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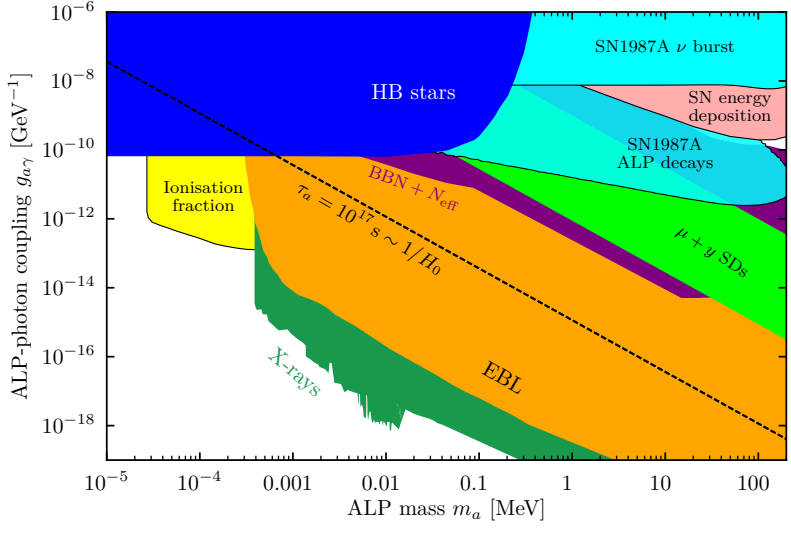
Cosmological constraints on decaying axion-like particles: a global analysis

8th Symposium on Prospects in the Physics of Discrete Symmetries – Baden-Baden (Germany)

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 | 8 November 2022

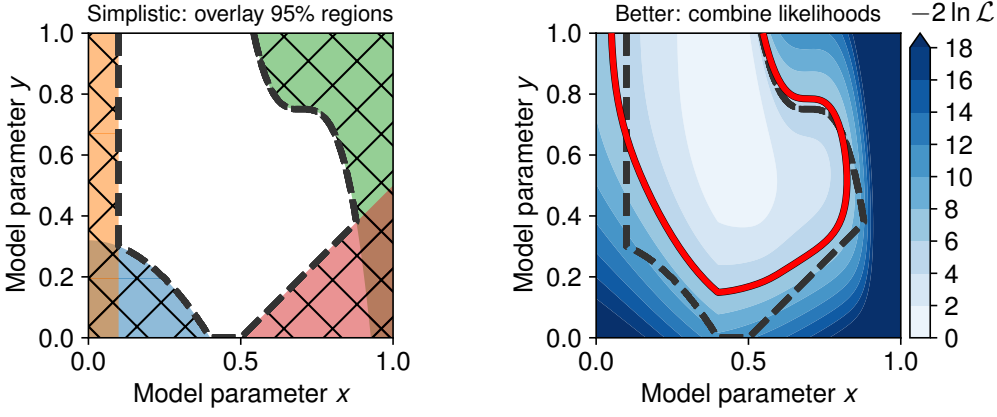
High-mass ALPs – cosmologically excluded?



[hep-ph/9503293]
[astro-ph/0603660]
[1110.2895]
[1406.6053]
[2002.08370]
C. O'Hare's Github repo

Also: talks about...
...thermal axions: F. D'Eramo (Thu)
...other axion DM constraints: J. Jaeckel (Fri)

The rationale for global fits



- Overplotted limits may be inconsistent, less powerful
- Better: combine likelihoods + use "smart" optimisers instead of grid scans[2012.09874]
- ➳ Captures effect of additional parameters when projecting down to lower-dimensional plots

Global fits with the GAMBIT framework

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The user...

- defines a model (collection of parameters),
- writes functions to calculate observables,
- takes experimental results and turns them into likelihoods.

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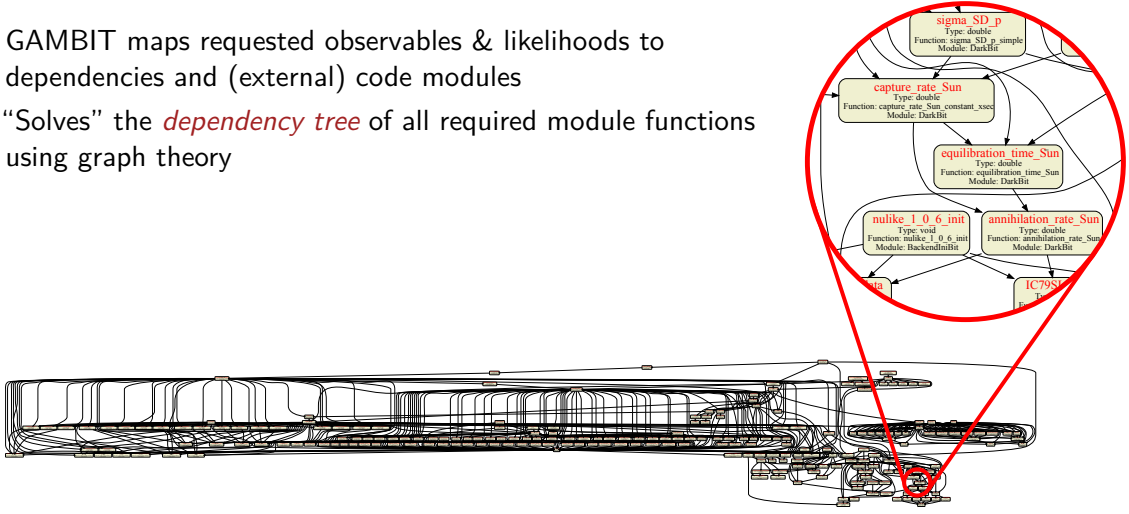
GAMBIT takes care of...

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

Global fits with the GAMBIT framework

- GAMBIT maps requested observables & likelihoods to dependencies and (external) code modules
- "Solves" the *dependency tree* of all required module functions using graph theory



Global fits with the GAMBIT framework

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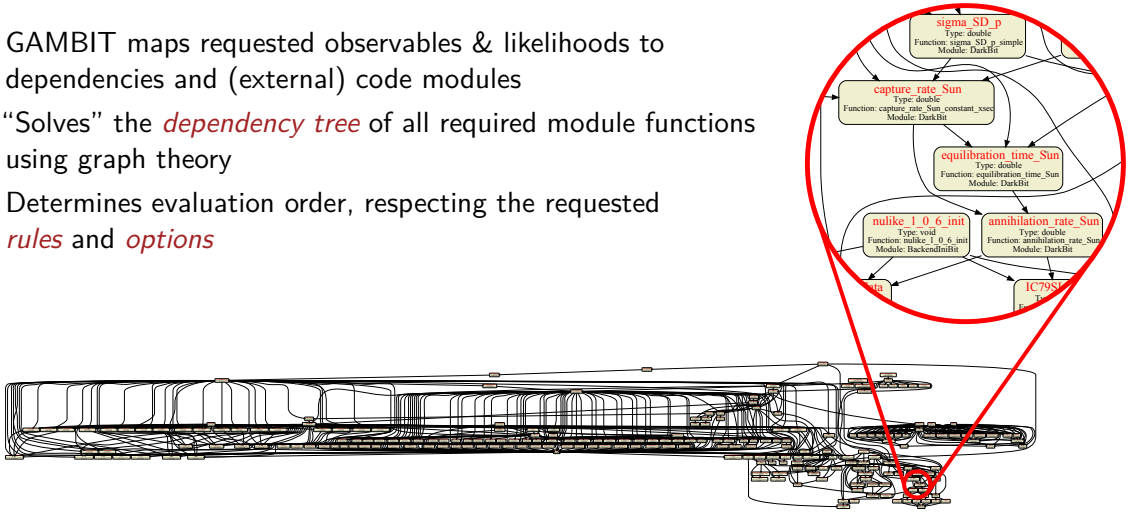

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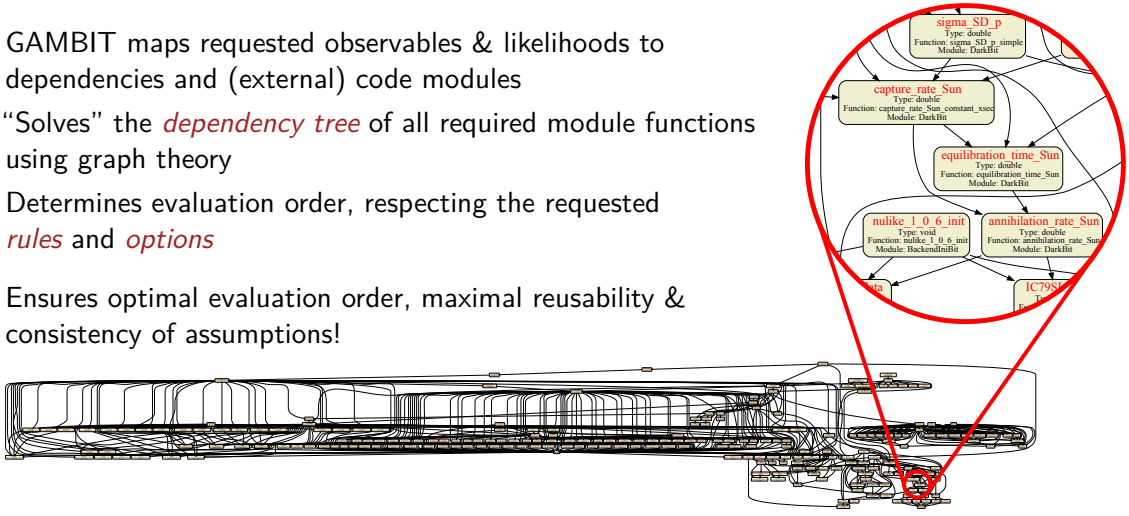
↠ Ensures optimal evaluation order, maximal reusability & consistency of assumptions!



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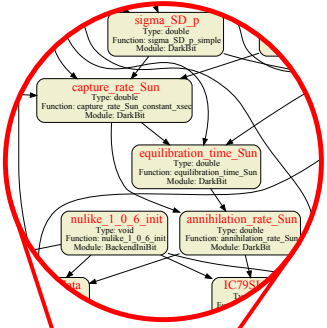
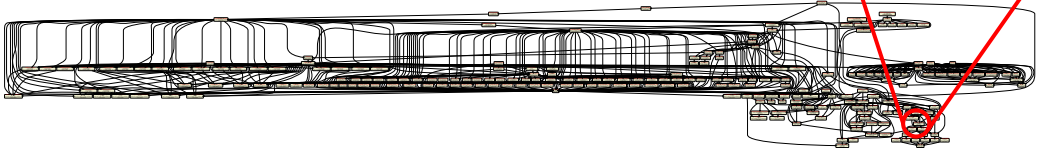
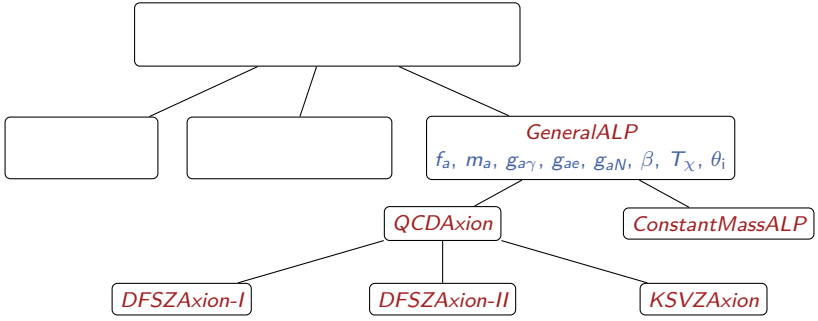
See also: talks by T. Gonzalo & Ch. Chang this session!





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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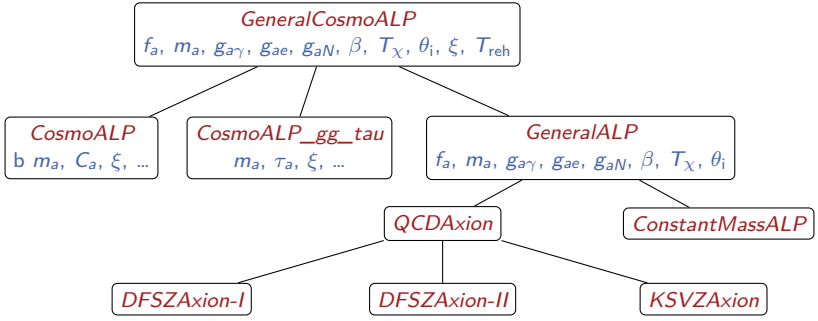

- New params: abundance ξ and reheating temperature T_{reh}
- Automatic parameter translation: can use pre-existing axion likelihoods out of the box

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.

The ALP model

GeneralCosmoALP

4 model parameters:

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- Thermal and realignment contributions to ξ but we focus on irreducible freeze-in production[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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The ALP model

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

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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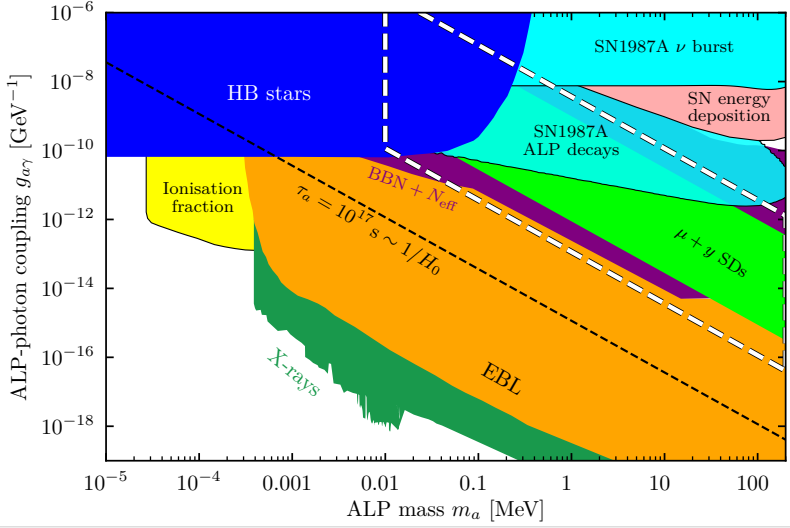
↠ Not all constraints are equally relevant in this study

Results – ALP limits [2205.13549]



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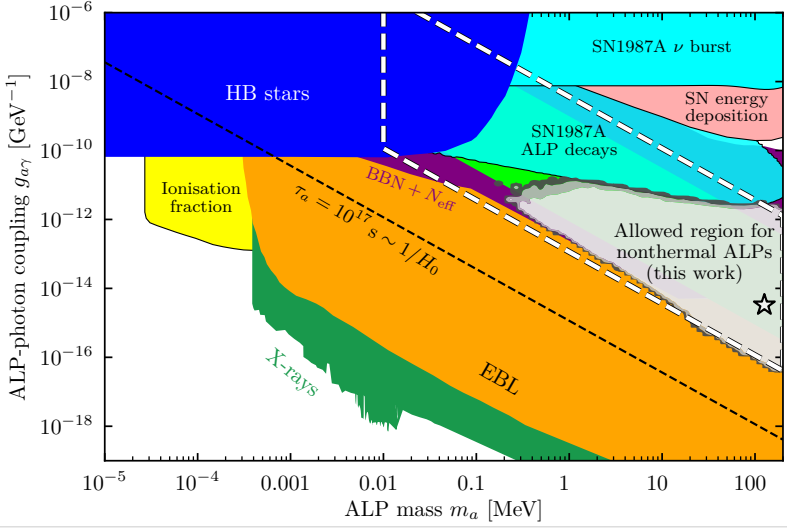


On the best-fitting point

- Find unique best-fitting point (☆) since ALPs can improve agreement between predicted and observed $[\mathrm{D/H}]$ ratio (photodisintegration of elements)
- However: not significant ($< 1\sigma$); also does not help with ^{7}Li problem
- Bayesian analysis: ΛCDM+ALP *not* preferred over ΛCDM (odds of 1:3 or 1:7, depending on priors)

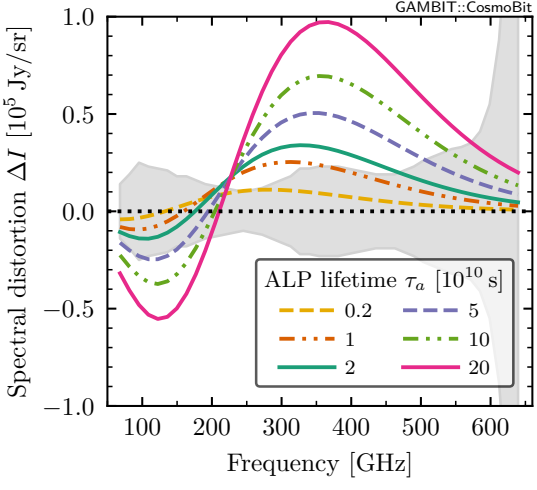
➳ Not a hint for ALPs; they slightly improve the fit but introduce too many new parameters

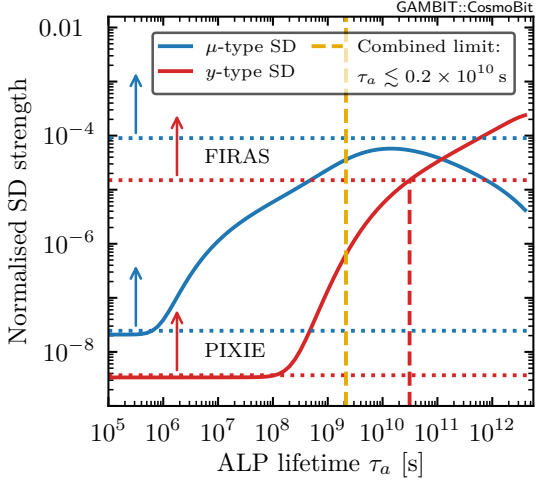
Summary

- 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 data, studying ALPs with ALP-electron interactions, etc.
- Future SD missions can exclude our best-fitting region around $m_a \sim 130\,\text{MeV}$, $g_{a\gamma} \sim 3 \times 10^{-15}\,\text{GeV}^{-1}$

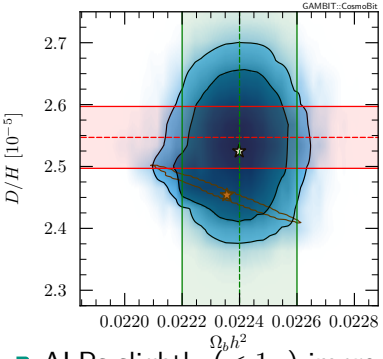
Backup slides

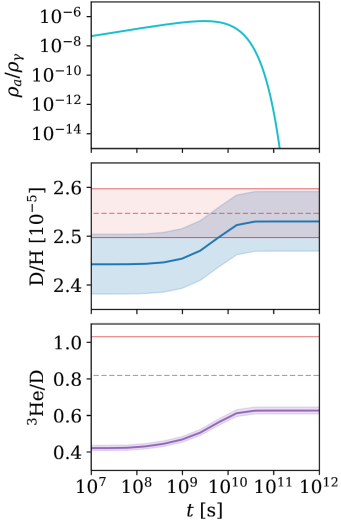
ALP constraints from spectral distortions (SDs)





Improvement of the fit

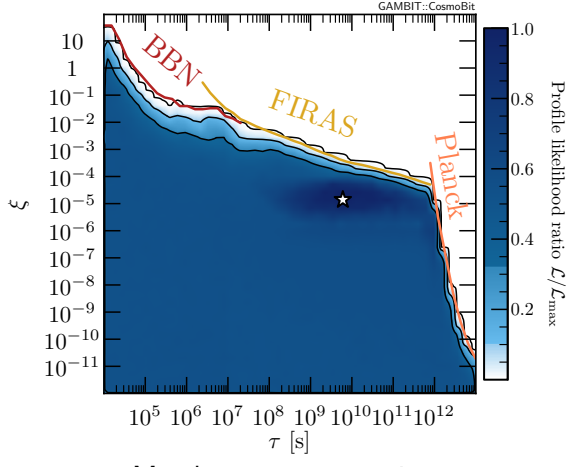




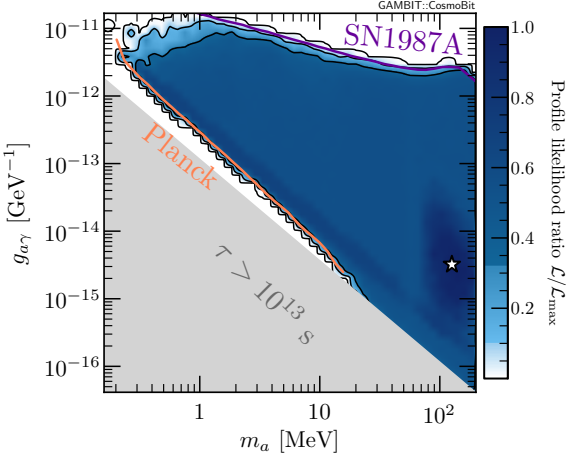
- ALPs slightly ($< 1\sigma$) improve fit
- ΛCDM: correlation between $\Omega_b h^2$ & [D/H]
- ΛCDM+ALPs: no corr. due to photodisintegration

Results – projected ALP limits

Profile likelihood for other parameter combinations and compare to individual constraints:

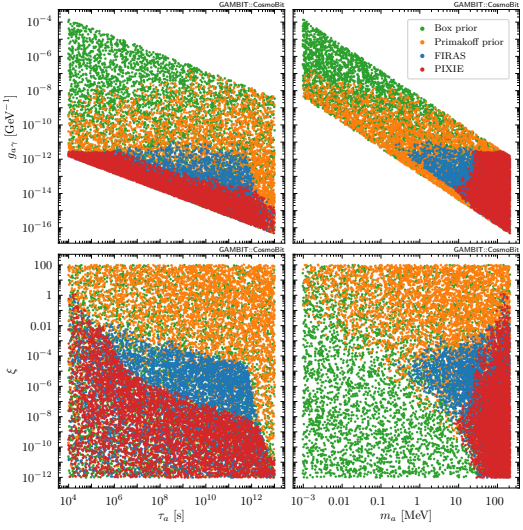


Mostly cosmo constraints



No loopholes (ξ) for astro constraints

Bayesian results



Nested sampling runs (with Polychord[1506.00171])