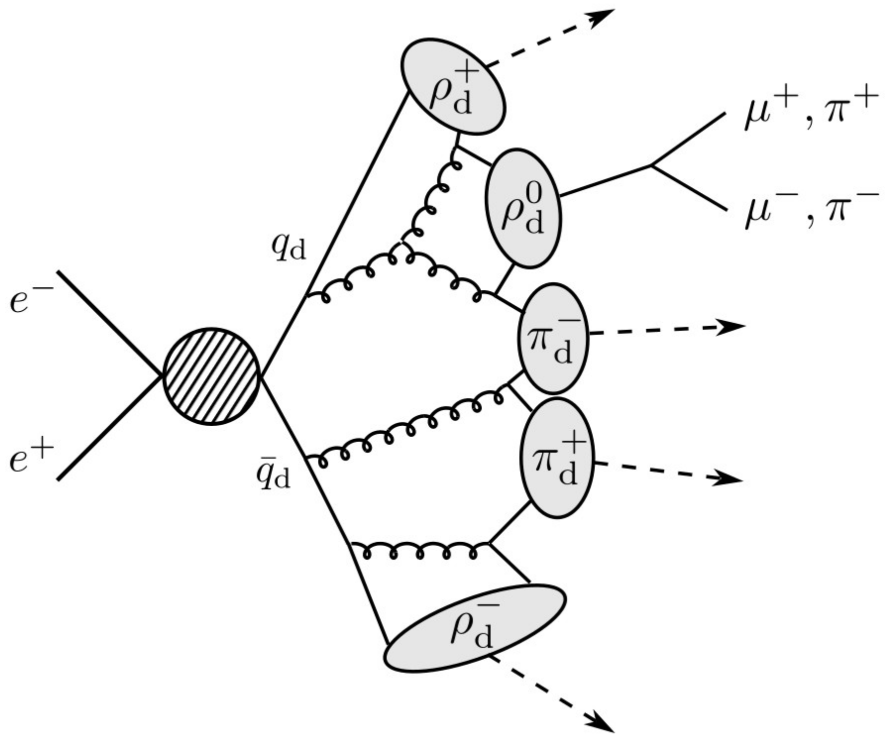
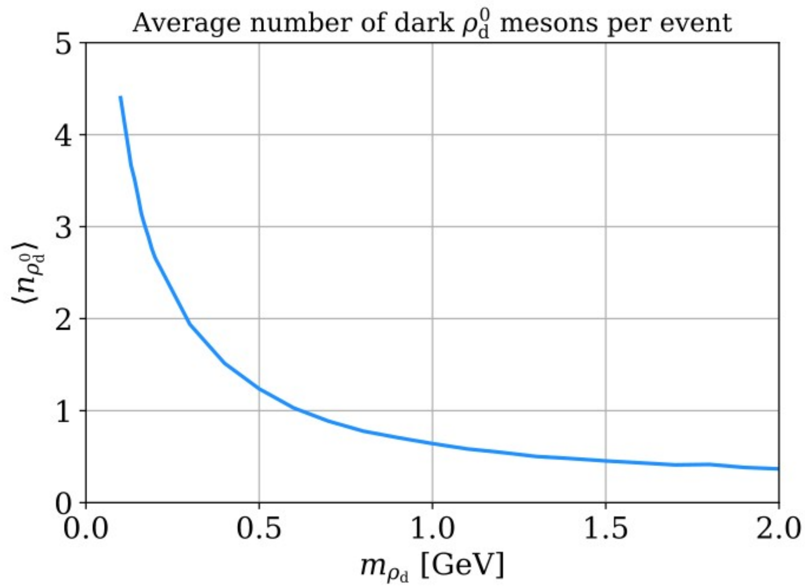
Dark showers

- 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 limits from BaBar and LHCb based on model-independent searches for long-lived particles

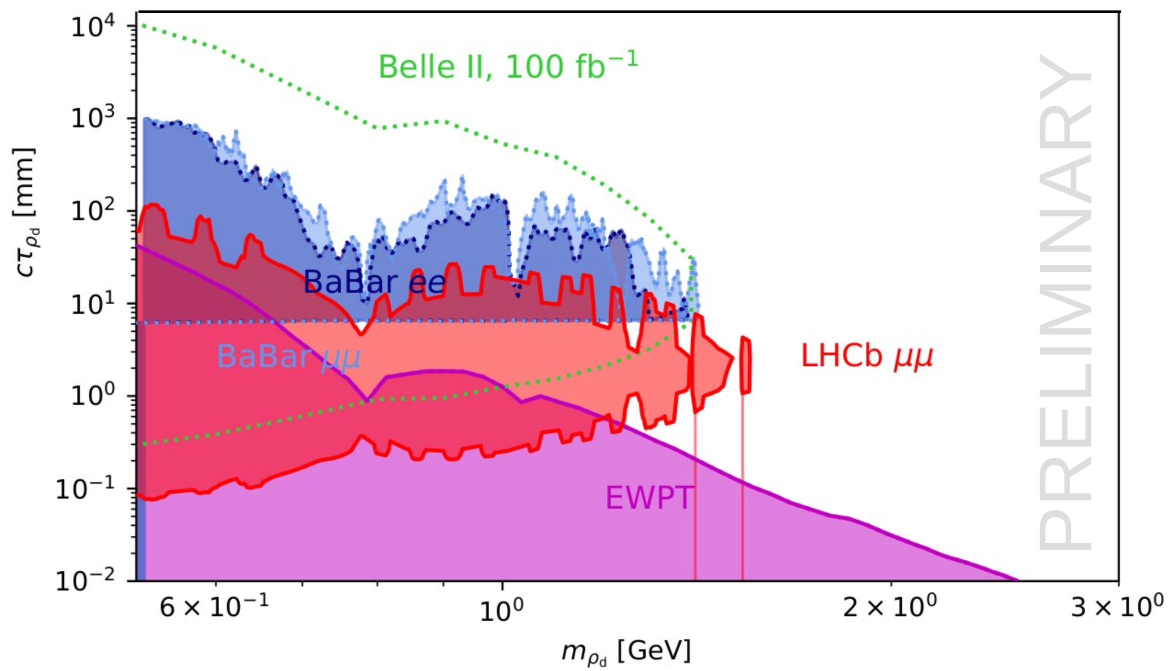
arXiv:1502.02580

arXiv:2007.03923

- Significant improvements expected from Belle II, in particular if a displaced vertex trigger is developed

arXiv:2012.08595

- Interesting parameter regions compatible with other constraints (EWPT, Z boson invisible width, …)



Kai Böse, Elias Bernreuther, Torben Ferber, Chris Hearty, FK, Michael Krämer, Alessandro Morandini and Kai Schmidt-Hoberg, in preparation

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arXiv:1508.03050

Inelastic dark matter

- **Basic idea:** Mass splitting Δ between ground state x_1 and excited state x_2
- Assume couplings to the mediator are off-diagonal*

$$\mathcal{L}_{\rm int} = \frac{i}{2} g_D \bar{\chi}_2 \gamma^\mu \chi_1 V_\mu + \text{h.c.}$$

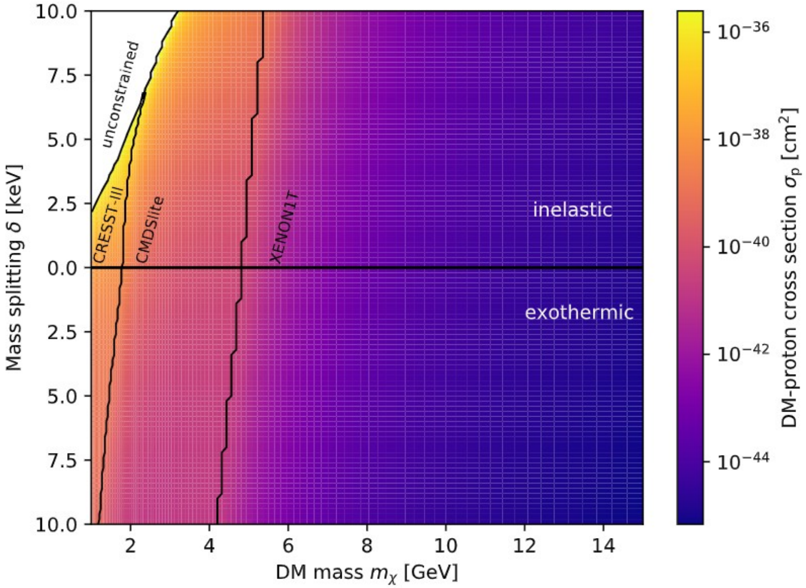
→ All interactions must involve one ground state and one excited state

- Relative abundance of excited state scales ~ exp(-Δ/T) in the early universe

→ Annihilation rate becomes suppressed for T < Δ

→ Inelastic splitting also suppresses direct detection

See talk by Sunniva Jacobsen tomorrow



* This can be automatically achieved if the DM particle has both a Dirac mass term m_D and a Majorana mass term m_M with $m_D >> m_M$ (Pseudo-Dirac DM)

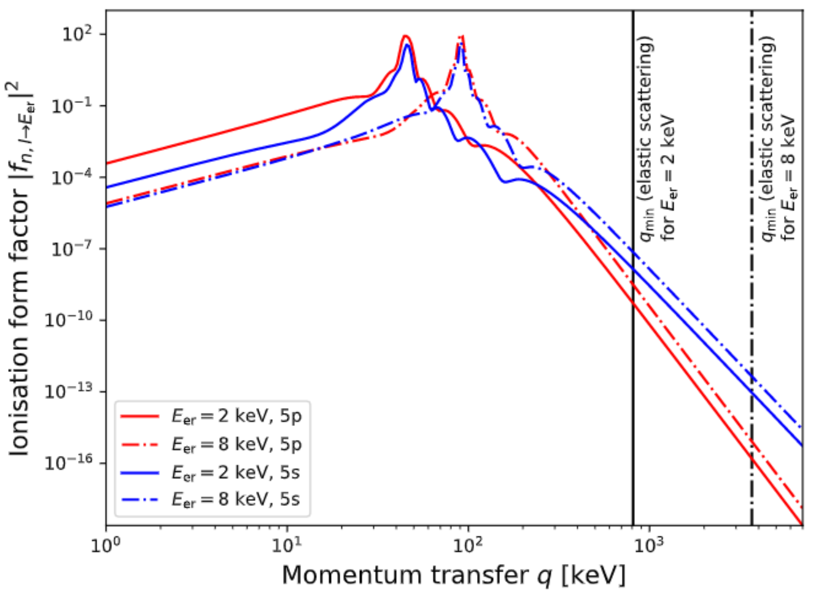
arXiv:1706.08985

Metastable excited states

- For mass splittings in the keV range, the excited state is very long lived (τ > 1s)
  - → Invisible at colliders
  - → Attractive target for direct detection experiments

- **Basic idea:** Excited states can down-scatter on electrons
  - → Electron recoil energy approximately equal to mass splitting Δ

- Ionisation probability strongly enhanced compared to elastic scattering
  - → Even a tiny fraction of excited states can induce observable signals

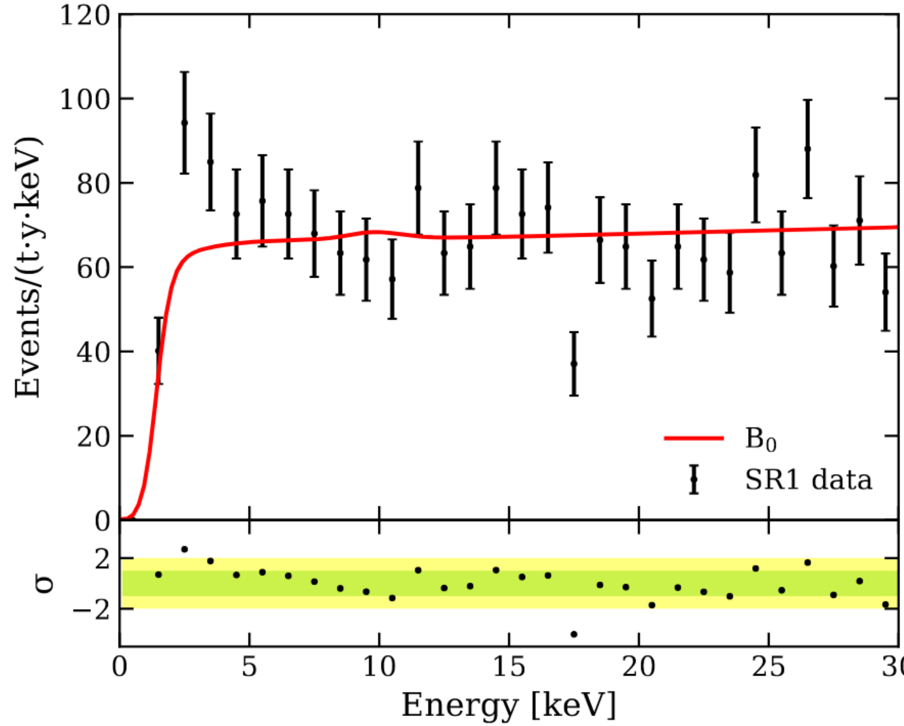


"Exothermic dark matter"

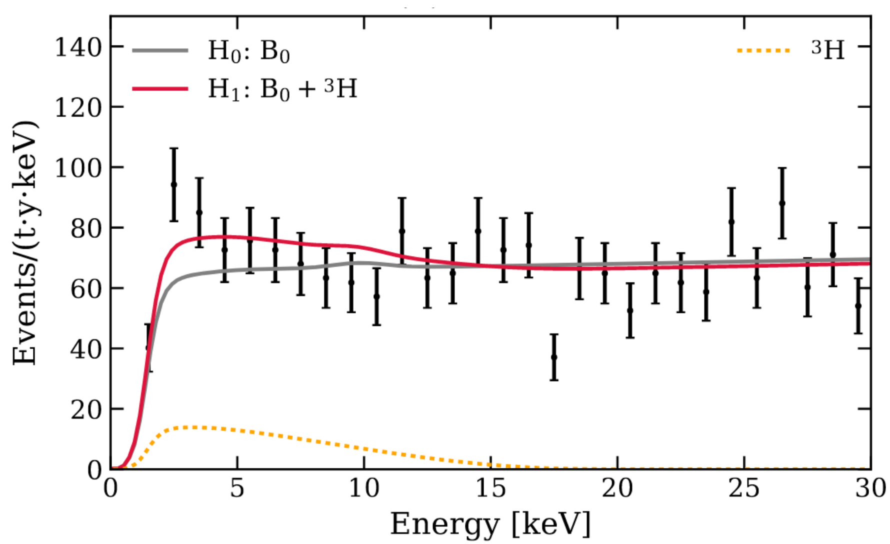
Electronic recoil events in XENON1T

- In 2020 the XENON Collaboration announced an **excess** in electronic recoil events with energy in the range 1-7 keV over known backgrounds

Aprile et al., arXiv:2006.09721



- For several different signal hypotheses the **significance** is >3σ



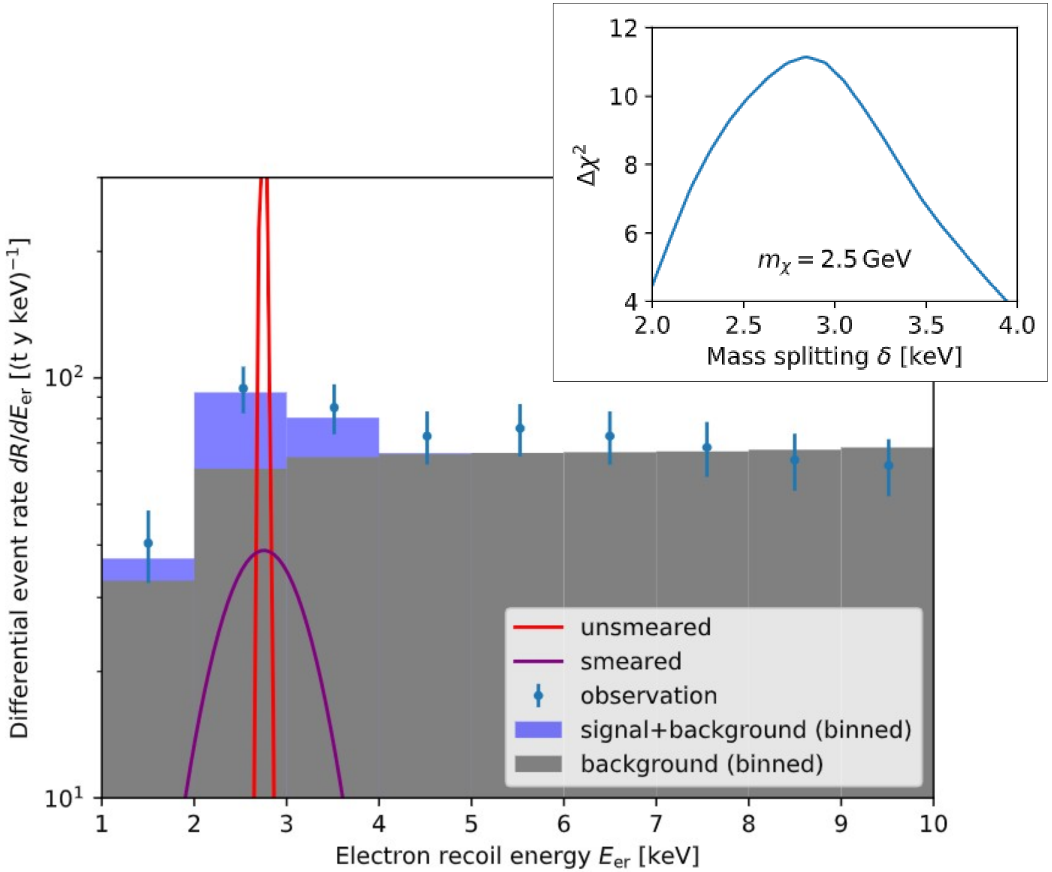
- A more conventional explanation of the signal is that it is due to an unaccounted tritium component

Fitting the XENON1T excess

- Because of the finite detector resolution, exothermic DM with δ ~ 2.8 keV gives an excellent fit to the excess ($\Delta\chi^2$ ~ 11)

arXiv:2006.14521

- **Remaining question:** What is the origin of the excited states?
  - Cosmological relic?
  - Upscattering on cosmic rays?
  - Upscattering in the sun?
  - …?



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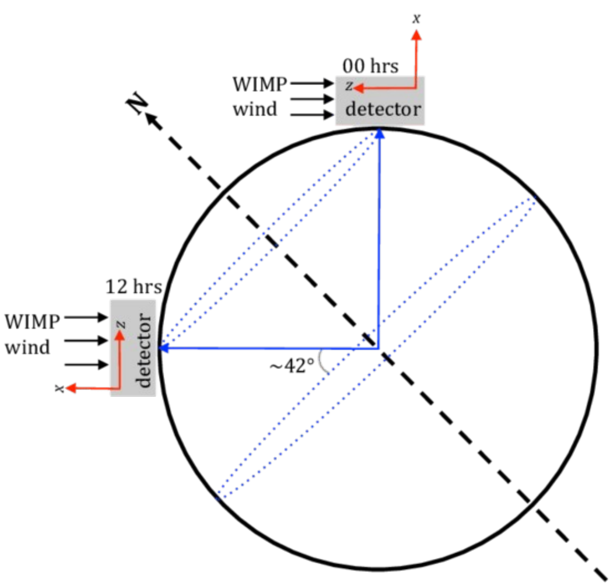
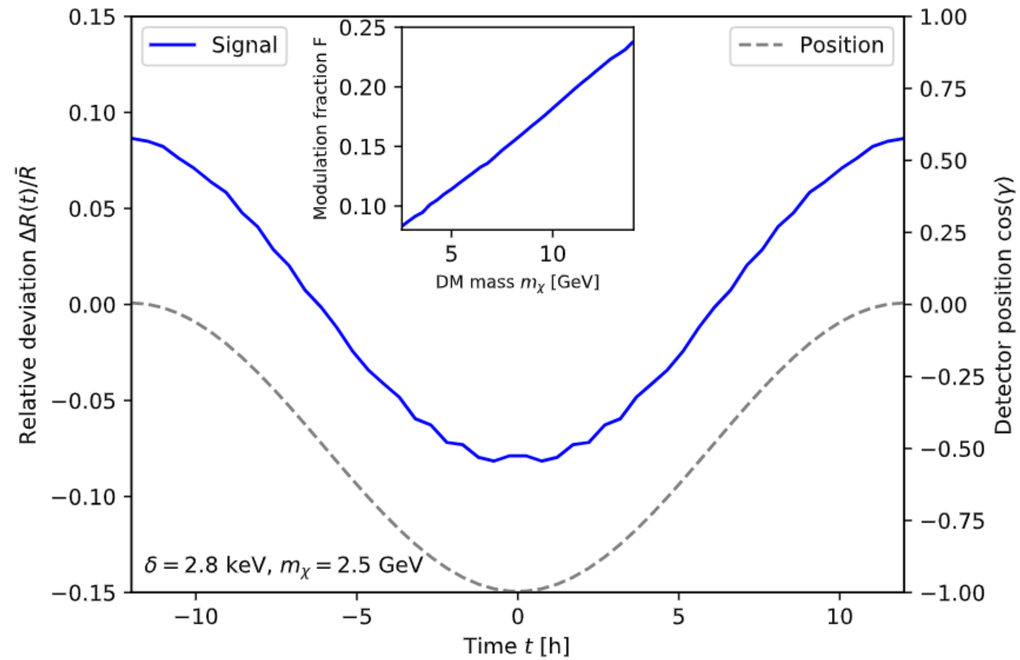
Excited states from terrestrial upscattering

- **Alternative possibility:** Upscattering occurs as DM particles pass through the Earth
  - → Only plausible origin of excited states for $\tau < 10^5$ s
  - → Works best for light DM with masses in the range 2-5 GeV

Timon Emken, Jonas Frerick, Saniya Heeba & FK, arXiv:2112.XXXXX

- **Exciting prediction:** Flux of excited states depends on the orientation of the position of the detector relative to the motion of the sun





- → Daily modulation of event rate at the level of 10-20%
- → Testable in future experiments (if excess confirmed)

Conclusions

- Huge variety of models for sub-GeV dark matter
- New mediators allow for reproducing observed relic abundance via freeze-out
- Constraints require annihilation rate with non-standard velocity dependence

- **Resonant dark matter**
  - s-channel resonance makes it possible to obtain correct relic density with tiny couplings
  - Promising strategy: Fixed-target experiments and searches for DM-electron scattering

- **Forbidden dark matter**
  - Confining dark sector allows for annihilation processes involving several dark sector states
  - Promising strategy: Search for displaced vertices at (electron-positron or hadron) colliders

- **Inelastic dark matter**
  - Interactions of DM require upscattering into an excited state with slightly larger mass
  - Downscattering of metastable excited states can induce distinctive signals (XENON1T?)