The many physics cases for axions

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Abridged story of the axion

- QCD before 1975: U(1) problem: why the η' does not behave as a 9th NGB ?
- Instantons (Belavin et al. '75), Yang-Mills vacuum periodicity (Callan et al. '76; Jackiw et al. '76).

=> Non-trivial vacuum + U(1) axial anomaly -> no conserved axial current -> no NGB

- New problem: $\mathcal{L}_{QCD}$ -> $\mathcal{L}_{QCD}$ + $\theta \frac{\alpha_s}{8\pi} G^{\mu\nu}_a \tilde{G}^a_{\mu\nu}$ brings in QCD P,T violation, and thus CP violation, intolerable (nEDM) unless $\theta < 10^{-10}$ [no anthropic expl.]
- PQ solution ('77): $\theta \to \theta(x)$; $V(\theta)$ s.t. $\langle\theta\rangle = 0$. It also predicts a $m \approx 0$ scalar: the NGB of a spontaneously broken global and QCD-anomalous $U(1)_{PQ}$: the Axion
- Unexpectedly, the axion has also the right properties to account for the DM !
- Axions physics still holds out a certain number of crucial open issues. Their solution might shed light on other unsolved problems of the SM

- Axion physics is replete with interconnections between particle physics, astrophysics, cosmology, & forefront detection technologies. This drives the axion hypothesis within the reach of experimental verification

The strong CP problem

- QCD is defined in terms of two parameters which are not predicted by the theory. Measurements yield:

$\alpha_s \sim O(1)$ [$\Lambda_{QCD} \sim 200$ MeV] and $\bar{\theta} < 10^{-10}$

$$\mathcal{L}_{\rm QCD} = \bar{q}\left(i\not{D} - m_q e^{i\theta_q}\right) q - \frac{1}{4} G_a^{\mu\nu} G^a_{\mu\nu} - \theta \frac{\alpha_s}{8\pi} G_a^{\mu\nu} \tilde{G}^a_{\mu\nu}$$

- The difference $\bar{\theta} = \theta - \theta_q$ gives the amount CP viol. in QCD

$q \to e^{i\gamma_5 \alpha} q$ → $\theta_q \to \theta_q + 2\alpha$ and $\theta \to \theta + 2\alpha$

- Change in θ is given by the change of the path integral measure:

$$\mathcal{D}q\mathcal{D}\bar{q} \to \exp\left(-i\alpha \int d^4x \, \frac{\alpha_s}{4\pi} G_a^{\mu\nu} \tilde{G}^a_{\mu\nu}\right) \mathcal{D}q\mathcal{D}\bar{q}$$

[Fujikawa (1979)]

A small value problem

- $\bar{\theta} \neq 0$ implies a non-zero neutron EDM [Baluni (1979), Crewther et al. (1979)]

$$d_n \approx \frac{e\,|\bar{\theta}|\,m_\pi^2}{m_n^3} \approx 10^{-16}\,|\bar{\theta}|\,e\,\mathrm{cm}$$

- However, $d_n \lesssim 3 \cdot 10^{-26} e\,\mathrm{cm}$ implying: → $\bar{\theta} \lesssim 10^{-10}$

- This is qualitatively different from other small values problems:
  - In the SM $\bar{\theta}$ receives the first finite Log corrections at $O(\alpha^2)$ [Ellis, Gaillard (1979)]

    Unlike m_H^2 that is quadratically sensitive to Λ^2_{UV}

  - Unlike $y_{e,u,d} \sim 10^{-6} \div 10^{-5}$ it evades explanations based on environmental selection [Ubaldi, 0811.1599]

Three types of solutions

- A massless quark. One exact chiral symmetry: $\overline{\theta} \to 0$
  - From lattice: $m_u \neq 0$ by more than 20 σ

[Aoki (2013)]
[Manhoar & Sachrajda, PDG(2014)]

- CP symmetry + Spontaneous CP violation [Barr (1984), Nelson (1984)]
  - Set $\overline{\theta}$ = 0 by imposing CP. Need to break spont. for CKM (+BAU)
  - High degree of fine tuning, or elaborated constructions to keep $\overline{\theta} < 10^{-10}$ at all orders. No unambiguous exp. signatures.

- The axion (or Peccei-Quinn) solution

[Peccei, Quinn (1977),
Weinberg (1978), Wilczek (1978)]

Basic ingredient of the axion solution

$$\underbrace{\frac{\alpha_s}{8\pi}\left(\frac{a(x)}{f_a}+\bar{\theta}\right)}_{a\,\to\,a\,+\,\text{const.}}G\tilde{G}+\underbrace{\mathscr{L}\left(\partial_\mu a(x),\psi,\varphi,A_\mu\right)}_{\partial_\mu a\,\to\,\partial_\mu a}+\underbrace{\left[\delta\mathscr{L}_{\text{eff}}(a(x),\ldots)\right]}_{\text{Tolerable if }\Lambda_{\text{eff}}\sim m_P\,\&\,d\geq 10}$$

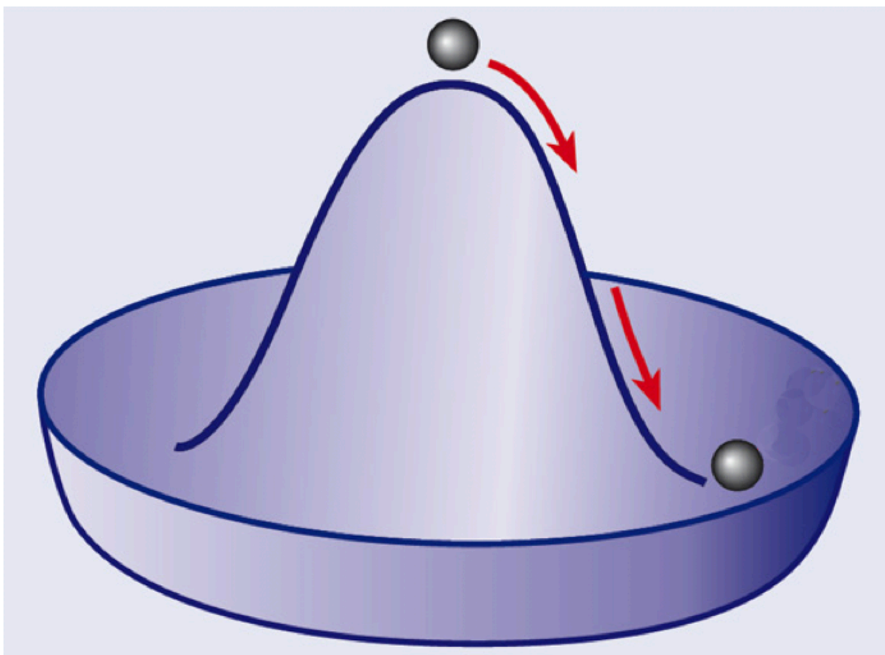
1. $\bar{\theta}$ is removed via a shift of the axion field $a \to a - \bar{\theta} f_a$

2. Minimum of the vacuum energy for $\langle a(x)\rangle \to 0$

[Vafa-Witten, Phys. Rev. Lett. **53** (6) 535]

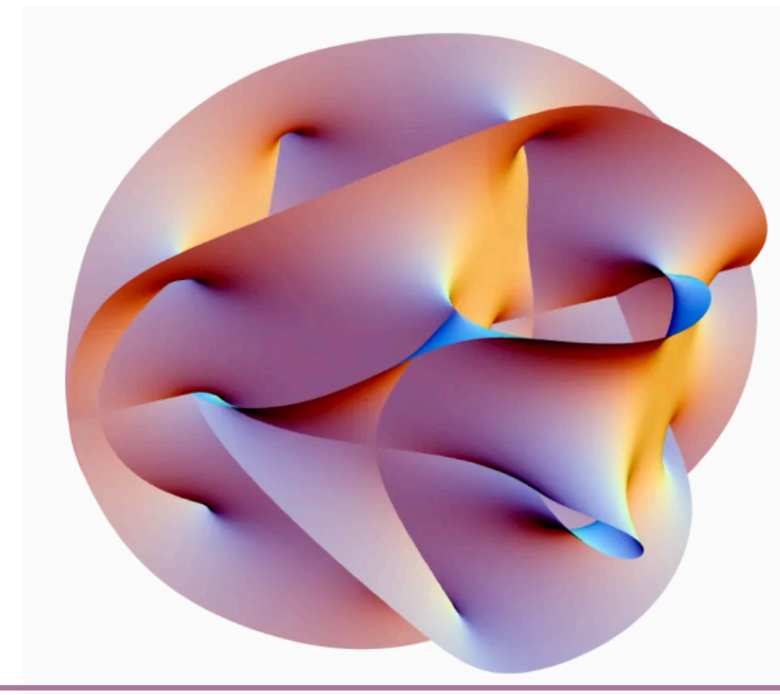
Two elegant realizations

The "QFT axion"



The axion is the NGB of a global U(1) symmetry, endowed with a QCD anomaly and broken spontaneously

The "superstring axion" (or "extra dim. axion")



The axion corresponds to gauge field components of extra dimensional theories

$M_D \rightarrow M_4 \times V_{D-4}$

$B_{[MN]} \rightarrow B_{[\mu\nu]} + B_{[ij]}$ [see next talk]

Basic ingredients of the QFT axion solution

[Peccei, Quinn (1977), Weinberg (1978), Wilczek (1978)]

- A scalar potential invariant under a **global** U(1): $\Phi \to e^{i\xi}\,\Phi$, $\delta\mathcal{L}(\Phi) = 0$
- U(1) **SSB**: $\Phi \to v_a\, e^{ia(x)/v_a}$. Shift symmetry $a(x) \to a(x) + \xi v_a$, $\delta\mathcal{L}(a) = 0$
- Couplings between the scalars and some quarks $\bar{Q}_L\, \Phi\, q_R \to \bar{Q}_L\, v_a\, q_R\, e^{ia(x)/v_a}$

  U(1) is then enforced by <u>identifying</u> chiral PQ charges $X(Q) - X(q) = X(\Phi)$
- The symmetry must have a mixed $U(1)\text{-}SU(3)_c^2$ anomaly: $\Sigma_q(X_Q - X_q) \neq 0$

By redefining the quark fields in the basis of real masses $\bar{Q}_L v_a\, q_R$:

$$(a(x)/v_a)G\tilde{G} \quad \to \quad (a(x)/v_a + \Theta)\, G\tilde{G} \quad \to \quad (a(x)/v_a)\, G\tilde{G}$$

Instanton related non-perturbative QCD effects generate a potential

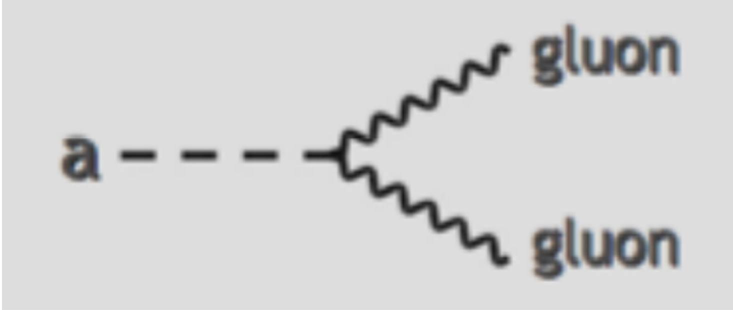
$V_{QCD}(a) = -(m_\pi\, f_\pi)^2 \cos(a/v_a)$ that drives $\langle a/v_a\rangle \to 0$ at the minimum

Axion couplings to matter & radiation

"Defining interaction"

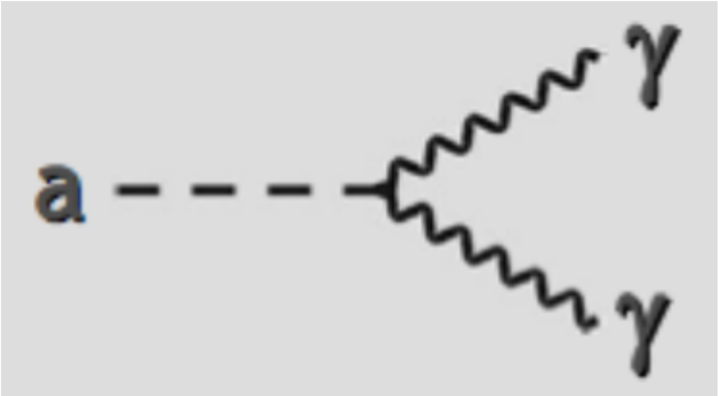
axion-gluon coupling ($f_a = v_a/N$)

$$\frac{\alpha_s}{8\pi f_a} a G\tilde{G}$$



Axion-photon coupling (EM anomaly + mixing with π^0)

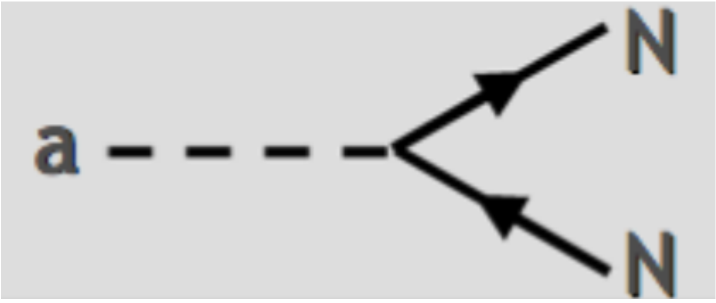
$$\frac{\alpha}{8\pi f_a}\left(\frac{E}{N} - 1.92\right) a F\tilde{F}$$



Axion-nucleon coupling:

$C_{aN} = C^0(X_{u,d}) + \Delta(m_{u,d})$

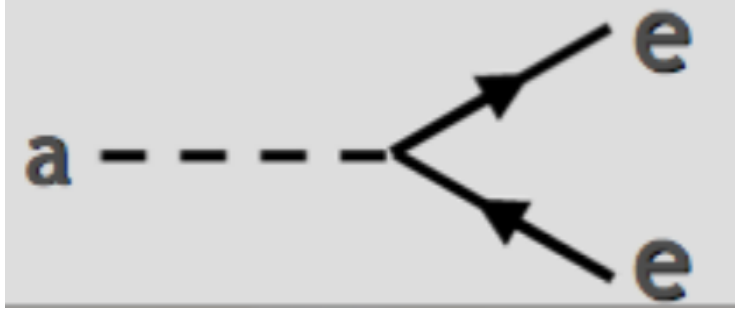
$$\frac{C_{aN}}{2f_a} \partial^\mu a \bar{N}\gamma_\mu\gamma_5 N$$



Axion-electron coupling:

$C_{ae} = C^0(X_e) + \delta_e^{loop}$

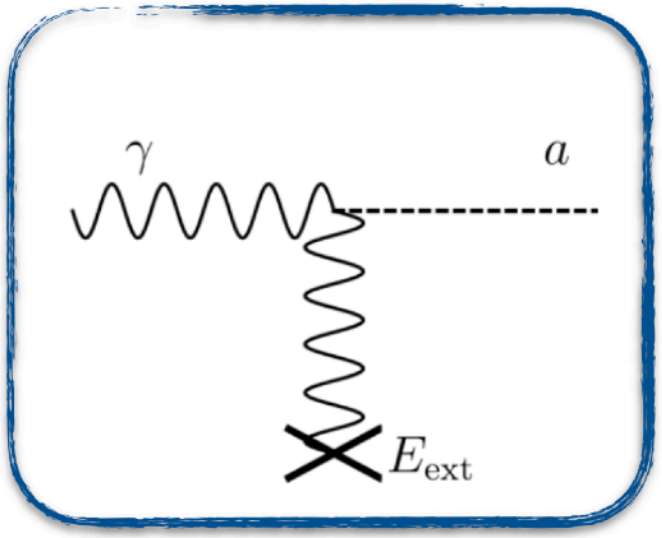
$$\frac{C_{ae}}{2f_a} \partial^\mu a \bar{e}\gamma_\mu\gamma_5 e$$



$X_{u,d,e}$: PQ charges (model dependent parameters.)

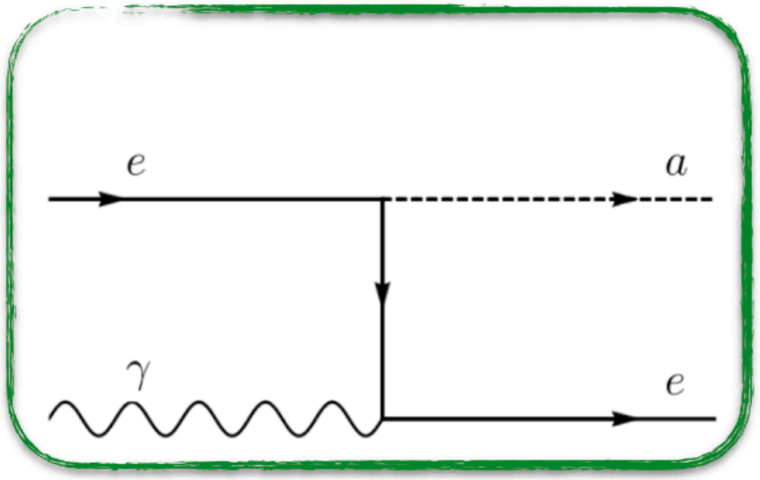
Astrophysics: Axion production processes

Energy released from a hot/dense plasma



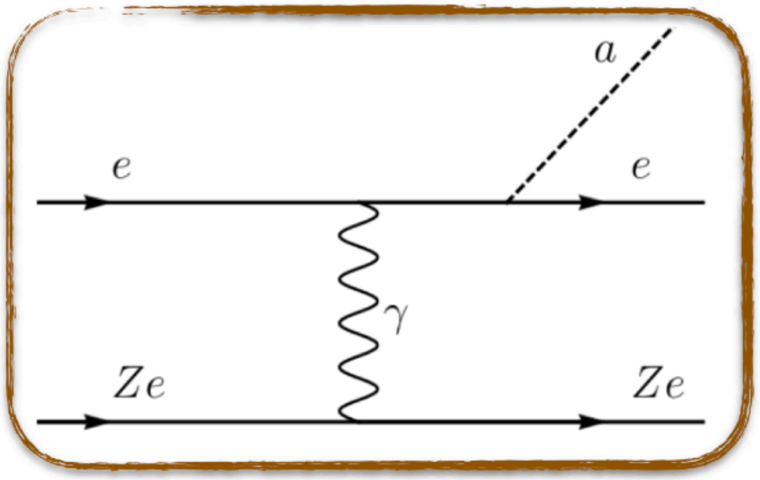
Primakoff

$$\varepsilon_P \propto \left(\frac{g_{a\gamma}}{\text{GeV}^{-1}}\right)^2 \frac{T^7}{\rho} \,\text{erg}\,\text{g}^{-1}\,\text{s}^{-1}$$



Compton

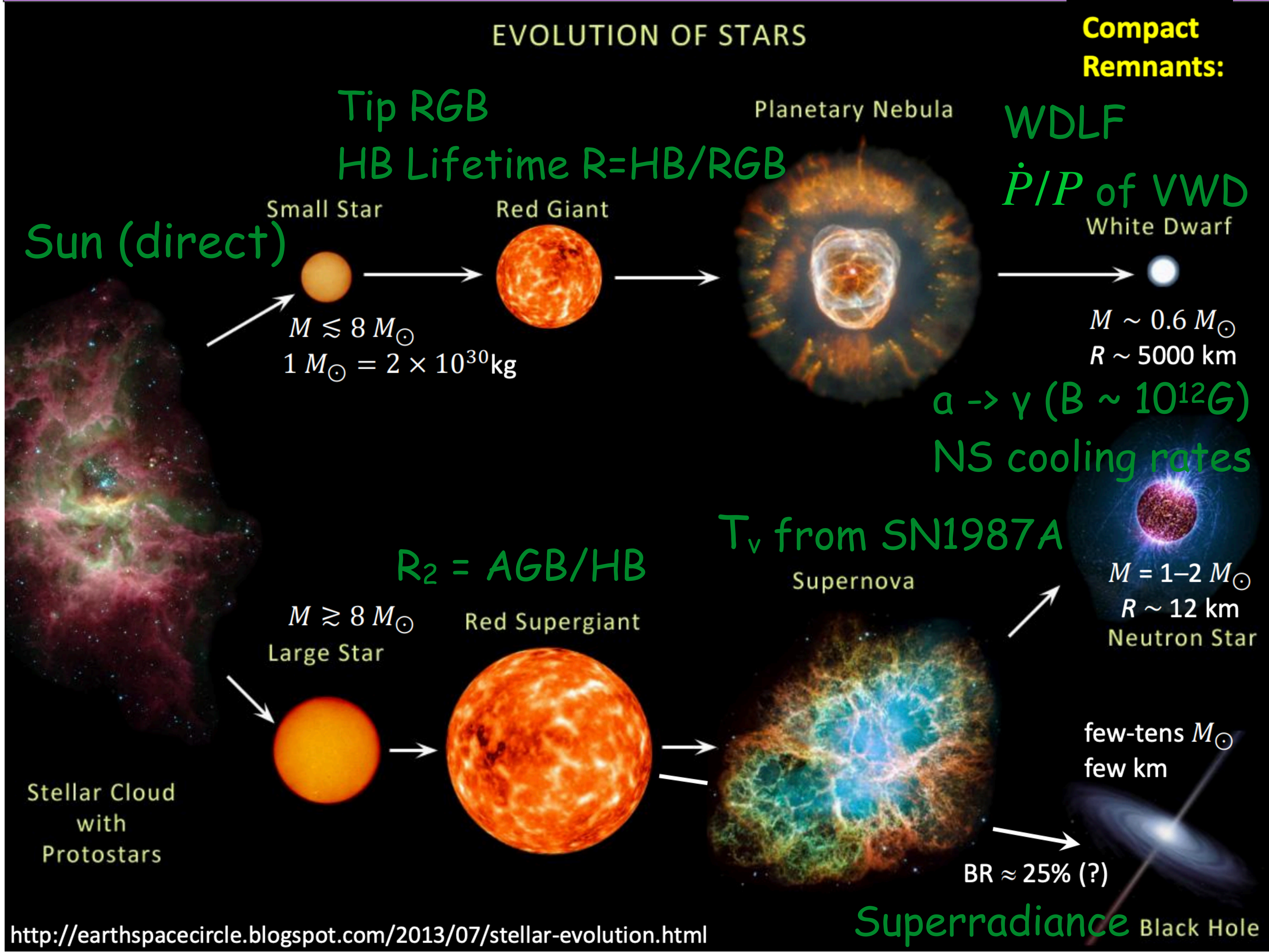
$$\varepsilon_C \propto g_{ae}^2 \left(\frac{n_e^{\text{eff}}}{n_e}\right) T^6 \,\text{erg}\,\text{g}^{-1}\,\text{s}^{-1}$$



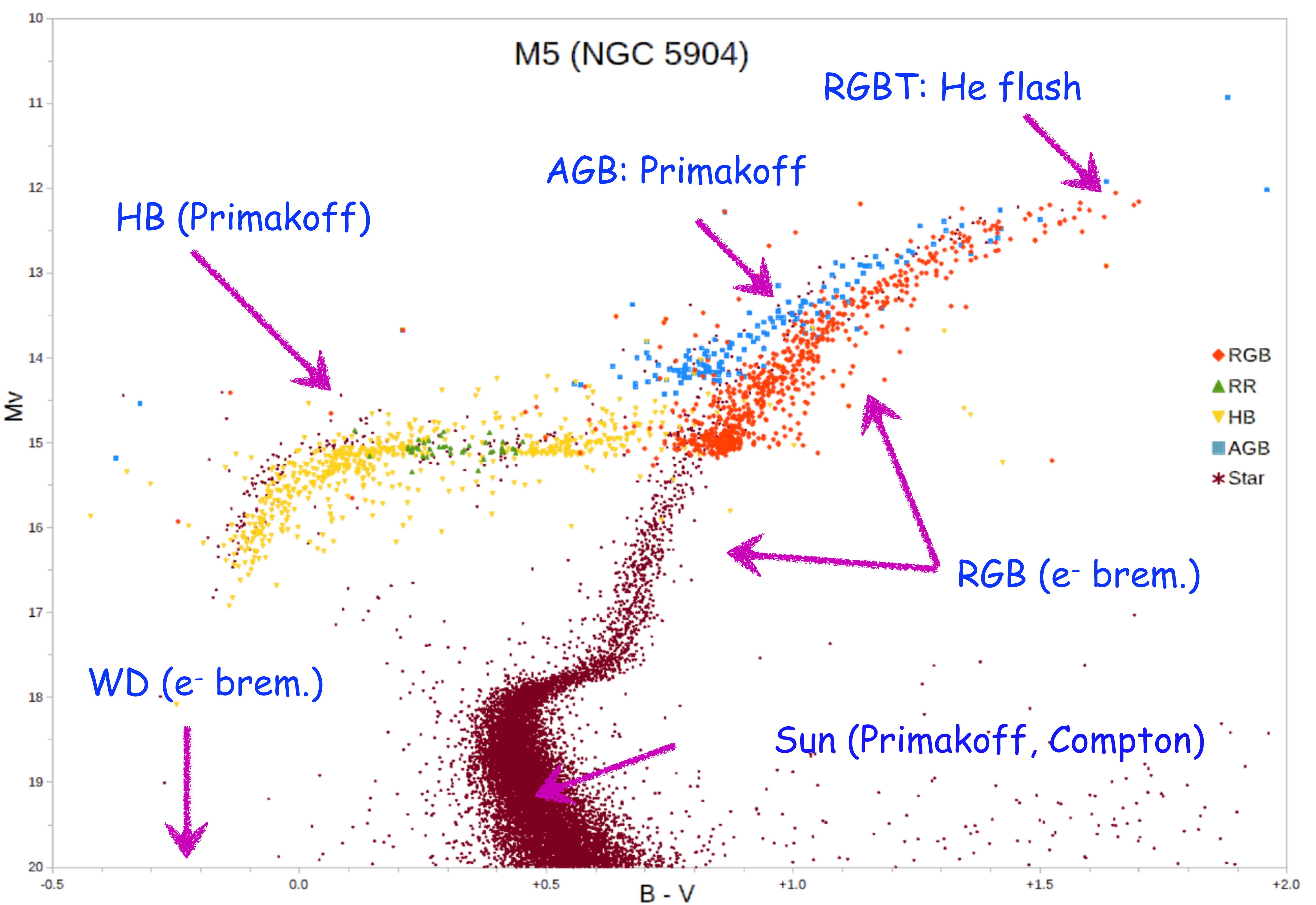
Bremsstrahlung

$$\varepsilon_B \propto g_{ae}^2 \left(\sum \frac{X_j Z_j^2}{A_j}\right) T^4 \,\text{erg}\,\text{g}^{-1}\,\text{s}^{-1}$$

Axion emission affects star evolution



Stellar evolution vs. axion extra cooling



Color-magnitude diagram for globular cluster M5

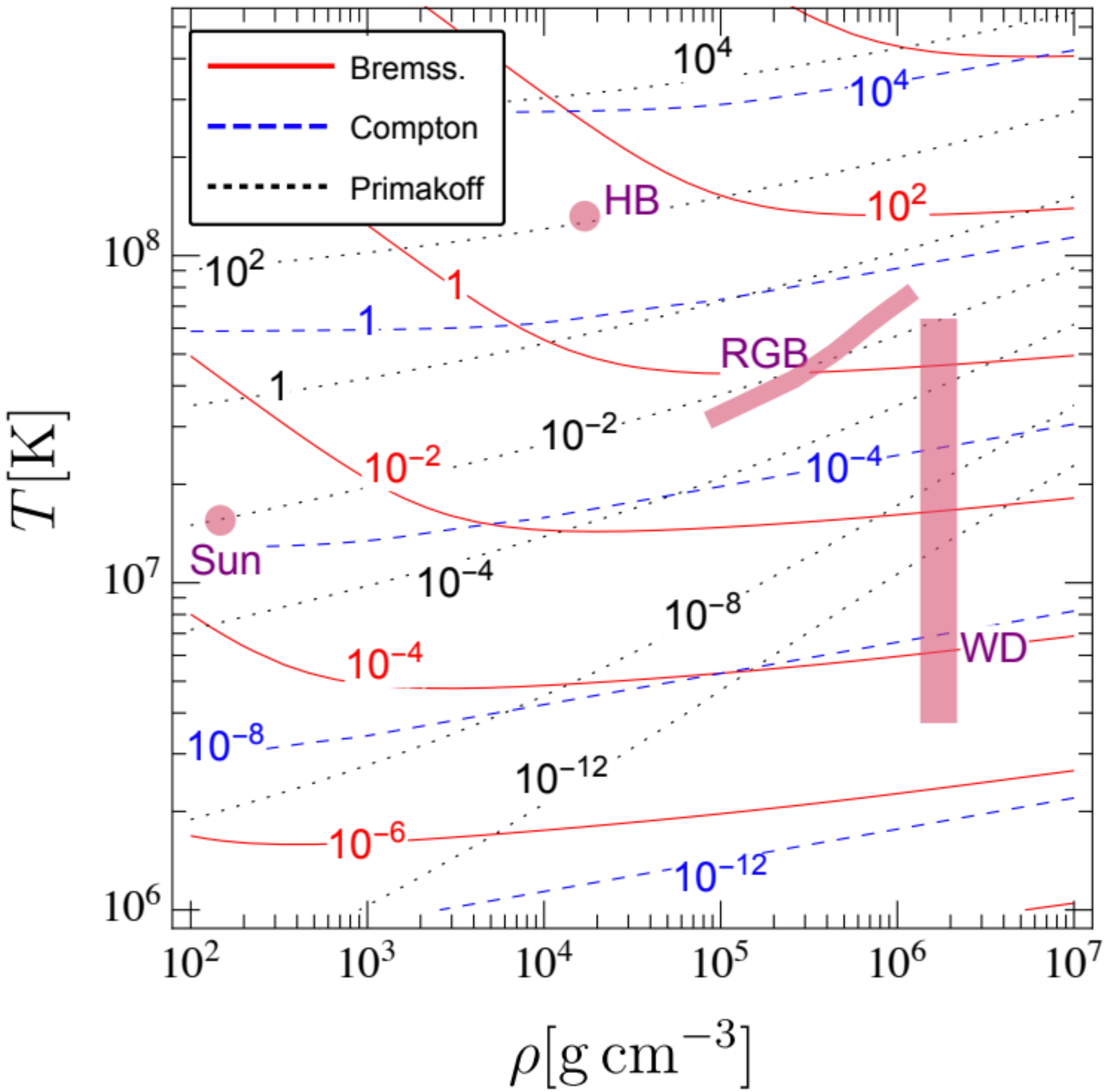


Figure 6: Contours of the axion energy-loss rates per unit mass, ε_a, in $\mathrm{erg\,g^{-1}s^{-1}}$, for a pure He plasma. Different lines represent different channels, as shown in the legend. The Primakoff process is calculated for $g_{a\gamma} = 0.65 \times 10^{-10}\mathrm{GeV}^{-1}$, corresponding to the bound from HB stars [386, 387]. The Bremsstrahlung and Compton processes are calculated for $g_{ae} = 4.3 \times 10^{-13}$, corresponding to the RGB bound from M5 [307]. The onset of the degeneracy region is visible in the bending of the bremsstrahlung contours. The central temperature and density of the Sun [388], RGB stars, HB stars and WDs are also shown, for reference. In the case of HB and RGB, these are the results of a numerical simulation of a 0.8 $M_\odot$ model as obtained with the FuNS code [389]. The WD region is estimated using a polytropic model of WDs with mass from 0.6 to $0.7M_\odot$, as discussed in Ref. [383], and spans luminosities in the range between 0.5×10^{-4} and $0.5L_\odot$. Except for the WD case, the thickness of the lines has no significance.

Hints for extra energy loss in stars

M. J. Dolan, F. J. Hiskens and R. R. Volkas [arXiv:2207.03102]

$g_{a\gamma} > 0.10 \times 10^{-10}$ GeV^{-1} $g_{a\gamma} < 0.45 \times 10^{-10}$ GeV^{-1}

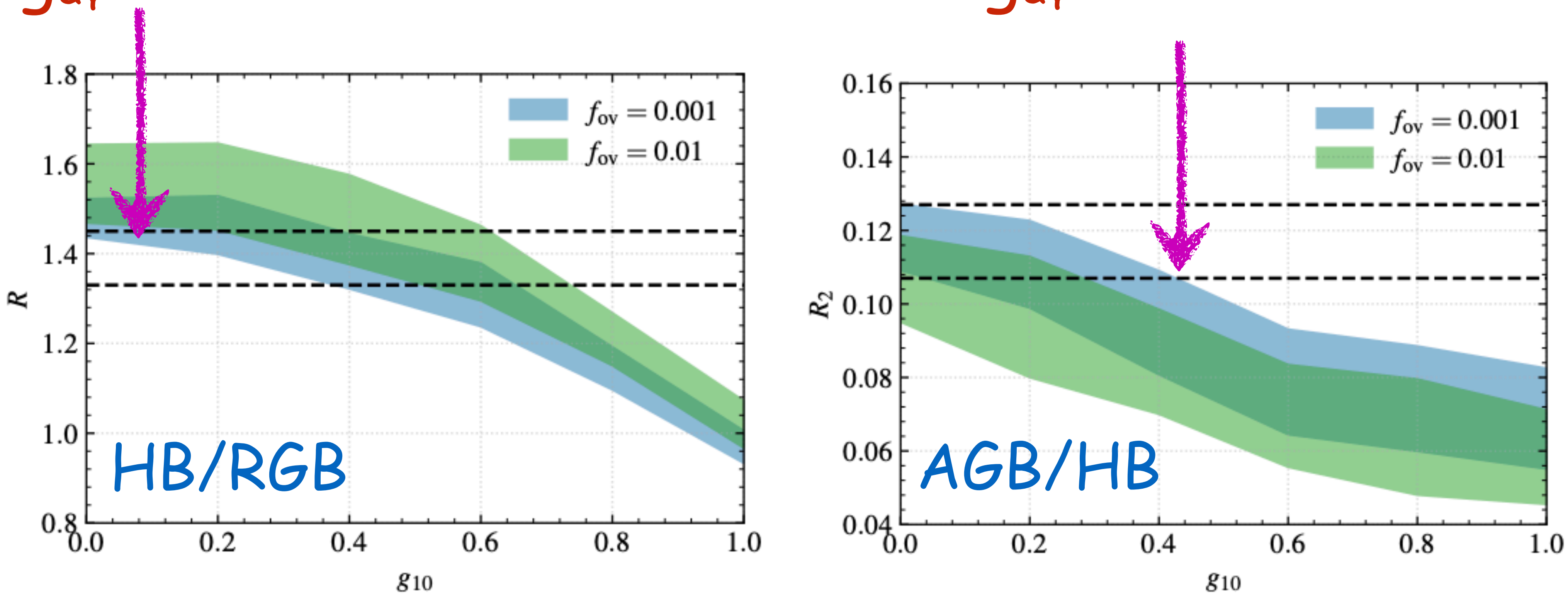
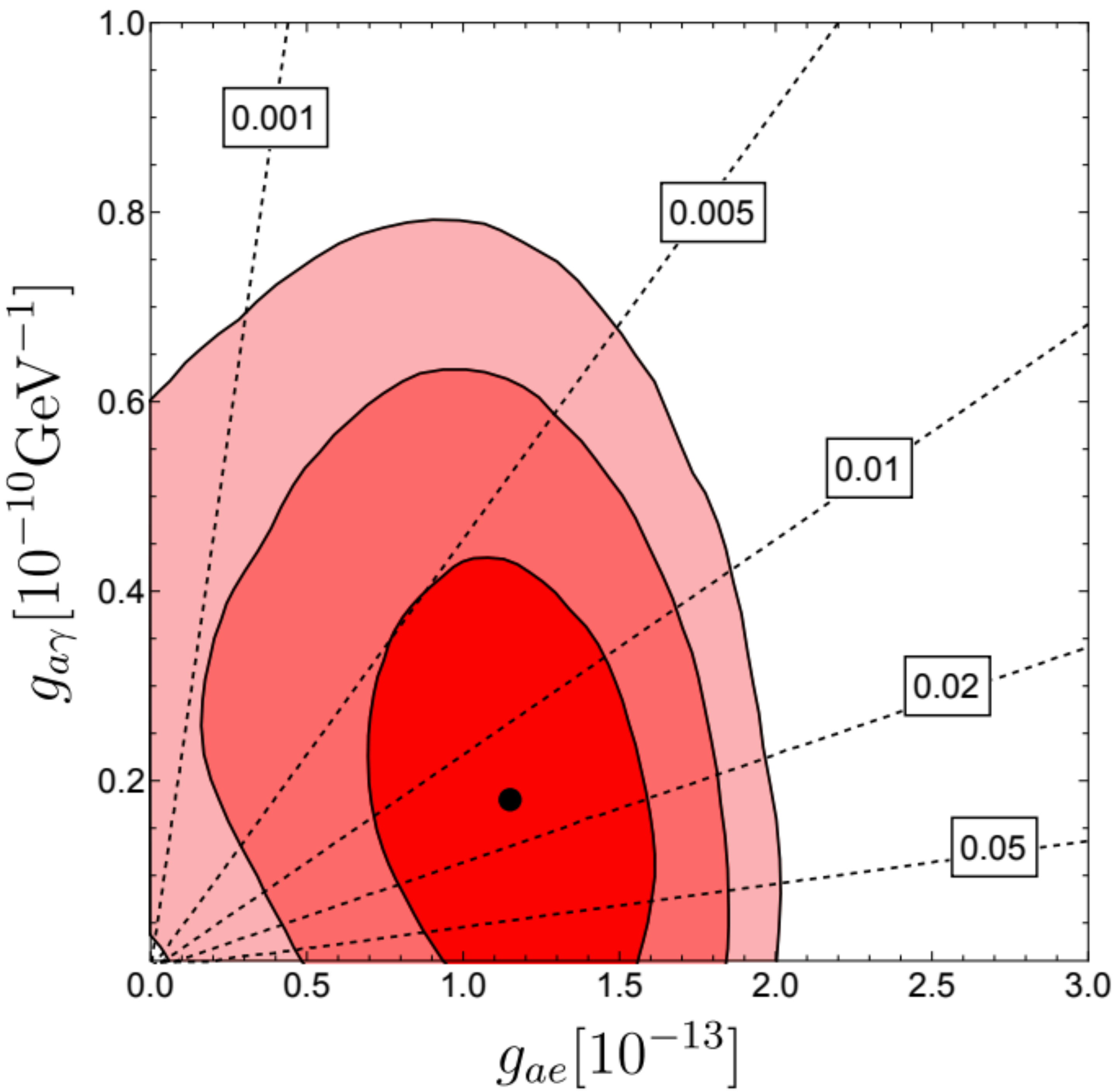


Figure 2. (Left panel): Predicted values of R as a function of g_{10} given standard convective core overshoot with $f_{ov} = 0.001$ (blue) and $f_{ov} = 0.01$ (green). The observed limit on R is indicated by the region between the dashed black lines (95% C.I.). (Right panel): The full range of R_2 values predicted as functions of g_{10} given standard overshoot with $f_{ov} = 0.001$ (blue) and $f_{ov} = 0.01$ (green). The observed limit is again shown by the dashed black lines.

High statistics GAIA data will allow to improve this situation

Hints for extra energy loss in stars



Model indep. global fit to TRGB, HB, WDLF, WDV
(g_{ae} $g_{a\gamma}$ assumed uncorrelated)

$$g_{a\gamma} = \frac{\alpha}{2\pi}\frac{C_{a\gamma}}{f_a} \qquad g_{af} = C_{af}\frac{m_f}{f_a}$$

Iso-lines for the ratio $C_{ae}/C_{a\gamma}$

SM: $g_{ae} = g_{a\gamma} = 0$
disfavoured at 3σ
[arXiv:2109.10368]

Preferred couplings: $g_{a\gamma} \sim 10^{-11}\,\mathrm{GeV}^{-1}$, $g_{ae} \sim 10^{-13}$, $g_{aN} \lesssim 10^{-9}$

June 2020: a signal of solar axions ?

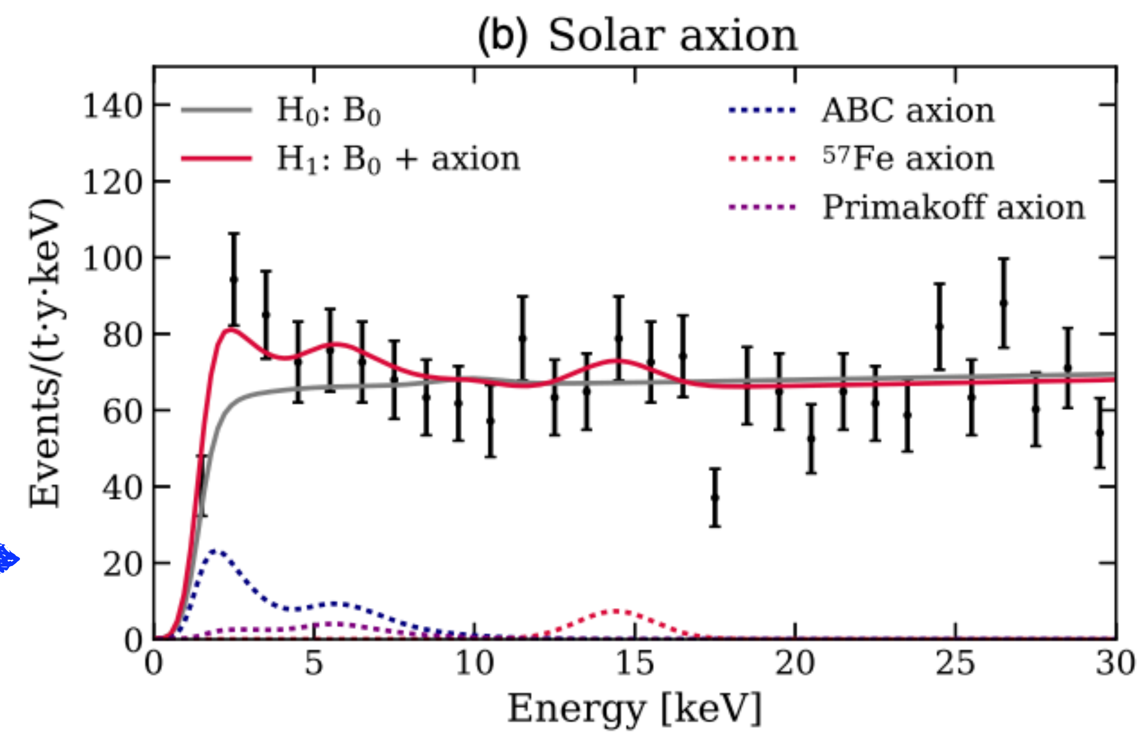
XENON1T (WIMP DM detector)

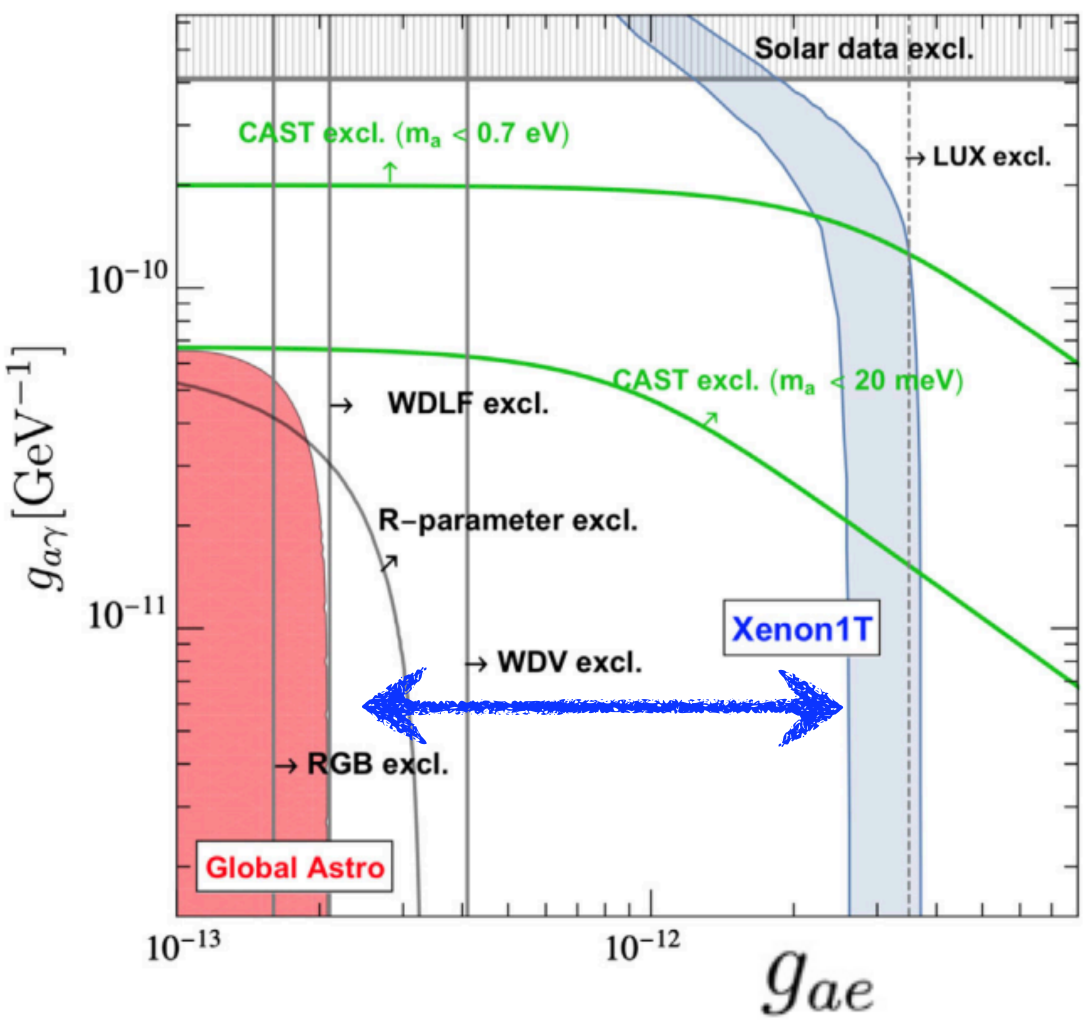
Excess electronic recoil events in XENON1T

PRD 102, 072004 (2020)

(Not confirmed by XENONnT [PRL 129 (2022) 16, 161805])

Detection via axioelectric effect (g_{ae})





However, confronting astrophysics:

Solar Axions Cannot Explain the XENON1T Excess

Di Luzio, Fedele, Giannotti, Mescia, EN, PRL 125, 131804 (2020)

Values of $g_{ae} \gtrsim 10^{-12}$ as required to account for the XENON1T excess would unavoidably turn other stars into bright "axion light-houses"

Axions in Cosmology

Axion cosmology involves and exceedingly large number of different topics:

- Thermal production and axion contribution to radiation (N_{eff})

  ($T \gg \Lambda_{QCD}$): $g\, q \leftrightarrow a\, q$, $g\, g \leftrightarrow a\, g$ $\langle \sigma v \rangle \sim \alpha_s^3\, T^3/f_a^2$

  ($T < \Lambda_{QCD}$): $\pi\, \pi \leftrightarrow \pi\, a$ $\langle \sigma v \rangle \sim \ldots ?$ (~~ChiPT~~)

- Production via misalignment (pre/post inflation scenarios)

- Isocurvature fluctuations (pre-inflation)

- Cosmic strings and walls contributions (post-inflation)

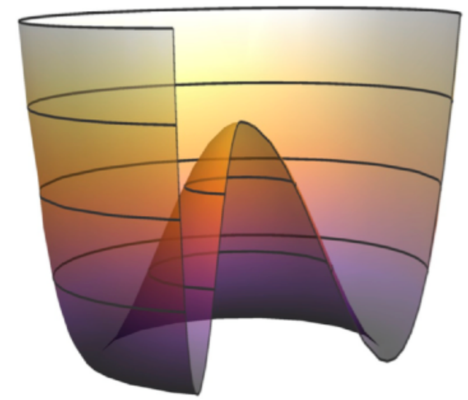
- Axion miniclusters

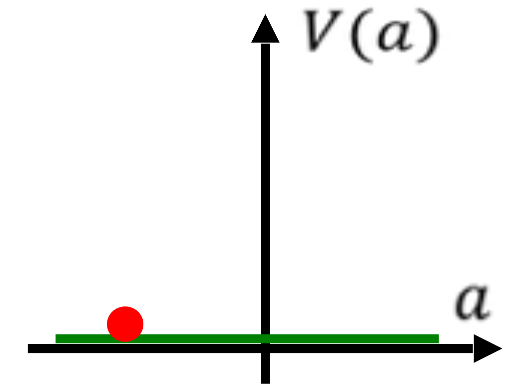
Axion CDM from misalignment

- **As long as $\Lambda_{QCD} < T < f_a$:**

  $U(1)_{PQ}$ broken only spontaneously,

  $m_a = 0$, $\langle a_0 \rangle = \theta_0 f_a \sim f_a$



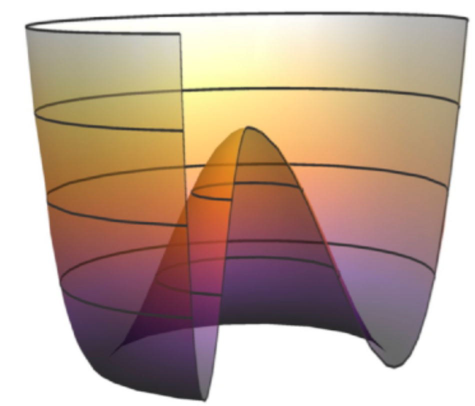


- **As soon as $T \sim \Lambda_{QCD}$:**

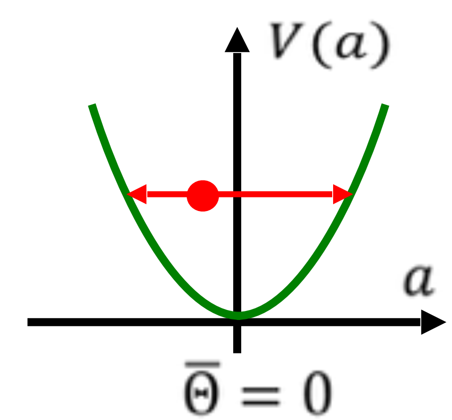
  $U(1)_{PQ}$ explicit breaking (instanton effects)

  $m_a(T)$ turns on. When $m_a^2(T) > 3H \sim 10^{-9}$ eV,

  $\langle a_0 \rangle \longrightarrow 0$ and it starts oscillating undamped



$$\ddot{a} + 3H\dot{a} + m_a^2(T) f_a \sin\left(\frac{a}{f_a}\right) = 0$$

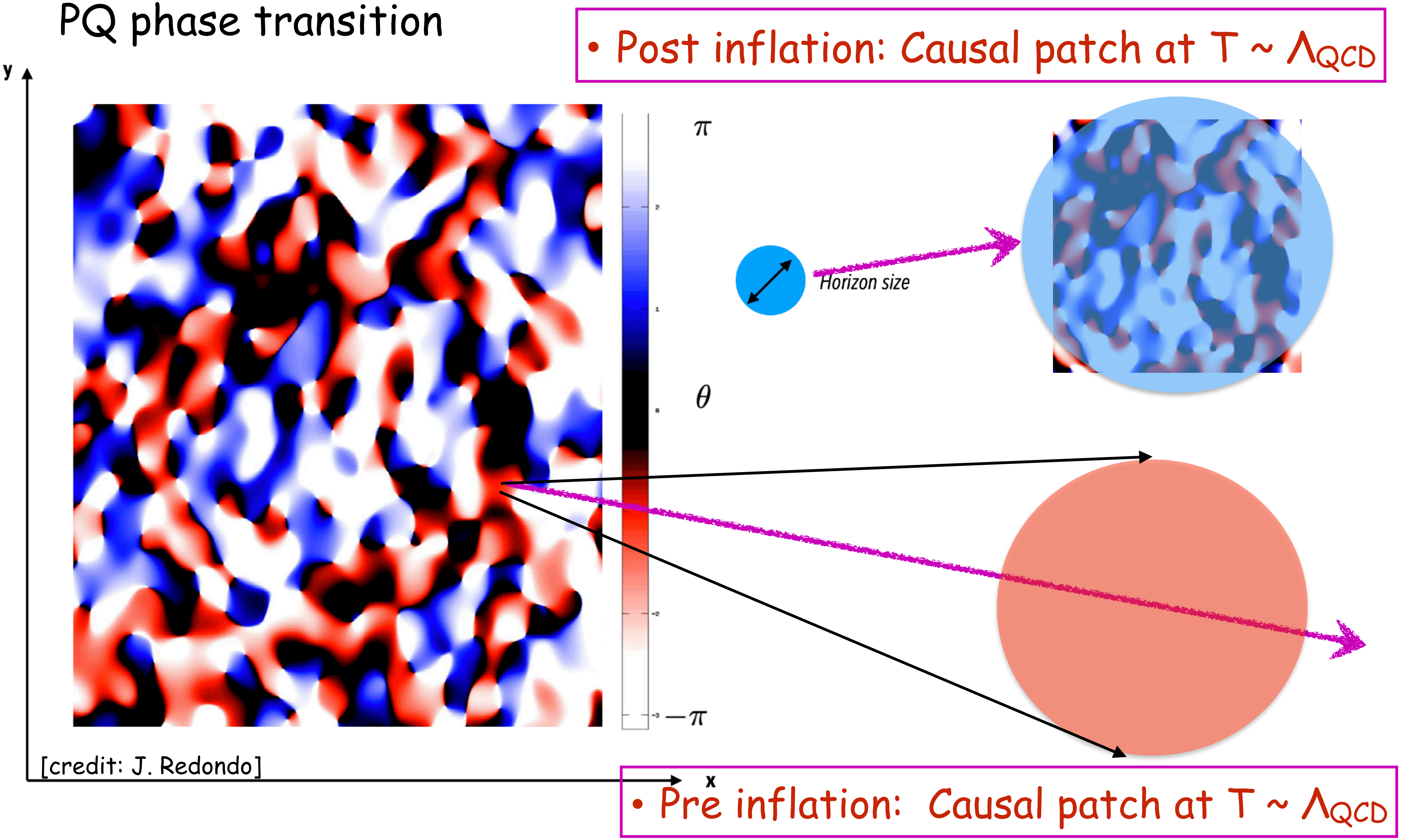


- **Energy stored in oscillations behaves as CDM**

[Preskill, Wise, Wilczek (1983), Abott, Sikivie (1983), Dine, Fischler (1983)]

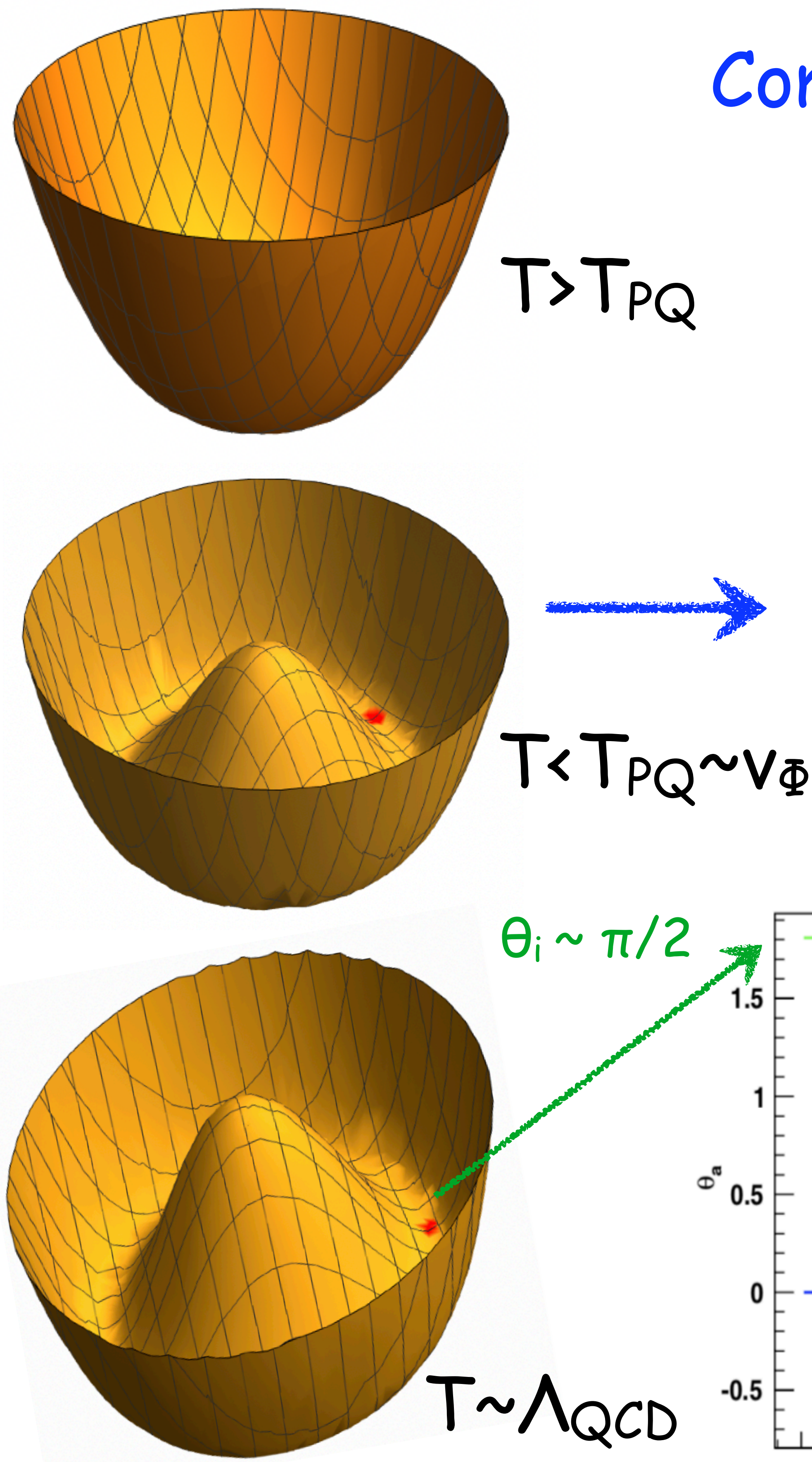
Initial condition: Pre/Post inflation scenarios

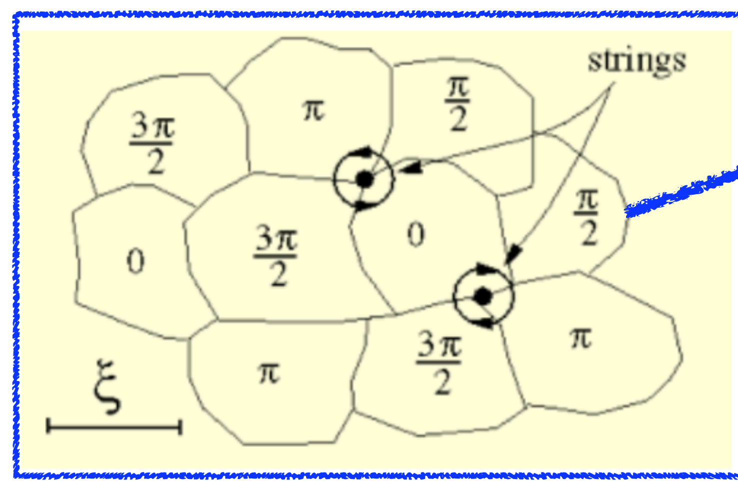
Slice of the universe after PQ phase transition

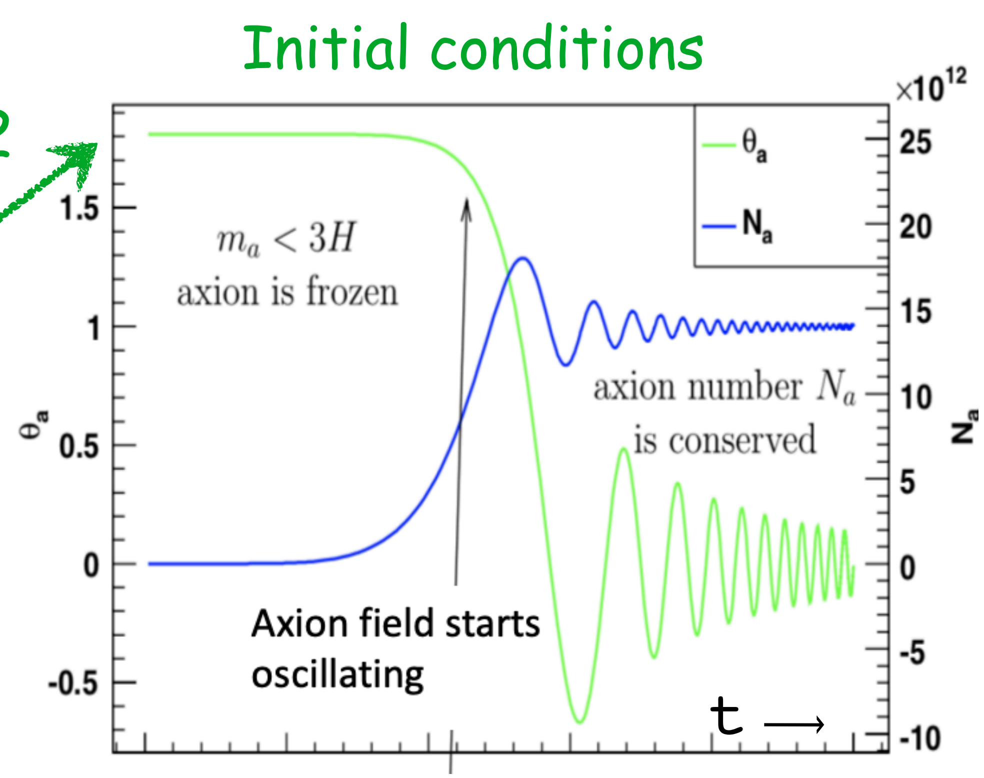


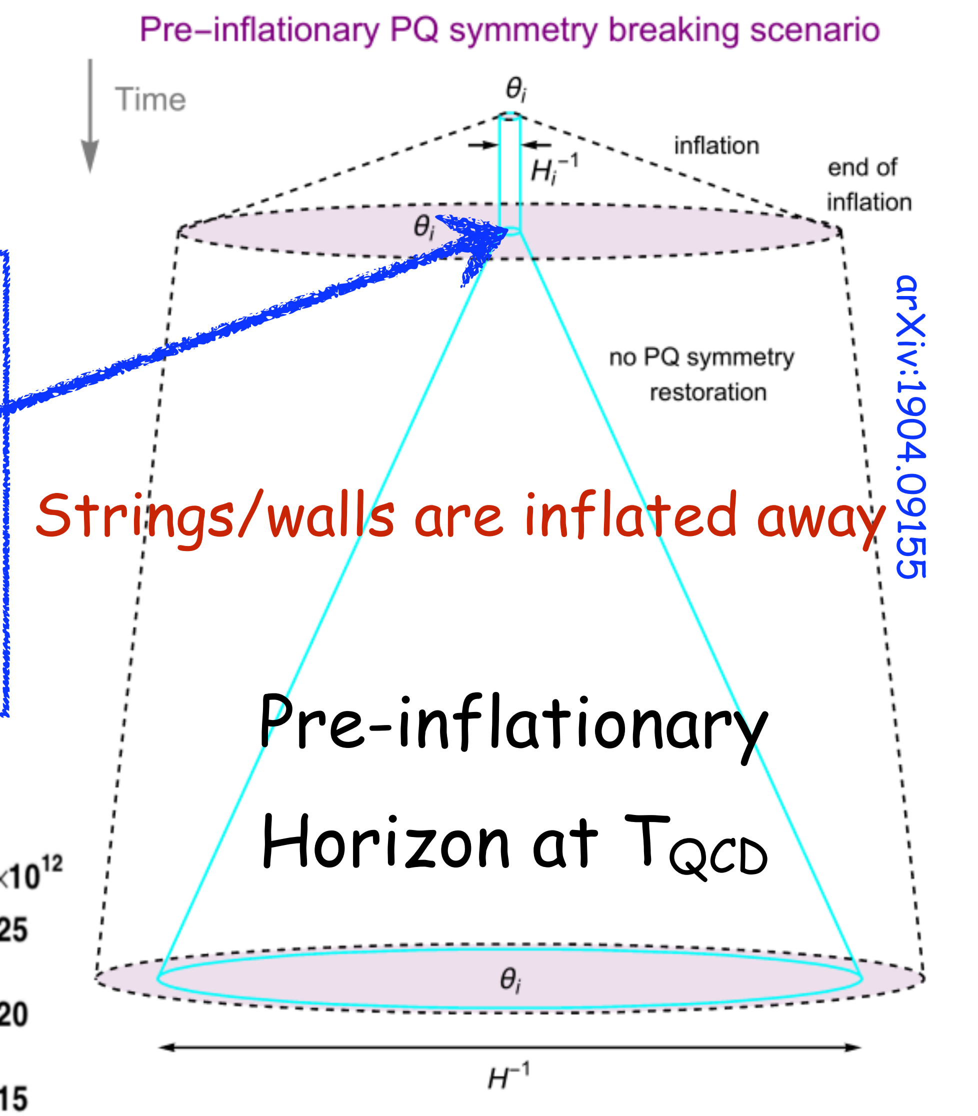
Spontaneous/explicit PQ symmt. breaking

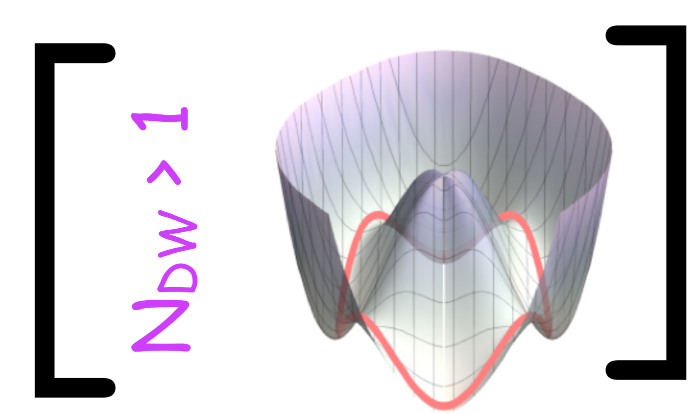
Complex scalar $V(\Phi) = (|\Phi|^2 - v^2)^2 + \lambda|\Phi|^4$



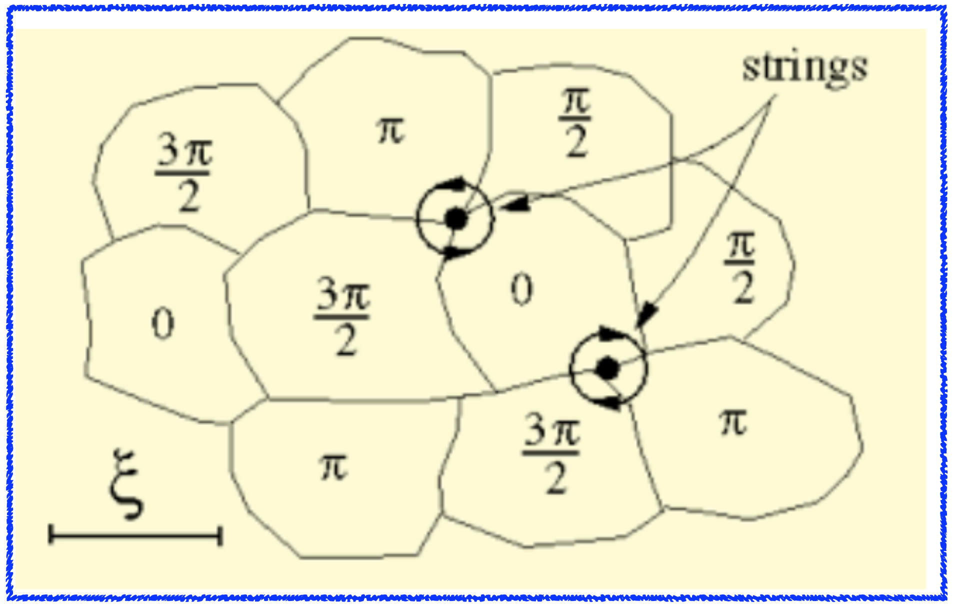




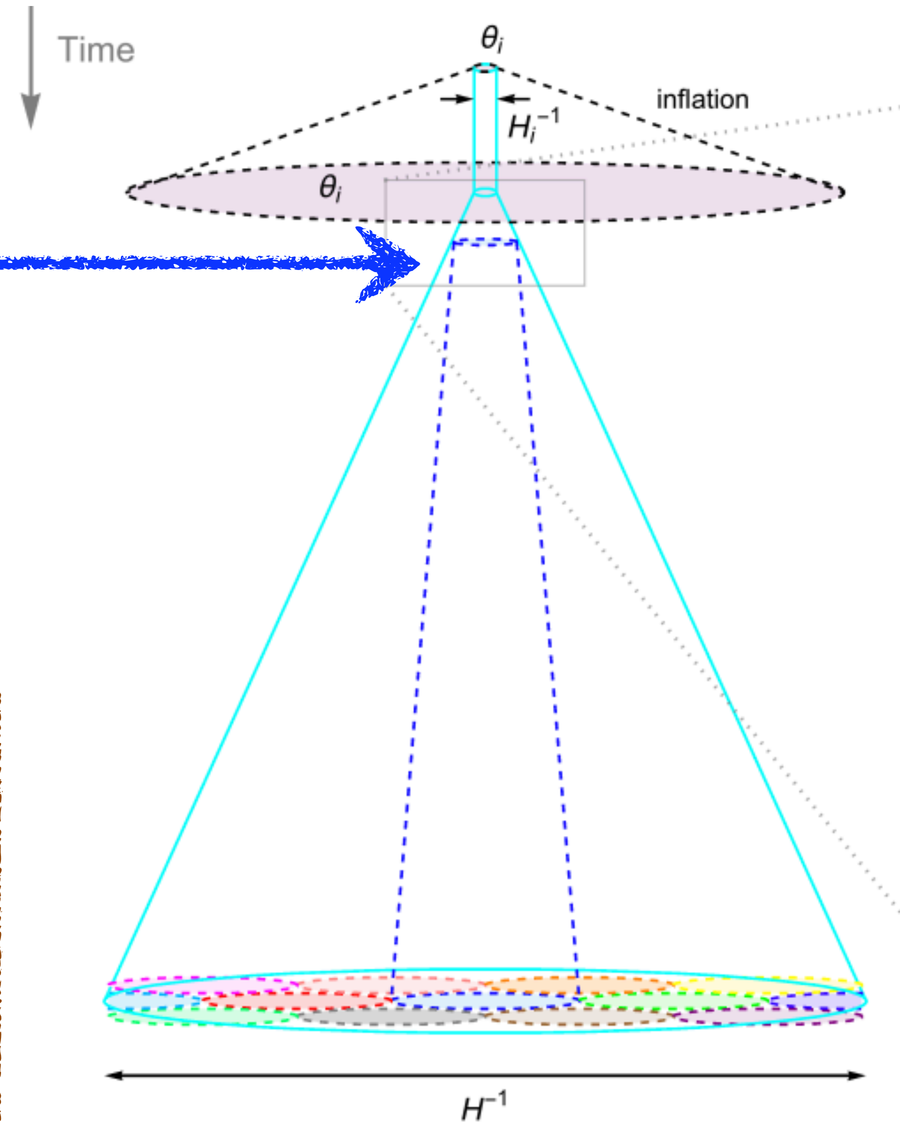




Post-inflationary scenarios: $T_{PQ} < T_{rh}$

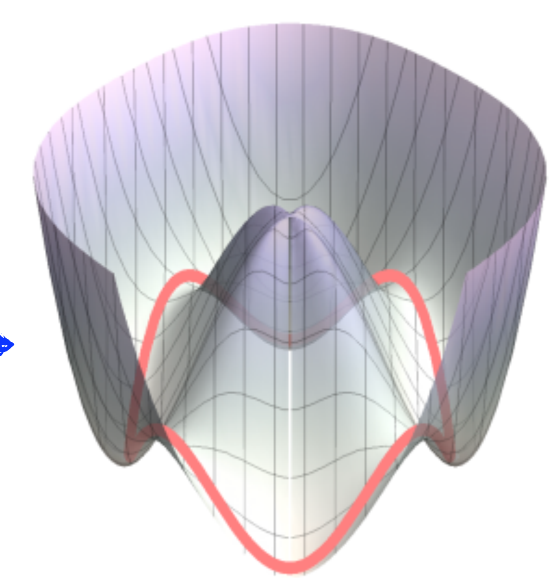


$T \sim T_{PQ}$



arXiv:1904.09155

- n_a independent of initial conditions: $\langle\theta_i^2\rangle = \pi^2/3$. More predictive for misalignment $\rho_{a\text{-mis}} \approx \rho_{DM}$ → $m_a \sim$ 20-50μeV
- Strings remain within the horizon (enter/annihilate) Eventually decay and contribute to ρ_a (important debate: spectrum/string density) masses up to $m_a \sim$ 0.5-3.5meV
- O(1) density contrasts: at matter/radiation equality (T ~ 1eV) overdensities start growing: axion miniclusters $R_{MC} \sim 1$ AU, $M_{MC} \sim 10^{-3}\, M_☾$, $\rho_{MC} \sim 10^6\, \rho_{DM\text{-local}}$
- $N_{DW} > 1$:
  Strings-DW network is stable. ρ_{DW} dominates $\rho_{Universe}$
  Solutions exist (e.g. small non-QCD explicit breaking)



The issue of QCD topological susceptibility

- How does the axion mass behave as a function of the temperature ?

[Bonati et al. 1512.06746, Petreczky et al. 1606.03145, Borsanyi et al. 1606.07494]

$$m_a^2(T) = \frac{\chi(T)}{\chi(0)}\, m_a^2(0)$$

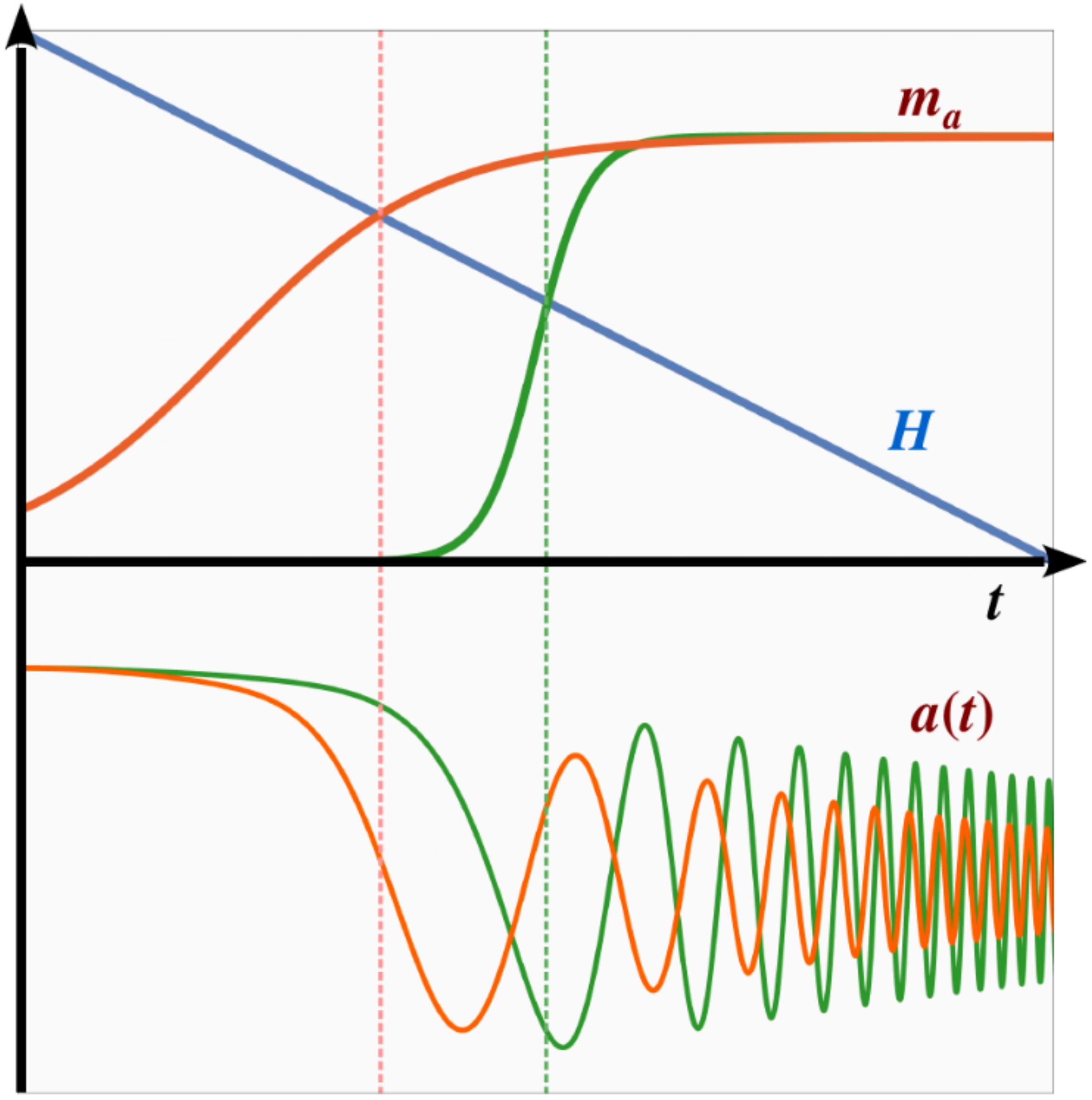
$\chi(T)$: QCD topological susceptibility

$$\rho_a = m_a^2 a^2$$

The larger f_a (the smaller m_a) the larger Ω_a

$$\Omega_a \approx \Omega_{DM}\, k\, \theta_0^2 \left[\frac{f_a}{10^{12}\ \mathrm{GeV}}\right]^{1+\epsilon}$$

$\varepsilon = 1/6$



Credits to G. Villadoro

Effective mass, lattice calculations

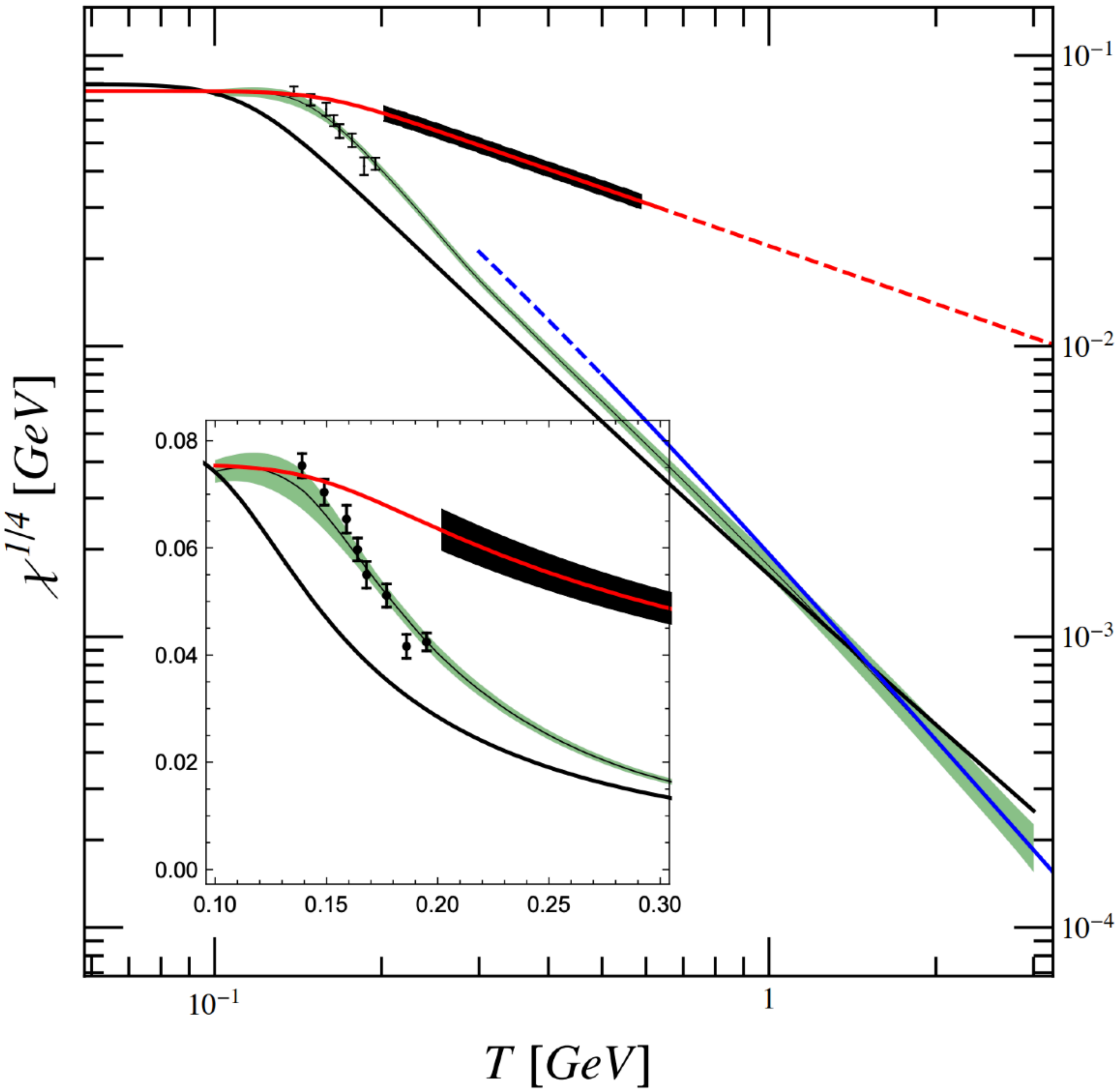
Lattice QCD: we can compute axion mass

$$m_a^2 f_a^2 = \chi(T)$$

At high T (no mesons)

we can analytically compute potential (DIGA)

$$V(\theta) = -\chi(T)\cos\theta$$



Lattice QCD 2+1+1 [Borsanyi]

Lattice QCD 2+1 [Bonati]

Lattice QCD (DWF) 2+1 [Buchoff] (points)

DIGA (T>>Tc) [Borsanyi]

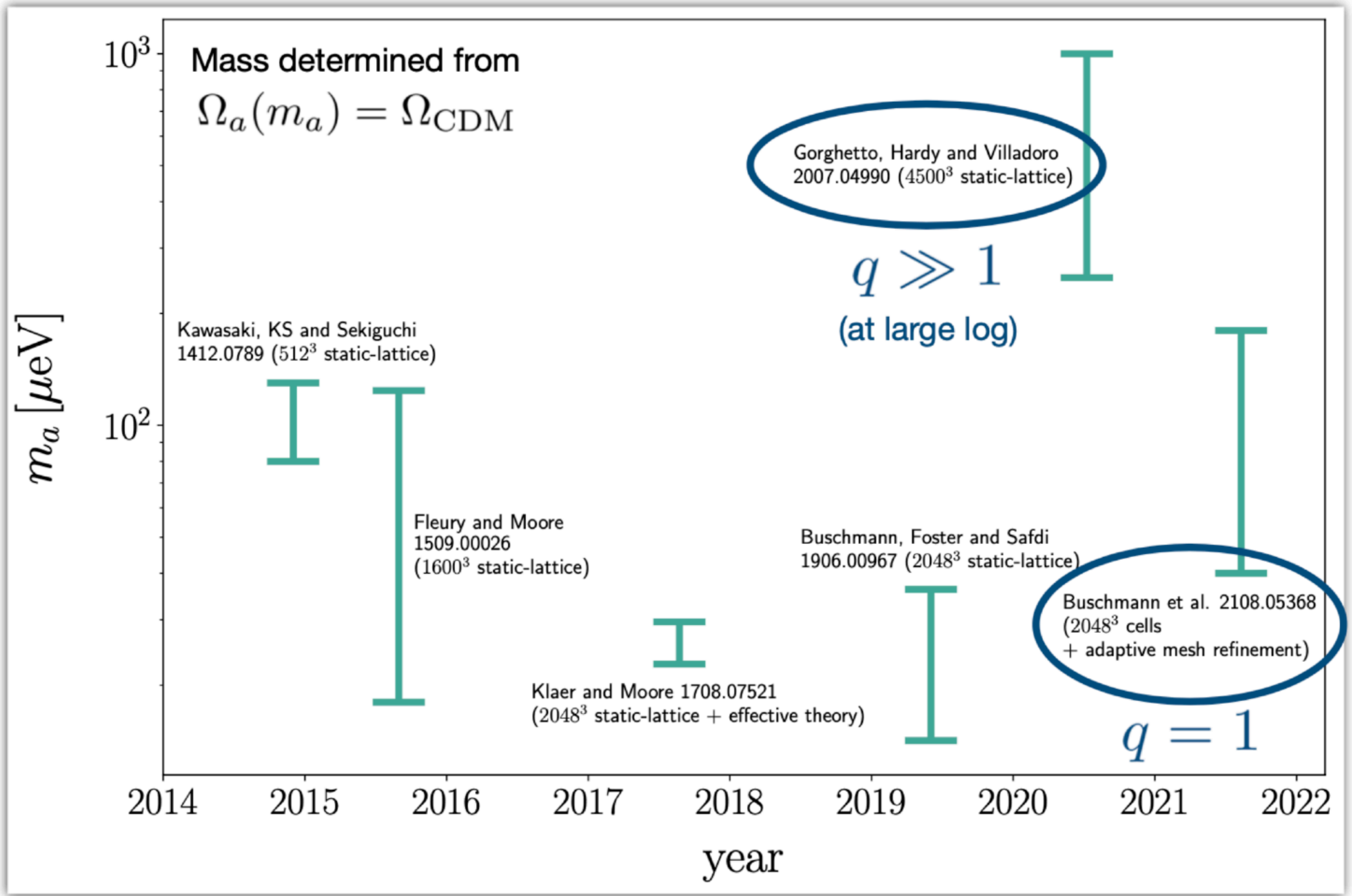
IILM [Wantz]

The issue of topological defects contributions

Only in post-inflation scenario (in pre-inflation defects are inflated away)

Only for the QFT axion (extra dim. compactified before inflation)

$\rho_a = n_a m_a = (n_{mis} + n_{strings})\, m_a$. For which value of m_a $\rho_a = \rho_{DM}$?



Current limits and search strategies

- Astrophysical bounds on axion couplings
  - Star evolution, RG lifetime $g_{a\gamma\gamma} \lesssim 6.6 \times 10^{-11}\,\mathrm{GeV}^{-1}$
  - White dwarf cooling $g_{aee} \lesssim 1.3 \times 10^{-13}\,\mathrm{GeV}^{-1}$
  - Supernova SN1987A $g_{aNN} \lesssim 3 \times 10^{-7}\,\mathrm{GeV}^{-1} \longrightarrow f_a \gtrsim 2 \times 10^{8}\,\mathrm{GeV}$

[For a collection see e.g. Raffelt, hep-ph/0611350]

- Most laboratory search techniques are sensitive to $g_{a\gamma\gamma}$
  - Light Shining trough Walls [see e.g. Redondo, Ringwald hep-ph/1011.3741]

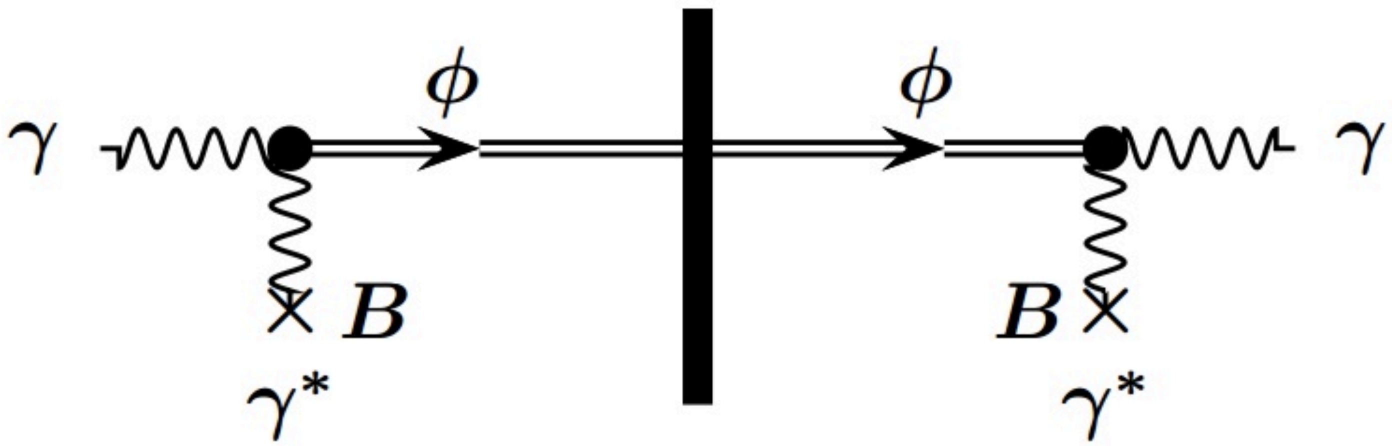
    Photon conversion into Axions, reconverted back into photons after passing a wall
  - Haloscopes [Sikivie 1983]

    Search for Axion Dark Matter
  - Helioscopes

    Search for Axions produced in the Sun

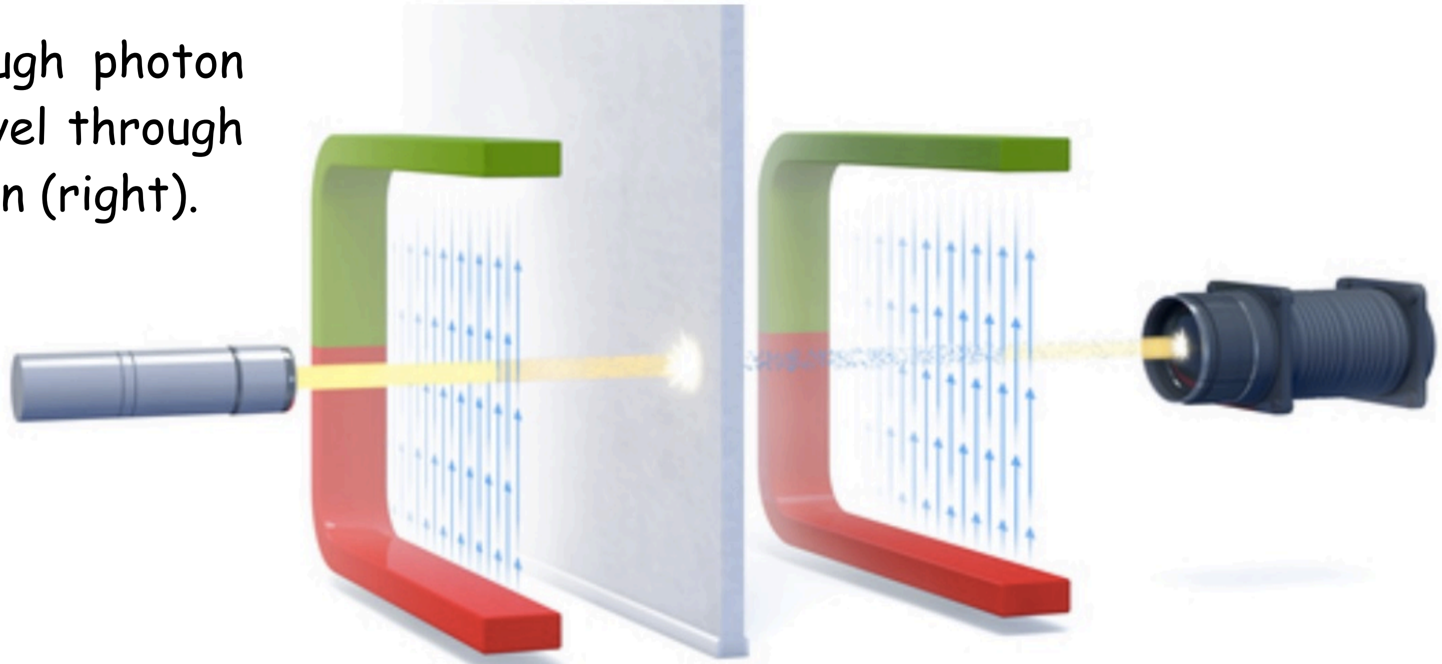
Light Shining trough Walls (LSW)

- Any Light Particle Search (DESY) Alps 1 (2007-2010) Alps 2



Schematic view of axion (or ALP) production through photon conversion in a magnetic field (left), subsequent travel through a wall, and final detection through photon regeneration (right).

Artist view of a light shining through a wall experiment

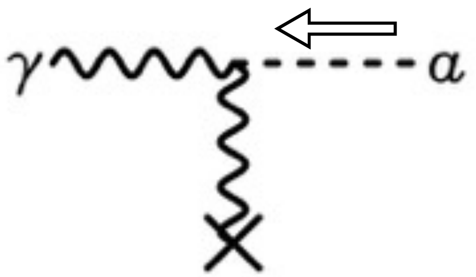


⟶ LSW experiments pay a $(g_{a\gamma\gamma})^4$ suppression

Haloscopes

- Look for halo DM axions with a microwave resonant cavity [Sikivie (1983)]
  - exploits inverse <u>Primakoff effect</u>: axion-photon transition in external E or B field

$$\mathcal{L}_{a\gamma\gamma} = -\frac{1}{4} g_{a\gamma\gamma}\, a\, F \cdot \tilde{F} = g_{a\gamma\gamma}\, a\, \mathbf{E} \cdot \mathbf{B}$$



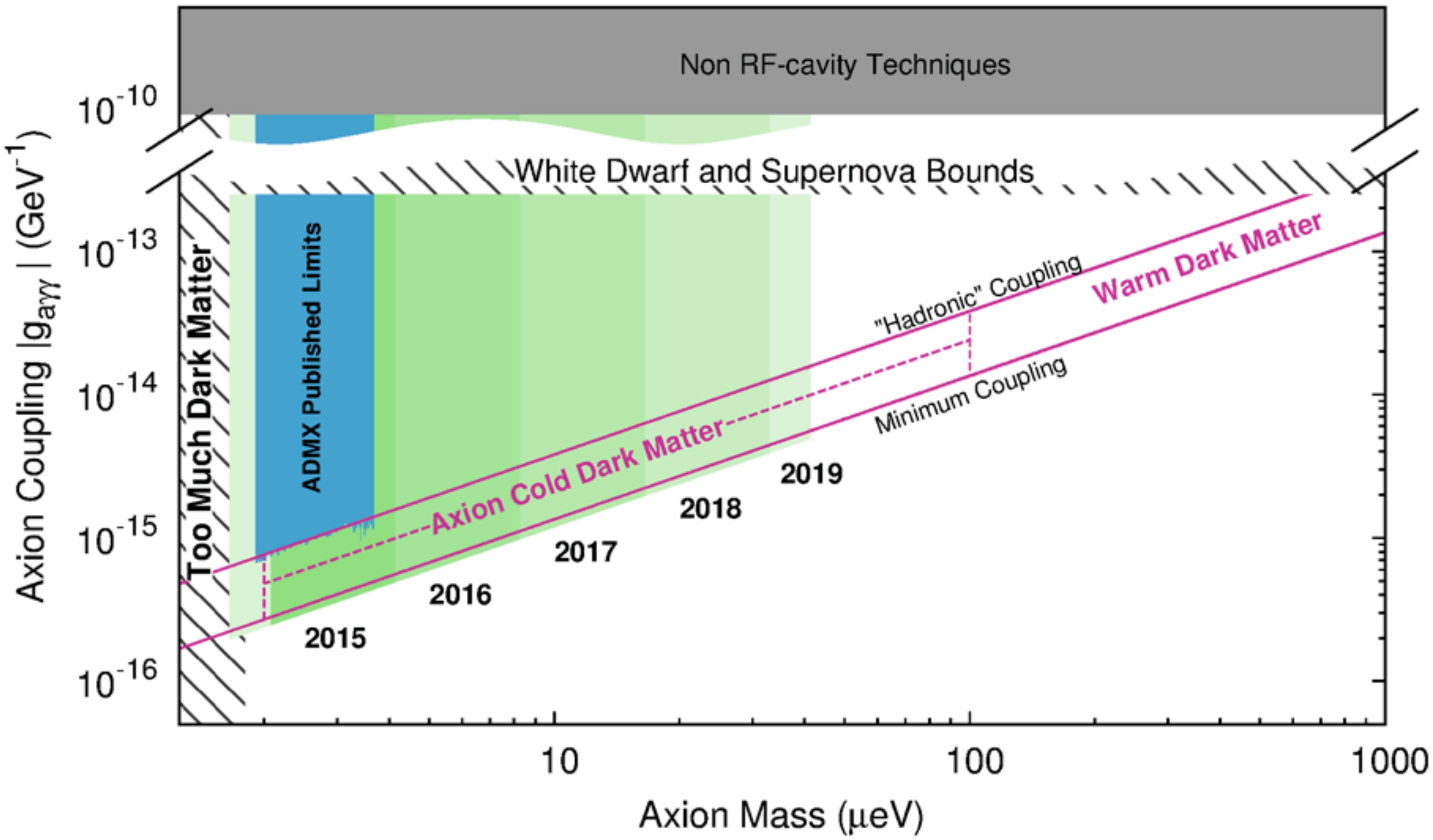
  - power of axions converting into photons in an EM cavity

$$P_a = C g_{a\gamma\gamma}^2 V B_0^2 \frac{\rho_a}{m_a} Q_{\rm eff}$$

  - resonance condition: need to tune the frequency of the EM cavity on the axion mass [good knowledge of m_a(DM) would be important]

Haloscopes

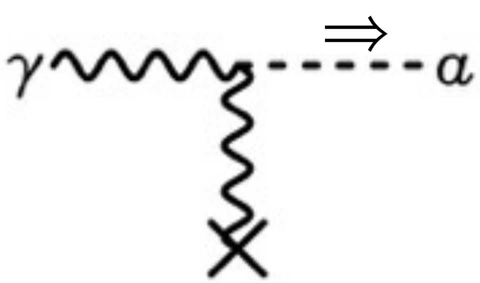
- Look for DM axions with a microwave resonant cavity
  - Axion Dark Matter eXperiment (ADMX) (U. of Washington)

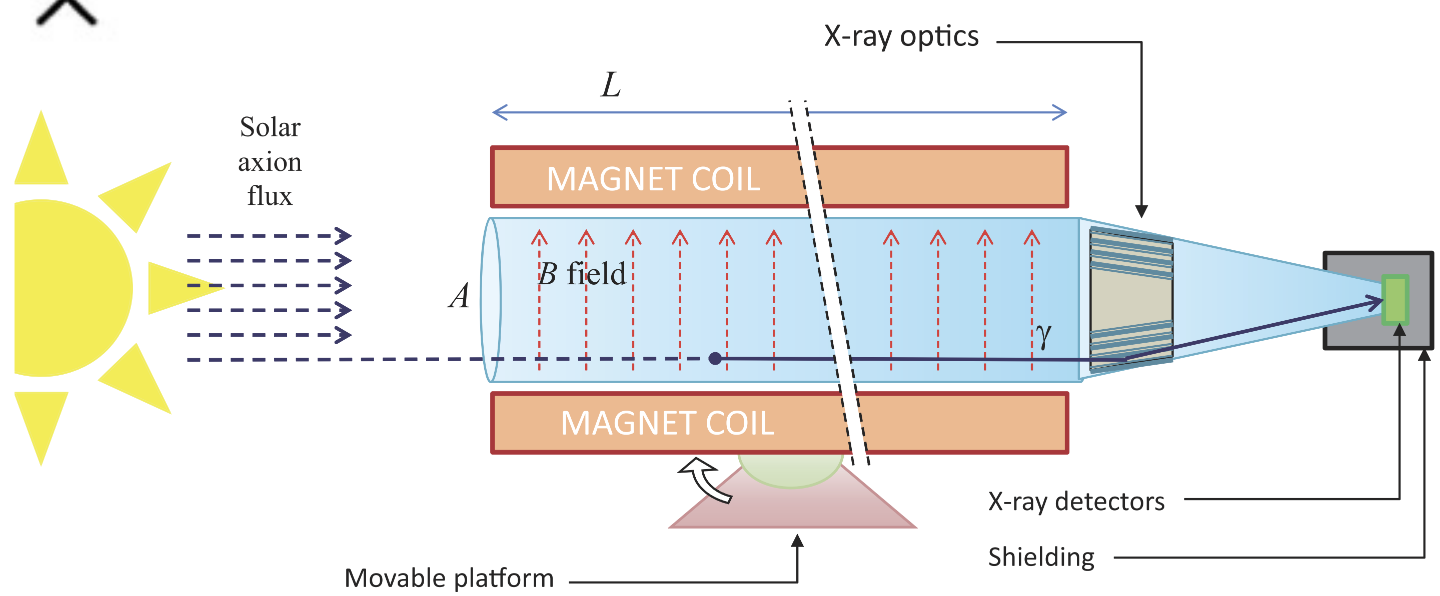


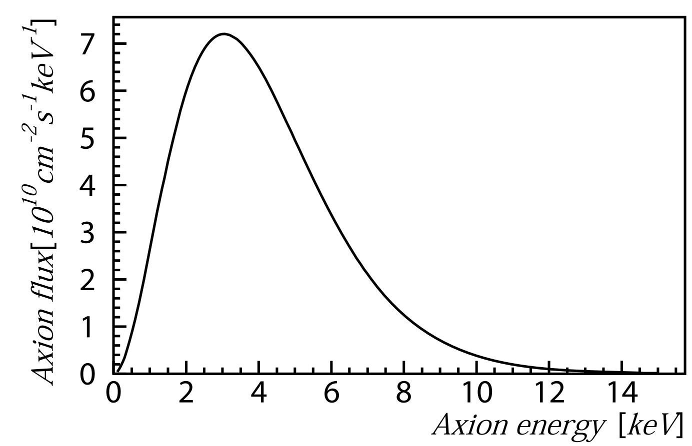
[ADMX Collaboration, 0910.5914]

Helioscopes

- The Sun is a potential source of a copious axion flux

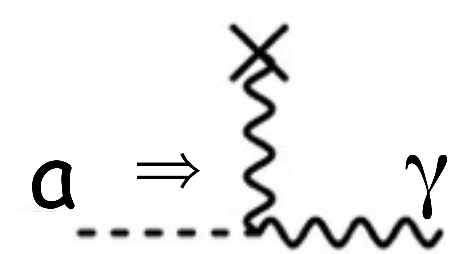






- macroscopic transverse B-field over a large volume triggers axion to photon (x-ray) conversion

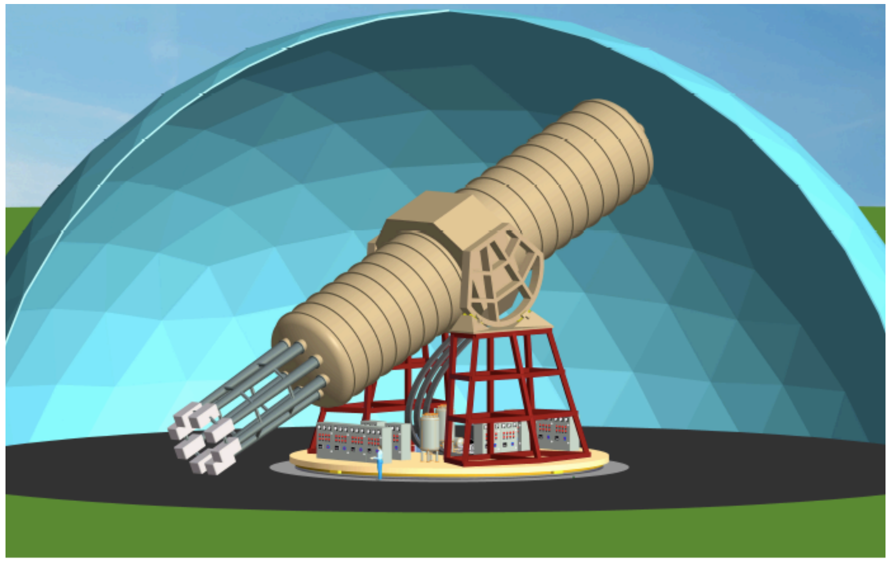
Detection via inverse-Primakoff ($g_{a\gamma}$)

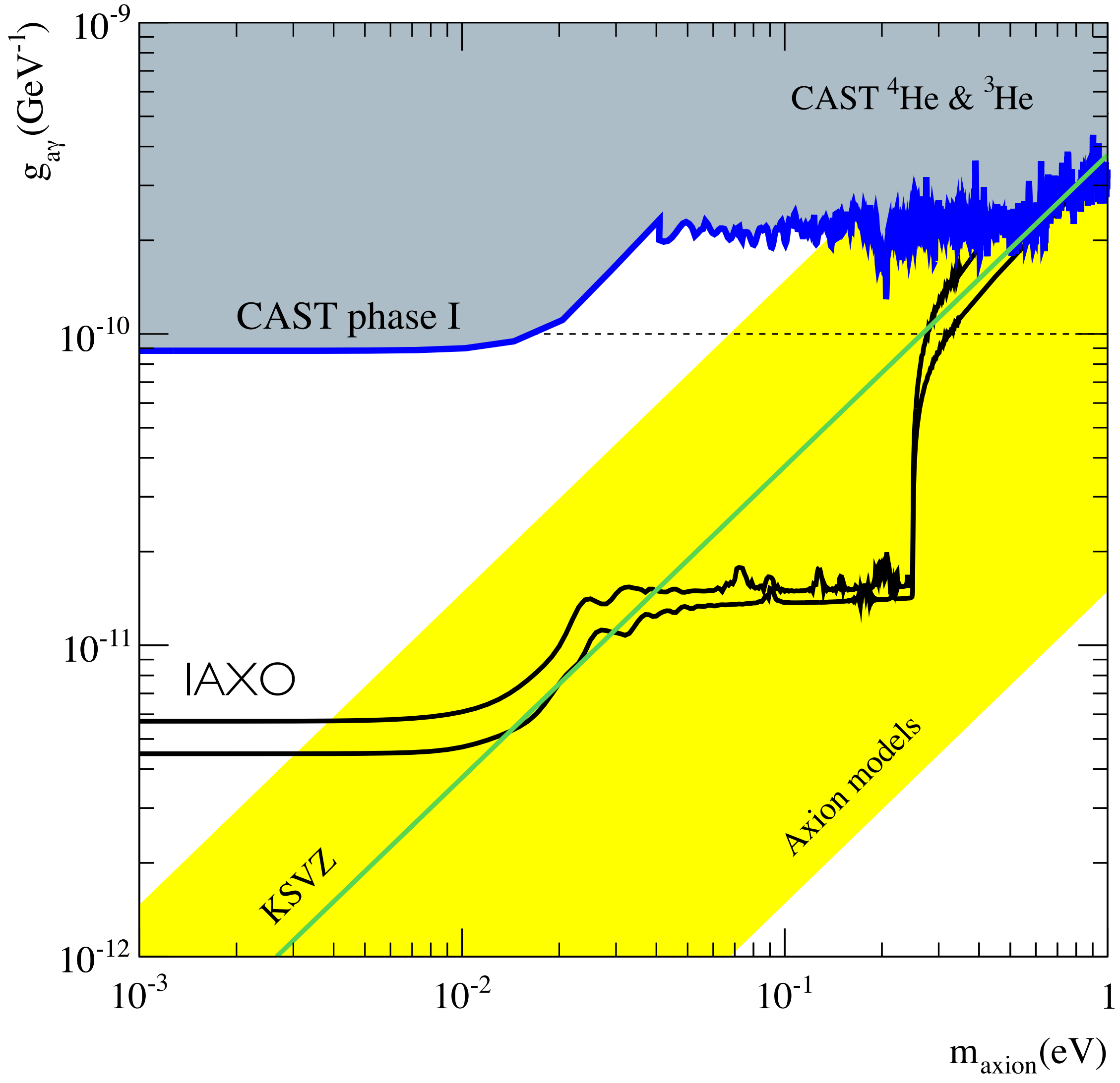


Helioscopes

- The Sun is a potential axion source (3rd and 4th generation axion-Sun telescopes)
  - CERN Axion Solar Telescope (CAST)

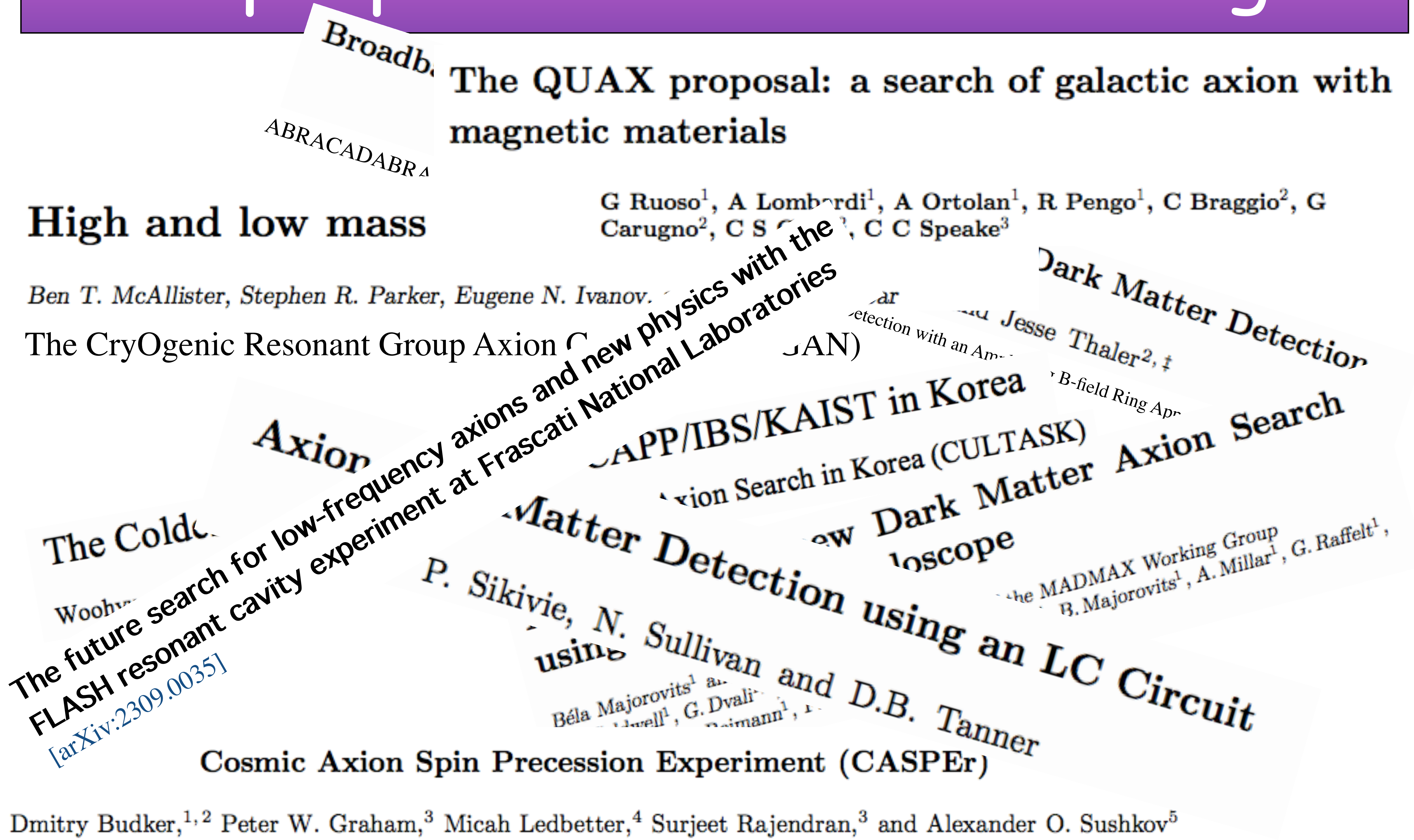
  - International AXion Observatory (IAXO)





[IAXO "Letter of intent", CERN-SPSC-2013-022]

New proposals & search strategies



Axion theory (QFT axion)

The PQ solution suffers from one serious issue:
Most model realizations can be considered "incomplete"

-The "origin" of the PQ "symmetry" is left unexplained

-The "high quality" of the PQ symmetry remains a puzzle

"quality" = absence of sources of explicit PQ-symmetry breaking, up to effective operators of dimension D$\gtrsim$10

This problem can be avoided in extra dim. axion models (gauge origin) [see Dvali talk]

The PQ "origin" and "quality" problems

- $U(1)_{PQ}$ is anomalous. Is not a (fundamental) symmetry of the theory: At the quantum level the theory is not invariant under $\psi \to e^{i\alpha\gamma_5}\psi$

$$Z \sim \int [DA_\mu D\Phi]\, D\psi D\bar{\psi}\ \exp(iS) \to \int [DA_\mu D\Phi]\, D\psi D\bar{\psi}\ \exp\left(iS + i\int d^4x \frac{\alpha}{16\pi} G\tilde{G}\right)$$

- In benchmark axion models, Φ is a complex scalar, and a gauge singlet. Renormalizable terms $\mu^3\Phi$, $\mu^2\Phi^2$, $\mu\Phi^3$, $\lambda\Phi^4$ do not break gauge or Lorentz and are not forbidden. No reasons not to write them in the Lagrangian…

  However, they would completely destroy the PQ solution !

- Moreover: Non-pt. quantum gravity effects break all global \`symmetries' Controlled semiclassical solutions [Euclid. wormholes] give:

$$O_{PQ} \sim M_P^3\, e^{-S_{wh}}\, \Phi + \text{h.c.}$$

Safe suppression requires $S_{wh} > 190$ (while typical wh actions are $S_{wh} \sim \text{Log}(M_P/v_a) \sim 15$)

[Kallosh et al. '95, Alonso & Urbano '17, Alvey & Escudero '20]

The PQ "origin" and "quality" problems

• PQ breaking higher dim. effective opts. $\lambda\, \Phi^d/\Lambda^{d-4}$ are also dangerous:

$$\lambda \frac{\Phi^d}{\Lambda^{d-4}} + \mathrm{h.c.} \approx |\lambda| \left(\frac{v_a}{\Lambda}\right)^{d-4} v_a^4 \cos(a/v_a + \varphi_\lambda) \quad \text{vs.} \quad V_{QCD}(a) = -(m_\pi f_\pi)^2 \cos(a/v_a)$$

To preserve $\langle a/v_a \rangle \approx 0$ we need: Eng. density eff.opt. $< 10^{-10}\, V_{QCD}(a)$

$$|\lambda|\, (v_a/\Lambda)^{d-4} < 10^{-10}\, (m_\pi f_\pi / v_a^2)^2$$

E.g. $|\lambda| \sim 1$, $\Lambda \sim M_P$ and $v_a \sim 10^{10}$ GeV imply $d \gtrsim 10$ [with $\lambda = g_{wh}$, $d \gtrsim 9$]

[Barr & Seckel '92, Kamionkowski & March-Russel '92, Holman et al. '92, Ghigna et al. '92]

The QFT axion solution requires a PQ symmetry of an <u>excellent quality:</u>

No PQ symmetry breaking operators up to a very large dimension $d \gtrsim 10$

In comparison, in the SM L-number can be violated at $d=5$, B-number at $d=6$

A sample of proposed solutions

$U(1)_{PQ}$ should arise automatically as a consequence of first principles.
SSB requires VEVs ⇒ Lorentz singlets. Rely on <u>local gauge symmetries</u>

- Discrete gauge symm. $\mathbb{Z}_n$: $\Phi \to e^{i\,2\pi/n}\,\Phi$;   1st $\not{PQ}$ opt. $\Lambda^{4-n}\,\Phi^n$
  Requires $\mathbb{Z}_{10}$ or larger [Krauss & Wilczek '89, Dias & al. '03, Carpenter & al. '09, Harigaya & al. '13]

- Local U(1) + 2 scalars with charges $q_1+q_2 \geq 10$ 1st $\not{PQ}$: $\Lambda^{4-q_1-q_2}\,(\Phi_1^\dagger)^{q_2}\,(\Phi_2)^{q_1}$
  (q1 and q2 relatively prime) [Barr & Seckel '92]

- Non-Abelian $SU(n)_L \times SU(n)_R$, $a(x) \in Y_{n\times n} \sim (n, \bar{n})$
  For $n > 4$ the ren. potential is very simple: $V(Y) = (T - \mu^2)^2 \pm T_4$
  where $T = Tr(Y^\dagger Y)$, $T_4 = Tr(Y^\dagger Y Y^\dagger Y)$. Automatic rephasing symm. $Y \to e^{i\xi}\,Y$
  1st $\not{PQ}$ opt. Λ^{4-n} det Y dim = n. This requires again $n \geq 10$
  [Fong, EN '14 [in SU(3)xSU(3)], Di Luzio, Ubaldi, EN '17]

🤔 Can we do any better? 🤔

Local gauge symmetries seem to be the only tool we have at disposal to generate accidentally a PQ symmetry and enforce the required level of protection….

- But can we obtain the required PQ protection without putting a "10" by hand ? ($\mathbb{Z}_{10}$, $q_1+q_2 \geq 10$, SU(10) x SU(10), …)

- Can we link the PQ origin and quality problem to other SM puzzles ?

- Hint: a gauge symmetry acting on scalars coupled to quarks, must also act on the quarks. Thus, it is by definition a Flavour Symmetry!

The "PQ quality - flavour" connection

By implementing accidentally a PQ symmetry via non-Abelian gauge protection, can we learn something beyond 'axion issues' ?

Origin + quality of acc. symmt. => Certain Non-Abelian gauge groups G_F acting on some set of scalar multiplets.

Promoting U(1) to a PQ symmt. requires a mixed QCD anomaly.

=> Quarks must transform under the $U(1)_{PQ}$ symmt.

=> Hence they must couple to the scalar multiplets

=> Hence they must also transform under G_F

Hence the local G_F is a flavour symmetry !

A property of certain gauge symmetries

- We have found that local SU(M) x SU(N) (M≠N) spontaneously broken by scalar multiplets $Y_{ai} \sim (m,\bar{n})$ [+ (m,1), (1,$\bar{n}$)] are well suited to enforce and protect an accidental global U(1)

Already with SU(3) x SU(2) the potential V(Y) for a scalar multiplet $Y_{ai} \sim (3,\bar{2})$ enjoys an automatic & exact global U(1) (Unfortunately, non-anomalous)

[Darmé & EN (2021)]

We have recently proven that with semi-simple gauge groups G_F, sufficient PQ protection together with $\det M_q \neq 0$ implies a vanishing PQ anomaly

[Darmé, EN, Smarra, JHEP 02 (2023) 201]

Useful groups are non-simple, of the form $G_F \times U(1)_F$

Non-simple gauge symmetries

The argument is circumvented by adding a U(1) gauge factor

[Darmé, EN, Smarra, JHEP 02 (2023) 201]

$$G_F \rightarrow G_F' = G_F \times U(1)_F$$

Curiously, the simplest symmt.: $G_F = [SU(3) \times SU(2) \times U(1)]_F$

- PQ: $U(1)_{PQ}$ remains protected up to $d=11$
  (no PQ breaking opts. at $d=12$, next ones at $d=13$)
- The physical axion is "invisible": $f_a \sim v_F \sim [10^8 - 10^{12}]$ GeV

- Flavor: First result: d/u-mass hierarchies arise naturally.
  Reproducing CKM mixings from dynamical minimization of $V(S)$ is a computationally demanding task (ongoing effort).
  No reason to suspect that this should not happen.

Summary and conclusions

- The axion mechanism provides an elegant and convincing solution to the strong CP problem. Axions can arise as NGB in QFT or from gauge forms in extr. dim. models. It might be possible, in some case, to identify the origin of the axion.

- The axion has far reaching implications in particle physics, astrophysics, and cosmology, and it represents an excellent (and discoverable) DM candidate. The (post-inflation) axion DM window can be fully probed within the next decade

- Ongoing and forthcoming cosmological surveys, astrophysics observations, and laboratory experiments will soon provide a wealth of data to exhaustively probe the axion hypothesis.

- Certain theoretical and computational issues should be addressed with dedicated efforts, and hopefully will be clarified soon. It is conceivable that a better understanding of the origin of the axion might shed light on some other unsolved puzzles in the SM.

Thank you !