Dark matter interpretation with global fits

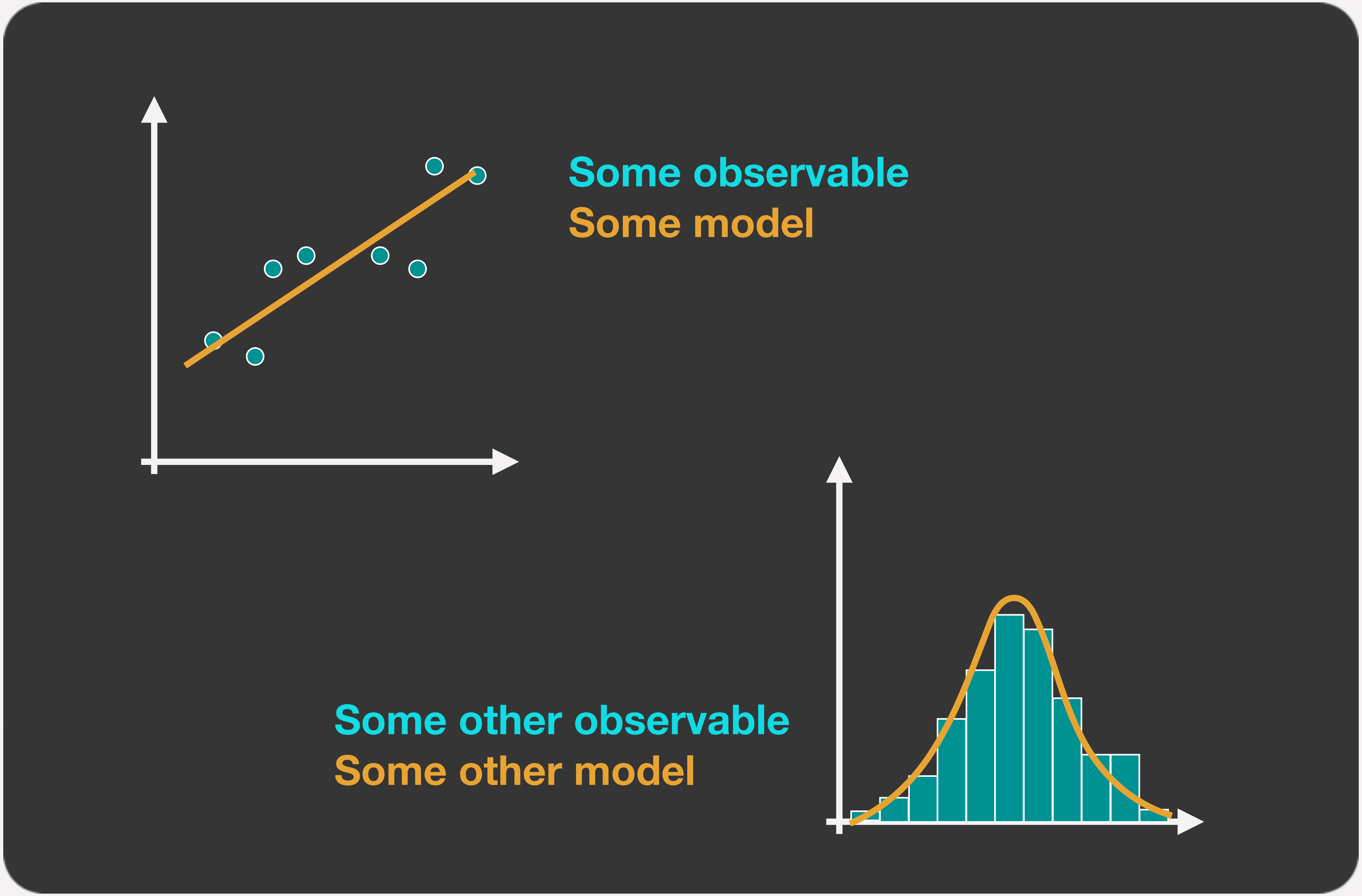
Anders Kvellestad, Imperial College London
on behalf of the GAMBIT Collaboration

DM @ LHC, Seattle, 15 August 2019

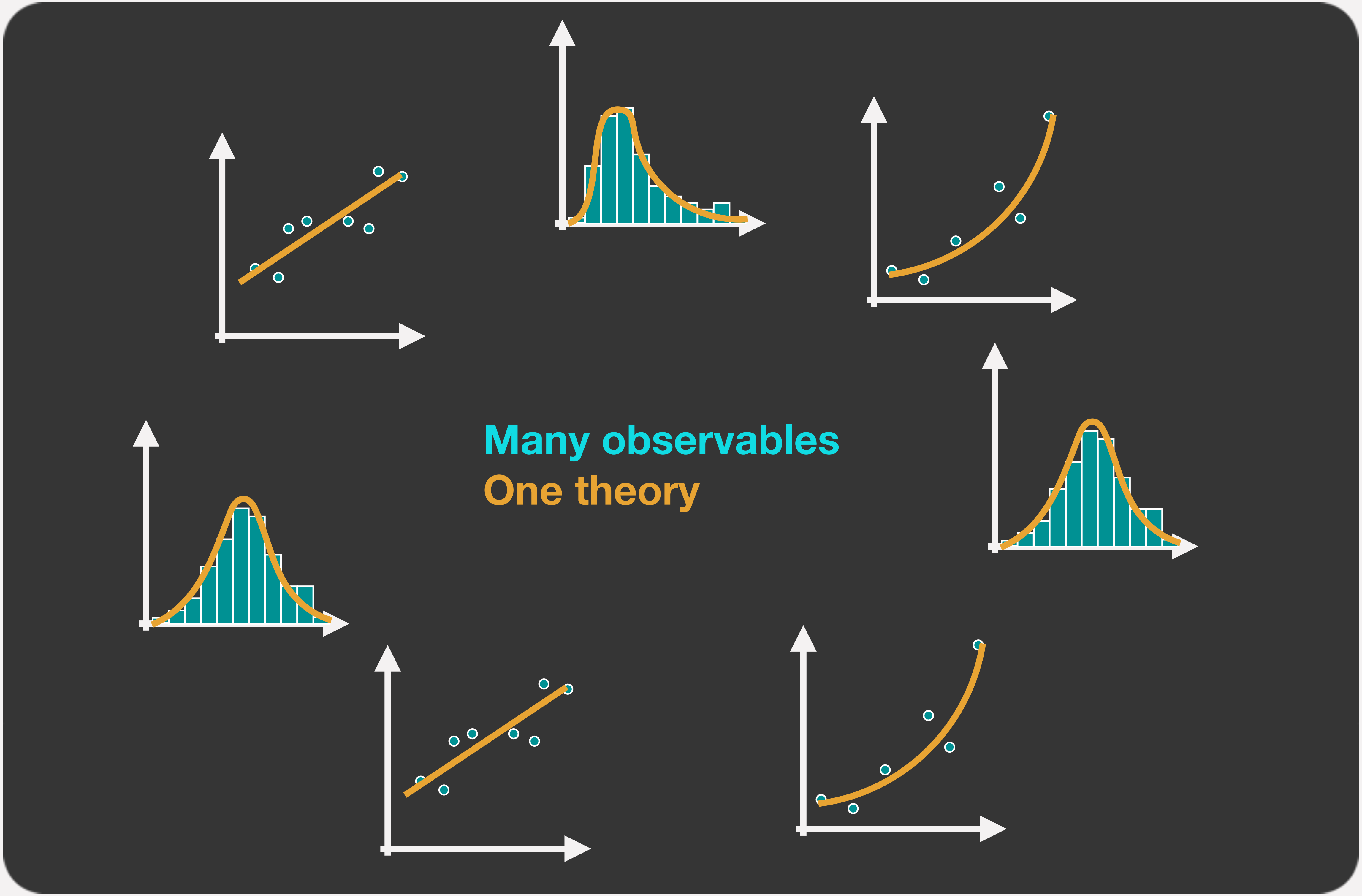
Imperial College London

1. Global fits?

Statistical fits



Global fits



The basic steps of a BSM global fit

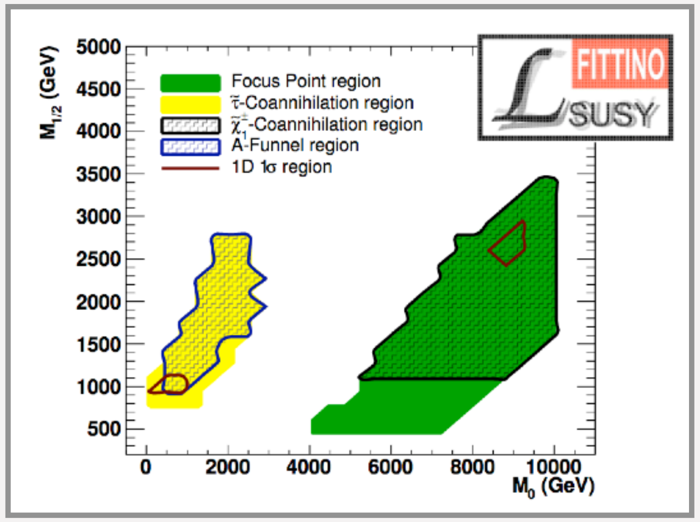
- Choose your **BSM model and parameterisation**
- Construct the **combined likelihood function** including observables from collider physics, dark matter, flavor physics, +++

$$\mathcal{L} = \mathcal{L}_{\text{collider}}\mathcal{L}_{\text{DM}}\mathcal{L}_{\text{flavor}}\mathcal{L}_{\text{EWPO}}\cdots$$

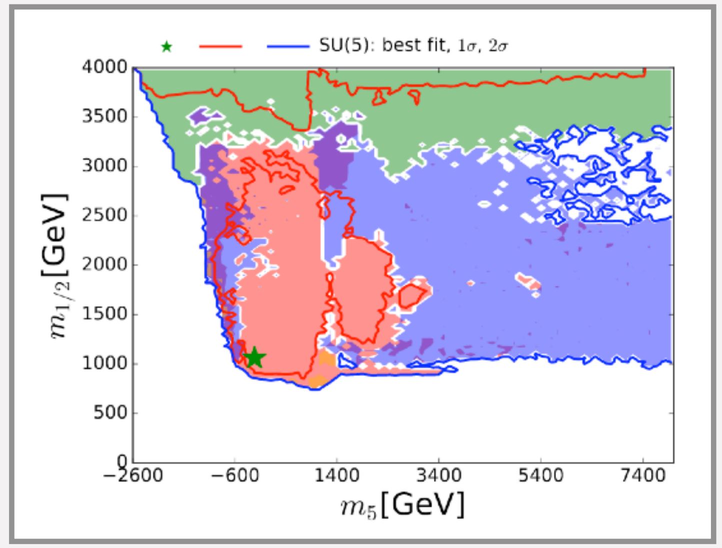
- Use **sophisticated scanning techniques** to explore the likelihood function across the parameter space of the theory
- Test **parameter regions** in a statistically sensible way — not just single points *(parameter estimation)*
- Test **different theories the same way** *(model comparison)*

2. Recent(ish) DM global fits

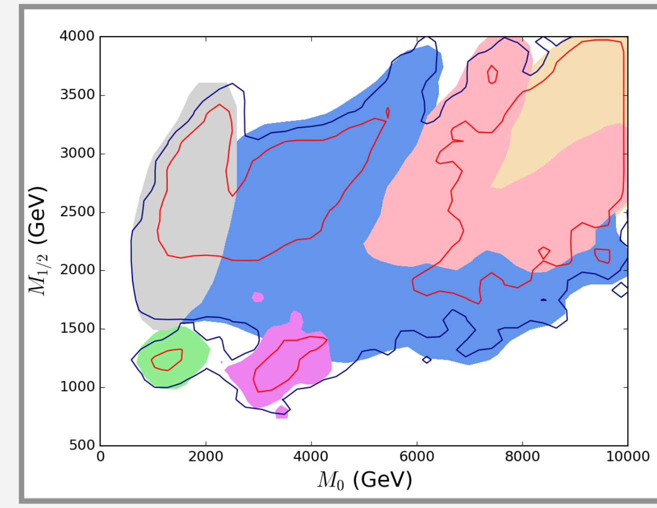
SUSY DM global fits (high scale)



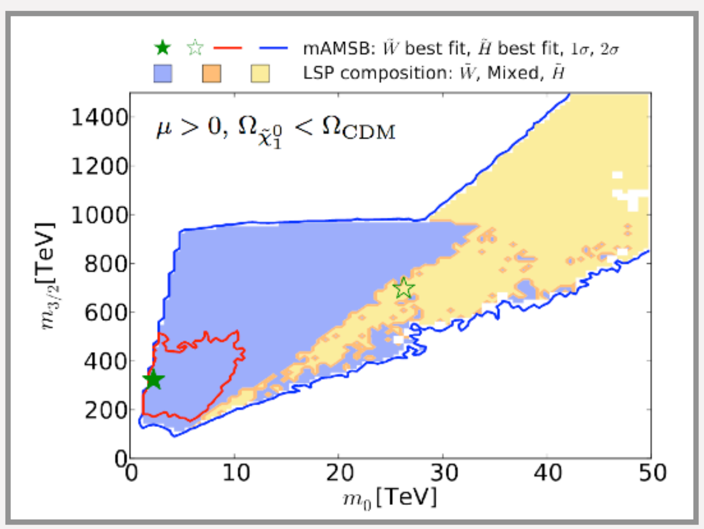
CMSSM
Fittino, 1508.05951



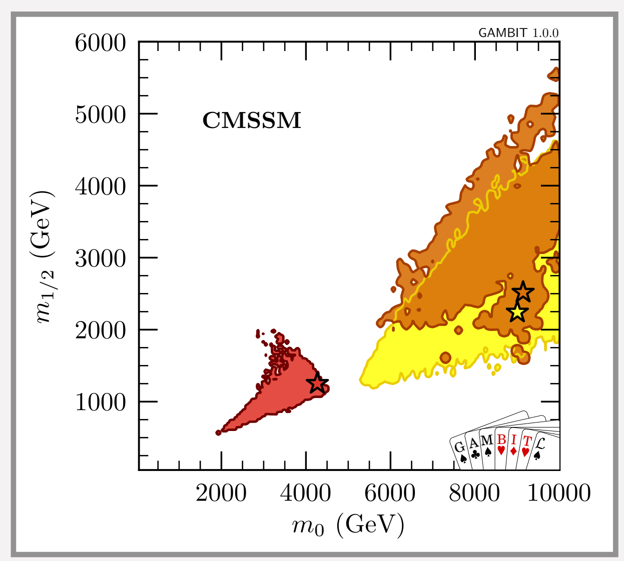
SUSY SU(5) GUTs
MasterCode, 1610.10084



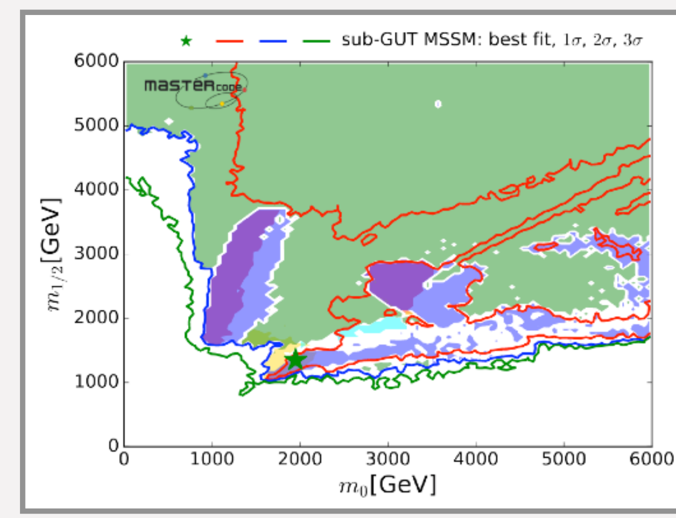
CMSSM
EasyScan_HEP, 1612.02296



mAMSB
MasterCode, 1612.05210

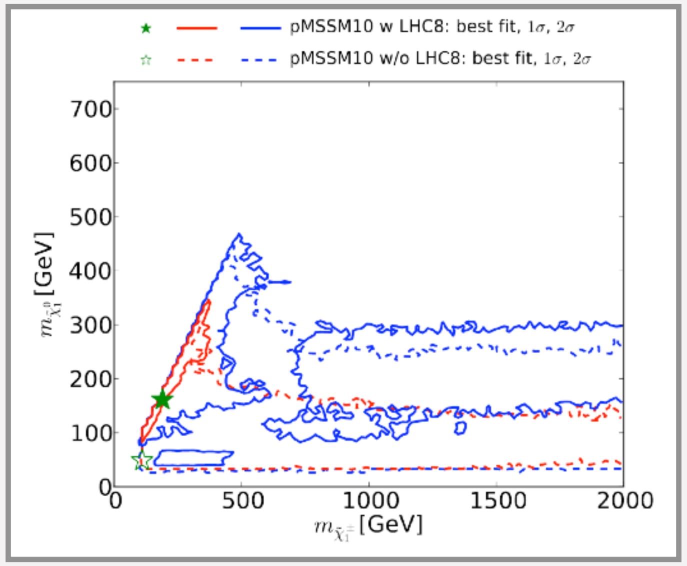


CMSSM, NUHM1, NUHM2
GAMBIT, 1705.07935

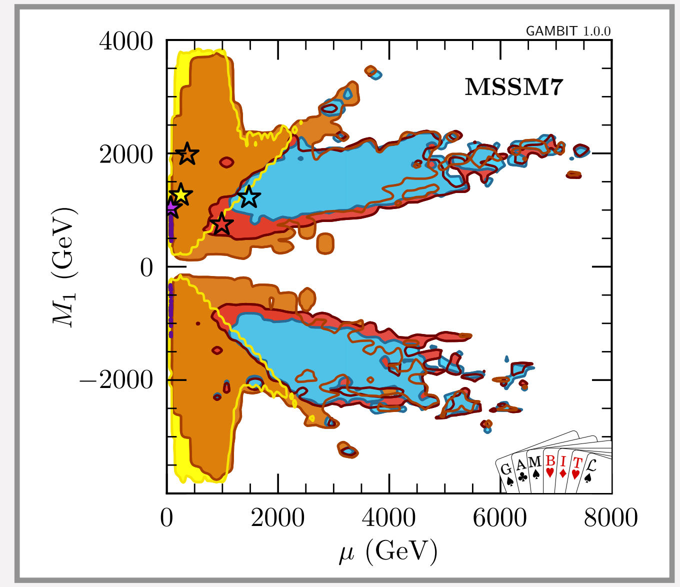


sub-GUT MSSM
MasterCode, 1711.00458

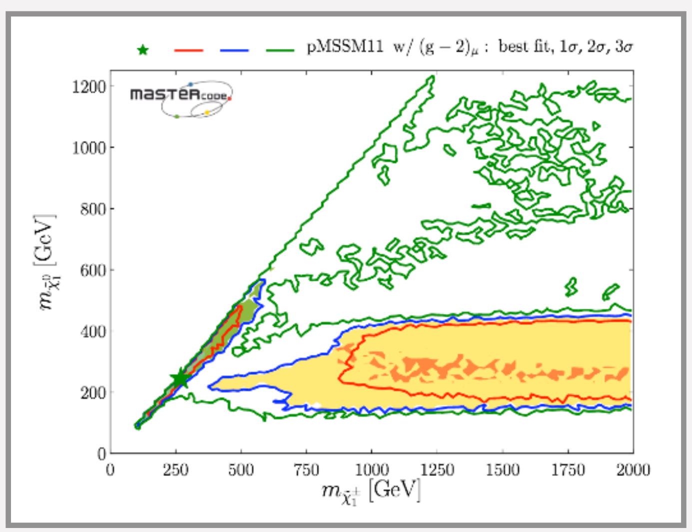
SUSY DM global fits (weak scale)



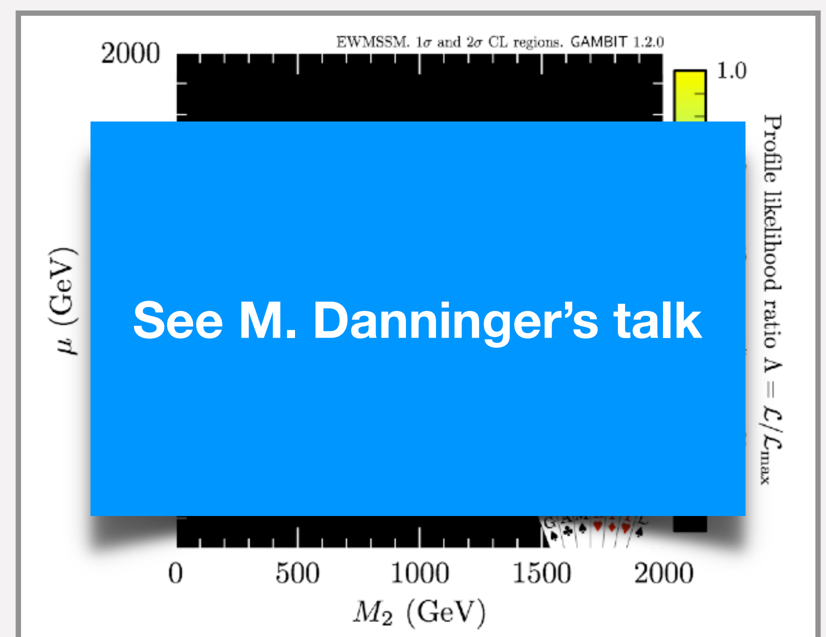
MSSM10
MasterCode, 1504.03260



MSSM7
GAMBIT, 1705.07917

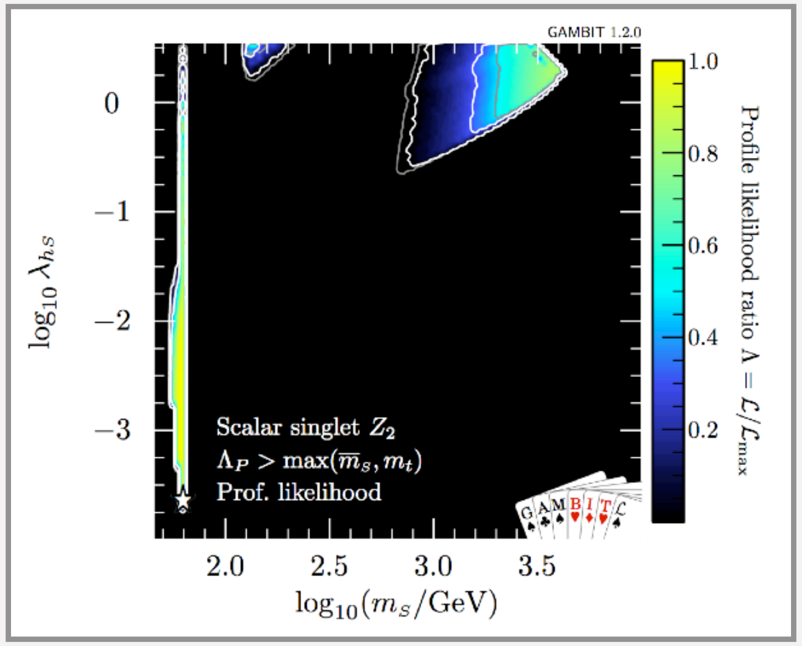


MSSM11
MasterCode, 1710.11091

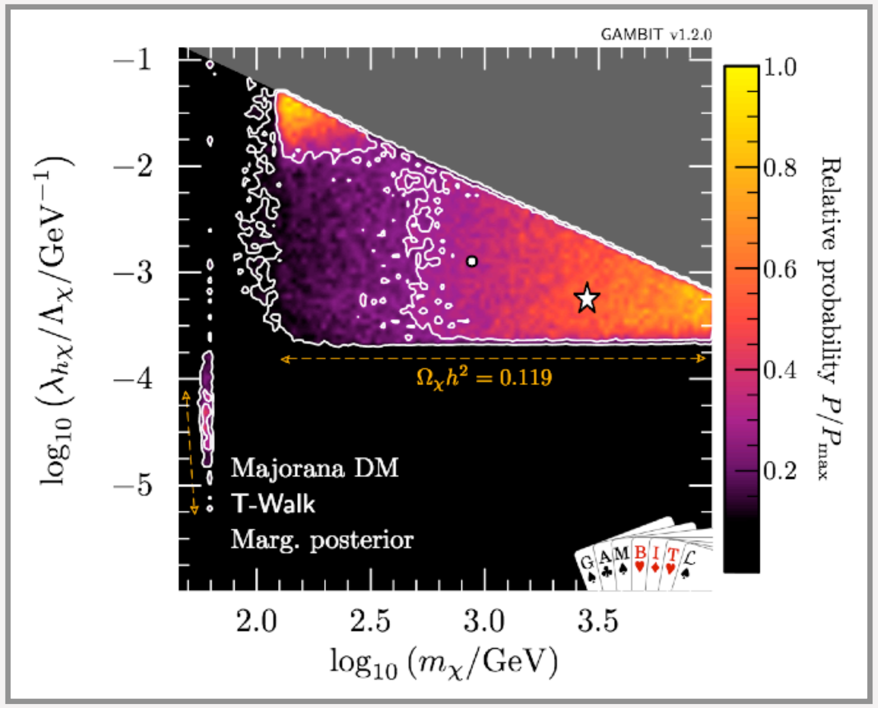


EW-MSSM
GAMBIT, 1809.02097

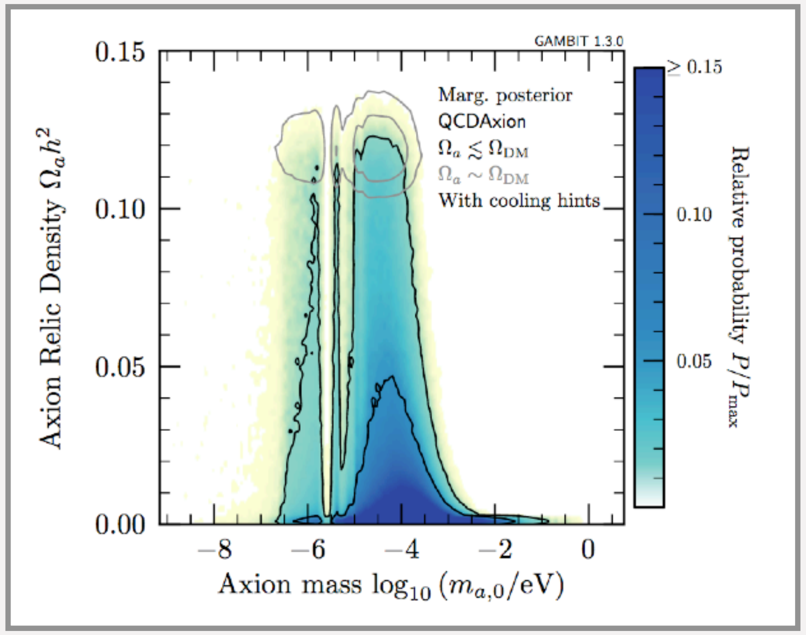
Non-SUSY DM global fits



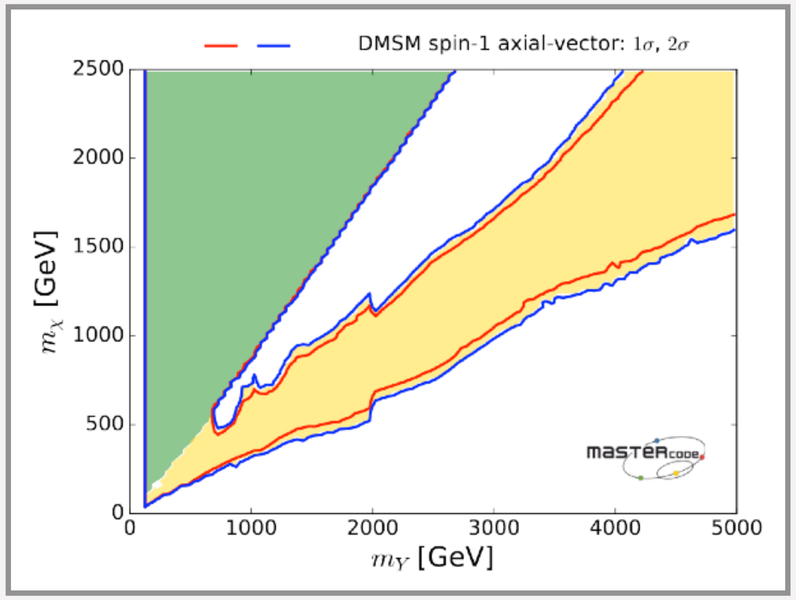
Scalar Higgs portal DM (Z2 & Z3)
GAMBIT, 1705.07931, 1806.11281



Vector and fermion Higgs portal DM
GAMBIT, 1808.10465.



Axions and axion-like particles
GAMBIT, 1810.07192



DM w/ leptophobic mediator
MasterCode, 1905.00892

3. GAMBIT

GAMBIT: The Global And Modular BSM Inference Tool

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

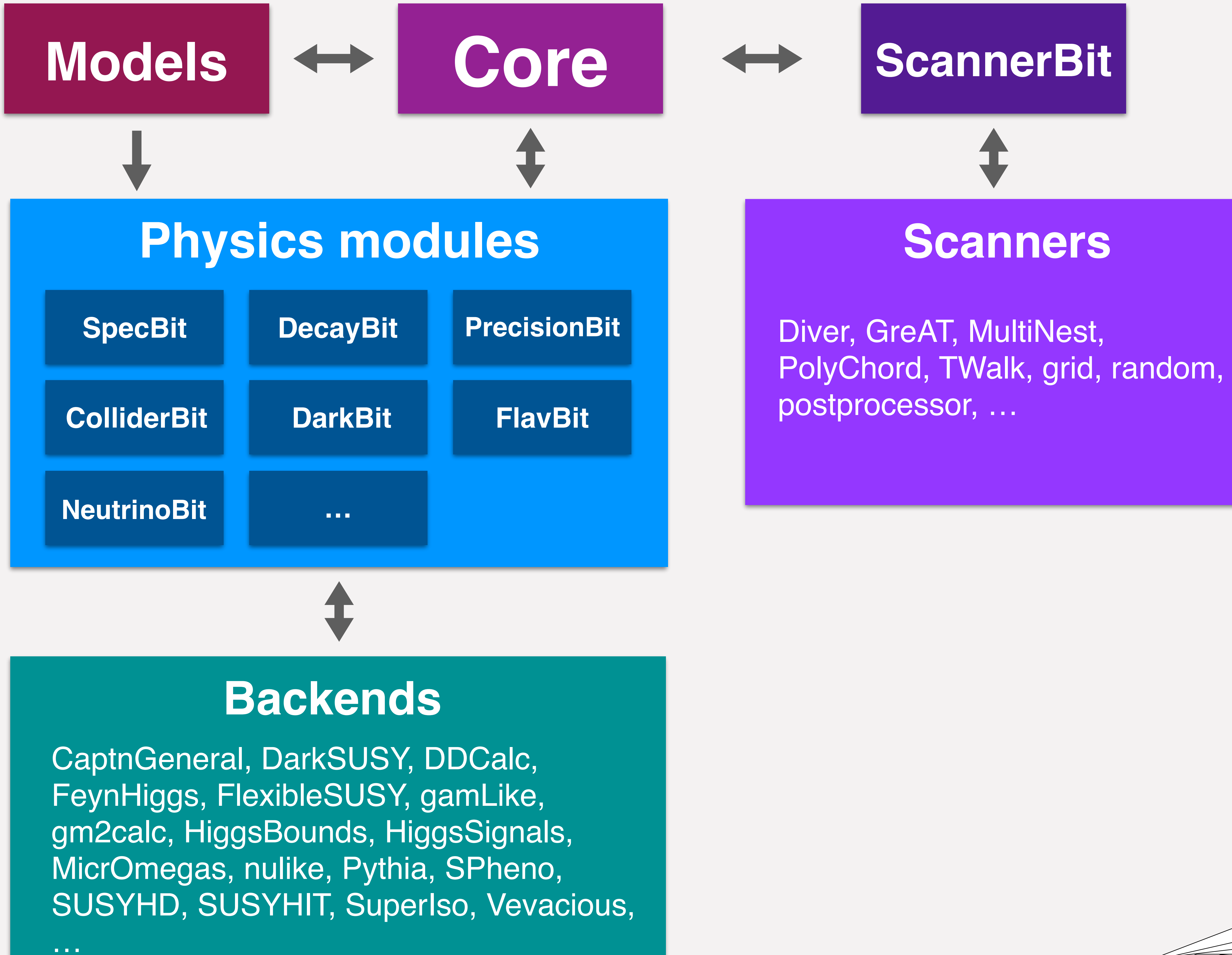
- Extensive model database – not just SUSY
- Extensive observable/data libraries
- Many statistical and scanning options (Bayesian & frequentist)
- *Fast* LHC likelihood calculator
- Massively parallel
- Fully open-source

- Fast definition of new datasets and theories
- Plug and play scanning, physics and likelihood packages

Members of:
ATLAS, Belle-II, CLiC, CMS, CTA, *Fermi*-LAT, DARWIN, IceCube, LHCb, SHiP, XENON
Authors of:
DarkSUSY, DDCalc, Diver, FlexibleSUSY, gamlike, GM2Calc, IsaTols, nulike, PolyChord, Rivet, SoftSUSY, SuperISO, SUSY-AI, WIMPSim

Recent collaborators:
Peter Athron, Csaba Balázs, Ankit Beniwal, Sanjay Bloor, Torsten Bringmann, Andy Buckley, José Eliel Camargo-Molina, Marcin Chrząszcz, Jonathan Cornell, Matthias Danninger, Joakim Edsjö, Ben Farmer, Andrew Fowlie, Tomás E. Gonzalo, Will Handley, Sebastian Hoof, Selim Hotinli, Felix Kahlhoefer, Anders Kvellestad, Julia Harz, Paul Jackson, Farvah Mahmoudi, Greg Martinez, Are Raklev, Janina Renk, Chris Rogan, Roberto Ruiz de Austri, Pat Scott, Patrick Stöcker, Aaron Vincent, Christoph Weniger, Martin White, Yang Zhang

40+ participants in 11 experiments and 14 major theory codes


Models
Core
ScannerBit
Physics modules
SpecBit
DecayBit
PrecisionBit
ColliderBit
DarkBit
FlavBit
NeutrinoBit
…
Scanners
Diver, GreAT, MultiNest, PolyChord, TWalk, grid, random, postprocessor, …
Backends
CaptnGeneral, DarkSUSY, DDCalc, FeynHiggs, FlexibleSUSY, gamLike, gm2calc, HiggsBounds, HiggsSignals, MicrOmegas, nulike, Pythia, SPheno, SUSYHD, SUSYHIT, SuperIso, Vevacious, …

[1705.07917]

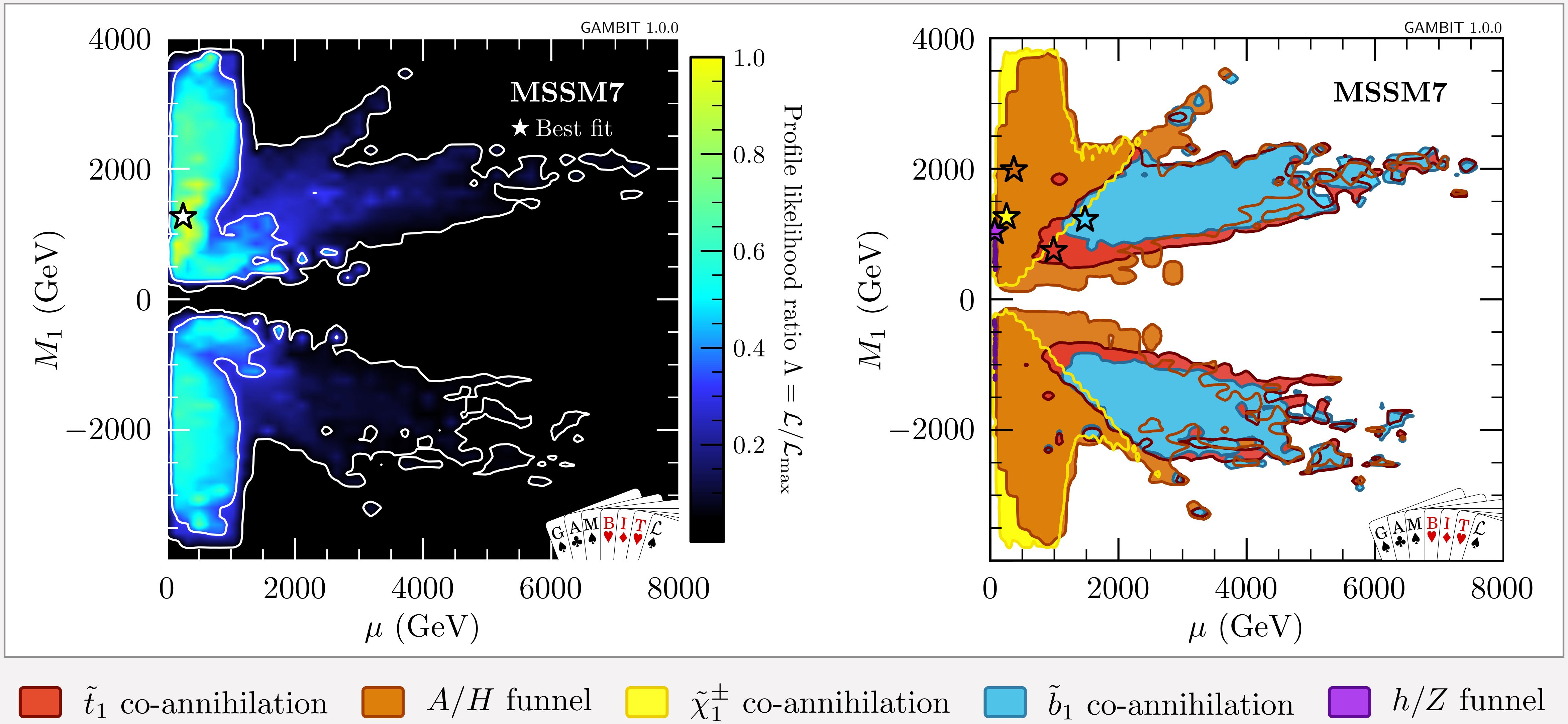
Results: SUSY dark matter

Likelihoods

- Nuisance parameter likelihoods
  (SM, local halo model, nuclear matrix elements)
- DM relic density *as upper bound*
- DM Indirect detection
  - Gamma rays: Fermi-LAT
    (dwarf spheriodal galaxies)
  - Neutrinos from DM annihilation in the Sun:
    IceCube79
- DM Direct detection:
  - XENON100 (2012)
  - LUX (2016)
  - Panda-X (2016)
  - PICO (2015)
  - SuperCDMS (2014)
  - SIMPLE (2014)

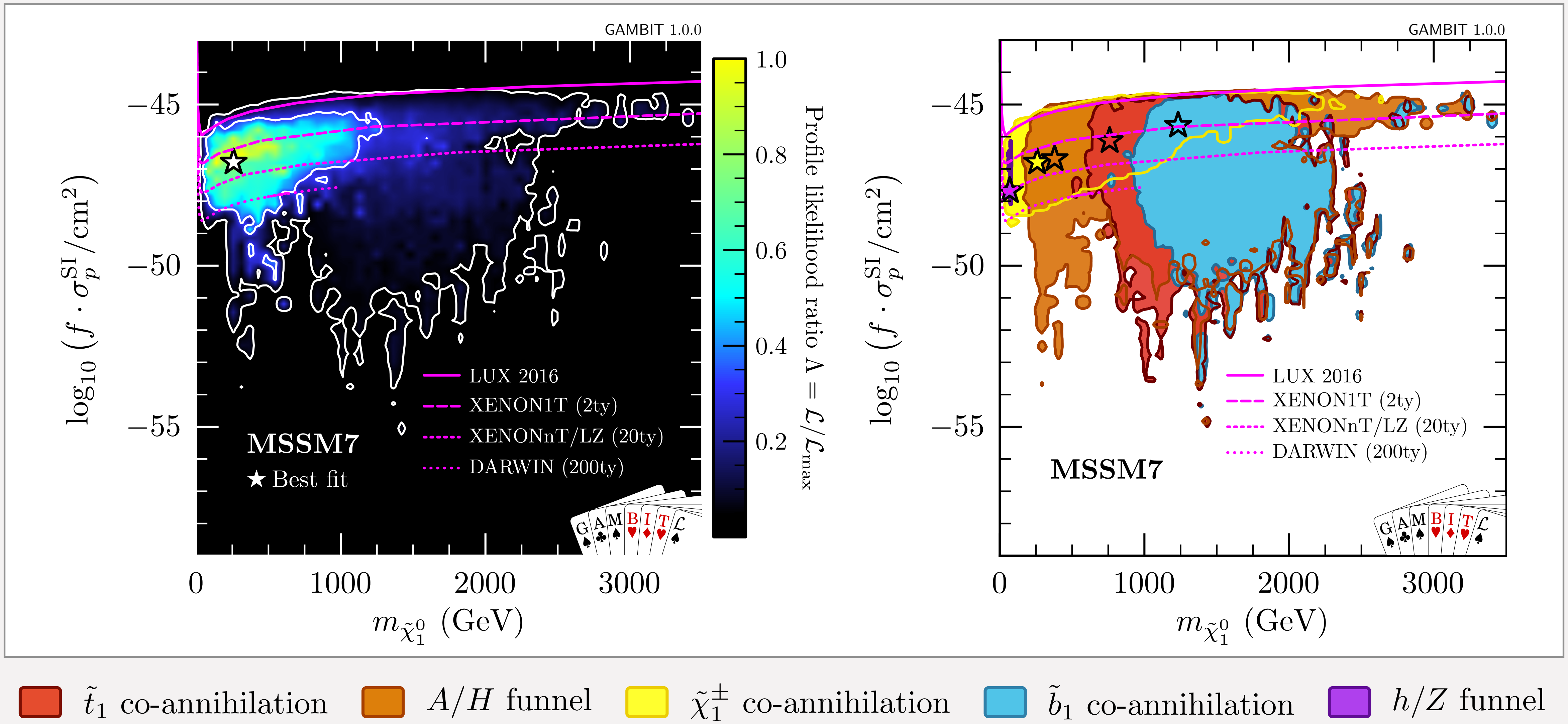
- Electroweak precision observables
  - W mass
  - muon g-2
- 59 flavour observables
- Higgs mass and signal strengths
- SUSY cross section limits from LEP
- SUSY searches at LHC (simulated)
  - 0 lepton searches (Run I & II, ATLAS & CMS)
  - Stop searches (Run I, ATLAS & CMS)
  - 2 & 3 lepton searches (Run I, ATLAS & CMS)

MSSM 7



- Three neutralino scenarios: higgsino-dominated, higgsino/bino mix, bino-dominated
- Wino-dominated neutralino not possible due to GUT relation $(M_2 \sim 2M_1)$

MSSM 7



- Best fit point in chargino co-annihilation region (chargino/neutralino mass ~260 GeV)
- Mass difference < 10 GeV (challenging for LHC)
- Under-abundant relic density at best fit point (but ~equally good fit with 1 TeV higgsinos)
- Entire chargino co-ann. and light Higgs funnel regions will be probed by future DD

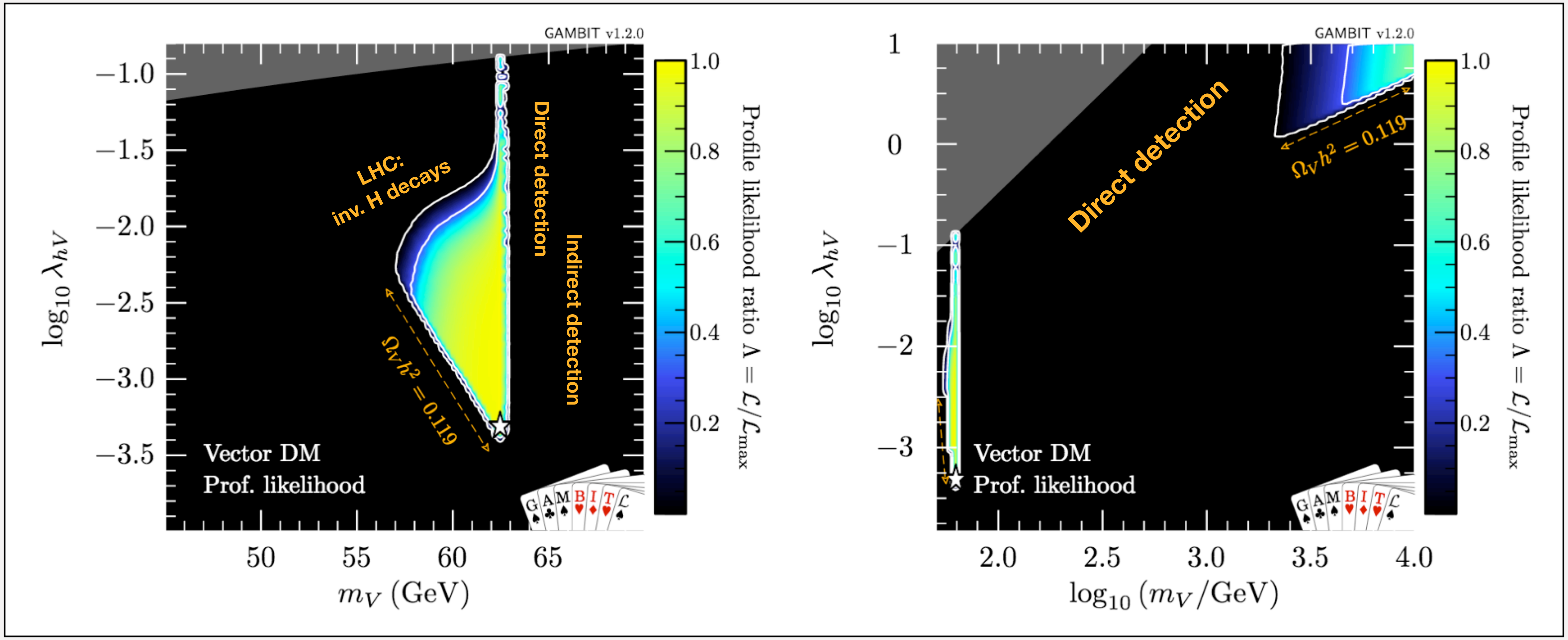
Results: Higgs portal dark matter

[1808.10465]

Likelihoods

- Nuisance parameter likelihoods
  (SM, local halo model, nuclear matrix elements)
- DM relic density *as upper bound*
- DM Indirect detection
  - Gamma rays: Fermi-LAT
    (dwarf spheriodal galaxies)
  - Neutrinos from DM annihilation in the Sun:
    IceCube79
- DM Direct detection:
  - XENON1T 2018
  - LUX 2016
  - Panda-X 2016, 2017
  - CDMSlite
  - CRESST-II
  - PICO-60
  - DarkSide-50
- Higgs invisible decay width
- Perturbative unitarity and EFT validity

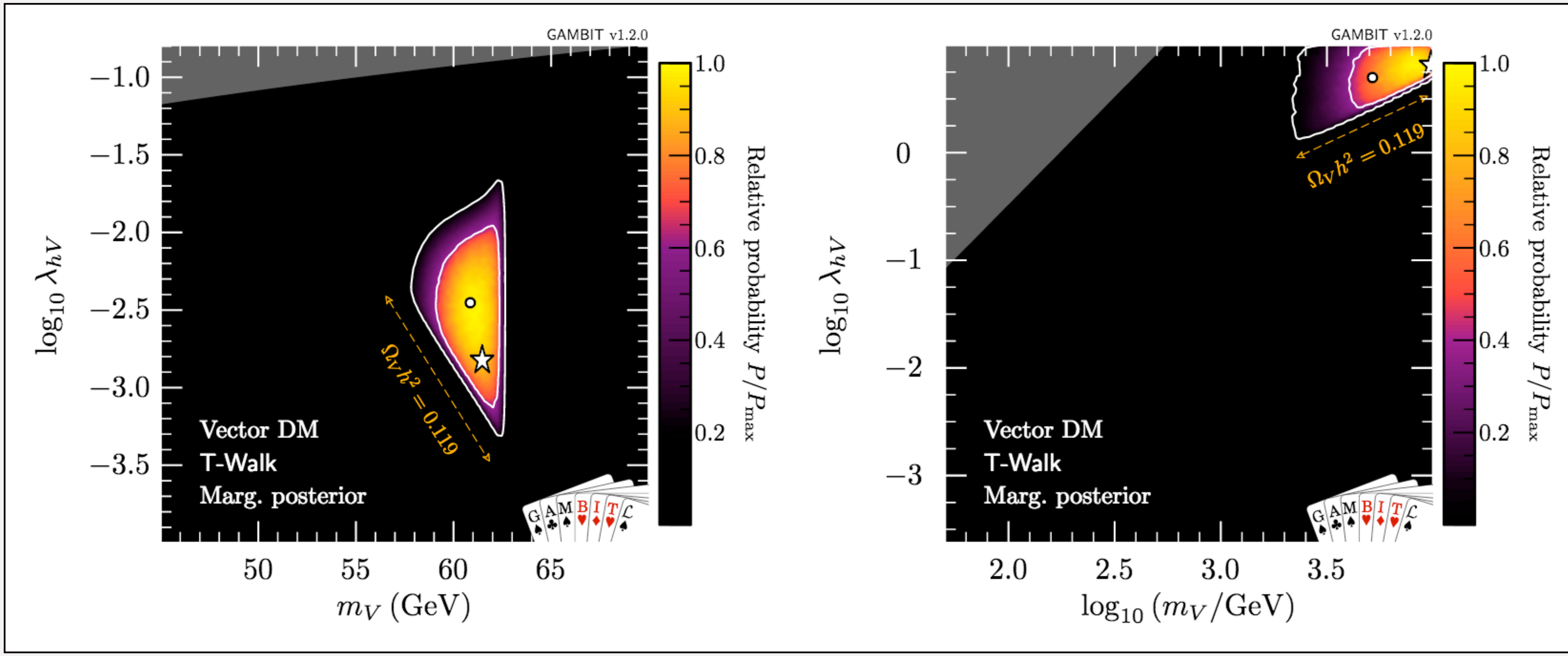
Higgs portal (vector/fermion)



Vector DM model

- Higgs resonance region and high-mass region consistent with all experiments
- Direct detection generally very constraining, but invisible H decays also important

Higgs portal (vector/fermion)

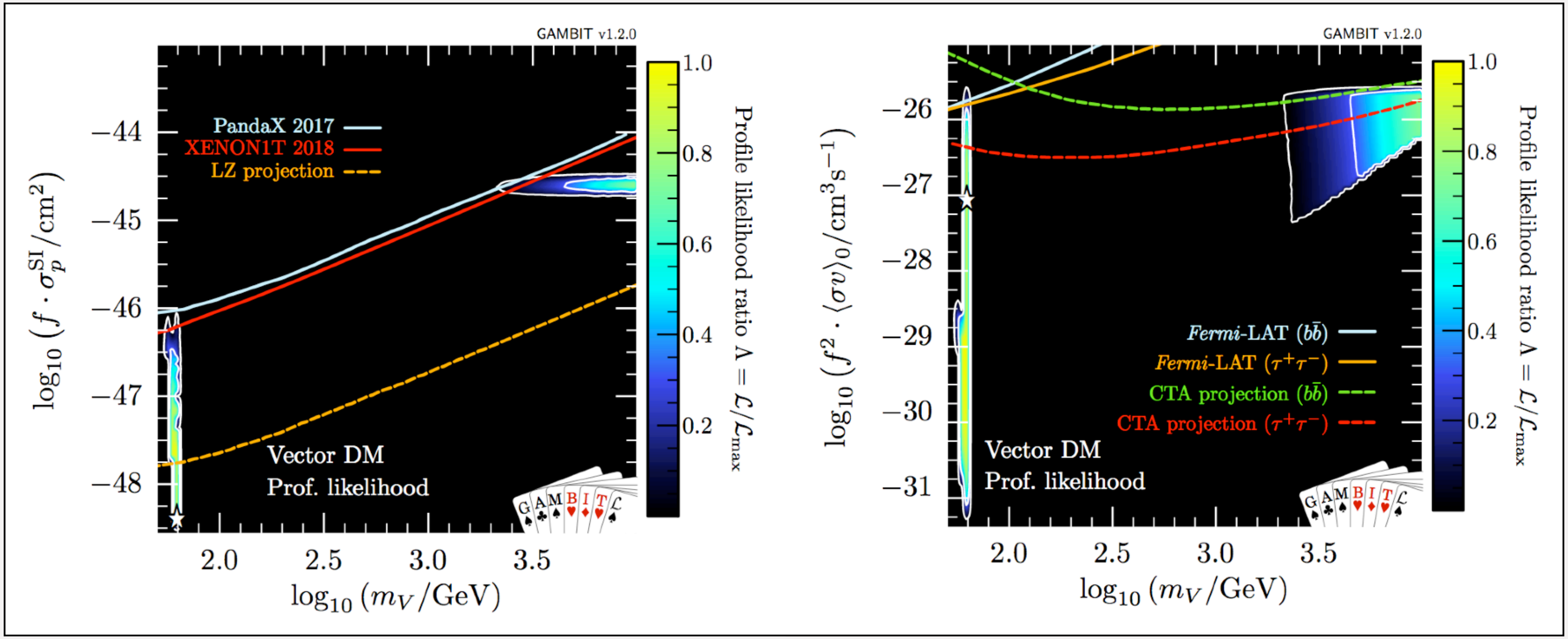


Vector DM model

- Bayesian posterior distributions: resonance region disfavoured due to being fine-tuned
- Similar effect seen for the scalar and fermion DM models

[1808.10465]

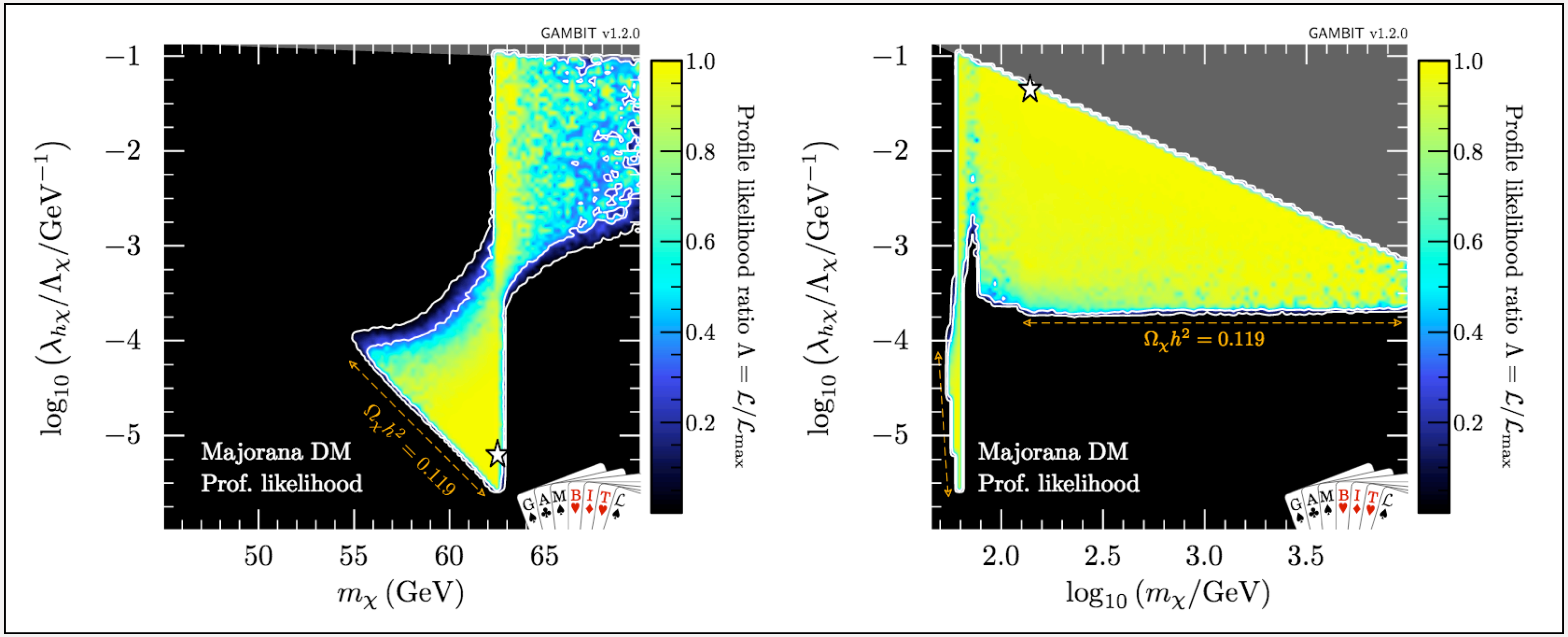
Higgs portal (vector/fermion)



Vector DM model

- Future experiments will probe entire high-mass region and part of resonance region

Higgs portal (vector/fermion)



Majorana fermion DM model (similar results for Dirac fermion)

- Additional free parameter: CP phase of portal interaction
- CP-violating interaction
  → momentum suppression in DD cross-section
  → larger viable parameter space

[1808.10465]

Higgs portal (vector/fermion)

Model	Comparison model and priors			Odds
$\xi = 0$	m_χ: log	$\lambda_{h\chi}/\Lambda_\chi$: log	ξ: flat	70:1
$g_\mathrm{p}/\Lambda_\mathrm{p} = 0$	m_χ: log	$g_\mathrm{s}/\Lambda_\mathrm{s}$: log	$g_\mathrm{p}/\Lambda_\mathrm{p}$: log	140:1

Model	Parameters and priors			Odds
S	m_S: log	λ_{hS}: log		1:1
V_μ	m_V: log	λ_{hV}: log		6:1
χ	m_χ: log	$\lambda_{h\chi}/\Lambda_\chi$: log	ξ: flat	1:1
ψ	m_ψ: log	$\lambda_{h\psi}/\Lambda_\psi$: log	ξ: flat	1:1

Bayesian model comparisons

- Fermion DM: **CP-conserving vs CP-violating portal coupling?**
  → «Strong evidence» against pure CP-conserving case (Jeffrey's scale)
- **Scalar, fermion or vector DM?**
  → «Positive evidence» against vector DM model, compared to scalar model

Summary

Summary

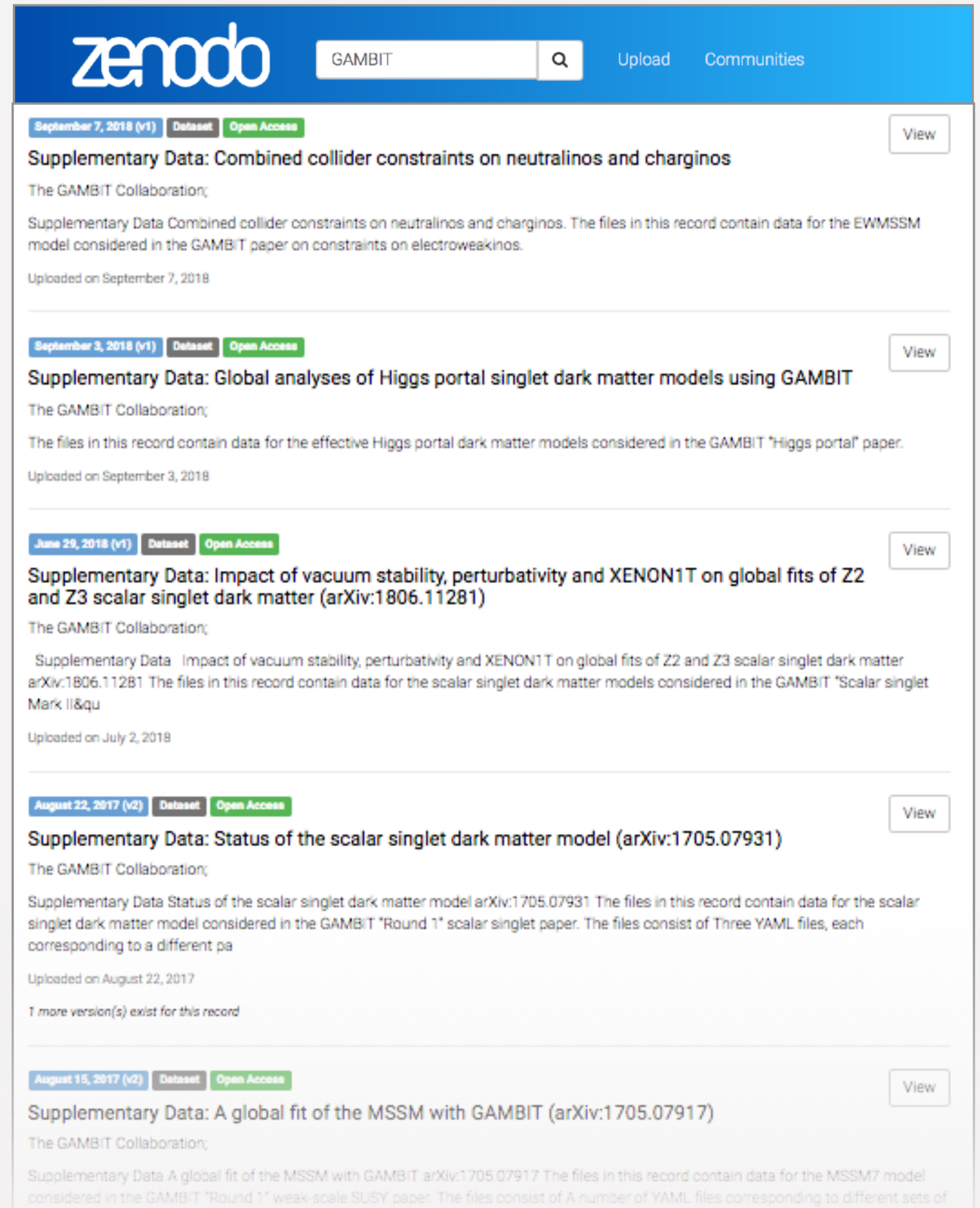
- There are *many* observables that may have implications for dark matter → **need global fits** to get the complete picture
- **Global fits for *any* BSM model?** GAMBIT is your friend!
  (But it's not automatic… yet…)
- SUSY global fits are still going strong
- Many constraints, but **«vanilla» MSSM dark matter remains viable and well-motivated**
- If you believe in fermion singlet dark matter, you **should not expect a CP-conserving Higgs portal interaction**
- Interesting parameter regions for MSSM and Higgs portal dark matter will be probed in upcoming experiments — in particular in direct detection
- *GAMBIT v1.4 is out:* gambit.hepforge.org

All GAMBIT results are publicly available

Results available on zenodo.cern.ch

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

Links at gambit.hepforge.org/pubs



Bonus tracks

Parameters and likelihoods

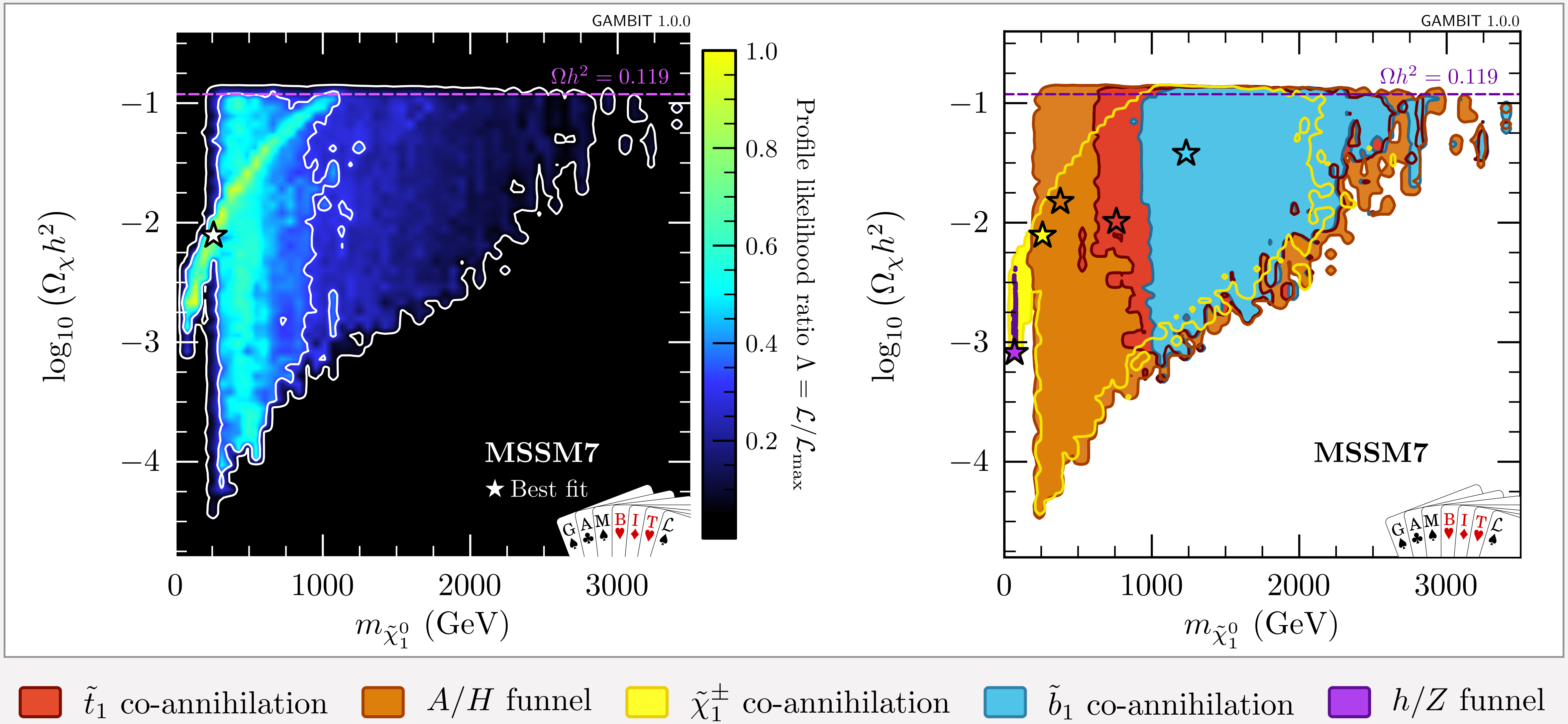
Parameter	Minimum	Maximum	Priors
$A_{u_3}(Q)$	-10 TeV	10 TeV	flat, hybrid
$A_{d_3}(Q)$	-10 TeV	10 TeV	flat, hybrid
$M^2_{H_u}(Q)$	$-(10\,\mathrm{TeV})^2$	$(10\,\mathrm{TeV})^2$	flat, hybrid
$M^2_{H_d}(Q)$	$-(10\,\mathrm{TeV})^2$	$(10\,\mathrm{TeV})^2$	flat, hybrid
$m^2_{\tilde{f}}(Q)$	0	$(10\,\mathrm{TeV})^2$	flat, hybrid
$M_2(Q)$	-10 TeV	10 TeV	split; flat, hybrid
$\tan\beta(m_Z)$	3	70	flat
$\mathrm{sgn}(\mu)$	$+$		fixed
Q	1 TeV		fixed

- 7 MSSM parameters + 5 nuisance parameters
- Assume GUT-inspired relation on gaugino mass parameters:

$$\frac{3}{5}\cos^2\theta_{\mathrm{W}} M_1 = \sin^2\theta_{\mathrm{W}} M_2 = \frac{\alpha}{\alpha_{\mathrm{s}}} M_3$$

- Same likelihoods as for the GUT-scale models

MSSM 7



- Best fit point in chargino co-annihilation region (chargino/neutralino mass ~260 GeV)
- Mass difference < 10 GeV (challenging for LHC)
- Under-abundant relic density

Effective Higgs portal models

[EPJC, arXiv:1808.10465]

- $H^\dagger H$ – lowest dimensional, gauge-invariant operator.
- Vector (V_μ) and Majorana fermion[1] (χ) fields with $\mathbb{Z}_2$ symmetry:

$$(V_\mu, \chi) \to -\,(V_\mu, \chi). \tag{2}$$

- Lagrangians after EWSB and chiral rotation: $\chi \to e^{i\gamma_5 \alpha/2}\chi$ are

$$\mathscr{L}_V \supset \frac{1}{2} m_V^2 V_\mu V^\mu + \frac{1}{2}\lambda_{hV} V_\mu V^\mu (v_0 h + \frac{1}{2}h^2), \tag{3}$$

$$\mathscr{L}_\chi \supset \frac{1}{2}\overline{\chi}(i\partial\!\!\!/ - m_\chi)\chi - \frac{1}{2}\frac{\lambda_{h\chi}}{\Lambda_\chi}(\cos\xi\,\overline{\chi}\chi + \sin\xi\,\overline{\chi} i\gamma_5\chi)(v_0 h + \frac{1}{2}h^2). \tag{4}$$

Note: $\xi = 0,\ \pi\ (\pi/2) \implies$ pure scalar (pseudo-scalar) interaction.

- Free model parameters: m_V, λ_{hV} (Vector DM); m_χ, $\lambda_{h\chi}/\Lambda_\chi$ and ξ (Majorana fermion DM).

[1] Similar for a Dirac fermion field ψ.

Constraints

Observational constraints

- Thermal relic density;
- Higgs invisible decays;
- Indirect detection using γ rays;
- Direct detection, e.g., XENON1T, LUX;
- Solar DM capture and annihilation.

Theoretical constraints

- Perturbative unitarity of $VV \to hh$ scattering amplitudes,

$$0 \leq \lambda_{hV} \leq \frac{2m_V^2}{v_0^2}.$$

- EFT validity of Majorana fermion DM model,

$$\frac{\lambda_{h\chi}}{\Lambda_\chi} < \frac{4\pi}{2m_\chi}.$$

Include 7 important Standard Model (SM), nuclear and astrophysical *nuisance parameters*.

Free model and nuisance parameters

Model	Parameter	Minimum	Maximum	Prior type
Vector DM	λ_{hV}	10^{-4}	10	Log
	m_V (low mass)	45 GeV	70 GeV	Flat
	m_V (high mass)	45 GeV	10 TeV	Log
Majorana/Dirac DM	$\lambda_{h\chi,h\psi}/\Lambda_{\chi,\psi}$	10^{-6} GeV^{-1}	1 GeV^{-1}	Log
	ξ	0	π	Flat
	$m_{\chi,\psi}$ (low mass)	45 GeV	70 GeV	Flat
	$m_{\chi,\psi}$ (high mass)	45 GeV	10 TeV	Log

Table 1: Free model parameter ranges and priors.

Parameter		Value ($\pm$ Range)
Local DM density	ρ_0	0.2–0.8 GeV cm^{-3}
Most probable speed	v_{peak}	240 (24) km s^{-1}
Galactic escape speed	v_{esc}	533 (96) km s^{-1}
Nuclear matrix element	σ_s	43 (24) MeV
Nuclear matrix element	σ_l	50 (45) MeV
Higgs pole mass	m_h	124.1–127.3 GeV
Strong coupling	$\alpha_s^{\overline{\text{MS}}}(m_Z)$	0.1181 (33)

Table 2: 7 SM, nuclear and astrophysical parameters varied simultaneously in our scans.