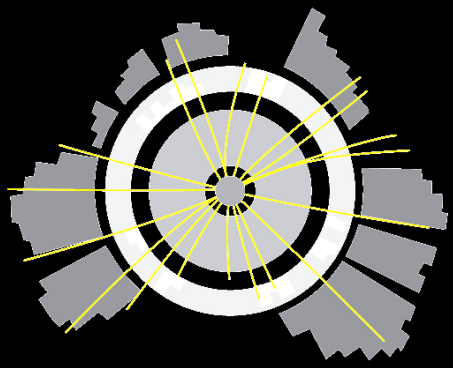
The status of supersymmetry according to GAMBIT

Csaba Balázs
for the GAMBIT collaboration



CoEPP
ARC Centre of Excellence for Particle Physics at the Terascale

outline

GAMBIT

global, modular, flexible, extendable…

SUSY with GAMBIT

CMSSM, NUHM1/2, MSSM-7, more…

Is SUSY dead?

Supersymmetry will never die.

People who do SUSY will.

Folklore

Is SUSY dead?

A simple question requiring complex investigation.

Global And Modular BSM Inference Tool

A global fitting code for generic beyond the Standard Model theories, designed to allow fast and easy definition of new models, observables, likelihoods, scanners and backend physics codes.

Open source: gambit.hepforge.org

EPJC 77 (2017) 784 arXiv:1705.07908

10 experiments

ATLAS, Belle-II, CMS, CTA, Fermi-LAT, DARWIN, IceCube, LHCb, SHiP, XENON

40+ participants

P Athron, C Balazs, A Beniwal, F Bernlochner, S Bloor, T Bringmann, A Buckley, E Camargo-Molina, M Chrzaszc, J Conrad, J Cornell, M Danninger, T Edwards, J Edsjo, B Farmer, A Fowlie, T Gonzalo, W Handley, S Hoof, S Hotinli, F Kahlhoefer, S Krishnamurthy, A Kvellestad, J Harz, P Jackson, T Li, G Martinez, N Mahmoudi, J McKay, A Raklev, J Renk, C Rogan, R Ruiz de Austri, P Stoecker, R Trotta, P Scott, N Serra, D Steiner, P Sun, A Vincent, C Weniger, S Wild, M White, Y Zhang

14 major theory codes

DarkSUSY, DDCalc, Diver, FlexibleSUSY, gamlike, GM2Calc, IsaJet, nulike, PolyChord, Rivet, SOFTSUSY, SuperIso, SUSY-AI, WIMPSim

Global And Modular BSM Inference Tool

A global fitting code for generic [illegible] Standard Model

40+ participants

P Athron, C B[illegible]

Blah…

Who cares about global fits?

Is this a glorified wrapper?

What can it do for *me*?

[illegible] Vincent, C Weniger, [illegible], M[illegible] Zhang

14 major theory codes

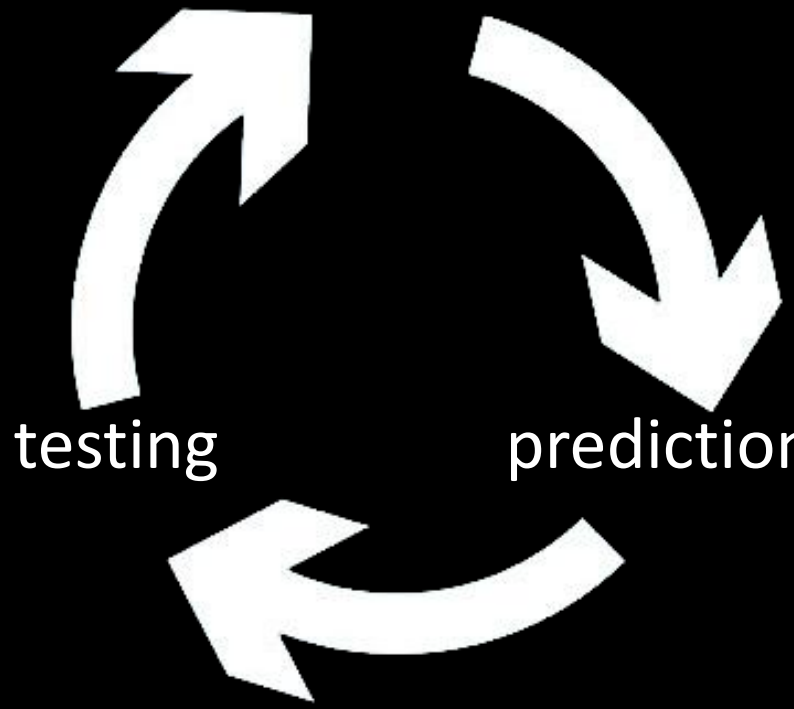
DarkSUSY, DDCalc, Diver, FlexibleSUSY, gamlike, GM2Calc, IsaJet, nulike, PolyChord, Rivet, SOFTSUSY, SuperIso, SUSY-AI, WIMPSim

ATLAS, Belle-II, CMS, CTA, Fermi-LAT, DARWIN, IceCube, LHCb, SHiP, XENON

global fits

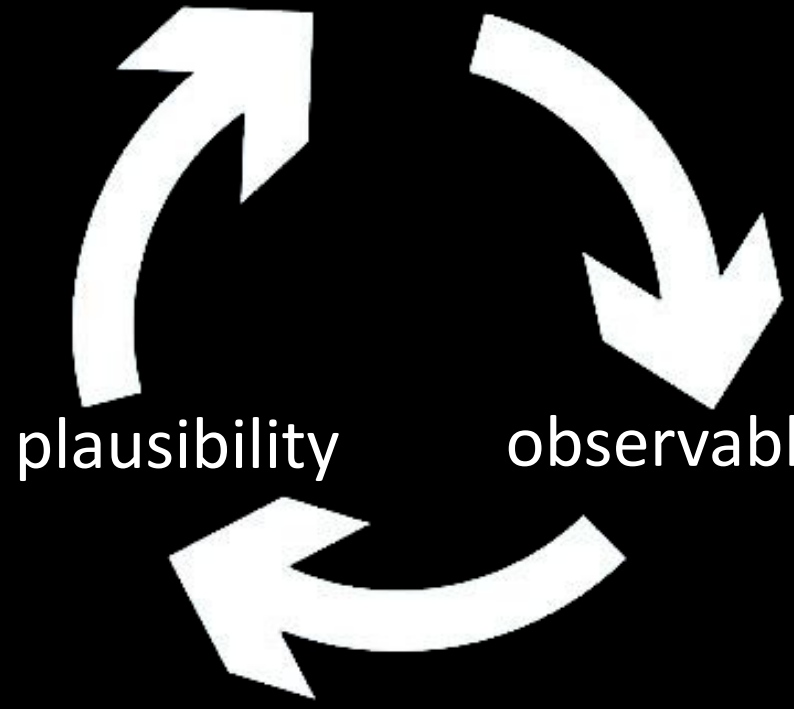
Scientific method

(simplified)



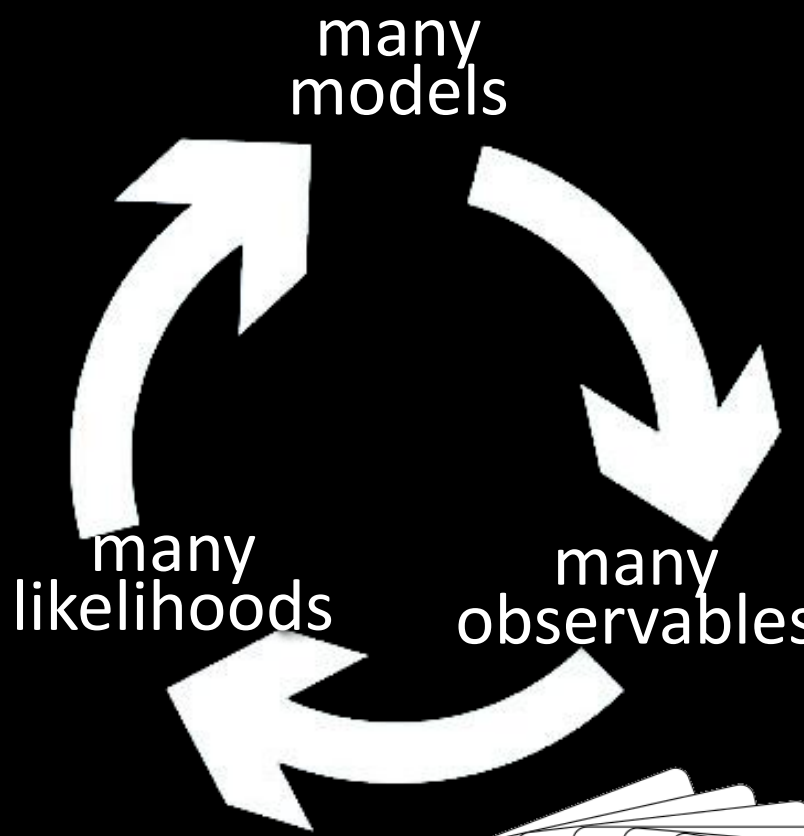
Phenomenology

(simplified)



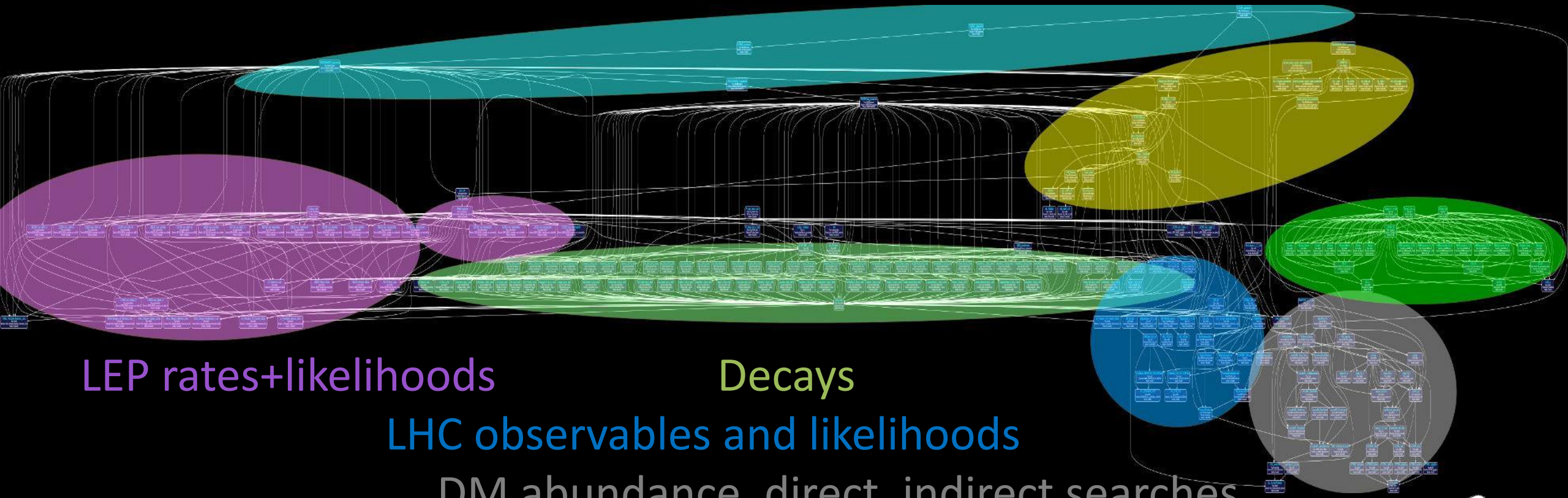
GAMBIT

(simplified)

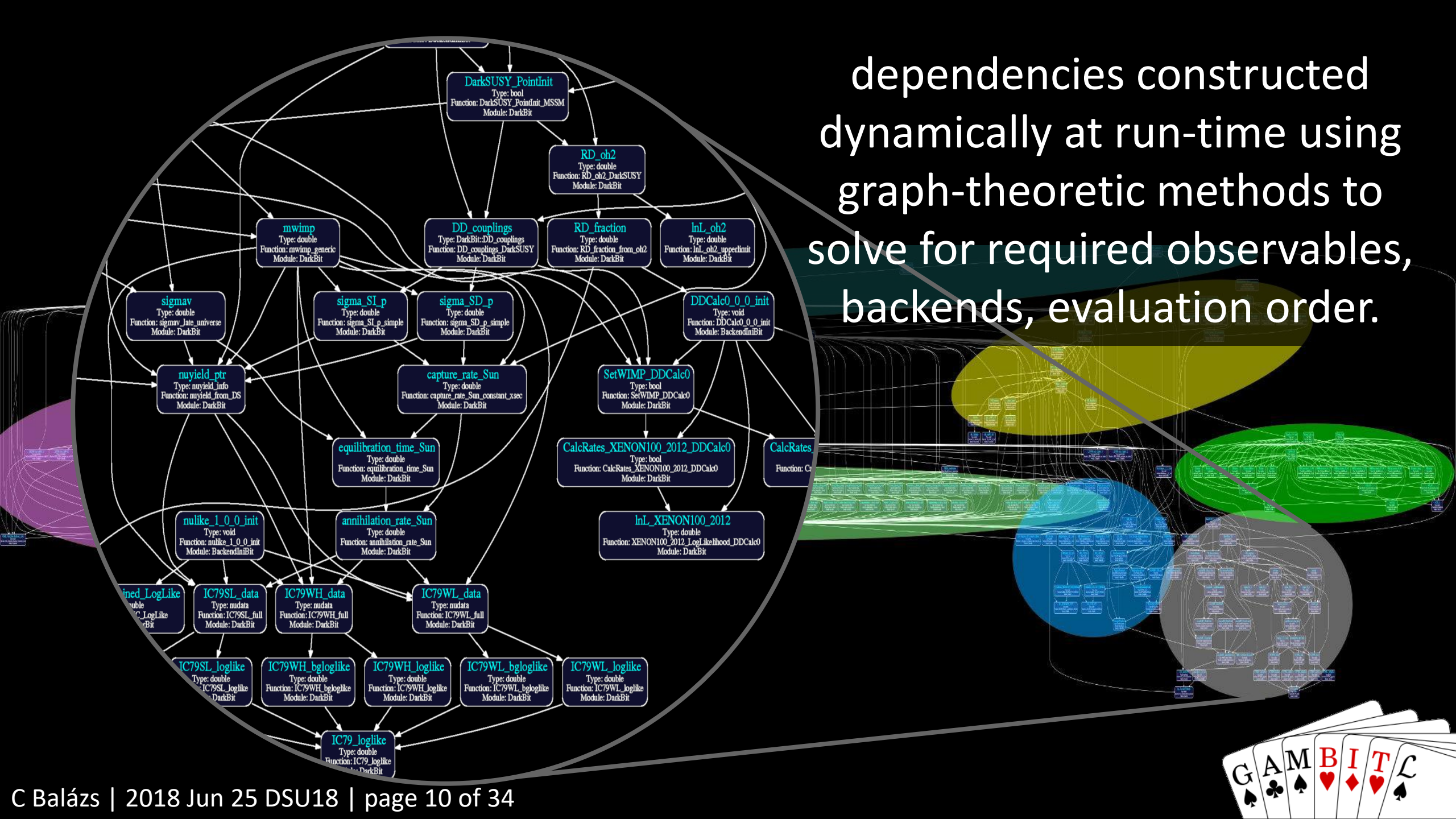


Wrapper?

GAMBIT dependency resolution for CMSSM



dependencies constructed dynamically at run-time using graph-theoretic methods to solve for required observables, backends, evaluation order.



GAMBIT modules

provide GAMBIT with a range of capabilities (to calculate a certain quantity)

- ColliderBit: fast LHC sim., Z, H obs.s, NP limits... arXiv:1705.07919
- DarkBit: abundance, direct, indirect detection... arXiv:1705.07920
- DecayBit: SM & NP (SUSY...) decay widths, BRs... arXiv:1705.07936
- FlavBit: NP (SUSY...) flavor obs.s, rare decays... arXiv:1705.07933
- PrecisionBit: EW precision observables, g − 2... arXiv:1705.07936
- SpecBit: NP masses, mixings, couplings, RGEs... arXiv:1705.07936
- ScannerBit: sampling, para est., model comp.... arXiv:1705.07959
- Coming soon: CosmoBit, NeutrinoBit, ...

GAMBIT features

Global and modular

- diverse BSM model database (SM+SS, EFTs, 2HDMs, MSSM63, axions, RHNs…)
- changeable model assumptions for astrophysics, nuclear, …
- built-in experimental likelihoods (LEP, ATLAS, CMS, LHCb, DM searches, …)
- composite likelihood (consistent treatment of uncertainties, nuisances, …)
- several scanning algorithms (MNMCMC, nested sampling, genetic, …)
- auto dependency resolution (ID functions, optimize execution order!)
- dual-level parallel execution: MPI and OpenMP
- …

GAMBIT features

Flexible and extendable

- fast definition of new models, data sets, sampling methods
- plug&play theory tools (auto-download, compile, dynamically link!)
- easily switch between backends calculating the same quantities
- C/C++, Fortran, Python, Mathematica interfaces for backends
- input: model, para.s, observables, sampler, stat. inference
- customizable output streams: ASCII, HDF5…
- GAMBIT 2: input Lagrangian, auto-generate code for obs.s, …
- …

GAMBIT results (non-SUSY: see talk by F Kahlhoefer)

CMSSM, NUHM1, NUHM2 (GUT scale BCs)

Eur.Phys.J. C77 (2017) no.12, 824, arXiv:1705.07935

MSSM-7 (weak scale BCs)

Eur.Phys.J. C77 (2017) no.12, 879, arXiv:1705.07917

EW-MSSM (weak scale BCs)

scans in progress (electroweakino MSSM-4)

MSSM-9 (weak scale BCs)

in preparation

E6SSM (GUT scale BCs)

coming up

MSSM-11

coming up

NMSSM

CMSSM, NUHM1, NUHM2 (GUT scale BCs)

$$\mathcal{L}_{soft} \sim M_{H_{u,d}}^2 |H_{u,d}|^2 + m_0^2 \tilde{F}_i^\dagger \tilde{F}_i + \frac{1}{2} m_{1/2} \tilde{G}_j \tilde{G}_j + A_0 \tilde{f}_i^c H_{u,d} \tilde{F}_i + \cdots$$

Constraints

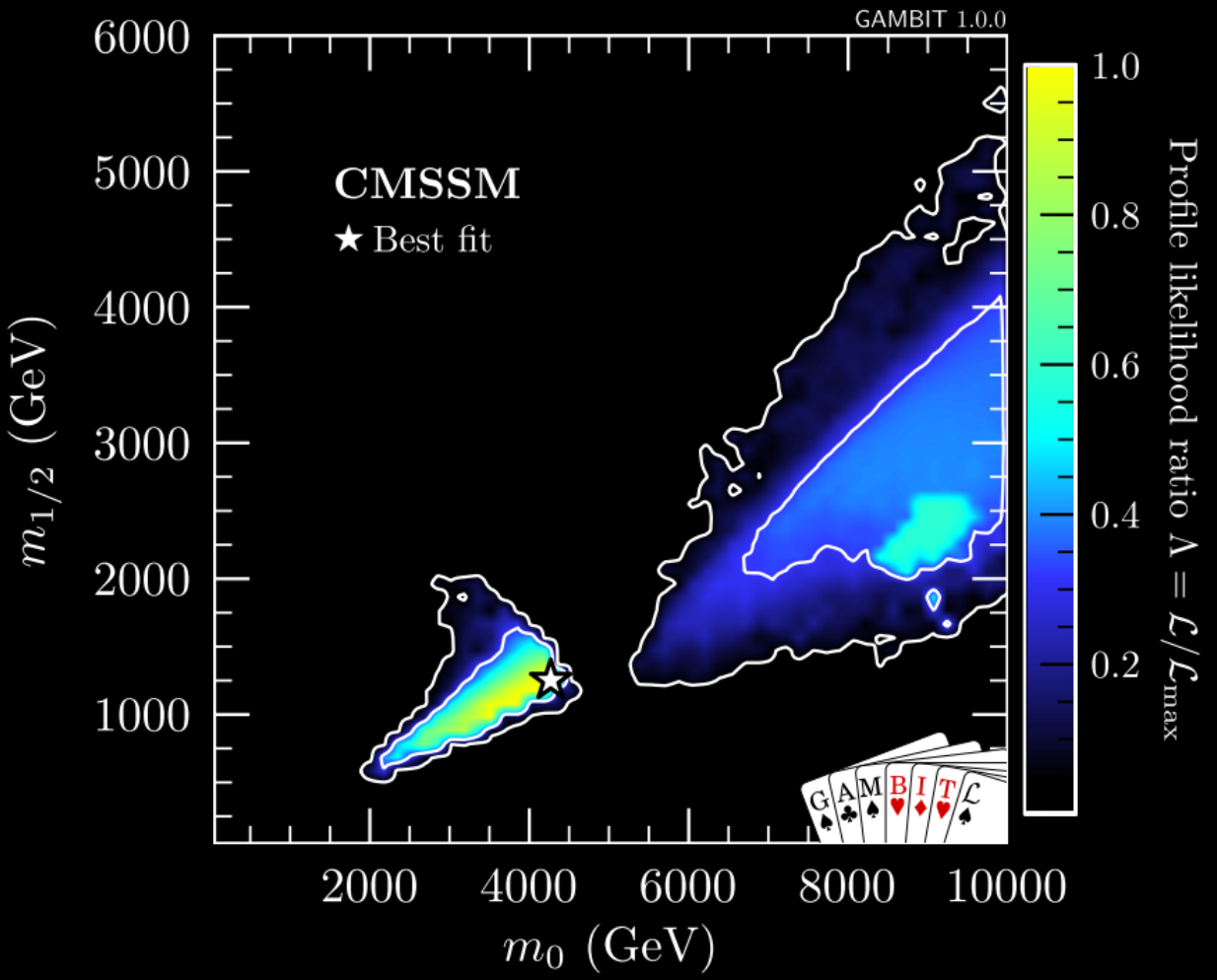
- DM relic density upper bound
- DM direct det. 6 experiments
- DM indirect det. Fermi-LAT (dSphs), IceCube79
- EW precision W mass, $g_\mu - 2$, …
- 59 flavor observables
- LHC Higgs data, SUSY searches, …

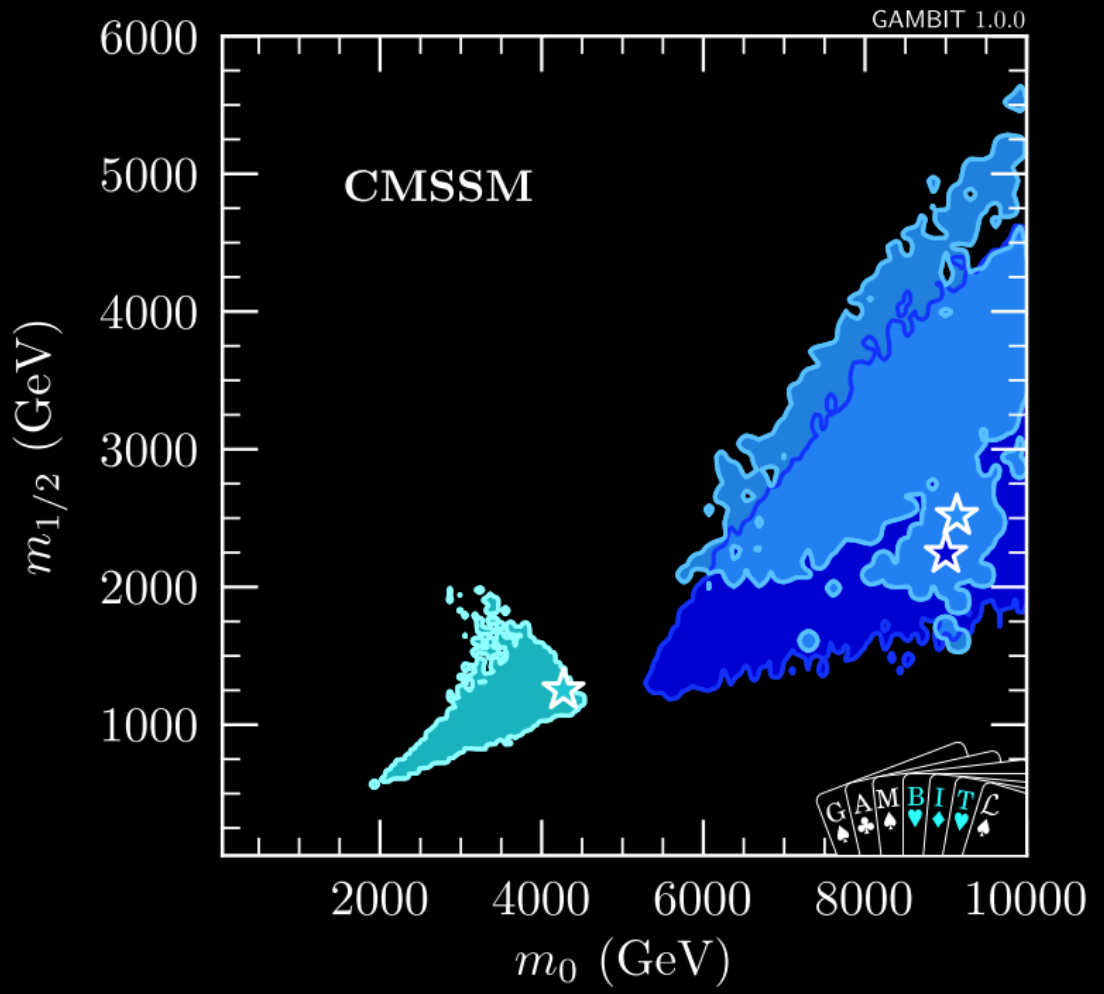
Uncertainties, nuisances

- local DM density
- nuclear physics parameters
- Higgs and quark masses
- gauge couplings

about 280 million valid samples for the three models

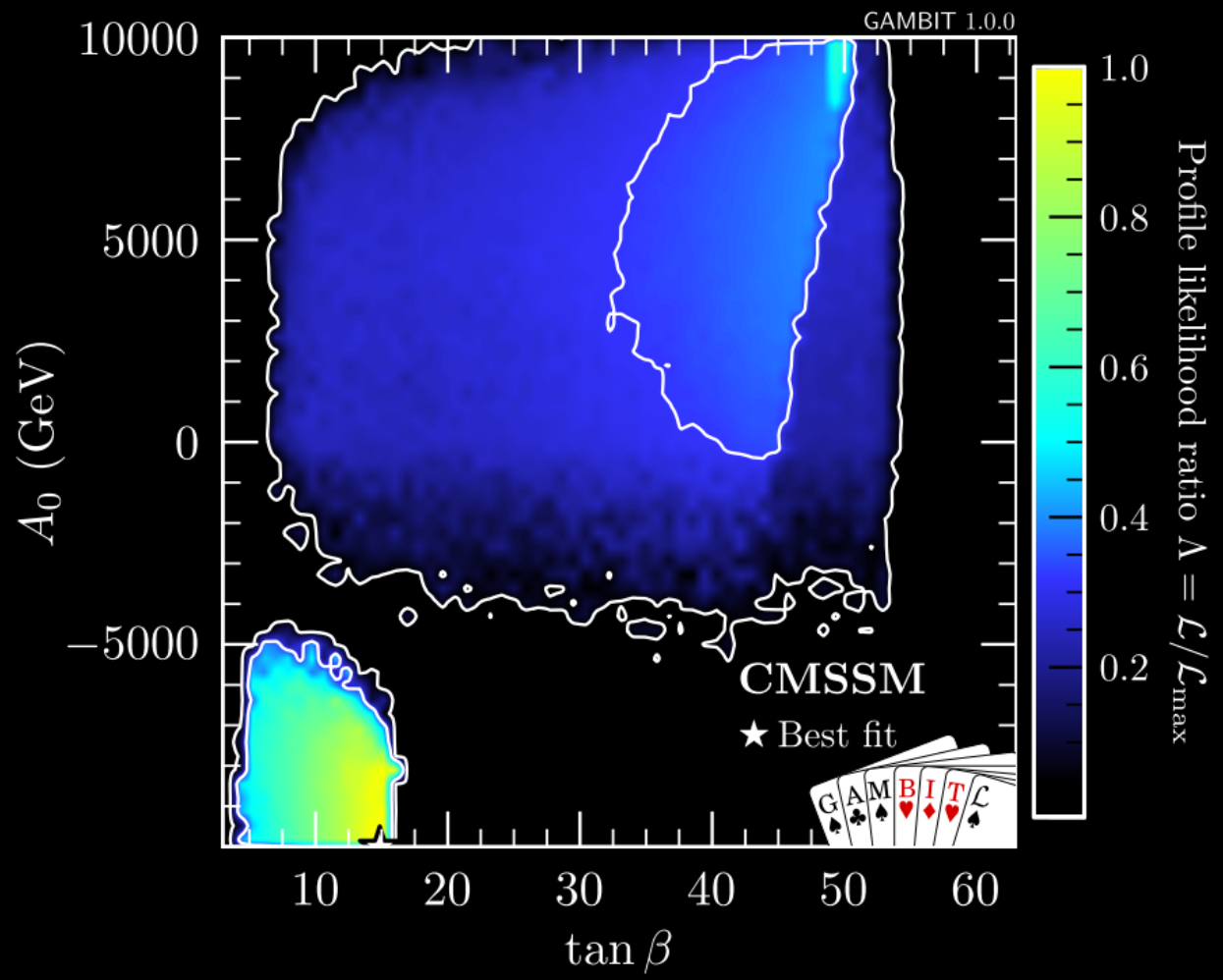
CMSSM ($M_0, M_{1/2}, A_0, \tan\beta, \mathrm{sign}\mu$ + 5 nuisances)

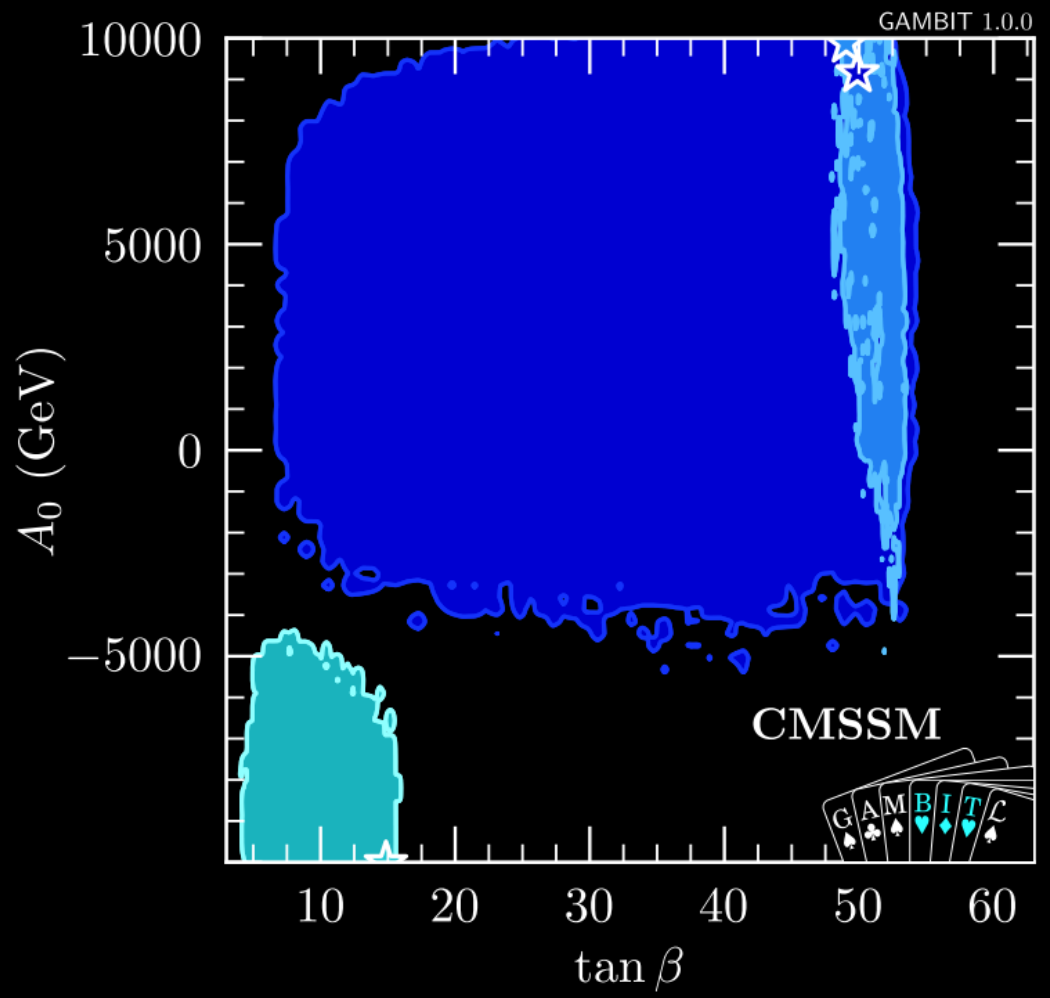




- $\tilde{t}$ co-ann. chargino co-ann. heavy Higgs funnel ($\tilde{\tau}$ co-ann. ruled out @95%CL)
- best fit point in stop co-ann. region (stop/neutralino mass about 600 GeV)

CMSSM ($M_0, M_{1/2}, A_0, \tan\beta, \mathrm{sign}\mu$ + 5 nuisances)





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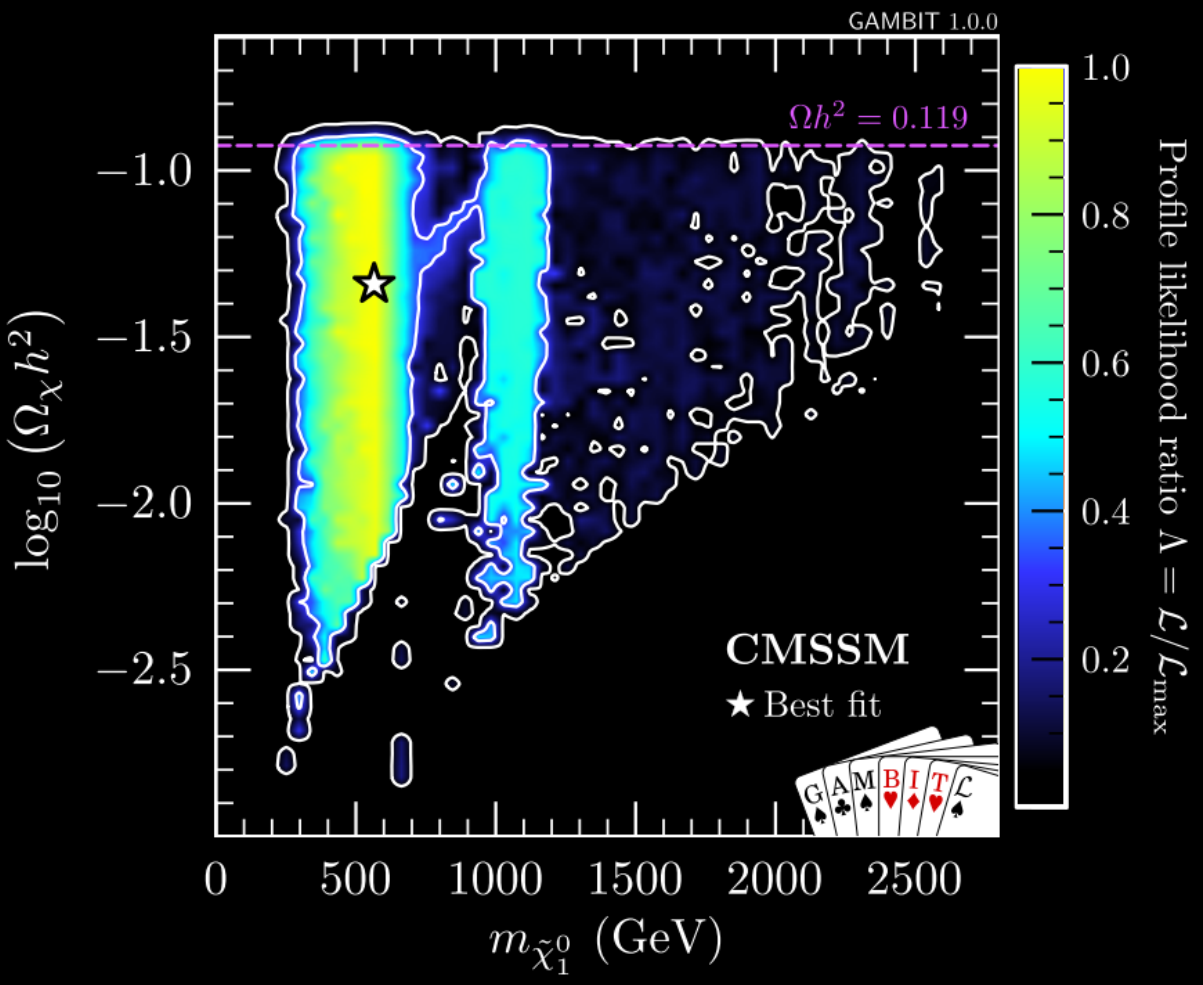
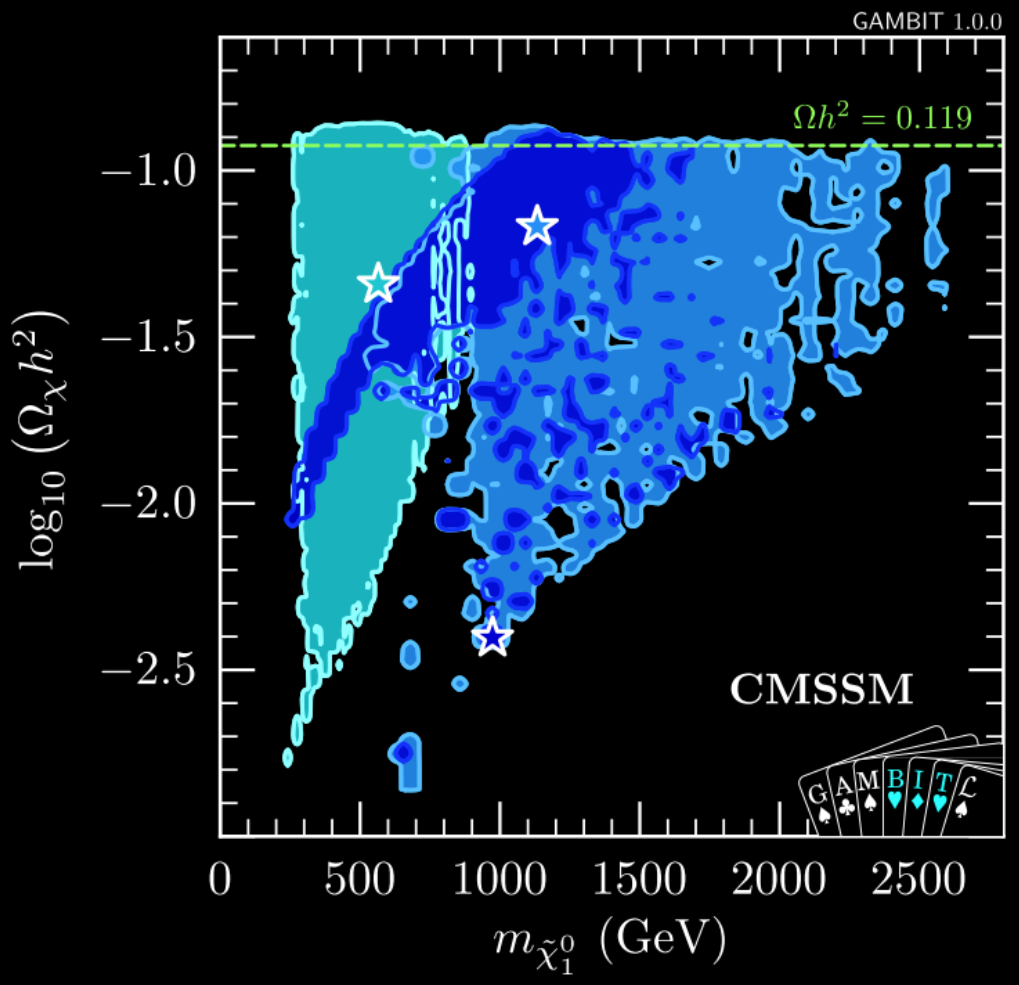
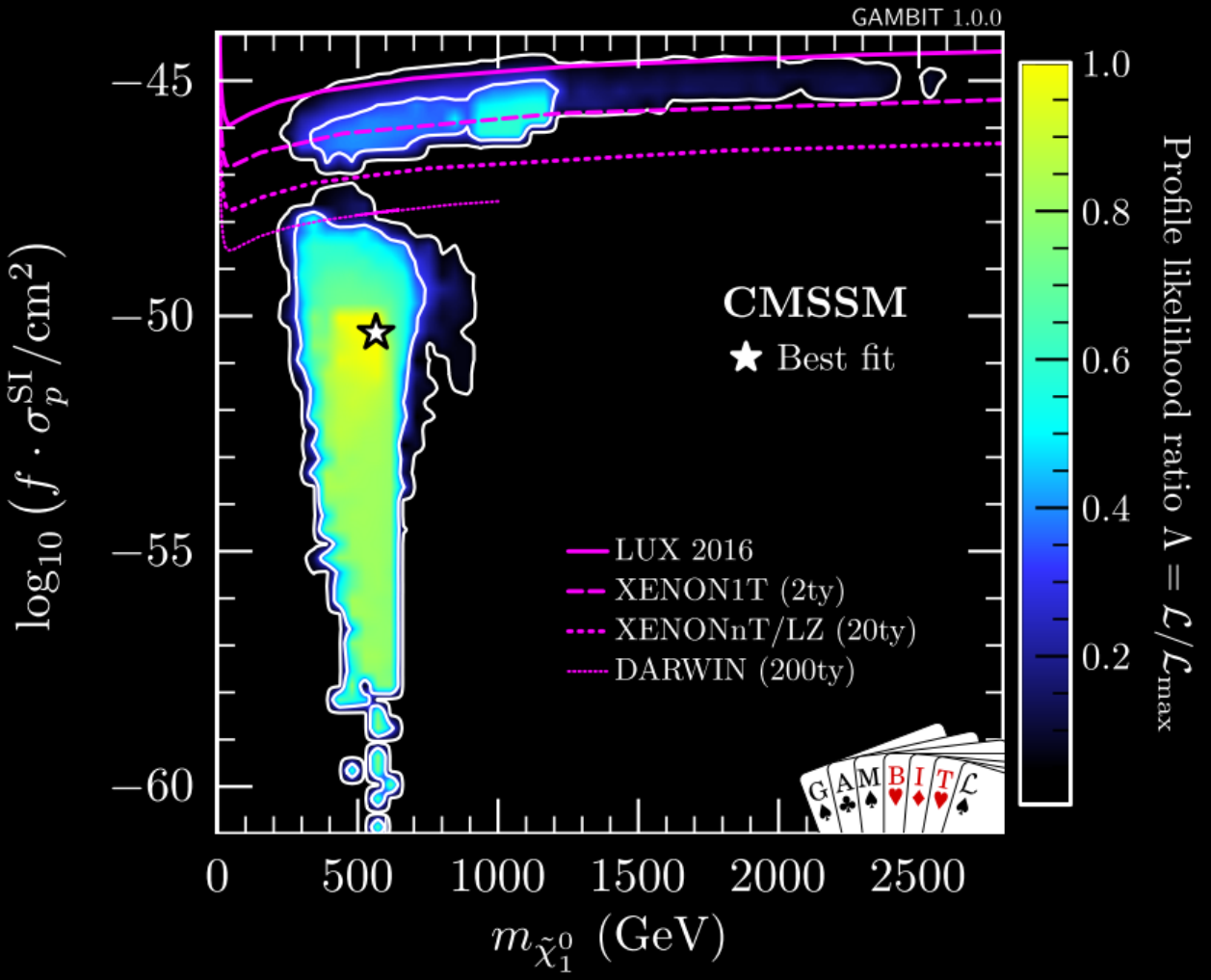
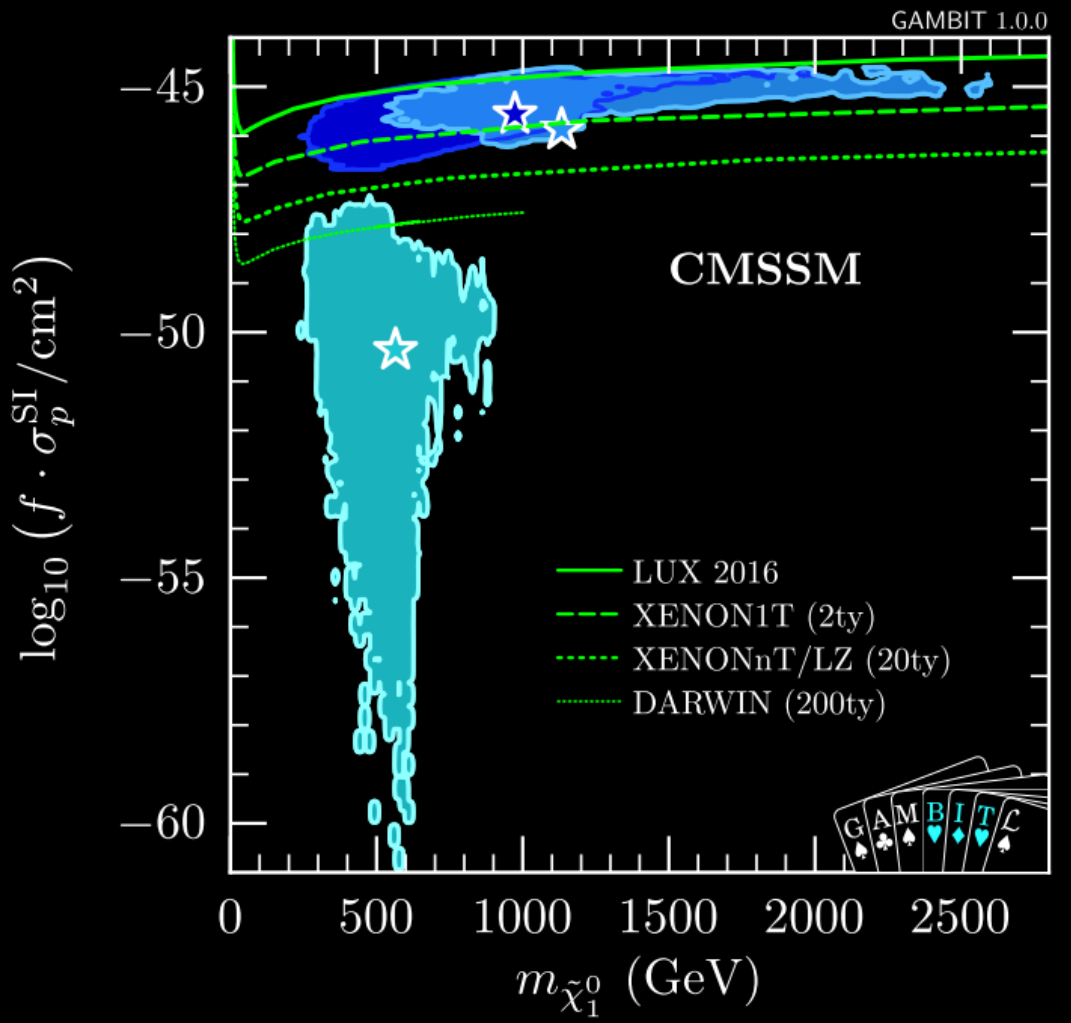




- $\tilde{t}$ co-ann. chargino co-ann. heavy Higgs funnel ($\tilde{\tau}$ co-ann. ruled out @95%CL)
- lightest neutralino mass is likely under 2 TeV

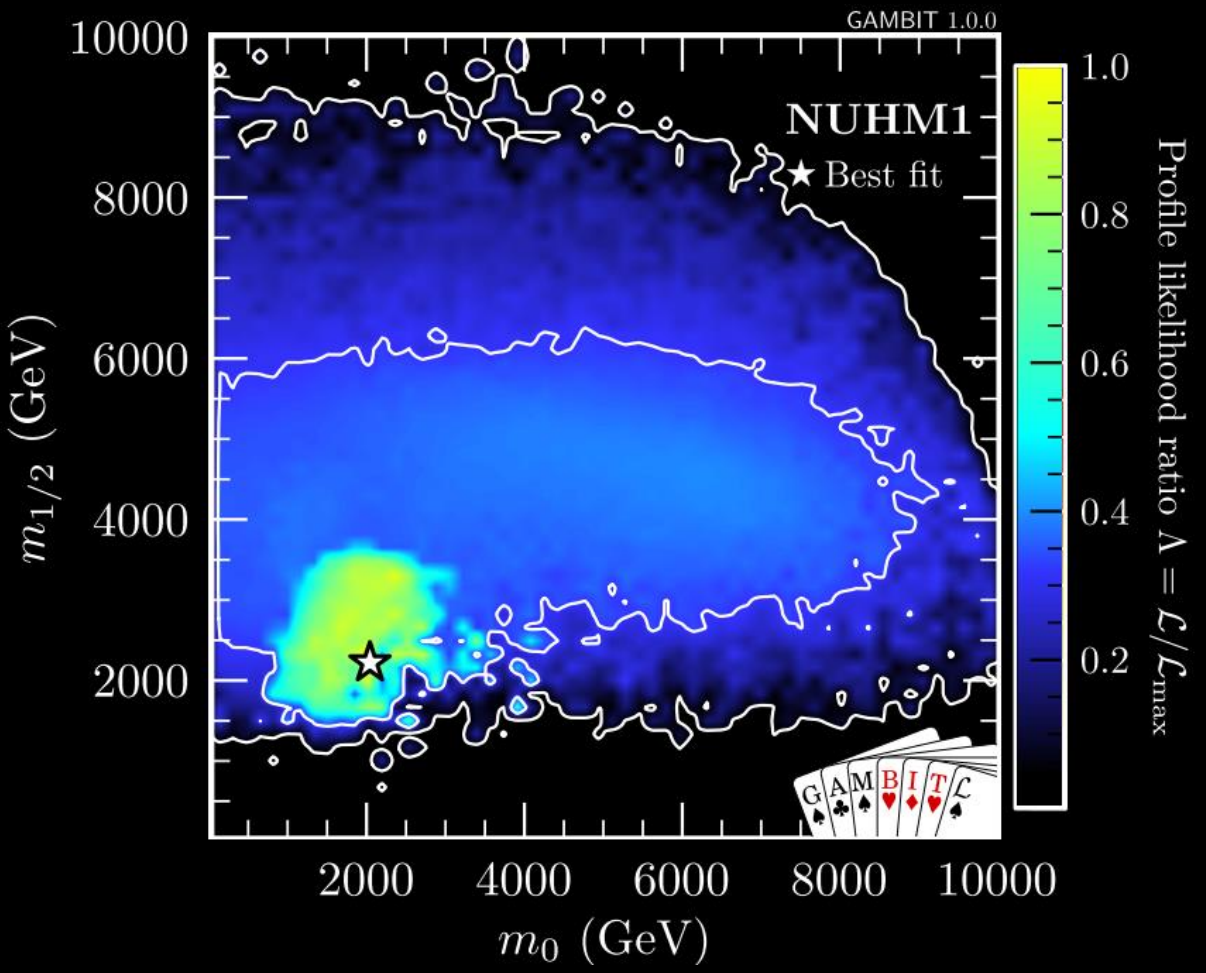
CMSSM ($M_0, M_{1/2}, A_0, \tan\beta, \mathrm{sign}\mu$ + 5 nuisances)

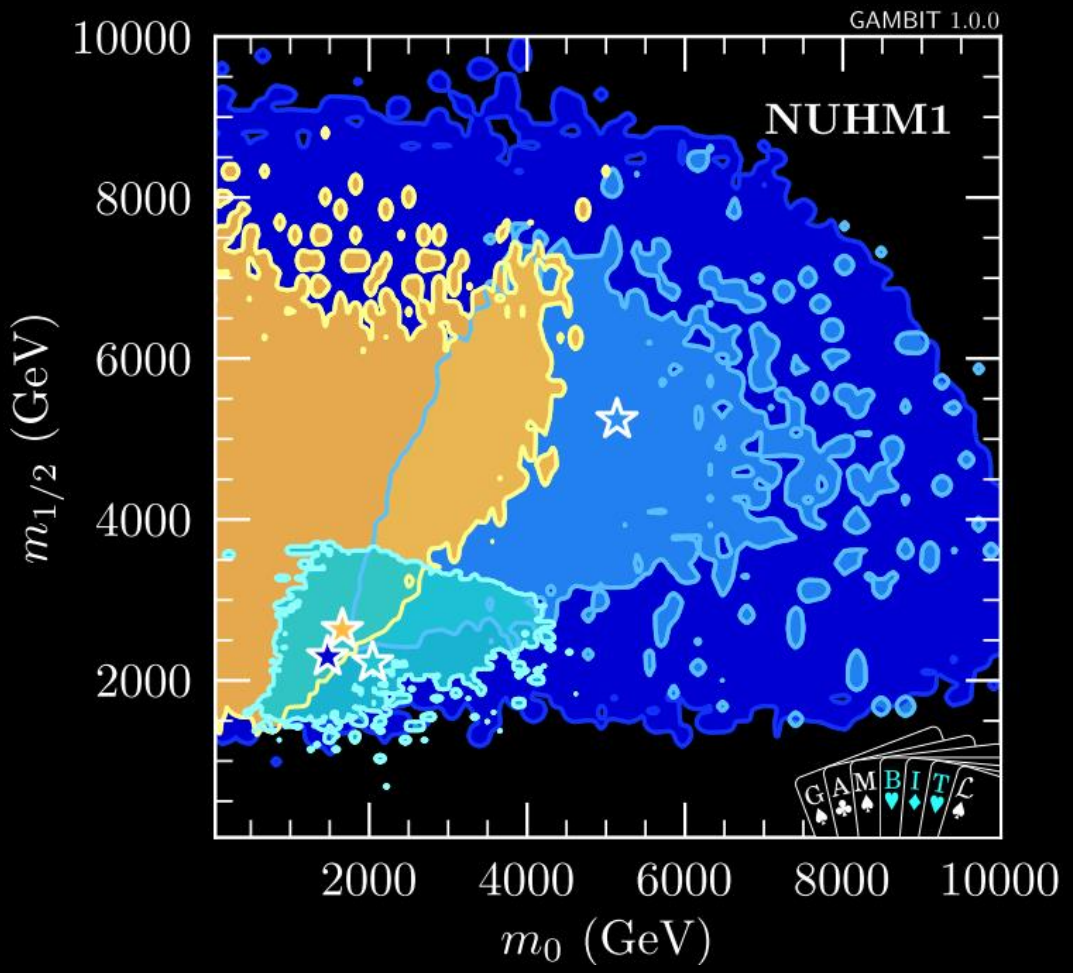




- $\tilde{t}$ co-ann. chargino co-ann. heavy Higgs funnel ($\tilde{\tau}$ co-ann. ruled out @95%CL)
- $\tilde{t}$ co-ann. poses challenge to direct det. unless loop corrections lift cross section

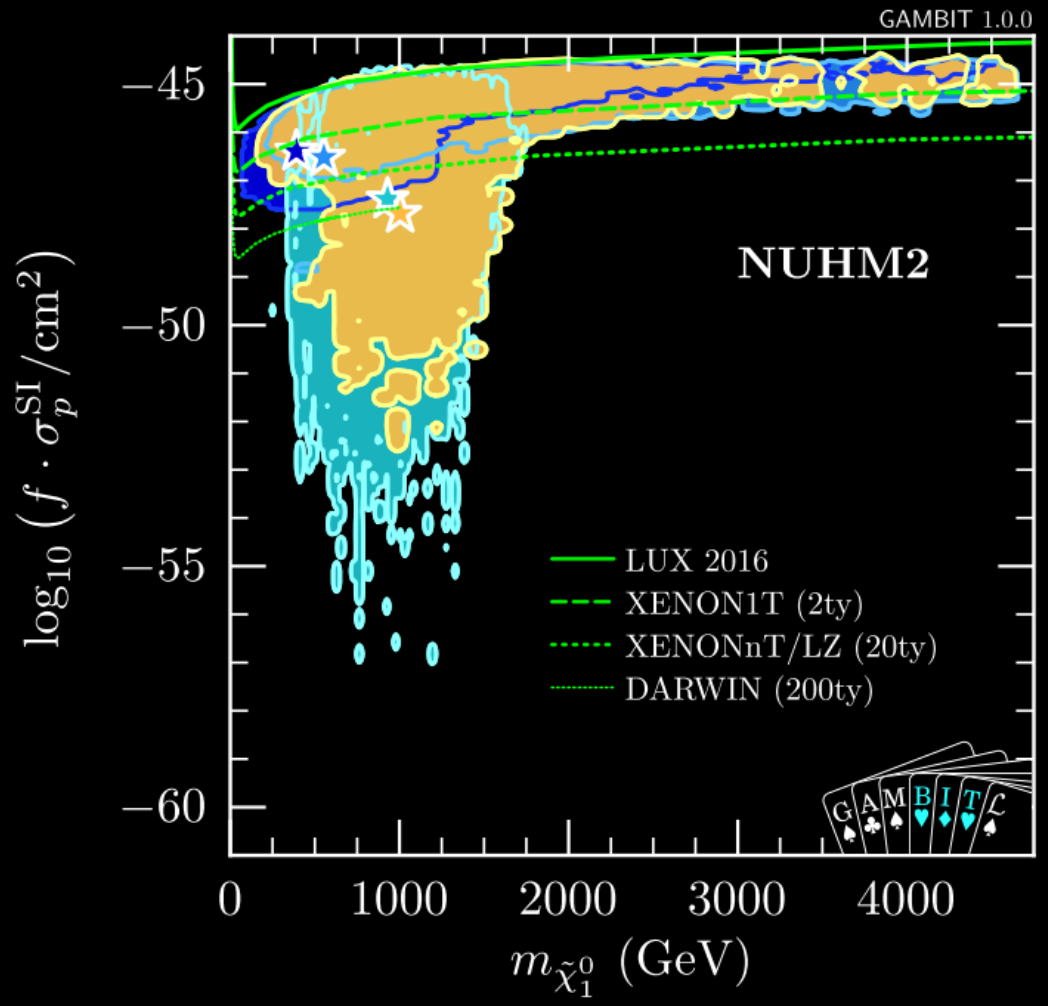
NUHM1 ($M_H, M_0, M_{1/2}, A_0, \tan\beta, \mathrm{sign}\mu$ + 5 nuisances)

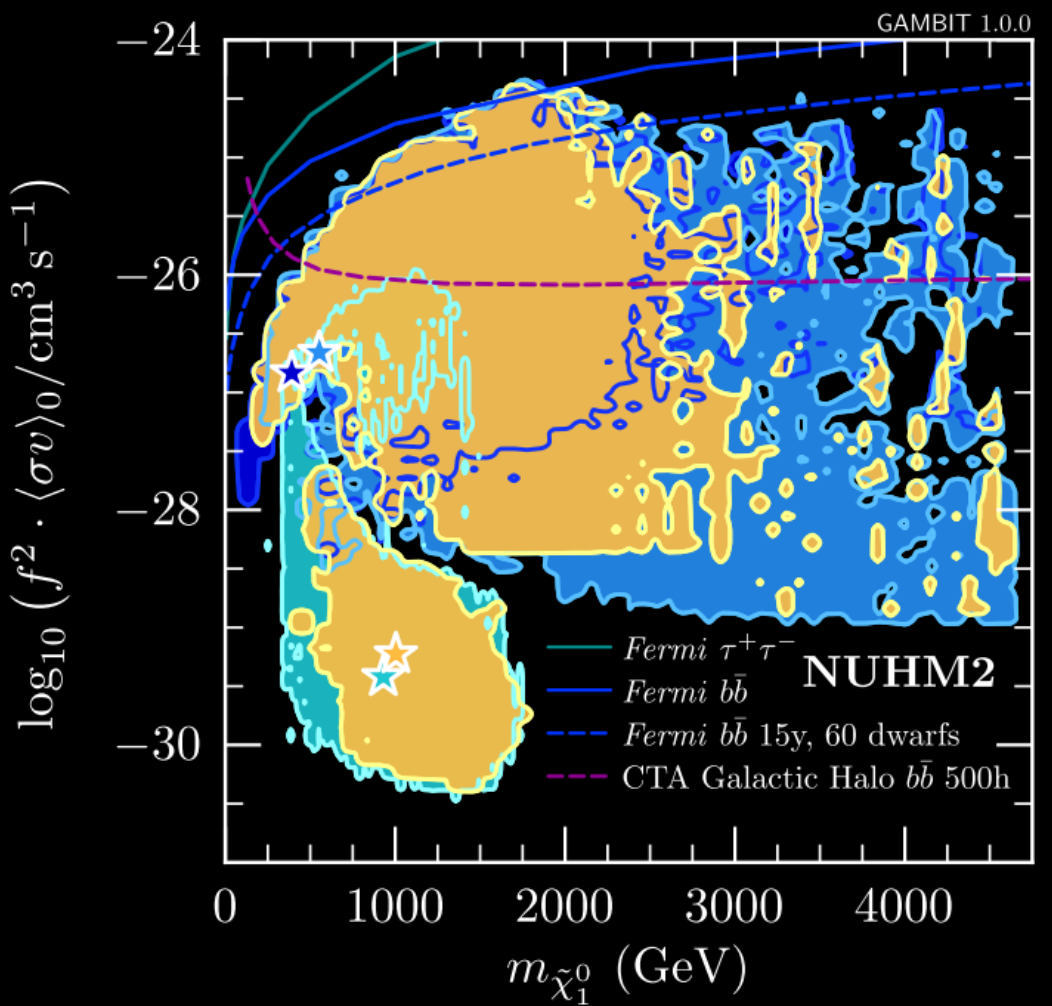




- $\tilde{t}$ co-ann. chargino co-ann. heavy Higgs funnel $\tilde{\tau}$ co-ann.
- more freedom allows for much wider plausible regions

NUHM2 ($M_{H_u}, M_{H_d}, M_0, M_{1/2}, A_0, \tan\beta, \mathrm{sign}\mu$ + 5 nuisances)





- $\tilde{t}$ co-ann. chargino co-ann. heavy Higgs funnel $\tilde{\tau}$ co-ann.
- similar to NUHM1; LHC Run2 stop and EW gaugino searches may impact low mass regions

MSSM-7 (weak scale BCs)

$$\mathcal{L}_{soft} \sim M_{H_{u,d}}^2 |H_{u,d}|^2 + m_{\tilde{f}_i}^2 \tilde{F}_i^\dagger \tilde{F}_i + \frac{1}{2} M_j \tilde{G}_j \tilde{G}_j + A_{f\,i} \tilde{f}_i^c H_{u,d} \tilde{F}_i + \cdots$$

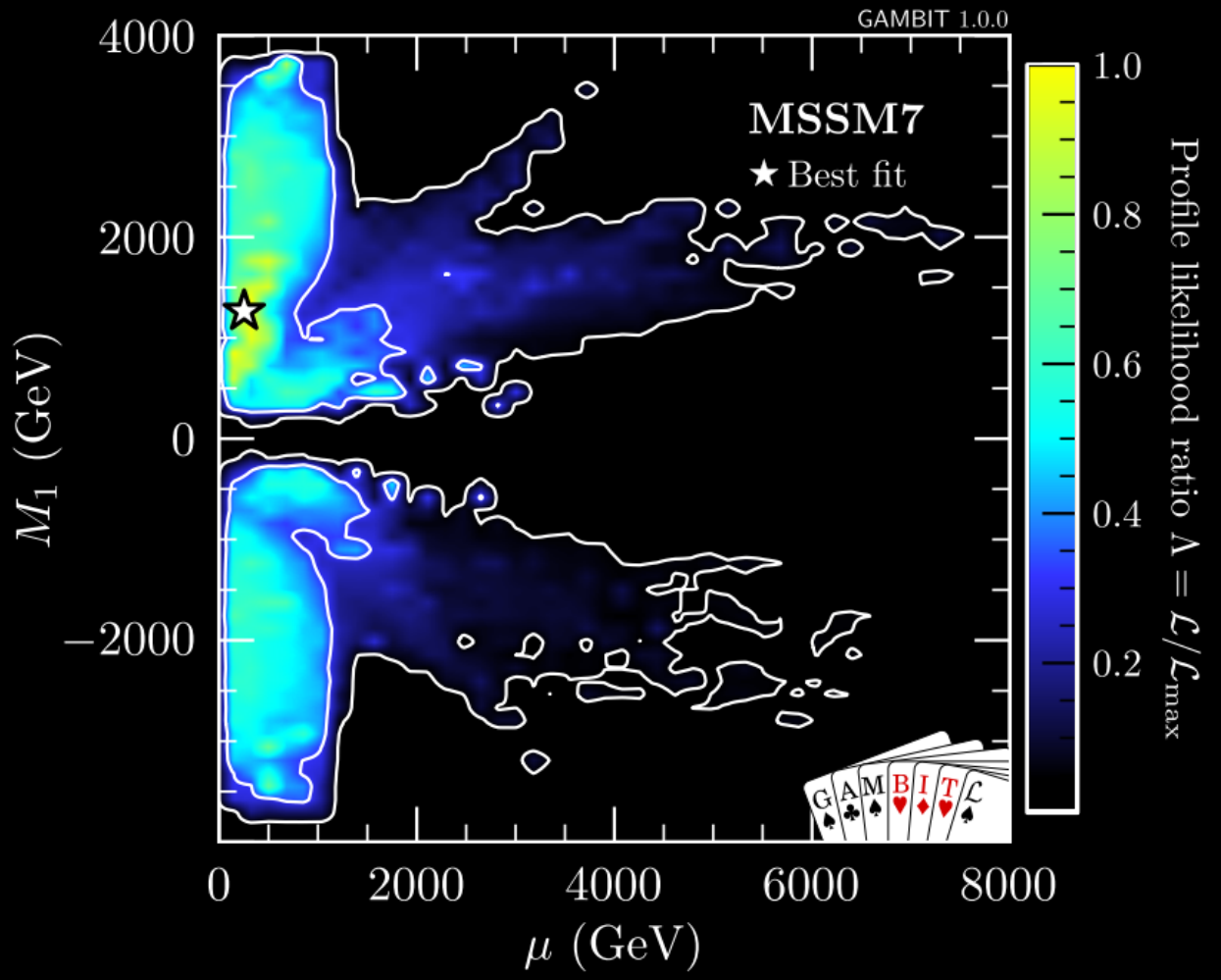
Constraints

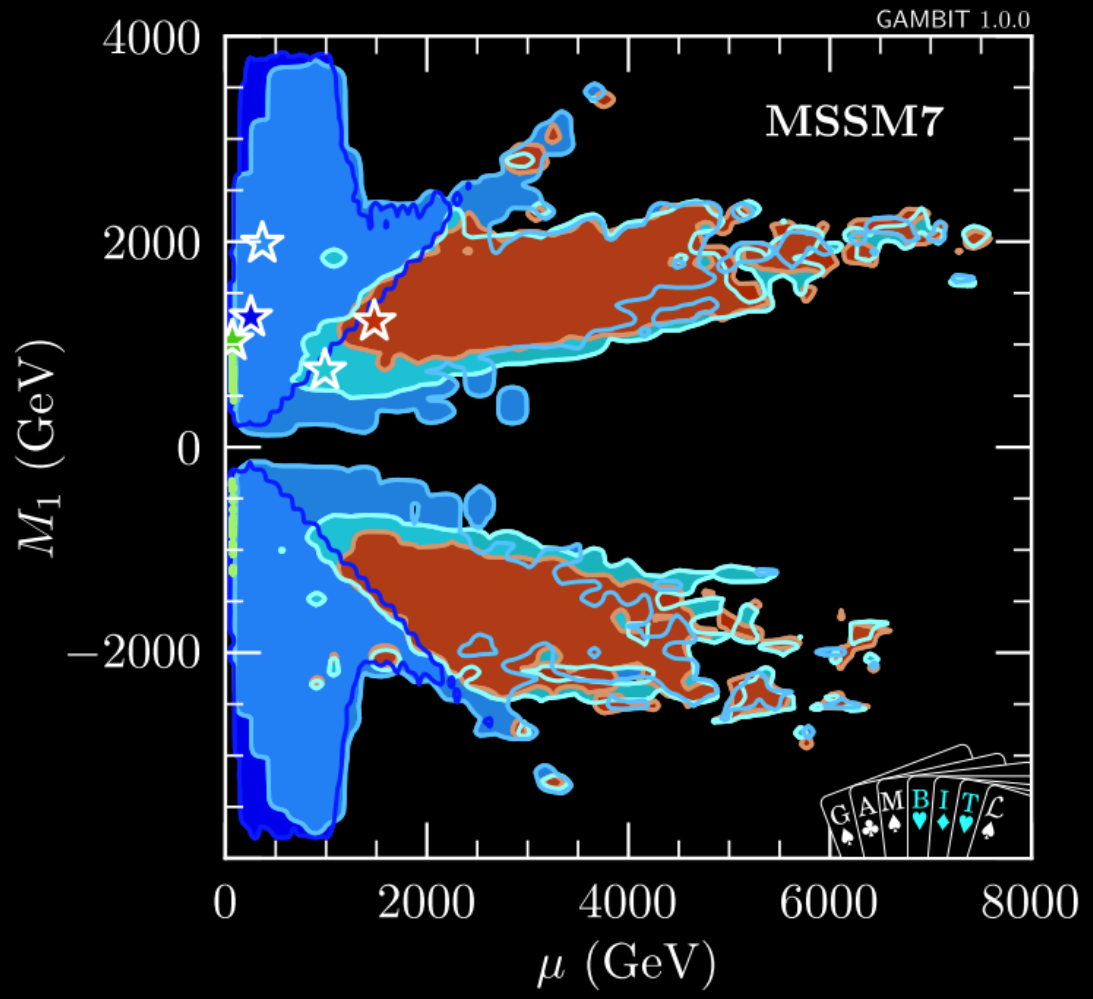
- DM relic density upper bound
- DM direct det. 6 experiments
- DM indirect det. Fermi-LAT (dSphs), IceCube79
- EW precision W mass, $g_\mu - 2$, …
- 59 flavor observables
- LHC Higgs data, SUSY searches, …

Uncertainties, nuisances

- local DM density
- nuclear physics parameters
- Higgs and quark masses
- gauge couplings

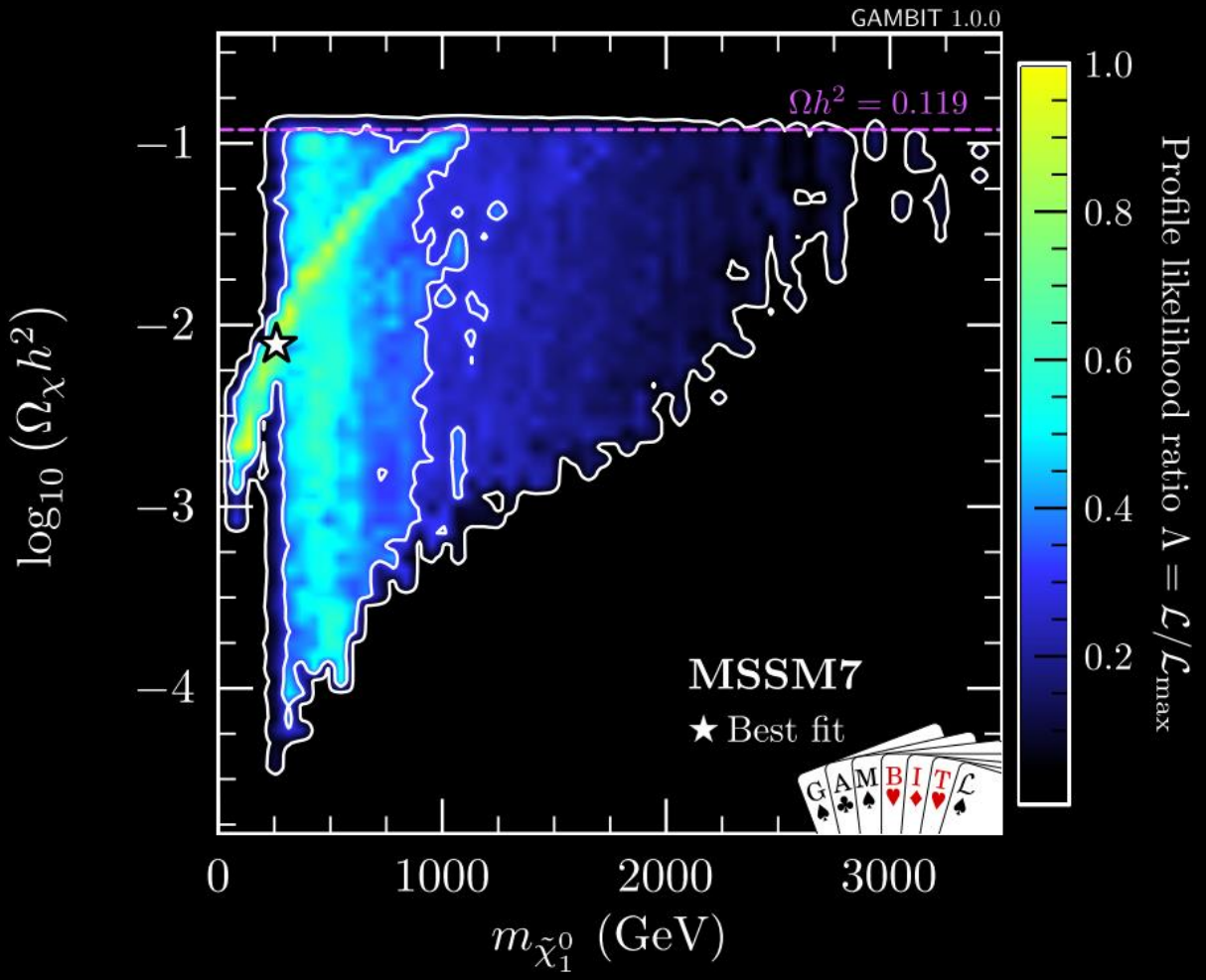
MSSM-7 ($M_{H_u}, M_{H_d}, m_{\tilde{f}}, M_2, A_{u_3}, A_{d_3}, \tan\beta$ + 5 nuisances)

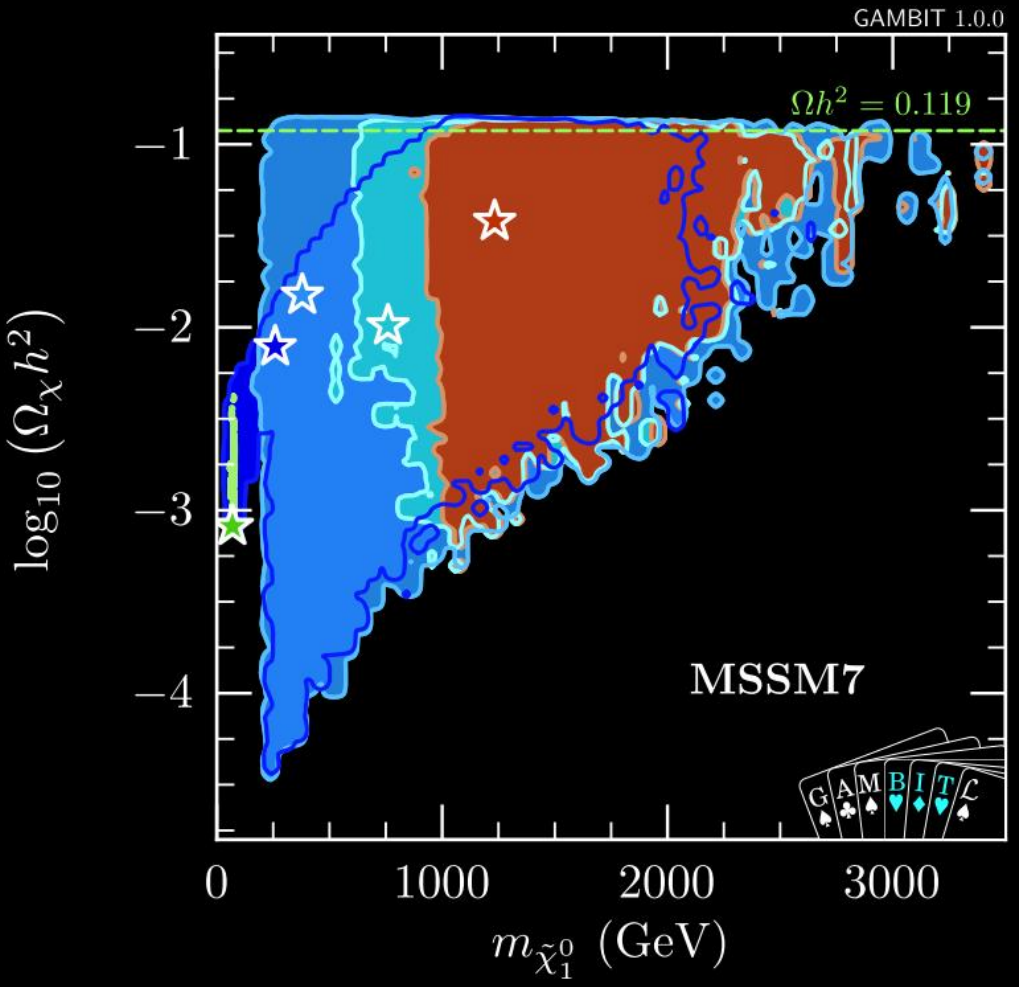




- $\tilde{t}_1$ co-annihilation
- A/H funnel
- $\tilde{\chi}_1^{\pm}$ co-annihilation
- $\tilde{b}_1$ co-annihilation
- h/Z funnel
- neutralino can be dominated by higgsino or bino (wino domination prevented by $M_2^{GUT} \sim 2M_1^{GUT}$)

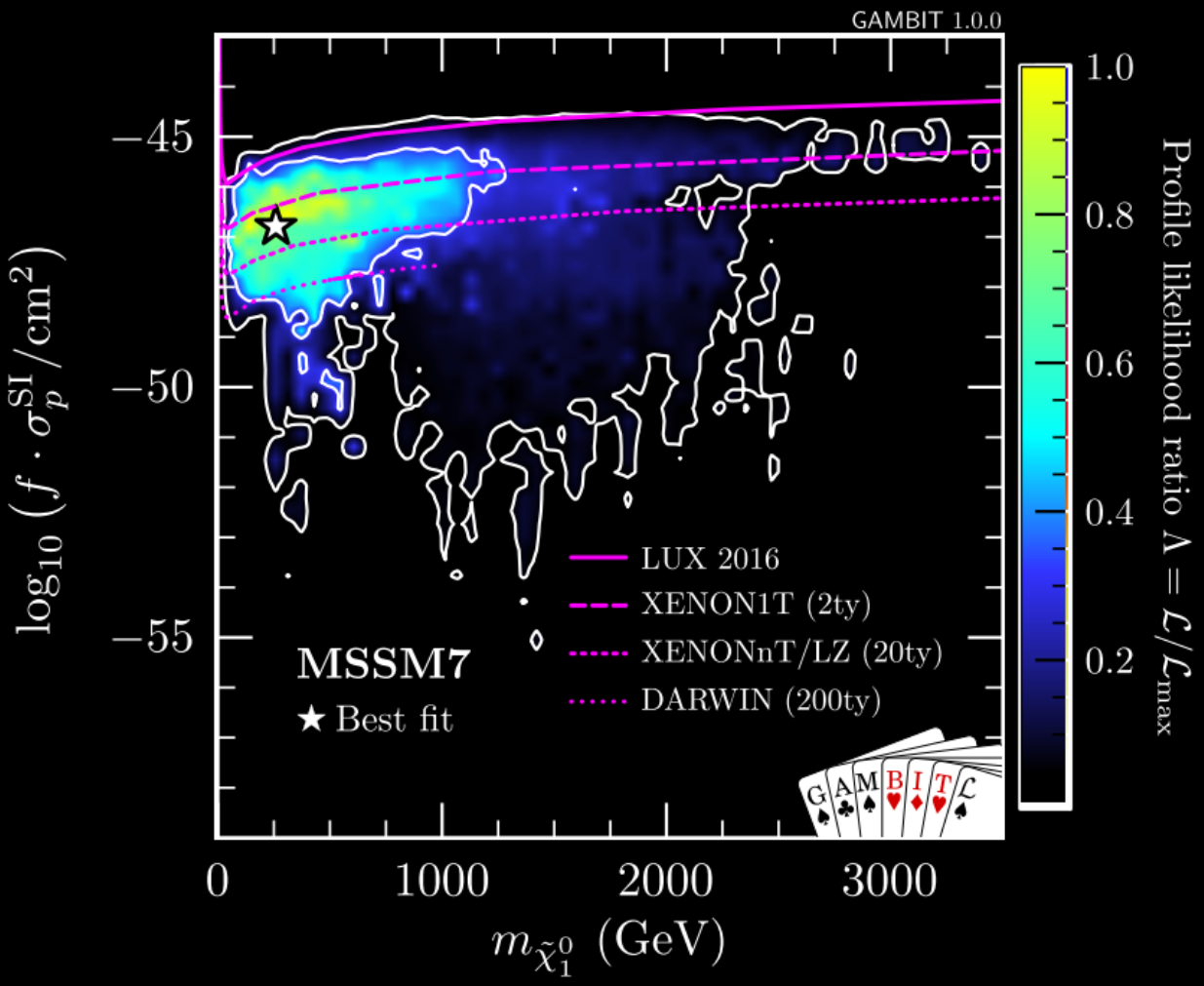
MSSM-7 ($M_{H_u}, M_{H_d}, m_{\tilde{f}}, M_2, A_{u_3}, A_{d_3}, \tan\beta$ + 5 nuisances)

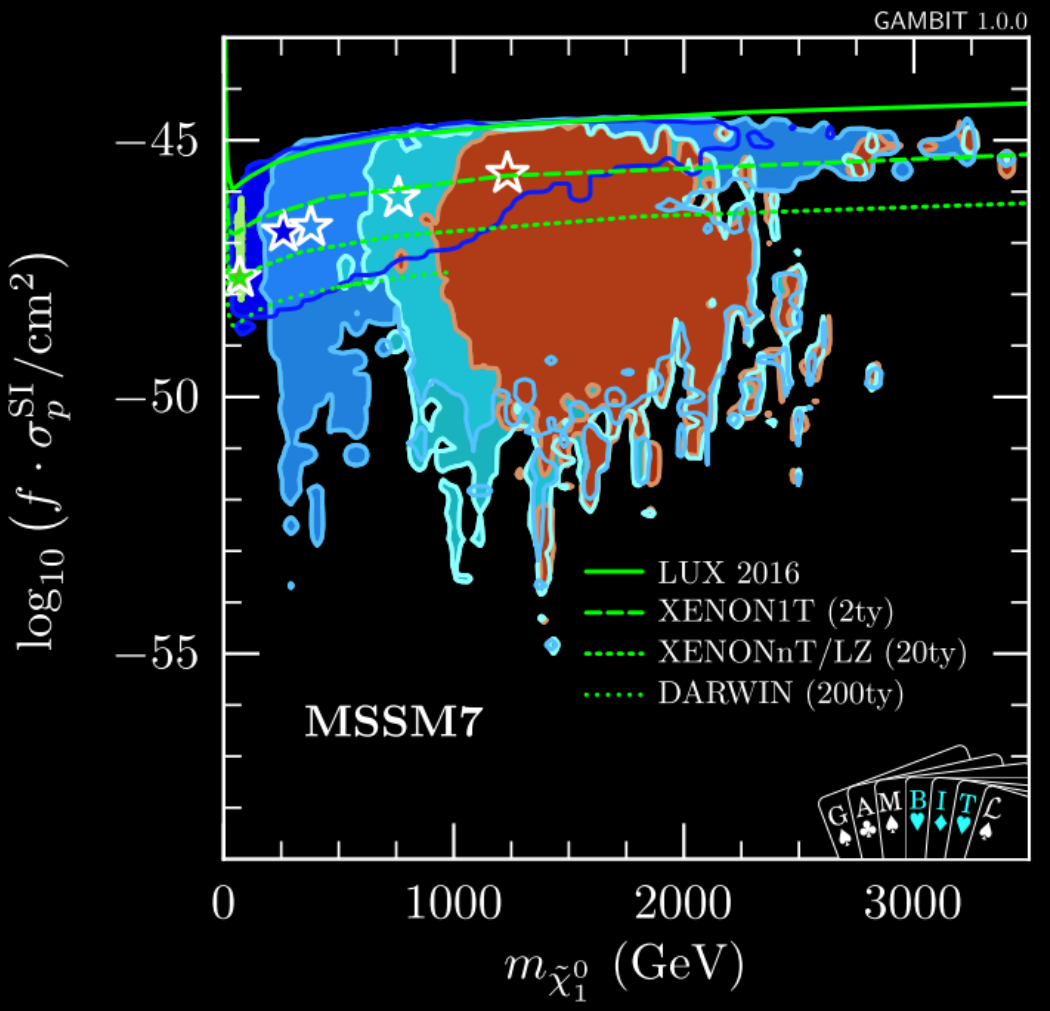




- $\tilde{t}_1$ co-annihilation, A/H funnel, $\tilde{\chi}_1^\pm$ co-annihilation, $\tilde{b}_1$ co-annihilation, h/Z funnel
- neutralino can be dominated by higgsino or bino (wino domination prevented by $M_2^{GUT} \sim 2M_1^{GUT}$)

MSSM-7 ($M_{H_u}, M_{H_d}, m_{\tilde{f}}, M_2, A_{u_3}, A_{d_3}, \tan\beta$ + 5 nuisances)



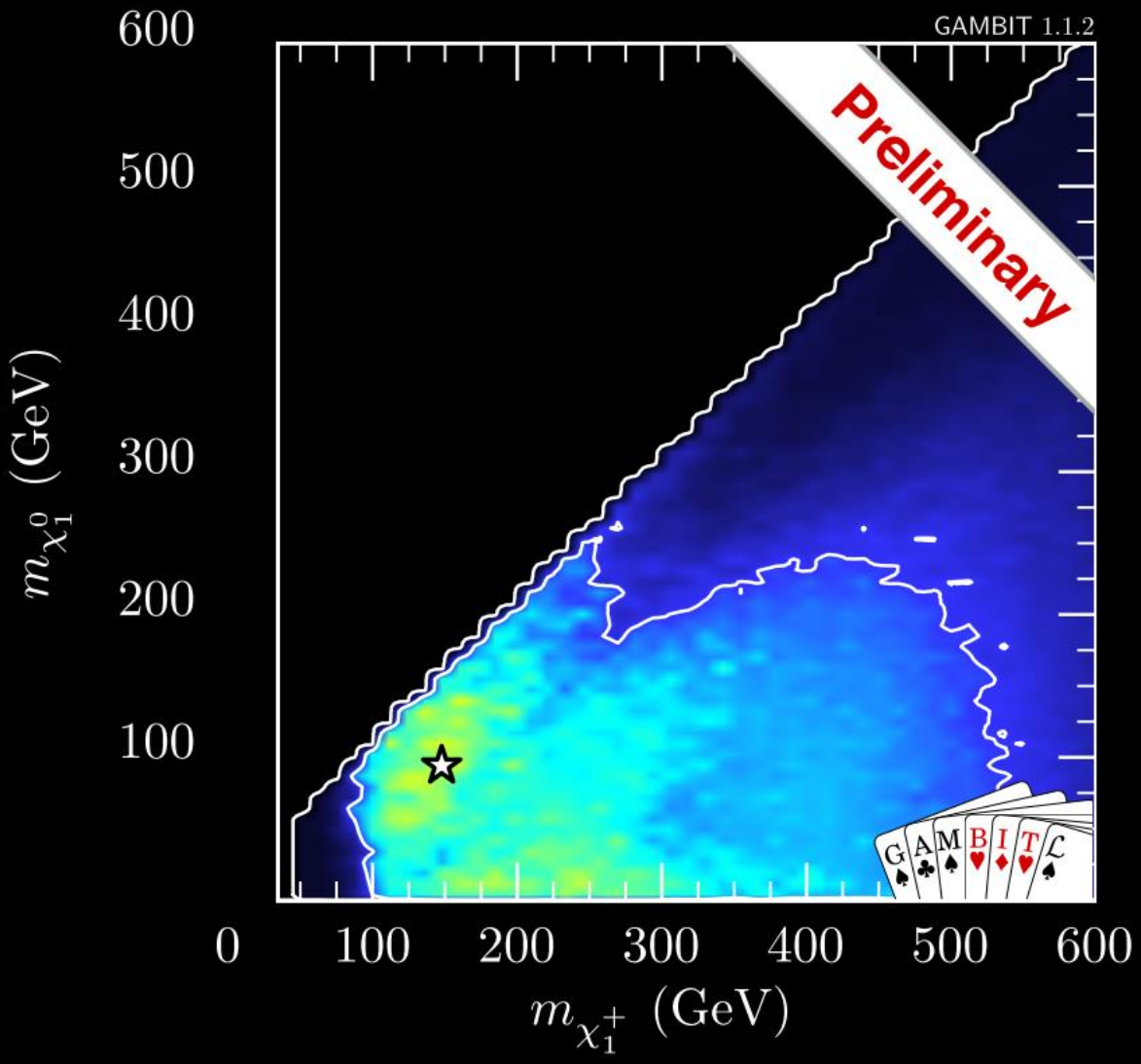


- $\tilde{t}_1$ co-annihilation, A/H funnel, $\tilde{\chi}_1^{\pm}$ co-annihilation, $\tilde{b}_1$ co-annihilation, h/Z funnel
- $\chi^{\pm}$ co-ann. and light Higgs will be probed by dark matter direct detection experiments

MSSM-EW in preparation

Decouple everything except $\chi^0, \chi^\pm$

- free (EW scale) parameters:
  $M_1, M_2, \mu, \tan\beta, \alpha_S, m_t$
- focus: impact of collider searches
  various LEP cross-section limits
  ATLAS multi-lepton: 2-3 leptons + 0-5 jets
  ATLAS RJ: 2-3 leptons, recursive jigsaw variables
  ATLAS 4lep: at least 4 leptons
  CMS multi-lepton: (similar to ATLAS)
  CMS 1lep(H)bb: 1 lepton plus bbar from H
  CMS 2SFOSlep-soft: two SFOS leptons (virtual W/Z)
  CMS 2SFOSlep: two SFOS leptons (on-shell W/Z dec.)



summary

GAMBIT: a modular, flexible, universal pheno tool - not only for global fitting.

First GAMBIT results show that SUSY is alive and well.

Stay tuned, much more to come.

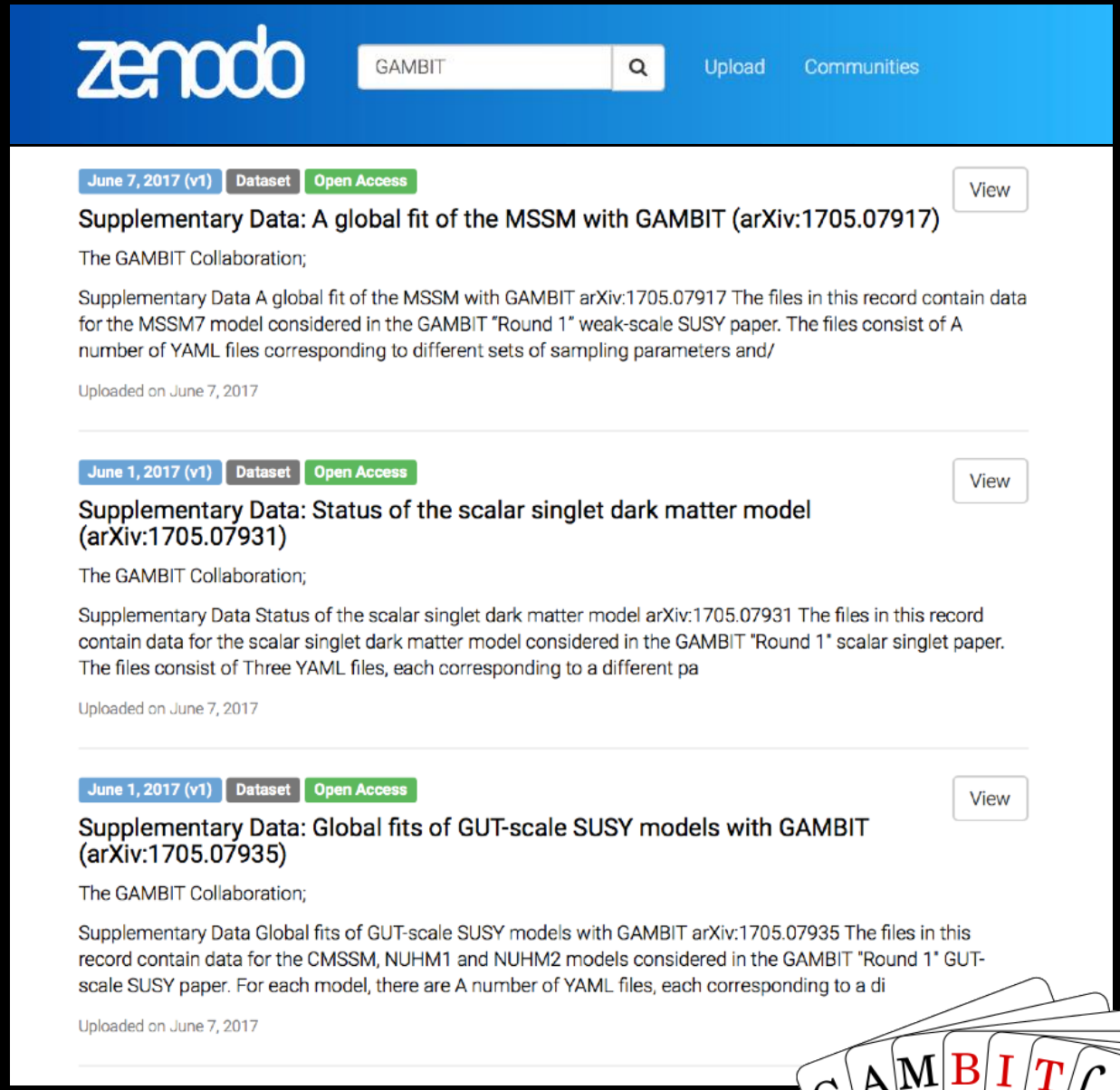
backup slides

public results

Results available on zenodo.cern.ch

- Parameter point samples (hdf5 files)
- GAMBIT input files for all scans
- Example plotting routines

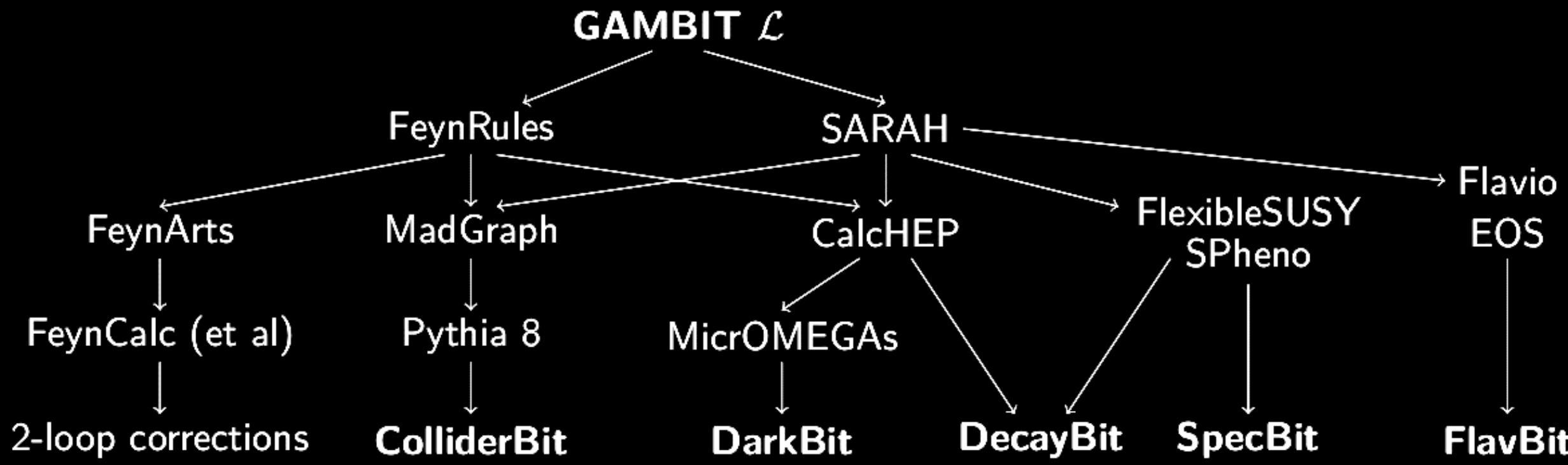
Links at gambit.hepforge.org/pubs



GAMBIT 2

Extension to model building

- GAMBIT Universal Model (GUM), interface to Lagrangian-level
- Auto code generation for spectra, cross sections, observables …



getting started

- clone git repo github.com/patscott/gambit_1.1 or
- download tarballs hepforge.org/downloads/gambit or
- get pre-compilied version docker run -it jmcornell/gambit and
- see quick start guide in arXiv:1705.07908

adding a new model to GAMBIT

1. Add the model to the **model hierarchy**:
   - Choose a model name, and declare any **parent model**
   - Declare the model's parameters
   - Declare any **translation function** to the parent model

```
#define MODEL NUHM1
#define PARENT NUHM2
  START_MODEL
  DEFINEPARS(M0,M12,mH,A0,TanBeta,SignMu)
  INTERPRET_AS_PARENT_FUNCTION(NUHM1_to_NUHM2)
#undef PARENT
#undef MODEL
```

2. Write the translation function as a standard C++ function:

```
void MODEL_NAMESPACE::NUHM1_to_NUHM2 (const ModelParameters &myP, ModelParameters &targetP)
{
   // Set M0, M12, A0, TanBeta and SignMu in the NUHM2 to the same values as in the NUHM1
   targetP.setValues(myP,false);
   // Set the values of mHu and mHd in the NUHM2 to the value of mH in the NUHM1
   targetP.setValue("mHu", myP["mH"]);
   targetP.setValue("mHd", myP["mH"]);
}
```

3. If needed, declare that existing module functions work with the new model, or add new functions that do.

from Pat Scott

adding a new observable/likelihood to GAMBIT

Adding a new module function is easy:

1. Declare the function to GAMBIT in a module's **rollcall header**
   - Choose a capability
   - Declare any **backend requirements**
   - Declare any **dependencies**
   - Declare any specific **allowed models**
   - other more advanced declarations also available

```
#define MODULE FlavBit                                  // A tasty GAMBIT module.
START_MODULE

  #define CAPABILITY Rmu                                // Observable: BR(K->mu nu)/BR(pi->mu nu)
  START_CAPABILITY
    #define FUNCTION SI_Rmu                             // Name of a function that can compute Rmu
    START_FUNCTION(double)                              // Function computes a double precision result
    BACKEND_REQ(Kmunu_pimunu, (my_tag), double, (const parameters*)) // Needs function from a backend
    BACKEND_OPTION( (SuperIso, 3.6), (my_tag) )                      // Backend must be SuperIso 3.6
    DEPENDENCY(SuperIso_modelinfo, parameters)          // Needs another function to calculate SuperIso info
    ALLOW_MODELS(MSSM63atQ, MSSM63atMGUT)               // Works with weak/GUT-scale MSSM and descendents
    #undef FUNCTION
  #undef CAPABILITY
```

2. Write the function as a standard C++ function (one argument: the result)

from Pat Scott

CMSSM, NUHM1, NUHM2 arXiv:1705.07935

Mechanisms to avoid DM overabundance

- $\tilde{t}$ co-ann. chargino co-ann. heavy Higgs funnel $\tilde{\tau}$ co-ann.

Definition of colored regions

– stau co-annihilation: $m_{\tilde{\tau}_1} \leq 1.2\, m_{\tilde{\chi}_1^0}$,
– stop co-annihilation: $m_{\tilde{t}_1} \leq 1.2\, m_{\tilde{\chi}_1^0}$,
– chargino co-annihilation: $\tilde{\chi}_1^0 \geq 50\%$ Higgsino,
– A/H-funnel: $1.6\, m_{\tilde{\chi}_1^0} \leq m_{\text{heavy}} \leq 2.4\, m_{\tilde{\chi}_1^0}$,