The cosmic QCD epoch at non-vanishing lepton asymmetry

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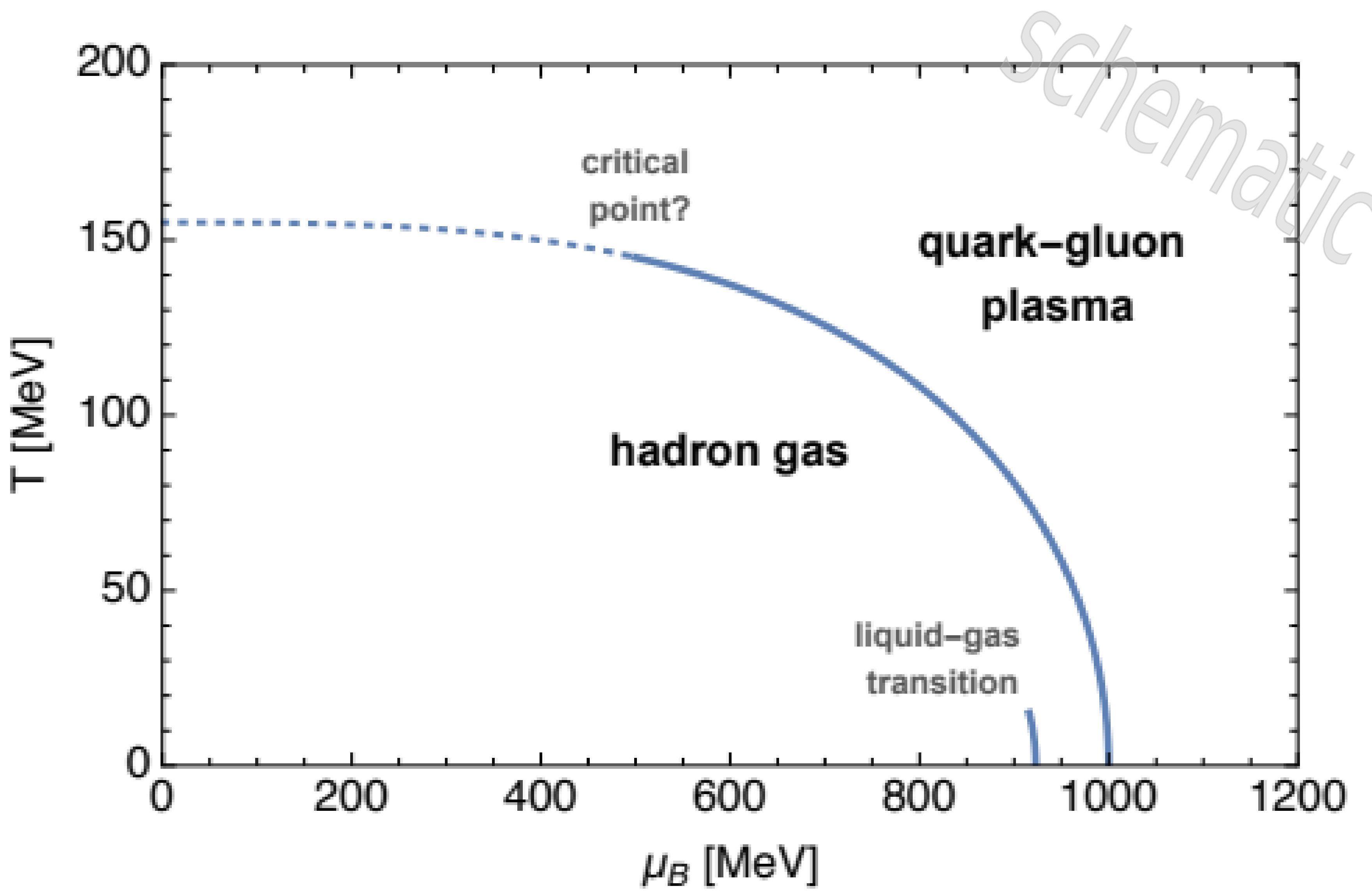

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hadron gas
liquid–gas
transition
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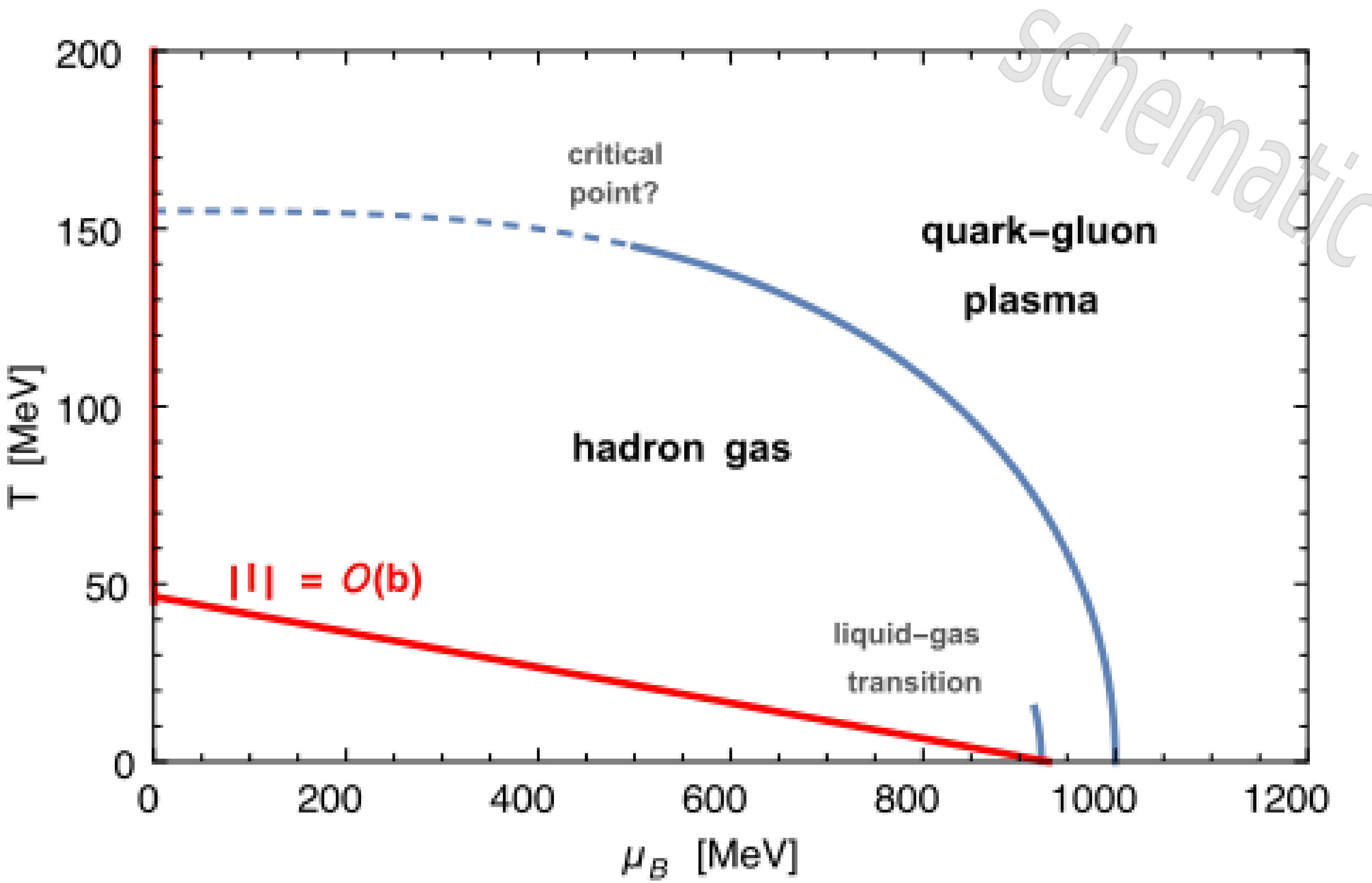
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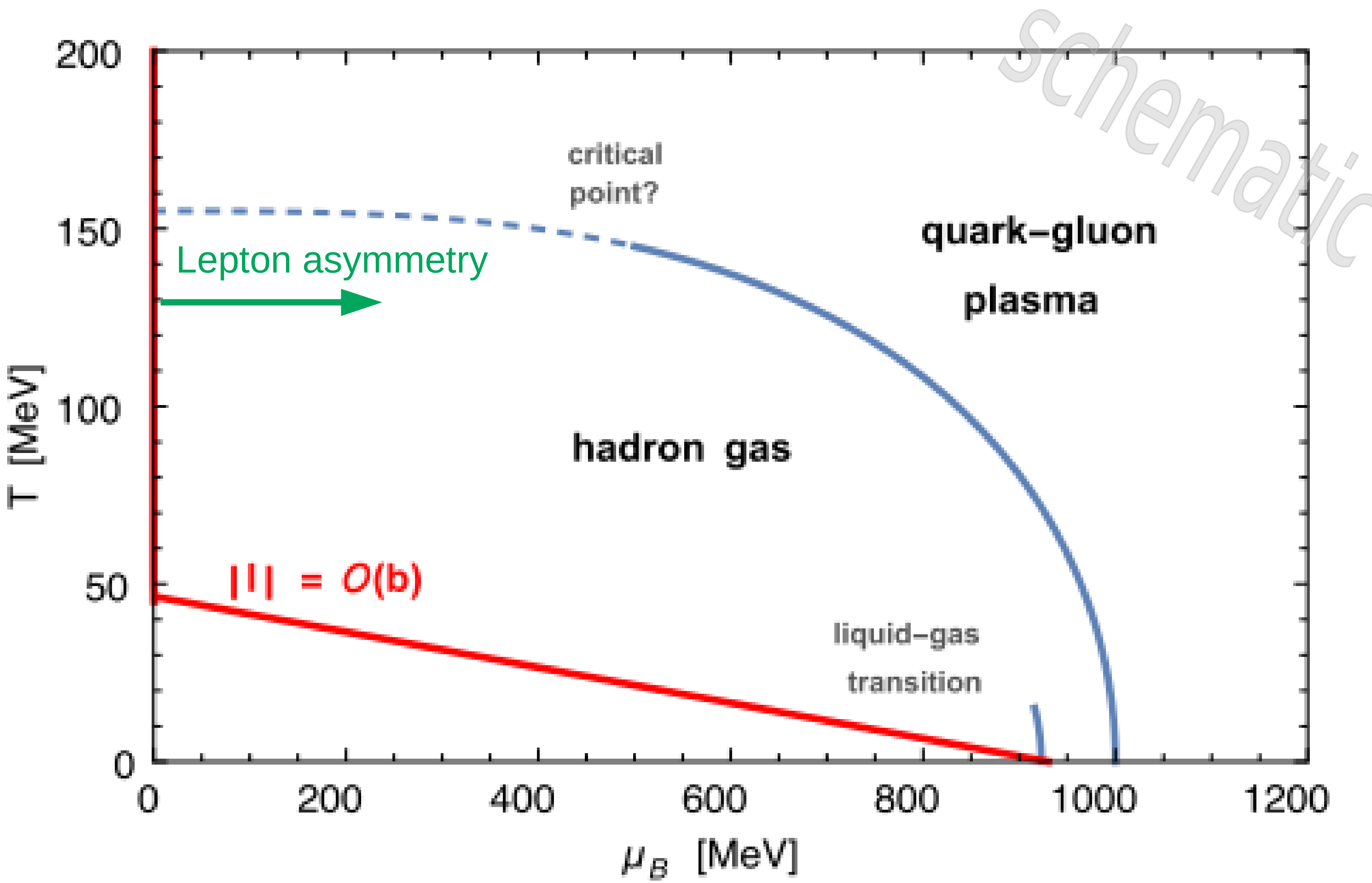

M. Stuke, D. Schwarz (2009)

Baryon asymmetry of Universe : $b = \dfrac{n_{\mathrm{B}}}{s} = (8.60 \pm 0.06) \times 10^{-11}$ *(Planck 2015)*

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Tiny, but why so big?

→ Baryogenesis, Leptogenesis

Leptogenesis: 1.) Mechanism for creation of lepton asymmetry

2.) Sphaleron processes transfer lepton asymmetry to baryon asymmetry

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Leptogenesis: 1.) Mechanism for creation of lepton asymmetry

2.) Sphaleron processes transfer lepton asymmetry to baryon asymmetry

$\rightarrow$ lepton asymmetry $\approx$ baryon asymmetry (i. e. tiny)

Possible caveats?

- sphaleron processes experimentally not confirmed
- suppress sphaleron processes?

  (S. Eijima, M. Shaposhnikov 2017; G. Barenboim, W. Park 2017;...)
- create large lepton asymmetry at later times, when sphaleron processes are inefficient

  (Affleck-Dine mechanism; active-sterile neutrino oscillations, Barbieri & Dolgov 1991; ...)

Lepton asymmetry = key parameter for origin of matter-antimatter asymmetry

What do we know about the lepton asymmetry of our Universe?

charge neutrality:

$\rightarrow$ possibly hidden in cosmic neutrino background

$\rightarrow$ no direct measurement possible $(T_\nu = 1.9\,\mathrm{K})$

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Any constraints?

CMB and BBN: $l \leq \mathcal{O}(0.01)$ *I. Oldengott, D. Schwarz 2017; Mangano et al. 2012*

$\rightarrow$ could be larger than baryon asymmetry by many orders of magnitude

Agnostic point of view: lepton asymmetry = free parameter for cosmology

How to compute the **cosmic trajectory**:

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5 conservation laws

$\rightarrow$ 5 equations

$\rightarrow$ 5 chemical potentials:

$\mu_{\mathrm{L}_e}, \mu_{\mathrm{L}_\mu}, \mu_{\mathrm{L}_\tau}, \mu_{\mathrm{B}}, \mu_{\mathrm{Q}}$

$\boxed{\text{At } \mathbf{T} \gg \mathbf{T}_{\mathrm{QCD}}}$

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$\rightarrow$thermal and chemical equilibrium:

Net particle densities:

$$n_i = \frac{g_i}{2\pi^2} \int_{m_i}^{\infty} \mathrm{d}E E \sqrt{E^2 - m_i^2} \times \left(\frac{1}{e^{(E-\mu_i)/T} \pm 1} - \frac{1}{e^{(E+\mu_i)/T} \pm 1} \right)$$

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where

$T \gg T_{\text{QCD}}$

$$\mu_{L_\alpha} = \mu_{\nu_\alpha} \ ,$$
$$\mu_Q = \mu_{\nu_\alpha} - \mu_\alpha = \mu_u - \mu_d \ ,$$
$$\mu_B = \mu_u + 2\mu_d$$

$T \ll T_{\text{QCD}}$

$$\mu_Q = \mu_\pi = \mu_p - \mu_n \ ,$$
$$\mu_B = \mu_n$$

etc.

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$\rightarrow$ Trick from lattice QCD: Expand around $\mu \approx 0$

$$p^{\rm QCD}(T,\mu) = p^{\rm QCD}(T,0) + \frac{1}{2}\mu_a \chi_{ab}(T)\mu_b + \mathcal{O}(\mu^4)$$

$$n_a(T,\mu) = \frac{\partial p^{\rm QCD}(T,\mu)}{\partial \mu_a} = \chi_{ab}\mu_b + \mathcal{O}(\mu^3)$$

susceptibilities: $\chi_{ab}(T) = \left.\frac{\partial^2 p^{\rm QCD}(T,\mu)}{\partial \mu_a \partial \mu_b}\right|_{\mu=0} = \chi_{ba}(T)$

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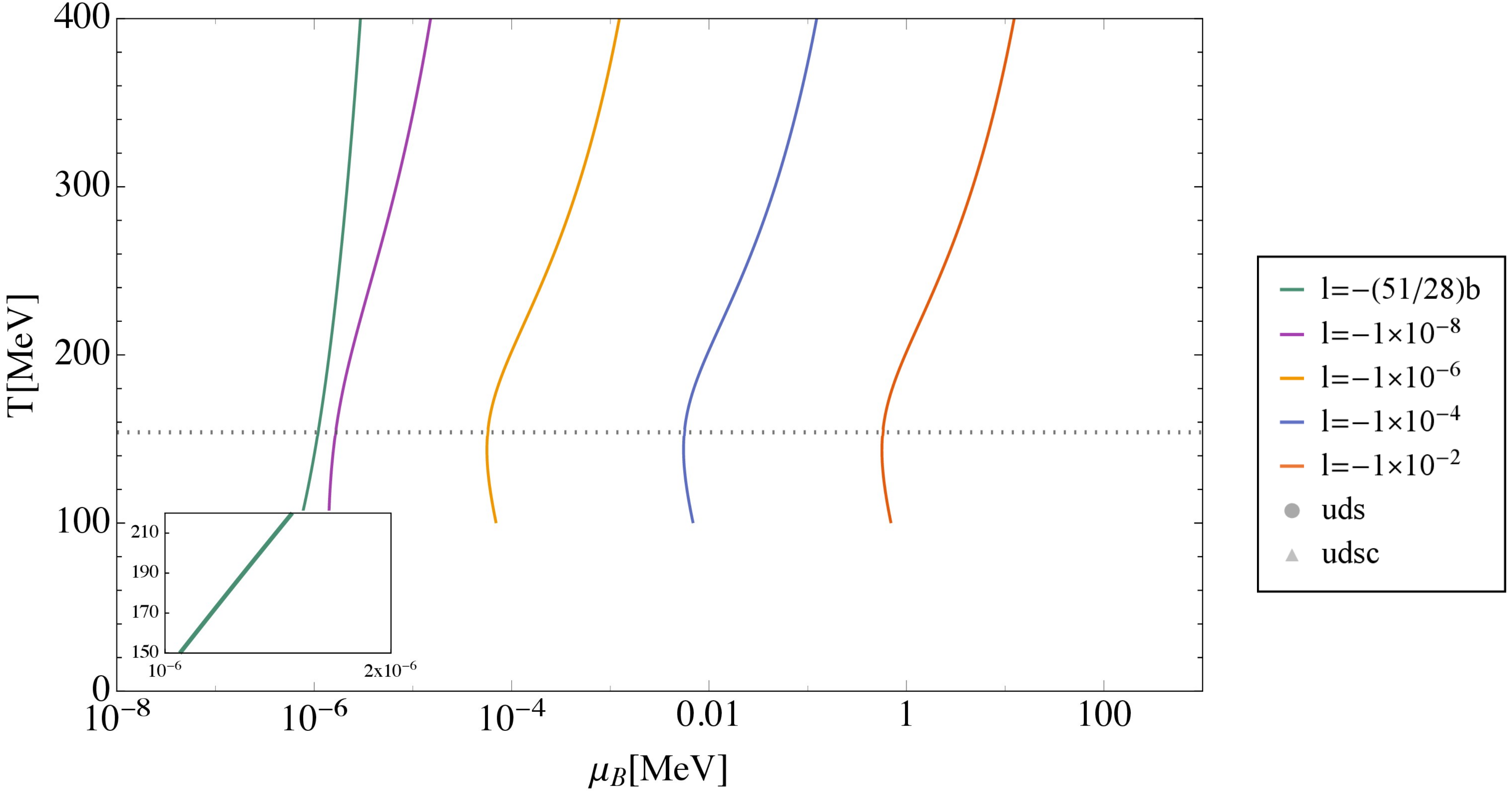
rewrite conservation laws:
$$\begin{cases} l_\alpha s = n_\alpha + n_{\nu_\alpha} \;, \\ bs = \mu_B \chi_{BB} + \mu_Q \chi_{BQ} \;, \\ qs = \mu_Q \chi_{QQ} + \mu_B \chi_{BQ} - \sum_\alpha n_\alpha \end{cases}$$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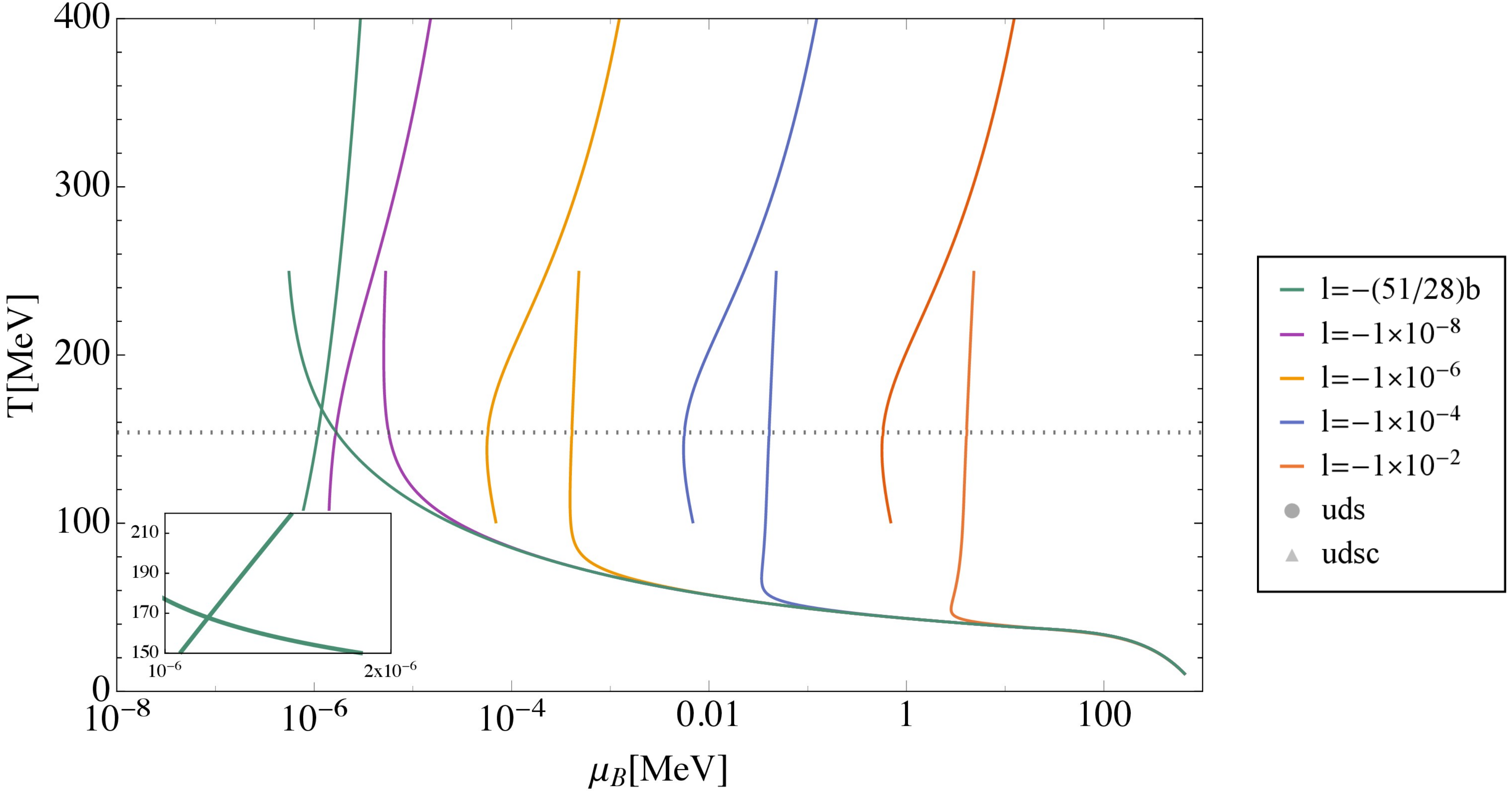

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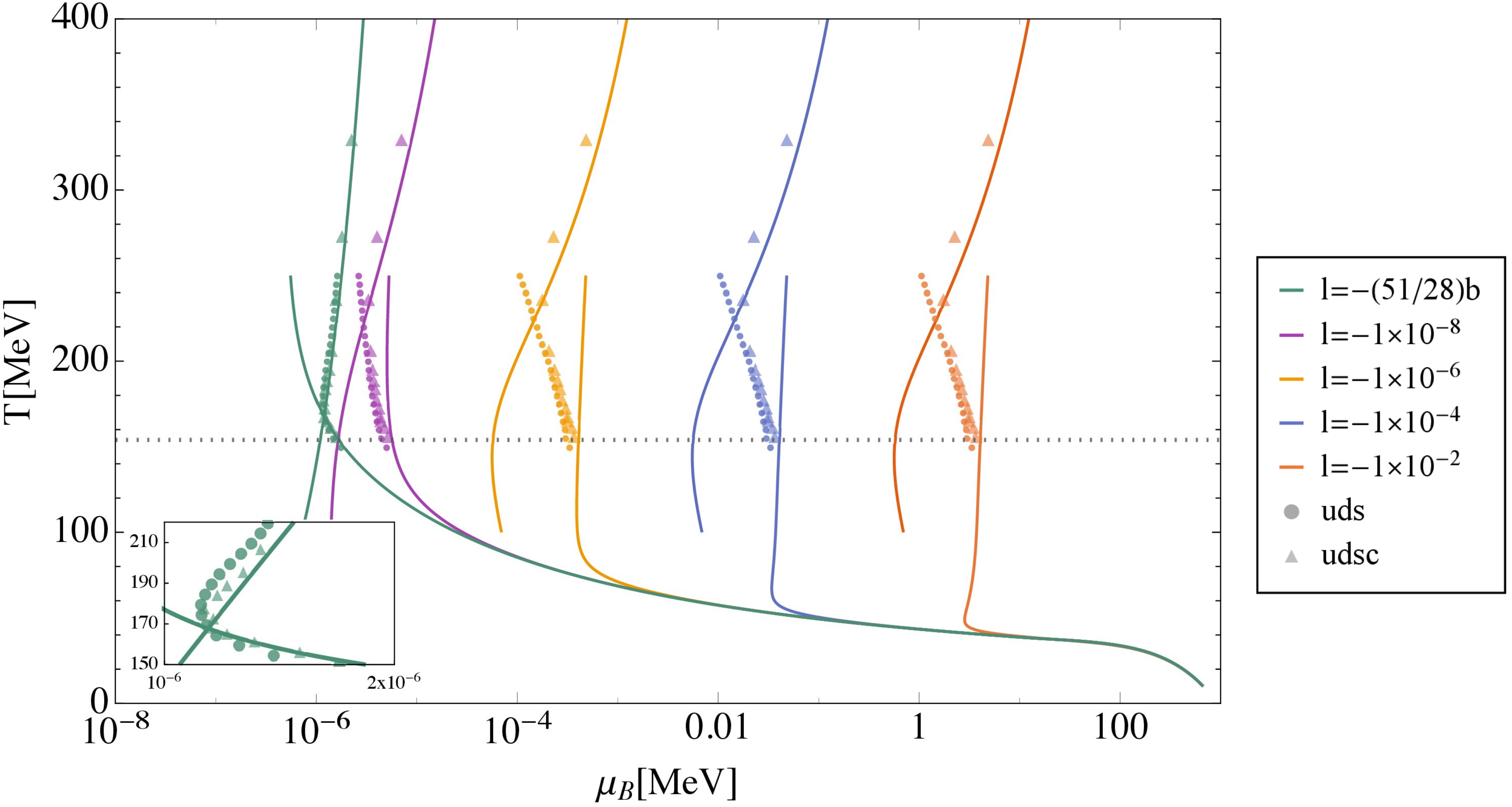

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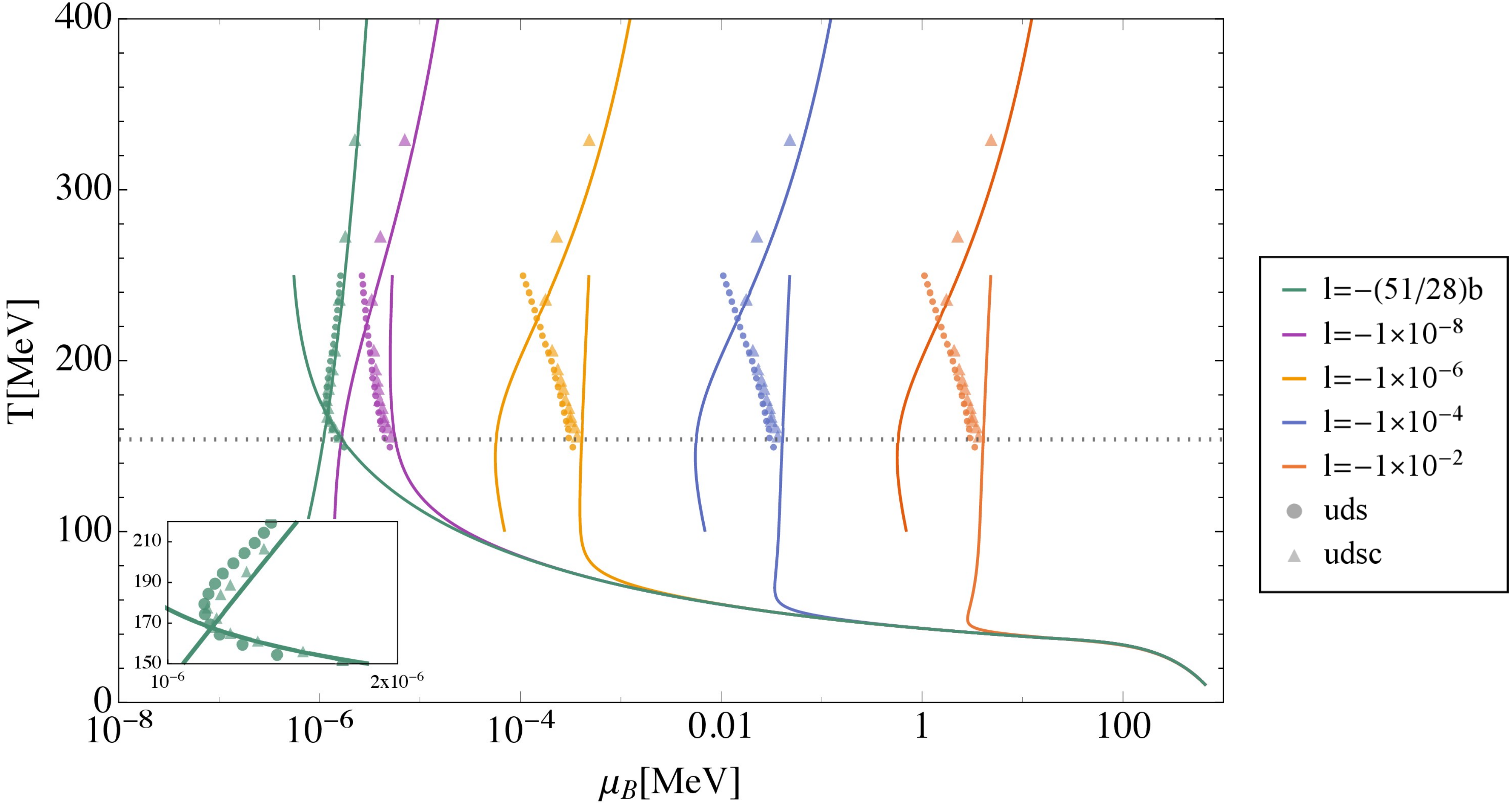

→ Looks smooth. No indication for a 1st order transition.

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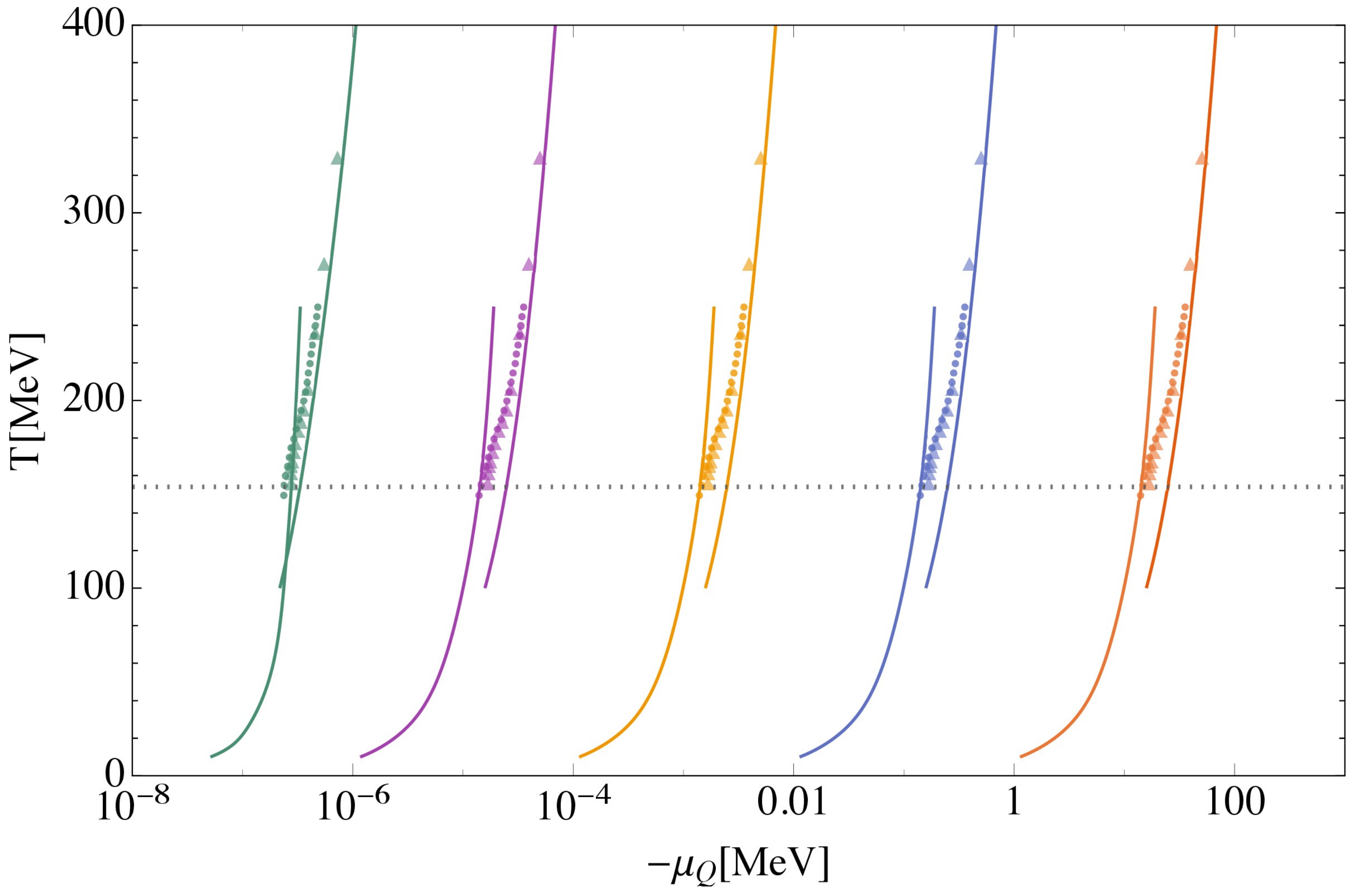
Thank you
for your attention!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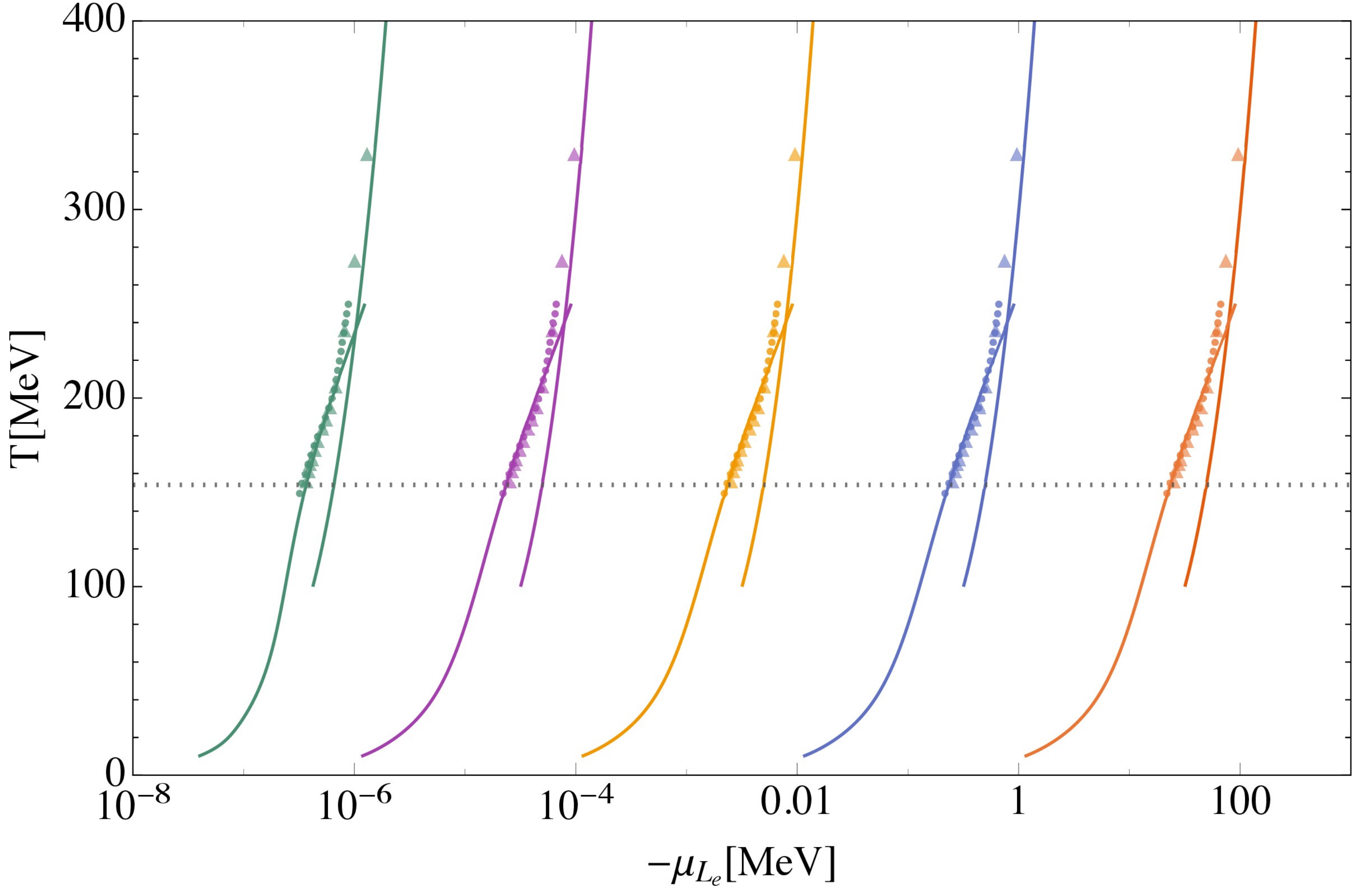
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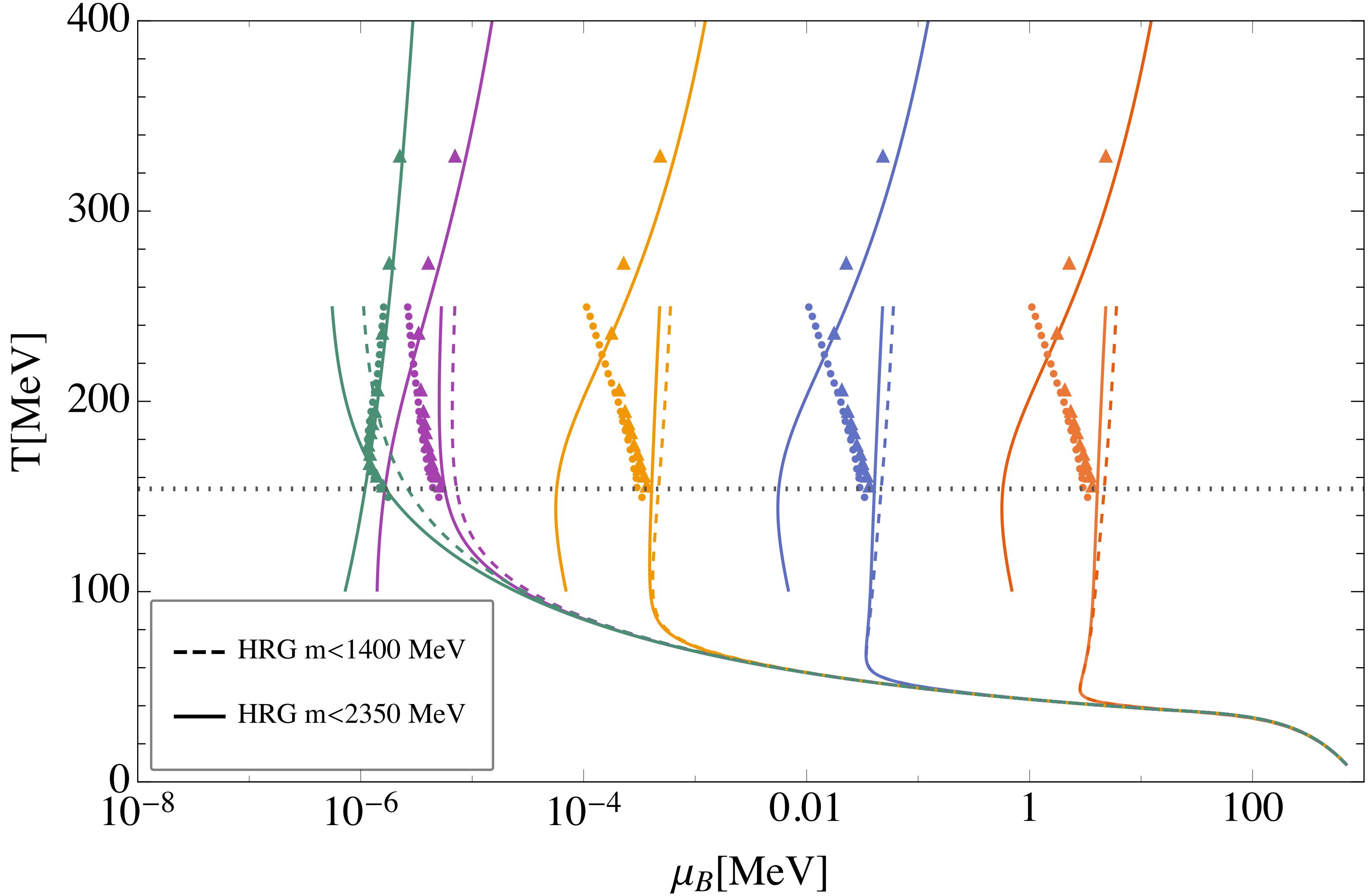

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