GAMBIT

an excerpted update

Csaba Balázs

for the GAMBIT Community

AIP 2022 Dec 13

outline

global fits

GAMBIT

main features

version 2.0

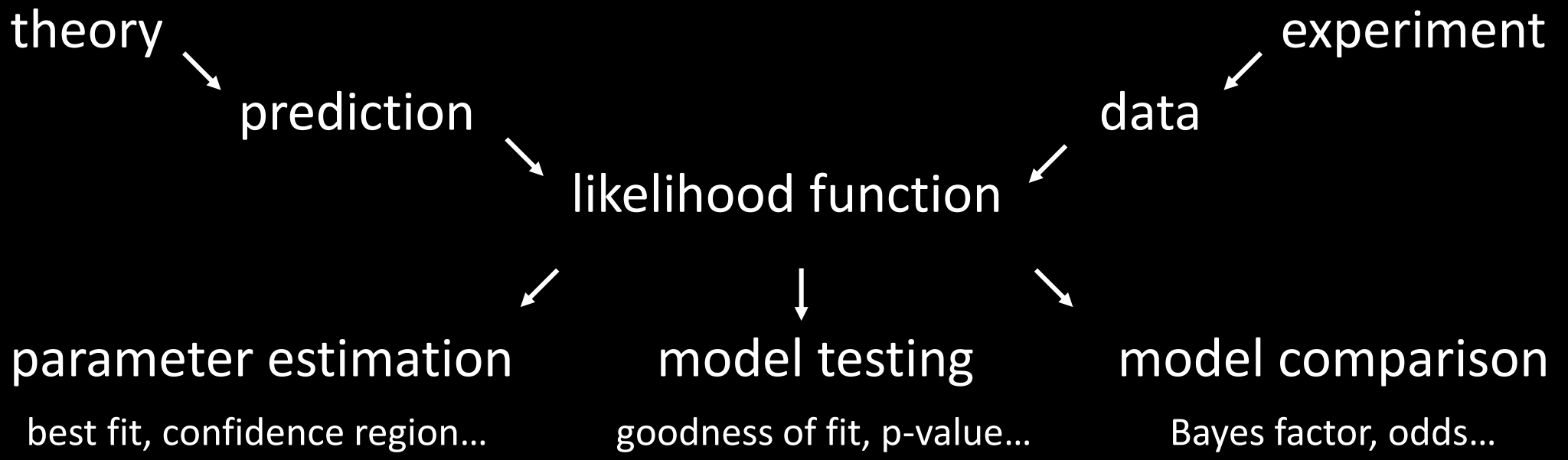
latest results

from M. Carena | Copyright: Screen Captures

particle pheno landscape 2022

global fitting simplified

finding the quickest
way through the maze



global fitting over simplified

finding the quickest
way through the maze

the idea of global fitting is simple, but it’s details can be complicated

GAMBIT: The Global And Modular BSM Inference Tool

gambit.hepforge.org github.com/GambitBSM EPJC 77 (2017) 784 arXiv:1705.07908

- Extensive model database, beyond SUSY
- Fast definition of new theories, datasets
- Extensive observable/data libraries
- Plug&play scanning/physics/likelihood packages
- Various statistical options (frequentist/Bayesian)
- Fast LHC likelihood calculator
- Massively parallel
- Fully open-source

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

Authors of: BubbleProfiler, Capt'n General, Contur, DarkAges, DarkSUSY, DDCalc, DirectDM, Diver, EasyScanHEP, ExoCLASS, FlexibleSUSY, gamLike, GM2Calc, HEPLike, IsaTools, MARTY, nuLike, PhaseTracer, PolyChord, Rivet, SOFTSUSY, Superlso, SUSY-AI, xsec, Vevacious, WIMPSim

Recent collaborators: P Athron, C Balázs, A Beniwal, S Bloor, T Bringmann, A Buckley, J-E 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, ++

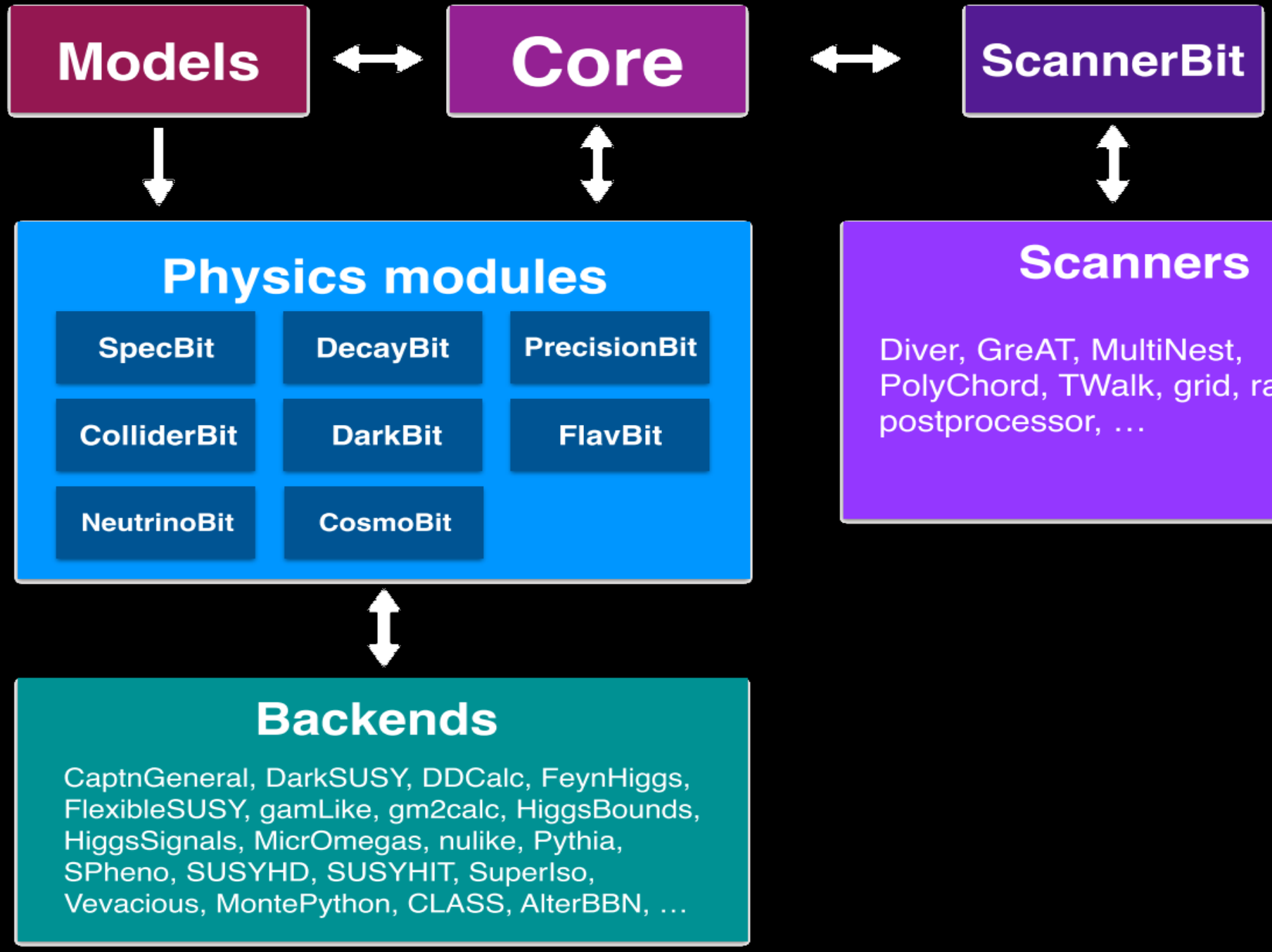
80+ participants in many experiments and numerous major theory codes

GAMBIT best features

global, modular, fast

- diverse BSM model database particle, nuclear, astrophysics, cosmology models
- many interfaced backends observable calculators (full list on later slide)
- built-in experimental likelihoods particle, nuclear, astrophysics, cosmology experiments
- composite likelihood consistent combination of searches, uncertainties, systematics, nuisances
- sampling algorithms for stat. inference MCMCs, T-walk, diff. evol., nested samplers…
- plug&play backends auto-download, configure, compile, dynamically link, dep. res., …
- auto dependency resolution ID functions, optimize execution order before run (!)
- dual-level parallel execution mixed-mode MPI+openMP, mostly auto, scale 10k+ cores
- all-in or module standalone modes easily implemented from single cmake script
- available as docker plugin https://gambit.hepforge.org/source

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 related to ancestor models
- database examples:
  - standard models of particle physics and cosmology
  - two-Higgs doublet models
  - Higgs portal dark matter models
  - simplified and effective field theory dark matter models
  - supersymmetric models (MSSM and daughters, NMSSM…)
  - dark matter halo models, nuclear uncert.s in DM direct detection
  - standard and right-handed neutrino models
  - axion, ALP models
  - and more…

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
- FlavBit: NP (SUSY…) 100s of flavor obs.s, rare decays… arXiv:1705.07933
- DecayBit: SM & NP (SUSY…) decay widths, BRs… arXiv:1705.07936
- 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

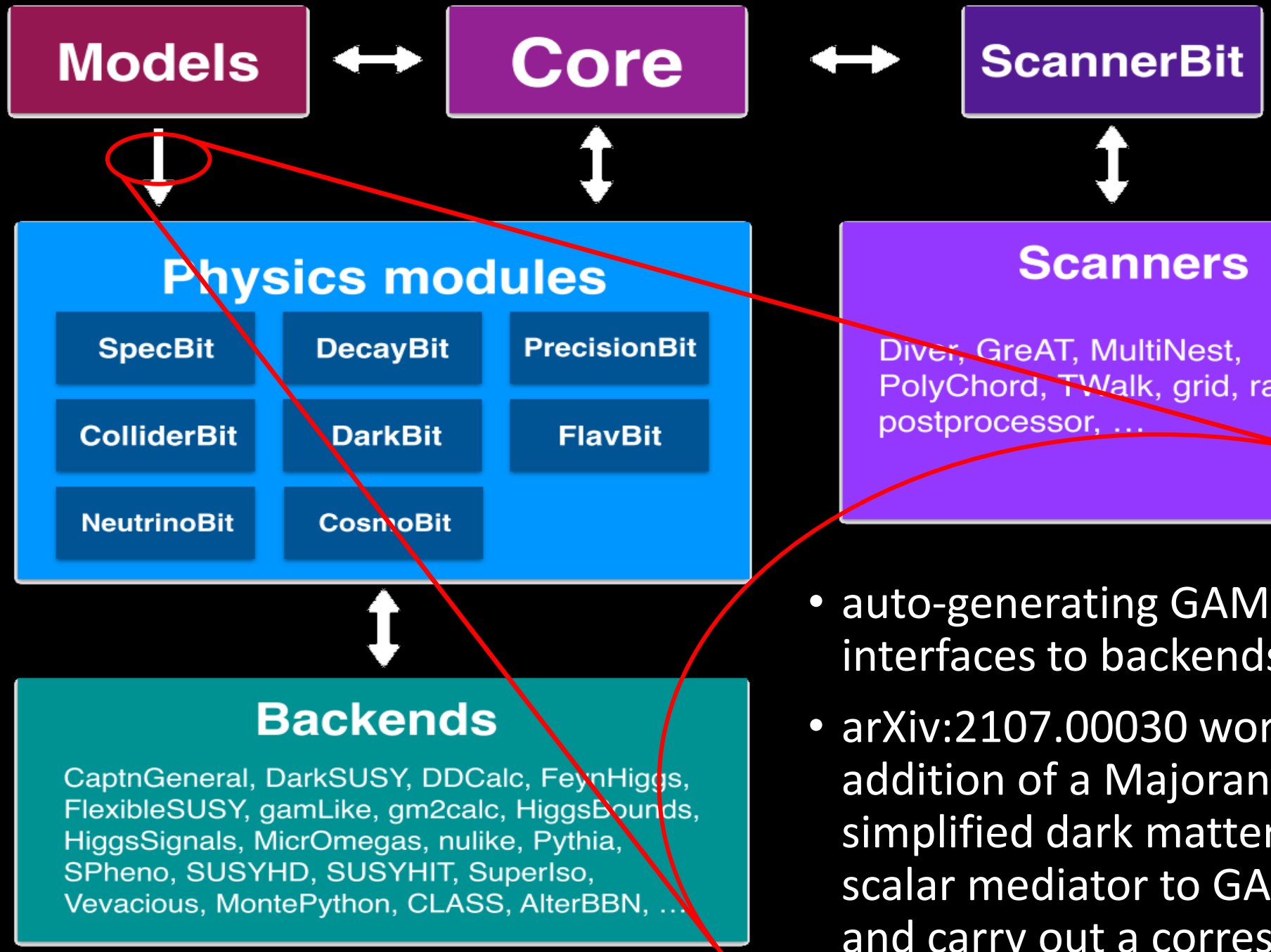
observable calculators for cosmology, astrophysics, collider, precision, flavor…

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

GAMBIT 2.0

GAMBIT Universal Model
from Lagrangian to likelihood

GAMBIT

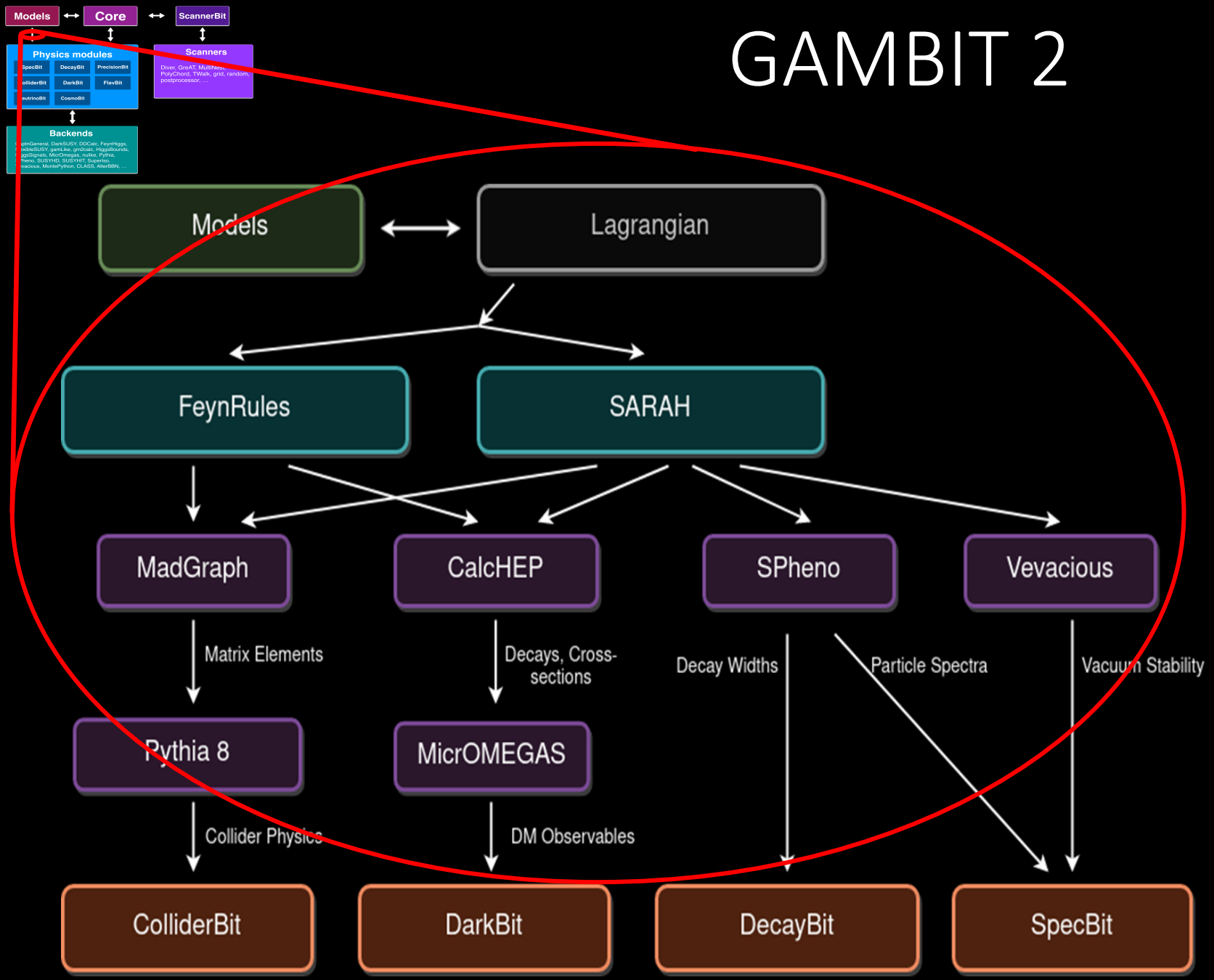


schematics

- auto-generating GAMBIT code and interfaces to backends
- arXiv:2107.00030 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 2

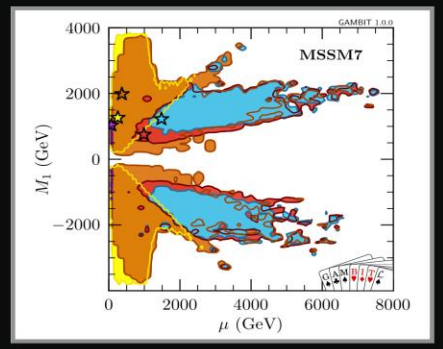
GUM schematics



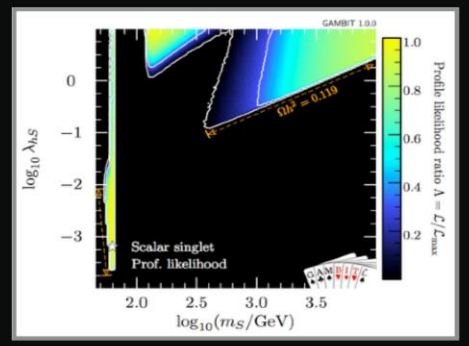
- from Lagrangian-level input use FeynRules, SARAH, MadGraph, CalcHEP to generate GAMBIT model, collider, dark matter, decay and spectrum code
- GUM also writes C++ GAMBIT interfaces to SPheno, micrOMEGAs, Pythia, Vevacious

GAMBIT

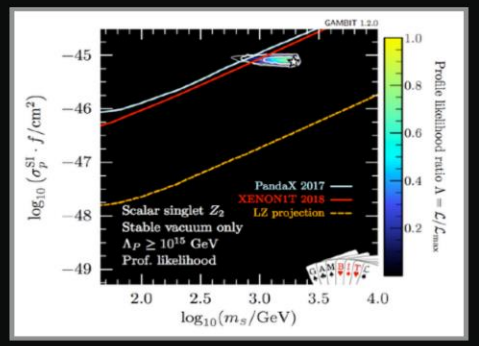
some results



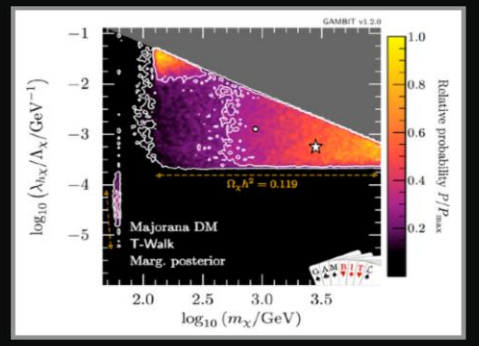
CMSSM 1705.07935/EPJC
MSSM7 1705.07917/EPJC



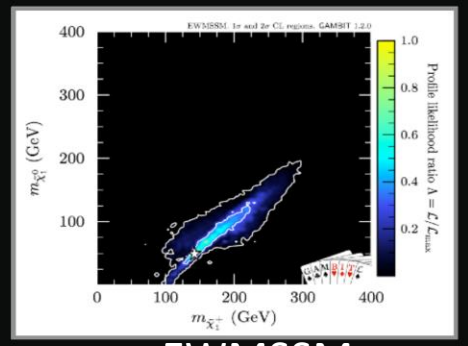
scalar H-portal DM
1705.07931 / EPJC



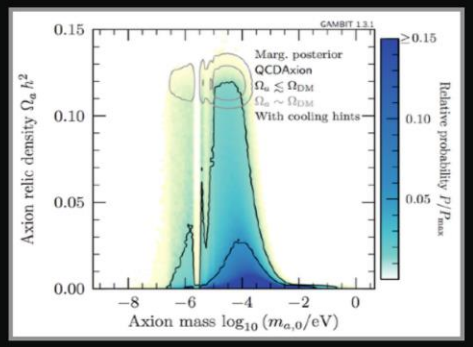
sc. HP DM vac. stab.
1806.11281 / EPJC



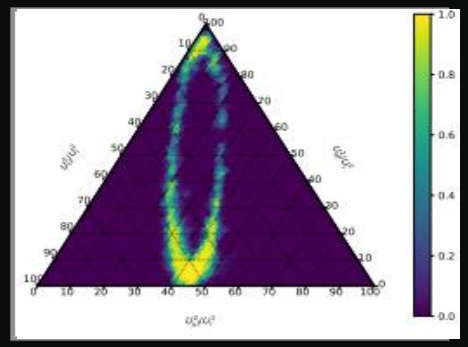
vect., ferm. HP DM
1808.10465 / EPJC



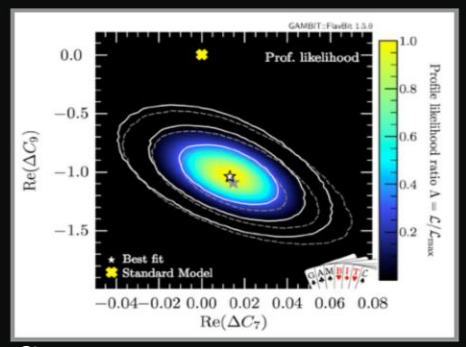
EWMSSM
1809.02097 / EPJC



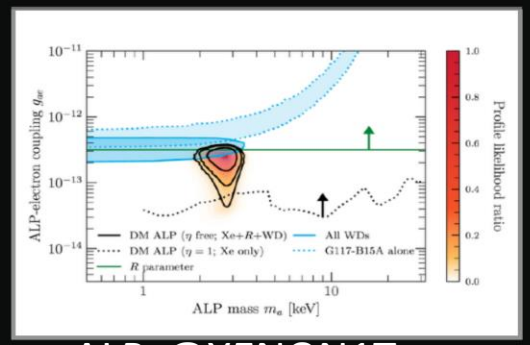
axion-like particles
1810.07192 / JHEP



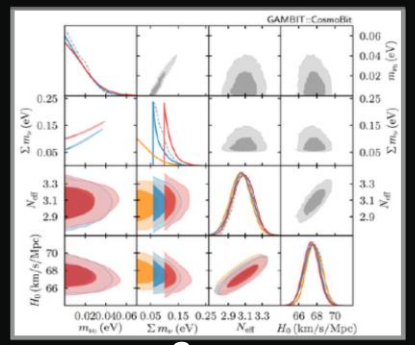
right-handed neut.s
1908.02302 / EPJC



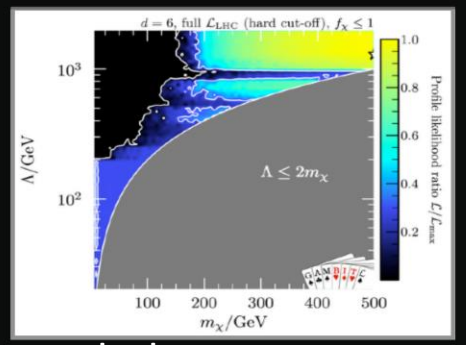
flavor EFT 2006.03489
/ EPJC



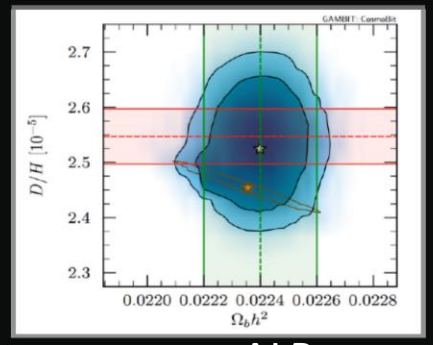
ALPs@XENON1T
2007.05517 / JHEP



m_ν & cosmo
2009.03287 / PRD



dark matter EFTs
2106.02056 / EPJC



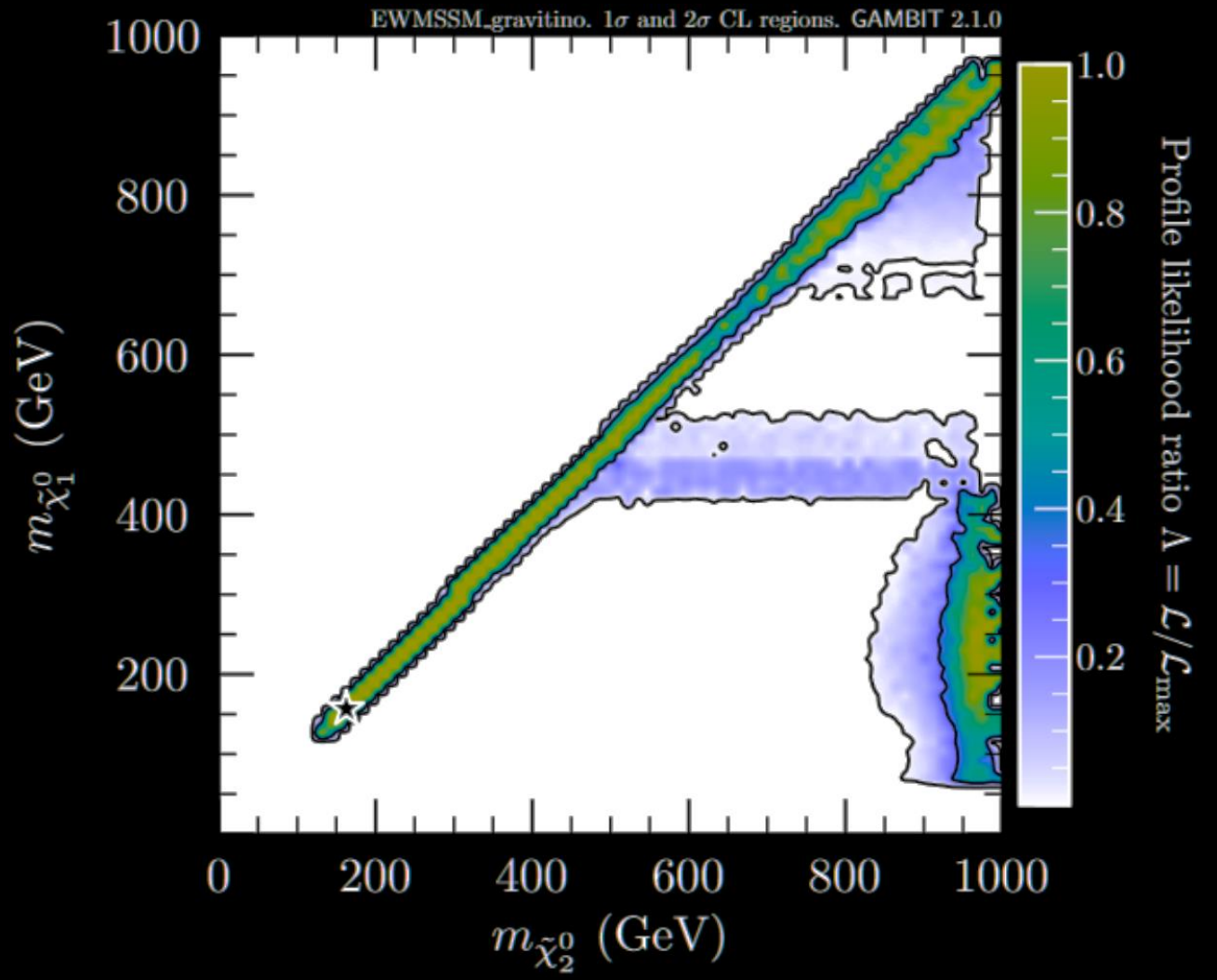
cosmo ALPs
2205.13549

from A. Kvellestad

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

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 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
- massively parallel

Community

80+members, 14 countries, 30+ institutes

a subset: 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…

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, Superlso, SUSY-AI, xsec, Vevacious, WIMPSim…

Community

subset

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

global fitting

How?

main steps

- establish model hierarchy
- Lagrangian → spectrum
- spectrum → 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”

GAMBIT

overview

open-source global fitting framework

modular and flexible architecture

models beyond the standard

sophisticated statistical inference

plug&play tools to calc observables

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

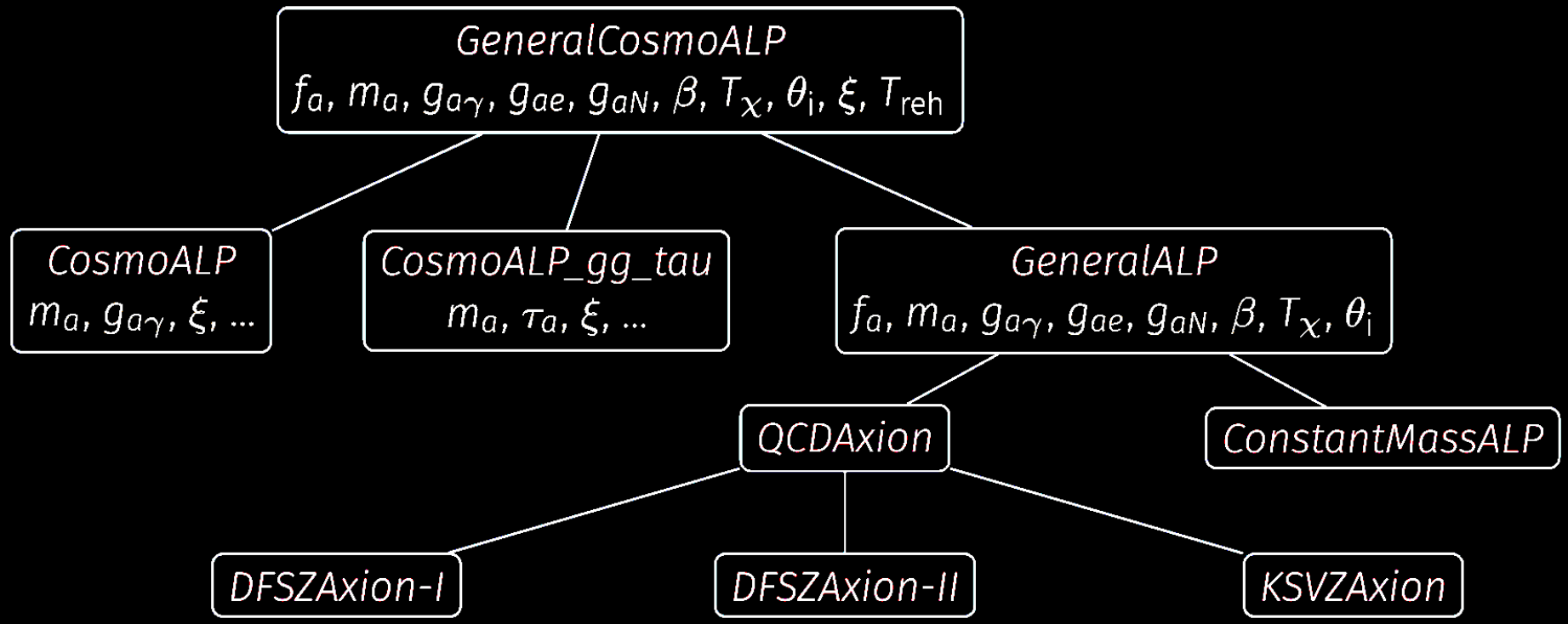
global and modular

- 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

Models

model database examples

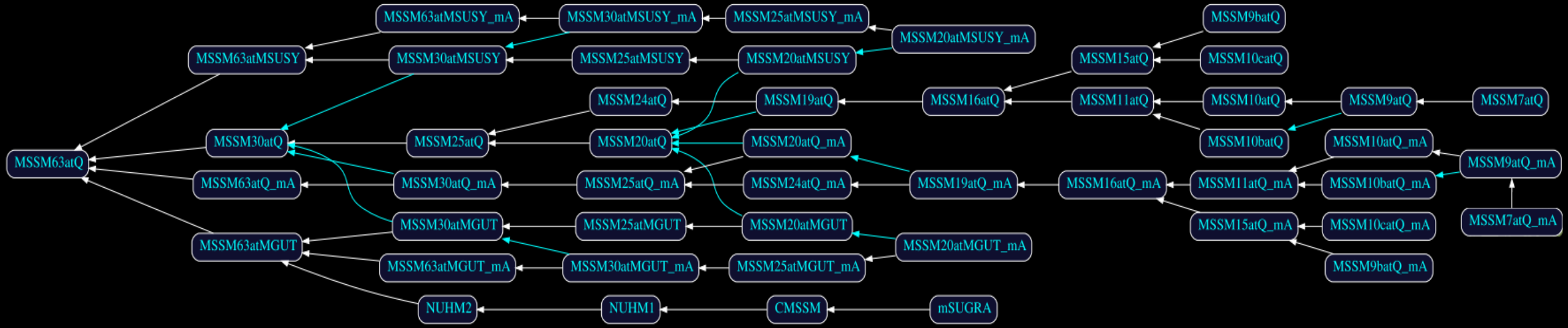
- axions and ALPs



Models

model database examples

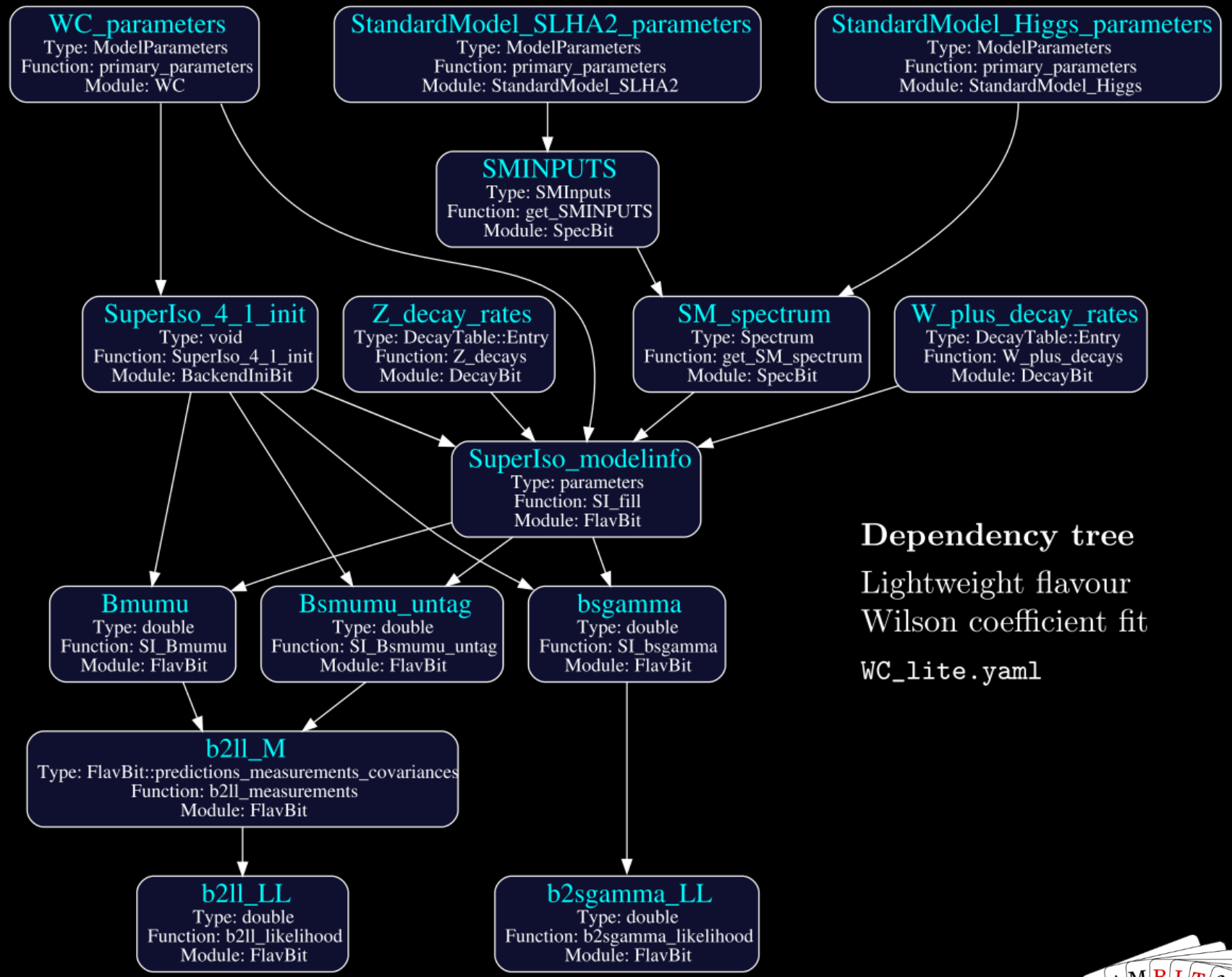
- MSSM



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



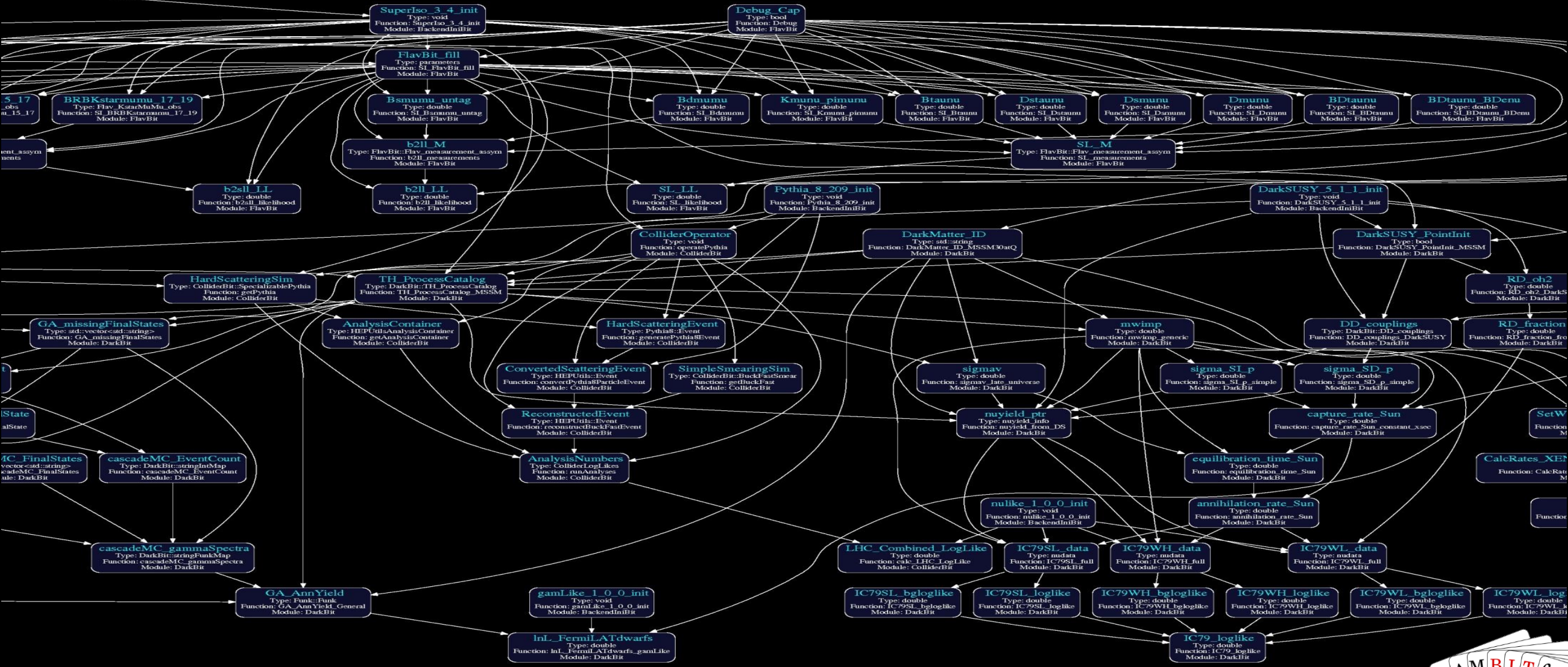
Dependency tree

Lightweight flavour Wilson coefficient fit

`WC_lite.yaml`

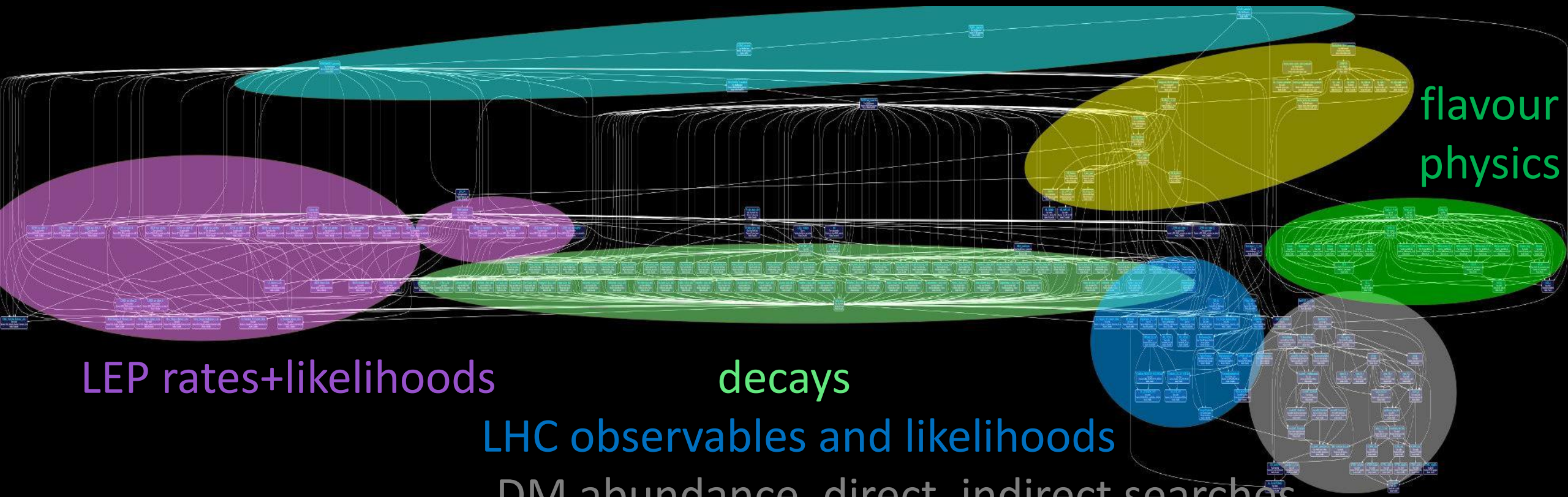
Dependency resolution

for CMSSM



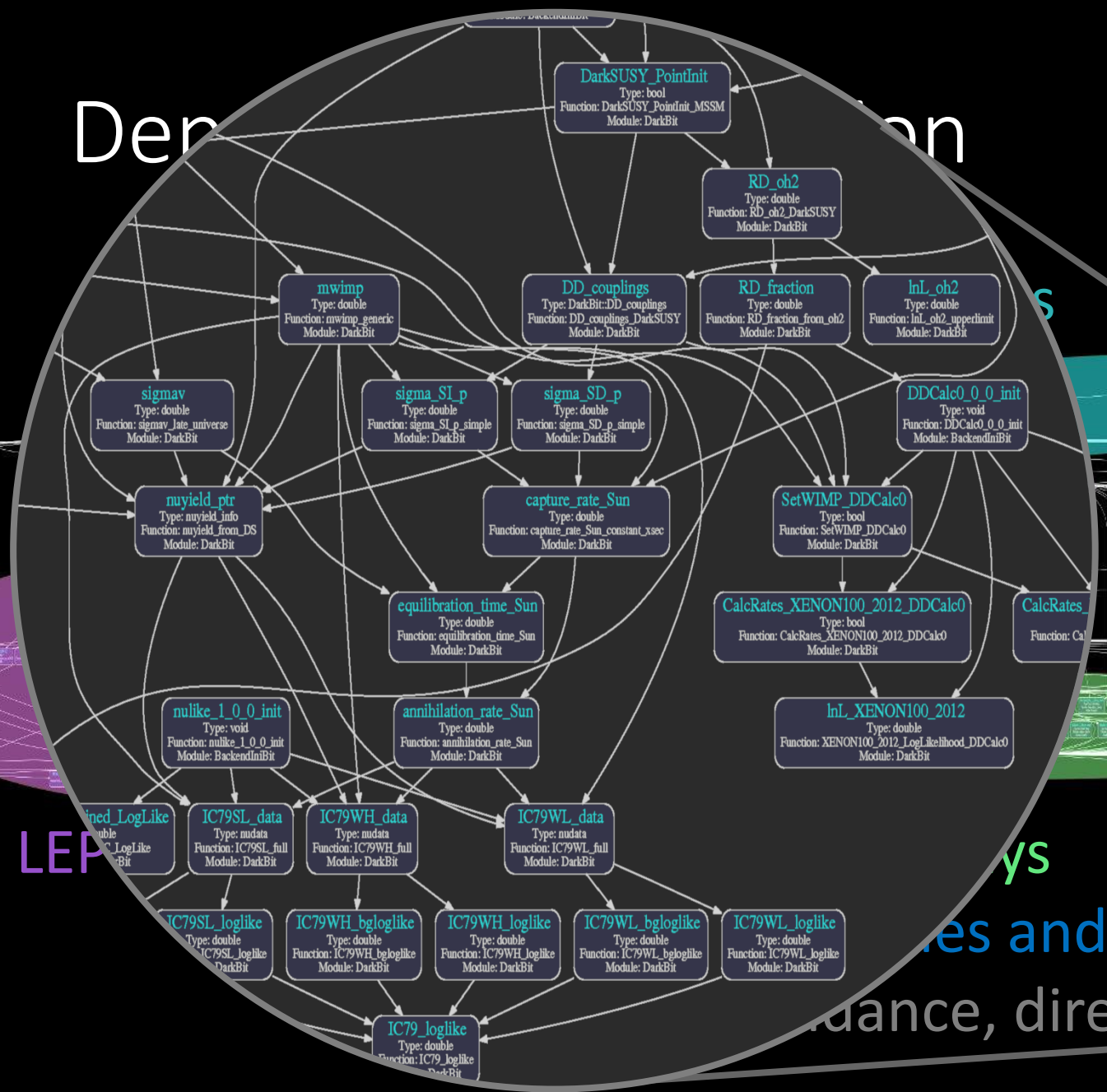
Dependency resolution

for CMSSM



Dep…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

dance, direct, indirect searches

getting started

- clone git repo github.com/GambitBSM 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 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

GAMBIT dark matter related results

EFTs

SM + scalar, fermion, vector singlet

EPJ C77 (2017) 8 568 arXiv:1705.07931

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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

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low-dim SUSY

MSSM-7, EW-MSSM weak scale BCs

EPJ C77 (2017) 12 879 arXiv:1705.07917

EPJ C79 (2019) 5 395 arXiv:1809.02097

EW-MSSM + light gravitino

Neutrinos

RHN, SM

EPJ C80 (2020) 6 569 arXiv:1908.02302

PRD 103 (2021) 12 123508 arXiv:2009.03287

Generic

modules, backends

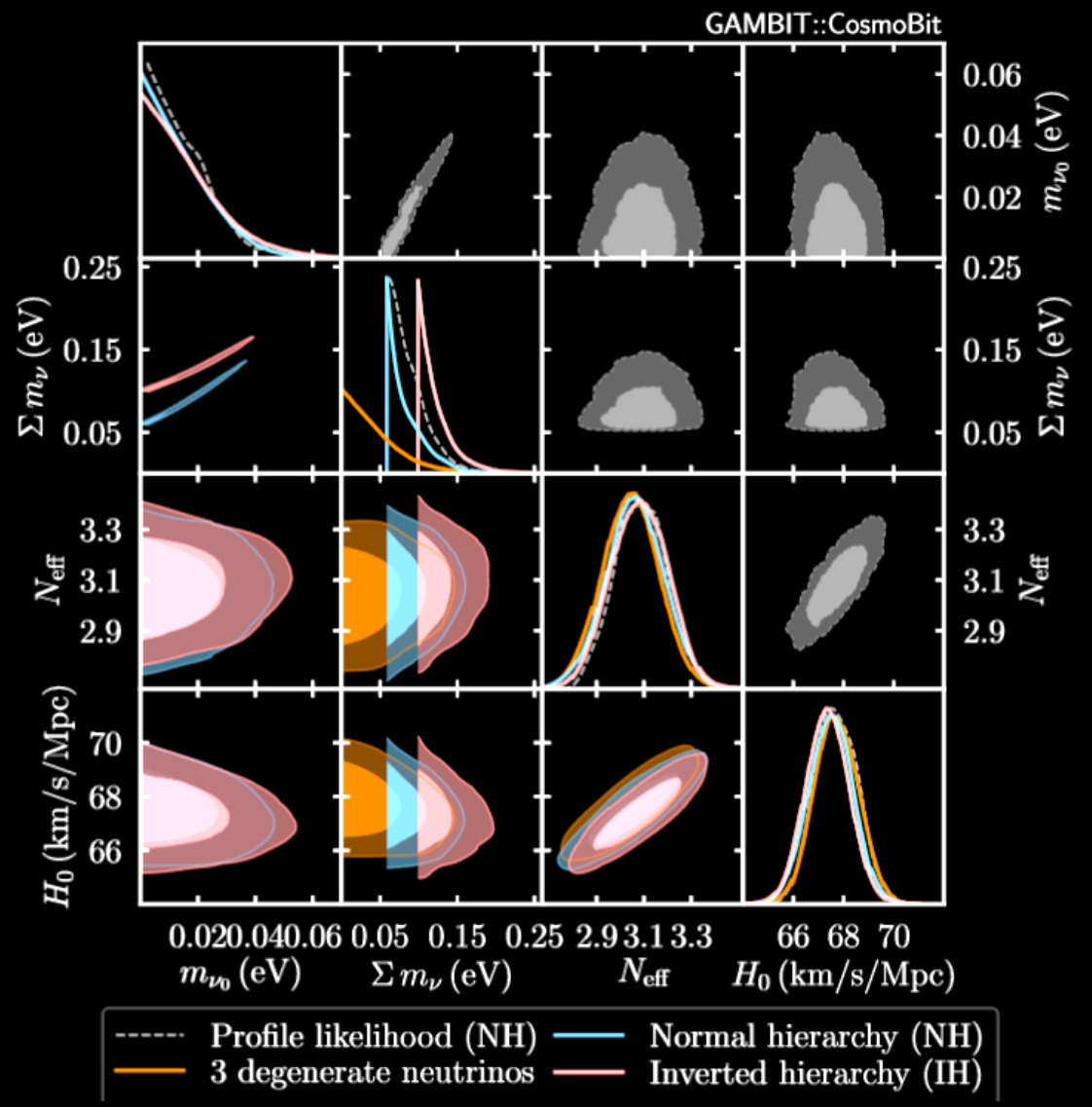
JCAP 02 (2021) 022 arXiv:2009.03286

EPJ C81 (2021) 12 1103 arXiv:2107.00030

bound on the lightest neutrino mass

2009.03287

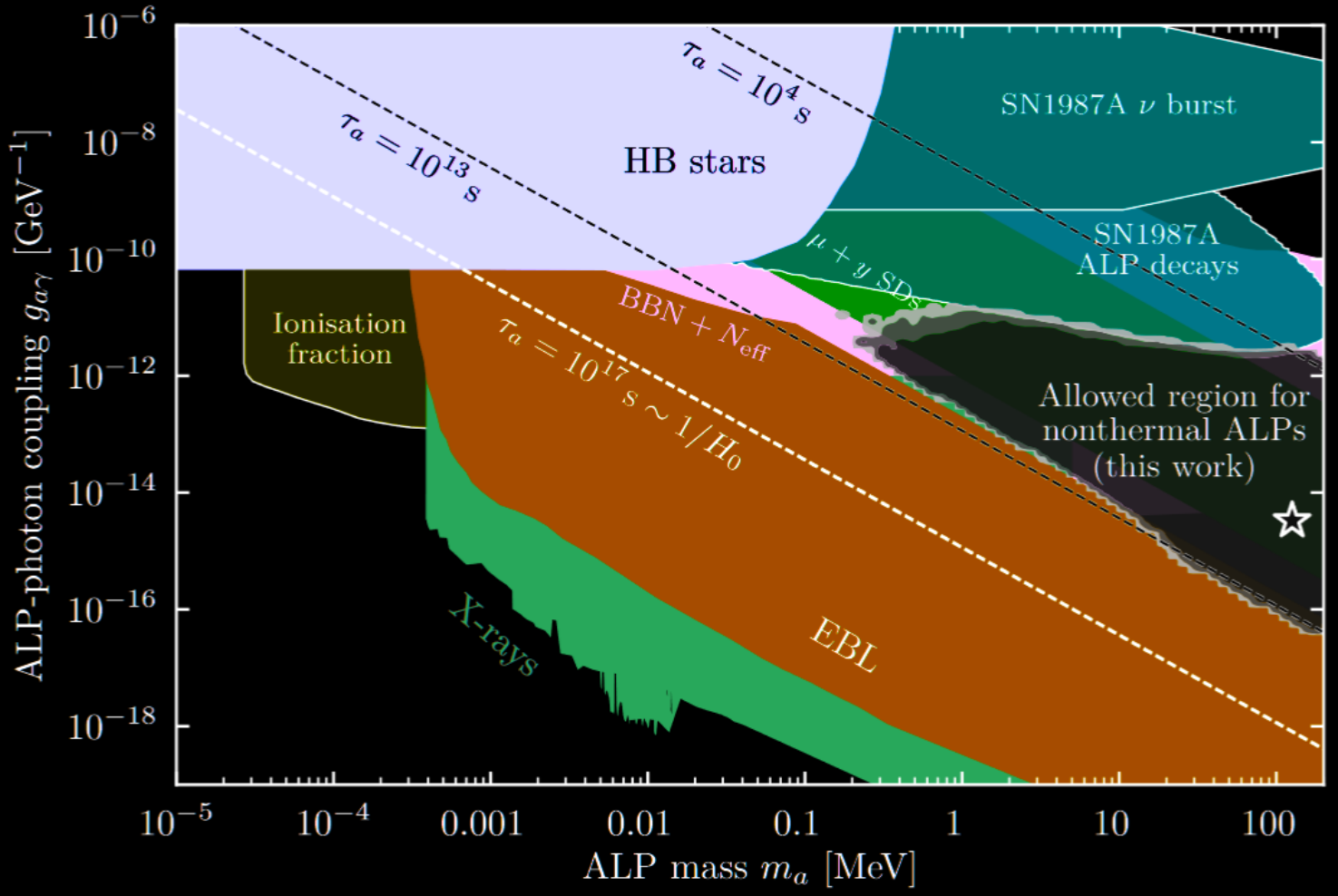
- GAMBIT uses terrestrial and cosmological experiments to set a 95% CL range on the lightest neutrino mass and the sum of neutrino masses assuming normal (NO) or inverse (IO) mass ordering
- first combined particle physics/cosmology global fit
- $m_\nu < 0.037$ eV (NO)
- $m_\nu < 0.042$ eV (IO)
- $0.058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



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



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:

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

from P. Scott

Dark matter effective field theory arXiv:2106.02056

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

Direct detection signals:
- Spin-independent – not suppressed
- Spin-independent – suppressed
- Spin-dependent – not suppressed
- Spin-dependent – suppressed

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

$$\mathcal{Q}_1^{(7)} = \frac{\alpha_s}{12\pi}(\bar{\chi}\chi)G^{a\mu\nu}G^a_{\mu\nu}$$
$$\mathcal{Q}_2^{(7)} = \frac{\alpha_s}{12\pi}(\bar{\chi}i\gamma_5\chi)G^{a\mu\nu}G^a_{\mu\nu}$$
$$\mathcal{Q}_3^{(7)} = \frac{\alpha_s}{8\pi}(\bar{\chi}\chi)G^{a\mu\nu}\widetilde{G}^a_{\mu\nu}$$
$$\mathcal{Q}_4^{(7)} = \frac{\alpha_s}{8\pi}(\bar{\chi}i\gamma_5\chi)G^{a\mu\nu}\widetilde{G}^a_{\mu\nu}$$
$$\mathcal{Q}_{5,q}^{(7)} = m_q(\bar{\chi}\chi)(\bar{q}q)$$

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

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

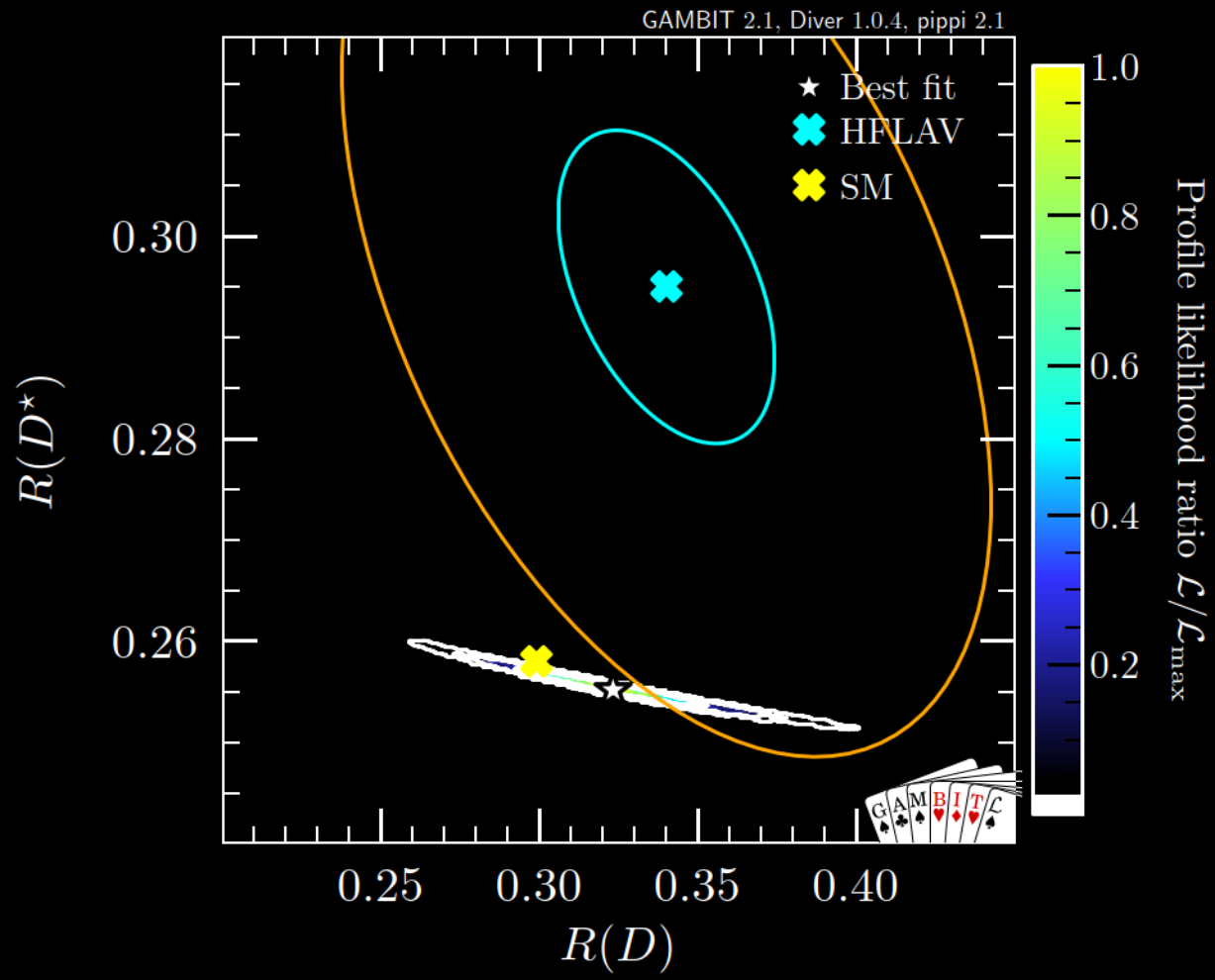
- interface between all of these and Diver differential sampler fully automated in GAMBIT

from P. Scott

general two-Higgs doublet model flavor fit

2111.10464

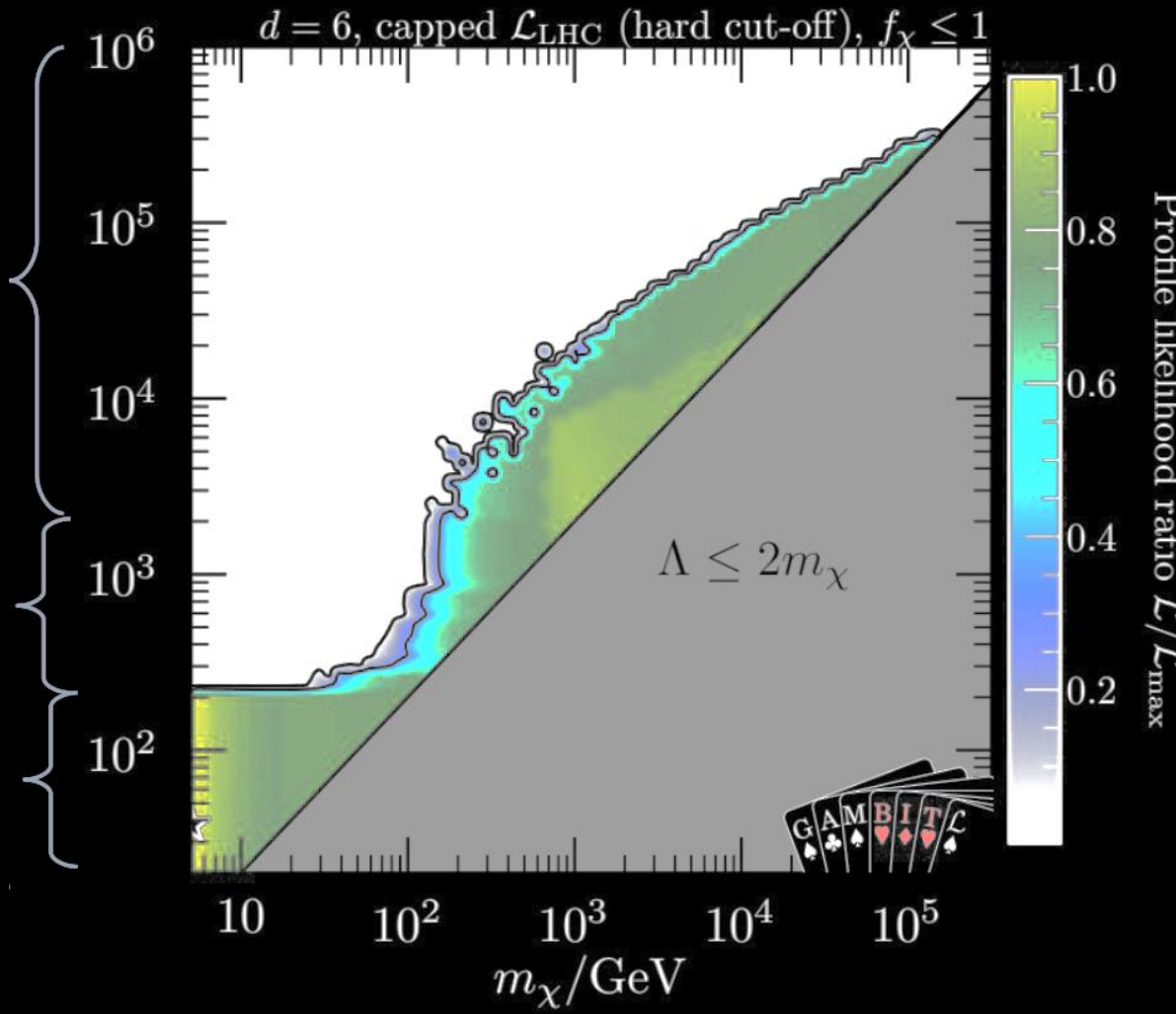
- the 2HDM explains $b \to s\,\mu^+\mu^-$
- it can simultaneously fit the experimental values of the $R(D)$ charged current ratio at 1σ
- but it can not accommodate the D^* charmed meson observables $R(D^*)$ and $FL(D^*)$
- muon $g-2$ and charged anomalies can be fit together, but not the neutral anomalies



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

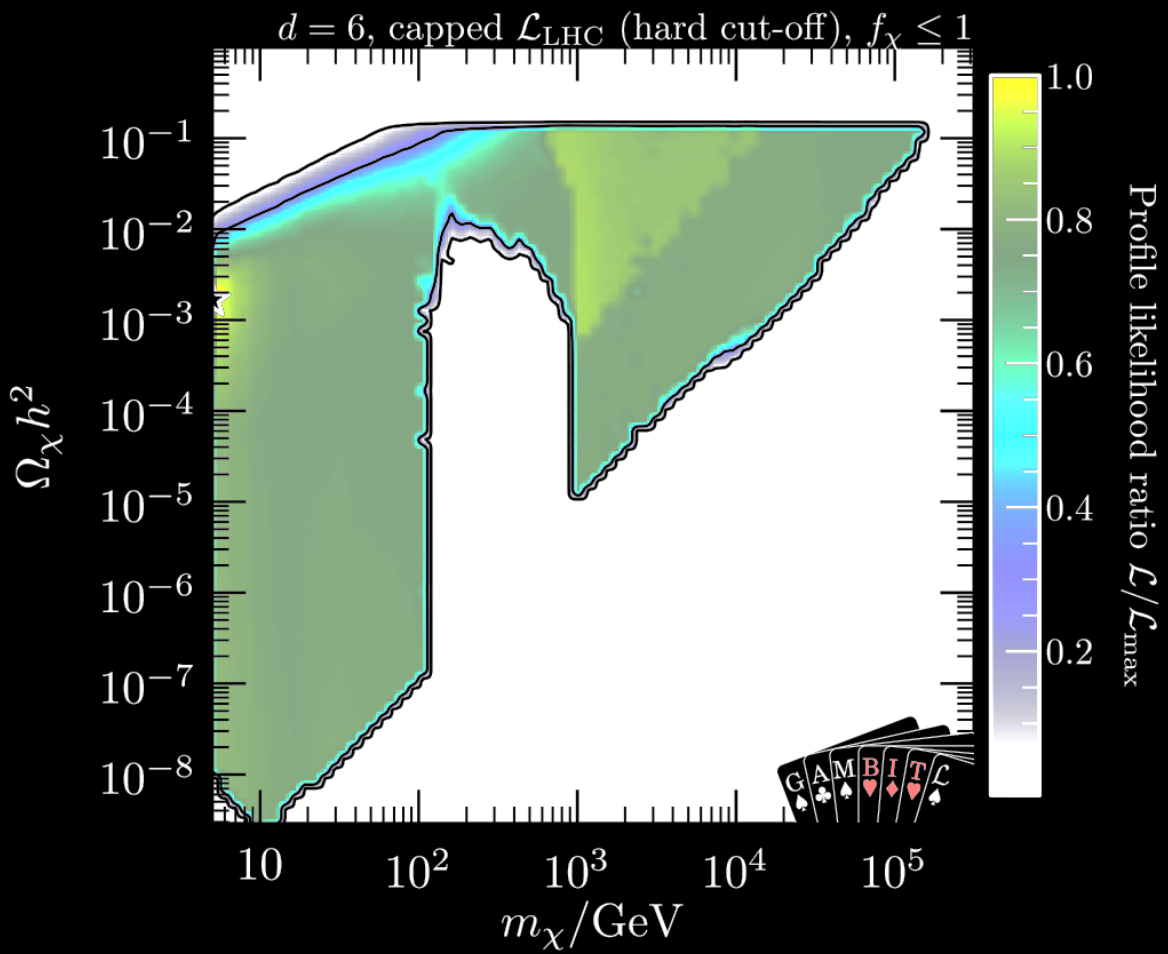
light DM particles

- 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)

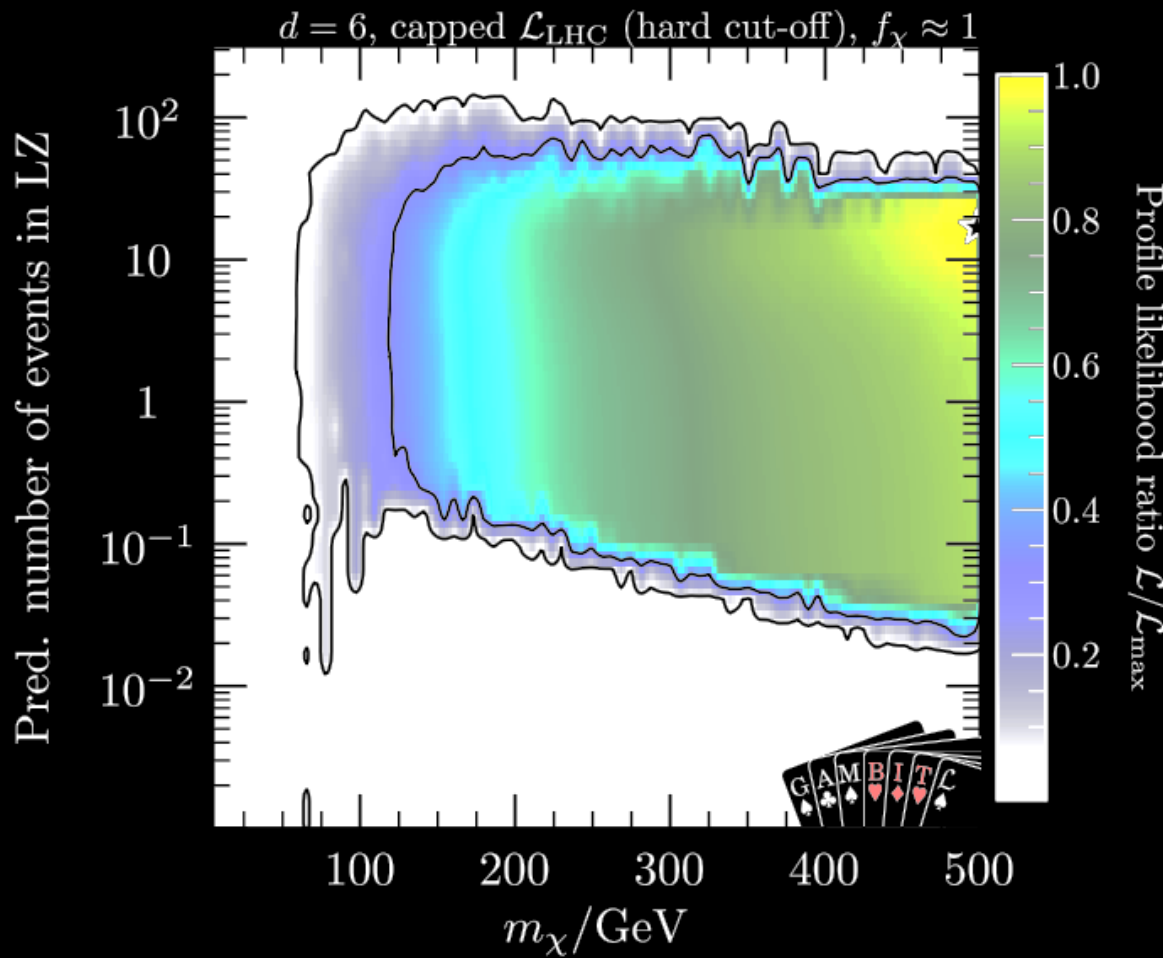


from F. Kahlhoefer, P. Scott

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

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…