GEORG-AUGUST-UNIVERSITÄT
GÖTTINGEN

Alexander von Humboldt
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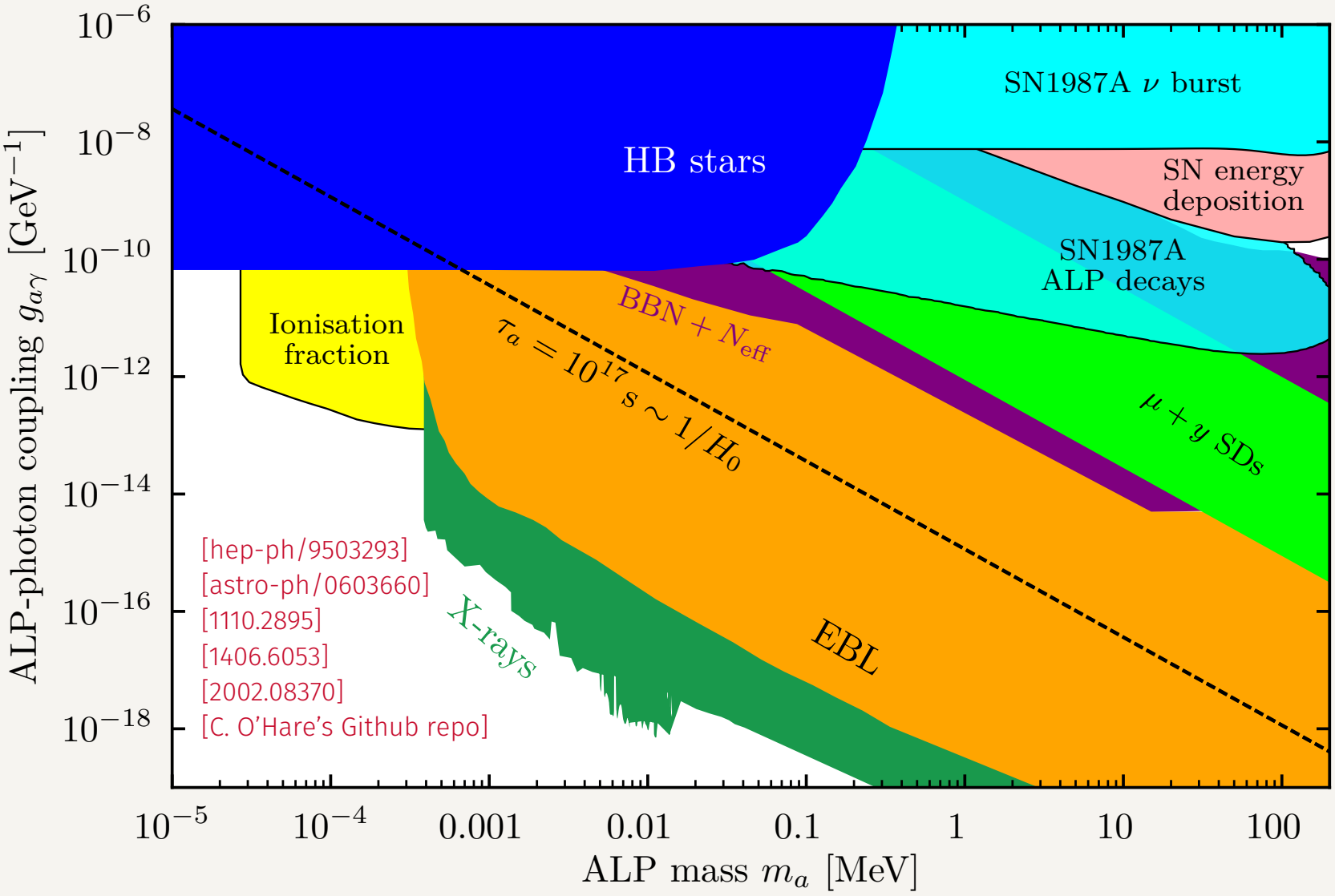
Cosmological constraints on decaying axion-like particles: a global analysis

C. Balázs, S. Bloor, T. E. Gonzalo, W. Handley, **Sebastian Hoof**, F. Kahlhoefer, M. Lecroq, D. J. E. 'Doddy' Marsh, J. J. Renk, P. Scott, and P. Stöcker;

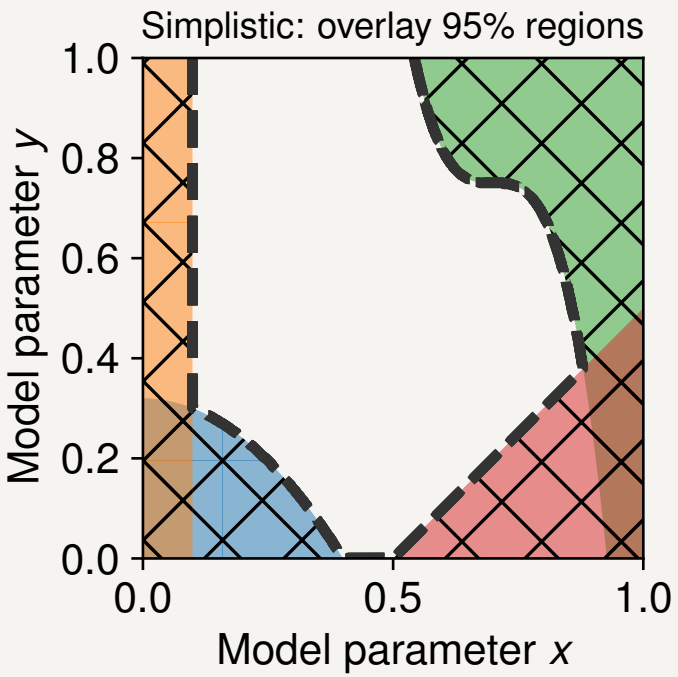
submitted to JCAP [arXiv:2205.13549]

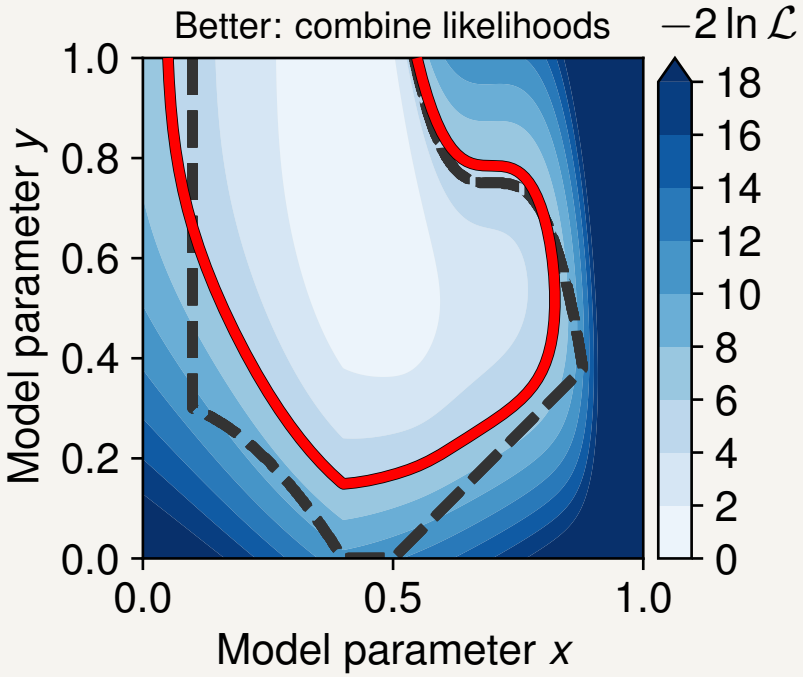
17th Patras Workshop on Axions, WIMPs and WISPs
Mainz, Germany
11 August 2022

High-mass ALPs – cosmologically excluded?



The rationale for global fits





- Overplotted limits may be inconsistent, less powerful
- Better: combine likelihoods + use “smart” optimisers/samplers instead of grid or random scans[2012.09874]

➳ Automatically captures the effect of additonal parameters when projecting down to lower-dimensional plots

Overview

- Global fits with GAMBIT[1705.07908]
- Our ALP model and setup
- Constraints and likelihoods
- Results

Global fits

- We want to *select* the “best” models and *estimate* their parameters using *all available information*
- Information = assumptions, experiments and observations, theoretical reasoning, ...

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- Both Bayesian and frequentist analyses are based on the composite likelihood function as a starting point
- Ideally, this is done within an easily extendable, consistent, modular software framework $\rightarrow$ GAMBIT

The GAMBIT framework

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- defines a model (collection of parameters),
- writes functions to calculate observables,
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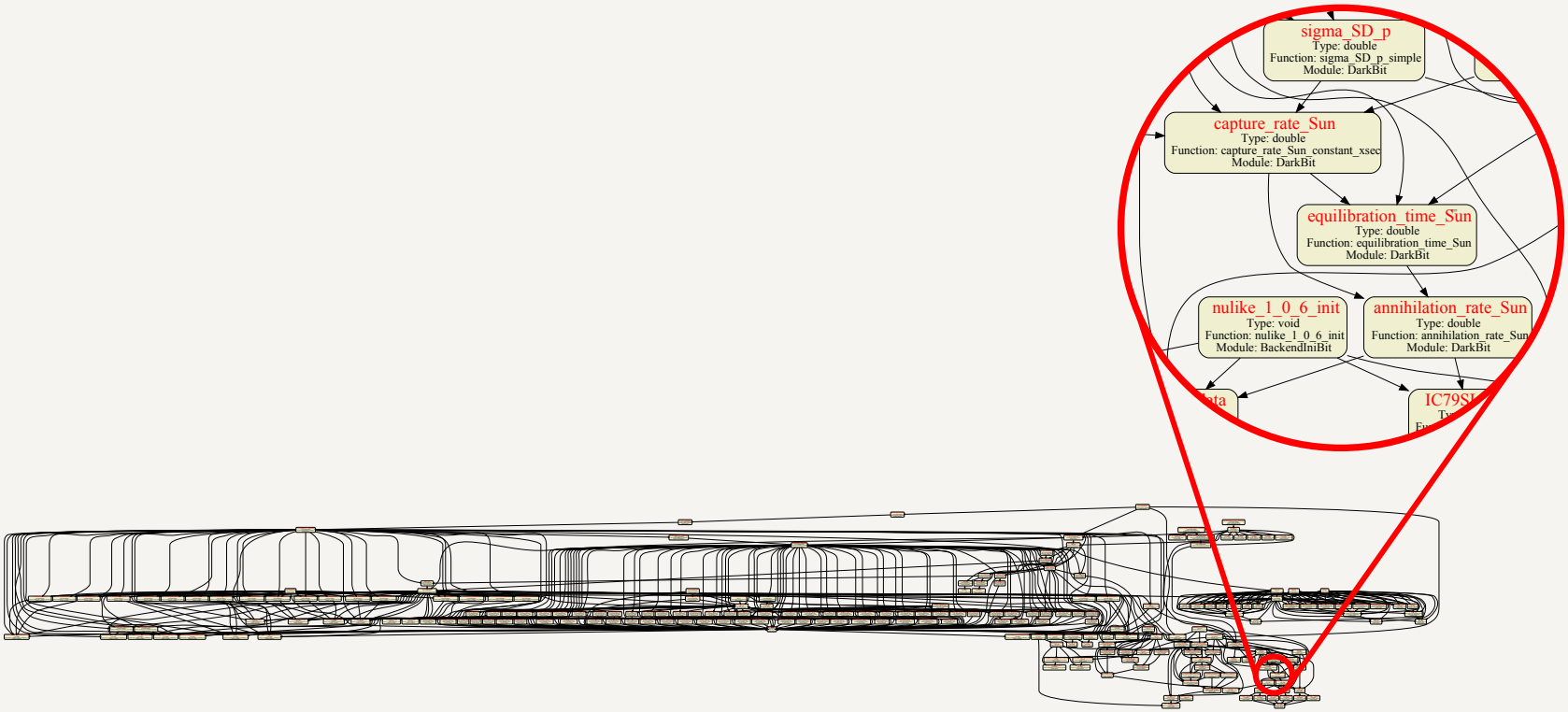
GAMBIT takes care of...

- the order in which all elements are calculated,
- connecting external software,
- communication with sampling algorithms,
- bookkeeping of observables and likelihoods.

The GAMBIT framework

- Internally, GAMBIT "solves" the *dependency tree* of all required module functions using graph theory
- Requested observables & likelihoods $\mapsto$ dependencies and (external) code requirements



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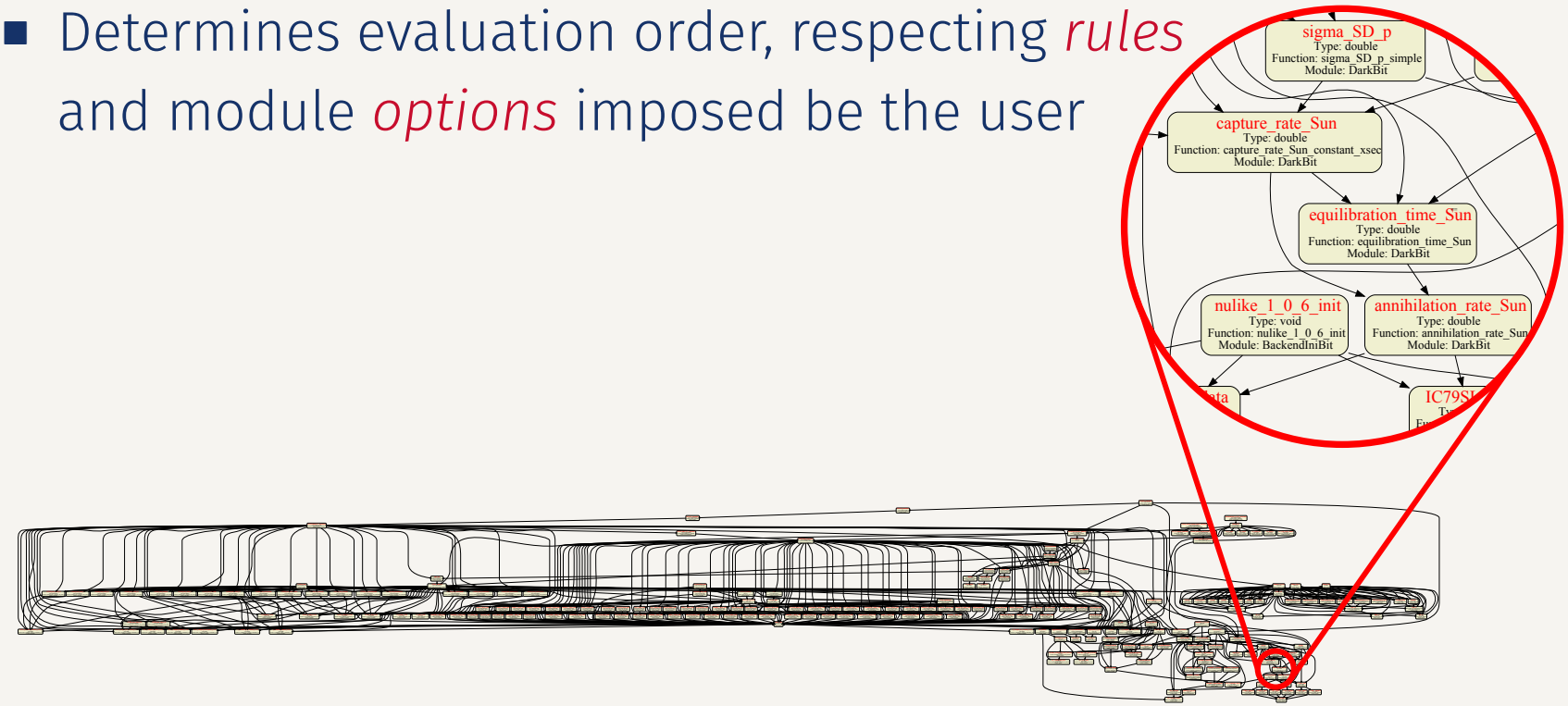

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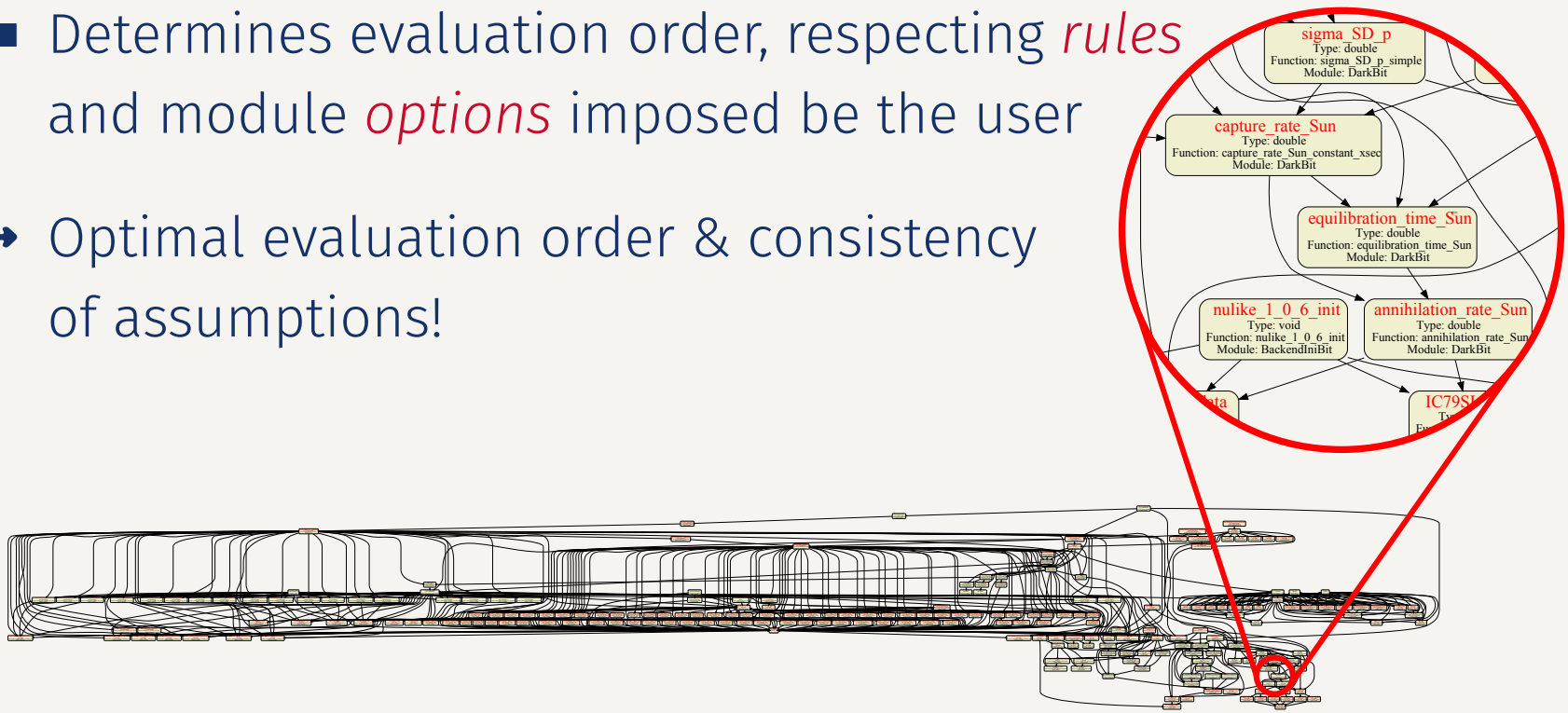
➳ Optimal evaluation order & consistency of assumptions!



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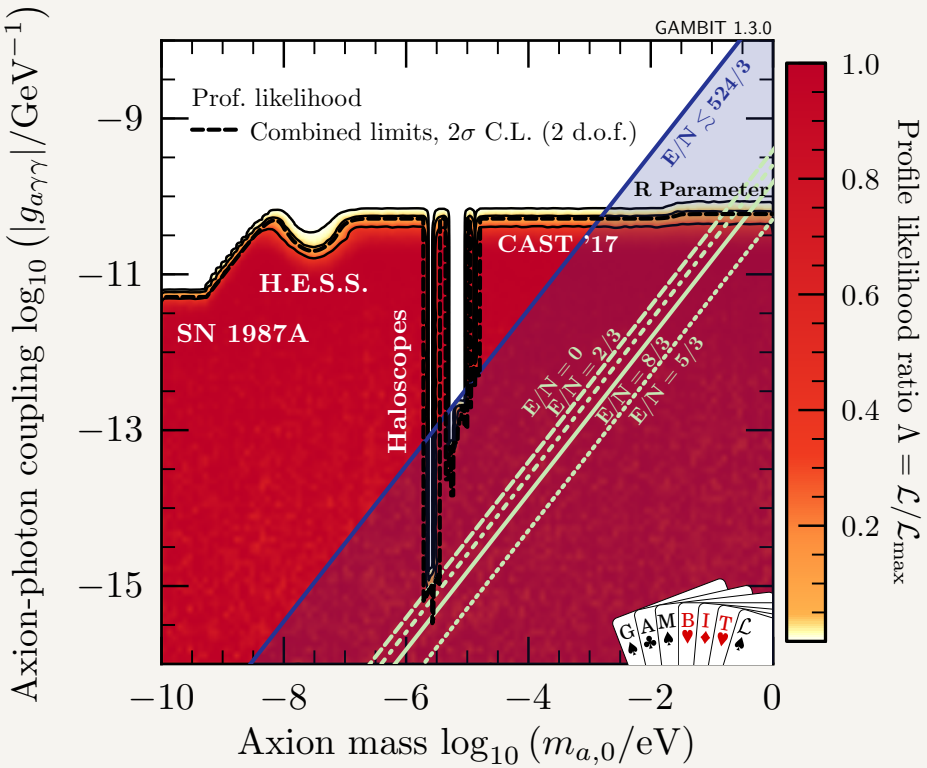
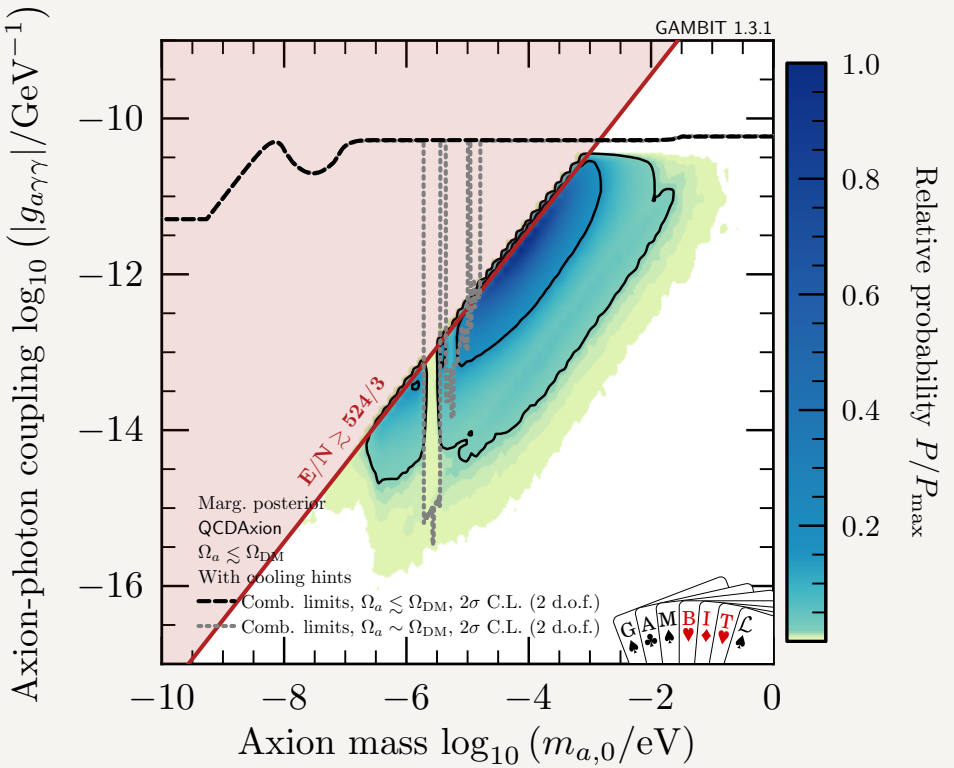
- Studies on SUSY models, WIMPs, scalar singlet, Higgs portal, RHNs, cosmological neutrino mass limits, axion models, Xenon1T excess, ... GAMBIT publication list
- Code on Github, statistical samples, likelihood values, plotting tools for most studies available on Zenodo!

GitHub zenodo

Previous study – axions with preinflation PQ breaking





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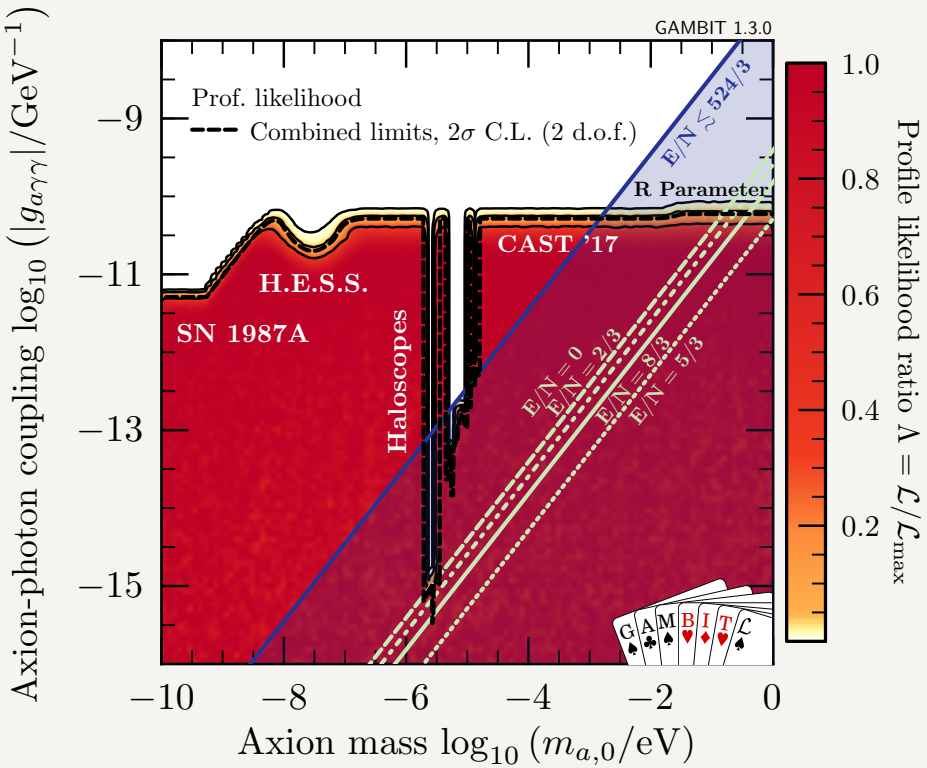
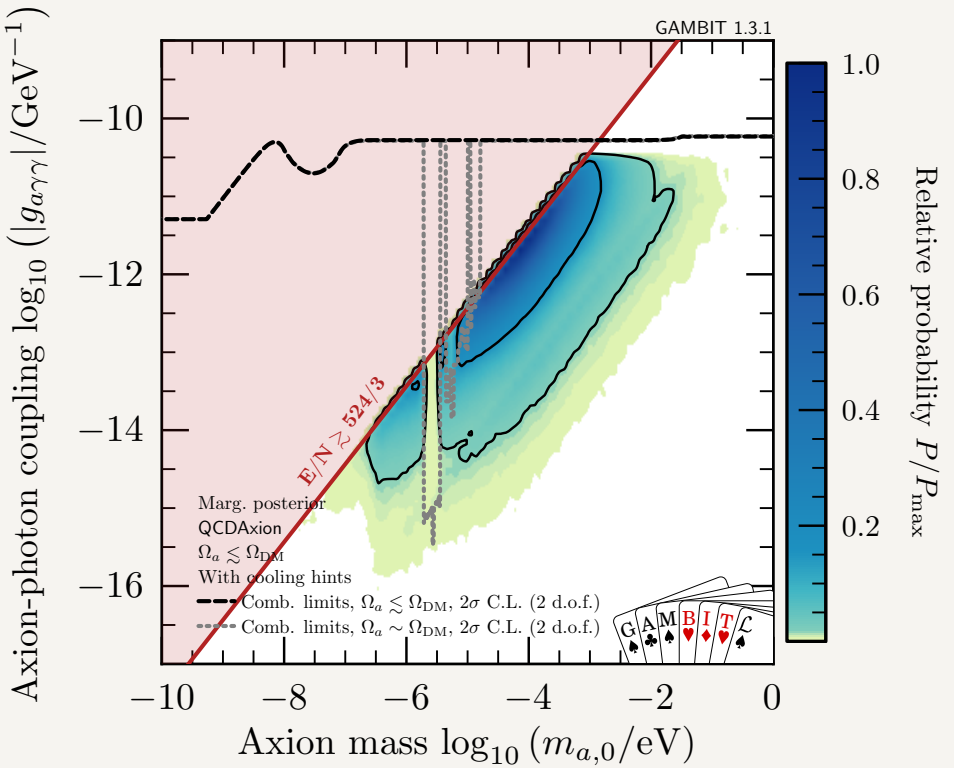
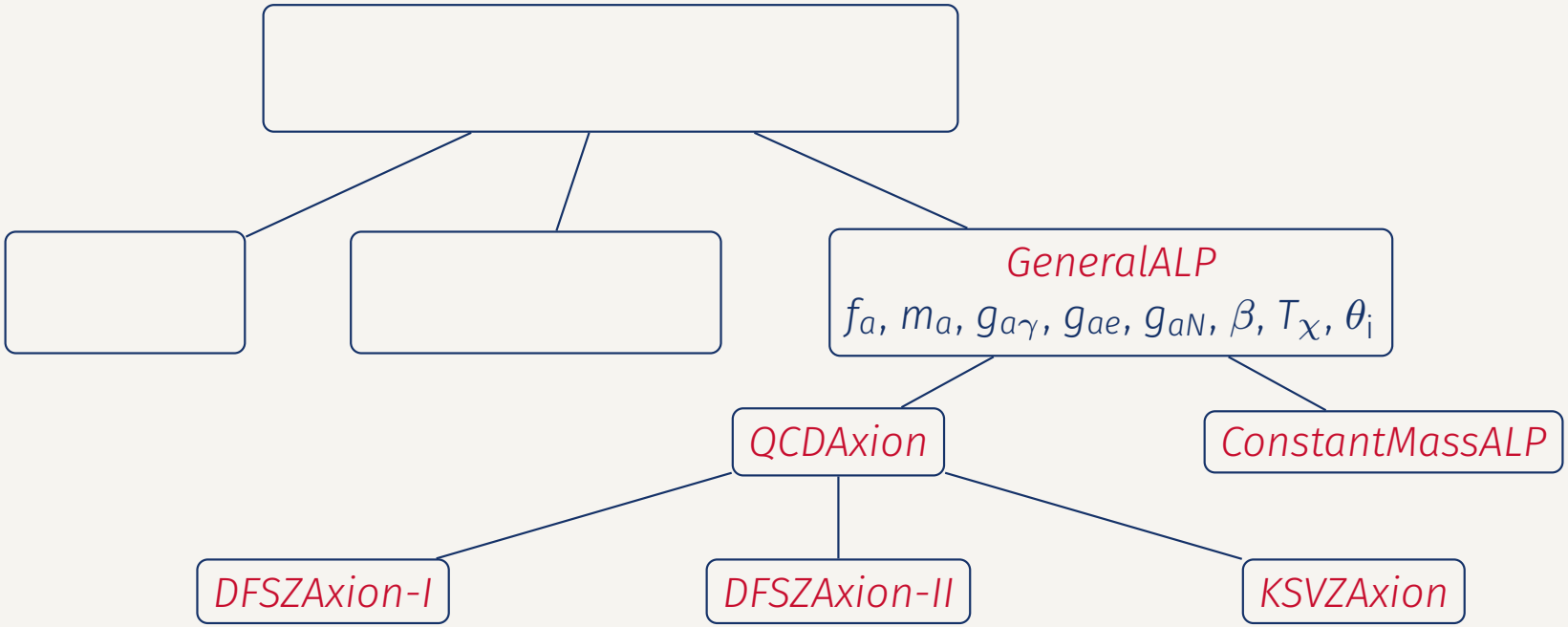




- Incl. many constraints, also Bayesian analysis to identify "natural" mass ranges, abundances[1810.07192]
- Drawback: prior dependence; improved now by theory-informed priors on E/N from complete catalogue of "theoretically preferred"[1705.05370] KSVZ models[2107.12378]

The GAMBIT framework – models

Can extend "family tree" of ALP models from the previous study[1810.07192] to work with "CosmoBit" extension[2009.03286, 2009.03287]



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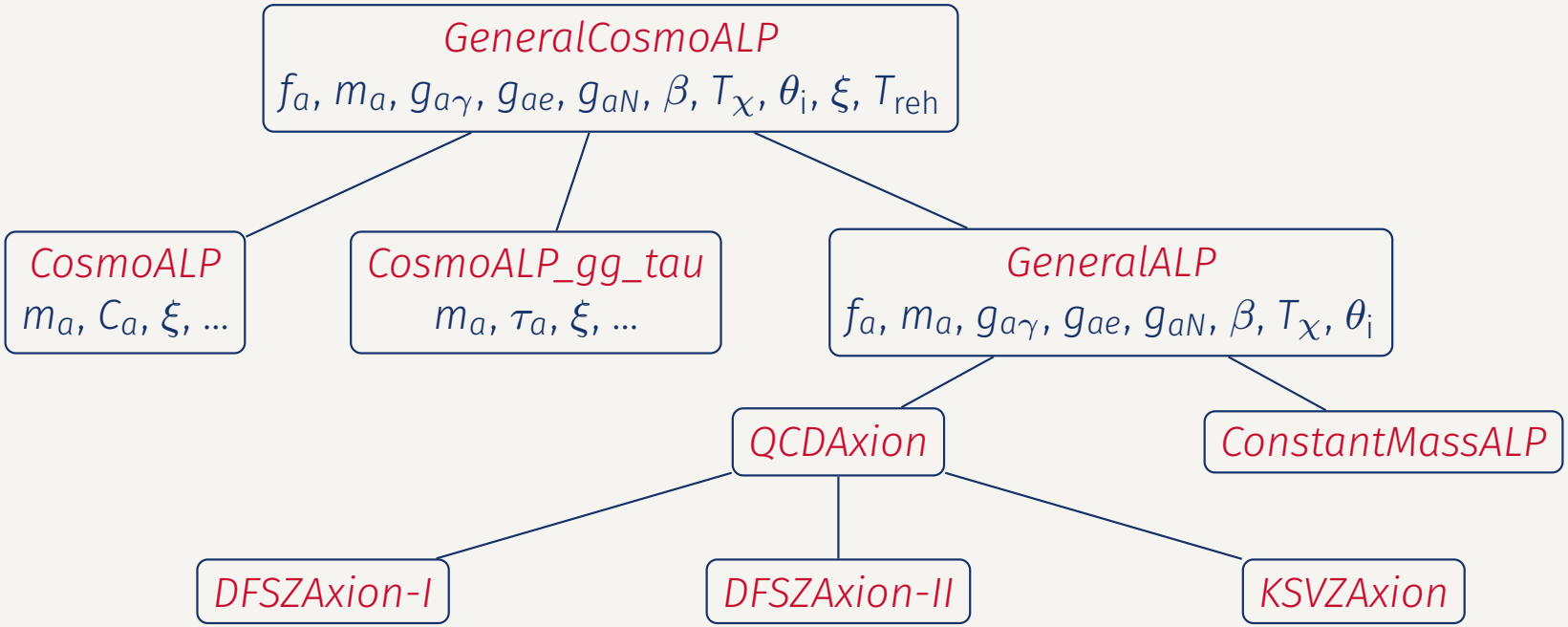

- New params: abundance ξ and reheating temperature T_{reh}
- Automatic parameter translation: can use pre-existing axion likelihoods out of the box

The ALP model

GeneralCosmoALP
8 model parameters:
f_a, m_a, $g_{a\gamma}$, g_{ae}, g_{aN}, β, T_χ, θ_i, ξ, T_reh

- Only interaction: coupling to photons via $\mathcal{L} \propto g_{a\gamma}\, \vec{E} \cdot \vec{B}$

The ALP model

GeneralCosmoALP
6 model parameters:
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- Simple ALP: m_a const.

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- Simple ALP: m_a const.
- Thermal and realignment contributions to ξ but we focus on irreducible freeze-in mechanism[0911.1120]

$$\xi_{\rm FI} \sim \left(\frac{m_a}{50\,\text{MeV}}\right)\left(\frac{T_{\rm reh}}{5\,\text{MeV}}\right)\left(\frac{g_{a\gamma}}{10^{-10}\,\text{GeV}^{-1}}\right)^2 \mathrm{e}^{-m_a/T_{\rm reh}}$$

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3 model parameters:
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- Choose ξ as free parameter (multi-component DM model), fix $T_\mathrm{reh} = 5\,\mathrm{MeV}$ to ignore degeneracies

The ALP model

CosmoALP_gg_tau
3 model parameters:
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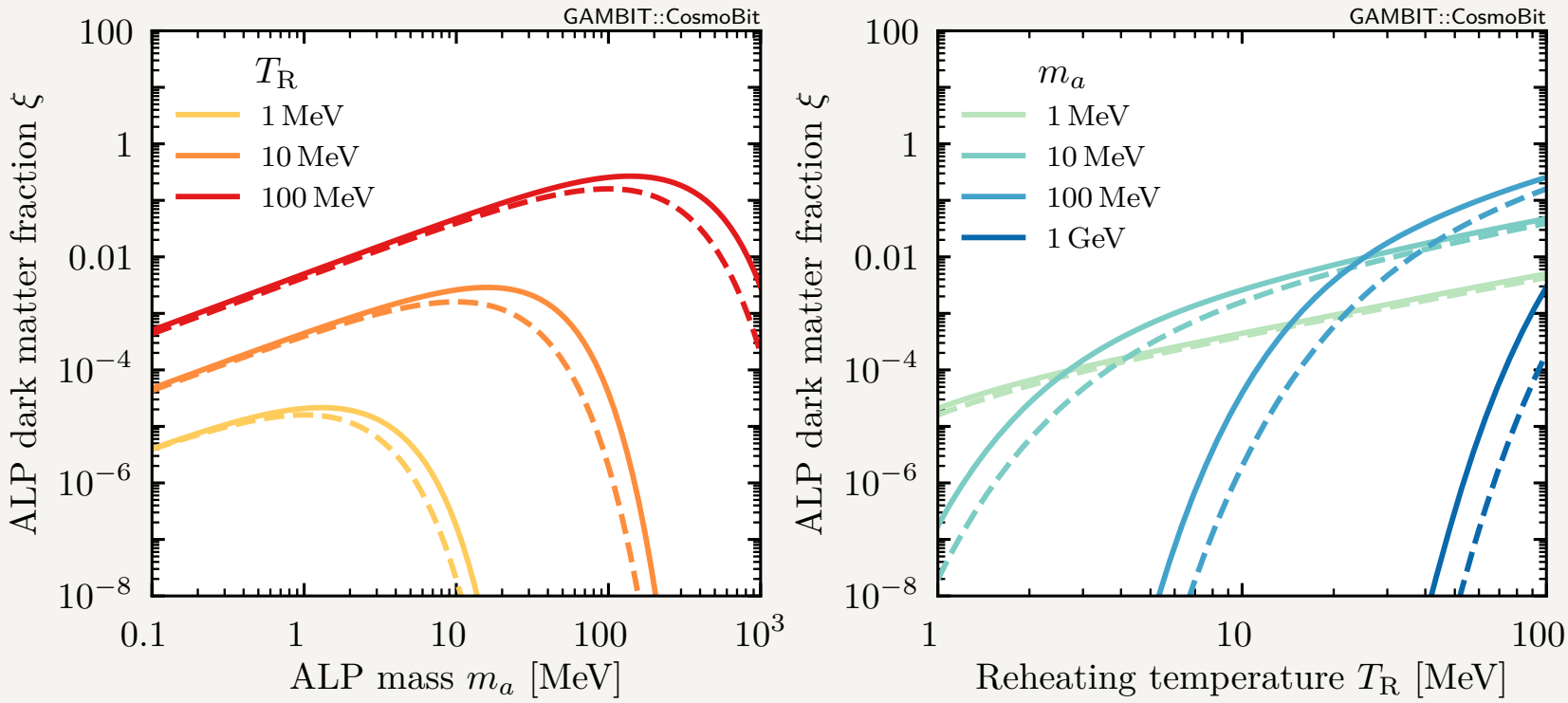
➳ Parameters: mass m_a, lifetime $\tau_a \leftrightarrow g_{a\gamma}$, abundance ξ

ALP DM from freeze-in



- Precalculate and tabulate freeze-in contribution to nonthermal abundance (ξ_{FI}) with micrOMEGAs
- Ensure consitently that $\xi \geq \xi_{FI}$ by invalidating points otherwise

The cosmological model

- 6-parameter ΛCDM model: ω_b, ω_c, H_0, z_{re}, A_s, n_s
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- Can the ^{7}Li problem[1203.3551] be improved by ALPs?[2011.06519]
- ROI: $0.01\,\mathrm{MeV} < m_a < 200\,\mathrm{MeV}$; $10^4\,\mathrm{s} < \tau_a < 10^{13}\,\mathrm{s}$, i.e. decays between BBN and CMB formation

Constraints & likelihoods in target region

Cosmology

- CMB anisotropies (modification of recombination history)
- CMB spectral distortions (SDs; energy injection from ALPs)
- BBN element abundances (photodisintegration)
- $\Delta N_{\rm eff}$, $\eta_{\rm b}$ (photon injection/higher T_γ)
- BAO (structure formation)

Astrophysics

- SN1987A missing gamma-ray burst (ALP decays), our update of [1702.02964]
- HB vs RGB star counts (stellar evolution, cooling)
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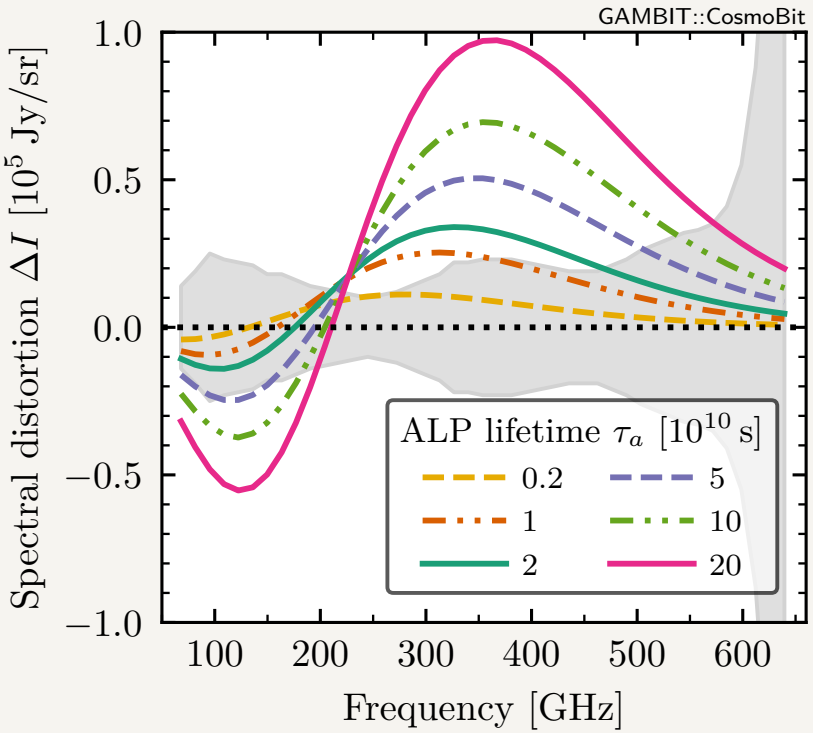
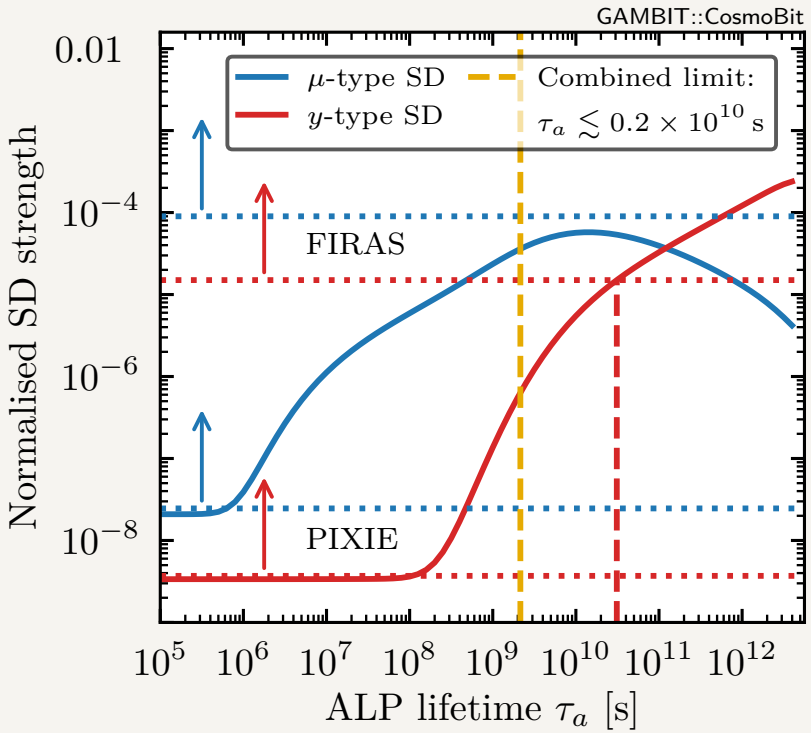
➽ Not all constraints are equally relevant in this study

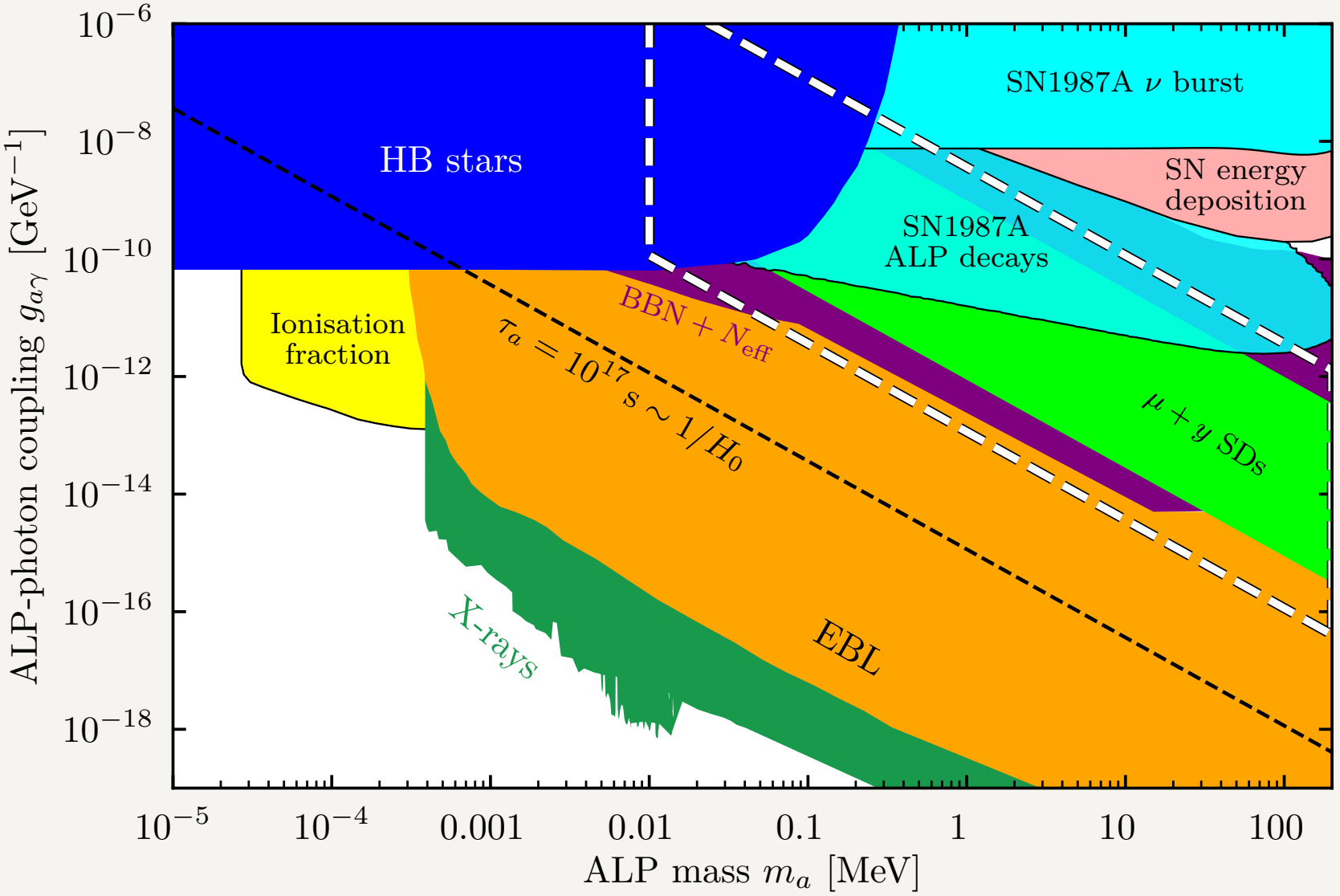
ALP constraints from spectral distortions (SDs)





- ALPs with $\tau_a \lesssim 10^{10}$ s induce larger-than-observed SDs
- Total SD shape (from CLASS/MontePython) is significantly more constraining than μ or y SDs individually
- Proposed future CMB missions (e.g. PIXIE) would give orders of magnitude stronger constraints

Results – ALP limits



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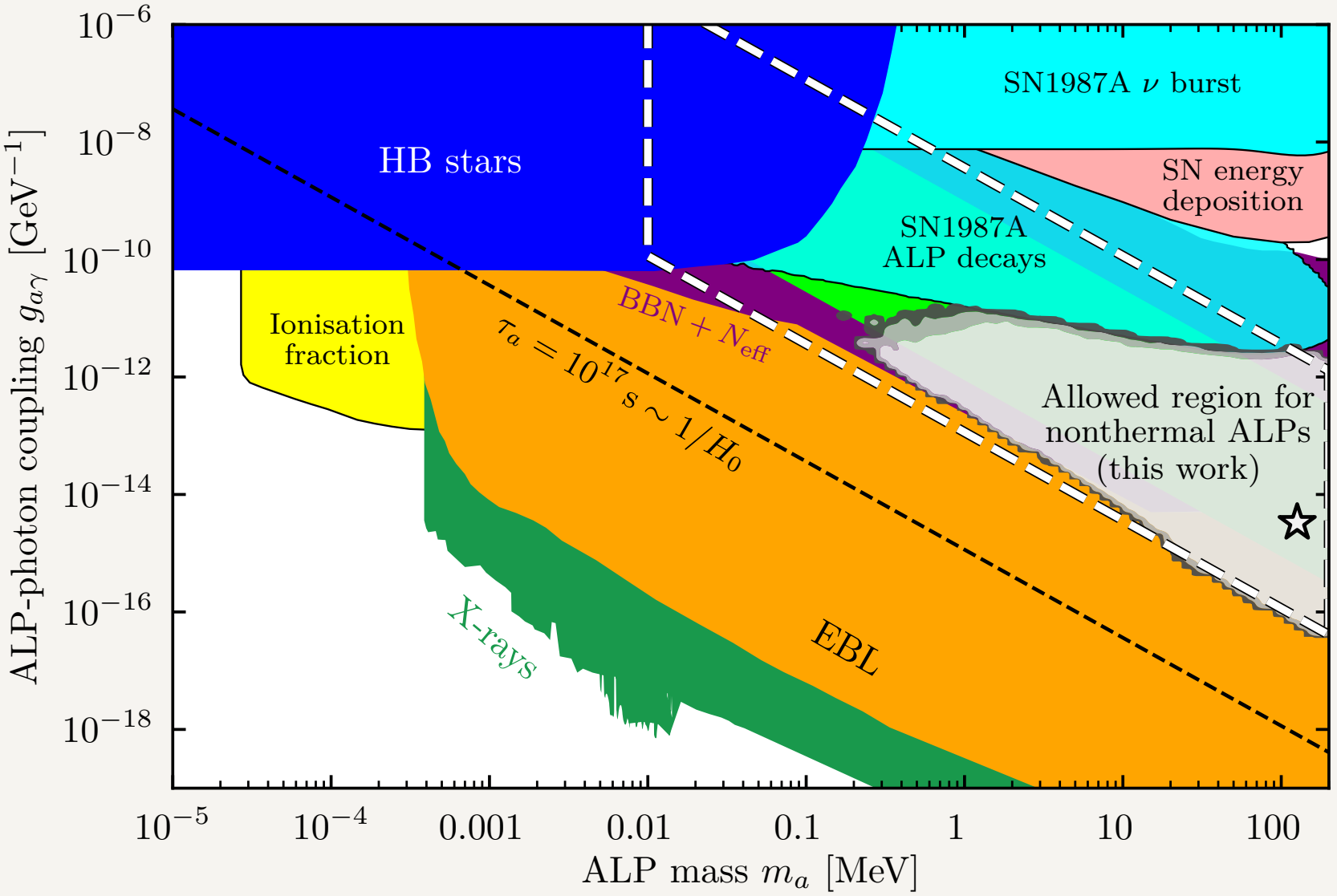
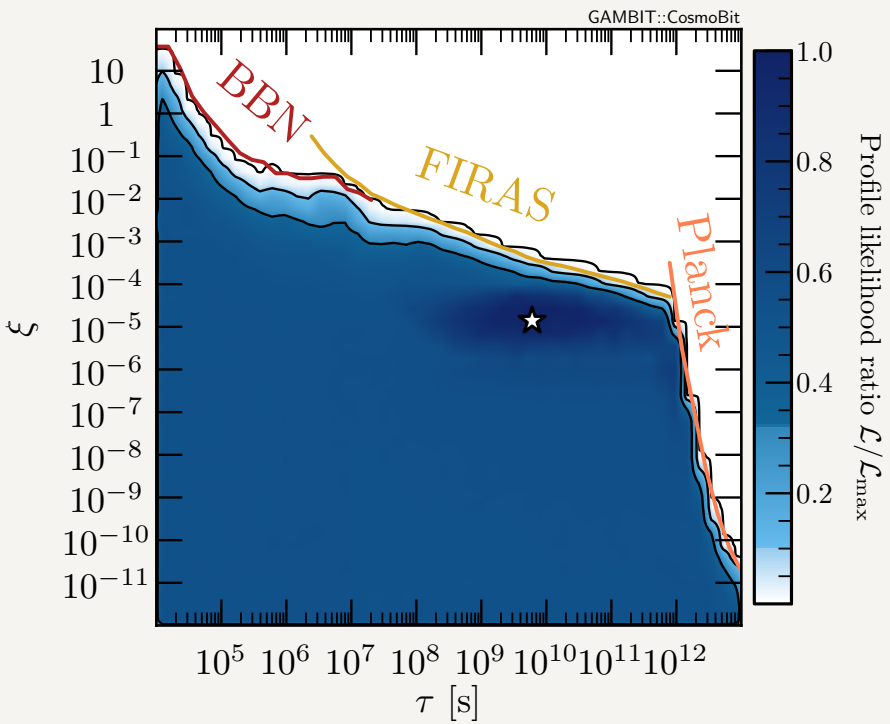
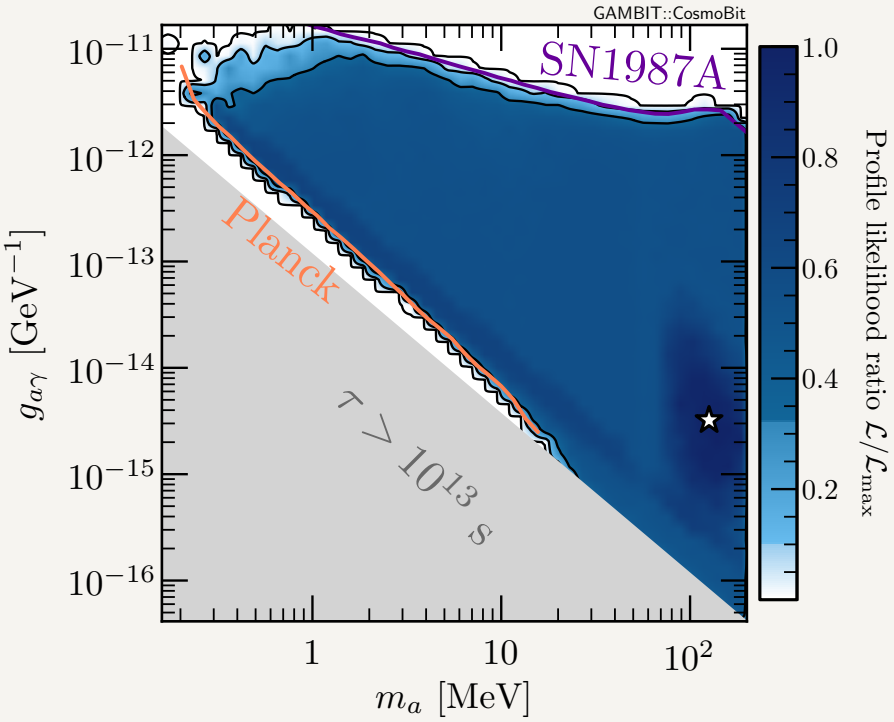


Results – projected ALP limits

Can also easily plot the profile likelihood for other paramter combinations and compare to individual constraints:





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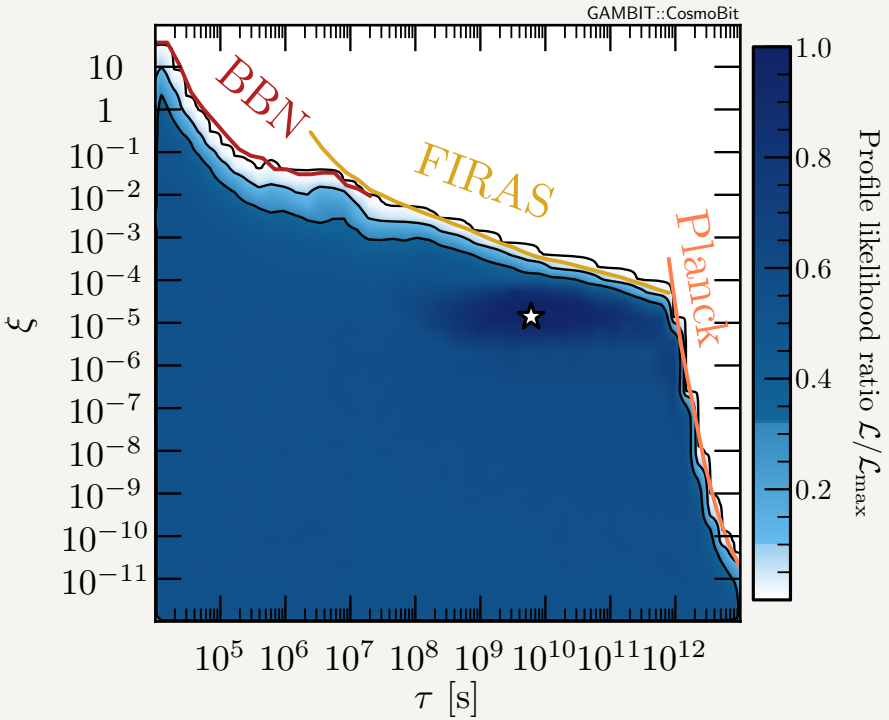
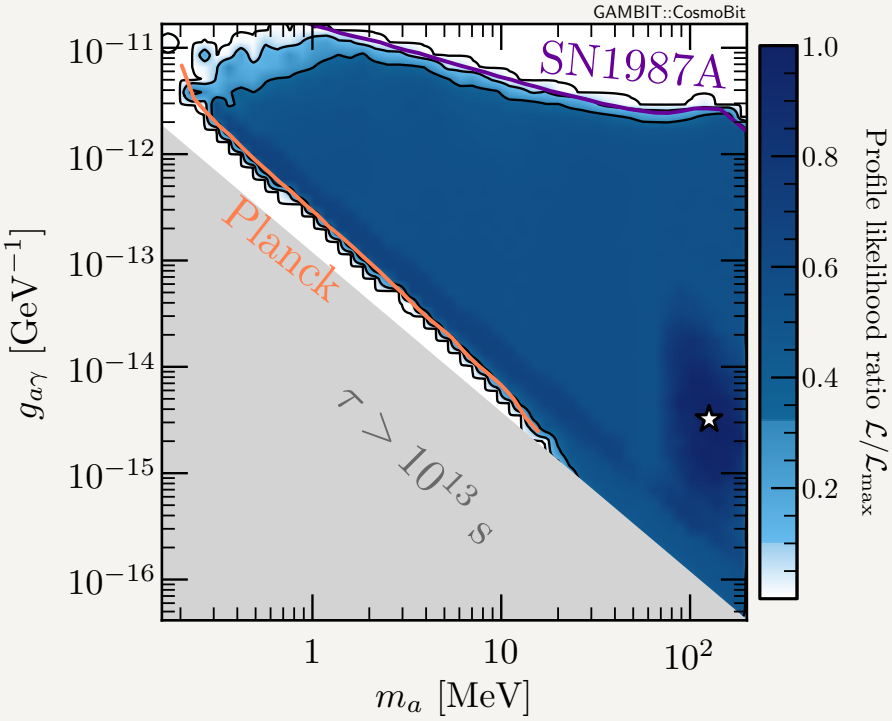


Mostly cosmo constraints



No loopholes (ξ) for astro constraints

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- However: very low significance $< 1\sigma$; also does not help with ^{7}Li problem
- Bayesian analysis with two prior choices: ΛCDM+ALP *not* preferred over ΛCDM (odds of 1:3 and 1:7)

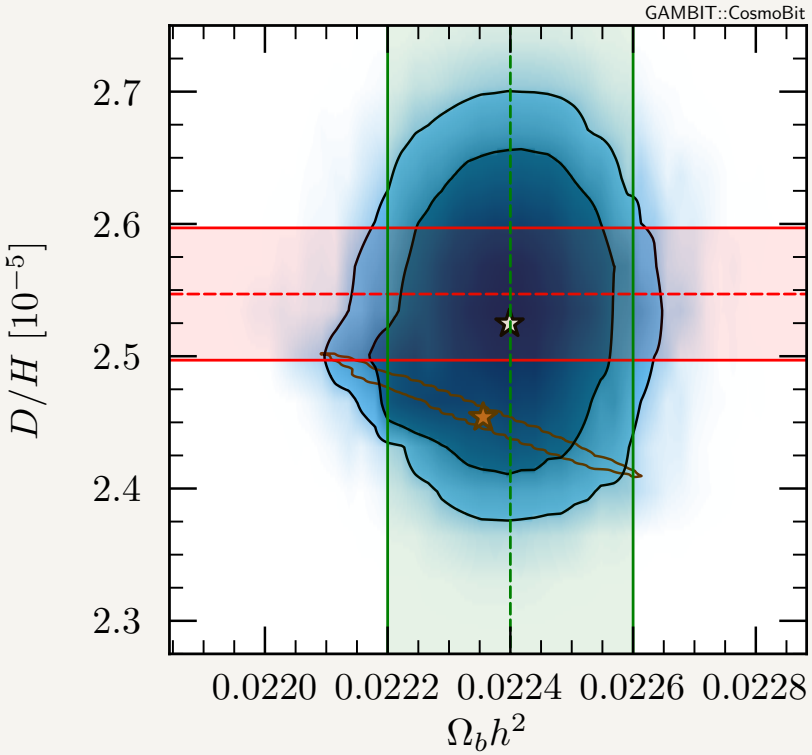
↣ Not a hint for ALPs; they slightly improve the fit but introduce too many new parameters

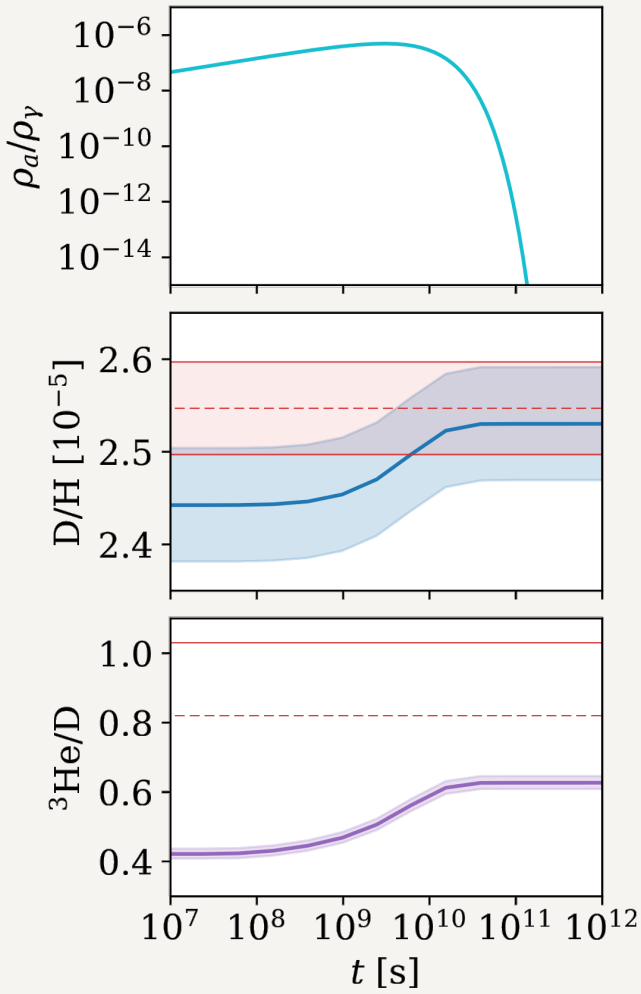
Summary

- Global-fitting frameworks (GAMBIT) can perform powerful analyses in many parameter dimensions consistently by including complementary constraints
- Heavy ALPs are still viable in cosmology ...
- ... but cannot solve ^{7}Li problem due to SD constraints
- Look forward to future CMB missions, studying ALPs with ALP-electron interactions, etc.
- Future SD missions can exclude our best-fitting region around $m_a \sim 130\,\text{MeV}$, $g_{a\gamma} \sim 3 \times 10^{-15}\,\text{GeV}^{-1}$

Backup slides

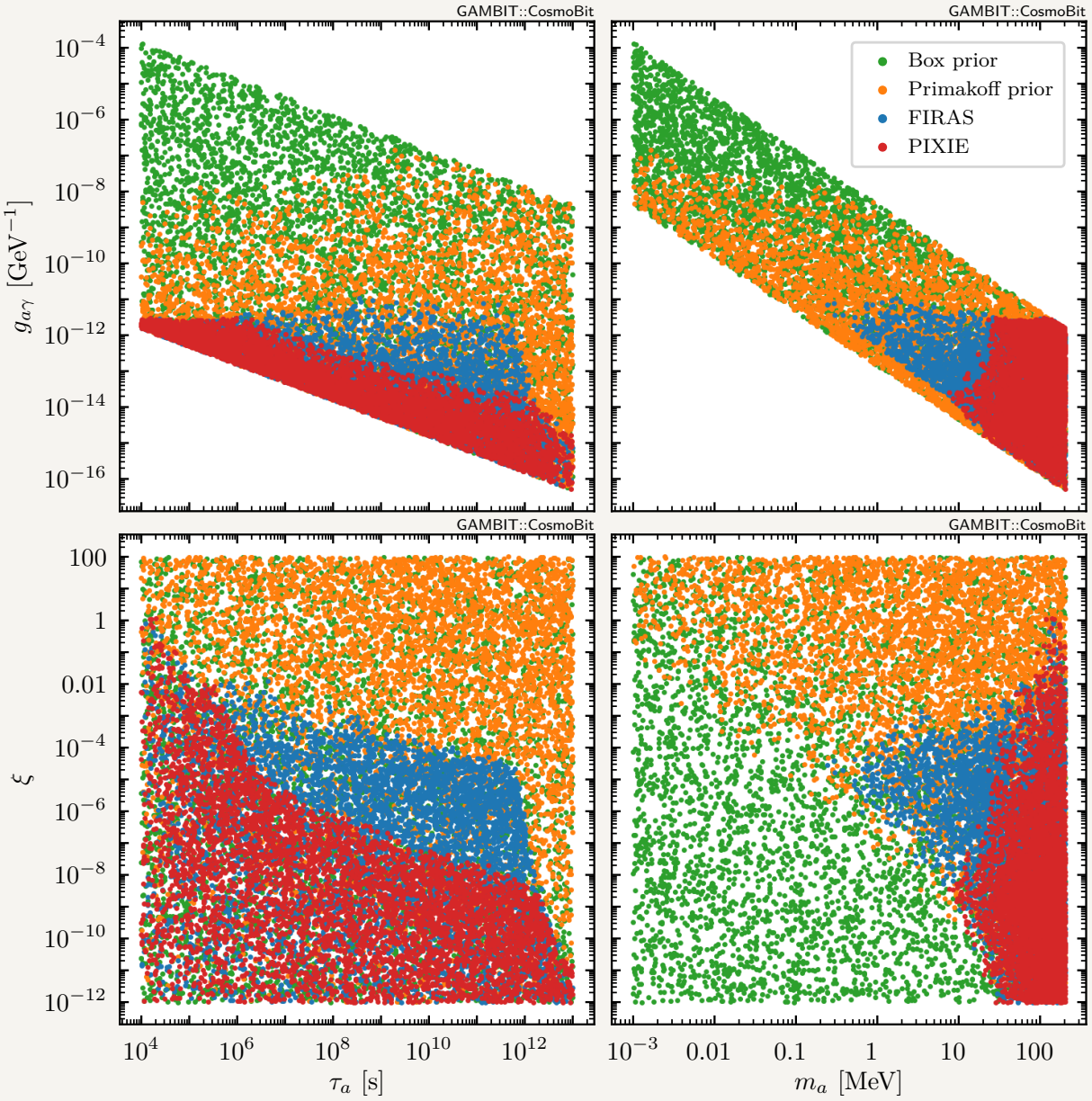
Improvement of the fit





- ALPs slightly ($< 1\sigma$) improve fit
- In ΛCDM: correlation between $\Omega_b h^2$ & [D/H]; for ΛCDM+ALPs: no corr. due to photodisintegration

Bayesian results



Nested sampling runs (with Polychord)