Axions/ALPs as DM and/or as DM Mediators: Phenomenology

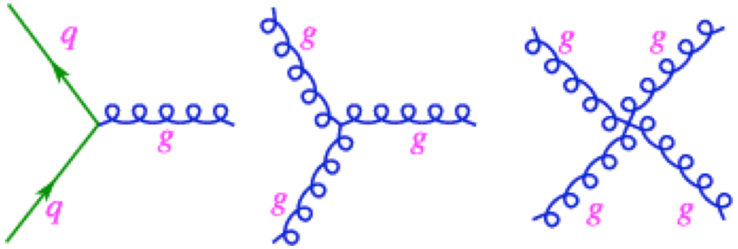
Andreas Ringwald
FIPs 2020
Virtual Workshop
31 Aug - 04 Sep 2020

Strong CP Puzzle

Theta term in Quantum Chromodynamics

- Quantum Chromodynamics (QCD): [Gross,Wilczek 73;Politzer 73; Fritzsch,Gell-Mann,Leutwyler 73]

$$S_{\rm QCD} = \int d^4x \left\{ \overline{q} \left(i\gamma_\mu D^\mu - \mathcal{M}_q \right) q - \frac{1}{4} G^a_{\mu\nu} G^{a,\mu\nu} \right\}$$



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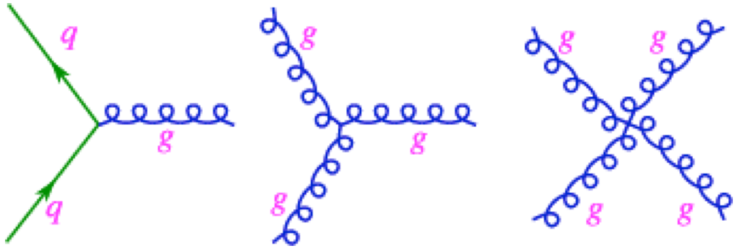

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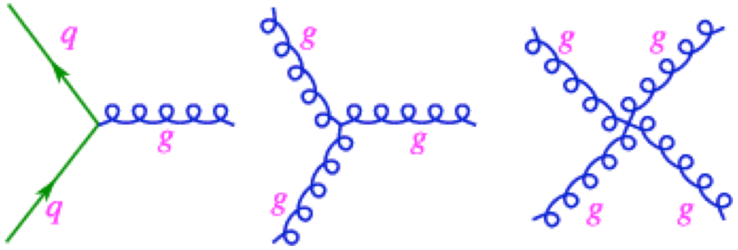

$$\int d^4x\, \partial_\mu J^\mu_{\rm CS} = 0, \pm 1, \pm 2, \ldots$$

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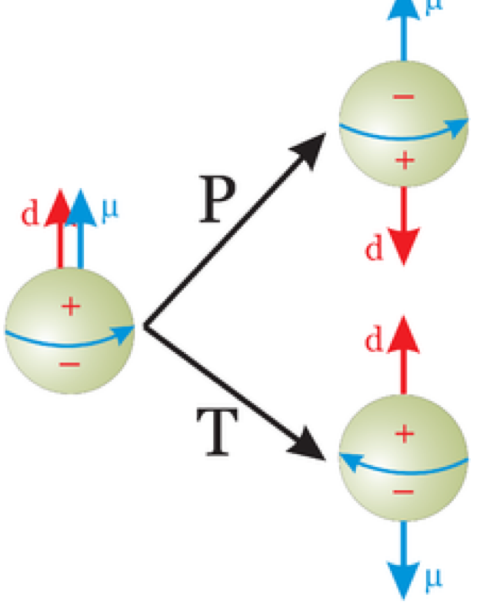
- Most sensitive probe of T and P violation in flavor conserving interactions: electric dipole moment of neutron



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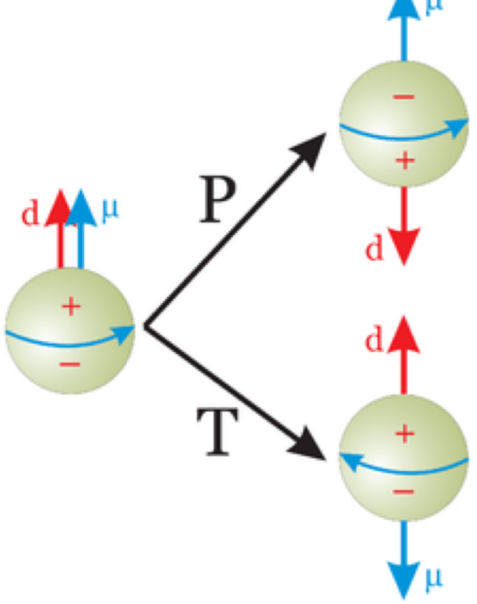
$$d_n(\overline{\theta}) = 2.4(1.0) \times 10^{-16}\,\overline{\theta}\,e\,{\rm cm}$$



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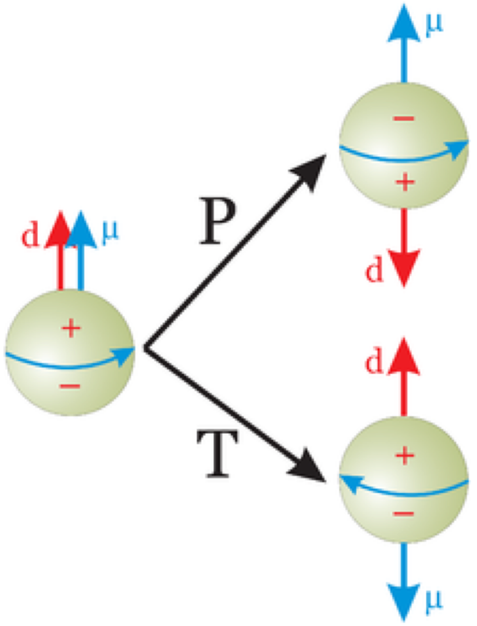
- Experiment: [Abel et al. 20]

$$|d_n| < 1.8 \times 10^{-26}\, e\,{\rm cm}$$

$$\Rightarrow |\overline{\theta}| < 10^{-10}$$



Axionic Solution of Strong CP Puzzle

In a nutshell: replace theta parameter by dynamical theta field

- Add to SM Nambu-Goldstone field, $\theta(x) \equiv A(x)/f_A \in [-\pi, \pi]$, respecting a non-linearly realized $U(1)_{\rm PQ}$ symmetry ($\theta(x) \to \theta(x) + {\rm const.}$), broken by coupling to gluonic topological charge density: [Peccei,Quinn 77]

$$\mathcal{L} \supset -\theta(x)\, q(x)\,; \qquad q(x) \equiv \frac{\alpha_s}{8\pi}\, G^b_{\mu\nu}(x) \tilde{G}^{b,\mu\nu}(x)$$

  - Can eliminate QCD $\overline{\theta}$-parameter

$$\mathcal{L} \supset -\frac{\alpha_s}{8\pi}\left[\overline{\theta} + \theta(x)\right] G^b_{\mu\nu}\tilde{G}^{b,\mu\nu}$$

    by shift $\theta(x) \to \theta(x) - \overline{\theta}$

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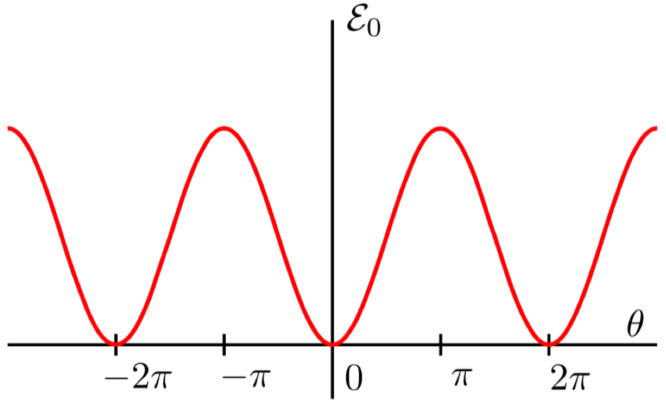
  - Effective potential at energies below $\Lambda_{\rm QCD}$ has absolute minimum at $\theta = 0$ and thus predicts vanishing vev, $\langle\theta(x)\rangle = 0$
    No strong CP violation in vacuum [Vafa,Witten 84]



$$V(\theta) = \Sigma\,(m_u + m_d)\left(1 - \frac{\sqrt{m_u^2 + m_d^2 + 2m_u m_d\cos\theta}}{m_u + m_d}\right)$$

$$\Sigma \equiv -\langle\bar{u}u\rangle = -\langle dd\rangle$$

[Di Vecchia,Veneziano `80; Leutwyler,Smilga 92]

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  - Particle excitation: pseudo Nambu-Goldstone boson "axion" [Weinberg 78; Wilczek 78]
  - Topological susceptibility in QCD, $\chi \equiv \int d^4x \langle q(x) q(0) \rangle$, determines mass in units of decay constant: $m_A = \sqrt{\chi}/f_A$
  - Recent precise determination (ChPT; lattice QCD):

$$m_A = 5.691(51) \left(\frac{10^9\,{\rm GeV}}{f_A} \right) {\rm meV}$$

[Grilli di Cortona et al. \`16; Borsanyi et al. \`16; Gorghetto, Villadoro \`19]

Peccei-Quinn Extension of Standard Model

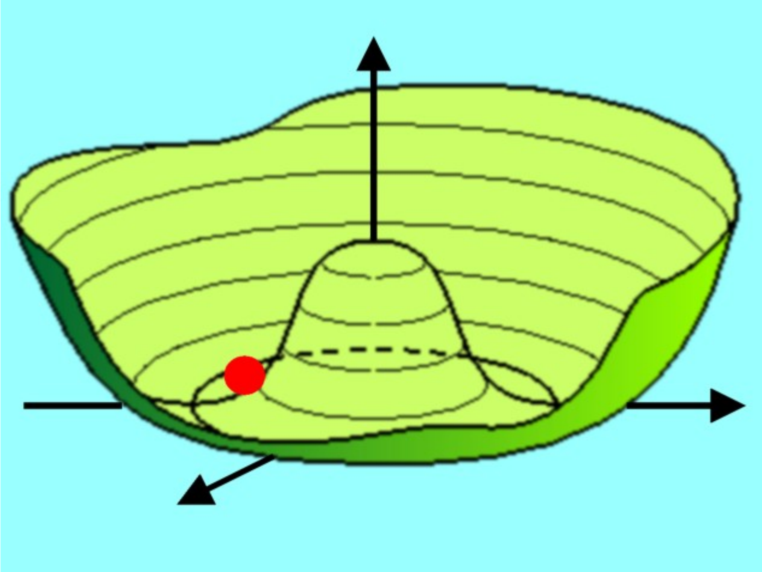
Simple way to get dynamical theta field

- Add singlet complex scalar field σ, featuring a spontane-ously broken global $U(1)_{\rm PQ}$ symmetry

- Particle excitations:

$$\sigma(x) = \frac{1}{\sqrt{2}}\left(v_{\rm PQ} + \rho(x)\right) {\rm e}^{iA(x)/v_{\rm PQ}}$$

  - Mass of particle excitation of modulus: $m_\rho \sim v_{\rm PQ}$
  - Mass of particle excitation of phase: $m_A = 0$



[Raffelt]

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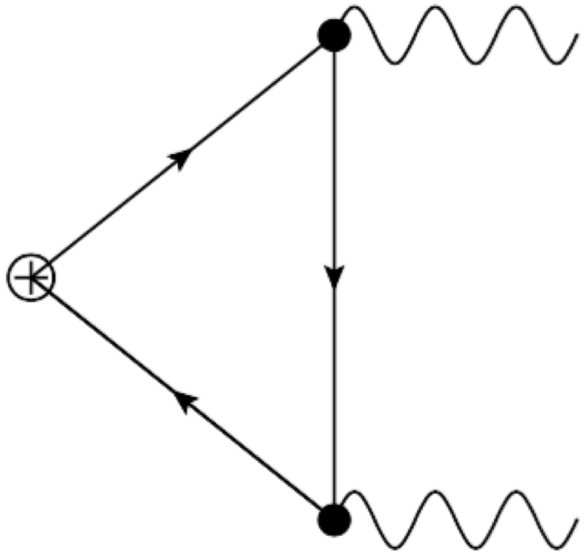
- Coloured fermions carry PQ charges such that $U(1)_{\rm PQ}$ is broken due to gluonic triangle anomaly:

$$\partial_\mu J^\mu_{U(1)_{\rm PQ}} \supset -\frac{\alpha_s}{8\pi} N\, G^b_{\mu\nu} \tilde{G}^{b,\mu\nu}$$



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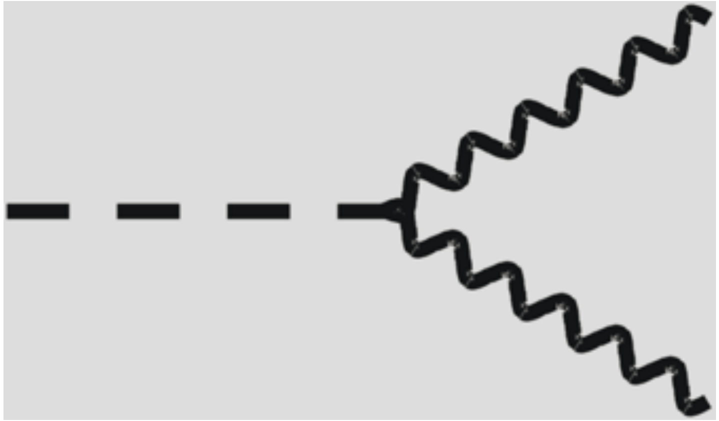
- Low energy effective field theory at energies above $\Lambda_{\rm QCD}$ but below v ($\ll v_{\rm PQ}$): [Peccei,Quinn 77; Weinberg 78; Wilczek 78]

$$\mathcal{L} \supset -\frac{\alpha_s}{8\pi}\,\theta(x)\, G^b_{\mu\nu}\tilde{G}^{b,\mu\nu}\,; \qquad \theta(x) = A(x)/f_A\,; \qquad f_A = v_{\rm PQ}/N$$

[Kim 79;Shifman,Vainshtein,Zakharov 80;Zhitnitsky 80;Dine,Fischler,Srednicki 81;...]



Peccei-Quinn Extension of Standard Model

Axion couplings to SM at energies below QCD scale

$$\mathcal{L}_A \supset -\frac{i}{2}\frac{C_{AD}}{f_A} A\,\overline{\Psi}_N \sigma_{\mu\nu}\gamma_5 \Psi_N F^{\mu\nu} - \frac{\alpha}{8\pi}\frac{C_{A\gamma}}{f_A} A\, F_{\mu\nu}\tilde{F}^{\mu\nu} - \frac{1}{2}\frac{C_{Af}}{f_A}\partial_\mu A\,\overline{\Psi}_f \gamma^\mu \gamma_5 \Psi_f$$

- Couplings to SM suppressed by inverse power of $f_A = v_{\rm PQ}/N \gg v = 246\,\text{GeV}$

  proportional to mass, since $m_A = 5.691(51)\left(\frac{10^9\,\text{GeV}}{f_A}\right)\text{meV}$

  - EDM coupling: $C_{AD} = 2.4(1.0)\times 10^{-16}\,e\,\text{cm}$ [Pospelov,Ritz `00]
  - Photon coupling: $C_{A\gamma} = \frac{E}{N} - 1.92(4)$ [Kaplan 85;Srednicki `85; Grilli di Cortona et al. `16]
  - Nucleon couplings:

$$C_{Ap} = -0.47(3) + 0.88(3)C_{Au} - 0.39(2)C_{Ad} - 0.038(5)C_{As} - 0.012(5)C_{Ac} - 0.009(2)C_{Ab} - 0.0035(4)C_{At}\,,$$

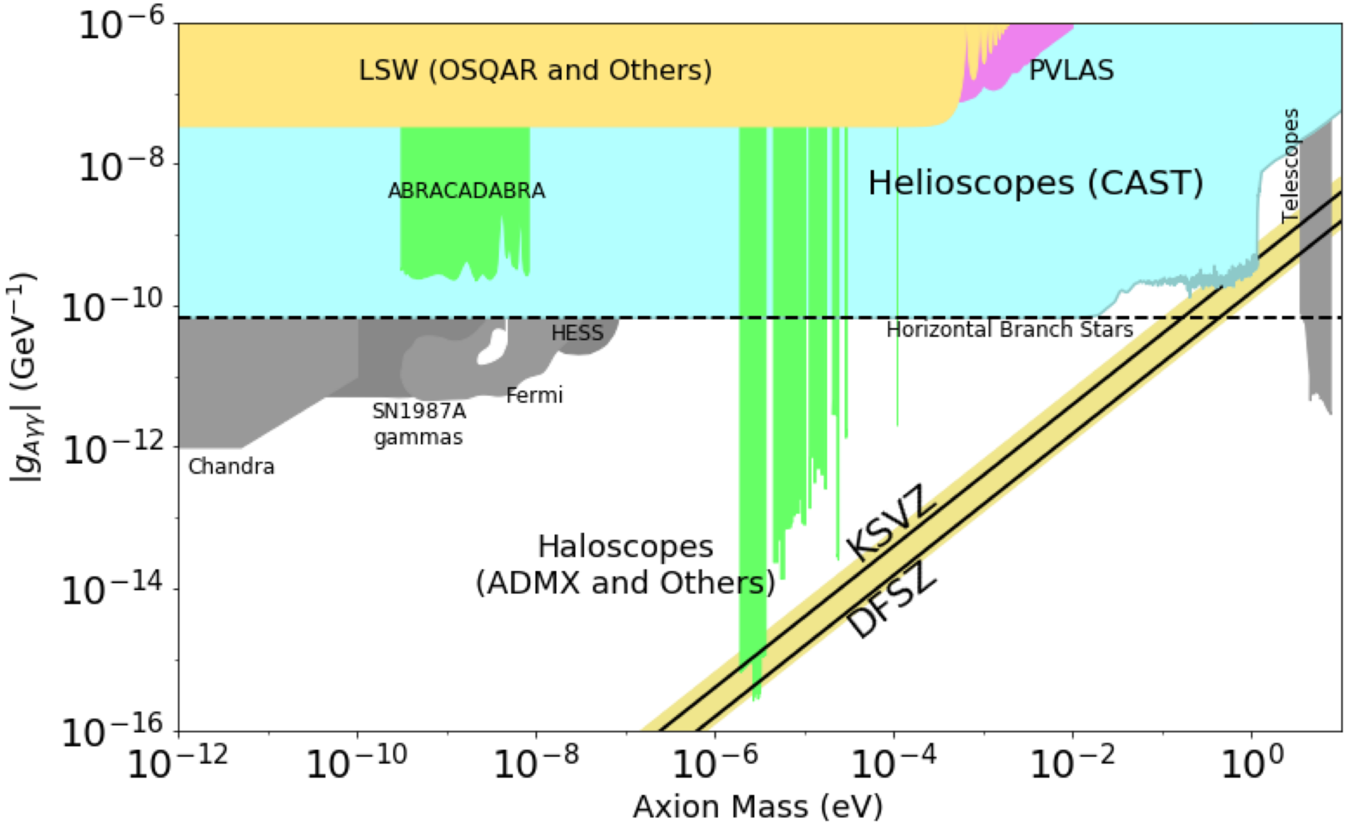
$$C_{An} = -0.02(3) + 0.88(3)C_{Ad} - 0.39(2)C_{Au} - 0.038(5)C_{As} - 0.012(5)C_{Ac} - 0.009(2)C_{Ab} - 0.0035(4)C_{At}$$

- Axion-Like Particle (ALP): PNGB from breaking of another approximate global symmetry, e.g. Majoron, Familon, etc.

Constraints on Axion/ALP Couplings

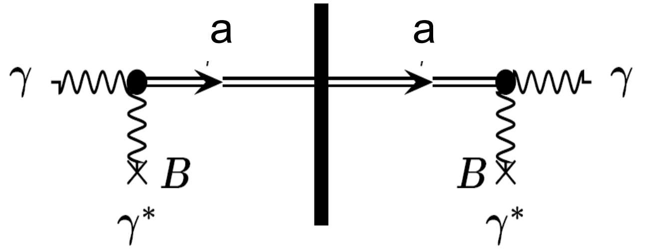
Coupling to the photon

$$g_{A\gamma\gamma} \equiv \frac{\alpha}{2\pi f_A} C_{A\gamma}$$

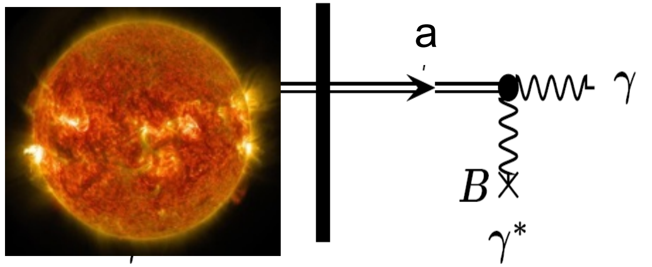


[AR,Rosenberg,Rybka in: Review of Particle Physics, PTEP 2020 (2020) 8, 083C01]

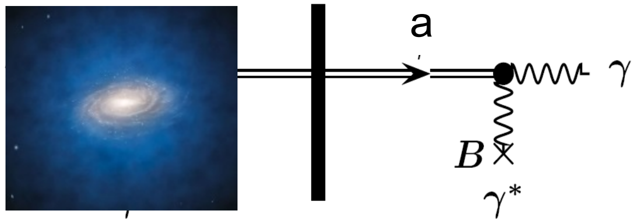
Laser shining through a wall (LSW)



Sun shining through a wall (Helioscope)



DM shining through a wall (Haloscope)



[Axel Lindner]

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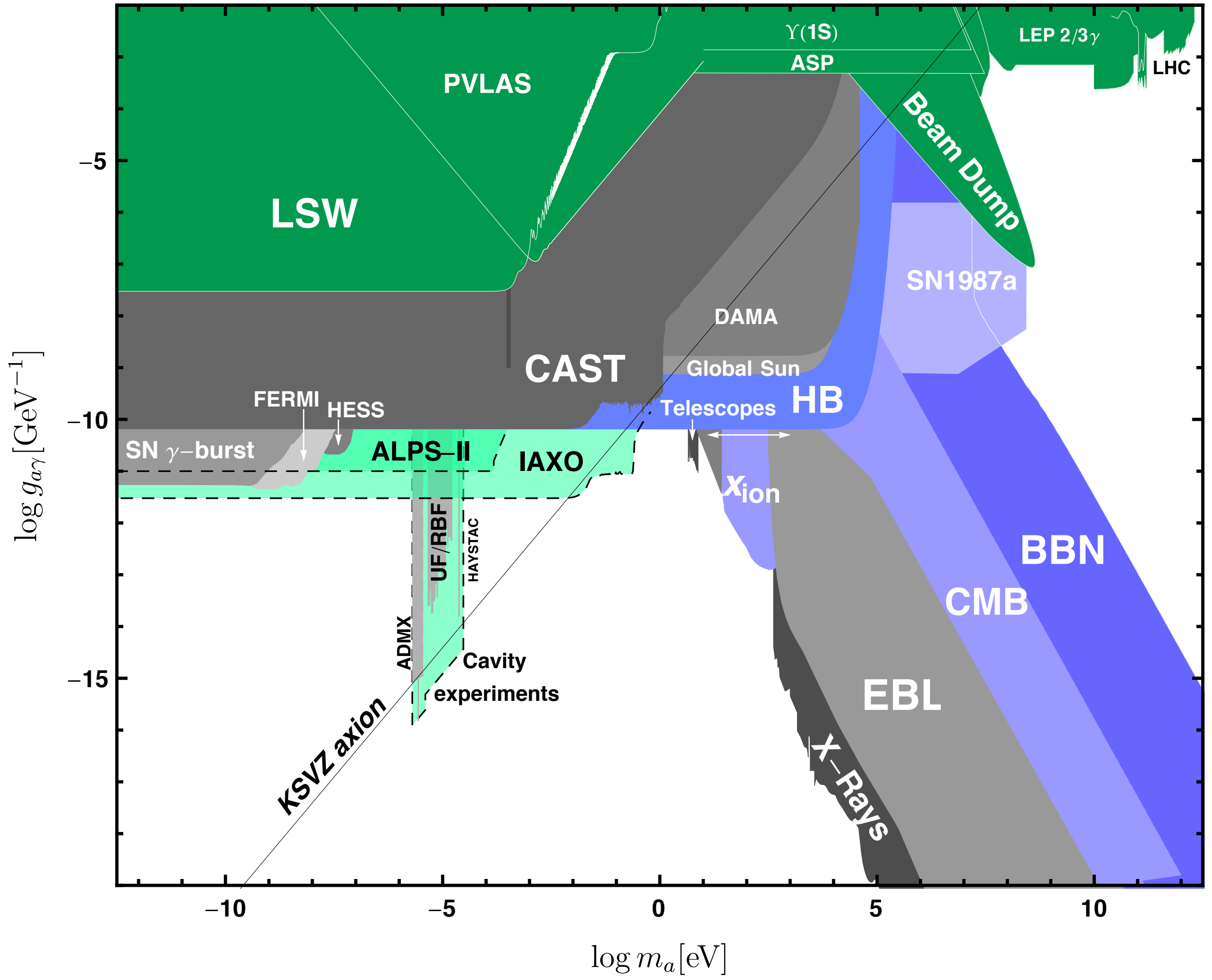
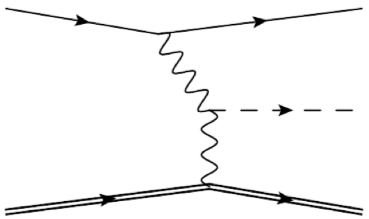
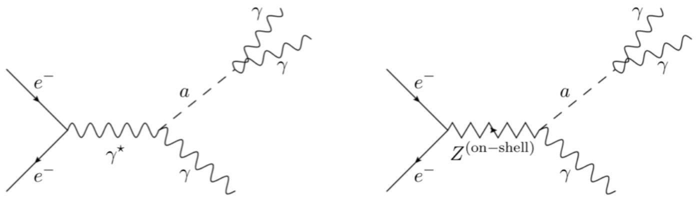


[Brun et al. [MADMAX], 1901.07401]

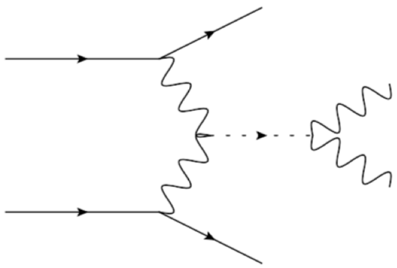
- Beam dumps



- LEP



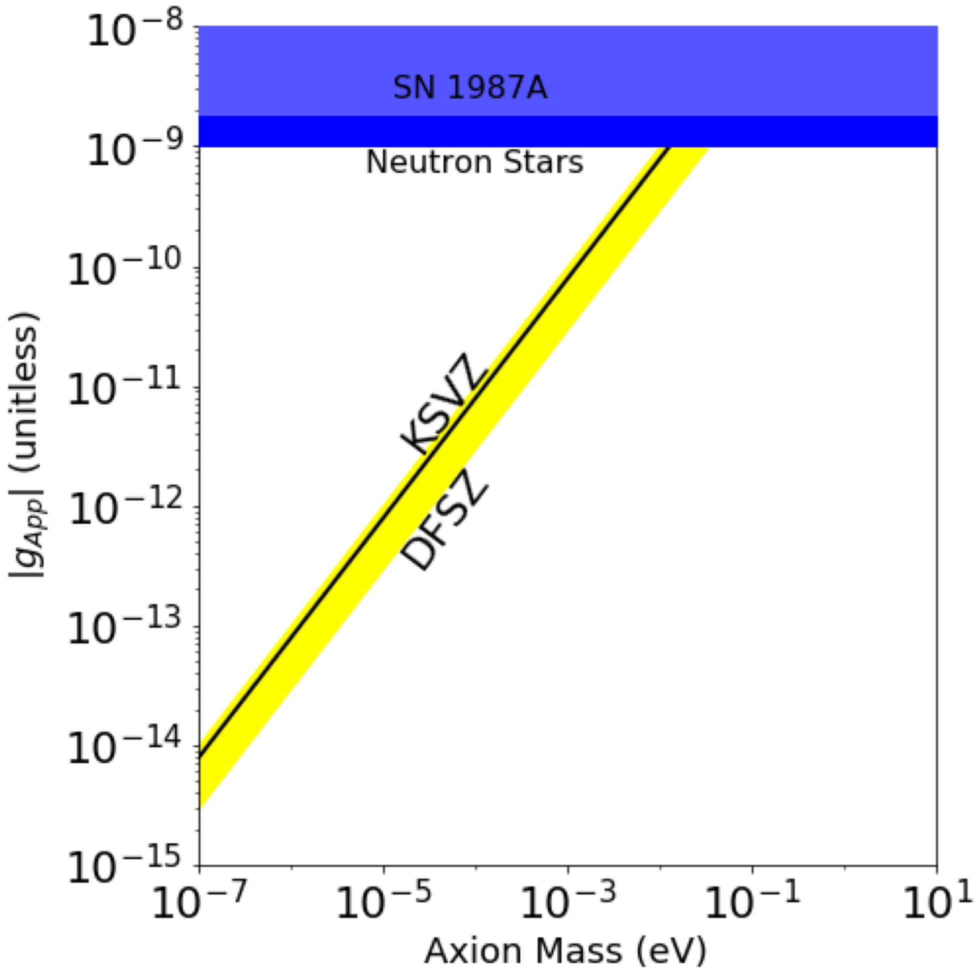
- LHC

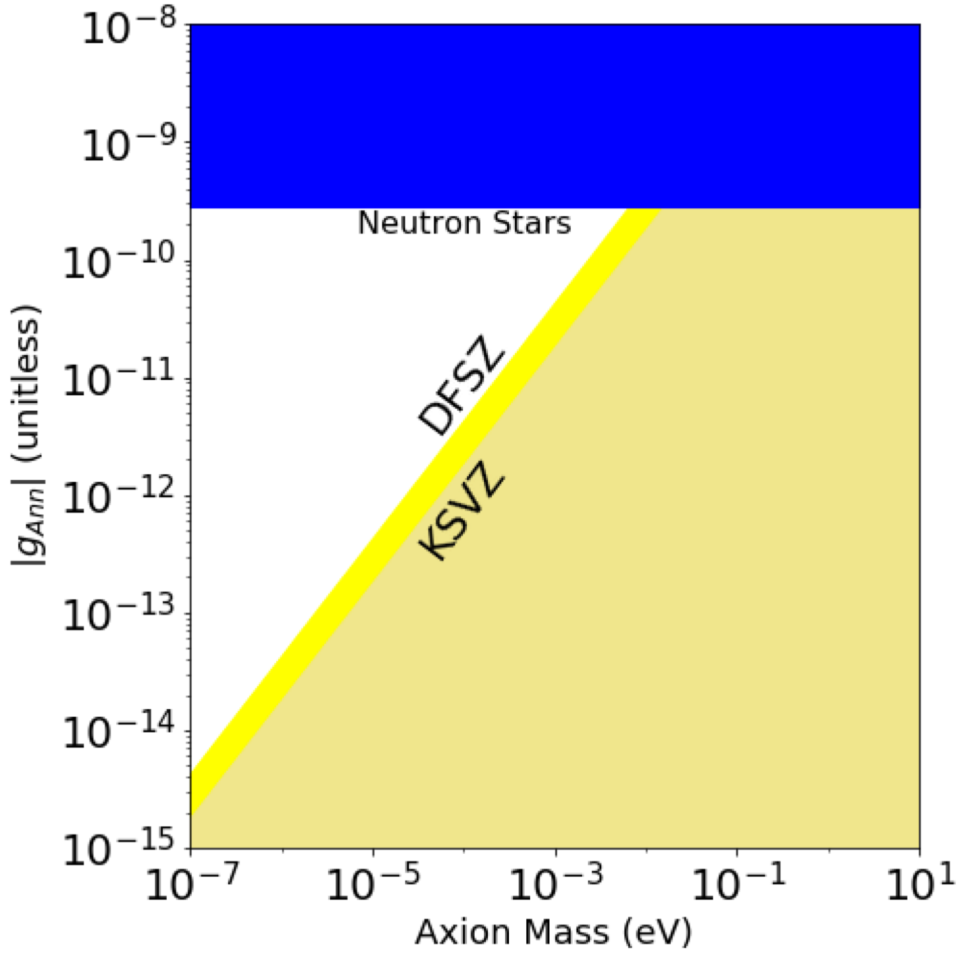


Constraints on Axion/ALP Couplings

Coupling to protons and neutrons

$$g_{ANN} \equiv \frac{m_N}{f_A} C_{AN}$$

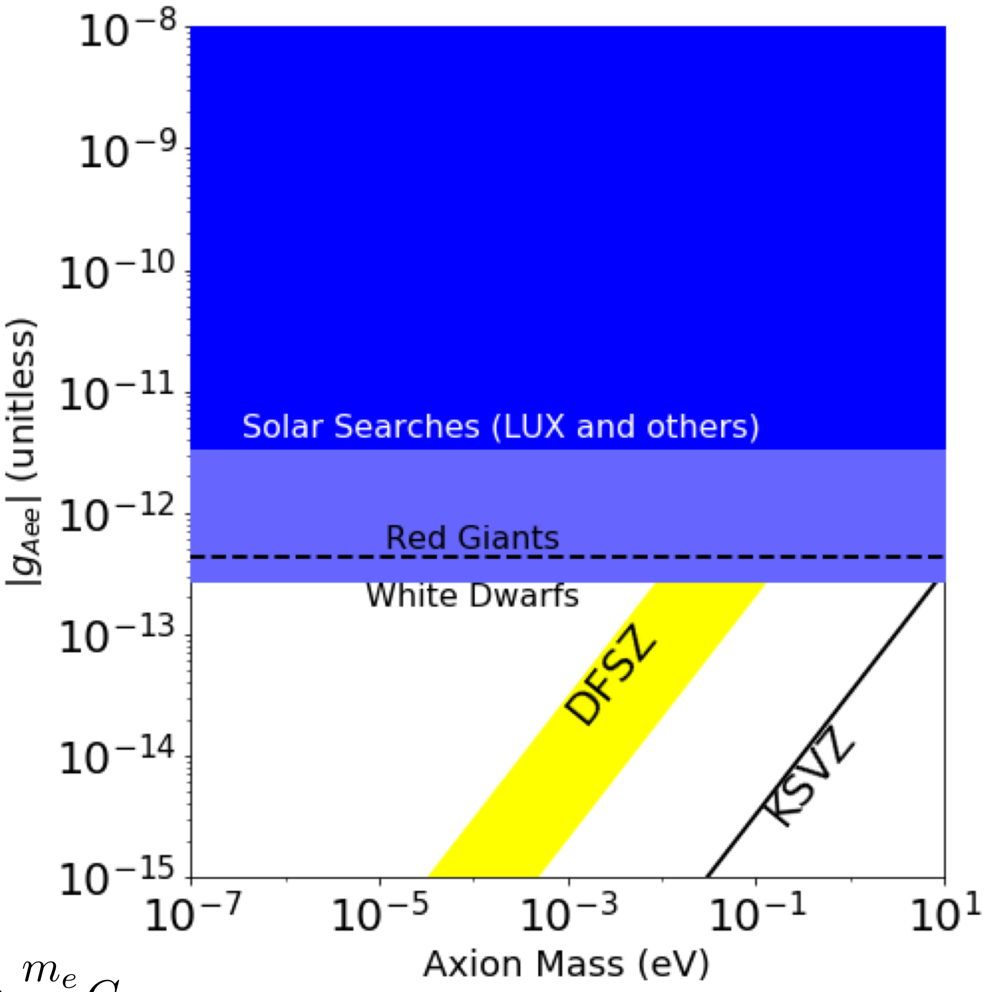


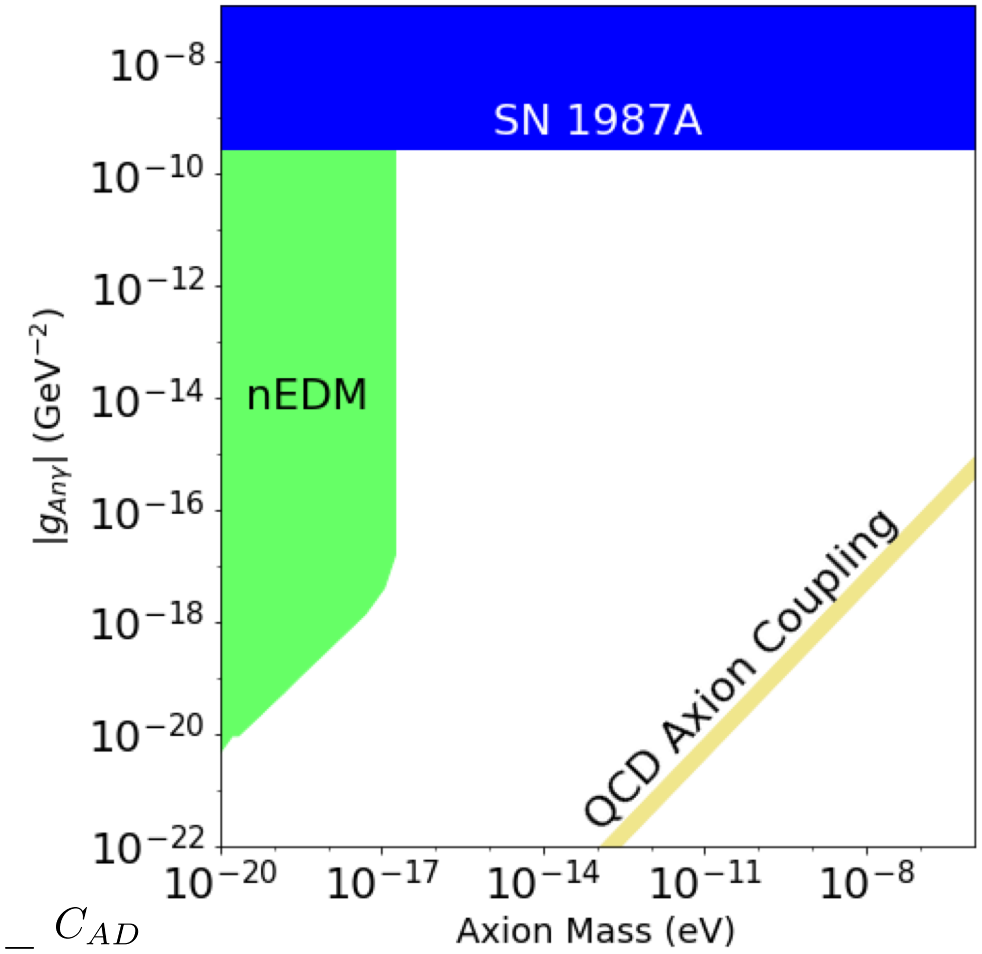


[AR,Rosenberg,Rybka in: Review of Particle Physics, PTEP 2020 (2020) 8, 083C01]

Constraints on Axion/ALP Couplings

Coupling to the electron and the neutron EDM





$$g_{Aee} \equiv \frac{m_e}{f_A} C_{Ae}$$

$$g_{An\gamma} \equiv \frac{C_{AD}}{f_A}$$

[AR,Rosenberg,Rybka in: Review of Particle Physics, PTEP 2020 (2020) 8, 083C01]

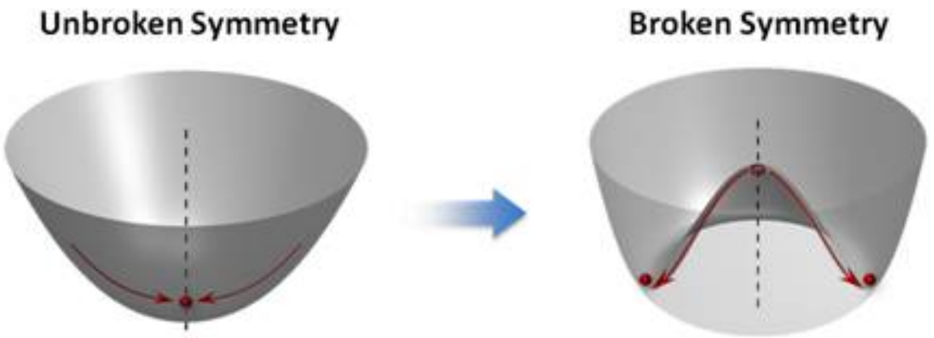
Axion Dark Matter

Vacuum re-alignment mechanism

- PQ phase transition takes place at

$$T \lesssim T_c^{\rm PQ} \sim v_{\rm PQ} = N f_A$$

- Axion takes random initial values in causally connected domains



[Peking University]

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Vacuum re-alignment mechanism

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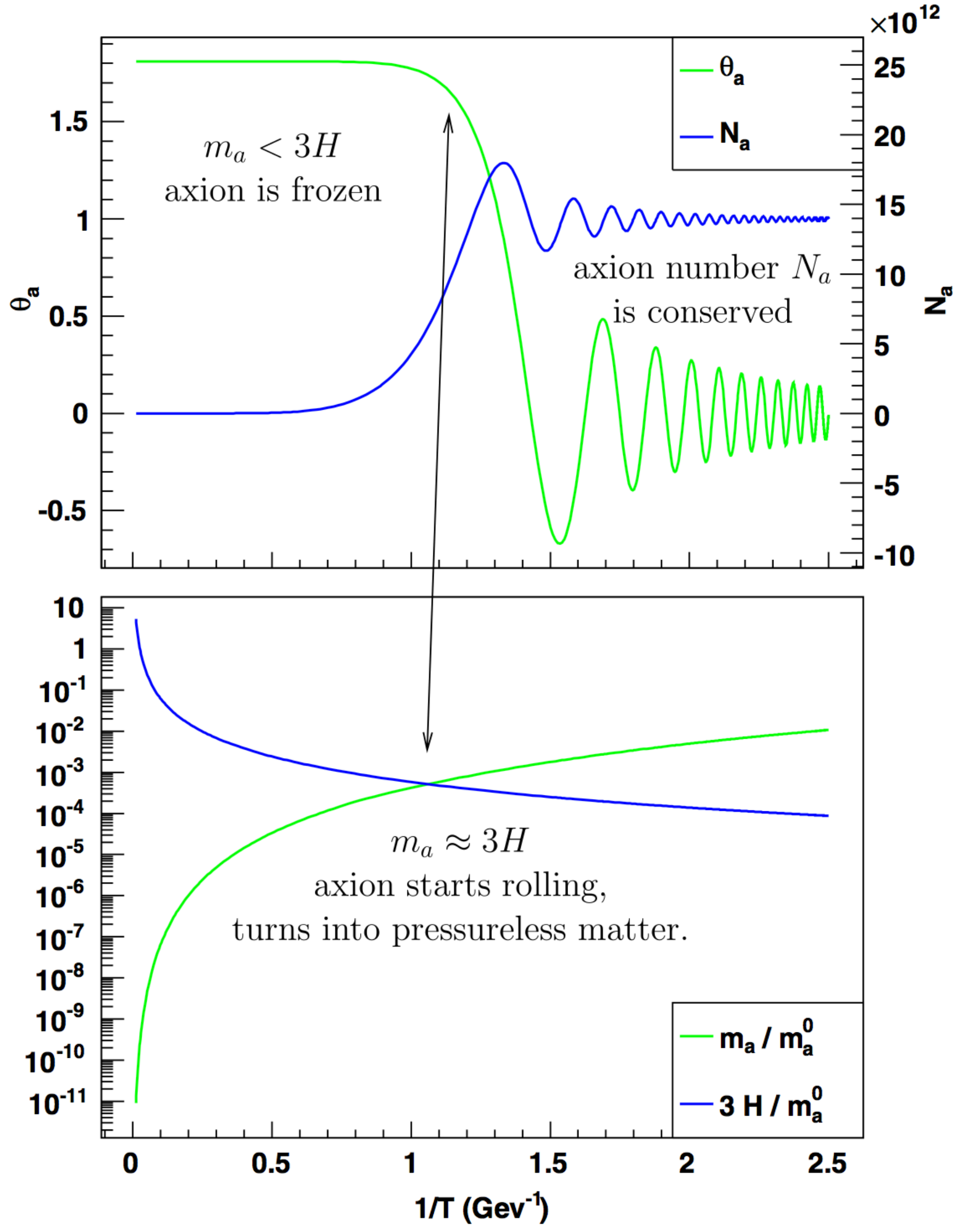
$$T \lesssim T_c^{\rm PQ} \sim v_{\rm PQ} = N f_A$$

- Axion takes random initial values in causally connected domains
- When $H(T) \sim m_A(T)$, axion field starts to oscillate around minimum of potential; behaves like cold dark matter: $w_A = p_A/\rho_A \simeq 0$

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

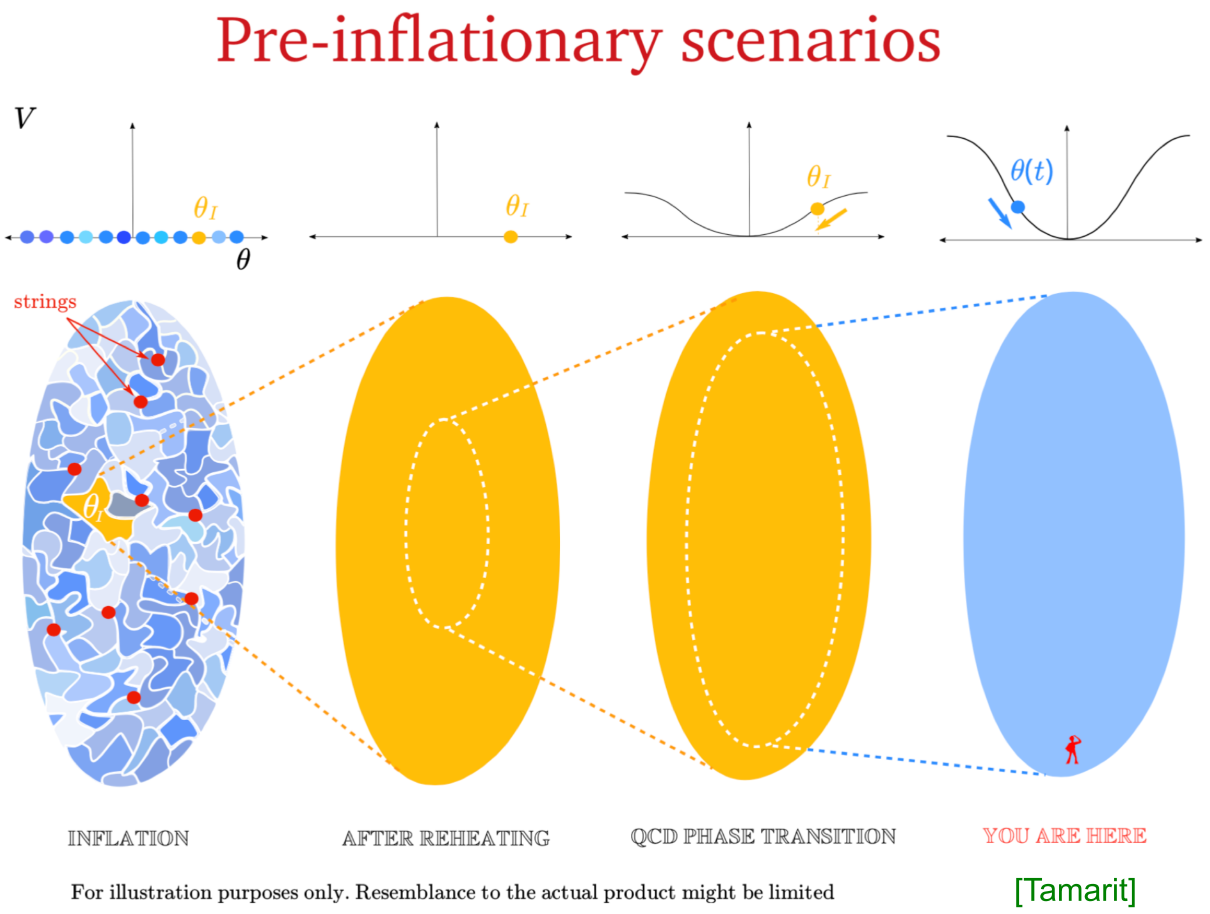


[Wantz,Shellard `09]

Axion Dark Matter

Pre-inflationary PQ SSB scenario

- If PQ symmetry broken before or during inflation $(f_A > H_I/(2\pi))$ and not restored afterwards
  - Axion CDM density depends on single initial value in patch which becomes observable universe and f_A



[Tamarit]

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$$\Omega_A^{\rm vr} h^2 \approx 0.12 \left(\frac{f_A}{9\times 10^{11}\ {\rm GeV}}\right)^{1.165} \theta_{\rm i}^2$$
$$\approx 0.12 \left(\frac{6\ \mu{\rm eV}}{m_A}\right)^{1.165} \theta_{\rm i}^2 \, ,$$

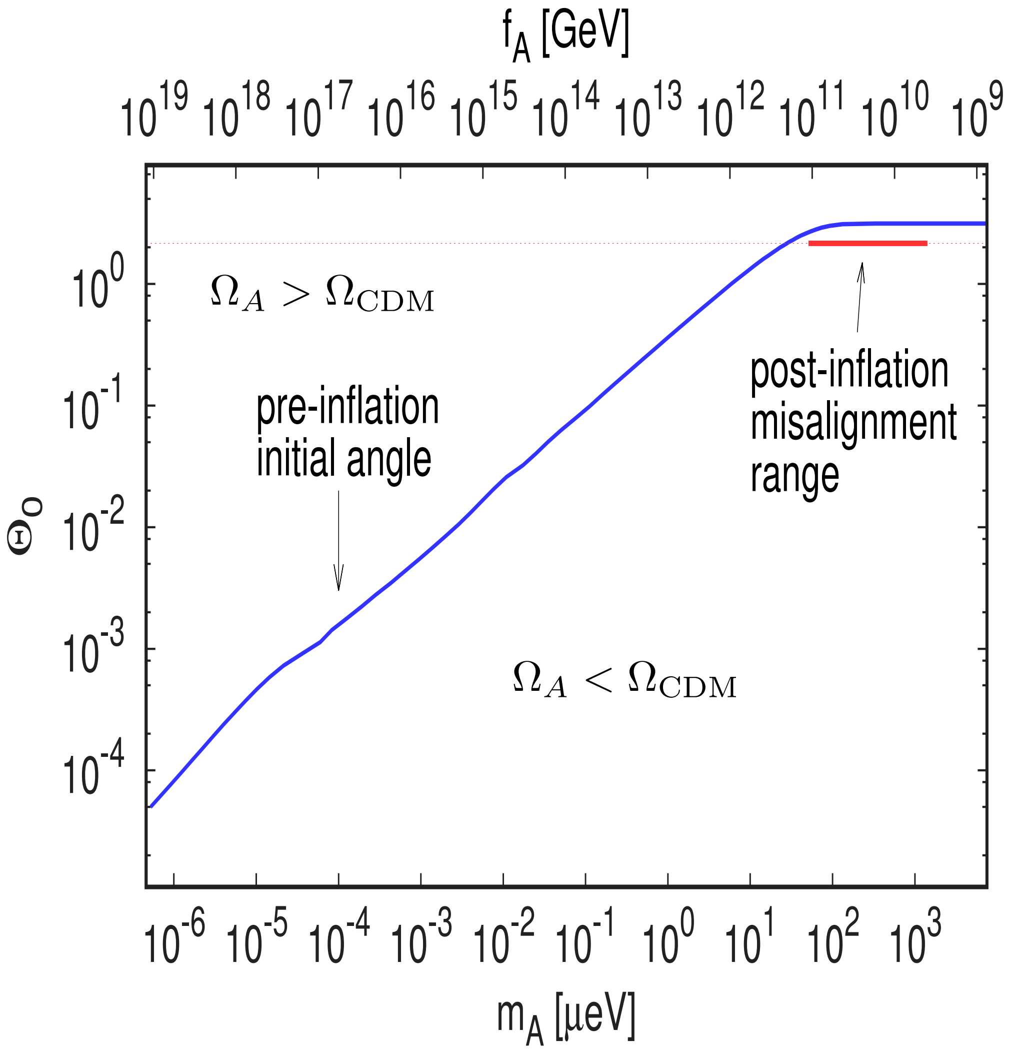
  - VR works also for ALP: [Arias et al., `12]

$$\Omega_A^{\rm vr} h^2 \approx 0.12 \left(\frac{m_A}{\rm neV}\right)^{1/2} \left(\frac{f_A}{4.7\times 10^{13}\,{\rm GeV}}\right)^2 \theta_i^2$$

(if mass independent of decay constant)

  - In general, ALP can be 100 % of DM if

$$f_a \gtrsim 10^9\,{\rm GeV} \left(\frac{\rm neV}{m_a}\right)^{1/2}$$



[Borsanyi et al., Nature `16]

Axion Dark Matter

Post-inflationary PQ SSB scenario

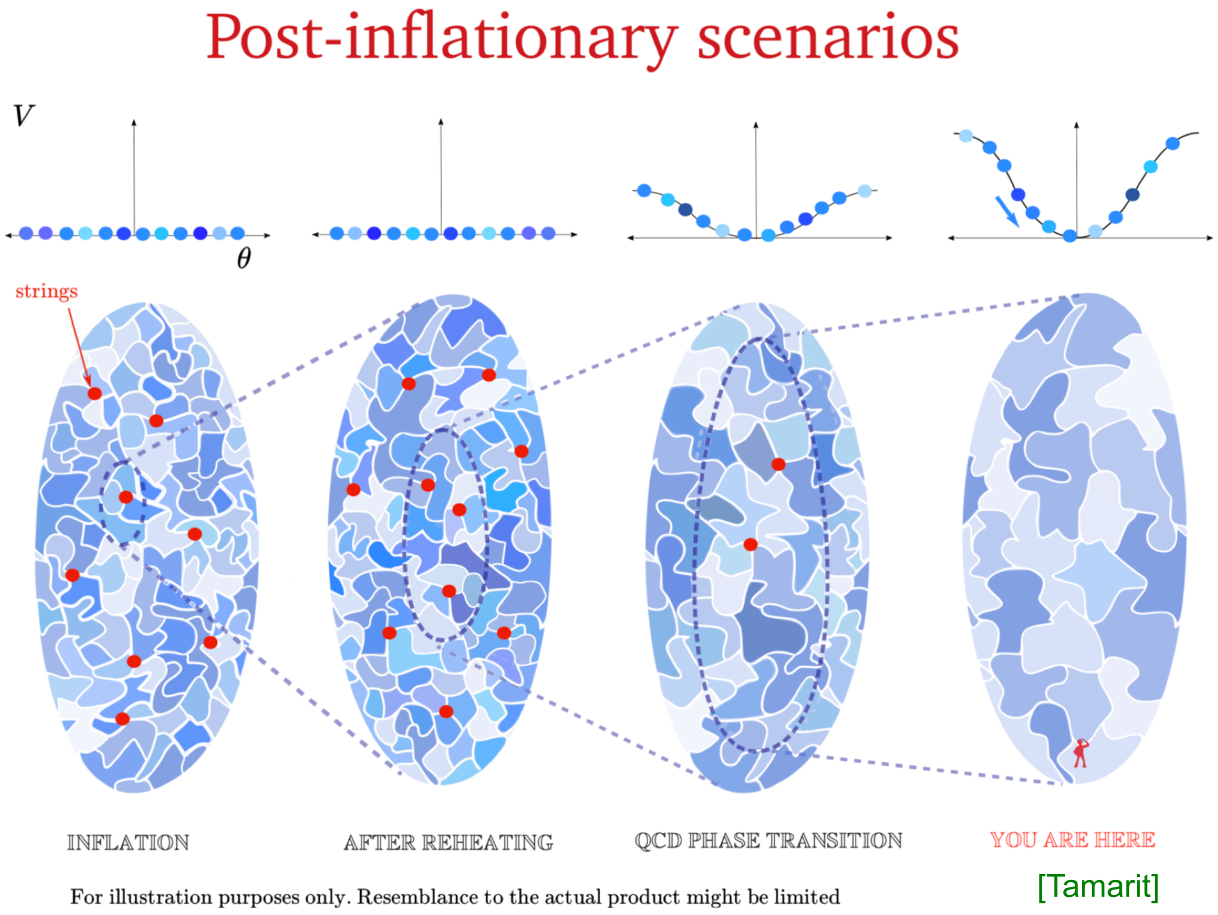
- Averaging over random initial axion field values

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

- Does not exceed observed CDM abundance for

$$m_A > 28(2)\,\mu\text{eV}$$

[Borsanyi et al., Nature `16]



[Tamarit]

Axion Dark Matter

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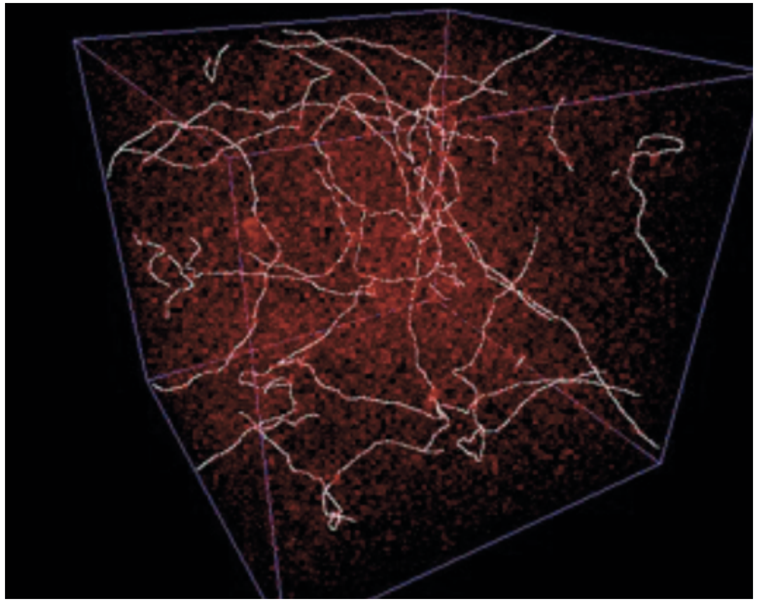
[Borsanyi et al., Nature `16 [1606.0794]]

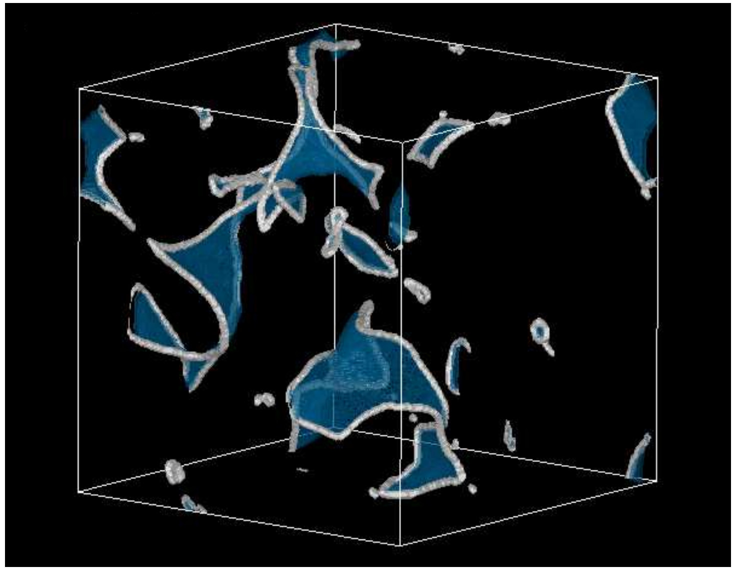
- Axions also produced by collapse of network of topological defects – strings and domain-walls –
- Axion can be 100% of DM for

$$m_A \approx 25\ \mu\text{eV} - 40\ \text{meV}$$

[Hiramatsu et al. 11,12,13;
Kawasaki,Saikawa,Segikuchi 15;
Ballesteros et al. 16;
AR,Saikawa `16;
Klaer,Moore `17;
Gorghetto,Hardy,Villadoro `18;
Buschmann et al. 19;
Hindmarsh 19]



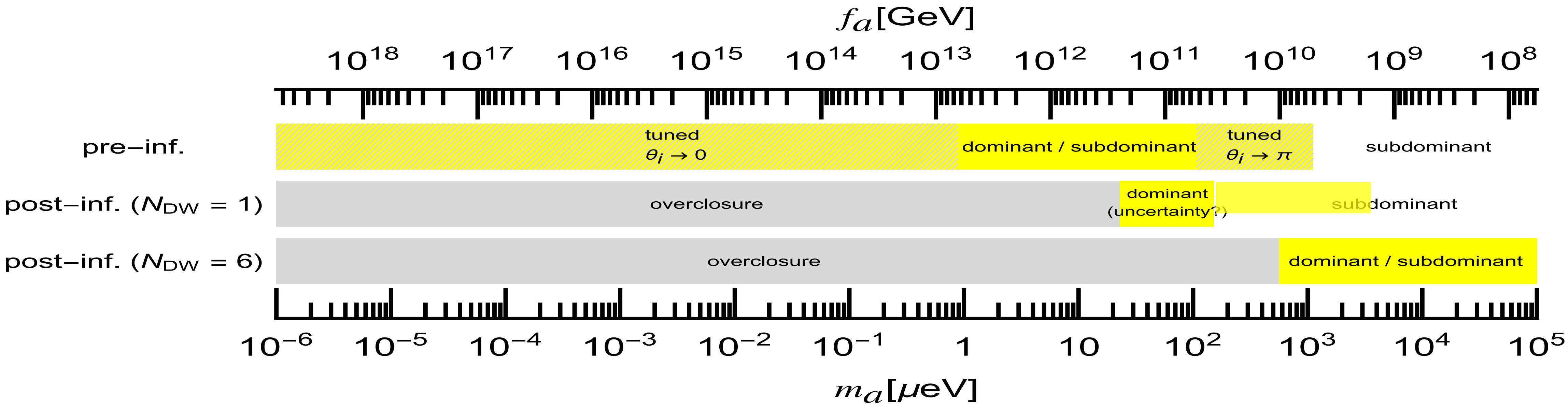
[Hiramatsu et al.]



Axion Dark Matter

Worldwide experimental efforts

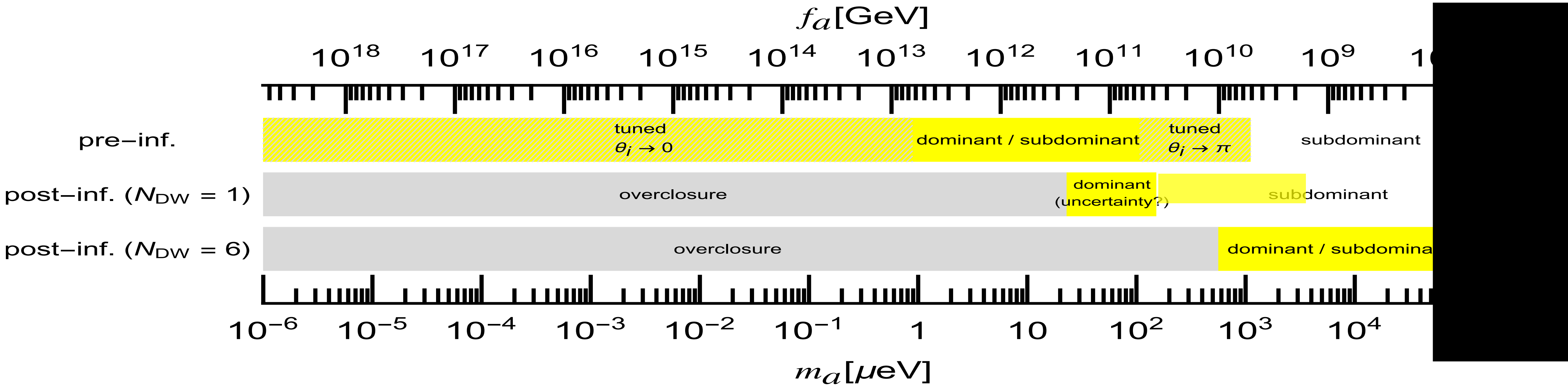
- Dark-matter axion mass spans a huge range:



Axion Dark Matter

Worldwide experimental efforts

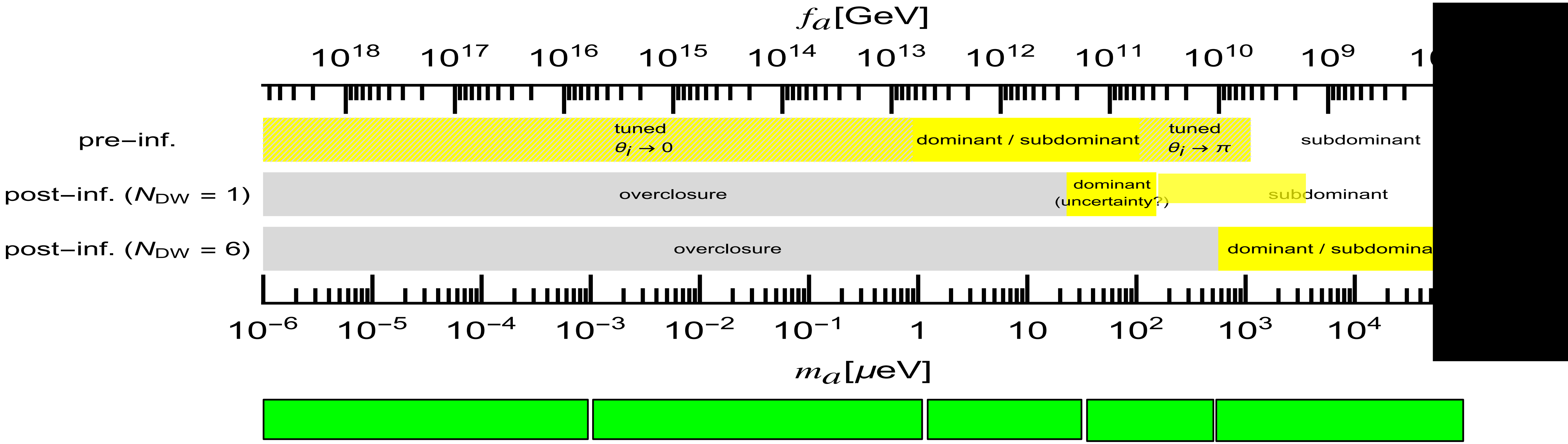
- “Axion revelation“: DM axion mass starts right at border of stellar energy loss exclusion bounds:



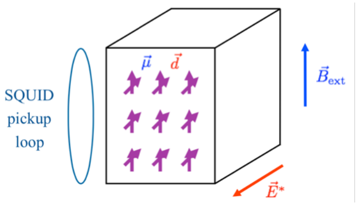
Axion Dark Matter

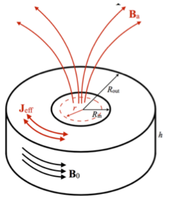
Worldwide experimental efforts

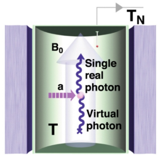
- Strong motivation for current und upcoming axion DM experiments:

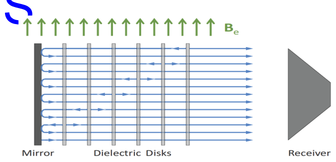


CASPEr | ABRACADABRA | **ADMX** **HAYSTAC** **CAPP** | MADMAX ORPHEUS **ORGAN** QUAX | BRASS





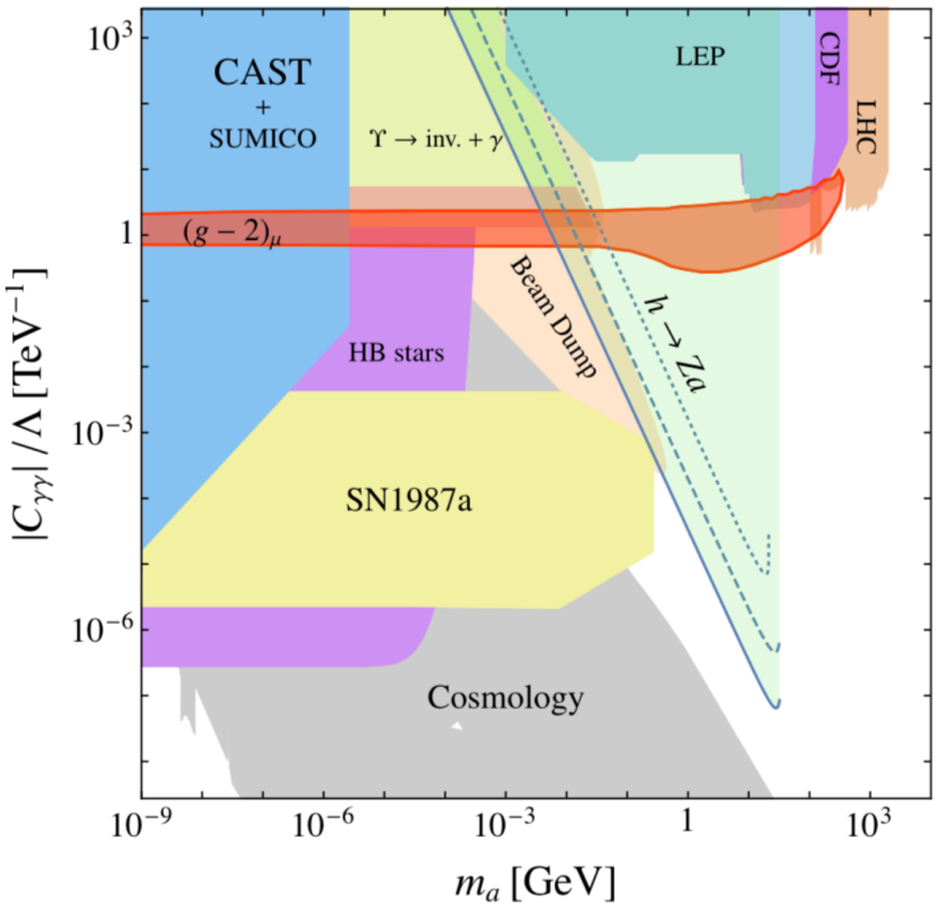




Physics Case for Heavy ALPs

- Heavy ALPs coupling the visible and dark sector attractive for DM phenomenology, because they
  - easily reproduce the observed DM relic abundance from thermal freeze-out,
  - predict, at tree-level, a strong suppression of event rates in direct detection experiments,
  - may allow for observable indirect detection signals

- Heavy ALP with relatively large photon coupling may explain muon g-2 discrepancy [Chang et al. hep-ph/0009292, Marciano et al., 1607.01022]



[Bauer et al., 1704.08207]

Conclusions

- Axion extensions of SM very attractive:
  - Axion solves strong CP puzzle
  - Axion is dark matter candidate (for $f_A \gtrsim 10^8\,\mathrm{GeV} \Leftrightarrow m_A \lesssim 60\,\mathrm{meV}$)
- Boom in axion searches!
- Heavy ALPs also very attractive as
  - DM mediators
  - Solution of muon g-2 puzzle

Axion Dark Matter

Vacuum re-alignment mechanism

- PQ phase transition takes place at

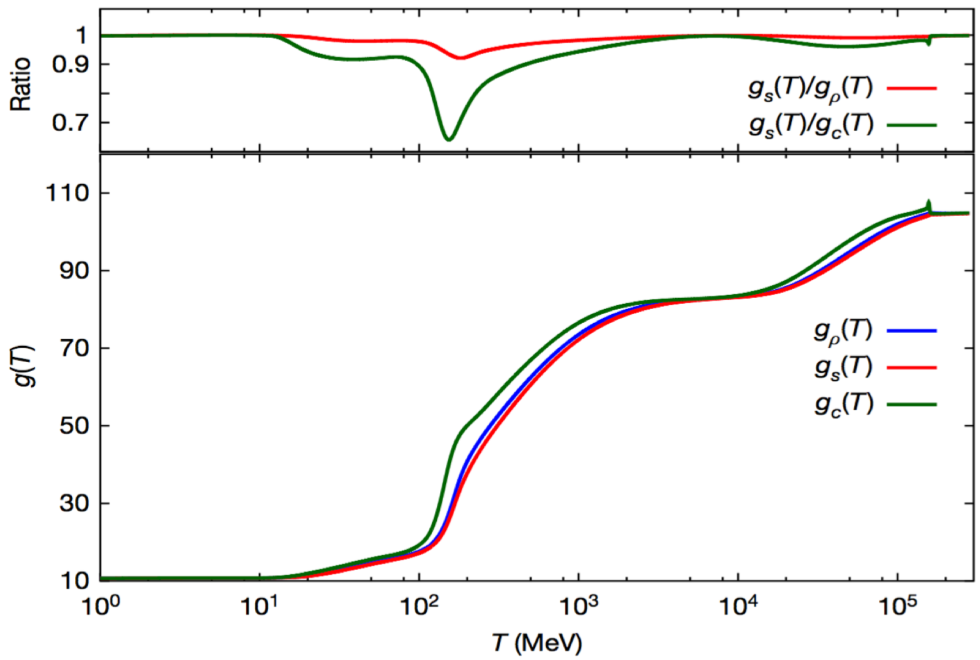
$$T \lesssim T_c^{\rm PQ} \sim v_{\rm PQ} = N f_A$$

- Axion takes random initial values in causally connected domains

- When $H(T) \sim m_A(T)$, axion field starts to oscillate around minimum of potential; behaves like cold dark matter: $w_A = p_A/\rho_A \simeq 0$

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

- QCD input from lattice:
  - Equation of state $\Rightarrow H(T)$



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

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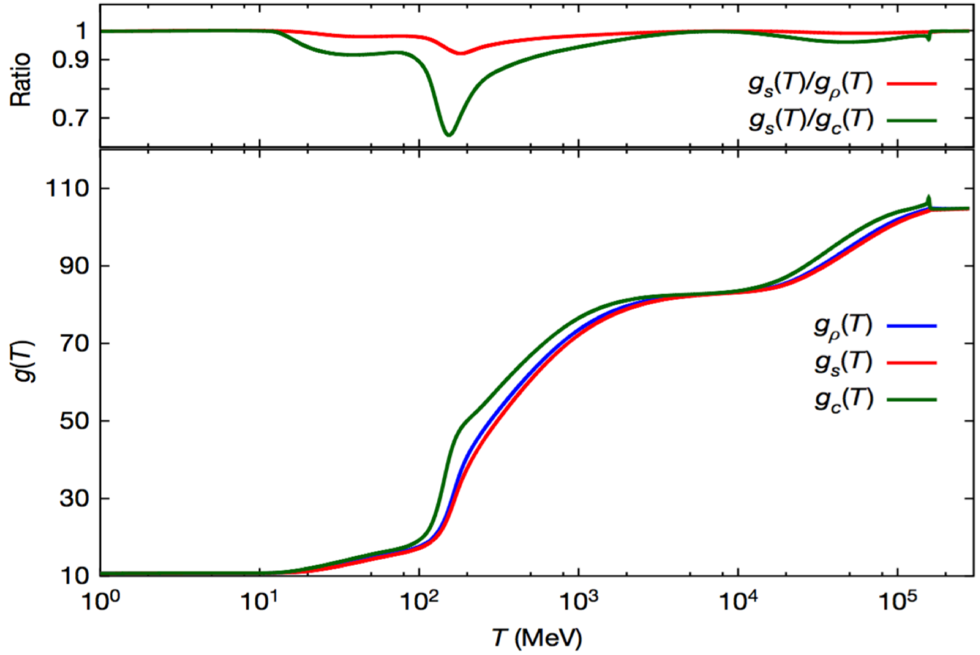
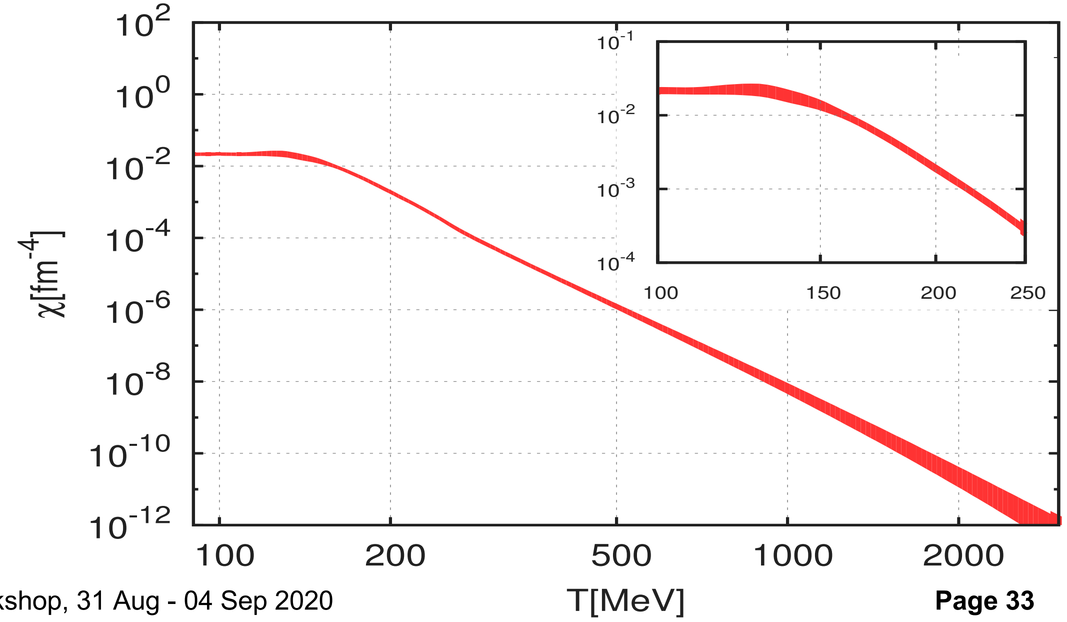
- QCD input from lattice:
  - Equation of state $\Rightarrow H(T)$
  - Topological susceptibility $\Rightarrow m_A(T) = \dfrac{\sqrt{\chi(T)}}{f_A}$



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



Searches for FCNC Interactions

Minimal flavored SMASH

- Introduce right-handed singlet neutrinos N_α and complex scalar field σ with flavor-dependent spontaneously broken global chiral $U(1)_{\rm FN}$ Froggatt-Nielsen (FN) symmetry
  - Explains SM fermionic mass hierarchies and mixings by FN mechanism
  - Explains neutrino masses and mixing by seesaw
  - FN symmetry is at the same time a PQ symmetry
    - Nambu-Goldstone boson of FN breaking solves also strong CP problem ("axion"): "flaxion" or "axiflavon"
  - Flaxion has flavor changing neutral current (FCNC) interactions
    - Currently best bound from ${\rm Br}\,(K^+\to\pi^+ A)\lesssim 7.3\times 10^{-11}$

$$\Rightarrow \quad f_A \gtrsim 2\times 10^{10}\,{\rm GeV}\left(\frac{26}{N_{\rm DW}}\right)\left|\frac{(\kappa^d_{\rm ah})_{12}}{m_s}\right|$$

[Ema et al., 1612.05492;1802.07739; Calibbi et al., 1612.08040]

- Flaxion properties:
  - Decay constant:

$$f_A=\frac{v_{\rm FN}}{N_{\rm DW}},\qquad N_{\rm DW}={\rm Tr}\,(n^u+n^d)$$

  - Typically large domain wall number
    - Viable example:

$$\begin{pmatrix} q_{Q_1} & q_{Q_2} & q_{Q_3}\\ q_u & q_c & q_t\\ q_d & q_s & q_b\end{pmatrix}=\begin{pmatrix} 3 & 2 & 0\\ -5 & -1 & 0\\ -4 & -3 & -3\end{pmatrix}$$

$$\begin{pmatrix} q_{L_1} & q_{L_2} & q_{L_3}\\ q_e & q_\mu & q_\tau\end{pmatrix}=\begin{pmatrix} 1 & 0 & 0\\ -8 & -5 & -3\end{pmatrix}$$

$$\Rightarrow\quad n^u_{ij}=\begin{pmatrix} 8 & 4 & 3\\ 7 & 3 & 2\\ 5 & 1 & 0\end{pmatrix},\quad n^d_{ij}=\begin{pmatrix} 7 & 6 & 6\\ 6 & 5 & 5\\ 4 & 3 & 3\end{pmatrix},\quad n^l_{ij}=\begin{pmatrix} 9 & 6 & 4\\ 8 & 5 & 3\\ 8 & 5 & 3\end{pmatrix}$$

$$\Rightarrow N_{\rm DW}=26$$

  - Coupling to photon:

$$C_{A\gamma}=\frac{2}{N_{\rm DW}}\sum_{f=u,d,l}\left[N_f{\rm Tr}\,(n^f)\left(q_f^{(\rm em)}\right)^2\right]-1.92(2)$$

  - For example above: $C_{A\gamma}=113/39-1.92\simeq 0.97$

- NA62: reach in decay constant increased by order of magnitude!