New perspective of QCD cosmology with Beyond the Standard Model

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Bin Wang (JLU); Jimin Wang (JLU); Xinru Wang (JLU)

PARTICLE AND NUCLEAR | FEATURE

Discovering the Higgs boson: a day in physics like no other

The big day Fabiola Gianotti (foreground, wearing red top) leads the applause in the packed CERN auditorium on 4 July 2012. (Courtesy: CERN)

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But……….
No clear BSM signal seen yet, though…
(2012….   already 12 years ago….)

--- 2012 should NOT be the end of particle physics!

still lots of stuff left needed, theoretically or phenomenologically, to account for :

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e.g. Calls for BSM due:

---- BAU ---- dark matter

---- neutrino mass ---- dark energy

---- inflation (flatness, homogeneity) ---- stochastic GW bkgd,

and (theor. unsatisfactory)

---- strong CP ---- dynamical origin of mass, Higgs mass, EW vacuum stability

etc.

This talk's proposal is:

New physics around QCD scale

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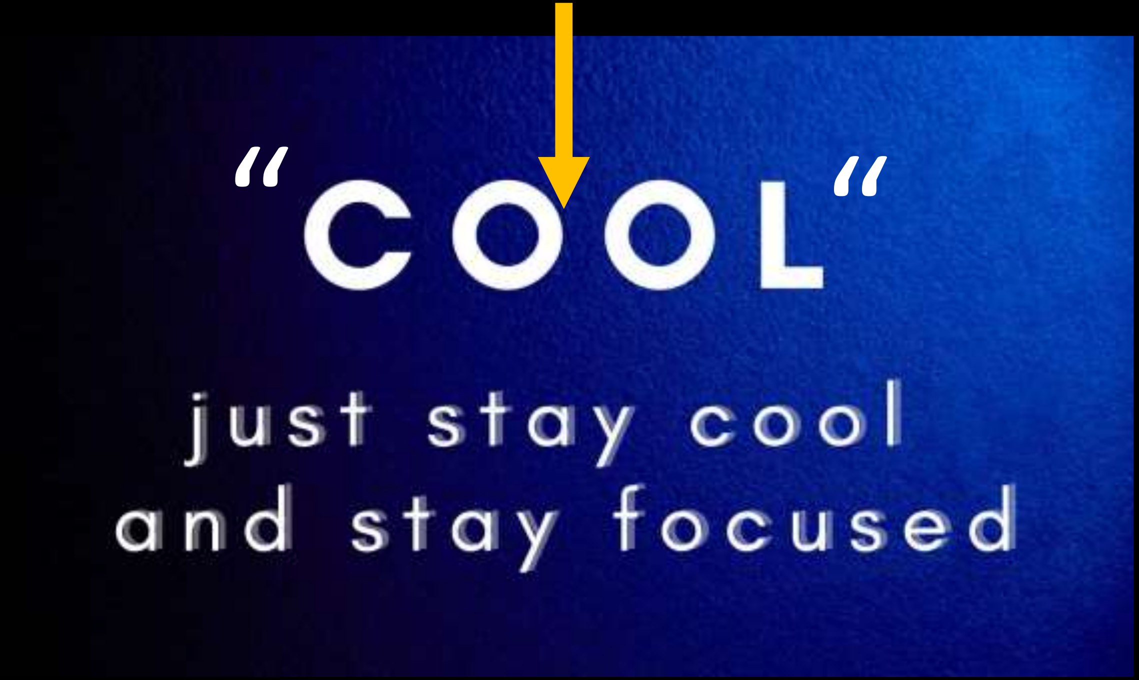
Contrast to High energy frontier: scales sub TeV down to O(100 MeV) – O(sub GeV)



potentially able to address necessary BSM pieces

e.g. Calls for BSM due:

BAU, dark matter,
neutrino mass, dark energy,
inflation (flatness, homogeneity),
stochastic GW

and

strong CP,
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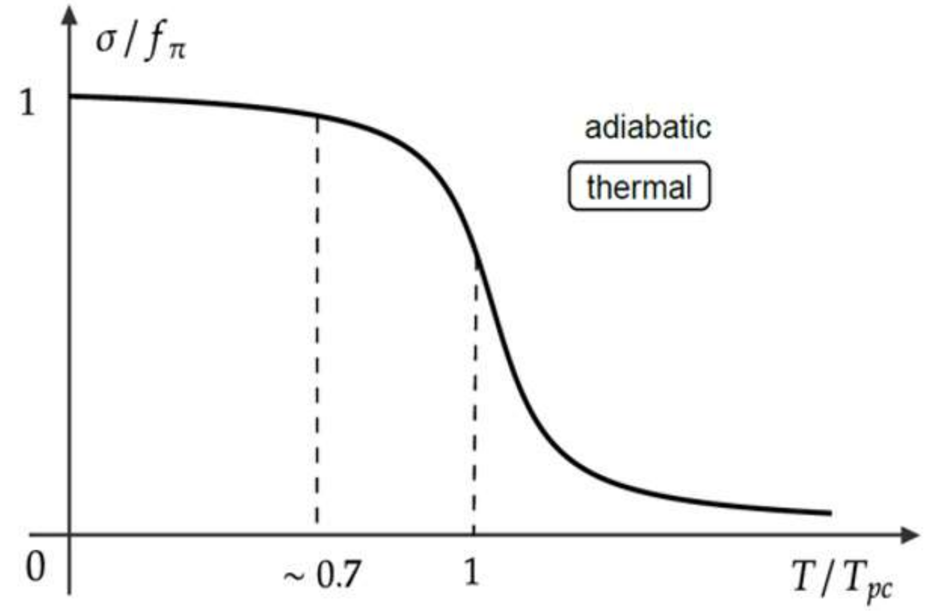
This talk's proposal is:

New physics around QCD scale

makes conventional QCD thermal history



a'. chiral crossover transition

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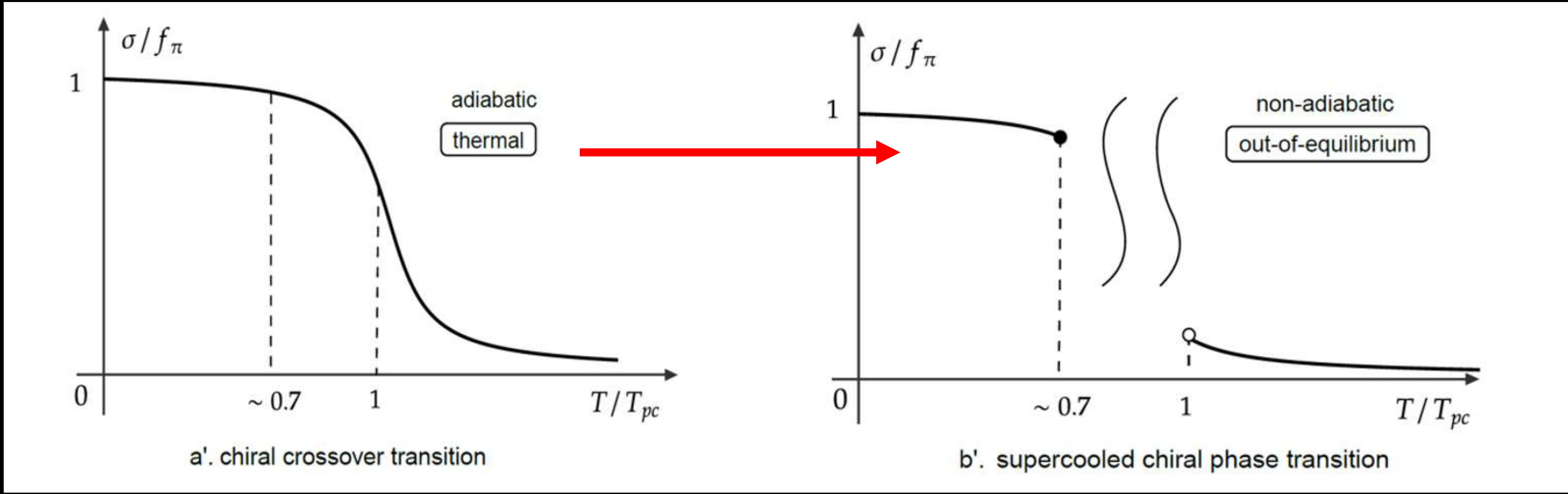
→ New one w/ BSM



Preheating: dynamical and nonadiabatic time evolution of the vacuum

[L. Kofman, A. D. Linde and A. A. Starobinsky,   Phys. Rev. Lett. 73 (1994),Phys. Rev. D 56 (1997)]

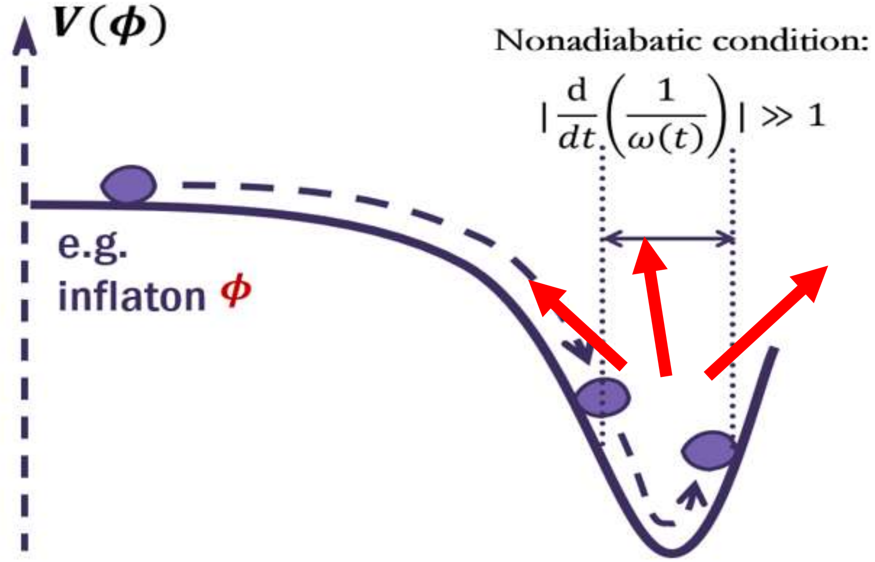


Fig.1: Evolution of the inflaton

➢ Features of preheating:

- Nonadiabatic evolution and oscillation;
- Nonperturbative particle production;
- The universe is slightly reheated;

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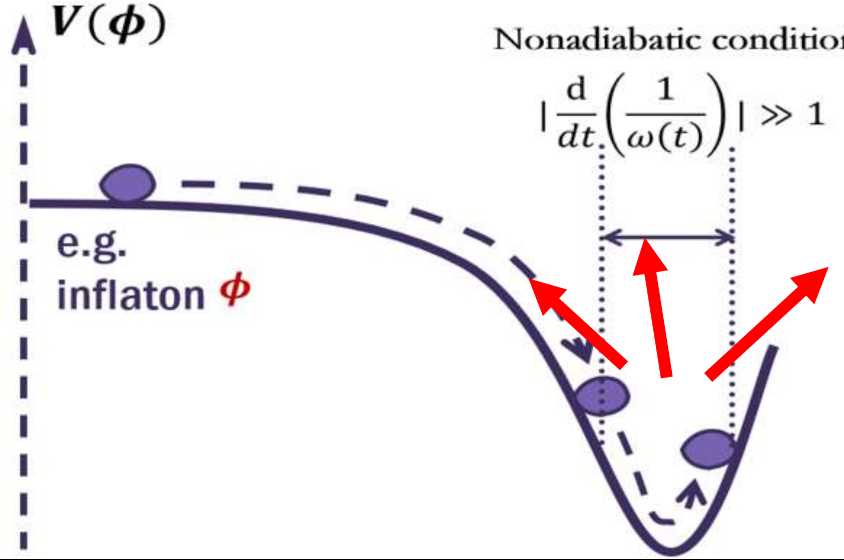
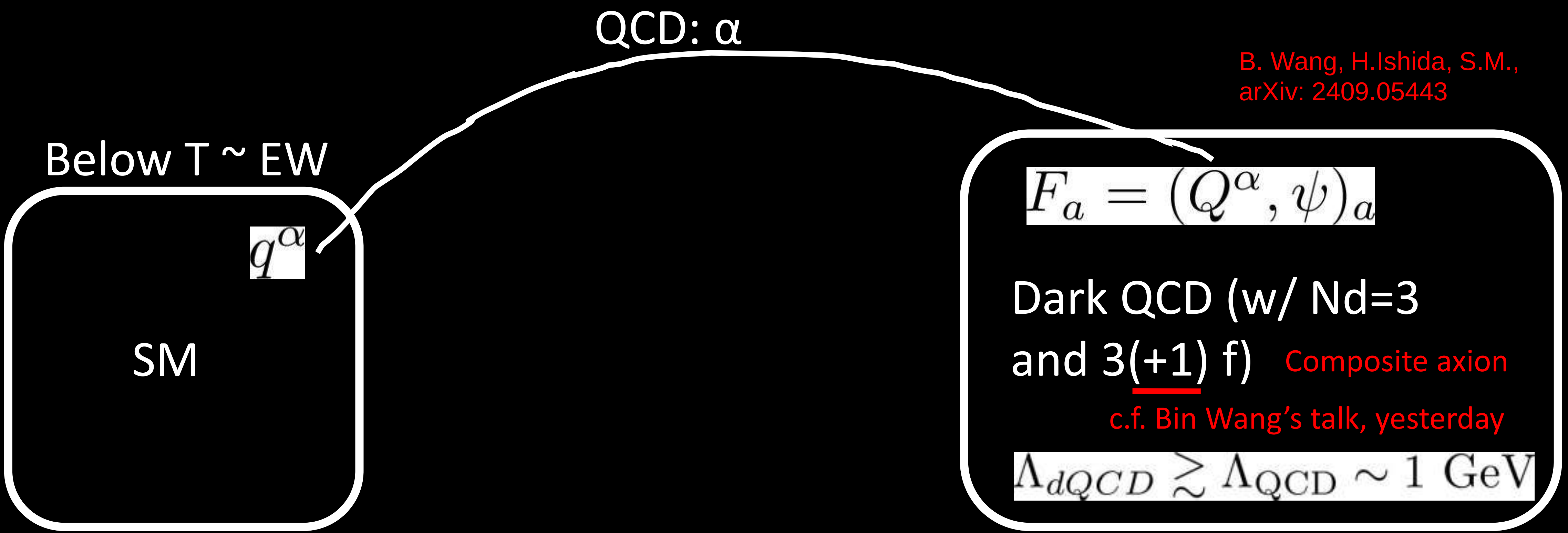


Fig.1: Evolution of the inflaton

The new proposal:
Even after main inflationary epoch, QCD undergoes preheating and reheating

- Nonperturbative particle production;
- The universe is slightly reheated;

The overall scenario description:



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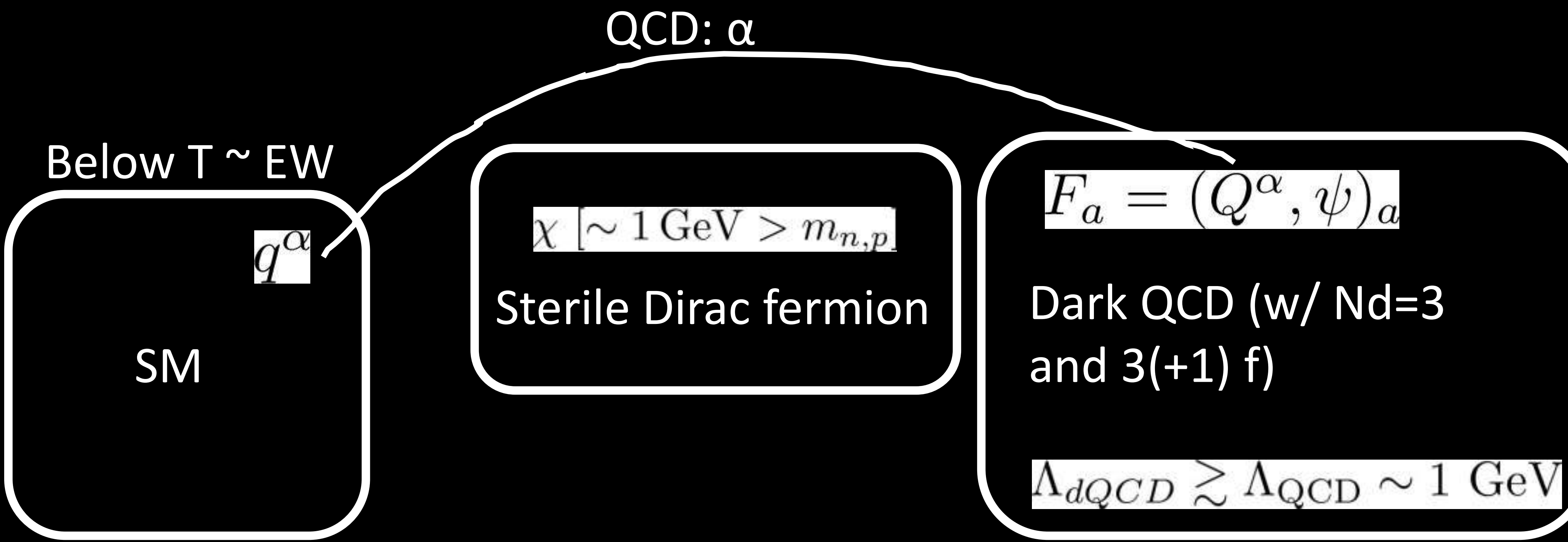

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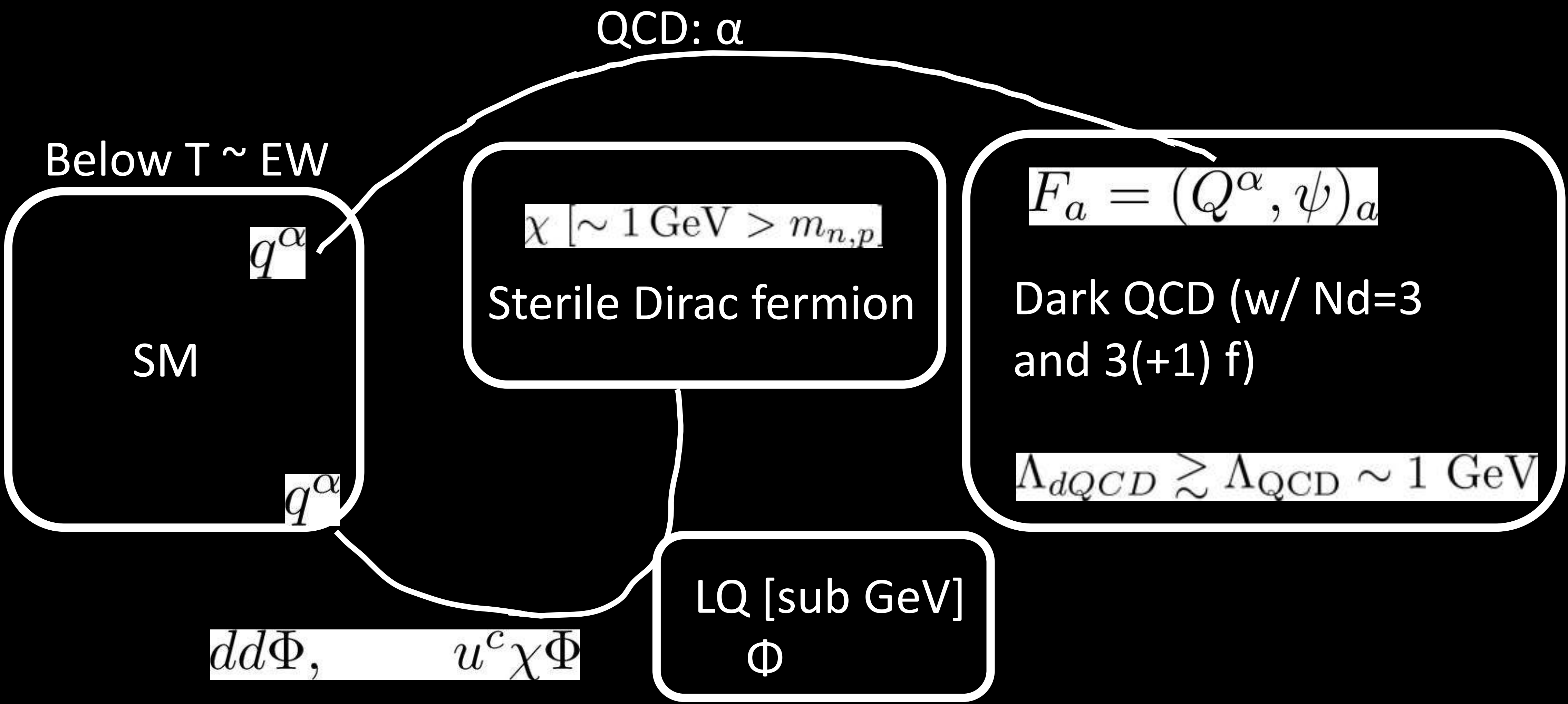

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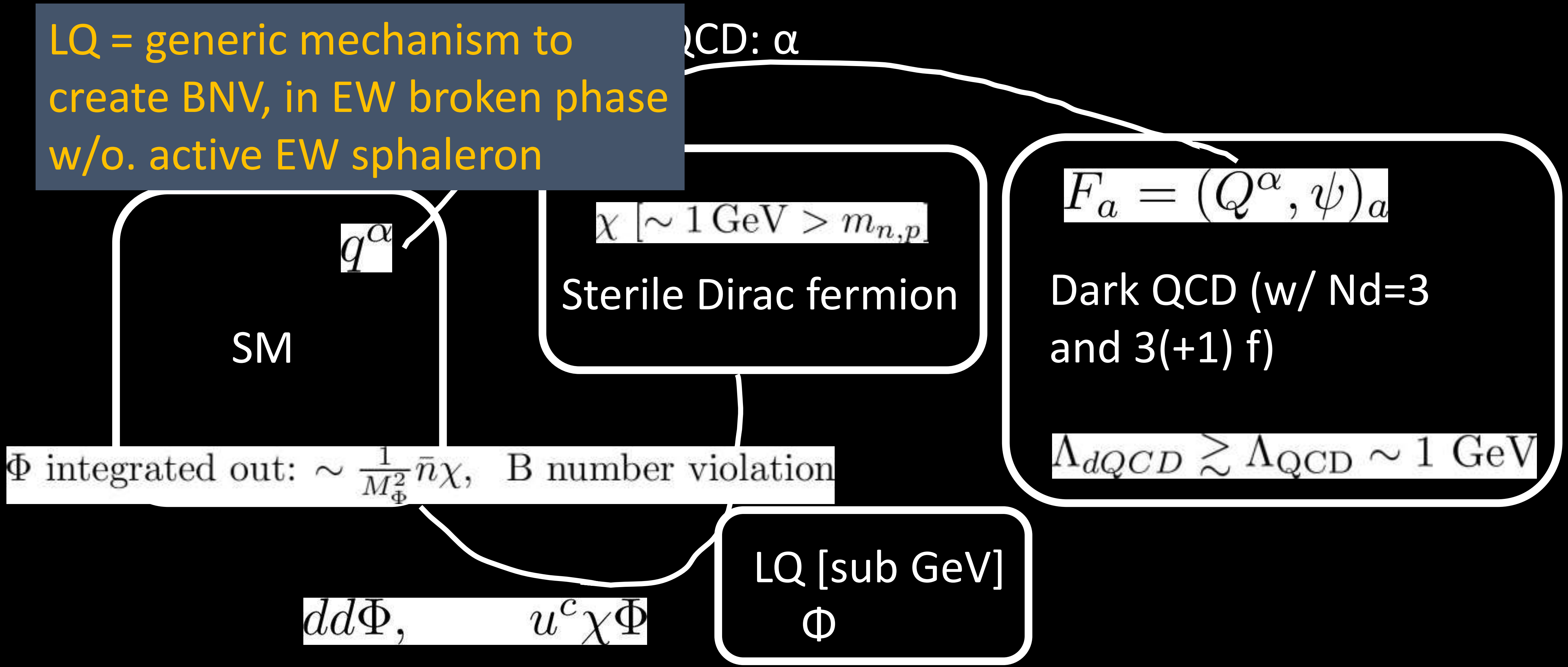

- **LSM with the light quarks $q = (u,d)^T$ monitoring the low-energy chiral dynamics in QCD:**

$$\mathcal{L}_{\rm LSM} = \mathrm{tr}\left[\partial_\mu M^\dagger \partial^\mu M\right] - V + \bar{N} i\gamma^\mu \partial_\mu N - \frac{2m_N}{f_\pi}\left(\bar{N}_L M N_R + \bar{N}_R M^\dagger N_L\right),$$

$$V = m_\pi^2 f_\pi \,\mathrm{tr}\left[\mathrm{Re}(M)\right] + m^2 \,\mathrm{tr}\left[M^\dagger M\right] + \lambda\left(\mathrm{tr}\left[M^\dagger M\right]\right)^2$$

where $M \sim \bar{q}_R q_L$ is parameterized as $M = \sigma \cdot 1_{2\times 2}/2 + i\pi^a\tau^a/2$ with the Pauli matrices $\tau^a \;(a = 1,2,3)$, and the nucleon-doublet field $N_{L,R} = (p,n)^T_{L,R}$.

- **The VEV $\langle\sigma\rangle$ is treated as the order parameter of the chiral symmetry breaking and monitors the dynamic $\langle\bar{q}q\rangle$.**

- **Take into account a higher dimensional interaction (just come from QCD of SM, w/o. BSM):**

$$\mathcal{L}_{\mu_{\rm dyn}} = -\frac{c}{(4\pi f_\pi)^2} \cdot \partial_\mu {\rm tr}[M^\dagger M] J_B^\mu$$

where $J_B^\mu = \bar{N}\gamma^\mu N$

w/ homogeneity in space:

$$\mathcal{L}_{\mu_{\rm dyn}} = -\mu_{\rm dyn}(t) \cdot n_B(t)\,,$$

$$\mu_{\rm dyn}(t) \equiv \frac{c}{(4\pi f_\pi)^2}\partial_0 {\rm tr}[M(t)^\dagger M(t)] = \frac{c}{32\pi^2 f_\pi^2}\frac{d}{dt}\langle\sigma^2(t)\rangle$$

$n_B(t) = N^\dagger(t)N(t)$

Analogous, but more evident than others in a similar context:

spontaneous baryogenesis/leptogenesis
via Higgs relaxation or axion inflation

Kusenko:2014uta,Ibe:2015nfa,Daido:2015gqa,Takahashi:2015waa, Adshead:2015jza,Takahashi:2015ula,Kusenko:2016vcq,Maleknejad:2016dci, DeSimone:2016ofp,DeSimone:2016juo,Son:2018avk,Dasgupta:2018eha, Bae:2018mlv,Domcke:2019qmm,Wu:2020pej,Berbig:2023uzs

- **Nonzero dynamic $\mu_{\rm dyn}(t)$ "locally" breaks the C and CP symmetries as well as T symmetry: but, no violation left in hadron phase.**

- **Communication with dQCD and sterile Dirac fermion**

$$V_{MM_d} = \lambda_{\rm mix} {\rm tr}[M^\dagger M](M_d^\dagger M_d)$$

$$m_\chi \bar{\chi}\chi + g(\bar{n}\chi + \bar{\chi}n)$$

Φ integrated out: $\sim \frac{1}{M_\Phi^2}\bar{n}\chi$, B number violation

- **Communication with dQCD and sterile**

$dd\Phi, \qquad u^c\chi\Phi$

LQ [sub GeV]
Φ

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--- dQCD exhibits **1st order χPT** with order parameter $\langle\sigma_d\rangle$ and **couples to QCD** in a double chiral invariant manner: <σ> gets jumped down/up, into out-of-Eq

- **Communication with dQCD and sterile Dirac fermion**

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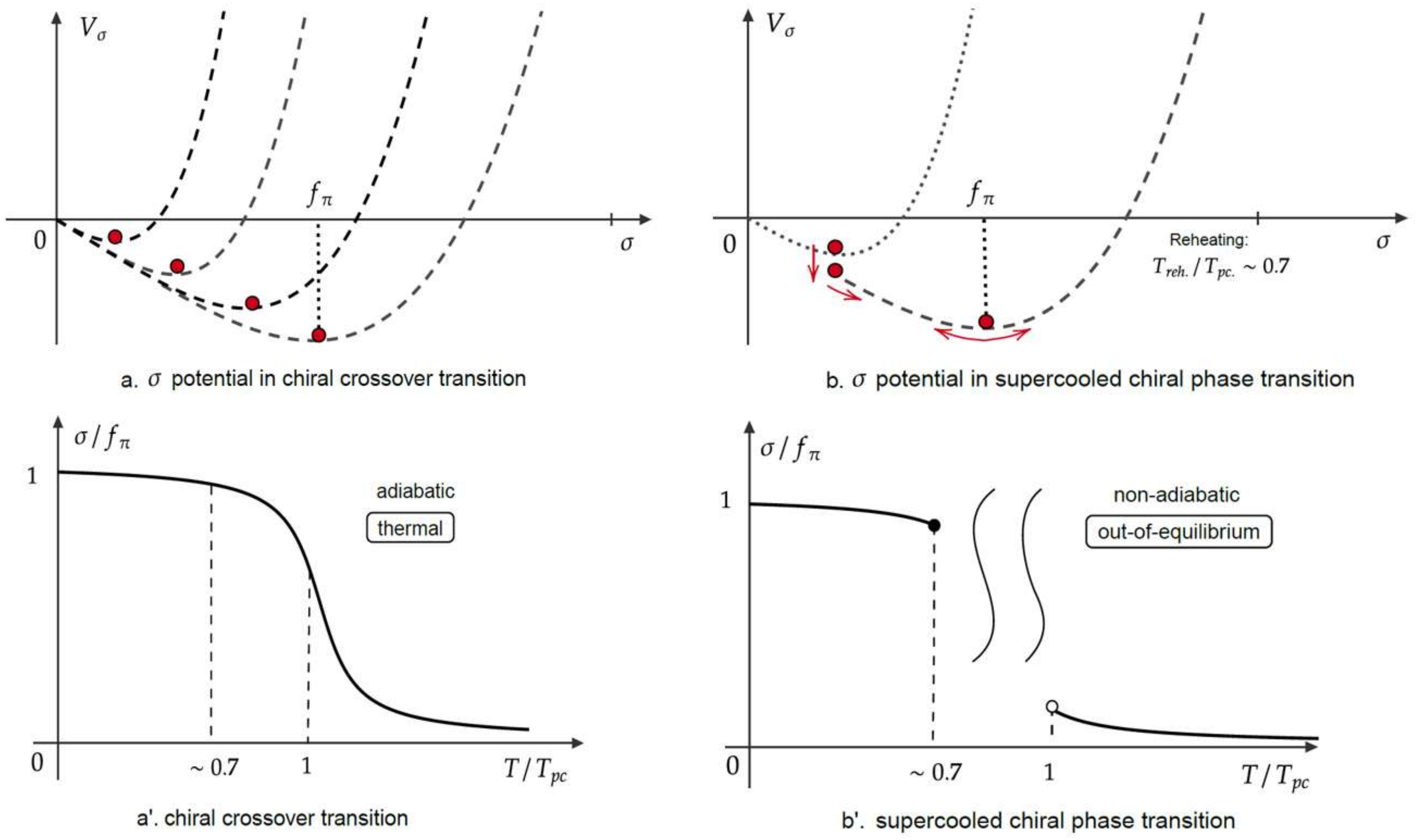
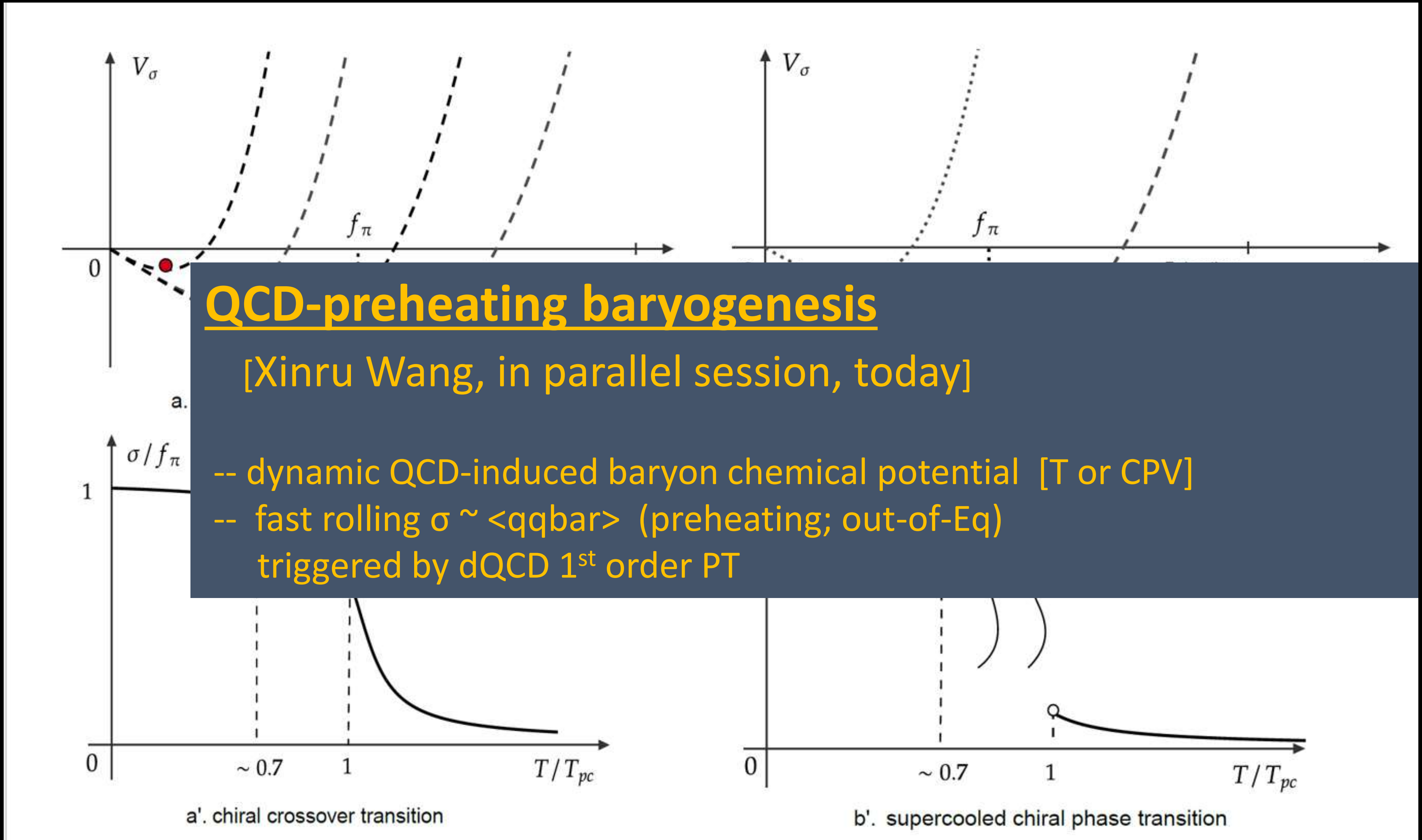
- Sakharov's criteria: A. D. Sakharov, Pisma Zh. Eksp. Teor. Fiz. 5, 32-35 (1967)
  - Baryon number violation;
  - C and CP violation;
  - Departure from equilibrium



different cosmological setups between the chiral crossover and supercooled χPT



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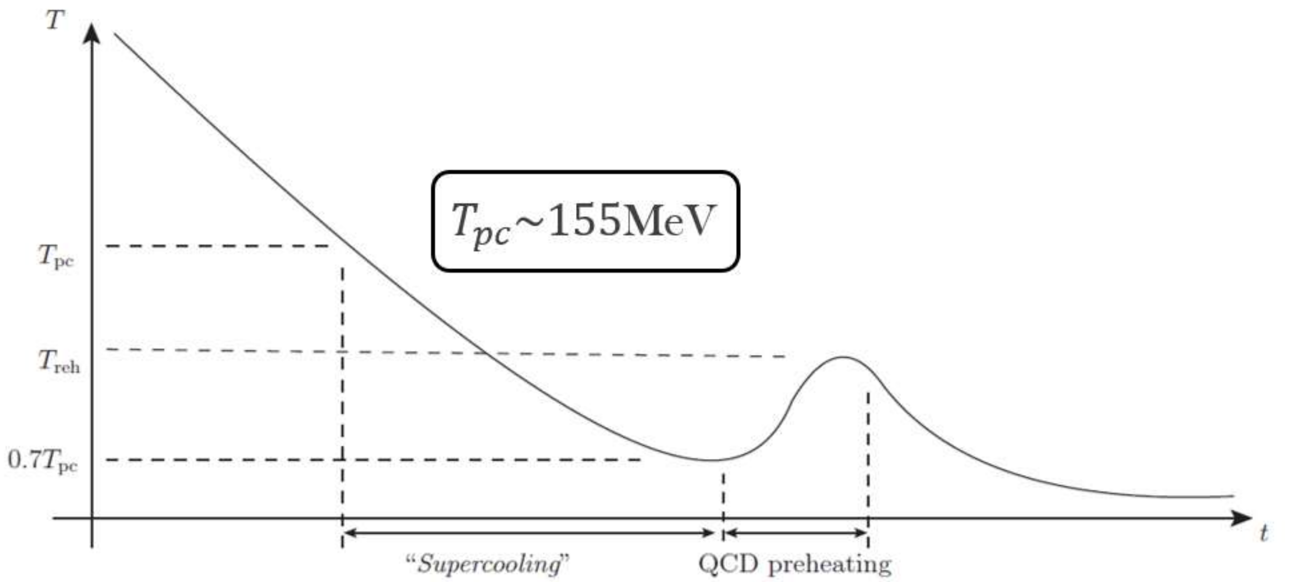
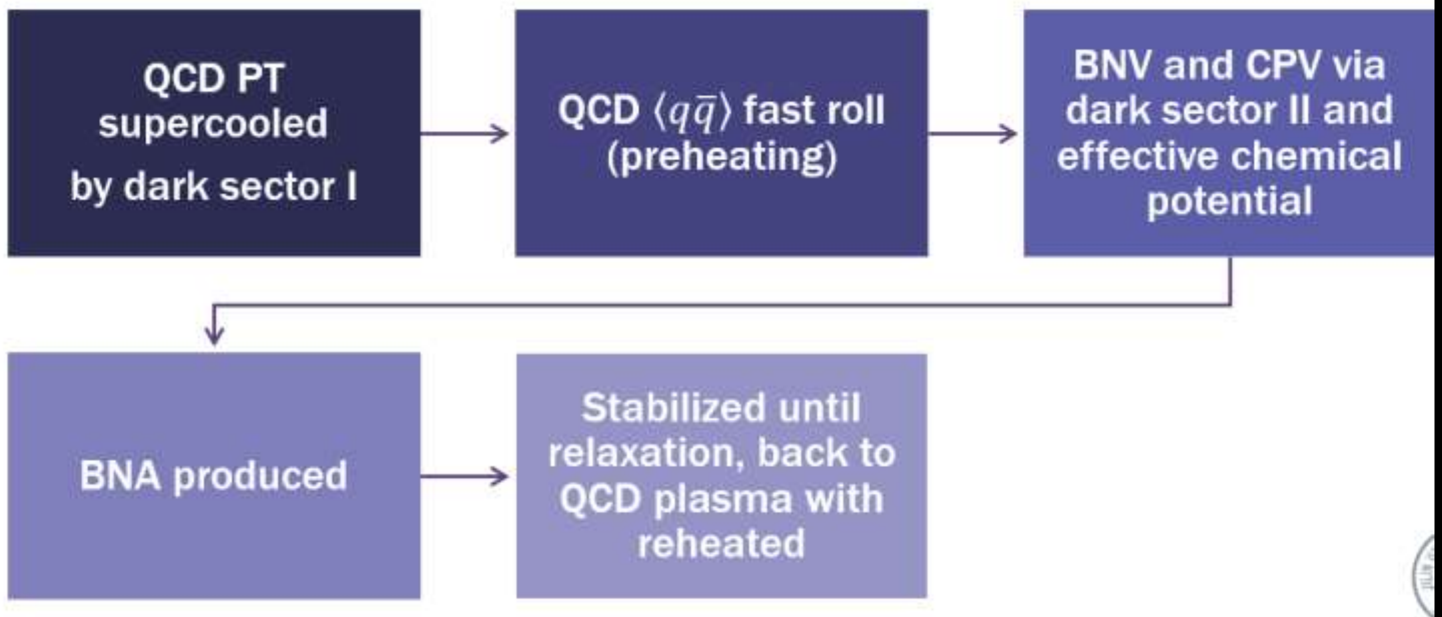
QCD-preheating baryogenesis

[Xinru Wang, in parallel session, today]

-- dynamic QCD-induced baryon chemical potential [T or CPV]
-- fast rolling σ ~ <qqbar> (preheating; out-of-Eq)
triggered by dQCD 1^{st} order PT

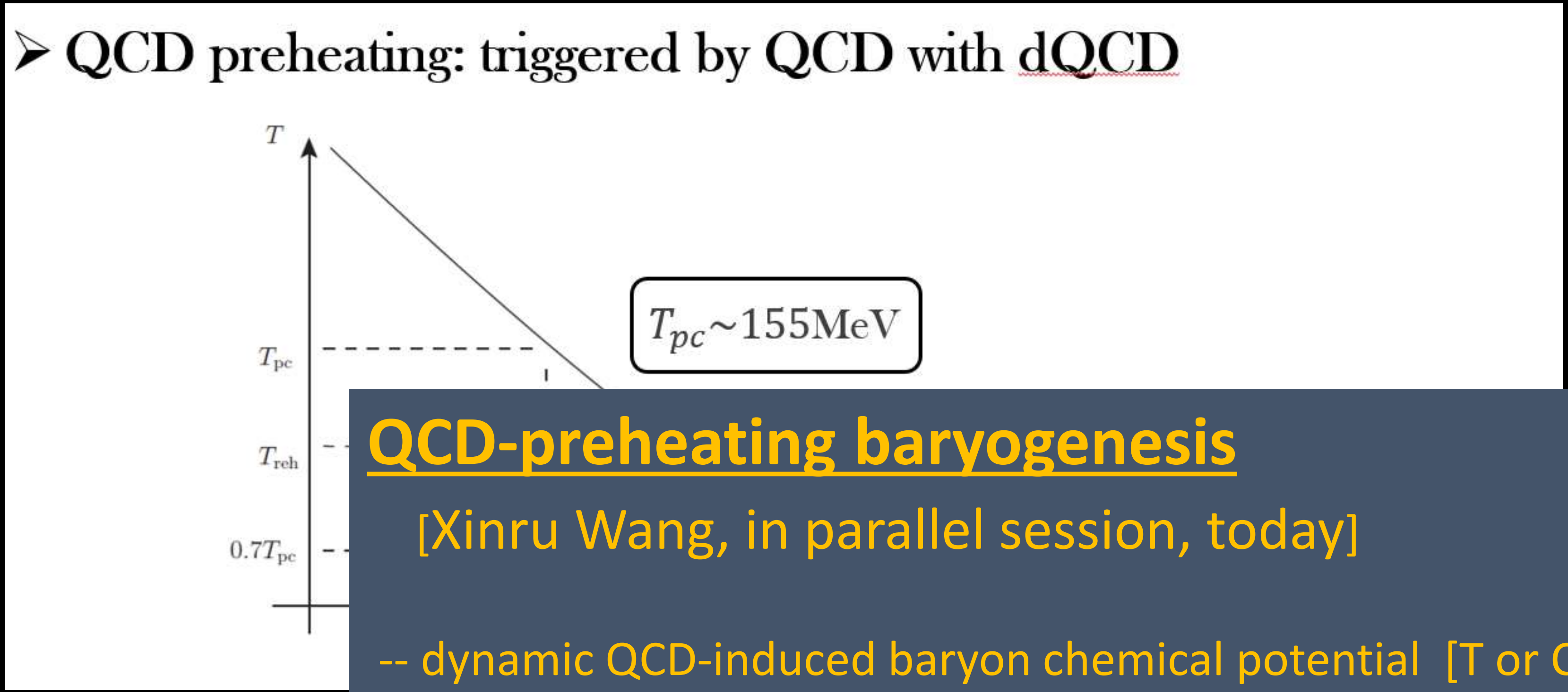
➢ QCD preheating: triggered by QCD with dQCD





Thermal history:

Everything done around Tpc with reheating



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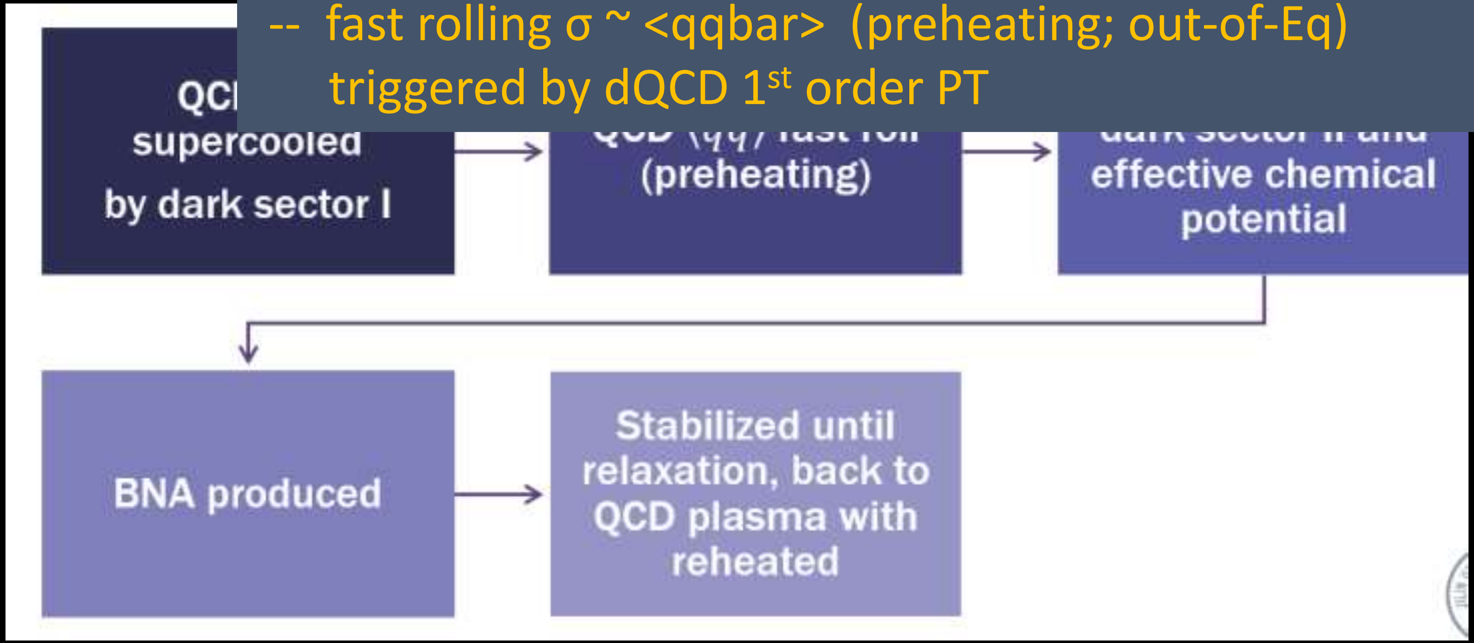

Thermal history:

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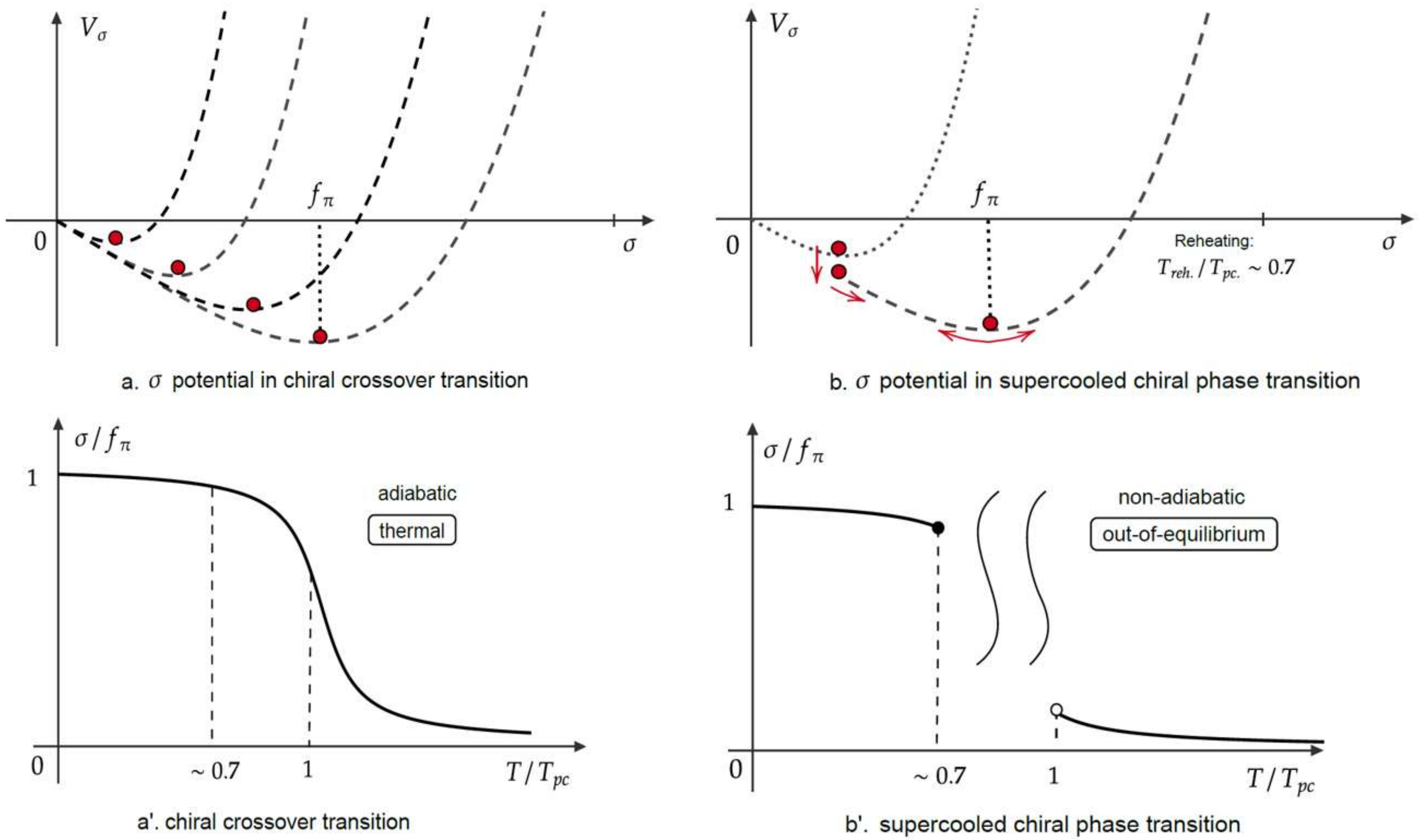
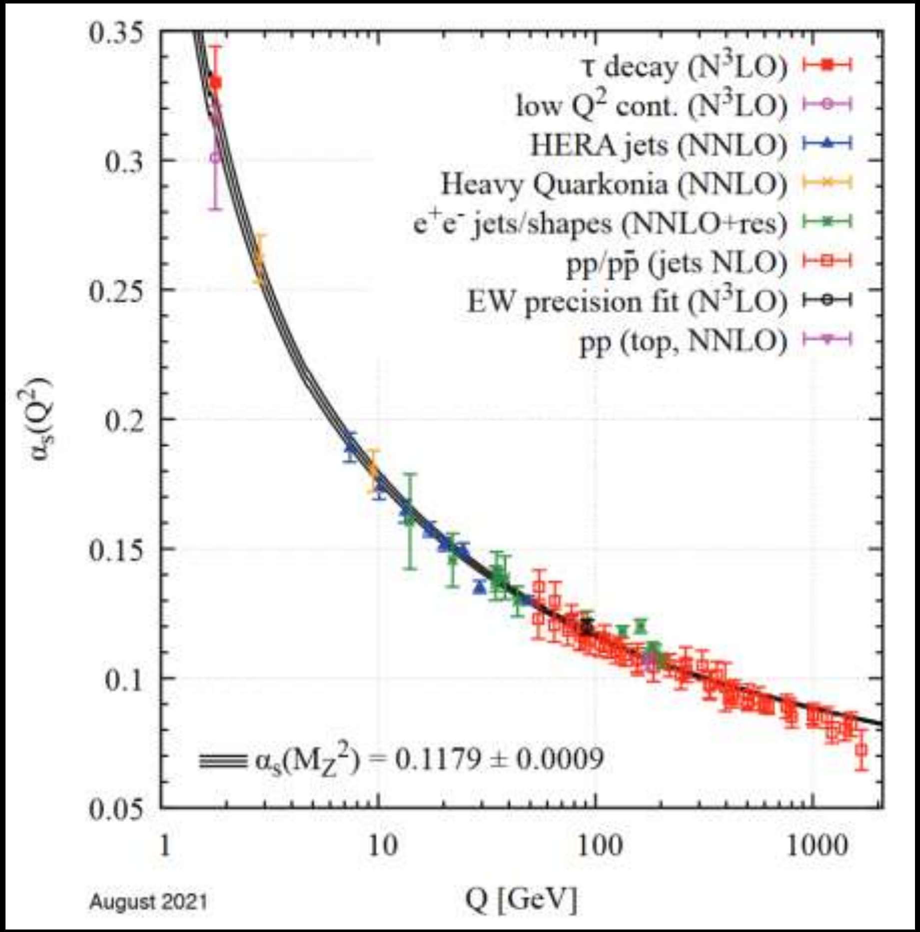


different cosmological setups between the chiral crossover and supercooled χPT

Pheno. constraints on new QCD scale phys.

[1] Surviving from high energy bound on dQCD (w/ Nd=3 and 3+1 f)



From PDG (2024)

Fixing αs(Mz) to EW precision test,

{ Asymptotic freedom > TeV
IR scaling < 10 GeV } can be sensitive to new quarks (Q)

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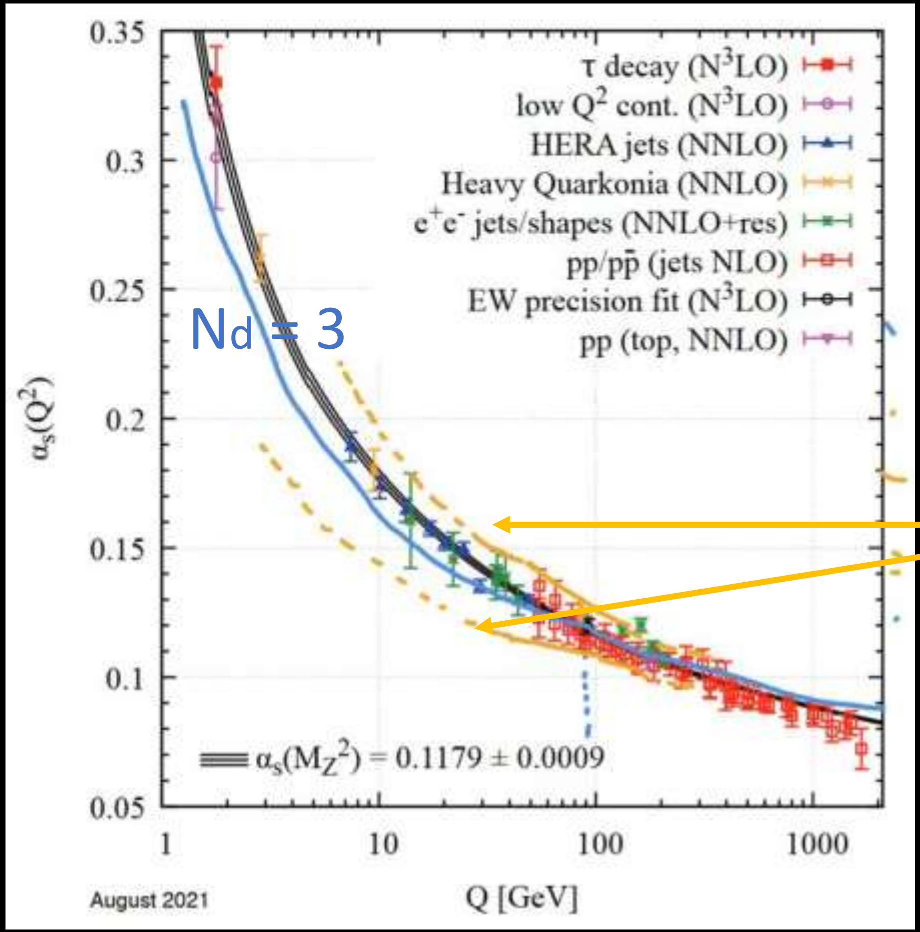

From PDG (2024)

Fixing αs(Mz) to EW precision test,

{ Asymptotic freedom > TeV
IR scaling < 10 GeV

can be sensitive to new quarks (Q) with # of Nd

With LHC, Tevatron large uncertainties to reproduce αs(Mz)

Still, consistent with two-loop perturbative running with Nd < 5

J.Wang, X.R.Wang and S.M, JHEP 08 (2024)

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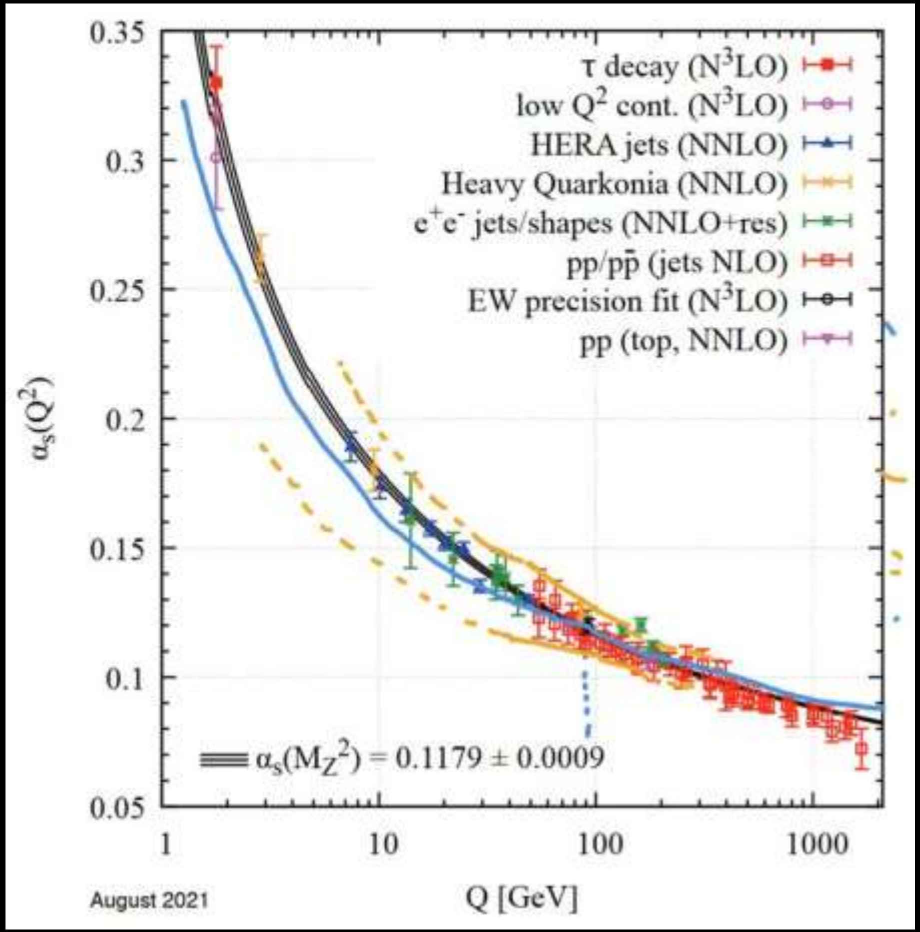

From PDG (2024)

Clarifying IR running
crucial to place limits further on Nd

e.g. FRG method: nearly conformal, or else

A.Deur, S.J.Brodsky and C.D.Roberts, Prog. Part. Nucl. Phys. 134 (2024)

Pheno. constraints on new QCD scale phys.

[2] n- mixing partner: Dirac sterile fermion $\chi \sim 1$ GeV > $m_{n,p}$

Like a "dark baryon" only coupled to n $m_\chi \bar{\chi}\chi + g(\bar{n}\chi + \bar{\chi}n)$

Free from cosmo. and pheno. constraints, if short-lived enough to decay before BBN: $t_{\rm BBN} \simeq 0.1{\rm s}$

$\Delta m = m_\chi - m_n$

D.McKeen, M.Pospelov and N.Raj, PRD 103 (2021)

$$\Gamma[\chi \to n\gamma] \simeq \frac{1}{2200\,{\rm s}} \left(\frac{\theta}{10^{-10}}\right)^2 \left|\frac{\Delta m}{10\,{\rm MeV}}\right|^3$$

Decay via n – X converting anomalous magnetic moment int.

$$\mathcal{L}_{\chi n\gamma} = \frac{\mu_n}{2} \cdot \theta \cdot \bar{\chi}\sigma_{\mu\nu}F^{\mu\nu}n + {\rm h.c.}\,,$$

$\mu_n \simeq 1.91\mu_N$

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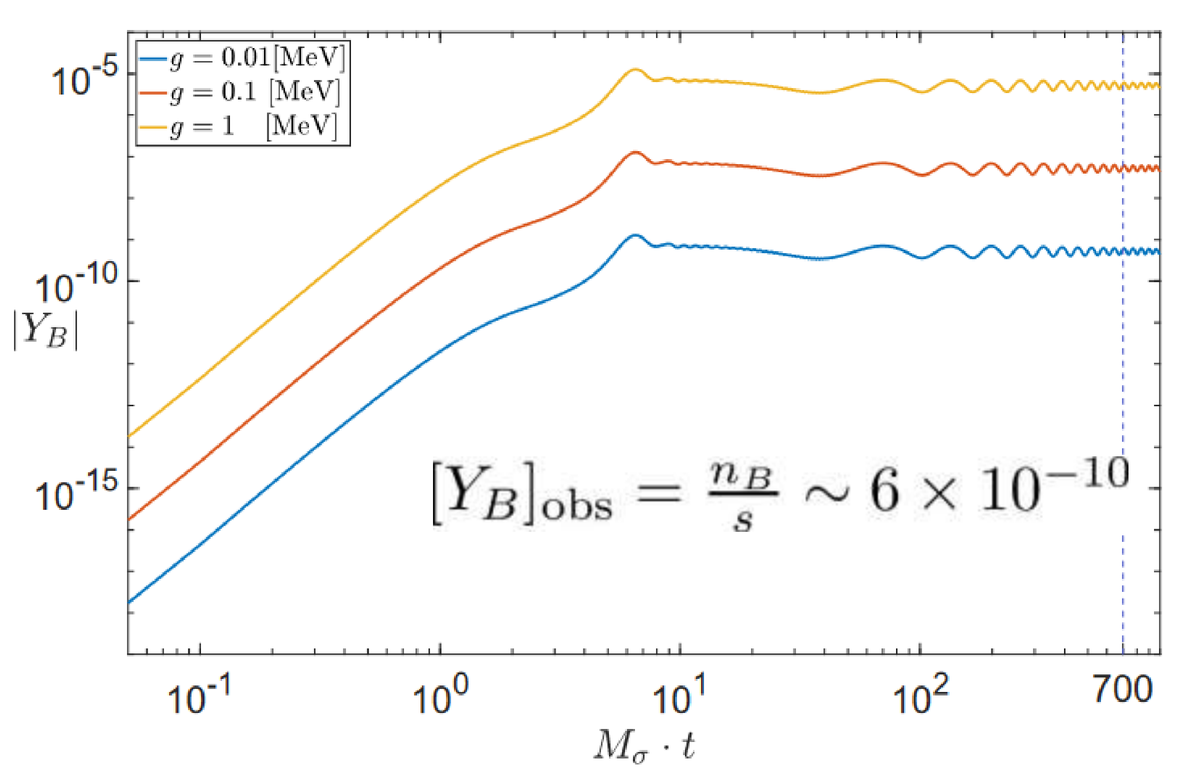

Consistent with successful QCD-preheating baryogenesis

g ~ 0.1 – 1 MeV

Xinru Wang, in parallel session, today

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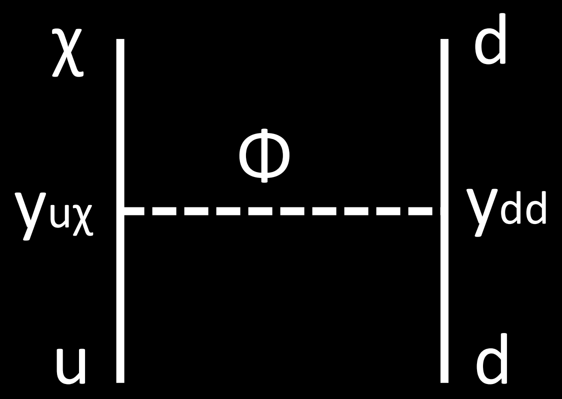
--- generated from LQ (Φ) exchange



$$g \sim \frac{y_{u\chi} y_{dd} \cdot \beta}{M_\Phi^2} \sim 0.3\,\mathrm{MeV} \times \left(\frac{y_{u\chi} y_{dd}}{0.1}\right) \left(\frac{2\,\mathrm{GeV}}{M_\Phi}\right)^2$$

$$\beta = \langle n|qqq|0\rangle \simeq 0.014\,\mathrm{GeV}^3$$ from lattice QCD

Y.Aoki, T.Izubuchi, E.Shintani and A.Soni, Phys. Rev. D96 (2017)

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g ~ 0.1 – 1 MeV

Also survives upper bound from LEP squark search: gets less sensitive as m < 10 GeV

D.E.Kaplan and M.D.Schwartz, Phys. Rev. Lett. 101 (2008)

R.Barate et al. [ALEPH], Z. Phys. C76 (1997)

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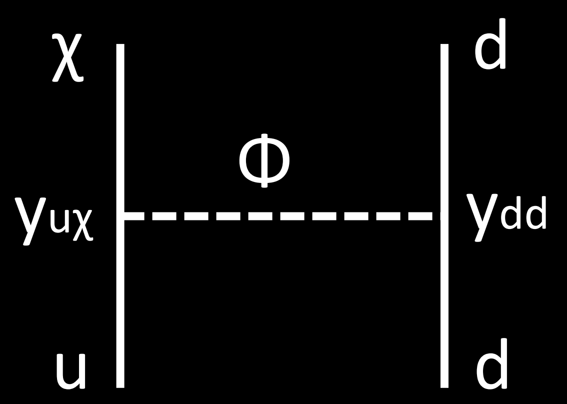

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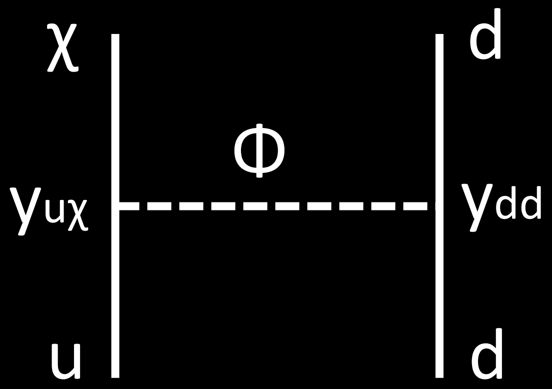
QCD-preheating BG



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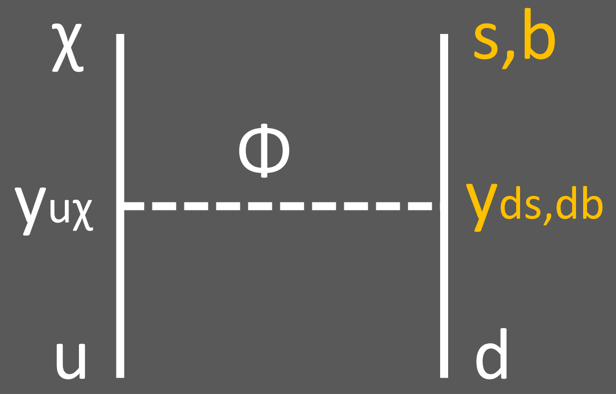

Compared to another QCD BG: “Mesogenesis”

s,b s,b

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G.Alonso-'Alvarez, G.Elor, M.Escudero, B.Fornal, B.Grinstein and J.Martin Camalich, Phys. Rev. D105 (2022)
G.Elor and R.McGehee, Phys. Rev. D103 (2021)
G.Elor, M.Escudero and A.Nelson, Phys. Rev. D99 (2019)
F.Elahi, G.Elor and R.McGehee, Phys. Rev. D105 (2022)
J.Berger and G.Elor, Phys. Rev. Lett.132 (2024)

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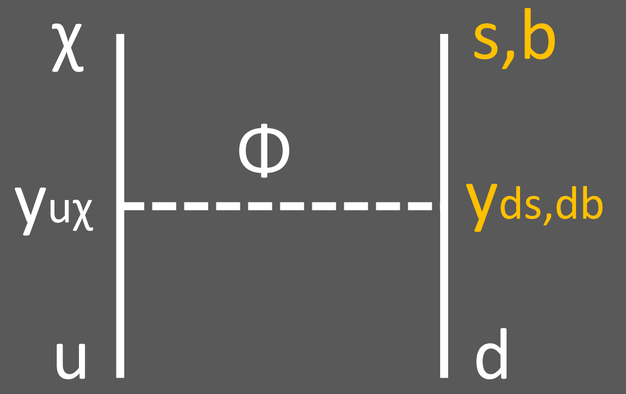
QCD-preheating BG

→ Characteristic low-mass LQ

Compared to another QCD BG: "Mesogenesis"



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G.Elor and R.McGehee, Phys. Rev. D103 (2021)

G.Elor, M.Escudero and A.Nelson, Phys. Rev. D99 (2019)

F.Elahi, G.Elor and R.McGehee, Phys. Rev. D105 (2022)

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QCD-preheating BG

→ Characteristic low-mass LQ

Belle II (~11 GeV) and/or BES III (~ 5GeV) might hunt it, in soft-collinear multijets channels, like light squark search

e+ e- -> Z*/γ* -> q q -> jets + 2 LQ -> multijets

Pheno. constraints on new QCD scale phys.

[3] **QCD production** of dQCD hadrons at collider exp.

--- QCD – dQCD color inv. forbids to form light extra hadrons, e.g., qbar Q,

--- chiral symmetries in both QCD and dQCD require new hadrons to be exotic and show up in chiral singlet channel:

$$\sim \bar{q}_L q_R \bar{q}_R q_L \bar{Q}_L Q_R \bar{Q}_R Q_L$$

That is, sigma scattering process:

$\sigma\ \sigma \rightarrow \sigma_d\ \sigma_d$ **Highly challenging to probe in exp...**

Summary

New cosmo. and pheno: look at QCD scale

Scale PT [1st order]

→ inflation

→ EWSB

→ dQCD PT [1st order]

→ QCD-preheating BG

→ QCD PT [crossover end]

→ BBN

Rich in QCDPT epoch at around T ~ 100 MeV

New cosmo. and pheno: look at QCD scale

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BNV messenger: LQ at ~ 2 GeV
multijets events at Belle II and/or BES III [maybe]

n - mixing partner: χ at 1 GeV > $m_{n,p}$

X -> nγ **[no prospect at present, challenging at exp]**

New cosmo. and pheno: look at QCD scale

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walking hadrons, B-L Higgs, gauge, S-scalar
~{10^9, 10^9, 10^2} TeV
[except FIMP: walking pion ~ 500 GeV]
-- Jie Liu's talk, today

BNV messenger: LQ at ~ 2 GeV
multijets events at Belle II and/or BES III [maybe]

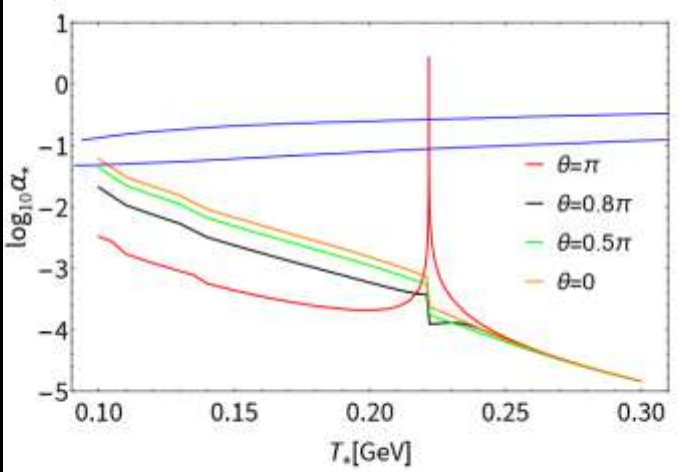
dQCD hadrons: σ_d, η_d, …
at = O(sub GeV)
3γ events at Belle II, BESIII, EIC
-- Bin Wang's talk, yesterday

n - mixing partner: χ at 1 GeV > $m_{n,p}$

X -> nγ **[no prospect at present, challenging at exp]**

More on new aspect of QCDPT epoch. [not covered & to be pursued]

--- ALP-DW with QCD sphaleron vs. nano Hz GW



[Linlin Huang's talk, today]

L.Huang, Y.Wang, H.X.Zhang, S.M, H.Ishida, M.Kawaguchi and A.Tomiya, Phys. Rev. D109 (2024) , and further investigations still in progress

Clarifying QCD thermal history
w/ θ(=a/fa)=π and $\dot{\theta}$=nonzero

--- GW & PBH productions via dQCD 1st order PT

--- DM (dQCD hadrons) production via dQCD-preheating

--- etc.