



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

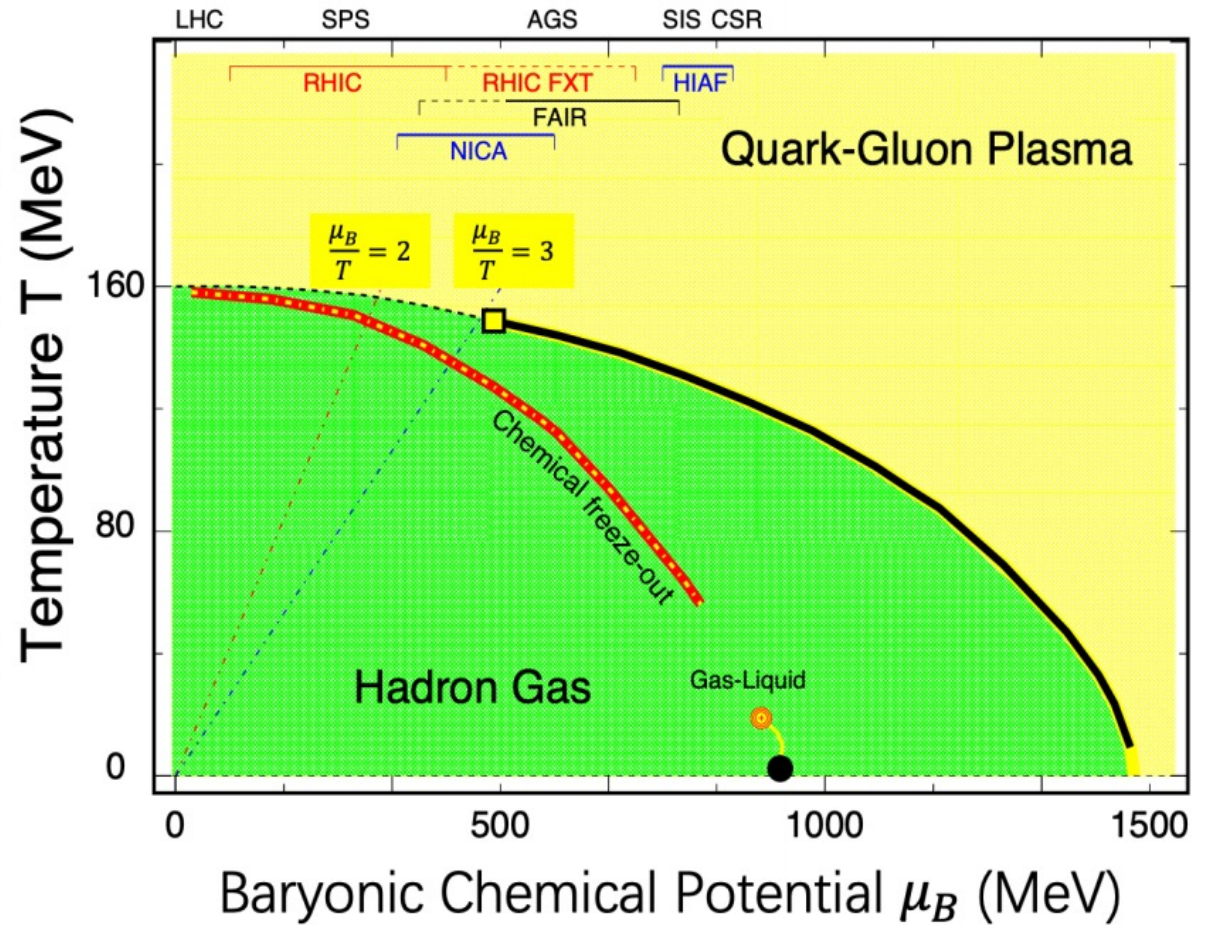
# QCD Phase Structure at high baryon density

Mei Huang



高能与低能核物理交叉学术研讨会，华东师范大学， 2026年5月15-18日

# High baryon density QCD phase structure @HIAF



CEP 许怒报告

# Why there must be CEP at high baryon density

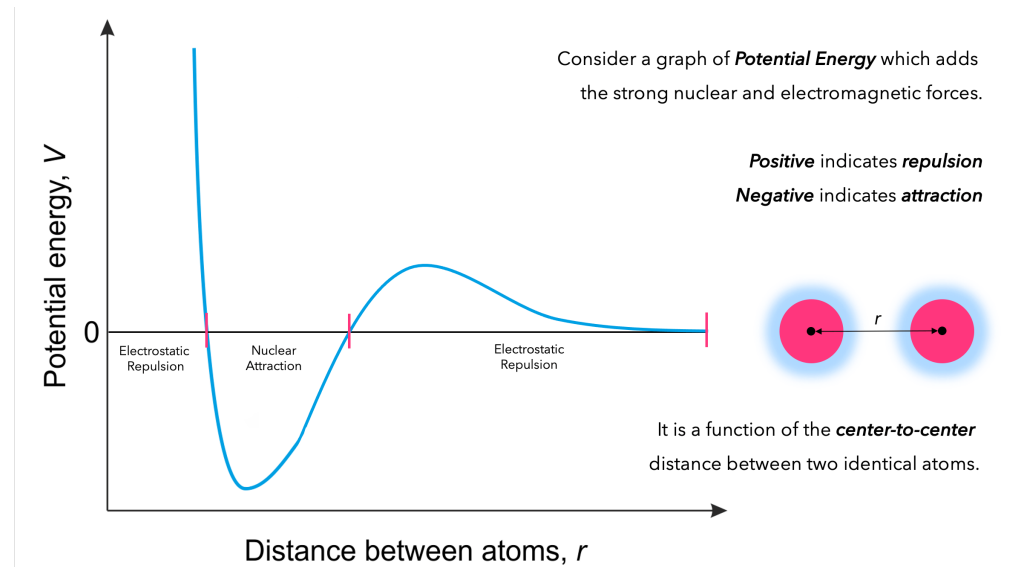
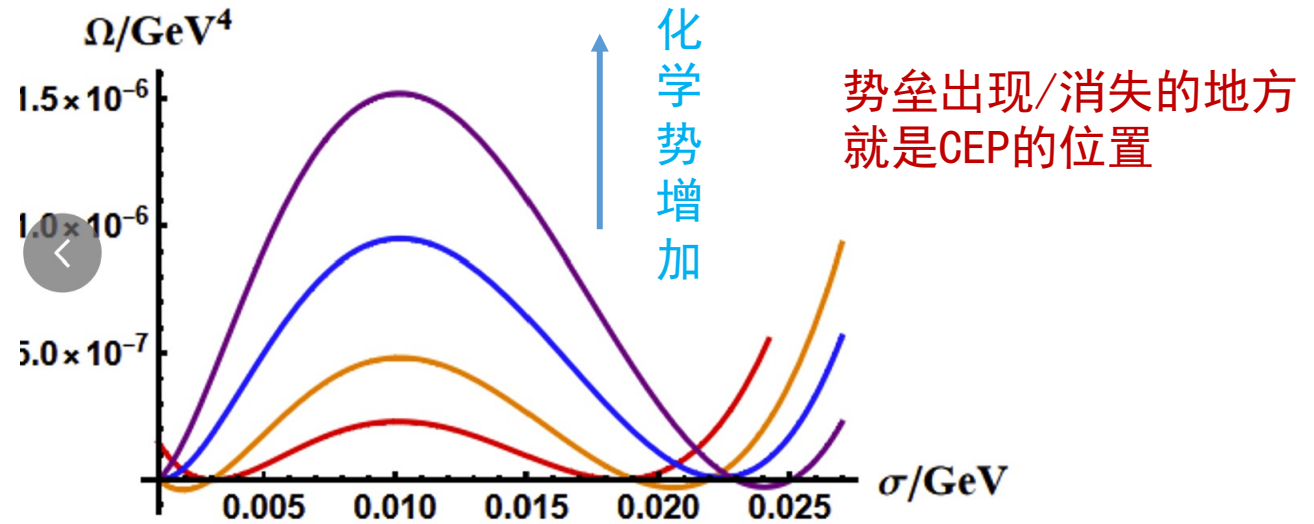
CEP is the end point of 1<sup>st</sup> order phase transition.

potential barrier is needed for 1<sup>st</sup>-order phase transition.

Baryon chemical potential, an effective repulsive vector interaction, develops a potential barrier at high baryon density

夸克化学势与排斥矢量相互作用物理等价，排斥矢量相互作用对应一个势垒如库伦势垒

$$\mathcal{L}_\mu = \mu_q \bar{\psi} \gamma_0 \psi$$

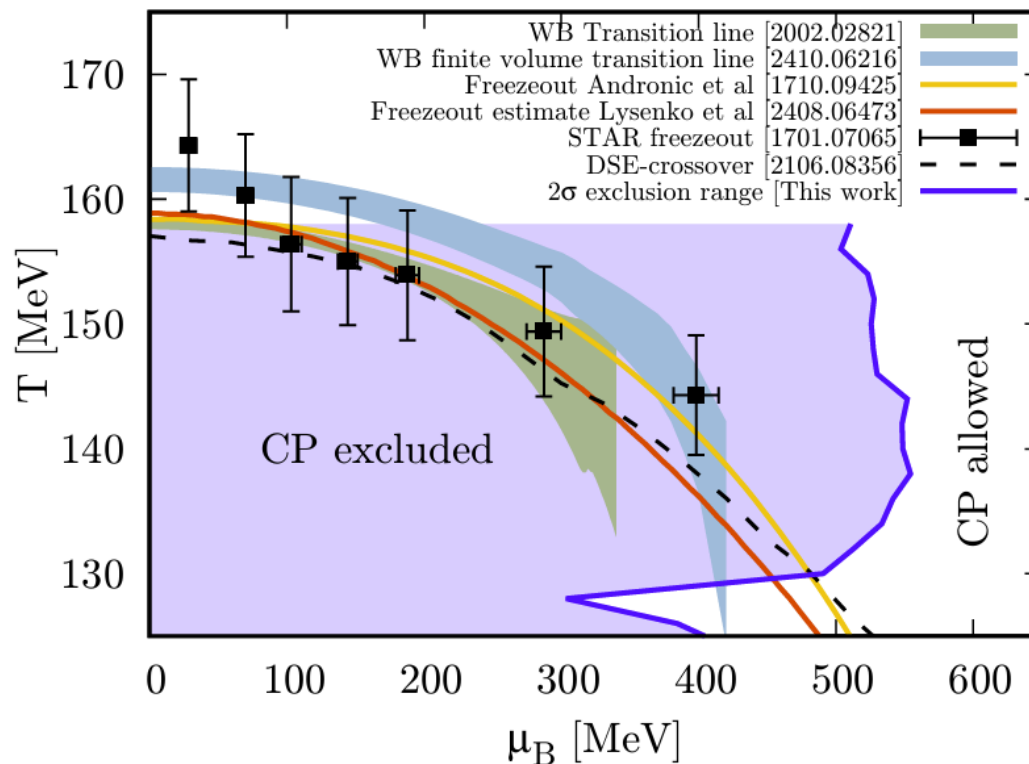


# CEP 位置：最新格点结果

虚化学势+解析延拓，  
格点结果排除CEP位于低密区，

排除了重子化学势低于 450 MeV，  
对应重离子碰撞能量7.7 GeV。

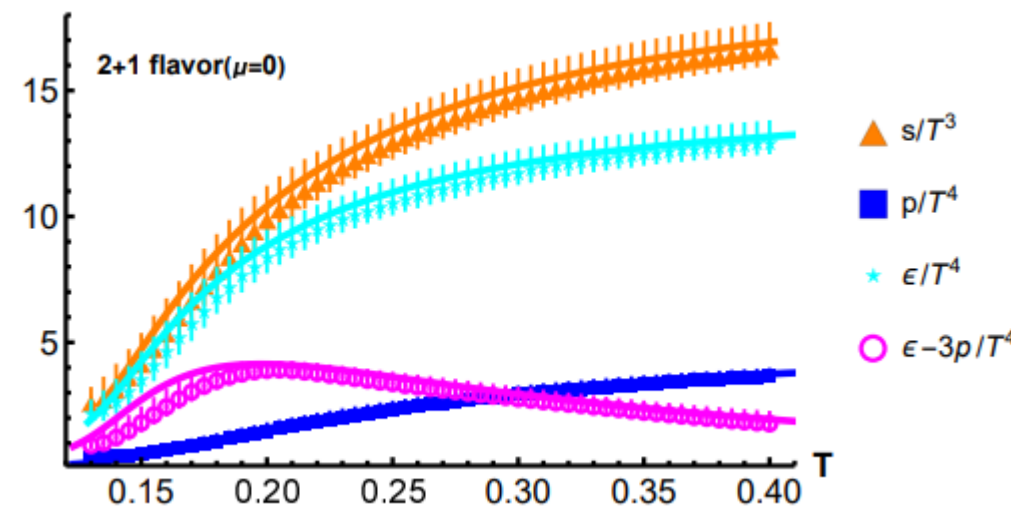
$$\mu_B(\sqrt{s}) = \frac{1.477}{1 + 0.343\sqrt{s}}.$$



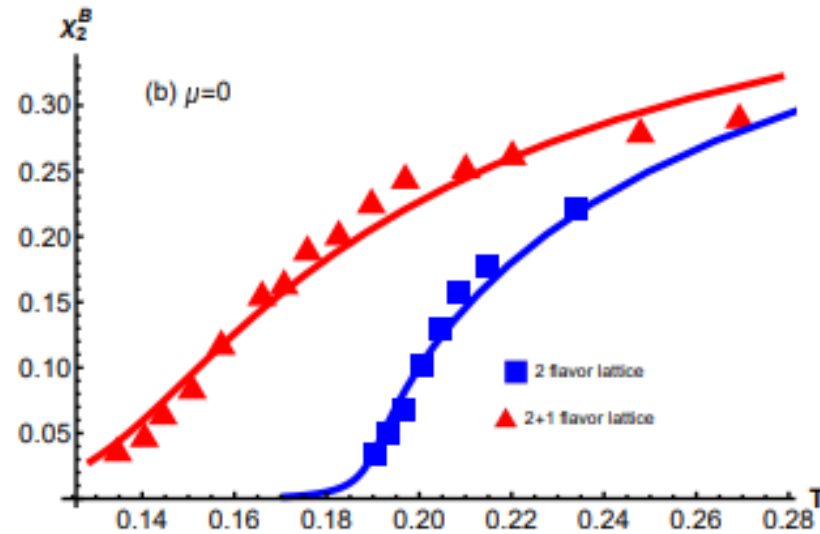
Lattice QCD constraints on the critical point,  
Szabolcs Bors'anyi,1 Zolt'an Fodor, et.al., ...arXiv: 2502.10267

# CEP 位置：理论结果

需在 $\mu=0$ , 与格点QCD结果在有限温的热力学性质一致

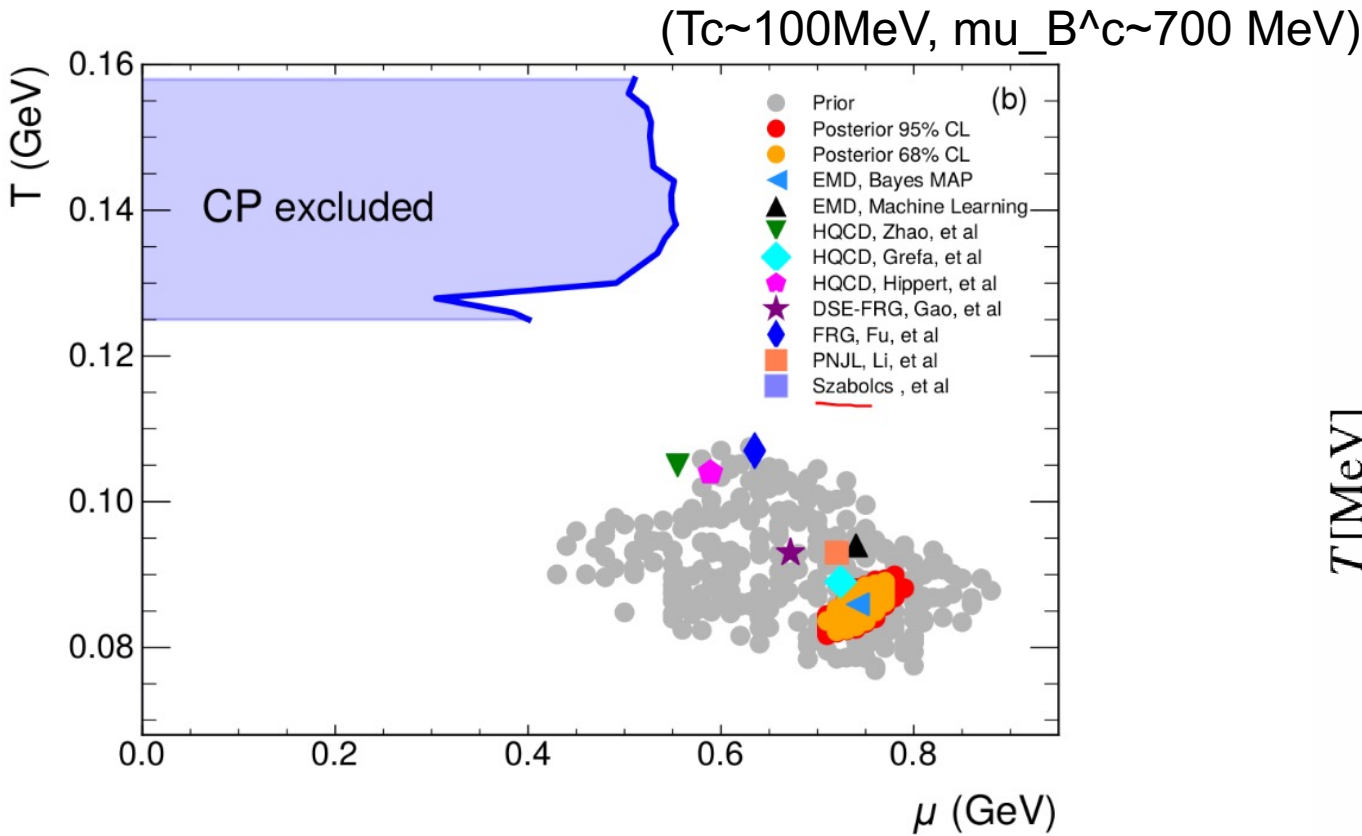


确定 $\mu=0$ 时的 $T_c$

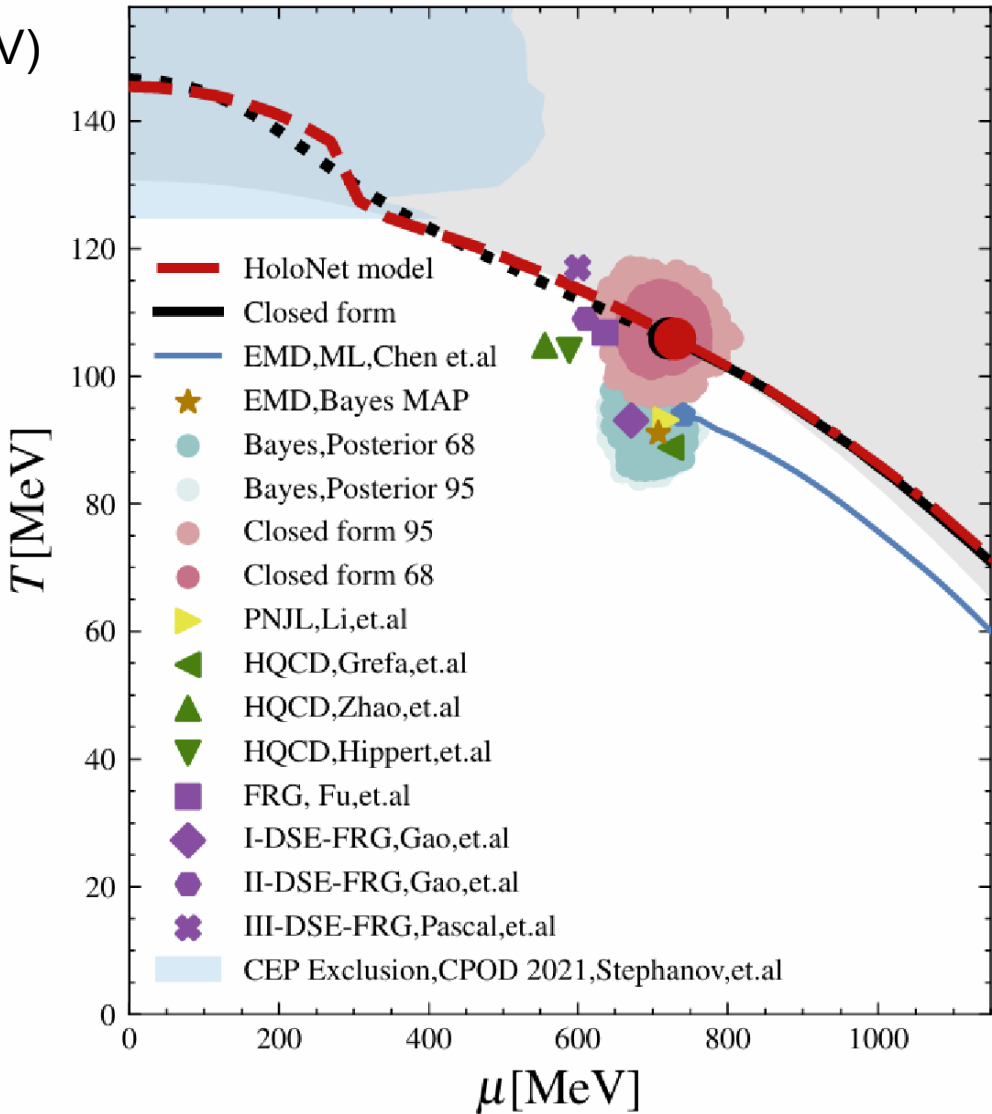


确定 $T_c$ 随 $\mu$ 的变化

CEP 位置：理论结果



*Bayesian+hQCD: Liqiang Zhu, Xun Chen, Kai Zhou,  
PRD(2025), e-Print: 2501.17763*

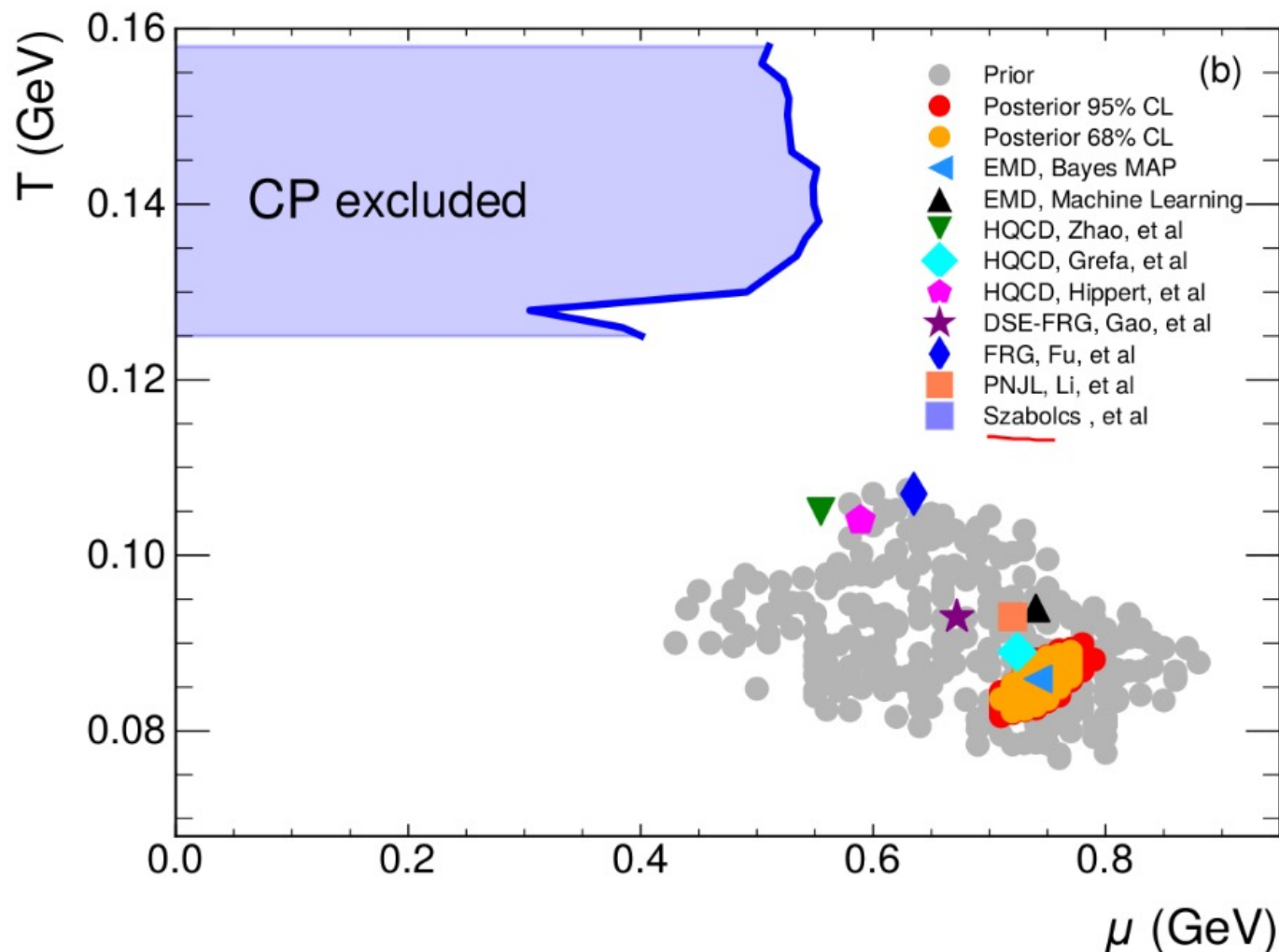


*Hongan Zeng, Lingxiao Wang, MH, arXiv:2602.21618*

## CEP 位置：理论结果

只要在 $\mu=0$ , 与格点QCD结果在有限温度的热力学性质一致, 各非微扰模型得到的**CEP**位置趋向一致

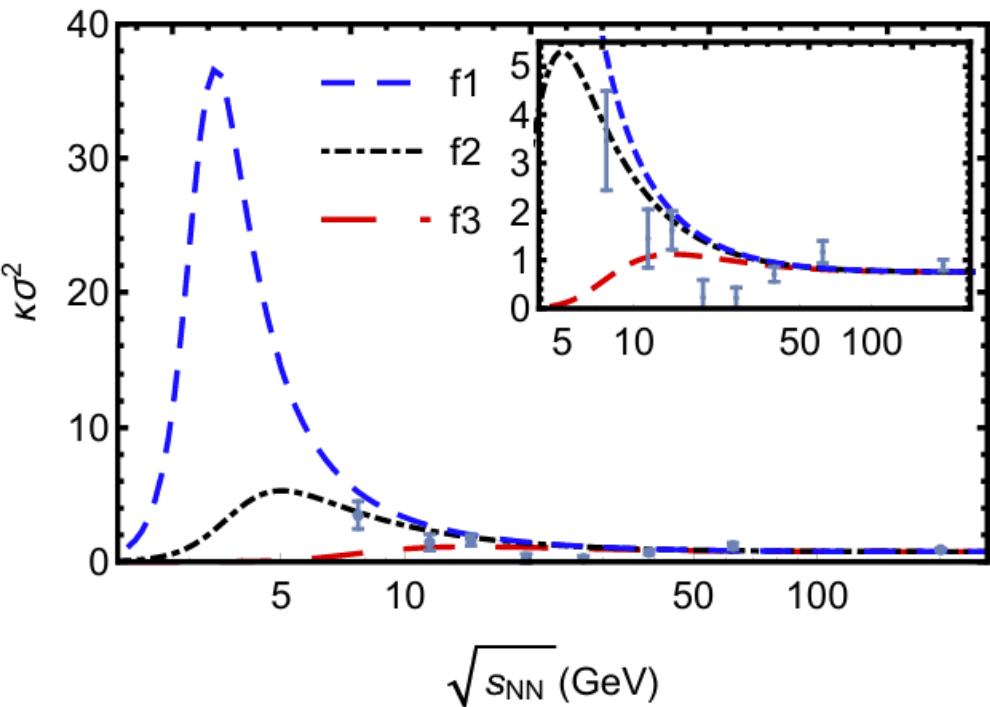
*Bayesian+hQCD: Liqiang Zhu, Xun Chen, Kai Zhou, e-Print: 2501.17763, PRD(2025)*



*ML+hQCD: Xun Chen (陈勋), MH, Phys.Rev.D 109 (2024) 5, L051902, J. Grefa, J. Noronha, J. Noronha-Hostler, I. Portillo, C. Ratti, and R. Rougemont, Phys. Rev. D 104, 034002 (2021) 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 (李志斌), Kun Xu (许坤), Xinyang Wang (王昕杨) and MH, arXiv:1801.09215 DSE-fRG: F. Gao (高飞) and J. M. Pawłowski, Phys. Rev. D 102, 034027 (2020), arXiv:2002.07500 [hep-ph]. fRG: W.-j. Fu (付伟杰), J. M. Pawłowski, and F. Rennecke, Phys. Rev. D 101, 054032 (2020), arXiv:1909.02991 [hep-ph].*

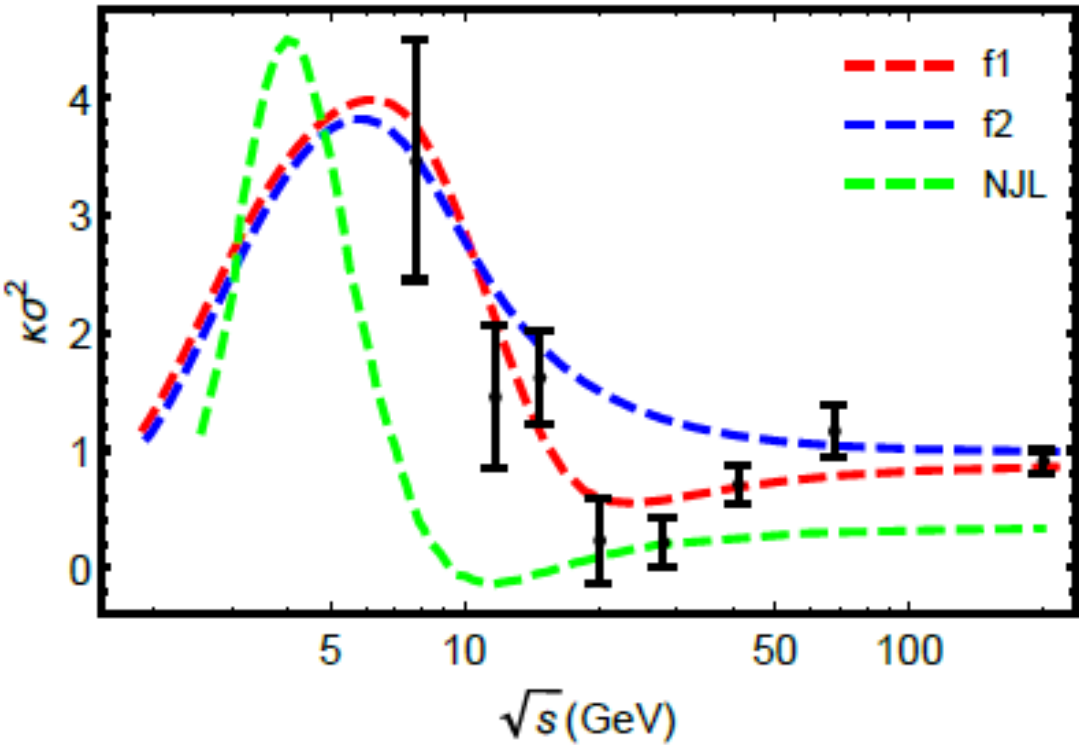
# CEP 位置：理论结果

2017-2018， 通过重子数扰动的峰做为CEP信号， 出现在3-5GeV碰撞能量区



Zhibin Li, Yidian Chen, Mei Huang. e-Print: 1706.02238, Chin.Phys.C 42 (2018) 1, 013103

Chinese Physics C Vol. 42, No. 1 (2018) 013103

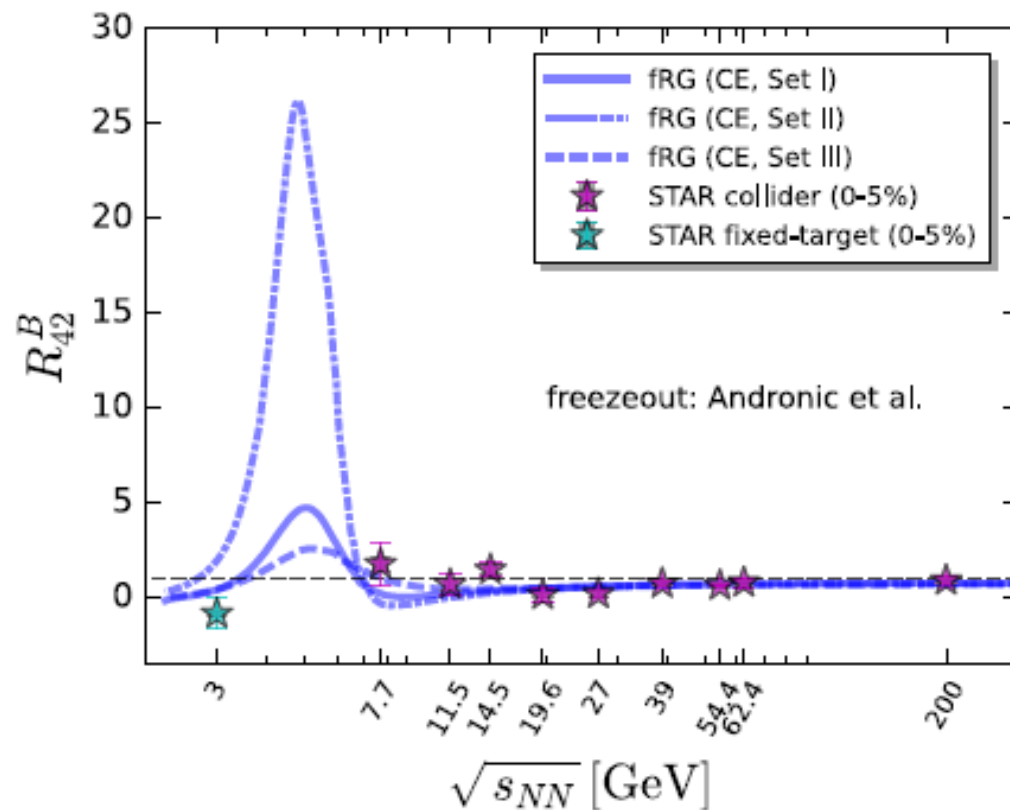
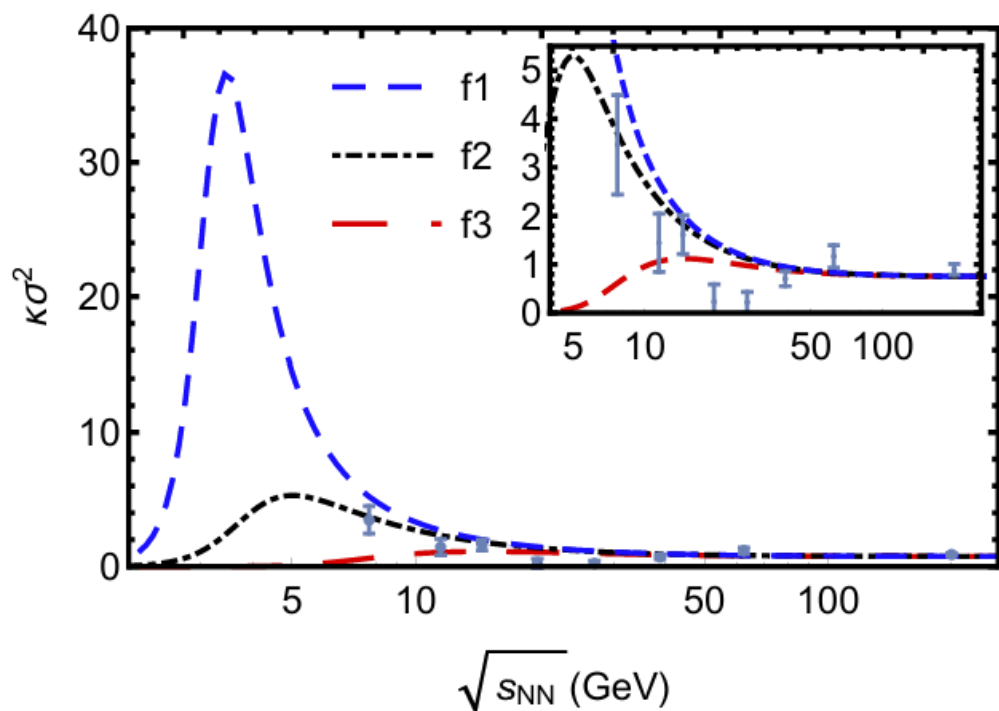


Zhibin Li, Kun Xu, Xinyang Wang and Mei Huang, arXiv:1801.09215, EPJC 2019

Locating the QCD critical end point through peaked baryon number susceptibilities along the freeze-out line\*

Zhibin Li(李志斌)<sup>1,2;1)</sup> Yidian Chen(陈亦点)<sup>1,2;2)</sup> Danning Li(李丹凝)<sup>3;3)</sup> Mei Huang(黄梅)<sup>1,2,4;4)</sup>

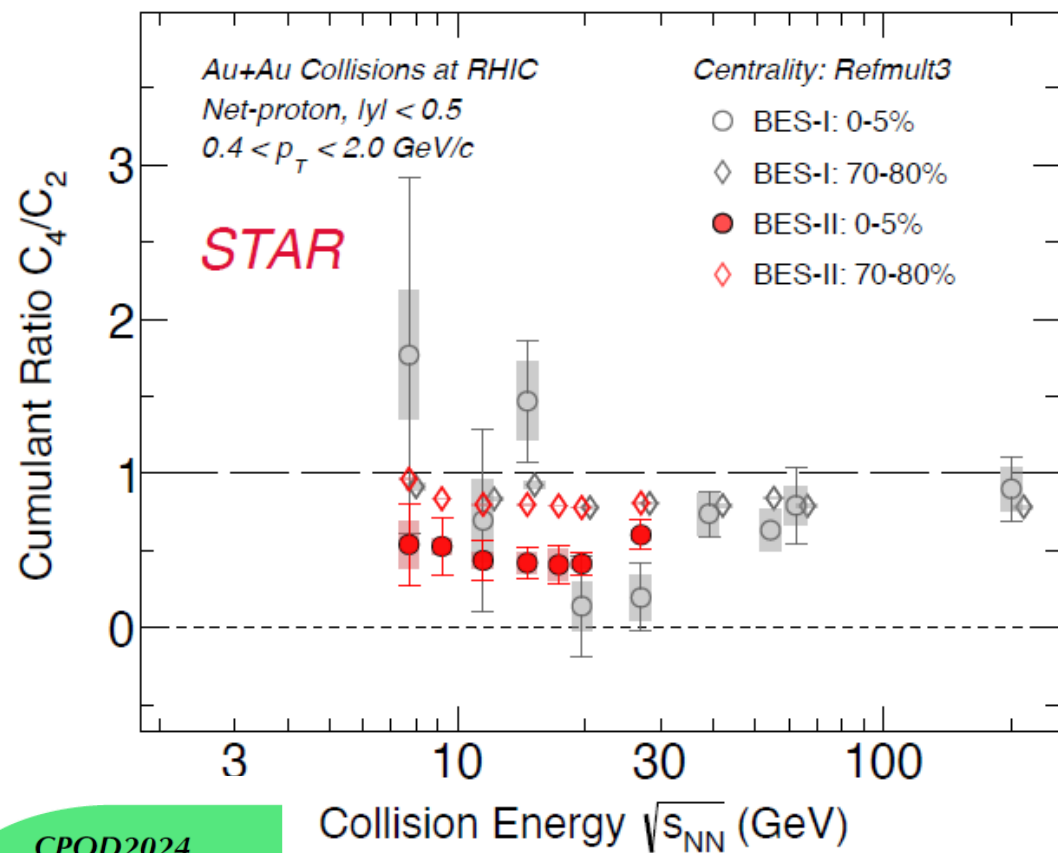
# Waiting for results around 5GeV (NICA,FAIR,HIAF) !



全息QCD: Zhibin Li, Yidian Chen, M.H. e-Print: 1706.02238,  
Chin.Phys.C 42 (2018) 1, 013103

fRG: Weijie Fu (付伟杰), Luo, Pawłowski, Rennecke, Yin,  
arXiv: 2308.15508, Phys.Rev.D 111 (2025) 3, L031502

# CEP 位置：实验结果



**CPOD2024**  
Berkeley, CA  
May 20 - 24, 2024

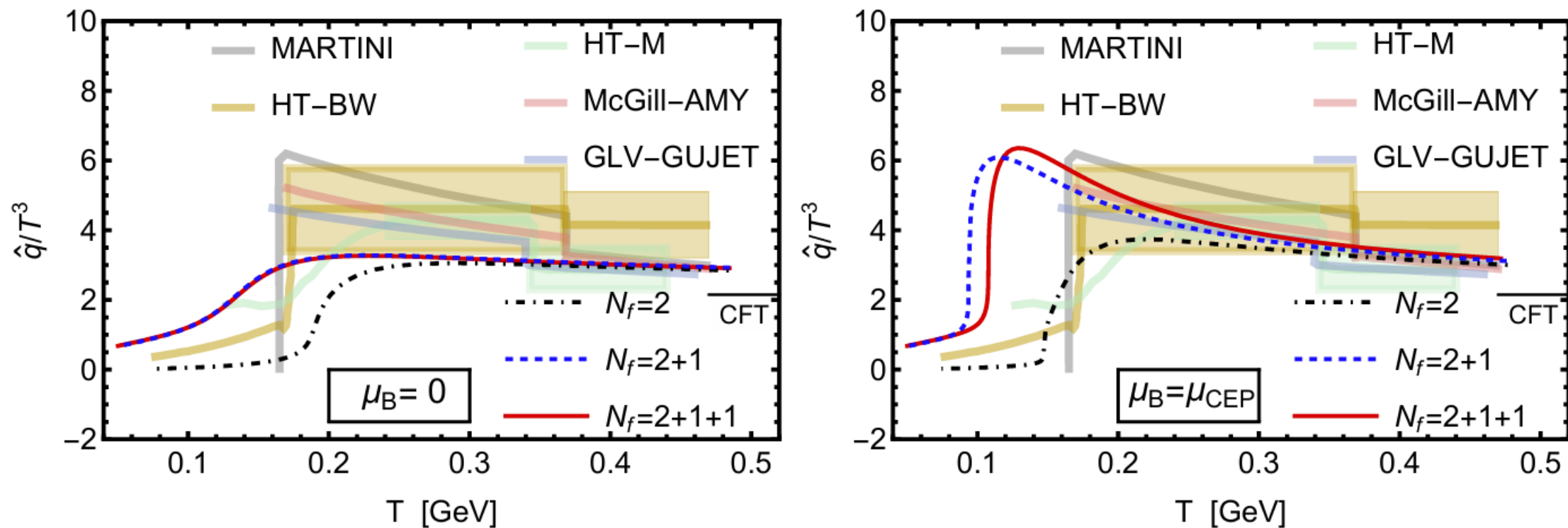
Ashish Pandav for STAR Collaboration  
Lawrence Berkeley National Laboratory  
May 21, 2024

碰撞能量7.7GeV以上无明显CEP信号！  
与最新格点结果和理论结果自洽

最好时机@HIAF！

STAR: Phys. Rev. Lett. 135, 142301(2025)

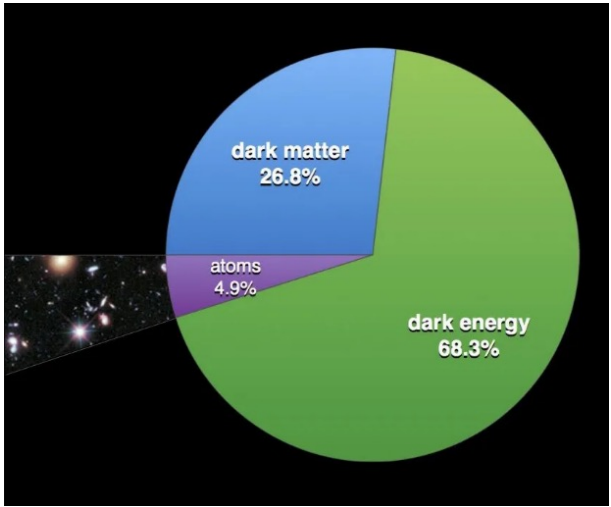
其它CEP 信号, e.g., jet quenching? Dilepton, photon production?



Is there any signals from jet quenching around 5 GeV ?

全息QCD: Zhibin Li, Danning Li, M.H., e-Print: [2504.04147](https://arxiv.org/abs/2504.04147) [hep-ph], PRD2025

# 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**.

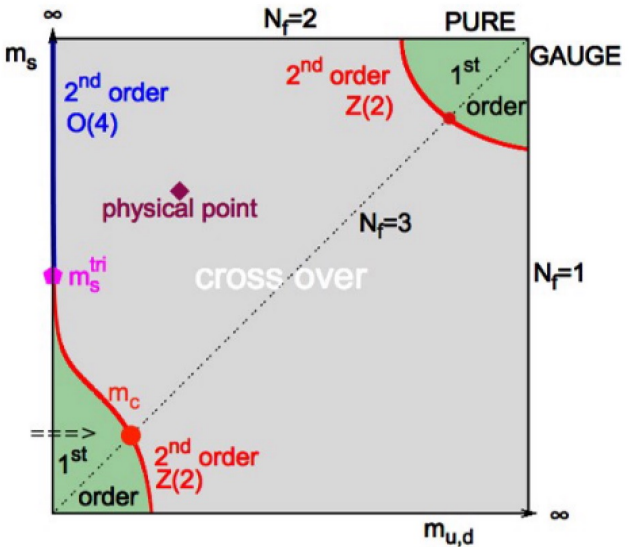
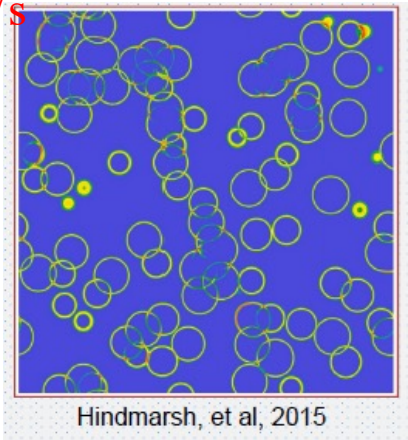
At around  $10^{-5}$ s, the early universe experiences QCD phase transition.

## Connecting *Quarks* with the *Cosmos*

*Eleven Science Questions for the New Century*

$$\text{GWs } \square h_{ij} \sim T_{ij}$$

Stochastic background GWs



1st order PT (FOPT) in QCD epoch:

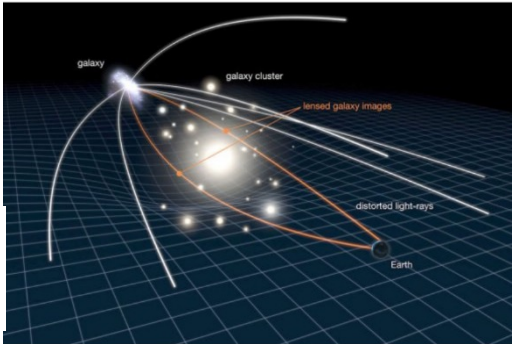
pure gluon system,  
chiral phase transition

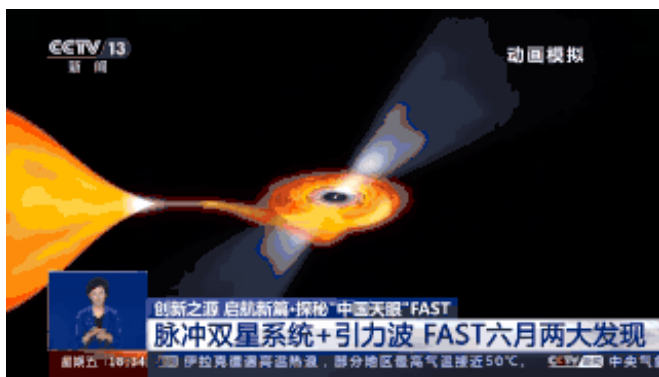
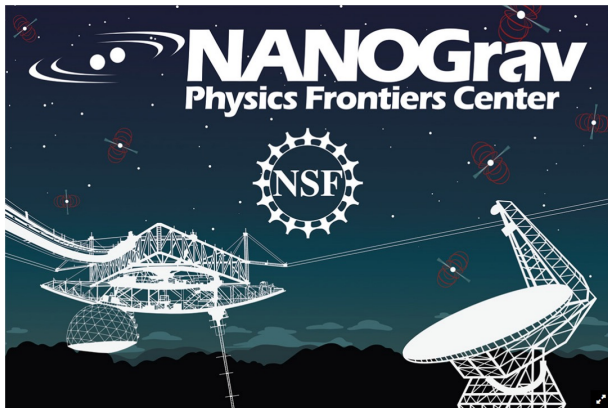
.....

PBHs

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

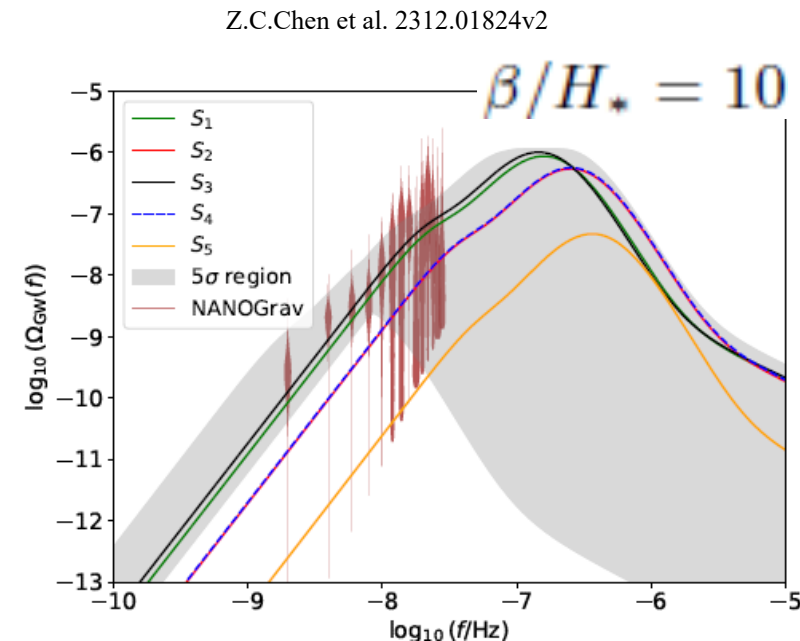
$$\frac{d^2 \delta}{dt^2} + 2H \frac{d\delta}{dt} + \left( \frac{k^2 v_s^2}{a^2} - 4\pi G \rho \right) \delta = 0$$





NANOGrav, EPTA, CPTA, PPTA

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



$$\frac{\beta}{H} = T_n \left. \frac{d(\frac{S_3}{T})}{dT} \right|_{T_n}$$

Measure the inverse duration  
of the phase transition

The bubble nucleation rate per Hubble volume per time

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

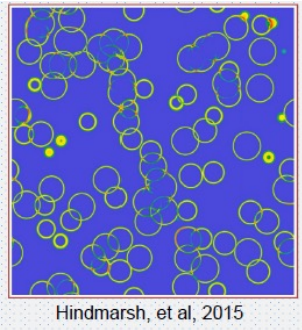
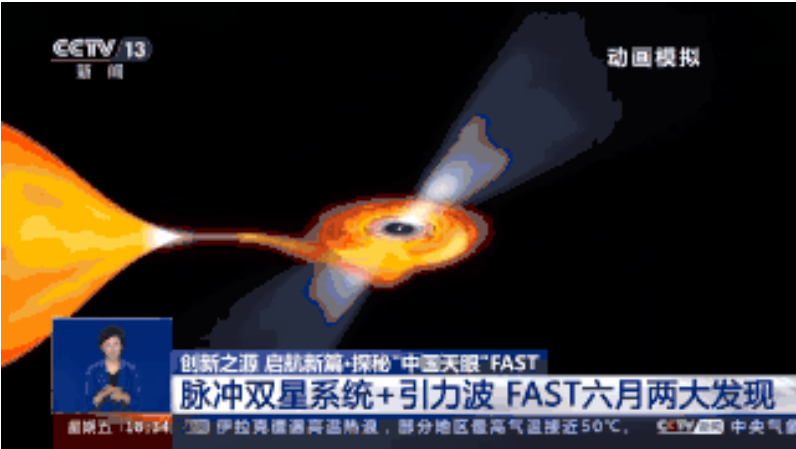
$$\frac{\Gamma(T_n)}{H^4} \sim 1$$

Nucleation at  $T_n$

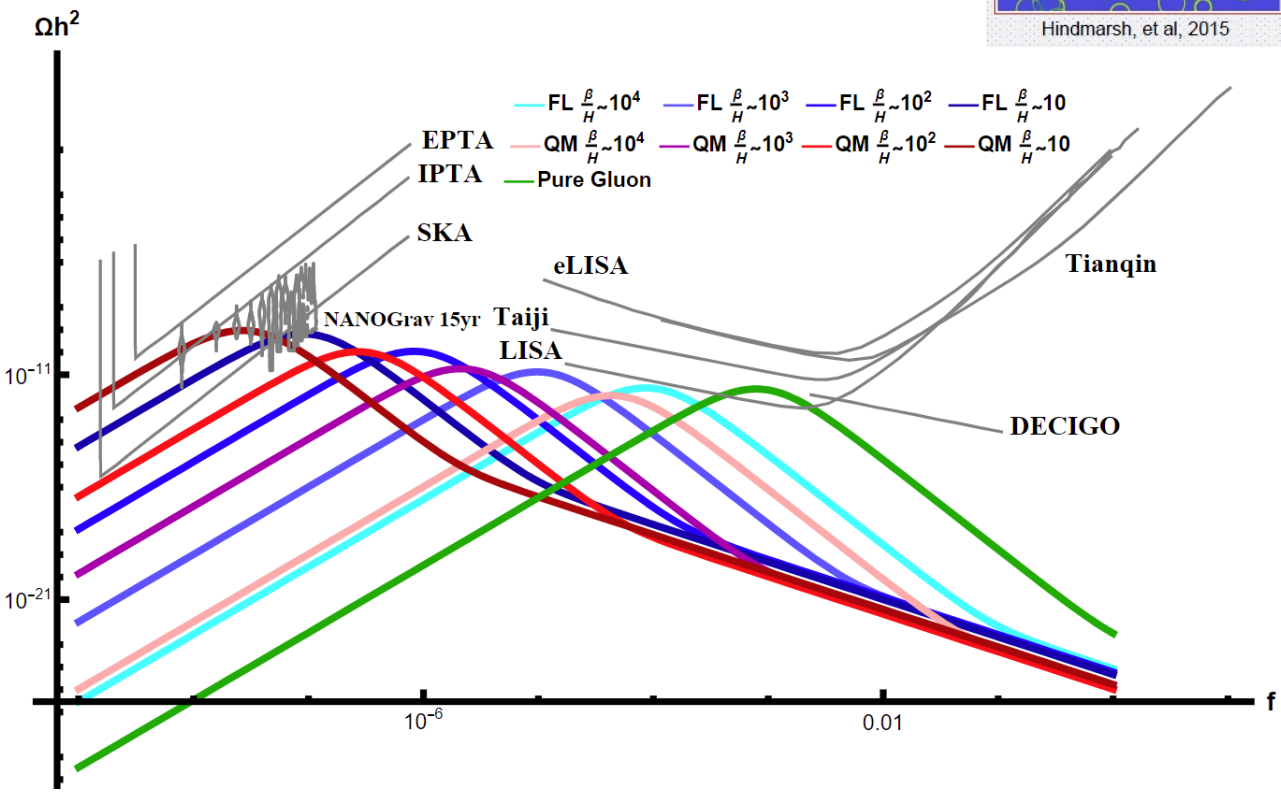
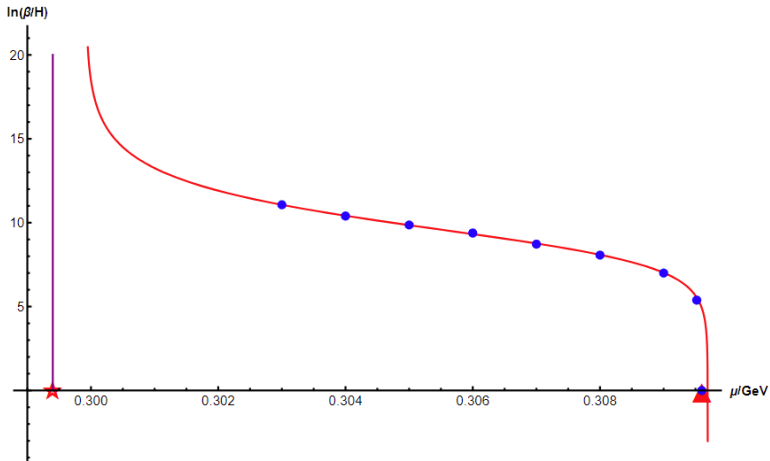
假真空衰变：量子隧穿

# 缓慢衰变的QCD假真空产生纳赫兹引力波

2023年6月29日，FAST探测到宇宙中神秘的纳赫兹引力波

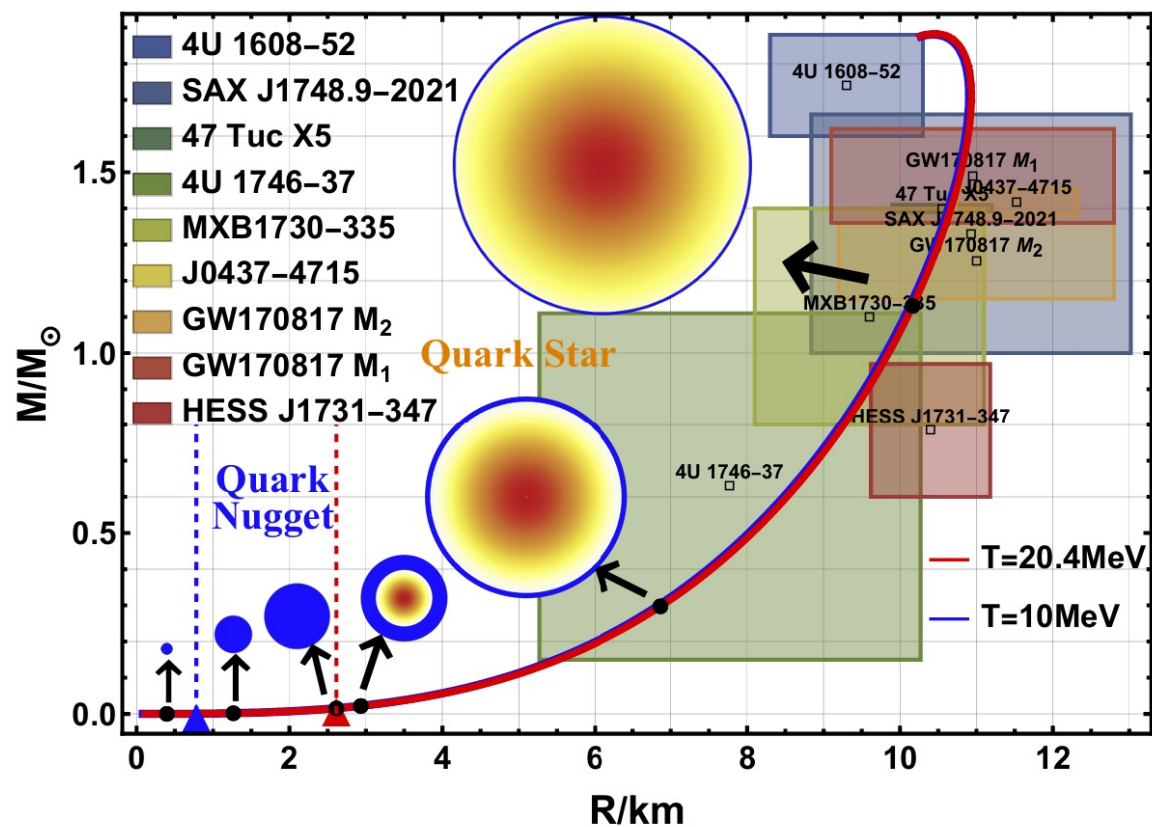
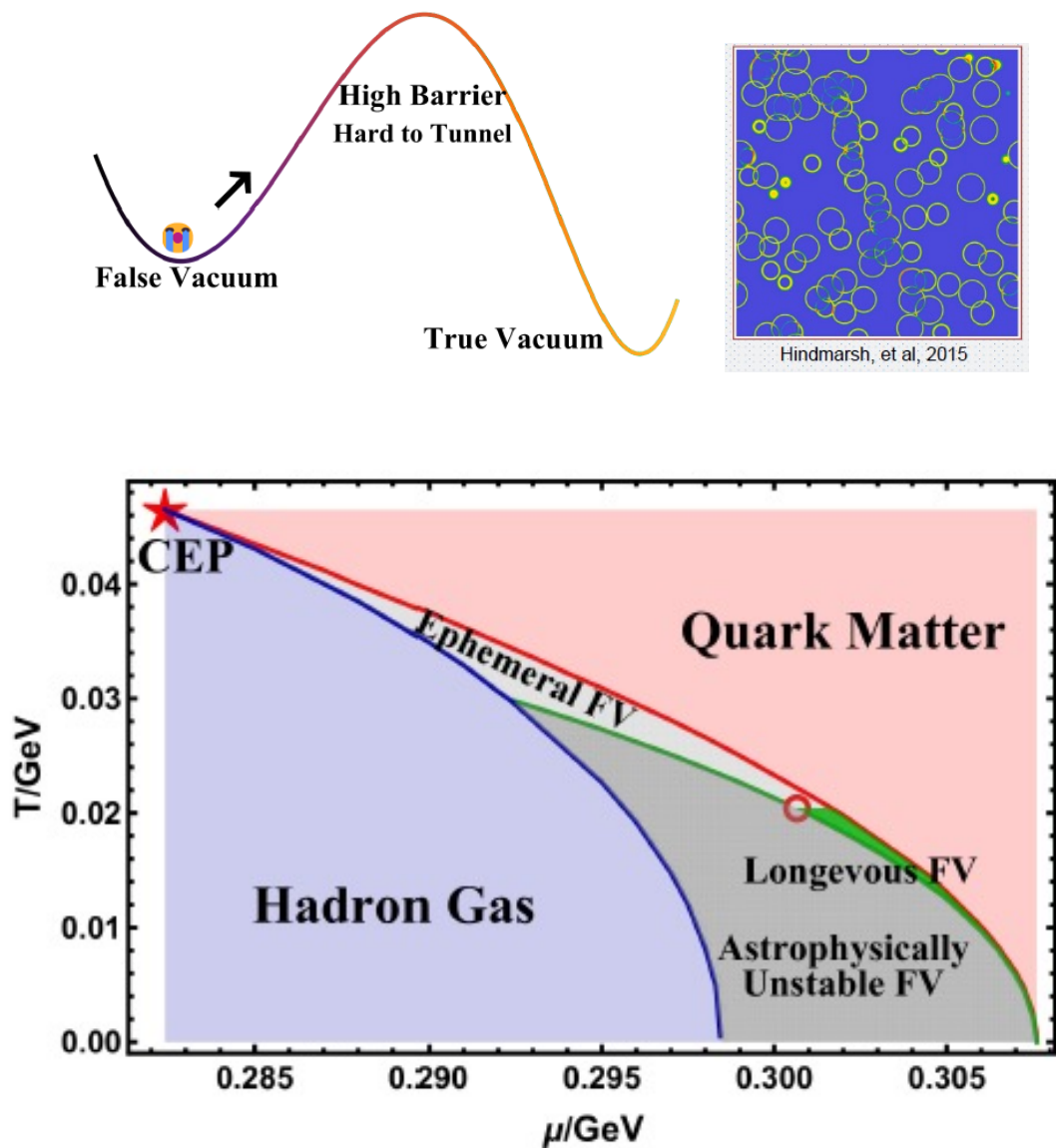


NANOGrav, EPTA, CPTA, PPTA



J. Shao, H. Mao, and M. H. *Physical Review D* 111.2 (2025): 023052

宇宙早期会产生局域高密区，发现化学势会抬高势垒使得动力学一级相变真减缓，会出现跟宇宙年龄可比的长寿命假真空态，从而得到不同于平衡态的QCD相图。长寿命假真空可以构成原初夸克星，可以解释质量轻的致密星体。



J. Shao, and MH. *Physical Review D* 107.4 (2023): 043011.

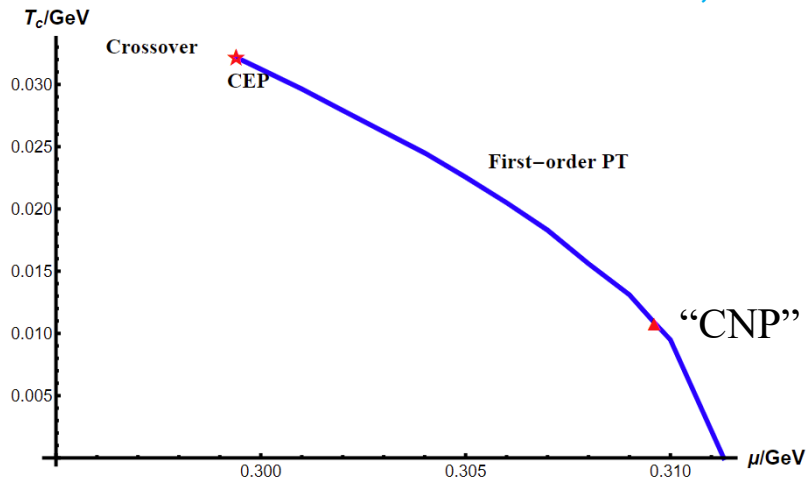
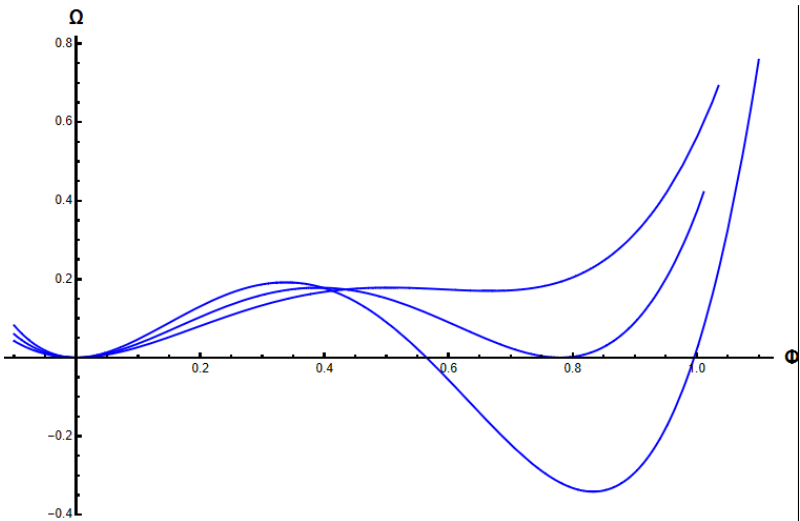
J. Shao, H. Mao, and MH. *Physical Review D* 111.2 (2025): 023052

J. Shao, H. Mao, and MH, *Chinese Physics C* 49.6 (2025): 065103.

J. Shao, MH. *arXiv:2510.06065* (2025).

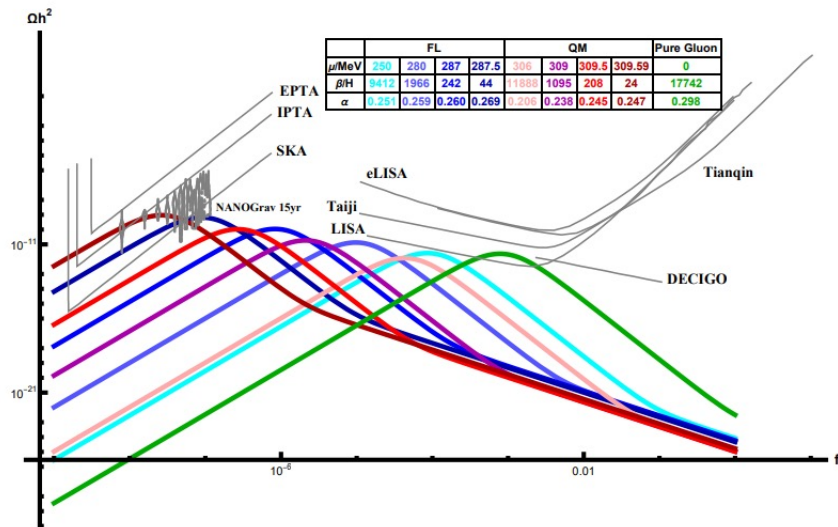
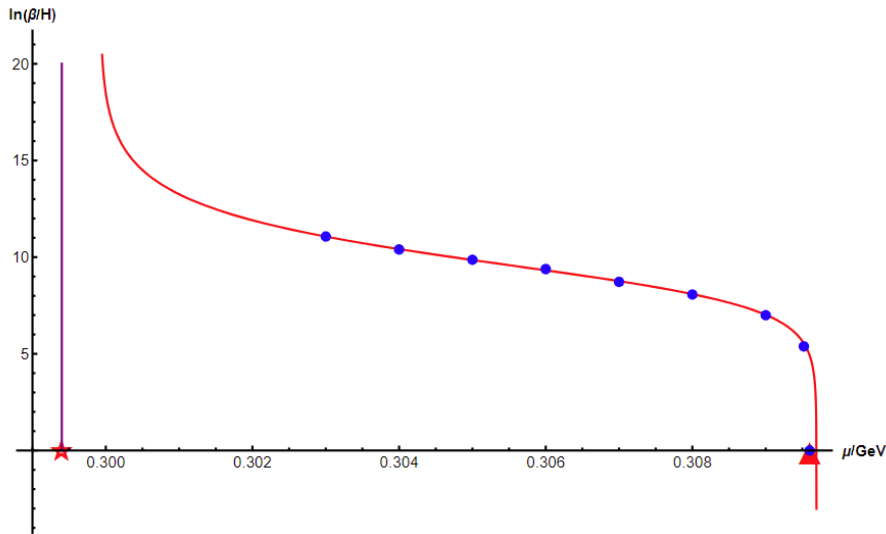
# Dynamical 1<sup>st</sup>-order phase transition: false vacuum decay rate

Jingdong Shao (邵惊冬), Hong Mao (毛鸿), MH,  
arXiv: 2410.06780, 2410.00874

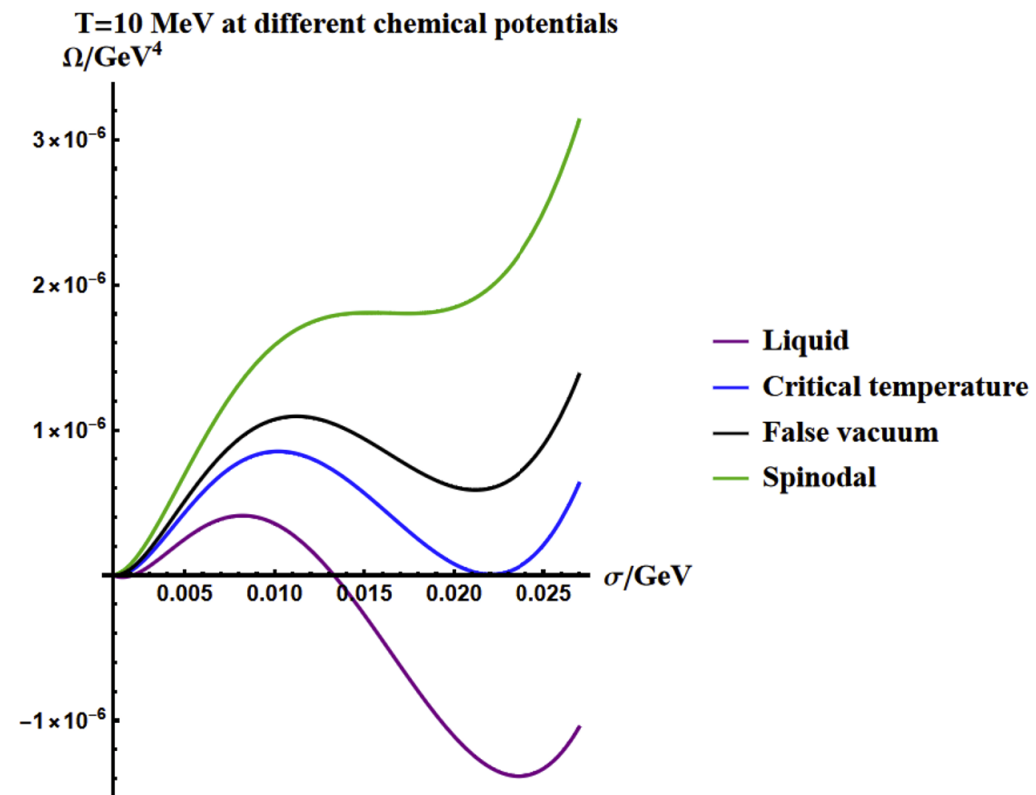
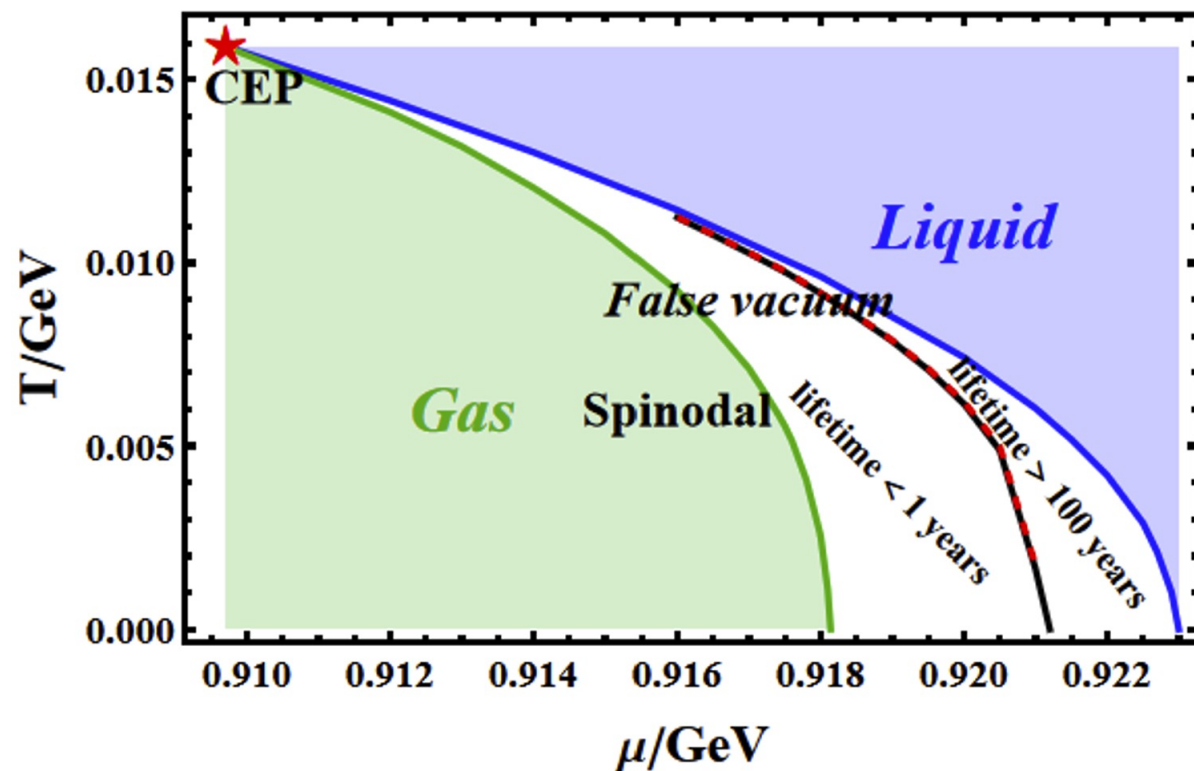


临界成核点  
Long-lived false vacuum

高密核物质- >蓄核能池?



## 长寿命假真空：核物质气液相变



J. Shao, and MH. *In preparation*

Thanks for your attention!