

# GAMBIT

dark matter update

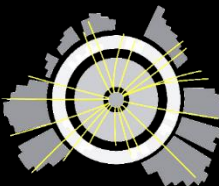
Csaba Balázs

for the GAMBIT Community

DSU 2022 Dec 9



MONASH  
University



**CoEPP**

ARC Centre of Excellence for  
Particle Physics at the Terascale

**MoCA**

Monash Centre for Astrophysics



# other talks by GAMBIT members at DSU

Aaron Vincent

Dark matter and dark sectors in stars

Tue 06/12 9:30

Christopher Chang

Global Fits of vector-mediated simplified models for Dark Matter

Tue 06/12 17:00

Julia Harz

Charting the leptogenesis landscape

Wed 07/12 9:30

Ankit Beniwal

Thermal WIMPs and the Scale of New Physics

Thu 08/12 15:00



# outline

global fits

**GAMBIT**

main features

version 2.0

latest results



# Consensus particle theorist's view of the road ahead: @LHC start in 2009

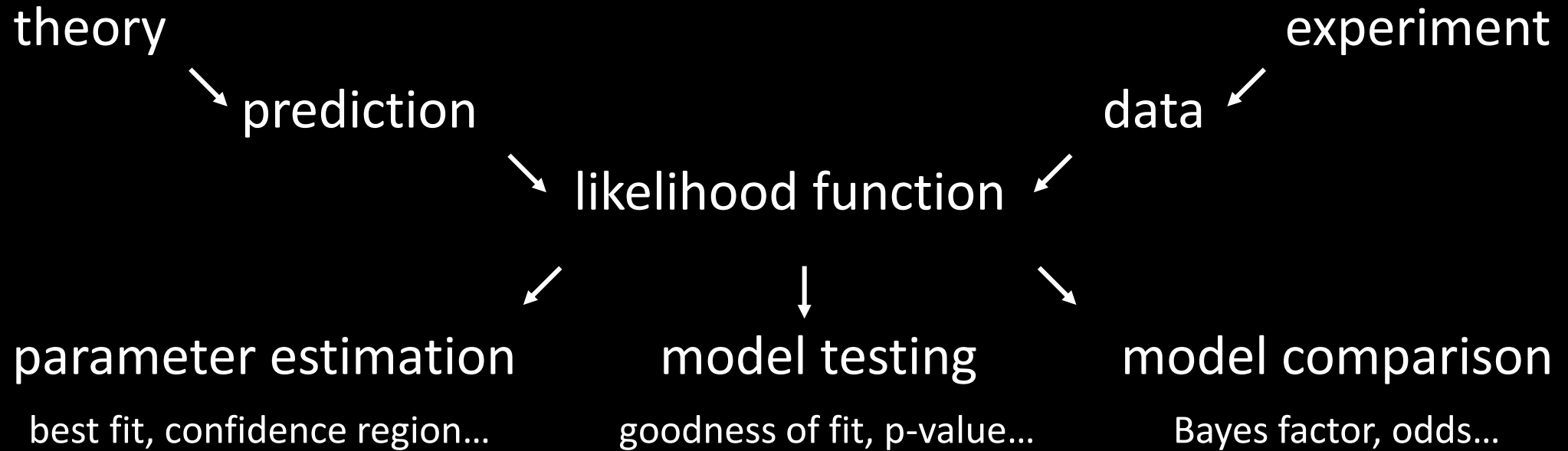


# Consensus particle theorist's view of the road ahead: @LHC RUN 3 in 2022



# global fitting

mapping the maze  
one shrub at a time



the idea of global fitting is simple, but global fitting can be complicated



# Global And Modular BSM Inference Tool

[gambit.hepforge.org](http://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+ 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, SABRE, 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, nested samplers...
- **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:  $\Lambda$ CDM+, 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
- Contur
- DarkAges
- DarkCast
- DDCalc
- DarkSUSY
- FeynHiggs
- FeynRules
- Flavio
- FlexibleSUSY
- gamLike
- GM2Calc
- HepLike
- HiggsBounds
- HiggsSignals
- MadGraph
- micrOMEGAs
- MontePython
- MultiModeCode
- nulike
- pic
- Pythia
- Rivet
- SARA
- Spheno
- SUSYHD
- SUSY-HIT
- SuperIso
- Vevacious
- ...



# GAMBIT 2.0

from Lagrangian to likelihood

GAMBIT Universal Model



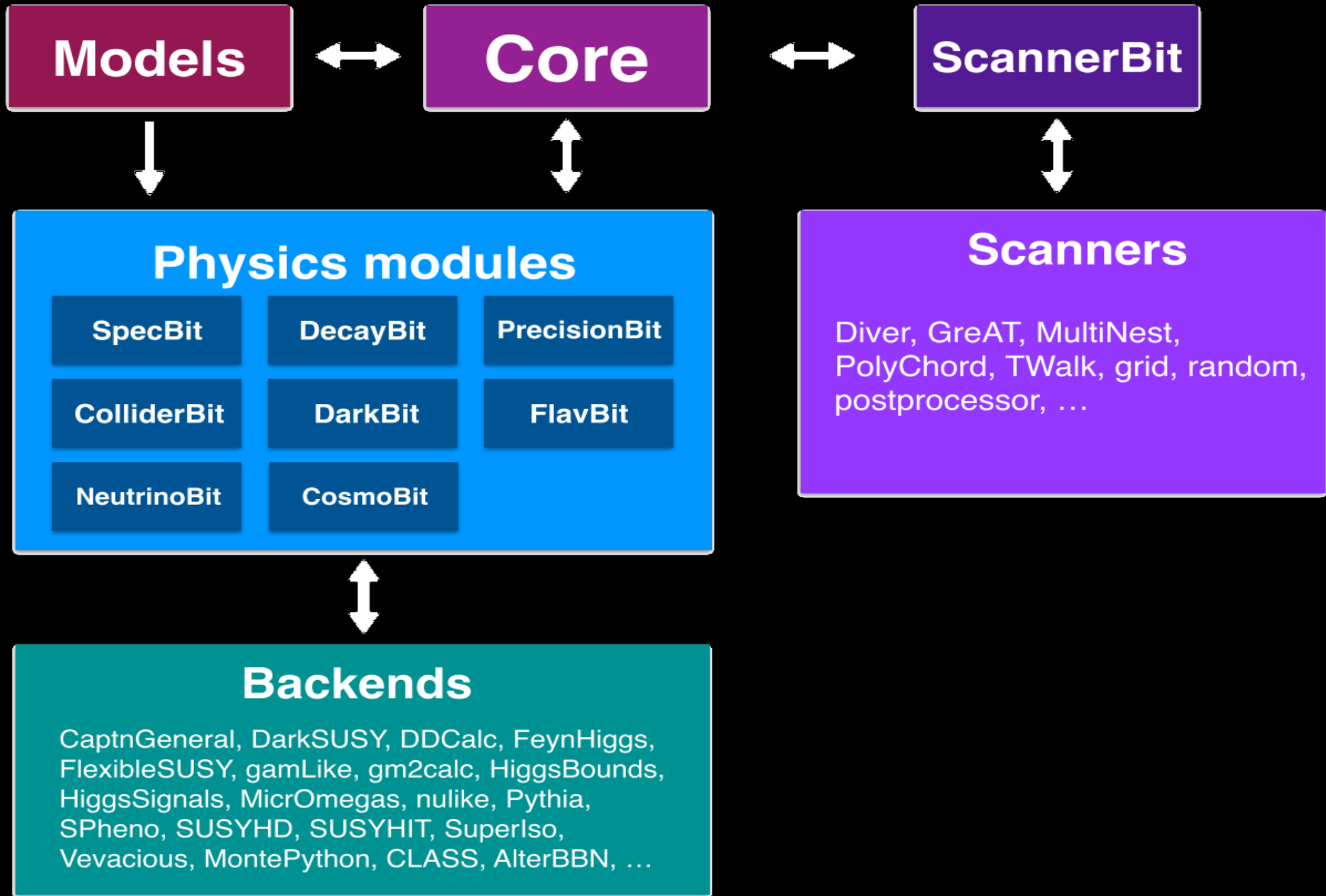
# GUM

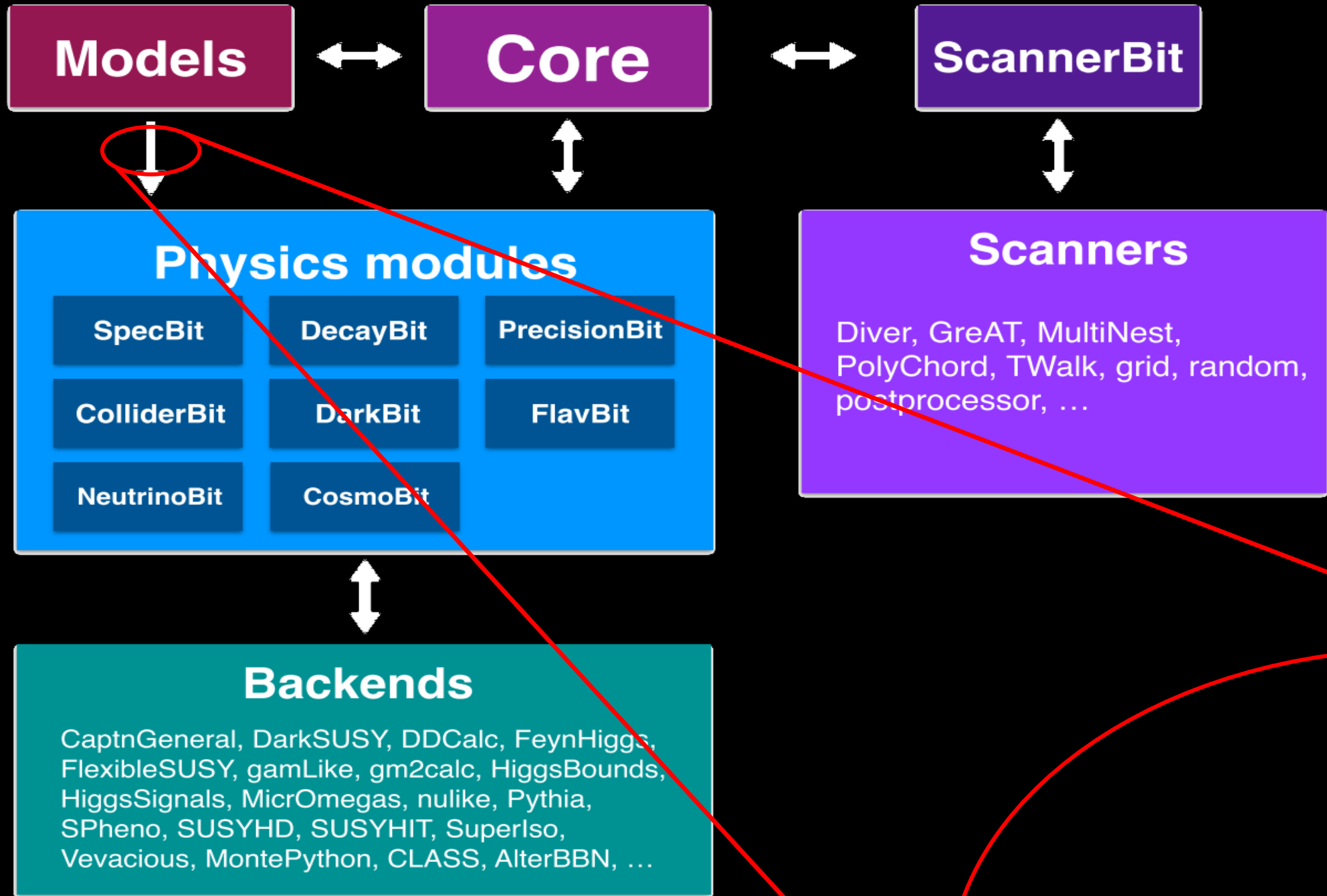
## The GAMBIT Universal Model Machine

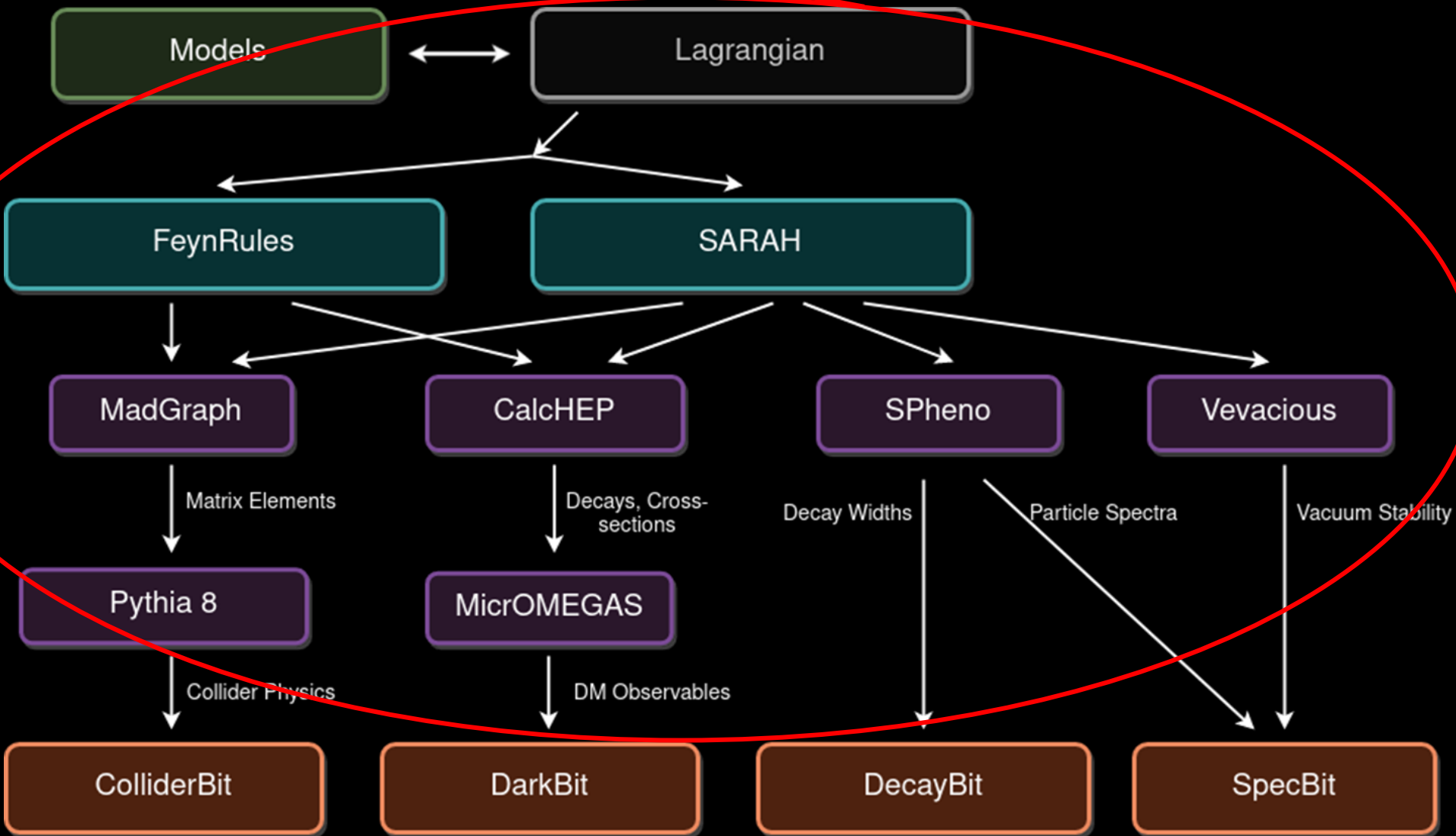
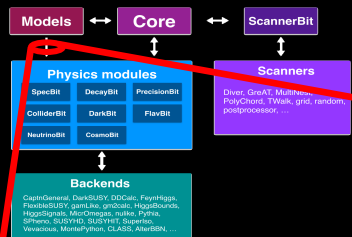
- auto-generating GAMBIT code and interfaces to backends
- from Lagrangian-level input use FeynRules, SARAH, MadGraph, CalcHEP to generate GAMBIT model, collider, dark matter, decay and spectrum code
- GUM also writes C++ GAMBIT interfaces to SPheno, micrOMEGAs, Pythia, Vevacious
- arXiv:2107.00030 (EPJC) 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

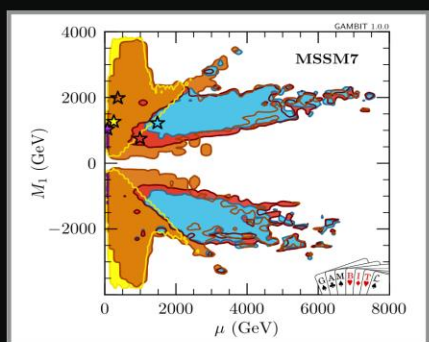




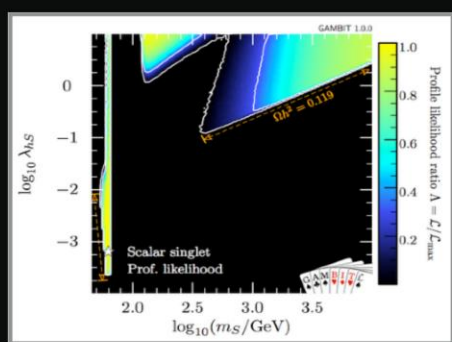




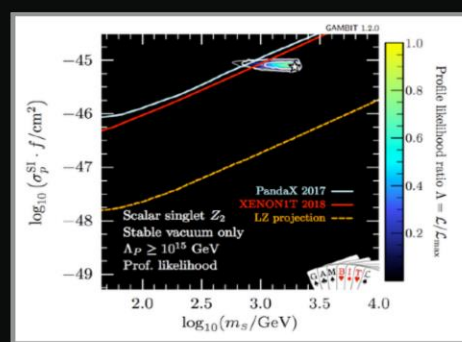




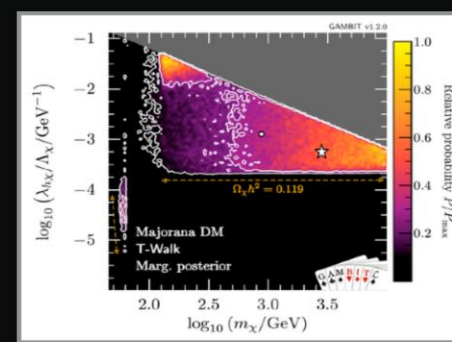
CMSSM 1705.07935/EPJC  
MSSM7 1705.07917/EPJC



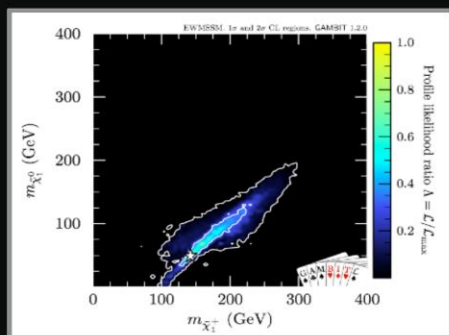
scalar H-portal DM  
1705.07931 / EPJC



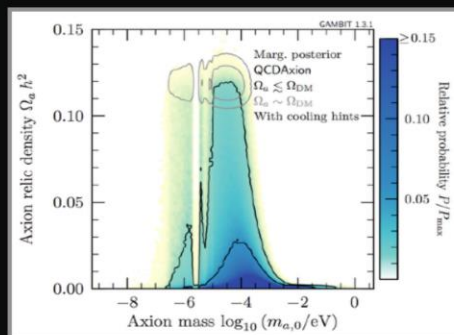
sc. HP DM vac. stab.  
1806.11281 / EPJC



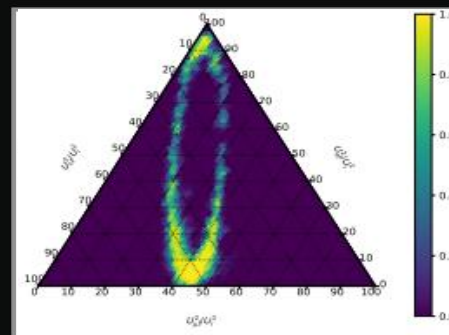
vect., ferm. HP DM  
1808.10465 / EPJC



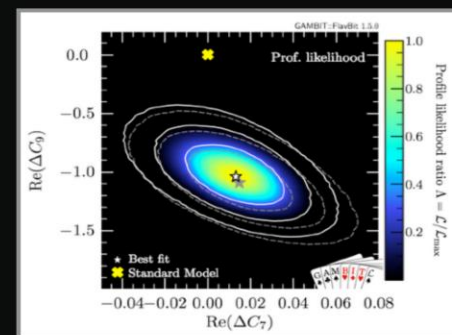
EWMSSM  
1809.02097 / EPJC



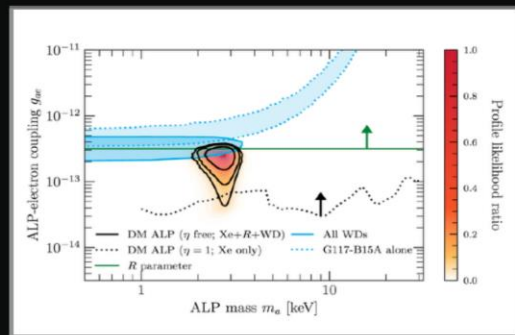
axion-like particles  
1810.07192 / JHEP



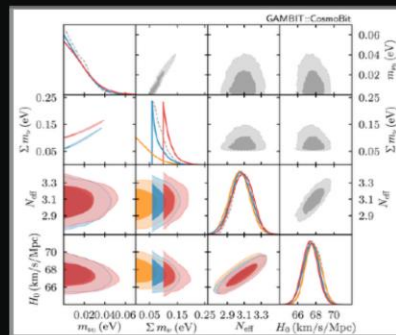
right-handed neut.s  
1908.02302 / EPJC



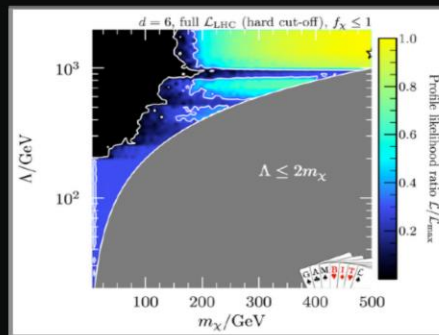
flavor EFT 2006.03489  
/ EPJC



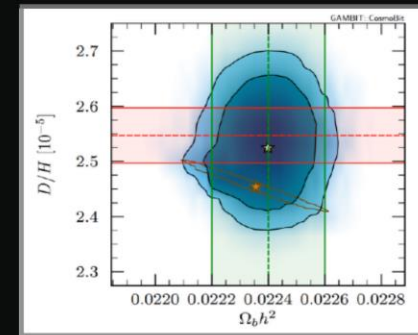
ALPs@XENON1T  
2007.05517 / JHEP



$m_\nu$  & cosmo  
2009.03287 / PRD



dark matter EFTs  
2106.02056 / EPJC



cosmo ALPs  
2205.13549



# GAMBIT dark matter related results

## EFTs

SM + scalar, fermion, vector singlet

EPJ C77 (2017) 8 568 arXiv:1705.07931

EPJ C78 (2018) 10 830 arXiv:1806.11281

EPJ C79 (2019) 1 38 arXiv:1808.10465

EPJ C81 (2021) 11 992 arXiv:2106.02056

arXiv:2209.13266

## axions, axion-like particles

QCD axion, DFSZ, KSVZ, generic ALP

JHEP 1903 (2019) 191 arXiv:1810.07192

JHEP 05 (2021) 159 arXiv:2007.05517

arXiv:2205.13549

## 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

## Neutrinos

RHN, SM

EPJ C80 (2020) 6 569 arXiv:1908.02302

PRD 103 (2021) 12 123508 arXiv:2009.03287

## Generic

modules, backends

EPJ C81 (2021) 12 1103 arXiv:2107.00030

JCAP 02 (2021) 022 arXiv:2009.03286



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EW-MSSM + light gravitino

## Neutrinos

RHN, SM

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PRD 103 (2021) 12 123508 arXiv:2009.03287

## Generic

modules, backends

JCAP 02 (2021) 022 arXiv:2009.03286

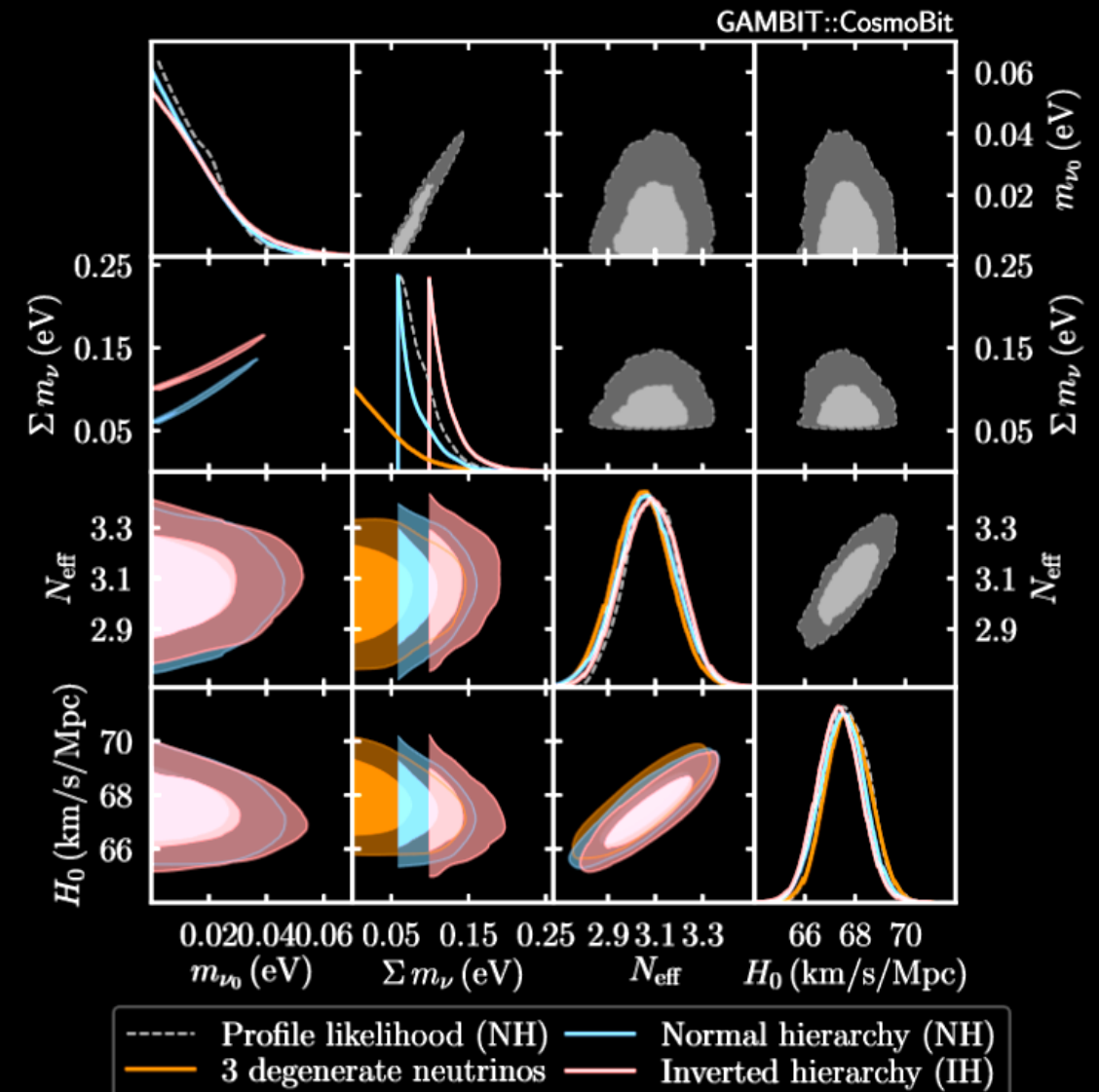
EPJ C81 (2021) 12 1103 arXiv:2107.00030



# 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
- first combined particle physics/cosmology global fit
- $m_\nu < 0.037$  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)

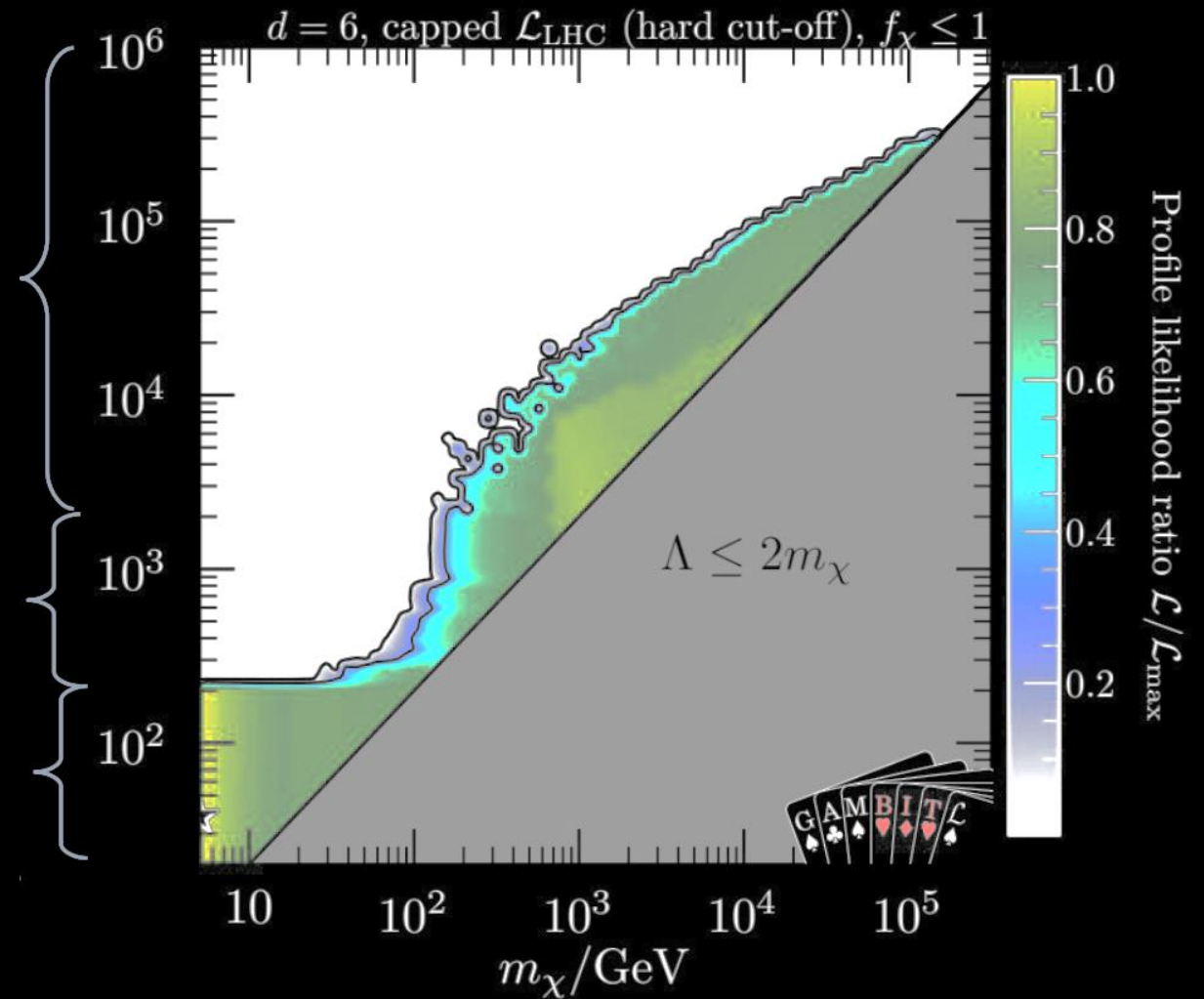


# thermal WIMPs and the scale of new physics

2106.02056

new physics scale  $\Lambda$ :

- EFT valid for all constraints  
most experiments are insensitive  
constraints driven by relic density
- $\Lambda$  comparable to LHC energies  
strong LHC constraints
- $\Lambda$  below LHC energies  
large viable parameter space

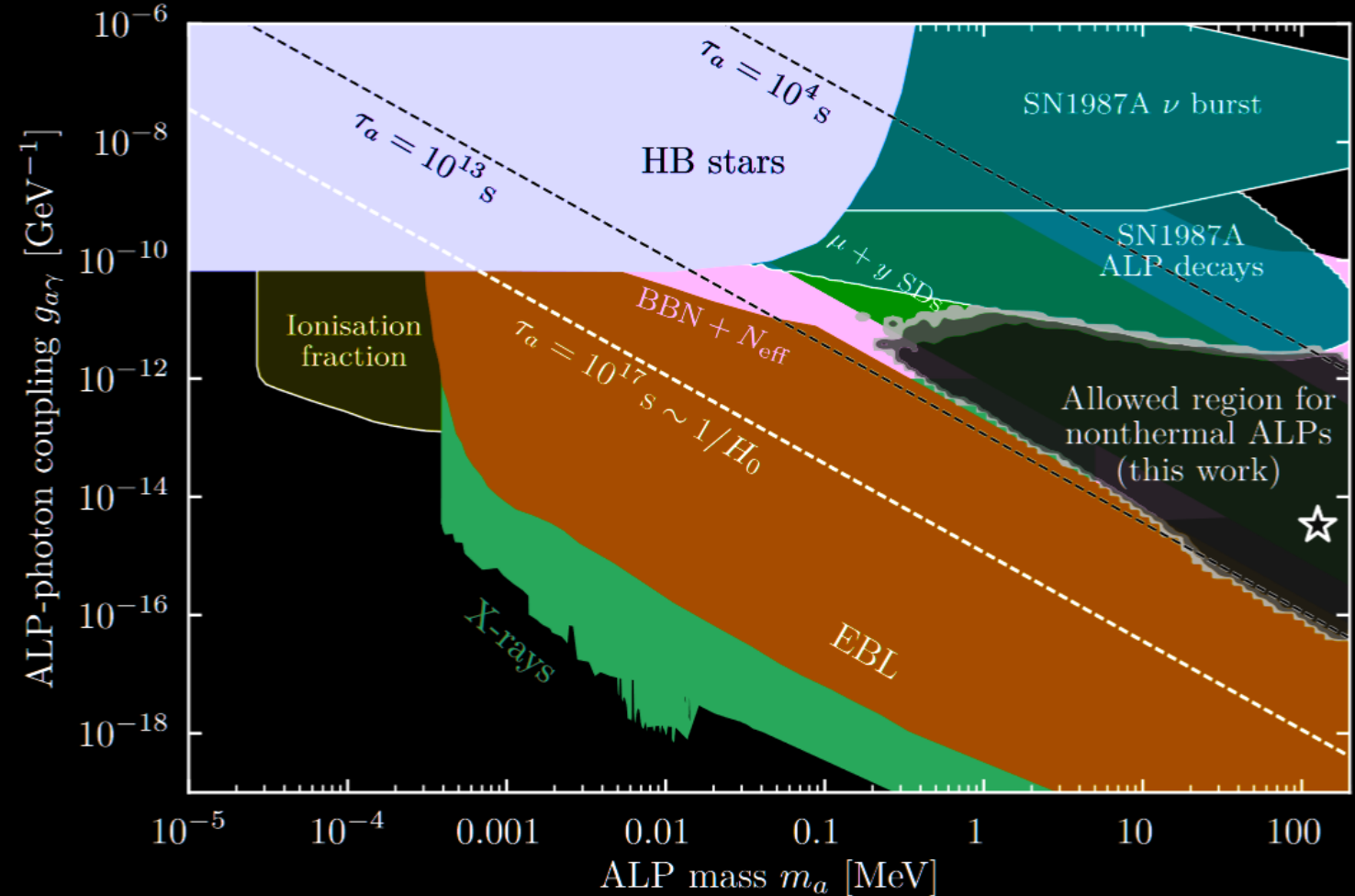




# cosmological constraints on decaying ALPs

arXiv:2205.13549

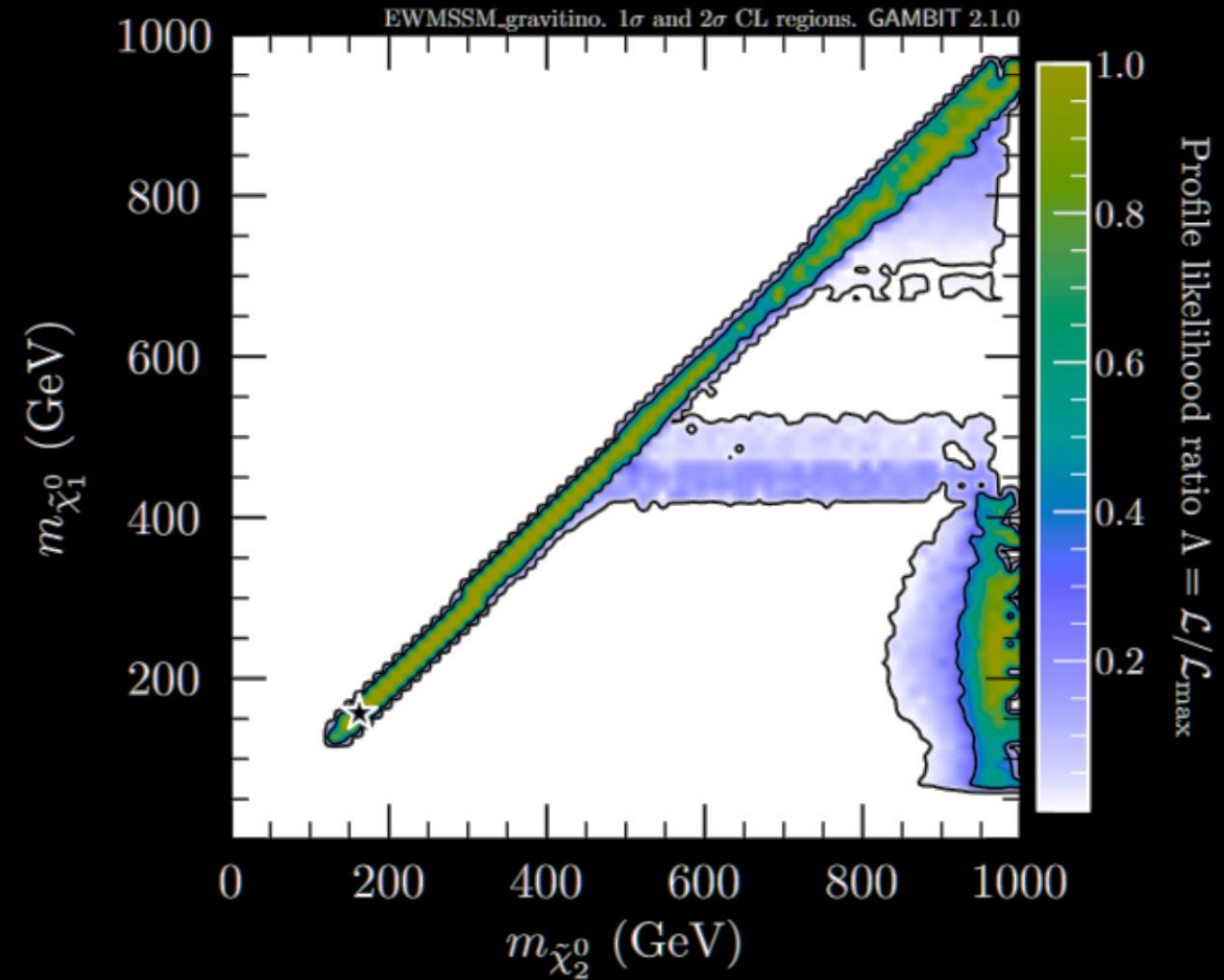
- cosmo constraints: CMB anisotropies & spectral distortions, BBN abundances,  $\Delta N_{\text{eff}}$  (photon injection), BAO (struct. form.)
- astro constraints: SN1987A, HB vs RGB star counts (stellar evolution, cooling), type-Ia SNe, extragalactic bg. light (EBL), X-ray searches
- some non-thermal,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



# collider constraints on electroweakinos + a light gravitino

to appear soon

- gravitino is LSP
- the only light particles in reach of LHC are 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



public results available on  
zenodo.cern.ch

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

links at [gambit.hepforge.org/pubs](http://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 record contain data for the CMSSM, NUHM1 and NUHM2 models considered in the GAMBIT "Round 1" GUT-scale SUSY paper. For each 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 dark matter, 2HDMs (incl. inert doublet), dark matter direct detection, neutrinos, axions, leptoquarks...
- new web-site with highly improved doco <https://gambitbsm.github.io>
- getting long-haired fluffy white cat and taking over the world...



# summary

- global fitting maps the maze and paves the way to discoveries
- GAMBIT is an open source, flexible, modular global fitting framework
- GUM significantly enhances the capabilities of GAMBIT 2.0
- GAMBIT version 2.3 is out <https://github.com/GambitBSM>
- over a dozen physics papers since 2017 and many more to come
- stay tuned for much more...





backup slides

# 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

Why?

various new discoveries historically were heralded by global fits

global fits indicated e.g. mass of top quark, Higgs boson before discovery

global fitting might provide us with valuable precursors for dark matter





# GAMBIT

overview

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?

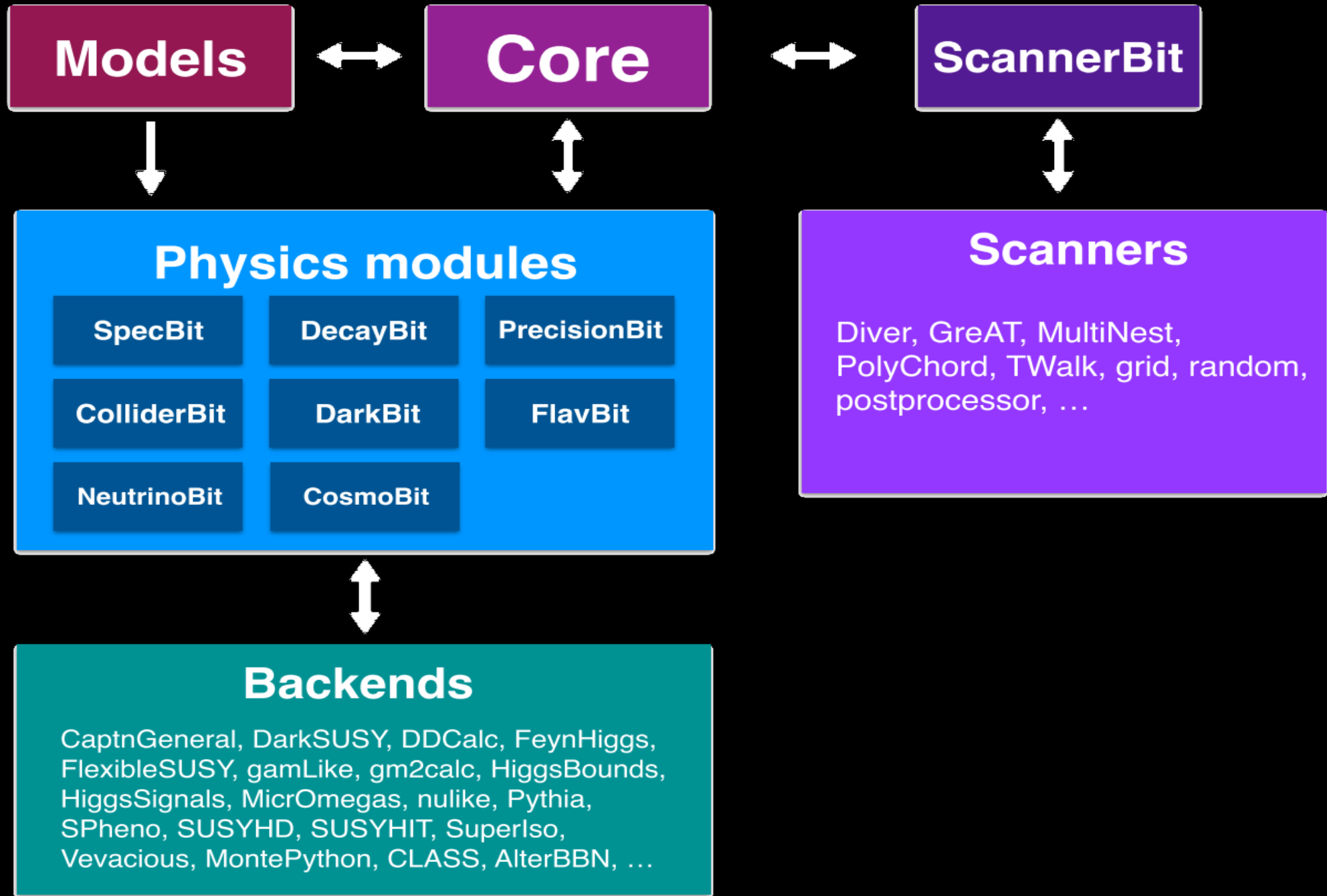
## main steps

- establish model hierarchy
- Lagrangian  $\rightarrow$  spectrum
- spectrum  $\rightarrow$  observables
- parameter space sampling
- statistical treatment

## main challenges

- 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”



**Physics modules**

SpecBit	DecayBit	PrecisionBit
ColliderBit	DarkBit	FlavBit
NeutrinoBit	CosmoBit	

**Scanners**

Diver, GreAT, MultiNest, PolyChord, TWalk, grid, random, postprocessor, ...

**Backends**

CaptnGeneral, DarkSUSY, DDCalc, FeynHiggs, FlexibleSUSY, gamLike, gm2calc, HiggsBounds, HiggsSignals, MicrOmegas, nulyke, Pythia, SPheno, SUSYHD, SUSYHIT, SuperIso, Vevacious, MontePython, CLASS, AlterBBN, ...



# Models

hierarchical model database

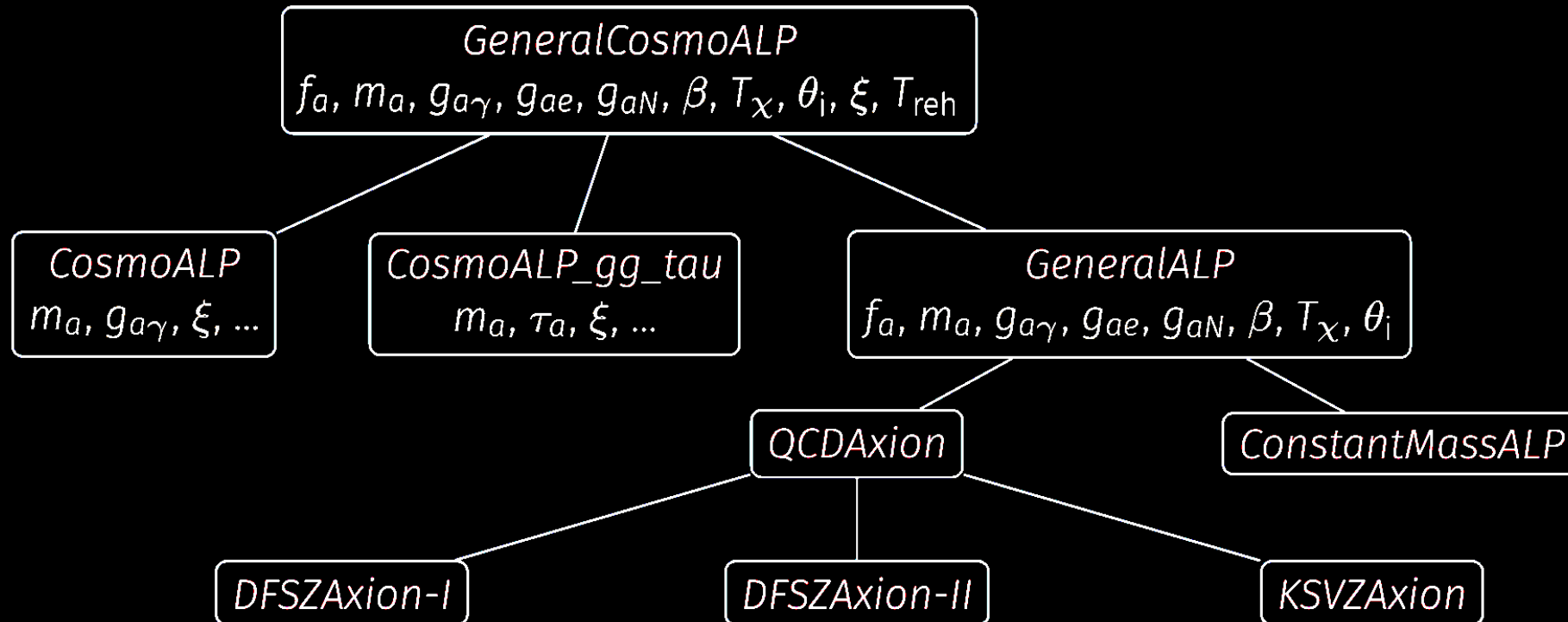
- models defined by their parameters and relations to each other
- models can inherit from (be subspaces of) parent models
- child models can be automatically translated to ancestor models
- database examples:
  - standard model
  - nuclear uncertainties
  - two-Higgs doublet models
  - Higgs portal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



# Models

model database examples

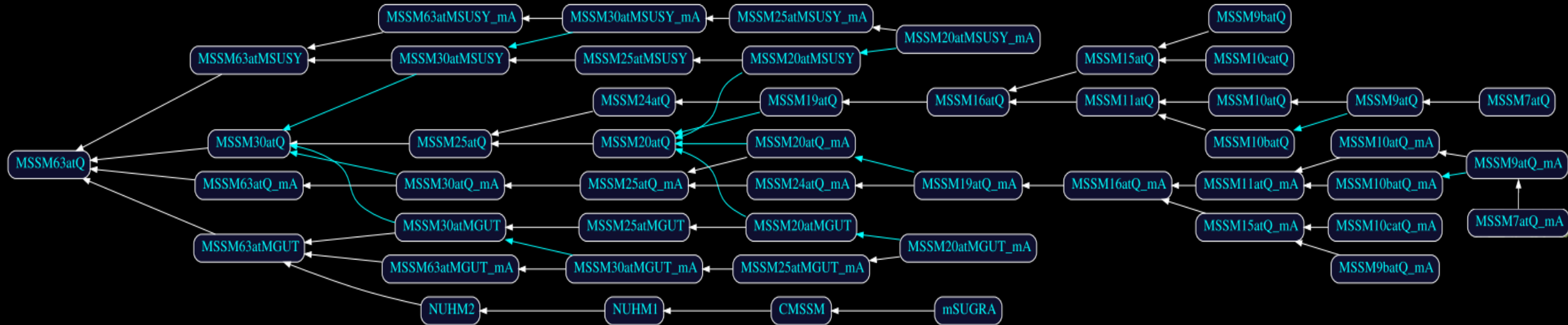
- axions and ALPs



# Models

model database examples

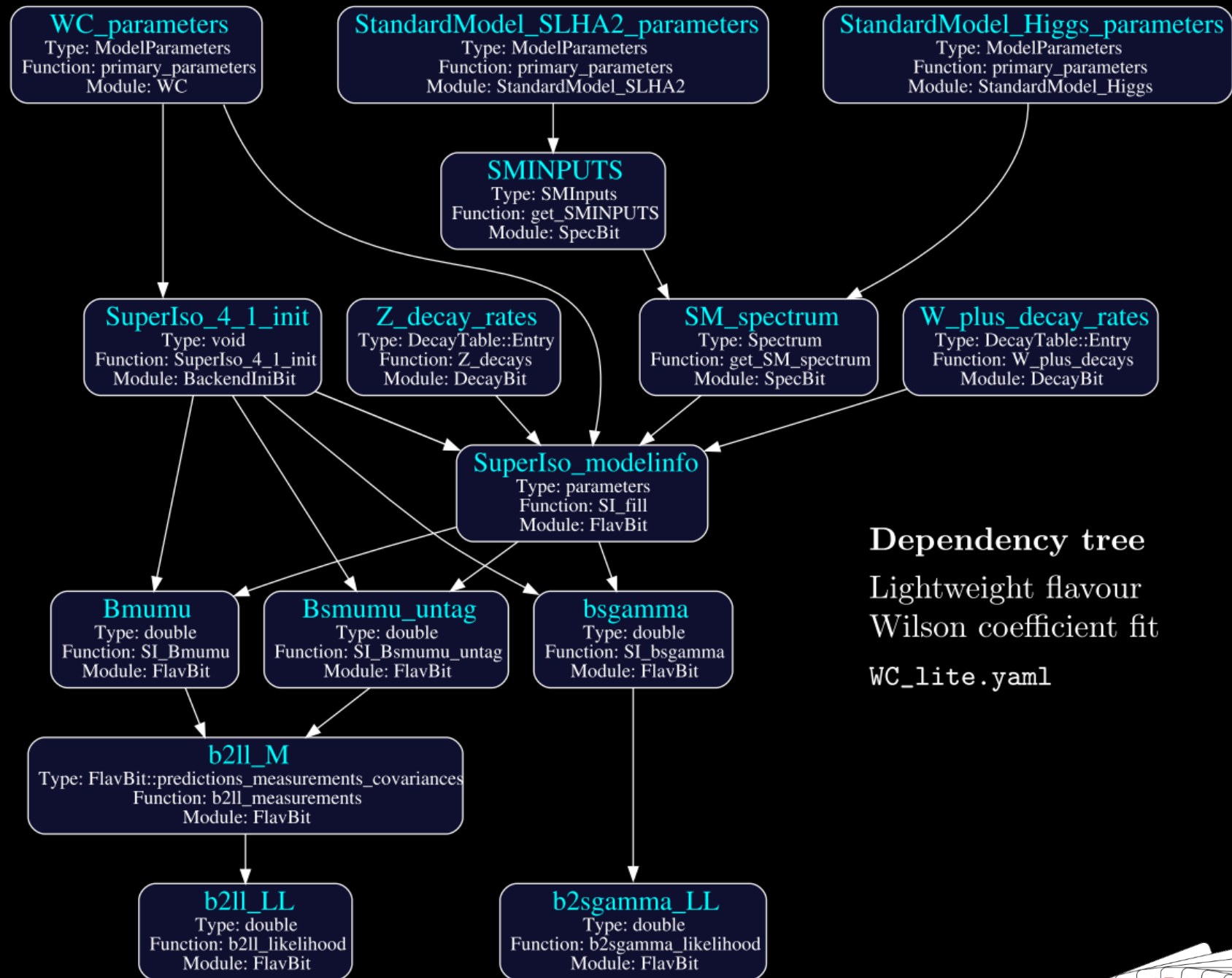
- MSSM



# 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

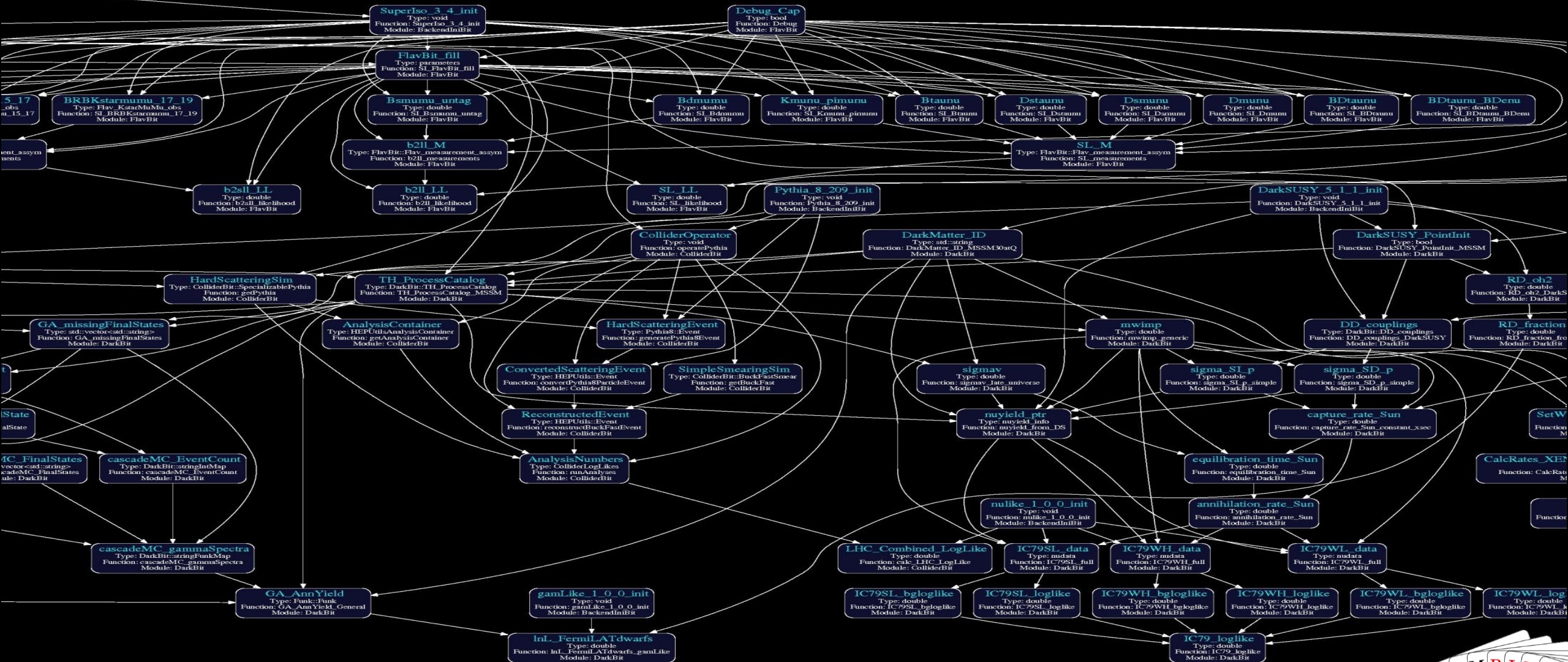


Dependency tree  
Lightweight flavour  
Wilson coefficient fit  
WC\_lite.yaml



# Dependency resolution

for CMSSM



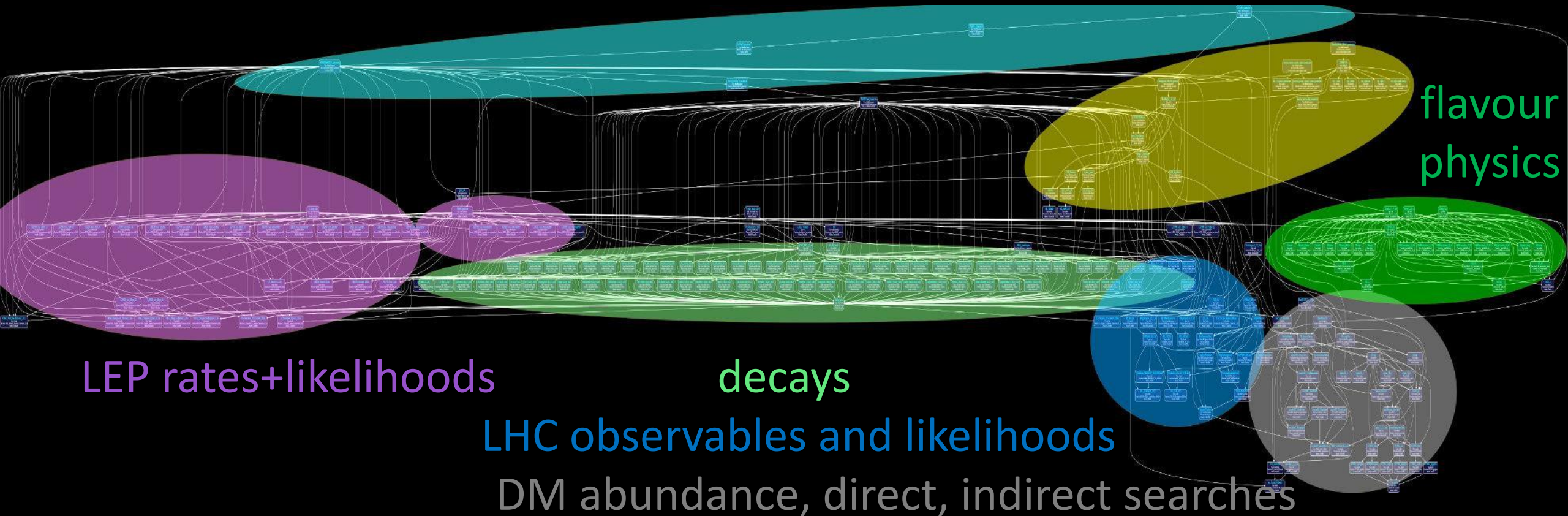


# Dependency resolution

for CMSSM

model parameter translations

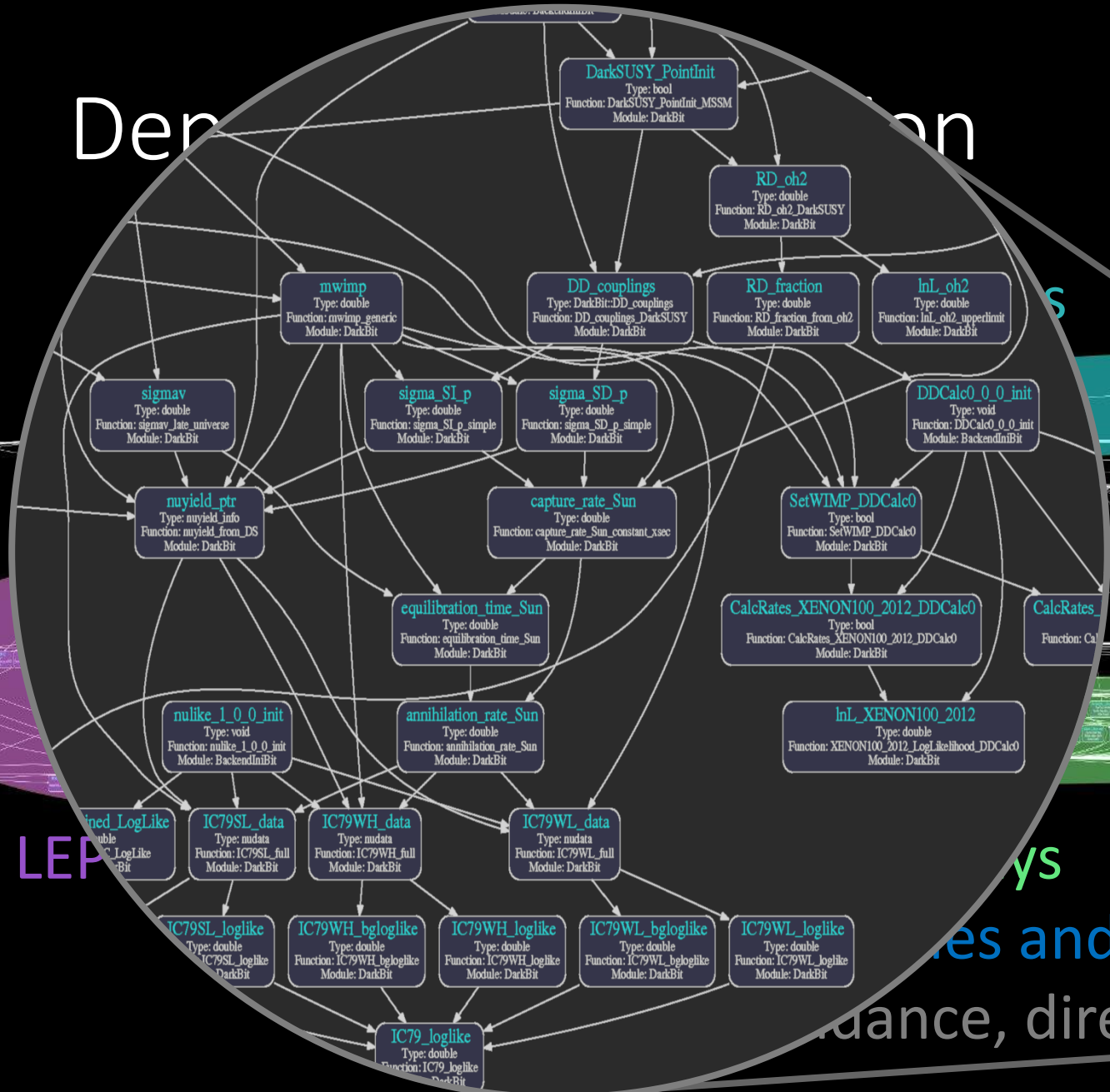
precision calculations



Der

on

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



for CMSSM precision calculations

flavor physics

LEP

ys

es and likelihoods

ance, direct, indirect searches



# getting started

- clone git repo [github.com/GambitBSM](https://github.com/GambitBSM) or
- download tarballs <https://gambit.hepforge.org/source> or
- get pre-compiled version docker
- see quick start guides in [arXiv:1705.07908](https://arxiv.org/abs/1705.07908) and [arXiv:2107.00030](https://arxiv.org/abs/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.



# 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)



# 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:

$$\mathcal{L}_\chi = \bar{\chi} (i\not{\partial} - m_\chi) \chi + \sum_{a,d} \frac{C_a^{(d)}}{\Lambda^{d-4}} Q_a^{(d)}$$



# Dark matter effective field theory arXiv:2106.02056

$$\mathcal{L}_\chi = \bar{\chi} (i\not{\partial} - m_\chi) \chi + \sum_{a,d} \frac{C_a^{(d)}}{\Lambda^{d-4}} Q_a^{(d)}$$

Direct detection signals:

Spin-independent – not suppressed

Spin-independent – suppressed

Spin-dependent – not suppressed

Spin-dependent – suppressed

$$Q_{1,q}^{(6)} = (\bar{\chi} \gamma_\mu \chi) (\bar{q} \gamma^\mu q)$$

$$Q_{2,q}^{(6)} = (\bar{\chi} \gamma_\mu \gamma_5 \chi) (\bar{q} \gamma^\mu q)$$

$$Q_{3,q}^{(6)} = (\bar{\chi} \gamma_\mu \chi) (\bar{q} \gamma^\mu \gamma_5 q)$$

$$Q_{4,q}^{(6)} = (\bar{\chi} \gamma_\mu \gamma_5 \chi) (\bar{q} \gamma^\mu \gamma_5 q)$$

$$Q_1^{(7)} = \frac{\alpha_s}{12\pi} (\bar{\chi} \chi) G^{a\mu\nu} G_{\mu\nu}^a$$

$$Q_2^{(7)} = \frac{\alpha_s}{12\pi} (\bar{\chi} i \gamma_5 \chi) G^{a\mu\nu} G_{\mu\nu}^a$$

$$Q_3^{(7)} = \frac{\alpha_s}{8\pi} (\bar{\chi} \chi) G^{a\mu\nu} \tilde{G}_{\mu\nu}^a$$

$$Q_4^{(7)} = \frac{\alpha_s}{8\pi} (\bar{\chi} i \gamma_5 \chi) G^{a\mu\nu} \tilde{G}_{\mu\nu}^a$$

$$Q_{5,q}^{(7)} = m_q (\bar{\chi} \chi) (\bar{q} q)$$

$$Q_{6,q}^{(7)} = m_q (\bar{\chi} i \gamma_5 \chi) (\bar{q} q)$$

$$Q_{7,q}^{(7)} = m_q (\bar{\chi} \chi) (\bar{q} i \gamma_5 q)$$

$$Q_{8,q}^{(7)} = m_q (\bar{\chi} i \gamma_5 \chi) (\bar{q} i \gamma_5 q)$$

$$Q_{9,q}^{(7)} = m_q (\bar{\chi} \sigma^{\mu\nu} \chi) (\bar{q} \sigma_{\mu\nu} q)$$

$$Q_{10,q}^{(7)} = m_q (\bar{\chi} i \sigma^{\mu\nu} \gamma_5 \chi) (\bar{q} \sigma_{\mu\nu} q)$$





# EFT validity

arXiv:2106.02056

- the scale of new physics  $\Lambda$  is an independent parameter
- relic density calculation requires  $\Lambda > 2m_\chi$
- if  $\Lambda >$  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*  $E_T > \Lambda$



# Other key innovations

arXiv:2106.02056

- direct detection
  - DirectDM: fully automated RG evolution from  $\Lambda$  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



# Other key innovations

arXiv:2106.02056

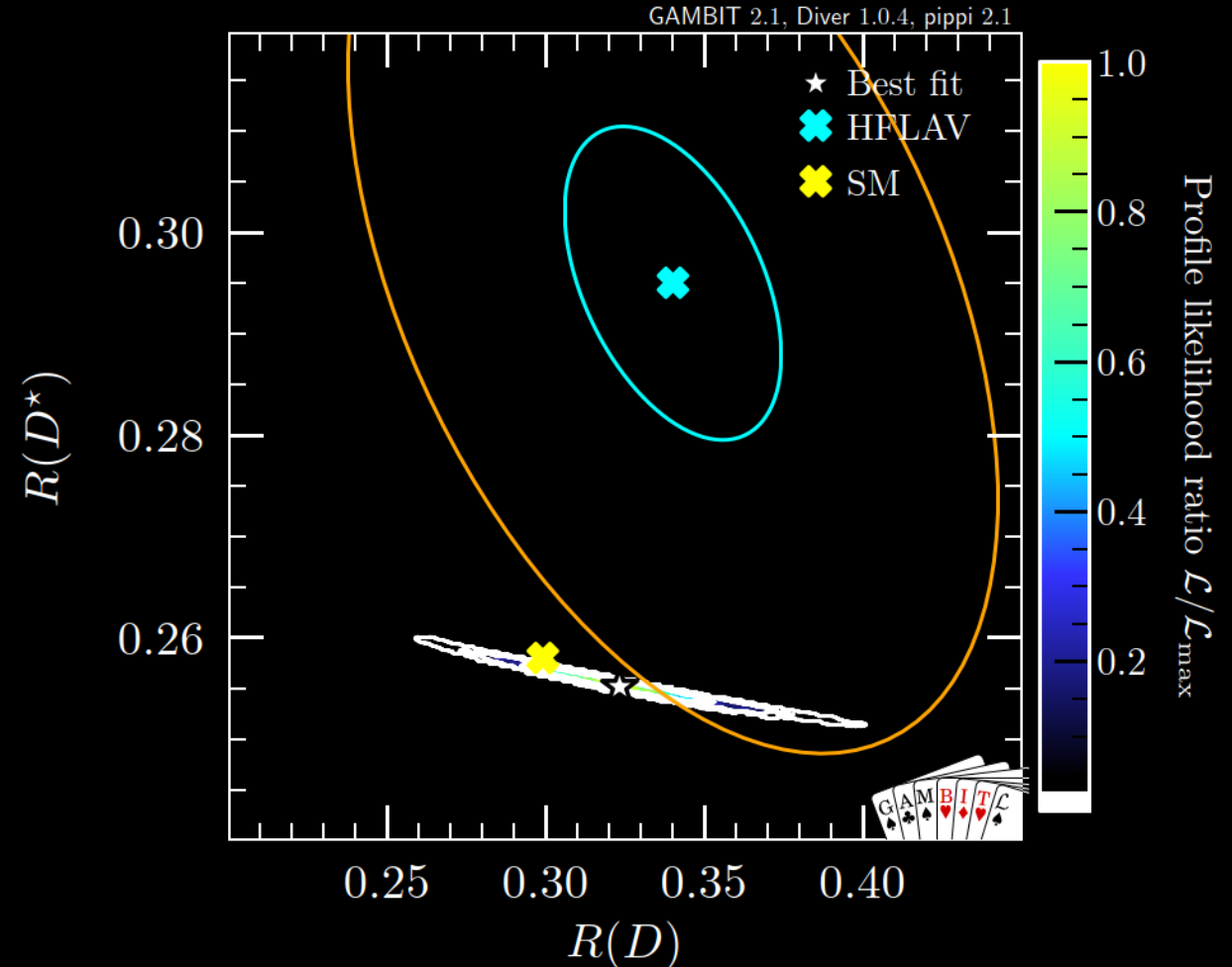
- indirect detection
  - DarkSUSY: highly accurate relic density calculation
  - GUM: automated calculation of cross sections and  $\gamma$ -ray spectra
  - CosmoBit: CMB constraints on energy injection from DM annihilation
  - Capt'n General: solar capture + neutrinos with arbitrary DM-nucleon interactions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



# general two-Higgs doublet model flavor fit

2111.10464

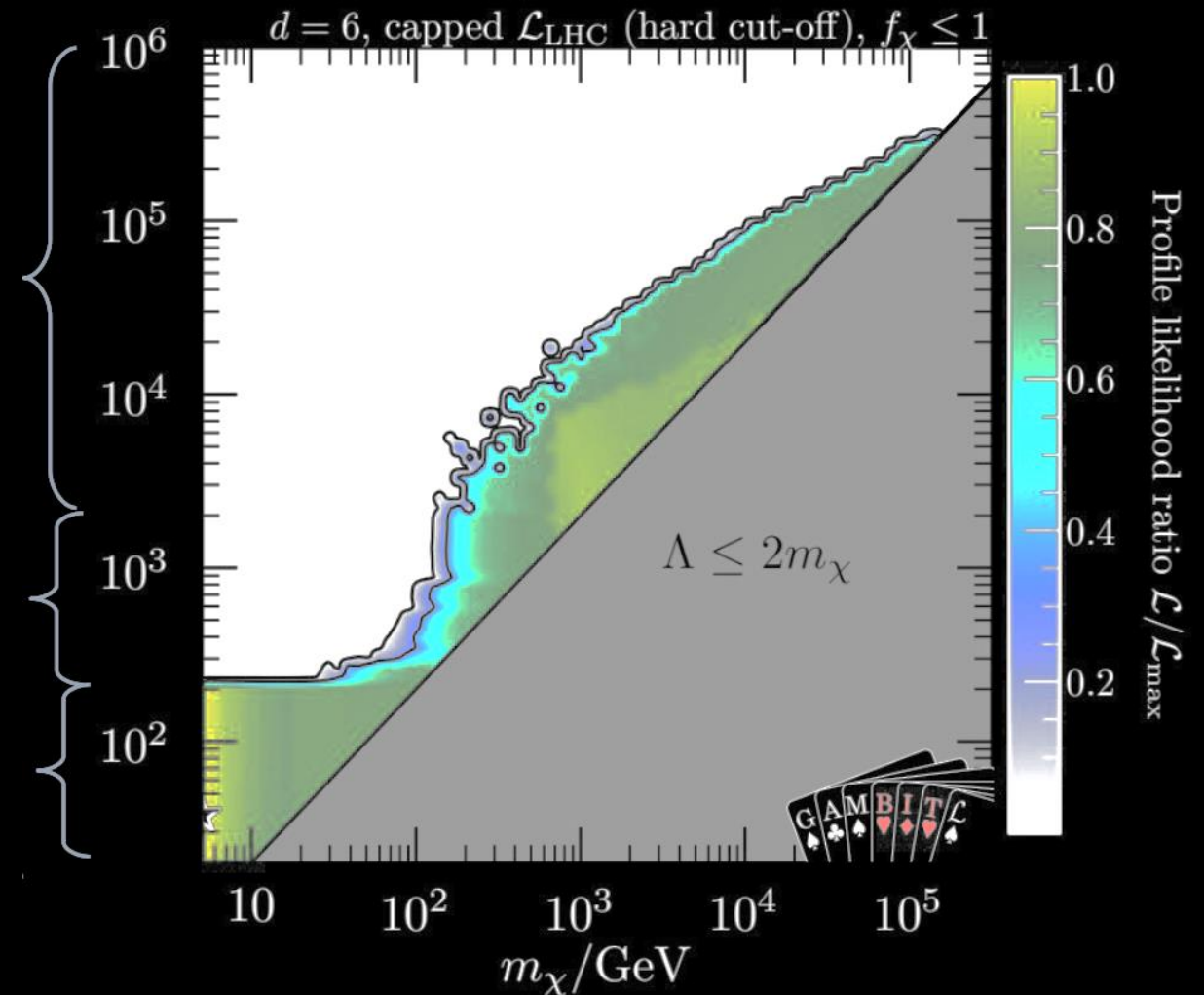
- the 2HDM explains  $b \rightarrow s \mu^+ \mu^-$
- it can simultaneously fit the experimental values of the  $R(D)$  charged current ratio at  $1\sigma$
- but it can not accommodate the  $D^*$  charmed meson observables  $R(D^*)$  and  $FL(D^*)$
- muon  $g - 2$  and charged anomalies can be fit together,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



# DMEFT results

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

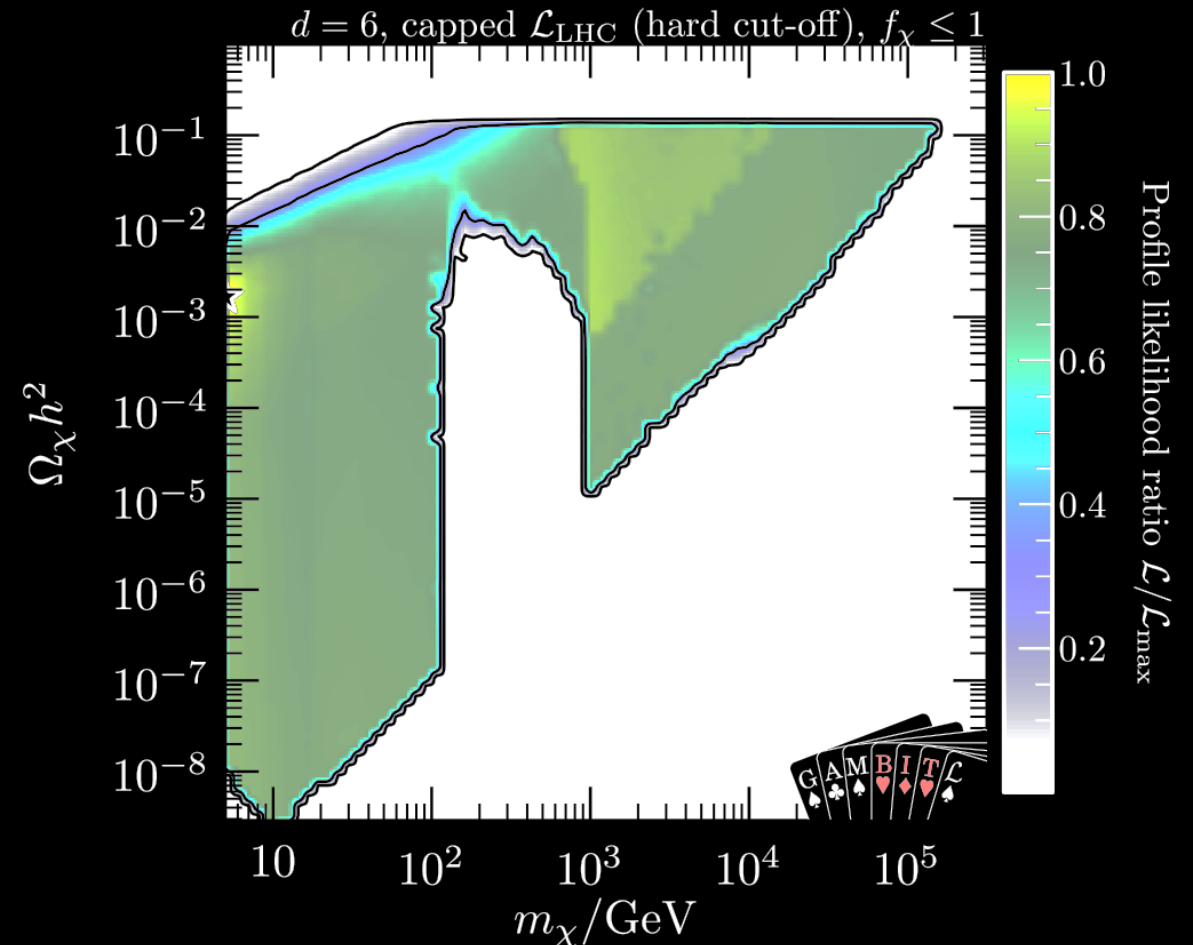
general picture



# DMEFT results

- light DM ( $m_\chi < 100$  GeV) is viable if both of the following hold:
  - $\chi$  has CP-violating interactions OR is very sub-dominant
  - $\Lambda$  is so low that EFT breaks down entirely at LHC  $\Rightarrow$  LHC would (probably) be sensitive to mediator
- significant to model building, suggests light WIMPs require light mediator (e.g. dark photon)

light DM particles



# DMEFT results

- demanding  $\chi$  to be all of DM pushes viable parameter space to large  $m_\chi$
- leads to detectable signals at LZ
- mostly due to loop-induced operator mixing  $Q(6)_{3,q} \rightarrow Q(6)_{1,q}$
- could be spoilt by including other effective operators (e.g. leptons, non-MFV)  $\Rightarrow$  interesting avenue for future investigation

heavy DM particles

