



# Global fits of the scalar singlet model using GAMBIT

on behalf of the GAMBIT collaboration

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James McKay

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Imperial College London

# Outline

1. Introduce GAMBIT
2. Scalar singlet results
3. Scanner performance tests

## Global fits

What do we mean by *global fits*?

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- Many beyond standard model theories
  - → many parameters
- Many experiments/observations
  - → many constraints

Combining all constraints to explore the parameter space of models, and make statistical comparisons between models → global fits.

# GAMBIT

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# The GAMBIT Collaboration

31 members, 11 countries, 9 Experiments, 4 major theory codes

- **ATLAS** A. Buckley, P. Jackson, C. Rogan, M. White
- **LHCb** M. Chrzaszcz, N. Serra
- **Belle-II** F. Bernlochner, P. Jackson
- **Fermi-LAT** J. Conrad, J. Edsjö, G. Martinez,  
P. Scott
- **CTA** C. Balázs, T. Bringmann,  
J. Conrad, M. White
- **HESS** J. Conrad
- **IceCube** J. Edsjö, P. Scott
- **XENON/DARWIN** J. Conrad, R. Trotta
- **Theory** P. Athron, C. Balázs, T. Bringmann,  
J. Cornell, J. Edsjö, B. Farmer, T. Gonzales, A. Fowlie,  
J. Harz, S. Hoof, F. Kahlhoefer, A. Krislock,  
A. Kvellestad, M. Pato, F. Mahmoudi,  
J. McKay, A. Raklev, P. Scott, R. Trotta,  
C. Weniger, M. White, S. Wild.



## The Global and Modular Beyond the SM Inference Tool

- **modular and flexible**
- plug and play with other tools for scanning and physics
- a large set of models, not just SUSY – e.g. SingletDM, many MSSM variants + future generalised SingletDM, Minimal DM, 2 Higgs doublet models ...
- Extensive observable/data libraries (likelihood modules)
- Statistical flexibility – Bayesian/frequentist, likelihood definitions, scanning algorithms
- A smart and *fast* LHC likelihood calculator
- Massively parallel
- Full open-source code release

# Dependency Resolution



- Module functions and backend functions get arranged into a **dependency tree**
- Starting with requested observables and likelihoods, GAMBIT fills each dependency and backend requirement
- Obeys **rules** at each step: allowed models, allowed backends, constraints from input file, etc
- → tree constitutes a directed acyclic graph
- → GAMBIT uses graph-theoretic methods to 'solve' the graph to determine function evaluation order

## Scalar singlet results

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## Scalar singlet model

One of the simplest classes of dark matter models – one new scalar  $S$

$$\mathcal{L}_S = \frac{1}{2} \partial_\mu S \partial^\mu S - m_S^2 S^2 - \lambda_{SH} S^2 |H|^2 - \lambda_S S^4$$

$\mathbb{Z}_2$  ( $S \rightarrow -S$ ) symmetry stabilises  $S$

- Stable dark matter candidate
- Viable regions of parameter space yet to be excluded
- Stabilises electroweak potential

For this global fit we deal with the  $\lambda_S = 0$  model.

## Included likelihoods

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- SM nuisance parameters – Higgs and quark masses,  $G_F$
- Higgs invisible width
  - simple implementation of LHC limits on  $\Gamma_{hh} \rightarrow \text{invisible}$
- Direct detection
  - XENON100 (2012)
  - LUX (2015) + (2016)
  - PandaX (2016)
  - SuperCDMS (2014)
- Indirect detection
  - Fermi-LAT observations of dwarf spheroidal galaxies
- IceCube (79 string) – bounds on DM annihilation to solar neutrinos
- Relic density,  $\Omega$ , and local DM density,  $\rho_0$
- Nuclear uncertainties –  $\sigma_s, \sigma_I$ , these affect the Higgs-nucleon coupling – important for direct detection

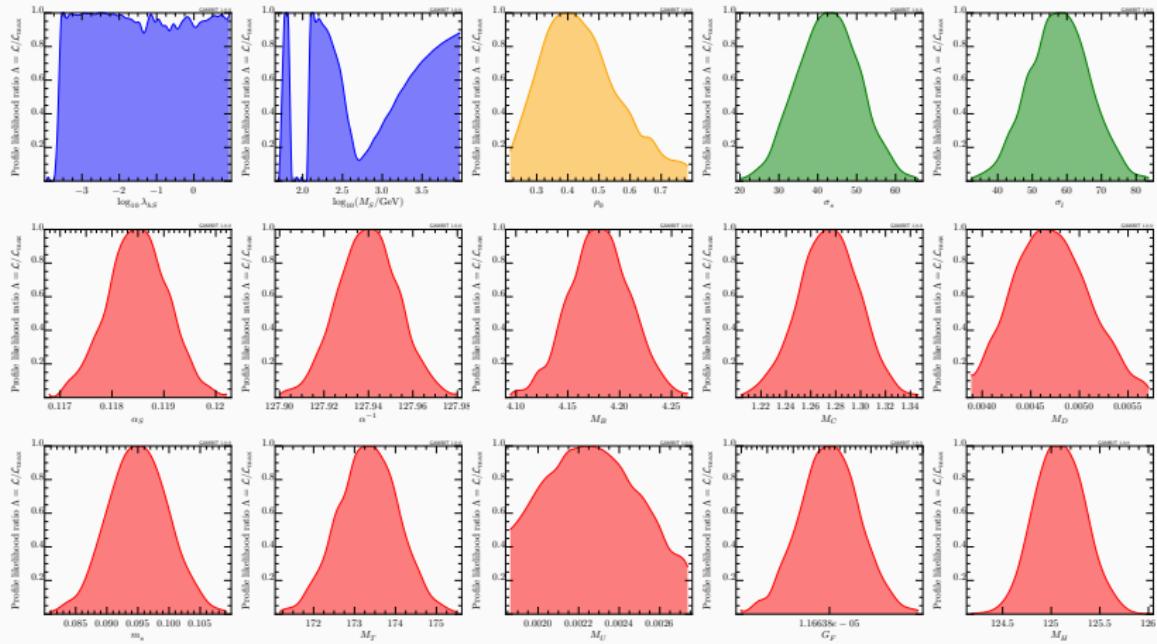
## Backends/external codes utilised in this study

- DarkSUSY
  - Boltzman solver for relic density
- gamLike
  - indirect detection of gamma rays
- DDCalc 1.0
  - direct detection
- nulike
  - neutrino telescope likelihoods (IceCube)
- Multinest, GreAT
  - parameter scanning
- *Micromegas* – relic density (is available but not primarily used in this study)

## SM and astrophysical nuisance parameters

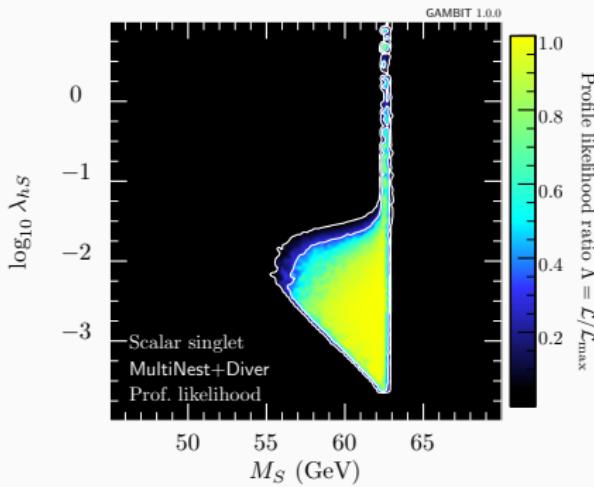
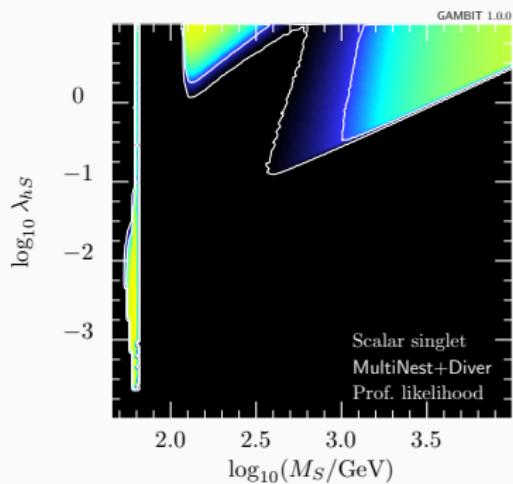
Parameter	Range
$G_F$	$(1.1663775 - 1.1663799) \times 10^{-5}$
$\alpha_s(M_Z)$	$0.1173 - 0.1197$
$\alpha^{-1}(M_Z)$	$127.898 - 127.982$
$m_d(2 \text{ GeV})$	$(4.2 - 5.8) \times 10^{-3} \text{ GeV}$
$m_u(2 \text{ GeV})$	$(1.3 - 3.7) \times 10^{-3} \text{ GeV}$
$m_s(2 \text{ GeV})$	$(85 - 105) \times 10^{-3} \text{ GeV}$
$m_b(m_b)$	$(4.09 - 4.27) \text{ GeV}$
$m_c(m_c)$	$(1.2 - 1.35) \text{ GeV}$
$m_t$	$(171.06 - 175.62) \text{ GeV}$
$m_h$	$(124.1 - 127.3) \text{ GeV}$
$\sigma_s$	$27.0 - 59.0 \text{ MeV}$
$\sigma_I$	$40.0 - 76.0 \text{ MeV}$
$\rho_0$	$0.2 - 0.8 \text{ GeV cm}^{-3}$

# 1D profile likelihoods



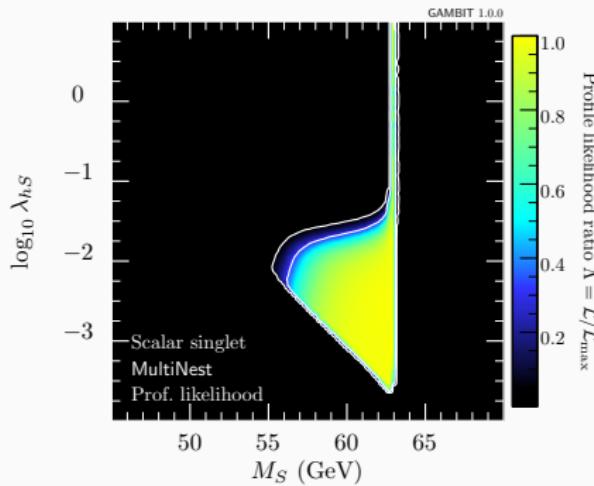
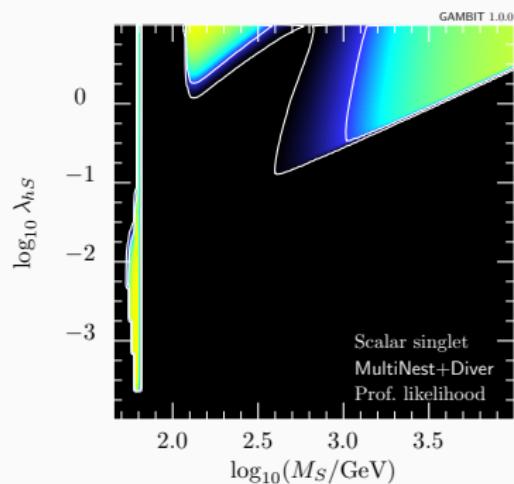
# 2D profile likelihood

15 dimensional scan – all nuisance parameters varied



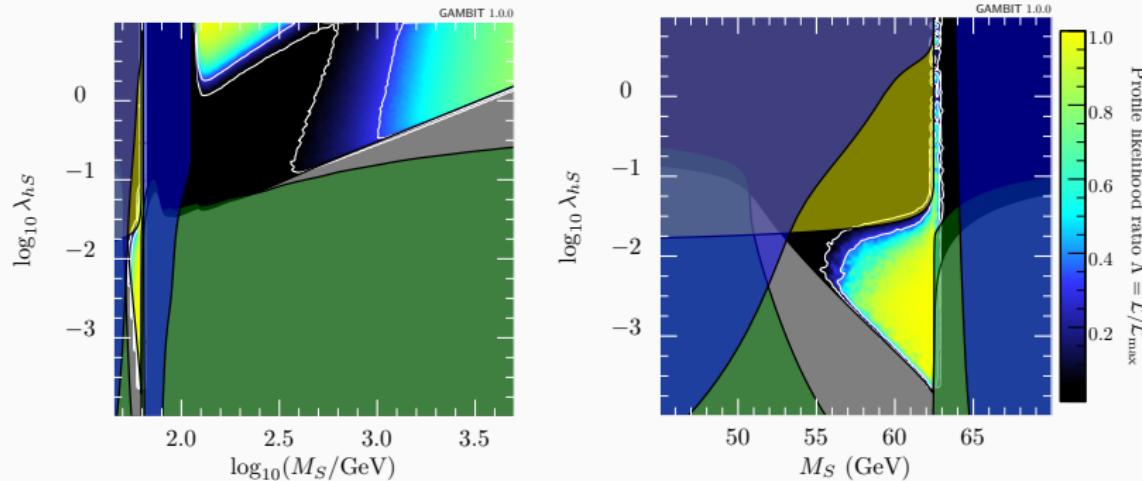
# 2D profile likelihood

2 dimensional scan –  $\lambda_{hS}$  and  $M_S$



## 2D profile likelihood

Compared to most recent study: *Combined analysis of effective Higgs portal dark matter models* [Beniwal et al., 2016].



Blue – Direct detection (LUX 2013 90% CI)

Green – Indirect detection (Fermi-LAT)

Grey – relic density

Yellow – Higgs invisible width

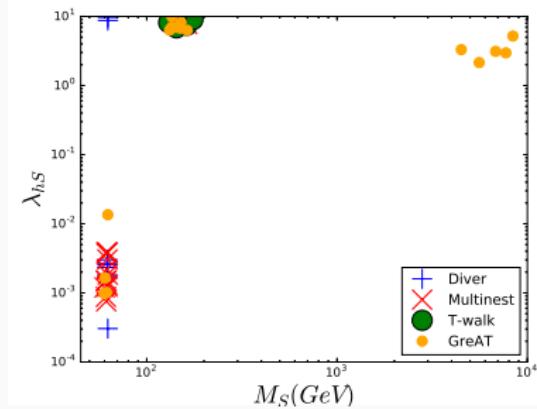
# The best-fit point

Best-fit point:

$$(\lambda_{hS}, M_S) = (3.8 \times 10^{-3}, 62.5 \text{ GeV})$$

Gives near identical quality fit to the SM, it is also highly degenerate across parameter space.

Best-fit points from various scans:



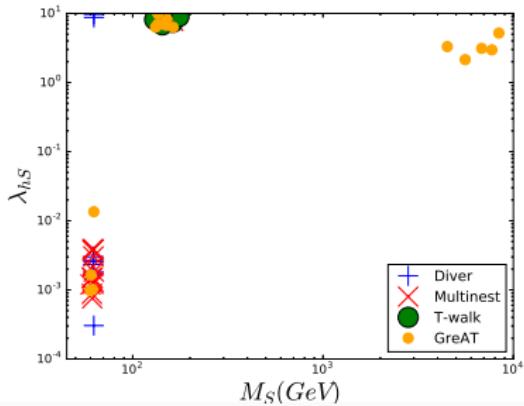
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Best-fit point:

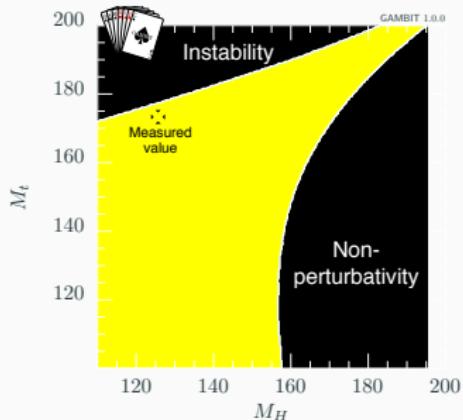
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Best-fit points from various scans:



- Some of these points would be non-perturbative.
- Full study of perturbativity and vacuum stability in preparation.
- The  $M_H$ ,  $M_t$  parameter space of the scalar singlet model:



## **Scanner comparisons**

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## Parameter scanning algorithms

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- **Multinest** – *existing package*

Nested sampling – efficient sampling of posterior distribution while also providing profile likelihood and optimisation

- **GreAT** – *existing package*

Markov Chain Monte Carlo (MCMC)

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- **Diver** – *new in GAMBIT!*

Differential evolution – efficient global optimisation in multi-modal many dimensional problems. Vector addition between population members provides highly adaptive sampling

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Ensemble MCMC – adaptive proposal distribution based on all chains

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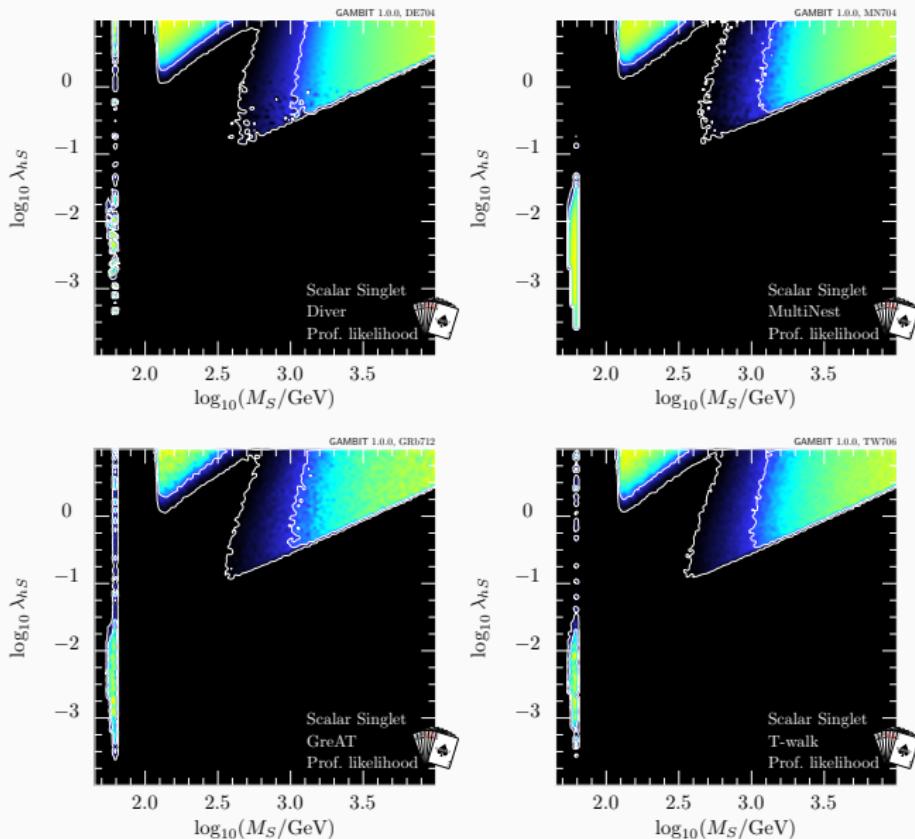
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- **“Toy scanners”**

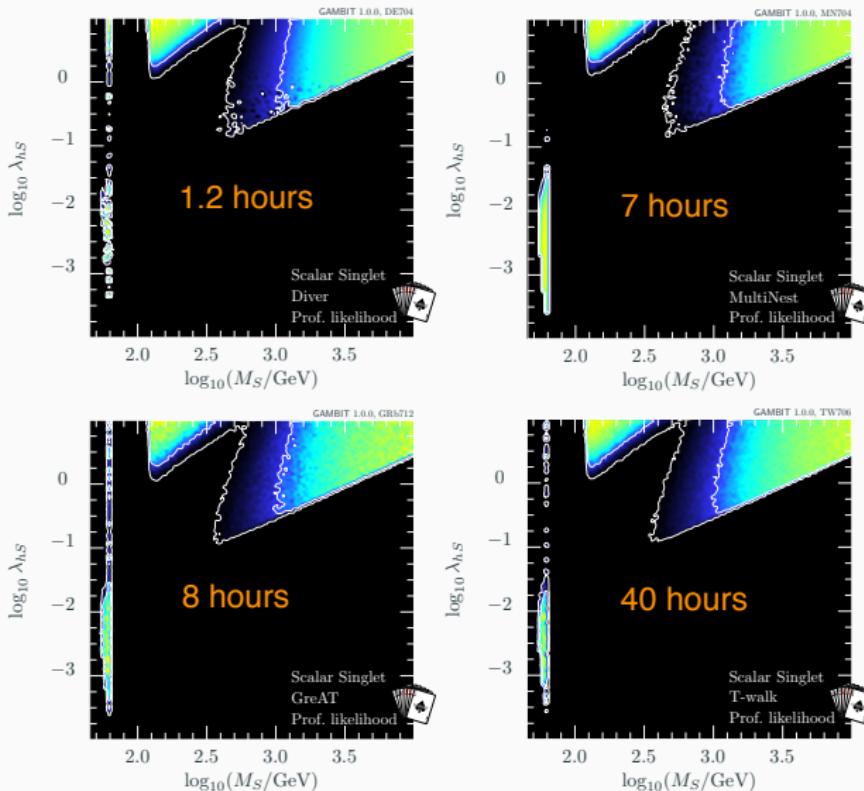
Grid, random sampler, list based sampler ...

# Extensive scanner comparisons (preliminary example in 7D)

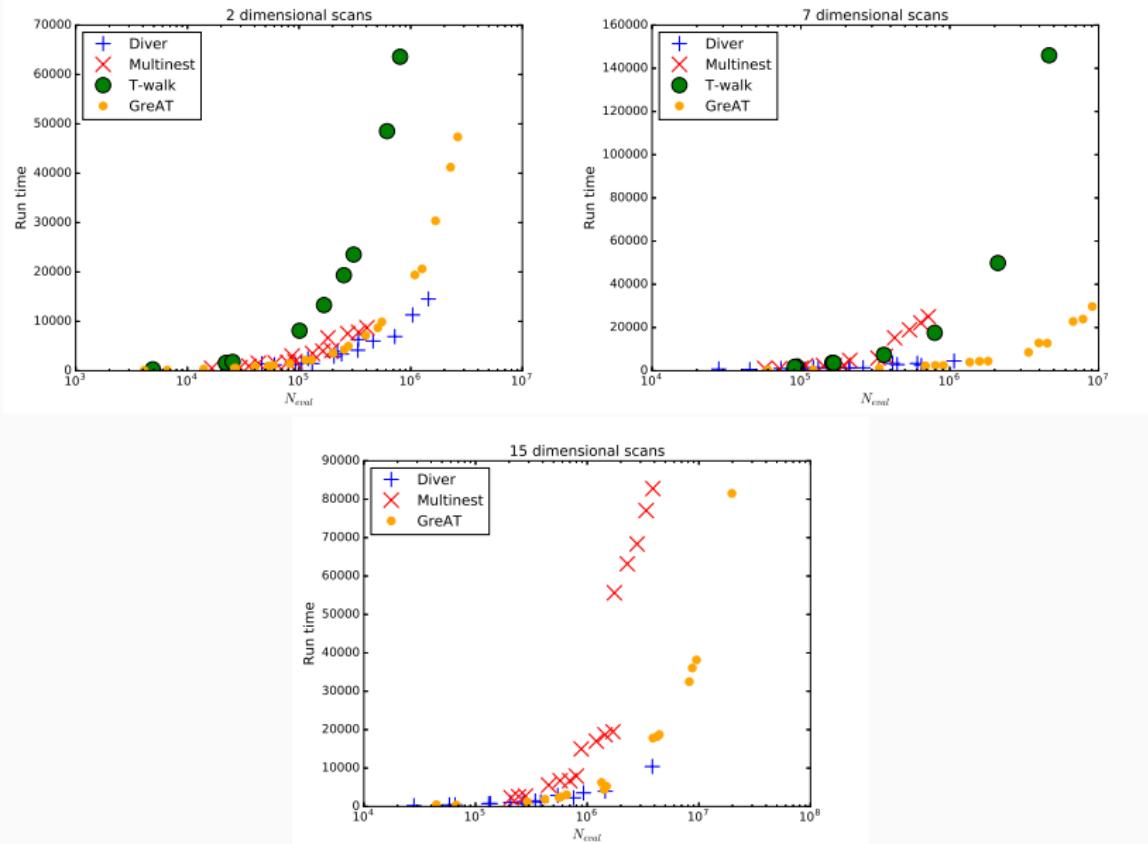


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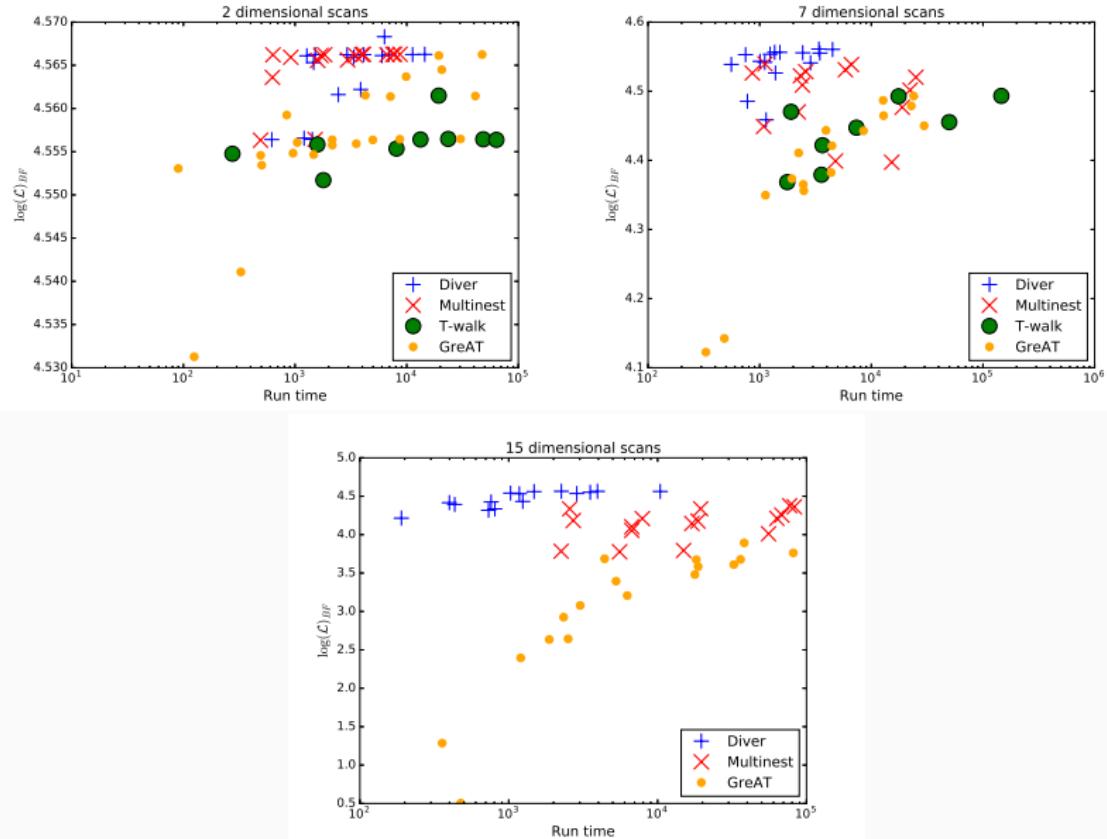
Fair comparisons are difficult – time is one metric



# Extensive scanner comparisons (preliminary example)



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# Outlook

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- Public code release in Jan/Feb
- Simultaneous with 9 papers: 3 physics papers (SingletDM, GUT-scale MSSM, Weak-scale MSSM), 1 “GAMBIT Core” paper, 5 module papers
- Future releases with
  - more models!
  - interfaces with SARAH, FeynRules, MadGraph, CalcHEP, etc

## References

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-  Beniwal, A., Rajec, F., Savage, C., Scott, P., Weniger, C., White, M., and Williams, A. G. (2016).  
**Combined analysis of effective Higgs portal dark matter models.**  
*Physical Review D*, 93:115016.