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
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?
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**Answer**

Combine constraints in a statistically valid way → 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)

→ global fits
Combining searches III

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Answer

Need to
- scan the parameter space (smart numerics)
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→ 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

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

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

40+ participants in 11 experiments and 14 major theory codes

*Multimessenger astroparticle physics for dark matter*
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
   → 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**
Dark matter constraints in GAMBIT

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- Direct detection: XENON1T, LZ, LUX, PandaX, PICO, DarkSide, SuperCDMS, CDMSLite, CRESST-II, SIMPLE
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- **various models for Milky Way halo** ($\rho$ & $\nu$)
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- 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)
- $3.3\sigma$ 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:
- 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)
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  
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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

\[ \mathcal{L}_X \approx -\frac{\mu_X^2}{2} X^2 - \frac{\lambda h X}{2} X^2 H^\dagger H + \ldots \]

- \( X \) = gauge singlet scalar (spin 0), fermion (spin \( \frac{1}{2} \)) or vector (spin 1)
- \( X \) odd under an unbroken \( \mathbb{Z}_2 \) 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

White = 1σ, 2σ with XENON1T 2018

Direct detection and relic density the most constraining
Scalar Higgs Portal dark matter

(EJPC, arXiv:1806.11281)

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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, $\sigma_{\text{SI}} \sim 10^{-45}$ cm$^2$ to do so
- explains all of dark matter
- matches slight preference for signal in XENON1T data
- good fit to all observables ($p \sim 0.5$) $\rightarrow$ 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 $S \rightarrow SM + SM$
- Can be achieved with any other discrete symmetry, e.g. $\mathbb{Z}_3$
- $\mathcal{L}_S = -\mu S S^\dagger S - \lambda_{hs} S^\dagger SH^\dagger H - \frac{\mu_3}{2} (S^3 + S^3) + \ldots$
- Complex scalar dark matter $\rightarrow$ singlet ($S$) and anti-singlet ($S^*$)
- Semi-annihilation: $SS \rightarrow S^* h$, $S^* S^* \rightarrow Sh$
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.
Model has mixed CP-even and CP-violating portal coupling

\[ \mathcal{L}_\chi = \frac{\lambda h_\chi}{\Lambda_\chi} (\cos \xi \overline{\chi}\chi + \sin \xi \overline{\chi}i\gamma_5\chi) H^\dagger H + \ldots \]

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

$\Omega \chi^2 = 0.119$

$\log_{10}(\Omega \chi^2)$

Profile likelihood ratio $\Lambda = L/L_{\text{max}}$

$m_{\tilde{\chi}^0_1}$ (GeV)

$Z$ and $h$ funnel mechanisms can give sensible relic densities → models consistent with LHC electroweak excesses can also naturally explain dark matter
Axion-like Particles (ALPs)

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

Likelihoods:
- Light shining through wall: ALPS
- 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 $\theta_i$ 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 $0.1 \mu$eV and $10 \text{ meV} \left(10^{-7} - 10^{-2} \text{ eV}\right)$

- 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)
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Lifetime for decay to the global minimum is $\gg$ age of the Universe

$\Rightarrow$ metastable
Background: Vacuum Stability

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

- Can be spoilt by Planck-scale effects
- Unclear how inflation would have put us in a metastable state
  $\Rightarrow$ metastability makes Standard Model seem rather fine-tuned
Background: Vacuum Stability

The electroweak vacuum of the Standard Model is not stable. The lifetime for decay to the global minimum is $\gg$ age of the Universe, which implies that it is metastable.

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.
Electroweak analyses included in likelihood:

- ATLAS multi-lepton: $\tilde{\chi}_2^0 \tilde{\chi}_1^\pm$, $\tilde{\chi}_2^\pm \tilde{\chi}_1^\pm$, $\ell\ell$; 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 $Z^*$ → $ll$; 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

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

$\to$ 3.3$\sigma$ (local) combined signal significance
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- ATLAS 4-lepton SUSY search
- ATLAS 4-\textit{b} Higgsino search
- CMS 1lep(H)bb: single-lepton final states including $H \rightarrow bb$
- CMS 2SFOSlep-soft: $\tilde{\chi}_2^0\tilde{\chi}_1^\pm$, virtual $W^*$ and $Z^* \rightarrow ll$; final state with two same-flav. opp. sign leptons
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Likelihood contributions of individual analyses