Quark matter under strong magnetic fields

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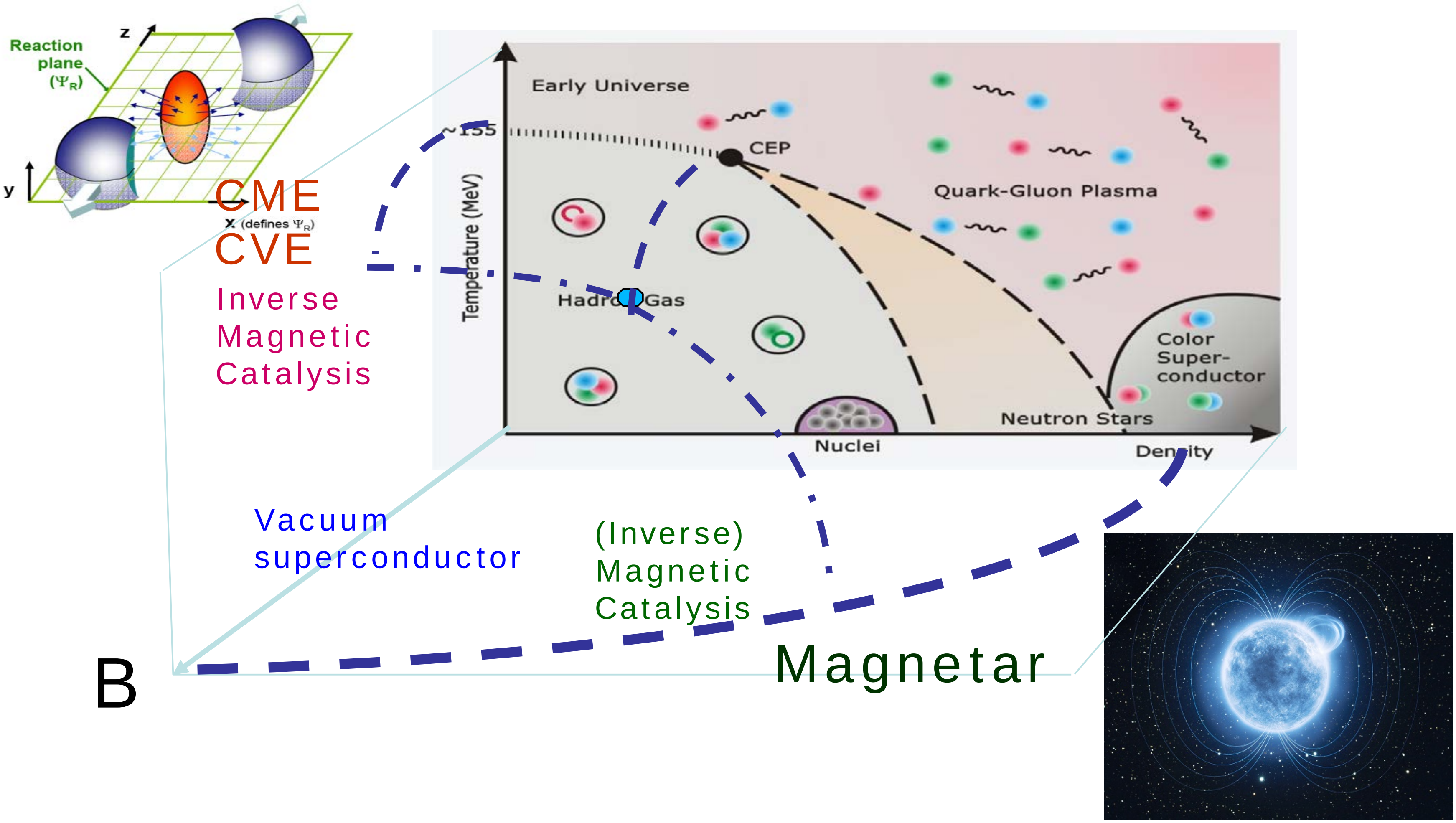
Quark matter under magnetic fields (2014)



CME

CVE

Inverse Magnetic Catalysis

Vacuum superconductor

(Inverse) Magnetic Catalysis

B

Magnetar

Recently, more interests on fast rotating system, finite size system, neutron star merge, gravitation wave…..

Update information about:

I. Inverse magnetic catalysis

II. Vacuum superconductor

III. Phase structure under B

IV. Summary

I. Inverse magnetic catalysis

Magnetic catalysis at zero temperature

S.P. Klevansky and R. H. Lemmer ('89); H. Suganuma and T. Tatsumi ('91);
V. P. Gusynin, V. A. Miransky and I. A. Shovkovy ('94, '95, '96,...)

$$\mathscr{L} = \bar{\Psi} i\gamma^{\mu} D_{\mu}\Psi + \frac{G}{2}\left[(\bar{\Psi}\Psi)^2 + (\bar{\Psi} i\gamma^5\Psi)^2\right]$$

$$D_{\mu} = \partial_{\mu} - ieA_{\mu}^{\mathrm{ext}}, \qquad \mathbf{A}^{\mathrm{ext}} = (0, Bx^1, 0)$$

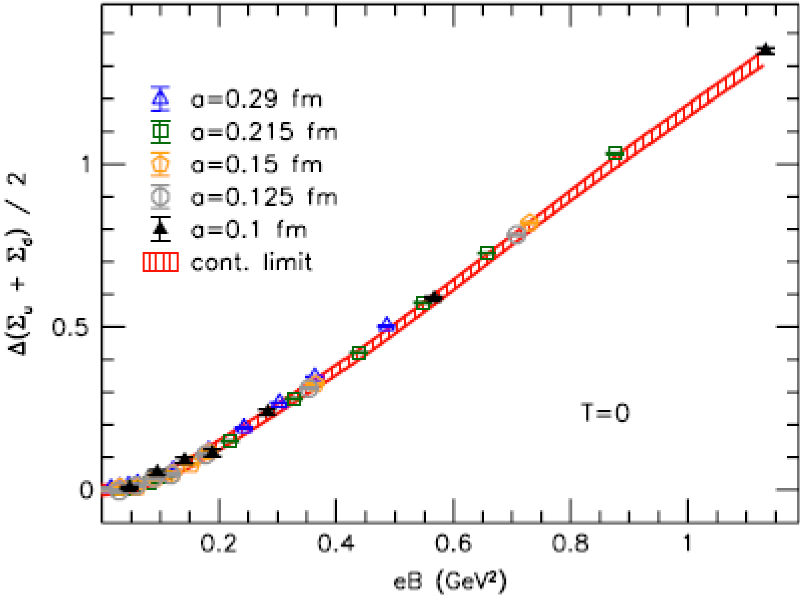
$$m = G\,\mathrm{tr}\left[S(x,x)\right] \approx \frac{Gm}{(2\pi)^2}\left(\Lambda^2 + |eB|\ln\frac{|eB|}{\pi m^2} + O\left(m^2\right)\right)$$

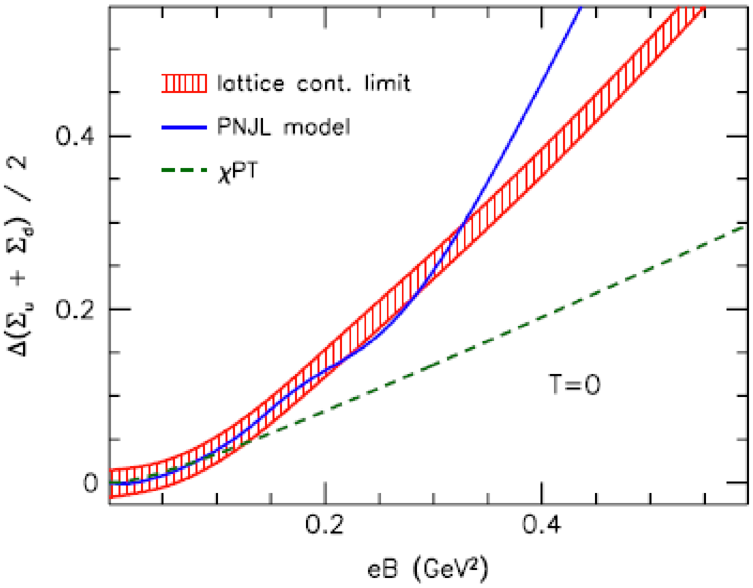
$$m \propto \exp\left(-\frac{2\pi^2}{G|eB|}\right)$$

nonzero mass for arbitrary small G

Magnetic catalysis at zero temperature

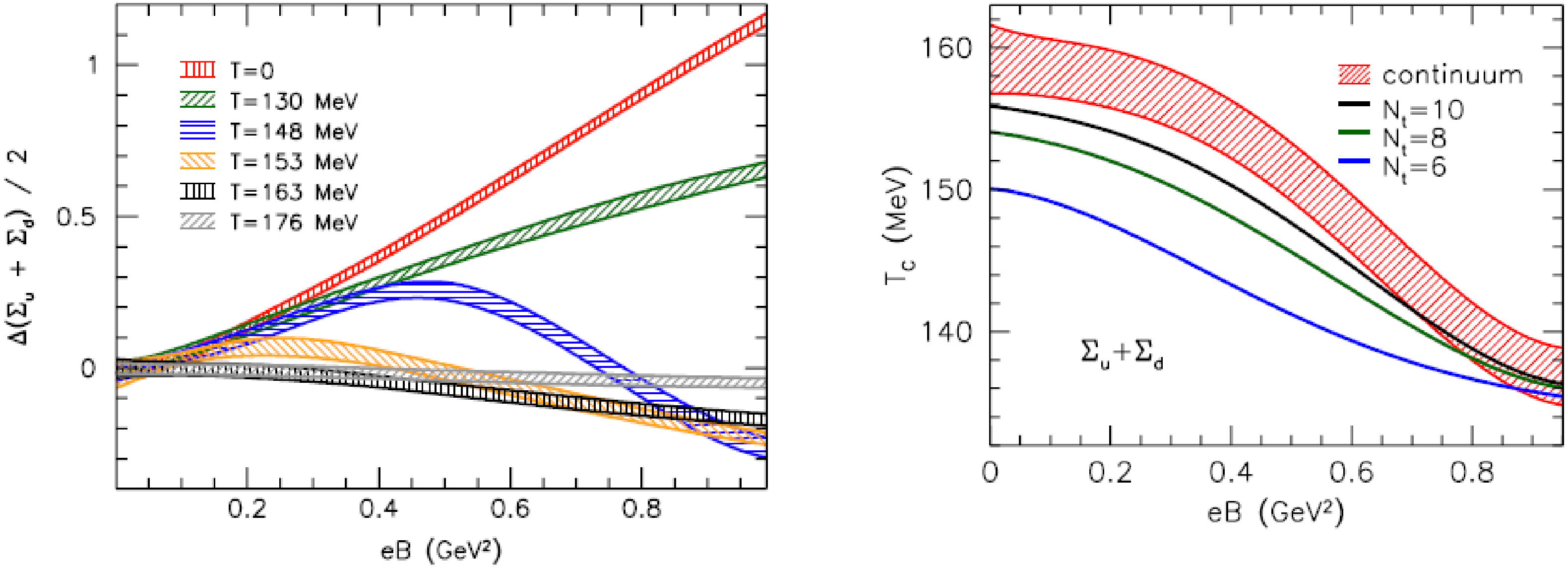
Bali et al. arXiv:1206.4205 [hep-lat]





Inverse magnetic catalysis at nonzero temperature

Bali et al. arXiv:1206.4205 [hep-lat]



How to understand inverse magnetic catalysis ?

1) Magnetic inhibition


K. Fukushima, Y. Hidaka, PRL 110, 031601 (2013)

Contribution from neutral pions

2) Contribution from sea quarks

Bruckmann et.al. arXiv:1303.3972

3) Polyakov holomoly

Nowak et.al. arXiv:1304.6020

4) Running coupling

M. Ferreira, et.al. arXiv:1404.5577

5) Chirality imbalance

Sphaleron transition

Jingyi Chao, Pengcheng Chu, MH,
arXiv:1305.1100, PRD88(2013)

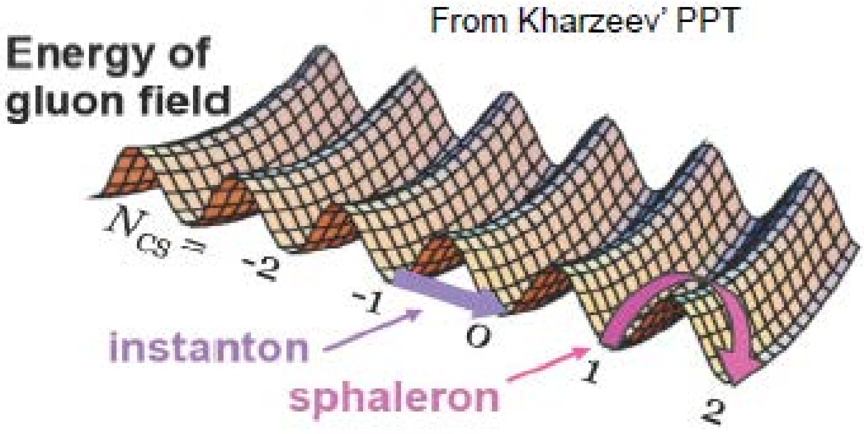
Instanton-anti-instanton pairing condensate

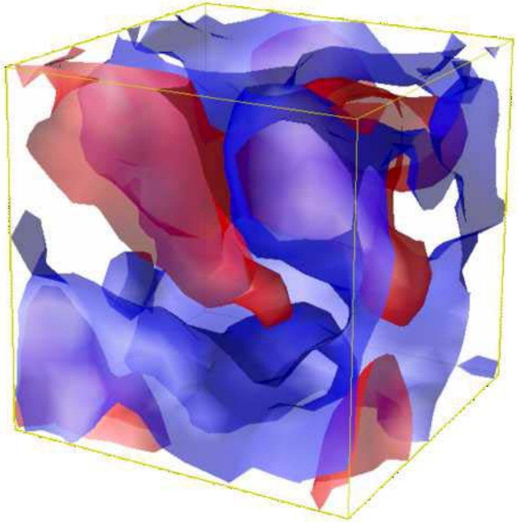
Lang Yu, Hao Liu, MH, arXiv:1404.6969,
PRD90(2014)

Theta vacuum, instantons and sphalerons

QCD vacuum has non-trivial topological structure characterized by an integer valued Chern-Simons number

Buividovich et al. arXiv:1111.6733



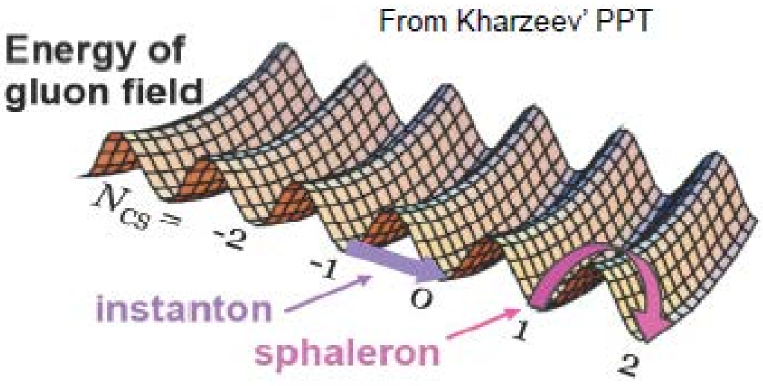


$$\Delta N_{\rm cs} = \frac{g^2}{32\pi^2}\int d^4x\, {\rm Tr}[F_{a\mu\nu}\tilde{F}^{a\mu\nu}]$$

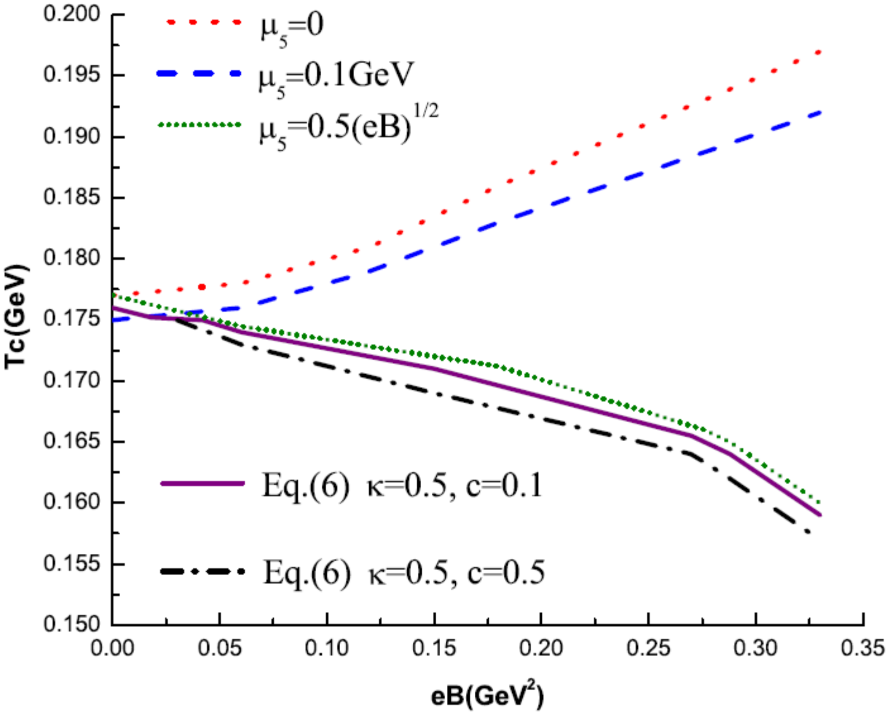
Induce chirality imbalance:

$$(N_R - N_L)_{t=+\infty} - (N_R - N_L)_{t=-\infty} = -2N_f\Delta N_{\rm cs}$$

Inverse magnetic catalysis induced by chirality imbalance



From Kharzeev' PPT



Debye mass for longitudinal gluons:

$$g(T + c\sqrt{eB})$$

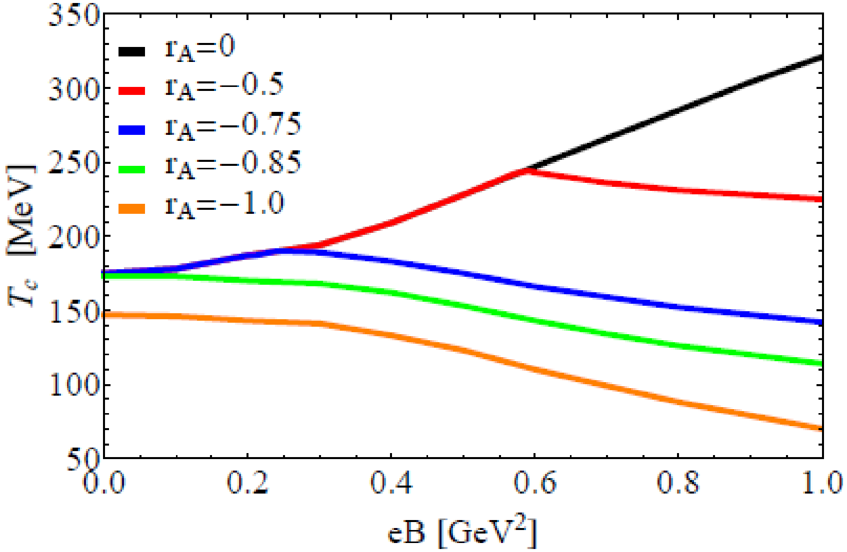
Sphaleron transition rate:

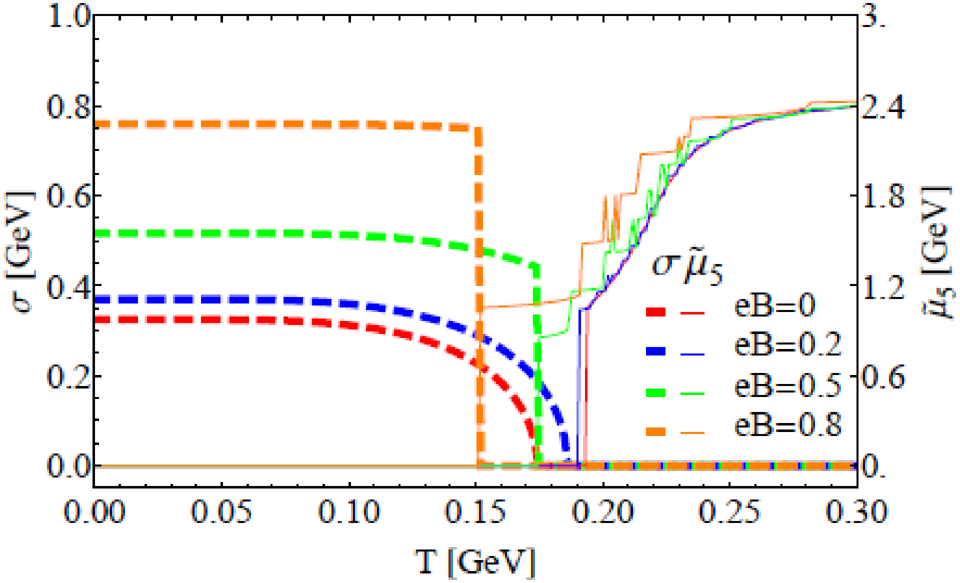
$$\Gamma_{ss} \sim (T^4 + c^2 eBT^2)$$

$$\mu_5 = \sqrt{3}\pi\left(\frac{320N_f^2\Gamma_{ss}}{T^2} - \frac{T^2}{3}\right)^{\frac{1}{2}}$$

Jingyi Chao, P.C. Chu, MH,
arXiv:1305.1100, PRD88(2014)

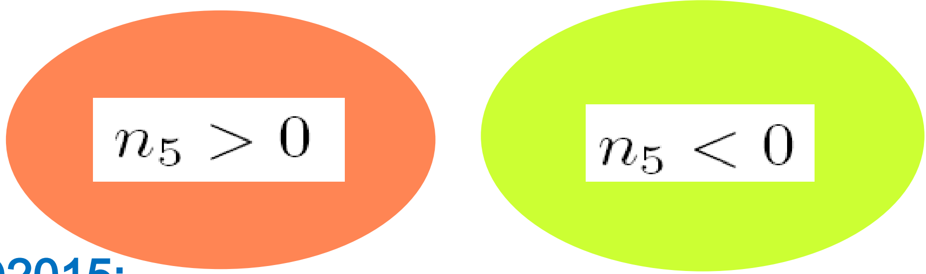
Inverse magnetic catalysis induced by chirality imbalance





First order phase transition!

Maybe more suitable for EW!

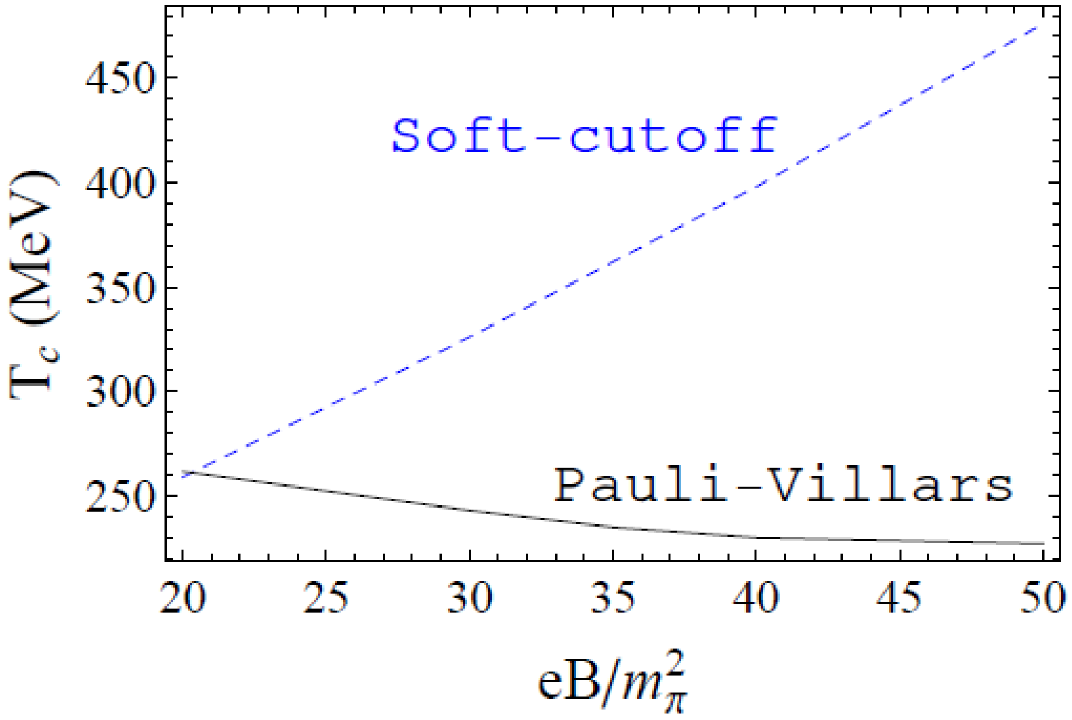


$n_5 > 0$

$n_5 < 0$

Lang Yu, Hao Liu, MH, arXiv:1404.6969, PRD90,074009(2014); arXiv:1411.7552,PRD2015; arXiv:1511.03073, PRD2016

Inverse magnetic catalysis induced by neutral pions

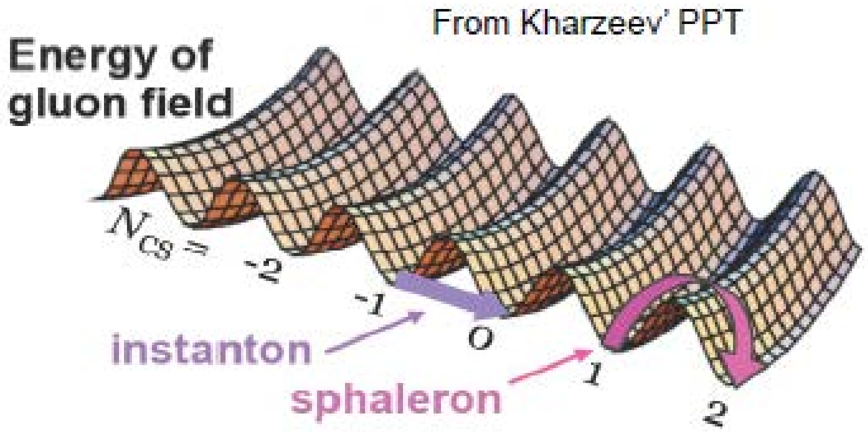


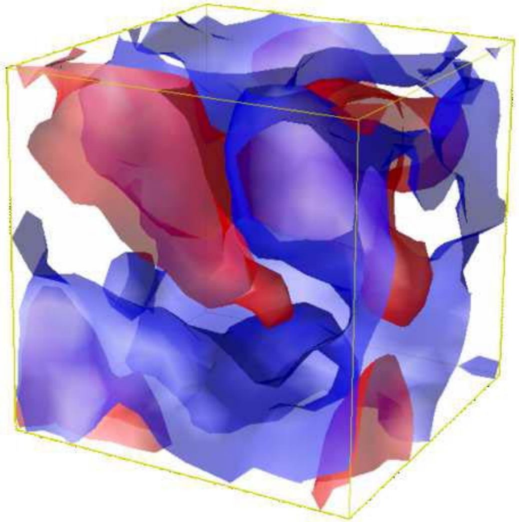
Shijun Mao, arXiv:1602.06503,PRD2016

Massless neutral pion in chiral limit!

Inverse magnetic catalysis …

More understanding is needed on nontrivial gluodynamics under B and T!





More discussion from Hengtong Ding's talk!

II. Is there vacuum superconductor?

Point particles under B

- M. N. Chernodub, Phys. Rev. Lett. 106 (2011) 142003 [arXiv:1101.0117 [hep-ph]]

-Energy of relativistic particle in the external magnetic field B:

$$\varepsilon^2_{n,s_z}(p_z) = p_z^2 + (2n - 2\mathrm{sgn}(q)s_z + 1)|qB| + m^2$$

nonnegative integer number

the momentum along the external magnetic field

projection of spin on the direction of magnetic field

-Masses of ρ mesons and π in magnetic field:

$$\mathrm{m}^2_{\pi^\pm}(\mathrm{B}) = \mathrm{m}^2_{\pi^\pm} + \mathrm{eB}$$ becomes larger

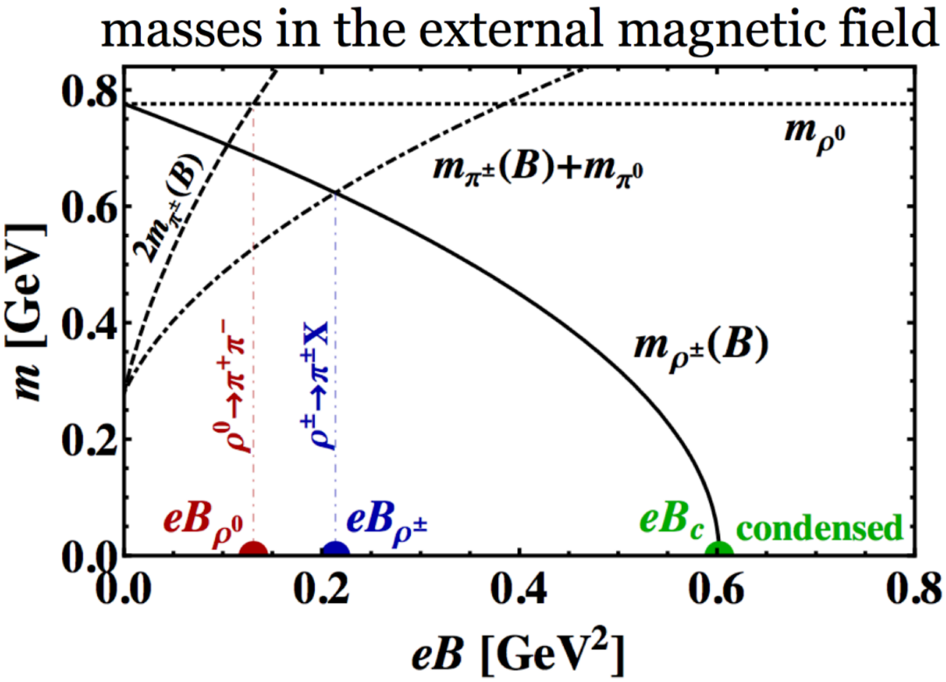
$$\mathrm{m}^2_{\rho^\pm}(\mathrm{B}) = \mathrm{m}^2_{\rho^\pm} - \mathrm{eB}$$ becomes lighter

where $\mathrm{m}_{\rho\pm} = 768\mathrm{MeV}$, $\mathrm{m}_{\pi\pm} = 140\ \mathrm{MeV}$

Vacuum Superconductor

The charged rho becomes massless and condensate at a critical magnetic fields : $\mathrm{eB}_c = \mathrm{m}_{\rho^\pm}^2$

M. N. Chernodub, Phys. Rev. Lett. 106 (2011) 142003 [arXiv:1101.0117 [hep-ph]]

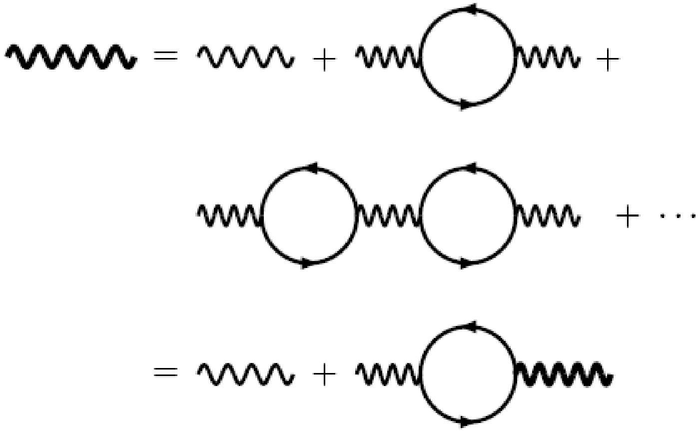


The pions become heavier while the charged vector mesons become lighter in the external magnetic field

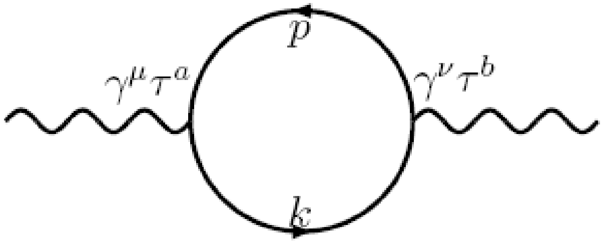
The $\rho^\pm \to \pi^\pm\pi^0$ decay stops at a critical eB

Charged and neutral vector meson in NJL model

$$\begin{aligned}\mathcal{L} \;=\; & \bar{\psi}(i\not{D} - \hat{m})\psi + G_S\left[(\bar{\psi}\psi)^2 + (\bar{\psi}i\gamma^5\vec{\tau}\psi)^2\right] \\ & -G_V\left[(\bar{\psi}\gamma^\mu\tau^a\psi)^2 + (\bar{\psi}\gamma^\mu\gamma^5\tau^a\psi)^2\right] \\ & -\frac{1}{4}F_{\mu\nu}F^{\mu\nu}.\end{aligned}$$



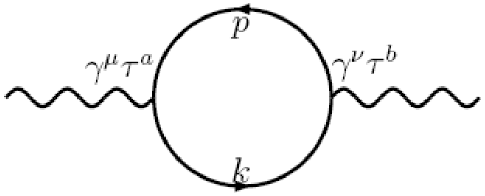
$-i\Pi^{\mu\nu,ab}(q) =$

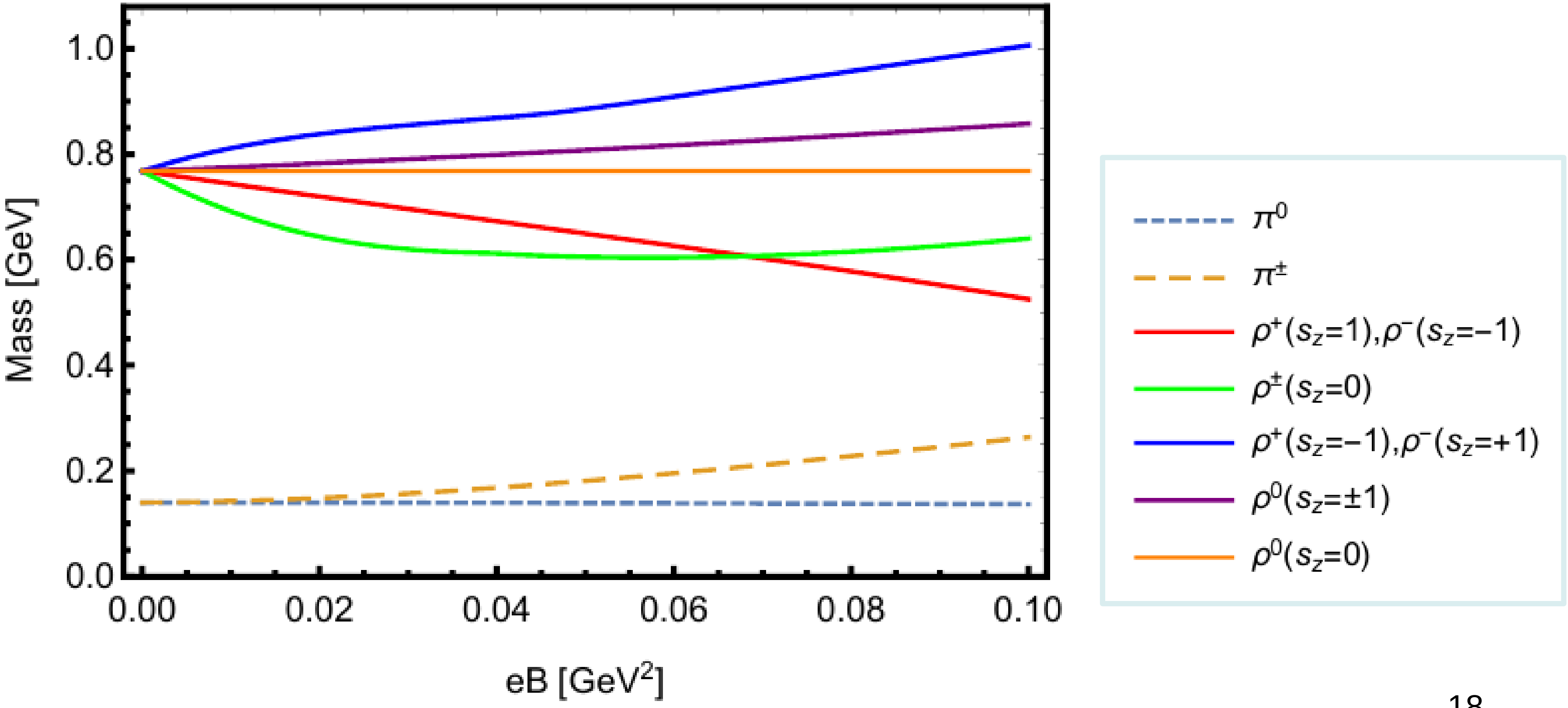


Vector meson under B: spin decomposition!

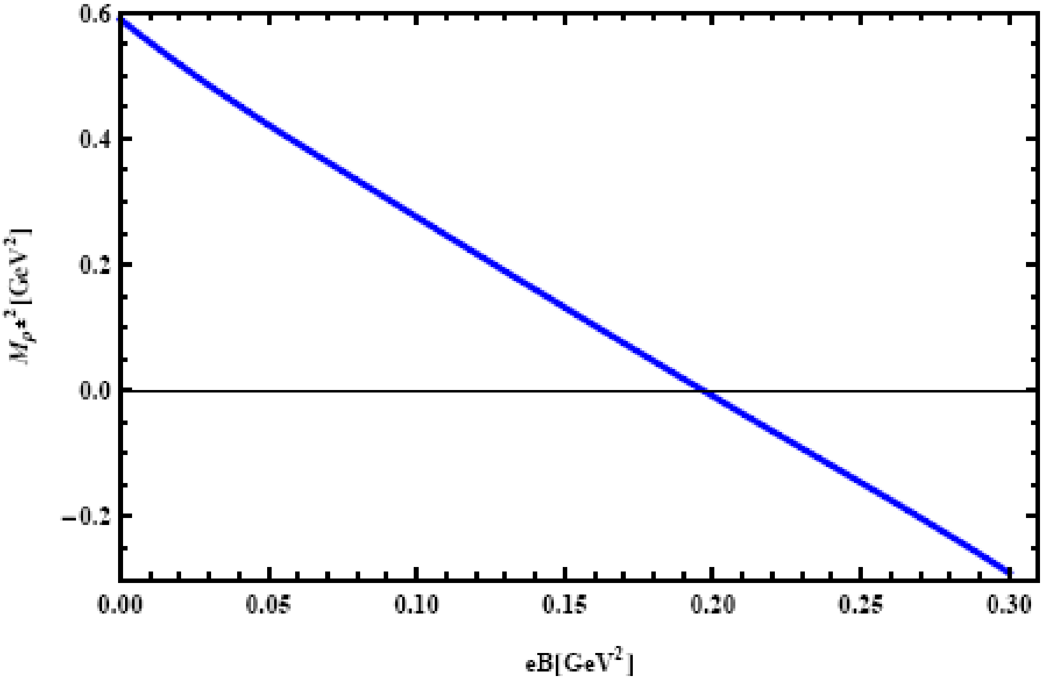
$$\Pi^{\mu\nu}_{\rho^0} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & \Pi^{11}_{\rho^0} & 0 & 0 \\ 0 & 0 & \Pi^{22}_{\rho^0} & 0 \\ 0 & 0 & 0 & \Pi^{33}_{\rho^0} \end{pmatrix} \qquad \Pi^{\mu\nu}_{\rho^\pm} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & \Pi^{11} & \Pi^{12} & 0 \\ 0 & \Pi^{21} & \Pi^{22} & 0 \\ 0 & 0 & 0 & \Pi^{33} \end{pmatrix}$$

$$\text{-i}\Pi^{\mu\nu,ab}(q) =$$





Charged vector meson in vacuum



Hao Liu, **Lang Yu, MH,**
arXiv:1408.1318, PRD2015

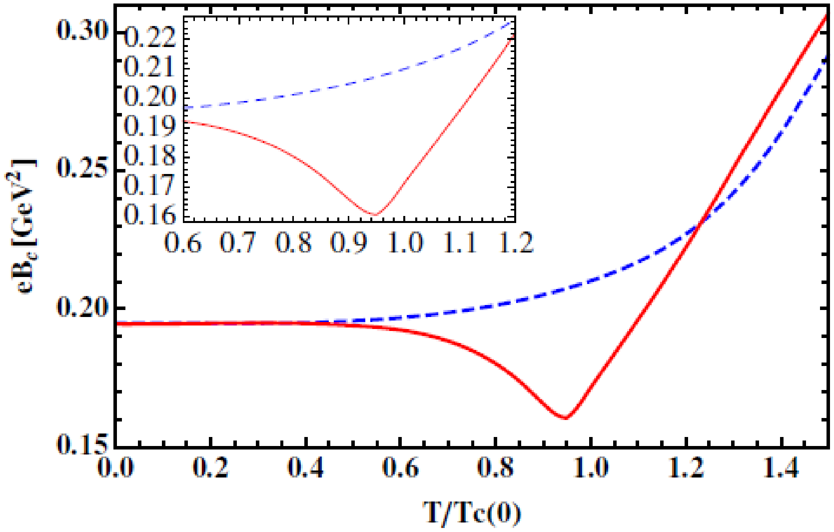
FIG. 4: The mass square of charged $\rho^\pm$ with spin component $s_z = \pm 1$ as a function of eB.

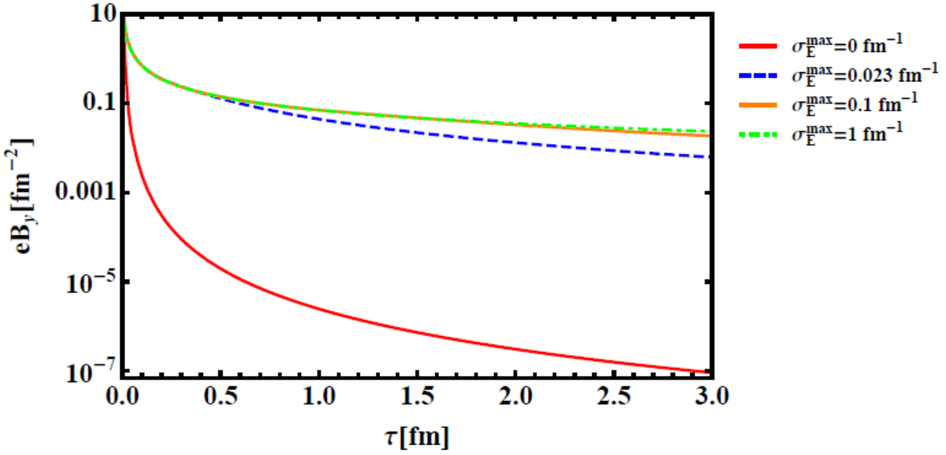
$\boxed{eB_c \simeq 0.2\mathrm{GeV}^2}$ ≈1/3 $\boxed{\mathrm{eB}_c = \mathrm{m}_{\rho^\pm}^2}$!

Quark polarization is important!

Charged vector meson at finite temperature

High-T superconductor! A natural source for high conductivity and induces long lifetime for magnetic field!

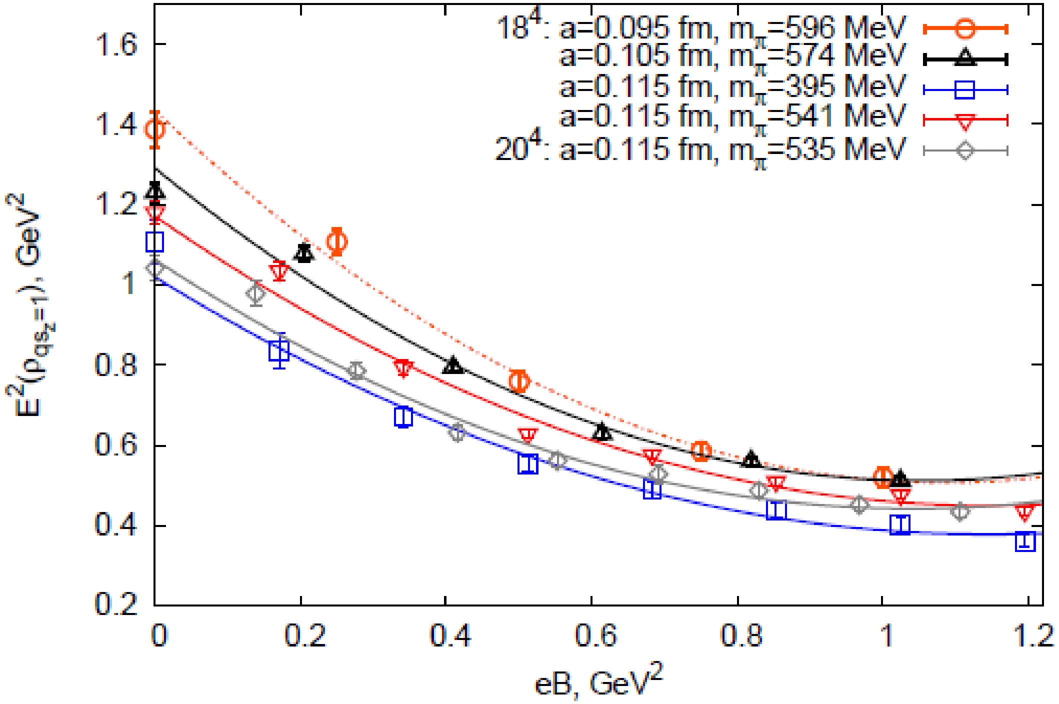


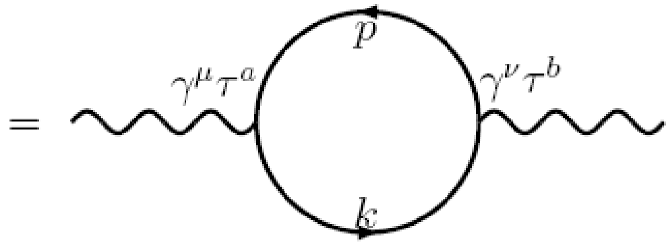


Hao Liu, Lang Yu, MH, arXiv:1507.05809

Hao Liu, Lang Yu, M.Chernodub, MH, arXiv:1604.06662

Lattice QCD on charged vector meson under B





Pion mass (quark mass) is still too heavy!

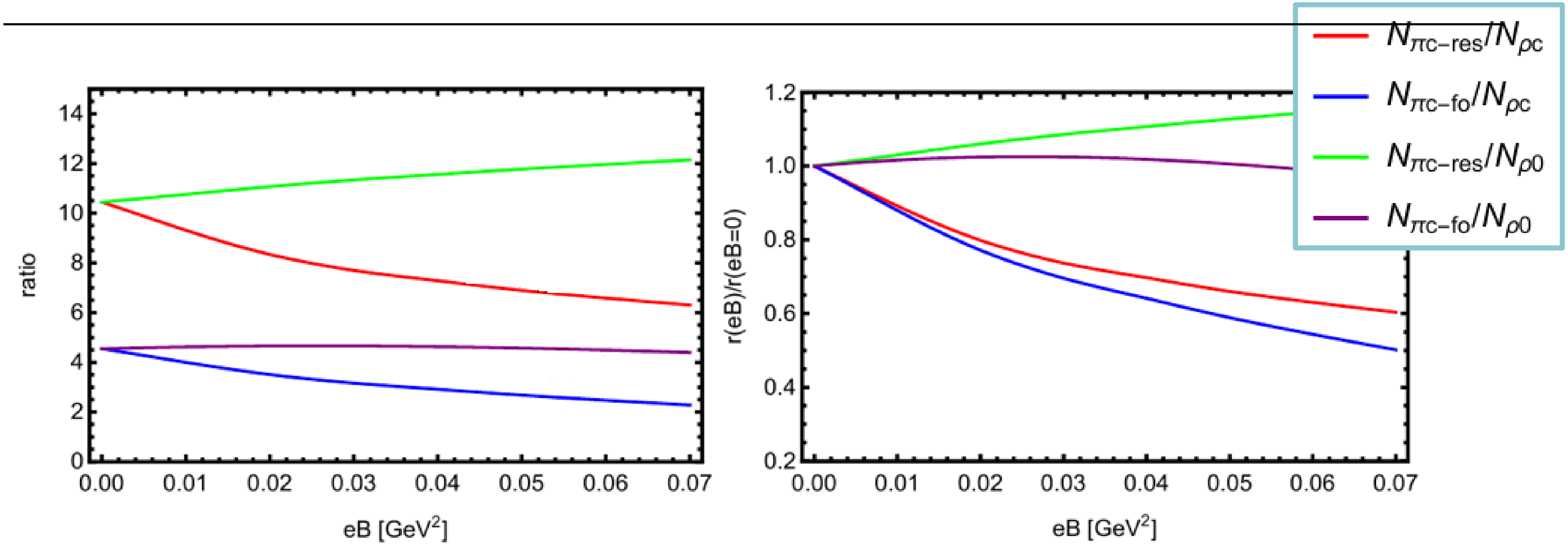
Looking forward to physical pion mass case!

E.V. Luschevskaya^{a,b} O.E. Solovjeva^{a} O.V. Teryaev^{c,d}

E.V. Luschevskaya^{a,b} O.V. Teryaev^{c,a} D.Yu. Golubkov^{a} O.V. Solovjeva^{a} R.A.Ishkuvatov^{a,b}

arXiv:1608.03472, 1811.02344

Meson mass M(B)→Meson production number N(B) → Measurement of B at freeze-out



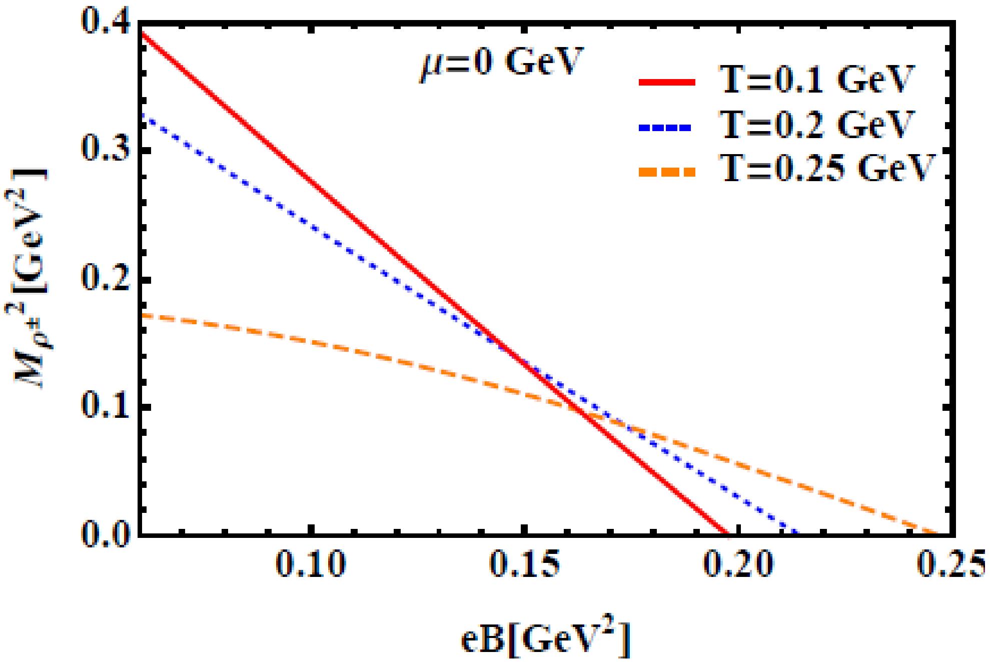
(a)

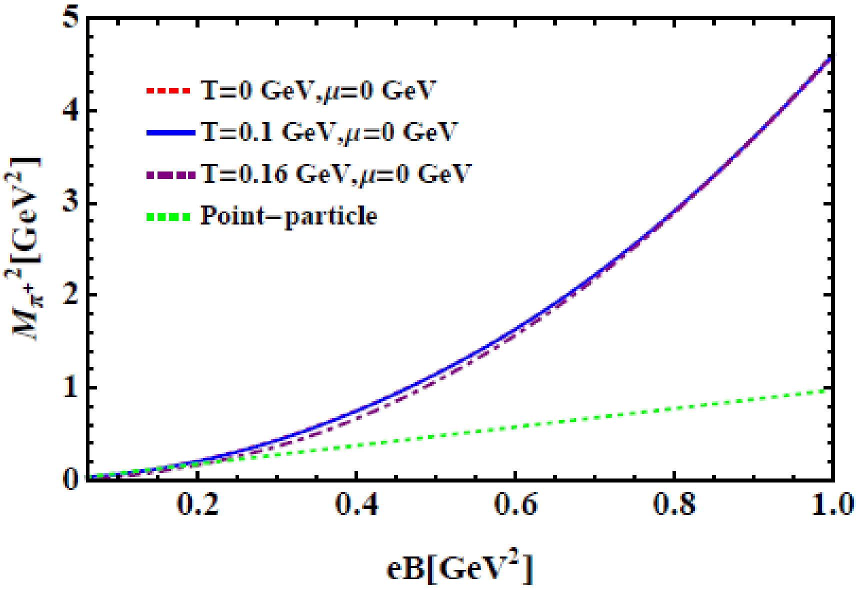
(b)

Magnetic field influences the ratio of N(charged pion)/N(charged rho) significantly!

Kun Xu, Hui Zhang,Shuzhe Shi, Xinyang Wang, Jinfeng Liao, Defu Hou, MH, to appear!

Meson mass M(B,T)→Meson production number N(B,T) → Measurement of B at freeze-out (T)

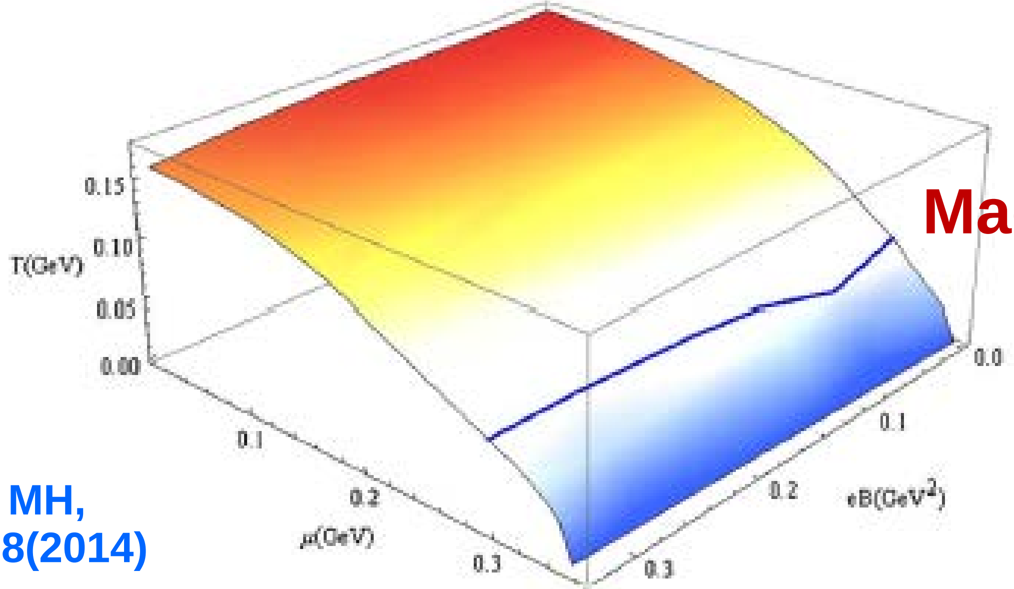




Magnetic field influences the ratio of N(charged pion)/N(charged rho) more significantly!

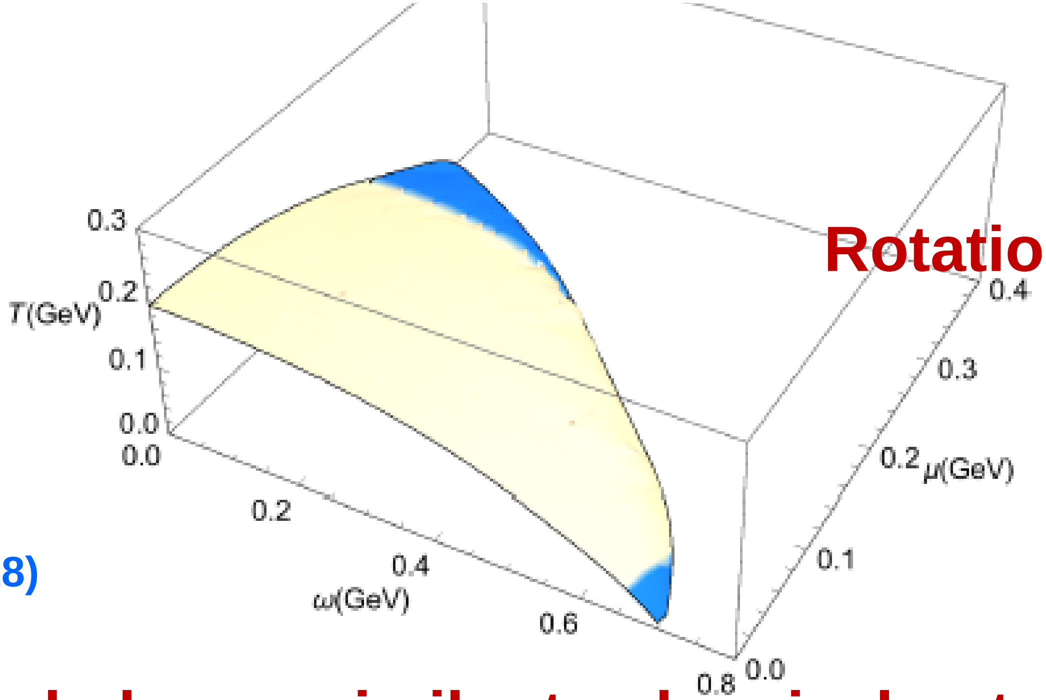
III. Phase structure under B revisited

Jingyi Chao, **P.C. Chu, MH,**
arXiv:1305.1100, PRD88(2014)



Magnetic field

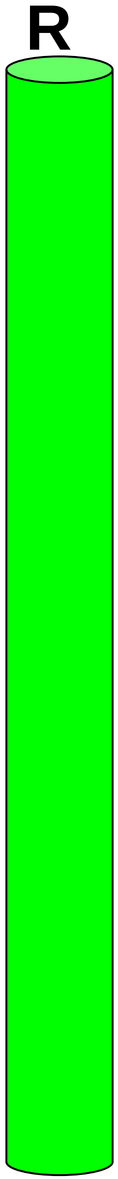
Xinyang Wang, **Minghua,**
Zhibin Li, MH,
arXiv:1808.01931,PRD88(2018)

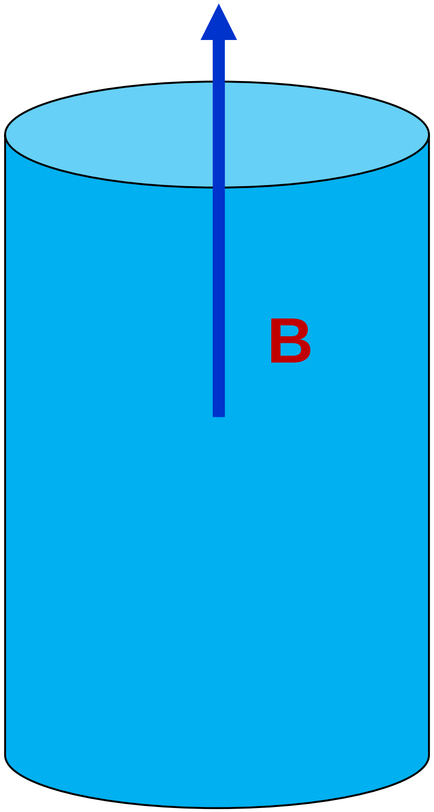


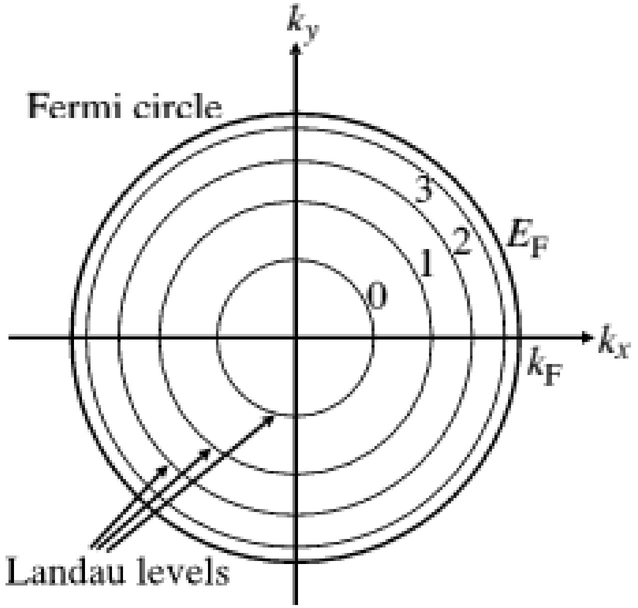
Rotation

Angular velocity behaves similar to chemical potential!

Strong magnetic field vs small Size







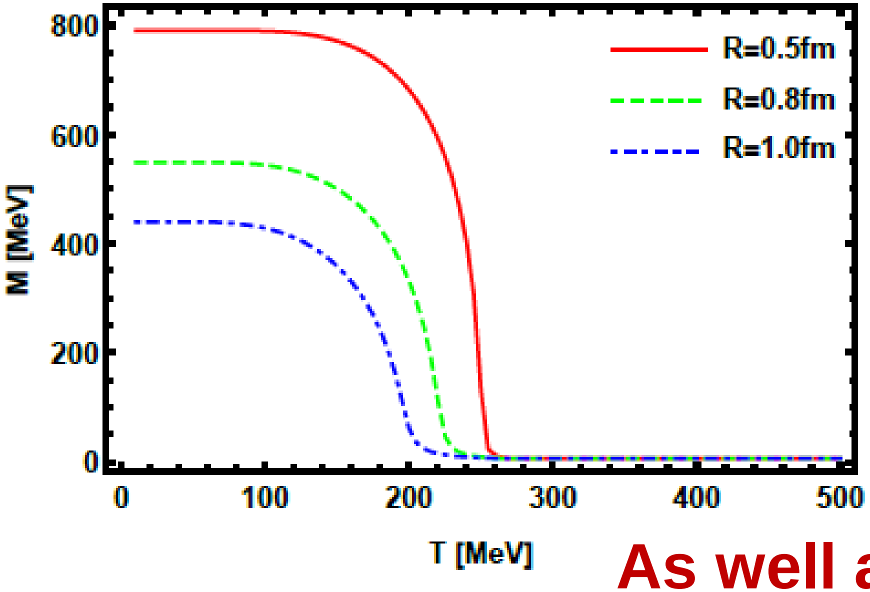
$$R \sim 1/\sqrt{eB}$$

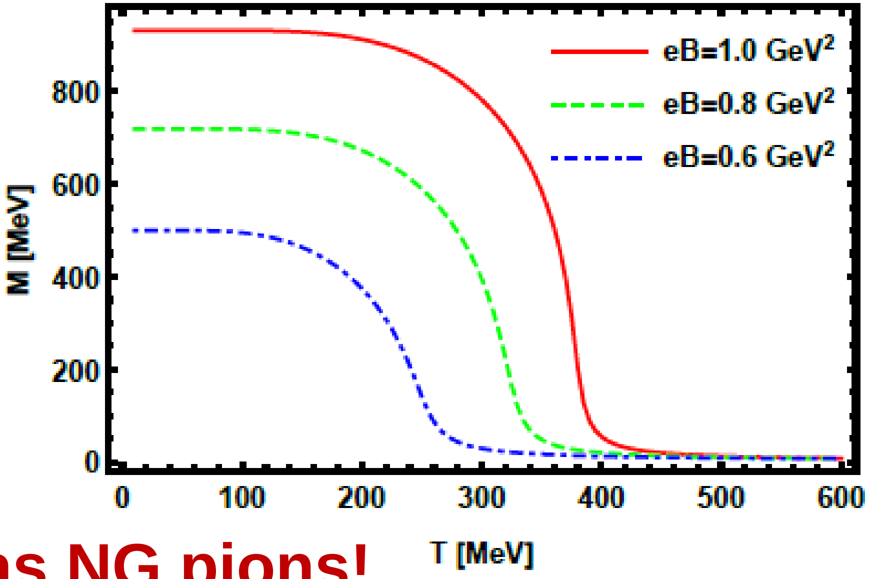
Small size catalysis vs magnetic catalysis

$$\Omega = \frac{(M-m_0)^2}{4G} - \boxed{\frac{2N_cN_f}{R^2}} \int \frac{dp_z}{2\pi} \left\{E + 2T\ln(1+e^{-\frac{E}{T}})\right\}$$

$$R \sim 1/\sqrt{eB}$$

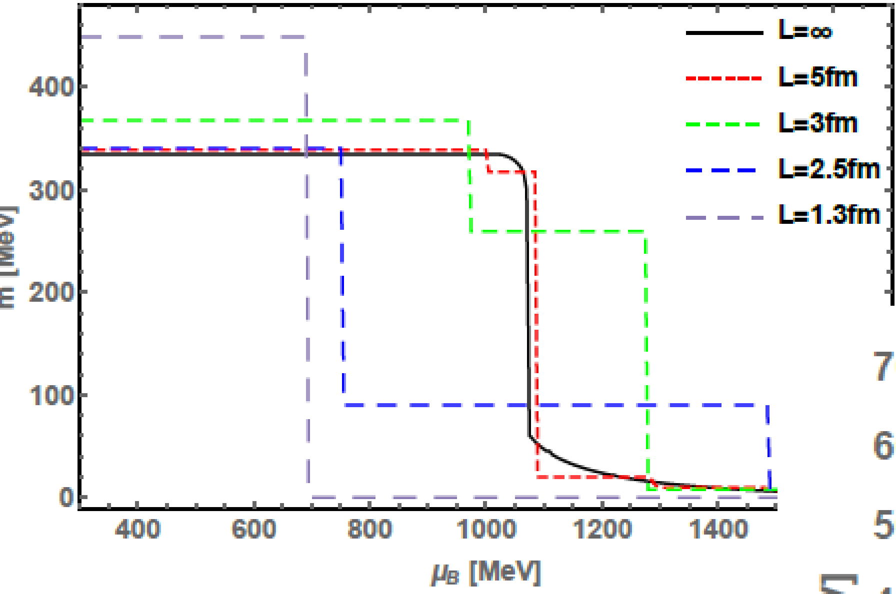
$$\Omega = \frac{(M-m_0)^2}{4G} - \boxed{N_c \sum_{f=u,d} \frac{|q_f B|}{2\pi}} \int \frac{dp_z}{2\pi} \left\{E + 2T\ln(1+e^{-\frac{E}{T}})\right\}$$



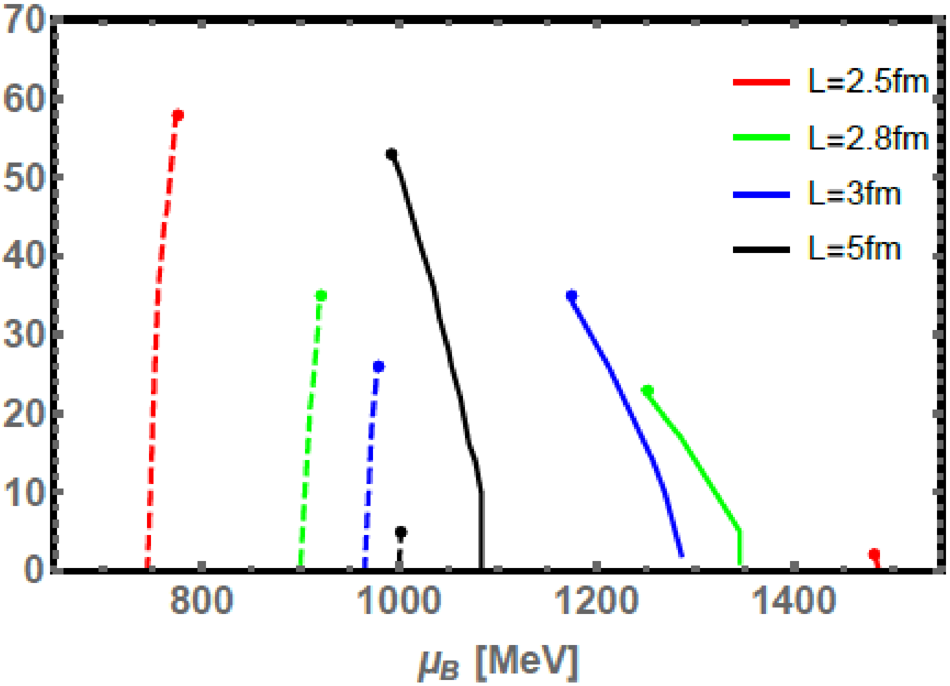


As well as NG pions!

Quantized 1st-order phase transition and two sets of CEP!

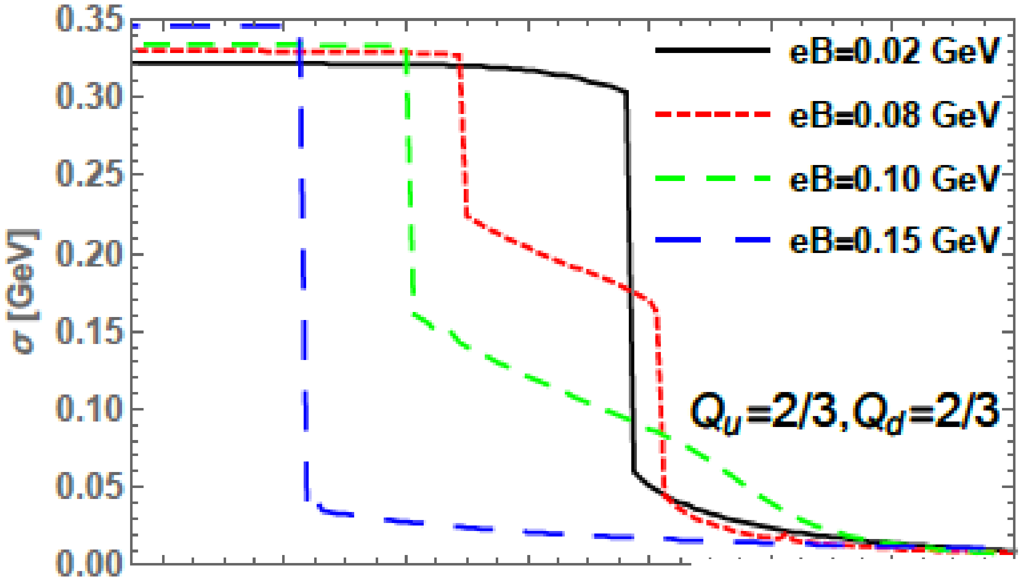


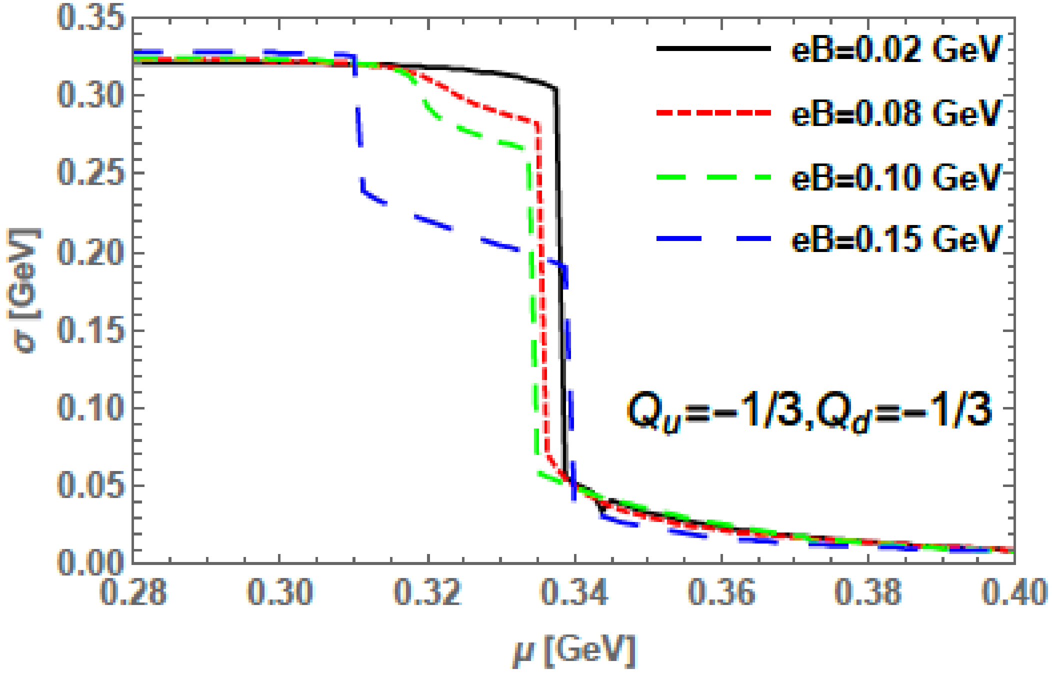
Zero mode contribution dominant at small size!



Kun Xu, M.H., arXiv:1903.08416, 1904.1154

Phase transition under B revisited!

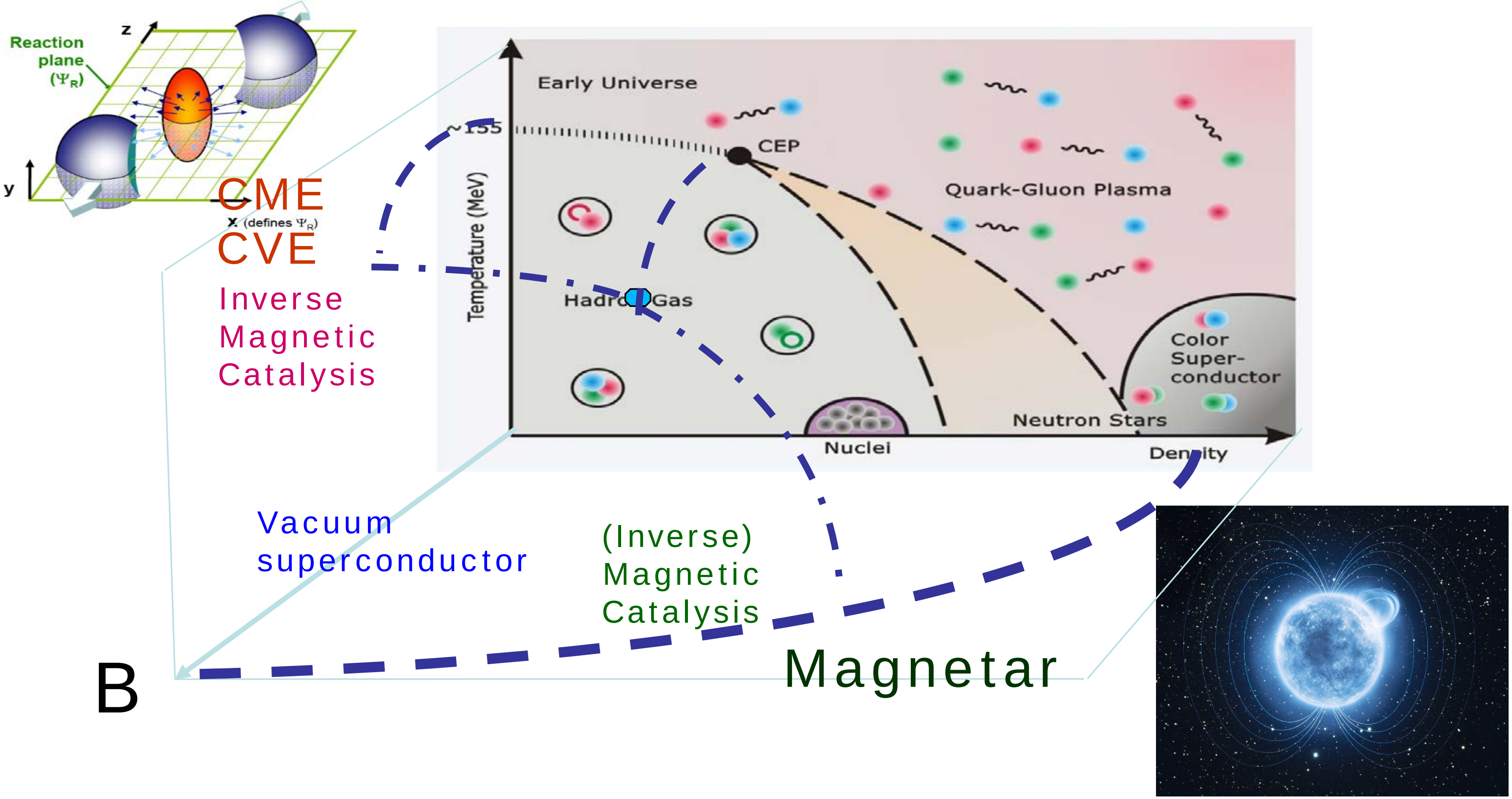




Quantized 1st-order phase transition and two sets of CEP for each flavor under B!

Kun Xu, M.H., in progress!

IV. Summary



CME

CVE

Inverse Magnetic Catalysis

Vacuum superconductor

(Inverse) Magnetic Catalysis

Magnetar

B

Still lots of open questions remain !

No much conclusive statement we can make!

Thanks for your attention!