Where are the WIMPs?

Felix Kahlhoefer
Dark Side of the Universe 2018
Annecy-le-Vieux
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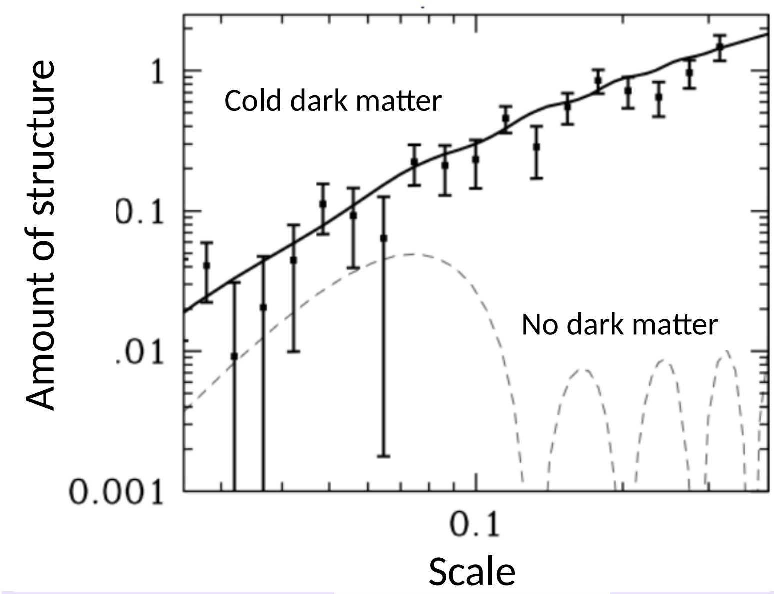
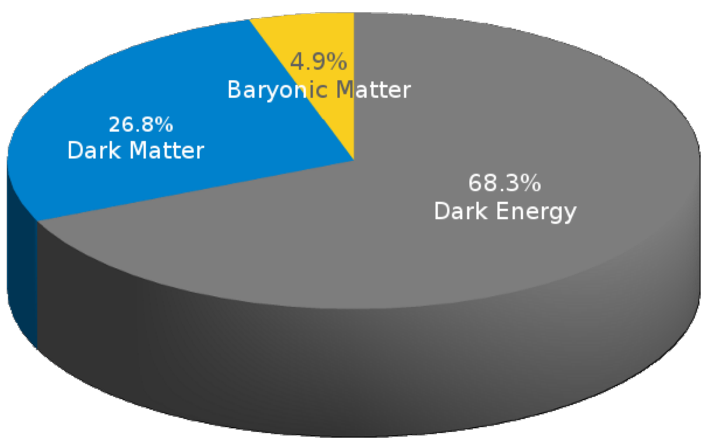
Emmy Noether-Programm
DFG Deutsche Forschungsgemeinschaft

Institute for Theoretical Particle Physics and Cosmology
RWTH AACHEN UNIVERSITY

Why dark matter?

- Dark matter (DM) is an **essential ingredient** to describe Early Universe cosmology
  - Not affected by photon pressure
  - Acts as the early seed for **structure formation**
  - Creates the **potential wells** for stars and galaxies
- DM **explains** the amount and distribution of structure that we observe today

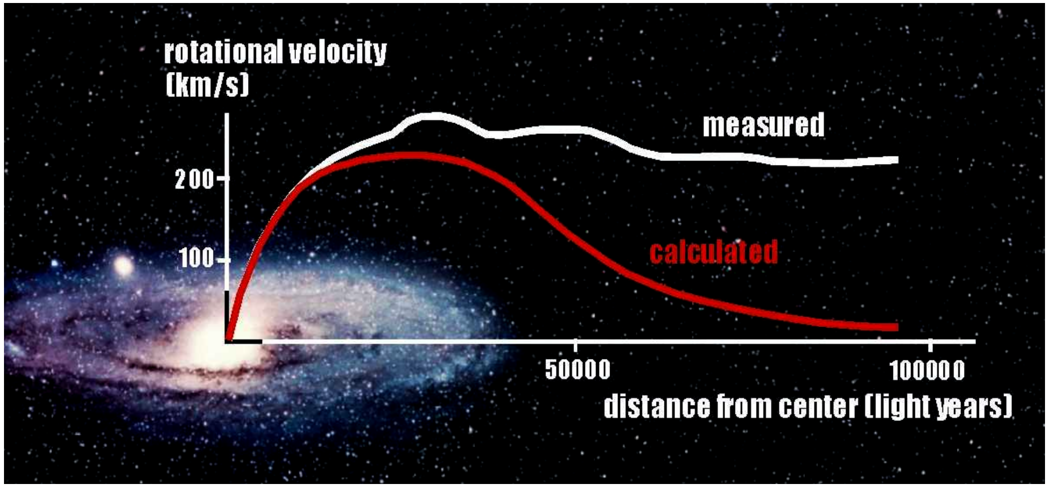




- A wealth of **successful predictions** from a very simple model
- Only draw-back: We understand only **5%** of the Universe!

Why dark matter?

- Astrophysical observations clearly confirm the **existence of DM** in the Universe…



Galactic rotation curves

Gravitational lensing of (colliding) galaxy clusters

…but they give almost no indications concerning **its nature**

- Is it an elementary particle?
- A complicated bound state?
- Black holes produced right after the Big Bang?

Particle dark matter

- The one thing we know about dark matter is how much there is in the Universe:

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

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

- **Particle physics** is the language of the early Universe
  - Example: Cosmology depends on the number, mass and interaction strength of neutrinos

- Likewise, we would like to understand DM in terms of particle physics

- **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 stable particle**!
  - What is its *mass* and *spin*?
  - What are its *interactions* with known particles?

The bottom-up approach

- Extend the SM by a particle with the required properties for a **viable DM candidate**
  - Stable (or sufficiently long-lived)
  - Electrically neutral (or sufficiently small milli-charge)
  - Collisionless (or sufficiently weak self-interactions)

- General expectation: New particles **enter into thermal equilibrium** with bath of SM particles in the Early Universe

  - No need to specify initial conditions (e.g. details of reheating) for the DM particle

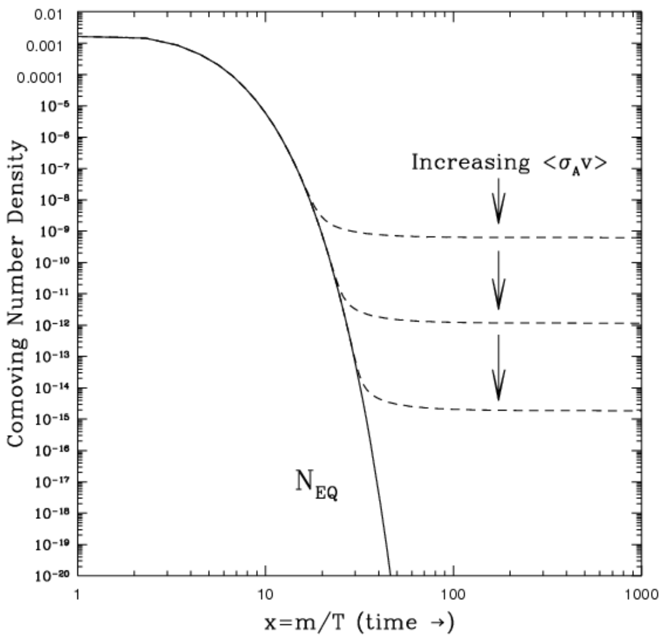
  - Well-established calculations of distribution functions and reaction rates

- Many exceptions: Very small couplings, very large suppression scale, low reheating temperature…

See talks by Javier Redondo, Lawrence Hall, Andreas Goudelis

Thermal freeze-out

- We can understand the departure from thermal equilibrium in terms of **freeze-out mechanism**
  - Annihilation and production processes happened frequently in the early Universe
  - As the Universe cools down, interactions become less frequent
  - Finally, dark matter particles decouple from equilibrium



- Similar calculations are known to work well for **Big Bang Nucleosynthesis** (predicting the abundance of elements) and **recombination** (predicting the Cosmic Microwave Background)
  - Note 1: Observation of cosmic neutrino background still missing
  - Note 2: The analogous calculation for the baryon abundance fails by many orders of magnitude (due to the initial baryon asymmetry)

Relic abundance

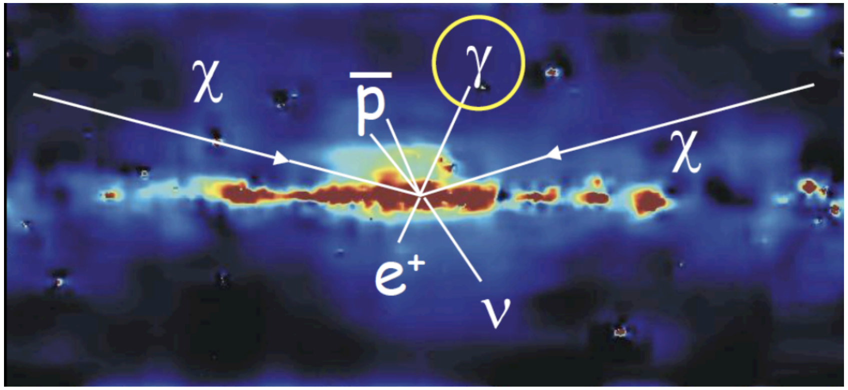
- Boltzmann equations allows to **calculate the abundance of any thermal relic** (assuming standard cosmological evolution)
- Observed DM abundance implies <σv> ~ 3 · 10^{-26} cm^3/s
  - Very **generic constraint** on DM models
  - Required cross section quite large → **great discovery potential**
  - Subdominant DM components would require even larger cross sections **→ strong experimental constraints**
- Two remarkable coincidences:
  - Cross section corresponds roughly to the one expected for a new particle with weak-scale mass and interactions (so-called WIMPs)
  - WIMPs occur generically in many extensions of the Standard Model (developed for very different reasons) such as SUSY

See talks by Keith Olive and Csaba Balazs

- How do we probe these generic predictions?

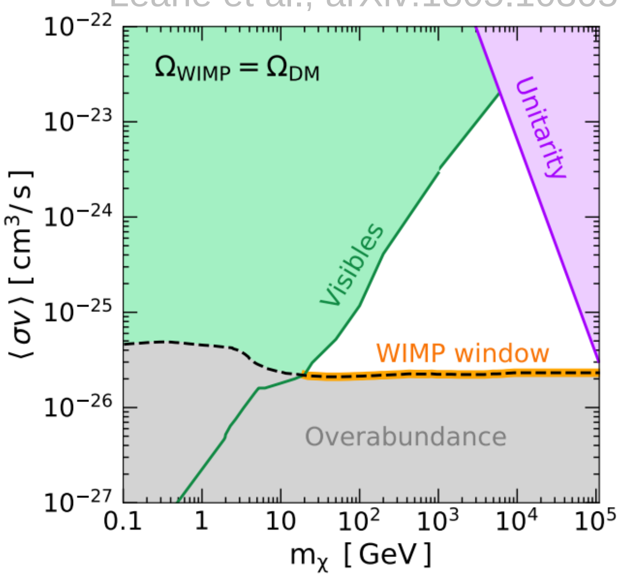
Indirect detection

- Search for the products of DM annihilations in regions of high DM density (e.g. the Galactic centre)
- Indirect detection probes the same cross section as thermal freeze-out (although at a different velocity) → **Clear target**



See talk by Marco Regis

Leane et al., arXiv:1805.10305

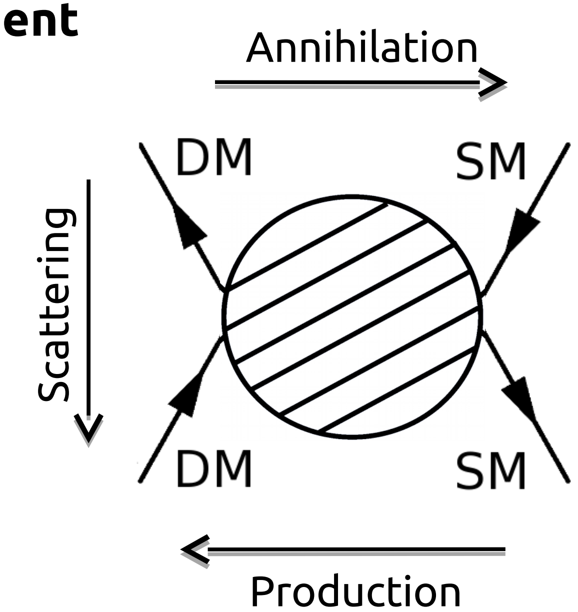


- Constraints get stronger for smaller masses
- For velocity-independent annihilations into visible final states, it is **impossible to have m_{DM} < 20 GeV**
- Bounds for heavier DM will get a lot stronger (AMS-02, CTA, ...)
- Some hints of unclear status (e.g. the Fermi Galactic Centre Excess)

See Parallel Session II on Tuesday

Direct detection and collider searches

- Comparison with thermal freeze-out **more model-dependent**



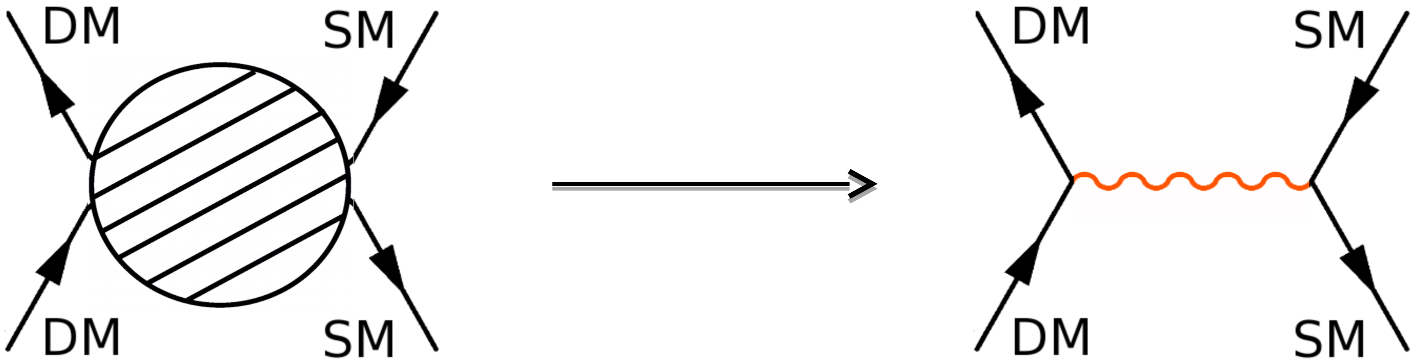
- Direct detection: Comparison possible using an **effective field theory (EFT)** approach
  - Detailed phenomenology depends on the effective operator under consideration
  - For example, one can have velocity-suppressed scattering but velocity-independent annihilations or vice versa
  - No general conclusion possible without more fundamental understanding

See talk by Bradley Kavanagh

- Colliders: EFT approach questionable, because suppression scales can be quite low
  - Need truncation procedure to restrict search to kinematic regions where effective field theory (EFT) is valid
  - Many interesting features are not captured by effective operators

From EFTs to simplified models

- We can address the shortcomings of effective interactions by introducing a **new mediating particle** connecting DM to the SM

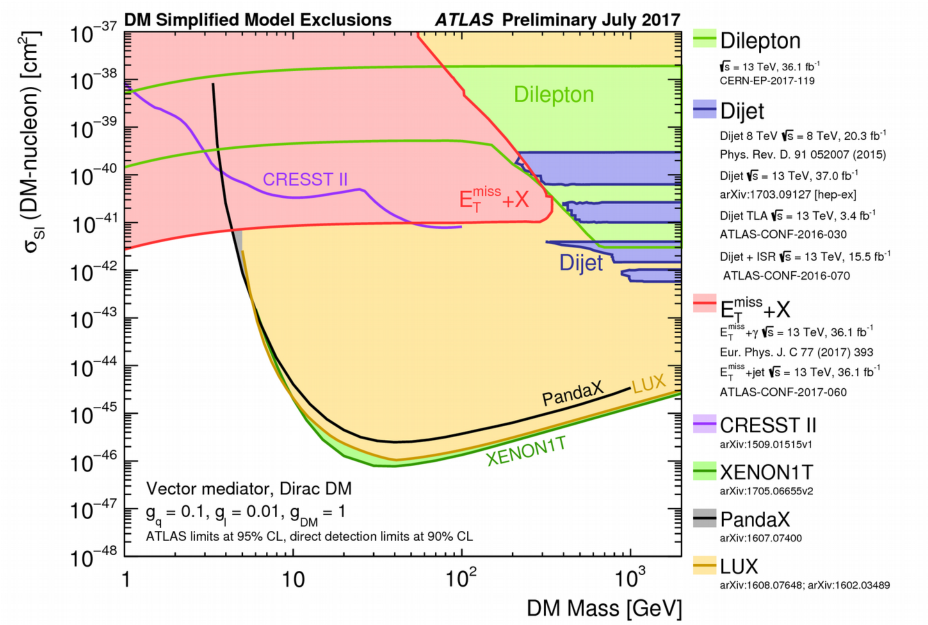


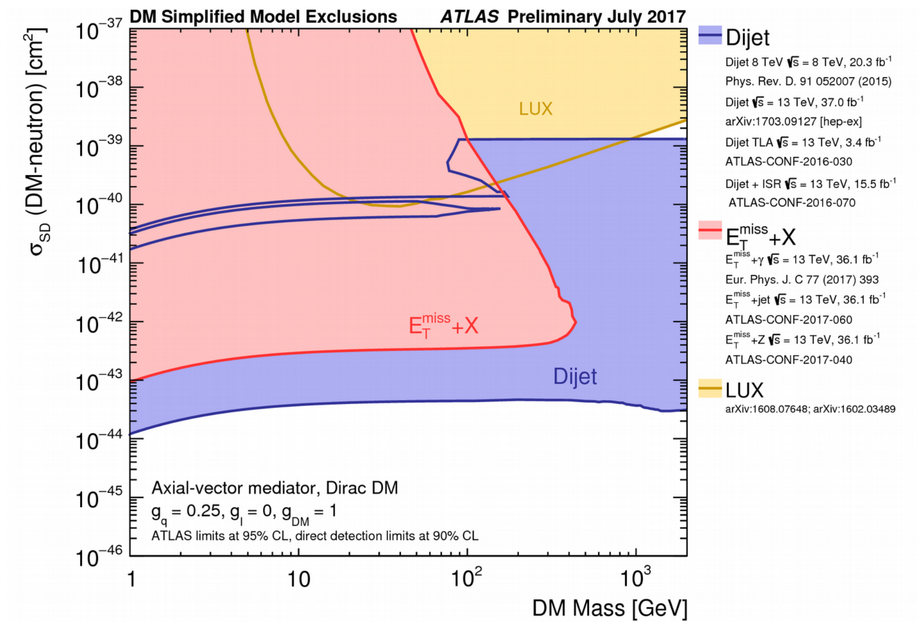
- The move to renormalisable models comes at a high price
  - Large number of possible models → **loss of generality**
  - Large number of parameters for each model → **increase of complexity**

Simplified model results

- Simplified models make it possible to compare direct and indirect detection and collider searches for **specific benchmark points**

See talk by Barbara Clerbaux





- Conclusions depend very sensitively on parameter choices and **cannot easily be generalised**
  - Break-down of the bottom-up approach
  - Some inspiration from UV necessary

Consistent simplified models

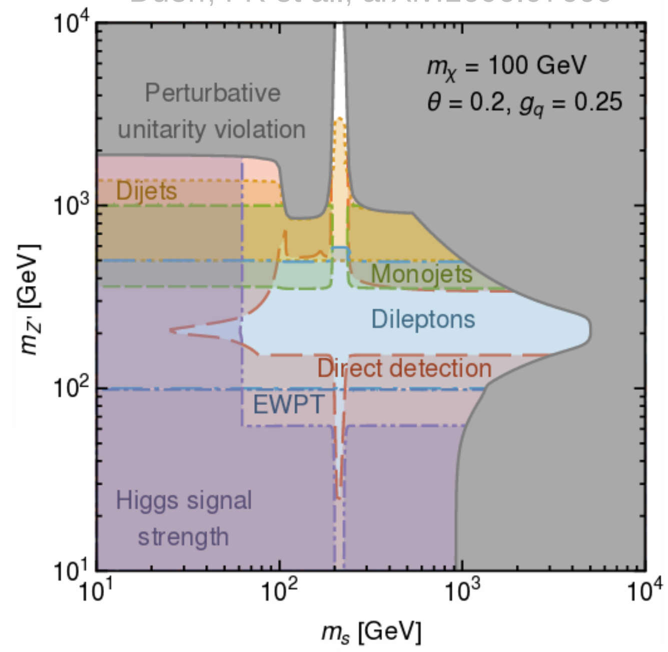
- Attractive direction: Impose **theoretical consistency requirements** on simplified models
  - Renormalisability
  - Gauge-invariance
  - Anomaly freedom

FK et al., arXiv:1510.02110
Bell et al., arXiv:1512.00476
Haisch, FK et al., arXiv:1603.01267
Ellis et al., arXiv:1704.03850

- Examples:
  - Extended gauge groups, e.g. a new U(1)', spontaneously broken by a Higgs mechanism
  - Extended Higgs sectors, e.g. a 2HDM, that mixes with the mediator of the simplified model

No, arXiv:1509.01110
Ipek et al., arXiv:1404.3716
Goncalves et al., arXiv:1611.04593
Bauer, Haisch & FK, arXiv:1701.07427

Duerr, FK et al., arXiv:1606.07609



- Underlying structure imposes correlations between different search channels

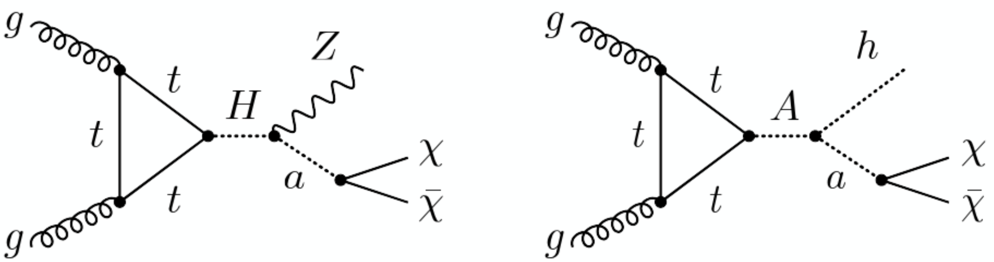
See talk by Pyungwon Ko

Novel predictions

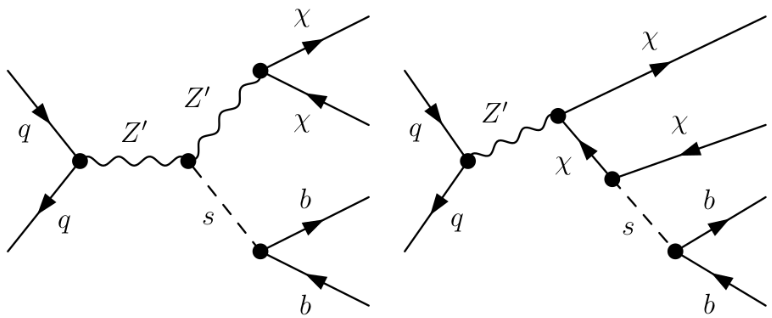
- Replacing simplified models with models of dark sectors predicts **many new signatures**

- For example, SM particles can also be produced together with invisible particles…

…in the **decays of heavier states**:



…via **final-state radiation**:



- Very different kinematics, potentially very striking signals (e.g. mono-Higgs or mono-dark-Higgs)

Bauer, FK et al., arXiv:1701.07427
Duerr, FK et al., arXiv:1701.08780

Where do we stand?

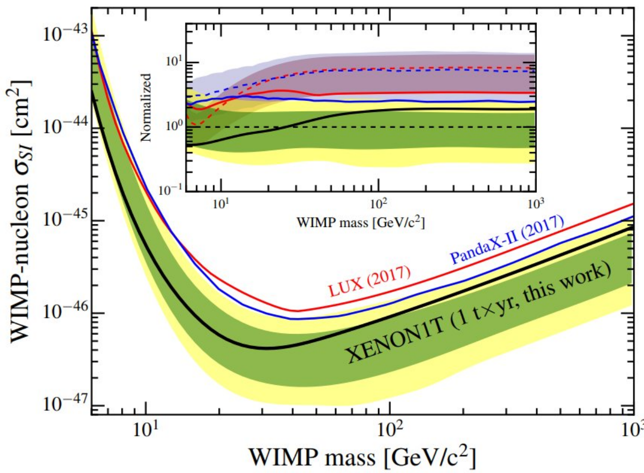
LHC

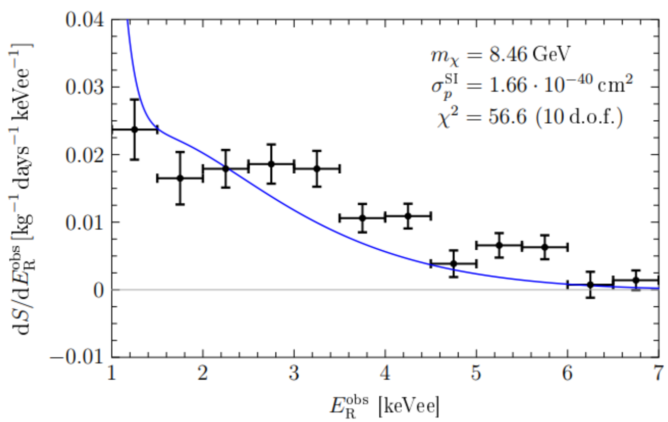
- Broad range of missing-energy searches (SUSY, Mono-X, invisible Higgs, …)
- No clear excess in any (published) search channel

Direct detection

- New result from XENON1T!
  - No significant excess
  - Strongest bound on DM interactions

See talk by Ranny Budnik





- Long-standing DAMA **annual modulation signal**
  - Cannot be explained with spin-independent scattering
  - Model-independent tests require new experiments: SABRE, COSINE, ANAIS, COSINUS, …

FK et la., arXiv:1802.10175

What does it all mean?

SCIENTIFIC AMERICAN

In the Dark about Dark Matter

Recent disappointments have physicists looking beyond WIMPs for dark matter particles

- Are WIMPs no longer the most attractive solution to the DM problem? **Maybe!**
- Or is it just more fun to cheer with the **underdogs**?

What does it all mean?


SCIENTIFIC AMERICAN.

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What does it all mean?

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In the Dark about Dark Matter

Recent disappointments have physicists looking beyond WIMPs for dark matter particles

- Are WIMPs no longer the most attractive solution to the DM problem? **Maybe!**
- Or is it just more fun to cheer with the **underdogs**?
- Are we really ready to conclude that there are no undiscovered stable thermal relics in the Universe? **Clearly not!**
- Let's look at two specific cases
  - A very simple WIMP model
  - A rather exotic realisation of the WIMP idea

A simple WIMP: Scalar singlet DM

- Very simple idea: Consider DM particles that **couple only to the Higgs field**
- Particularly appealing: scalar singlet DM
  - Model remains **valid up to very high scales** (potentially up to M_{GUT} or M_{planck})
  - The contribution of the scalar singlet can **stabilise the electroweak vacuum**
  - Scalar field can **act as the inflaton** (via non-minimal coupling to gravity)

FK & McDonald, arXiv:1507.03600

- Simplest realisation: Real scalar stabilised by a Z_2 symmetry

$$\mathcal{L} = \frac{1}{2}\mu_S^2 S^2 + \frac{1}{2}\lambda_{hs} S^2 |H|^2 + \frac{1}{4}\lambda_S S^4 + \frac{1}{2}\partial_\mu S \partial^\mu S.$$

- Only **three relevant parameters** (2 couplings, 1 mass)
- Very **rich phenomenology** – ideal to assess the viability of the WIMP idea

Constraints on scalar singlet dark matter

- Relic density (underabundance OK)
- Direct detection (including the new XENON1T result)
- Indirect detection: Fermi-LAT (dwarfs)
- Higgs mass (obtained from RGE evolution of scalar potential using FlexibleSUSY)
- Higgs invisible width
- Lifetime of the Universe (for metastable vacua)

- Combining all this information is challenging!
  - Need to construct **global likelihood functions**
  - Details matter → need to include **nuisance parameters**
    - Astrophysical uncertainties
    - Nuclear physics parameters
    - SM parameters (Higgs mass, top quark mass, gauge couplings)

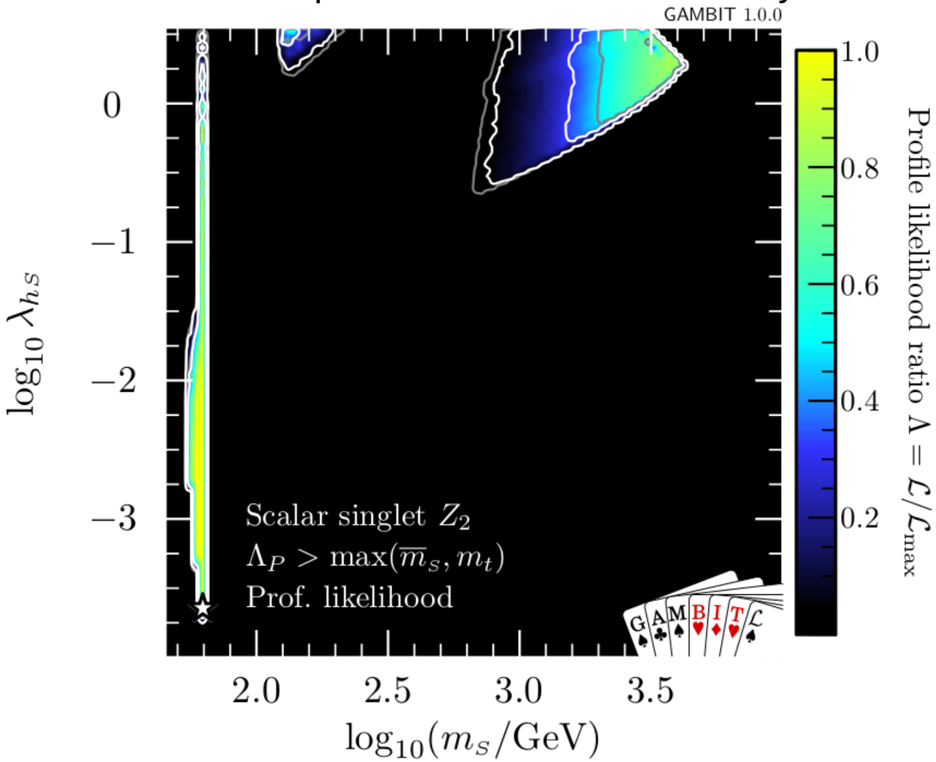
See talks by Nassim Bozorgnia and Thomas Lacroix

- Ideal for the global fitting framework **GAMBIT**

See talk by Csaba Balazs and arXiv:1705.07908

The status of scalar singlet DM

No requirement on vacuum stability



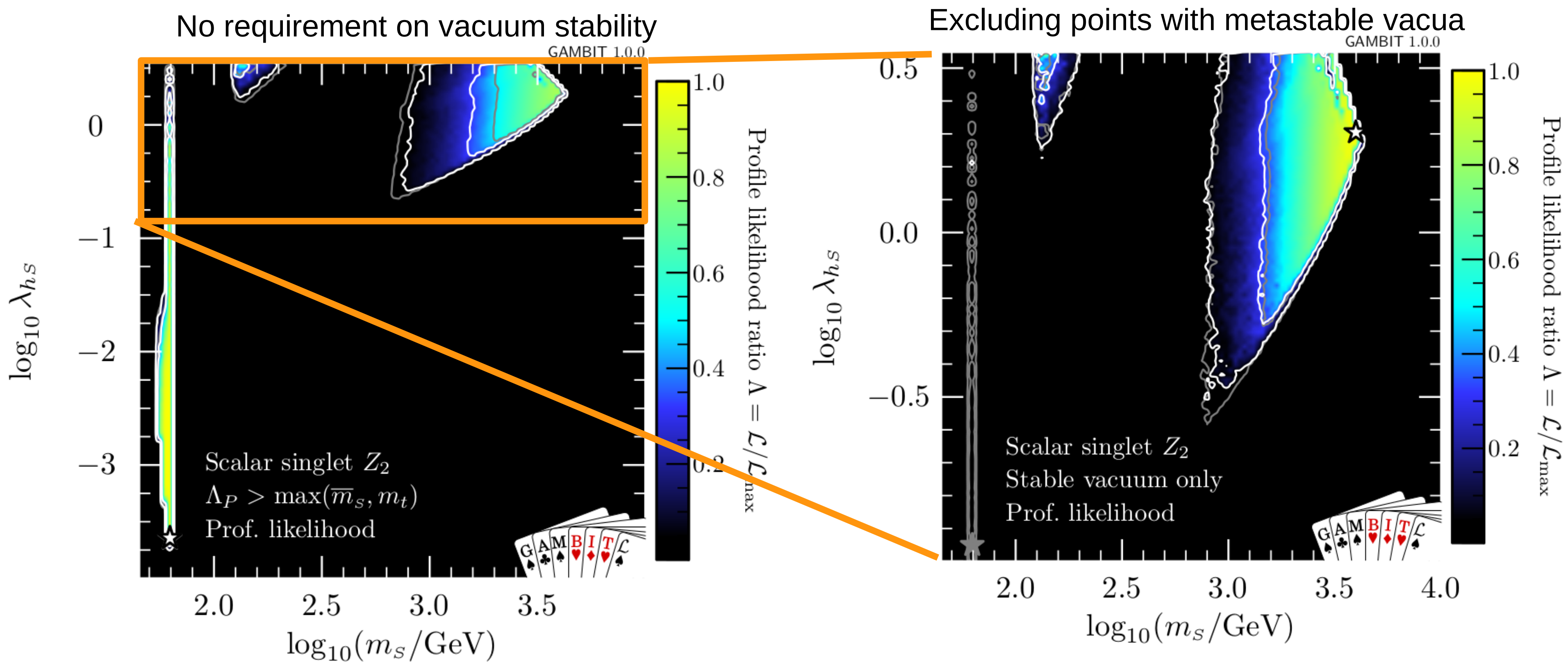
Impact of vacuum stability, perturbativity and XENON1T on global fits of Z_2 and Z_3 scalar singlet dark matter

Peter Athron, Jonathan Cornell, FK, James McKay, Pat Scott, Sebastian Wild

arXiv:1807.?????

- Two viable parameter regions:
  - $m_s \sim m_h / 2$ (relic density via resonantly enhanced annihilation into quarks)
  - $m_s \sim$ TeV (relic density via annihilation into gauge and Higgs bosons)

The status of scalar singlet DM

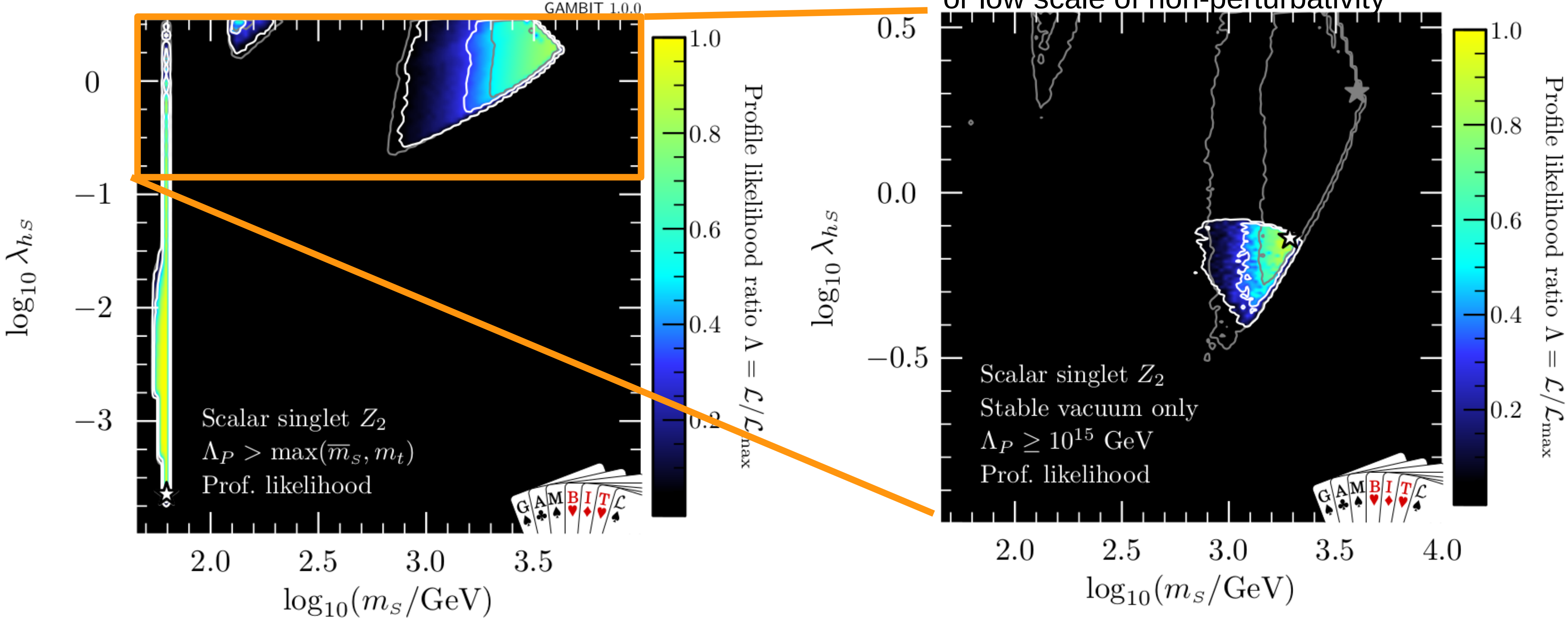


- λ_{hs} ~ 1 required to prevent λ_h from becoming negative at high scales
- Only high-mass solution remains

The status of scalar singlet DM

No requirement on vacuum stability

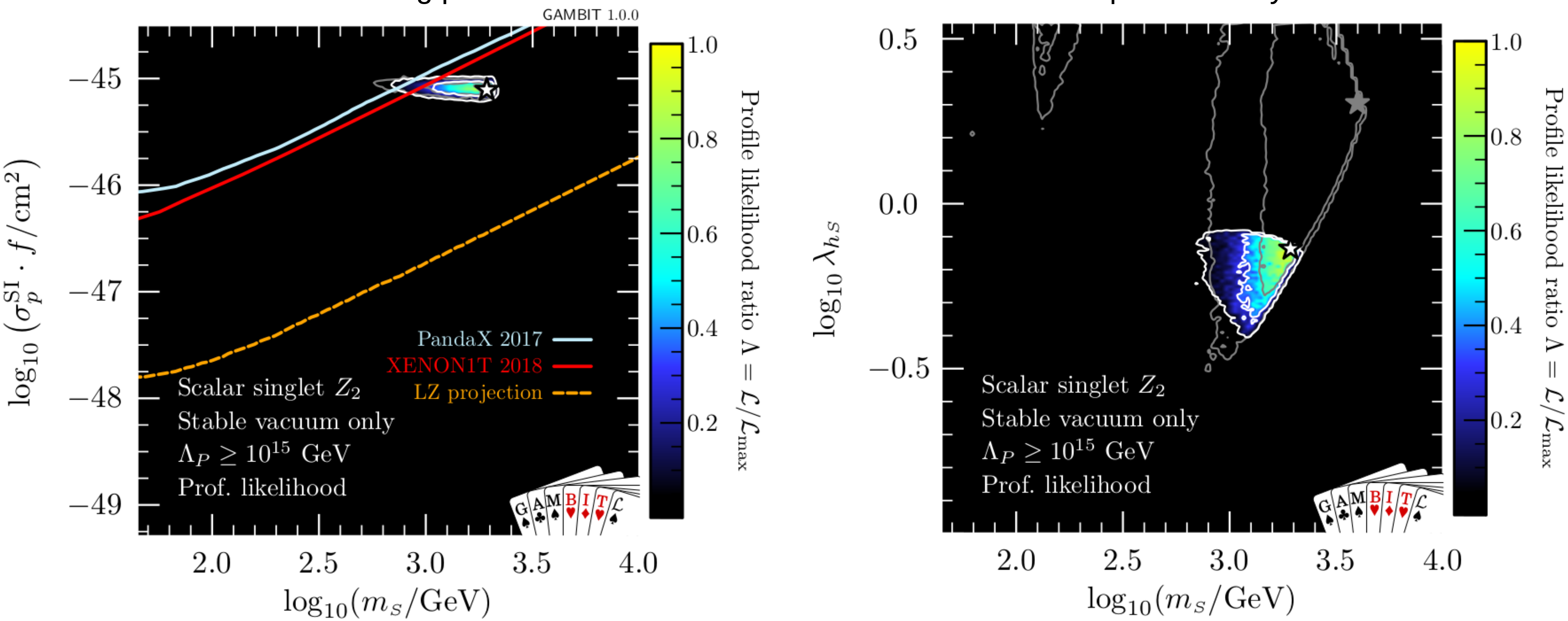
Excluding points with metastable vacua or low scale of non-perturbativity



- $\lambda_{hs} < 1$ required to ensure that all couplings remain perturbative up to about M_{GUT}
- Only well-defined parameter region remains with $m_s \sim 2$ TeV

The status of scalar singlet DM

Excluding points with metastable vacua or low scale of non-perturbativity



- Slight tension (~ 1σ) with the most recent direct detection experiments
- Final verdict possible with next generation of detectors

Alternative Higgs portal models

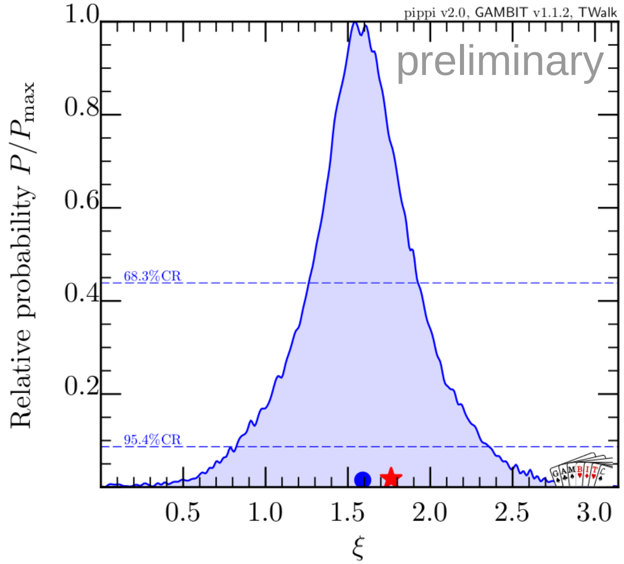
- Also interesting to consider a complex scalar singlet with a **Z_3 stabilising symmetry**
  - Additional parameter (μ_3) allowing for **semi-annihilations** Belanger et al., arXiv:1211.1014
  - **Considerable tension** (> 2σ) with direct detection experiments

- Alternative: fermionic DM

$$\mathcal{L}_\psi = \mathcal{L}_{\rm SM} + \overline{\psi}(i\partial\!\!\!/ - m_\psi)\psi - \frac{\lambda_{h\psi}}{\Lambda_\psi}\left[\cos\xi\,\overline{\psi}\psi + \sin\xi\,\overline{\psi}i\gamma_5\psi\right]\left(v_0 h + \frac{1}{2}h^2\right)$$

  - Higgs portal coupling via dimension-5 effective operator
  - Suppression of direct detection constraints via **CP-violating coupling** (ξ ~ π/2)
  - Large allowed parameter space but significant tuning

Global analyses of Higgs portal singlet dark matter models
The GAMBIT collaboration
arXiv:180?.????



Assessing the viability of WIMP models

- In case of a non-observation, experimental data will push WIMP models into more and more **finely tuned regions** of parameter space

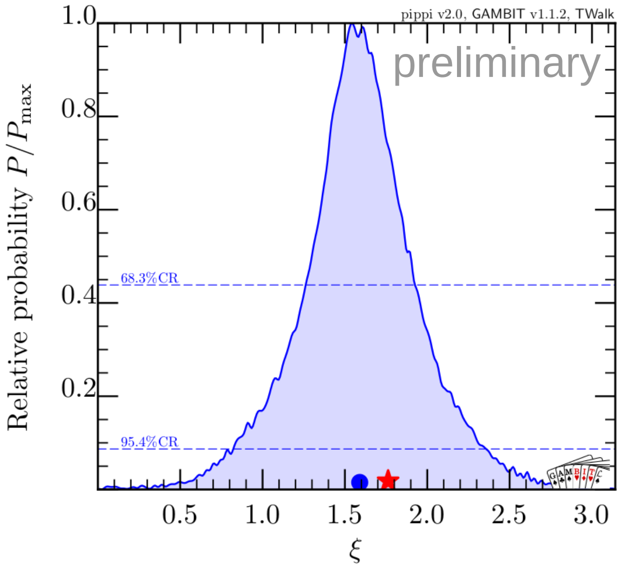
- How do we assess whether WIMPs remain viable in spite of these constraints?

- **Frequentist** approach: Calculate p-values
  - Requires knowledge of the probability distribution of the test statistic (e.g. from MC simulations)
  - Analytical approximations indicate that scalar singlets have perfectly acceptable p-values (> 0.1 even if we require a stable vacuum and scalar singlets to be all of DM)

- **Bayesian** approach: Calculate Bayesian evidence
  - Requires specification of the prior probabilities of underlying parameters
  - Allows for the comparison of different models (Bayes factors)

Bayesian evidence and model comparison

- Are experimental constraints pushing us towards more complicated WIMP models?



- Yes! In the case of the fermionic Higgs portal, there is **strong preference** for introducing a CP-violating phase

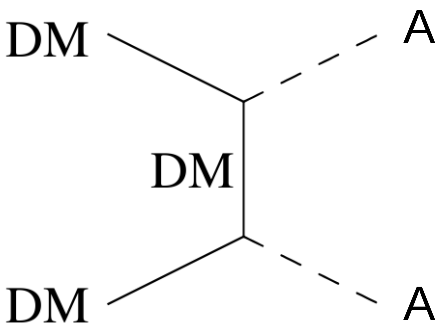
- This preference persists even though the additional parameter needs to be quite finely tuned

- By calculating the Bayes factor, we find that the **odds against the CP-conserving case** are approximately 20:1 (with only mild prior dependence)

- Well-motivated to think about more complex WIMP models!

An exotic WIMP: Secluded DM

- Assume that DM couples to a **light mediator**, which in turn couples to the SM
- Relic abundance set by annihilations into pairs of mediators (dark sector freeze-out)



Pospelov et al., arXiv:0711.4866

- Always possible to fix coupling in dark sector such that observed relic abundance is reproduced
- **Tiny couplings** between the mediator and SM are sufficient to ensure that the mediator decays into SM final states
  - Direct detection and LHC constraints can be suppressed (almost) arbitrarily

FK, et al., arXiv:1704.02149, see also Parallel Session II on Thursday

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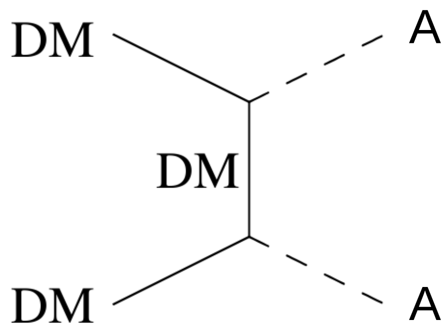


Pospelov et al., arXiv:0711.4866

- Always possible … c abundance is reproduced

- **Tiny couplings** … e that the mediator decay…
  - Direct detecti… …ly

Does this still qualify as a WIMP?

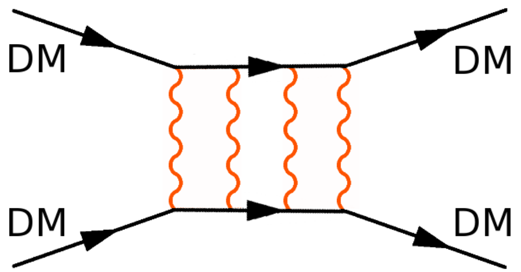
Depends on your definition…

No, if you insist on weak-scale interactions
Yes, if you define WIMPs as cold thermal relics

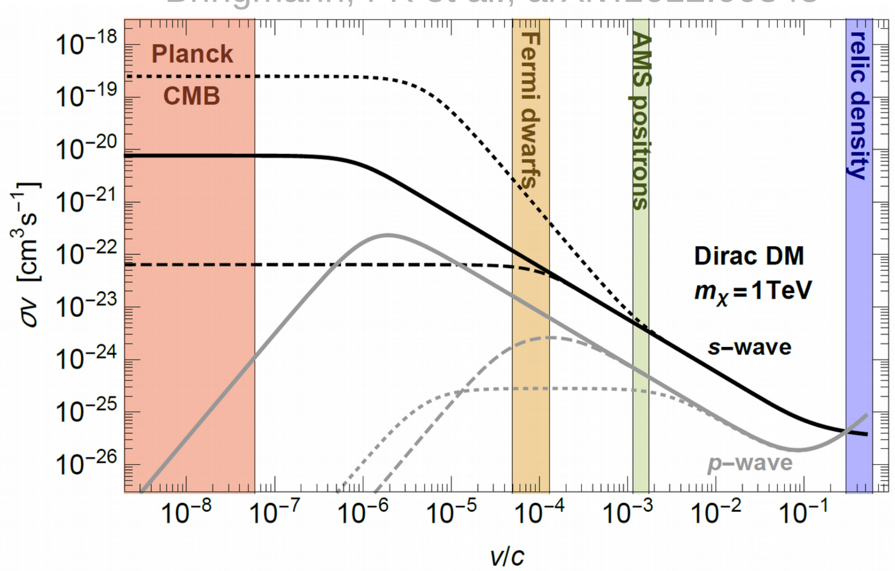
FK, et al., arXiv:1704.02149, see also Parallel Session II on Thursday

Constraints on secluded DM

- Astrophysical constraints remain strong!
- Annihilation and self-interaction cross sections are enhanced by small mediator mass and **non-perturbative effects**



Bringmann, FK et al., arXiv:1612.00845

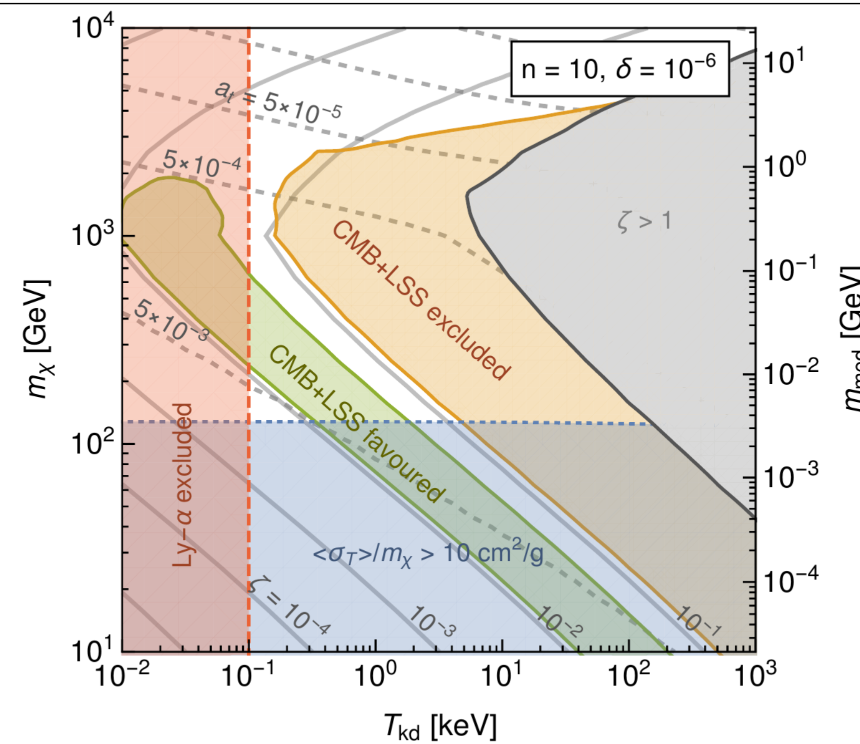


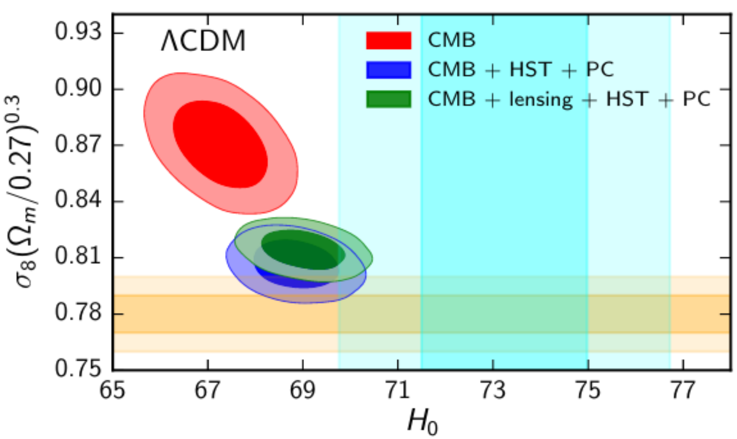
- Exciting possibility of observing the effects of **DM self-scattering** in astrophysical systems!
- Strong constraints from the **CMB** and indirect detection experiments

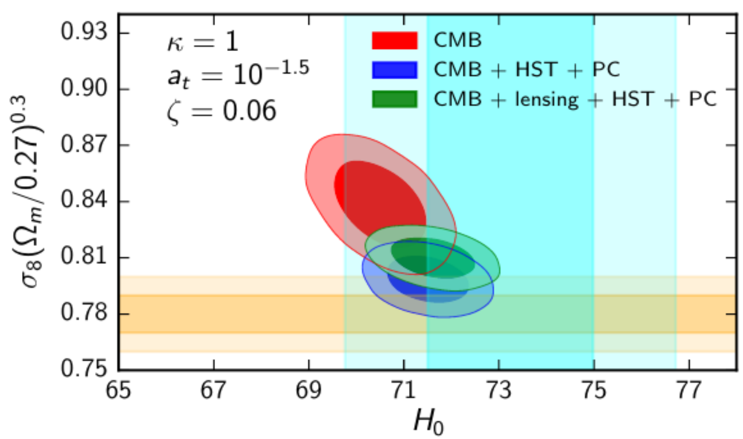
See talks by Marco Taoso, Francis-Yan Cyr-Racine and David Harvey

Hiding secluded DM

- If the light mediators decay into invisible particles (e.g. sterile neutrinos), the model is impossible to test even with indirect detection experiments
- But **late-time conversion of DM into dark radiation** can potentially be constrained with CMB data
- In fact, Sommerfeld-enhanced DM annihilations may even **reduce H_0 tension**!







Bringmann, FK et al., arXiv:1803.03644

What if it's not a WIMP?

- Many exciting alternatives!

- **Modified thermal production**
  - Asymmetric DM
  - SIMPs (and other models with 3 → 2 processes)
  - Sub-GeV WIMPs ("WIMPs next door")
- Exciting prospects for novel direct detection experiments

See talk by Julien Billard and Parallel Session 1 today

- **Non-thermal production**
  - Sterile neutrinos
  - Axions
  - FIMPs
- Difficult to see in direct detection and at the LHC – need alternative searches

See talks by Javier Redondo, Lawrence Hall and Andreas Goudelis

Great overview at **DSU2018**!

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Interested in DM direct detection?
Try DDCalc!

DDCalc v2

Dark matter direct detection phenomenology package

DDCalc is a software package for performing various dark matter direct detection calculations, including signal rate predictions and likelihoods for several experiments.

A full description of this package and the physics framework behind it can be found in the GAMBIT DarkBit paper:

- T Bringmann, J Conrad, JM Cornell, LA Dal, J Edsjö, B Farmer, F Kahlhoefer, A Kvellestad, A Putze, C Savage, P Scott, C Weniger, M White & S Wild 2017, EPJC 77 (2017) 831, arXiv:1705.07920

If you write a paper that uses DDCalc, please cite this paper.

Version history:

- **`v2.0.0 - June 2018`:** Support for full set of non-relativistic operators with general momentum and velocity dependence, new features for the definition of complex experiments with several signal regions and/or target elements, improved user interface including several new example files, new results from XENON1T (2018).
- `v1.2.0 - January 2018`: Added implementation of PandaX (2017).
- `v1.1.0 - June 2017`: Added implementation of Xenon1T (2017) and PICO-60 (2017).
- `v1.0.0 - May 2017`: Initial release in combination with GAMBIT v1.0.0.

DDCalc releases can be obtained as tarballs from Hepforge. The latest and greatest version, along with a full revision history, can always be found in the git repository. Compilation and usage instructions, as well as a number of example programs, can be found in the code release.

Maintainers: The GAMBIT Dark Matter Workgroup (ddcalc@projects.hepforge.org)
Many of the routines in DDCalc were originally contributed by Chris Savage (chris@savage.name)

Brand-new!
DDCalc v2.0.0
including the full set of non-relativistic effective operators

Conclusion: The status of WIMPs

- There are **many strong constraints** on WIMP models
- Still, even some of the simplest WIMP models **remain viable**
- Example: (Scalar) Higgs portal
  - Theoretically preferred parameter region (where the model remains perturbative and stabilises the electroweak vacuum) is only **beginning to be probed** by direct detection
- Constraints on WIMP models can be **relaxed** by introducing additional parameters (e.g. CP-violating phases) or mechanisms to hide signals (e.g. secluded DM)
- Essential to **quantify the complexity and fine-tuning** of WIMP models to assess their viability (e.g. using Bayesian evidence and model comparison)