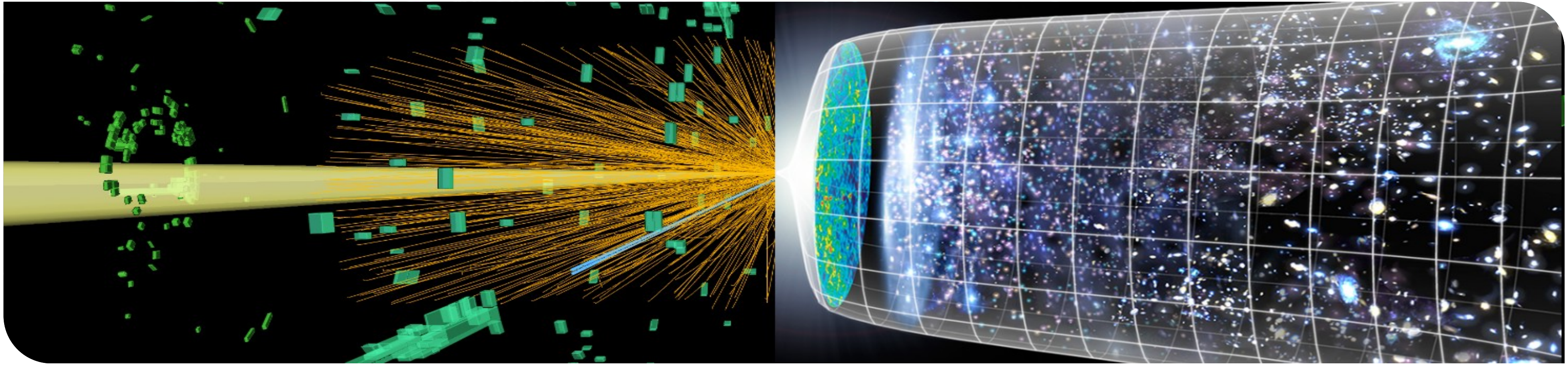
Karlsruhe Institute of Technology

Emmy Noether-Programm
DFG Deutsche Forschungsgemeinschaft

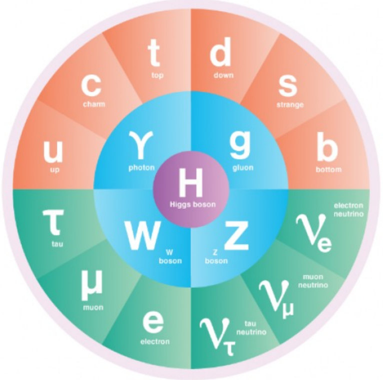
The collider cosmology connection

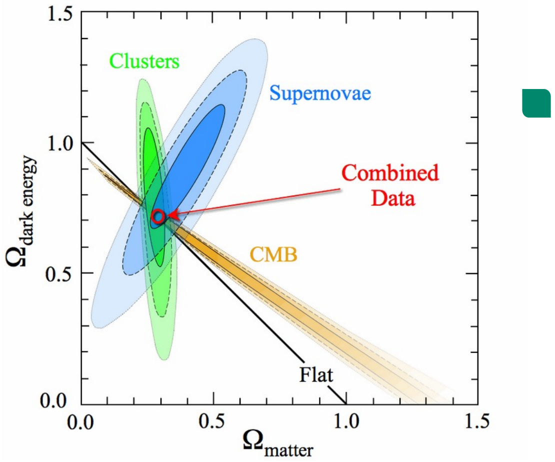
Felix Kahlhoefer
Gentner Kolloquium
Max-Planck-Institut für Kernphysik Heidelberg, 08 February 2023



Particle physics and cosmology: Two success stories

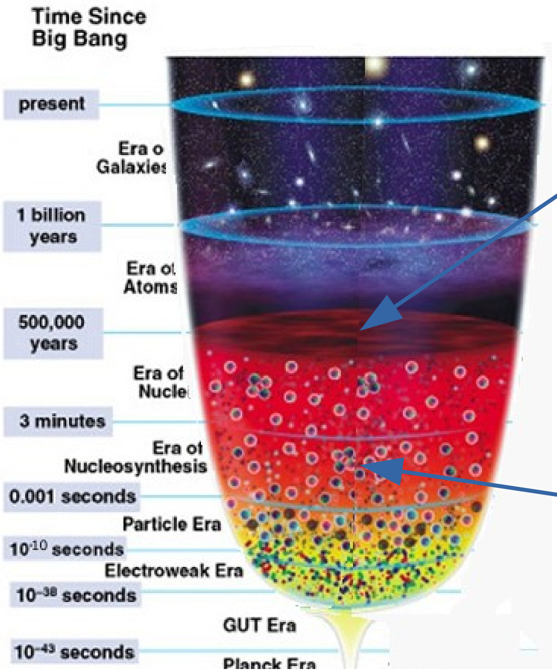
- The Standard Model successfully predicts a **wide range of measurements** at colliders and precision experiments
- The discovery of the Higgs boson at the LHC provides the **final ingredient** necessary for theoretical consistency



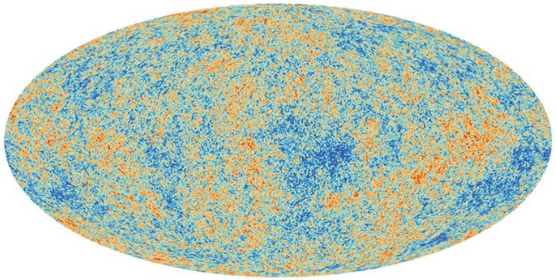


- The cosmological concordance model ΛCDM successfully fits a **huge wealth of data** in terms of only six parameters
  - Cosmic microwave background (CMB)
  - Distribution of large-scale structure
  - Expansion history of the universe

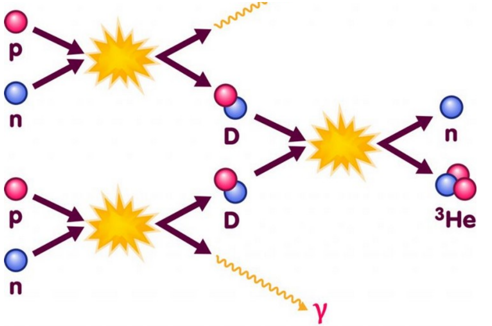
Evolution of the early universe



10^{12} – 10^{13} s after Big Bang:
Recombination
→ Formation of atoms

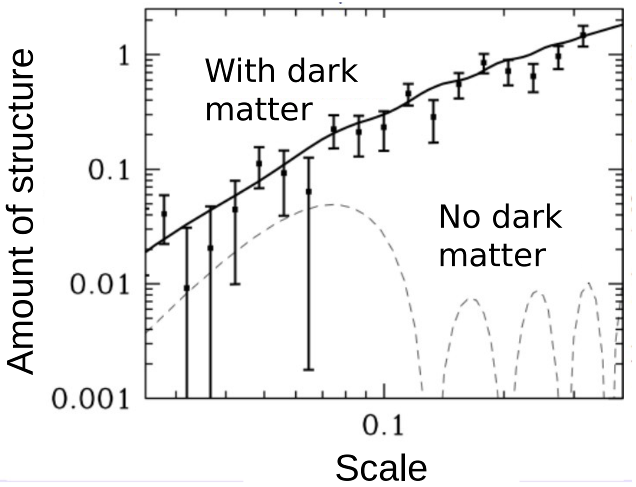


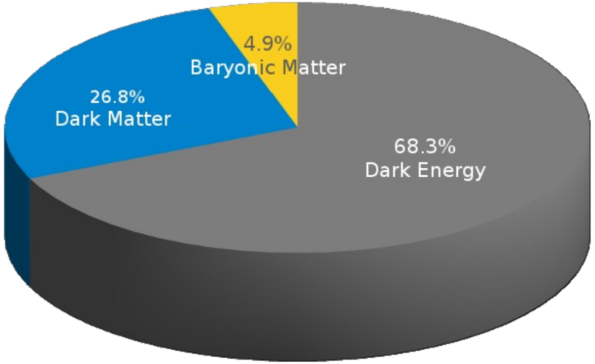
1 – 100 s after Big Bang:
Big Bang Nucleosynthesis
→ Formation of nuclei



The puzzle of dark matter

- A key ingredient of ΛCDM: **Dark matter (DM)**
  - Not affected by the high density of energetic photons after the Big Bang
  - Faster gravitational collapse (i.e. more efficient structure formation) than for visible matter

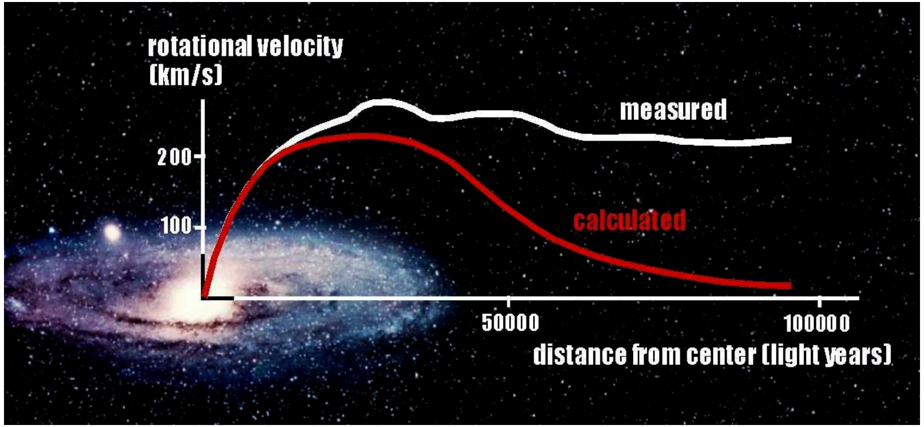




There must be about **5 times more** dark than visible matter to explain observed amounts of structure in the present universe

Astrophysical evidence for DM

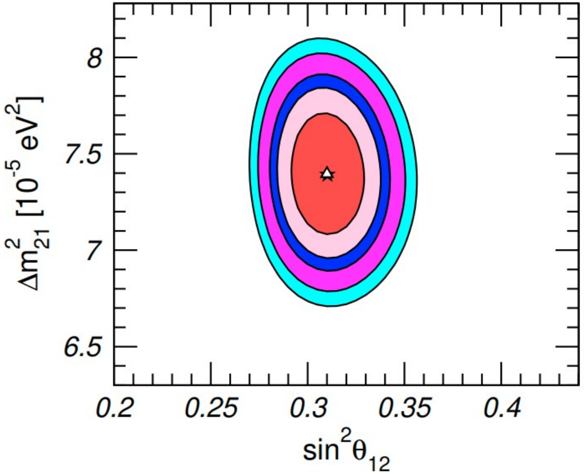
- Cosmological evidence for DM corroborated by wide range of astrophysical observations
  - Galactic rotation curves
  - Weak lensing of galaxy clusters

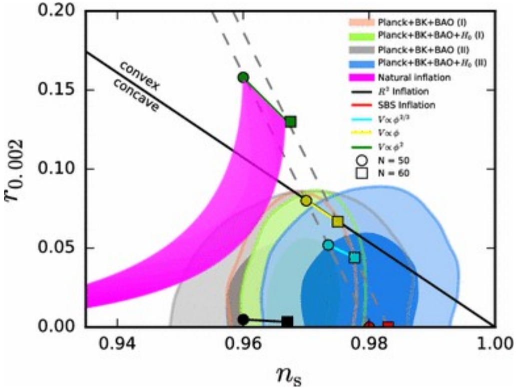


- Almost all astrophysical systems need contribution to gravitational potential from **“invisible” mass**

Particle physics and cosmology: Successes or shortcomings?

- The Standard Model works **almost too well**
  - No evidence for BSM Physics that would provide deeper understanding of the SM parameters
  - No viable explanation for dark matter, neutrino masses and the baryon asymmetry of the universe





- ΛCDM works **almost too well**
  - All data consistent with DM being a perfect fluid without pressure or friction and conserved (comoving) energy density
  - No evidence for deviations from ΛCDM that would provide clues regarding the nature of DM, dark energy or inflation

Particle physics and cosmology: Profound connections

- The past two decades have revealed profound connections between the **largest** and **smallest** scales in nature
- Cosmological observables are sensitive to the properties of elementary particles
  - Neutron lifetime and nuclear reaction rates affect the primordial abundances of light elements, which in turn affect the physics of recombination
  - The expansion rate of the universe is highly sensitive to the effective number of active neutrinos and confirms the Standard Model prediction
  - Cosmology places strong bounds on the sum of neutrino masses

- **Expect similar connections** also for the case of dark matter

DM beyond the simplest assumptions

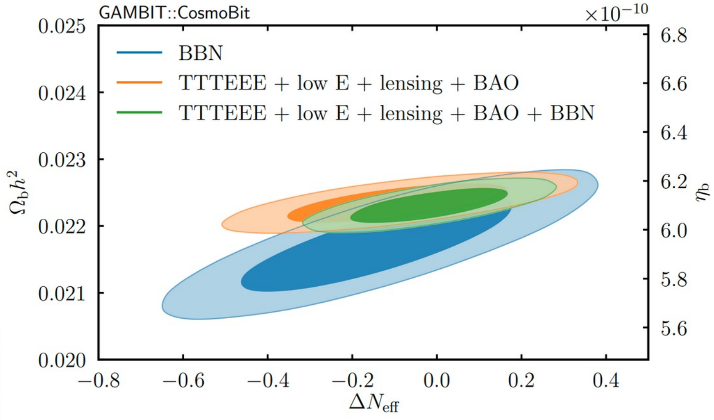
- Any particle physics model of DM predicts **deviations from ΛCDM** predictions
  - DM particles can be produced or destroyed (via annihilation or decay)
  - DM particles have non-negligible kinetic energy
  - DM particles experience self-scattering or dissipation
  - DM particles have non-gravitational interactions with other particle species
  - Macroscopic quantum effects (Pauli exclusion, de Broglie wavelength)
- **Key challenge:** Need to correlate cosmological observations with bounds from laboratory experiments

Example 1: Relativistic degrees of freedom

- **Expansion rate** of universe depends on **total energy density** of all particles and fields
- Important contribution: Energy density of Standard Model neutrinos
  - Parametrised by the effective number of relativistic particles N_eff
  - Standard Model prediction: $N_\mathrm{eff} = 3$
    (more precisely 3.045 due to non-zero interactions)
  - Deviation from this prediction (called ΔN_eff) strongly constrained by combination of cosmological observables

Current bound: $|\Delta N_\mathrm{eff}| < 0.3$ (95% CL)

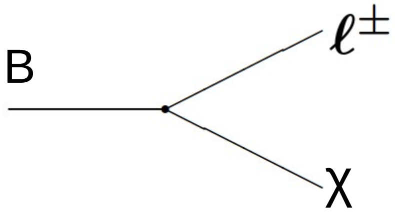
Sensitivity projection: $|\Delta N_\mathrm{eff}| < 0.06$ (CMB-S4)



Non-thermal dark radiation

- Contributions to ΔN_{eff} arise from any type of (nearly) massless particles

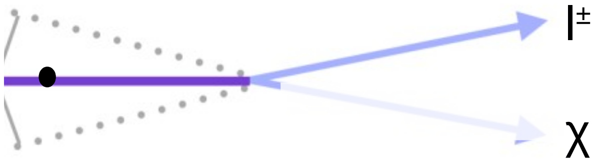
- **Simple toy model:** Consider a new particle *B* that decays into a lepton and a very light fermion χ



- Energy density of χ depends on lifetime τ_B of *B* compared to the age of the universe, given by the inverse Hubble expansion rate: $\tau_U \sim 1/H(T)$
  - For $\tau_B < \tau_U$ the decays are *fast*: → χ enters into thermal equilibrium → $\Delta N_{\mathrm{eff}} \sim 1$
  - For $\tau_B > \tau_U$ the decays are *slow*: → χ remains non-thermal → $\Delta N_{\mathrm{eff}} << 1$

Particle physics – cosmology connections

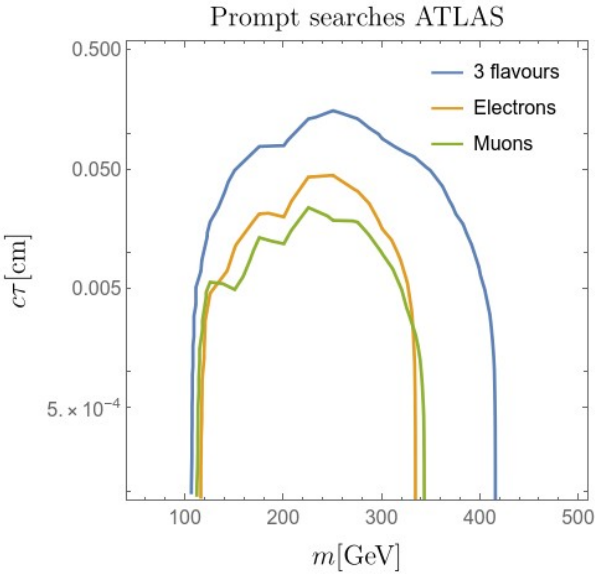
- During radiation domination, age of the universe is given by $\tau_U \sim M_P / T^2$
- For **$T = 250$ GeV** find **$\tau_U \sim 4 \times 10^{-12}$ s**
- The requirement of non-thermal dark radiation implies **$c\tau_B > c\tau_U \sim 1$mm**
- If the particle *B* can be produced at the LHC, it will travel a typical distance $l_B = \beta\gamma c\tau_B$ before decaying
- Lepton track has non-zero transverse impact parameter d_0 (i.e. track does not point back to interaction point)
- If d_0 is larger than vertex resolution ($\sigma \sim 0.1$mm), events will be rejected by cuts on vertex quality



Very slightly displaced leptons

- Reinterpretation of LHC SUSY searches for slepton pair production

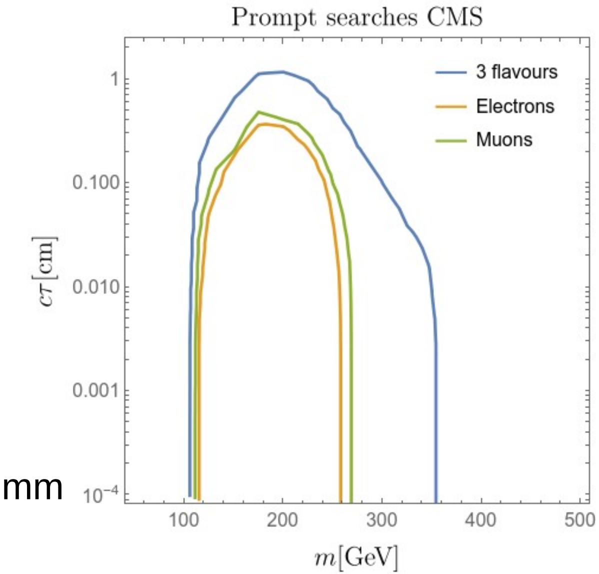
Bernreuther, FK et al., arXiv:2204.01759



Electrons: $d_0 < 0.1$ mm

Muons: $d_0 < 0.06$ mm

Electrons/muons: $d_0 < 0.5$ mm

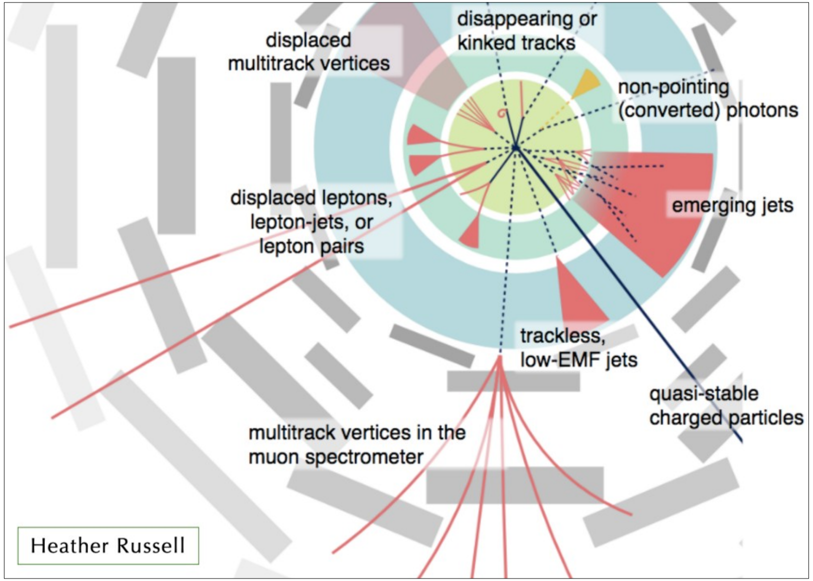


LHC searches for long-lived particles

- Loss of sensitivity for conventional searches compensated by broad experimental search programme for specific signatures of long-lived particles

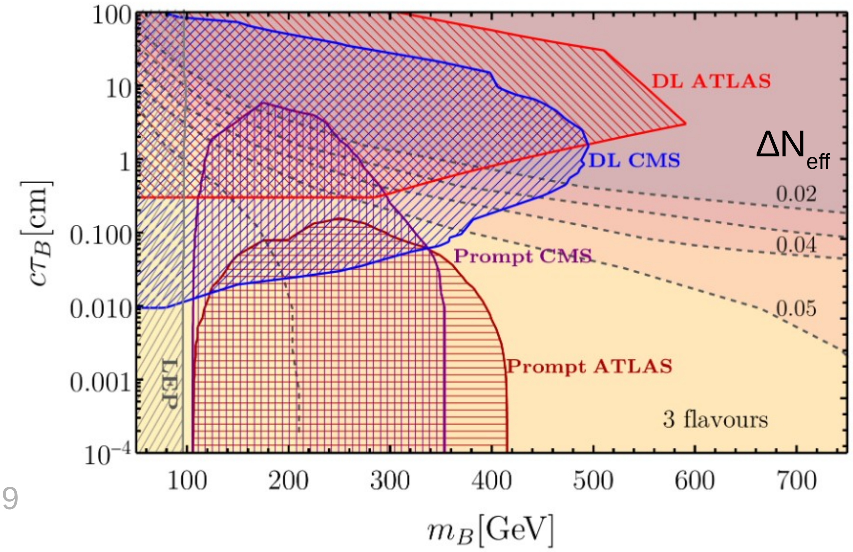
- Of interest here: Searches for displaced leptons
  - ATLAS: $3 \text{ mm} < d_0 < 300 \text{ mm}$
  - CMS: $0.1 \text{ mm} < d_0 < 100 \text{ mm}$

- Assume *B* has SM gauge interactions
  → Production cross section depends only on m_B
  → Constraints can be directly translated



LHC searches for dark radiation

- The same parameters that determine the LHC constraints also govern the production of dark radiation in the early universe
- Possible to predict ΔN_eff in terms of $c\tau_B$ and m_B
- Correlation between LHC constraints and cosmological observations
- Can constrain the most interesting parameter regions for future CMB missions



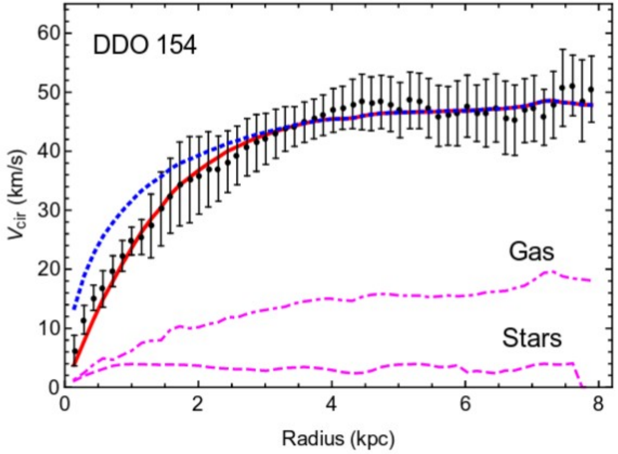
Bernreuther, FK et al., arXiv:2204.01759

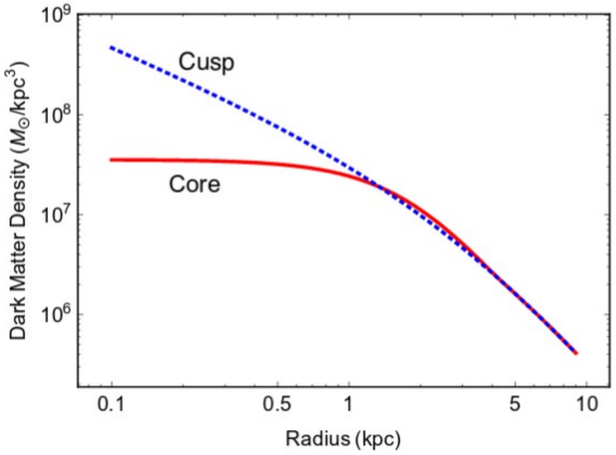
Example 2: Dark matter self-interactions

- In the ΛCDM model, DM particles are assumed to be perfectly collisionless
- However, for almost any particle physics model of DM this approximation is predicted to break down at some point
- Indeed, with the exception of neutrinos all fermions in the Standard Model experience large self-interactions (either through long-range interactions or through the strong force)
- As new (and more precise) observations become available, we can expect that deviations from the simplest predictions emerge
- These deviations may tell us something about the kinds of DM models that we should search for in the laboratory

The cusp-core problem

- There are various observations that favour DM halos with constant-density cores, in apparent disagreement with the predictions of collisionless cold DM





Tulin & Yu: arXiv:1705.02358

- DM self-interactions may potentially resolve this discrepancy

Spergel & Steinhard: astro-ph/990938

Back-of-the-envelope estimate

- We can estimate the required cross section through simple dimensional arguments

- Consider a Milky Way-like galaxy: mass $M \sim 10^{12}\,M_{\mathrm{sun}}$
  radius $r \sim 100$ kpc
  → Surface density $\Sigma \sim M/r^2 \sim 10^8\,M_{\mathrm{sun}}/\mathrm{kpc}^2 \sim 2\ \mathrm{g}/\mathrm{cm}^2$

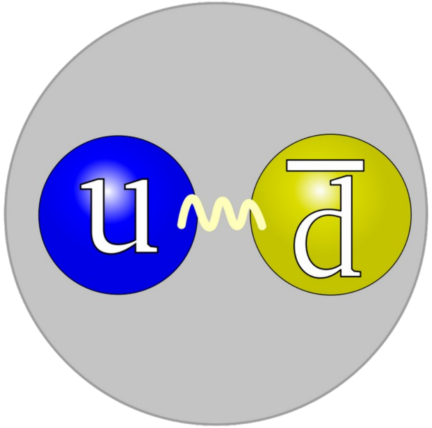
- Self-interactions will be important if the cross section σ satisfies $\Sigma\,\sigma / m_{\mathrm{DM}} > 1$
  → $\sigma / m_{\mathrm{DM}} > 0.5\ \mathrm{cm}^2/\mathrm{g} \sim 1\ \mathrm{barn}/\mathrm{GeV} \sim \Lambda_{\mathrm{QCD}}^{-3}$

- Similar to nucleon-nucleon scattering cross section!

Strongly-interacting dark sectors

- This surprising result compels us to think about dark matter particles with interactions similar to QCD
- Consider a dark sector that **contains dark gluons and dark quarks:**

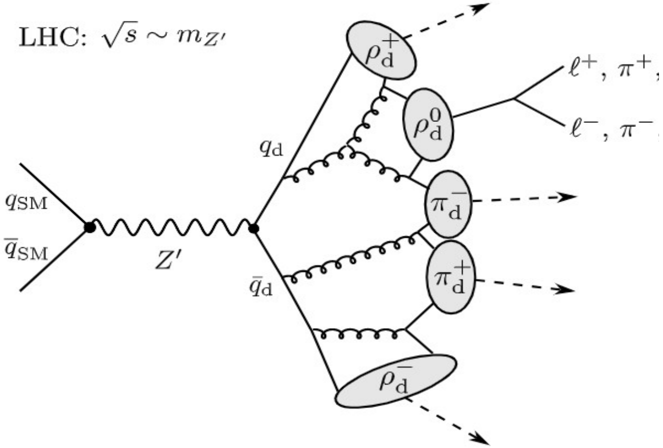
$$\mathcal{L} = -\frac{1}{4} F^a_{\mu\nu} F^{\mu\nu a} + \overline{q}_\mathrm{d} i \not{D} q_\mathrm{d} - \overline{q}_\mathrm{d} M_q q_\mathrm{d}$$



- For energies below some scale Λ_d the dark sector **confines**, giving rise to dark mesons and dark baryons
- In contrast to the SM, it is possible that the lightest dark mesons (i.e. the dark pions) are stable and possible DM candidates

Dark showers

- Assume that dark quarks also couple to SM particles (details irrelevant here)
  - → Possible to pair-produce dark quarks at the LHC
  - → Dark quarks will undergo fragmentation and hadronisation in the dark sector
  - → Result: Dark shower with high multiplicity of dark mesons

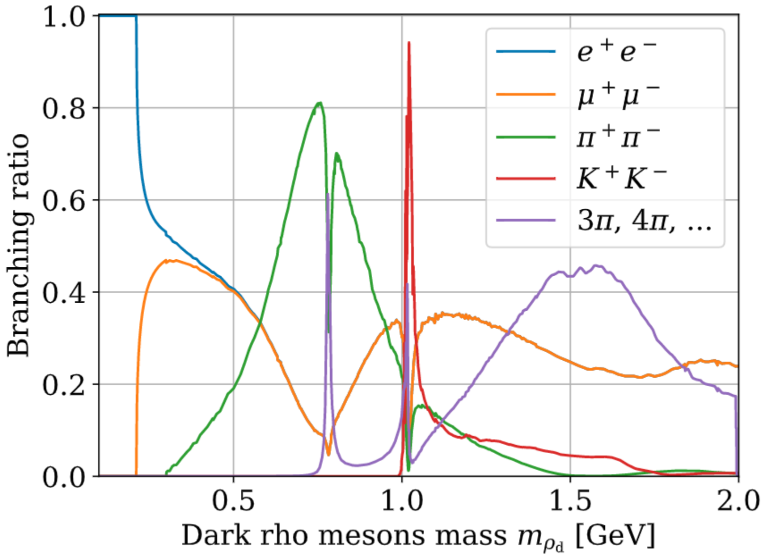


- Dark pions are stable, but other mesons may decay
- Of particular interest: Dark rho mesons
- For $m_\pi > m_\rho/2$ invisible decays are kinematically forbidden, so dark rho mesons decay into SM particles

Displaced vertices from dark showers

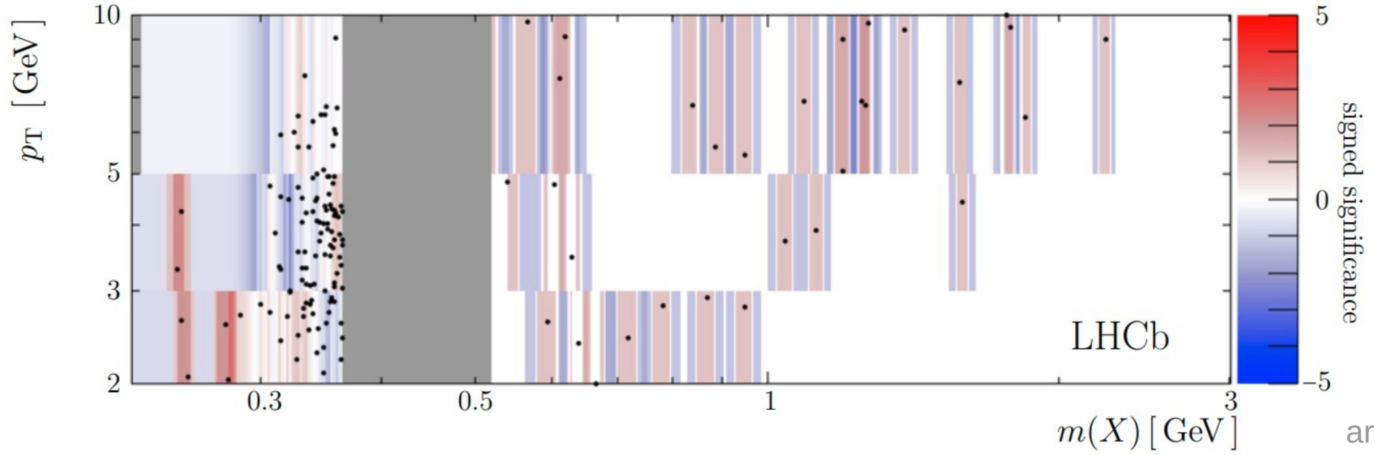
- GeV-scale dark rho meson predicted to decay dominantly into pairs of charged particles
- If the dark rho mesons decay promptly, the dark shower results in a semi-visible jet
- Difficult to distinguish from ordinary QCD jets
- But if the dark rho mesons are long-lived, we can hope to reconstruct individual displaced vertices

→ Striking signature very different from SM



Displaced vertex search at LHCb

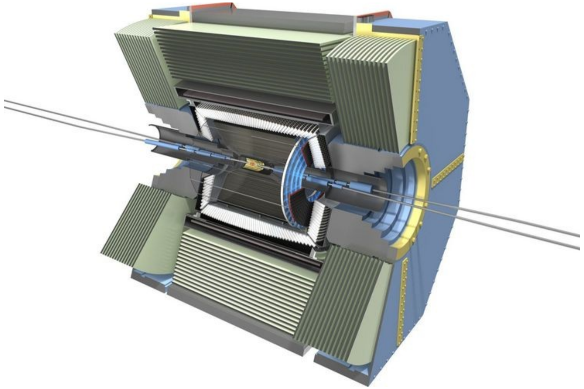
- LHCb has searched for GeV-scale LLPs decaying into a pair of muons
  - Requirement: Transverse displacement 12–30 mm
  - Veto invariant mass close to K meson mass
  - Present model-independent results in different p_T bins

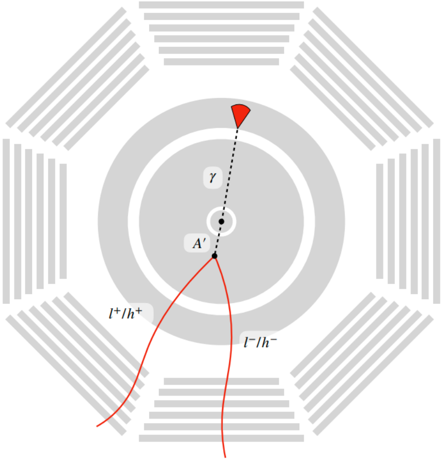


arXiv:2007.03923

What about Belle II?

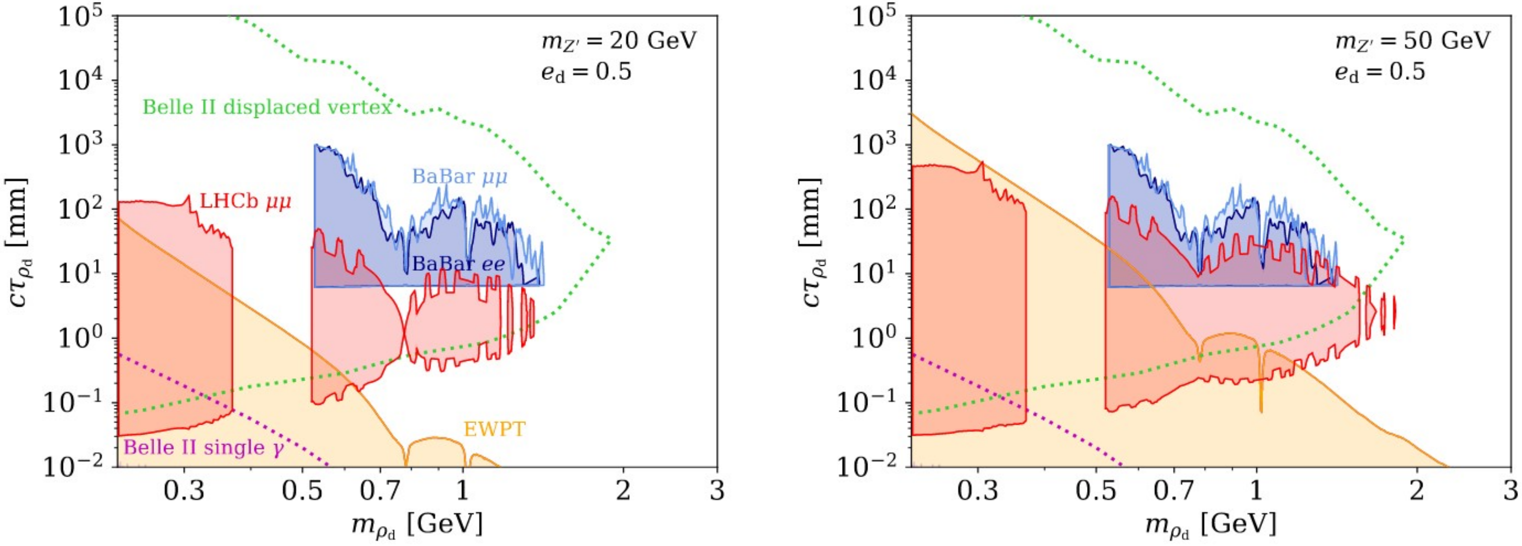
- Since 2020 Belle II is using e^+e^- collisions at $\sqrt{s} \sim 10.6$ GeV to compete with LHCb for the most precise measurements of B mesons





- The Belle II detectors are highly suited to search also for DVs from exotic LLPs
- Transverse distance of DV can be as large as 60cm
- Smaller energies ↔ smaller boost factors
- Expect sensitivity to much larger lifetimes

Comparison of sensitivities



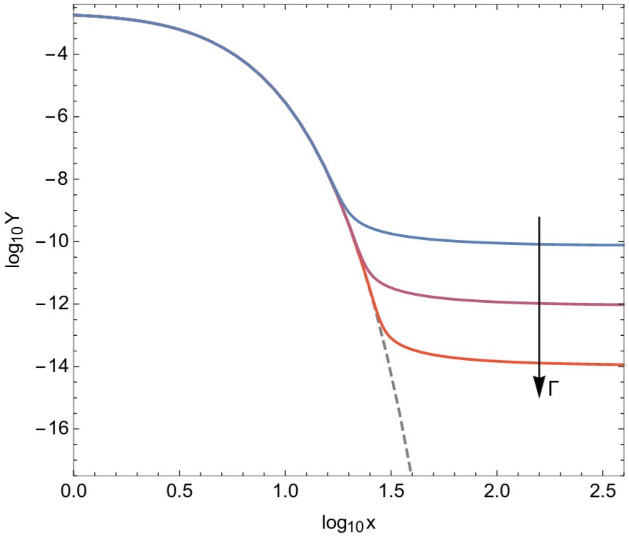
Bernreuther, FK et al.,
arXiv:2203.08824

- Mass reach of LHCb and Belle II comparable, but Belle II sensitive to larger decay lengths
- Note: LHCb constraint depends on details of interaction between SM and dark sector

Example 3: Dark matter relic abundance

- In many models, the DM abundance can be calculated in terms of fundamental parameters

- Simple example: **Thermal freeze-out**
  - DM production and annihilation processes are in equilibrium in early universe
  - As universe cools down, DM particles depart from equilibrium (freeze-out)
  - DM abundance set by freeze-out temperature



WIMP mechanism

- The contribution of DM to the energy density of the present universe can be estimated as

  $\Omega \sim (c\tau_U)^2\,(T_{CMB}/M_{Pl})^3 <\sigma v>^{-1}$

  with

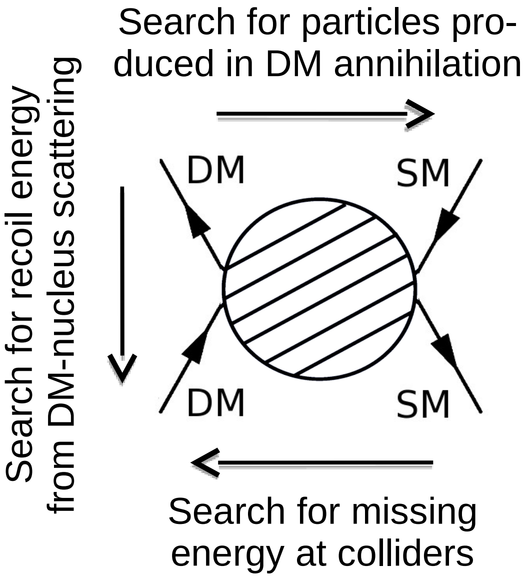
with	$c\tau_U \sim 10^{26}$ m:	present size of the observable universe
	$T_{CMB} \sim 2.7$K:	present-day CMB temperature
	$<\sigma v>$:	effective annihilation cross section

- Find $\Omega \sim 25\%$ for $<\sigma v> \sim 10^{-9}\ \text{GeV}^{-2} \sim \alpha^2 / v_{EW}^2$

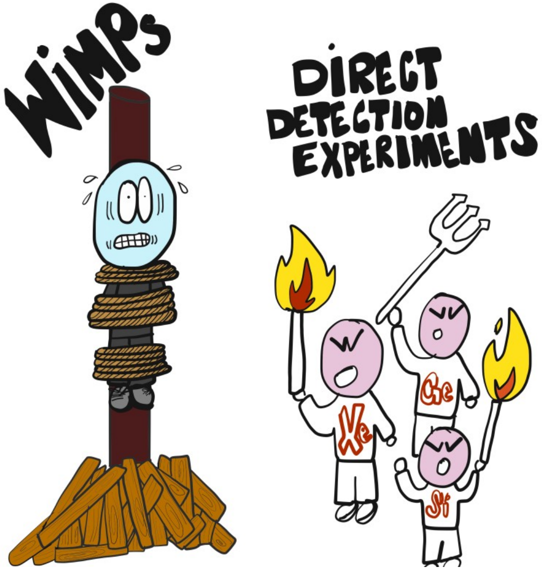
- Observations reproduced for particles with weak interactions and mass close to the electroweak scale

“WIMP mechanism”

Where **I**s **M**y **P**article?



- The **same processes** that set the DM relic abundance should also be **observable in laboratory** experiments
- **Lack of evidence** for WIMP signals at direct detection experiments and colliders **puts pressure** on this idea
- Is the WIMP mechanism still viable?



By Saniya Heeba

Particle physics and cosmology: It’s complicated

- Joint analyses of particle physics and cosmology face many challenges
- **Challenge 1:** Theory predictions
    - Need mapping from fundamental particle theory to effective cosmological description
    - Need wide range of different numerical tools to calculate signal predictions

DarkSUSY
MicrOMEGAs
Monte Python
MADGRAPH5 aMC@NLO
ACROPOLIS
DDCalc
CHECKMATE
CLASS
AlterBBN
DirectDM
vevacious

Particle physics and cosmology: It’s complicated

- Joint analyses of particle physics and cosmology face many challenges
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  - Need wide range of different numerical tools to calculate signal predictions
- **Challenge 2:** Wealth of data
  - Need to consider huge number of measurements across many different experiments
  - Need simplified likelihoods to allow for flexible reinterpretation

$$\mathcal{L} = \mathcal{L}_{\mathrm{LHC}} \cdot \mathcal{L}_{\Omega h^2} \cdot \mathcal{L}_{\mathrm{DM}} \cdots$$

Particle physics and cosmology: It’s complicated

- Joint analyses of particle physics and cosmology face many challenges
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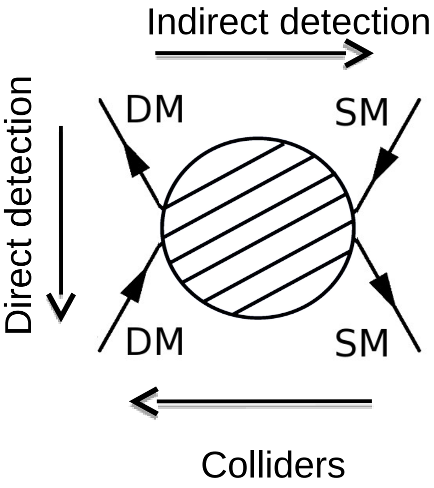
- **Challenge 2:** Wealth of data
  - Need to consider huge number of measurements across many different experiments
  - Need simplified likelihoods to allow for flexible reinterpretation
- **Challenge 3:** Analysis methods
  - Need advanced sampling methods (grid or random scans inefficient in high dimension)
  - Need consistent statistical framework to answer underlying questions

GAMBIT
The Global And Modular BSM Inference Tool

- **International community** with 50+ collaborators (10+ experiments, 10+ theory codes)
- A **software framework** for global fits developed over the past decade
  - Automated construction of composite likelihoods
  - Efficient scans of multi-dimensional parameter space
  - Consistent treatment of nuisance parameters
  - Maximum of flexibility and modularity in terms of data sets and models
  - Optimized for parallel computing & fully open source

So what about WIMPs?

- **Model-independent approach:** Use effective description of interactions between WIMPs and SM particles



$$\mathcal{L}_{\text{int}} = \sum_{a,d} \frac{\mathcal{C}_a^{(d)}}{\Lambda^{d-4}} \mathcal{Q}_a^{(d)}$$

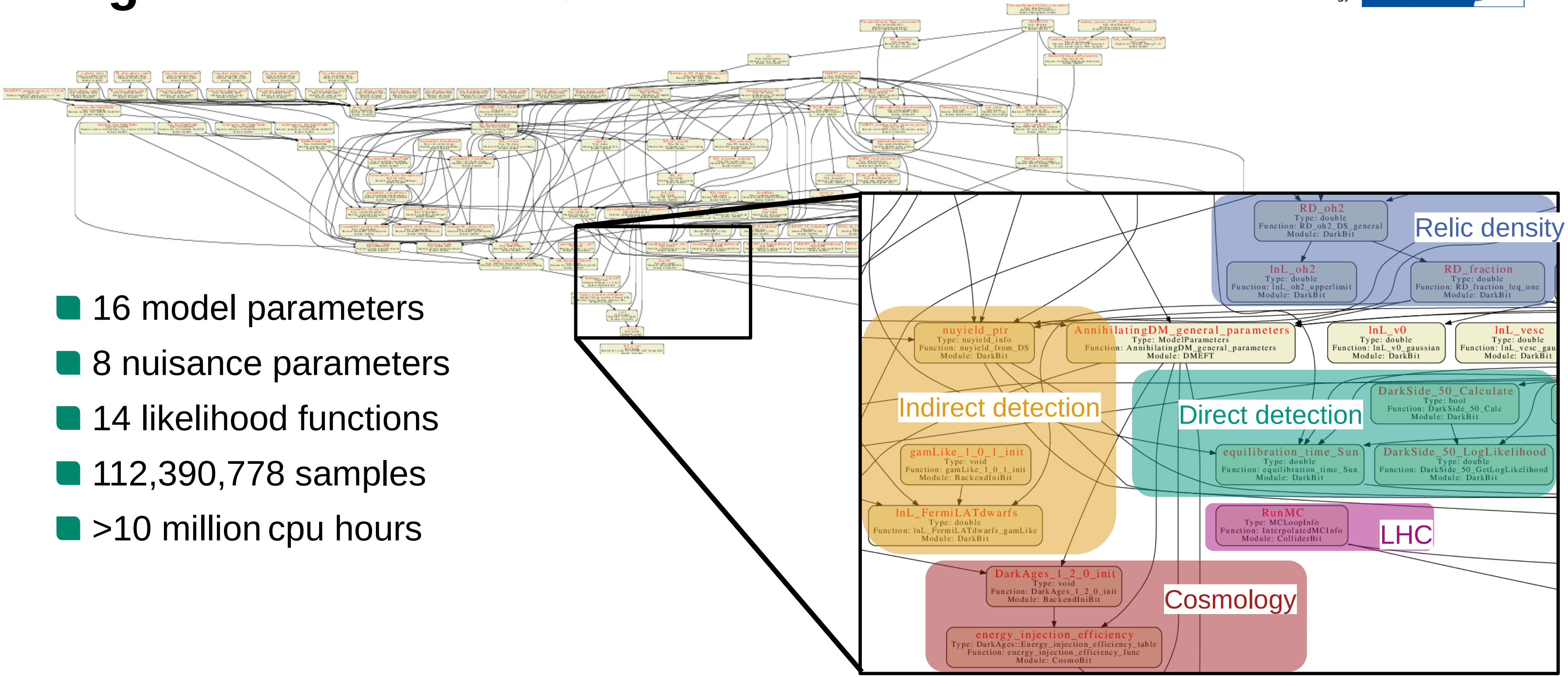
Dimension 6

$$\mathcal{Q}_{1,q}^{(6)} = (\overline{\chi}\gamma_\mu\chi)(\overline{q}\gamma^\mu q)\,,$$
$$\mathcal{Q}_{2,q}^{(6)} = (\overline{\chi}\gamma_\mu\gamma_5\chi)(\overline{q}\gamma^\mu q)\,,$$
$$\mathcal{Q}_{3,q}^{(6)} = (\overline{\chi}\gamma_\mu\chi)(\overline{q}\gamma^\mu\gamma_5 q)\,,$$
$$\mathcal{Q}_{4,q}^{(6)} = (\overline{\chi}\gamma_\mu\gamma_5\chi)(\overline{q}\gamma^\mu\gamma_5 q)\,.$$

Dimension 7

$$\mathcal{Q}_1^{(7)} = \frac{\alpha_s}{12\pi}(\overline{\chi}\chi)G^{a\mu\nu}G^a_{\mu\nu}\,,$$
$$\mathcal{Q}_2^{(7)} = \frac{\alpha_s}{12\pi}(\overline{\chi}i\gamma_5\chi)G^{a\mu\nu}G^a_{\mu\nu}\,,$$
$$\mathcal{Q}_3^{(7)} = \frac{\alpha_s}{8\pi}(\overline{\chi}\chi)G^{a\mu\nu}\widetilde{G}^a_{\mu\nu}\,,$$
$$\mathcal{Q}_4^{(7)} = \frac{\alpha_s}{8\pi}(\overline{\chi}i\gamma_5\chi)G^{a\mu\nu}\widetilde{G}^a_{\mu\nu}\,,$$
$$\mathcal{Q}_{5,q}^{(7)} = m_q(\overline{\chi}\chi)(\overline{q}q)\,,$$
$$\mathcal{Q}_{6,q}^{(7)} = m_q(\overline{\chi}i\gamma_5\chi)(\overline{q}q)\,,$$
$$\mathcal{Q}_{7,q}^{(7)} = m_q(\overline{\chi}\chi)(\overline{q}i\gamma_5 q)\,,$$
$$\mathcal{Q}_{8,q}^{(7)} = m_q(\overline{\chi}i\gamma_5\chi)(\overline{q}i\gamma_5 q)\,,$$
$$\mathcal{Q}_{9,q}^{(7)} = m_q(\overline{\chi}\sigma^{\mu\nu}\chi)(\overline{q}\sigma_{\mu\nu}q)\,,$$
$$\mathcal{Q}_{10,q}^{(7)} = m_q(\overline{\chi}i\sigma^{\mu\nu}\gamma_5\chi)(\overline{q}\sigma_{\mu\nu}q)\,.$$

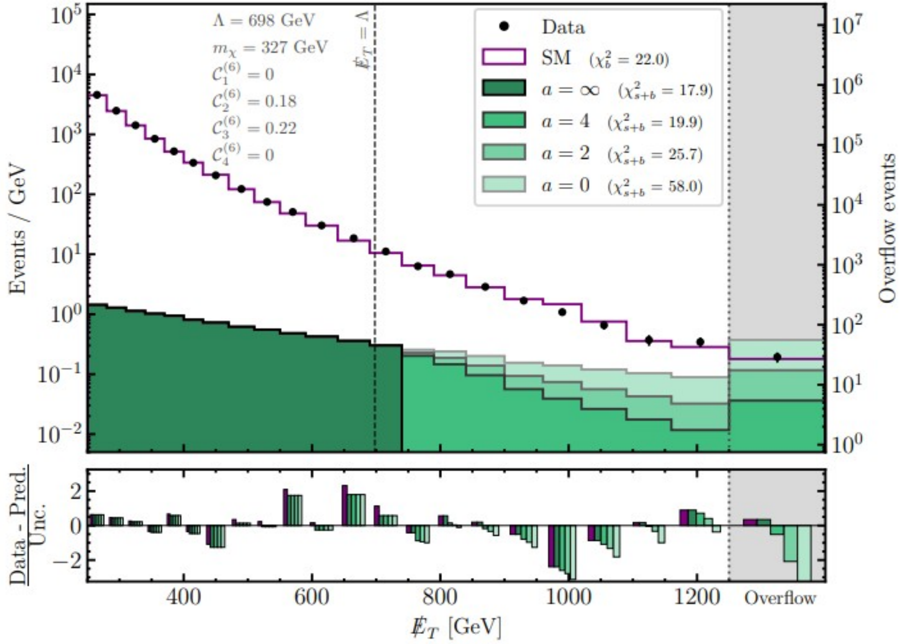
A global fit of WIMPs



- 16 model parameters
- 8 nuisance parameters
- 14 likelihood functions
- 112,390,778 samples
- >10 million cpu hours

Role of the LHC

- Leading LHC constraints come from searches for jets + missing energy (MET)
- DM signal leads to harder spectrum than SM background
- Expect EFT to break down for MET > Λ
- Nuisance parameter a governs resulting suppression of MET spectrum
- Many different correlated signal regions
- Publicly available information makes reinterpretation possible



Athron, FK et al., arXiv:2106.02056

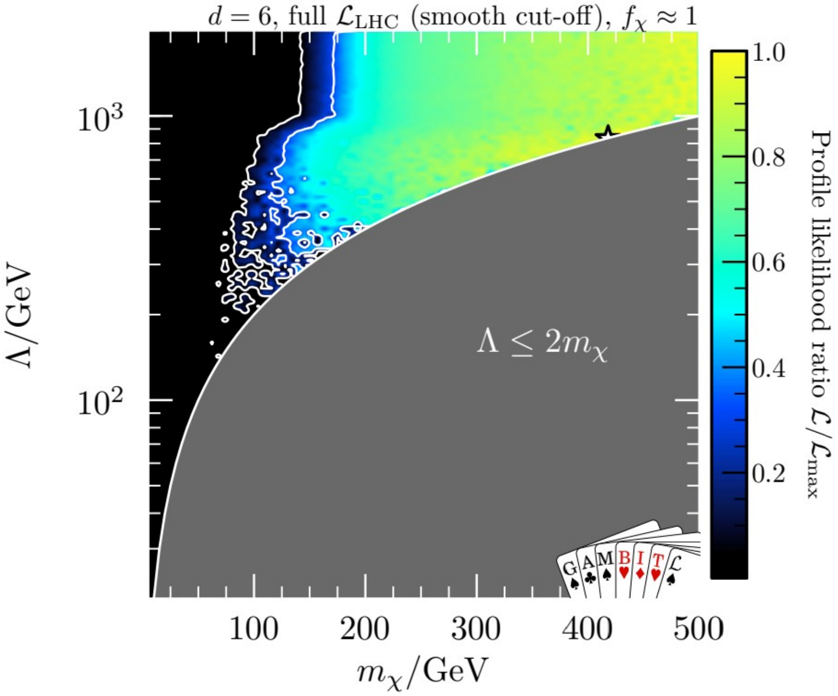
Main results

- Grey: Effective description invalid
- Black: Excluded experimentally
- Colour: Viable parameter space

- **Lower bound** on the WIMP mass:

  $m_{\text{WIMP}} > 100$ GeV

- Best-fit point requires contribution from at least two different effective operators to satisfy all constraints

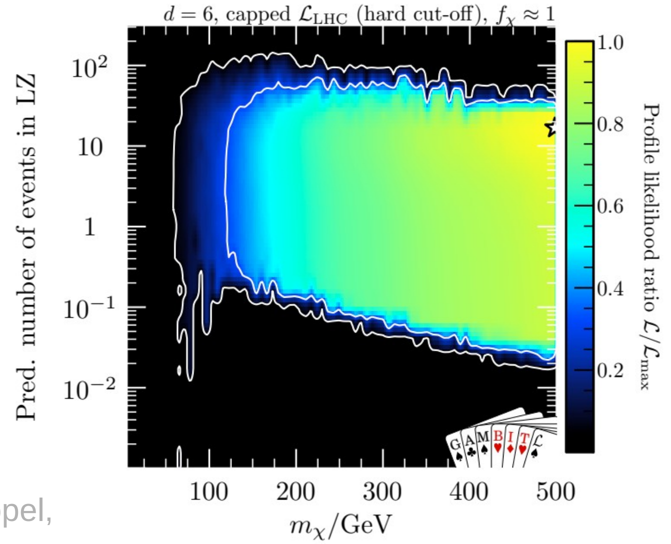


Athron, FK et al., arXiv:2106.02056

Outlook

- **Interesting finding:** Viable parameter region corresponds to sizable signals in near-future direct detection experiments (like XENONnT)

Athron, FK et al., arXiv:2106.02056



- **Ongoing work:** Consider also likelihood from AMS-02 anti-proton data using neural network predictions

Balan, FK, Korsmeier, Manconi & Nippel, in preparation

- WIMP models remain viable but will soon be comprehensively probed

Conclusions

- Many deep connections between particle physics and cosmology

- Three curious coincidences:
  - $cM_{pl} / v_{EW}^2 \sim 1$ mm $\sim \sigma_{vertex}$ → Long-lived particle searches at the LHC constrain models of non-thermal dark radiation
  - $r_{gal}^2 / M_{gal} \sim 0.5$ cm^2 / g $\sim \Lambda_{QCD}^{-3}$ → Hints for DM self-interactions motivate LHC searches for strongly-interacting dark sectors
  - $(c\tau_U)^2 (T_{CMB}/M_{Pl})^3 \sim 10^{-9}$ GeV$^{-2} \sim \alpha^2 / v_{EW}^2$ → Thermal freeze-out mechanism can be tested by global analysis of searches for WIMPs at the electroweak scale