Update on the dark-matter axion mass.

Andreas Ringwald

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DESY
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HELMHOLTZ ASSOCIATION

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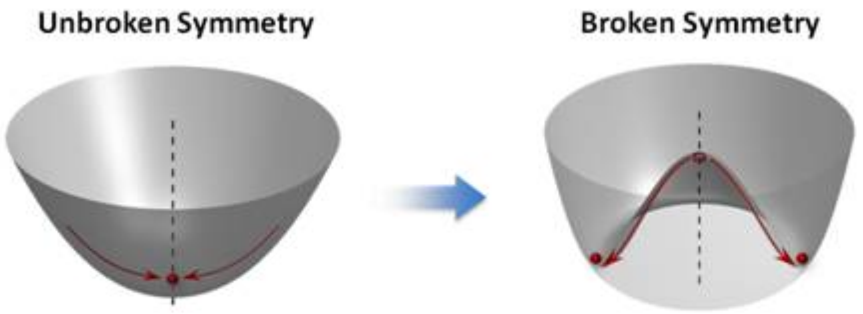
Birth of Axion in Cosmic Evolution

> Axion field is born after PQ symmetry breaking

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



[Peking University]

Birth of Axion in Cosmic Evolution

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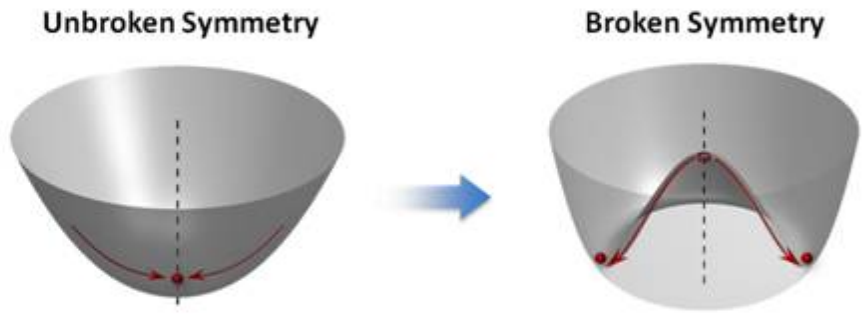
- Cosmological evolution of axion angular field $\theta = A/f_A$ determined by

$$\ddot{\theta} + 3H(T(t))\,\dot{\theta} - \frac{\nabla^2}{a^2(t)}\theta = -\frac{1}{f_A^2}\frac{\partial}{\partial\theta}V(\theta, T(t))$$

$$V(\theta, T) = \chi(T)\,(1-\cos\theta)$$



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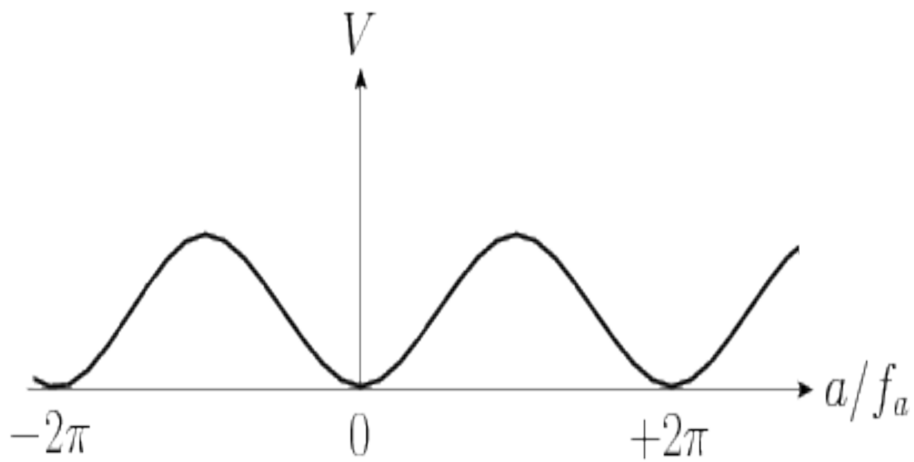

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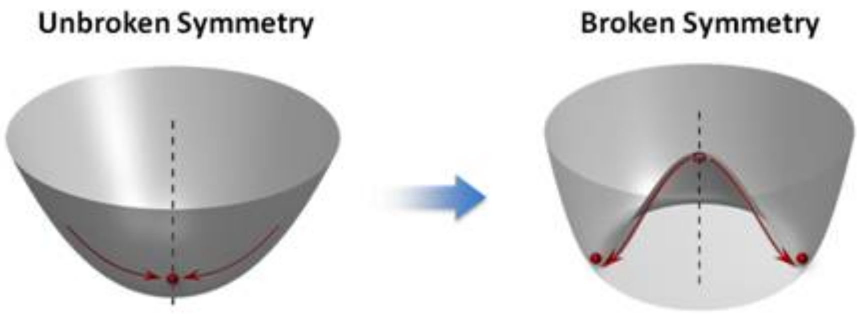

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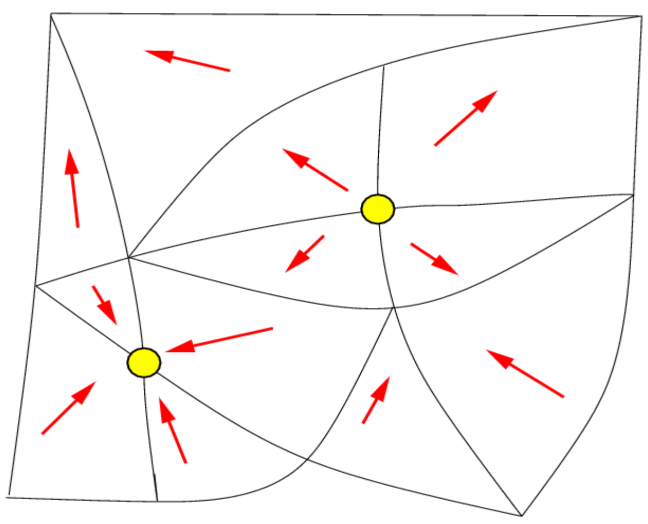


[Uhlmann et al. `10]

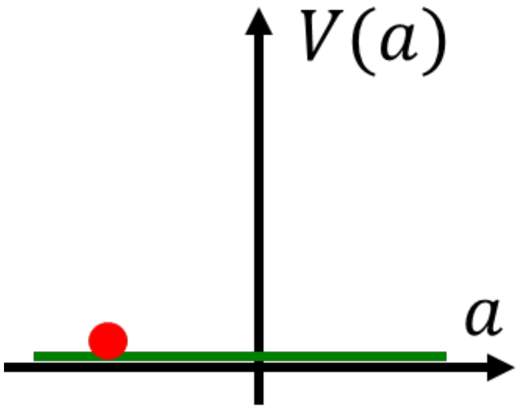
Vacuum Realignment Mechanism

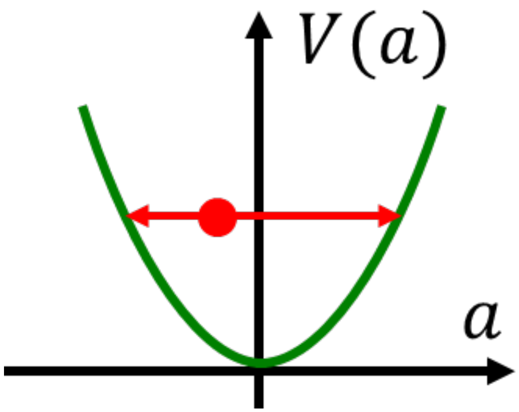
> DM from vacuum realignment:

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

- In causally connected region at phase transition, axion frozen at random initial value
- Later when $H(T) \sim m_A(T)$, axion field starts to oscillate around zero; behaves like cold dark matter:

$$w_A = p_A/\rho_A \simeq 0$$





[Raffelt]

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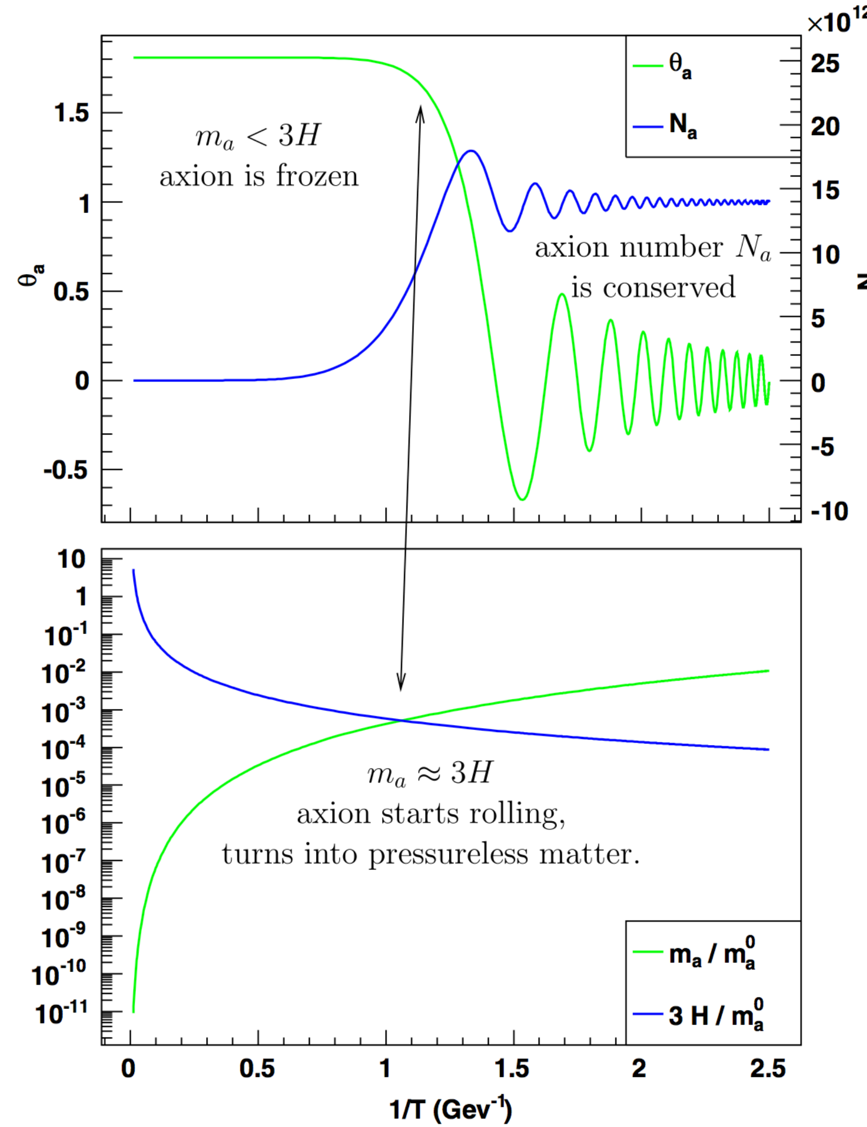

[Wantz,Shellard `09]

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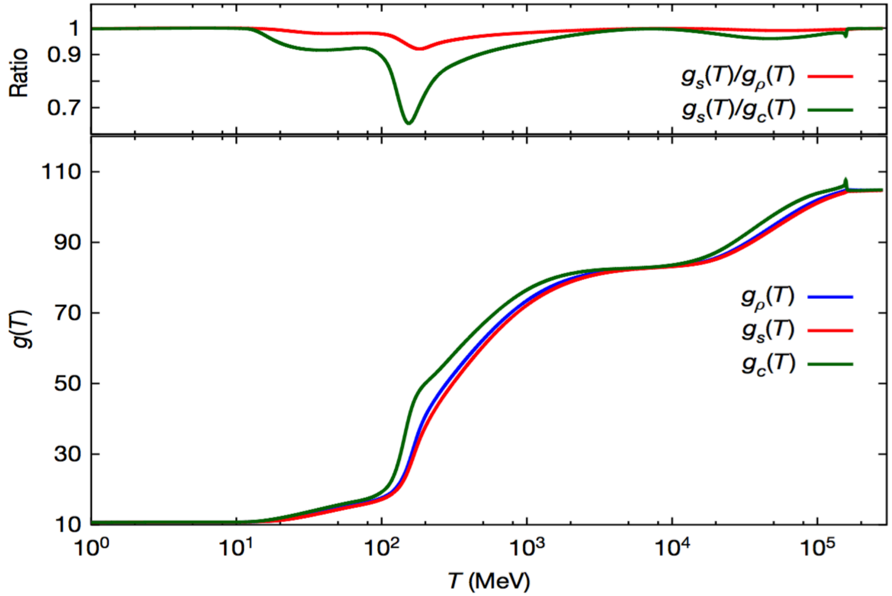

[Borsanyi et al., Nature `16 [1606.0794]]

> Crucial QCD input for prediction of axion DM abundance:

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

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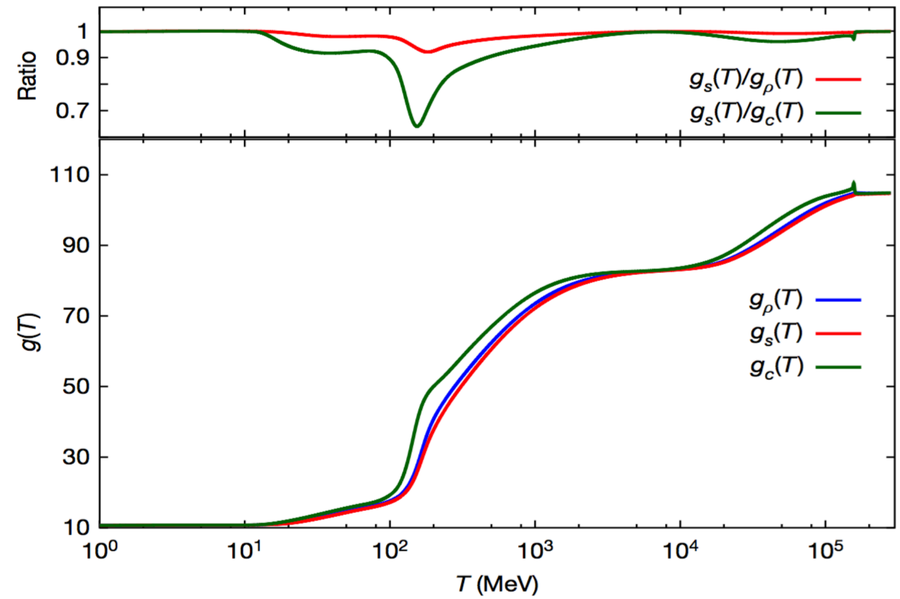
> Crucial QCD input for prediction of axion DM abundance:

- 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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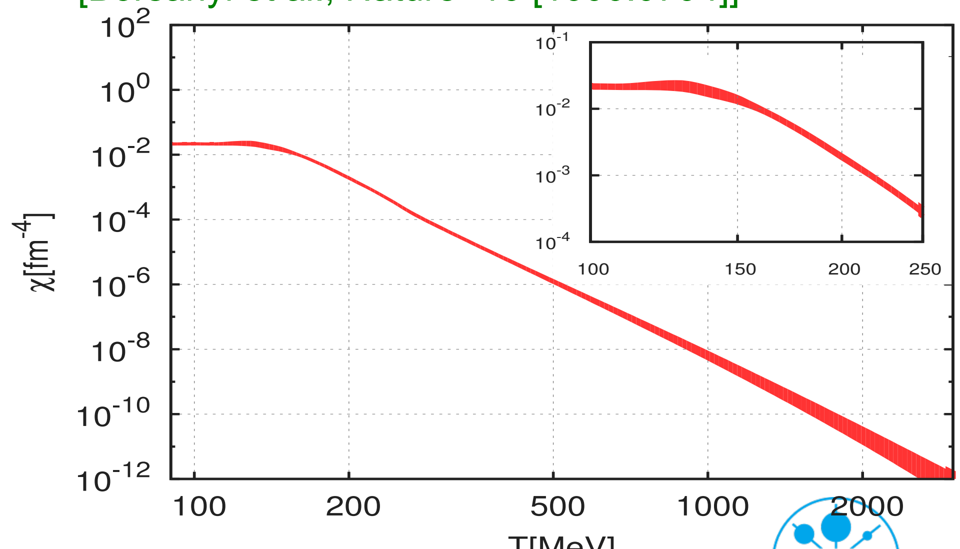
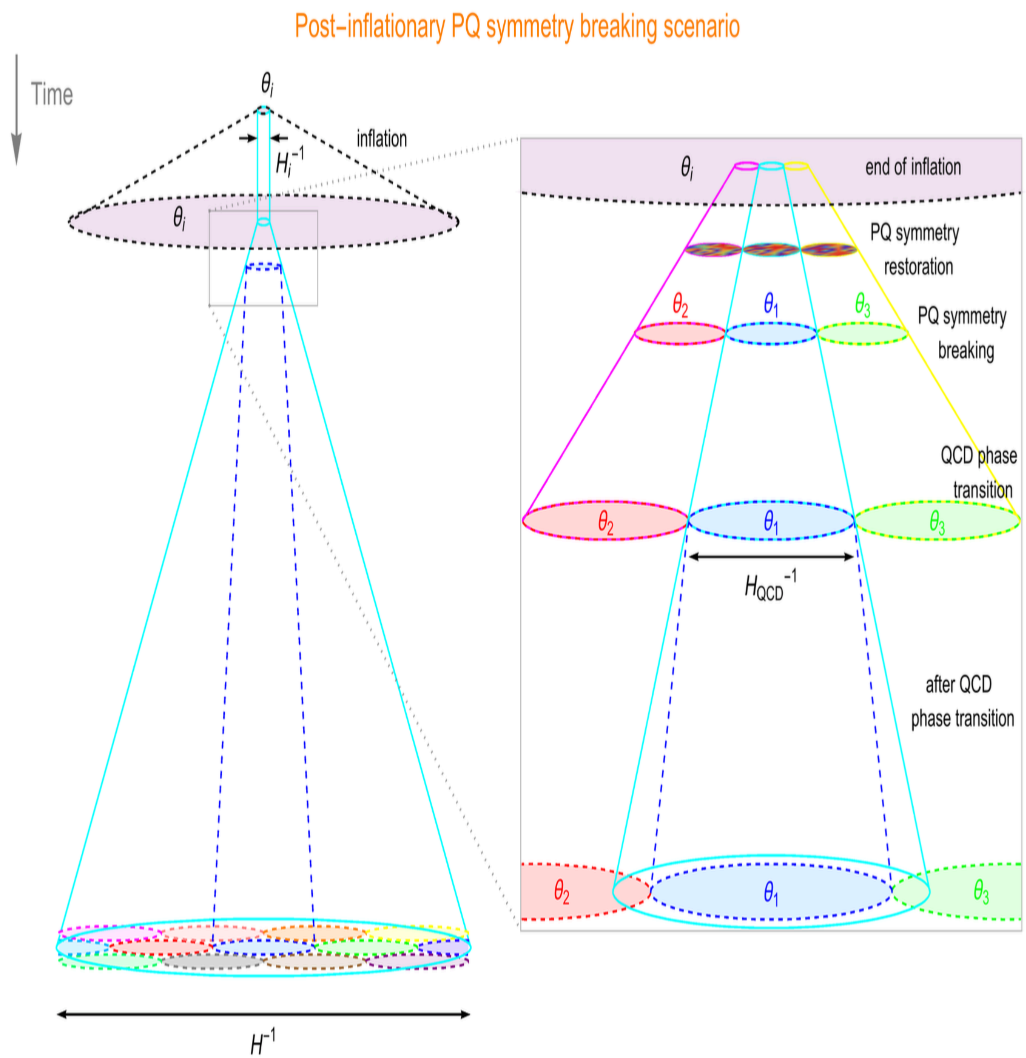


Post-inflationary PQ Symmetry Breaking Scenario

- If Peccei-Quinn symmetry breaking occurs after inflation
  - Present universe consists of many causally disconnected patches with random initial values of axion field
  - Naive average over patches, ignoring inhomogeneities at boundaries

$$\Omega_A^{\rm vr} h^2 = 0.12 \left(\frac{29.7\ \mu{\rm eV}}{m_A}\right)^{1.165}$$



[Saikawa]

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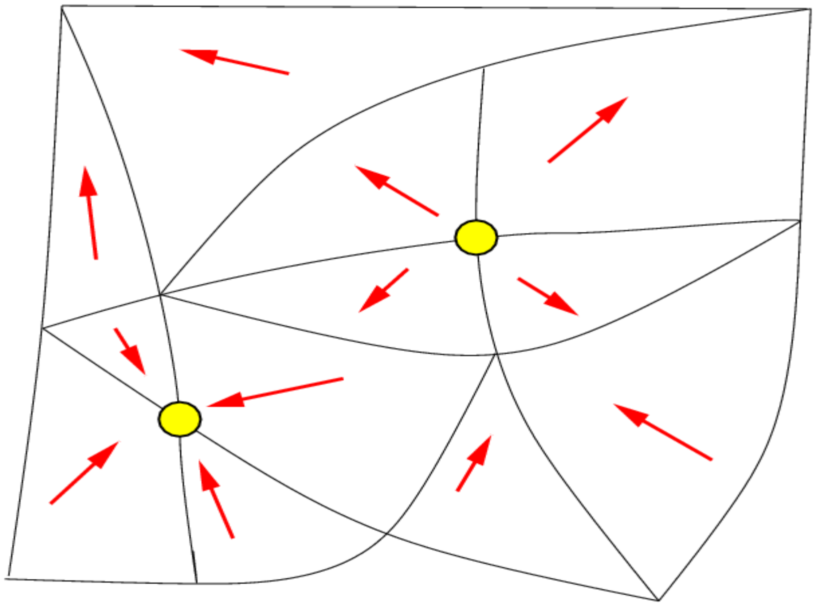

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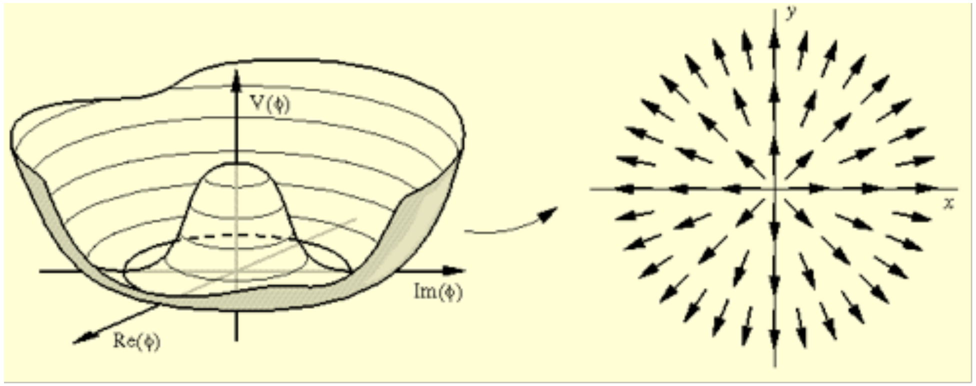

[ctc.cam.ac.uk]

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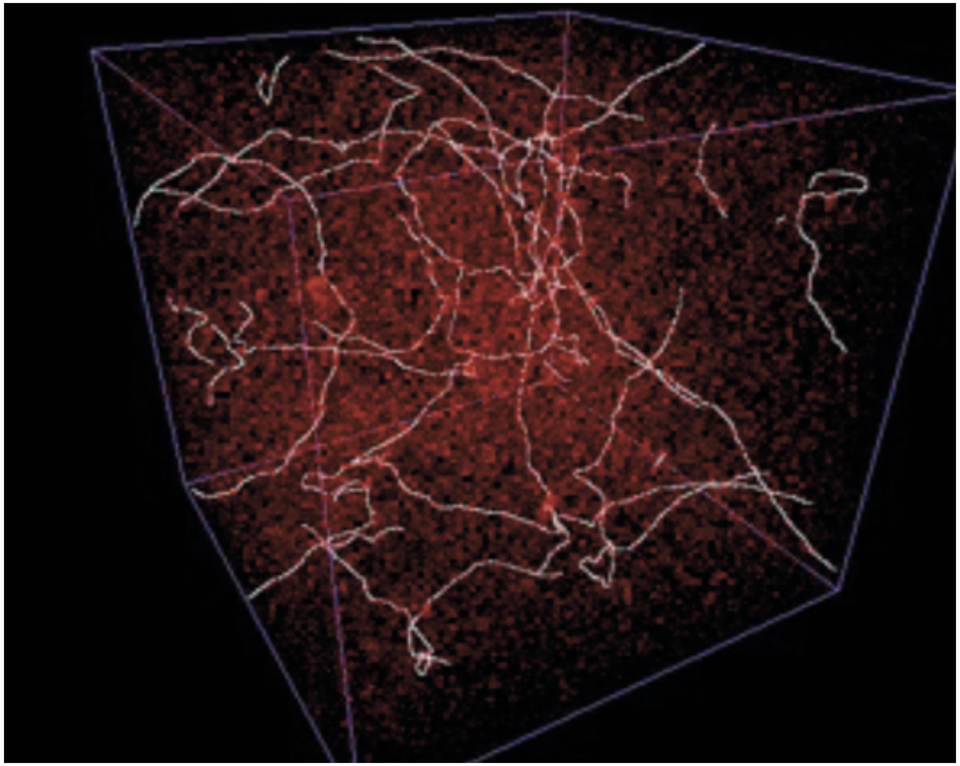

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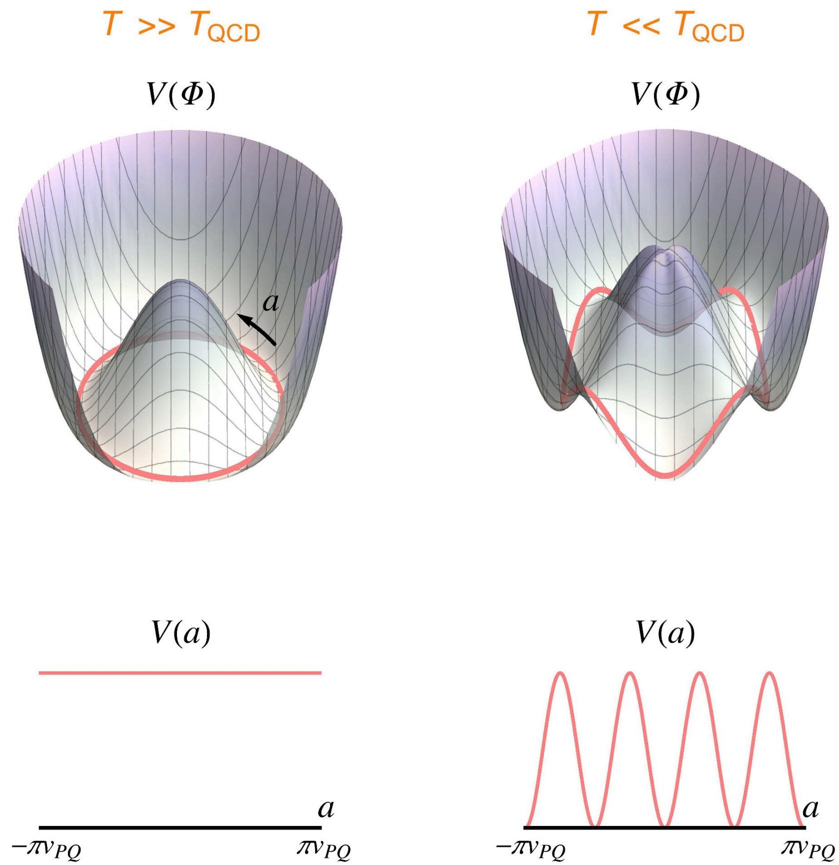
  - Non-negligible inhomogeneities: cosmic strings and domain walls
  - Around QCD phase transition, axion potential develops,

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



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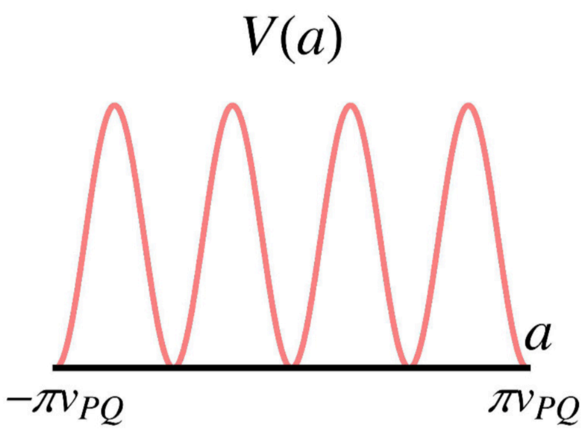
N domain walls end at string



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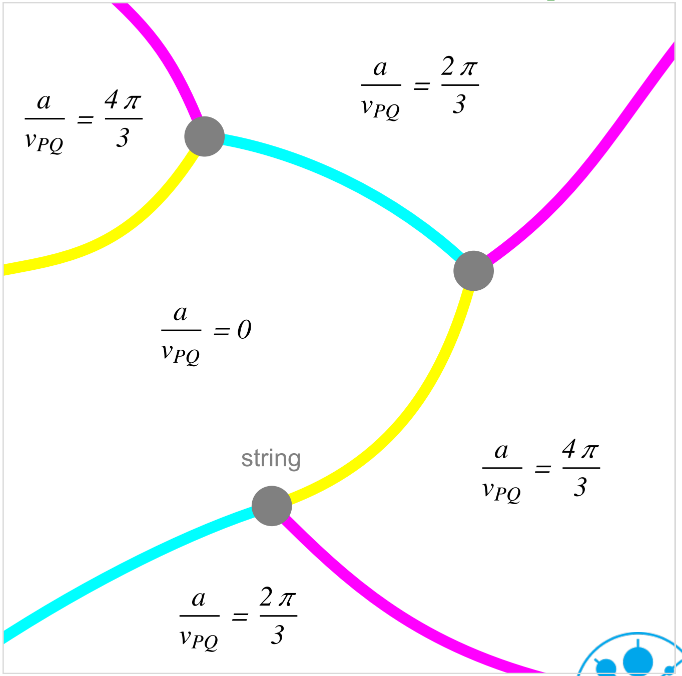

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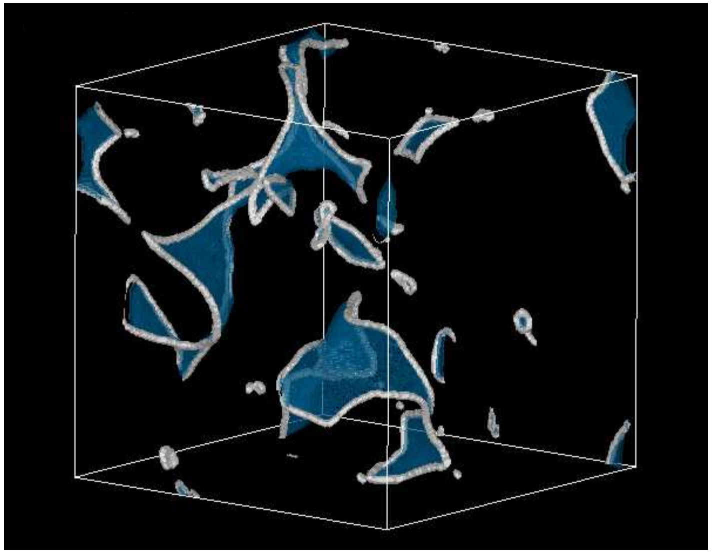

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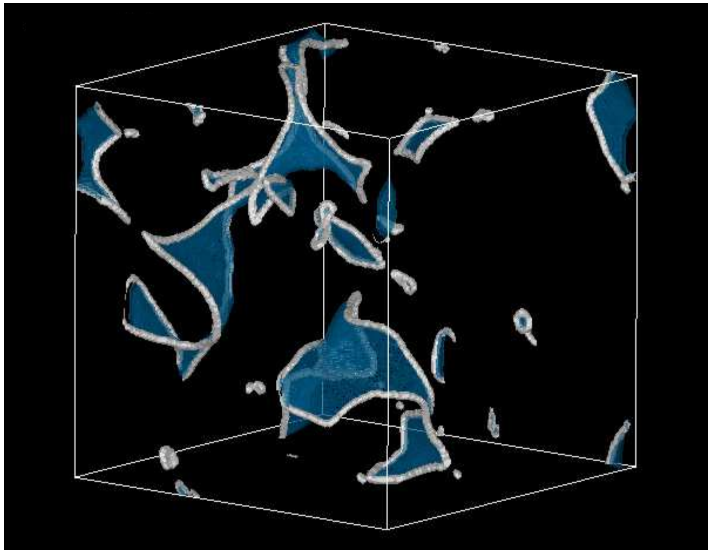
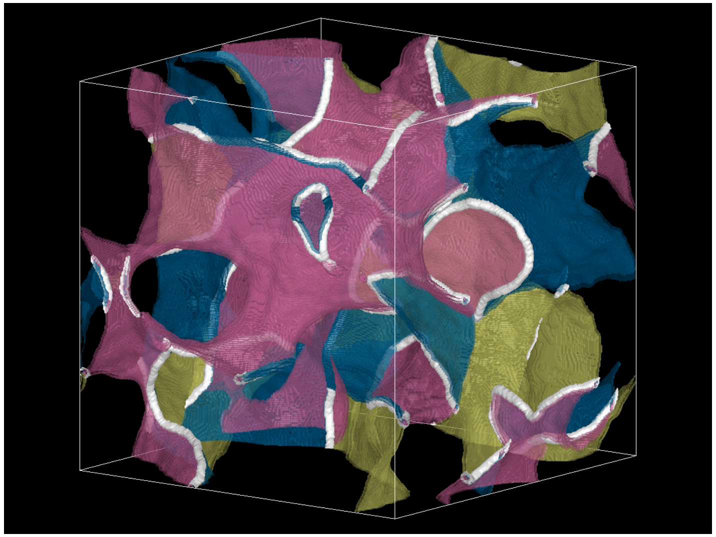
N domain walls end at string

- $N = 1$: String-wall system decays
- $N > 1$: Domain wall problem

$N = 1$



$N = 3$



[Hiramatsu et al.]

Dark-Matter Axion Mass in Post-inflationary PQ SB Scen.

- In $N = 1$ post-inflationary PQ breaking scenario:
- Exploiting results from field theoretic lattice simulations, updated to latest determination of topological susceptibility, and artificially separating

$$\Omega_A^{\rm tot} = \Omega_A^{\rm vr} + \Omega_A^{\rm string+wall}$$

find

$$\Omega_{A,\rm tot} h^2 \approx 1.6^{+1.0}_{-0.7} \times 10^{-2} \times \left(\frac{f_A}{10^{10}\,\rm GeV}\right)^{1.165}$$

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

CDM explained for

$$m_A \approx (50\text{–}200)\,\mu\rm eV$$

- Large uncertainty to account for errors due to extrapolation of string tension $T_{\rm str} = \pi f_A^2 \kappa$, with $\kappa = \ln(\sqrt{2\lambda_\sigma} f_A/H)$, from the values affordable in the simulations, $\kappa \lesssim 7$, to physical values, $\kappa \in [48, 67]$
- New simulation method allows to simulate at physical string tension

[Klaer,Moore `17]

Dark-Matter Axion Mass in Post-inflationary PQ SB Scen.

- For $\kappa \gg 1$, string's interactions with the long range PQ field ($\propto f_A^2$) become less important relative to string evolution under tension ($\propto f_A^2 \kappa$)
- For $\kappa \gg 1$, string behavior should approach that of infinitely thin, i.e. local Nambu-Goto strings [Klaer,Moore `17]

$$
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\mathcal{L} &= \mathcal{L}_{\rm NG} + \mathcal{L}_{\rm GS} + \mathcal{L}_{\rm KR}\,, \\
\mathcal{L}_{\rm NG} &= \bar\kappa \pi f_A^2 \int d\sigma \sqrt{y'^2(\sigma)(1-\dot y^2(\sigma))}\,, \\
\mathcal{L}_{\rm GS} &= f_A^2 \int d^3x\, \partial_\mu\theta\partial^\mu\theta\,, \\
\mathcal{L}_{\rm KR} &= \int d^3x\, A_{\mu\nu} j^{\mu\nu}\,, \\
H_{\mu\nu\alpha} &= f_A \epsilon_{\mu\nu\alpha\beta}\partial^\beta\theta = \partial_\mu A_{\nu\alpha} + \text{cyclic}\,, \\
j^{\mu\nu} &= -2\pi f_A \int d\sigma\, \left(v^\mu y'^\nu - v^\nu y'^\mu\right) \delta^3(x - y(\sigma))
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-\mathcal{L}(\varphi_1,\varphi_2,A_\mu) = &\frac{1}{4e^2}F_{\mu\nu}F^{\mu\nu} + \left|(\partial_\mu - iq_1A_\mu)\varphi_1\right|^2 + \left|(\partial_\mu - iq_2A_\mu)\varphi_2\right|^2 \\
&+ \frac{m_1^2}{8v_1^2}\left(2\varphi_1^*\varphi_1 - v_1^2\right)^2 + \frac{m_2^2}{8v_2^2}\left(2\varphi_2^*\varphi_2 - v_2^2\right)^2 + \frac{\lambda_{12}}{2}\left(2\varphi_1^*\varphi_1 - v_1^2\right)\left(2\varphi_2^*\varphi_2 - v_2^2\right)
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- New method: exploit UV extension of PQ field theory, with additional complex scalar and additional local U(1) symmetry, reducing in IR to Nambu-Goto string plus axion
  - Local U(1) attaches Abelian-Higgs string onto every global string, enhancing $T_{\rm str}$
  - Added degrees of freedom massive off string

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Dark-Matter Axion Mass in Post-inflationary PQ SB Scen.

- Exploiting lattice results on topological susceptibility of [Borsanyi et al. `16]:

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

[Klaer,Moore `17]

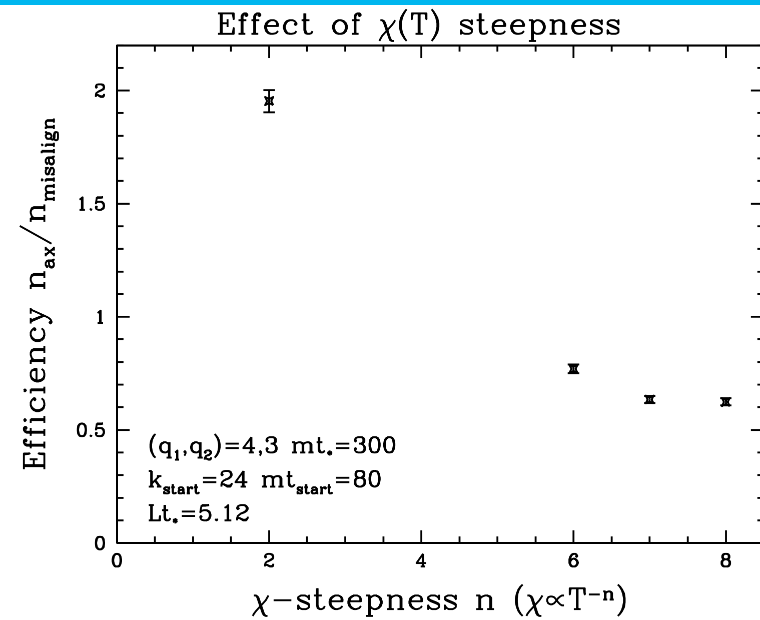
- Axion production efficiency smaller than angle-average of ``realignment'' mechanism

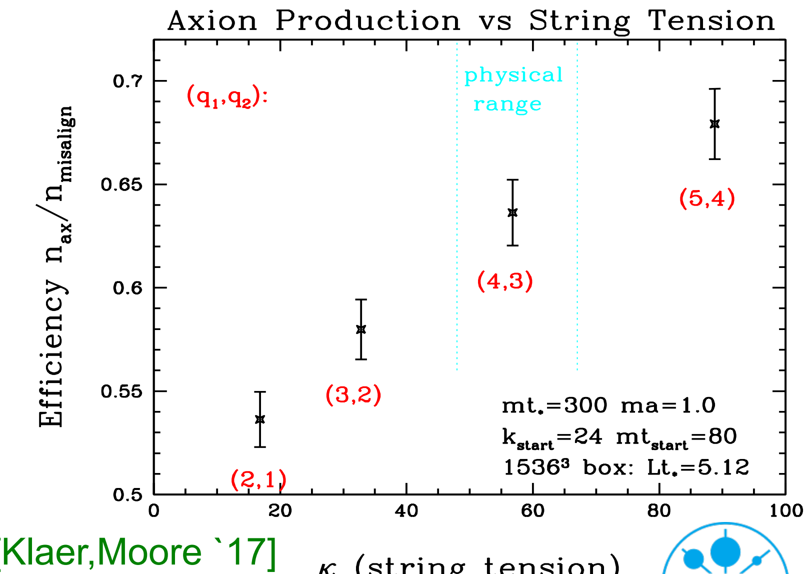
$$\Omega_A^{\rm vr} h^2 = 0.12 \left(\frac{29.7\ \mu\text{eV}}{m_A}\right)^{1.165}$$

  - Simple sum

$$\Omega_A^{\rm tot} = \Omega_A^{\rm vr} + \Omega_A^{\rm string+wall}$$

    double counts
  - Energy in domain walls is the energy of field misalignment, from values $\theta \sim \pi$





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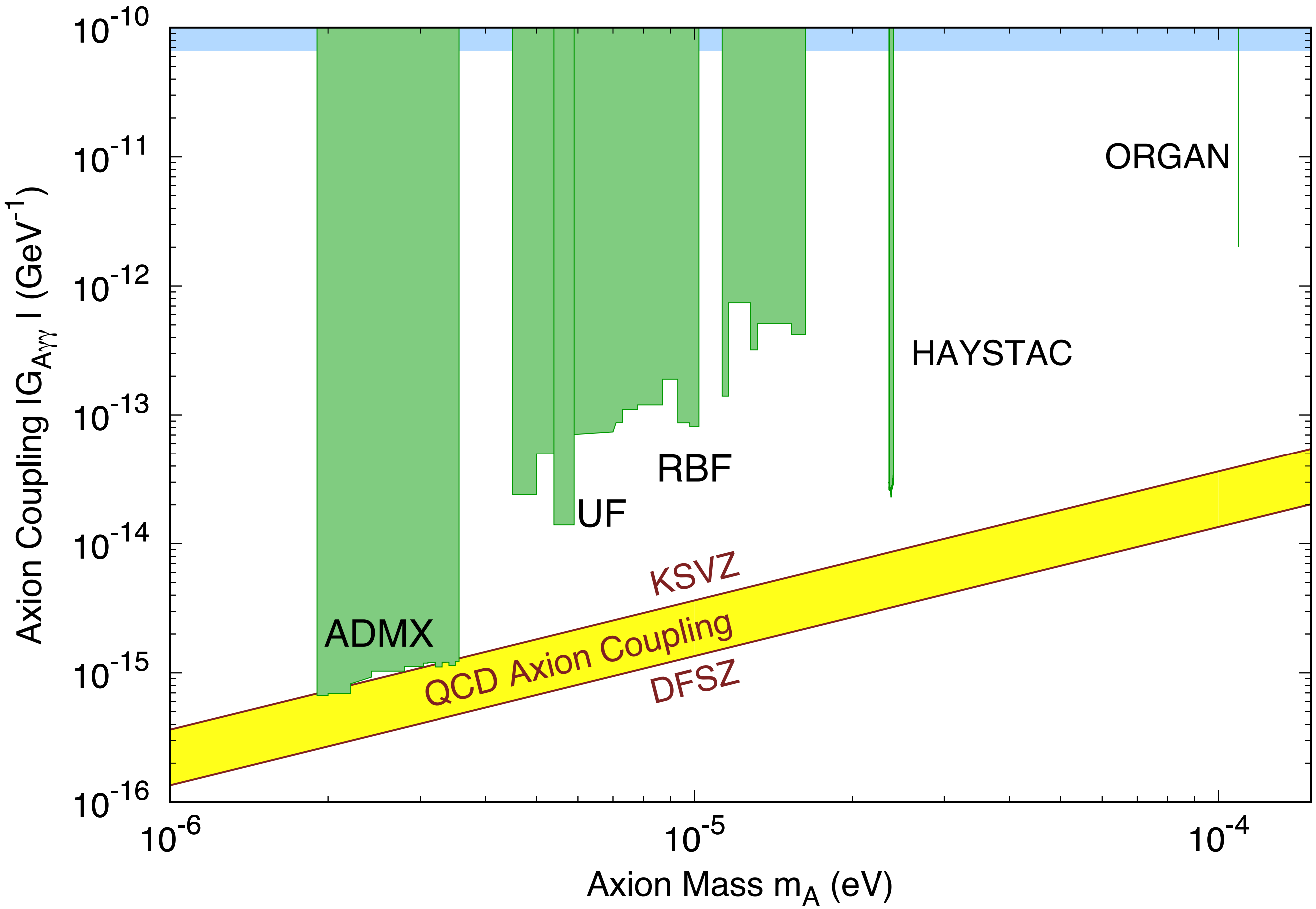
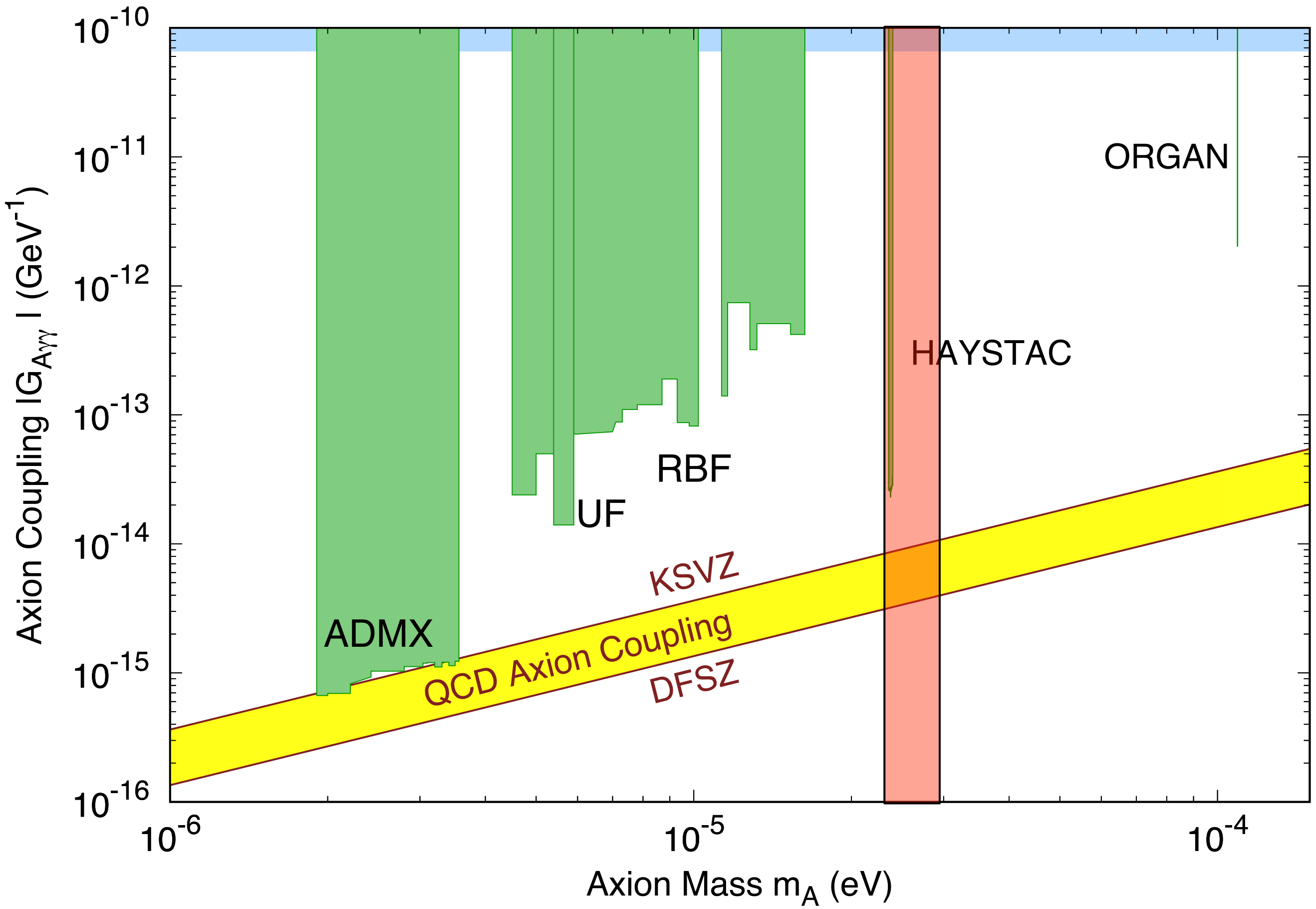
Dark-Matter Axion Mass in Post-inflationary PQ SB Scen.

- Current experimental bounds:



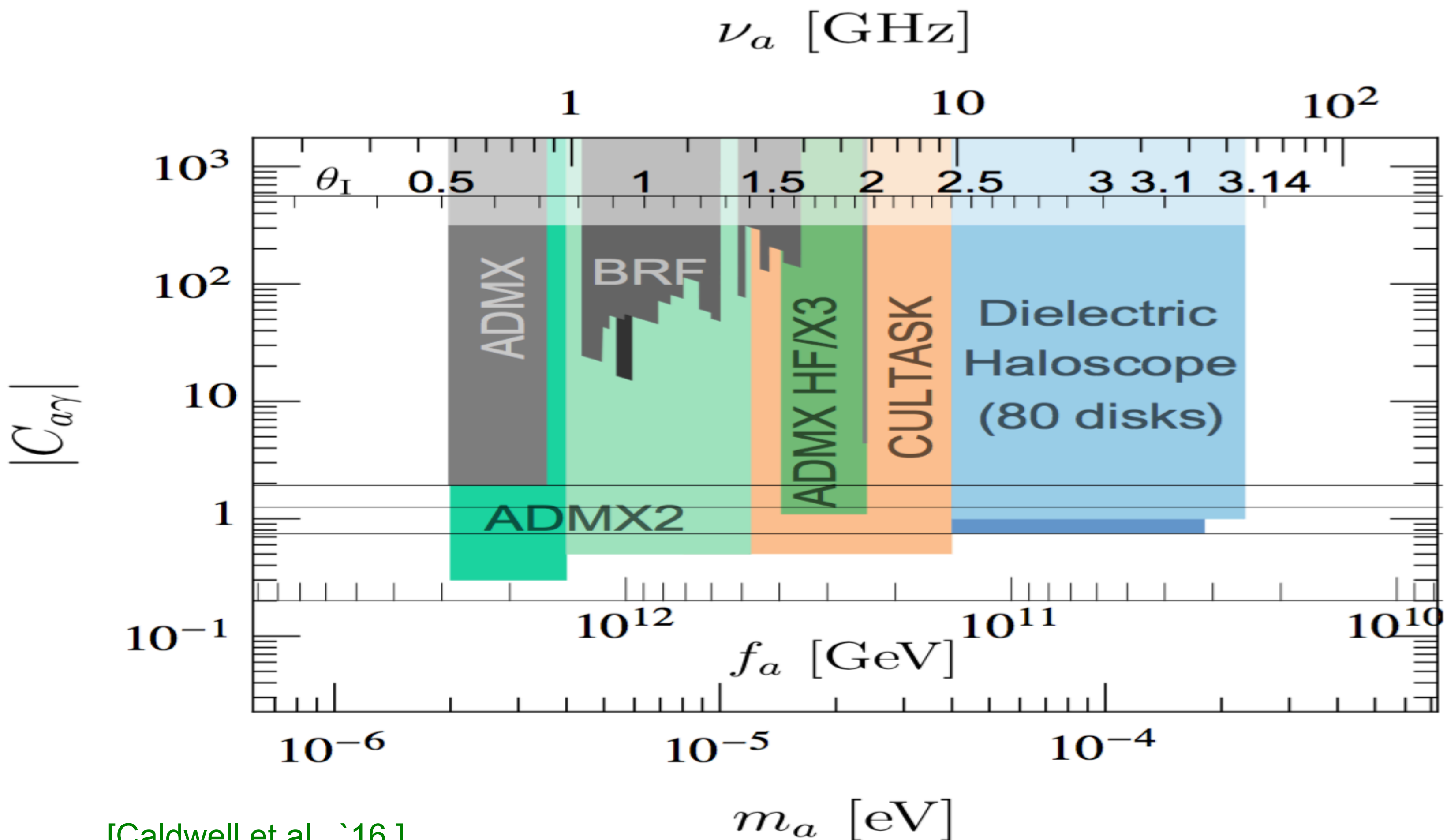
Dark-Matter Axion Mass in Post-inflationary PQ SB Scen.

> Current experimental bounds vs. prediction:



Dark-Matter Axion Mass in Post-inflationary PQ SB Scen.

- Projected experimental sensitivities:



[Caldwell et al. `16]

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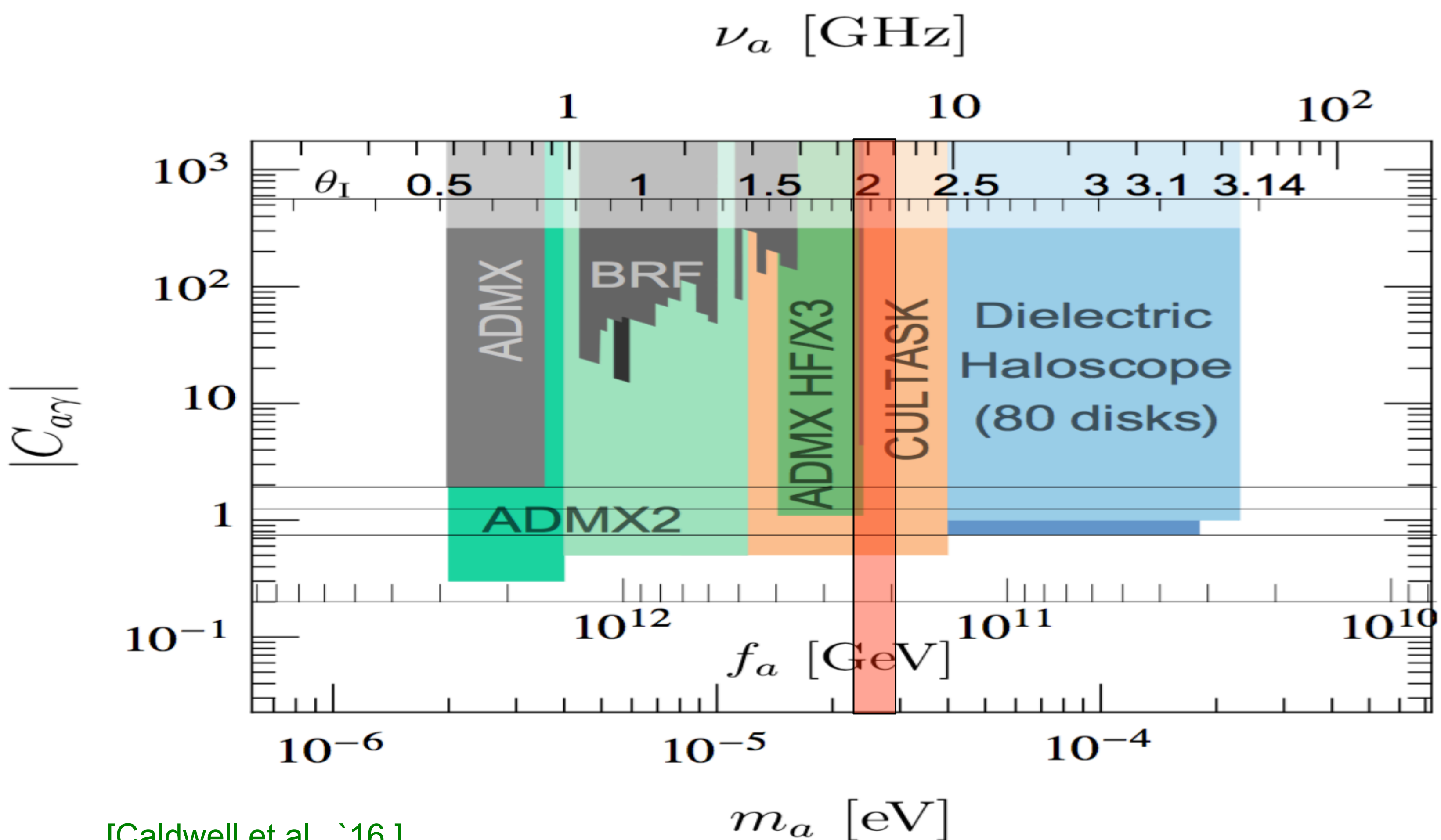


[Caldwell et al. `16]

Discussion and Conclusions

- Most realistic simulations, as far as string tension is concerned, find significantly lower dark-matter axion mass in $N = 1$ post-inflationary PQ SSB scenario than previously estimated:

$$m_A = 26.2 \pm 3.4 \, \mu\mathrm{eV}$$

- Need independent confirmation:
  - Small distances resolved in effective way
  - Is there complete decoupling between short distances and long distances?
- If confirmed: Mass in reach of conventional microwave cavity technique
  - However, this assumes axion 100 % of dark matter!
  - Dark-matter axion mass will move to higher values if axion sub-dominant dark matter or if $N > 1$

Back-Up: Topological Susceptibility

> Topological susceptibility notoriously difficult to calculate on lattice

1. Large cutoff effects when exploiting action with non-chiral quarks to calculate topological observables
2. Tiny topological susceptibility needs extremely long simulation threads to observe enough changes of topological sectors

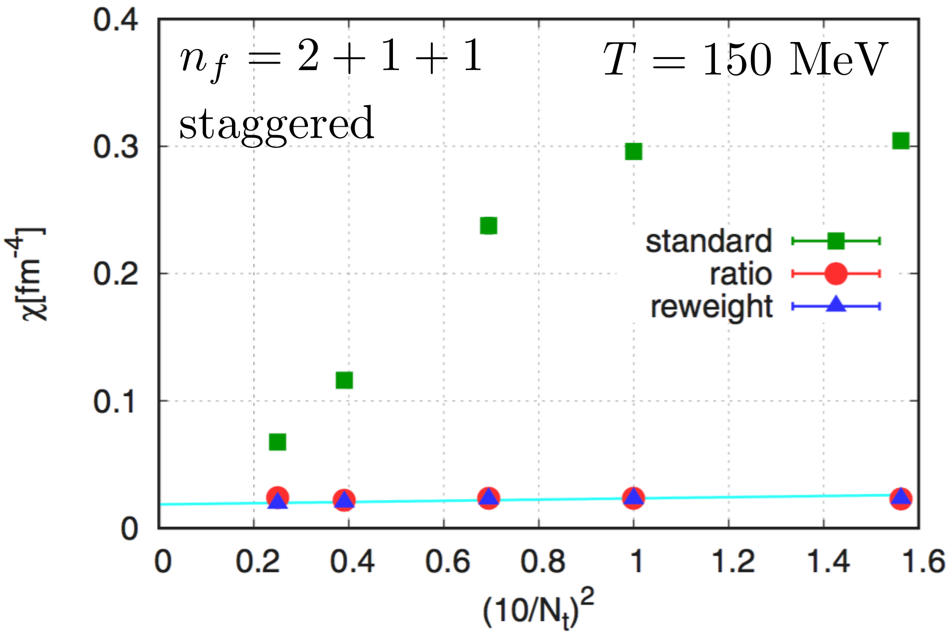
> Solutions of these problems:

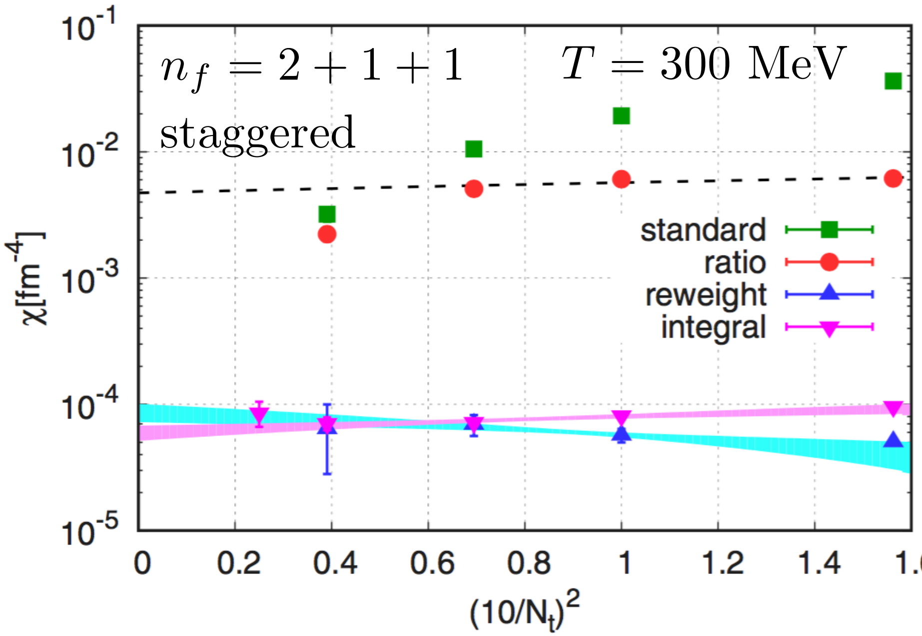
[Borsanyi et al. `16]

1. Eigenvalue reweighting technique: Substitute topology related eigenvalues of non-chiral quark Dirac operator with its corresponding eigenvalues in continuum
2. Fixed sector integral technique: Measure logarithmic differential of topological susceptibility which is related to quantities to be measured in fixed topological sectors. Then integrate.

Back-Up: Topological Susceptibility

- Comparison of lattice spacing dependence of topological susceptibility determined via different methods:





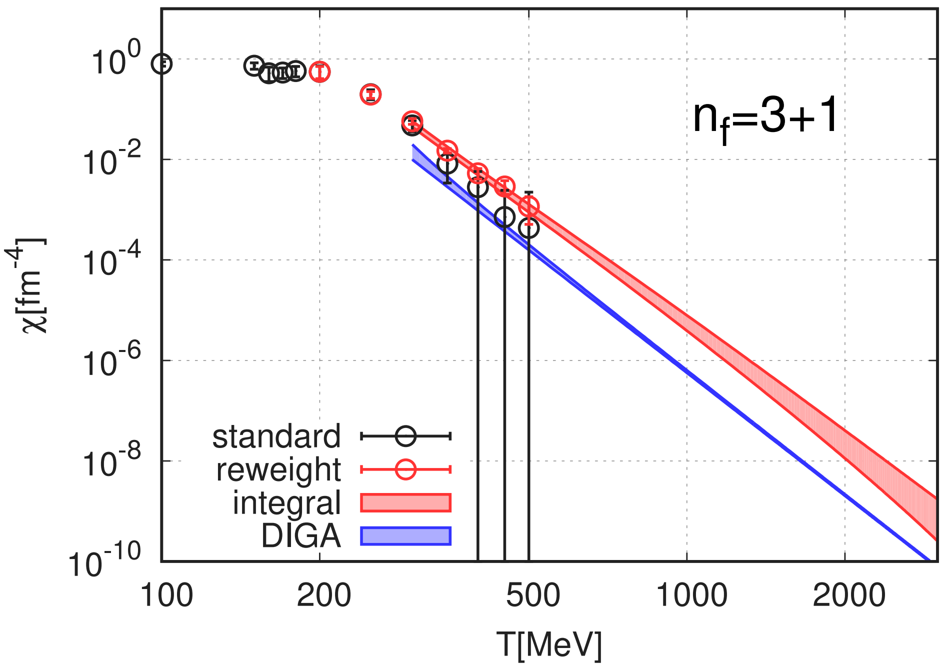
[Borsanyi et al. `16]

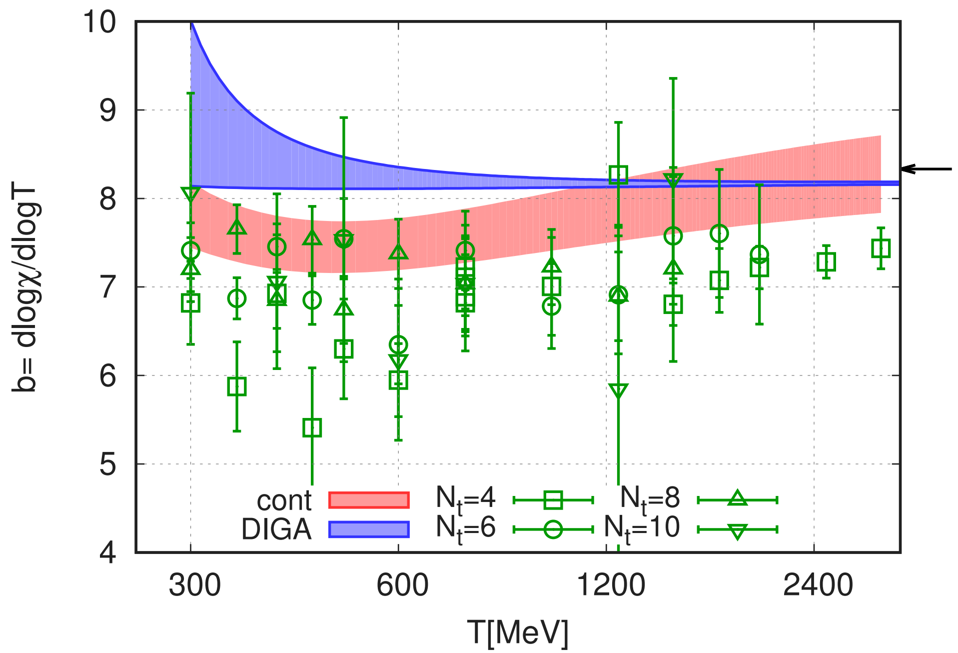
- At high temperatures, brute force („standard") method and ratio method suffer from strong cutoff effects

Back-Up: Topological Susceptibility

- Result:

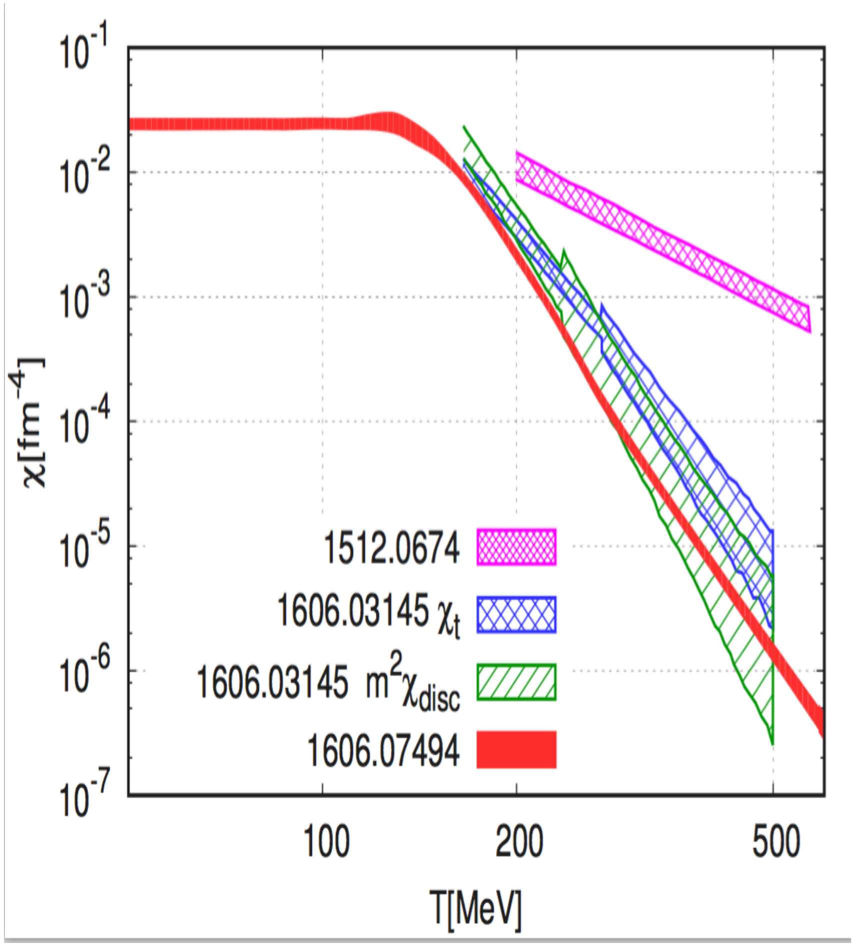
[Borsanyi et al. `16]



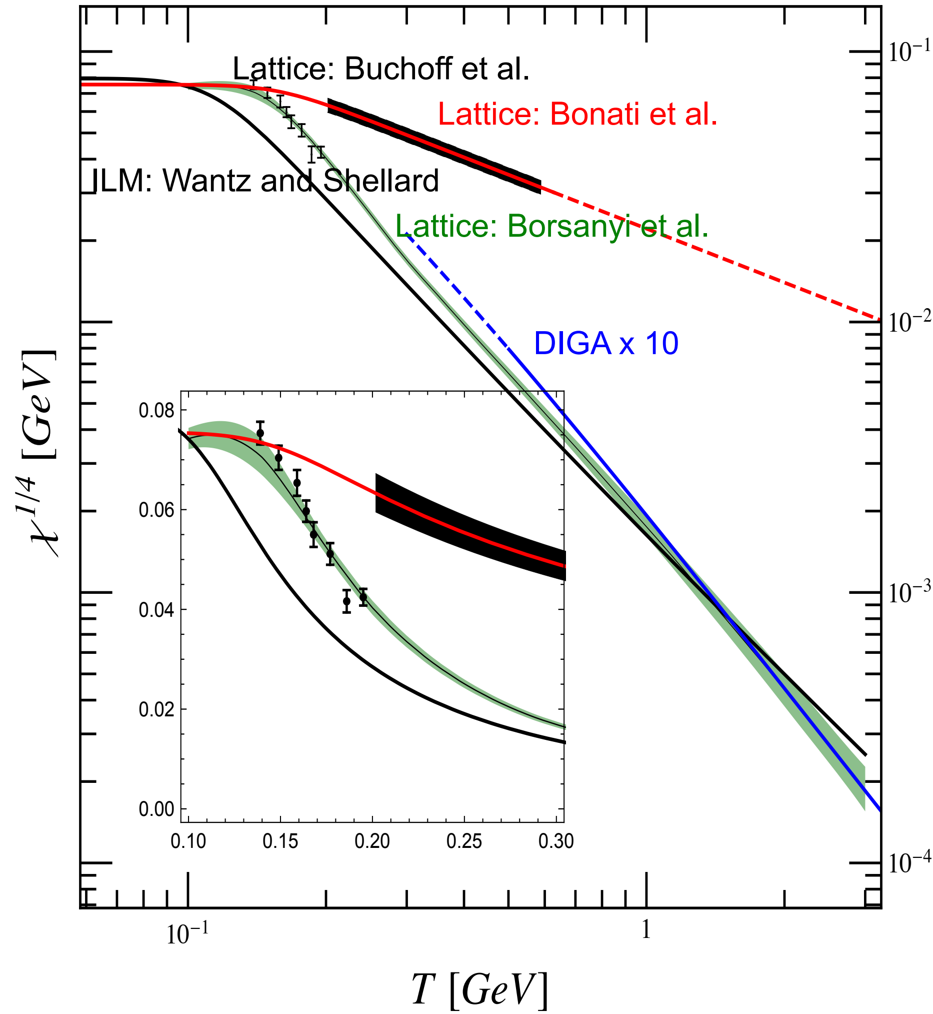


- Temperature slope close to dilute instanton gas approximation (DIGA)
- DIGA underestimates topological susceptibility by overall normalization „K factor“ of order ten (should be improved in two-loop DIGA)

Back-Up: Topological Susceptibility



[Borsanyi `16]



[Ballesteros,Redondo, AR,Tamarit `16]