Università degli Studi di Padova

Visions of Axion Multi-Messenger Physics with Helioscopes

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msca_axitools

Overview

- Brief intro to axions, their role in astrophysics
- The solar axion flux, its uncertainties[2101.08789]
- Helioscopes as solar thermometers[2306.00077]
- More post-discovery uses of axions in astrophysics

A brief intro to axions

- QCD axions solve strong CP problem, explain smallness of $\theta G\widetilde{G}$ term[Peccei & Quinn '77] (nEDM measurement:[2001.11966] $\theta \lesssim 10^{-10}$)
- Unintended bonus: excellent dark matter (DM) candidates!

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- String theory: potentially many axionlike particles (ALPs)
- Astrophysical hints: TeV transparency,[0704.3044, 0707.4312] stellar cooling,[1512.08108] neutron star X-ray excess,[1910.04164] ...

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

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[1511.02867] depends on model-dependent (recent review[2003.01100]) anomaly ratio E/N

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

- ALP properties less predictive, no connection to QCD

Axions in astrophysics

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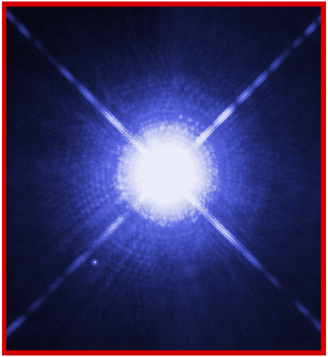
➽ *Great lecture by G. Raffelt at GGI 2023*

A brief overview of White Dwarfs (WDs)



Sirius B & Sirius A

HST image: NASA, ESA, H. Bond (STScI), M. Barstow (U Leicester)

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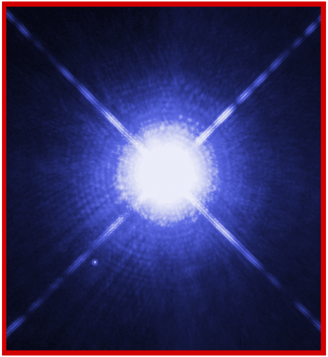

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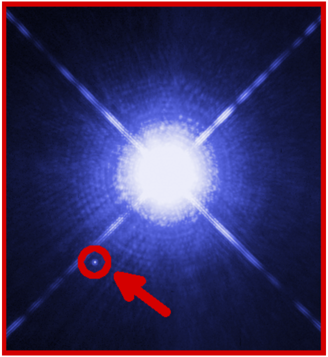

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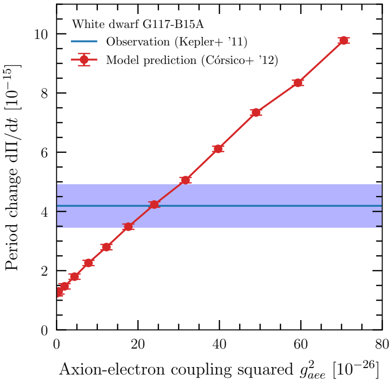
WD cooling hints



- Variable WDs "pulsate" with period Π (typically mins to hrs; possibly different modes)
- Π changes over time Winget+ '83

$$\frac{\dot{\Pi}}{\Pi} \sim \frac{\dot{R}}{R} - \frac{1}{2}\frac{\dot{T}}{T}$$

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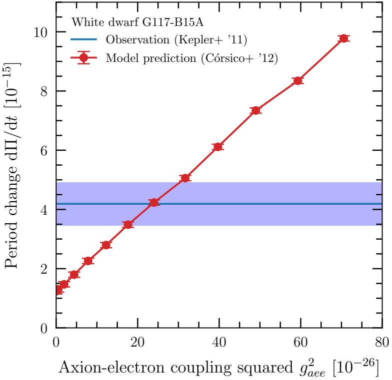

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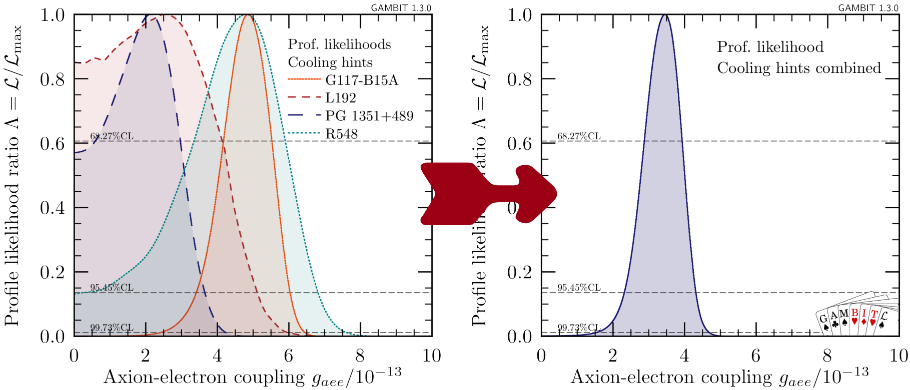
$$\frac{\dot{\Pi}}{\Pi} \sim \frac{\dot{R}}{R} - \frac{1}{2}\frac{\dot{T}}{T}$$

➽ Measuring $\dot{\Pi} \sim 1\,\mu\text{s}/1\,\text{yr}$ (!), modelling the WD = constraining additional cooling, axion interactions

WD cooling hints

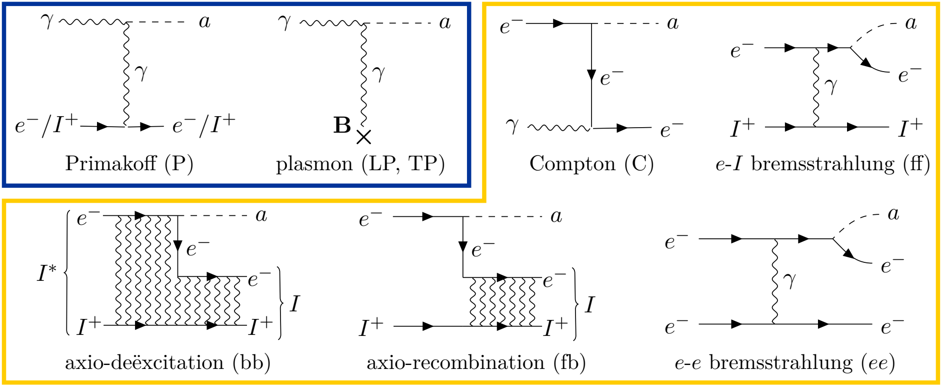
Unexpectedly large $\dot{\Pi}$ in multiple WDs: one of a few “cooling hints” for axions[1512.08108]



Combined effect $> 3\sigma$[e.g. 1810.07192] but possible systematics: careful interpretation required (reviews[2202.02052, 1907.00115])

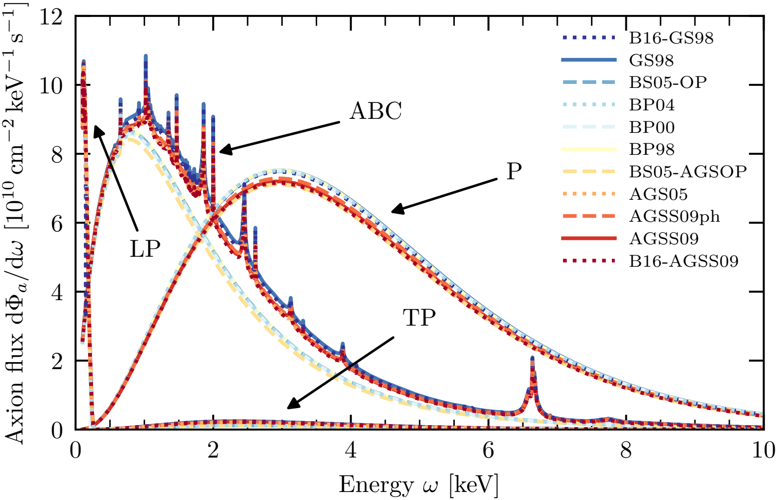
Now: axions from the Sun

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

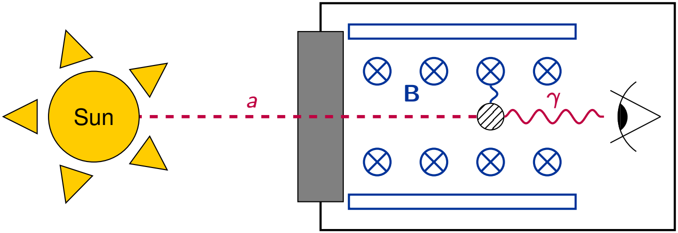


Both $g_{a\gamma}$ and g_{ae} can be relevant Raffelt & Stodolsky '88, Redondo '13, ...

Predictions from solar models

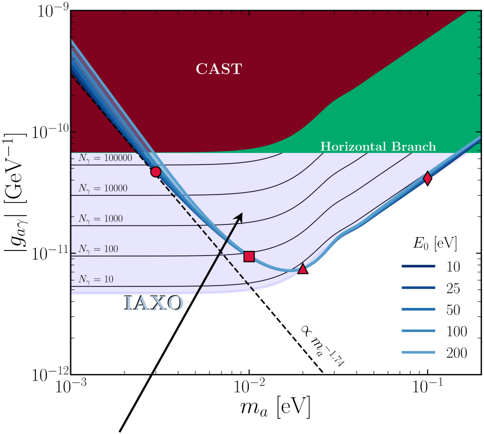


Helioscopes



- Axions produced in the Sun escape and travel outwards
- Track the Sun with a B field inside an opaque setup, allowing axions to convert into photons
- Use X-ray optics and detectors to detect the photons

Discovery potential of IAXO



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

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

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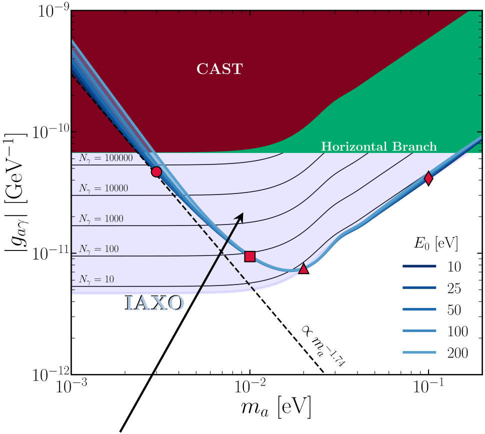

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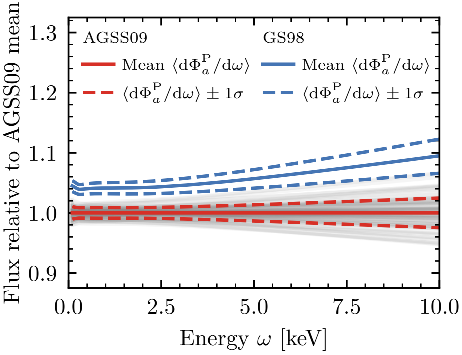
- IAXO = upcoming helioscope experiment to be built in Hamburg at DESY [1401.3233, 2010.12076]
- Can determine m_a and $g_{a\gamma}$ for the region of parameter space on the left
- ➽ Opportunity to discover realistic QCD axion models!
- ➽ Exciting prospect of post-discovery physics

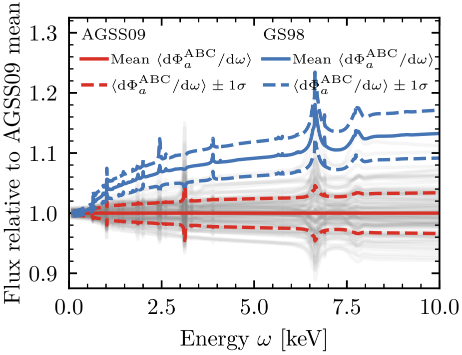
Solar axion flux uncertainties

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

Primakoff fluxes



ABC fluxes



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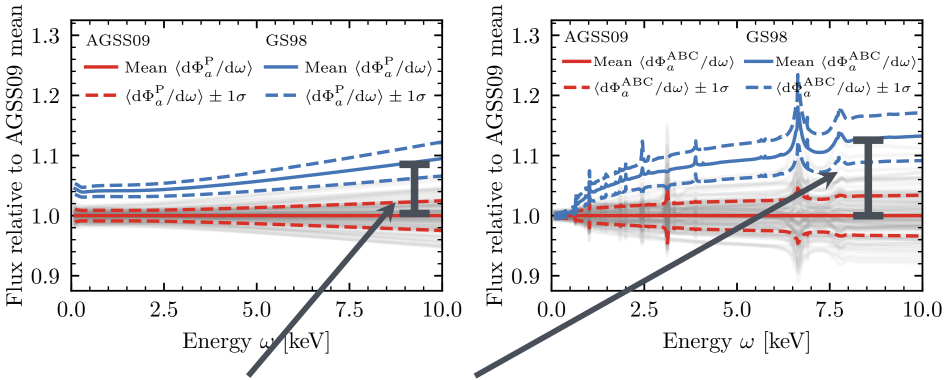

Systematic shift between low-Z and high-Z models (metallicity problem)

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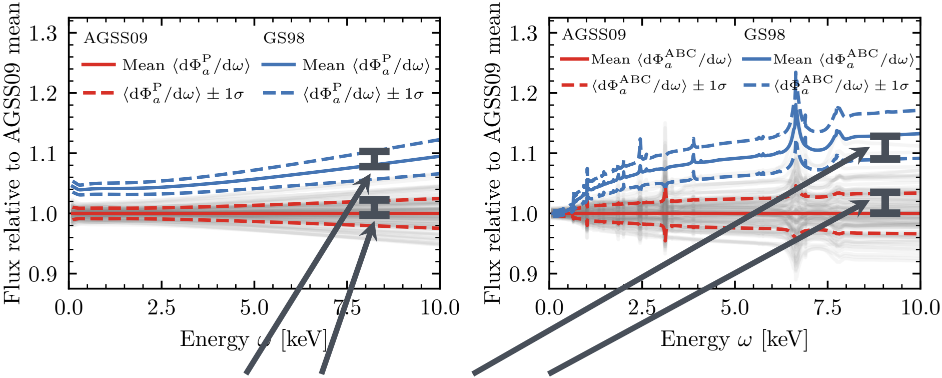

Statistical fluctuations; similar for low-Z and high-Z models, smaller than systematics

Solar metallicity problem solved?

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

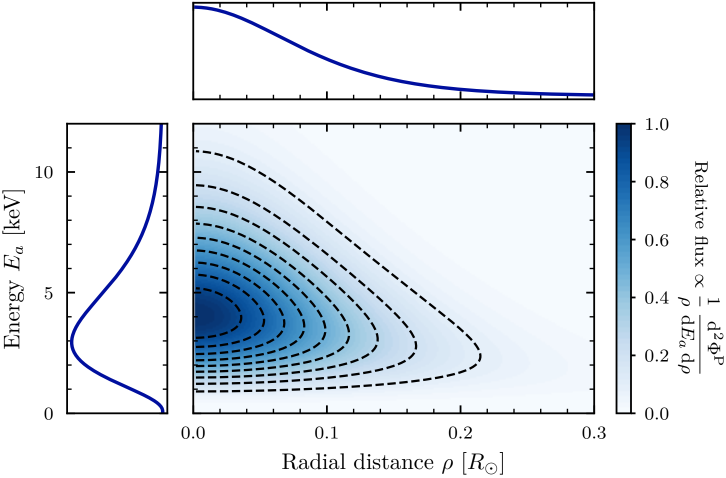
Observational constraints on the origin of the elements

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]

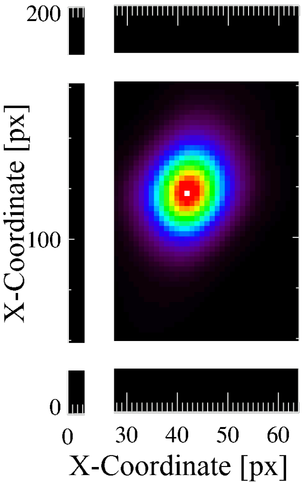
- New composition: MB22[2203.02255]
- Claims to reproduce sound velocity profile $c(r)$ with both photospheric and meteoritic abundances
- However: potential issues?[2308.13368]

Primakoff flux on the solar disc



N.B. 50% (99%) of Primakoff flux contained within 0.15 $R_\odot$ (0.5 $R_\odot$)

The solar axion image



- Simulated axion image in CAST helioscope[hep-ex/0702006]

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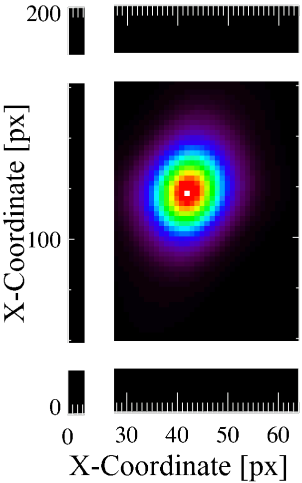

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- Availability of photon-counting detectors with many pixels

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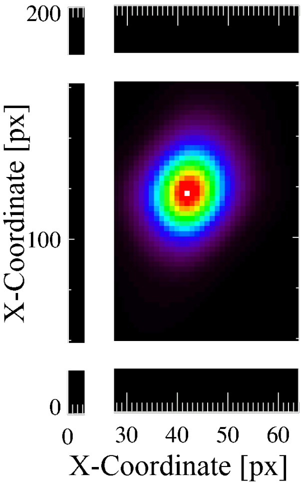

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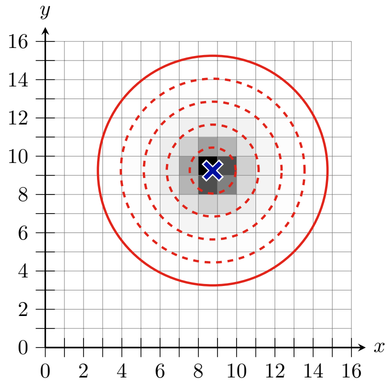
➽ Estimate photon counts in rings about the centre of the signal region to obtain radial information

The solar axion image



- Expected idealised signal in IAXO (actually 128×128 pixels, 20 radial, 4 spectral bins)

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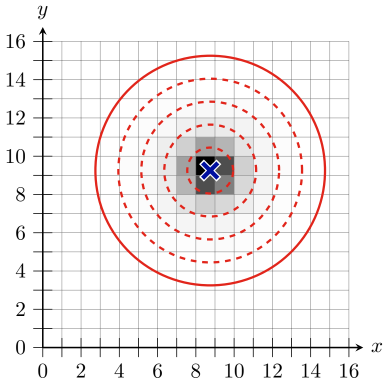

- Expected idealised signal in IAXO (actually 128 $\times$ 128 pixels, 20 radial, 4 spectral bins)
- Many pixels: photon counts/pixel $\approx$ equally distributed, integrate flux over radial bins

➽ Generate 1000 pseudodata sets for IAXO, “invert” solar axion image, fit axion and solar model parameters

The (simplified) Primakoff production rate

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

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

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➽ 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 $\bar{\Gamma}_j^{\mathrm{P}}$

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

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

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

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

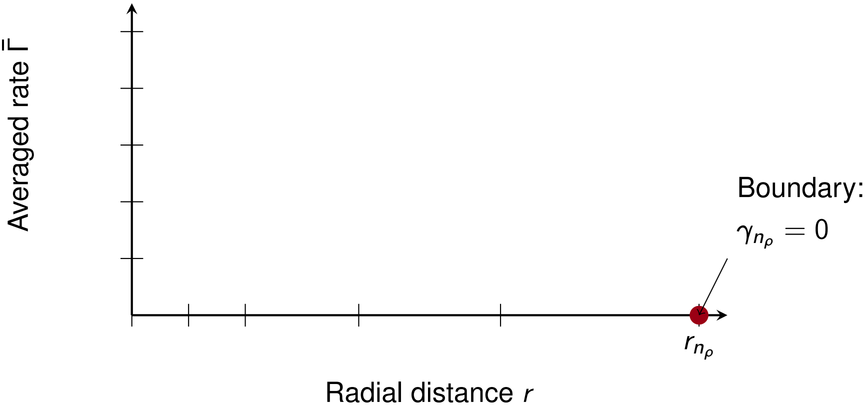
$$= \frac{1}{3} \left[\gamma_{i,j} \, \Delta^3_{i+1;i} + \sum_{k=i+1}^{n_\rho} \gamma_{k,j} \left(\Delta^3_{k+1;i} - \Delta^3_{k+1;i+1} + \Delta^3_{k;i+1} - \Delta^3_{k;i} \right) \right]$$

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

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

Reconstruction

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



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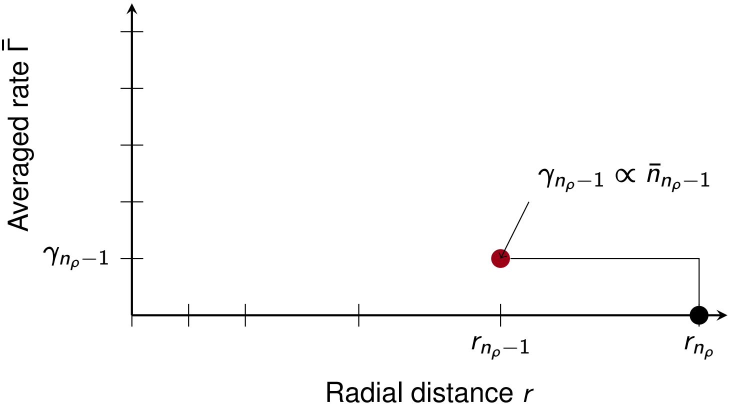

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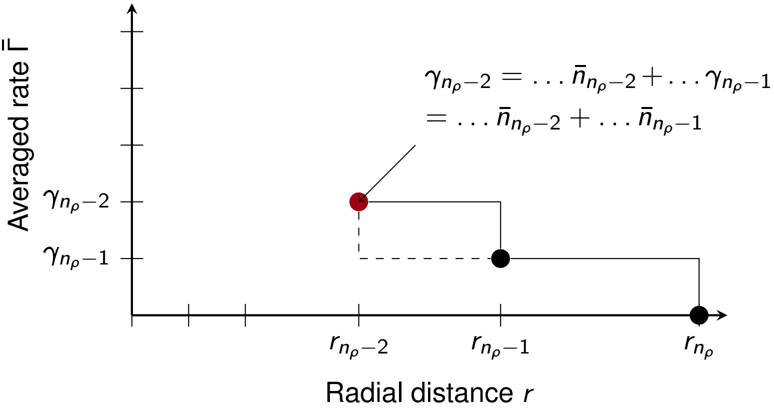

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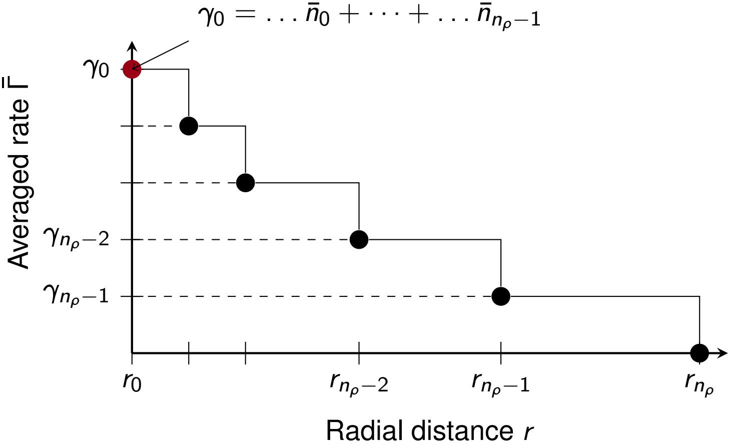

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We write this as a matrix equation $\bar{n}_{i,j} = \sum_{k=1}^{n_\rho} \mathcal{M}_{ik}\, \gamma_{k,j}$ with

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

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

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➸ Choose direct fitting approach: general (shape-preserving) spline interpolation, compute integral again:

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

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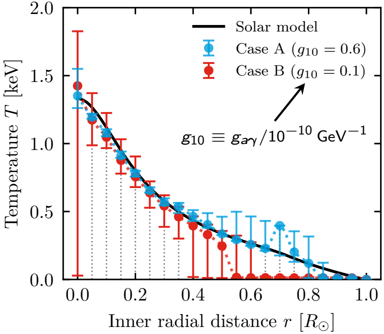
- Problem: matrix not square, no inversion; need to directly fit $g_{a\gamma}$, T_i and κ_i to the $n_{i,j}$:

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

Results



- Accurate $T(r)$ reconstruction up to 0.5 $R_\odot$ (0.8 $R_\odot$), expected median statistical errors of 10% (16%)[2306.00077]

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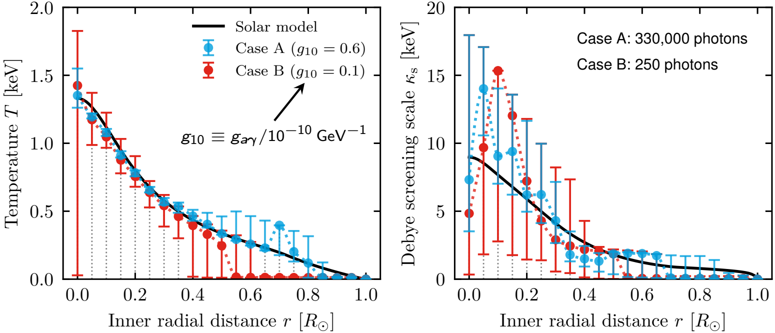
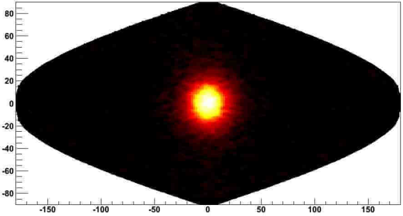
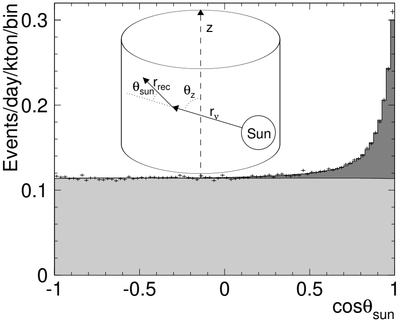


- Accurate $T(r)$ reconstruction up to 0.5 $R_\odot$ (0.8 $R_\odot$), expected median statistical errors of 10% (16%)[2306.00077]
- Difficulties for κ_s: shallow minima, weaker functional dependence, approximation used for Γ^P

Could we do the same reconstruction using neutrinos?



Super-K Collaboration 1998–2018



1606.07538

Solar ν image with $> 10^5$ events!

Reconstruct $T(r)$ with νs?!

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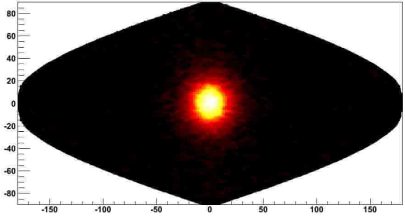

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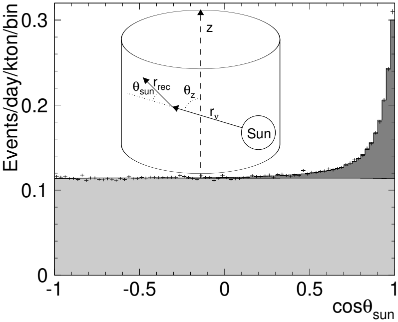


1606.07538

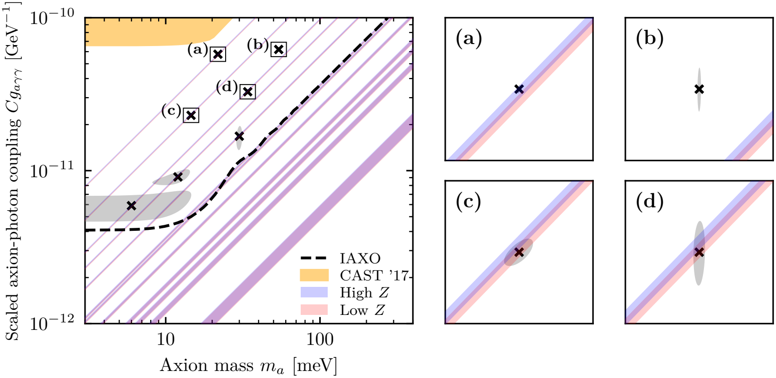
Solar ν image with $> 10^5$ events!

Reconstruct $T(r)$ with νs?!

No. Angular resolution $\sim 40^\circ$ vs the Sun's apparent size $\sim 0.5^\circ$, e^- recoil and ν path not aligned

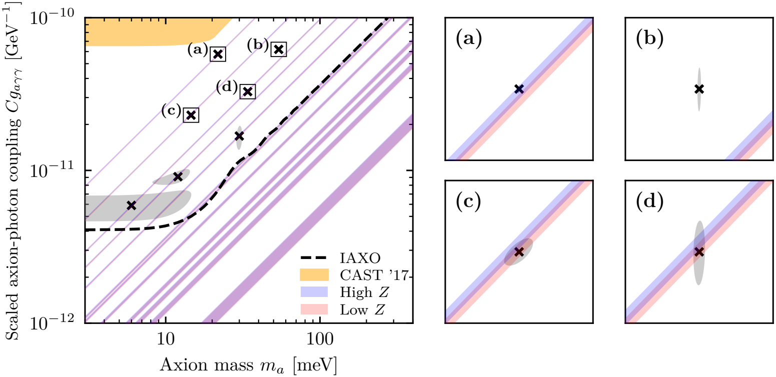
➽ Helioscope X-ray optics offer superior spatial resolution

Other use cases: QCD axion models & metallicity



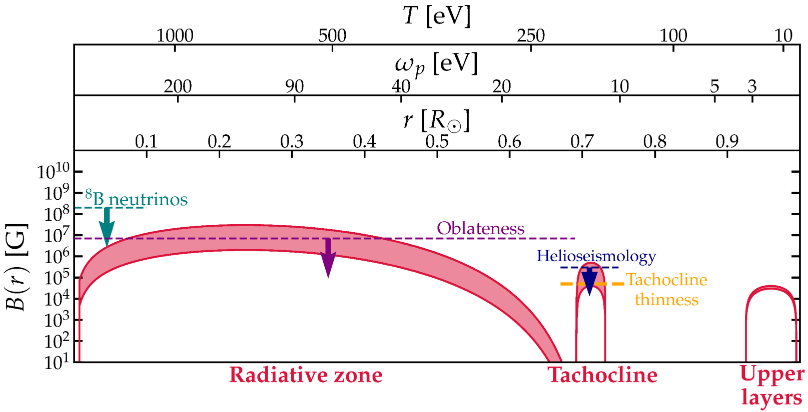
- May simultaneously distinguish QCD axion and solar models,[2101.08789] hint for solar metallicity problem solution

Other use cases: QCD axion models & metallicity



- May simultaneously distinguish QCD axion and solar models,[2101.08789] hint for solar metallicity problem solution
- Lines = 15 KSVZ models; more complete KSVZ[2107.12378] and DFSZ model catalogues[2302.04667] available now
- Can also determine g_{ae},[1811.09278] metallicities[1908.10878]

Other use cases: axions as solar magnetometers



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

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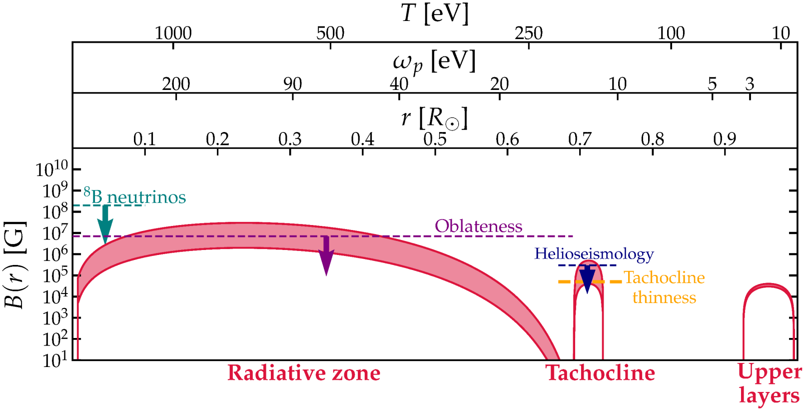


- Axions are produced in macroscopic solar B fields through plasmon interactions[2005.00078, 2006.10415, 2010.06601]
- Resonant phenomenon: relates $r \leftrightarrow \omega_{\text{pl}} \leftrightarrow E_a$
- ➽ Can map $B(r)$, axions = solar magnetometers[2006.10415]
- N.B. currently only limits on B: another axion advantage!

Other use cases: local DM halo with axion astrometry

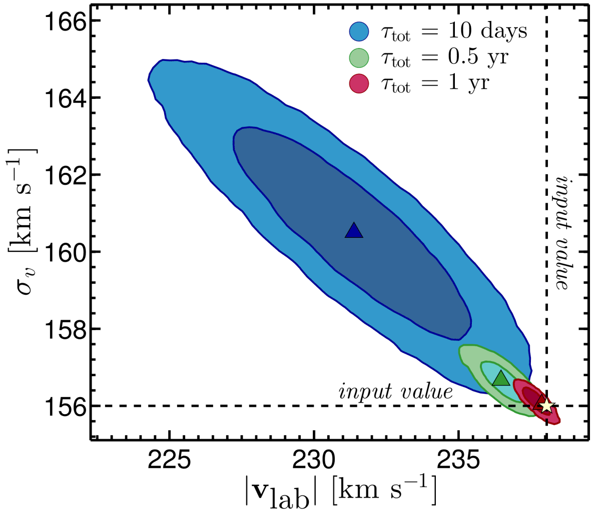
- Axion haloscopes = cavity experiments, tuning the resonant frequency until it matches m_a

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

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

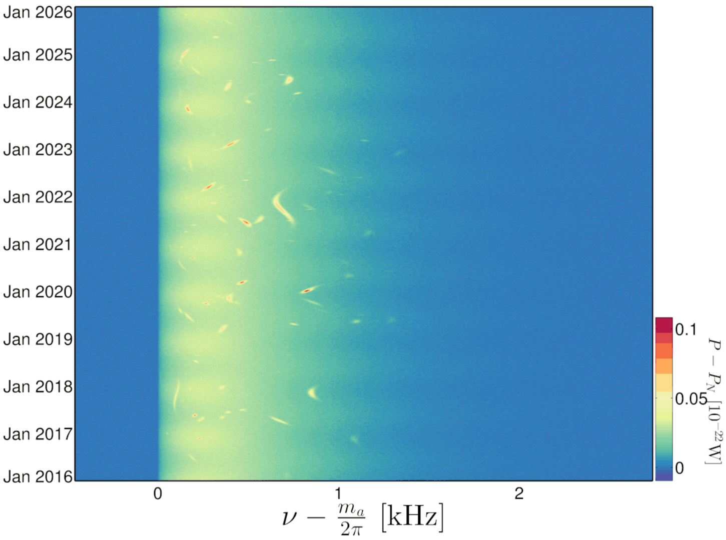
➽ Use axions to study local halo properties[1701.03118, 1711.10489]

Local halo properties



Can determine relative halo speed and its dispersion[1701.03118]

Local halo properties



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

Summary

- Next-gen helioscopes can discover realistic QCD axion models, determine their mass & couplings
- Axion pheno $\approx$ neutrinos: may influence stellar evolution, explain potential astrophysical anomalies
- Axions = messengers for stellar or DM halo physics; here: accurate, model-independent reconstruction of solar temperature profile $T(r)$
- Growing open-source software framework for axions and other WISPs to support these efforts

KSVZ models beyond $N_Q = 1$

- What about $N_Q \geq 1$? Arbitrarily many models?

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➽ *No:* selection criteria for *preferred* models! Adding too many new Qs will eventually introduce Landau Poles at low energies

➽ Finite number of KSVZ models and E/N values

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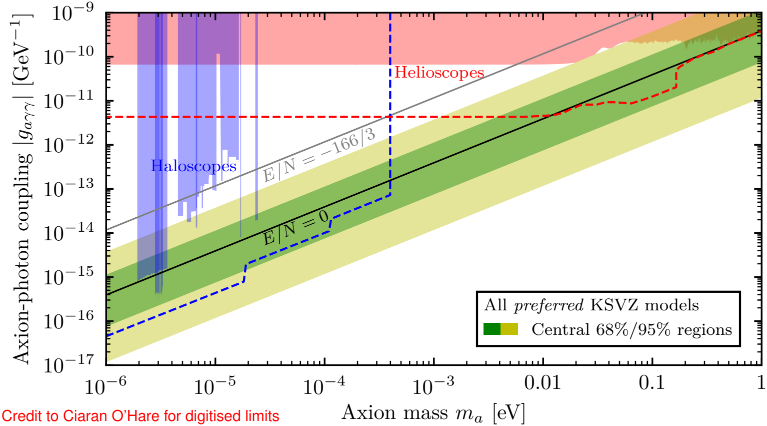
➽ Finite number of KSVZ models and E/N values

- For our choice, we find $N_Q \leq 28$ and 820 different E/N values (443 for "additive models")[2107.12378]

The model band of *preferred* KSVZ models

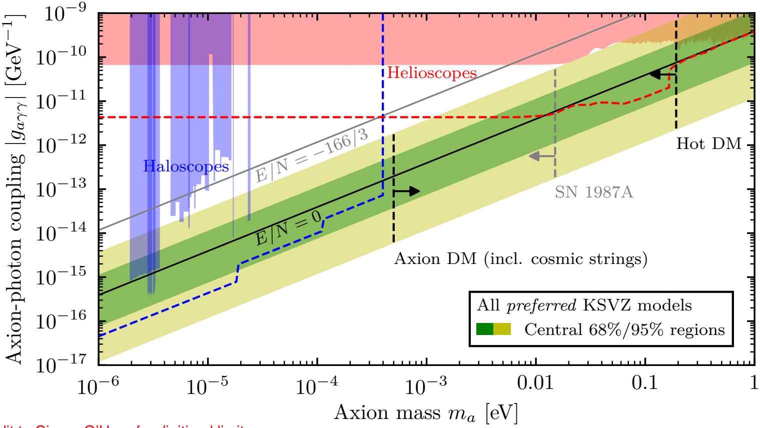
- Model band of "all" KSVZ models from KSVZ model catalogue; here: equally probable *preferred* representations
  - ➽ Theory prior on $|g_{a\gamma\gamma}| \propto |E/N - 1.92(4)|$



Credit to Ciaran O'Hare for digitised limits

“Boxing in” the axion

Recent activity in string simulations[e.g. 1806.04677, 2007.04990] but still controversial[2108.05368, 2109.09679], also still work for $\Delta N_{\rm eff}$ prediction needed[2101.10330] (underway[2108.04259, 2108.05371])



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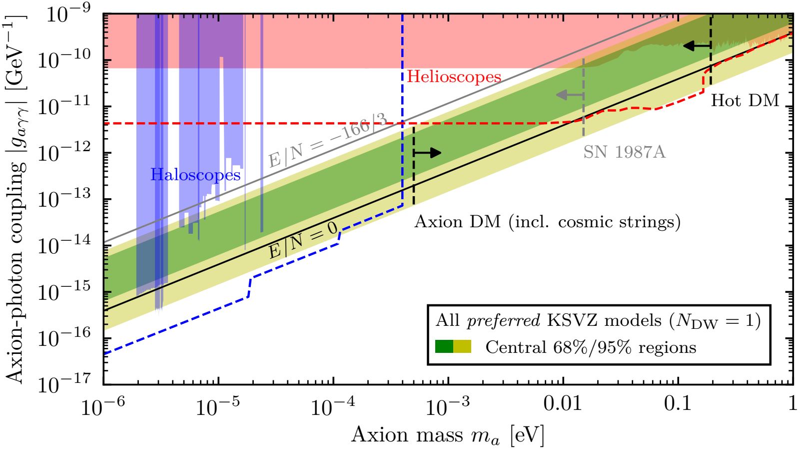
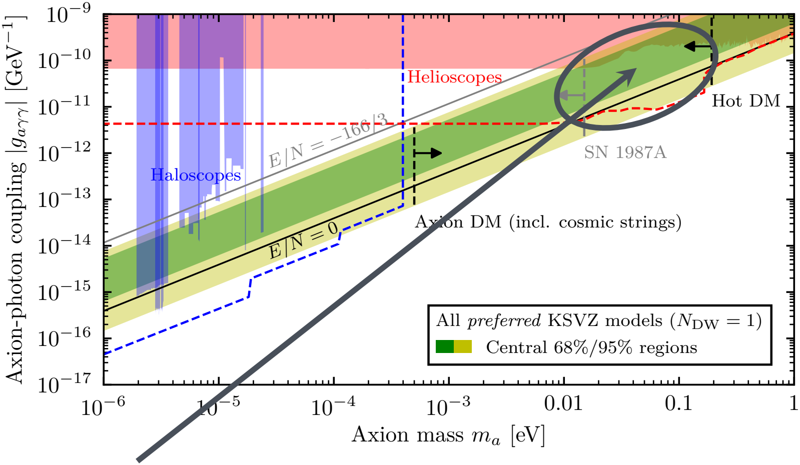
Avoid the DW problem with $N_{DW} = 1$ models

Definition not unique: e.g. the band for “additive” models would be lower, more DFSZ-like or the $N_{DW} = 1$ subsets also looks different...



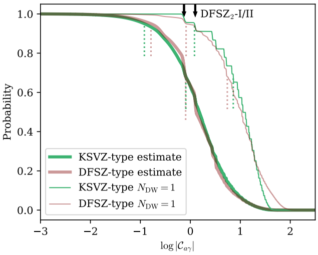
...which can be intriguing!

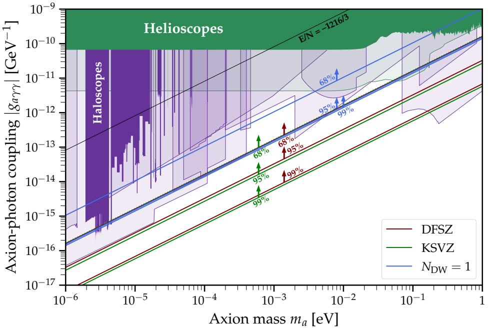
Avoid the DW problem with $N_{DW} = 1$ models



SN1987A limits potentially problematic;
region will be probed by IAXO! What can we learn?

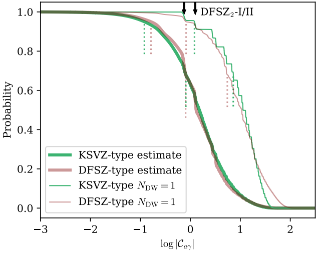
QCD model band including KSVZ models

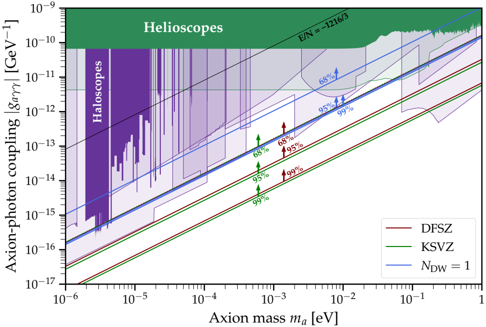




- Now: model catalogues for KSVZ[2107.12378] and DFSZ[2302.04667]

QCD model band including KSVZ models





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- Possible interpretation as "theory priors" on E/N
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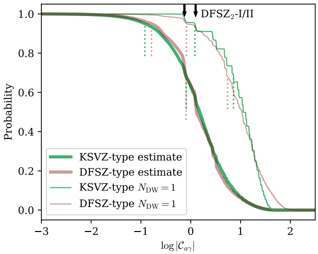

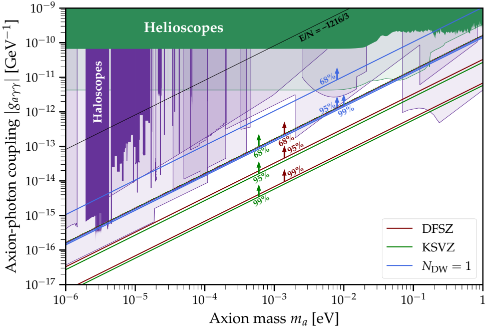

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➽ Catalogues can help to find UV models after detection[e.g. 2101.08789]

Three different reconstruction techniques