Status of the WIMP

Felix Kahlhoefer

Dark Matter at the Dawn of Discovery?

Heidelberg

9-11 April 2018

On behalf of the GAMBIT collaboration

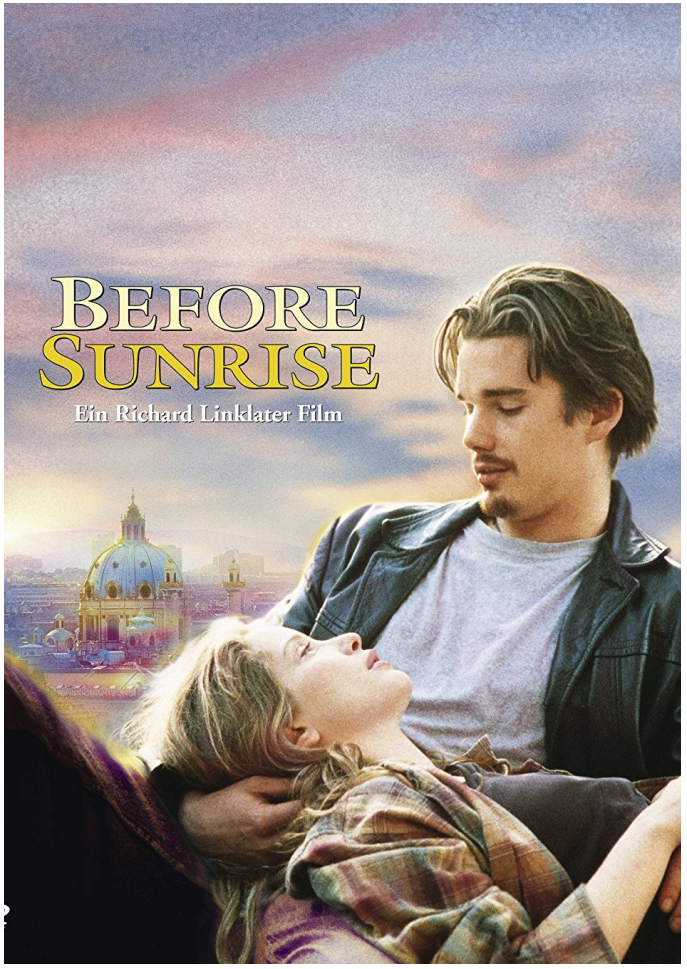
gambit.hepforge.org

TTK Institute for Theoretical Particle Physics and Cosmology

RWTH AACHEN UNIVERSITY

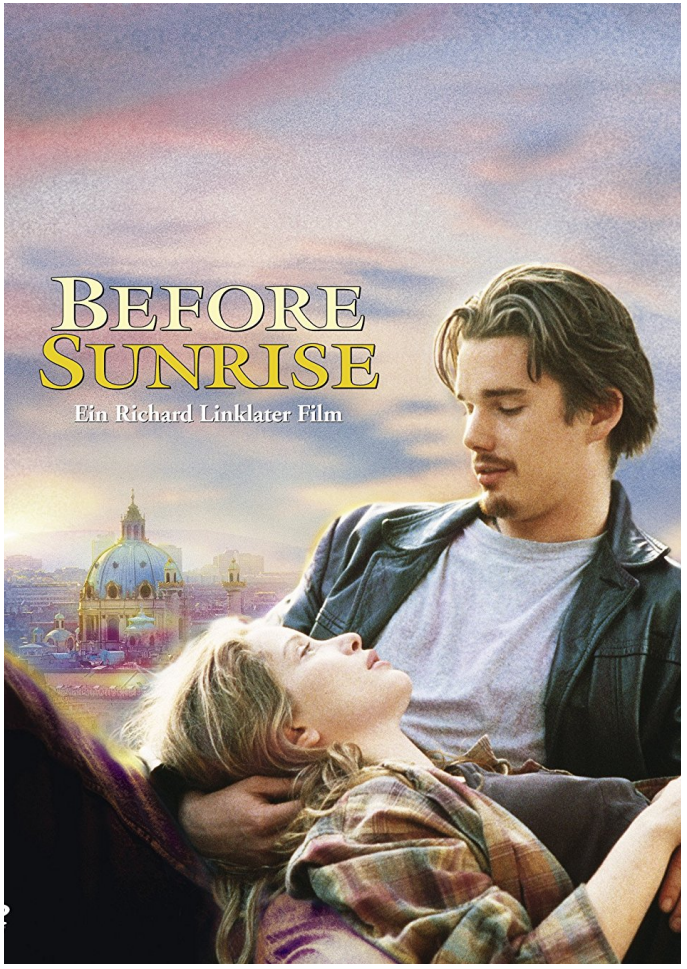
WIMPs before dawn

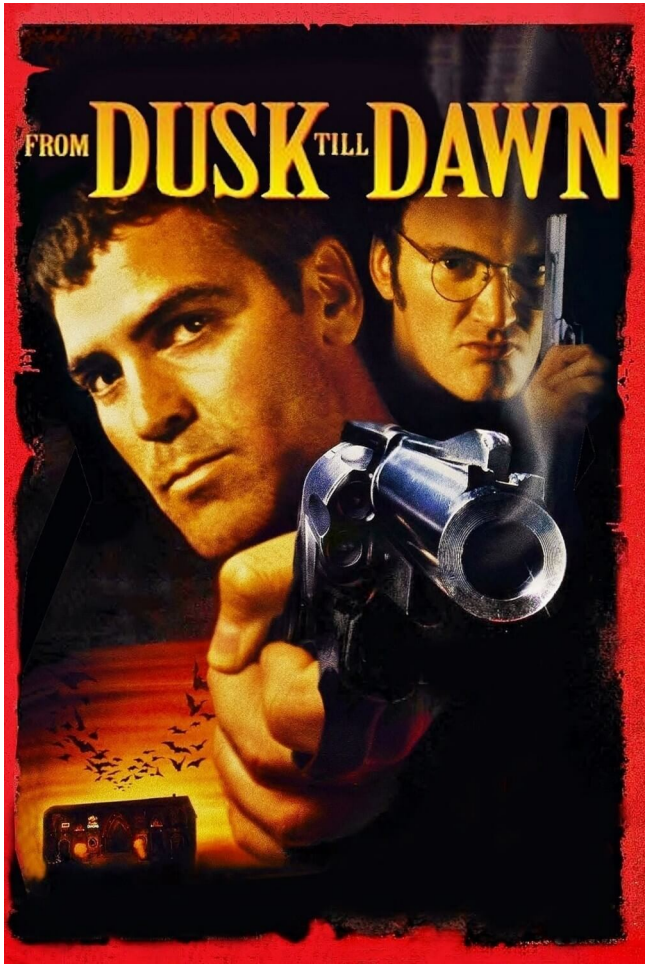
Romance?



WIMPs before dawn

Romance? Or massacre?





Quantifying the “status of the WIMP”

- Need to consider a wide range of experimental results and associated uncertainties
  - Cosmology
  - Direct detection
  - Indirect detection
  - Collider constraints
  - Precision measurements

- Need to consider a wide range of different models
  - Effective (low-energy) theories
  - Simple models (minimal DM, scalar singlets, …)
  - Complicated models (e.g. MSSM)

- Need to study different statistical approaches
  - Frequentist (e.g. goodness of fit)
  - Bayesian (e.g. model comparison)

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- Need database of constraints
- Simple overplotting of different constraints insufficient
- Need to construct composite likelihood functions to combine all data in a consistent way

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  - Potentially complicated parameter spaces
  - Need highly efficient scanning algorithms
  - Need a framework that can handle many different models in a flexible and modular way

GAMBIT

The Global And Modular BSM Inference Tool

- New software framework for global fits developed over the past five years
- Optimized for parallel computing & fully open source
- First public code release in May 2017 (gambit.hepforge.org)!
  - Code papers: arXiv:1705.07936, arXiv:1705.07933, arXiv:1705.07919, arXiv:1705.07959, arXiv:1705.07920, arXiv:1705.07908
  - Physics papers: arXiv:1705.07917, arXiv:1705.07935, arXiv:1705.07931

- Collaboration with 31 members from 11 countries (9 experiments, 12 major theory codes)

GAMBIT

The Global And Modular BSM Inference Tool

- **DarkBit** – dark matter observables
  - DDCalc (constantly updated database for likelihoods from direct detection experiments)
  - gamlike (Fermi likelihoods)
  - nulike (Icecube likelihoods)
- **ColliderBit** – collider observables (Higgs + SUSY searches from ATLAS, CMS, LEP)
- **FlavBit** – flavour physics (g – 2, b → sγ, B decays)
- **SpecBit** – RGE running, masses, mixings, ...
- **DecayBit** – decay widths for all relevant particles
- **PrecisionBit** – SM likelihoods, electroweak precision tests
- **ScannerBit** – manages statistics, sampling and optimisation

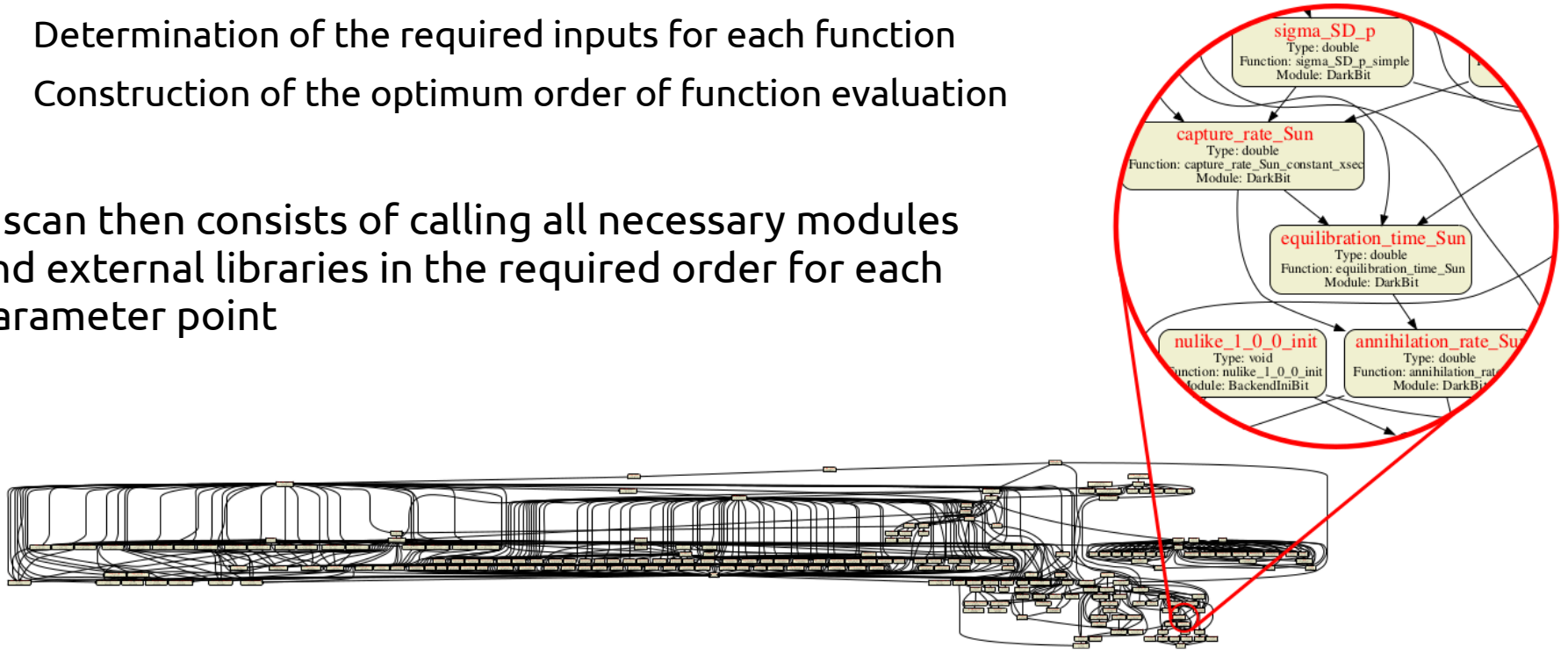
- Coming soon: **NeutrinoBit** & **CosmoBit**

How does GAMBIT work?

- User specifies the model, parameter space, observables and scanning technique

- GAMBIT then performs the *dependency resolution*
  - Identification of all functions necessary to calculate requested observables
  - Dynamic adaptation to the user's system
  - Determination of the required inputs for each function
  - Construction of the optimum order of function evaluation

- A scan then consists of calling all necessary modules and external libraries in the required order for each parameter point



Global fits of WIMP models

- Remaining problem: Talk too short to cover full range of WIMP models
- Today's focus: Higgs portal models
  - DM particles interact with SM by coupling to the Higgs field
  - Extremely simple model (essentially only two parameters – mass and coupling)
  - Rich phenomenology – many relevant constraints

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Simple but representative WIMP model

Ideal to asses the viability of the WIMP idea

Scalar singlet dark matter

- Simplest realisation of the Higgs portal: real scalar singlet stabilised by Z_2 symmetry

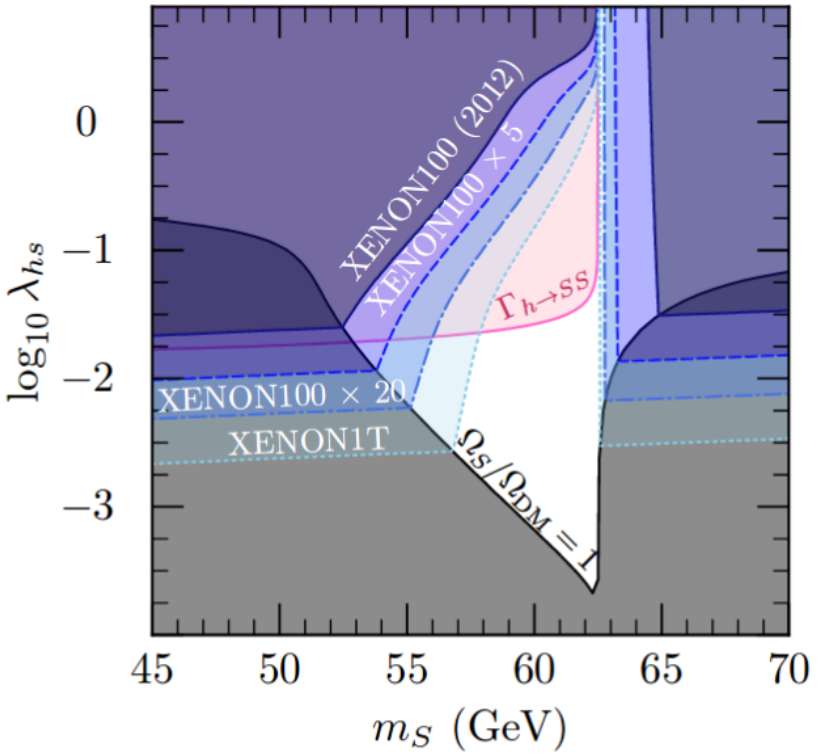
$$\mathcal{L} = \frac{1}{2}\mu_S^2 S^2 + \frac{1}{2}\lambda_{hS} S^2 |H|^2 + \frac{1}{4}\lambda_S S^4 + \frac{1}{2}\partial_\mu S \partial^\mu S.$$

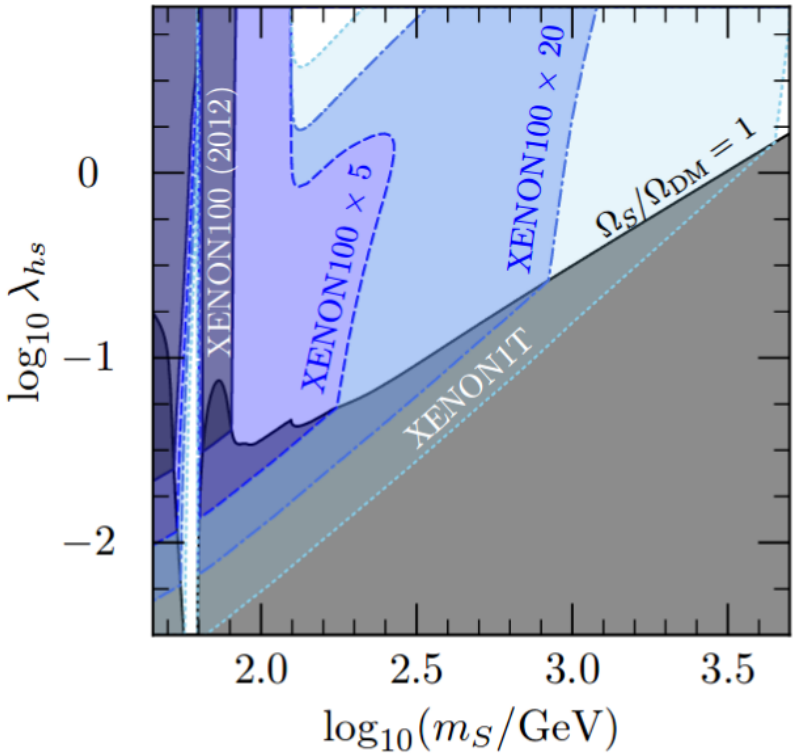
- Constraints
  - Relic density (underabundance OK)
  - LHC: Higgs invisible width
  - Direct detection: LUX, PandaX, …
  - Indirect detection: Fermi-LAT (dwarfs)
  - IceCube solar neutrinos
- Uncertainties / nuisance parameters
  - Local DM density
  - Nuclear physics parameters
  - Quark masses
  - Higgs mass
  - Gauge couplings

Status of scalar singlets

- Overplotting of exclusion limits

Cline et al., arXiv:1306.4710

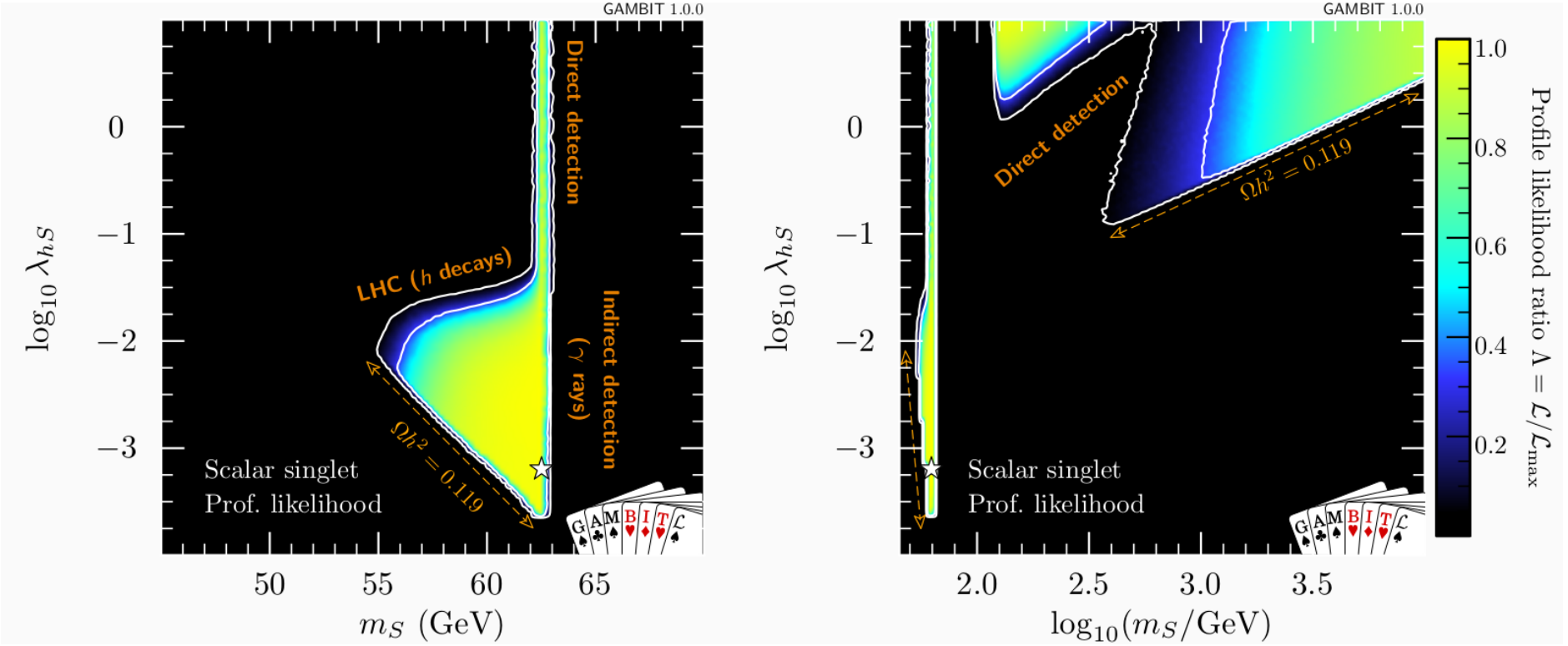




Status of scalar singlets

- Profile likelihood from global analysis

GAMBIT collaboration, arXiv:1705.07931



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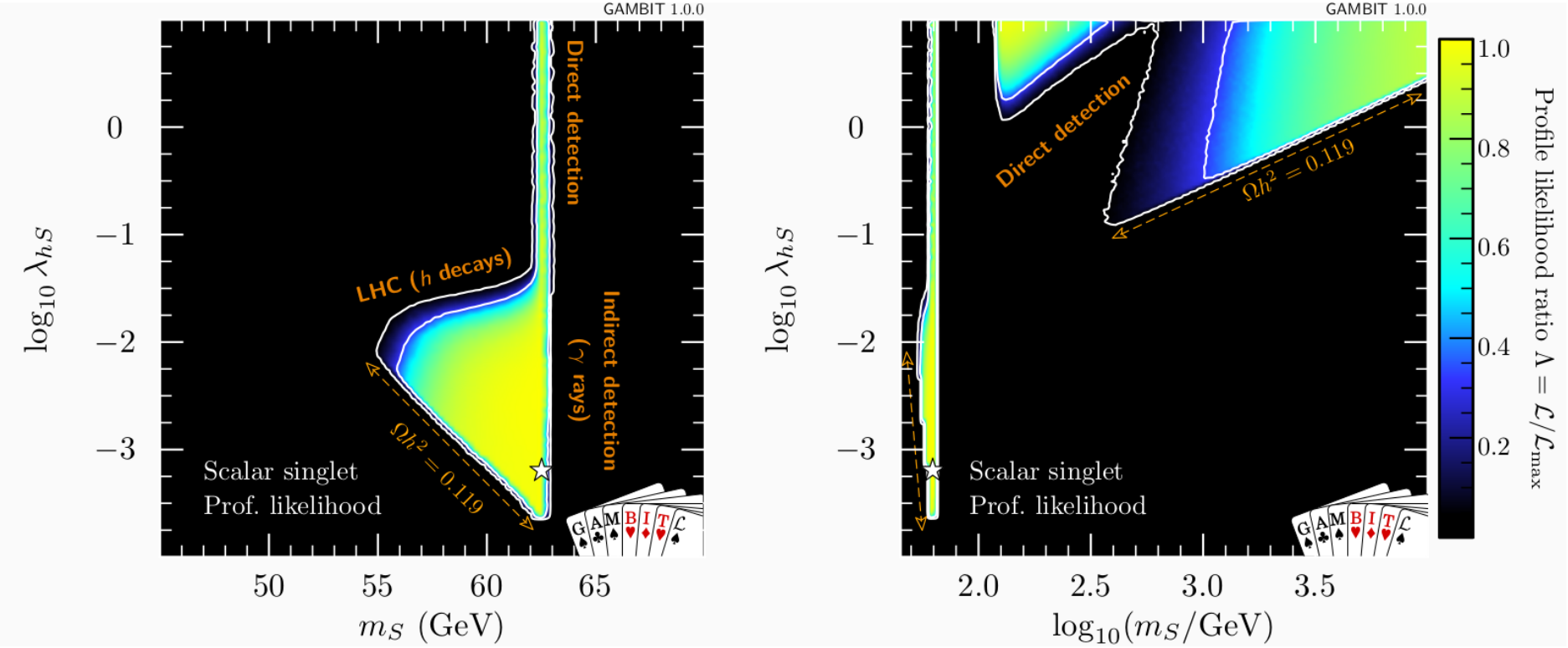
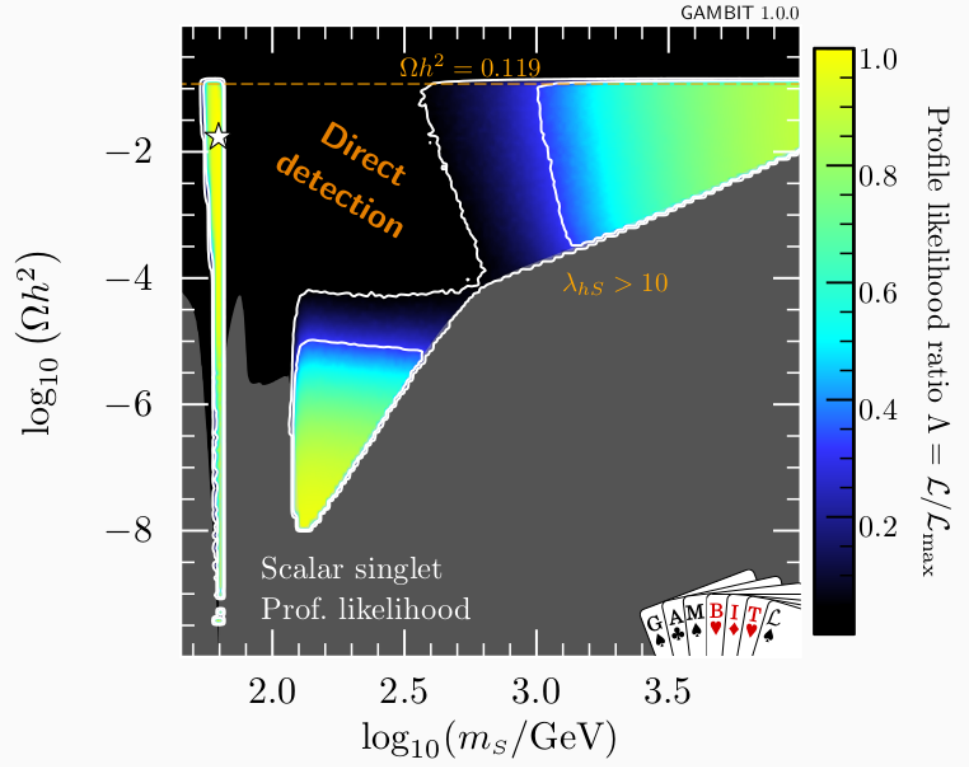
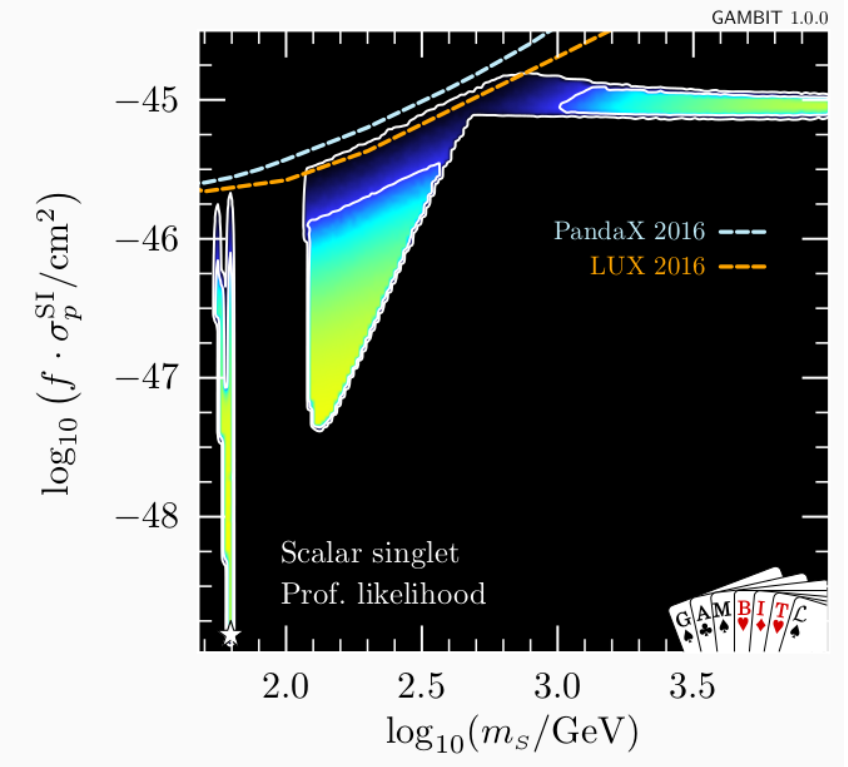


- Two viable parameter regions:
  - $m_S \sim m_h / 2$ (relic density via resonantly enhanced annihilation into quarks)
  - $m_S \sim$ TeV (relic density via annihilation into gauge and Higgs bosons)

Status of scalar singlets – a closer look

- Instructive to consider predictions for specific observables





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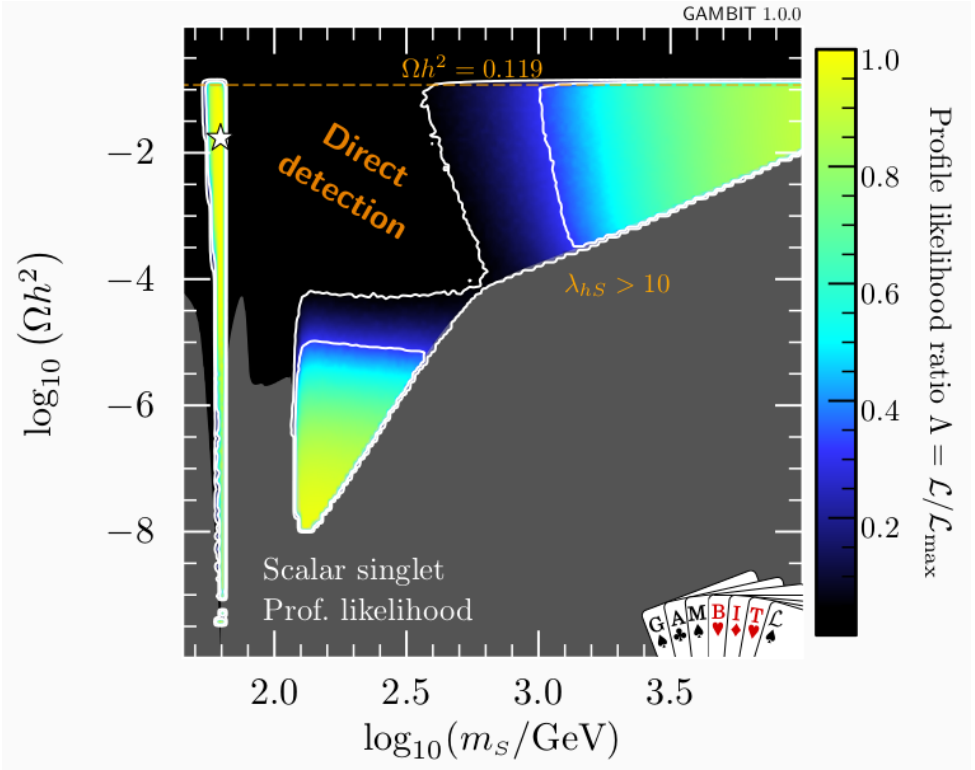

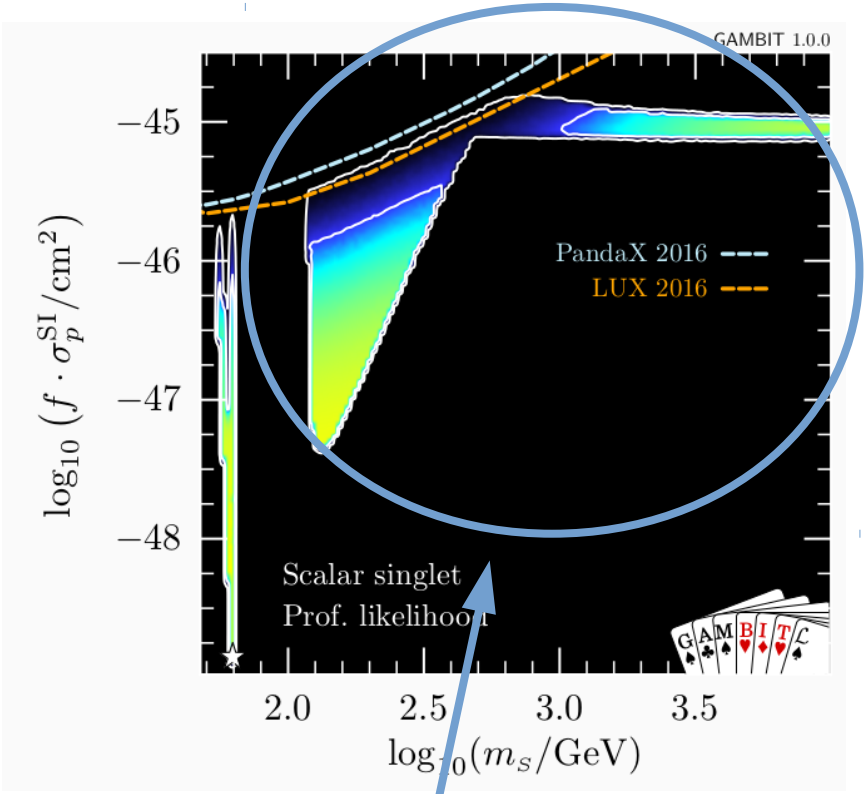

Will be tested in next-generation direct detection experiments

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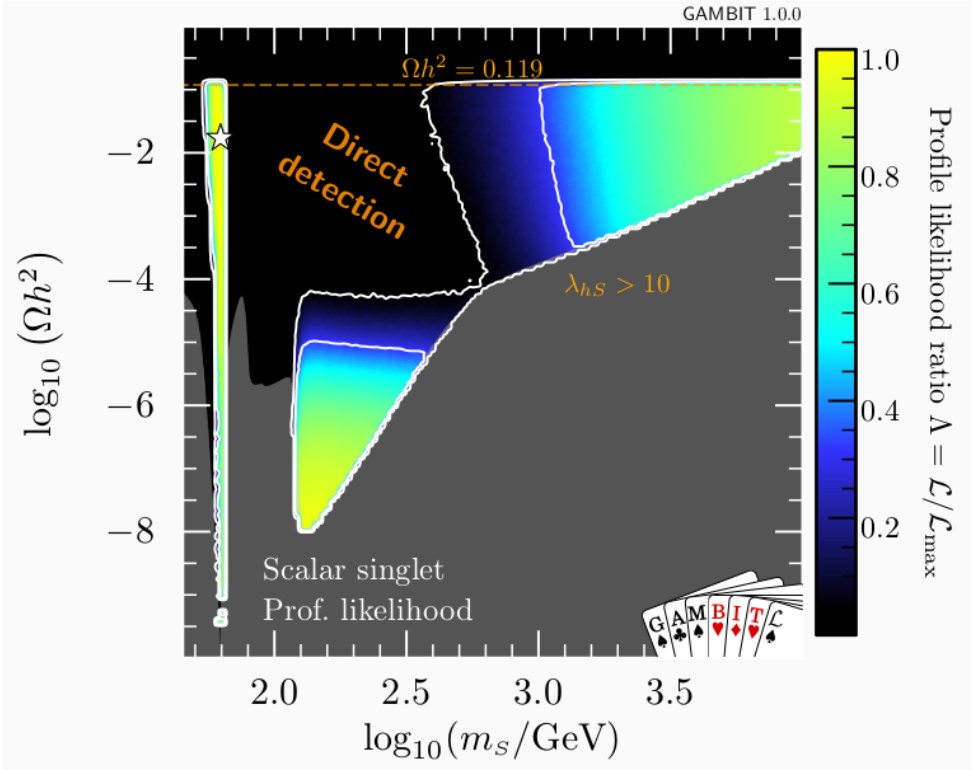
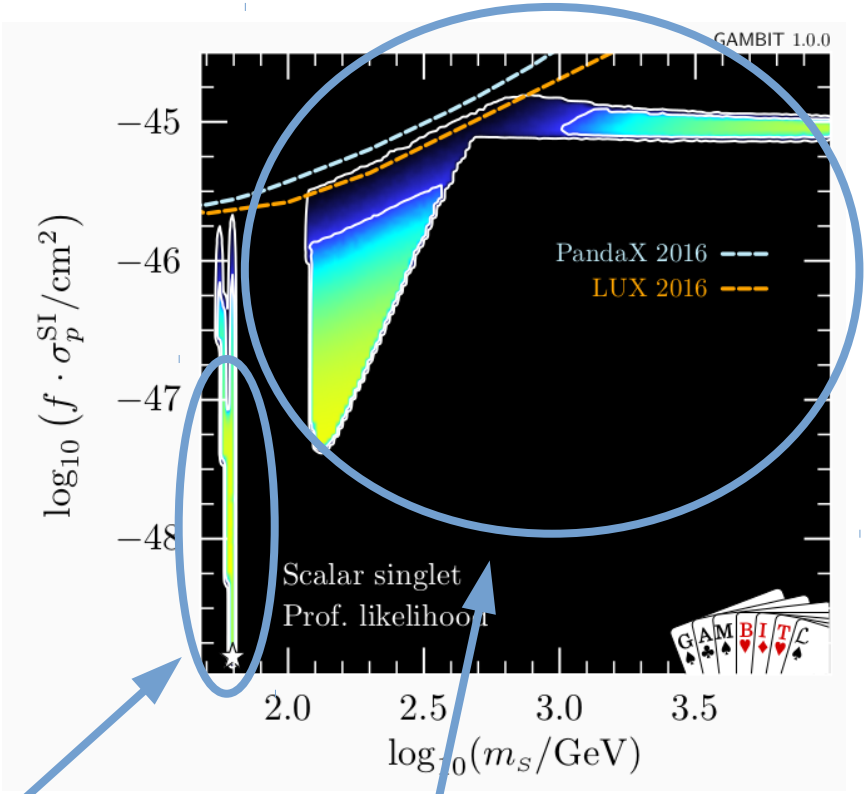


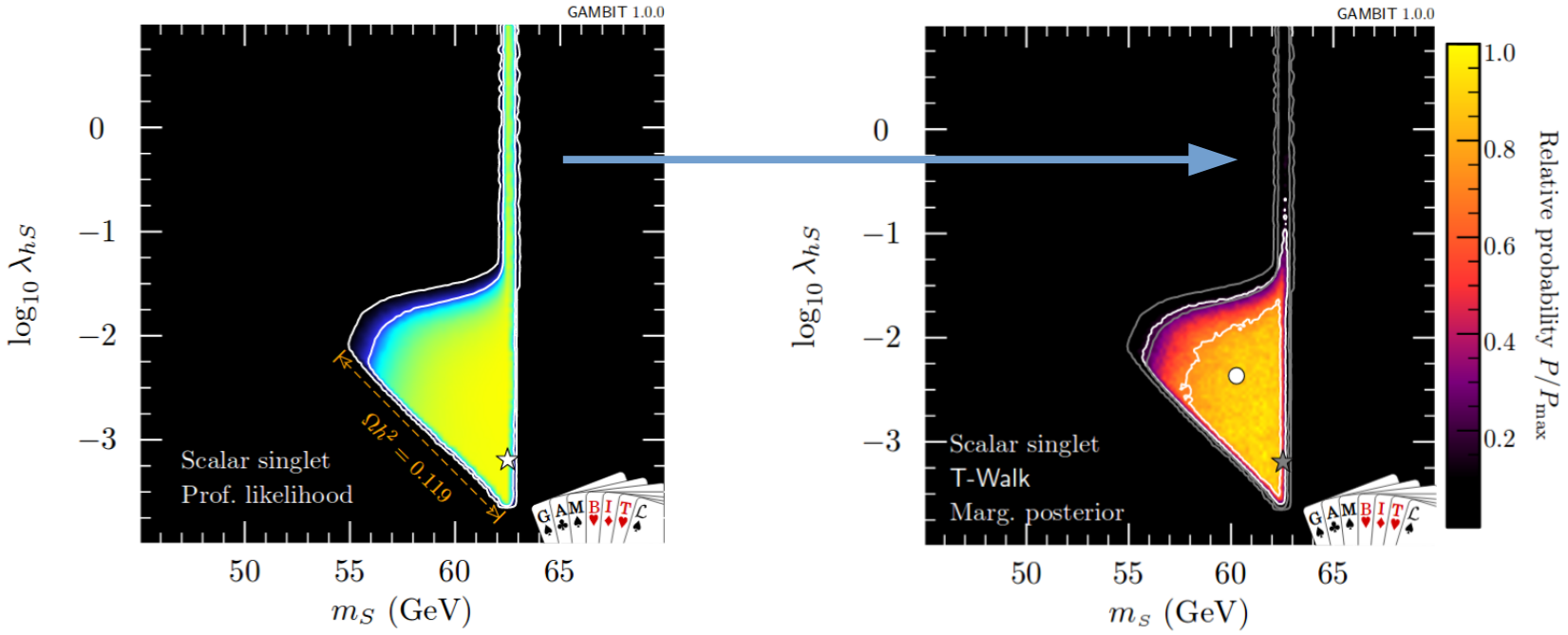


Very challenging to probe experimentally

Will be tested in next-generation direct detection experiments

Assessing fine-tuning with Bayesian scans

- 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 such tuning?
- Possible answer: Penalise fine-tuning with Bayesian statistics



Emmy Noether-Programm DFG Deutsche Forschungsgemeinschaft

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Fermionic Higgs portal

- Interesting variation: Fermionic DM instead of scalar

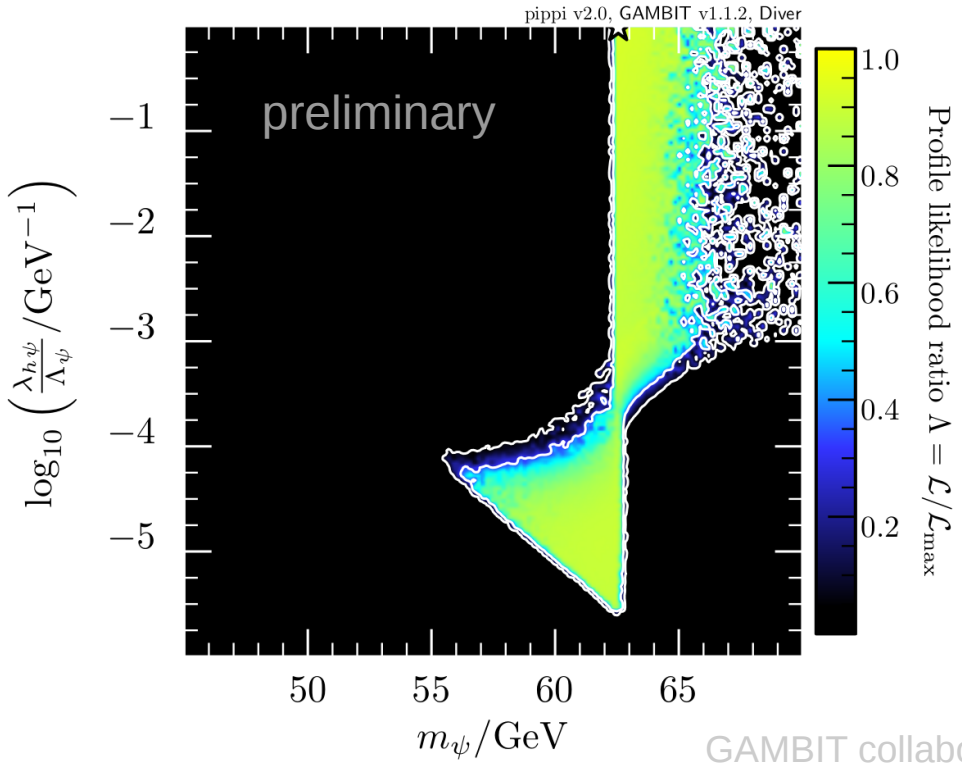
$$\mathcal{L}_\psi = \mathcal{L}_{\rm SM} + \overline{\psi}(i\partial\!\!\!/ - \mu_\psi)\psi - \frac{\lambda_{h\psi}}{\Lambda_\psi}\left(\cos\theta\,\overline{\psi}\psi + \sin\theta\,\overline{\psi}i\gamma_5\psi\right)H^\dagger H$$

  - Higgs portal operator is now dimension 5: description only valid at low energies
  - DM particle can be Dirac or Majorana fermions (phenomenology similar)
  - Additional parameter: CP phase θ, which distinguishes scalar and pseudoscalar coupling
  - For $\theta \sim \pi/2$, direct detection constraints are momentum-dependent and hence suppressed

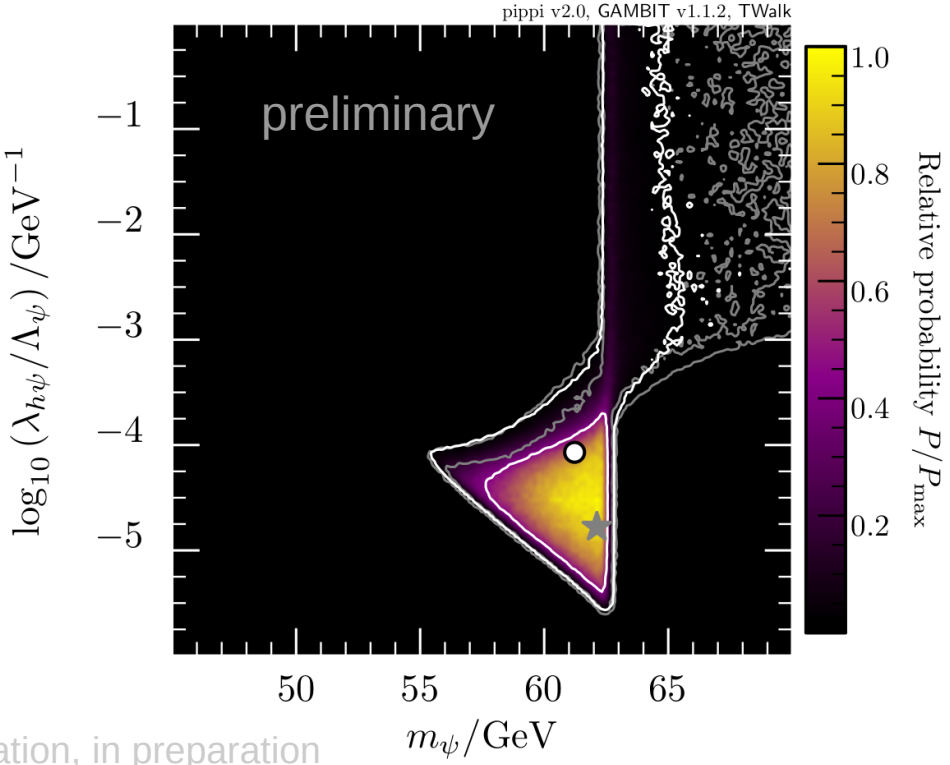
- GAMBIT analysis in preparation!
  - Full calculation of direct detection constraints and solar capture & many new experiments
  - Including additional nuisance parameters for the DM velocity distribution

Status of the fermionic Higgs portal

Profile likelihood (frequentist scan)



Marginalised posterior (Bayesian scan)



GAMBIT collaboration, in preparation

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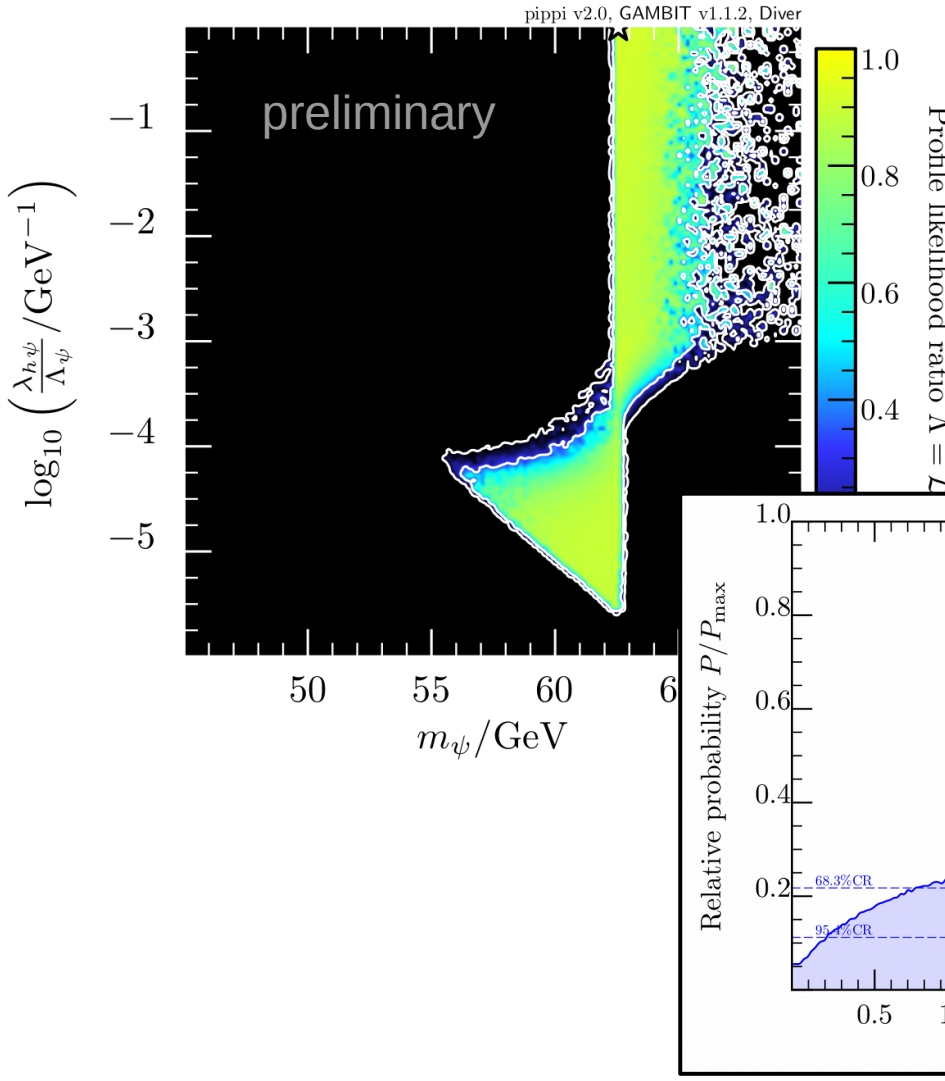

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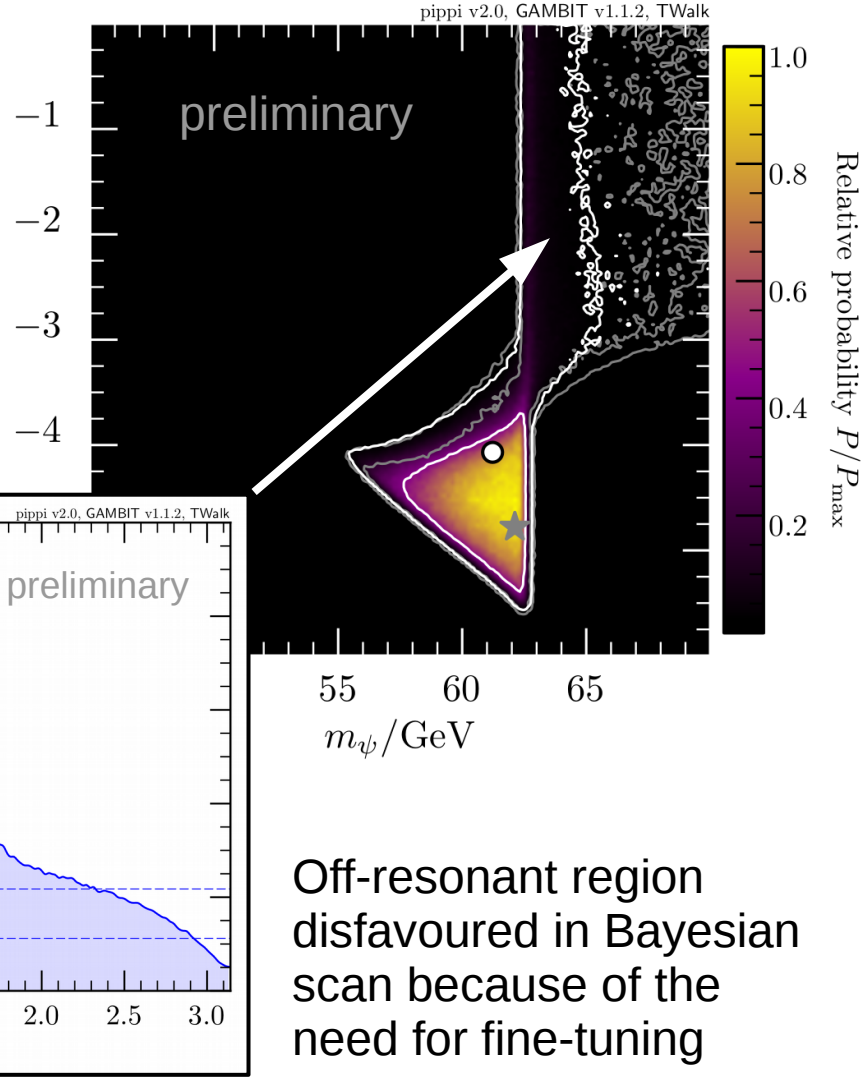
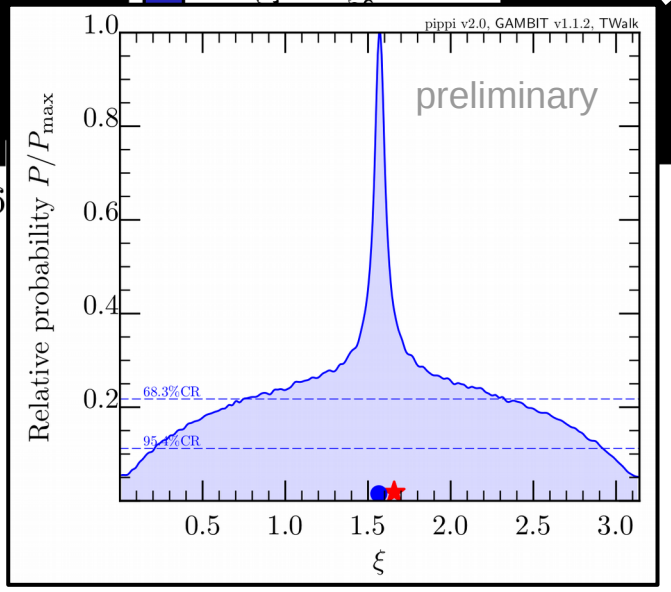




Off-resonant region disfavoured in Bayesian scan because of the need for fine-tuning

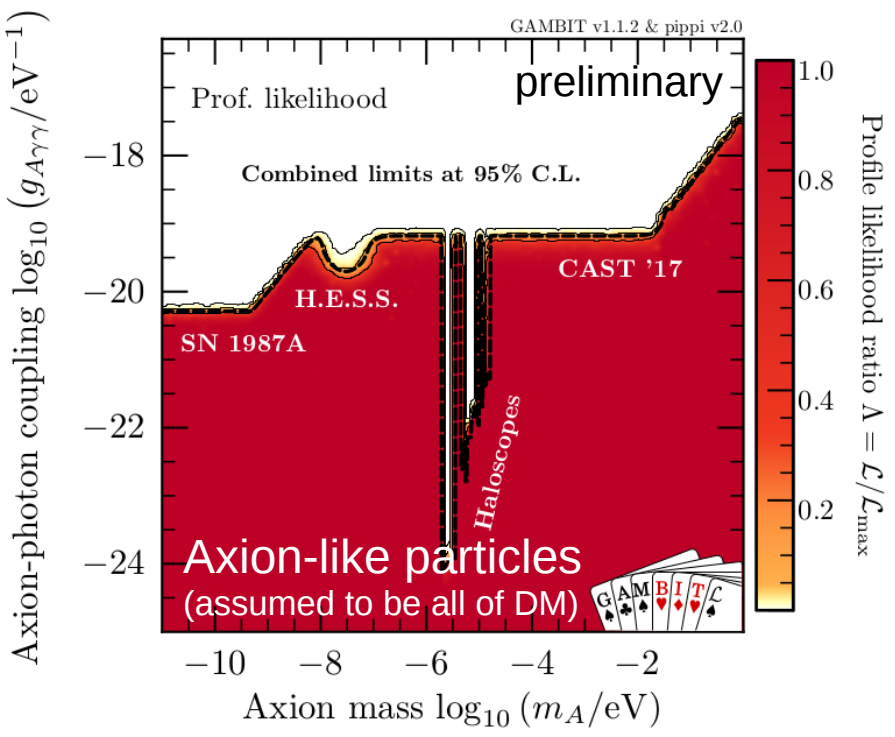
The status of WIMPs

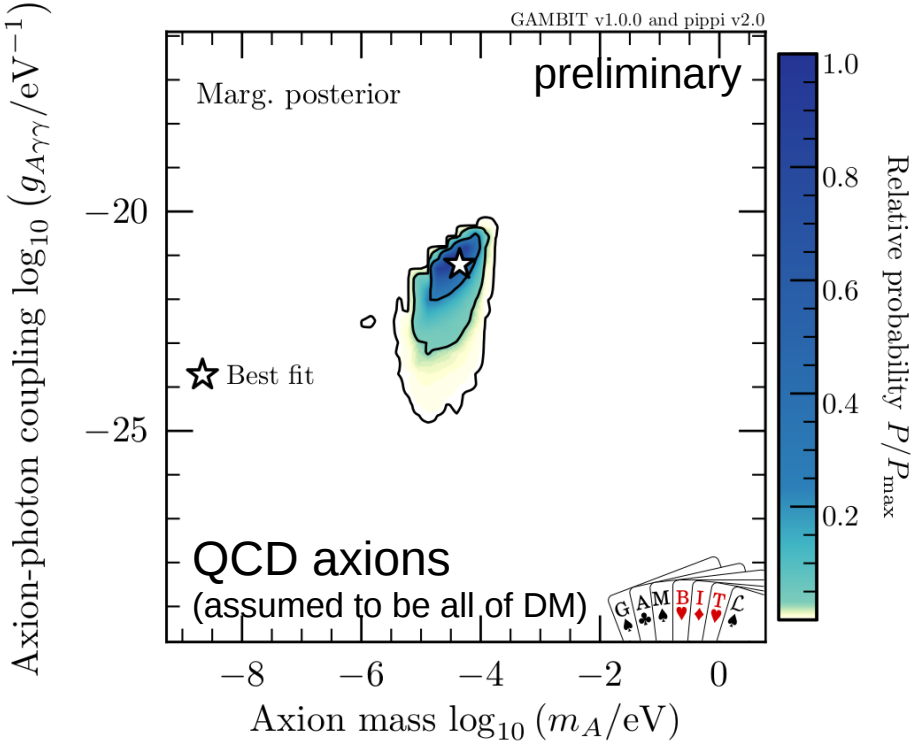
- There are many strong constraints on WIMP models
- Even some of the simplest WIMP models are still viable
- Example: (Scalar) Higgs portal
  - High-mass region will soon be probed by direct detection experiments
  - Resonance region difficult to probe, but somewhat fine-tuned
- Constraints can be further relaxed by introducing additional parameters (e.g. CP-violating phases)
- Essential to quantify the complexity and fine-tuning of WIMP models to assess their viability (e.g. using Bayesian evidence and model comparison)

What if it's not WIMPs?

- GAMBIT can also be used to explore a wide range of alternatives to the WIMP idea
  - Axions
  - Sterile neutrinos
  - Asymmetric dark matter
  - …

Hoof, Bloor, FK, Scott, Weniger & White, in preparation





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Interested in DM direct detection?
Try DDCalc!

DDCalc

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:

- `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)
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Coming soon
DDCalc v2.0.0
including the full set of non-relativistic effective operators