From little bang to big bang: imprints of QCD epoch in the early universe?

Mei Huang 黄梅

中国科学院大学
University of Chinese Academy of Sciences

第十六届 粒子物理、核物理和宇宙学交叉学科前沿问题研讨会，天津，2023年6月30日-7月4日

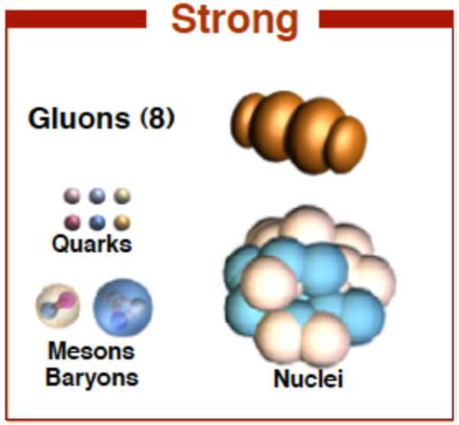
I. A short review on QCD phase transitions

II. Imprints of QCD epoch in the early universe?

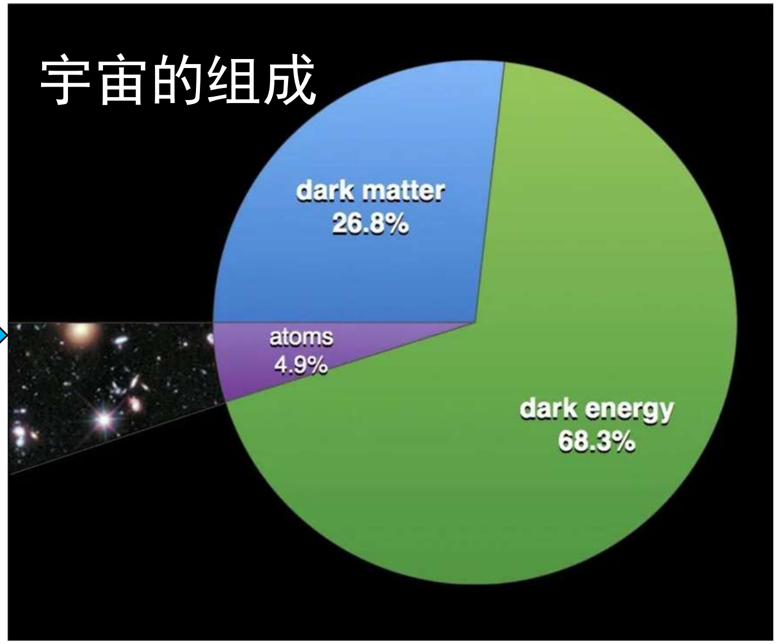
IV. Conclusion and outlook

A short review on QCD phase transitions

Quantum
Chromodynamics (QCD)



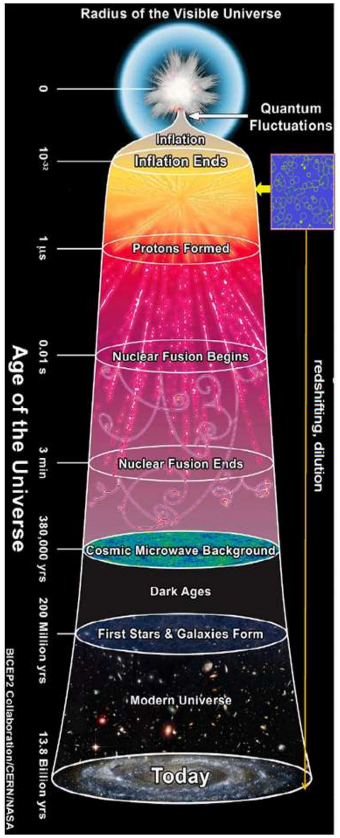
99% of Visible matter

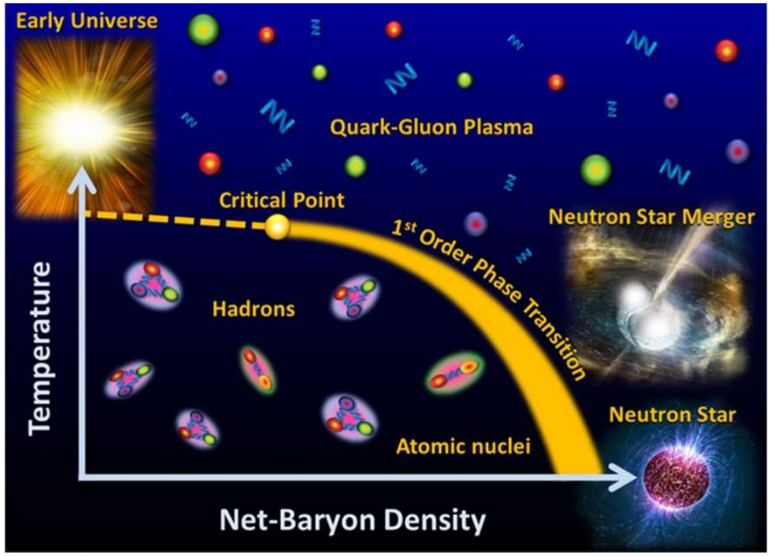


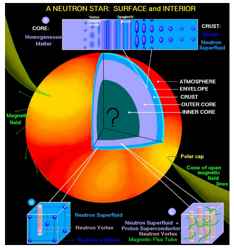
Origin of mass: spontaneous chiral symmetry breaking

QCD matter and phase structure

Early universe







Compact stars

What are the new state of matter at exceedingly
high density and temperature?
How were the elements from iron to uranium made?

Connecting Quarks with the Cosmos

Eleven Science Questions for the New Century

QCD phase structure at finite temperature

Chiral phase transition: **light quark** m=0

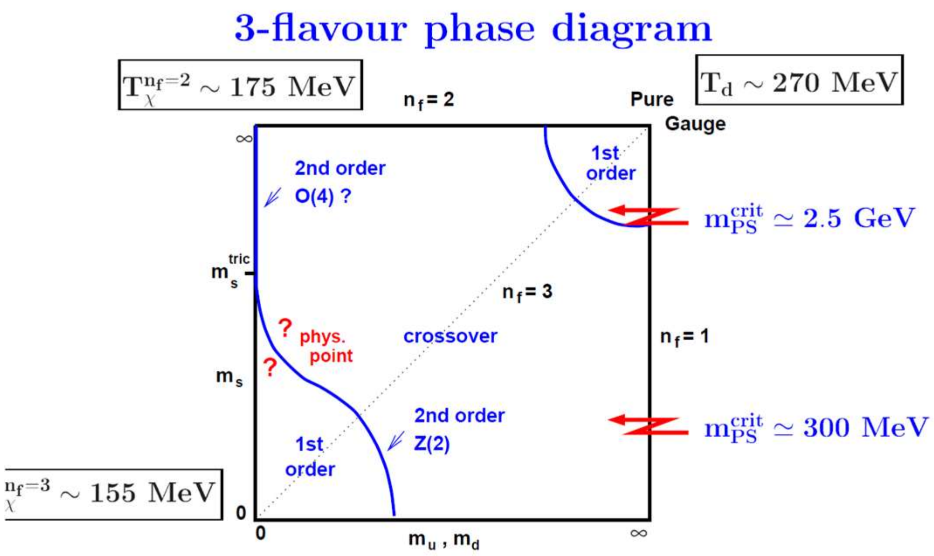
Chiral condensate $\langle\bar{\psi}\psi\rangle$

Deconfinement phase transition: **heavy quark limit** for m= infinity

Polyakov loop $$L(\vec{x}) = \frac{1}{N_c}\mathrm{tr}\,\mathcal{P}(\vec{x}) \text{ with } \mathcal{P}(\vec{x}) = \mathrm{P}\, e^{ig\int_0^\beta dt\, A_0(t,\vec{x})}$$

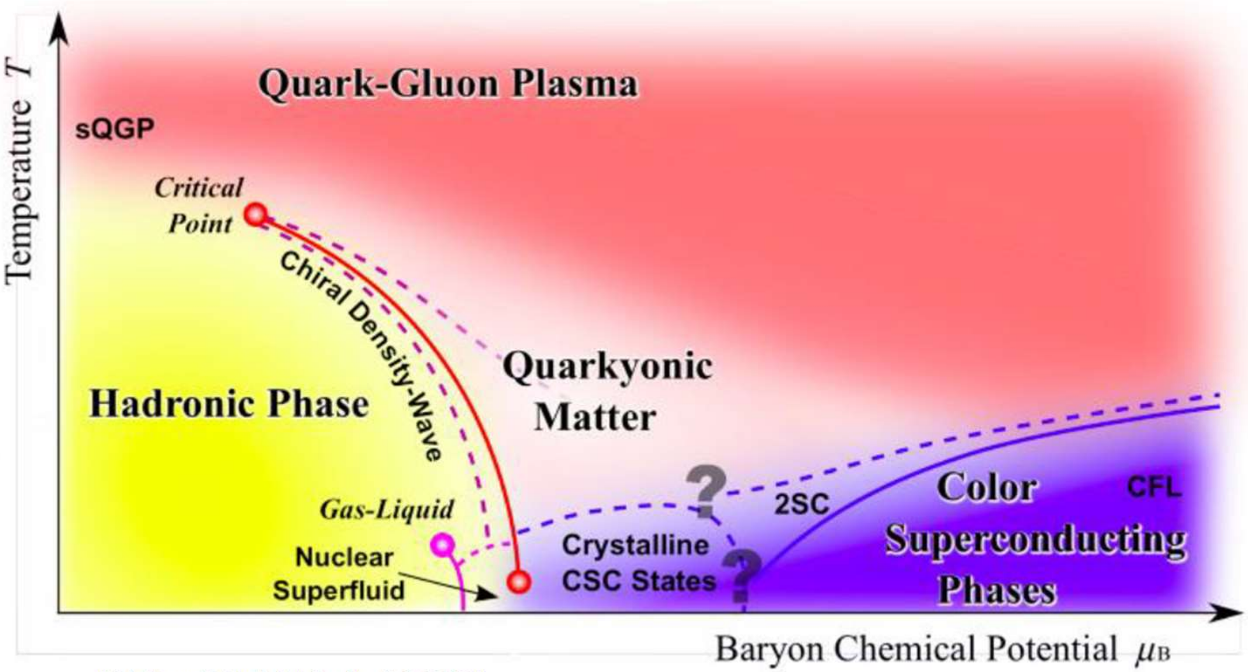
$$\langle L(\vec{x})\rangle \sim \exp(-\beta F_q)$$

Columbia plot:



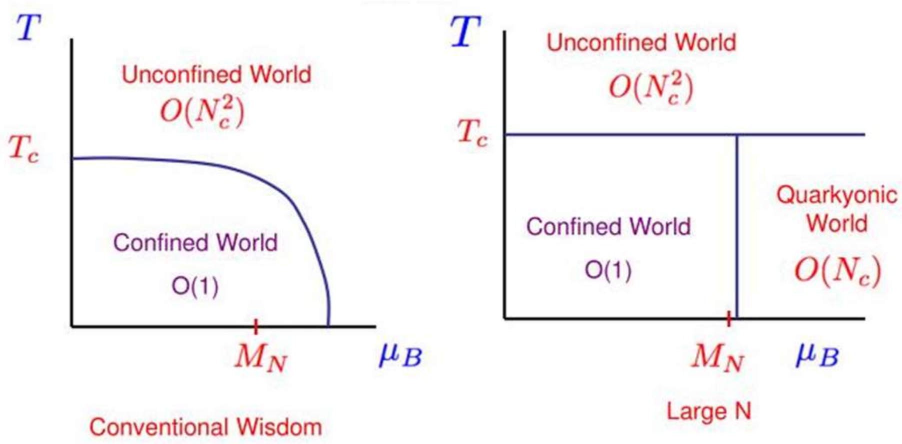
Karsch, F.
Lect. Notes Phys. 2002, 583, 209–249, 215
[hep-lat/0106019]

QCD phase structure at finite baryon chemical potential



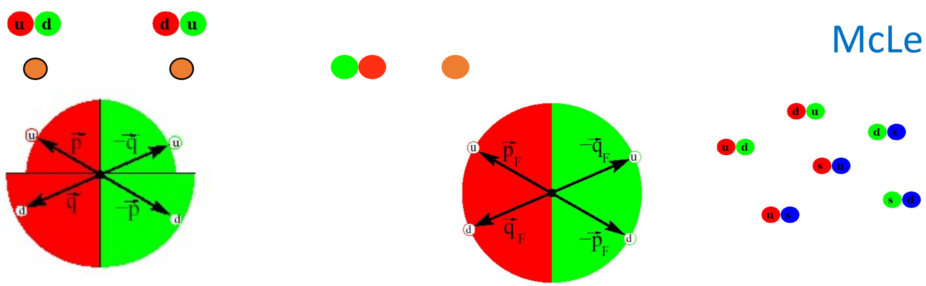
K. Fukushima and T. Hatsuda, Rept. Prog. Phys. 74, 014001(2011); arXiv: 1005.4814

Quarkyonic matter



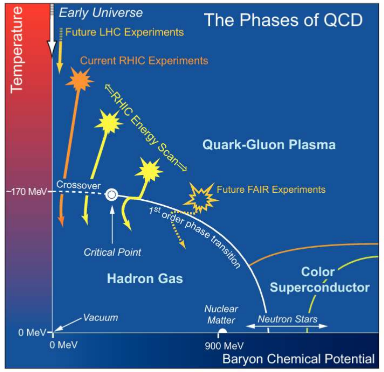
Separation of quark dynamics and gluodynamics?

McLerran, Pisarski, Nucl. Phys. A 796 (2007) 83.

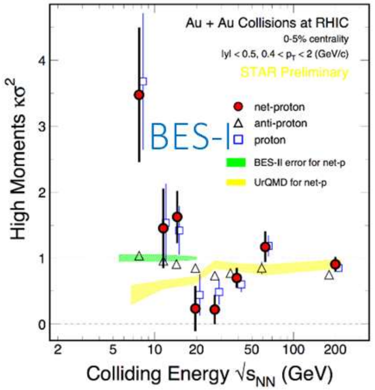


QCD phase structure at finite baryon chemical potential

CEP searching at HICs

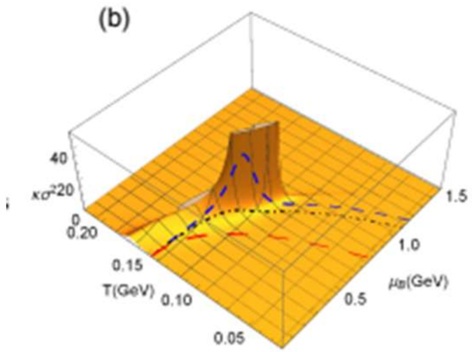


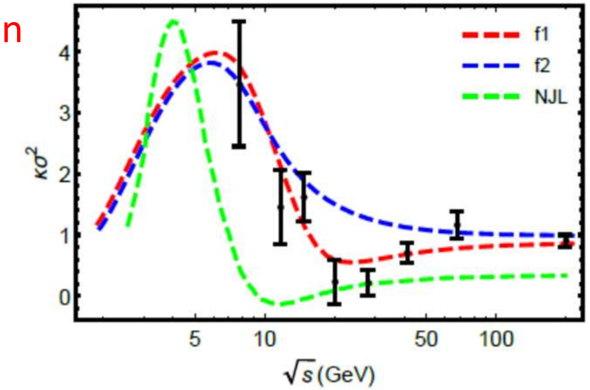
Kurtosis 峰度



STAR: **PRL112**, 32302(14);

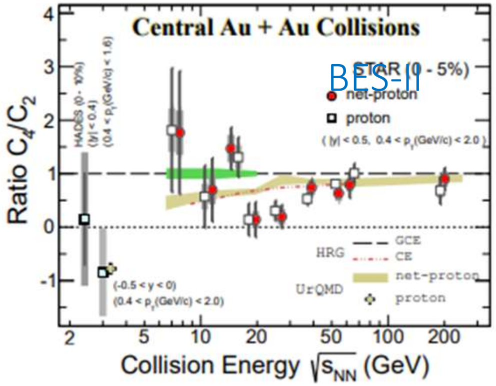
CEP of chiral phase transition



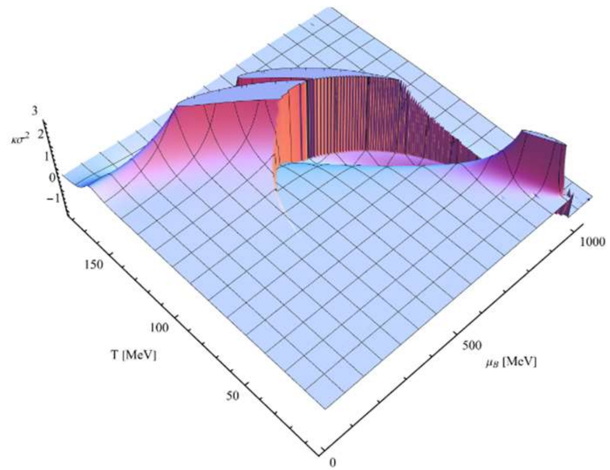


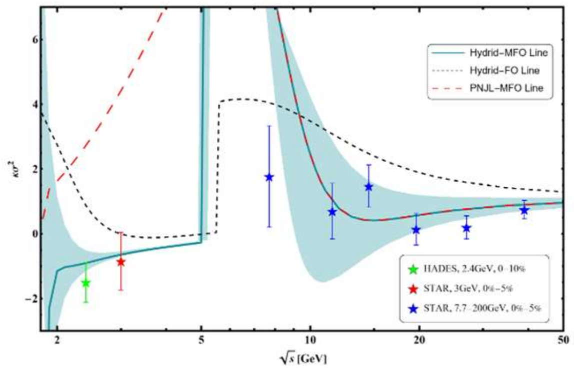
Z.B.Li et.al, Chin.Phys.C 42 (2018) 1, 013103； EPJC 79，2019

CEP of chiral phase transition meets CEP of nuclear liquid-gas phase transition!



STAR: Phys. Rev. Lett. 128 (2022) 202303

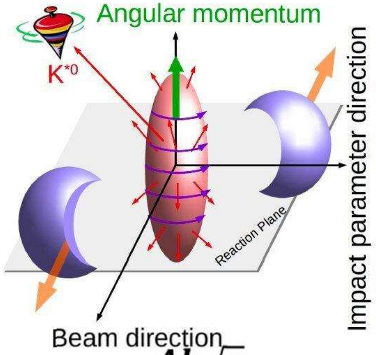




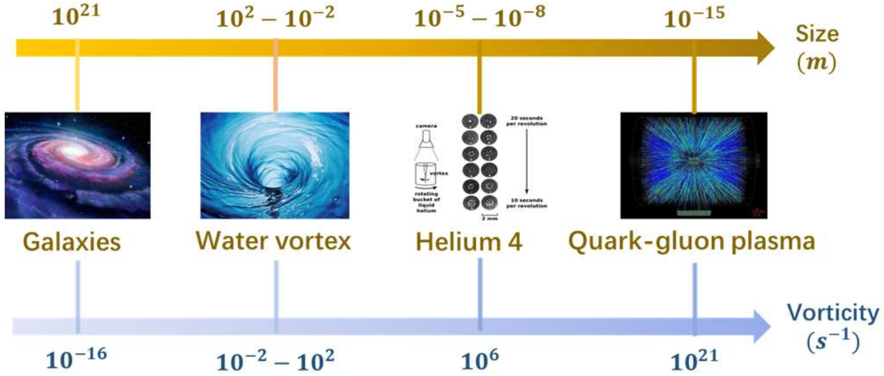
Kun Xu, Mei Huang, to appear soon

QCD phase structure under strong magnetic field and rotation

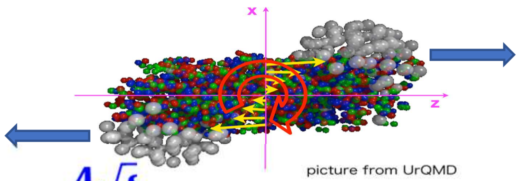
非对心重离子碰撞产生地表最强磁场最快转动的环境



$$L_0 \sim \frac{Ab\sqrt{s}}{2} \sim 10^6\hbar$$

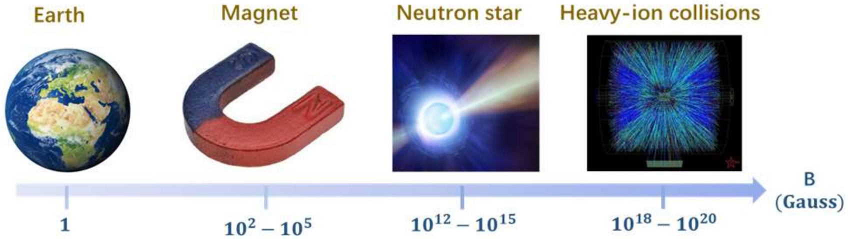


$$\omega \sim 10^{22}\,\mathrm{s}^{-1}$$



$$P_z \sim \frac{A\sqrt{s}}{2}$$

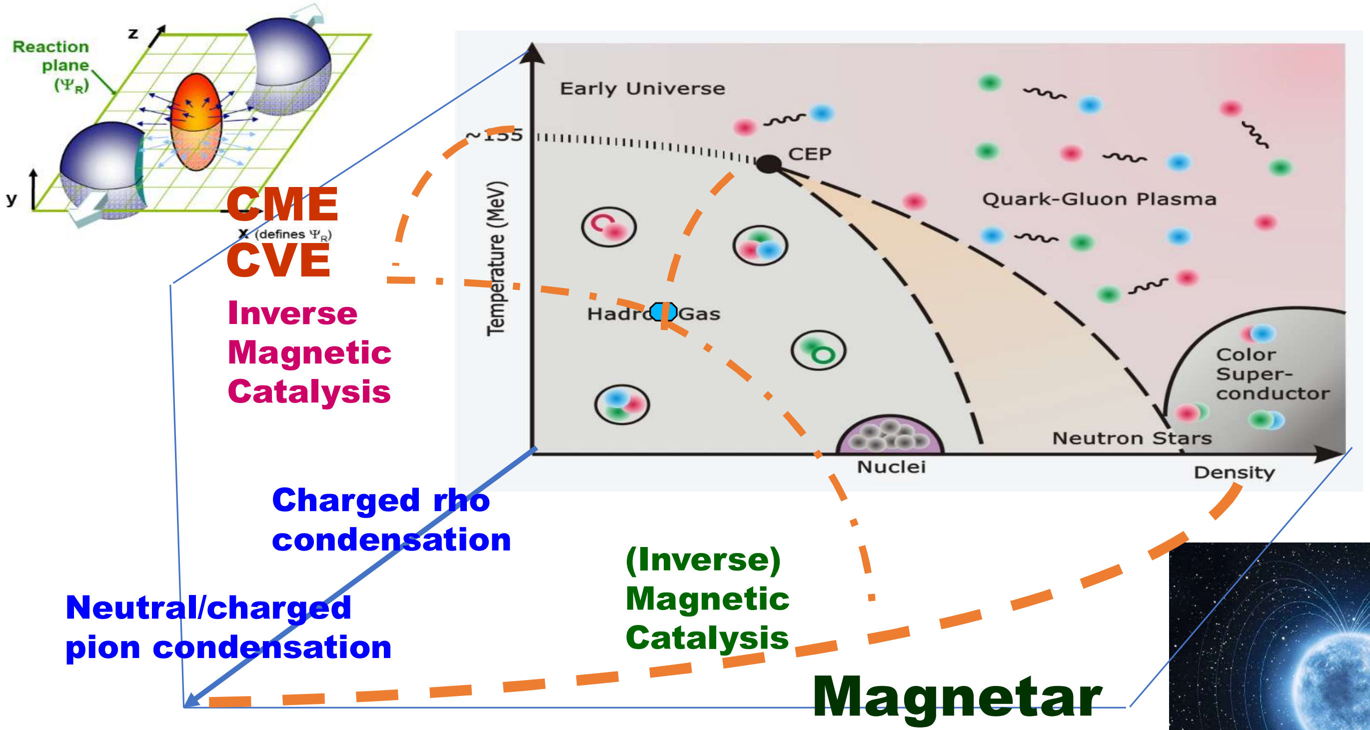
$$eB \sim \gamma\alpha_{\mathrm{EM}}\frac{Z}{b^2} \sim 10^{18}\ \mathrm{G}$$

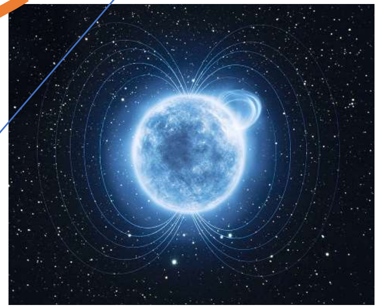


磁场强度 $\langle|B_y|\rangle \sim 10^{18-20}G$

from Xuguang's slides

QCD phase structure under strong magnetic field and rotation



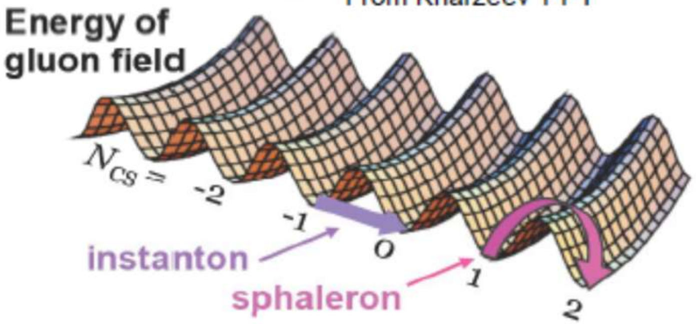


$$\mathbf{B}, \mathbf{E}\cdot\mathbf{B}, \boldsymbol{\omega}, \mu_{\mathrm{I}}, \boldsymbol{L}$$

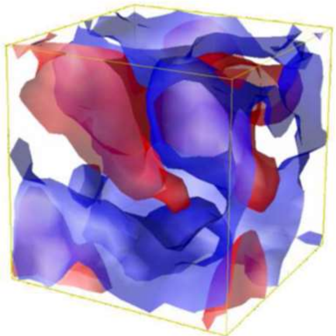
Theta vacuum, instantons and sphalerons

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

From Kharzeev' PPT



Buividovich et al. arXiv:1111.6733



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

Induce chirality imbalance: local PV and CPV

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

Sphaleron diffusion rate at finite T: variation of topological number per unit time and per unit volume

$$\Gamma_{ss} \sim T^4$$

$$\Gamma_{ss} \sim (g^2 T)^4$$

$$\Gamma_{ss} \sim g^4 \log(1/g^2) T (g^2 T)^3$$

$$\frac{\partial n_5}{\partial t} = (4N_f)^2 \frac{\Gamma_{ss}}{T}\frac{\partial F}{\partial n_5}$$

$$n_5 = \frac{\mu_5^3}{3\pi^2} + \frac{\mu_5 T^2}{3}.$$

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

$$\langle n_5 \rangle = 0 \text{ but } \langle n_5^2 \rangle \neq 0.$$

Khlebnikov, Shaposhnikov 1988, Bodeker,1998, Son, Starinets 2002

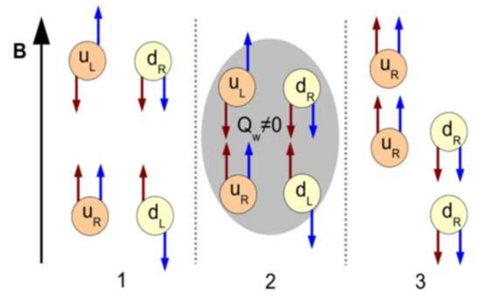
S. Y. .Khlebnikov and M. E. Shaposhnikov, Nucl. Phys. B **308**, 885 (1988).
G. D. Moore, C. -r. Hu and B. Muller, Phys. Rev. D **58**, 045001 (1998); G. D. Moore and M. Tassler, JHEP **1102**, 105 (2011).

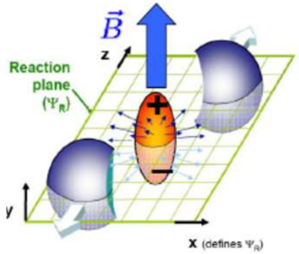
Chiral Magnetic Effect reveals the topology of gauge fields in heavy-ion collisions

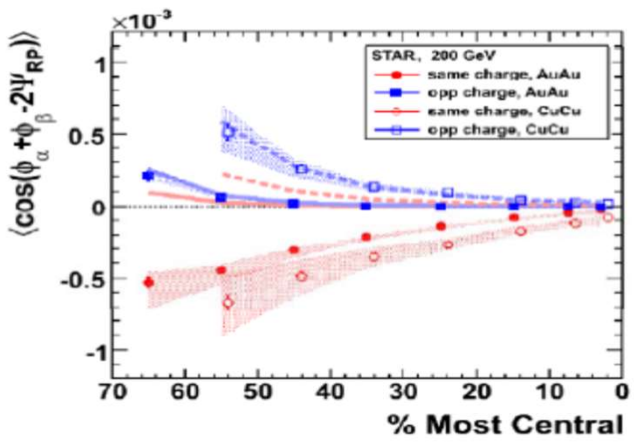
Kharzeev,Liao, 2021, Nature Rev.Phys. 3 (2021) 1, 55-63

Fukushima,Kharzeev,Warringa 2008

CME ⟷ Charge Separation







STAR Collaboration PRL103(2009)251601

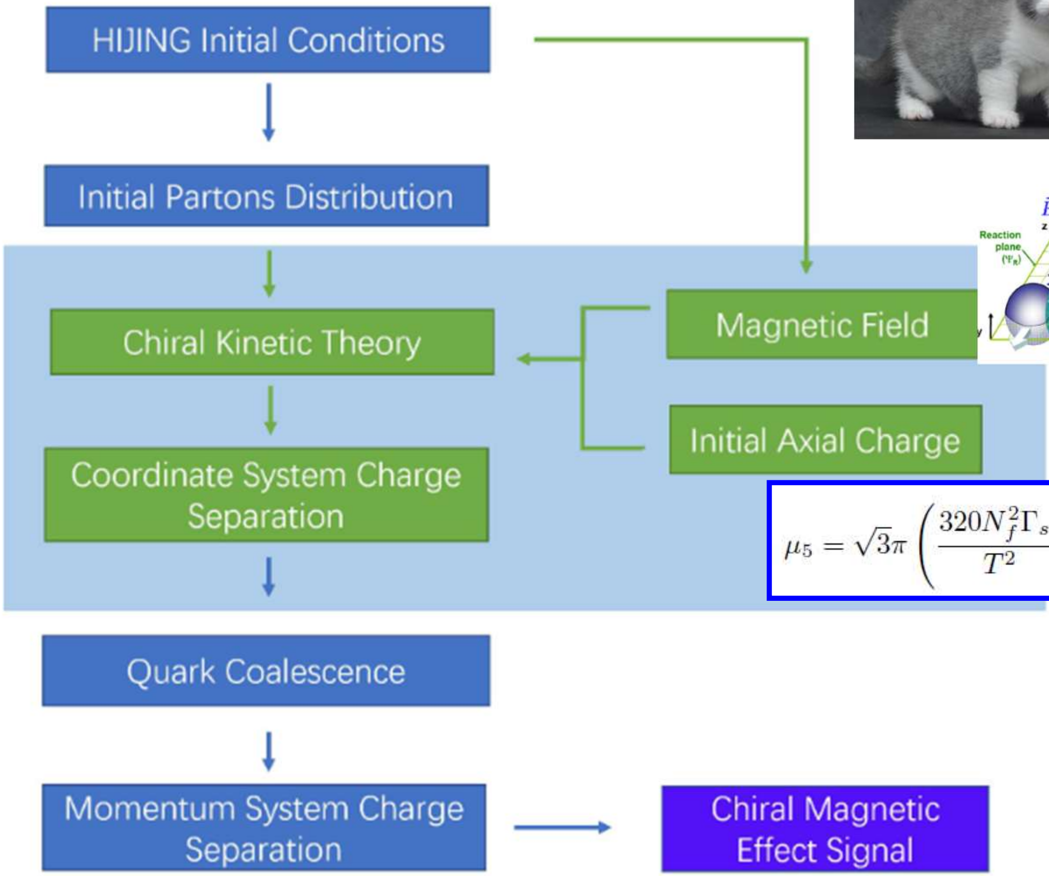
Dmitri Kharzeev

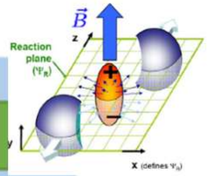
Update: Chiral Magnetic Effect has not been confirmed from HICs!

Chiral Magnetic Effect reveals the topology of gauge fields in heavy-ion collisions

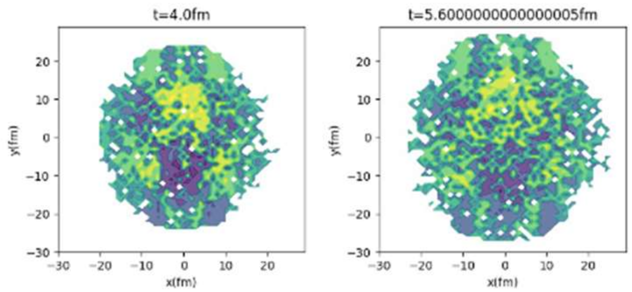
Zilin Yuan@UCAS et al, Chiral anomaly Transport (CAT) to appear!

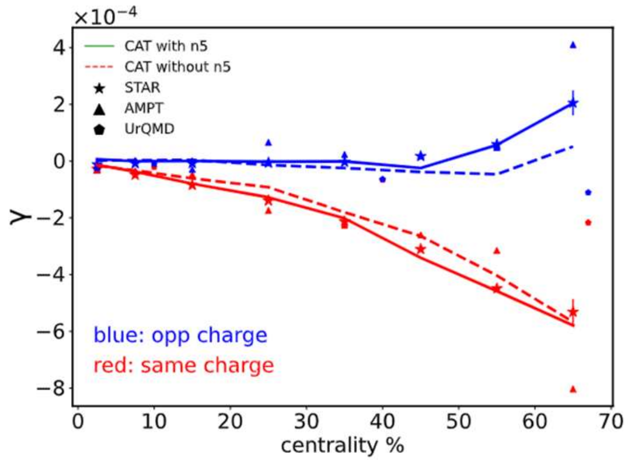
国科大猫





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



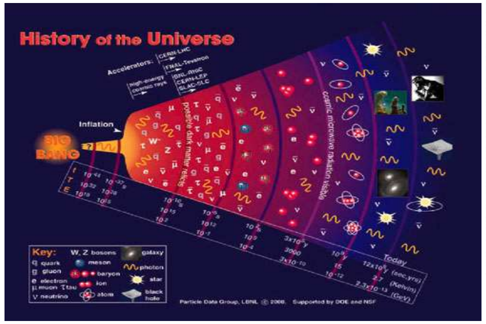


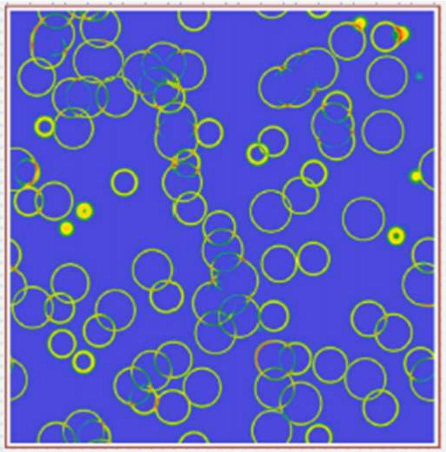
Zilin Yuan@UCAS et al, in preparation!

Chirality imbalance explains exp. measurement!

Imprints of QCD epoch in the early universe?

GWs, Primordial Black holes,……



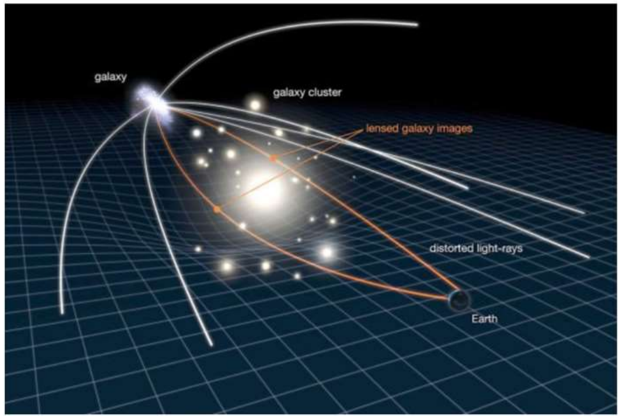


Hindmarsh, et al, 2015

GWs $\Box h_{ij} \sim T_{ij}$

1st order PT in QCD epoch:

1,pure gluon system,
2,Topological phase transition



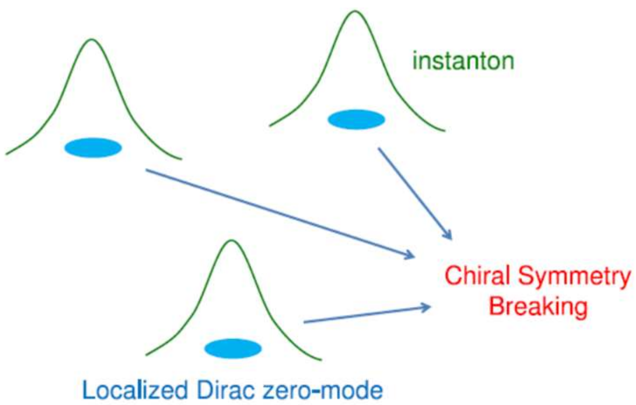
PBHs

$$R_S \equiv 2GM/c^2.$$

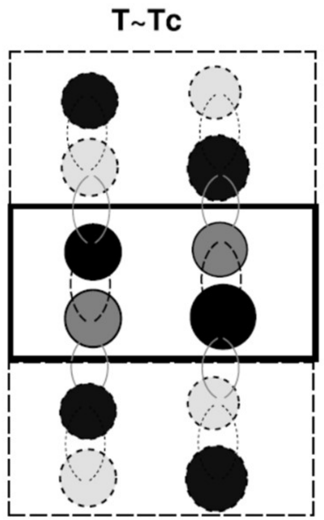
$$\frac{d^2\delta}{dt^2} + 2H\frac{d\delta}{dt} + \left(\frac{k^2 v_s^2}{a^2} - 4\pi G\rho\right)\delta = 0$$

Chirality imbalance induced by instanton anti-instanton molecule pairing:

T. Schafer, E. V. Shuryak and J. J. M. Verbaarschot, Phys. Rev. D **51**, 1267 (1995) [hep-ph/9406210].



$$\mathcal{L}_{mol\ sym} = G\left\{ \frac{2}{N_c^2}\left[(\bar\psi\tau^a\psi)^2 - (\bar\psi\tau^a\gamma^5\psi)^2\right] - \frac{1}{2N_c^2}\left[(\bar\psi\tau^a\gamma^\mu\psi)^2 + (\bar\psi\tau^a\gamma^\mu\gamma^5\psi)^2\right] + \frac{2}{N_c^2}(\bar\psi\gamma^\mu\gamma^5\psi)^2 \right\} + \mathcal{L}_8\ ,$$



$T \gtrsim T_c$:

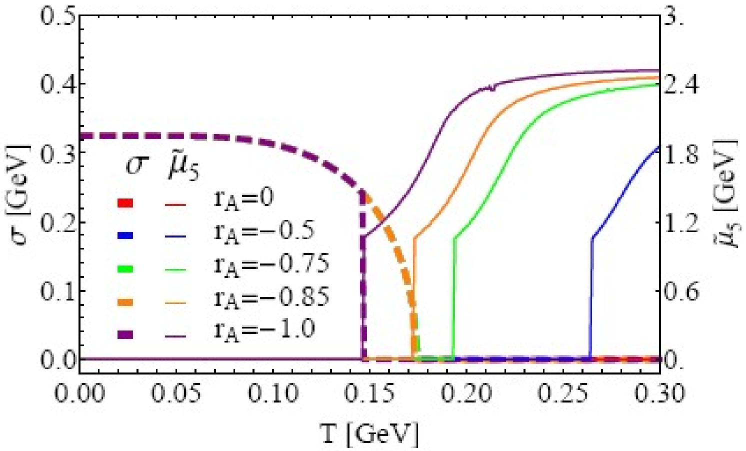
$$G_S = \frac{2G}{N_c^2},\ G_V = \frac{G}{2N_c^2},\ G_A = -\frac{3G}{2N_c^2}$$

$$\mathcal{L} = \bar\psi i\gamma_\mu D^\mu\psi + G_S\left[(\bar\psi\psi)^2 + (\bar\psi i\gamma^5\boldsymbol{\tau}\psi)^2\right] - G_V(\bar\psi\gamma^\mu\psi)^2 - G_A(\bar\psi\gamma^\mu\gamma^5\psi)^2\ .$$

Negative axial vector interaction spontaneously induces chirality imbalance

$$\tilde\mu_5 = -2G_A\langle\bar\psi\gamma^0\gamma^5\psi\rangle$$

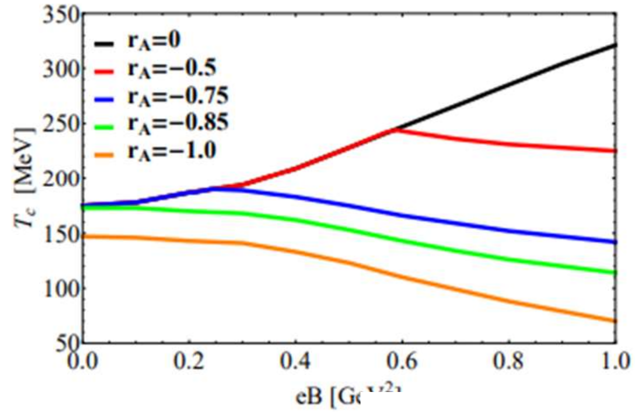
Spontaneous generation of CP-violation above Tc even at zero magnetic field, 1st order phase transition ！

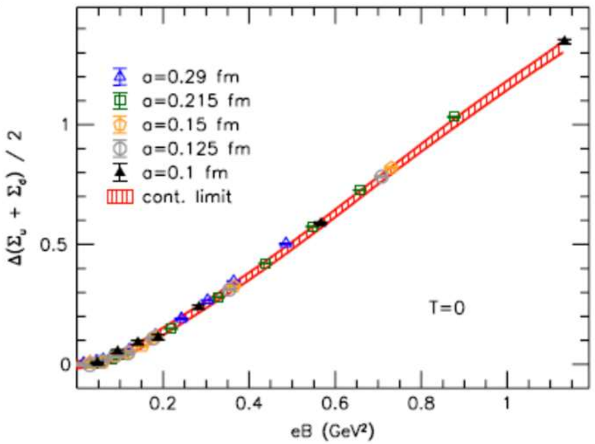


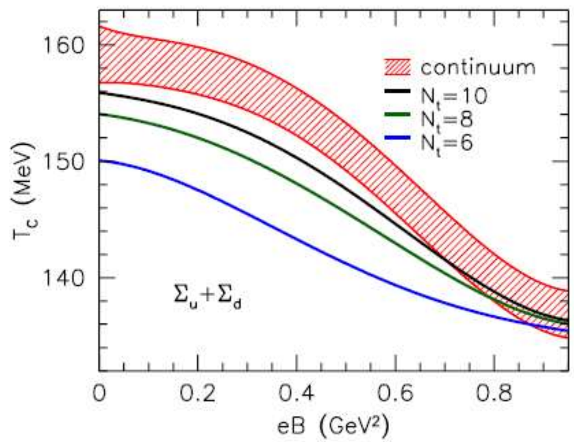
(a) σ and $\tilde{\mu}_5$ at $eB = 0$ for different values of r_A.

Lang Yu, Hao Liu, MH, arXiv:1404.6969, PRD90,074009(2014)

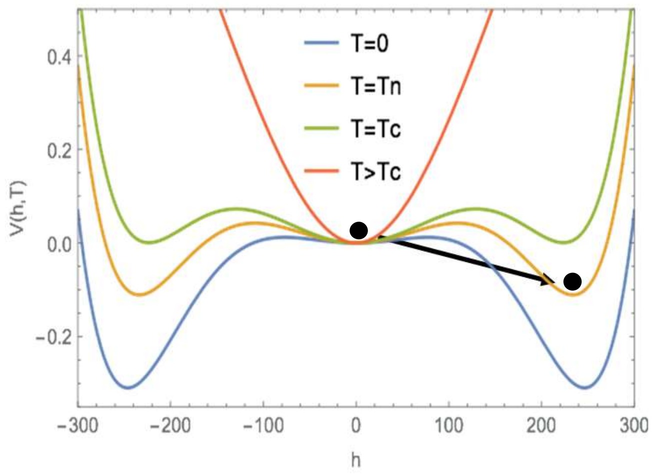
Magnetic Catalysis and Inverse magnetic catalysis







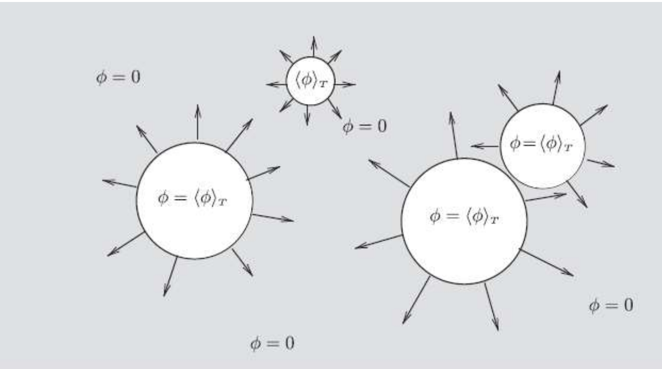
Bali et.al. arXiv:1206.4205 [hep-lat]



Bounce solution

$$S_3(T) = \int 4\pi r^2 dr \left[\frac{1}{2}(\frac{d\phi_b}{dr})^2 + V(\phi_b, T)\right]$$

$$\lim_{r\to\infty} \phi_b = 0 \ , \qquad \frac{d\phi_b}{dr}|_{r=0} = 0$$



Bubble nucleation

$$\Gamma \approx A(T) e^{-S_3/T} \sim 1$$

PT strength

$$\alpha \equiv \frac{1}{\rho_r}\left(\Delta V_{\rm eff}(\phi, T) - \frac{T}{4}\Delta \frac{\partial V_{\rm eff}(\phi, T)}{\partial T}\right)$$

Phase transition inverse duration

$$\frac{\beta}{H_n} = T\frac{d(S_3(T)/T)}{dT}|_{T=T_n}$$

Jingdong Shao, Mei Huang,e-Print: 2209.13809 [hep-ph], Phys.Rev.D 107 (2023) 4, 043011

B/GeV^2	r_A	T_n/GeV	α	β/H_*
0	−0.3	0.3648	0.7343	27582
0	−0.5	0.2561	1.741	16274
0	−0.8	0.1679	4.850	6105.7
0.3	−0.3	0.3634	0.7727	30478
0.3	−0.5	0.2535	1.790	14660
0.3	−0.8	0.1635	5.375	12028
0.5	−0.3	0.3517	0.7384	22859
0.5	−0.5	0.2393	1.745	11136
0.5	−0.8	0.1389	8.364	2579.0
0.8	−0.3	0.3402	1.166	25235
0.8	−0.5	0.2126	2.633	11171
0.8	−0.8	0.1079	28.67	2819.5

TABLE I: Nucleation temperature T_n, parameters α and β corresponding to different values of r_A and eB.

Huge β/H : 10^4 rare case!

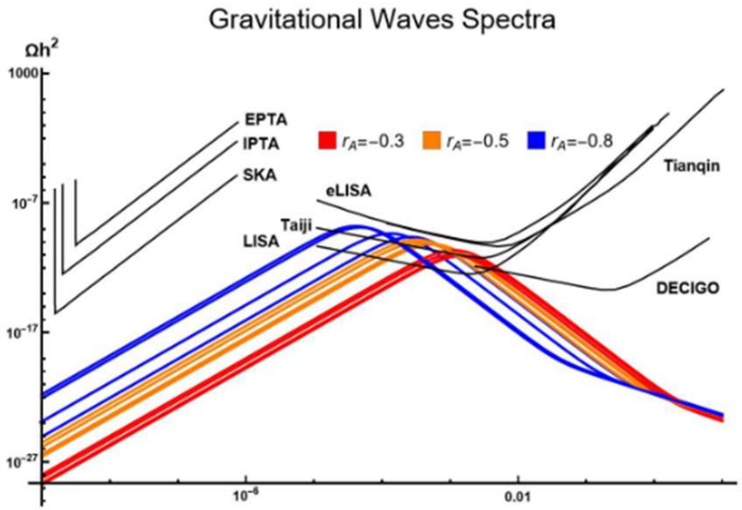
The typical value β/H from EW: 1-100

The parameter β/H describes the duration and the number of nucleated bubbles the phase transition generates, and is evaluated when the phase transition has completed, i.e. at the percolation temperature Tp. large

Delayed phase transition, Liu et al. 2106.05637, small β/H is required!

Huge β/H : 10^4

Thin-wall approx	QCDPT	EWPT
α	4-6	0.4-0.6
β/H	30000-60000	6000-20000
v_w	0.04	0.1



(a) Gravitational waves spectra grouped by r_A.

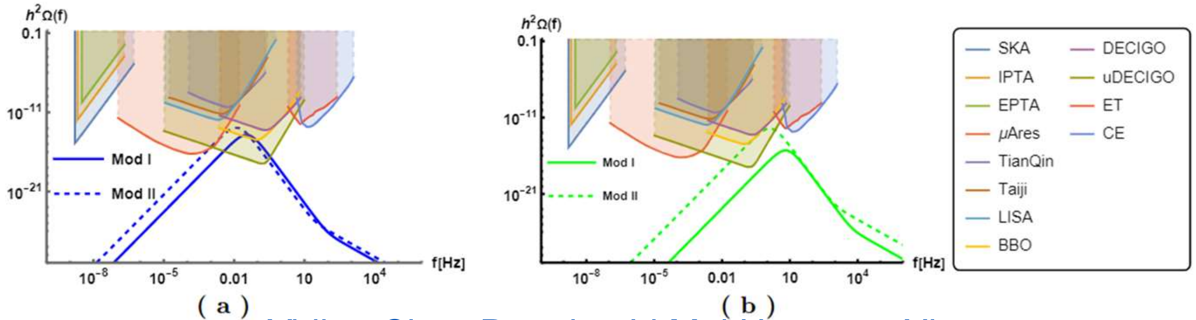
Jingdong Shao, Mei Huang,e-Print: 2209.13809 [hep-ph]

Phys.Rev.D 107 (2023) 4, 043011

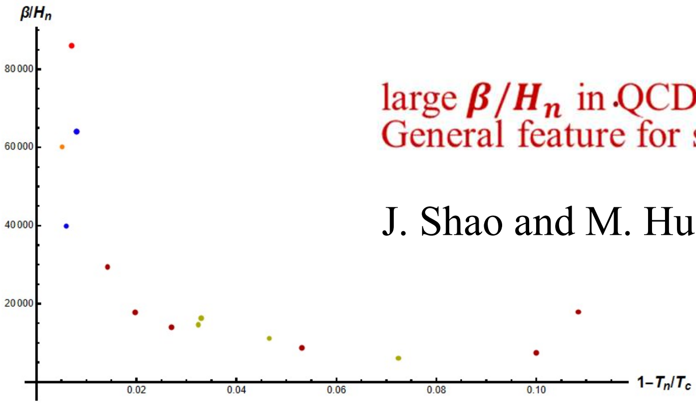
Holographic QCD method

Yidian Chen,Danning Li,Mei Huang, arXiv: 2212.06591

Enrico Morgante, Nicklas Ramberg, and Pedro Schwaller. Echo of the Dark: Gravitational Waves from Dark SU(3) Yang-Mills Theory. 10 2022.



Yidian Chen,Danning Li,Mei Huang, arXiv: 2212.06591



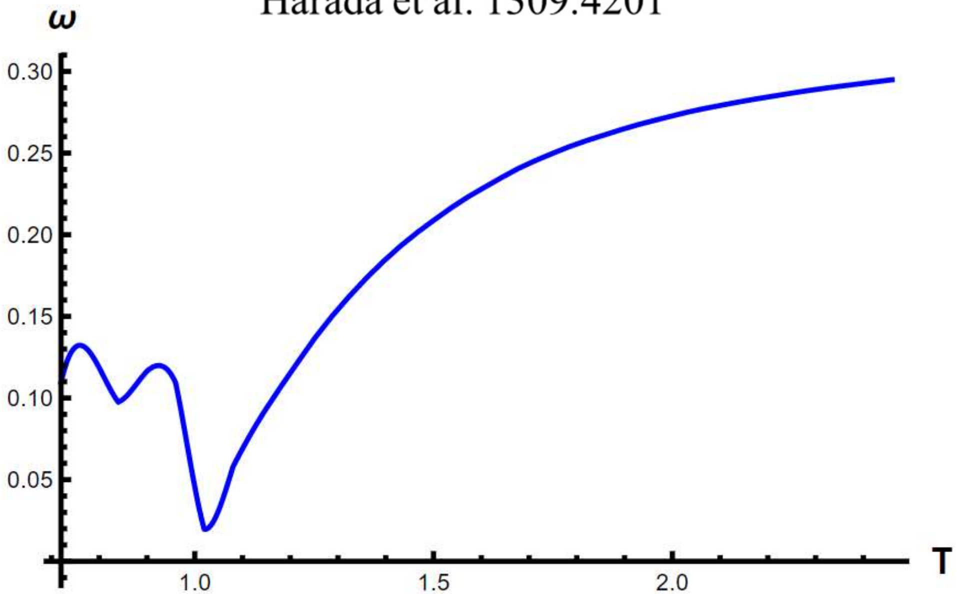
large β/H_n in QCD phase transitions!
General feature for strongly coupled system?

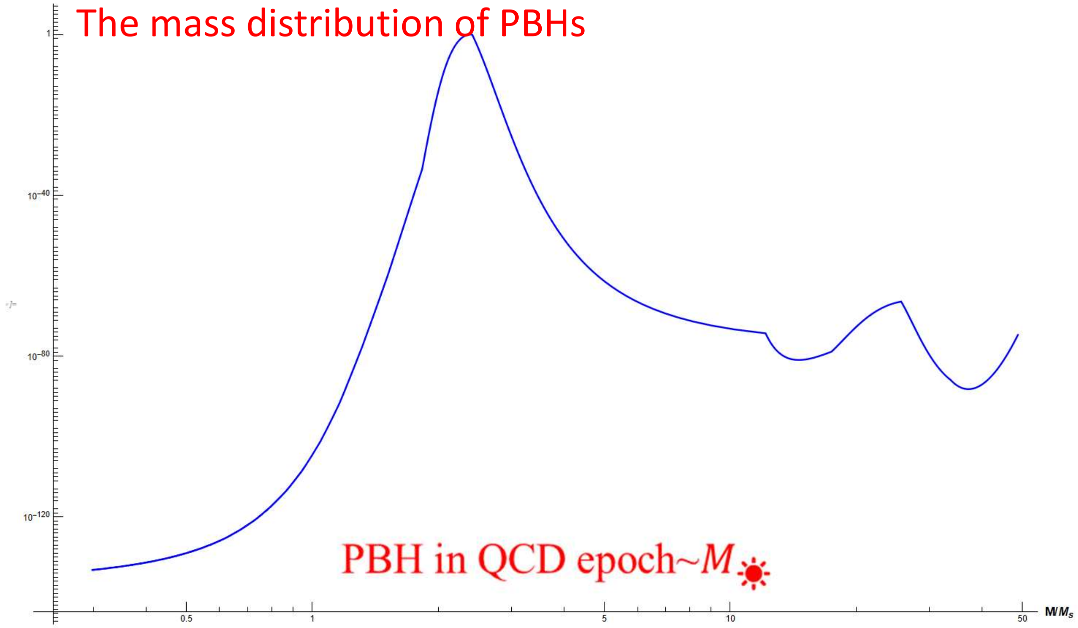
J. Shao and M. Huang, in preparation

Small sound velocity around Tc in 1st order QCD phase transitions gives the critical density perturbation for collapse!

$$w = \frac{p}{\rho} \qquad \delta_c = \frac{3+3w}{3+5w} sin^2(\pi \frac{\sqrt{w}}{1+3w})$$

Harada et al. 1309.4201





$\Omega_{PBH} \sim \mathbf{0.01} \Omega_{CDM}$

J. Shao and M. Huang, in preparation.

Future Work: From little bang to big bang
Possible observables of PV, CPV in QCD epoch from early universe? Role of QCD phase transition on the evolution of the early Universe?

$$\mathcal{L} = (1/4)f(\phi)(-F^2 + \gamma F\tilde{F})$$

$$S = \int d^4x\sqrt{-g}f(\phi)\left(-\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \frac{\gamma}{4}\tilde{F}^{\mu\nu}F_{\mu\nu}\right)$$