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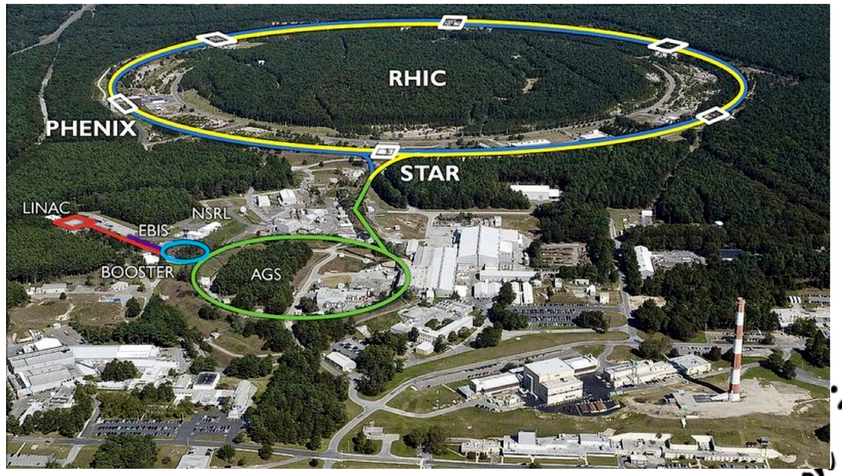
# Lattice QCD: A Journey from RHIC to EIC

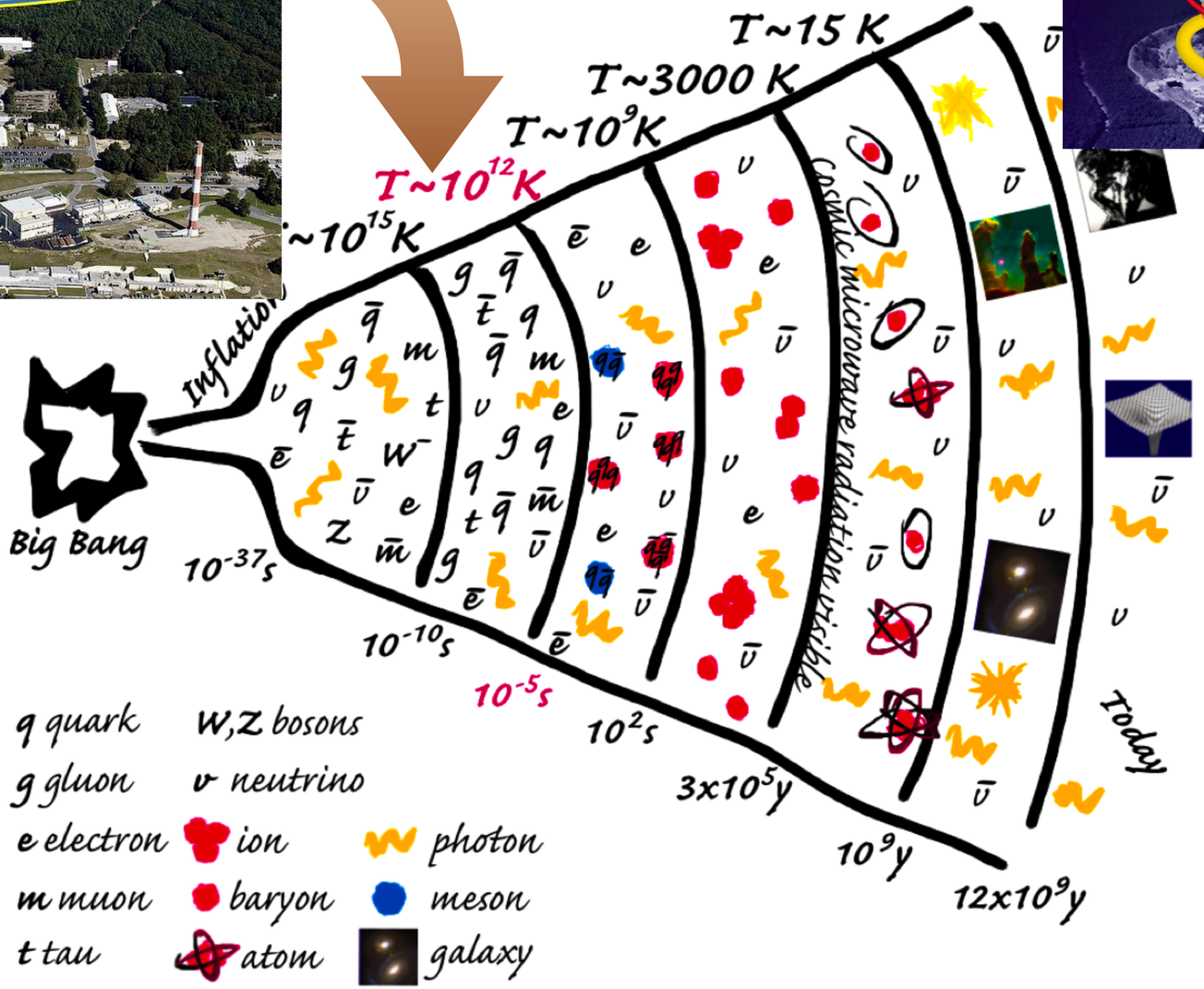
**Swagato Mukherjee**

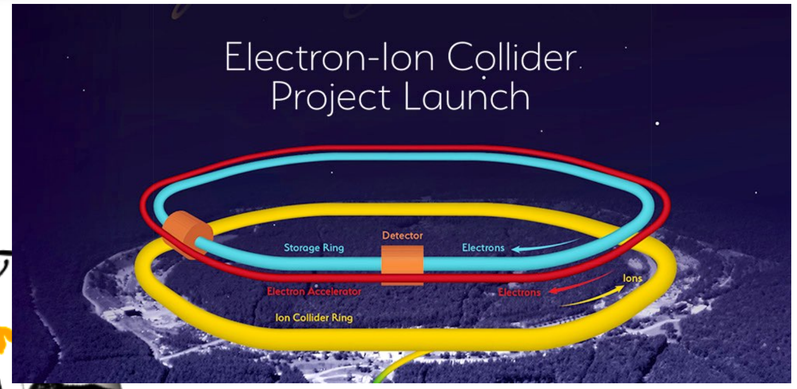
April 2023, GHP, Minneapolis, MN

# my 14-year long journey across 14 billion years




RHIC

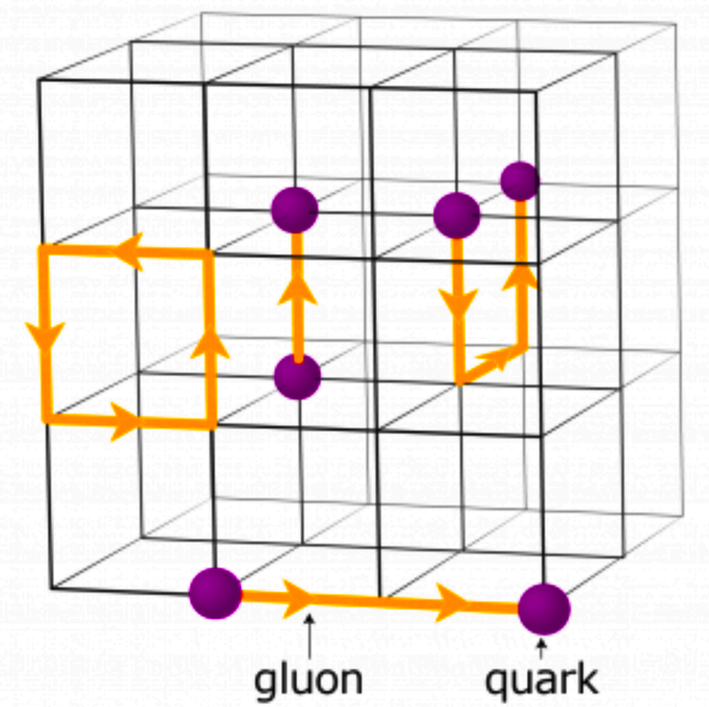



EIC

# the time machine — lattice QCD

**QCD in its full glory**: non-perturbative, gauge invariant regularization of QCD path integral



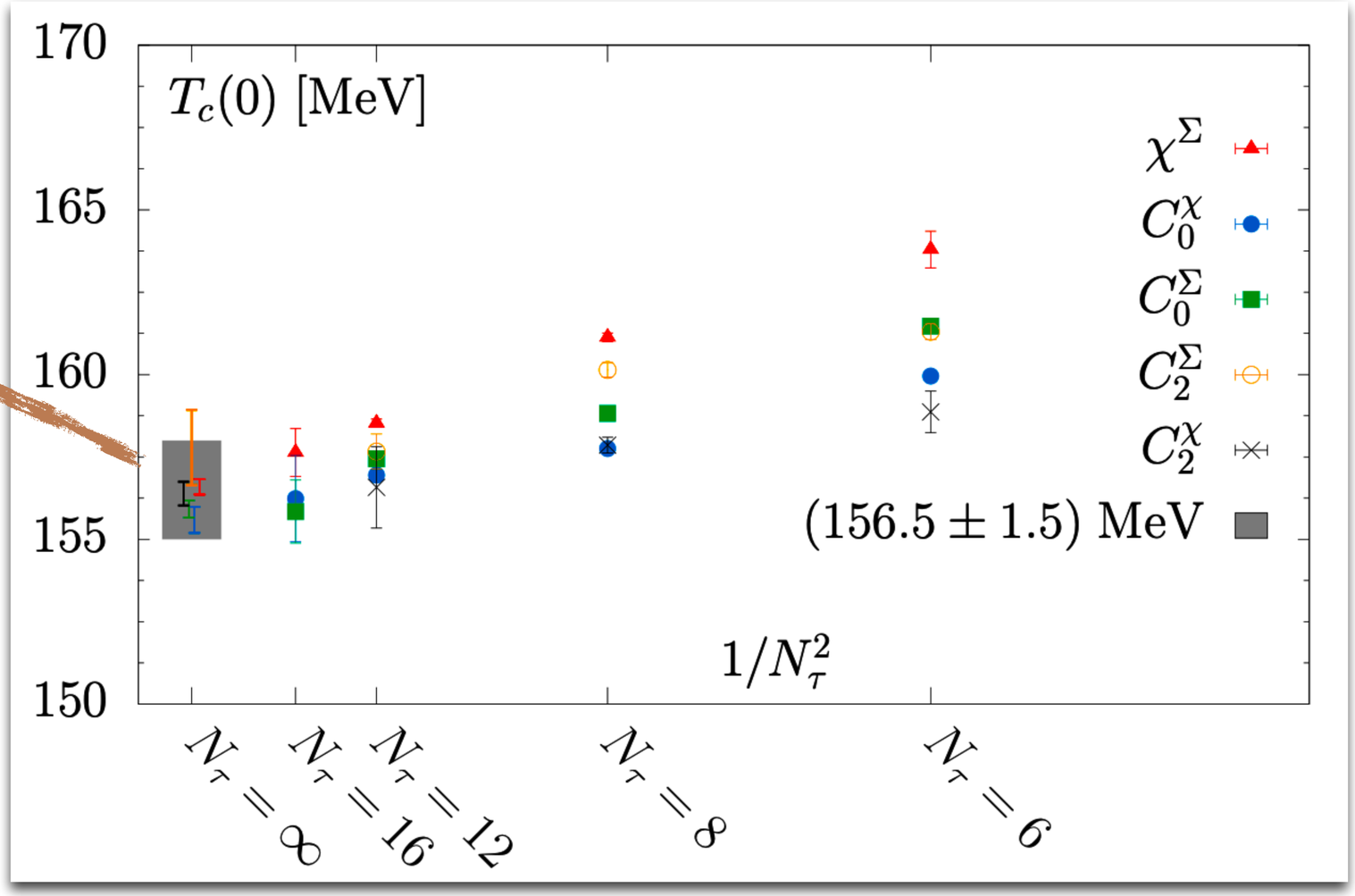

almost all results shown in this talk are for physical quark masses and in the continuum limit

# … swimming through quark gluon plasma …

# pseudocritical temperature

$$T_c = 156.5 \pm 1.5 \text{ MeV}$$

studying multiple observables related to punctuation of order parameter



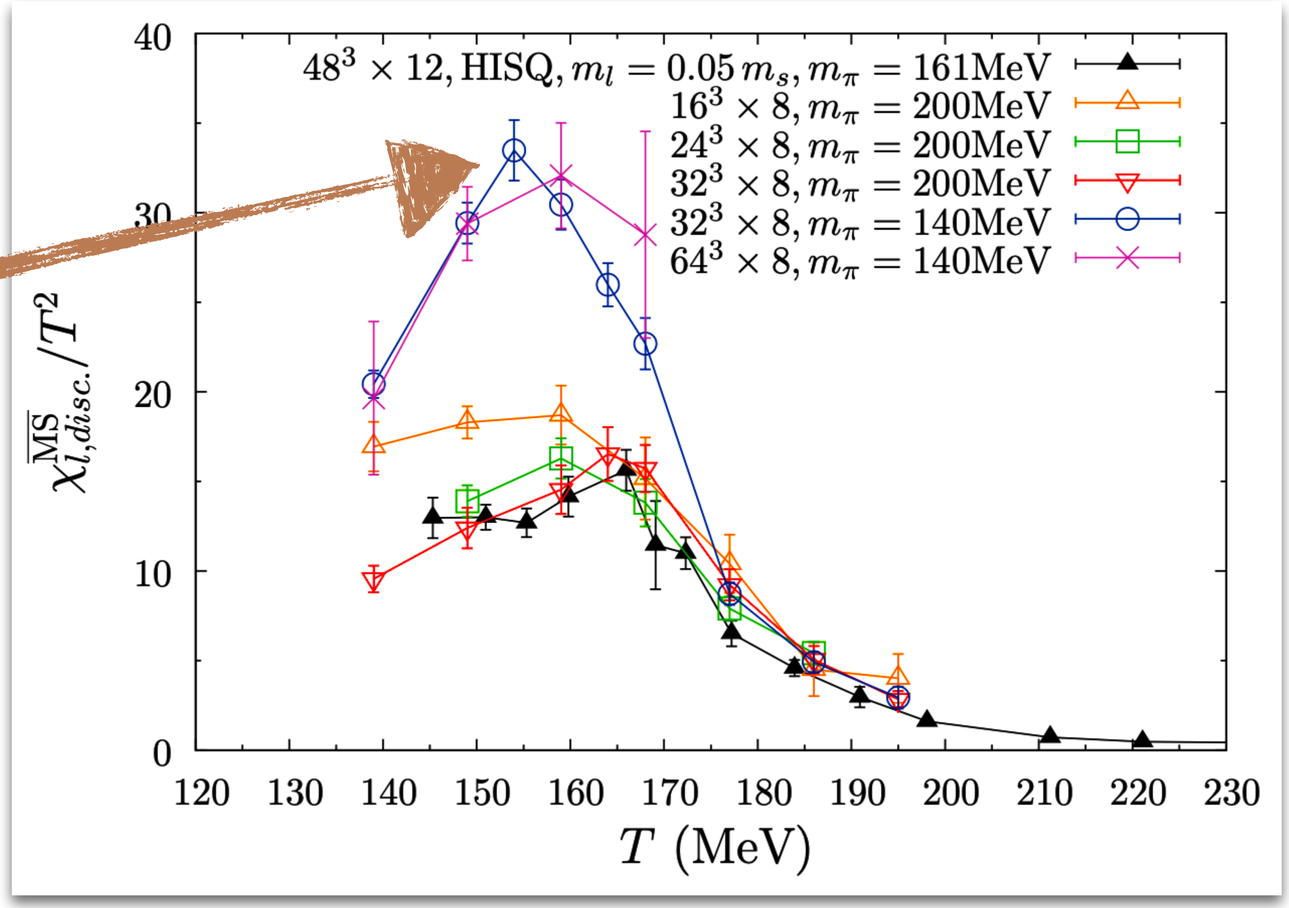

HotQCD, Phys. Lett. B 795,15 (2019)

HotQCD, Phys. Rev. D 85, 054503 (2012)

# QCD transition is a crossover

no volume scaling observed in fluctuation of the order parameter

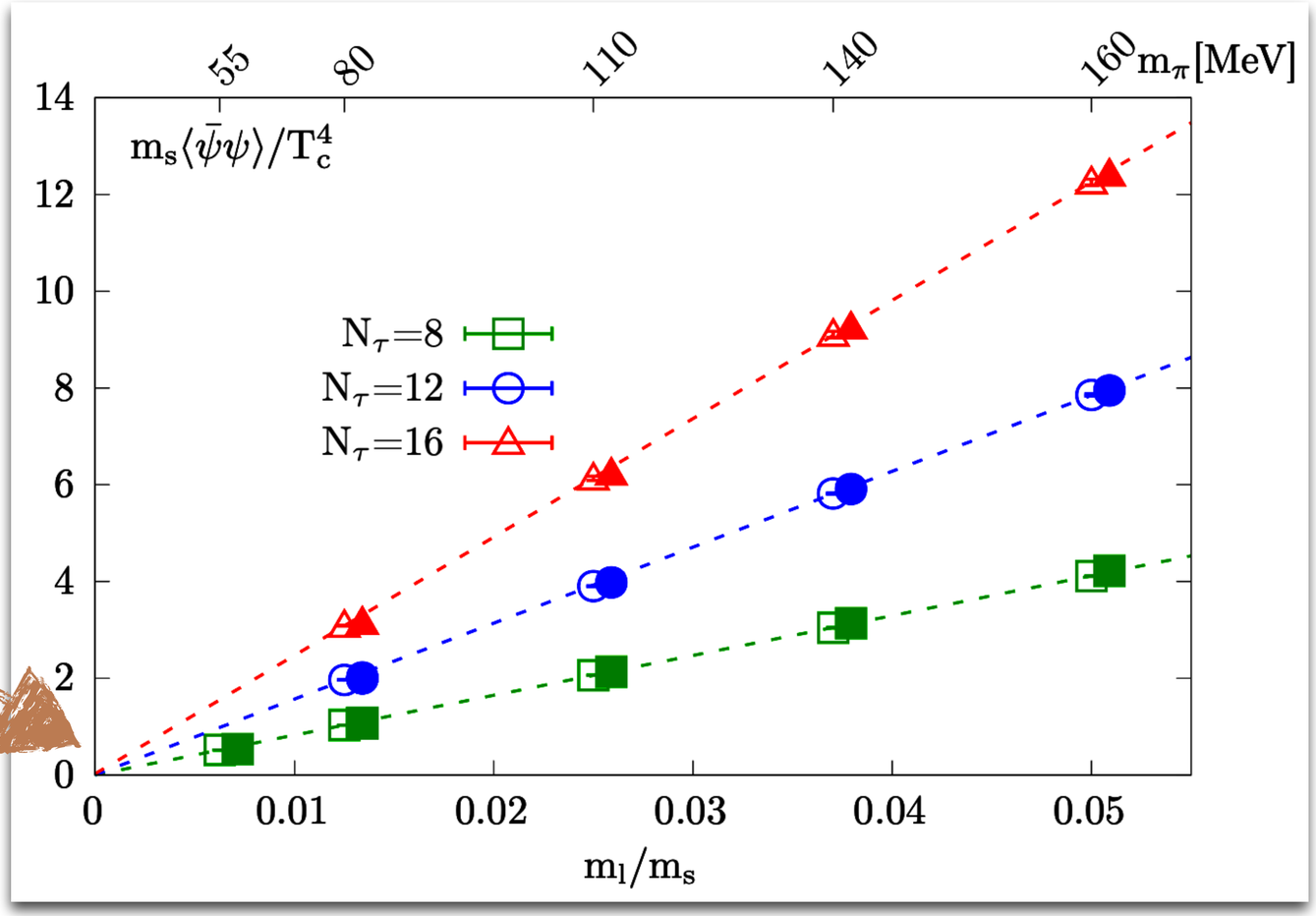
using chiral fermions




HotQCD, Phys. Rev. Lett. 113, 8, 082001(2014)

# chiral symmetry is restored in the chiral limit …

order parameter with vanishing light quark mass

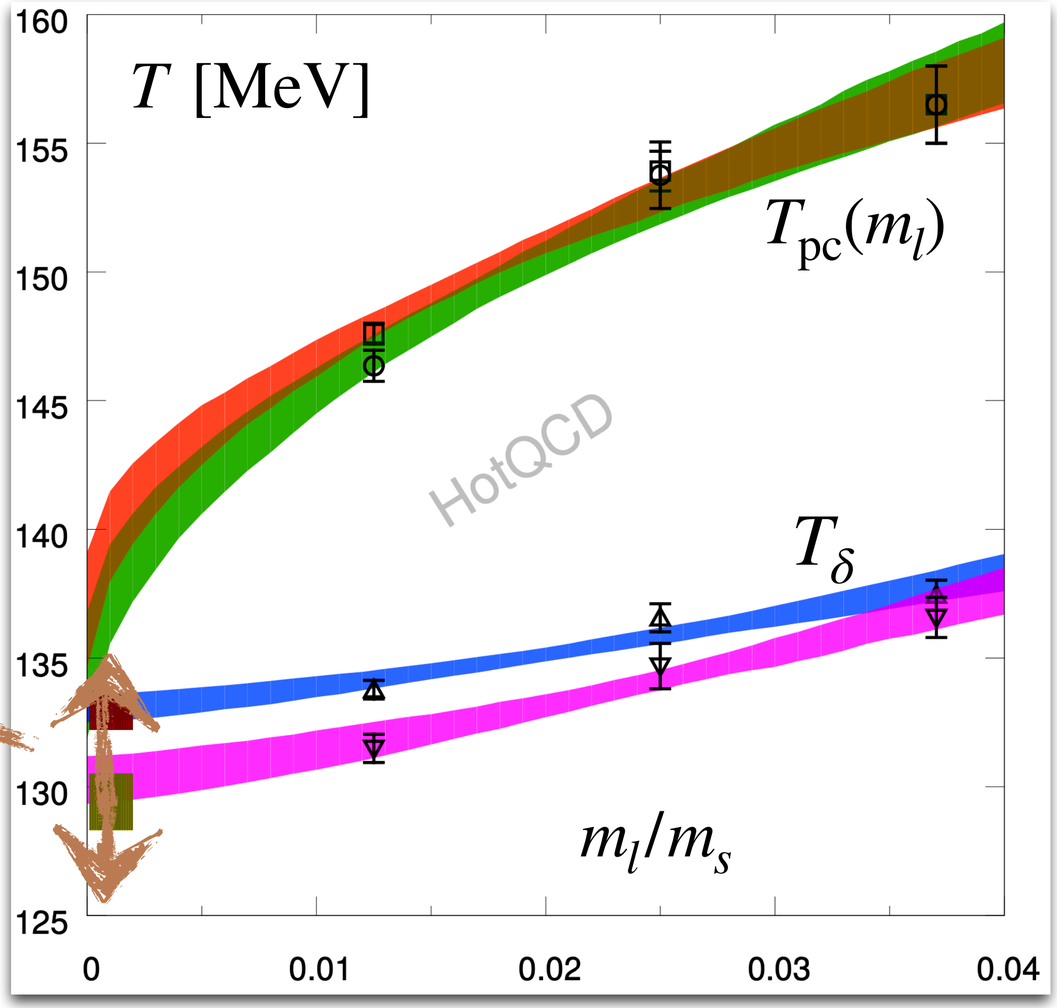



HotQCD, Phys. Rev. Lett. 126, 8, 082001 (2021)

# chiral symmetry is restored in the chiral limit …

second order transition in the chiral limit

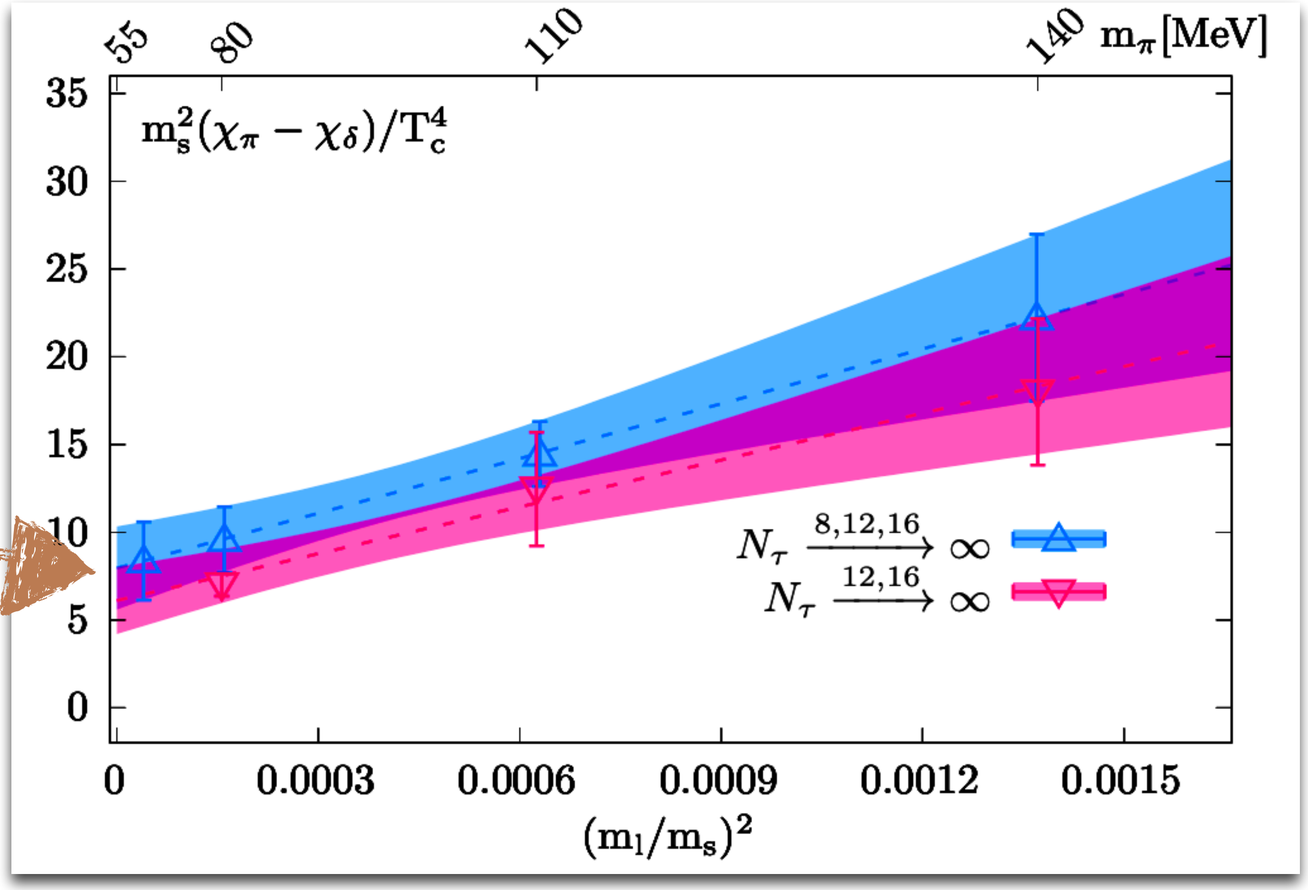
$$T_c^0 = 132^{+3}_{-6}\ MeV$$




HotQCD, Phys. Rev. Lett. 123, 6, 062002 (2019)

# … but anomalous axial symmetry remains broken

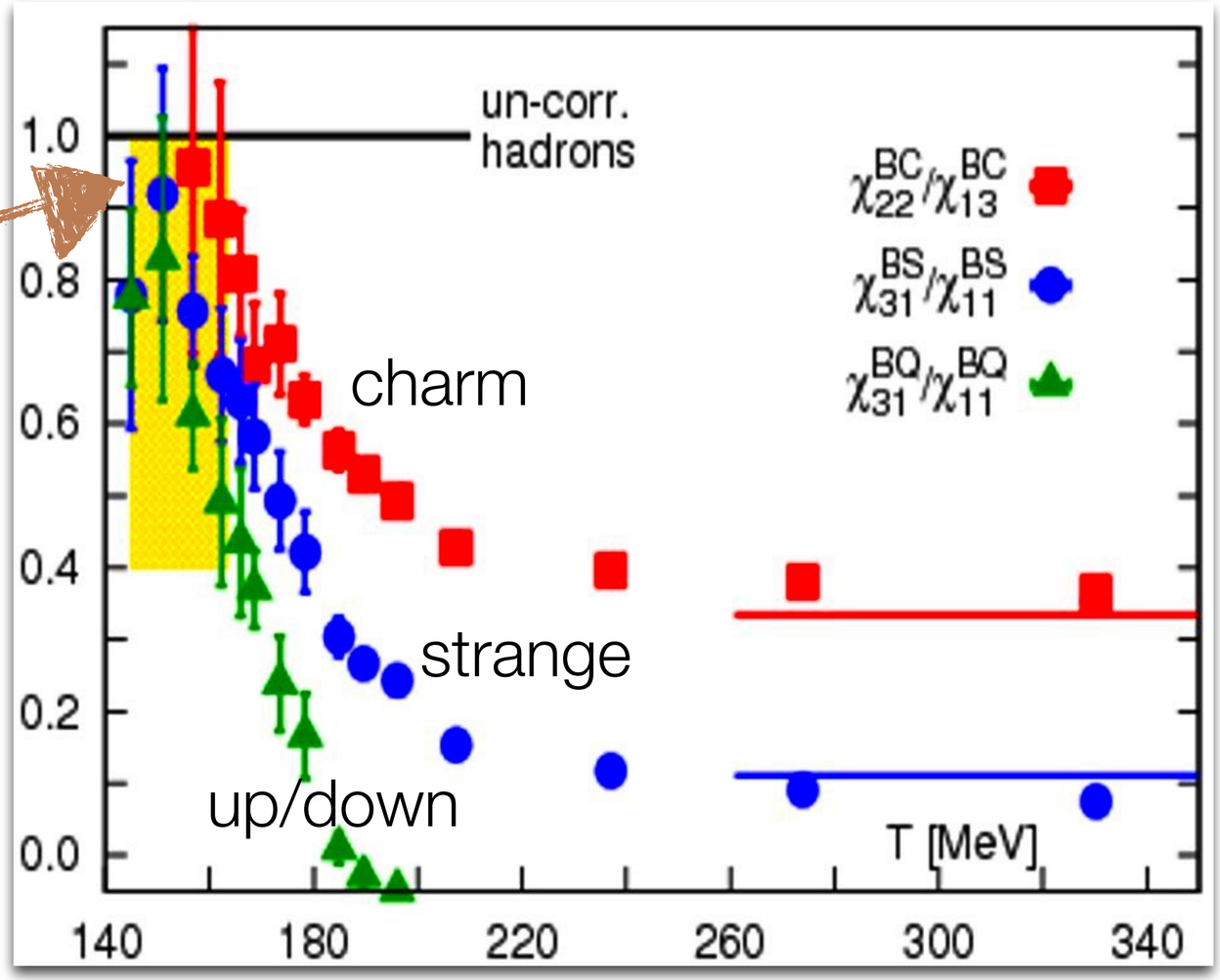
measures of axial symmetry breaking do not vanish in the chiral limit




HotQCD, Phys. Rev. Lett. 126, 8, 082001 (2021)

# deconfinement — QGP

liberation of degrees of freedom
carrying factional charges
around $T \approx 155$ MeV



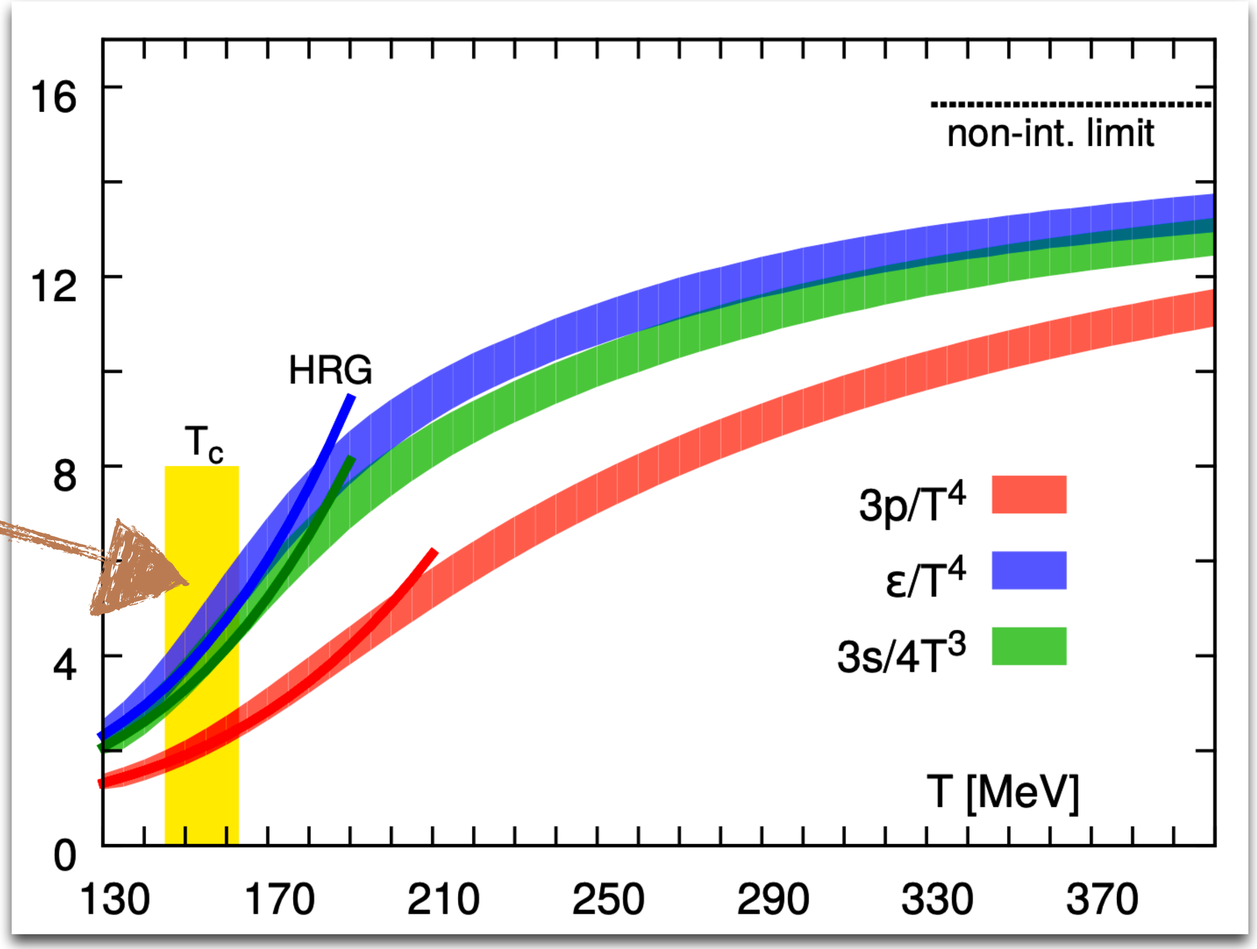

HotQCD, Phys. Rev. Lett. 111, 082301 (2013)

HotQCD, Phys. Lett. B 737, 210 (2014)

# deconfinement — QGP

rapidly rising pressure, energy & entropy density around $T \approx 155$ MeV

equation of state




HotQCD, Phys. Rev. D 90, 094503 (2014)

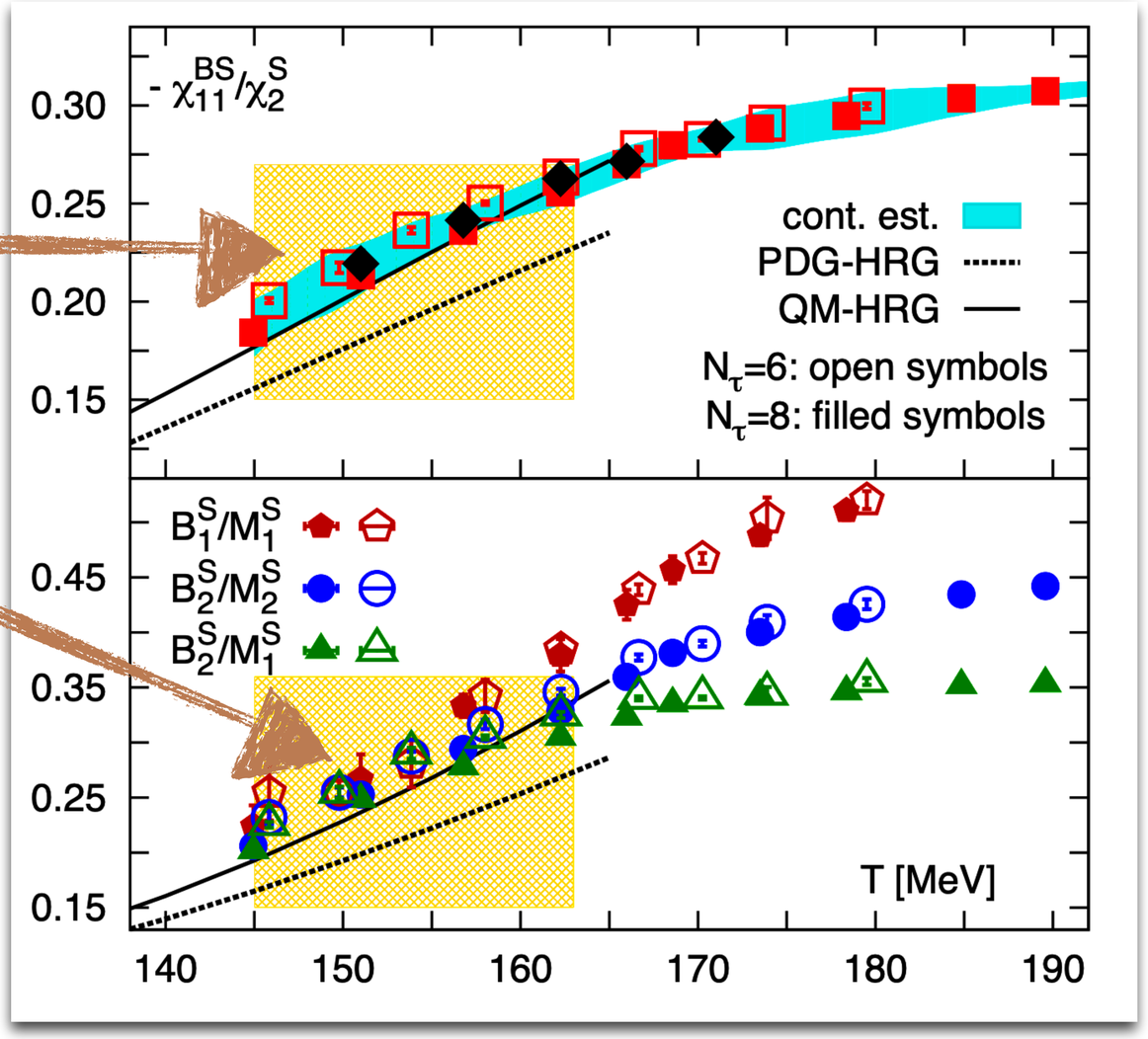
HotQCD, Phys. Rev. D 81, 054504 (2010)

# signatures of yet unobserved hadrons

partial pressures of strange baryons can be described only by accommodating yet unobserved strange baryons

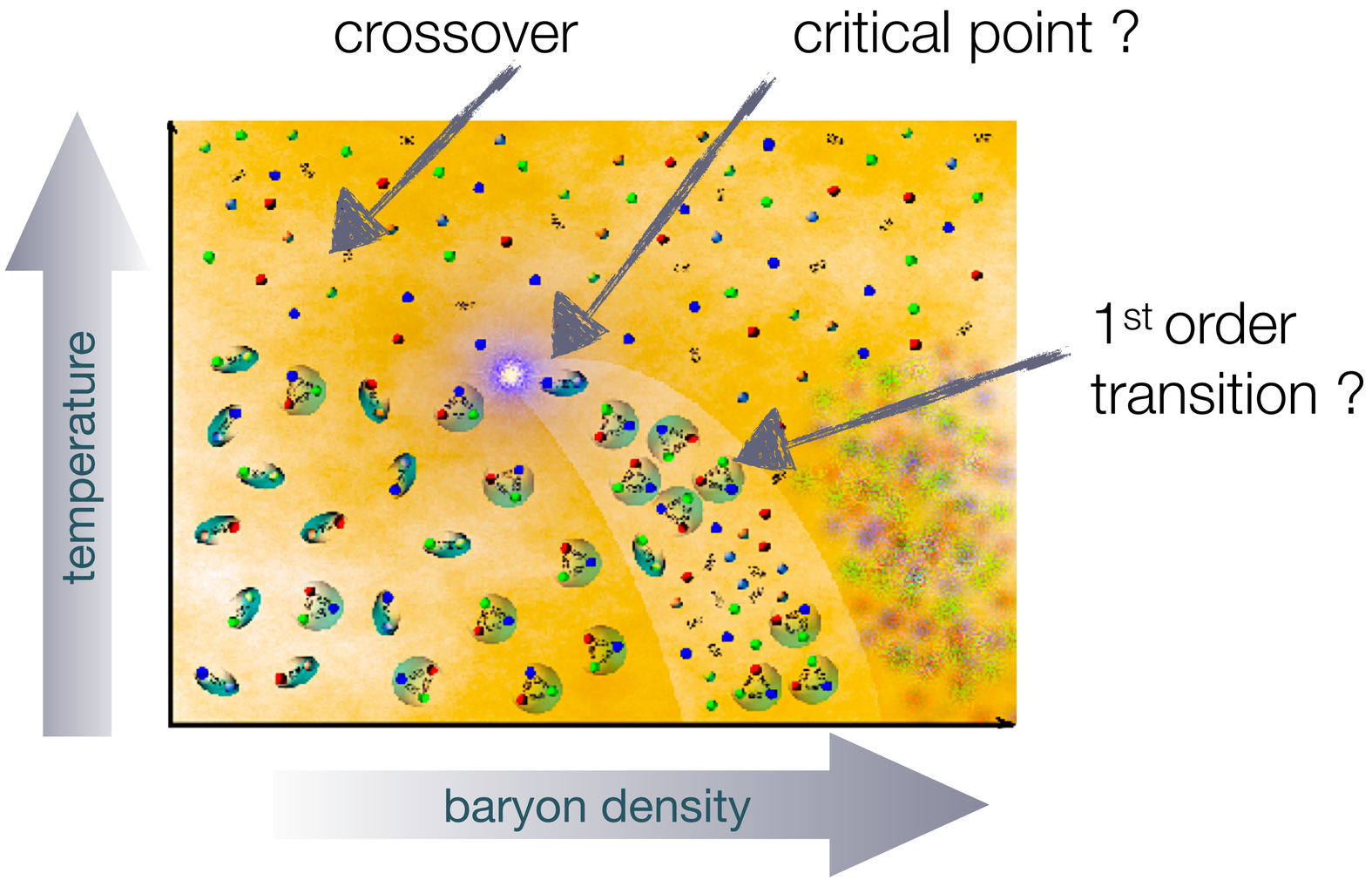
same for charm baryons

HotQCD, Phys. Lett. B 737, 210 (2014)



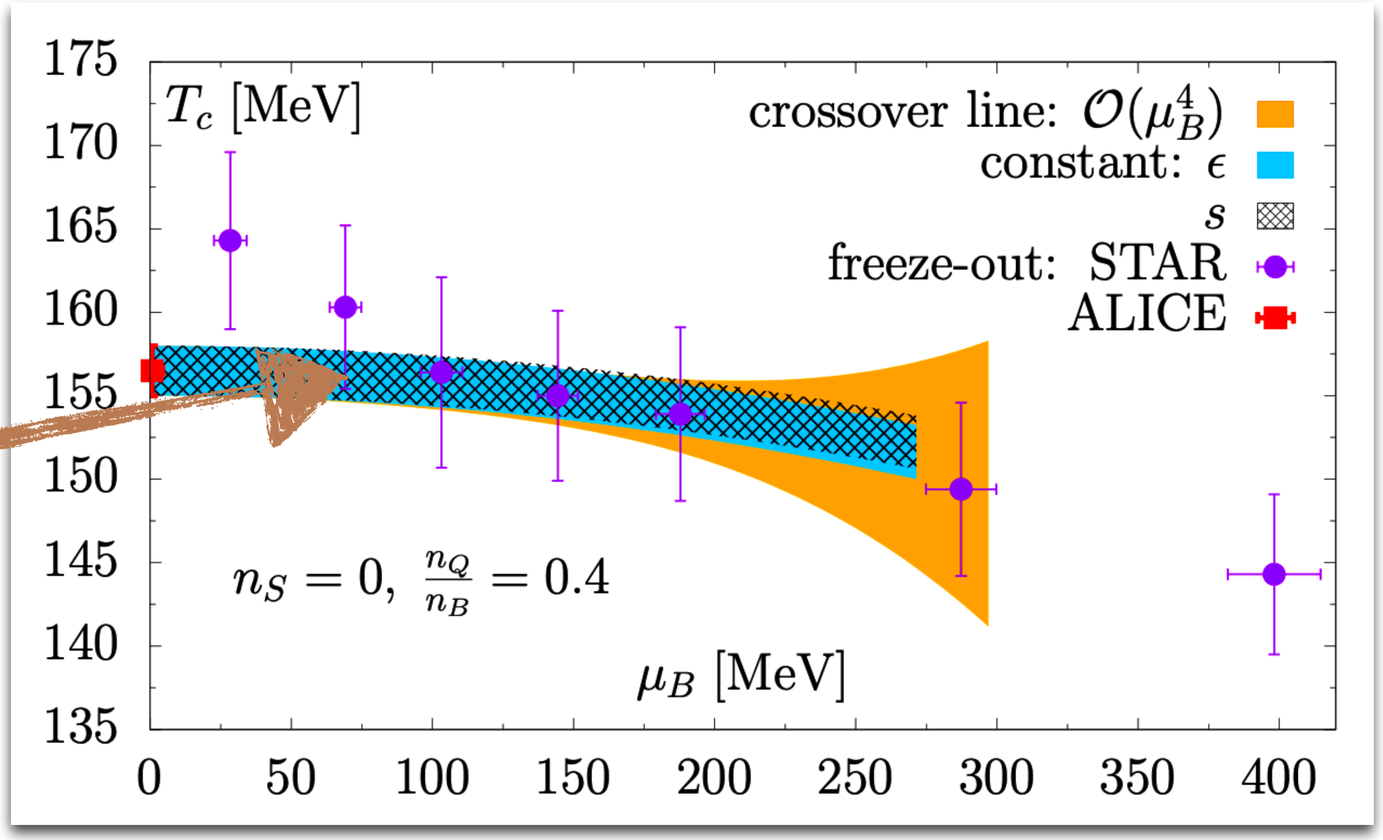

HotQCD, Phys. Rev. Lett. 113, 7, 072001 (2014)

# … wondering through QCD phase diagram …



# QCD phase boundary in $T - \mu_B$ plane

freeze-out (hadronization) at RHIC BES takes place along the QCD phase boundary

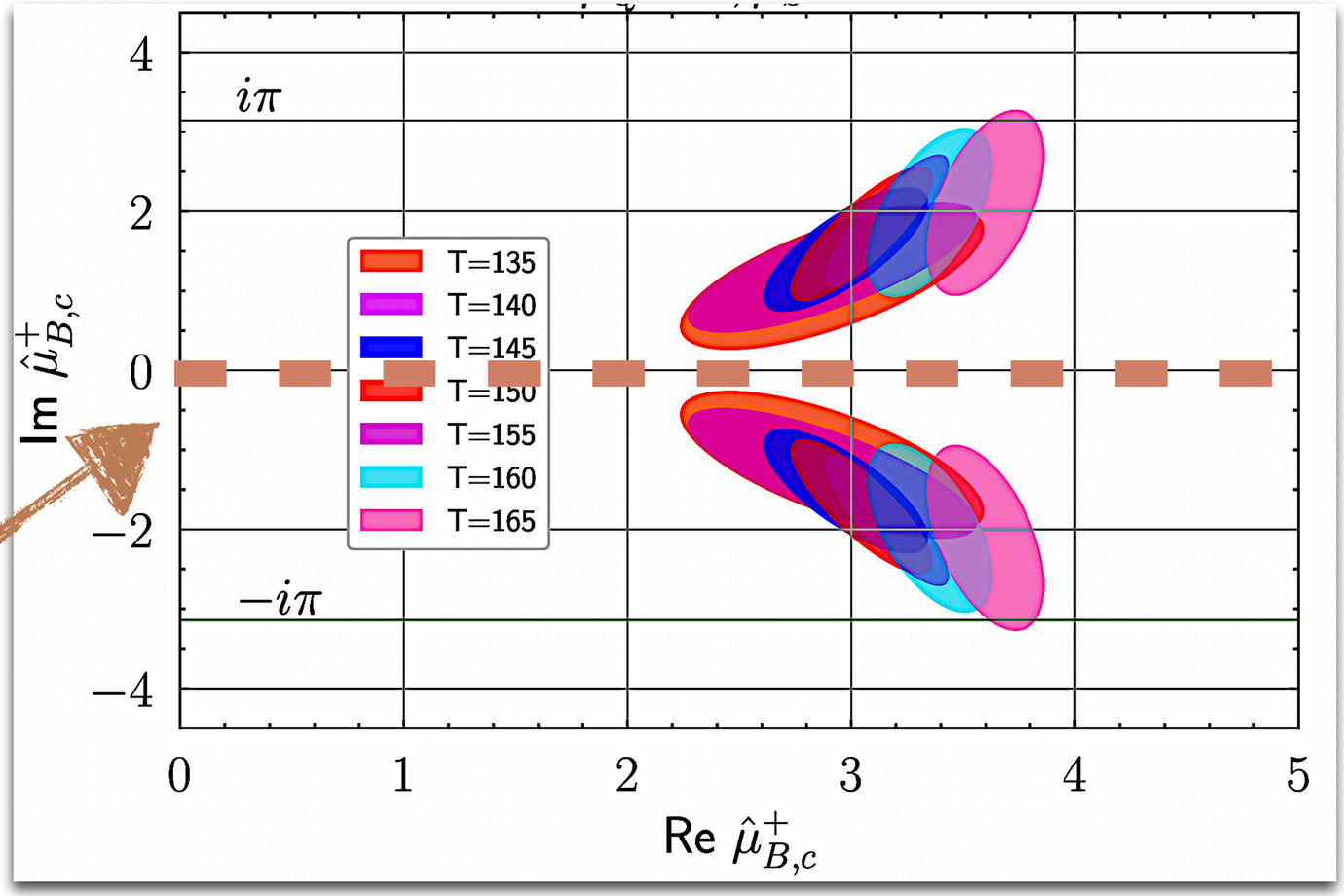



HotQCD, Phys. Lett. B 795,15 (2019)

# where is QCD critical point ?

looking for zeros of QCD partition function in complex-$\mu_B$ plane

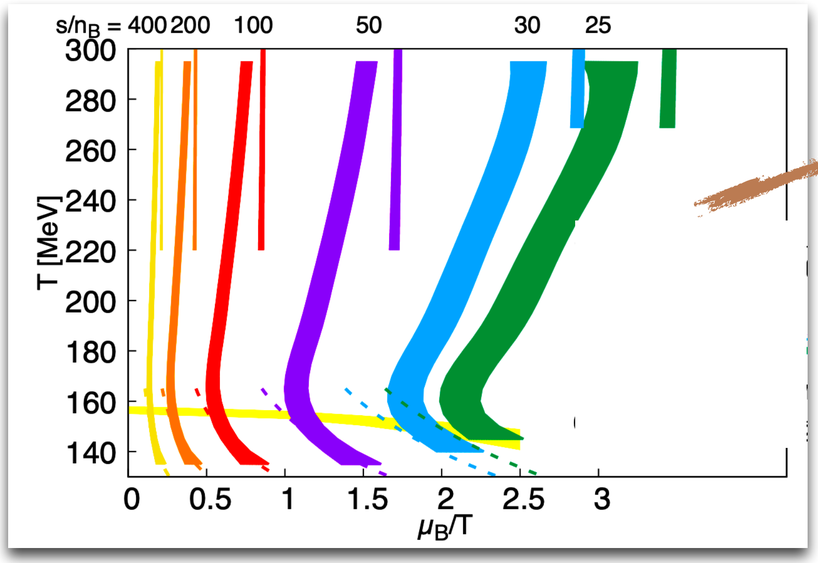
no hint of critical point for temperatures > 135 MeV



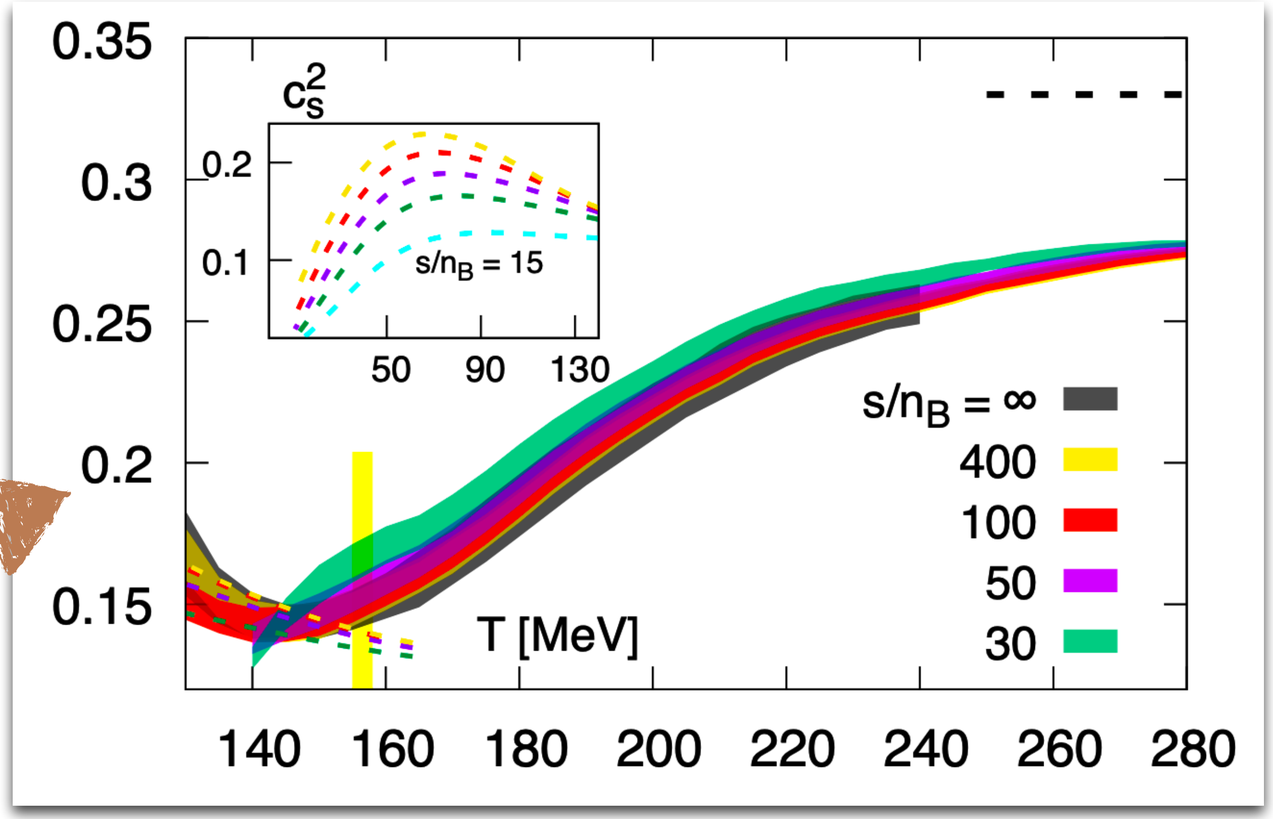

HotQCD, Phys. Rev. D 105, 074511 (2022)

# equation of state at $\mu_B > 0$

along the trajectories of ideal hydrodynamic evolution in the $T - \mu_B$ plane




speed of sound




HotQCD, 2212.09043

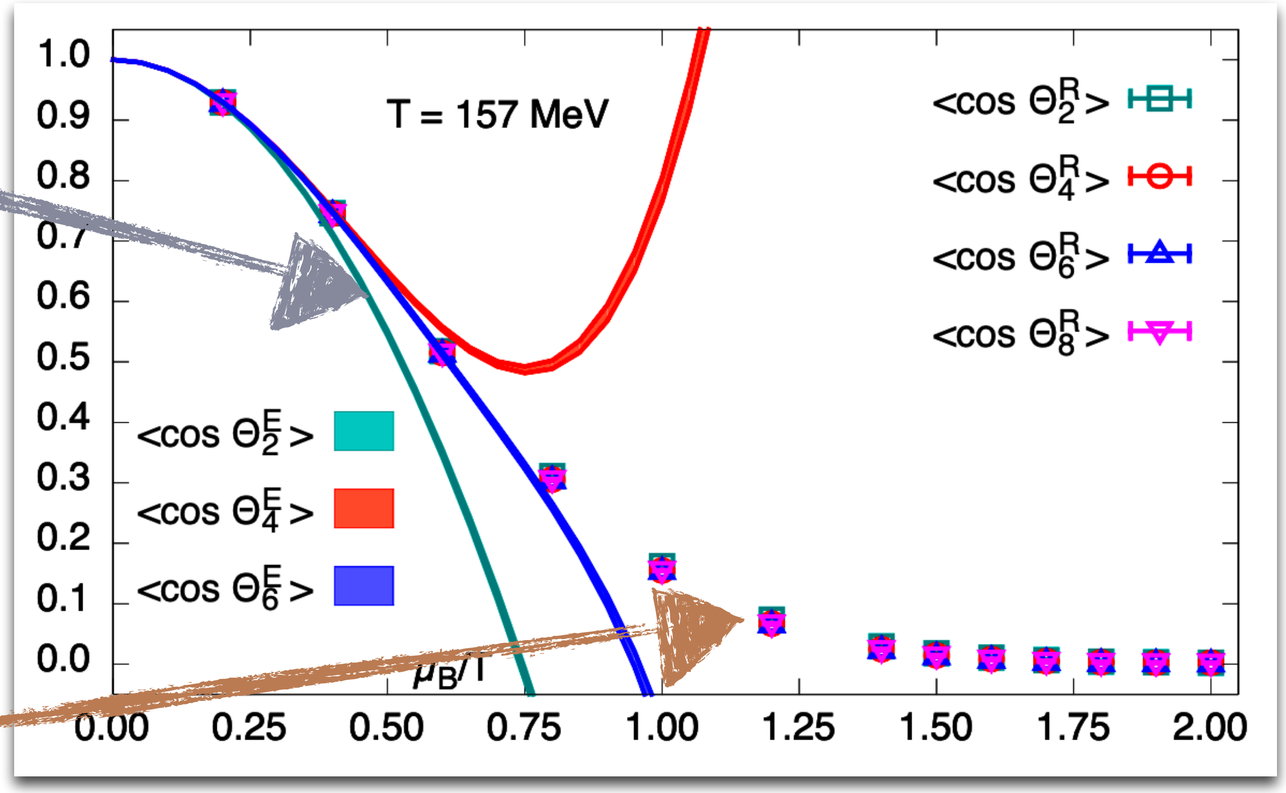
HotQCD, Phys. Rev. D 95, 054504 (2017)

# QCD equation of state at $\mu_B > 0$

average phase of the QCD partition function

very slow convergence of Taylor series in powers of $\mu_B$

resumming up to 8-point correlation functions of baryon current to all orders in $\mu_B$

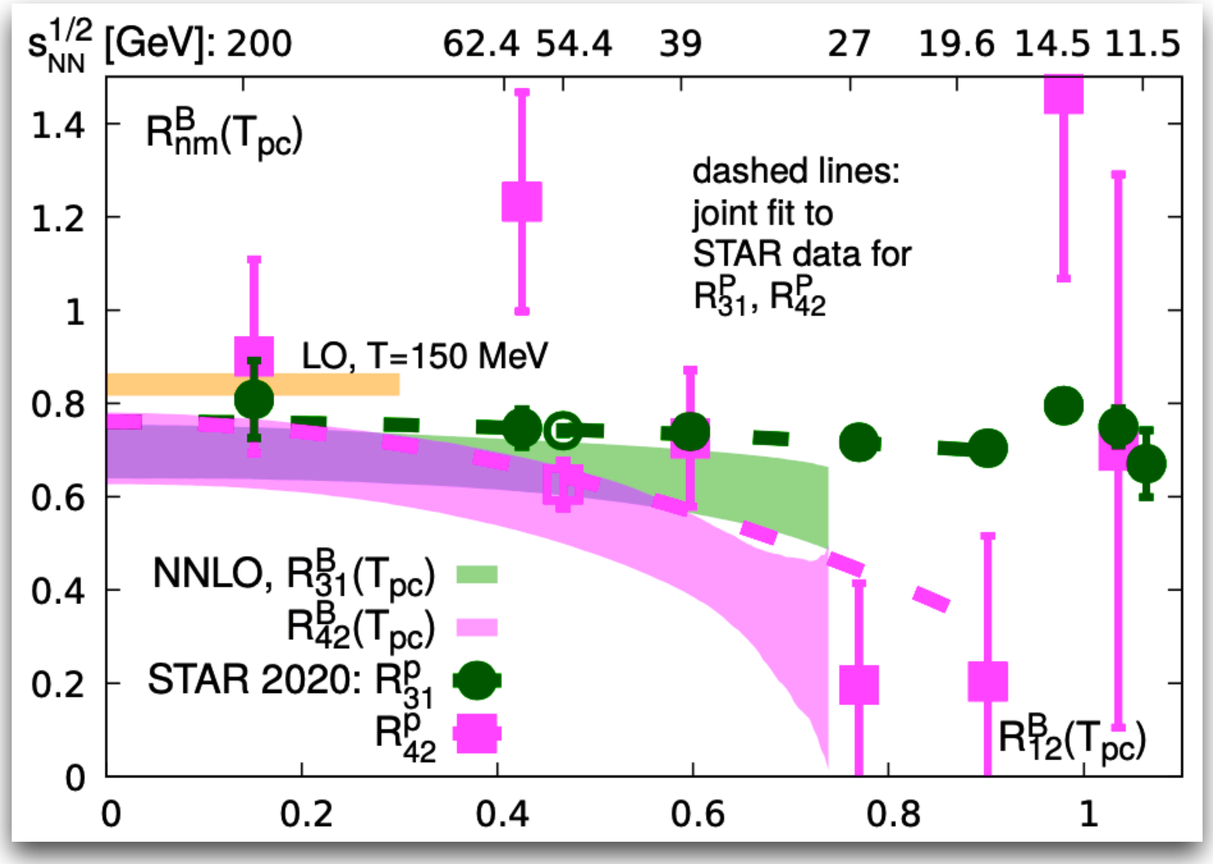



Mondal *et al.*, Phys. Rev. Lett. 128, 2, 022001 (2022)

# lattice meets experiments: from $T - \mu_B$ to $\sqrt{s}$

lattice QCD: ratios of cumulants of net baryon fluctuations along $T - \mu_B$ phase boundary

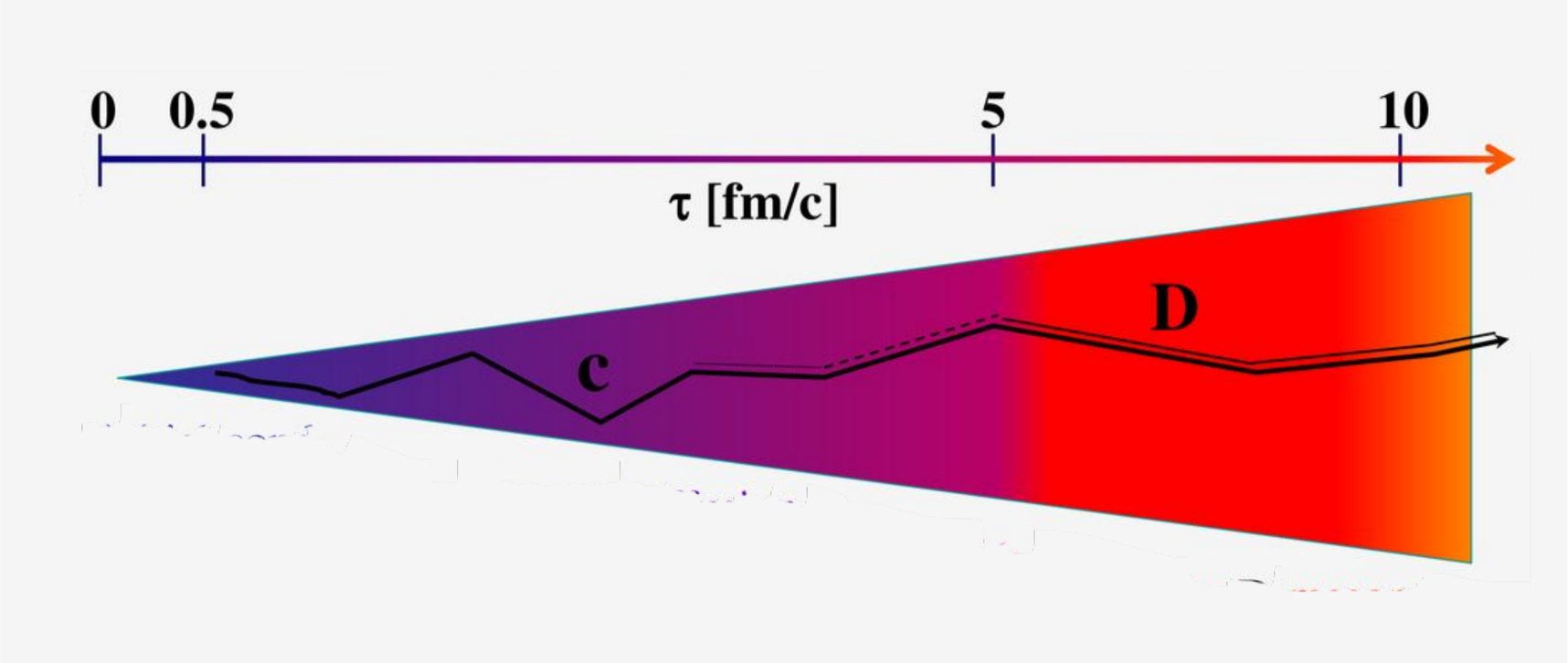
STAR: ratios of cumulants of net proton fluctuations for different collision energies $(\sqrt{s})$




HotQCD, Phys. Rev. Lett. 109, 192302 (2012)

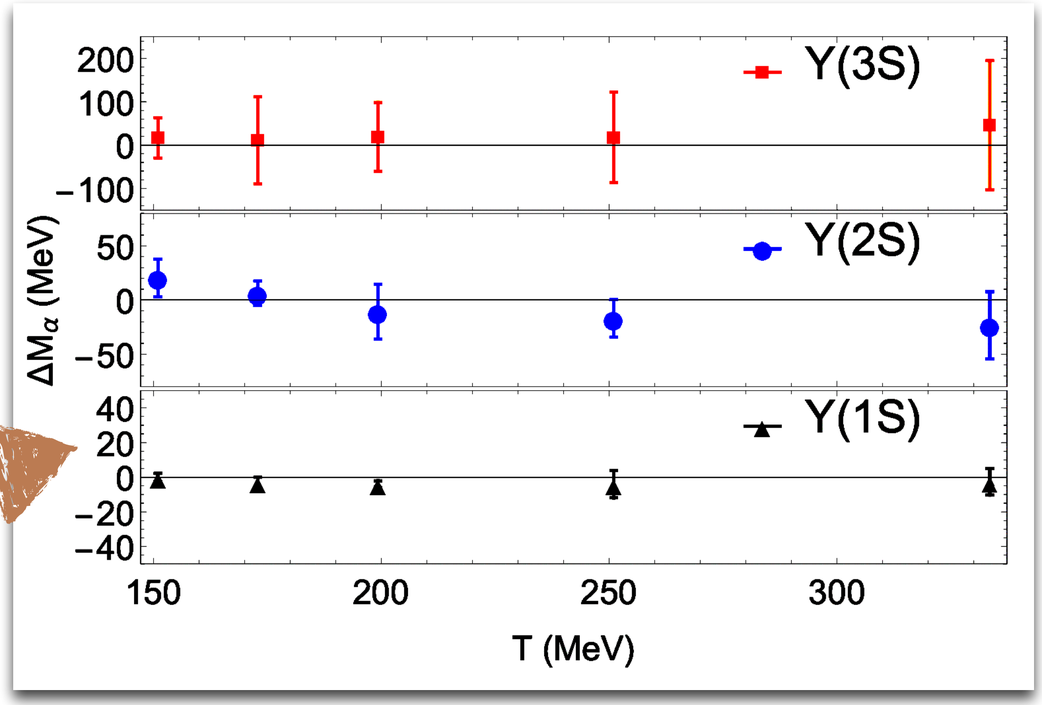
HotQCD, Phys. Rev. D 101, 7, 074502 (2020)

# … dancing with heavy quarks in QGP …



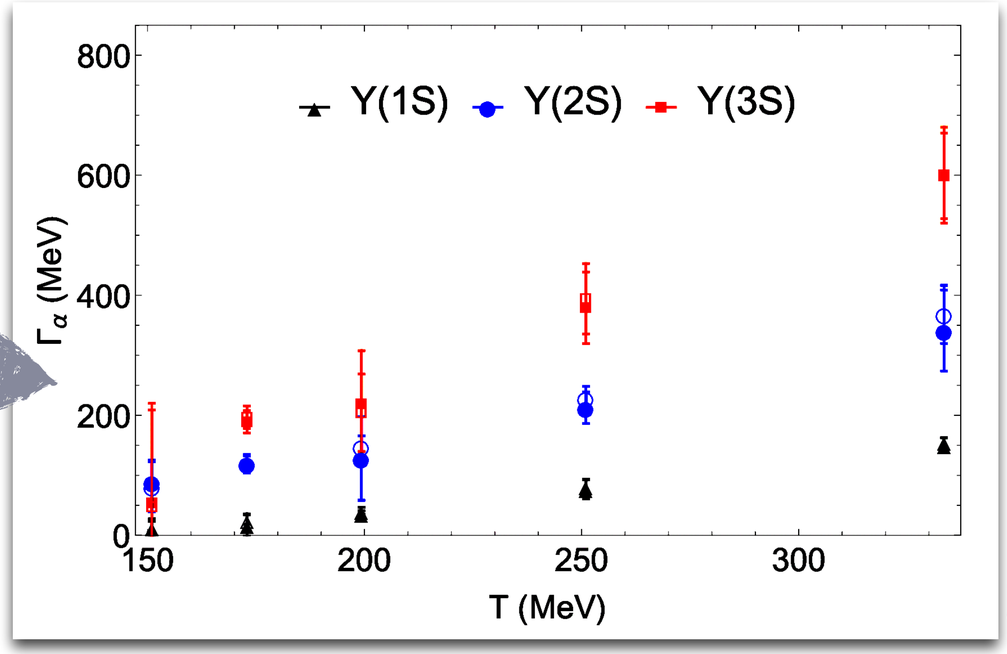
# excited bottomonia in QGP

first lattice QCD results for up to 3S & 2P bottomonia in QGP




small thermal mass shift

large thermal widths




Larsen *et al.*, Phys. Lett. B 800, 135119 (2020)

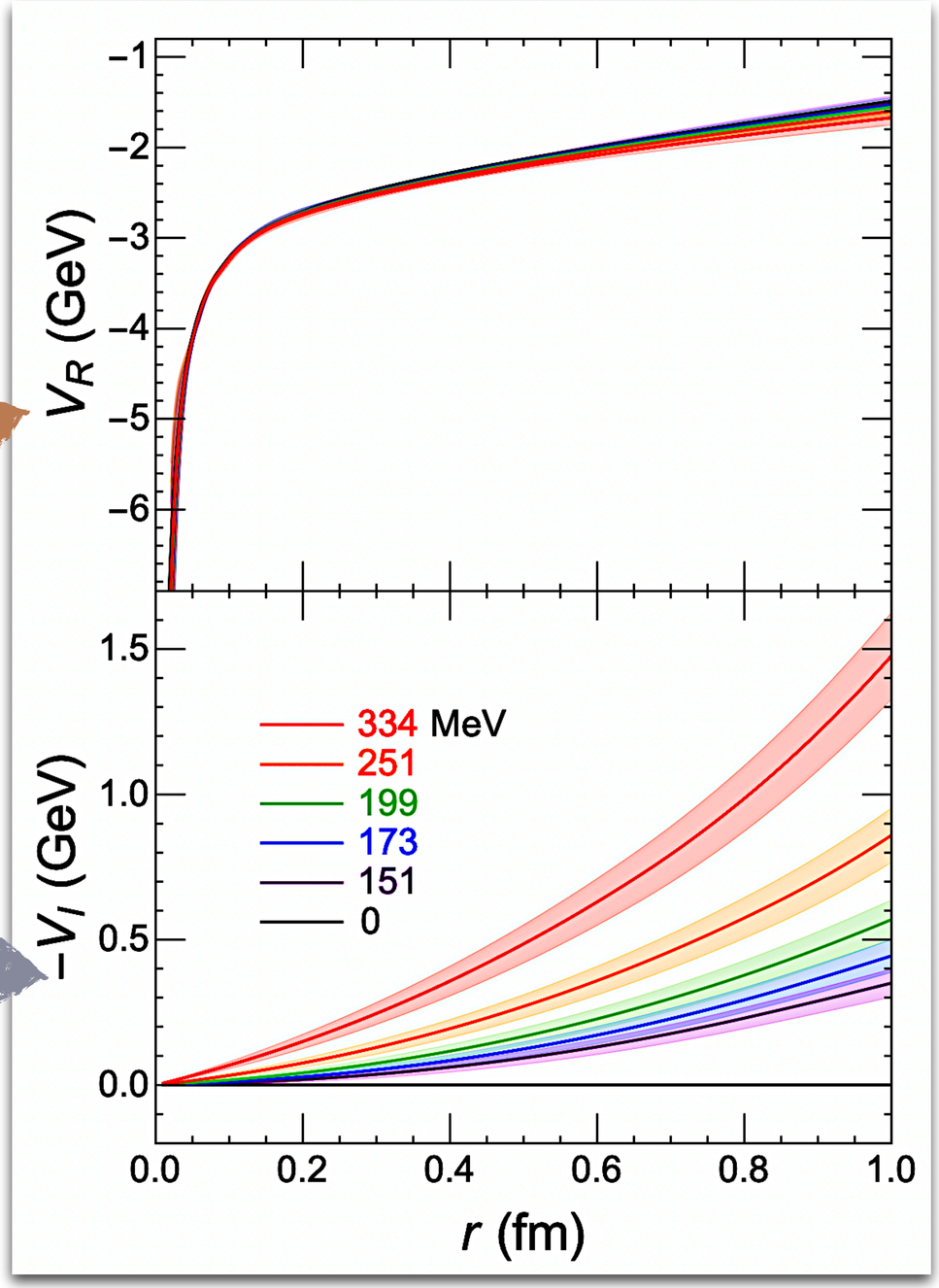
# heavy quark interactions in QGP

## heavy quark potential

from neural netwrok fits to in-medium bottonomia masses and widths

real part: almost no temperature dependence

imaginary part: strong temperature dependence



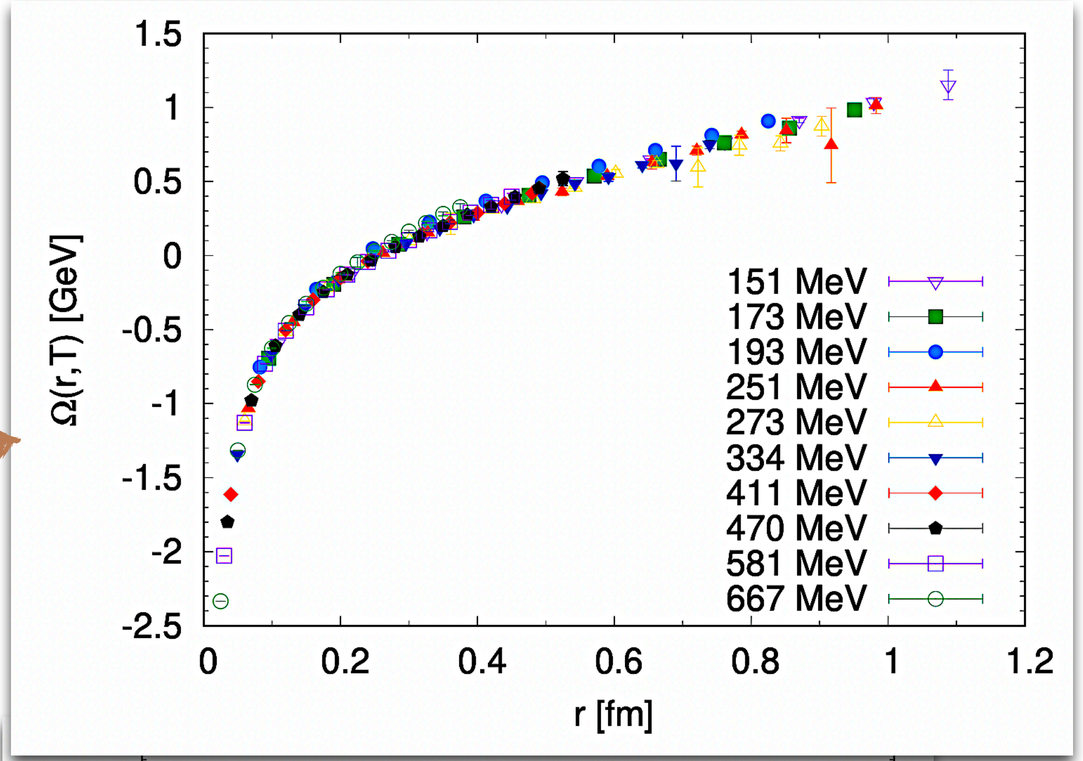

Shi et al., Phys. Rev. D 105, 1, 014017 (2022)

# heavy quark interactions in QGP

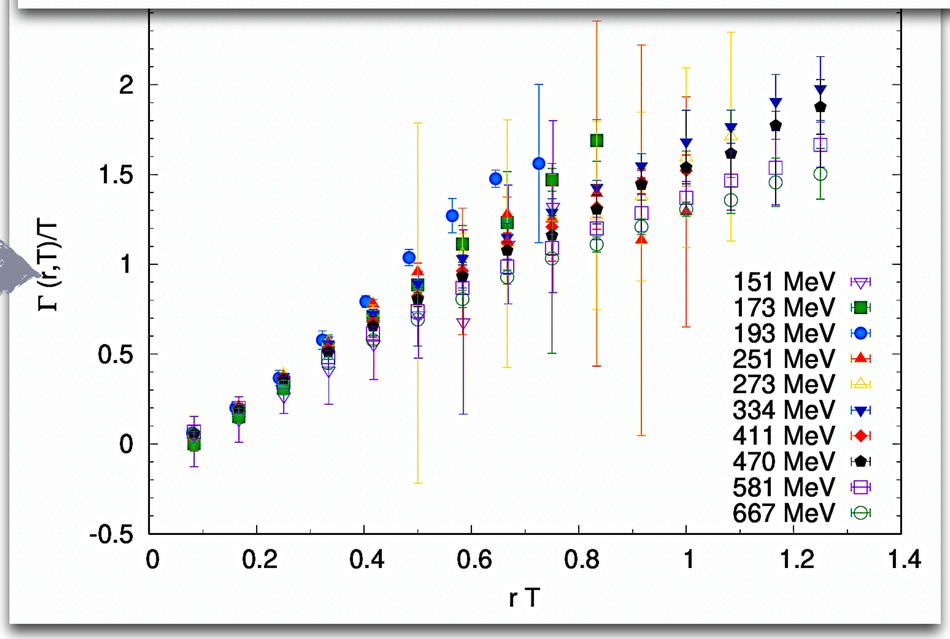
static quark potential

where is color screening ?

real part: almost no temperature dependence




imaginary part: strong temperature dependence




HotQCD, Phys. Rev. D 105, 054513 (2022)

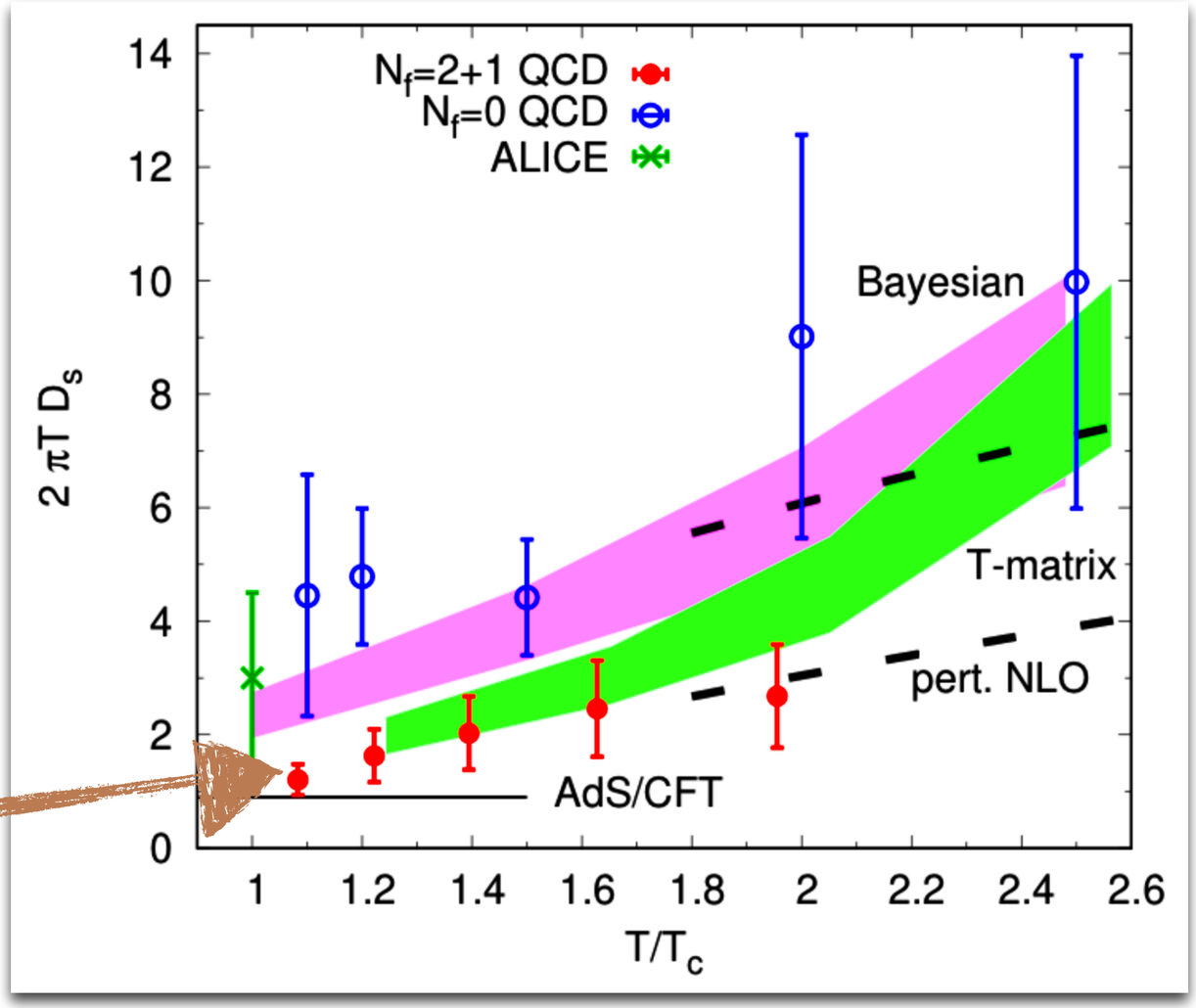
# heavy quark diffusion

static quark spatial diffusion coefficient

first lattice QCD calculations of transport coefficient including light dynamical fermions

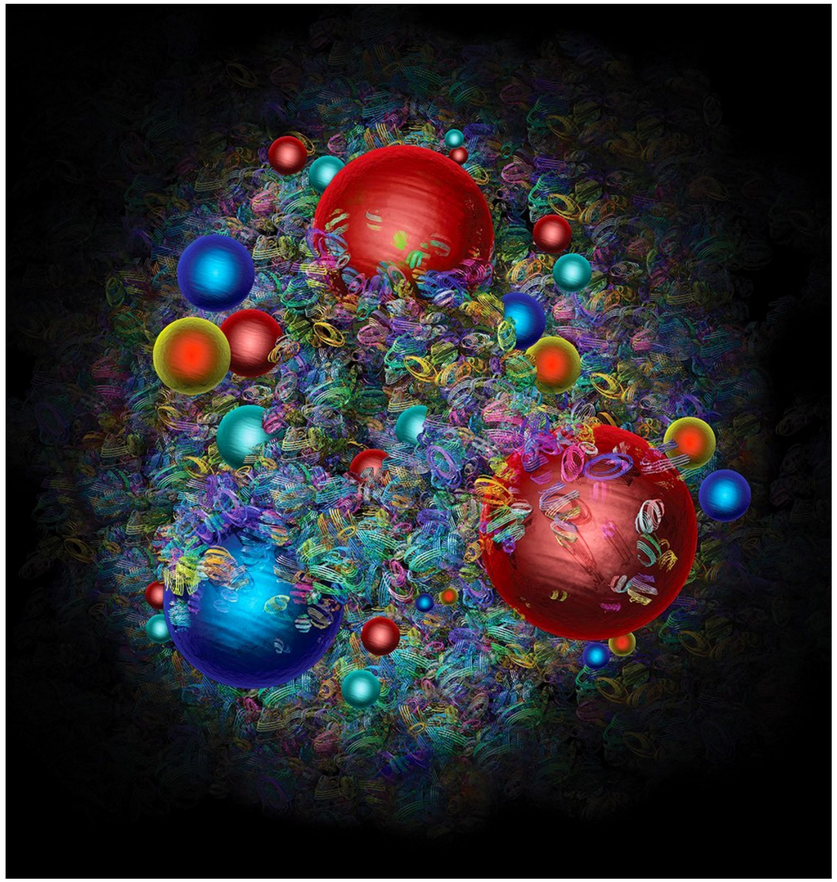
HotQCD, 2302.08501

very fast equilibration of heavy quark in QGP



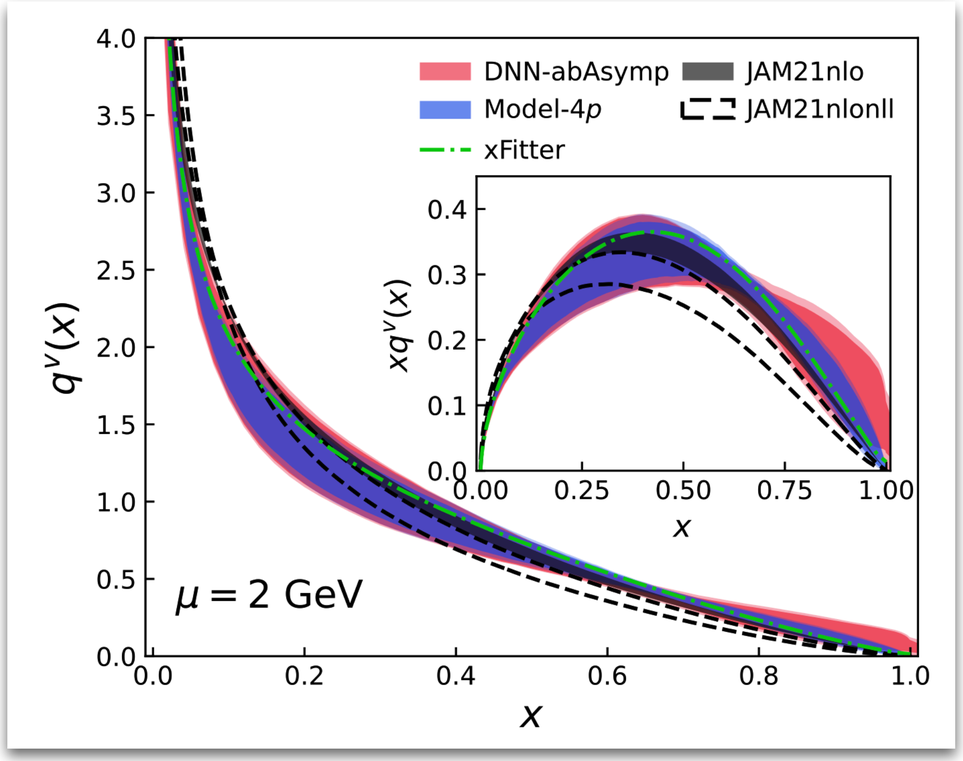
… 14 billion year later …

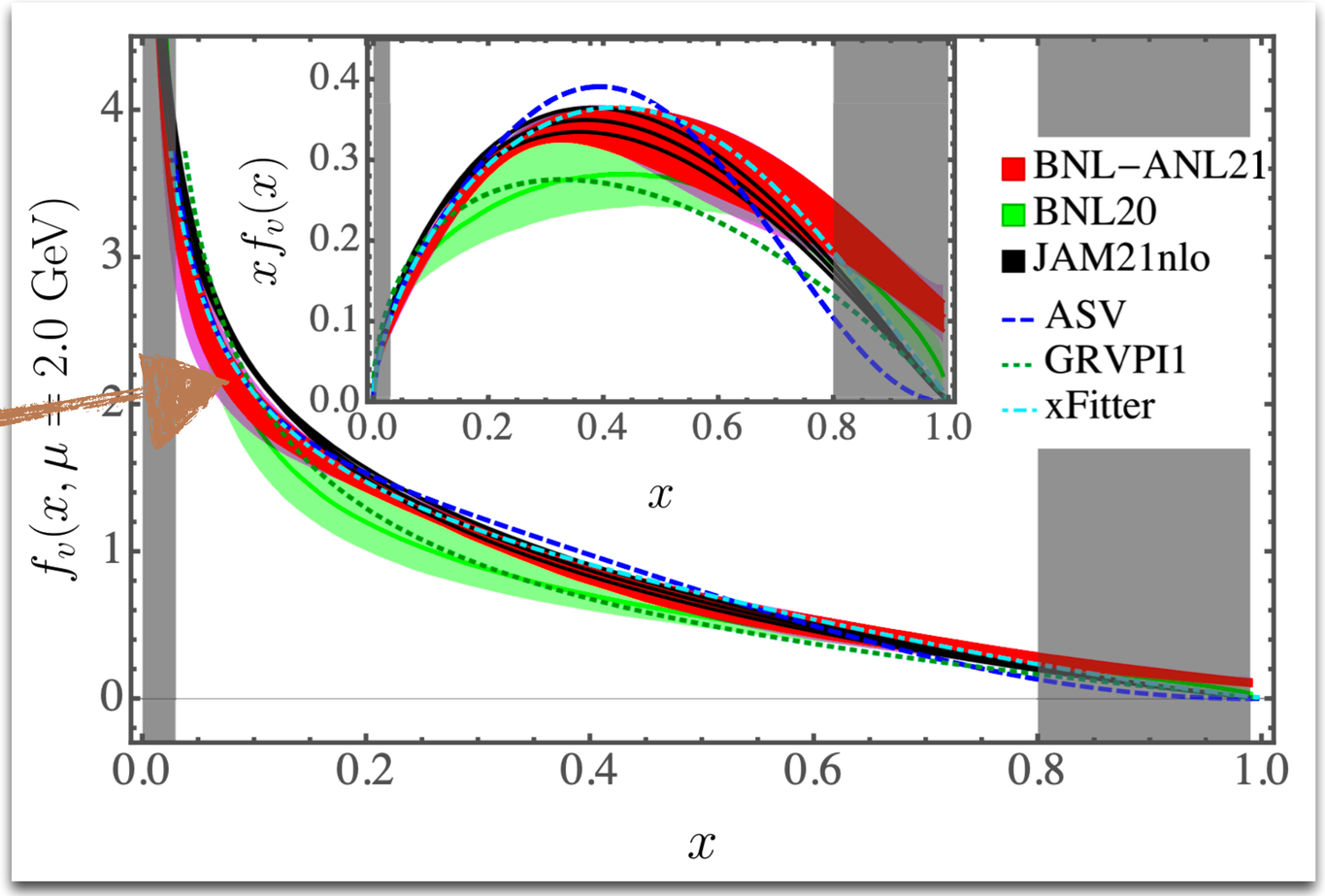
… lost in hadronic heartland …



# peeking inside pion

first lattice QCD calculations of valance quark distribution of pion at NNLO



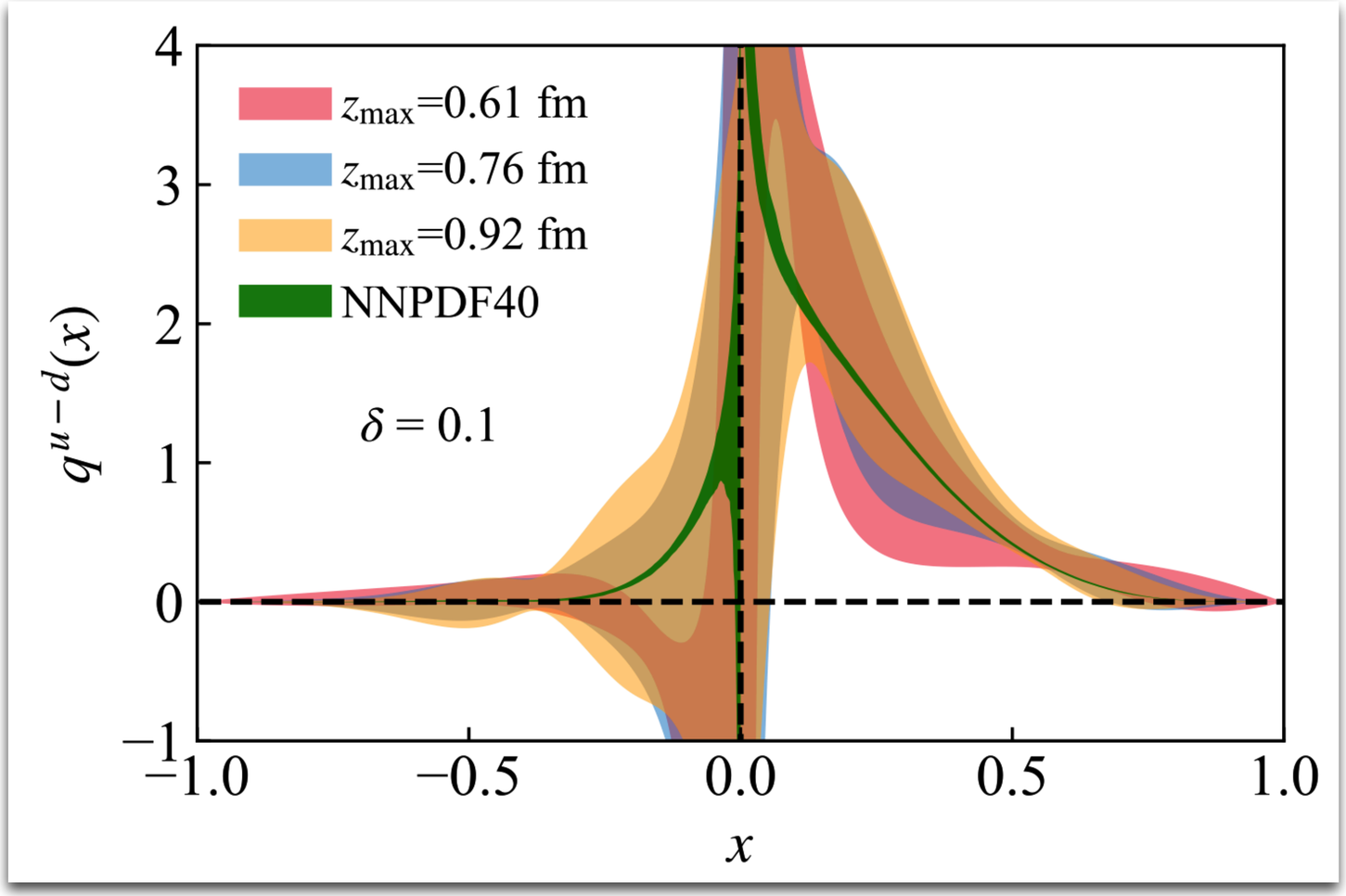




Gao *et al.*, Phys. Rev. Lett. 128, 14, 142003 (2022)

Gao *et al.*, Phys. Rev. D 106, 11, 114510 (2022)

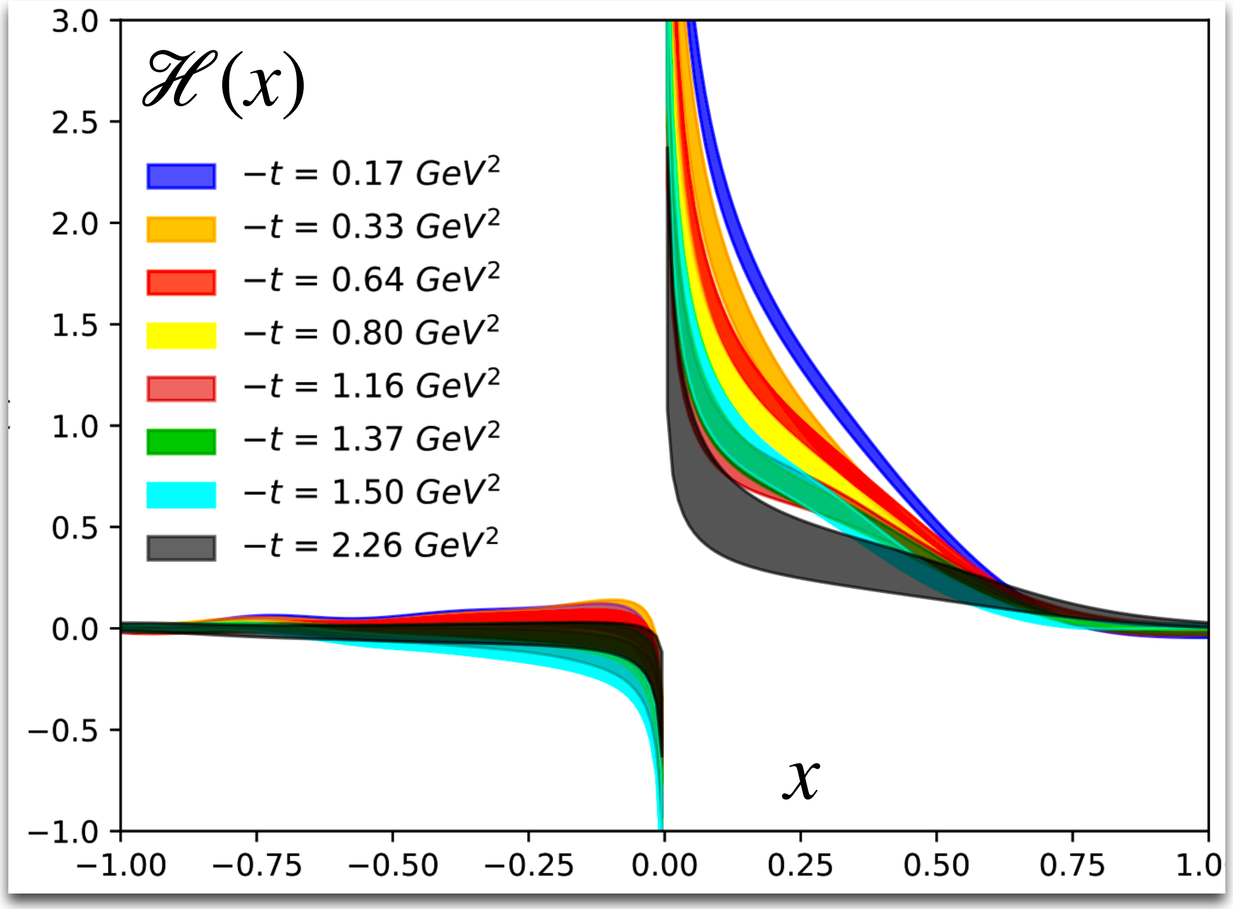
# diving into proton

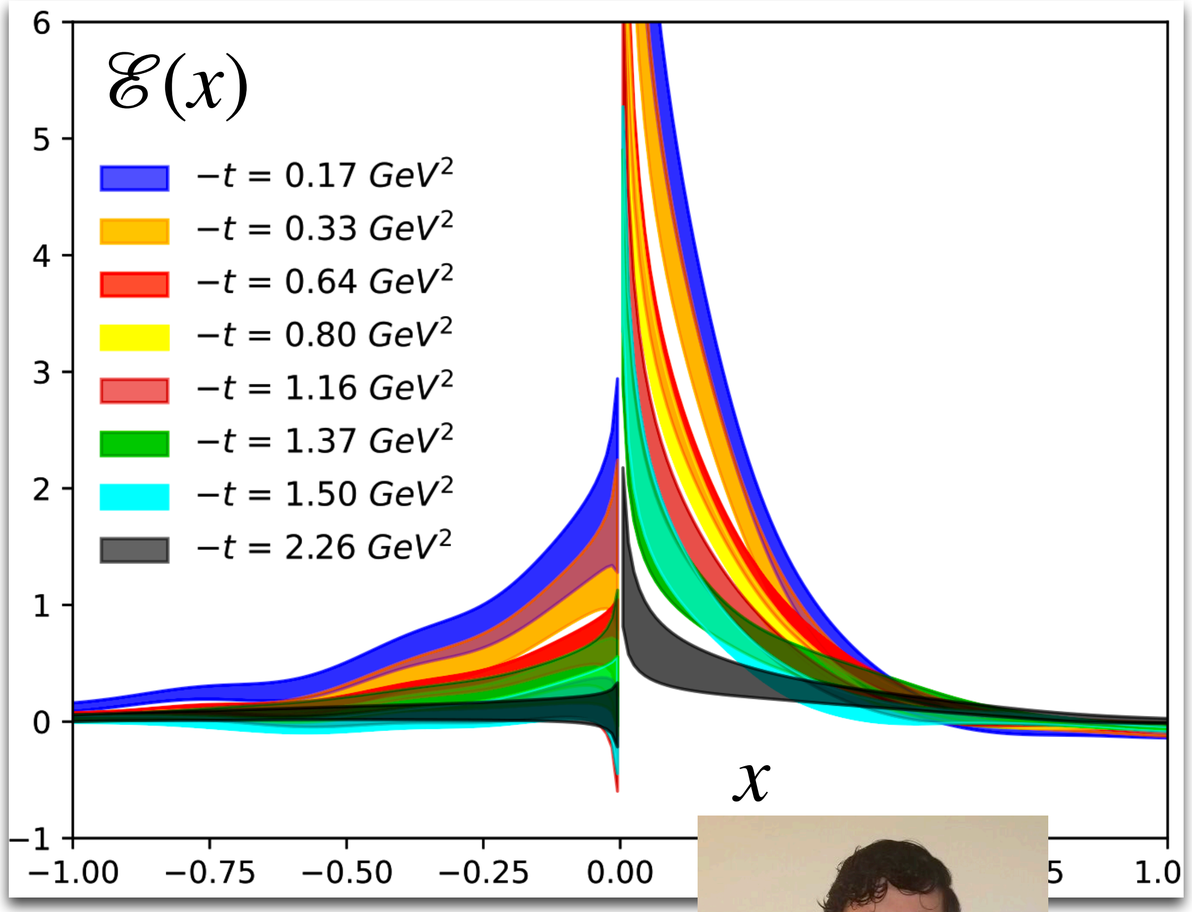
first lattice QCD calculations with physical quark masses of valance quark distribution of proton at NNLO




Gao *et al.*, Phys. Rev. D, to be published (2212.12569)

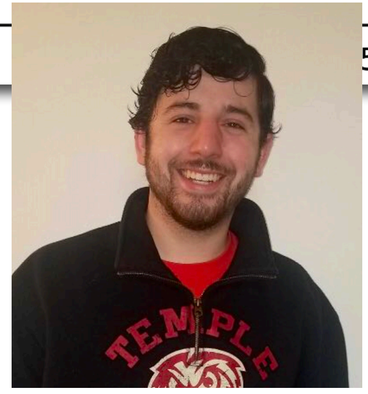
# 2+1dimensional image of proton …



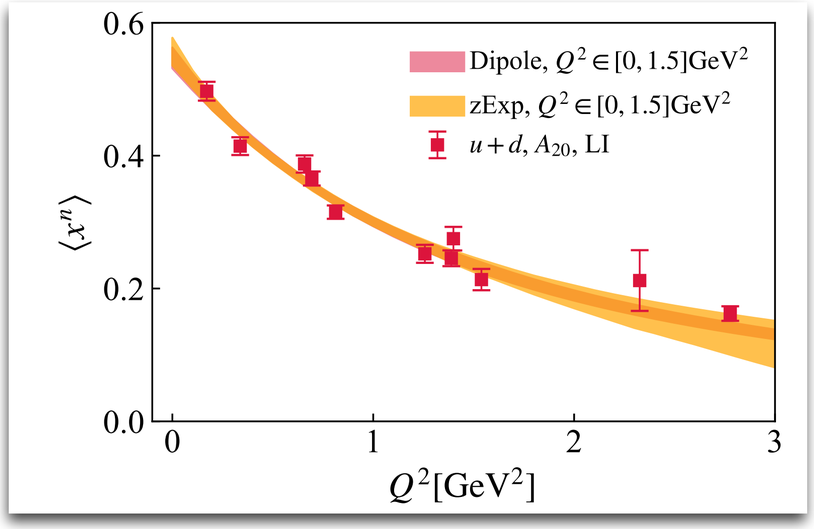



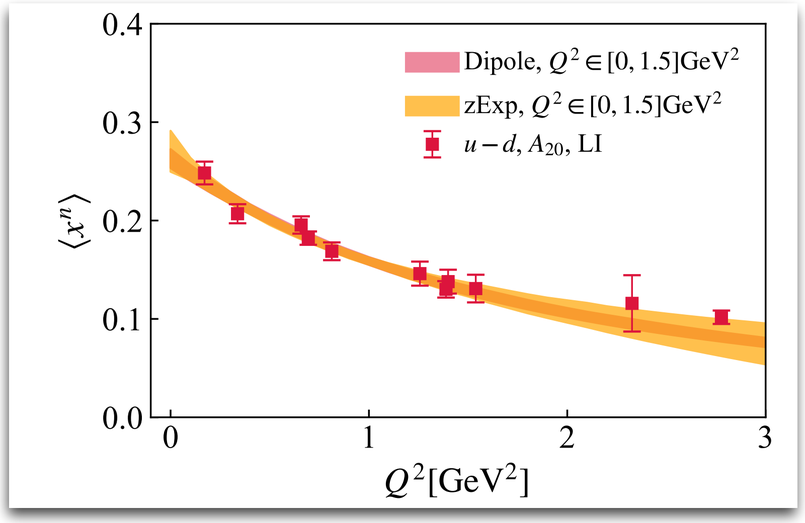

Bhattacharya *et al.*, Phys. Rev. D 106, 1, 114512 (2022)

talk: Joshua Miller



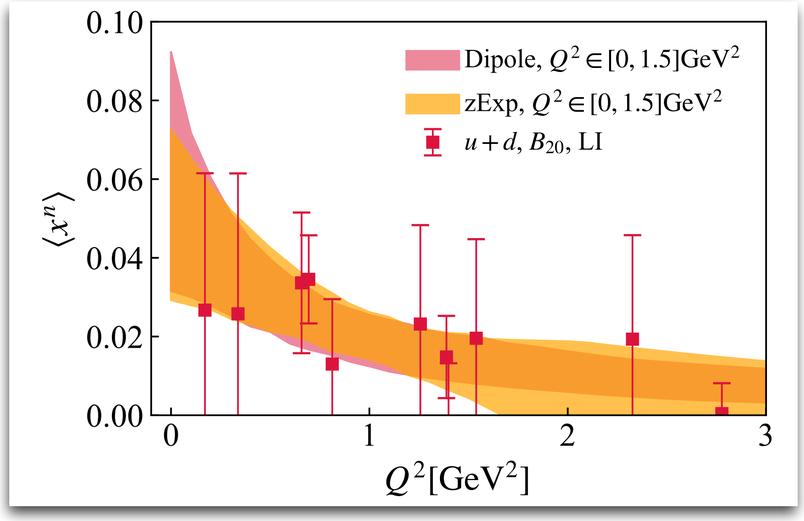
# … from GPD to quark angular contribution to proton spin

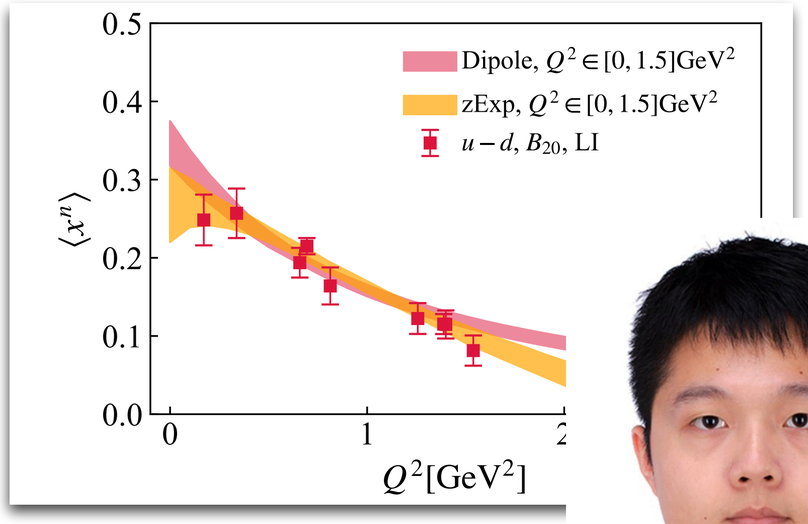



$$J^{u-d} = 0.267(27)(39)$$

$$J^{u+d} = 0.301(14)(02)$$




$$J^q = \frac{1}{2}(A^q_{20}(0) + B^q_{20}(0))$$

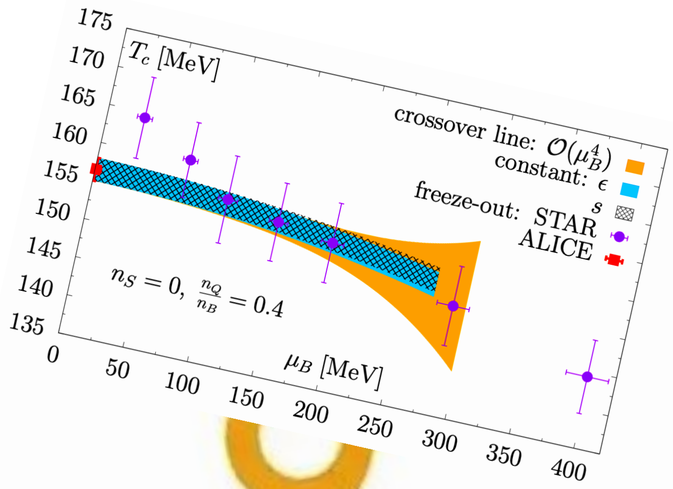
$$\int_{-1}^{1} dx x^n H^q(x, \xi = 0, t) = A^q_{n+1,0}(t)$$

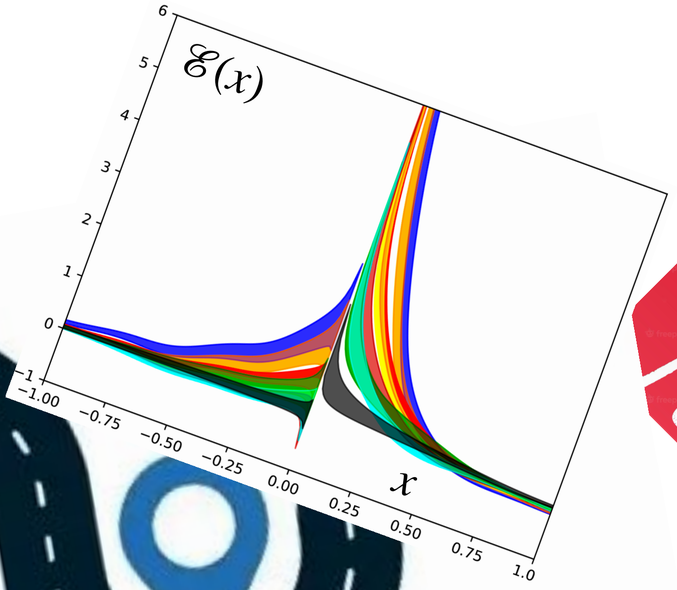
$$\int_{-1}^{1} dx x^n E^q(x, \xi = 0, t) = B^q_{n+1,0}(t)$$

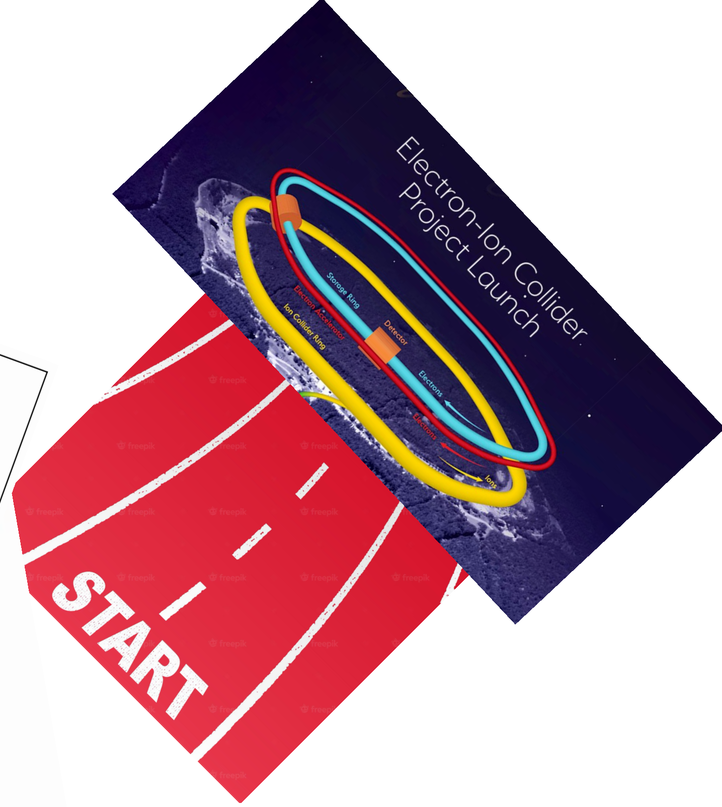


talk: Xiang Gao

# at the end ...







... beginning of new journey