Reaching the chiral limit in many flavor systems

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SCGT12, Nagoya
Dec 4 2012

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ArXiv:1111:2317,1207.7162,1207.7164

4^{th} of July Independence Day Fireworks

4th of July Fireworks, 2012

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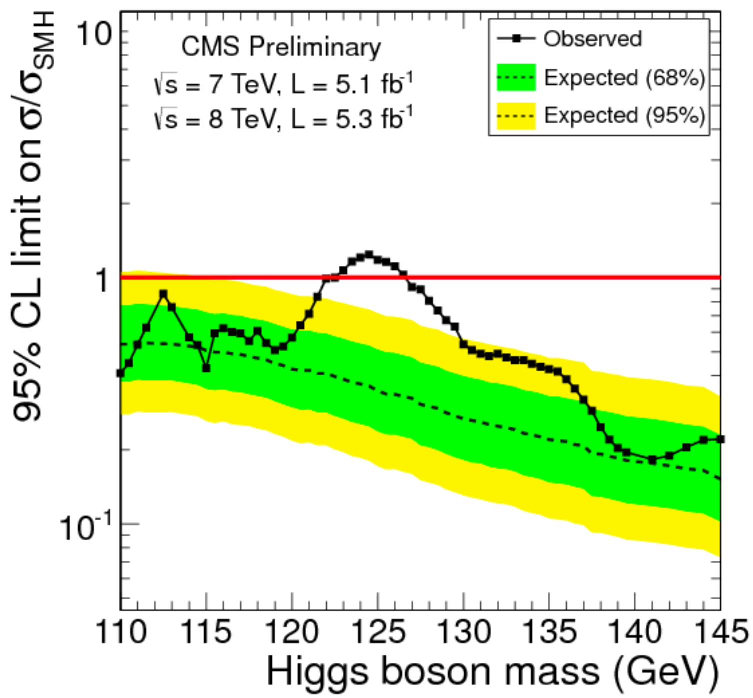
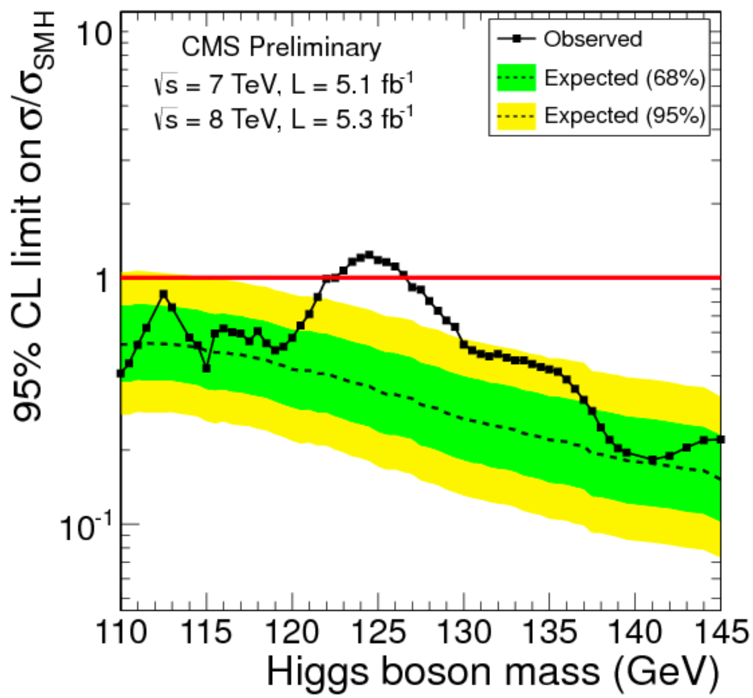


Discovery
of a Higgs-like state at 125GeV

4th of July Fireworks, 2012



Discovery
of a Higgs-like state at 125GeV

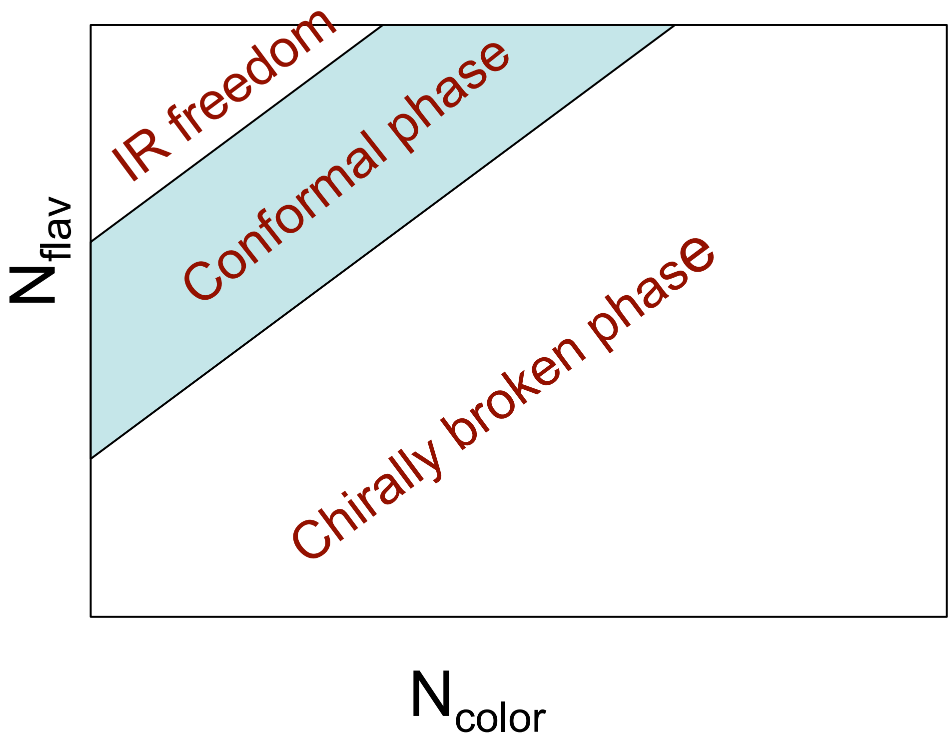
This is not what we expected, but we have to deal with it.

Is there room for a composite (strongly coupled) Higgs?

Composite Higgs in strongly coupled systems:

Still an attractive idea:

SU($N_{color} \geq 2$) gauge fields + N_{flavor} fermions in some representation



Composite Higgs in strongly coupled systems:

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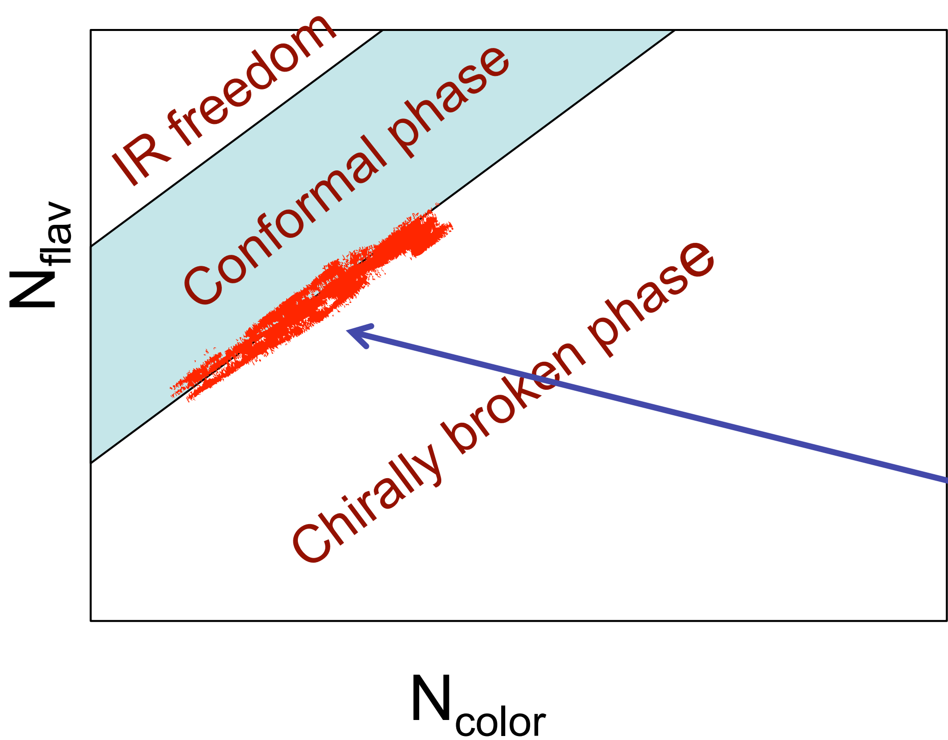
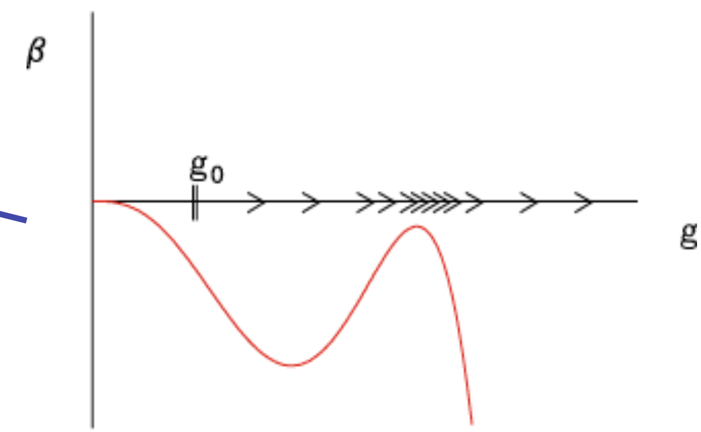


Strongly coupled conformal or near-conformal systems are the most interesting



Which model? What representation, N_c, N_f ?
What property? What method?

In Colorado we developed several methods to study conformal and near-conformal systems:

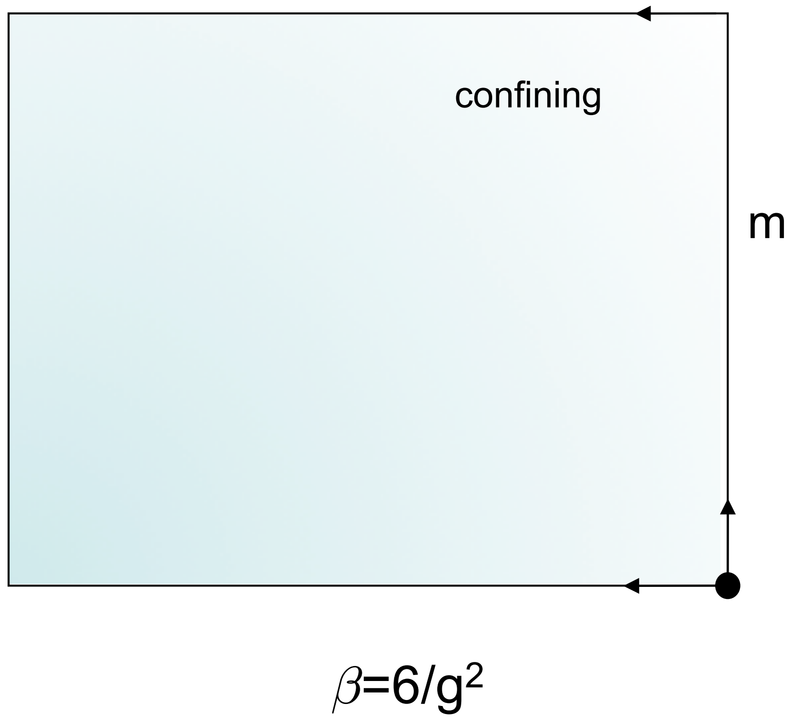
- Phase diagram at zero and finite temperature ArXiv:1111:2317,1207.7162
- Dirac eigenmodes & the mass anomalous dimension ArXiv:1207.7164
- Monte Carlo renormalization group matching ArXiv:1212.xxxx

We tested with N=4, 8 and 12 fundamental fermions with SU(3) gauge
Found some surprising results

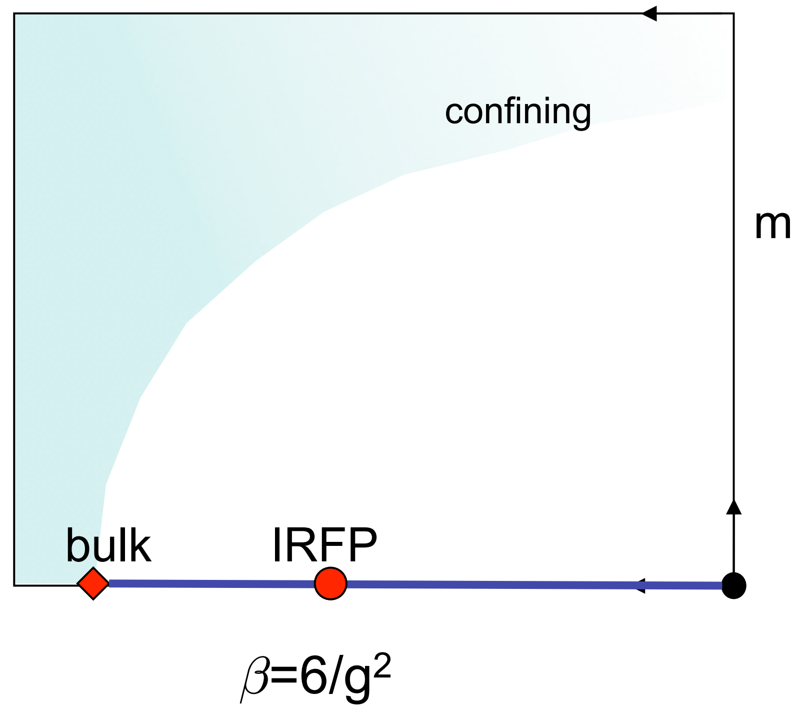
Phase diagrams

(arrows: UV to IR)

QCD like



Conformal

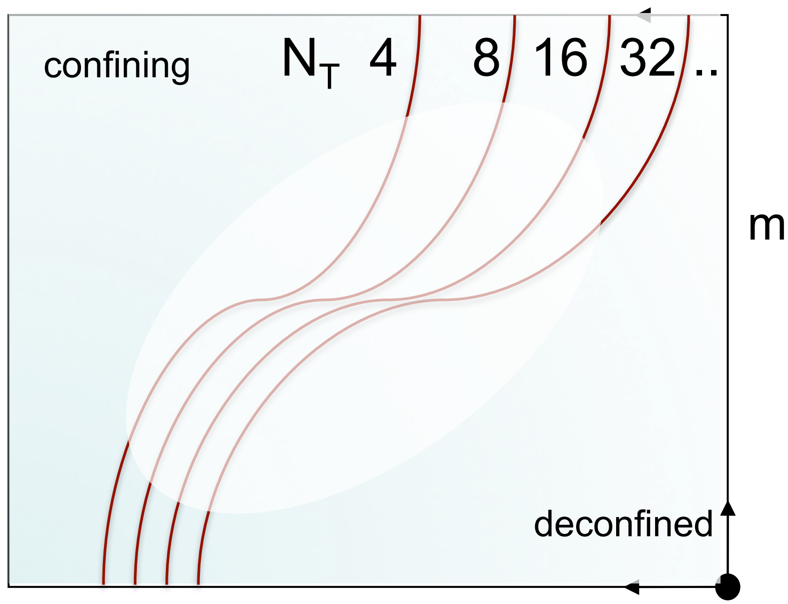


Bulk transition: lattice artifact but a real phase transition

IRFP: its location is scheme dependent, not physically observable

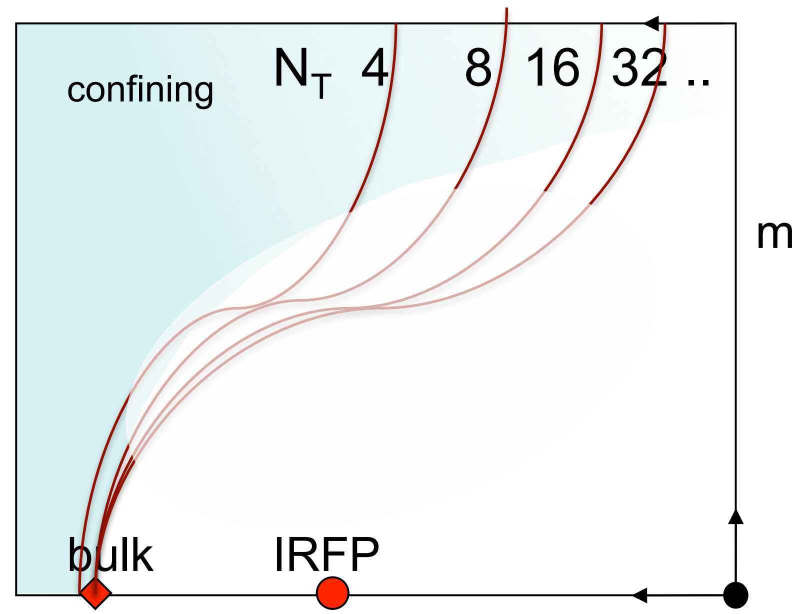
Finite temperature and bulk phase transitions

QCD like



$\beta_c \to \infty$ as $N_T \to \infty$

Conformal



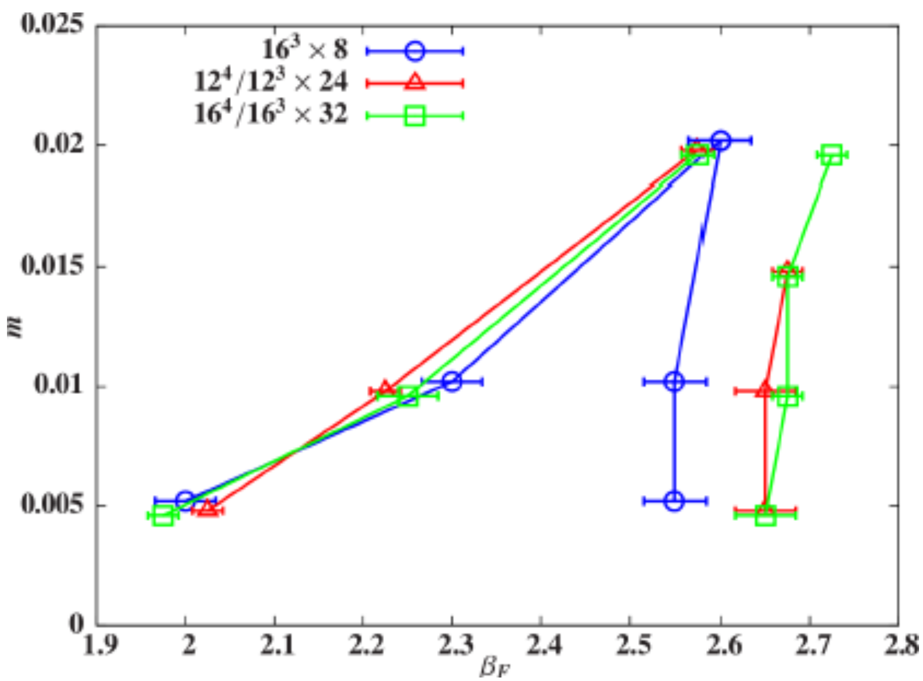
$\beta_c \to \beta_{bulk}$ as $N_T \to \infty$

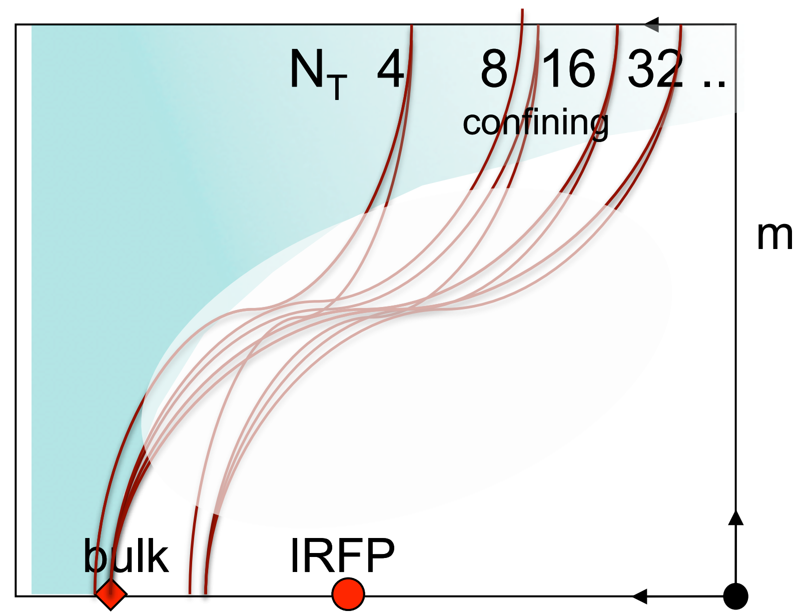
In a conformal system

- finite temperature transitions run into a bulk (T=0) transition
- β_{bulk} separates strong coupling (confining) and weak coupling (conformal) phases

Phase diagram in β-m space for N_f=12

Intermediate phase bordered by bulk 1st order transitions
The chiral bulk transition fissioned into two
(This has been observed by Deuzeman et al, LHC collab. as well)





$\beta_c \rightarrow \beta_{bulk}$ as $N_T \rightarrow \infty$

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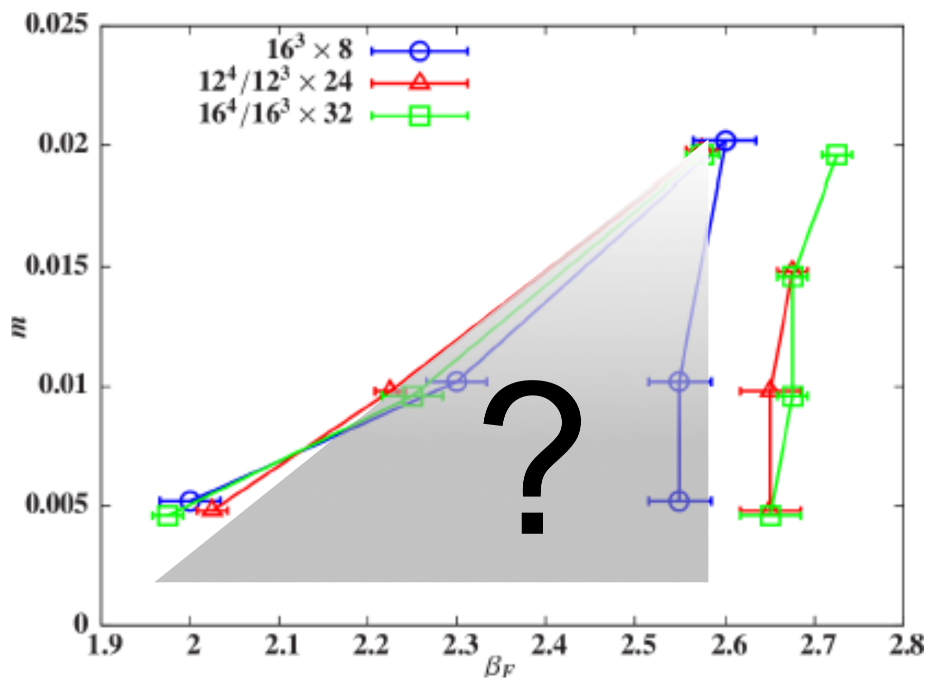

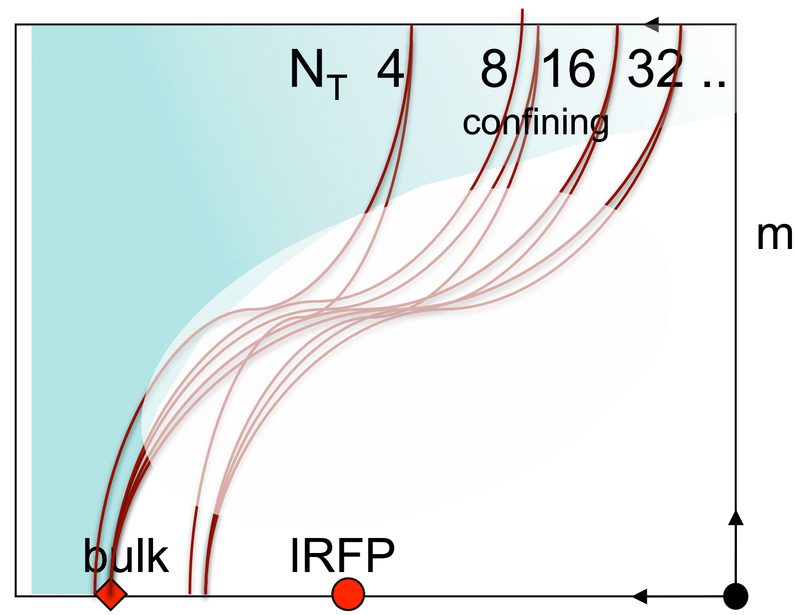

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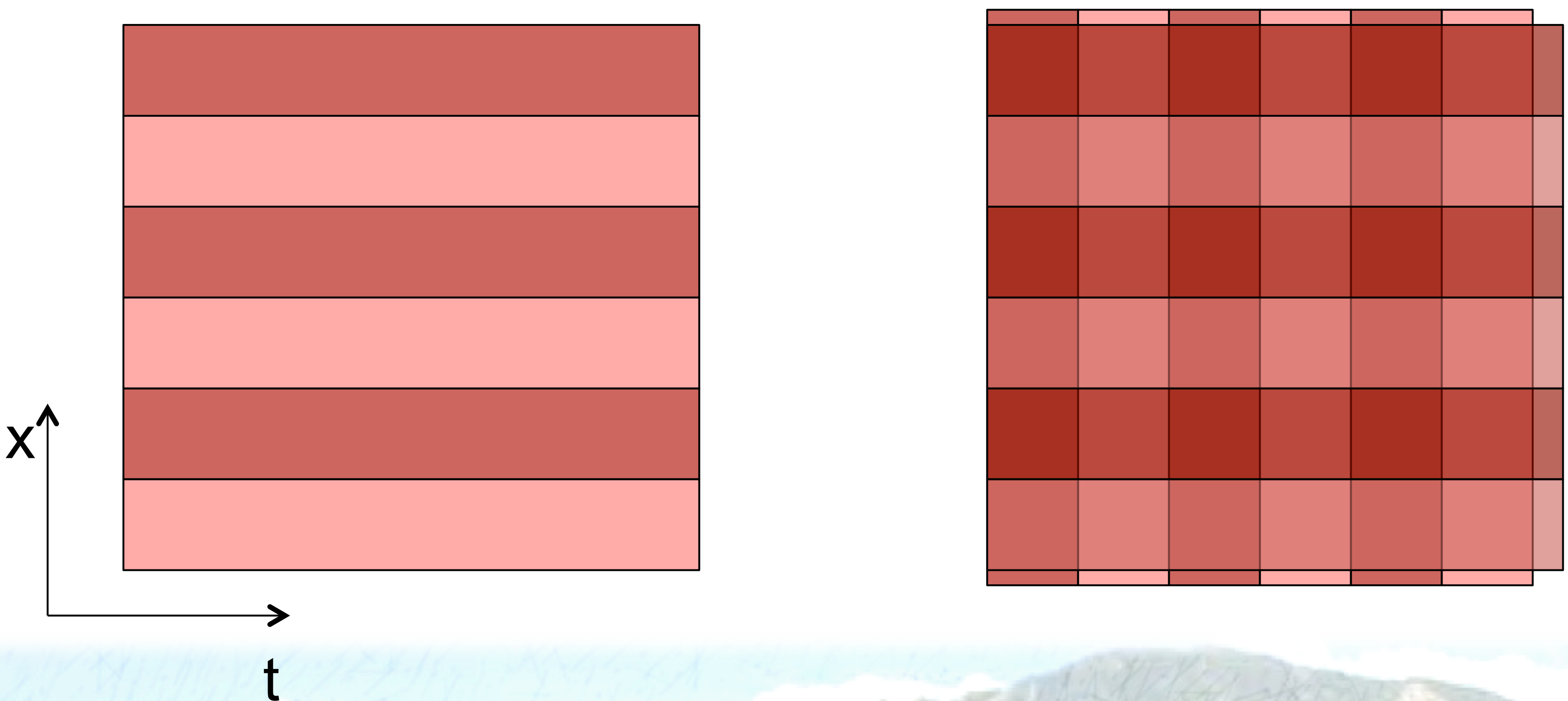
A new symmetry breaking pattern

Single-site shift symmetry (S^4): $x_\mu \to x_\mu + \mu$
is exact symmetry of the action but broken in the IM phase
→ plaquette expectation value is "striped"



A new symmetry breaking pattern

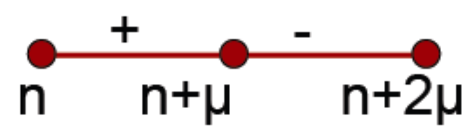
Order parameters:

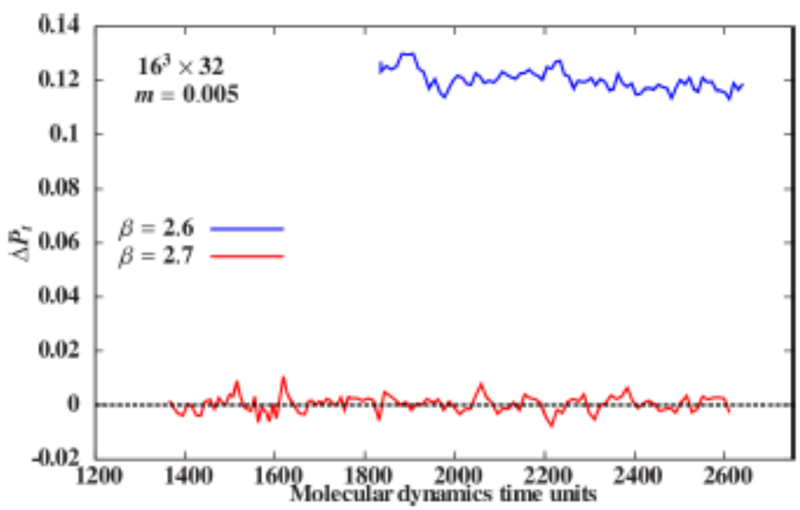
Plaquette difference:

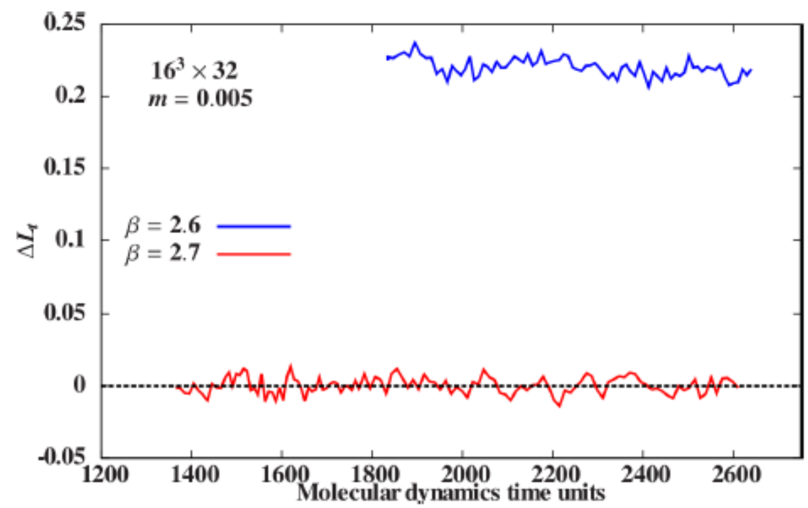
Link difference:

$$\Delta P_\mu = \langle \mathrm{Re}\,\mathrm{Tr}\,\Box_n - \mathrm{Re}\,\mathrm{Tr}\,\Box_{n+\mu} \rangle_{n_\mu \mathrm{even}}$$

$$\Delta L_\mu = \langle \alpha_\mu(n)\overline{\chi}(n)U_\mu(n)\chi(n+\mu) - \alpha_\mu(n+\mu)\overline{\chi}(n+\mu)U_\mu(n+\mu)\chi(n+2\mu) \rangle_{n_\mu \mathrm{ev}}$$







β = 2.6 IM phase β=2.7 weak coupling phase

S^4b symmetry breaking pattern

- Single-site shift symmetry is exact in the action, S^4b phase has to be bordered by a “real” phase transition
- Exist with 8 & 12 flavors, not with 4

S^4b phase

- Could signal a special taste breaking
- Confining (static potential, Polyakov loop)
- Chirally symmetric (meson spectrum, Dirac eigenvalue spectrum)

Such phase does not exist in the continuum limit

Must be pure lattice artifact

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Such phase does not exist in the continuum limit

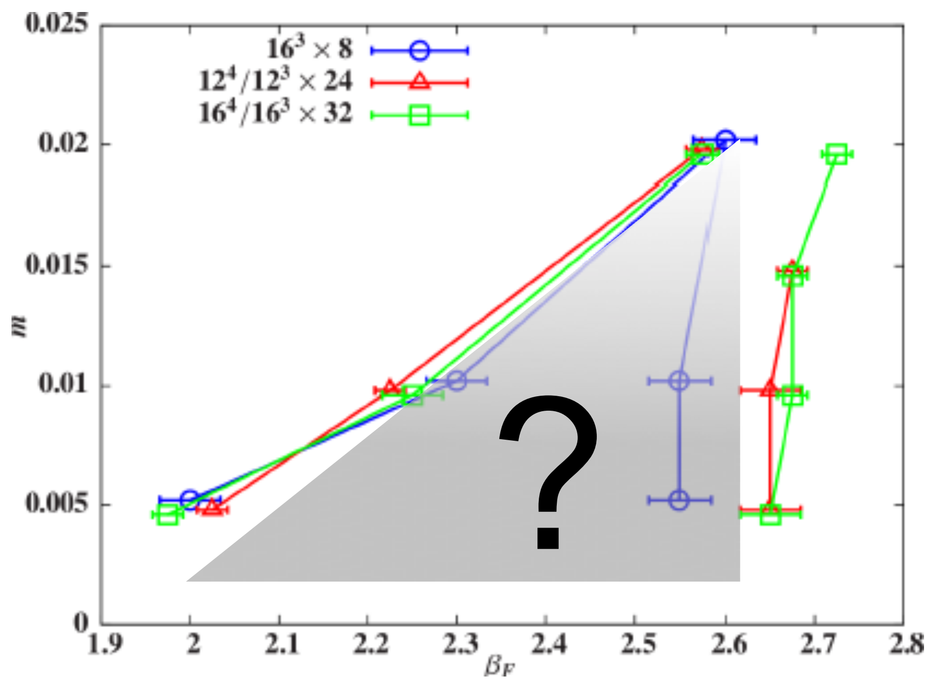
in gauge-fermion systems

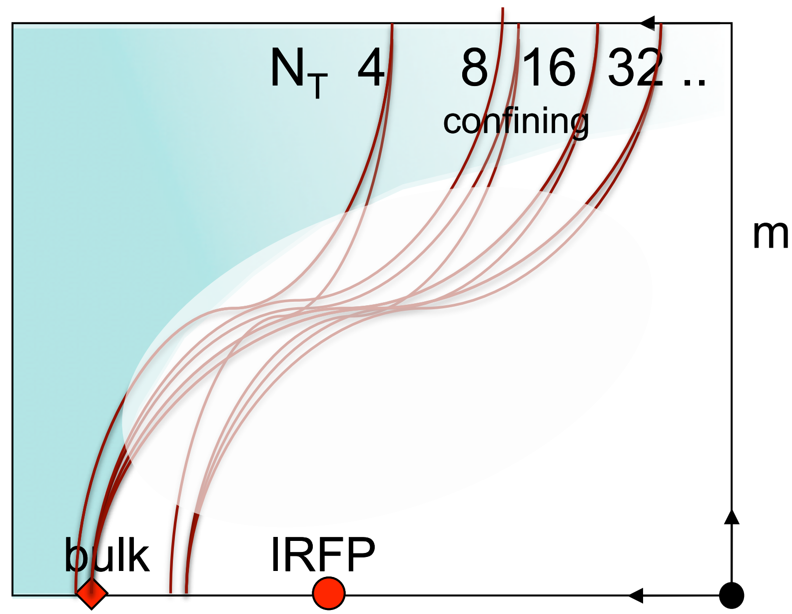
Must be pure lattice artifact **within gauge fermion systems**

Could become physical with some other interaction

Phase diagram in β-m space for N_f=12

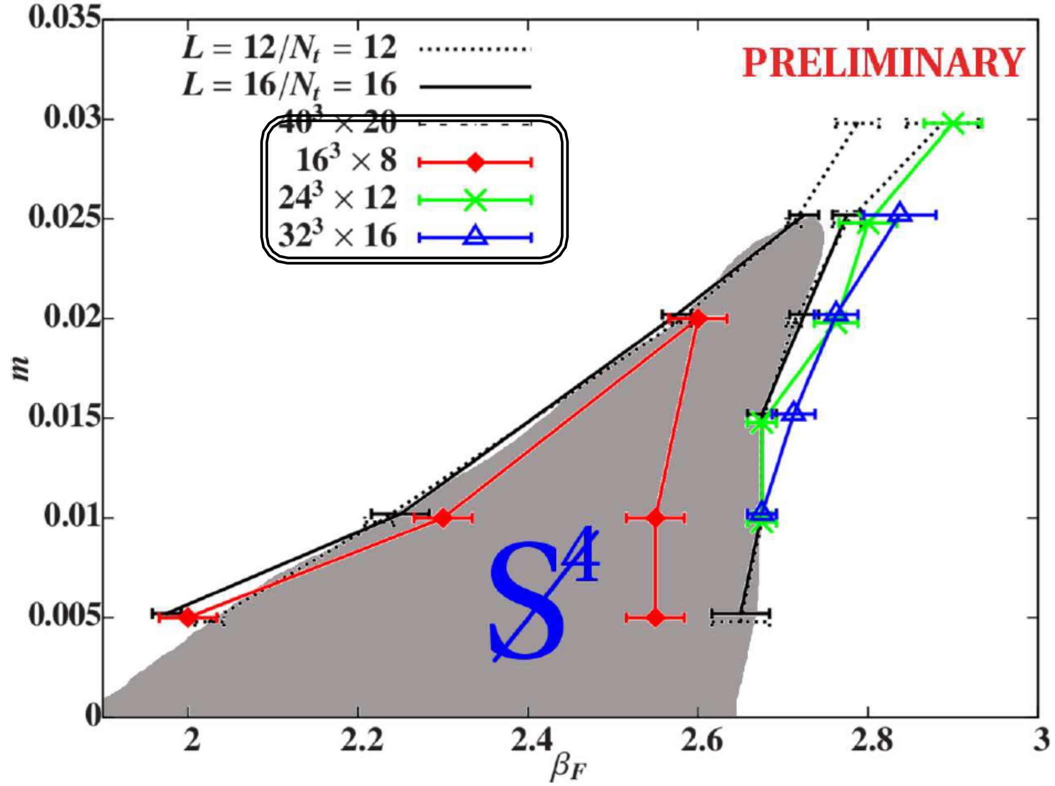
What is the relation between bulk and finite T transitions?
Finite T = $1/(N_t a)$ simulations with N_t=8,12,16,20





Phase diagram in β-m space for N_f=12

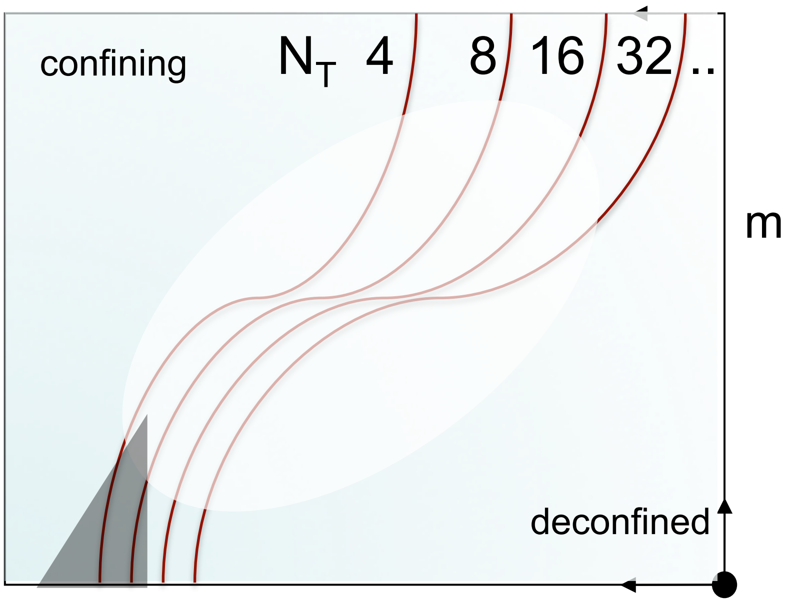
Finite T transitions are stuck to the S^4 phase boundary
No confining phase at weak coupling:
transition from S^4 b→ chirally symmetric



Consistent with IR-conformality.

Phase diagram in β-m space for N_f=8

N_f=8 is expected to be chirally broken –
S^4b phase … must be an irrelevant lattice artifact ?



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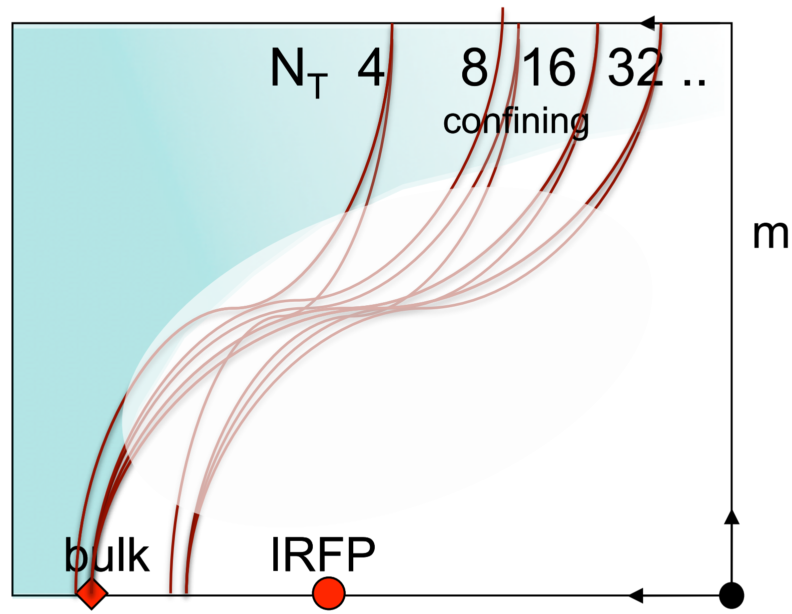

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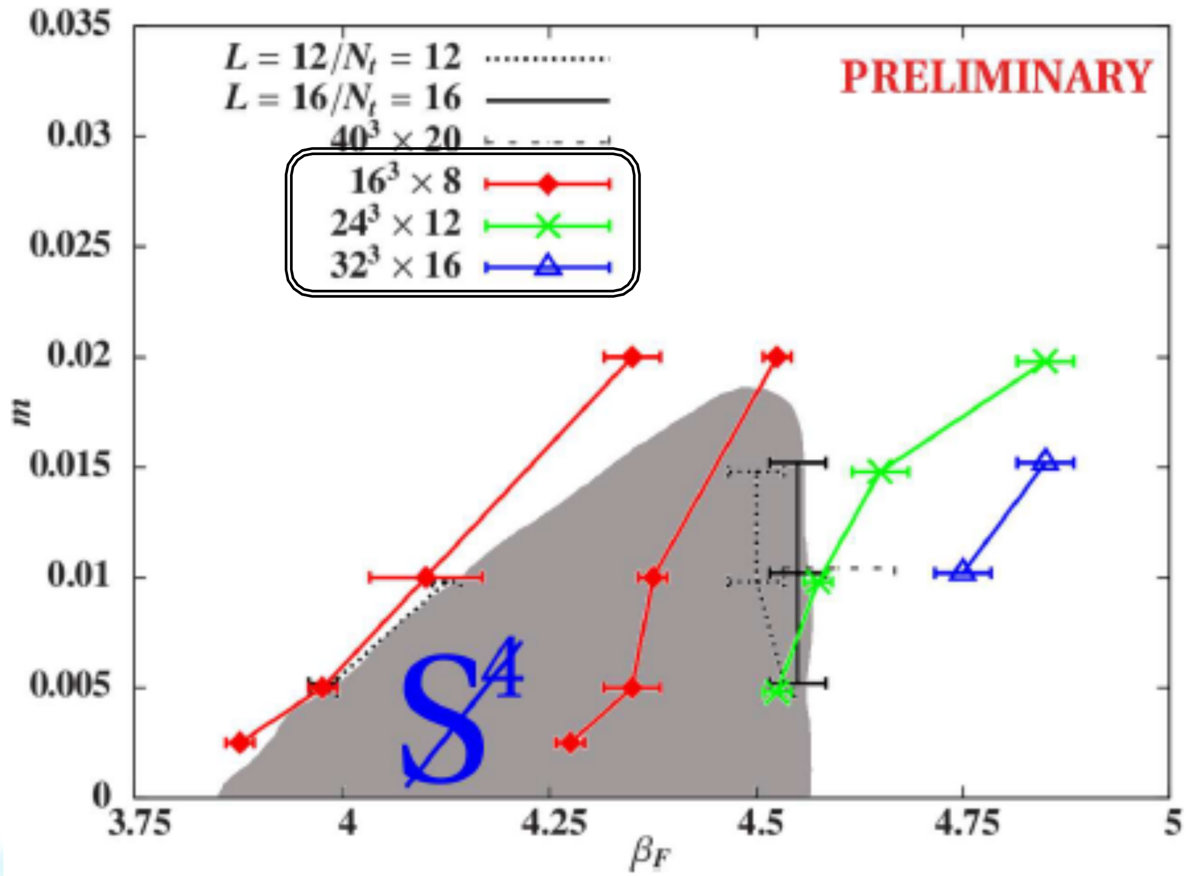
Finite temperature phase structure – N_f =8

N_t = 8,12,16 looks OK at m≥0.01.

- Weak coupling side shows both confining and deconfined phases
- Consistent with 2-loop PT



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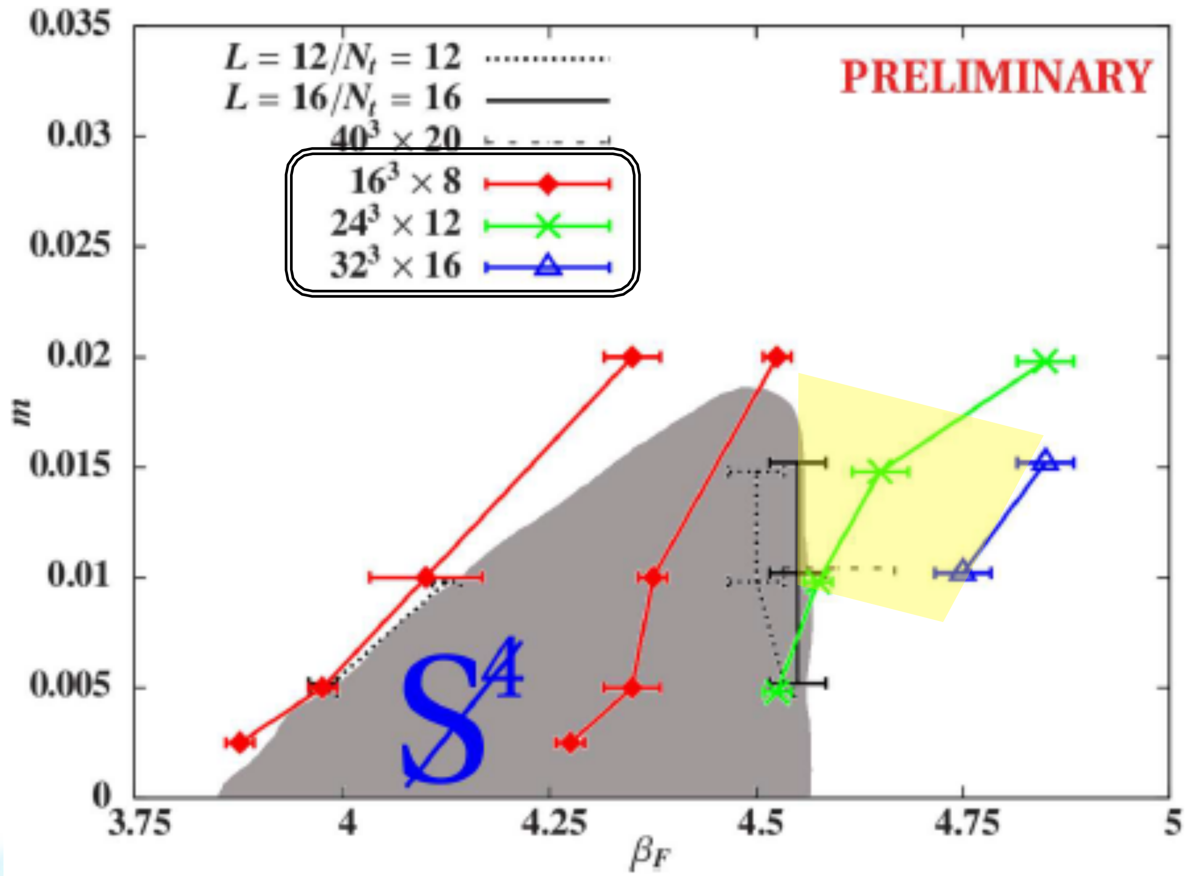

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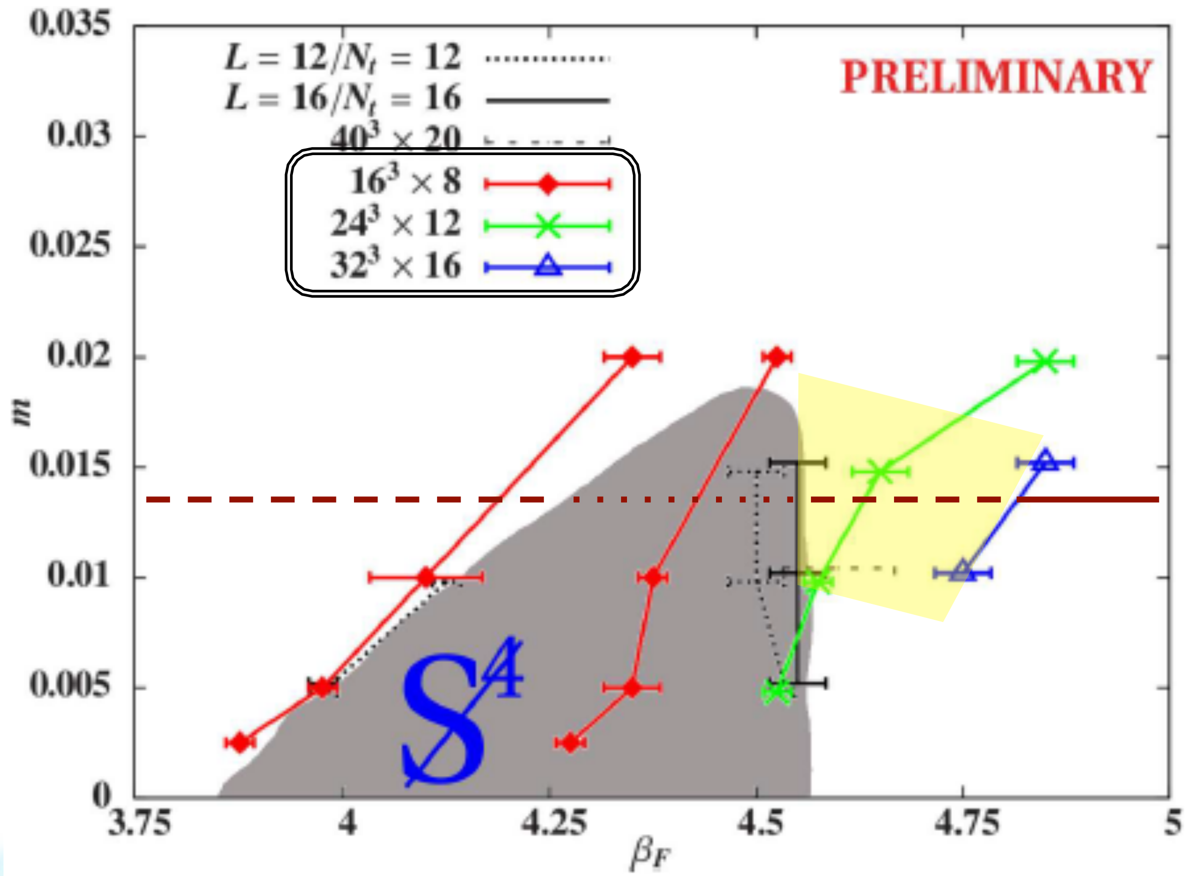
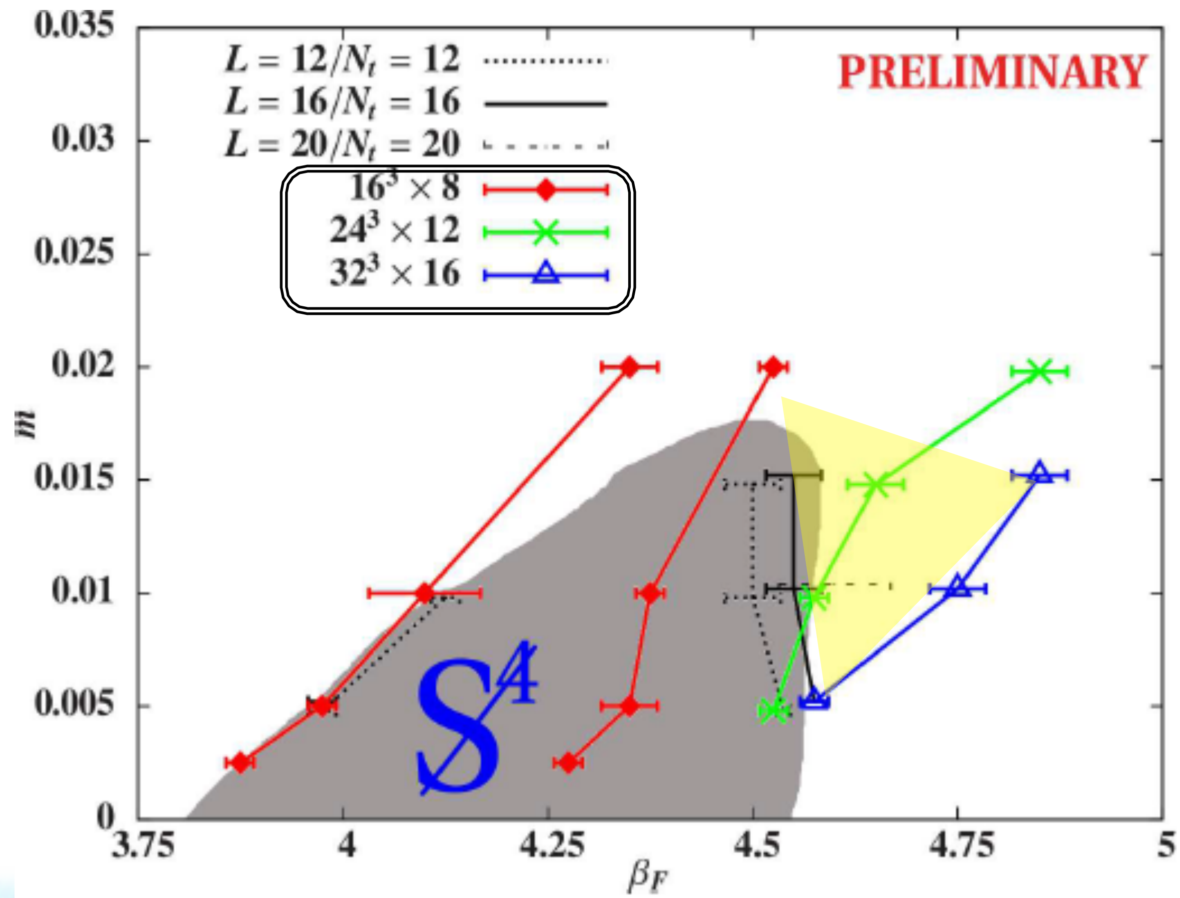


Finite temperature phase structure – N_f =8

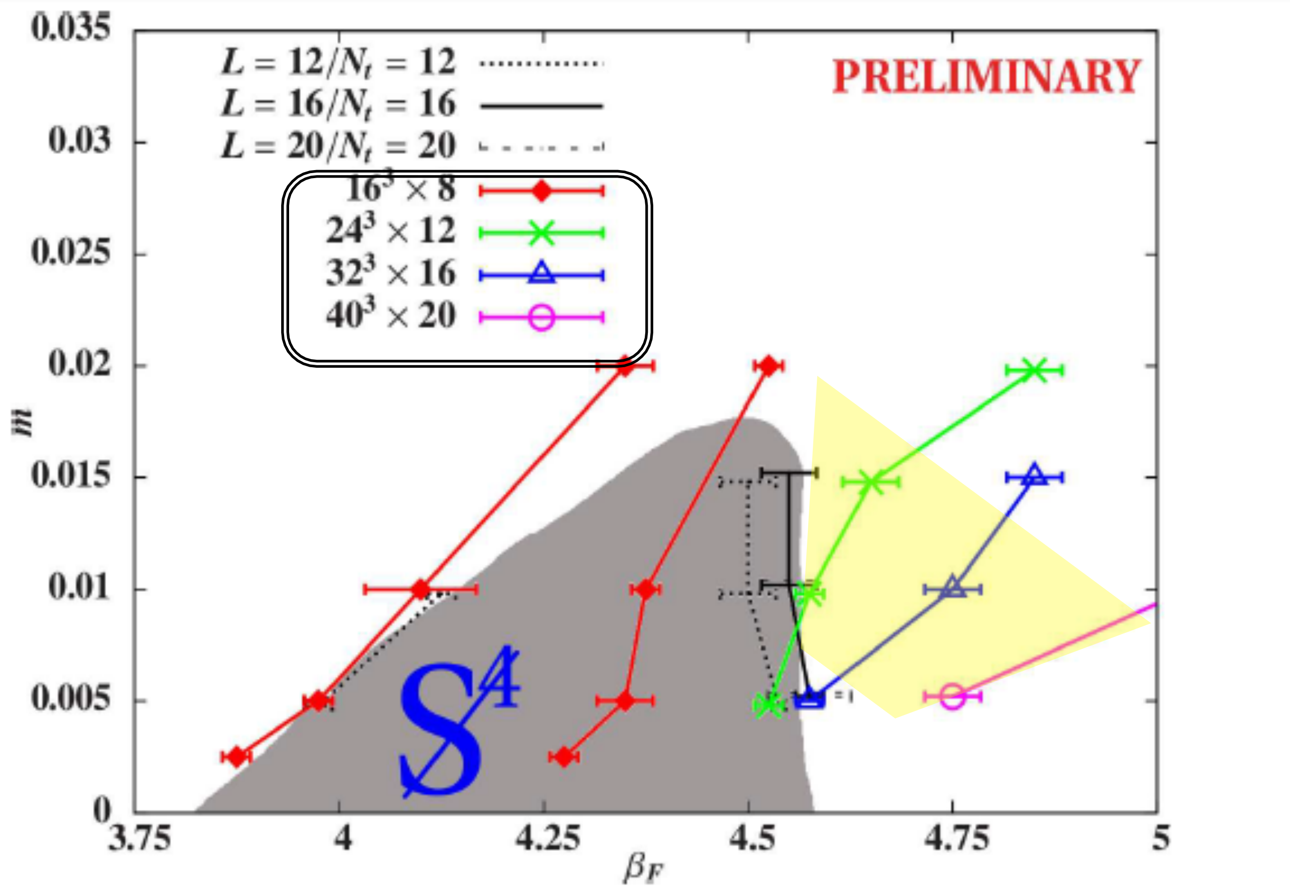
At m=0.005 no confining phase on N_t≤16
the N_t =12-16 looses scaling ??



Finite temperature phase structure – N_f =8

At m=0.005 no confining phase on $N_t \leq 16$

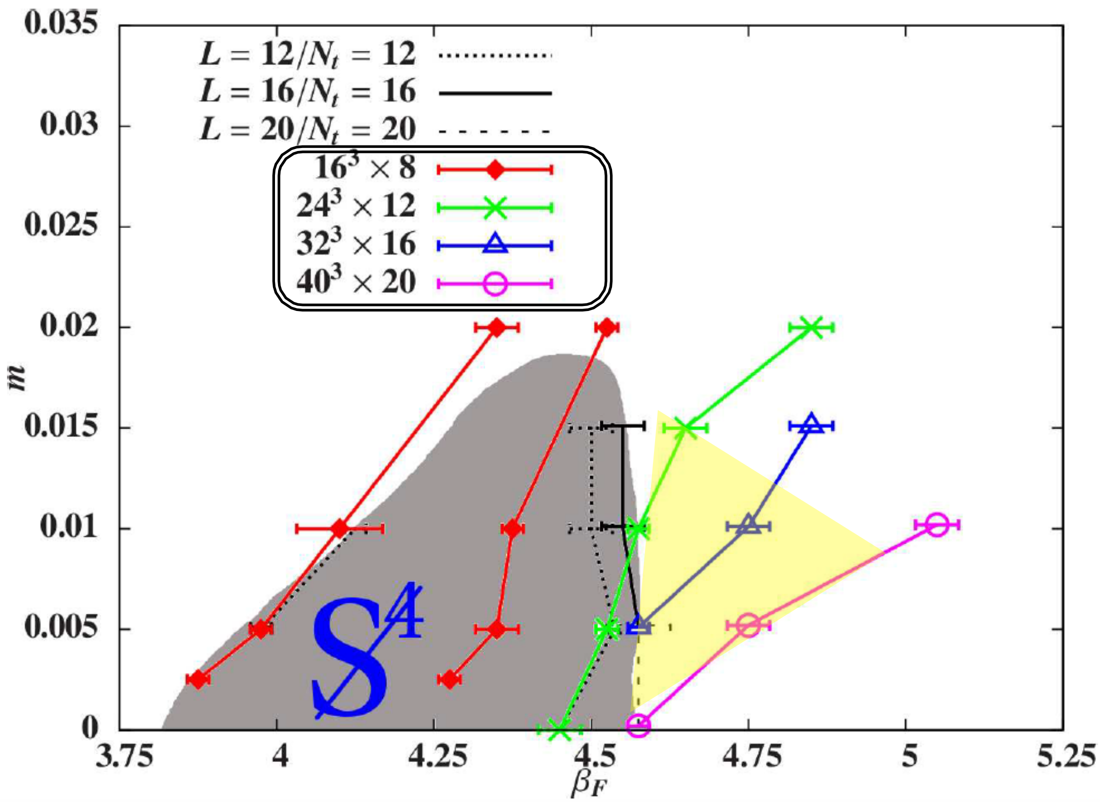
Let's try N_t =20 : looks OK.



Finite temperature phase structure – N_f =8

We can check this in the chiral limit with direct m=0 simulations!

→ lost the confining phase in the chiral limit even on N_t=20



Could N_f=8 be conformal?

If N_f=8 is not conformal, it will require huge volumes to find a confining regime.

Even small mass can change the qualitative behavior significantly

Dirac eigenvalue spectrum

Eigenvalues at small λ are related to IR physics

In conformal systems the eigenvalue density ρ scales as $\rho(\lambda) \propto \lambda^{\alpha}$

.

The mode number $\nu(\lambda) = V \int_{-\lambda}^{\lambda} \rho(\omega) d\omega \propto V \lambda^{\alpha+1}$ is RG invariant

(Giusti,Luscher)

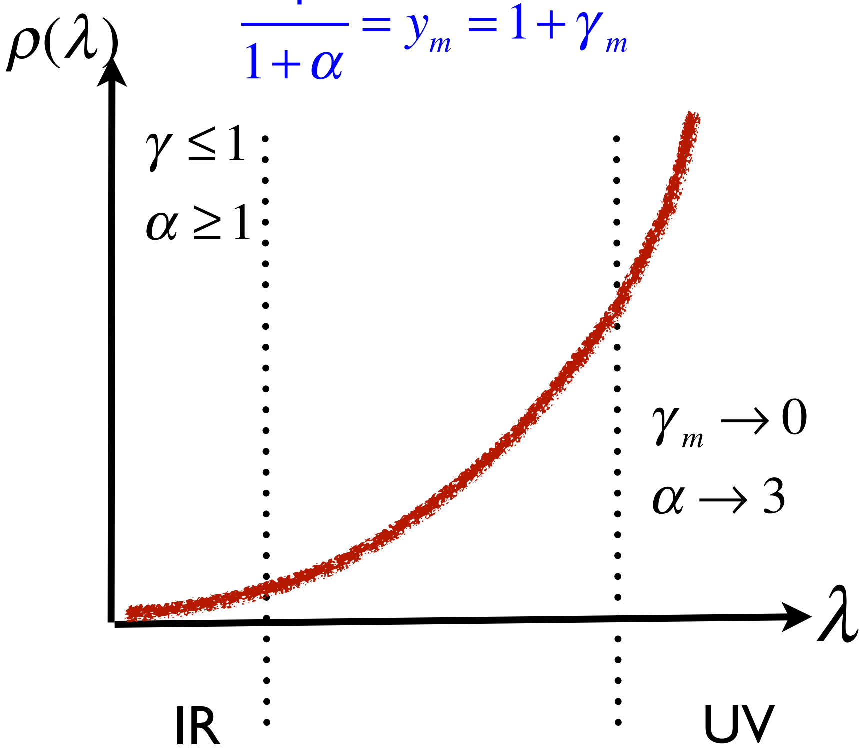
→ α is related to the anomalous dimension $\frac{4}{1+\alpha} = y_m = 1 + \gamma_m$

(Zwicky,DelDebbio;Patella)

The energy dependence of γ_m

γ_m depends on the energy scale :
this is manifest as λ dependence of the eigenmode scaling

$$\frac{4}{1+\alpha} = y_m = 1 + \gamma_m$$



IR – small λ region:

$$\gamma_m(\lambda \to 0) \to \gamma^*$$

predicts the universal anomalous dimension at the IRFP

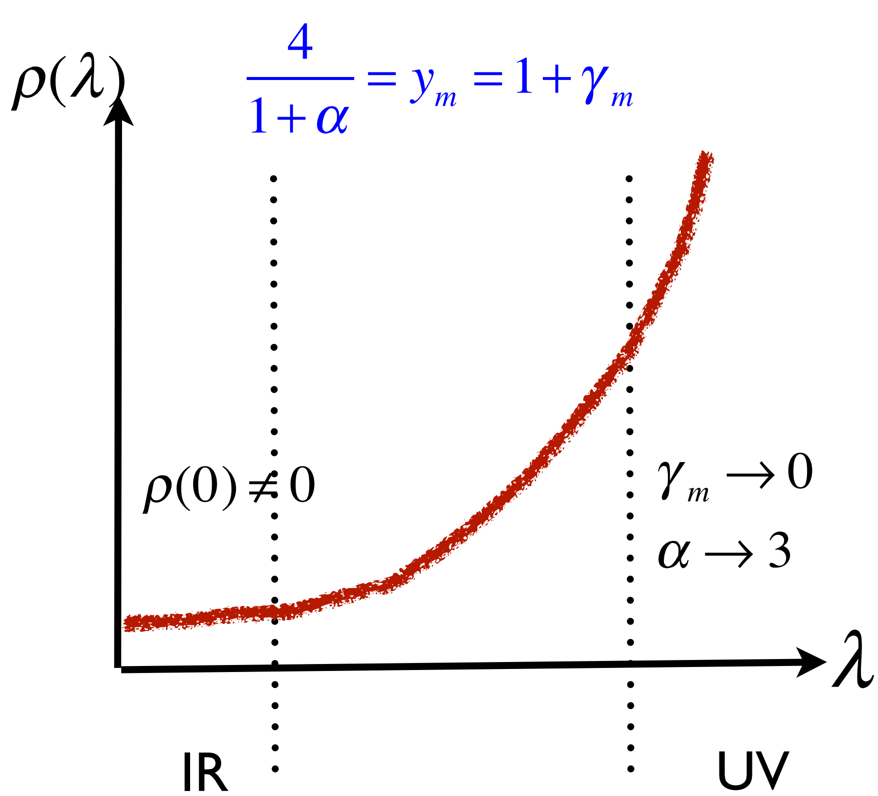
UV – large λ =O(1) region:
Governed by the UVFP
(asymptotically free perturbative FP)

$$\gamma_m(\lambda) \to 0$$

In between:
Energy dependent γ_m

The energy dependence of γ_m :Chirally broken systems

The picture is still valid in the UV and moderate energy range



IR – small λ region:

$$\rho(0) \neq 0$$

predicts the chiral condensate.
Fit gives α=0 → γ_m>3, but that is not physical!

UV – large λ =O(1) region:
Governed by the UVFP
(asymptotically free perturbative FP)

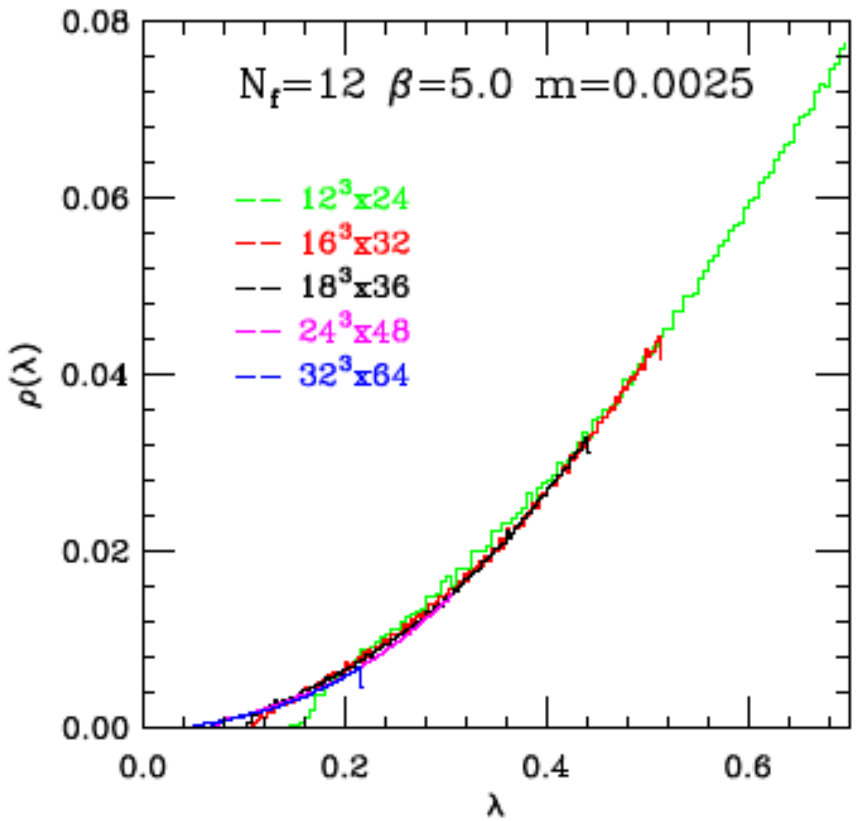
$$\gamma_m(\lambda) \to 0$$

In between:
Energy dependent γ_m

Volume dependence

The scaling form is valid in V→∞ only!

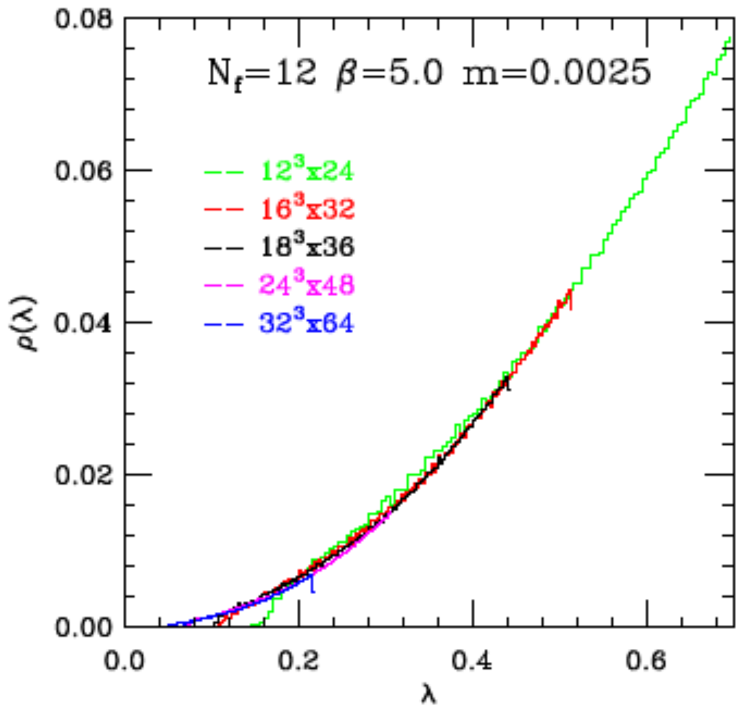
- Increase the volume until volume dependence vanishes
- **OR** combine different volumes & use the finite volume as advantage

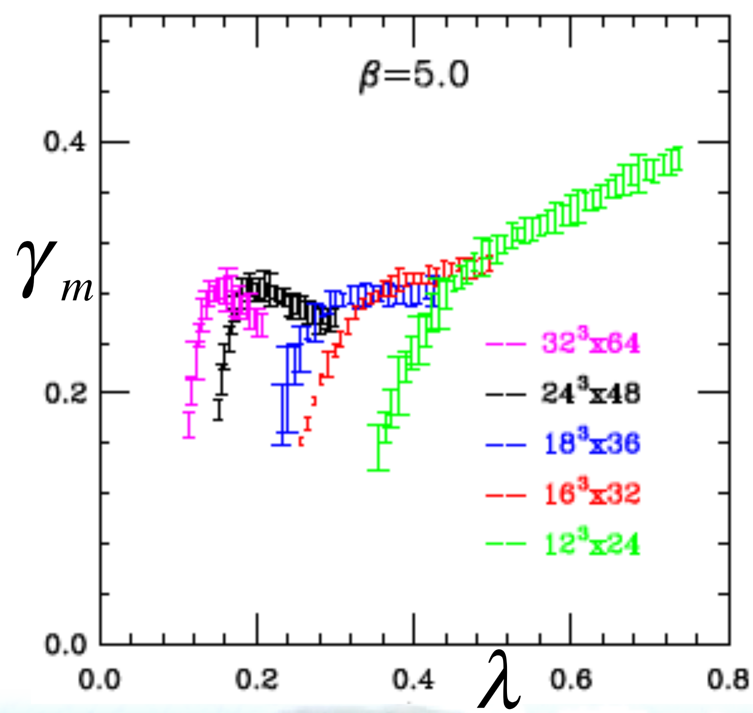


1000 eigenmodes on 12^3x24→32^3x64 volumes

Extracting γ_m

- Fit: $\log(\nu(\lambda))=c+(\alpha+1)\log(\lambda)$
- Volume dependence:
  - Ignore small λ /volume transient
  - Look for overall "envelope"





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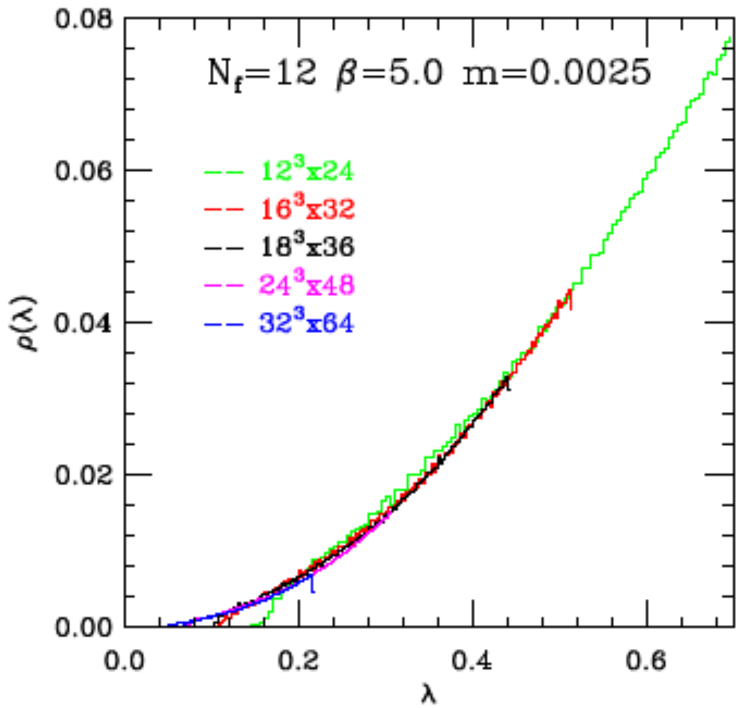
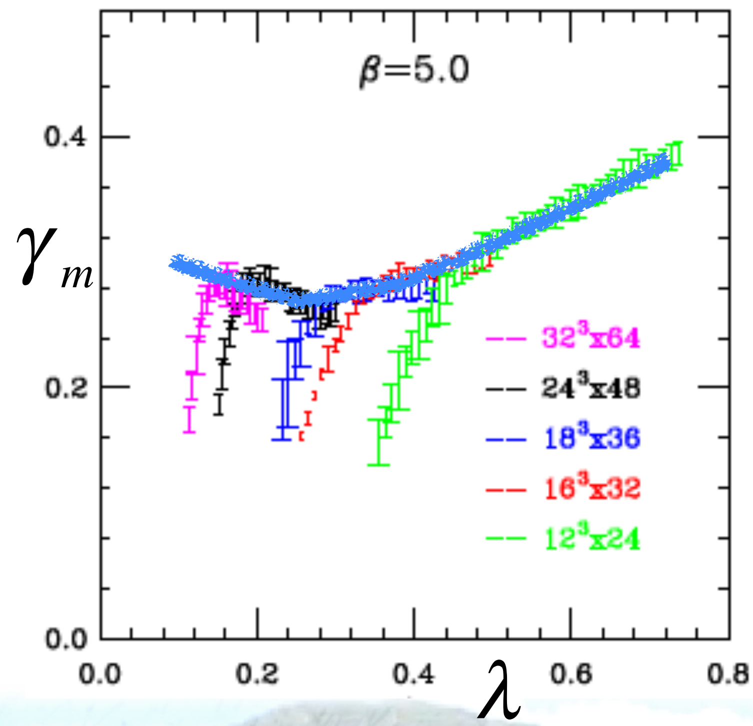
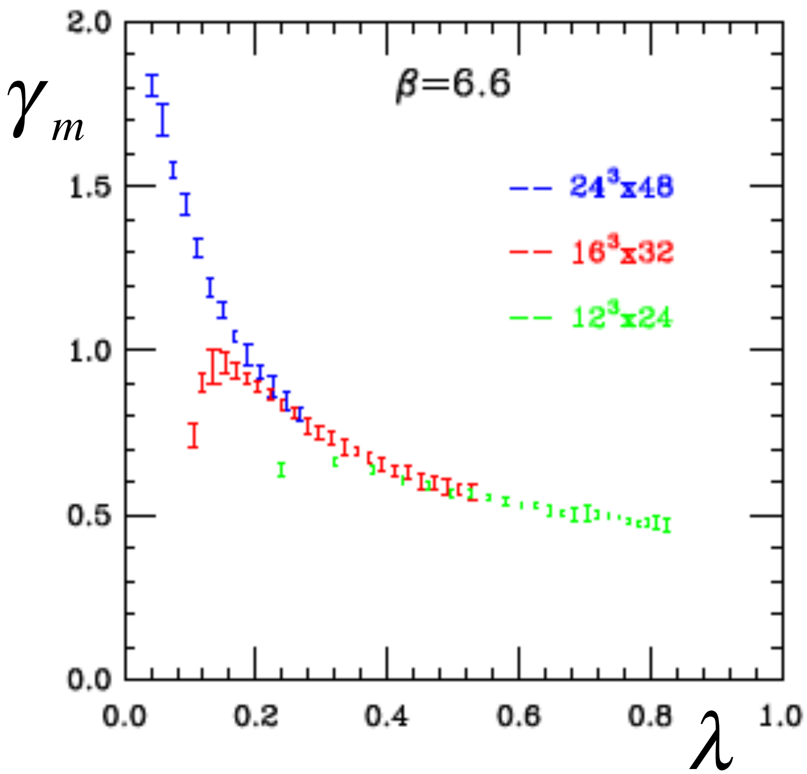




Anomalous dimension N_f =4

We know what to expect:

broken chiral symmetry in IR, asymptotic freedom in UV



- β=6.6, m=0.0025:
  Chirally broken → γ_m >1

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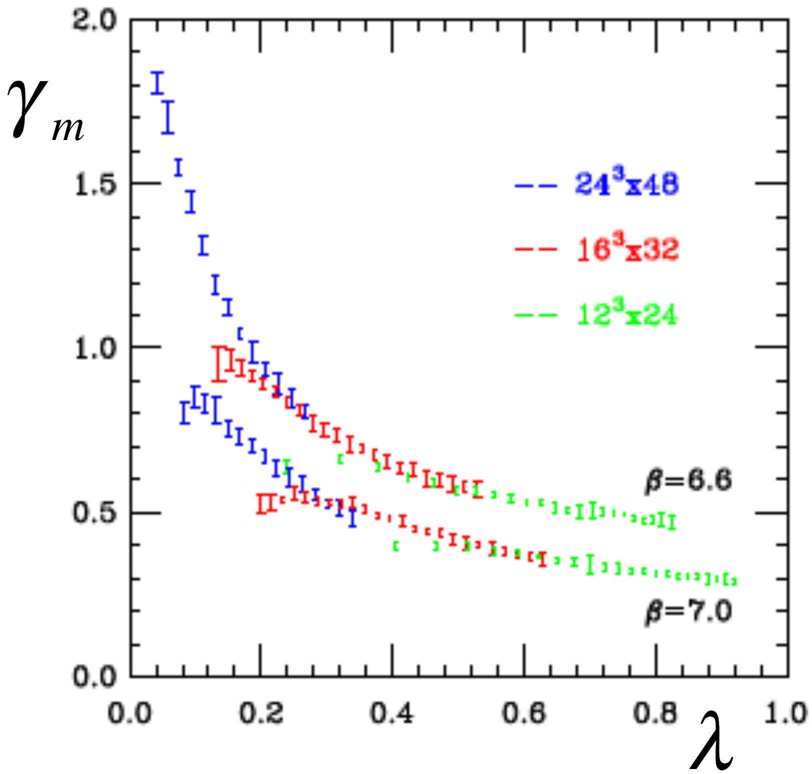

- β=6.6, m=0.0025:
  Chirally broken → γ_m >1
- β=7.0, m=0.0 :

Can we relate the two couplings?

$$\lambda_{\text{latt}} = \lambda_{\text{phys}} a(\beta)$$

$$a(\beta = 6.6) \approx 1.3 a(\beta = 7.0)$$

rescale:

$$\lambda_{6.6} \rightarrow \left(\frac{a_{7.0}}{a_{6.6}}\right)^{1+\gamma_m} \lambda_{6.6}$$

Anomalous dimension $N_f = 4$

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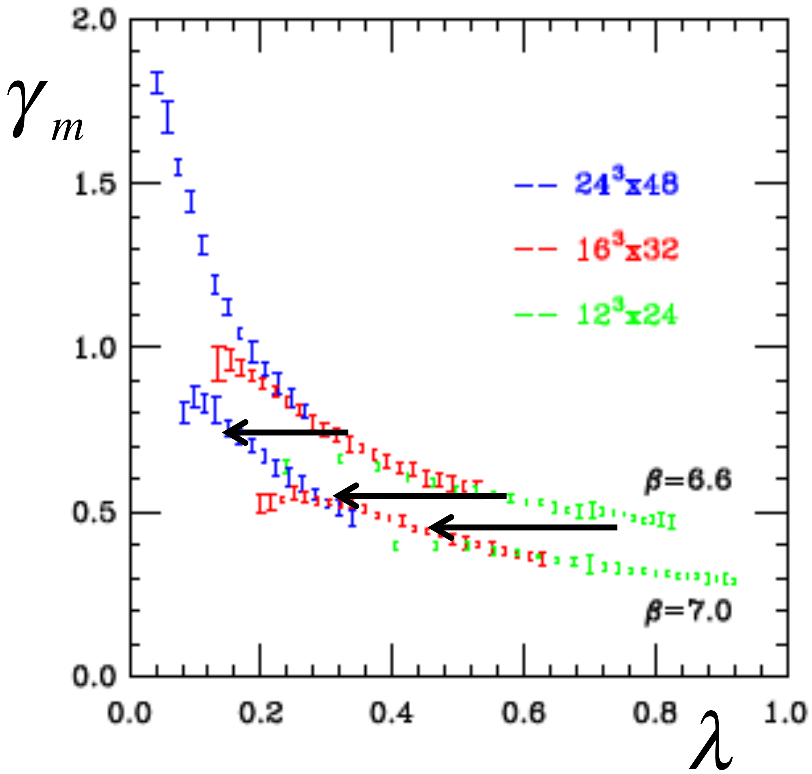

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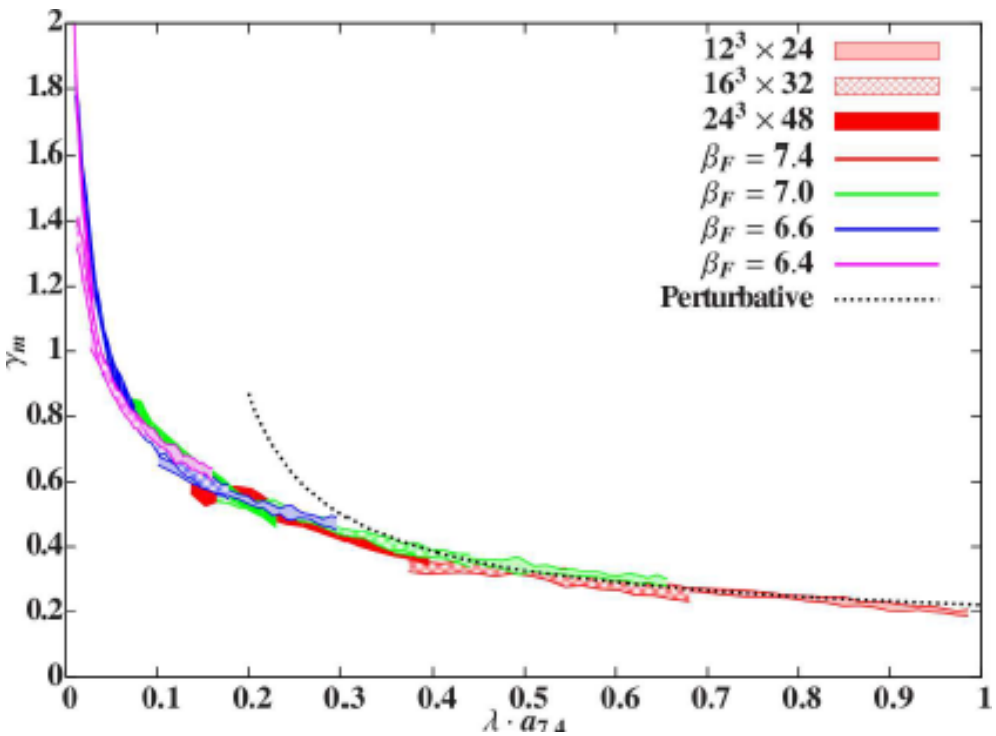

Combine

β=6.4, 6.6, 7.0, 7.4

$$\lambda_\beta \rightarrow \left(\frac{a_{7.4}}{a_\beta}\right)^{1+\gamma_m} \lambda_\beta$$

$$a_{6.6} \approx 2a_{7.4}$$

$$a_{6.4} \approx 2a_{7.0}$$

$$a_{6.4} \approx 1.3a_{6.6}$$

$$a_{8.0} \approx 0.7a_{7.4}$$

Well over a magnitude in energy

Agrees with 1-loop PT as well

Anomalous dimension $N_f = 4$

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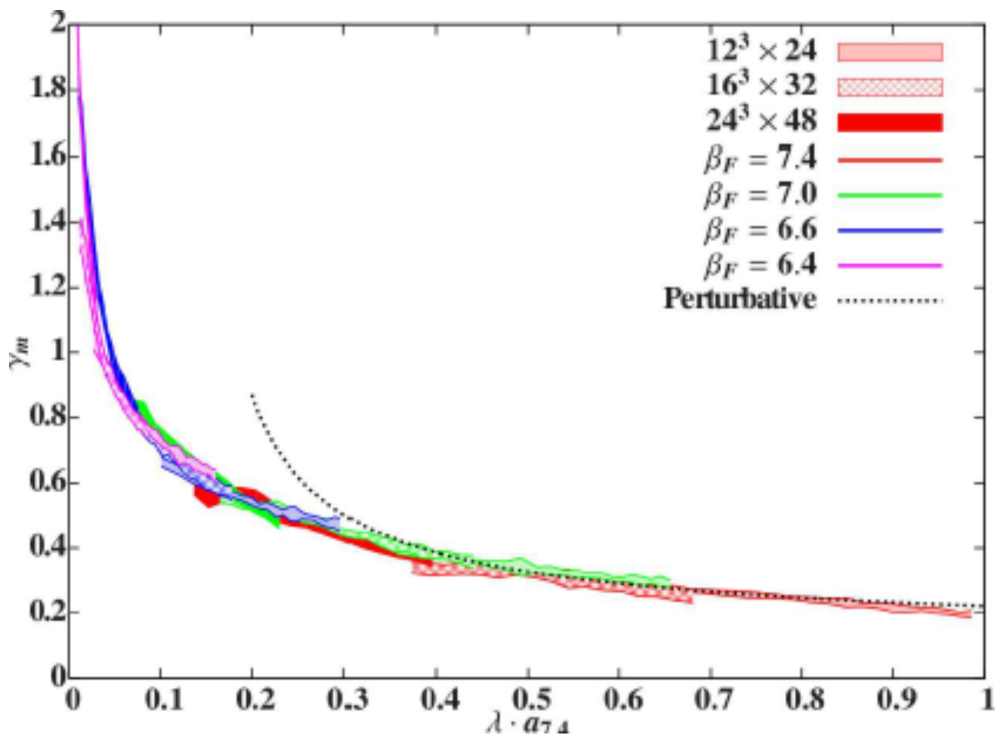

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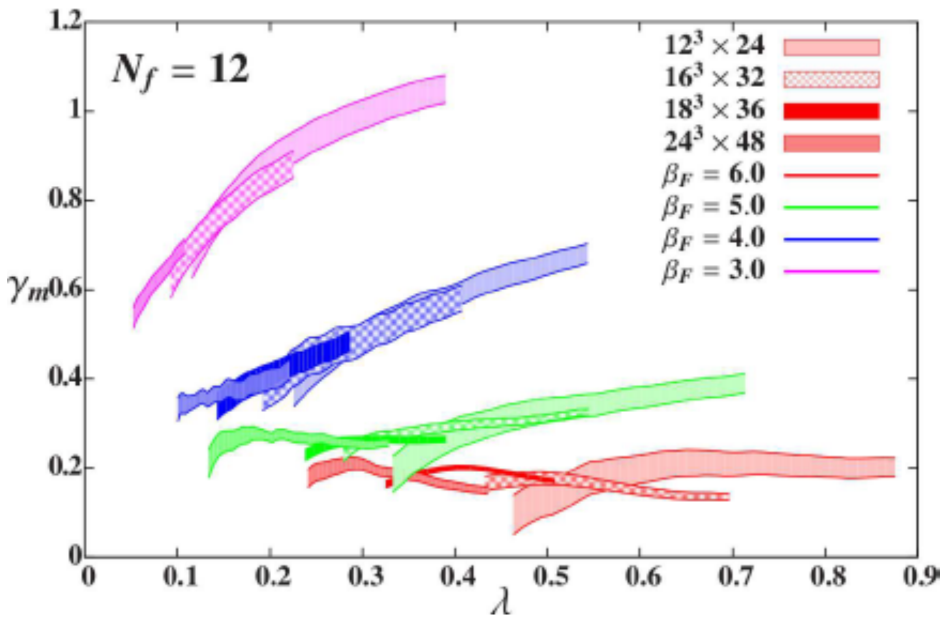
Well over a magnitude in energy

Agrees with 1-loop PT as well

Most of these data were obtained on deconfined (small) volumes at m=0!

Anomalous dimension N_f =12

Every test we have done in /near the chiral limit suggests IR conformality but the system is still controversial



β=3.0, 4.0, 5.0, 6.0

- There is no sign of asymptotic freedom behavior for β<6.0, γ_m grows towards UV
- Not possible to rescale different β's

Looks as if there were an IRFP around β=5.0

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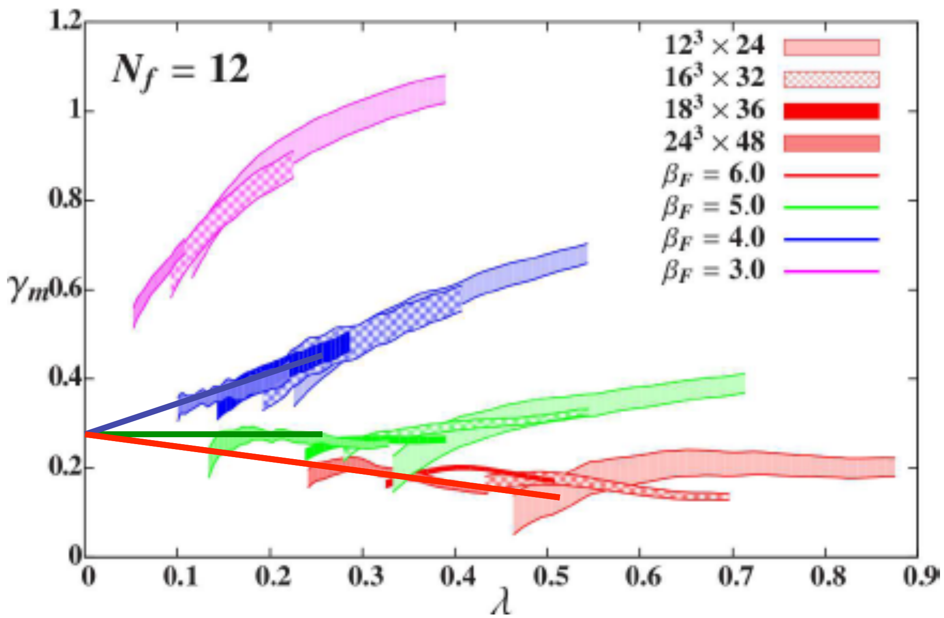

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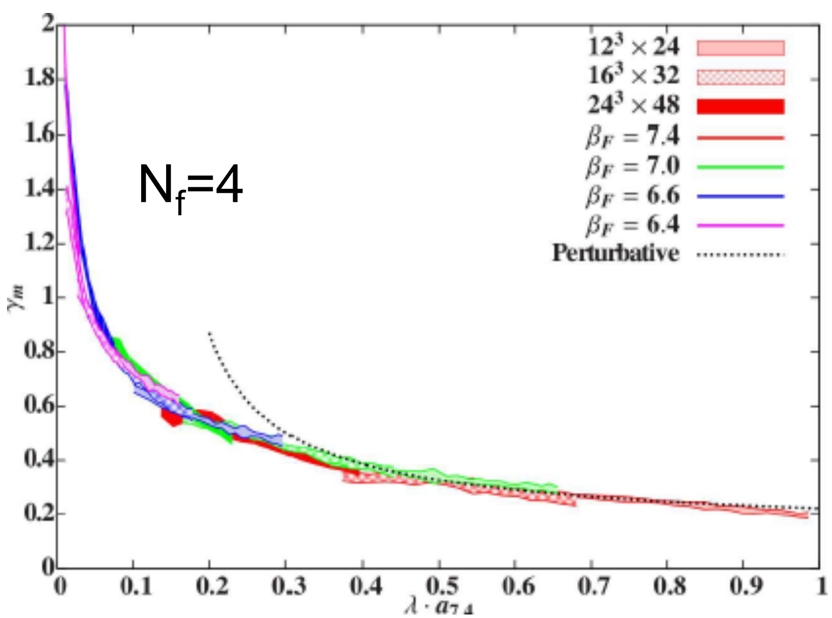
Looks as if there were an IRFP around β=5.0

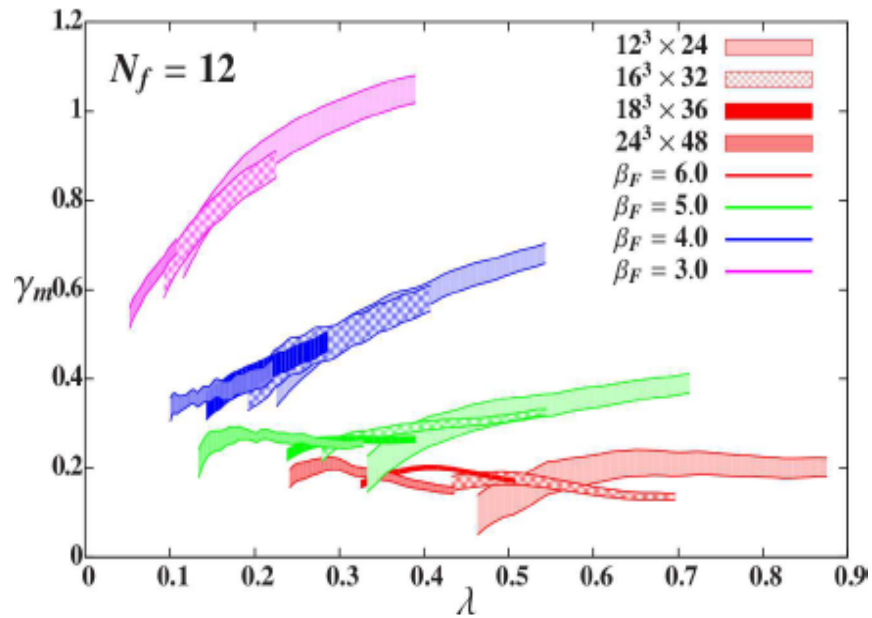
Extrapolate to λ=0: $\gamma_m(\lambda \to 0) \to \gamma^* \approx 0.30(3)$

The mode number

A few lessons on γ_m and the mode number

- Volume dependence is important, especially deep in the weak coupling
- γ_m depends on λ, a constant fit will not work
- γ_m shows strong β dependence : λ → 0 extrapolation is tricky

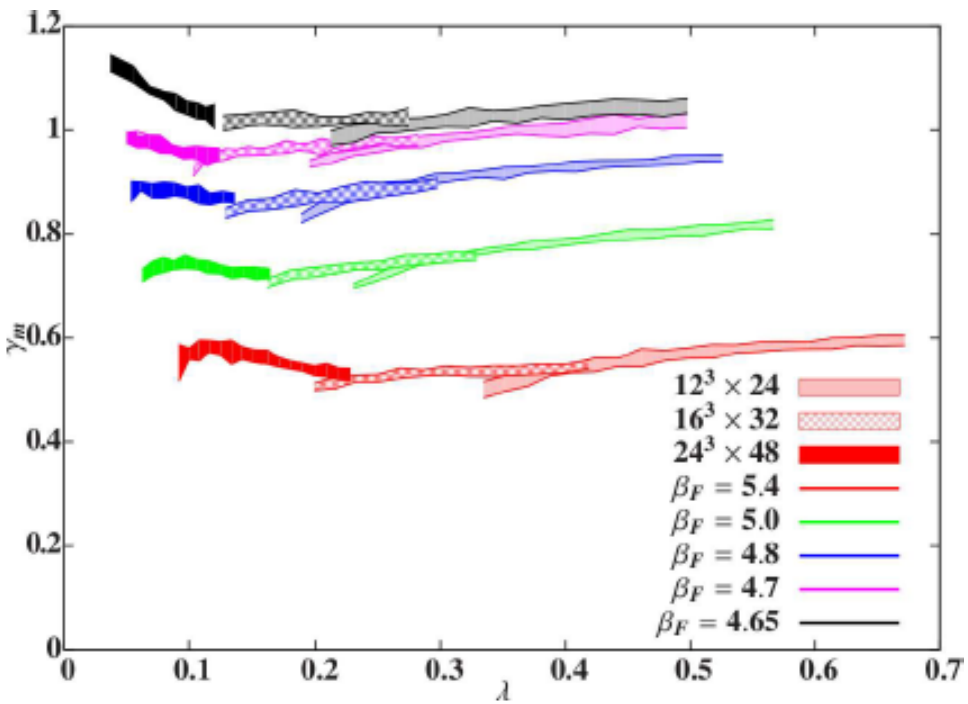




Anomalous dimension, N_f =8

The finite temperature structure shows strange behavior.

Eigenmodes are also closer to 12 than 4 flavors:



No asymptotic free scaling

No rescaleability of different couplings

When $\gamma_m \sim 2$ in the UV, the S^4b phase develops

If N_f=8 is not conformal, it must be slowly walking.

Conclusion & summary

Even after the 4th of July fireworks, strongly coupled systems are worth investigating:

- Lattice regularized models can show unexpected phases : S^4b phase
- Finite temperature studies are reliable to study the phase structure only in the chiral limit (or **very small** bare mass)
- Dirac eigenmodes predict the energy dependent anomalous dimension but careful control of finite volume and $\lambda \to 0$ extrapolation is needed

SU(3) gauge + fundamental fermions:

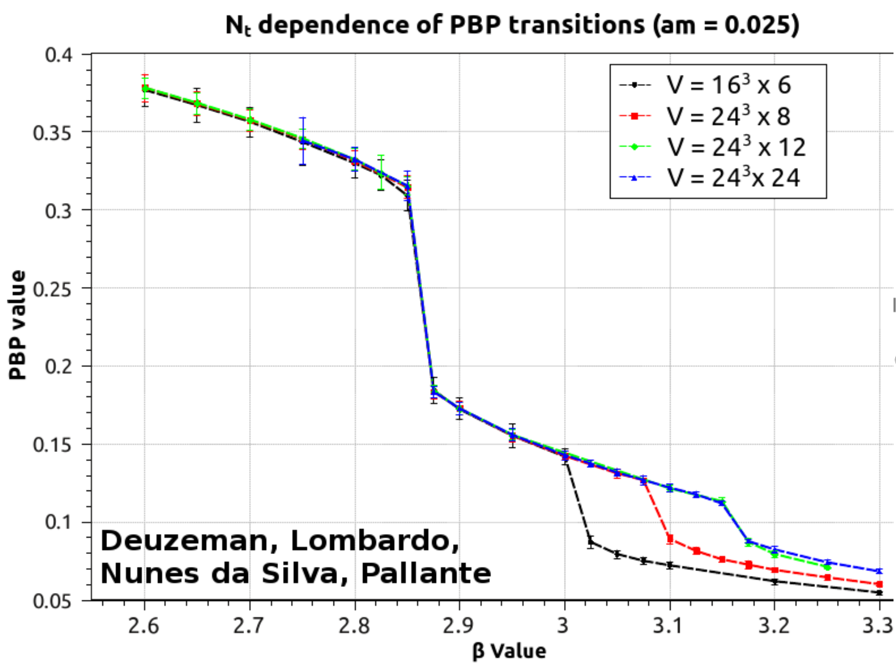
- N_f=12 system looks conformal
- N_f=8 system is unexpected: if not conformal, it must be slowly walking

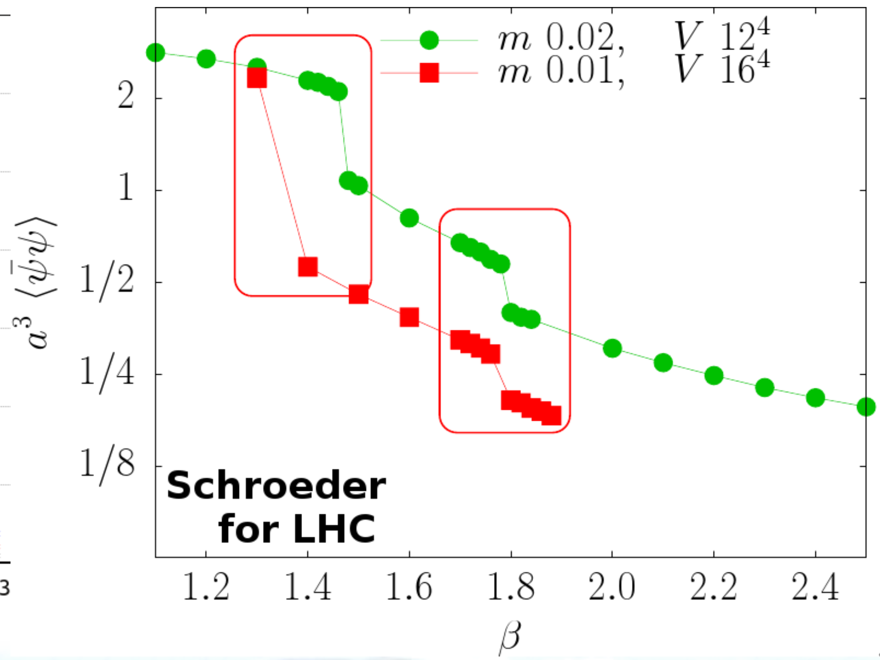
EXTRA SLIDES

The finite temperature phase structure of N_f=12

were among the first BSM studies :

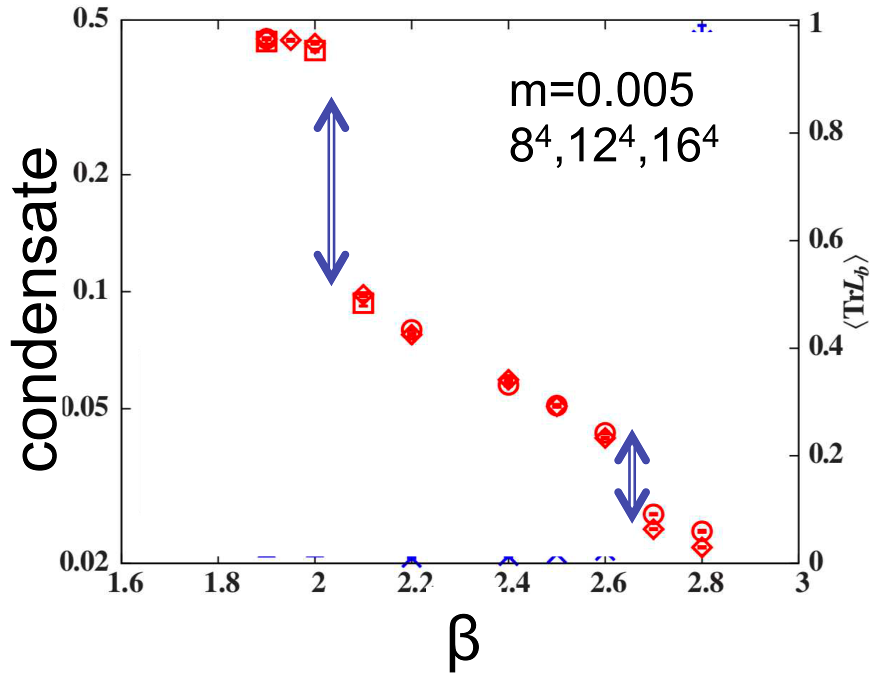
- –Finite T transition with $N_f \geq 4$ flavors is expected to be first order
- – First results were as expected (2008) (Deuzeman, Lombardo, Pallante)
- – Second generation studies found 2 first order transitions in the chiral condensate (both Deuzeman et al and LHC)

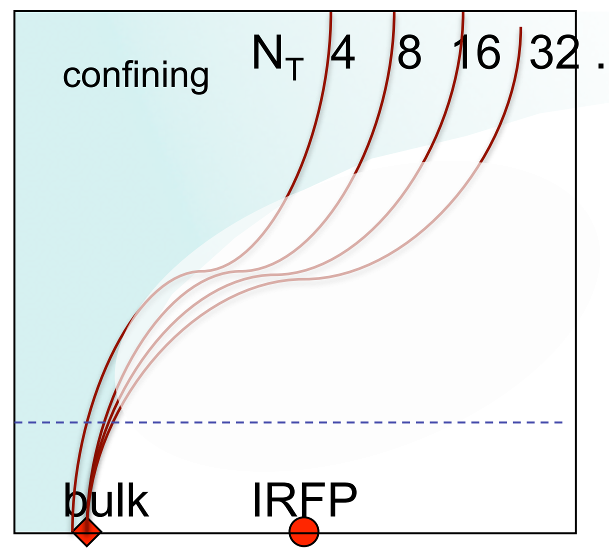




The phase structure of N_f=12

2 jumps in the fermion condensate on T=0 lattices (at finite T as well)





$\beta_c \rightarrow \beta_{bulk}$ as $N_T \rightarrow \infty$

These are bulk transitions, present at T=0 and independent of the volume.

Dirac eigenvalue spectrum

Much less is known about chirally symmetric systems:

- $\rho(0)=0$ suggests the scaling form $\rho(\lambda) \propto \lambda^{\alpha}$
  λ_0 is a "soft edge", in conformal systems $\lambda_0 = 0$

- The exponent α is related to the mass anomalous dimension

(Luscher&Giusti,Zwicky& DelDebbio)

The mode number

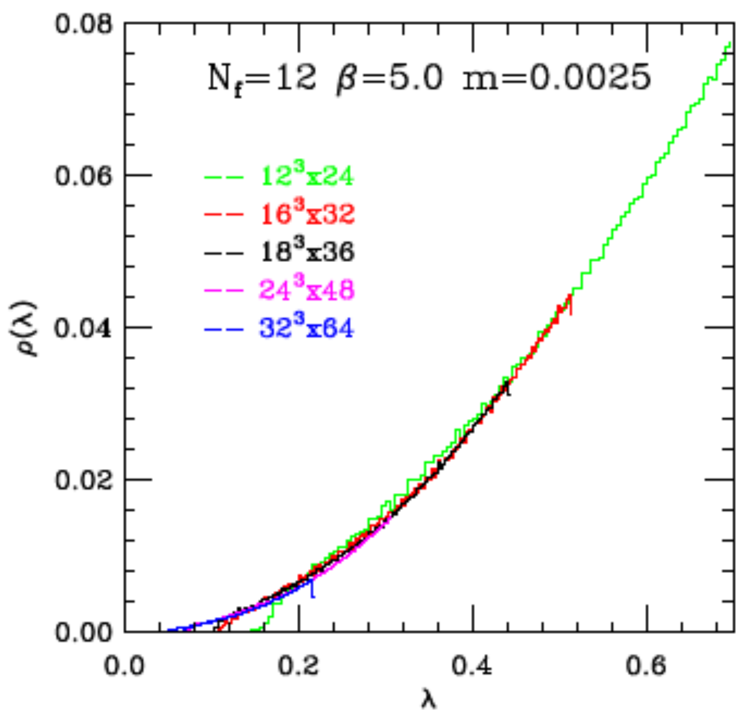
$$\nu(\lambda) = V\int_{-\lambda}^{\lambda} \rho(\omega)d\omega \propto V\lambda^{1+\alpha} = (L\lambda^{(1+\alpha)/4})^4$$

is RG invariant →

$$\frac{1+\alpha}{4} = y_m = 1+\gamma_m$$

Extracting γ_m

- Configurations: 20-50 independent, 12^3x24 → 32^3x64 volumes
- mass: 0.0025 → 0
  no observable mass effect (but m=0.01 would be too large!)
- Calculate eigenmodes: ~1000 per configuration
  Different volumes cover different λ range



- Volume dependence:
  The scaling form is valid in V→∞ only!
  - Increase the volume until volume dependence vanishes
  - Combine different volumes & use the finite volume as advantage