Title: Insightful supersymmetry

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Abstract: It has recently been realized that some studies of supersymmetric gauge theories, when properly interpreted, lead to insights whose importance transcends supersymmetry. I will illustrate the insightful nature of supersymmetry by two examples having to do with the microscopic description of the thermal deconfinement transition, in non-supersymmetric pure Yang-Mills theory and in QCD with adjoint fermions. A host of strange ``topological" molecules will be seen to be the major players in the confinement-deconfinement dynamics. Interesting connections between topology, ``condensed-matter" gases of electric and magnetic charges, and attempts to interpret the divergent perturbation series will emerge. Much of the presentation will be aimed at non-experts.

Insightful supersymmetry

Erich Poppitz

U of Toronto

in collaboration with

Mithat Ünsal SFSU 0812.2085 0905.0634 0906.5256 0910.1245 0911.0358 1005.3519 1105.3969 1112.6389 1205.0290 1212.1238

Mohamed Anber Toronto 1105.0940 1112.6389 1211.2824 1310.3522

Thomas Schäfer NCSU 1205.0290 1212.1238

Scott Collier Toronto 1211.2824 1310.3522

Tin Sulejmanpasic Regensburg 1307.1317

Seth Strimas-Mackey Toronto 1310.3522

Brett Teeple Toronto 1310.3522

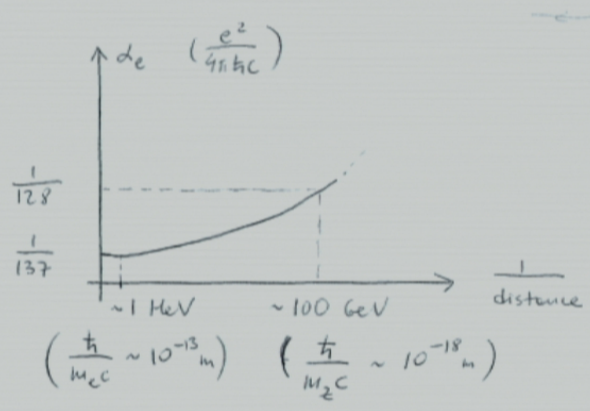
1. deconfinement

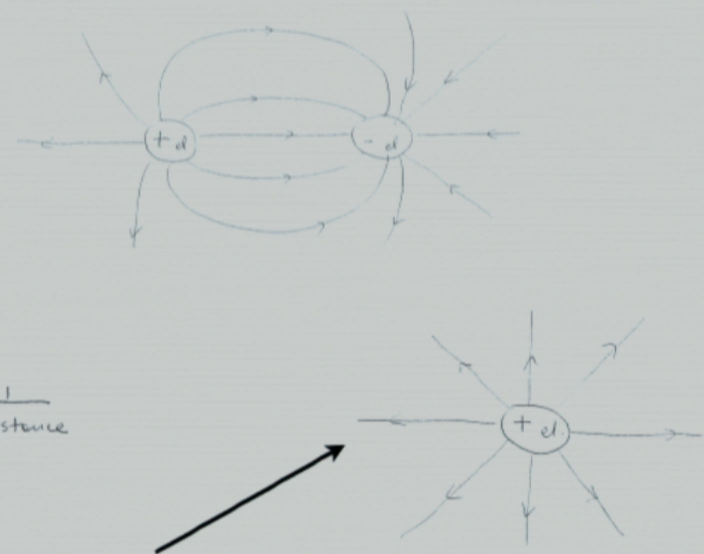
what is it and how do we study it?

QCD - theory of the strong interactions:
quarks and gluons, discovered in 1970s

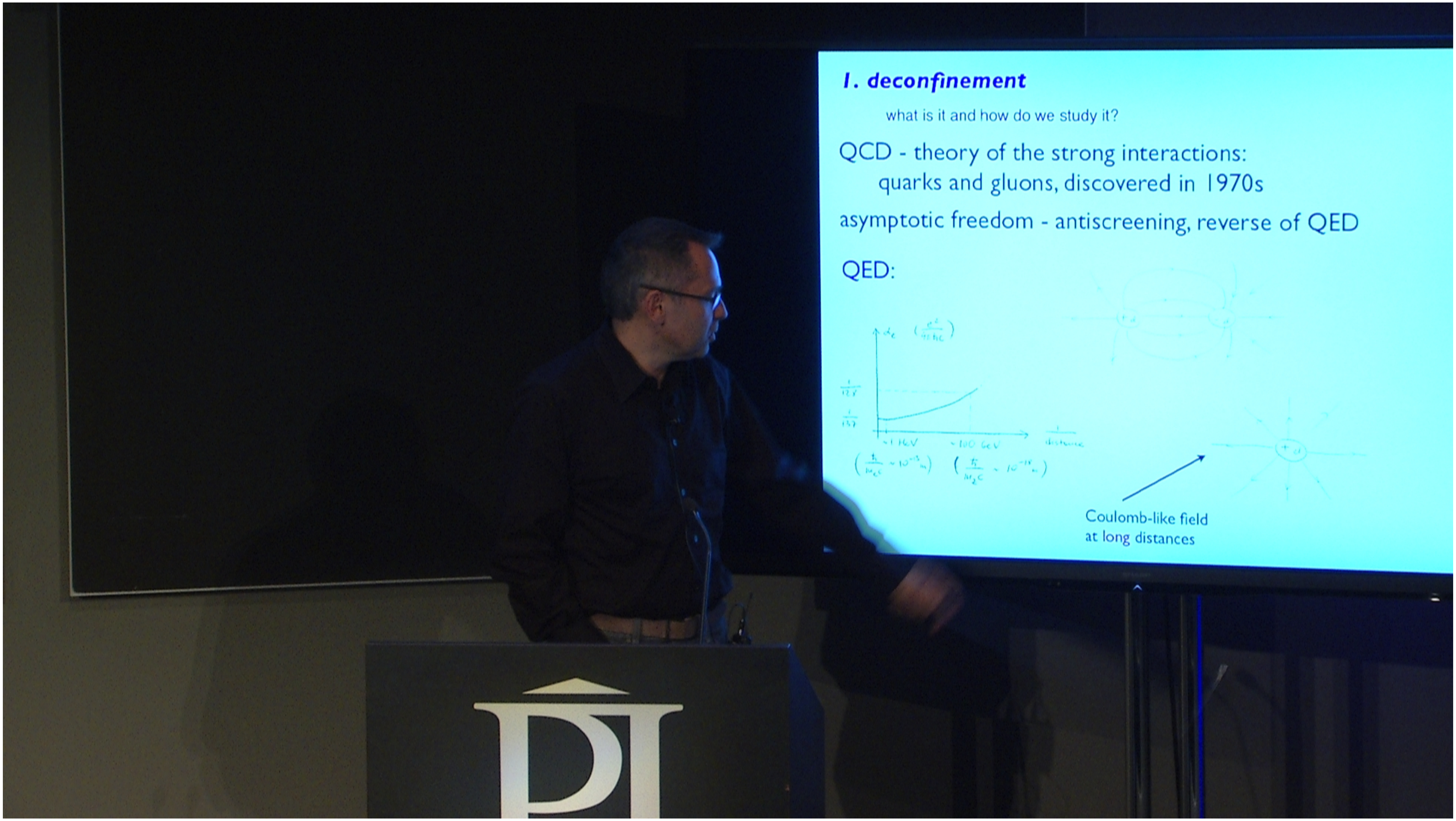
asymptotic freedom - antiscreening, reverse of QED

QED:





Coulomb-like field
at long distances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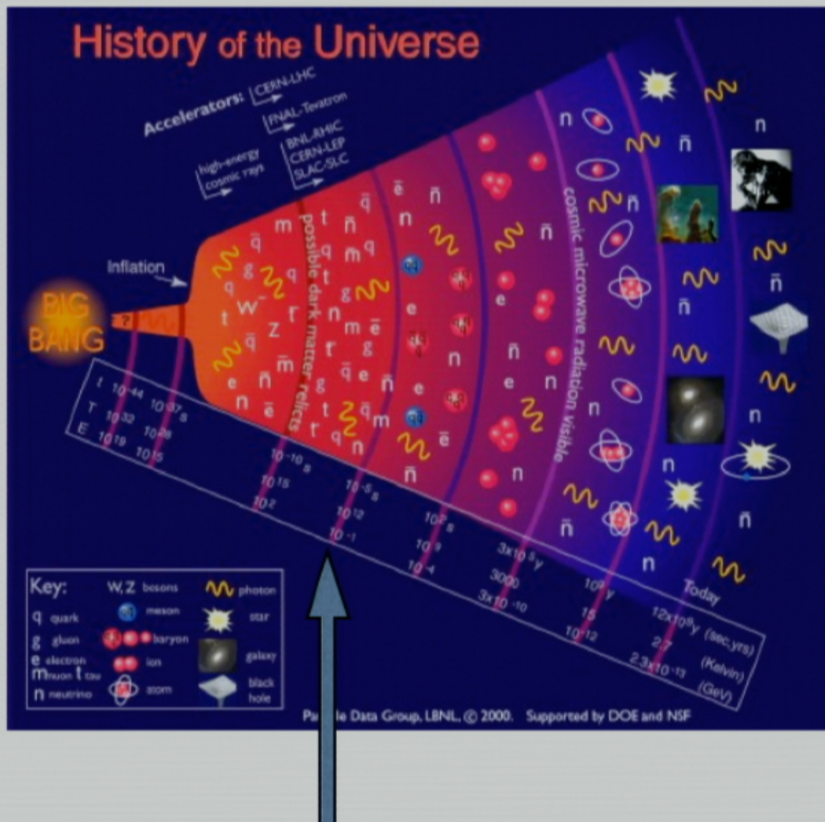
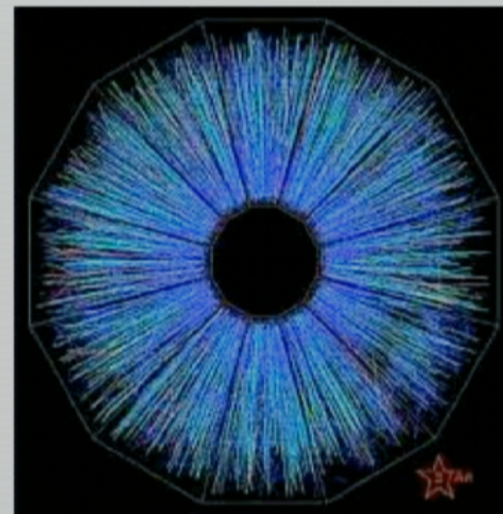
What happens when quarks and gluons are "heated up"?

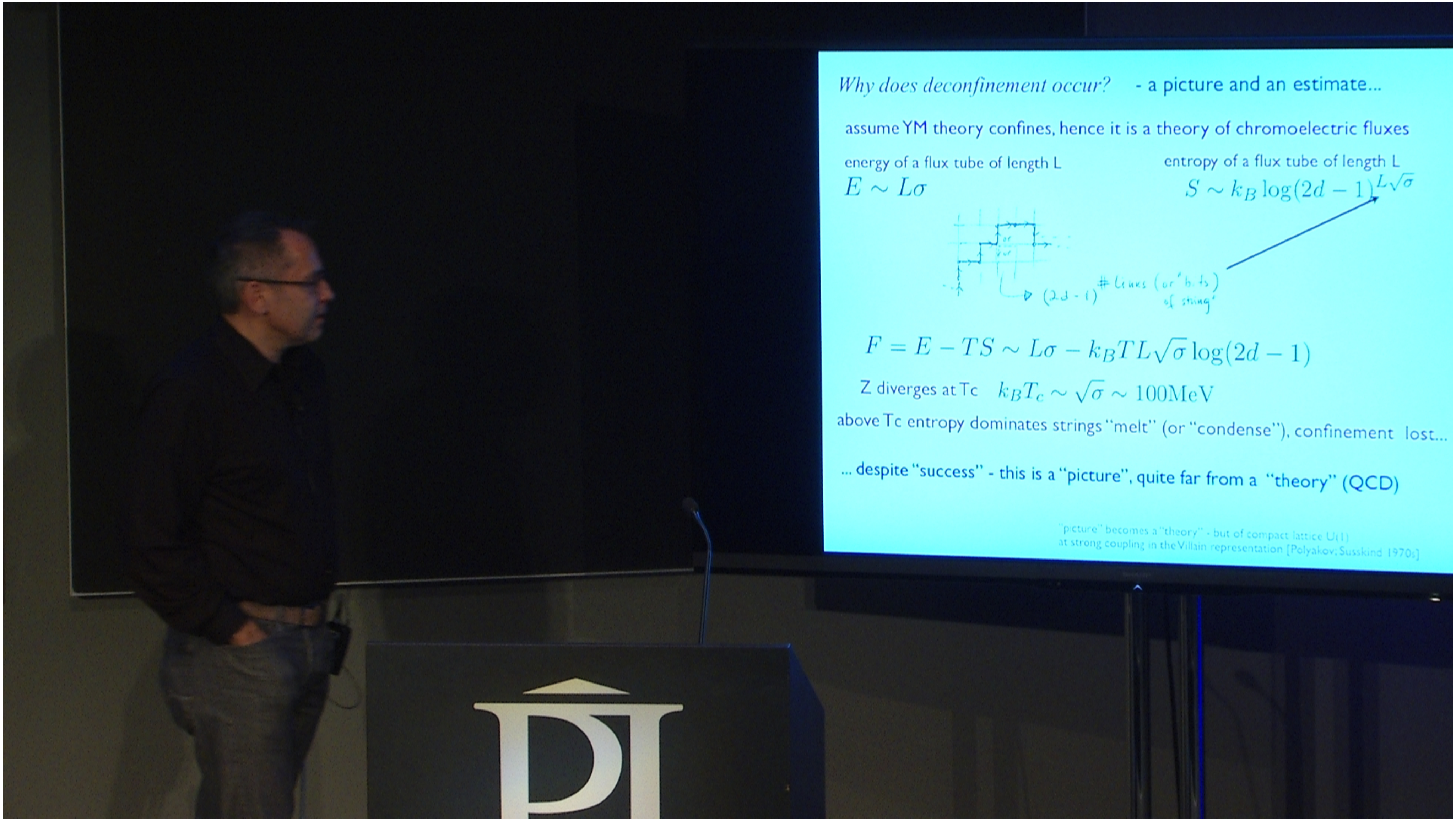




$k_B T \sim 100\text{MeV} \quad T \sim 10^{12}\text{K}$

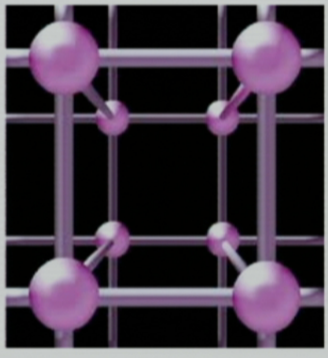
(10^{-10}s after big bang)

- quarks and gluons are "liberated" or "deconfined"


Why does deconfinement occur? - a picture and an estimate...
assume YM theory confines, hence it is a theory of chromoelectric fluxes
energy of a flux tube of length L
$E \sim L\sigma$
entropy of a flux tube of length L
$S \sim k_B \log(2d-1)^{L\sqrt{\sigma}}$
$F = E - TS \sim L\sigma - k_B T L \sqrt{\sigma} \log(2d-1)$
Z diverges at Tc $k_B T_c \sim \sqrt{\sigma} \sim 100\text{MeV}$
above Tc entropy dominates strings "melt" (or "condense"), confinement lost...
... despite "success" - this is a "picture", quite far from a "theory" (QCD)
"picture" becomes a "theory" - but of compact lattice U(1)
at strong coupling in the Villain representation [Polyakov; Susskind 1970s]

How do people actually study deconfinement?

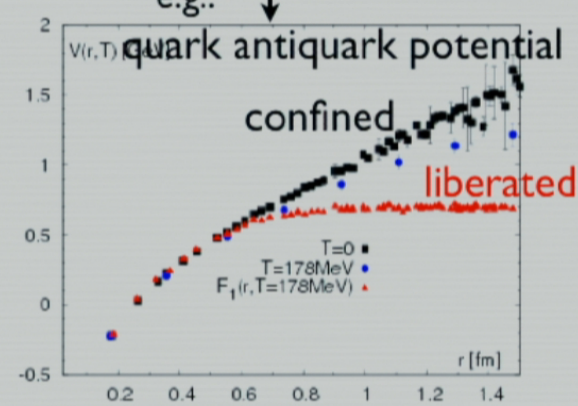
experiment: real or lattice, *i.e. numerical*



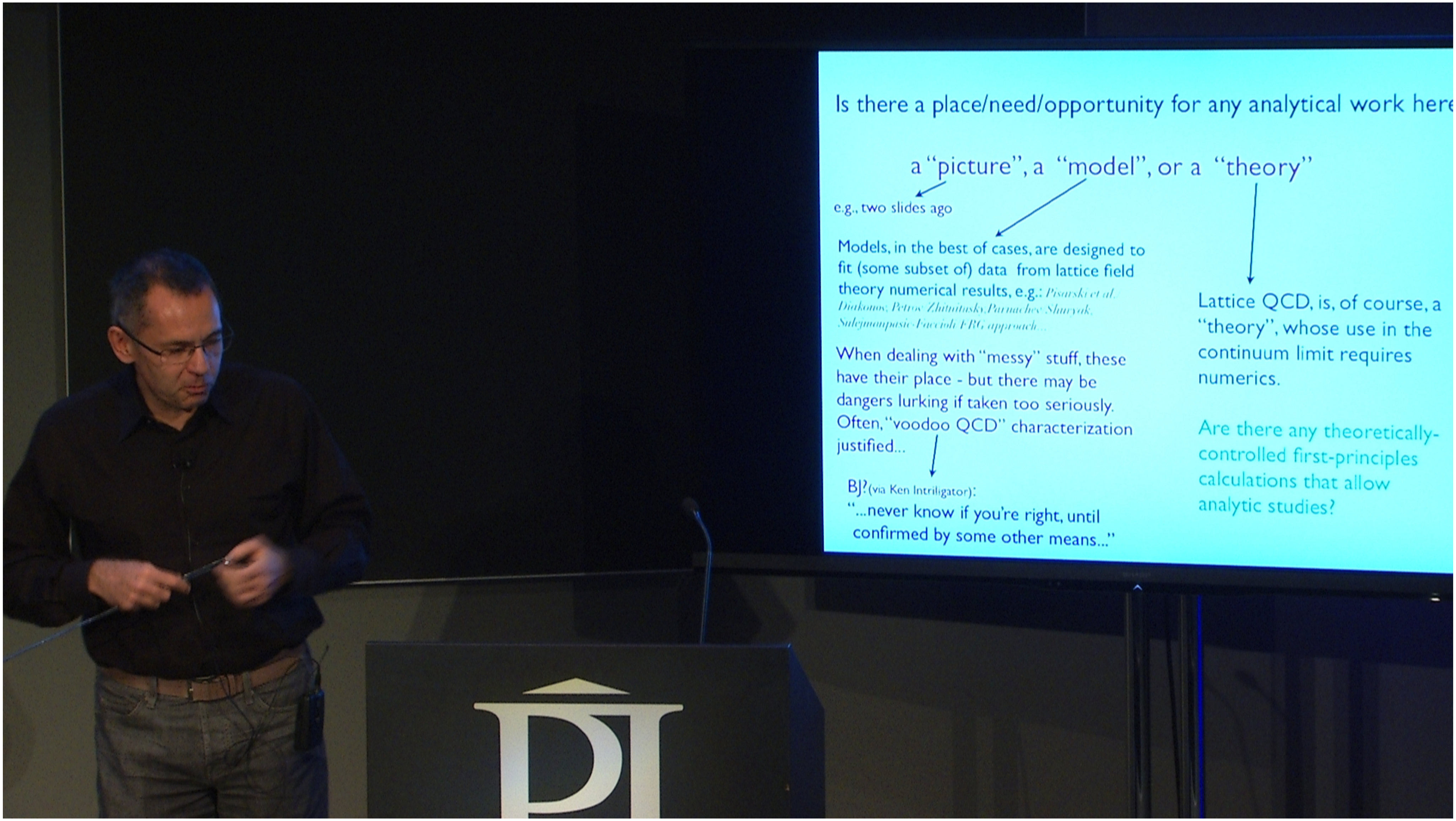
+

- description of hydrodynamic flow
- equation of state...

e.g.:




How do people actually study deconfinement?
experiment: real or lattice, i.e. numerical
- description of hydrodynamic flow
- equation of state...
e.g.:
quark antiquark potential
confined
liberated
ALICE
+


Is there a place/need/opportunity for any analytical work here
a "picture", a "model", or a "theory"
e.g., two slides ago
Models, in the best of cases, are designed to fit (some subset of) data from lattice field theory numerical results, e.g.: Pisarski et al./ Diakonov; Petrov/Zhitnitsky, Parnachev/Shuryak, Sulejmanpasic-Faccioli/FRG approach...
When dealing with "messy" stuff, these have their place - but there may be dangers lurking if taken too seriously. Often, "voodoo QCD" characterization justified...
BJ?(via Ken Intriligator):
"...never know if you're right, until confirmed by some other means..."
Lattice QCD, is, of course, a "theory", whose use in the continuum limit requires numerics.
Are there any theoretically-controlled first-principles calculations that allow analytic studies?

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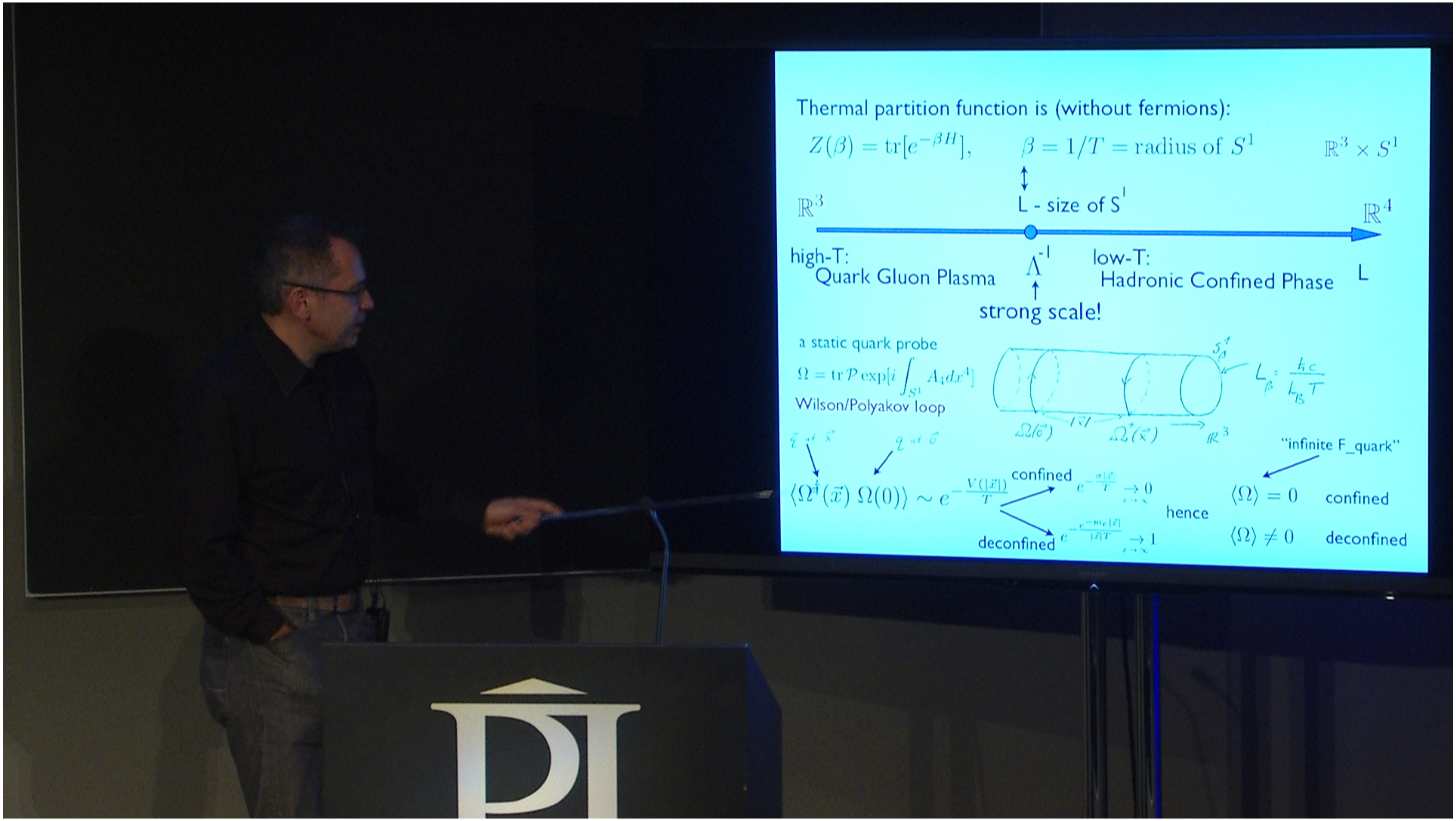
There are a only a few of these.

None of them captures all features of real QCD.

So why do we care?

Before answering, recall some facts about thermal theories.



Thermal partition function is (without fermions):
$Z(\beta) = \mathrm{tr}[e^{-\beta H}]$,
$\beta = 1/T = \text{radius of } S^1$
$\mathbb{R}^3 \times S^1$
L - size of S^1
$\mathbb{R}^3$
$\mathbb{R}^4$
high-T:
Quark Gluon Plasma
Λ^{-1}
low-T:
Hadronic Confined Phase
L
strong scale!
a static quark probe
$\Omega = \mathrm{tr}\,\mathcal{P}\exp[i\int_{S^1} A_4 dx^4]$
Wilson/Polyakov loop
"infinite F_quark"
$\langle \Omega^\dagger(\vec{x})\, \Omega(0)\rangle \sim e^{-\frac{V(|\vec{x}|)}{T}}$
confined
deconfined
hence
$\langle\Omega\rangle = 0$
confined
$\langle\Omega\rangle \neq 0$
deconfined

Thermal partition function is (without fermions):

$Z(\beta) = \mathrm{tr}[e^{-\beta H}]$, $\beta = 1/T = \text{radius of } S^1$ $\qquad \mathbb{R}^3 \times S^1$

L - size of S^1

$\mathbb{R}^3$ ——————●——————→ $\mathbb{R}^4$

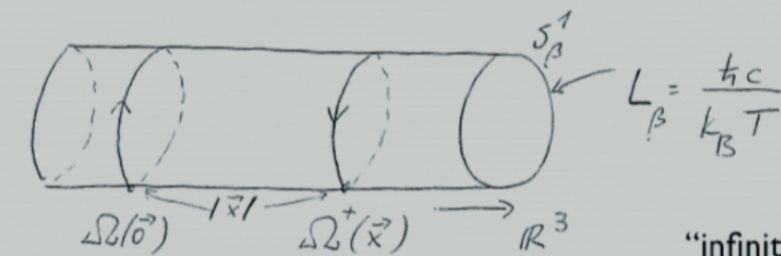
high-T: Quark Gluon Plasma $\quad \Lambda^{-1} \quad$ low-T: Hadronic Confined Phase $\quad$ L

strong scale!

a static quark probe

$\Omega = \mathrm{tr}\,\mathcal{P}\exp[i\int_{S^1} A_4 dx^4]$

Wilson/Polyakov loop



$\bar{q}$ at $\vec{x}$ $\qquad$ q at $\vec{0}$

$\langle \Omega^\dagger(\vec{x})\,\Omega(0)\rangle \sim e^{-\frac{V(|\vec{x}|)}{T}}$

confined: $e^{-\frac{\sigma|\vec{x}|}{T}} \underset{x\to\infty}{\to} 0$

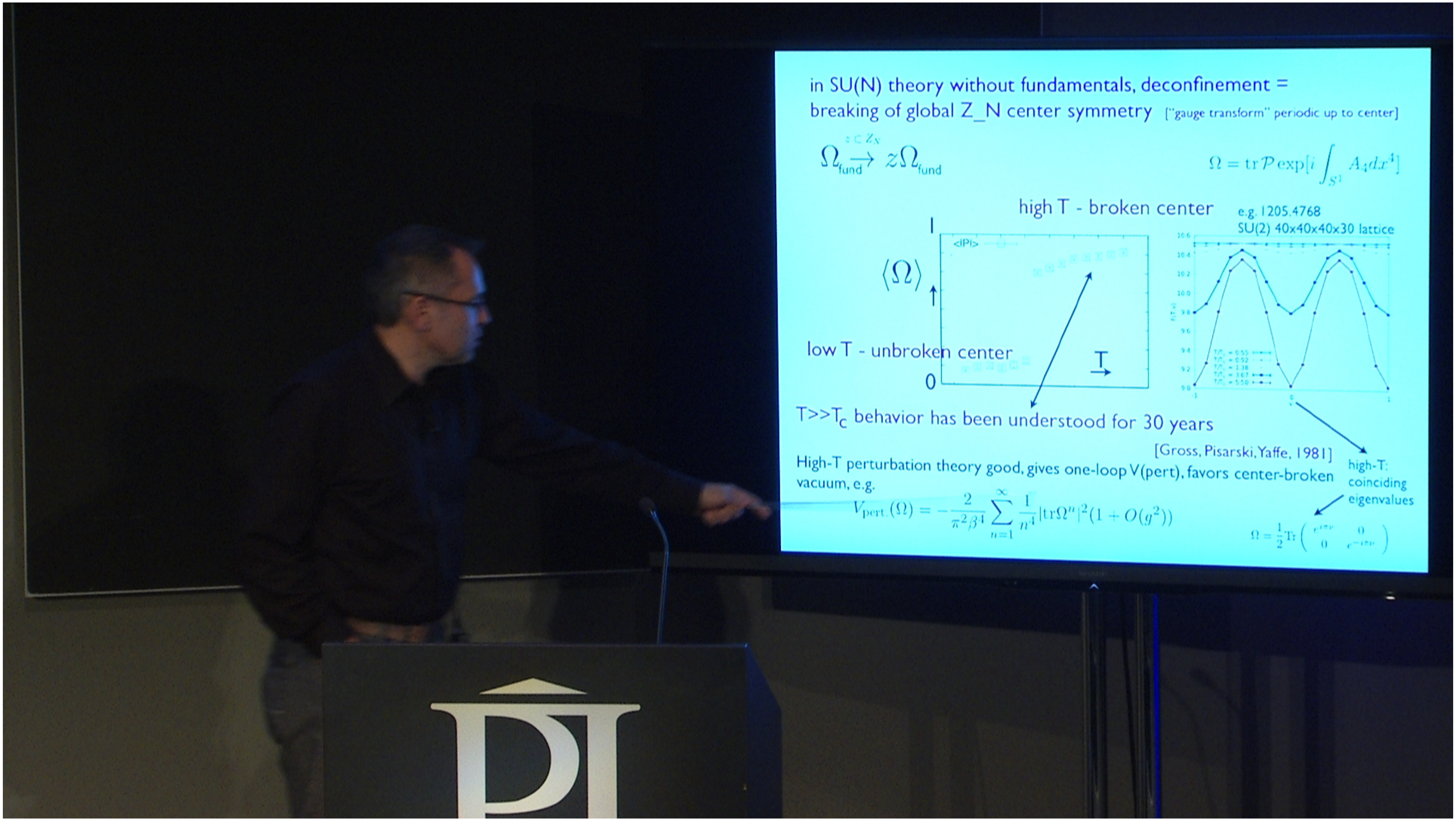
deconfined: $e^{-\frac{e^{-m_e|\vec{x}|}}{|\vec{x}|T}} \underset{x\to\infty}{\to} 1$

hence

"infinite F_quark"

$\langle\Omega\rangle = 0$ confined

$\langle\Omega\rangle \neq 0$ deconfined


in SU(N) theory without fundamentals, deconfinement =
breaking of global Z_N center symmetry ["gauge transform" periodic up to center]
$\Omega_{\text{fund}} \xrightarrow{z \in Z_N} z\Omega_{\text{fund}}$
$\Omega = \text{tr}\,\mathcal{P}\exp[i\int_{S^1} A_4 dx^4]$
high T - broken center
e.g. 1205.4768
SU(2) 40x40x40x30 lattice
1
$\langle\Omega\rangle$
<|P|>
low T - unbroken center
0
T
T>>T_c behavior has been understood for 30 years
[Gross, Pisarski, Yaffe, 1981]
High-T perturbation theory good, gives one-loop V(pert), favors center-broken vacuum, e.g.
$V_{\text{pert.}}(\Omega) = -\frac{2}{\pi^2\beta^4}\sum_{n=1}^{\infty}\frac{1}{n^4}|\text{tr}\Omega^n|^2(1+O(g^2))$
high-T: coinciding eigenvalues

1. Gauge-gravity duality [many, after Witten 1998, ...]

pro: semiclassical string theory provides a weak-coupling description of strongly-coupled gauge theory
deconfinement=Hawking-Page
useful macroscopically (especially out-of-equilibrium)

con: comes with extra baggage - non decoupling KK modes;
no asymptotic freedom;
microscopic connection ?

2. $S^1 x S^3$ compactifications [Aharony, Marsano, Minwalla, Papadodimas, van Raamsdonk, 2003-5]

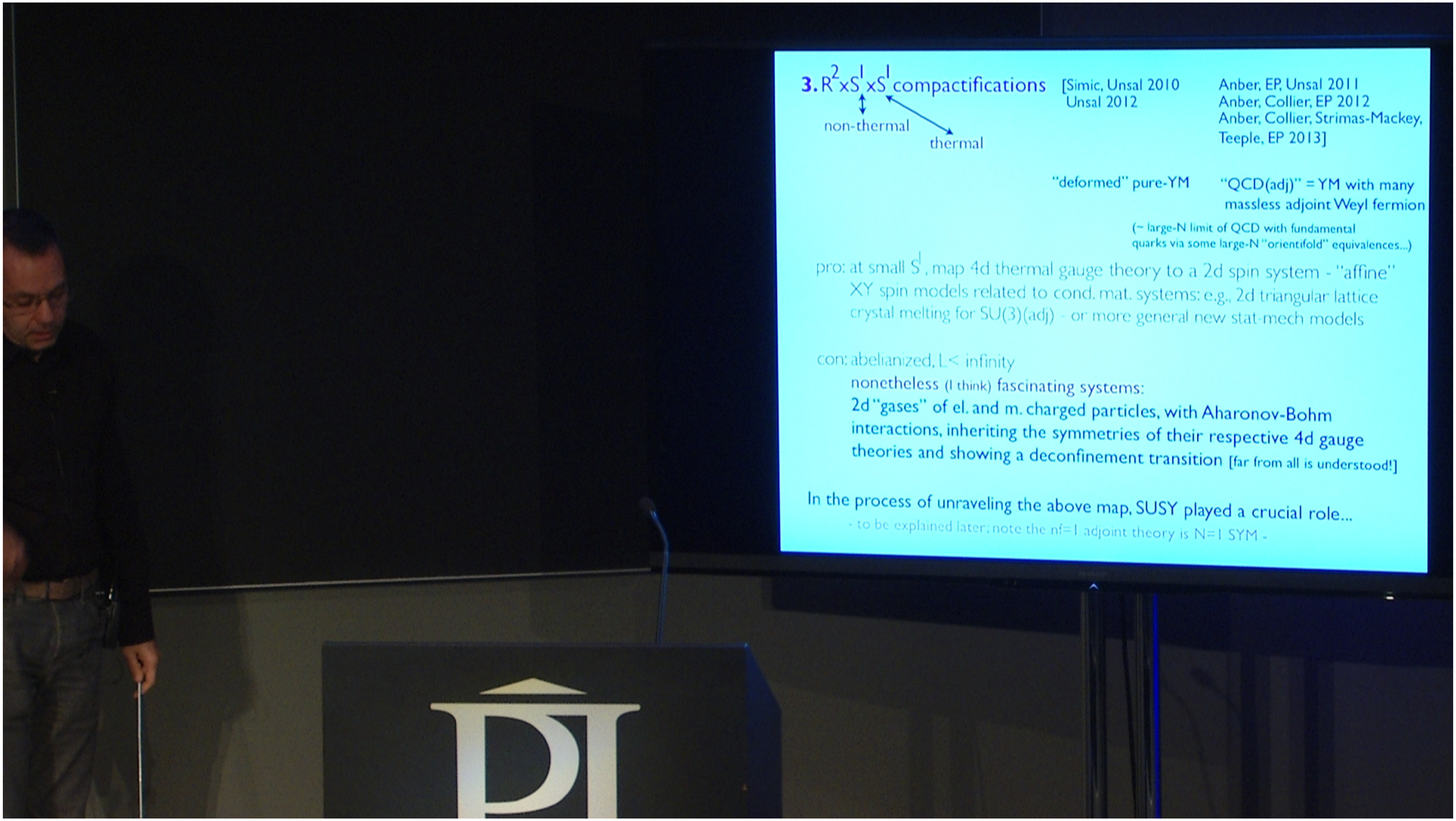
thermal (S^1), non-thermal (S^3)

pro: at small S^3, a weakly coupled matrix model
low-T: Vandermonde repulsion of EVs
high-T: pert. attraction of Polyakov loop EVs

con: thermodynamic limit means large-N transition only

These authors rejected the possibility of finding a weak-coupling transition at infinite volume...

such a description has been found:


3. R2xS1xS1 compactifications
non-thermal
thermal
[Simic, Unsal 2010
Unsal 2012
Anber, EP, Unsal 2011
Anber, Collier, EP 2012
Anber, Collier, Strimas-Mackey,
Teeple, EP 2013]
"deformed" pure-YM
"QCD(adj)" = YM with many
massless adjoint Weyl fermion
(~ large-N limit of QCD with fundamental
quarks via some large-N "orientifold" equivalences...)
pro: at small S1, map 4d thermal gauge theory to a 2d spin system - "affine"
XY spin models related to cond. mat. systems: e.g., 2d triangular lattice
crystal melting for SU(3)(adj) - or more general new stat-mech models
con: abelianized, L< infinity
nonetheless (I think) fascinating systems:
2d "gases" of el. and m. charged particles, with Aharonov-Bohm
interactions, inheriting the symmetries of their respective 4d gauge
theories and showing a deconfinement transition [far from all is understood!]
In the process of unraveling the above map, SUSY played a crucial role...
- to be explained later; note the nf=1 adjoint theory is N=1 SYM -

4. $R^3 \times S^1$ compactifications of SYM*

(non-) thermal

[Schaefer, Unsal, EP 1205.0290, 1212.1238
Anber 1302.2641; Sulejmanpasic, EP 1307.1317;
early remarks in Unsal, Yaffe 1006.2101]

DEFINITIONS:

1

super YM = "SYM" = YM + massless quark, a triplet of SU(2), aka "gaugino"

fields: gauge bosons + gauginos; Z_4 chiral symmetry

2

SYM* = SYM + mass for the triplet quark, i.e. with a "gaugino mass" m

supersymmetry and Z_4 chiral symmetry explicitly broken by m

we study SYM* on $\mathbb{R}^3 \times S^1_L$ with periodic (supersymmetric, non-thermal) boundary condition for gaugino

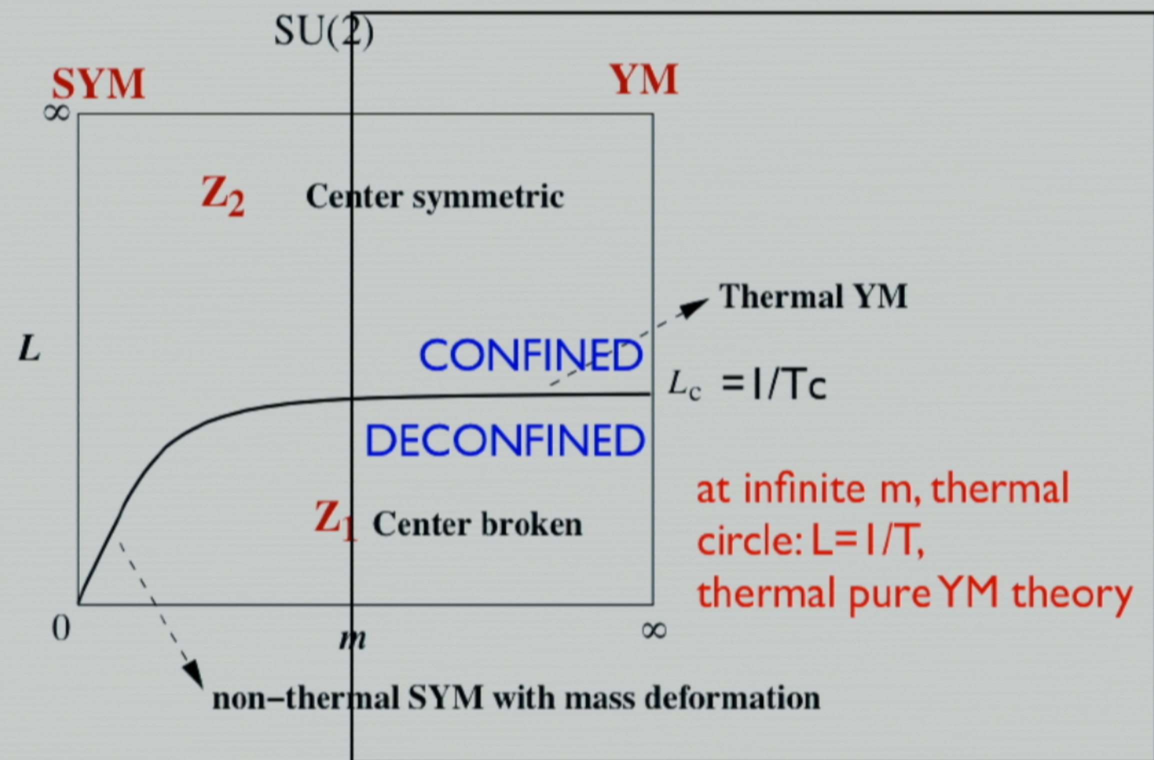
there are only two parameters to vary: L and m

Z_2 center symmetry- S^1_L

the theory is asymptotically free with a strong scale! Λ $\frac{m}{\Lambda}$ ΛL

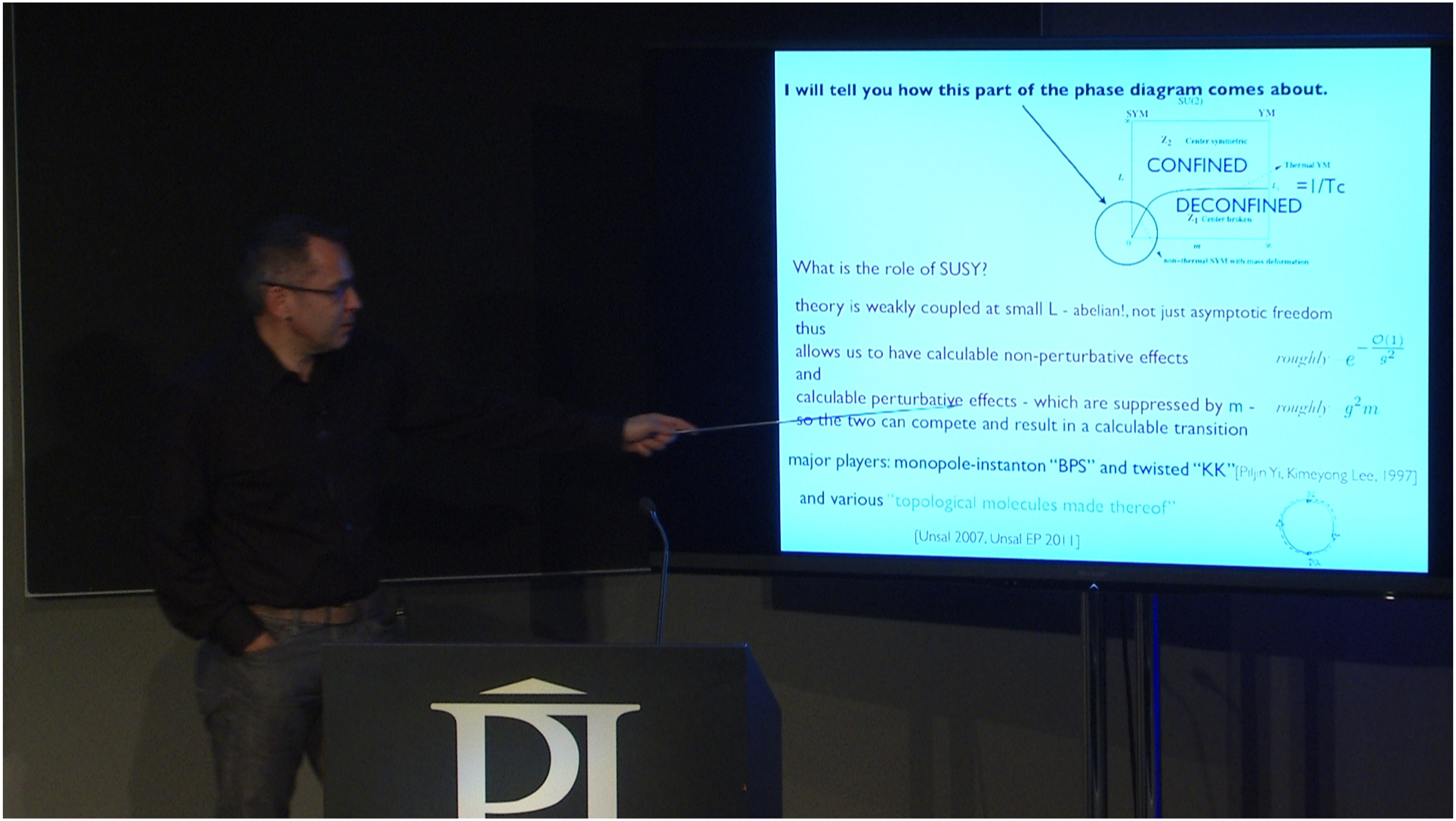
4. $R^3 x S^1$ compactifications of SYM*

(non-) thermal

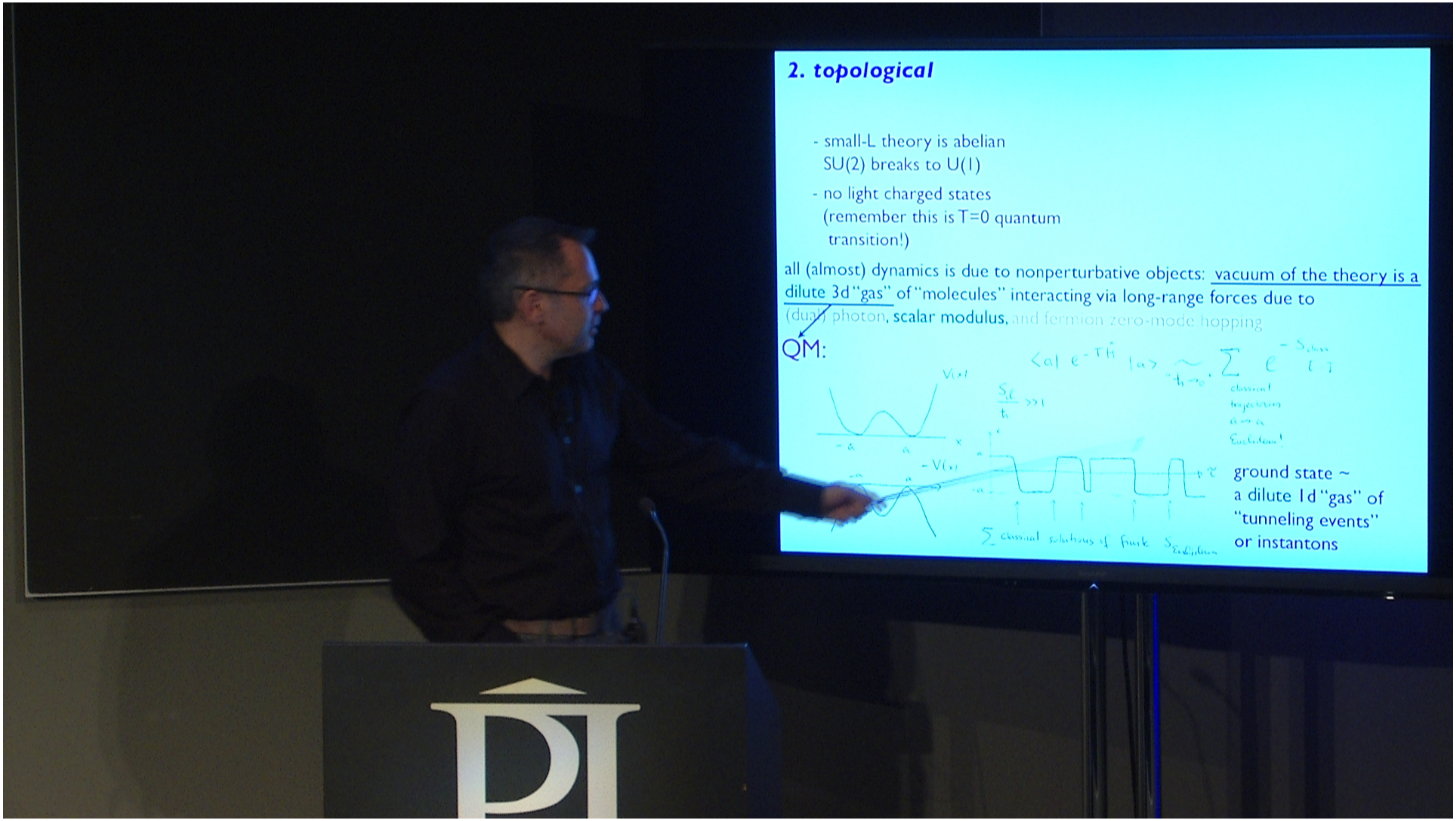


at infinite m, thermal circle: L=1/T, thermal pure YM theory

thermal deconfinement transition, e.g., from lattice experiment


I will tell you how this part of the phase diagram comes about.
CONFINED
DECONFINED
=1/Tc
What is the role of SUSY?
theory is weakly coupled at small L - abelian!, not just asymptotic freedom
thus
allows us to have calculable non-perturbative effects roughly $\sim e^{-\frac{\mathcal{O}(1)}{g^2}}$
and
calculable perturbative effects - which are suppressed by m - roughly $\sim g^2 m$
so the two can compete and result in a calculable transition
major players: monopole-instanton "BPS" and twisted "KK" [Piljin Yi, Kimeyong Lee, 1997]
and various "topological molecules made thereof"
[Unsal 2007, Unsal EP 2011]


2. topological
... how this part of the phase diagram comes about ...
- small-L theory is abelian
SU(2) breaks to U(1)
- no light charged states
(remember this is T=0 quantum
transition!)
SU(2)
SYM
YM
CONFINED
=1/Tc
DECONFINED
relevant bosonic fields: A4 - gauge field in compact direction -
and Ai - 3d gauge field - in the unbroken U(1) of SU(2), equivalent to:
σ - 3d dual to Ai = "dual photon" (potential for magnetic charge)
φ - deviation of A4 from center symmetric value Tr Ω = 0
...ithout taking into account nonpertubative physics, these are FREE...


2. topological
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(remember this is T=0 quantum
transition!)
all (almost) dynamics is due to nonperturbative objects: vacuum of the theory is a
dilute 3d "gas" of "molecules" interacting via long-range forces due to
(dual) photon, scalar modulus, and fermion zero-mode hopping
QM:
ground state ~
a dilute 1d "gas" of
"tunneling events"
or instantons

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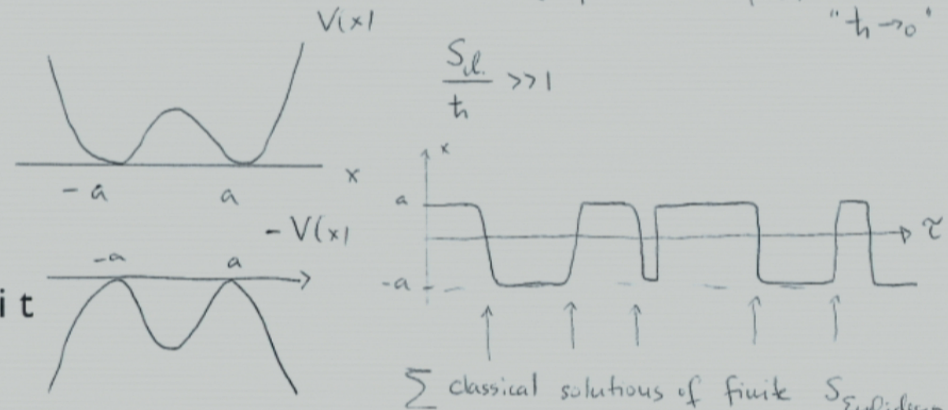
QM:

$$\langle a| e^{-T\hat{H}} |a\rangle \underset{\text{"}\hbar\to 0\text{"}}{\sim} \sum_{\substack{\text{classical}\\ \text{trajectories}\\ a\to a\\ \text{Euclidean!}}} e^{-S_{class}} [\ldots]$$

$t \Rightarrow i\, t$



ground state ~
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"tunneling events"
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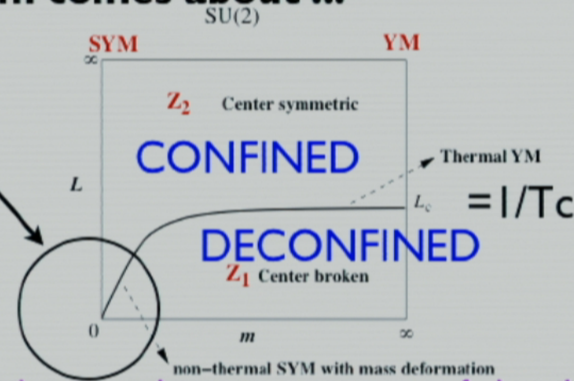
2. *topological*

... how this part of the phase diagram comes about ...



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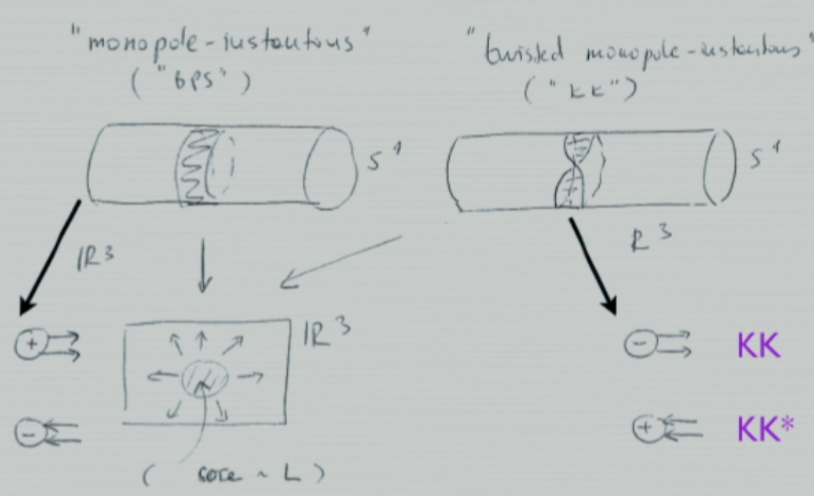
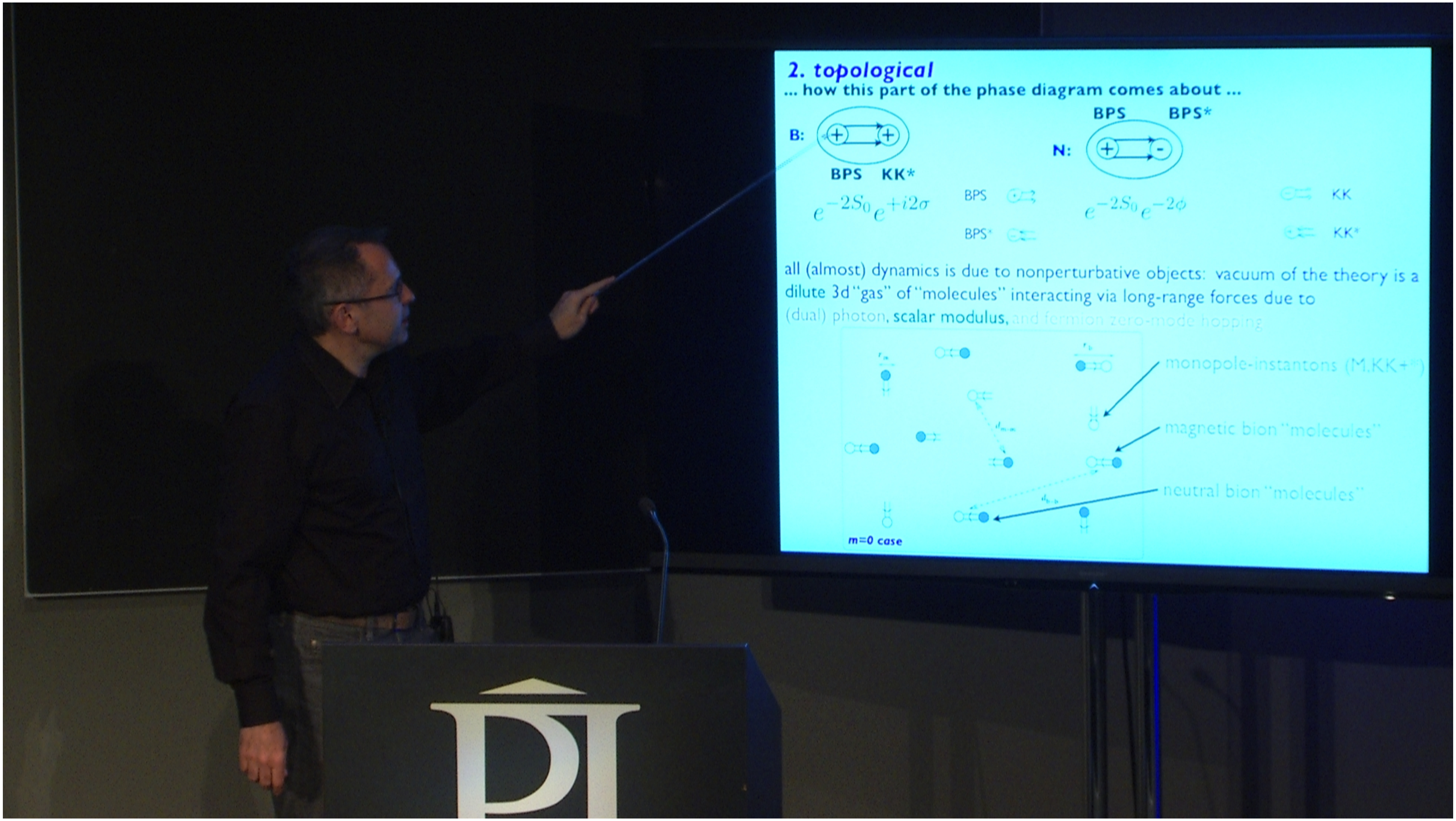
QFT: $\frac{S_{cl.}}{\hbar} \gg 1$

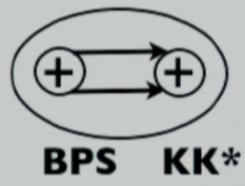
$$\langle 0 | e^{-T\hat{H}} | 0 \rangle \overset{\text{"}\hbar \to 0\text{"}}{\sim} \sim \sum \begin{pmatrix} \text{finite action} \\ \text{saddle points} \\ \text{of path integral} \end{pmatrix}$$



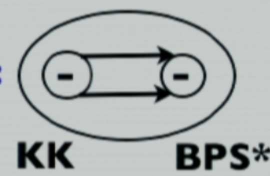

2. topological
... how this part of the phase diagram comes about ...
B:
BPS KK*
$e^{-2S_0}e^{+i2\sigma}$
BPS
BPS*
BPS BPS*
N:
$e^{-2S_0}e^{-2\phi}$
KK
KK*
all (almost) dynamics is due to nonperturbative objects: vacuum of the theory is a dilute 3d "gas" of "molecules" interacting via long-range forces due to (dual) photon, scalar modulus, and fermion zero-mode hopping
monopole-instantons (M,KK+*)
magnetic bion "molecules"
neutral bion "molecules"
m=0 case

(BPS-KK* "molecules") "magnetic bions" - confinement!

B:



B*:



$$e^{-2S_0}e^{+i2\sigma}$$

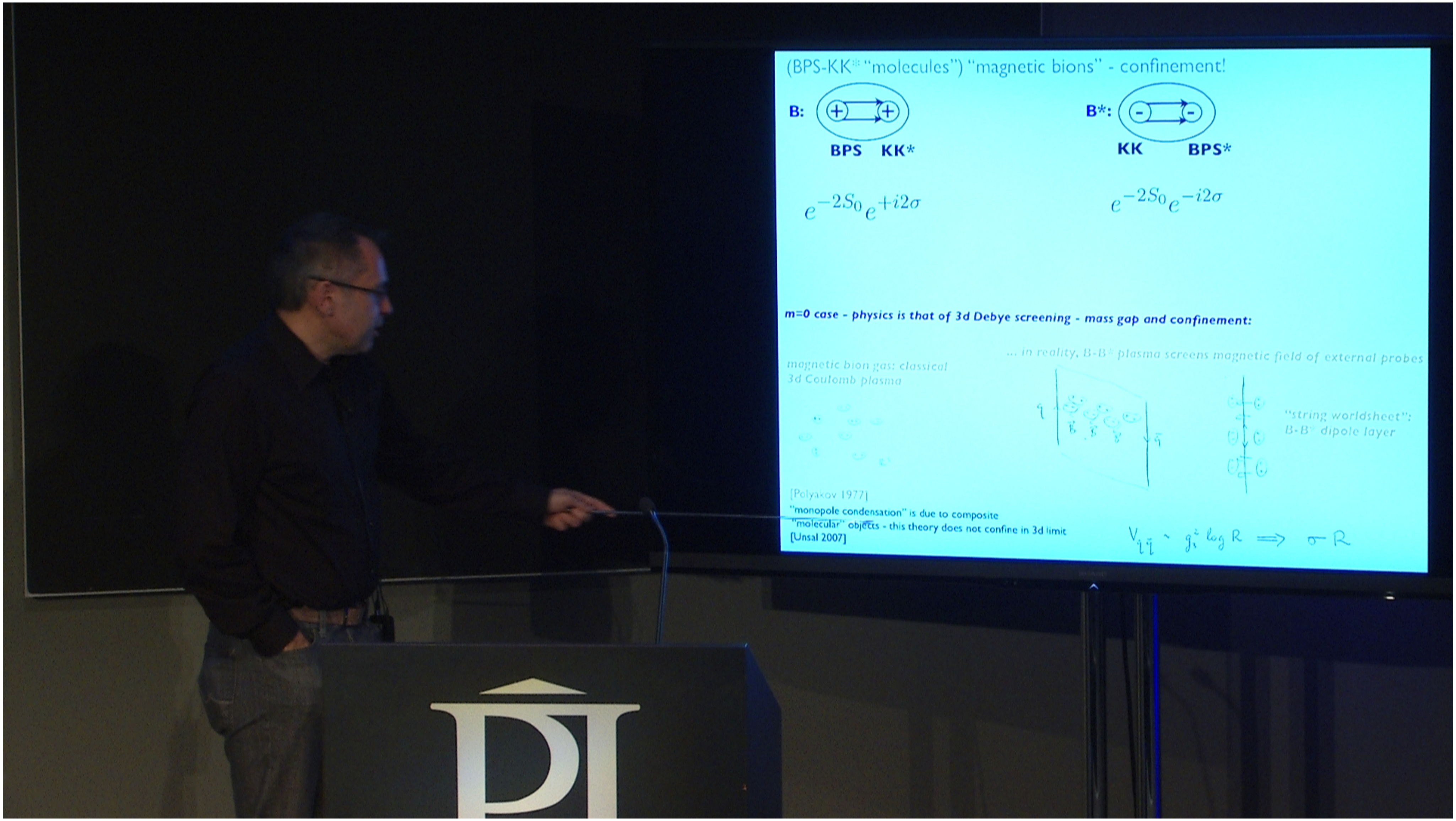
$$e^{-2S_0}e^{-i2\sigma}$$

m=0 case - physics is that of 3d Debye screening - mass gap and confinement:

magnetic bion gas: classical 3d Coulomb plasma

if nonperturbative saddle points are not summed over...

$V_{q\bar{q}} \sim g_3^2 \log R$ ***- 2d Coulomb potential***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B*:
KK BPS*
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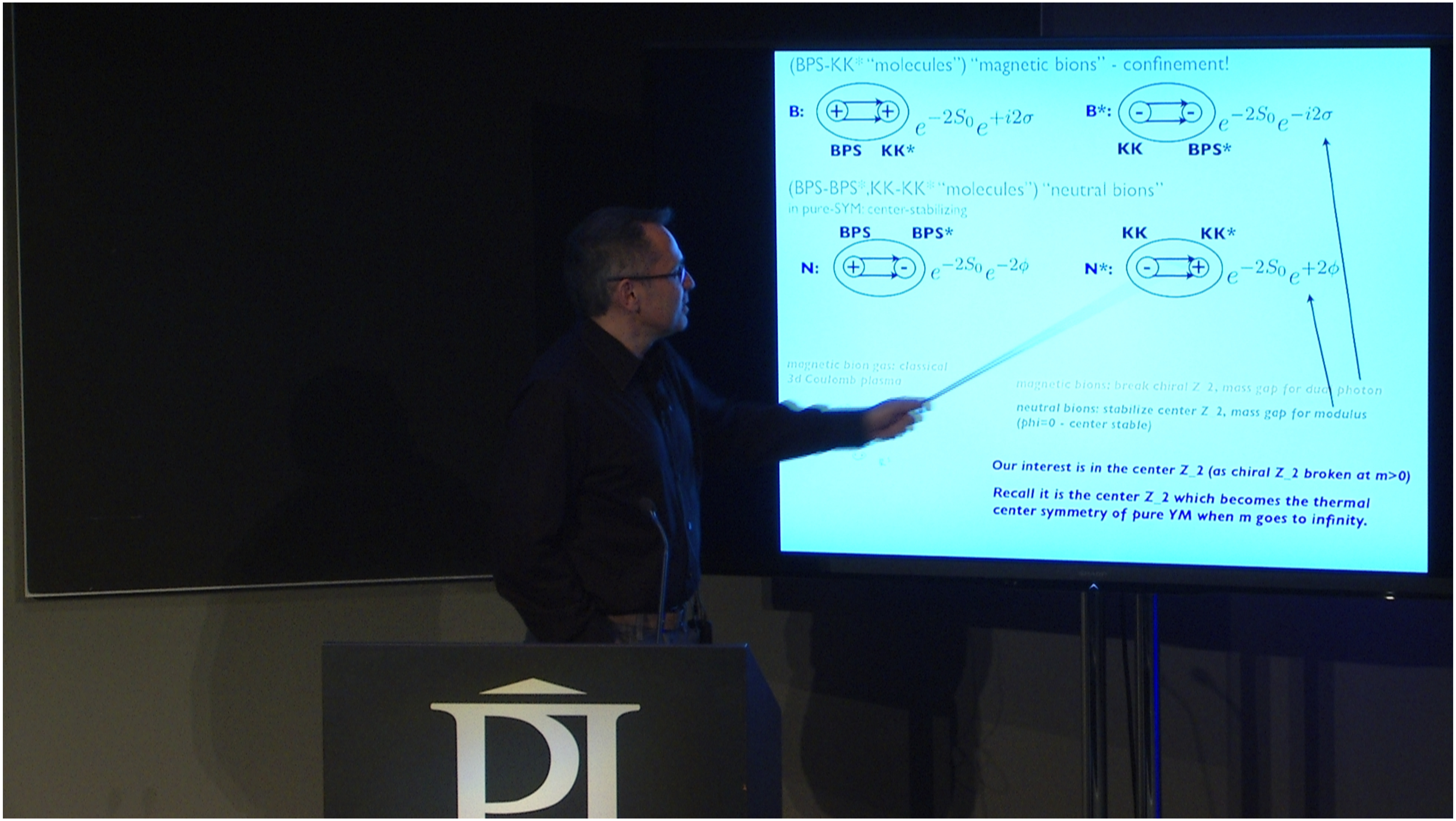
e^{-2S_0} e^{-i2σ}
m=0 case - physics is that of 3d Debye screening - mass gap and confinement:
magnetic bion gas: classical 3d Coulomb plasma
... in reality, B-B* plasma screens magnetic field of external probes
"string worldsheet": B-B* dipole layer
[Polyakov 1977]
"monopole condensation" is due to composite "molecular" objects - this theory does not confine in 3d limit
[Unsal 2007]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BPS KK*
B*:
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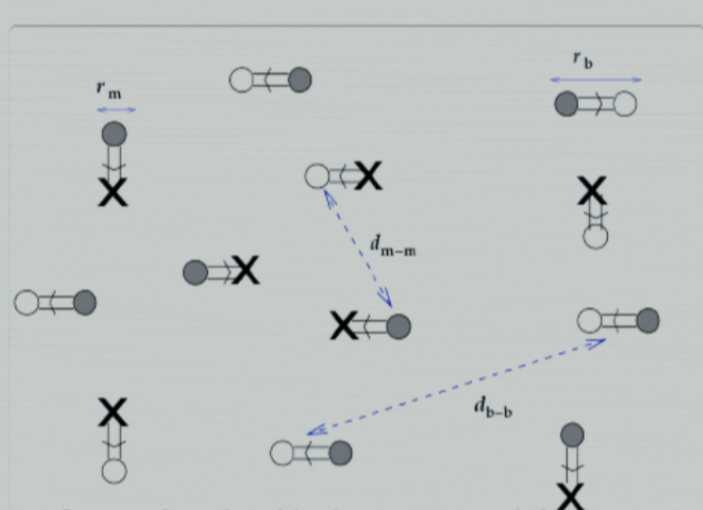
KK BPS*
(BPS-BPS*,KK-KK* "molecules") "neutral bions"
in pure-SYM: center-stabilizing
BPS BPS*
N:
$e^{-2S_0}e^{-2\phi}$
KK KK*
N*:
$e^{-2S_0}e^{+2\phi}$
magnetic bion gas: classical
3d Coulomb plasma
magnetic bions: break chiral Z_2, mass gap for dual photon
neutral bions: stabilize center Z_2, mass gap for modulus
(phi=0 - center stable)
Our interest is in the center Z_2 (as chiral Z_2 broken at m>0)
Recall it is the center Z_2 which becomes the thermal
center symmetry of pure YM when m goes to infinity.

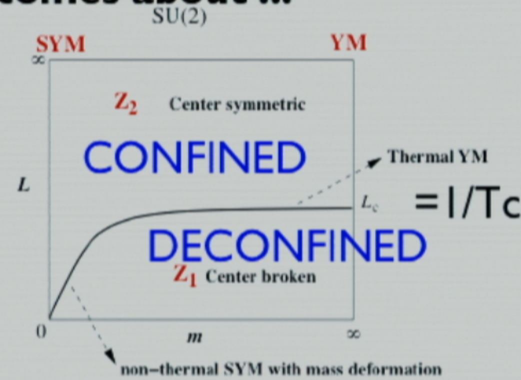
... how this part of the phase diagram comes about ...



m>0 case: breaks chiral symmetry, yields:

1. extra nonperturbative contributions from monopole-instantons (no fermion zero modes)

2. extra perturbative Gross-Pisarski-Yaffe-like contribution (small since m is small)



monopole-instantons (BPS,KK+*)

magnetic bion "molecules"

[breaking of discrete chiral symmetry]

neutral bion "molecules"

[stability of Z2 center symmetry [non-thermal]]

small SUSY breaking "m" allows us to have perturbative and nonperturbative contributions compete while under theoretical control, resulting in a center-breaking transition as $\frac{m}{L^2\Lambda^3}$ becomes O(1) (2nd order for SU(2); 1st for SU(N)...)

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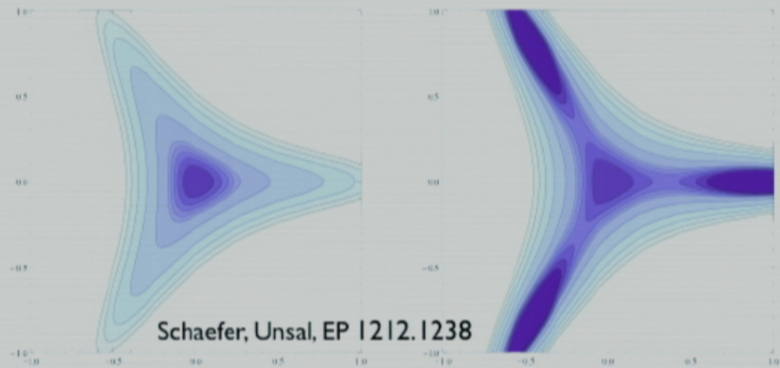
instead of formulae, plot of potential due to "neutral bions" for SU(3):
Z3-symmetric vs Z3-breaking as $\frac{m}{L^2\Lambda^3}$ ***increases*** (deviation of Ω EVs from Z3)

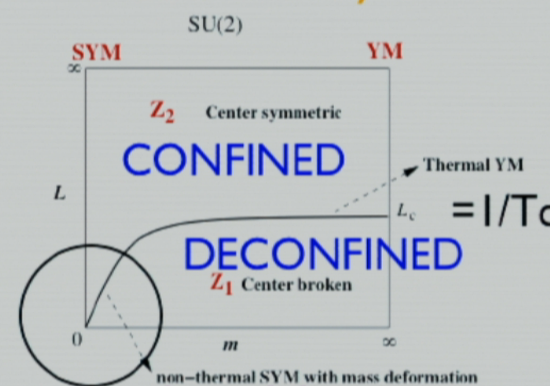


Schaefer, Unsal, EP 1212.1238

Same objects that were identified in SYM also exist in pure thermal YM. What is lost is the theoretical control...

Instanton-liquid type models of the deconfinement transition can be considered, incorporating "molecular" contributions...
[Shuryak, Sulejmanpasic...'13]

- one can build models and/or compare small-L calculations with lattice ... eventually entire m/L



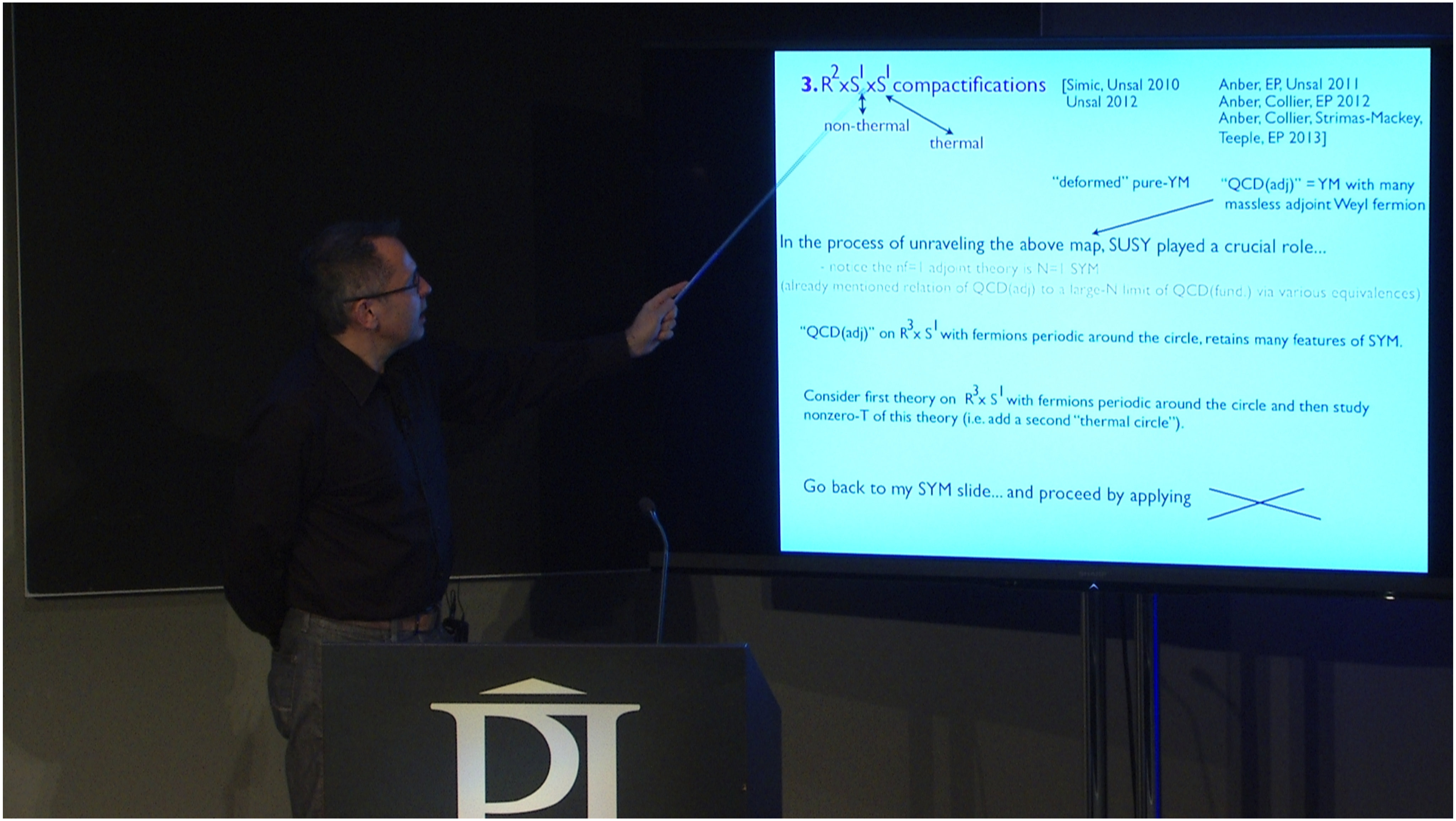
So far I told you about

1. a quantum center-breaking transition continuously connected (? ... gave evidence) to thermal deconfinement

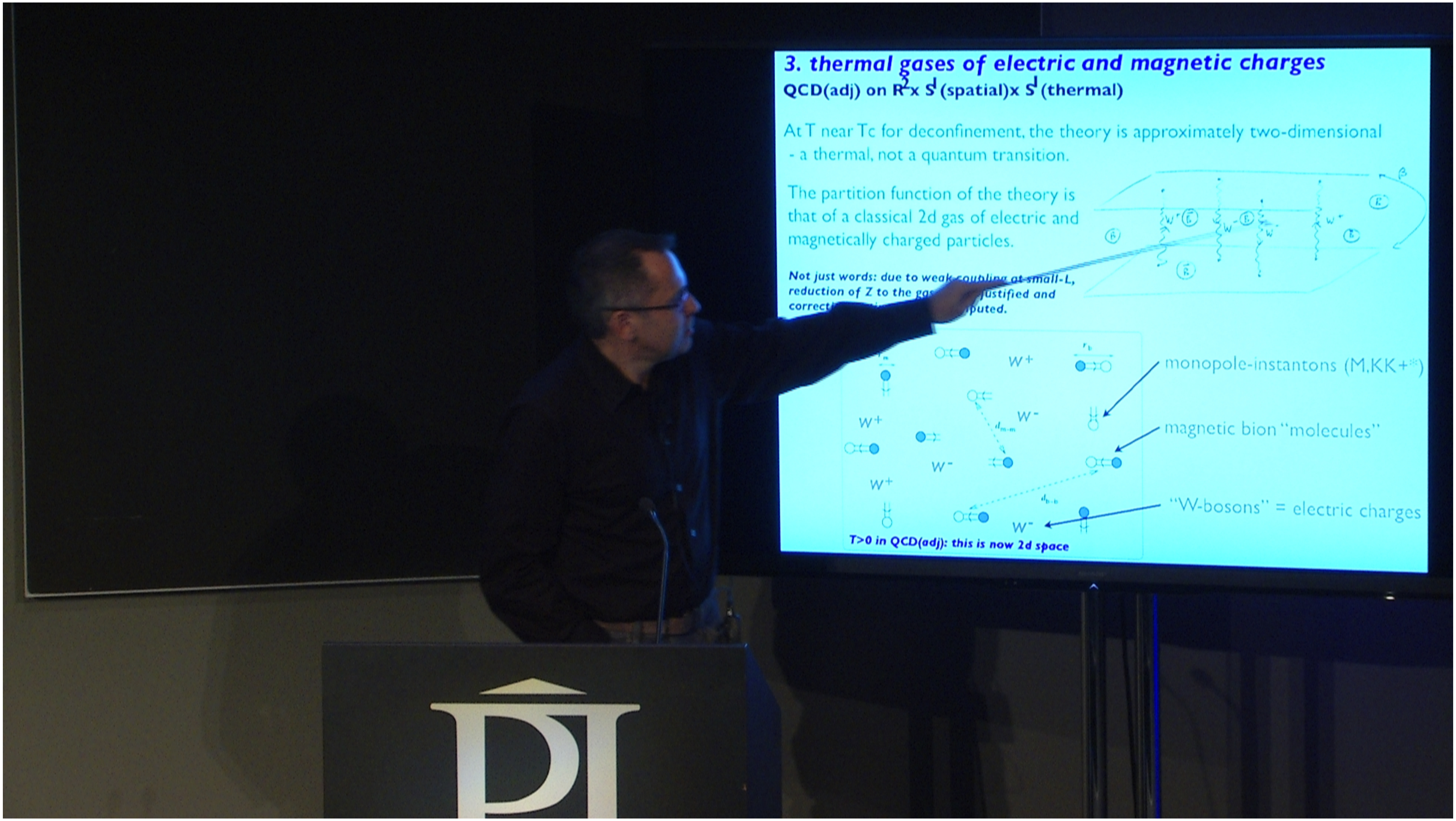
2. driven by topological molecules, incl. some rather strange ones - appear related to renormalons and needed to make sense of the divergent perturbation series... and even define the theory?
[Argyres, Dunne, Unsal ... 2012-]

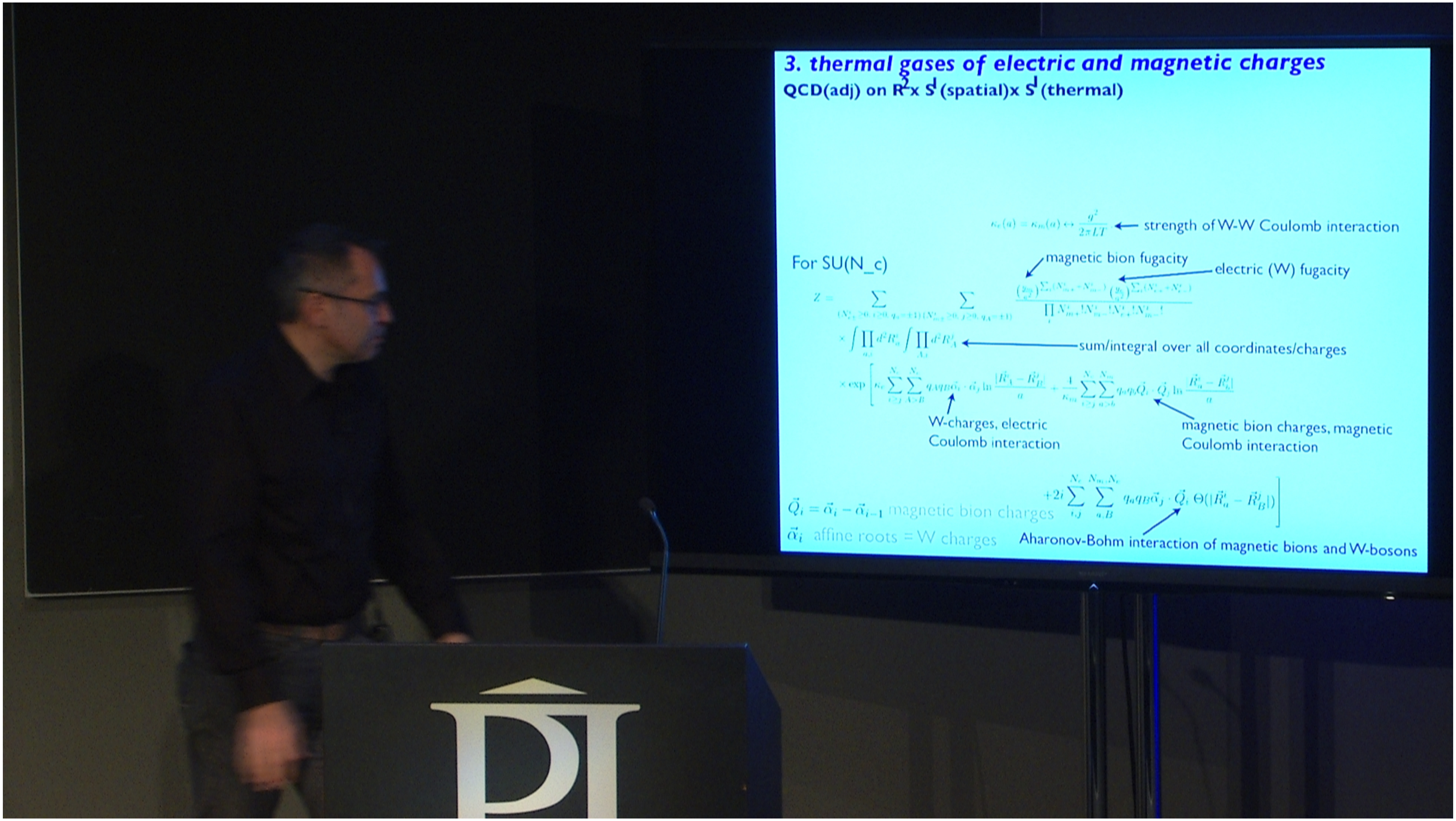
All of this was non-thermal -but quantum connected to thermal (electric charges were not directly present).

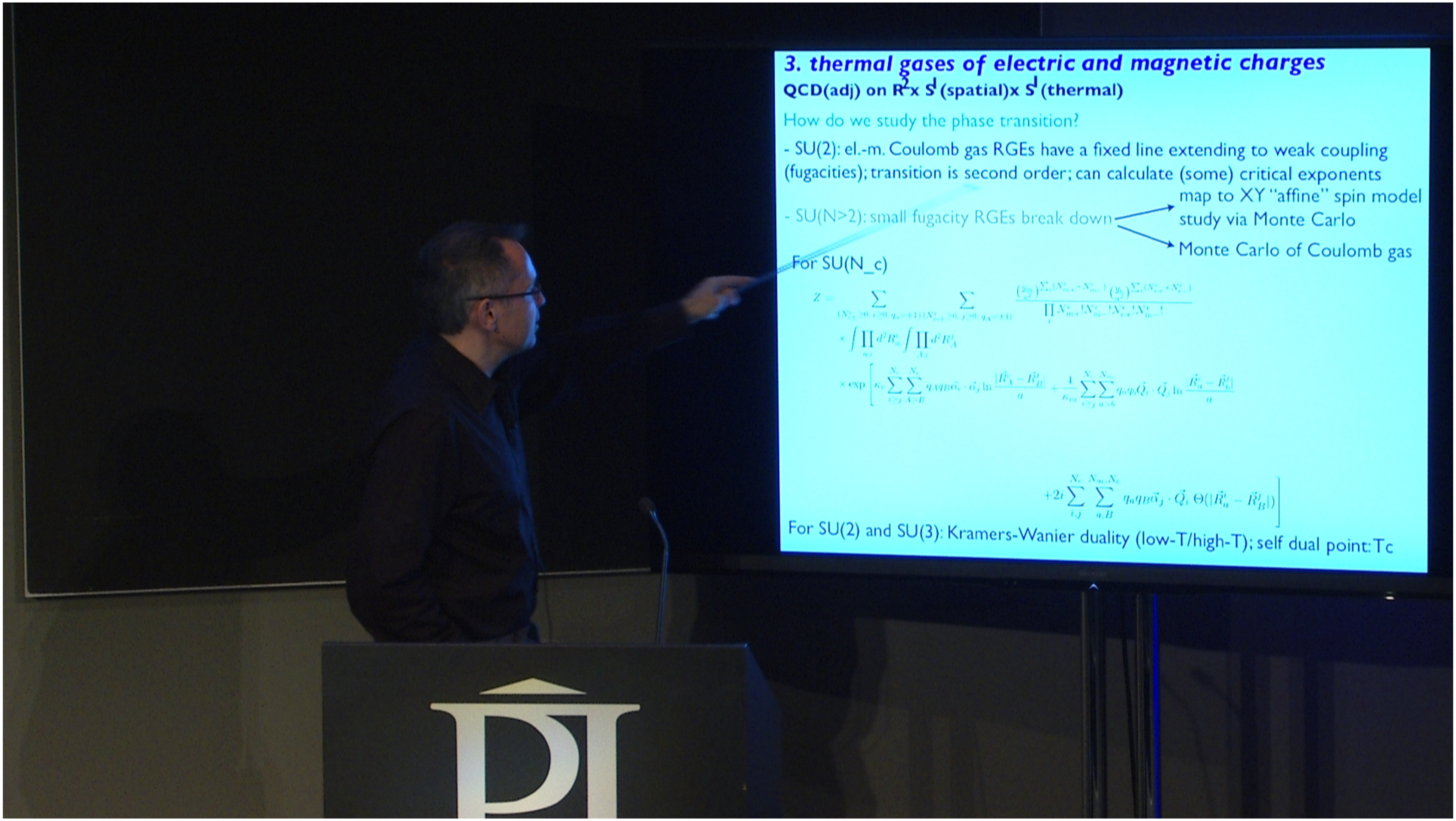
Can one have a controllable thermal deconfinement transition? - YES

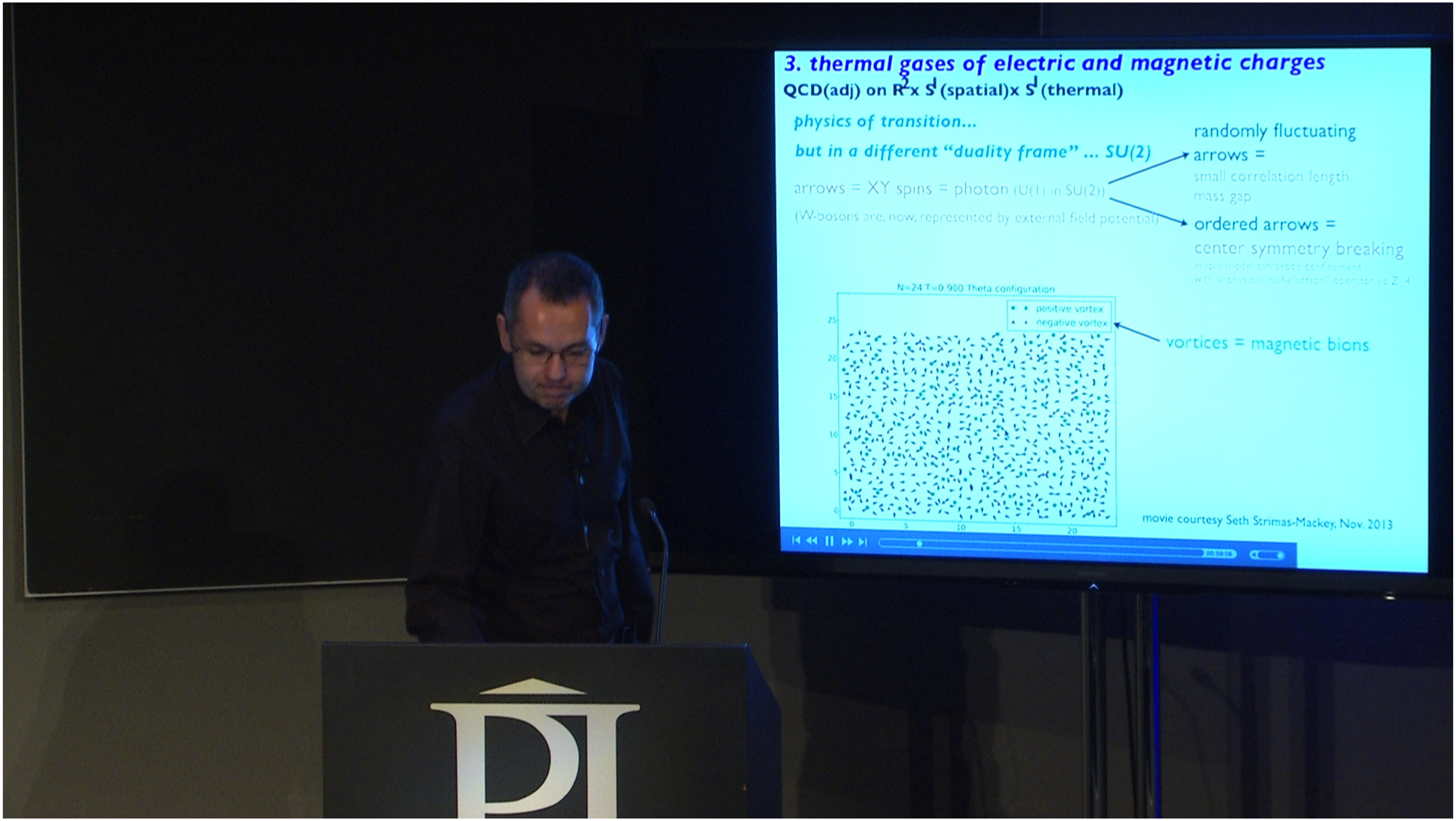

3. R2xS1xS1 compactifications
non-thermal
thermal
[Simic, Unsal 2010
Unsal 2012
Anber, EP, Unsal 2011
Anber, Collier, EP 2012
Anber, Collier, Strimas-Mackey,
Teeple, EP 2013]
"deformed" pure-YM
"QCD(adj)" = YM with many
massless adjoint Weyl fermion
In the process of unraveling the above map, SUSY played a crucial role...
- notice the nf=1 adjoint theory is N=1 SYM
(already mentioned relation of QCD(adj) to a large-N limit of QCD(fund.) via various equivalences)
"QCD(adj)" on R3x S1 with fermions periodic around the circle, retains many features of SYM.
Consider first theory on R3x S1 with fermions periodic around the circle and then study
nonzero-T of this theory (i.e. add a second "thermal circle").
Go back to my SYM slide... and proceed by applying


QCD(adj) on R3x S1 (spatial)
- small-L theory is abelian
SU(2) breaks to U(1)
- no light charged states
(remember this is T=0 quantum
transition!)
(same features as SYM before)
all (almost) dynamics is due to nonperturbative objects: vacuum of the theory is a
dilute 3d "gas" of "molecules" interacting via long-range forces due to
(dual) photon, scalar modulus, and fermion zero-mode hopping
monopole-instantons (M,KK+
magnetic bion "molecules"
neutral bion "molecules"
more precisely:
no role in thermal center; spatial-circle
center stabilized perturbatively
T=0 in QCD(adj)


3. thermal gases of electric and magnetic charges
QCD(adj) on R2 x S1 (spatial)x S1 (thermal)
At T near Tc for deconfinement, the theory is approximately two-dimensional
- a thermal, not a quantum transition.
The partition function of the theory is
that of a classical 2d gas of electric and
magnetically charged particles.
monopole-instantons (M,KK+*)
magnetic bion "molecules"
"W-bosons" = electric charges
T>0 in QCD(adj): this is now 2d space


3. thermal gases of electric and magnetic charges
QCD(adj) on R^2 x S^1 (spatial)x S^1 (thermal)
strength of W-W Coulomb interaction
For SU(N_c)
magnetic bion fugacity
electric (W) fugacity
sum/integral over all coordinates/charges
W-charges, electric Coulomb interaction
magnetic bion charges, magnetic Coulomb interaction
magnetic bion charges
affine roots = W charges
Aharonov-Bohm interaction of magnetic bions and W-bosons


3. thermal gases of electric and magnetic charges
QCD(adj) on R2 x S1 (spatial)x S1 (thermal)
How do we study the phase transition?
- SU(2): el.-m. Coulomb gas RGEs have a fixed line extending to weak coupling (fugacities); transition is second order; can calculate (some) critical exponents
- SU(N>2): small fugacity RGEs break down
map to XY "affine" spin model study via Monte Carlo
Monte Carlo of Coulomb gas
For SU(N_c)
For SU(2) and SU(3): Kramers-Wanier duality (low-T/high-T); self dual point: Tc


3. thermal gases of electric and magnetic charges
QCD(adj) on R2 x S1 (spatial)x S1 (thermal)
physics of transition...
but in a different "duality frame" ... SU(2)
arrows = XY spins = photon (U(1) in SU(2))
(W-bosons are, now, represented by external field potential)
randomly fluctuating arrows =
small correlation length, mass gap
ordered arrows =
center symmetry breaking
N=24 T=0.900 Theta configuration
positive vortex
negative vortex
vortices = magnetic bions
movie courtesy Seth Strimas-Mackey, Nov. 2013

BRIEF SUMMARY AND A FEW MORE QUESTIONS:

I told you about how SUSY can - directly or otherwise - help in finding calculable realizations of deconfinement - generally, a complicated strongly-coupled (non-BPS, non-protected, non-holomorphic) problem.

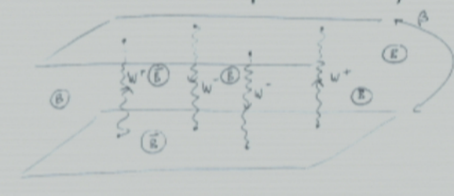
SYM with gaugino mass on $R^3 x S^1$

where a quantum phase transition appears continuously related to thermal deconfinement

QCD(adj) on $R^2 x S^1 x S^1$

where deconfinement maps to the transition in a "simple" electric magnetic "Coulomb gas"

(potential use in nonequilibrium?)

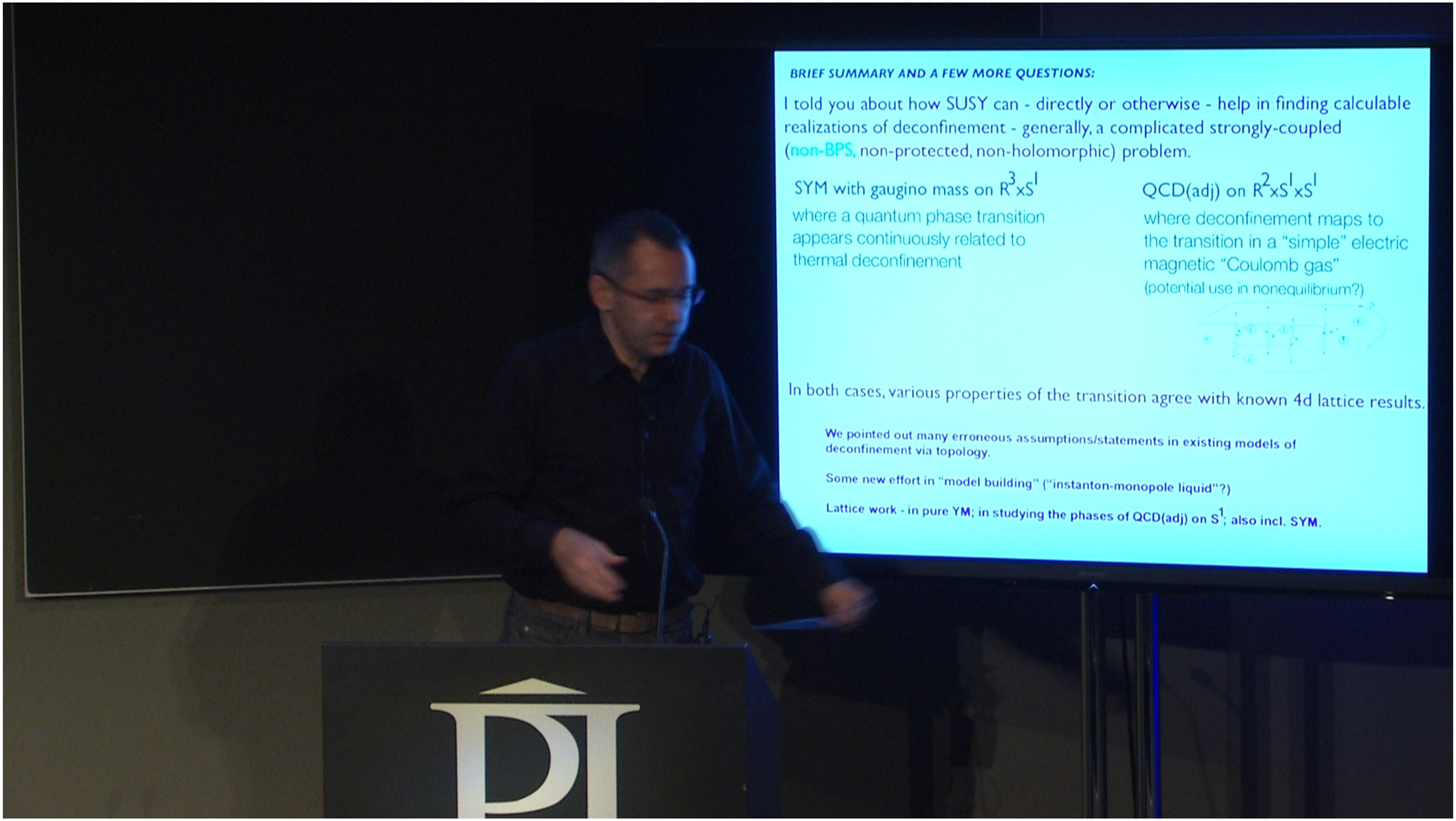


In both cases, various properties of the transition agree with known 4d lattice results.

We pointed out many erroneous assumptions/statements in existing models of deconfinement via topology.

Some new effort in "model building" ("instanton-monopole liquid"?)

Lattice work - in pure YM; in studying the phases of QCD(adj) on S^1; also incl. SYM.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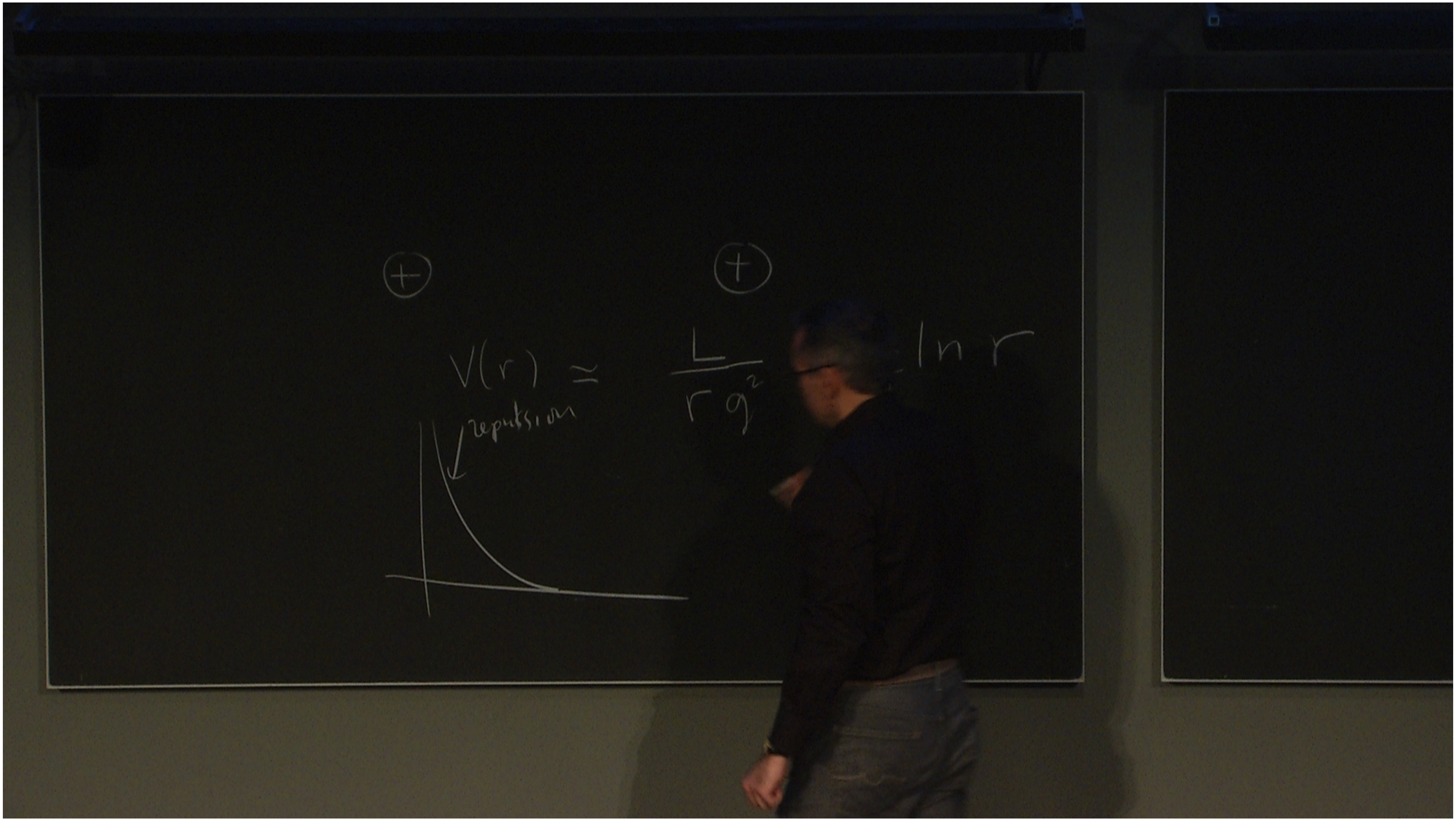
V(r) ≃ L/(rg²) ln r
repulsion