# The QCD Transition in the Early Universe

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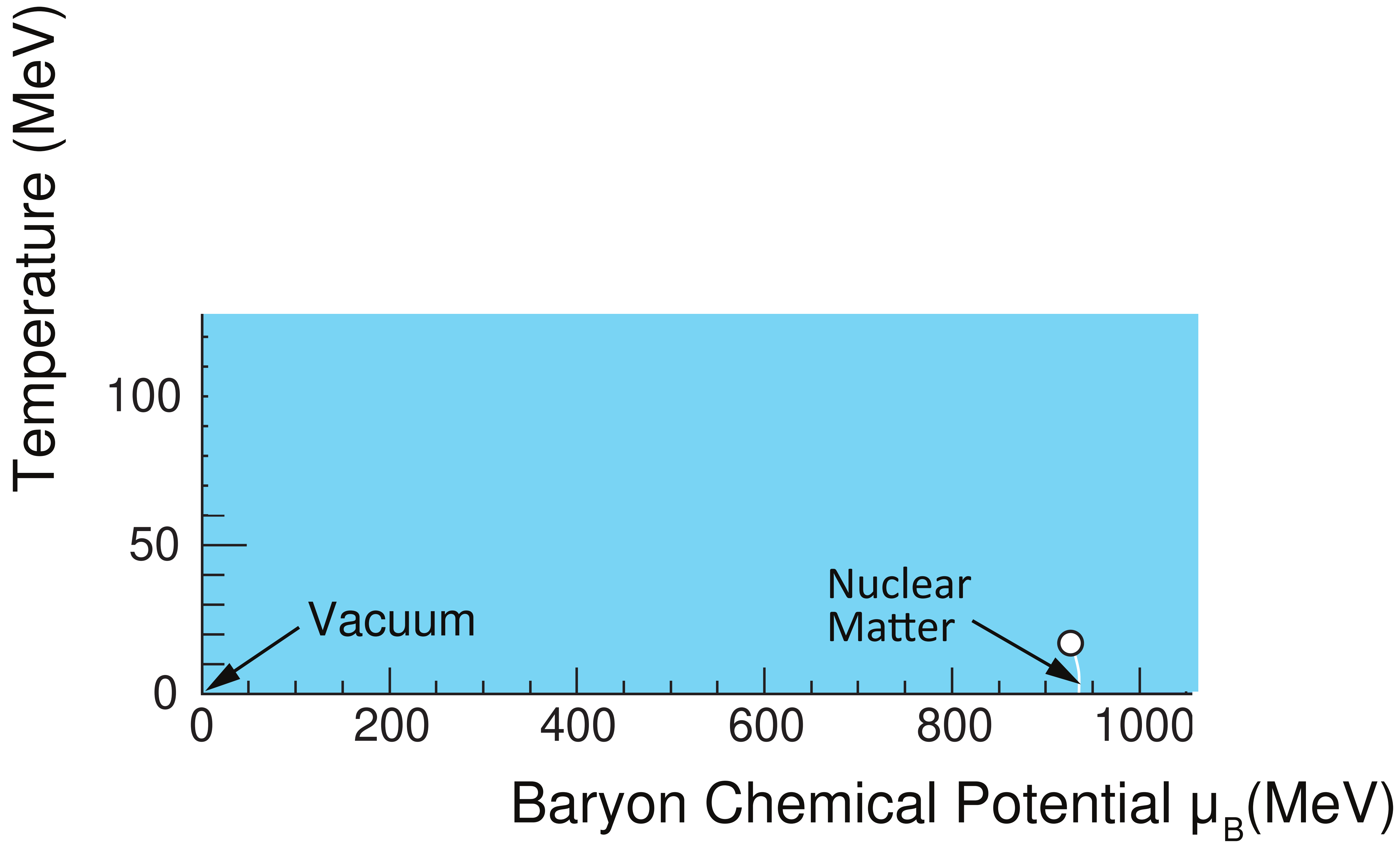
Gdr-QCD/DPhN seminar, Saclay, December 12th 2024

# Outline

- Phase diagram and thermodynamics of QCD
- The early universe at the QCD epoch
  - Was the temperature ever $T \gtrsim 200$ MeV?
  - Trajectories in the QCD phase diagram in standard and non-standard scenarios
- A partial and probably biased perspective. My apologies for all relevant work I may have missed

# The QCD phase diagram



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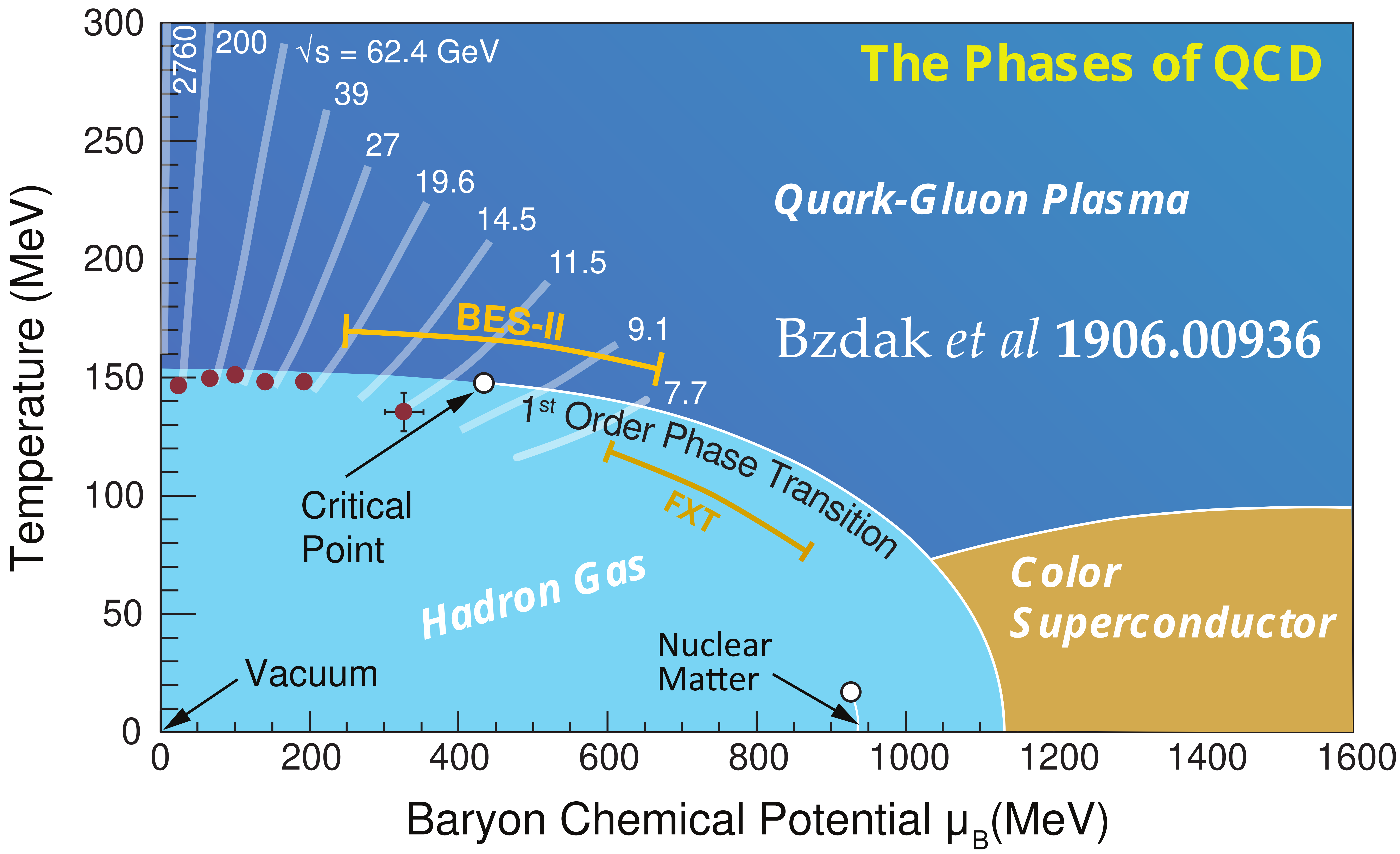


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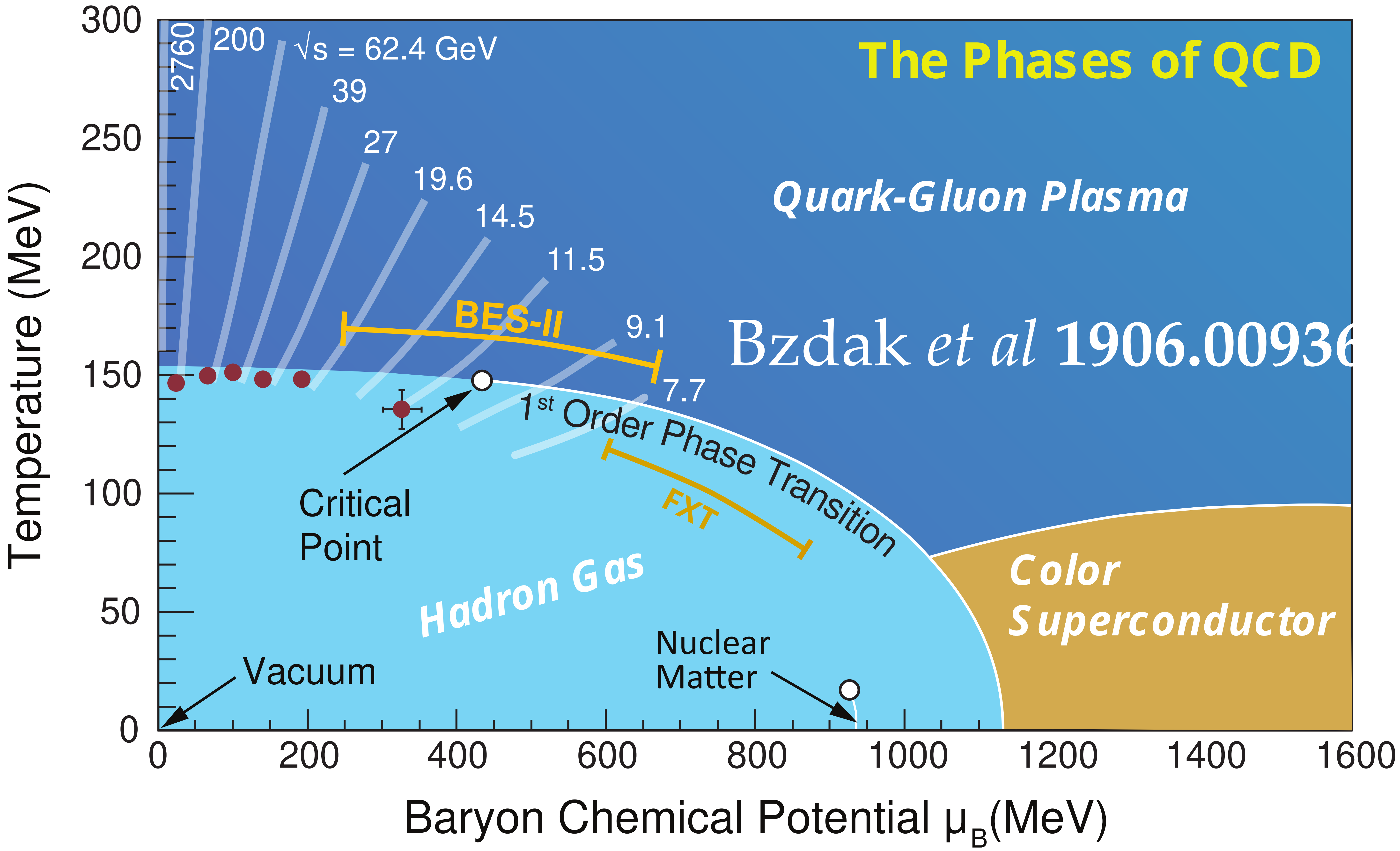
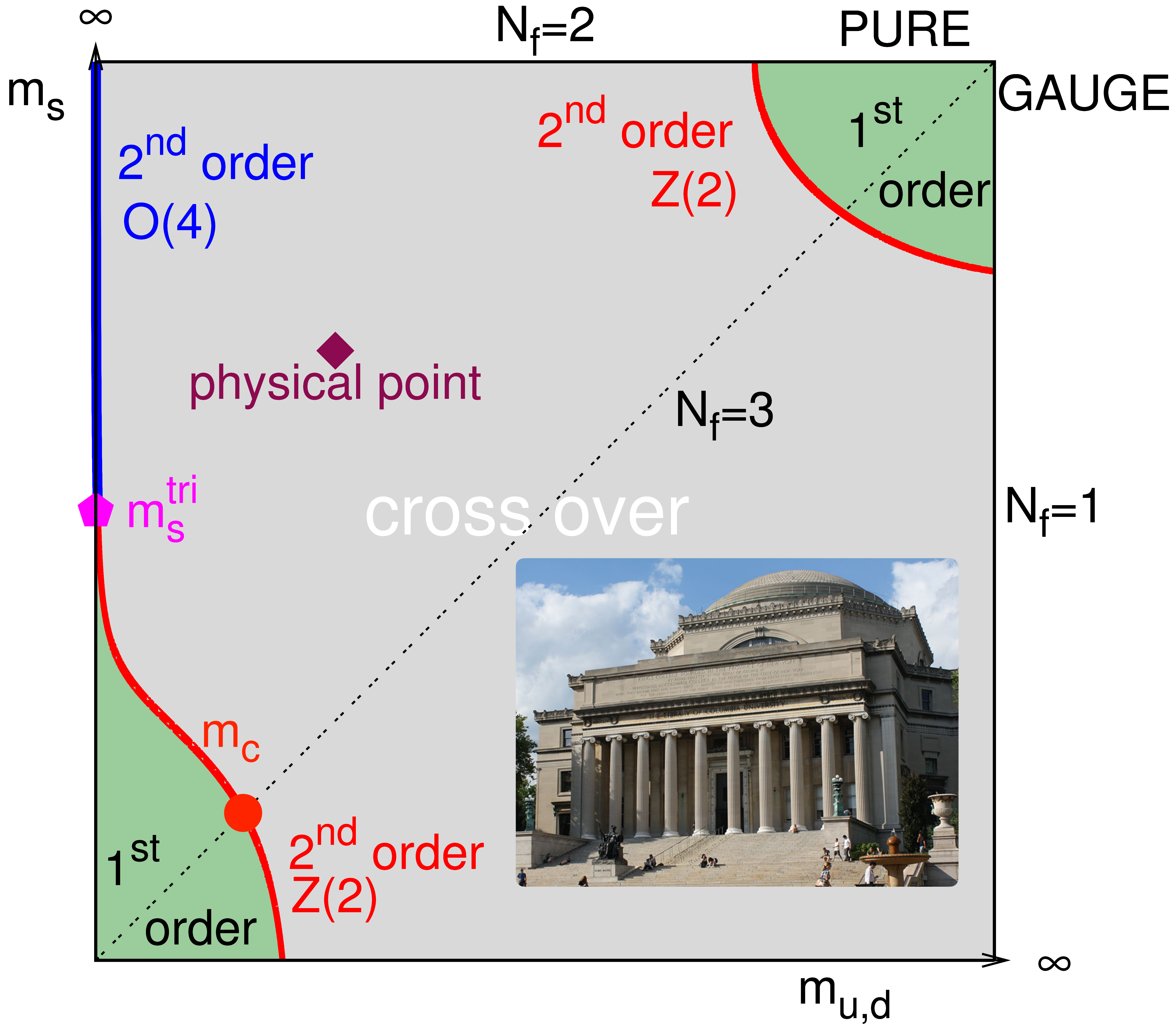



- Most solid theory knowledge at $\mu_B \approx 0$ (lattice QCD, mostly)
- Region explored by highest-$\sqrt{s_{NN}}$ heavy-ion collisions (LHC, 200 AGeV RHIC)
- $\mu_B \approx 0$ is also the scenario in standard cosmology (more later)

# The QCD transition at vanishing $\mu_B$



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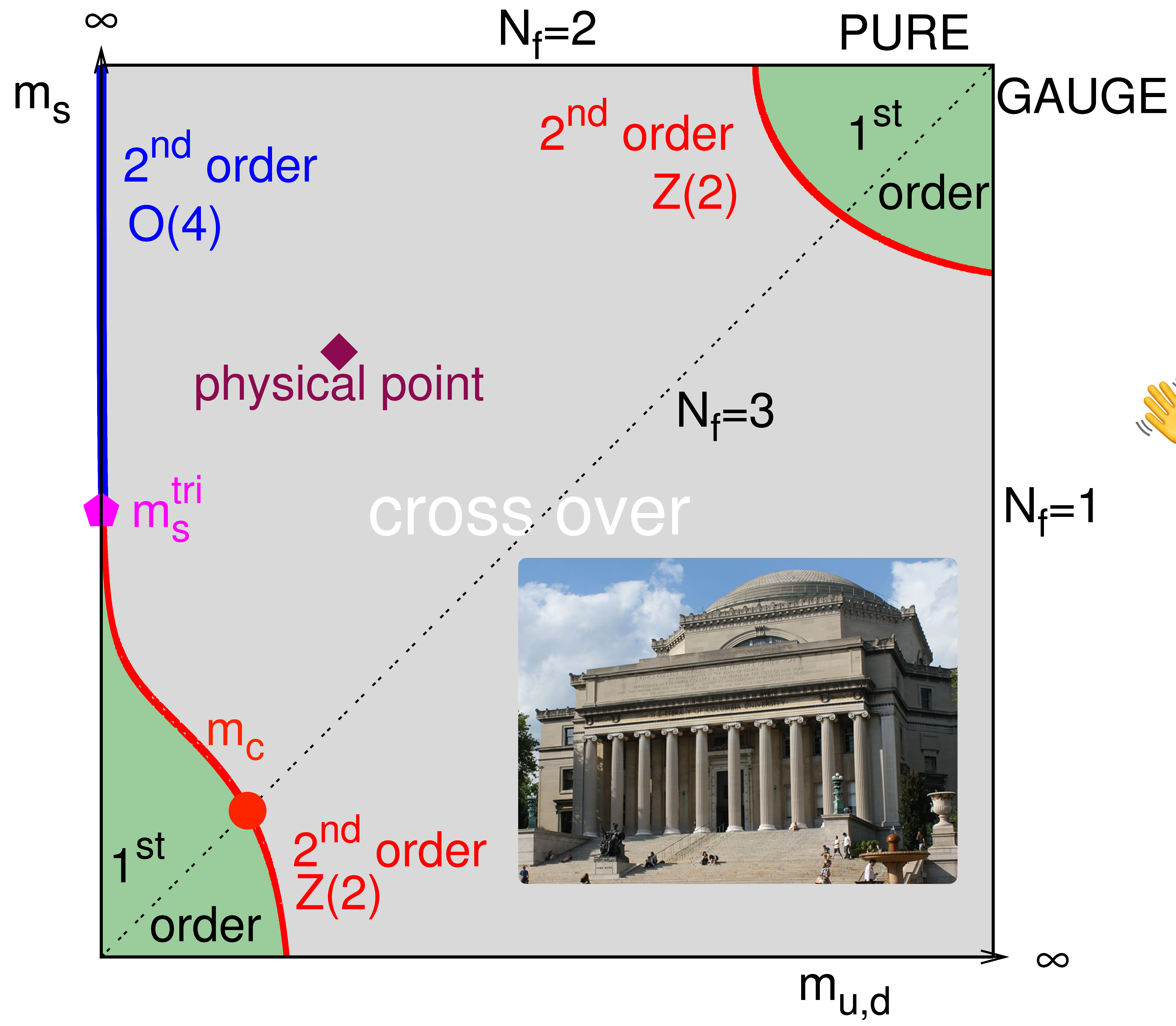
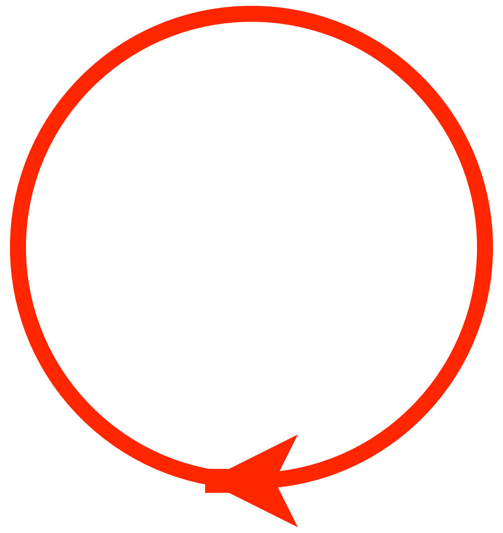



- **Center symmetry** in the Lagrangian **explicitly** broken by dynamical quarks: no **deconfinement phase transition** but **crossover**

👋 No confinement as in "infinite energy to break apart hadron" in real QCD because of quark-induced string breaking, so no phase transition

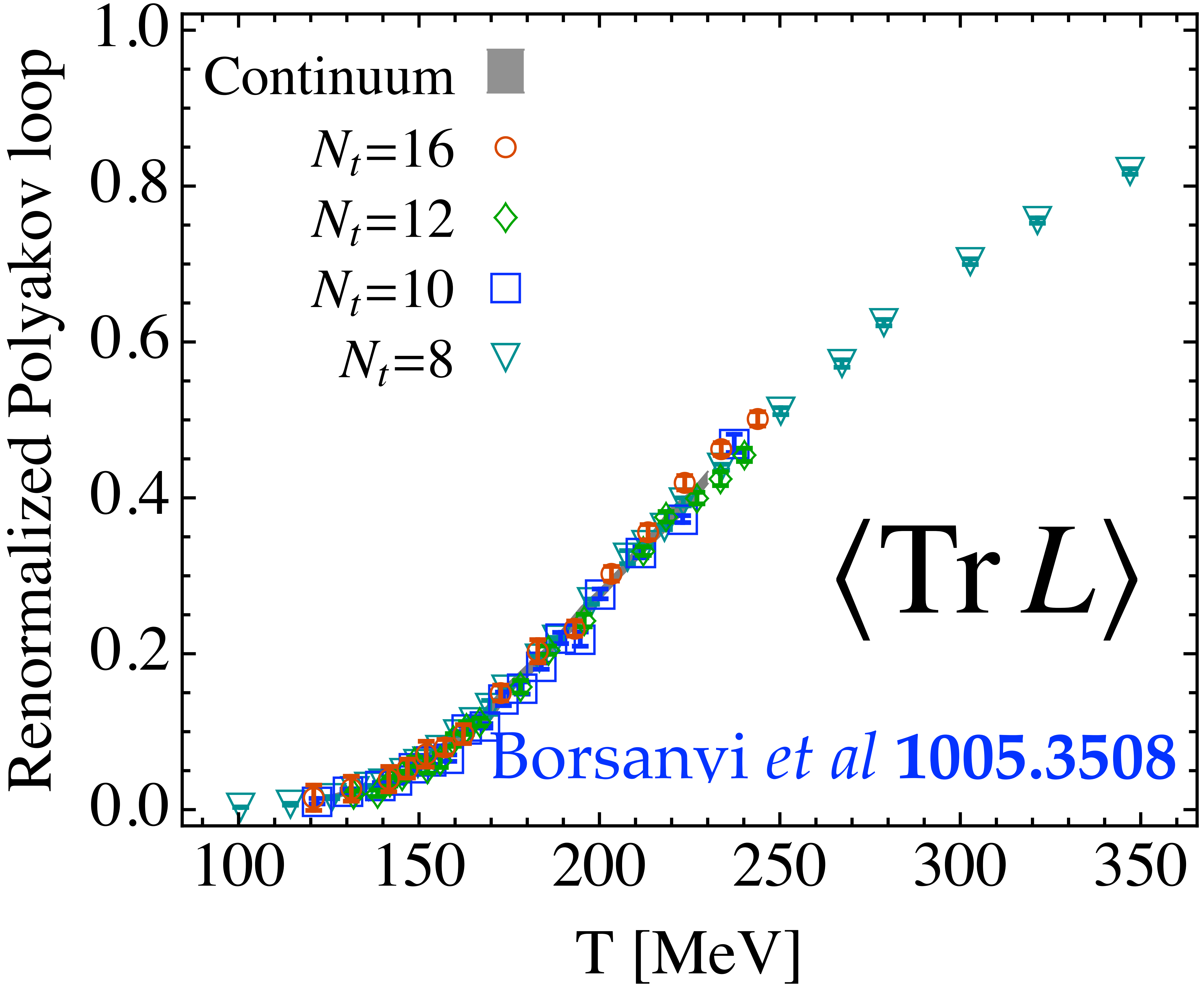
- Would-be order parameter: Polyakov loop $\langle \mathrm{Tr}\, L \rangle$

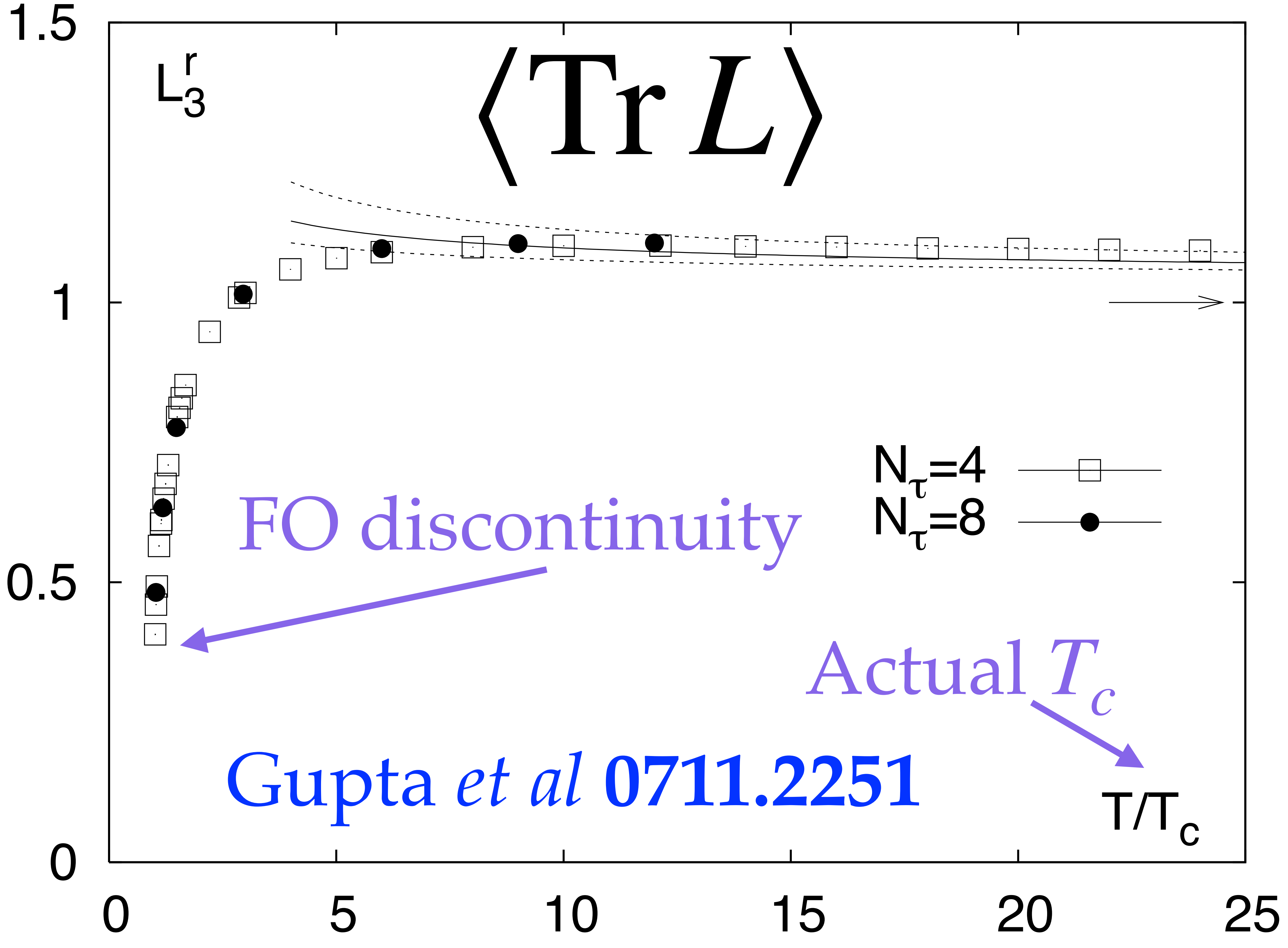
$$L = P \exp\left( ig \int_0^\beta d\tau A^0(\tau, \mathbf{x}) \right)$$



# The deconfinement transition at vanishing $\mu_B$

With or without u (d,s)



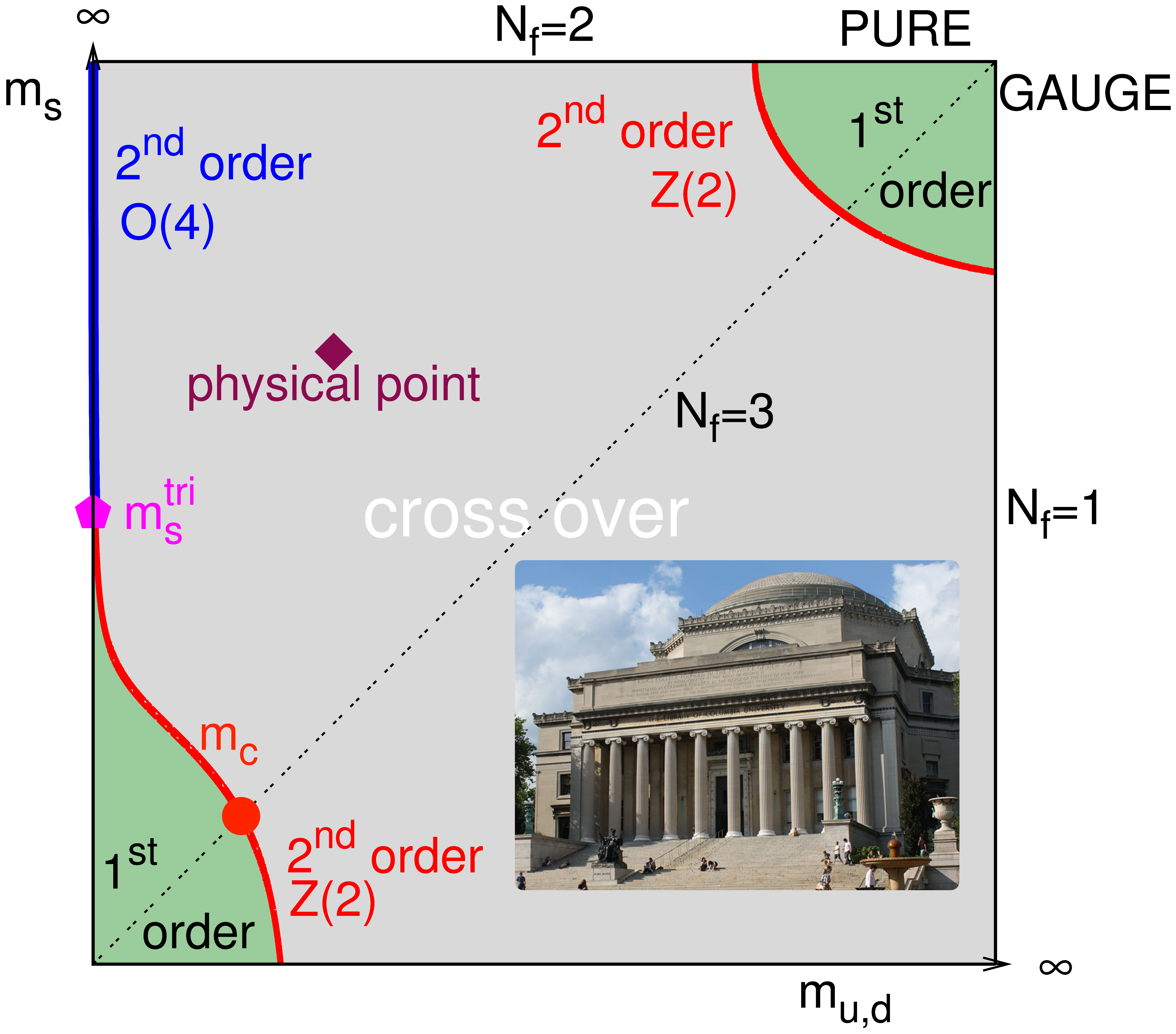
# The QCD transition at vanishing $\mu_B$

- **Chiral symmetry** in the Lagrangian **explicitly** broken by nonzero quark masses: no **chiral phase transition**

$$f_\pi^2 m_\pi^2 = 1/2(m_u + m_d)\langle\bar{\psi}\psi\rangle$$

- Lots of intricacies related to the relative strength of the axial anomaly

- Would-be order parameter: chiral condensate $\langle\bar{\psi}\psi\rangle$



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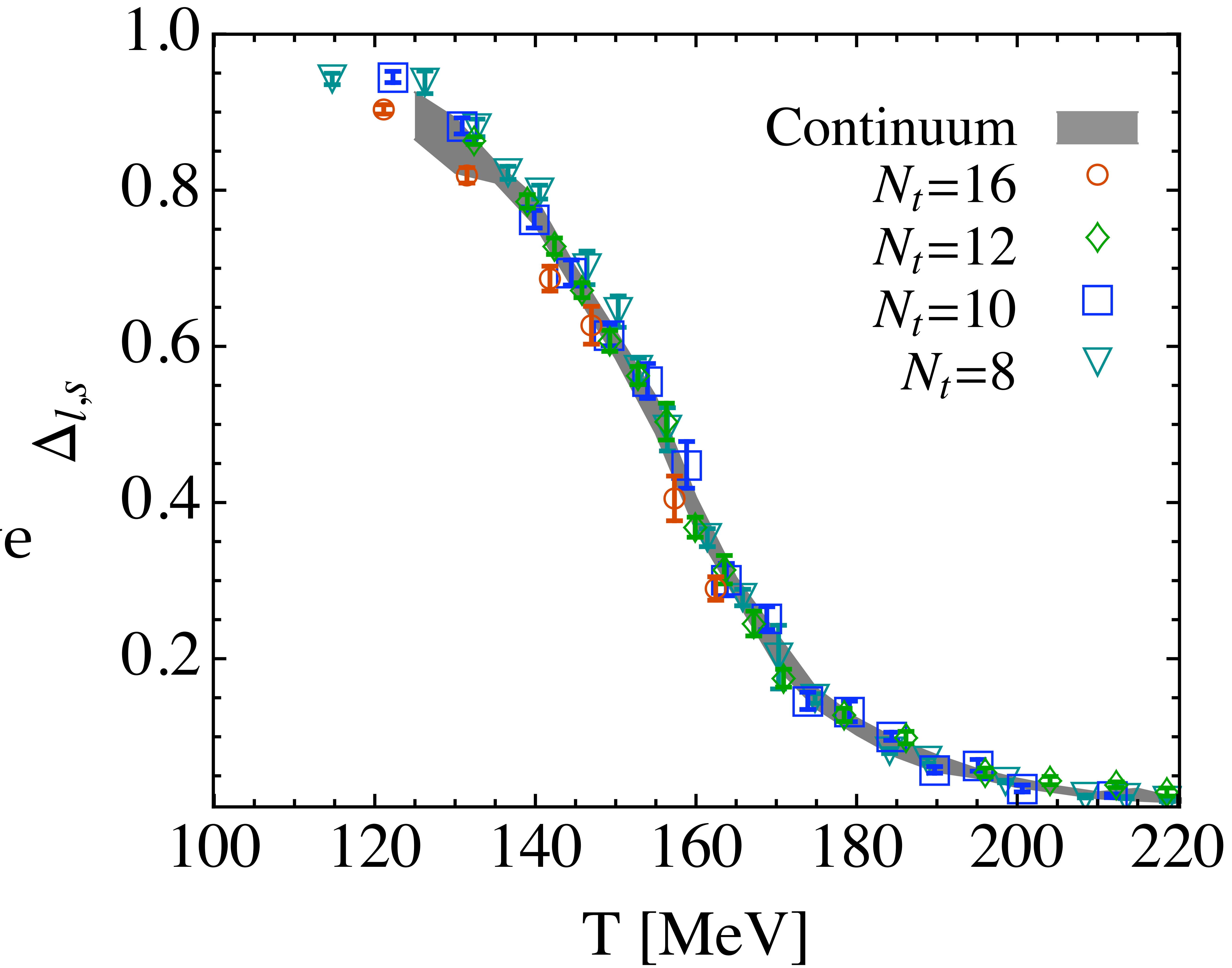
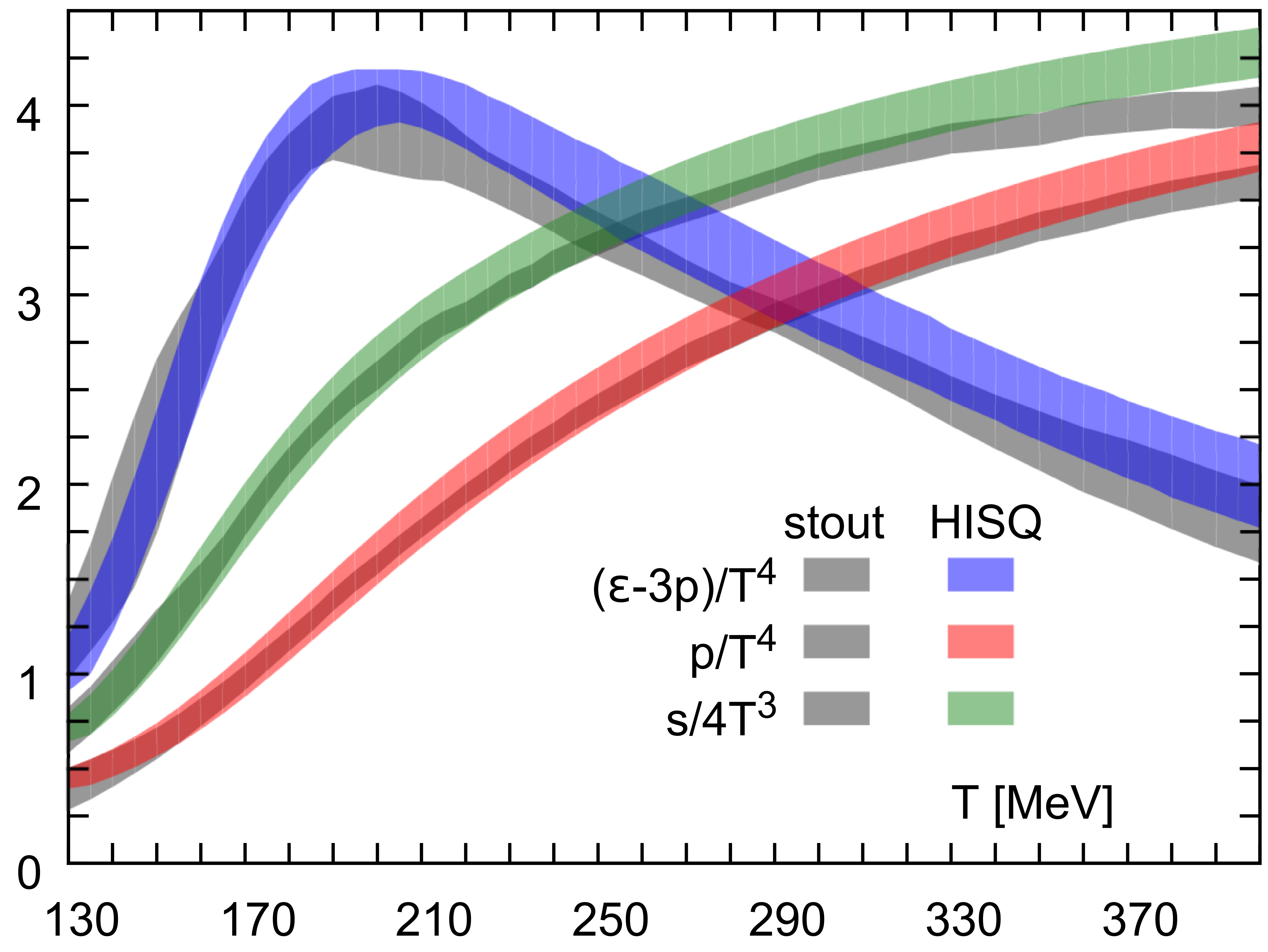
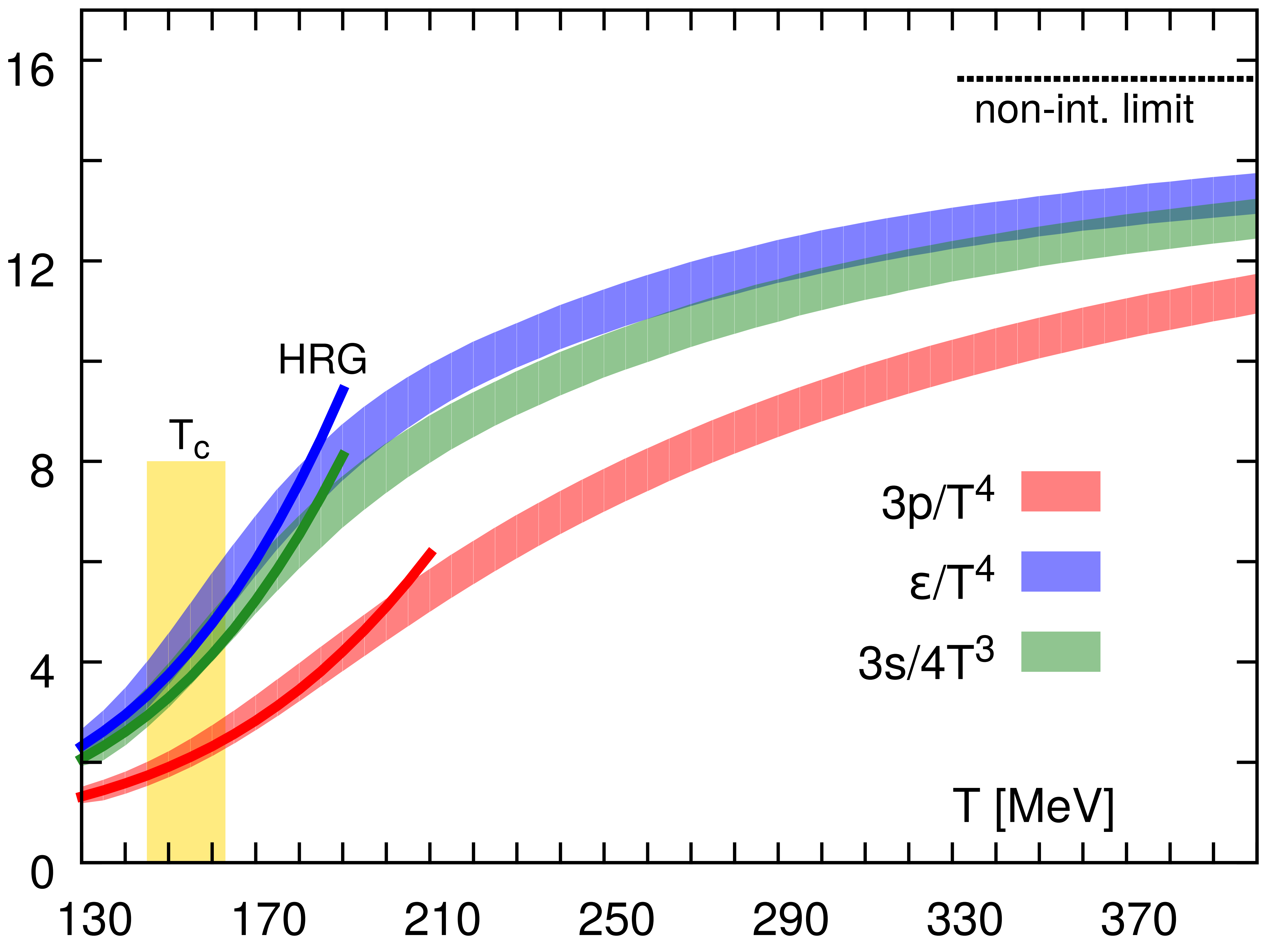



2+1 chiral condensate over $T = 0$ value
Borsanyi *et al* **1005.3508**

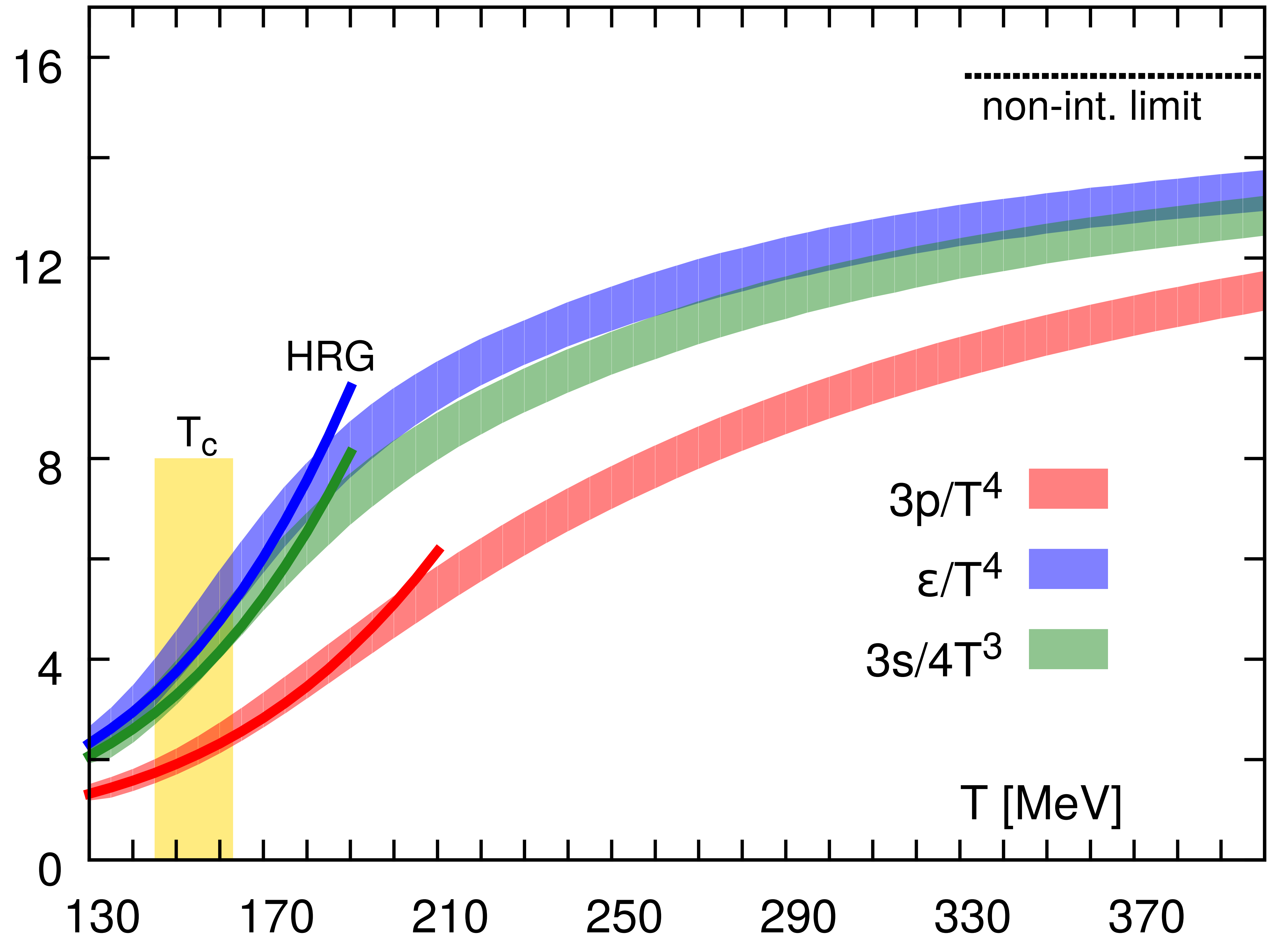
# The QCD EoS at vanishing $\mu_B$




stout: Borsanyi *et al* **1309.5258**
HISQ: HOTQCD collab. **14076387**

# The QCD EoS at vanishing $\mu_B$




stout: Borsanyi *et al* **1309.5258**
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- In the non-interacting limit we have a Stefan-Boltzmann form

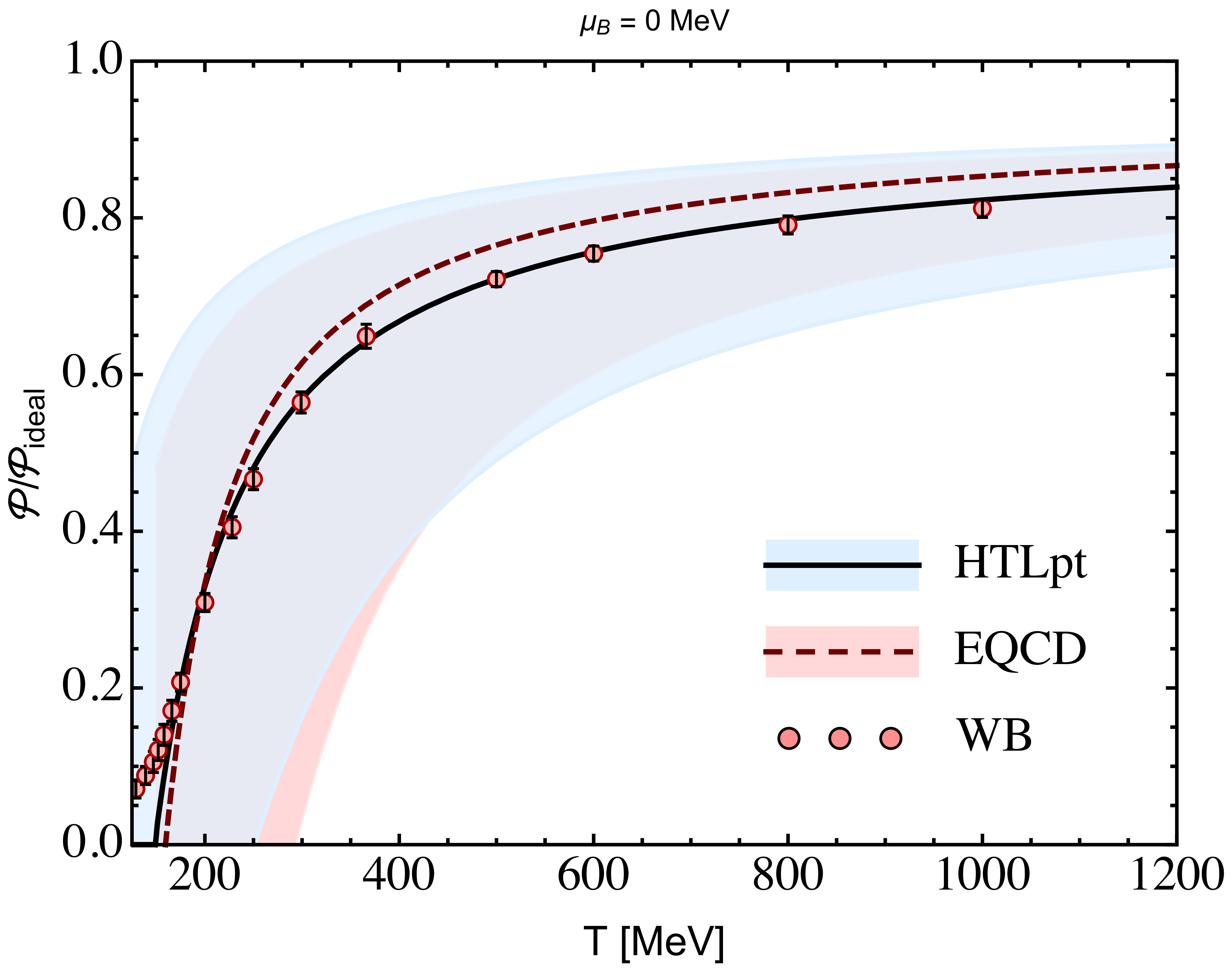
$$\varepsilon \equiv U/V \overset{\text{non-int}}{=} \frac{N_{\text{dof}}\pi^2}{30} \frac{k_{\text{b}}^4}{(\hbar c)^3} T^4$$

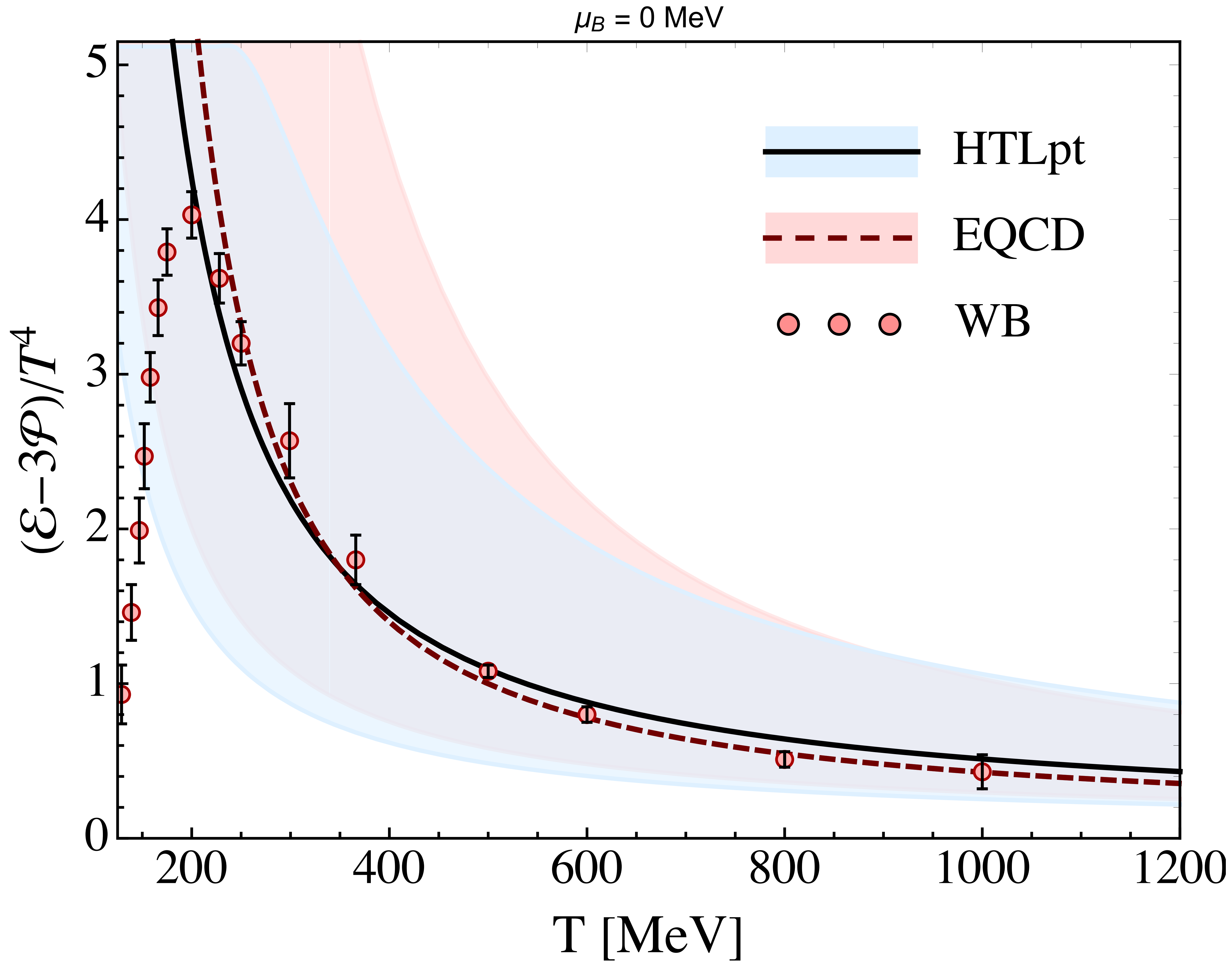
with

$$N_{\text{dof}} = 2 \times 8 + \frac{7}{8} \times 2 \times 2 \times 3 \times 3 = 47.5$$

- Deep in the QGP phase bulk thermodynamics is never $\mathcal{O}(1)$ far from the ideal gas. In $\mathcal{N} = 4$ AdS/CFT at infinite coupling $s = 3/4 s_{\text{non-int}}$
Gubser Klebanov Polyakov **hep-th/9802109**

# The QCD EoS at vanishing $\mu_B$




*pQCD review*: JG Kurkela Strickland Vuorinen **Phys. Rep. 880** (2020)

*Lattice:* Budapest-Wuppertal, Borsanyi *et al* **JHEP1011** (2010)

# The QCD phase diagram at finite $\mu_B$

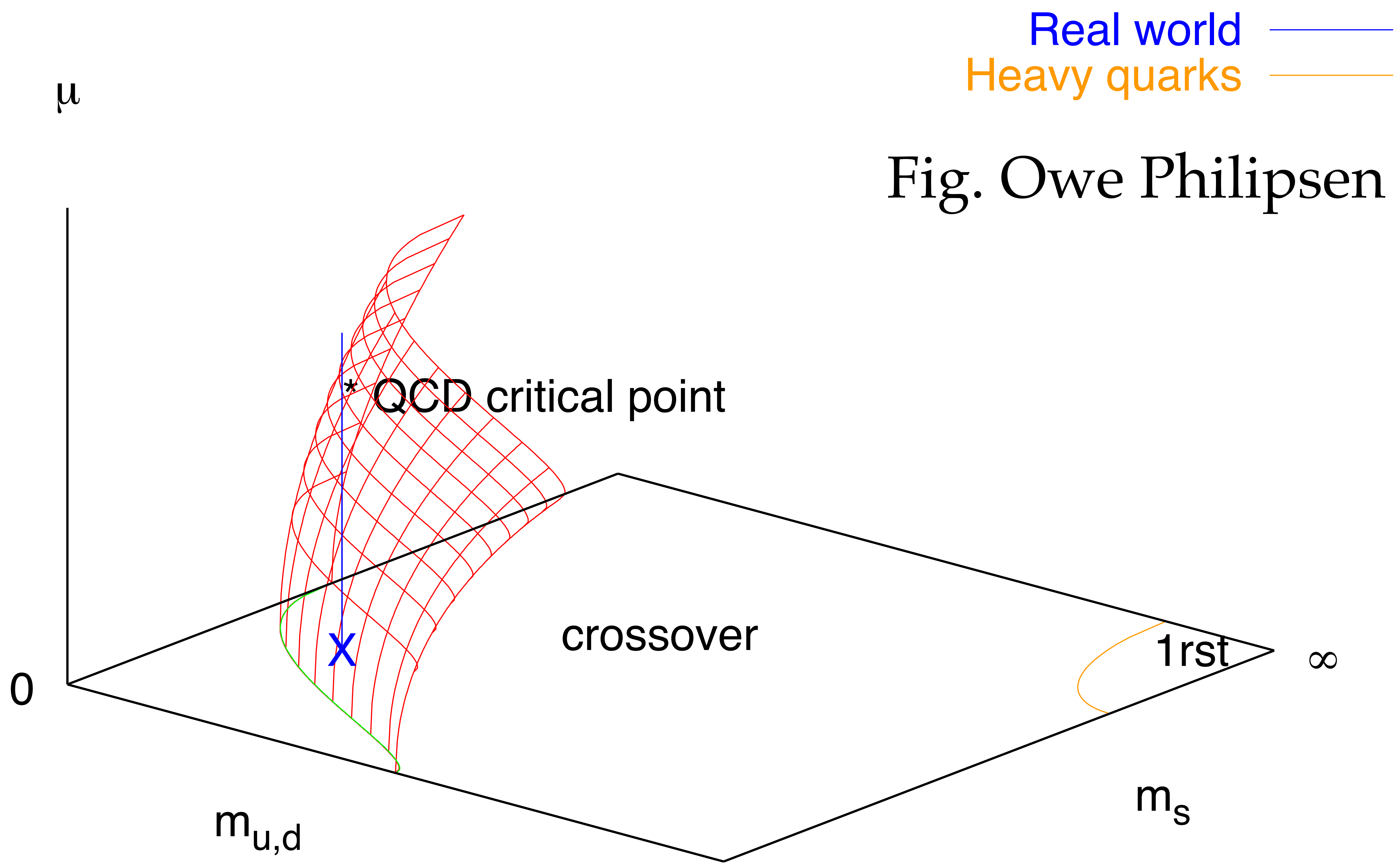
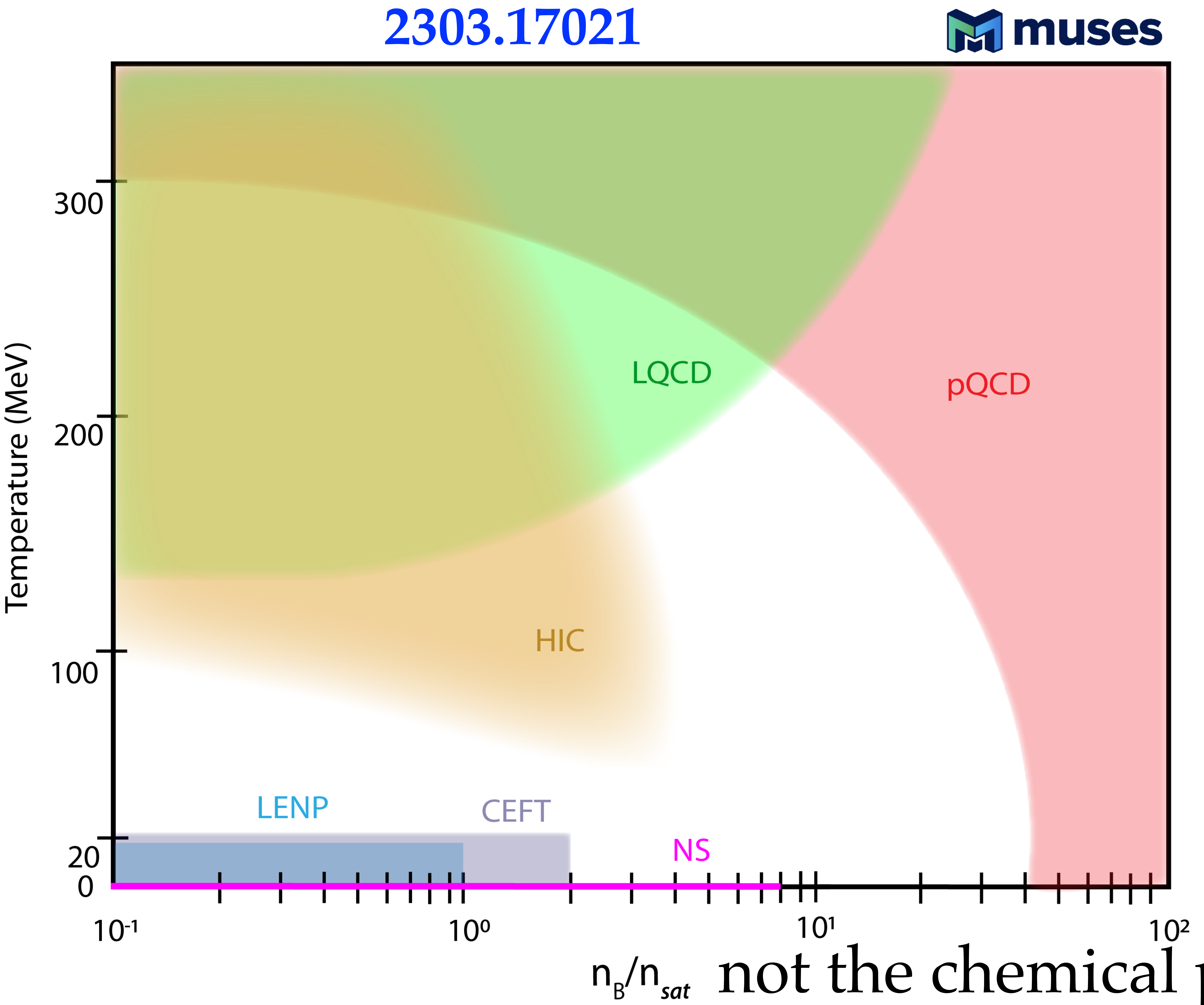



Fig. Owe Philipsen

- A **critical point** and a **first-order PT** expected to emerge at finite $\mu_B$
- Lattice QCD in its current numerical form hampered by a *sign problem*. Employ effective models or functional methods
- Currently searched in heavy-ion collisions at lower energies, keywords: fluctuations, correlations, cumulants, …

# The QCD phase diagram at finite $\mu_B$

2303.17021




not the chemical potential

- A **critical point** and a **first-order PT** expected to emerge at finite $\mu_B$
- Lattice QCD in its current numerical form hampered by a *sign problem* for $\mu_B \neq 0$. Employ effective models or functional methods
- Will we have early-universe input on this plot at some point?

# The QCD phase diagram at finite $\mu_B$

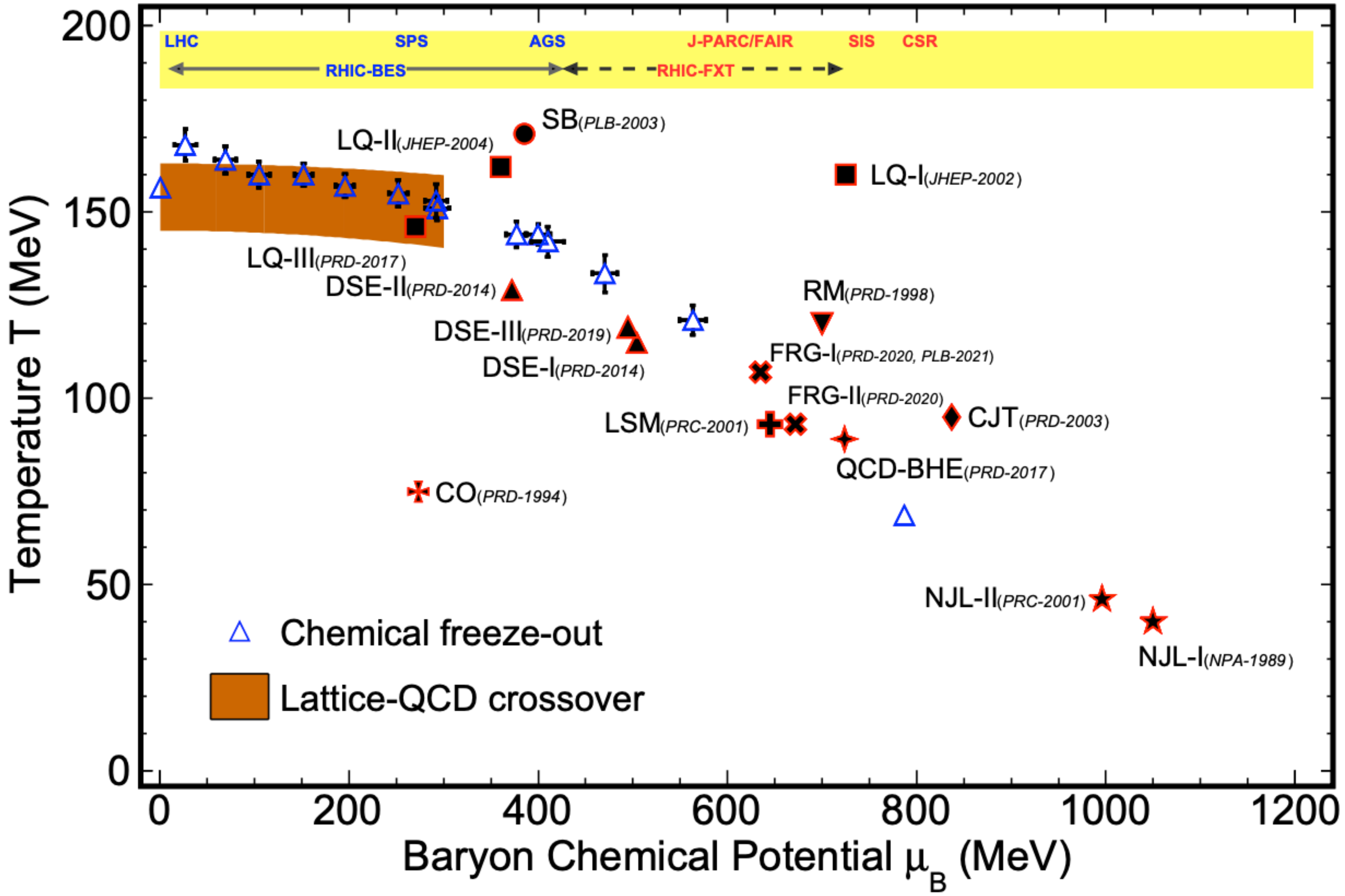



Figure adapted from A. Pandav, D. Mallick, B. Mohanty, Prog. Part. Nucl. Phys. 125 (2022)

from V. Vovchenko's slides at Quark Matter 2023

Including the possibility that the QCD critical point does not exist at all

de Forcrand, Philipsen, JHEP 01, 077 (2007); VV, Steinheimer, Philipsen, Stoecker, PRD 97, 114030 (2018)

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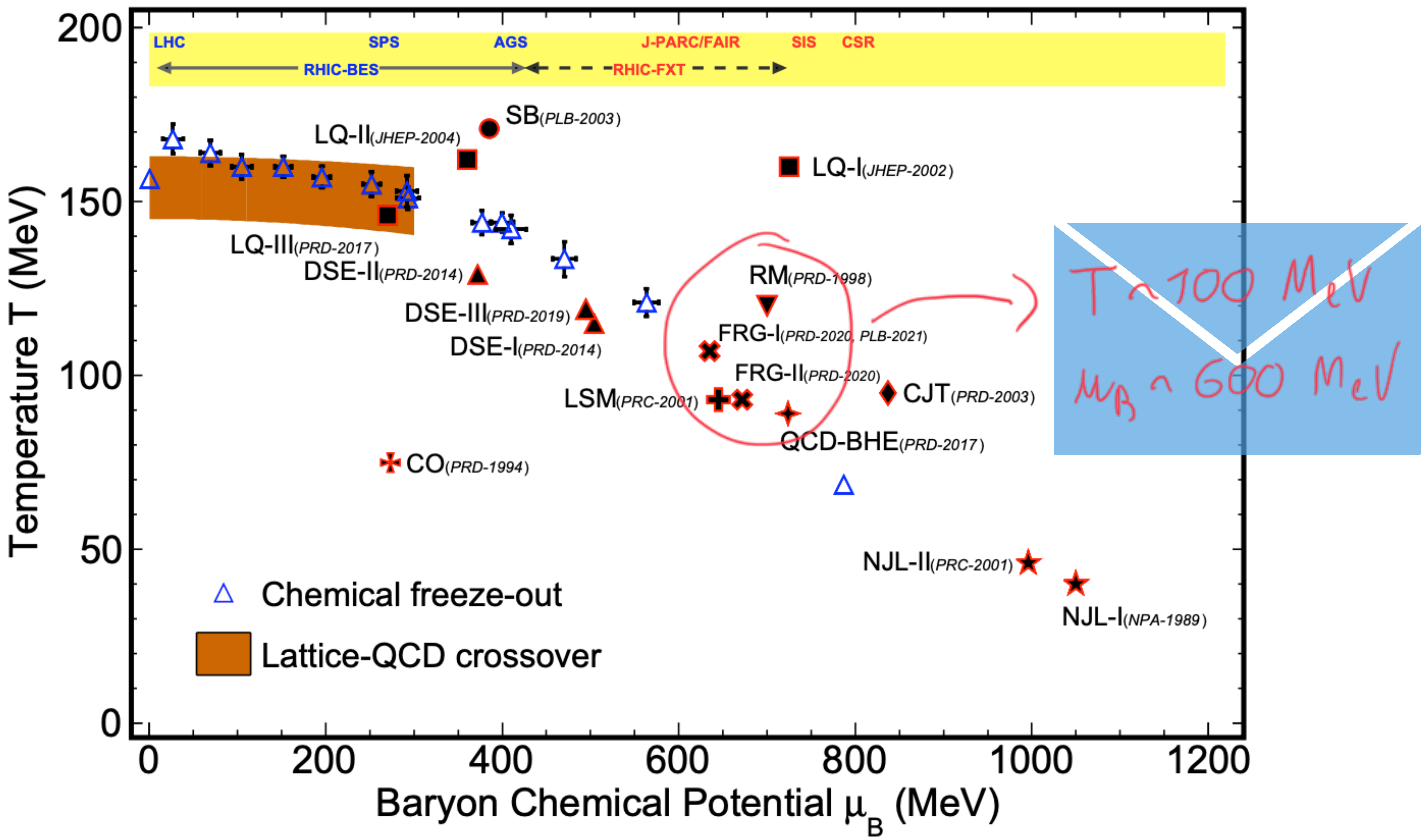


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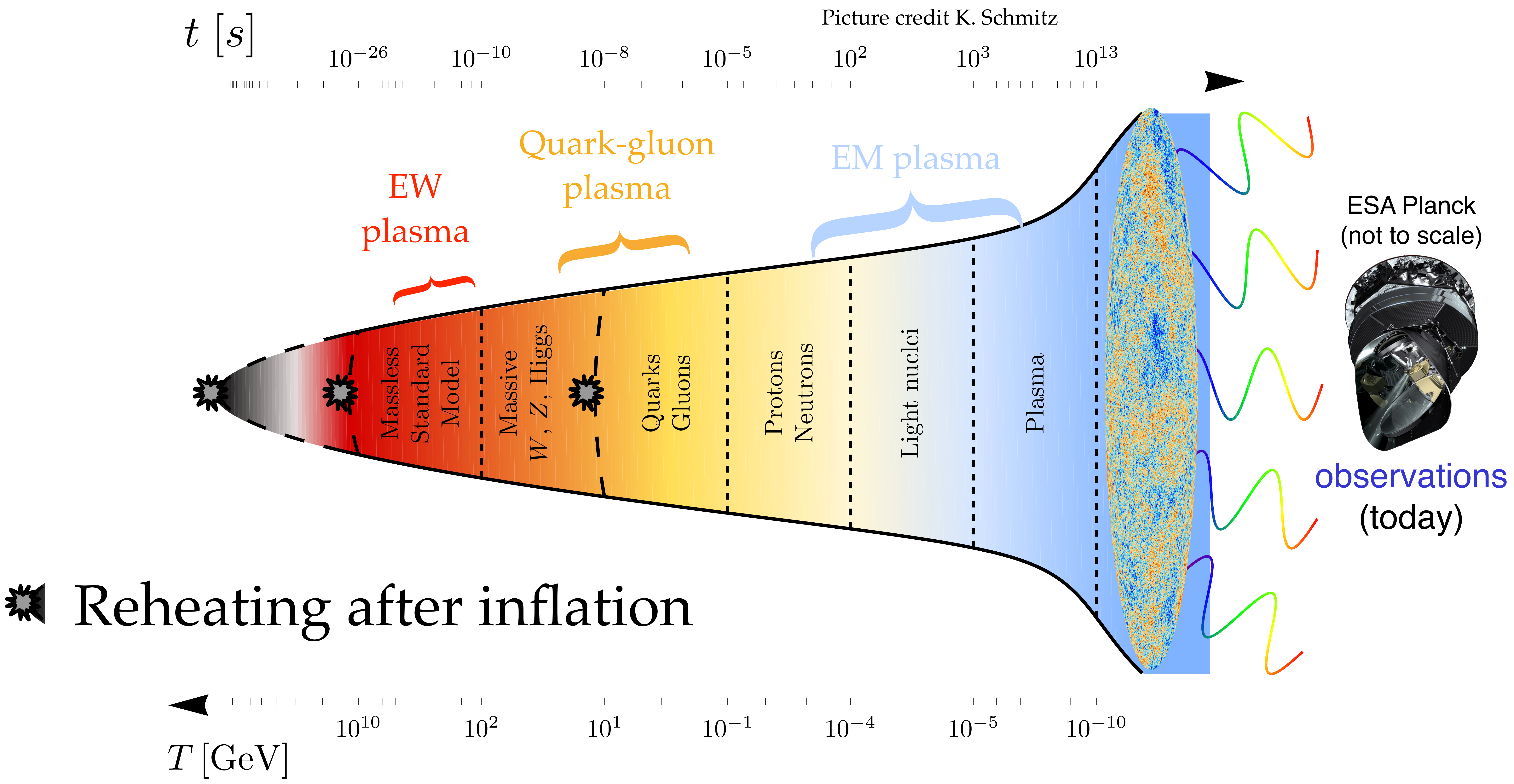
# QCD and the standard cosmological history

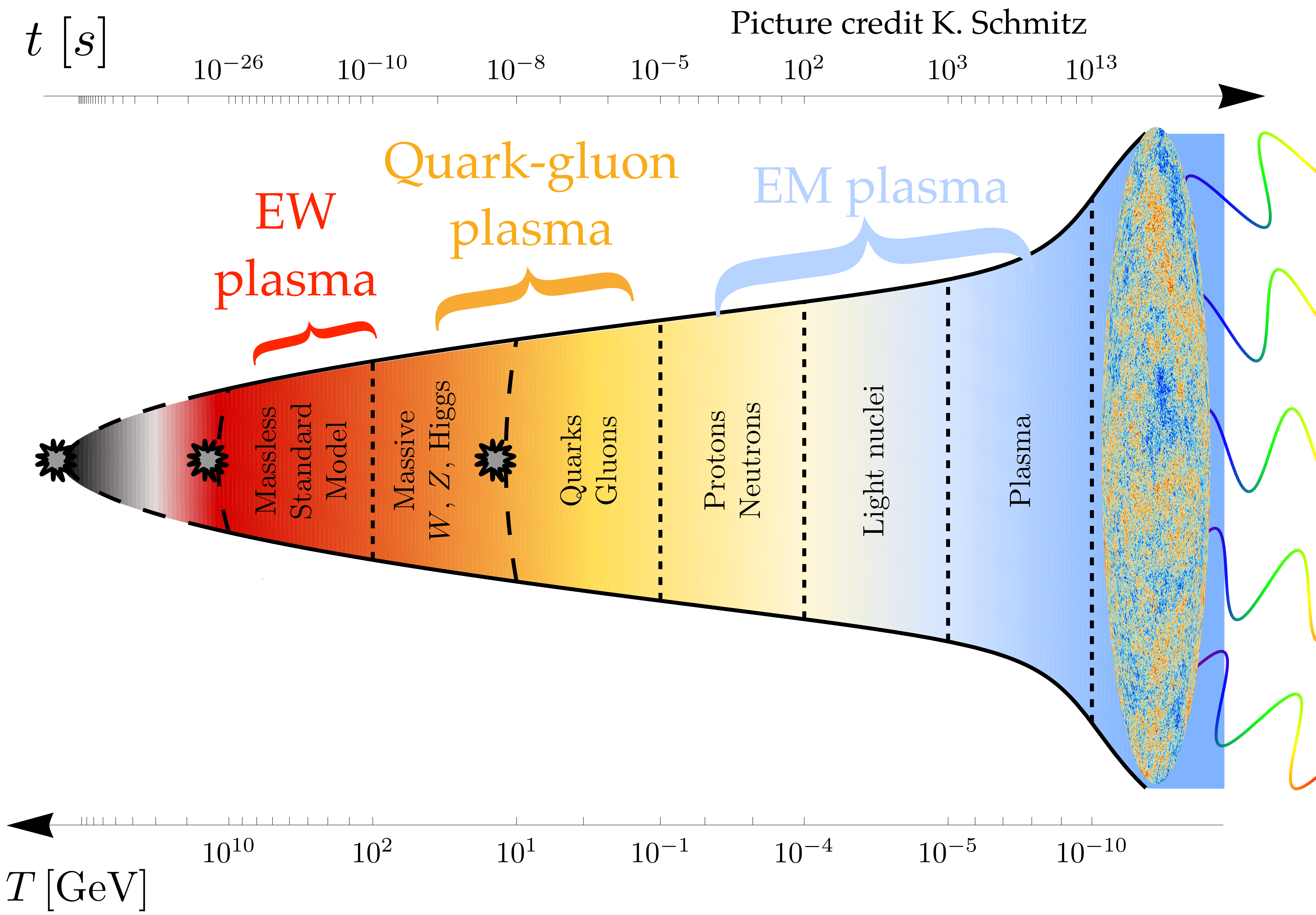
- Does the universe go through $T \sim 150$ MeV ?
- If so, at which values of $\mu_B$?

# The Early Universe



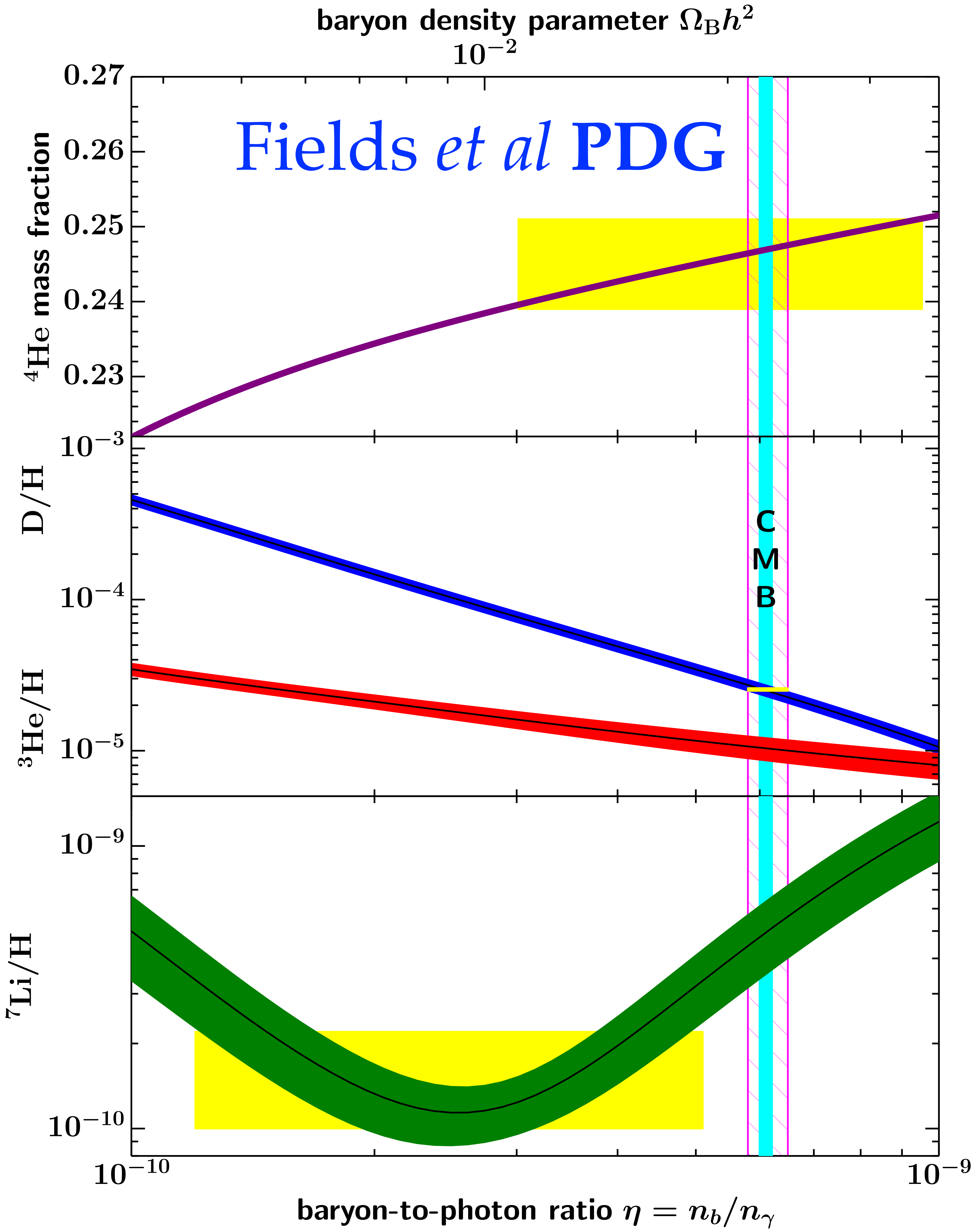
# The Early Universe

- Long thermal history, but how long?
- Reheating at the earliest at $T \lesssim 10^{16}$ GeV from Planck constraints
- Reheating at the latest at $T \gtrsim 4$ MeV for Big Bang Nucleosynthesis
  Hannestad **astro-ph/0403291**



# Big Bang Nucleosynthesis

- Earliest data point: Big Bang Nucleosynthesis. Successful prediction (except for lithium) of light-nuclei abundance from equilibrium plasma at sub-MeV $T$
- It tells us that at sub-MeV temperatures the baryon density was in excellent agreement with that at the much later CMB epoch
- $\Omega_b h^2 \approx 0.022$ means "5% baryonic matter" or 6 $10^{-10}$ baryons per (CMB) photon
- Whatever creates the baryon asymmetry in the universe, it must do it before



# Before Big Bang Nucleosynthesis

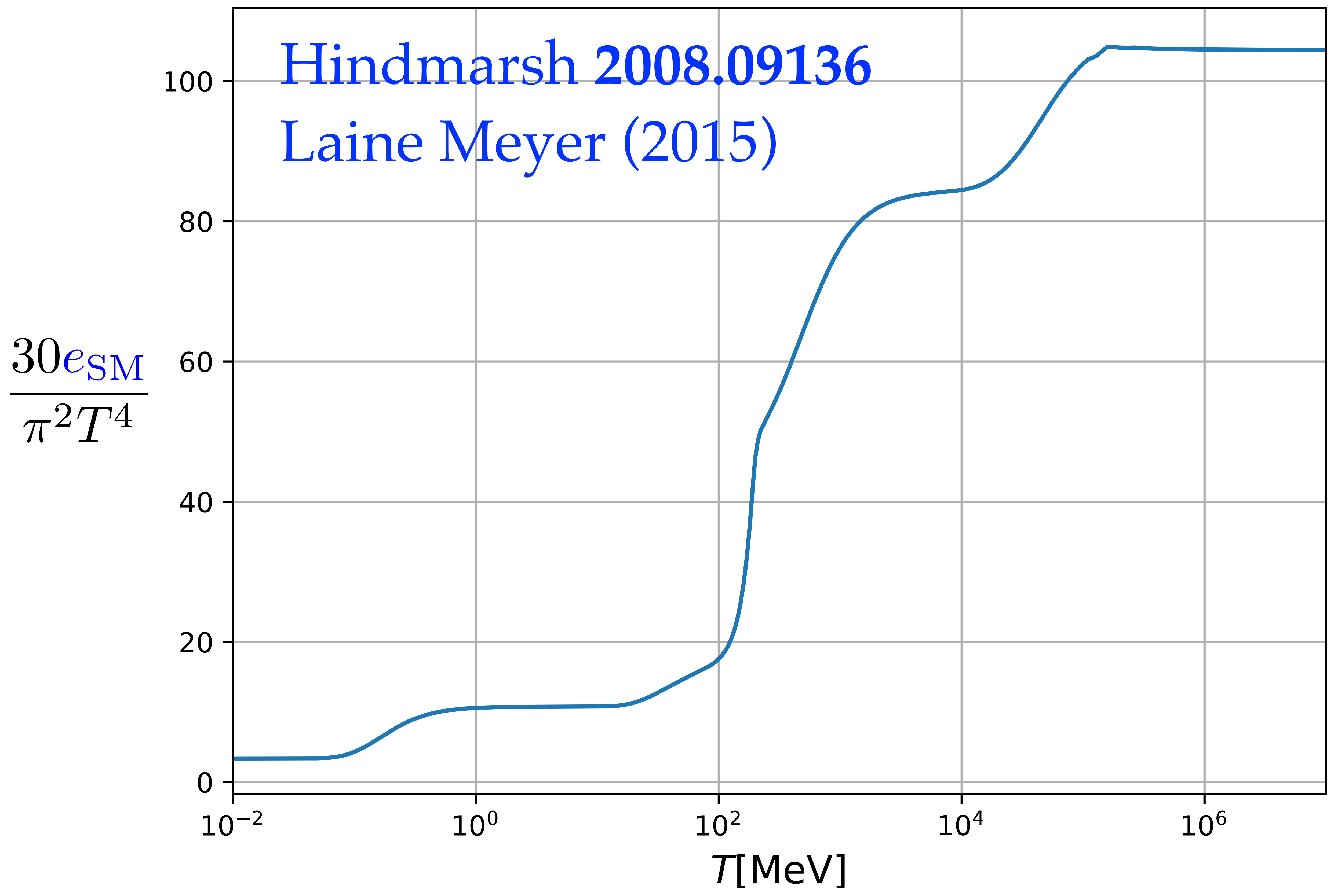
- What happens before BBN? We need to address baryogenesis and dark matter production, which strongly suggest (much) higher reheating temperatures

# Before Big Bang Nucleosynthesis

- The Hubble rate is proportional to the energy density

$$H = \sqrt{\frac{8\pi e}{3m_{\rm Pl}^2}} \sim \frac{T^2}{m_{\rm Pl}}$$

| energy scale | event |
|---|---|
| 100 GeV | $t$ non-relativistic |
| 1 GeV | $b$ non-relativistic |
| 500 MeV | $c$, $\tau$ non-relativistic |
| 200 MeV | QCD phase transition |
| 30 MeV | $\mu$ non-relativistic |
| 2 MeV | $\nu$ freeze-out |
| 0.2 MeV | $e$ non-relativistic |
| 1 eV | matter-radiation equality |
| 0.1 eV | photon decoupling |




- At $T \approx 200$ MeV, $H/T \sim 10^{-19}$. Very different from heavy-ion collisions, early universe is an effectively static and infinite system.

# Before Big Bang Nucleosynthesis

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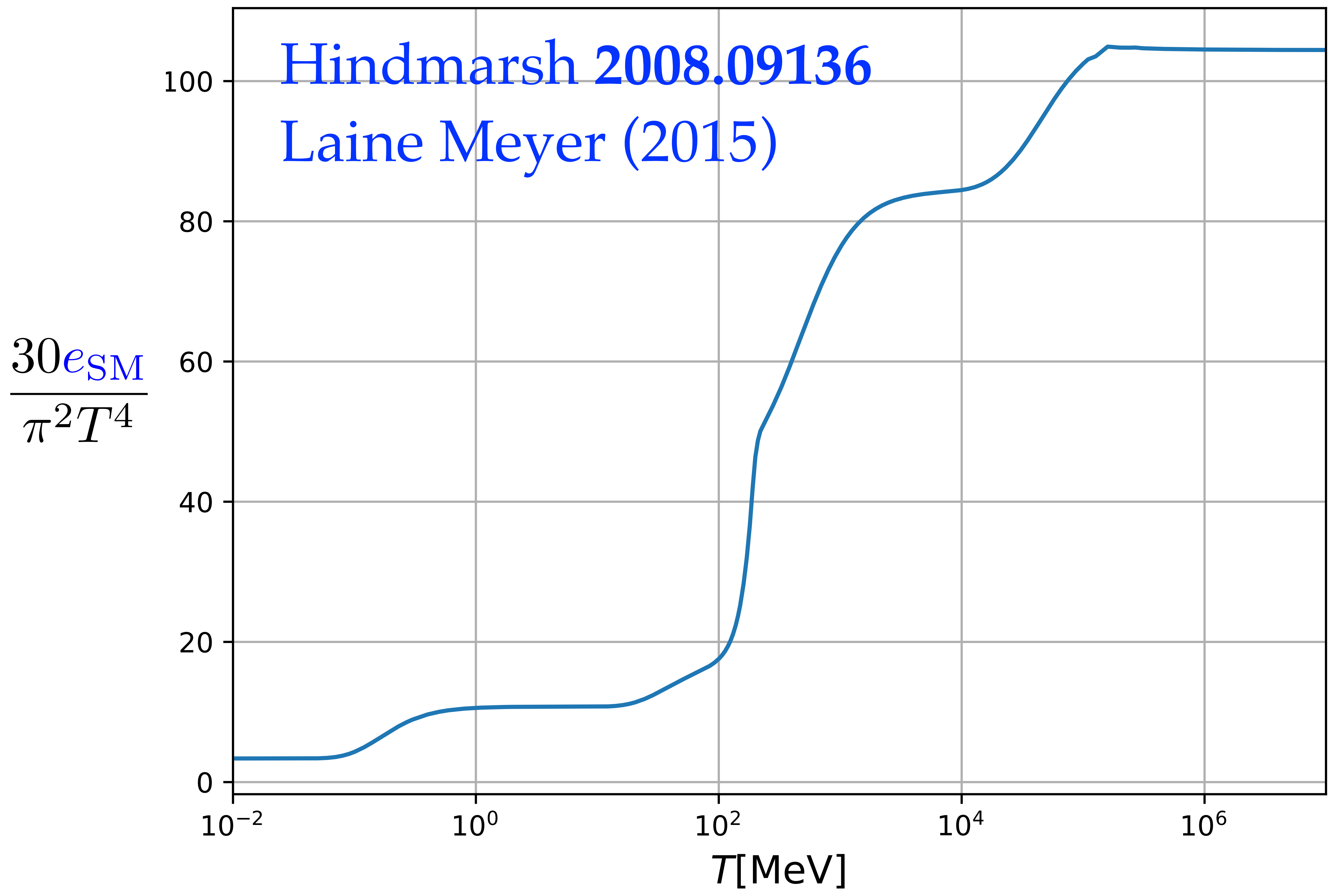



- And baryogenesis? Needs BSM, but SM can tell us something about $\mu_B$ at the QCD epoch

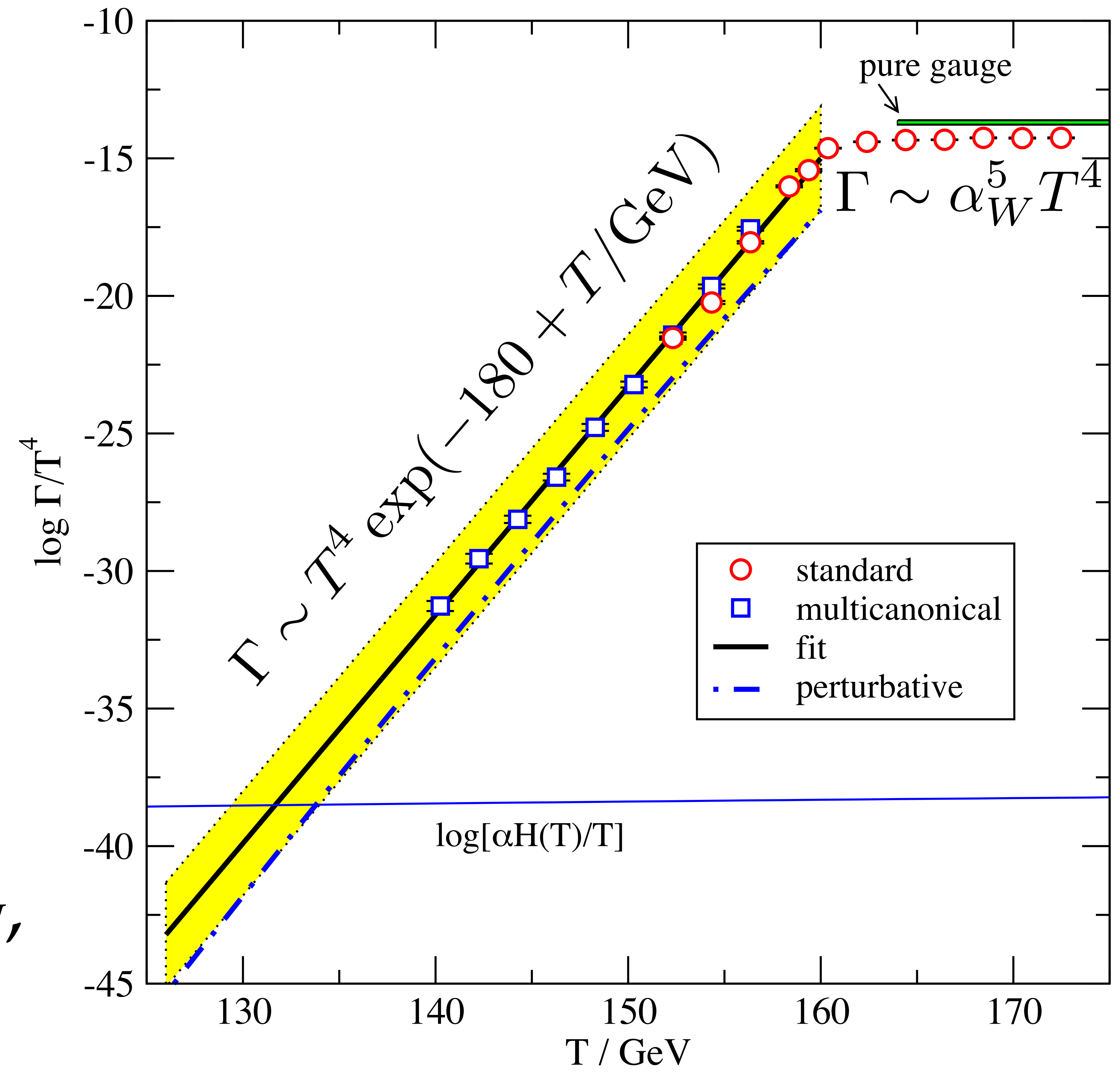
# Baryogenesis

- Need to satisfy Sakharov's conditions
  - B violation
  - C and CP violation
  - Deviations from thermal equilibrium

# B violation in the SM

- Need to satisfy Sakharov's conditions
  - B violation
  - C and CP violation
  - Deviations from thermal equilibrium

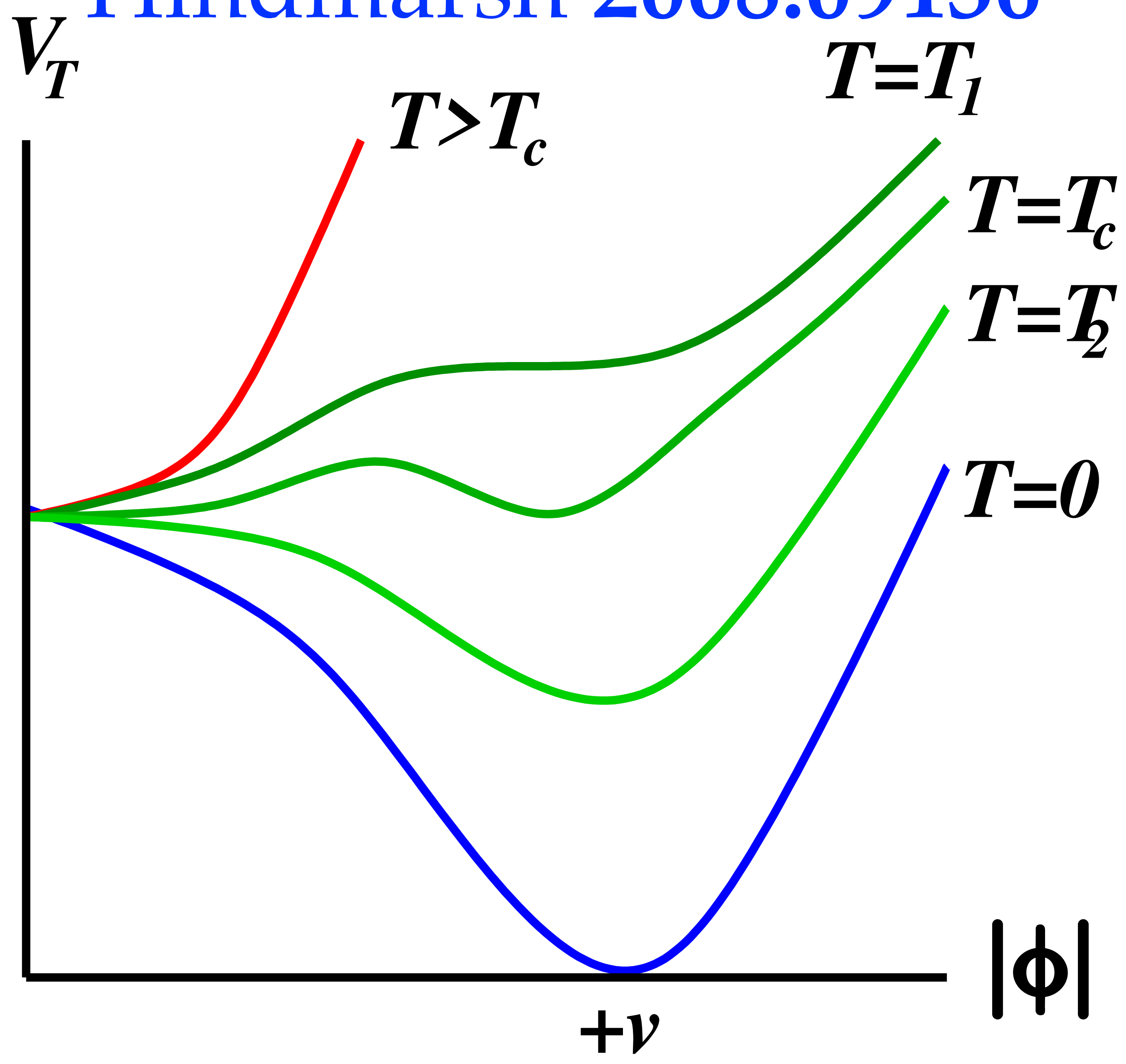
- Feynman rules always conserve B, but sphaleron processes **violate B+L and conserve B-L**
  Non-perturbative solutions, in equilibrium at $T > T_{EW}$, exponentially suppressed below. Decouple at $T\sim130$ GeV D'Onofrio Rummukainen Tranberg **PRL113** (2014)



# Electroweak baryogenesis

- Need to satisfy Sakharov's conditions
  - B violation
  - C and CP violation
  - Deviations from thermal equilibrium

Hindmarsh **2008.09136**




- The CKM phase violates CP
- A strong first order electroweak phase transition is needed. Sphaleron rate suppressed in bubbles of the broken phase nucleating within the symmetric phase
- Bubble dynamics would also create a gravitational wave signature, potentially observable by LISA

# Electroweak baryogenesis

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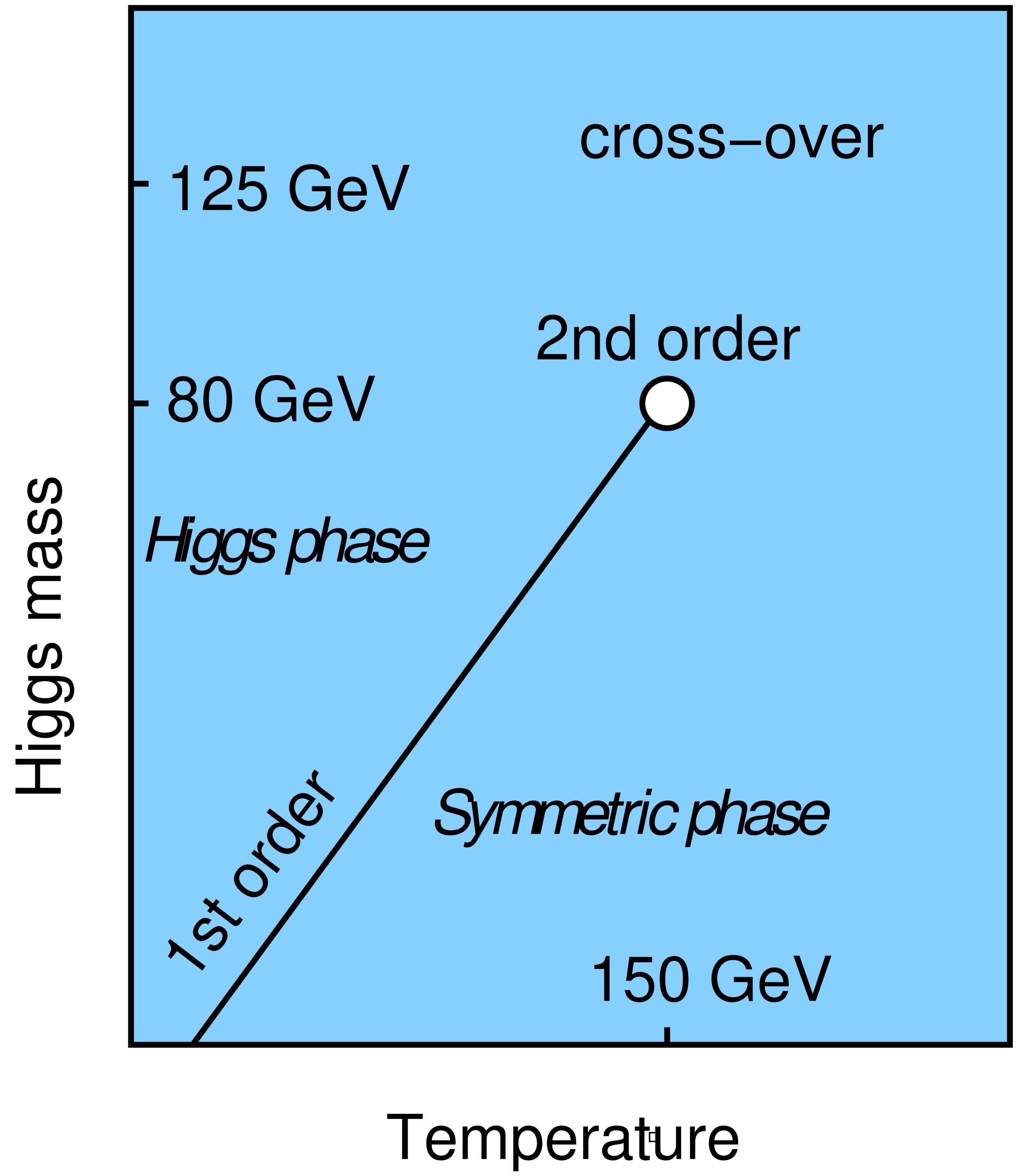


Plot from Hindmarsh **2008.09136** see original refs there

- The CKM phase violates CP
- A strong first order electroweak phase transition is needed. Sphaleron rate suppressed in bubbles of the broken phase nucleating within the symmetric phase
- Very active community effort in BSM extensions with EW phase transitions, GWs and baryogenesis

# Leptogenesis

- Need to satisfy Sakharov's conditions
  - B violation
  - L, C and CP violation: extend SM with massive right-handed neutrinos, with CP phases in Yukawa couplings to leptons and Higgs
  - Deviations from thermal equilibrium
    - In (possibly resonant) decays after freeze-out for $M \gg T_{EW}$
      Fukugita Yanagida **PLB174** (1986)
    - Oscillating during freeze-in production before equilibrium
      Akhmedov Rubakov Smirnov **PRL81** (1998)

# Other testable (low-energy) ideas

- Post-sphaleron baryogenesis through
  - Higher-dimension $|\Delta B| = 2$ operators
  - Mesogenesis: matter-dominated universe at the QCD epoch through a massive scalar that later decays to produce $n_B$

brief Snowmass review in Barrow *et al* **2203.07059**

# Baryogenesis: intermediate summary

- Assume baryogenesis somehow takes place before sphaleron freeze out
- At $T_B > 130$ GeV $n_B/s$ is then fixed to today's value ($8.7\ 10^{-11}$). Hubble expansion conserves entropy $S$ and thus any *number density/entropy density* $s$

# Baryogenesis: intermediate summary

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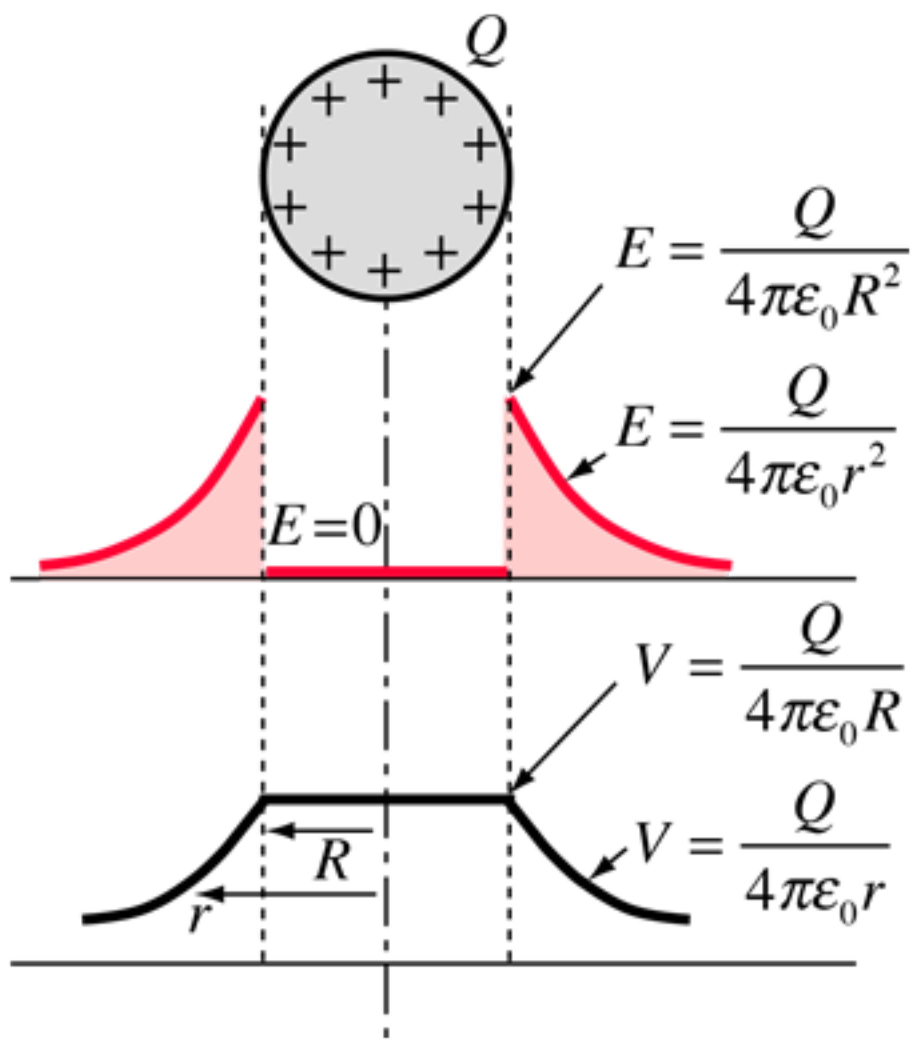
- Sphalerons will equilibrate B+L (conserving B-L)
- $n_B \neq -\sum_a n_{L_a}$ but rather $n_B = -C_{\rm sphal}\sum_a n_{L_a}$, with $C_{\rm sphal}$ $\mathcal{O}(1)$ accounting for hypercharge neutrality of the plasma. $C^{\rm SM}_{\rm sphal} = 28/51$ (at tree level)
- In the standard scenario we thus have that $n_B/s$ and $n_L/s$ are very small constants at the QCD epoch. But what about the chemical potentials?

# Chemical potentials, densities and pressure

- Reminder $n_i = \partial p / \partial_{\mu_i}$ $\qquad p^{\text{ideal}} = \sum_i \int_0^\infty dp \frac{p^4}{6\pi^2 E_p} \frac{1}{\exp[(E_p \mp \mu_i)/T] \pm 1}$
- What are the $\mu_i$? Baryon and lepton chemical potentials only?
- In EM any conductor is charged on the boundary only and has a non-zero electrostatic potential in the bulk



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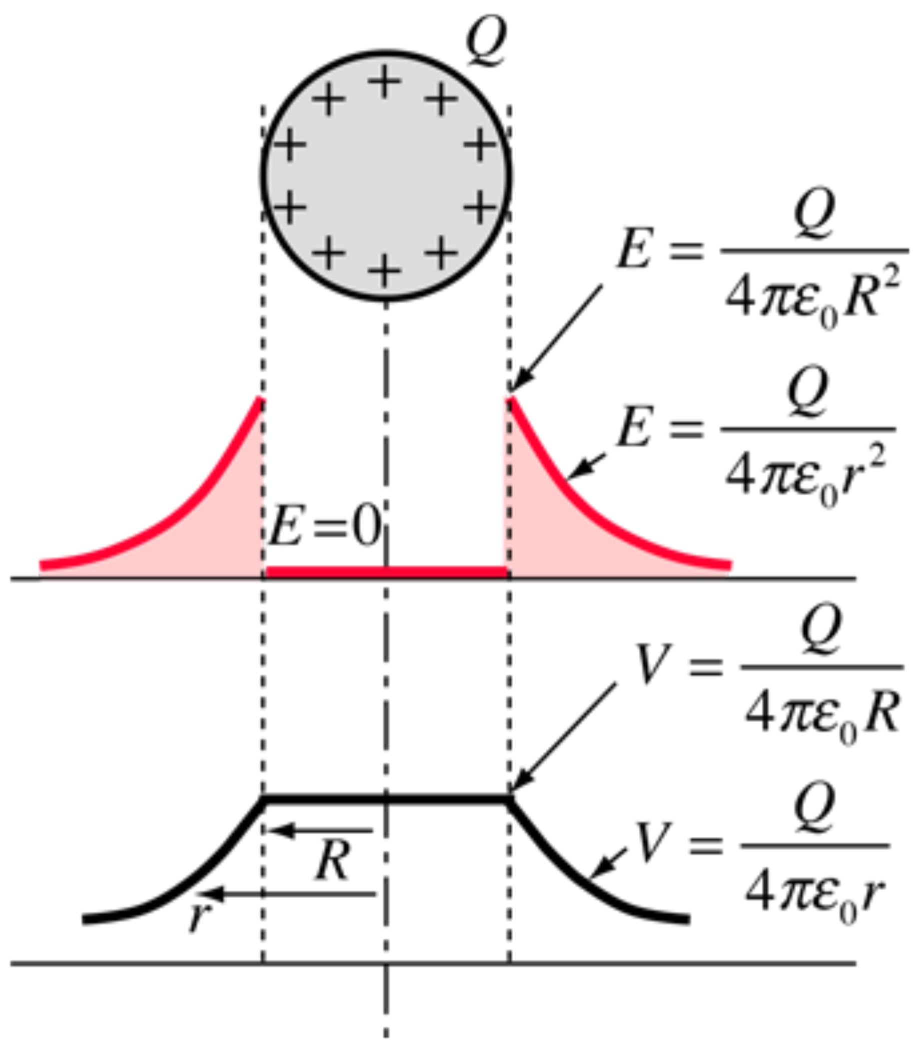
- In EM any conductor is charged on the boundary only and has a non-zero electrostatic potential in the bulk
- A plasma such as in the Early Universe must behave as the bulk of our conductor
- We then have nonzero charge chemical potentials, e.g. $\mu_Y = g_1 \langle B^0 \rangle$, which correspond to the "electrostatic" potential



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- E.g. $\mu_{Q_L} = \mu_B/3 + \mu_Y/6$, $\mu_{e_R} = \mu_1 - \mu_Y$

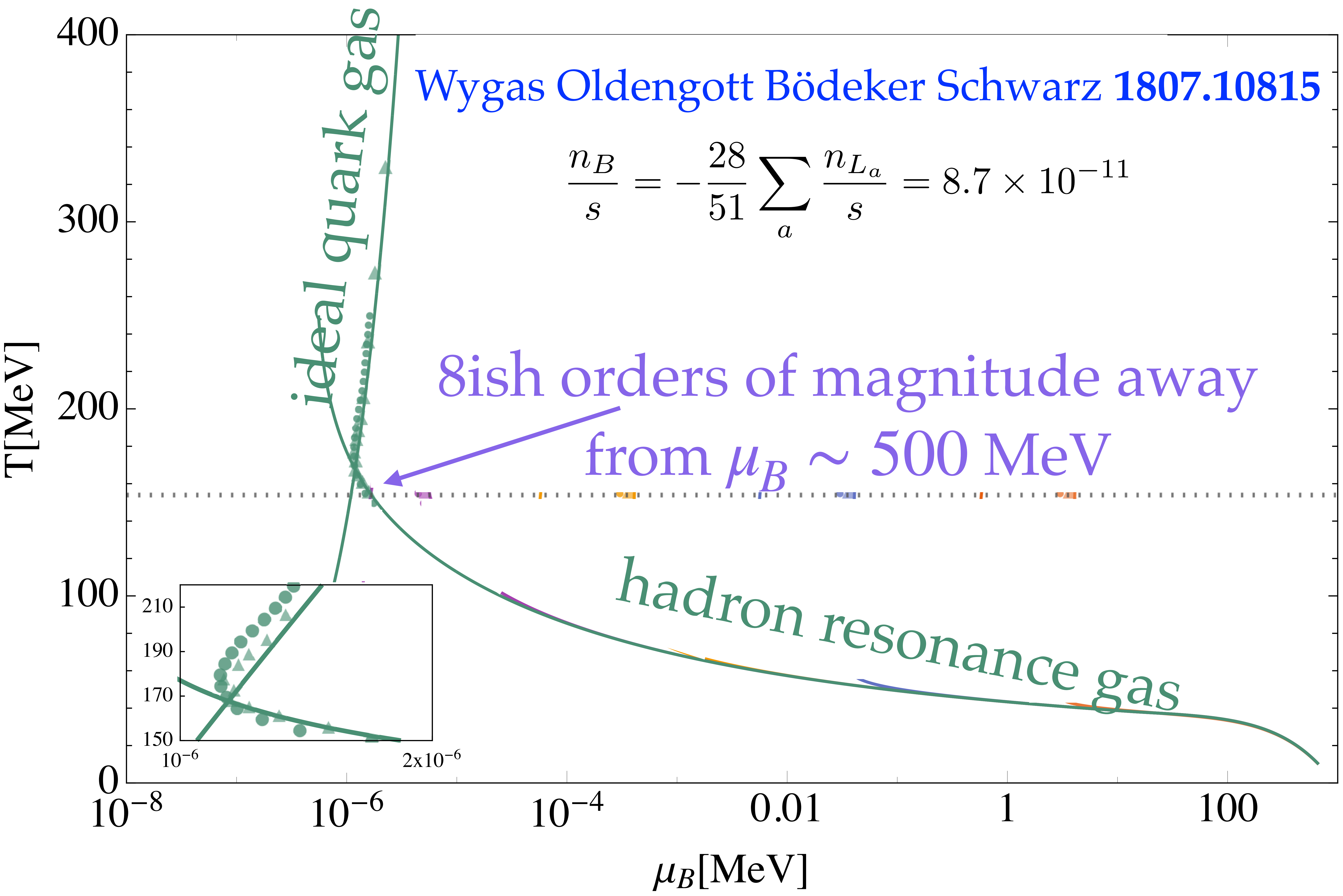
$$p^{\rm ideal}_{\rm SM}(T > T_{\rm EW}) = \frac{106.75 T^4}{90\pi^2} + \frac{T^2}{6}\left[2\mu_B^2 + 2\mu_Y\mu_B + \sum_a \left(\frac{3}{2}\mu_a^2 - 2\mu_Y\mu_a\right) + \frac{11}{2}\mu_Y^2\right] + \mathcal{O}(\mu^4)$$

- By setting charge chemical potentials so that corresponding charge densities vanish we fix charge neutrality of the bulk
- Important consequence: a vanishing $n_B$ does not imply $\mu_B = 0$, as charge gets redistributed among carriers

# $\mu_B$ in the standard scenario

symbols: using susceptibilities $\chi_{ab}$ from lQCD

$$p(T,\mu) = p(T,0) + \mu_a \chi_{ab} \mu_b + \mathcal{O}(\mu^4)$$



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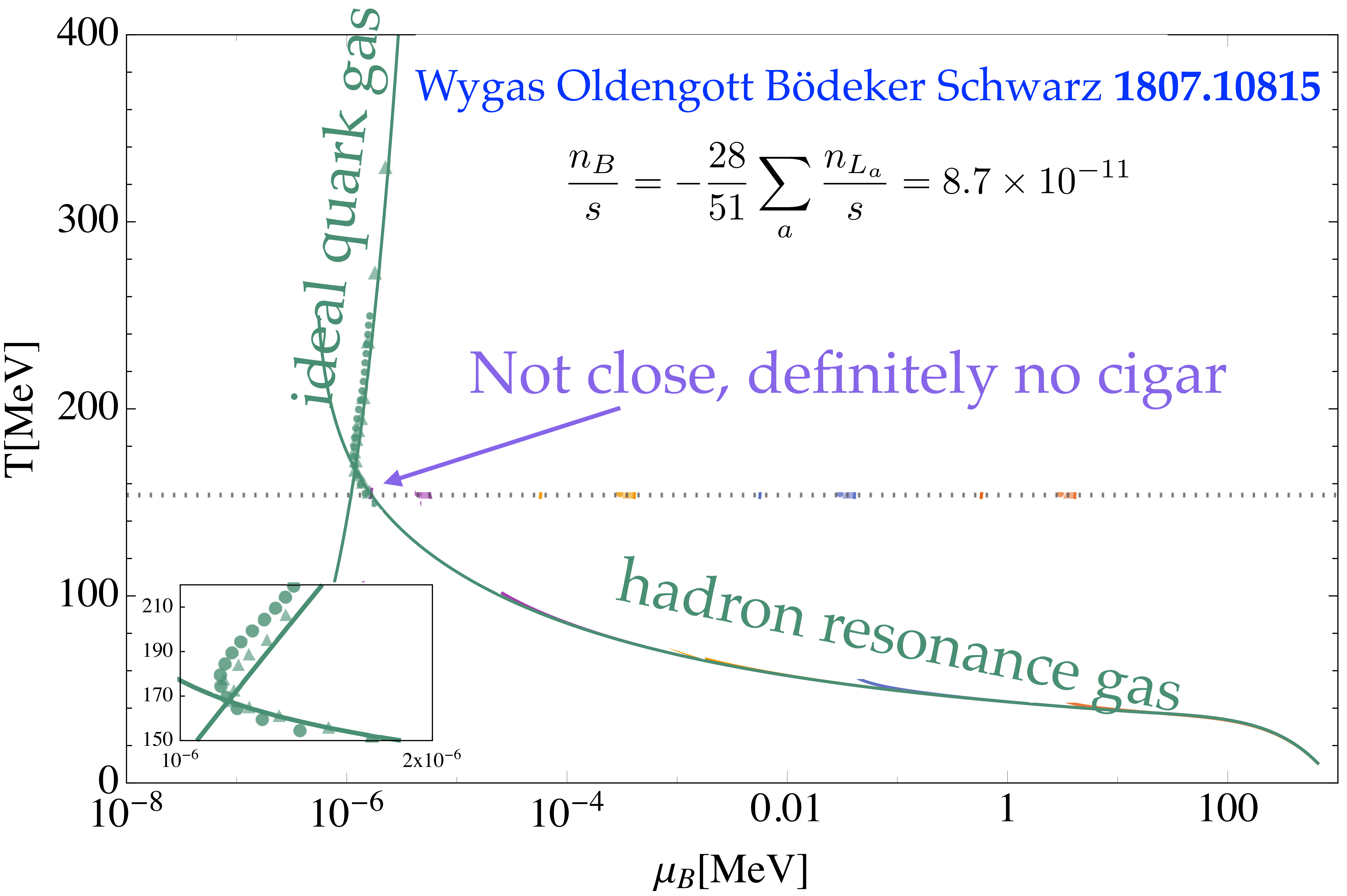


# $\mu_B$ in not-so-standard scenarios

- What could we do to turn the table?
  - Exploit potentially large lepton densities
  - Invoke cosmological magnetic fields or vorticities at the QCD epoch, which can alter the phase diagram
  - …

Reminder: obey all constraints from BBN, CMB, particle and nuclear physics, etc

# $\mu_B$ from large lepton densities

- Main idea: total lepton density $n_L$ poorly constrained (can "hide" in neutrinos) $\left|\frac{n_L}{s}\right| < 0.012$ Oldengott Schwarz **1706.01705** from Planck data

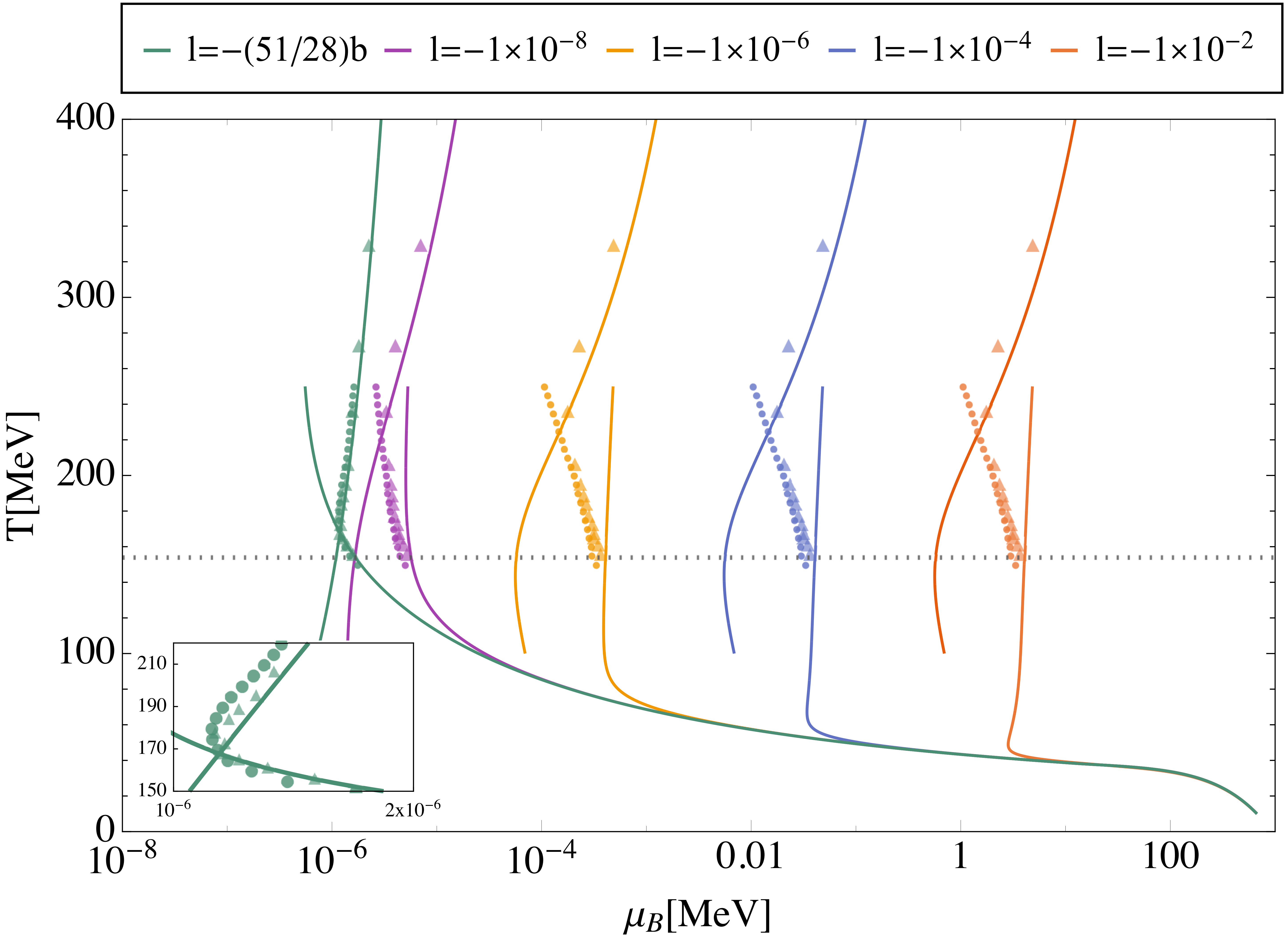
- There can be scenarios where a significant $n_L$ is generated post-sphaleron, evading $n_L \sim n_B$. For instance in leptogenesis with GeV-scale right-handed neutrinos

- $\left|\frac{n_L}{s}\right| < 0.012$ means e.g. $|n_{L_1}| \gg |n_{L_1} + n_{L_2} + n_{L_3}| < 0.012s$ is possible

Schwarz Stuke **0906.3434**
Wygas Oldengott Bödeker Schwarz **1807.10815** **2009.00036**
Gao Oldengott **2106.11991**

# $\mu_B$ from large lepton densities

- $l \equiv n_L/s$ up to maximum value with $n_{L_a} = n_L/3$
- We can get to 2ish orders of magnitude below the critical-point region

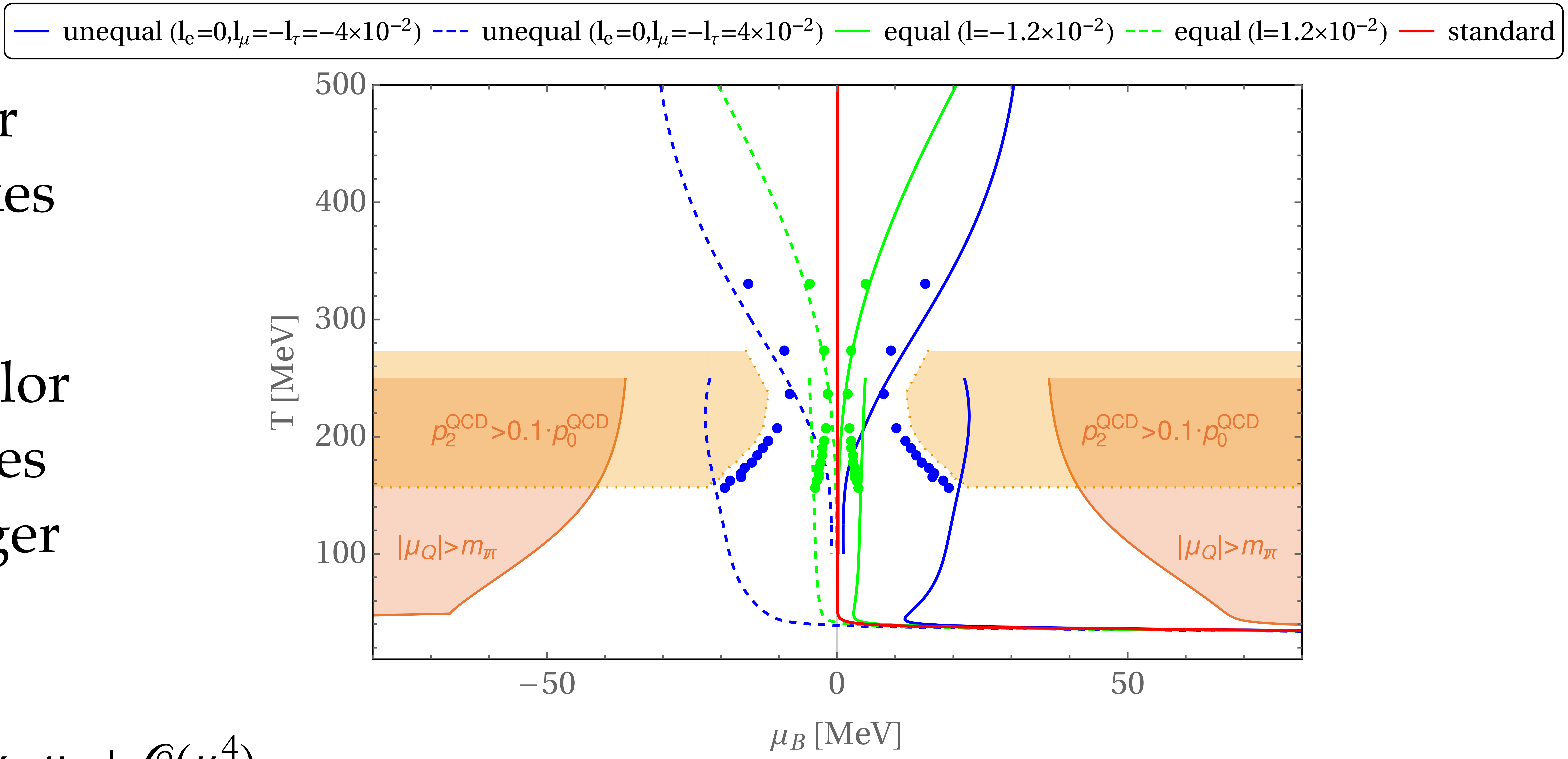



Wygas Oldengott Bödeker Schwarz **1807.10815**

# $\mu_B$ from large lepton densities

- Exploiting flavour asymmetries makes larger $\mu_B$ possible
- Second-order Taylor expansion becomes unreliable for larger lepton flavor asymmetries

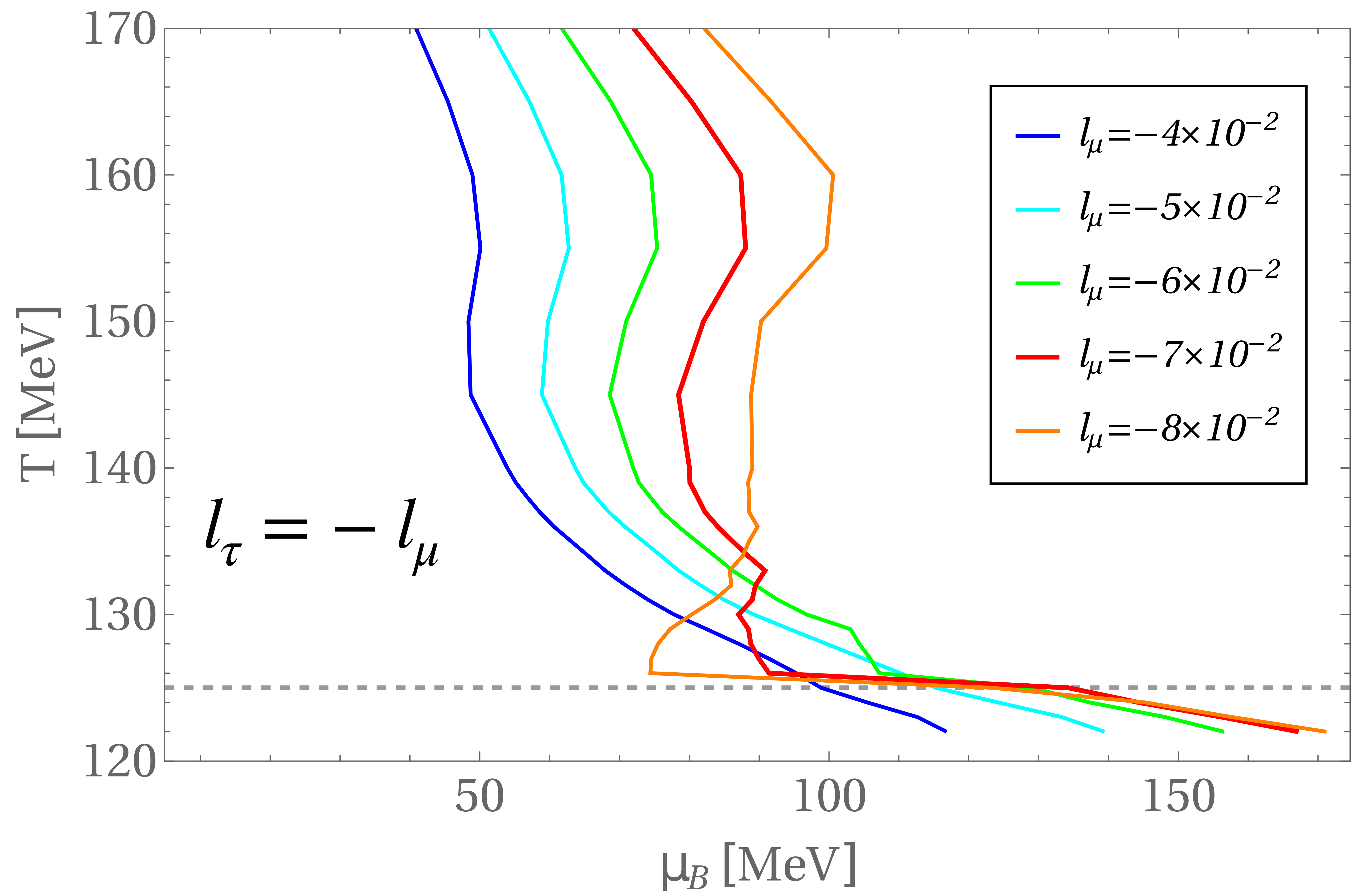
$$p(T,\mu) = p(T,0) + \mu_a \chi_{ab} \mu_b + \mathcal{O}(\mu^4)$$




Wygas Oldengott Bödeker Schwarz **2009.00036**

# $\mu_B$ from large lepton densities

- Exploiting flavour asymmetries makes larger $\mu_B$ possible
- Using less first-principles Dyson-Schwinger/functional RG EoS instead




Gao Oldengott **2106.11991**

# $\mu_B$ from large lepton densities: a model

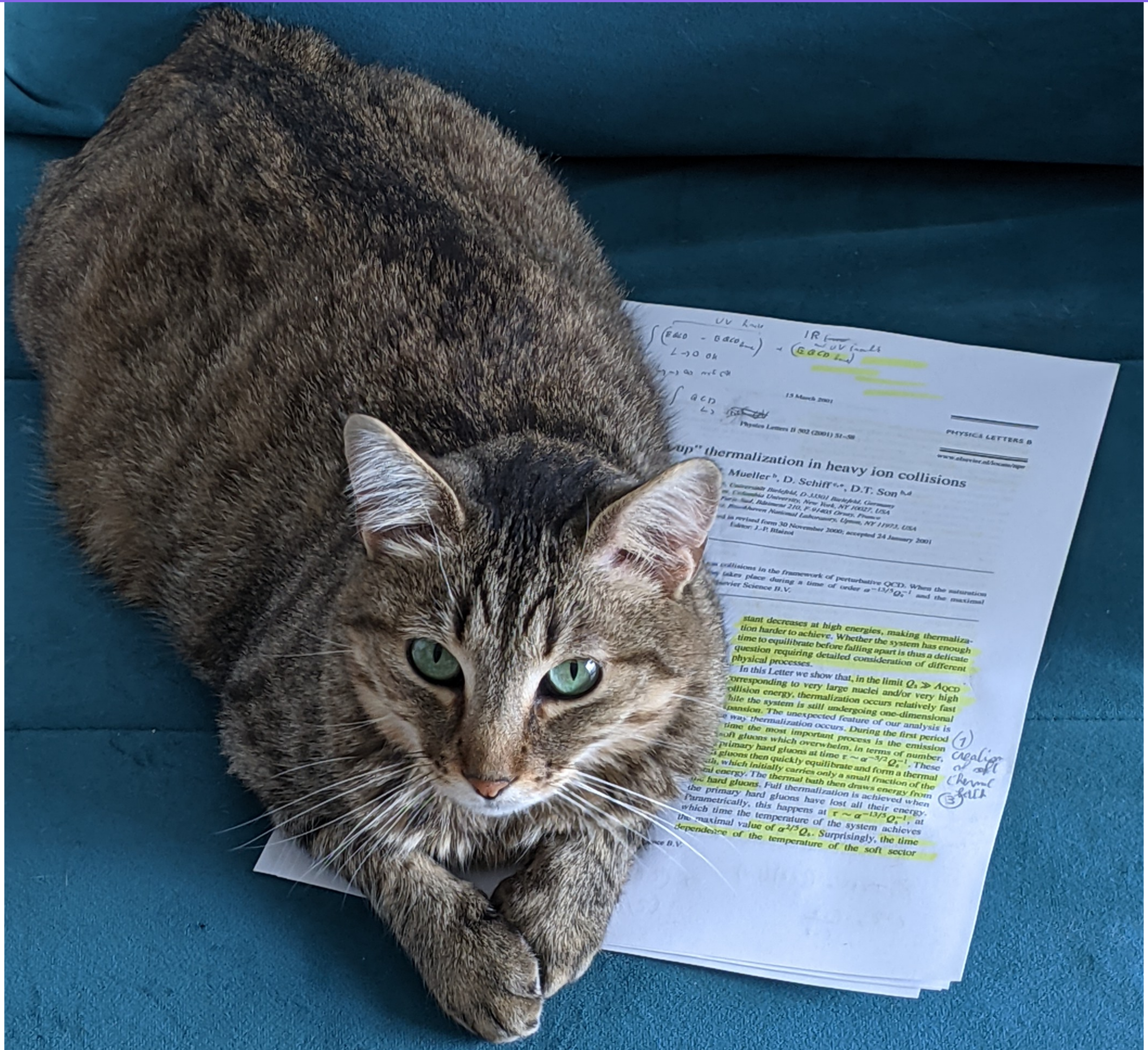
- A very large lepton asymmetry is generated early on, in the would-be symmetric phase of the SM. A sufficiently large asymmetry can trigger the breaking of the EW symmetry and thereby suppress sphalerons McDonald **hep-ph/9908300** March-Russel *et al* **hep-ph/9908396** Barenboim Park **1703.08258**
- Small B asymmetry from large L asymmetry
- Surviving large L can induce a QCD phase transition. However, some extra entropy injection is needed to get baryogenesis and the QCD transition simultaneously while obeying CMB and BBN constraints

Gao Harz Hati Lu Oldengott White **2309.00672** **2407.17549**

# Summary

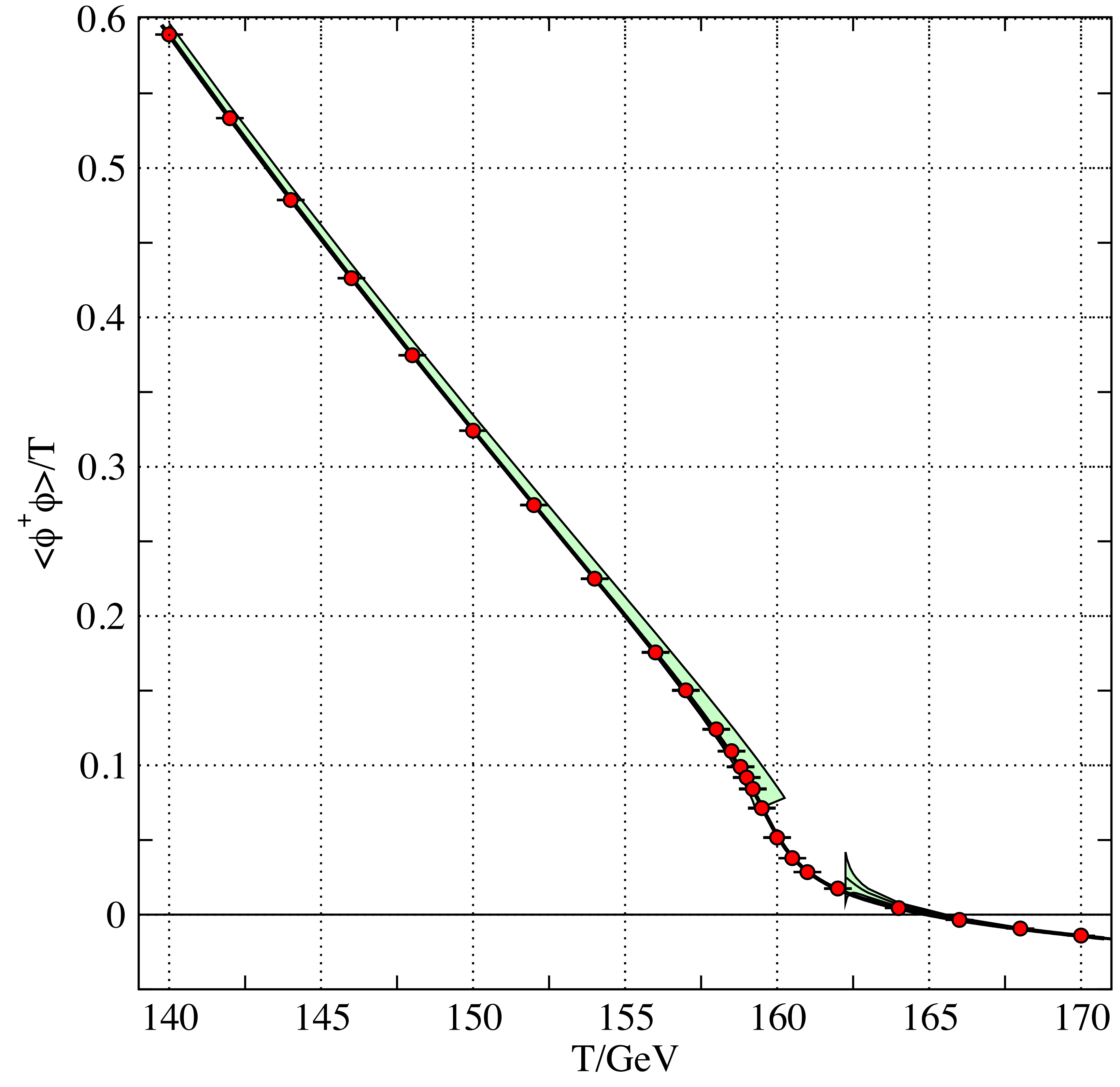
- QCD phase diagram: crossover at $\mu_B \ll T$ from QGP to hadronic phase, likely critical point and first order PT for $\mu_B > T \sim 100$ MeV
- Vanilla cosmology with SM (EW+QCD) particle physics: no EW phase transition, no QCD phase transition
- Addressing baryon asymmetry and/or dark matter requires BSM physics which can induce transitions, for instance through large lepton densities at the QCD epoch

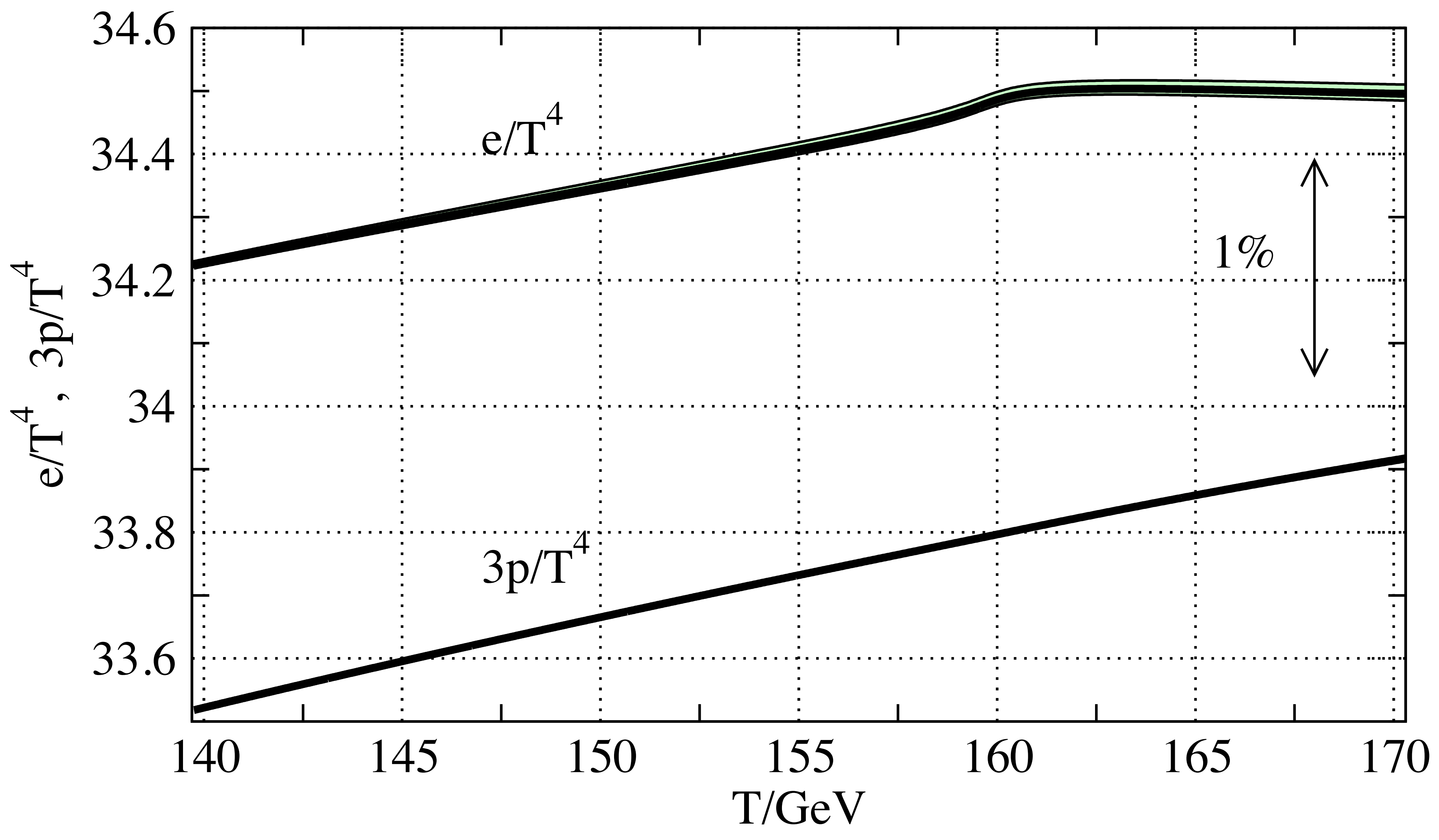
# Backup



# The EW transition

- State of the art for the SM at $M_H$=125 GeV. Lattice D'Onofrio Rummukainen (2015), pert thy Laine Meyer (2015)

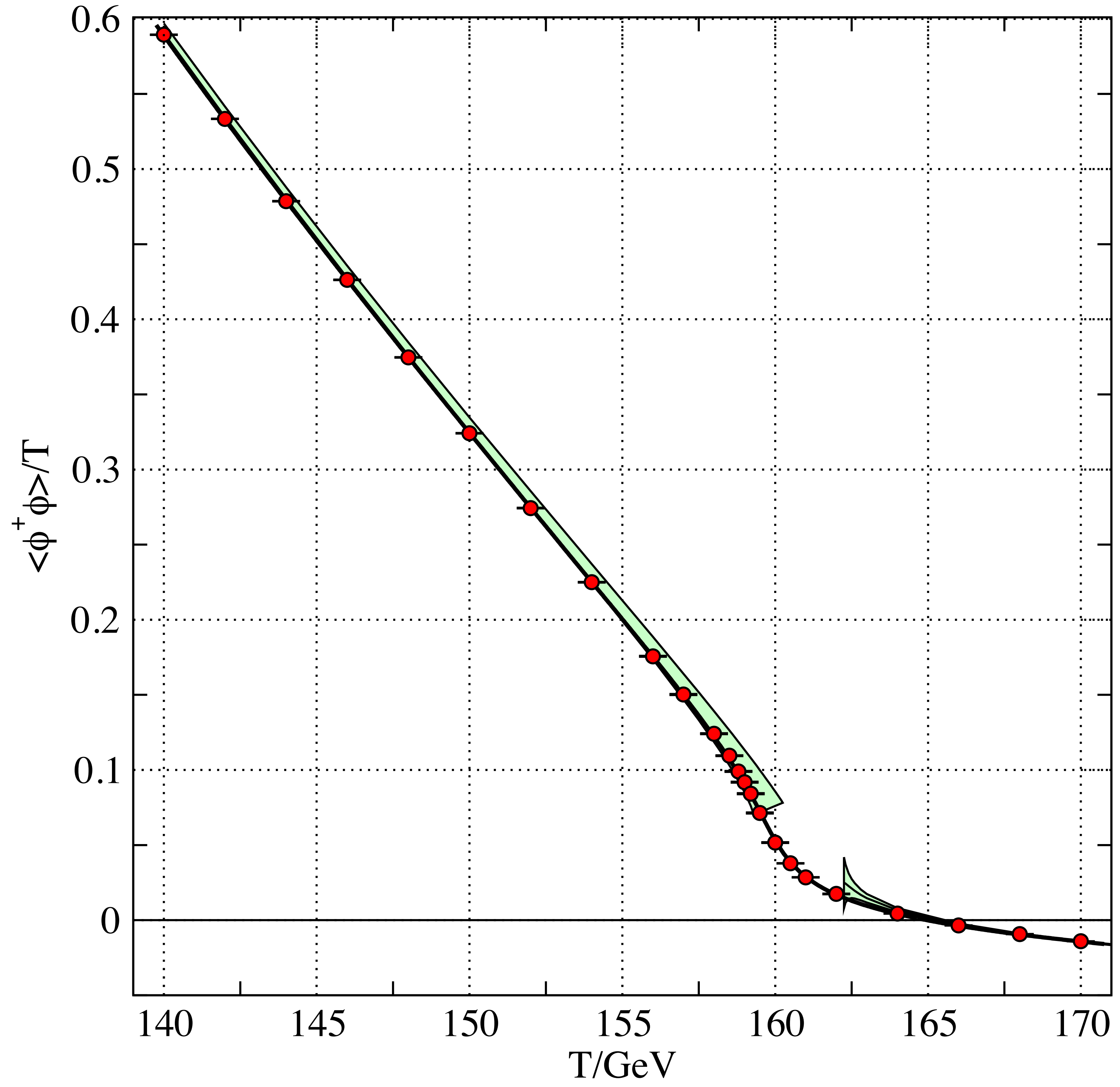


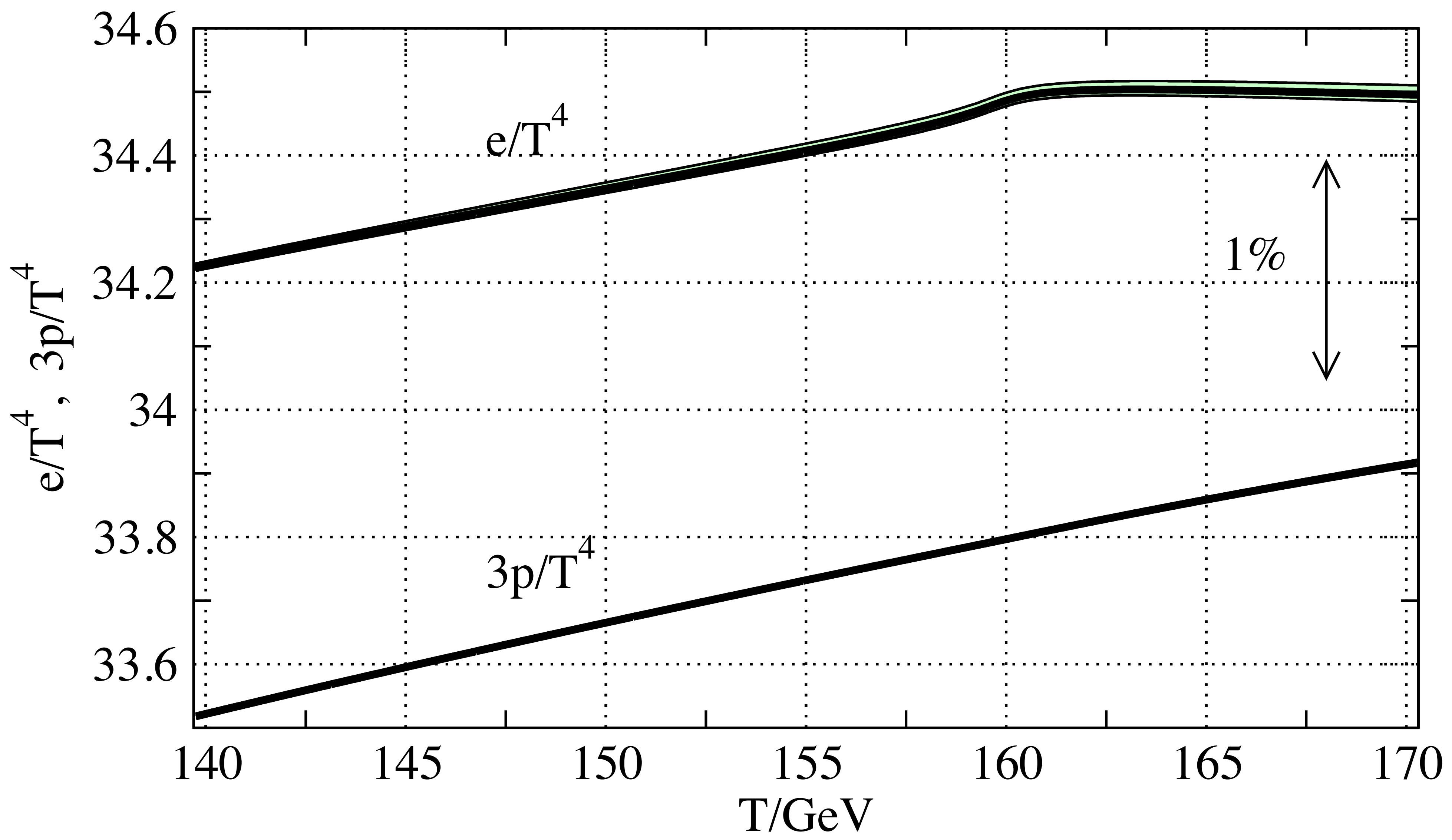




- Narrow non-perturbative window for the SM. Thermodynamics at the 1% level. Below the ideal gas result $e$=106.75 $\pi^2/30\ T^4 \approx 35.1\ T^4$

# The EW transition

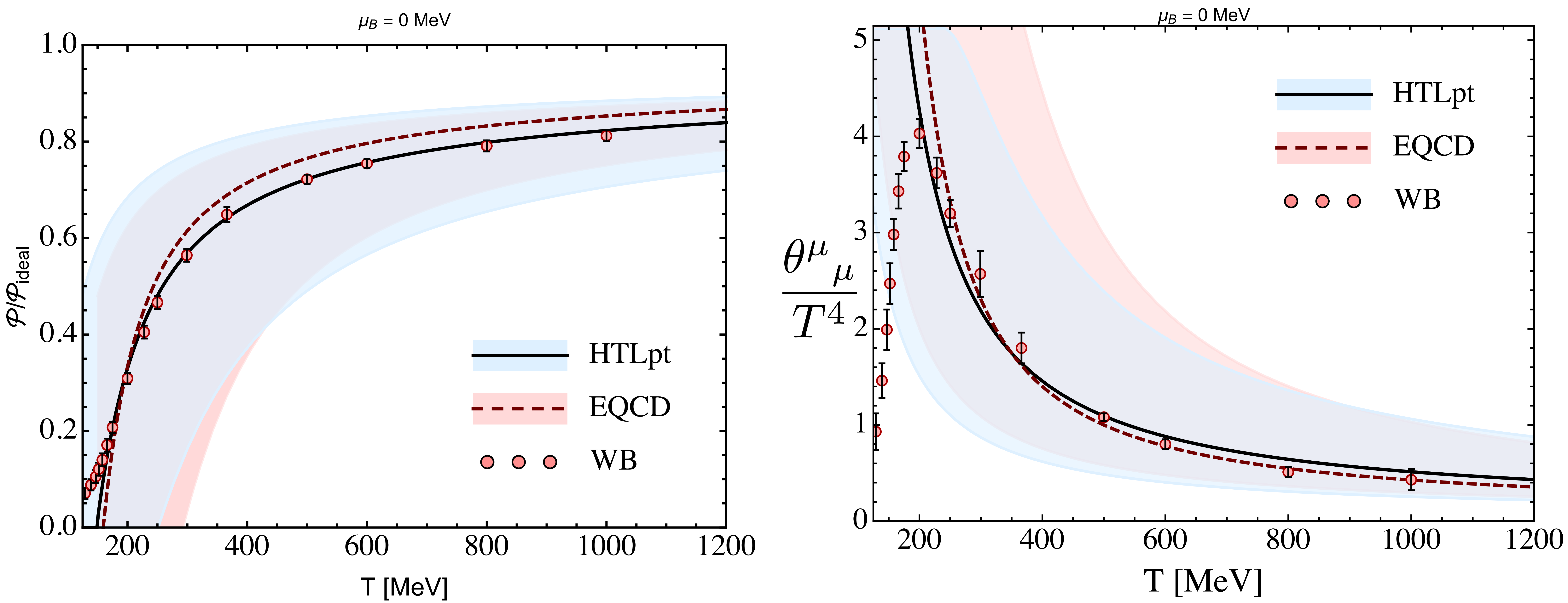
- State of the art for the SM at $M_H$=125 GeV. Lattice D’Onofrio Rummukainen (2015), pert thy Laine Meyer (2015)




- Very active research in adapting existing lattice measurements or performing new ones for BSM scenarios who promise phase transitions and GW signatures

# The QCD transition




*Review*: JG Kurkela Strickland Vuorinen **Phys. Rep. 880** (2020)
*Lattice:* Budapest-Wuppertal, Borsanyi *et al* **JHEP1011** (2010)

- Very different from QCD transition: here all but a handful of dofs are weakly-coupled

# A way to large lepton asymmetries?

- Right-handed neutrino interaction rate $\Gamma$ for a specific seesaw parametrisation