Multimessenger astroparticle physics for testing theories of dark matter and new particles

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on behalf of the GAMBIT Collaboration

gambit.hepforge.org

Combining searches I

Question

How do we know which dark matter theories are good and which are bad?

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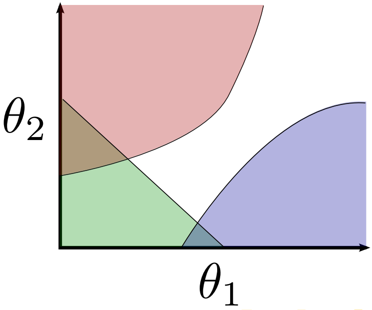
Answer

Combine the results from different searches

- Simplest method: overplot exclusions



That's all well and good if there are only 2 parameters and few searches. . .

Question

What if there are many different constraints?

Combining searches II

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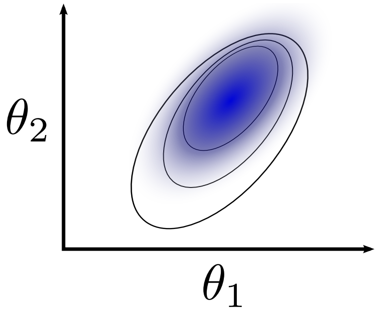
Question

What if there are many different constraints?

Answer

Combine constraints in a statistically valid way
$\rightarrow$ composite likelihood



Combining searches III

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What if there are many parameters?

Answer

Need to

- scan the parameter space (smart numerics)
- interpret the combined results (Bayesian / frequentist)
- project down to parameter planes of interest (marginalise / profile)

$\rightarrow$ global fits

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$\rightarrow$ global fits

Question

And what if you want to do it all again for many different models?

GAMBIT: The Global And Modular BSM Inference Tool

gambit.hepforge.org EPJC **77** (2017) 784 arXiv:1705.07908

- Extensive model database – not just SUSY
- Extensive observable/data libraries
- Many statistical and scanning options (Bayesian & frequentist)
- *Fast* LHC likelihood calculator
- Massively parallel
- Fully open-source
- Fast definition of new datasets and theories
- Plug and play scanning, physics and likelihood packages

Members of:
ATLAS, Belle-II, CLiC, CMS, CTA, *Fermi*-LAT, DARWIN, IceCube, LHCb, SHiP, XENON

Authors of:
DarkSUSY, DDCalc, Diver, FlexibleSUSY, gamlike, GM2Calc, IsaTols, nulike, PolyChord, Rivet, SoftSUSY, SuperISO, SUSY-AI, WIMPSim

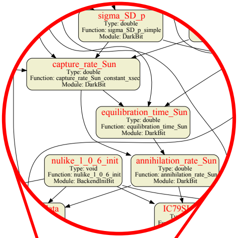
Recent collaborators:
Peter Athron, Csaba Balázs, Ankit Beniwal, Sanjay Bloor, Torsten Bringmann, Andy Buckley, José Eliel Camargo-Molina, Marcin Chrząszcz, Jonathan Cornell, Matthias Danninger, Joakim Edsjö, Ben Farmer, Andrew Fowlie, Tomás E. Gonzalo, Will Handley, Sebastian Hoof, Selim Hotinli, Felix Kahlhoefer, Anders Kvellestad, Julia Harz, Paul Jackson, Farvah Mahmoudi, Greg Martinez, Are Raklev, Janina Renk, Chris Rogan, Roberto Ruiz de Austri, Pat Scott, Patrick Stöcker, Aaron Vincent, Christoph Weniger, Martin White, Yang Zhang

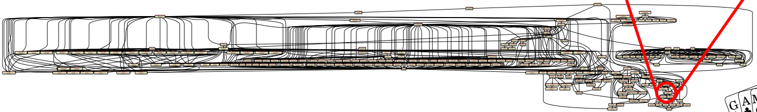
40+ participants in 11 experiments and 14 major theory codes

GAMBIT in a nutshell

[Eur. Phys. J. C (EPJC), arXiv:1705.07908]

- User chooses a model to scan, which observables to include, and the scanning method
- GAMBIT constructs a **dependency tree**
  1. Identifies which functions and inputs are needed to compute the requested observables
  2. Obeys **rules** at each step: allowed models, allowed backends, constraints from input file, etc
     $\rightarrow$ tree constitutes a directed acyclic graph
  3. Uses graph-theoretic methods to ‘solve’ the graph to determine function evaluation order
- GAMBIT scans the parameter space by calling the necessary module and backend functions in the optimal order, for each parameter point





Dark matter is in **DarkBit**

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- Direct detection: XENON1T, LZ, LUX, PandaX, PICO, DarkSide, SuperCDMS, CDMSLite, CRESST-II, SIMPLE

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Dark matter constraints in GAMBIT (EPJC, arXiv:1705.07920)

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- various models for Milky Way halo (ρ & v)
- interfaces to other codes: `nulike`, `DDCalc`, `DirectDM`, `DarkSUSY`, `MicrOmegas`, `gamLike`, `Capt'n General`

GAMBIT results

Supersymmetric dark matter:

- CMSSM/NUHM1/NUHM2 (EPJC, arXiv:1705.07935)
- MSSM7 (EPJC, arXiv:1705.07917)
- 3.3σ local excess in combination of 12 different SUSY searches at the LHC, consistent in the (*non-simplified*) MSSM (EPJC, arXiv:1809.02097)

Other dark matter theories:

- Higgs portal: scalar singlet (EPJC, arXiv:1806.11281)
- Higgs portal: fermionic and vector singlet (EPJC, arXiv:1808.10465)
- Axions and axion-like particles (JHEP arXiv:1810.07192)

Not focused on dark matter:

- Right-handed neutrinos (arXiv:1908.02302)
- Two Higgs Doublet Models (coming soon)
- Heavy(ish) unstable axion-like particles (ALPs) (coming soon)

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A couple of important notes about the parameter scans:

- All dark matter signals consistently scaled for predicted abundance
- Both profile likelihoods and Bayesian posteriors
- Sampling mostly with Diver (differential evolution) & T-walk (ensemble MCMC)

Higgs Portal Singlet Dark Matter

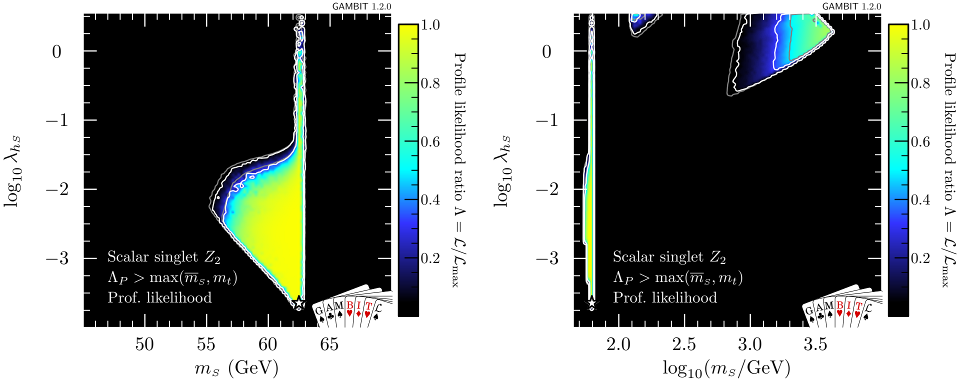
Simplest example of a dark matter theory

$$\mathcal{L}_X \approx -\frac{\mu_X^2}{2}X^2 - \frac{\lambda_{hX}}{2}X^2H^\dagger H + \ldots$$

- X = gauge singlet scalar (spin 0), fermion (spin $\frac{1}{2}$) or vector (spin 1)
- X odd under an unbroken $\mathcal{Z}_2$ symmetry $\rightarrow$ absolutely stable
- Interaction with Higgs boson h gives usual WIMP-like phenomenology:
  - direct detection
  - indirect detection
  - thermal production
  - monojets @LHC
    but also: potential for invisible Higgs decays $h \rightarrow XX$ @LHC

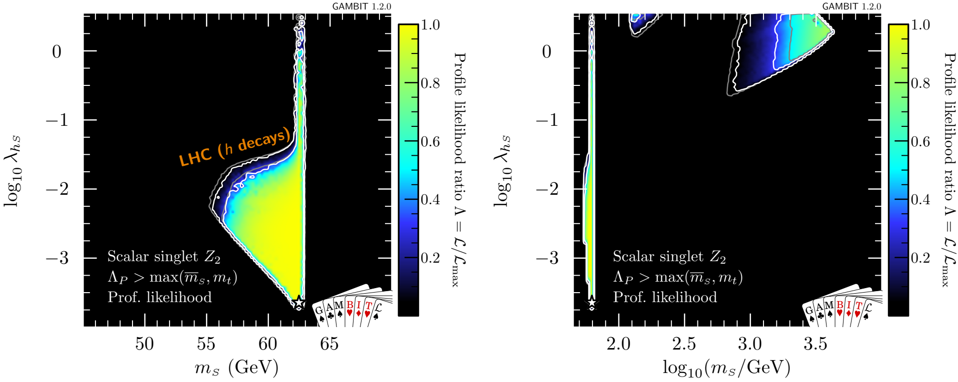
Scalar Higgs Portal dark matter

(EPJC, arXiv:1806.11281)



White = 1σ, 2σ with XENON1T 2018

Direct detection and relic density the most constraining



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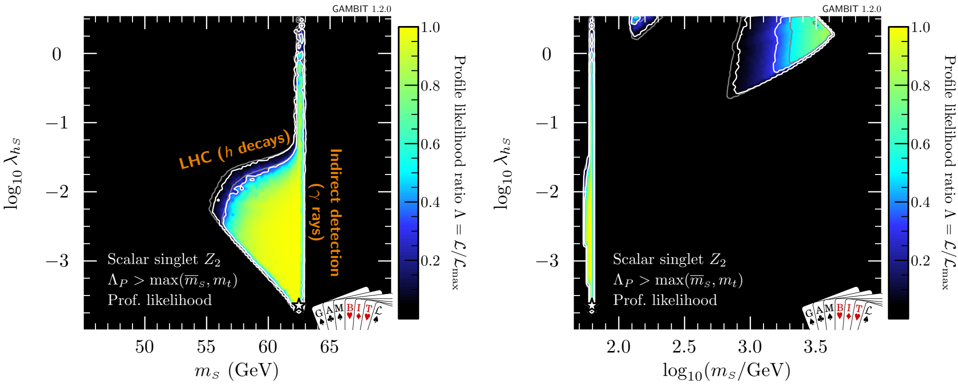

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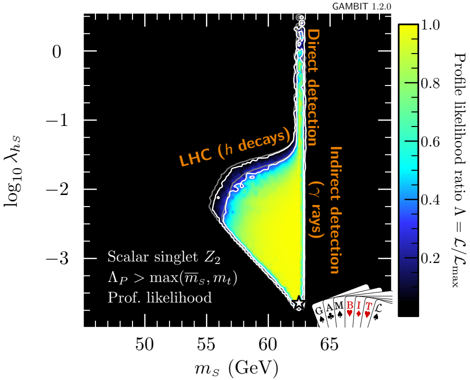

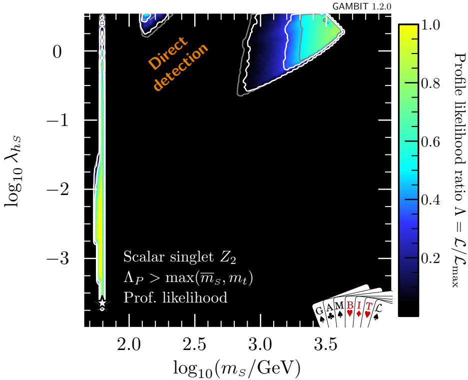

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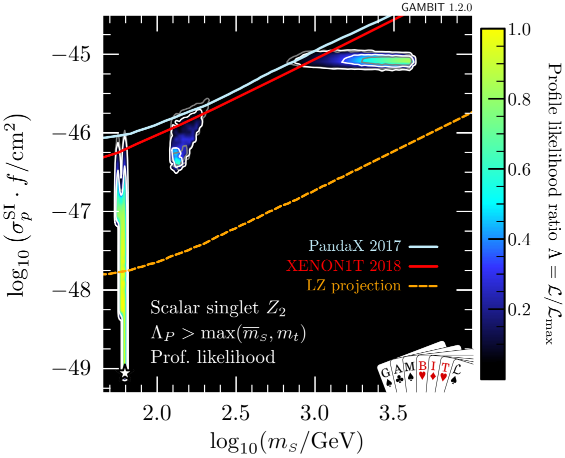

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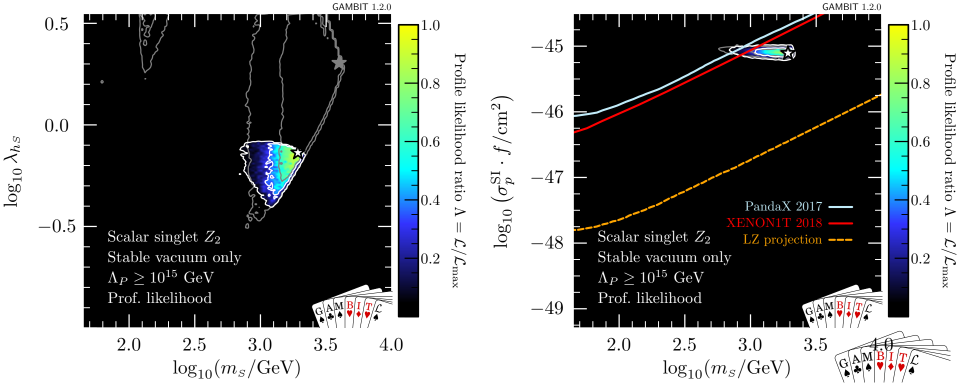
Direct detection and relic density the most constraining

Can the $\mathbb{Z}_2$ scalar singlet provide vacuum stability?

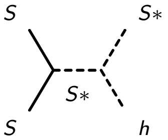
$\mathbb{Z}_2$ scalar singlet can stabilise the vacuum of the Universe

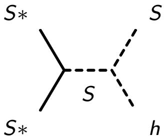
- Preferred mass of $\sim$2 TeV, $\sigma_{\rm SI} \sim 10^{-45}$ cm^2 to do so
- explains all of dark matter
- matches slight preference for signal in XENON1T data
- good fit to all observables ($p \sim 0.5$) $\implies$ interesting... (?)



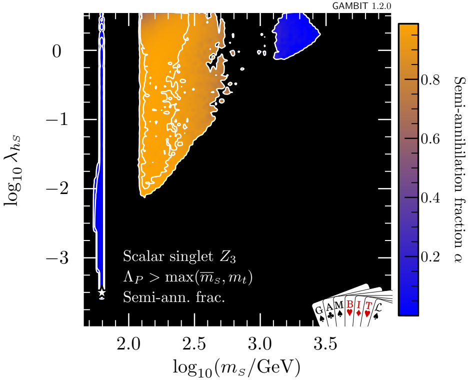
But why only $\mathbb{Z}_2$? $\mathbb{Z}_3$ works too, right? (EPJC, arXiv:1806.11281)

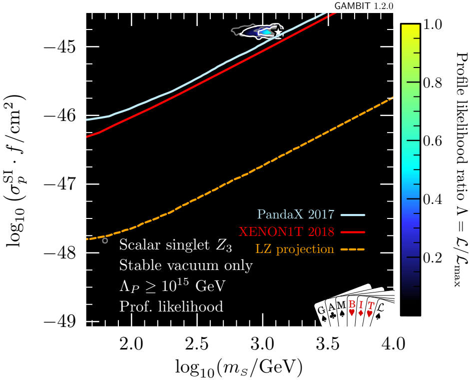
- All we were trying to achieve with the $\mathbb{Z}_2$ symmetry was to prevent dark matter decay $S \to SM + SM$
- Can be achieved with any other discrete symmetry, e.g. $\mathbb{Z}_3$
- $\mathcal{L}_S = -\mu_S S^\dagger S - \lambda_{hs} S^\dagger S H^\dagger H - \frac{\mu_3}{2}(S^3 + S^{\dagger 3}) + \ldots$
- Complex scalar dark matter $\to$ singlet (S) and anti-singlet (S^*)
- Semi-annihilation: $SS \to S^* h$, $S^* S^* \to Sh$





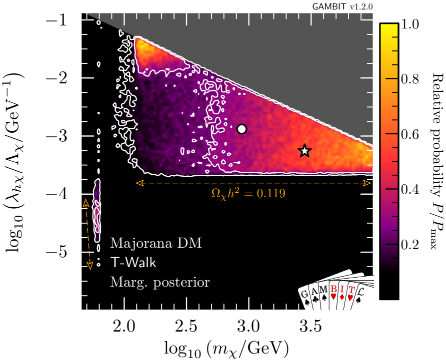
$\mathbb{Z}_3$-symmetric scalar singlet dark matter (EPJC, arXiv:1806.11281)

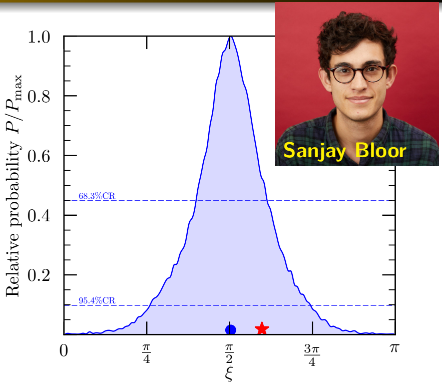




Can the $\mathbb{Z}_3$-symmetric scalar singlet stabilise the vacuum?
Excluded at >99% CL ($p < 0.01$) as all of dark matter
Excluded at >98% CL ($p < 0.02$) as *any* of dark matter
mainly due to extra factors of 2 from complex vs real scalar

Fermionic Higgs-Portal dark matter (EPJC, arXiv:1808.10465)





Model has mixed CP-even and CP-violating portal coupling

$$\mathcal{L}_\chi = \lambda_{h\chi}/\Lambda_\chi(\cos\xi\,\overline{\chi}\chi + \sin\xi\,\overline{\chi}i\gamma_5\chi)H^\dagger H + \ldots$$

→Momentum-independent (from CP-even) and q^2-dependent (from CP-violating) nuclear-scattering cross-sections

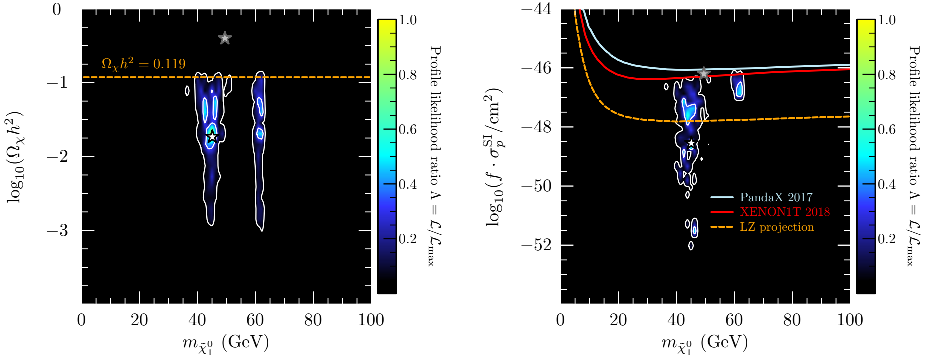
→Evading direct detection requires reduced CP-even coupling ($\xi \to \frac{\pi}{2}$)

→Bayesian model selection favours CP-violating version roughly 100:1

Supersymmetry

(EPJC, arXiv:1809.02097)

Just taking the points within our 3σ regions from an LHC-only fit to the superpartners of Higgs, Z and photon:



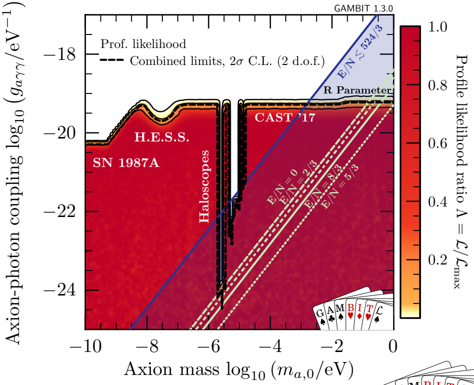
Z and h funnel mechanisms can give sensible relic densities
$\rightarrow$ models consistent with LHC electroweak excesses can also naturally explain dark matter

Parameters:

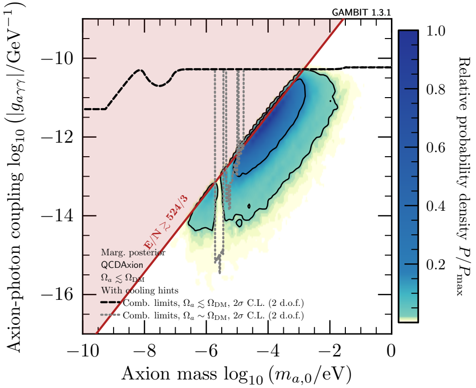
- couplings $g_{a\gamma\gamma} + g_{aee}$
- decay constant f_a
- initial misalignment angle θ_i
- zero-temperature mass $m_{a,0}$
- $2\times$ nuisance parameters for T-dependence of mass

Likelihoods:

- Light shining through wall: ALPS
- Helioscopes: CAST(2007), CAST(2017)
- Haloscopes: RBF, UF, ADMX(1998-2009), ADMX(2018)
- dark matter relic density: *Planck*
- Astrophysics: HESS, SN1987a, HB/RGB stars (R parameter)



Bayesian analysis gives preferred axion mass range and couplings:
- small $m_a \Rightarrow$ fine-tuning in θ_i to avoid dark matter overproduction
- large $m_a \Rightarrow$ fine-tuning in E/N (i.e. $g_{a\gamma\gamma}$) to avoid experiments



(with log priors on f_a, C_{aee}; flat priors prefer slightly lower masses)

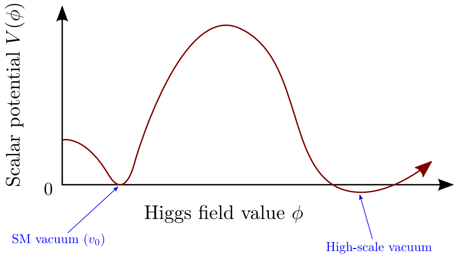
Summary

- If dark matter is singlet Higgs portal & responsible for stabilising the vacuum of the Universe, it is real not complex, and is already starting to appear in XENON1T data
- If it is fermionic Higgs portal, it almost certainly violates CP
- Supersymmetry is *not* “ruled out” by the LHC (quite the contrary) – and models that fit LHC excesses also fit dark matter
- The QCD axion mass is expected to be between 0.1 μeV and 10 meV (10^{-7} – 10^{-2} eV)

- Global analyses complete for many models
- GAMBIT results, samples, run files, best fits, benchmarks, etc are *all* available to download from Zenodo: www.zenodo.org/communities/gambit-official/
- GAMBIT code is public: gambit.hepforge.org
- Coming soon: CosmoBit & GUM (GAMBIT fist directly from a Lagrangian)

Backup slides

Background: Vacuum Stability



- The electroweak vacuum of the Standard Model is not stable

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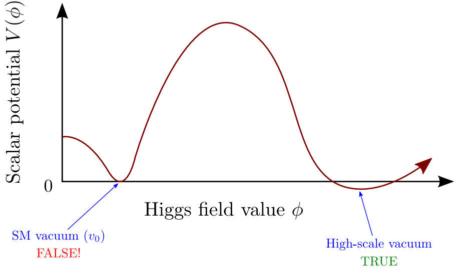

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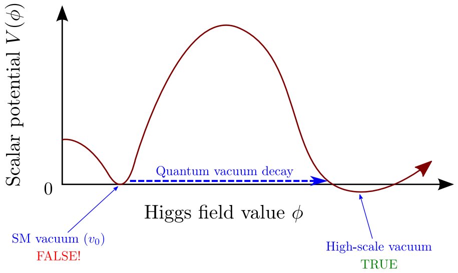

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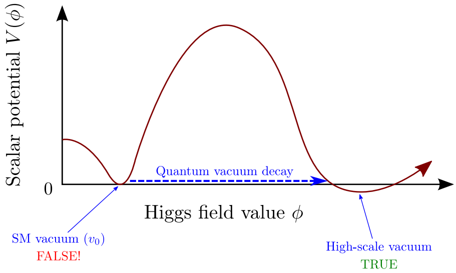

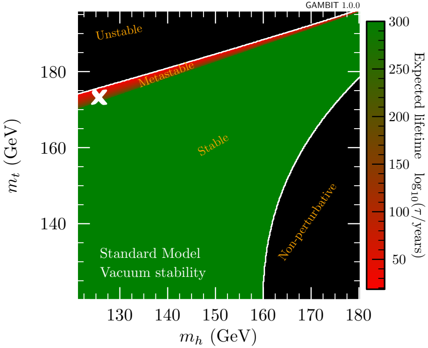

- The electroweak vacuum of the Standard Model is not stable
- Lifetime for decay to the global minimum is $\gg$ age of the Universe $\implies$ metastable

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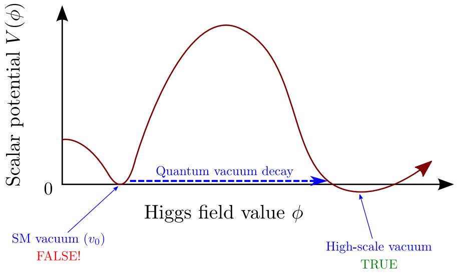

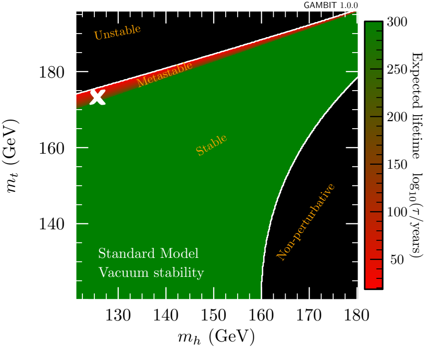

- Can be spoilt by Planck-scale effects
- Unclear how inflation would have put us in a metastable state
  → metastability makes Standard Model seem rather fine-tuned

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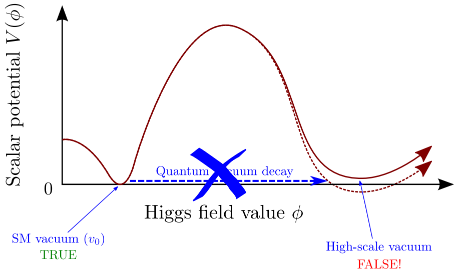
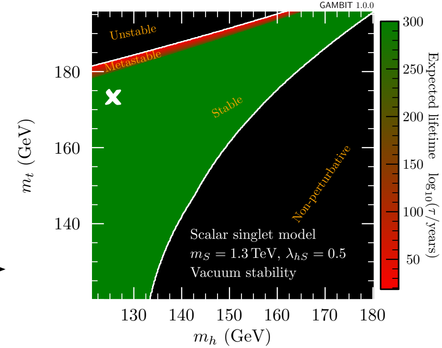
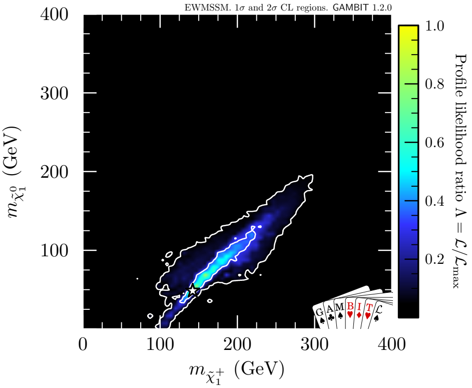




- Exact depth of minimum is very sensitive to running of couplings due to renormalisation
  $\rightarrow$ new particles can make our vacuum absolutely stable
  & remove the fine-tuning issue

Electroweakino simplified models @36 fb^{-1} (EPJC, arXiv:1809.02097)



- Low-mass neutralinos & charginos
- everything else decoupled
- $M_1, M_2, \mu, \tan\beta$ free
- m_h fixed to 125.09 GeV

→ 3.3σ (local) combined signal significance

Electroweak analyses included in likelihood:

- ATLAS multi-lepton: $\tilde{\chi}_2^0\tilde{\chi}_1^\pm$, $\tilde{\chi}_2^\pm\tilde{\chi}_1^\pm$, $\tilde{l}\tilde{l}$; final states with 2–3 leptons + 0–5 jets
- ATLAS 2/3-lepton recursive jigsaw searches for $\tilde{\chi}_2^0\tilde{\chi}_1^\pm$
- ATLAS 4-lepton SUSY search
- ATLAS 4-b Higgsino search
- CMS 1lep(H)bb: single-lepton final states including $H \to bb$
- CMS 2SFOSlep-soft: $\tilde{\chi}_2^0\tilde{\chi}_1^\pm$, virtual W^* and $Z^* \to ll$; final state with two same-flav. opp. sign leptons
- CMS 2SFOSlep: as above but with hard leptons (W, Z not virtual)
- CMS multi-lepton: similar to ATLAS, but exclusively $\tilde{\chi}_2^0\tilde{\chi}_1^\pm$ production
- Assorted LEP likelihoods & h/Z invisible widths

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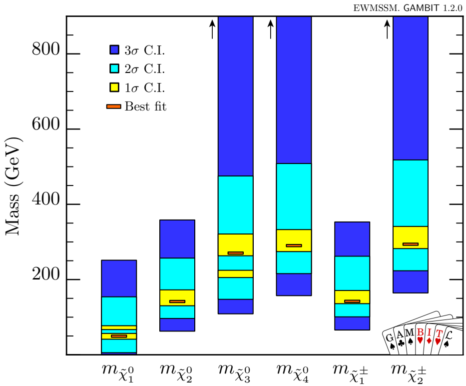

- Low-mass neutralinos & charginos
- everything else decoupled
- $M_1, M_2, \mu, \tan\beta$ free
- m_h fixed to 125.09 GeV

$\rightarrow$ 3.3σ (local) combined signal significance

Electroweak analyses included in likelihood:

- ATLAS multi-lepton: $\tilde\chi^0_2\tilde\chi^\pm_1$, $\tilde\chi^\pm_2\tilde\chi^\pm_1$, $\tilde{l}l$; final states with 2–3 leptons + 0–5 jets
- ATLAS 2/3-lepton recursive jigsaw searches for $\tilde\chi^0_2\tilde\chi^\pm_1$
- ATLAS 4-lepton SUSY search
- ATLAS 4-b Higgsino search
- CMS 1lep(H)bb: single-lepton final states including $H \rightarrow bb$
- CMS 2SFOSlep-soft: $\tilde\chi^0_2\tilde\chi^\pm_1$, virtual W^* and $Z^* \rightarrow ll$; final state with two same-flav. opp. sign leptons
- CMS 2SFOSlep: as above but with hard leptons (W, Z not virtual)
- CMS multi-lepton: similar to ATLAS, but exclusively $\tilde\chi^0_2\tilde\chi^\pm_1$ production
- Assorted LEP likelihoods & h/Z invisible widths

Likelihood contributions of individual analyses