the WIMP situation

Csaba Balázs

CTA, Monash, CoEPP, GAMBIT

48,868 views | Feb 22, 2019, 02:00am

The 'WIMP Miracle' Hope For Dark Matter Is Dead

Ethan Siegel Senior Contributor
Starts With A Bang Contributor Group
Science
The Universe is out there, waiting for you to discover it.

The quest for particle dark matter has led us to look for WIMPs that may recoil with atomic nuclei. The LZ Collaboration will provide the best limits on WIMP-nucleon cross-sections of all, but the best motivated scenarios for having a weak-force-driven particle at or near the electroweak scale make up 100% of the dark matter are already ruled out. LUX-ZEPLIN (LZ) COLLABORATION / SLAC NATIONAL ACCELERATOR LABORATORY

Dark matter is not only the most abundant form of matter in the Universe, it's also the most mysterious. Whereas all the other particles we know of — atoms, neutrinos, photons, antimatter and all the other particles in the Standard Model — interact through at least one of the known quantum forces, dark matter appears to interact through gravity alone.

According to many, it would be better to have called it invisible matter, rather than dark matter. It not only doesn't emit or absorb light, but it doesn't interact with any of the known, directly detectable particles through the electromagnetic, strong, or weak nuclear forces. The most sought after dark matter candidate is the WIMP: the Weakly Interacting Massive Particle. The big hope was for a WIMP miracle, a great prediction of supersymmetry.

It's 2019, and that hope is now dashed. Direct detection experiments have

https://www.forbes.com/sites/startswithabang/2019/02/22/the-wimp-miracle-is-dead-as-dark-matter-experiments-come-up-empty-again

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outline

lessons from Higgstory

lessons about fundamental discoveries from the Higgs discovery

plausibility of WIMPs

and

CTA reach for WIMPs

lessons about fundamental discoveries from the Higgstory

1964 Higgs particle proposed

VOLUME 13, NUMBER 16 PHYSICAL REVIEW LETTERS 19 OCTOBER 1964

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland
(Received 31 August 1964)

In a recent note[1] it was shown that the Goldstone theorem,[2] that Lorentz-covariant field theories in which spontaneous breakdown of symmetry under an internal Lie group occurs contain zero-mass particles, fails if and only if the conserved currents associated with the internal group are coupled to gauge fields. The purpose of the present note is to report that, as a consequence of this coupling, the spin-one quanta of some of the gauge fields acquire mass; the longitudinal degrees of freedom of these particles (which would be absent if their mass were zero) go over into the Goldstone bosons when the coupling tends to zero. This phenomenon is just the relativistic analog of the plasmon phenomenon to which Anderson[3] has drawn attention: that the scalar zero-mass excitations of a super-

about the "vacuum" solution $\varphi_1(x) = 0$, $\varphi_2(x) = \varphi_0$:

$$\partial^\mu\{\partial_\mu(\Delta\varphi_1) - e\varphi_0 A_\mu\} = 0, \tag{2a}$$

$$\{\partial^2 - 4\varphi_0^2 V''(\varphi_0^2)\}(\Delta\varphi_2) = 0, \tag{2b}$$

$$\partial_\nu F^{\mu\nu} = e\varphi_0\{\partial^\mu(\Delta\varphi_1) - e\varphi_0 A_\mu\}. \tag{2c}$$

Equation (2b) describes waves whose quanta have (bare) mass $2\varphi_0\{V''(\varphi_0^2)\}^{1/2}$; Eqs. (2a) and (2c) may be transformed, by the introduction of new variables

$$B_\mu = A_\mu - (e\varphi_0)^{-1}\partial_\mu(\Delta\varphi_1),$$

$$G_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu = F_{\mu\nu}, \tag{3}$$

1978 Higgs discovery mode proposed

VOLUME 40, NUMBER 11 PHYSICAL REVIEW LETTERS 13 MARCH 1978

Higgs Bosons from Two-Gluon Annihilation in Proton-Proton Collisions

H. M. Georgi, S. L. Glashow, M. E. Machacek, and D. V. Nanopoulos
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138
(Received 27 December 1977)

We estimate the cross section for Higgs-boson production in proton-proton collisions. We find that most of the cross section comes from a two-gluon annihilation process, in which the gluons couple to Higgs bosons via heavy-quark loops.

Today's recipe for elementary particle physics calls for four basic ingredients: leptons, quarks, gauge bosons with spin 1, and Higgs bosons with spin 0. Alas, there is no direct evidence for the existence of the Higgs boson even though theory demands that there be at least one such particle, H. We show that the inclusive cross section for

$$p + p \to H + \text{anything}, \qquad (1)$$

though small, may permit the discovery of Higgs bosons at proposed (or even existing) colliding pp facilities. Moreover, since we find that H's are produced primarily by virtual gluon-gluon collisions, their discovery could shed light on

the very small current-algebra masses[3] of the light quarks makes their contribution to (2) very small. While H does couple strongly to heavy quarks, the chance to find simultaneously a heavy quark in one protnon and a heavy antiquark in the other is negligible. Thus, the contribution of quark-antiquark annihilation [Fig. 1(a)] to Higgs-boson production is very small.

Illustrated in Fig. 1(b) is another mechanism for Higgs-boson production which depends upon the coupling of H to two gluons.[4] This coupling leads to a two-gluon annihilation contribution to $d\sigma_H/dy$ which is

1983 LEP construction begins

photo: https://timeline.web.cern.ch/timeline-header/88

1994 LHC construction approved

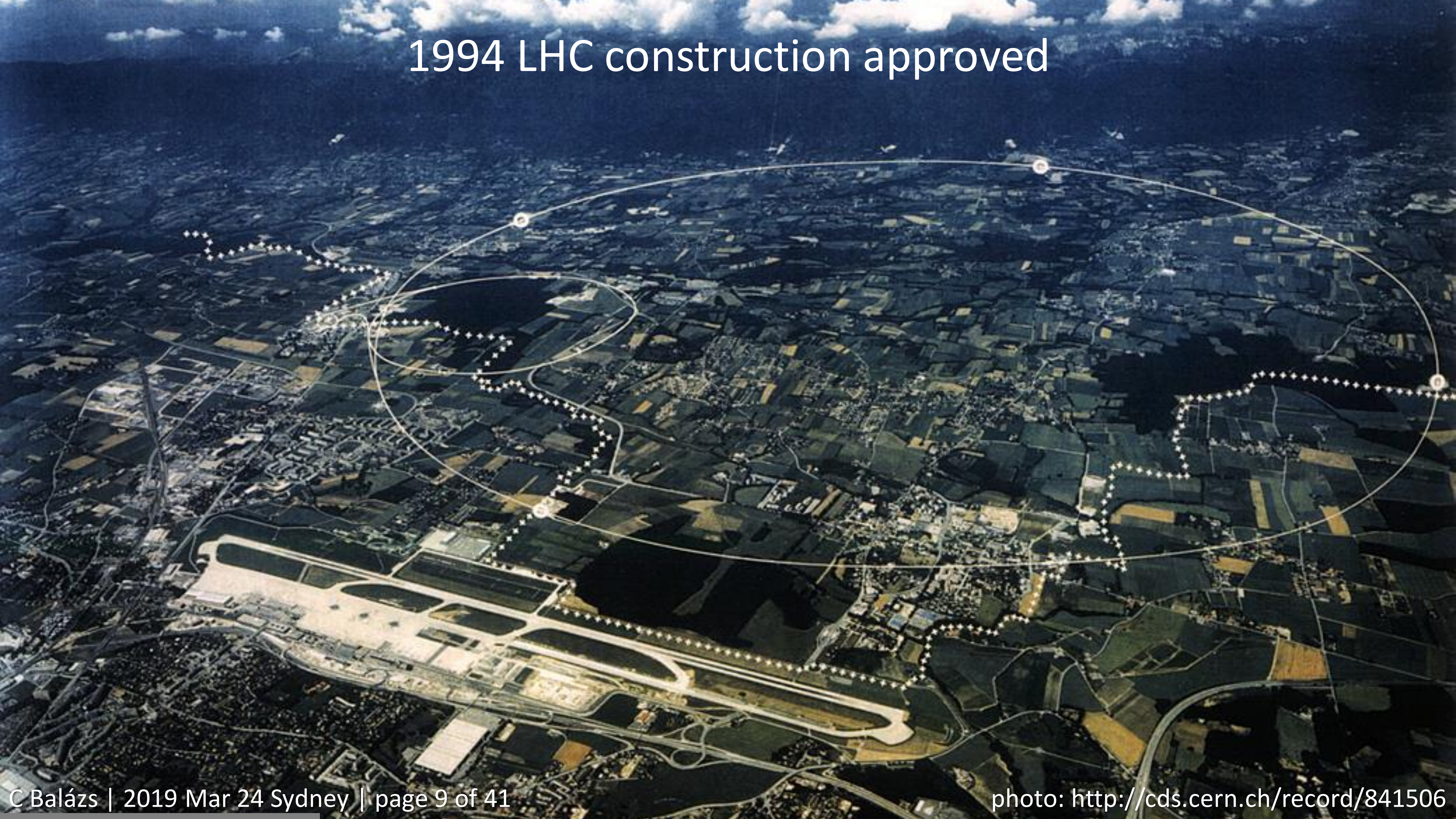

photo: http://cds.cern.ch/record/841506

2008 LHC operation begins

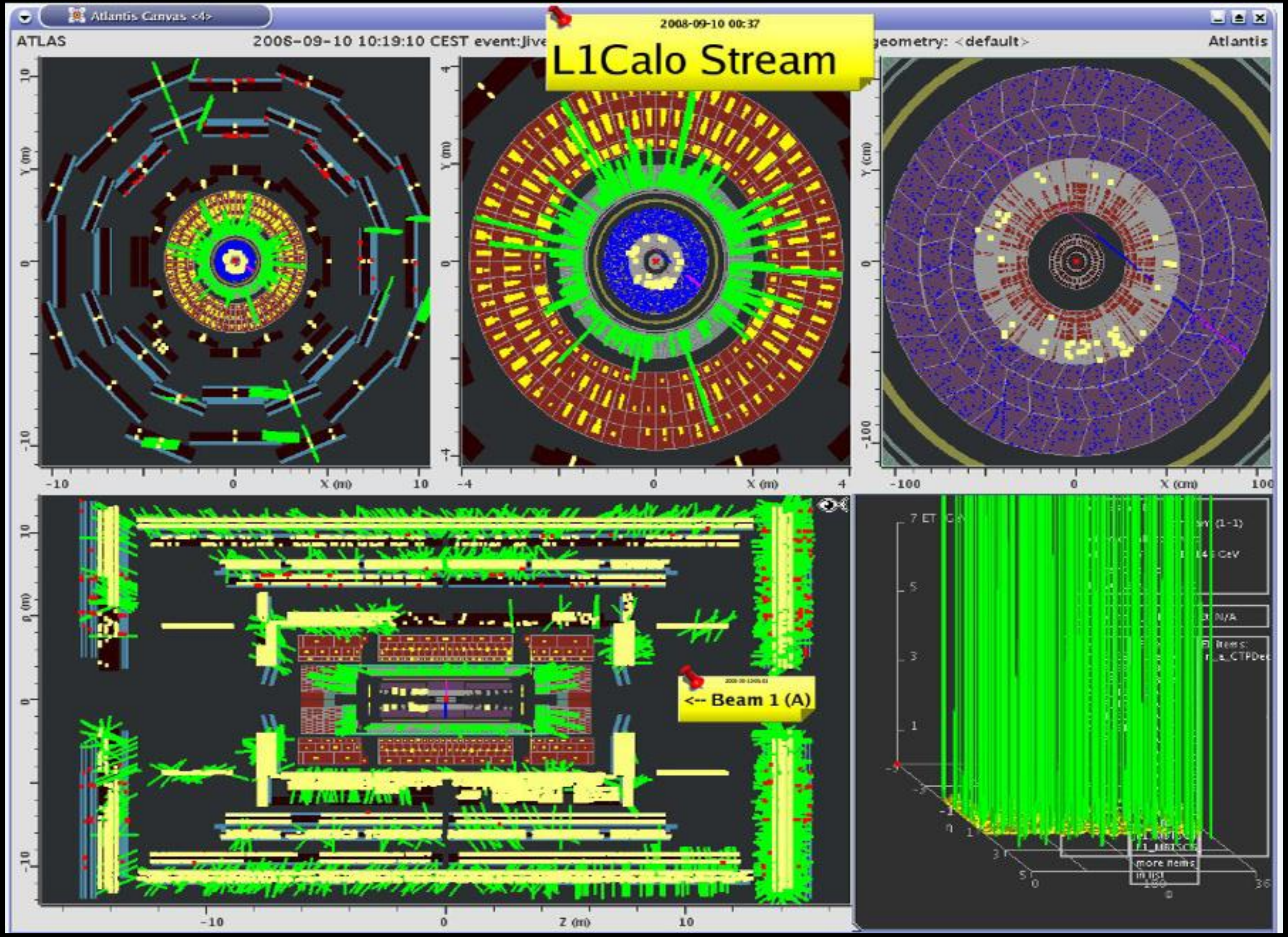

photo: http://cds.cern.ch/record/1703489

2012 Higgs boson discovered

photo: https://www.gettyimages.com.au/detail/news-photo/s-scientists-celebrates-with-champagne-after-the-news-photo/183634730

lessons learned

fundamental discoveries require good ideas,
hard work and take decades

during those decades we got confused and we got cold feet

hep-ph/0308038
Saclay t03/112

Towards a Realistic Model of Higgsless Electroweak Symmetry Breaking

Csaba Csáki[a], **Christophe Grojean**[b],
Luigi Pilo[b], and **John Terning**[c]

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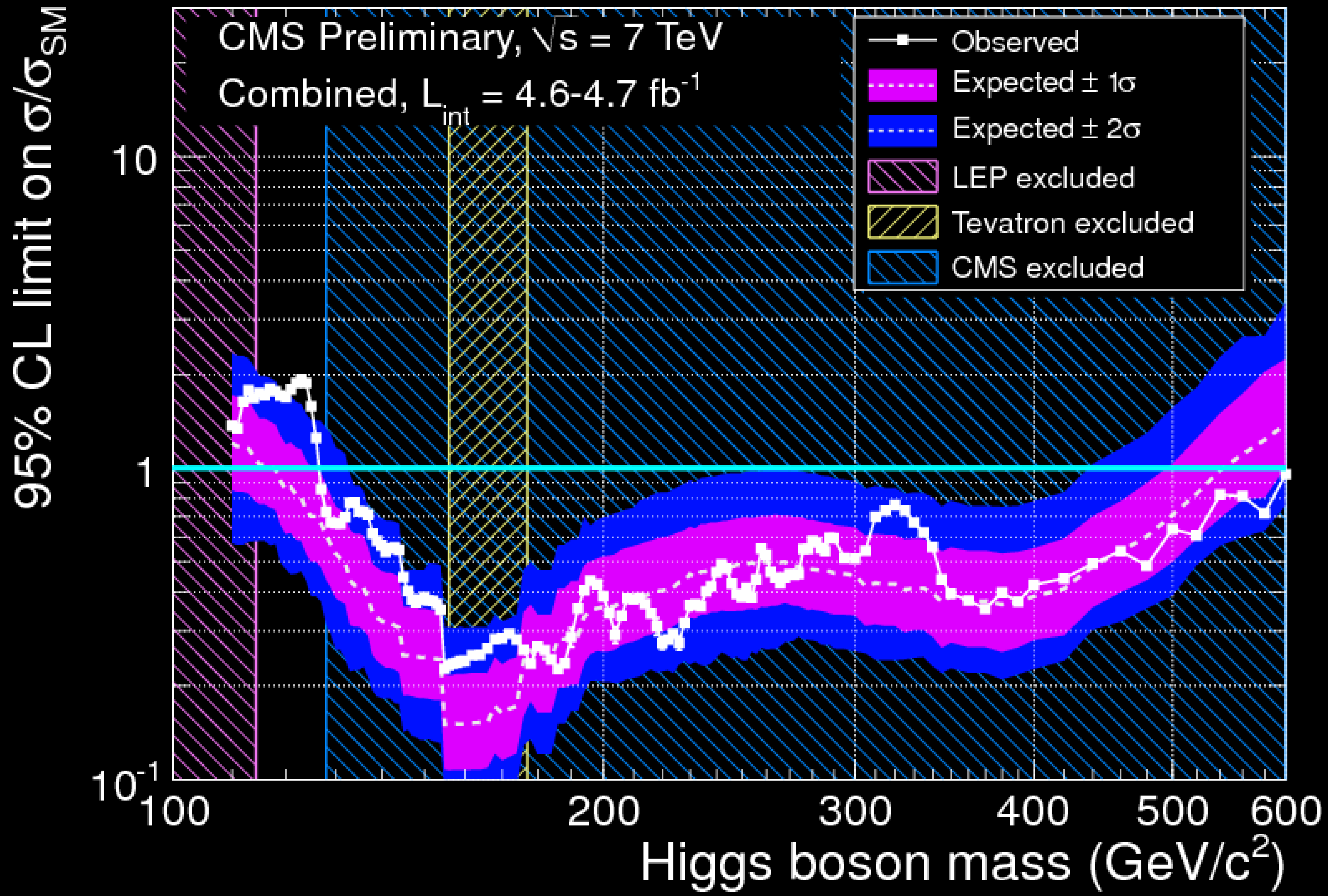
[b] *Service de Physique Théorique, CEA Saclay, F91191 Gif–sur–Yvette, France*

[c] *Theory Division T-8, Los Alamos National Laboratory, Los Alamos, NM 87545, USA*

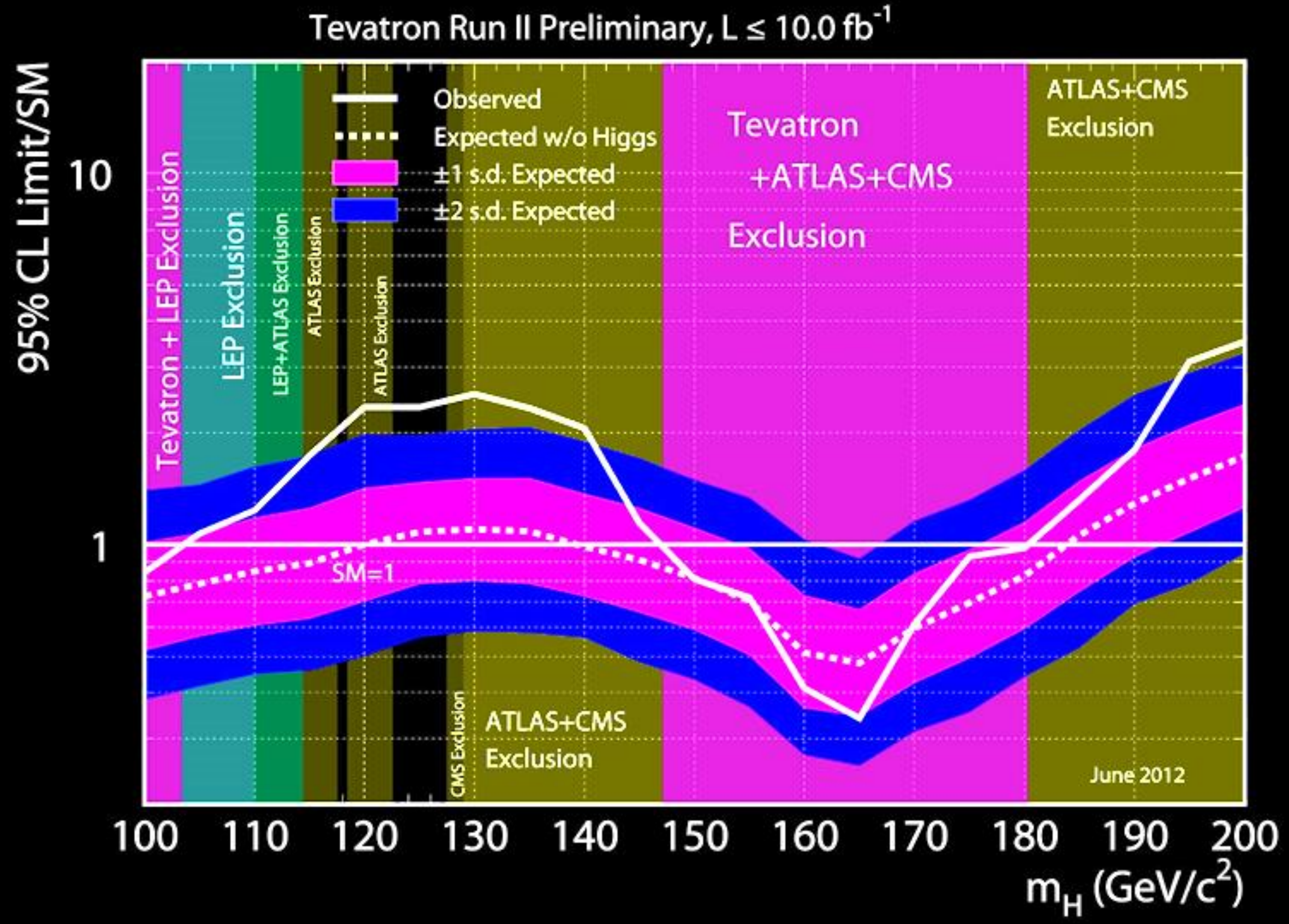
csaki@mail.lns.cornell.edu, grojean@spht.saclay.cea.fr,

confusion



plot: http://cms.web.cern.ch/sites/cms.web.cern.ch/files/styles/large/public/field/image/ltc_cls_comb_logx.png?itok=LcPZF-aH

cold feet and confusion



plot: http://www.fnal.gov/pub/today/archive/archive_2012/today12-03-08_ROWReadMore.html
https://cerncourier.com/the-tevatrons-data-continue-to-excite

FermiNews

Fermi National Accelerator Laboratory

Volume 21 | Friday, January 23, 1998 | Number 2

What Is Electroweak Symmetry Breaking, Anyway?

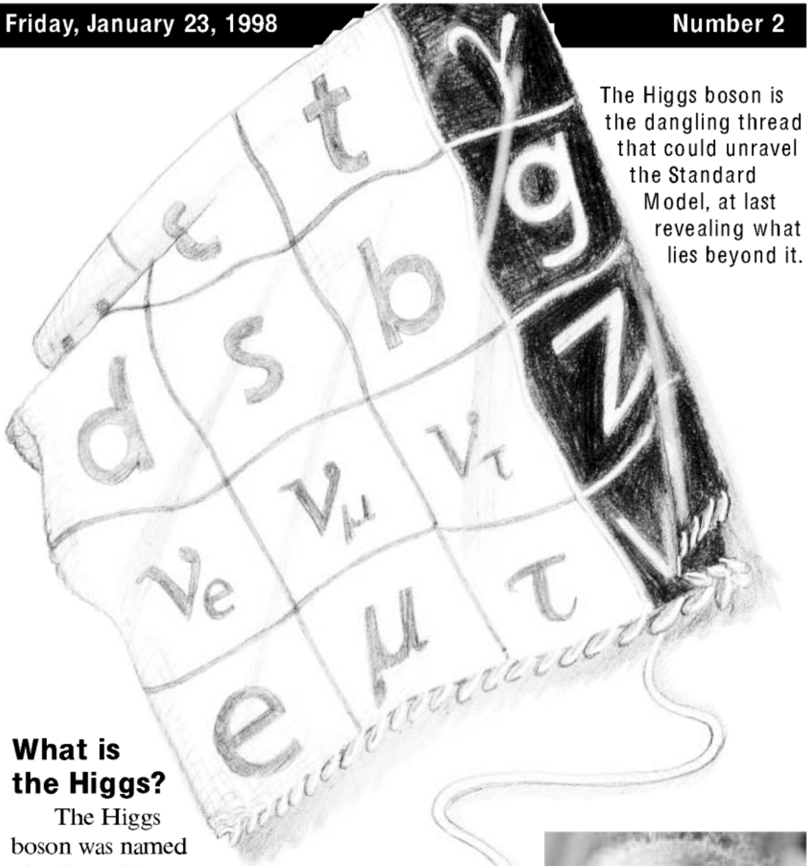
At high-energy physics labs, including Fermilab, the search is on for the Higgs boson.

By David Kestenbaum

"I drive the sea!"
~Captain Ahab, peg-legged whale hunter, Moby Dick

"We will find the Higgs.... I promise!"
~Gordy Kane, theoretical physicist, University of Michigan

It is only once in a long, long while that a discovery causes a complete rewriting of the textbooks. But physicists think that will happen in the coming decade. They are on the verge of



The Higgs boson is the dangling thread that could unravel the Standard Model, at last revealing what lies beyond it.

What is the Higgs?

The Higgs boson was named after Peter Higgs, a Scottish theorist who, in the early 1960s, was among the first to find it hiding in the equations that would become the Standard Model. Physicists know that the Higgs, or something like it, must exist because otherwise nothing would have any mass. Mass is vital—most obviously because it keeps things still. Without mass, the universe would be a chaotic sea of

Palmer

WIMP discovery will be a different story

but let’s see how timelines compare so far…

discovery timelines

Higgs discovery	*year*	*WIMP discovery*	*year*
particle proposed	1964	particle proposed	1971[1]
discovery mode	1978	discovery mode(s)	1985[1]
LEP construction	1983	DAMA construction	1994
LHC approval	1994	Fermi-LAT launched	2008
Higgsless models	2003	WIMPless models	now
LHC operation	2008	CTA construction	now
Higgs exclusion	2010	CTA operation	2020s
Higgs discovery	2012	WIMP discovery	2030s

[1] Bertone, Hooper A History of Dark Matter

we're (being) confused

APS physics | Journals | Physics | PhysicsCentral | APS News

Physics ABOUT BROWSE PRESS COLLECTIONS

Meetings: WIMP Alternatives Come Out of the Shadows

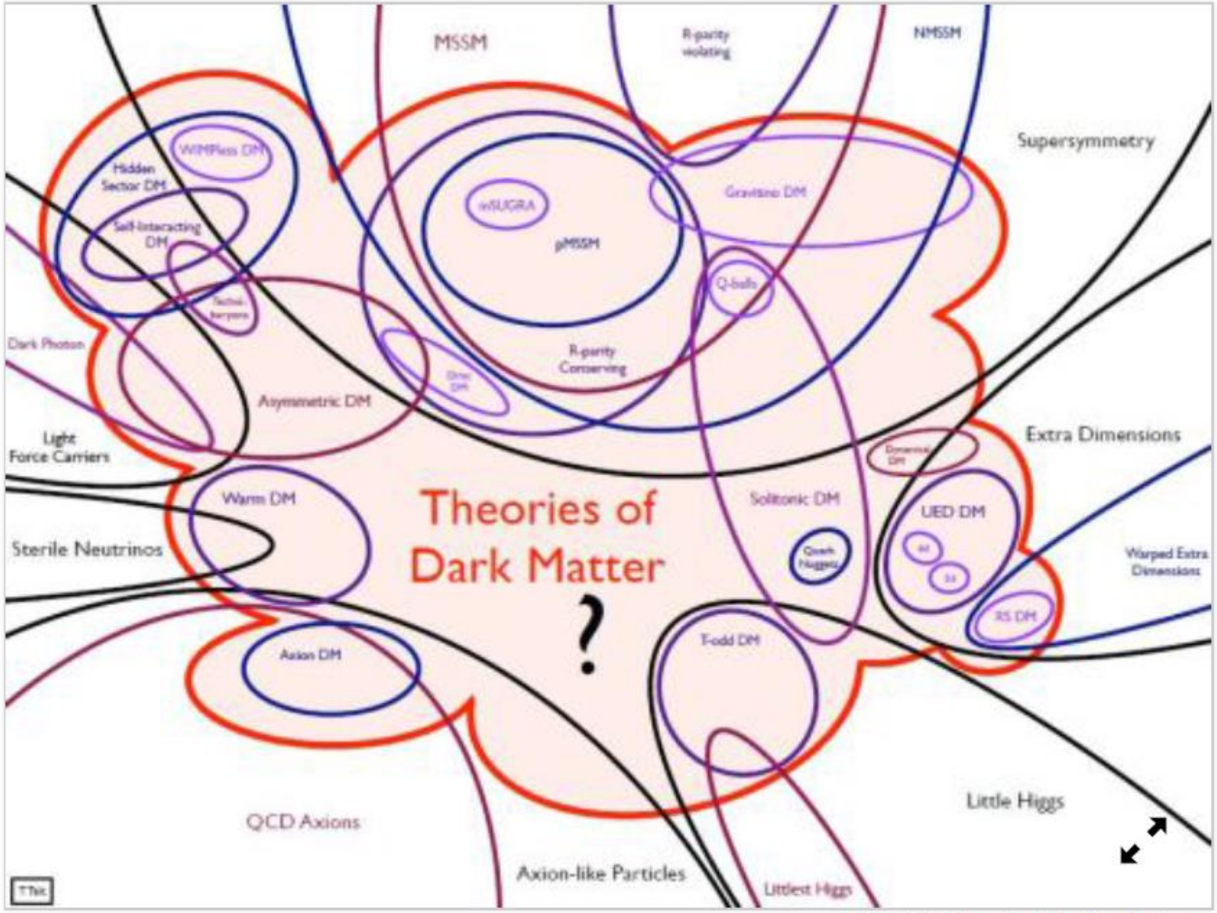
May 14, 2018 • *Physics* 11, 48

At an annual physics meeting in the Alps, WIMPs appeared to lose their foothold as the favored dark matter candidate, making room for a slew of new ideas.

The Rencontres de Moriond (Moriond Conferences) have been a fixture of European high-energy physics for over half a century. These meetings—typically held at an Alpine ski resort—have been the site of many big announcements, such as the first public talk on the top quark discovery in 1995 and important Higgs updates in 2013. One day, perhaps, a dark matter detection will headline at Moriond.

https://physics.aps.org/articles/v11/48

we’re (being) confused

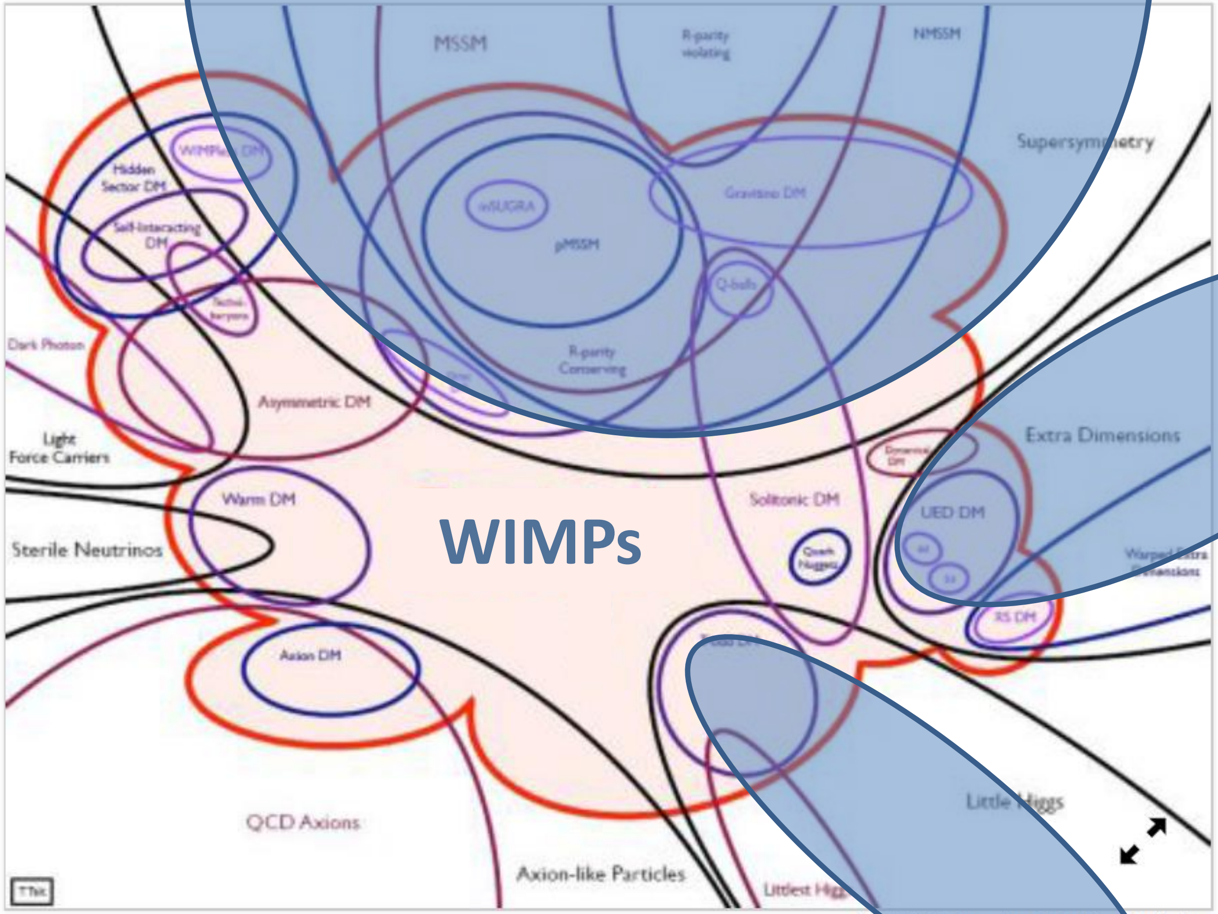


T. Tait/University of California, Irvine

Dark matter theory is no longer dominated by WIMPs.

https://physics.aps.org/articles/v11/48

we're (being) confused



T. Tait/University of California, Irvine

Dark matter theory is no longer dominated by WIMPs.

https://physics.aps.org/articles/v11/48

anti-WIMP sentiment

SIMPler realisation of Scalar Dark Matter

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Abstract. With growing agony of not finding a dark matter (DM) particle in direct search experiments so far (for example in XENON1T), frameworks where the freeze-out of DM is driven by number changing processes within the dark sector itself and do not contribute to direct search, like Strongly Interacting Massive Particle (SIMP) are gaining more attention. In this analysis, we ideate a simple scalar DM framework stabilised by Z_3 symmetry to serve with a SIMP-like DM (χ) with additional light scalar mediation (ϕ) to enhance DM self interaction. We identify that a large parameter space for such DM is available from correct relic density and self interaction constraints coming from Bullet or Abell cluster data. We derive an approximate analytic solution for freeze-out of the SIMP like DM in Boltzmann Equation describing $3 \to 2$ number changing process within the dark sector. We also provide a comparative analysis of the SIMP like solution with the Weakly Interacting Massive Particle (WIMP) realisation of the same model framework here.

Keywords: SIMP Dark Matter

plausibility of WIMPs

and

CTA reach for WIMPs

So, are WIMPs dead?

only multiple experiments can tell

this is why we need CTA and other observations

the Higgs discovery was a single parameter, one experiment venture

dark matter will be more complicated; this is why we need GAMBIT

based on the latest data GAMBIT can can calculate plausibility measures for various WIMPs

Global And Modular BSM Inference Tool

- open-source universal phenomenology tool for generic Beyond the Standard Model(s) theories
- designed to allow easy definition of new models, observables, likelihoods, scanners and backend physics codes

https://gambit.hepforge.org

EPJC 77 (2017) 784 arXiv:1705.07908

11 experiments

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

40+ participants

P Athron, C Balázs, A Beniwal, S Bloor, T Bringmann, A Buckley, J Camargo-Molina, M Chrząszcz, J Cornell, M Danninger, J Edsjö, B Farmer, A Fowlie, T Gonzalo, W Handley, S Hoof, S Hotinli, F Kahlhoefer, A Kvellestad, J Harz, P Jackson, F Mahmoudi, G Martinez, A Raklev, J Renk, C Rogan, R de Austri, P Scott, P Stöcker, A Vincent, C Weniger, M White, Y Zhang

14 major theory codes

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

the WIMP miracle: defining property of WIMPs

thermal production implies

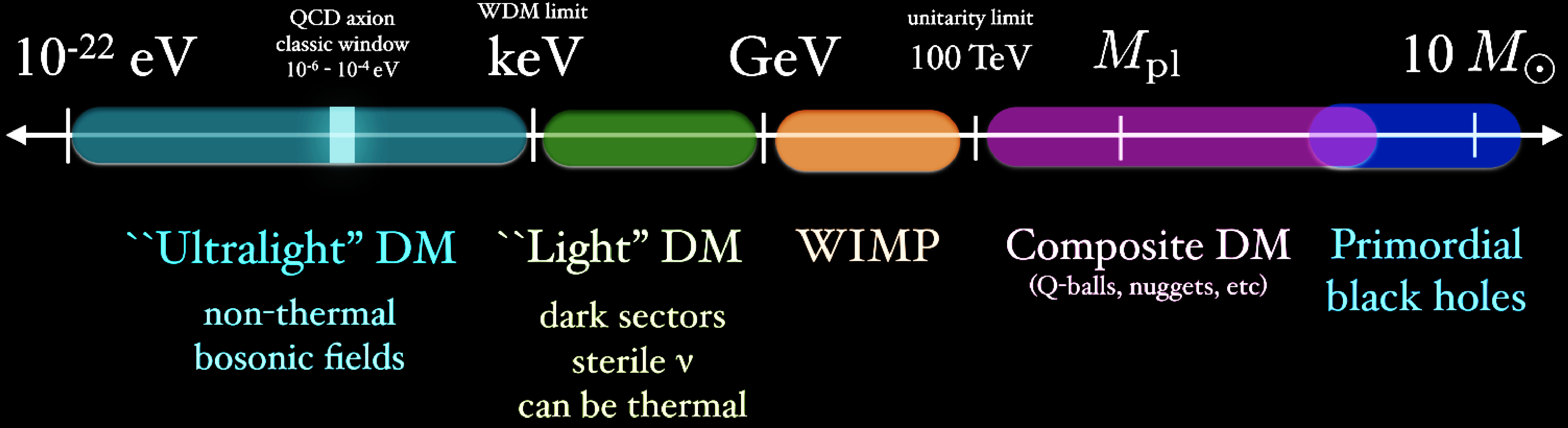
$$DM\ abundance\ \sim\ pre\text{–}factor\ *\ coupling^2_{SM\cdot DM}/mass^2_{DM}$$

the WIMP miracle: weak scale SM-DM coupling and weak scale DM mass yields the observed dark matter abundance

note: wide range of coupling/mass works

diagram: https://arxiv.org/pdf/1904.07915.pdf

WIMP masses range from (keV) GeV to TeV



caveats: above diagram is one dimensional, approximate, variable scale

diagram: https://arxiv.org/pdf/1904.07915.pdf

the simplest WIMP: a new spin 0 particle

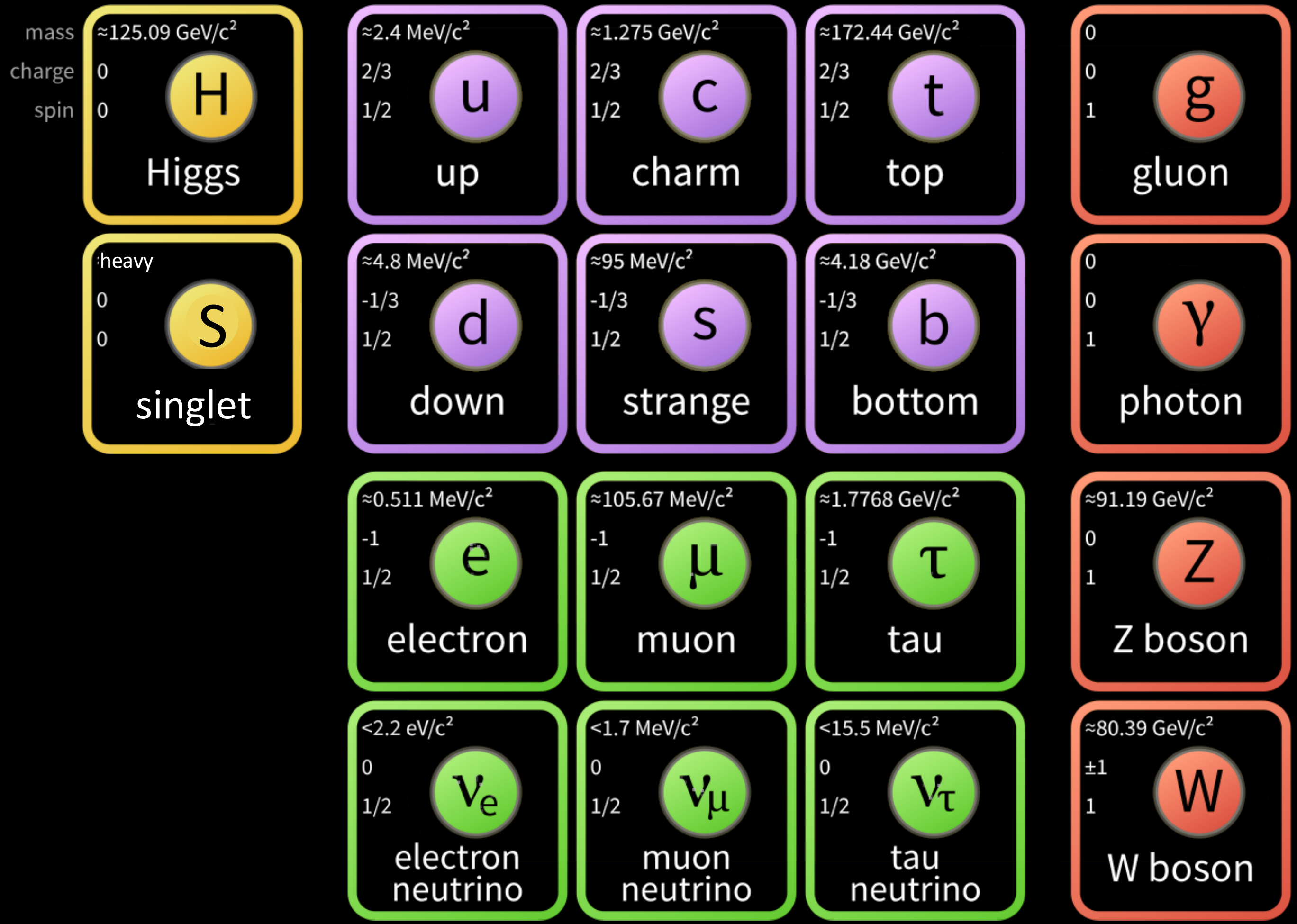


diagram: MissMJ & ProfCB PBS NOVA FNAL US DoE PDG

the simplest WIMP: a new spin 0 particle

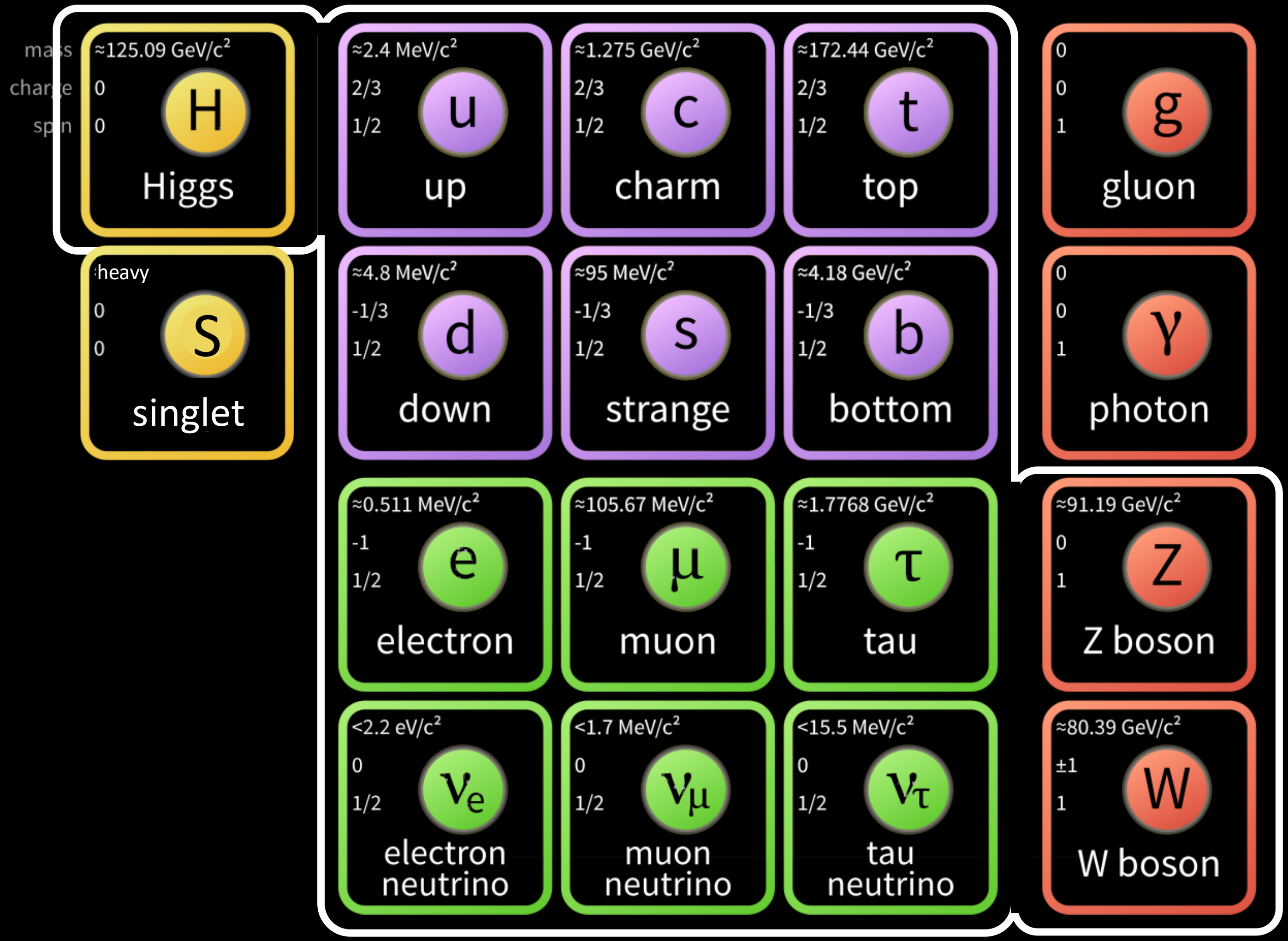


diagram: MissMJ & ProfCB PBS NOVA FNAL US DoE PDG

the simplest WIMP: a new spin 0 particle

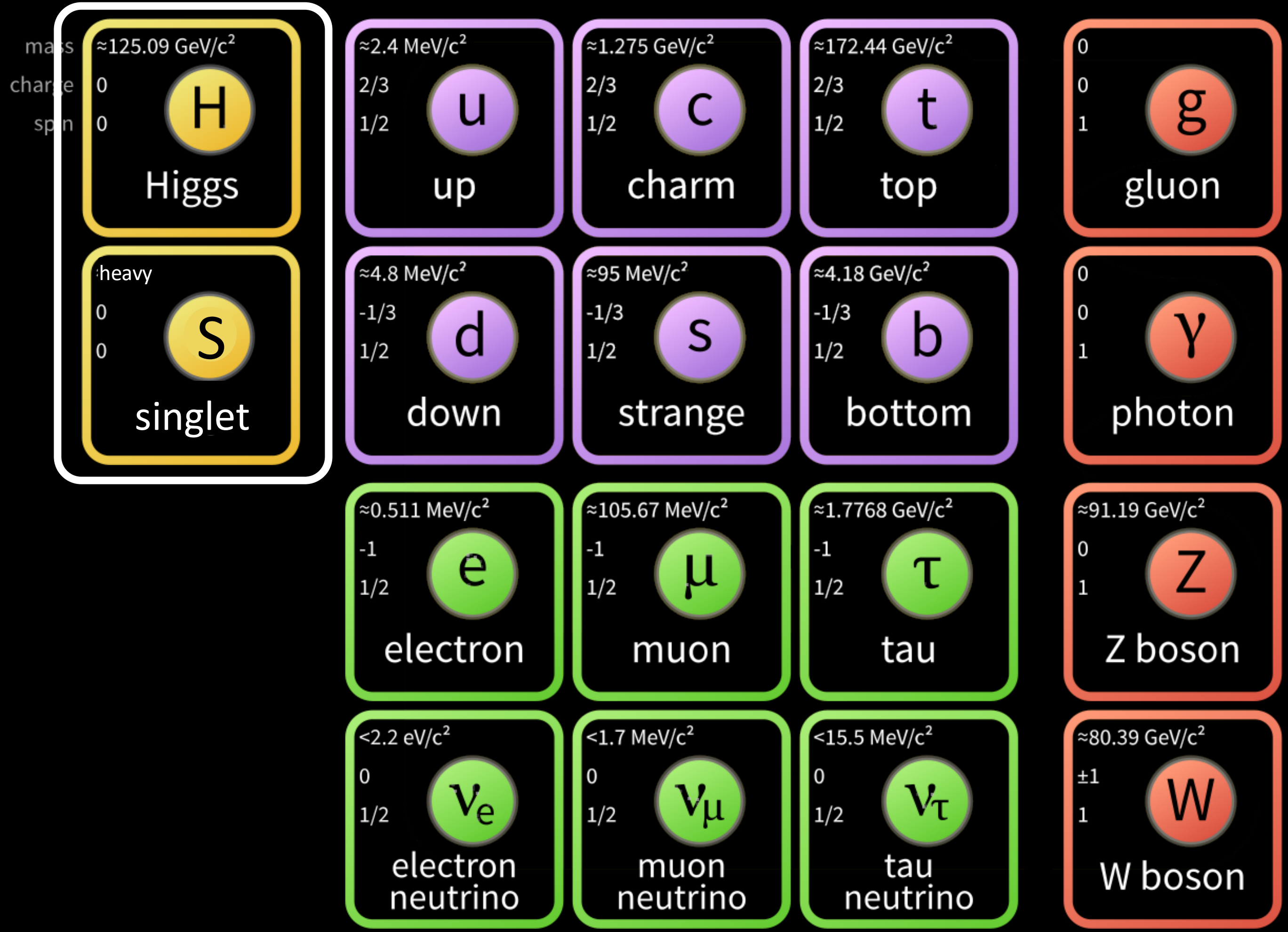


diagram: MissMJ & ProfCB PBS NOVA FNAL US DoE PDG

scalar singlet WIMP – GAMBIT analysis

$$\mathcal{L}_{SH} \sim \frac{1}{2}\mu_S^2 S^2 + \frac{1}{2}\lambda_{HS} S^2 |H|^2 + \frac{1}{4}\lambda_S S^4 \qquad m_S^2 = \mu_S^2 + \frac{1}{2}\lambda_{HS} v_H^2$$

Constraints

- DM abundance upper bound
- DM direct det.

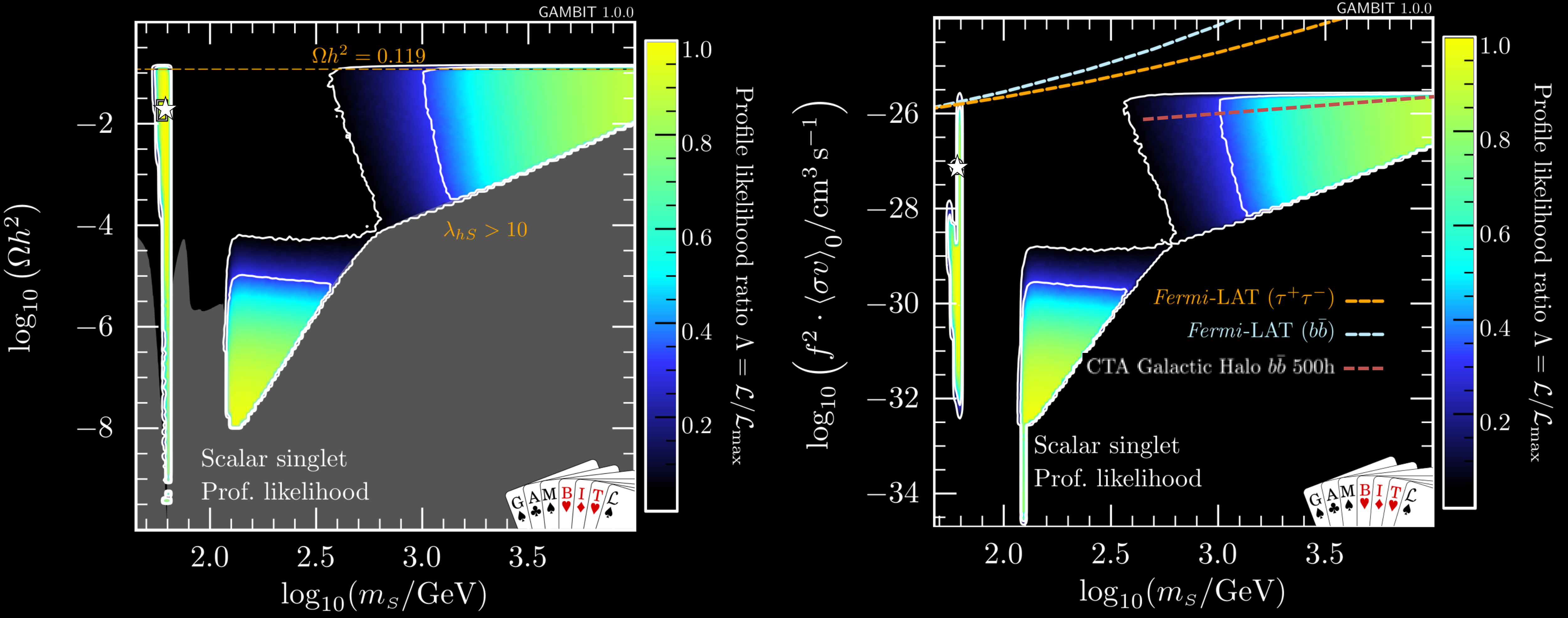
  LUX, PandaX, SuperCDMS, XENON100
- DM indirect det.

  Fermi-LAT (dSphs), IceCube79
- LHC Higgs data

Uncertainties, nuisances

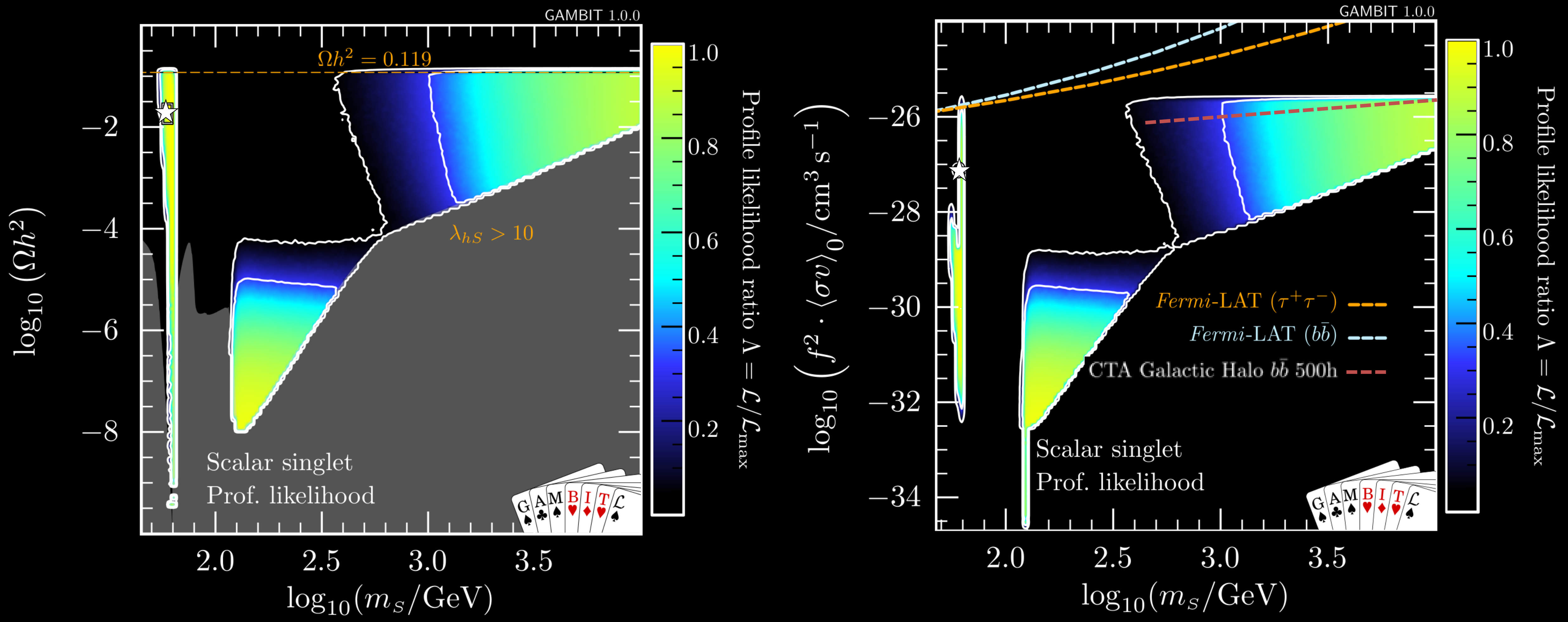
- local DM density
- nuclear physics parameters
- Higgs and quark masses
- gauge couplings

scalar singlet WIMP



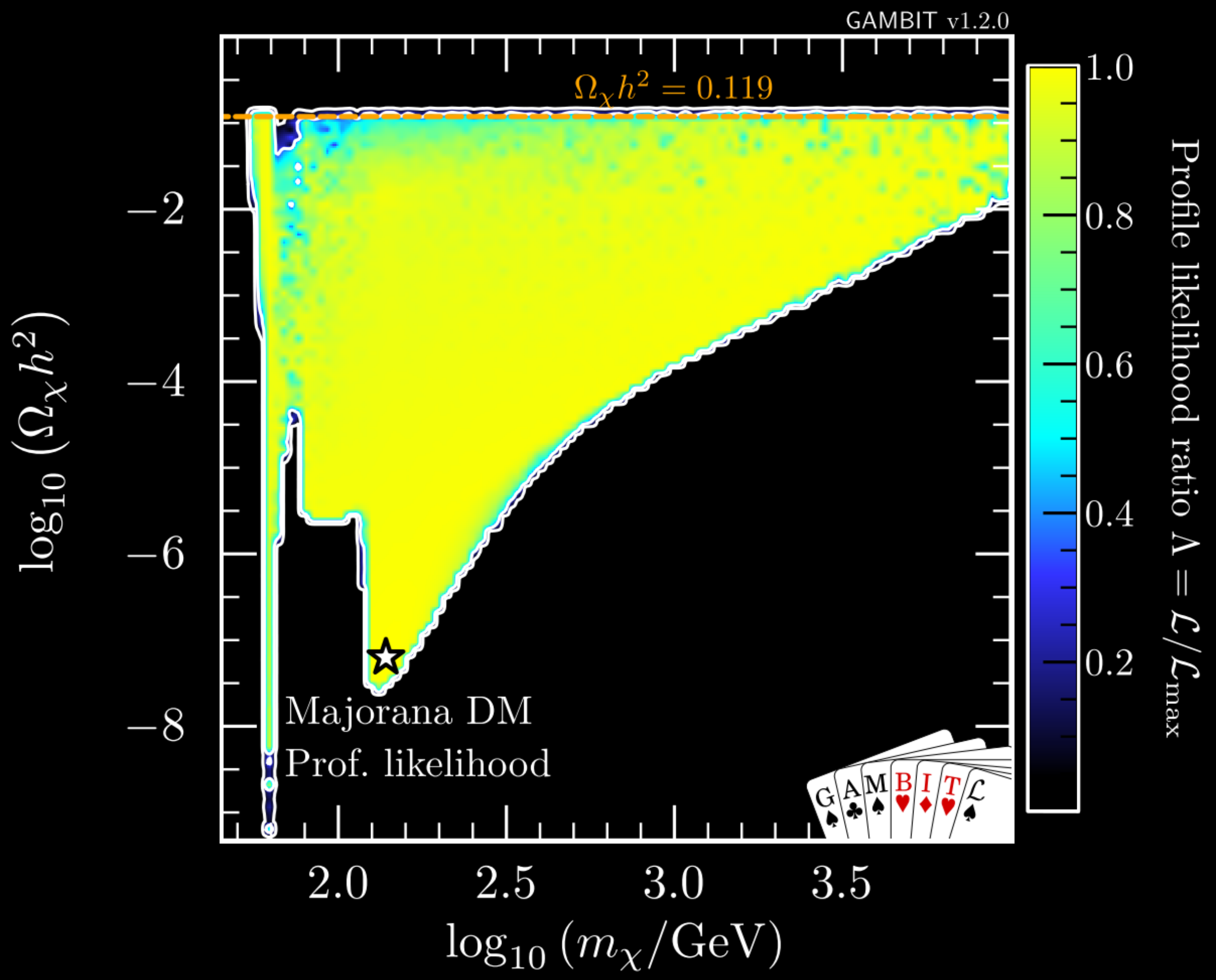
- left frame: constraints are closing in, but plenty of parameter space is still open

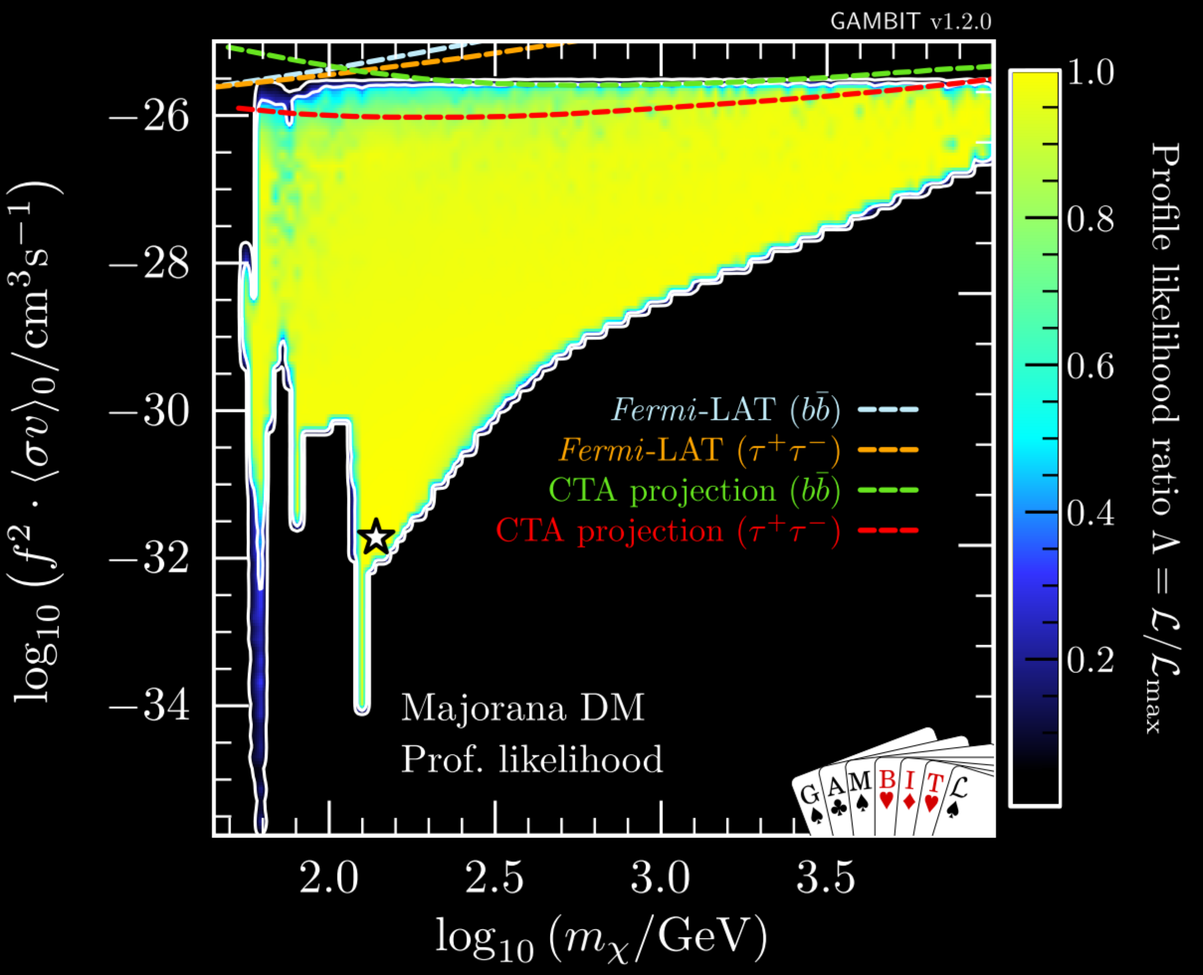
scalar singlet WIMP



- right frame: CTA will probe the region with high m_S and annihilation cross section

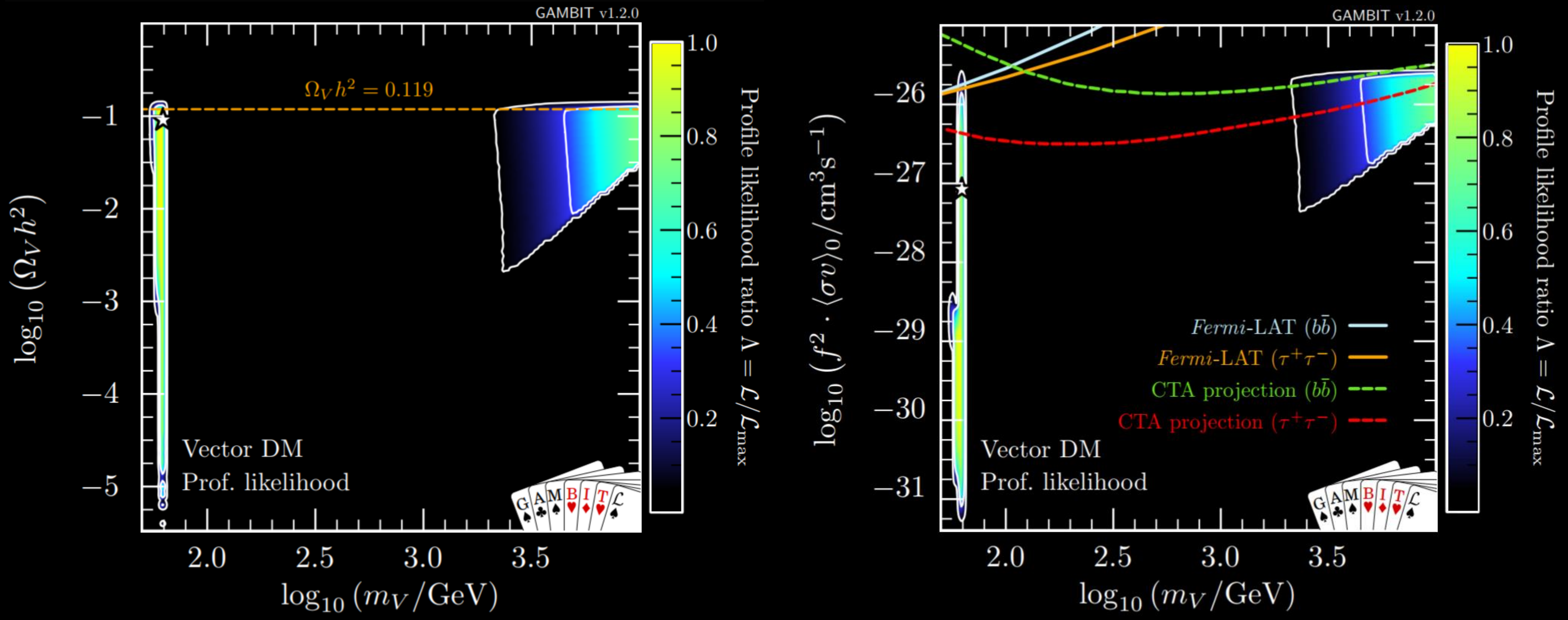
Majorana fermion singlet WIMP





- situation is similar for a Majorana singlet WIMP

vector singlet WIMP



- situation is similar for a vector singlet WIMP

simplest SUSY WIMP (CMSSM, NUHM1&2 GUT BCs) GAMBIT analysis

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

Constraints

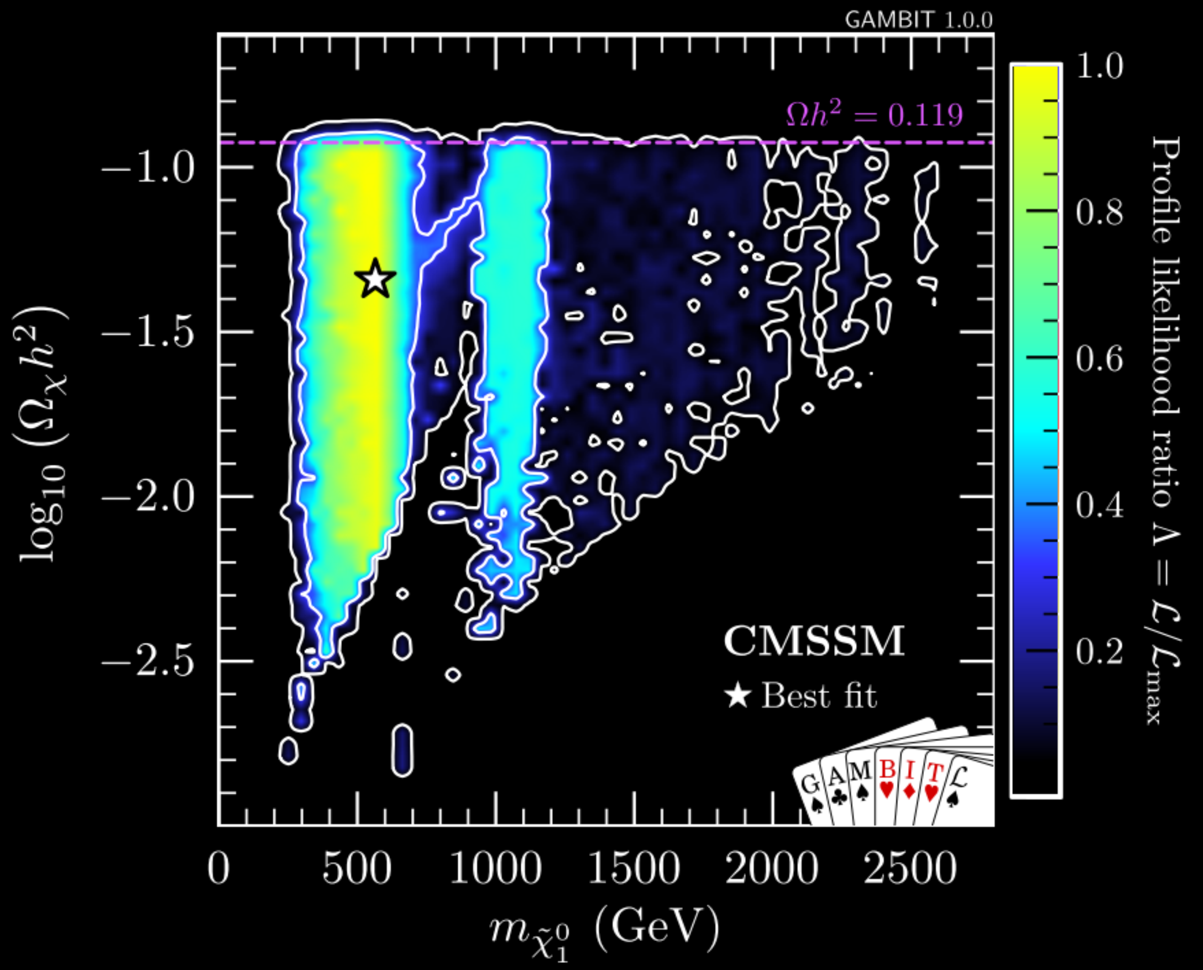
- DM abundance upper bound
- DM direct det. 8 experiments
- DM indirect det.
  Fermi-LAT (dSphs), IceCube79
- EW precision W mass, $g_\mu - 2$, …
- 59 flavor observables
- LHC Higgs data, SUSY searches, …

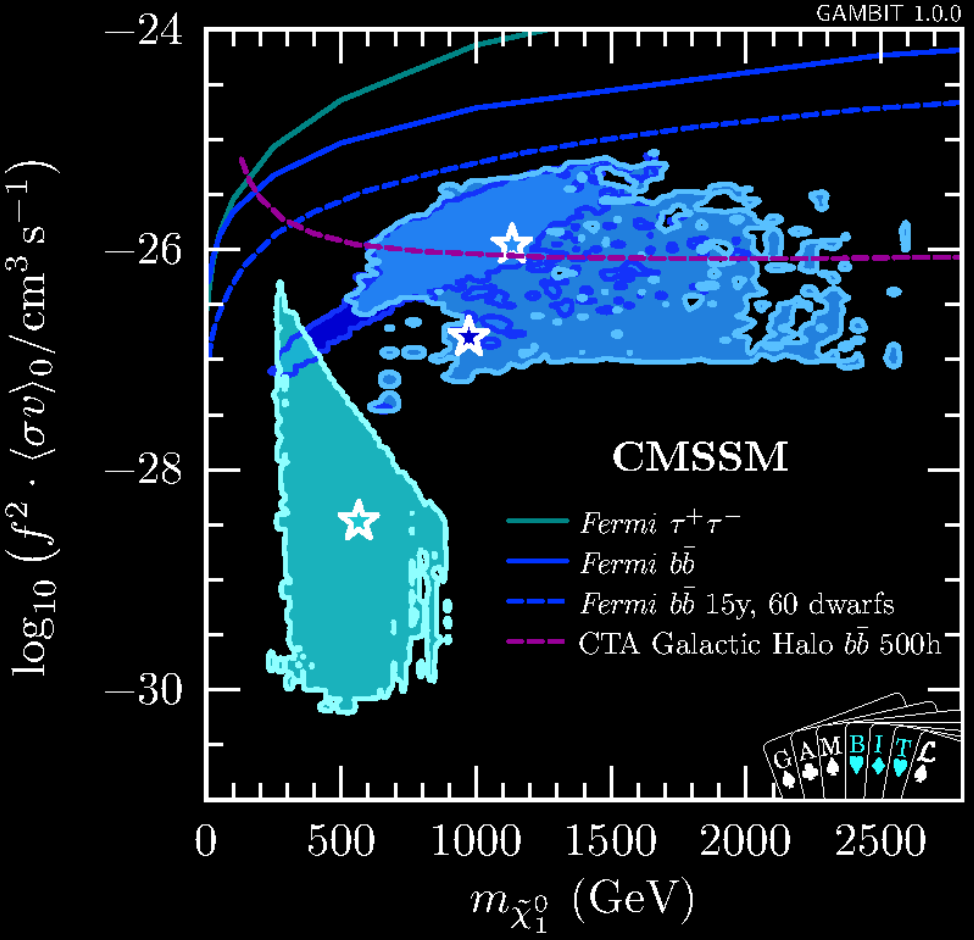
Uncertainties, nuisances

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

about 280 million full likelihood calculations for the three models

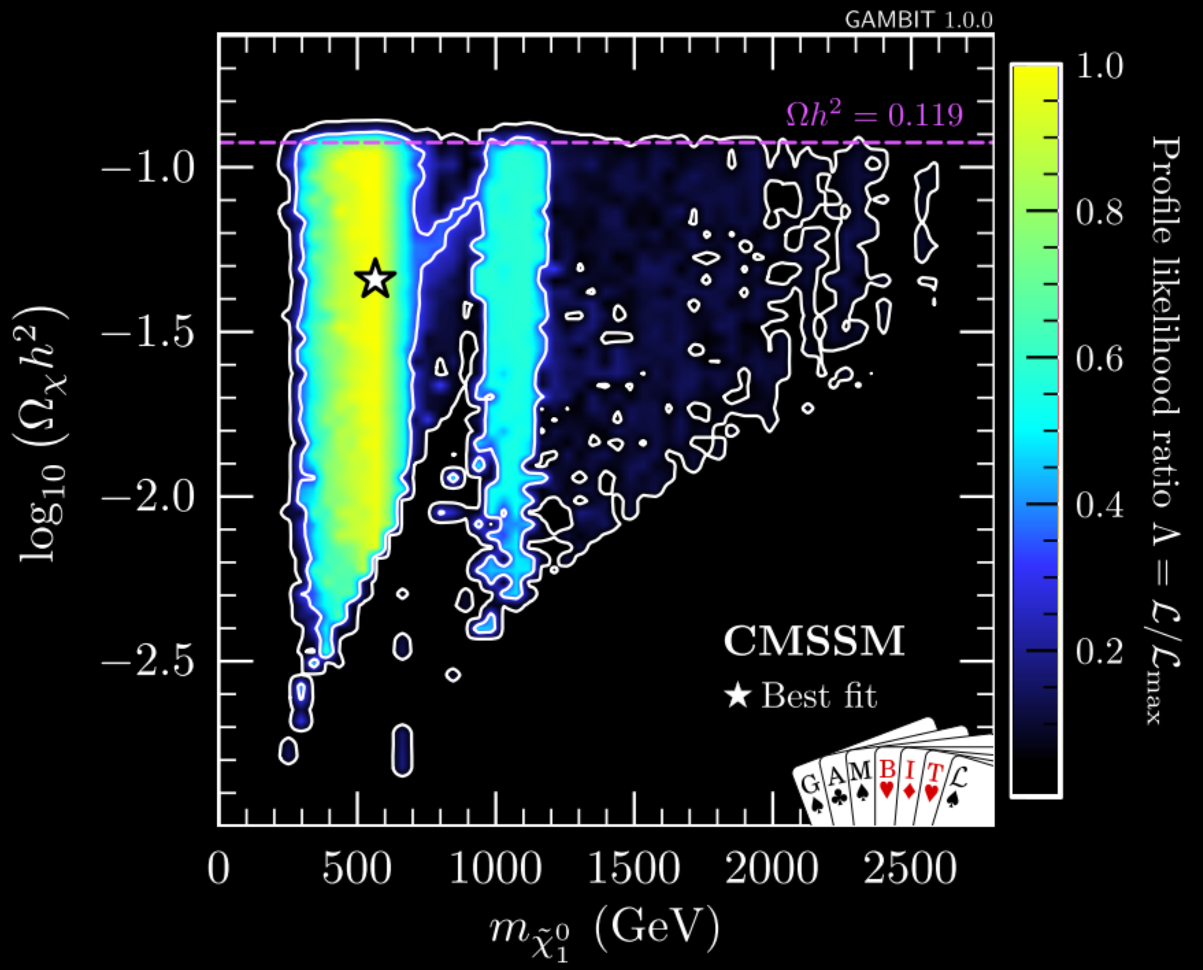
neutralino WIMP in CMSSM

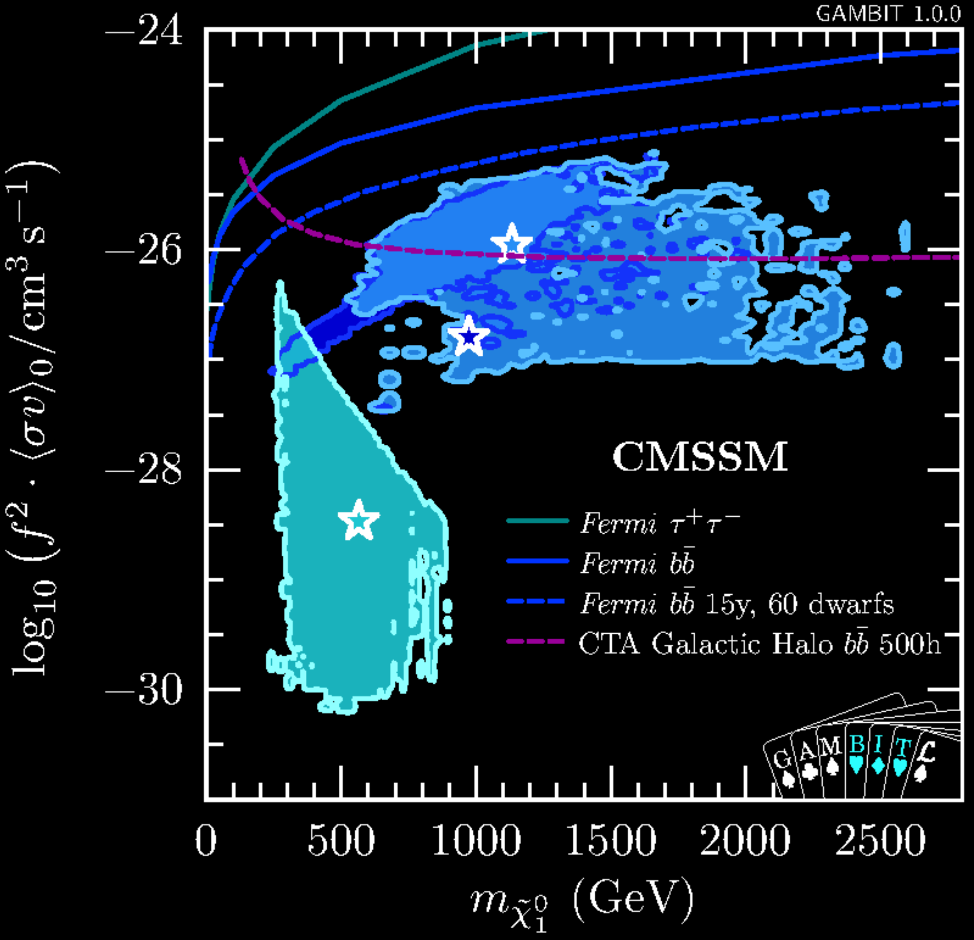




- left frame: dark matter particle mass is most likely under 2 TeV in perfect reach of CTA
- $\tilde{t}$ co-ann. chargino co-ann. heavy Higgs funnel ($\tilde{\tau}$ co-ann. ruled out @95%CL)

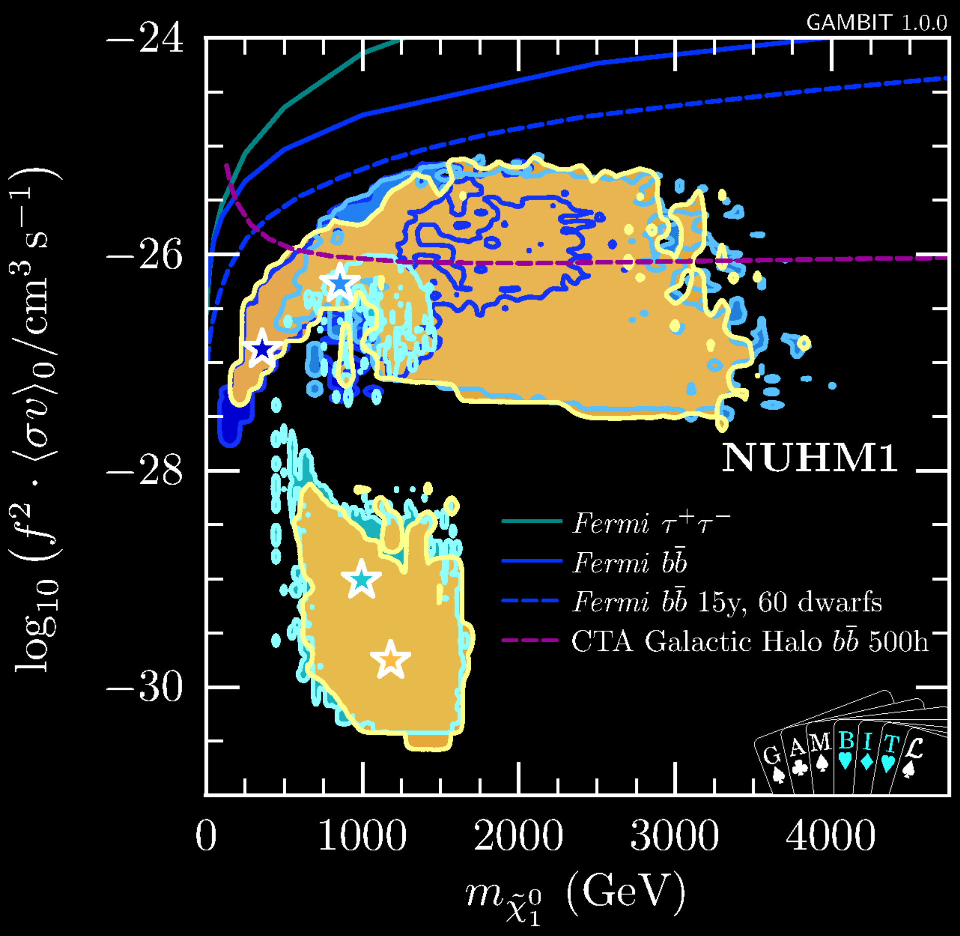
neutralino WIMP in CMSSM

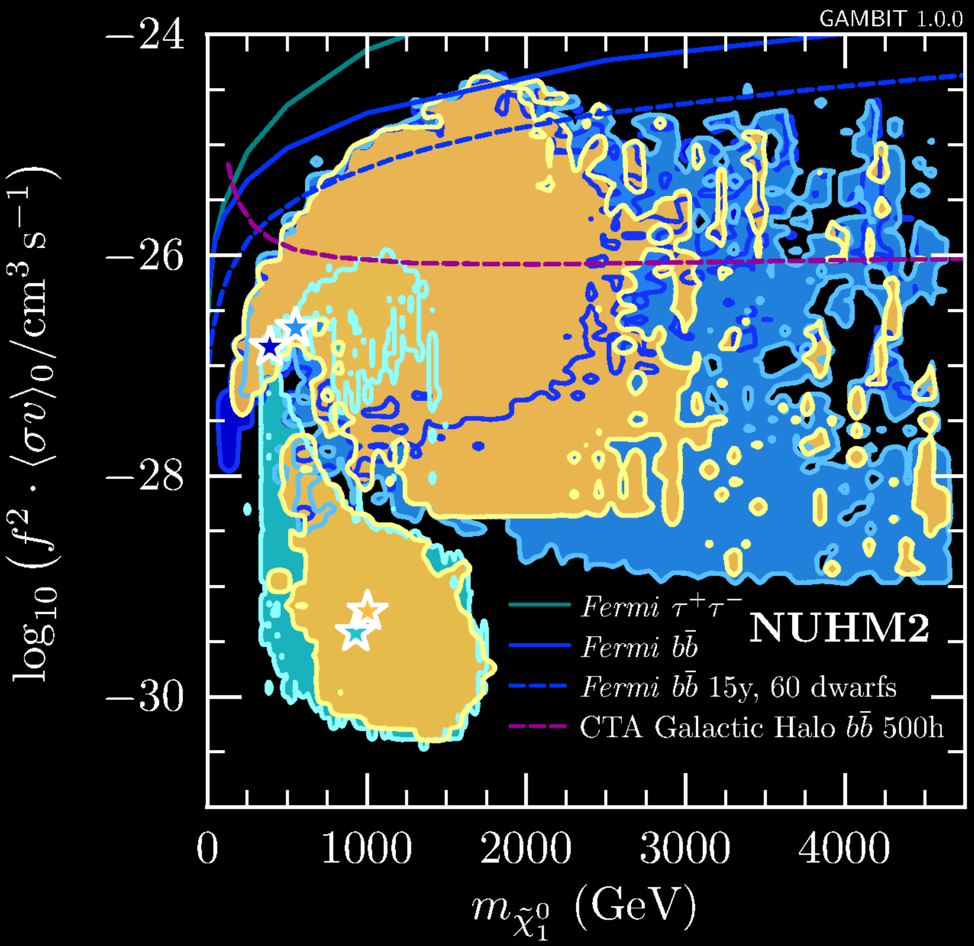




- right frame: CTA will cover a substantial part of chargino co-ann. And Higgs funnel regions
- $\tilde{t}$ co-ann. chargino co-ann. heavy Higgs funnel ($\tilde{\tau}$ co-ann. ruled out @95%CL

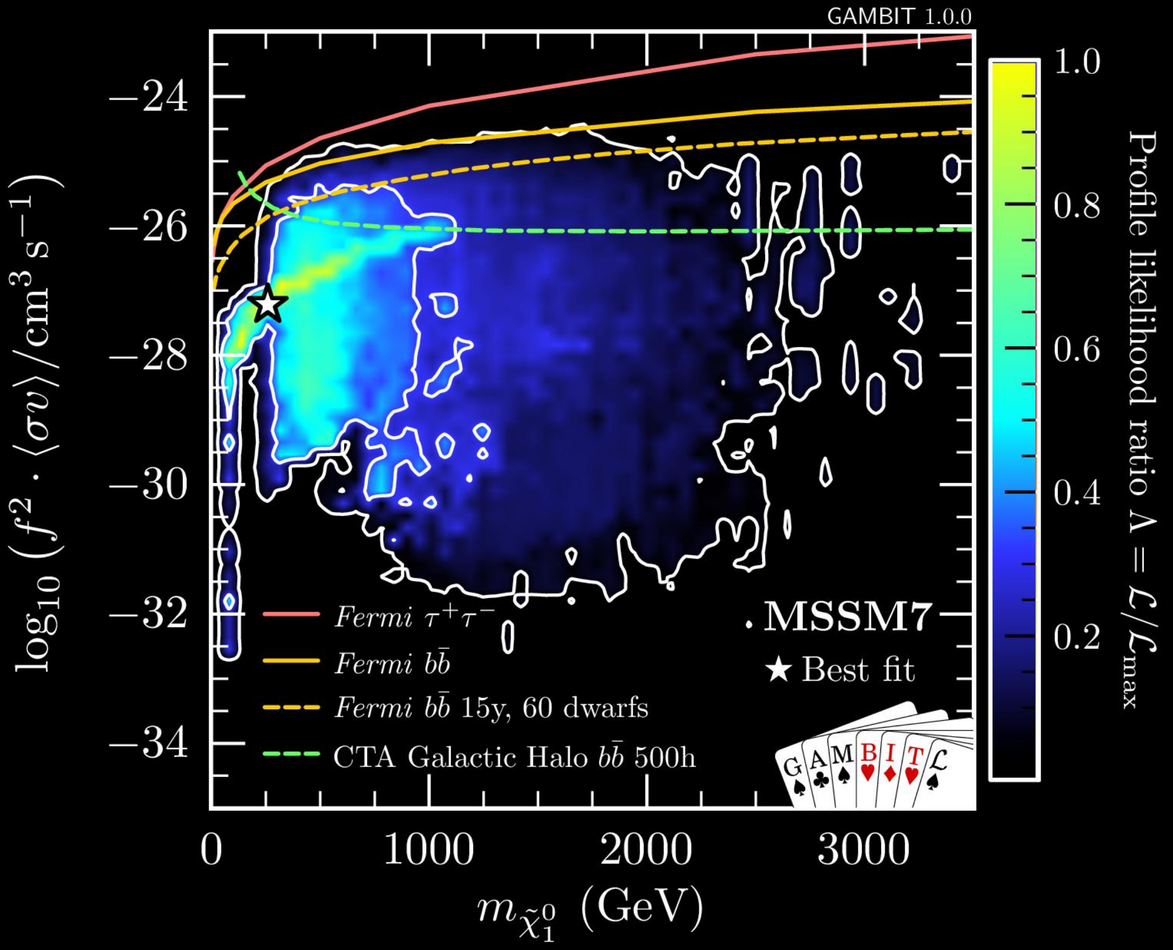
neutralino WIMP in NUHM1&2 $(M_{H_u}, M_{H_d}, m_0, m_{1/2}, A_0, \tan\beta, \text{sign}\mu$ + 5 nuisances)

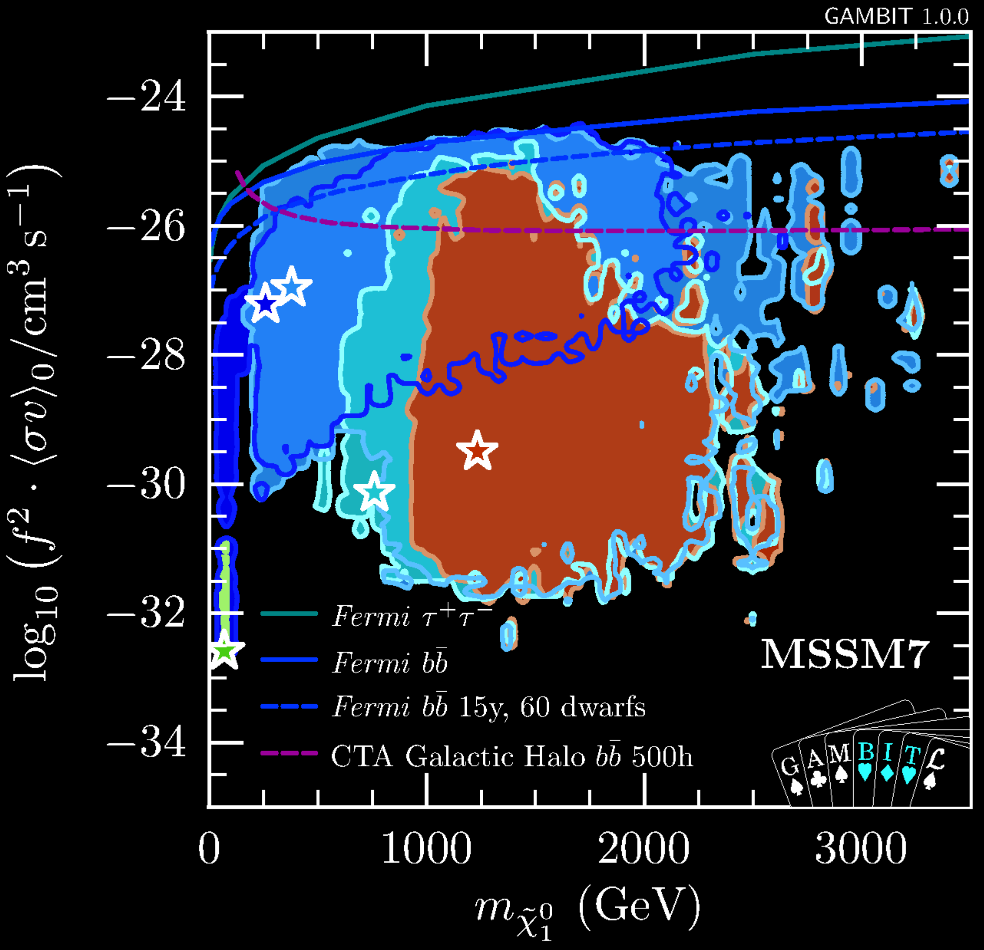




- substantial part of the promising parameter space is probed by CTA
- $\tilde{t}$ co-ann. chargino co-ann. heavy Higgs funnel $\tilde{\tau}$ co-ann.

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





- CTA will start probing regions not far from the ones with the highest likelihood
- $\tilde{t}_1$ co-annihilation, A/H funnel, $\tilde{\chi}_1^{\pm}$ co-annihilation, $\tilde{b}_1$ co-annihilation, h/Z funnel

summary

WIMPs are still experimentally plausible

multiple experiments will be needed to exclude them
or confirm that they form dark matter

CTA may play a pivotal role in the WIMP exclusion/discovery

the road to discovery is via exclusion (elimination of hypotheses),
so GAMBIT keeps assessing the status of the most popular DM models…

backup slides

public results

results available on zenodo.cern.ch

- parameter point samples
- GAMBIT input files for all scans
- example plotting routines

links at gambit.hepforge.org/pubs

GAMBIT

a universal phenomenology tool

- **pseudo-observable calculations** auto-generation of masses and couplings (soon from $\mathcal{L}$)
- **observable calculations** cosmology, astrophysics (dark matter), collider, precision, flavor…
- **many different models** effective, simplified, Higgs extensions, neutrinos, SUSY, axions…
- **parameter scans** grid, random, (ensemble) MCMC, nested sampling, differential evolution…
- **statistical inference** parameter estimation, Frequentists goodness of fit calculation, Bayesian model comparison

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 (ensemble MCMC, differential evolution, nested…)
- auto dependency resolution (ID functions, optimize execution order!)
- dual-level parallel execution: MPI and OpenMP
- …

GAMBIT features

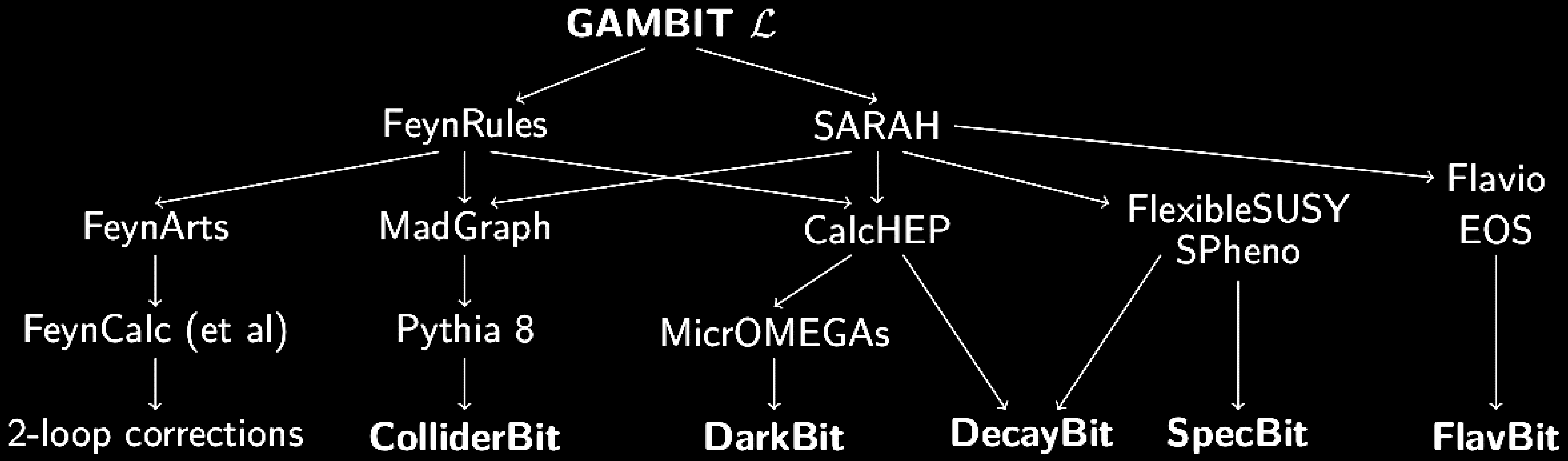
flexible and extendable

- 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 observables…
- …

GAMBIT 2

Extension to model building

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



the future

statistically reliable determination of model plausibility: p values, Bayesian odds (for nested models), …

fast and systematic model comparison and selection based on robust statistical tools

papers focusing on various models and future facilities: future dark matter detection, future colliders, …

more models, more data, more projections, more automation, …

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

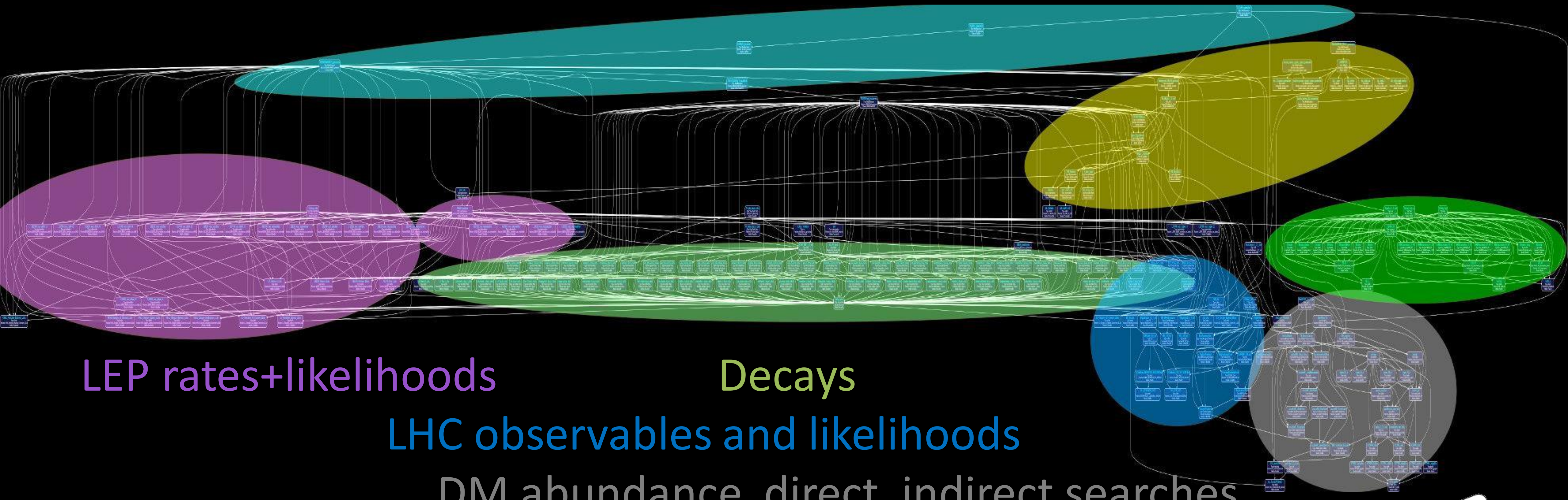
```
#define MODULE FlavBit                                  // A tasty GAMBIT module.
START_MODULE

  #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

Wrapper?

GAMBIT dependency resolution for CMSSM



Model parameter translations

Precision calculations

LEP rates+likelihoods

Decays

LHC observables and likelihoods

DM abundance, direct, indirect searches

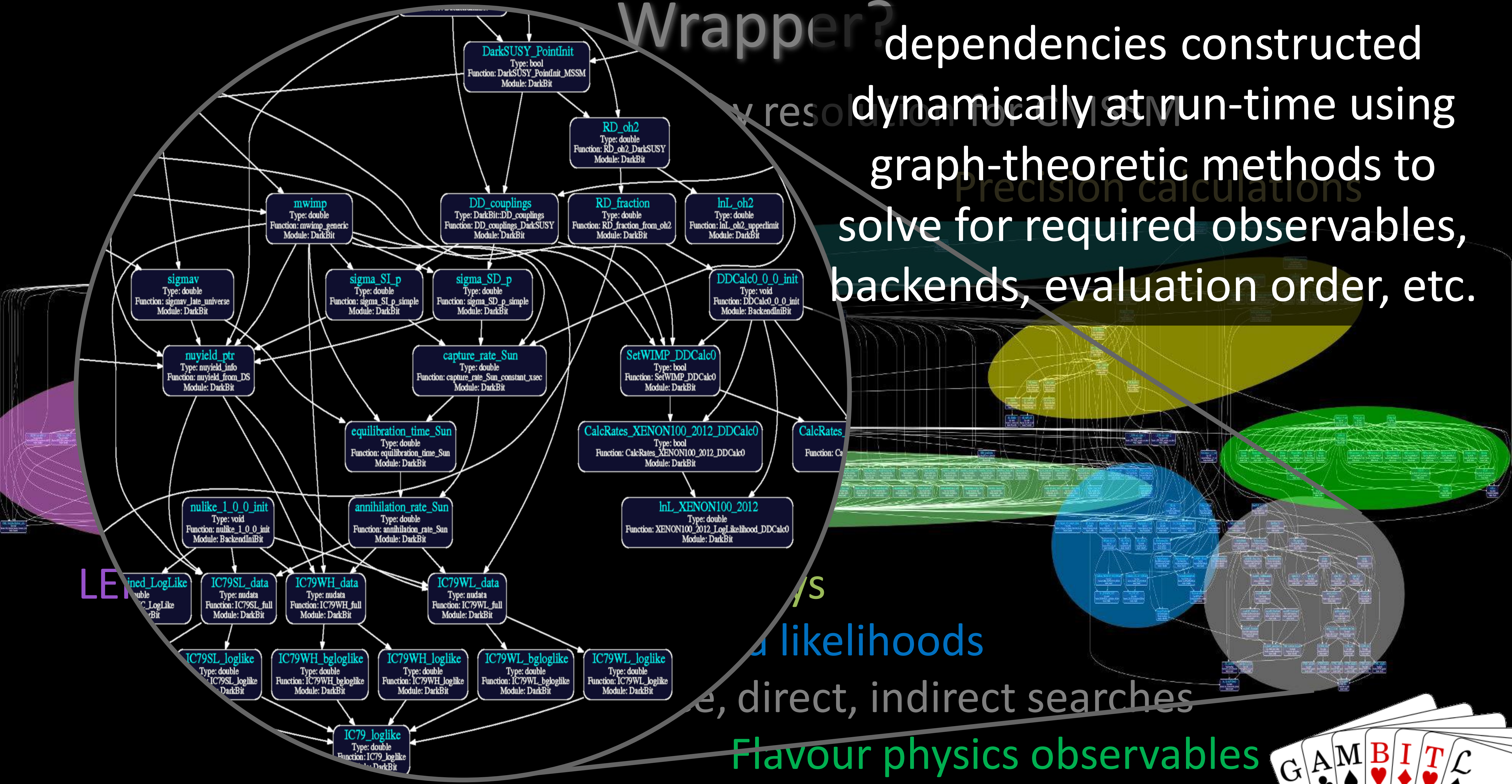
Flavour physics observables

Wrapper?

...y resolution for CMSSM

Precision calculations

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



LE...

...ys

...d likelihoods

...e, direct, indirect searches

Flavour physics observables

CMSSM, NUHM1, NUHM2 arXiv:1705.07935

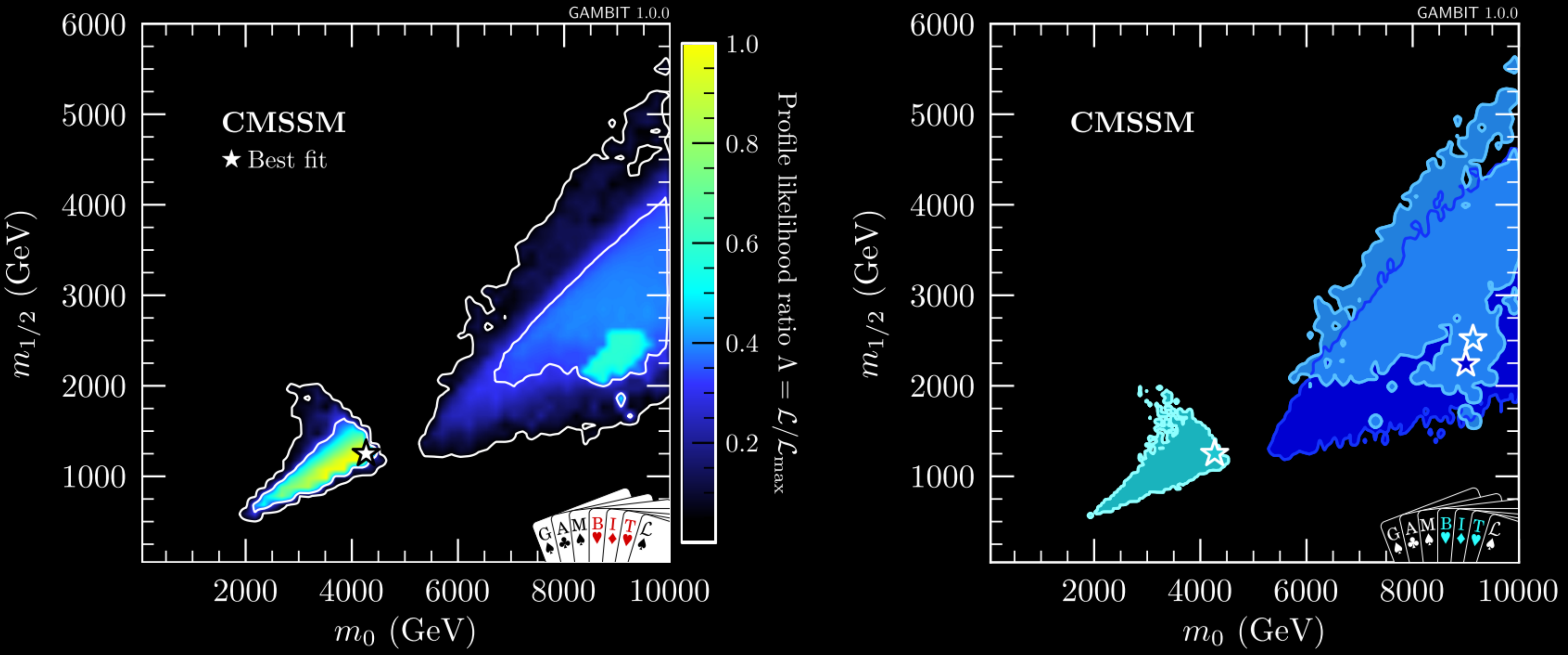
Mechanisms to avoid DM overabundance

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

Definition of colored regions

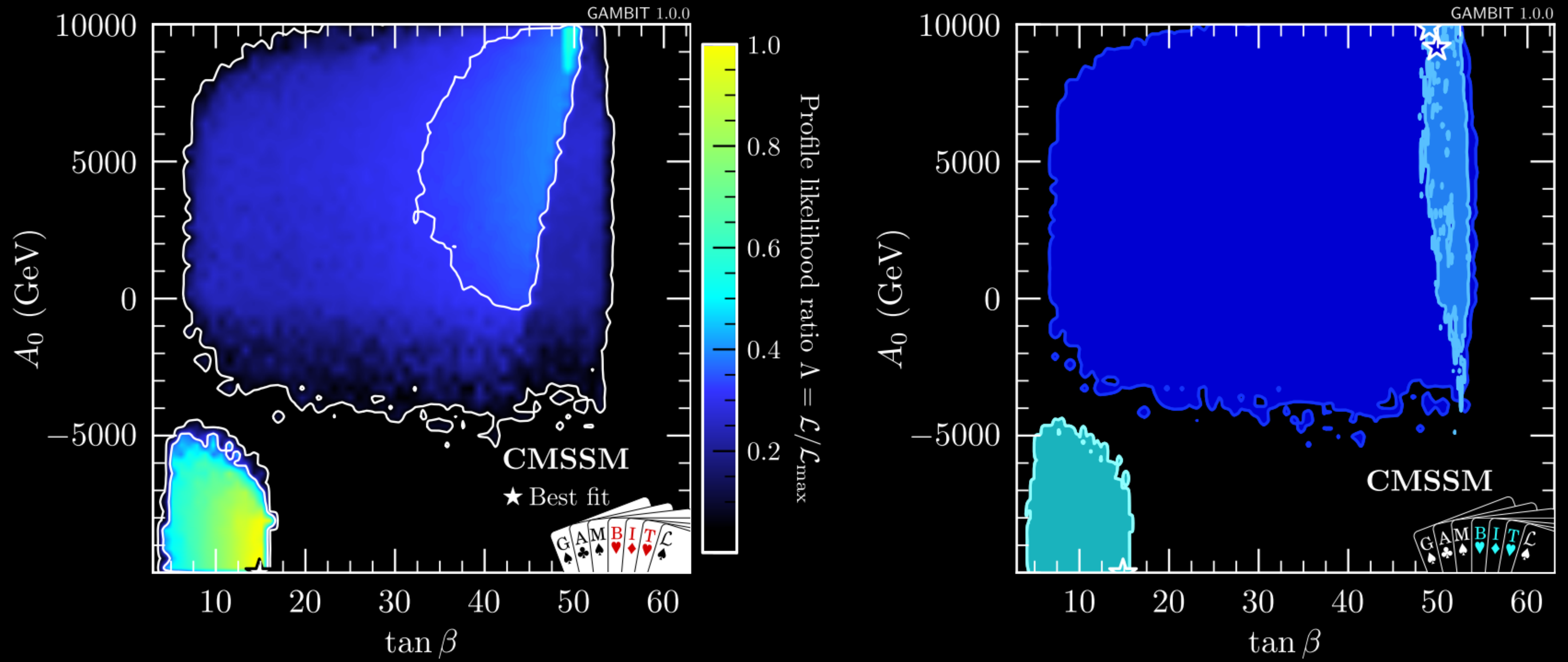
– stau co-annihilation: $m_{\tilde{\tau}_1} \leq 1.2\, m_{\tilde{\chi}_1^0}$,
– stop co-annihilation: $m_{\tilde{t}_1} \leq 1.2\, m_{\tilde{\chi}_1^0}$,
– chargino co-annihilation: $\tilde{\chi}_1^0 \geq 50\%$ Higgsino,
– A/H-funnel: $1.6\, m_{\tilde{\chi}_1^0} \leq m_{\text{heavy}} \leq 2.4\, m_{\tilde{\chi}_1^0}$,

CMSSM $(m_0, m_{1/2}, A_0, \tan\beta, \mathrm{sign}\mu$ + 5 nuisances)



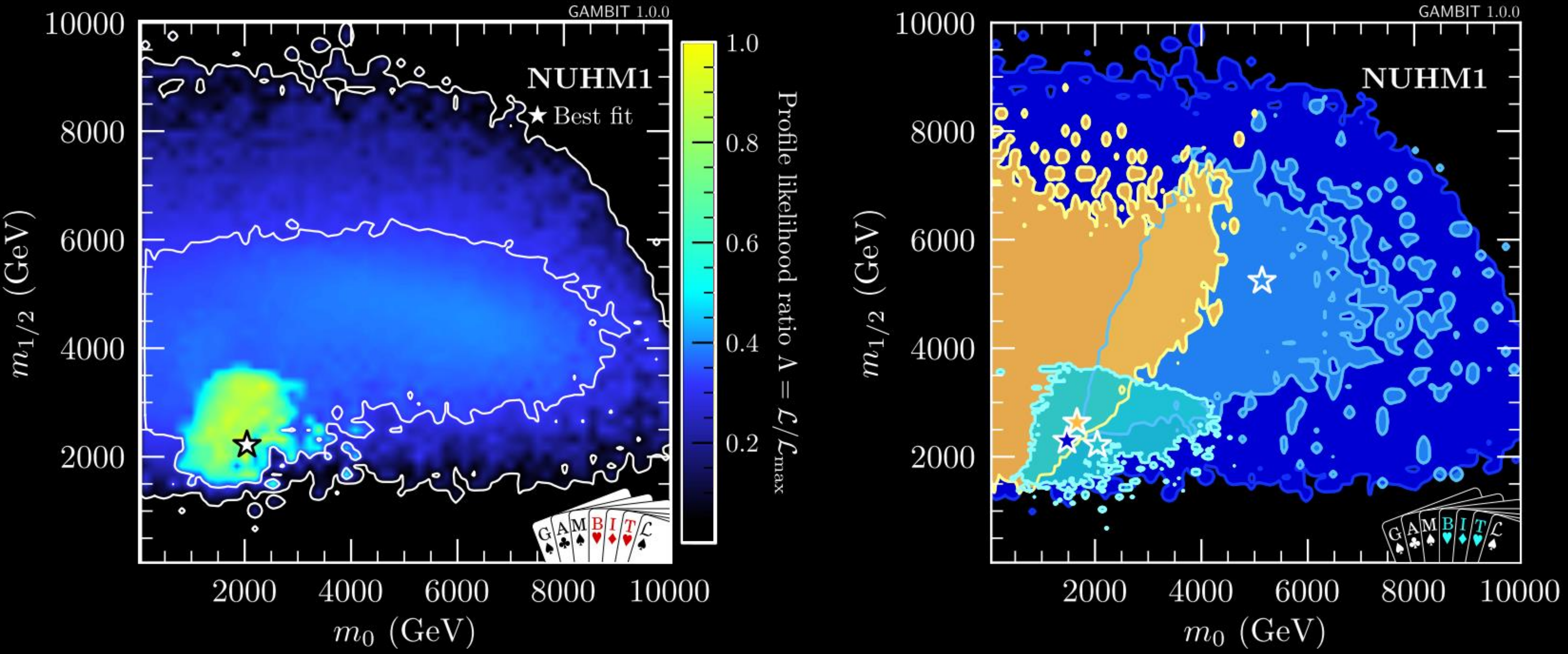
- $\tilde{t}$ co-ann. chargino co-ann. heavy Higgs funnel ($\tilde{\tau}$ co-ann. ruled out @95%CL)
- best fit point in stop co-ann. region (stop/neutralino mass about 600 GeV)

CMSSM ($m_0, m_{1/2}, A_0, \tan\beta, \text{sign}\mu$ + 5 nuisances)



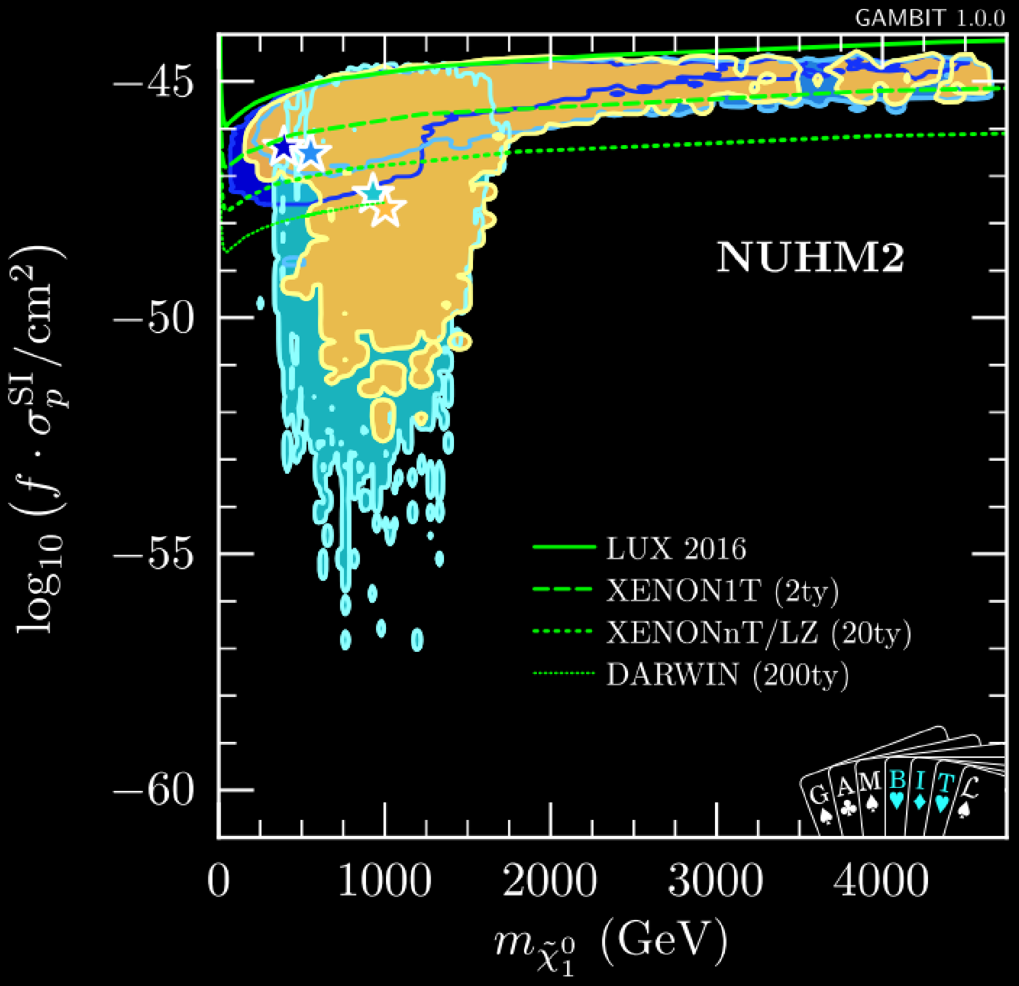
- $\tilde{t}$ co-ann. chargino co-ann. heavy Higgs funnel ($\tilde{\tau}$ co-ann. ruled out @95%CL)
- best fit point in stop co-ann. region (stop/neutralino mass about 600 GeV)

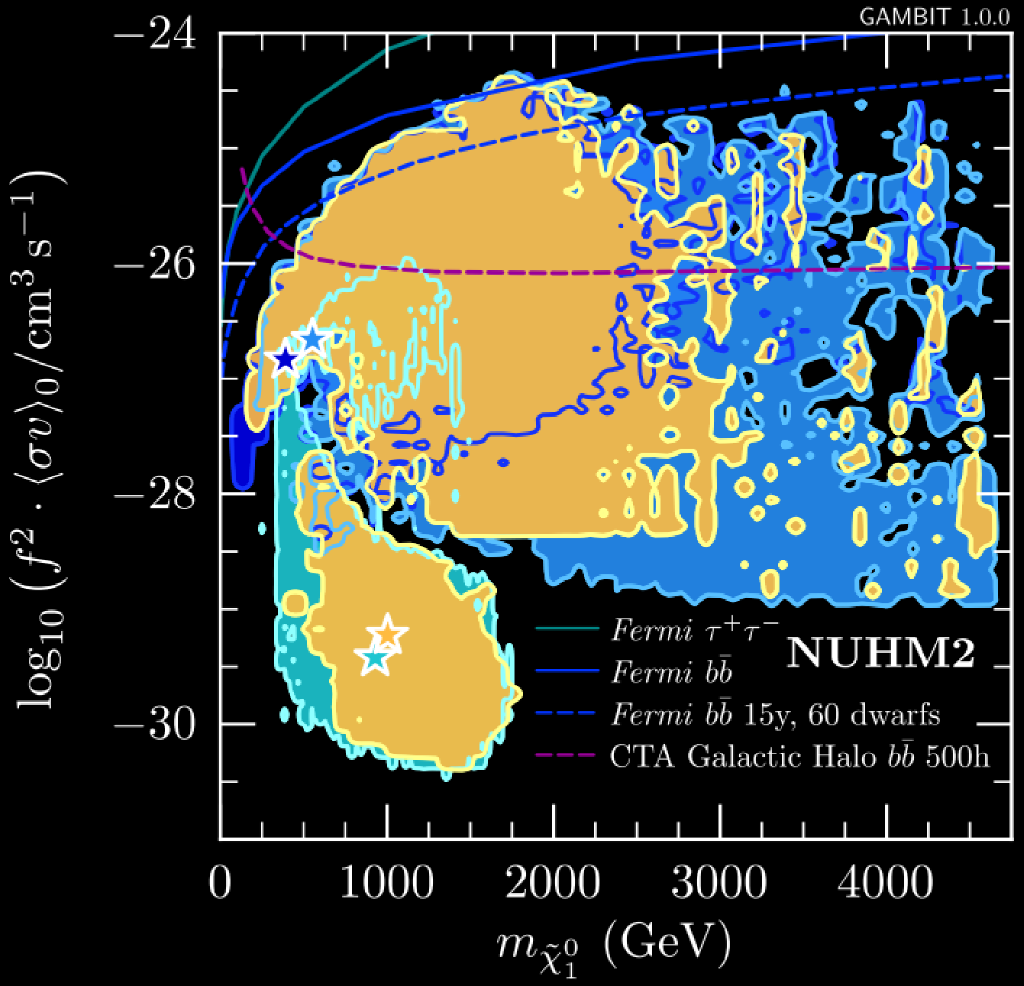
NUHM1 ($M_H, m_0, m_{1/2}, A_0, \tan\beta, \text{sign}\mu$ + 5 nuisances)



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

NUHM2 $(M_{H_u}, M_{H_d}, m_0, m_{1/2}, A_0, \tan\beta, \text{sign}\mu$ + 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

NUHM1 $(M_H, m_0, m_{1/2}, A_0, \tan\beta, \mathrm{sign}\mu + 5\ \text{nuisances})$

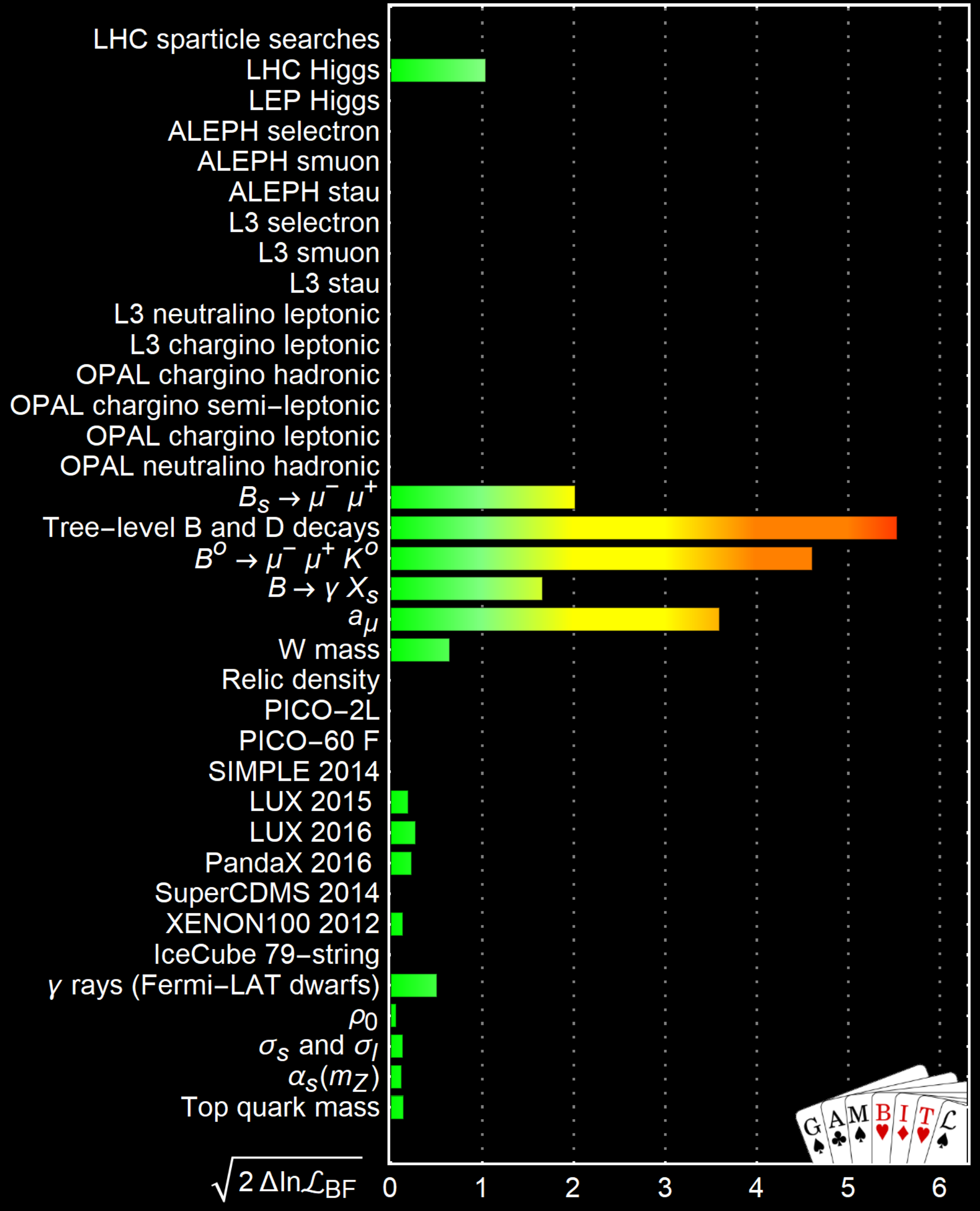
- pull: deviation from ideal likelihood

$$\sqrt{2\Delta \ln\mathcal{L}_{BF}} = \sqrt{2(\ln\mathcal{L}_{BF} - \ln\mathcal{L}_{ideal})}$$

(for χ^2 distributed test statistic this is the sqrt of deviation from the optimal: $\sqrt{\Delta\chi^2}$)

- NUHM1 is in excellent shape except it can't fit flavor anomalies

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



MSSM-7 (weak scale BCs)

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

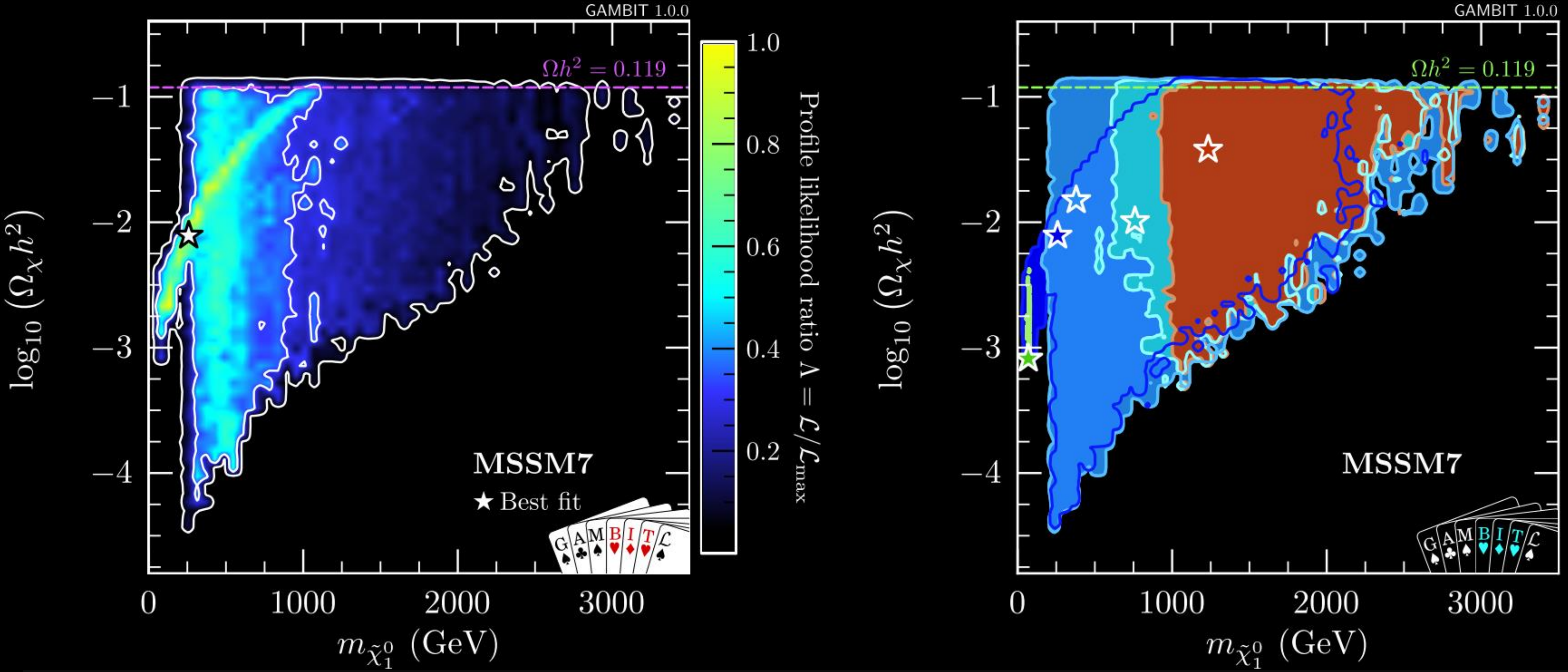
Constraints

- DM abundance upper bound
- DM direct det. 8 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

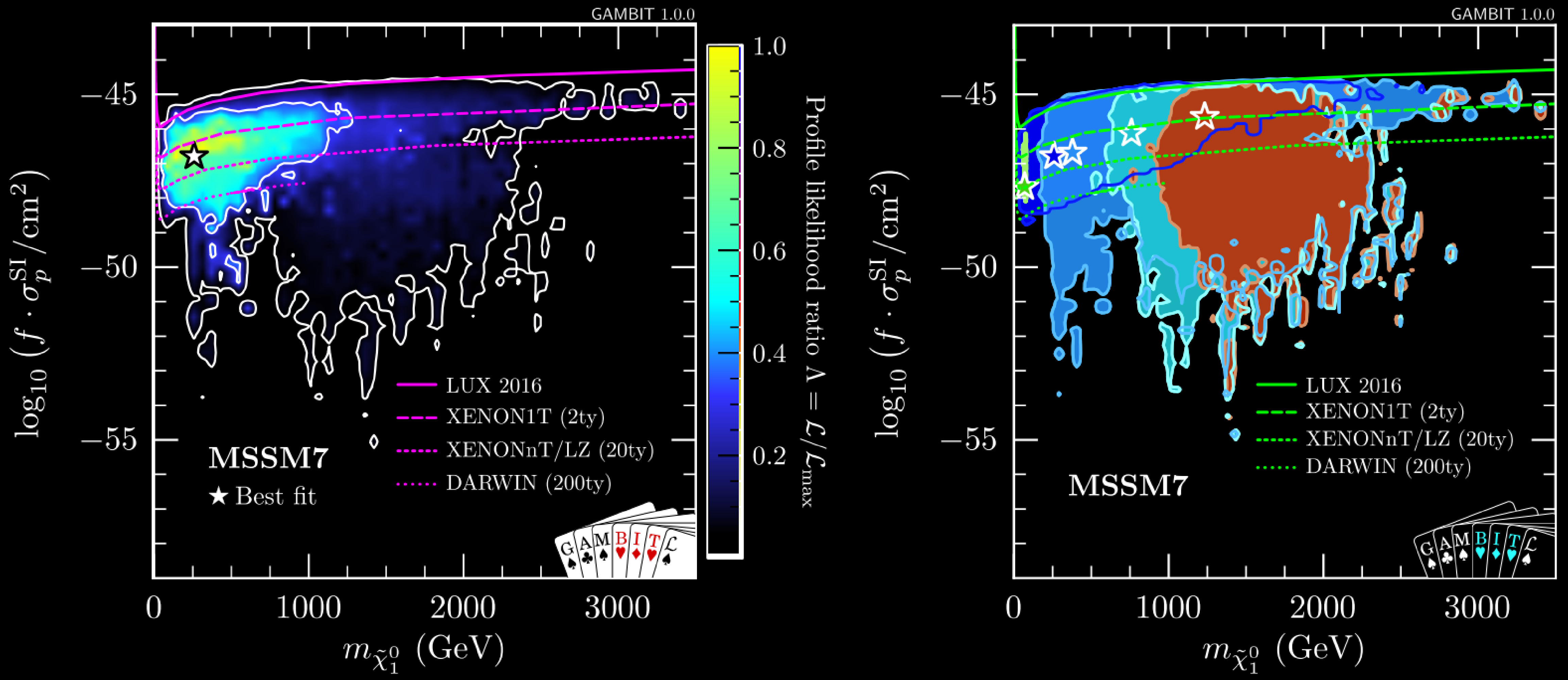
- local DM density
- nuclear physics parameters
- Higgs and quark masses
- gauge couplings

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
- $\chi^{\pm}$ co-ann. and light Higgs will be probed by dark matter direct detection experiments

we’re (being) confused

Physicists Just Debunked One of The Most Promising Candidates For Dark Matter

BRENDAN COLE 27 APR 2016

You probably know that just 15 percent of the known Universe is made up of matter that we can actually see. The majority of the Universe - some 85 percent of it - is made up of dark matter and dark energy - two phenomena that are currently 100 percent unknown to science, despite the best efforts of researchers worldwide.

But now, thanks to a paper authored by over 100 physicists... well, it’s still unknown, but it’s just a little less unknown than it was before, because one of the top candidates for dark matter has pretty much been debunked.

The kind of matter that makes up everything we’ve ever seen in the Universe, from tiny quarks to massive galaxies, is only 15 percent of the matter that’s actually out there. The rest is known enigmatically as dark matter, because we can't see it and no one knows what it is, but we’re almost positive that it’s out there, unless we have to seriously rethink our understanding of the laws of gravity - the force that governs everything in the known Universe.

There are some scientists out there doing this kind of rethinking, but most agree that dark matter has to be something. They just disagree about what that something *actually* is. The leading contender is a class of Weakly Interacting Massive Particles, or WIMPs. But there are other possibilities with exciting names like axions, axion-like particles, and supersymmetric particles.

Now, thanks to the Fermi Large Area Telescope, the array of possibilities is starting to thin out.

https://www.sciencealert.com/physicists-just-debunked-one-of-the-most-promising-dark-matter-candidates