August 5 2021

vConfXIV 2021

University of Michigan & RIKEN (Theoretical Quantum Physics + iTHEMS)

ENRICO RINALDI

COMPOSITE DM & GW SIGNATURES

http://lsd.physics.yale.edu

L — S

D

Lattice Strong Dynamics collaboration

Argonne: Jin, Osborn

Bern: Gasbarro

Boston: Brower, Rebbi

Nvidia: Weinberg

Colorado: Neil, Hasenfratz

Siegen: Witzel

Liverpool: Schaich

LLNL: Vranas, Howarth

UC Davis: Kiskis

Yale: Appelquist, Fleming, Cushman

Oregon: Kribs

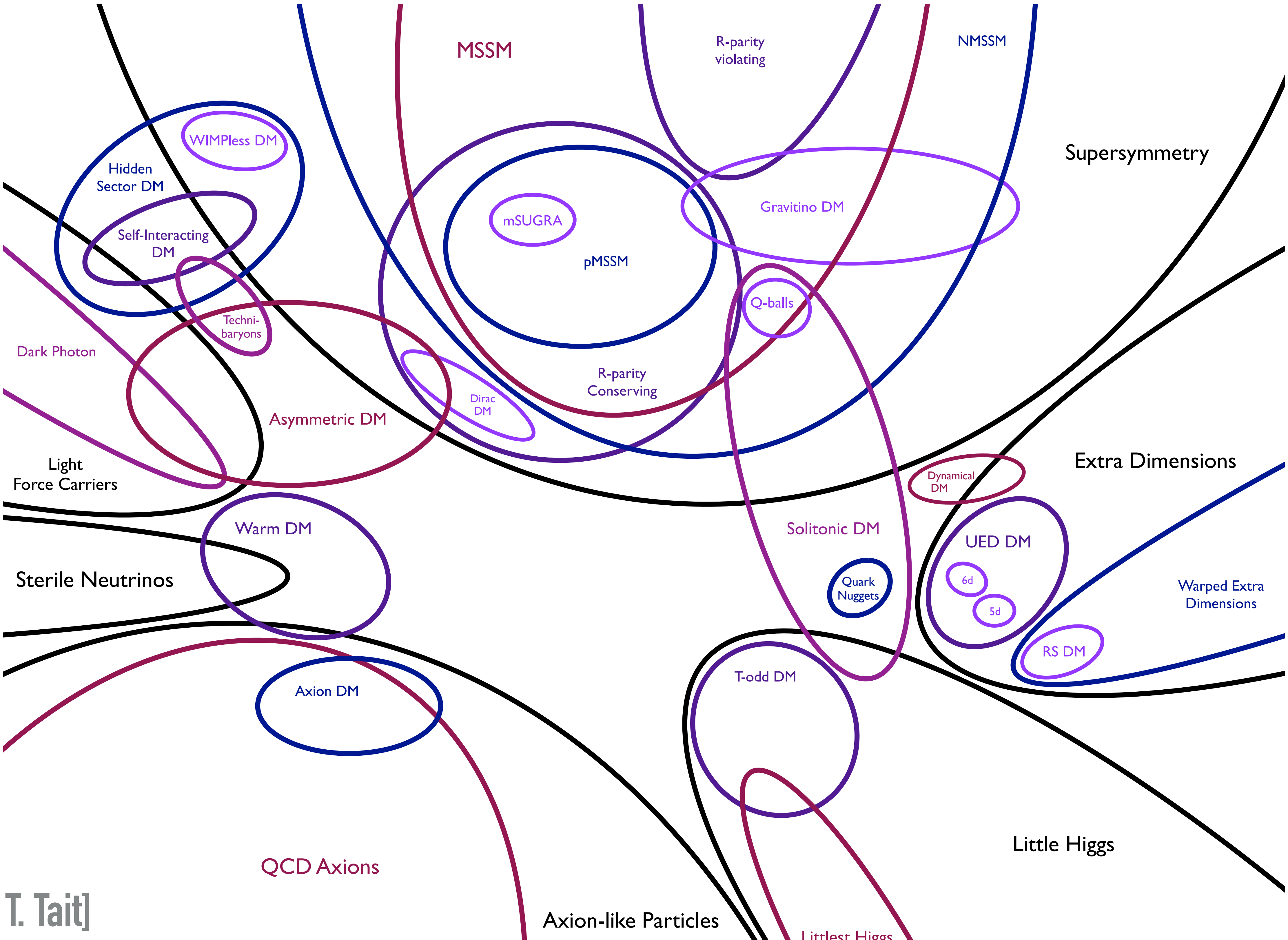
RIKEN: ER

Full results on arXiv and submitted to PRD

Preliminary results presented at Lattice 2019

[The Particle Zoo] (website)

THE DARK MATTER THEORY LANDSCAPE



[picture by T. Tait]

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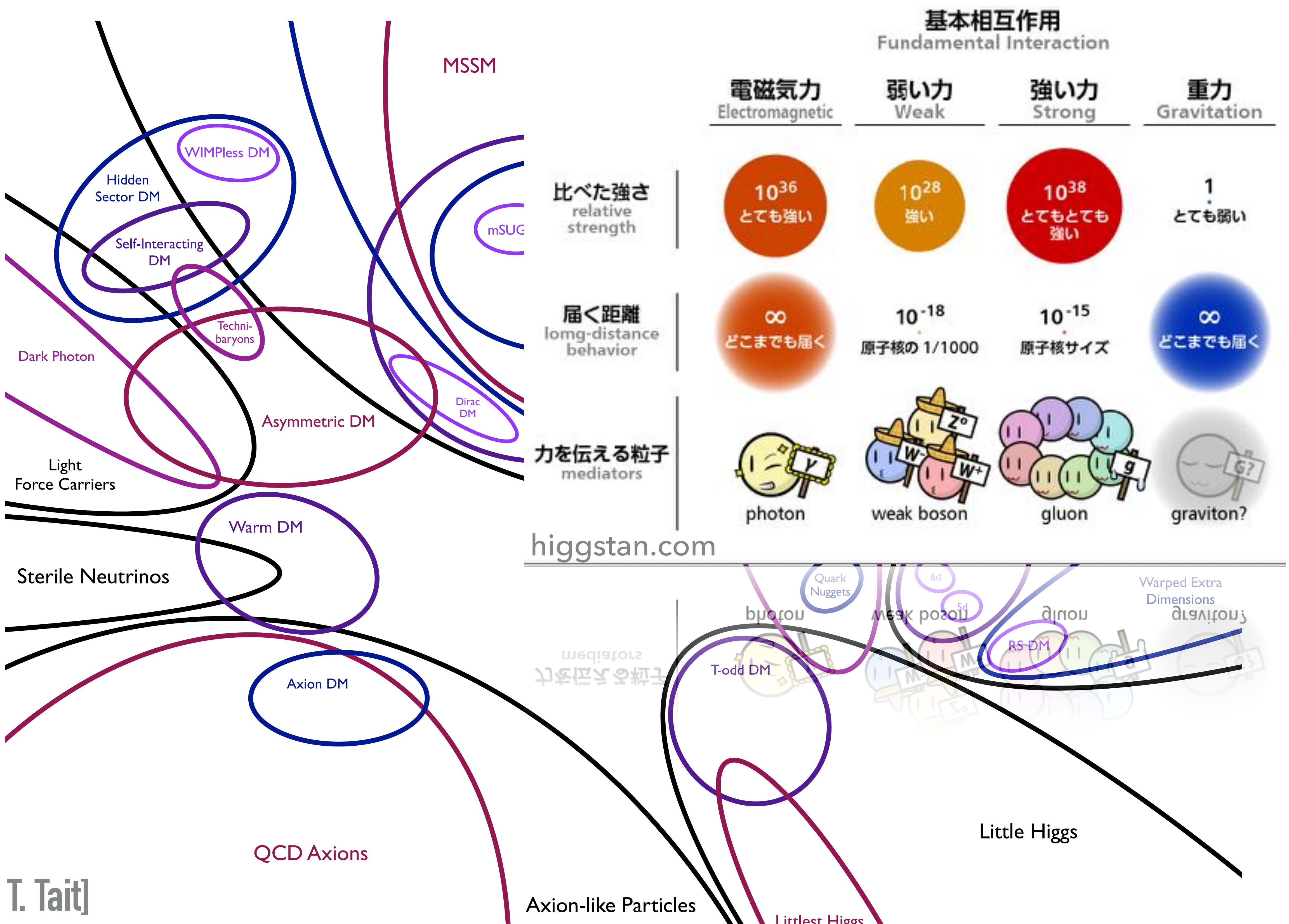

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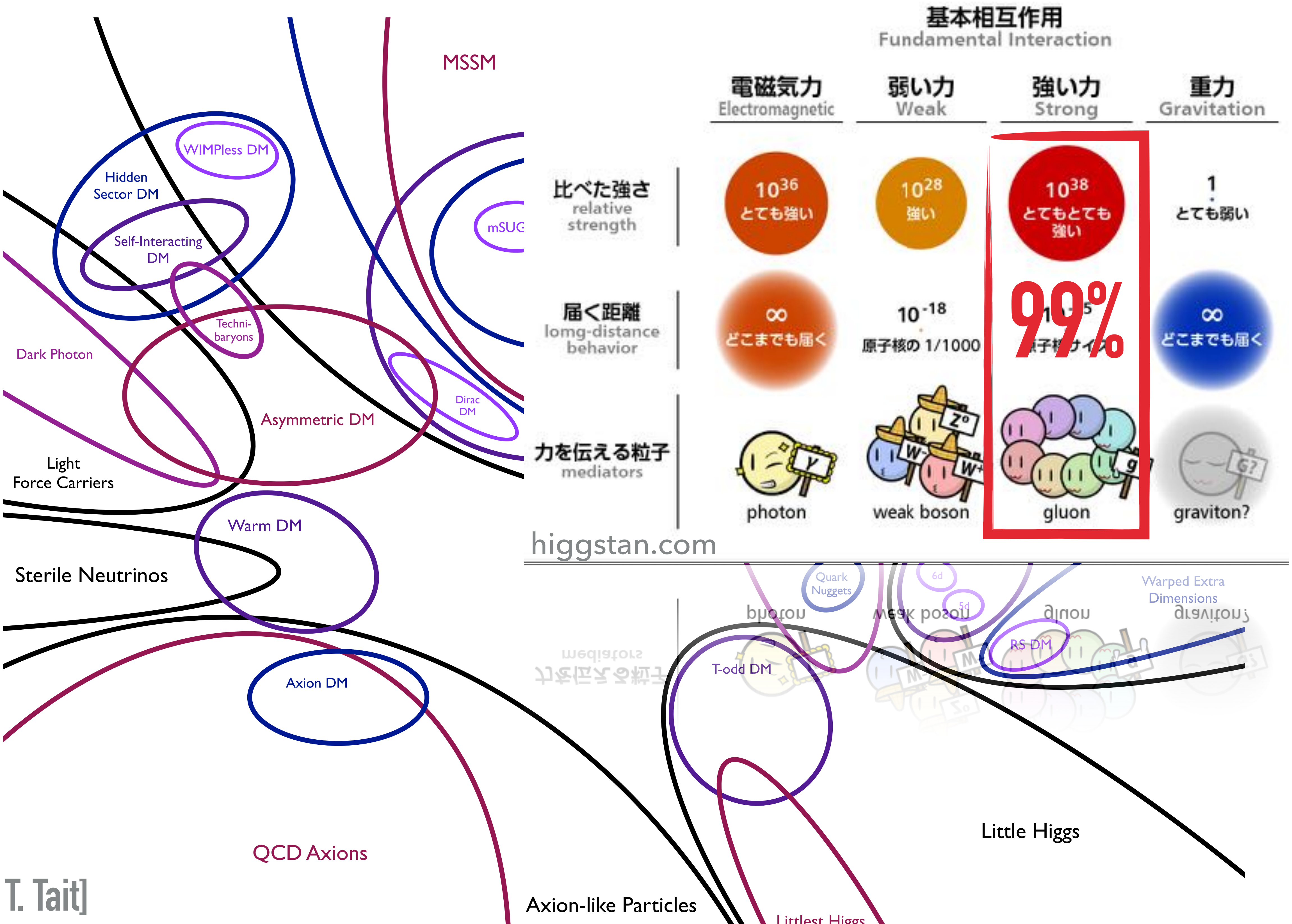

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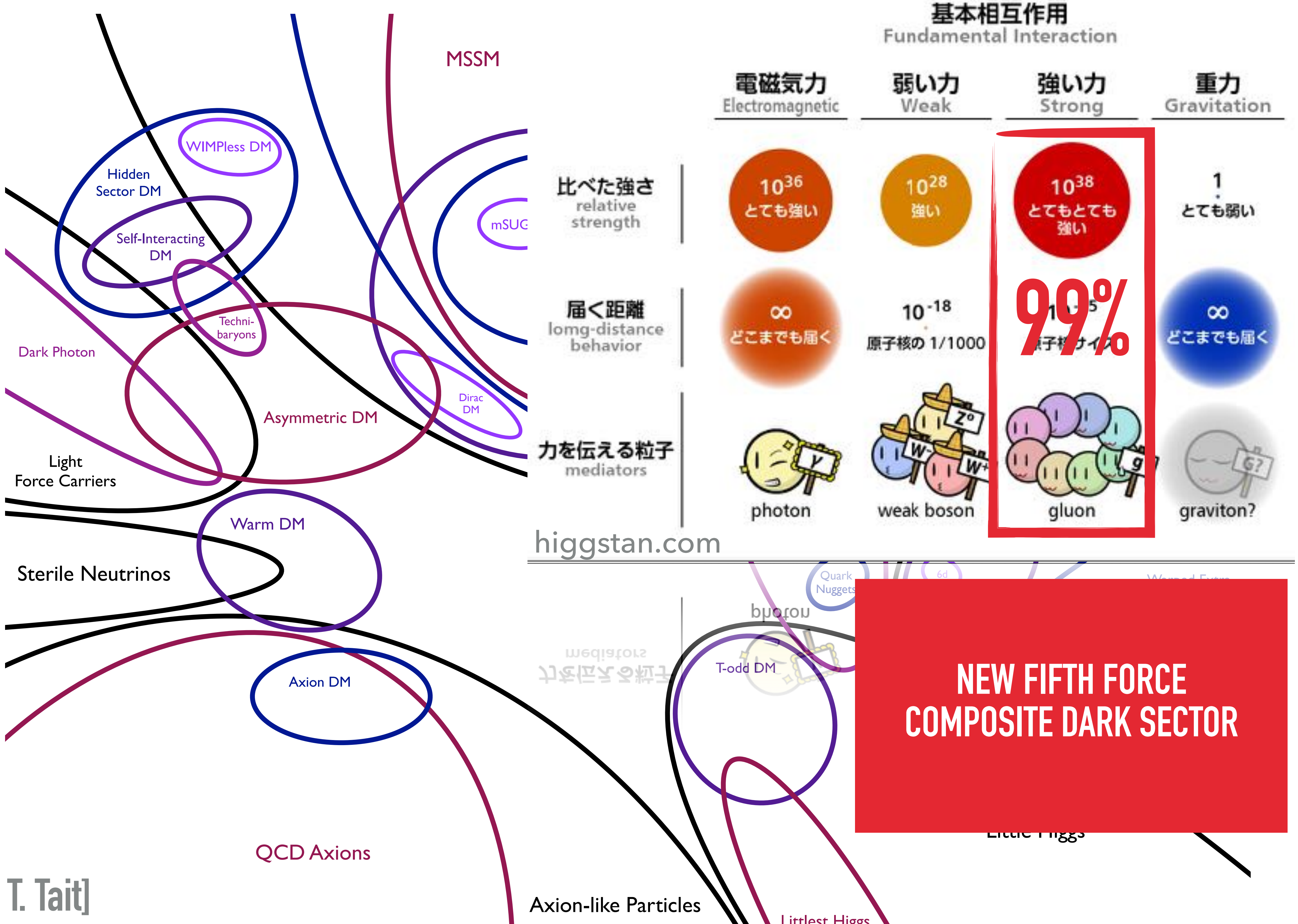

NEW FIFTH FORCE
COMPOSITE DARK SECTOR

[picture by T. Tait]

UNDERSTAND FIFTH FORCE TO GUIDE EXPERIMENTAL DISCOVERY

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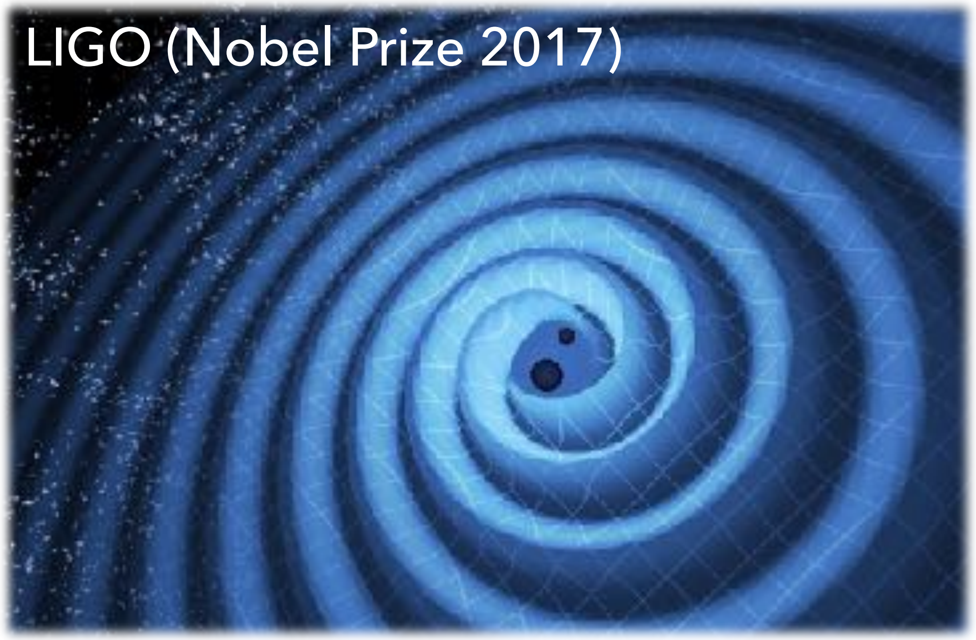
DARK PHASE TRANSITION GENERATING GRAVITATIONAL WAVES



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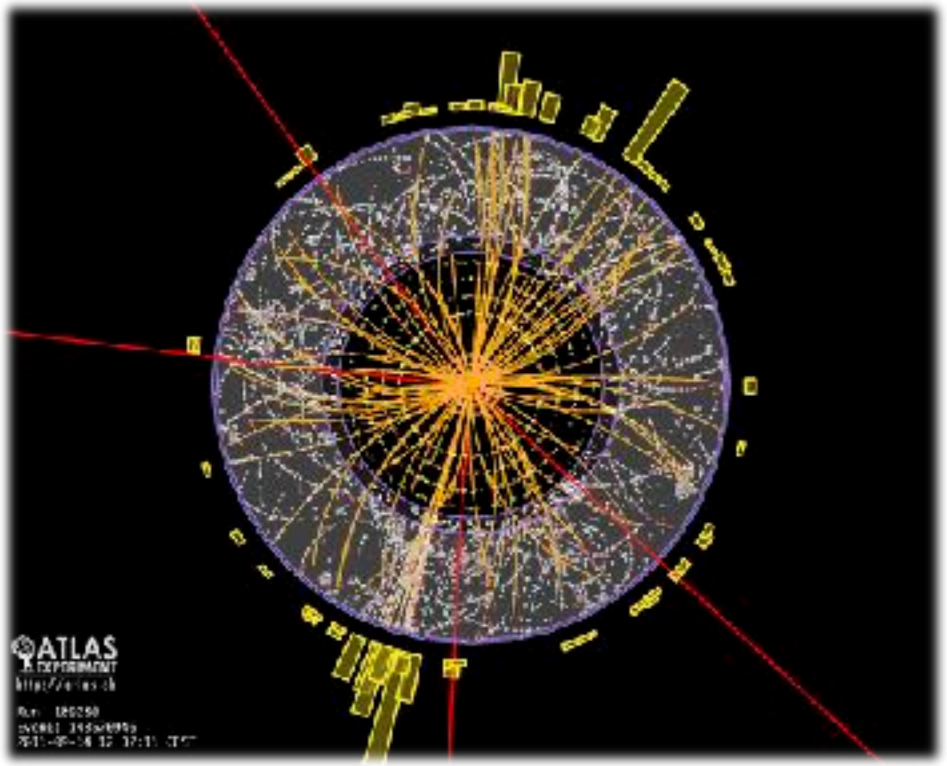
DARK SECTOR PARTICLES PRODUCED AT HIGH-ENERGY COLLIDERS



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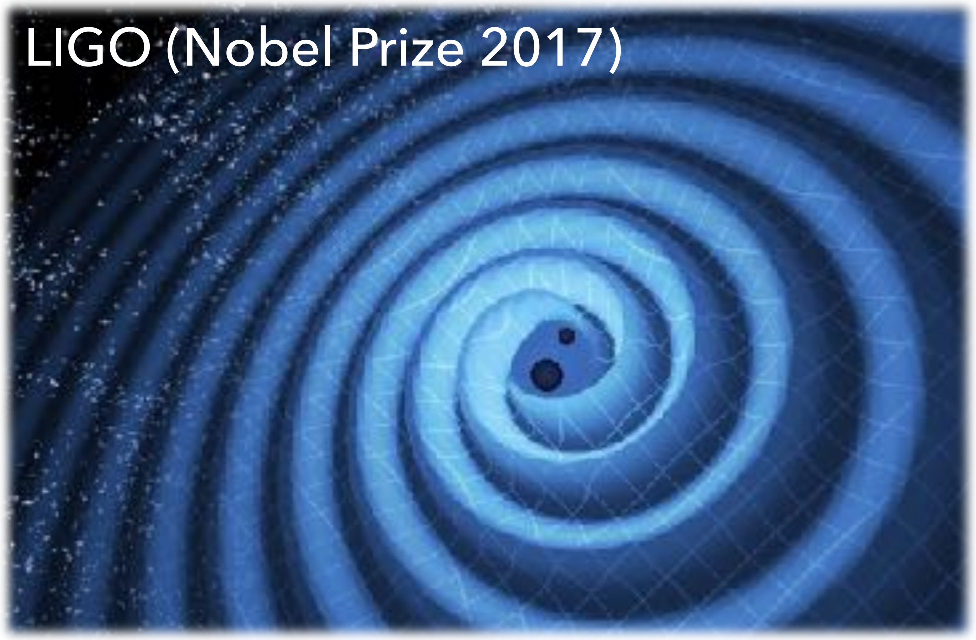


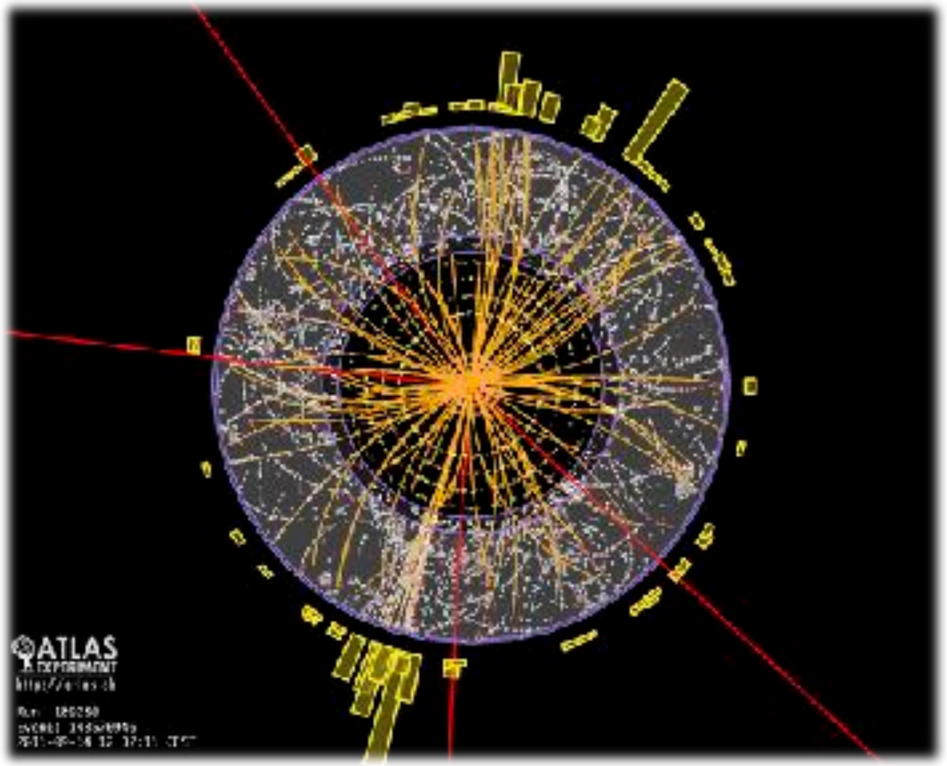
DETECTING COMPOSITE DARK SECTORS AND NEW PHYSICS: THE TRIAD

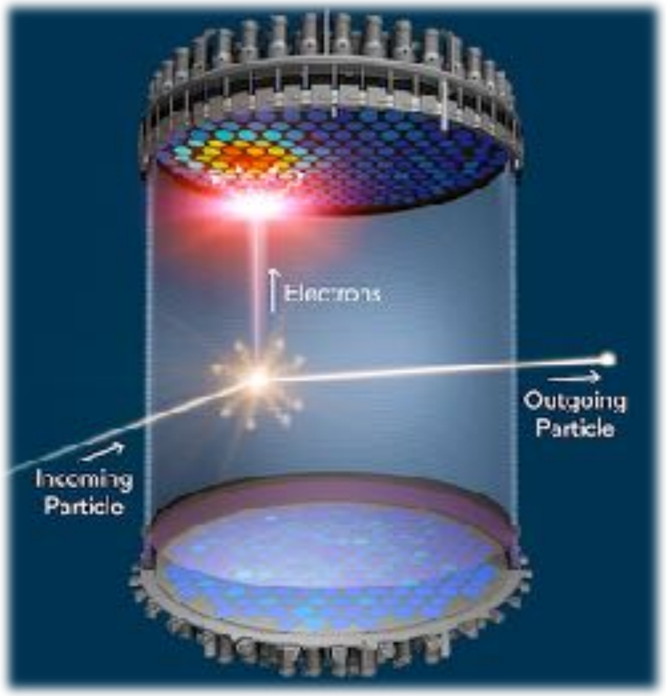
UNDERSTAND FIFTH FORCE TO GUIDE EXPERIMENTAL DISCOVERY

DARK SECTOR PARTICLES PRODUCED AT HIGH-ENERGY COLLIDERS

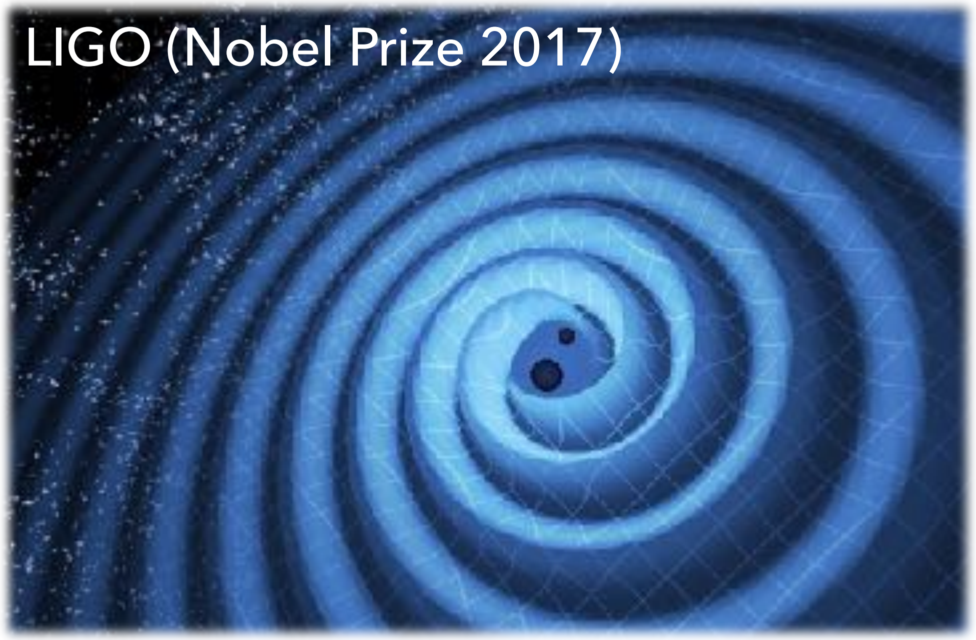
DIRECT DETECTION THROUGH DARK AND NUCLEAR FORM FACTORS

DARK PHASE TRANSITION GENERATING GRAVITATIONAL WAVES





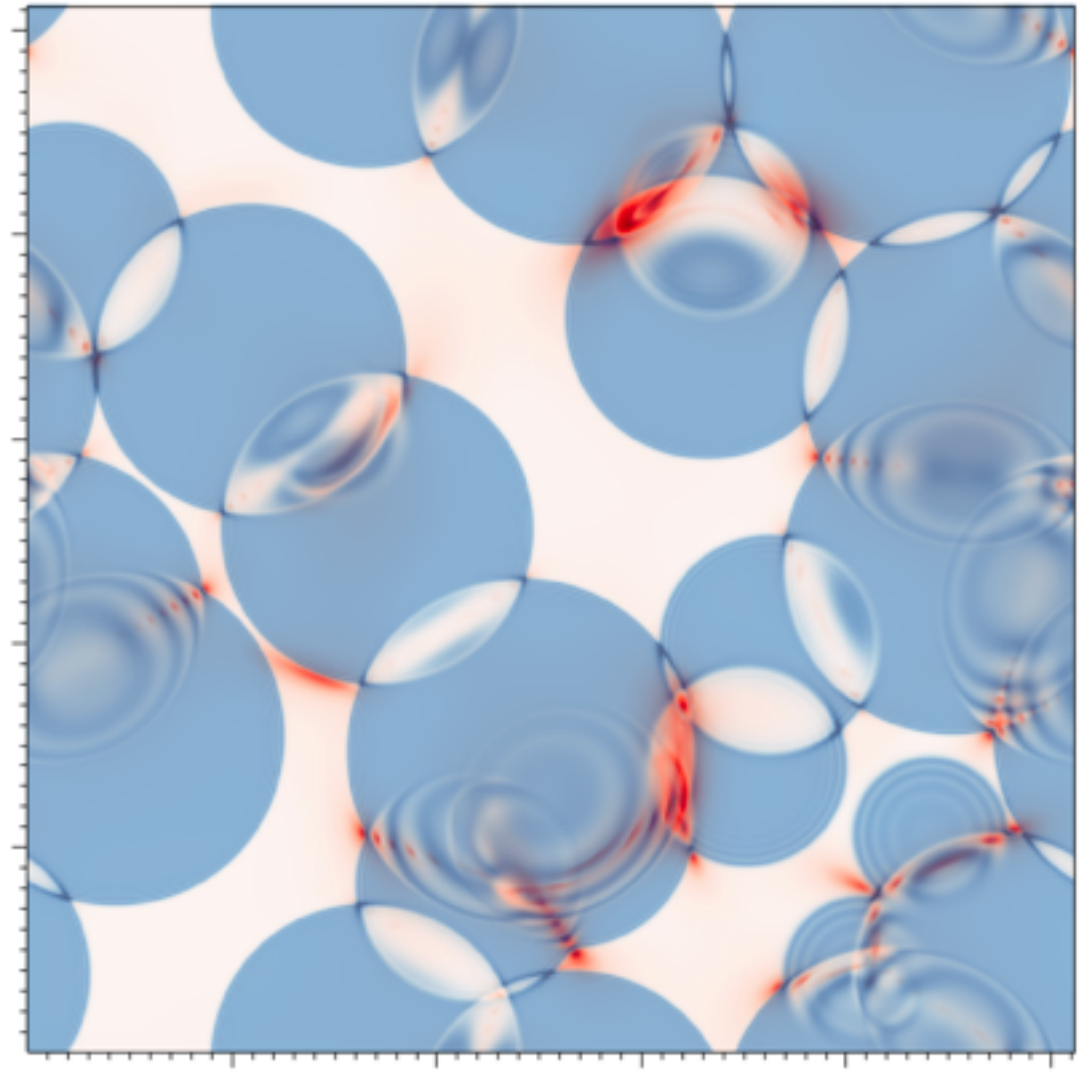
LIGO (Nobel Prize 2017)

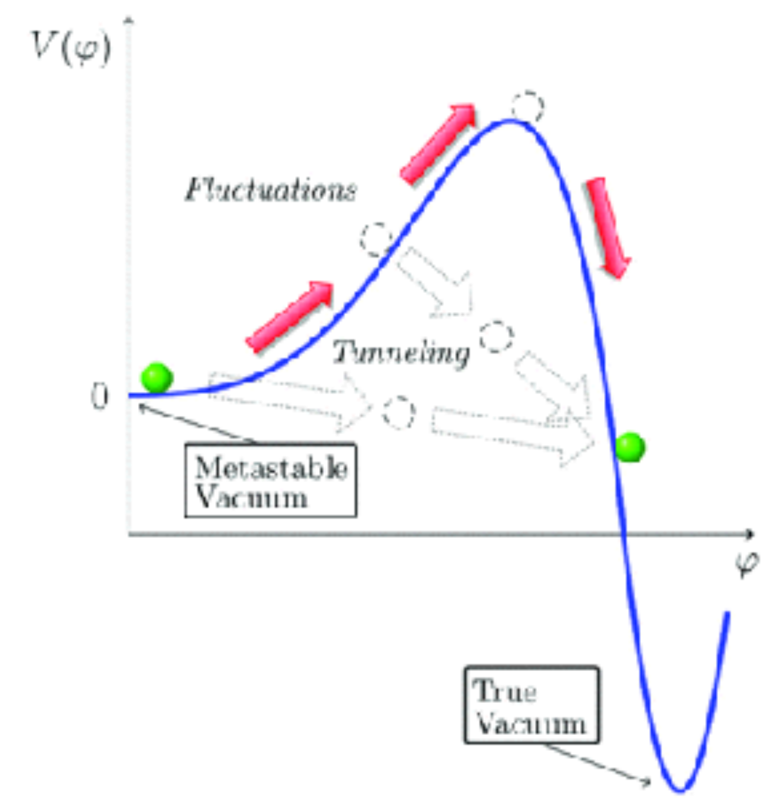


Phase Transitions (PT) are everywhere in nature!

They can be *cosmological*

Gravitational waves from vacuum first-order phase transitions





Cosmological Aspects of Higgs Vacuum Metastability

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Focus on 1st order PTs: the universe changes from a metastable high energy (symmetric) phase to a stable lower energy (broken) phase.

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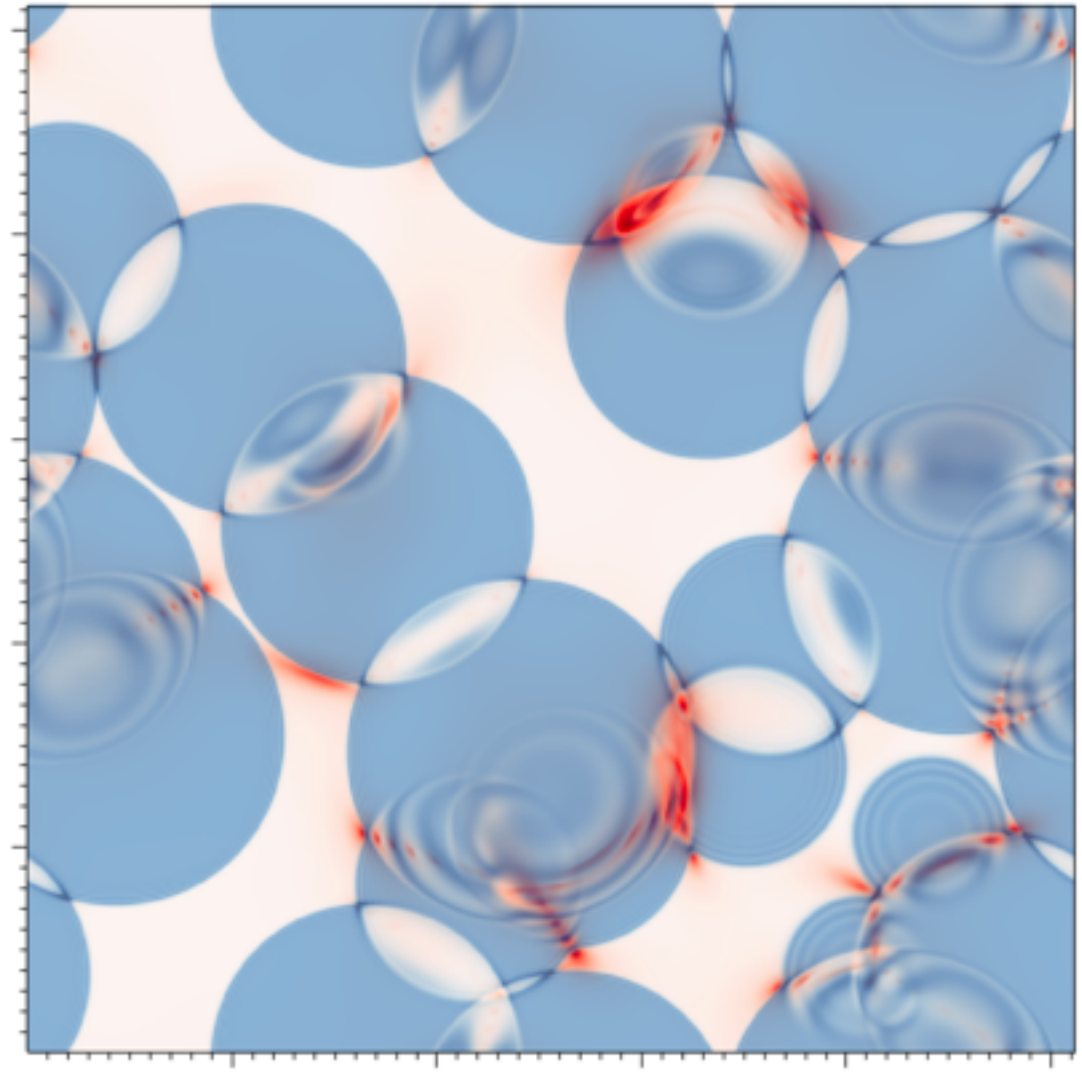

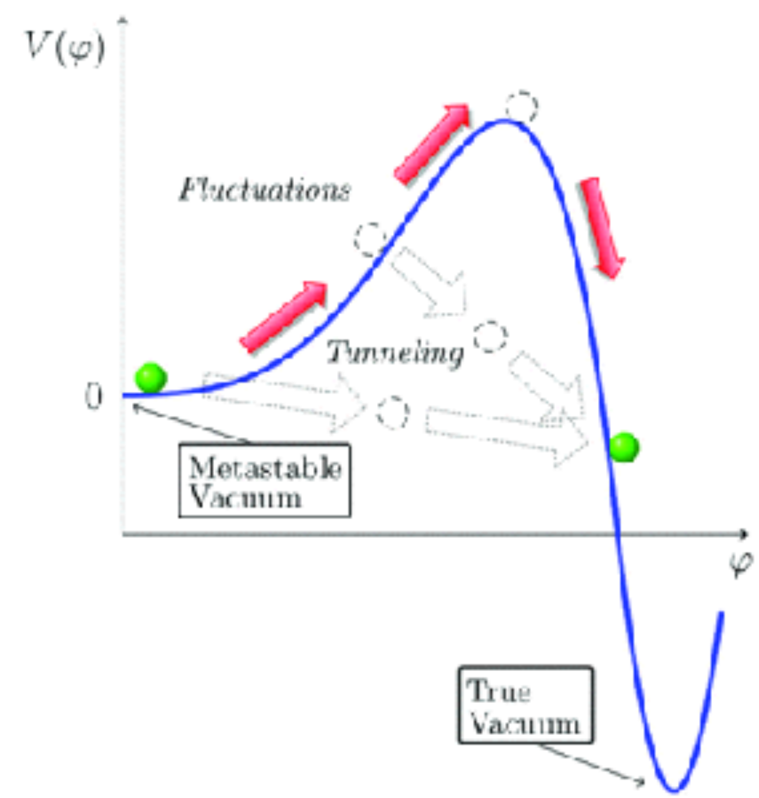

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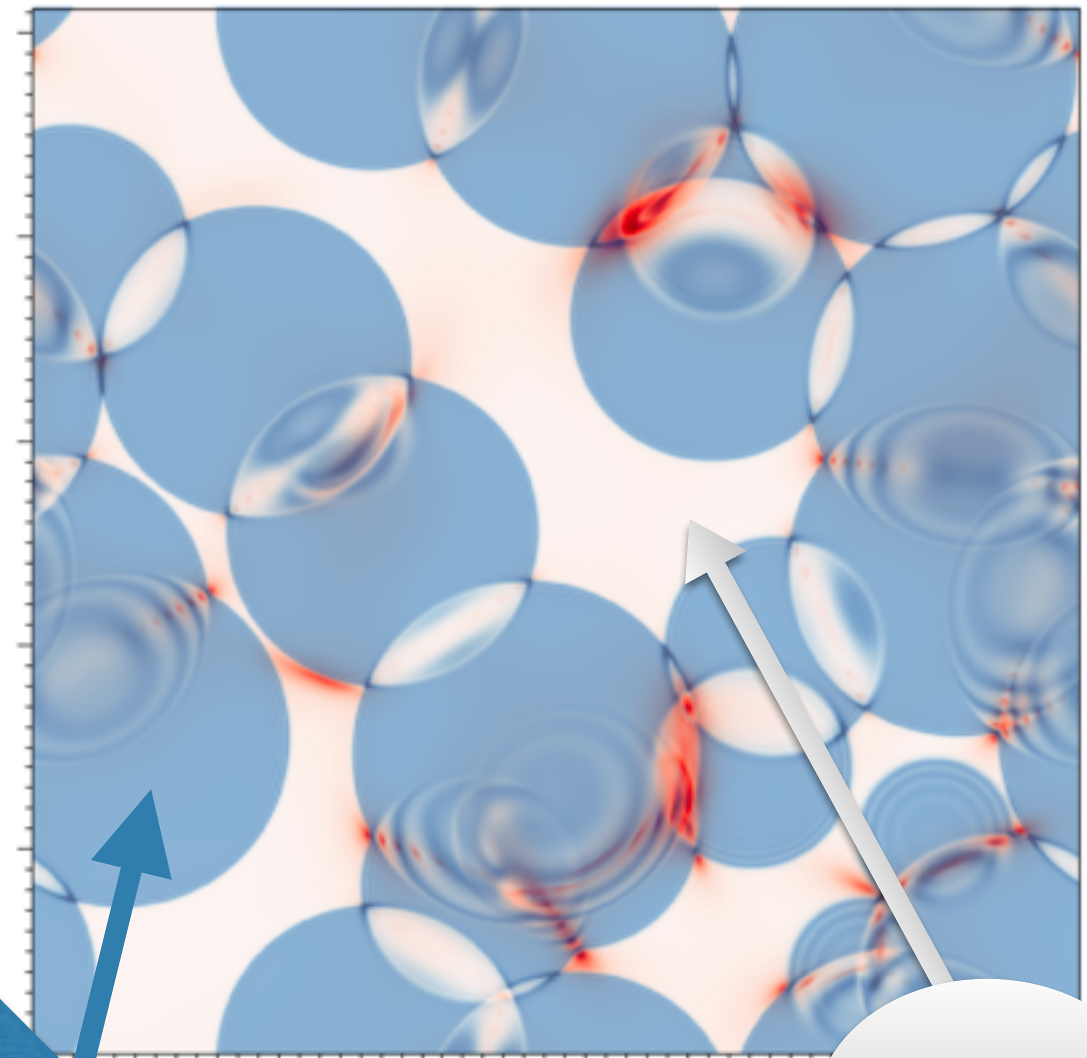

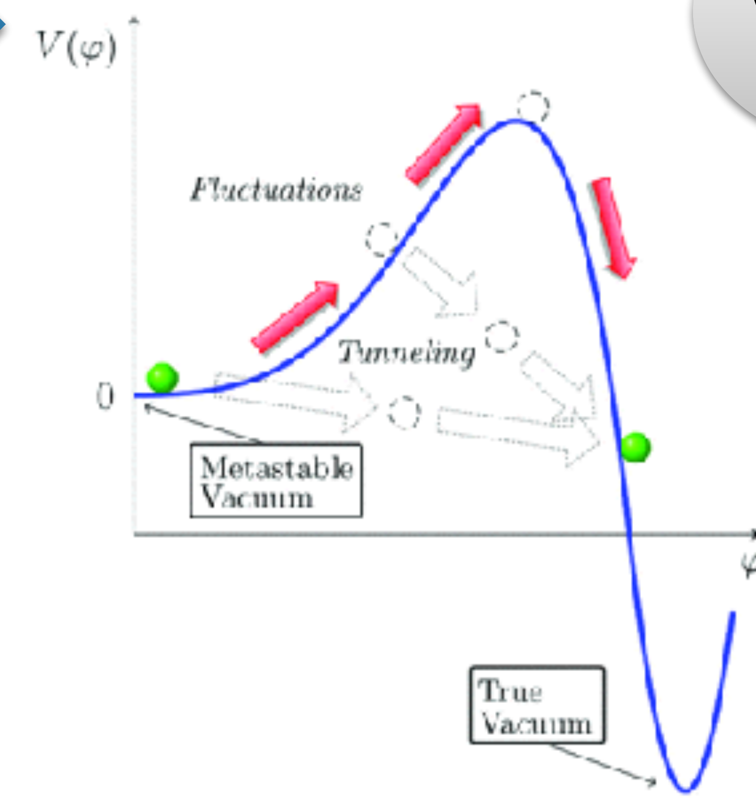

Cosmological Aspects of Higgs Vacuum Metastability

EARLY UNIVERSE TRANSITIONS

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QCD confinement-deconfinement

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Dark sector transition

EARLY UNIVERSE TRANSITIONS

QCD confinement-deconfinement

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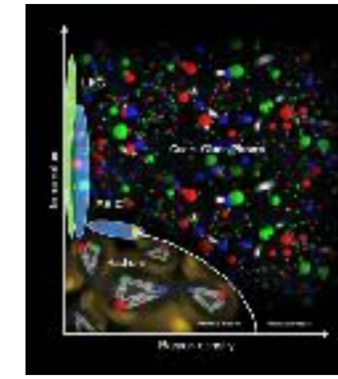
Electroweak symmetry breaking

Dark sector transition

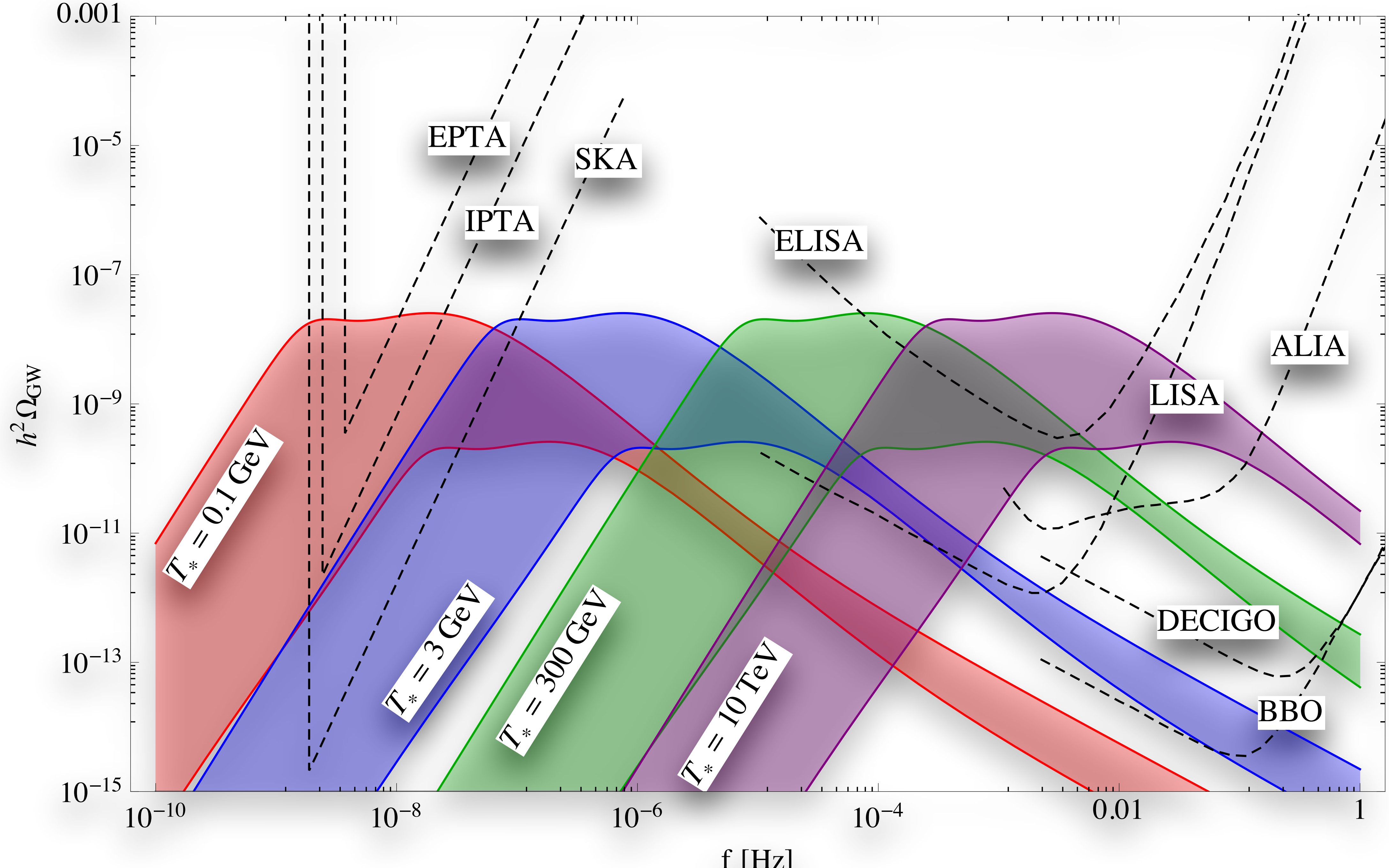
maybe strong 1st order if N is large…

Dark sector gravitational wave signatures

[RHIC]

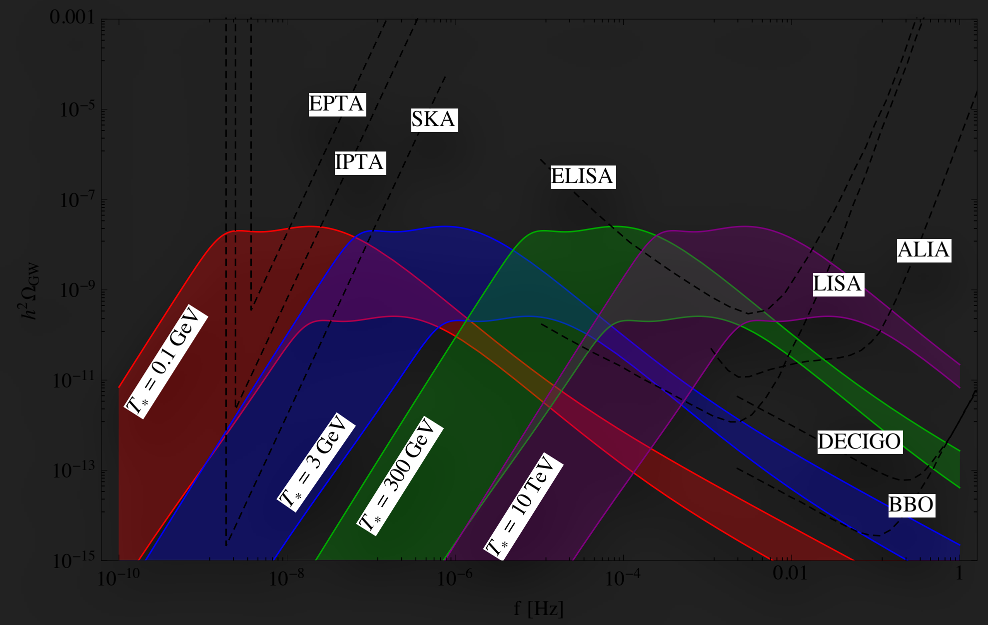


✦Spectrum of GW from a deconfinement 1st order phase transition in the dark sector



[P. Schwaller, PRL (115) 181101, 2015]

GRAVITATIONAL WAVES SPECTRUM

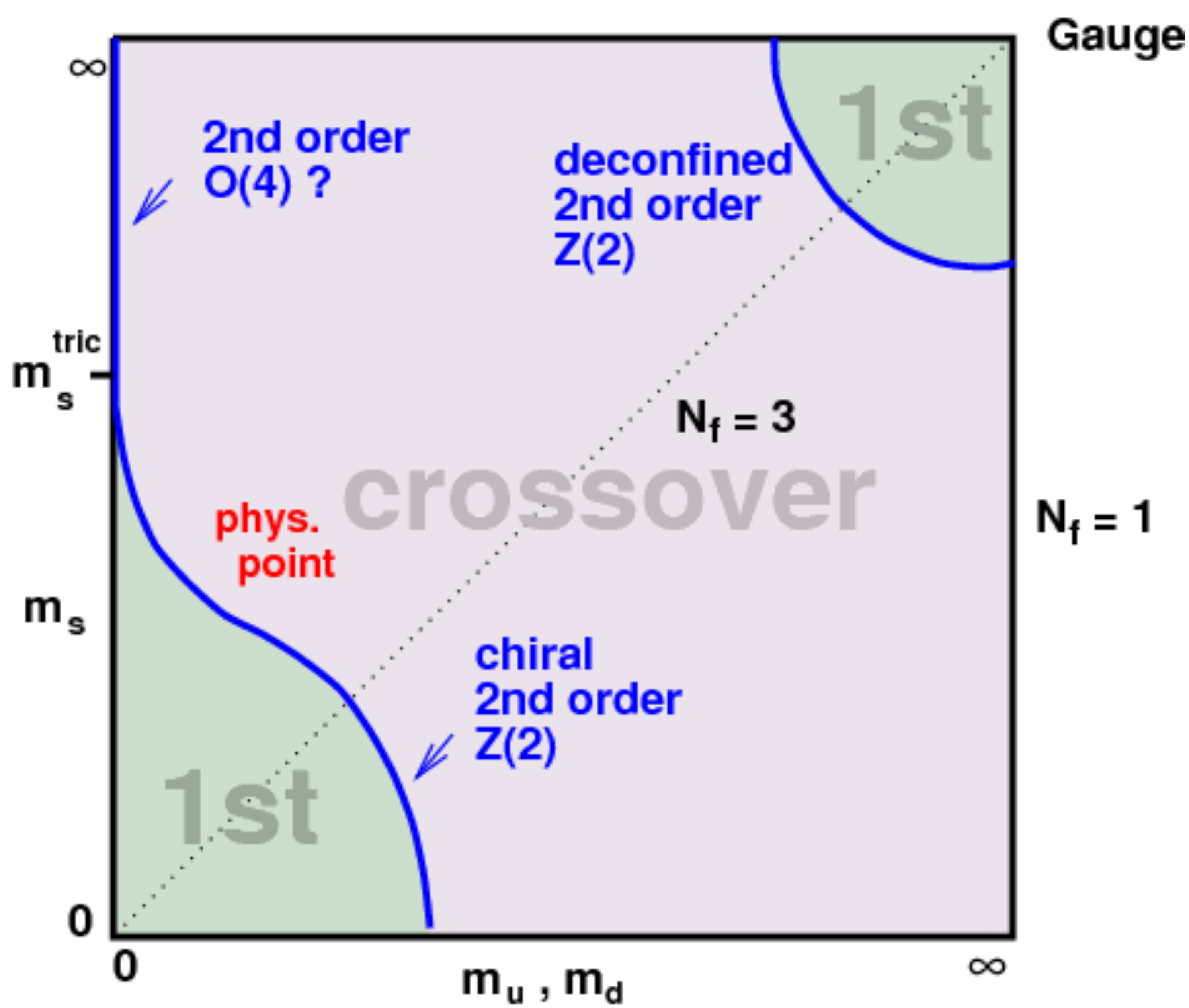


- Determined by 3 parameters:
  - α → relative energy density in the source (related to latent heat at the phase transition)
  - β → bubble nucleation rate proportional to inverse time of the transition (related to tunneling probability between vacua)
  - υ → bubble velocity
- Plus we need to know the temperature of the phase transition $T_\star \simeq T_c$

[Laermann, Philipsen, Ann, Rev, Nucl. Part. Sci. 53 (2003) 163-198]

Phase Transitions in Strongly-coupled Theories

QCD



"Columbia" plot

[Laermann, Philipsen, Ann, Rev, Nucl. Part. Sci. 53 (2003) 163-198]

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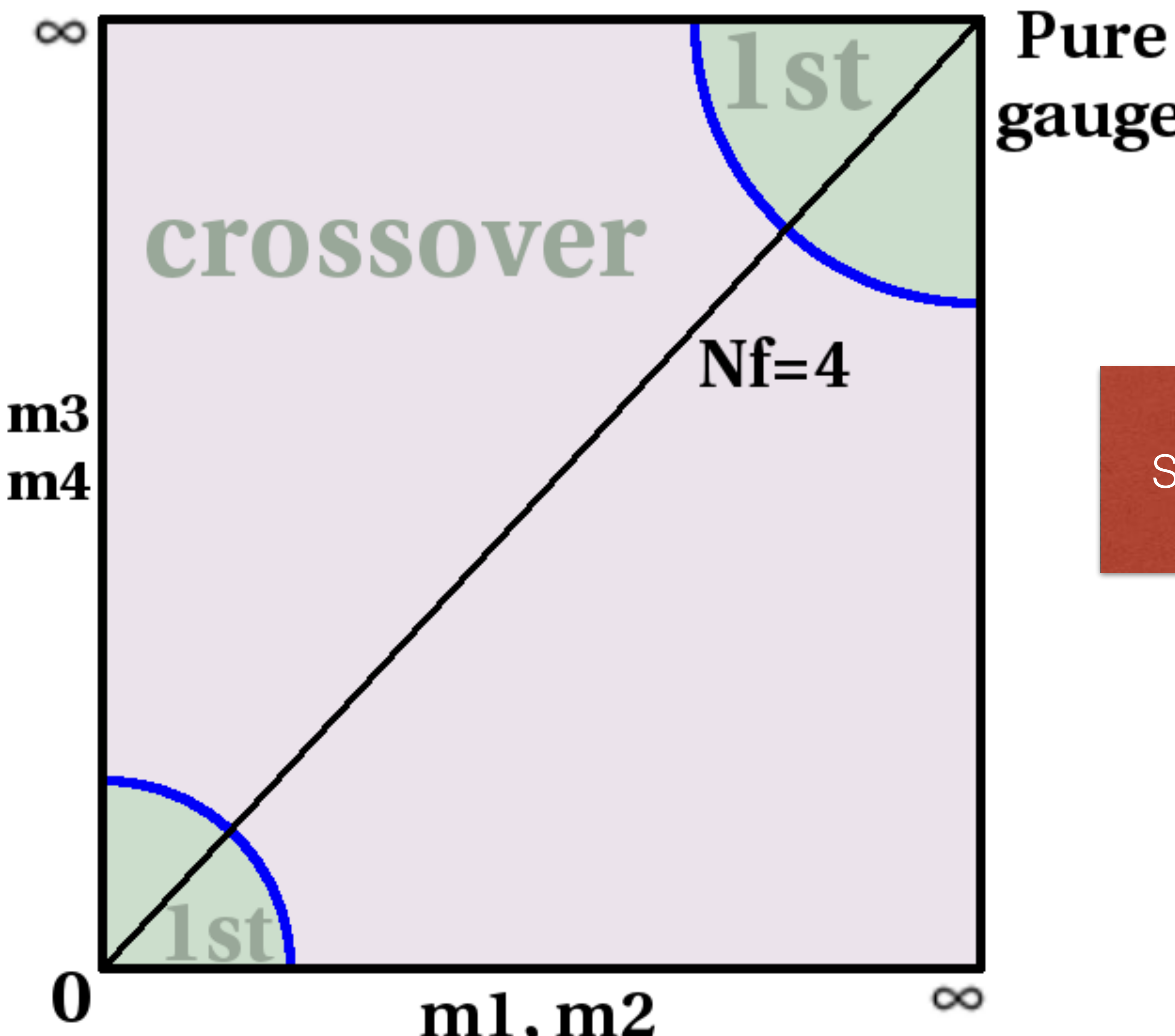

Stealth DM

[Laermann, Philipsen, Ann, Rev, Nucl. Part. Sci. 53 (2003) 163-198]

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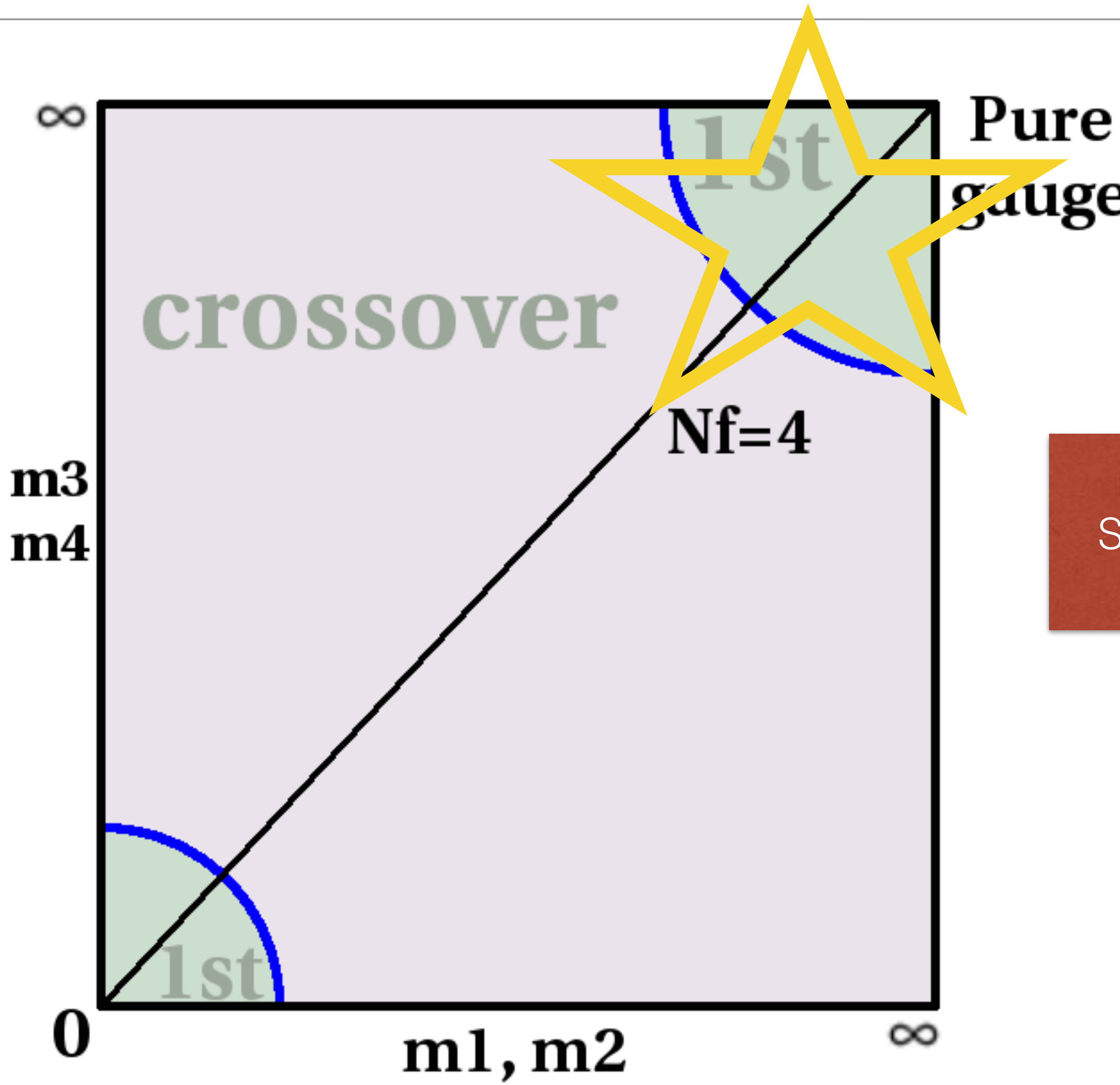

Stealth DM

BUILDING BLOCKS FOR THE PHASE DIAGRAM

$SU(4)$

with dynamical nHYP smeared staggered fermions

$a \cdot m$ $\{0.05, 0.1, 0.2, 0.4, \infty\}$

N_t $\{4, 6, 8, 12\}$

$\alpha = L/N_t$ $\{2, 3, 4, 6, 8\}$

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⇒ **Scan in** β_F

~ 1370 ensembles

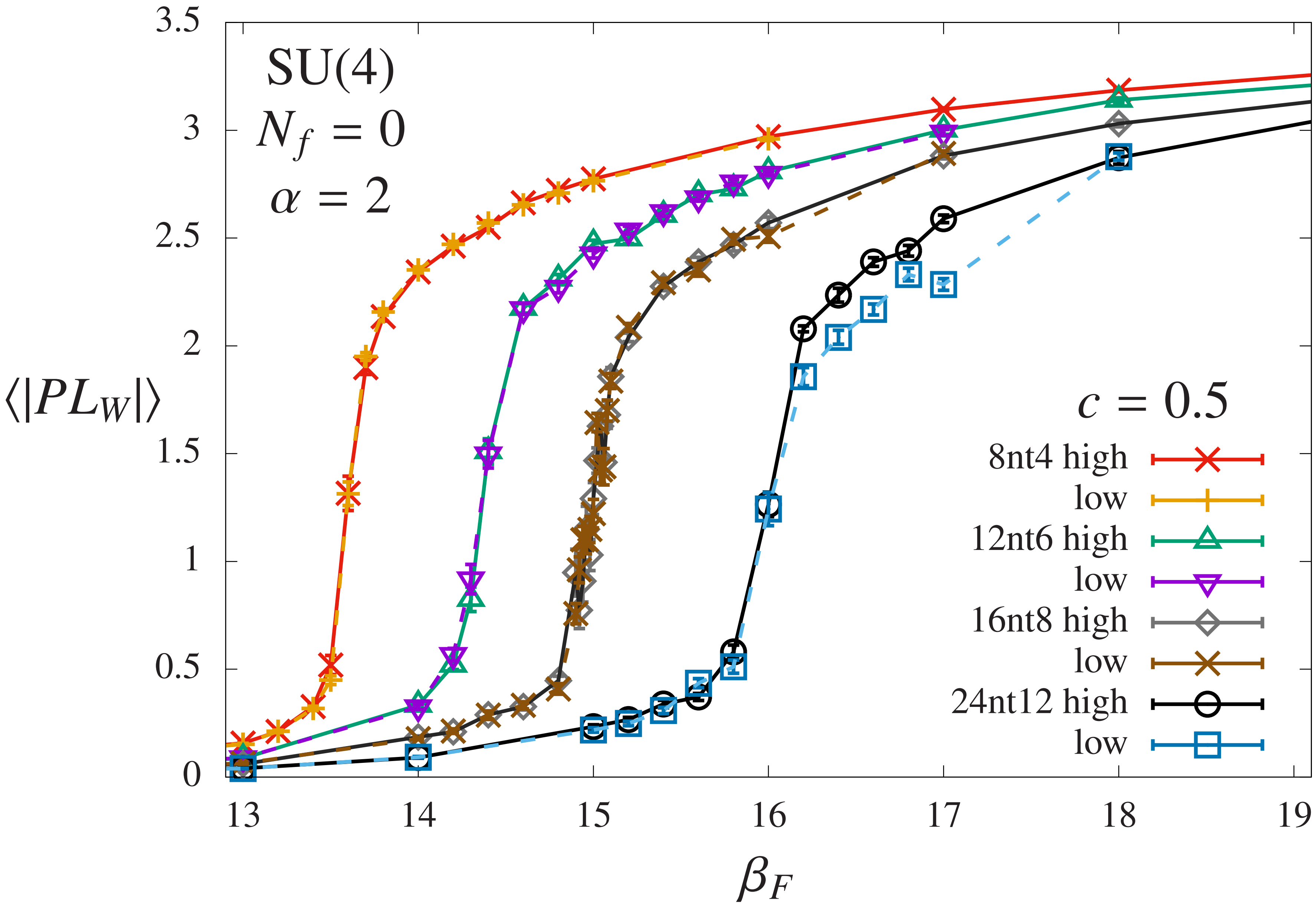
LATTICE OBSERVABLES

$|PL_W|$ and $\chi_O = L^3\left(\langle O^2\rangle - \langle O\rangle^2\right)$

$R_E(t) \equiv \left\langle \frac{E_{ss}(t)}{E_{s\tau}(t)} \right\rangle$ → ≈ 1 / > 1

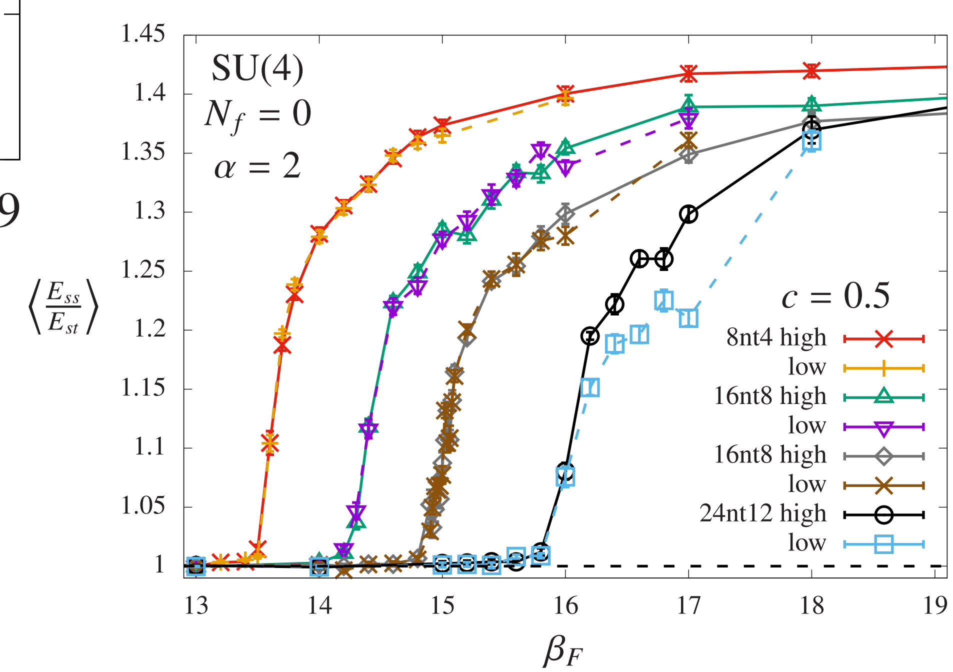
$f(\theta) \equiv \frac{\pi/4}{\pi/4-\theta}\left[\frac{N_{\mathbf{in}}}{N_{\mathbf{tot}}} - \frac{\theta}{\pi/4}\right]$ → $\to 0$ / $\to 1$

Results: Pure-Gauge system $a \cdot m = \infty$



- Long autocorrelations
- Topological freezing
- high-low starts

Flow time: $t = N_t^2/32$



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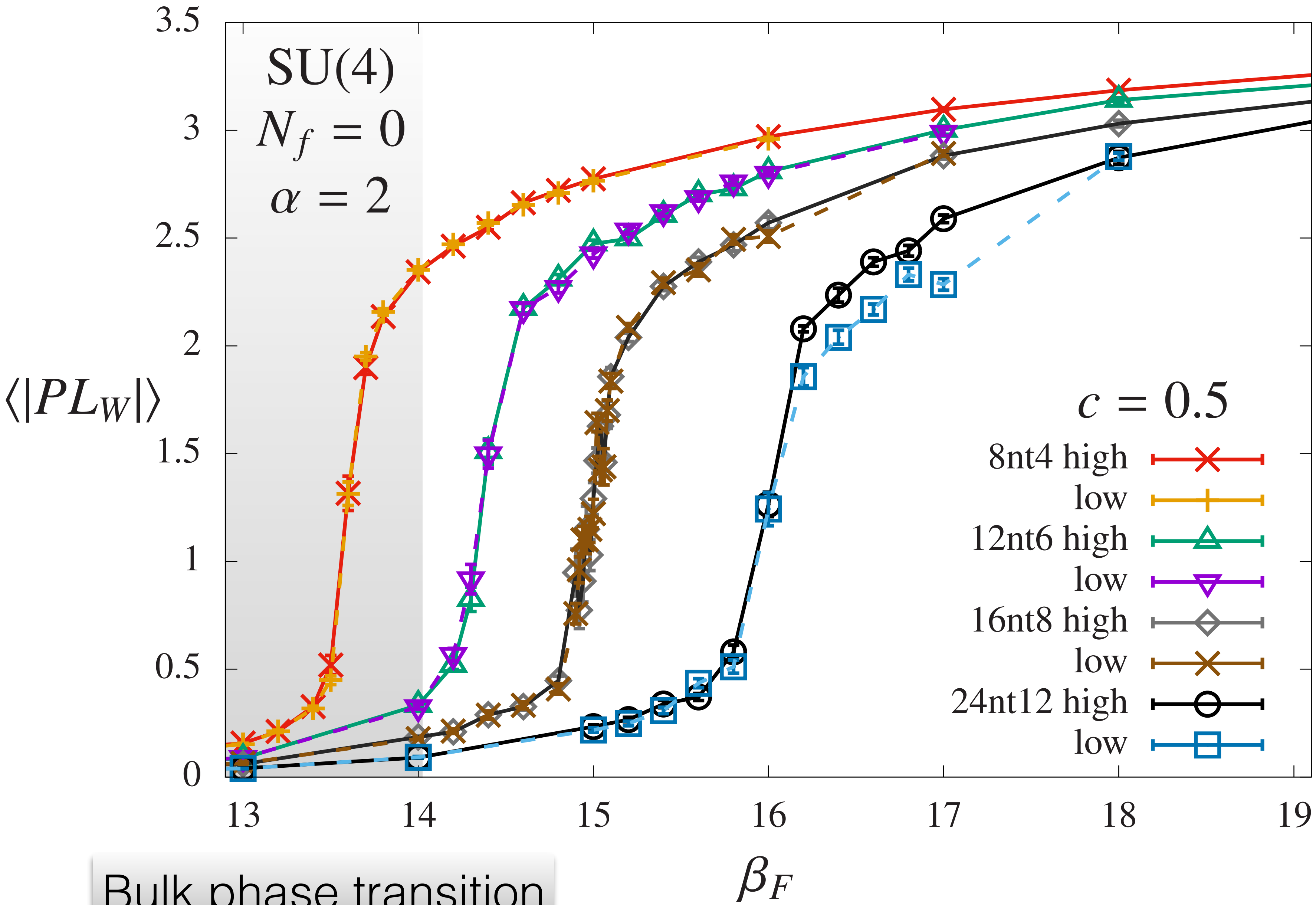

Bulk phase transition

- Long autocorrelations
- Topological freezing
- high-low starts

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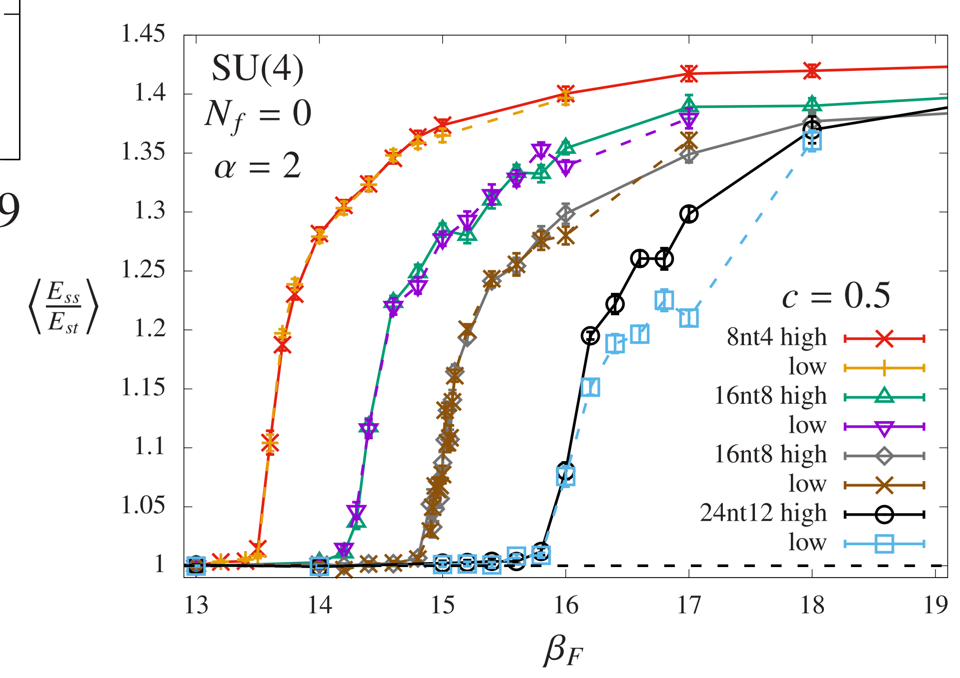
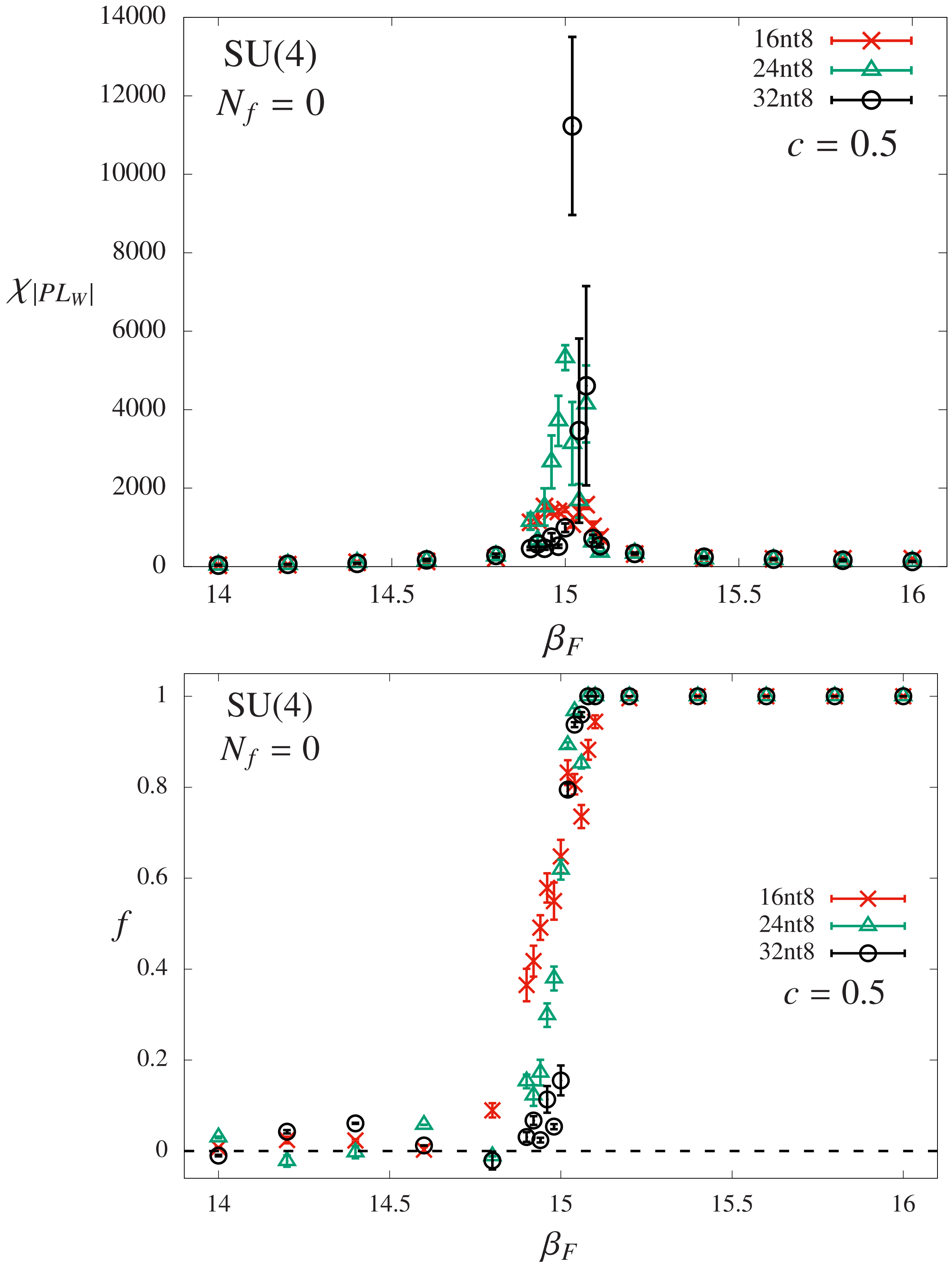


Results: Pure-Gauge system $N_t = 8$



- Peak of χ grows with volume
- Deconfinement fraction gets steeper

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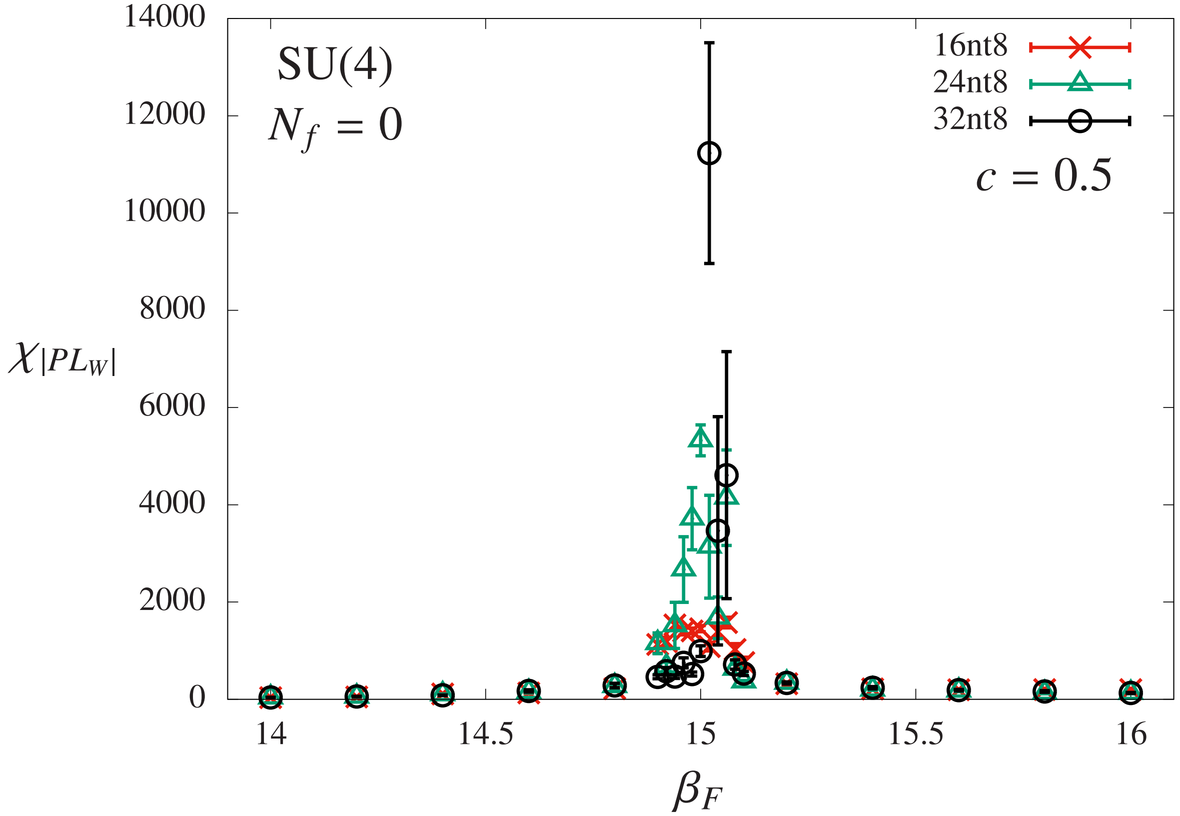

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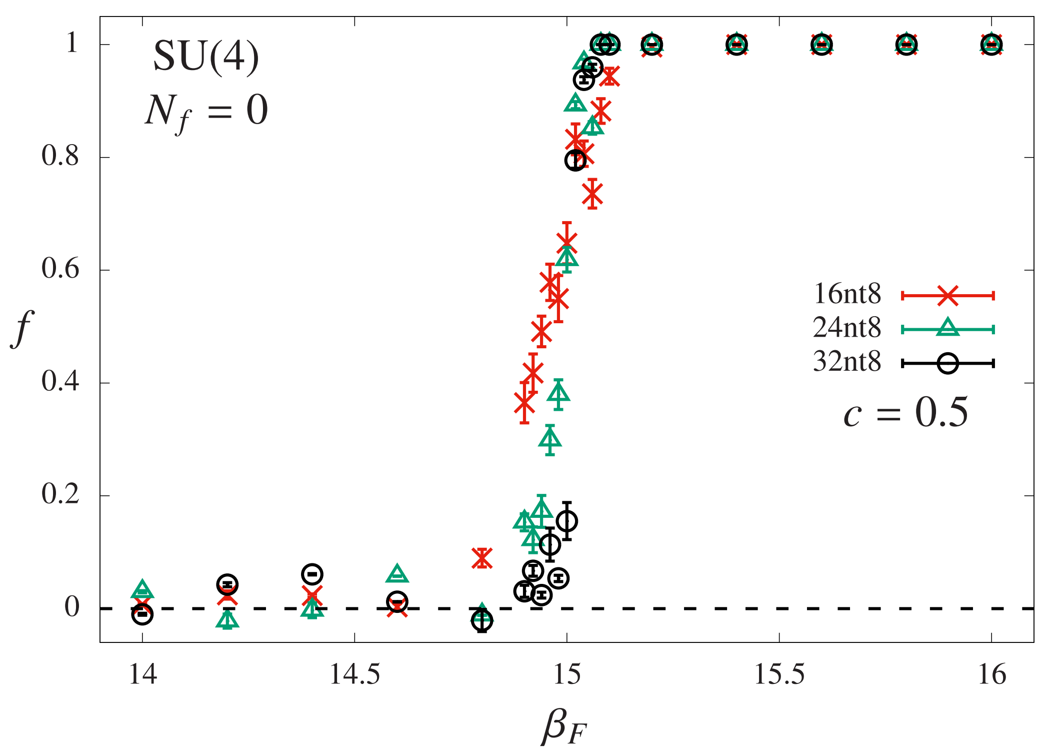

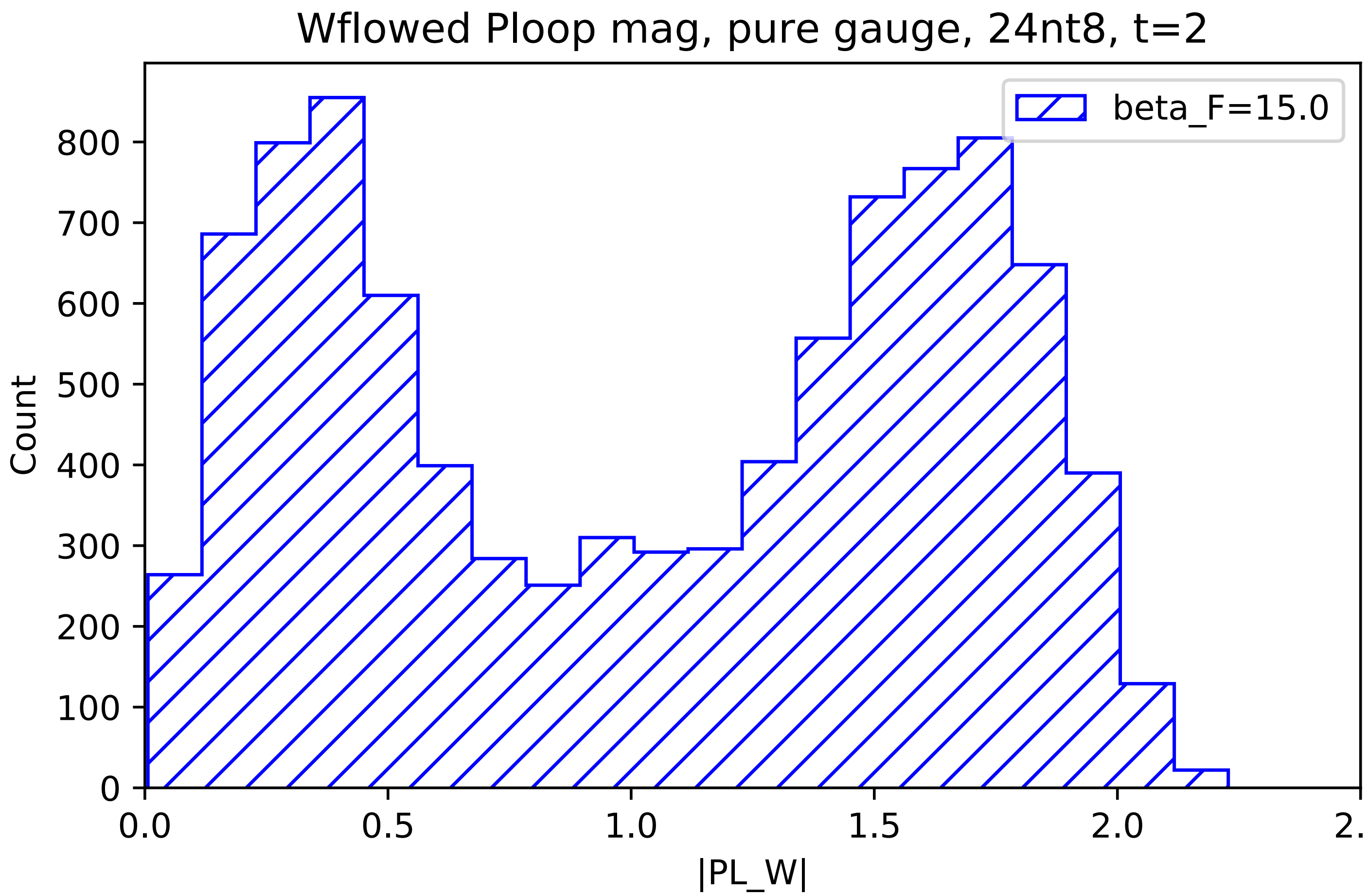

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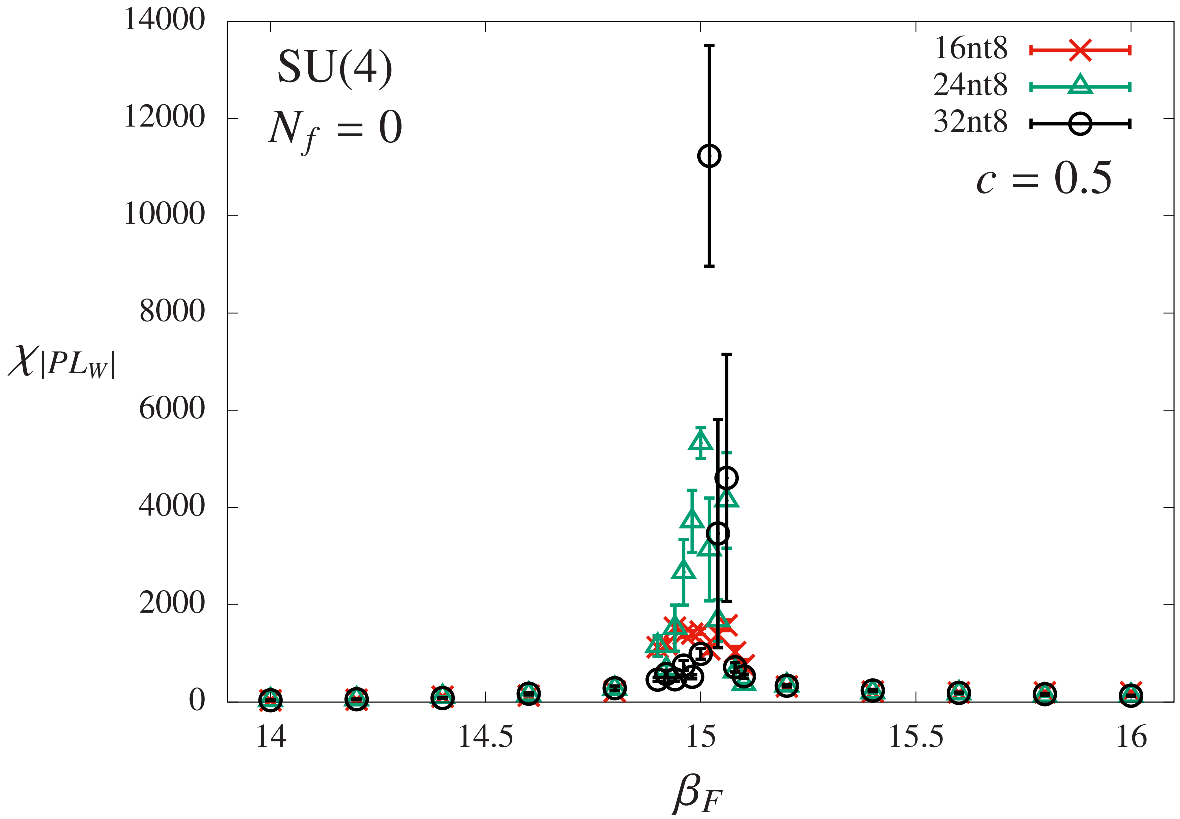

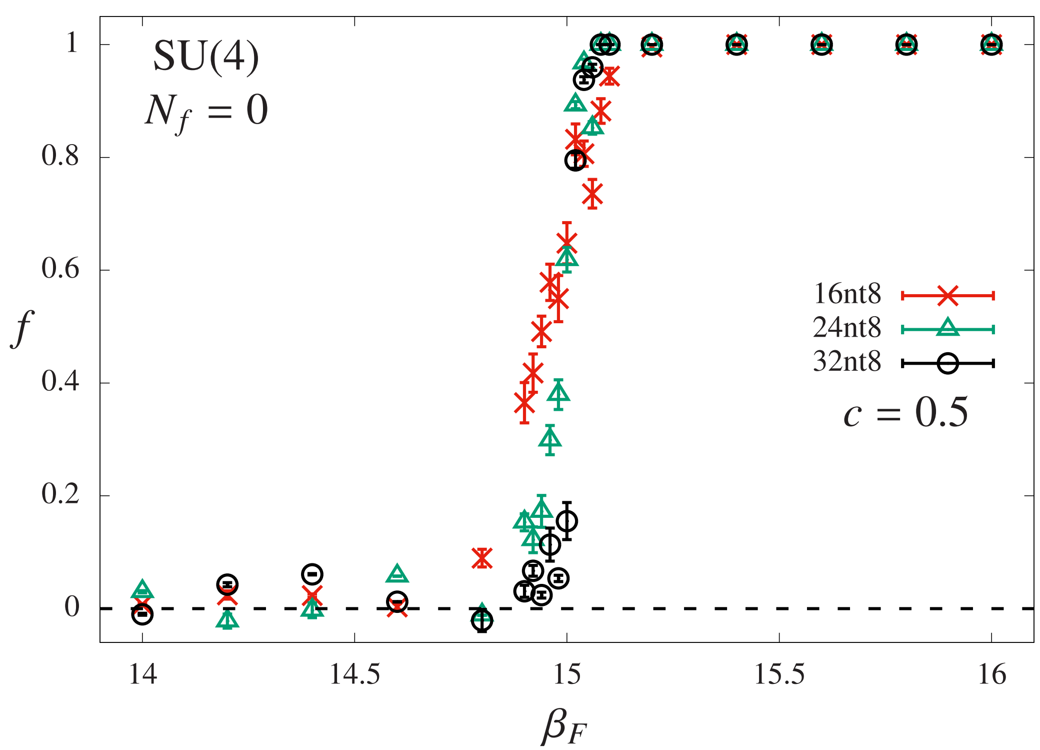

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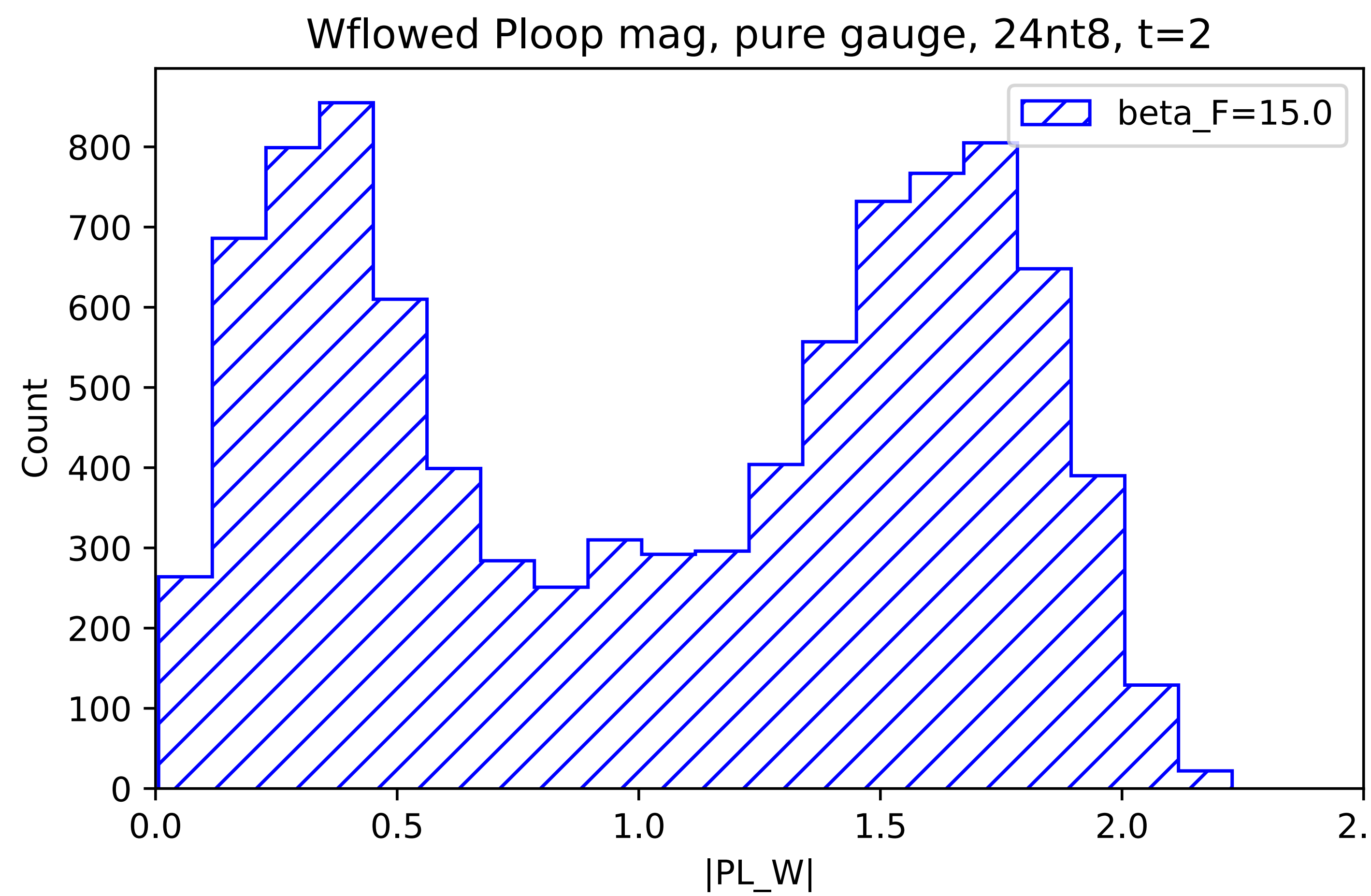
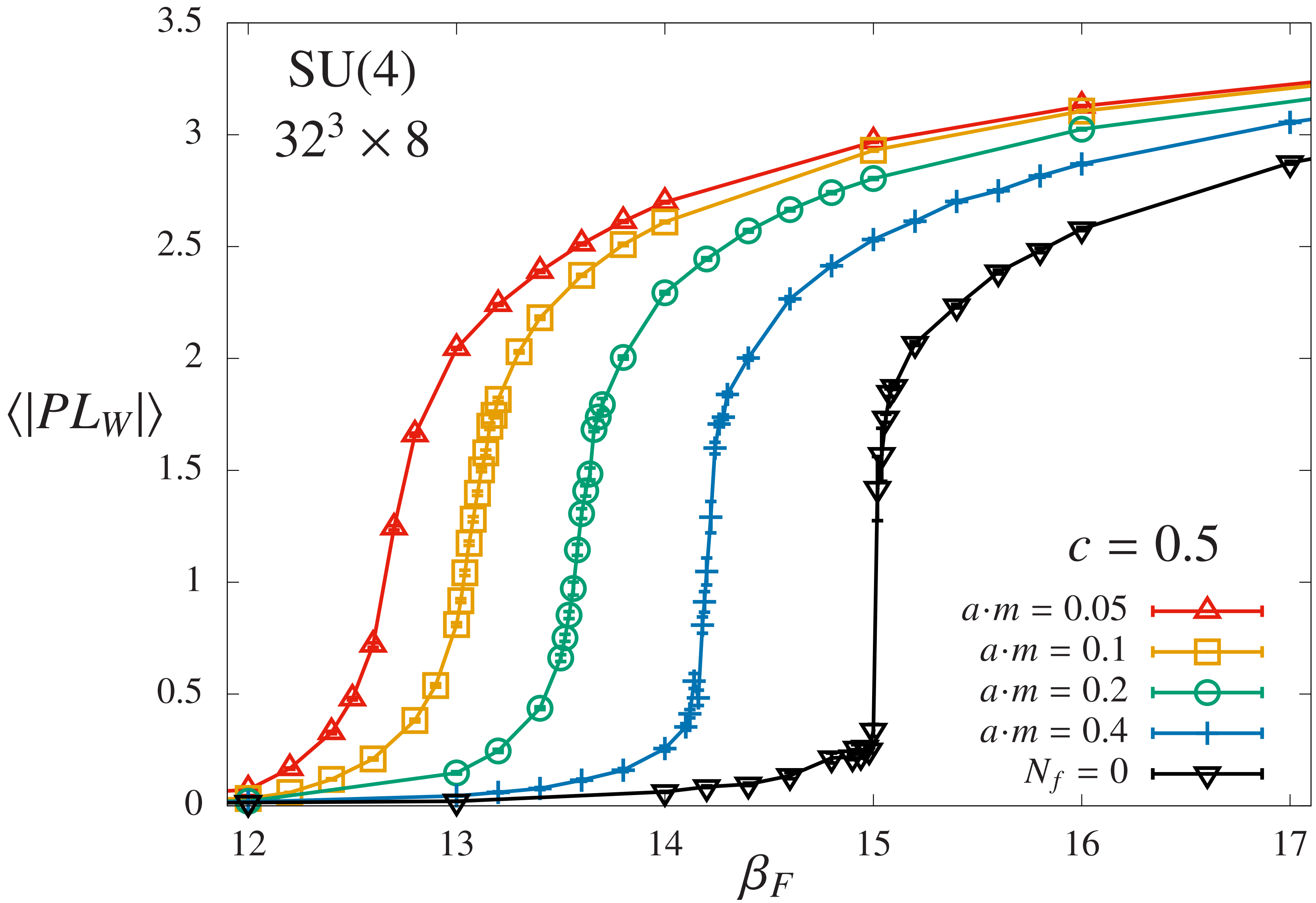


Signs of 1st order transition

Results: Dynamical Fermions $N_f = 4$



- Difference from quenched
- Stronger couplings needed at smaller mass
- Susceptibility scales for $a \cdot m > 0.2$
- Two-peak histogram
- Still no continuum limit

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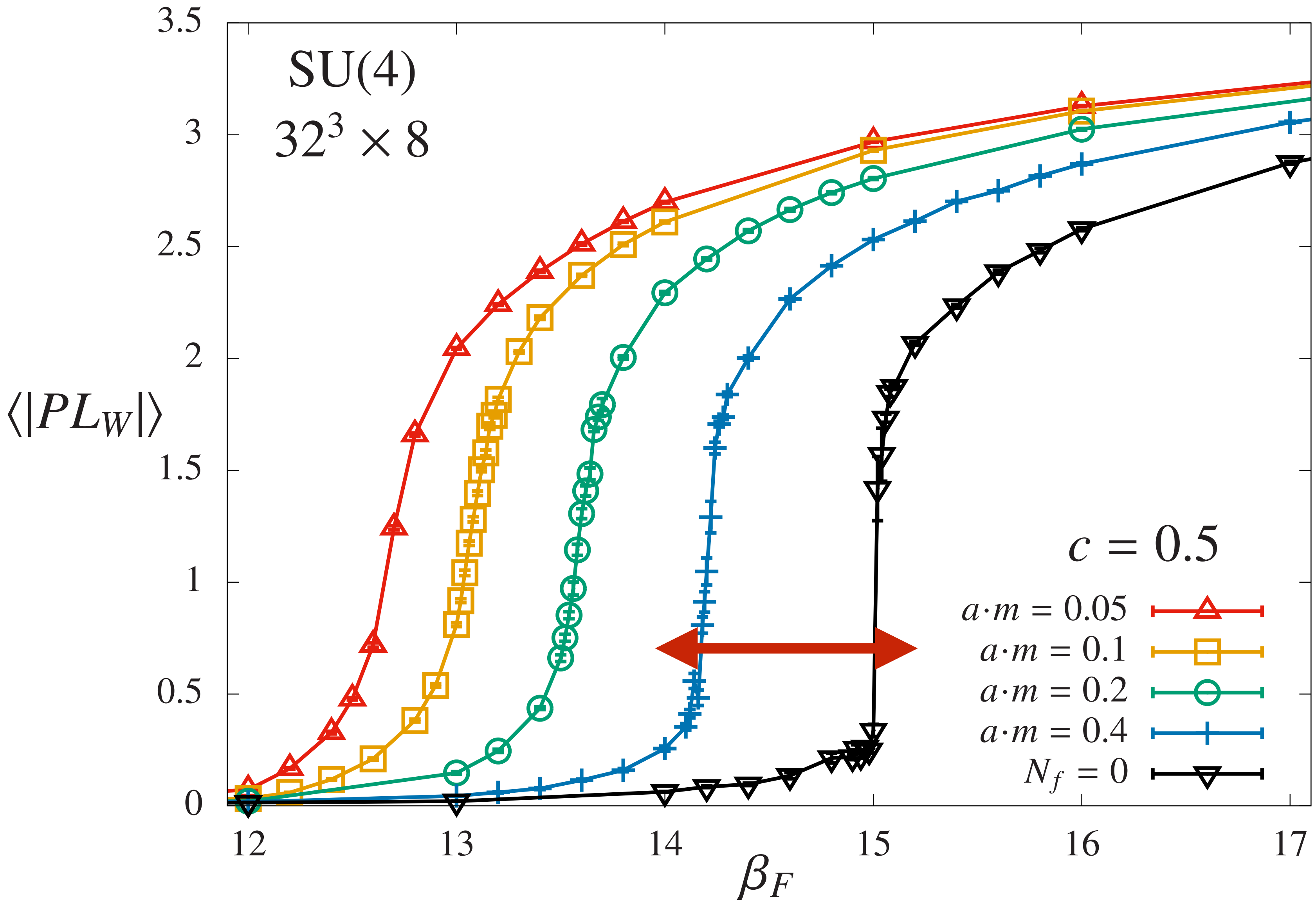

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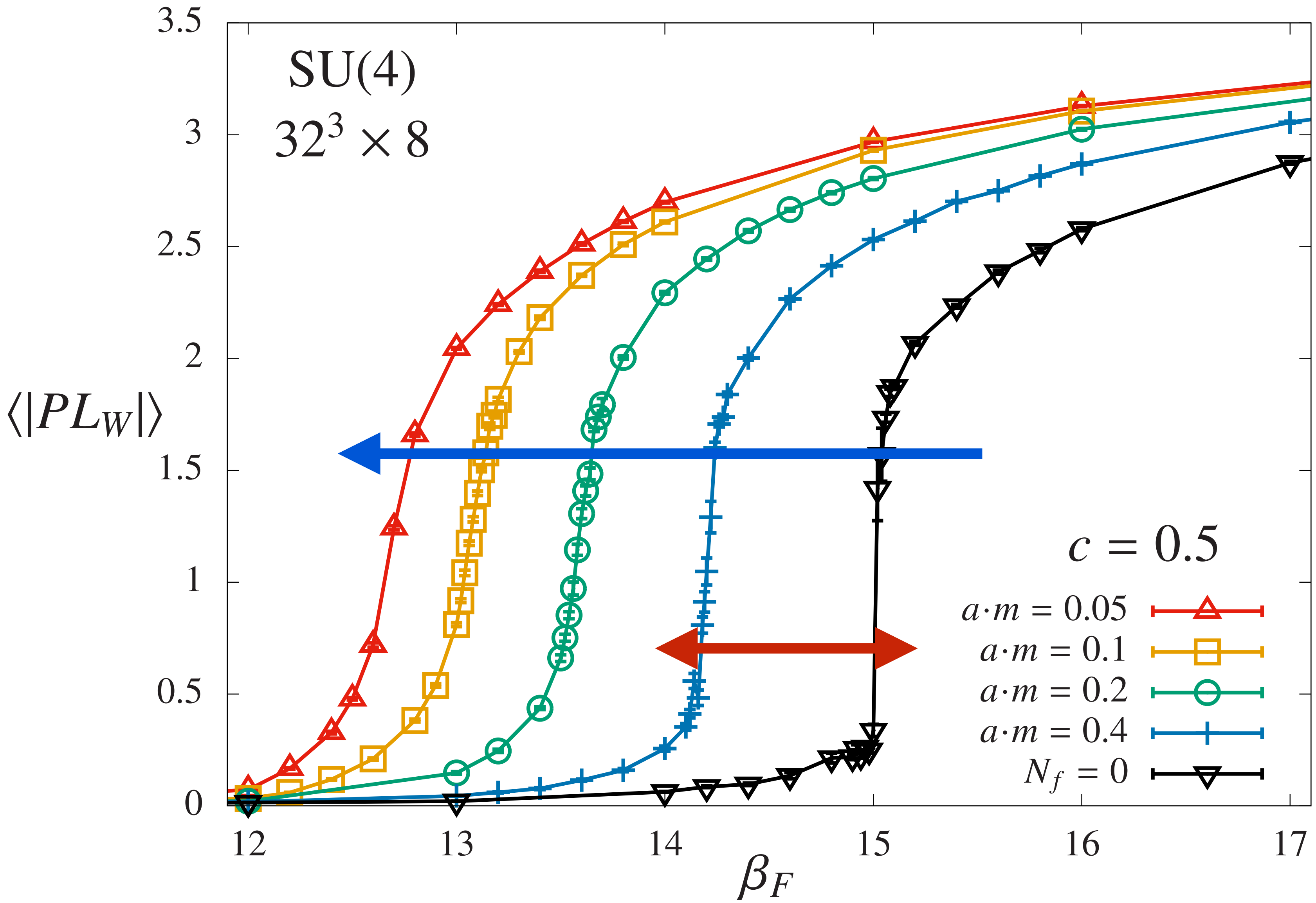

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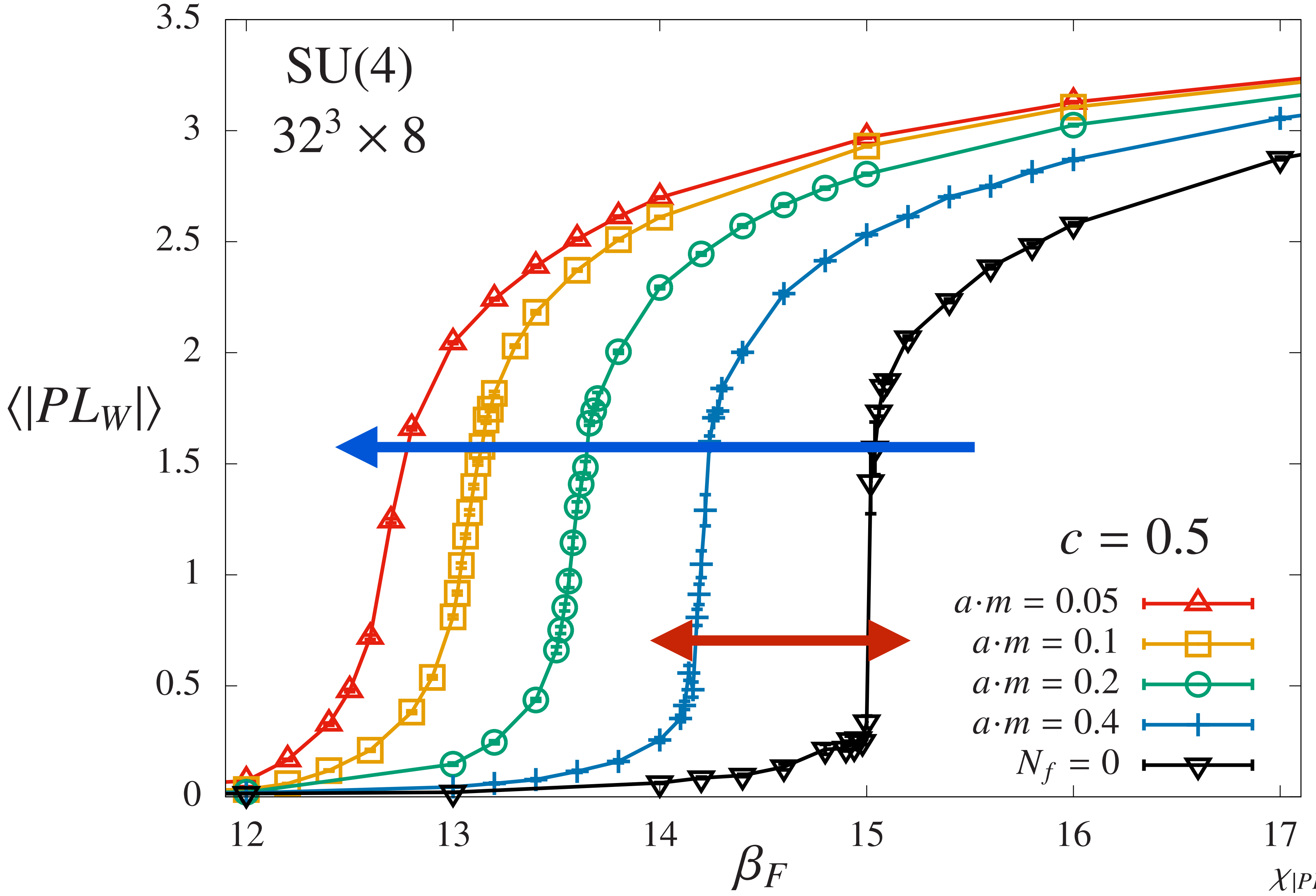

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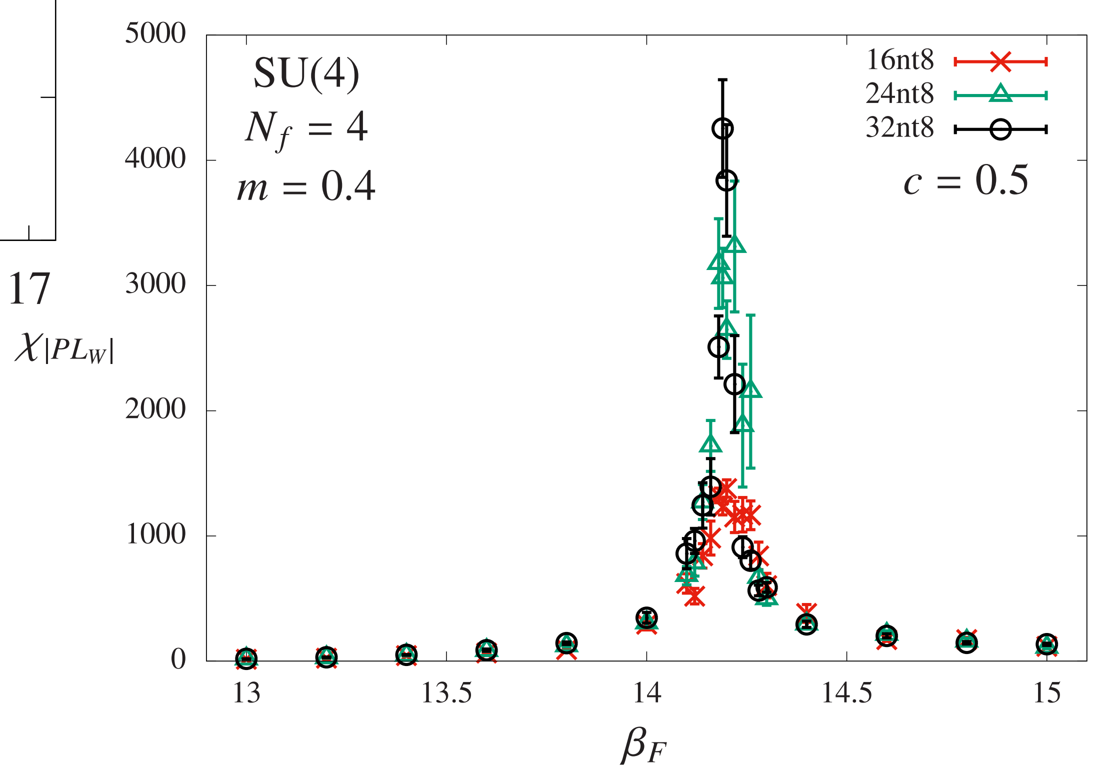

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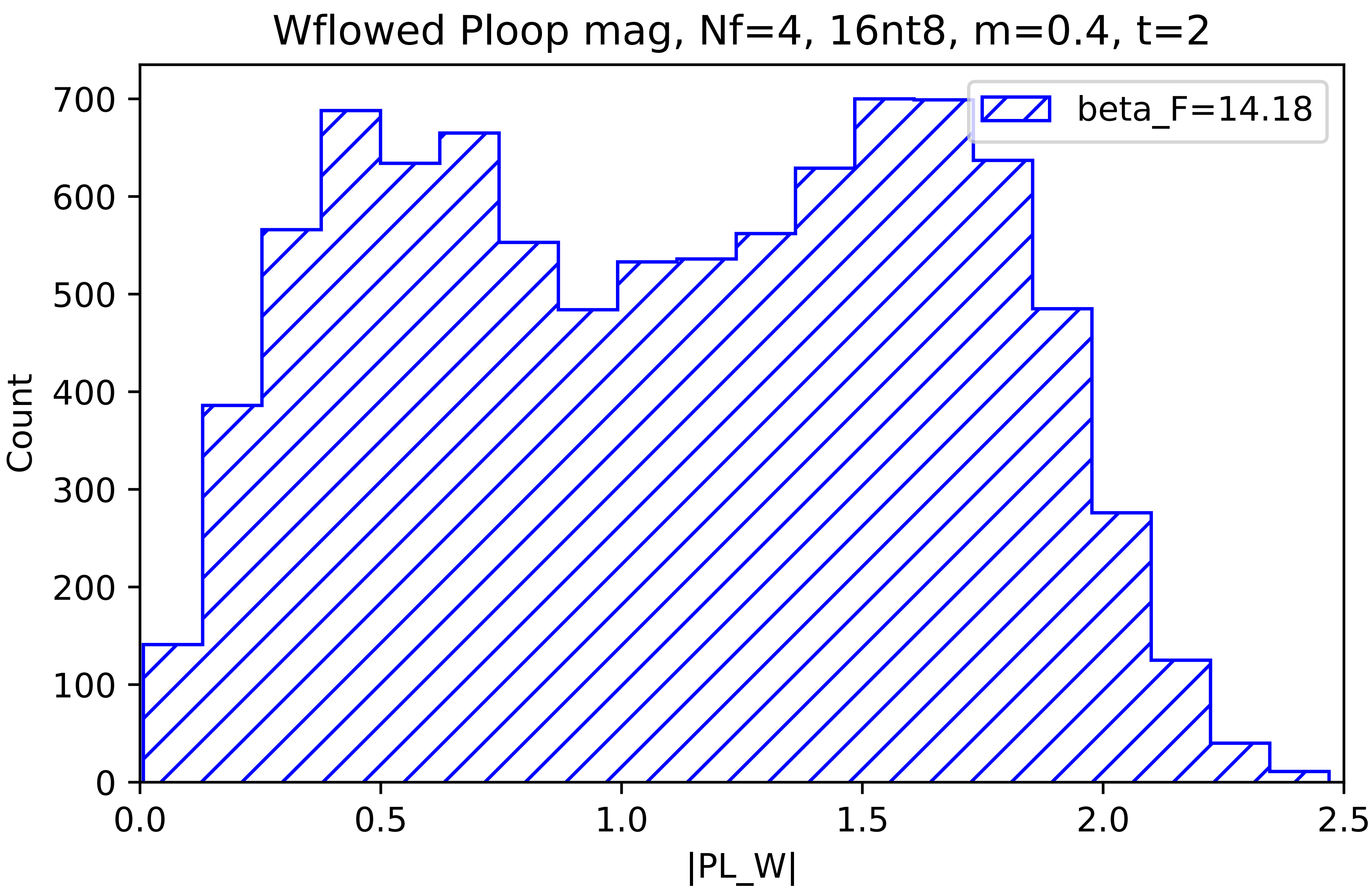

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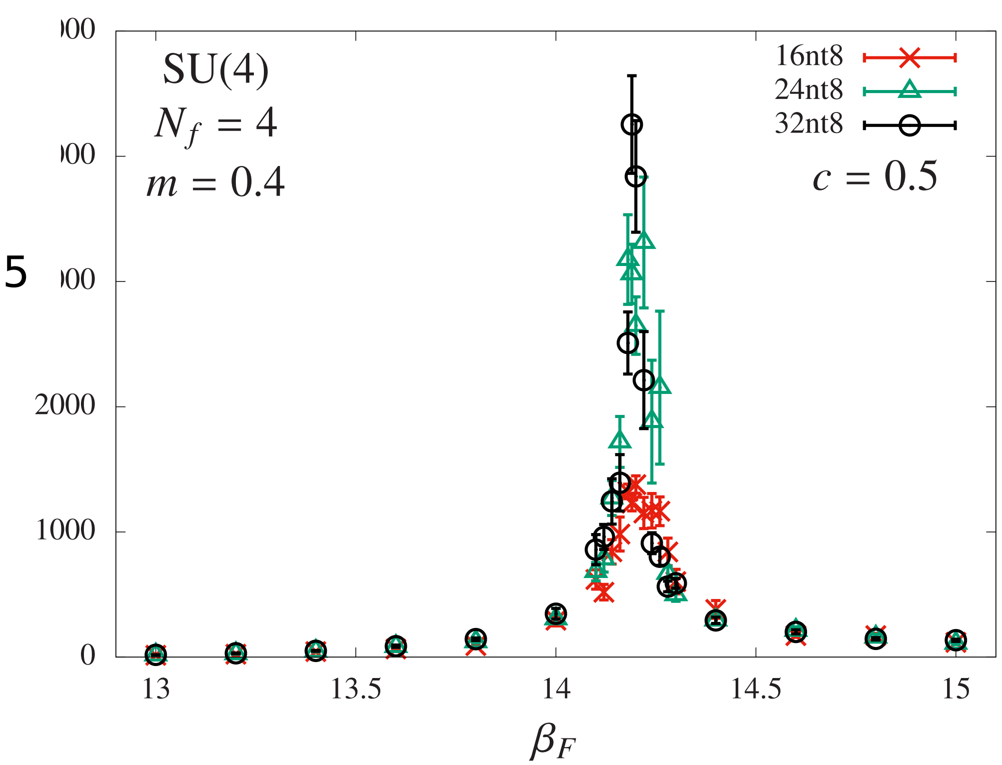
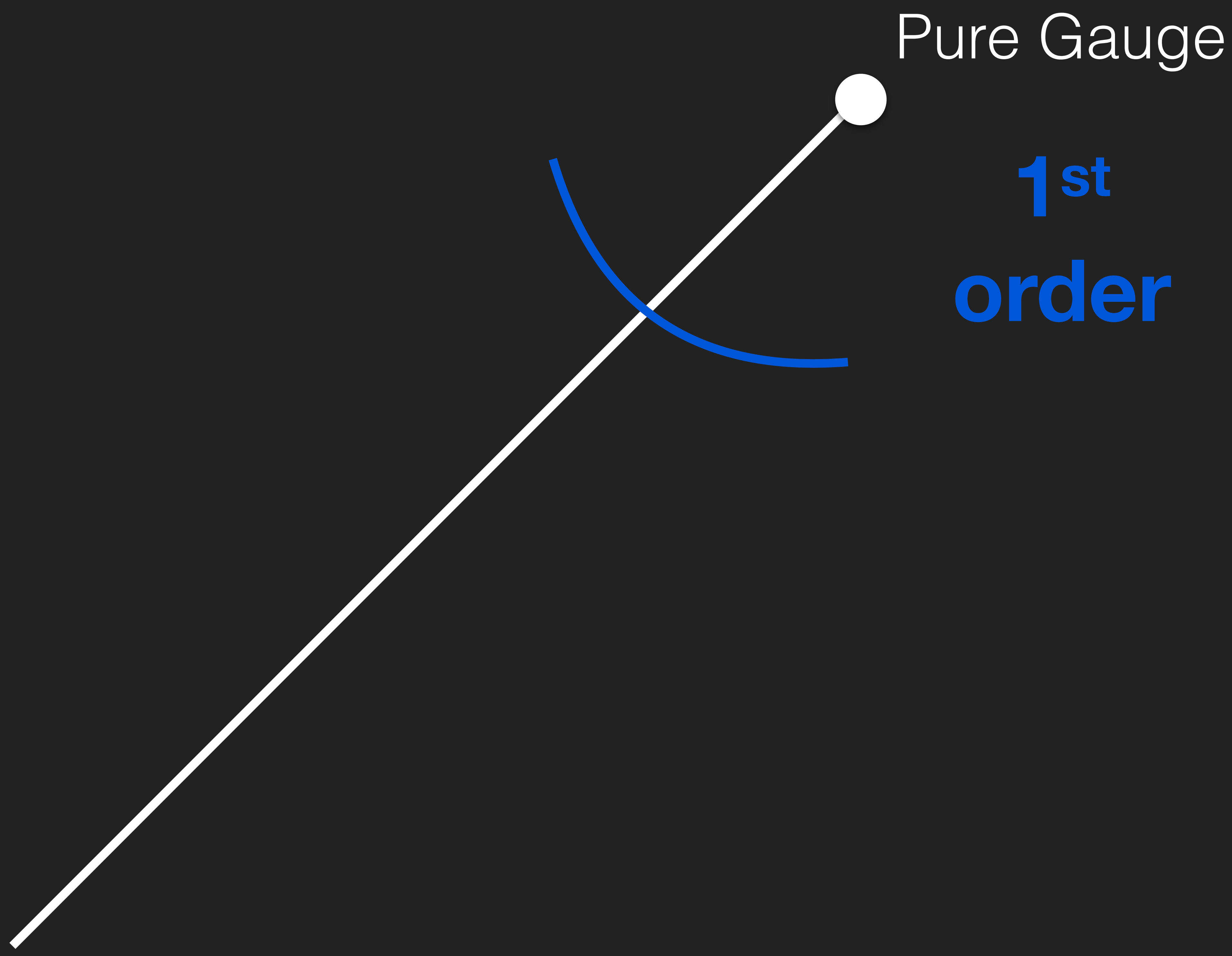


SPECTRUM



SPECTRUM

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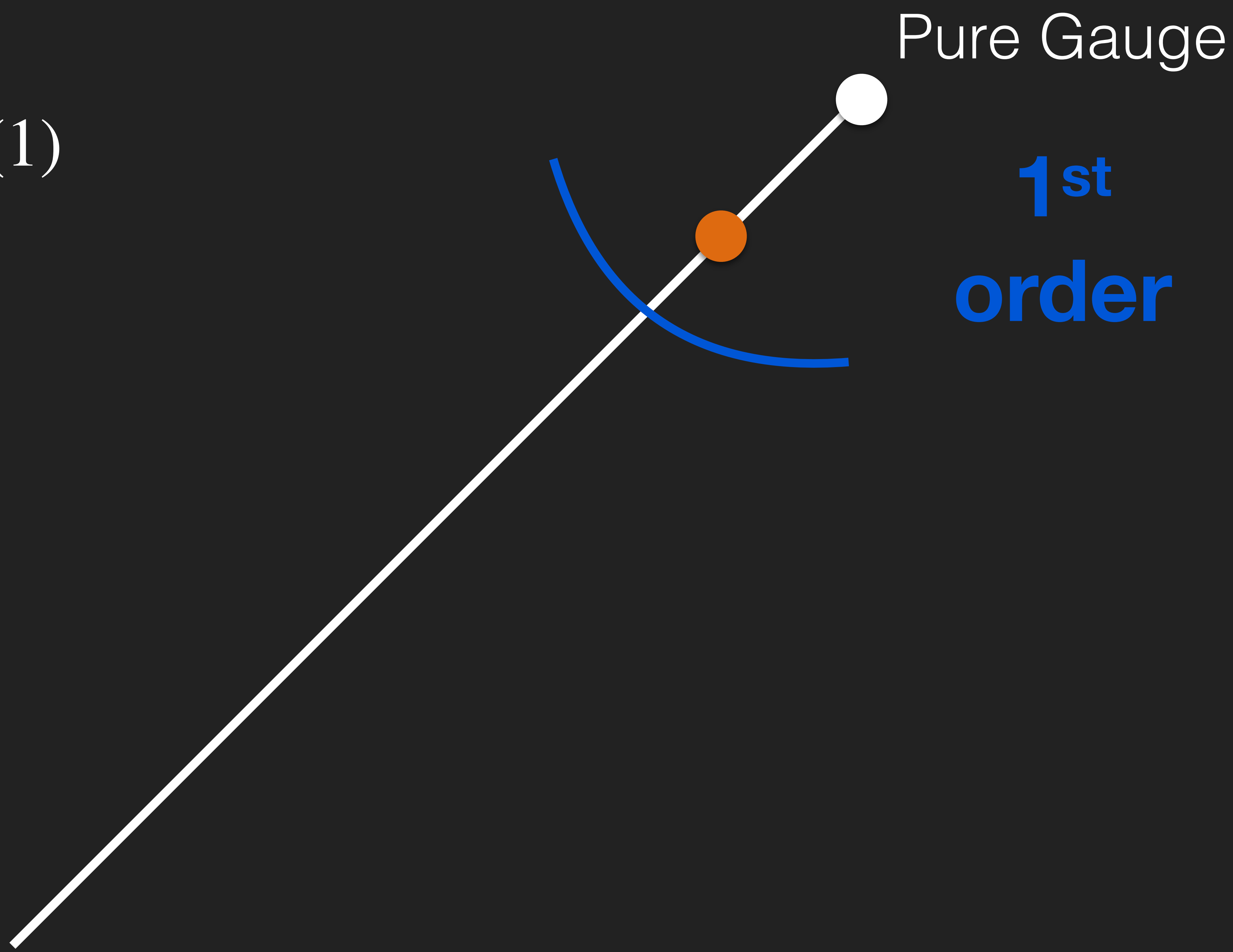

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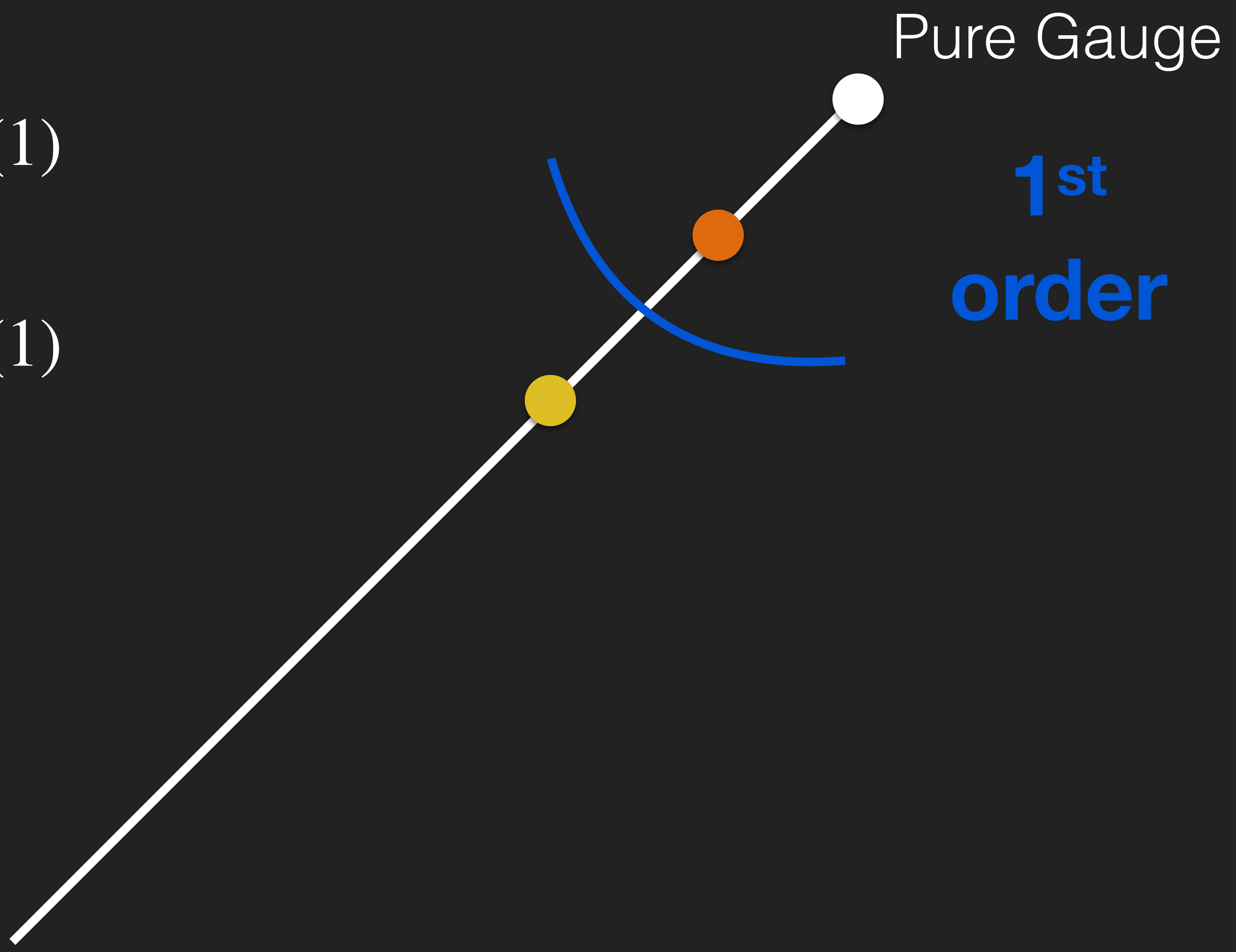

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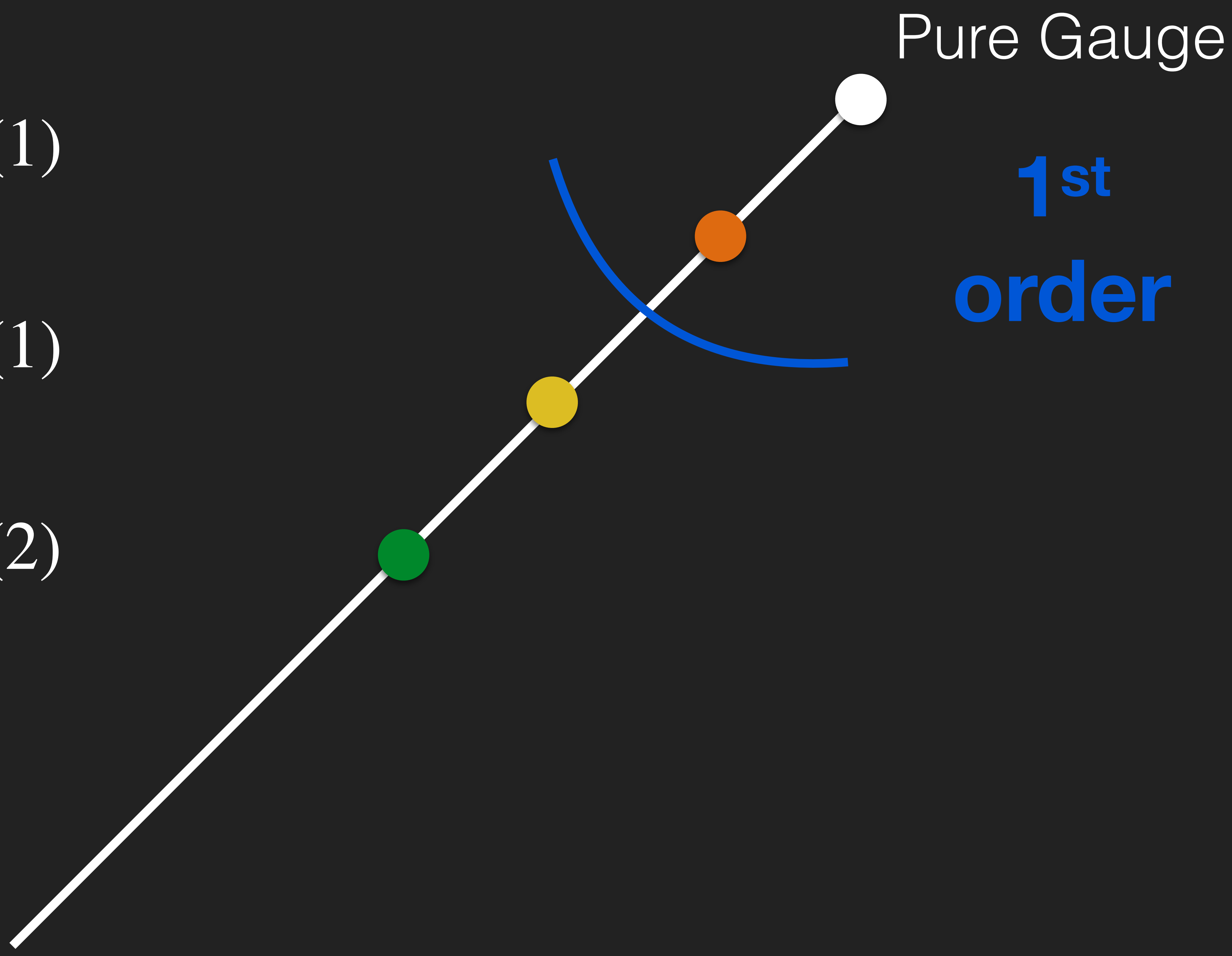

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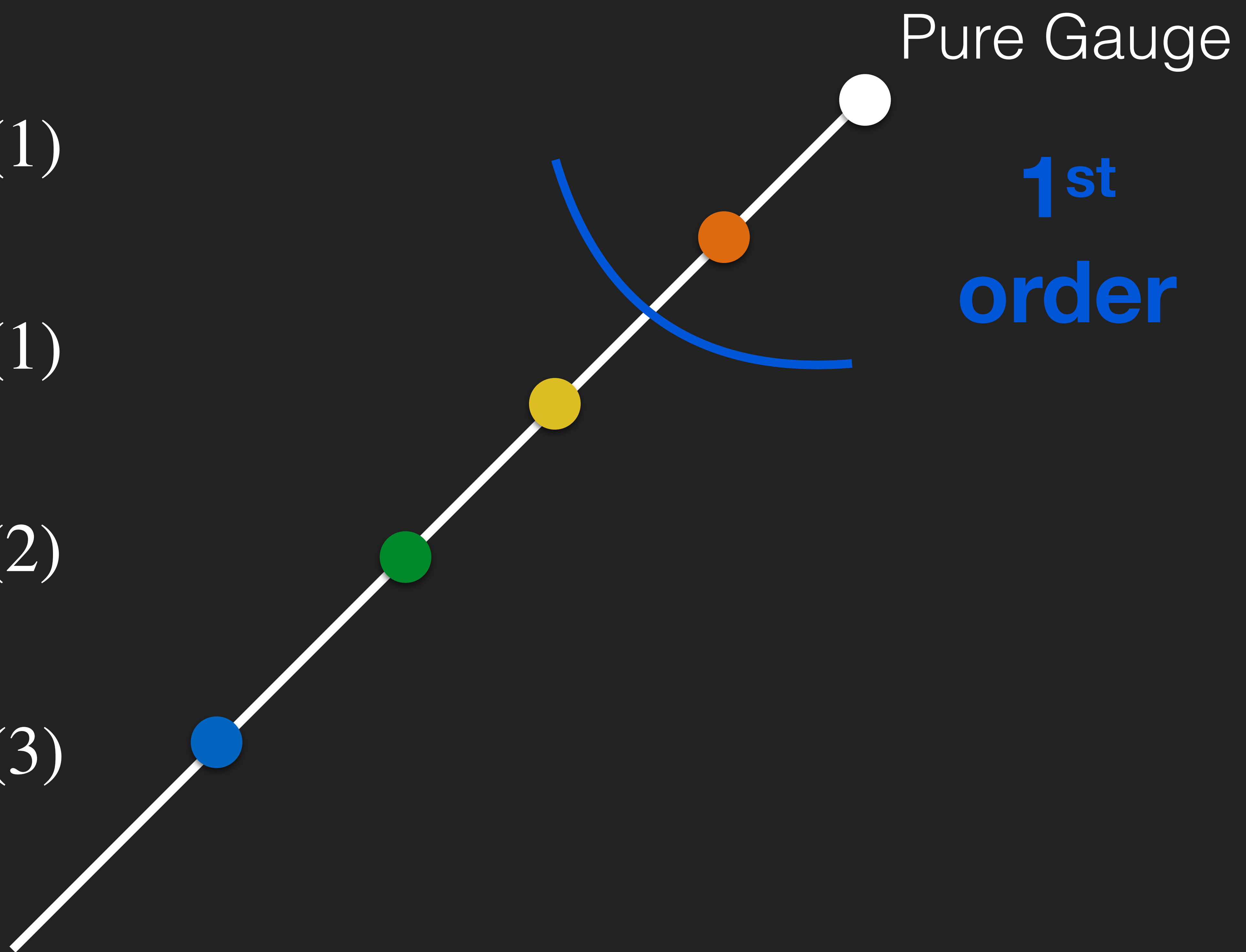

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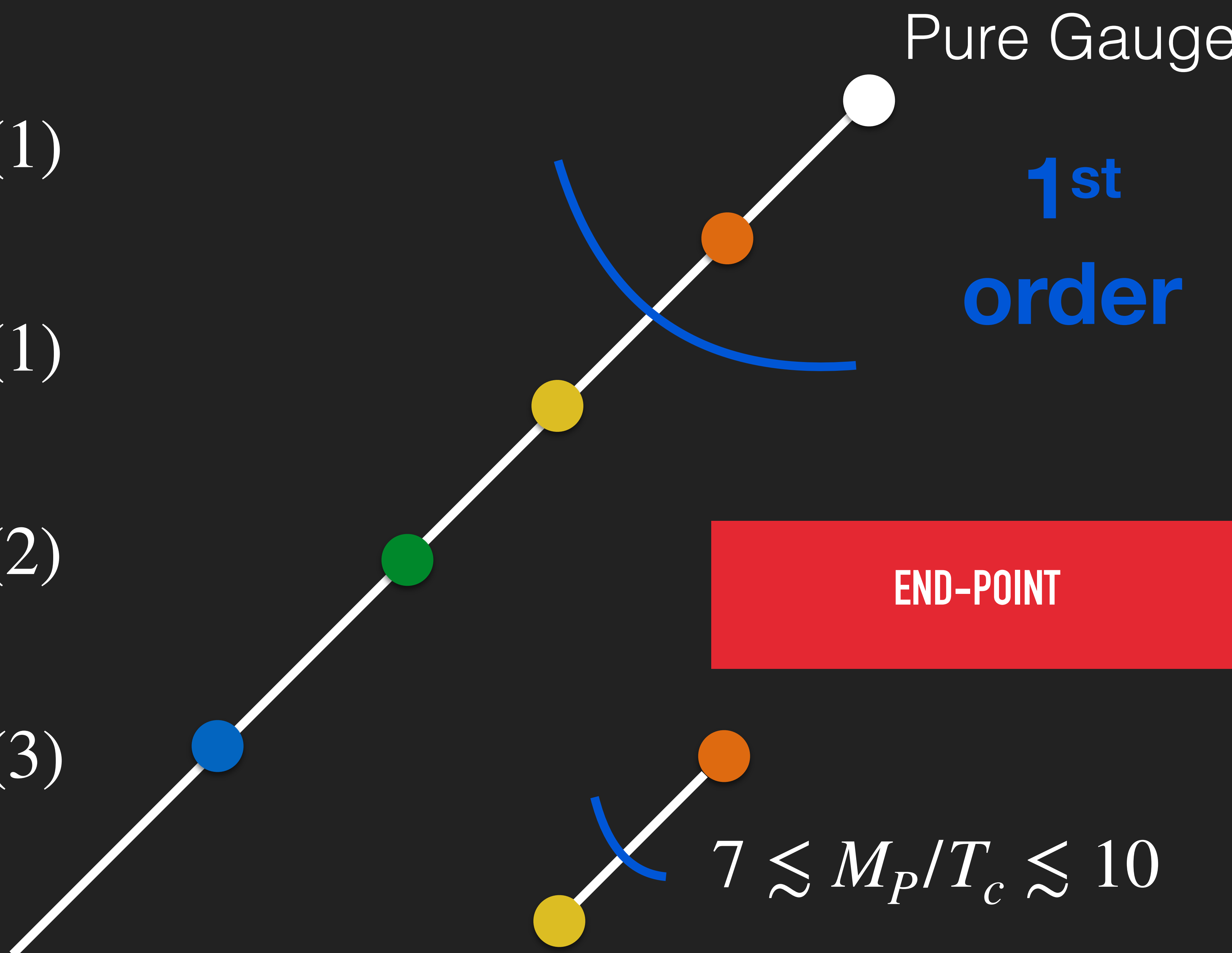
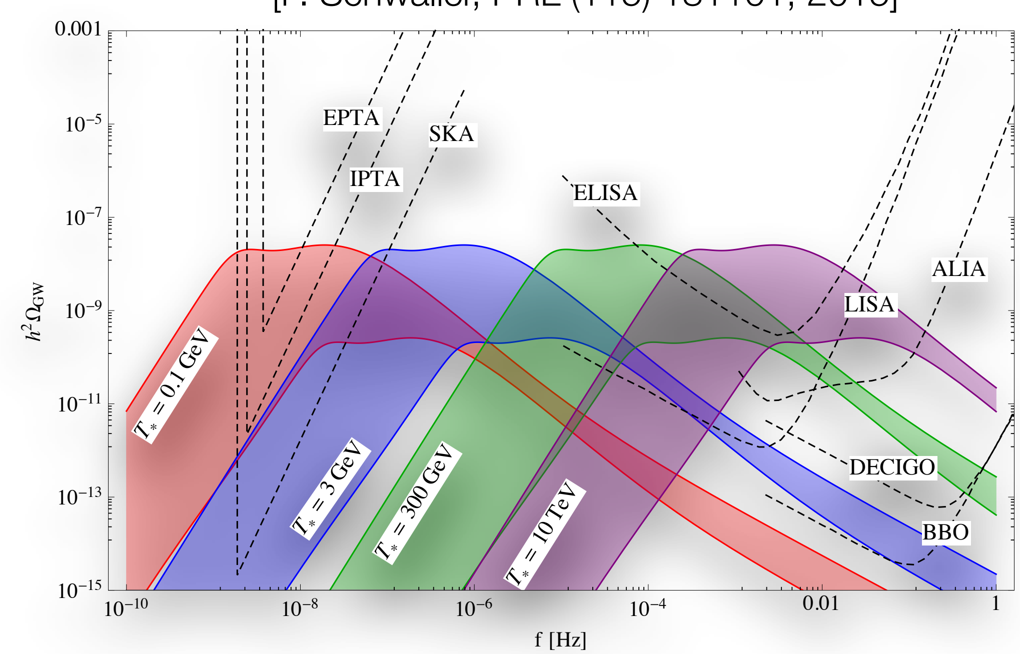


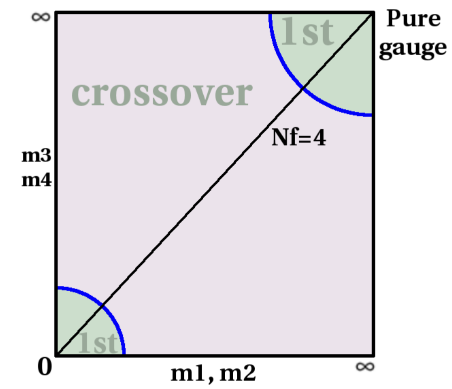
Conclusions

- ✦ Composite Dark Matter provides interesting signals for dark matter searches at colliders and in direct detection experiments
- ✦ With a 1st order confinement-deconfinement transition, the dark sector can be discovered and constrained using gravitational waves
- ✦ Stealth Dark Matter is a SU(4) dark sector model with 4 heavy fermions
- ✦ Our lattice exploration of the phase diagram shows a thermal phase transition of 1st order at sufficiently high masses
- ✦ Using current bounds from experimental searches at colliders and our spectrum results we can provide a lower bound for the critical temperature

$$T_c > 0.2\ \textbf{TeV}$$

[P. Schwaller, PRL (115) 181101, 2015]





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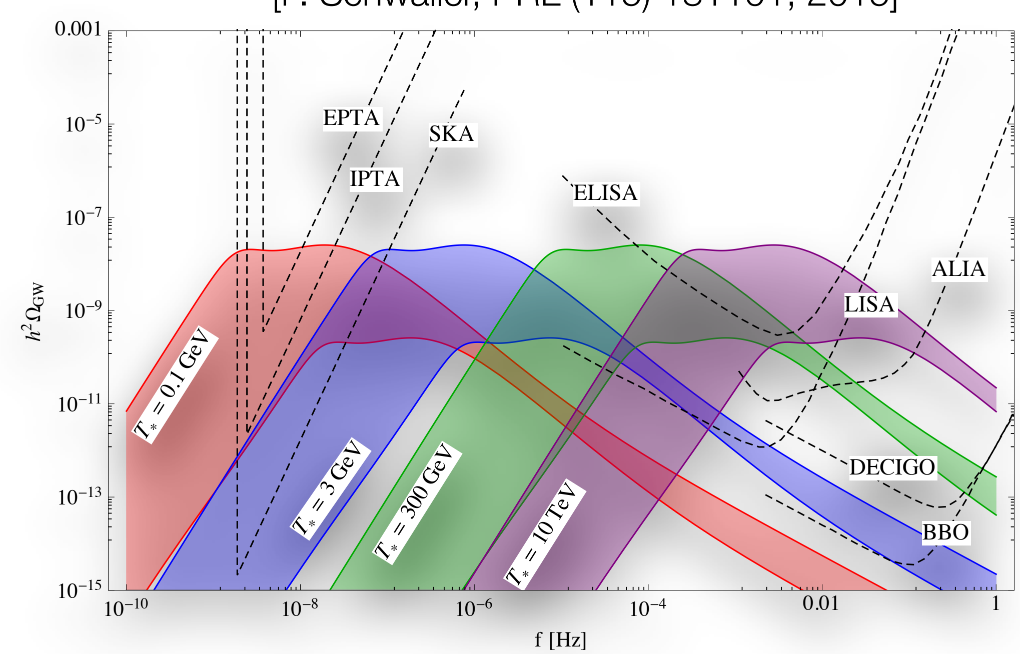
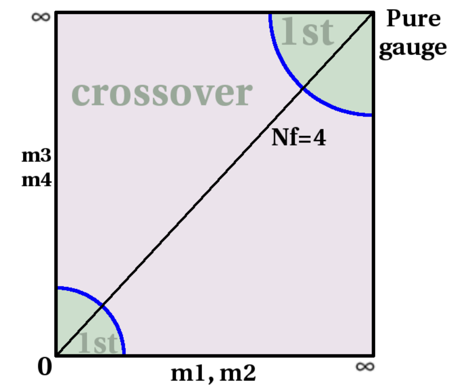
[P. Schwaller, PRL (115) 181101, 2015]



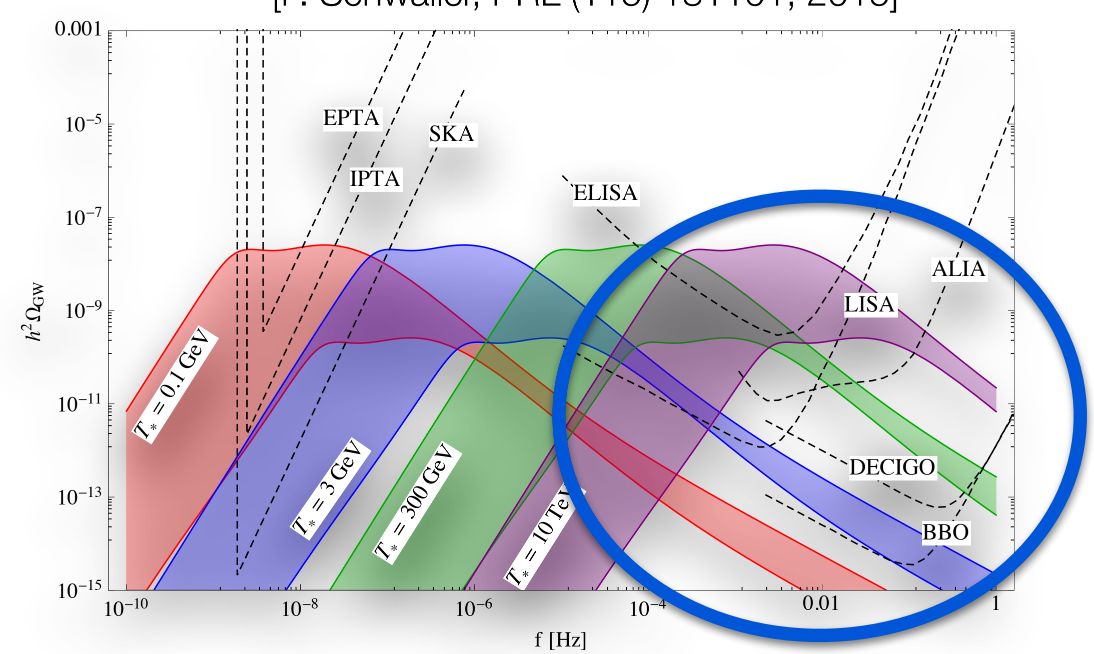


Conclusions

- ✦ Composite Dark Matter provides interesting signals for dark matter searches at colliders and in direct detection experiments
- ✦ With a 1st order confinement-deconfinement transition, the dark sector can be discovered and constrained using gravitational waves
- ✦ Stealth Dark Matter is a SU(4) dark sector model with 4 heavy fermions
- ✦ Our lattice exploration of the phase diagram shows a thermal phase transition of 1st order at sufficiently high masses
- ✦ Using current bounds from experimental searches at colliders and our spectrum results we can provide a lower bound for the critical temperature

$$T_c > 0.2 \text{ TeV}$$

[P. Schwaller, PRL (115) 181101, 2015]



Backup Slides

"Stealth Dark Matter" model

- The field content of the model consists in *8 Weyl fermions*
- Dark fermions interact with the SM Higgs and obtain current/ chiral masses
- Introduce vector-like masses for dark fermions that do not break EW symmetry
- Diagonalizing in the mass eigenbasis gives *4 Dirac fermions*
- Assume custodial SU(2) symmetry arising when ***u*** ↔ ***d***

Field	$SU(N)_D$	$(SU(2)_L, Y)$	Q
$F_1 = \begin{pmatrix} F_1^u \\ F_1^d \end{pmatrix}$	$\mathbf{N}$	$(\mathbf{2}, 0)$	$\begin{pmatrix} +1/2 \\ -1/2 \end{pmatrix}$
$F_2 = \begin{pmatrix} F_2^u \\ F_2^d \end{pmatrix}$	$\overline{\mathbf{N}}$	$(\mathbf{2}, 0)$	$\begin{pmatrix} +1/2 \\ -1/2 \end{pmatrix}$
F_3^u	$\mathbf{N}$	$(\mathbf{1}, +1/2)$	$+1/2$
F_3^d	$\mathbf{N}$	$(\mathbf{1}, -1/2)$	$-1/2$
F_4^u	$\overline{\mathbf{N}}$	$(\mathbf{1}, +1/2)$	$+1/2$
F_4^d	$\overline{\mathbf{N}}$	$(\mathbf{1}, -1/2)$	$-1/2$

$$\mathcal{L} \supset + y_{14}^u \epsilon_{ij} F_1^i H^j F_4^d + y_{14}^d F_1 \cdot H^\dagger F_4^u - y_{23}^d \epsilon_{ij} F_2^i H^j F_3^d - y_{23}^u F_2 \cdot H^\dagger F_3^u + h.c.$$

$$\mathcal{L} \supset M_{12} \epsilon_{ij} F_1^i F_2^j - M_{34}^u F_3^u F_4^d + M_{34}^d F_3^d F_4^u + h.c.$$

$$y_{14}^u = y_{14}^d \qquad y_{23}^u = y_{23}^d \qquad M_{34}^u = M_{34}^d$$

[references in Kribs & Neil, 1604.04627]

★ lattice
★ estimate
■ forbidden

Lattice results for Composite Dark Matter

Template Models	Spectrum	Higgs	Mag. Dip.	Charge r.	Polariz.
SU(2) N_f=1	★ (lattice)	★ (lattice)	[Francis, Hudspith, Lewis, Tulin 1809.09117]		
SU(2) N_f=2	★ (lattice)	★ (estimate)		★ (estimate)	★ (lattice)
SU(3) N_f=2,6	★ (lattice)		★ (lattice)	★ (lattice)	[Drach, et al. 1511.04370]
SU(3) N_f=8	★ (lattice)	★ (estimate)			
SU(3) N_f=2 (S)	★ (lattice)	[Fodor, et al. 1601.03302]			
SU(4) N_f=4	★ (lattice)	★ (lattice)			★ (lattice)
SO(4) N_f=2 (V)	★ (lattice)				
SU(N) N_f=0	★ (lattice)				

[references in Kribs & Neil, 1604.04627]

- lattice
- estimate
- forbidden

Lattice results for Composite Dark Matter

Template Models	Spectrum	Higgs	Mag. Dip.	Charge r.	Polariz.
SU(2) N_f=1	lattice	lattice			
SU(2) N_f=2	lattice	estimate	forbidden	estimate	lattice
SU(3) N_f=2,6	lattice		lattice	lattice	
SU(3) N_f=8	lattice	estimate			
SU(3) N_f=2 (S)	lattice				
SU(4) N_f=4	lattice	lattice	forbidden	forbidden	lattice
SO(4) N_f=2 (V)	lattice				
SU(N) N_f=0	lattice	forbidden	forbidden	forbidden	forbidden

[Francis, Hudspith, Lewis, Tulin 1809.09117]

forbidden in pNGB DM

[Drach, et al. 1511.04370]

[Fodor, et al. 1601.03302]

forbidden in Stealth DM

forbidden in SUNonia