



# Axion Global Fits with Peccei-Quinn Symmetry Breaking Before Inflation using GAMBIT

Sebastian Hoof, F. Kahlhoefer, P. Scott, C. Weniger, and M. White

arXiv:1810.0xxxx

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DESY Theory Workshop  
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## Global fits

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- Ideally, this is done within an easily expandable, consistent, modular software framework → GAMBIT.

# GAMBIT: The Global And Modular BSM Inference Tool

[gambit.hepforge.org](http://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

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

**Authors of:** DarkSUSY, DDCalc, Diver,  
FlexibleSUSY, gamlike, GM2Calc,  
IsaJet, nulike, PolyChord, Rivet,  
SOFTSUSY, SuperIso, SUSY-AI,  
WIMPSim



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



## Collaborators:

Peter Athron, Csaba Balázs, Ankit Beniwal, Florian Bernlochner, Sanjay Bloor, Torsten Bringmann, Andy Buckley, Eiel Camargo-Molina, Marcin Chrząszcz, Jan Conrad, Jonathan Cornell, Matthias Danninger, Tom Edwards, Joakim Edsjö, Ben Farmer, Andrew Fowlie, Tomás Gonzalo, Will Handley, Sebastian Hoof, Selim Hotinli, Felix Kahlhoefer, Suraj Krishnamurthy, Anders Kvellestad, Julia Harz, Paul Jackson, Tong Li, Greg Martinez, Nazilla Mahmoudi, James McKay, Are Raklev, Janina Renk, Chris Rogan, Roberto Ruiz de Austri, Patrick Stoecker, Roberto Trotta, Pat Scott, Nicola Serra, Daniel Steiner, Puwen Sun, Aaron Vincent, Christoph Weniger, Sebastian Wild, Martin White, Yang Zhang

40+ participants in 10 Experiments & 14 major theory codes

# What GAMBIT can do for you

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- takes experimental results and turns them into likelihoods.

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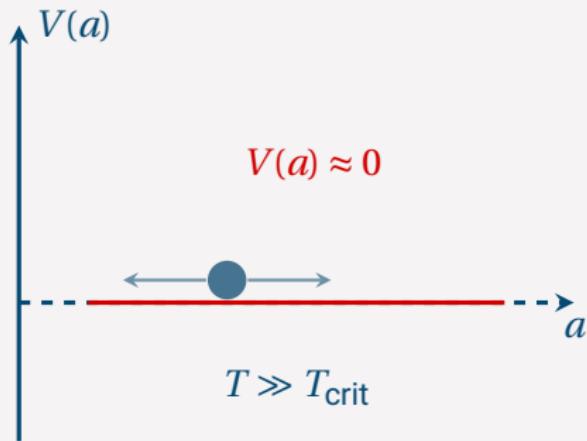
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## GAMBIT deals with...

- the order in which all elements are calculated,
- connecting external software,
- communication with sampling algorithms, Martinez+ (GAMBIT Collab. '17)
- bookkeeping of observables and likelihoods.

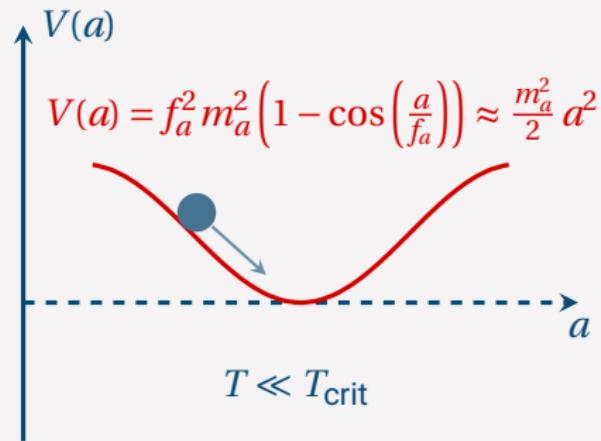
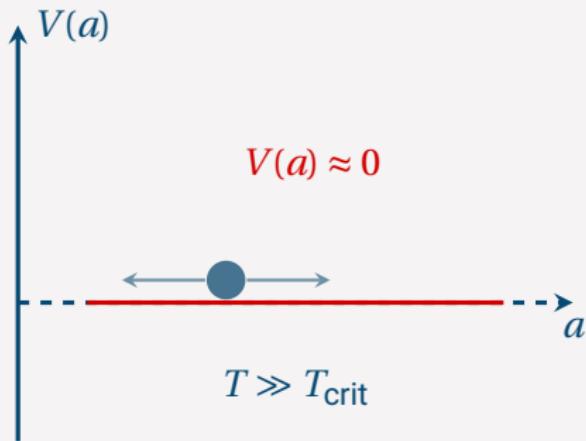
# Axion dark matter from realignment

- Early times, high temperatures: No potential, the field value can change freely.



# Axion dark matter from realignment

- Early times, high temperatures: No potential, the field value can change freely.
- Later times: Periodic axion potential is generated, field oscillates around the minimum.



## Post-inflationary scenario

- Universe consists of many causally disconnected axion field patches.
- Can calculate the DM energy density from realignment by averaging.
- But: Contribution from topological defects is hard to calculate. e.g. Gorghetto+ '18

# Two scenarios for Peccei-Quinn symmetry breaking

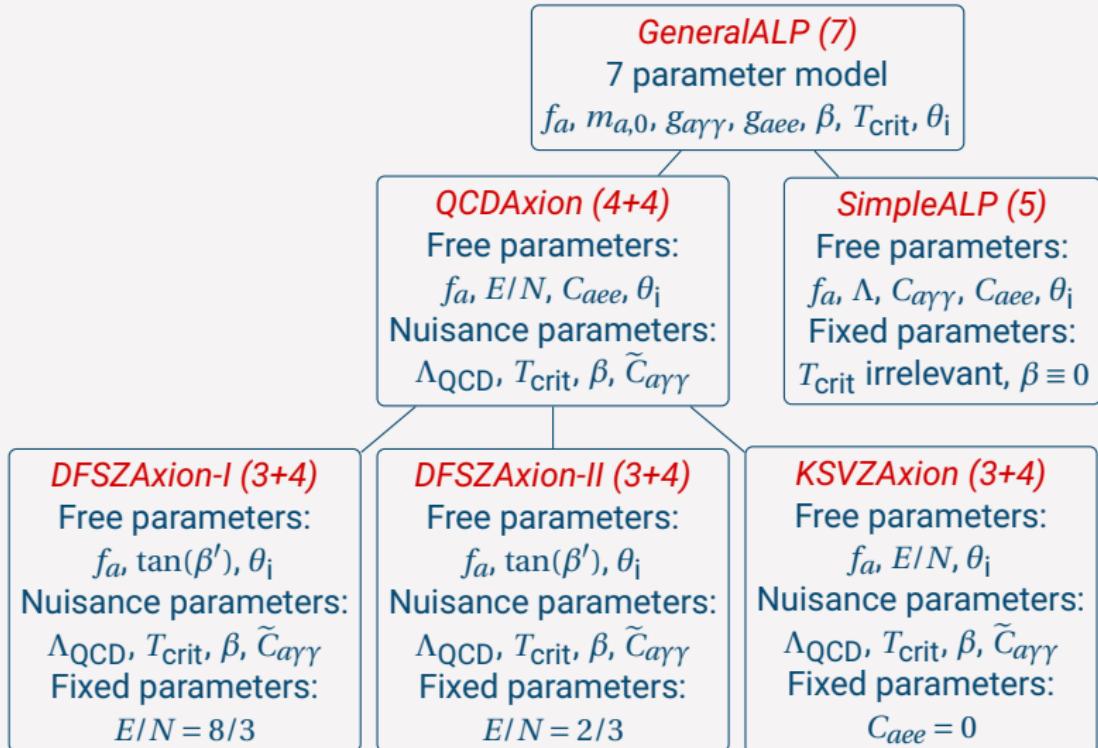
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e.g. Gorgetto+ '18

## Pre-inflationary scenario

- Inflation stretches one causally disconnected patch to the size of the observable universe.
- Initial field value of the axion field is random.
- Inflation dilutes away topological defects.

# Axion models in GAMBIT



# QCD axion models

## *QCDAxion (4+4)*

Free parameters:

$f_a, E/N, C_{aee}, \theta_i$

Nuisance parameters:

$\Lambda_{\text{QCD}}, T_{\text{crit}}, \beta, \tilde{C}_{a\gamma\gamma}$

- Symmetry breaking scale  $f_a$  and initial field value  $\theta_i$ .
- Interaction strengths determined by  $E/N, C_{aee}$ , and  $\tilde{C}_{a\gamma\gamma}$ :

$$g_{a\gamma\gamma} = \frac{\alpha_{\text{EM}}}{2\pi f_a} \left( \frac{E}{N} - \tilde{C}_{a\gamma\gamma} \right) \quad g_{aee} = \frac{m_e}{f_a} C_{aee}$$

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- Temperature-dependent axion mass:

$$m_a(T) = \frac{\Lambda_{\text{QCD}}^2}{f_a} \begin{cases} 1 & \text{if } T \leq T_{\text{crit}} \\ \left(\frac{T_{\text{crit}}}{T}\right)^{\beta/2} & \text{otherwise} \end{cases}$$

# Axion-related likelihoods in GAMBIT

## ■ Lab Experiments

- ▶ Light-shining-through-a-wall experiments: ALPS <sup>Ehret+ '09</sup>
- ▶ Helioscope searches: CAST <sup>Andriamonje+ '07, CAST '17</sup>
- ▶ Resonant cavities: ADMX <sup>Asztalos+ '10, Du+ '18</sup>, RBF <sup>Wuensch+ '89</sup>, UF <sup>Hagmann+ '90</sup>

## ■ Cosmology

- ▶ DM density today <sup>Planck '16</sup> vs axion realignment density

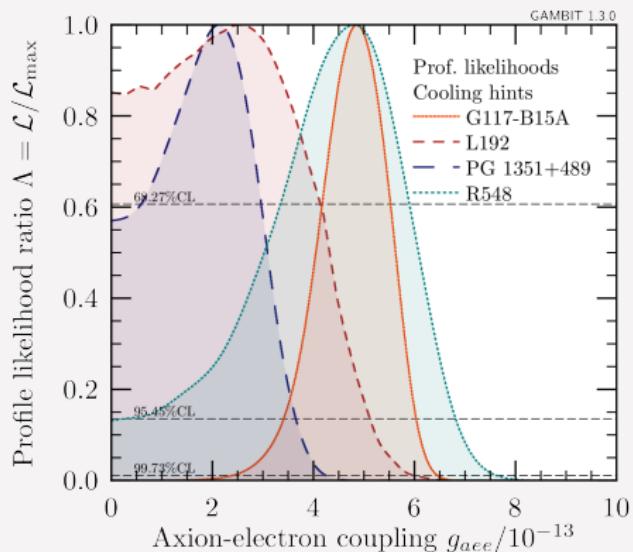
## ■ Astrophysics

- ▶ Supernovae <sup>Payez+ '15</sup> (axion-photon conversion in the Milky Way's B-field)
- ▶ R-parameter <sup>Giannotti+ '16</sup> (ratio of RGB to HB stars in globular clusters)
- ▶ White Dwarf cooling hints <sup>Battich+ '16; C  rsico+ '12, '12, '16</sup>
- ▶ H.E.S.S. <sup>H.E.S.S. '13</sup> (spectral distortions)

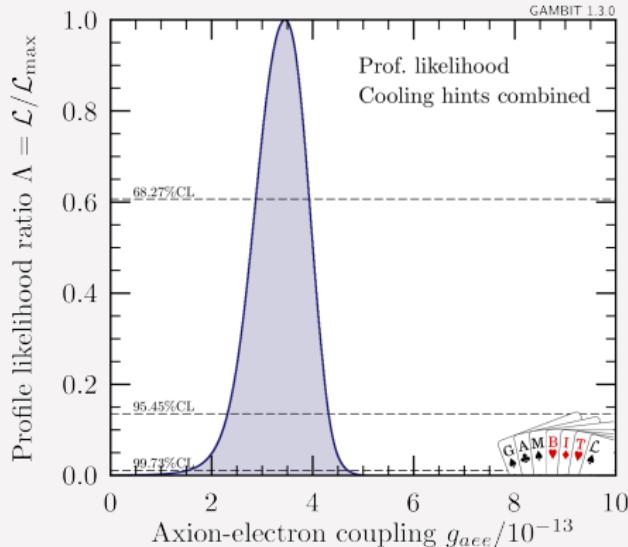
## ■ QCD parameters <sup>di Cortana+ '15, Borsanyi+ '16</sup>

# White Dwarf cooling hints

Axions can explain observed cooling anomalies! Giannotti+ '16

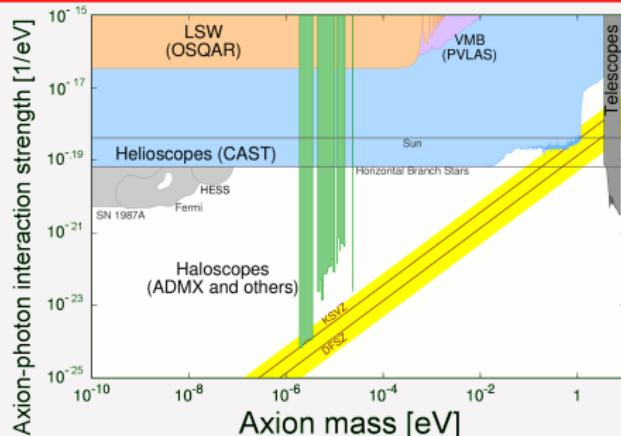


Overview: WD cooling hints in GAMBIT.



Combined fit of cooling hints.

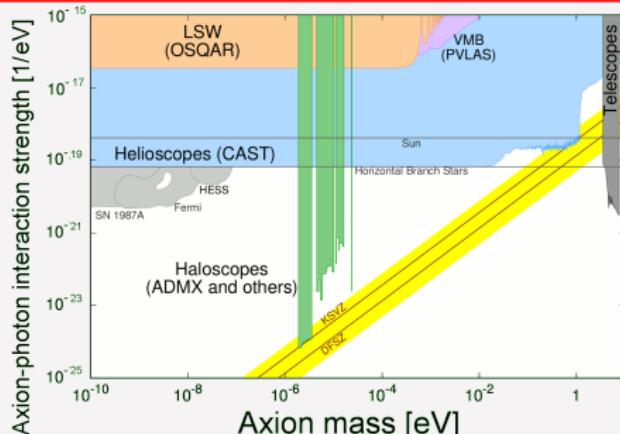
# Global fits: Dark matter axion-like particles



Overview of axion limits adapted from PDG '18

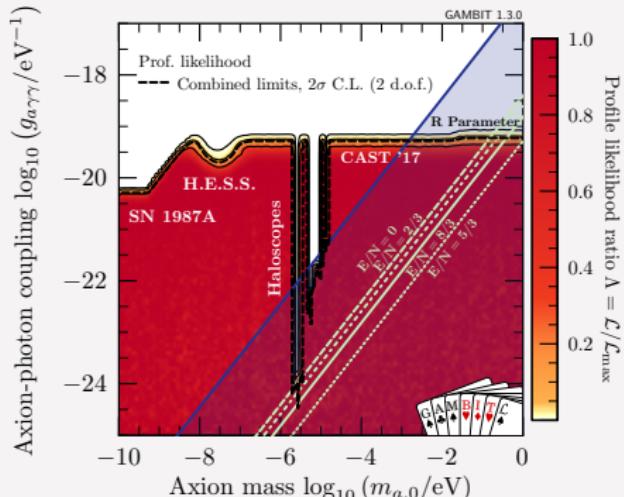
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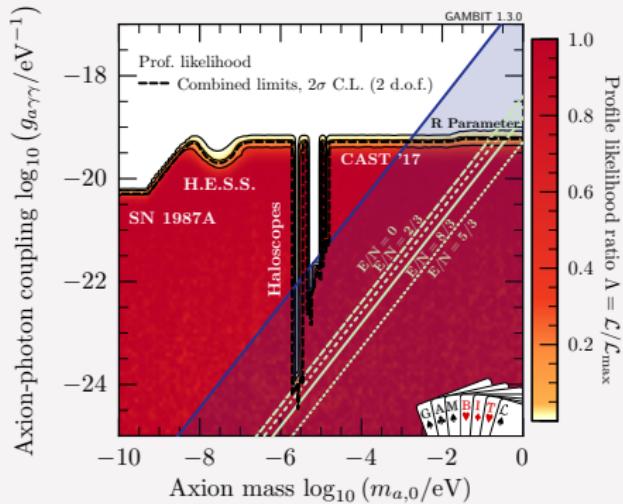
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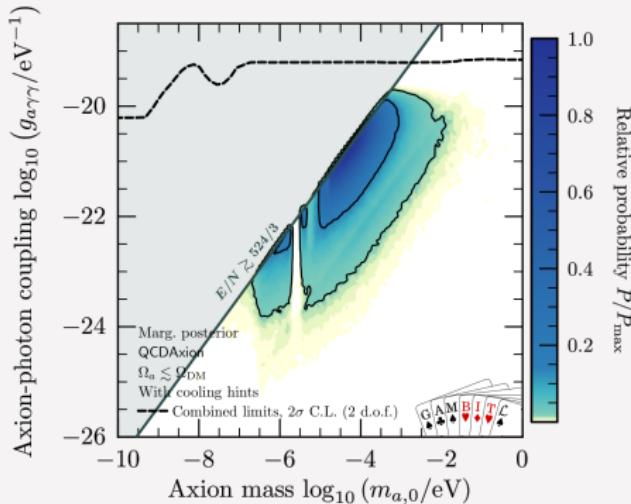
In our study

- Consistent treatment
- Full combination, incl. local DM dens. as nuisance parameter

# Global fits: QCD axions



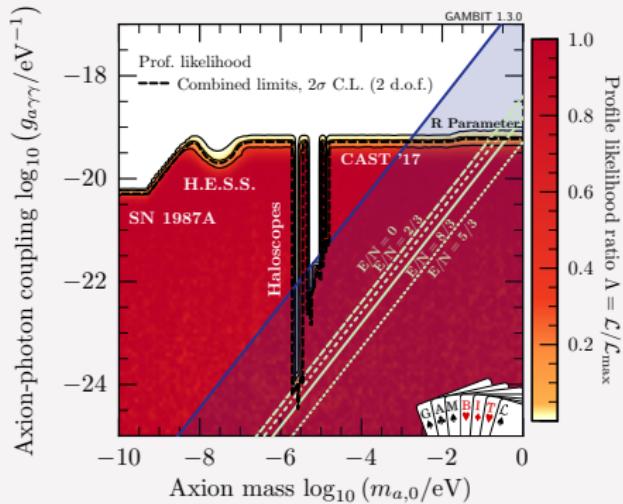
Phenomenological parameter space;  
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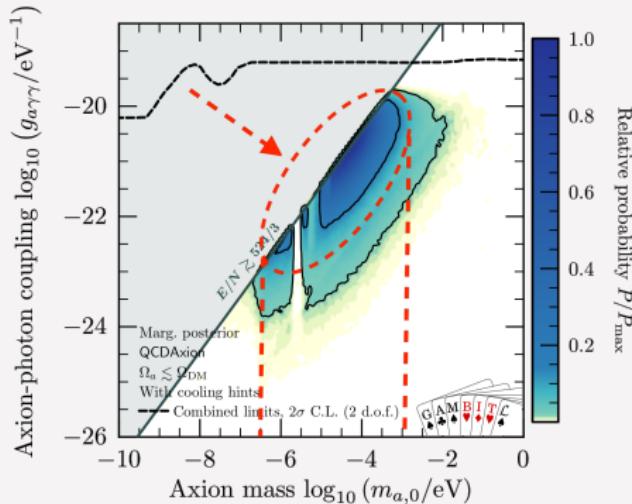
Subspace of the pheno parameter space corresponding to realistic models.  
di Luzio+ '17

DM constraints only as an upper limit.

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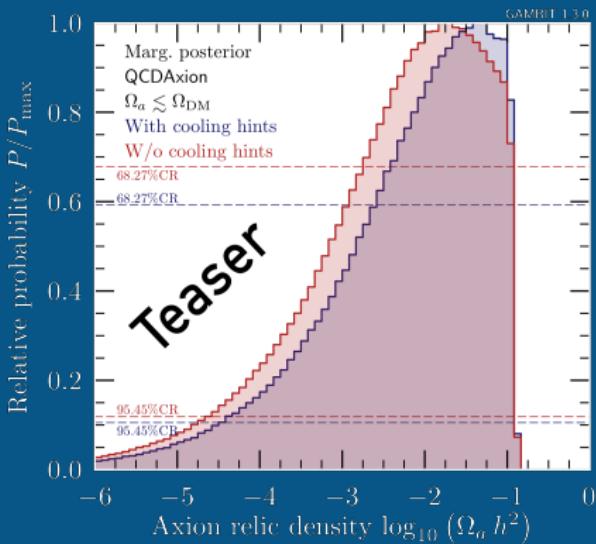


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# Summary

- We performed a global fit of axion models in the **pre-inflationary PQ symmetry breaking**.
- We show best-fit & posterior regions, calculate Bayes factors, investigate prior dependence & study the effects of WD cooling hints.



- QCD axions *can* be all of the DM and explain the cooling hints (but require  $C_{aee} \sim 100$ ). A Bayesian analysis suggests they probably are not all of the DM and gives bounds for the axion mass.

## Global fits: Model comparison

Bayes factors (= odds ratios with equal *a priori* probability for both hypotheses) vs QCDAxion models.

Model ( $E/N$ )	Bayes factors			
	W/o WD cooling		With WD cooling	
	$\Omega_a \lesssim \Omega_{\text{DM}}$	$\Omega_a \sim \Omega_{\text{DM}}$	$\Omega_a \lesssim \Omega_{\text{DM}}$	$\Omega_a \sim \Omega_{\text{DM}}$
DFSZAxion-I (8/3)	3:1	1:1	3:1	1:5
DFSZAxion-II (2/3)	1:1	1:2	1:1	1:5
KSVZAxion (0)	3:1	2:1	1:2	1:7
KSVZAxion (2/3)	2:1	2:1	1:2	1:5
KSVZAxion (5/3)	4:1	1:1	1:2	1:5
KSVZAxion (8/3)	3:1	2:1	1:2	1:5