Non-zero temperature study of spin 1/2 charmed baryons using lattice gauge theory

Gert Aarts, **Chris Allton**, Naeem Anwar, **Ryan Bignell**, Timothy Burns
Benjamin Jäger and Jon-Ivar Skullerud

FASTSUM Collaboration

Overview

- Baryons in medium
- Parity in Baryonic sector
- FASTSUM approach
- Results
    - T=0
    - “Reconstructed” approach
    - “Model of Ground State” approach
    - Signal of parity doubling

Baryons in medium

Previous Work:

Lattice studies of baryons at finite temperature very limited, ***(all quenched)***

- screening masses De Tar and Kogut 1987
- with a small chemical potential QCD-TARO: Pushkinaet al 2005
- temporal correlators Datta et al 2013

Effective models, mostly at $T \sim 0$ and nuclear density ⇒ parity doubling models

De Tar & Kunihiro 89; Mukherjee, Schramm, Steinheimer & Dexheimer, Sasaki 2017

Our Work:

PRD 92 (2015) 014503 [arXiv:1502.03603]

JHEP 06 (2017) 034 [arXiv:1703.09246]

Phys.Rev. D99 (2019) no.7, 074503 [arXiv:1812.07393]

Eur.Phys.J.A 60 (2024) 3, 59 [arXiv: 2308.12207]

Parity in the Baryonic Spectrum

No parity doubling in (T=0) Nature:

+ve parity: $m_+ = m_N = 0.939$ GeV
-ve parity: $m_- = m_{N^*} = 1.535$ GeV

Question: What happens as T increases?

Motivation: Phenomenological interest:
X. Yao and B. Müller Phys. Rev. D 97 (2018) 074003, [arXiv:1801.02652]

Lattice:

Parity operation: $P\mathcal{O}(\tau,\vec{x})P^{-1} = \gamma_4\mathcal{O}(\tau,-\vec{x})$

Construct correlation functions: $G_\pm(\tau) = \int \mathrm{d}\mathbf{x}\,\langle \mathrm{tr}\, O(\mathbf{x},\tau)P_\pm\overline{O}(\mathbf{0},0)\rangle\,, \qquad P_\pm = \frac{1}{2}(\mathbb{1}\pm\gamma_4)$

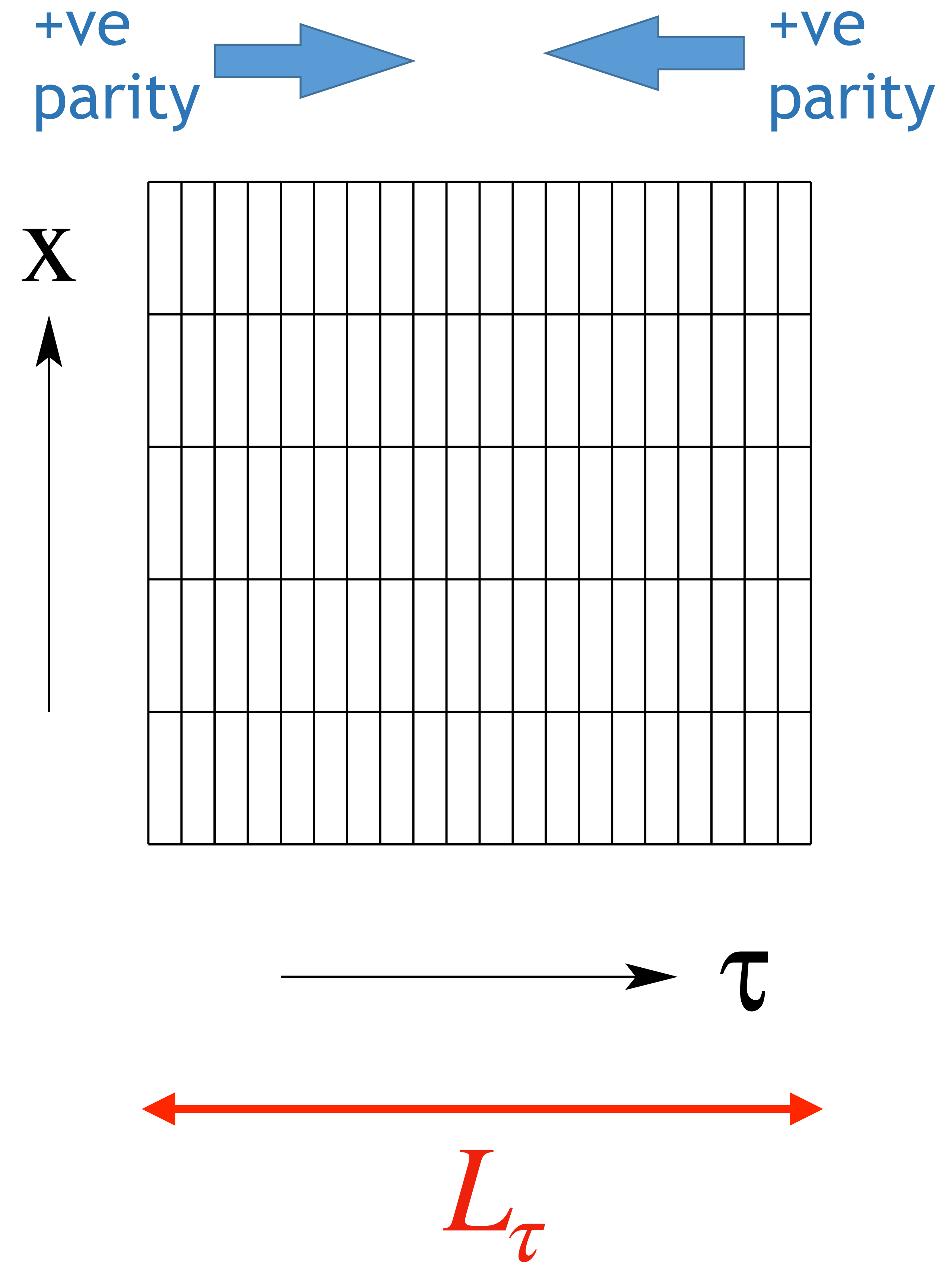
Symmetries

Charge conjugation (at zero density): $G_{\pm}(\tau) = -G_{\mp}(1/T - \tau)$ $(\star)$

i.e. positive/negative parity states propagate forward/backward in τ

Eg. for a single state: $G_{+}(\tau) = A_{+}e^{-m_{+}\tau} + A_{-}e^{-m_{-}(1/T-\tau)}$

(Contrasts with meson sector)



$1/T = N_\tau a_\tau \equiv L_\tau$

Chiral symmetry:

Constrains spinor structure $\rightarrow G_{+}(\tau) = -G_{-}(\tau)$

ie. parity doubling: **$m_{+} = m_{-}$**

Together with $(\star)$ $\longrightarrow G_{+}(\tau) = G_{+}(1/T - \tau)$

i.e. forward/back symmetry

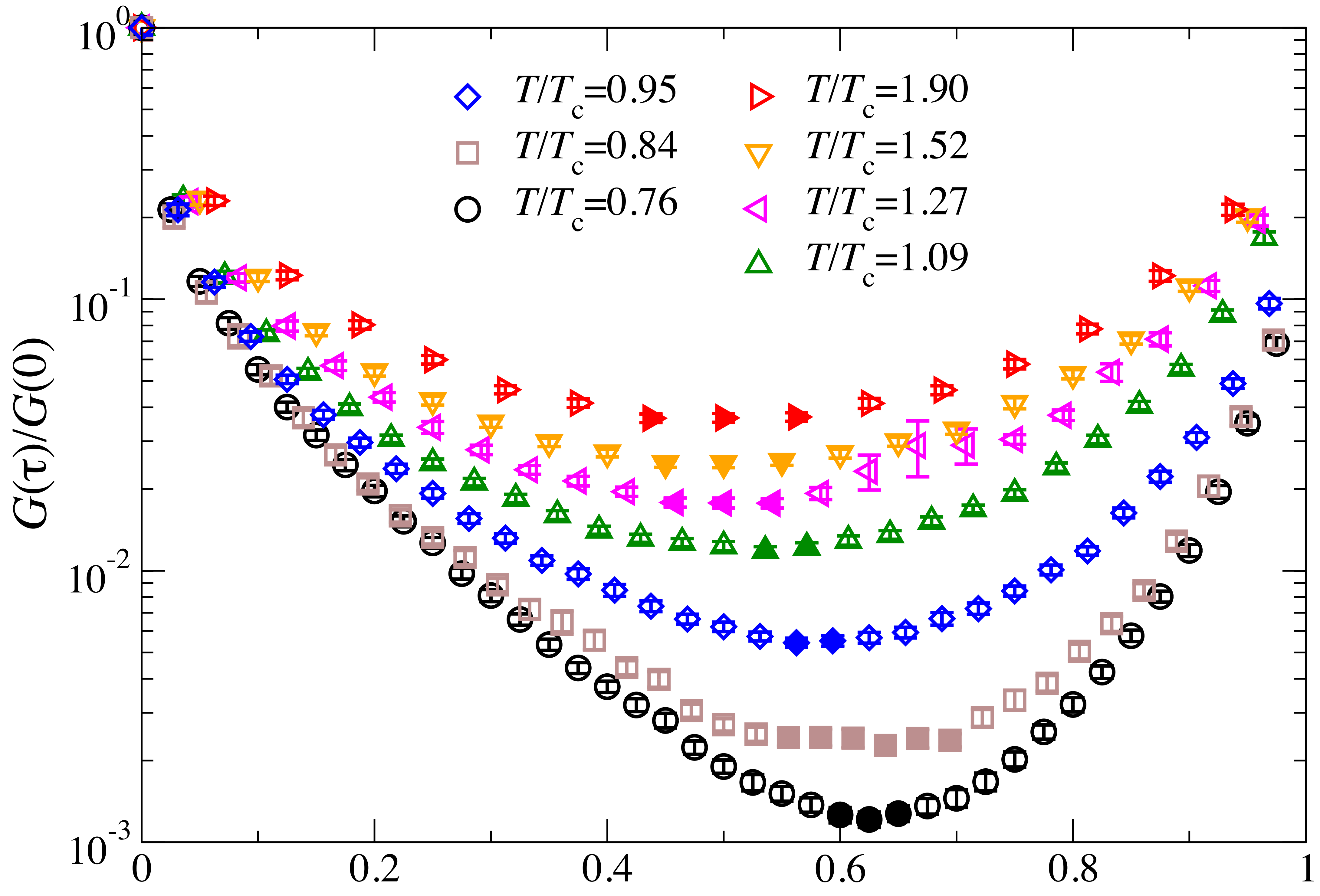
Question: Does this happen in Nature in deconfined phase?

- assuming $m_q \sim 0$
- what about the charm-quark sector

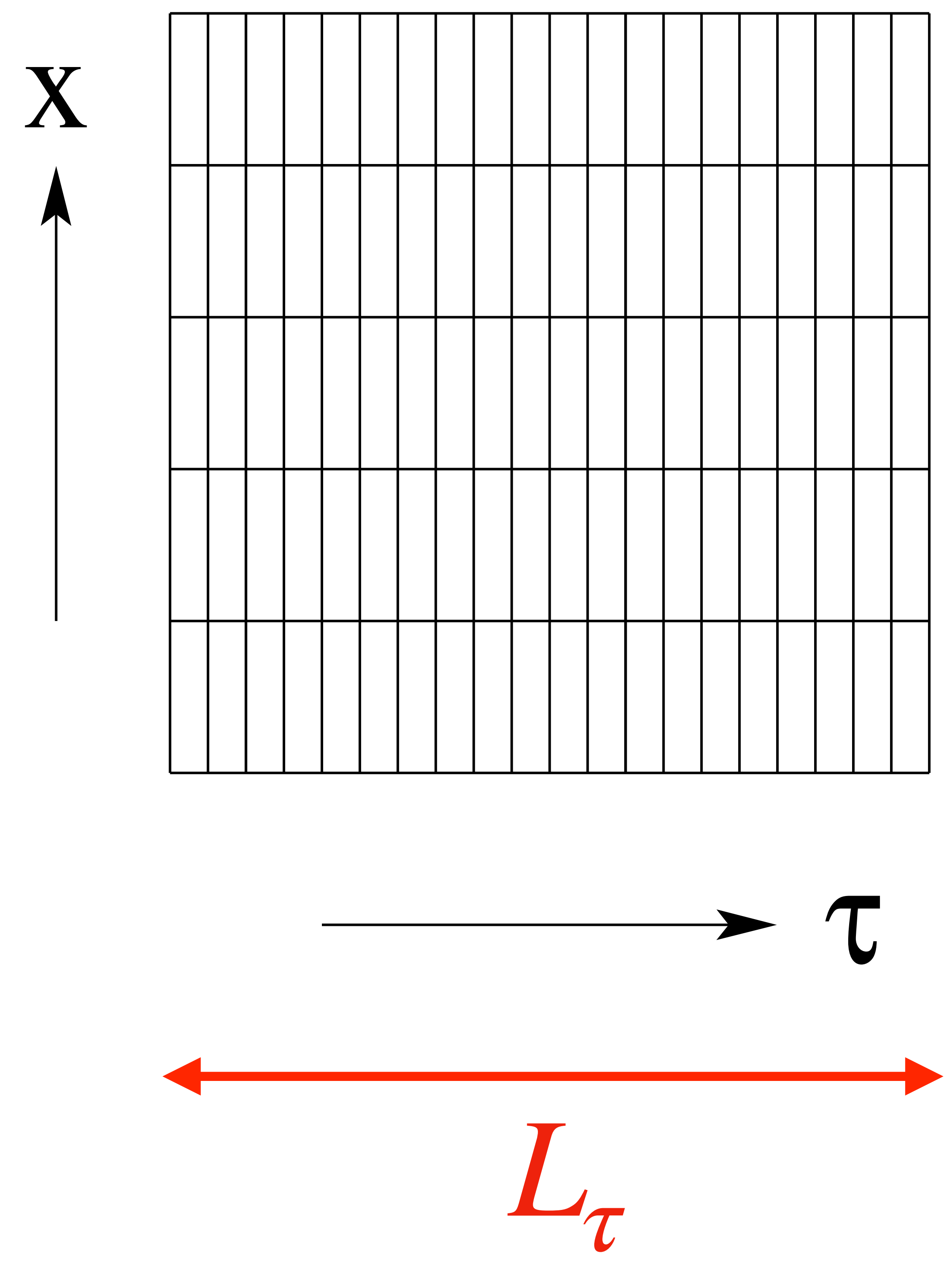
Lattice Nucleon Correlator: G_+

+ve parity

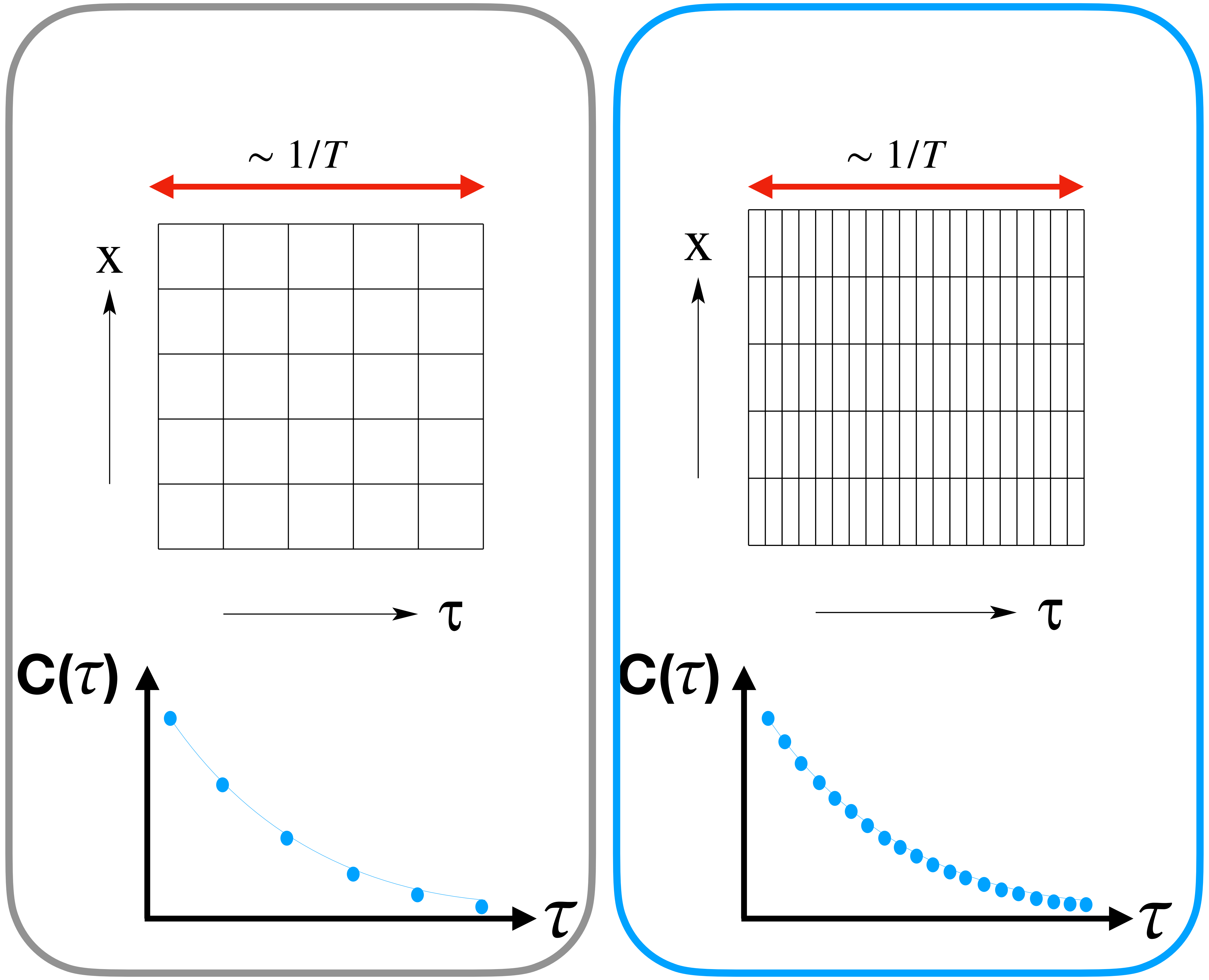
-ve parity



$$\tau T = \frac{\tau}{a_\tau N_\tau} \equiv \frac{\tau}{L_\tau}$$



FASTSUM Approach:
Anisotropic Lattice



$$T = \frac{1}{L_\tau} = \frac{1}{a_\tau N_\tau}$$

Spectral Quantities:
- Bottomonium
- Charmed mesons
- Heavy Baryons
- Light Hadrons

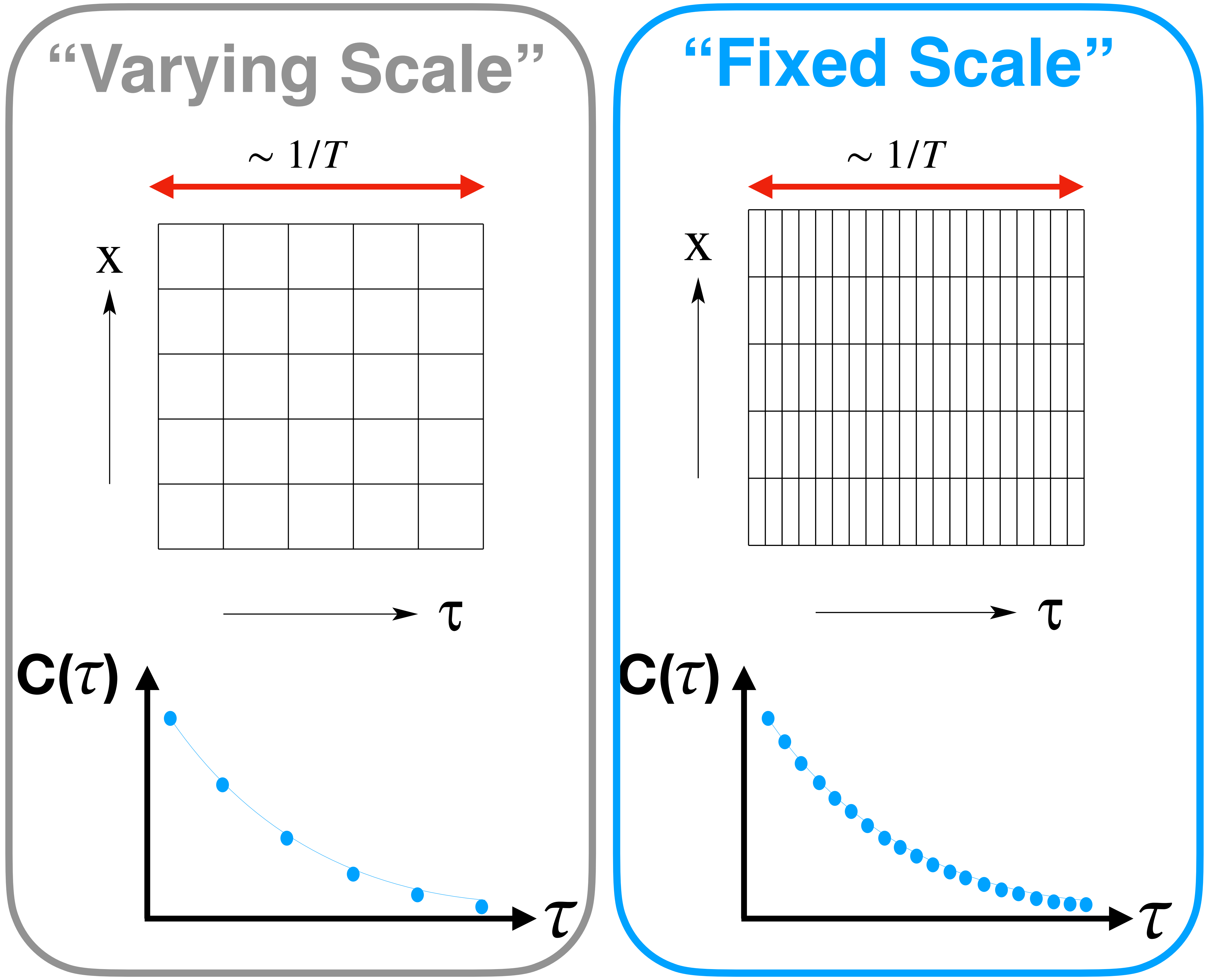
Interquark potential

Conductivity

…

FASTSUM Approach:

Anisotropic Lattice



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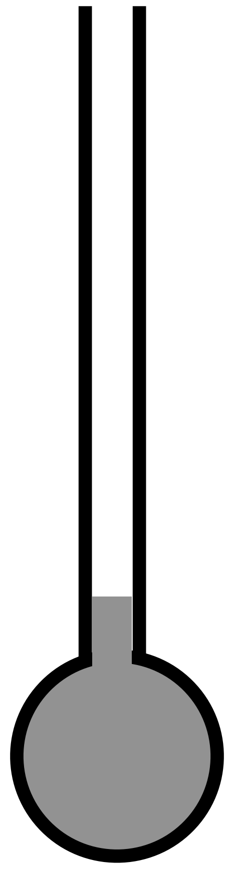

Going hotter…

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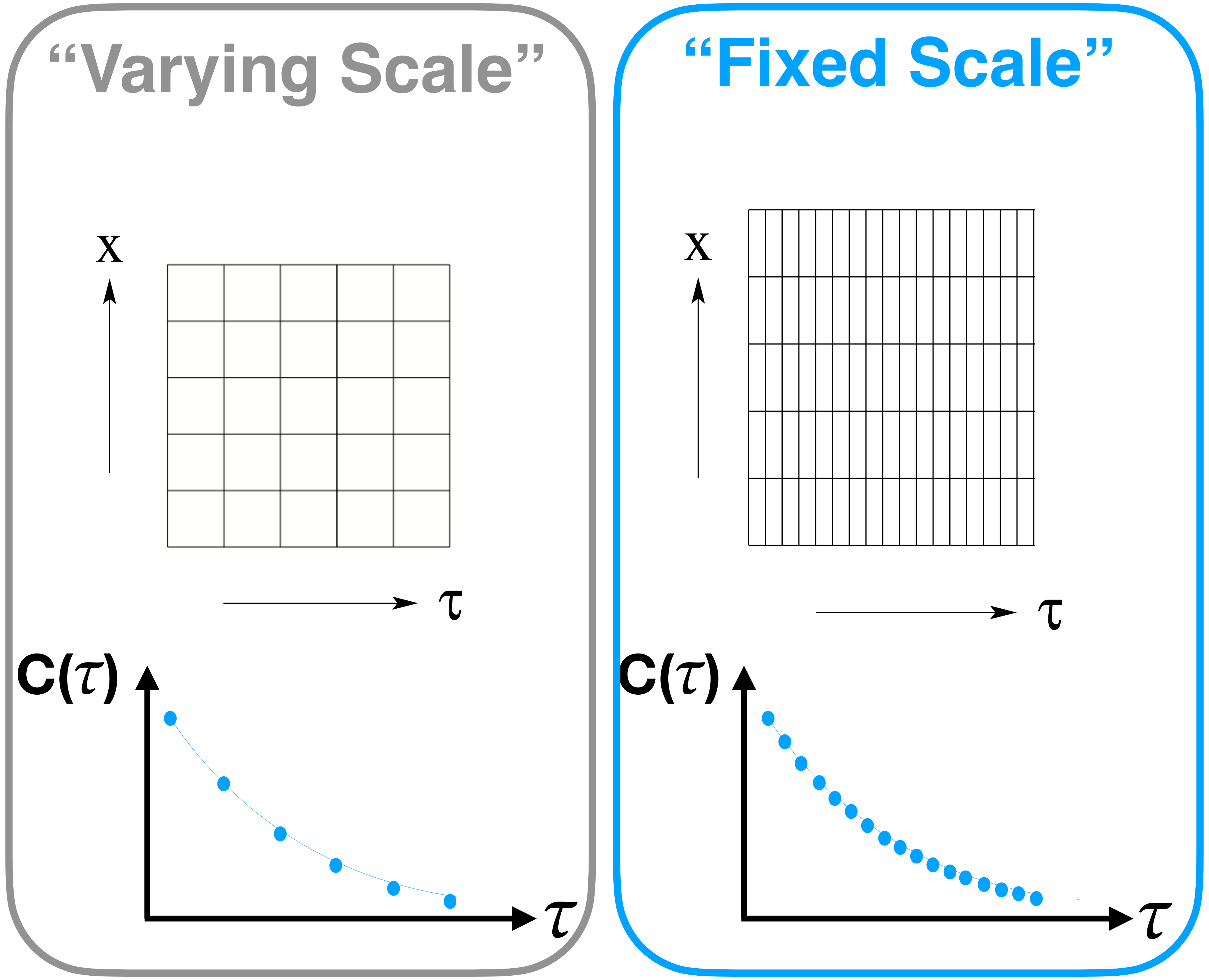

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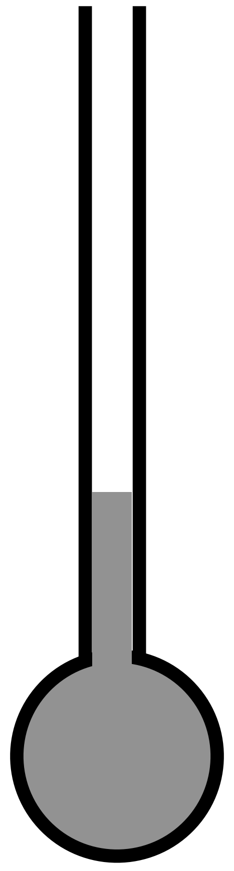

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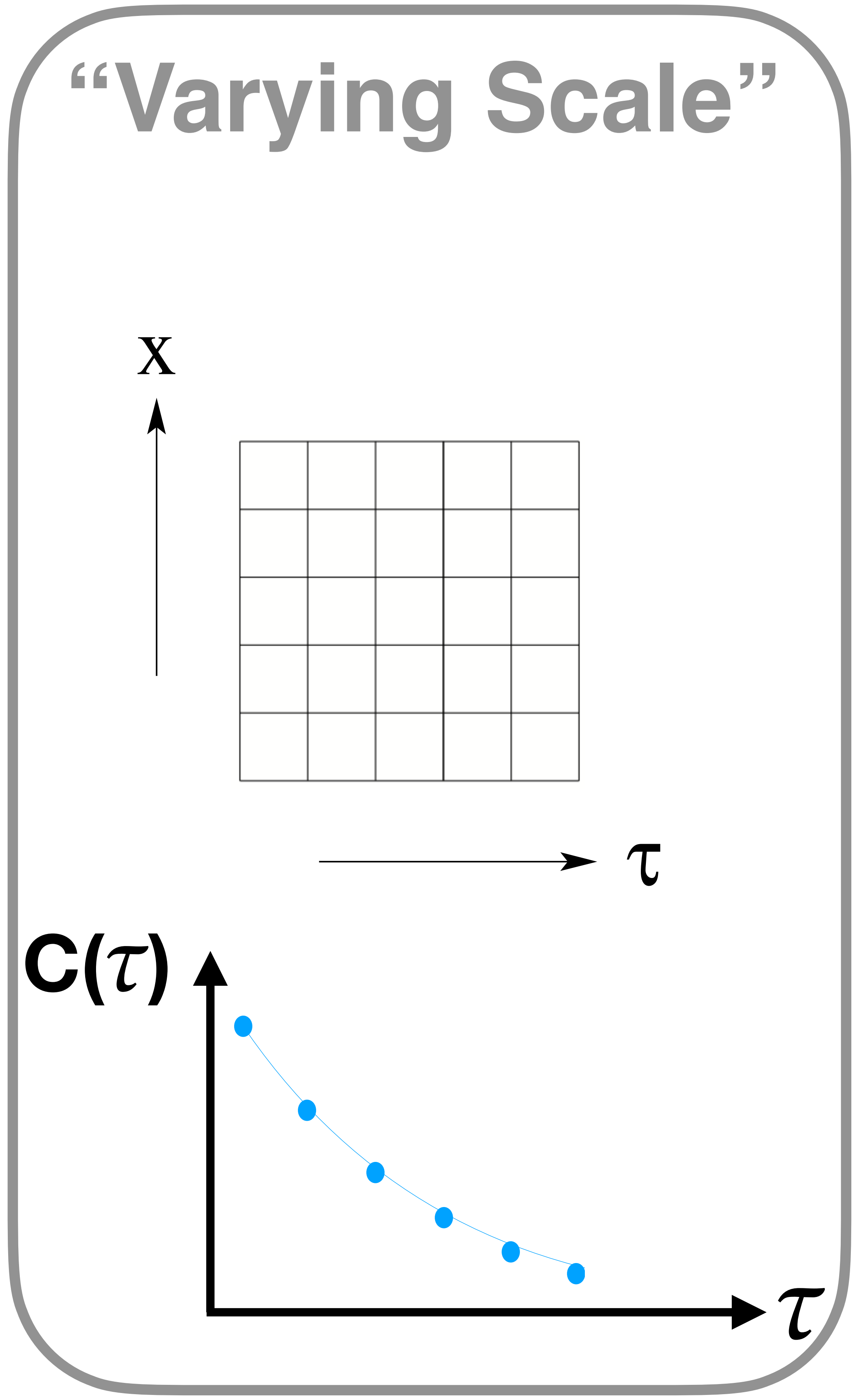

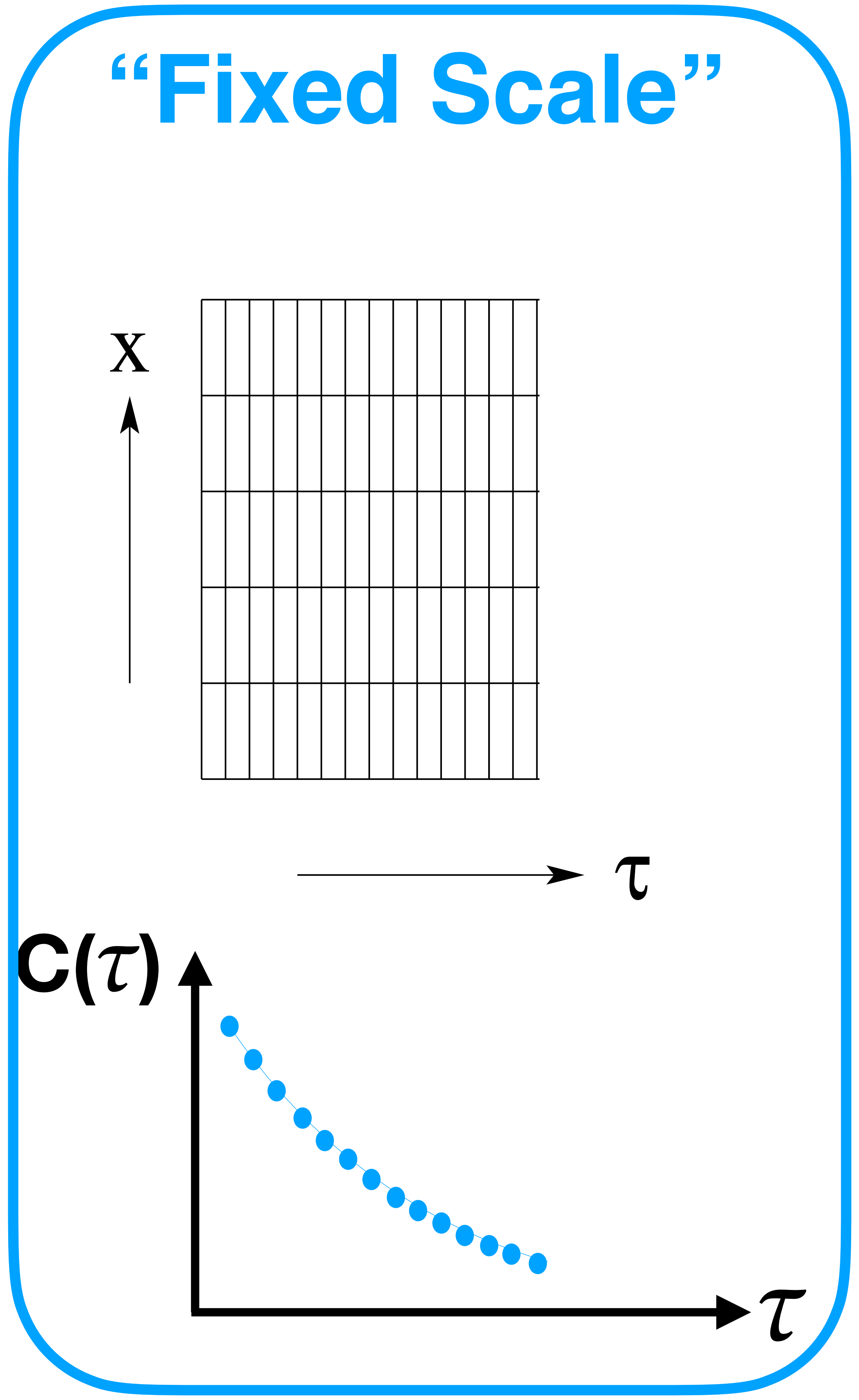

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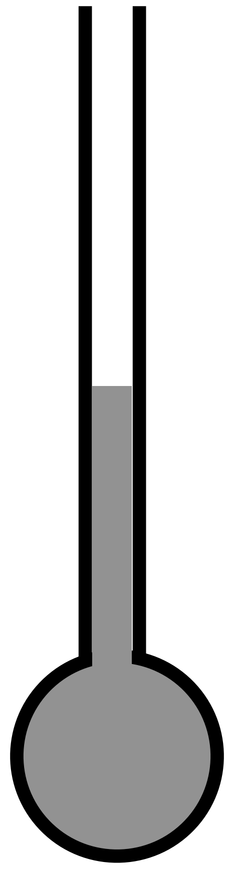

Going hotter…

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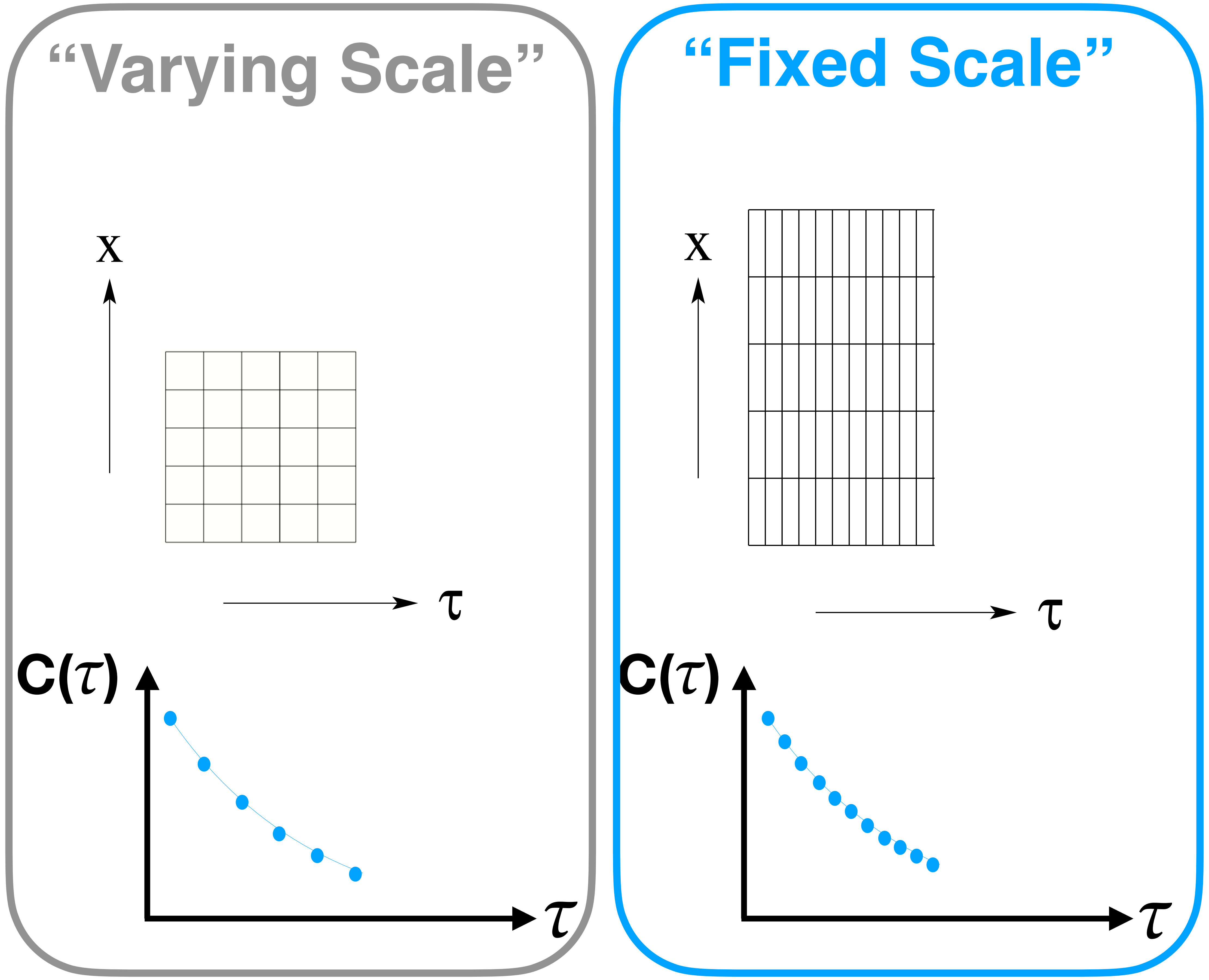
Anisotropic Lattice



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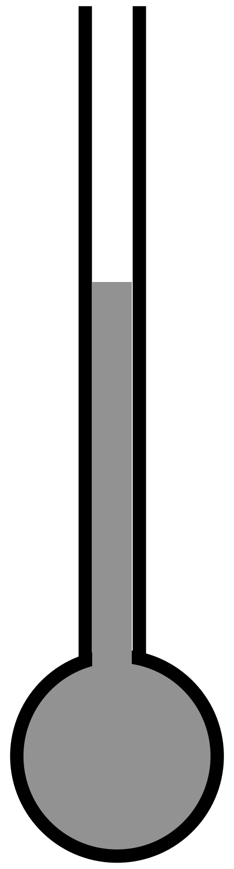

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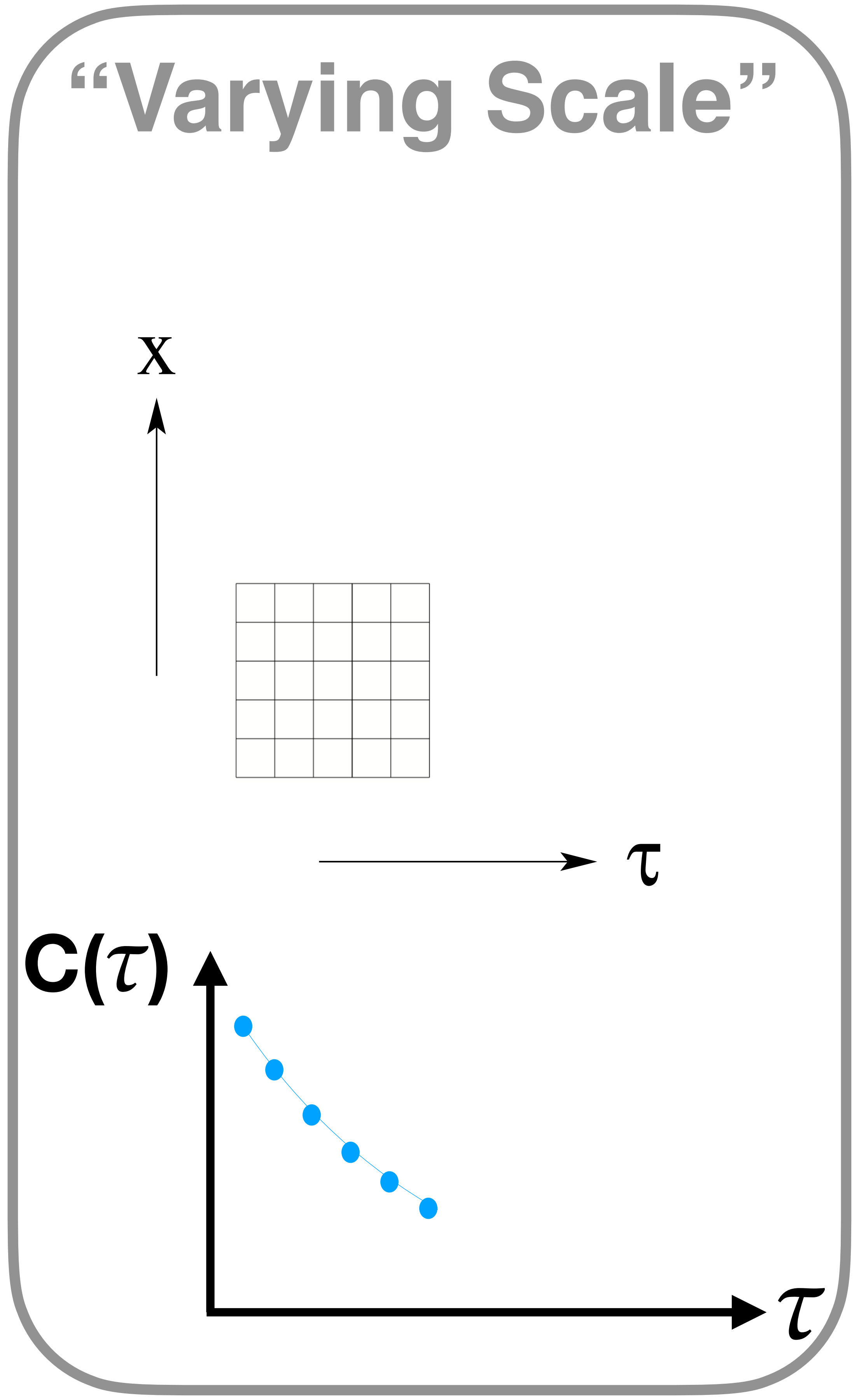

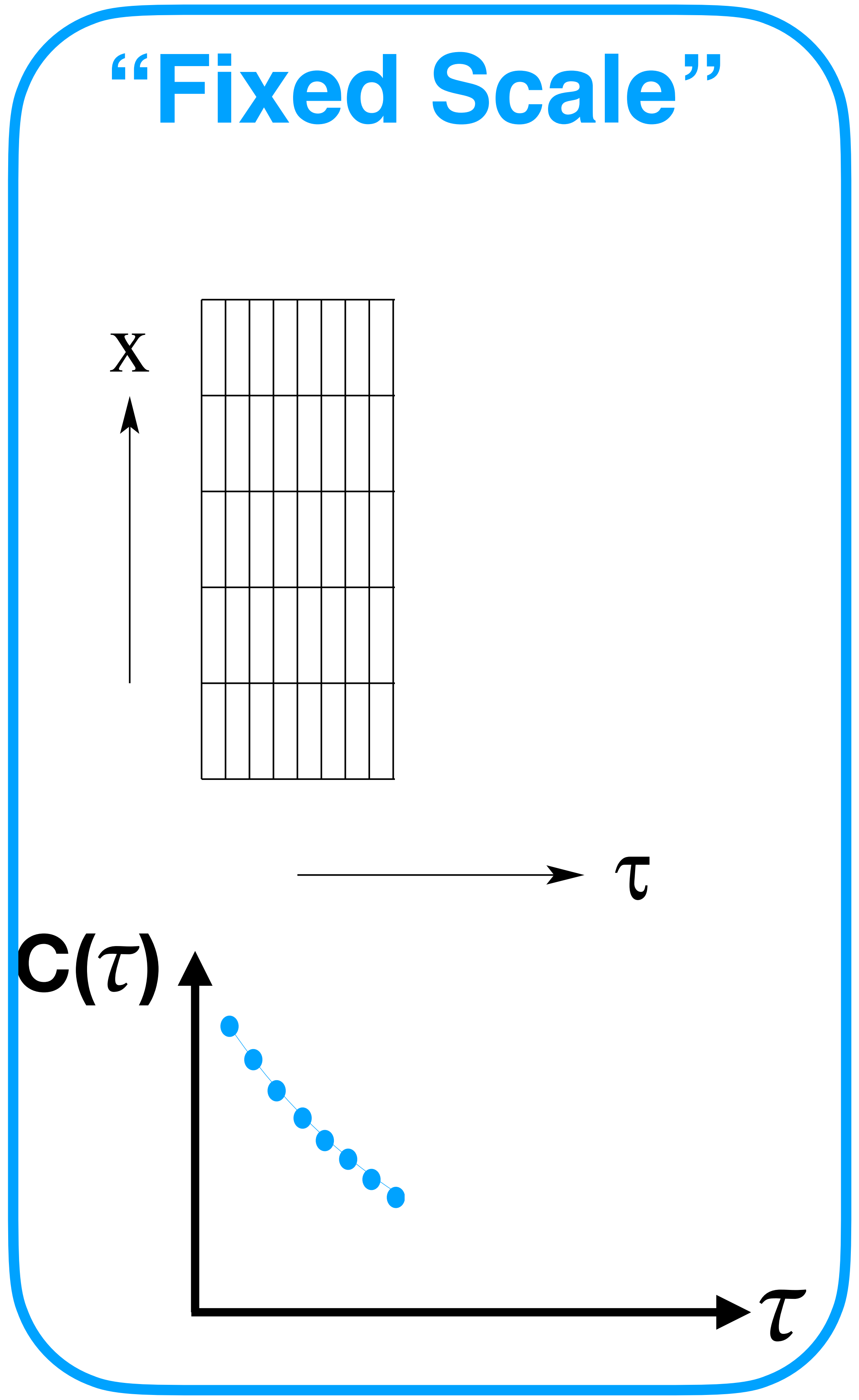

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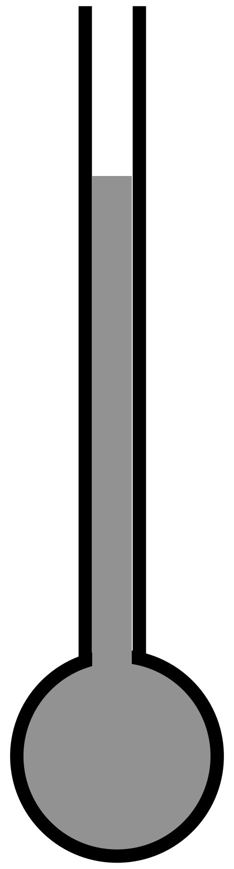
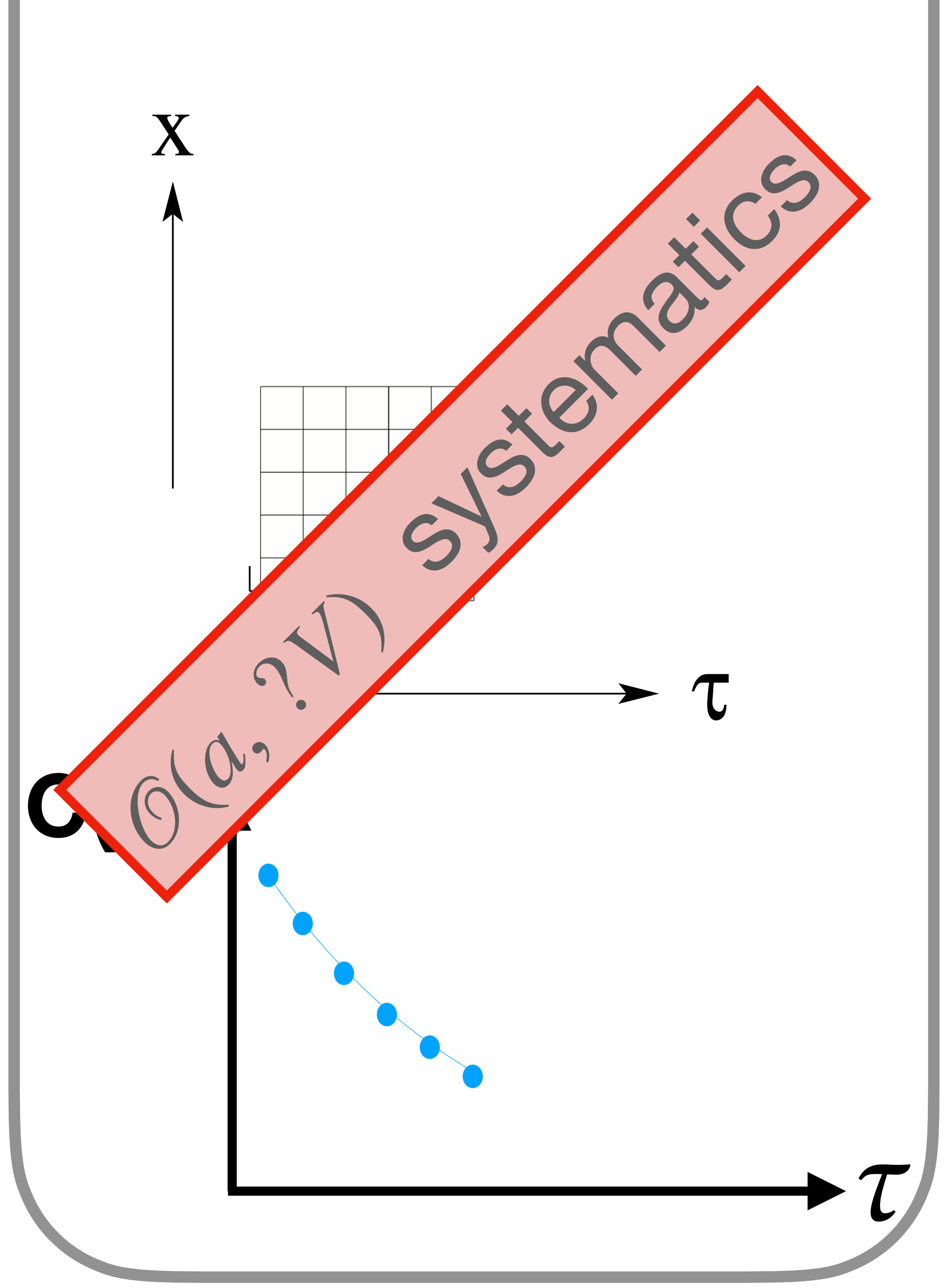


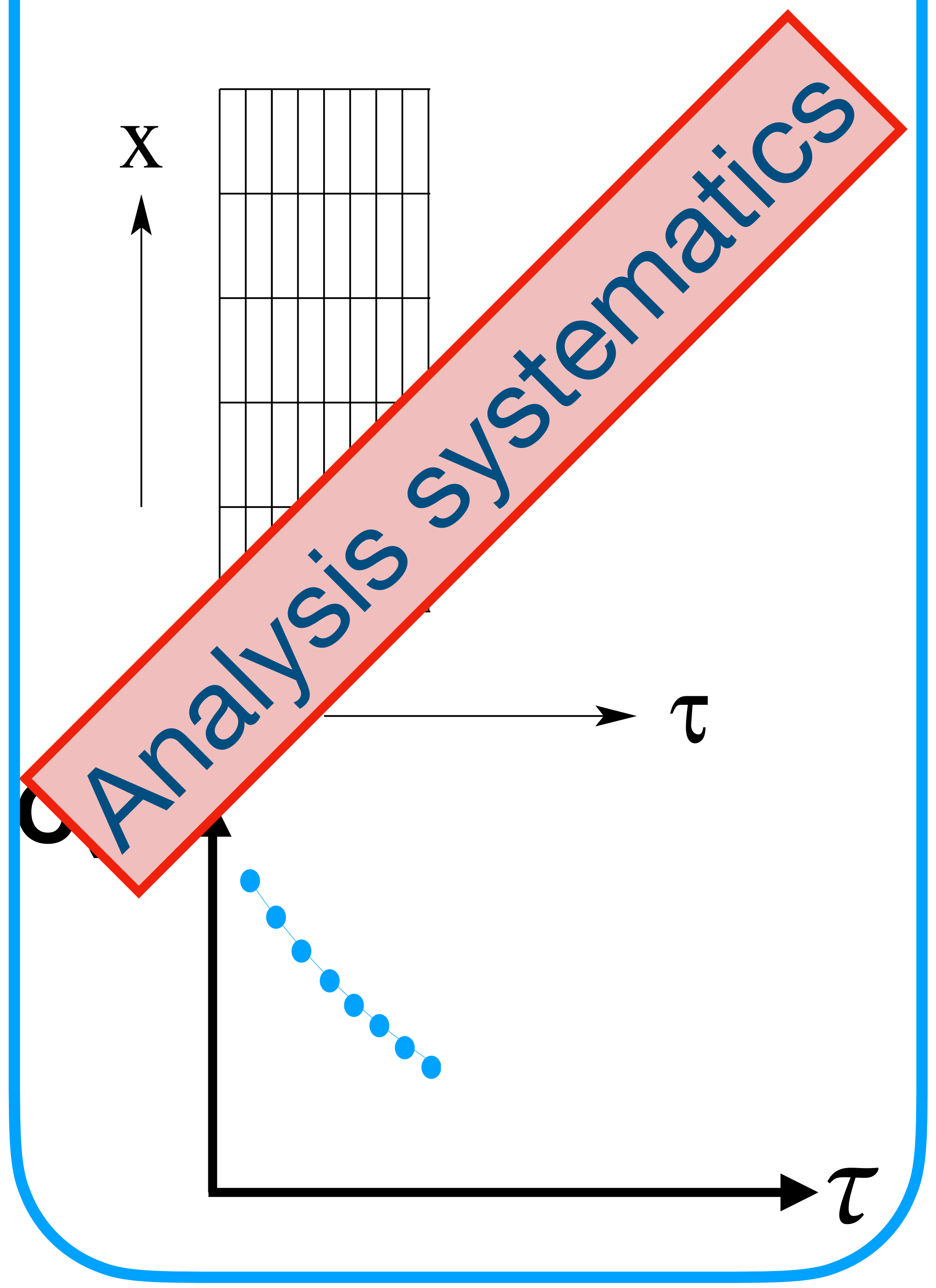
Going hotter…

FASTSUM Approach:
Anisotropic Lattice

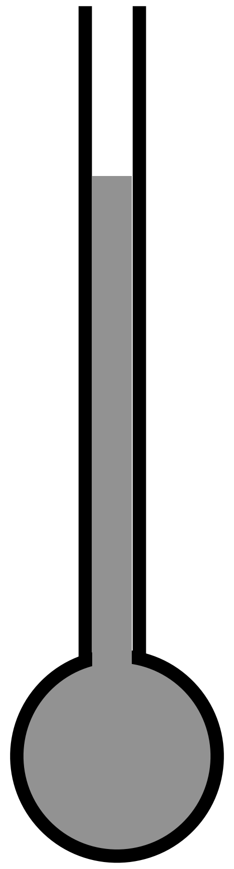
"Varying Scale"



"Fixed Scale"



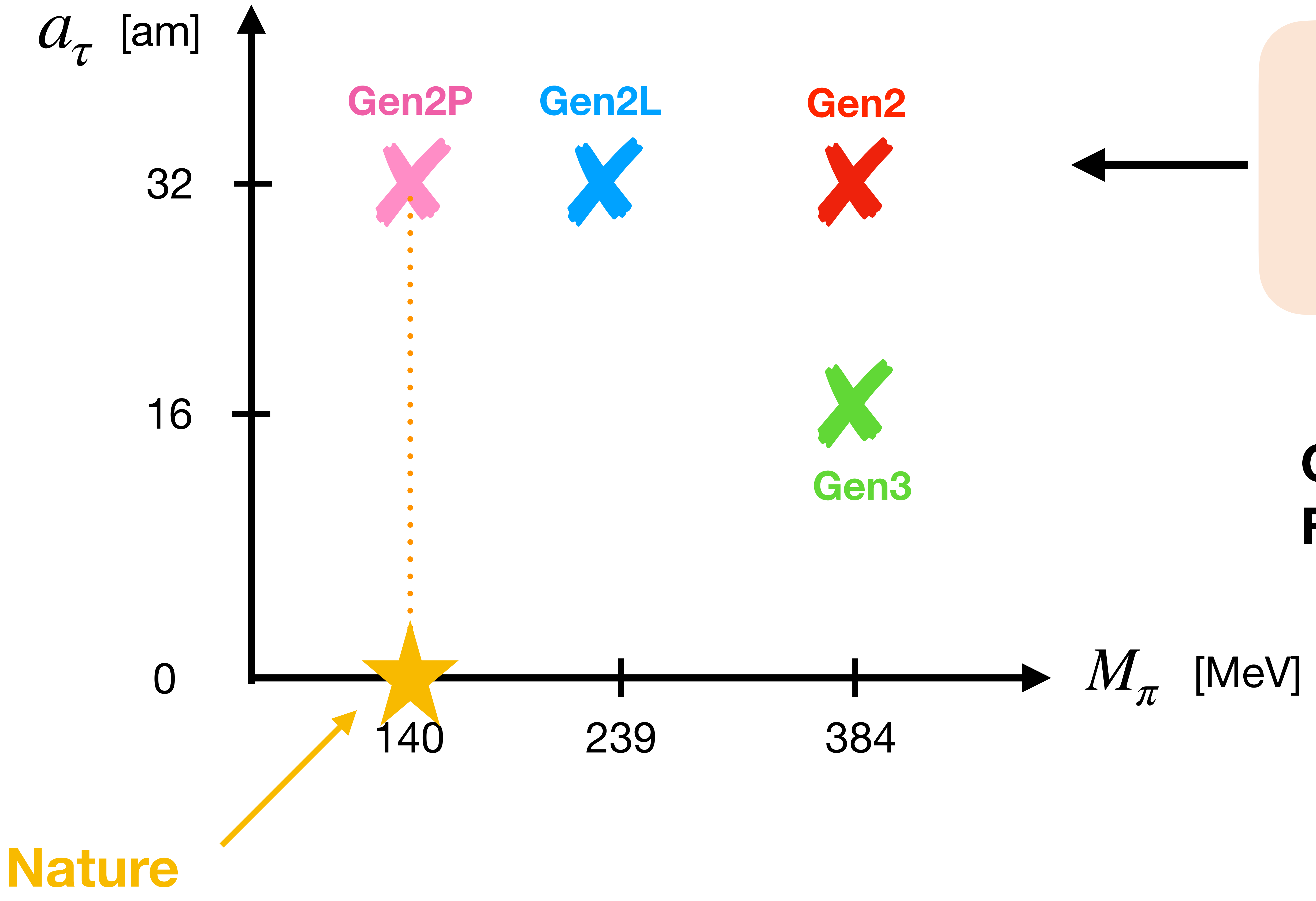
$$T = \frac{1}{L_\tau} = \frac{1}{a_\tau N_\tau}$$



Going hotter…

FASTSUM Approach:
Lattice Parameters

(2+1) flavour
a_s ~ 0.112 fm



Parameters from **HadSpec Collaboration**
R. G. Edwards, B. Joo and H. W. Lin,
Phys. Rev. D 78 (2008) 054501

Gauge Action: Symanzik-improved anisotropic
Fermion Action: Wilson-clover, tree-level tadpole with stout-smeared links

FASTSUM Approach:
Lattice Parameters

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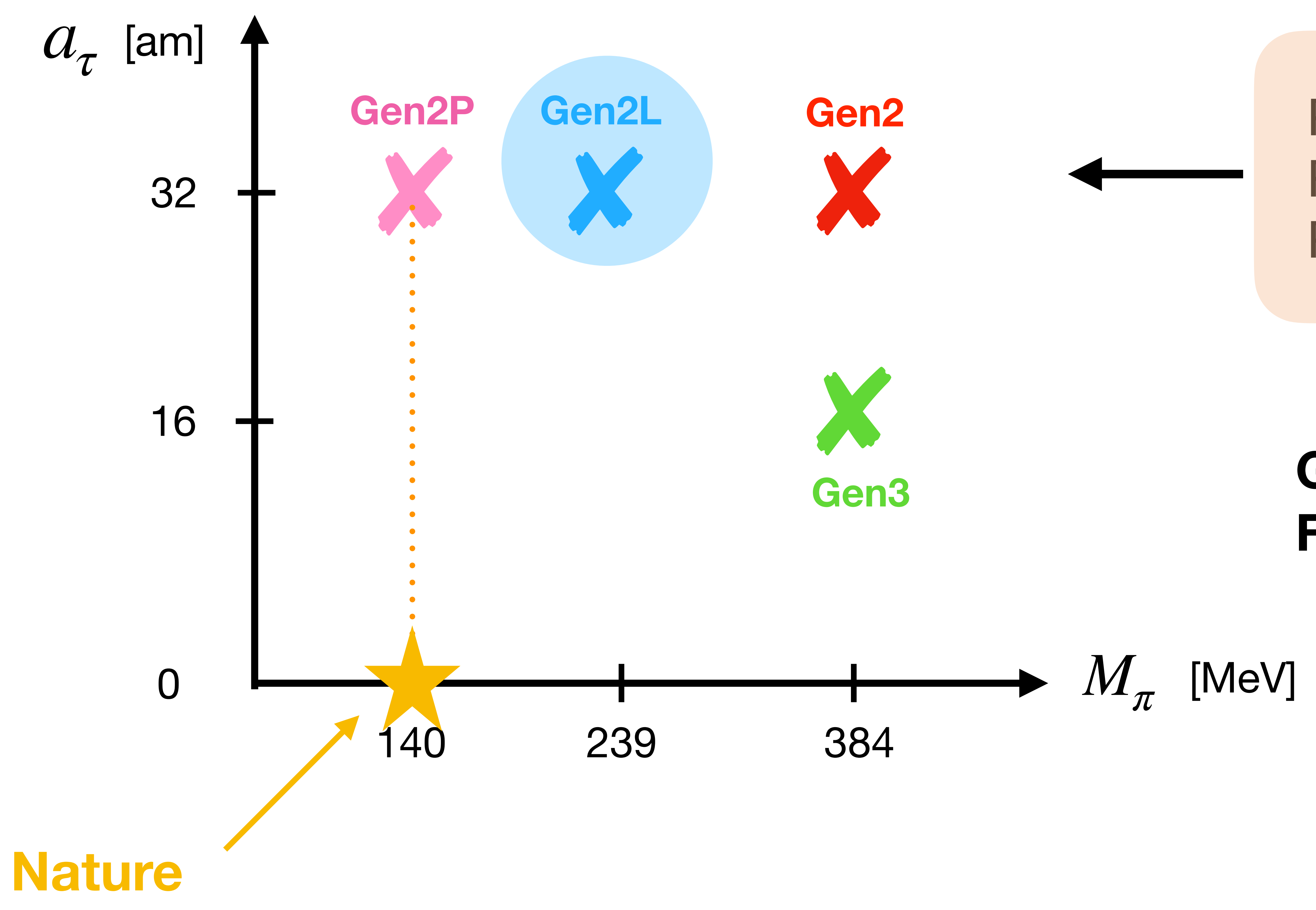

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Generation 2L

a_τ [am]	a_τ^{-1} [GeV]	$\xi = a_s/a_\tau$	a_s [fm]	m_π [MeV]	$T_{\rm pc}^{\bar\psi\psi}$ [MeV]
32.46(7)	6.079(13)	3.453(6)	0.1121(3)	239(1)	167(2)(1)

Generation 2L, $32^3 \times N_\tau$										
N_τ	128	64	56	48	40	36	32	28	24	20
T [MeV]	47	95	109	127	152	169	190	217	253	304
$N_{\rm cfg}$	1024	1041	1042	1123	1102	1119	1090	1031	1016	1030

↑

T_c ~ 167 MeV

a^{-1} = 6.079(13) GeV from HadSpec calculation of **Ω** baryon,

D. J. Wilson, et al., Phys. Rev. Lett. 123 (2019)

Results

J = 1/2 singly charmed baryons:

$$SU(3)\ \ \mathbf{\overline{3}} : \quad \Lambda_c\,(udc),\ \ \Xi_c\,(usc)$$

$$SU(3)\ \ \mathbf{6} : \quad \Sigma_c\,(udc),\ \ \Xi_c'\,(usc),\ \ \Omega_c\,(ssc)$$

J = 1/2 doubly charmed baryons:

$$SU(3)\ \times U(1)_{charm}\ \mathbf{20}_M : \ \Xi_{cc}\,(ccu),\ \ \Omega_{cc}\,(ccs)$$

Baryon correlation functions:

$$G^{\alpha\alpha'} = \langle \mathcal{O}^{\alpha}(x)\overline{\mathcal{O}}^{\alpha'}(0)\rangle$$ (Gaussian Smeared)

Results

Two fitting approaches, fits weighted according to

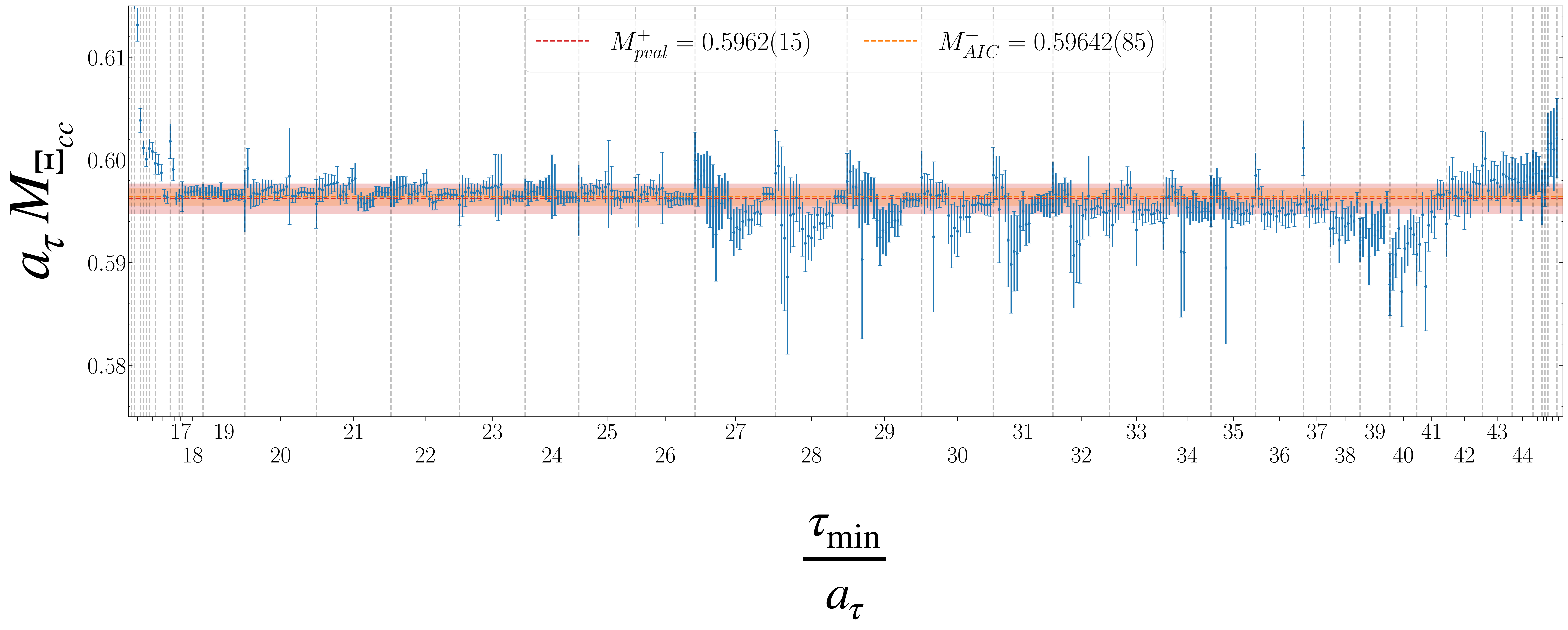
- *p*-value:

$$\overline{w}^{\mathrm{p}} = \frac{p_f \,/\, (\delta M_f)^2}{\sum_{f'=1}^{N} p_{f'} \,/\, (\delta M_{f'})^2}$$

- “Akaike" information criteria:

$$\overline{w}^{\mathrm{A}} = \exp\Big(-\frac{1}{2}\chi^2 - N_{\text{fit}} - N_{\text{cut}}\Big)$$

Results: T=0 +ve parity Ξ_{cc}



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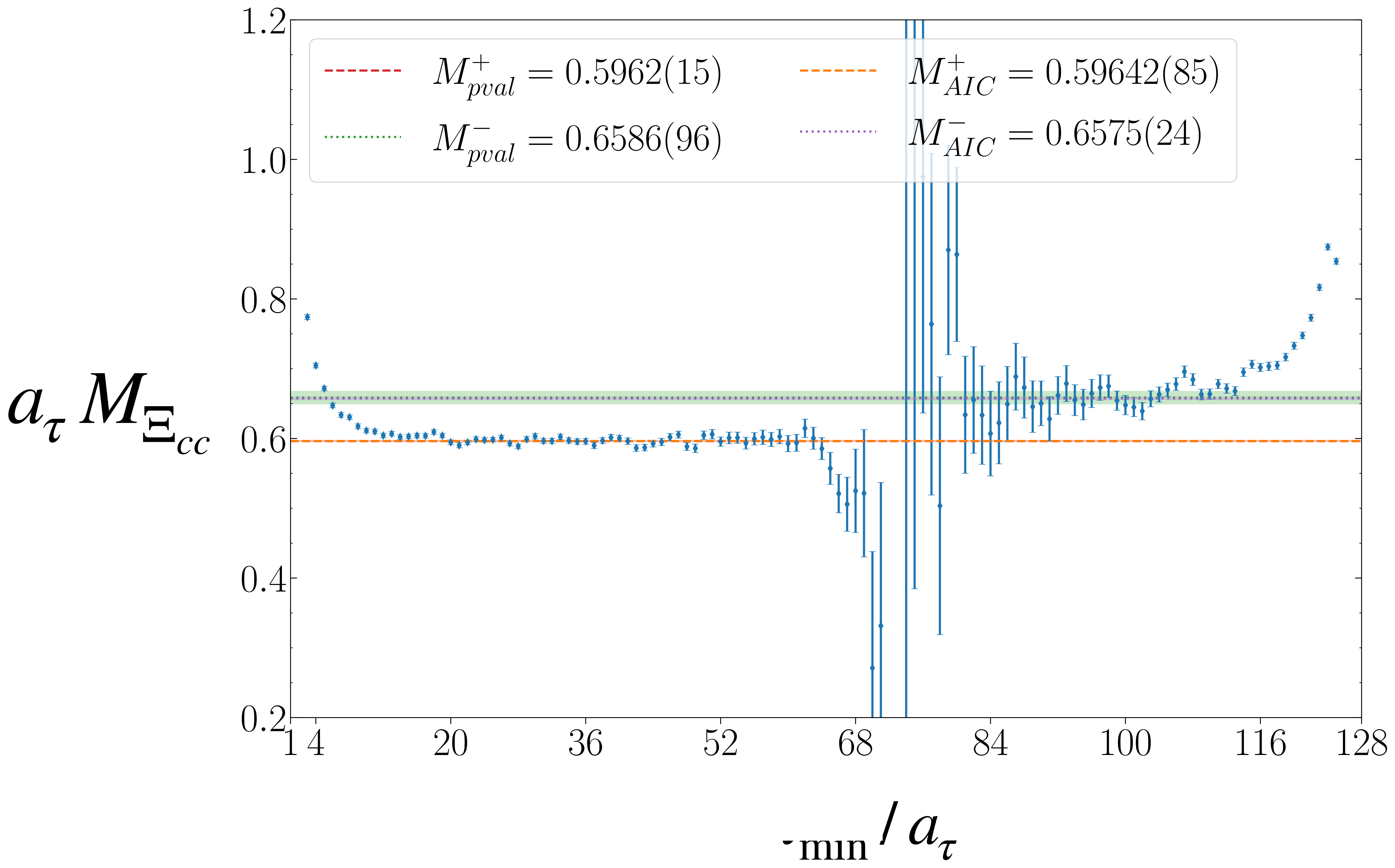
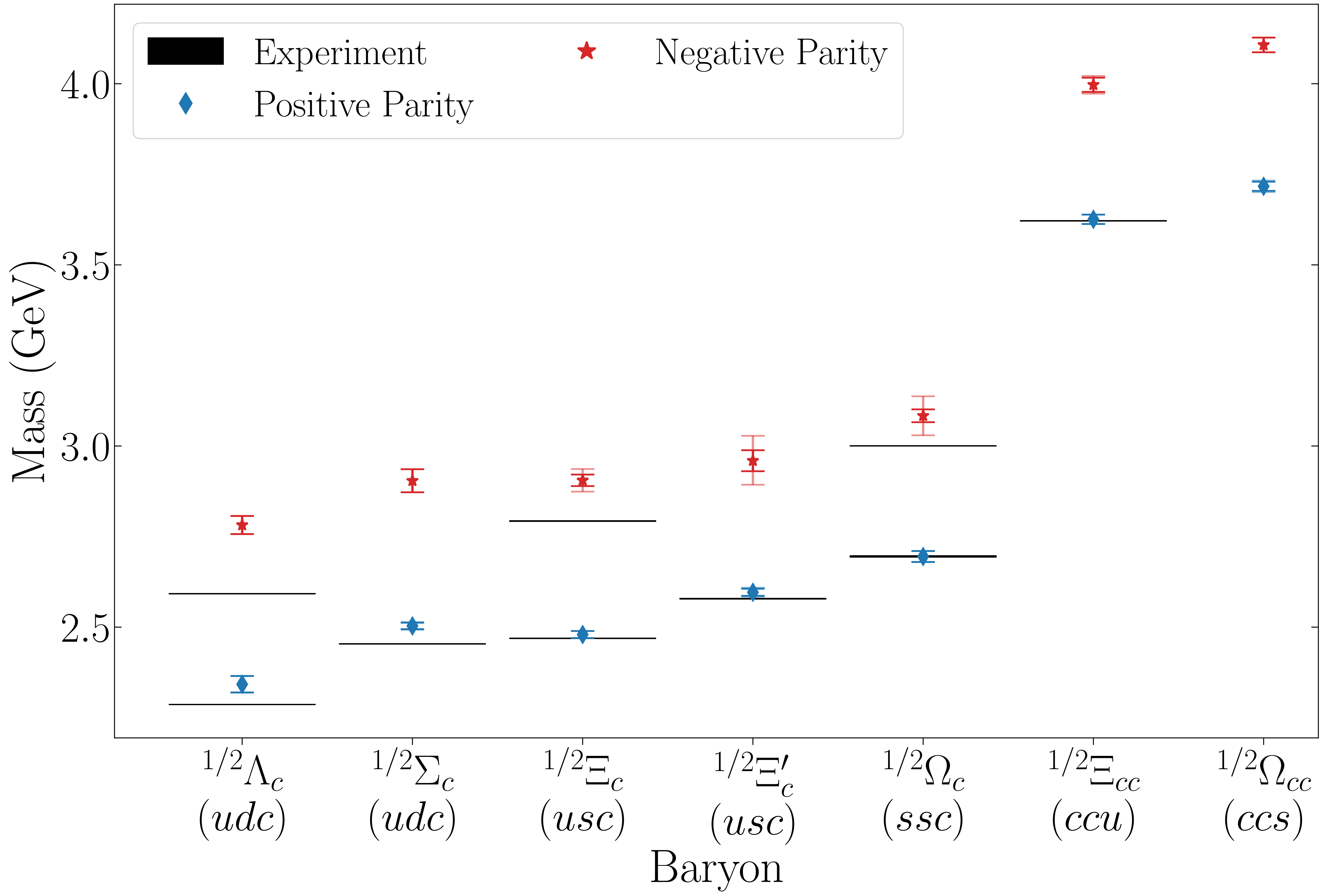


T=0 Spectrum Results



Results — "Reconstructed" Correlators

$$G(r;T) = \int_{-\infty}^{\infty} \frac{d\omega}{2\pi} K_F(\tau,\omega;T)\rho(\omega)$$ where the *fermonic* kernel is: $$K_F(\tau,\omega;T) = \frac{e^{-\omega T}}{1+e^{-\omega/T}}$$

Following: H. T. Ding et al, Phys. Rev. D 86 (2012) 014509, [arXiv:1204.4945]

we write $$1 + e^{-\omega m N_\tau} = (1+e^{-\omega N_\tau}) \sum_{n=0}^{m-1} (-1)^n e^{-n\omega N_\tau}$$ where $N_0 = m\, N_\tau$ and m is odd

$$K_F(\tau,\omega;1/N_\tau) = \frac{e^{-\omega\tau}}{1+e^{-\omega N_\tau}} = \sum_{n=0}^{m-1} (-1)^n \frac{e^{-\omega(\tau+nN_\tau)}}{1+e^{-\omega m N_\tau}} = \sum_{n=0}^{m-1} (-1)^n K_F(\tau+nN_\tau,\omega;1/(mN_\tau))$$

Suppose $\rho(\omega)$ was indept of T : $$G_{\text{rec}}(\tau;\,1/N_\tau;\,1/N_0) = \sum_{n=0}^{m-1} (-1)^n G(\tau+nN_\tau;\,1/N_0)$$

Results — "Model" Correlators

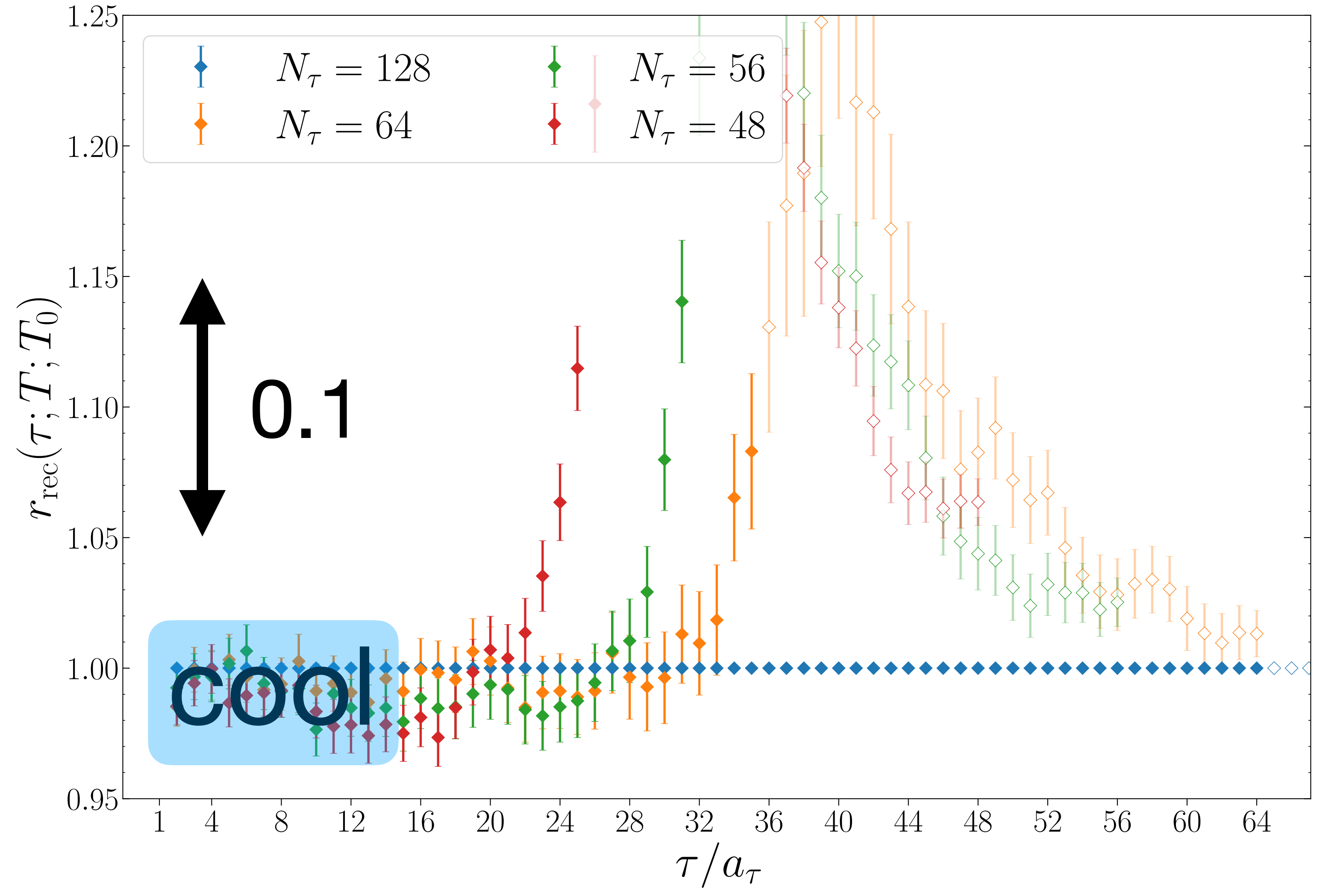
Suppose M_{gnd} was indept of T and dominated by ground state:

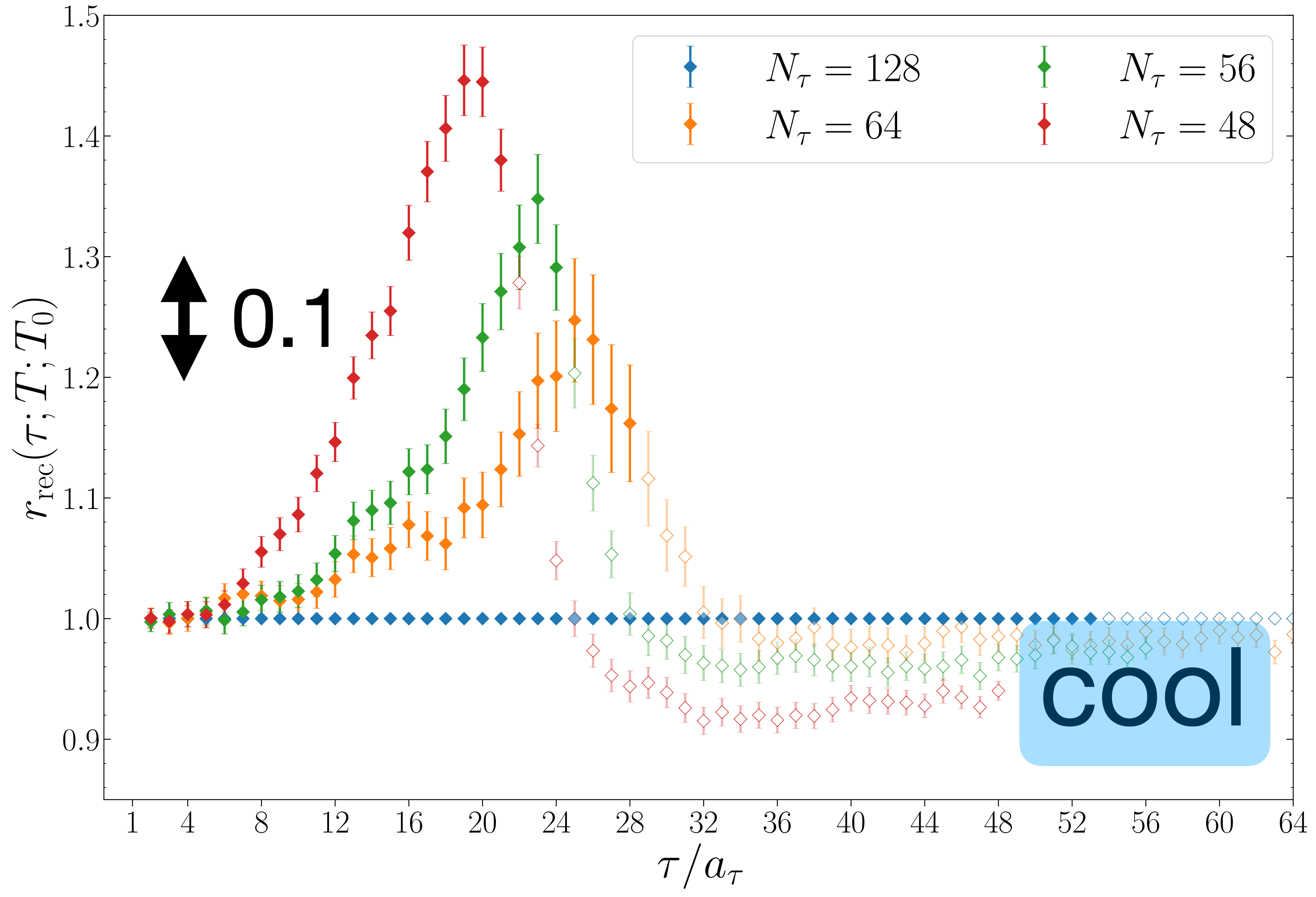
$$G_{\text{model}}(\tau;\, T, T_0) = A_+\, K_F(\tau, M_0^+) + A_-\, K_F(\tau,\, -M_0^-)$$

$$= \frac{A_+ e^{-M_0^+ \tau}}{1 + e^{-M_0^+/T}} + \frac{A_- e^{M_0^- \tau}}{1 + e^{M_0^-/T}}$$

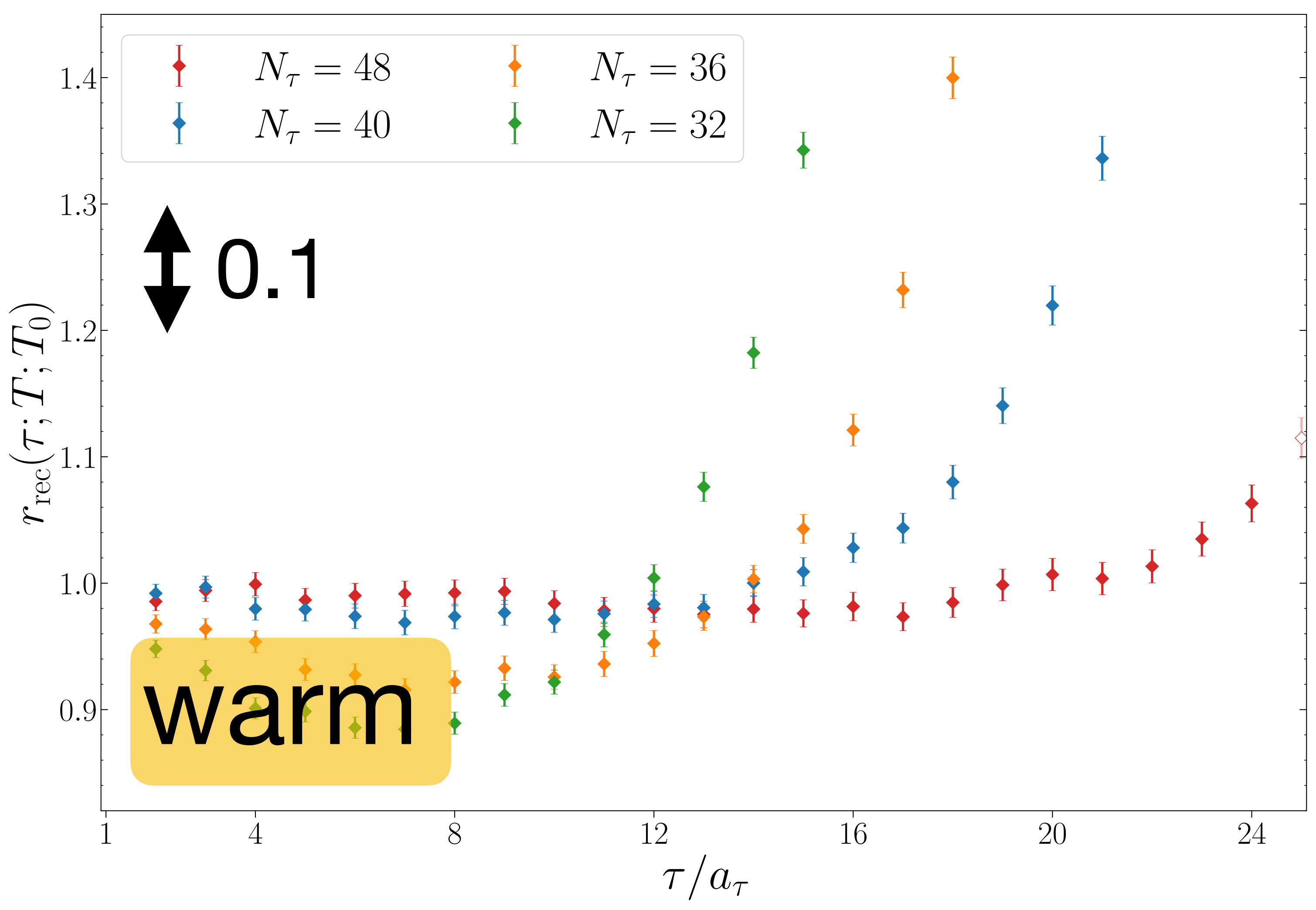
Results - “Reconstructed” ratio: G_{rec}/G $\Sigma_c\,(udc)$

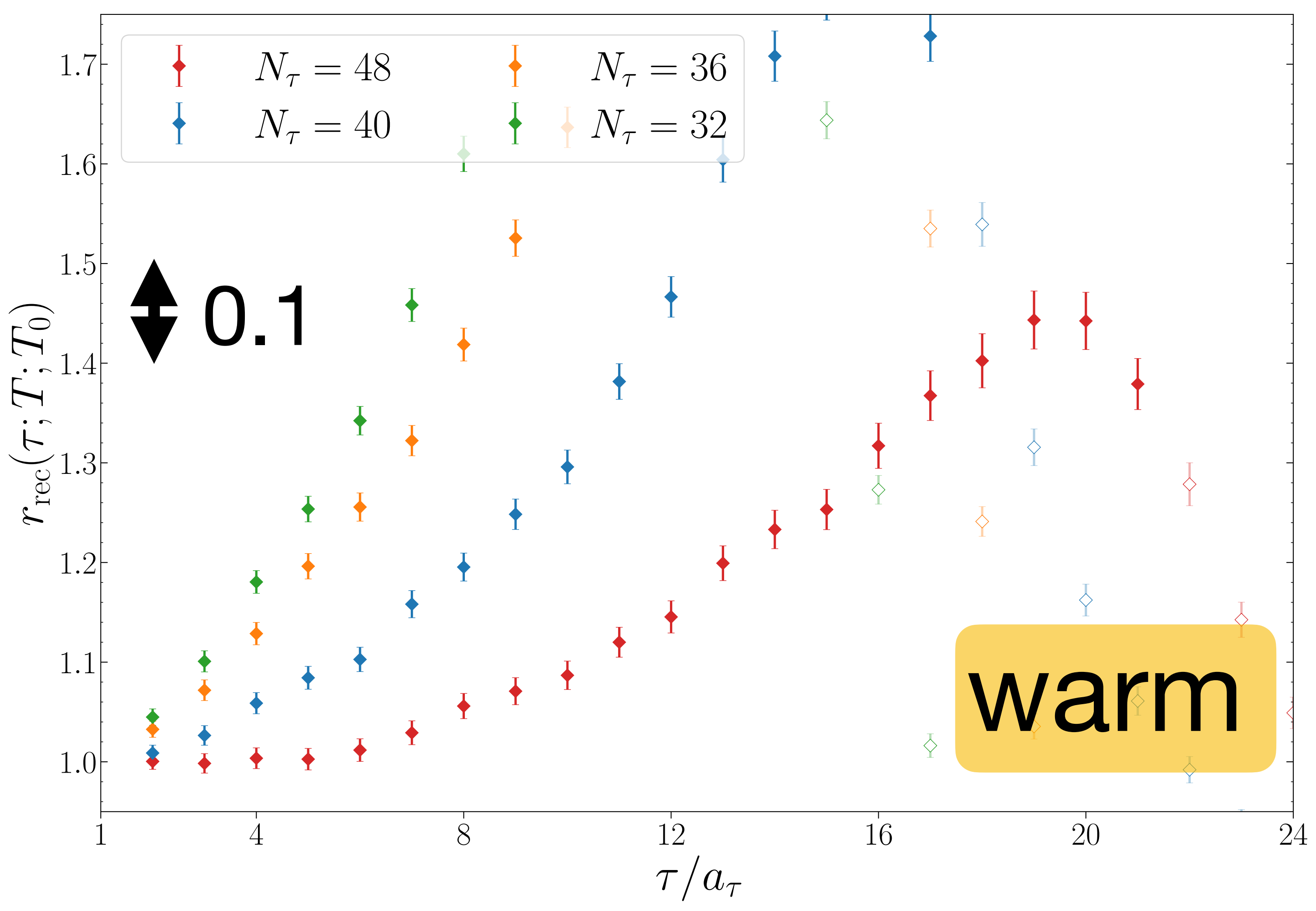
+ve parity



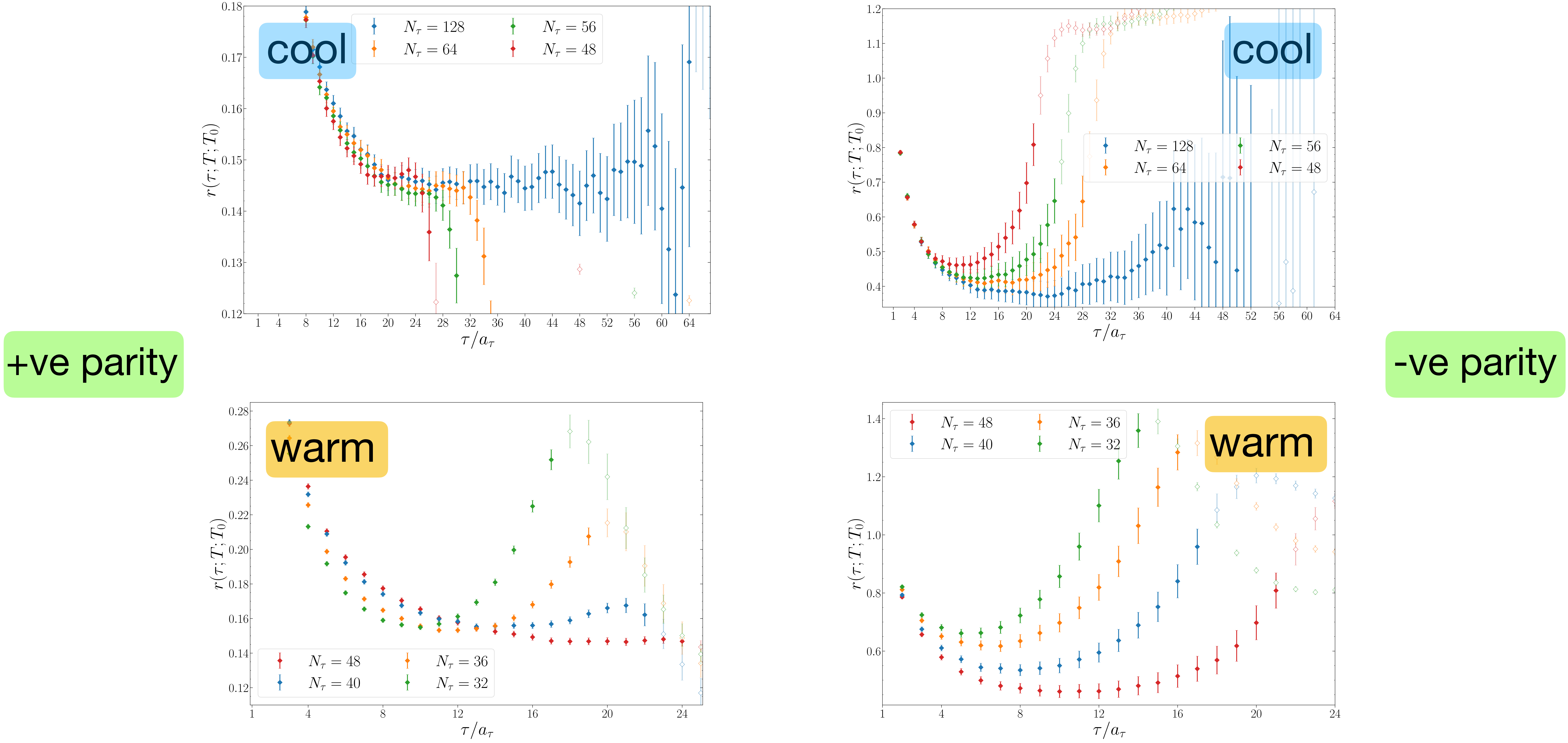


-ve parity





Results - "Model" ratio: G_{model}/G $\Sigma_c\,(udc)$



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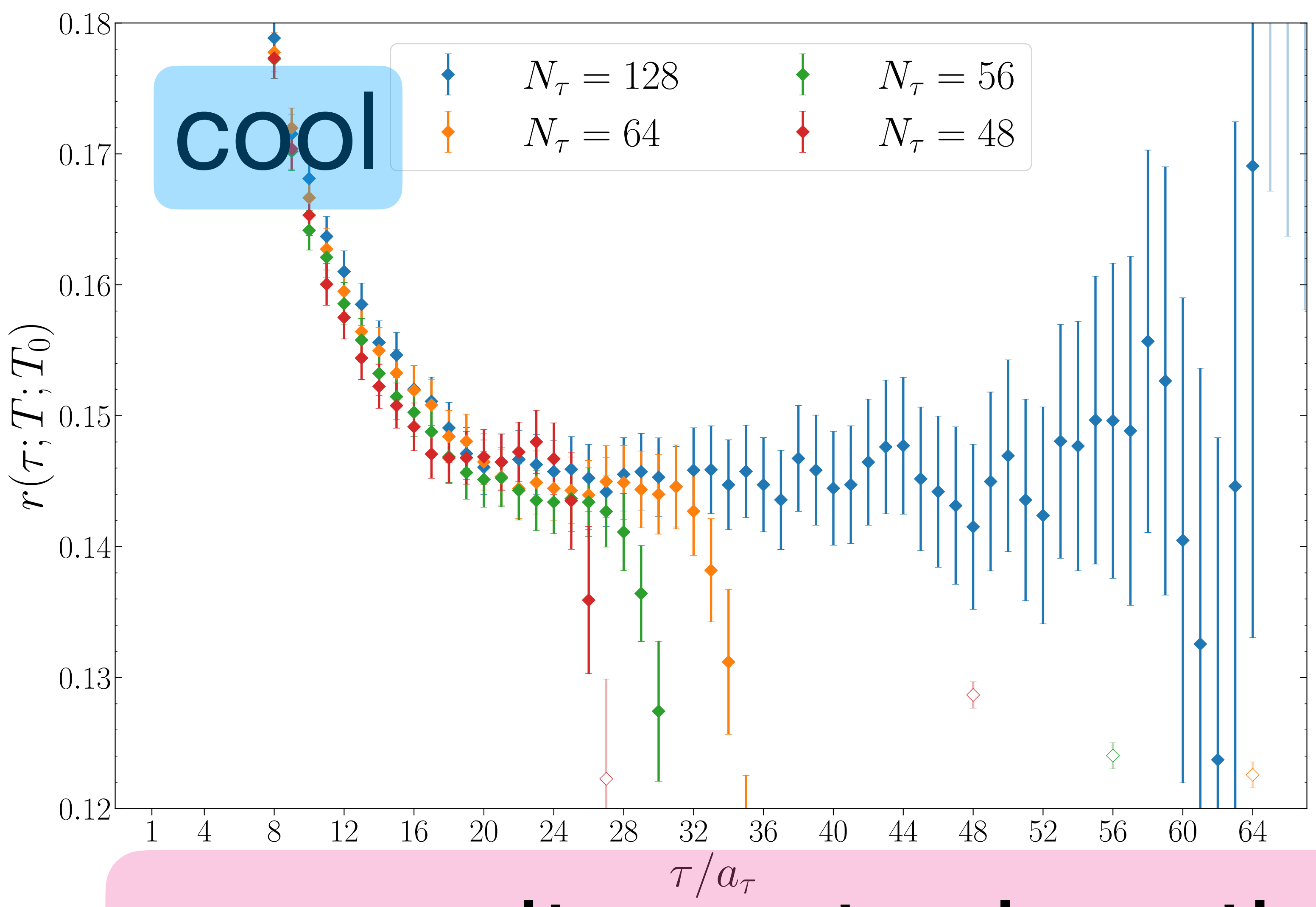
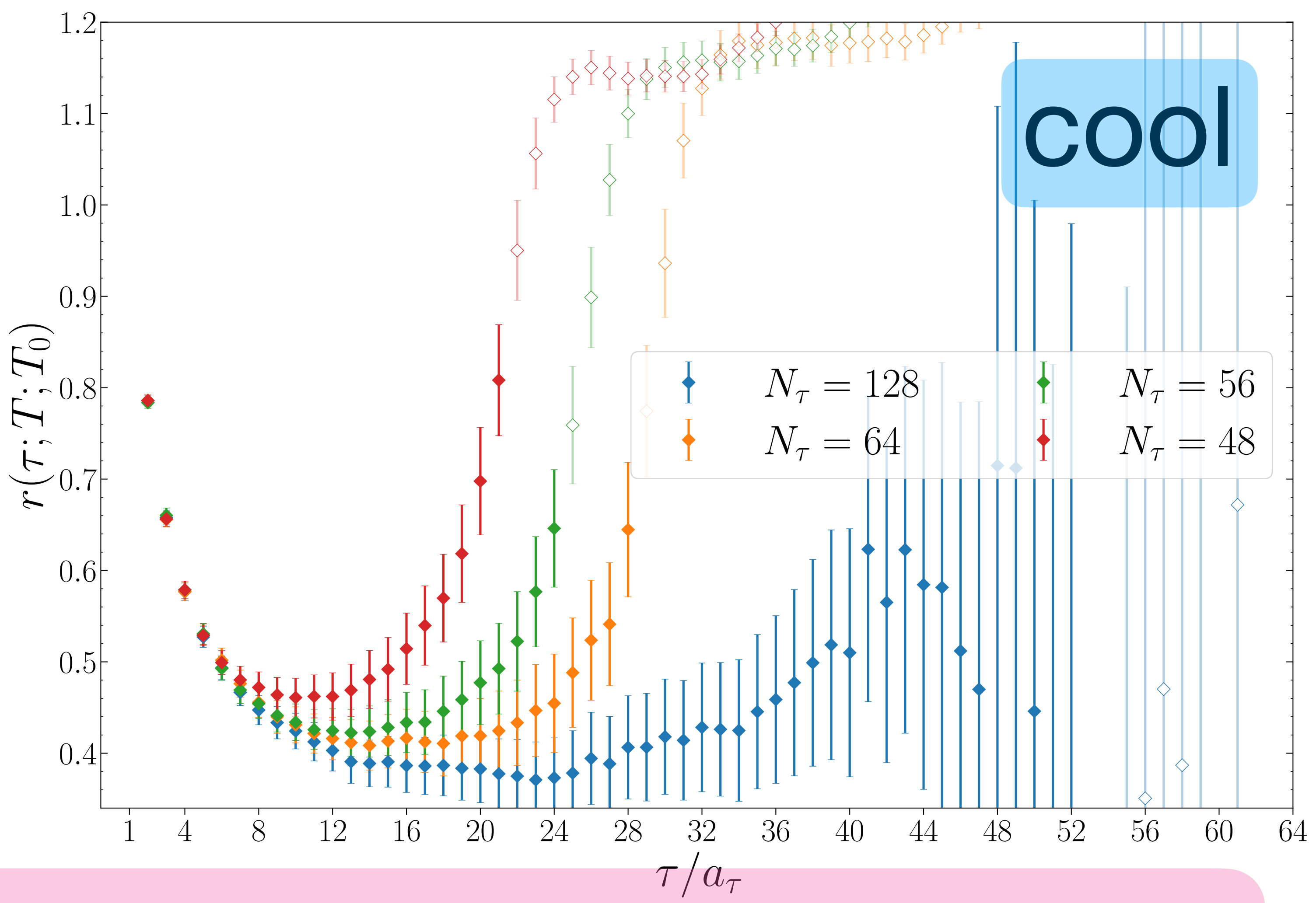
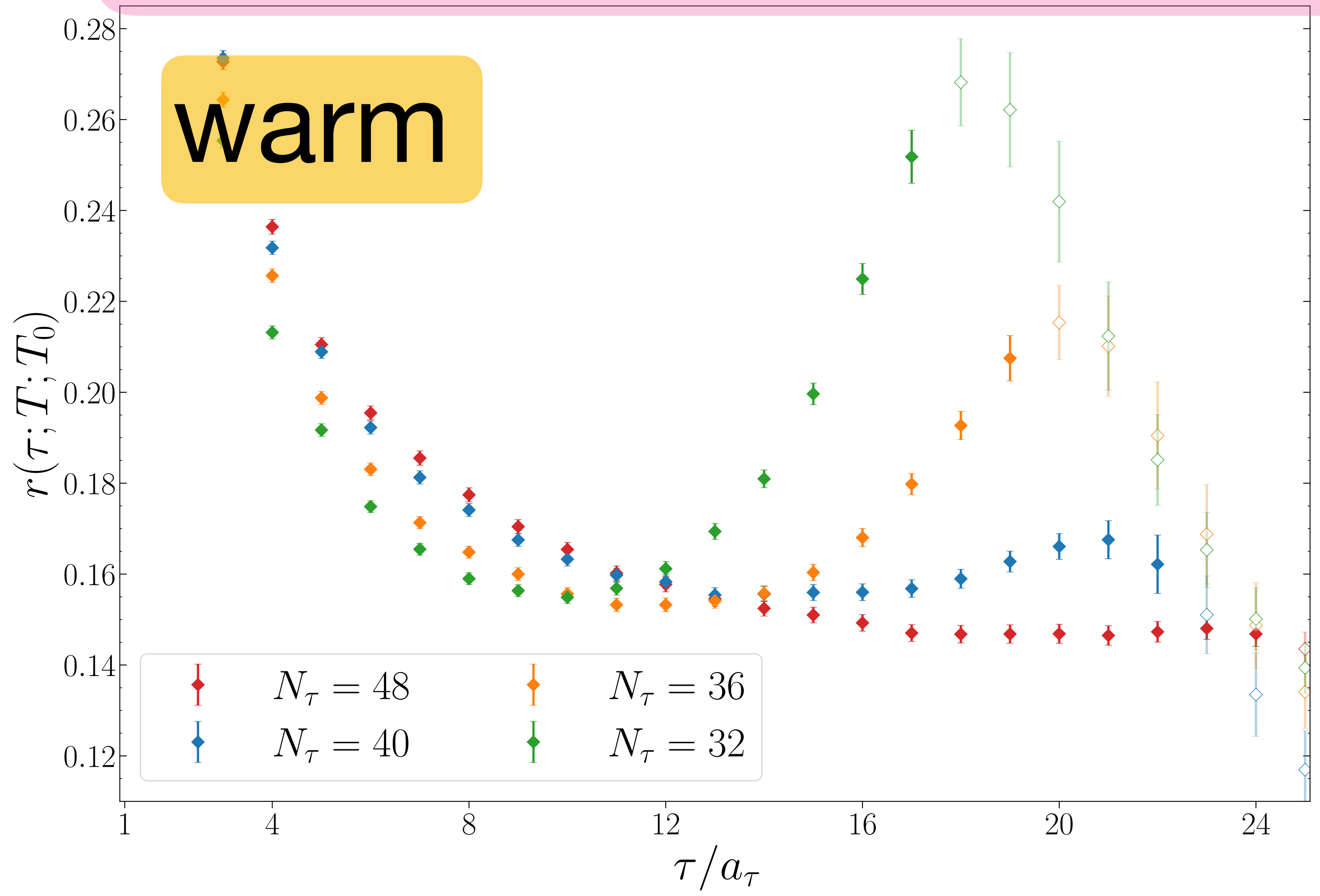


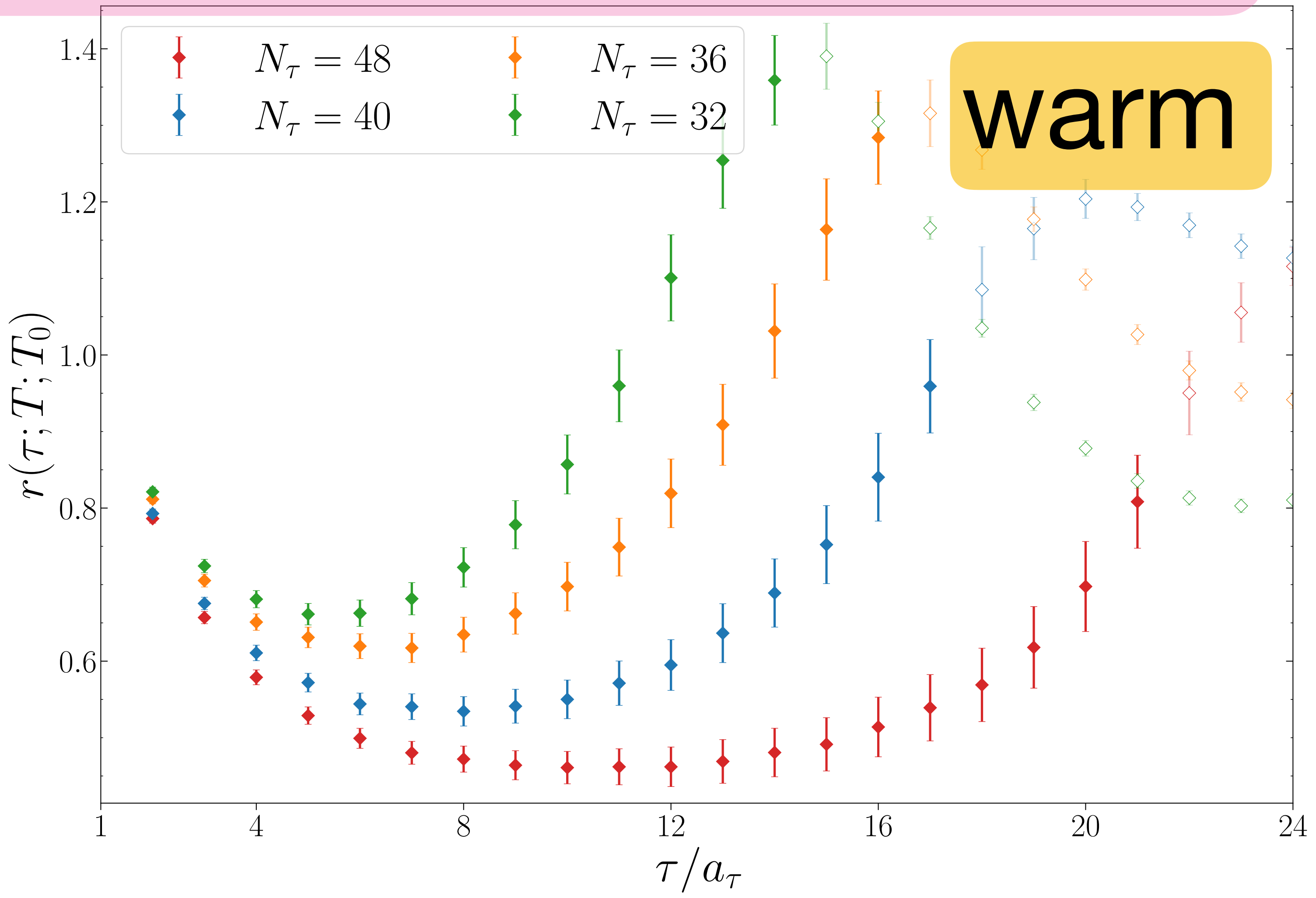


+ve parity

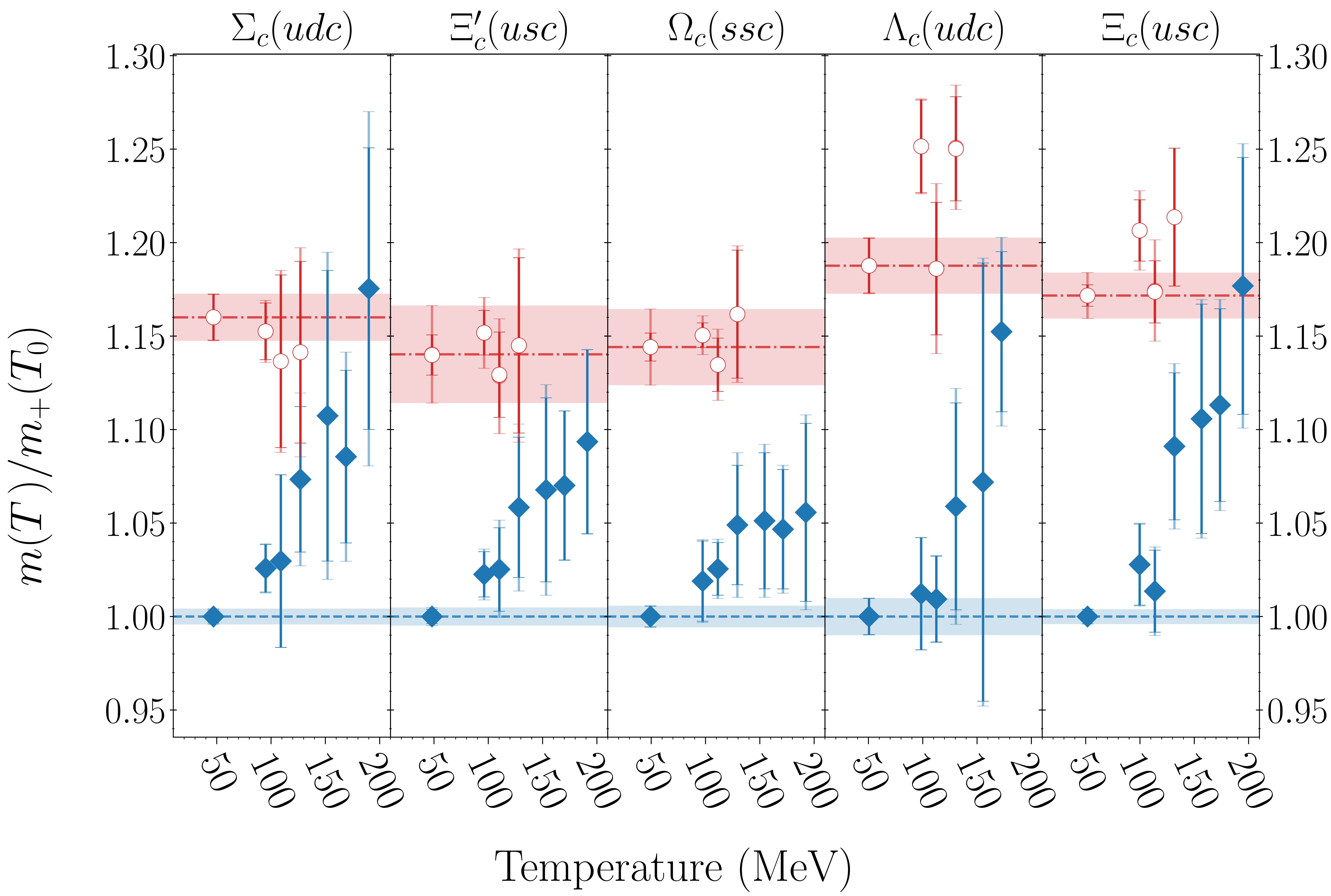
+ve parity sector less thermally sensitive than -ve parity

-ve parity

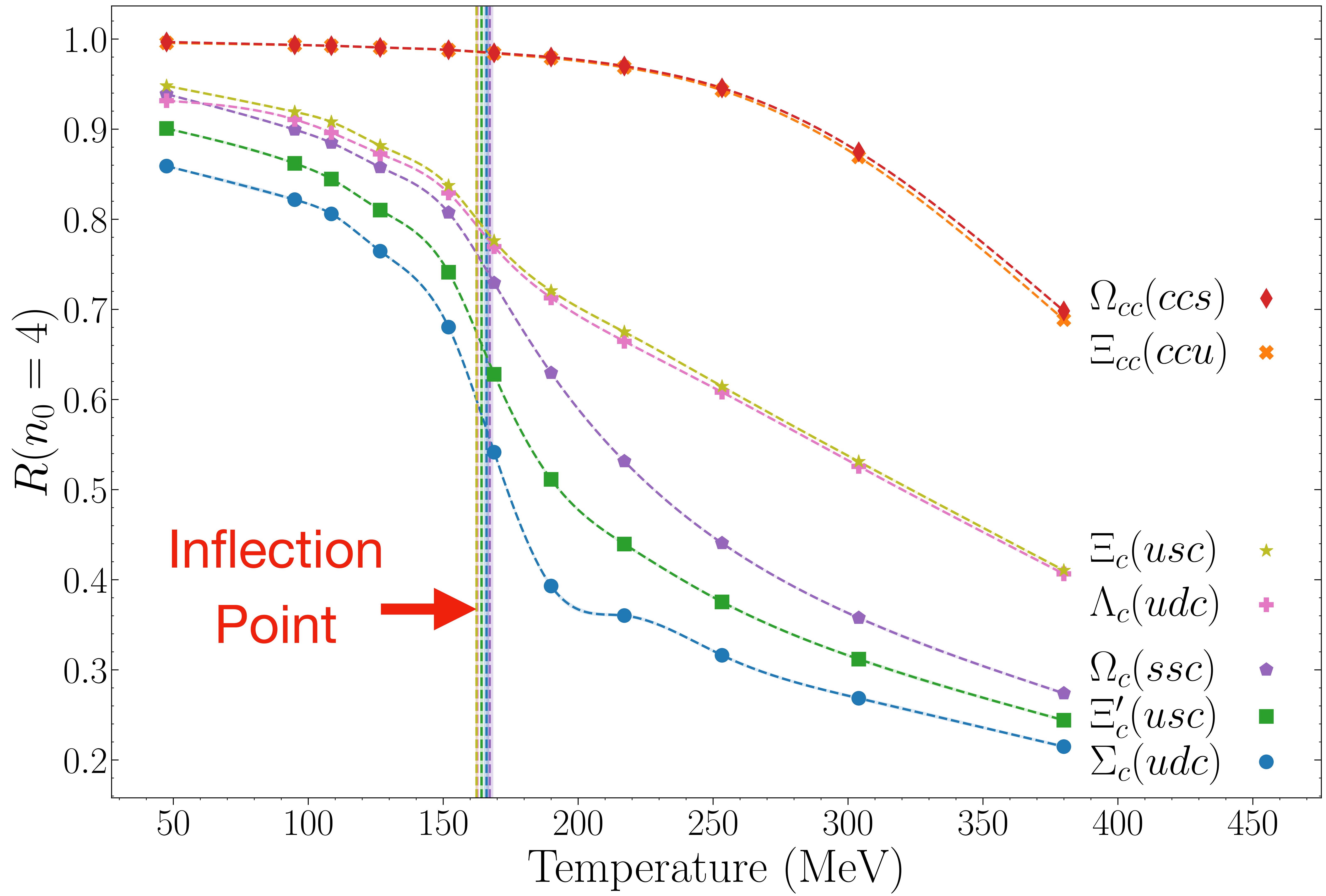




Results — Conventional Fits at T≠0



Parity doubling in the correlators



$$R(\tau) = \frac{G_+(\tau) - G_+(1/T - \tau)}{G_+(\tau) + G_+(1/T - \tau)}$$

Parity doubling:

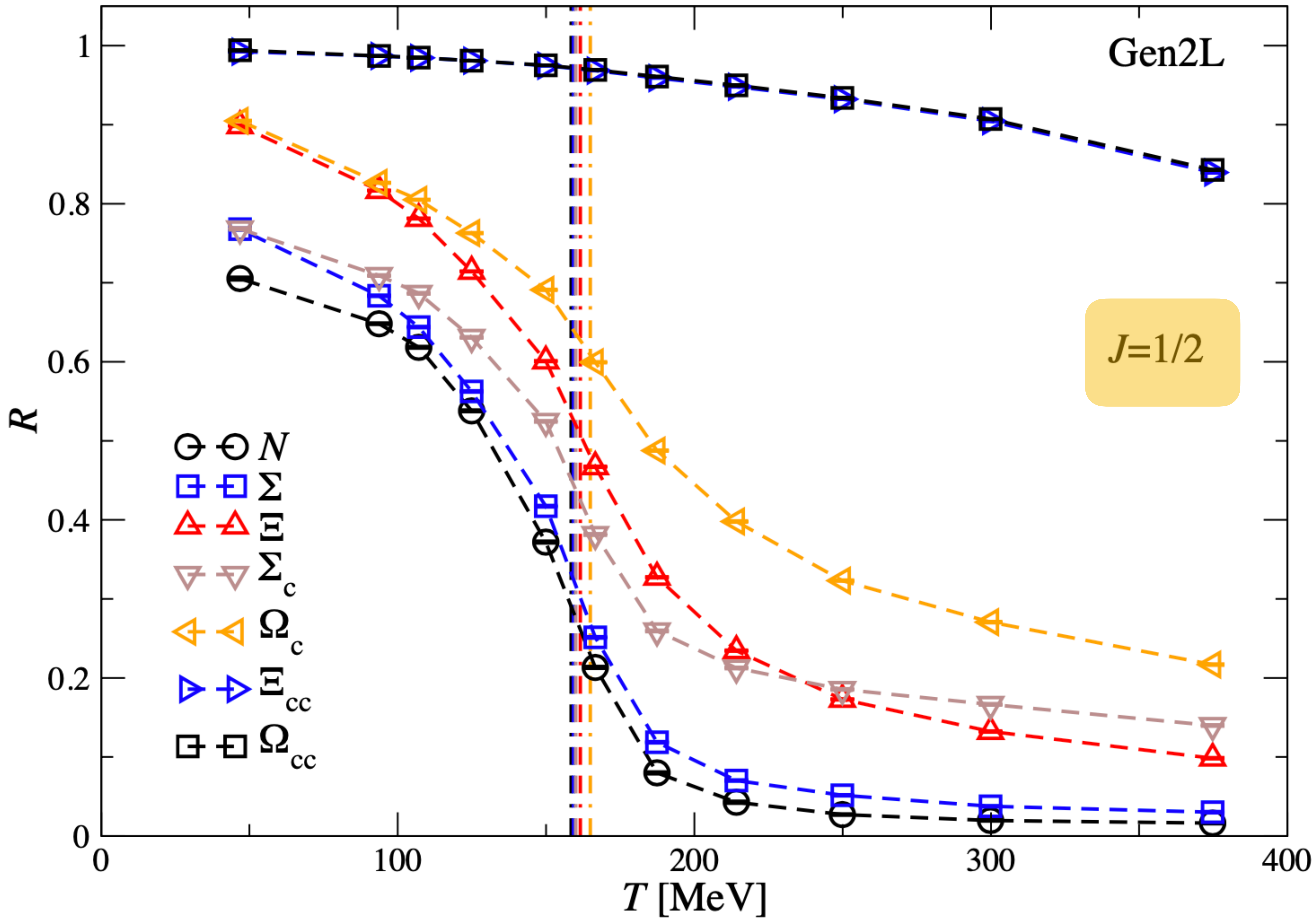
$G_+ = G_- \rightarrow R(\tau) \sim 0$

Parity max broken:

$G_+ \gg G_- \rightarrow R(\tau) \sim 1$

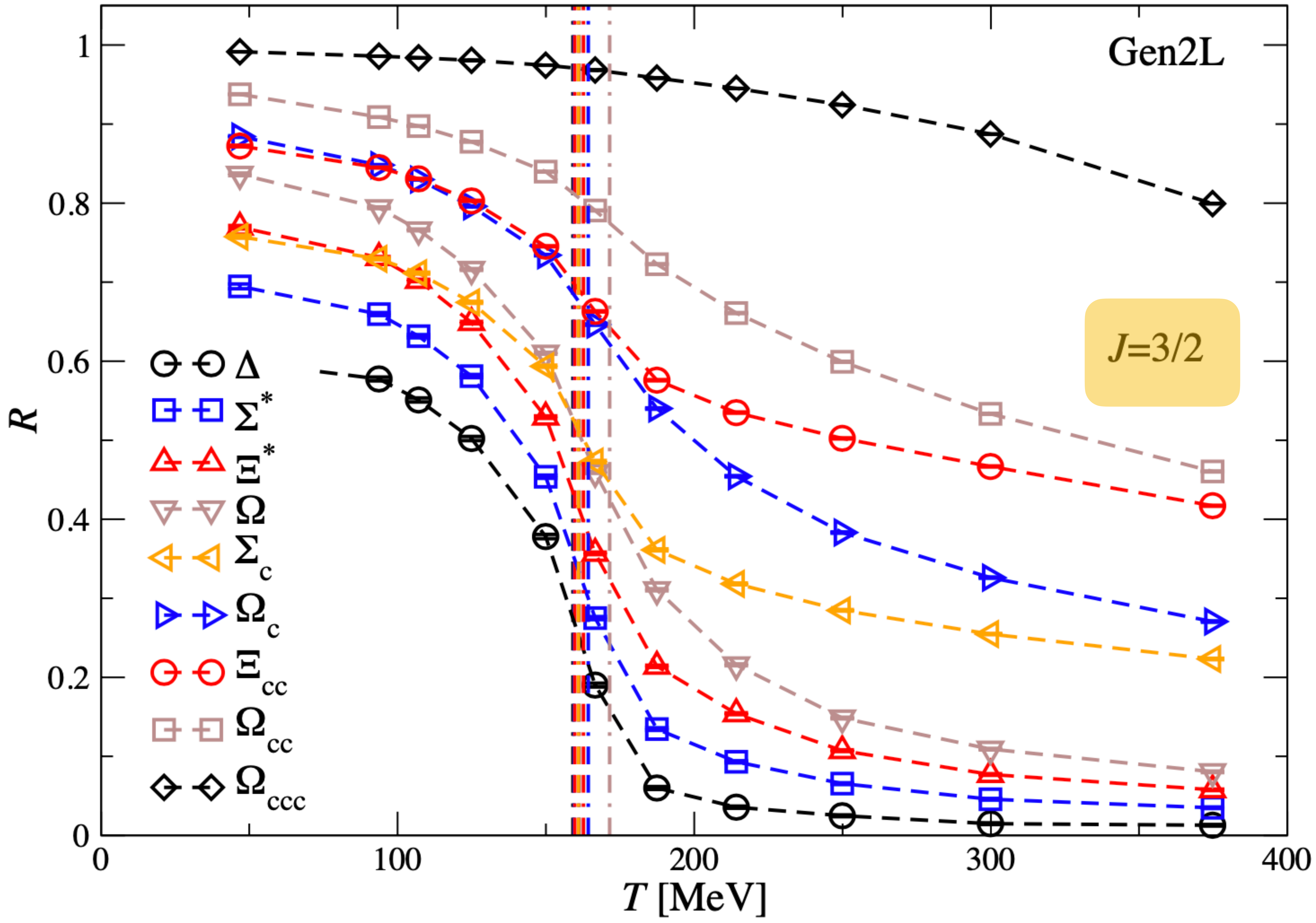
$$R = \frac{\sum_\tau R(\tau)/\sigma^2(\tau)}{\sum_\tau 1/\sigma^2(\tau)}$$

Generation 2L results -
Comparison with J=1/2 light hadrons

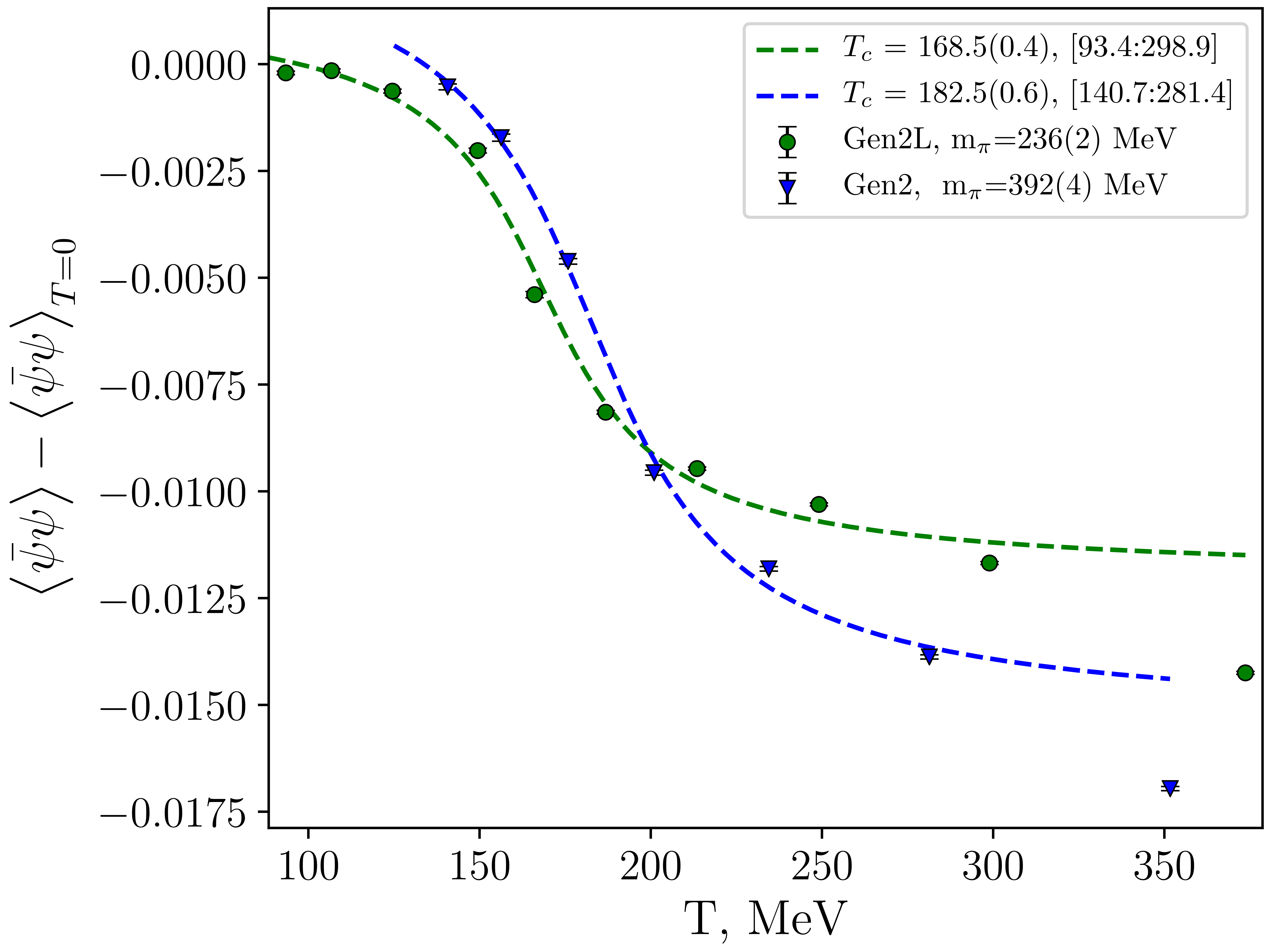


Generation 2L results -

Comparison with J=3/2 light hadrons



Generation 2 & 2L results -
Comparison with chiral condensate



Many Approaches to Extract Spectral Information

1. Exponential (Conventional δ f'ns)
2. Gaussian Ground State (+ δ f'n excited)

} Maximum Likelihood (Minimise χ^2)

3. Moments of Correlation F'ns

Direct Method - "no" fit
(talk by Maria Paola Lombardo)

4. Maximum Entropy Method
5. BR Method

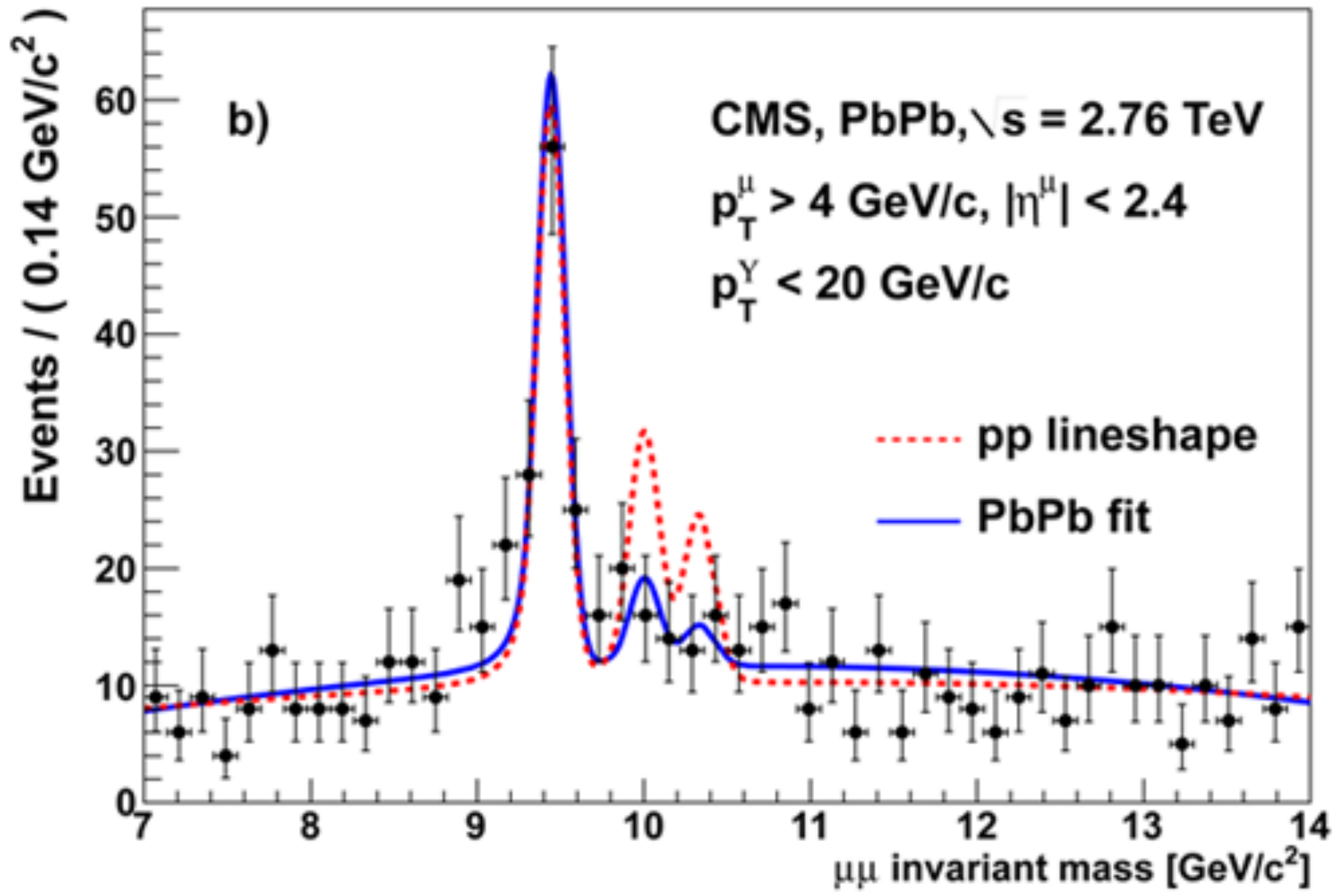
} Bayesian Approaches

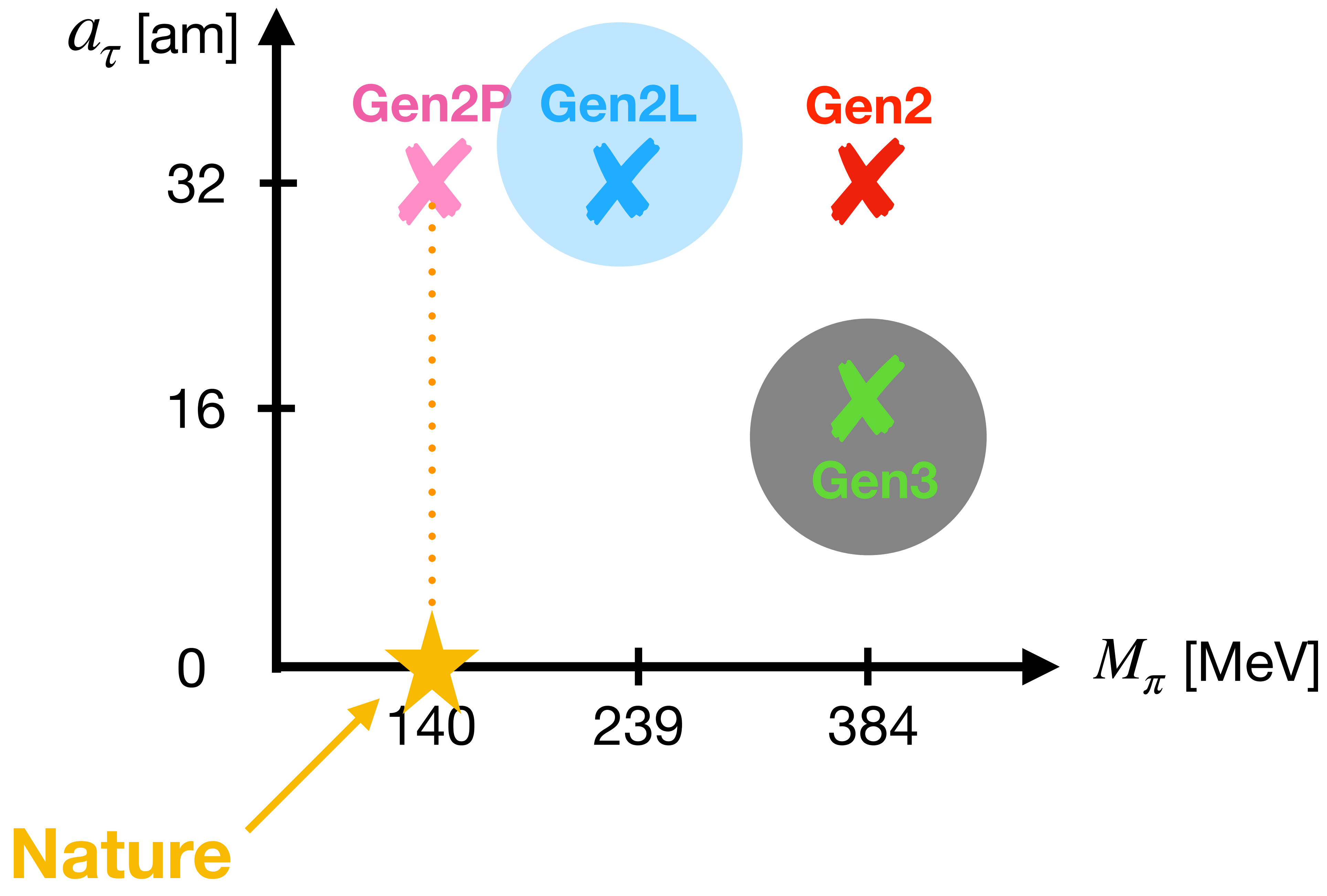
6. Kernel Ridge Regression

Machine Learning

7. Backus Gilbert
8. HLT
9. HMR

} from Geophysics





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- Parity in Baryonic sector
- FASTSUM approach
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  - “Model of Ground State” approach
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T=0 ground state mass obtained

- *(non-continuum, non-chiral)*

+ve parity sector less thermally sensitive than -ve parity

- *Doubly charmed, +ve parity ground state T-indept up to T~190MeV*

Analysis using ratios ➔ can use multi-exp fits:

- *+ve parity up to T~190 MeV (better for doubly charmed)*
- *-ve parity up to T~127 MeV*

R parameter shows crossover at same T as Tc