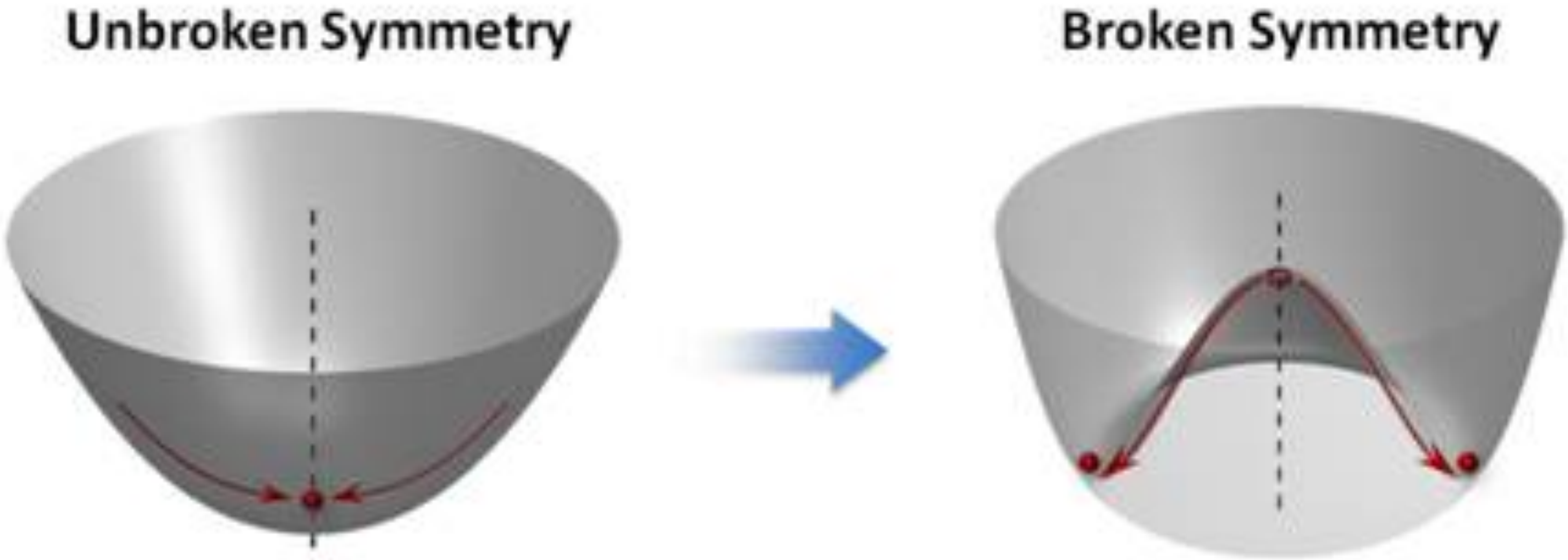
Axions in Astrophysics and Cosmology.

Andreas Ringwald

Annual Retreat of GRK and PRISMA
Kloster Johannisberg, D
21 September 2017

Axion Cold Dark Matter

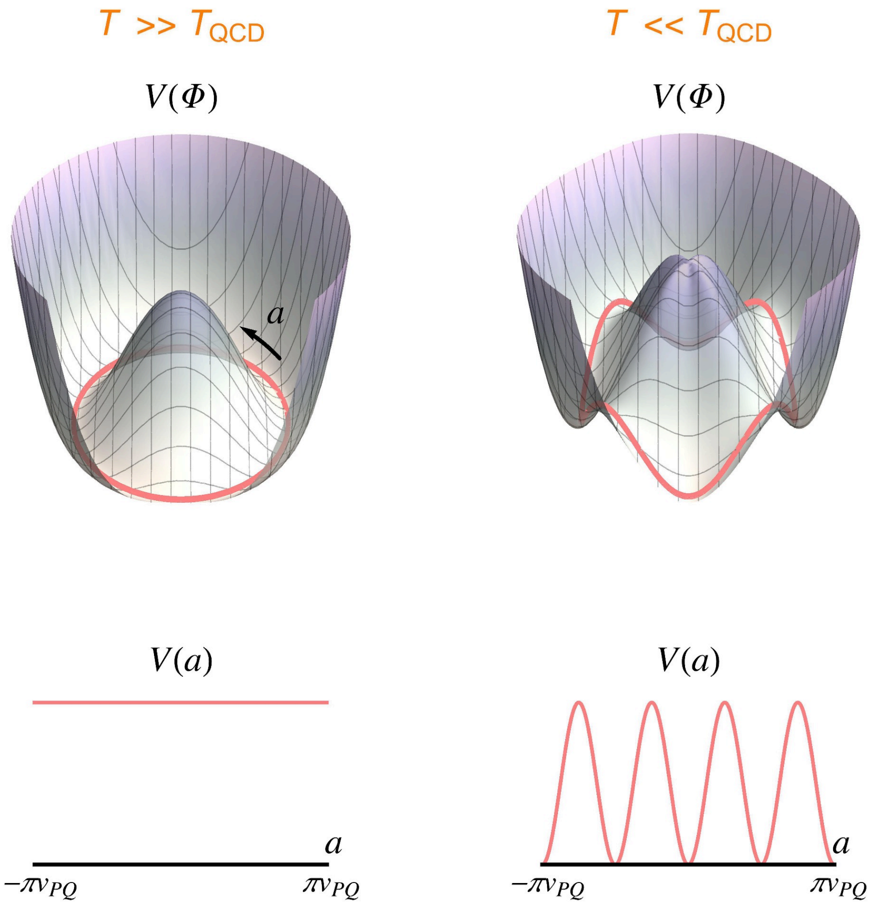
- Axion field is born after PQ symmetry breaking, $T \lesssim T_c^{\rm PQ} \sim v_{\rm PQ} = N_{\rm DW}\, f_A$



[Peking University]

Axion Cold Dark Matter

- Axion field becomes massive near QCD phase transition, $T_c^{\mathrm{QCD}} \sim 200\,\mathrm{MeV}$

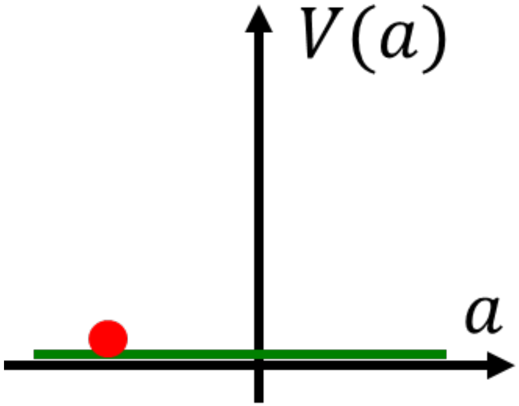


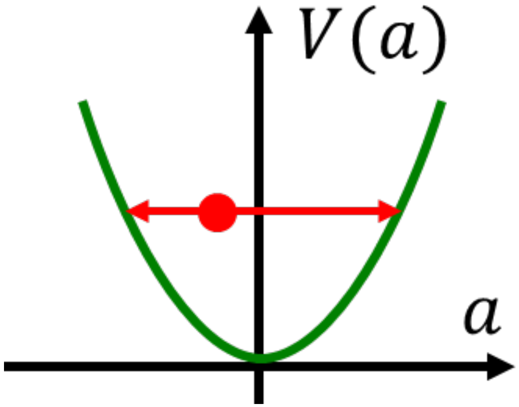
Axion Cold Dark Matter

- DM from vacuum realignment:

[Preskill,Wise,Wilczek 83; Abbott,Sikivie 83; Dine,Fischler 83,....]

  - In early universe, axion frozen at random initial value
  - Later, field feels pull of mass towards zero and oscillates around it





[Raffelt]

Axion Cold Dark Matter

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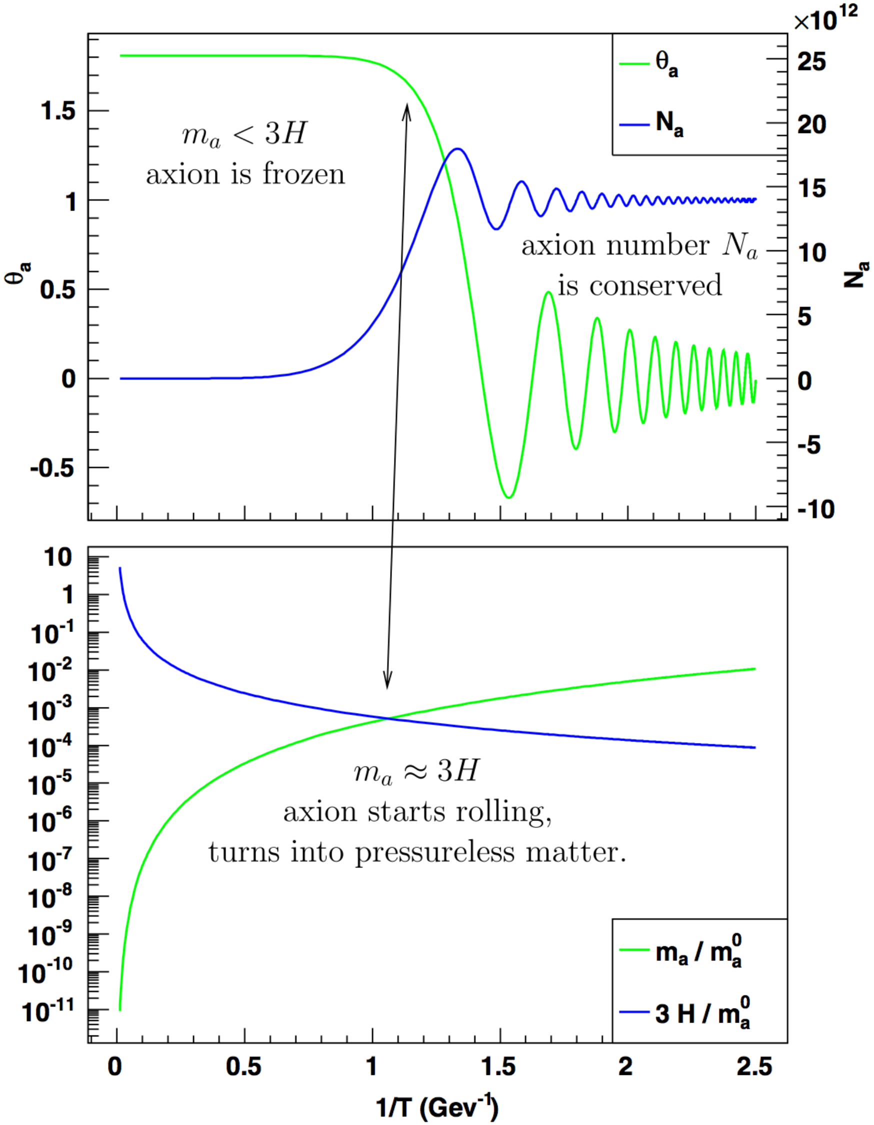
- Spatially uniform oscillating classical field = coherent state of many, extremely non-relativistic particles = CDM



[Wantz,Shellard `09]

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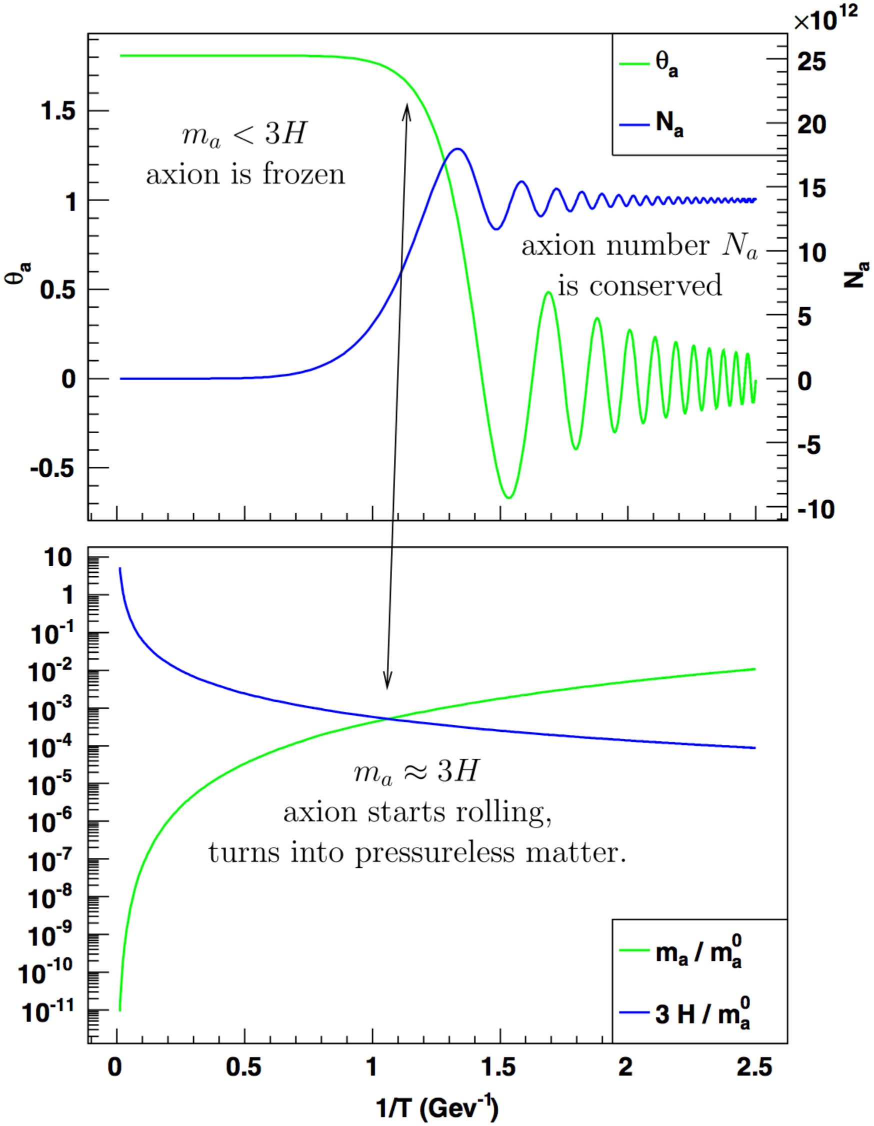
- Crucial QCD input for prediction of axion DM abundance:
  - Equation of state at temperatures around 1 GeV: determines $H(T)$
  - Topological susceptibility:

$$\chi(T) \equiv \int d^4x \langle q(x)q(0)\rangle_T$$

determines $m_A^2(T) = \chi(T)/f_A^2$



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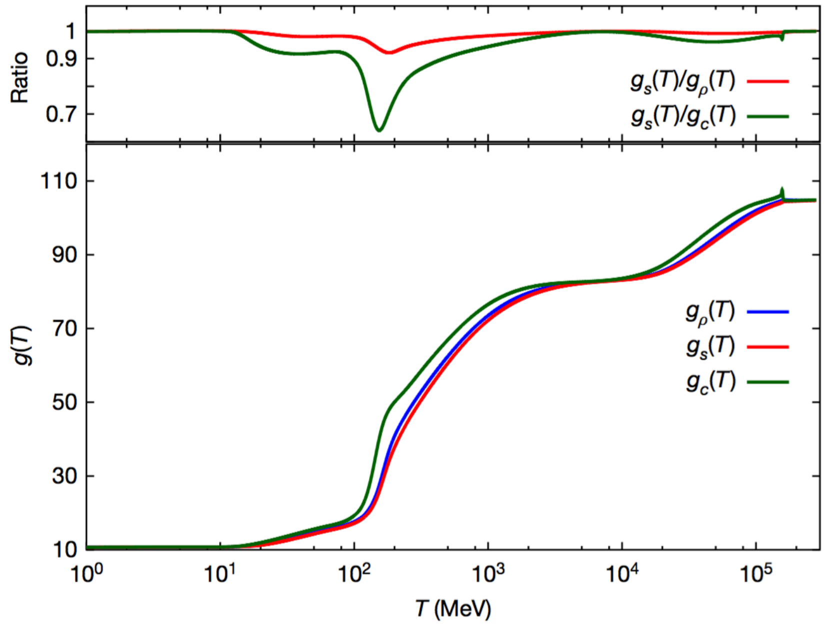
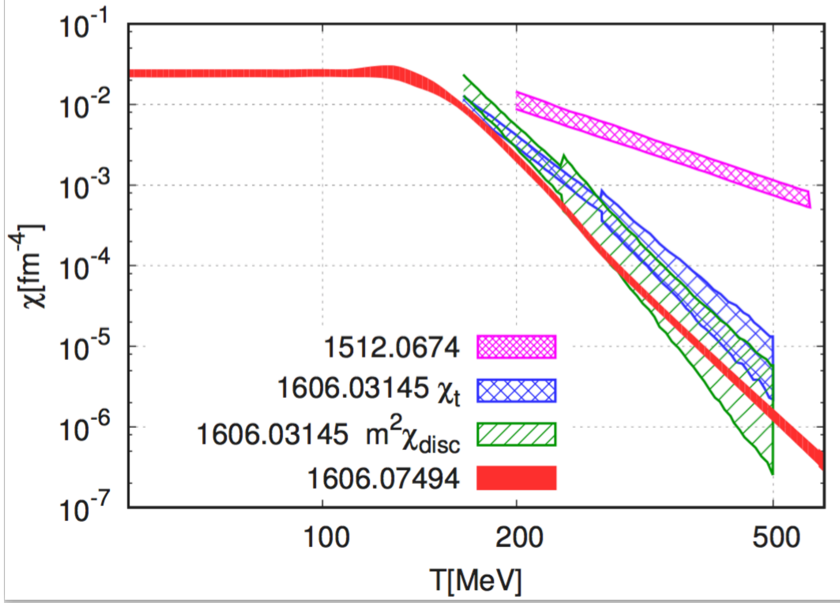
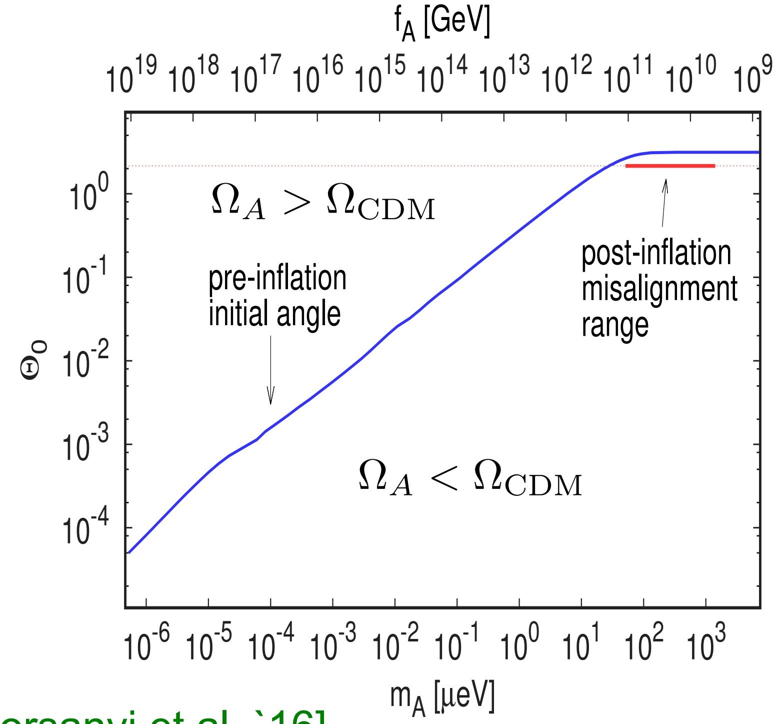


[Borsanyi et al., Nature `16 [1606.0794]]



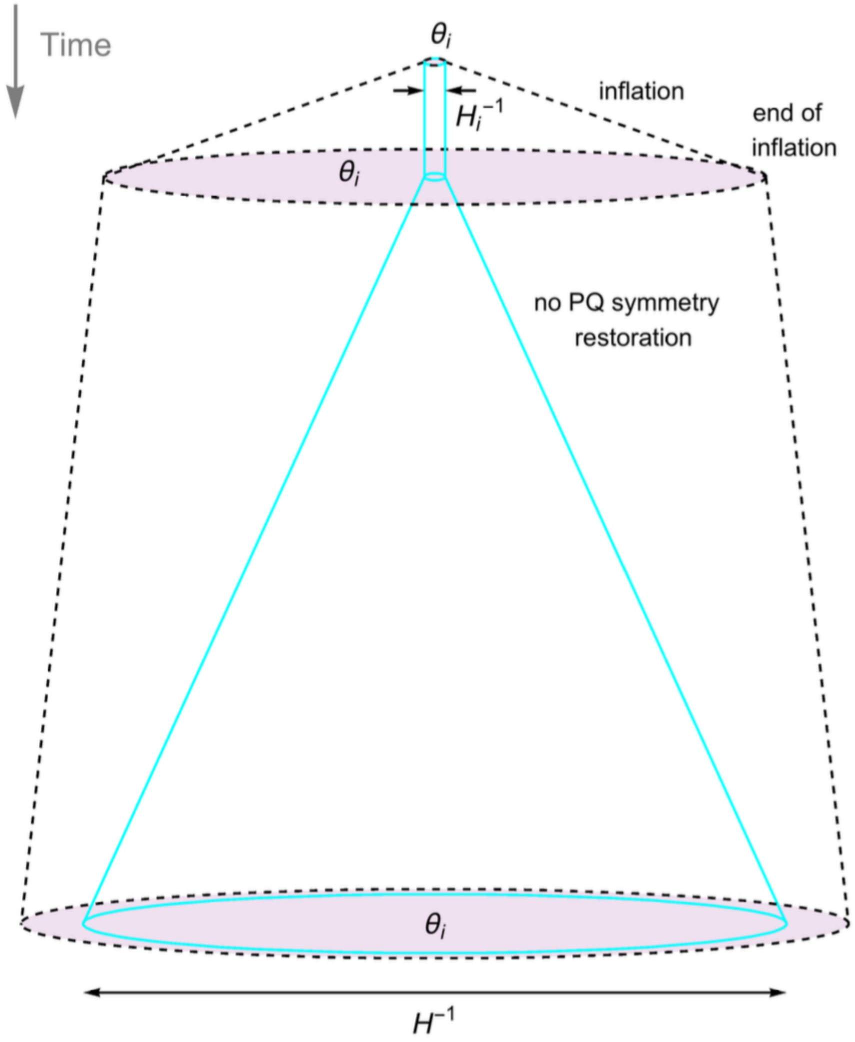
Axion Cold Dark Matter

- If PQ symmetry broken during inflation and not restored afterwards (pre-inflationary PQ breaking scenario)
  - Axion CDM density depends on single initial angle during inflation and f_A



[Borsanyi et al. `16]

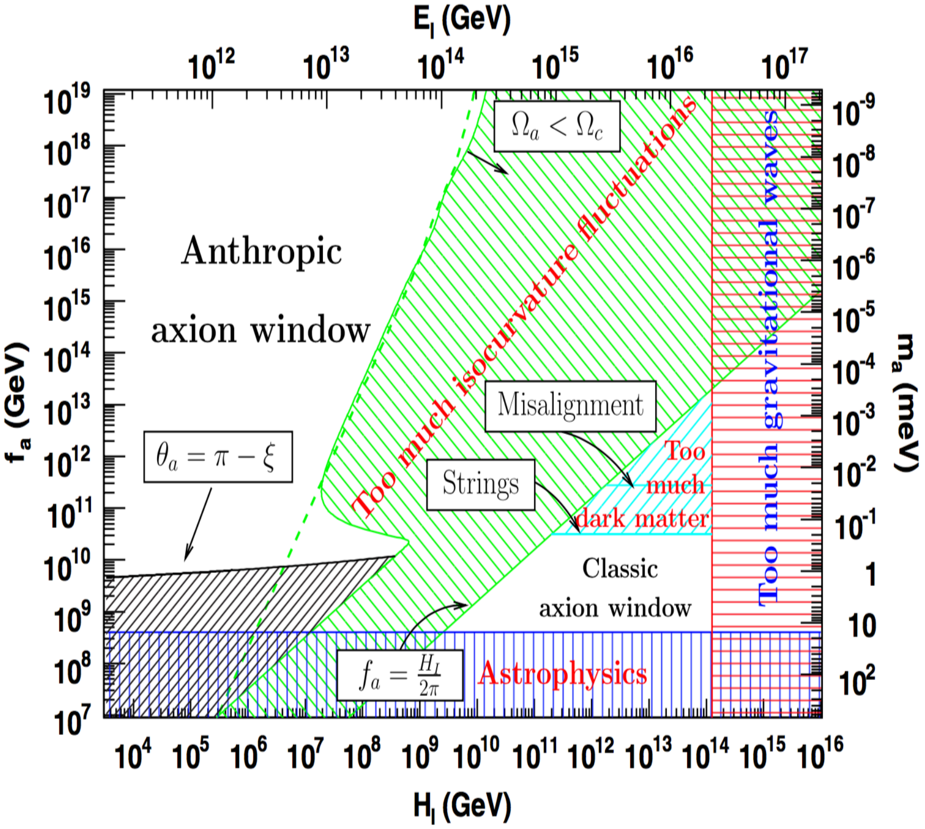
Pre–inflationary PQ symmetry breaking scenario



[Saikawa]

Axion Cold Dark Matter

- If PQ symmetry broken during inflation and not restored afterwards (pre-inflationary PQ breaking scenario)
  - Axion CDM density depends on single initial angle during inflation and f_A
  - Axion is present during inflation and creates isocurvature fluctuations which are not erased after inflation

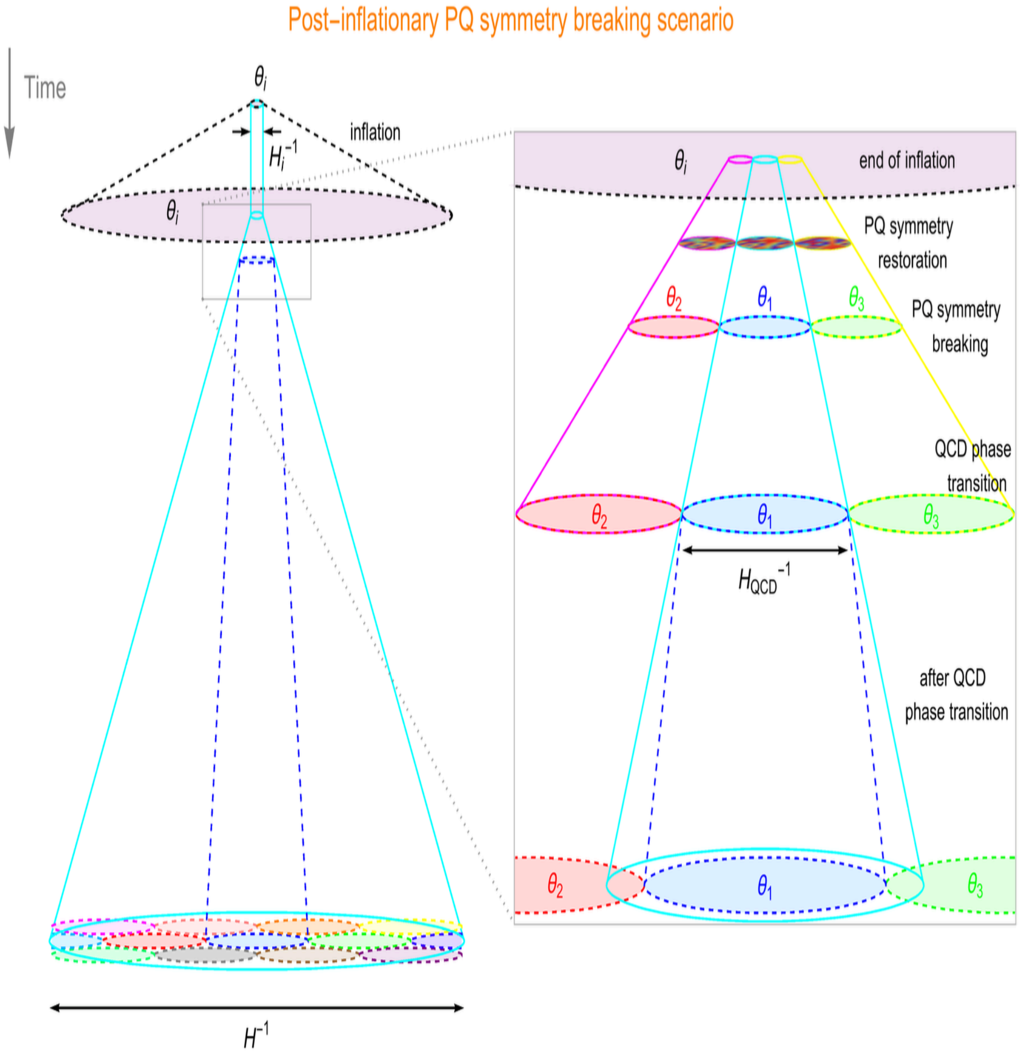


[Wilczek,Turner `91; Beltran et al. 06; Hertzberg,Tegmark,Wilczek 08; Visinelli,Gondolo 09; Hamann et al. 09; **Wantz,Shellard 09**]

Axion Cold Dark Matter

- If Peccei-Quinn symmetry restored after inflation (post-inflationary PQ breaking scenario)
  - Vacuum realignment contribution depends on spatially averaged initial misalignment angle and f_A

$$\Omega_A^{\rm real} h^2 \approx 0.12 \left(\frac{30\ \mu{\rm eV}}{m_A}\right)^{1.165}$$



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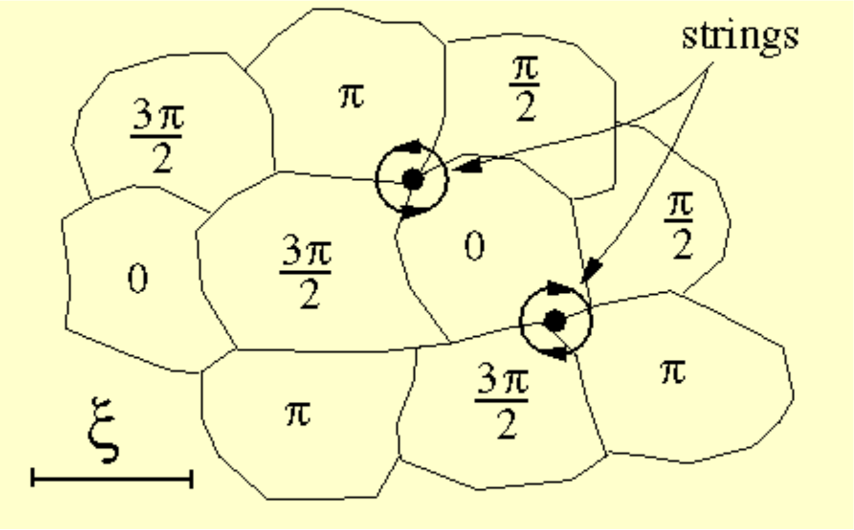

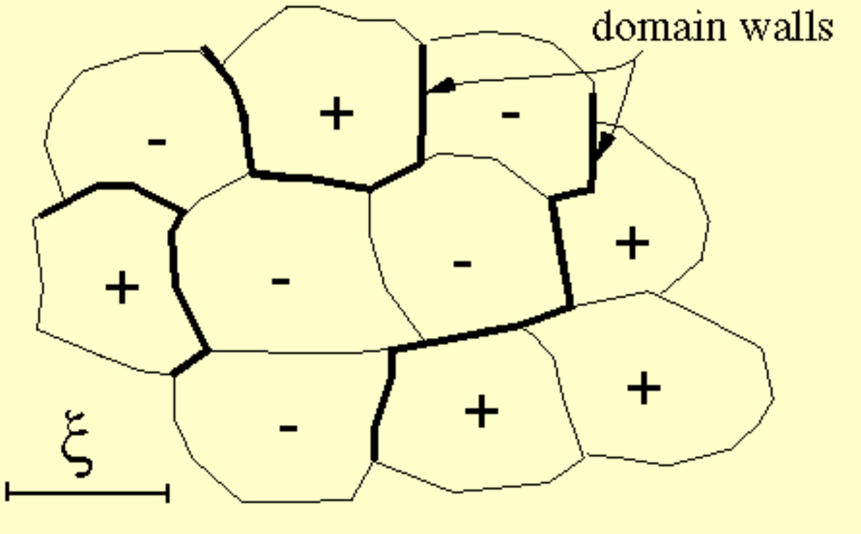

[DAMTP]

Axion Cold Dark Matter

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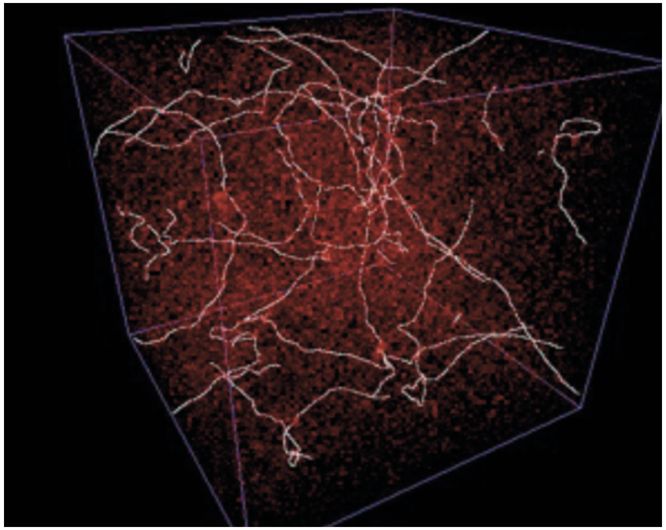
$$\Omega_A^{\rm real} h^2 \approx 0.12 \left(\frac{30\ \mu{\rm eV}}{m_A}\right)^{1.165}$$

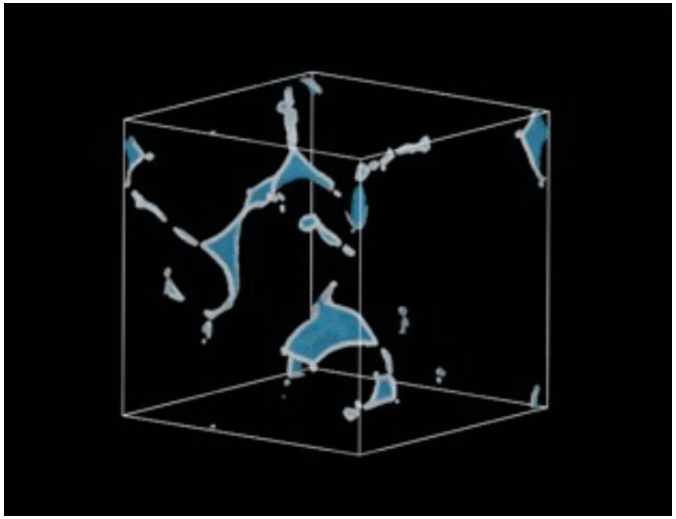
  - Additional contributions arise from decay of topological defects (axion strings and axion domain walls)
  - Latter determined by simulations of cosmic string and wall networks

    [Hiramatsu et al. 12; Kawasaki et al. 15]

  - May explain dark matter for

$$30\,\mu{\rm eV} \lesssim m_A \lesssim 10\,{\rm meV}$$

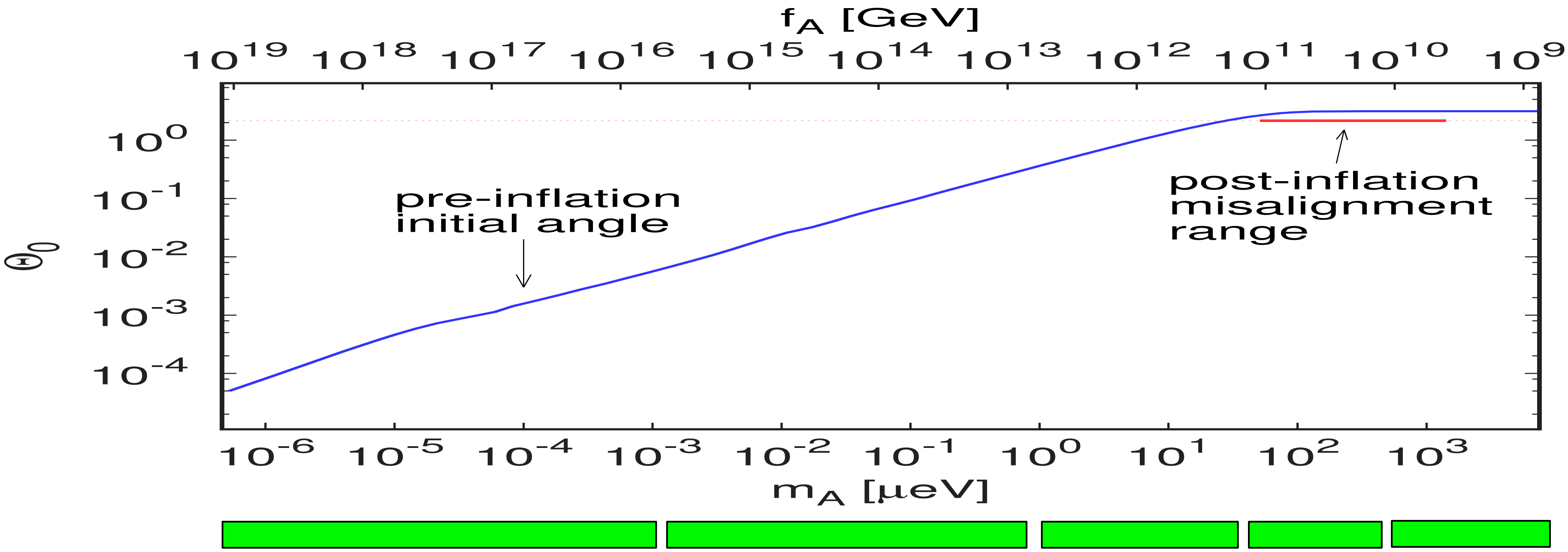




[Hiramatsu et al. 12]

Axion Dark Matter Direct Detection Experiments

- Upcoming generation of axion dark matter direct detection experiments can probe entire mass range:



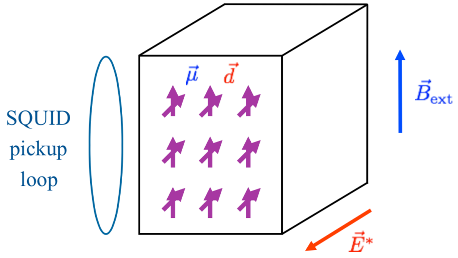
CASPEr

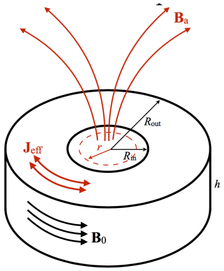
ABRACADABRA

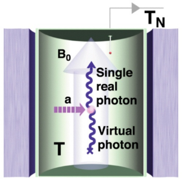
ADMX
HAYSTACK
CULTASK

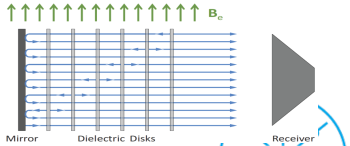
MADMAX
ORPHEUS
ORGAN
QUAX

BRASS







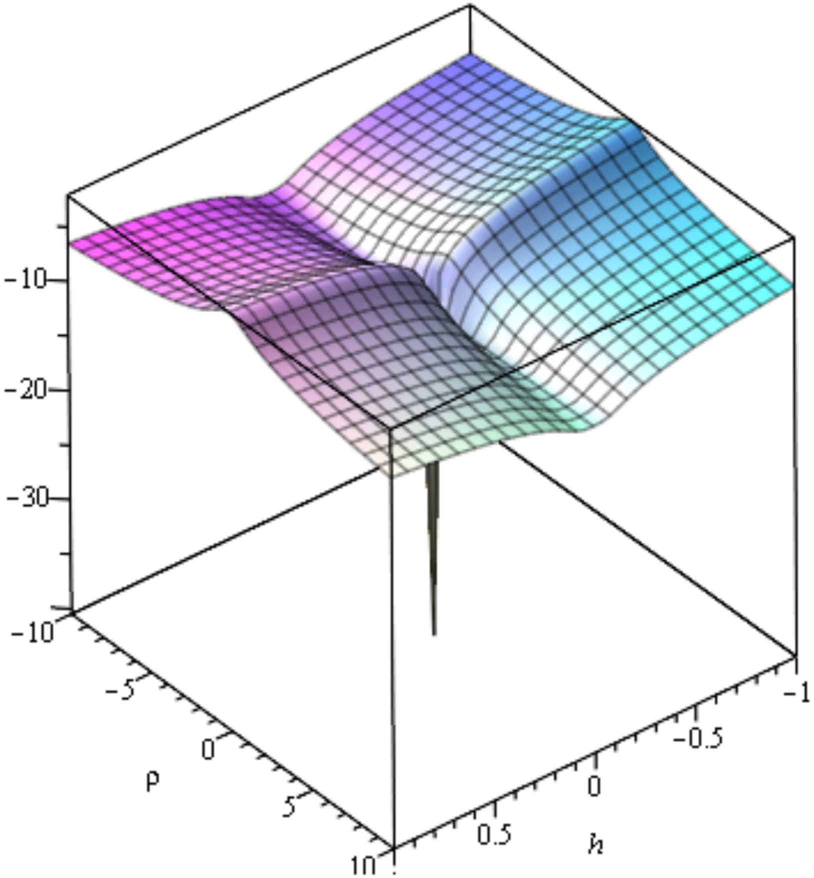


Unifying Inflation and Dark Matter with PQ Field

- $|\sigma| = \rho/\sqrt{2}$ or mixture with Higgs modulus may play role of inflaton, if it has non-minimal coupling to gravity,

$$S \supset -\int d^4x\sqrt{-g}\left[\frac{M^2}{2} + \xi_\sigma\,\sigma^*\sigma\right]R$$

[Fairbairn,Hogan,Marsh `14]



[Ballesteros,Redondo, AR,Tamarit `16]

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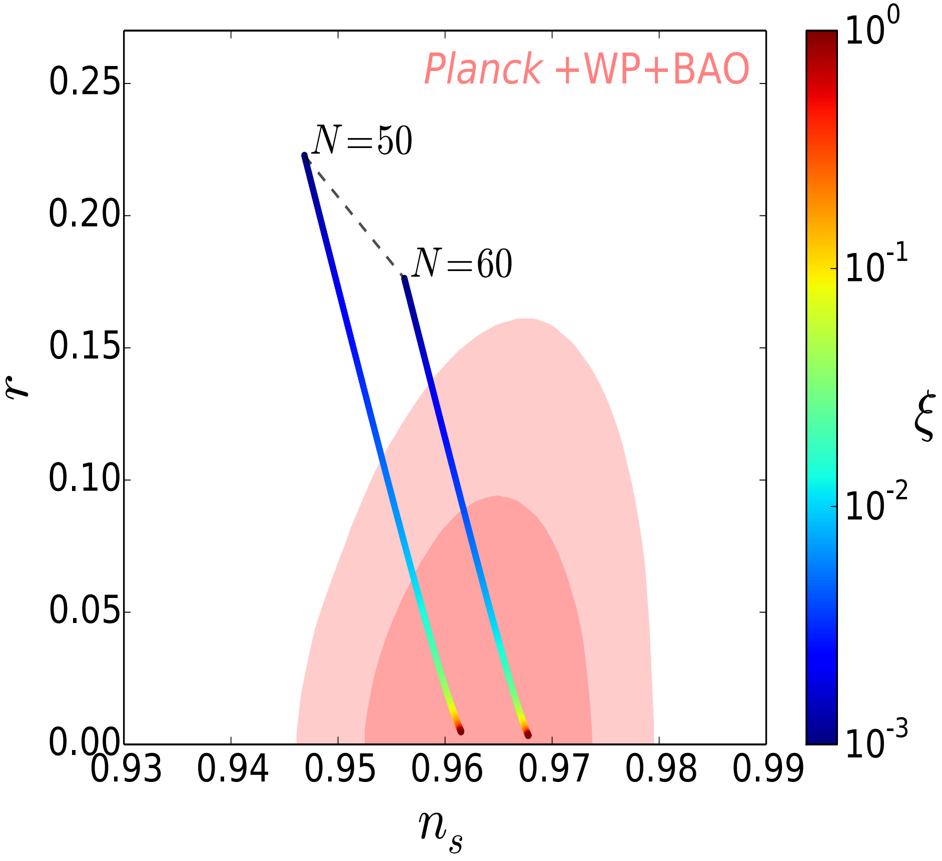
[Fairbairn,Hogan,Marsh `14]

- CMB observables

$$A_s = (2.20 \pm 0.08) \times 10^{-9}\,,$$
$$n_s = 0.967 \pm 0.004\,,$$
$$r < 0.07$$

fit by

$$\xi \simeq 2 \times 10^5 \sqrt{\lambda} \gtrsim 10^{-3}$$



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Unifying Inflation and Dark Matter with PQ Field

- PQ symmetry restored after inflation already in preheating stage when PQ field undergoes Hubble damped oscillations in quartic potential

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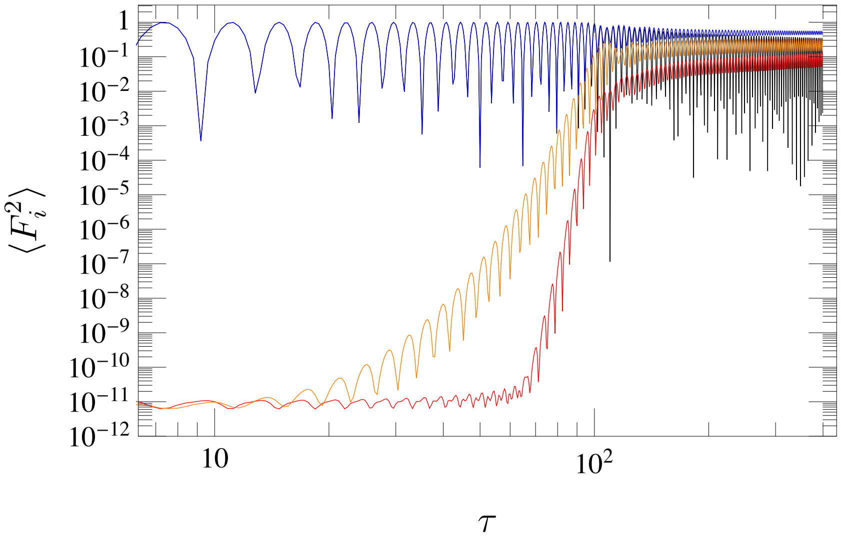

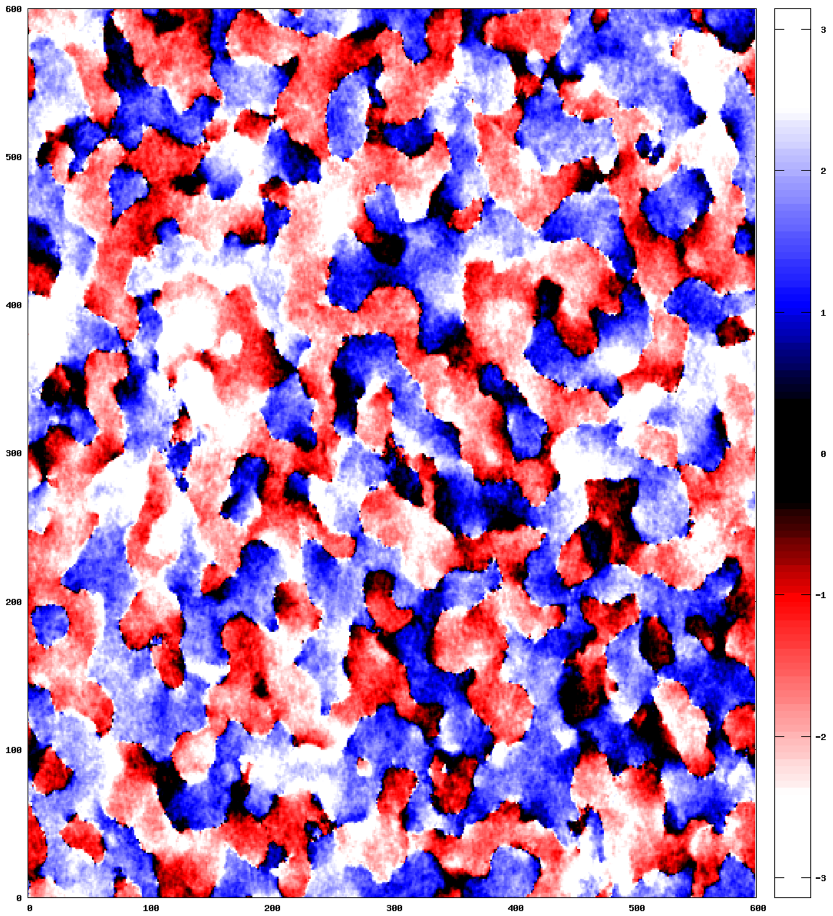

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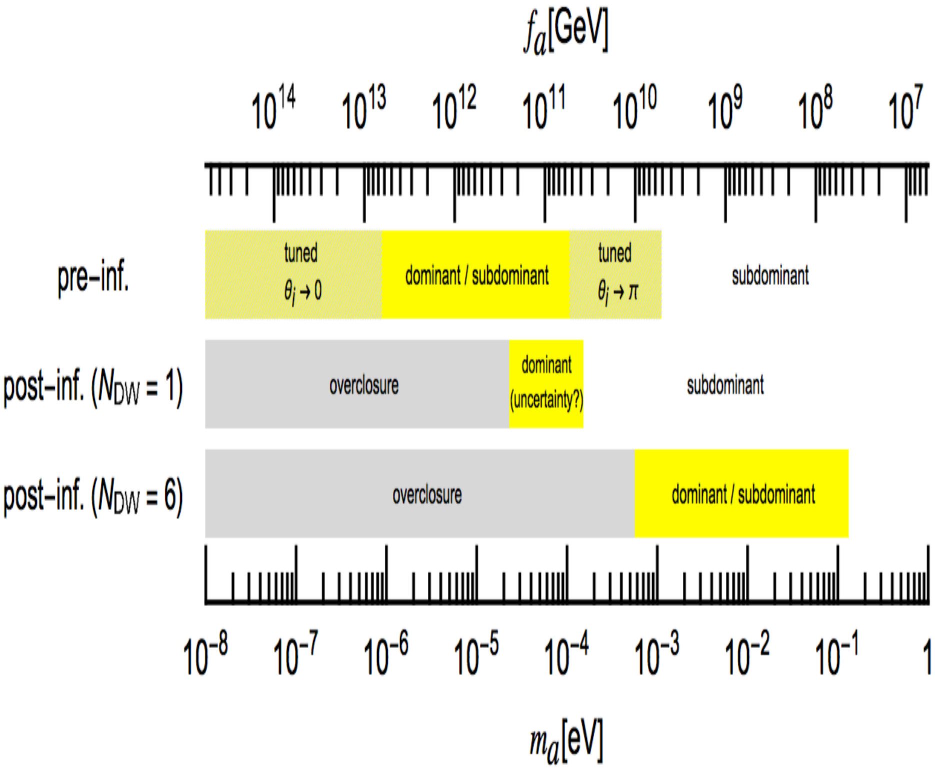
  [Ballesteros,Redondo, AR,Tamarit `16]

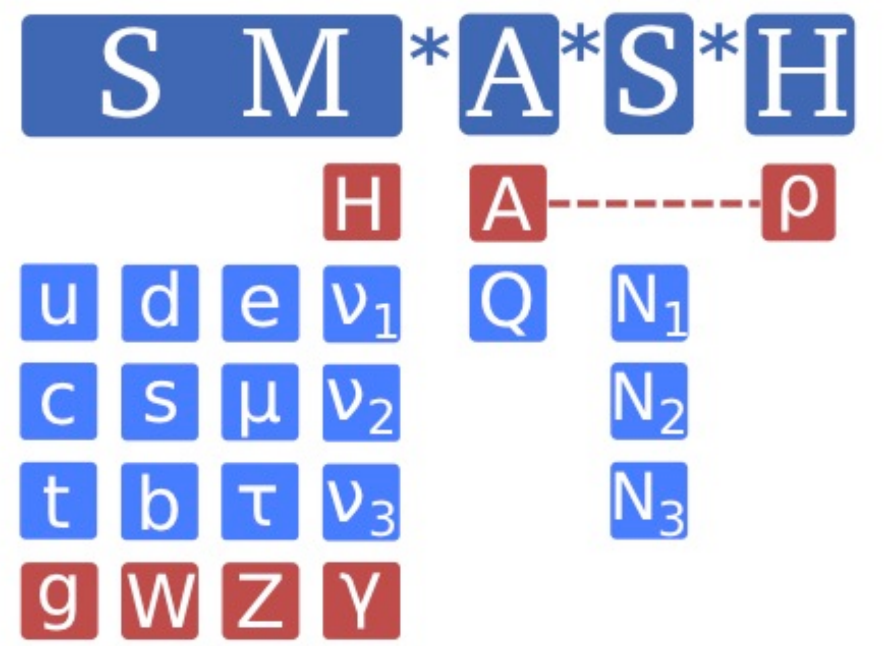
- CDM abundance fixes decay constant (mass) of axion



Unifying Inflation, Dark Matter, and Seesaw with PQ Field

- Augmenting axion models with three SM singlet neutrinos, getting their Majorana masses also through the vev $v_\sigma = N_{\rm DW} f_A$
  - no strong CP problem
  - dark matter
  - inflation
  - neutrino masses and mixing
  - baryogenesis via leptogenesis

[Dias et al. `14; Ballesteros et al. `16]



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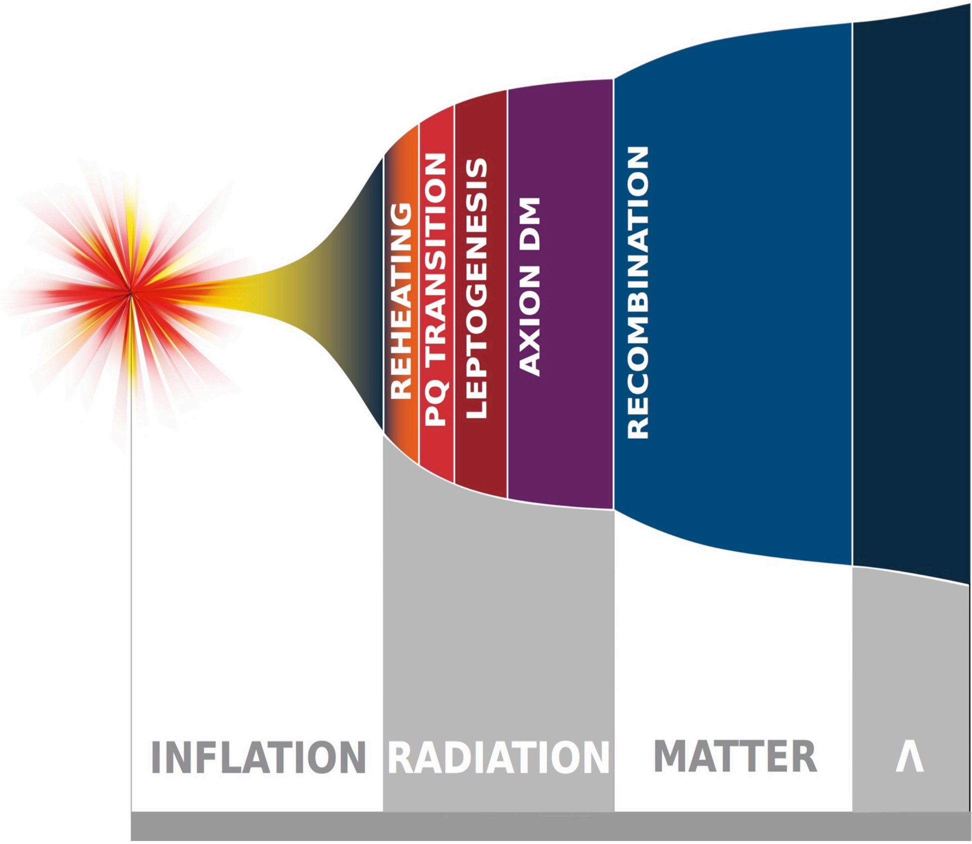
[Dias et al. `14; Ballesteros et al. `16]

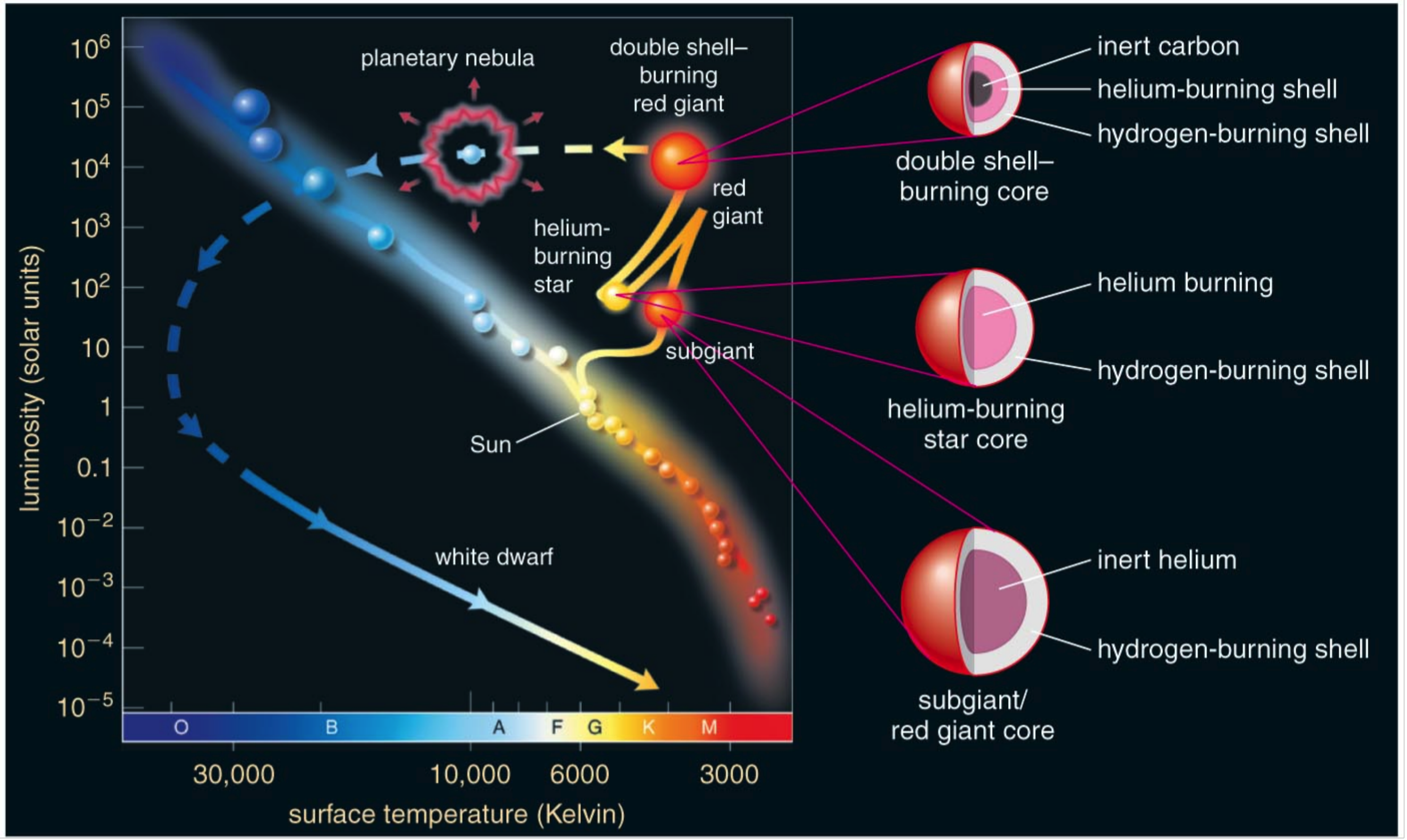
- Complete and consistent history of the universe from inflation to now



[desy.de]

Searching for Axion/ALP Energy Losses of Stars

- Evolution of stars (Main Sequence – Red-Giant (RG) – Helium Burning (HB) – White Dwarf (WD)) sensitive to additional energy losses



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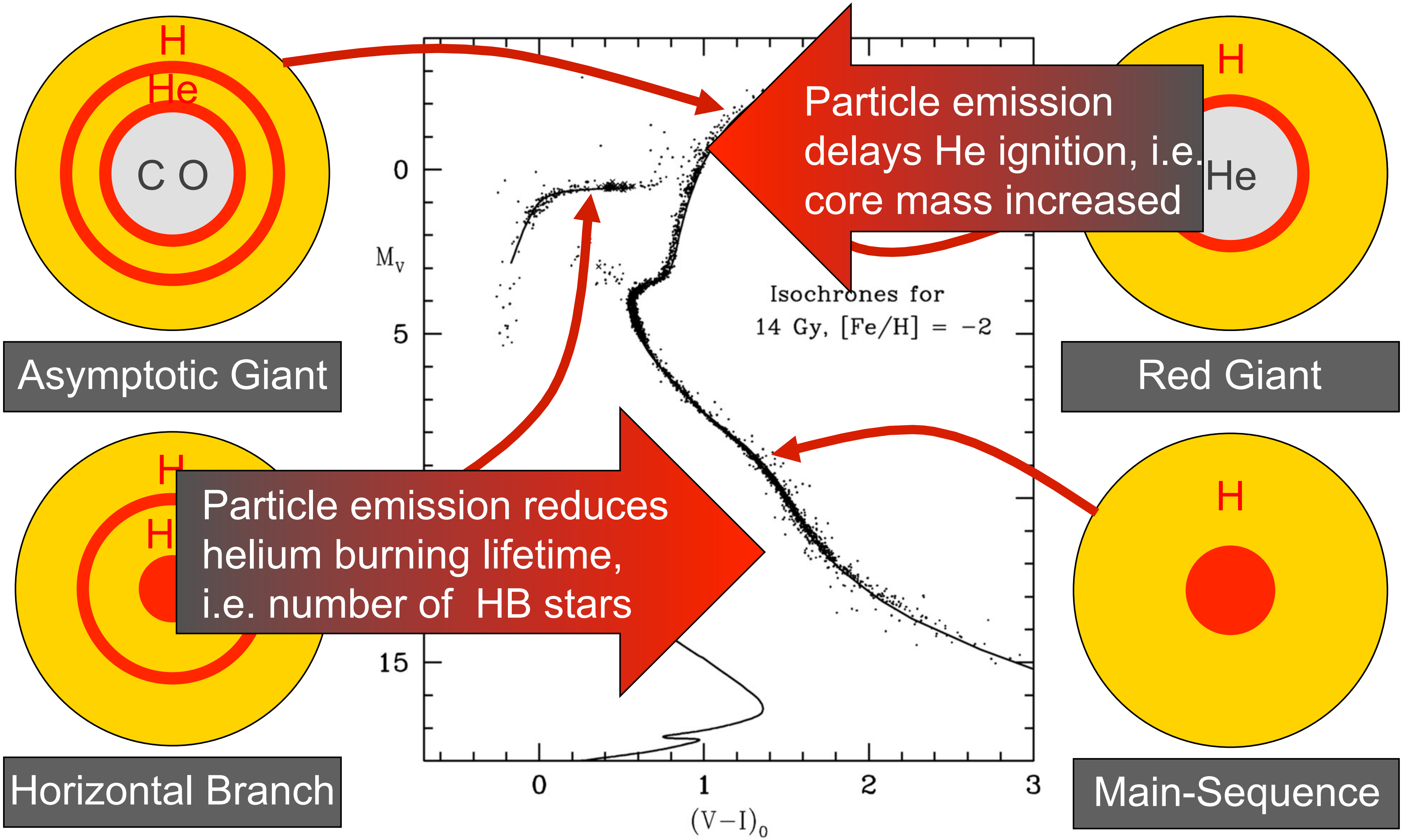
Searching for Axion/ALP Energy Losses of Stars



Particle emission delays He ignition, i.e. core mass increased

Particle emission reduces helium burning lifetime, i.e. number of HB stars

Asymptotic Giant

Red Giant

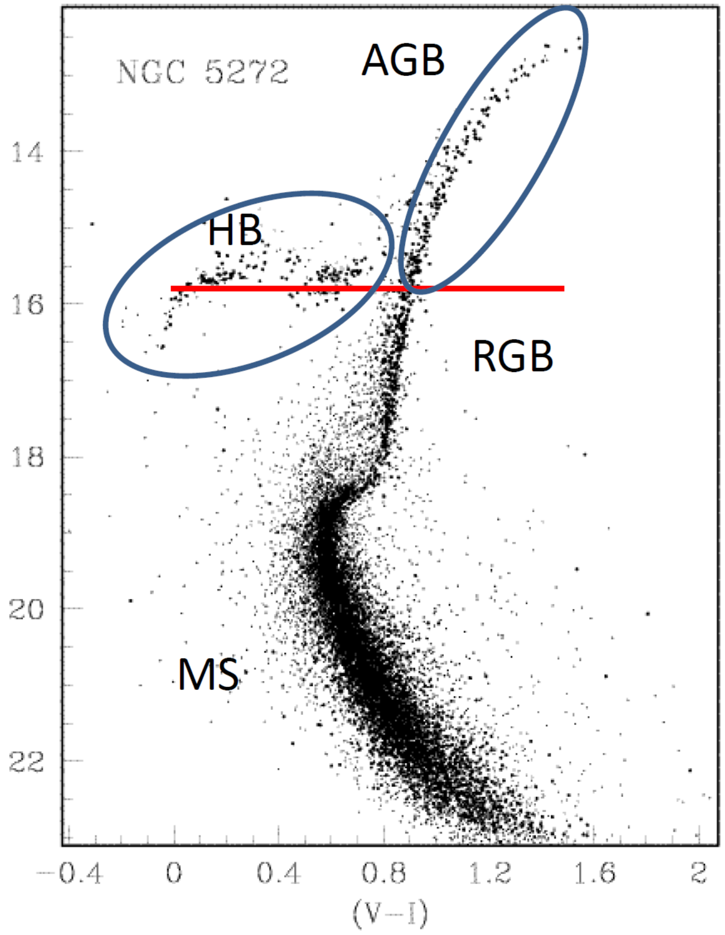
Horizontal Branch

Main-Sequence

[Raffelt 14]

Searching for Axion/ALP Energy Losses of Stars

- RG cooling rate: Brightness of tip of RG branch in color-magnitude diagram of globular cluster [Viaux et al. 13]
- HB cooling rate: Number of HB stars vs. number of RGs in color-magnitude diagram of globular cluster [Ayala et al. 14]



[Giannotti `16]

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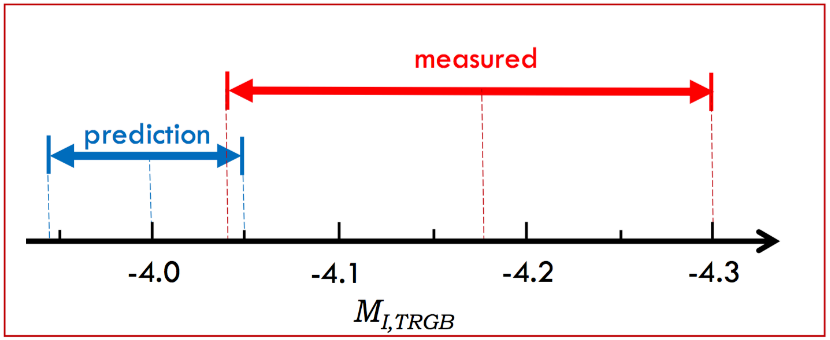

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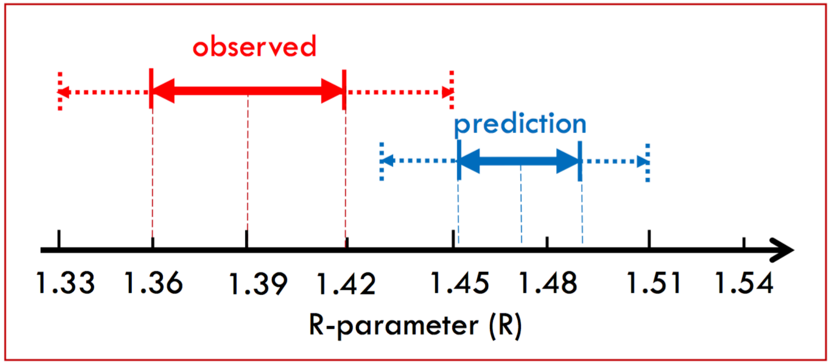

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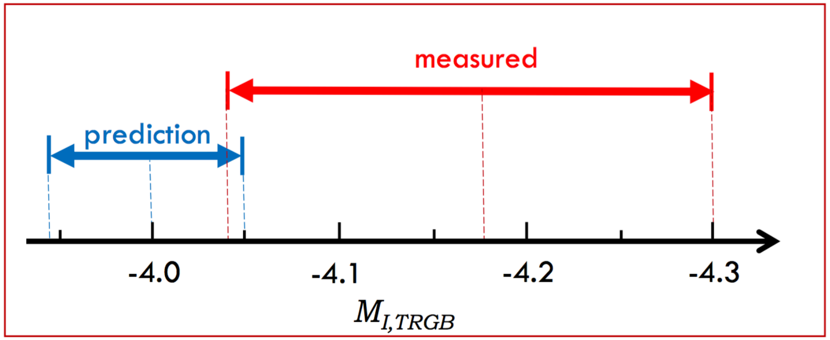

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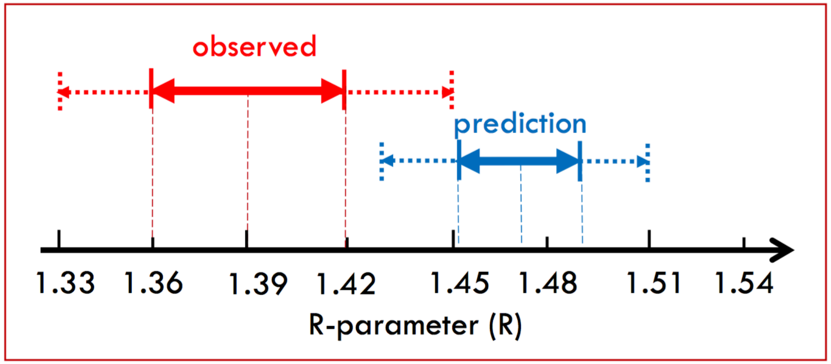
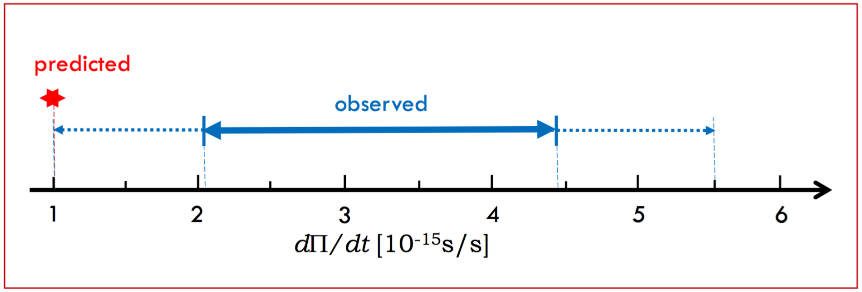


- WD cooling rate:
  - Period decrease of variable WDs [Kepler et al. 91,...]



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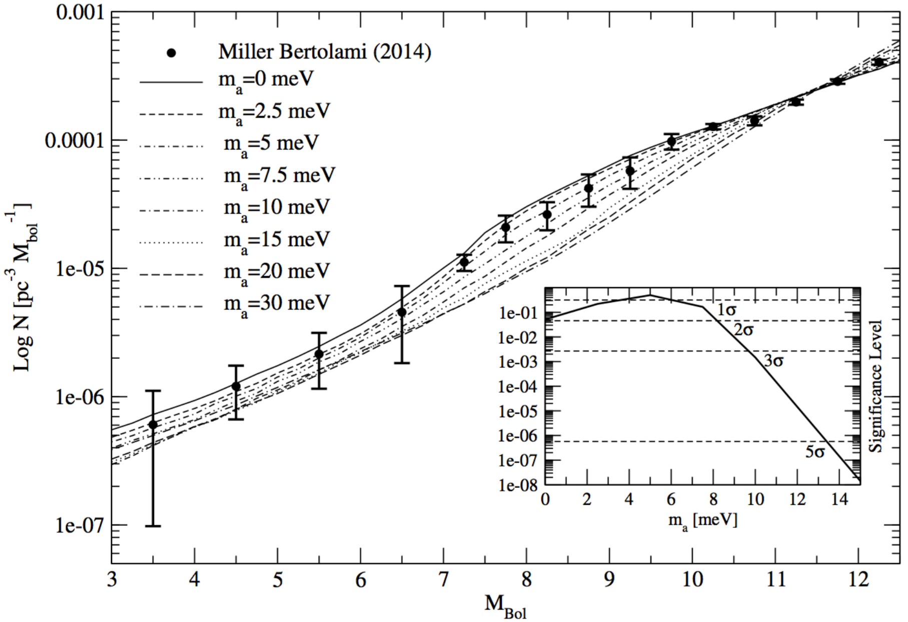
  - White dwarf luminosity function (WDLF) [Isern et al. 08-12]



[Bertolami et al. 15]

Searching for Axion/ALP Energy Losses of Stars

- RG cooling rate: Brightness of tip of RG branch in color-magnitude diagram of globular cluster [Viaux et al. 13]

$$g_{ae} \equiv \frac{m_e}{f_a}|C_{ae}| < 4.3 \times 10^{-13}$$

- HB cooling rate: Number of HB stars vs. number of RGs in color-magnitude diagram of globular cluster [Ayala et al. 14]

$$g_{a\gamma} \equiv \frac{\alpha}{2\pi f_a}|C_{a\gamma}| < 6.6 \times 10^{-11}\,\mathrm{GeV}^{-1}$$

- WD cooling rate:
  - Period decrease of variable WDs [Kepler et al. 91,...]
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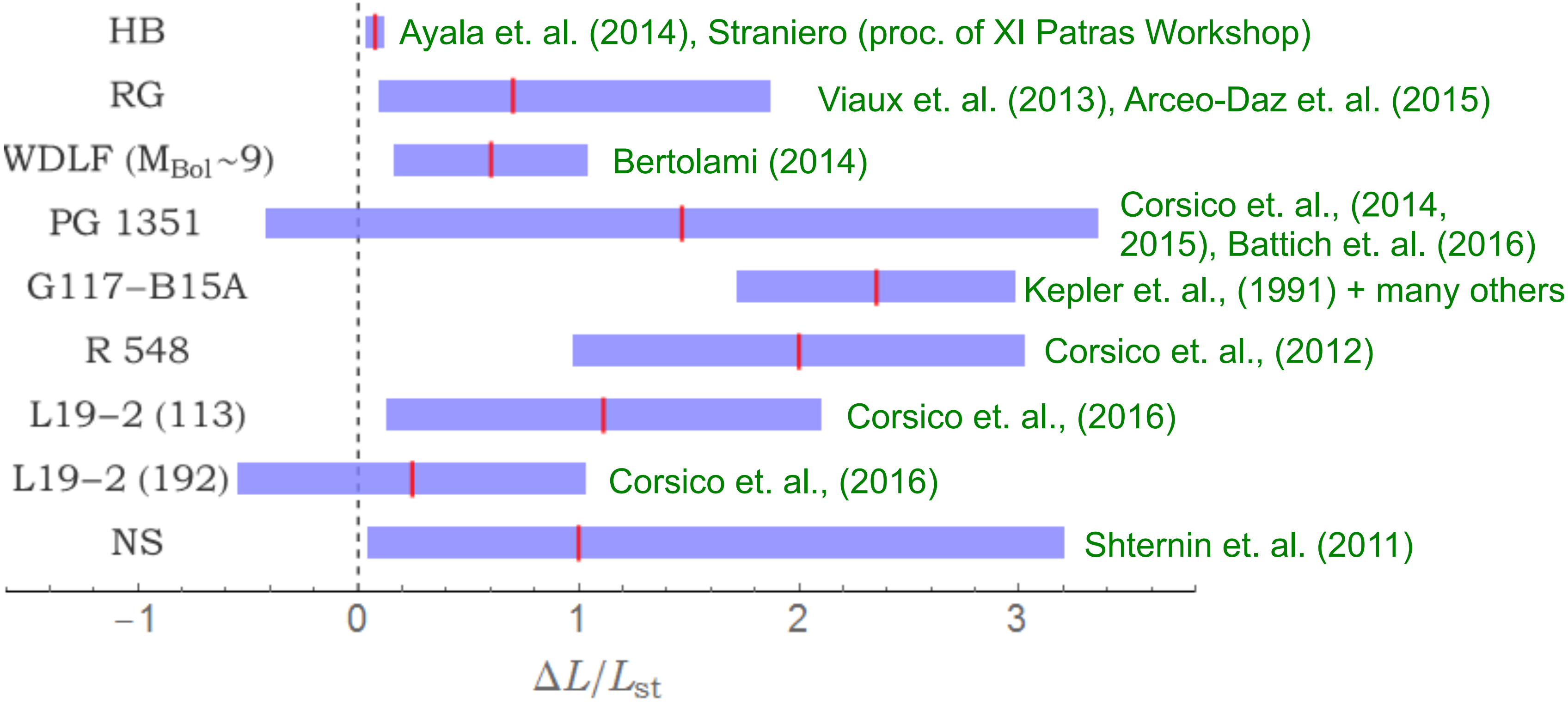
$$g_{ae} \equiv \frac{m_e}{f_a}|C_{ae}| < 2.8 \times 10^{-13}$$

Searching for Axion/ALP Energy Losses of Stars

- However, practically every stellar systems seems to be cooling a bit faster than predicted by models based on SM:



Ayala et. al. (2014), Straniero (proc. of XI Patras Workshop)

Viaux et. al. (2013), Arceo-Daz et. al. (2015)

Bertolami (2014)

Corsico et. al., (2014, 2015), Battich et. al. (2016)

Kepler et. al., (1991) + many others

Corsico et. al., (2012)

Corsico et. al., (2016)

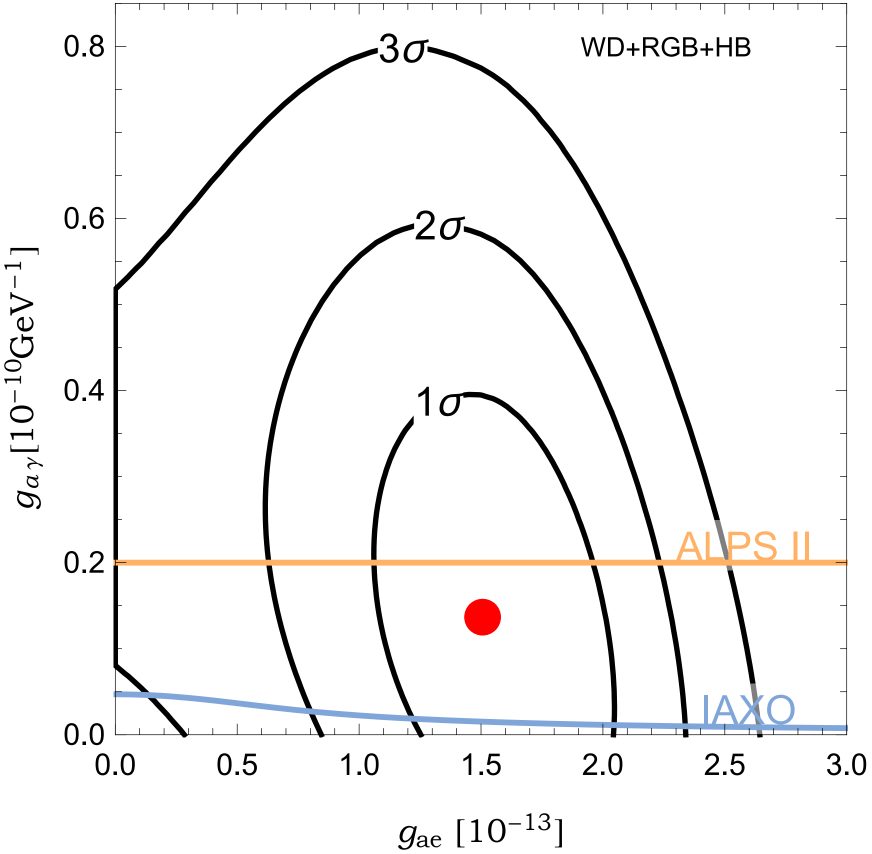
Corsico et. al., (2016)

Shternin et. al. (2011)

[Giannotti, Irastorza, Redondo, AR (2015); Giannotti, Irastorza, Redondo, AR 17]

Searching for Axion/ALP Energy Losses of Stars

- Excessive energy losses of HBs, RG, WDs can be explained at one stroke by production of axion/ALP with coupling to photons and electrons:



$$g_{a\gamma} = C_{a\gamma}\alpha/(2\pi f_a)$$

$$\gamma + Ze \to Ze + a$$

$$g_{ai} = C_{ai} m_i / f_a$$

$$e + Ze \to Ze + e + a$$

[Giannotti,Irastorza,Redondo,AR,Saikawa 17]

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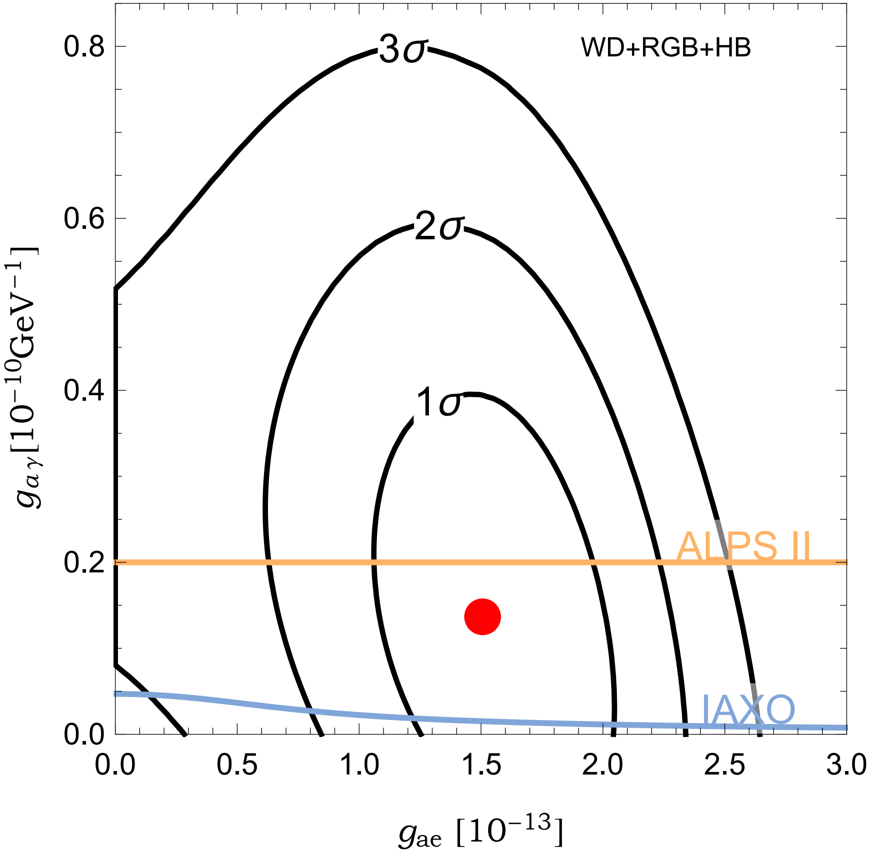
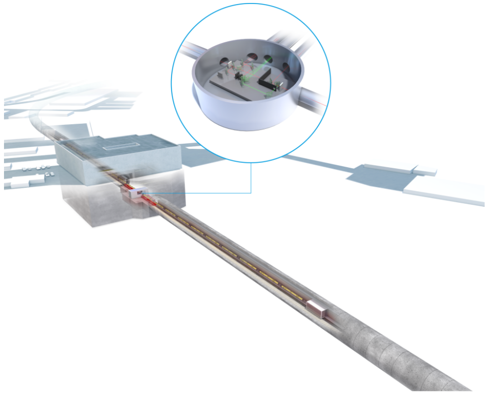
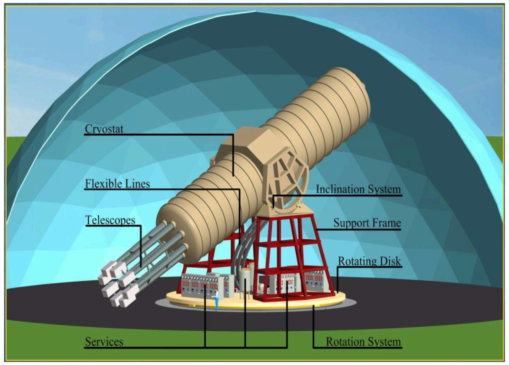


[Giannotti,Irastorza,Redondo,AR,Saikawa 17]

ALPS II

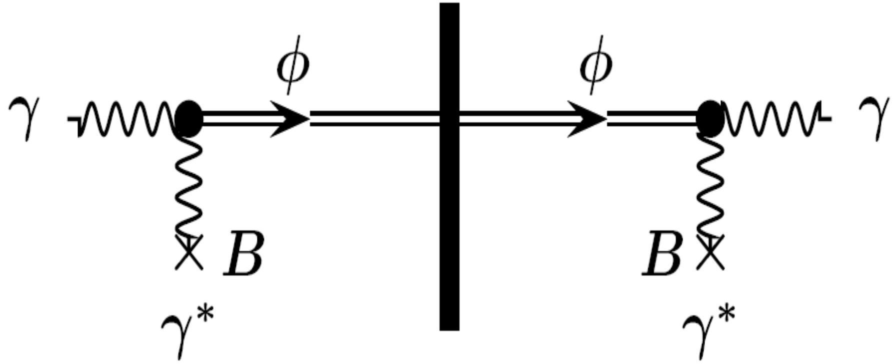


IAXO



Light-shining-through-a-wall Searches

- Axion/ALP so weakly interacting, that it passes any barrier
- Light-shining-through a wall:



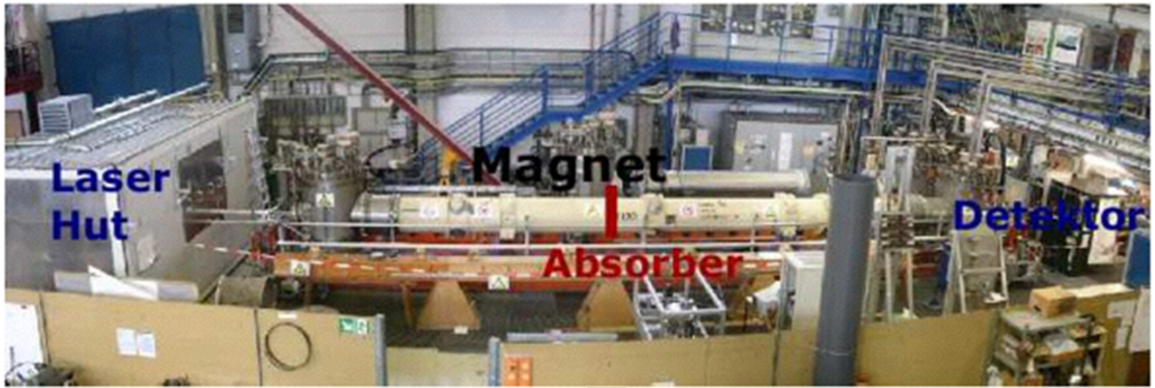
[Okun 1982, Sikivie 1983, Ansel‘m 1985, van Bibber et al. 1987]

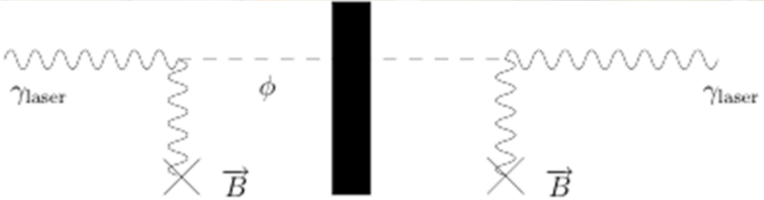
- Oscillation probability:

$$P(a \leftrightarrow \gamma) = 4\frac{(g_{a\gamma}\omega B)^2}{m_a^4}\sin^2\left(\frac{m_a^2}{4\omega}L_B\right)$$

Light-shining-through-a-wall Searches

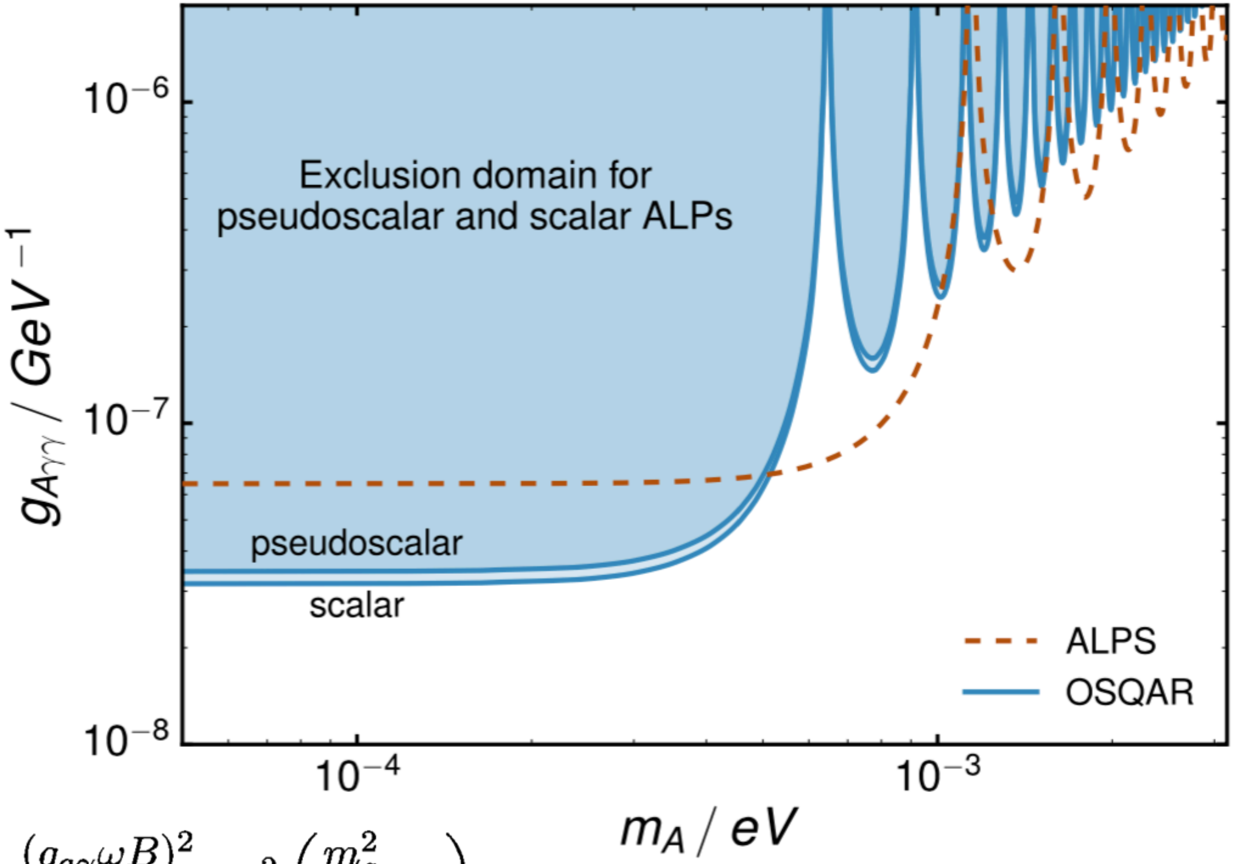
- Any Light Particle Search (ALPS) at DESY (in coll. with AEI, UHH)





Light-shining-through-a-wall Searches

- Currently best limits from LSW: ALPS (DESY) and OSQAR (CERN)

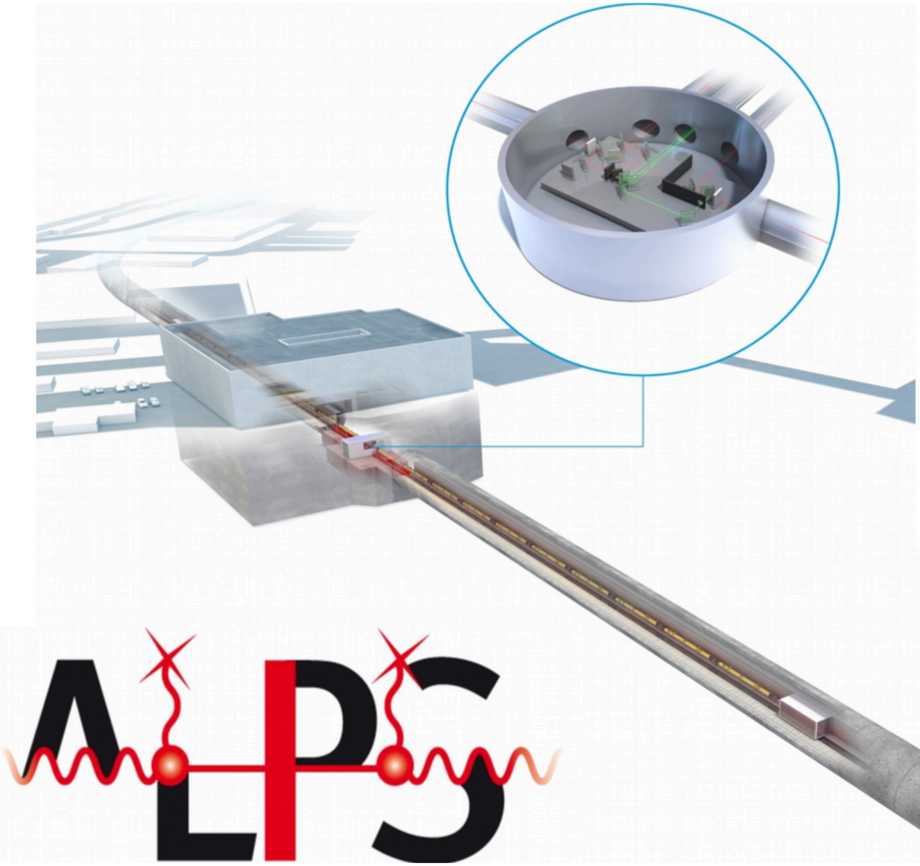


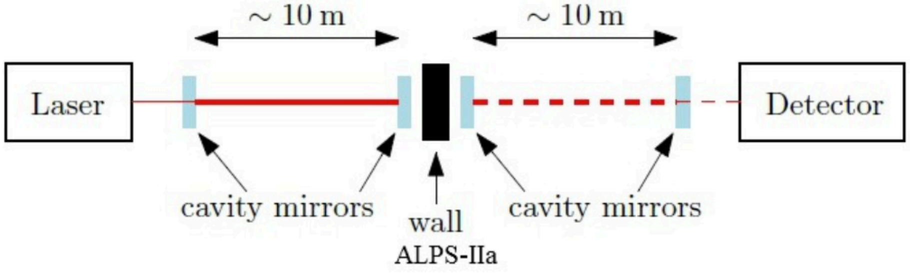
$$P(a \leftrightarrow \gamma) = 4\frac{(g_{a\gamma}\omega B)^2}{m_a^4}\sin^2\left(\frac{m_a^2}{4\omega}L_B\right)$$

[Ballou et al. 15]

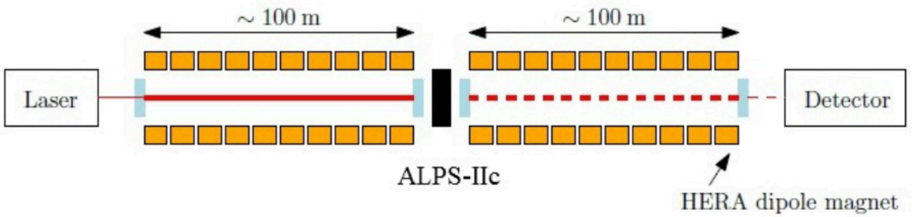
Light-shining-through-a-wall Searches

> **ALPS II** at DESY (in coll. with AEI, UFL, U Mainz)



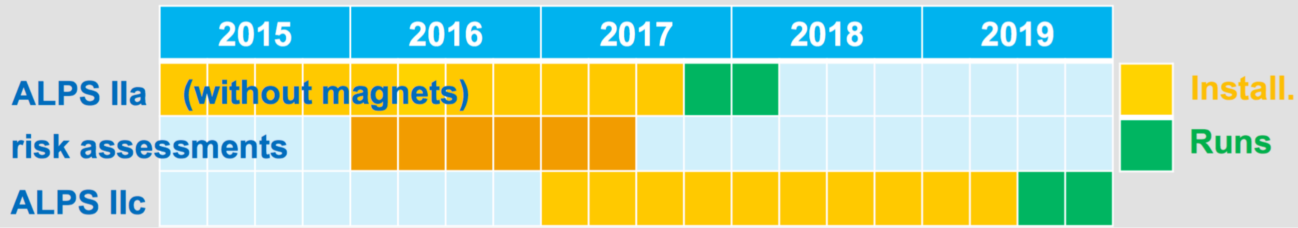


ALPS-IIa



ALPS-IIc

Parameter	Scaling	ALPS I	ALPS IIc	Sens. gain
Effective laser power $P_{\rm laser}$	$g_{a\gamma} \propto P_{\rm laser}^{-1/4}$	1 kW	150 kW	3.5
Rel. photon number flux n_γ	$g_{a\gamma} \propto n_\gamma^{-1/4}$	1 (532 nm)	2 (1064 nm)	1.2
Power built up in RC $P_{\rm RC}$	$g_{a\gamma} \propto P_{reg}^{-1/4}$	1	40,000	14
BL (before& after the wall)	$g_{a\gamma} \propto (BL)^{-1}$	22 Tm	468 Tm	21
Detector efficiency QE	$g_{a\gamma} \propto QE^{-1/4}$	0.9	0.75	0.96
Detector noise DC	$g_{a\gamma} \propto DC^{1/8}$	0.0018 s^{-1}	0.000001 s^{-1}	2.6
Combined improvements				3082



	2015	2016	2017	2018	2019
ALPS IIa	🟨🟨🟨🟨 (without magnets)	🟨🟨🟨🟨	🟨🟨🟨🟩	🟩⬜⬜⬜	⬜⬜⬜⬜
risk assessments	⬜⬜⬜⬜	🟧🟧🟧🟧	🟧🟧⬜⬜	⬜⬜⬜⬜	⬜⬜⬜⬜
ALPS IIc	⬜⬜⬜⬜	⬜⬜⬜⬜	🟨🟨🟨🟨	🟨🟨🟨🟨	🟨🟨🟩🟩

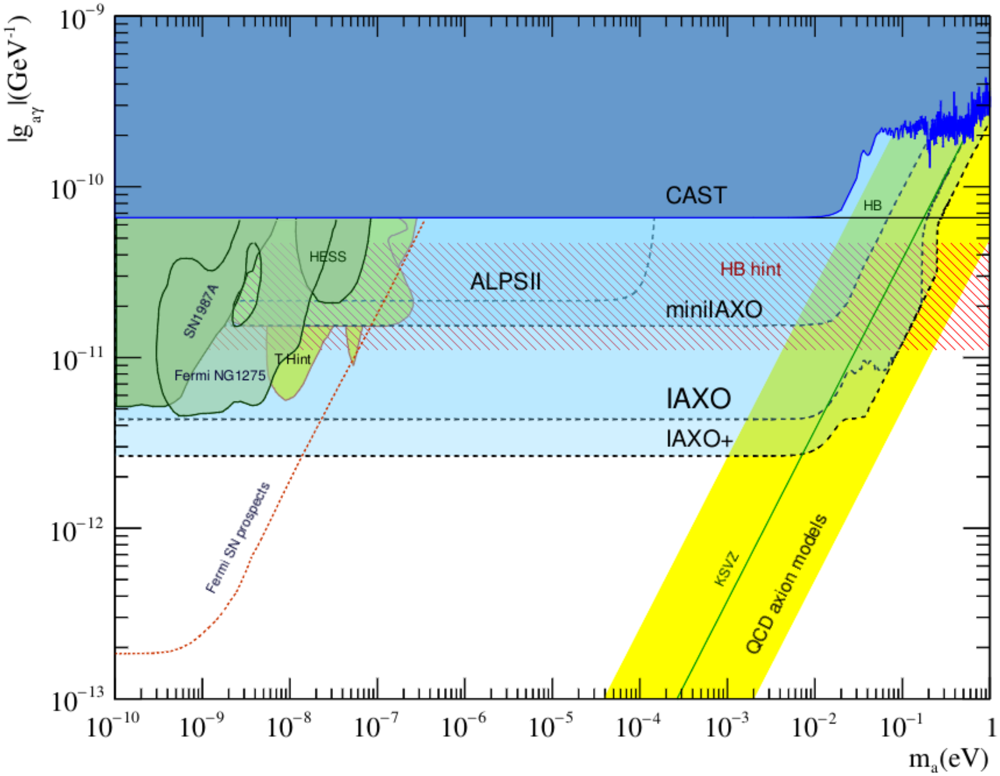
🟨 **Install.**
🟩 **Runs**

[Bähre et al (ALPS II TDR) 13]

Light-shining-through-a-wall Searches

> ALPS II

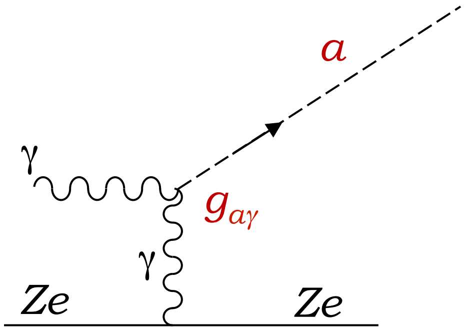
- First pure laboratory experiment to surpass stellar bounds
- Can probe part of parameter space relevant for astro hints



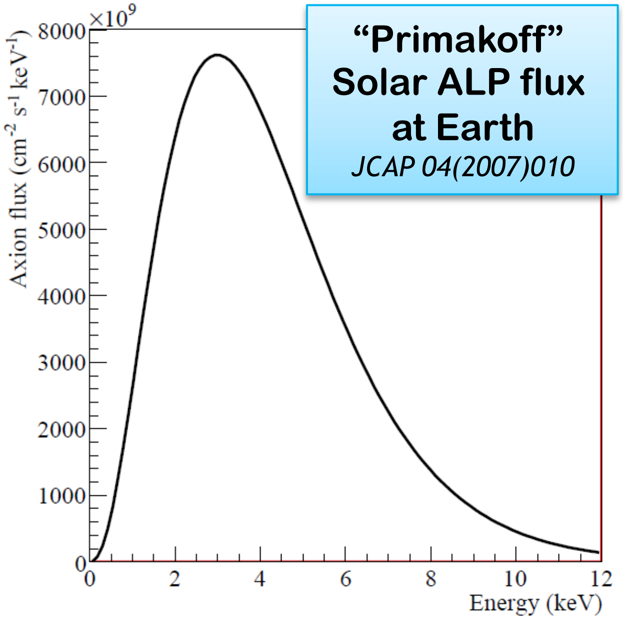
[Irastorza]

Helioscope Searches

- Appreciable flux of solar ALPs produced by Primakoff process in core:

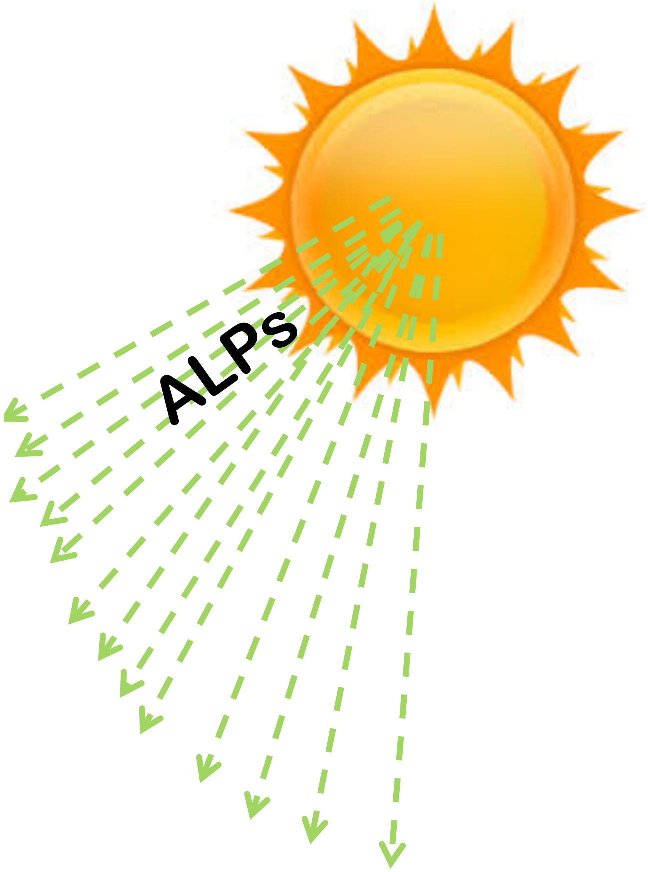


[Giannotti `16]



“Primakoff” Solar ALP flux at Earth

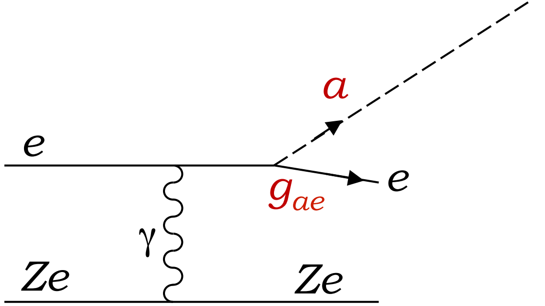
JCAP 04(2007)010



[Irastorza `16]

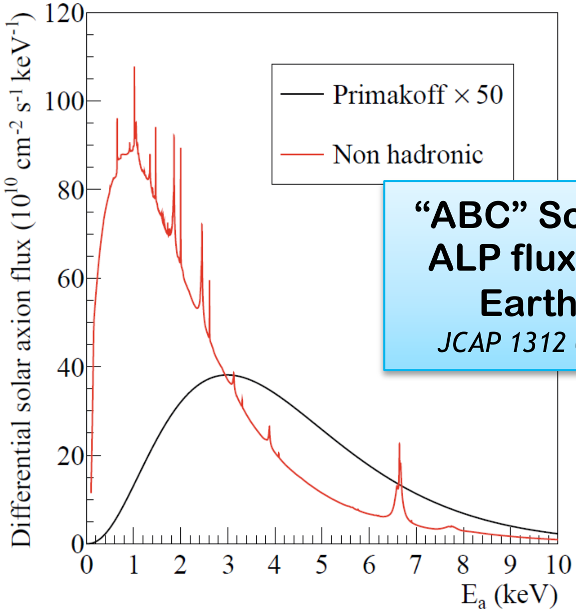
Helioscope Searches

- Even higher flux of solar ALPs produced by Atomic Recombination, Bremsstrahlung and Compton (ABC) processes:



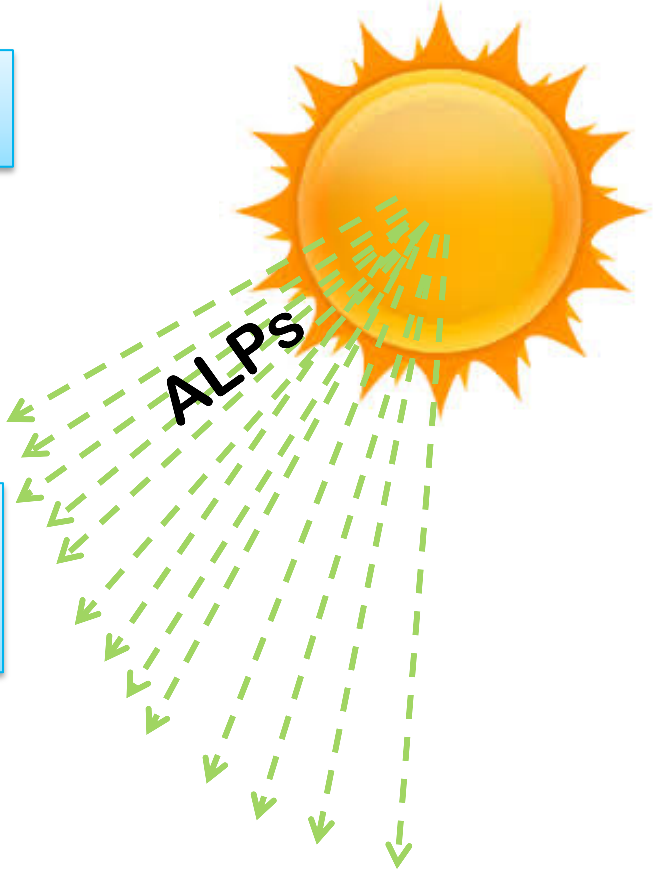
[Giannotti `16]

*** if the ALP couples with electron (g_{ae})**



"ABC" Solar ALP flux at Earth

JCAP 1312 008

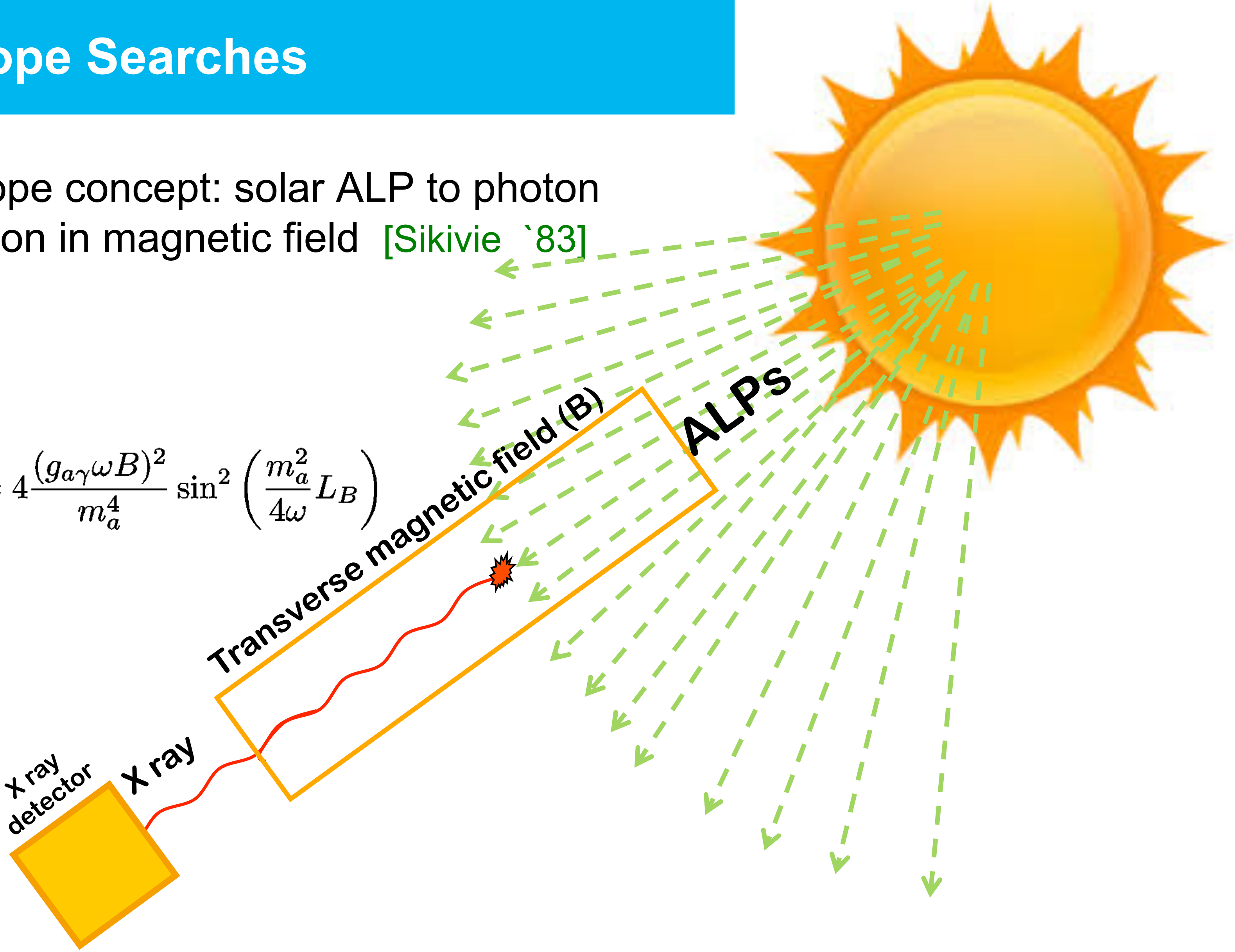


[Irastorza `16]

Helioscope Searches

- Helioscope concept: solar ALP to photon conversion in magnetic field [Sikivie `83]

$$P(a \leftrightarrow \gamma) = 4\frac{(g_{a\gamma}\omega B)^2}{m_a^4}\sin^2\left(\frac{m_a^2}{4\omega}L_B\right)$$



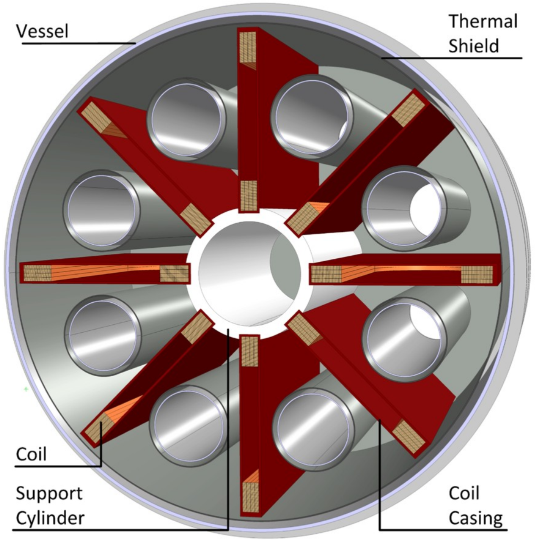
[Irastorza `16]

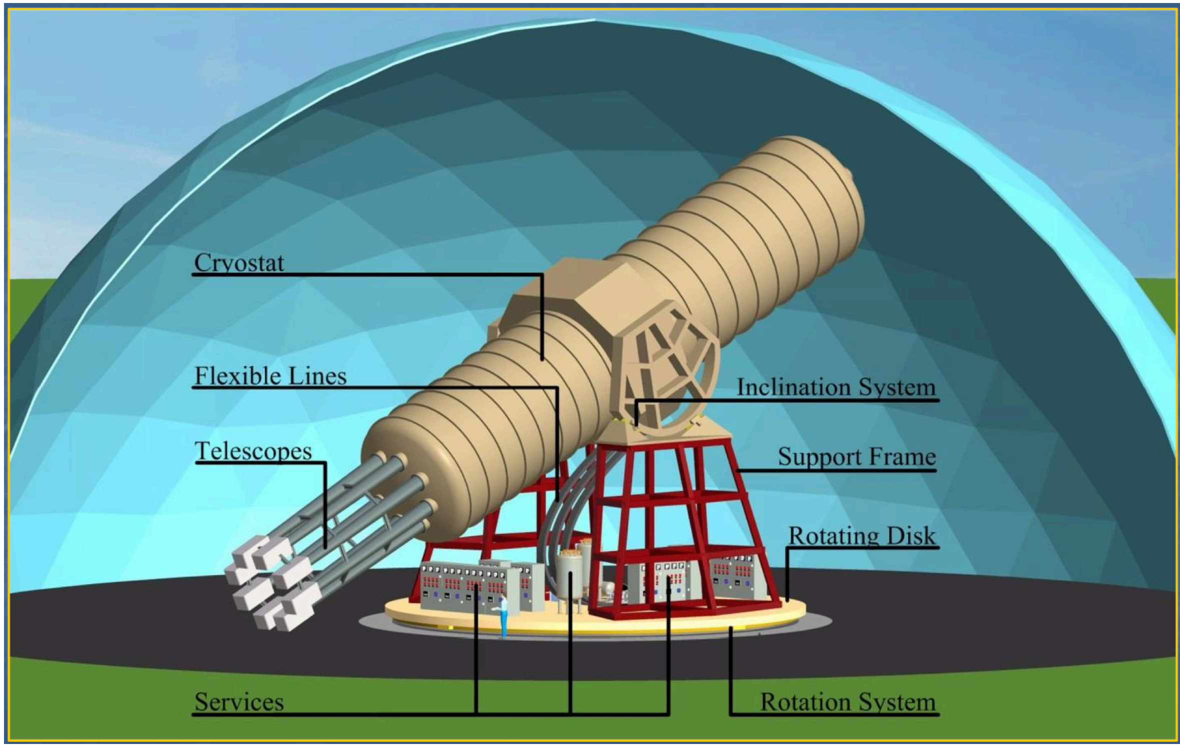
Helioscope Searches

- Most sensitive until now: CERN Axion Solar Telescope (CAST)
  - Superconducting LHC dipole magnet
  - X-ray detectors
  - Use of buffer gas to extend sensitivity to higher masses (axion band)

Helioscope Searches

- Proposed successor: International Axion Observatory (IAXO)
  - Dedicated superconducting toroidal magnet with much bigger aperture than CAST
  - Extensive use of X-ray optics
  - Low background X-ray detectors



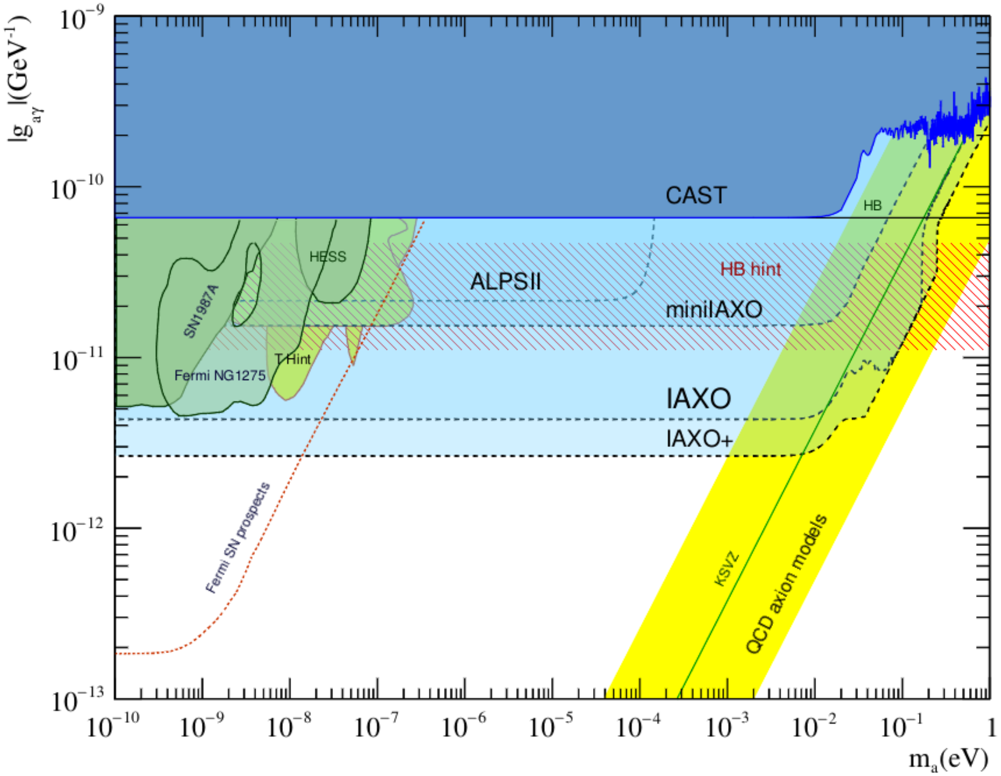


[Armengaud et al (IAXO CDR) 1401.3233]

Helioscope Searches

> IAXO

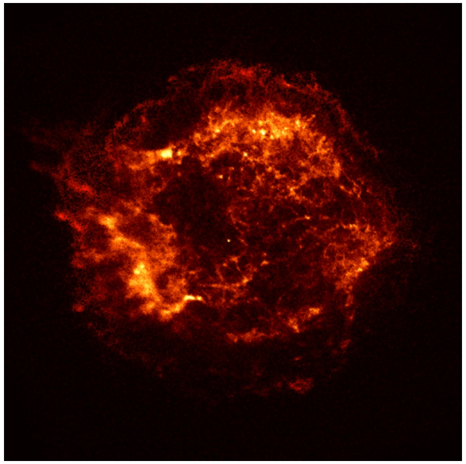
- Covers most of parameter space relevant for astro hints
- Able to probe meV mass axion

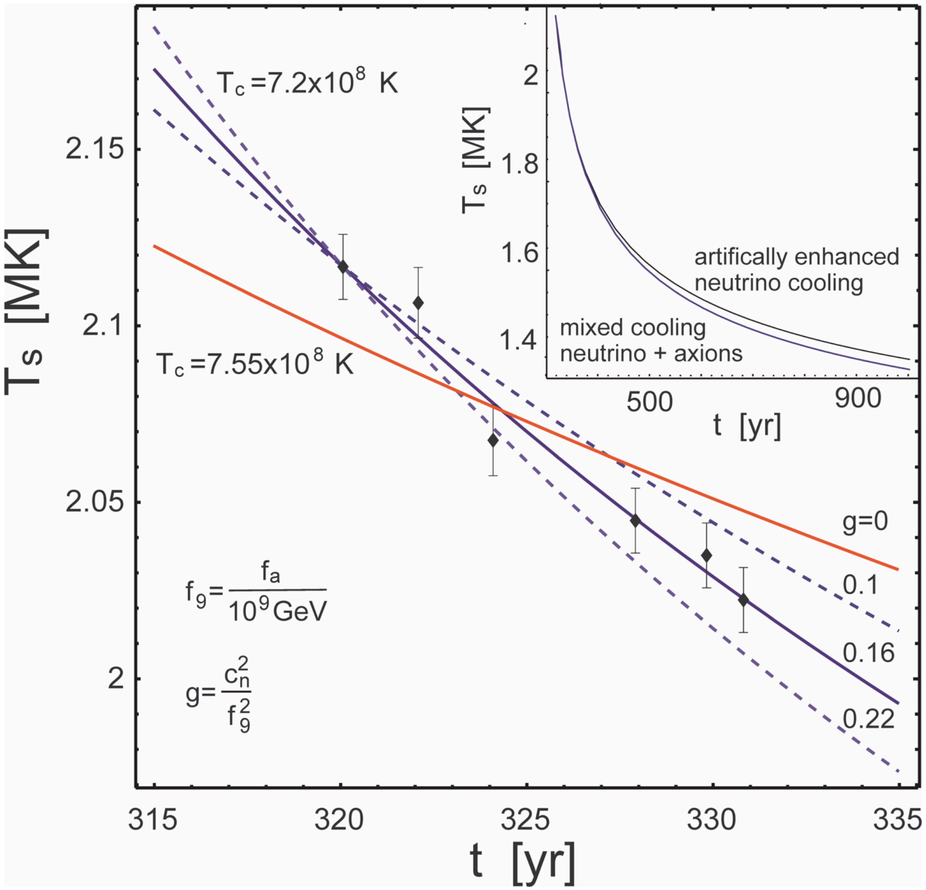


[Irastorza]

Searching for Axion/ALP Energy Losses of Stars

- Neutron star in Cas A:





[Leinson 14]

  - Measured surface temperature reveals unusually fast cooling rate
  - Hint on extra cooling by axion/ALP due to nucleon bremsstrahlung

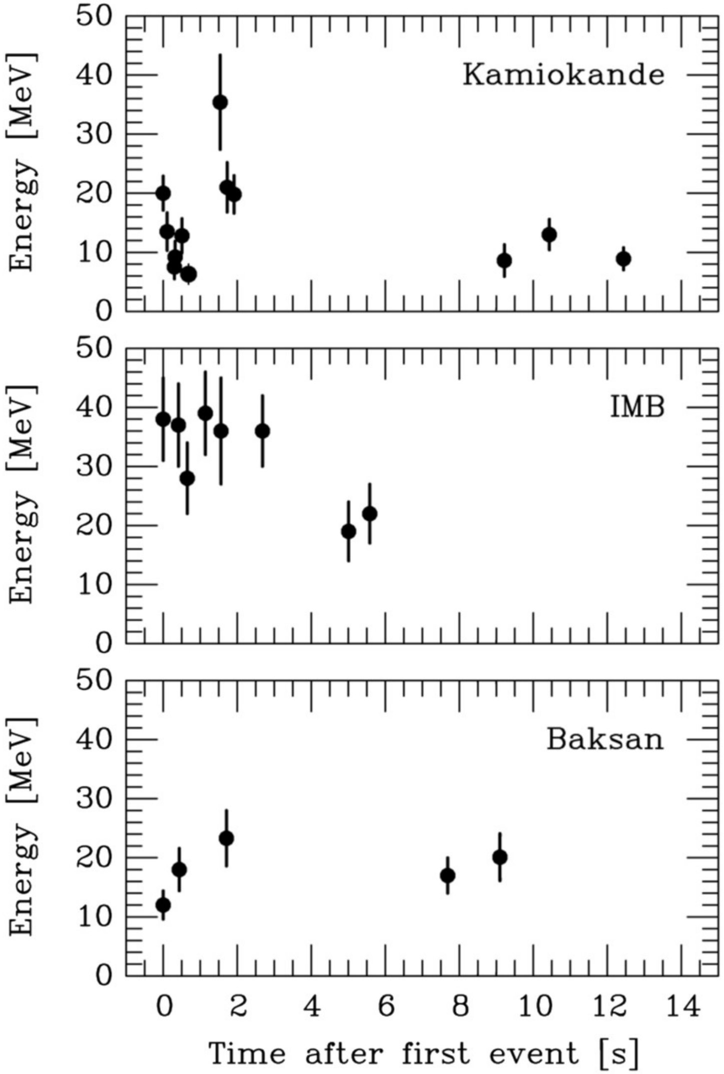
$$N + N \to N + N + a$$

  - Required coupling to neutron:

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

Searching for Axion/ALP Energy Losses of Stars

- SN 1987A:



[Raffelt]

  - Emission of axion/ALPs would take away energy from neutrino burst and shorten it

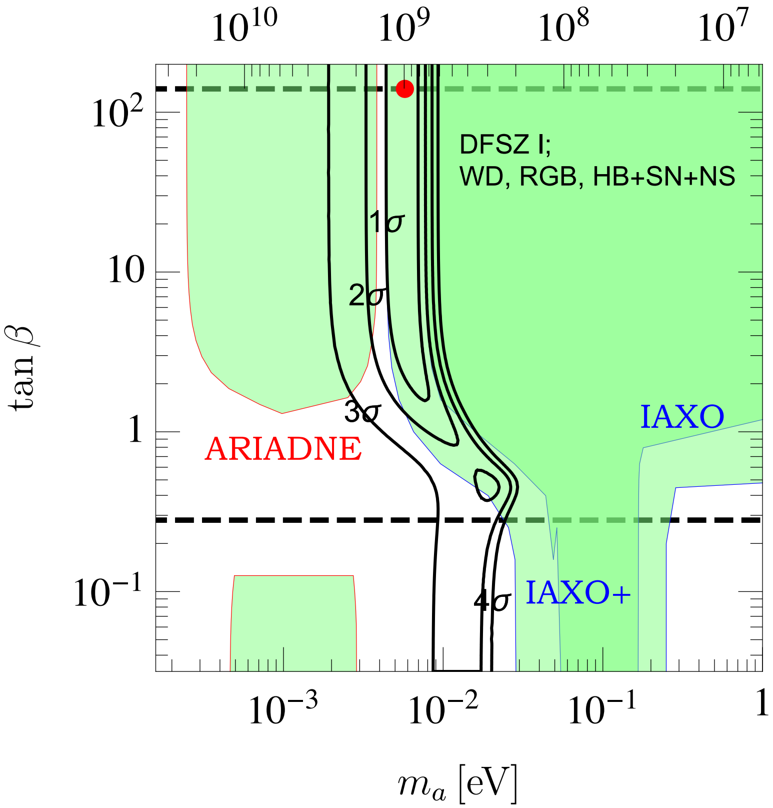
$$g_{ap}^2 + g_{an}^2 < 3.6 \times 10^{-19}$$

[Raffelt 08; Fischer et al. 16; Giannotti et al. (in prep.)]

  - Not very solid bound: sparse data and interaction difficult to model

Searching for Axion/ALP Energy Losses of Stars

- Excessive energy losses of HBs, RG, WDs, NS can be explained at one stroke by production of axion with coupling to photons, electrons, nucleons, e.g. for DFSZ axion model:



$$f_a = \frac{v_{\rm PQ}}{6},$$

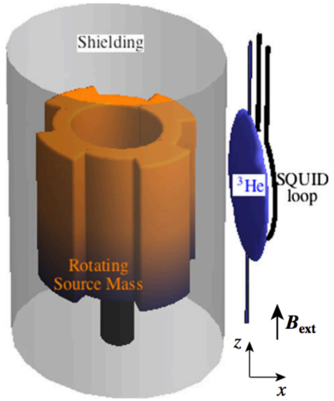
$$C_{ae}^{\rm DFSZ\ I} = \frac{1}{3}\sin^2\beta\,, \qquad C_{ae}^{\rm DFSZ\ II} = \frac{1}{3}(1-\sin^2\beta)$$

$$C_{a\gamma}^{\rm DFSZ\ I} = \frac{8}{3} - 1.92(4)\,, \qquad C_{a\gamma}^{\rm DFSZ\ II} = \frac{2}{3} - 1.92(4)\,,$$

$$C_{Ap} = -0.435\sin^2\beta + (-0.182\pm0.025)\ ,$$

$$C_{An} = 0.414\sin^2\beta + (-0.16\pm0.025)\ .$$

ARIADNE



[Giannotti,Irastorza,Redondo,AR,Saikawa 17]

Searching for Axion/ALP Energy Losses of Stars

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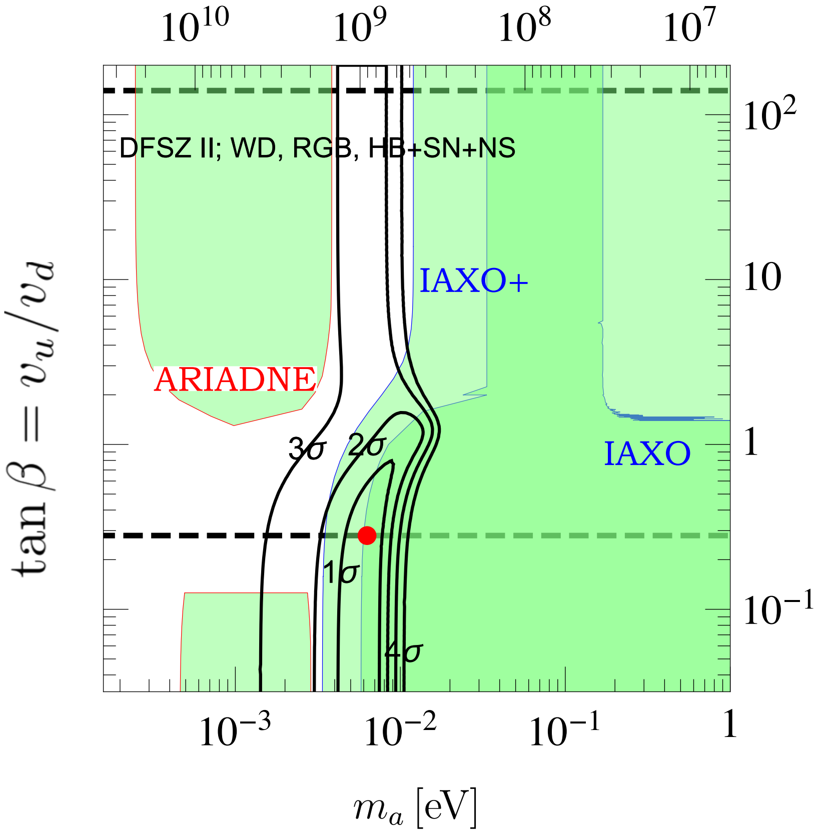

$$f_a = \frac{v_{PQ}}{6},$$

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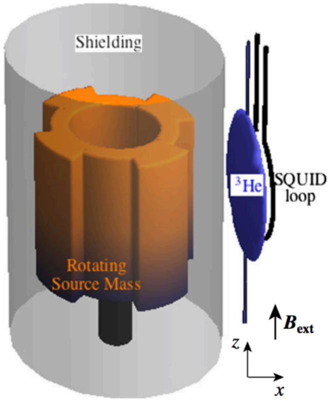
$$C_{a\gamma}^{\rm DFSZ\ I} = \frac{8}{3} - 1.92(4)\,, \qquad C_{a\gamma}^{\rm DFSZ\ II} = \frac{2}{3} - 1.92(4)\,,$$

$$C_{Ap} = -0.435\sin^2\beta + (-0.182 \pm 0.025)\ ,$$

$$C_{An} = 0.414\sin^2\beta + (-0.16 \pm 0.025)\ .$$

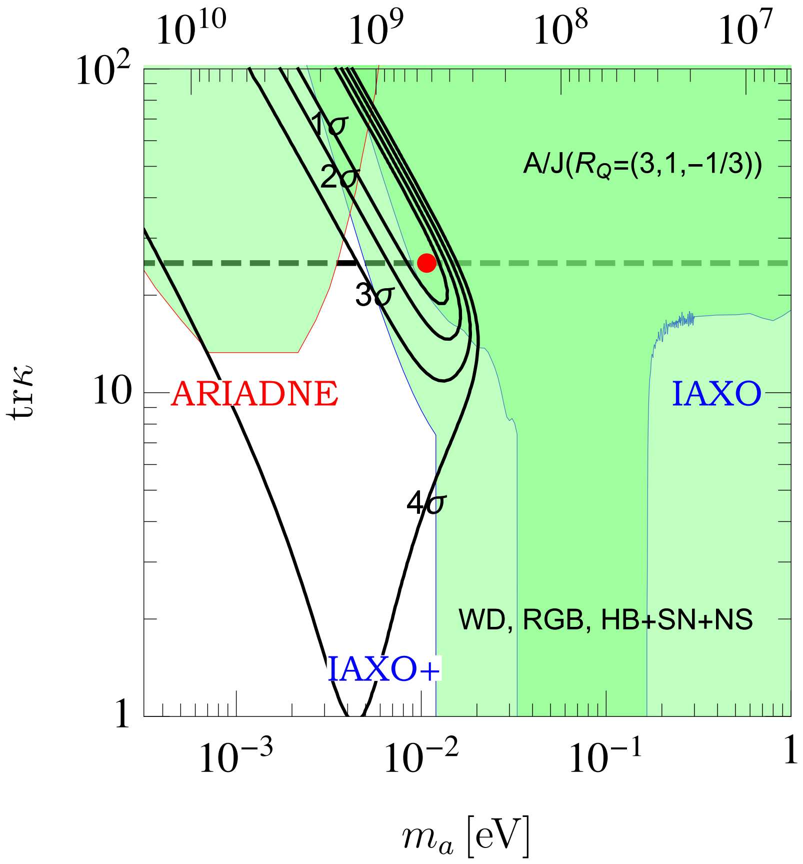
ARIADNE



[Giannotti,Irastorza,Redondo,AR,Saikawa 17]

Searching for Axion/ALP Energy Losses of Stars

- Excessive energy losses of HBs, RG, WDs, NS can be explained at one stroke by production of axion with coupling to photons, electrons, nucleons, e.g. for KSVZ axion/majoron model (as in SMASH):



$$\mathcal{L}_Y \supset -\overline{L}_i F_{ij} N_j H - \tfrac{1}{2}\overline{N}^c_i Y_{ij} N_j \sigma + \mathrm{h.c.}$$

$$C_{ae} \simeq \frac{1}{8\pi^2 N}\left(\kappa_{ee} - \frac{1}{2}\,\mathrm{tr}\kappa\right)$$

$$C_{aq} \simeq \frac{1}{8\pi^2 N} T_3^q\,\mathrm{tr}\kappa$$

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

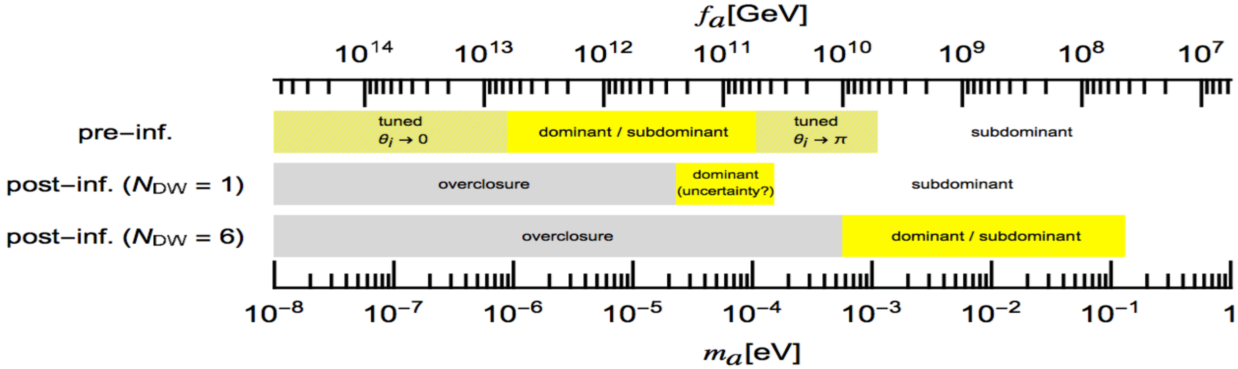
[Giannotti,Irastorza,Redondo,AR,Saikawa 17]

Searching for Axion/ALP Energy Losses of Stars

- meV mass DFSZ axion or KSVZ axion/majoron could at the same time explain stellar energy losses and dark matter!

Model	N_{DW}	Global fit includes	$f_a[10^8\,\mathrm{GeV}]$	$m_a[\mathrm{meV}]$	$\lvert g\rvert$	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	$(0.12\text{–}1.1) \times 10^{-7}$	$(0.32\text{–}2.9) \times 10^{-2}$
KSVZ A/J $R_Q = (3, 1, -\frac{1}{3})$	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
	6		0.86	66	$(0.17\text{–}7.1) \times 10^{-1}$	0.93–1.5
	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,AR,Saikawa 17]



- Direct axion dark matter detection in this mass range challenging!

Summary

- Axion/ALPs may explain puzzles from astrophysics and cosmology:
  - Dark matter
  - Stellar energy losses
- Relevant parameter range will be probed decisively by next generation experiments
- Stay tuned!