Karlsruher Institut für Technologie

# SU(2) Yang-Mills thermodynamics: Calorons and the deconfining thermal ground state

*60 years of Yang-Mills Gauge Field Theories*
*27 May 2015,  Nanyang Technological University, Singapore*


**R. Hofmann**

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$$S_\beta = \mathrm{tr}\,\frac{1}{2}\int_0^\beta d\tau \int d^3x\, F_{\mu\nu}F_{\mu\nu}$$

# motivation

- Andrei Linde (1980):
  *„Infrared Problem in the Thermodynamics of the Yang-Mills Gas“*

  - soft magnetic sector screened weakly in perturbation theory (infrared instability)

  - no „convergence“ of series since kinetic and interaction energies comparable in this sector

- issue of finite-volume constraints in lattice gauge theory

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# nonperturbative Yang-Mills thermodynamics: SU(2)

[Herbst & RH (2004), RH (2005-2007), Giacosa & RH (2006), Schwarz, Giacosa & RH (2007), Ludescher & RH (2008), Falquez, Baumbach & RH (2010- 2011), RH (2012), Krasowski & RH (2013), Grandou & RH (2015)]

**thermal ground state at high temperature:**

- **Euclidean action:**

$$\boxed{S=\frac{\mathrm{tr}}{2}\int_0^\beta d\tau\int d^3x\,F_{\mu\nu}F_{\mu\nu}\,,}\qquad (\,\beta\equiv 1/T\,)$$

where $F_{\mu\nu}\equiv\partial_\mu A_\nu-\partial_\nu A_\mu-ig[A_\mu,A_\nu]$ [Schafer et Shuryak (1996)]

- **(anti)selfdual gauge fields: [(anti)calorons]**

$$\boxed{F_{\mu\nu}[A]=\pm\tilde{F}_{\mu\nu}[A]\;\Rightarrow\;\theta_{\mu\nu}[A]\equiv 0\,.}$$

( $A_\mu$ periodic )

field configs. stabilized by gauge-field winding: $\partial\mathbf{R}^4=S_3\to SU(2)=S_3$

- **in particular:** (anti)calorons of winding number **unity**

## Calorons of top. charge unity (selfdual field configs. on $S_1 \times \mathbf{R}_3$ ):

(singular gauge)
['t Hooft, Rebbi & Jackiw (1977)]

**Harrington-Shepard (1977):**
**(trivial holonomy)**

$$\boxed{A_\mu = \bar{\eta}^a_{\mu\nu} t_a \partial_\nu \log \Pi(\tau, r)}$$

with $\Pi = \begin{cases} \left(1 + \frac{1}{3}\frac{s}{\beta}\right) + \frac{\rho^2}{x^2} & (|x| \ll \beta) \\ 1 + \frac{s}{r} & (r \gg \beta) \end{cases}$

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$\Rightarrow$ $F_{\mu\nu}$ that of singular-gauge instanton with $\rho'^2 = \frac{\rho^2}{1 + \frac{1}{3}\frac{s}{\beta}} \quad (|x| \ll \beta)\,.$

(action: $S_c = \frac{8\pi^2}{g^2}\int_{S_3^\delta} d\Sigma_\mu\, K_\mu = \frac{8\pi^2}{g^2}$ localised about instanton center in $S_1 \times \mathbf{R}_3$ )

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$\Rightarrow$

$$E^a_i=B^a_i=s\,\frac{\delta^a_i-3\,\hat{x}^a\hat{x}^i}{r^3}\qquad(r\gg s)\,.$$

(static selfdual dipole-field with dipole moment: $p^a_i=s\,\delta^a_i$)

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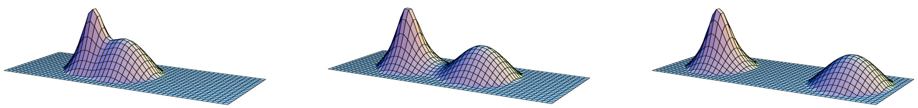
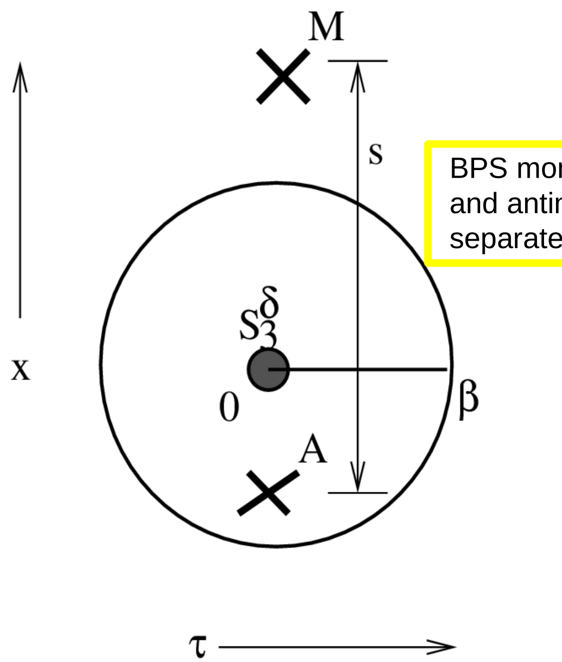


(action density on spatial slice)

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and antimonopole (A),
separated by distance $s$

(M-A separation, caloron center)

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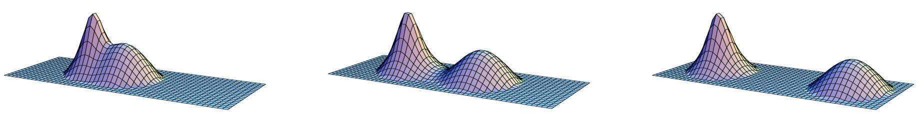

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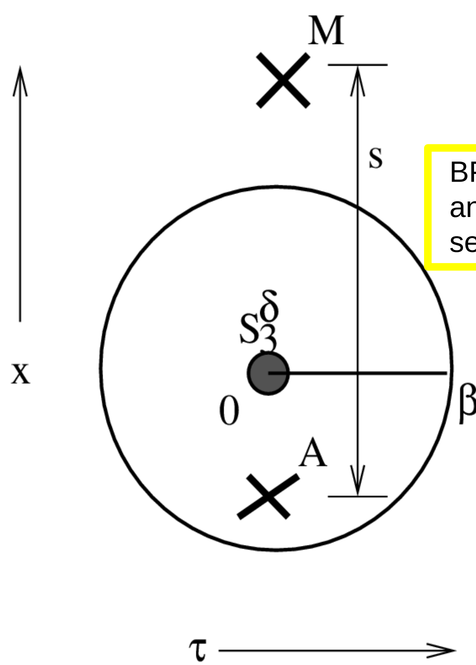


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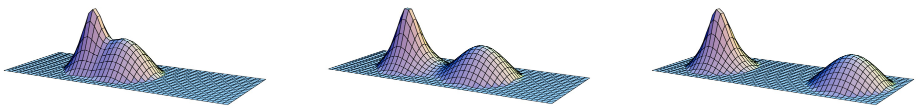

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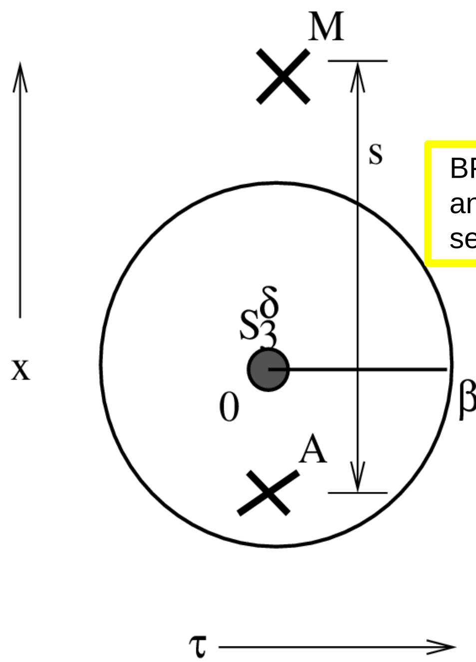


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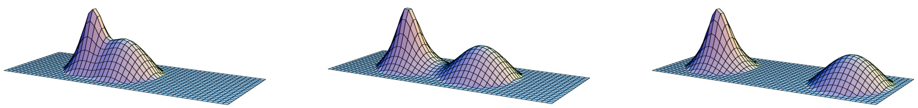

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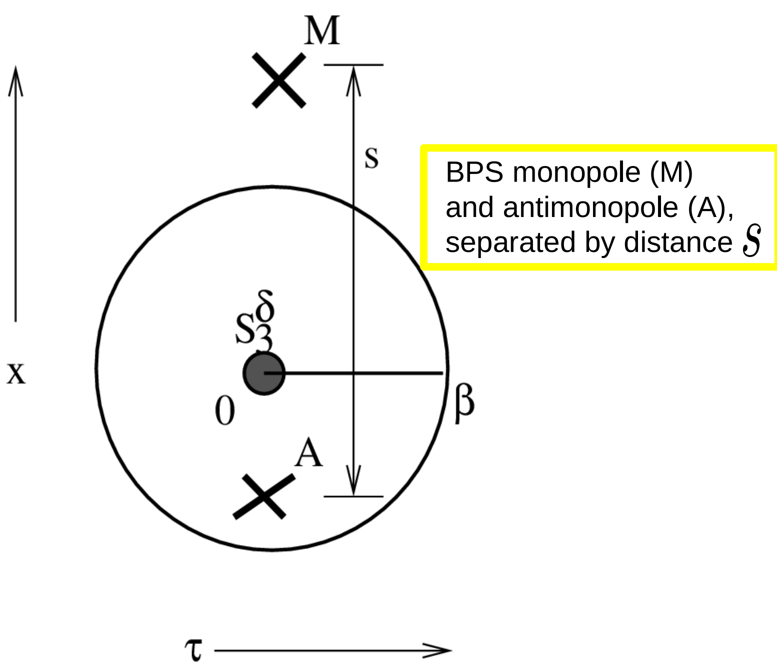


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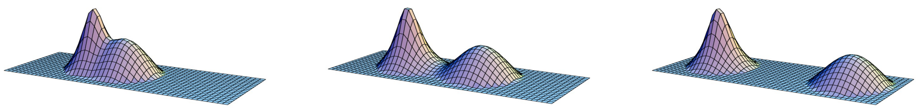

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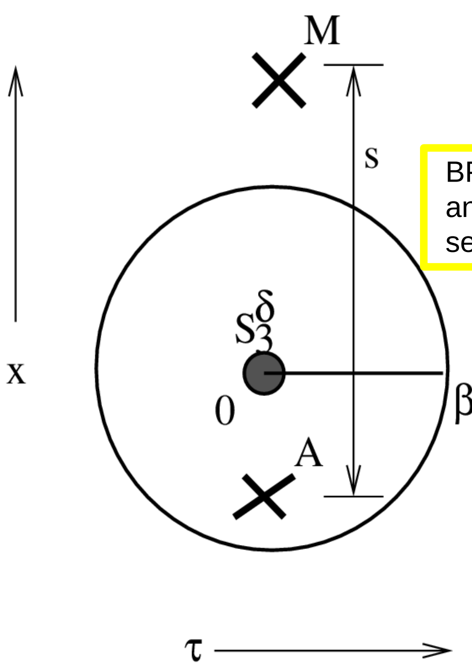


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- locus of action within $S_3^\delta \;(\delta \to 0)$

- trivial-holonomy limit:
  M massless, A still massive, stable

**spatial coarse-graining over pair of trivial-hol. (anti-)calorons:**
**inert, adjoint scalar field $\phi$**

[Herbst & RH (2004)]

$$\{\hat{\phi}^a\} \equiv \sum_{\pm} \mathrm{tr} \int d^3x \int d\rho\, t^a\, F_{\mu\nu}(\tau,\vec{0}) \left\{(\tau,\vec{0}),(\tau,\vec{x})\right\} F_{\mu\nu}(\tau,\vec{x}) \left\{(\tau,\vec{x}),(\tau,\vec{0})\right\}$$

- unique, dimensionless definition of **family of phases**, where

$$\left\{(\tau,\vec{0}),(\tau,\vec{x})\right\} \equiv \mathcal{P}\exp\left[i\int_{(\tau,\vec{0})}^{(\tau,\vec{x})} dz_\mu\, A_\mu(z)\right]$$ and

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- $\{\hat{\phi}^a\}$ sharply dominated by cut-off for $\rho$ integration

## spatial coarse-graining over (anti-)calorons: inert, adjoint scalar field $\phi$

- no explicit $\beta$ dependence in $\phi$ field dynamics (caloron action!)

- absorb $\beta$ dependence of operator $D$ into potential $V$

(BPS and EL yield: $$\frac{\partial V(|\phi|^2)}{\partial|\phi|^2} = -\frac{V(|\phi|^2)}{|\phi|^2} \Rightarrow$$

$$\boxed{V(|\phi|^2) = \frac{\Lambda^6}{|\phi|^2}}$$

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- BPS equation:

$$\partial_\tau\phi = \pm 2i\,\Lambda^3\,t_3\,\phi^{-1} = \pm i\,V^{1/2}(\phi)$$

$\Rightarrow$ **no additive ambiguity in $V$ !** (no **additive** ambiguity in $V$ !)

## effective action (deconfining phase), thermal ground state

- $$\mathcal{L}_{\rm eff}[a_\mu] = \mathrm{tr}\left(\frac{1}{2}\,G_{\mu\nu}G_{\mu\nu} + (D_\mu\phi)^2 + \frac{\Lambda^6}{\phi^2}\right)$$

(i) perturbative renormalizability ( $G^2$ highest power in effect. action)

(iiI) $\phi$'s inertness – no higher dim., mixed operators to mediate
4-momentum transfer between $\phi$ and $a_\mu$
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- effective YM equation $D_\mu G_{\mu\nu} = ie[\phi, D_\nu\phi]$ has ground-state solution:

$$\boxed{a_\mu^{\rm gs} = \mp\delta_{\mu 4}\frac{2\pi}{e\beta}\,t_3 \qquad (D_\nu\phi \equiv G_{\mu\nu} \equiv 0)}$$

$$\Longrightarrow \quad \boxed{P_{gs} = -\rho_{gs} = -4\pi\Lambda^3 T\,.}$$

interacting small and transient-holonomy (anti)calorons, (collapsing monopole-antimonopole pairs)

**(vanishing entropy density of ground state!)**

## adjoint Higgs mechanism (deconfining phase)

( SU(2) → U(1) )

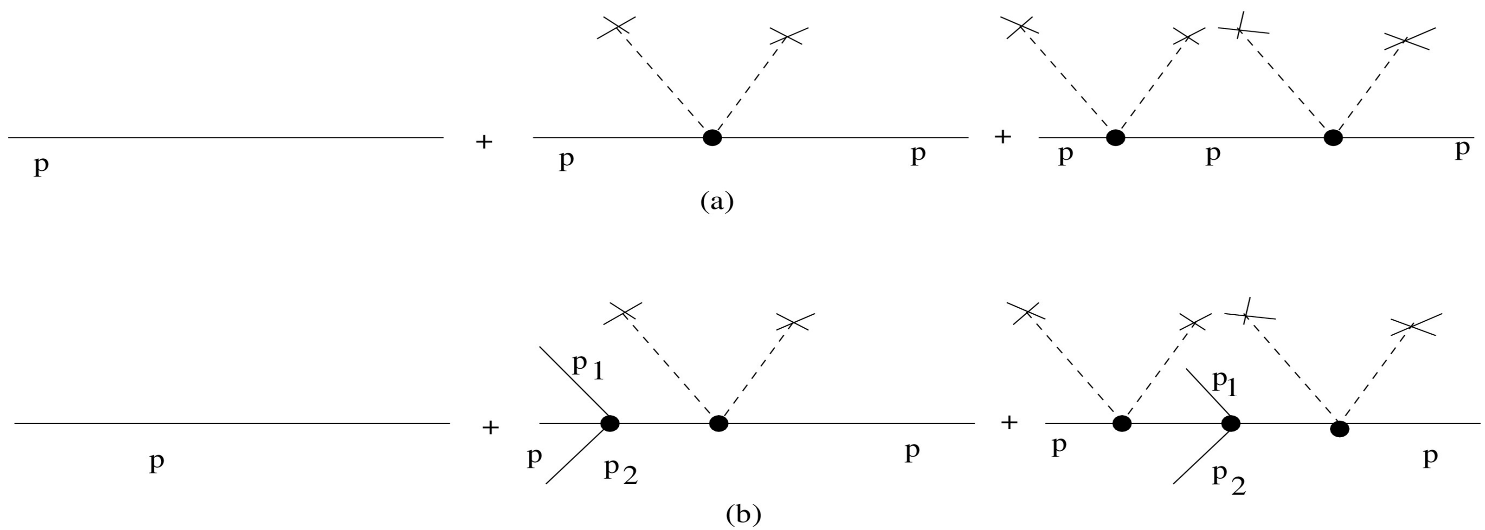
- from effective action:

$$m_a^2 = -2e^2 \mathrm{tr}\,[\phi, t_a][\phi, t_a]$$

unitary gauge

$$m_1^2 = m_2^2 = 4e^2 \frac{\Lambda^3}{2\pi T}\,, \quad m_3 = 0$$

- no momentum transfer to $\phi$, **but this infinitely often** (Dyson series for mass generation):

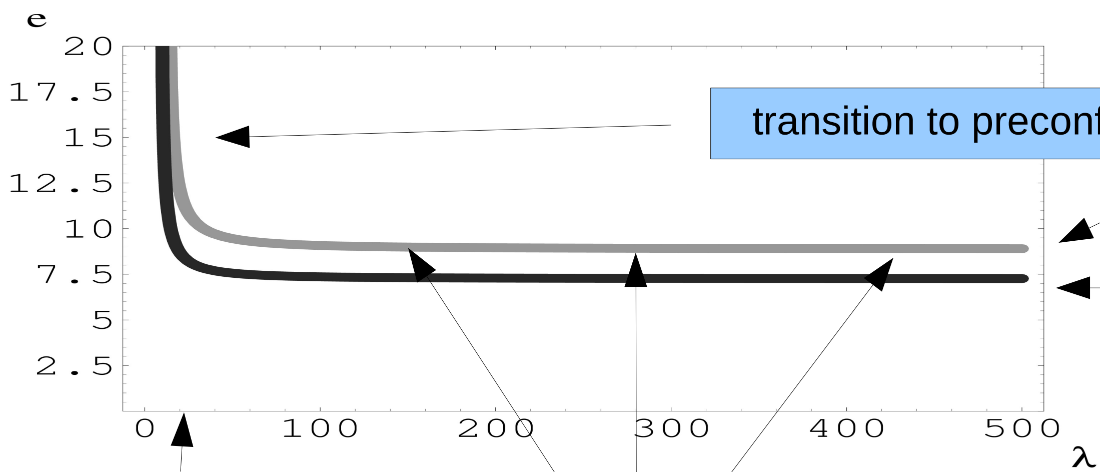



- no off-shell propagation of massive modes (otherwise: momentum transfer to $\phi$ !)

# effective gauge coupling

$e$

thermodynamical consistency




transition to preconfining phase

SU(2)

SU(3)

**small-mass expansion, pressure**
**[Dolan et Jackiw (1974)]**

$$\lambda_c = \frac{2\pi T_c}{\Lambda} = 13.87$$

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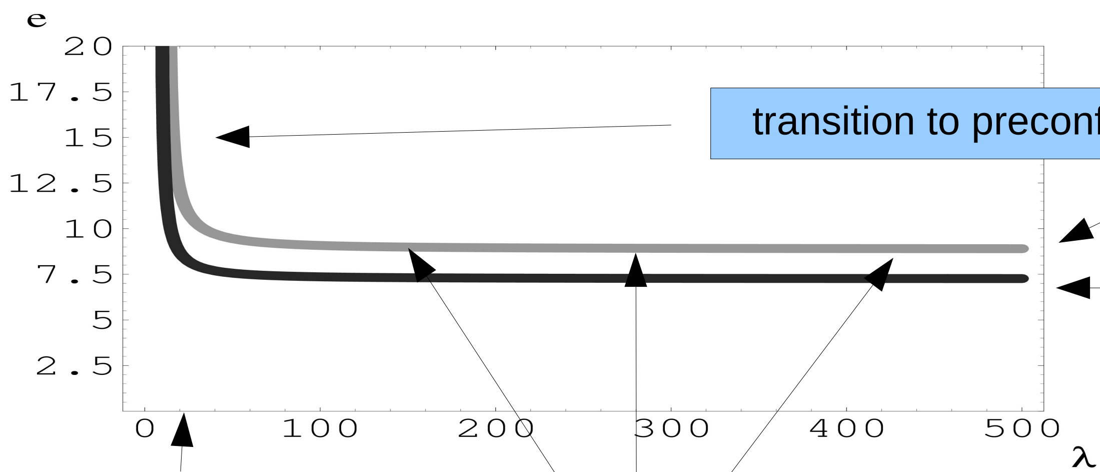


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coarse-graining dominated by $\rho \sim |\phi|^{-1}$

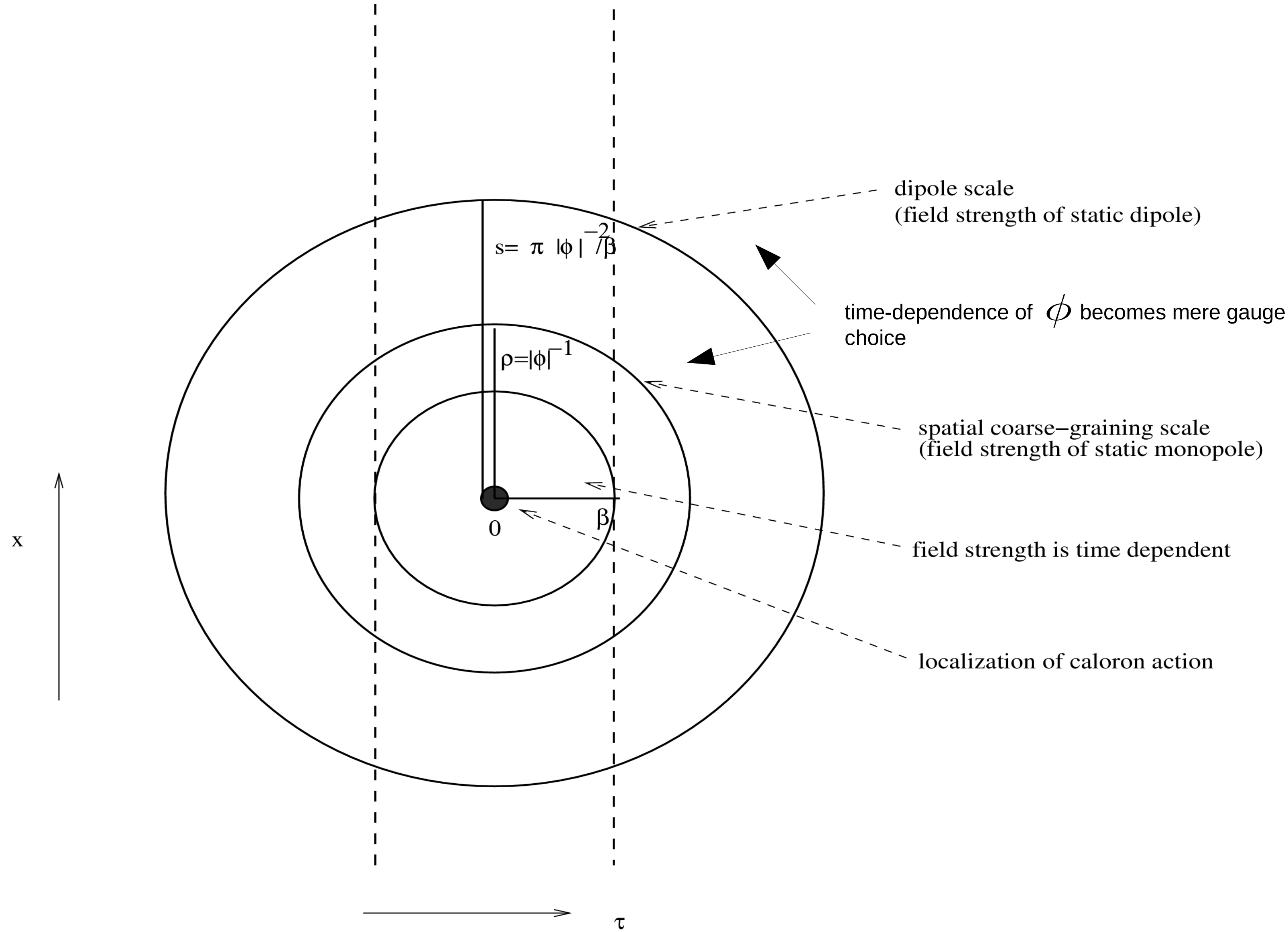
- restore $\hbar$

$$e = \frac{\sqrt{8}\pi}{\sqrt{\hbar}}\,.$$

$$S_{C/A} = \hbar\,.$$

[Brodsky et al. (2011); Kaviani & RH (2012), RH (2012,2013)]

# anatomy of caloron, inferred after spatial coarse-graining:



## summary: induced, effective thermal QFT

## convergence of loop expansions

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**small-holonomy** (anti)calorons of action $\hbar$ **constitute** effective **thermal ground state** and **mediate interactions** (vertices) between effectively propagating modes

[Kaviani & RH (2012), Krasowski & RH (2013)]

## summary: induced, effective thermal QFT; convergence of loop expansions

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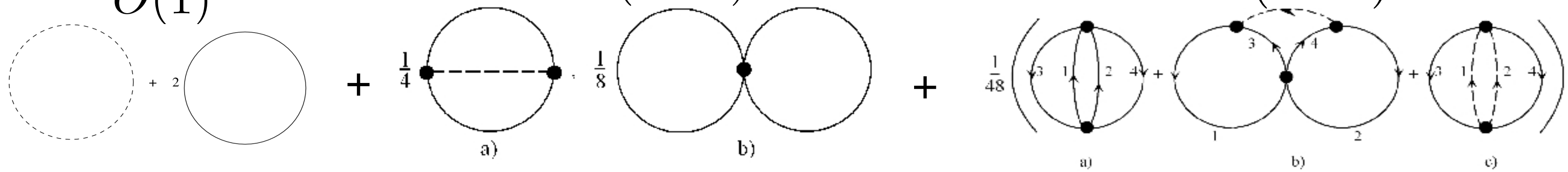
**kinematic constraints in (totally fixed) unitary-Coulomb gauge imply that radiative corrections** are extremely **well controlled**
[Schwarz, Giacosa, & RH (2006), Ludescher & RH (2008)]

**expansion** of thermodyn. quantities into **1PI loops** probably **terminates** at finite order, say, pressure
[RH (2006)]

$O(1)$ $\quad$ $O(10^{-2})$ $\quad$ $O(10^{-7})$



## real-world implications

**electric-magnetically dual interpretation of U(1) charge:**

if SU(2) something to do with photons [RH (2005), Grandou & RH (2015), etc]
then **electric-magnetically dual** interpretation required:
in units $c = \epsilon_0 = \mu_0 = k_B = 1$ fine-structure constant

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for $\alpha$ to be unitless:

$$\left( e = \frac{\sqrt{8\pi}}{\sqrt{\hbar}}\,. \right) \qquad \boxed{Q \propto \frac{1}{e}\,.}$$

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$$\boxed{Q \propto \frac{1}{e}\,.}$$

**But:** magnetic coupling in SU(2)

$$\boxed{g = \frac{4\pi}{e}\,.}$$

$\Rightarrow$ SU(2) to be interpreted in an **electric-magnetically dual way**.
(e.g., magnetic monopole $\longleftrightarrow$ electric monopole, etc.)

**electric/magnetic dipole density (permittivity/permeability of vacuum):**

**[temperature a fictitious quantity]**

$$\boxed{|\mathbf{D}_e| = \frac{2s}{V_{\rm cg}} \propto T^{1/2}}$$

external electric field strength (plane wave):

$$\boxed{\rho_{\rm gs} = 4\pi T\Lambda^3 = \rho_{\rm EM} = \epsilon_0 \mathbf{E}_e^2 \Rightarrow |\mathbf{E}_e| \propto T^{1/2}}$$

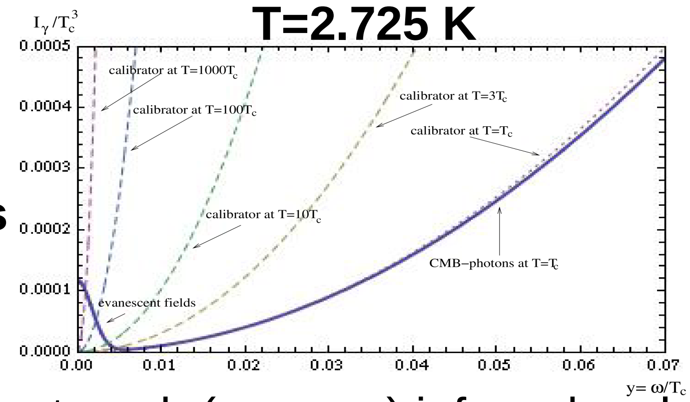
$$\Longrightarrow \qquad \boxed{\epsilon_0 \equiv \frac{|\mathbf{D}_e|}{|\mathbf{E}_e|} \neq f(T)}$$

similarily for magnetic permeability $\mu_0$ .

[Grandou & RH (2015)]

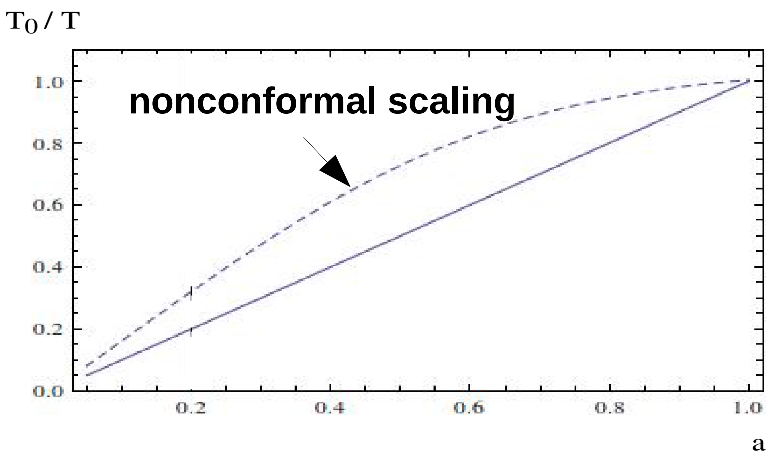
## evidences for $SU(2)_{\mathrm{CMB}}$ ($\Lambda_{\mathrm{CMB}} \sim 10^{-4}\,\mathrm{eV}$): photon at tree level

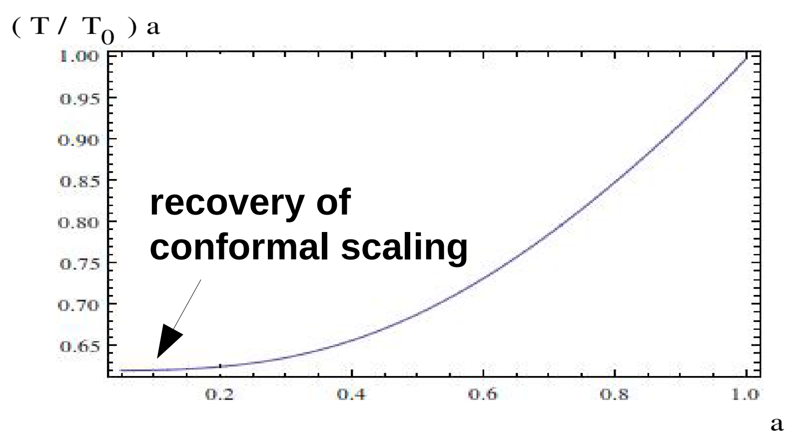
- cosmic radio background (UEGE),
  onset of Meissner effect →
  **evanescent modes at low frequencies**
  [terrestial observ. (1981-1999),
  Arcade 2 (2009), RH (2009) ]




- CMB angular spectrum vs. Gunn-Peterson trough (quasars) inferred early re-ionisation of intergalactic medium (z=11 vs. z=6 discrepancy),
  **non-conformal** $T-a$ **relation at late times**

  [Becker et al. (2001), WMAP coll. (2004), Planck coll. (2013)]

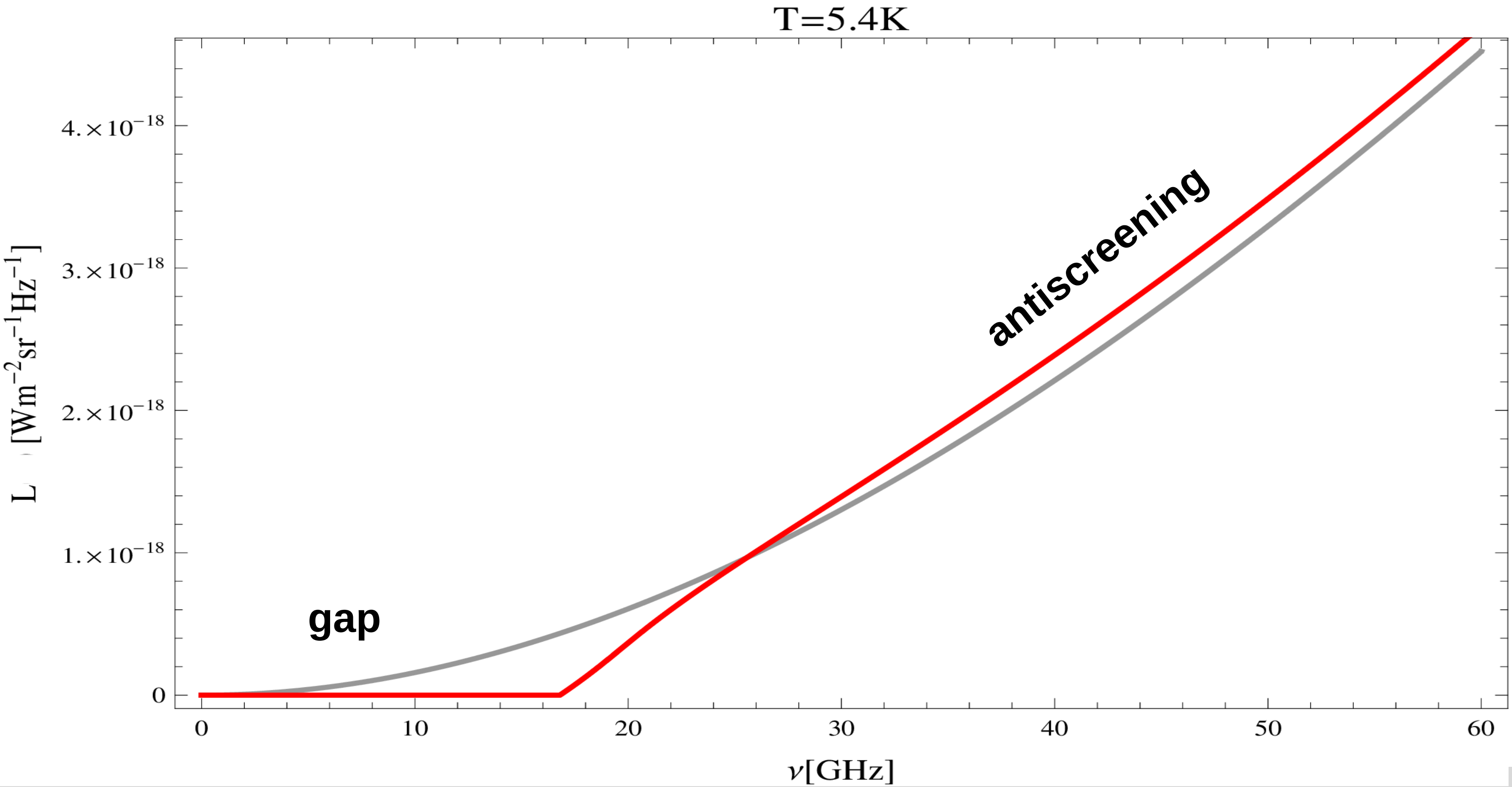



[RH (2014)]

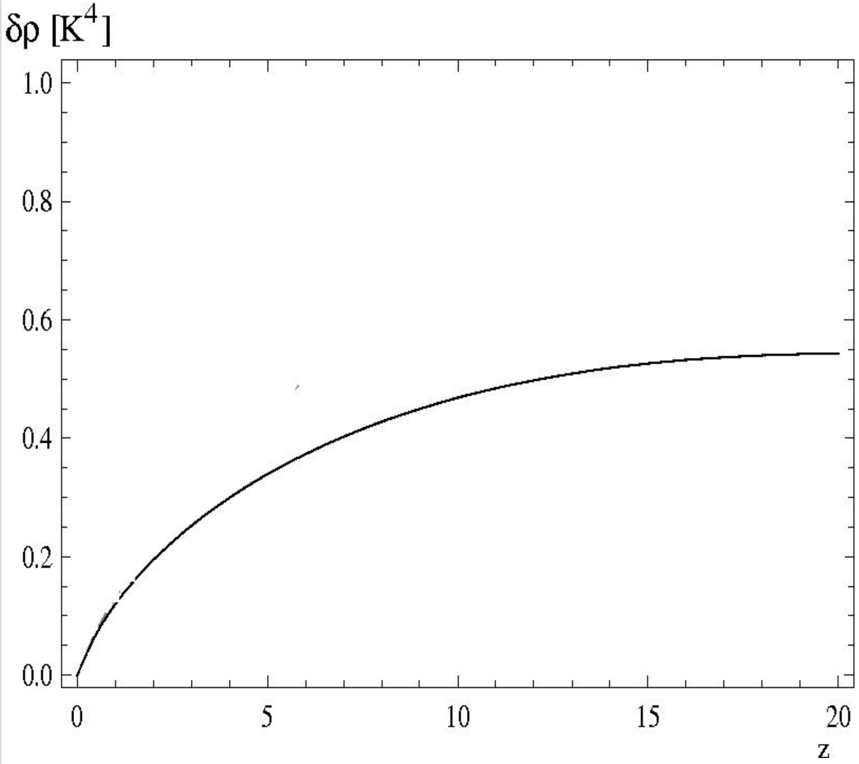
## evidences for $SU(2)_{\mathrm{CMB}}$ ($\Lambda_{\mathrm{CMB}} \sim 10^{-4}\,\mathrm{eV}$): one-loop polarization

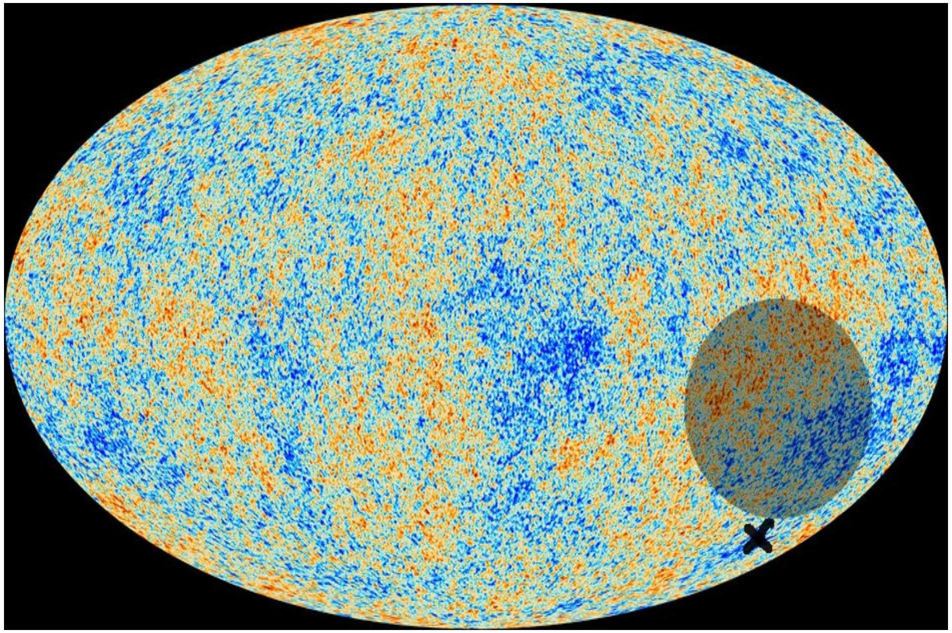
- **spectral blackbody anomaly:** max. gap in Rayleigh-Jeans reg. at $T \sim 5\,\mathrm{K}$, massless mode – transverse polarizations
  [Schwarz, Giacosa & RH (2006), Ludescher & RH (2008), Falquez, RH & Baumbach (2010,2011)]



## evidences for $SU(2)_{\rm CMB}$($\Lambda_{\rm CMB} \sim 10^{-4}\,{\rm eV}$): one-loop polarization

- **integral blackbody anomaly:**
  difference $\delta\rho$ between energy density of SU(2) and U(1), massless mode – transverse polarizations



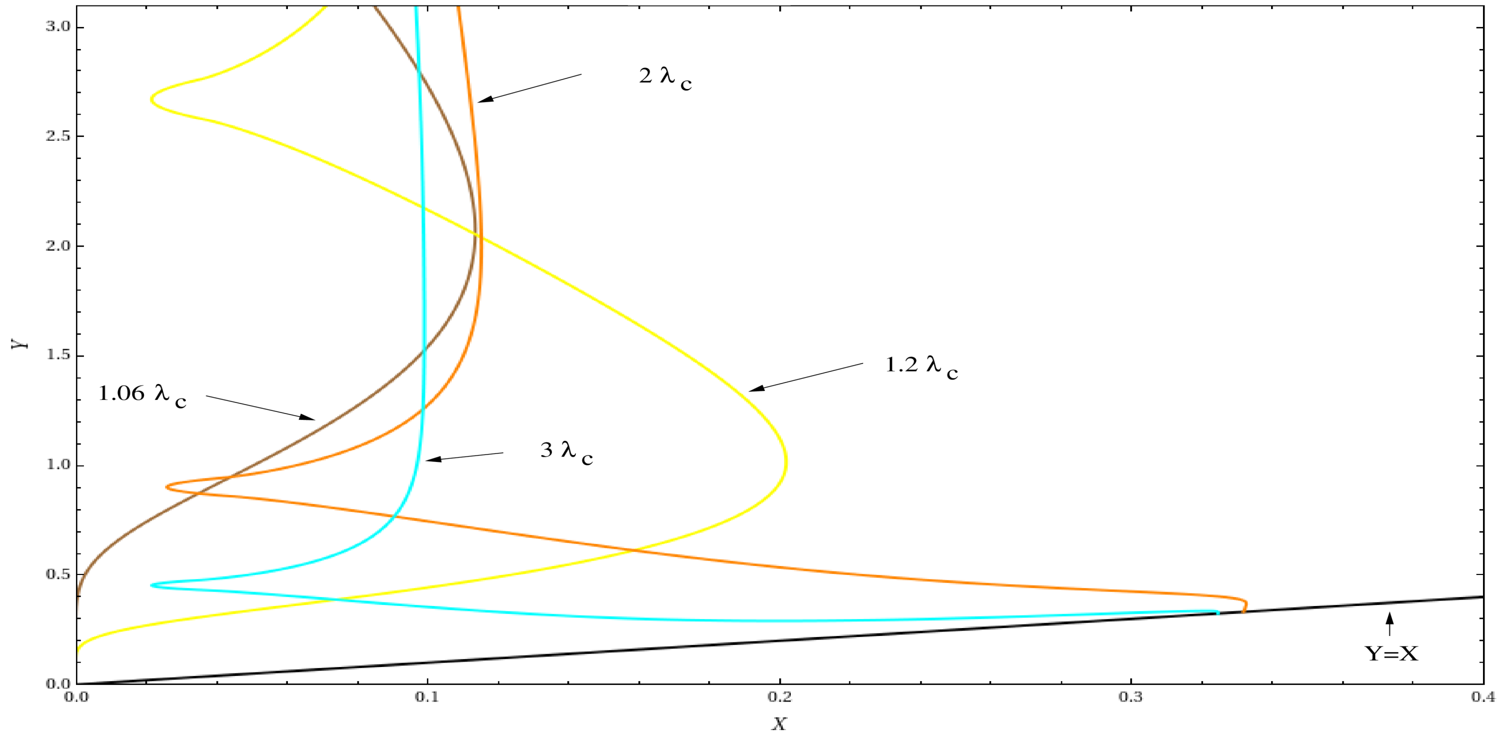



(**positive** slope of $\delta\rho$ bias for **negative** temperature fluctuations in late-time CMB)

[Szopa et al 2007, RH **Nature Physics** (2013)]

## evidences for $SU(2)_{\rm CMB}$($\Lambda_{\rm CMB} \sim 10^{-4}\,{\rm eV}$): one-loop polarization

- low-momentum support of magnetic branches (dual interpretation) massless mode – longitudinal polarization




$\overset{?}{\Longrightarrow}$ intergalatic magnetic fields [Falquez et al. (2011)]

## summary

- alternative to high-T perturbation theory:
  caloron induced dynamical gauge SB by thermal ground state

- effective theory for deconfining phase of SU(2) YM

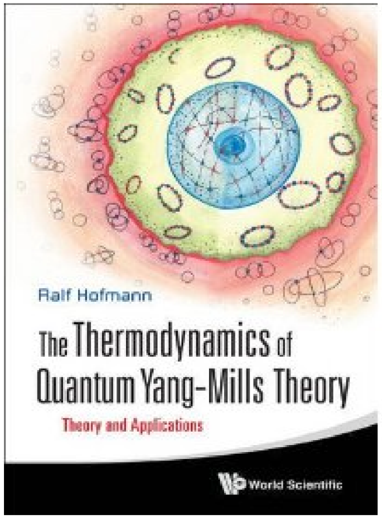
- effective coupling evolution: - caloron action $\hbar$ ,
  - caloron mediation of effective vertices,
  - e-m dual interpretation

- effective radiative corrections: extremely well controlled

- SU(2) photons: tree-level and one-loop polarization anomalies
  → CMB anomalies
  - cosmic radiobackground
  - quasar vs CMB wrt reionization,
  - spectral & integral BB anomalies
    (CMB at large angles)

  → extragalactic magnetic fields

*Theory:*




(World Scientific 2011)

*Cosmological applications (CMB photons):*

F. Giacosa and RH, Eur. Phys. J. C  (2005);
F. Giacosa, RH, M. Neubert, JHEP (2008);
M. Szopa, RH, JCAP (2008);
RH, Annalen d. Physik (2009);
RH, Nature Physics (2013);
RH, Annalen d. Physik (2015);
Grandou & RH (2015)

**Thank you !**