Dark-Matter Axion Mass.

Andreas Ringwald (DESY)

Workshop on Ultralight Dark Matter and Axions
Ann Arbor, MI, USA
5-7 March 2018

HELMHOLTZ | ASSOCIATION

DESY

Strong Case for Particles Beyond the Standard Model

> Standard Model (SM) of particle physics describes properties of known matter and forces to a great precision

> SM describes only about 15% of matter content of Universe

Dark Matter 26.8%

Ordinary Matter 4.9%

Dark Energy 68.3%
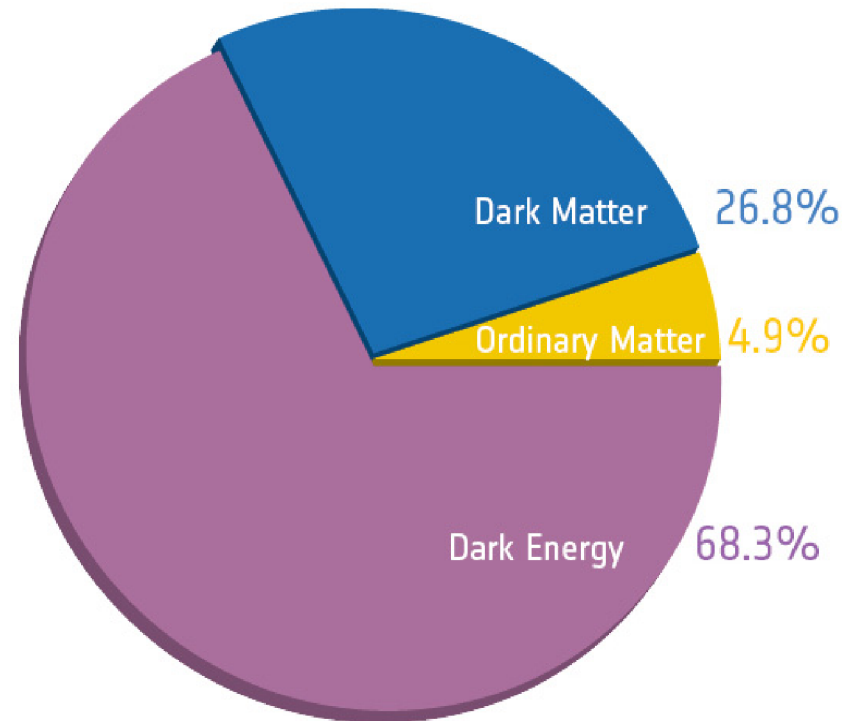
[PLANCK]

Strong Case for Particles Beyond the Standard Model

> Standard Model (SM) of particle physics describes properties of known matter and forces to a great precision

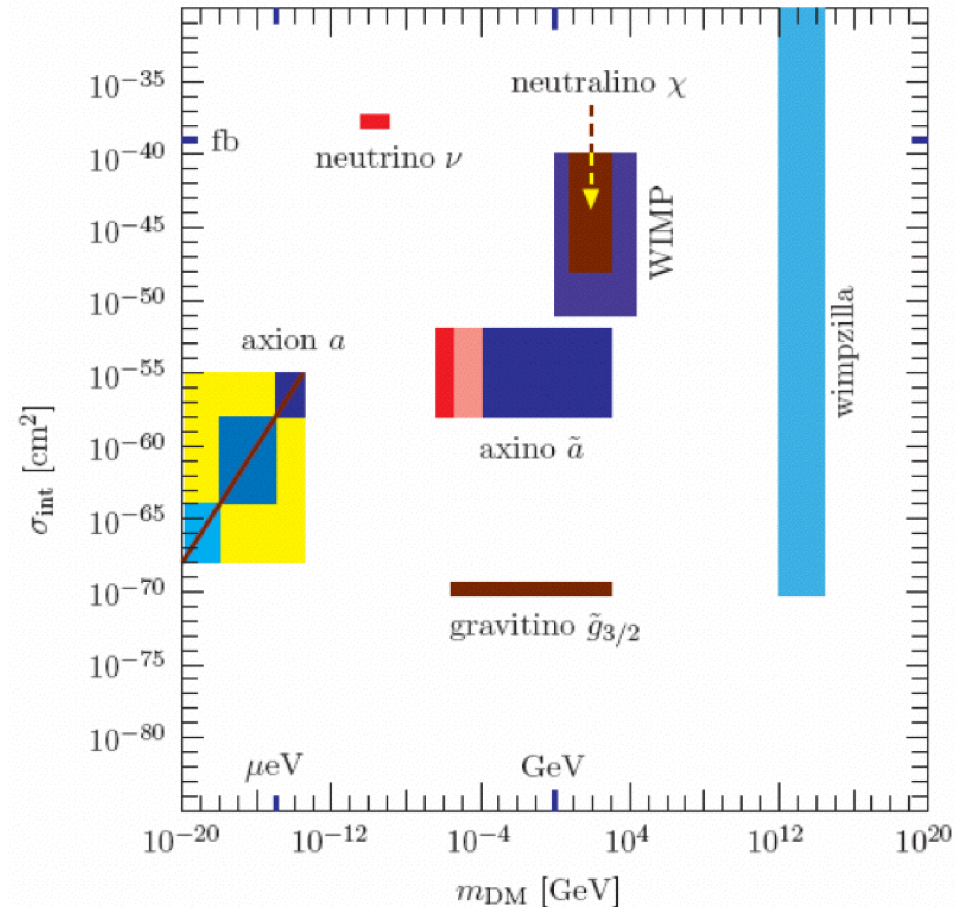> SM describes only about 15% of matter content of Universe

> Theorists have proposed plenitude of DM candidates, spanning a large parameter space in mass and interaction strength

> Best motivated candidates those which occur in SM extensions solving also other problems, such as

- Hierarchy problem: Neutralino in MSSM
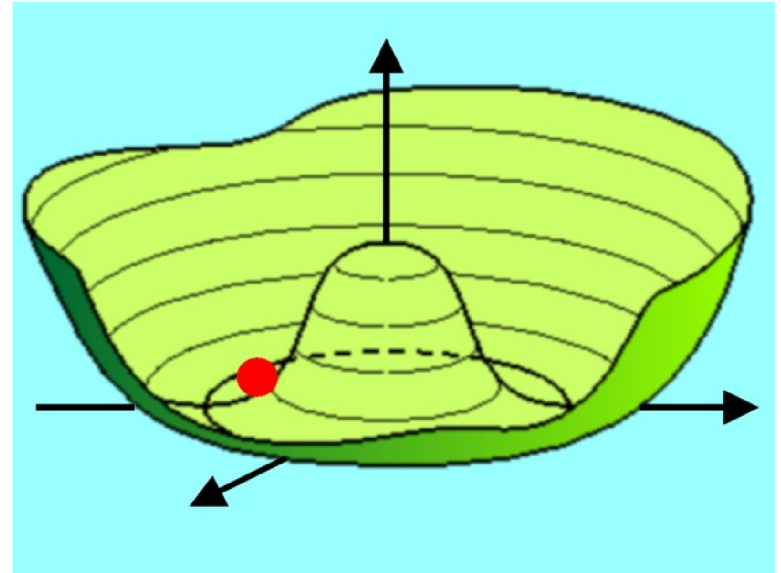
- Strong CP problem: Axion in PQSM

[Kim,Carosi 10]

> A singlet complex scalar field σ featuring a global $U(1)_{\mathrm{PQ}}$ symmetry is added to SM

> Symmetry is broken by vev $\langle\sigma\rangle = v_{\mathrm{PQ}}/\sqrt{2}$

$$\sigma(x) = \frac{1}{2}\left(v_{\mathrm{PQ}} + \rho(x)\right) e^{\mathrm{i}A(x)/v_{\mathrm{PQ}}}$$

- Excitation of modulus: $m_\rho \sim v_{\mathrm{PQ}}$

- Excitation of angle: NGB $m_A = 0$

[Raffelt]

PQSM: Peccei-Quinn Extensions of the Standard Model

> A singlet complex scalar field σ featuring a global $U(1)_{\mathrm{PQ}}$ symmetry is added to SM
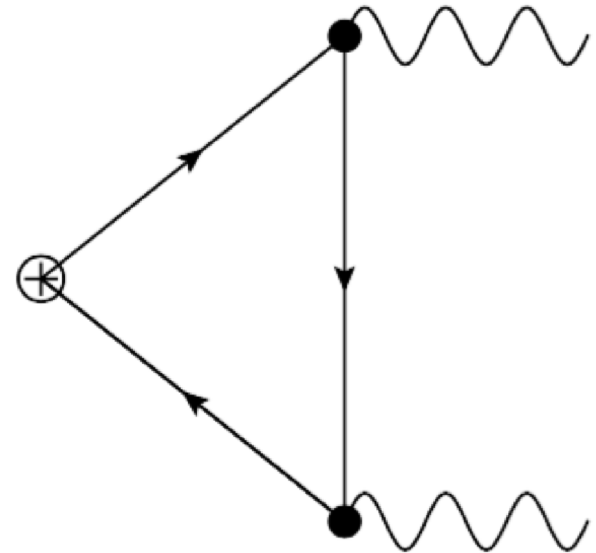
> Symmetry is broken by vev $\langle \sigma \rangle = v_{\mathrm{PQ}}/\sqrt{2}$

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

- Excitation of modulus: $m_\rho \sim v_{\mathrm{PQ}}$

- Excitation of angle: NGB $m_A = 0$

> Quarks (SM or extra) carry PQ charges such that $U(1)_{\mathrm{PQ}}$ is anomalously broken due to gluonic triangle anomaly:

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

> A singlet complex scalar field σ featuring a global $U(1)_{\mathrm{PQ}}$ symmetry is added to SM

> Symmetry is broken by vev $\langle\sigma\rangle = v_{\mathrm{PQ}}/\sqrt{2}$

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

- Excitation of modulus: $m_\rho \sim v_{\mathrm{PQ}}$
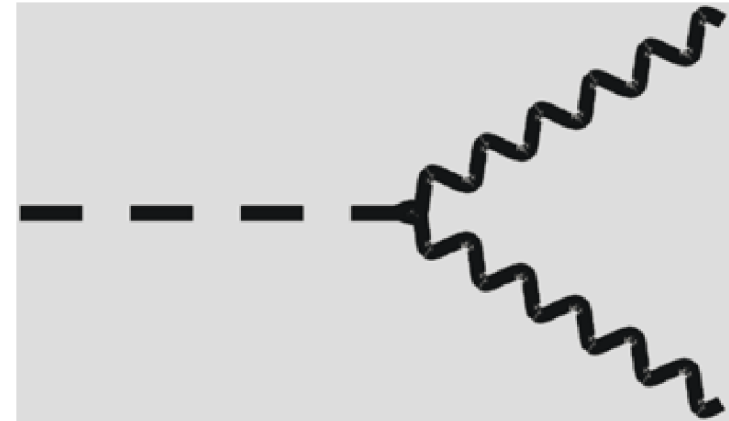
- Excitation of angle: NGB $m_A = 0$

> Quarks (SM or extra) carry PQ charges such that $U(1)_{\mathrm{PQ}}$ is anomalously broken due to gluonic triangle anomaly:

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

> Low energy effective field theory at energies below v ($\ll v_{\mathrm{PQ}}$), but above Λ_{QCD},

[Peccei,Quinn 77; Weinberg 78; Wilczek 78]

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

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

Axionic Solution of Strong CP Problem

> Can eliminate QCD theta term,

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

$$\theta(x) \equiv A(x)/f_A$$

by shift $\theta(x) \to \theta(x) - \overline{\theta}$
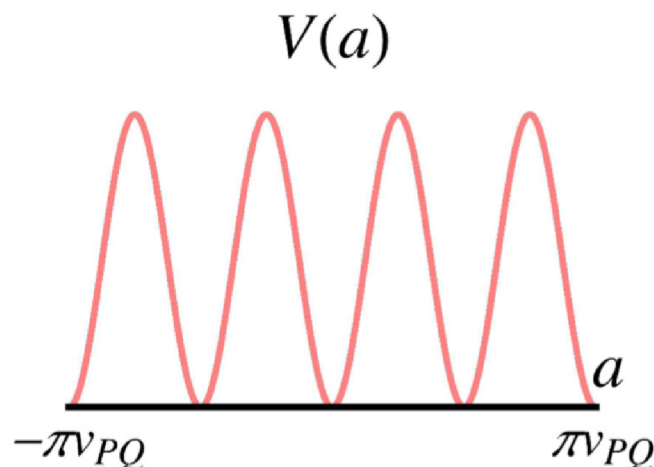
> Effective potential at energies below Λ_{QCD},

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

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

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

has absolute minimum at $\theta = 0$ and thus predicts vanishing vev, $\langle \theta(x) \rangle = 0$

[Peccei,Quinn 77]

$V(a)$

$-\pi v_{PQ}$ πv_{PQ}

Axionic Solution of Strong CP Problem

> Can eliminate QCD theta term,

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

$$\theta(x) \equiv A(x)/f_A$$

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

> Effective potential at energies below Λ_{QCD},

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

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

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

has absolute minimum at $\theta = 0$ and thus predicts vanishing vev, $\langle\theta(x)\rangle = 0$

[Peccei,Quinn 77]

> Particle excitation: pseudo NG boson "axion"   [Weinberg 78; Wilczek 78]

> Mass: $m_A \simeq \dfrac{\sqrt{\Sigma}}{f_A}\sqrt{\dfrac{m_u m_d}{m_u + m_d}} \simeq \dfrac{m_\pi f_\pi}{f_A}\dfrac{\sqrt{m_u m_d}}{m_u + m_d} \simeq 6\ \mathrm{meV}\left(\dfrac{10^9\ \mathrm{GeV}}{f_A}\right)$

  ▪ Precisely (NLO CPT; Lattice QCD):

  $$m_A = 57.0(7)\left(\frac{10^{11}\ \mathrm{GeV}}{f_A}\right)\mu\mathrm{eV}$$

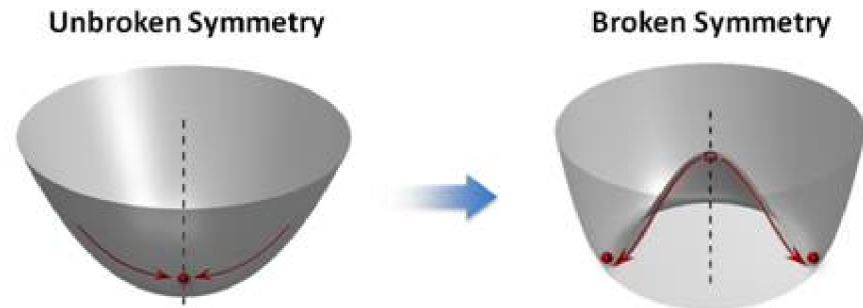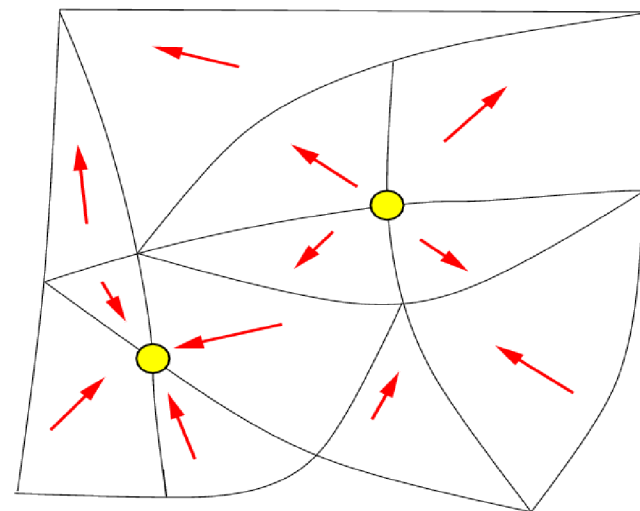[Grilli di Cortona et al. `16 ; Borsanyi et al. `16]

Axion Cold Dark Matter

> Axion field is born after PQ sym-
metry breaking

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

> In causally connected regions at
phase transition, axion takes
random initial values

Unbroken Symmetry   Broken Symmetry

[Peking University]

[Uhlmann et al. `10]

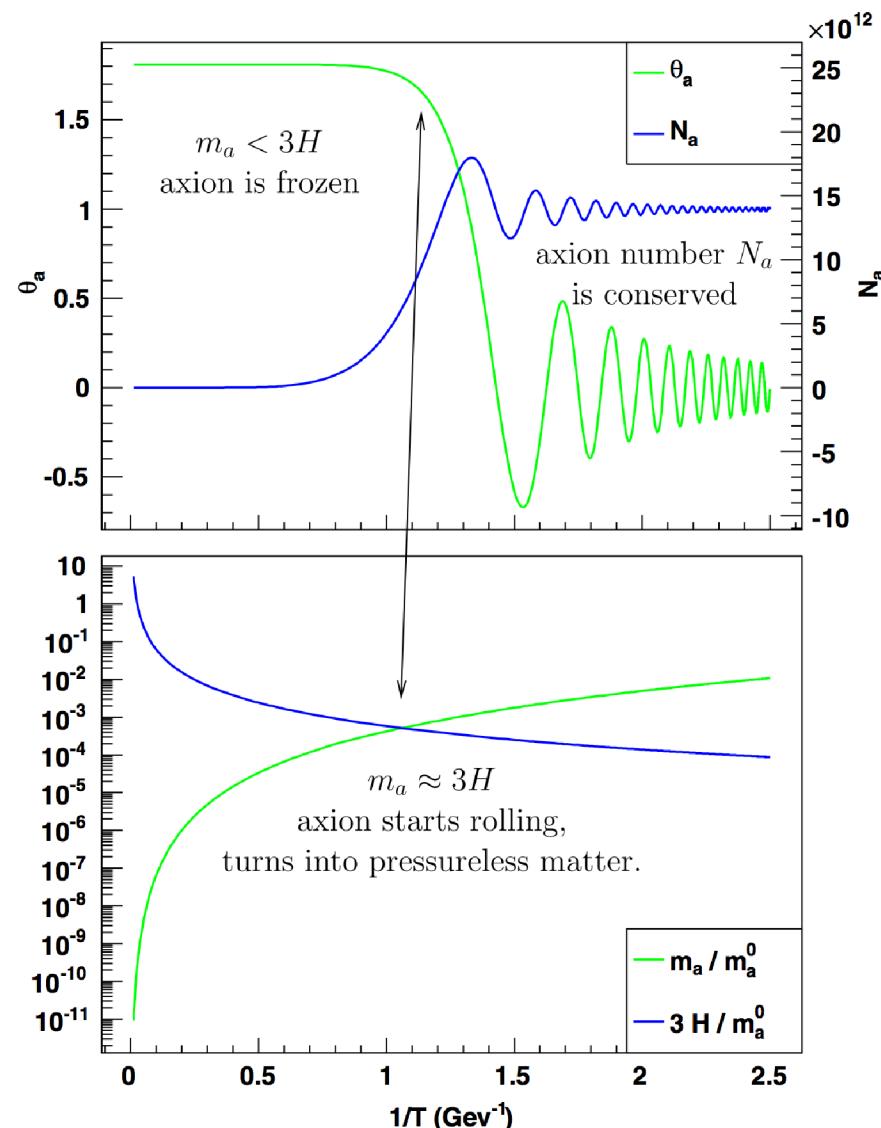> Axion field is born after PQ sym-metry breaking

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

> In causally connected regions at phase transition, axion takes random initial values and stucks

> Later 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 Cold Dark Matter

> Precise determination of evolu-
tion needs QCD input:

1. Equation of state at temperatu-
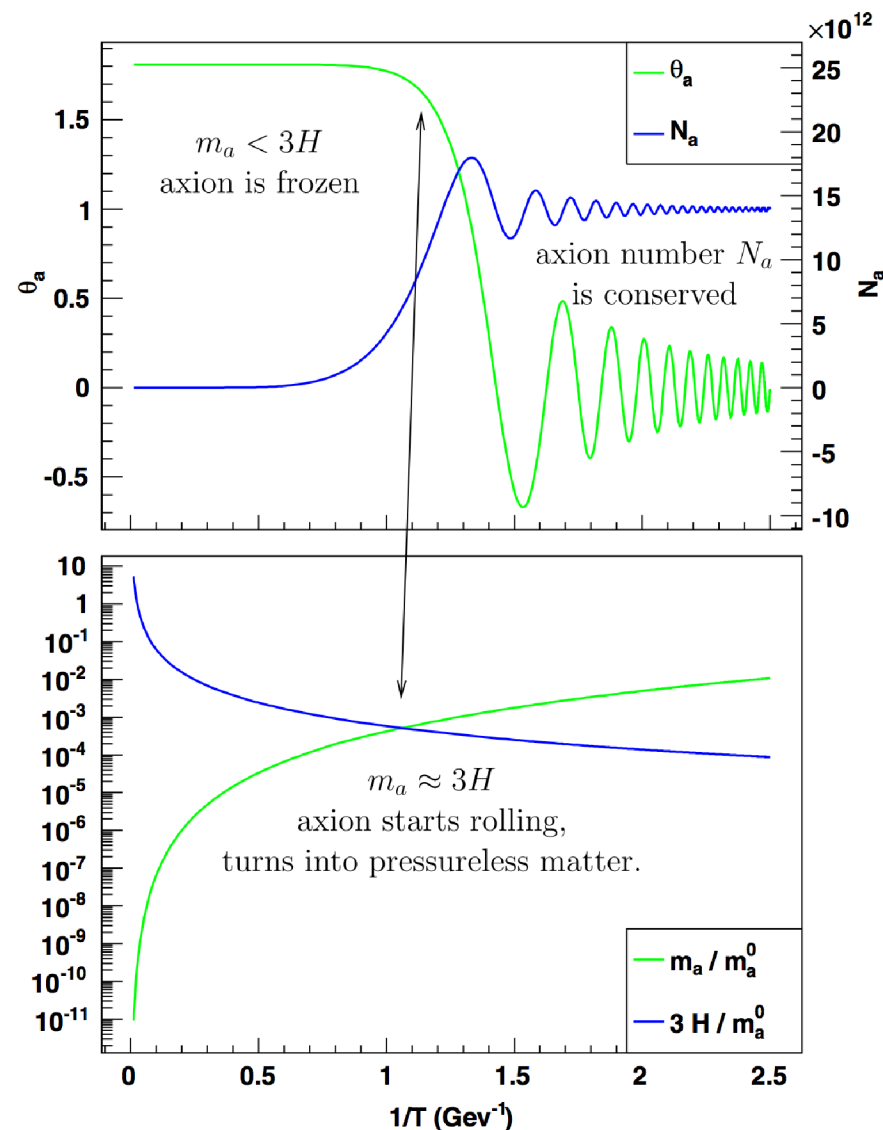   res around 1 GeV: determines

$$H(T)$$

2. Topological susceptibility:

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

determines

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

$m_a < 3H$
axion is frozen

axion number N_a
is conserved

$m_a \approx 3H$
axion starts rolling,
turns into pressureless matter.

[Wantz,Shellard `09]

> Precise determination of evolution needs QCD input:

1. Equation of state at temperatures around 1 GeV: determines
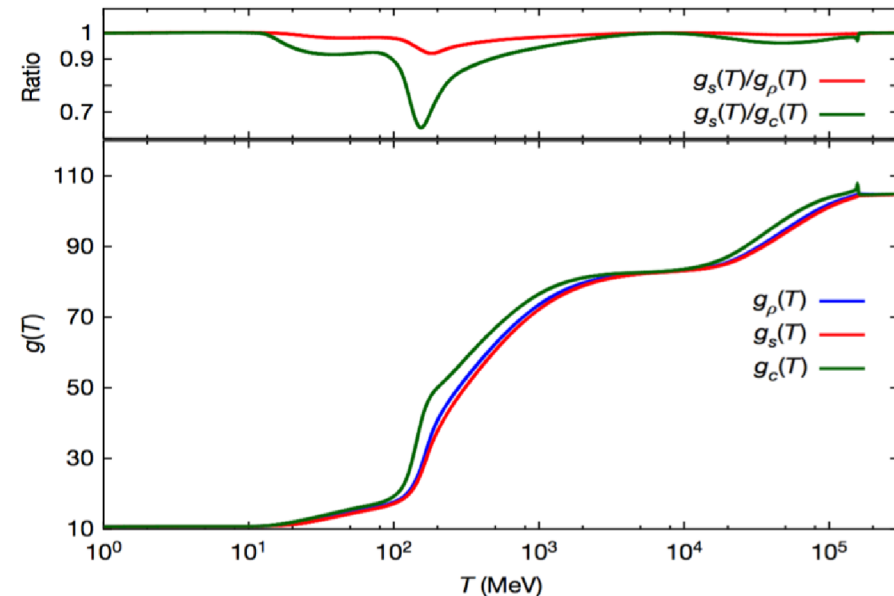
$$H(T)$$

2. Topological susceptibility:

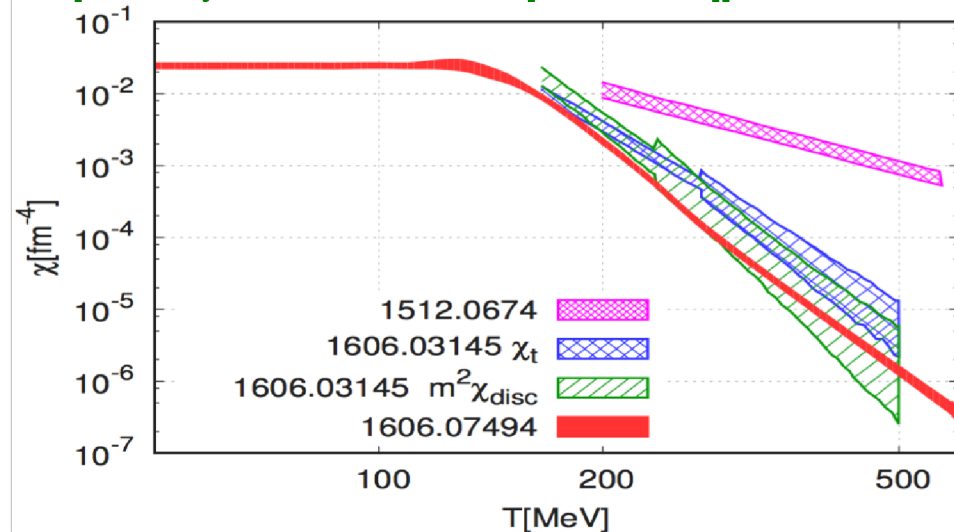$$\chi(T) \equiv \int d^4x \langle q(x)q(0)\rangle_T$$

determines

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

> Both obtained recently with high precision via lattice QCD

  ▪ Temperature slope of $\chi(T)$ remarkably close to prediction from dilute instanton gas; latter underestimates normalization by factor of order ten

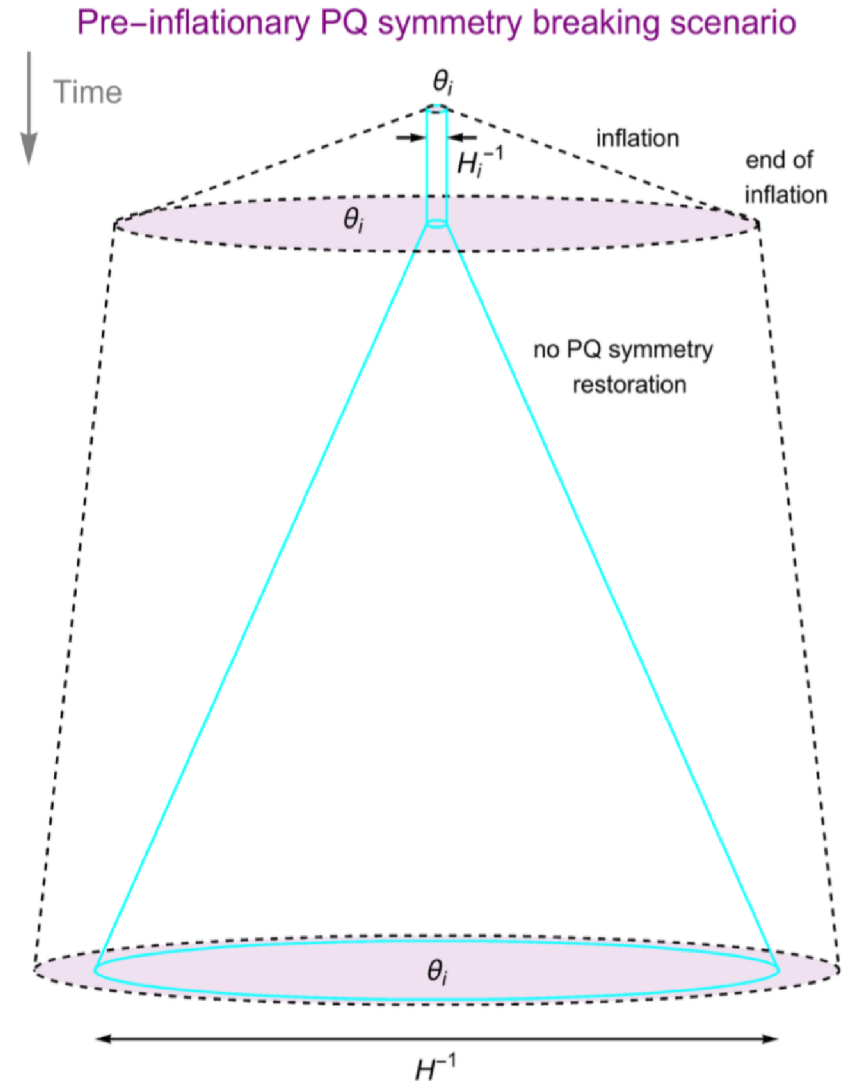[Borsanyi et al., Nature `16 [1606.0794]]

Axion Cold Dark Matter

> If PQ symmetry broken before or during inflation ($f_A > H_I/(2\pi)$) and not restored afterwards (pre-inflationary PQ breaking scenario):

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

- Axion CDM density depends on single initial value in patch which becomes observable universe and f_A :

$$\Omega_A^{\mathrm{vr}} h^2 \approx 0.12 \left(\frac{f_A}{9 \times 10^{11} \ \mathrm{GeV}} \right)^{1.165} \theta_{\mathrm{i}}^2$$

$$\approx 0.12 \left(\frac{6 \ \mu\mathrm{eV}}{m_A} \right)^{1.165} \theta_{\mathrm{i}}^2 ,$$

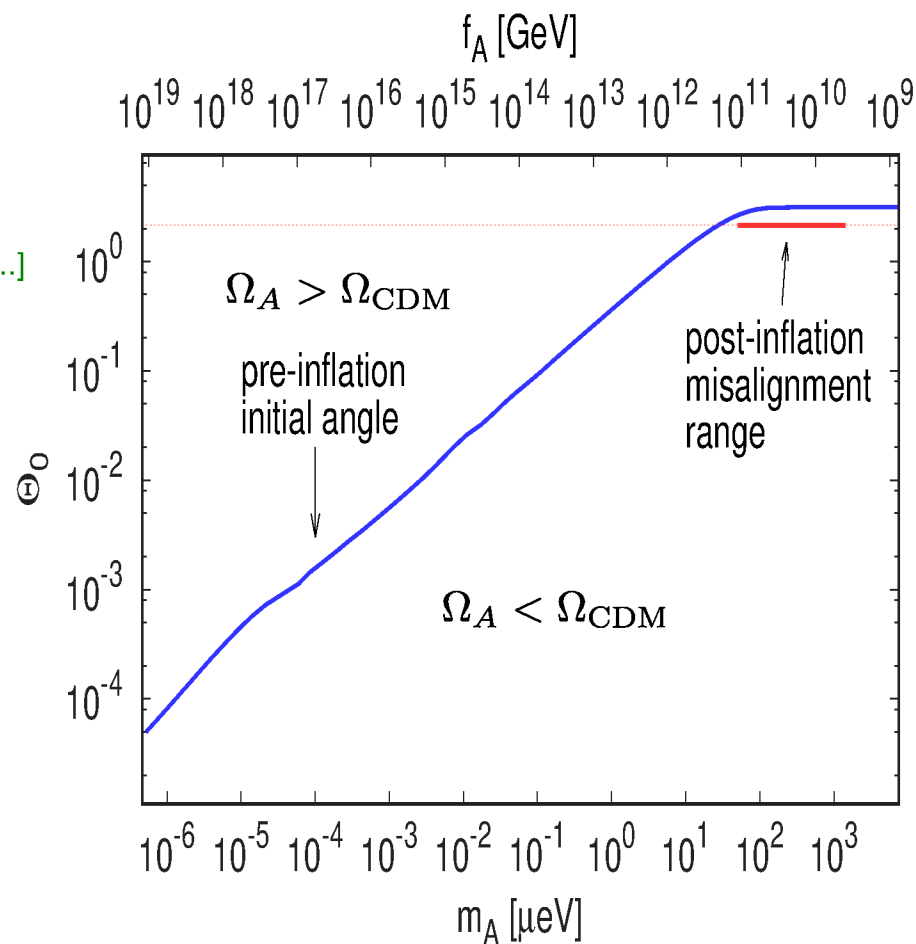Pre–inflationary PQ symmetry breaking scenario

[Saikawa]

Axion Cold Dark Matter

> If PQ symmetry broken before or during inflation ($f_A > H_I/(2\pi)$) and not restored afterwards (pre-infla-tionary PQ breaking scenario):

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

- Axion CDM density depends on single initial value in patch which becomes observable universe and f_A :

$$\Omega_A^{\mathrm{vr}} h^2 \approx 0.12 \left(\frac{f_A}{9 \times 10^{11} \mathrm{\ GeV}} \right)^{1.165} \theta_{\mathrm{i}}^2$$

$$\approx 0.12 \left(\frac{6 \ \mu\mathrm{eV}}{m_A} \right)^{1.165} \theta_{\mathrm{i}}^2 \ ,$$

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

> If PQ symmetry broken before or during inflation ($f_A > H_I/(2\pi)$) and not restored afterwards (pre-inflationary PQ breaking scenario):
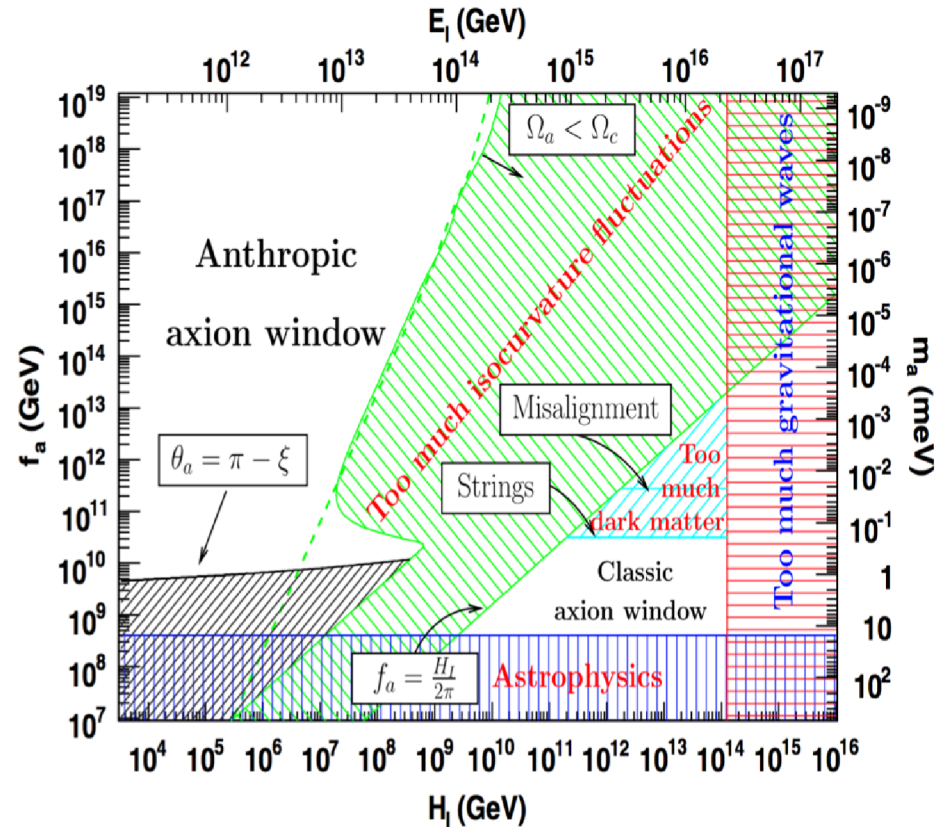
[Preskill,Wise,Wilczek 83; Abbott,Sikivie 83; Dine,Fischler 83,..

- ▪ Axion CDM density depends on single initial value in patch which becomes observable universe and f_A :

$$\Omega_A^{\mathrm{vr}} h^2 \approx 0.12 \left(\frac{f_A}{9 \times 10^{11} \ \mathrm{GeV}} \right)^{1.165} \theta_{\mathrm{i}}^2$$

$$\approx 0.12 \left(\frac{6 \ \mu\mathrm{eV}}{m_A} \right)^{1.165} \theta_{\mathrm{i}}^2 \ ,$$

- ▪ Upper bound on scale of inflation from isocurvature fluctuations produced by the axion during inflation and not erased afterwards

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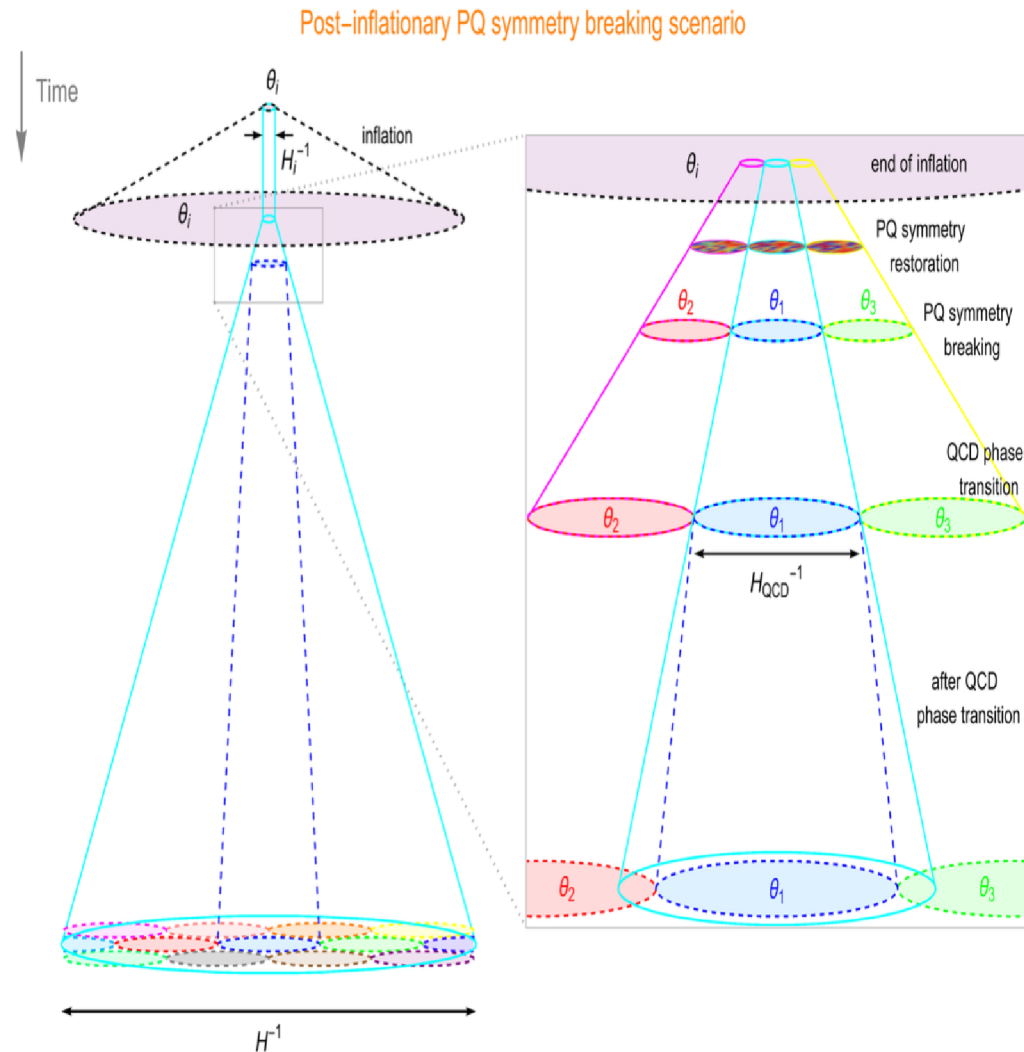
Axion Cold Dark Matter

> If Peccei-Quinn symmetry re-stored after inflation (post-in-flationary PQ breaking scena-rio):

- Random initial axion field values in regions of post-inflationary causal contact; naive average:

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

[Saikawa]

Axion Cold Dark Matter

> If Peccei-Quinn symmetry re-
stored after inflation (post-in-
flationary PQ breaking scena-
rio):

- Random initial axion field values in
  regions of post-inflationary causal
  contact

- Network of axionic cosmic strings
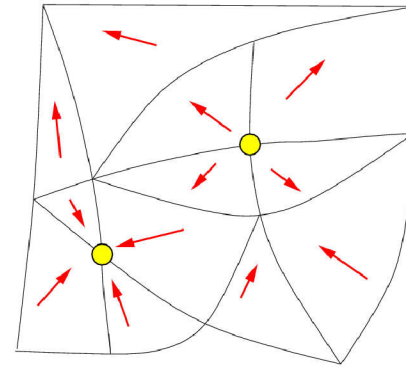 created by Kibble mechanism

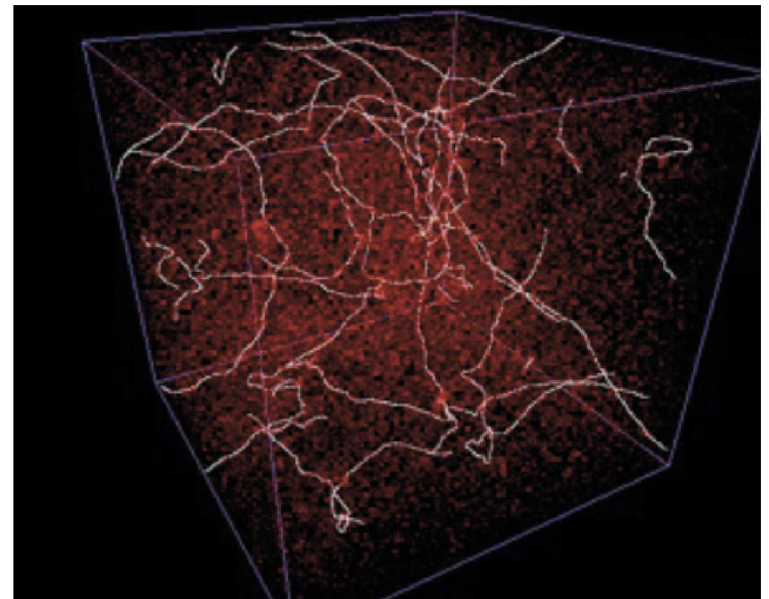[Uhlmann et al. `10]

[Hiramatsu et al.]

Axion Cold Dark Matter

> If Peccei-Quinn symmetry re-stored after inflation (post-inflationary PQ breaking scenario):

- Random initial axion field values in regions of post-inflationary causal contact

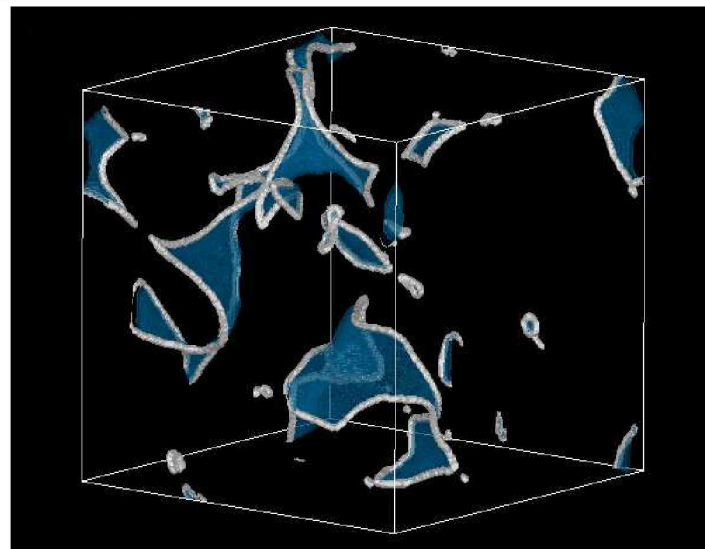- Network of axionic cosmic strings created by Kibble mechanism

- Around QCD phase transition, axion potential develops,

$$V(A,T) = \chi(T) \left[1 - \cos\left(N\frac{A}{v_{\mathrm{PQ}}} \right) \right]$$
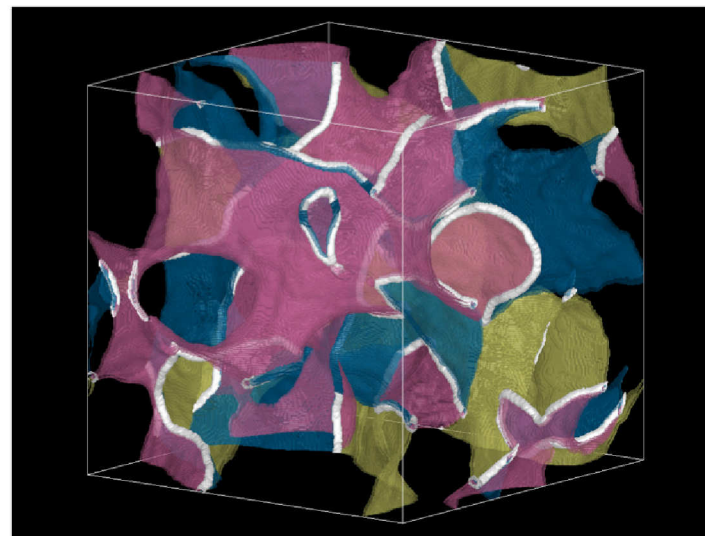
  N domain walls end at string

- $N = 1$: String-wall system decays

- $N > 1$: Domain wall problem

$N = 1$

$N = 3$

[Hiramatsu et al.]

Axion Cold Dark Matter

> If Peccei-Quinn symmetry restored after inflation (post-inflationary PQ breaking scenario):

- For $N = 1$, exploiting results from field theoretic lattice simulations, updated to latest determination of topological susceptibility, find CDM explained for

$$m_A \approx (30{-}200)\,\mu\text{eV}$$

[Hiramatsu et al. 11,12,13; Kawasaki,Saikawa,Segikuchi 15; Borsanyi et al. 16; Ballesteros et al. 16]

Large uncertainty due to extrapolation of string tension to physical value

- New method allows to simulate directly at physical string tension, resulting in

$$m_A = (26.2 \pm 3.4)\,\mu\text{eV}$$

[Klaer,Moore `17]

Axion Cold Dark Matter

> If Peccei-Quinn symmetry restored after inflation (post-inflationary PQ breaking scenario)

- For $N = 1$, exploiting results from field theoretic lattice simulations, updated to latest determination of topological susceptibility, find CDM explained for

$$m_A \approx (30\text{--}200)\ \mu\text{eV}$$

[Hiramatsu et al. 11,12,13;
Kawasaki,Saikawa,Segikuchi 15;
Borsanyi et al. 16;
Ballesteros et al. 16]

Large uncertainty due to extrapolation of string tension to physical value

- New method allows to simulate directly at physical string tension, resulting in

$$m_A = (26.2 \pm 3.4)\ \mu\text{eV}$$

[Klaer,Moore `17]

- For $N > 1$, domain wall problem can be avoided if PQ symmetry explicitly broken, e.g. by Planck suppressed operators, $\mathcal{L} \supset g M_{\mathrm{P}}^4 \left(\sigma/M_{\mathrm{P}}\right)^{\mathcal{N}} + \text{h.c.}$, for $\mathcal{N} = 9, 10$,

$$0.2\,\text{meV} \lesssim m_A \lesssim 50\,\text{meV}$$

[AR,Saikawa `16;
Giannotti,Irastorza,Redondo,AR,Saikawa`17]

May employ discrete symmetry to forbid lower dimensional operators   e.g. [Dias et al. `14]

A DFSZ axion ($N = 6$) in this mass range explains excessive stellar energy losses
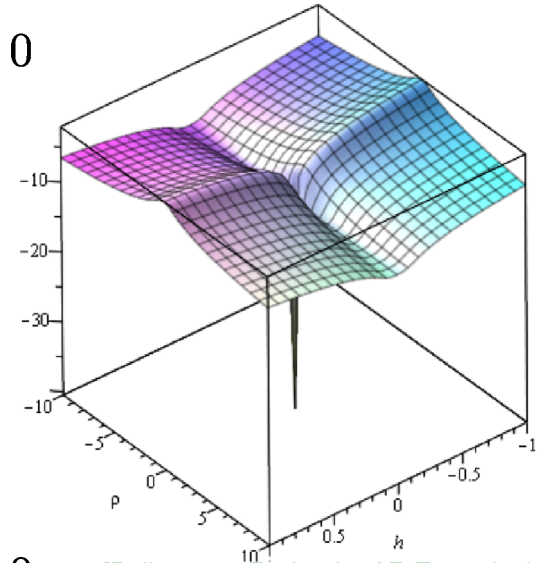
> Saxion,$| \sigma | = \rho/\sqrt{2}$, or mixture with Higgs modulus, may play role of inflaton, if it has non-minimal coupling to gravity: [Fairbairn,Hogan,Marsh `14; Ballesteros,Redondo,AR,Tamarit `16]
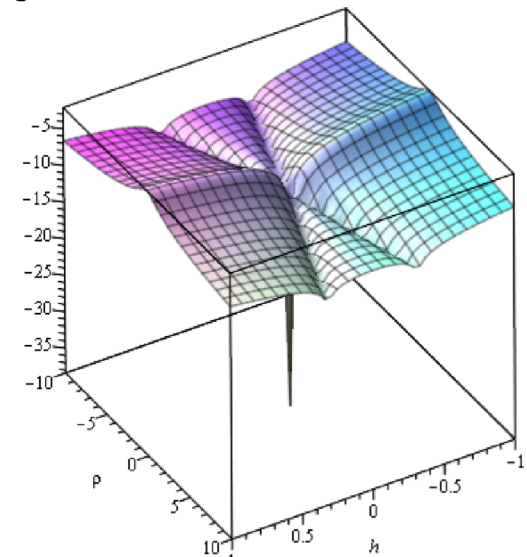
$$S \supset - \int d^4x \sqrt{-g} \, \xi_\sigma \, \sigma^* \sigma R$$

$\lambda_{H\sigma} > 0$

$\lambda_{H\sigma} < 0$ [Ballesteros,Redondo, AR,Tamarit, 1610.01639]

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

$$S \supset -\int d^4x \sqrt{-g}\, \xi_\sigma\, \sigma^* \sigma R$$

> CMB observables fit by

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

> PQ symmetry restored after inflation already in preheating stage

> Dark-matter axion mass:

$$30\,\mu\text{eV} \lesssim m_A \lesssim 50\,\text{meV}$$

> Large reheating temperature: $10^{10}\,\text{GeV}$

> Axion dark radiation: $\Delta N_\nu^{\text{eff}} \simeq 0.03$
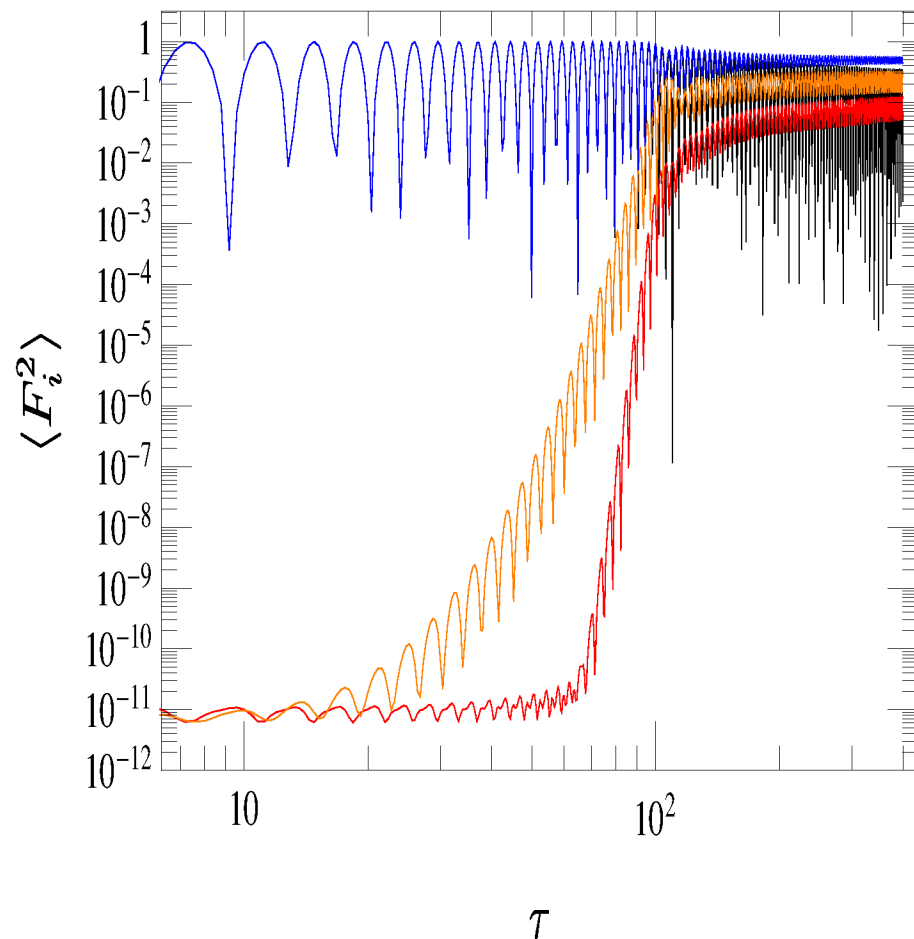
[Ballesteros,Redondo, AR,Tamarit `16]

> Sharp prediction of r vs n_s for fixed pivot scale, e.g. $k_0 = 0.002\ \mathrm{Mpc}^{-1}$

[Tamarit]
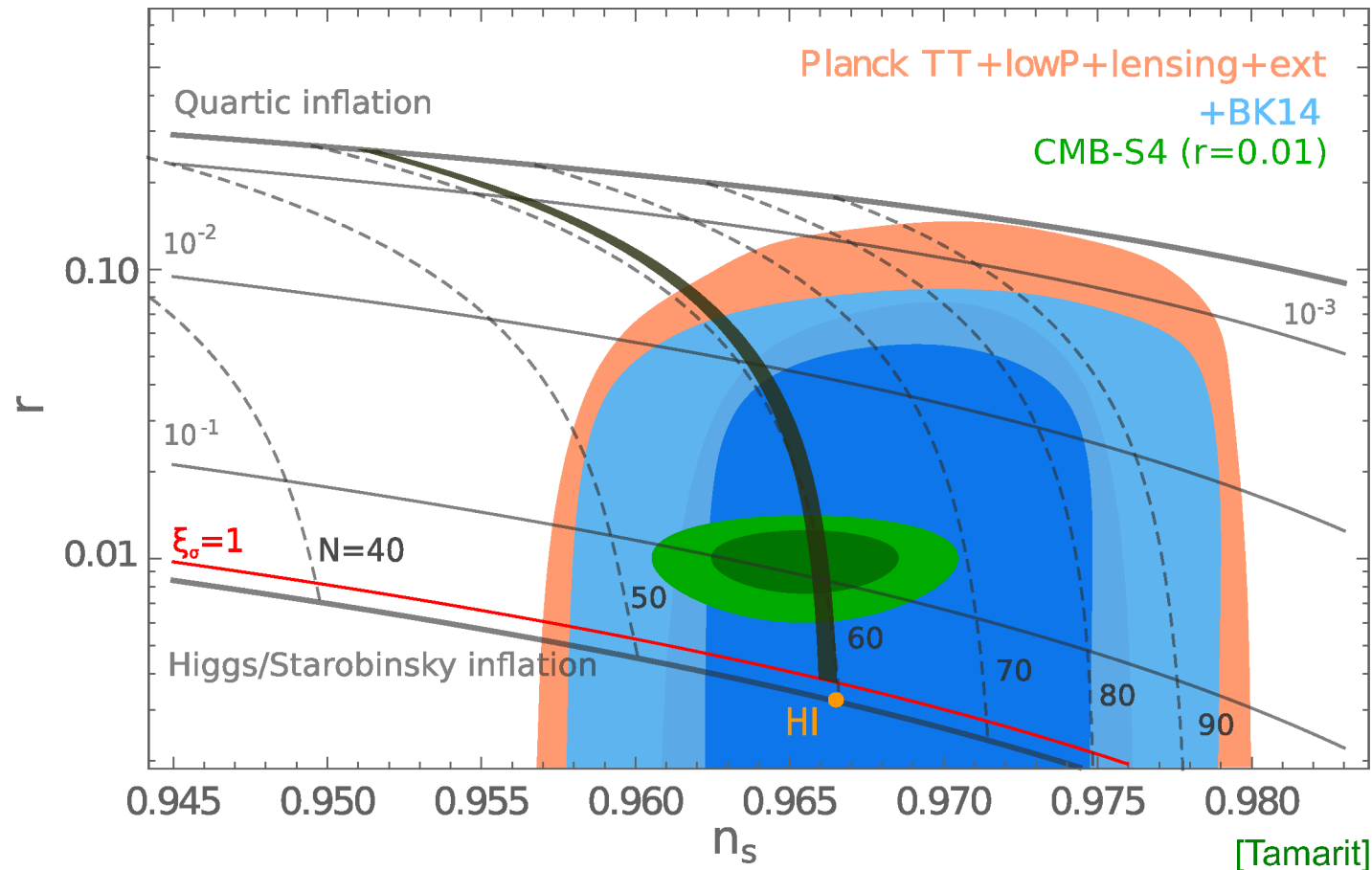
> Can be probed by next generation CMB experiments (e.g. CMB-S4)

> Augmenting axion models with three SM singlet neutrinos, getting their Majorana masses also through the vev $v_\sigma = N f_A$

  - no strong CP problem

  - dark matter

  - inflation

  - neutrino masses and mixing

  - baryogenesis via leptogenesis

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

> Augmenting axion models with three SM singlet neutrinos, getting their Majorana masses also through the vev $v_\sigma = N f_A$

- no strong CP problem

- dark matter

- inflation

- neutrino masses and mixing

- baryogenesis via leptogenesis

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

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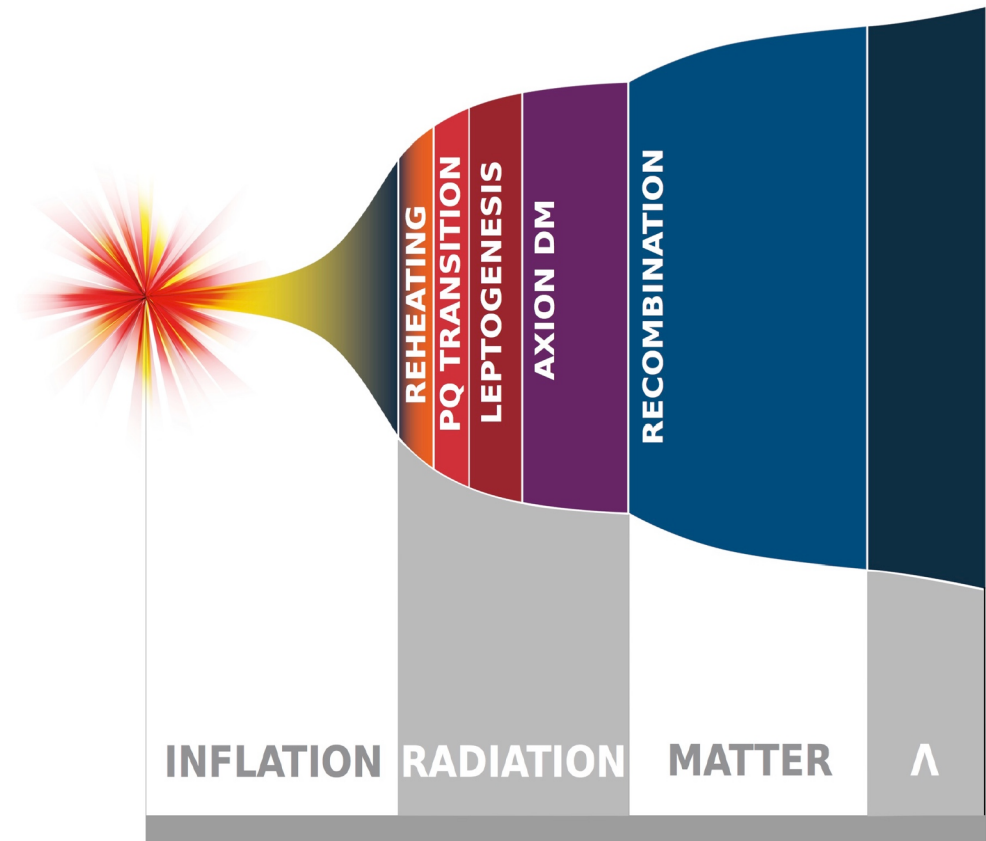

[desy.de]

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 $v_\sigma = N f_A$

- no strong CP problem

- dark matter

- inflation

- neutrino masses and mixing

- baryogenesis via leptogenesis

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

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

> $SO(10)$ GUT SMASH?

[Ernst,AR,Tamarit `18 and in prep.]

> Minimal $SO(10) \times U(1)_{\mathrm{PQ}}$ models:

	16_F	$\overline{126}_H$	10_H	210_H	45_H	S	10_F	N
Model 1	1	-2	-2	4	$-$	$-$	$-$	3
Model 2.1	1	-2	-2	0	4	$-$	$-$	3
Model 2.2	1	-2	-2	0	4	$-$	-2	1
Model 3.1	1	-2	-2	0	$-$	4	$-$	3
Model 3.2	1	-2	-2	0	$-$	4	-2	1

> 16_F automatically features:

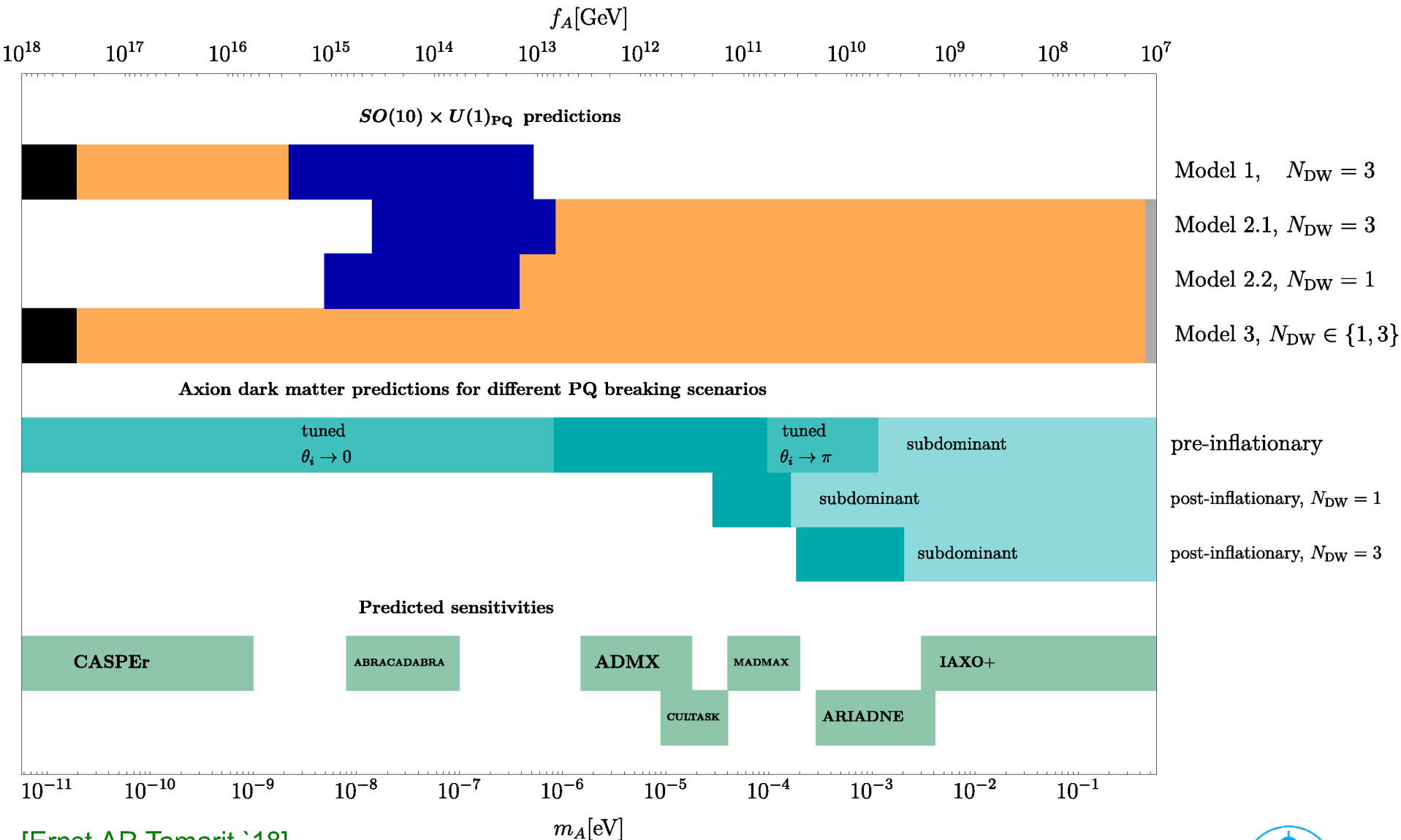- Neutrino masses and mixing

- Baryogenesis via leptogenesis

> PQ extension adds

[Bajc et al. 06; Altarelli,Meloni 13; Babu,Khan 15]

- Predictivity of fermion masses/mixing

- Solution of strong CP problem

- Axion dark matter

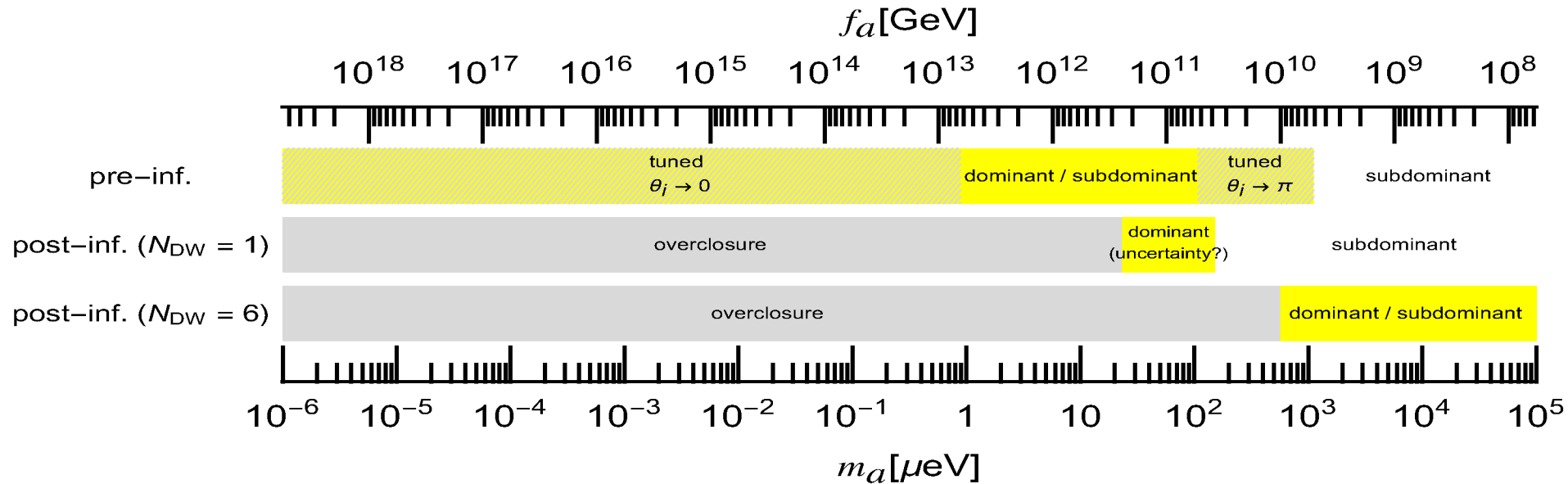[Ernst,AR,Tamarit `18]

> Dark-matter axion mass spans a huge range:

Summary

> **Strong motivation for current und upcoming axion DM experiments:**

$$f_a [\text{GeV}]$$

| 10^{18} | 10^{17} | 10^{16} | 10^{15} | 10^{14} | 10^{13} | 10^{12} | 10^{11} | 10^{10} | 10^9 | 10^8 |

pre-inf. — tuned $\theta_i \to 0$ — dominant / subdominant — tuned $\theta_i \to \pi$ — subdominant

post-inf. ($N_{DW} = 1$) — overclosure — dominant (uncertainty?) — subdominant

post-inf. ($N_{DW} = 6$) — overclosure — dominant / subdominant

| 10^{-6} | 10^{-5} | 10^{-4} | 10^{-3} | 10^{-2} | 10^{-1} | 1 | 10 | 10^2 | 10^3 | 10^4 | 10^5 |

$$m_a [\mu\text{eV}]$$

CASPEr   ABRACADABRA   **ADMX**   MADMAX   BRASS

KLASH   **HAYSTAC**   ORPHEUS

CAST-CAPP   **ORGAN**

CULTASK   QUAX