The Axion Quark Nugget (AQN) Dark Matter Model

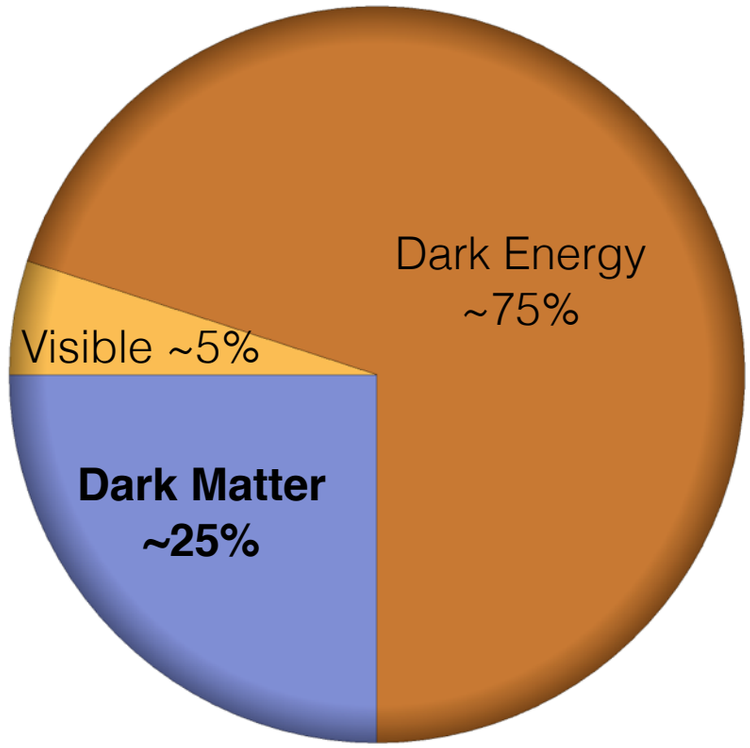
Shuailiang Ge

PhD at the University of British Columbia (UBC)

Supervisor: Ariel Zhitnitsky

THE UNIVERSITY OF BRITISH COLUMBIA

Dark Matter Candidates



- The conventional idea is that dark matter requires new (unknown) fields, such as the WIMPs (weakly interacting massive particles)…

- This proposal:
  "new fields" → "new phases" (color superconducting phase) of "old fields" (quarks) from the Standard Model.
  quark nugget

The idea of quark nuggets as DM is not new…

The idea that dark matter could be in form of very dense quark nugget has been advocated by E.Witten in 1984.

The quark nuggets are qualified as dark matter candidates because

$$\frac{\sigma}{M} << 1\mathrm{cm}^2/\mathrm{g}$$

A small geometrical parameter $\frac{\sigma}{M}$ replaces a weak coupling constant.

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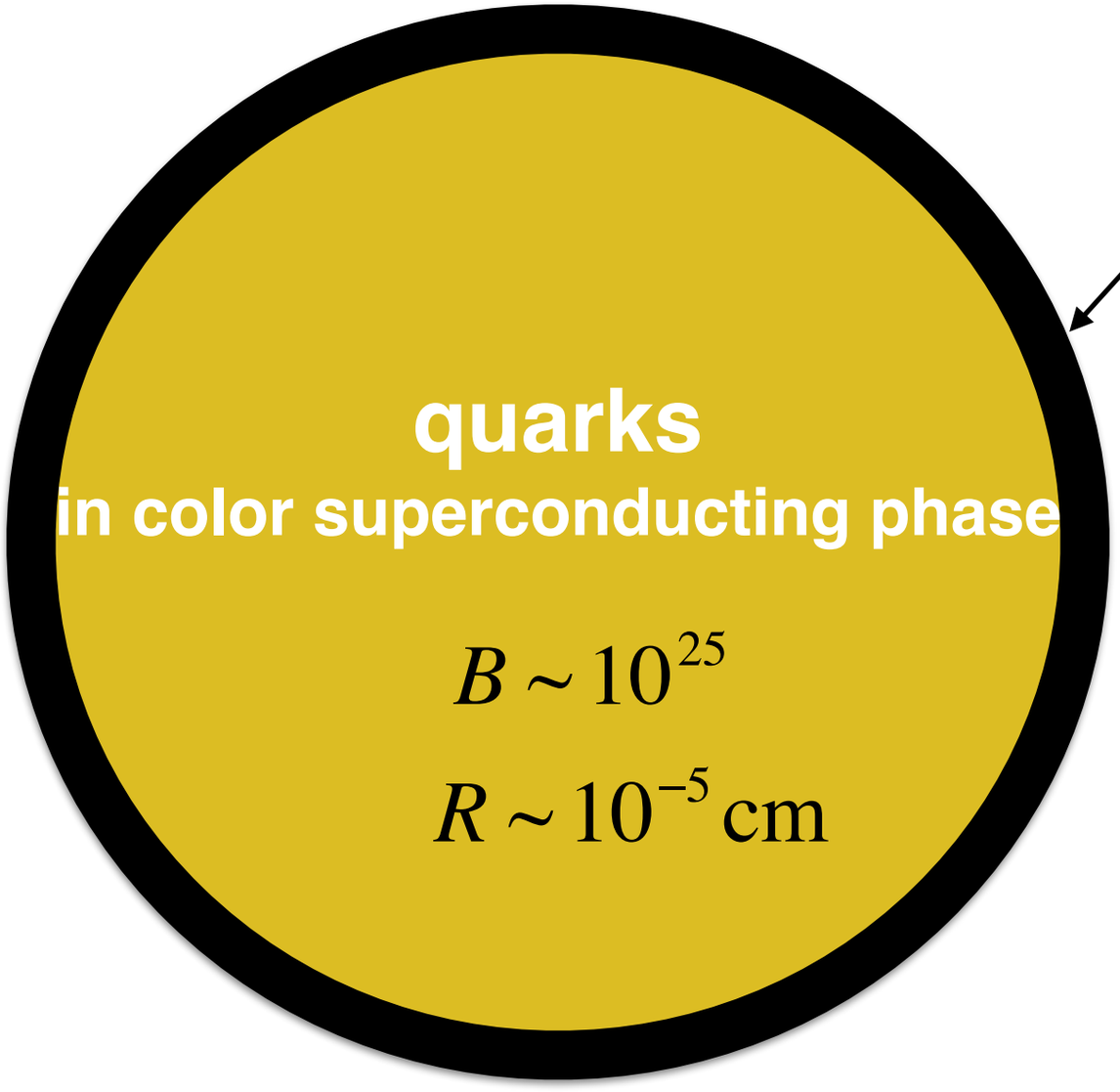
axion quark nugget (AQN)

Structure of an axion quark nugget (AQN)



axion domain wall as the shell
"squeezer"

$$\Delta_{\mathrm{gap}} \sim 100\ \mathrm{MeV}$$

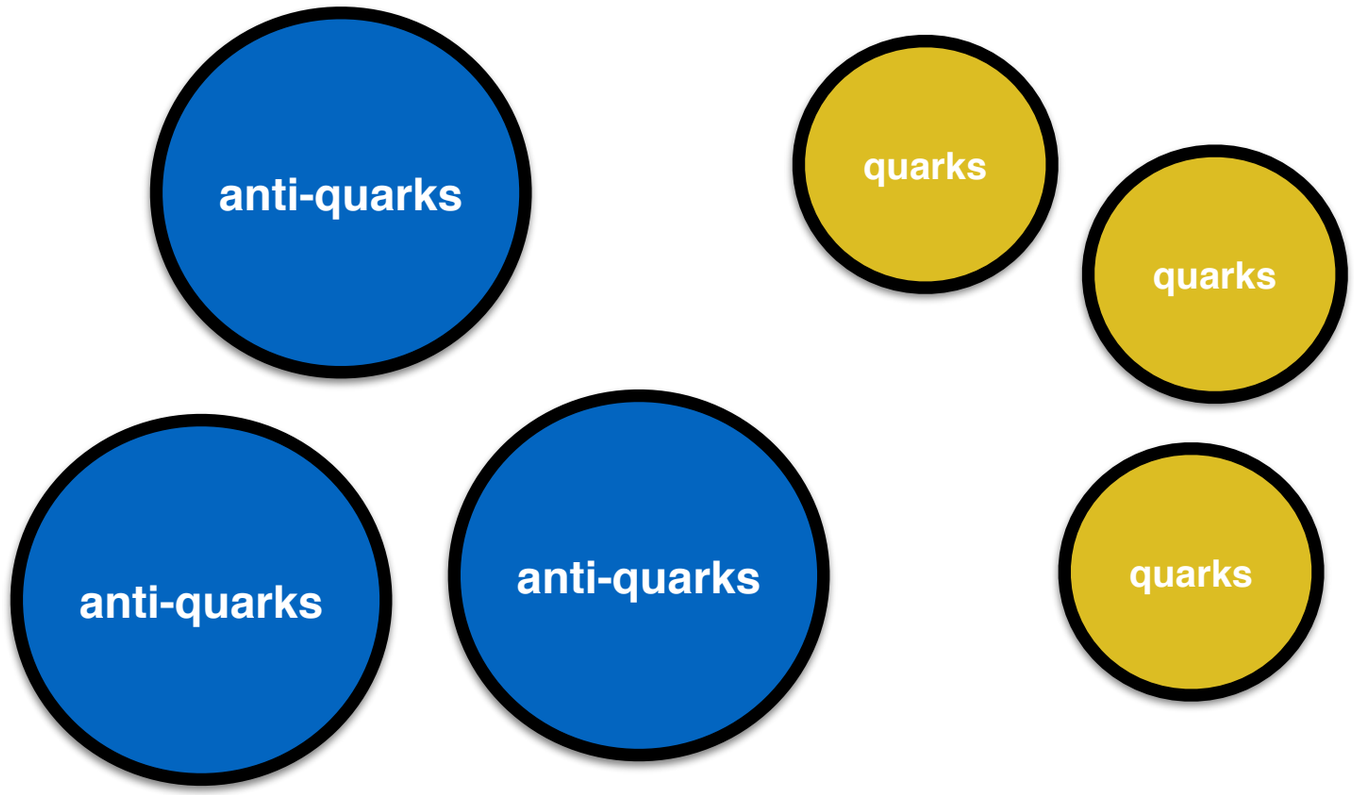
$$\frac{\sigma}{M} \sim 10^{-10}\,\mathrm{cm}^2/\mathrm{g} << 1\,\mathrm{cm}^2/\mathrm{g}$$

structure of a single axion quark nugget (AQN)

Matter-antimatter asymmetry in scenario of the AQN model

$$c \equiv \left| \frac{B_{\text{nuggets}}}{B_{\text{anti-nuggets}}} \right|$$

$$\Omega_{\text{DM}} \simeq \left(\frac{1+c}{1-c} \right) \Omega_{\text{visible}}$$



Anti-nuggets *nuggets*

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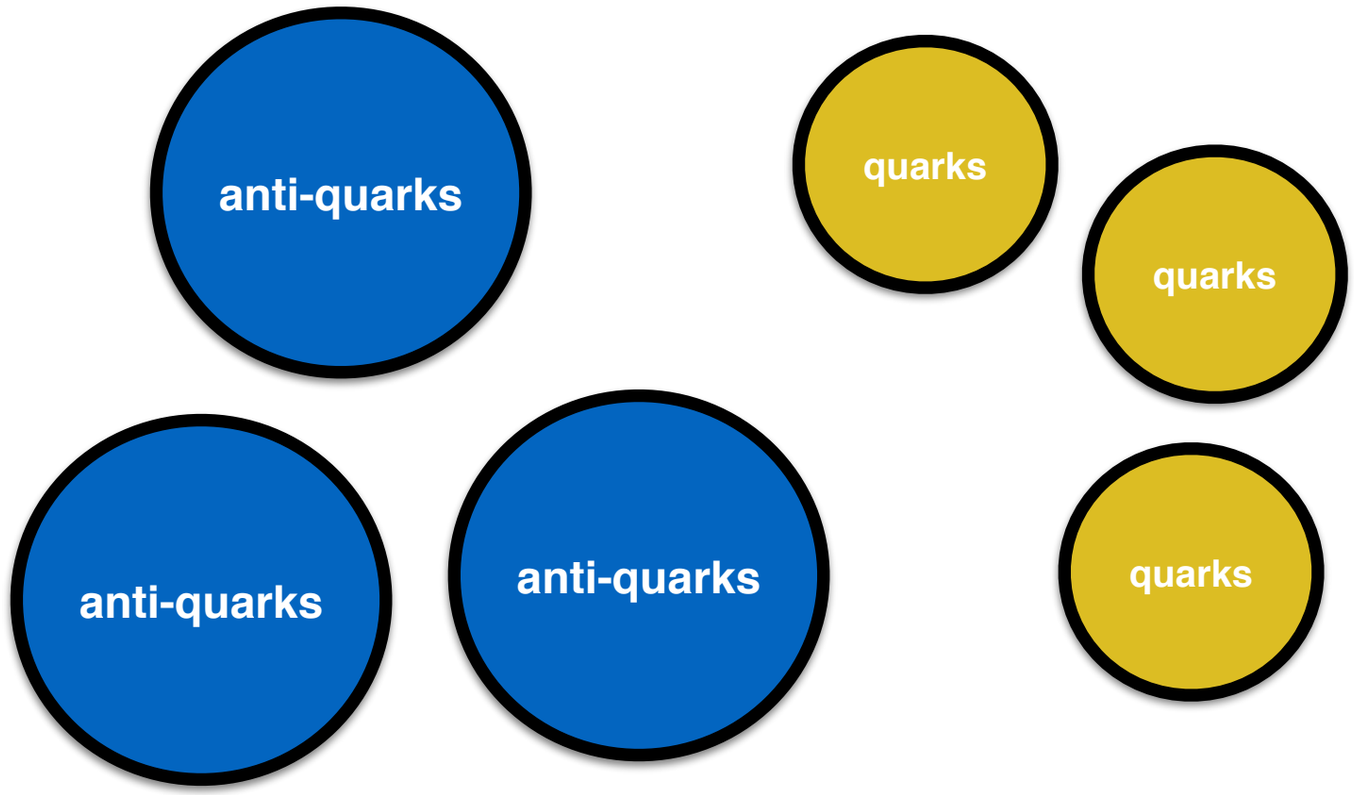

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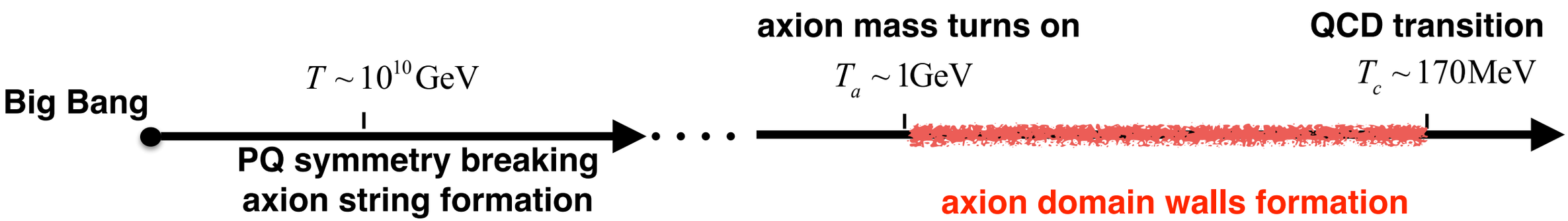
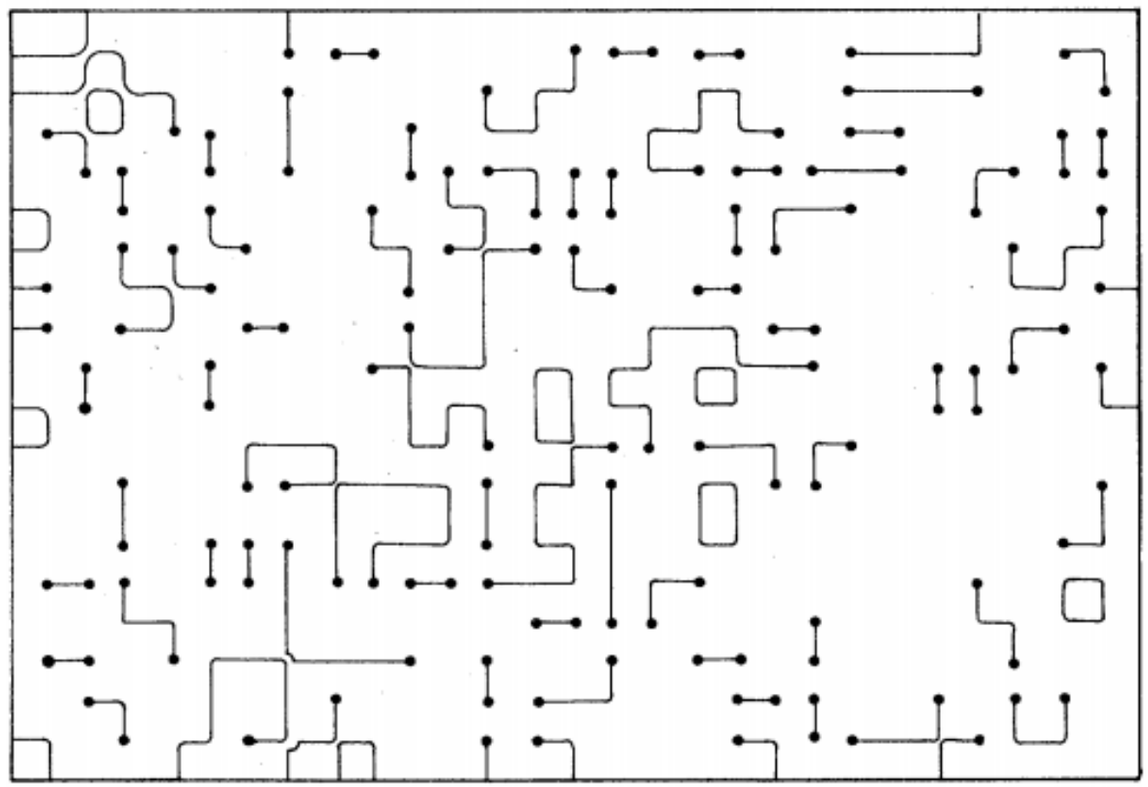
Formation of nuggets: axion domain walls



$$V_a \sim m_a^2(T)(1-\cos N_{\mathrm{DW}}\theta)$$



simulations of the formation axion strings and domain walls in 2D.
(Vachaspati and Vilenkin, 1984)

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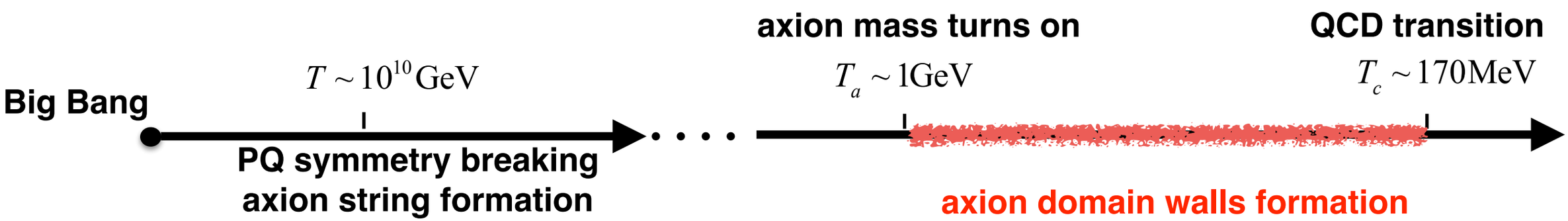

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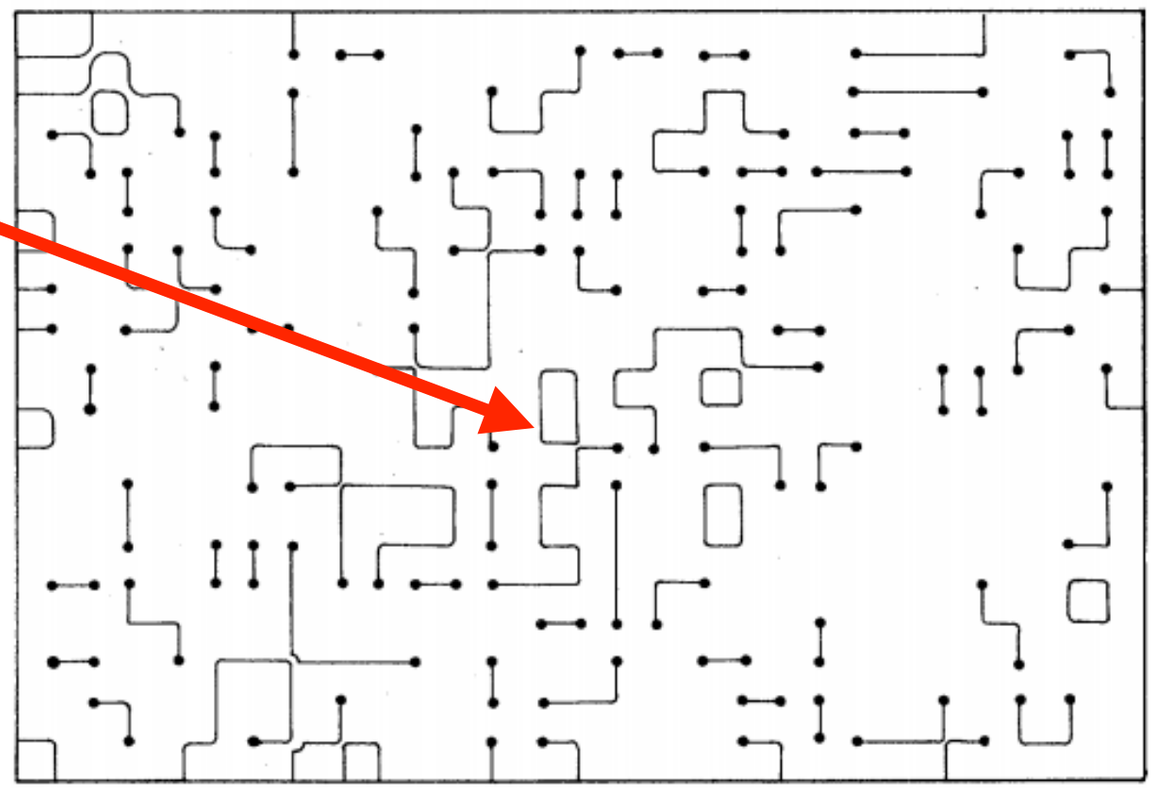
closed axion domain walls "bubbles"



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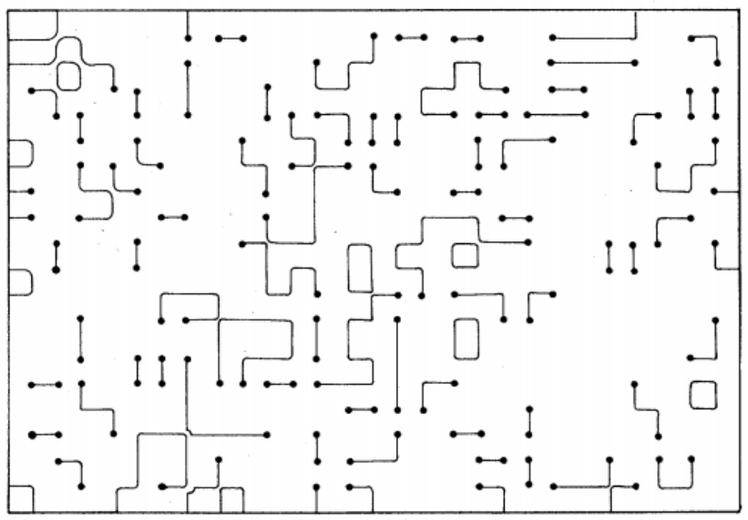

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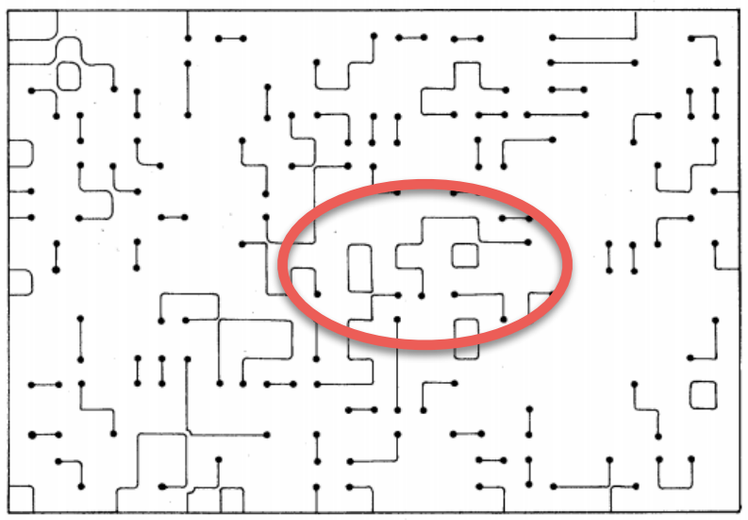

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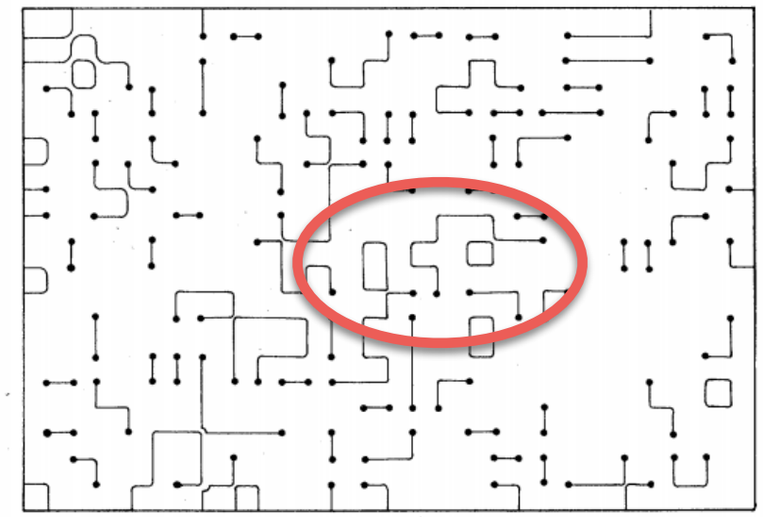

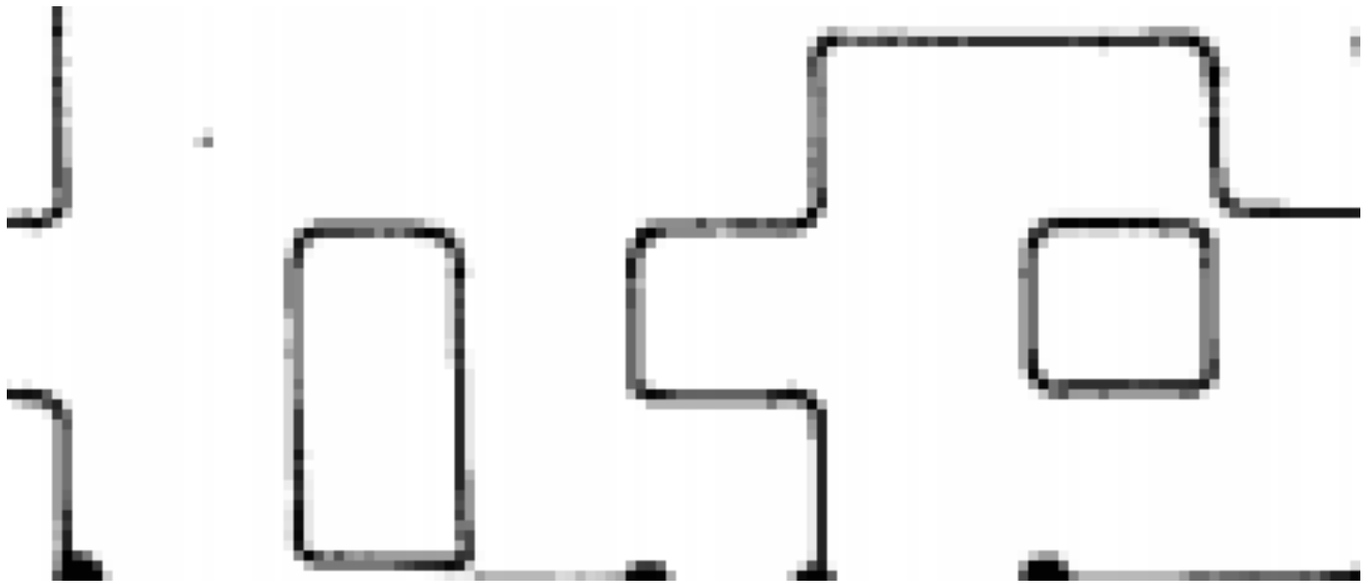

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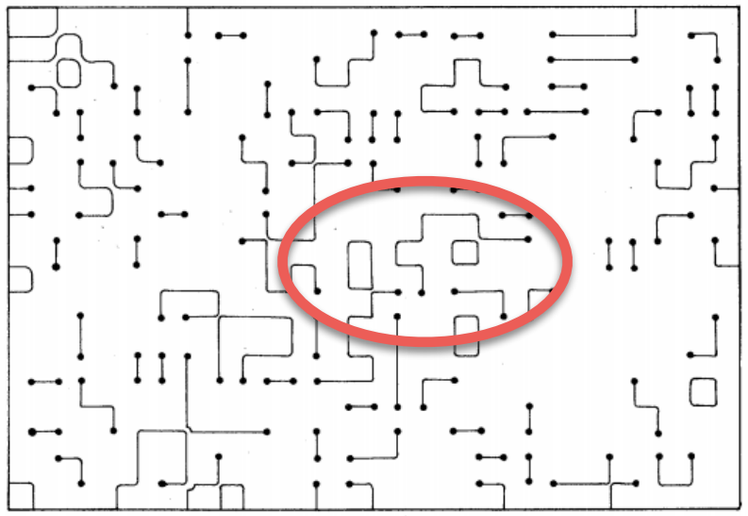

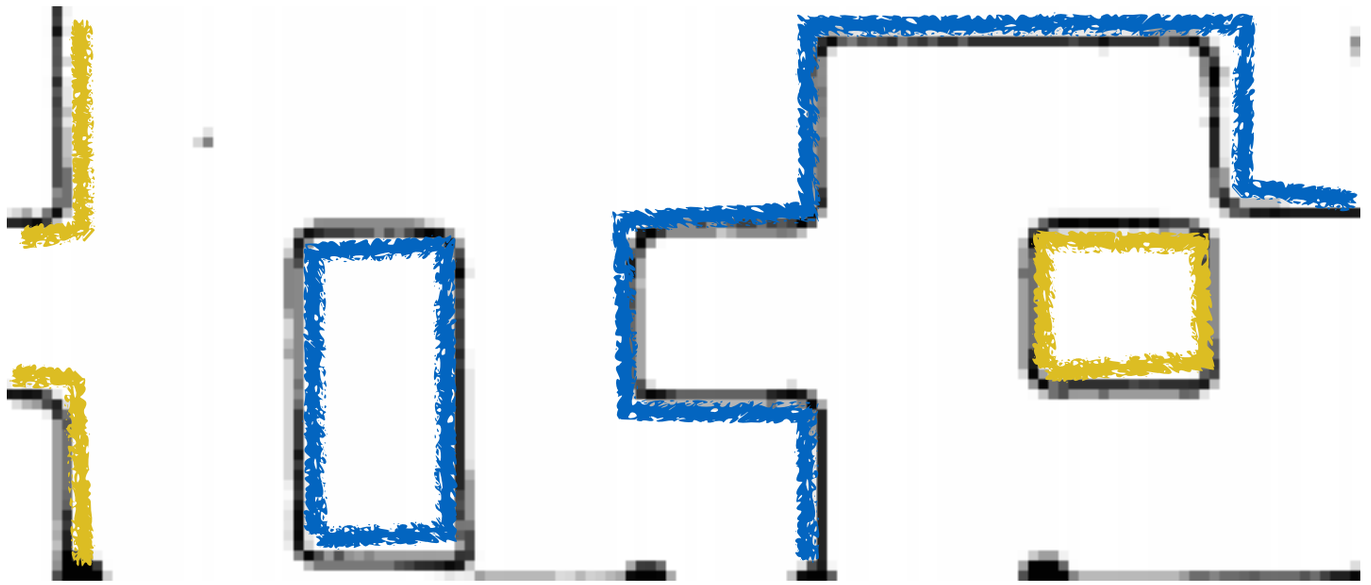

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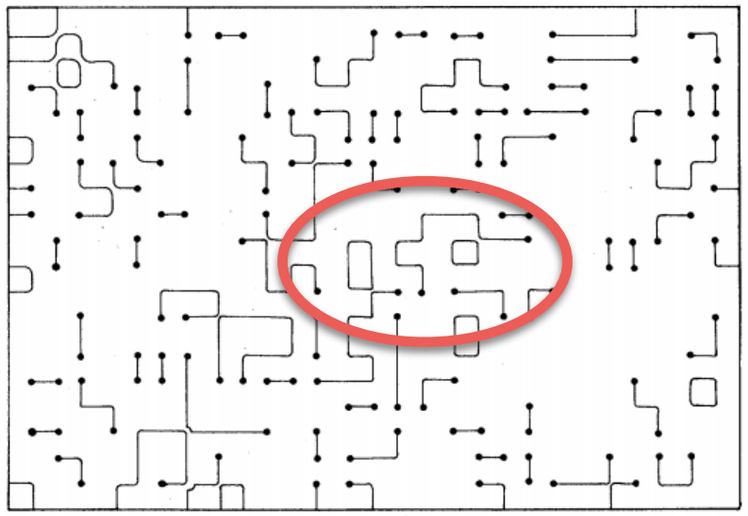
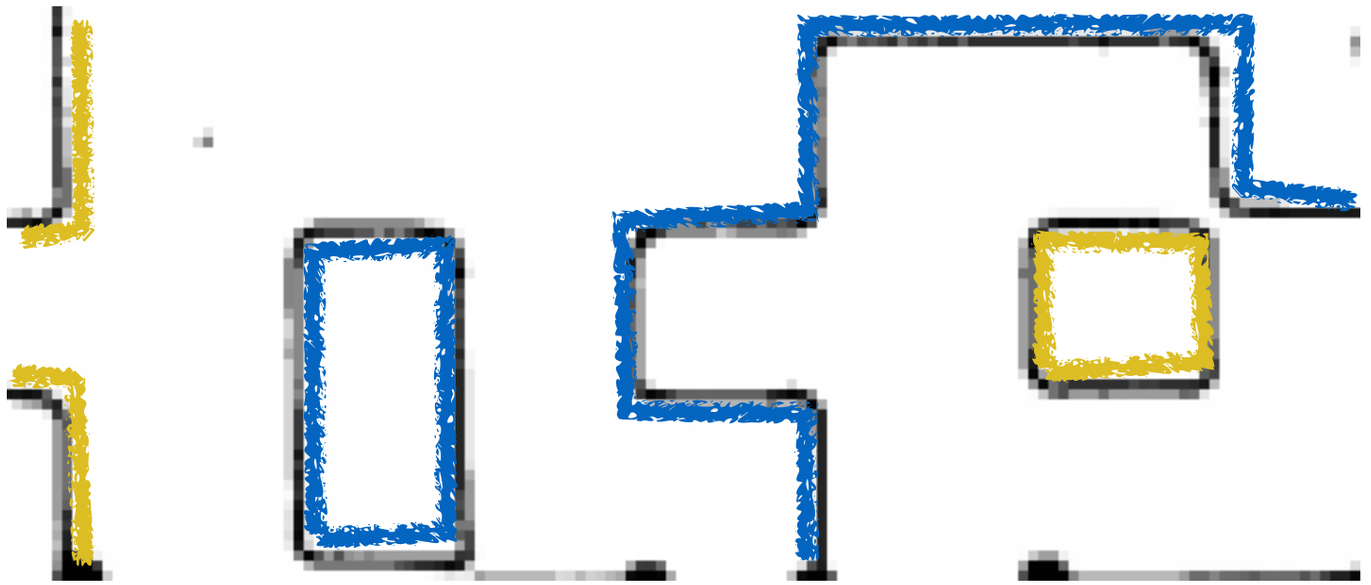


separation of baryon charges



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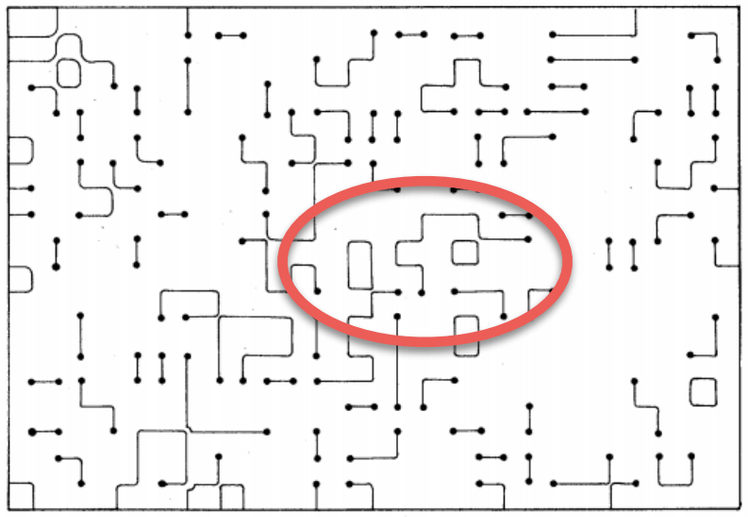

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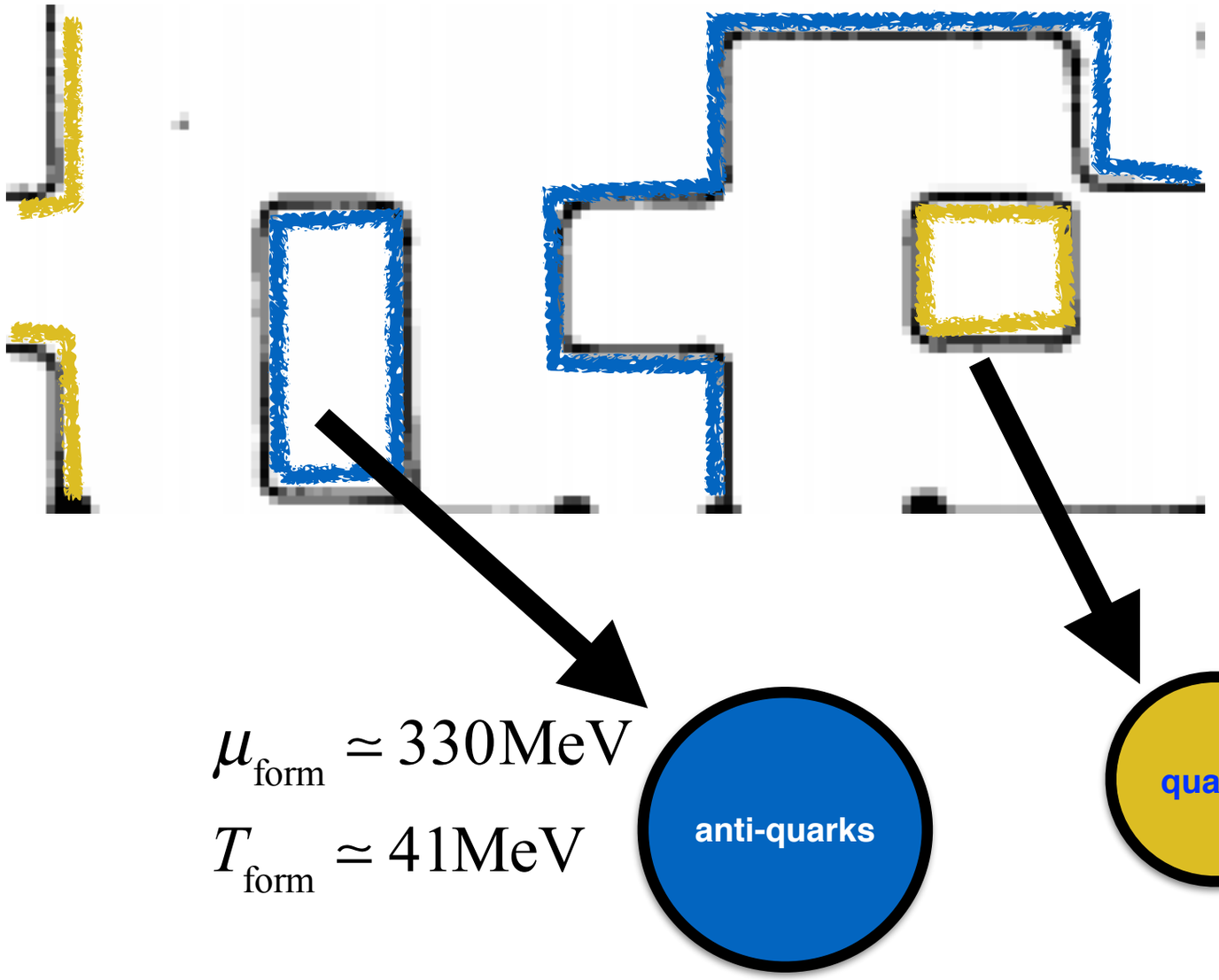

stable (anti-)nuggets

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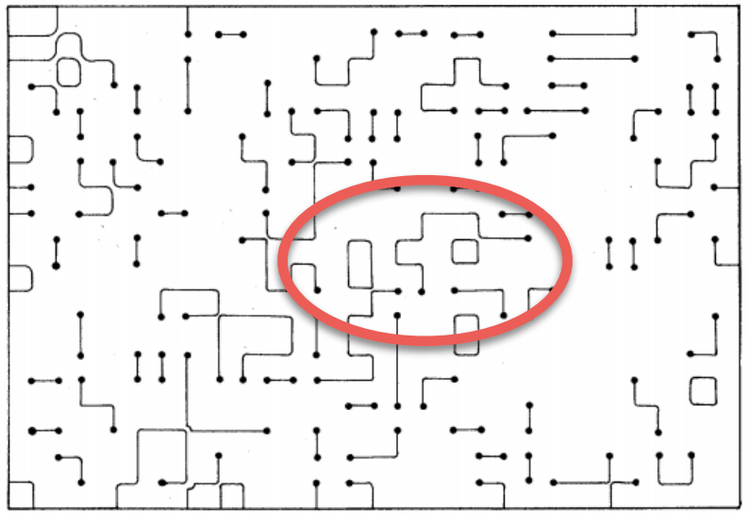
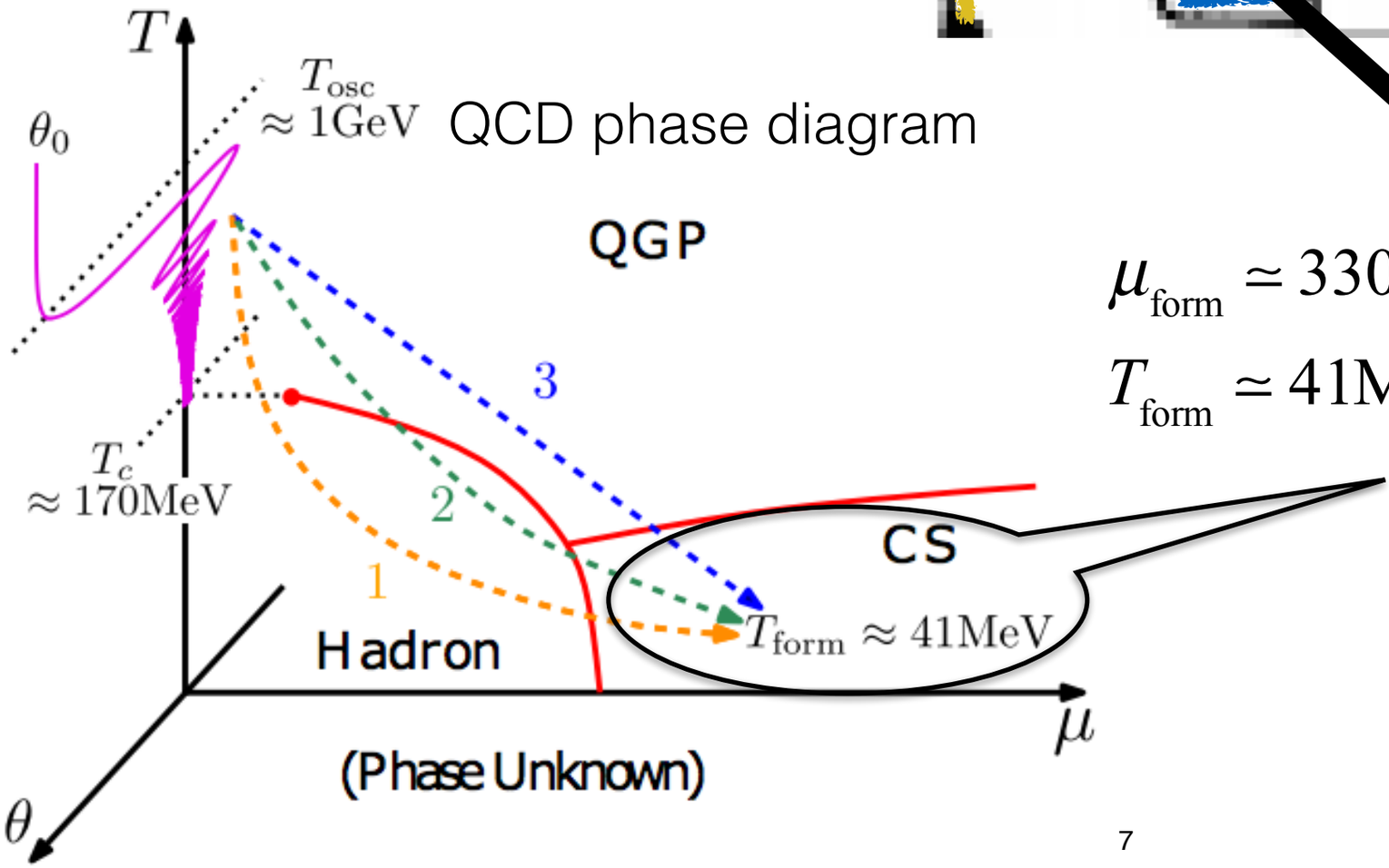
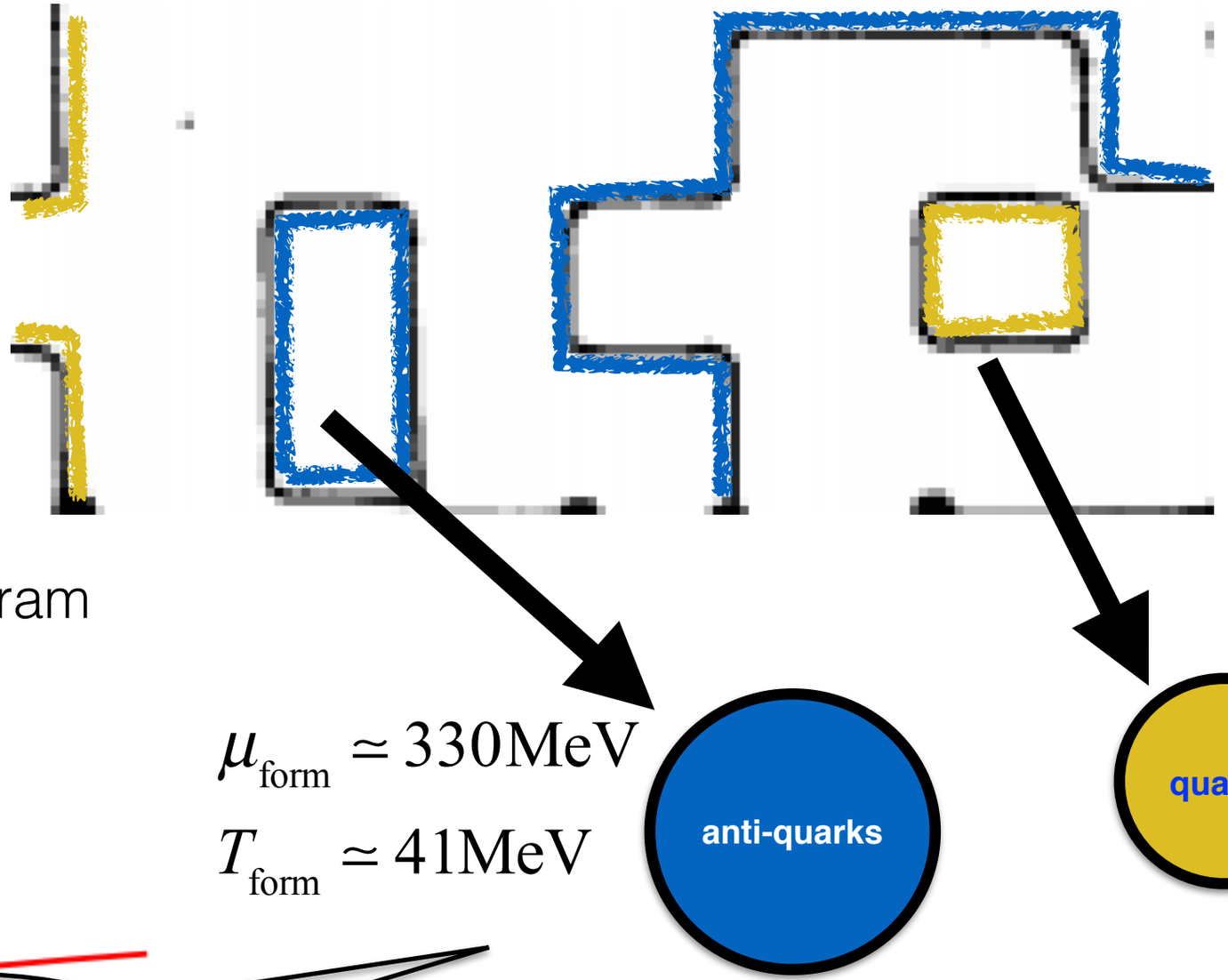




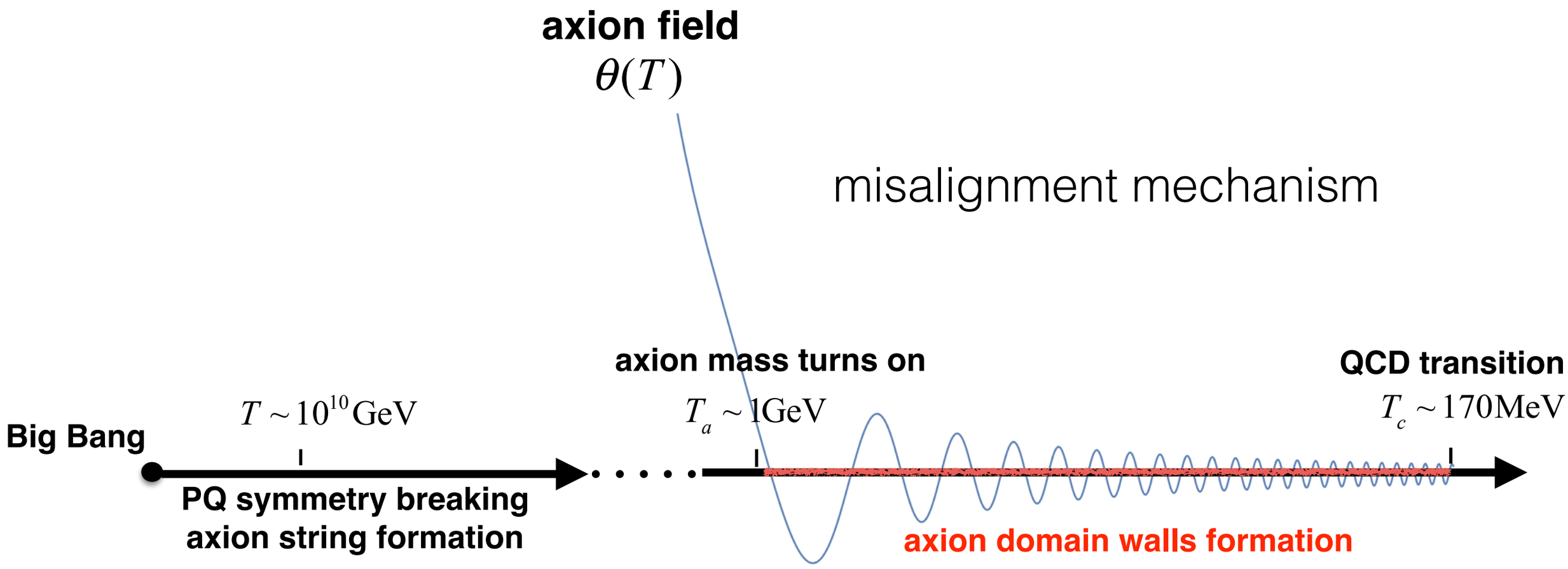
QCD phase diagram

separation of baryon charges



stable (anti-)nuggets

Asymmetry between nuggets and anti-nuggets



CP-violating process due to the **nonzero** axion field θ creates the asymmetry between nuggets and anti-nuggets.

$$c \equiv \left| \frac{B_{\text{nuggets}}}{B_{\text{anti-nuggets}}} \right|$$

$$\Omega_{\text{DM}} \simeq \left(\frac{1+c}{1-c} \right) \Omega_{\text{visible}}$$

Observational consequences

$$\frac{\sigma}{M} \sim 10^{-10}\,\mathrm{cm}^2/\mathrm{g} << 1\,\mathrm{cm}^2/\mathrm{g} \qquad\qquad |B| \sim 10^{25}$$

Annihilation events between visible matter in dense regions and anti-AQNs generate observational consequences.

Anti-nuggets hitting the Sun

- "**Solar corona mystery**", characterized by the the anomalous radiations in extreme ultraviolet (EUV) and x-ray bands from corona. The energy that feeds these anomalous radiations comes from the complete annihilation of anti-nuggets that enter the Sun.

$$\text{"solar nanoflares} \equiv \text{anti-nuggets annihilation events"}$$

- On the other hand, the annihilation of anti-nuggets in the Sun could release free axions which could be possibly detected by the upgraded CAST experiment.

Summary

- Nuggets and anti-nuggets are composite objects with (anti)baryons in color superconducting phase squeezed by the axion domain wall as the shell;

- The axion quark nugget (AQN) model could also possibly explain the matter-antimatter asymmetry problem, with more anti-baryons stored inside anti-nuggets than baryons stored inside nuggets;

- The asymmetry between nuggets and anti-nuggets comes from the non-zero CP-odd axion field θ in the formation stage of initial closed axion domain walls near the QCD transition.

- Anti-nuggets entering dense regions (such as the Sun) could generate significant observational consequences due to the annihilation events between visible matter and antiquarks inside the anti-nuggets.

Thank you

Backup slides

for answering questions

Formation of AQNs: accretion of (anti-)baryons

Interaction between axion domain wall and fermions (*Liang and Zhitnitsky, 2016*):

$$\mathcal{L} = \bar{\Psi}(i\partial\!\!\!/ - me^{i[\theta(z)-\phi(z)]\gamma_5} - \mu\gamma_0)\Psi$$

Mathematical procedure: bosonization. We get

$$\mathcal{L}_2 = \frac{1}{2}(\partial_\mu\theta_1)^2 + \frac{1}{2}(\partial_\mu\theta_2)^2 - U(\theta_1,\theta_2) + \frac{\mu}{\sqrt{\pi}}\frac{\partial(\theta_2+\theta_1)}{\partial z},$$

where the potential

$$\begin{aligned} U(\theta_1,\theta_2) = &-mm_0[\cos(2\sqrt{\pi}\theta_1 - \phi + \theta)] \\ &- mm_0[\cos(2\sqrt{\pi}\theta_2 + \phi - \theta)]. \end{aligned}$$

The minimal potential occurs at the following boundary conditions

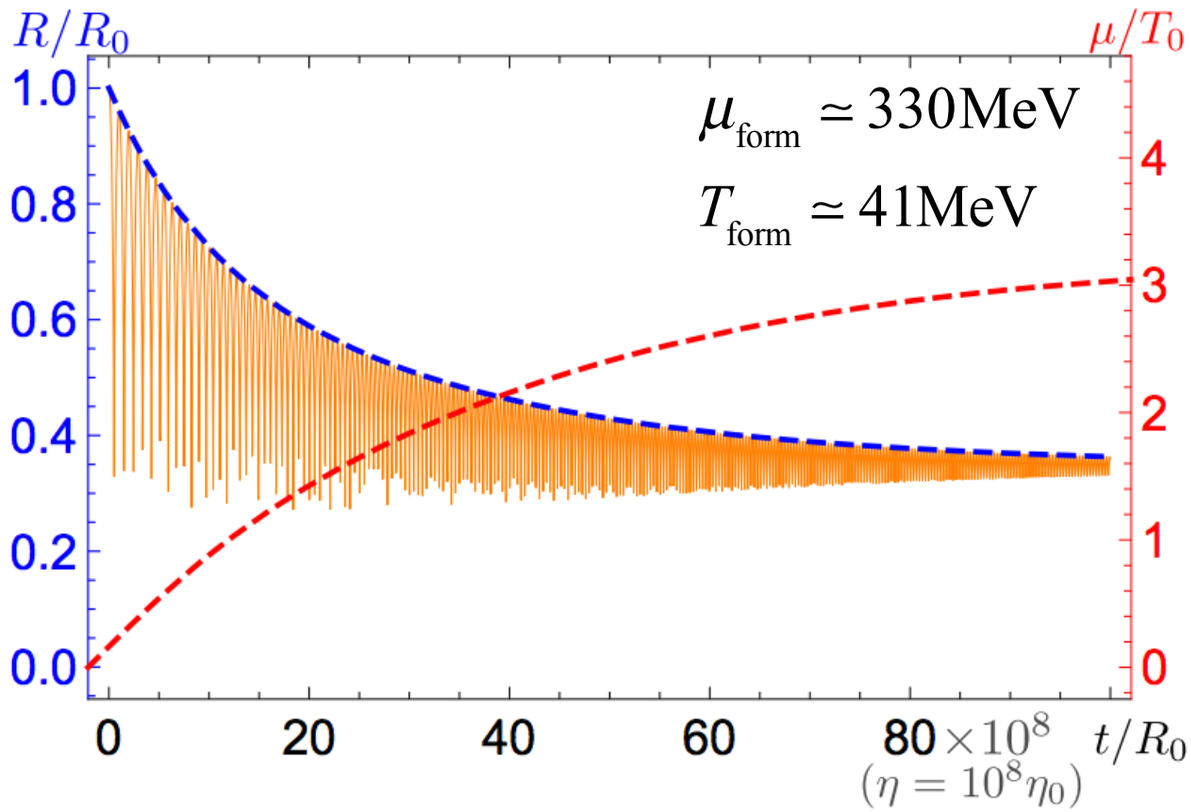
$$\begin{aligned} 2\sqrt{\pi}\theta_1(z=+\infty) - 2\sqrt{\pi}\theta_1(z=-\infty) &= 2\pi n_1 \\ 2\sqrt{\pi}\theta_2(z=+\infty) - 2\sqrt{\pi}\theta_2(z=-\infty) &= 2\pi n_2 \end{aligned}$$

Then the baryons accumulated on the domain wall is

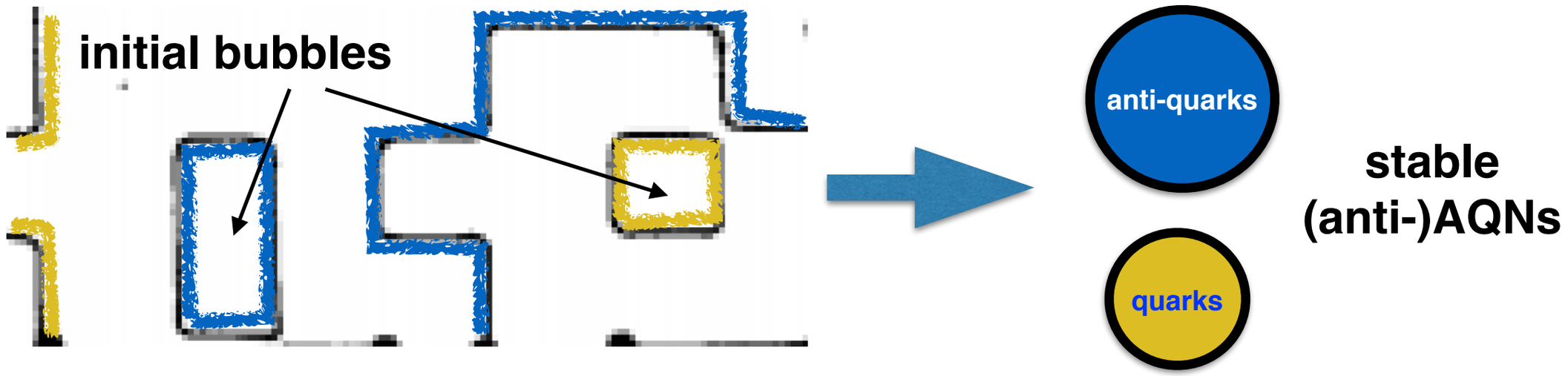
$$\begin{aligned} N &= \int d^3x\bar{\Psi}\gamma_0\Psi = \int dz(\bar{\Psi}_1\hat{\gamma}_0\Psi_1 + \bar{\Psi}_2\hat{\gamma}_0\Psi_2) \\ &= -\frac{1}{\sqrt{\pi}}\int_{-\infty}^{+\infty} dz\frac{\partial}{\partial z}(\theta_1+\theta_2) = -(n_1+n_2), \end{aligned}$$

Formation of AQNs: stable in color-superconducting phase

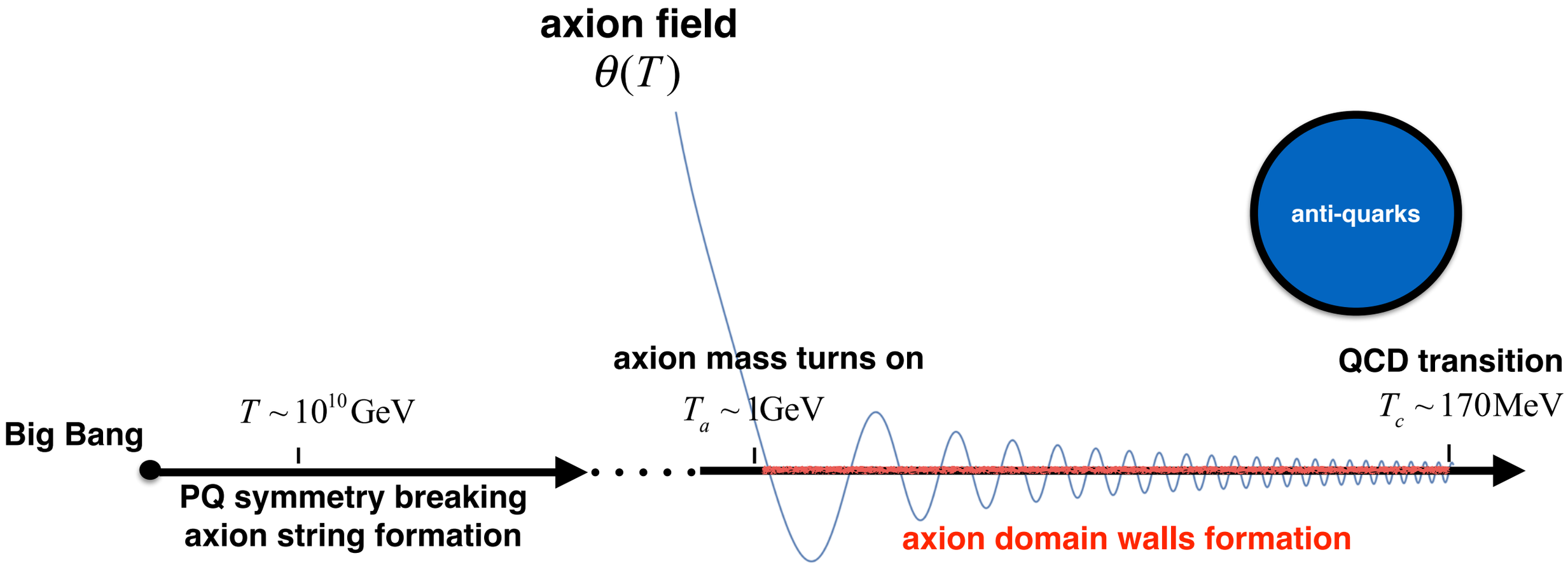
Equation of motion: $$\sigma\ddot{R}(t) = -\frac{2\sigma}{R(t)} - \frac{\sigma\dot{R}^2(t)}{R(t)} + \Delta P(\mu) - 4\eta\frac{\dot{R}(t)}{R(t)},$$



Evolution of AQNs (*Liang and Zhitnitsky, 2016*)



Asymmetry between AQNs and anti-AQNs



CP-violating process $\quad asymmetry\ \ effect \sim \int \theta(t)dt \sim \mathcal{O}(1)$

$$B_{\text{visible}} : B_{\text{AQNs}} : B_{\text{anti-AQNs}} \simeq 1:2:3$$