Stellar hints for axion hunters

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in collaboration with
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Abstract

- Discuss impacts of a light pseudoscalar Nambu-Goldstone boson (axion) on stellar evolution, and speculate the existence of hints for additional energy losses.
- Explore the possibility to explain excessive stellar energy losses in terms of the QCD axion.
- Provide the best fit parameters to guide their experimental discovery potential.

Plan

- Energy-loss arguments of stars
  - Observables
  - Cooling hints for new physics ?
- Axion models
  - DFSZ models
  - KSVZ models
- Experimental potential
- Axion hints compatible with axion dark matter ?
- Conclusion

Axions and stellar energy-losses

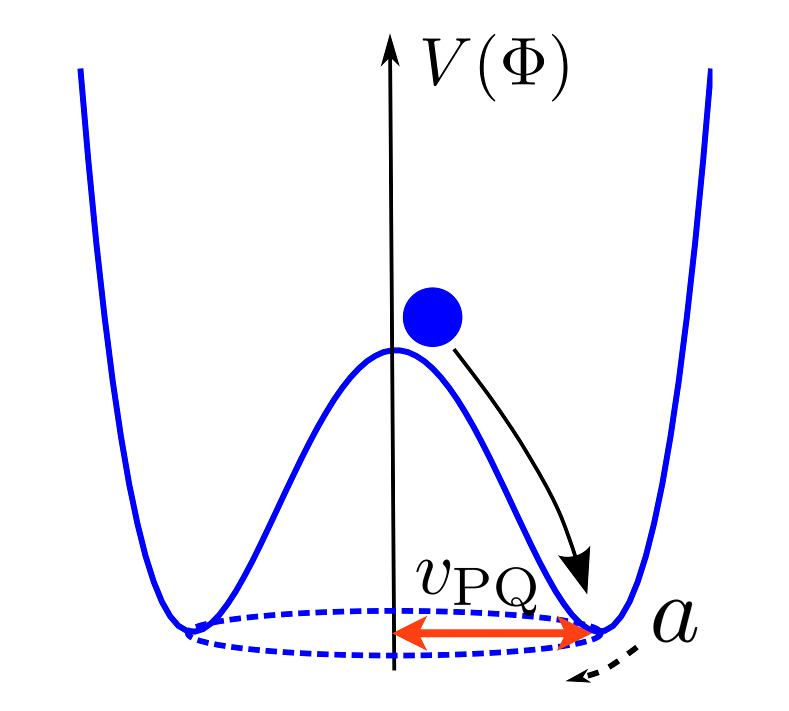
Axion

- Motivated by the Peccei-Quinn (PQ) mechanism as a solution to the strong CP problem.
  Peccei and Quinn (1977)
- Nambu-Goldstone boson associated with the spontaneous breaking of global U(1) symmetry.

  It can be identified as the phase of a complex scalar field:

  $$\Phi(x) = \frac{1}{\sqrt{2}} [v_{\rm PQ} + \rho(x)] e^{ia(x)/v_{\rm PQ}}$$

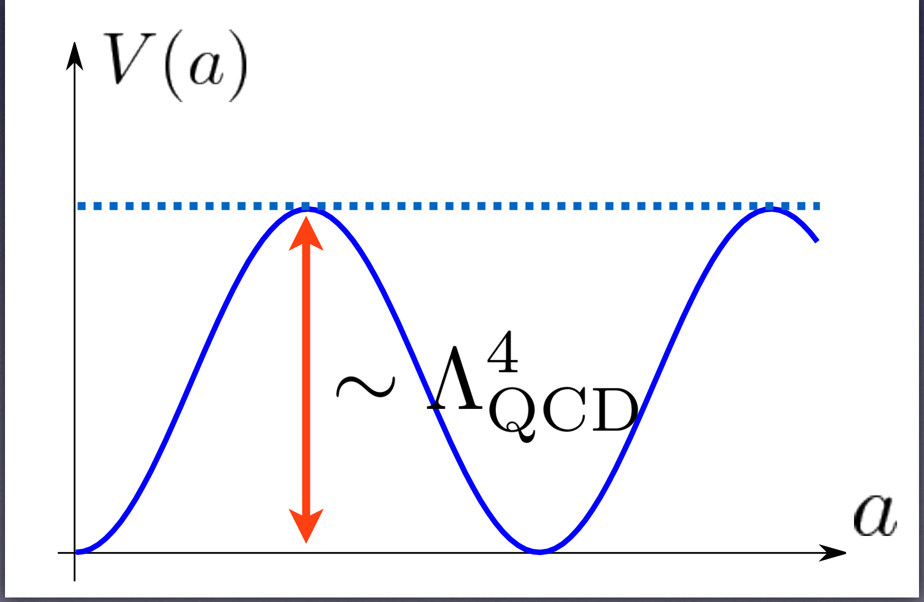
  $v_{\rm PQ}$: symmetry breaking scale



- Axion acquires a small mass (QCD effect).

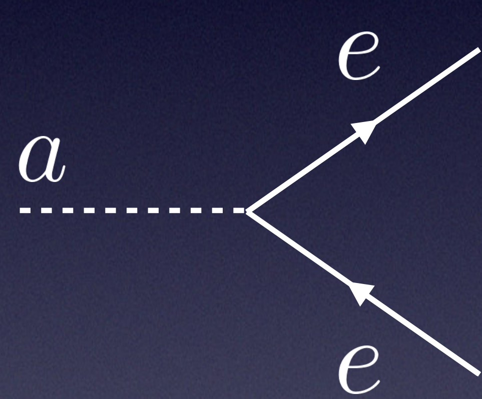
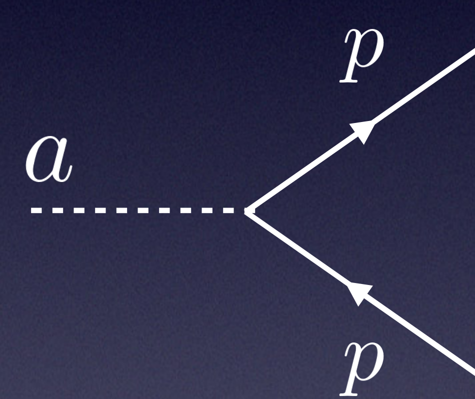
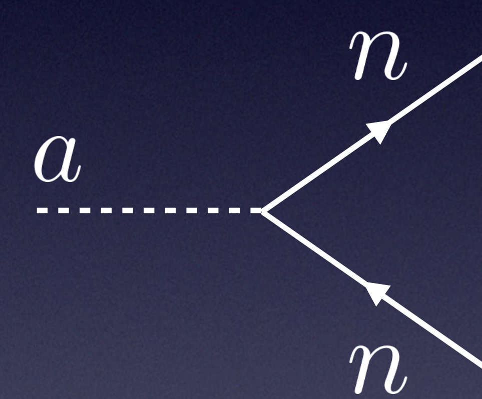
  $$\boxed{m_a \sim \frac{\Lambda_{\rm QCD}^2}{f_a} \sim 6\,{\rm meV} \left(\frac{10^9\ {\rm GeV}}{f_a}\right)}$$

  $f_a = v_{\rm PQ}/N$ $\qquad$ N : QCD anomaly coefficient



- Stable and weakly interacting particle.
  → Good candidate of cold dark matter.

Axion couplings

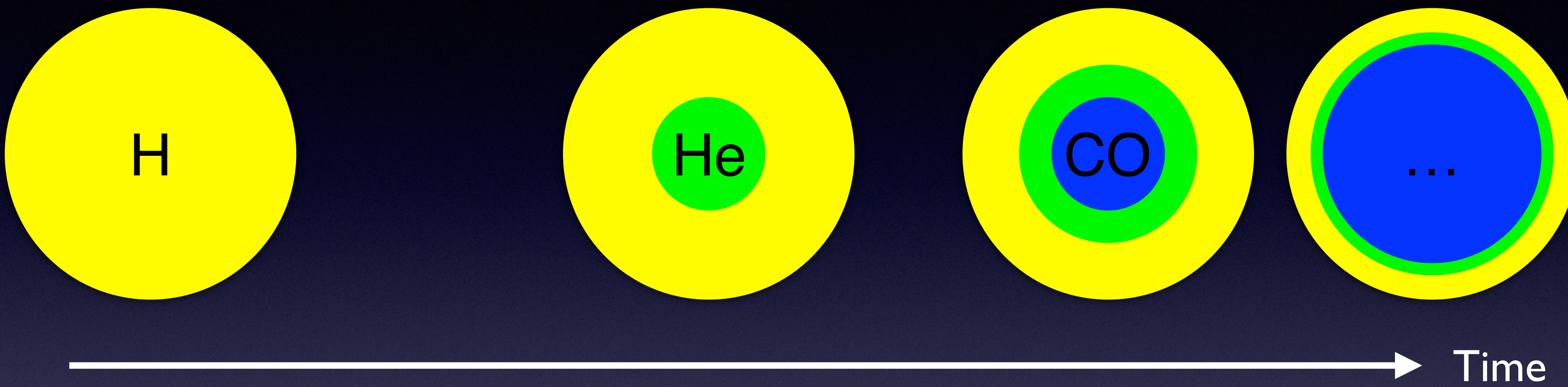
Photon	Electron	Proton	Neutron
$\frac{\alpha}{2\pi} C_{a\gamma} \frac{a}{f_a} \frac{F_{\mu\nu}\tilde{F}^{\mu\nu}}{4}$	$C_{ae} m_e \frac{a}{f_a} [i\bar{e}\gamma_5 e]$	$C_{ap} m_p \frac{a}{f_a} [i\bar{p}\gamma_5 p]$	$C_{an} m_n \frac{a}{f_a} [i\bar{n}\gamma_5 n]$
 $g_{a\gamma} \equiv \frac{\alpha}{2\pi f_a} C_{a\gamma}$	 $g_{ae} \equiv C_{ae} \frac{m_e}{f_a}$	 $g_{ap} \equiv C_{ap} \frac{m_p}{f_a}$	 $g_{an} \equiv C_{an} \frac{m_n}{f_a}$

Generic feature: $g_{a\gamma}, g_{ae}, g_{ap}, g_{an} \propto f_a^{-1}$

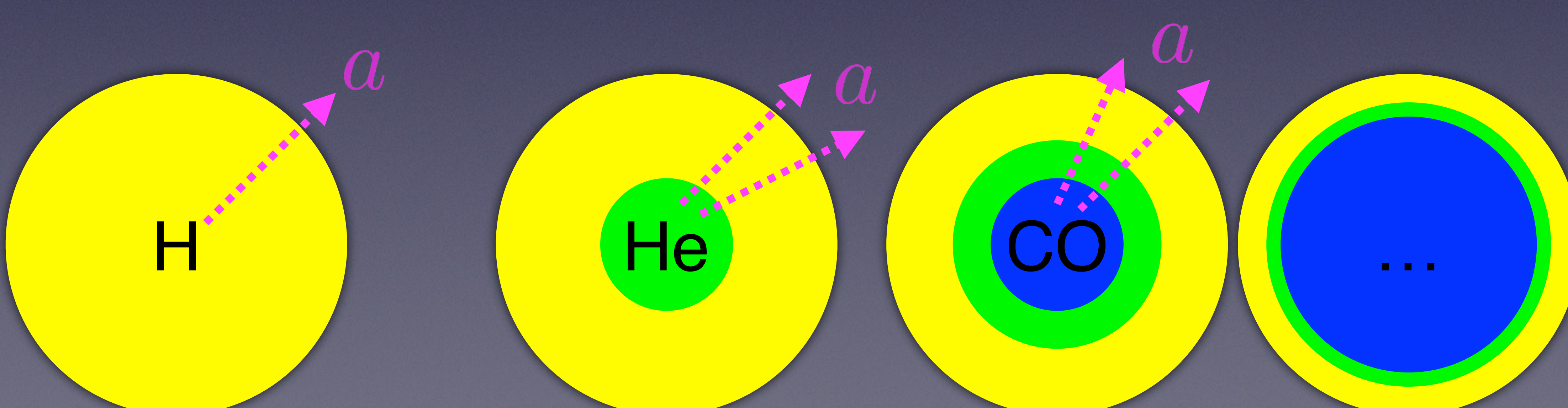
Model dependence: $C_{a\gamma}, C_{ae}, C_{ap}, C_{an}$

Axions and stars

- Stellar evolution



- Axion emission:
  Additional energy loss → accelerates (or delays) stellar evolution.

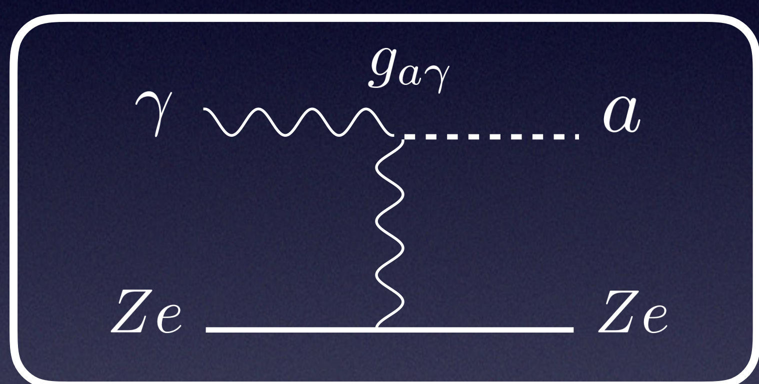


Horizontal Branch (HB) stars in globular clusters

- Observable: "R-parameter"

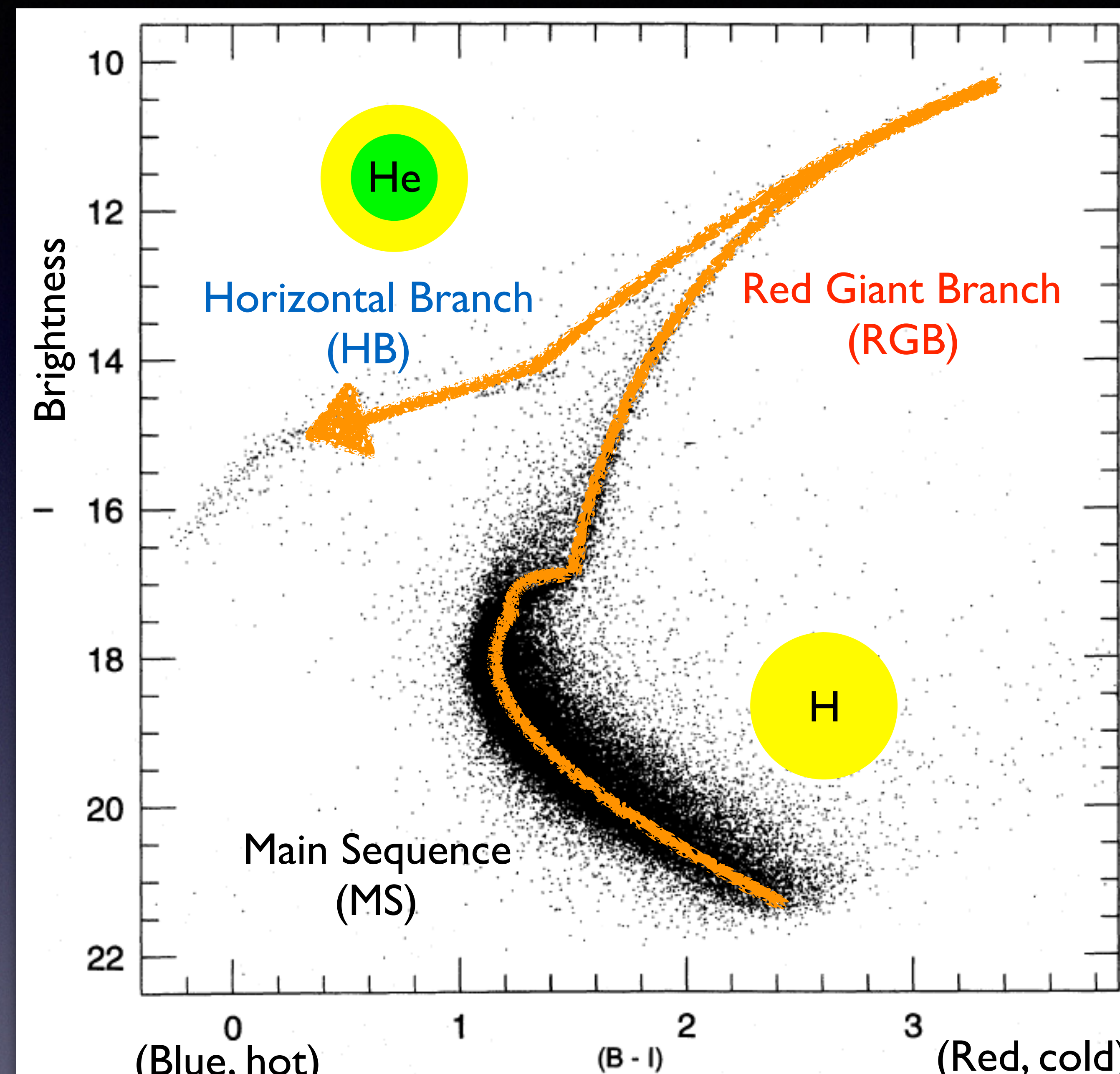
$$R = \frac{\#\text{ of HB stars}}{\#\text{ of RGB stars}}$$

- Primakoff process



Relevant in HB (not dense)
but not in RGB core (very dense).

$\rightarrow$ Decrease in R.



Sandquist, Bolte, Stetson, and Hesser (1996)

- Recent study

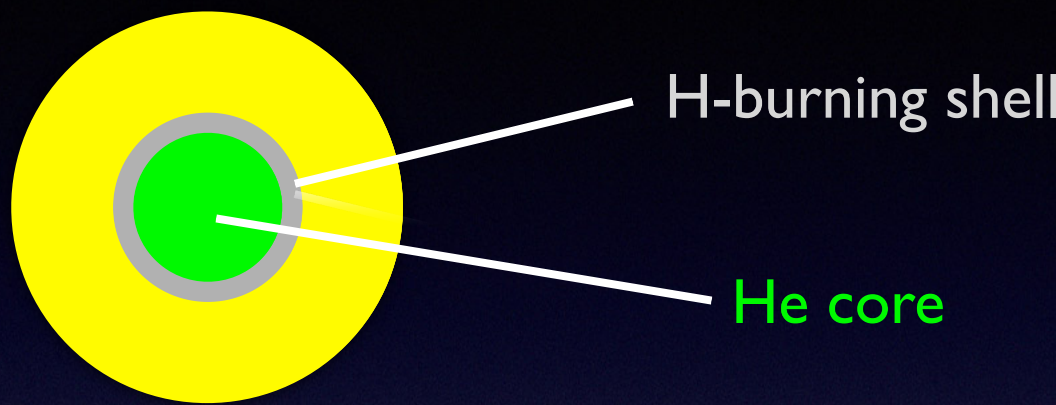
Ayala, Dominguez, Giannotti, Mirizzi, and Straniero (2014)

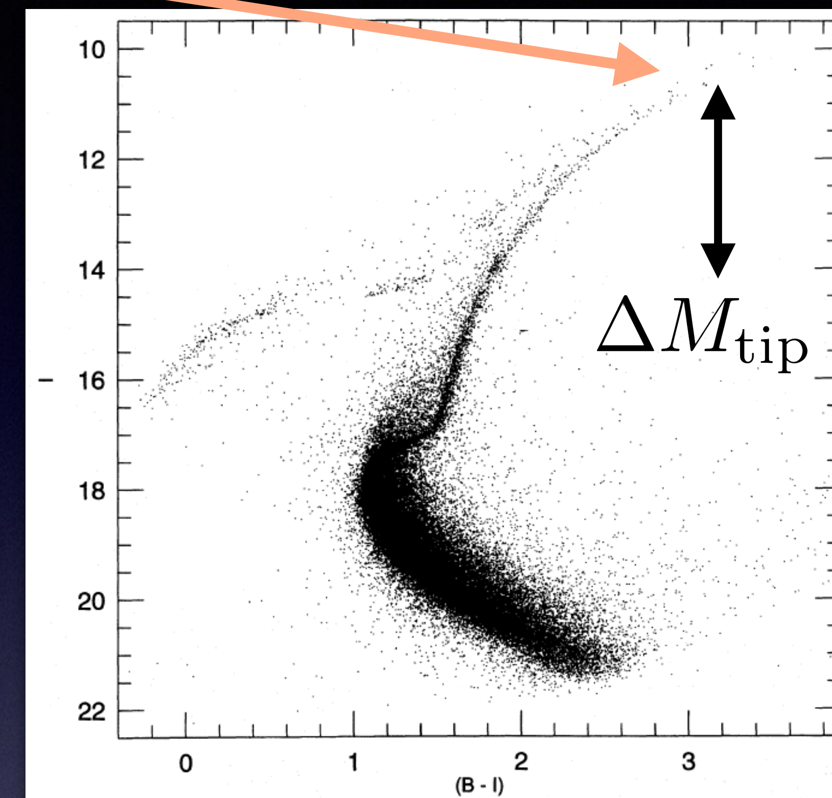
Bound (2σ): $g_{a\gamma} < 0.66 \times 10^{-10}\,\mathrm{GeV}^{-1}$

But a mild preference: $g_{a\gamma} = 0.45^{+0.12}_{-0.16} \times 10^{-10}\,\mathrm{GeV}^{-1}$

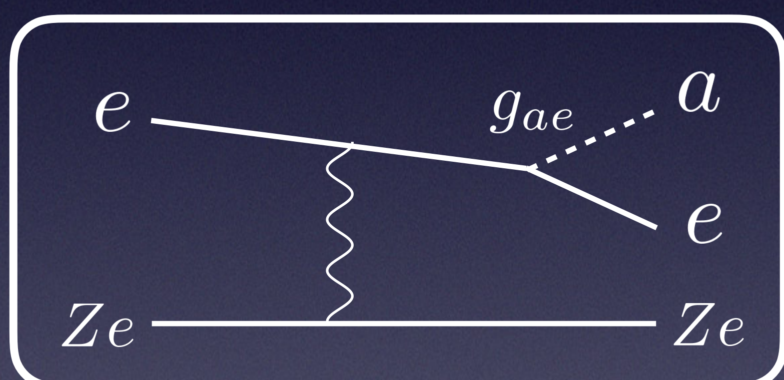
Tip of the Red Giant Branch (RGB)

- Increase He core until 3α ignition ($3\alpha \to {}^{12}C$).





- Axion bremsstrahlung off electrons



→ Cools down the core, delays ignition.

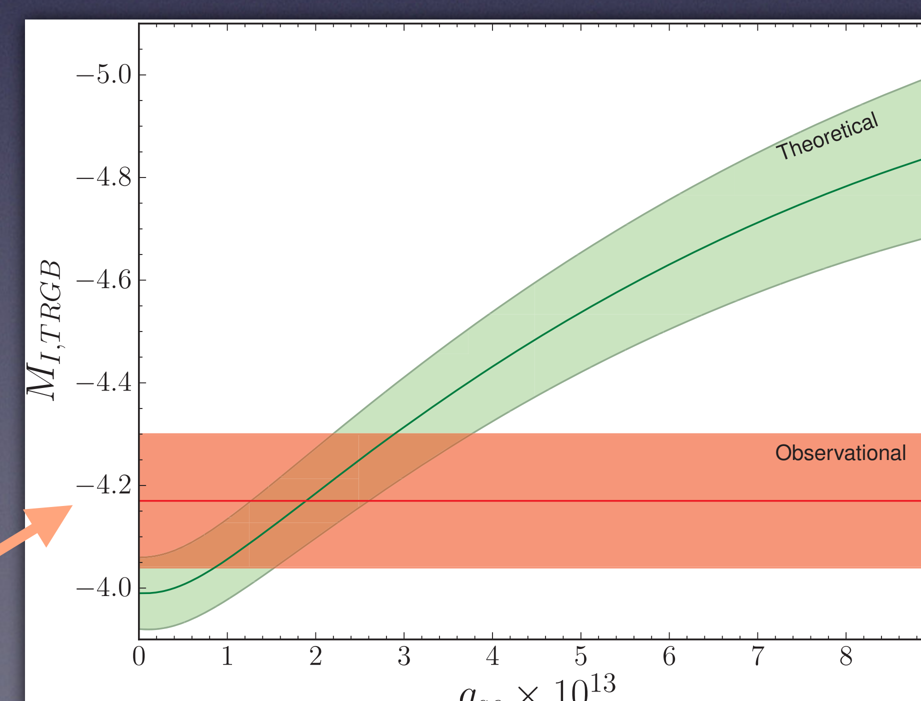
→ More massive and brighter at ignition.

- Recent study of globular cluster M5

Viaux et al. (2013)

Bound (2σ): $g_{ae} < 4.3 \times 10^{-13}$

But also shows a small hint for $g_{ae} > 0$.



White Dwarf Luminosity Function (WDLF)

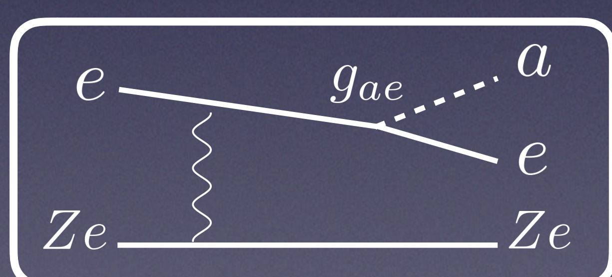
- White Dwarfs (WDs):
  - Final phase of low mass stars, no further fusion of C and O.
  - Their evolution is viewed as a cooling process.

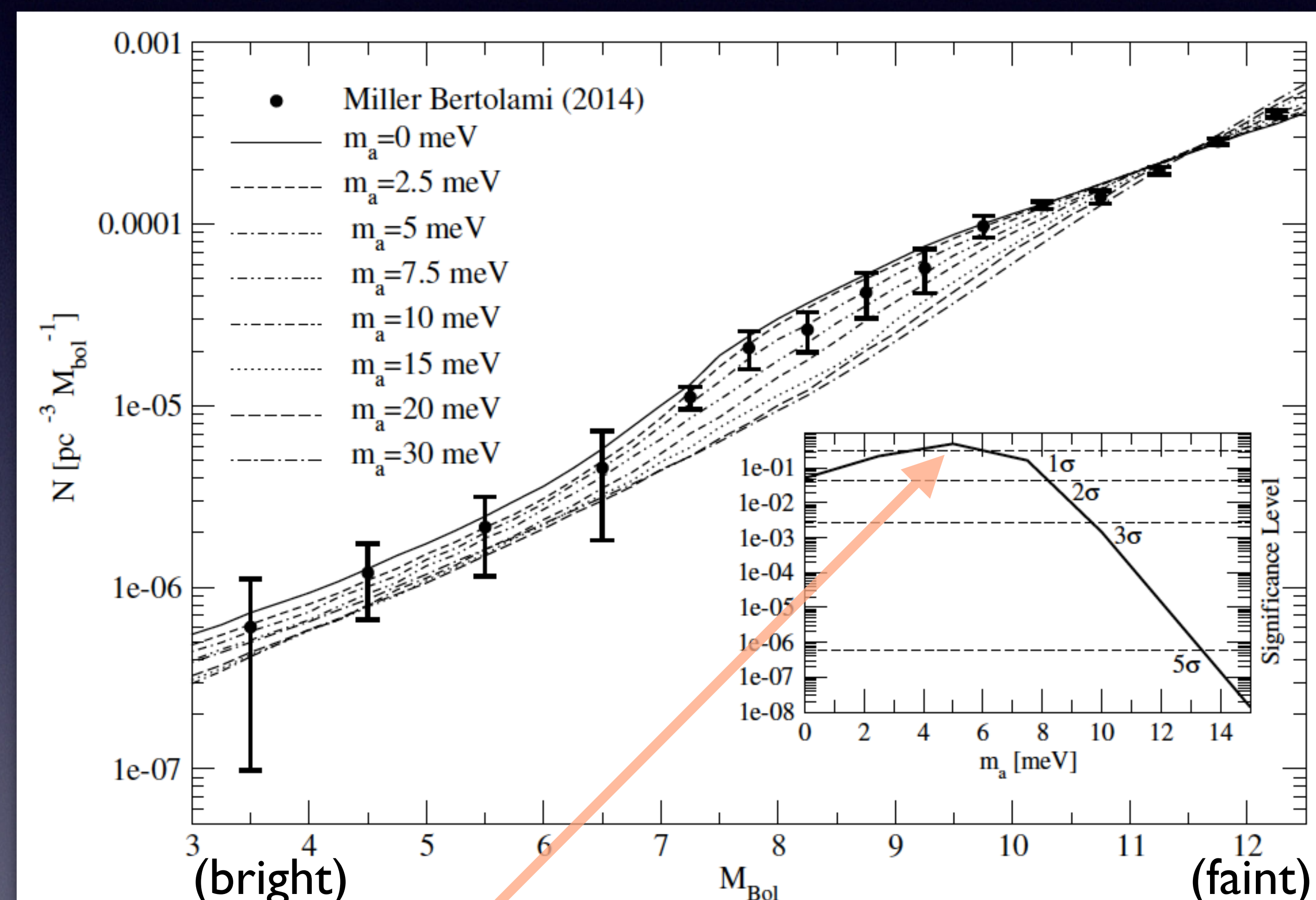
- WDLF:

  # of WDs per unit luminosity

$$\frac{dN_{\mathrm{WD}}}{dV\,dL} \propto \frac{1}{L_\gamma + L_\nu + L_a}$$

Sensitive to the efficiency
of axion-electron bremsstrahlung.





- Recent study

  Bertolami, Melendez, Althaus, and Isern (2014)

  Bound (2σ): $g_{ae} < 2.1 \times 10^{-13}$

  But a mild preference: $g_{ae} = 1.4^{+0.3}_{-0.3} \times 10^{-13}$

White Dwarf variables

WD	class	$\dot{P}_{\rm obs}$[s/s]	$\dot{P}_{\rm th}$[s/s]
G117-B15A	DA	$(4.19 \pm 0.73) \times 10^{-15}$	$(1.25 \pm 0.09) \times 10^{-15}$
R548	DA	$(3.33 \pm 1.1) \times 10^{-15}$	$(1.1 \pm 0.09) \times 10^{-15}$
PG 1351+489	DB	$(2.0 \pm 0.9) \times 10^{-13}$	$(0.81 \pm 0.5) \times 10^{-13}$

Giannotti, Irastorza, Redondo, and Ringwald (2016)

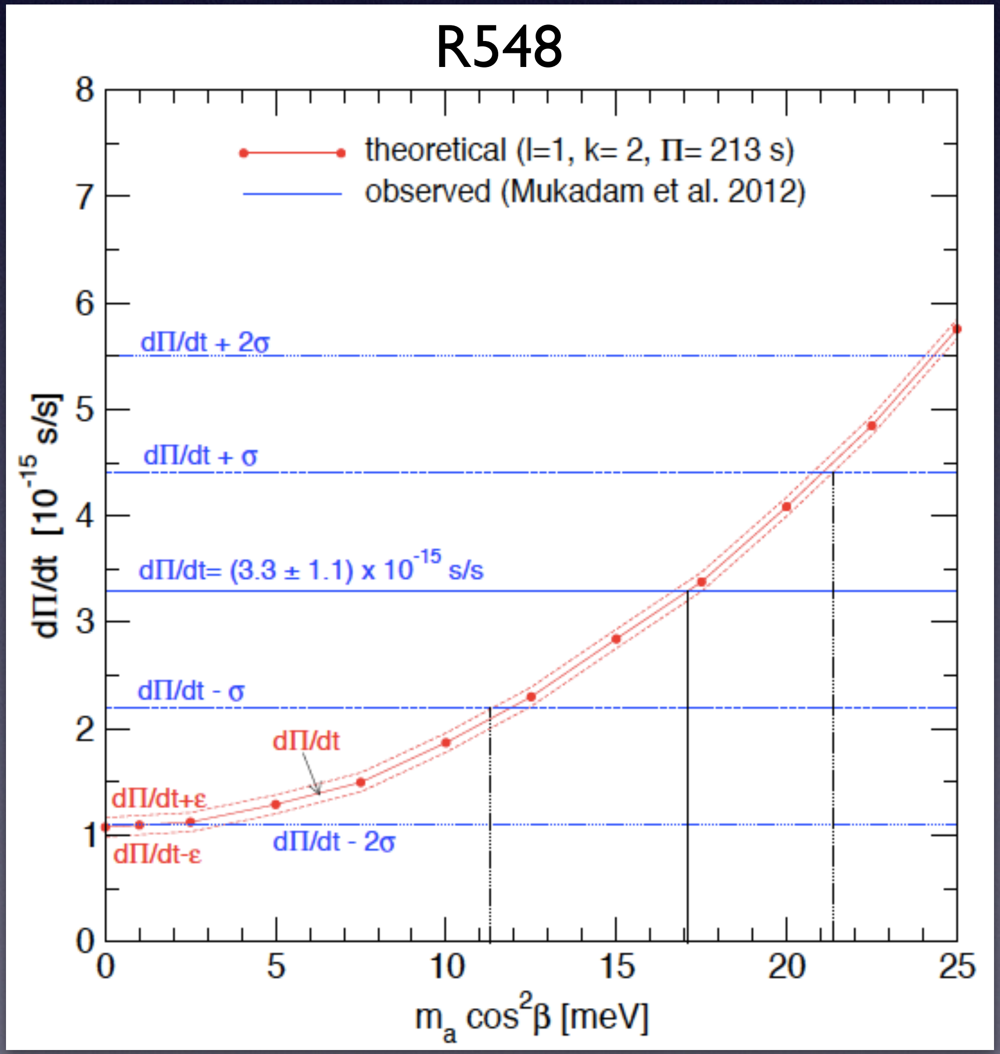
- Period decrease of pulsating WDs traces cooling rate.

$$\dot{T}/T \nearrow \Rightarrow \dot{P}/P \nearrow$$

- Observations and theory models show some discrepancy.
- Prefer additional energy losses due to axion-electron bremsstrahlung.

$$\frac{L_a}{L_{\rm st}} \simeq \frac{\dot{P}_{\rm obs}}{\dot{P}_{\rm th}} - 1$$

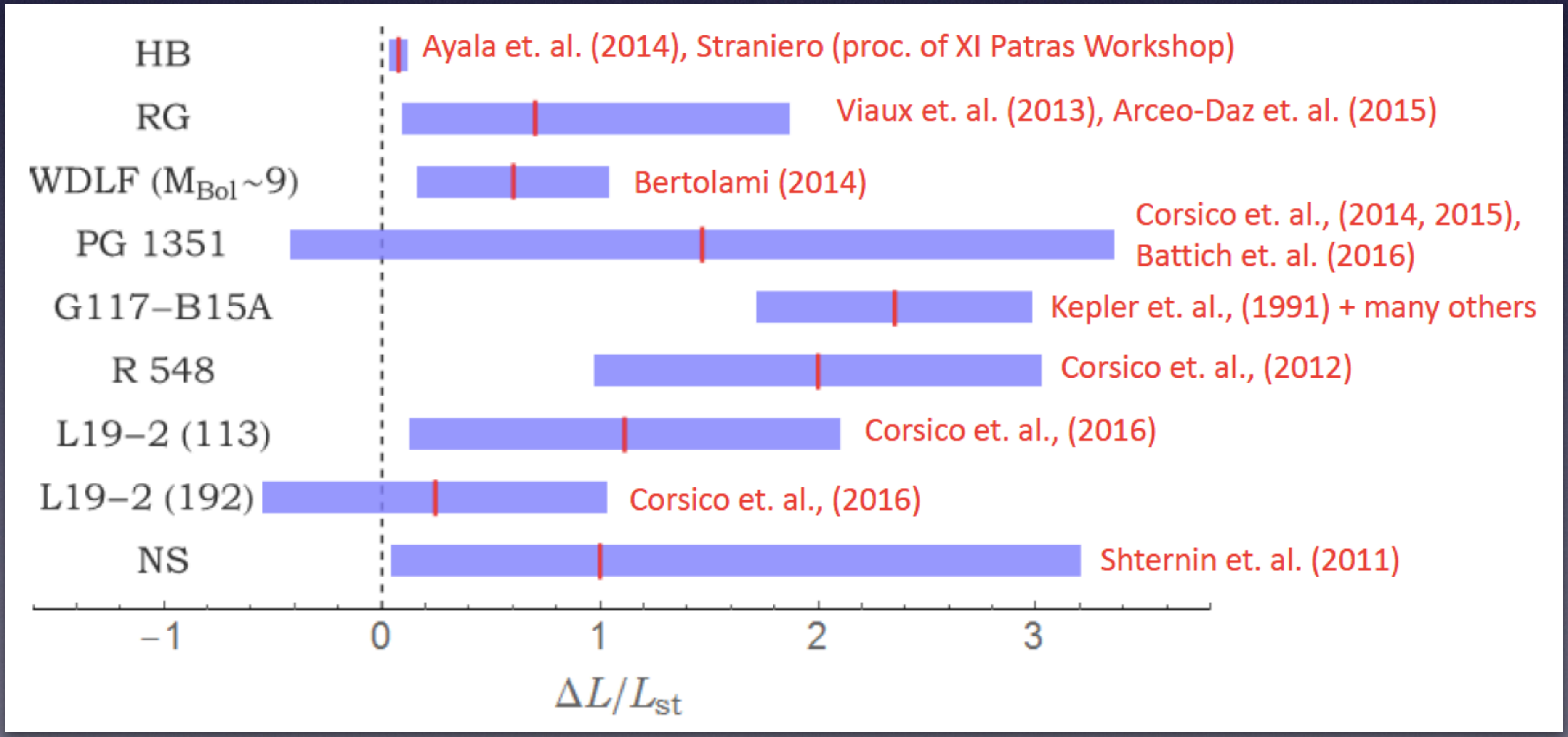
Isern, Hernanz, and Garcia-Berro (1992)



Corsico et al. (2012)

Hints for new physics?

- Observations of different stellar systems show some deviations from the expected behavior.
- Although each deviation has a small statistical significance, all the results seem to indicate a faster cooling than the standard prediction.
- Results should be taken carefully, but at this point one cannot discard the new physics option: Axion could provide a simple explanation.



M. Giannotti, talk at 7th General IAXO Collaboration Meeting (2017)

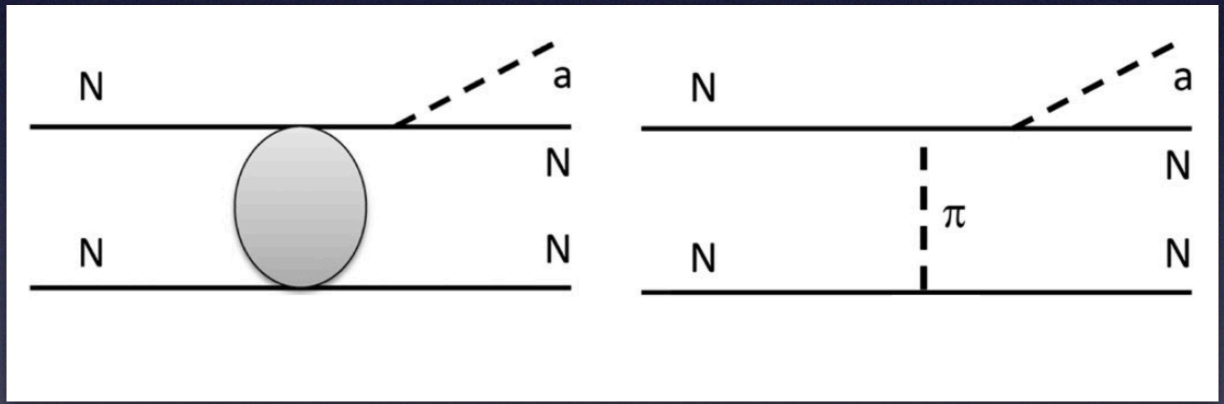
Caveat 1: Supernova (SN) 1987A

- Additional cooling due to axion nucleon-nucleon bremsstrahlung shortens the observed neutrino pulse duration from SN.

  → constrains axion-nucleon couplings $g_{ap},\ g_{an}$.

- Difficult to evaluate the axion production rate in the dense nuclear medium from first principles:

  - Crudely modeled by the one-pion exchange (OPE) approximation.
  - The emission can be suppressed by many-body and multiple-scattering effects. Raffelt and Seckel (1995); Sigl (1996)



- Numerical simulations with a "modified" OPE emission rate imply

$$\boxed{g_{ap}^2 + g_{an}^2 < 3.6 \times 10^{-19}}$$

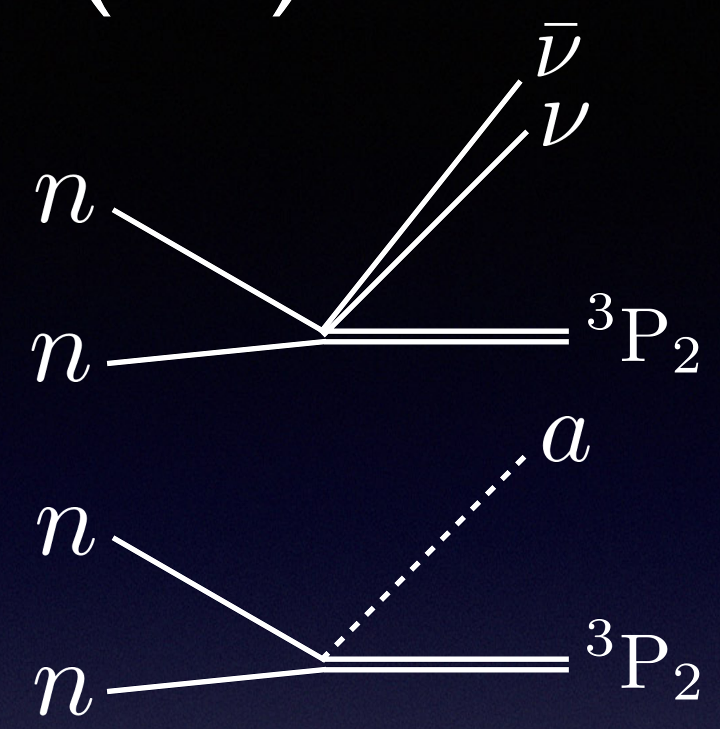
Keil et al. (1996); Fischer et al. (2016)

- Conclusion is not robust. It should be taken as an indicative result rather than a sharp bound.

Caveat 2: Neutron Star (NS)

- Cooling rate of NS in Cassiopeia A is inferred from X-ray observations of its surface temperature.

- Evidence of $\nu\bar{\nu}$ emission in Cooper pair $^3P_2$ formation.
  Page et al. (2011); Shternin et al. (2011)



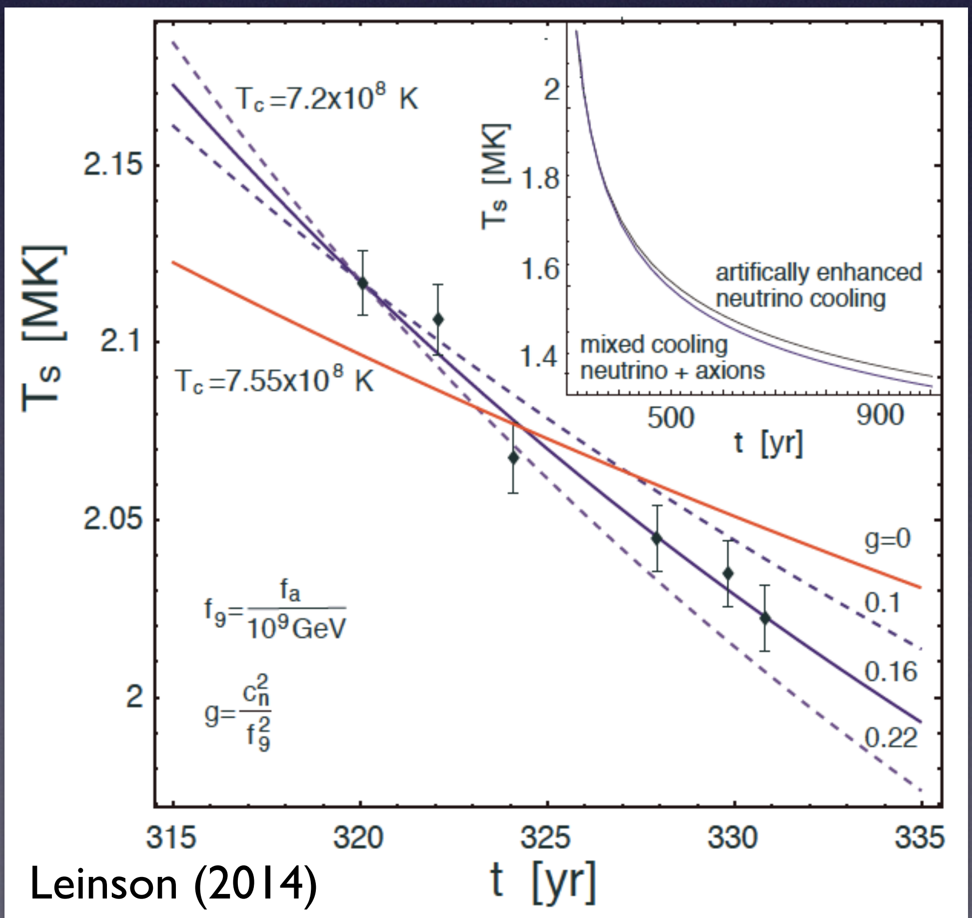
- Slight extra cooling required, axion hints? Leinson (2014)

$$g_{an}^2 \sim (1.4 \pm 0.5) \times 10^{-19}$$

- Or can be explained in the minimal cooling scenario, implying a stronger bound?
  Hamaguchi, Nagata, Yanagi, and Zheng, 1806.07151

$$f_a > 5\,(7)\ \times 10^8\,\mathrm{GeV} \quad \mathrm{KSVZ\ (DFSZ)}$$

(seems to be a discrepancy in proton induced processes)



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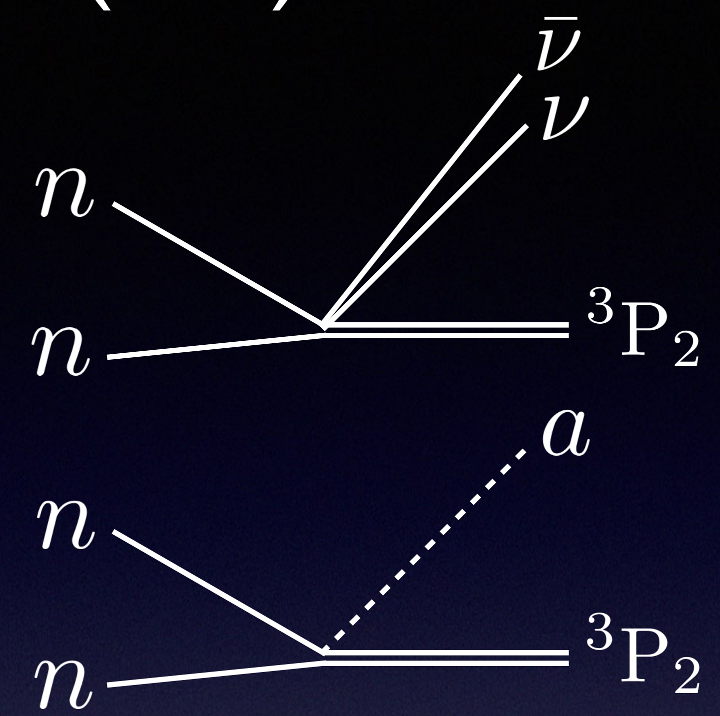

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> The neutrino pair emission caused by recombination of thermally broken Cooper pairs [34, 35] occurs through neutral weak currents generated by spin fluctuations of the nucleons [36, 37]. Since the proton condensation occurs with a zeroth total spin of a Cooper pair the spin fluctuations of the proton condensate are strongly suppressed in the non-relativistic system [34]. As a result, the dominating energy losses occur owing to the PBF neutrino radiation from triplet pairing of neutrons, while the proton superfluidity quenches the other neutrino reactions which efficiently operate in normal (nonsuperfluid) nucleonic systems ($\bar{\nu}\nu$ bremsstrahlung, murca processes etc.) Leinson (2014)

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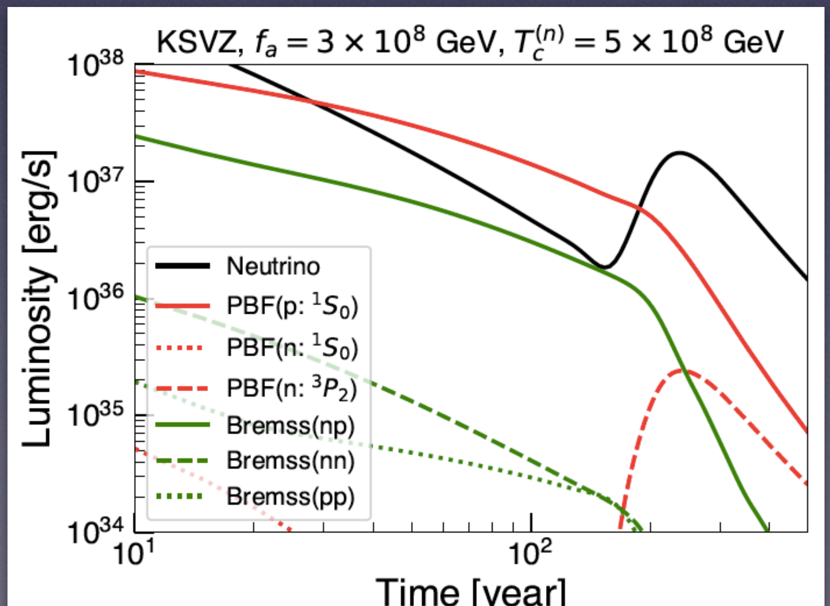
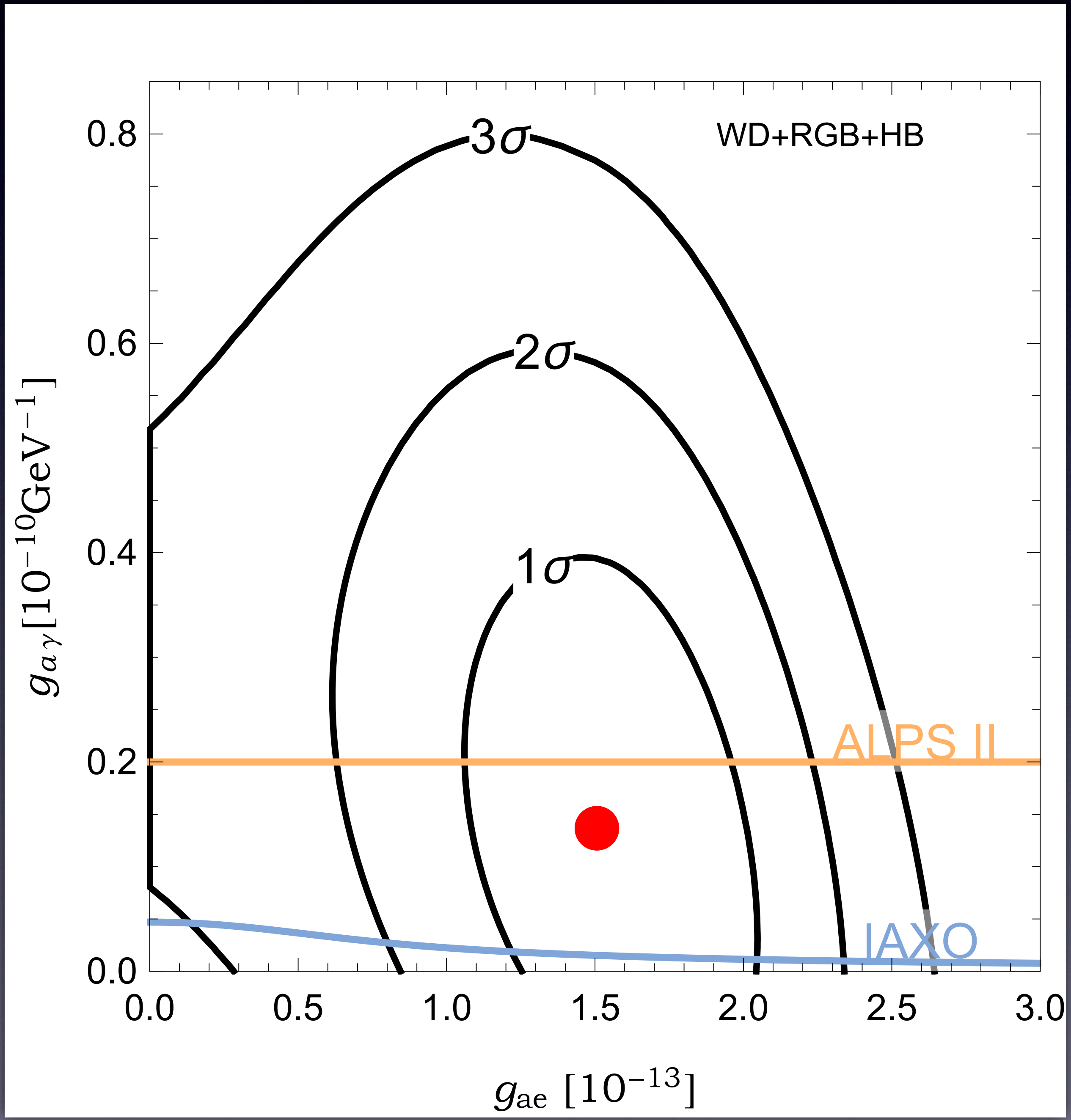


Hamaguchi, Nagata, Yanagi, and Zheng, 1806.07151

Axion models

Axion interpretation

A mild preference for non-vanishing couplings with both electrons and photons.



Giannotti, Irastorza, Redondo, Ringwald, and KS (2017)

Best fit:

$$g_{ae} = 1.5 \times 10^{-13}$$

$$g_{a\gamma} = 0.14 \times 10^{-10}\ \mathrm{GeV}^{-1}$$

corresponds to

$$\boxed{\left|\frac{C_{ae}}{C_{a\gamma}}\right| \approx 2.5 \times 10^{-2}}$$

$$g_{ae} = C_{ae}\frac{m_e}{f_a}, \quad g_{a\gamma} = \frac{\alpha}{2\pi f_a}|C_{a\gamma}|$$

Can typical axion models accommodate this ratio?

DFSZ models

Zhitnitsky (1980);
Dine, Fischler, and Srednicki (1981)

- A SM singlet complex scalar Φ and two Higgs doublets H_u and H_d .

$$\mathcal{L}_{\text{yukawa}} = \begin{cases} \Gamma_{ij}\bar{q}_{iL}H_d d_{jR} + Y_{ij}\bar{q}_{iL}\tilde{H}_u u_{jR} + \boxed{G_{ij}\bar{L}_i H_d l_{jR}} + \text{H.c.} & \text{(DFSZ I)} \\ \Gamma_{ij}\bar{q}_{iL}H_d d_{jR} + Y_{ij}\bar{q}_{iL}\tilde{H}_u u_{jR} + \boxed{G_{ij}\bar{L}_i H_u l_{jR}} + \text{H.c.} & \text{(DFSZ II)} \end{cases}$$

$$V(H_u, H_d, \Phi) = \lambda H_d^\dagger H_u \Phi^{*2} + \text{H.c.} + (\text{Hermitian terms})$$

- The electron coupling depends on $\tan\beta = |\langle H_u^0\rangle|/|\langle H_d^0\rangle| = v_u/v_d$.

DFSZ I:	$C_{ae} = \dfrac{1}{3}\cos^2\beta,$	$C_{a\gamma} = \dfrac{2}{3} - 1.92$
DFSZ II:	$C_{ae} = \dfrac{1}{3}\sin^2\beta,$	$C_{a\gamma} = \dfrac{8}{3} - 1.92$

- Both models can explain observed data,
preferring a small (large) $\tan\beta$ for the DFSZ I (II) axion.

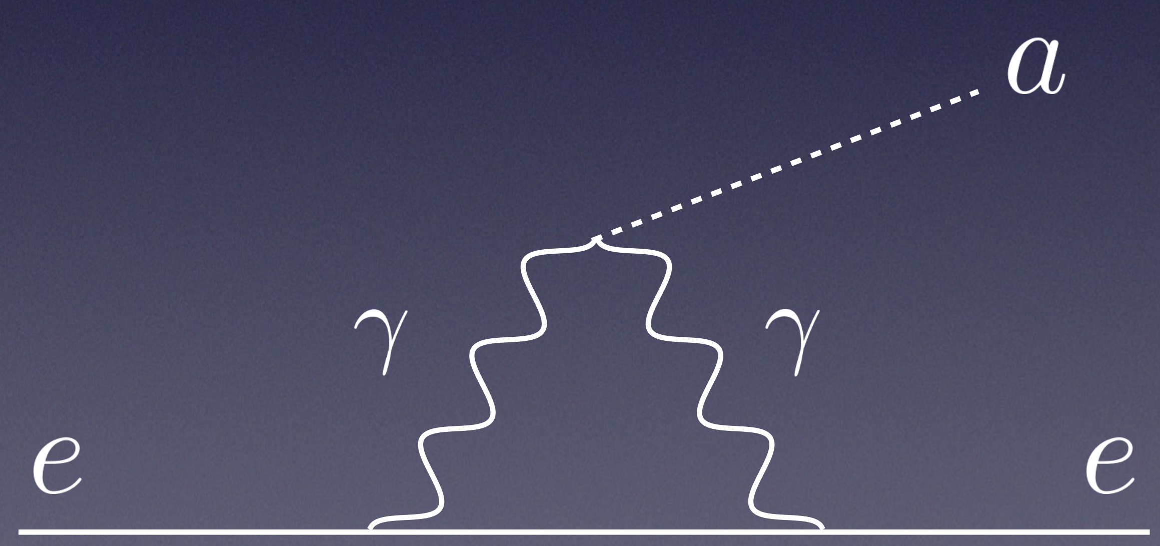
KSVZ models

Kim (1979);
Shifman, Vainshtein, and Zakharov (1980)

- A SM singlet complex scalar Φ and additional exotic quark(s) Q.
- The photon coupling is determined by fixing the representation of Q under the SM gauge group (color and EM anomaly coefficients N and E).

$$C_{a\gamma} = \frac{E}{N} - 1.92$$

- The electron coupling emerges only at the loop level. Srednicki (1985)



$$C_{ae} \propto \frac{\alpha^2}{4\pi}$$

Too small to explain observations: $|C_{ae}/C_{a\gamma}| \approx \mathcal{O}(10^{-3})$

KSVZ axion/majoron (A/J)

- Extend KSVZ models by three right-handed neutrinos N_{Ri}.

$$\mathcal{L}_{\text{Yukawa}} \supset -F_{ij}\bar{L}_i N_{Rj} H - \frac{1}{2} Y_{ij} \bar{N}^c_{Ri} N_{Rj} \Phi + \text{h.c.}$$

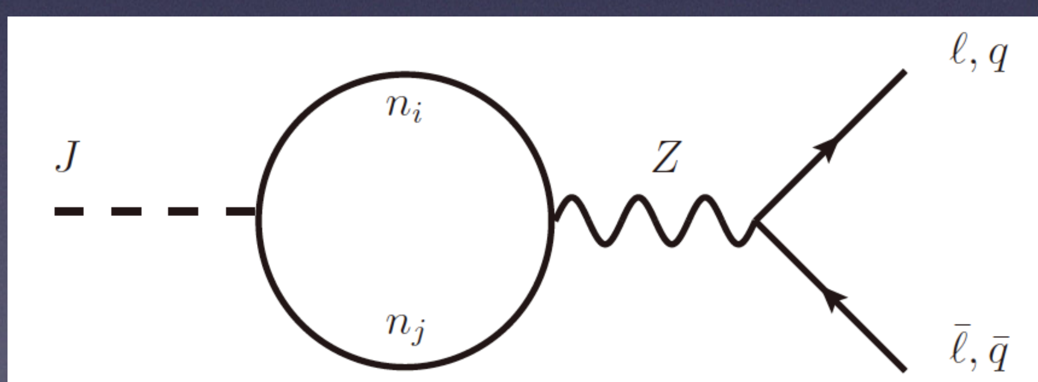
SM Higgs PQ scalar

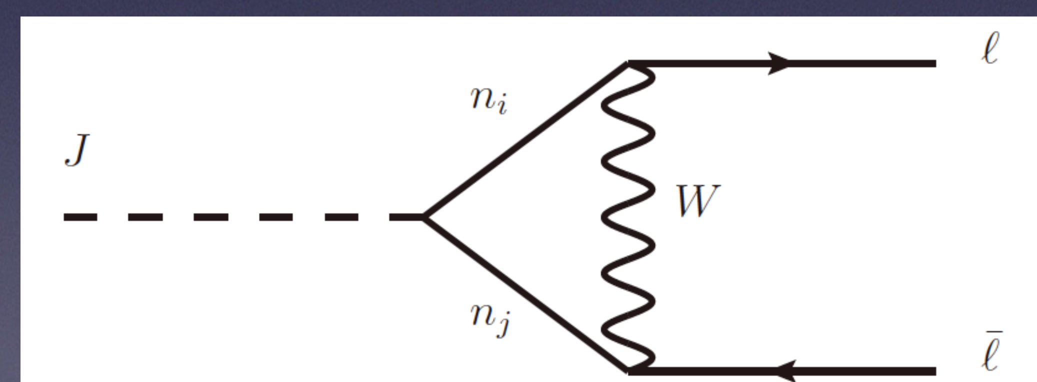
- The PQ mechanism is unified with the seesaw mechanism.

Langacker, Peccei, and Yanagida (1986); Shin (1987)

- The axion A is at the same time the majoron J (pNG boson from spontaneous breaking of the lepton symmetry).

- The one-loop axion-electron coupling gets extra contributions from neutrinos.





Garcia-Cely and Heeck (2017)

$$\boxed{C^{A/J}_{ae} \simeq -\frac{1}{16\pi^2 N}(\text{tr}\kappa - 2\kappa_{ee})}$$

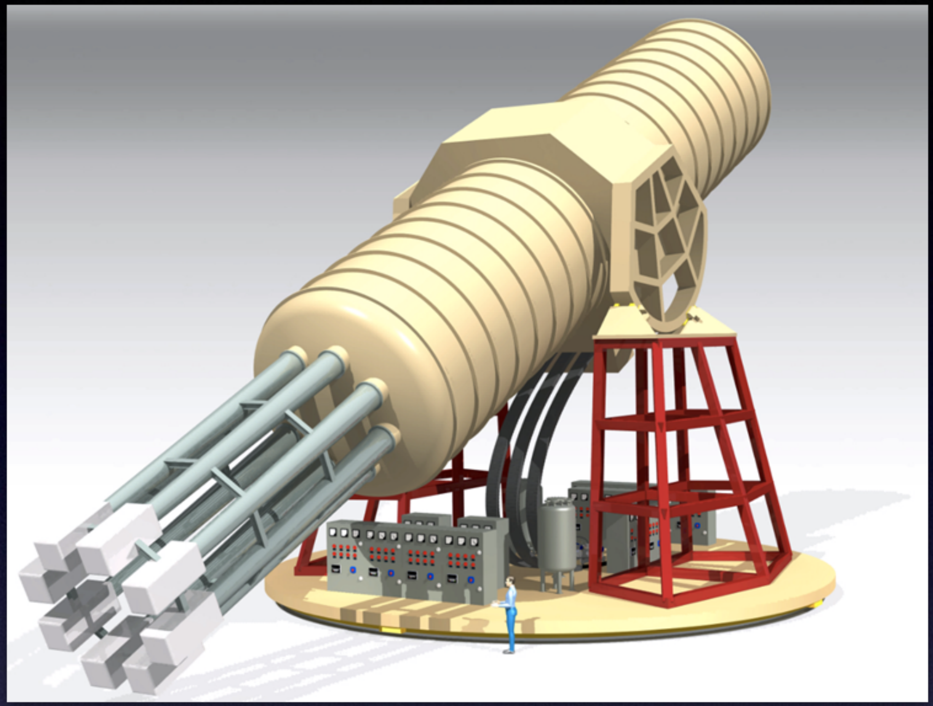
where $\kappa \equiv \frac{m_D m_D^\dagger}{v^2} = \frac{FF^\dagger}{2}$

The fit can improve considerably.

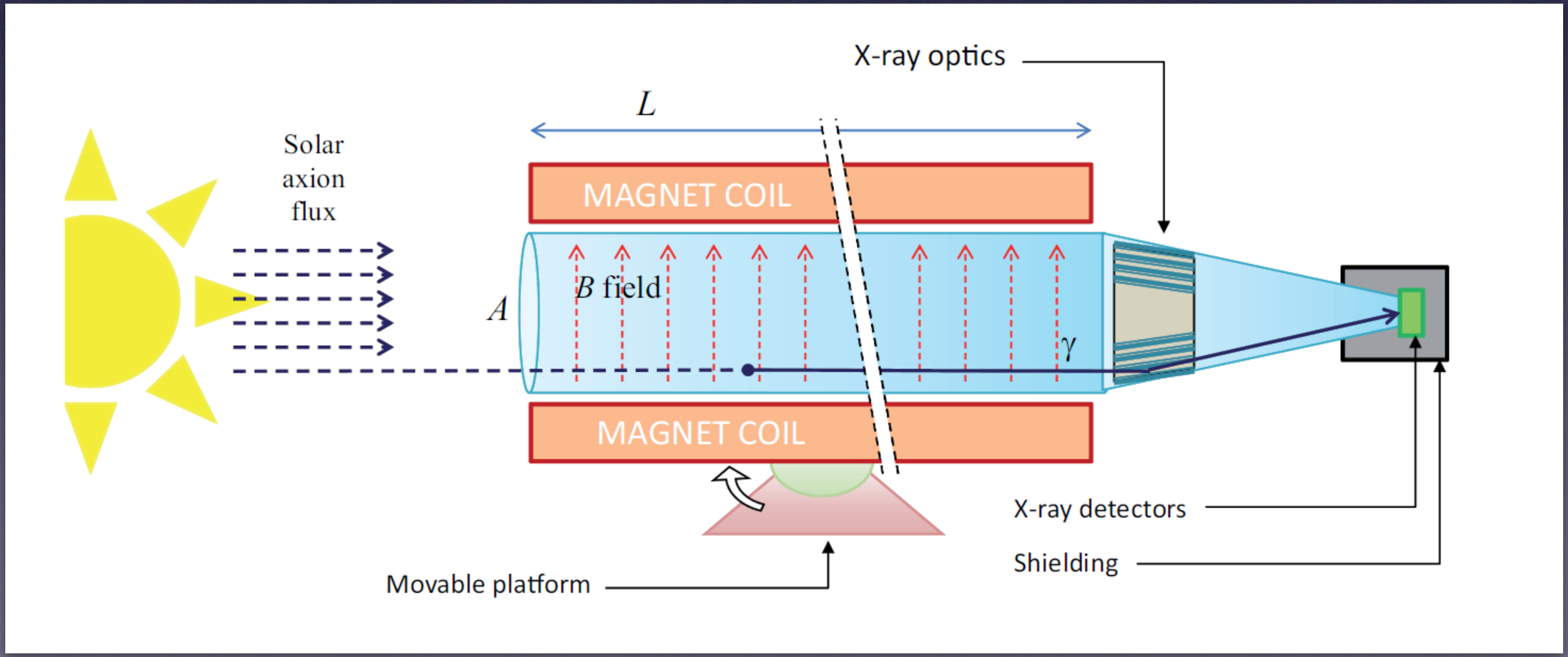
Experimental potential and preferred parameter range

The International Axion Observatory (IAXO)

- The proposed next generation axion helioscope.
- A sensitivity much improved with respect to past and current experiments such as CAST at CERN.
- A prototype version will be presumably located at DESY.



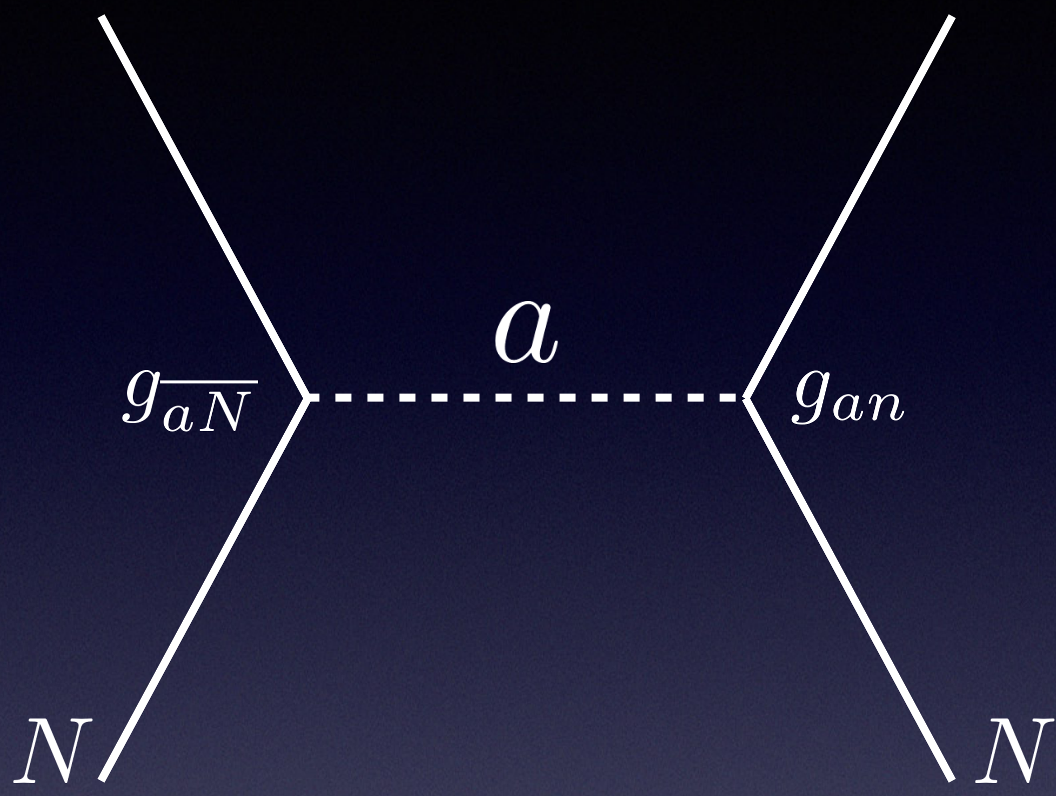
http://iaxo.web.cern.ch

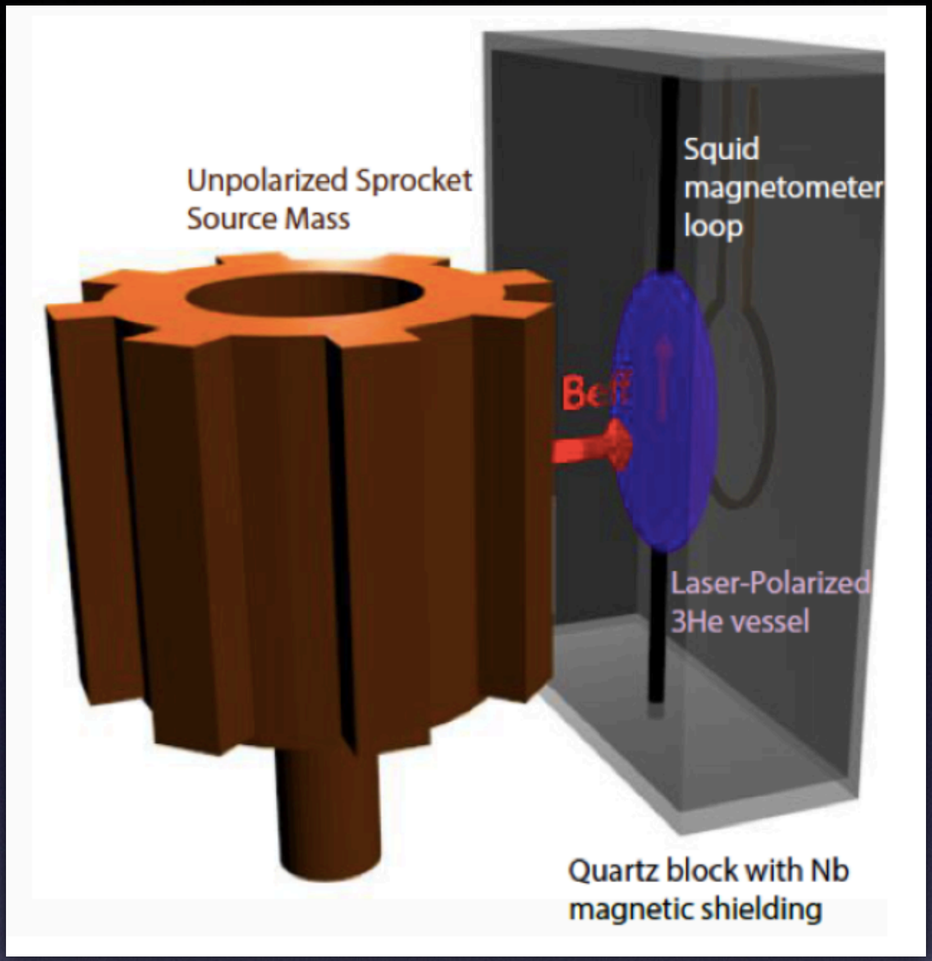


The IAXO Letter of Intent, Armengaud et al. (2013)

ARIADNE

Arvanitaki and Geraci (2014)





- Search for long range forces mediated by axions.

Moody and Wilczek (1984)

- Need to assume the existence of a CP-violating interaction.

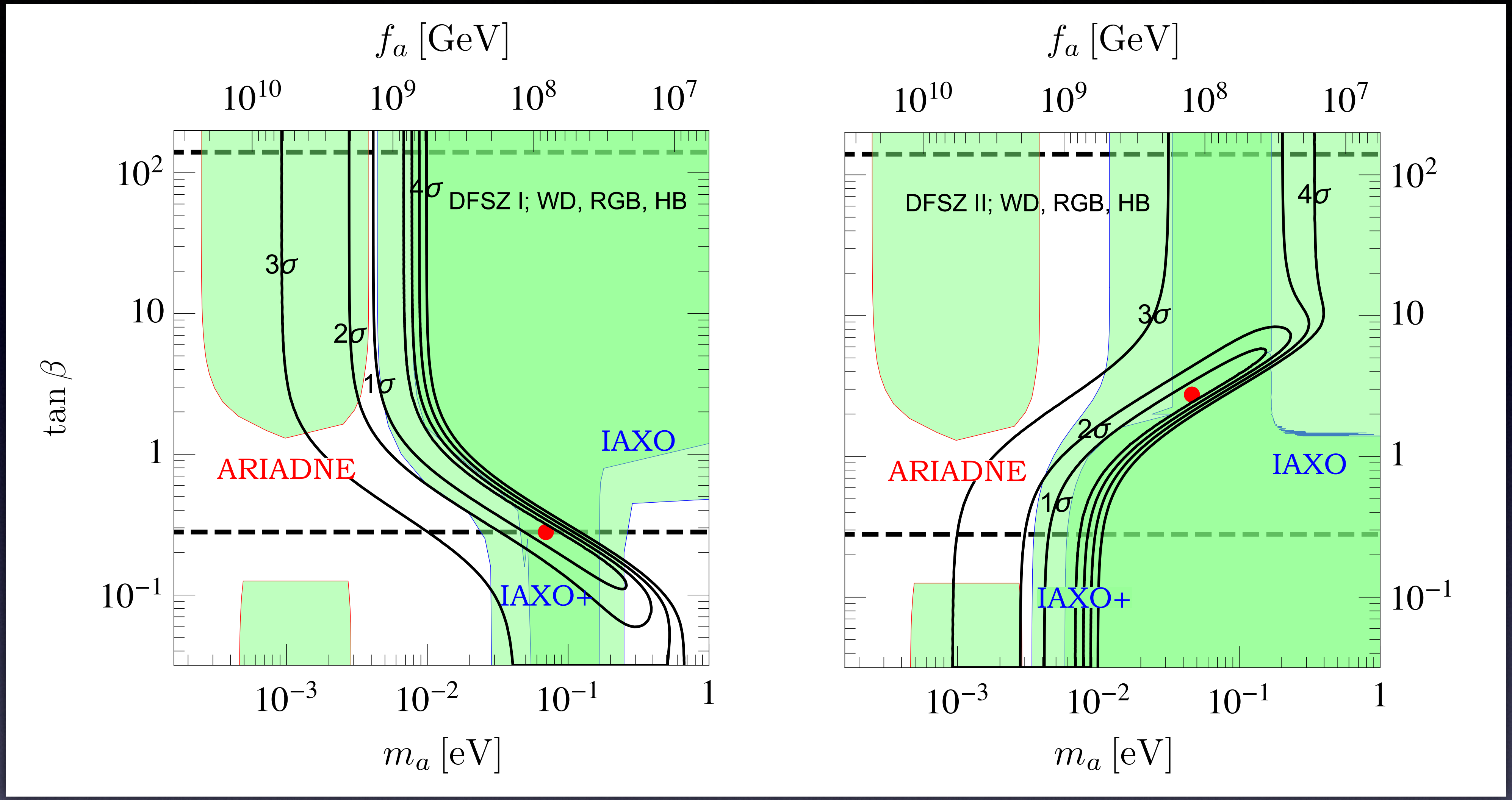
$$\mathcal{L}_{\rm CP} = g_{\overline{aN}} a \bar{N} N$$

Constraint from neutron EDM:

$$g_{\overline{aN}} \lesssim 10^{-21} (f_a / 10^9\,\mathrm{GeV})^{-1}$$

- Covers the low mass end of the axion parameter space: A complementary role with respect to IAXO.

Fit and experimental potential: DFSZ models

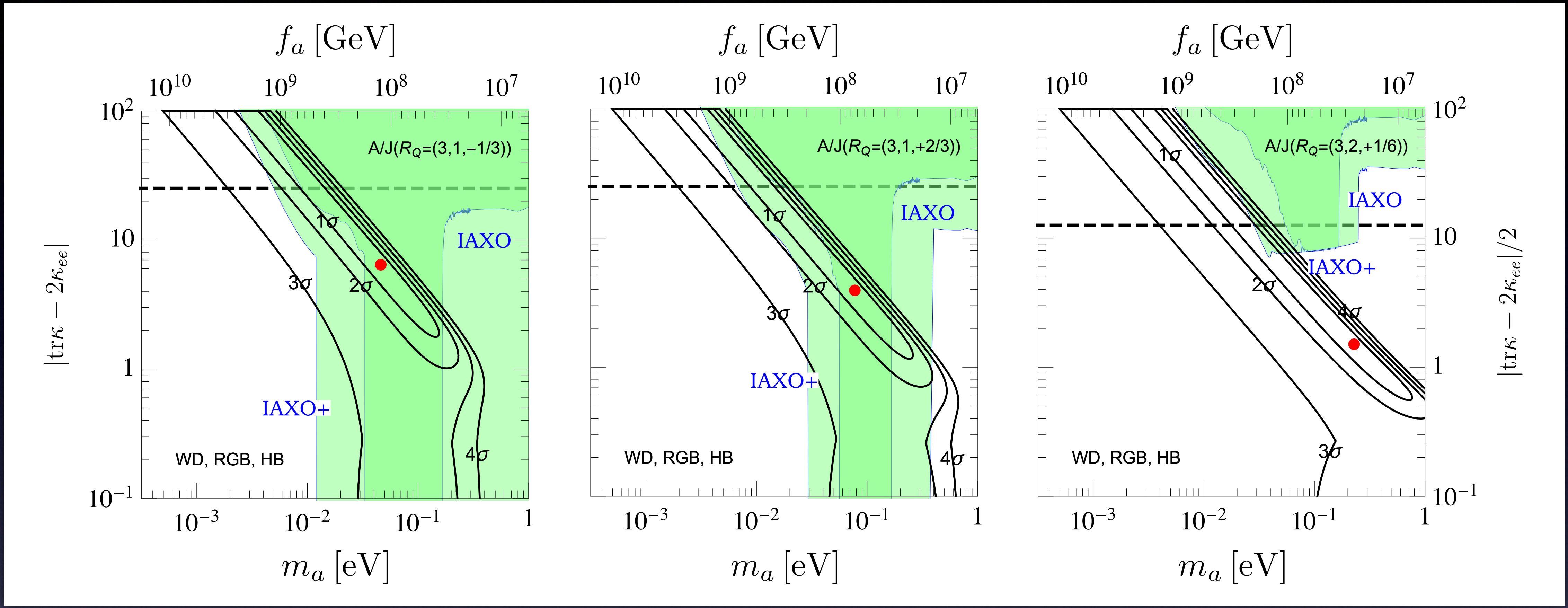


Giannotti, Irastorza, Redondo, Ringwald, and KS (2017)

$$g_{ae} = C_{ae}\frac{m_e}{f_a}, \quad C_{ae} = \begin{cases} \sin^2\beta/3 & \text{for} \quad \text{DFSZ I} \\ (1-\sin^2\beta)/3 & \text{for} \quad \text{DFSZ II} \end{cases}$$

- Finite values of f_a are favored.
- Diagonal contour lines since WDLF drives $g_{ae} \sim 1.5\times 10^{-13}$.
- 1σ region can be entirely probed by IAXO.

Fit and experimental potential: KSVZ A/J models



Giannotti, Irastorza, Redondo, Ringwald, and KS (2017)

$$C_{ae}^{A/J} \simeq -\frac{1}{16\pi^2 N}(\mathrm{tr}\kappa - 2\kappa_{ee})$$

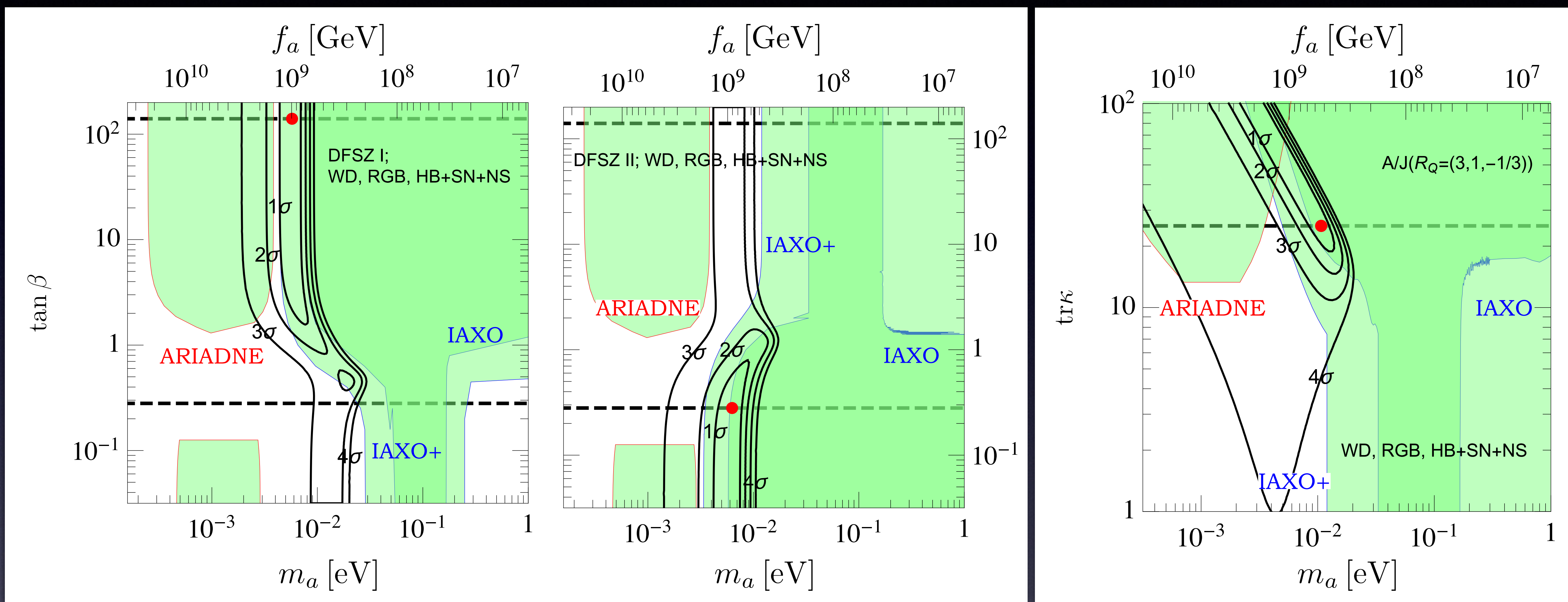
- Three possibilities on the representations R_Q of exotic quarks under the SM gauge groups $SU(3)_C \times SU(2)_L \times U(1)_Y$ are considered:

$$R_Q = (3,1,-1/3),\ (3,1,+2/3),\ \text{or}\ (3,2,+1/6)$$

- IAXO can probe entire 1σ region except for the case $R_Q = (3,2,+1/6)$ (cancellation in $C_{a\gamma} = E/N - 1.92$ with $E/N = 5/3 \approx 1.67$).

Adding the SN 1987A constraint and NS hint

DFSZ I | DFSZ II | KSVZ A/J [R_Q = (3,1,-1/3)]



Giannotti, Irastorza, Redondo, Ringwald, and KS (2017)

- Small f_a is disfavored and the fit becomes slightly worse.
- For KSVZ A/J models, a large value of $\mathrm{tr}\kappa$ is required, which may conflict with perturbative unitarity ($\mathrm{tr}\kappa \lesssim 8\pi$).

Axion hints compatible with axion dark matter?

Cosmological implications of axion models

- Can DFSZ and KSVZ A/J models giving a good fit to stellar cooling hints also explain dark matter?
- Key feature:
  Models can lead to $N_{DW} > 1$ degenerate minima in the low energy effective potential.

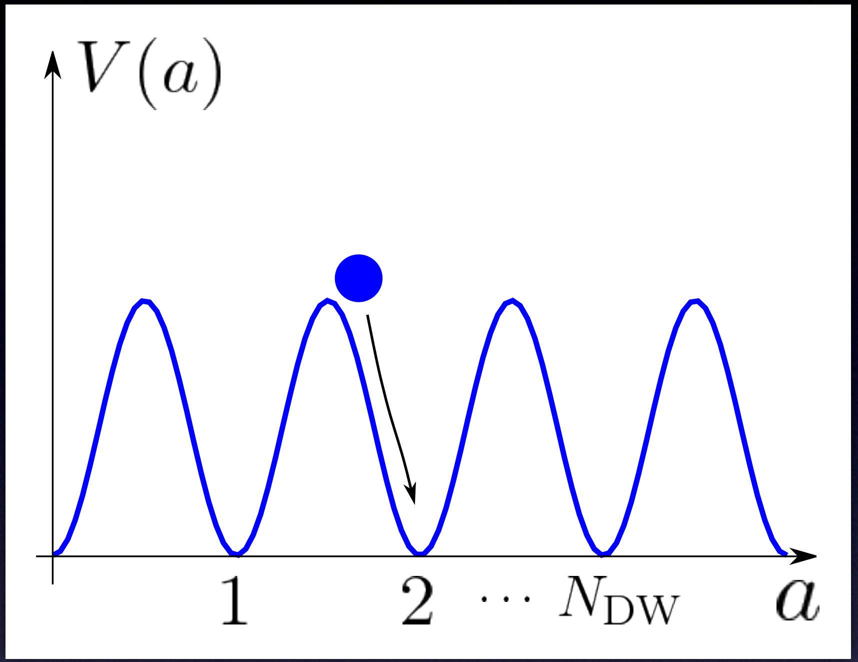
$$V(a) = \frac{m_a^2 v_{\rm PQ}^2}{N_{\rm DW}^2}\left(1 - \cos\left(N_{\rm DW}\frac{a}{v_{\rm PQ}}\right)\right)$$

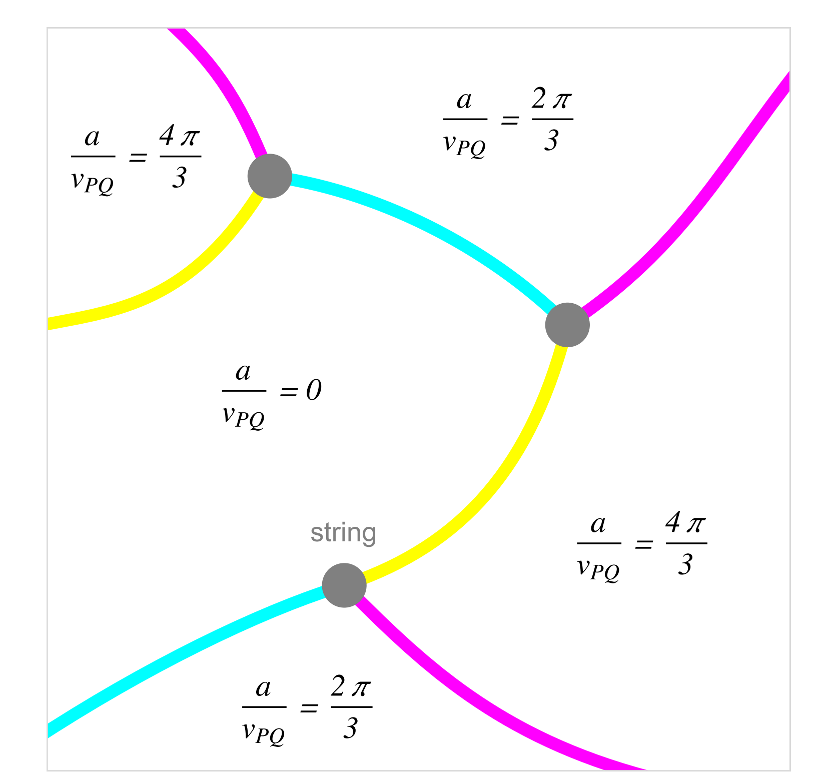
$N_{\rm DW}$: integer determined by QCD anomaly

$$N_{\rm DW} = \begin{cases} 6 & \text{for} \quad \text{DFSZ models} \\ N_Q & \text{for} \quad \text{KSVZ models} \end{cases}$$

N_Q : number of exotic quarks Q
(assuming Q's are $SU(2)_L$ singlet)

- Formation of domain walls if the PQ symmetry has been broken after inflation. Sikivie (1982)

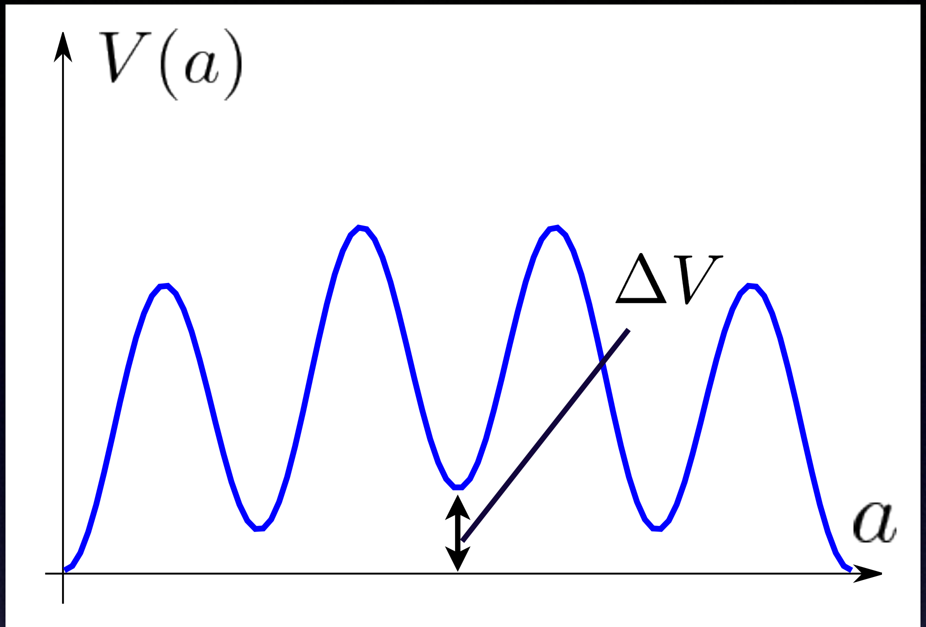




$N_{\rm DW} = 3$

Evolution of domain walls

- Domain walls are stable and eventually overclose the universe.
  Zel'dovich, Kobzarev and Okun (1975)
- This problem can be avoided if there exists a breaking of degeneracy between the different vacua.

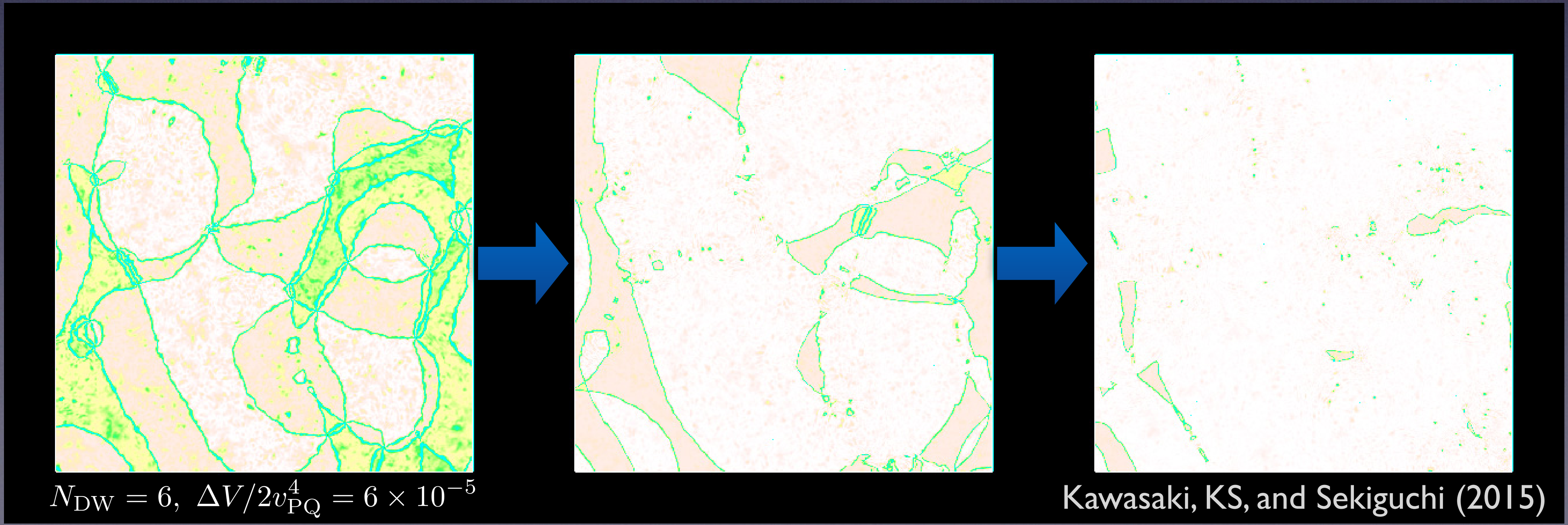


e.g. Planck-suppresed operator

$$\mathcal{L} \supset g M_{\rm Pl}^4 \left(\frac{\Phi}{M_{\rm Pl}}\right)^{\mathcal{N}} + \text{h.c.}$$

Φ : PQ symmetry breaking field

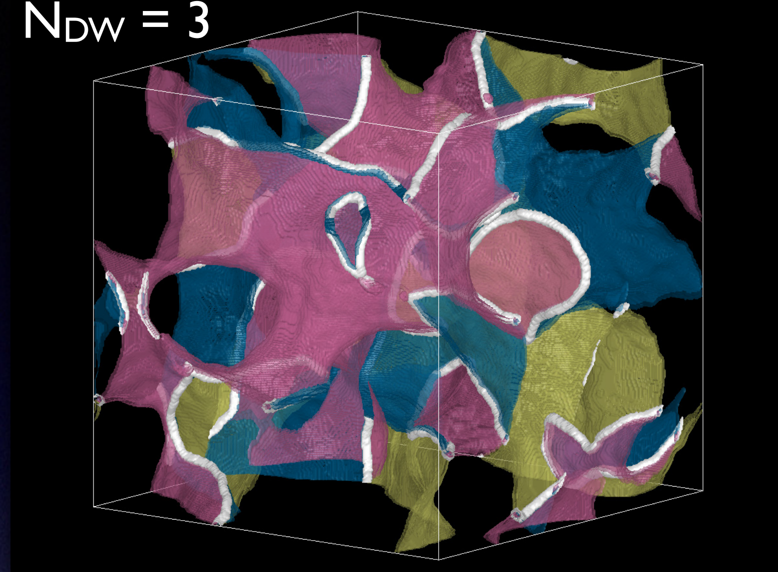
- The breaking term leads to the late-time collapse of domain walls.

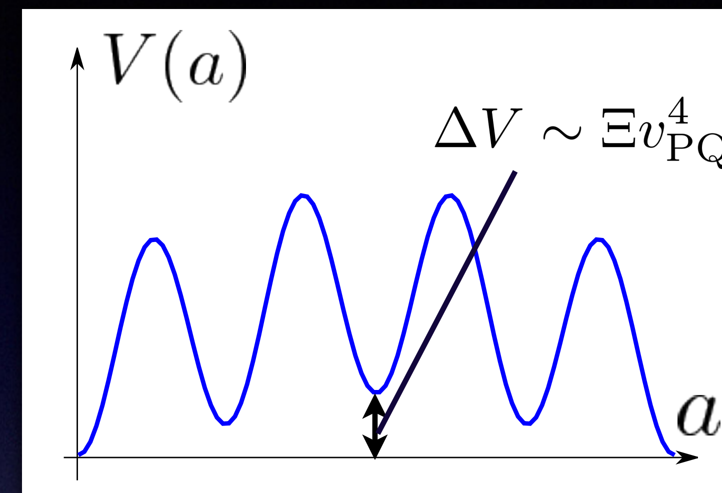


Axion dark matter from long-lived domain walls

Hiramatsu, Kawasaki, KS and Sekiguchi (2013);
Kawasaki, KS and Sekiguchi (2015); Ringwald and KS (2016)

N$_{DW}$ = 3





- Axions produced by the collapse of N$_{DW}$ > 1 domain walls contribute to the dark matter density.

- The observed dark matter abundance can be explained at lower f_a or larger m_a than usual.

$$\Omega_a h^2 \simeq (3.4\text{–}6.2) \times N_{\rm DW}^{-2} \left(\frac{\Xi}{10^{-52}}\right)^{-1/2} \left(\frac{F_a}{10^9\ {\rm GeV}}\right)^{-1/2} \quad \text{where} \quad \Xi = \frac{|g| N_{\rm DW}^{\mathcal{N}-4}}{(\sqrt{2})^{\mathcal{N}}} \left(\frac{f_a}{M_{\rm Pl}}\right)^{\mathcal{N}-4}$$

- The explicit symmetry breaking term ΔV shifts the minimum of the axion effective potential $\theta_{\rm min} = a_{\rm min}/f_a$.

  → Constraints from the neutron electric dipole moment observations:

$$|\theta_{\rm min}| < 7 \times 10^{-11}$$ Barker et al. (2006); Guo et al. (2015)

Parameters for benchmark models

Model	$N_{\rm DW}$	Global fit includes	$f_a[10^8 \text{ GeV}]$	$m_a[\text{meV}]$	$\lvert g\rvert$	Upper limit on Δ
DFSZ I	6	HB,RGB,WD	0.77	74	0.033–1.8	1.1–1.5
	6	HB,RGB,WD,NS,SN	9.9	5.8	$(0.72\text{–}6.2)\times 10^{-8}$	$(0.26\text{–}2.4)\times 10^{-2}$
DFSZ II	6	HB,RGB,WD	1.2	47	$(0.23\text{–}5.7)\times 10^{-2}$	0.52–1.5
	6	HB,RGB,WD,NS,SN	9.1	6.3	$(0.12\text{–}1.1)\times 10^{-7}$	$(0.32\text{–}2.9)\times 10^{-2}$
	2	HB,RGB,WD	1.2	46	$(0.031\text{–}2.8)\times 10^{2}$	0.74–1.6
	4		1.2	46	0.064–4.1	0.21–2.3
KSVZ A/J	6		0.86	66	$(0.17\text{–}7.1)\times 10^{-1}$	0.93–1.5
$R_Q=(3,1,-\frac{1}{3})$	2	HB,RGB,WD,NS,SN	4.1	14	$(0.19\text{–}7.6)\times 10^{-2}$	$(0.39\text{–}9.9)\times 10^{-1}$
	4		6.1	9.2	$(0.049\text{–}1.0)\times 10^{-4}$	$(0.31\text{–}6.6)\times 10^{-2}$
	6		8.0	7.1	$(0.26\text{–}2.5)\times 10^{-7}$	$(0.44\text{–}4.2)\times 10^{-2}$

Giannotti, Irastorza, Redondo, Ringwald, and KS (2017)

$$V_g = -2|g|M_{\rm Pl}^4\left(\frac{v_{\rm PQ}}{\sqrt{2}M_{\rm Pl}}\right)^{\mathcal{N}}\cos\left(\mathcal{N}\frac{a}{v_{\rm PQ}}+\Delta\right)$$

with

$$\Delta = \arg(g) - \frac{\mathcal{N}}{N_{\rm DW}}\bar{\theta}$$

$$\mathcal{N}=9$$

- Dark matter abundance can be explained in the mass range preferred by HB+RGB+WD hints.
- Tuning of parameters is required if NS and SN constraints are included.

Conclusion

- DFSZ and KSVZ A/J models allow a good global fit to stellar cooling observations, preferring an axion mass

$$m_a \sim \mathcal{O}(10)\,\mathrm{meV}.$$

- The preferred mass range can be probed in future experiments.
- Additional constraints from supernova and neutron star physics, but potentially large systematic uncertainties.
- The axion in the preferred mass range can also be the main constituent of dark matter.

Backup slides

χ^2 function for the global fits

$$\chi^2 = \sum_{i=1,11}^{\mathrm{WDLF}} \frac{(M_i - N(g_{ae})M(g_{ae}))^2}{\sigma_{M_i}^2} + \sum_{s=1,4}^{\mathrm{WD-var}} \frac{\left(\dot{\Pi}_s - \dot{\Pi}_s(g_{ae})\right)^2}{\sigma_{\dot{\Pi}_s}^2 + \sigma_{\dot{\Pi}}^2}$$
$$+ \frac{(1.39 - R(g_{ae}, g_{a\gamma}))^2}{\sigma_R^2 + \sigma_Y^2} + \frac{(-4.17 - M_{\mathrm{TRB}}(g_{ae}))^2}{\sigma_{M_{\mathrm{TRB}}}^2}.$$

For the SN constraint and NS hint we add

$$\left(\frac{g_{an}^2 + g_{ap}^2}{3.6 \times 10^{-19}}\right)^2 + \left(\frac{g_{an}^2 - 1.4 \times 10^{-19}}{0.5 \times 10^{-19}}\right)^2$$

Best fit parameters

Fits include HB, RGB, WDLF, and WD variables.

Model	E/N	$\lvert \mathrm{tr}\kappa - 2\kappa_{ee} \rvert$	$\tan\beta$	f_a [10^8 GeV]	m_a [meV]	χ^2/d.o.f.
DFSZ I	8/3	-	0.28	0.77	74	0.99
DFSZ II	2/3	-	2.7	1.2	46	0.99
KSVZ	0	-	-	0.77	74	1.58
	2/3	-	-	0.49	120	1.58
	5/3	-	-	0.064	880	1.31
	8/3	-	-	0.22	260	1.47
KSVZ A/J	2/3	6.2	-	1.2	46	0.99
	8/3	3.7	-	0.73	77	0.99
	5/3	2.5	-	0.25	230	0.99

Giannotti, Irastorza, Redondo, Ringwald, and KS (2017)