New perspective of QCD cosmology with Beyond the Standard Model

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Related collaborators:

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Yuanyuan Wang (JLU)
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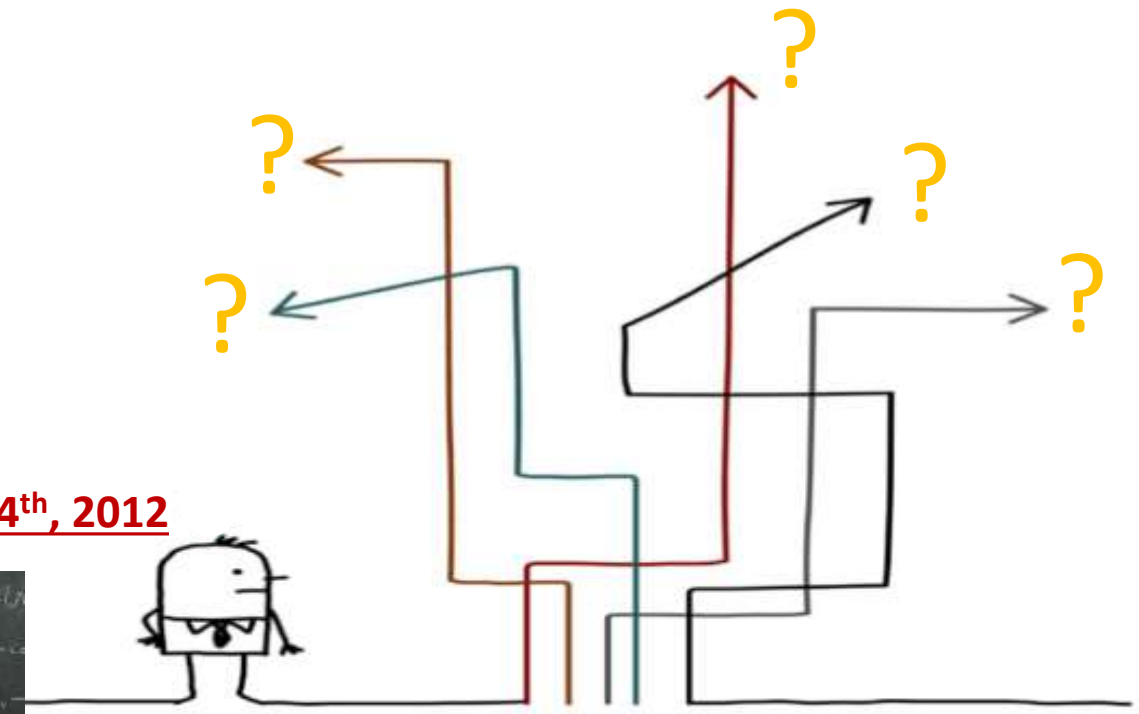
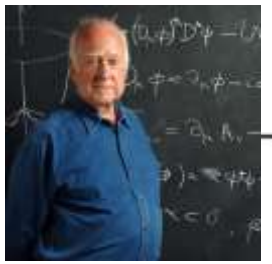
Yuepeng Guan (JLU); Linlin Huang (JLU); Jie Liu (JLU)
Bin Wang (JLU); Jimin Wang (JLU); Xinru Wang (JLU)

Where To Next?

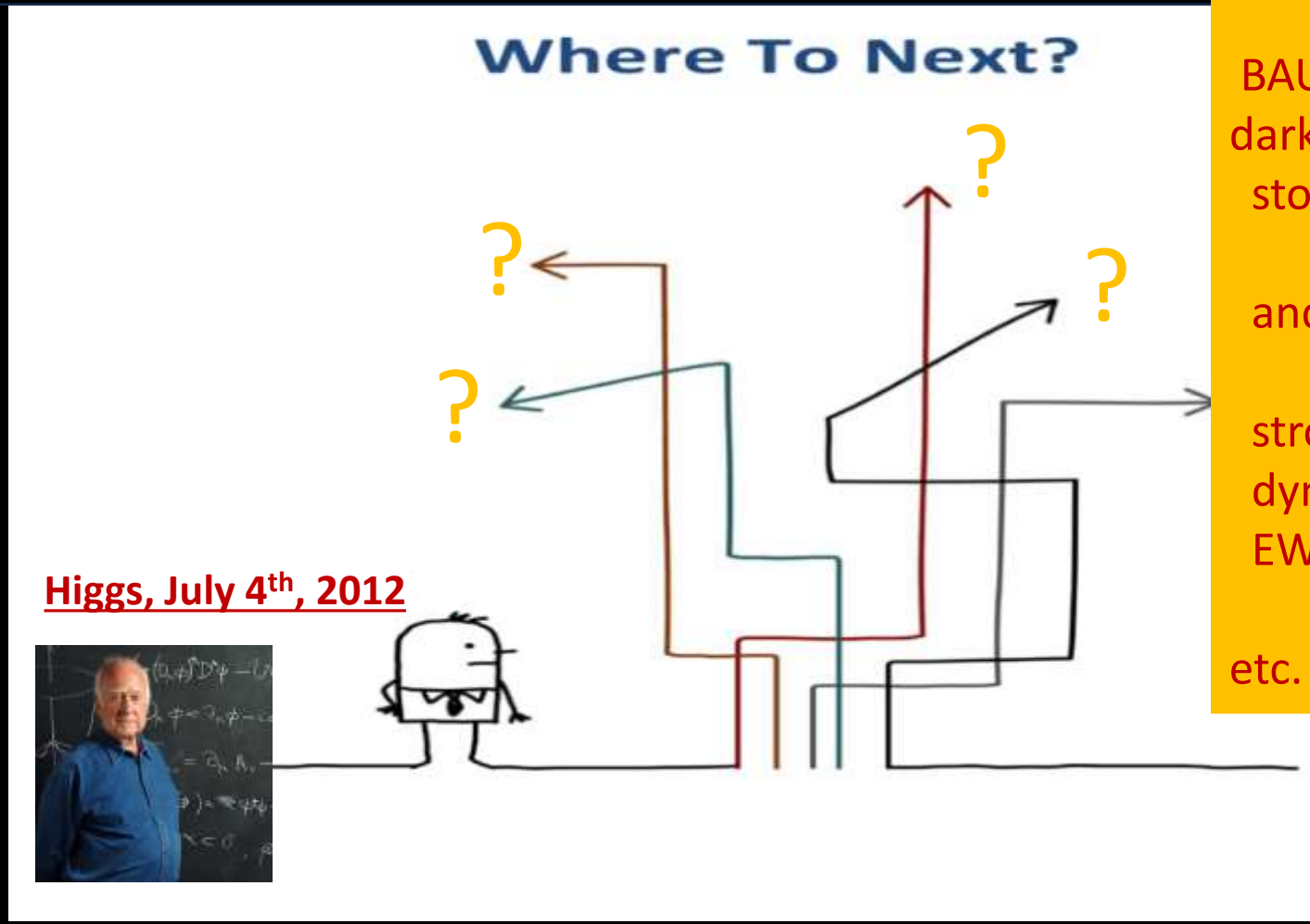


Higgs, July 4th, 2012



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

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



Higgs, July 4th, 2012

e.g. Calls for BSM due:

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

and

strong CP,
dynamical origin of mass (Higgs mass),
EW vacuum stability

etc.

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

This talk's proposal is:

New physics around QCD scale

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potentially able to address
necessary BSM pieces

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New physics around QCD scale

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

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New physics around QCD scale

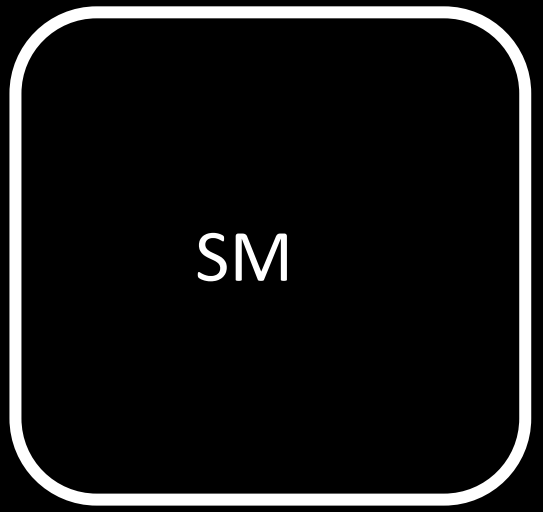
Contrast to High energy frontier: scales sub TeV down to O(100 MeV) – O(sub GeV)

--- leaves heavy ALP-like signals accessible at Belle II: ~ sub GeV
(e+ e- → 3γ events)

-- generic smoking-gun
= sub GeV LQ,
140 MeV pionic (flavorful) ALP

--- GW predictions
at nano Hz (ALP-DW, dark QCD PT),
or higher (scale PT: origin of mass >> TeV)

The overall scenario description:



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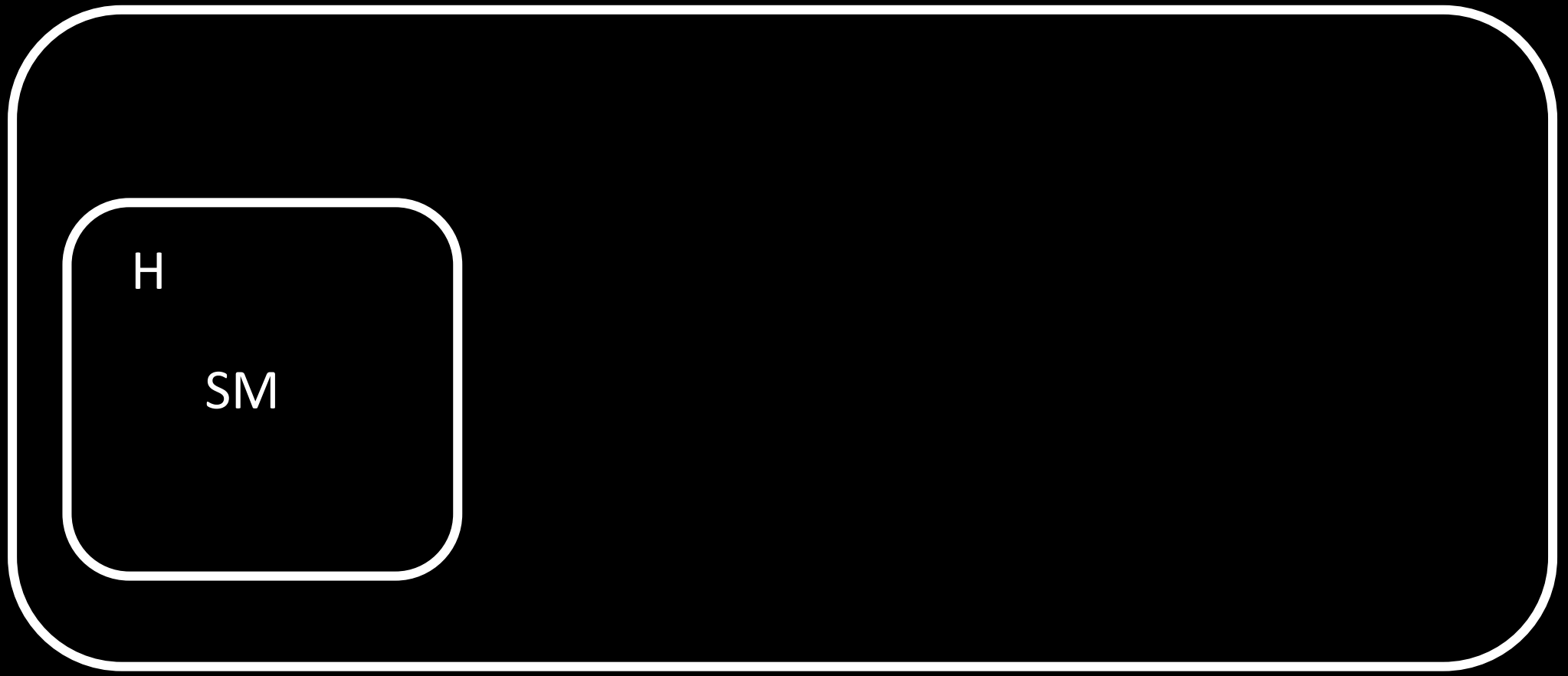
CSI (classical scale inv.) w/ $m_H(M_p)=0$



The overall scenario description:

Nonperturbative scale anomaly

$\phi^4 \ln \phi$

CSI (classical scale inv.) w/ $m_H(M_P)=0$

almost scale inv. gauge (“walking”) dyn. yields Higgs portal

Φ

$\lambda_{\phi H} \phi^2 |H|^2$

$m_H^2 = -\lambda_{\phi H} < \phi >^2$

H

triggers EW symmetry breaking;

$v_{\rm EW}$

SM

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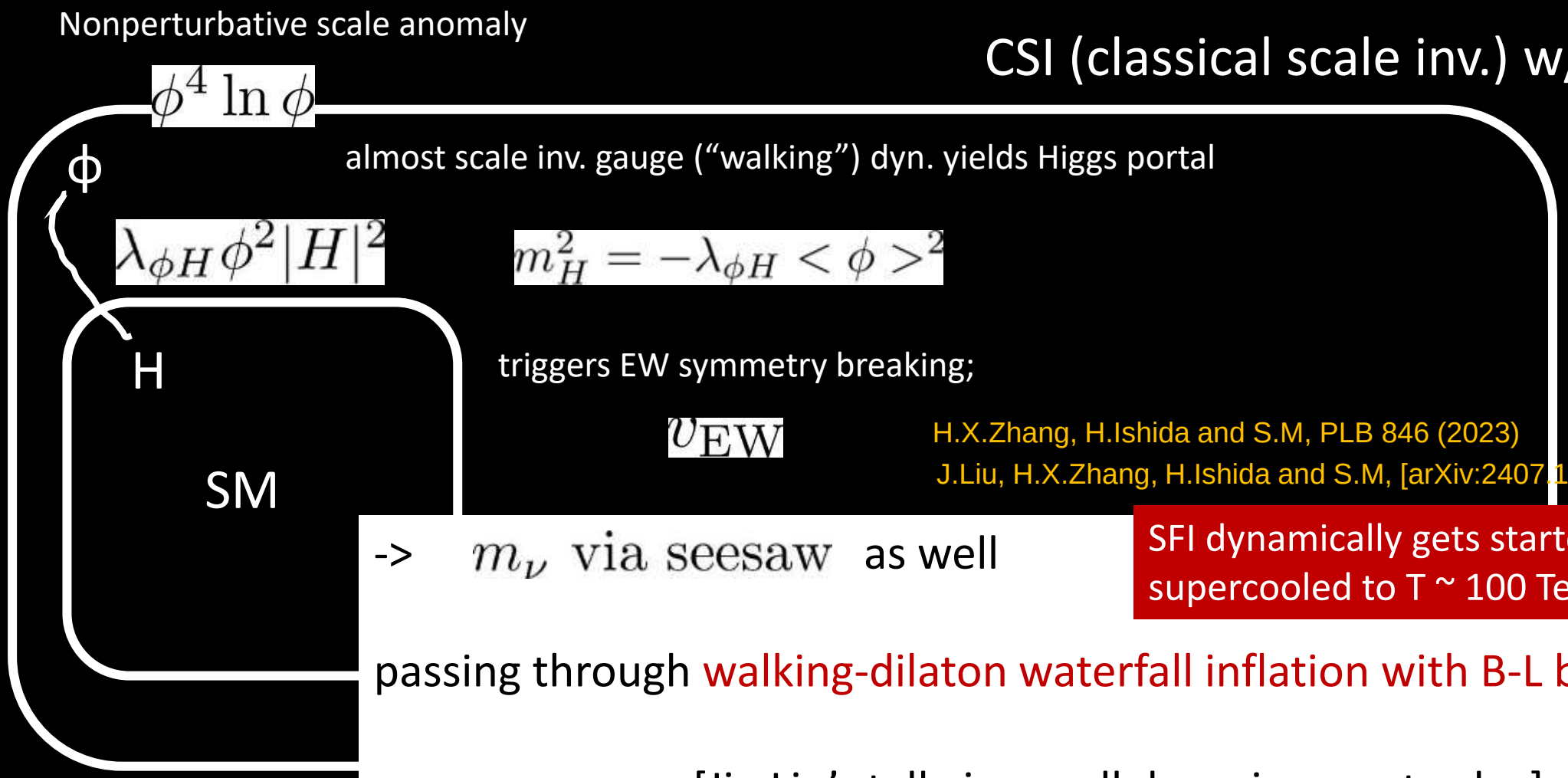

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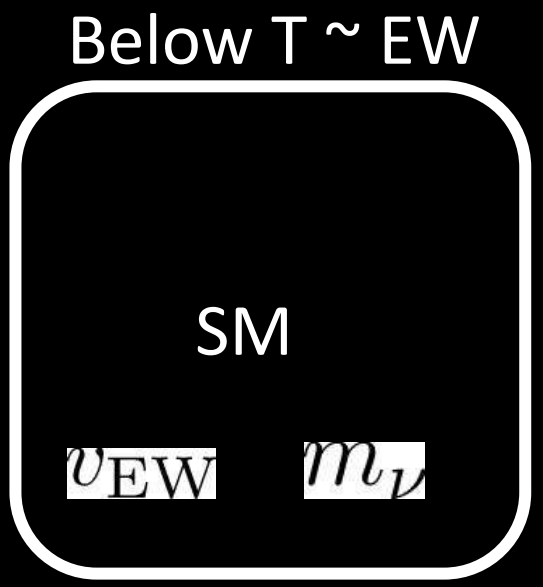

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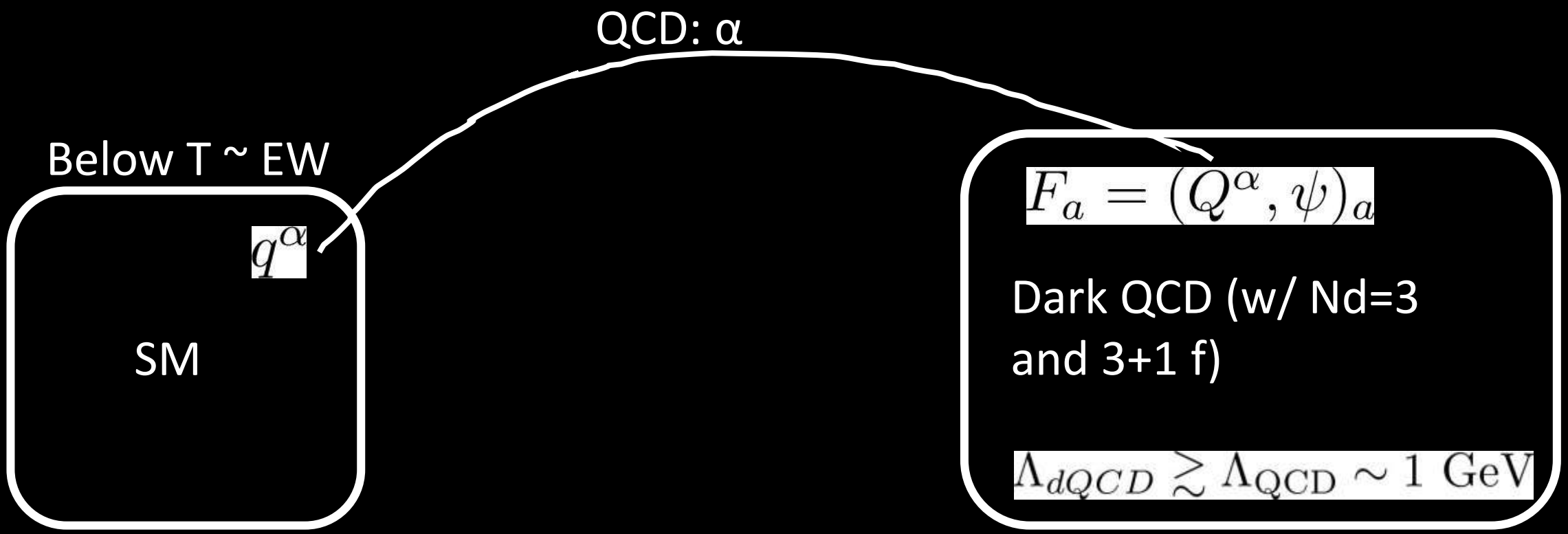

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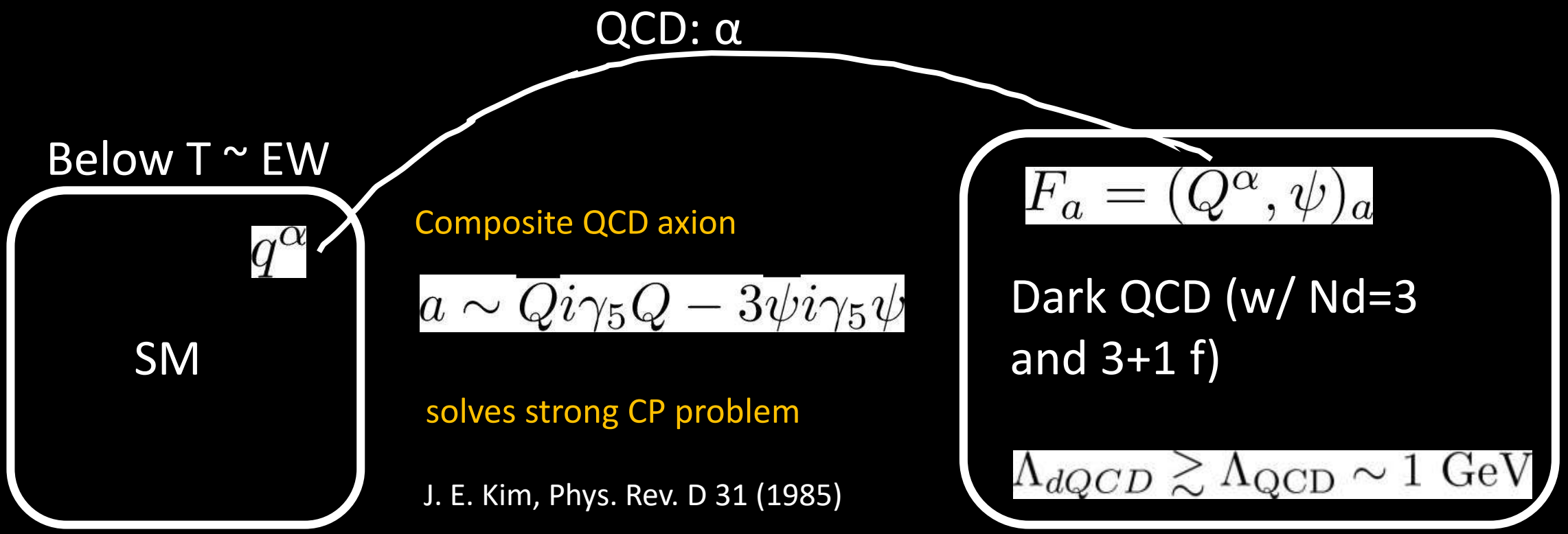

J. E. Kim, Phys. Rev. D 31 (1985)

K. Choi and J. E. Kim, Phys. Rev. D 32 (1985)

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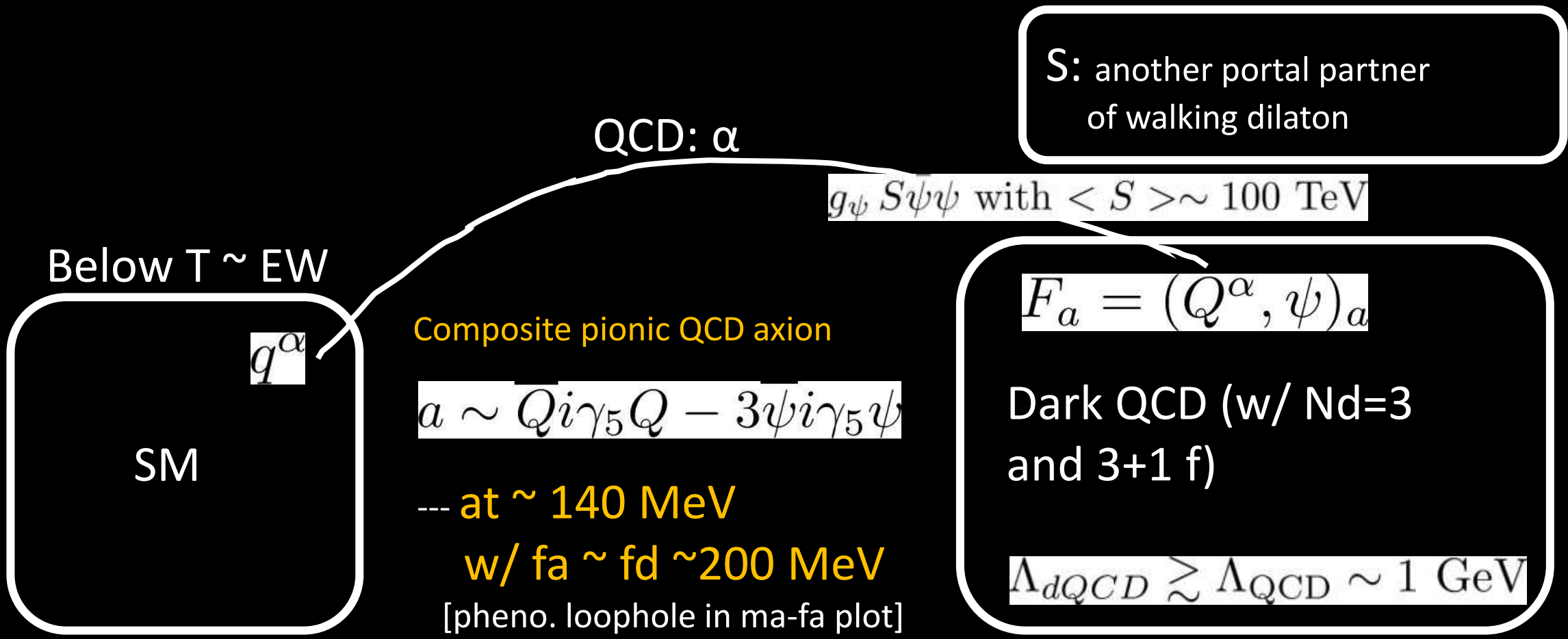

--- first-second generation-phobic

H.Ishida, S.M. and Y.Shigekami, Phys. Rev. D 103 (2021)

The overall scenario description:

S: another portal partner of walking dilaton

QCD: α

$g_\psi S\bar{\psi}\psi$ with $< S >\sim 100$ TeV

Below T ~ EW

q^α

SM

Composite pionic QCD axion

$a \sim Q i\gamma_5 Q - 3\psi i\gamma_5 \psi$

$F_a = (Q^\alpha, \psi)_a$

Dark QCD (w/ Nd=3 and 3+1 f)

$\Lambda_{dQCD} \gtrsim \Lambda_{\rm QCD} \sim 1$ GeV

ALP (a,η_d, η'..) mixing significant:
-> 3 γ at Belle II
[more to be discussed later]

B. Wang, H.Ishida, S.M., arXiv: 2408.xxxx [hep-ph].

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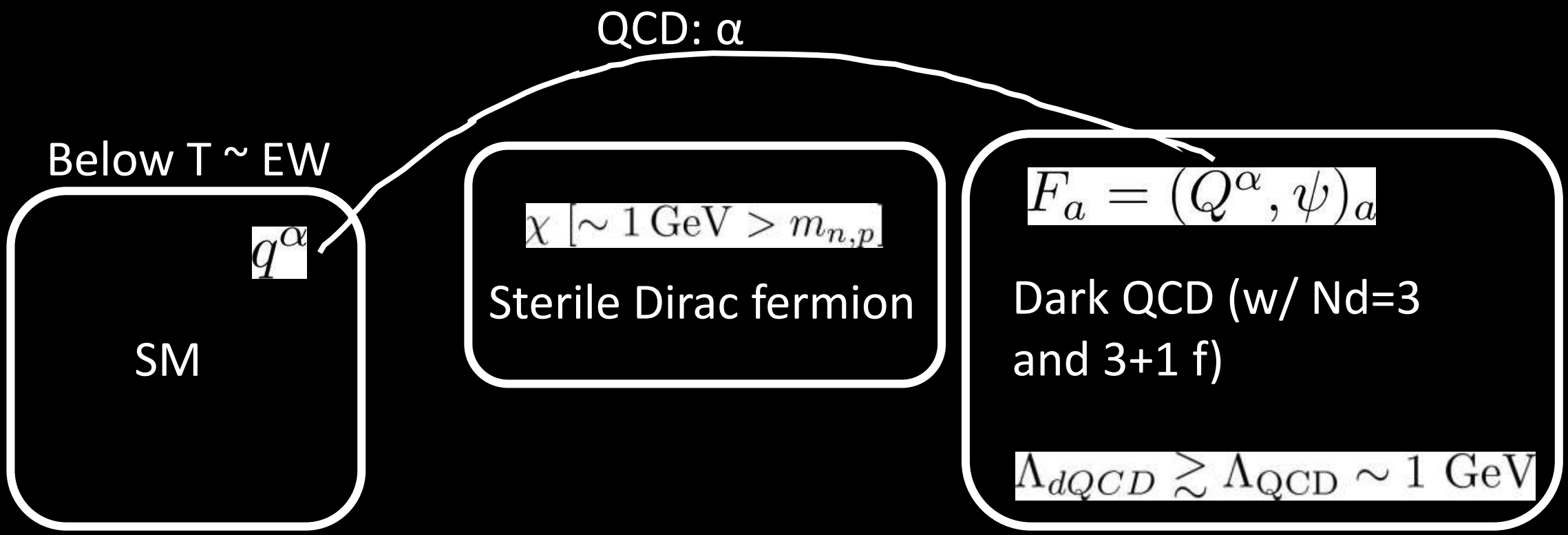

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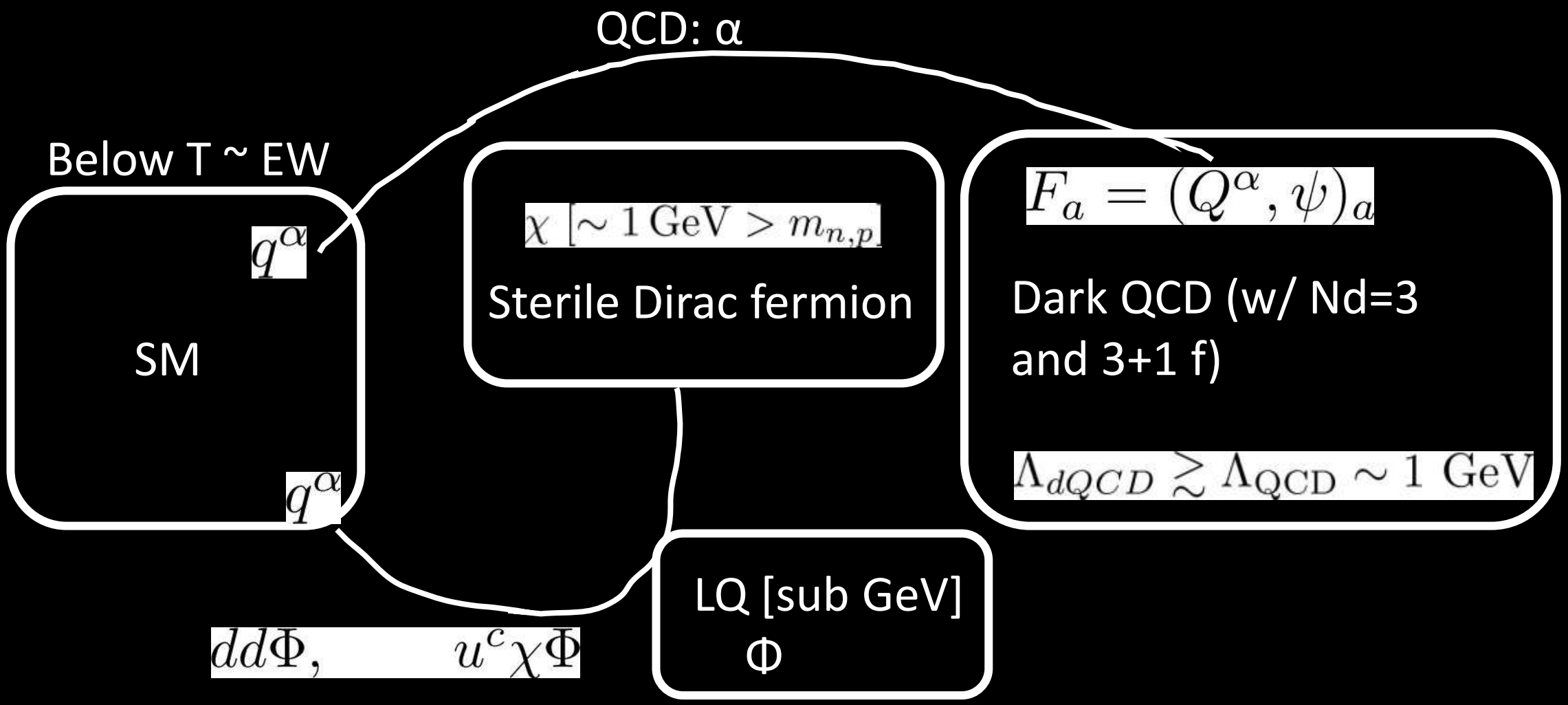

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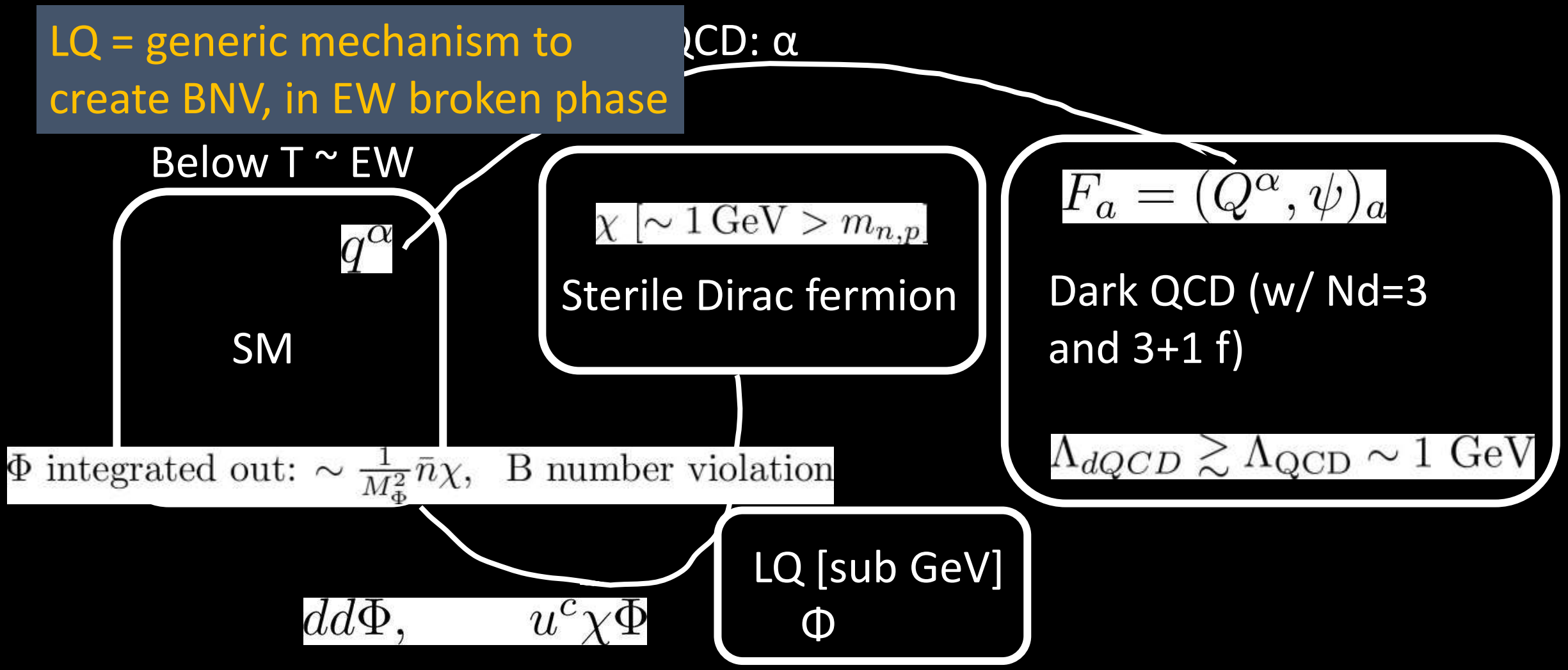


QCD-preheating baryogenesis

[Jimin Wang, in parallel session, yesterday]

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

X.R.Wang, J.Y.Li, S.Enomoto, H.Ishida and S.M., PRD 108 (2023)

-- dynamic QCD-induced baryon chemical potential [T or CPV]

-- fast rolling σ ~ <qqbar> (preheating; out-of-Eq) triggered by dQCD 1st order PT

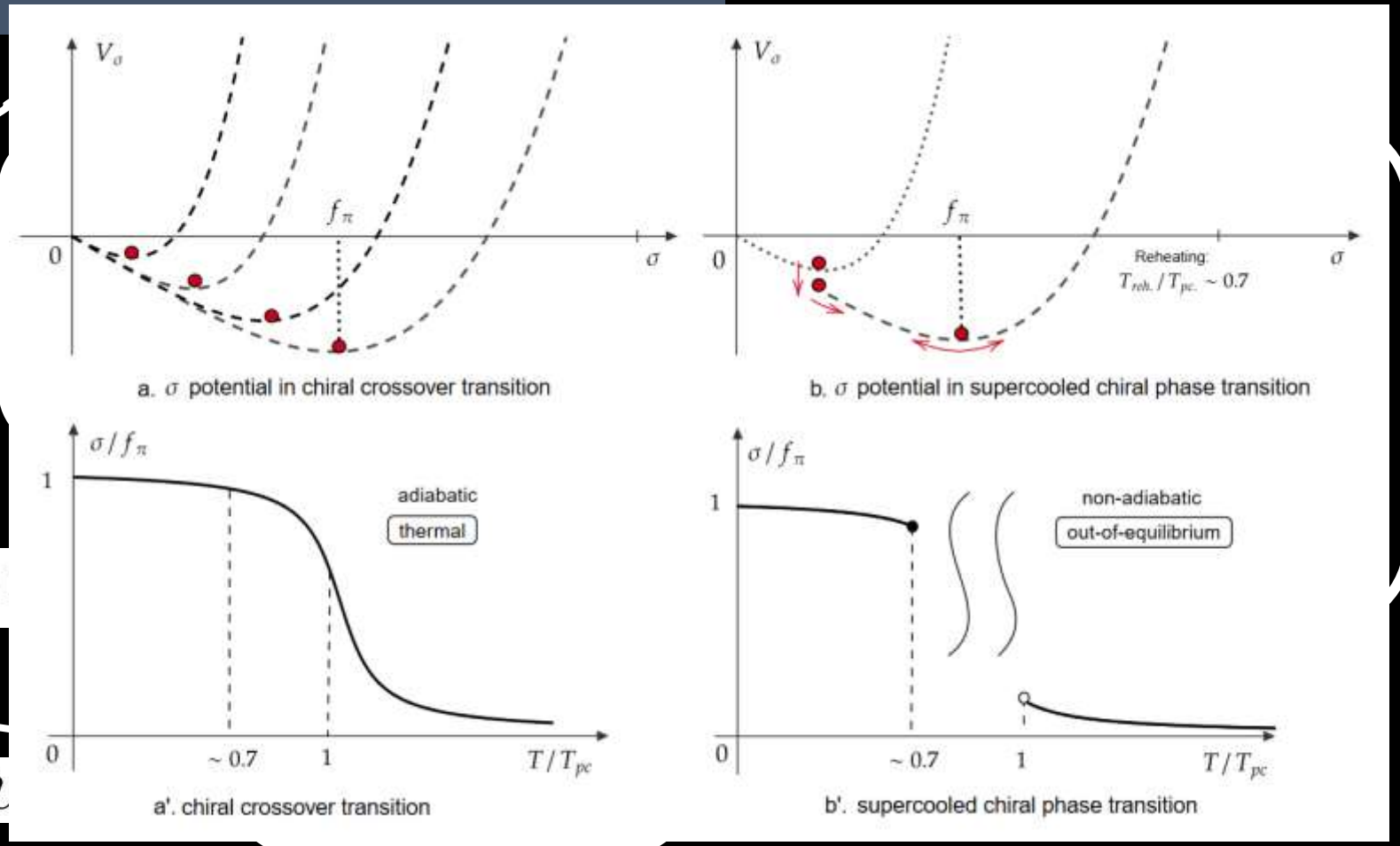
Around T ~ O(100MeV)

q^α

SM

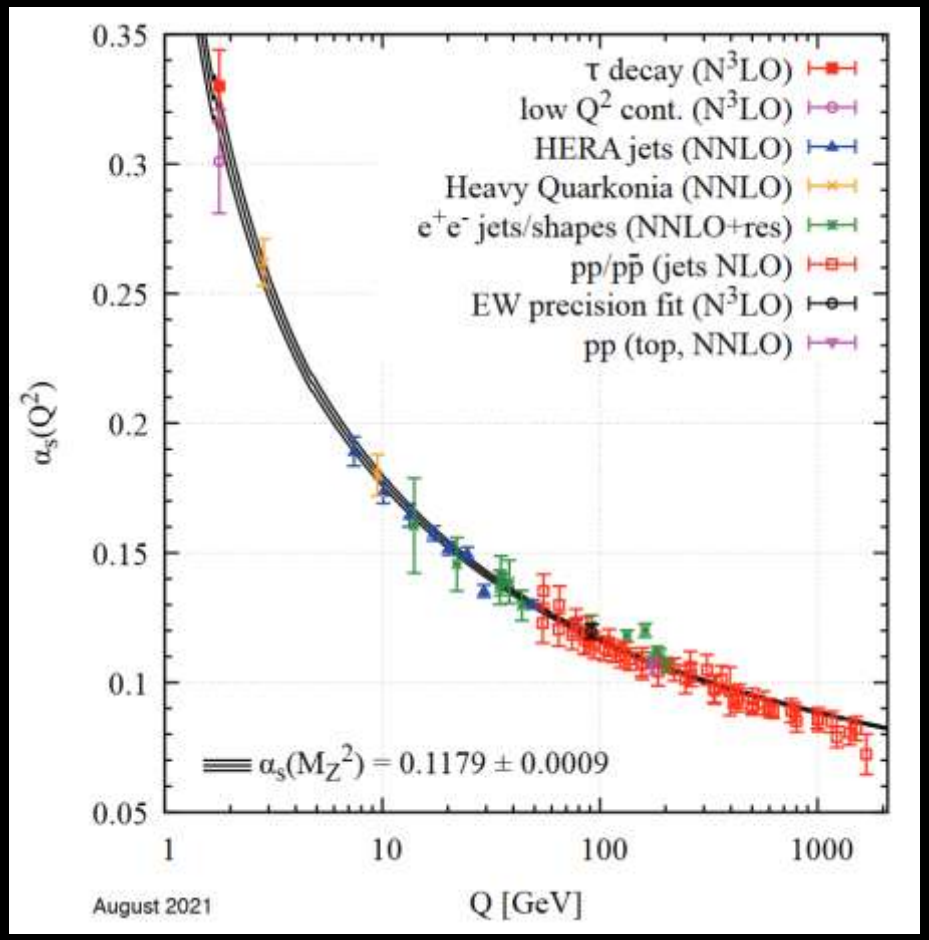
Φ integrated out: $\sim \frac{1}{M_\Phi^2}\bar{n}\chi$, B

$dd\Phi$, ι



Pheno. constraints on new QCD scale phys.

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



Fixing αs(Mz) to EW precision test,

- Asymptotic freedom > TeV
- IR scaling < 10 GeV

can be sensitive to new quarks (Q)

From PDG (2024)

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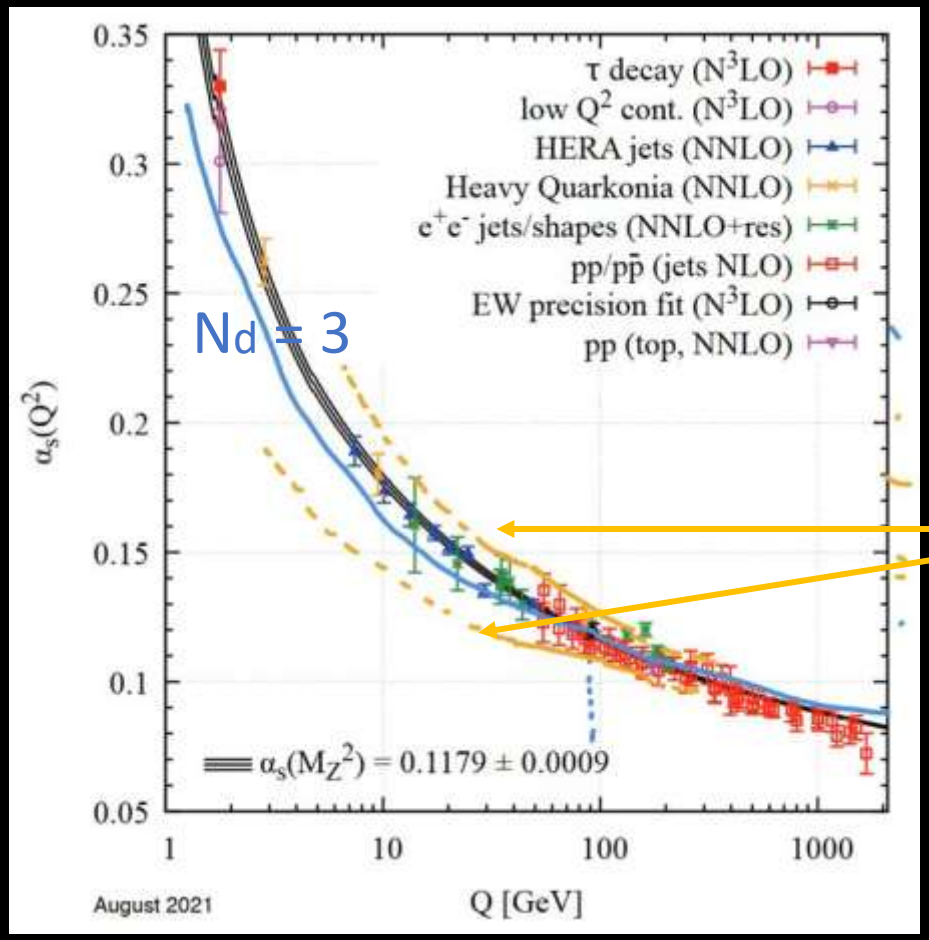

Fixing αs(Mz) to EW precision test,

- 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 $N_d < 5$

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

From PDG (2024)

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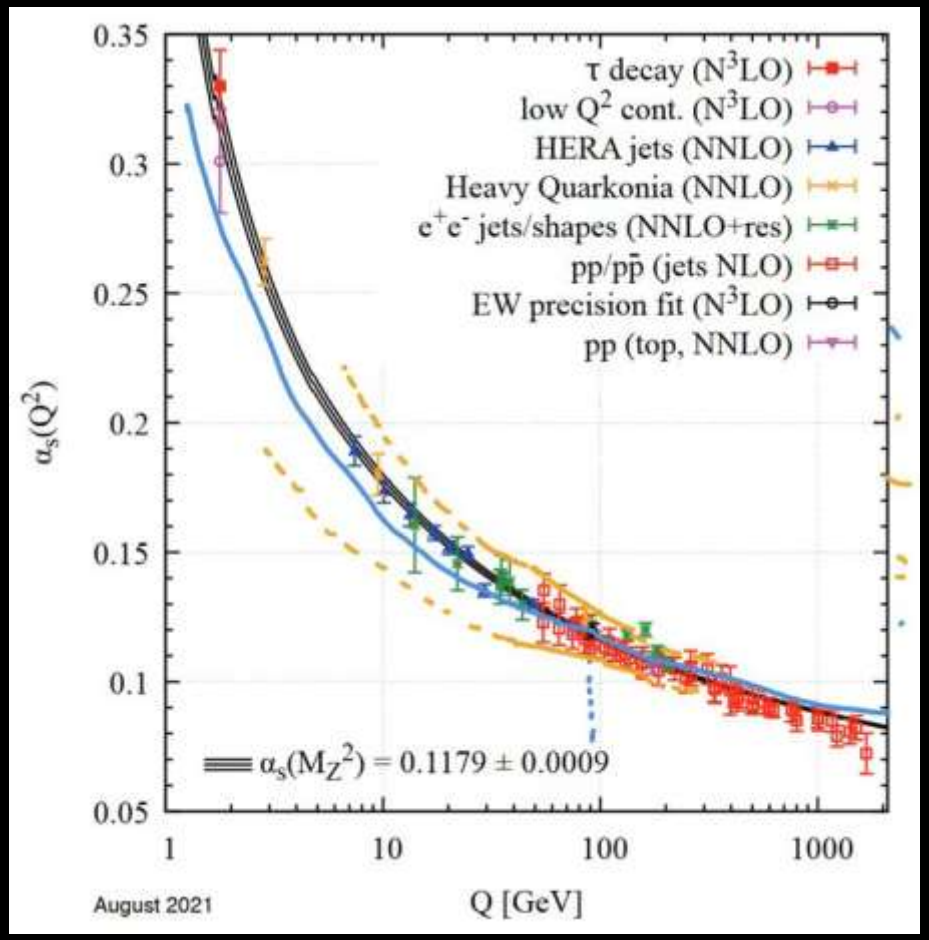

From PDG (2024)

Clarifying IR running
crucial to place limits further on N_d

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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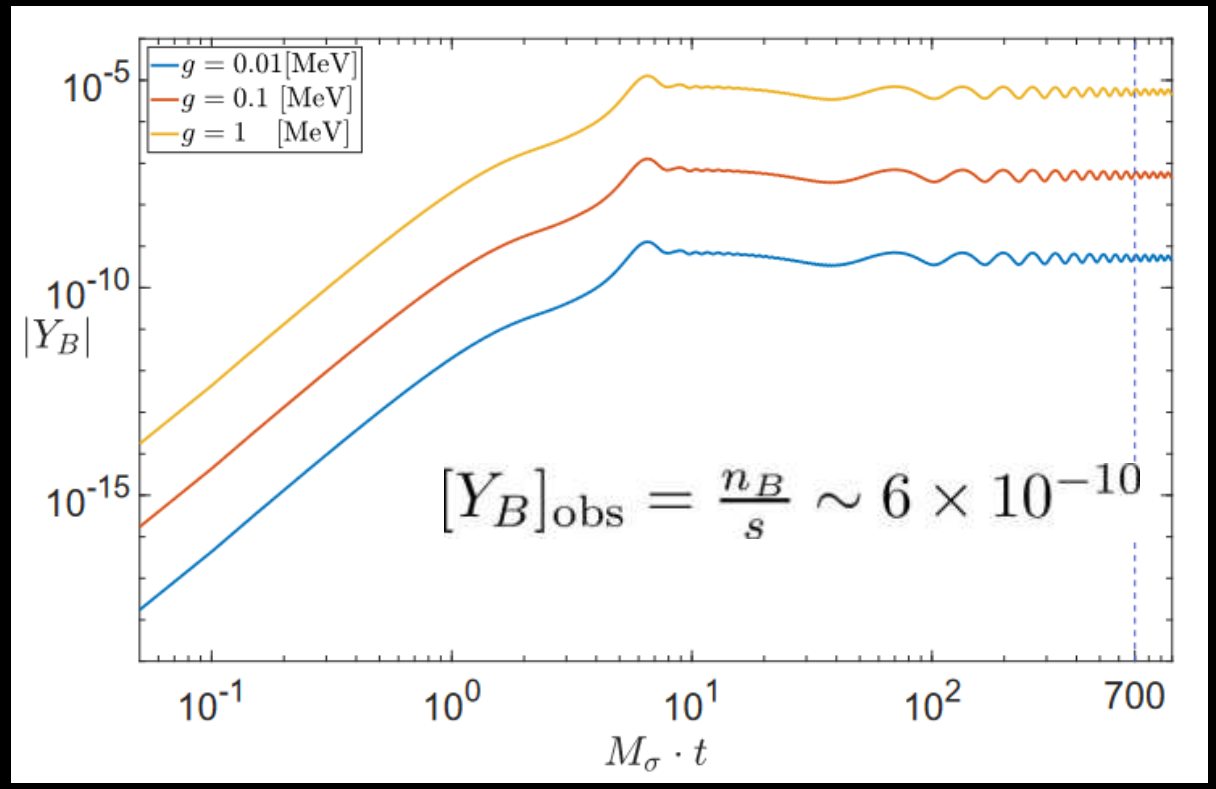

Consistent with successful QCD-preheating baryogenesis

g ~ 0.1 – 1 MeV

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

[Jimin Wang, in parallel session, yesterday]

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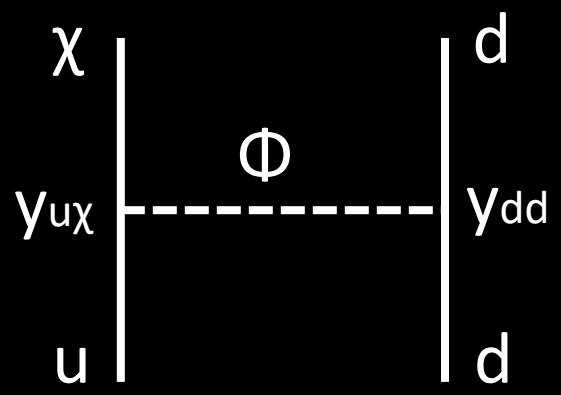
[2] n- mixing partner: Dirac sterile fermion χ w/ mx ~ 1 GeV > $m_{n,p}$

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

g ~ 0.1 – 1 MeV

--- 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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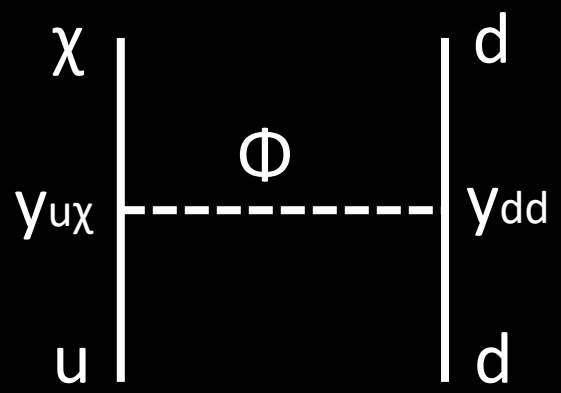

Also survives upper bound from LEP squark search: gets less sensitive as m < 10 GeV

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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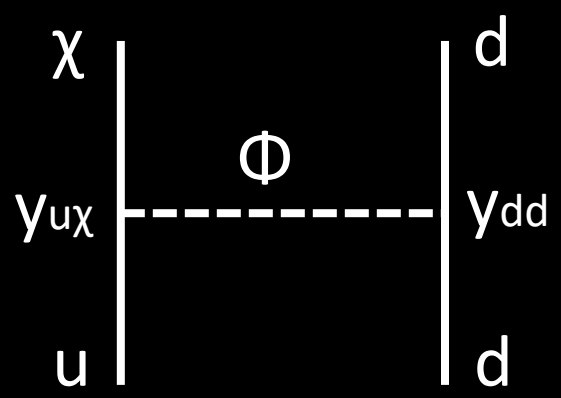
QCD-preheating BG



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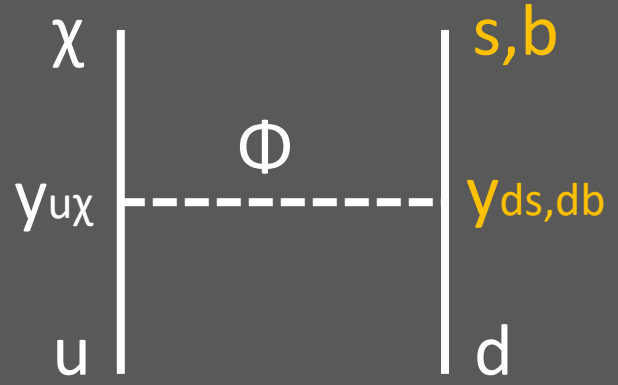

Compared to another QCD BG: "Mesogenesis"

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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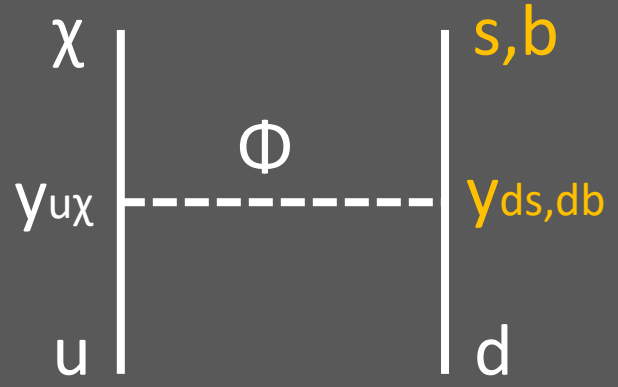
QCD-preheating BG

→ Characteristic low-mass LQ

Compared to another QCD BG: "Mesogenesis"



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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] i) **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:

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

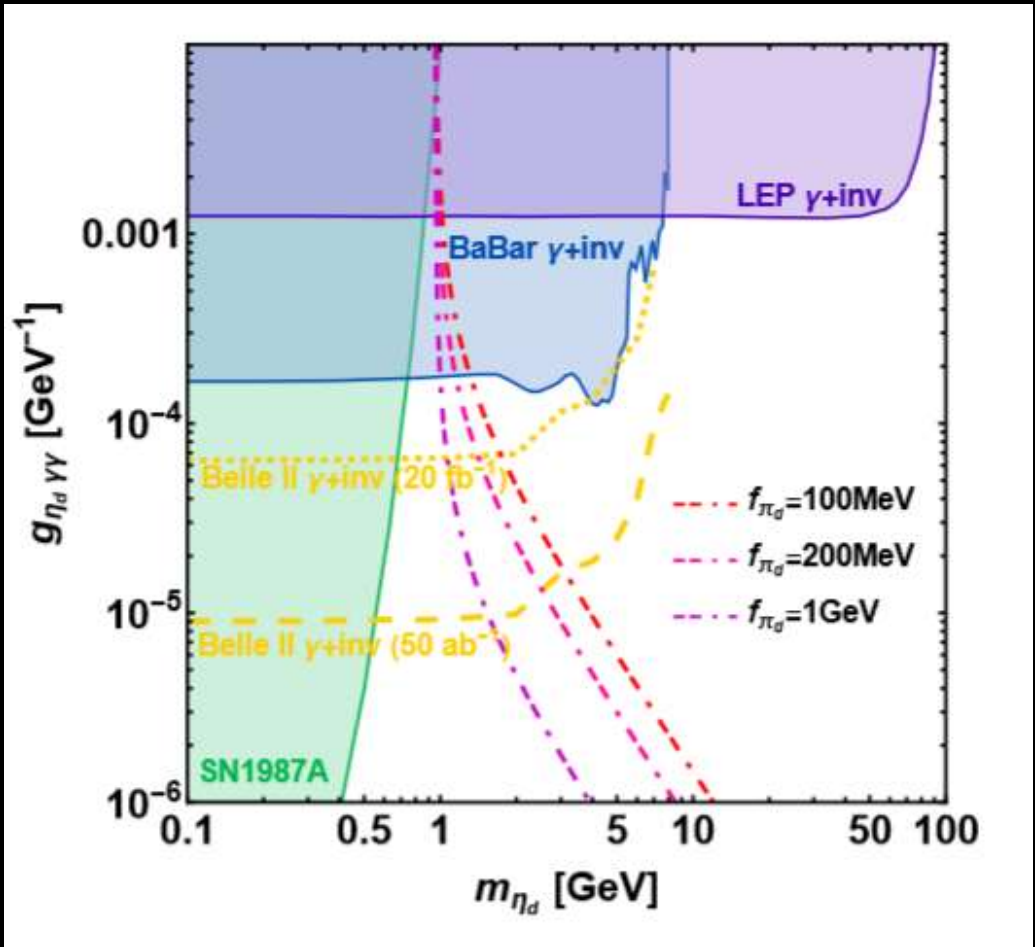
That is, sigma scattering process:

$\sigma\,\sigma \rightarrow \sigma_d\,\sigma_d$

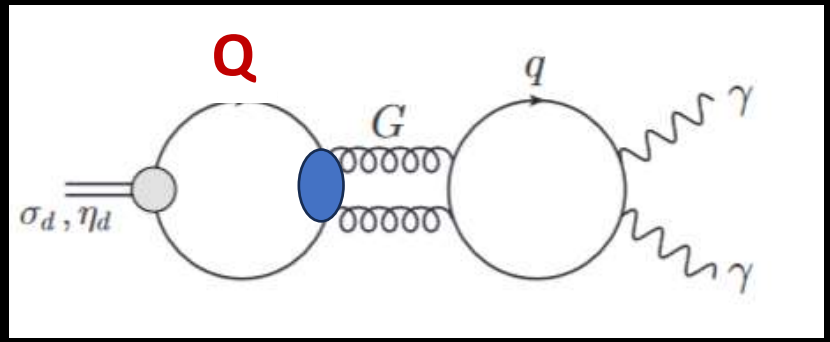
Highly challenging to probe in exp…

Pheno. constraints on new QCD scale phys.

[3] i) **EM production** of σ_d and/or η_d



$$\eta_d - a - \eta' \text{ mixing}$$



Possible to probe at Belle II with 20/ab, in 3γ events

B. Wang, H.Ishida, S.M., arXiv: 2408.xxxx [hep-ph].

Summary

New cosmo. and pheno: look at QCD scale

Scale PT [1st order]

→ waterfall 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

Scale PT [1st order]
→ waterfall inflation
→ EWSB
➔ dQCD PT [1st order]
➔ QCD-preheating BG
➔ QCD PT [crossover end]
➔ BBN

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

BNV messanger: 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 [20/ab]

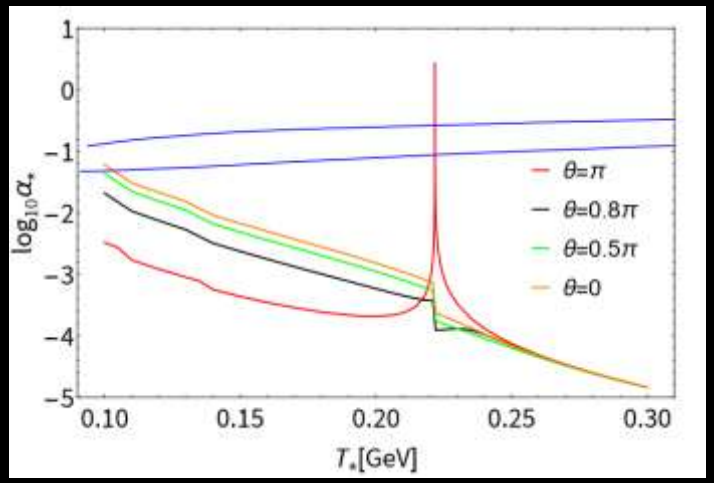
n - mixing partner: χ at 1 GeV > $m_{n,p}$
X -> nγ **[no prospect at present, challenging at exp]**

3rd-gene-phlic flavorful
pionic ALP: a at 140 MeV
B -> K π[a] γ

H.Ishida, S.M. and Y.Shigekami, Phys. Rev. D 103 (2021), and another work to be pursed

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

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



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.