Università degli Studi di Padova

Finding Axions in a Universe of Data and Envisioning Their Use as Multi-Messenger Probes

Sebastian Hoof

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msca_axitools

Overview

- Brief axion intro
- Axion global fits and model space
- The solar axion flux, its uncertainties, and the discovery potential for future helioscopes
- Post-discovery physics of axions

The strong CP problem

The QCD Lagrangian contains the "θ term"

$$\mathcal{L}_{\mathrm{QCD}} = \cdots - \frac{\alpha_s}{8\pi}\,\theta\, G^a_{\mu\nu}\widetilde{G}^{\mu\nu,a} = \cdots + \frac{\alpha_s}{2\pi}\,\theta\,\mathbf{E}^a \cdot \mathbf{B}^a$$

with gluon field dual $\widetilde{G}^{\mu\nu,a} \equiv \frac{1}{2}\epsilon^{\mu\nu\alpha\beta}G^a_{\alpha\beta}$ and a constant θ.

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with gluon field dual $\widetilde{G}^{\mu\nu,a} \equiv \frac{1}{2}\epsilon^{\mu\nu\alpha\beta}G^a_{\alpha\beta}$ and a constant θ.

- $\mathbf{E}^a \cdot \mathbf{B}^a \propto \partial_\alpha(\epsilon^{\alpha\beta\gamma\delta}A^a_\beta\partial_\gamma A^a_\delta)$ i.e. a total derivative, **but** also anomalous: can't be ignored due to instanton solutions

- $\alpha_s(m_Z) = 0.1183(9)$[2309.12986] ➽ measure θ

The strong CP problem

- $\theta \sim \mathcal{O}(1)$ should induce a measurable electric dipole moment of the neutron, d_n
- Current bound: $|d_n| < 1.8 \times 10^{-26}\, e\,\text{cm}$ (90% CL)[2001.11966] implies $|\theta| \lesssim 10^{-10}$ (N.B. SM @ HO: $|d_n| \sim 10^{-32}\, e\,\text{cm}$)

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- *Why is θ so small?* Puzzling because ...

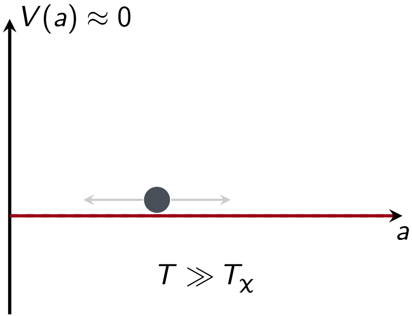
... CP violation exists in weak interactions (kaon decay, 1964), EM doesn't have CP-violating diagrams (at tree level)

... actually $\theta \mapsto \theta - \arg\det(M_q)$, so small θ is even more surprising

... all allowed terms should be $\sim \mathcal{O}(1)$!?

Axion dark matter – realignment mechanism

- At early times, $T \gg T_\chi \sim T_{\text{QCD,c}} = 158.1(5)\,\text{MeV}$,[2002.02821] the axion field a can fluctuate freely



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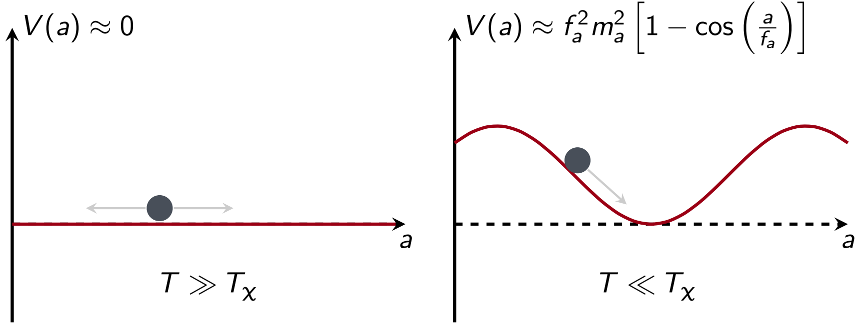

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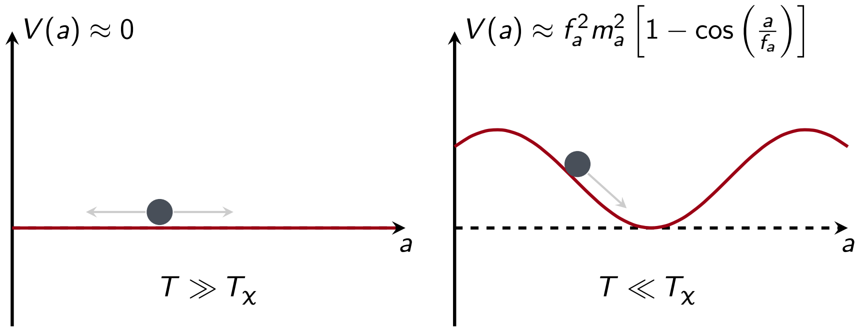
➽ *Strong CP problem solved dynamically by promoting $\theta \mapsto a/f_a$*

➽ *Oscillating scalar field behaves as DM*



Axion dark matter – predictions

Axion = pNGB from $\mathrm{U}(1)$ symmetry breaking (PQ symmetry)

Pre-inflationary PQ breaking

- Universe = single patch of constant θ stretched out by inflation
- Initial axion field value is random ☹
- Inflation dilutes away topological defects ☺

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Post-inflationary PQ breaking

- Universe = huge number of causally disconnected axion field patches
- Axion DM density from realignment = average ☺
- Contribution from top. defects, very difficult to compute ☹ 2007.04990, 2108.05368

QCD axion properties

- QCD axion mass from chiral perturbation theory[1812.01008]

$$m_a = 5.69(5)\,\mu\text{eV}\left(\frac{10^{12}\,\text{GeV}}{f_a}\right)$$

- Axion-photon coupling depends on UV model through anomaly ratio E/N and axion-meson mixing[1511.02867]

$$g_{a\gamma\gamma} = \frac{\alpha_{\text{EM}}}{2\pi f_a}\left[\frac{E}{N} - 1.92(4)\right] \propto m_a$$

- Axion-like particles (ALPs): no connection to QCD = less predictable; however, e.g. mass spectra in string theory[2103.06812]

Short summary

- Axions solve strong CP problem, explain smallness of $\theta G\widetilde{G}$ term[Peccei & Quinn '77] by promoting $|\theta| \lesssim 10^{-10}$ to a dynamical field
- Unintended bonus: excellent dark matter (DM) candidates!
- Success of axions doesn't depend on PQ scale $\sim f_a$ ☺ But what's the axion's mass? Where to find it? ☹

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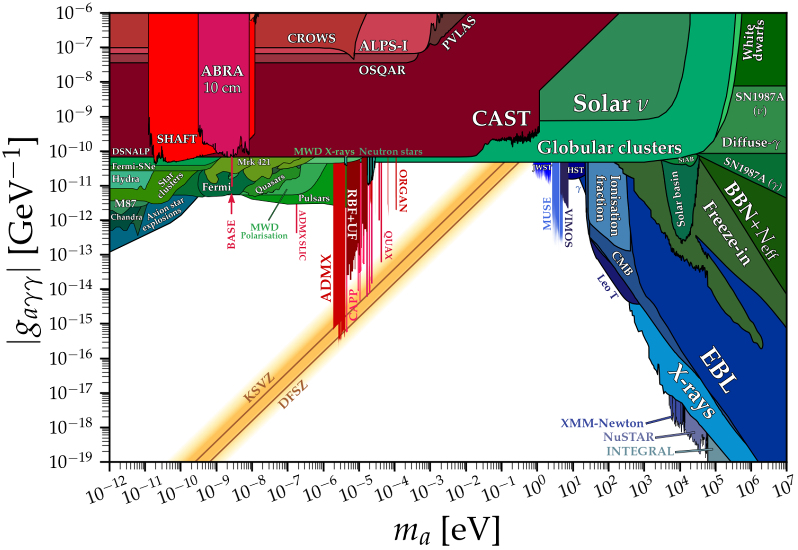
- Success of axions doesn’t depend on PQ scale $\sim f_a$ ☺ But what’s the axion’s mass? Where to find it? ☹

- String theory: potentially many axion-like particles (ALPs)

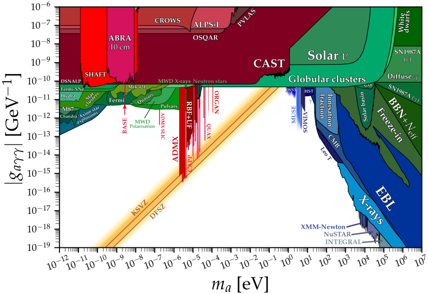
- Related ideas: relaxion,[1504.07551] SMASH model,[1610.01639], ALP cogenesis,[2006.04809] …

Current limits on the axion-photon coupling



Credit to C. O'Hare, "AxionLimits" repo

Global fits for DM ALPs



- Consistency of assumptions?
- Overplotted, not combined
- Effects of "hidden parameters"?
- $g_{a\gamma\gamma}$ = pheno parameter; no connection to UV model

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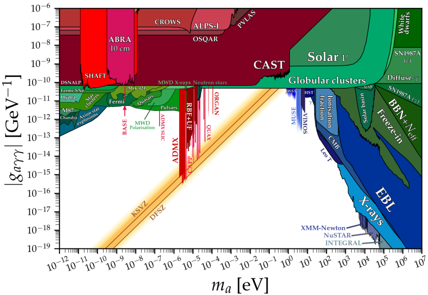

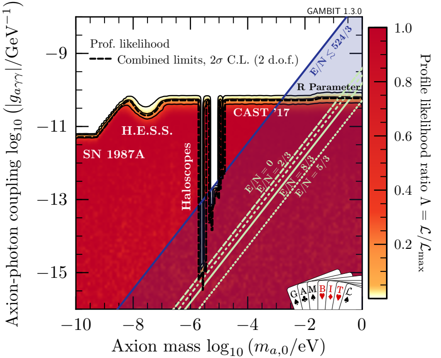

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With a global fit, we ensure[1810.07192]

- self-consistent combination and analysis of data
- likelihoods can include all model and nuisance parameters

Global fits for QCD axions

Where are the most probable, natural QCD axion models in the pre-inflationary PQ breakling scenario?

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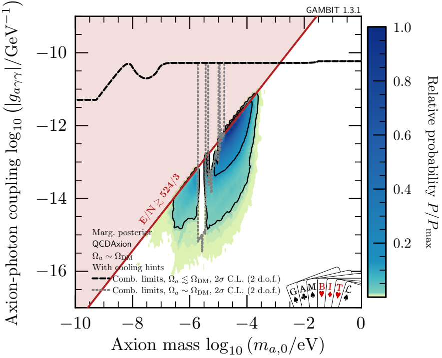
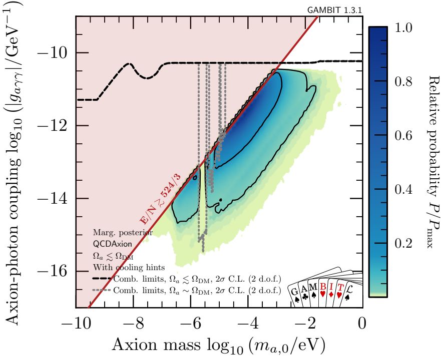


QCD axions = DM



DM density as an upper limit

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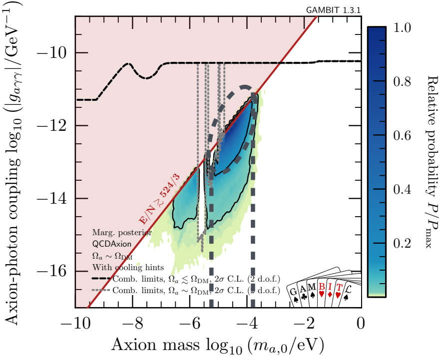

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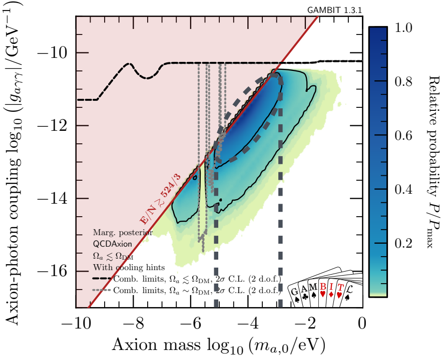
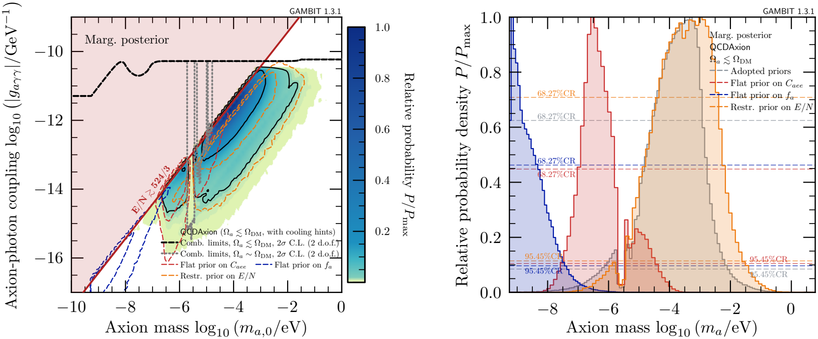


DM density as an upper limit

Prior dependence of the results

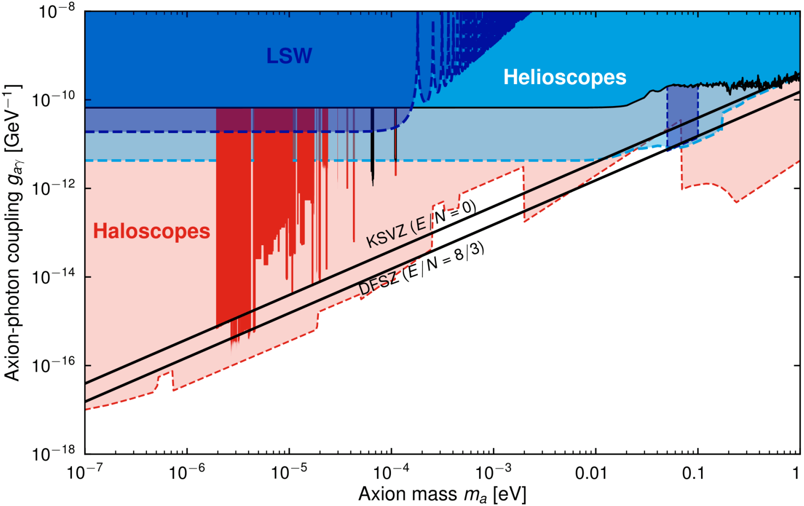
Investigate the prior dependence of the results:



- Uniform vs log uniform priors give very different results
- Are there any "physically motivated" priors?

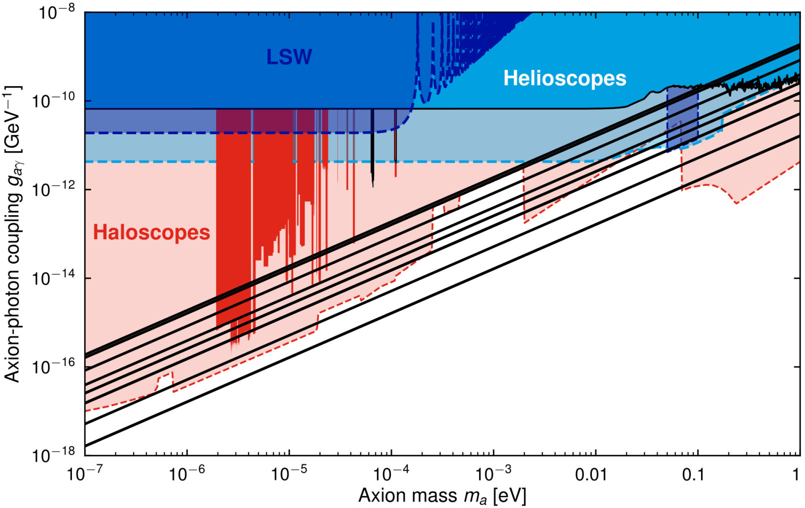
Aside #1: The genesis of the QCD axion model band

In the beginning there were KSVZ and DFSZ models . . .



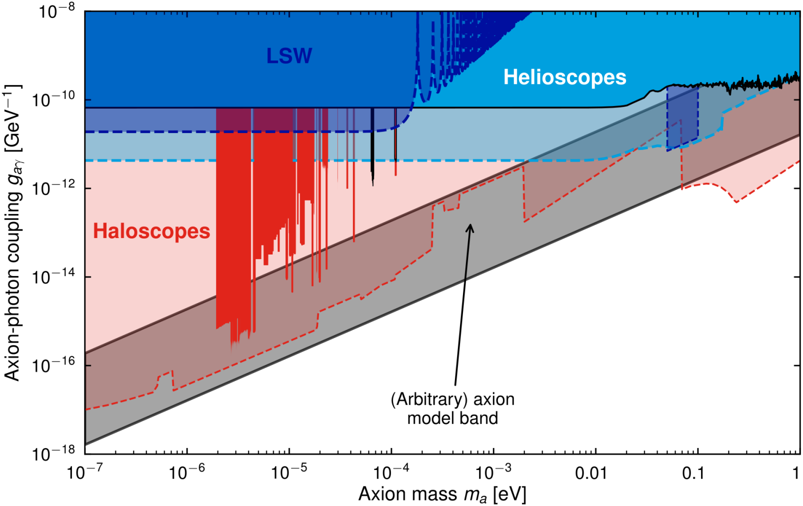
Aside #1: The genesis of the QCD axion model band

…and then theorists found more models[e.g. hep-ph/9506295] …



Aside #1: The genesis of the QCD axion model band

…and experimentalists said "let there be a band!" e.g. hep-ex/0702006



Defining the QCD axion model band

- Prior dependence: how to define the “QCD axion band”? Just add more and more models from the vast landscape?[2003.01100]

- Are there infinitely many discrete lines/models? Is the band effectively continuous due to QCD uncertainties?

- Beyond Bayesian analysis and priors: it would just be useful to have a catalogue of models.

Catalogue of KSVZ models

Let's start with KSVZ models:

- KSVZ models introduce one new heavy, chiral quark $\mathcal{Q}$, charged under PQ; charge assignments determine E/N
- Multiple $\mathcal{Q}$s: $E/N = \left(\sum_i E_i\right) / \left(\sum_i N_i\right)$

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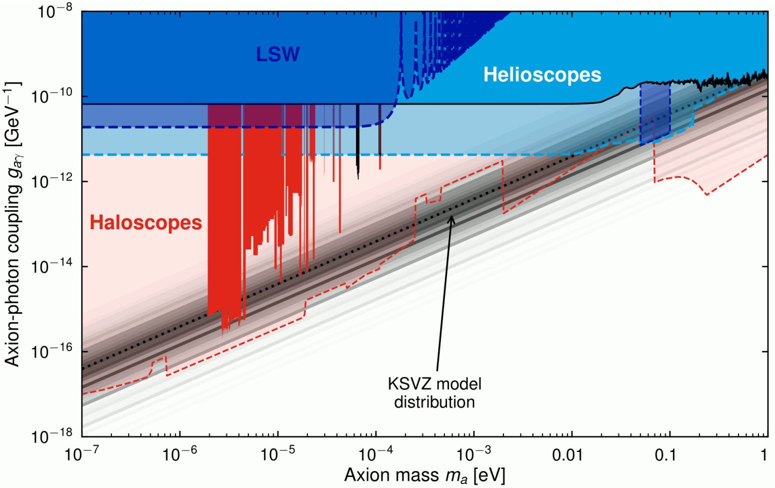
- Multiple $\mathcal{Q}$s: $E/N = \left(\sum_i E_i\right) / \left(\sum_i N_i\right)$
- Adding too many $\mathcal{Q}$s will lead to LP below m_{Pl}; gives a *finite number of models*[2107.12378]

➽ Creating a (finite) catalogue = combinatorial exercise with selection criteria[1610.07593, 1705.05370]

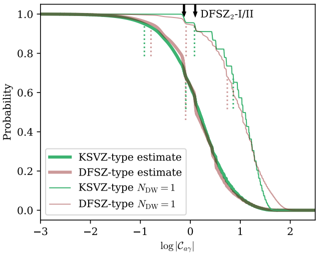
- N.B. $N = 0$ possible and the axion does not solve the strong CP problem! *New selection criterion:* $N \neq 0$[2107.12378]

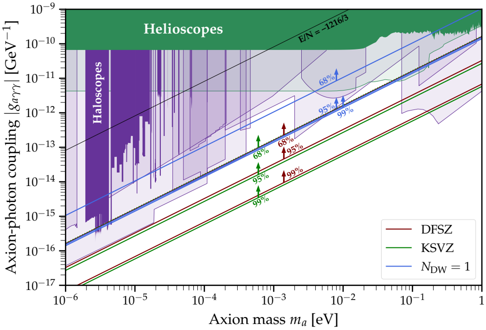
The KSVZ model band

Define distribution of "all" KSVZ models (here: equally probable *preferred* reps)[2107.12378] ➻ theory prior on $|g_{a\gamma\gamma}| \propto |E/N - 1.92(4)|$



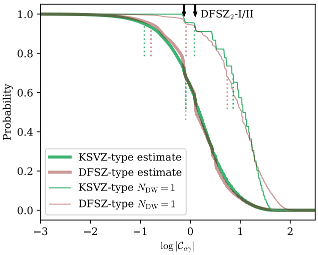
QCD model band

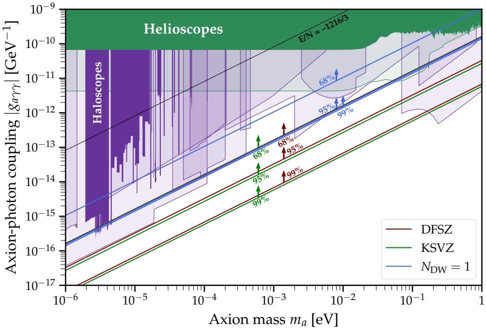




- Also: DFSZ catalogue available![2302.04667] Both our[Zenodo] and their[Zenodo] catalogues can be found online
- Discrete E/N distribution + uncertainties from 1.92(4) term

QCD model band





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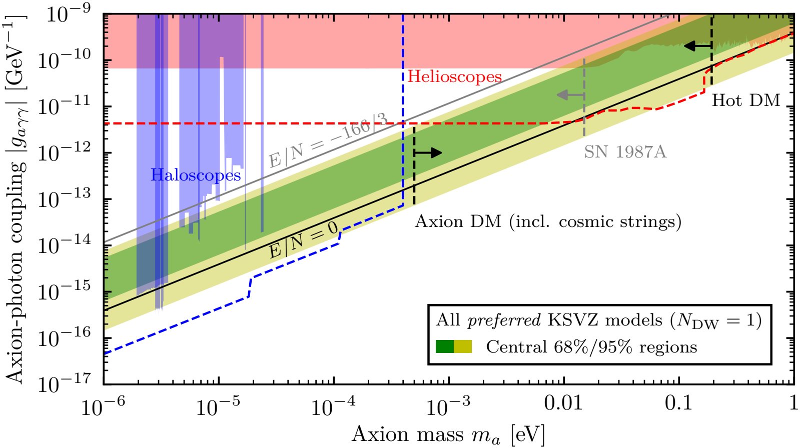
➽ Catalogues can be interpreted as "theory priors" on E/N, or simply as a database to identify UV models (wait for slide 27)

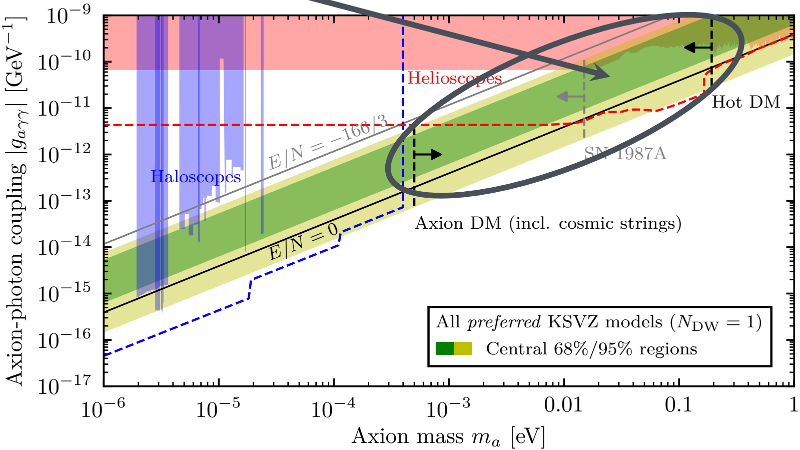
Example for “boxing in” the axion

Select $N_{\mathrm{DW}} = 1$ models from KSVZ catalogue (avoids “DW problem” in post-inflationary PQ breaking).

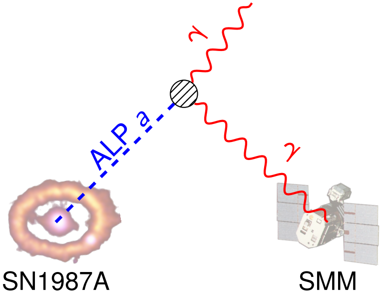


Example for "boxing in" the axion

Select $N_{\mathrm{DW}} = 1$ models from KSVZ catalogue (avoids "DW problem" in post-inflationary PQ breaking). For more reliable axion top. defect and thermal production computations: define and probe the m_a-$g_{a\gamma\gamma}$ regions



Aside #2: ALP Constraints from SN1987A



- Heavy ALPs, produced in the SN, can decay into photons, SMM satellite would have detected gamma-rays
- We make analytical progress for computations with arbitrary decay lengths; fast code[2212.09764]

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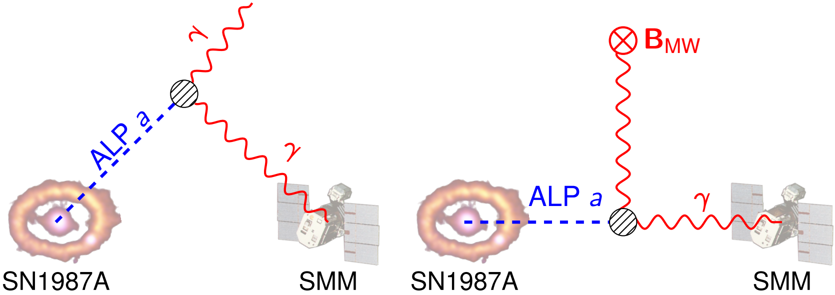
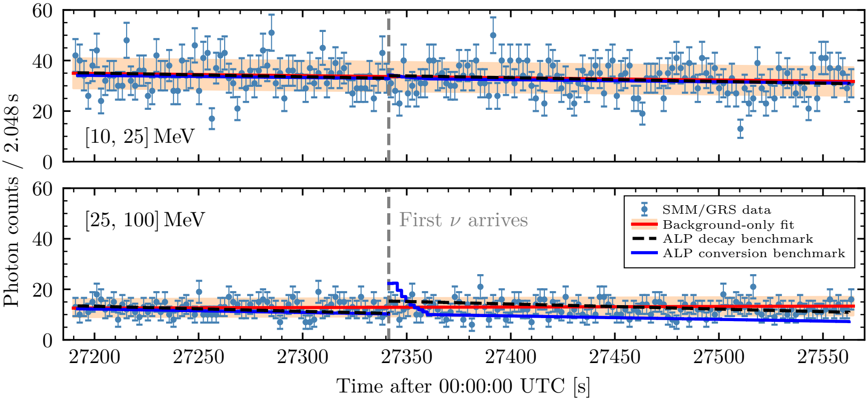


- Heavy ALPs, produced in the SN, can decay into photons, SMM satellite would have detected gamma-rays
- We make analytical progress for computations with arbitrary decay lengths; fast code[2212.09764]
- Alternatively: Light ALPs can convert to photons in the Galactic B-field

SMM data



- Previously: only integrated data was used; no timing info
- Justified for decays: signal is stretched out, approx. const.

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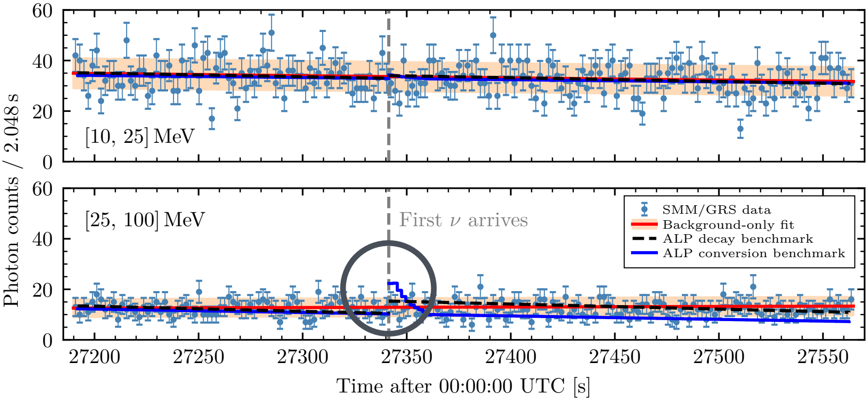
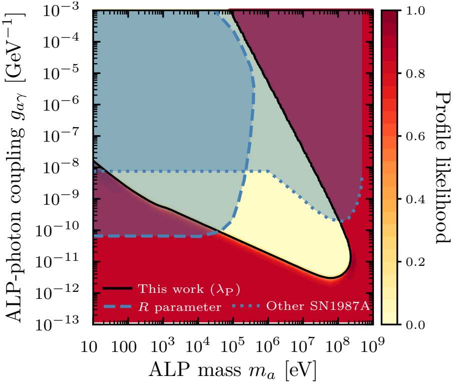


- Previously: only integrated data was used; no timing info
- Justified for decays: signal is stretched out, approx. const.
- For decays: $\frac{dN_\gamma}{dt} \propto \frac{dN_a}{dt}$, time dependence is manifest

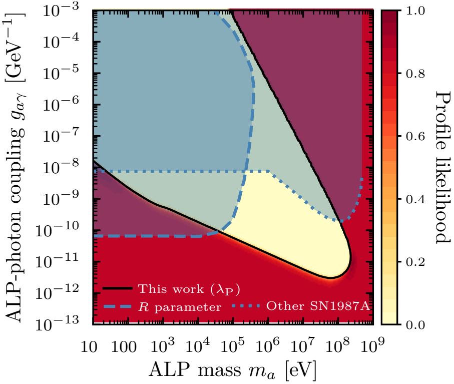
Updated exclusion limits for SN1987A

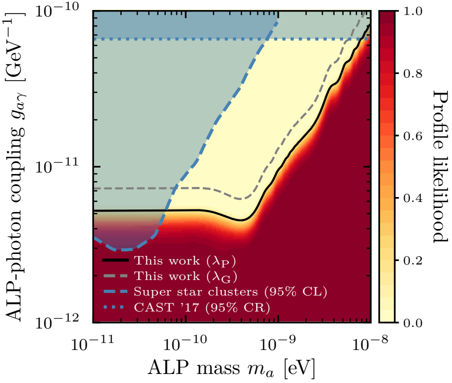
- ALP decays: only slight improvement due to additional energy bin, but no significant change (signal $\approx$ constant)[2212.09764]



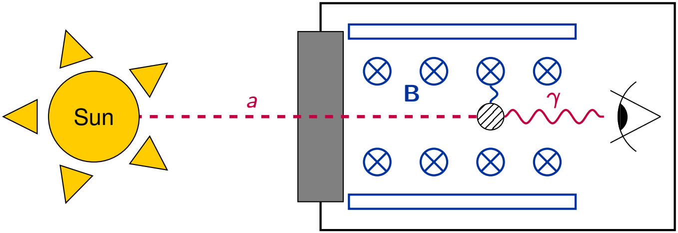
Updated exclusion limits for SN1987A

- ALP decays: only slight improvement due to additional energy bin, but no significant change (signal ≈ constant)[2212.09764]
- ALP conversions: *factor 1.4 stronger limits* ➻ "global fitting mindset" can help to get more out of the data





Helioscopes: detecting solar axions

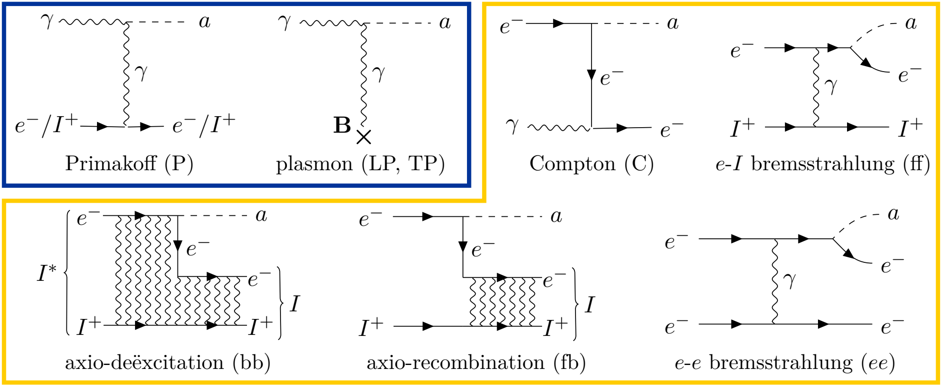


- $T_\odot \sim$ keV: produce (relativistic) axions in solar plasma
- Axions escape the solar interior $\approx$ unimpeded

➽ Track the Sun across the sky with B-field + X-ray detector

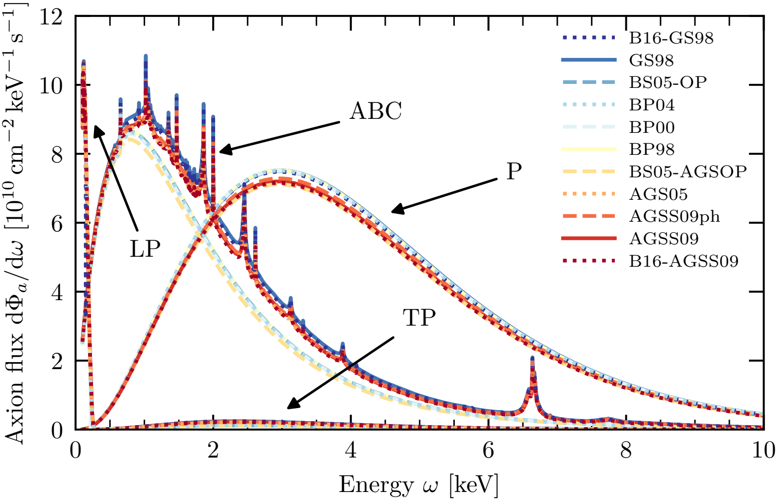
Axions production in the Sun

$$\mathcal{L}_{\mathrm{ALP}} = \frac{(\partial_\mu a)^2}{2} - \underbrace{\frac{m_a^2 a^2}{2}}_{m_a \ll T_\odot} - \underbrace{\frac{g_{a\gamma\gamma}}{4} a F \widetilde{F} + \frac{g_{aee}}{2 m_e} (\partial_\mu a)\, \bar{e} \gamma^\mu \gamma^5 e}_{[2101.08789]} + \underbrace{\mathcal{L}_{\mathrm{nucl}}}_{[2111.06407]} + \mathcal{L}_{\not{CP}}$$



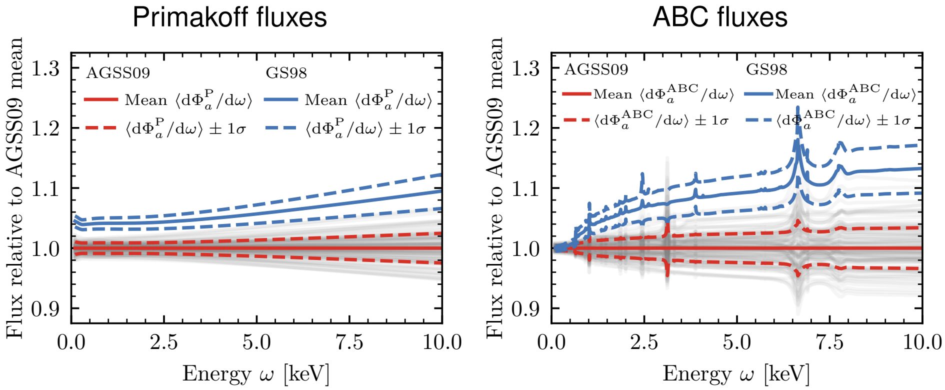
Production = $g_{a\gamma\gamma}$, g_{aee}, …, Raffelt+ '88, …, Redondo '13, … detection: $g_{a\gamma\gamma}$ Sikivie '83

Predictions from solar models



Solar axion flux uncertainties

10,000 Monte Carlo sims of low-Z (AGSS09) & high-Z (GS98) solar models[astro-ph/0511337 + Serenelli update] to estimate uncertainties[2101.08789]



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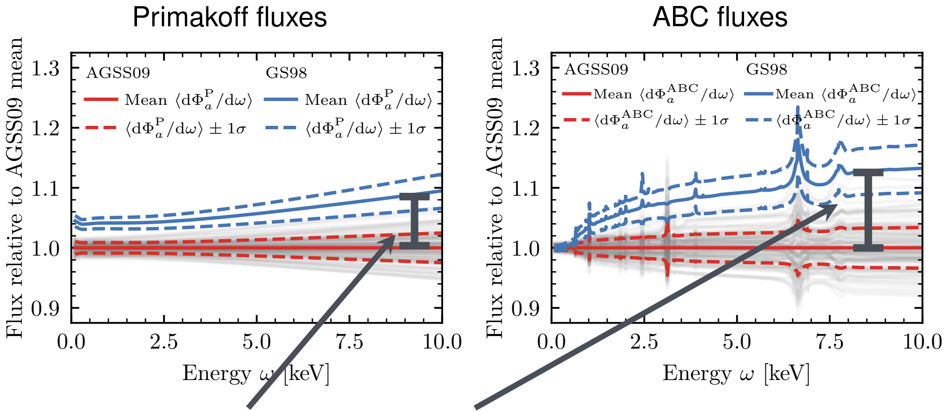

Systematic shift between low-Z and high-Z models (metallicity problem)

Solar axion flux uncertainties

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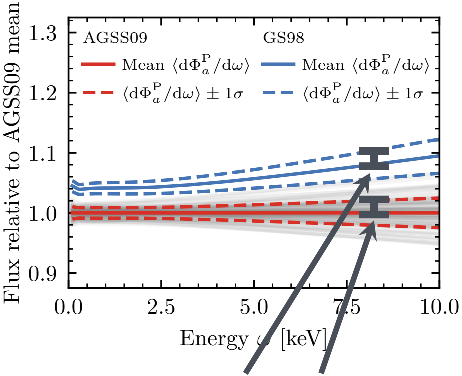
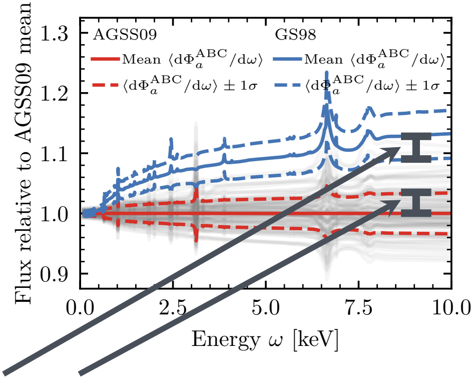
Primakoff fluxes

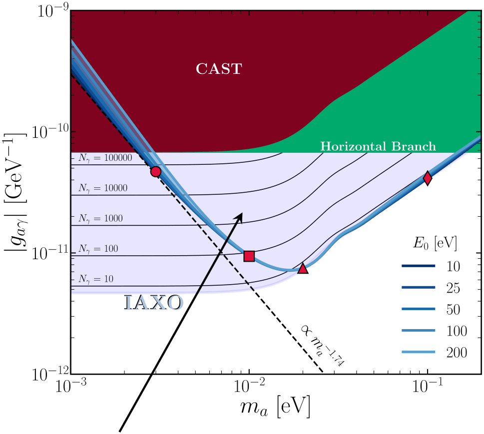


ABC fluxes



Statistical fluctuations; similar for low-Z and high-Z models, smaller than systematics

Discovery potential of IAXO



Parameter regions where IAXO detects m_a & $g_{a\gamma\gamma}$ with $> 3\sigma$ significance, given energy resolution E_0[1811.09290]

- IAXO = helioscope experiment under construction at DESY, Hamburg[1401.3233, 2010.12076]
- Can determine m_a and $g_{a\gamma\gamma}$ for the region of parameter space on the left

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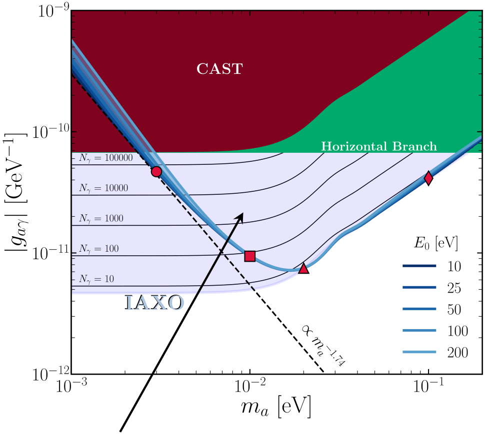

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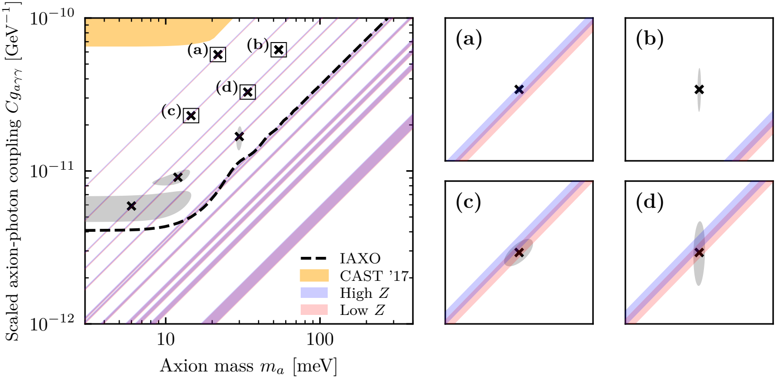
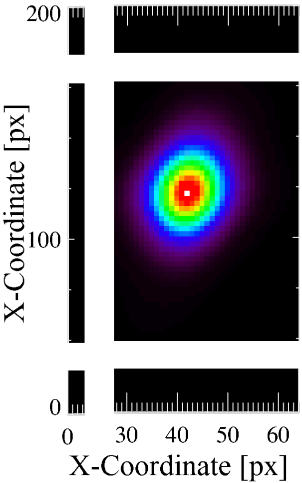
- Can determine m_a and $g_{a\gamma\gamma}$ for the region of parameter space on the left
- ➽ Opportunity to discover realistic QCD axion models!
- ➽ Exciting prospect of post-discovery physics

Other use cases: QCD axion models



- May simultaneously distinguish QCD axion and solar models,[2101.08789] hint for solar metallicity problem solution
- Assume Primakoff flux, 15 KSVZ models (pre-catalogue era)
- Can also determine g_{aee},[1811.09278] metallicities[1908.10878]

The solar axion image



- Simulated axion image in CAST helioscope[hep-ex/0702006]
- $\approx$ spherically symmetric projection thanks to great X-ray optics
- Availability of photon-counting detectors with many pixels

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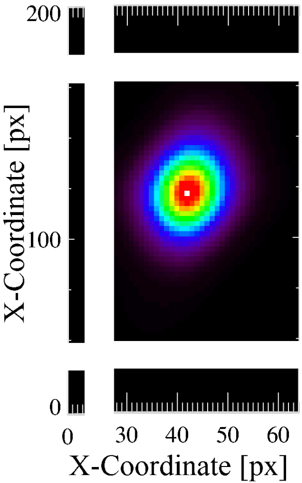

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- ≈ spherically symmetric projection thanks to great X-ray optics
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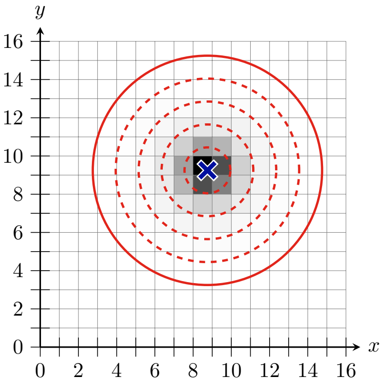
➽ Estimate photon counts in rings about the centre of the signal region to obtain radial information

The solar axion image



- Expected idealised signal in IAXO (actually 128 $\times$ 128 pixels, 20 radial, 4 spectral bins)
- Many pixels: photon counts/pixel $\approx$ equally distributed, integrate flux over radial bins

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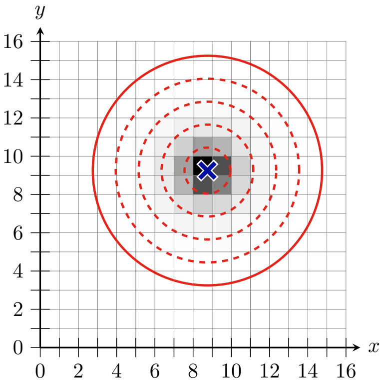

- Expected idealised signal in IAXO (actually 128 $\times$ 128 pixels, 20 radial, 4 spectral bins)
- Many pixels: photon counts/pixel $\approx$ equally distributed, integrate flux over radial bins
- Generate 1000 pseudodata sets for IAXO, "invert" solar axion image, fit axion and solar model parameters

The (simplified) Primakoff production rate

$$\Gamma^{\mathrm{P}}(E_a) = \frac{g_{a\gamma\gamma}^2\,\kappa_{\mathrm{s}}^2\,T}{32\pi}\left[\left(1+\frac{\kappa_{\mathrm{s}}^2}{4E_a^2}\right)\log\left(1+\frac{4E_a^2}{\kappa_{\mathrm{s}}^2}\right)-1\right]\frac{2}{\mathrm{e}^{E_a/T}-1}$$

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- Ignores e^- degeneracy and other corrections (few %)

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- Only depends on $T(r)$, $\kappa_{\mathrm{s}}(r)$ (local) and $g_{a\gamma\gamma}$ (global quantity)
- Ignores e^- degeneracy and other corrections (few %)

➸ Can break parameter degeneracies with spectral information!

$$\bar{n}_{i,j} \propto \int_{\rho_i}^{\rho_{i+1}}\mathrm{d}\rho\,\int_{\rho}^{1}\mathrm{d}r\,\frac{r\,\rho}{\sqrt{r^2-\rho^2}}\,\underbrace{\left(\int_{\omega_j}^{\omega_{j+1}}\mathrm{d}\omega\,\frac{\omega^2}{2\pi^2}\,\Gamma^{\mathrm{P}}(r,\,\omega)\right)}_{\equiv\bar{\Gamma}_j^{\mathrm{P}}(r)}$$

A simple reconstruction example

Piecewise-constant interpolation for $\bar{\Gamma}_j^{\mathrm{P}}$

$$\bar{\Gamma}_j^{\mathrm{P}}(r) = \sum_i \underbrace{\left(\int_{\omega_j}^{\omega_{j+1}} \mathrm{d}\omega \, \frac{\omega^2}{2\pi^2} \, \Gamma^{\mathrm{P}}(r_i, \omega) \right)}_{\gamma_{i,j}} \, \Theta(r - r_i) \, \Theta(r_{i+1} - r)$$

A simple reconstruction example

Piecewise-constant interpolation for $\bar{\Gamma}_j^{\mathrm{P}}$ + compute the $\bar{n}_{i,j}$ integral

$$\bar{\Gamma}_j^{\mathrm{P}}(r) = \sum_i \underbrace{\left(\int_{\omega_j}^{\omega_{j+1}} \mathrm{d}\omega \, \frac{\omega^2}{2\pi^2} \, \Gamma^{\mathrm{P}}(r_i, \omega) \right)}_{\gamma_{i,j}} \Theta(r - r_i) \, \Theta(r_{i+1} - r)$$

$$\bar{n}_{i,j} \propto \int_{r_i}^{r_{i+1}} \mathrm{d}\rho \, \rho \sum_{k=1}^{n_\rho} \int_\rho^1 \mathrm{d}r \, \frac{r}{\sqrt{r^2 - \rho^2}} \gamma_{k,j} \, \Theta(r - r_k) \, \Theta(r_{k+1} - r)$$

$$= \frac{1}{3} \left[\gamma_{i,j} \, \Delta^3_{i+1;i} + \sum_{k=i+1}^{n_\rho} \gamma_{k,j} \left(\Delta^3_{k+1;i} - \Delta^3_{k+1;i+1} + \Delta^3_{k;i+1} - \Delta^3_{k;i} \right) \right]$$

with $\Delta^3_{\ell;m} \equiv (r_\ell^2 - r_m^2)^{3/2}$

➽ Can compute $\bar{n}_{i,j}$ analytically!

A simple reconstruction example

We write this as a matrix equation $\bar{n}_{i,j} = \sum_{k=1}^{n_\rho} \mathcal{M}_{ik}\,\gamma_{k,j}$ with

$$\mathcal{M}_{ik} \propto \begin{cases} \Delta^3_{i+1;i} & \text{for } i = k, \\ \Delta^3_{k+1;i} - \Delta^3_{k+1;i+1} + \Delta^3_{k;i+1} - \Delta^3_{k;i} & \text{for } k > i, \\ 0 & \text{otherwise.} \end{cases}$$

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➸ Triangular matrix: set expected = observed counts, invert

$$n_{i,j} = \mathcal{M}_{ii}\gamma_{i,j} + \sum_{k=i+1}^{n_\rho} \mathcal{M}_{ik}\, \gamma_{k,j} \Rightarrow \gamma_{i,j} = \frac{1}{\mathcal{M}_{ii}} \left(n_{i,j} - \sum_{k=i+1}^{n_\rho} \mathcal{M}_{ik}\, \gamma_{k,j} \right)$$

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➽ Can also propagate errors; use when fitting $g_{a\gamma\gamma}$, T_i and κ_i

$$\sigma^2_{i,j} \equiv (\Delta\gamma_{i,j})^2 = \frac{1}{\mathcal{M}^2_{ii}}\left[n_{i,j} + \sum_{k=i+1}^{n_\rho} \mathcal{M}^2_{ik}\,\sigma^2_{k,j}\right]$$

Reconstruction in practice

- Matrix only invertible if $n_{i,j} \neq 0 \Rightarrow$ uneven bin sizes ☹
- More accurate approx. of $T(r)$ with splines? Ringing ☹

Reconstruction in practice

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- ➻ Choose general (shape-preserving) spline interpolation, compute integral again:

$$\bar{\Gamma}_j^{\mathrm{P}}(r) = \sum_i \left[\gamma_{i,j} + \sum_{k=1}^{3} c_{k;i,j}(r - r_i)^k \right] \Theta(r - r_i)\,\Theta(r_{i+1} - r)\,.$$

Reconstruction in practice

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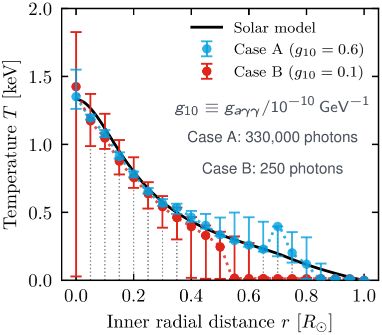
- Matrix not square, no inversion ☹
- ➻ Direct fitting needed to infer $g_{a\gamma\gamma}$, T_i and κ_i from the generated pseudodata $n_{i,j}$. Optimise:

$$\Delta\chi^2 \equiv -2\log L(g_{a\gamma\gamma}, \{\kappa_i, T_i\}) = 2\sum_j \bar{n}_{i,j} - n_{i,j}\,\log(\bar{n}_{i,j})$$

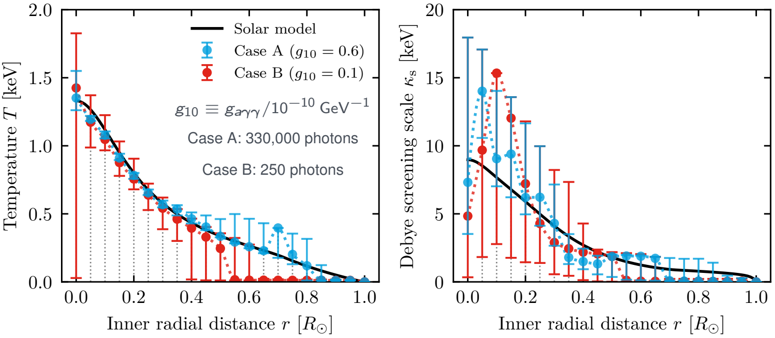
Temperature reconstruction



We find[2306.00077]

- Accurate $T(r)$ reconstruction up to 0.5 $R_\odot$ (0.8 $R_\odot$)
- Expected median statistical errors of 10% (16%)

Temperature reconstruction



We find[2306.00077]

- Accurate $T(r)$ reconstruction up to $0.5\,R_\odot$ ($0.8\,R_\odot$)
- Expected median statistical errors of 10% (16%)
- Difficulties for κ_s: shallow minima, weaker functional dependence, approximation used for Γ^P

Post-discovery multi-messenger physics with IAXO

The upcoming IAXO helioscope can…

… probe more realistic QCD axion models than CAST

… determine mass & couplings[1811.09278, 1811.09290], *simultaneously distinguish QCD axion and solar models*[2101.08789]

… measure solar metallicities[1908.10878, 2101.08789]

… solar B-field (profiles),[2005.00078, 2006.12431, 2010.06601]

… *measure the solar temperature profile*[2306.00077]

Other post-discovery uses: axion astrometry

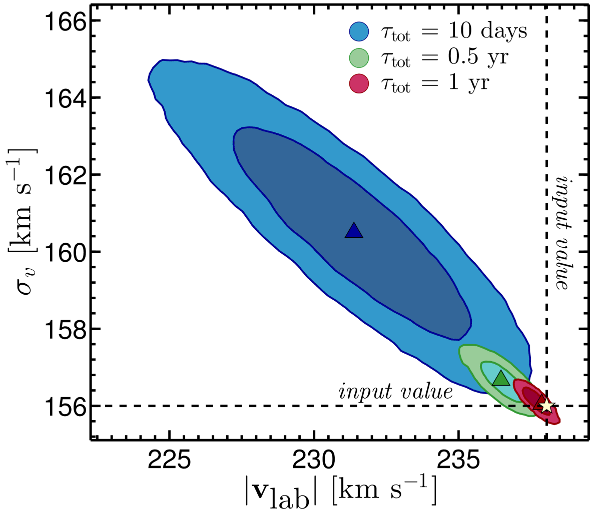
- Axion haloscopes = cavity experiments, tuning the resonant frequency until it matches m_a

- The observed axion power spectrum $|\mathcal{A}(\omega)|^2$ depends on speed distribution in lab frame f_{L}:

$$|\mathcal{A}(\omega)|^2 = 2\pi \frac{\rho_a}{m_a^2} \frac{\mathrm{d}v}{\mathrm{d}\omega} f_{\mathrm{L}}(v)$$

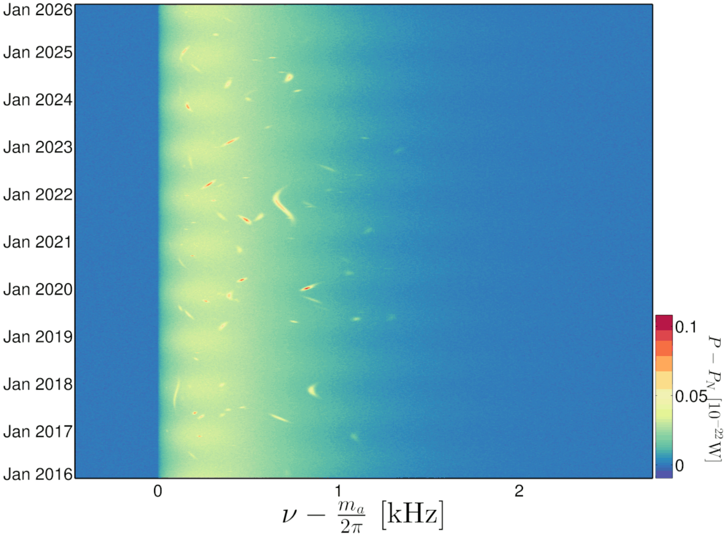
➻ Use axions to study local halo properties[1701.03118, 1711.10489]

Other post-discovery uses: axion astrometry



Can determine relative halo speed and its dispersion[1701.03118]

Other post-discovery uses: axion astrometry



Multi-year obs. can study axion minicluster tidal streams[1701.03118]

Disentangling axion parameters after a discovery – HyperLSW

- Imagine we find a 5σ signal in a haloscope: is it an axions? Is it a QCD axion? What is $g_{a\gamma\gamma}$?
- N.B. we would know m_a but can only fit $\rho_{\rm loc}\, g_{a\gamma\gamma}^2$
- Can we break the degeneracy? Follow-up experiments needed, but no detailed strategies exist

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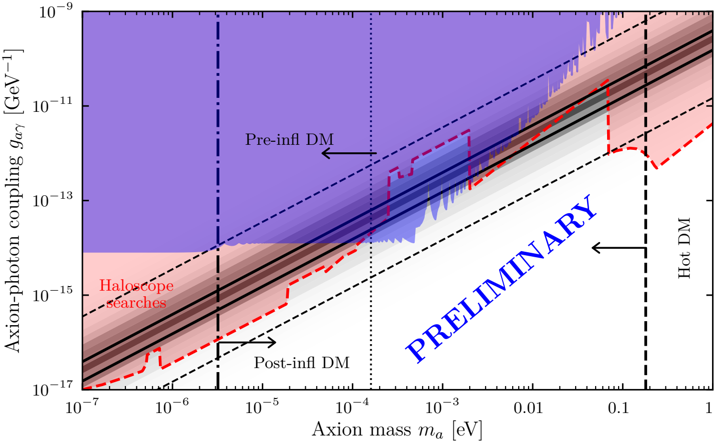
➽ Use idea for tuning light-shining-though-a-wall experiments with alternating magnet orientations[1009.4875]

Disentangling axion parameters after a discovery – HyperLSW

Enter HyperLSW† Total addressable parameter space = union of many individual, tuned magnet arrangements; this only works if you know m_a since the resonance is narrow!



†Working title. Ongoing project w/ J. Jaeckel & G. Lucente

Summary

- Axions can solve the strong CP problem, explain DM
- Vast model landscape: value of m_a? Where to look?
- DFSZ/KSVZ axion catalogues available now!
- Next-gen helioscopes can discover realistic QCD axion models, determine their mass & couplings
- Solar Primakoff flux predicted at %-level: axions = messengers for solar physics (and beyond)
- Example: accurate, model-independent(!) reconstruction of solar temperature profile $T(r)$ with axions
- Growing range of open-source software tools for axions: GAMBIT, SolarAxionFlux, snax, ...

Bonus Slides

KSVZ models with one new quark

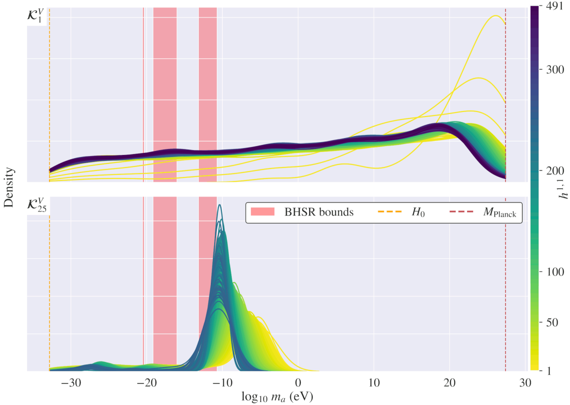
Repr.	Operator	E/N	N_{DW}
$(3, 1, -\frac{1}{3})$	$\overline{Q}_L d_R$	$2/3$	1
$(3, 1, +\frac{2}{3})$	$\overline{Q}_L u_R$	$8/3$	1
$(3, 2, +\frac{1}{6})$	$\overline{Q}_R q_L$	$5/3$	2
$(3, 2, -\frac{5}{6})$	$\overline{Q}_L d_R H^\dagger$	$17/3$	2
$(3, 2, +\frac{7}{6})$	$\overline{Q}_L u_R H$	$29/3$	2
$(3, 3, -\frac{1}{3})$	$\overline{Q}_R q_L H^\dagger$	$14/3$	3
$(3, 3, +\frac{2}{3})$	$\overline{Q}_R q_L H$	$20/3$	3
$(3, 3, -\frac{4}{3})$	$\overline{Q}_L d_R H^{\dagger 2}$	$44/3$	3
$(\bar{6}, 1, -\frac{1}{3})$	$\overline{Q}_L \sigma d_R \cdot G$	$4/15$	5
$(\bar{6}, 1, +\frac{2}{3})$	$\overline{Q}_L \sigma u_R \cdot G$	$16/15$	5
$(\bar{6}, 2, +\frac{1}{6})$	$\overline{Q}_R \sigma q_L \cdot G$	$2/3$	10
$(8, 1, -1)$	$\overline{Q}_L \sigma e_R \cdot G$	$8/3$	6
$(8, 2, -\frac{1}{2})$	$\overline{Q}_R \sigma \ell_L \cdot G$	$4/3$	12
$(15, 1, -\frac{1}{3})$	$\overline{Q}_L \sigma d_R \cdot G$	$1/6$	20
$(15, 1, +\frac{2}{3})$	$\overline{Q}_L \sigma u_R \cdot G$	$2/3$	20

- Define selection criteria for *phenomenologically preferred* models[1610.07593]
- Constraints from lifetimes, DM relic density, Landau poles, ...

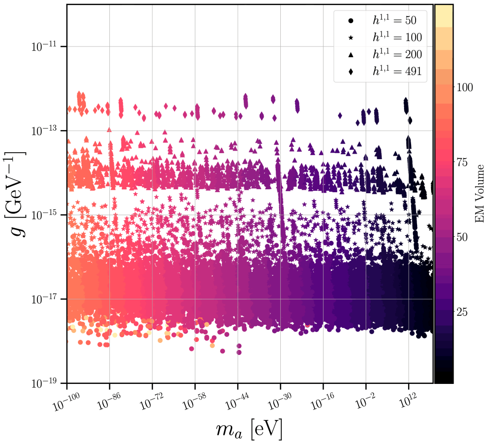
➽ 15 *preferred* KSVZ-type models with one new exotic quark

Properties of string theory ALPs

- String theory: many axion-like particles (ALPs) exist[Witten '84, ...]
- How to compute their properties? One approach is to generate random mass matrices etc.[1706.03236, 1909.05257, 2311.13658]
- Recently: explicitly computed mass spectra; can exclude some string theory solutions with BH superradiance?[2103.06812]



Properties of string theory ALPs



- Even more recently: compute ALP-photon couplings $g_{a\gamma\gamma}$, so we can do more phenomenology![2309.13145]

➽ Q: how do deal with the complexity of multi-ALP theories?

Multi-ALP systems from string theory

Considering 100s of ALPs (from string theory) is tricky:

- Mass oscillations over longer distances – even without explicit ALP-ALP interactions[2107.12813]
- $\mathcal{H}$ for ALP-photon system $\approx$ sparse, but grows as $\propto N_{\text{ALP}}^2$!

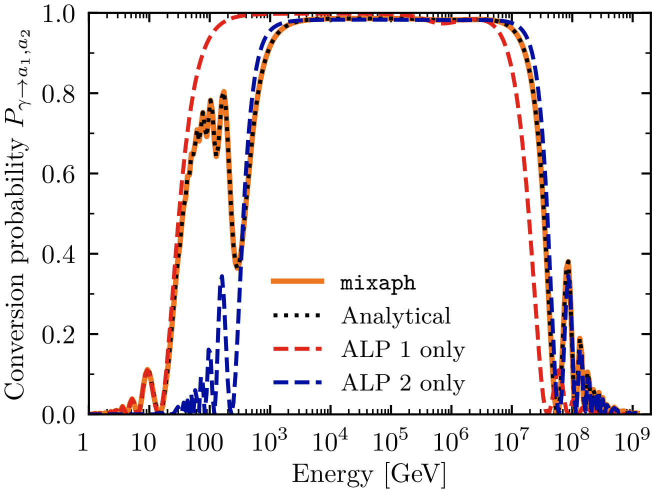
➽ Numerical approach needed!

We can make our life easier:

- Can sum up (effectively) massless states and ignore "heavy" states[1909.05257, 2107.12813]
- Relevant length and energy scales will depend on the ALP search[2311.13658]

➽ Still need a code to solve a system of $\mathcal{O}(10)$ ALPs

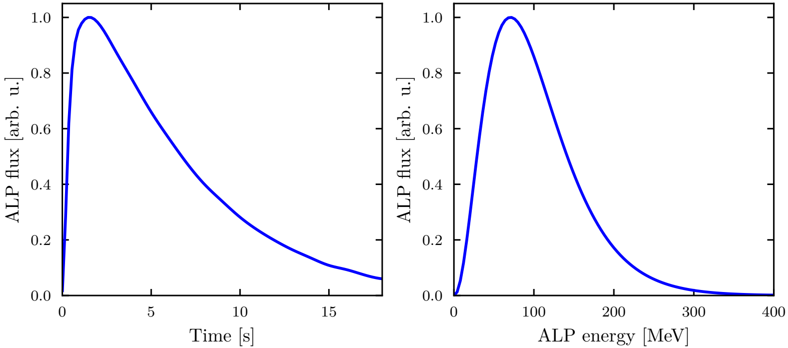
Mixaph (WIP)



Enter `mixaph`! Upcoming software code to compute predictions of multi-ALP systems; esp. relevant for astrophysical constraints

ALP spectrum from SN1987A

- Use the ALP spectrum computed in previous work[1410.3747]
- Rescale cross section to approximate massive case[1702.02964]
- Ignore photon coalescence[2008.04918, 2107.12393]



Solar metallicity problem solved?

A&A 661, A140 (2022)
https://doi.org/10.1051/0004-6361/202142971

Astronomy & Astrophysics

Observational constraints on the origin of the elements

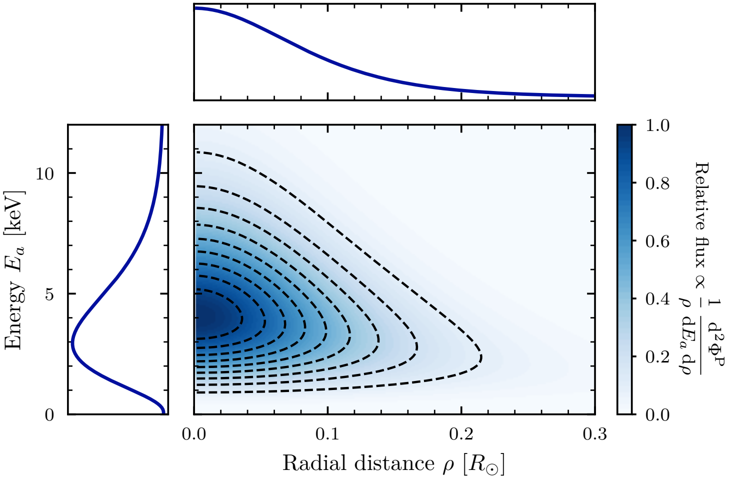
IV. Standard composition of the Sun

Ekaterina Magg[1], Maria Bergemann[1,5], Aldo Serenelli[2,3,1], Manuel Bautista[4], Bertrand Plez[7], Ulrike Heiter[6], Jeffrey M. Gerber[1], Hans-Günter Ludwig[8], Sarbani Basu[9], Jason W. Ferguson[10], Helena Carvajal Gallego[11], Sébastien Gamrath[11], Patrick Palmeri[11], and Pascal Quinet[11,12]

- New composition: MB22[2203.02255] (models available now[Zenodo])
- Claims to reproduce sound velocity profile $c(r)$ with both photospheric and meteoritic abundances? (However: potential issues?[2308.13368])

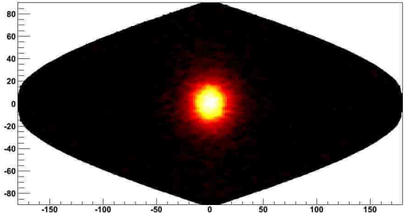
➽ Benefits of our open-source code: re-compute all fluxes for models based on new compositions once available

Primakoff flux on the solar disc

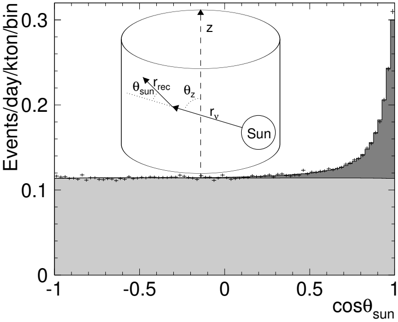


- Primakoff process dominant for KSVZ
- 50% (99%) of P flux contained within 0.15 $R_\odot$ (0.5 $R_\odot$)
- Few % stat. and sys. errors

Can we reconstruct solar $T(r)$ with νs?



Super-K Collaboration 1998–2018



1606.07538

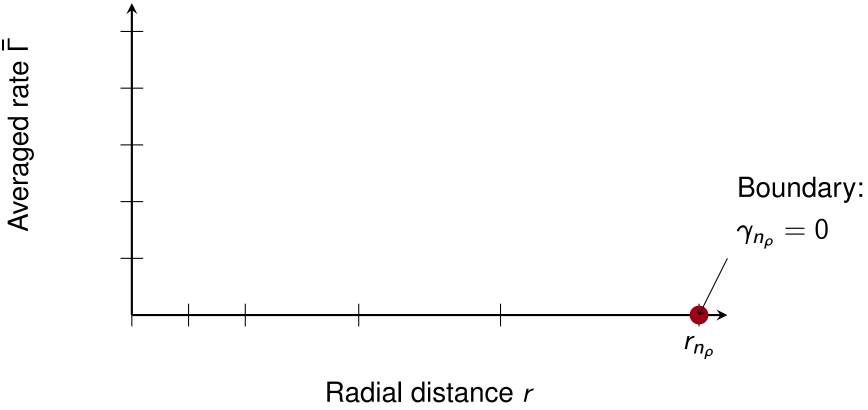
Solar ν image with more than 10^5 events!

Sadly: angular res. $\sim 40^\circ$ vs the Sun's apparent size of $\sim 0.5^\circ$, e^- recoil and ν path not aligned

➽ Helioscope X-ray optics offer superior spatial resolution

Reconstruction

For the jth energy bin, the reconstruction works as follows:



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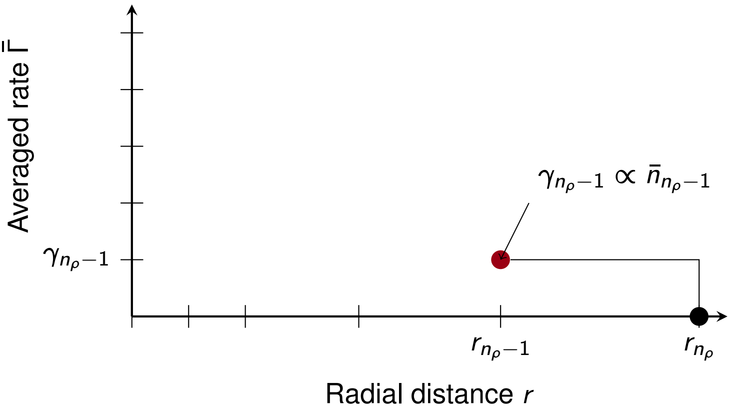

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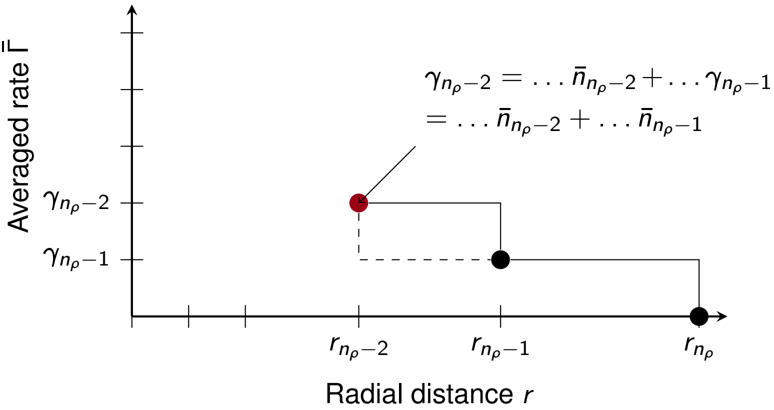

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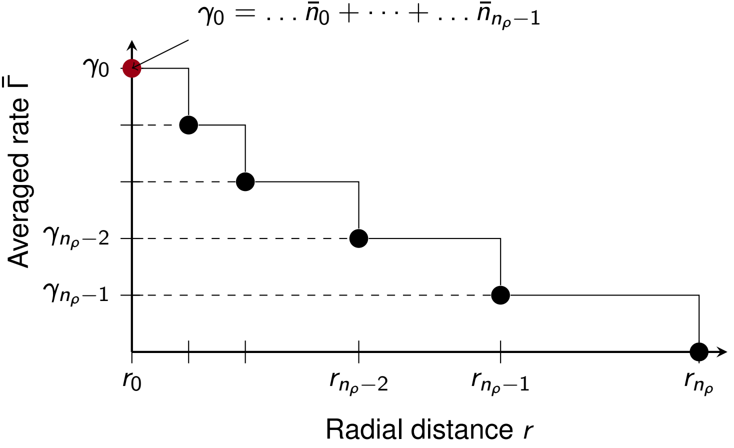
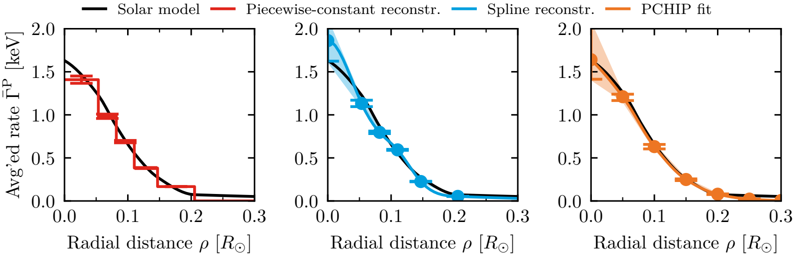
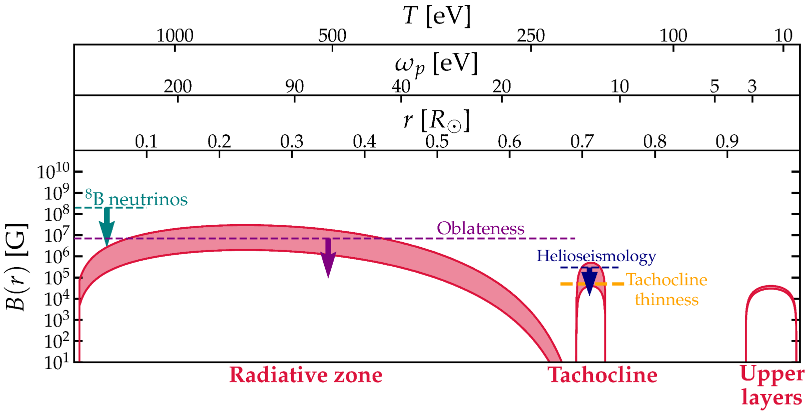


Different reconstruction techniques for *T(r)*



Axions as solar magnetometers



- Axions are produced in macroscopic solar B fields through plasmon interactions[2005.00078, 2006.10415, 2010.06601]
- Mostly resonant phenomenon: relates $r \leftrightarrow \omega_{\mathrm{pl}} \leftrightarrow E_a$

➻ Can map $B(r)$[2006.10415] — impossible w/o axions!?