GAMBIT

update

Csaba Balázs
for the GAMBIT Community

TeVPA 2022 Aug 11

outline

global fits

GAMBIT

main features

version 2.0

latest results

global fitting

Why?

standard models emerge from a set of competing theories

the simplest theory best fitting the most data becomes standard model

global fitting is to quantify “simplest”, “best” and “most” above

global fitting

What?

theory → prediction

experiment → data

prediction, data → likelihood function

likelihood function → parameter estimation, model testing, model comparison

parameter estimation
best fit, confidence region…

model testing
goodness of fit, p-value…

model comparison
Bayes factor, odds…

Global And Modular BSM Inference Tool

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

- open-source code to calculate observables and likelihoods for generic Beyond the Standard Model(s) theories
- designed to allow easy definition of new models, observables, likelihoods, samplers and backend physics codes
- extensive
  - model database
  - observable calculators
  - data libraries
- various sampling and stat options
- fast likelihood calculators (LHC…)
- massively parallel

Community

subset

80+ community members

F Agócs, P Athron, C Balázs, A Beniwal, S Bloor, T Bringmann, A Buckley, JE Camargo-Molina, C Chang, M Chrzaszcz, J Conrad, J Cornell, M Danninger, J Edsjö, T Emken, A Fowlie, T Gonzalo, W Handley, J Harz, S Hoof, F Kahlhoefer, A Kvellestad, P Jackson, D Jacob, C Lin, N Mahmoudi, G Martinez, MT Prim, A Raklev, C Rogan, R Ruiz, P Scott, N Serra, P Stöcker , W. Su, A Vincent, C Weniger, M White, Y Zhang…

from 14+ countries, 29+ institutes

Community

subset

Community

linkages

members of various experiments

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

authors of numerous theory codes

BubbleProfiler, Capt'n General, DarkSUSY, DDCalc, Diver, FlexibleSUSY, gamlike, GM2Calc, HEPLike, IsaJet, nulike, PhaseTracer, PolyChord, Rivet, SOFTSUSY, SuperIso, SUSY-AI, xsec, Vevacious, WIMPSim…

GAMBIT features

global and modular

- diverse BSM model database SM+SS, EFTs, 2HDMs, MSSM63, axions, RHNs, cosmo…
- changeable model assumptions for cosmology, astro-, particle-, nuclear physics…
- composite likelihood consistent combination of searches, uncertainties, nuisances…
- built-in experimental likelihoods LEP, ATLAS, CMS, LHCb, DM searches…
- sampling algorithms (ensemble) MCMC, T-walk, diff. evolution, particle swarm, nested…
- auto dependency resolution ID functions, optimize execution order! before run
- diskless generalization of various Les Houches Accords
- dual-level parallel execution mixed-mode MPI+openMP, mostly auto, scale 10k+ cores
- many interfaced backends observable calculators for cosmology, astrophysics, collider, precision, flavor… (full list on later slide)

GAMBIT features

global and modular

- fast definition of new models, data sets, sampling methods
- plug&play theory tools auto-download, configure, compile, dynamically link
- easily switch between backends calculating the same quantities
- C/C++, Python, Fortran, Mathematica interfaces for backends
- BOSS dynamic loading of C++ classes from backend shared libraries!
- all-in or module standalone modes easily implemented from single cmake script
- YAML input model, parameters, observables, sampler, stat. inference
- customizable output streams ASCII, HDF5, databases…
- advanced statistical inference parameter estimation, Bayesian model comparison
- available as docker plugin https://gambit.hepforge.org/source

Modules model independent, interdependent physics structures

- ColliderBit: event gen., fast sim., Z, H obs.s, search limits… arXiv:1705.07919
- DarkBit: DM abundance, direct-, indirect detection… arXiv:1705.07920
- DecayBit: SM & NP (SUSY…) decay widths, BRs… arXiv:1705.07936
- FlavBit: NP (SUSY…) 100s of flavor obs.s, rare decays… arXiv:1705.07933
- PrecisionBit: EW precision observables, g−2… arXiv:1705.07936
- SpecBit: SM & NP masses, mixings, couplings, RGEs... arXiv:1705.07936
- ScannerBit: sampling, parameter est., model comparison… arXiv:1705.07959
- NeutrinoBit: neutrino observables, likelihoods, RHNs… arXiv:1908.02302
- CosmoBit: ΛCDM+, inflation, neutrinos, axions… arXiv:2009.03286
- GUM: auto-generation (spectrum, interfaces, observables)… arXiv:2107.00030

Backends

observable calculators for cosmology, astrophysics, collider, precision, flavor…

- AlterBBN
- CalcHEP
- Capt'n General
- CLASS
- DarkAges
- DarkCast
- DDCalc
- DarkSUSY
- FeynHiggs
- FeynRules
- Flavio
- FlexibleSUSY
- gamLike
- GM2Calc
- HepLike
- HiggsBounds
- HiggsSignals
- MadGraph
- micrOMEGAs
- MontePython
- MultiModeCode
- nulike
- pic
- Pythia
- SARAH
- Spheno
- SUSYHD
- SUSY-HIT
- SuperIso
- Vevacious
- …

GAMBIT 2.0
from Lagrangian to likelihood

GAMBIT Universal Model

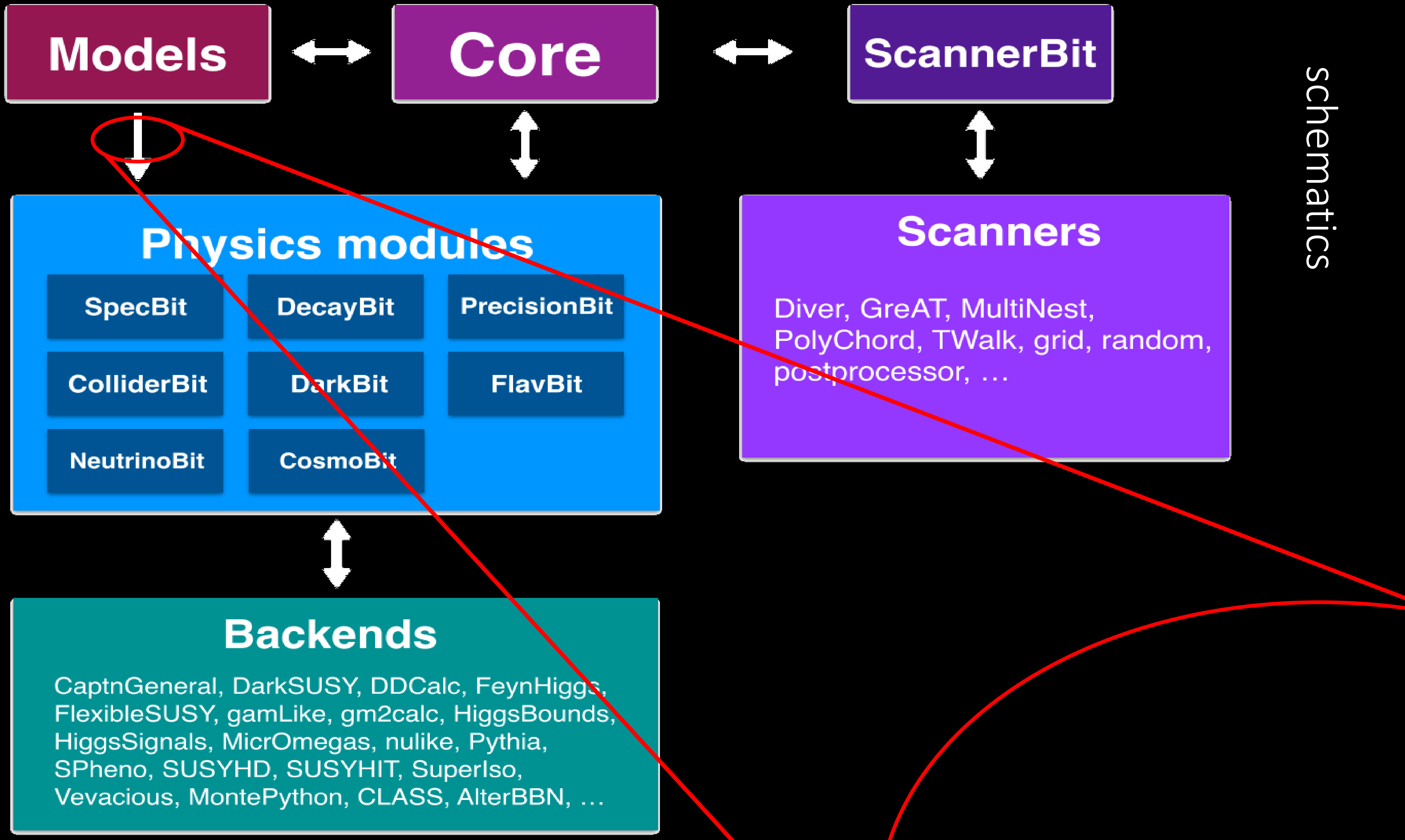
GUM

The GAMBIT Universal Model Machine

- auto-generating GAMBIT code and interfaces to backends
- from Lagrangian-level input use FeynRules, SARAH, MadGraph, CalcHEP to generate GAMBIT model, collider, dark matter, decay and spectrum code
- GUM also writes C++ GAMBIT interfaces to SPheno, micrOMEGAs, Pythia, Vevacious
- arXiv:2107.00030 (EPJC) worked example: addition of a Majorana fermion simplified dark matter model with a scalar mediator to GAMBIT via GUM, and carry out a corresponding fit

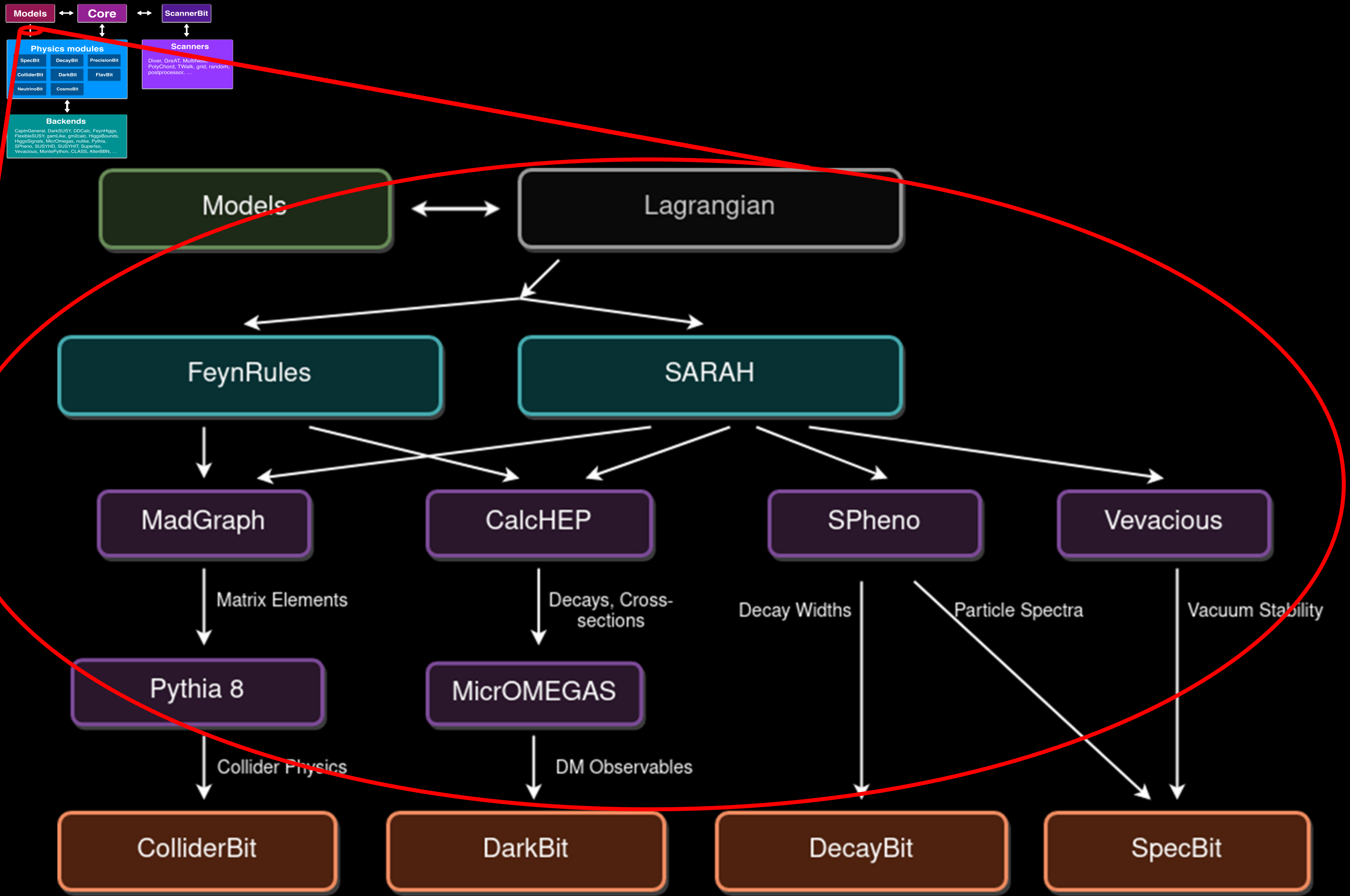
GAMBIT

schematics



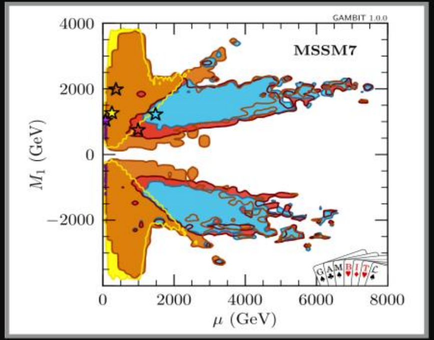
GAMBIT 2

GUM schematics

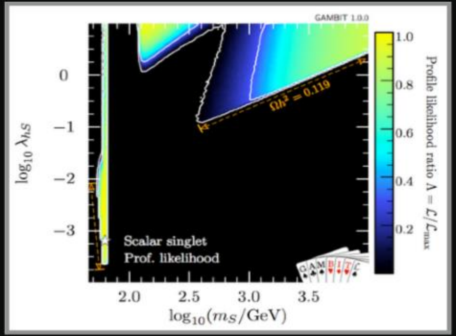


GAMBIT

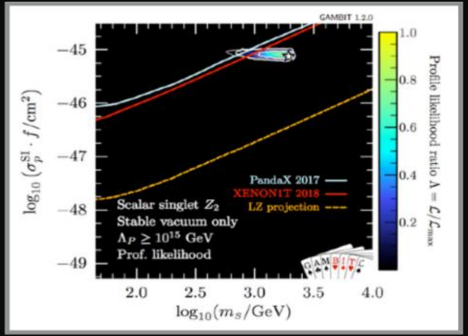
some results



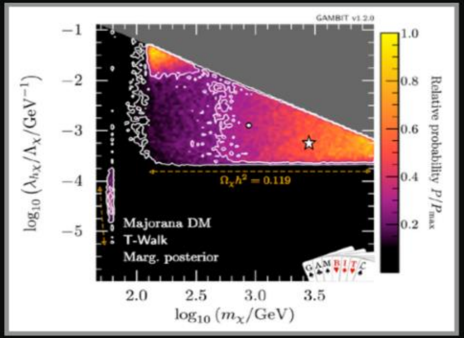
CMSSM 1705.07935/EPJC
MSSM7 1705.07917/EPJC



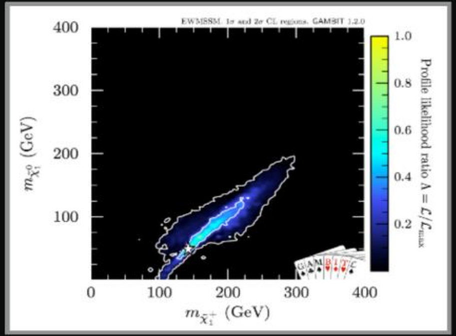
scalar H-portal DM
1705.07931 / EPJC



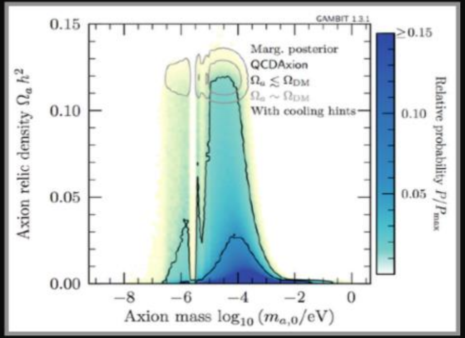
sc. HP DM vac. stab.
1806.11281 / EPJC



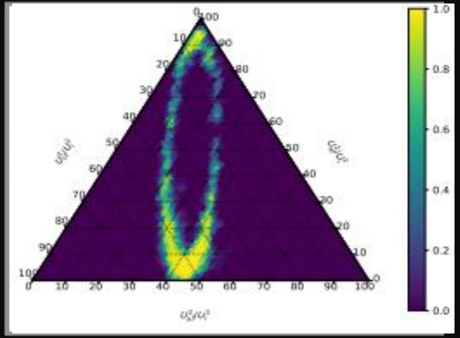
vect., ferm. HP DM
1808.10465 / EPJC



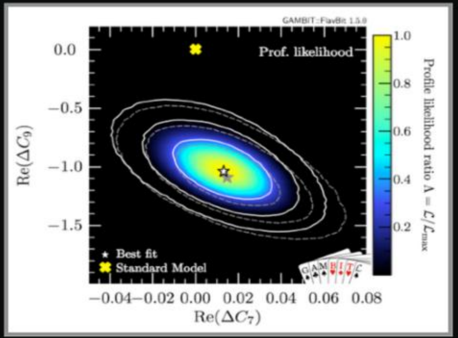
EWMSSM
1809.02097 / EPJC



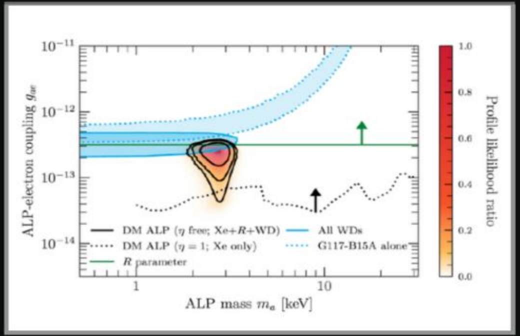
axion-like particles
1810.07192 / JHEP



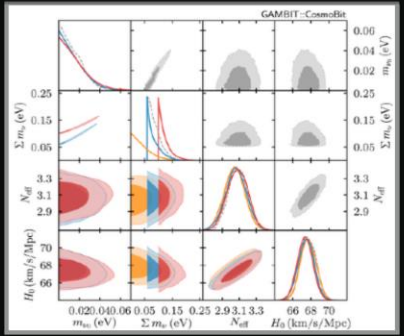
right-handed neut.s
1908.02302 / EPJC



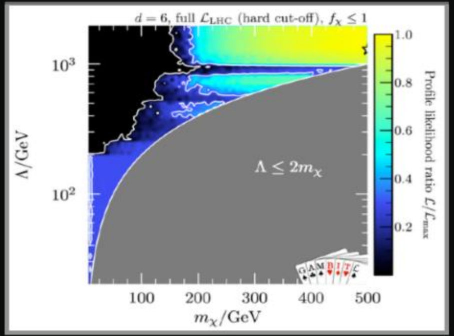
flavor EFT 2006.03489
/ EPJC



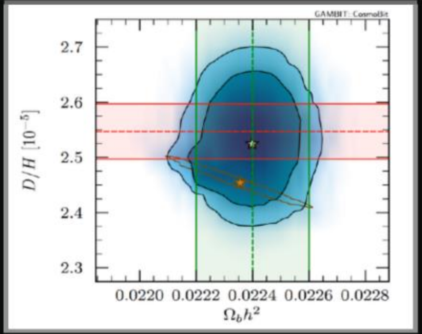
ALPs@XENON1T
2007.05517 / JHEP



m_ν & cosmo
2009.03287 / PRD



dark matter EFTs
2106.02056 / EPJC



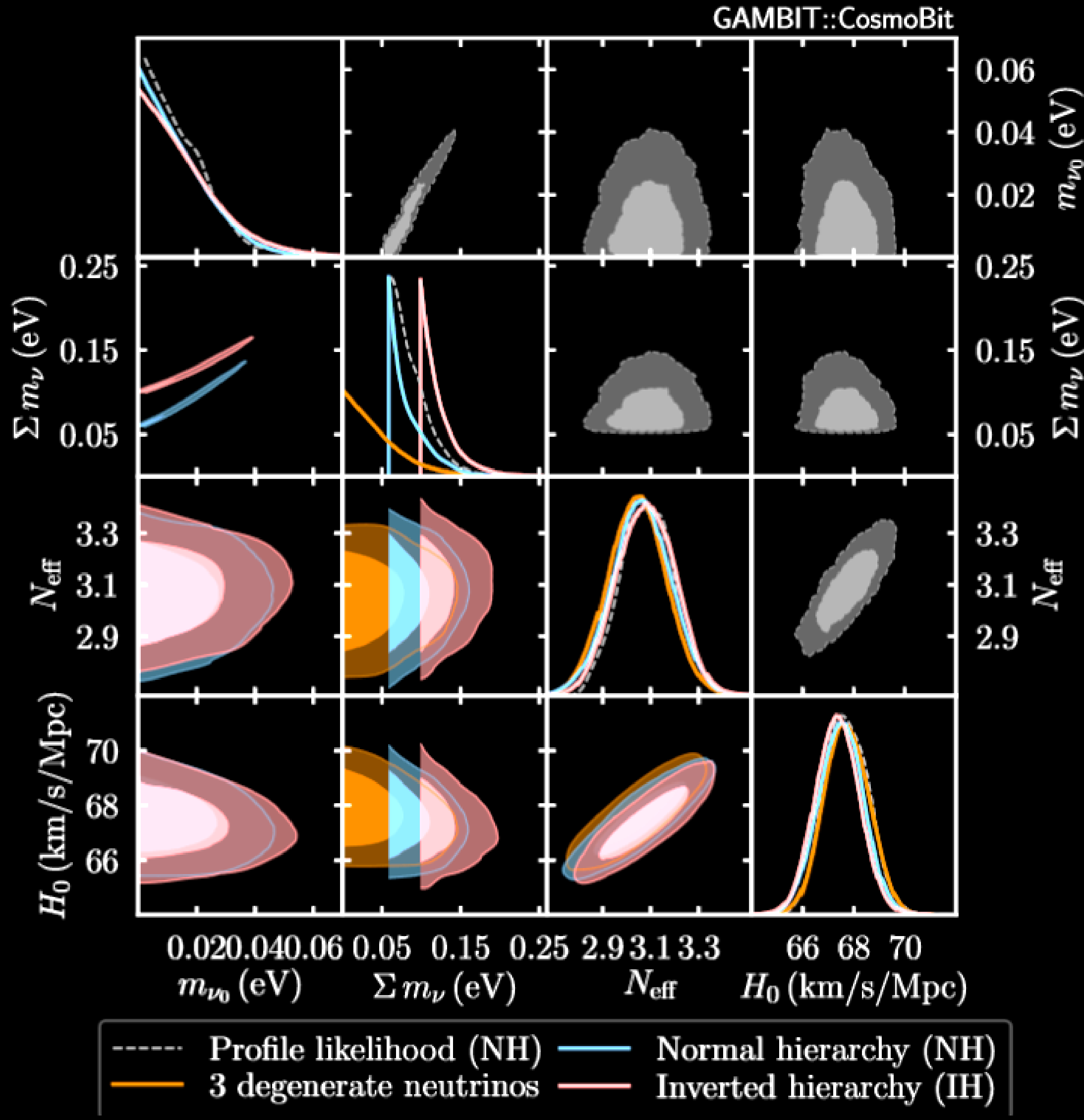
cosmo ALPs
2205.13549

from A. Kvellestad

bound on the lightest neutrino mass

2009.03287

- GAMBIT uses terrestrial and cosmological experiments to set a 95% CL range on the lightest neutrino mass and the sum of neutrino masses assuming normal (NO) or inverse (IO) mass ordering
- $m_\nu < 0.037$ eV (NO)
- $m_\nu < 0.042$ eV (IO)
- $0.058 < \sum m_\nu < 0.139$ eV (NO)
- $0.098 < \sum m_\nu < 0.174$ eV (IO)



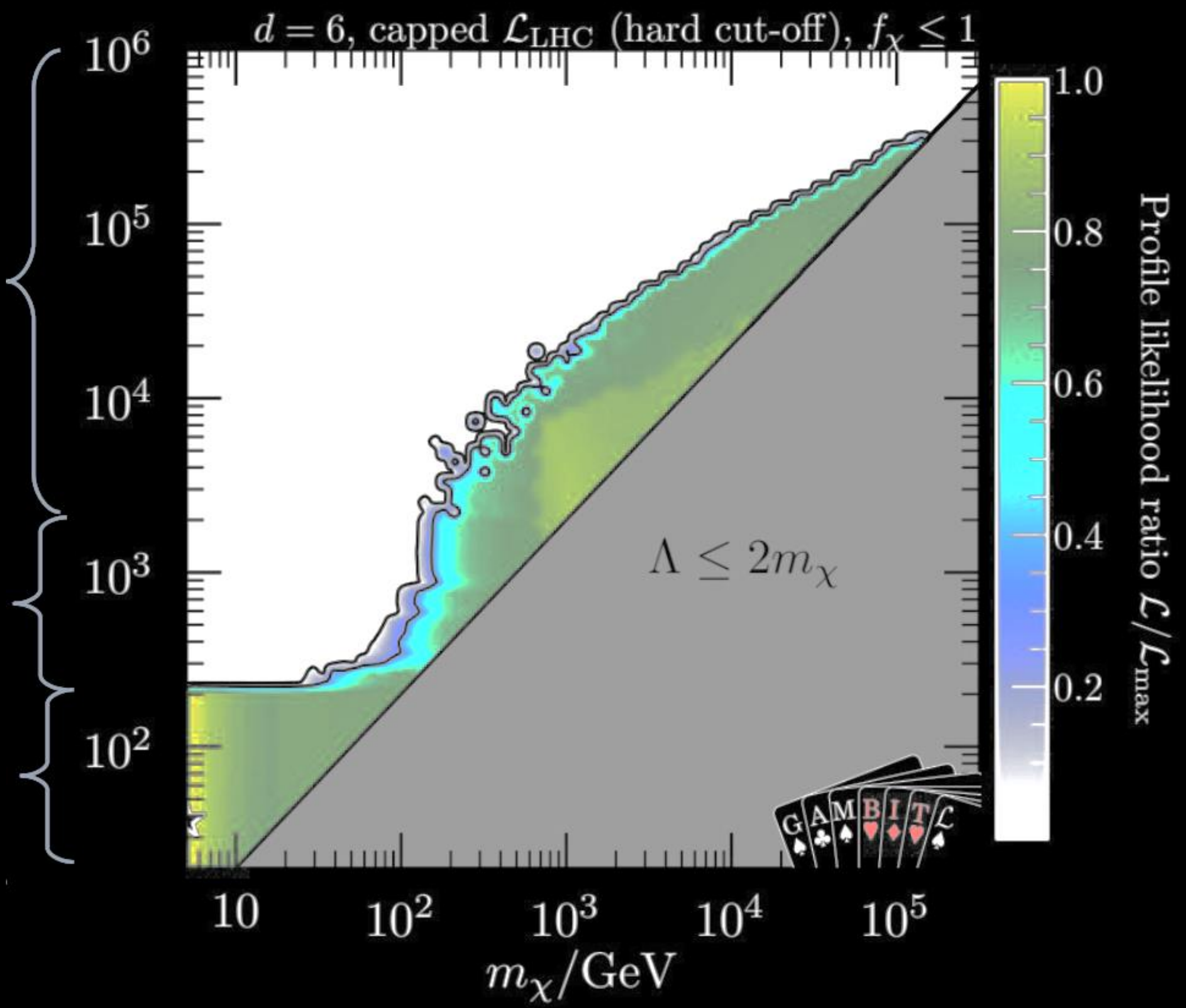
thermal WIMPs and the scale of new physics

2106.02056

new physics scale Λ:

- EFT valid for all constraints
  most experiments are insensitive
  constraints driven by relic density

- Λ comparable to LHC energies
  strong LHC constraints
- Λ below LHC energies
  large viable parameter space

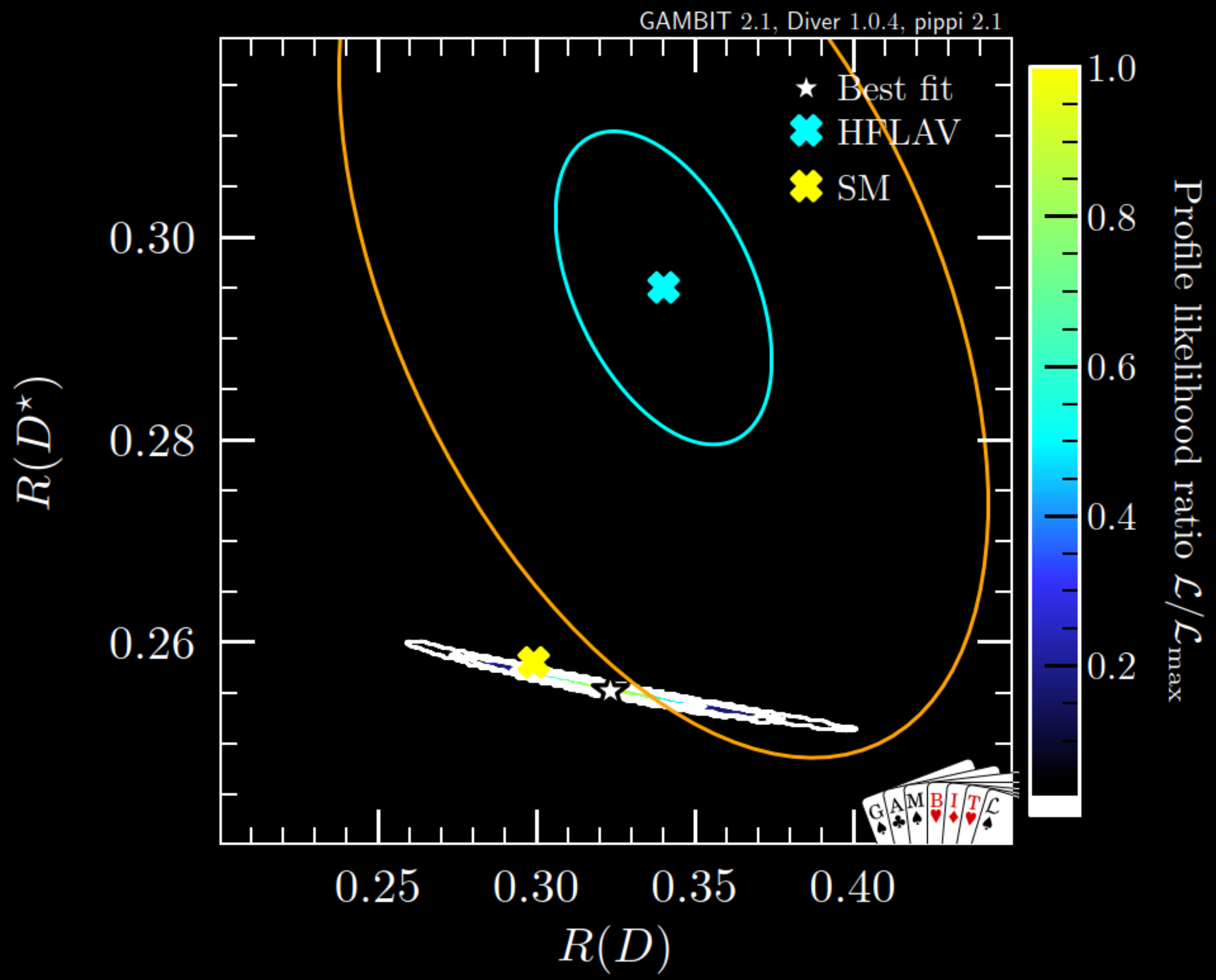


from F. Kahlhoefer, P. Scott

general two-Higgs doublet model flavor fit

2111.10464

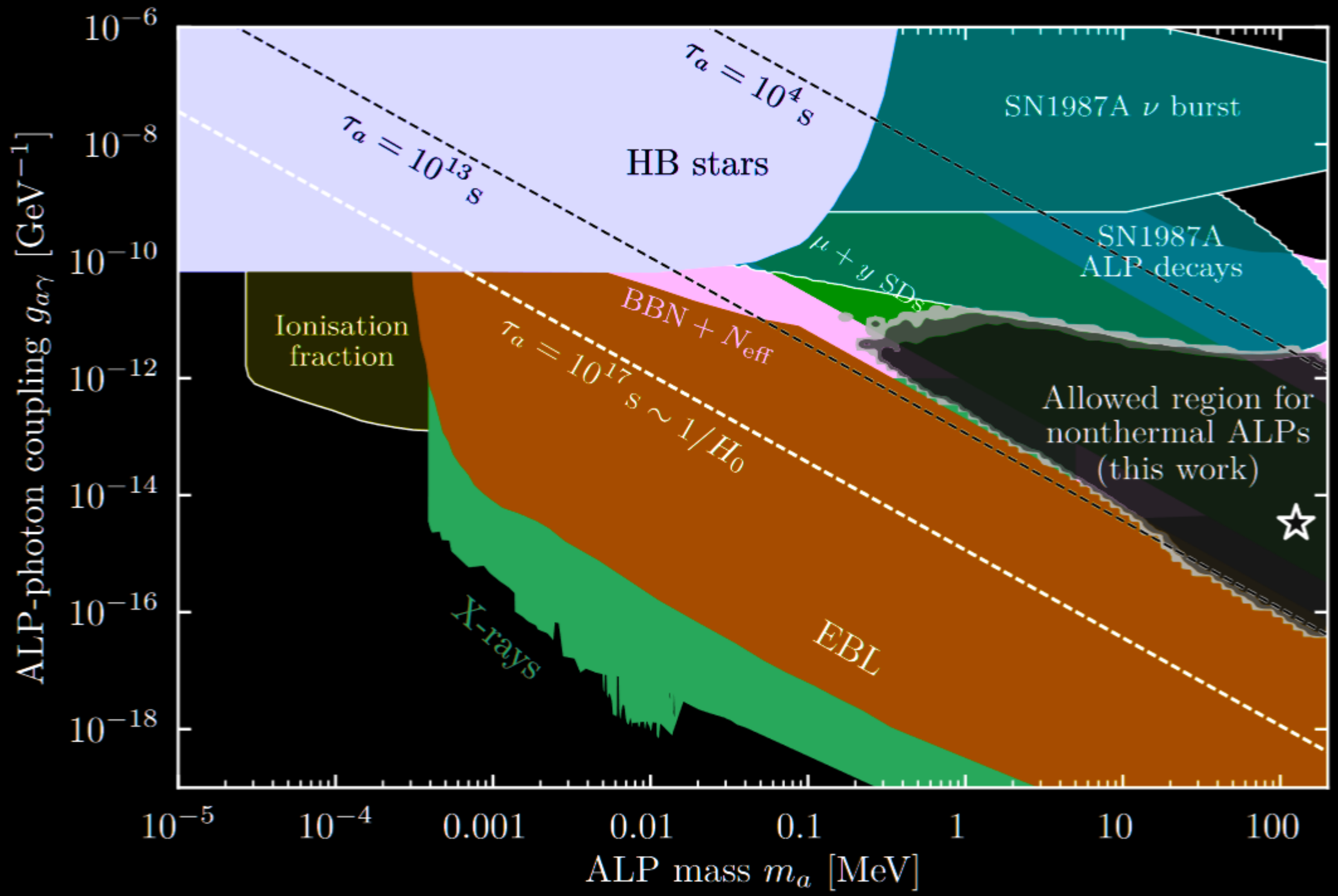
- the 2HDM explains $b \to s\, \mu^+ \mu^-$
- it can simultaneously fit the experimental values of the $R(D)$ charged current ratio at 1σ
- but it can not accommodate the D^* charmed meson observables $R(D^*)$ and $FL(D^*)$
- muon $g-2$ and charged anomalies can be fit together, but not the neutral anomalies



cosmological constraints on decaying ALPs

arXiv:2205.13549

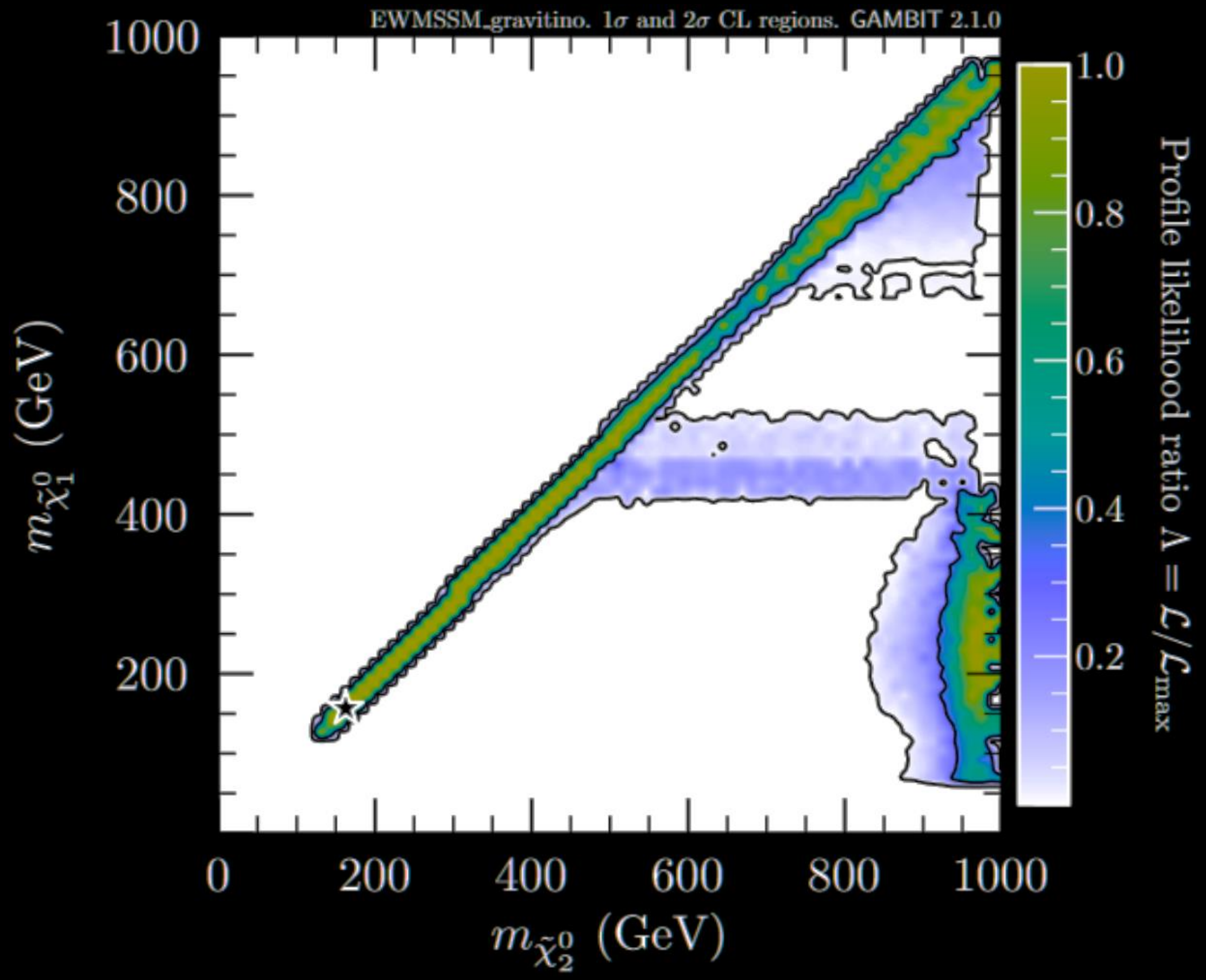
- cosmo constraints: CMB anisotropies & spectral distortions, BBN abundances, ΔNeff (photon injection), BAO (struct. form.)
- astro constraints: SN1987A, HB vs RGB star counts (stellar evolution, cooling), type-Ia SNe, extragalactic bg. light (EBL), X-ray searches
- some non-thermal, high-mass ALP parameter region is still not excluded



collider constraints on electroweakinos + a light gravitino

arXiv:22nn.nnnnn

- gravitino is LSP
- the only light particles in potential reach of LHC is the LSP and the lightest electroweakinos
- latest Atlas and CMS data constrain large part of the 1x1 TeV neutralino mass plane (mostly) due to di-photons plus missing E ('capped' likelihood shown)
- paper to appear soon with more



public results available on zenodo.cern.ch

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

links at gambit.hepforge.org/pubs


zenodo

GAMBIT

Upload Communities

June 29, 2018 (v1) Dataset Open Access

View

Supplementary Data: Impact of vacuum stability, perturbativity and XENON1T on global fits of Z2 and Z3 scalar singlet dark matter (arXiv:1806.11281)

The GAMBIT Collaboration;

Supplementary Data Impact of vacuum stability, perturbativity and XENON1T on global fits of Z2 and Z3 scalar singlet dark matter arXiv:1806.11281 The files in this record contain data for the scalar singlet dark matter models considered in the GAMBIT "Scalar singlet Mark II&qu

Uploaded on July 2, 2018

August 22, 2017 (v2) Dataset Open Access

View

Supplementary Data: Status of the scalar singlet dark matter model (arXiv:1705.07931)

The GAMBIT Collaboration;

Supplementary Data Status of the scalar singlet dark matter model arXiv:1705.07931 The files in this record contain data for the scalar singlet dark matter model considered in the GAMBIT "Round 1" scalar singlet paper. The files consist of Three YAML files, each corresponding to a different pa

Uploaded on August 23, 2017

1 more version(s) exist for this record

August 15, 2017 (v2) Dataset Open Access

View

Supplementary Data: A global fit of the MSSM with GAMBIT (arXiv:1705.07917)

The GAMBIT Collaboration;

Supplementary Data A global fit of the MSSM with GAMBIT arXiv:1705.07917 The files in this record contain data for the MSSM7 model considered in the GAMBIT "Round 1" weak-scale SUSY paper. The files consist of A number of YAML files corresponding to different sets of sampling parameters and/

Uploaded on August 16, 2017

1 more version(s) exist for this record

August 15, 2017 (v2) Dataset Open Access

View

Supplementary Data: Global fits of GUT-scale SUSY models with GAMBIT (arXiv:1705.07935)

The GAMBIT Collaboration;

Supplementary Data Global fits of GUT-scale SUSY models with GAMBIT arXiv:1705.07935 The files in this r… data for the CMSSM, NUHM1 and NUHM2 models considered in the GAMBIT "Round 1" GUT-scale SUSY p… model, there are A number of YAML files, each corresponding to a di

future of GAMBIT

- more GAMBIT: more models, more observables, more automation, more data, more stats…
- machine learning of cross sections, cosmic ray fluxes…
- observable calculation on parallel GPUs
- ColliderBit Solo
- papers focusing on light SUSY, 2HDMs, DM direct detection, neutrinos, axions, leptoquarks…
- getting long-haired fluffy white cat and taking over the world…

summary

- global fitting paves the way to the next standard model(s)
- GAMBIT is an open source, flexible, modular global fitting framework
- GUM significantly enhances the capabilities of GAMBIT 2.0
- GAMBIT version 2.2 is out https://github.com/GambitBSM/gambit_2.2
- over a dozen physics papers since 2017 and many more to come
- stay tuned for much more…

more GAMBIT at TeVPA:

Neal Avis Kozar: Global fit of non-rel. eff. operator DM using solar neutrinos

Christopher Chang: Global fits of s-chan. simp. models for DM with GAMBIT

Tomas Gonzalo: A global analysis of decaying ALPs

backup slides

GAMBIT

open-source global fitting framework

modular and flexible architecture

models beyond the standard

sophisticated statistical inference

plug&play tools to calc observables

global fitting

How?

<u>main steps</u>

- establish model hierarchy
- Lagrangian → spectrum
- spectrum → observables
- parameter space sampling
- statistical treatment

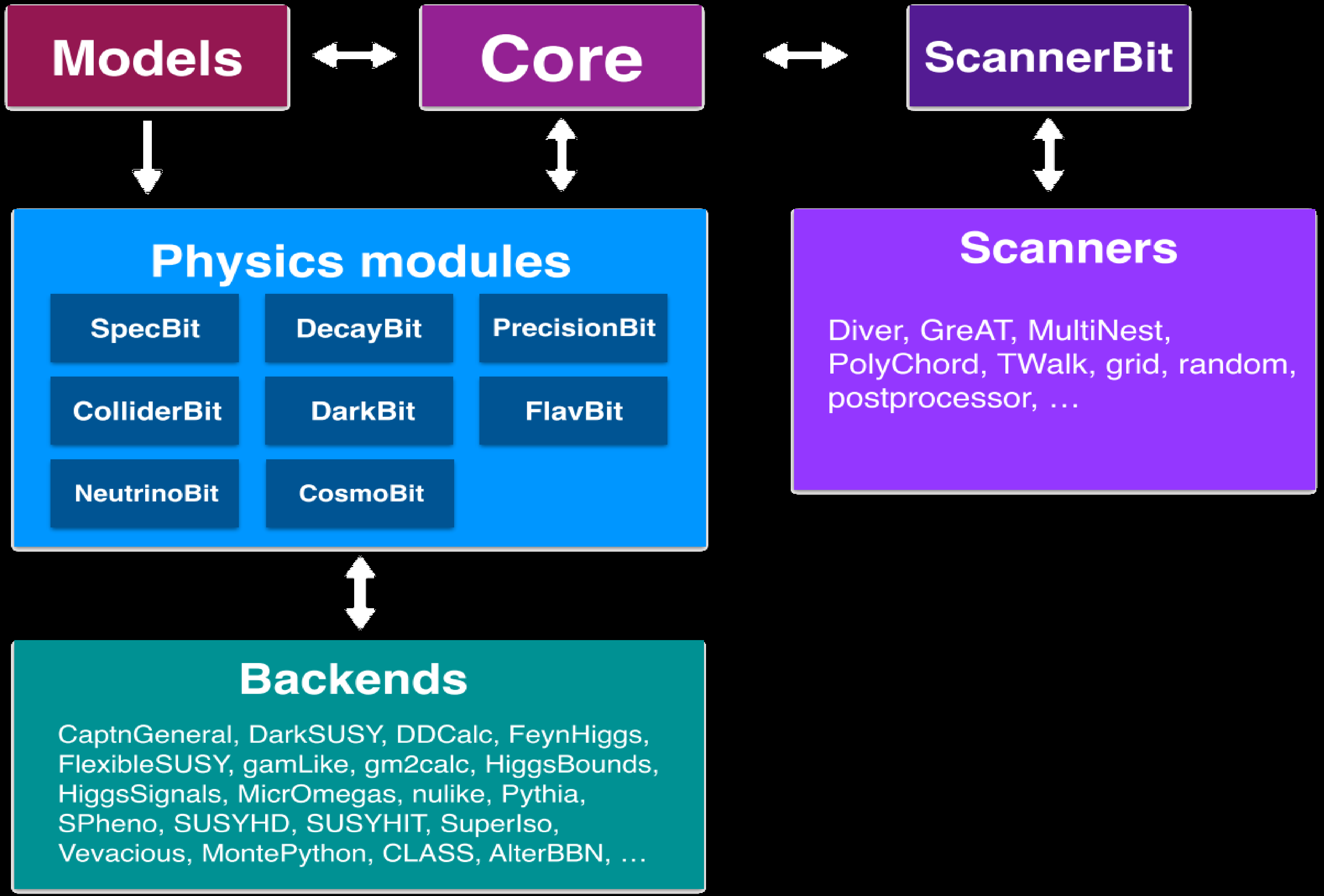
<u>main challenges</u>

- many models (& parameters)
- spectrum auto-generation
- fast backends, auto-generation
- efficiency: need for speed
- rigorous, meaningful inference

these steps and challenges can be tackled “model independently”

GAMBIT

schematics



Models

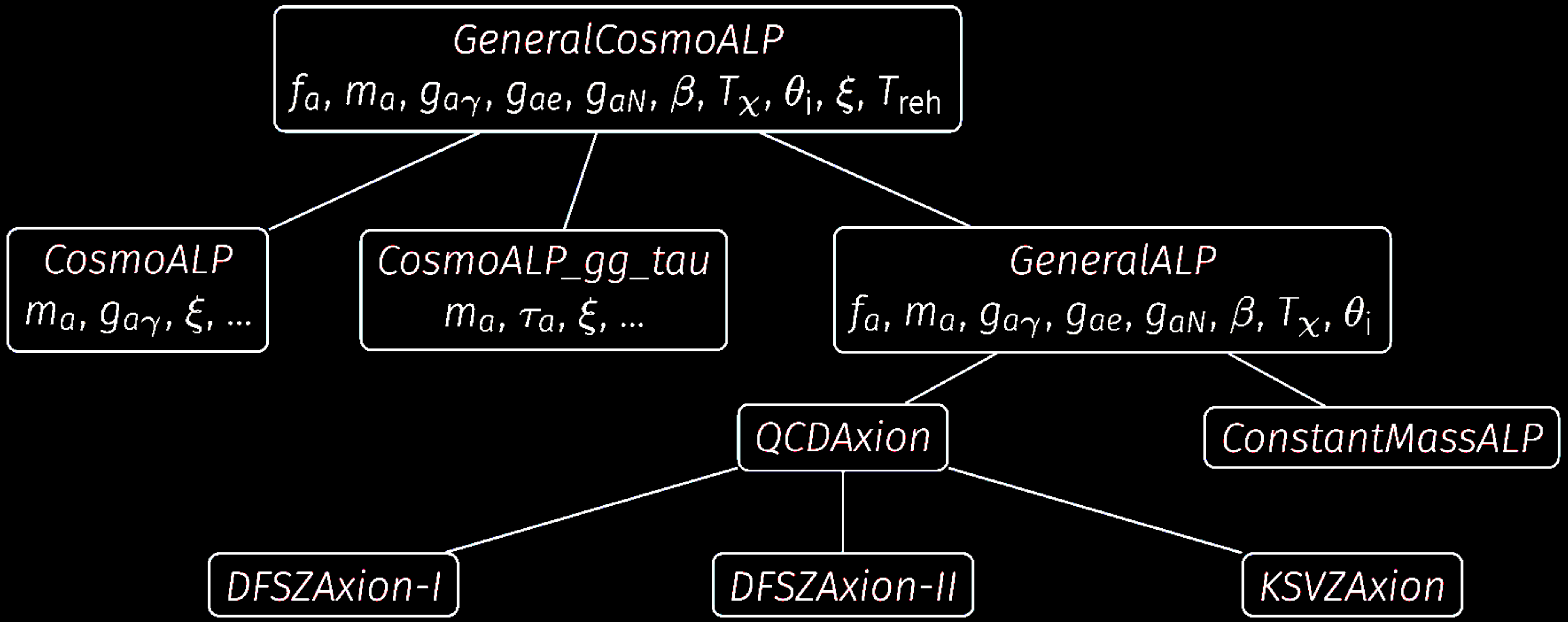
hierarchical model database

- models defined by their parameters and relations to each other
- models can inherit from (be subspaces of) parent models
- child models can be automatically translated to ancestor models
- database examples:
  - standard model
  - nuclear uncertainties
  - two-Higgs doublet models
  - Higgs portal dark matter models
  - dark matter halo models
  - right-handed neutrino models
  - effective field theory dark matter models…

Models

model database examples

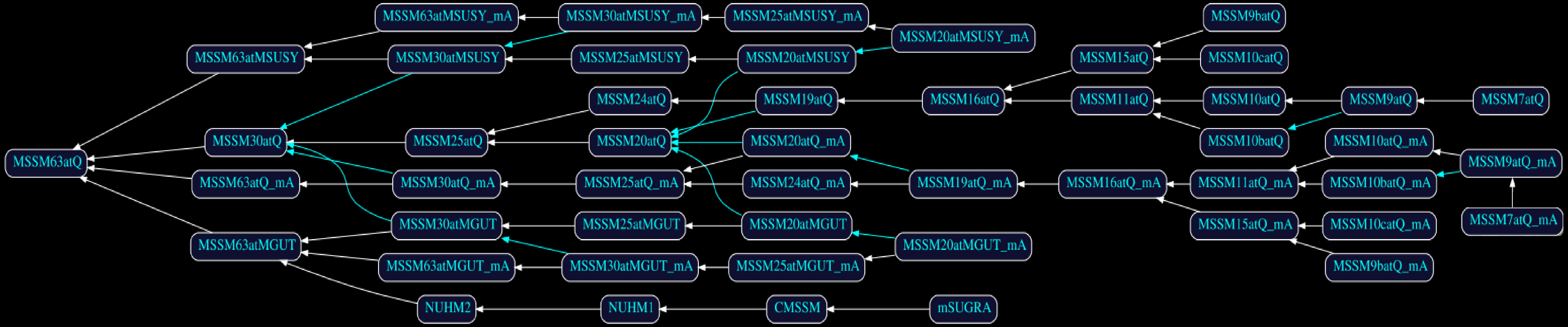
- axions and ALPs



Models

model database examples

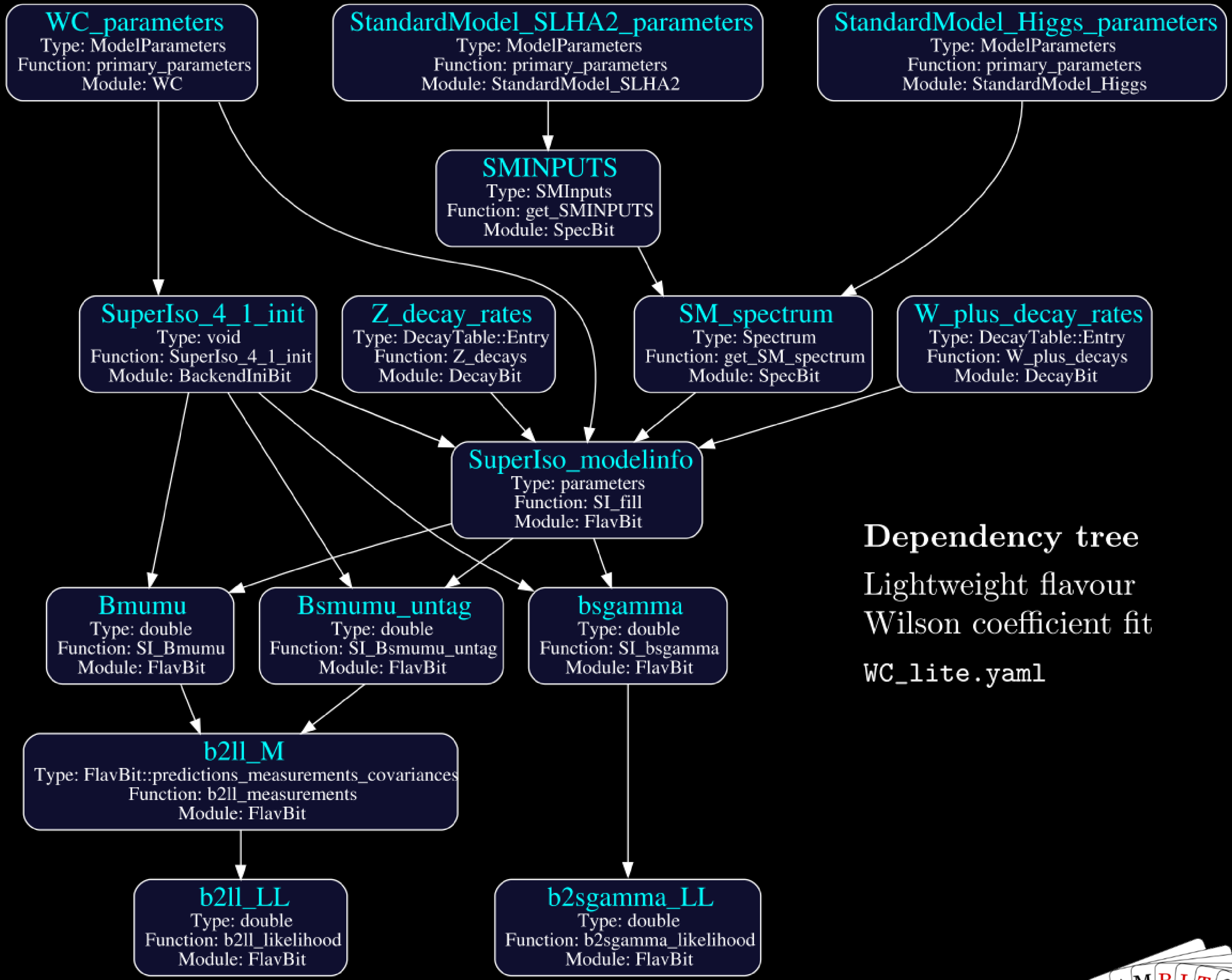
- MSSM



GAMBIT

run overview

- user chooses model, observables, sampler
- using graph-theory GAMBIT constructs a dependency tree to optimize the calculation
- GAMBIT samples para. space by calling the necessary module and backend functions for each parameter point



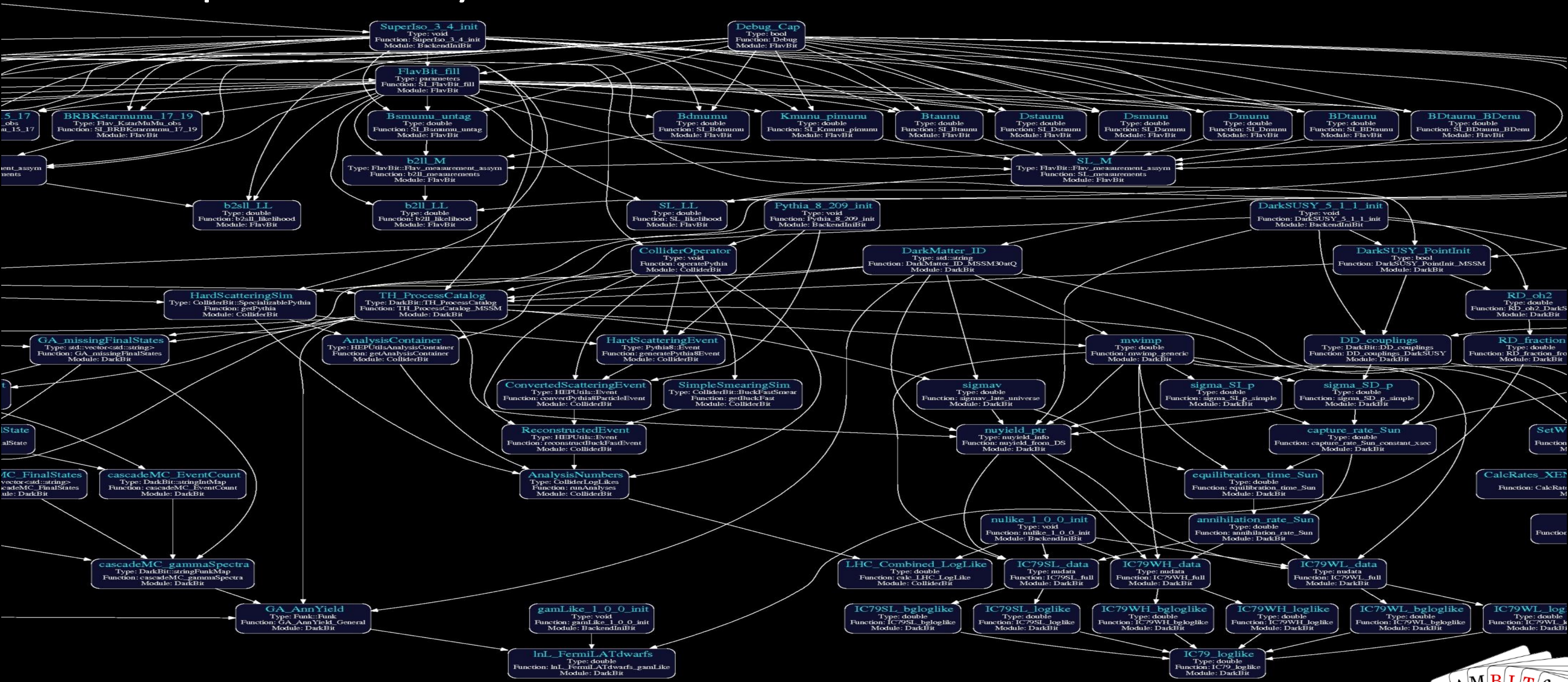
Dependency tree

Lightweight flavour Wilson coefficient fit

`WC_lite.yaml`

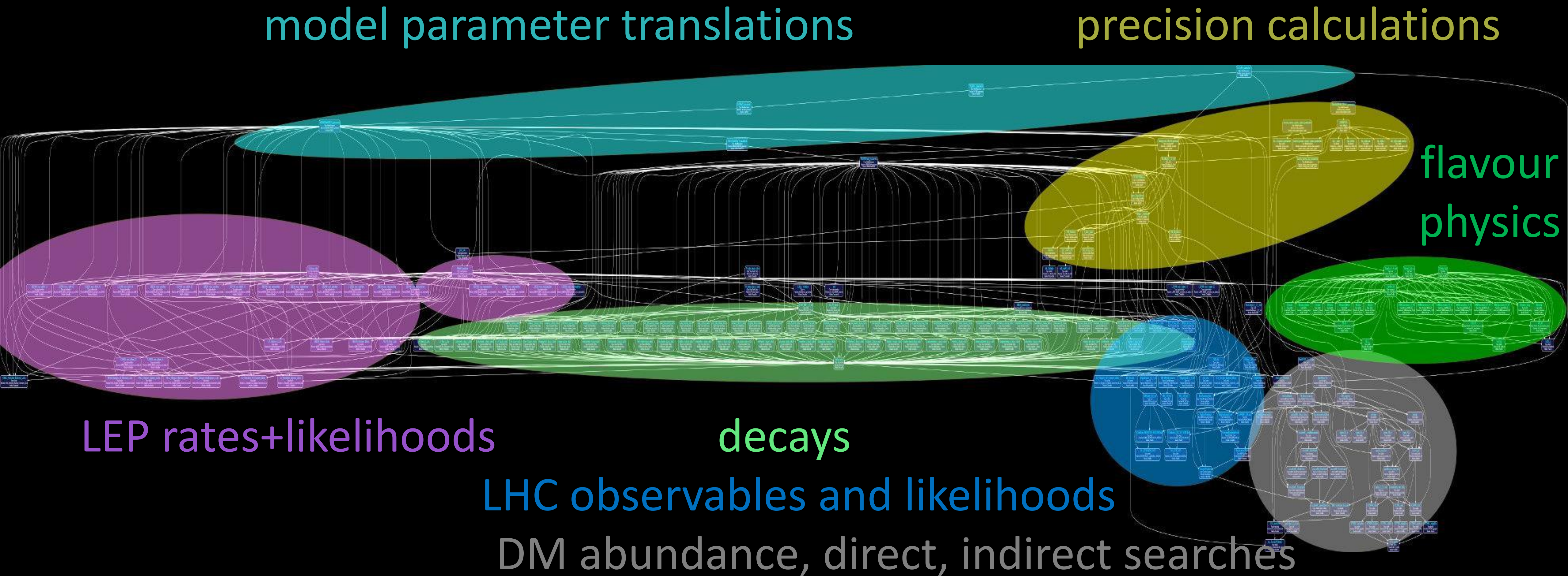
Dependency resolution

for CMSSM

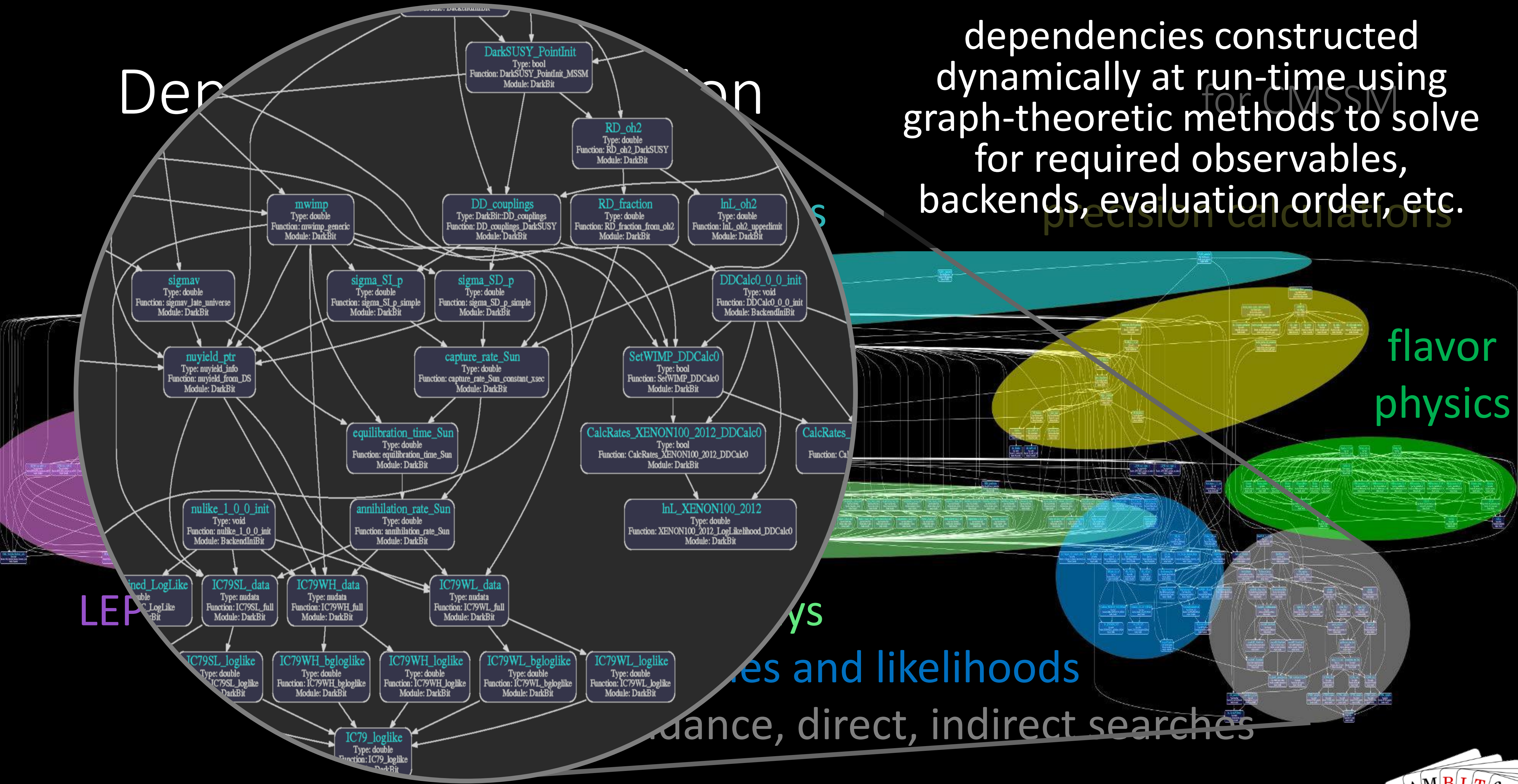


Dependency resolution

for CMSSM



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



getting started

- clone git repo github.com/GambitBSM/gambit_2.2   or
- download tarballs https://gambit.hepforge.org/source or
- get pre-compilied version docker
- see quick start guides in arXiv:1705.07908 and arXiv:2107.00030

adding a new model to GAMBIT manually

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 manually

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

GAMBIT results related to dark matter

EFTs: SM + scalar, fermion, vector singlet (simplest DM model)

EPJ C77 (2017) 8 568 arXiv:1705.07931

EPJ C78 (2018) 10 830 arXiv:1806.11281

EPJ C79 (2019) 1 38 arXiv:1808.10465

arXiv:2106.02056

axions, axion-like particles (QCD axion, DFSZ, KSVZ, generic ALP)

JHEP 1903 (2019) 191 arXiv:1810.07192

arXiv:2006.03489

constrained SUSY: CMSSM, NUHM1, NUHM2 (GUT scale BCs)

EPJ C77 (2017) 12 824 arXiv:1705.07935

low-dim SUSY: MSSM-7, MSSM-EW (weak scale BCs)

EPJ C77 (2017) 12 879 arXiv:1705.07917

EPJ C79 (2019) 5 395 arXiv:1809.02097

more EFTs, more ALPs, more SUSY and other models in prep

Dark matter effective field theory arXiv:2106.02056

- general DMEFT: all DM-SM effective interactions up to dimension *n*
- in principle, a global fit of the general theory is possible with GAMBIT
- we focus on the 16D space of Dirac DM interactions with SM quarks and gluons:

$$\mathcal{L}_\chi = \overline{\chi}\left(i\partial\!\!\!/ - m_\chi\right)\chi + \sum_{a,d} \frac{\mathcal{C}_a^{(d)}}{\Lambda^{d-4}} \mathcal{Q}_a^{(d)}$$

from P. Scott

Dark matter effective field theory arXiv:2106.02056

$$\mathcal{L}_\chi = \overline{\chi}\left(i\partial\!\!\!/ - m_\chi\right)\chi + \sum_{a,d} \frac{\mathcal{C}_a^{(d)}}{\Lambda^{d-4}} \mathcal{Q}_a^{(d)}$$

Direct detection signals:

- Spin-independent – not suppressed
- Spin-independent – suppressed
- Spin-dependent – not suppressed
- Spin-dependent – suppressed

$$\mathcal{Q}_{1,q}^{(6)} = (\overline{\chi}\gamma_\mu\chi)(\overline{q}\gamma^\mu q)$$
$$\mathcal{Q}_{2,q}^{(6)} = (\overline{\chi}\gamma_\mu\gamma_5\chi)(\overline{q}\gamma^\mu q)$$
$$\mathcal{Q}_{3,q}^{(6)} = (\overline{\chi}\gamma_\mu\chi)(\overline{q}\gamma^\mu\gamma_5 q)$$
$$\mathcal{Q}_{4,q}^{(6)} = (\overline{\chi}\gamma_\mu\gamma_5\chi)(\overline{q}\gamma^\mu\gamma_5 q)$$

$$\mathcal{Q}_{1}^{(7)} = \frac{\alpha_s}{12\pi}(\overline{\chi}\chi)G^{a\mu\nu}G^a_{\mu\nu}$$
$$\mathcal{Q}_{2}^{(7)} = \frac{\alpha_s}{12\pi}(\overline{\chi}i\gamma_5\chi)G^{a\mu\nu}G^a_{\mu\nu}$$
$$\mathcal{Q}_{3}^{(7)} = \frac{\alpha_s}{8\pi}(\overline{\chi}\chi)G^{a\mu\nu}\widetilde{G}^a_{\mu\nu}$$
$$\mathcal{Q}_{4}^{(7)} = \frac{\alpha_s}{8\pi}(\overline{\chi}i\gamma_5\chi)G^{a\mu\nu}\widetilde{G}^a_{\mu\nu}$$
$$\mathcal{Q}_{5,q}^{(7)} = m_q(\overline{\chi}\chi)(\overline{q}q)$$

$$\mathcal{Q}_{6,q}^{(7)} = m_q(\overline{\chi}i\gamma_5\chi)(\overline{q}q)$$
$$\mathcal{Q}_{7,q}^{(7)} = m_q(\overline{\chi}\chi)(\overline{q}i\gamma_5 q)$$
$$\mathcal{Q}_{8,q}^{(7)} = m_q(\overline{\chi}i\gamma_5\chi)(\overline{q}i\gamma_5 q)$$
$$\mathcal{Q}_{9,q}^{(7)} = m_q(\overline{\chi}\sigma^{\mu\nu}\chi)(\overline{q}\sigma_{\mu\nu} q)$$
$$\mathcal{Q}_{10,q}^{(7)} = m_q(\overline{\chi}i\sigma^{\mu\nu}\gamma_5\chi)(\overline{q}\sigma_{\mu\nu} q)$$

from P. Scott

EFT validity

arXiv:2106.02056

- the scale of new physics Λ is an independent parameter
- relic density calculation requires $\Lambda > 2m_\chi$
- if Λ > scale probed by other experiments, we compute $\ln\mathcal{L}_{\text{experiment}}$
- otherwise, we set $\ln\mathcal{L}_{\text{experiment}} = 0$
- for LHC we smoothly cut off the spectrum to suppress events with $missing\ E_T > \Lambda$

from F. Kahlhoefer, P. Scott

Other key innovations

arXiv:2106.02056

- direct detection

  - DirectDM: fully automated RG evolution from Λ to low energies and matching to non-relativistic effective operators at hadronic scale

  - DDCalc: large database of direct detection constraints for arbitrary DM-nucleon interactions including astrophysical and nuclear uncertainties

- LHC constraints (ColliderBit)

  - monojet analyses: ATLAS 139/fb (full Run 2 dataset) + CMS 36/fb

  - fast profiling of LHC nuisance parameters

from P. Scott

Other key innovations

arXiv:2106.02056

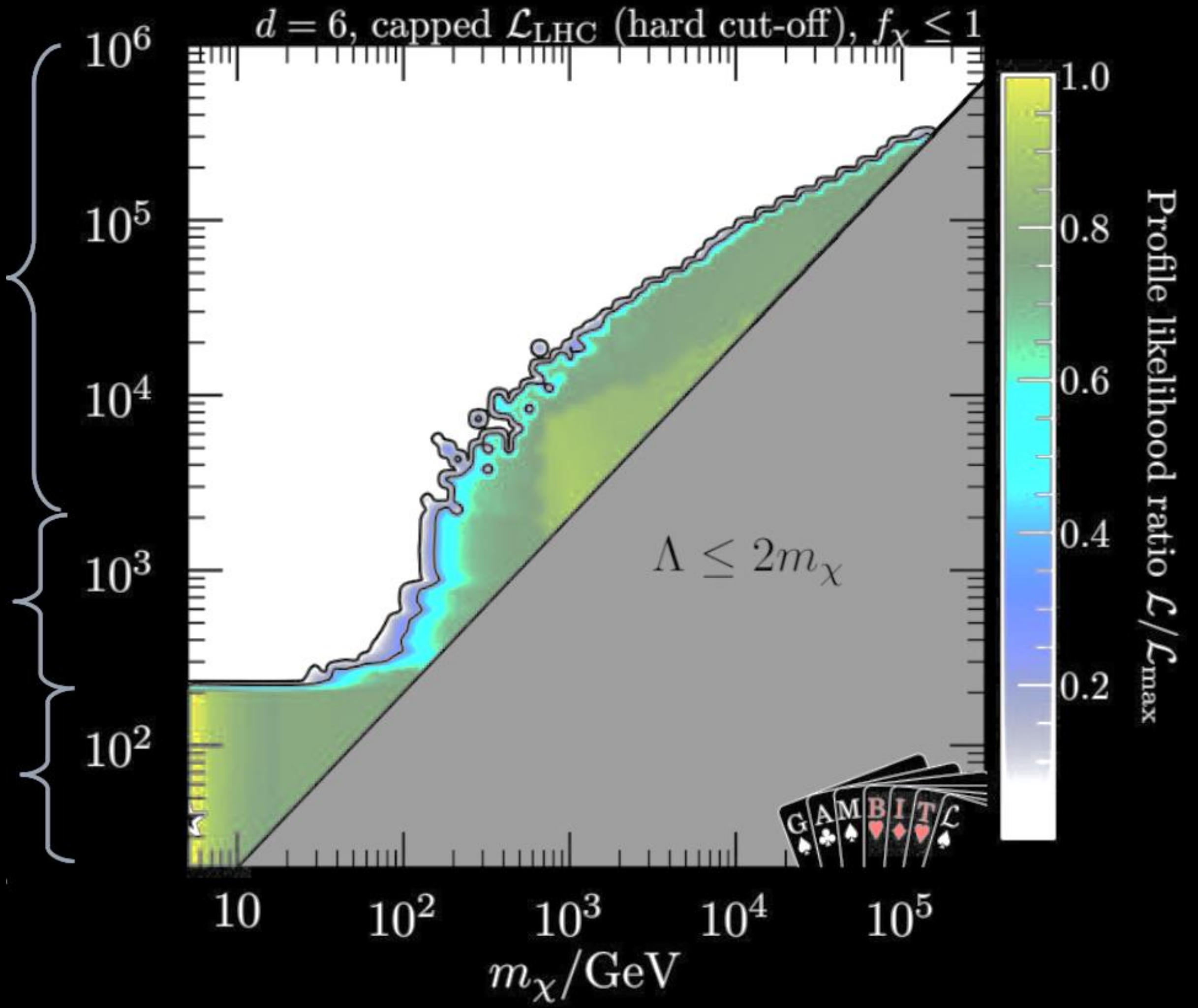
- indirect detection
  - DarkSUSY: highly accurate relic density calculation
  - GUM: automated calculation of cross sections and γ-ray spectra
  - CosmoBit: CMB constraints on energy injection from DM annihilation
  - Capt’n General: solar capture + neutrinos with arbitrary DM-nucleon interactions
- interface between all of these and Diver differential sampler fully automated in GAMBIT

from P. Scott

DMEFT results

general picture

- new physics scale Λ:
- EFT valid for all constraints
- most experiments are insensitive
- constraints driven by relic density requirement
- Λ comparable to LHC energies
- strong LHC constraints
- Λ below LHC energies
- large viable parameter space



from F. Kahlhoefer, P. Scott

DMEFT results

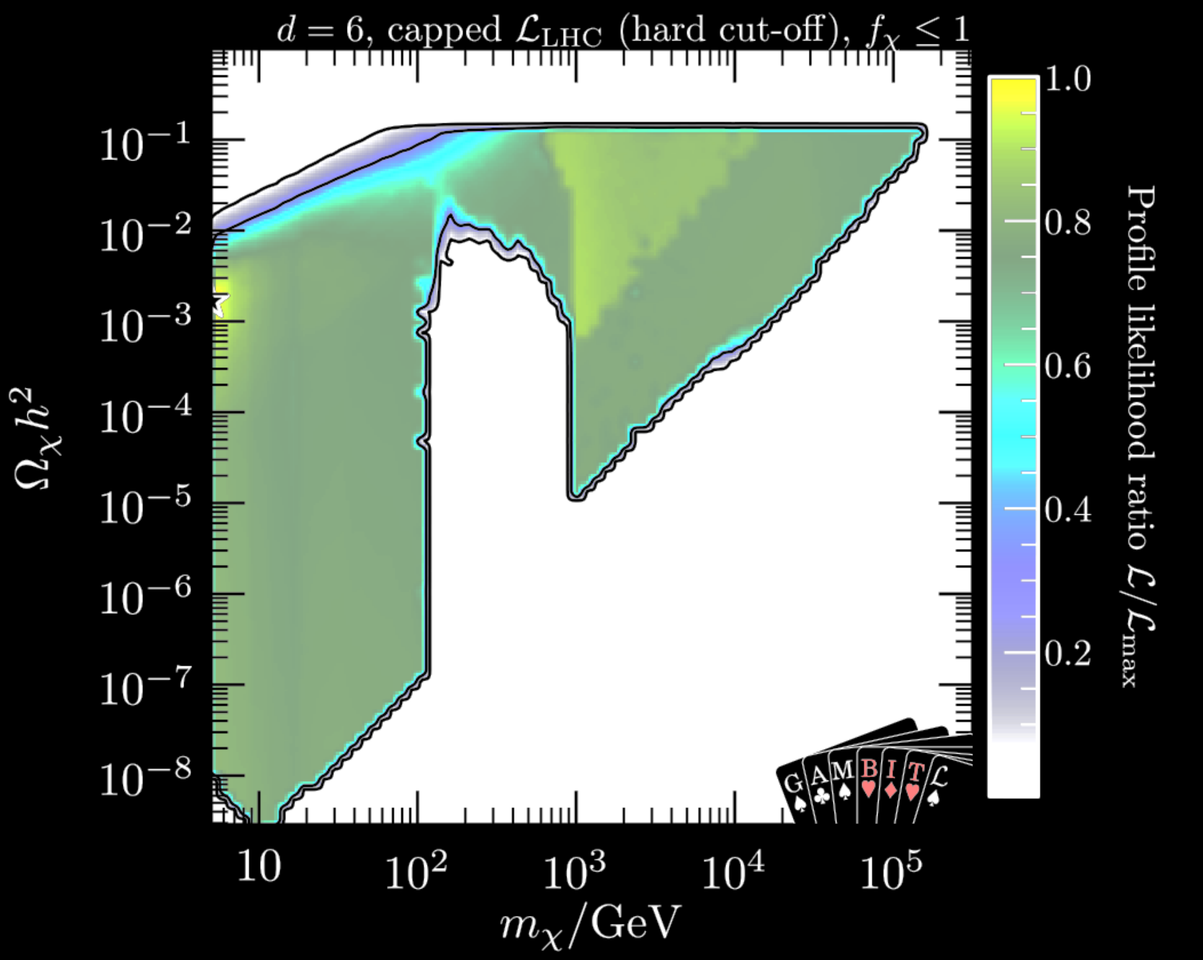
light DM particles

- light DM ($m_\chi < 100$ GeV) is viable if both of the following hold:

  - χ has CP-violating interactions OR is very sub-dominant

  - Λ is so low that EFT breaks down entirely at LHC ⇒ LHC would (probably) be sensitive to mediator

- significant to model building, suggests light WIMPs require light mediator (e.g. dark photon)

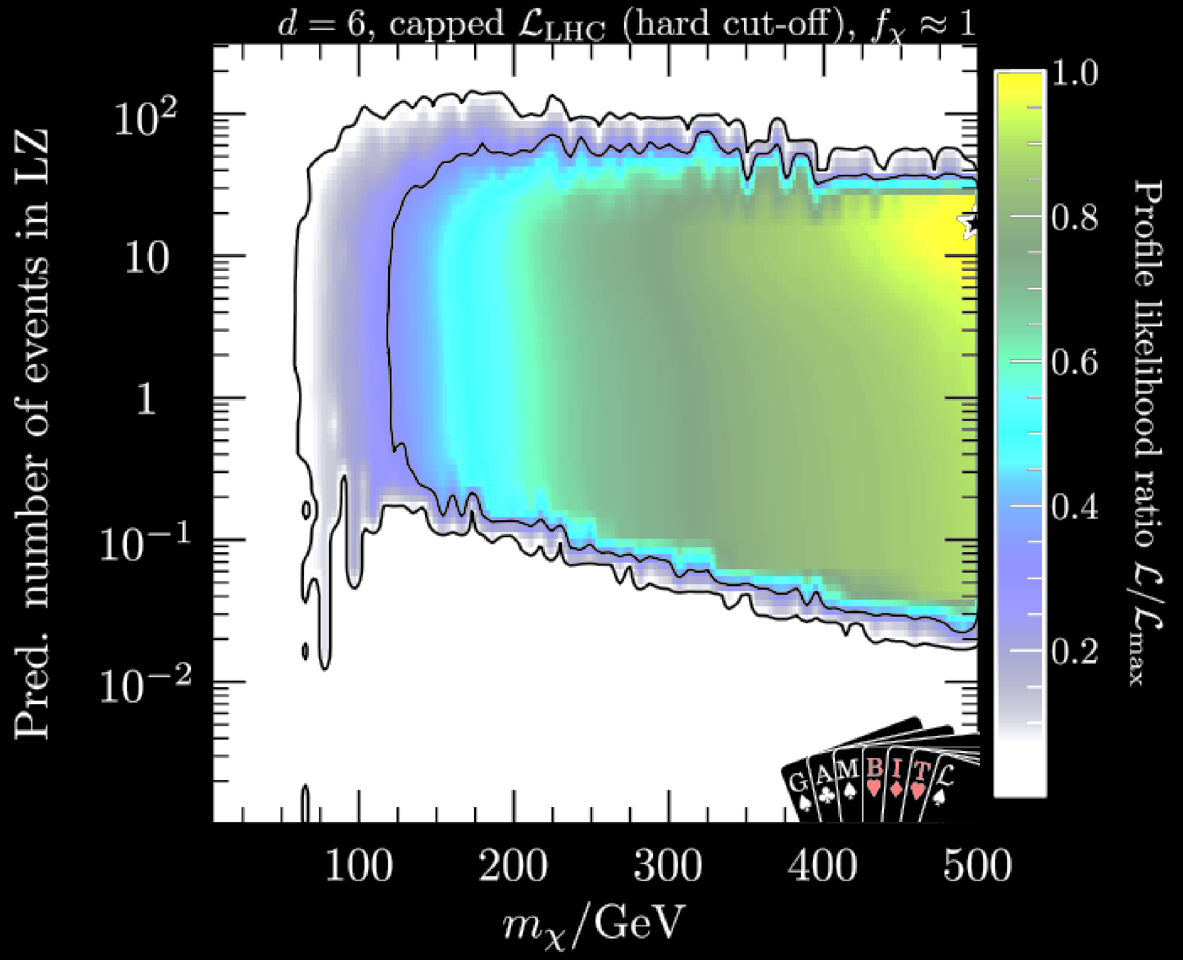


from F. Kahlhoefer, P. Scott

DMEFT results

heavy DM particles

- demanding χ to be all of DM pushes viable parameter space to large mχ
- leads to detectable signals at LZ
- mostly due to loop-induced operator mixing Q(6)3,q → Q(6) 1,q
- could be spoilt by including other effective operators (e.g. leptons, non-MFV) ⇒ interesting avenue for future investigation



from F. Kahlhoefer, P. Scott