Dark-Matter Axion Mass.

Andreas Ringwald (DESY)

Workshop on Ultralight Dark Matter and Axions
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HELMHOLTZ ASSOCIATION

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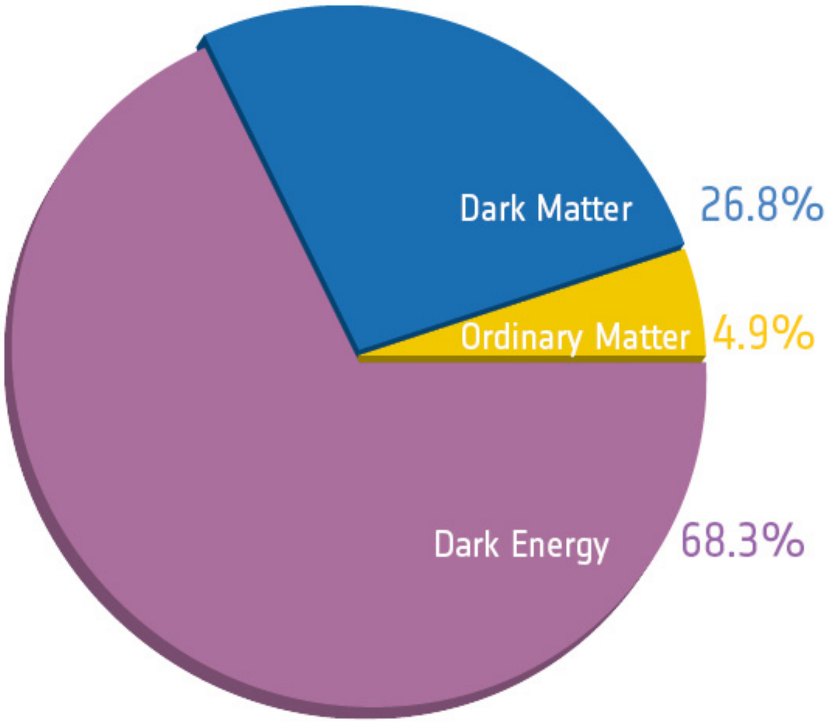
Strong Case for Particles Beyond the Standard Model

- 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



[PLANCK]

Strong Case for Particles Beyond the Standard Model

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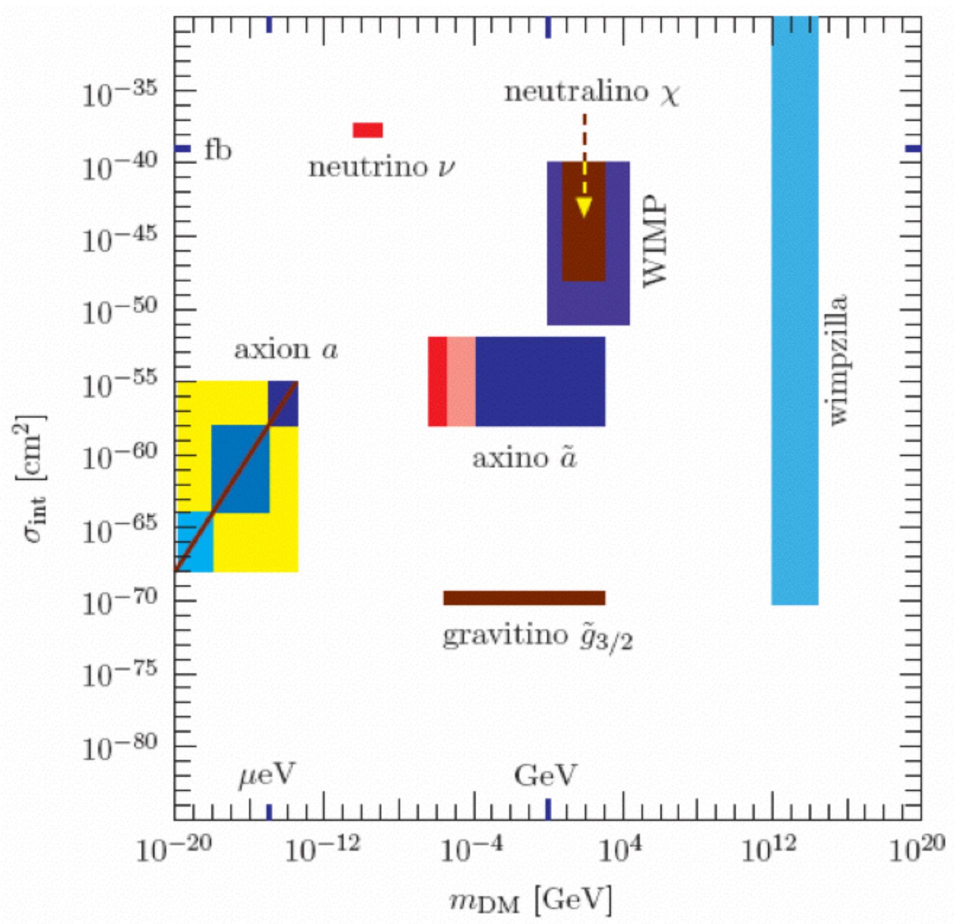
- SM describes only about 15% of matter content of Universe
- Theorists have proposed plenitude of DM candidates, spanning a large parameter space in mass and interaction strength
- Best motivated candidates those which occur in SM extensions solving also other problems, such as
  - Hierarchy problem: Neutralino in MSSM
  - Strong CP problem: Axion in PQSM



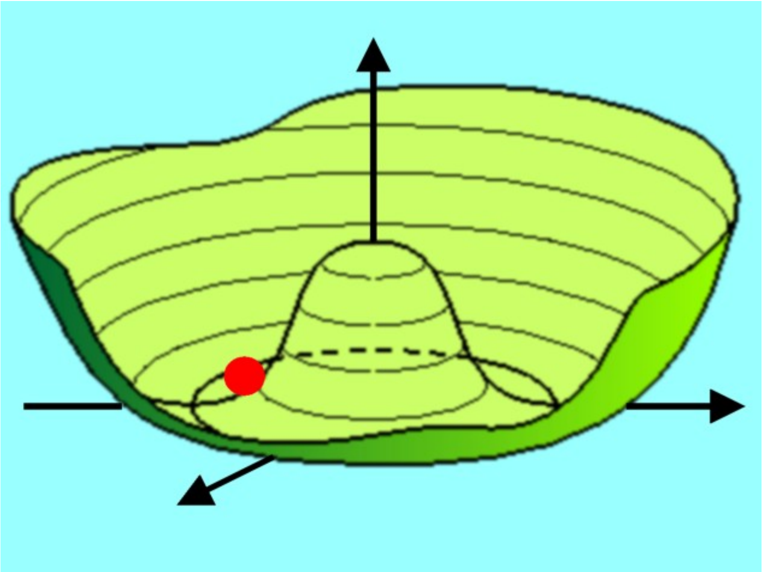
[Kim,Carosi 10]

PQSM: Peccei-Quinn Extensions of the Standard Model

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

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

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



[Raffelt]

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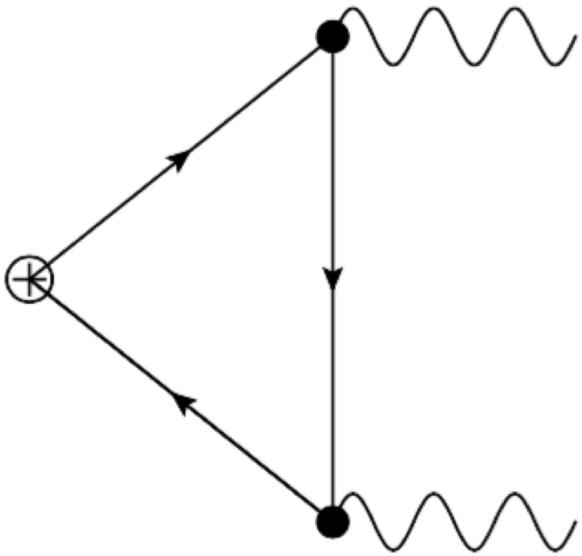
$$\partial_\mu J^\mu_{U(1)_{\rm PQ}} \supset -\frac{\alpha_s}{8\pi} N\, G^b_{\mu\nu}\tilde{G}^{b,\mu\nu}$$



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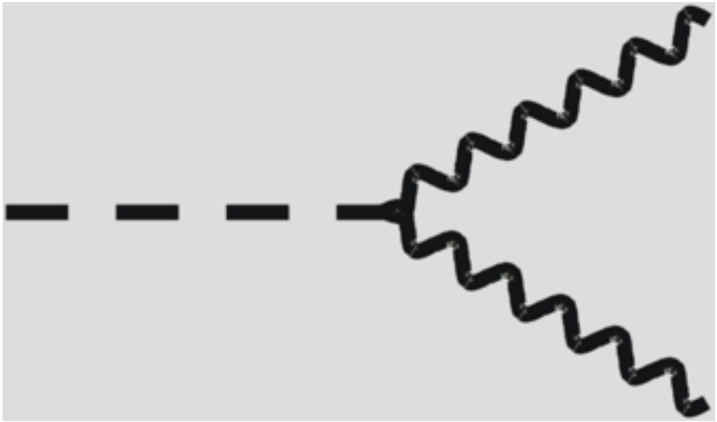

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- Low energy effective field theory at energies below v ($\ll v_{\rm PQ}$), but above $\Lambda_{\rm QCD}$,

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

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

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

Axionic Solution of Strong CP Problem

- Can eliminate QCD theta term,

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

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

- Effective potential at energies below $\Lambda_{\rm QCD}$,

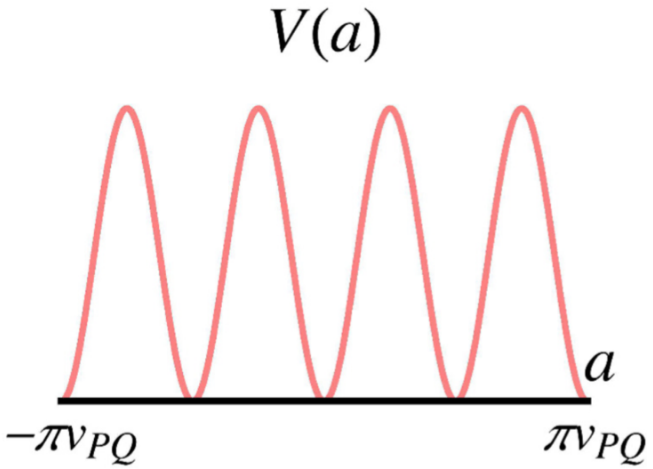
$\Sigma \equiv -\langle \bar{u}u\rangle = -\langle dd\rangle$

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

[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]



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[Peccei,Quinn 77]

- Particle excitation: pseudo NG boson "axion" [Weinberg 78; Wilczek 78]
- Mass: $m_A \simeq \frac{\sqrt{\Sigma}}{f_A}\sqrt{\frac{m_u m_d}{m_u + m_d}} \simeq \frac{m_\pi f_\pi}{f_A}\frac{\sqrt{m_u m_d}}{m_u + m_d} \simeq 6\ {\rm meV}\left(\frac{10^9\ {\rm GeV}}{f_A}\right)$
  - Precisely (NLO CPT; Lattice QCD):

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

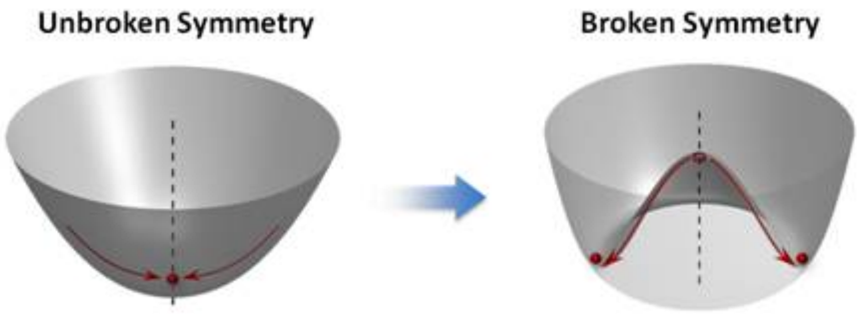
[Grilli di Cortona et al. \`16 ; Borsanyi et al. \`16]

Axion Cold Dark Matter

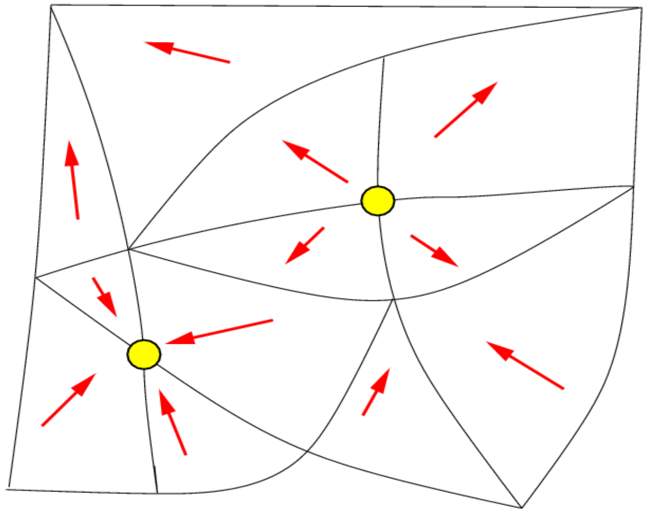
- Axion field is born after PQ symmetry breaking

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

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



[Peking University]



[Uhlmann et al. `10]

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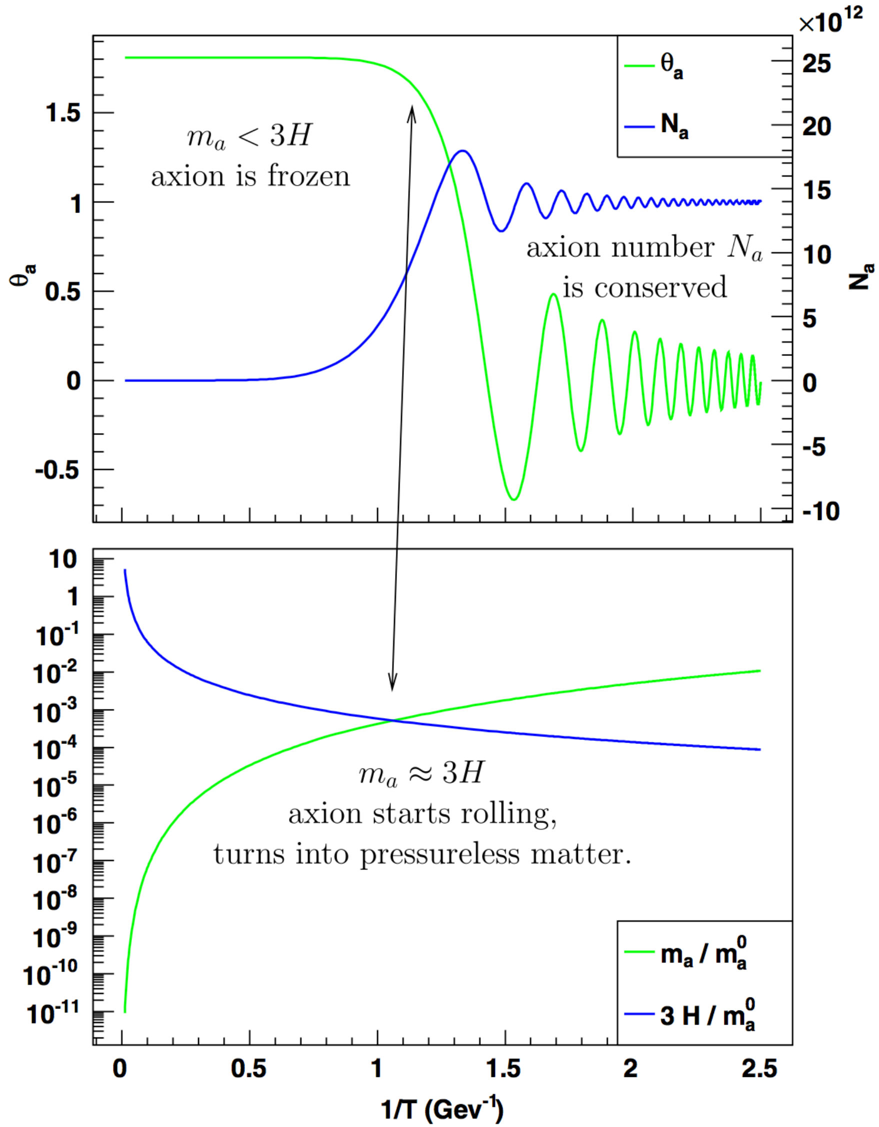
- In causally connected regions at phase transition, axion takes random initial values and stucks

- 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 evolution needs QCD input:

1. Equation of state at temperatures around 1 GeV: determines

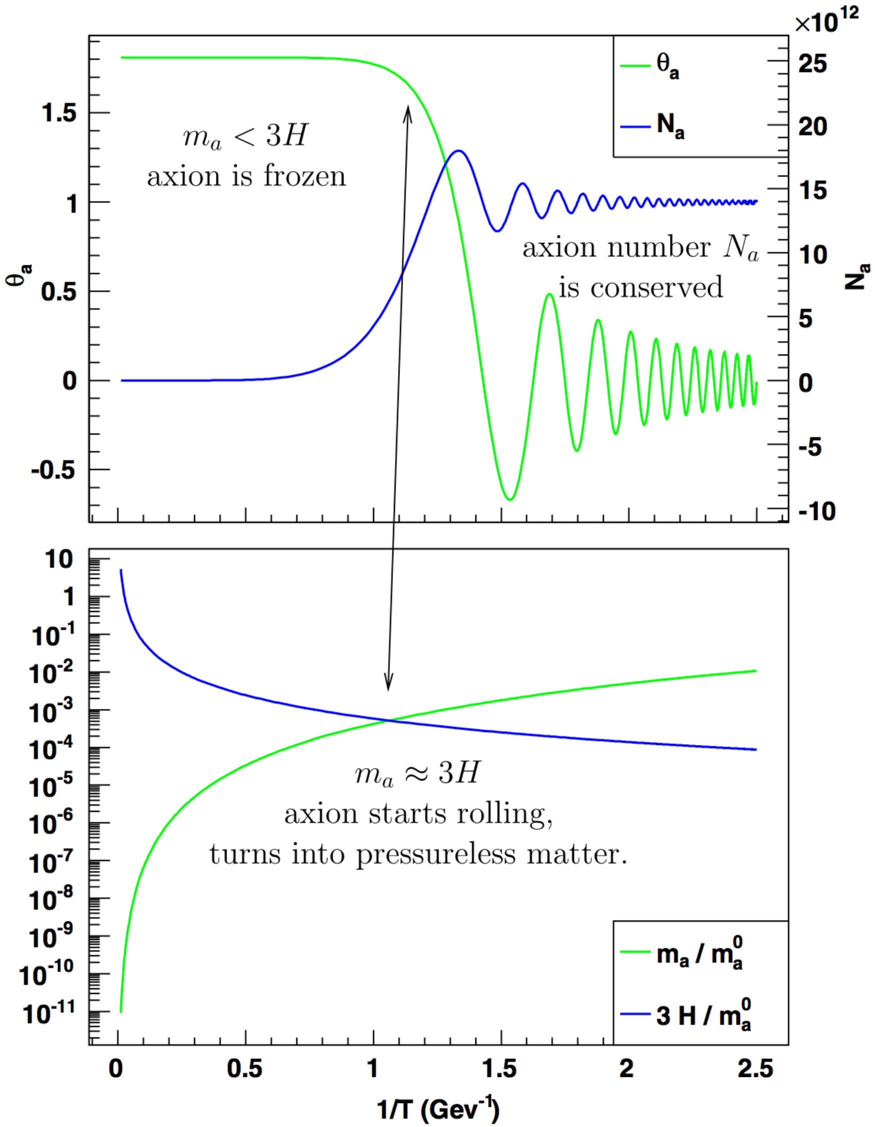
$$H(T)$$

2. Topological susceptibility:

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

determines

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



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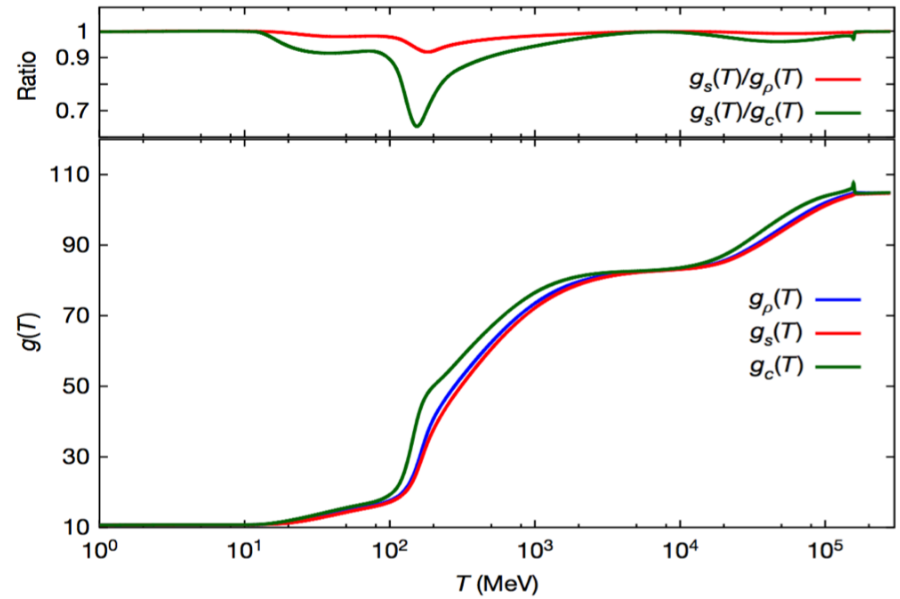
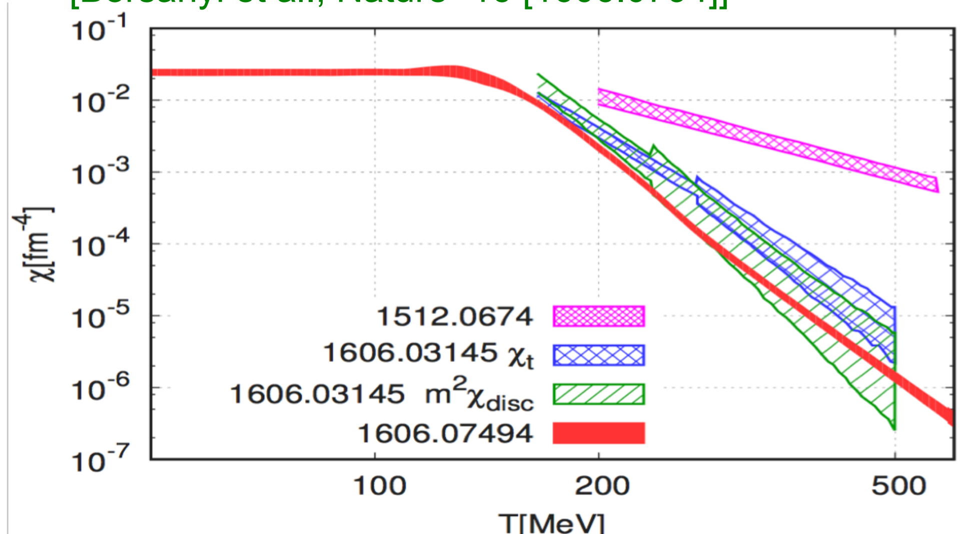
- Both obtained recently with high precision via lattice QCD
  - Temperature slope of $\chi(T)$ remarkably close to prediction from dilute instanton gas; latter underestimates normalization by factor of order ten



[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):

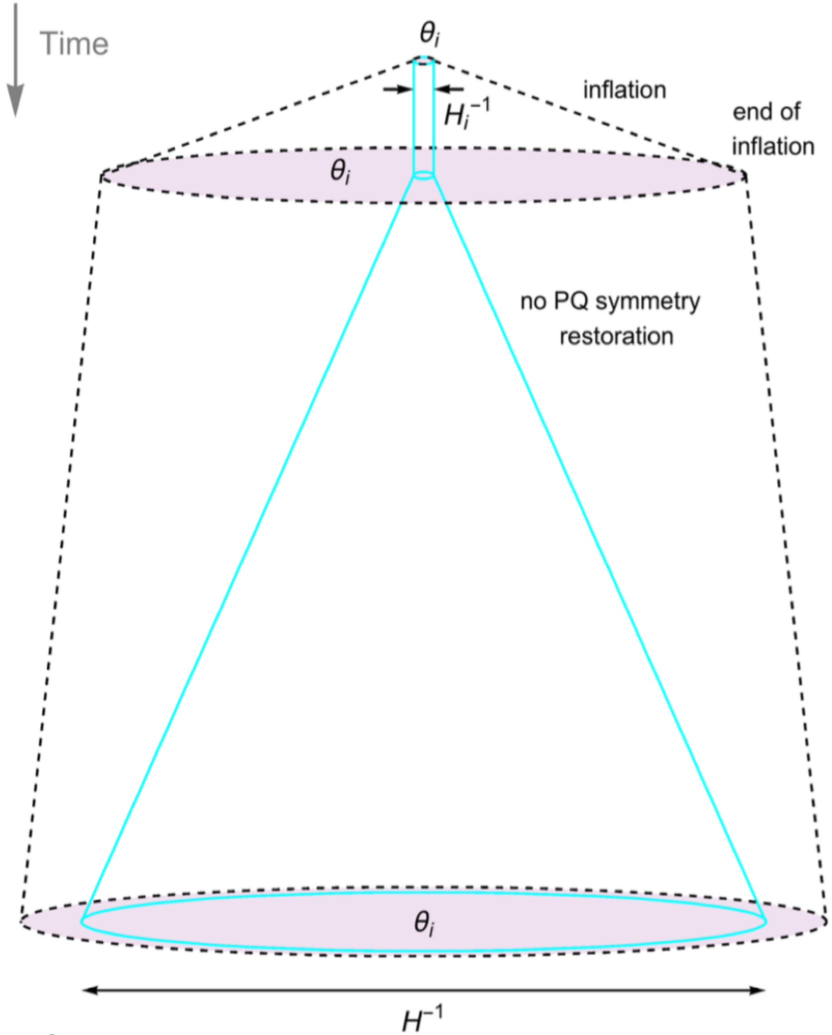
[Preskill,Wise,Wilczek 83; Abbott,Sikivie 83; Dine,Fischler 83,....]

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

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

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

Pre–inflationary PQ symmetry breaking scenario



[Saikawa]

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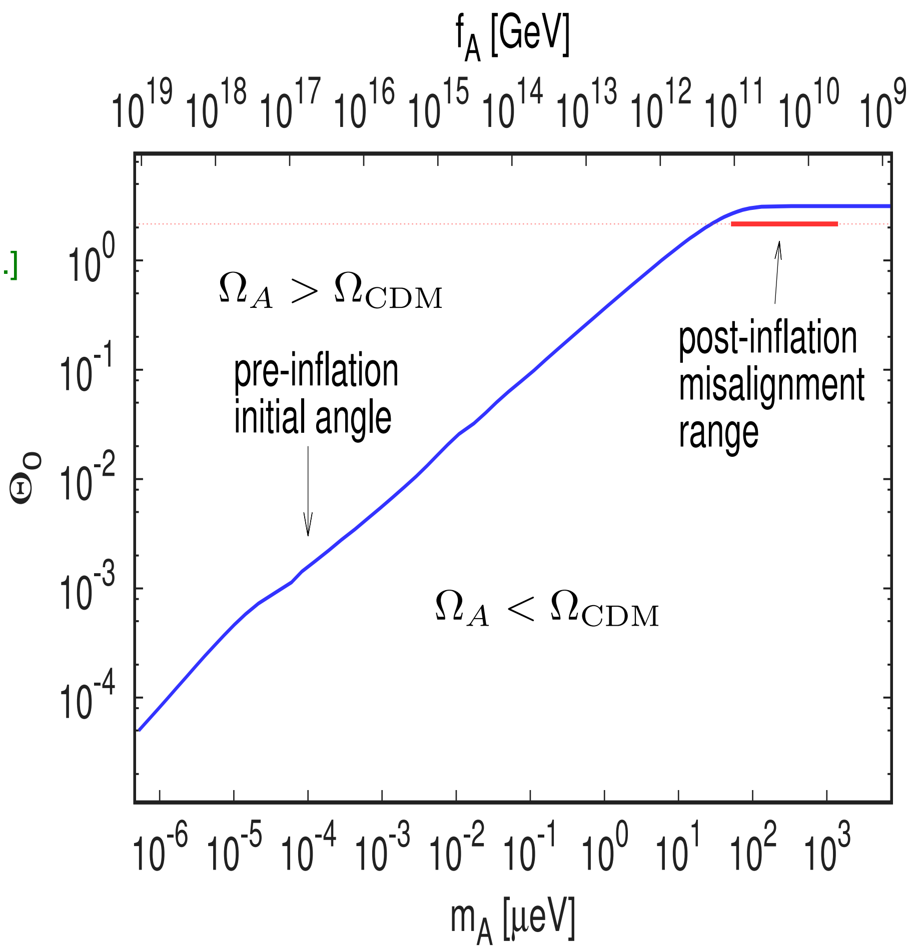

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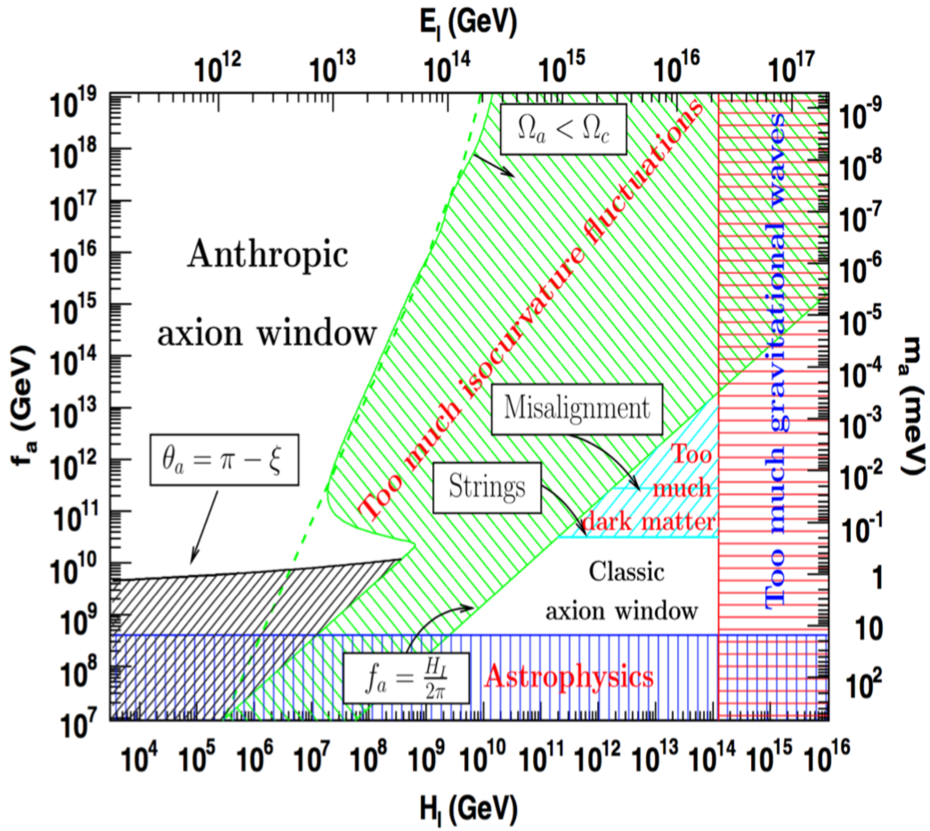
  - Upper bound on scale of inflation from isocurvature fluctuations produced by the axion during inflation and not erased afterwards

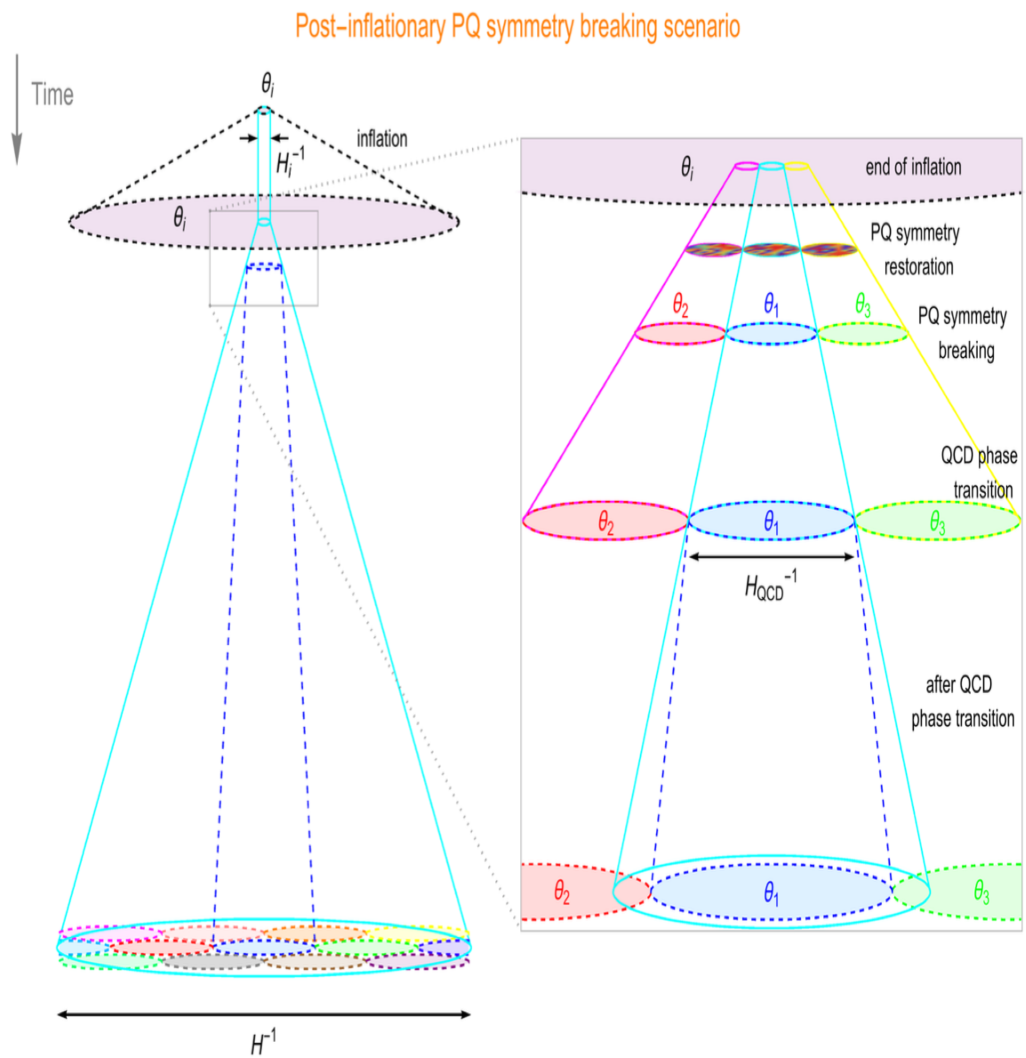


[Wilczek,Turner `91; Beltran et al. 06; Hertzberg,Tegmark,Wilczek 08; Visinelli,Gondolo 09; Hamann et al. 09; **Wantz,Shellard 09**]

Axion Cold Dark Matter

- If Peccei-Quinn symmetry restored after inflation (post-inflationary PQ breaking scenario):
  - Random initial axion field values in regions of post-inflationary causal contact; naive average:

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



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Axion Cold Dark Matter

- If Peccei-Quinn symmetry restored after inflation (post-inflationary PQ breaking scenario):
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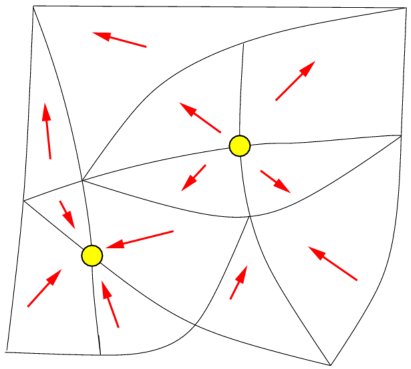
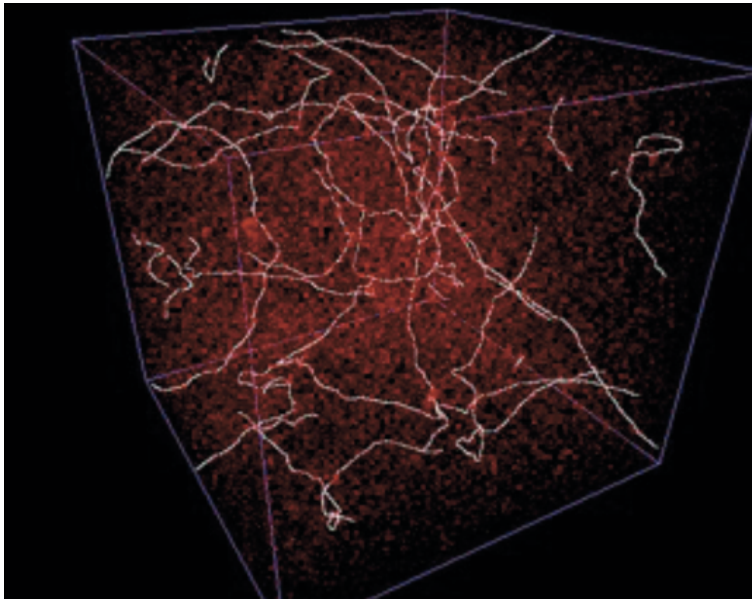
  - Network of axionic cosmic strings created by Kibble mechanism



[Uhlmann et al. `10]



[Hiramatsu et al.]

Axion Cold Dark Matter

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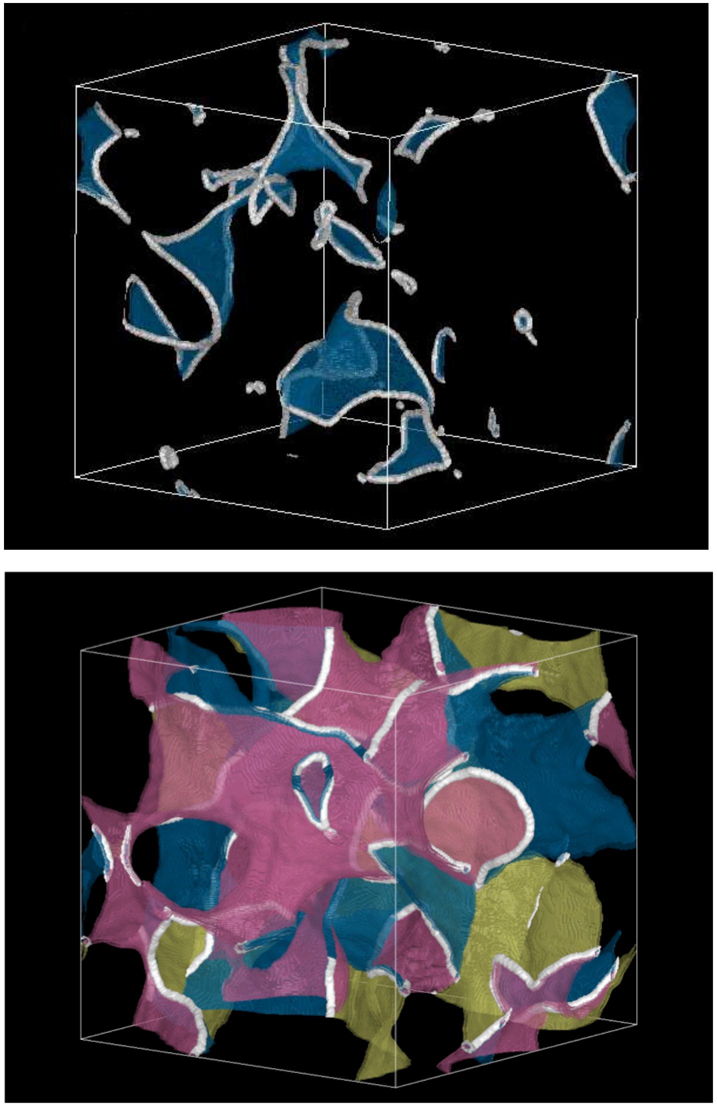
  - Random initial axion field values in regions of post-inflationary causal contact
  - Network of axionic cosmic strings created by Kibble mechanism
  - Around QCD phase transition, axion potential develops,

$$V(A,T) = \chi(T)\left[1-\cos\left(N\frac{A}{v_{\rm PQ}}\right)\right]$$

    N domain walls end at string
  - $N=1$: String-wall system decays
  - $N>1$: Domain wall problem

$N=1$

$N=3$



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Axion Cold Dark Matter

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  - 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]

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[Klaer,Moore `17]

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

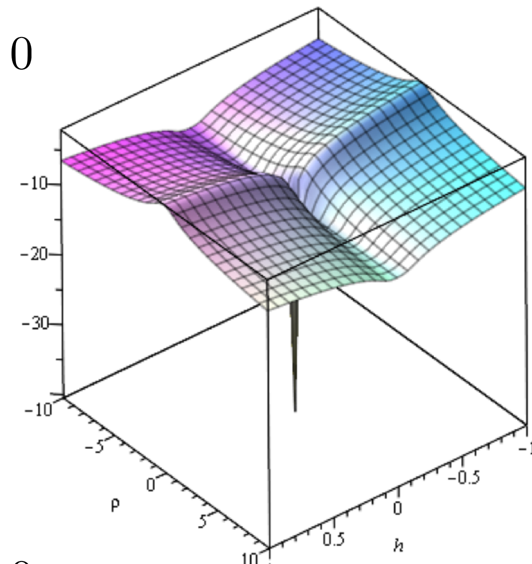
A DFSZ axion ($N = 6$) in this mass range explains excessive stellar energy losses

Unifying Inflation and Dark Matter with PQ Field

- 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]

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

$\lambda_{H\sigma} > 0$



[Ballesteros,Redondo, AR,Tamarit, 1610.01639]

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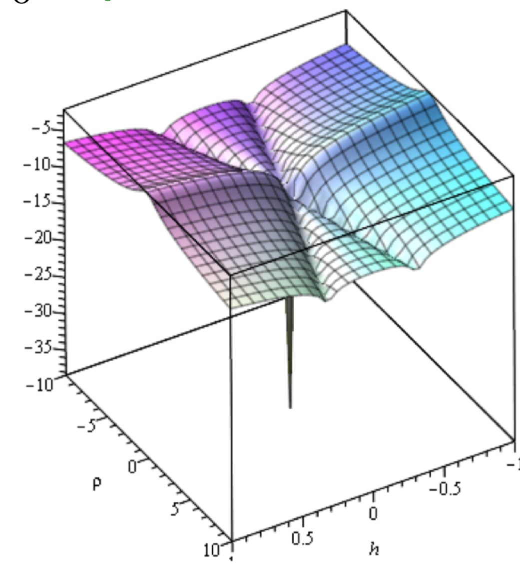

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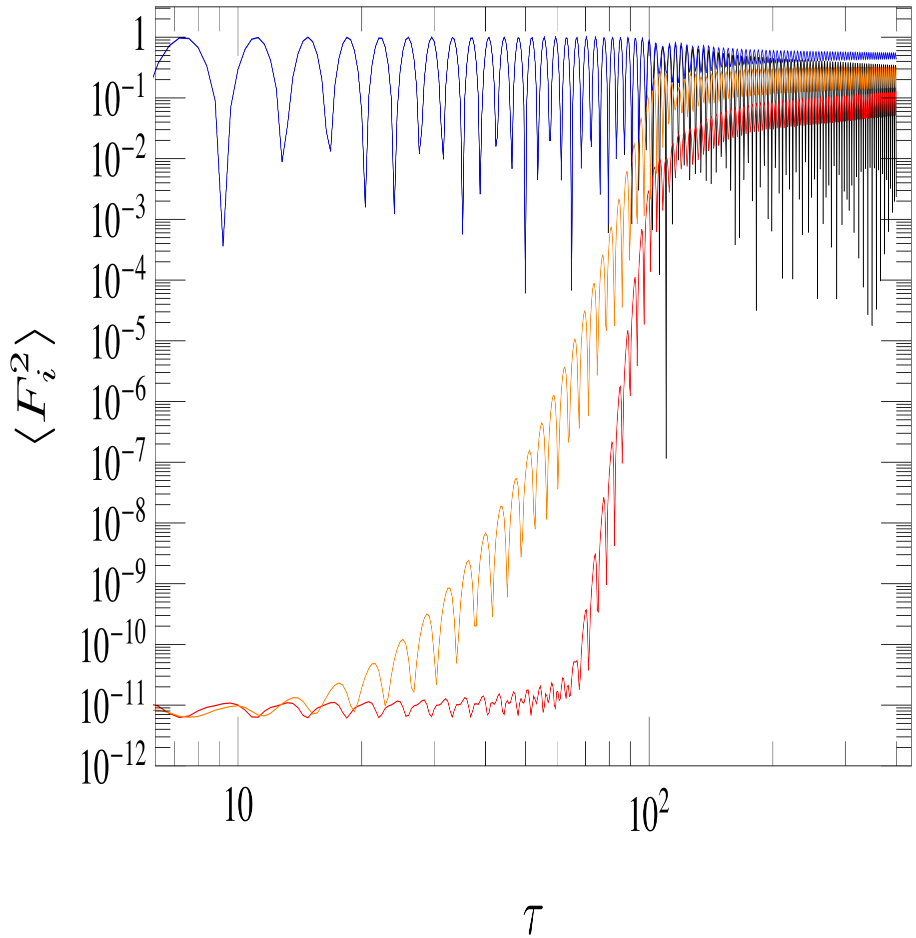
- CMB observables fit by

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

- PQ symmetry restored after inflation already in preheating stage
- Dark-matter axion mass:

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

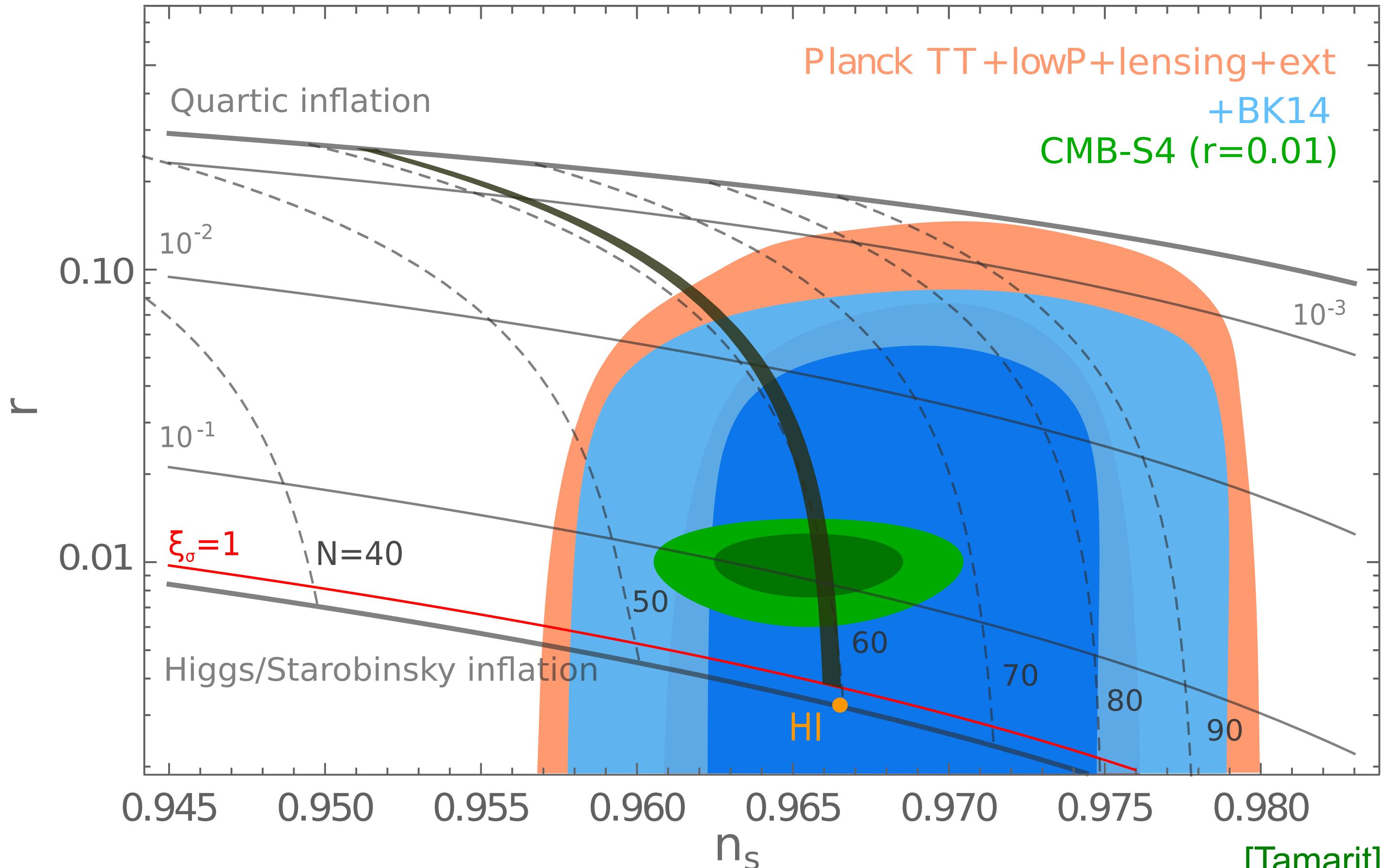
- Large reheating temperature: $10^{10}\,\mathrm{GeV}$
- Axion dark radiation: $\Delta N_\nu^{\rm eff} \simeq 0.03$



[Ballesteros,Redondo, AR,Tamarit `16]

Unifying Inflation and Dark Matter with PQ Field

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



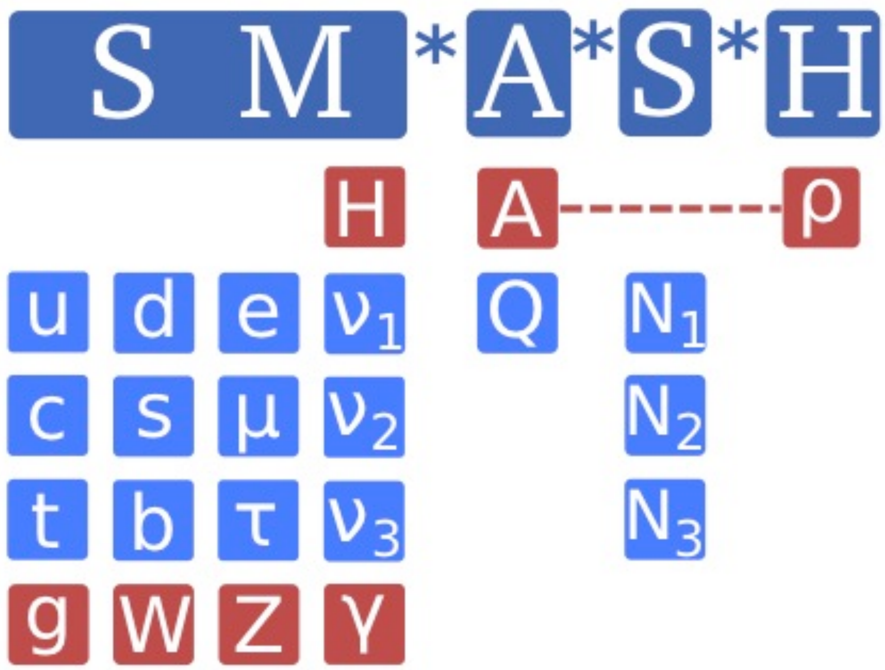
[Tamarit]

- Can be probed by next generation CMB experiments (e.g. CMB-S4)

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]



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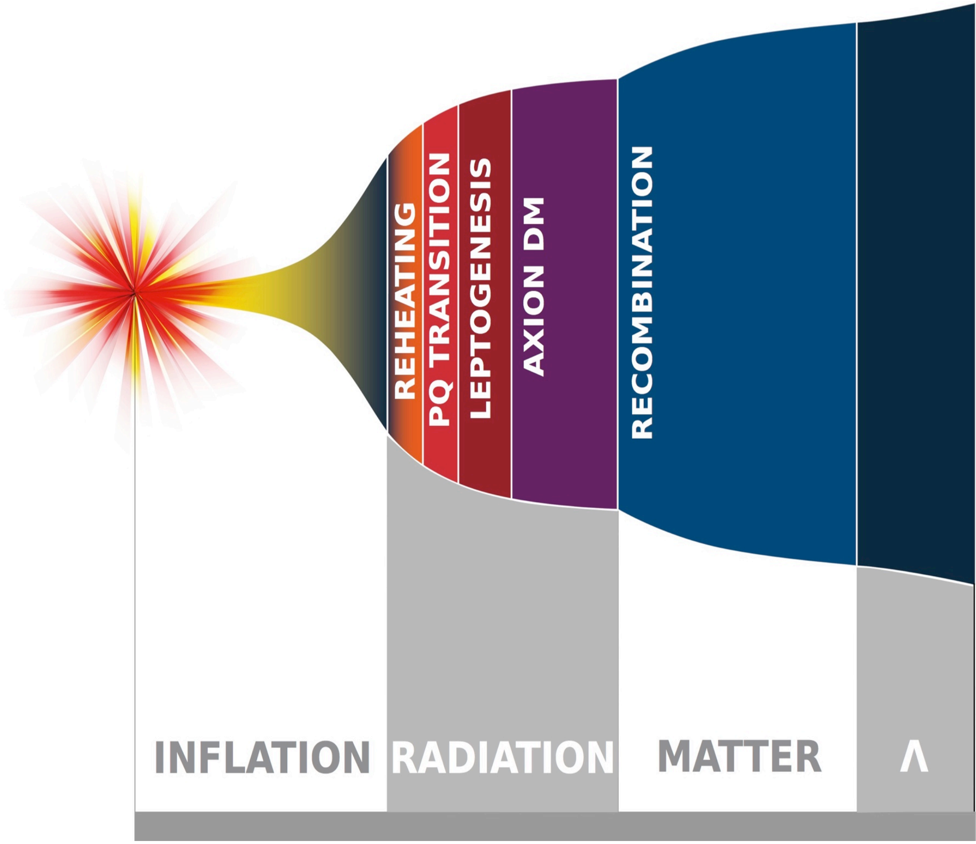
> Complete and consistent history of the universe from inflation to now



[desy.de]

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[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 $SO(10) \times U(1)_{\rm PQ}$ models:

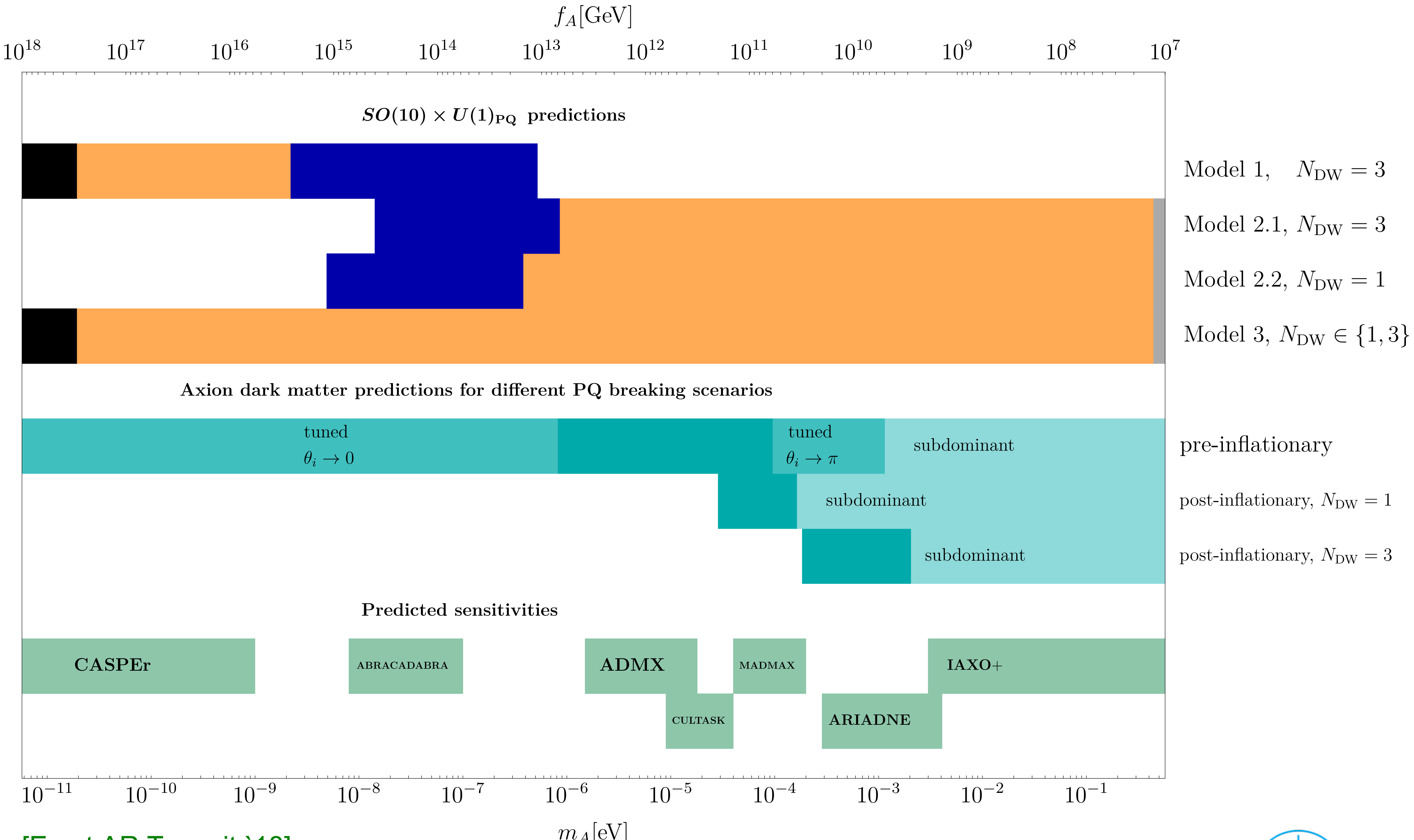
	16_F	$\overline{126}_H$	10_H	210_H	45_H	S	10_F	N
Model 1	1	−2	−2	4	–	–	–	3
Model 2.1	1	−2	−2	0	4	–	–	3
Model 2.2	1	−2	−2	0	4	–	−2	1
Model 3.1	1	−2	−2	0	–	4	–	3
Model 3.2	1	−2	−2	0	–	4	−2	1

- 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

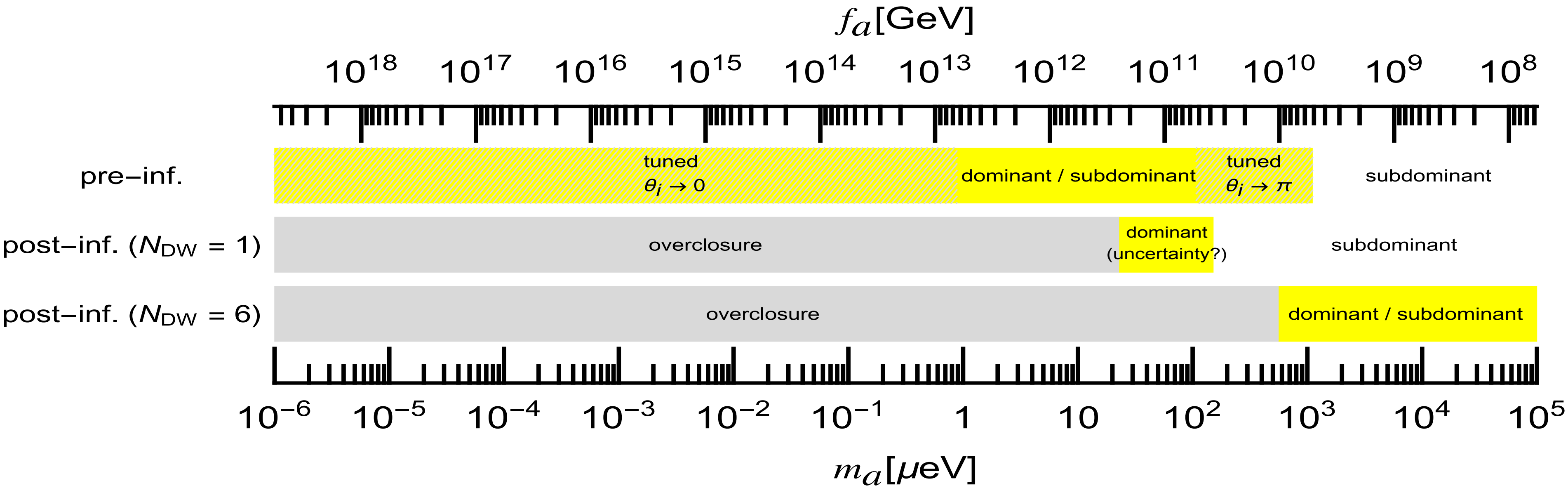
Unifying Inflation, Dark Matter, and Seesaw with PQ Field



[Ernst,AR,Tamarit `18]

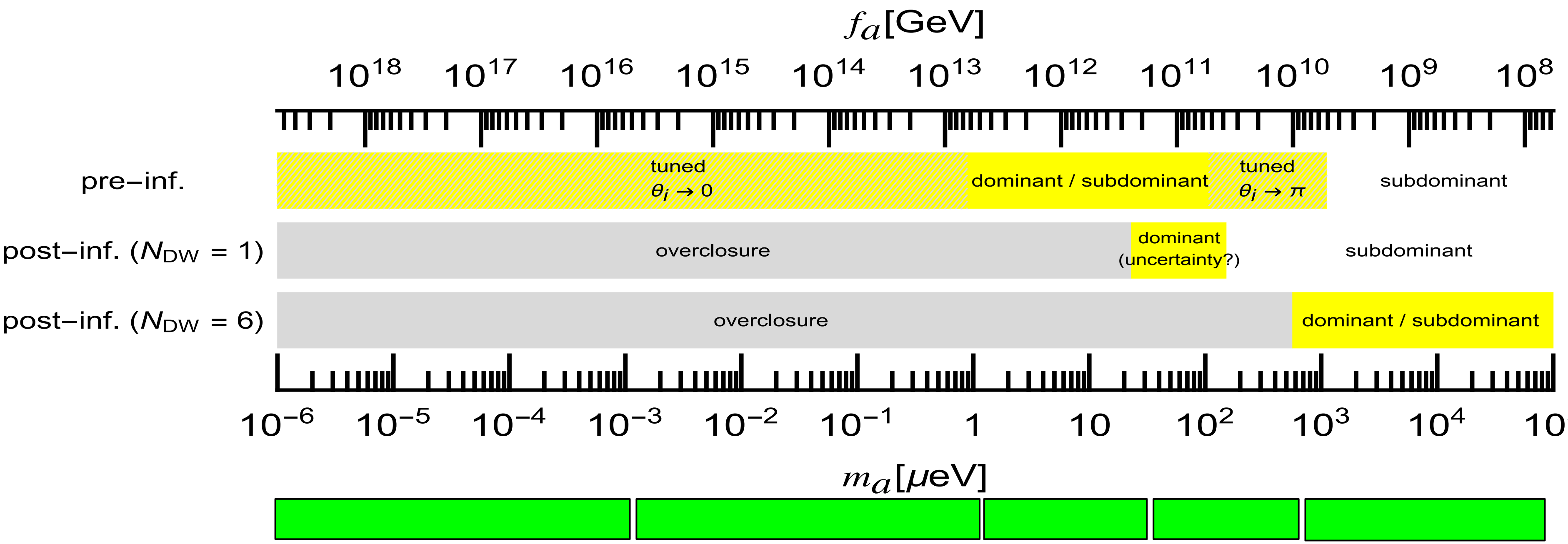
Summary

- Dark-matter axion mass spans a huge range:



Summary

> Strong motivation for current und upcoming axion DM experiments:



CASPEr

ABRACADABRA

KLASH

ADMX

HAYSTAC

CAST-CAPP

CULTASK

MADMAX

ORPHEUS

ORGAN

QUAX

BRASS