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Small-scale tensions and self-interacting dark matter

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Outline

- Part 1: Astrophysics (not my own work)
- Part 2: Collider physics (partially my own work)

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References

Small-Scale Challenges to the ΛCDM Paradigm

James S. Bullock[1] and Michael Boylan-Kolchin[2]

Dark Matter Self-interactions and Small Scale Structure

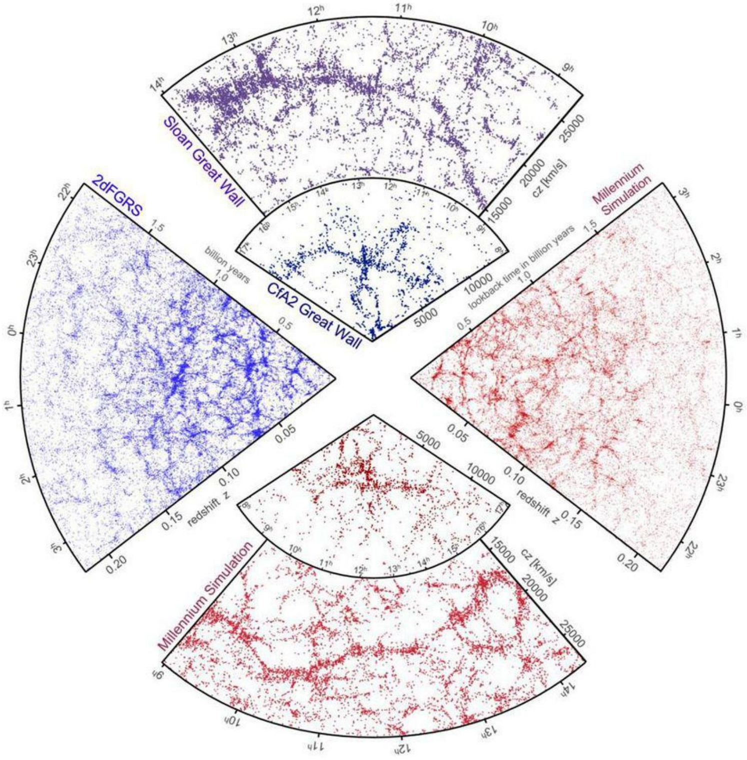
Sean Tulin[1,*] and Hai-Bo Yu[2,†]

Baryonic solutions and challenges for cosmological models of dwarf galaxies

Laura V. Sales[1,*], Andrew Wetzel[2], and Azadeh Fattahi[3]

Structure formation in the early universe

- ΛCDM is extremely successful in predicting the structure of the universe at the largest scales
- At smaller scales (comparable to the size of individual galaxies) structure formation is strongly non-linear, and baryonic effects become important
- These scales are also the most sensitive to the particle physics properties of dark matter (DM)
  - Free-streaming DM (not perfectly non-relativistic)
  - Self-interacting or dissipative DM (not collisionless)
  - Fuzzy DM (macroscopic de Broglie wavelength)
- Interesting to look for tensions and anomalies!



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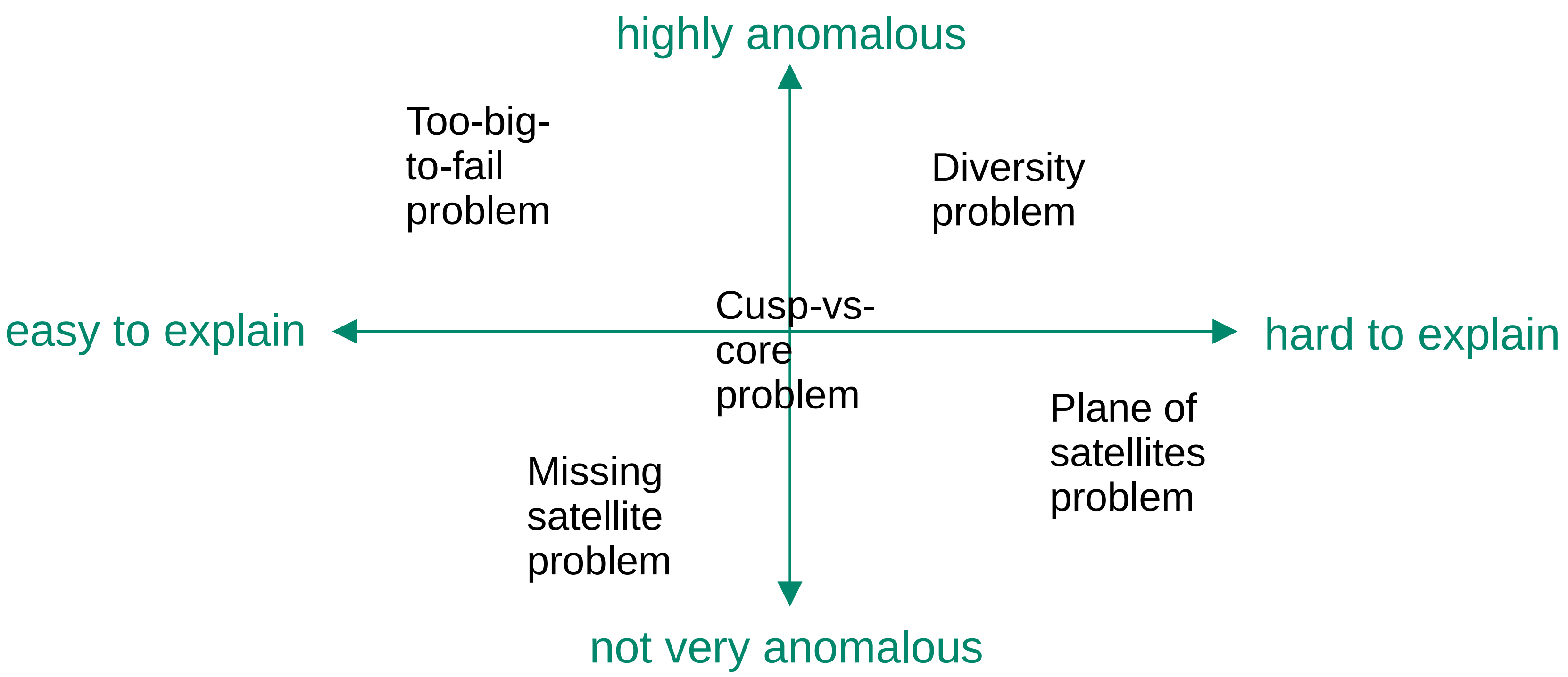
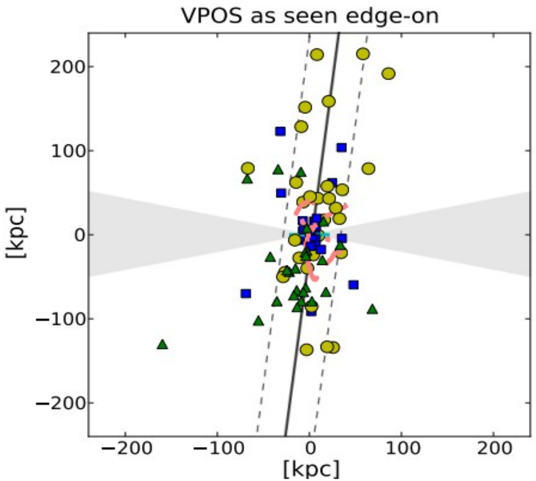
A chart of anomalies

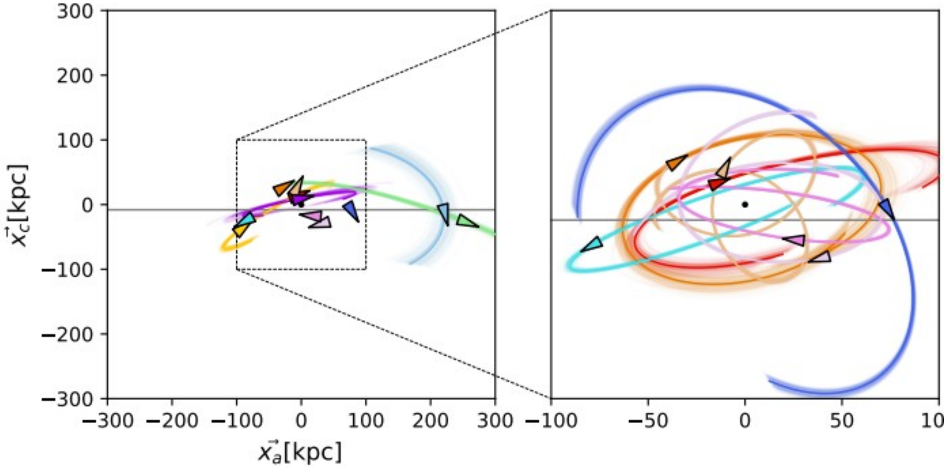


The plane of satellites problem

- The 11 brightest MW satellites appear to lie in a plane that is unlikely to arise from standard structure formation
- Data from the Gaia satellite makes it possible for the first time to infer the orbital motion of these satellites



Pawlowski et al., arXiv:1505.07465



- Conclusion: The plane of satellites is of transient nature and statistically not very unlikely

Sawala et al., arXiv:2205.02860

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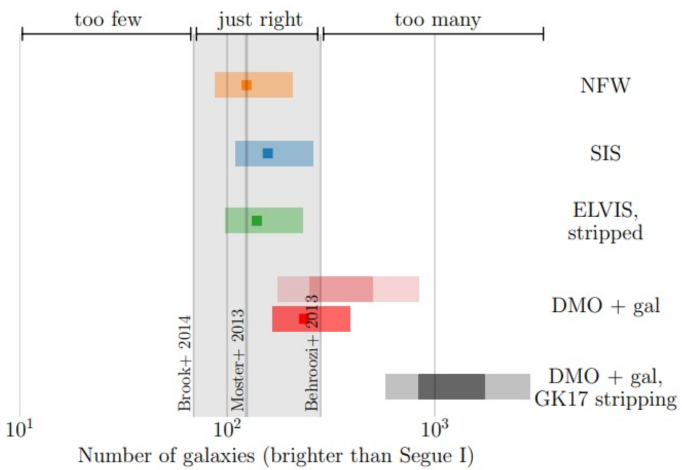
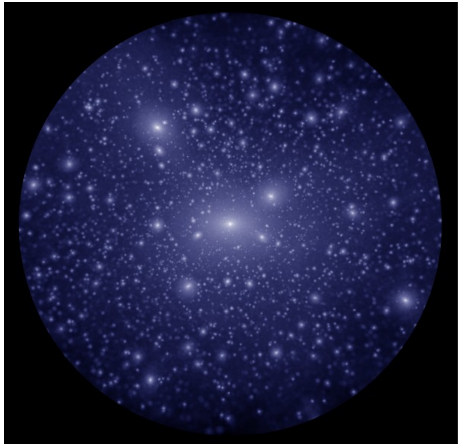
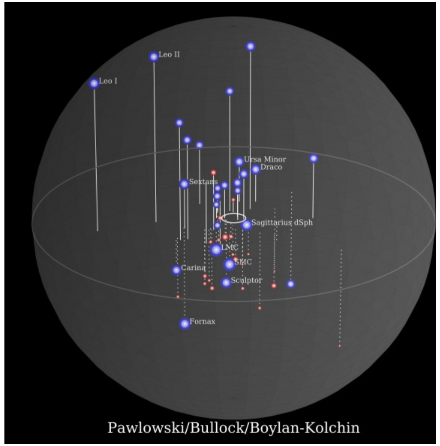
The missing satellite problem

- Where are all the Milky Way satellites seen in N-body simulations?
- Many new discoveries in recent years!







- Applying completeness correction for the detection efficiency, the missing satellite problem is likely solved

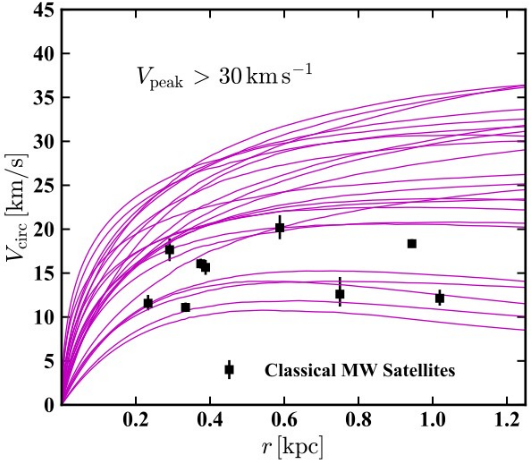
Kim et al., arXiv:1711.06267

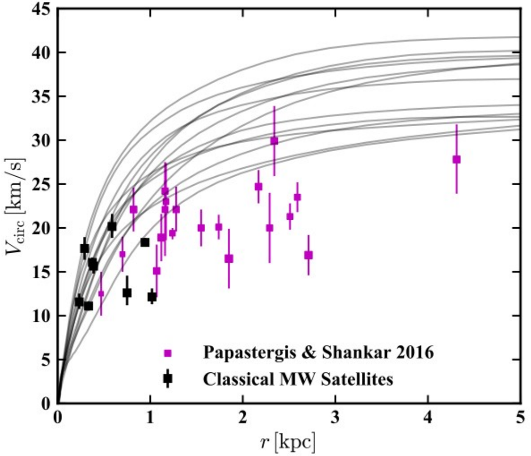
The too-big-to-fail problem

Boylan-Kolchin et al., arXiv:1111.2048

- For very massive MW satellites, detection efficiency should be close to unity, because they are guaranteed to be bright

- Nevertheless, none of the known MW satellites have a circular velocity (i.e. mass) as large as predicted by simulations





- However, these are also the systems, for which baryonic effects are most important

- Baryon-induced cores from stellar feedback reduce the central mass of these systems

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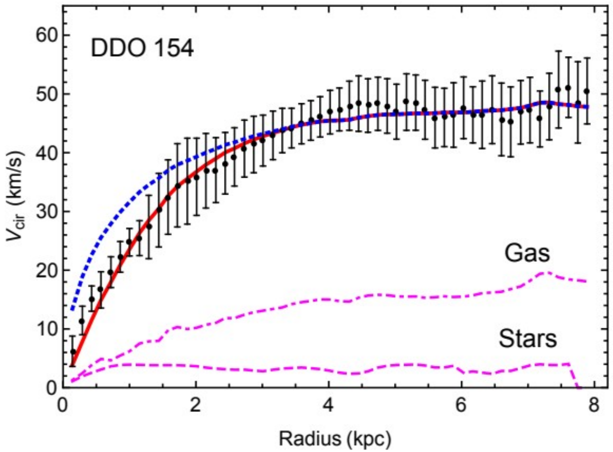
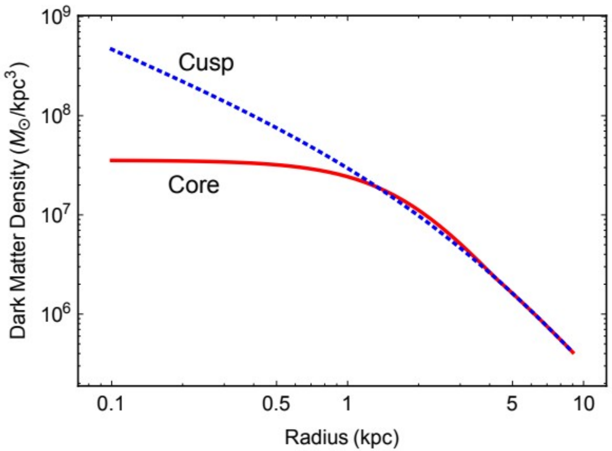
The cusp-core problem

- Discrepancy between predicted and observed circular velocities is largest in the central region
- Deficit in mass points to constant-density cores rather than cuspy density profiles

Tulin & Yu, arXiv:1705.02358





- Problem: Small baryonic effects → few stars → unreliable observations

  Reliable observations → many stars → large baryonic effects

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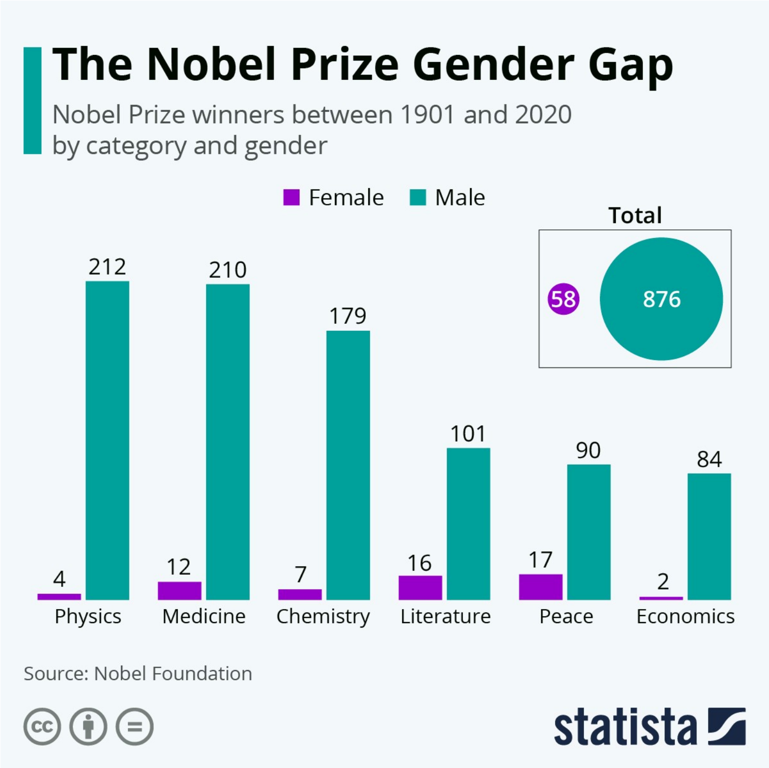
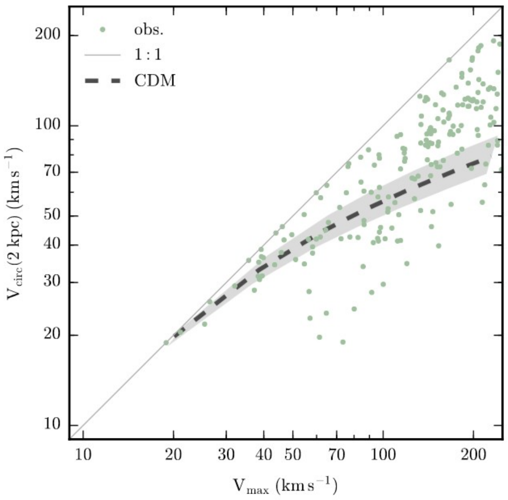
The diversity problem



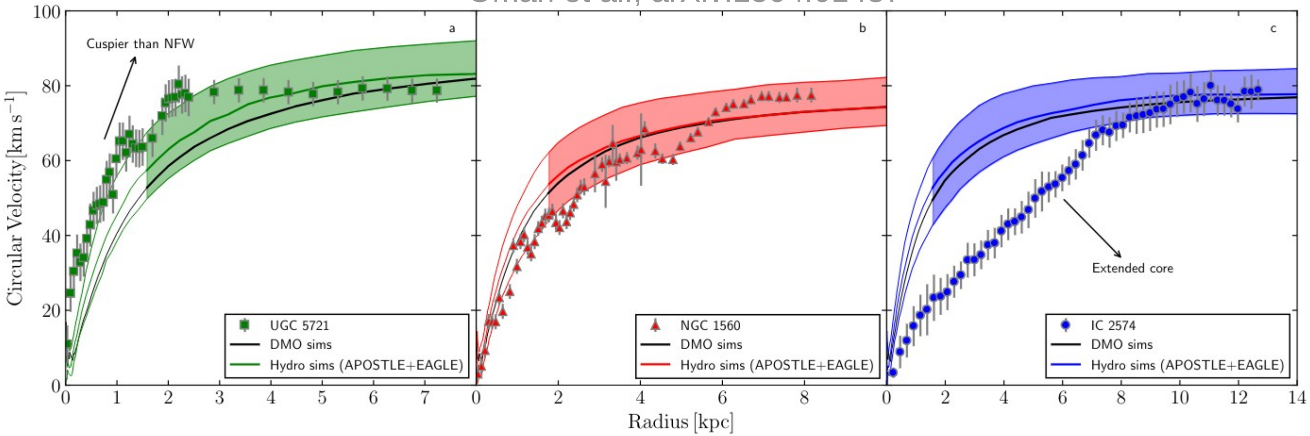
The other diversity problem

- Dwarf galaxy rotation curves exhibit much more diversity than expected

Creasey et al., arXiv:1612.03903



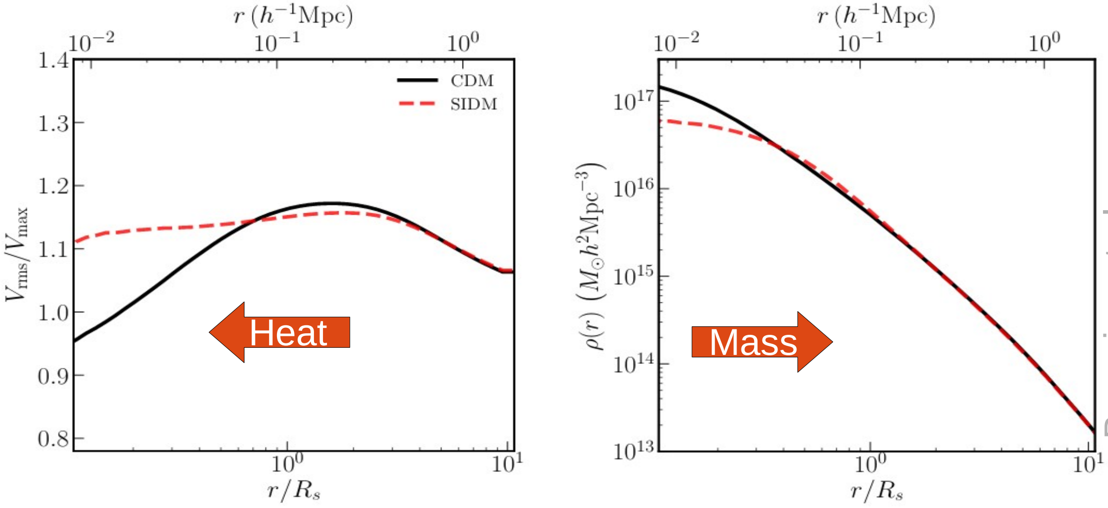
Oman et al., arXiv:1504.01437



- In fact, some dwarf galaxies are even cuspier than in ΛCDM!
- Speculated to be a projection effect due to non-circular motion
- No conclusive demonstration that enough diversity is achieved
- Possibly greatest challenge for ΛCDM on small scales

Resolving the small-scale tensions

- Dark matter (DM) self-interactions can transfer energy from hot regions of a DM halo (shallow gravitational potential) to cold regions (deep gravitational potential)
- As a result, they transform halos with cuspy profile into halos with central cores



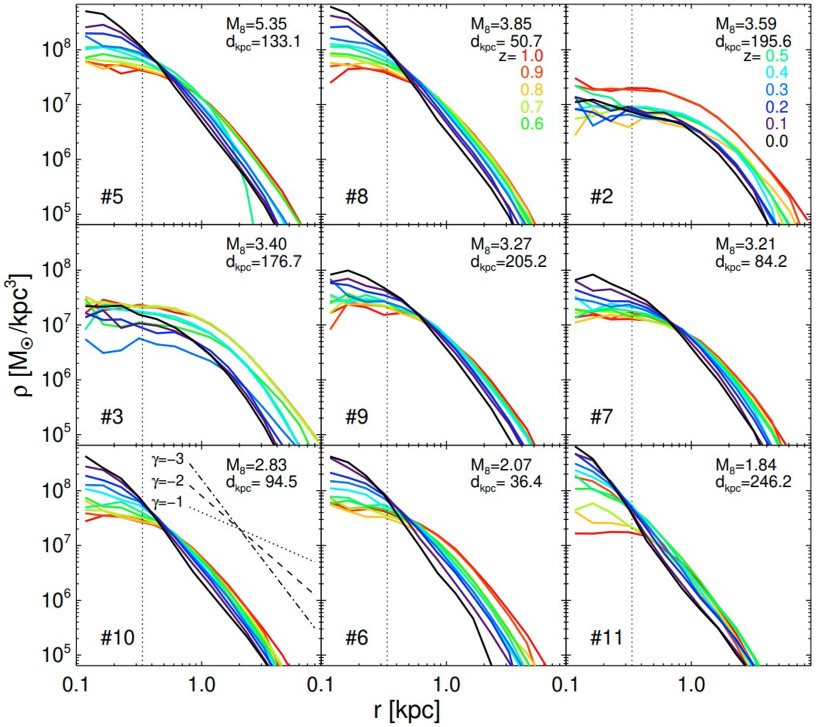
Banerjee et al., arXiv:1906.12026

Gravothermal collapse

- Cores created by DM self-interactions are not stable
- Once the inner region is fully thermalised, the direction of the heat flow reverses and the central region starts cooling down
- After sufficiently long times (or for very large cross sections) cores experience gravitational collapse and cusps reappear

  → gravothermal catastrophe

Turner et al., arXiv:2010.02924



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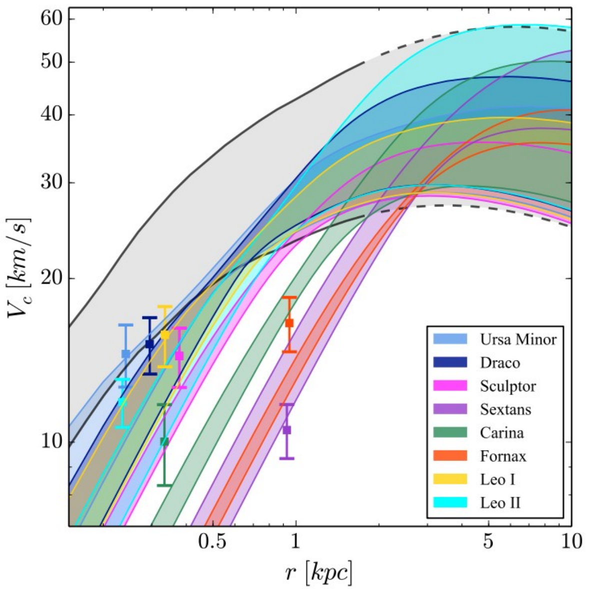
The impact of tidal forces

- If the outer parts of a DM halo are stripped by tidal forces (e.g. from a nearby galaxy), the heat loss increases and core collapse accelerates



- High concentration halos become even denser while low concentration halos are disrupted

Sameie et al., arXiv:1904.07872; FK et al., arXiv: 1904.10539

- Moreover, central density of a Milky Way satellite depends on its precise orbit (i.e. the pericenter distance)

- Possible explanation of the observed diversity of MW satellites

Valli & Yu, arXiv:1711.03502

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Back-of-the-envelope estimate

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

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

- Self-interactions will be important if the cross section σ satisfies $\Sigma\, \sigma / m_{DM} > 1$
- → $\sigma / m_{DM} > 0.5\text{ cm}^2 / \text{g} \sim 1\text{ barn / GeV} \sim m_\pi / f_\pi^4 \sim \Lambda_{QCD}^{-3}$

- Similar to pion-pion and nucleon-nucleon scattering cross section!

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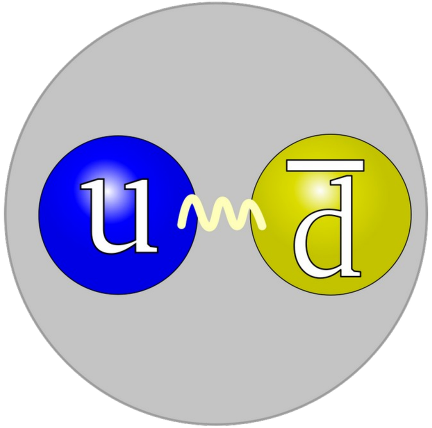
Strongly-interacting dark sectors

- 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



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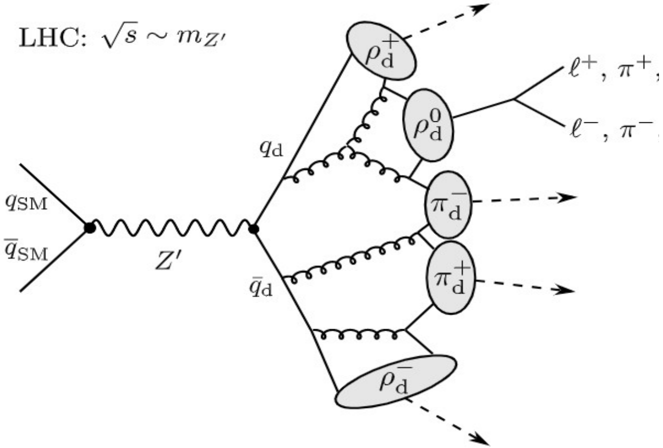
Dark showers

- 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

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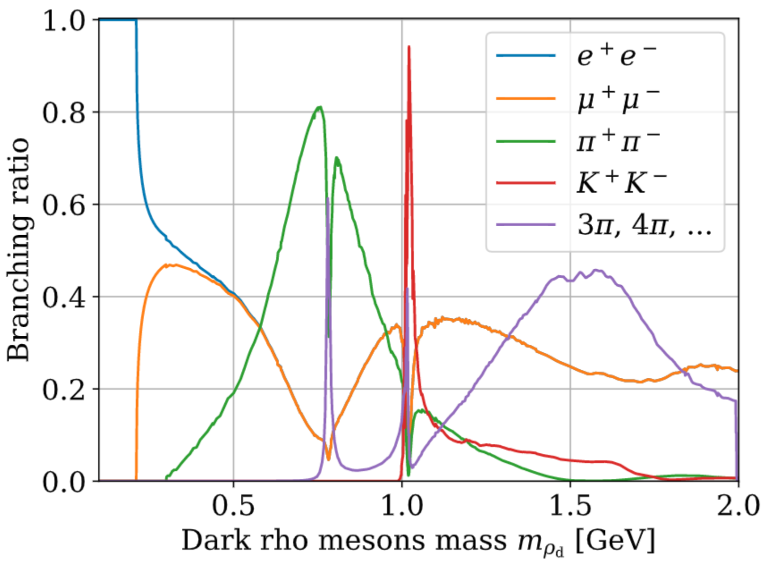
Displaced vertices from dark showers

- 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



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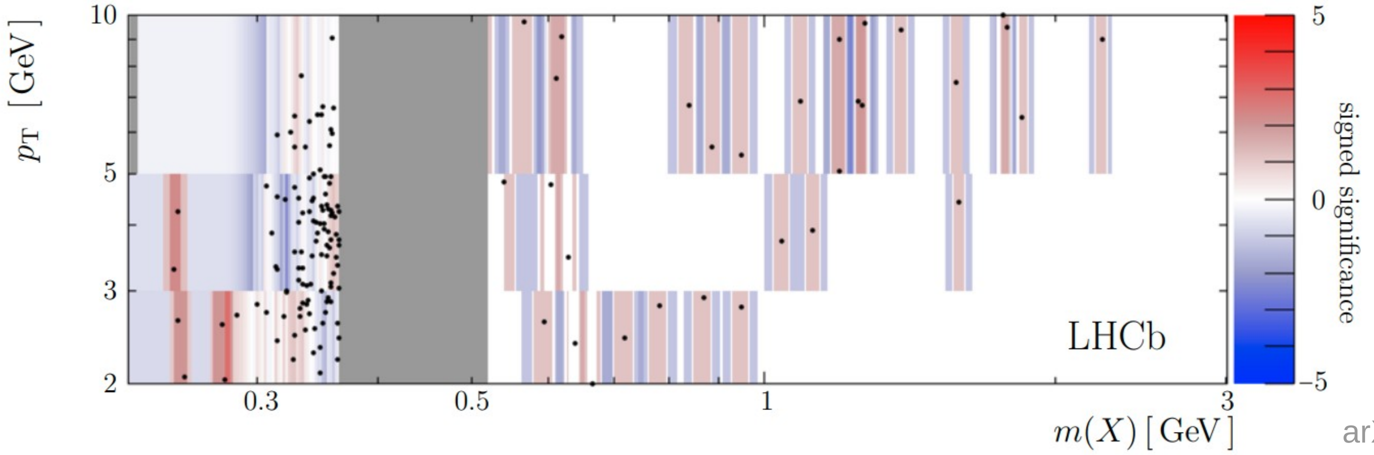
Displaced vertex search at LHCb

- 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

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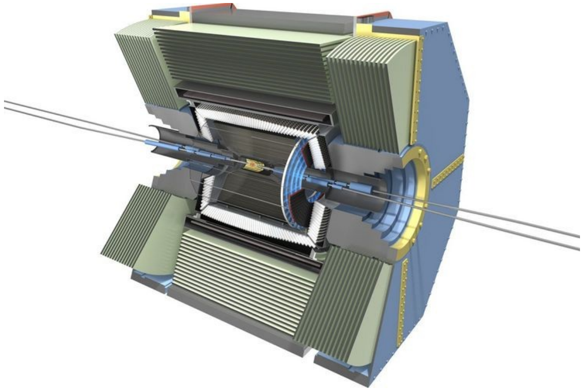
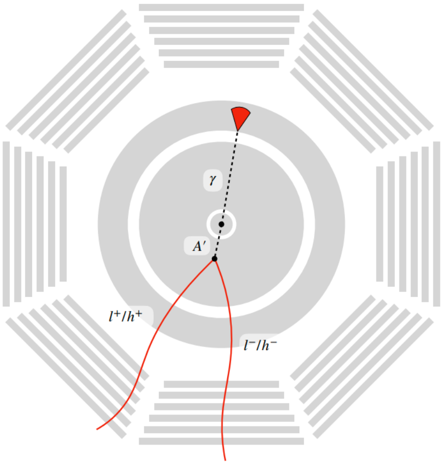
What about Belle II?

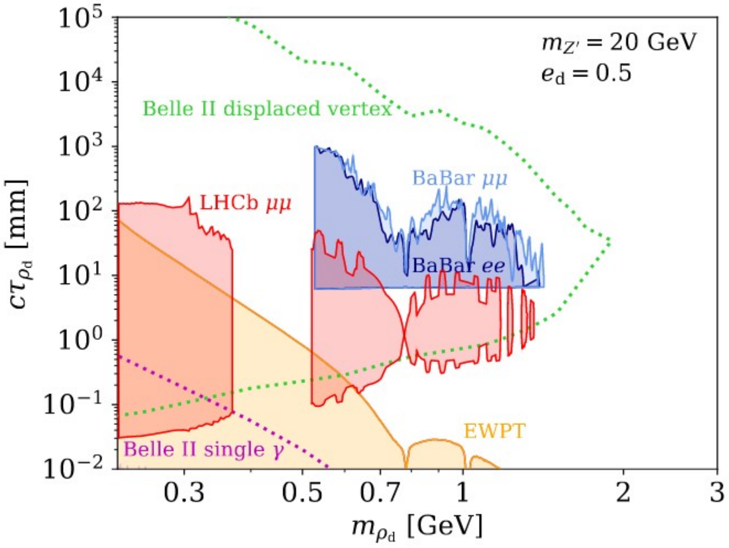
- Since 2020 Belle II is using e^+e^- collisions at $\sqrt{s} \sim 10.6$ GeV to compete with LHCb for the most precise measurements of B mesons

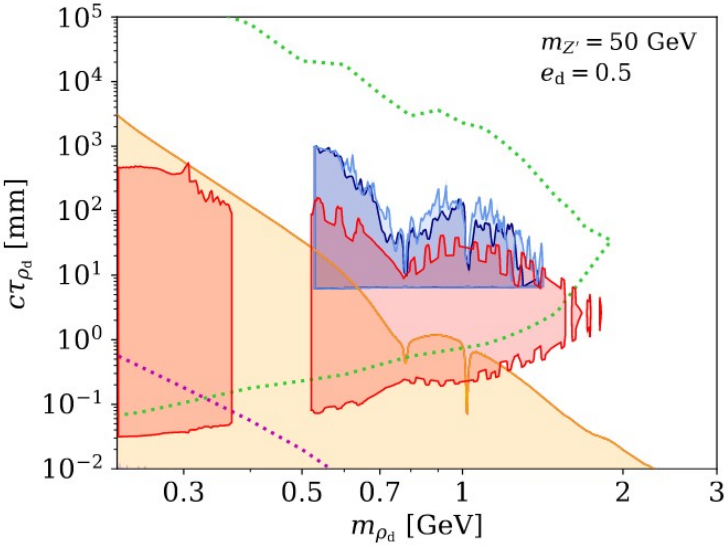




- The Belle II detectors are highly suited to search also for DVs from exotic LLPs
- Transverse distance of DV can be as large as 60cm
- Smaller energies ↔ smaller boost factors
- Expect sensitivity to much larger lifetimes

Comparison of sensitivities

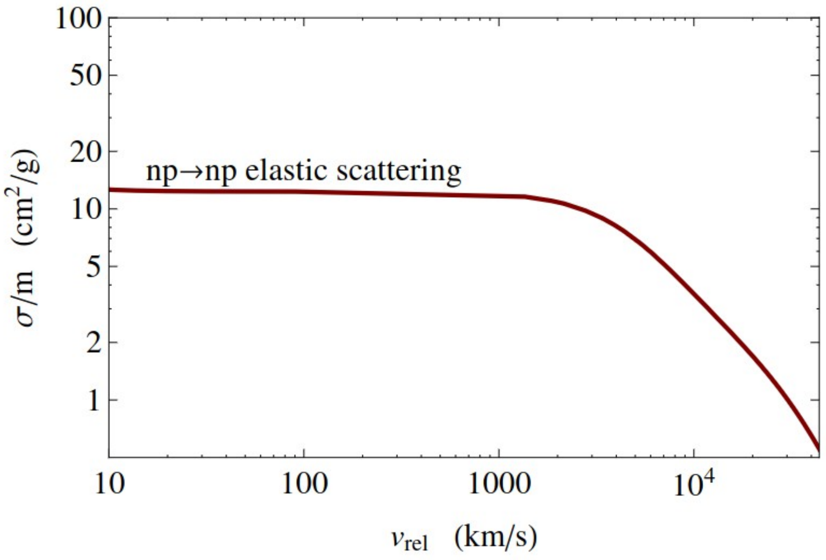




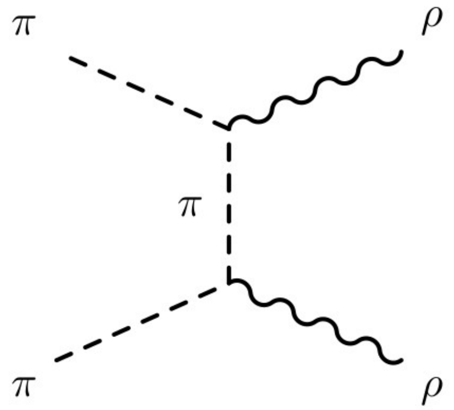
Bernreuther, FK et al., arXiv:2203.08824

- 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

Open questions



- Can these models evade the strong bounds on DM self-interactions from the Bullet Cluster?
- How reliable are dark shower simulations with PYTHIA?



- How do dark mesons from strongly-interacting dark sectors obtain their relic abundance?

Conclusions

- The small-scale crisis of ΛCDM is evolving with new observations and better understanding of baryonic effects
- The (diversity of) density profiles of dwarf galaxies remain puzzling
- Dark matter self-interactions can lead to core formation and collapse
- Required cross sections are large! New strong dynamics in the dark sector?
- Collider signature: Dark showers, semi-visible jets and displaced vertices
- Ongoing searches at the LHC and Belle II

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