# Hyperons in a thermal medium: chiral symmetry, parity doubling and the lattice

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# Mesons in a medium

mesons in a medium very well studied

- hadronic phase: thermal broadening, mass shift
- QGP: deconfinement/dissolution/melting
- quarkonia survival as thermometer
- transport: conductivity/dileptons from vector current
- chiral symmetry restoration

relatively easy on the lattice

- high-precision correlators

what about baryons?

# Baryons in a medium

lattice studies of baryons at finite temperature very limited

- screening masses De Tar and Kogut 1987
- ... with a small chemical potential QCD-TARO: Pushkina, de Forcrand, Kim, Nakamura, Stamatescu et al 2005
- temporal correlators Datta, Gupta, Mathur et al 2013

not much more ...

- effective models, mostly at $T \sim 0$ and nuclear density $\Rightarrow$ parity doubling models De Tar & Kunihiro 89 Mukherjee, Schramm, Steinheimer & Dexheimer, Sasaki 17

# Baryons in a medium

but understanding of in-medium effects highly relevant for

- hadron resonance gas descriptions in confined phase
- benchmarking models for dense QCD
- extensions into QCD phase diagram
- ...

# Outline

baryons across the deconfinement transition:

- baryon correlators
- FASTSUM collaboration
- in-medium effects below $T_c$
- parity doubling above $T_c$
- spectral functions

FASTSUM: PRD 92 (2015) 014503 [arXiv:1502.03603 [hep-lat]]
+ JHEP 06 (2017) 034 [arXiv:1703.09246 [hep-lat]]
+ EPJ WoC 171 (2018) 14005 [arXiv:1710.00566 [hep-lat]]
+ in preparation

# Baryons

- correlators $$G^{\alpha\alpha'}(x) = \langle O^\alpha(x)\,\overline{O}^{\alpha'}(0)\rangle$$
- examples: $N, \Delta, \Omega$ baryons

$$O_N^\alpha(x) = \epsilon_{abc}\, u_a^\alpha(x) \left(d_b^T(x) C\gamma_5 u_c(x)\right)$$
$$O_{\Delta,i}^\alpha(x) = \epsilon_{abc} \left[2u_a^\alpha(x) \left(d_b^T(x) C\gamma_i u_c(x)\right) + d_a^\alpha(x) \left(u_b^T(x) C\gamma_i u_c(x)\right)\right]$$
$$O_{\Omega,i}^\alpha(x) = \epsilon_{abc}\, s_a^\alpha(x) \left(s_b^T(x) C\gamma_i s_c(x)\right)$$

- essential difference with mesons: role of parity

$$\mathcal{P} O(\tau, \mathbf{x}) \mathcal{P}^{-1} = \gamma_4 O(\tau, -\mathbf{x})$$

- positive/negative parity operators

$$O_\pm(x) = P_\pm O(x) \qquad P_\pm = \frac{1}{2}(1 \pm \gamma_4)$$

# Baryons

- positive/negative parity operators

$$O_{\pm}(x) = P_{\pm}O(x) \qquad\qquad P_{\pm} = \frac{1}{2}(1 \pm \gamma_4)$$

- no parity doubling in Nature: nucleon ground state

  positive parity: $\quad m_{+} = m_N \quad = 0.939$ GeV

  negative parity: $\quad m_{-} = m_{N^*} = 1.535$ GeV

- thread: what happens as temperature increases?

how are pos/neg parity states encoded in correlators?

$$G_{\pm}(x-x') = \langle \mathrm{tr} P_{\pm} O(x)\overline{O}(x')\rangle \qquad\qquad \rho_{\pm}(x-x') = \langle \mathrm{tr} P_{\pm}\{O(x), \overline{O}(x')\}\rangle$$

# Charge conjugation

charge conjugation symmetry (at vanishing density):

$$G_\pm(\tau, \mathbf{p}) = -G_\mp(1/T - \tau, \mathbf{p}) \qquad \rho_\pm(-\omega, \mathbf{p}) = -\rho_\mp(\omega, \mathbf{p})$$

- relates pos/neg parity channels

using $G_+(\tau, \mathbf{p})$ and $\rho_+(\omega, \mathbf{p})$

- positive- (negative-) parity states propagate forward (backward) in euclidean time
- negative part of spectrum of $\rho_+ \leftrightarrow$ positive part of $\rho_-$

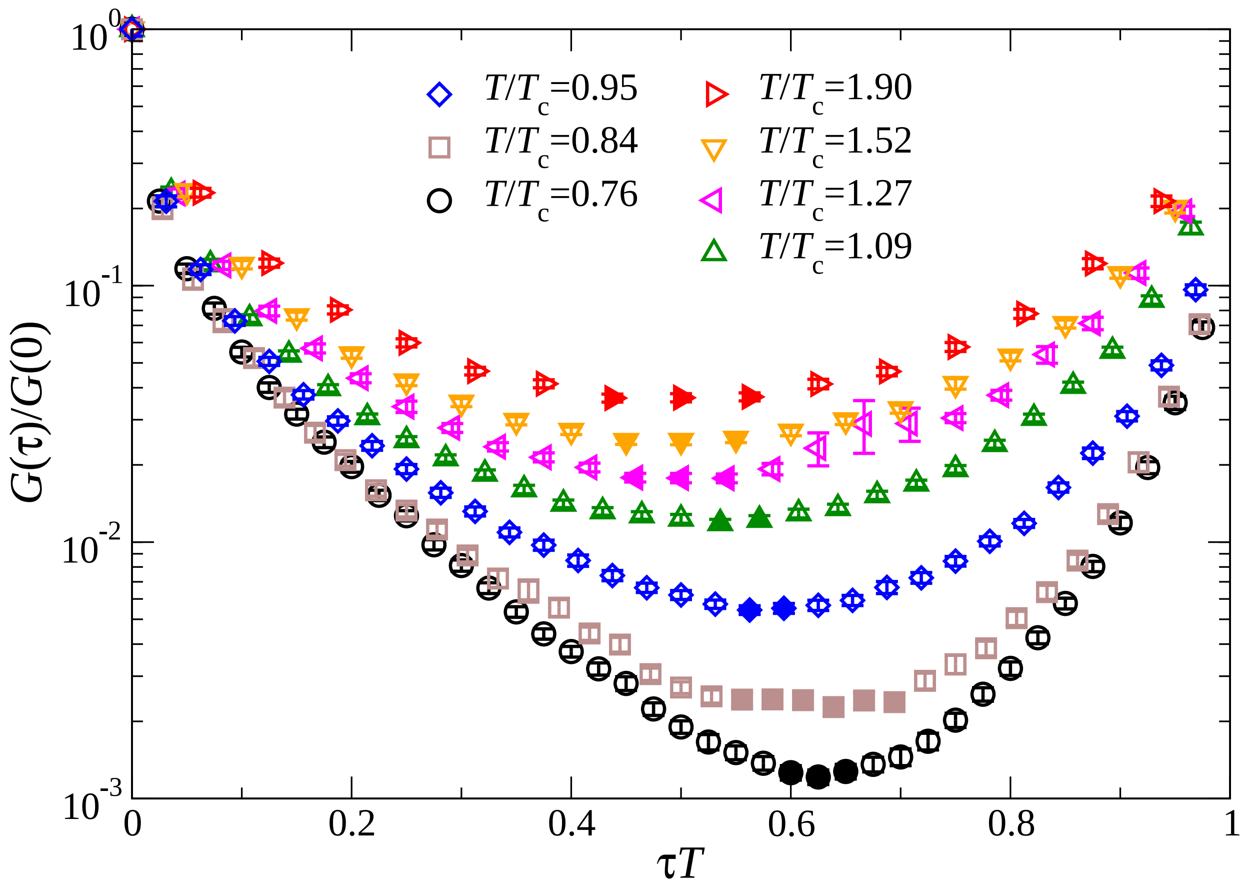
example: single state

$$G_+(\tau) = A_+ e^{-m_+\tau} + A_- e^{-m_-(1/T-\tau)}$$

$$\rho_+(\omega)/(2\pi) = A_+\delta(\omega - m_+) + A_-\delta(\omega + m_-)$$

# Nucleon correlators

- euclidean correlator $G_+(\tau)$




- not symmetric around $\tau = 1/2T$ below $T_c$
- more symmetric as temperature increases

# Chiral symmetry

- propagator

$$G(x) = \sum_\mu \gamma_\mu G_\mu(x) + \mathbb{1} G_m(x)$$

- chiral symmetry $\qquad \{\gamma_5, G\} = 0 \quad \Rightarrow \quad G_m = 0$
- hence

$$G_+(\tau, \mathbf{p}) = -G_-(\tau, \mathbf{p}) = G_+(1/T - \tau, \mathbf{p}) = 2G_4(\tau, \mathbf{p})$$

degeneracy of $\pm$ parity channels

$$\rho_+(p) = -\rho_-(p) = \rho_+(-p) = 2\rho_4(p)$$

- parity doubling
- in Nature at $T = 0$: no chiral symmetry/parity doubling

# Parity and chiral symmetry

however, if chiral symmetry is unbroken ($m_q = 0$ and no SSB)

- degeneracy between pos/neg parity channels already at the level of the correlators

what happens at the confinement/deconfinement transition?

- SU(2)$_{\mathrm{A}}$ chiral symmetry restored
- expect degeneracies to emerge
- how does this affect mass spectrum?
- role of $m_s > m_{u,d}$?

# FASTSUM

- anisotropic $N_f = 2 + 1$ Wilson-clover ensembles

*FASTSUM* collaboration

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Alan Kirby (Swansea)
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Tim Harris (TCD->Mainz->Milan)
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Wynne Evans (Swansea->Bern->)
Pietro Giudice (Swansea->Münster->)
Aoife Kelly (Maynooth->)
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Kristi Praki (Swansea->)

# This work

GA, Chris Allton, Simon Hands, Kristi Praki, Jonivar Skullerud

Davide de Boni, Benjamin Jäger

PRD 92 (2015) 014503, arXiv:1502.03603 [hep-lat]

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# FASTSUM ensembles

- $N_f = 2+1$ dynamical quark flavours, Wilson-clover
- many temperatures, below and above $T_c$
- anisotropic lattice, $a_s/a_\tau = 3.5$, many time slices
- strange quark: physical value
- two light flavours: somewhat heavy $m_\pi = 384(4)$ MeV

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| $N_s$ | 24 | 24 | 24 | 24 | 24 | 24 | 24 | 24 |
| $N_\tau$ | 128 | 40 | 36 | 32 | 28 | 24 | 20 | 16 |
| $T/T_c$ | 0.24 | 0.76 | 0.84 | 0.95 | 1.09 | 1.27 | 1.52 | 1.90 |
| $N_{\rm cfg}$ | 140 | 500 | 500 | 1000 | 1000 | 1000 | 1000 | 1000 |
| $N_{\rm src}$ | 16 | 4 | 4 | 2 | 2 | 2 | 2 | 2 |

- tuning and $N_\tau = 128$ data from HadSpec collaboration

# Baryon correlators

computed all octet and decuplet baryon correlators

| | | | |
|---|---|---|---|
| $S=0$: | $N$ | $\Delta$ | |
| $S=-1$: | $\Lambda$ | $\Sigma$ | $\Sigma^*$ |
| $S=-2$: | $\Xi$ | $\Xi^*$ | |
| $S=-3$: | $\Omega$ | | |

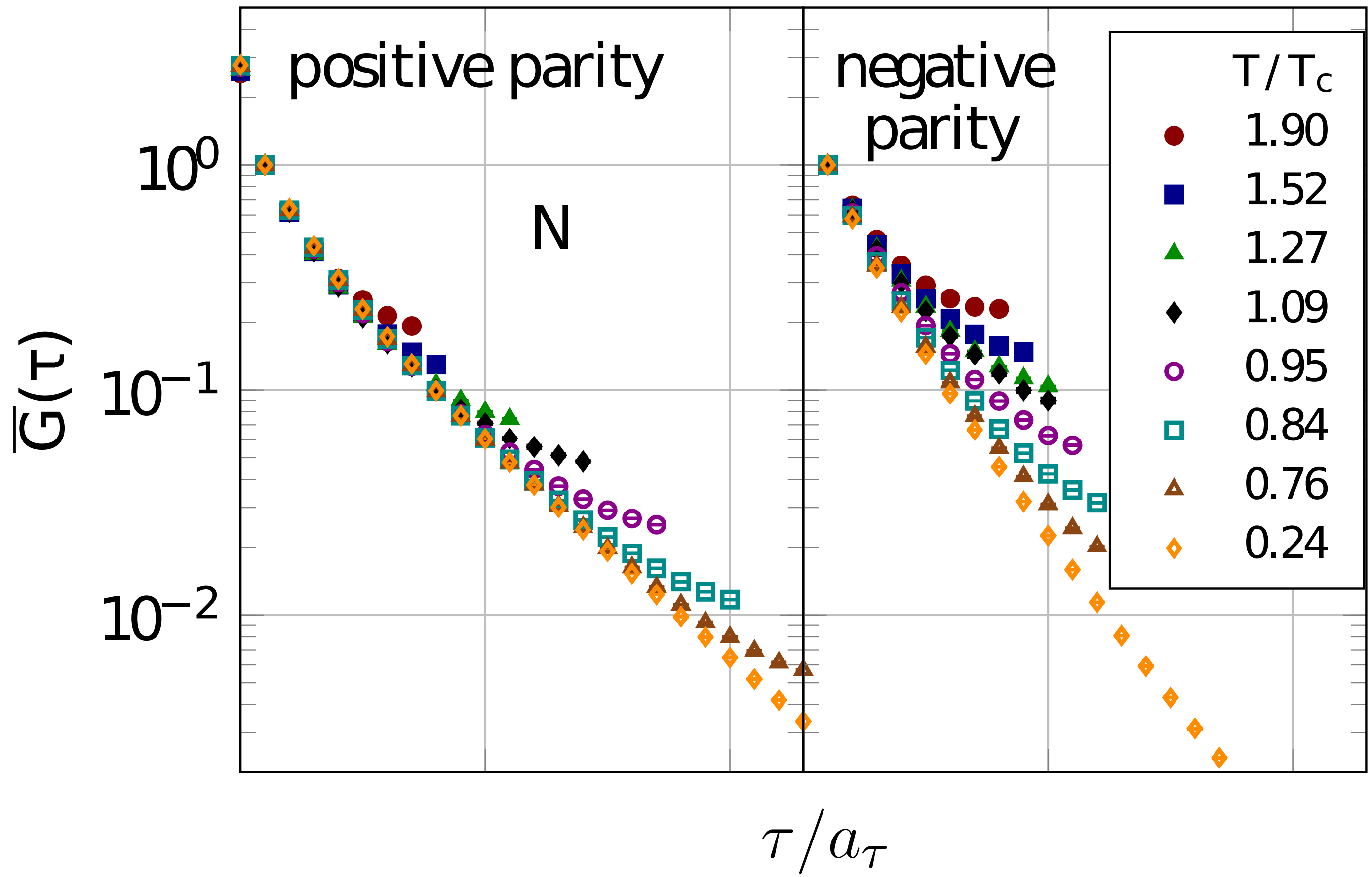
for each baryon: positive and negative parity channels

technical remarks

- studied various interpolation operators
- Gaussian smearing for multiple sources and sinks
- same smearing parameters at all temperatures

# Lattice correlators

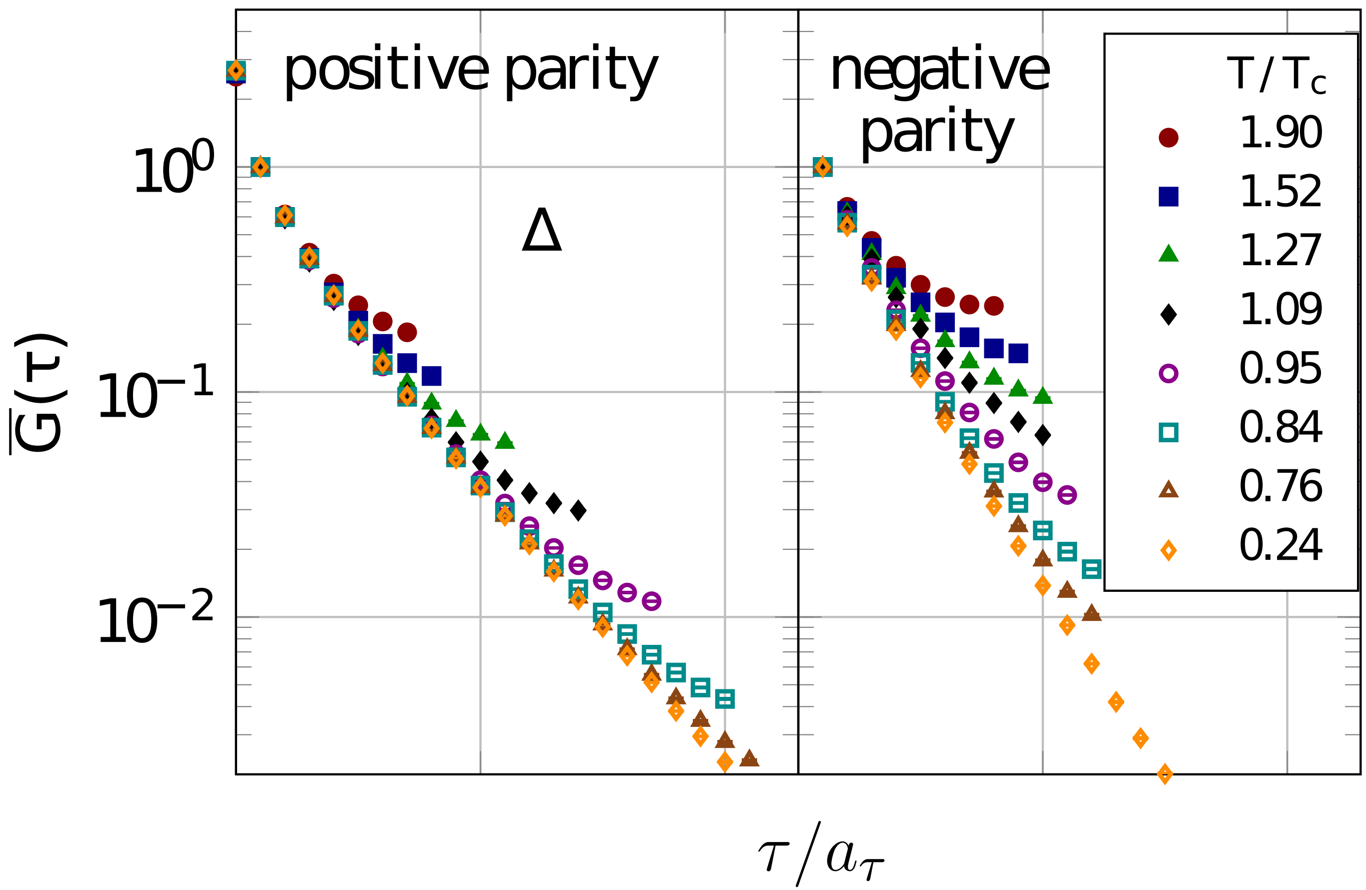
- nucleon




- pos/neg parity channels nondegenerate
- more $T$ dependence in negative-parity channel

# Lattice correlators

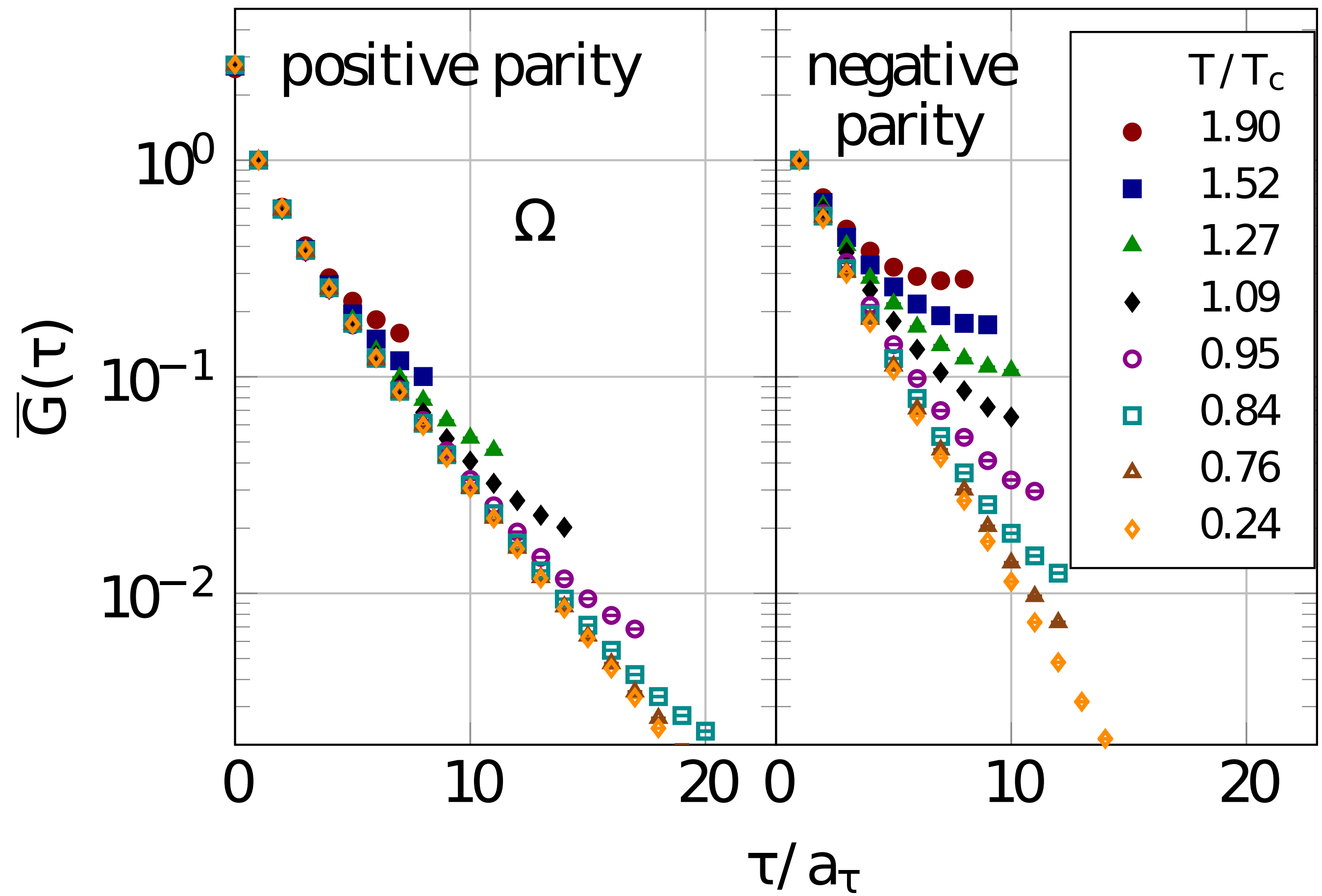
- $\Delta$




- at low $T$ pos/neg parity channels nondegenerate
- more $T$ dependence in negative-parity channel

# Lattice correlators

- $\Omega$




- at low $T$ pos/neg parity channels nondegenerate
- more $T$ dependence in negative-parity channel

# Baryons in the hadronic phase

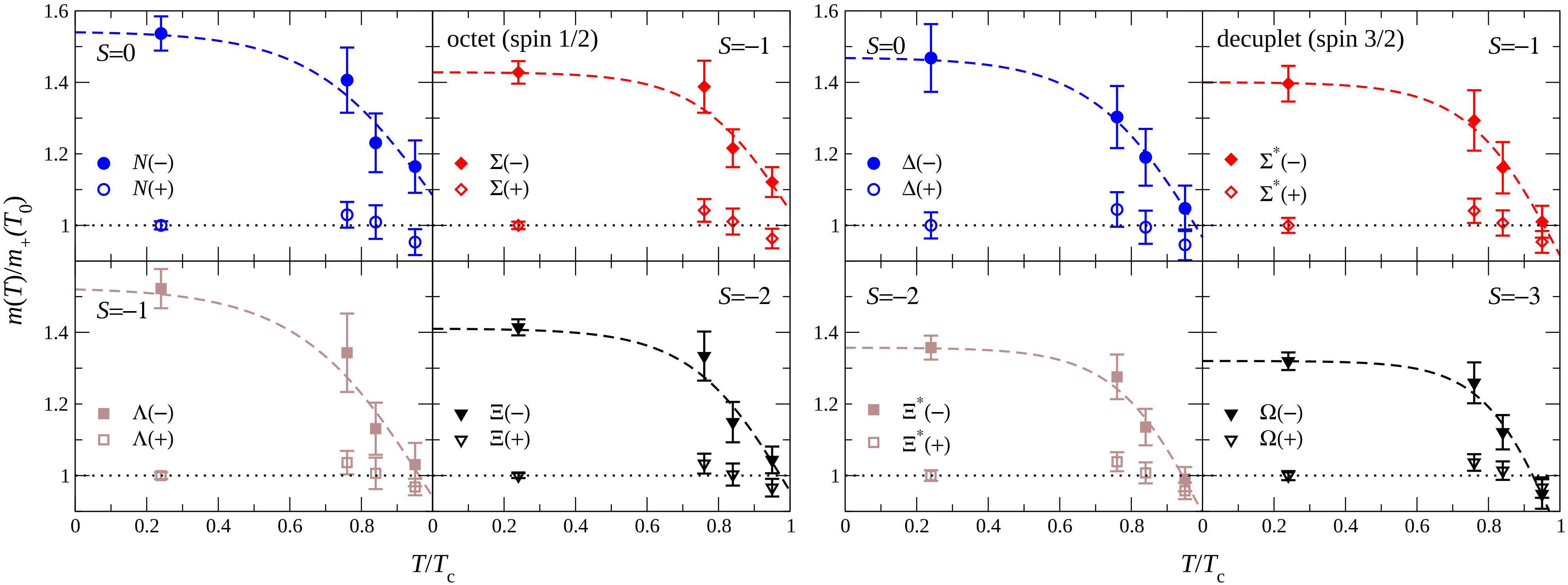
- determine masses of pos/neg parity groundstates
- in-medium effects

# Masses of pos/neg parity groundstates (in MeV)

| $S$ | $T/T_c$ | 0.24 | 0.76 | 0.84 | 0.95 | PDG ($T=0$) |
|---|---|---|---|---|---|---|
| 0 | $m_+^N$ | 1158(13) | 1192(39) | 1169(53) | 1104(40) | 939 |
| | $m_-^N$ | 1779(52) | 1628(104) | 1425(94) | 1348(83) | 1535 |
| | $m_+^\Delta$ | 1456(53) | 1521(43) | 1449(42) | 1377(37) | 1232 |
| | $m_-^\Delta$ | 2138(114) | 1898(106) | 1734(97) | 1526(74) | 1700 |
| $-1$ | $m_+^\Sigma$ | 1277(13) | 1330(38) | 1290(44) | 1230(33) | 1193 |
| | $m_-^\Sigma$ | 1823(35) | 1772(91) | 1552(65) | 1431(51) | 1750 |
| | $m_+^\Lambda$ | 1248(12) | 1293(39) | 1256(54) | 1208(26) | 1116 |
| | $m_-^\Lambda$ | 1899(66) | 1676(136) | 1411(90) | 1286(75) | 1405–1670 |
| | $m_+^{\Sigma^*}$ | 1526(32) | 1588(40) | 1536(43) | 1455(35) | 1385 |
| | $m_-^{\Sigma^*}$ | 2131(62) | 1974(122) | 1772(103) | 1542(60) | 1670–1940 |
| $-2$ | $m_+^\Xi$ | 1355(9) | 1401(36) | 1359(41) | 1310(32) | 1318 |
| | $m_-^\Xi$ | 1917(27) | 1808(92) | 1558(76) | 1415(50) | 1690–1950 |
| | $m_+^{\Xi^*}$ | 1594(24) | 1656(35) | 1606(40) | 1526(29) | 1530 |
| | $m_-^{\Xi^*}$ | 2164(42) | 2034(95) | 1810(77) | 1578(48) | 1820 |
| $-3$ | $m_+^\Omega$ | 1661(21) | 1723(32) | 1685(37) | 1606(43) | 1672 |
| | $m_-^\Omega$ | 2193(30) | 2092(91) | 1863(76) | 1576(66) | 2250 |

# Baryons in the hadronic phase

masses $m_{\pm}(T)$, normalised with $m_+$ at lowest temperature




in each channel:

- emerging degeneracy around $T_c$
- negative-parity masses reduced as $T$ increases
- positive-parity masses nearly $T$ independent

# Baryons in the hadronic phase

findings

- positive-parity masses nearly $T$ independent
- negative-parity masses reduced as $T$ increases
- characteristic behaviour

$$m_-(T) = w(T,\gamma)m_-(0) + [1 - w(T,\gamma)]m_-(T_c)$$

with one-parameter transition function

$$w(T,\gamma) = \tanh[(1 - T/T_c)/\gamma]/\tanh(1/\gamma)$$

- small (large) $\gamma \Leftrightarrow$ narrow (broad) transition region

fits in each channel

- $0.22 \lesssim \gamma \lesssim 0.35$, mean $\gamma = 0.27(1)$
- $0.85 \lesssim m_-(T_c)/m_+(0) \lesssim 1.1$

# Baryons and parity partners

- distinct temperature dependence in hadronic phase
- understand further using
  - effective parity doublet models?

    Mukherjee, Schramm, Steinheimer & Dexheimer, Sasaki 17
  - holography?
- relevant for heavy-ion phenomenology?

# Baryons and parity partners

- distinct temperature dependence in hadronic phase
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  - holography?
- relevant for heavy-ion phenomenology?

application to HRG

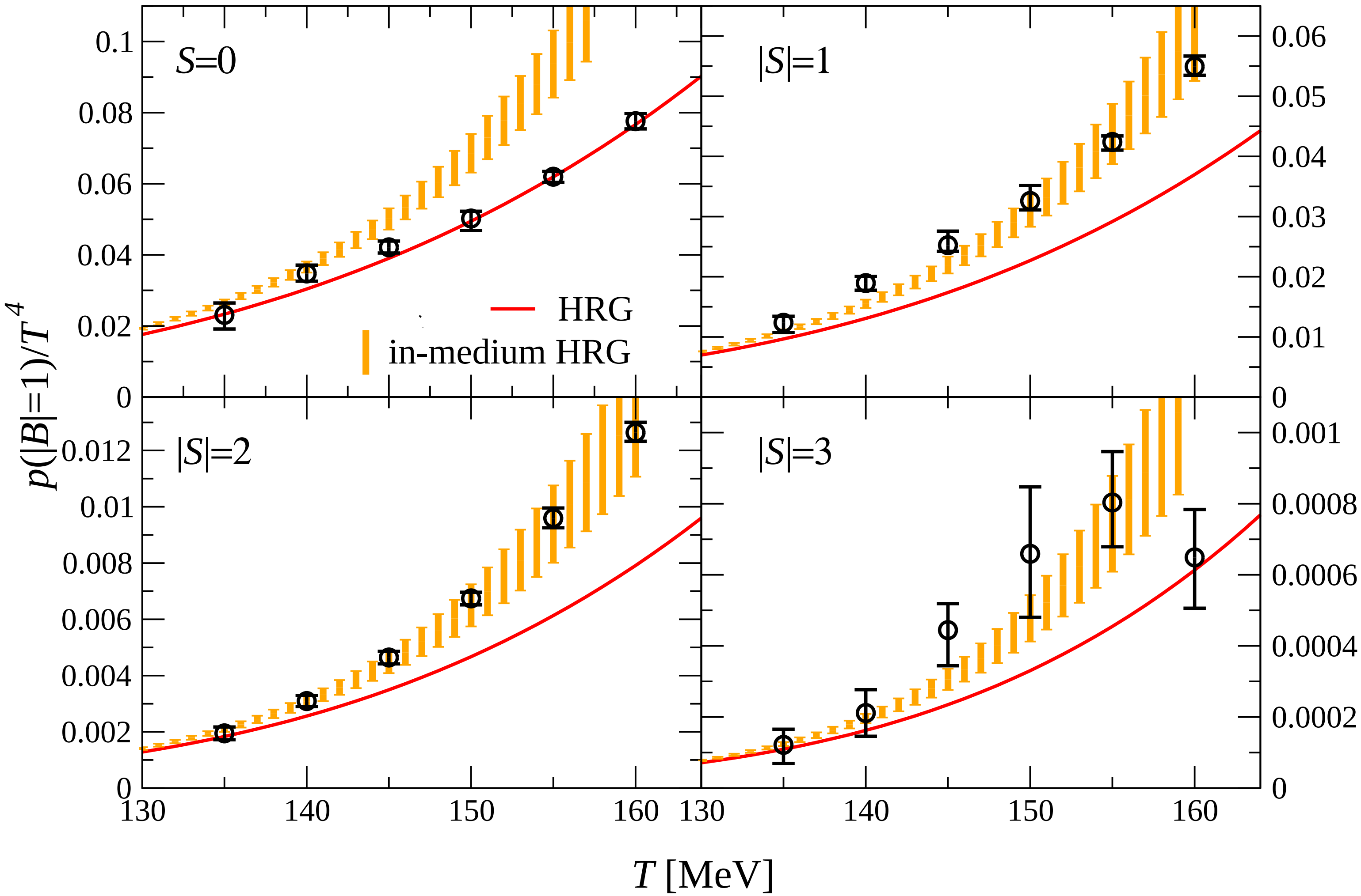
- use states in PDG (not QM)
- $T$-dependent groundstates in neg parity channels

$$m_-(T) = w(T,\gamma)m_-(0) + [1 - w(T,\gamma)]m_-(T_c)$$

with $\gamma = 0.3$ and $1 < m_-(T_c)/m_+(0) < 1.1$

# In-medium HRG

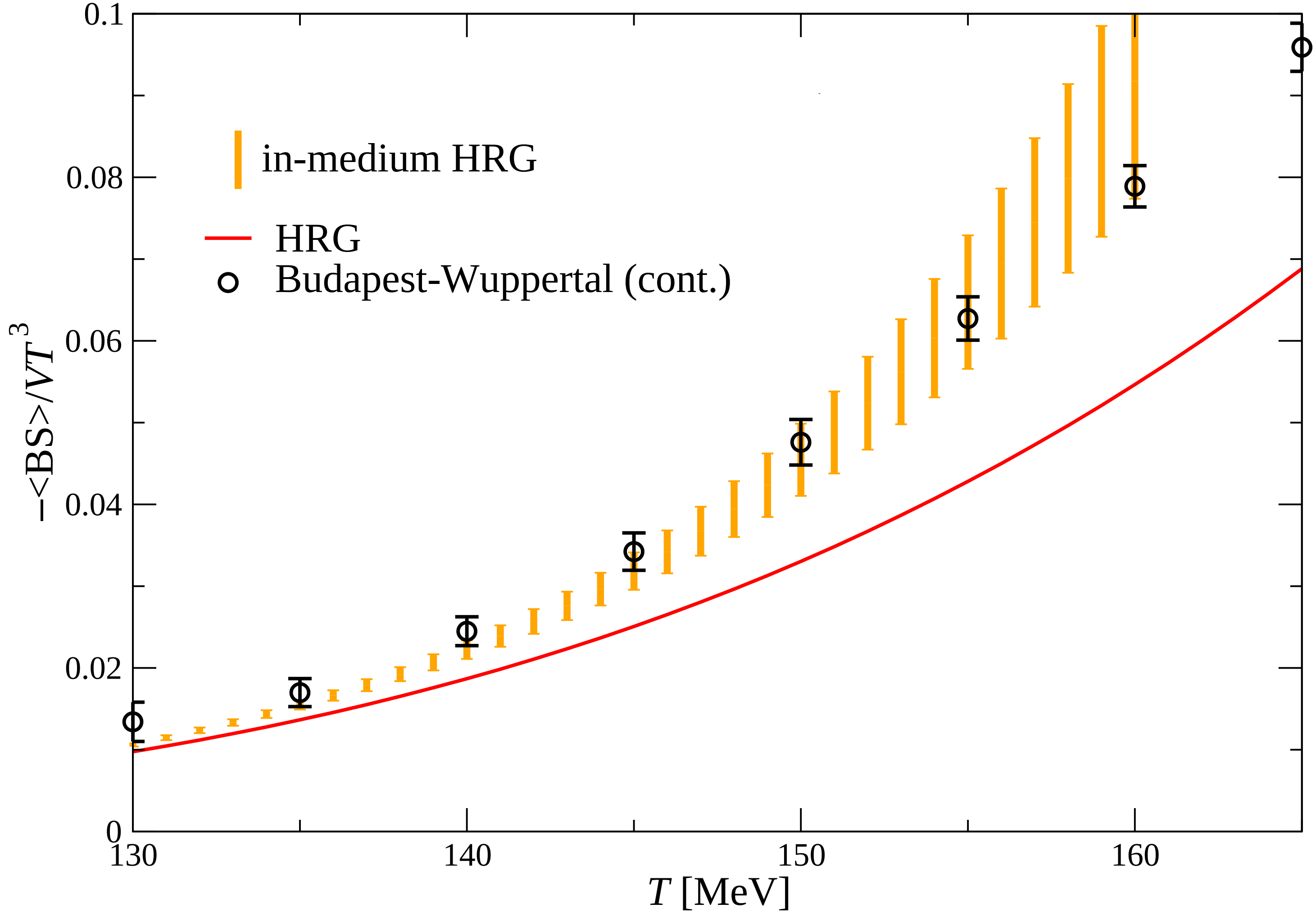
contributions to pressure from baryons with strangeness




compare with lattice data from Alba, Ratti et al, 1702.01113

# In-medium HRG

fluctuations of strange baryons $\langle BS \rangle$



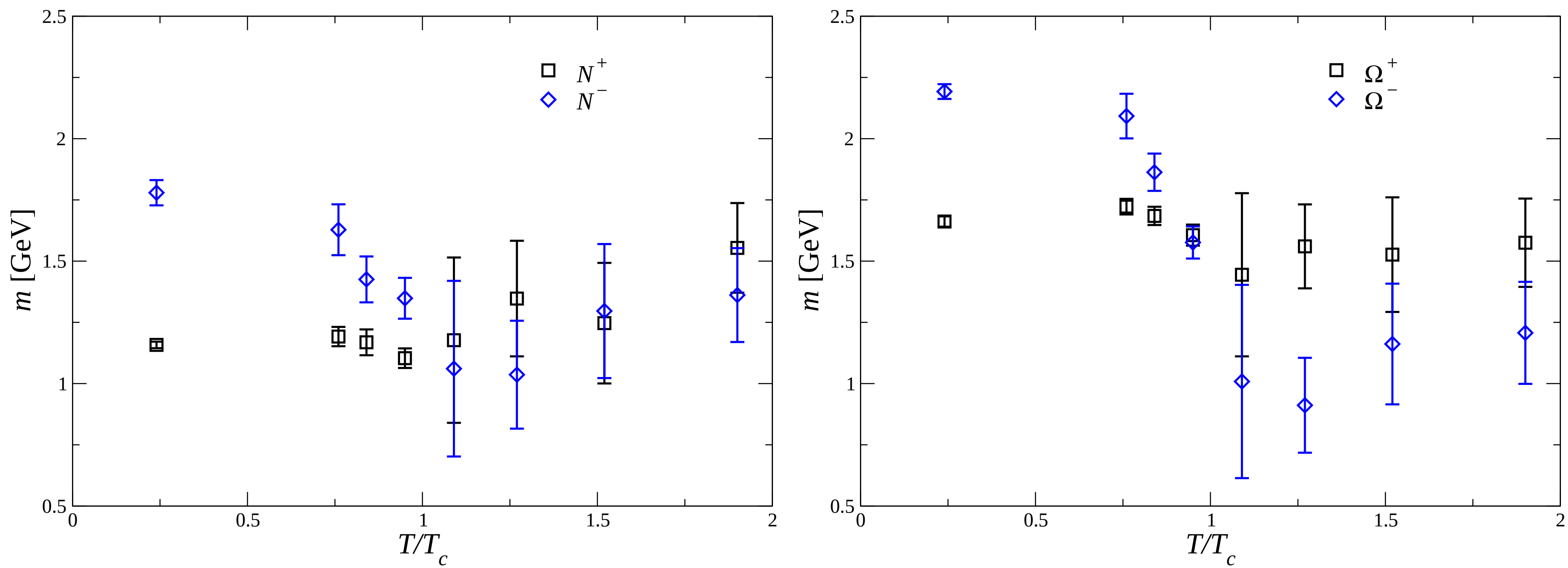

compare with lattice data from Budapest-Wuppertal

# QGP: fate of light baryons

consider now the quark-gluon plasma

- no clearly identifiable groundstates: baryons dissolved

example: use conventional exponential fits




no clearly defined groundstates above $T_c$

# QGP: fate of light baryons

- no clearly identifiable groundstates: baryons dissolved
- chiral symmetry restoration $\Leftrightarrow$ parity doubling
- study correlator ratio Datta, Gupta, Mathur et al 2013

$$R(\tau) = \frac{G_+(\tau) - G_-(\tau)}{G_+(\tau) + G_-(\tau)}$$

- no parity doubling and $m_- \gg m_+$: $R(\tau) = 1$
- parity doubling: $R(\tau) = 0$

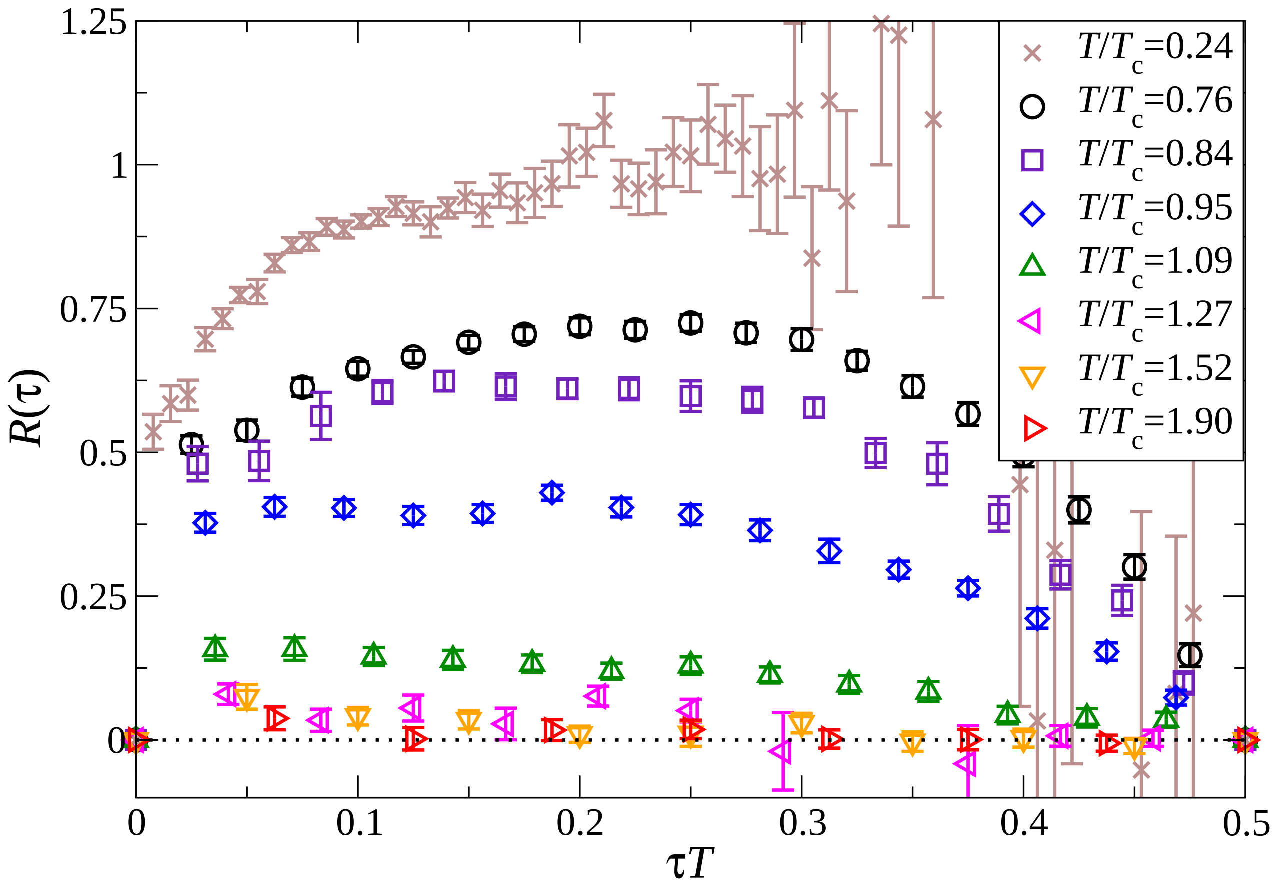
by construction: $R(1/T - \tau) = -R(\tau)$ and $R(1/2T) = 0$

- integrated ratio

$\Rightarrow$ quasi-order parameter

$$R = \frac{\sum_n R(\tau_n)/\sigma^2(\tau_n)}{\sum_n 1/\sigma^2(\tau_n)}$$

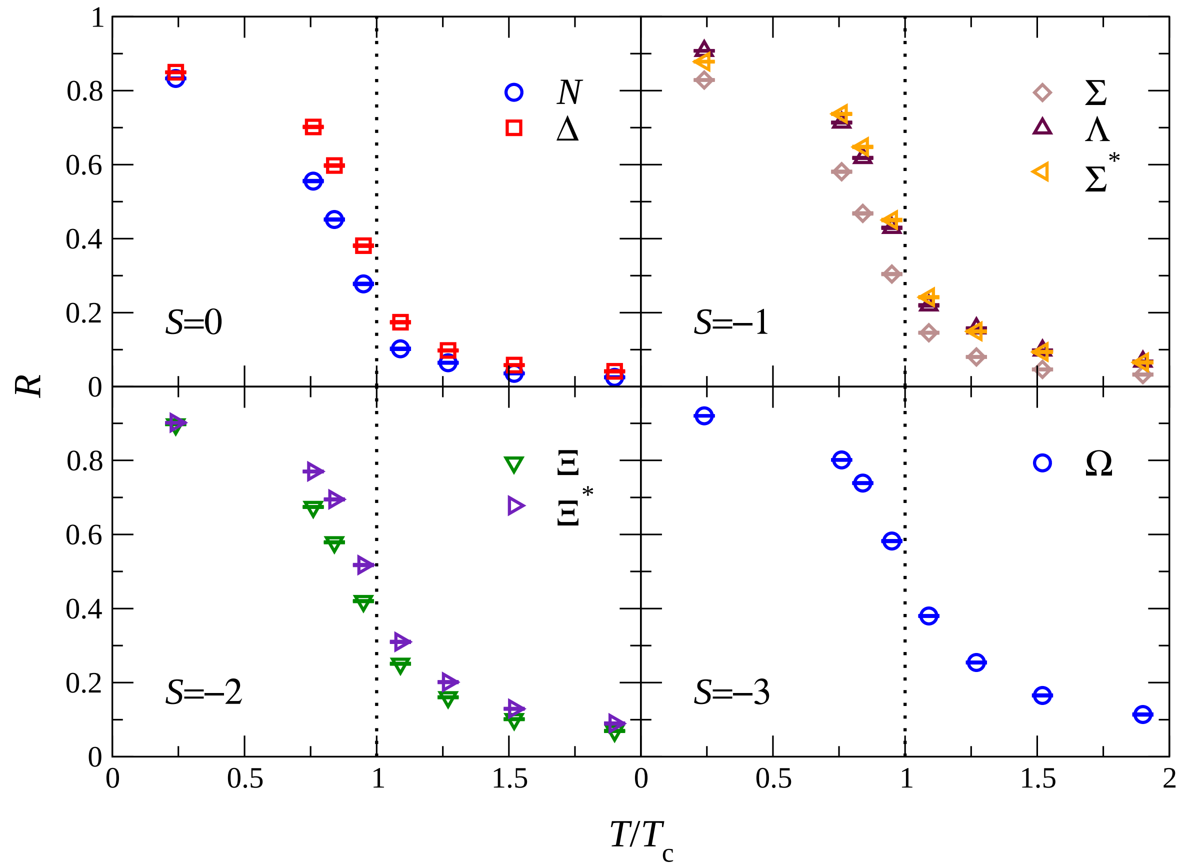
# Nucleon channel




- ratio close to 1 below $T_c$, decreasing uniformly
- ratio close to 0 above $T_c$, parity doubling

# Quasi-order parameter

parity doubling in the QGP: $R \sim 1 \to 0$




- crossover behaviour, tied with deconfinement transition and hence chiral transition – note: $m_q \neq 0$
- effect of heavier $s$ quark visible

# Parity doubling

- clear signal for parity doubling
  even with finite quark masses
- crossover behaviour, coinciding with transition to QGP
- visible effect of heavier $s$ quark

spectral functions

# Spectral properties: fermions

$$G^{\alpha\alpha'}(\tau,\mathbf{p}) = \int_{-\infty}^{\infty} \frac{d\omega}{2\pi} K(\tau,\omega)\rho^{\alpha\alpha'}(\omega,\mathbf{p})$$

- fermionic Matsubara frequencies

$$K(\tau,\omega) = T\sum_n \frac{e^{-i\omega_n\tau}}{\omega - i\omega_n} = \frac{e^{-\omega\tau}}{1+e^{-\omega/T}} = e^{-\omega\tau}\left[1-n_F(\omega)\right]$$

- kernel not symmetric, instead

$$K(1/T-\tau,\omega) = K(\tau,-\omega)$$

- positivity: $\rho_4(p), \pm\rho_\pm(p) \geq 0$ for all $\omega$
- $\rho_m(p) = [\rho_+(p) + \rho_-(p)]/4$ not sign definite

# Spectral functions

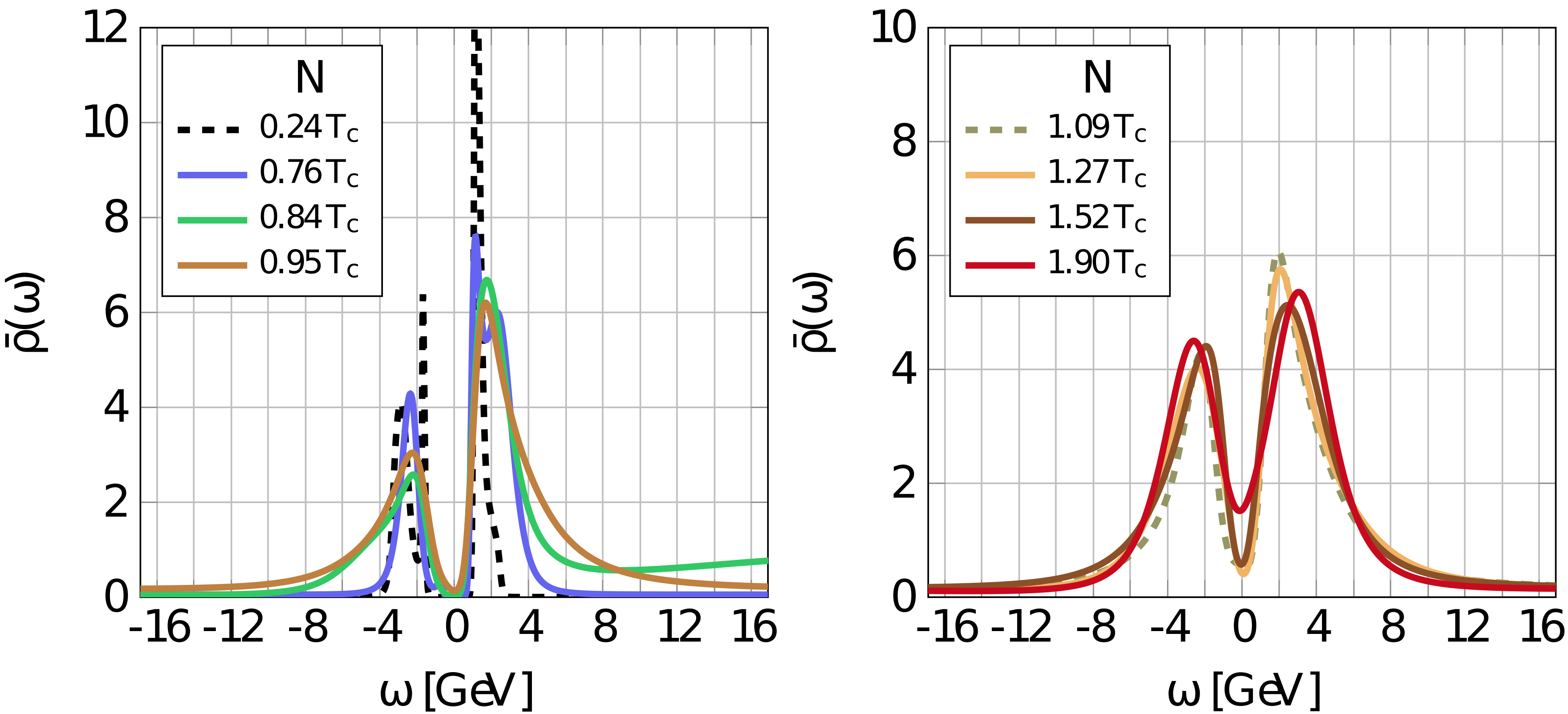
extract same information from spectral functions

$$G_{\pm}(\tau) = \int_{-\infty}^{\infty} \frac{d\omega}{2\pi} K(\tau,\omega)\rho_{\pm}(\omega) \qquad K(\tau,\omega) = \frac{e^{-\omega\tau}}{1+e^{-\omega/T}}$$

- *ill-posed* inversion problem
- use Maximum Entropy Method (MEM)
- featureless default model
- construct $\rho_+(\omega) \geq 0$ for all $\omega$
- $\rho_-(\omega) = -\rho_+(-\omega)$

# Baryon spectral functions

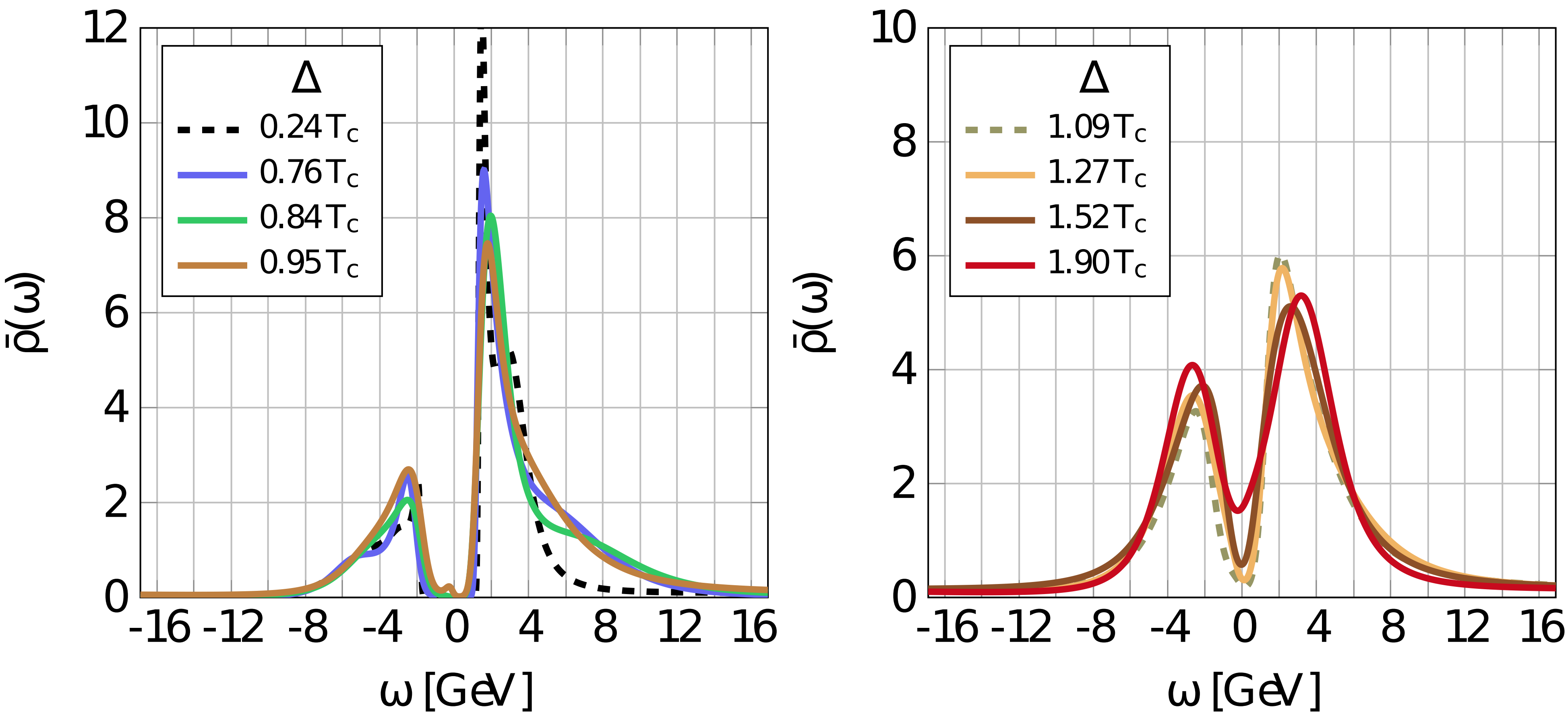
- nucleon




- groundstates below $T_c$
- degeneracy emerging above $T_c$

# Baryon spectral functions

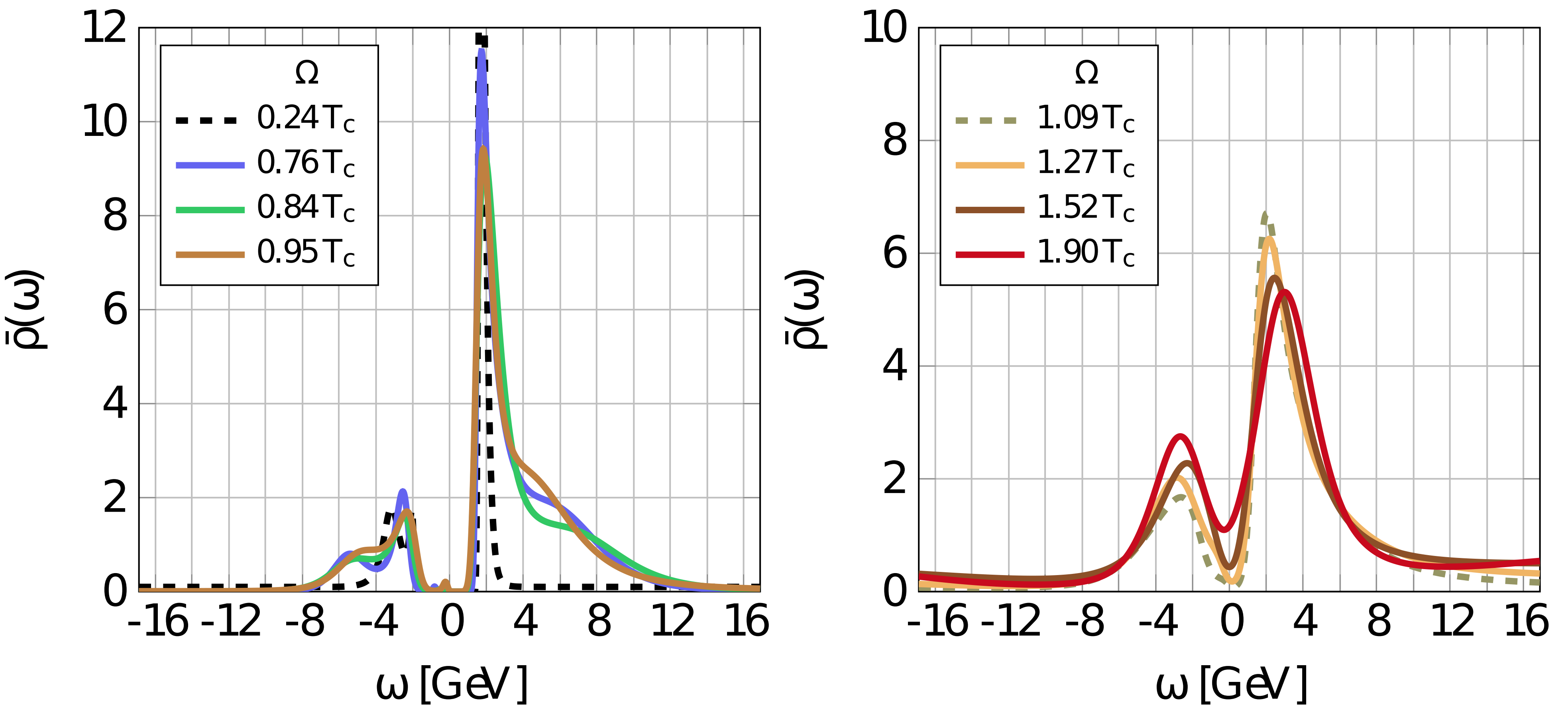
- $\Delta$




- groundstates below $T_c$
- degeneracy emerging above $T_c$

# Baryon spectral functions

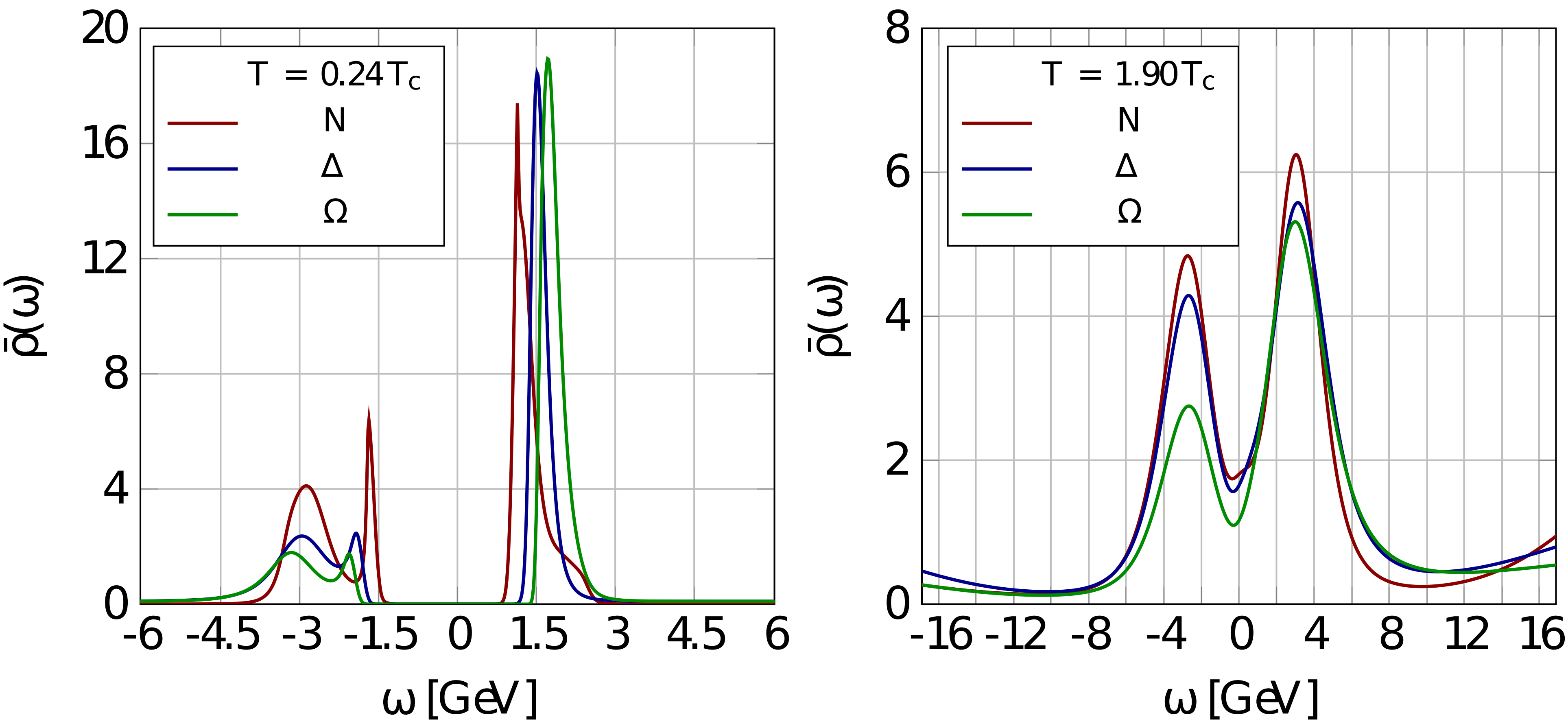
- $\Omega$




- groundstates below $T_c$
- degeneracy emerging above $T_c$, finite $m_s$

# Baryon spectral functions

- all channels: low and high temperature




- groundstates below $T_c$
- degeneracy emerging above $T_c$

# Baryon spectral functions

- results consistent with correlator analysis
- latter is on firmer ground, due to inversion uncertainties
- effect of heavier $s$ quark nevertheless visible

# Summary: hyperons in medium

in hadronic phase

- pos-parity groundstates mostly $T$ independent
- characteristic $T$ dep. in neg-parity groundstates
  reduction in mass, near degeneracy close to $T_c$

application

- heavy-ion phenomenology: in-medium HRG

in quark-gluon plasma

- pos/neg parity channels degenerate: parity doubling
- linked to deconfinement transition and chiral symmetry restoration
- effect of heavier $s$ quark noticeable