Centre vortices and gluon propagators in thermal lattice QCD with dynamical fermions

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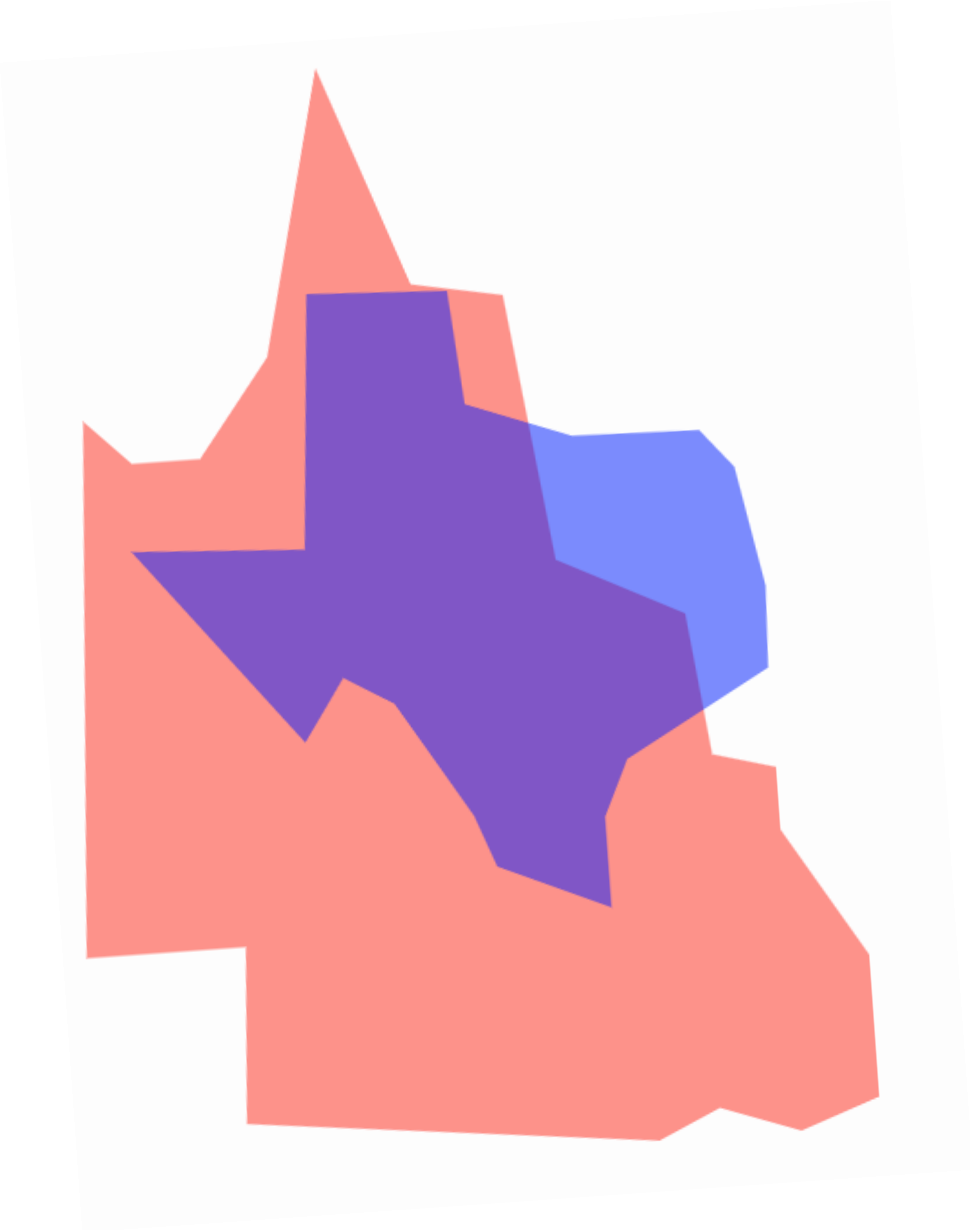
FASTSUM Collaboration

Scales

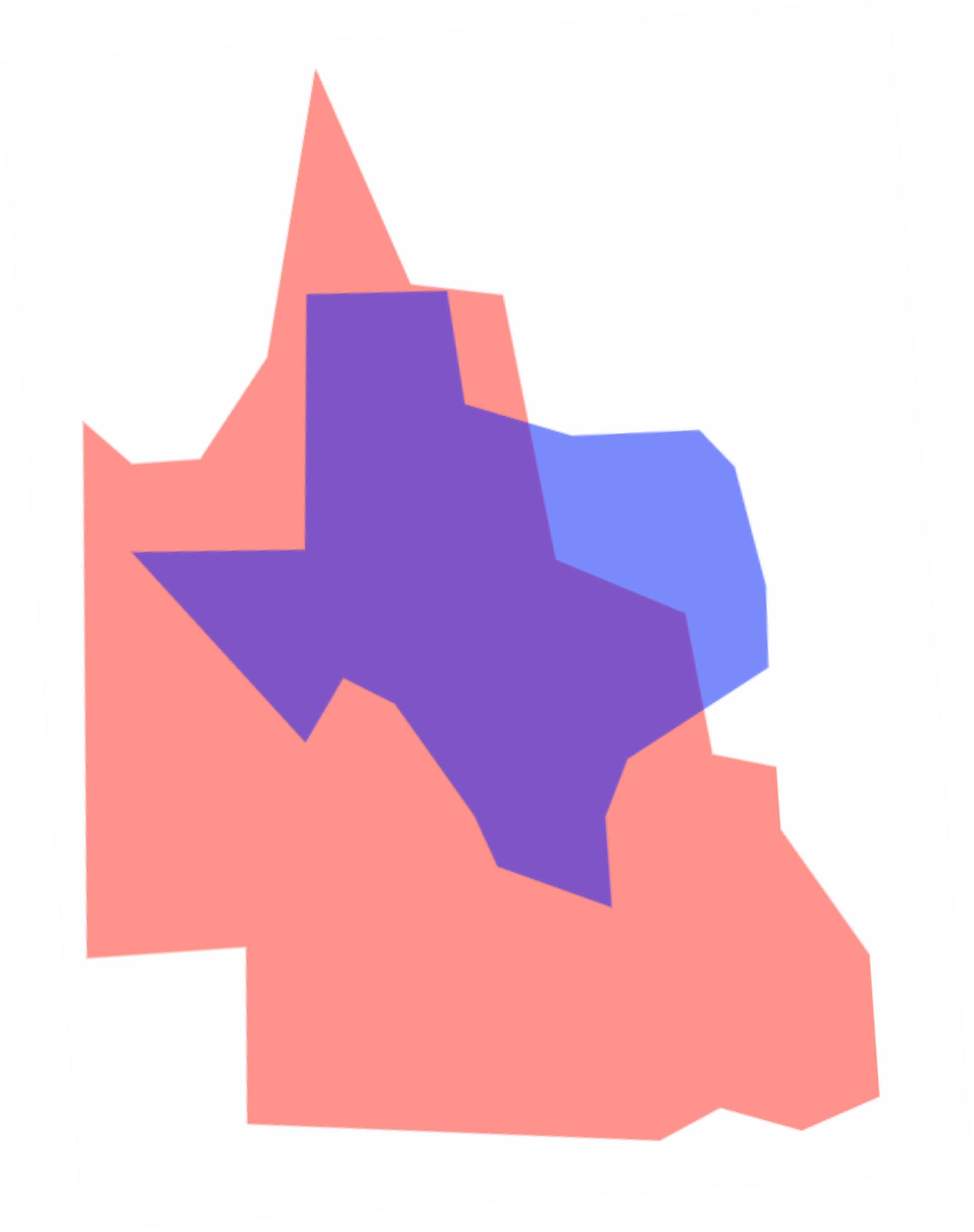


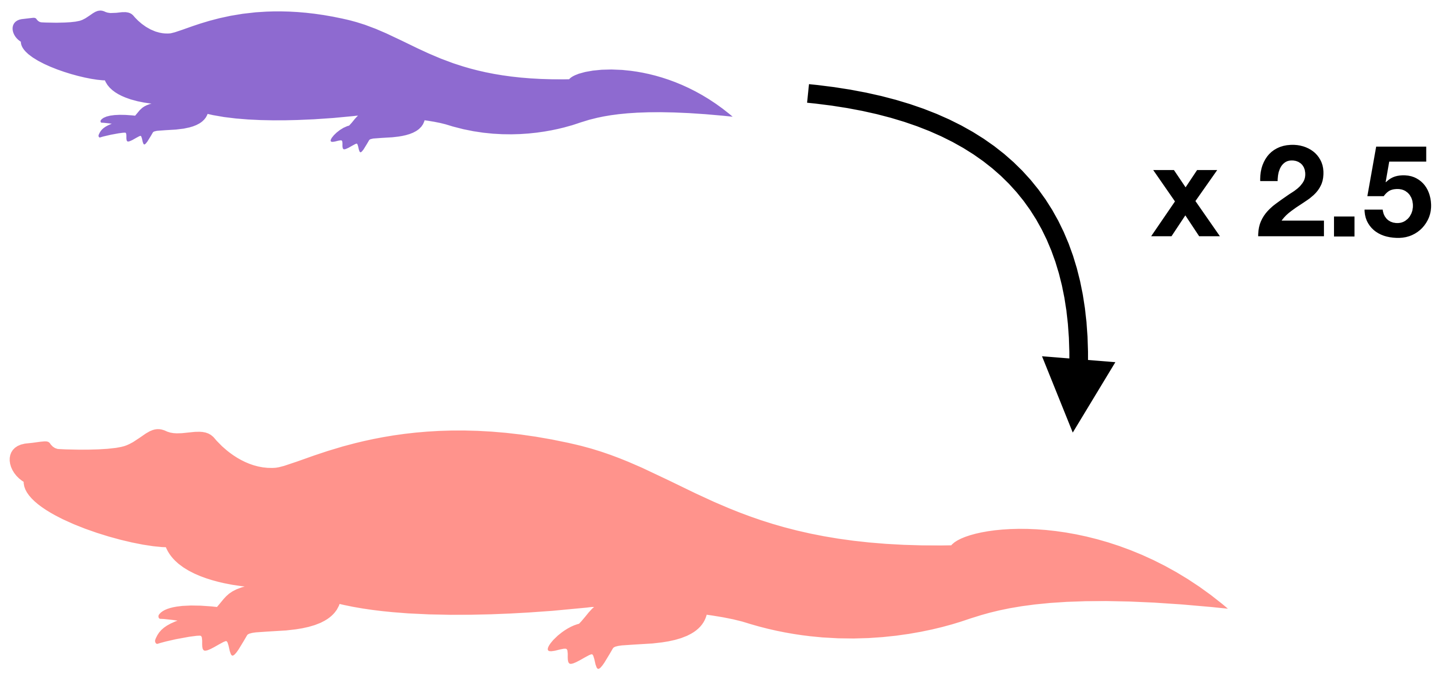
Texas

x 2.5

Queensland

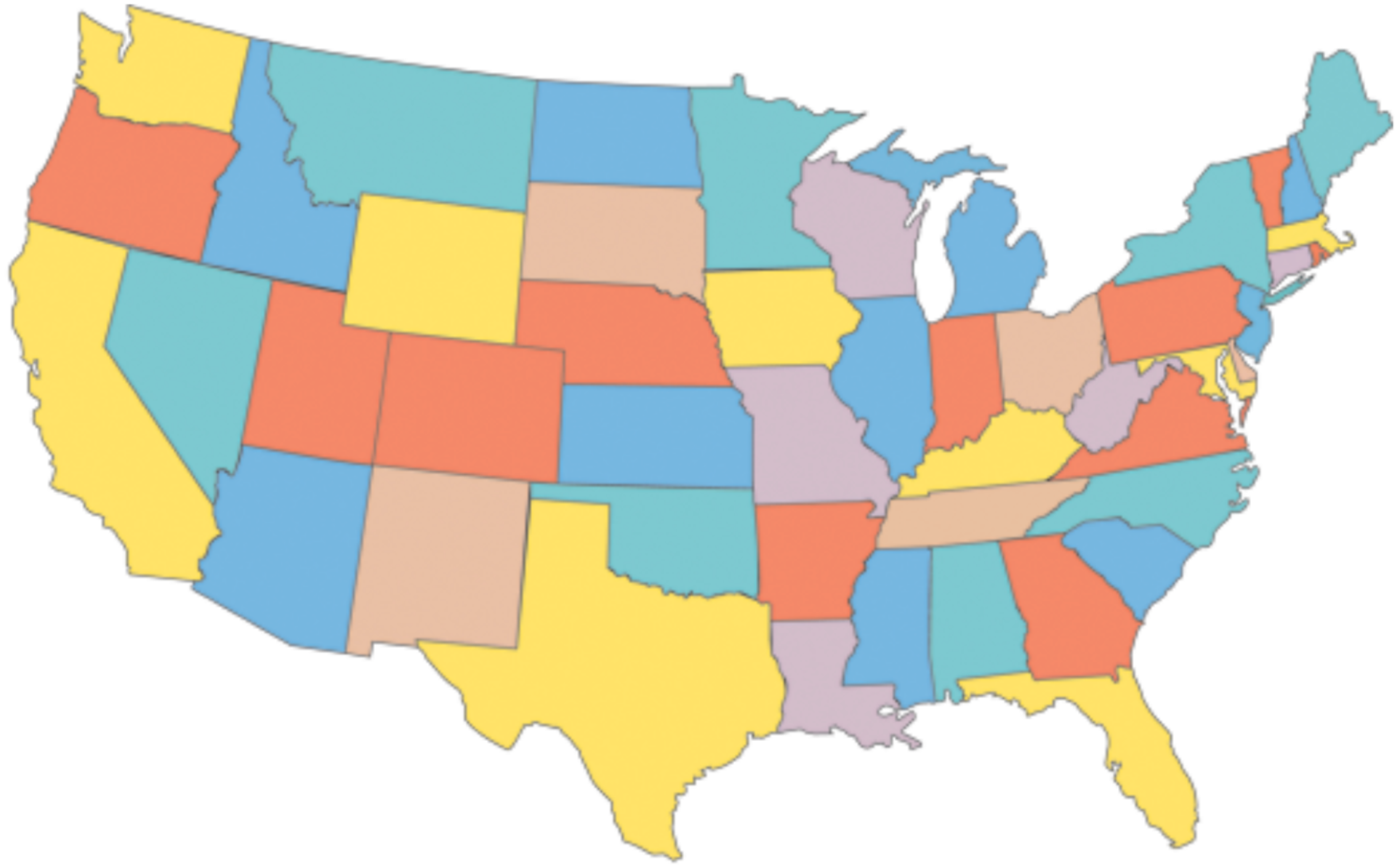
Scales





Scales


NORTHERN
TERRITORY
QUEENSLAND
WESTERN
AUSTRALIA
SOUTH
AUSTRALIA
NEW
SOUTH WALES
VICTORIA
TASMANIA

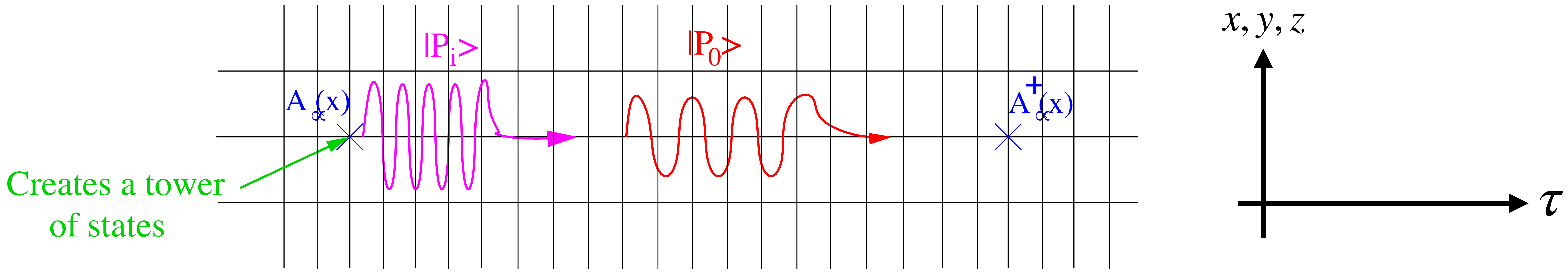


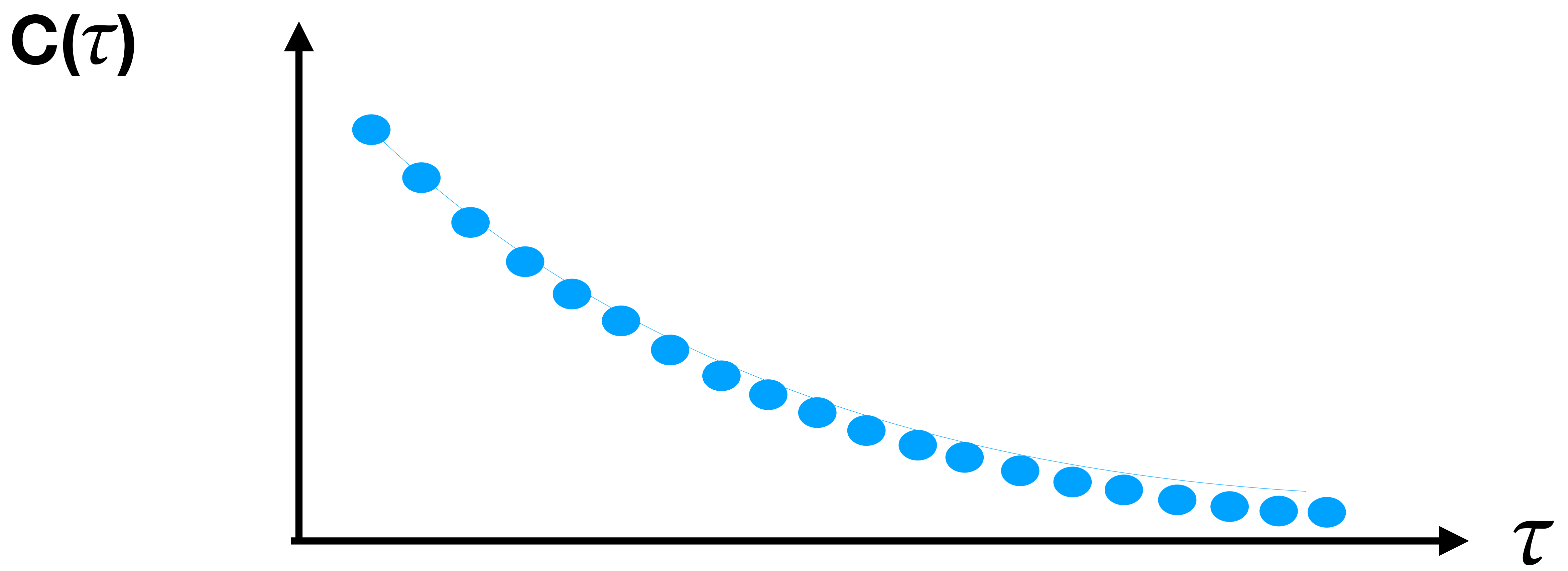
Overview

- FASTSUM approach
    - Anisotropic
- Maximal Centre Gauge
    - Vortices — Faber, Greensite, Olejník Phys.Lett.B 474 (2000) 177
- Measurements
    - Vortex & Branching Point Density
    - Cluster Extent
    - Correlations
- Transition(s) in QCD ?
    - Systematics

FASTSUM Approach:

Anisotropic Lattice





Spectral Quantities:

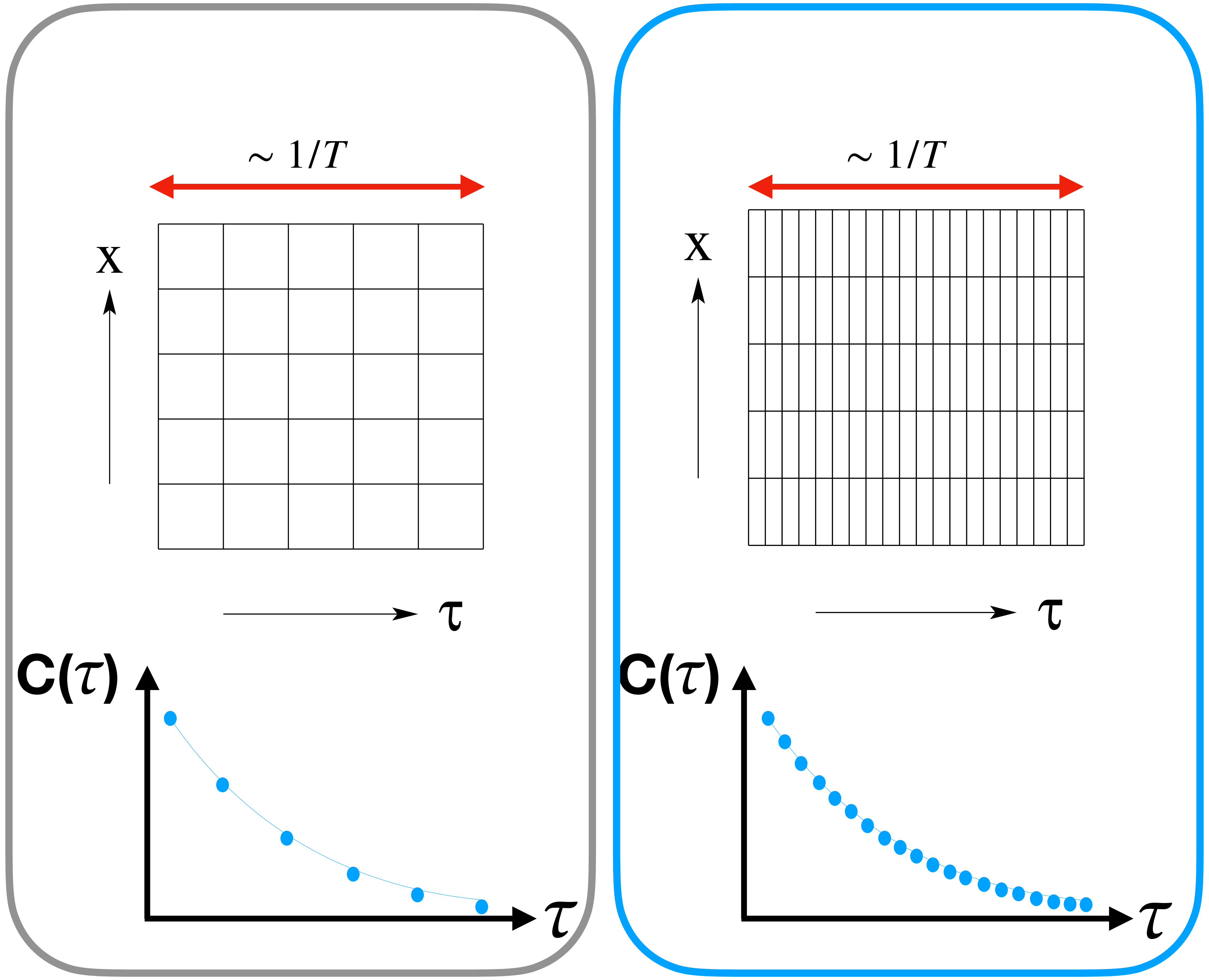
- Bottomonium
- Charmed mesons
- Heavy Baryons
- Light Hadrons

Interquark potential

Conductivity

FASTSUM Approach:

Anisotropic Lattice

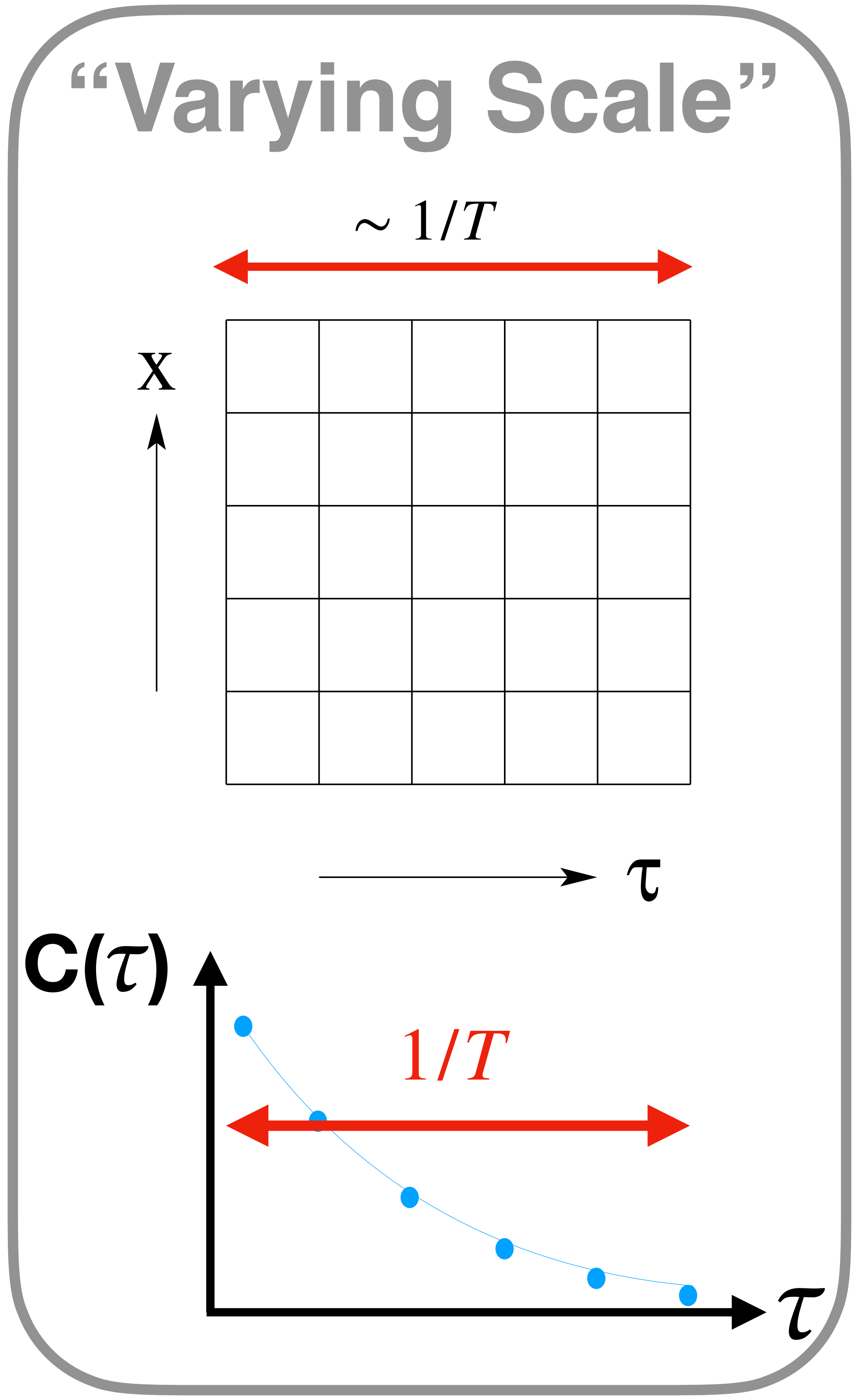


$$\sum_i \langle i | e^{-H L_\tau} | i \rangle = \sum_i \langle i | e^{-H/T} | i \rangle$$

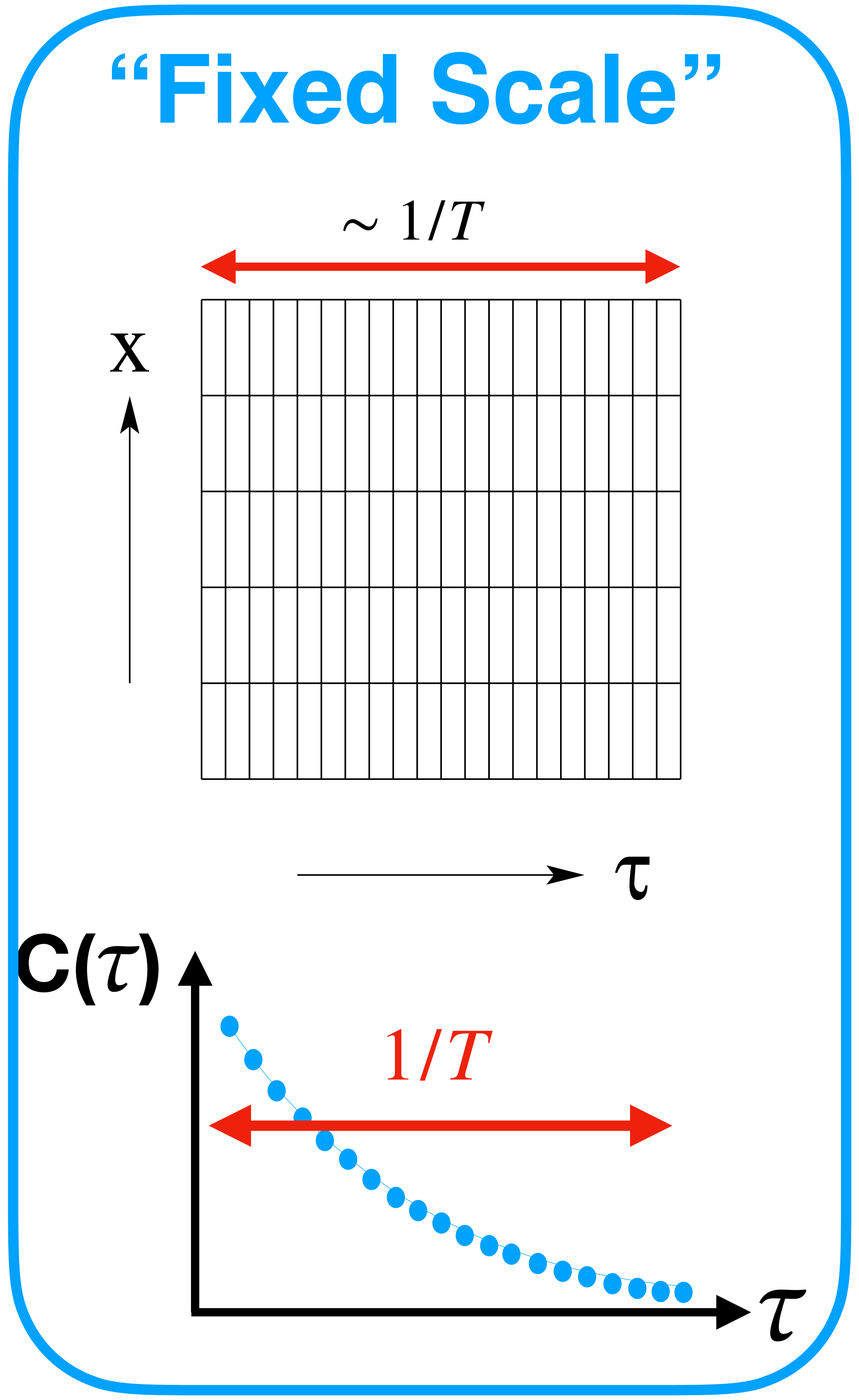
$$T = \frac{1}{L_\tau} = \frac{1}{a_\tau N_\tau}$$

FASTSUM Approach:

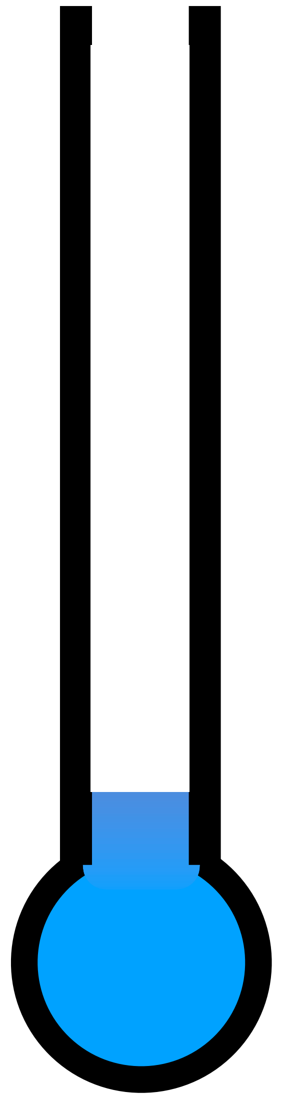
Anisotropic Lattice



$a_\tau \to 0$



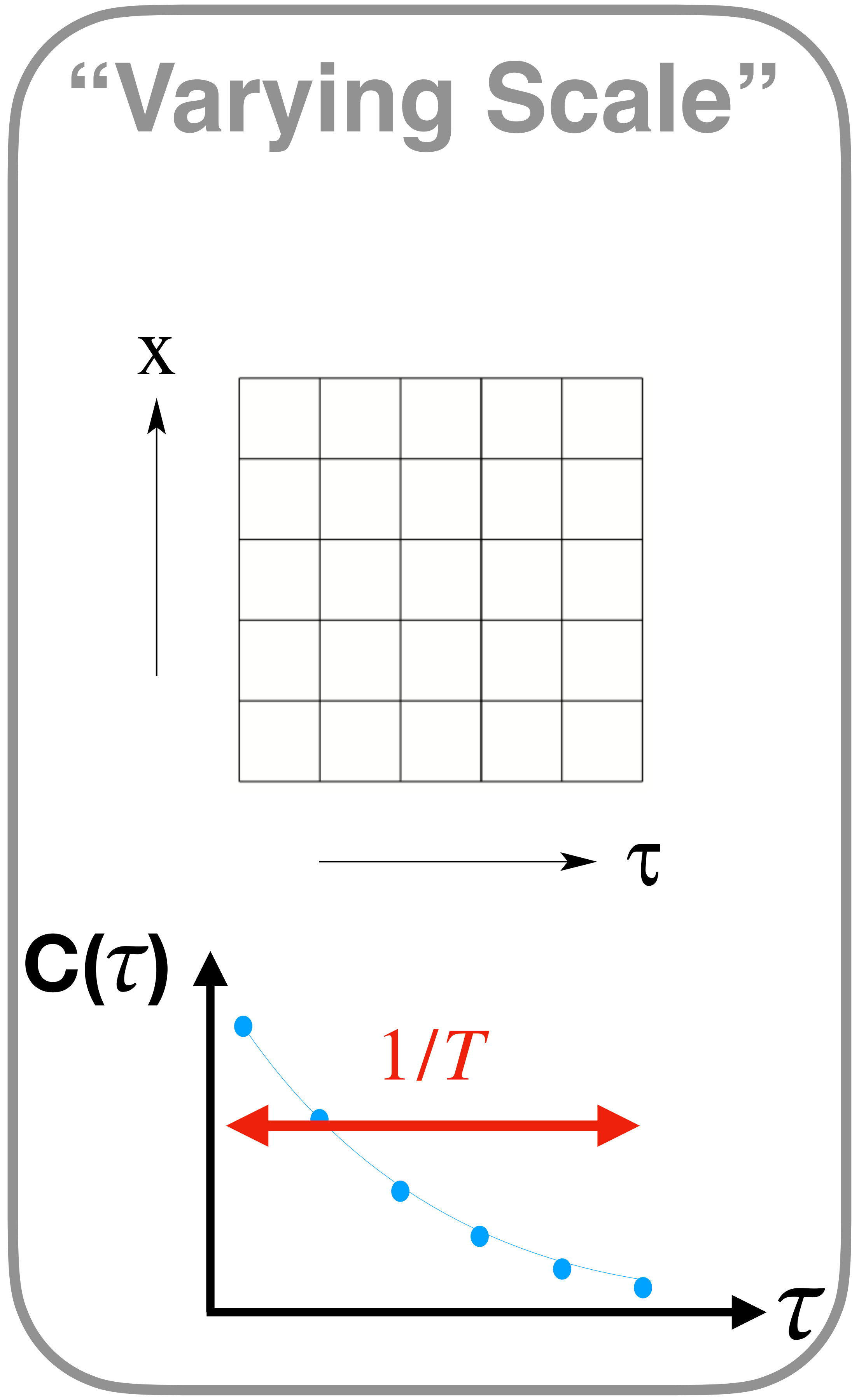
$N_\tau \to 0$



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

FASTSUM Approach:

Anisotropic Lattice



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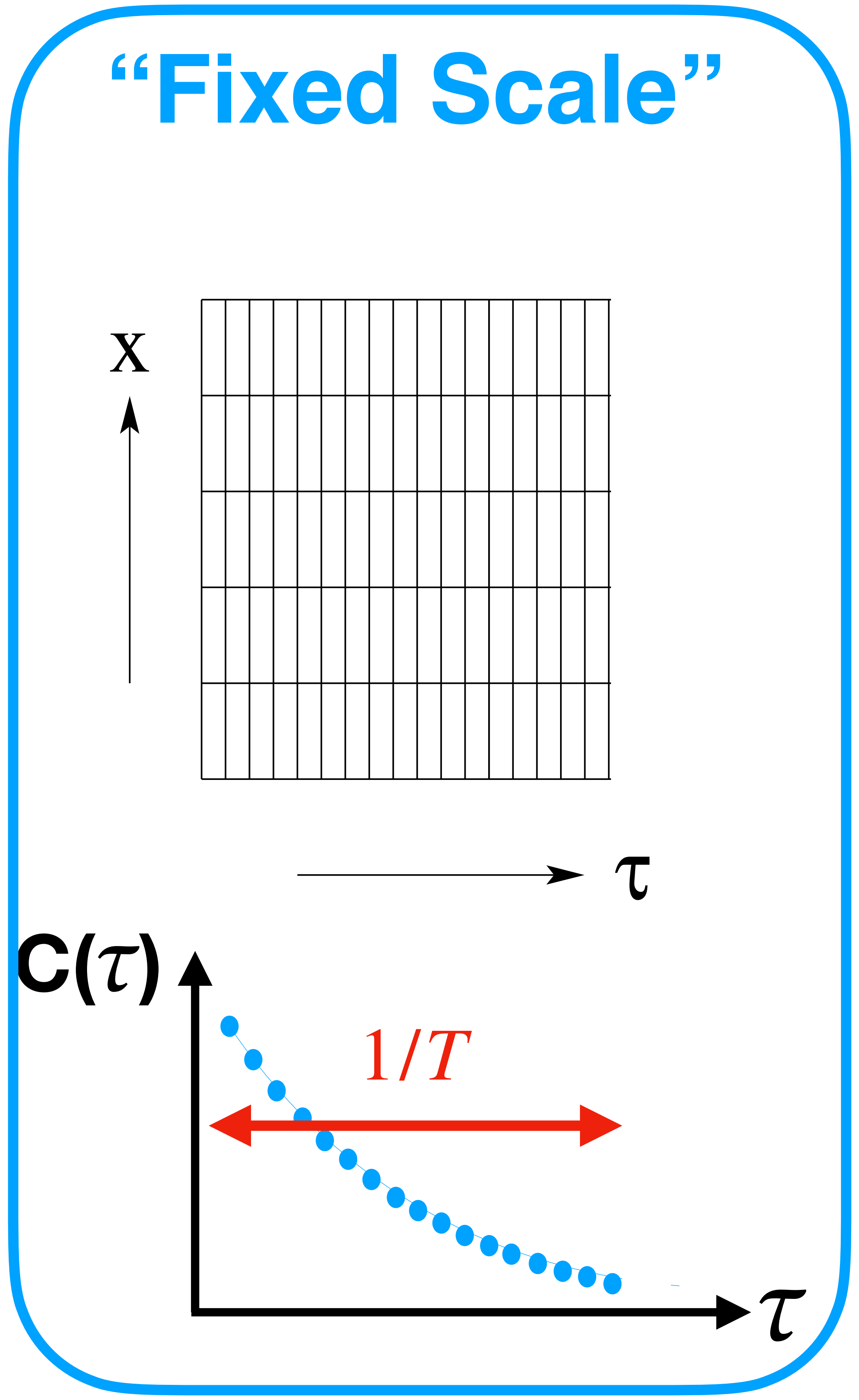
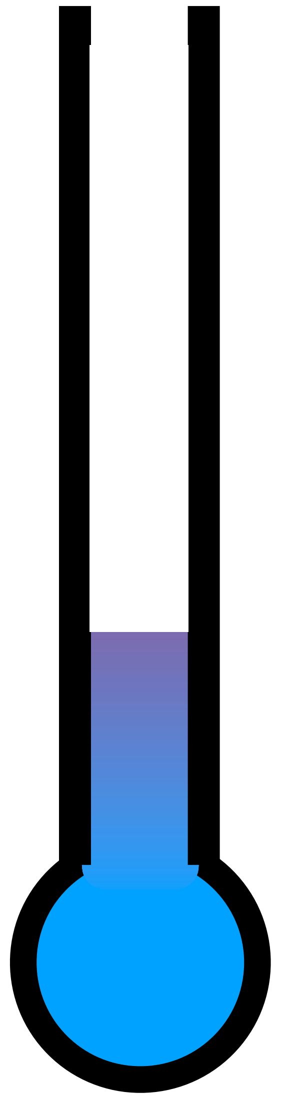


$N_\tau \to 0$

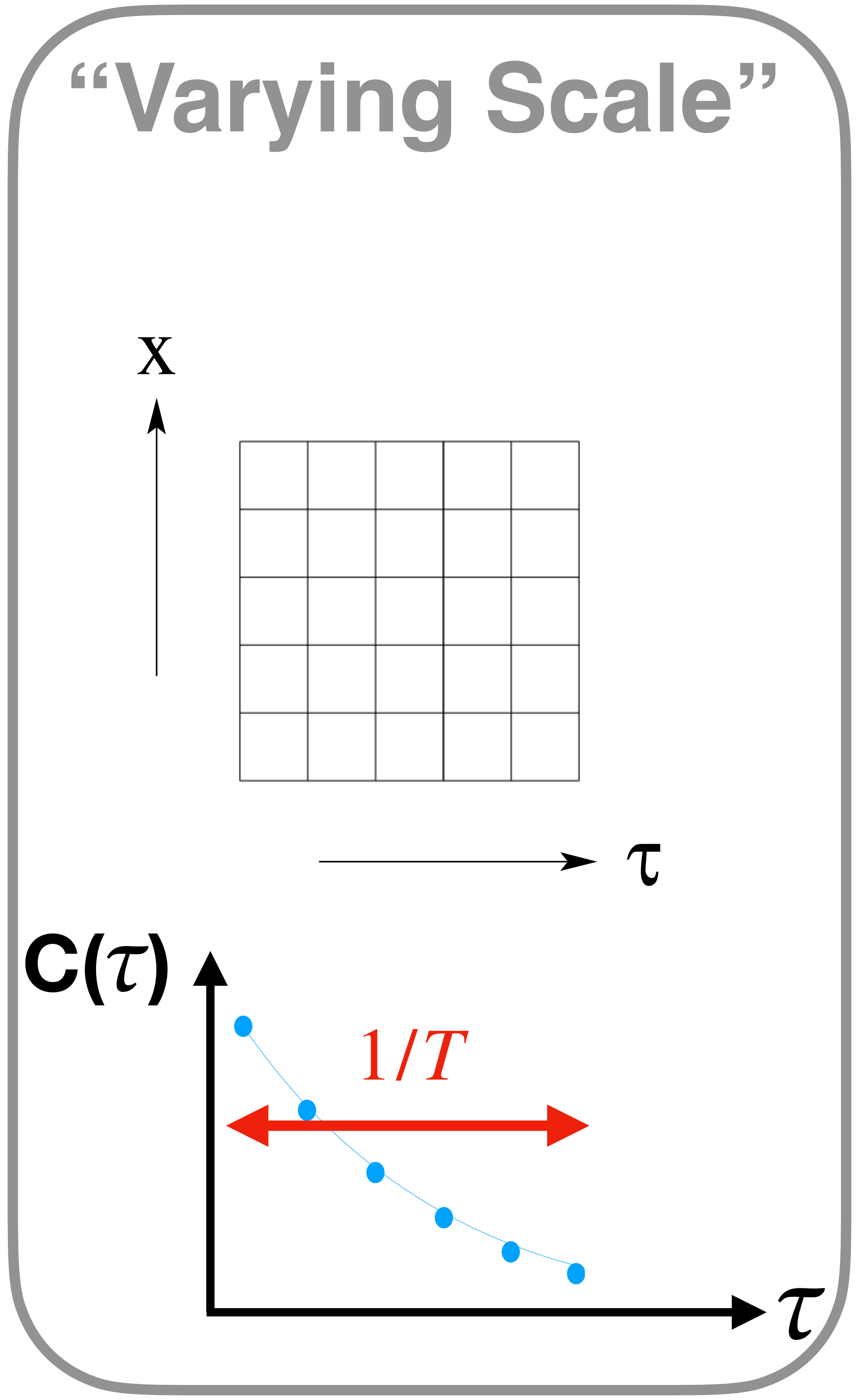


Going hotter…

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

FASTSUM Approach:

Anisotropic Lattice



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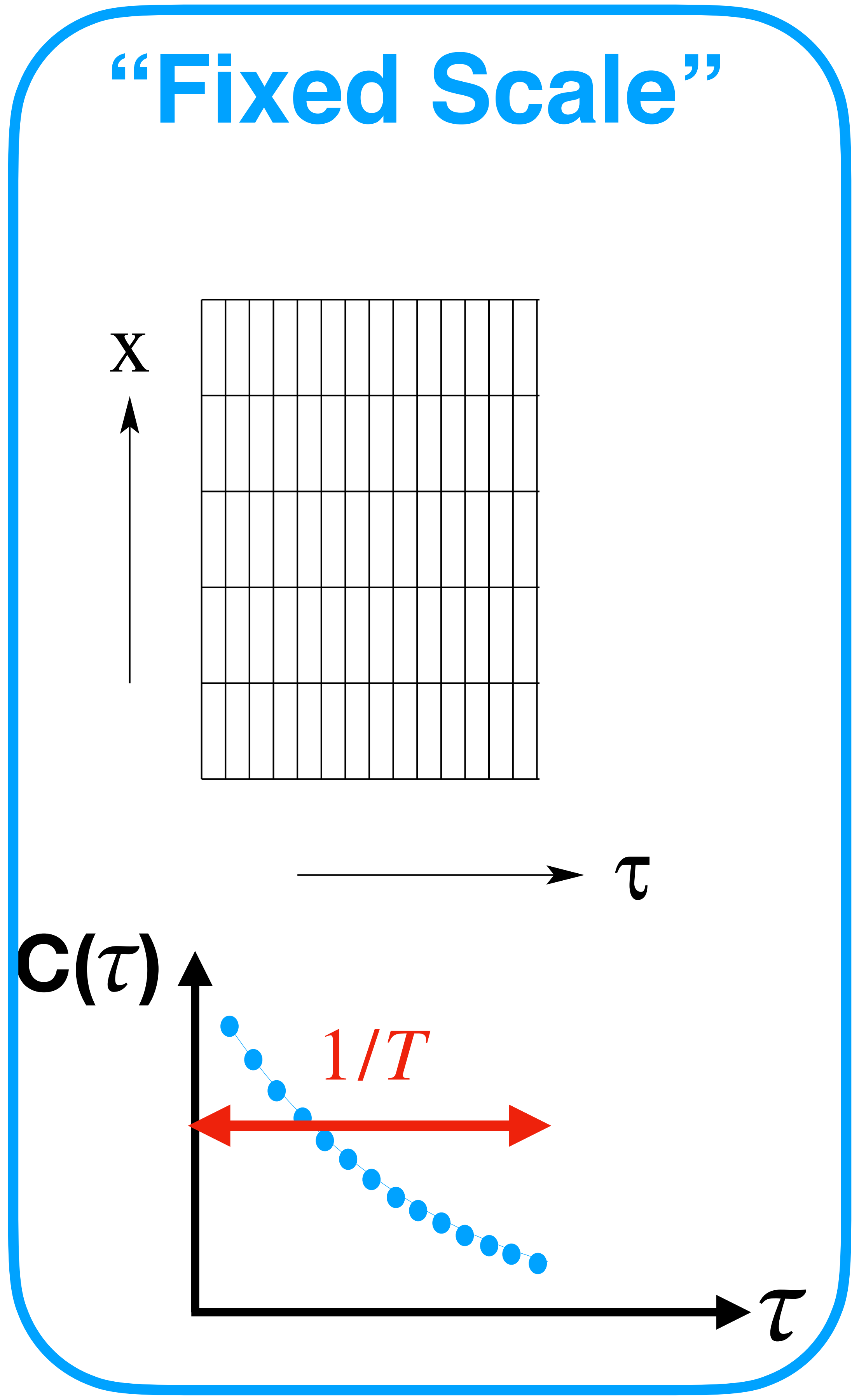
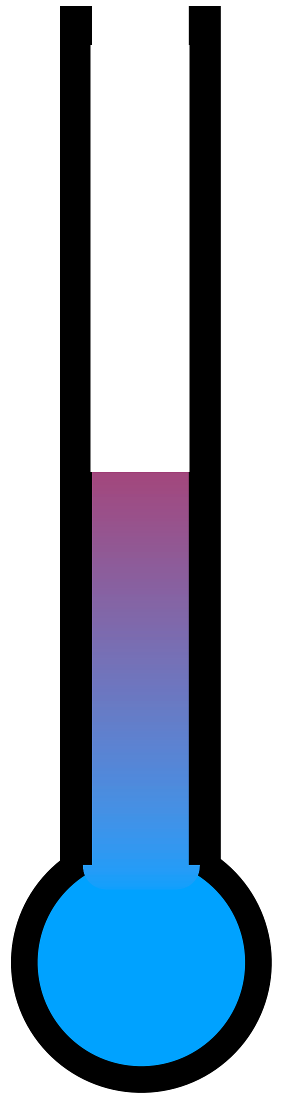


$N_\tau \to 0$

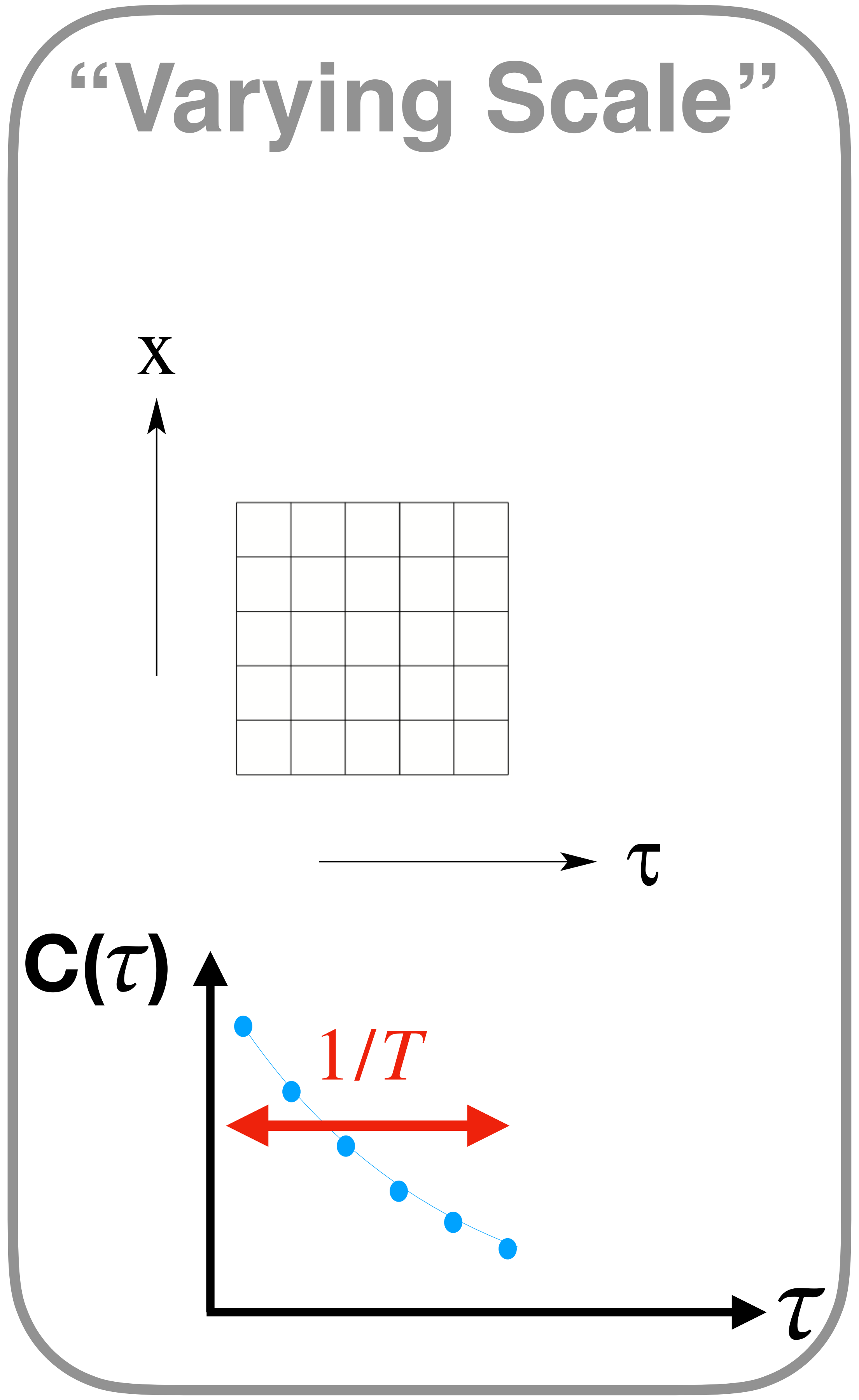


Going hotter…

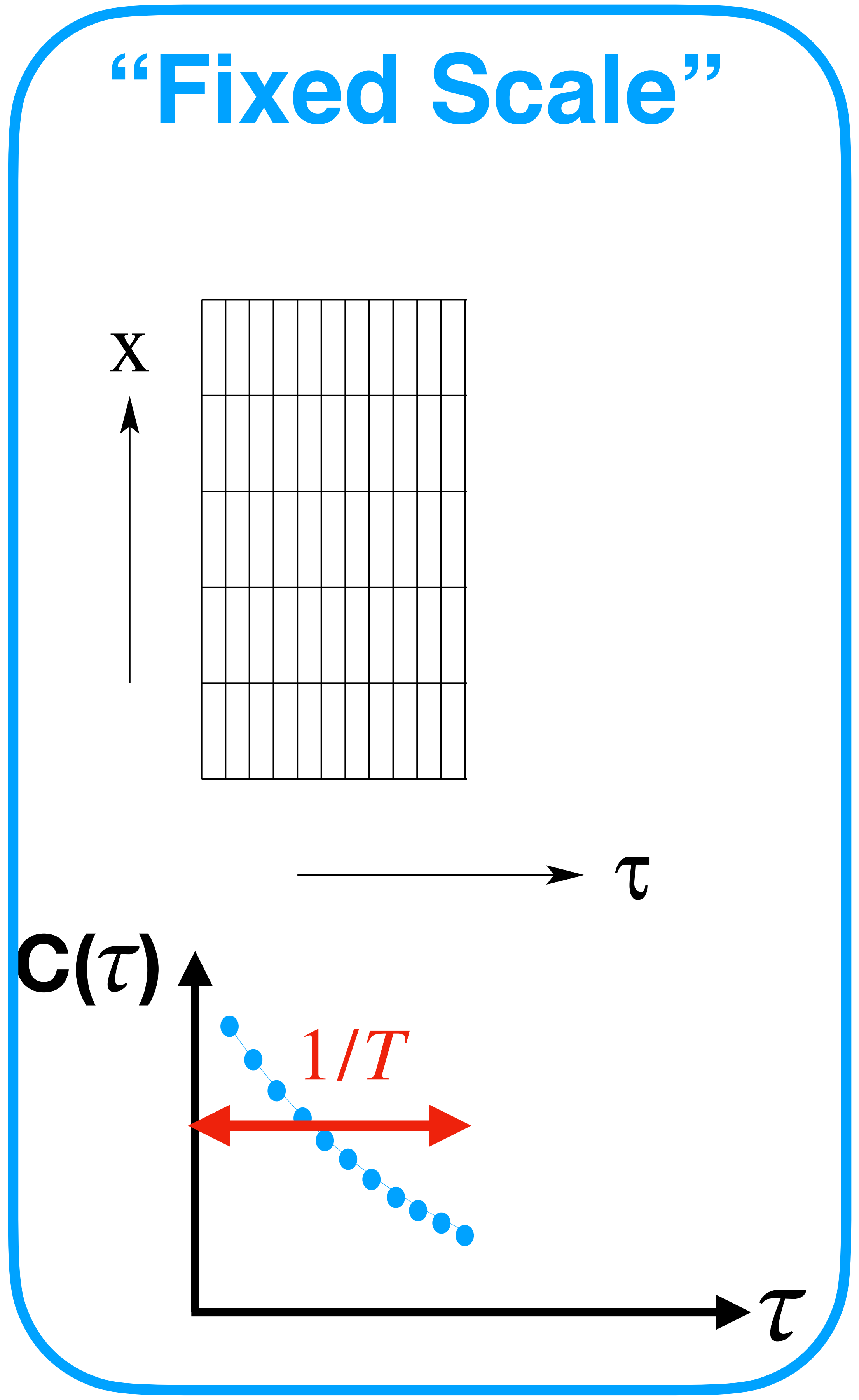
$$T = \frac{1}{L_\tau} = \frac{1}{a_\tau N_\tau}$$

FASTSUM Approach:

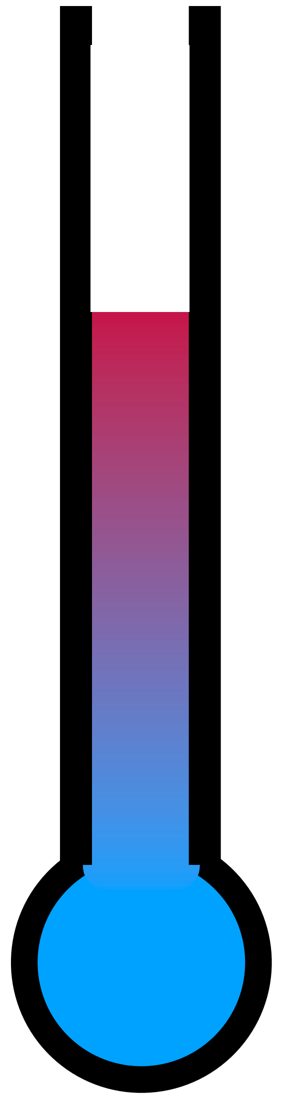
Anisotropic Lattice



$$a_\tau \to 0$$



$$N_\tau \to 0$$



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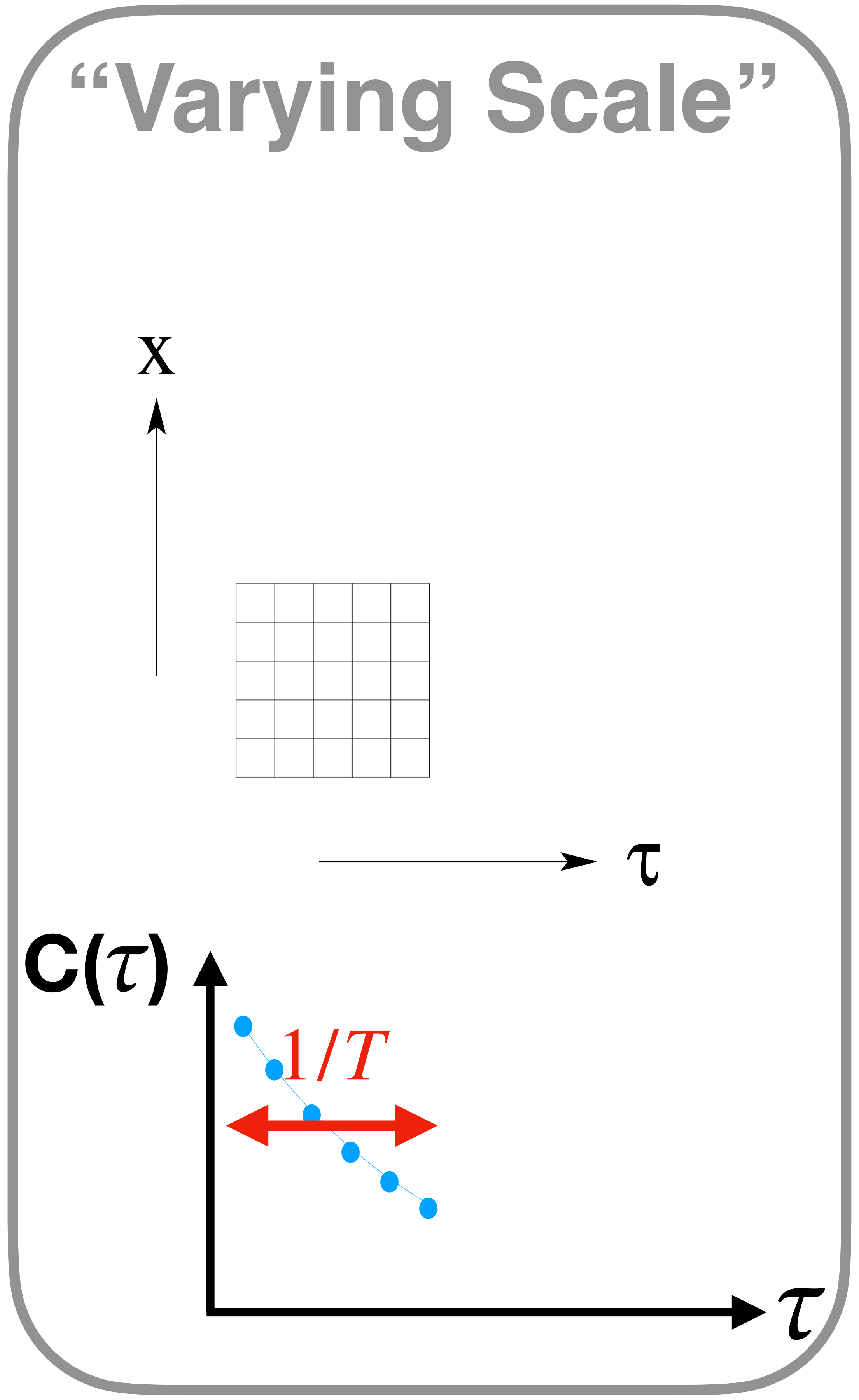
Anisotropic Lattice



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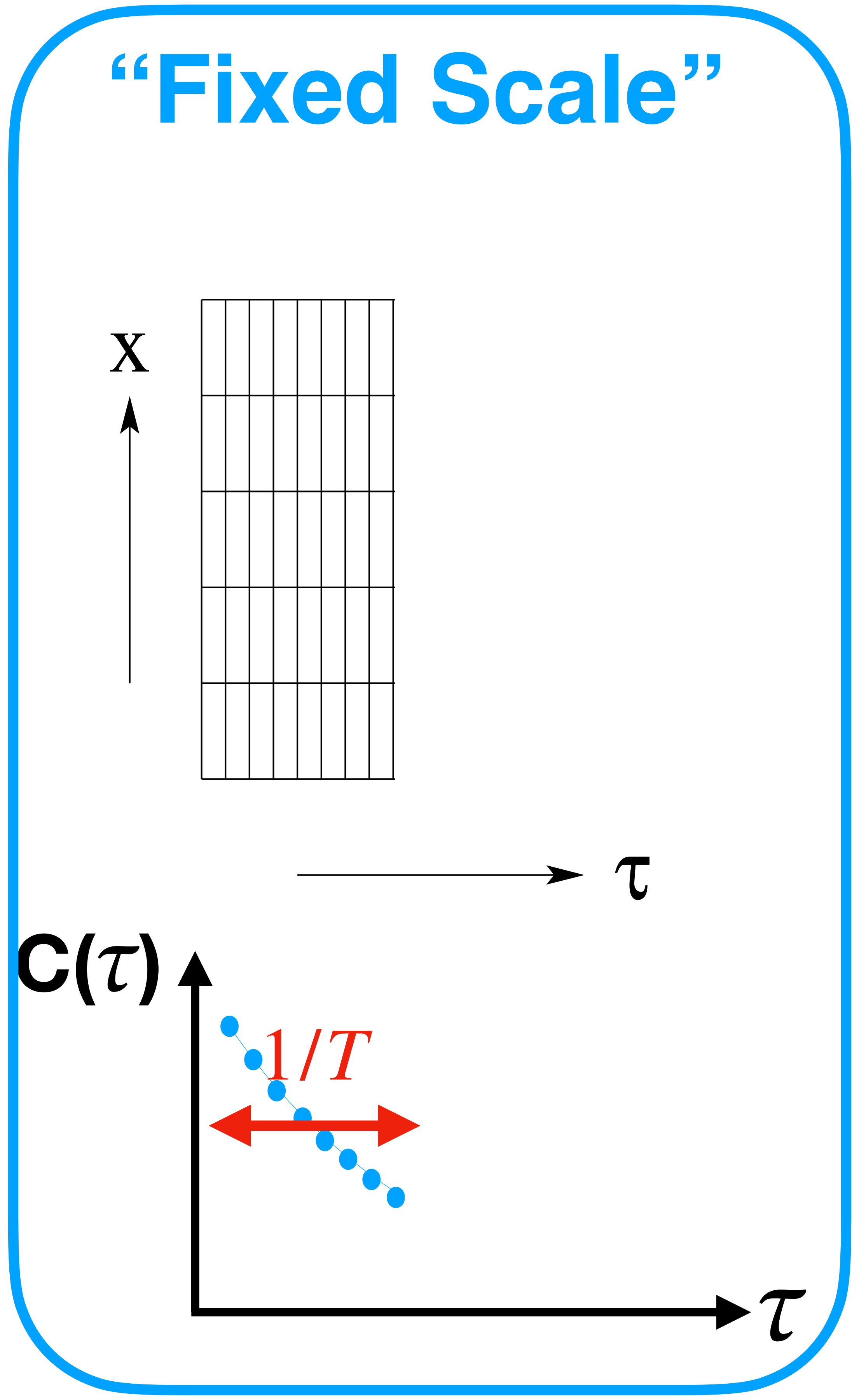

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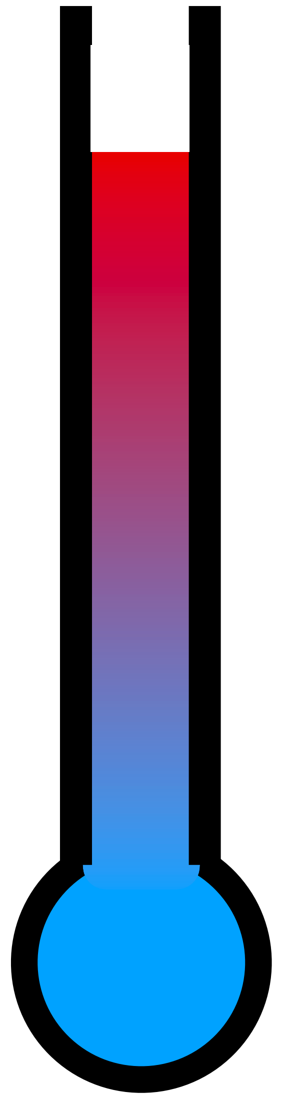

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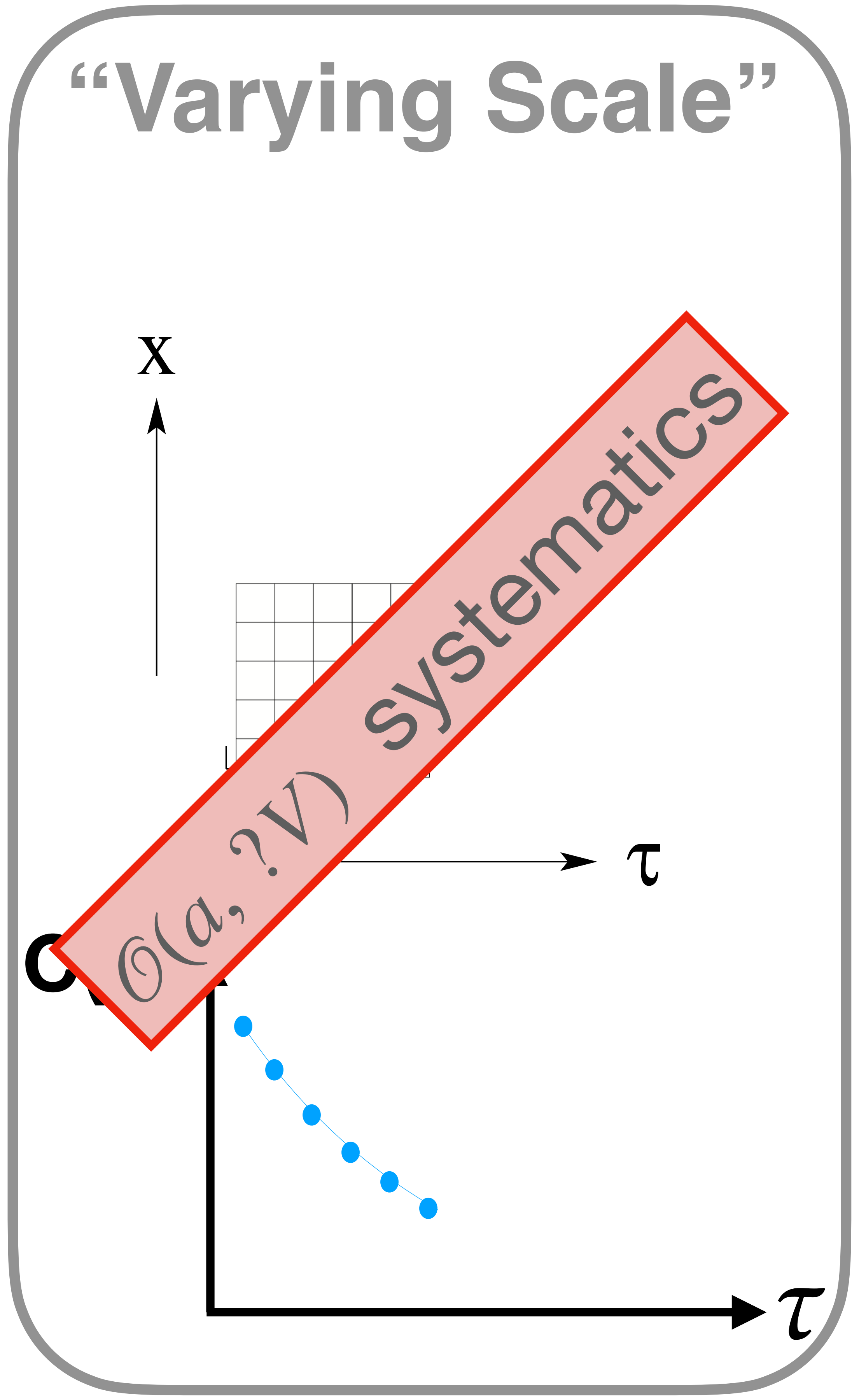
FASTSUM Approach:

Anisotropic Lattice



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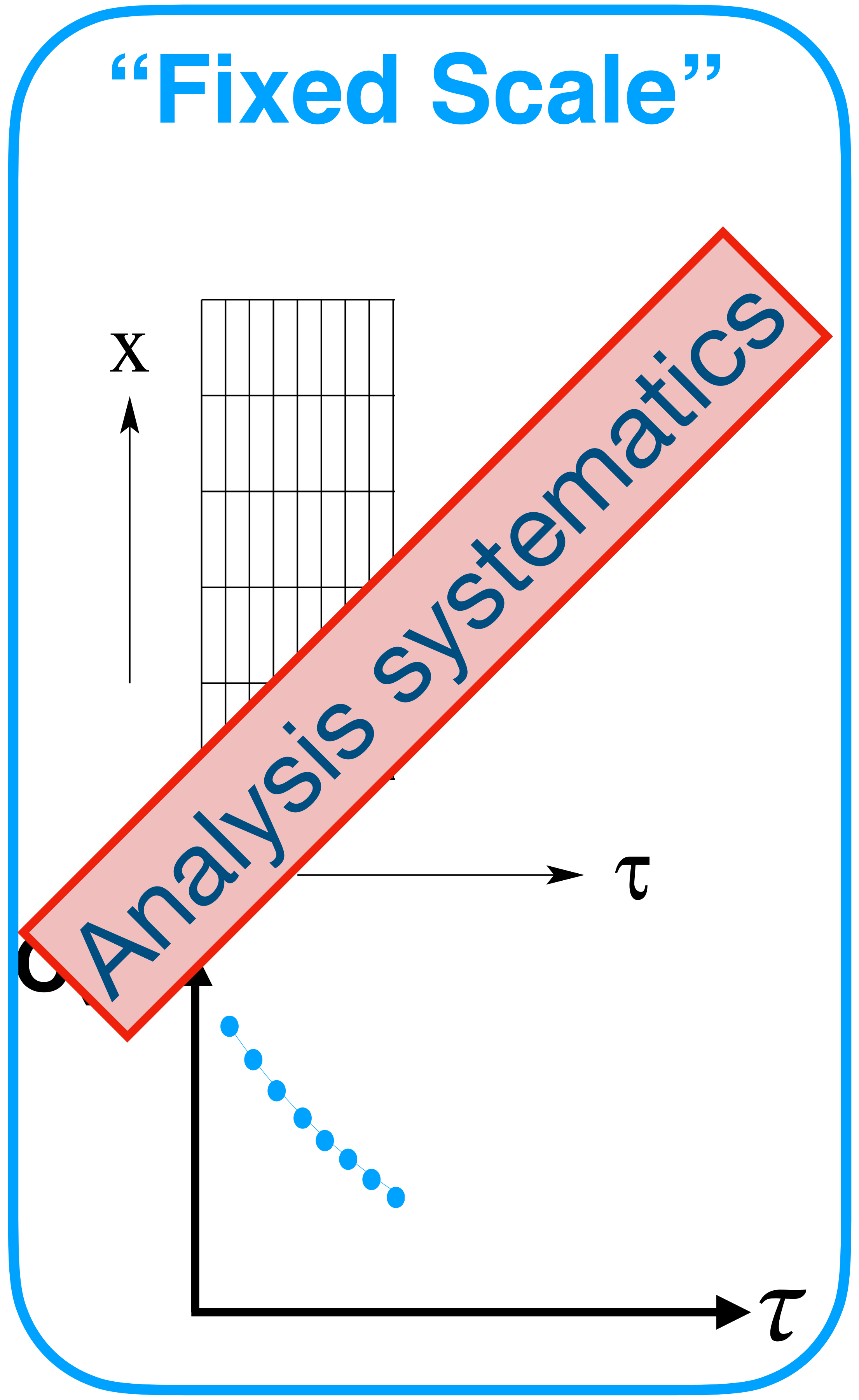
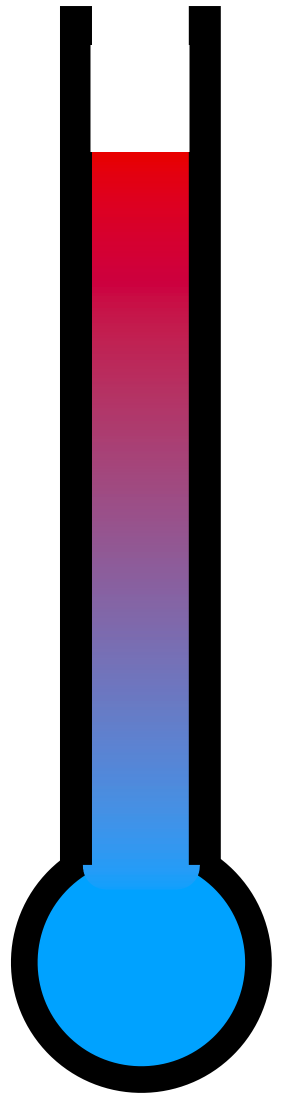


$N_\tau \to 0$

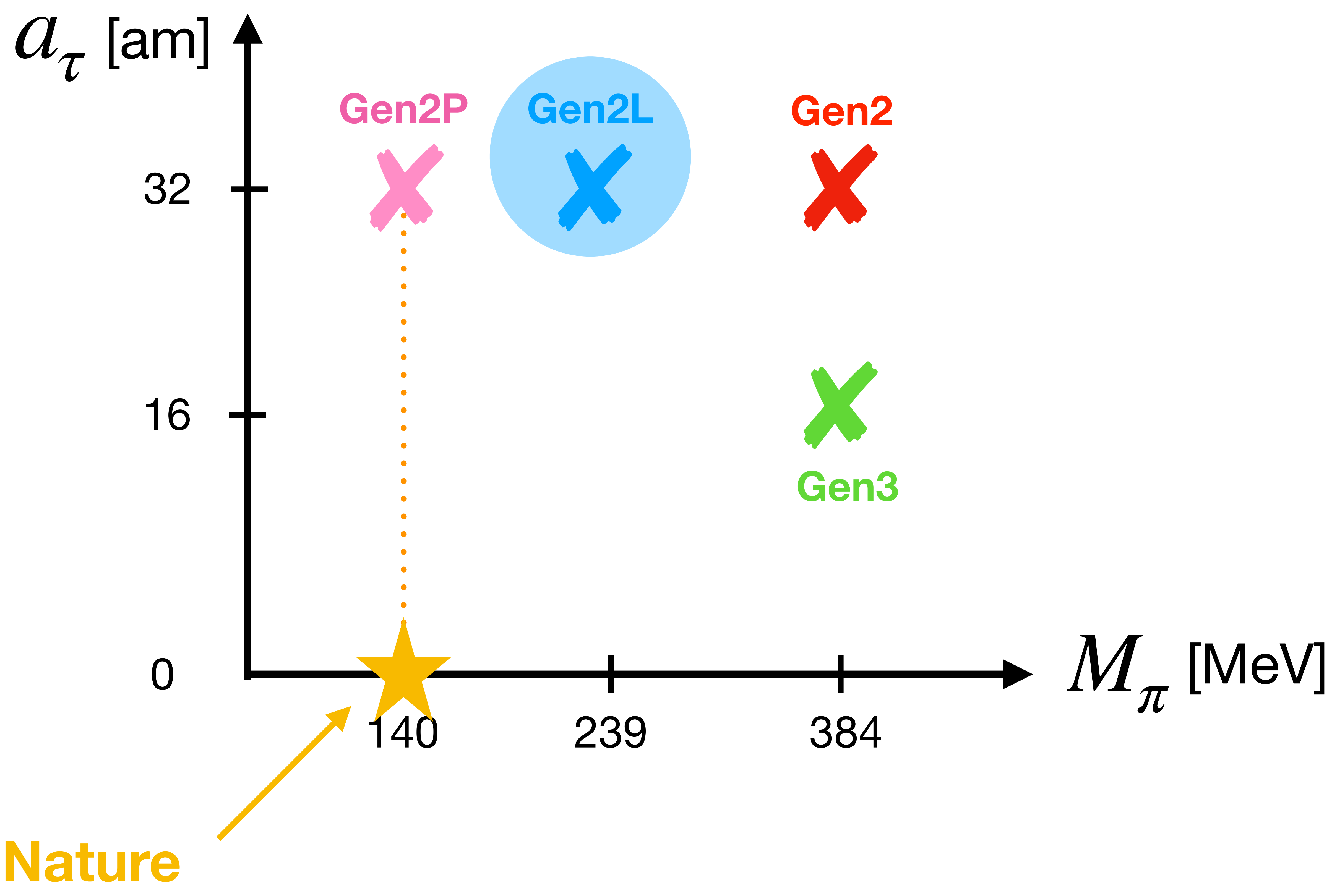


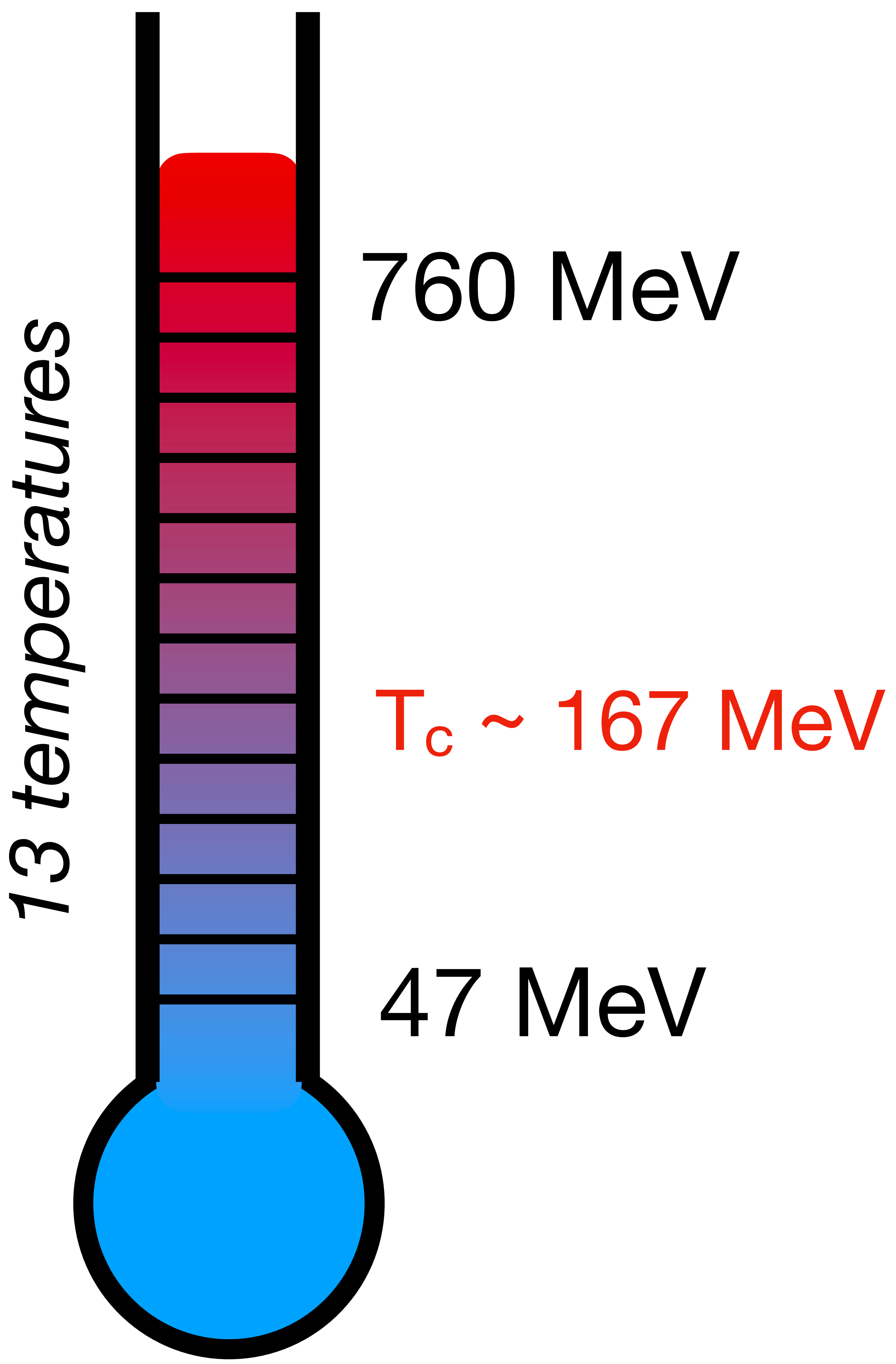
Going hotter…

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

FASTSUM Approach:

Lattice Parameters





Generation 2L
(2+1) flavour
a_s ~ 0.112 fm

Gauge Action:
Anisotropic,
Symanzik-improved

Fermion Action:
Wilson-clover,
tree-level tadpole,
stout-smeared links

FASTSUM Phys.Rev.D105(2022)3, 034504

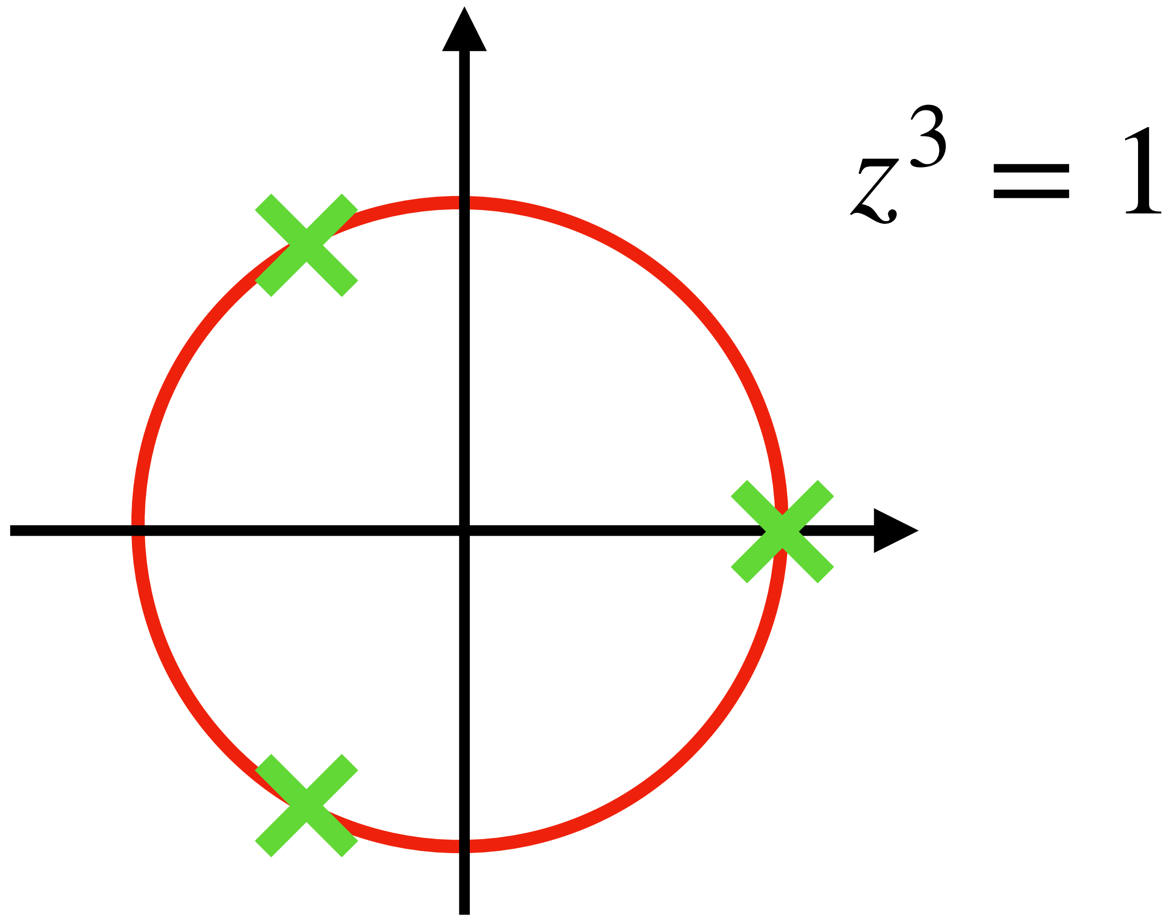
Maximal Centre Gauge

Choose gauge transform Ω

s.t. $U \longrightarrow \Omega\, U\, \Omega' \approx z\, V$ where $z \in Z(3)$ i.e. $z^3 = 1$

i.e. $\approx e^{i\,2\pi/3\,n}\, V$ where $n = \{-1,\, 0,\, +1\}$

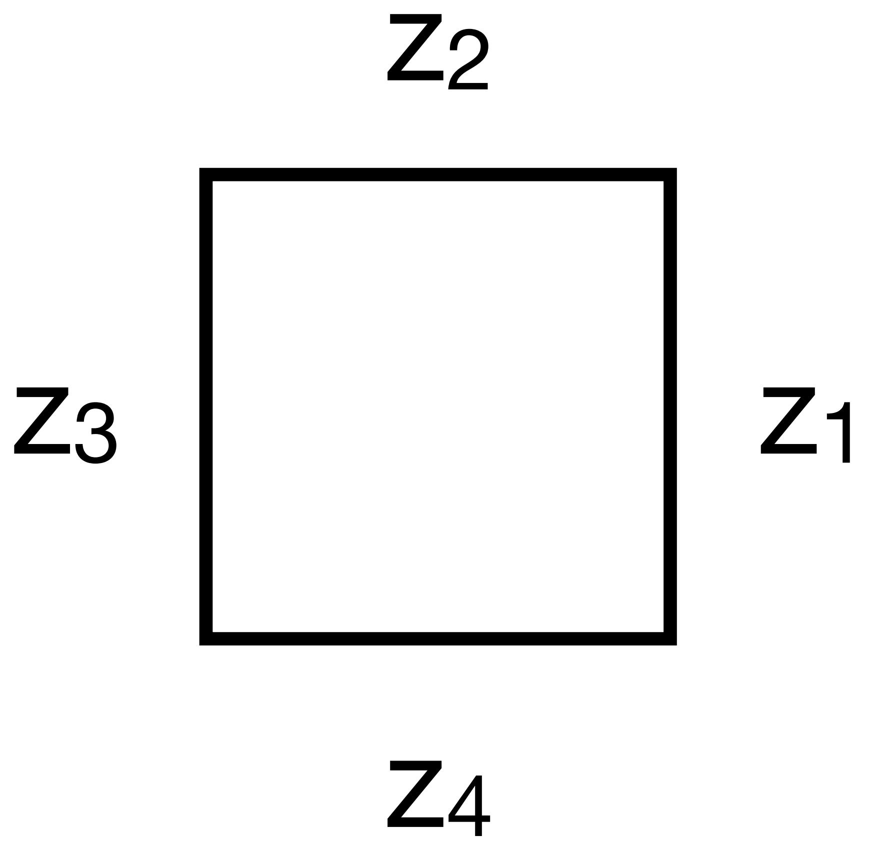
$V \sim$ Identity



Non-pert → $e^{i\,2\pi/3\,n}$; "Perturbative" → V_{pert}

Can factorise $\Omega\, U\, \Omega = e^{i\,2\pi/3\,n}\, V_{\text{pert}} = z\, V_{\text{pert}}$

Product around MCG Plaq = $U^{MCG}_{\text{plaq}} = \prod_{i=1}^{4} z_i \in Z(3)$

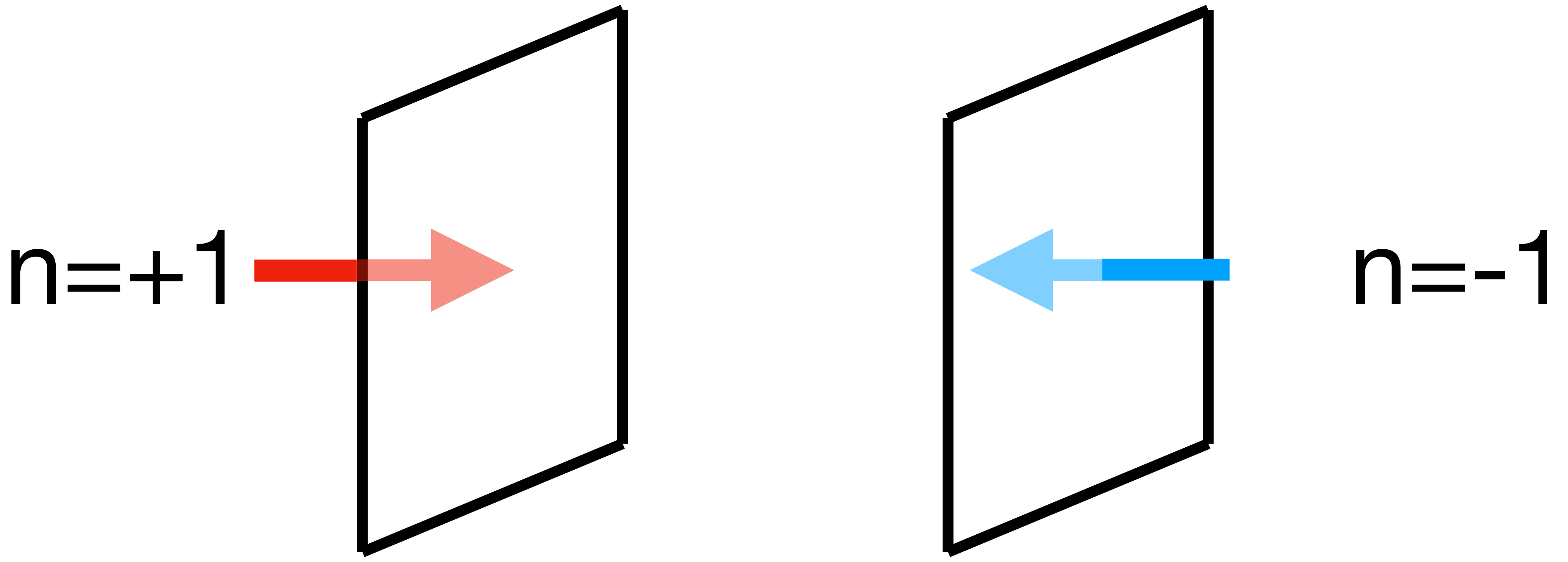


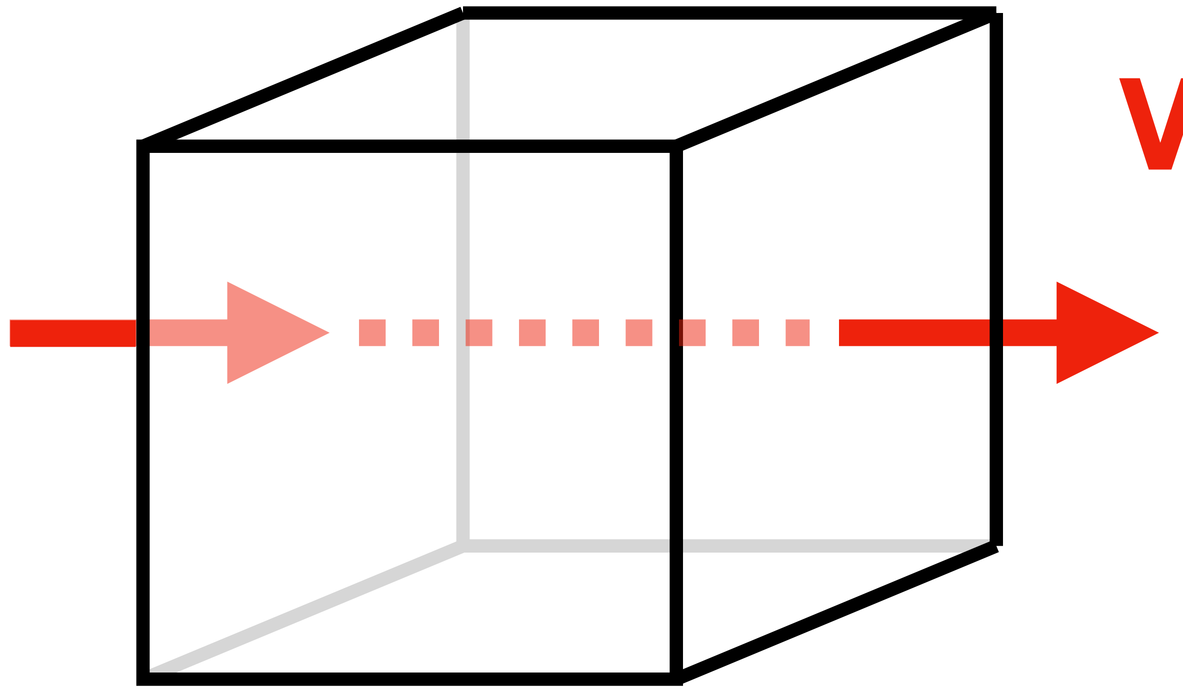
$\Longrightarrow U^{MCG}_{\text{plaq}}$ either $e^{\pm i\,2\pi/3}$ "pierced" or 1 not pierced

Maximal Centre Gauge

Vortices, Flux & Branching Points

U^{MCG}_{plaq} either
- $e^{\pm i\, 2\pi/3}$ "pierced"
- 1 not pierced

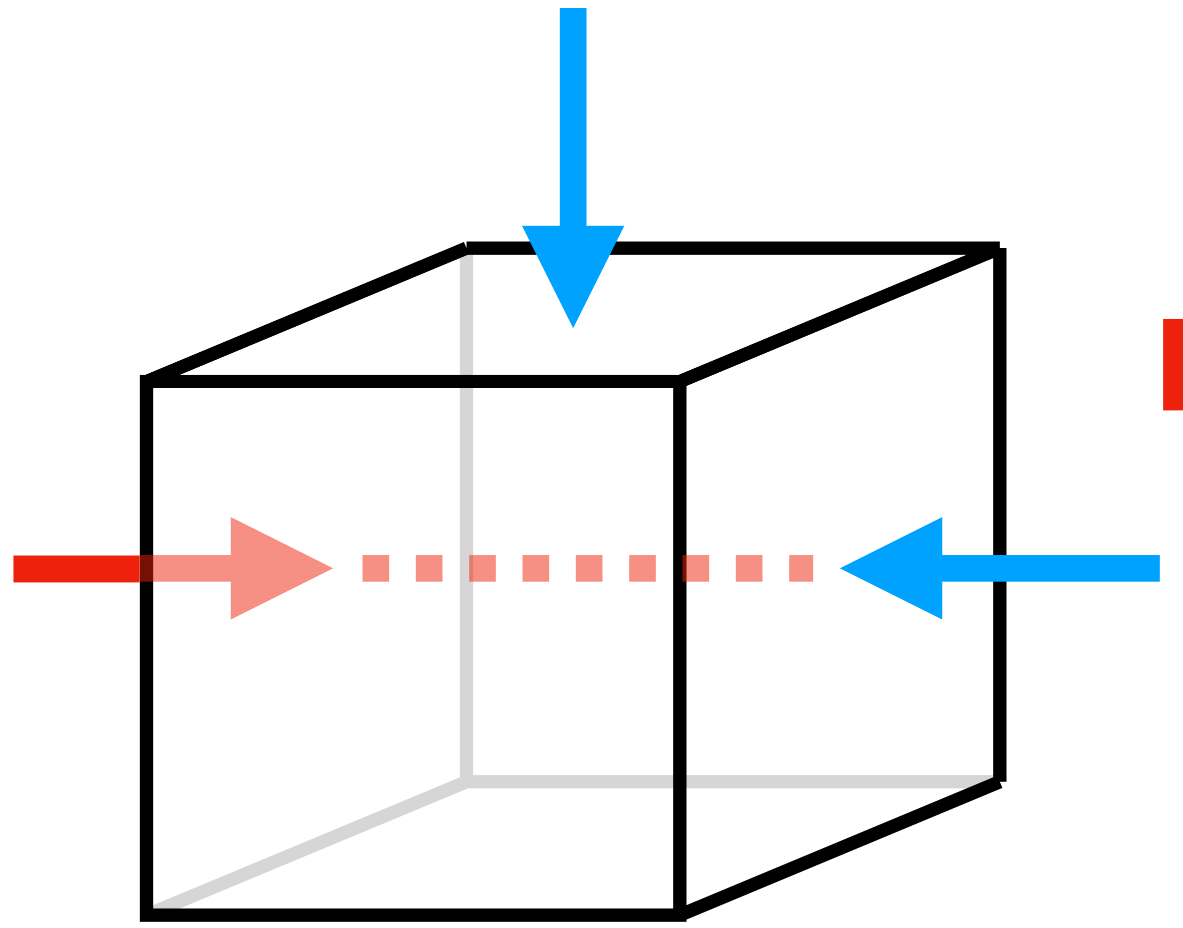




Vortex

$N_{tot} = +1 - 1 = 0$

i.e. $e^{2\pi i/3} \times e^{-2\pi i/3} = 1$



Branching Point

$N_{tot} = +1 + 1 + 1 \text{ mod } 3 = 0$

i.e. $e^{2\pi i/3} \times e^{2\pi i/3} \times e^{2\pi i/3} = 1$

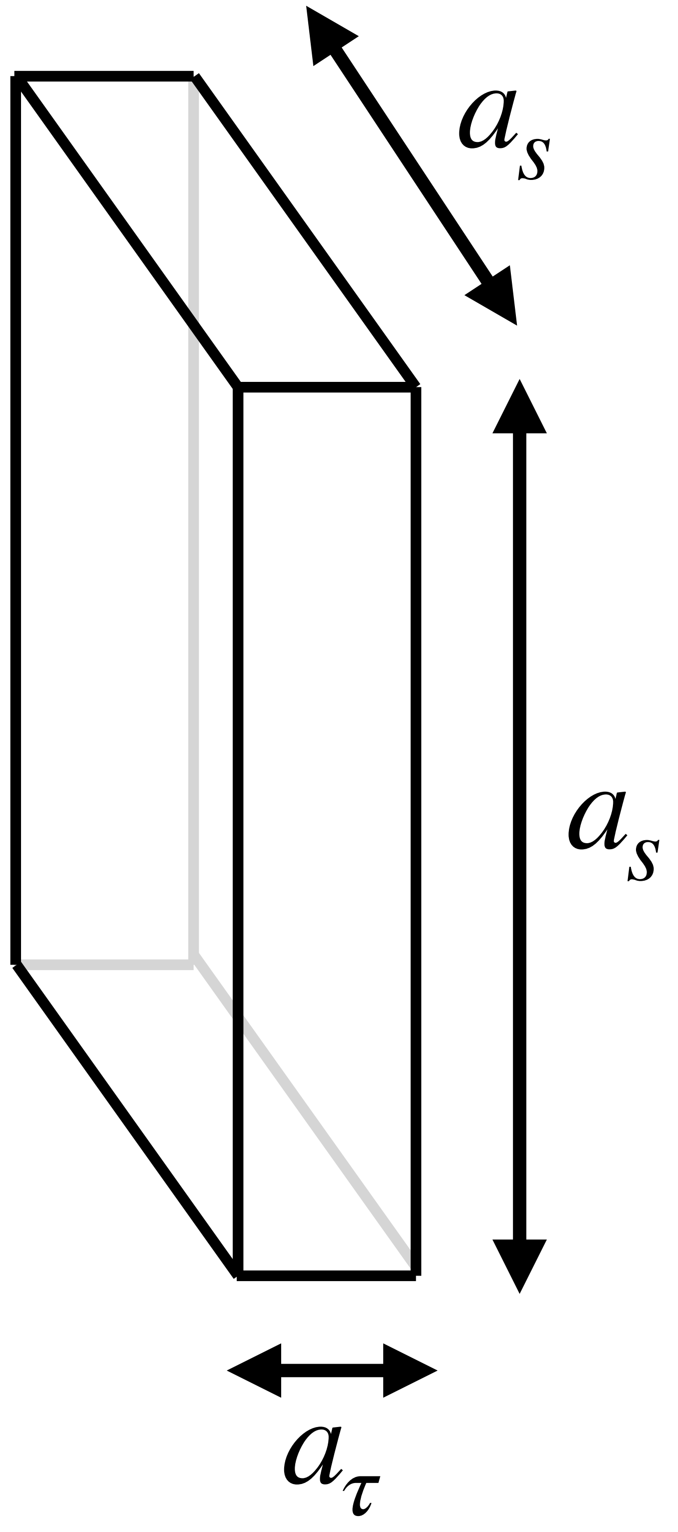
Conservation of Flux modulo 3

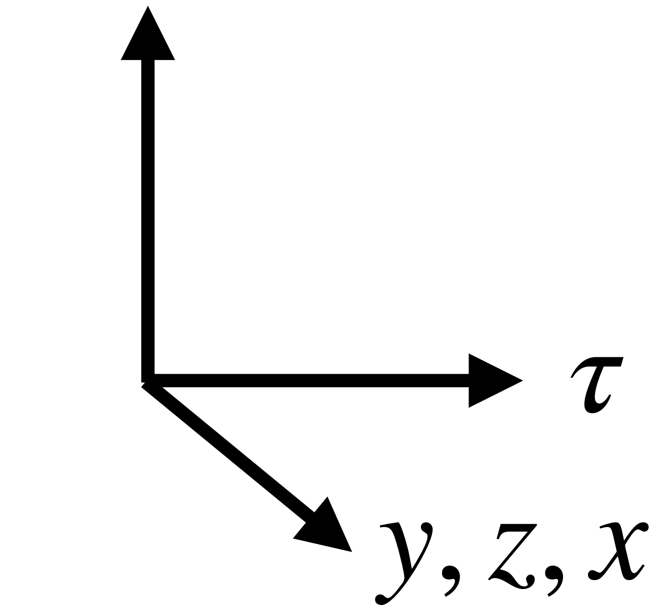
Maximal Centre Gauge

Anisotropic Lattices

Reminder: $a_\tau \ll a_s$

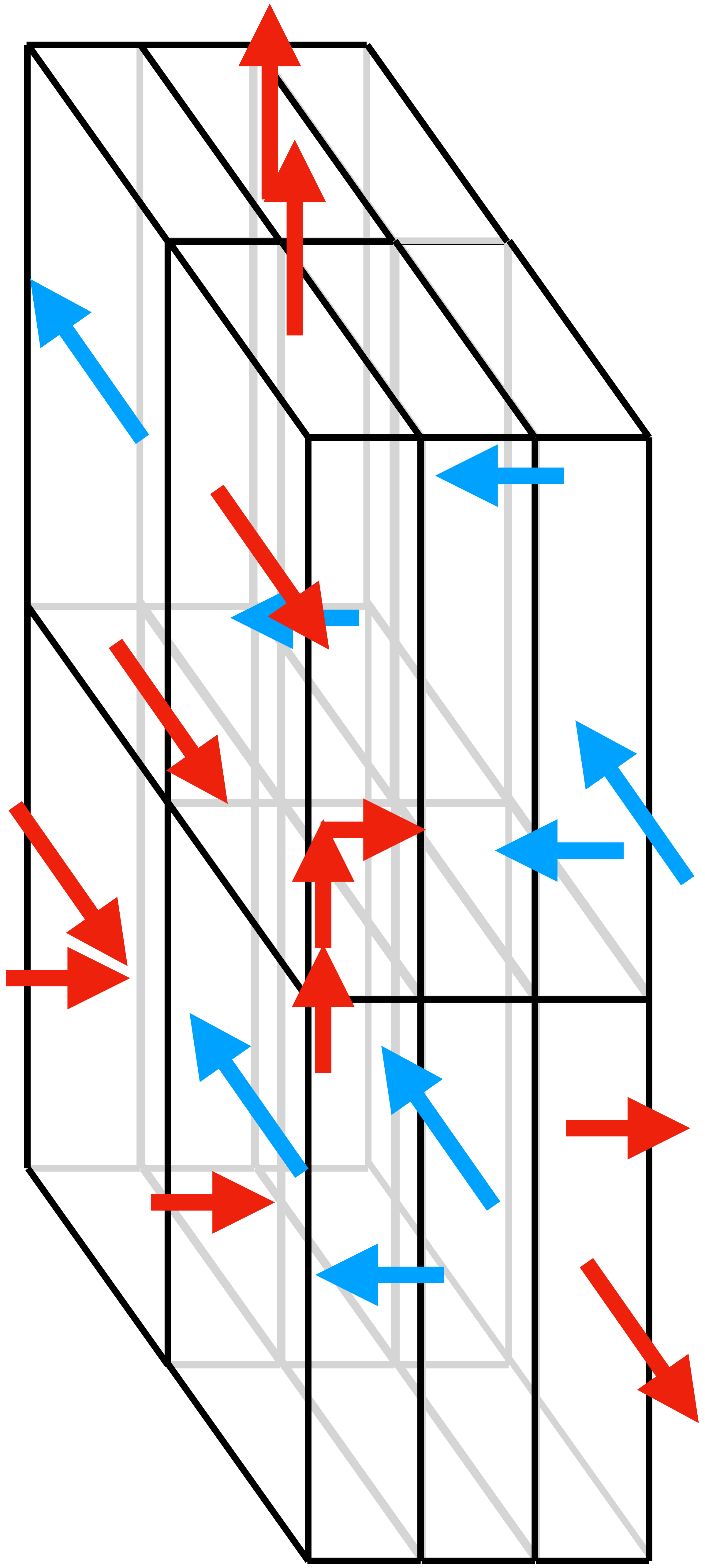
Fundamental 3-Vol:





Check:

No. of Vortices / Area is isotropic



Gauge Fixing

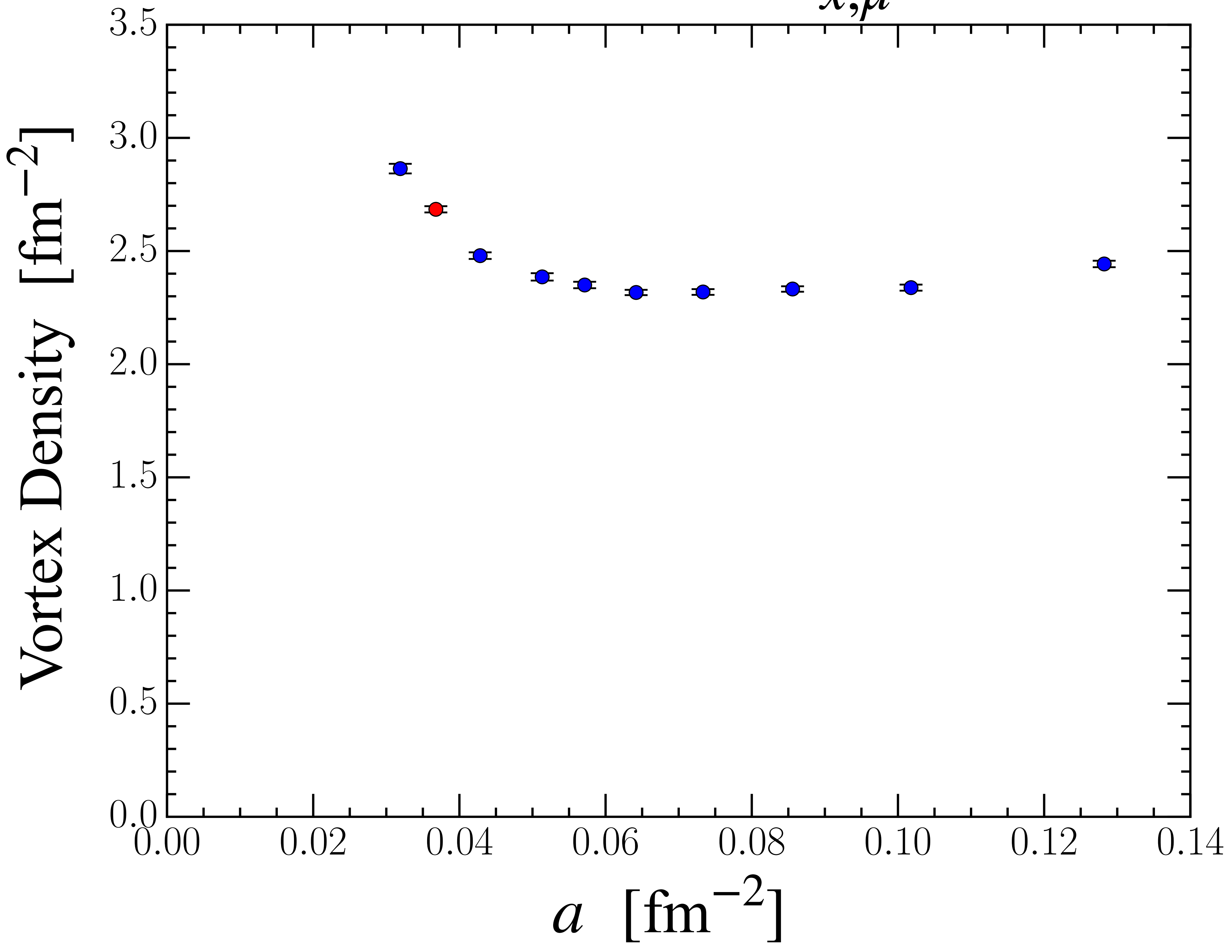
Quenched Isotropic Scaling Plots

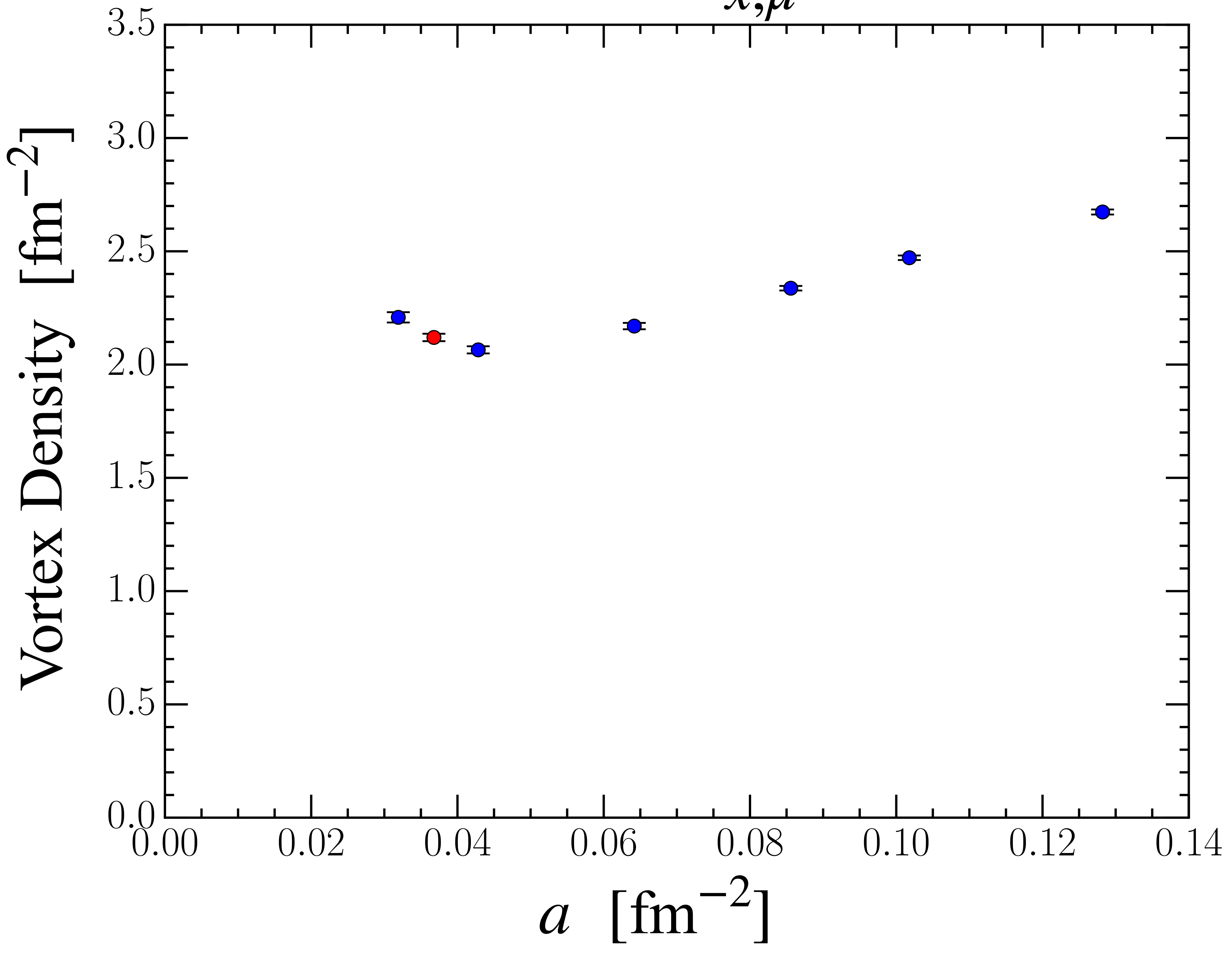
To fix to Maximal Centre Gauge, key idea is to maximise $\sum_p |TrU_p|$

Various functionals that can be used:

"Mesonic" $\mathscr{F} = \sum_{x,\mu} |TrU_\mu(x)|^2$

"Baryonic" $\mathscr{F} = \sum_{x,\mu} Re\{TrU_\mu(x)\}^3$





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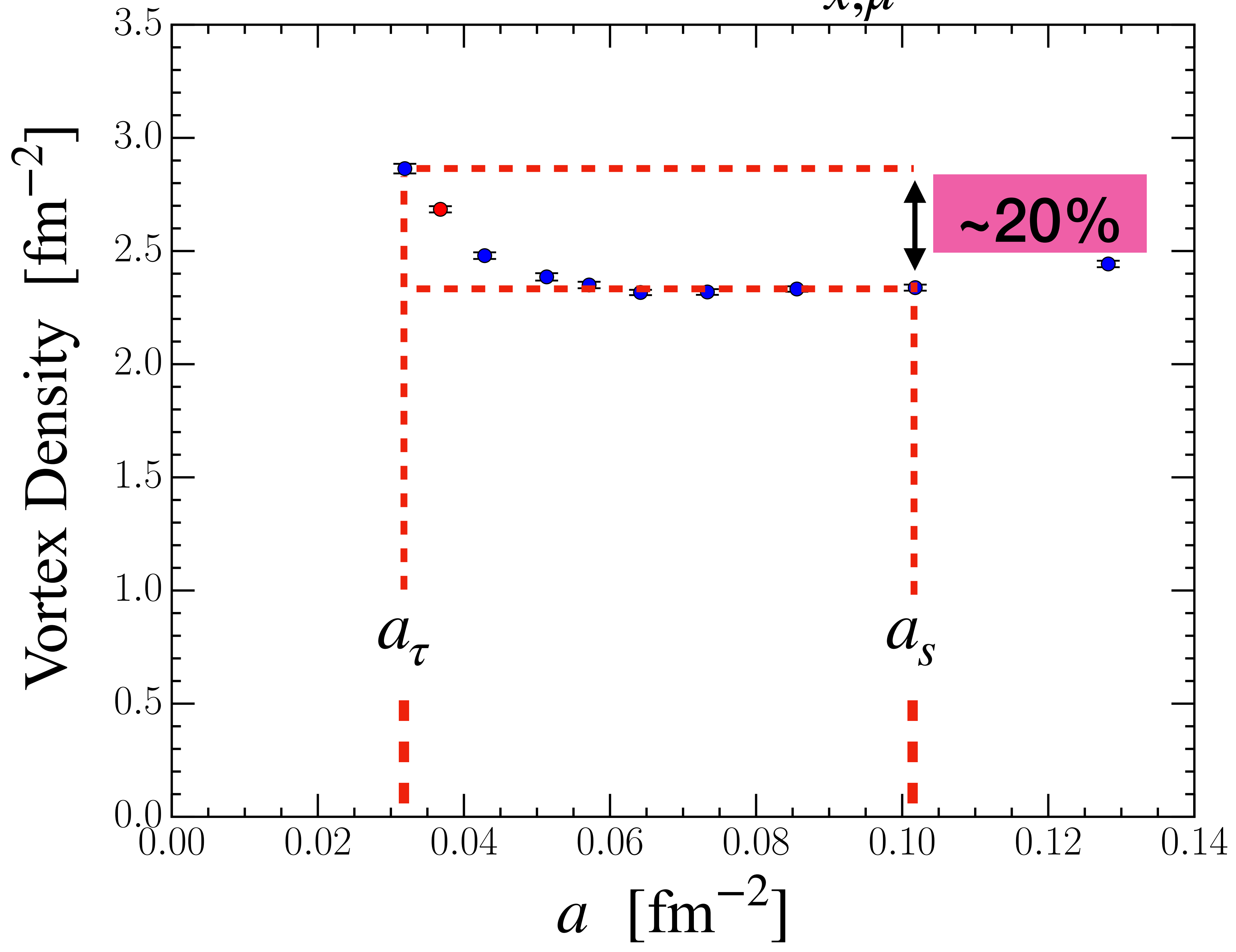
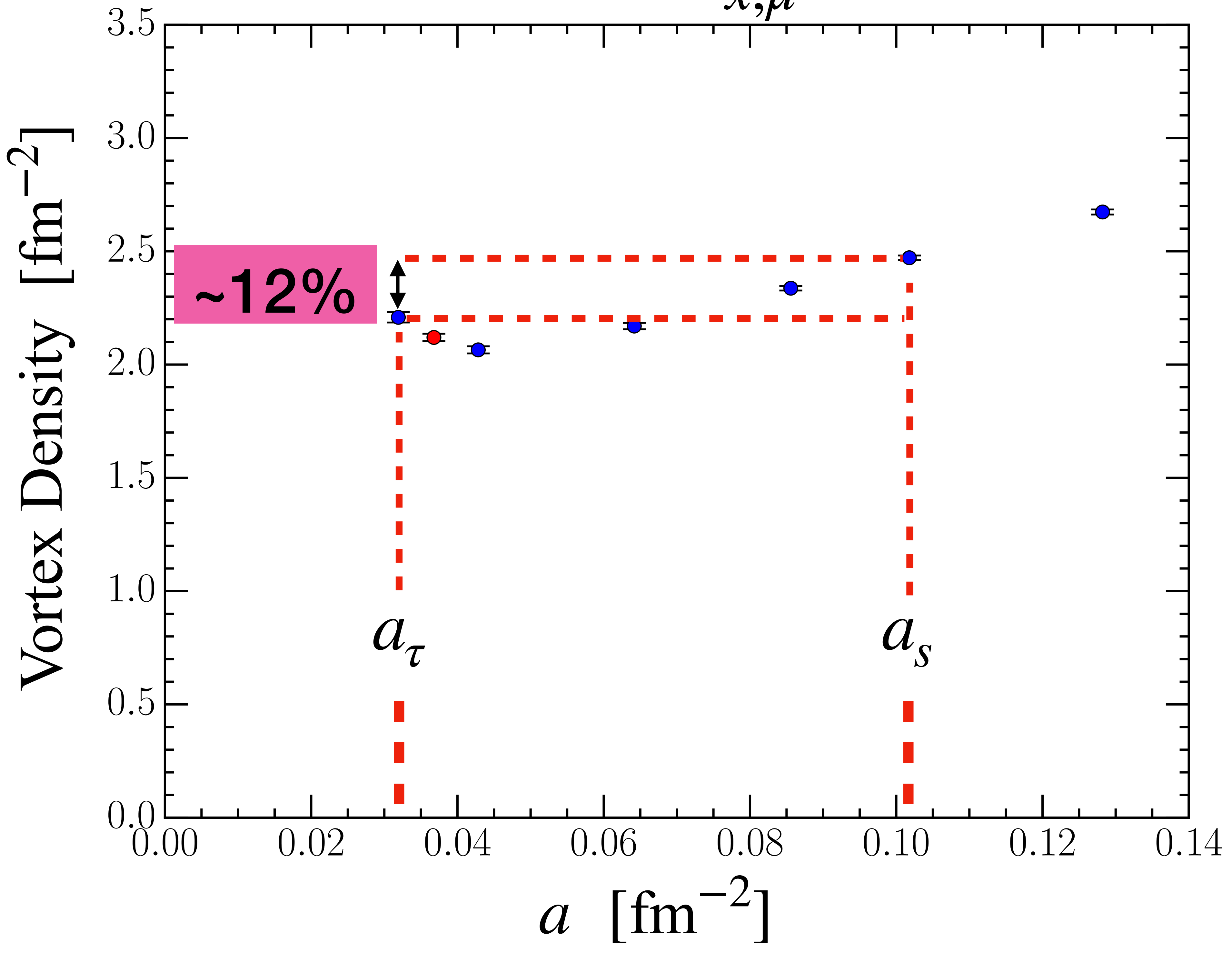
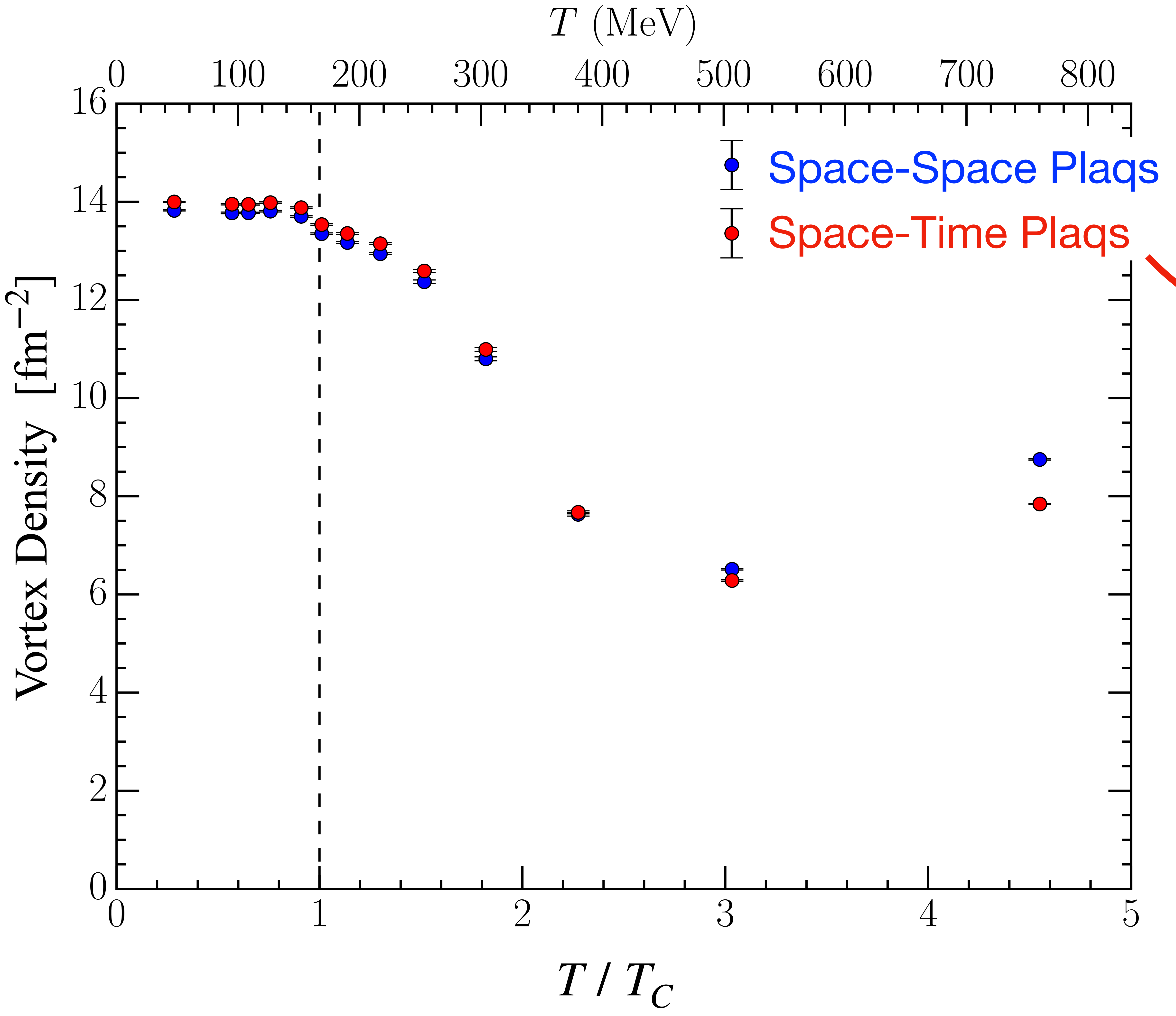
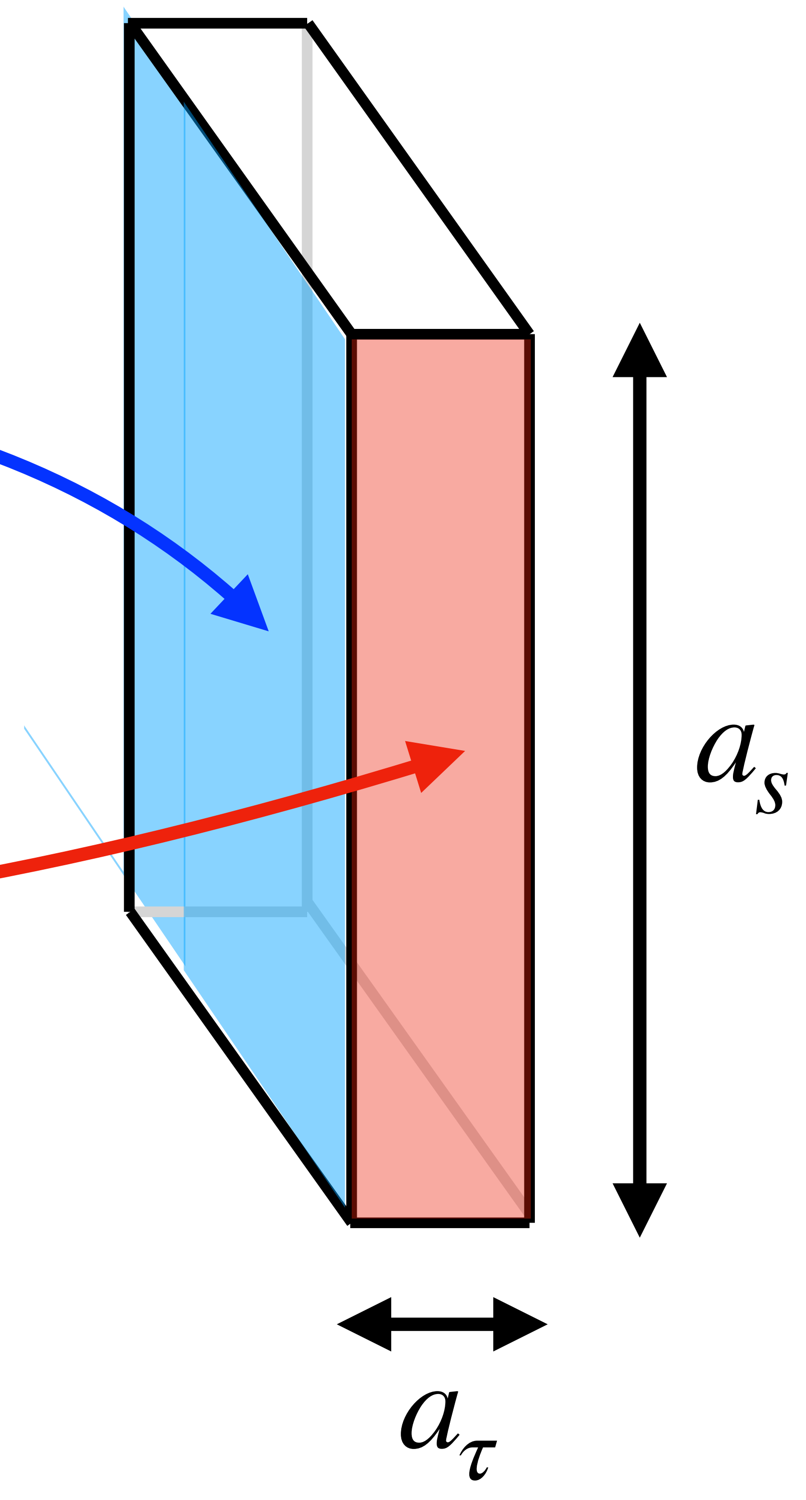




Vortex Density

Number per Area





Method:

1. MCG with isotopic functional
2. MCG with anisotropic

T_C from Chiral Condensate

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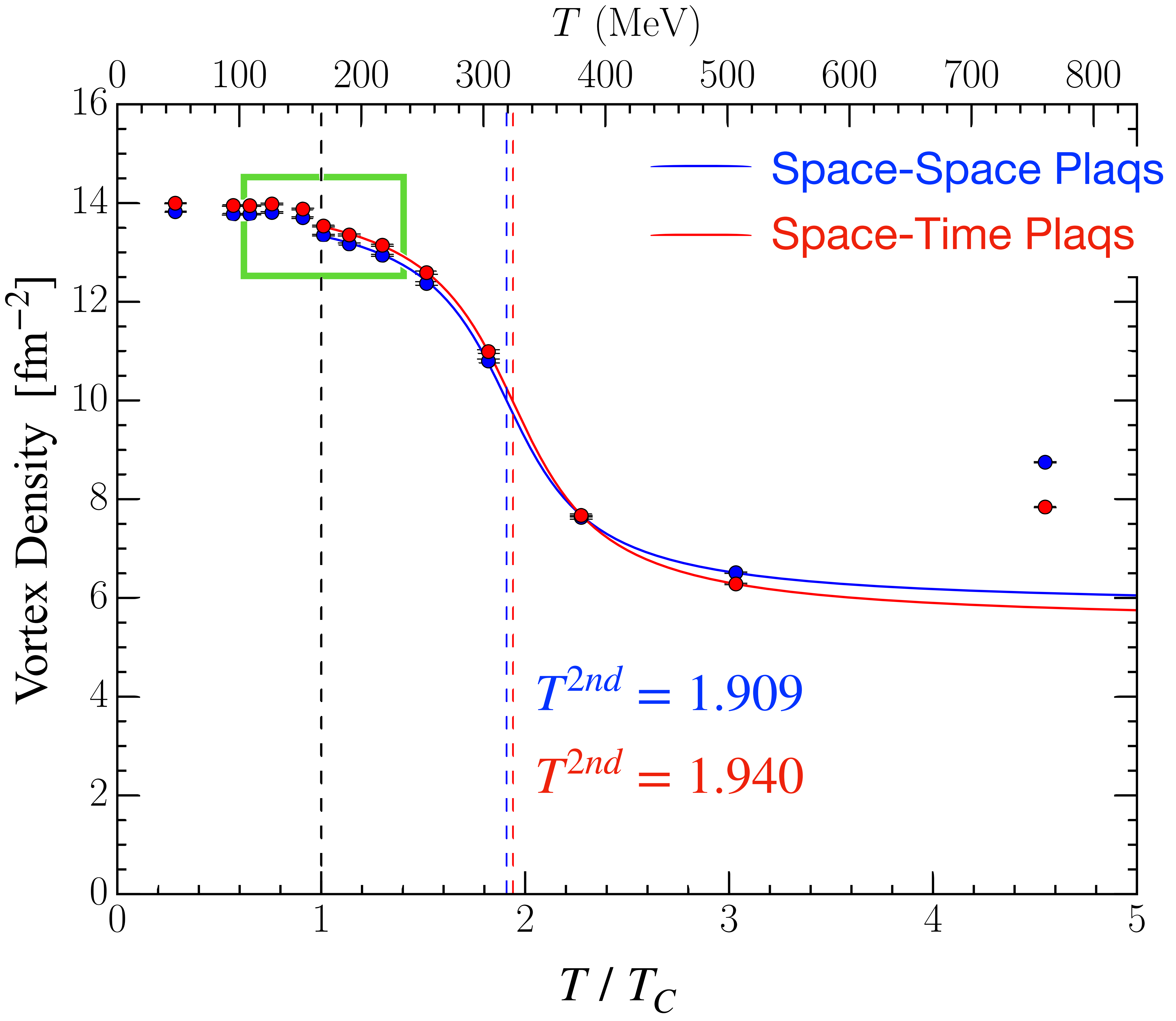
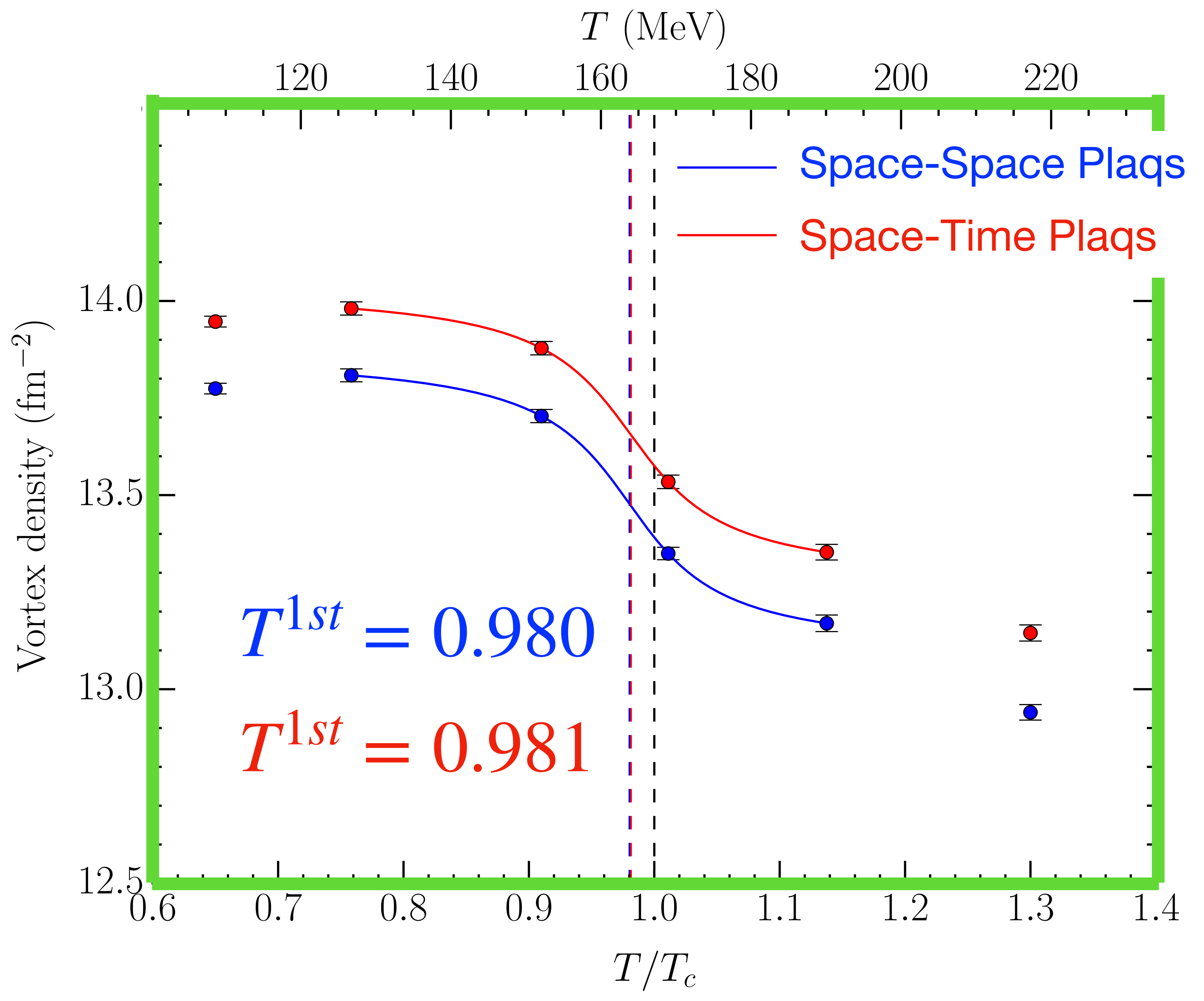
Vortex Density

Fits around transitions

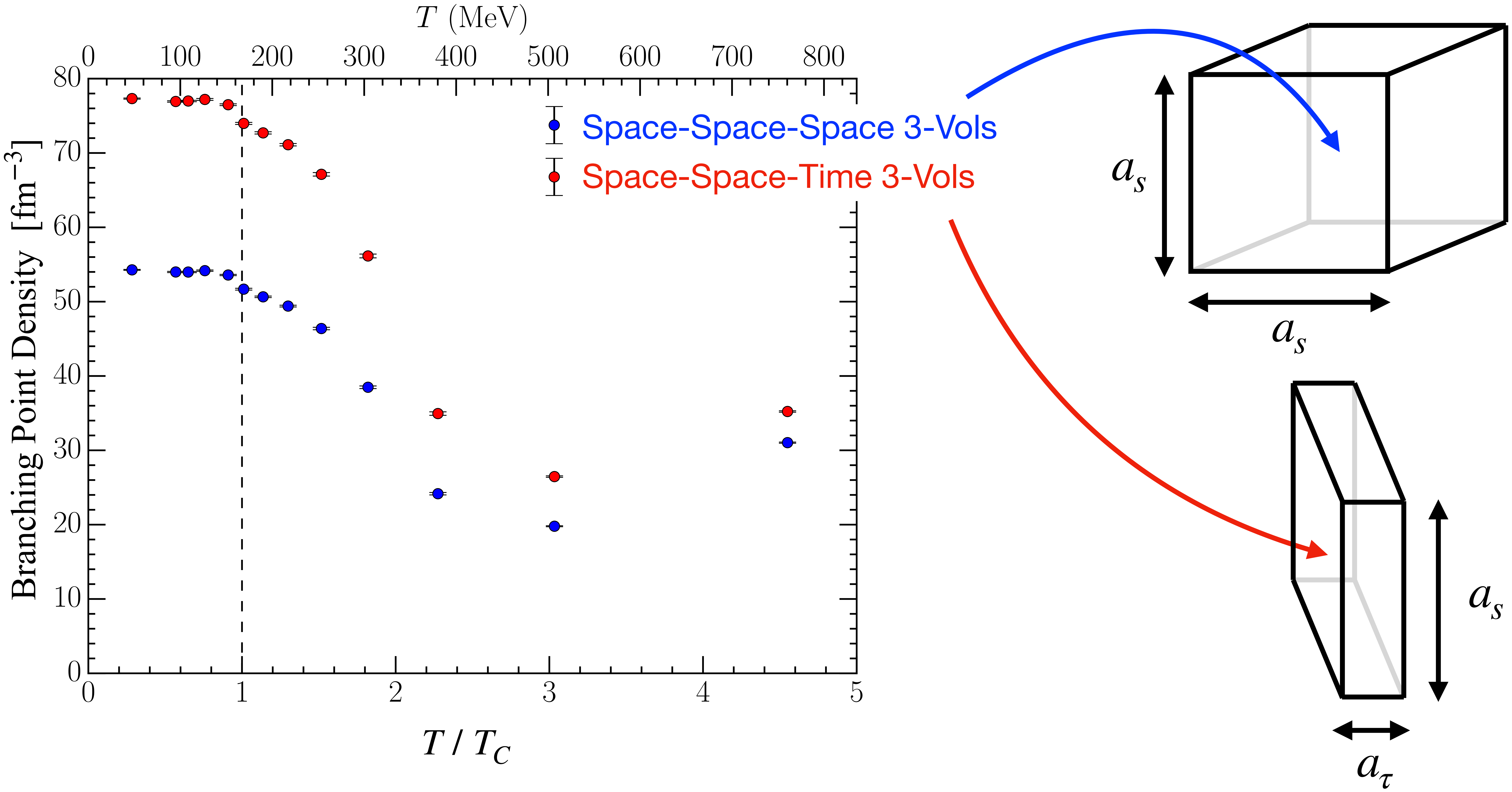


Fit around T_C



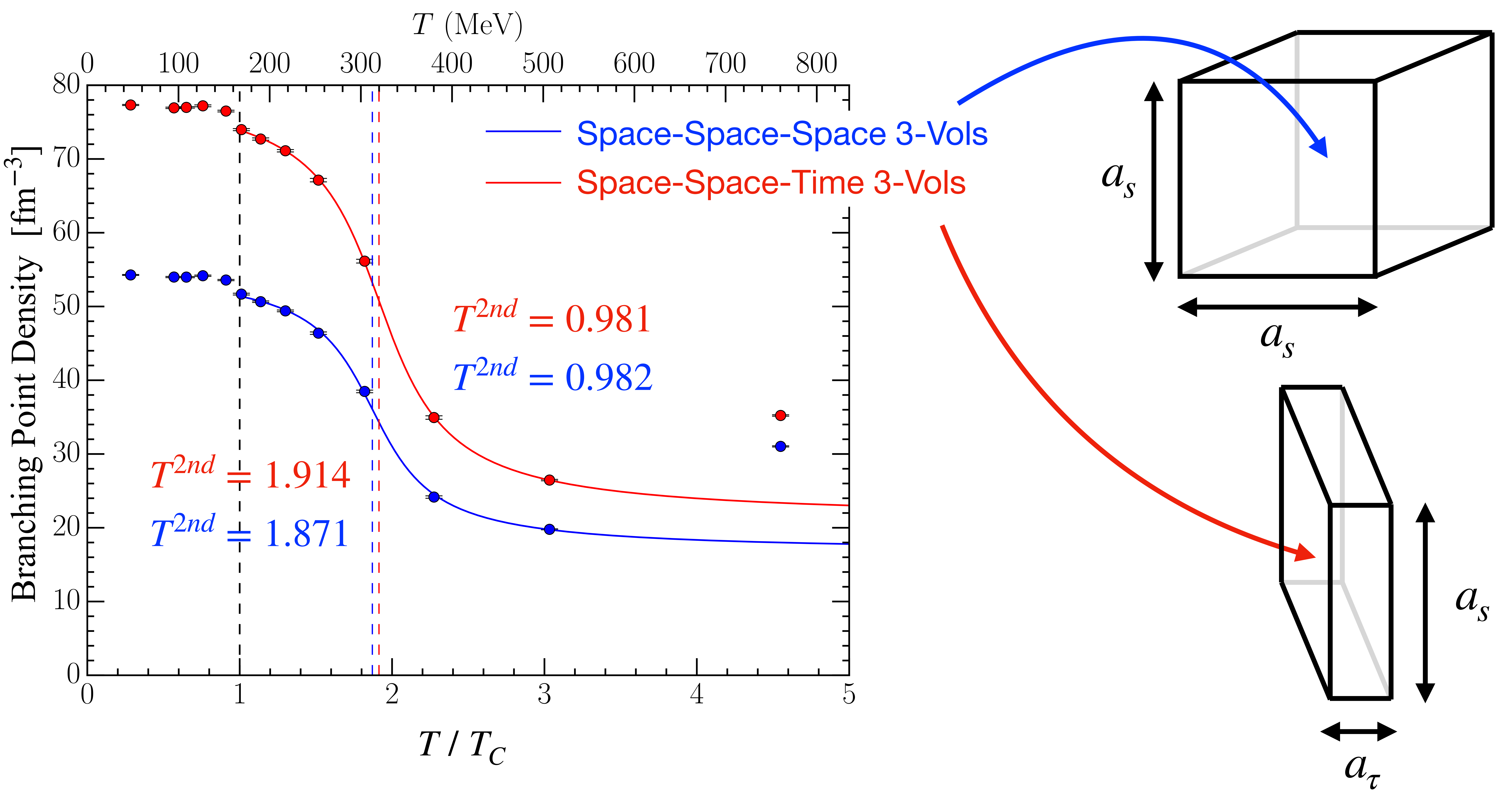
Branching Point Density

Number per 3-Volume



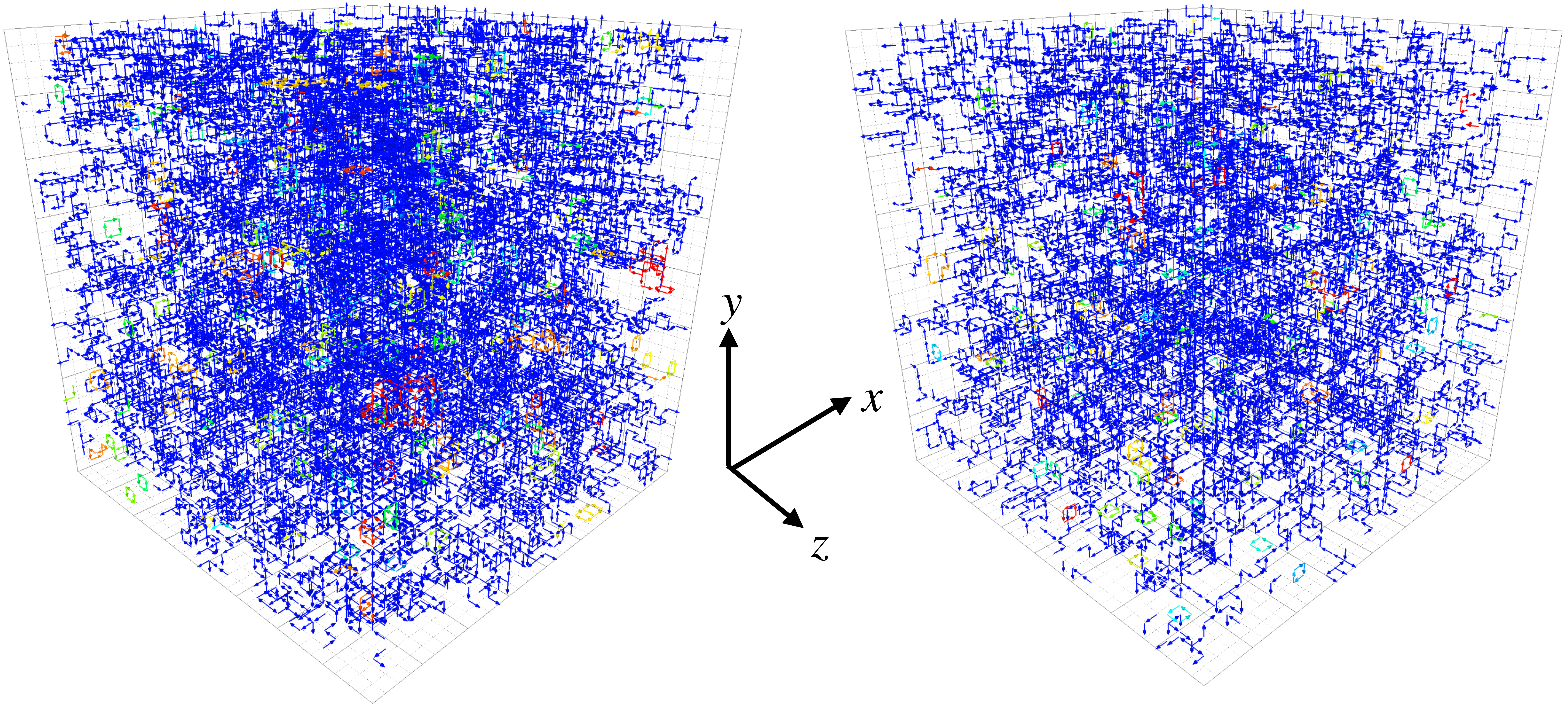
Branching Point Density

Number per 3-Volume



Visualisation

Space-Space-Space

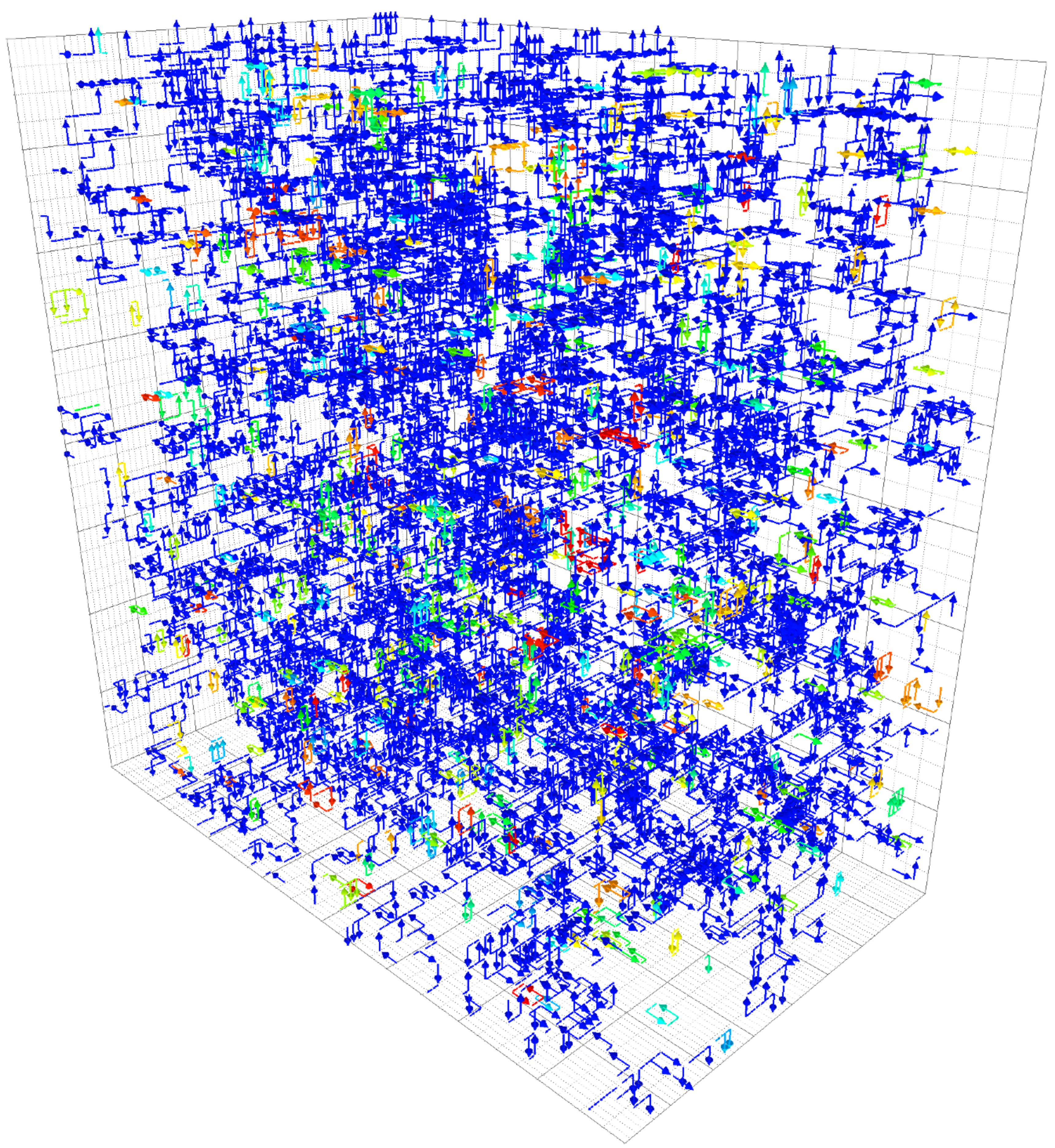


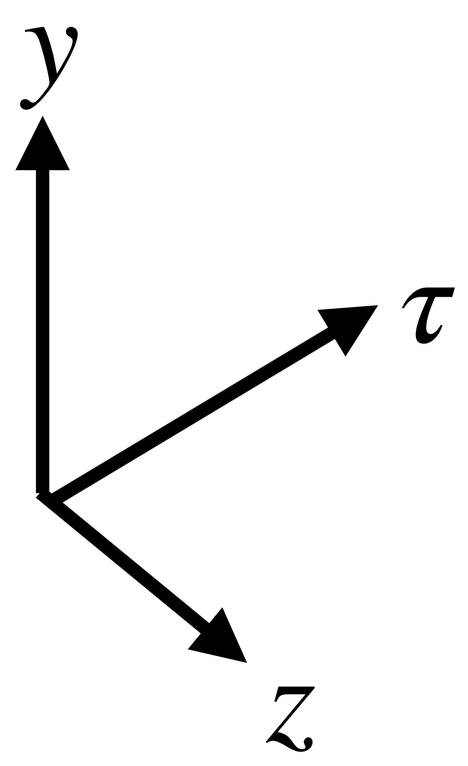
Nt=64 T=95MeV

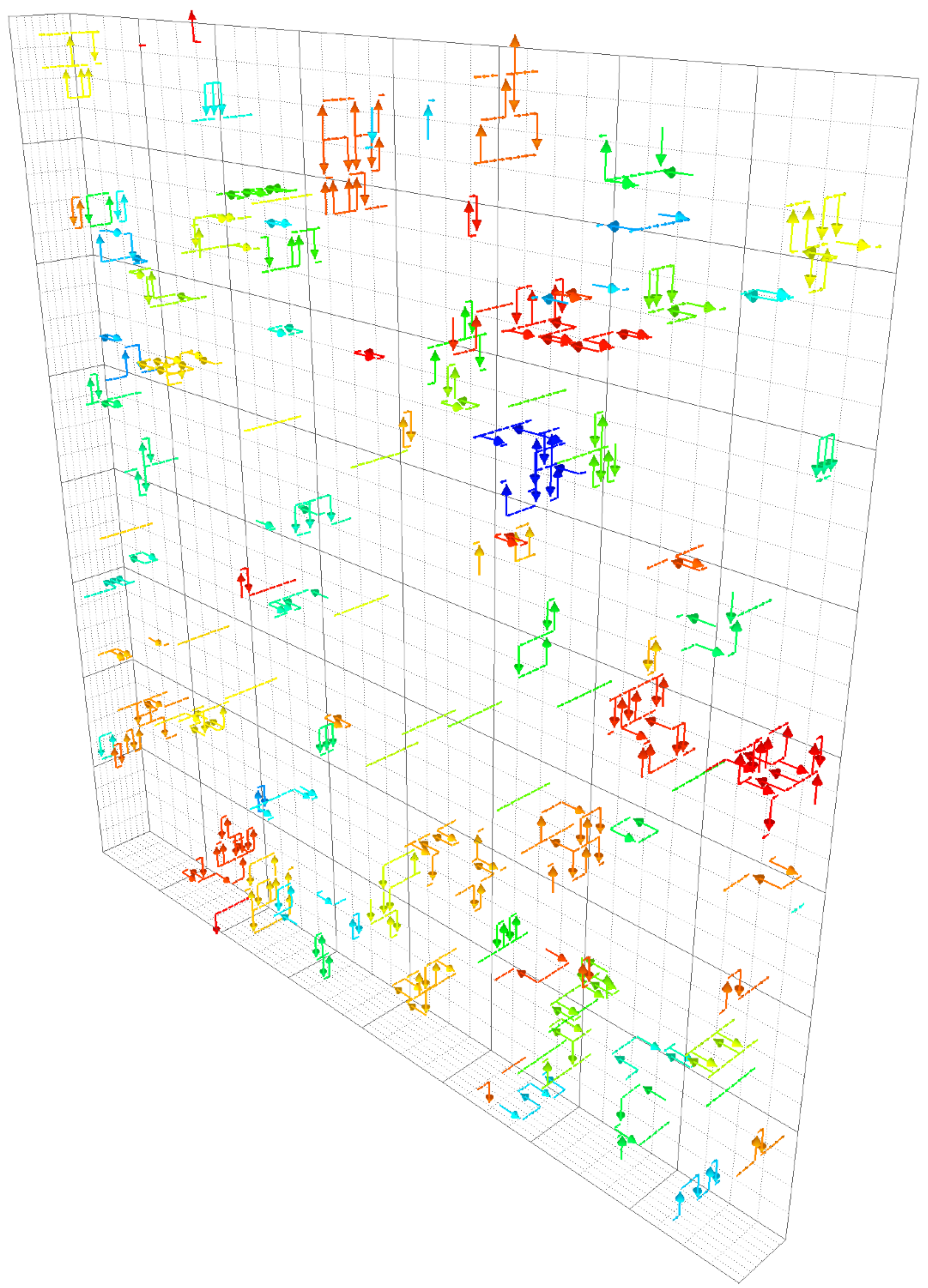
Nt=8 T=760MeV

Visualisation

Space-Space-Time







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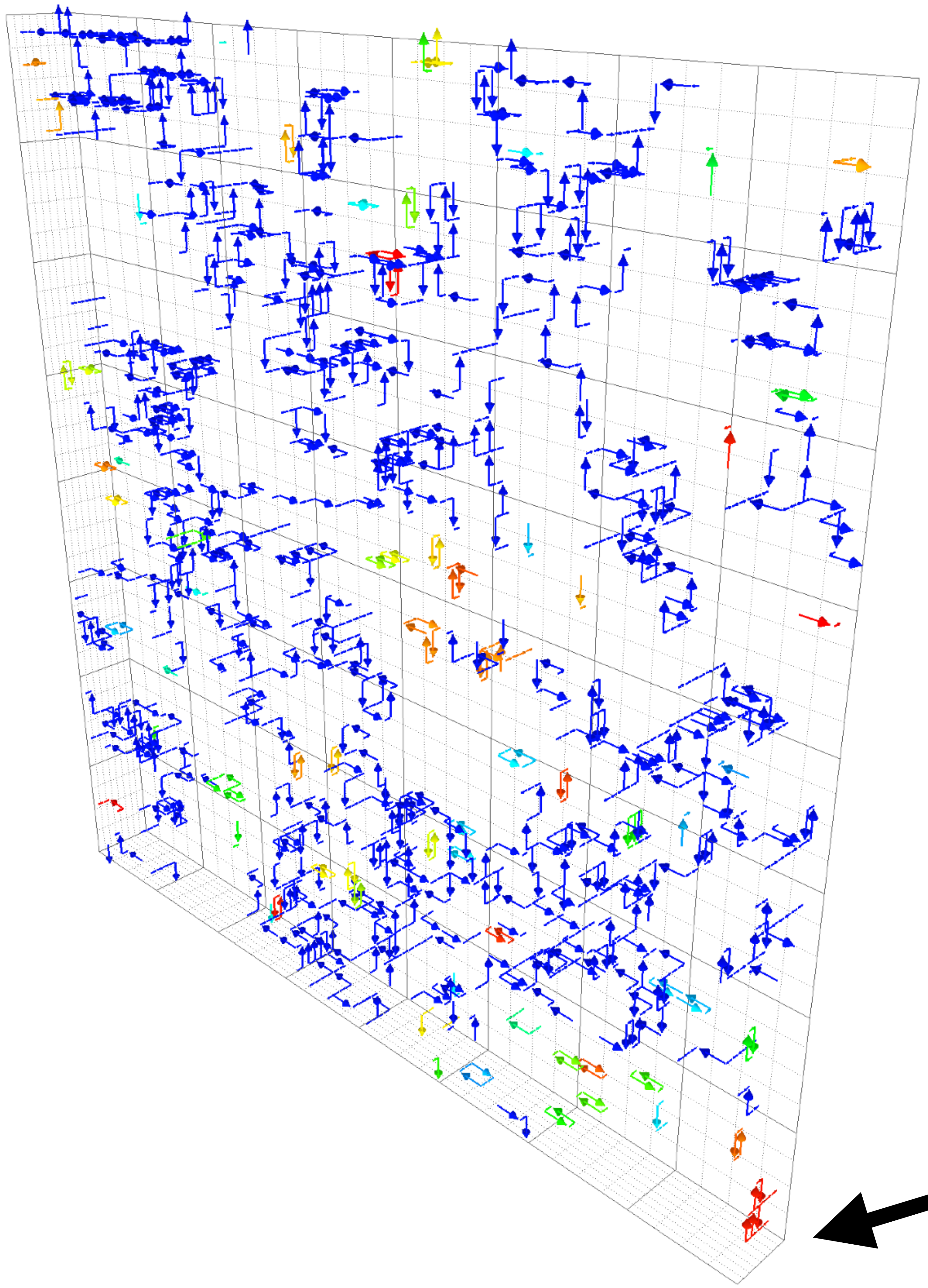
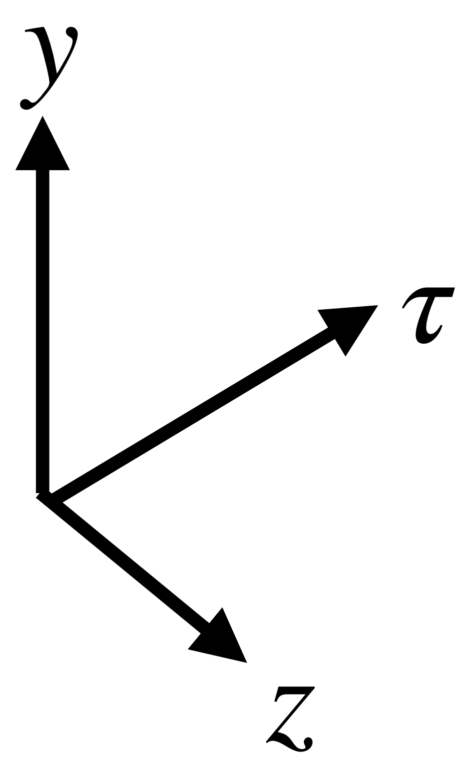
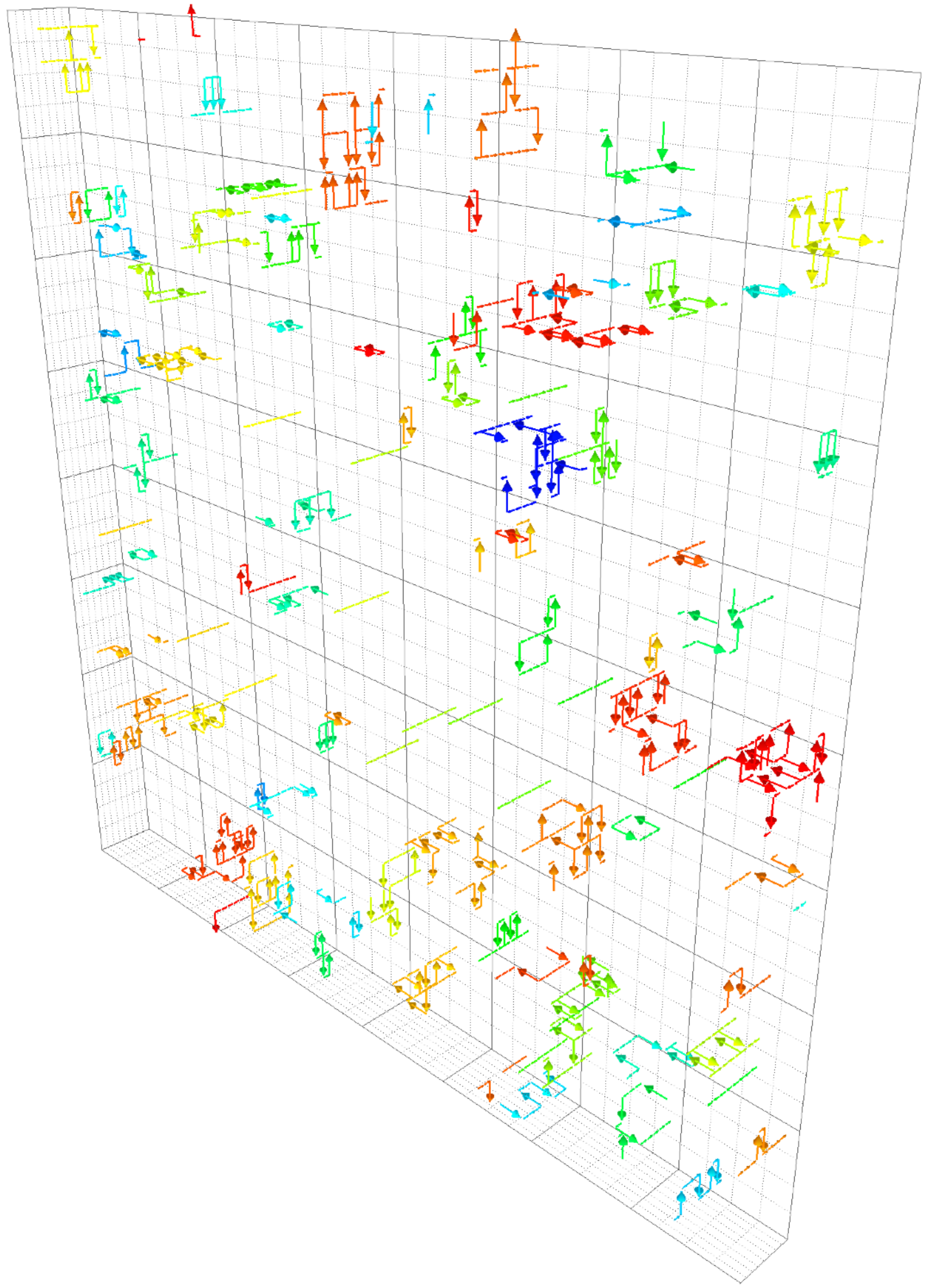
Nt=8 T=760MeV

Visualisation

Space-Space-Time







CROPPED
to 8 timeslices

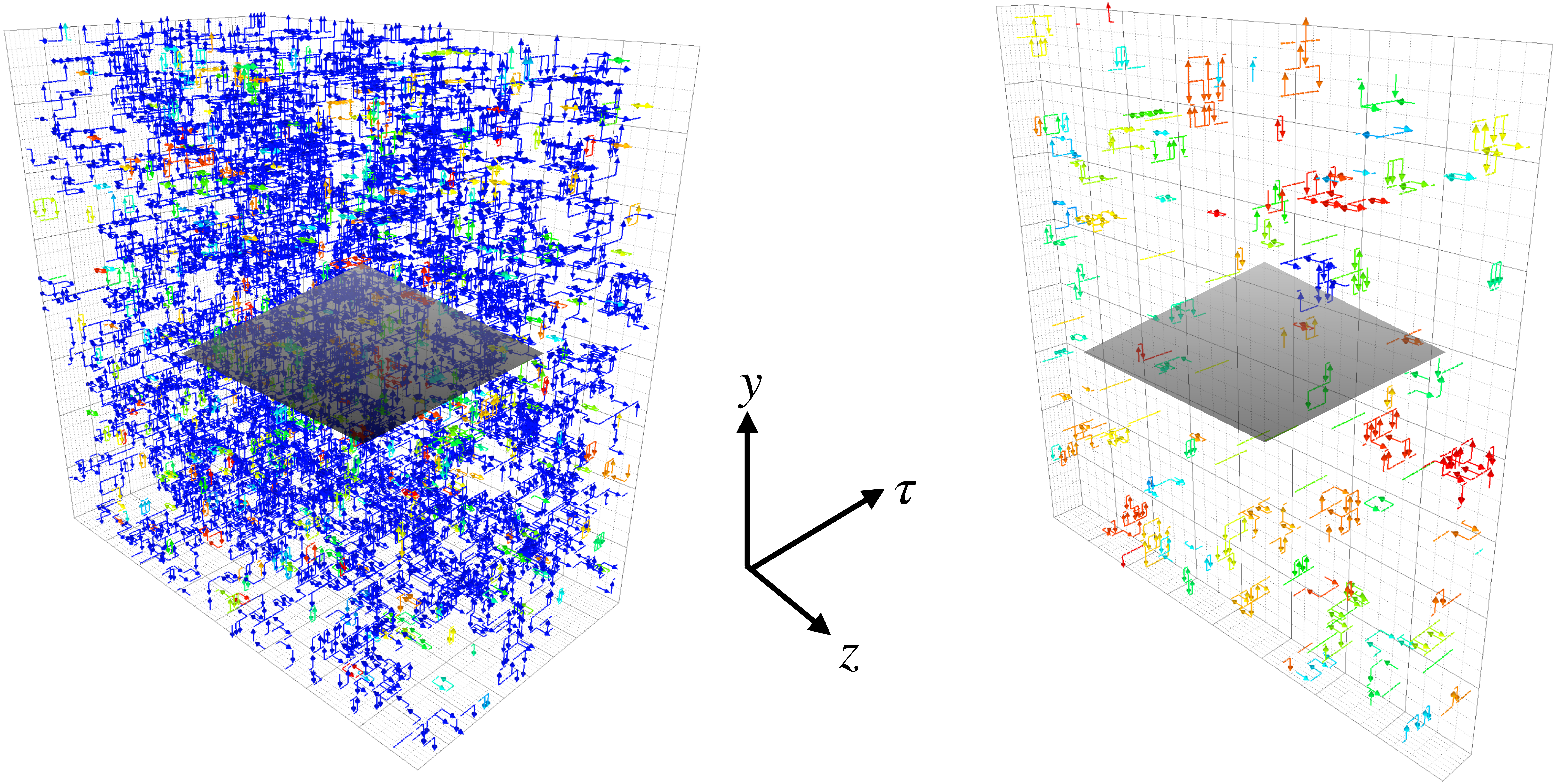
Nt=64 T=95MeV

Nt=8 T=760MeV

Connection with Percolation and Area Law

Engelhardt, Langfeld, Reinhardt, Tennert Phys.Rev.D 61 (2000) 054504

Mickley, Kamleh, Leinweber 2405.10670

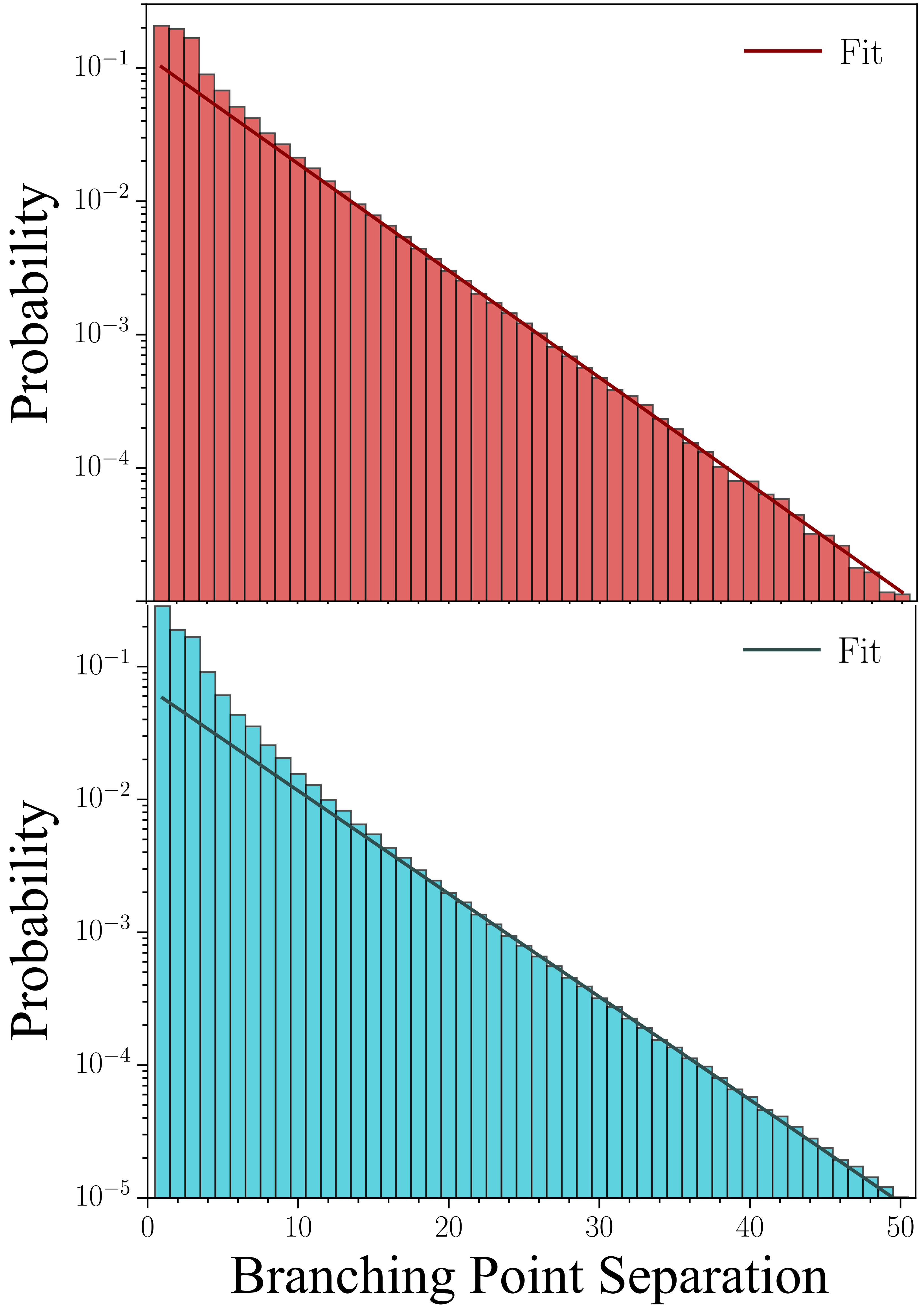


Nt=64 T=95MeV

Nt=8 T=760MeV

Branching Probability

Space-Space-Time

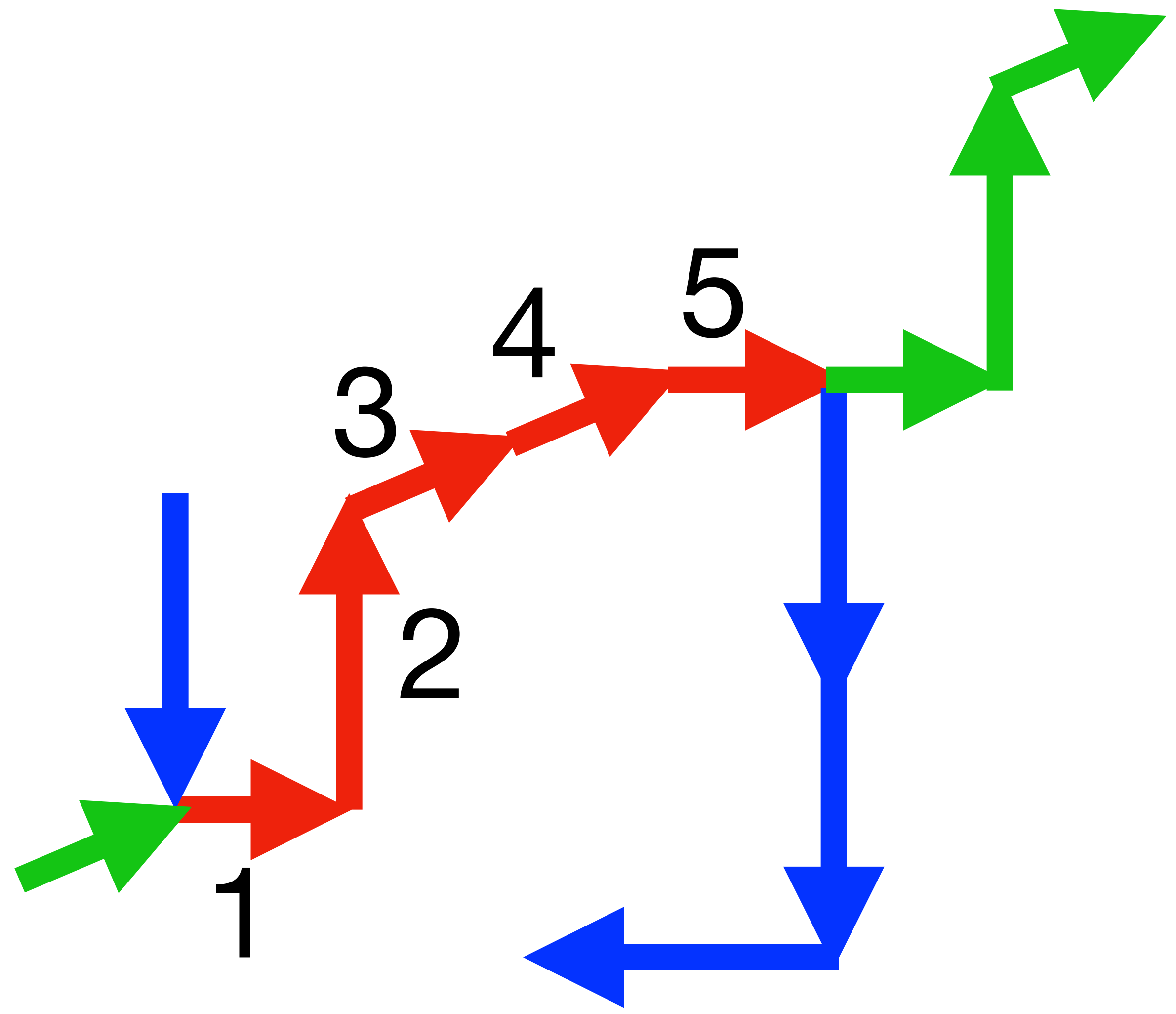


Nt=8

T=760MeV

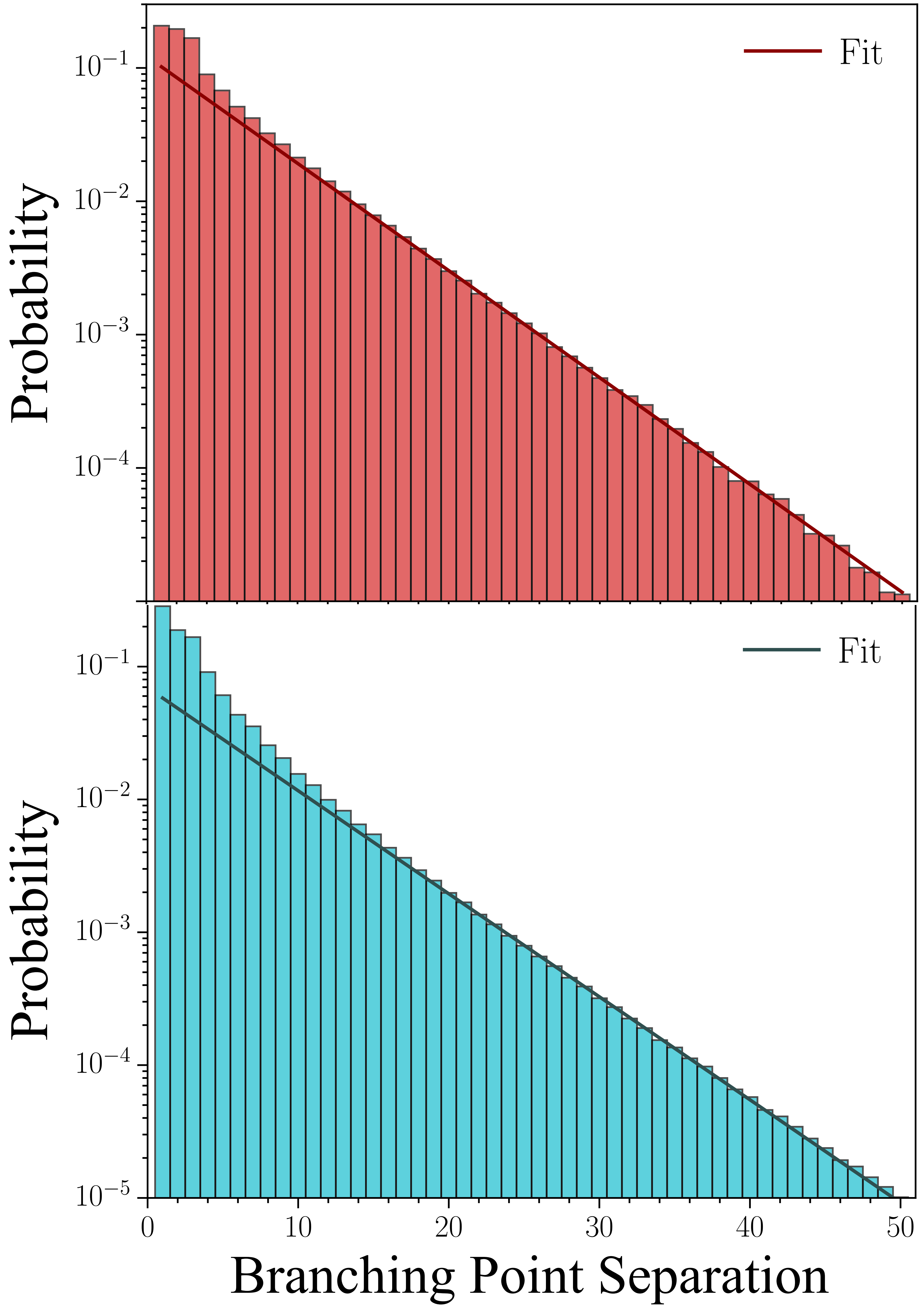
Nt=64

T=95MeV



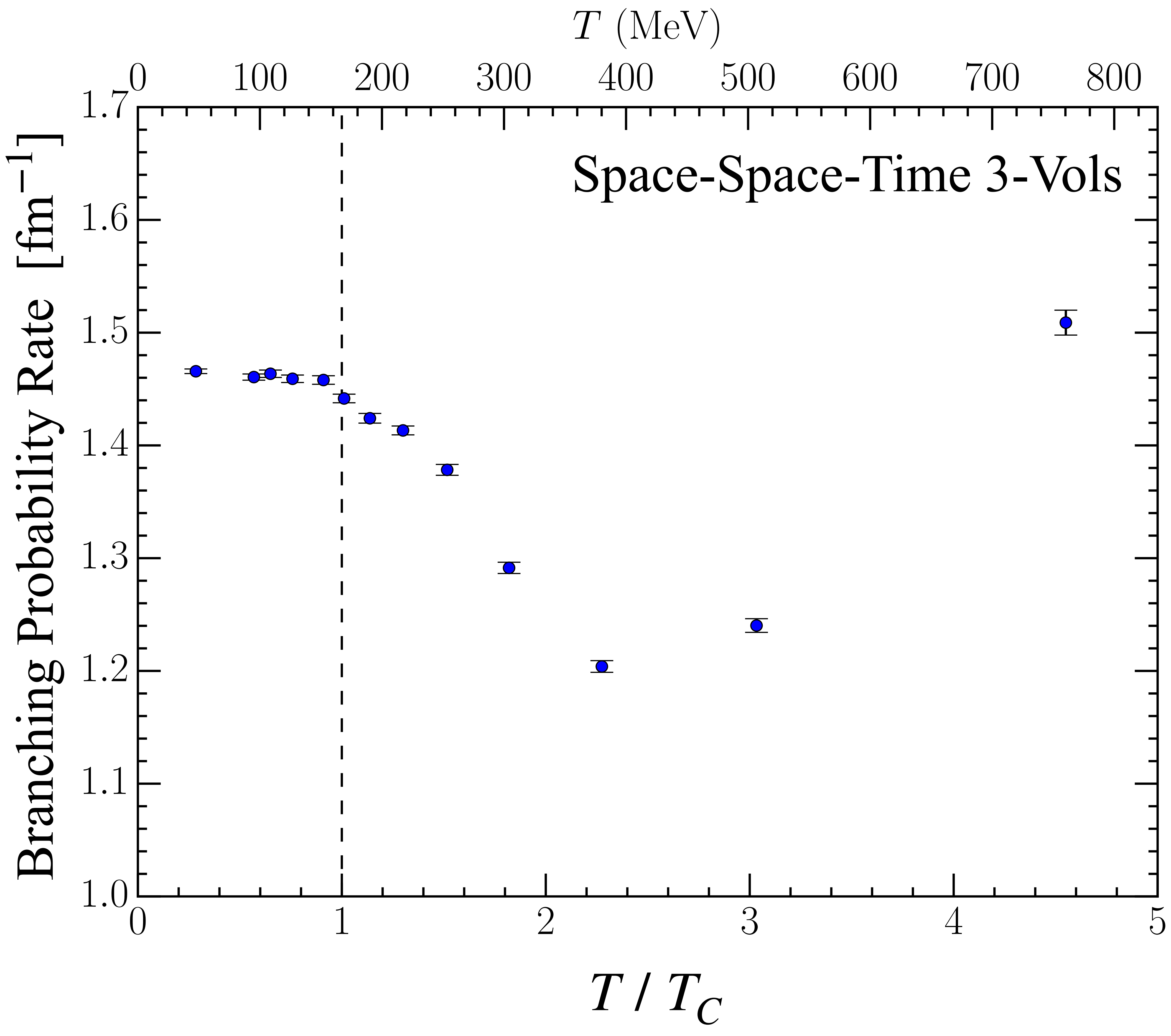
Branching Probability and Rate

Space-Space-Time



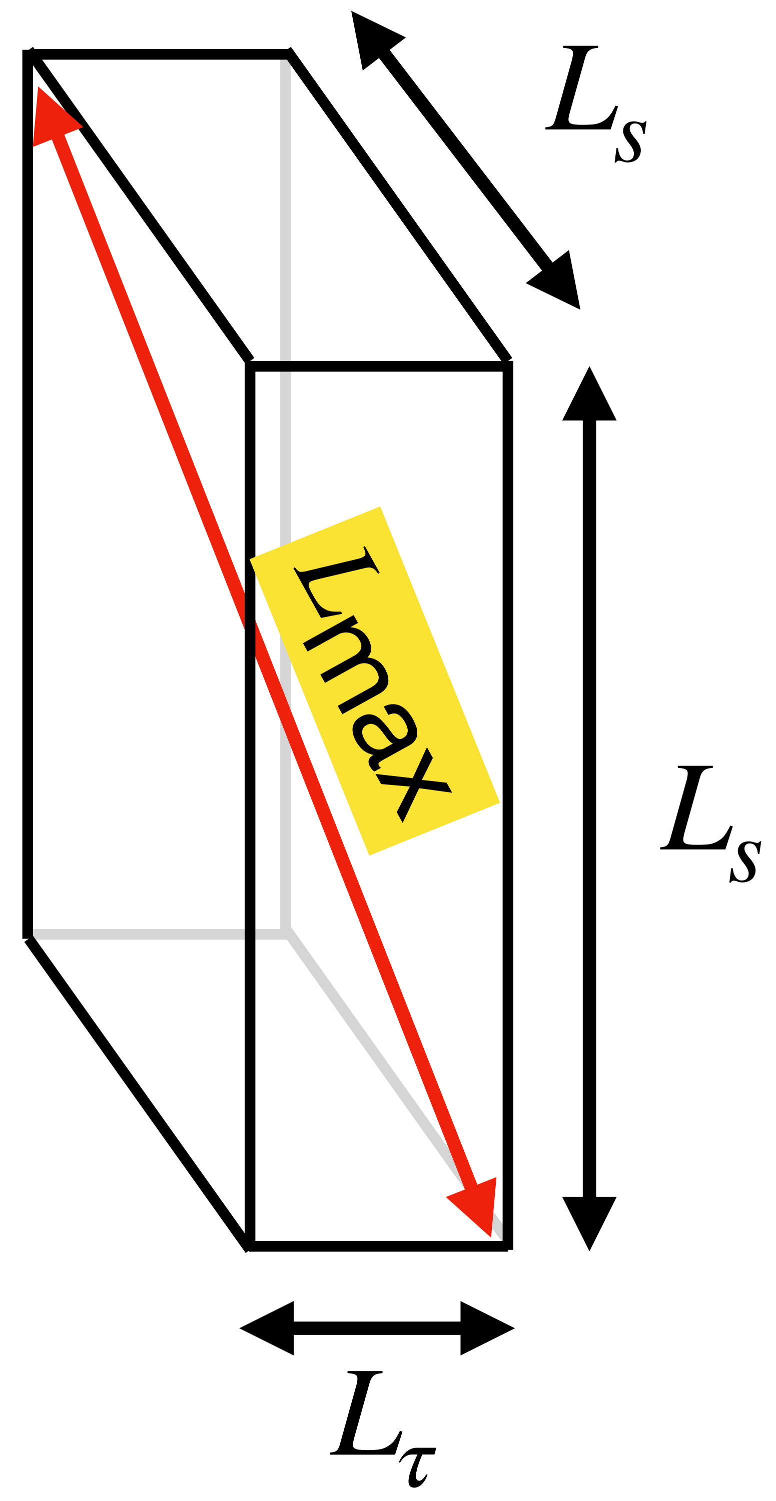
Nt=8
T=760MeV

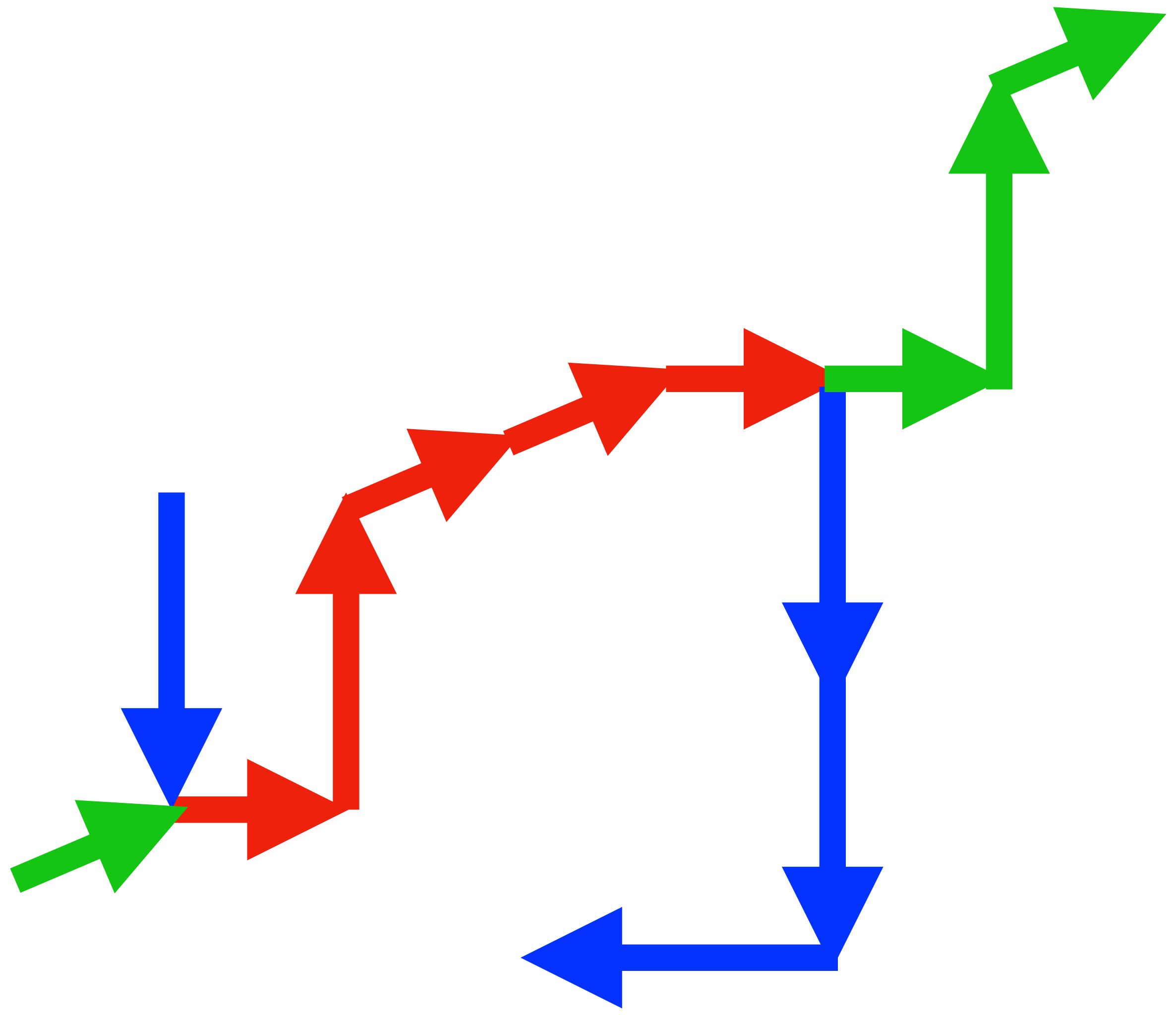
Nt=64
T=95MeV



Cluster Extent

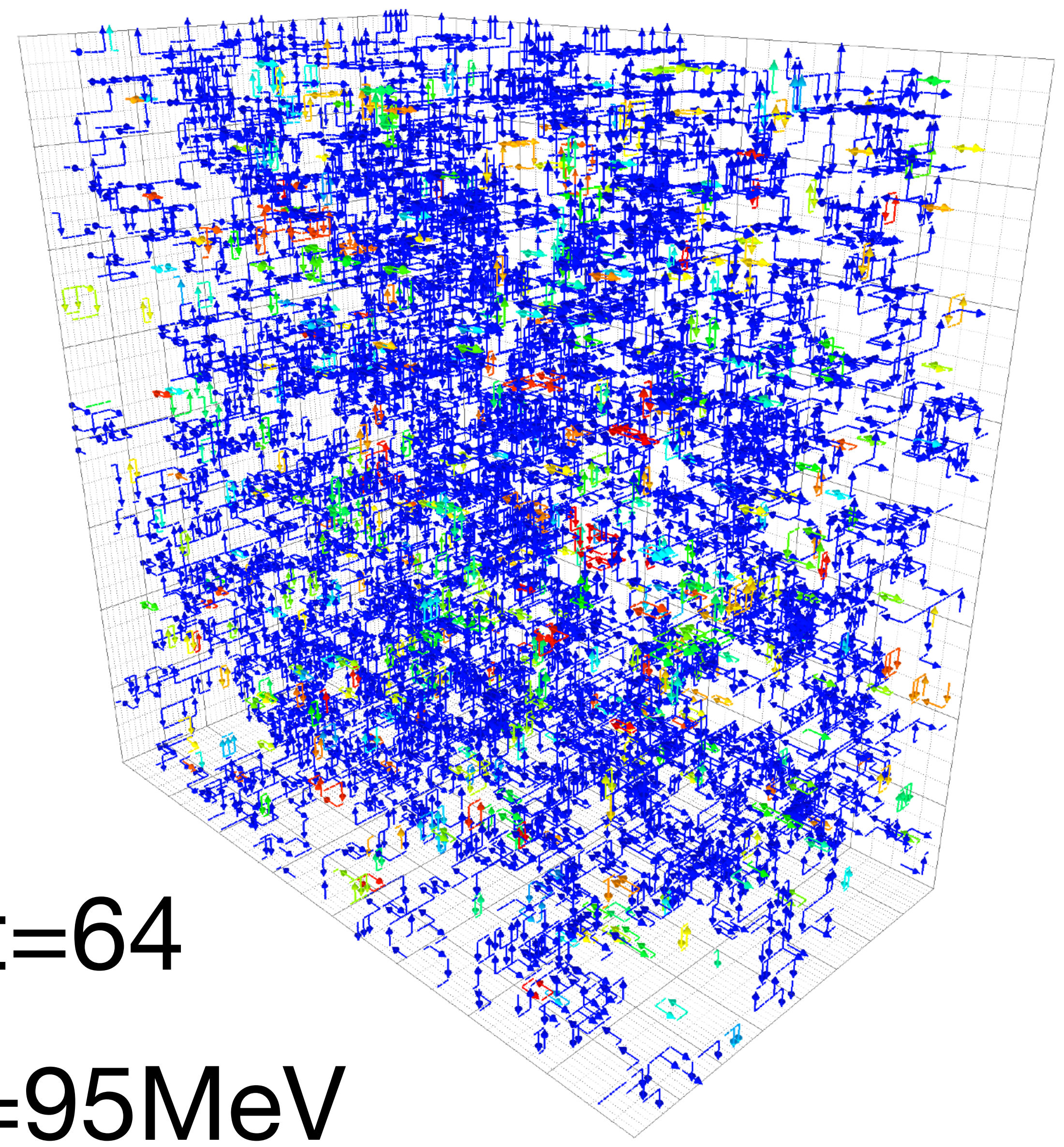
Space-Space-Time





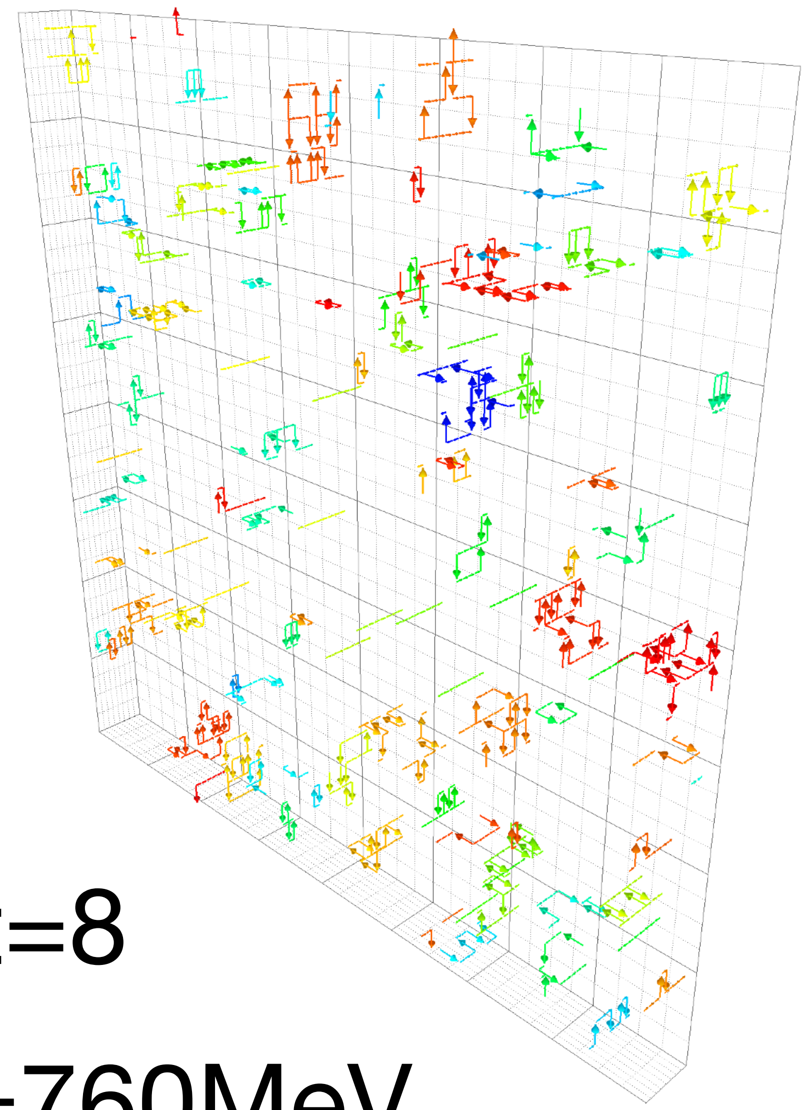
Normalised Cluster Extent $= \dfrac{\text{Cluster Extent}}{\frac{1}{2} L_{max}}$

Periodic B.C.'s



Nt=64

T=95MeV

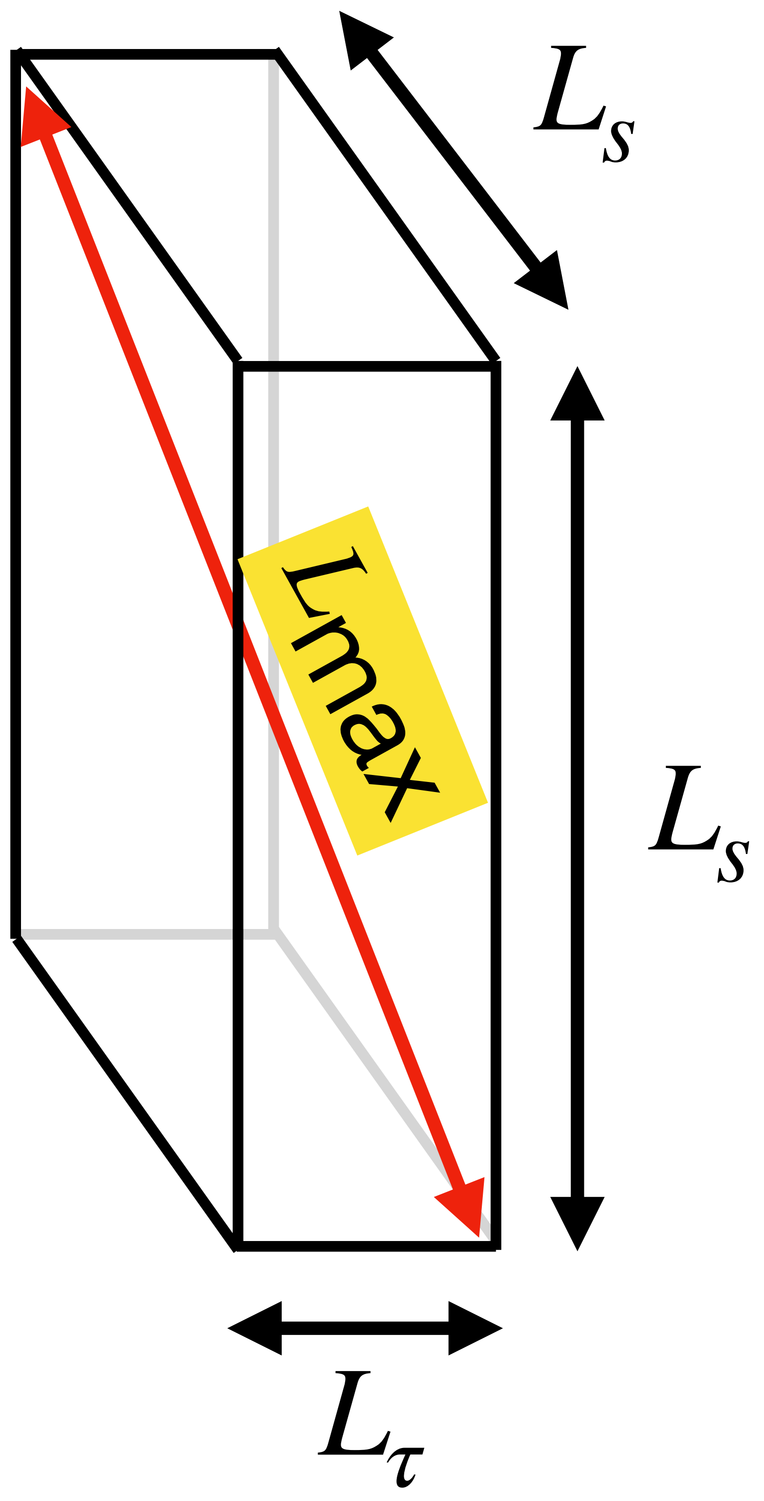


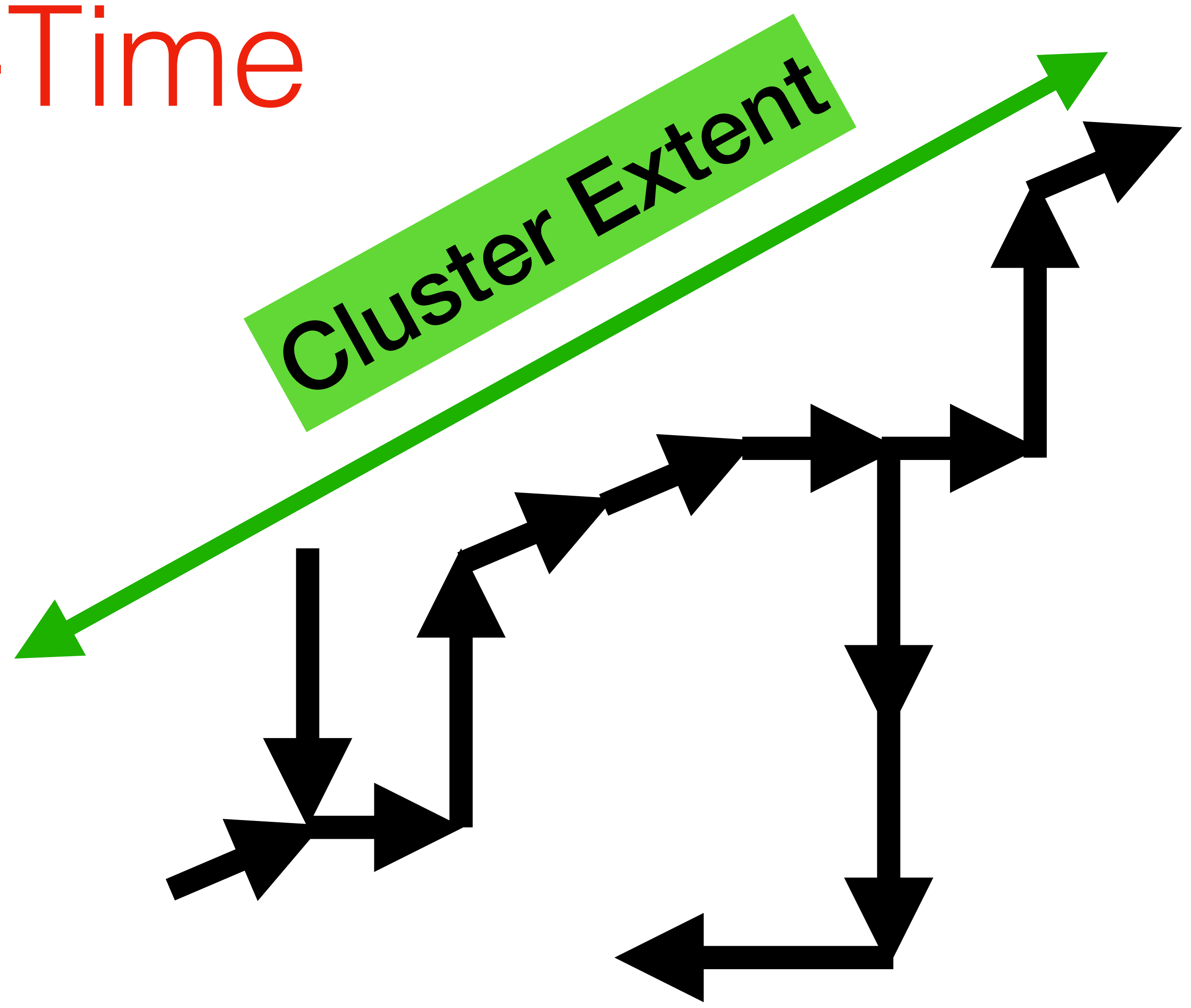
Nt=8

T=760MeV

Cluster Extent

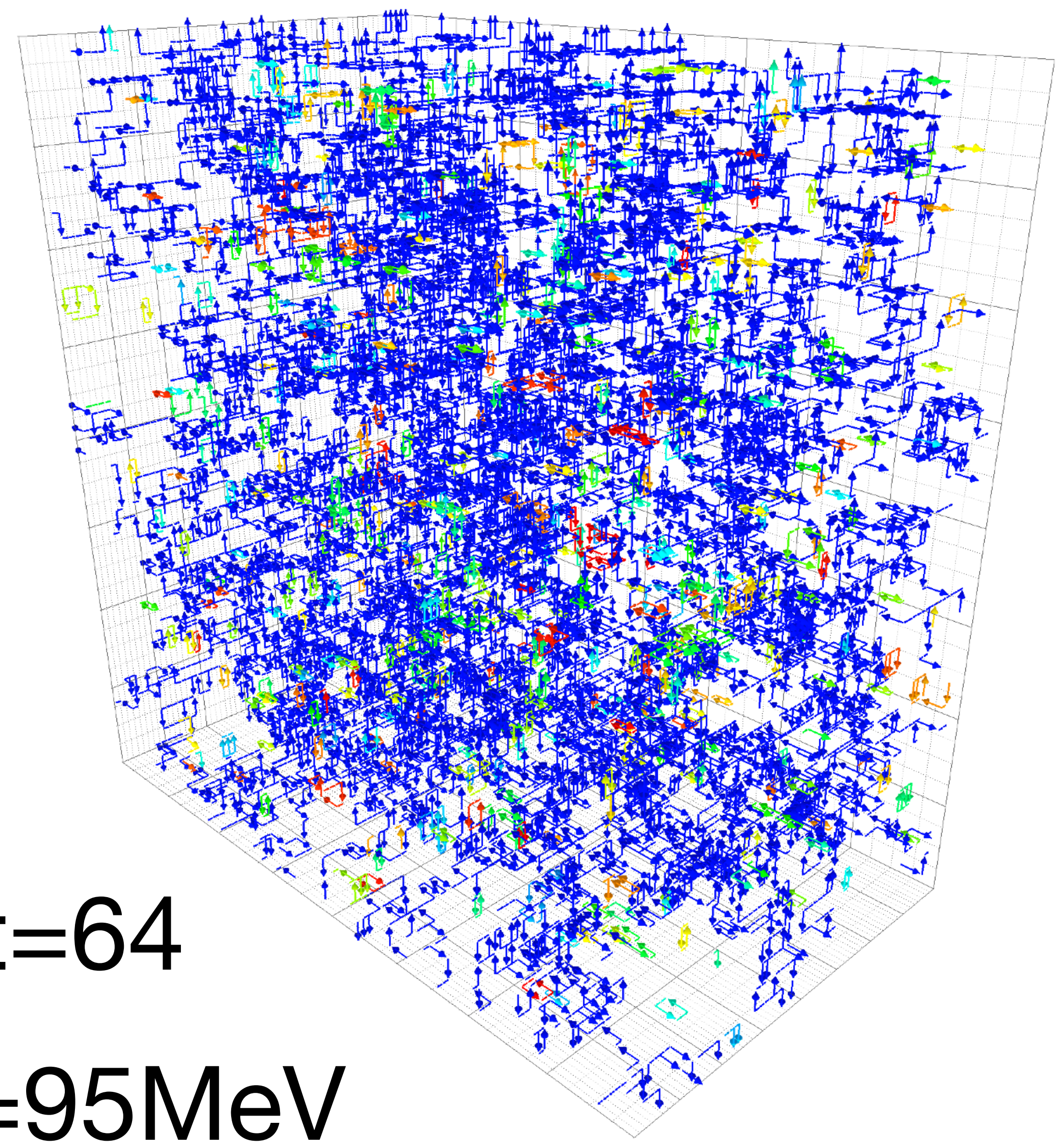
Space-Space-Time





$$\text{Normalised Cluster Extent} = \frac{\text{Cluster Extent}}{\frac{1}{2} L_{\text{max}}}$$

Periodic B.C.'s



Nt=64

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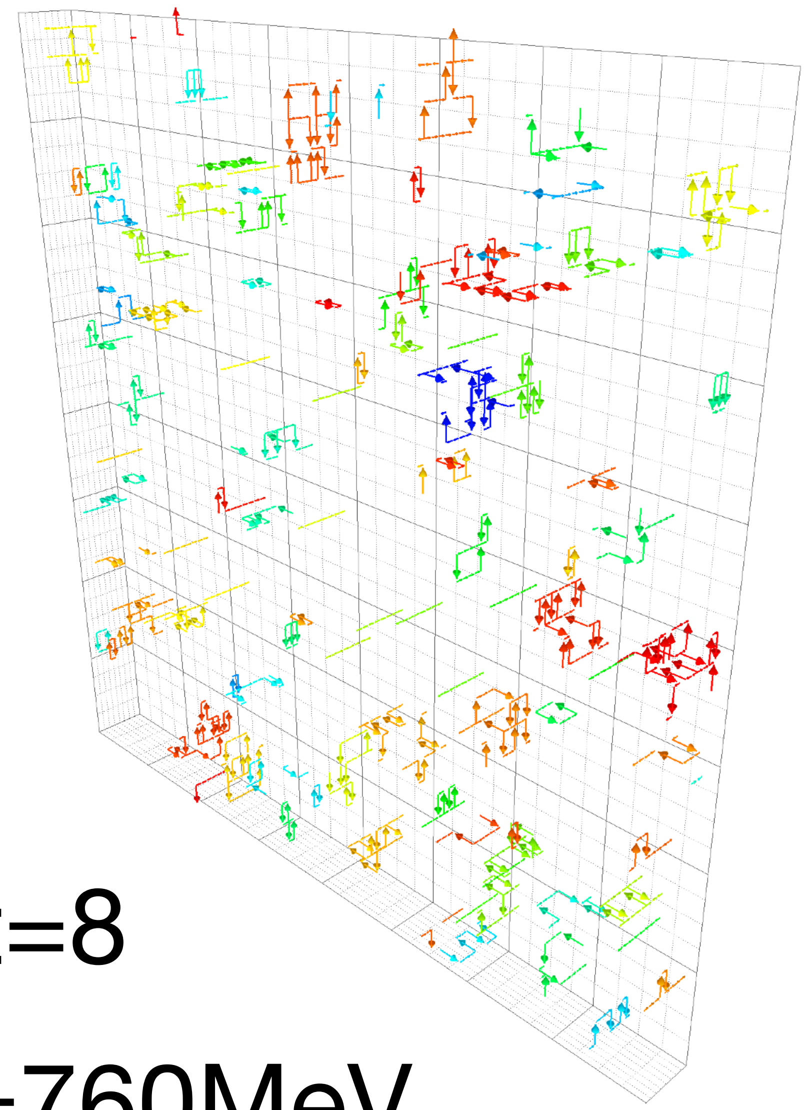
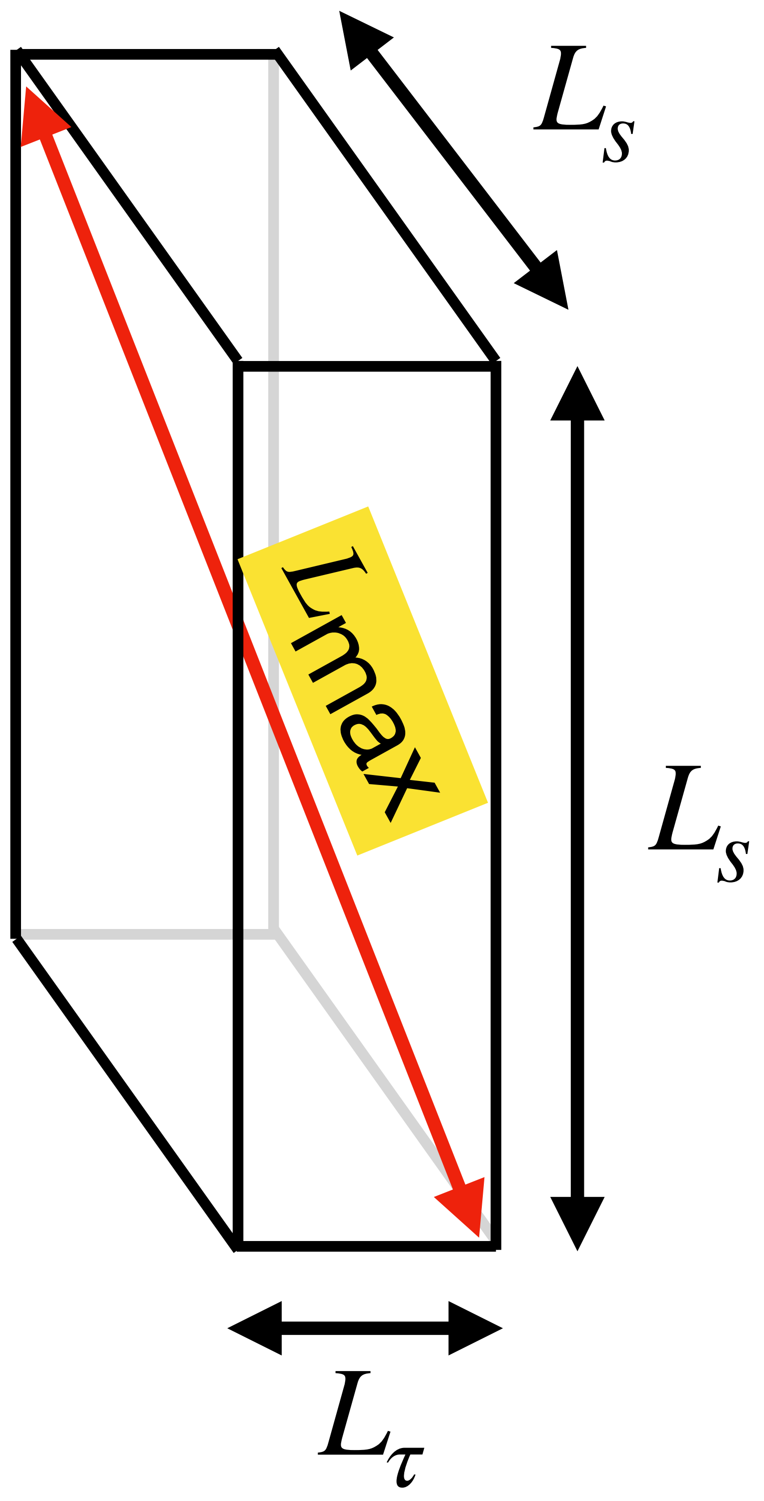


Nt=8

T=760MeV

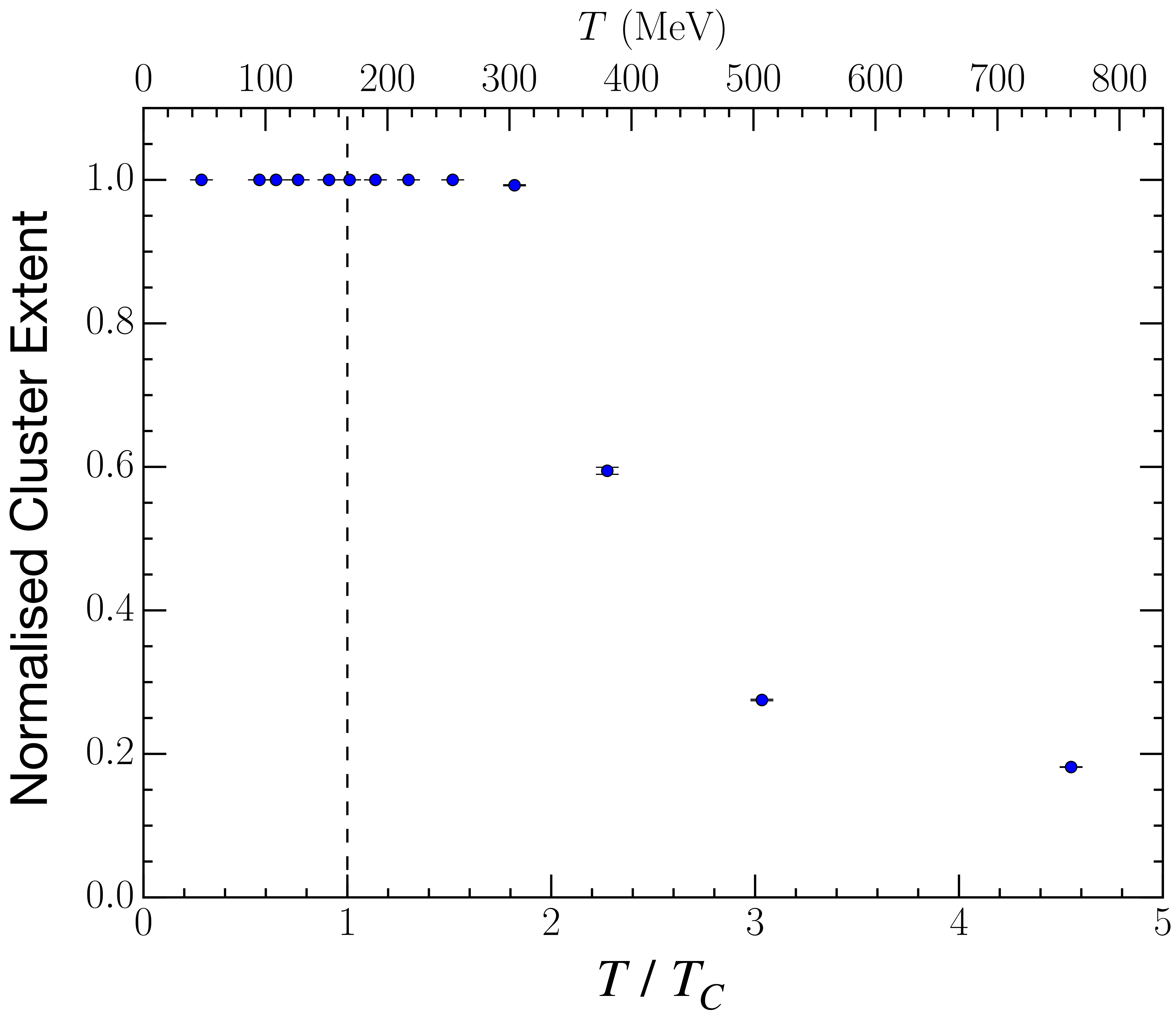
Cluster Extent

Space-Space-Time



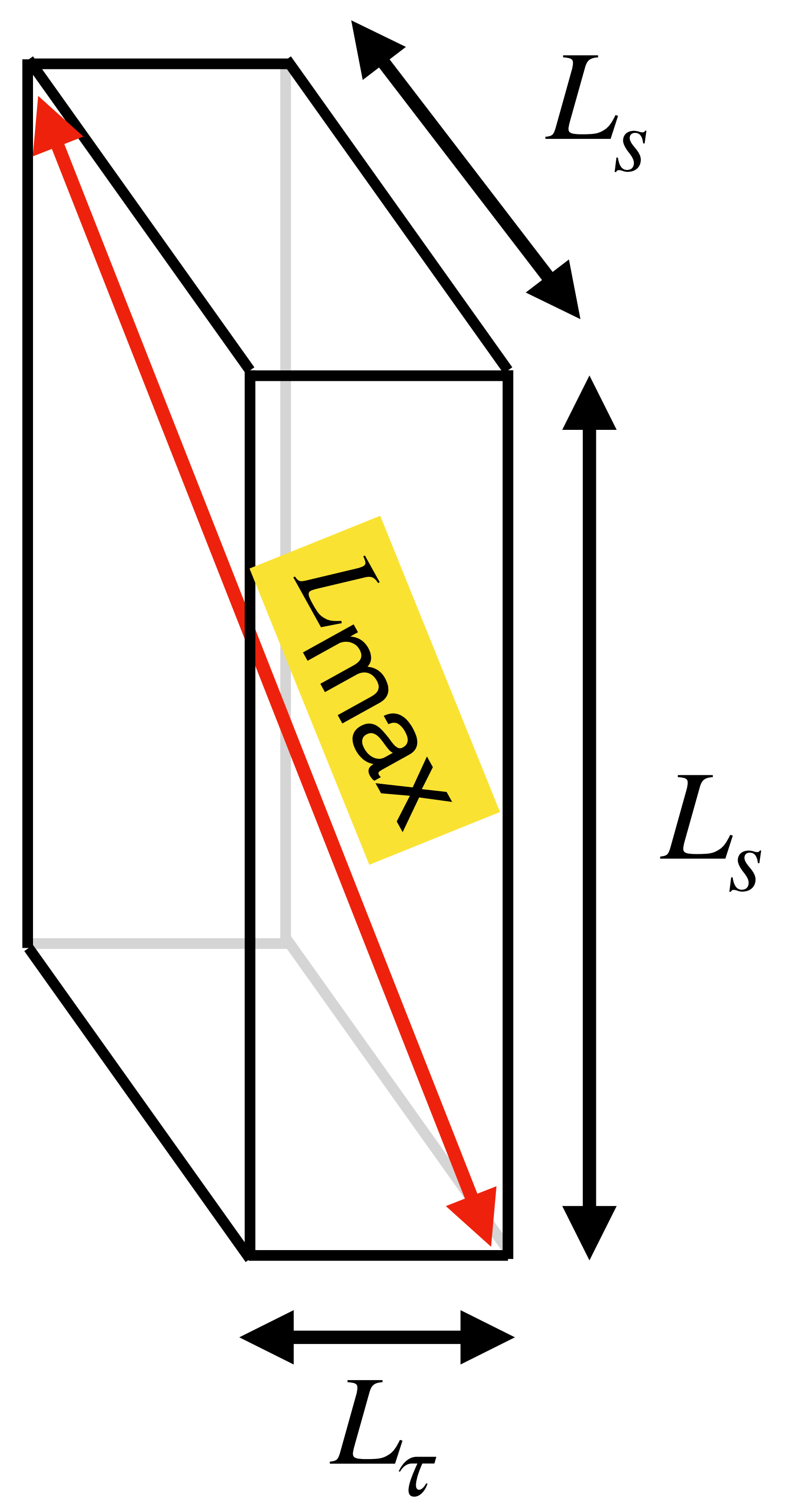
Normalised Cluster Extent $= \dfrac{\text{Cluster Extent}}{\frac{1}{2}\, L_{\text{max}}}$

Periodic B.C.'s



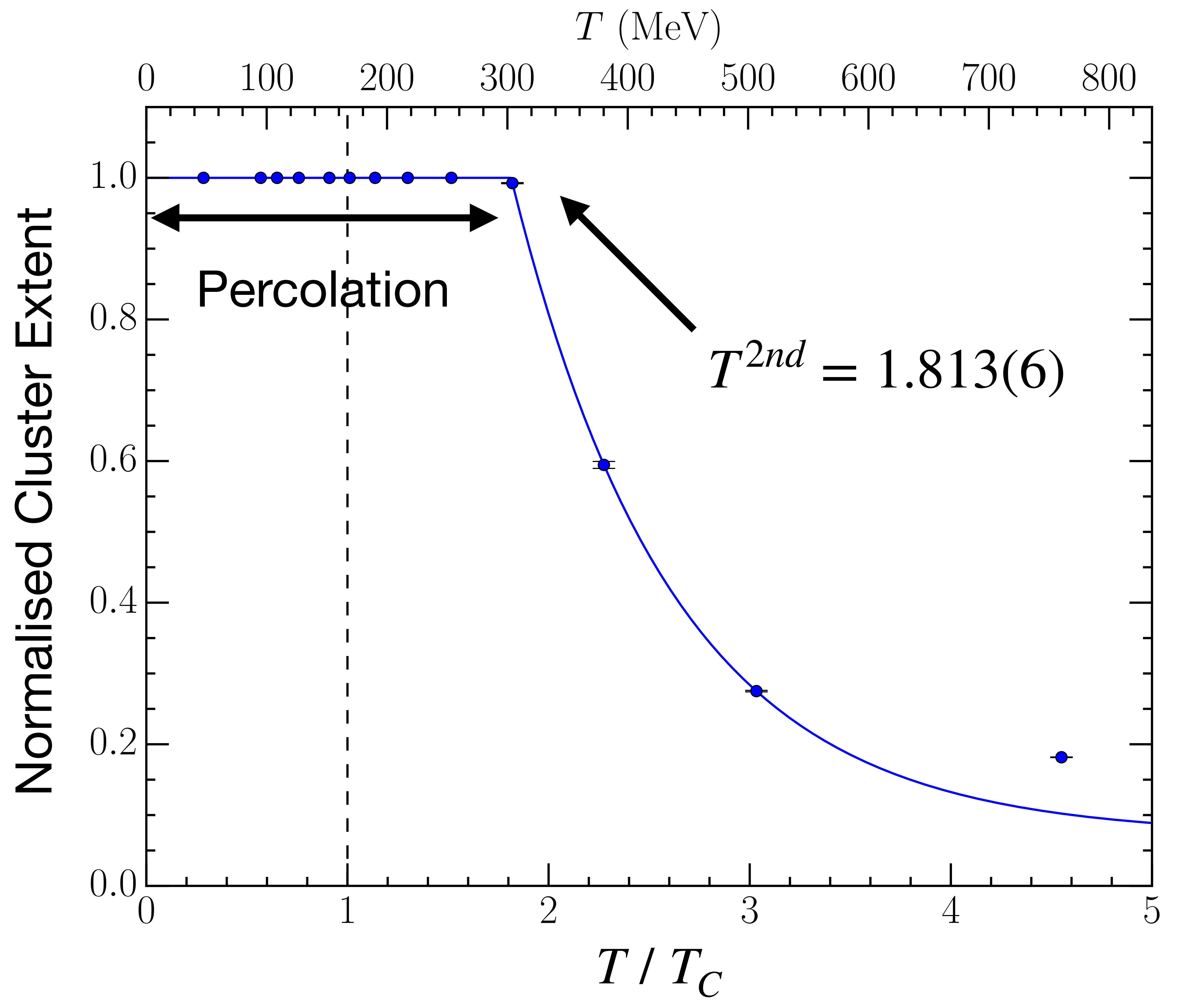
Cluster Extent

Space-Space-Time



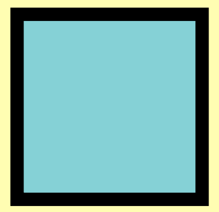
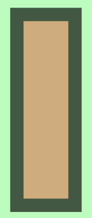
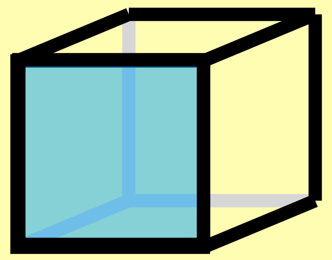
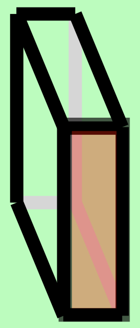
Normalised Cluster Extent $= \dfrac{\text{Cluster Extent}}{\frac{1}{2}\, L\text{max}}$

Periodic B.C.'s



Volume Effects to be Checked

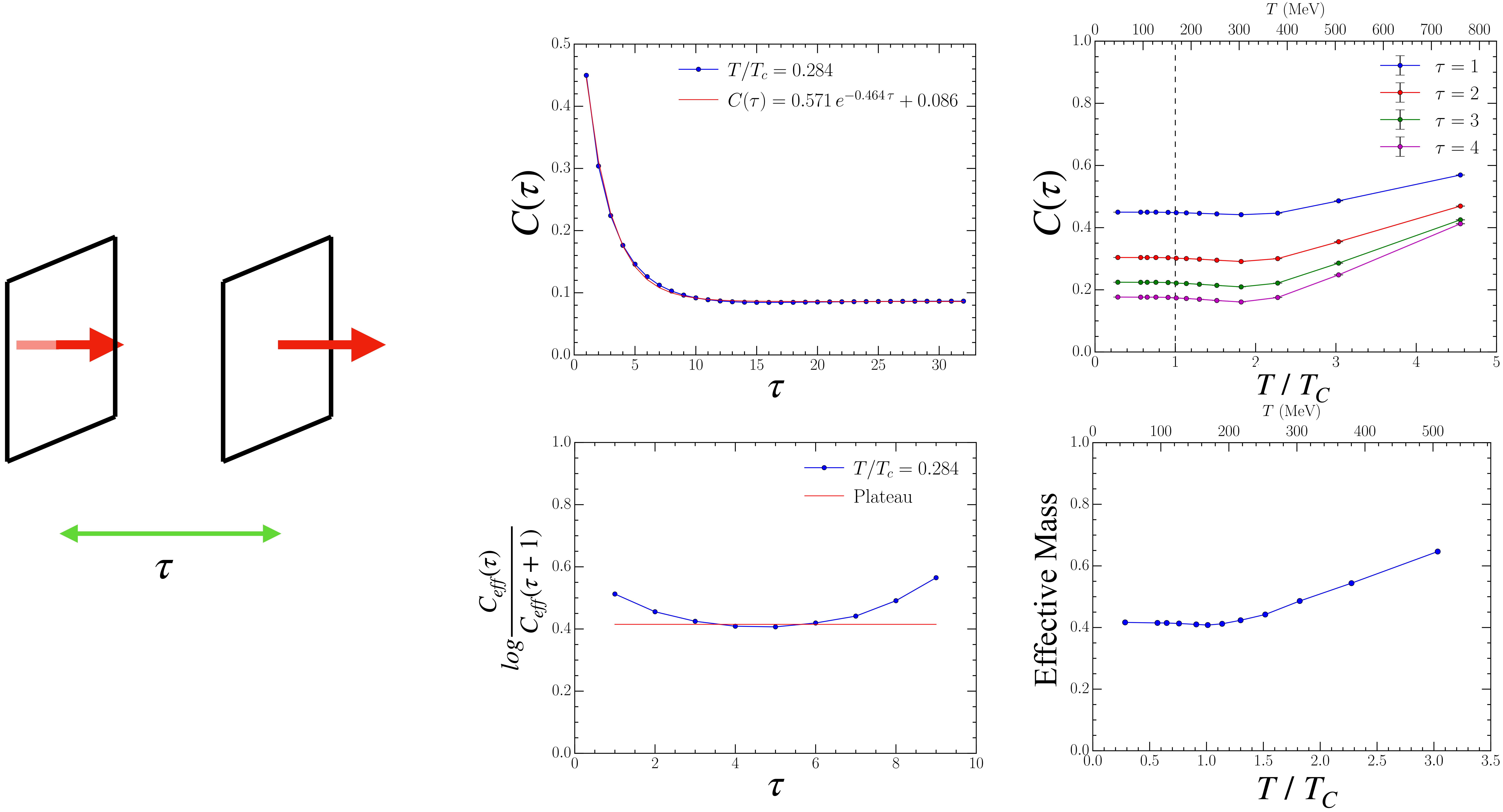
Estimates of “Transition” Temperatures

	Vortex Density *[fm $^{-2}$]*		Branching Point Density *[fm $^{-3}$]*		Cluster Extent
	Space-Space Plaqs *(Plaq’s with NO t dir’n)* 	Space-Time Plaqs *(Plaq’s with t dir’n)* 	Space^3 3-Vols *(3-Vol with NO t dir’n)* 	Space^2 x Time 3-Vols *(3-Vol with t dir’n)* 	–
$T^{(1st)} / T_C$	0.980	0.981	0.982	0.981	–
$T^{(2nd)} / T_C$	1.909	1.940	1.871	1.914	1.813(6)

T_C from Chiral Condensate

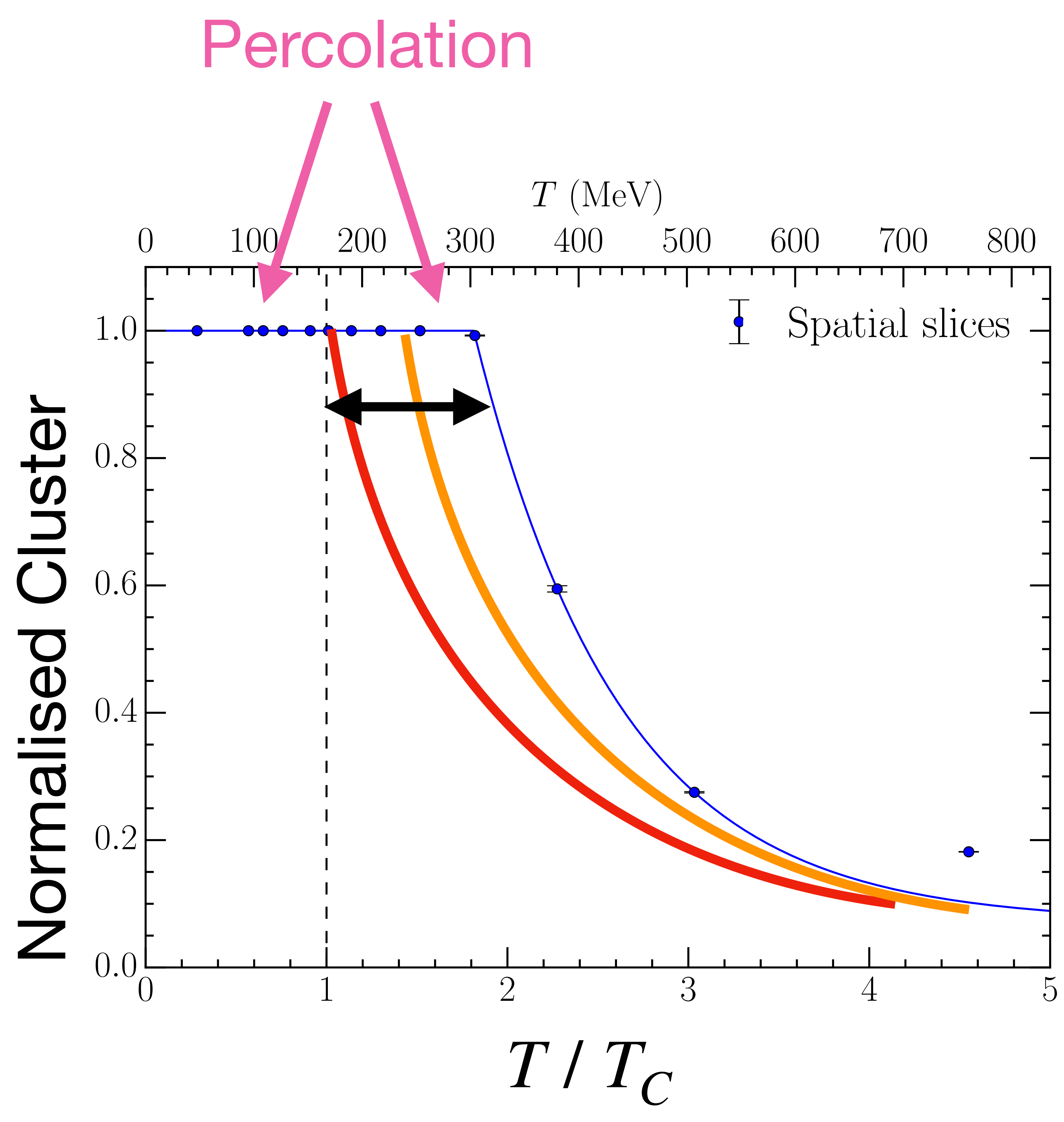
FASTSUM Phys.Rev.D 105 (2022) 3, 034504

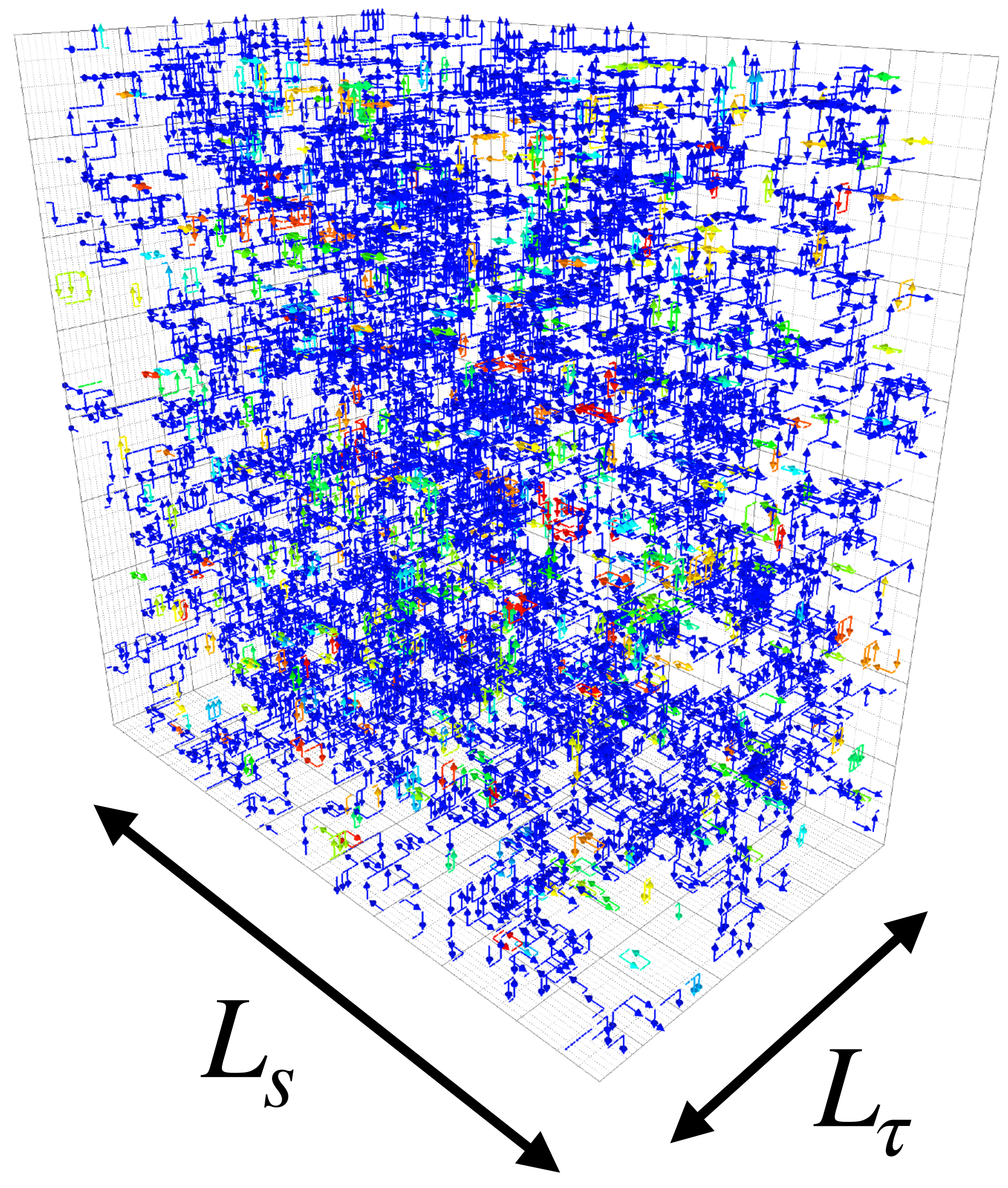
Temporal Vortex Correlators

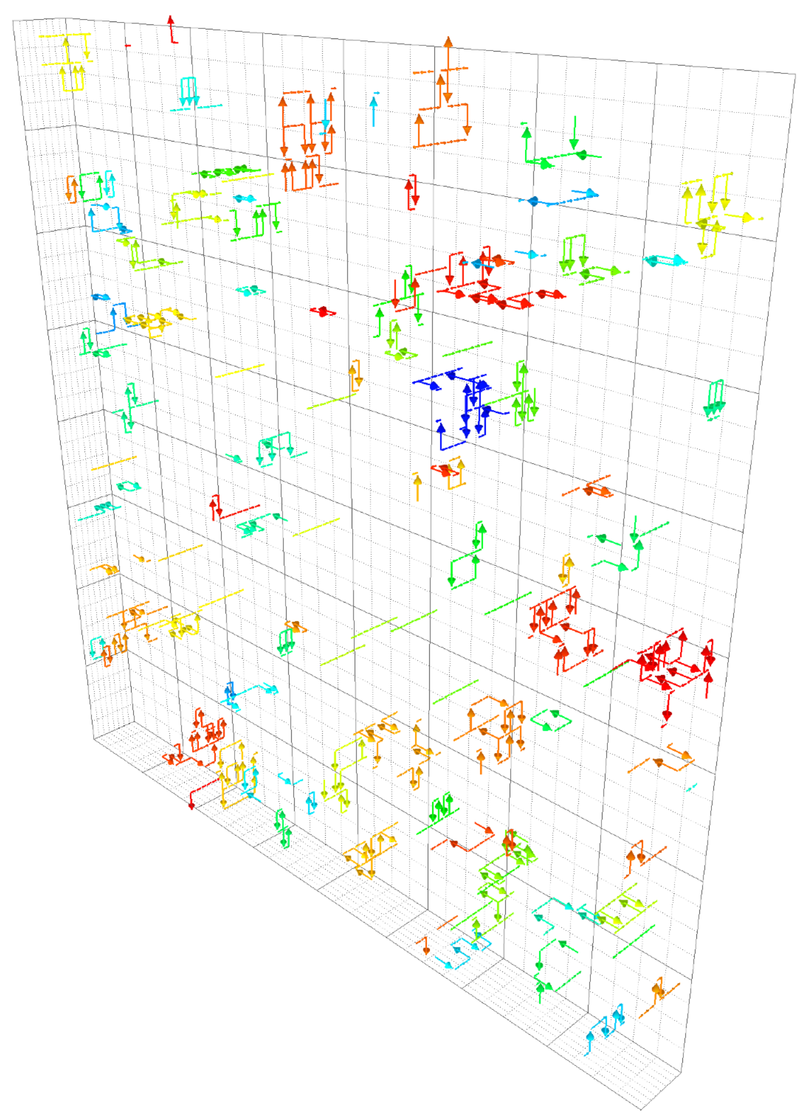


Systematics

Is the Volume Large Enough?

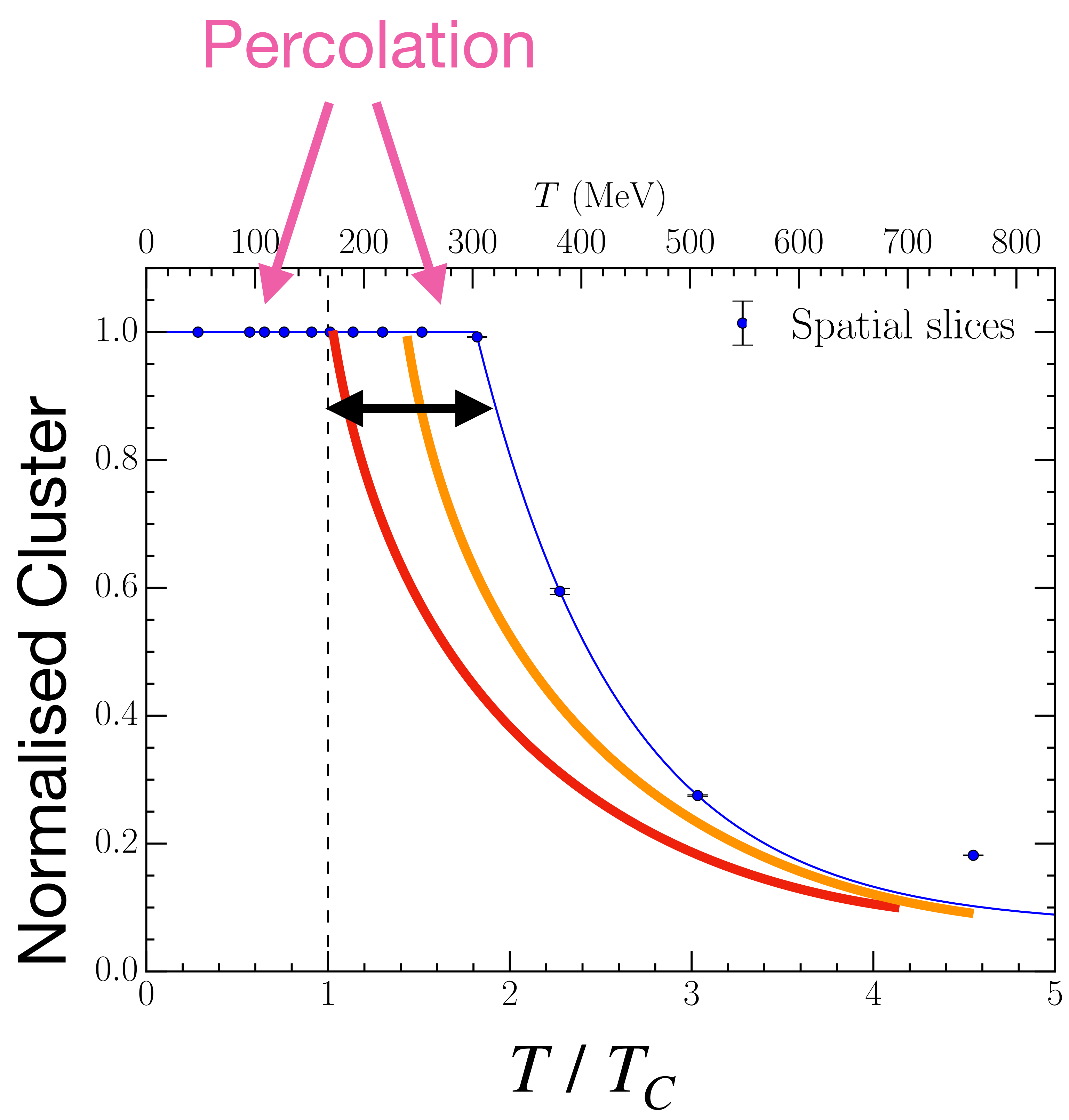


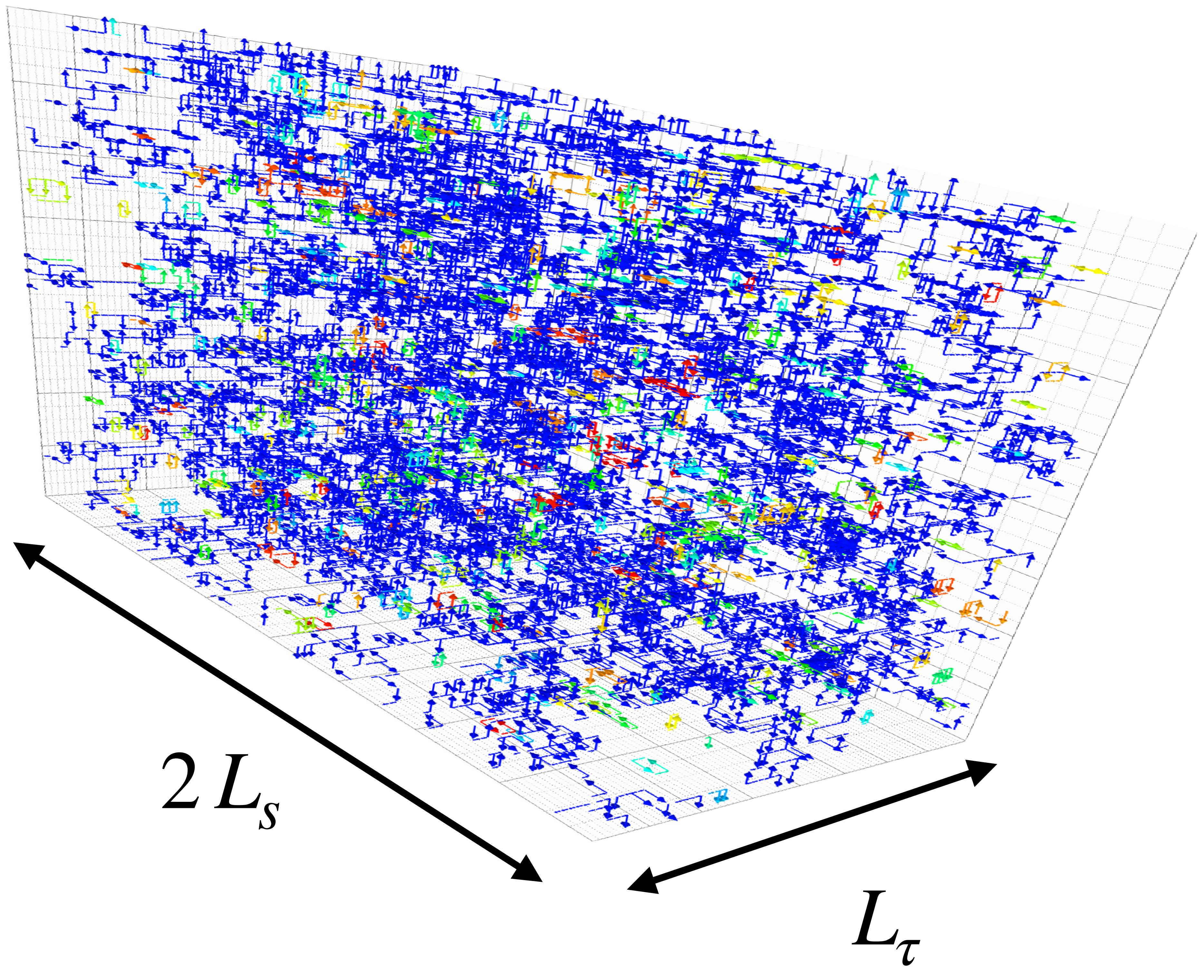


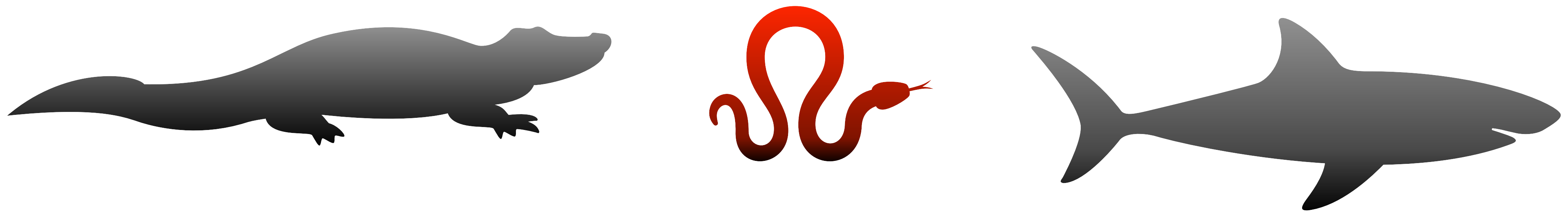


Systematics

Is the Volume Large Enough?





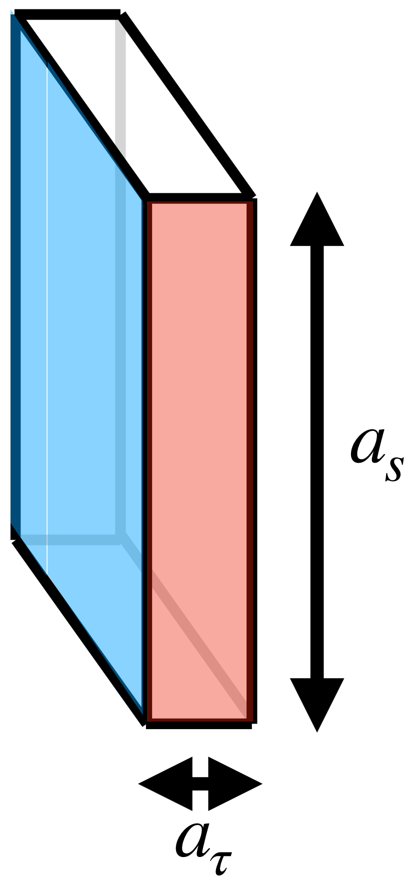


Local Quantities:

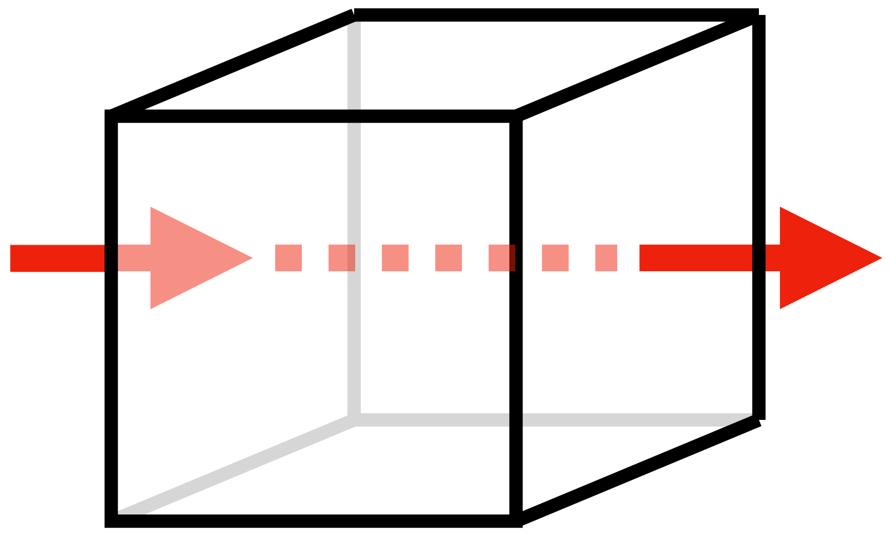
- Vortex Density
- Branching Pt Density
- Temporal Correlation

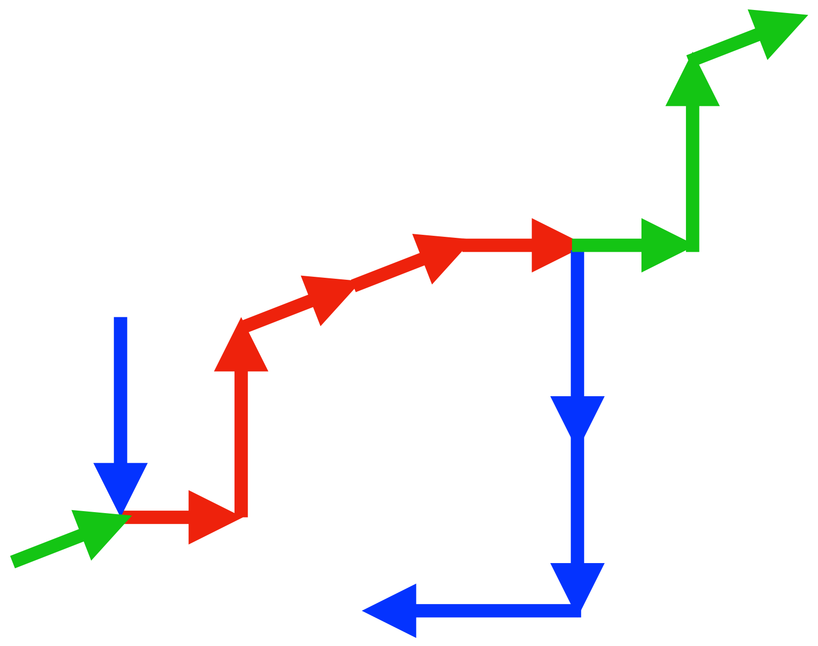
All show 2nd transition

Overview

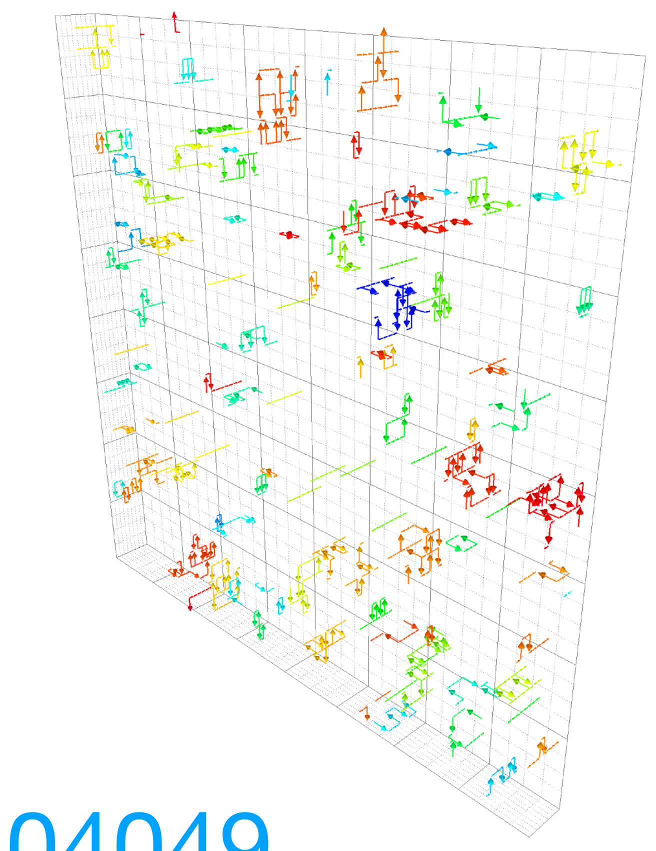


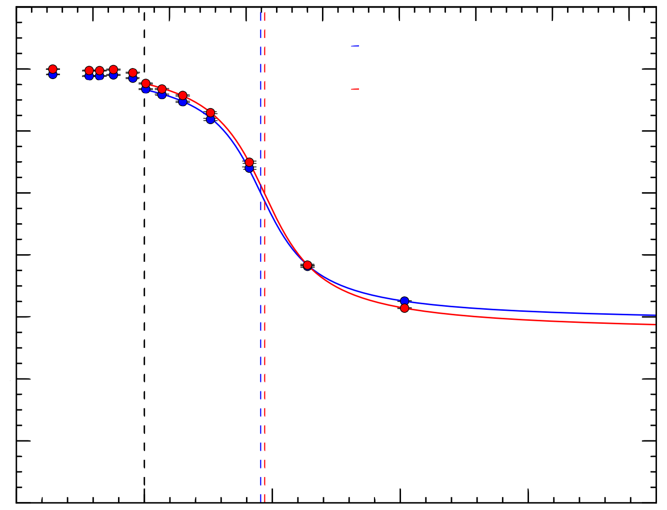
- FASTSUM approach
  - Anisotropic
- Maximal Centre Gauge
  - Vortices





- Measurements
  - Vortex & Branching Point Density
  - Cluster Extent
  - Correlations





- Transition(s) in QCD ?
  - Recent Proposals of new QCD phase:

Glozman, Prog.Part.Nucl.Phys. 131 (2023) 104049
Hanada, Ohata, Shimada, Watanabe PTEP 2024 (2024) 4, 041B02
…

Back-Up Slide

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)