University of Chinese Academy of Sciences

中国科学院大学

夸克胶子等离子体中的手征效应
加一点脑洞

黄 梅

“极端等离子体：从夸克-胶子到聚变能”研讨会，复旦大学，上海，2025年8月12-13,

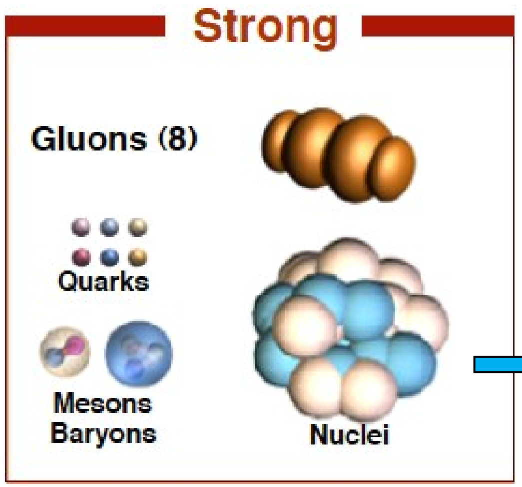
我与核聚变的一点关系

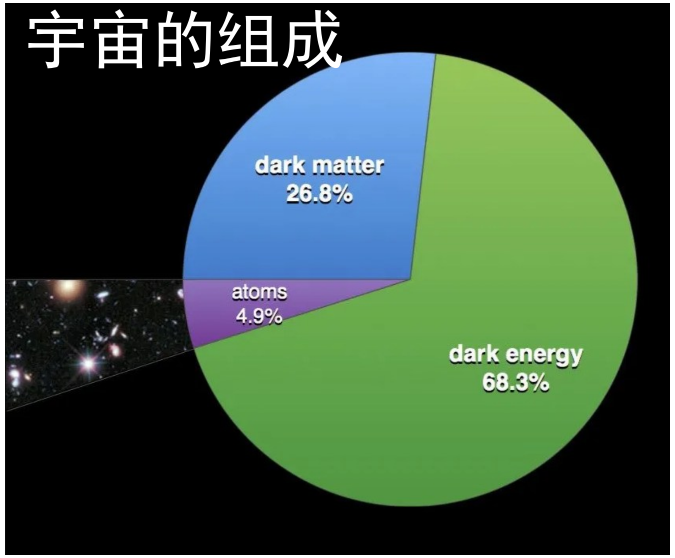
前排为于敏先生，

后排从左至右：赵维勤、张宗烨、赵恩广和吴慧芳（2016年）

相对论重离子对撞机产生小爆炸

量子色动力学QCD





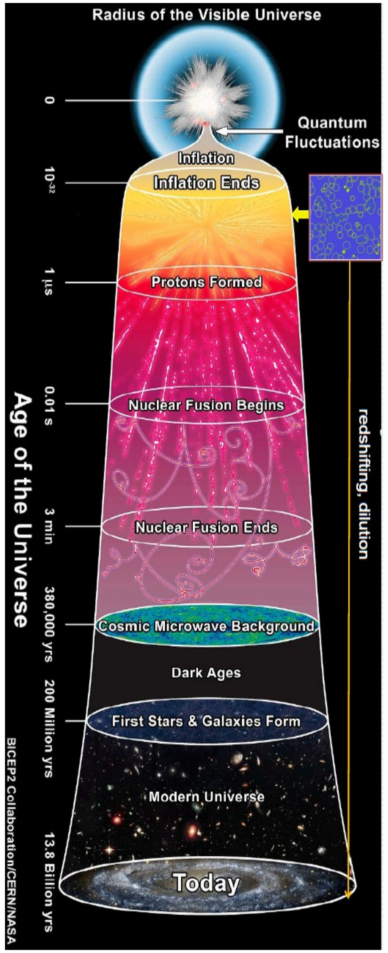
宇宙的可见物质占5%，这些可见物质的质量99%来自于强相互作用（QCD）的手征对称性自发破缺。

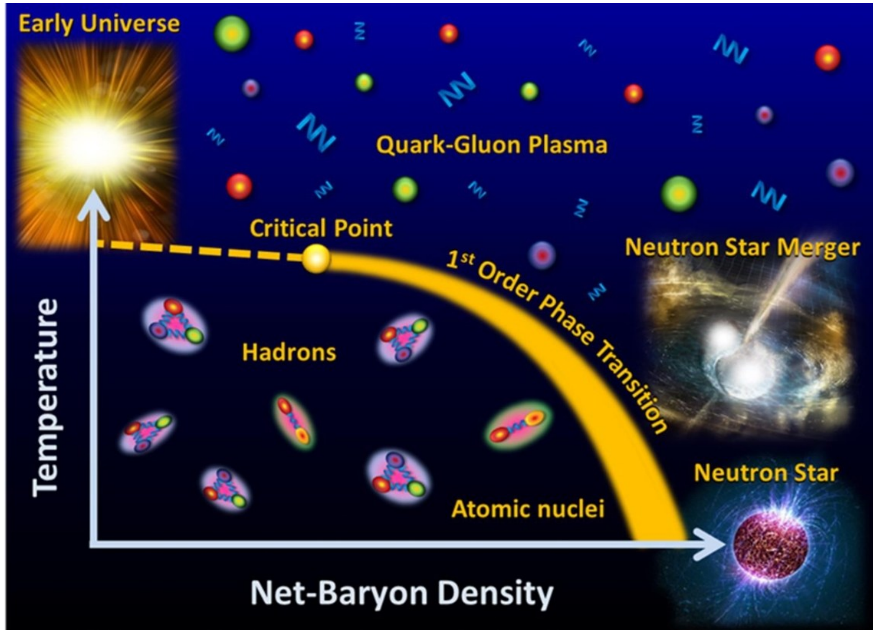
需要回答的基本问题：

质量起源，
宇宙起源和演化，
物质反物质不对称；
暗物质
……

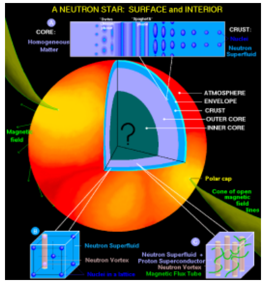
高温高密QCD相结构

宇宙早期



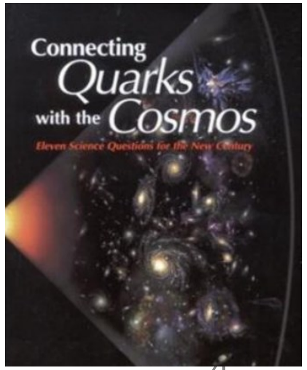


致密星体内部夸克物质



美国国家研究委员会由19名权威物理学家和天文学家联合执笔的2002年报告中列出了新世纪基础物理的最重要11个科学问题之一：

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



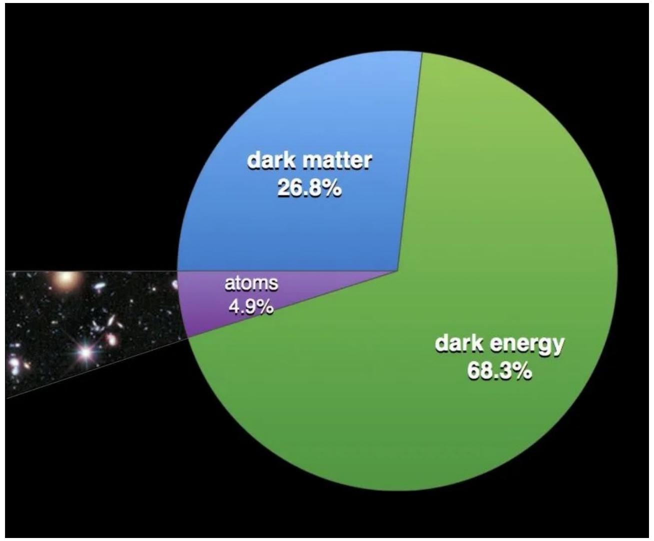
QCD: entanglement of quarks and gluons

Chiral phase transition:

quark-antiquark condensate (for m=0)

Chiral symmetry breaking: $\langle\bar{\psi}\psi\rangle \neq 0$

Chiral symmetry restoration: $\langle\bar{\psi}\psi\rangle = 0$



Deconfinement phase transition:

referring to the “permanent confinement”

Polyakov loop (for m= infinity)

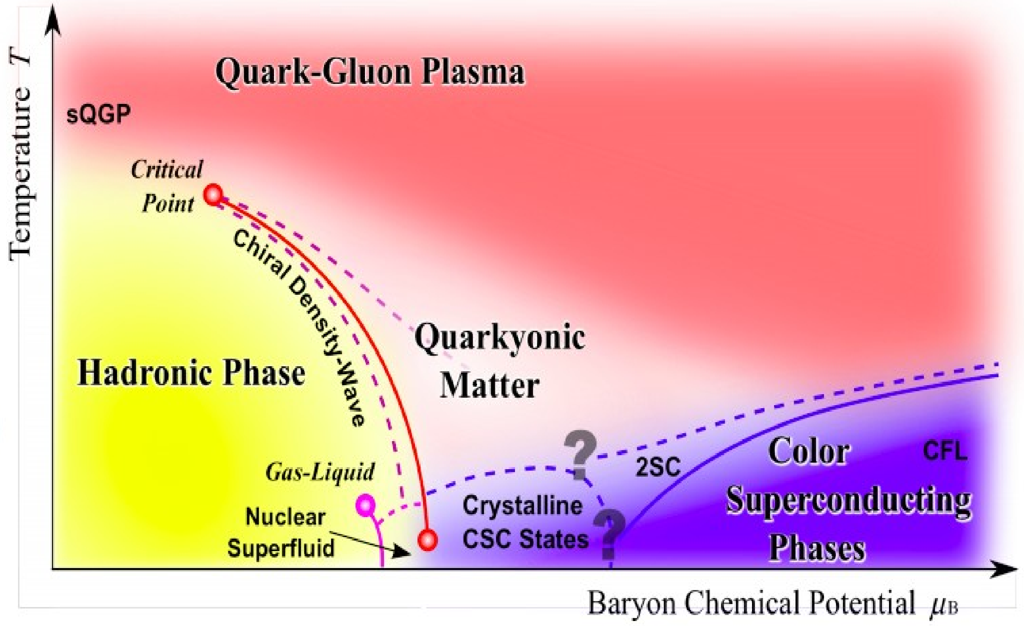
$$L(\vec{x}) = \frac{1}{N_c} \mathrm{tr}\, \mathcal{P}(\vec{x}) \text{ with } \mathcal{P}(\vec{x}) = \mathrm{P}\, e^{ig \int_0^\beta dt\, A_0(t,\vec{x})}$$

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

Confinement: center symmetric $\langle L\rangle = 0 \quad F_q \to \infty$

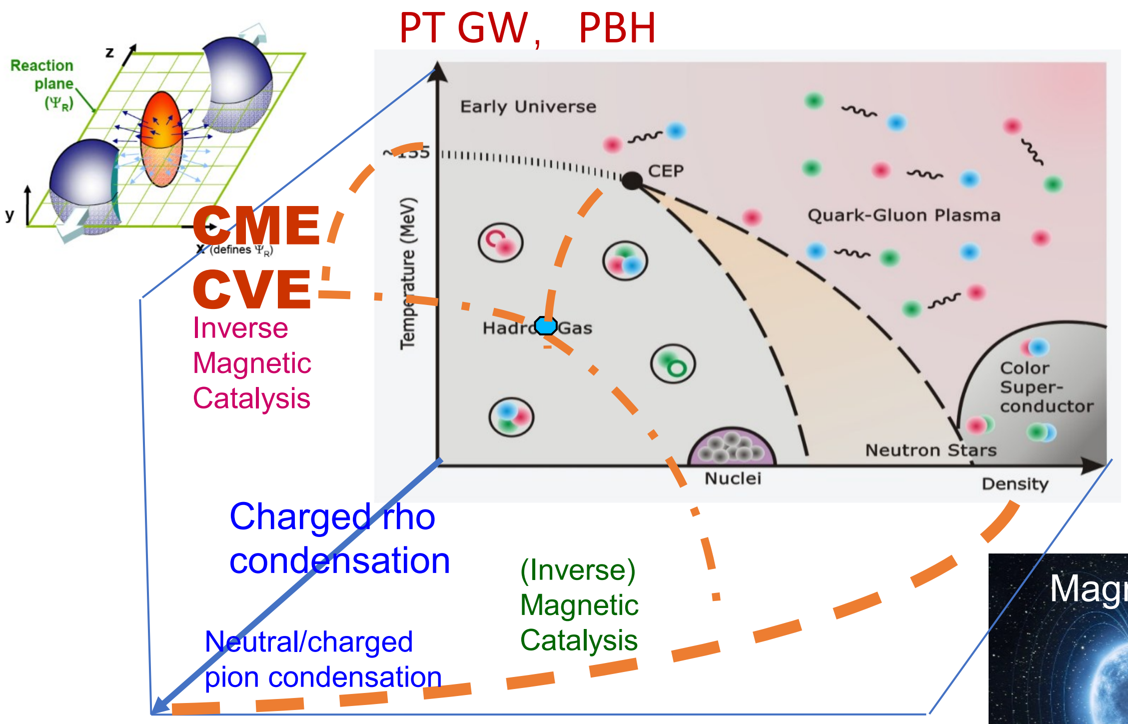
Deconfinement: center symmetry breaking $\langle L\rangle \neq 0 \quad F_q < \infty$

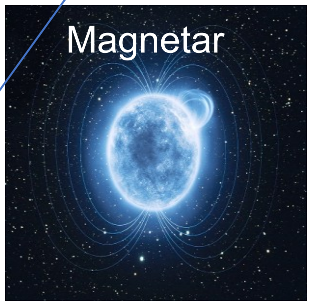
江山如此多娇，引无数英雄竞折腰



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

PT GW， PBH



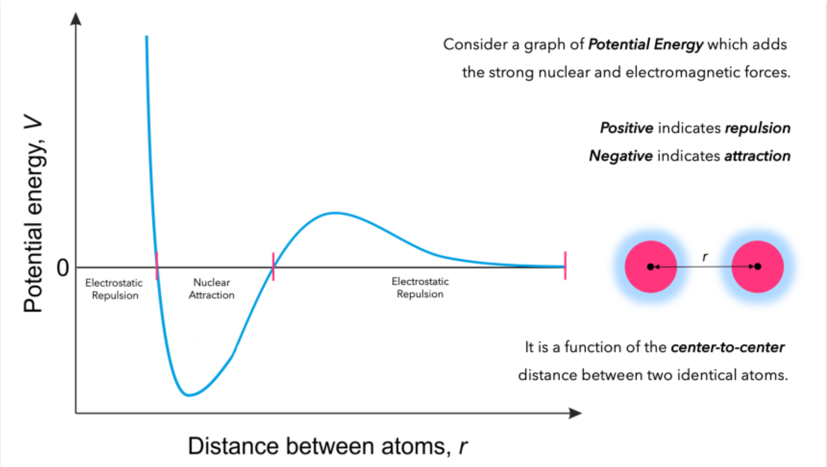


$$\mathbf{B}, \mathbf{E}\cdot\mathbf{B}, \boldsymbol{\omega}, \mu_I, \boldsymbol{L}$$

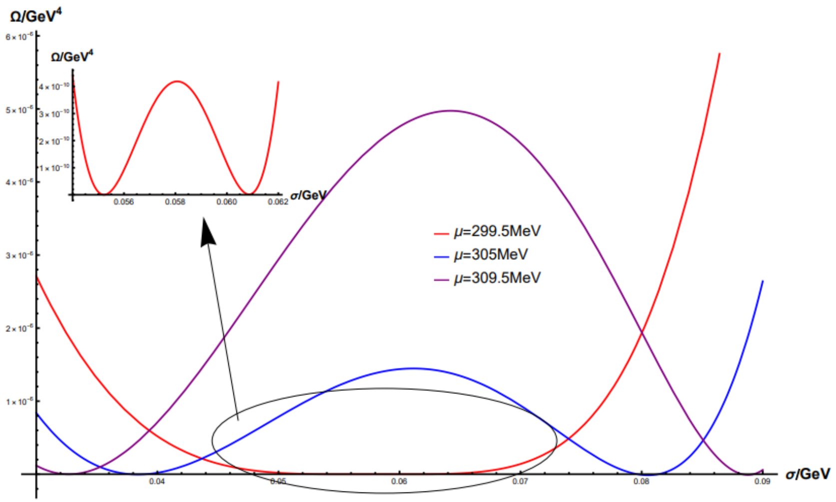
Explored QCD phase diagram *by theorists*

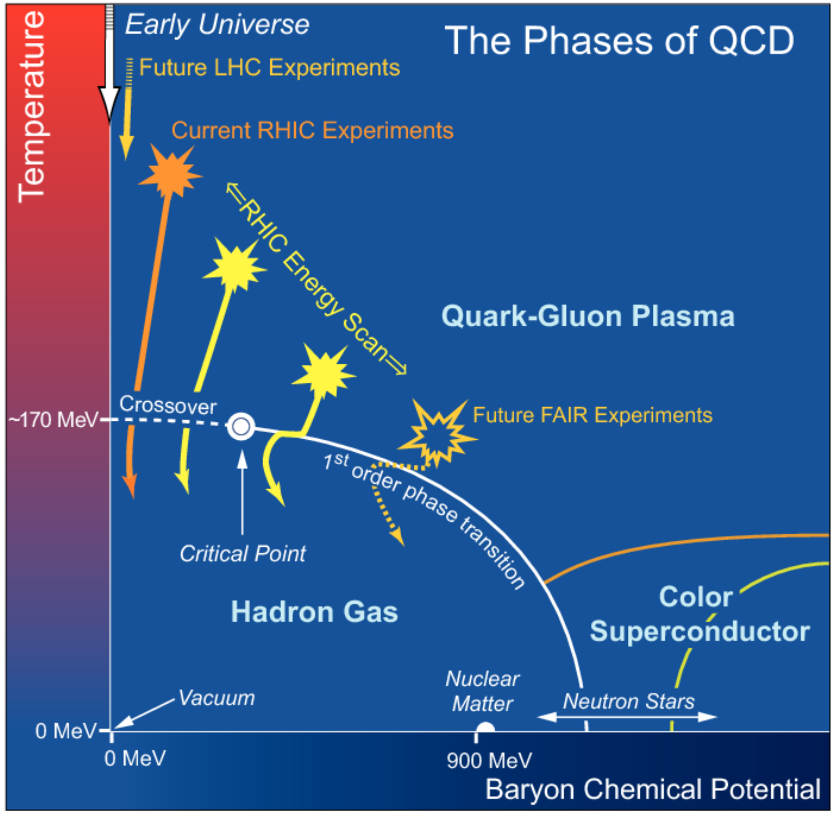
Existence of CEP at high baryon chemical potential

potential barrier is needed for 1st-order phase transition



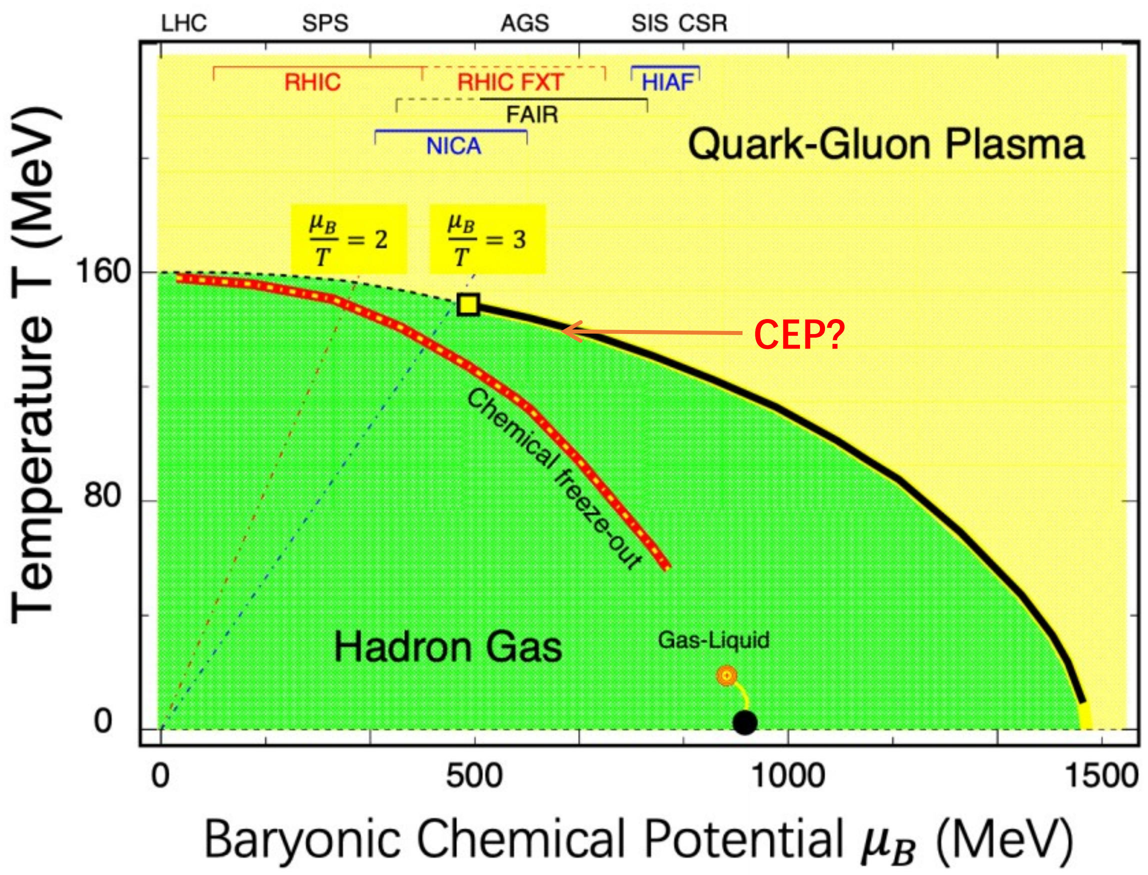
mu_B plays the role of repulsive vector interaction, potential barrier develops when mu_B increases, indicating a 1st-order phase transition.

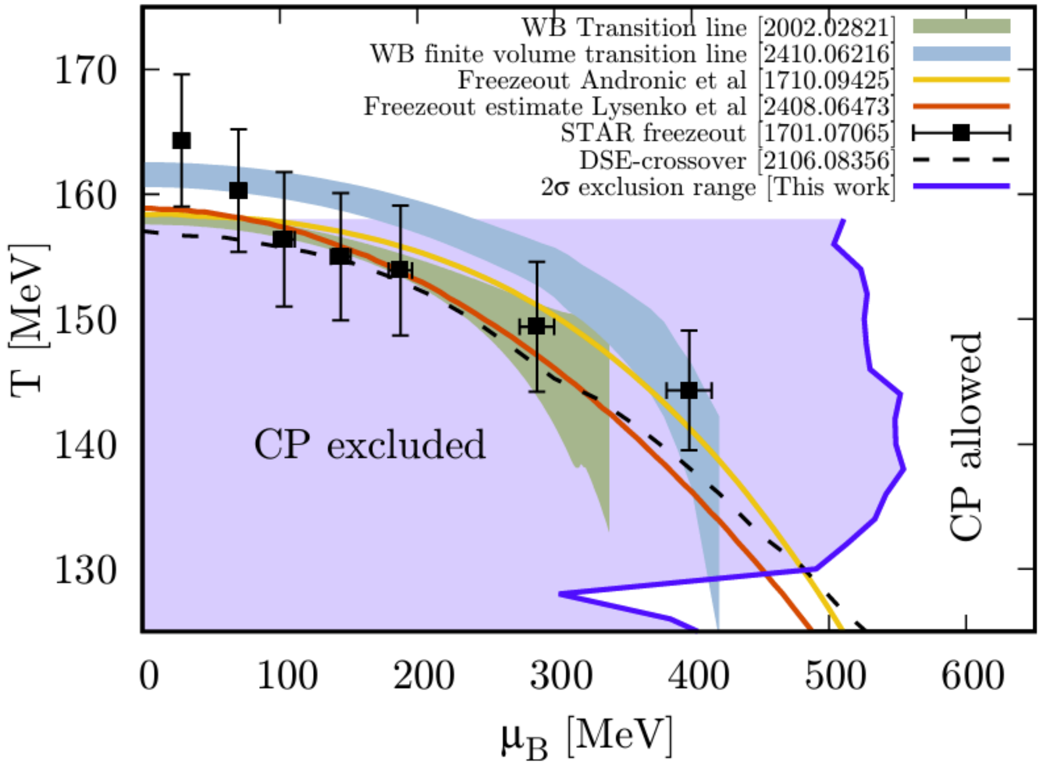




STAR results on CEP, 罗晓峰

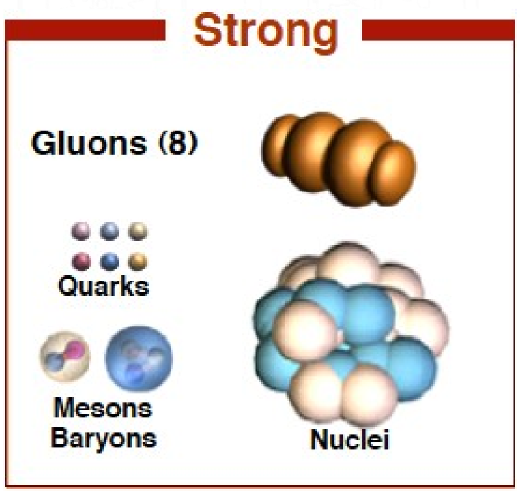
Latest lattice constraints on CEP





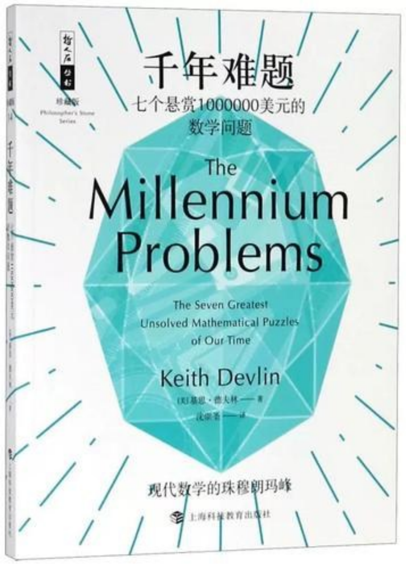
Lattice QCD constraints on the critical point,
Szabolcs Bors´anyi,1 Zolt´an Fodor, et.al., …arXiv: 2502.10267

量子色动力学QCD



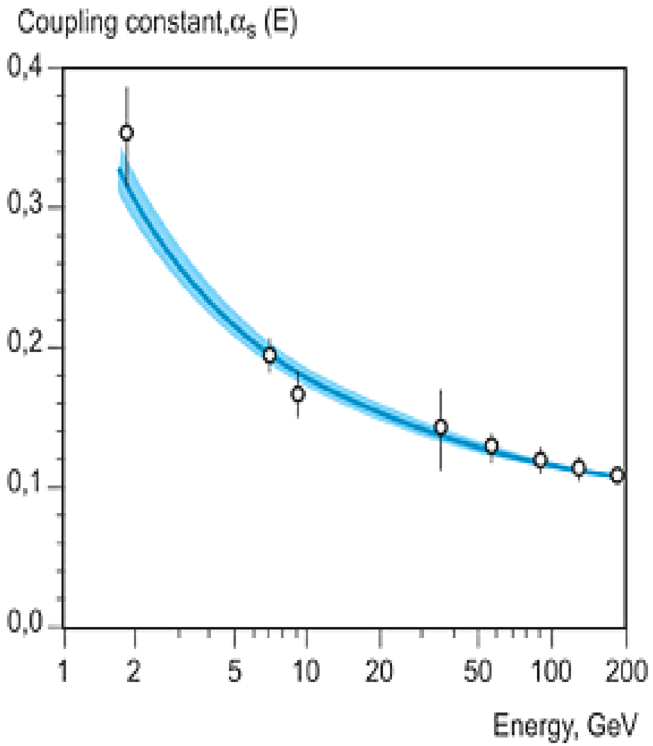
千禧年七大难题：NP完全问题、霍奇猜想、庞加莱猜想、黎曼猜想、杨-米尔斯存在性和质量间隙、纳斯-斯托克斯方程、BSD猜想.

杨 - 米尔斯存在性与质量间隙：粒子物理与数学的双重谜题

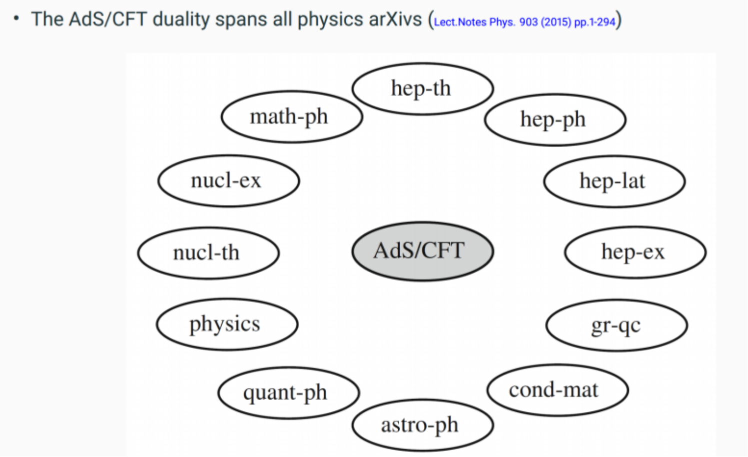


QCD两个重要非微扰性质：
色禁闭和手征对称性自发破缺

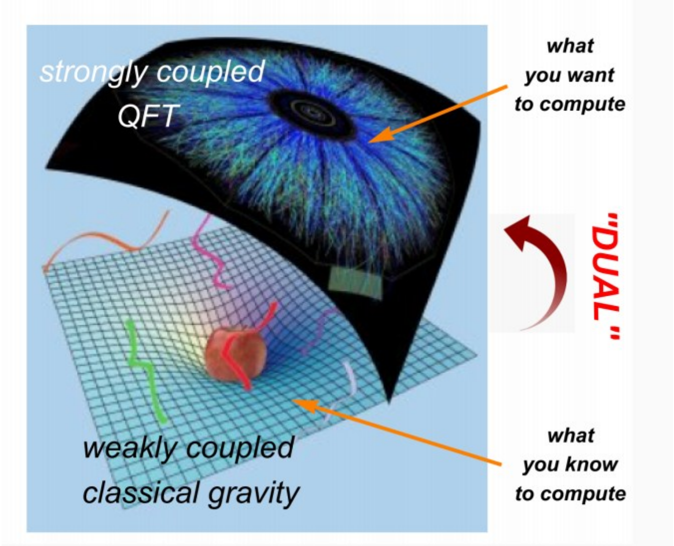
clay数学研究所在法兰西学院公布的千禧年七大难题之一，非微扰强耦合困难



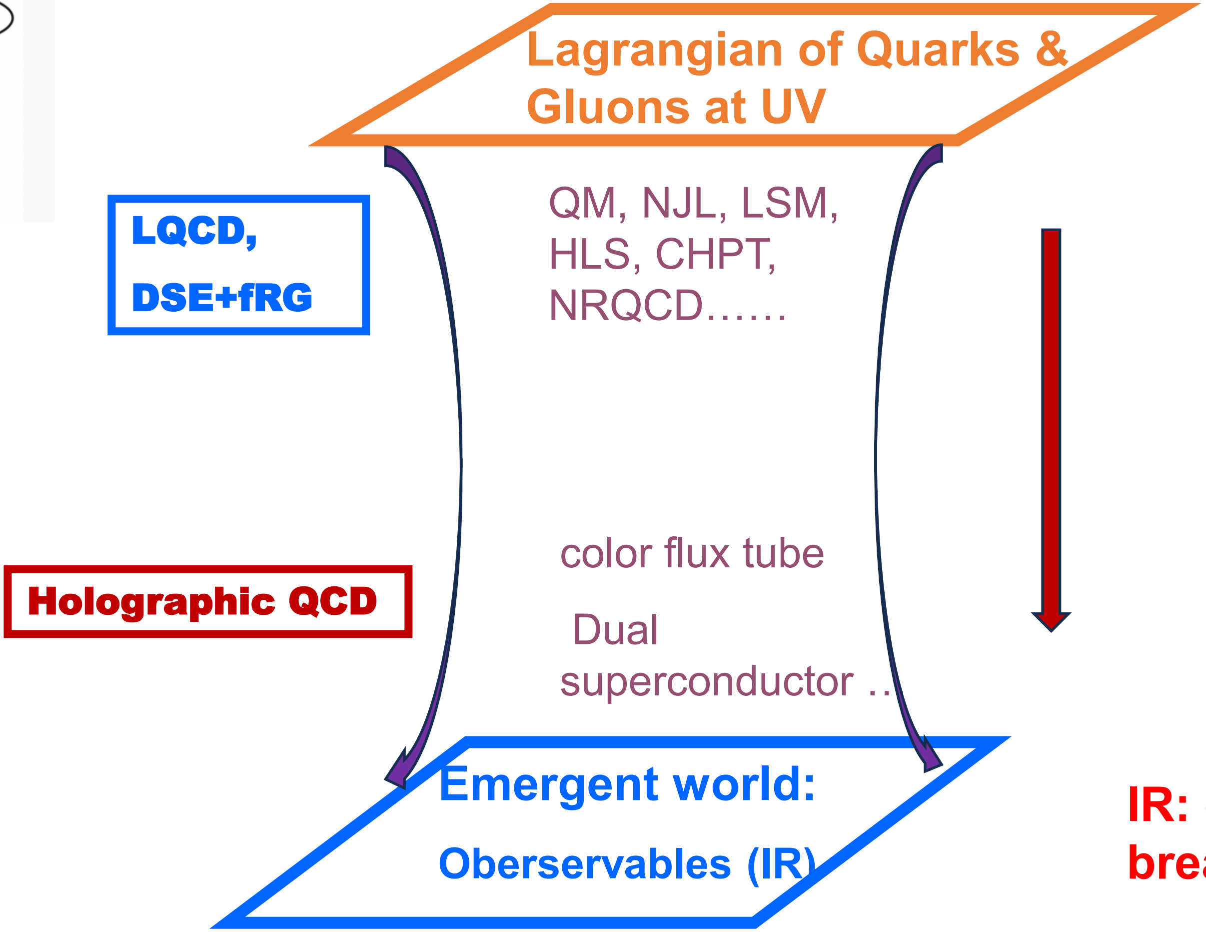
理论困难 Strong QCD: from UV to IR



Gauge/gravity duality



1908.02667v2 [hep-th]



UV: symmetries

$SU(N_f)_L \times SU(N_f)_R$

SU(Nc=3)

IR: chiral symmetry breaking & confinement

Effective Field Theory

Joseph Polchinski, TASI lecture 1992, hep-th/9210046

A characteristic energy scale E_0

Choose a cutoff Λ at or slightly below E_0

$$\phi = \phi_H + \phi_L$$

$\phi_H : \omega > \Lambda$ High frequency

$\phi_L : \omega < \Lambda.$ low frequency

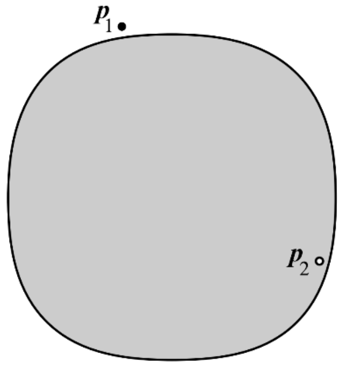
low energy or Wilsonian effective action:

$$S_\Lambda = \int d^D x \sum_i g_i \mathcal{O}_i.$$

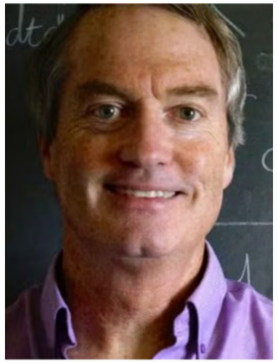
$$\int \mathcal{D}\phi_L\, \mathcal{D}\phi_H\, e^{iS(\phi_L,\phi_H)} = \int \mathcal{D}\phi_L\, e^{iS_\Lambda(\phi_L)},$$

only a finite number of relevant and marginal terms,
relevant or marginal operators can be regarded as effective DOF at E_0

$$e^{iS_\Lambda(\phi_L)} = \int \mathcal{D}\phi_H\, e^{iS(\phi_L,\phi_H)}$$



e.g., Cooper pairing for SC (BCS),
pion for low-energy effective QCD theory (χPT),
Chiral condensate for ciral symmetry breaking(NJL), ...



From UV to IR: Holographic Duality & RG flow

5D field theory
or bulk field theory

QFT on lattice equivalent to GR problem from Gravity
RG scale -> an extra spatial dimension
Coupling constant -> dynamical filed

Allan Adams, Lincoln D. Carr, Thomas Schäfer, Peter Steinberg,John E. Thomas,arXiv:1205.5180

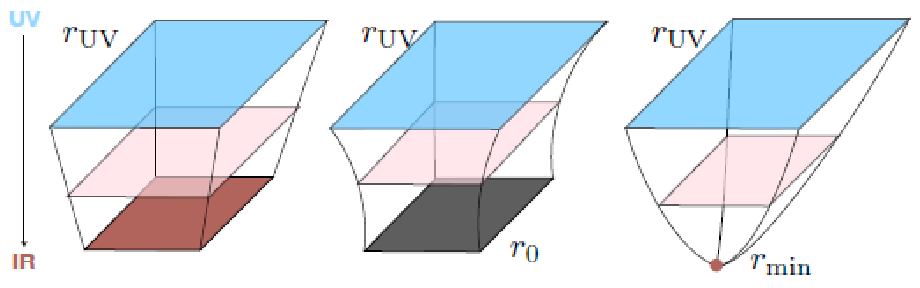
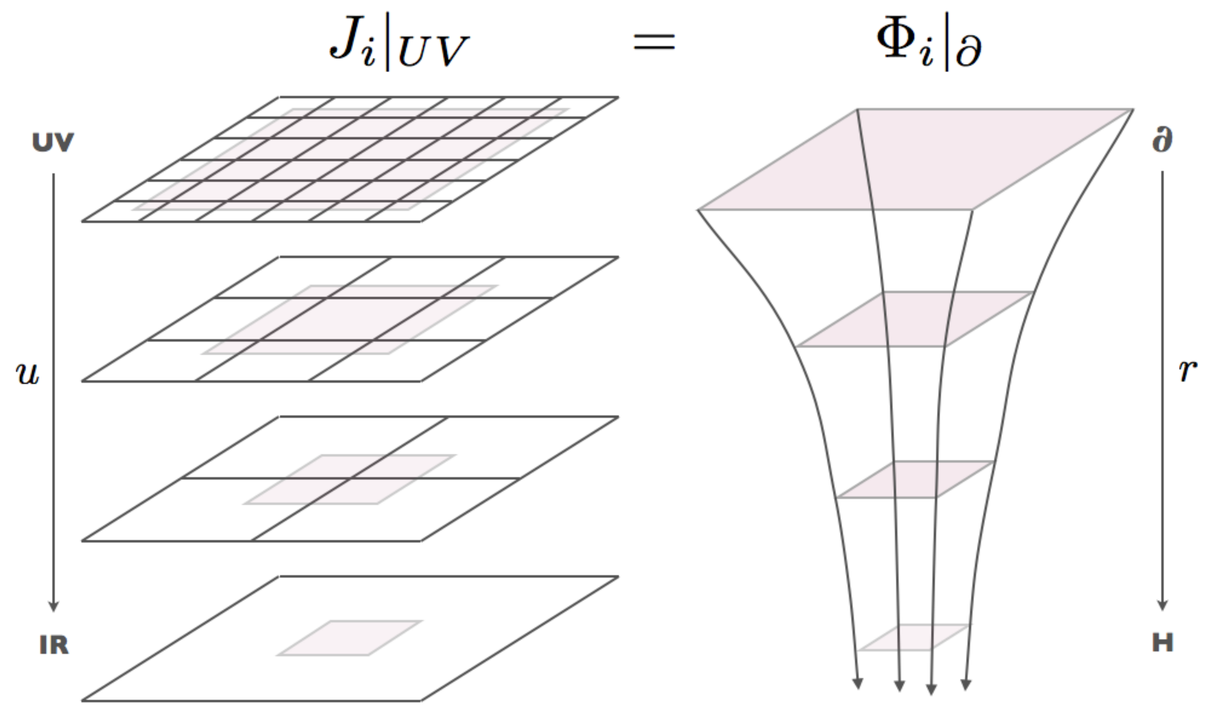


FIG. 1. AdS/CFT as an RG flow. The left panel represents an RG fixed point, so that the entire geometry is scale-invariant (empty AdS). The middle panel shows a thermal state, where the IR geometry is instead a black hole with horizon at r_0. The third panel represents an RG flow where the UV fixed point flows to gapped theory in the IR, ending smoothly at a minimum radius r_{min}. Only the first geometry is fully scale invariant.

Hong Liu, Julian Sonner, 1810.02367,
Rept.Prog.Phys. 83 (2019) 1, 016001



The extra dimension plays the role of energy scale in QFT, with motion along the extra dimension representing a change of scale, or renormalization group (RG) flow.

Principle of holographic Duality

Bulk field theory or
5D field theory

Boundary QFT **Bulk Gravity**

$$\Delta(d-\Delta) = m^2 L^2$$

Local operator $\mathcal{O}_i(x)$ **Bulk field** $\Phi_i(x, r)$

- Operator/Field correspondence:

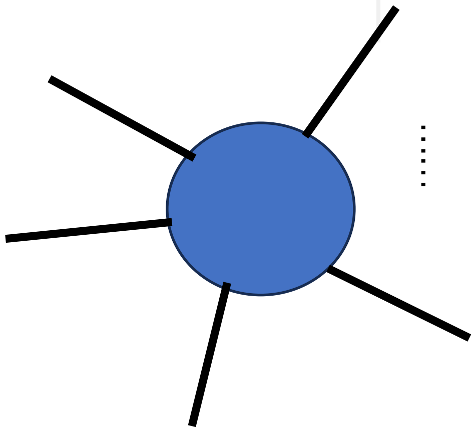
4D boundary operator $\mathcal{O}(x)$
local, gauge invariant, scaling dim. Δ $\Longleftrightarrow$ 5D bulk field
$\phi(x, z \to 0) \to z^{4-\Delta}\phi_0(x) + z^{\Delta} < \mathcal{O}(x) >$

$$\left\langle e^{i\int d^4x \phi_0(x)\mathcal{O}(x)} \right\rangle_{CFT} = e^{iS_{5D}[\phi(x,z)]}\Big|_{\phi(x,z\to 0)\to\phi_0(x)}$$

$$\boxed{Z_{\rm QFT}[J_i] = Z_{\rm QG}[\Phi[J_i]]} \qquad Z_{\rm QFT}[J] \simeq e^{-I_{\rm GR}[\Phi[J]]}$$

$$\langle \mathcal{O}_1(x_1)\ldots\mathcal{O}_n(x_n)\rangle = \frac{\delta^n I_{\rm GR}[\Phi[J_i]]}{\delta J_1(x_1)\ldots\delta J_n(x_n)}\Big|_{J_i=0}$$

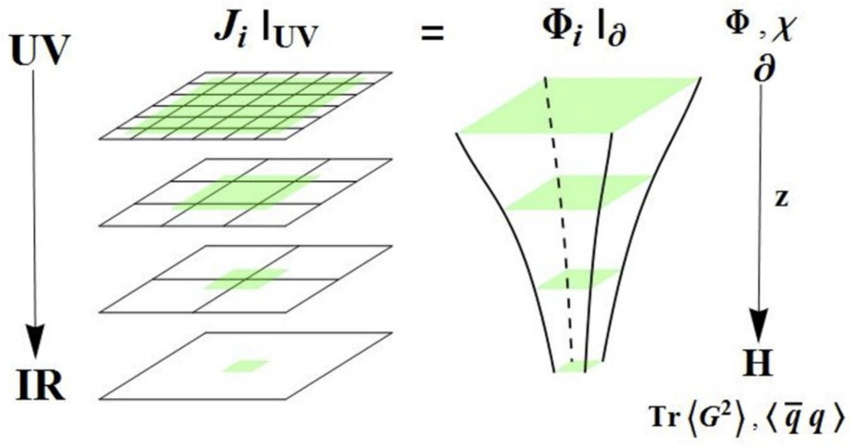
Correlators:



Using bulk field to calculate observables: two-point correlation gives mass spectra, three-point correlation gives form factor, and so on.

Dynamical Holographic QCD model (DhQCD)

Danning Li, M.H., JHEP2013, arXiv:1303.6929



QCD IR dynamics determines the metric

$$S = S_G + \frac{N_f}{N_c} S_{KKSS},$$

Gluonic background + matter field
(Confinement & chiral symmetry breaking)

$$S_G = \frac{1}{16\pi G_5}\int d^5x\sqrt{g_s}e^{-2\Phi}\left(R + 4\partial_M\Phi\partial^M\Phi - V_G(\Phi)\right),$$

$$S_{KKSS} = -\int d^5x e^{-\Phi(z)}\sqrt{g_s}Tr\left(|DX|^2 + V_X(|X|,\Phi) + \frac{1}{4g_5^2}(F_L^2 + F_R^2)\right).$$

Andreas Karch, Emanuel Katz, Dam T. Son, and Mikhail A. Stephanov, Phys. Rev. D, 74:015005, 2006.

DhQCD offers a systematic framework to describe the emergent real world from QCD theory, including linear confinement and chiral symmetry breaking, hadron spectra (glueball spectra, light-flavor and heavy flavor spectra) and form factors, QCD phase transitions, thermodynamical and transport propertities, and nonequilibrium evolution, hydro(in progress) , turbulance…
inhomogeneous system, Hadron structure (PDF), rotation and magnetic field, IMC, spin alignment…

Many thanks to my collaborators: Danning Li, Yidian Chen, Xun Chen, Hiwa Amhed, Akira Watanabe ….

Other groups hQCD: Elias Kiritsis and collaborators, S. Gubser and followers, Kapusta, I. Zahed, S. Brodsky, Yueliang Wu, Ronggen Cai, Defu Hou, Shu Lin, Song He, Yang Li, Tianbo Liu, ….

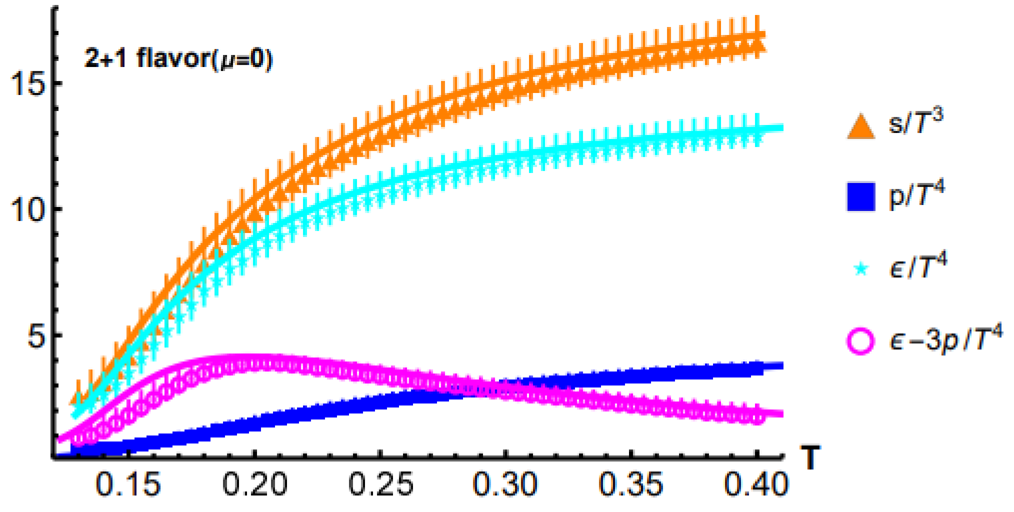
Equilibrium state

Theoretical predictions for the location of CEP

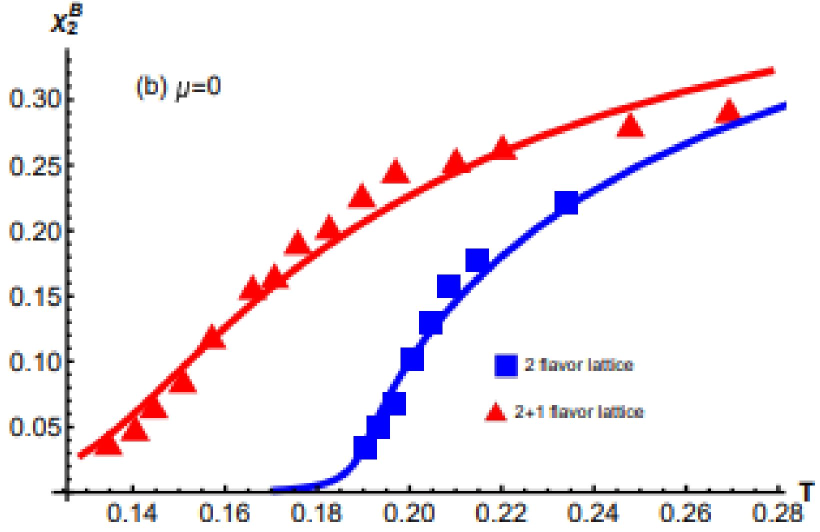
Nonperturbative theoretical calculations (rPNJL model, DSE-fRG,fRG,holographic QCD):

Strategy of model calculations:

1, Fit model paraters with Lattice QCD EOS and baryon number susceptibility at zero chemical potential;
2,Predictions at finite baryon number chemical potential.



Determine Tc at mu=0

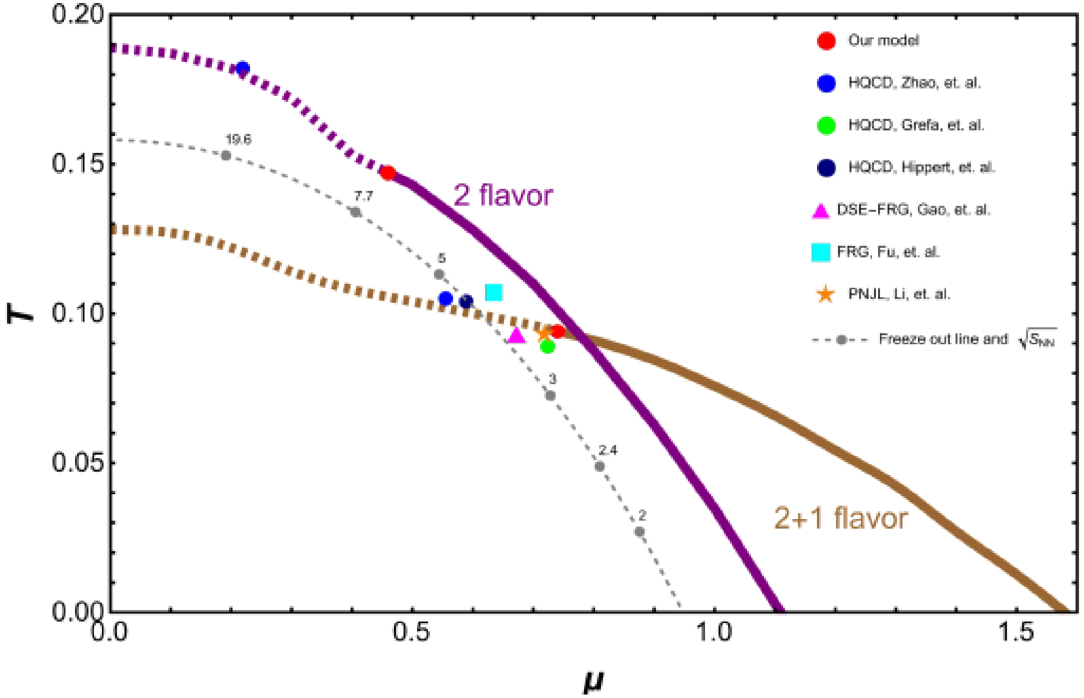


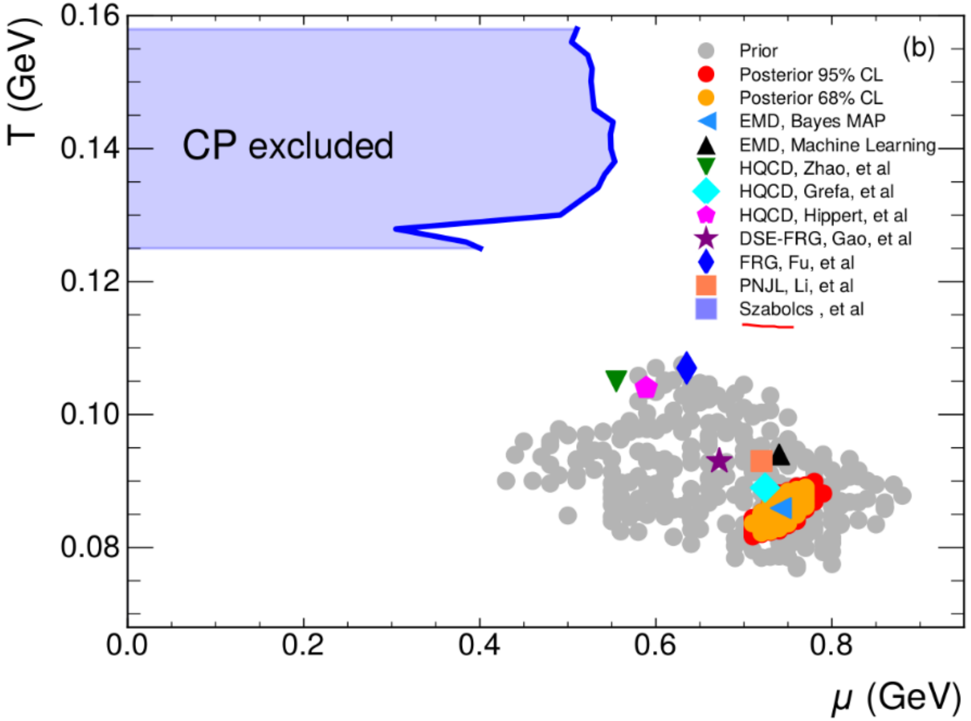
Determine mu dependent Tc

ML+hQCD:Xun Chen（陈勋）, MH, Phys.Rev.D 109 (2024) 5, L051902, e-Print:2401.06417

Equilibrium state

Locations of CEP from rPNJL model, holographic QCD models, DSE-fRG,fRG converge at around (Tc~90MeV, mu_B^c~700 MeV)





ML+hQCD:Xun Chen（陈勋）, MH, Phys.Rev.D 109 (2024) 5, L051902, e-Print:2401.06417 [hep-ph];e-Print: 2405.06179 [hep-ph]

J. Grefa, J. Noronha, J. Noronha-Hostler, I. Portillo, C. Ratti, and R. Rougemont, Phys. Rev. D 104, 034002 (2021), arXiv:2102.12042 [nucl-th]; M. Hippert, J. Grefa, T. A. Manning, J. Noronha, J. Noronha-Hostler, I. Portillo Vazquez, C. Ratti, R. Rougemont, and M. Trujillo (2023) arXiv:2309.00579 [nucl-th], Y.-Q. Zhao, S. He, D. Hou（侯德富）, L. Li, and Z. Li, JHEP 04, 115 (2023), arXiv:2212.14662 [hep-ph]

rPNJL:Zhibin Li （李志镔）, Kun Xu （许坤）, Xinyang Wang （王昕杨） and MH, arXiv:1801.09215

DSE-fRG: *F. Gao （高飞） and J. M. Pawlowski, Phys. Rev. D 102, 034027 (2020), arXiv:2002.07500 [hep-ph].*

fRG:W.-j. Fu （付伟杰）, J. M. Pawlowski, and F. Rennecke, Phys. Rev. D 101, 054032 (2020), arXiv:1909.02991 [hep-ph].

Bayesian+hQCD: Liqiang Zhu, Xun Chen, Kai Zhou, Hanzhong Zhang（张汉中）, M.H., e-Print: 2501.17763　　*朱力强*

Net proton number fluctuations near critical point

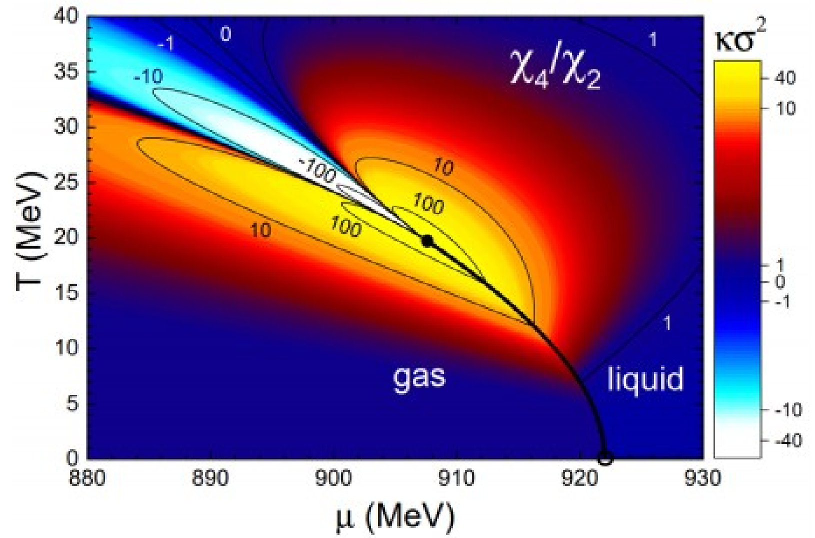
$$K_N = \ln(e^{tN}) = \sum_{n=1}^{\infty} k_n \frac{t^n}{n!}$$

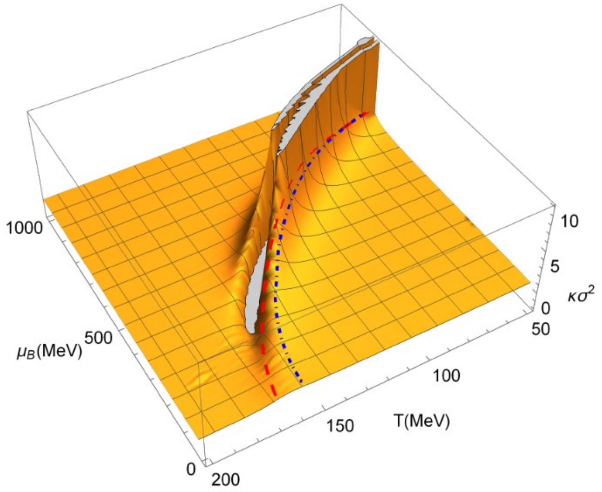
$$\ln Z^{gce}(T,V,\mu) = \ln[\sum_N e^{\mu N/T} Z^{ce}(T,V,N)]$$

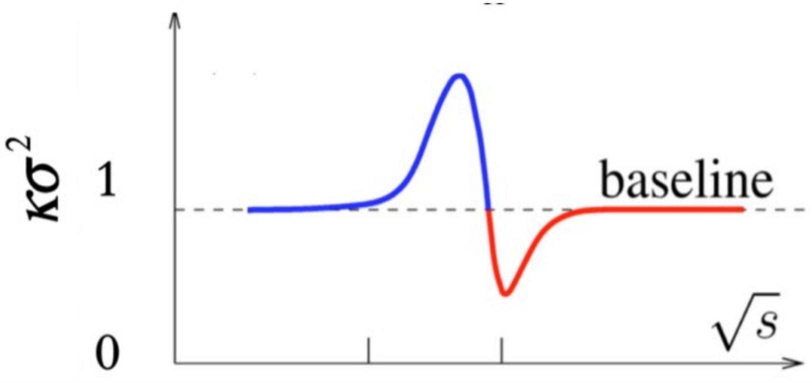
$$k_n \propto \frac{\partial^n (\ln Z^{gce})}{\partial \mu^n}$$

$$C_1 = \langle N \rangle = M$$
$$C_2 = \langle (\Delta N)^2 \rangle = \sigma^2$$
$$C_3 = \langle (\Delta N)^3 \rangle = S\sigma^3$$
$$C_4 = \langle (\Delta N)^4 \rangle - 3C_2^2 = \kappa\sigma^4$$

$$\frac{\sigma^2}{M} = \frac{C_2}{C_1}, S\sigma = \frac{C_3}{C_2}, \kappa\sigma^2 = \frac{C_4}{C_2}$$





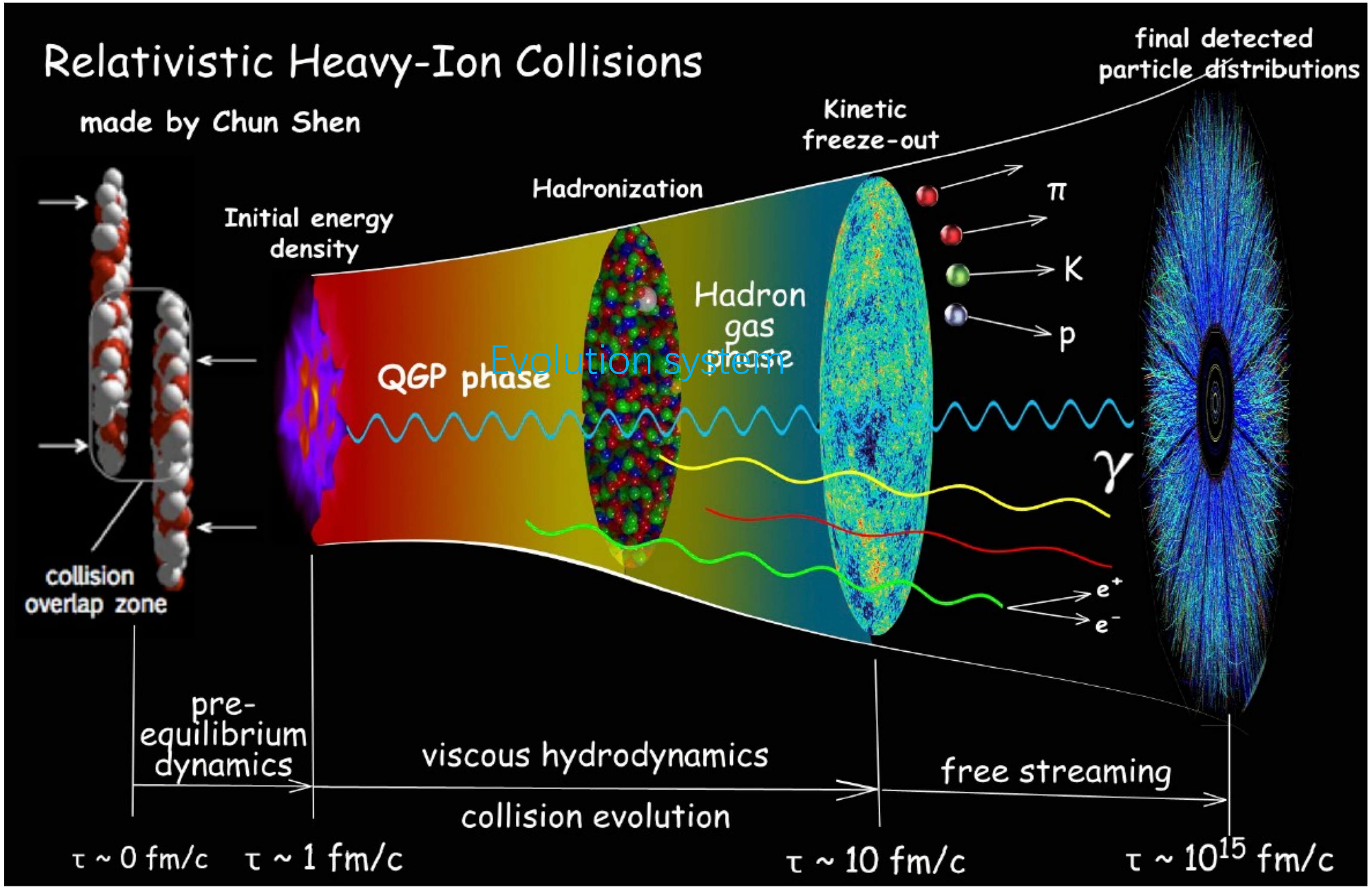


M.A.Stephanov,PRL107,052301(2011)

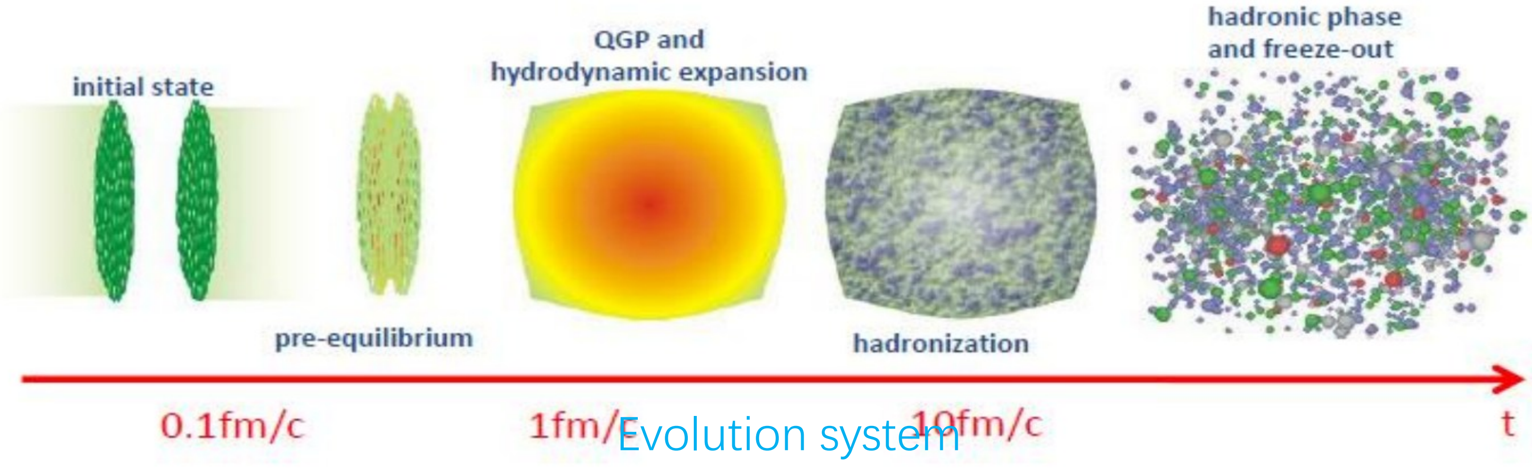
VV, Anchishkin, Gorenstein, Poberezhnyuk, PRC 92, 054901 (2015)

Relativistic Heavy-Ion Collisions

Relativistic heavy-ion collisions → hot QCD matter and its phase transition



Hybrid Model



Evolution system

Initial Conditions
SMASH

Hydro
CLVisc

Fist Sampler +
hadron cascade

arXiv:e-Print: 2404.02397 [hep-ph]

Collaborators: Yifan Shen（沈一凡）, Wei Chen（陈蔚）, Kun Xu（许坤）, Xiangyu Wu （吴翔宇）

Hydrodynamics（CLVisc)

Conservation laws of energy-monmentum and net baryon current：

$$\nabla_\mu T^{\mu\nu} = 0 \quad \text{with} \quad T^{\mu\nu} = eU^\mu U^\nu - P\Delta^{\mu\nu} + \pi^{\mu\nu}$$

$$\nabla_\mu J^\mu = 0 \quad \text{with} \quad J^\mu = nU^\mu + V^\mu$$

Evolution system

Input:

1. Initial conditions

2. EoS from rPNJL model
(carry CEP information)

$$\Delta^{\mu\nu}_{\alpha\beta} D\pi^{\alpha\beta} = -\frac{1}{\tau_\pi}(\pi^{\mu\nu} - \eta_v \sigma^{\mu\nu}) - \frac{4}{3}\pi^{\mu\nu}\theta - \frac{5}{7}\pi^{\alpha<\mu}\sigma^{\nu>}_\alpha + \frac{9}{70}\frac{4}{e+p}\pi^{<\mu}_\alpha \pi^{\nu>\alpha}$$

$$\Delta^{\mu\nu} DV_\nu = -\frac{1}{\tau_V}\left(V^\mu - \kappa_B \nabla^\mu \frac{\mu_B}{T}\right) - V^\mu\theta - \frac{3}{10}V_\nu \sigma^{\mu\nu}$$

L.Pang （庞龙刚）et al, Phys.Rev. C86 (2012) 024911
L.Pang et al, Phys. Rev. C 97, 064918 (2018)
X.Wu et al, Phys. Rev. C 105, 034909 (2022)

1, EoS with CEP: Polyakov-loop-Nambu-Jona-Lasinio(PNJL) Model

Thermal Potential of PNJL Model:

Zhibin Li, Kun Xu, Xinyang Wang, Mei Huang. Eur.Phys.J.C 79 (2019) 3, 245

(μ_{Bc} = 720MeV, T_c= 93MeV)

$$\Omega_{\mathrm{PNJL}} = U(\Phi,\bar{\Phi},T) + g_s\sum_f \sigma_f^2 - \frac{g_D}{2}\sigma_u\sigma_d\sigma_s + 3\frac{g_1}{2}(\sum_f \sigma_f^2)^2 + 3g_2\sum_f \sigma_f^4 - 6\sum_f\int_{-\Lambda}^{\Lambda}\frac{d^3p}{(2\pi)^3}E_f - 2T\sum_f\int_{-\infty}^{\infty}\frac{d^3p}{(2\pi)^3}\times\left\{\ln\left[1+3\Phi e^{-\frac{E_f-\mu_f}{T}}+3\bar{\Phi}e^{-2\frac{E_f-\mu_f}{T}}+e^{-3\frac{E_f-\mu_f}{T}}\right]+\ln\left[1+3\bar{\Phi}e^{-\frac{E_f+\mu_f}{T}}+3\Phi e^{-2\frac{E_f+\mu_f}{T}}+e^{-3\frac{E_f+\mu_f}{T}}\right]\right\}$$

2, EOS without CEP: numerical equation of state (NEOS) with multiple charges: net baryon (B), strangeness (S) and electric charge (Q)(NEOS-BQS) based on the lattice QCD EoS from the HotQCD collaboration

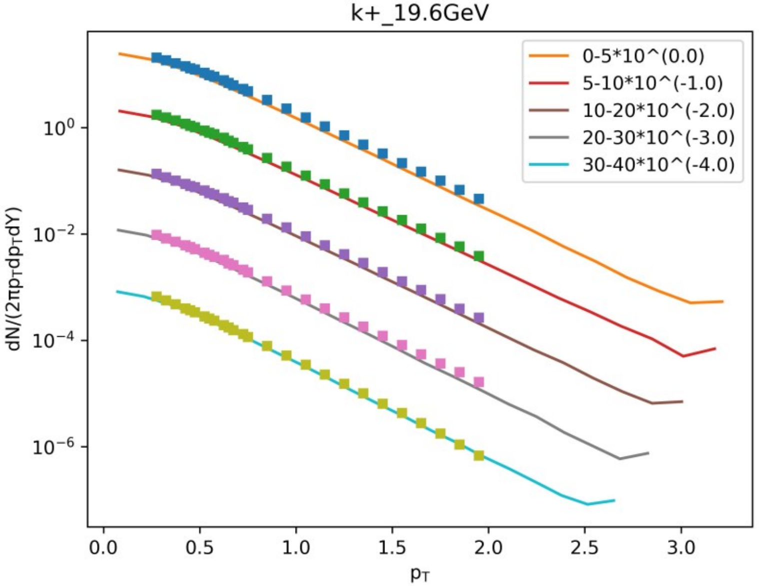
Parameters Table

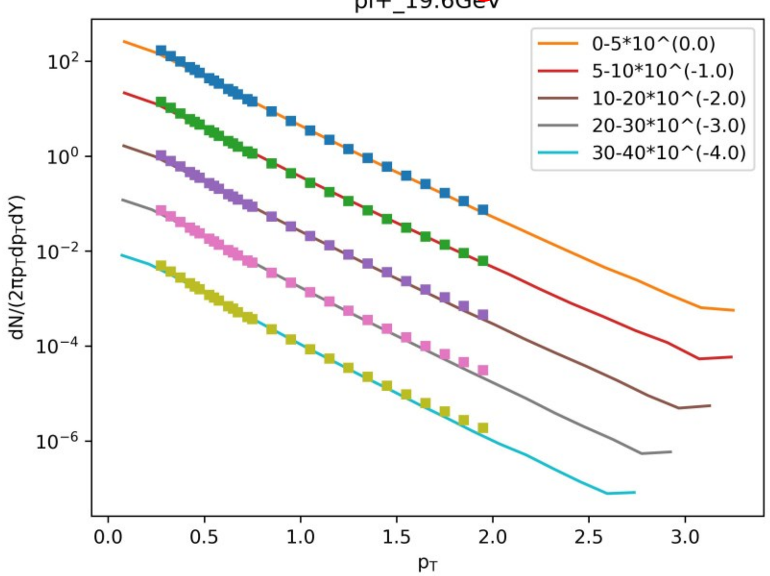
$\sqrt{s_{NN}}$ [GeV]	τ_0 [fm/c]	$R_\perp$ [fm]	R_η [fm]	C_{η_v}
7.7	3.2	1.4	0.5	0.2
14.5	1.68	1.4	0.5	0.2
19.6	1.22	1.4	0.5	0.15
27	1.0	1.2	0.5	0.12
39	0.9	1.0	0.7	0.08
62.4	0.7	1.0	0.7	0.08

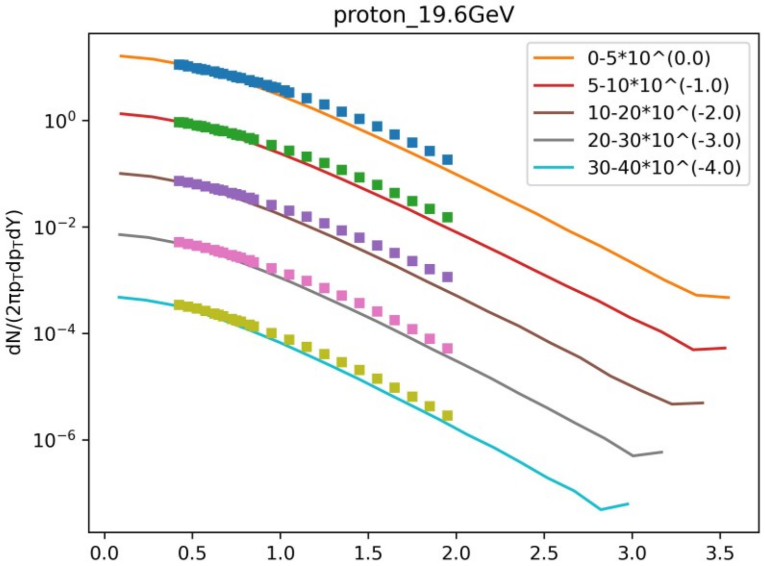
Evolution system

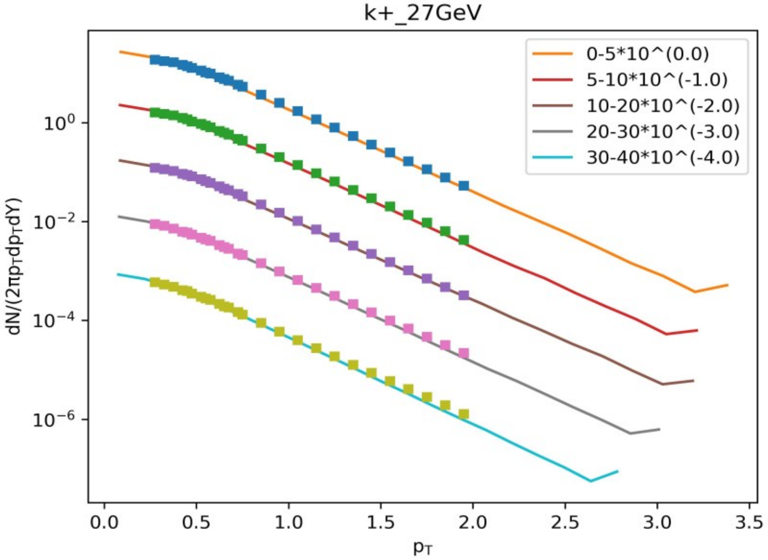
Identified particle spectra

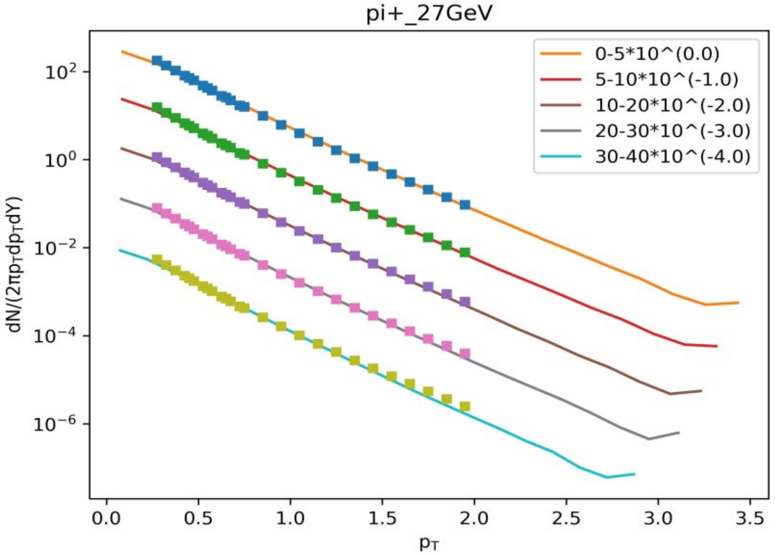
lines from simulation, points from STAR data,
and in agreement with experimental datas

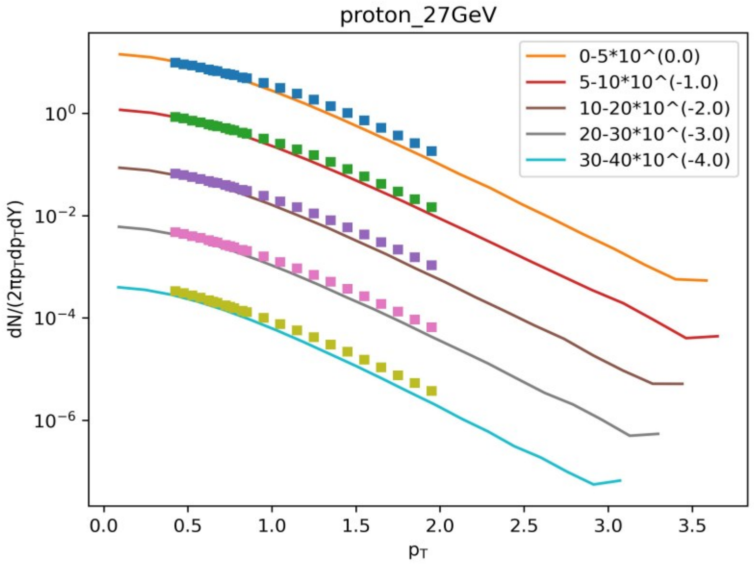




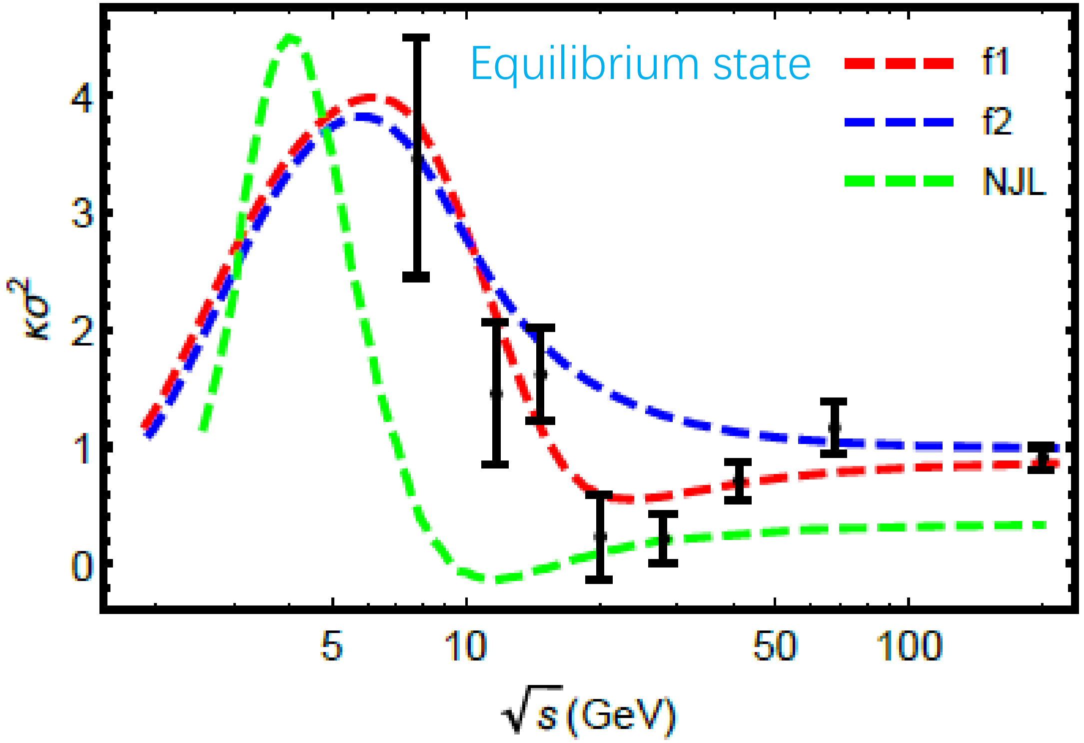




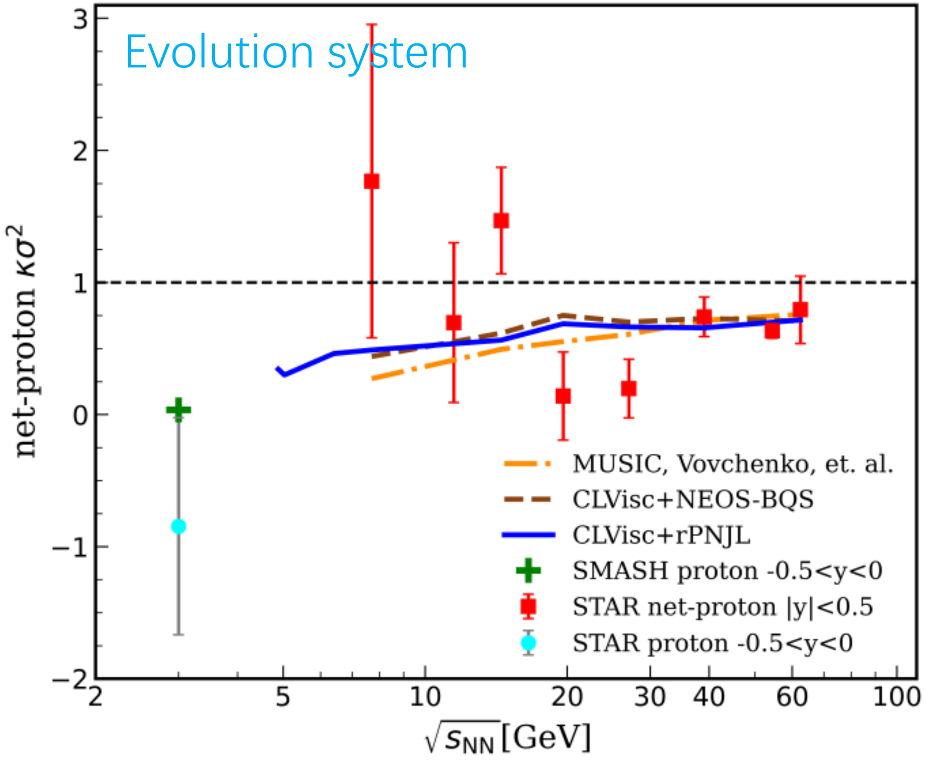




Bad news: Above 7.7 GeV, no peak structure and EOS independent



Zhibin Li, Kun Xu, Xinyang Wang and Mei Huang, arXiv:1801.09215， EPJC 2019

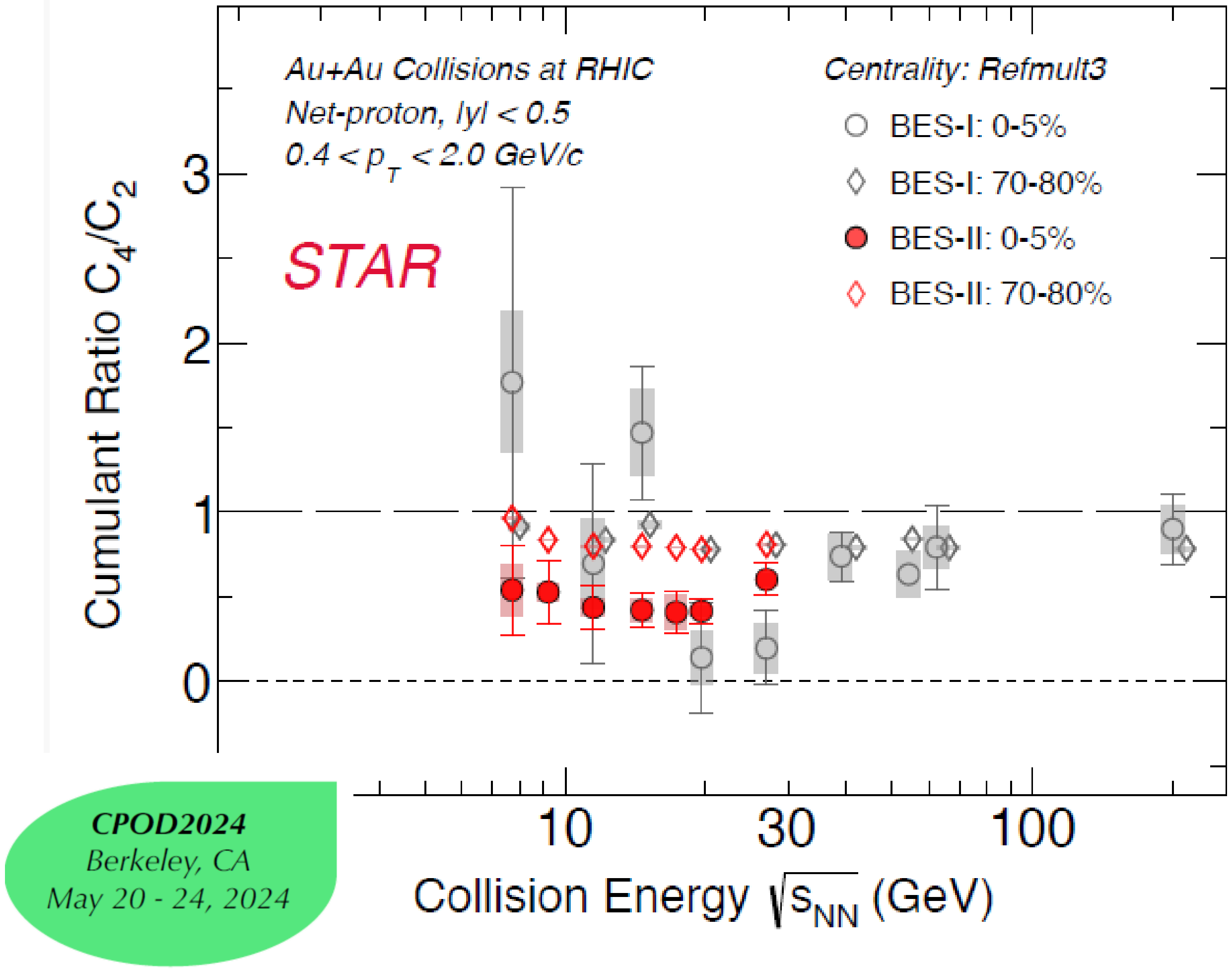


Yifan Shen, Wei Chen, Xiangyu Wu, Kun Xu, MH, arXiv:e-Print: 2404.02397 [hep-ph]

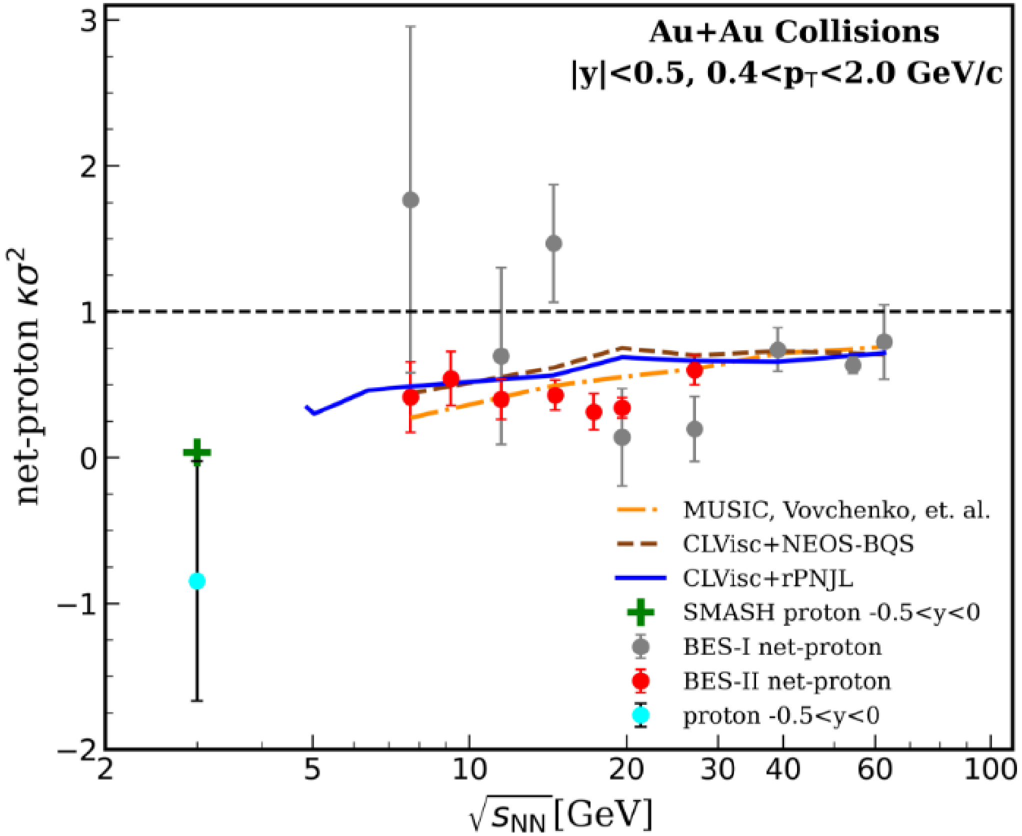
MUSIC: different hydrodynamics model

V. Vovchenko, V. Koch, and C. Shen, Phys. Rev.C 105, 014904 (2022)

Good news: Above 7.7 GeV, in agreement with latest Exp. results!

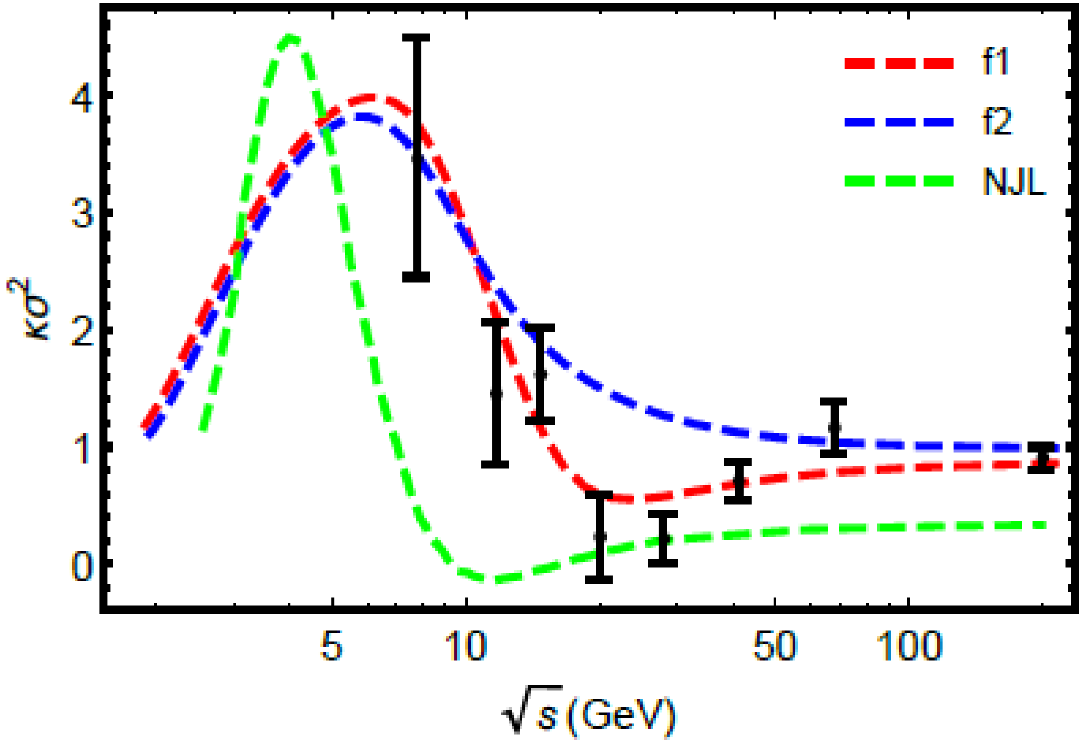


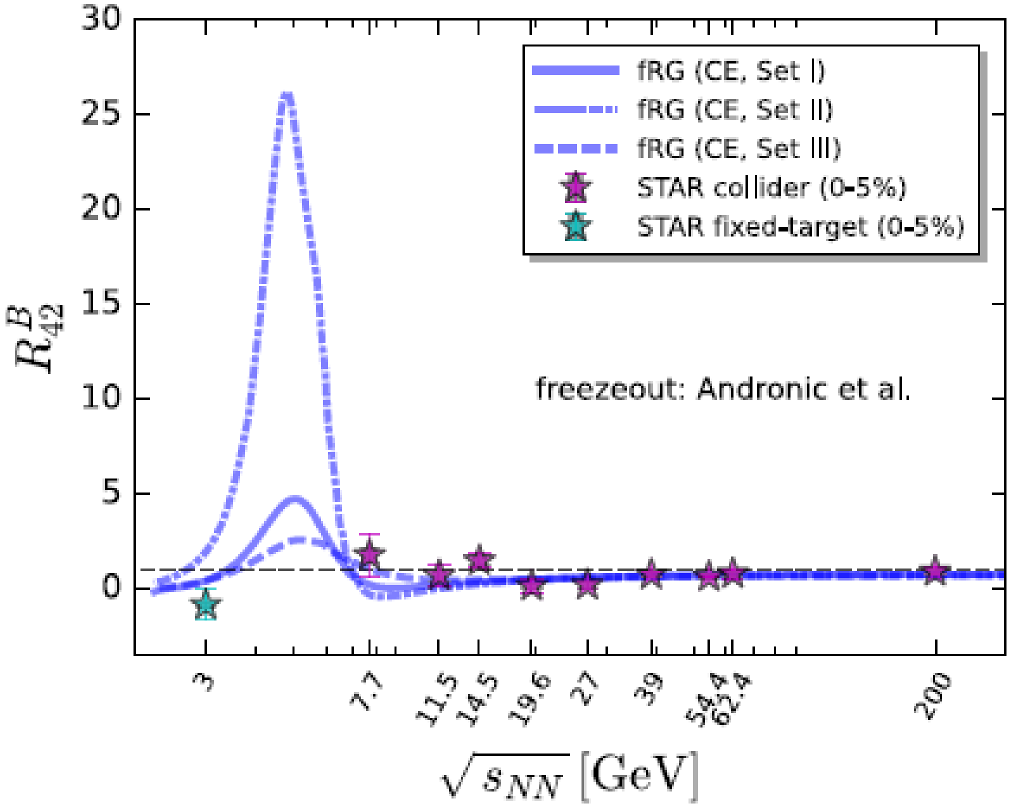
Ashish Pandav for STAR Collaboration
Lawrence Berkeley National Laboratory
May 21, 2024



Yifan Shen, Wei Chen, Xiangyu Wu, Kun Xu, MH,
arXiv:e-Print: 2404.02397 [hep-ph]

Waiting for results around 5GeV (NICA,FAIR,HIAF) !

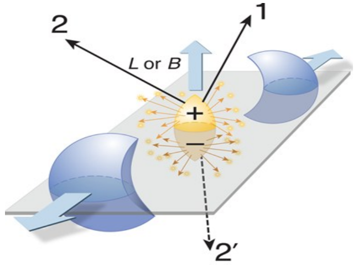




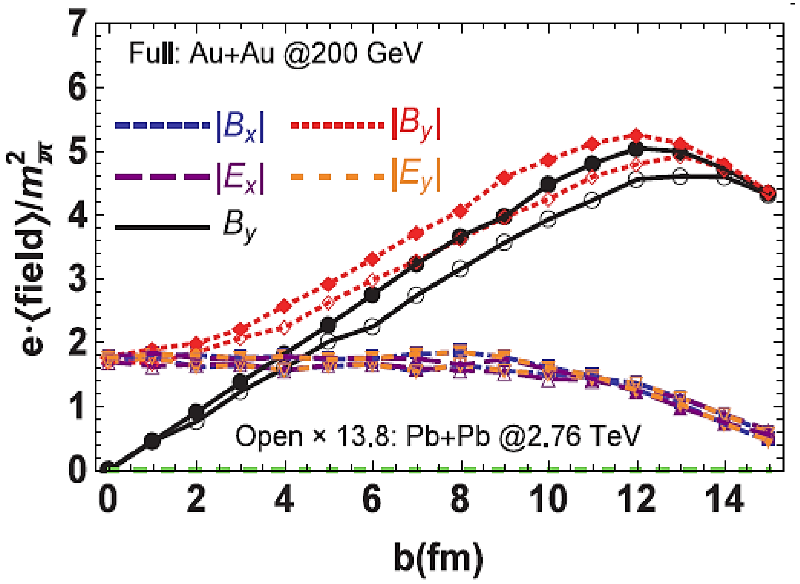
rPNJL：Zhibin Li（李志镔）, Kun Xu（许坤）, Xinyang Wang and MH, arXiv:1801.09215，EPJC 2019

fRG： Weijie Fu（付伟杰）, Luo, Pawlowski, Rennecke, Yin, arXiv: 2308.15508

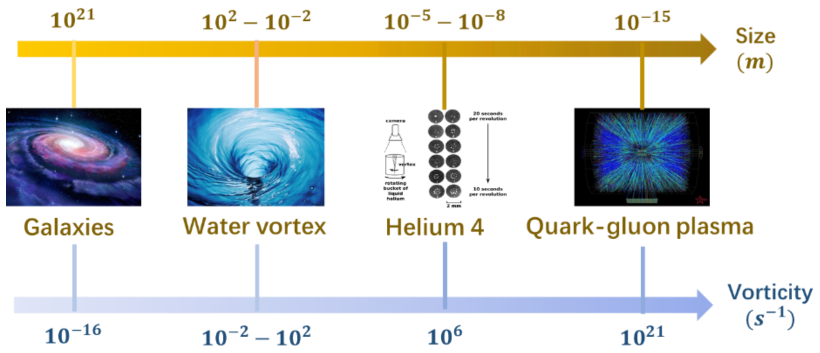
MAGNETIC FIELDS

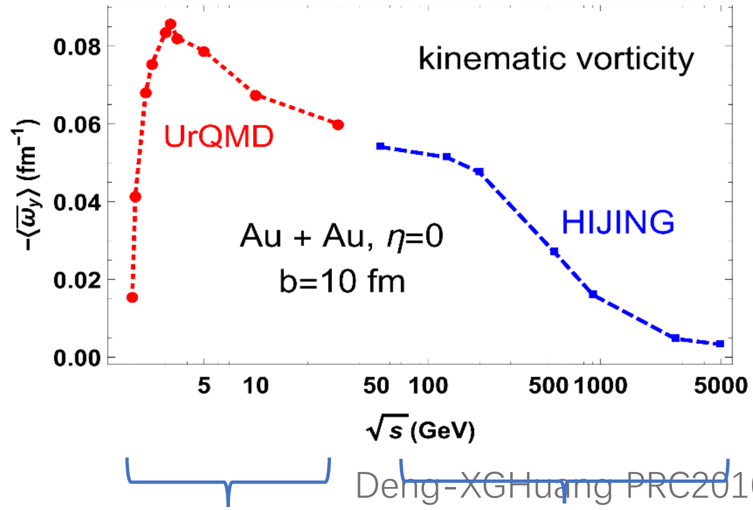


ROTATION

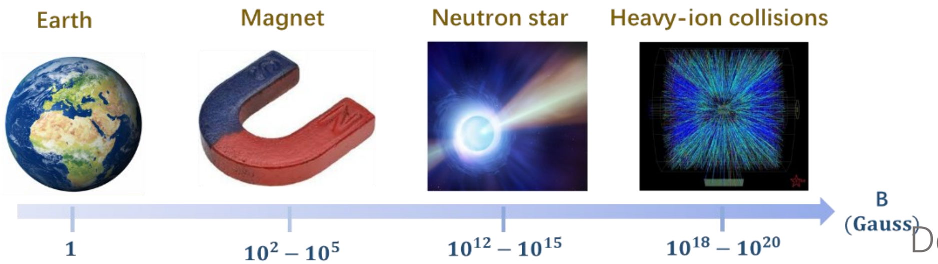


HIJING (Deng-XGHuang PRC2012)





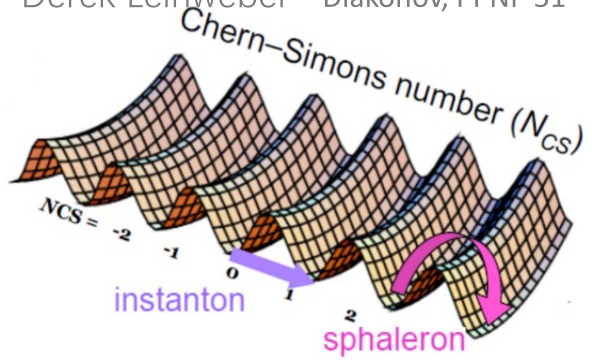
Deng-XGHuang PRC2016



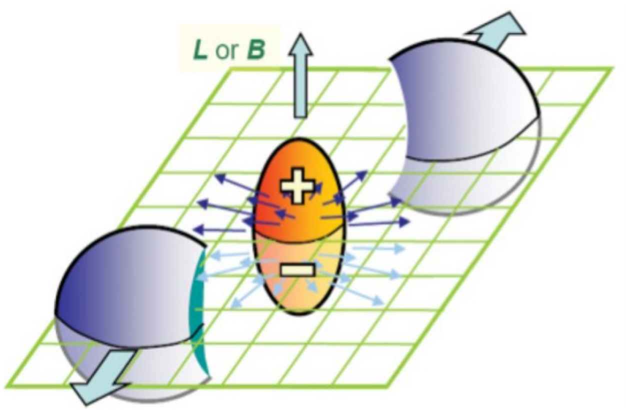
Deng-XGHuang-GLMa-Zhang PRC2020

手征反常及手征磁效应

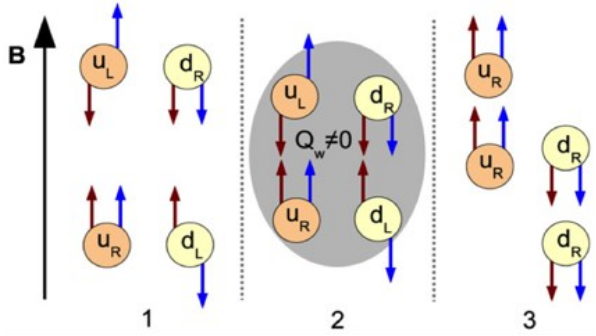
Derek Leinweber   Diakonov, PPNP 51



Kharzeev, et al. NPA 803 (2008) 227



- **QCD 真空涨落**
  - 非零拓扑荷规范场
  - 局域P/CP对称性破缺
  - 非零手征化学势μ_5
- **强磁场**
  - 依赖手征性和电荷的粒子运动
  - 相反的左右手电流



手征磁效应

磁场方向电流

$$J_{CME} = \frac{e^2}{2\pi^2}\mu_5 B$$

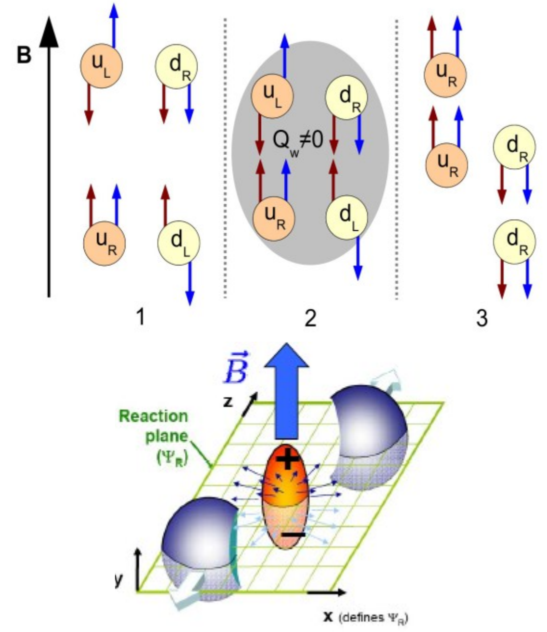
手征磁效应有助于理解QCD真空和P/CP对称性破缺

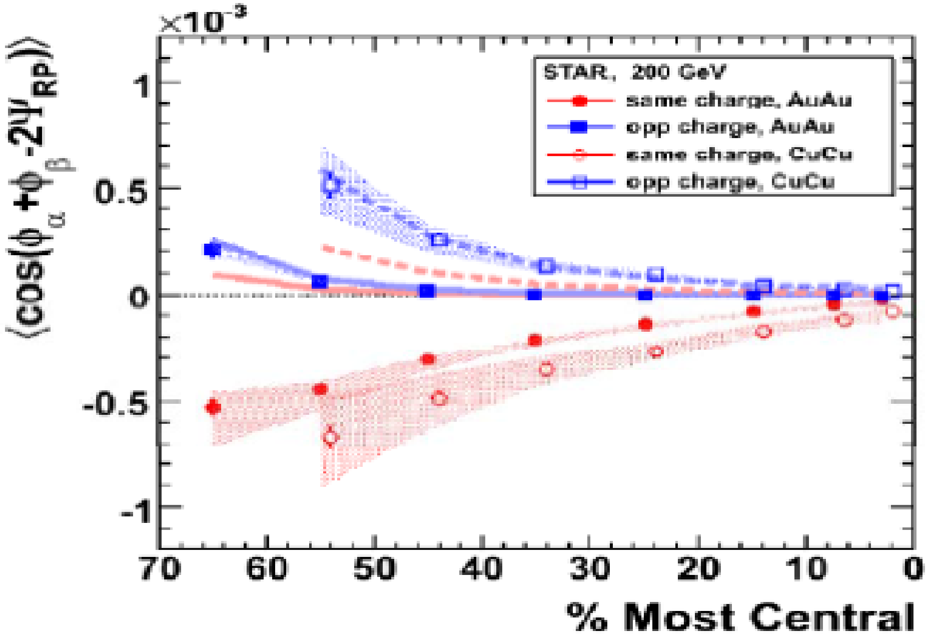
Chiral Magnetic Effect reveals the topology of gauge fields in heavy-ion collisions

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

Fukushima,Kharzeev,Warringa 2008

CME ⟺ Charge Separation





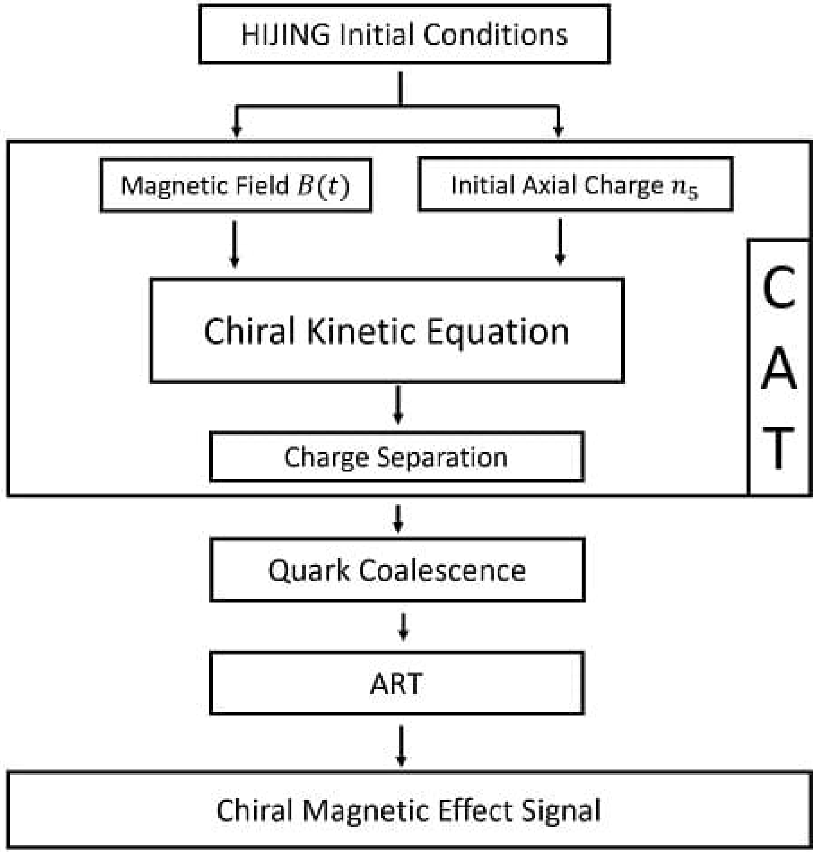
STAR Collaboration PRL103(2009)251601

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

Qiye Shou, …
Gang Wang, Huanzhong Huang, …
Fuqiang Wang, …

手征反常输运模型

	基础AMPT	AMPT-手征输运模型
磁场	不包含	$e\mathbf{E}(t,\mathbf{r}) = \frac{e^2}{4\pi}\sum_n Z_n \frac{\mathbf{R}_n - R_n\mathbf{v}_n}{(R_n - \mathbf{R}_n\cdot\mathbf{v}_n)^3}(1-v_n^2),$ $e\mathbf{B}(t,\mathbf{r}) = \frac{e^2}{4\pi}\sum_n Z_n \frac{\mathbf{v}_n \times \mathbf{R}_n}{(R_n - \mathbf{R}_n\cdot\mathbf{v}_n)^3}(1-v_n^2),$
手征性	不包含	$\mu_5 = f(T, eB)$ $n_5 = \pm(\frac{\mu_5^3}{3\pi^2} + \frac{\mu_5 T^2}{3})$
粒子动力学	$\dot{\vec{r}} = \hat{k}$ $\dot{\vec{k}} = 0$	$\dot{\mathbf{r}} = \frac{\hat{\mathbf{p}} + Q\lambda(\hat{\mathbf{p}}\cdot\mathbf{b})\mathbf{B} + 2\lambda p(\hat{\mathbf{p}}\cdot\mathbf{b})\boldsymbol{\omega}}{1 + Q\lambda\mathbf{b}\cdot\mathbf{B} + 6\lambda p(\mathbf{b}\cdot\boldsymbol{\omega})},$ $\dot{\mathbf{p}} = \frac{Q\hat{\mathbf{p}}\times\mathbf{B}}{1 + Q\lambda\mathbf{b}\cdot\mathbf{B} + 6\lambda p(\mathbf{b}\cdot\boldsymbol{\omega})},$
手征磁效应	人为输入初始信号	自然地产生电流和电荷分离
拓展性	有限	较好.可以添加涡旋,平均场作用等等量子效应



手征输运模型结构框架

Zilin Yuan, Anping Huang, Wen-Hao Zhou,Guo-Liang Ma, Mei Huang, Phys.Rev.C 109 (2024) 3, L031903
• e-Print: 2310.20194 [hep-ph]

手征动力学

Boltzmann equation

$$\left\{\partial_t + \dot{\mathbf{x}}\cdot\nabla_{\mathbf{x}} + \dot{\mathbf{p}}\cdot\nabla_{\mathbf{p}}\right\} f_\chi^i(x,\mathbf{p}) = C[f_\chi^i].$$

电磁场下的作用量

$$I = \int_{t_i}^{t_f} (\mathbf{p}\cdot\dot{\mathbf{x}} + \mathbf{A}\cdot\dot{\mathbf{x}} - \Phi - |\mathbf{p}| - \mathbf{a_p}\cdot\dot{\mathbf{p}})dt$$

电磁场下的运动方程

$$\dot{\mathbf{x}} = \frac{1}{\sqrt{G}}\left(\tilde{\boldsymbol{v}} + \hbar q_i(\tilde{\boldsymbol{v}}\cdot\mathbf{b}_\chi)\mathbf{B} + \hbar q_i\widetilde{\mathbf{E}}\times\mathbf{b}_\chi\right),$$

$$\dot{\mathbf{p}} = \frac{q_i}{\sqrt{G}}\left(\widetilde{\mathbf{E}} + \tilde{\boldsymbol{v}}\times\mathbf{B} + \hbar q_i(\widetilde{\mathbf{E}}\cdot\mathbf{B})\mathbf{b}_\chi\right).$$

其中:

螺旋度 $\chi = \pm 1$

Jacobian $\sqrt{G} = (1 + \hbar q_i \mathbf{b}_\chi \cdot \mathbf{B})$

Berry curvature $b_\chi = \dfrac{\chi\,\hat{p}}{2|p|^2}$

M. A. Stephanov and Y. Yin. Phys. Rev. Lett., 109:162001, 2012.
Dam Thanh Son and Naoki Yamamoto. Phys. Rev. Lett., 109:181602, 2012.
Dam Thanh Son and Naoki Yamamoto. Phys. Rev. D, 87(8):085016, 2013.
Jiunn-Wei Chen, Shi Pu, Qun Wang, and XinNian Wang. Phys. Rev. Lett., 110(26):262301, 2013

金金200GeV碰撞模拟结果

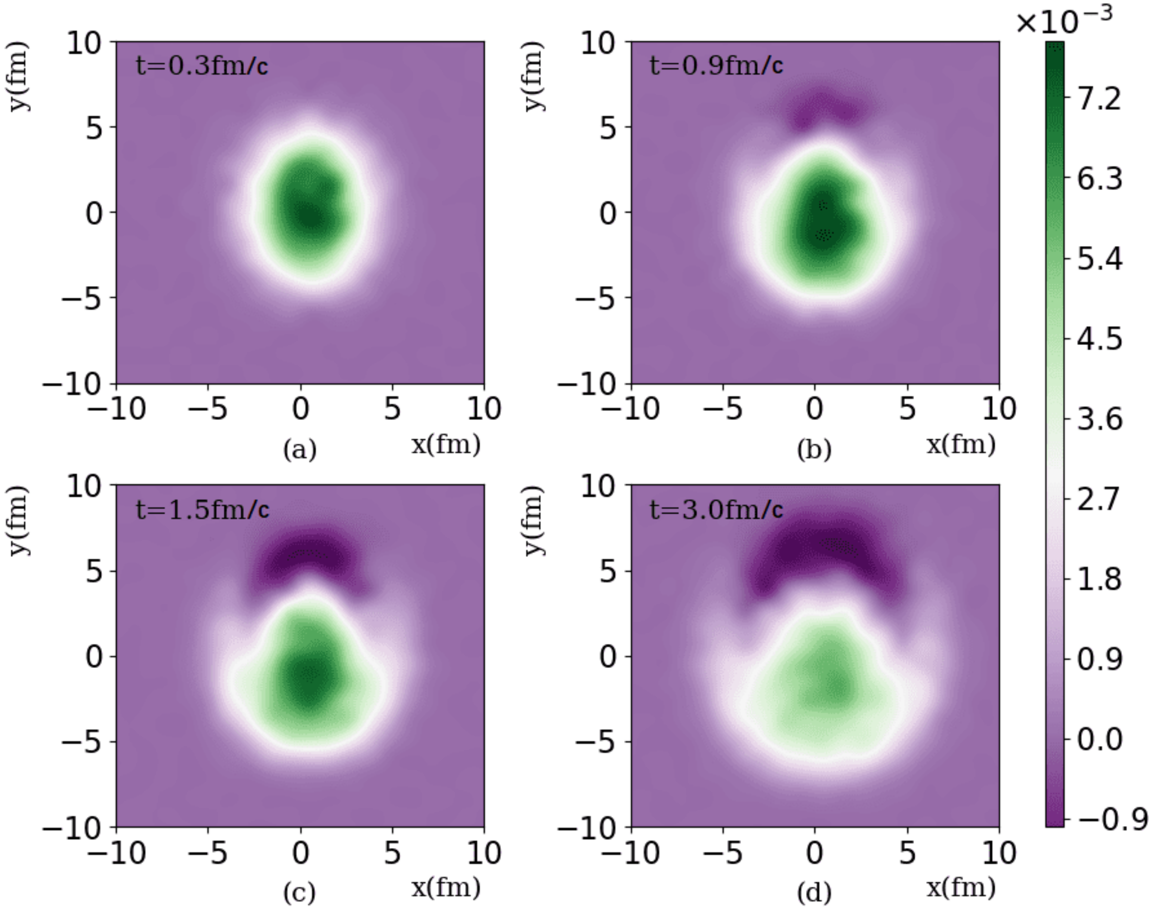
引入磁场和手征反常后
电荷随时间发生上下分离
即沿磁场方向(y轴方向)出现电流

系统演化中出现手征磁效应

由于系统整体带正电,电荷分离并不对称

$$n_5 = \pm(\frac{\mu_5^3}{3\pi^2} + \frac{\mu_5 T^2}{3})$$

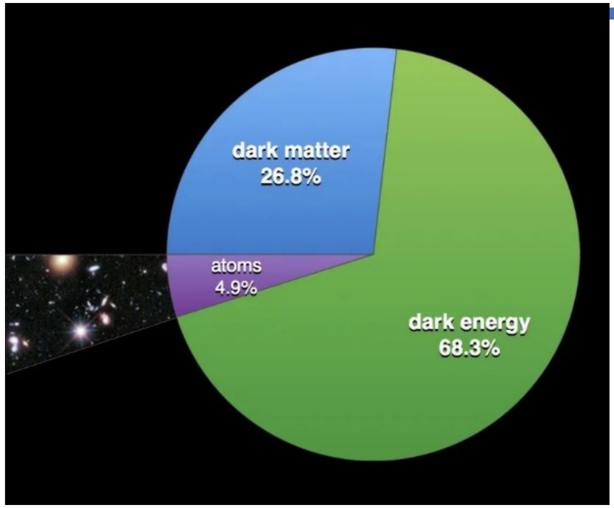
n_5正负性决定电荷分离图案的方向



局域电荷在碰撞平面上分布

Zilin Yuan, Anping Huang, Wen-Hao Zhou,Guo-Liang Ma, Mei Huang, Phys.Rev.C 109 (2024) 3, L031903
- e-Print: 2310.20194 [hep-ph]

Searching for imprints of QCD epoch in the early universe



Our universe is composed of 5% visible matter, 99% mass of visible matter is obtained from chiral symmetry breaking of QCD.

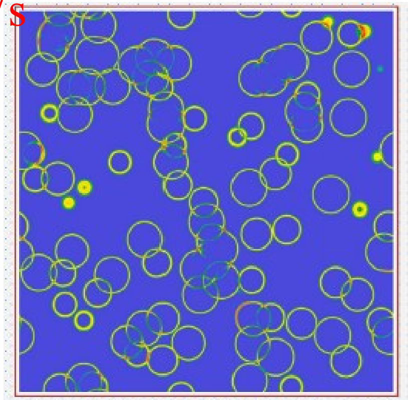
At around 10^{-5}s, the early universe experiences QCD phase transition.

Connecting Quarks with the Cosmos

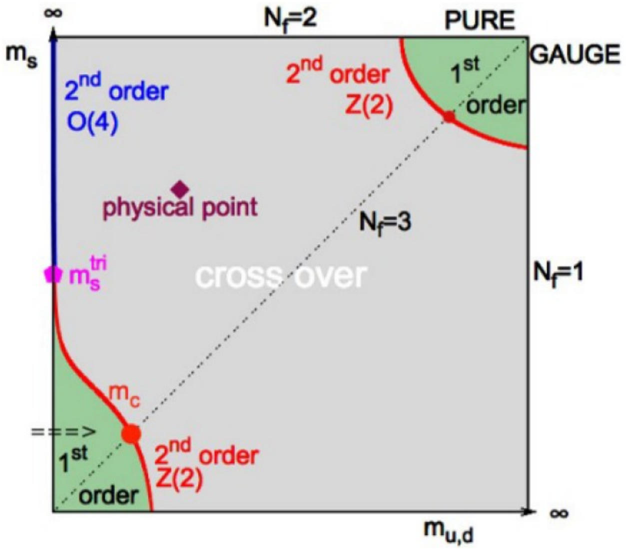
Eleven Science Questions for the New Century

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

Stochastic background GWs



Hindmarsh, et al, 2015



1^{st} order PT (FOPT) in QCD epoch:

pure gluon system,

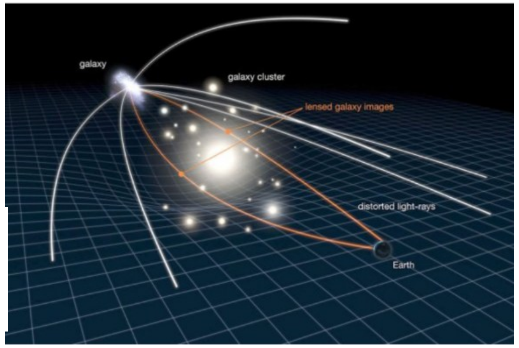
chiral phase transition

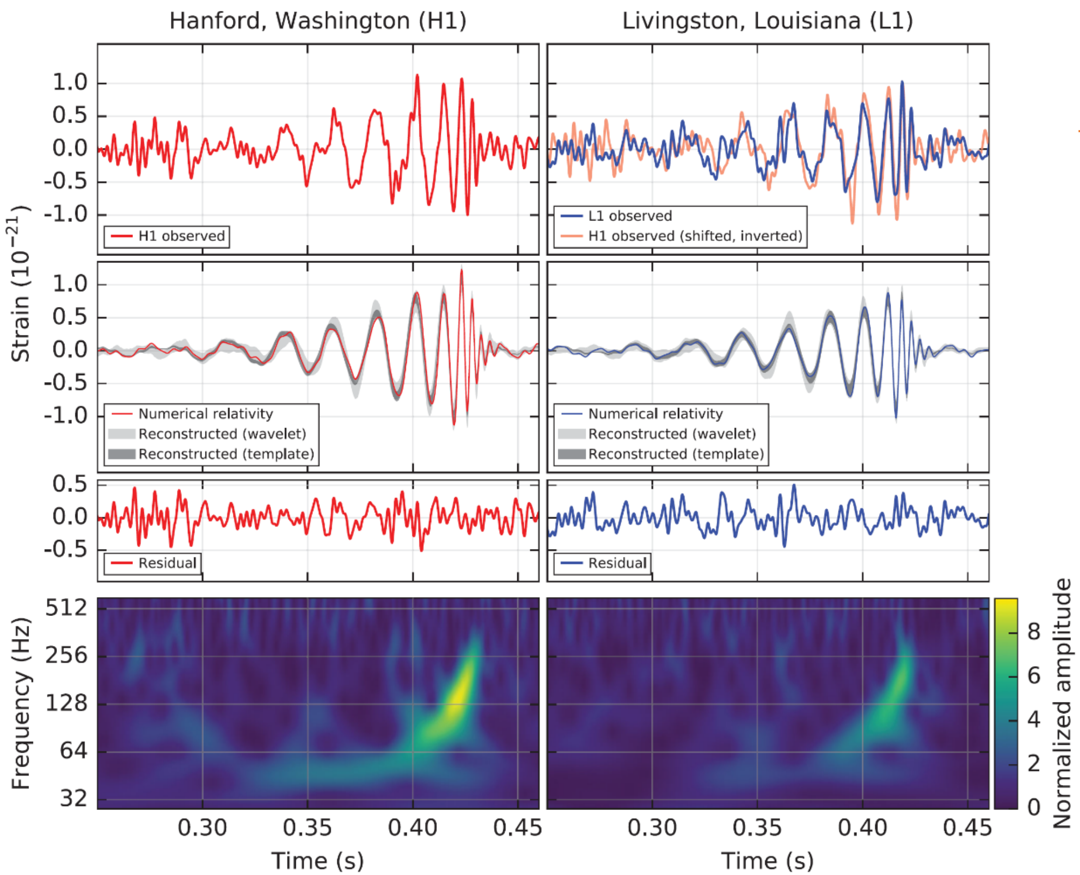
……

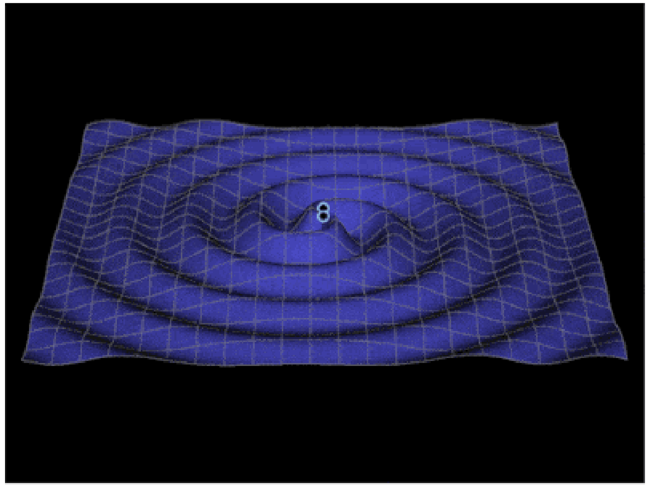
PBHs

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

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







GW150914

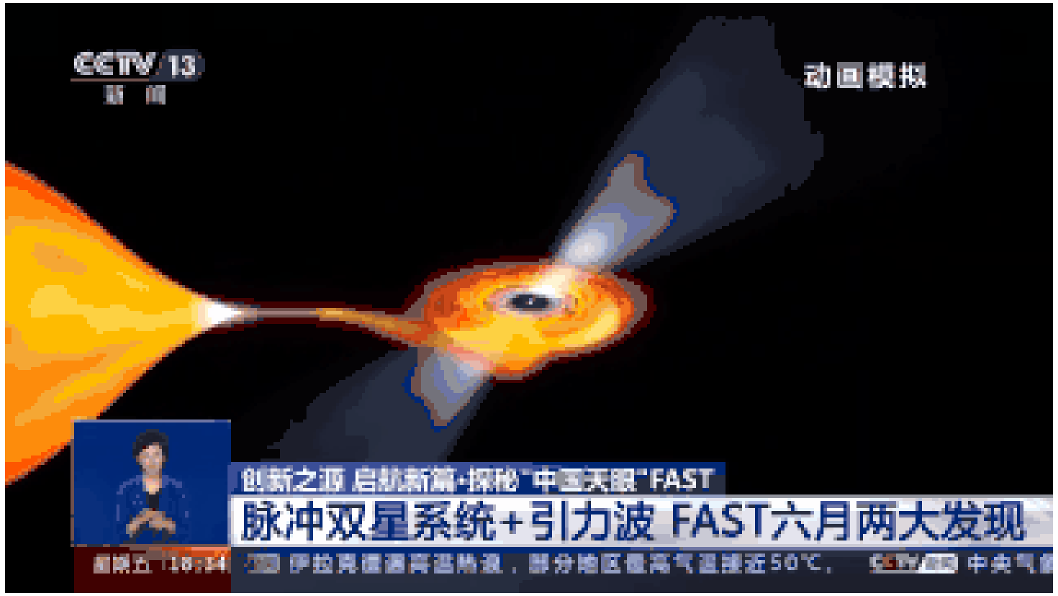
距离地球 410 兆秒差距的两个质量分别 36 个太阳质量和 29 个太阳质量的黑洞并合为一个质量为 62 个太阳质量的黑洞。

GW170817

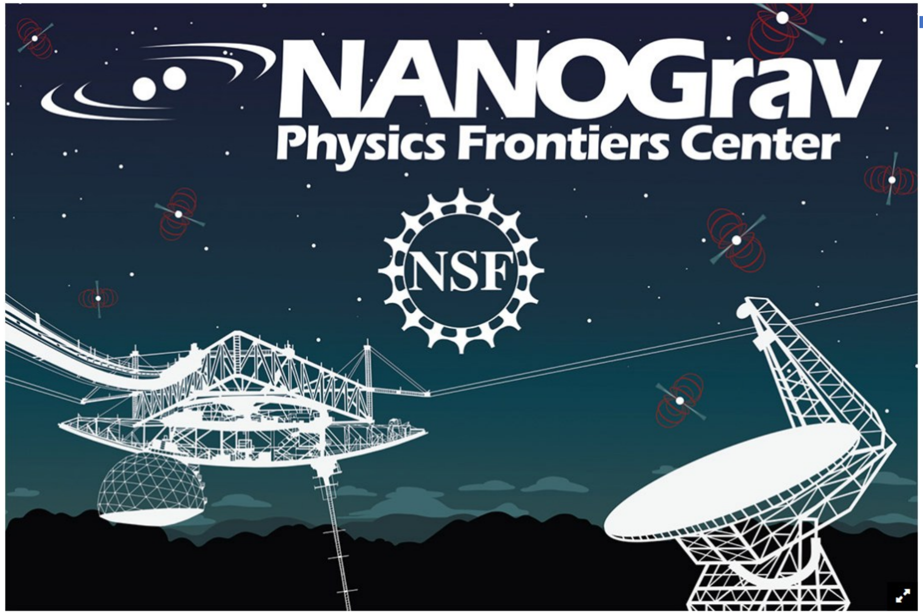
两个中子星并合事件

Nobel Prize in Physics 2017

中国科学院国家天文台
500米口径球面射电望远镜FAST



2023年6月29日，FAST探测到宇宙中神秘的纳赫兹引力波



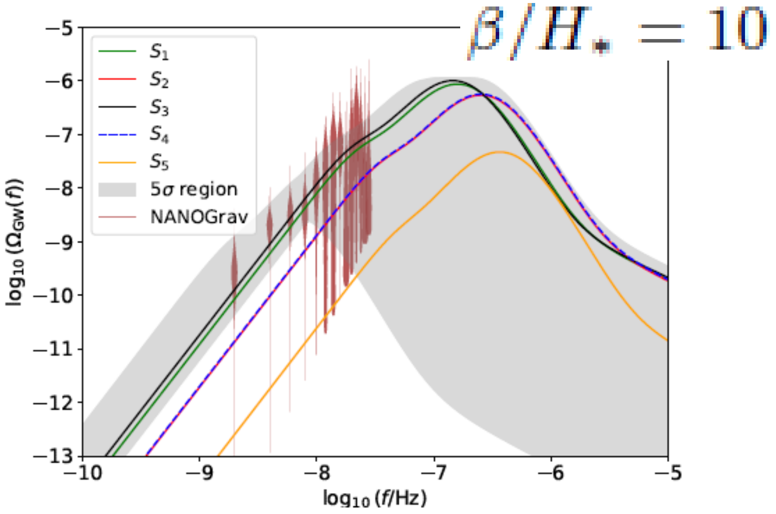
https://www.rit.edu/news/nsf-renews-funding-rit-help-detect-and-characterize-low-frequency-gravitational-waves

nHz GWs needs $\frac{\beta}{H}\sim 10$

Constrained Transition rate

$$\frac{\beta}{H_*} = T_n \frac{\mathrm{d}(\frac{S_3}{T})}{\mathrm{dT}}\Big|_{T_n}$$

Z.C.Chen et al. 2312.01824v2



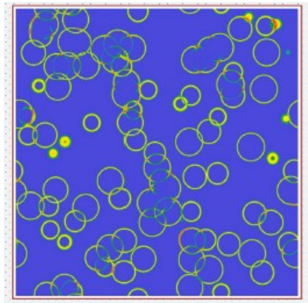
Measure the inverse duration of the phase transition

The bubble nucleation rate per Hubble volume per time

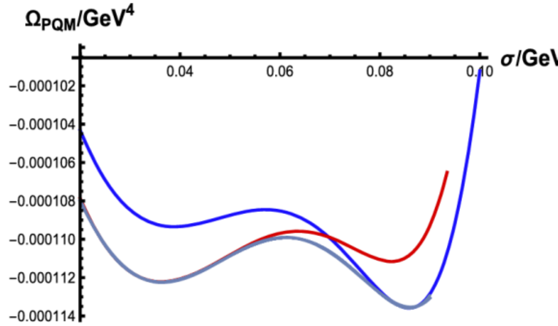
$$\Gamma(T) = T^4\left(\frac{S_3}{2\pi T}\right)^{\frac{3}{2}} e^{-\frac{S_3}{T}}$$

$$\frac{\Gamma(T_n)}{H^4}\sim 1$$

Nucleation at T_n



Hindmarsh, et al, 2015



(b)

Huge $\frac{\beta}{H}$ in 1st-order QCD Phase transitions?

Chirality imbalanced system: a FOPT

Described by Integer Chern-Simons Number Q_w, N_{cs}

$$Q_w = \frac{g^2}{32\pi^2}\int \mathrm{d}^4x F^a_{\mu\nu}\tilde{F}^{\mu\nu}_a \in \mathbb{Z}$$

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

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

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

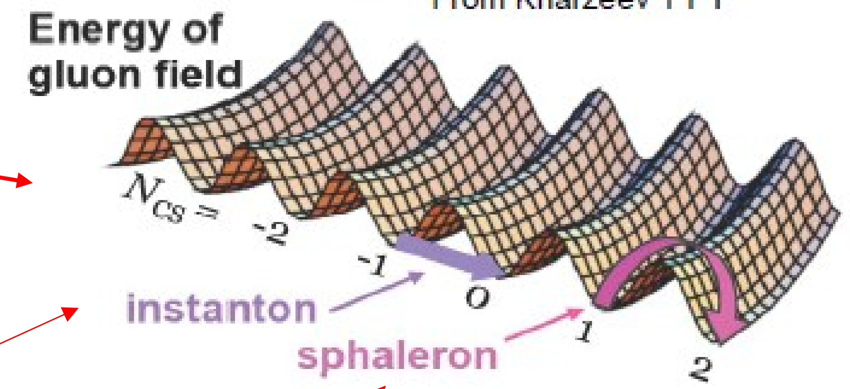
Instanton-anti-instanton pairing molecule.

$Tc \sim 2Tc$, induce negative G_A

Transition at low or zero temperature: instanton

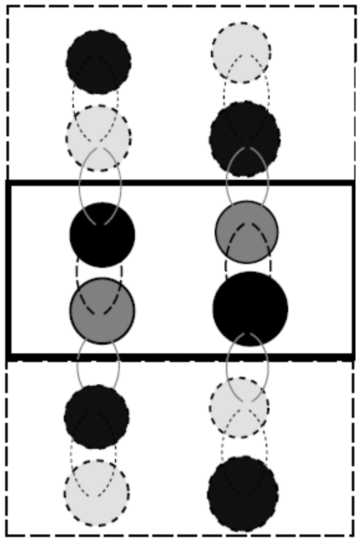
QCD θ vacuum structure

From Kharzeev' PPT

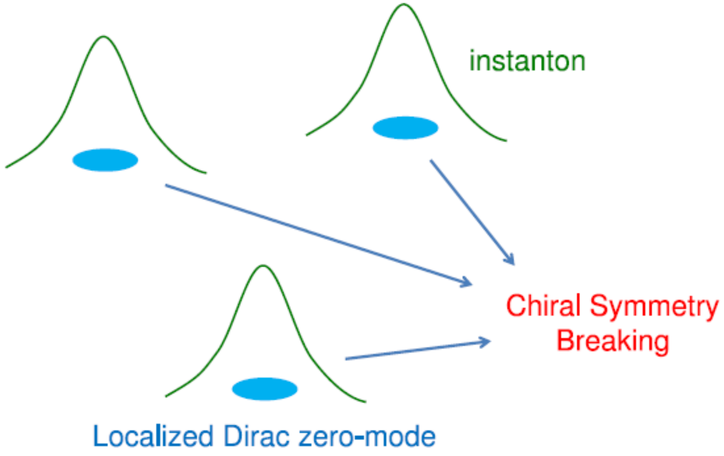


Transition at finite temperature: sphaleron

T~Tc



Schafer, Shuryak, Verbaarschot 9406210



Can QCD phase transitions generate NanoGWs?

$\frac{\beta}{H} \sim 10^{4-5}$

NanoGWs need, but…

$\beta / H = 10$

Chiral PT: A.J. Hemboldt et al. Phys. Rev. D, 100(5):055025, 2019

benchmark point	effective model	T_c [MeV]	T_n [MeV]	$g_* \alpha$	β/H [10^4]	γ	b
A	NJL	71.7	70.5	3.4	1.8	1.76	$1.3 \cdot 10^{-1}$
	PNJL	121.8	121.4	1.1	9.4	1.82	$5.0 \cdot 10^{-3}$
	LSM	101.8	101.0	0.8	4.4	1.86	$1.8 \cdot 10^{-2}$
B	NJL	107.1	106.4	2.6	4.3	1.80	$2.3 \cdot 10^{-2}$
	PNJL	140.5	140.2	2.0	13.8	1.87	$2.0 \cdot 10^{-3}$
	LSM	145.8	145.3	0.7	8.6	1.89	$4.6 \cdot 10^{-3}$
C	NJL	90.8	90.6	1.2	11.1	1.81	$4.0 \cdot 10^{-3}$
	PNJL	131.3	131.1	0.9	45.7	1.85	$2.4 \cdot 10^{-4}$
	LSM	100.5	99.9	1.1	5.7	1.87	$1.1 \cdot 10^{-2}$
D	NJL	180.3	180.3	0.4	162.6	1.92	$1.4 \cdot 10^{-5}$
	PNJL	198.3	198.3	0.3	244.9	1.86	$9.7 \cdot 10^{-6}$
	LSM	175.3	174.5	1.2	7.8	1.91	$5.0 \cdot 10^{-3}$

J. Shao and M. Huang, Phys.Rev. D 107 043011 (2023)
doi:10.1103/PhysRevD.107.043011 [arXiv:2209.13809 [hep-ph]].

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

Holographic QCD

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

Yidian Chen et al. 2212.06591v1

	α	β/H ($v_w = 1$)	β/H (0.1)	β/H (0.01)
$T_c = 50$ MeV	0.343	9.0×10^4	8.6×10^4	8.2×10^4
100 GeV	0.343	6.8×10^4	6.4×10^4	6.1×10^4

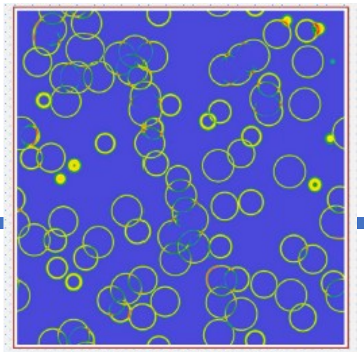
Enrico Morgante et al. 2210.11821v3

Deconfinement PT: Fei Gao et al. 2405.00490v1

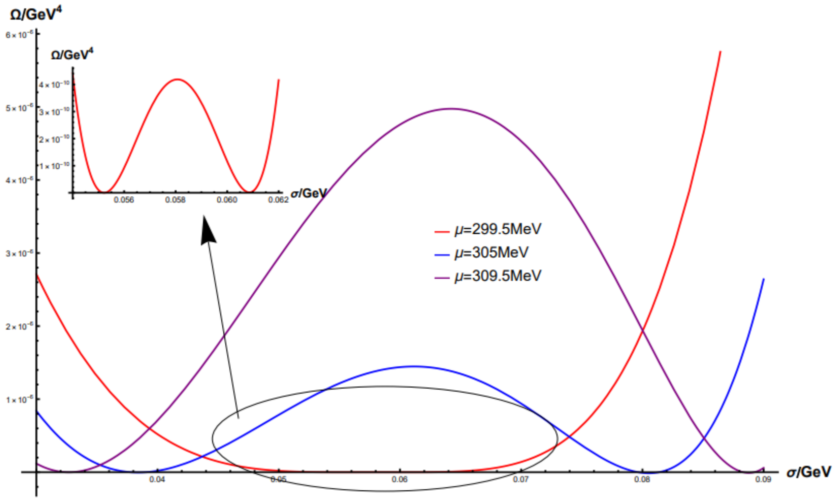
N_c	3	5	10	25	50
$g_* \alpha$	0.65	2.14	5.72	49.76	197.74
$\beta/H \times 10^{-5}$	1.36	1.02	1.18	1.43	1.66

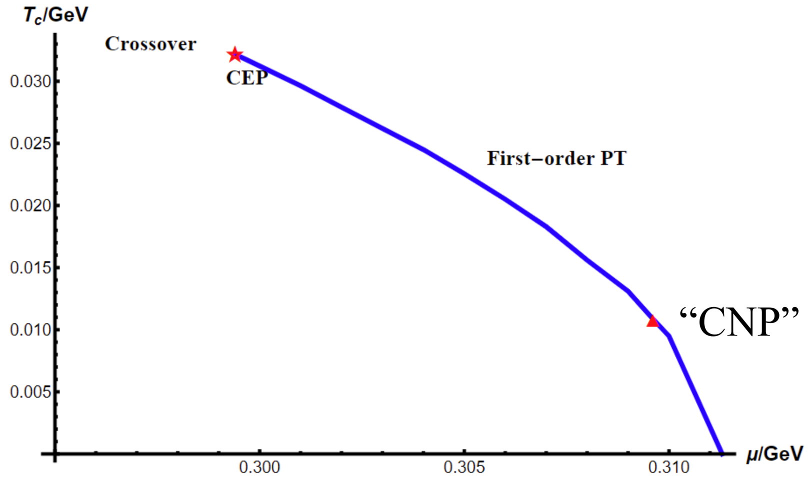
Dynamical 1st-order phase transition: false vacuum decay rate

Jingdong Shao, Hong Mao, MH,
arXiv: 2410.06780, 2410.00874



Hindmarsh, et al, 2015

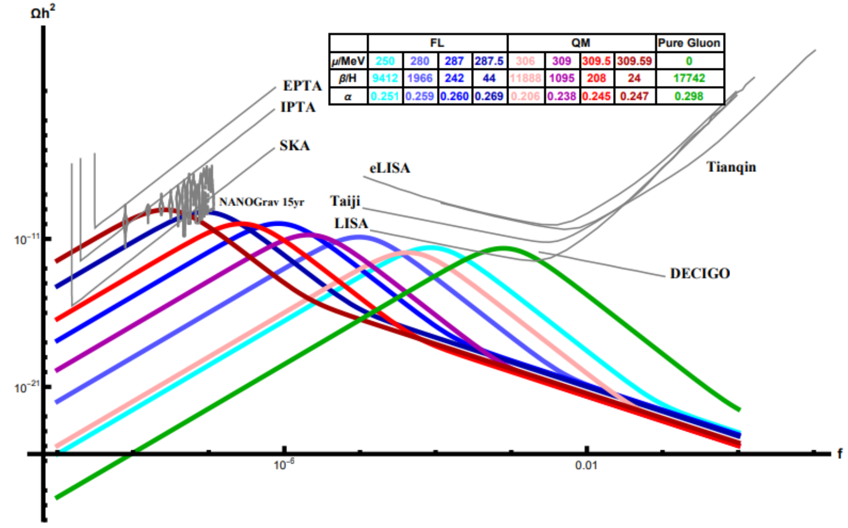




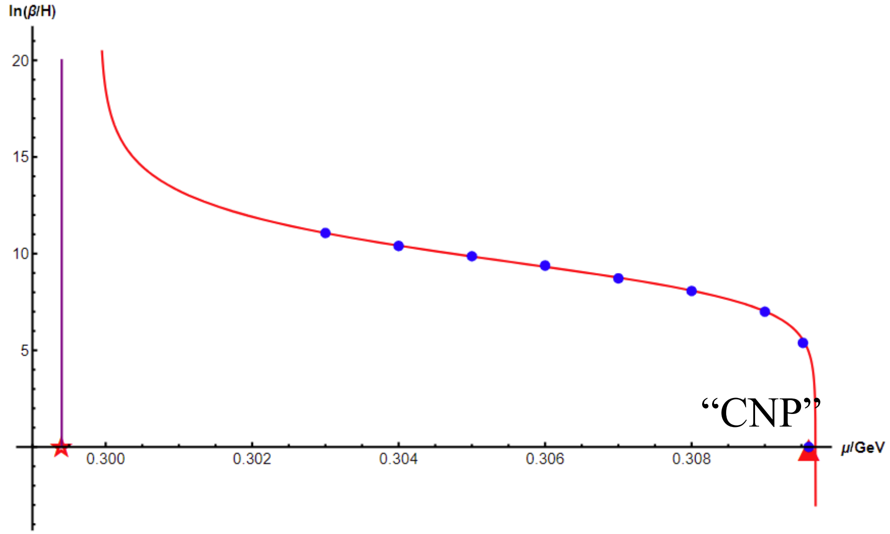
临界成核点

Long-lived false vacuum

高密核物质- >蓄核能池？



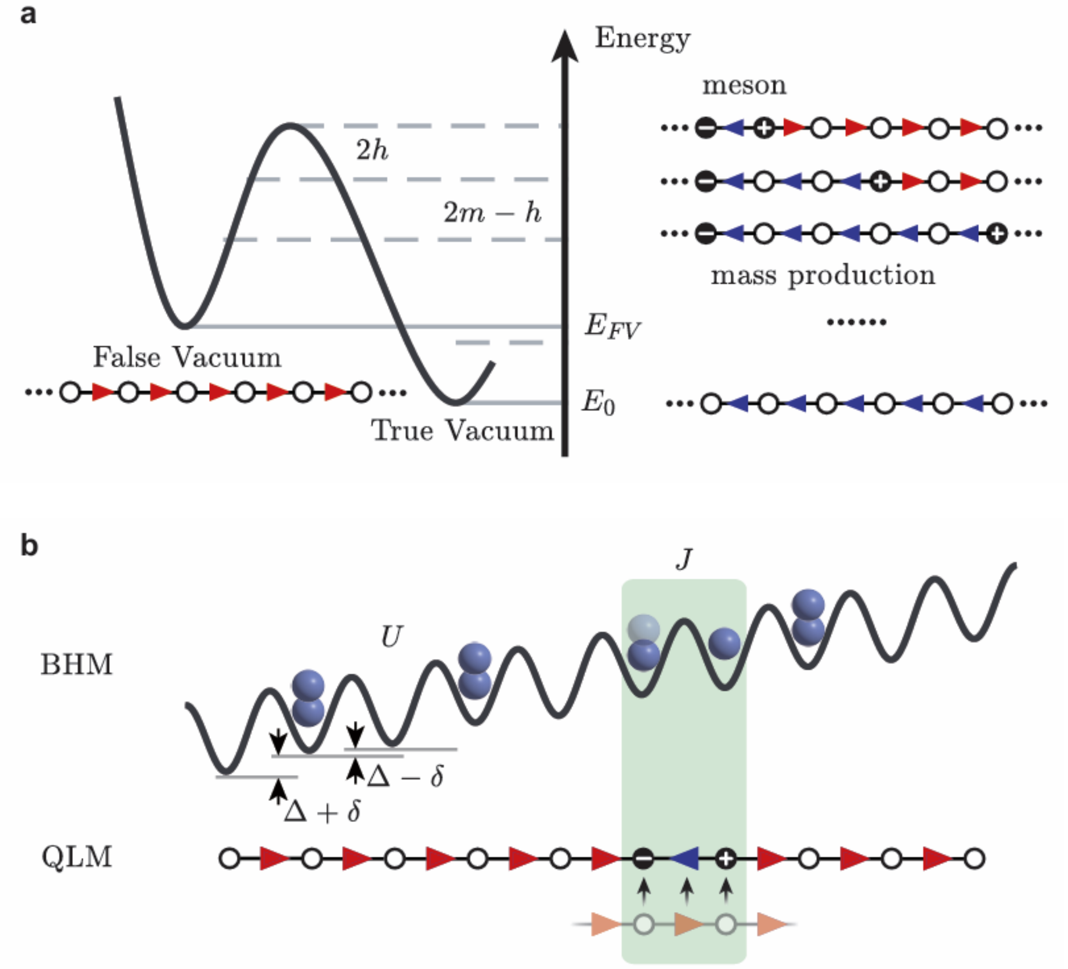
	FL				QM				Pure Gluon
μ/MeV	250	280	287	287.5	306	309	309.5	309.59	0
β/H	9412	1966	242	44	11888	1095	208	24	17742
α	0.251	0.259	0.260	0.269	0.206	0.238	0.245	0.247	0.298



10^45GeV/m^3

Probing false vacuum decay on a cold-atom gauge-theory quantum simulator

Zi-Hang Zhu, Ying Liu, Gianluca Lagnese, Federica Maria Surace, Wei-Yong Zhang, Ming-Gen He, Jad C. Halimeh, Marcello Dalmonte, Siddhardh C. Morampudi, Frank Wilczek, Zhen-Sheng Yuan, Jian-Wei Pan



arXiv:2411.12565

总结

- 基于规范/引力对偶的全息QCD模型提供了一种求解夸克和胶子强耦合系统的理论方案，在强子物理（强子谱和结构）、QCD相变、非平衡演化等问题有较好的描述，进一步的发展和完善在进行中…
- 近几年多种非微扰方法对手征相变的临界点的位置达到了一致。期待实验上的后续测量结果。
- 宇宙早期QCD相变的痕迹以及对宇宙演化的贡献仍然在进行中。
- 动力学一级相变假真空衰变的能量的方式是否可以做为一种新的能源方式？（脑洞）


中国科学院大学
University of Chinese Academy of Sciences
感谢！
Many Thanks