SU(2) Quantum Yang-Mills Thermodynamics: some theory and some applications

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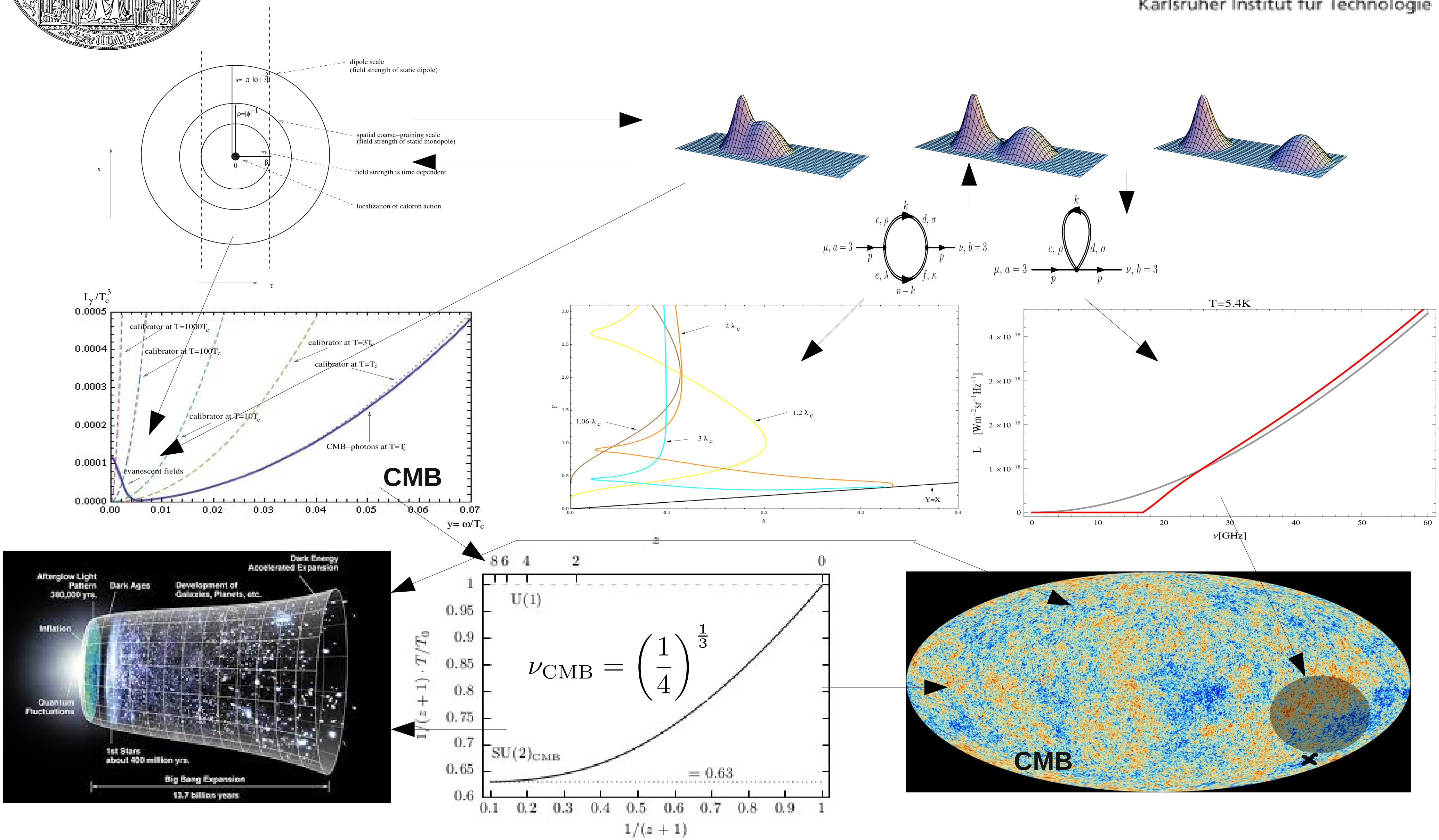
Int. Conf. New Frontiers in Physics, Kolymbari, 5-12 July 2018



Overview

- (anti)selfdual gauge fields, stable and unstable **(anti)calorons**

- deconfining **thermal ground state**
  - sketch of **a priori estimate**
  - ground-state permittivity and permeability
  - excitations: waves vs. particles

- deconfining thermodynamics
  - evolution of **coupling**
  - **pressure and energy density**

- radiative corrections
  - **loop expansion** of pressure
  - **polarisation tensor**

Overview, continued:

- thermal photon gases:
  cosmic microwave background (CMB) and beyond

- postulate $\mathrm{SU}(2)_{\mathrm{CMB}}$

  - **temperature (T) -redshift (z) relation** in FLRW Universe:
    implications for **high-z cosmological model, 3D Ising exponent**

  - high-z – Λ CDM interpolation:
    Planck-scale axion and its vortices, **dark-sector** physics

  - angular power spectra, resolving the trouble with H_0
    and early-reionisation puzzle; low baryon density

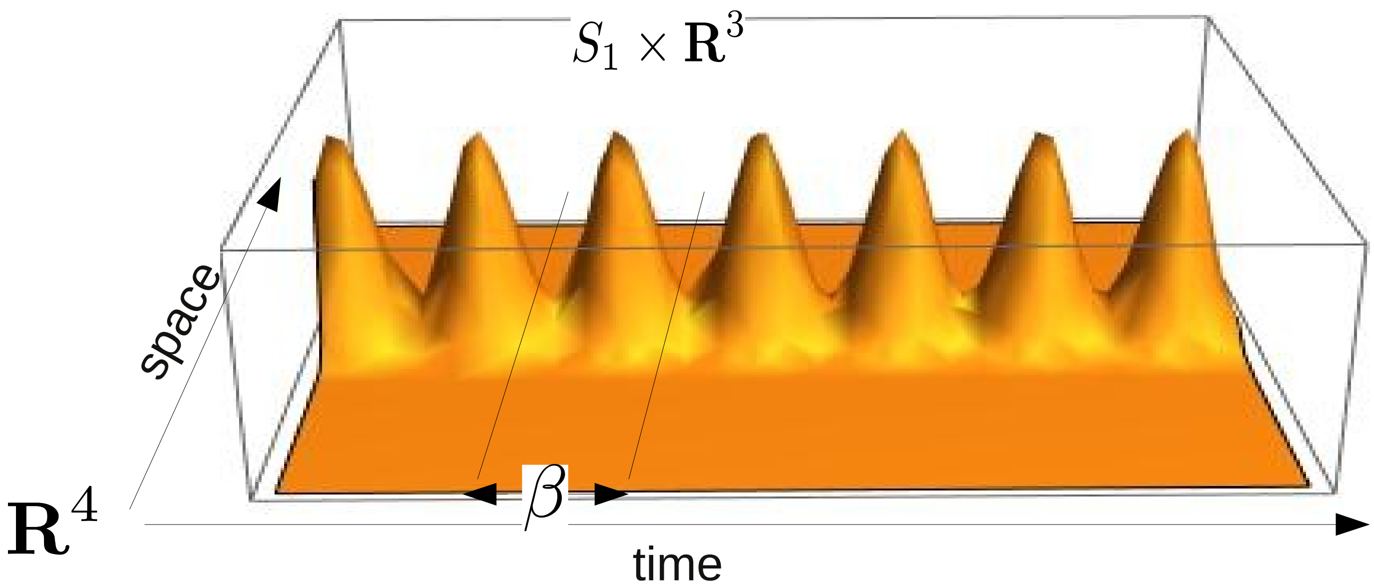
The gauge group SU(2), (anti)selfdual gauge fields at finite temperature T :

- J. Schwinger and R. P. Feynman argued in 1953 (see also A. Migdal) that finite temperature is introduced by reducing Euclidean spacetime to a cylinder,

$$\mathbf{R}^4 \quad \to \quad S_1 \times \mathbf{R}^3 \quad \longrightarrow \quad S_\beta \equiv \frac{1}{2g^2}\int_0^\beta dx_4 \int dx^3 \,\mathrm{tr}\, F^2 \,.$$

and by demanding periodictiy of field configurations:

$$A_\mu(x_4,\vec{x}) = A_\mu(x_4+\beta,\vec{x})\,, \quad \text{where} \quad \beta \equiv \frac{1}{T} \,.$$



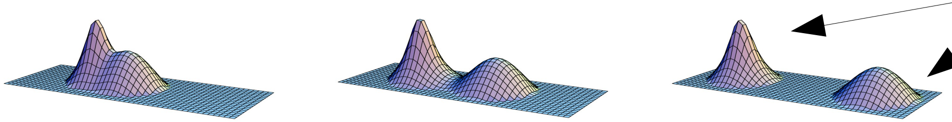
superposition of (anti) instanton centers along temporal coordinate enforces **periodicity**

[Harrington & Shepard 1977]

This **(anti) caloron** has topological charge $k=\pm 1$ on $S_1 \times \mathbf{R}^3$.

(Anti)calorons: trivial vs. non-trivial holonomy

- behavior of adjoint „Higgs field“ A_4 at spatial infinity determines magnetic substructure: non-trivial holonomy
  [Atiyah, Drinfeld,Hitchin,Manin 1978; Nahm 1983; Lee & Lu 1998; Kraan & Van Baal 1998]



pair of magnetic monopole and its antimonopole
['t Hooft 1974, Polyakov 1974, Prasad & Sommerfield 1975]

static config.: attraction A_i cancelled by repulsion A_4

action density of $k=1$ caloron with non-trivial holonomy on spatial plane

- Harrington-Shepard caloron:
  special case where monopole delocalized and zero mass and antimonopole localized and finite mass

- „integrating out“ Gaussian quantum fluctuations about non-trivial holonomy caloron:
  [Diakonov 2004 along lines of 't Hooft 1976 for instanton]

$\longrightarrow$

- small holonomy (likely): fall-back to **trivial holonomy** → **stable**
- large holonmy (unlikely): dissociation of caloron into its **monopole-antimonopole constituents** → **unstable**

Deconfining thermal ground-state estimate

Anatomy of (stable) HS caloron: [Gross & Pisarski & Yaffe 1983]

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

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

$$\longrightarrow \quad E^a_i = B^a_i \sim -\frac{\hat{x}^a \hat{x}_i}{r^2} \qquad (\,\beta \ll r \ll s\,)\;,$$

(static selfdual **monopole-field**)

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

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

Deconfining thermal ground-state estimate

– **Strategy (ground-state estimate):** [Herbst & Hofmann 2004, Hofmann 2005, Giacosa & Hofmann 2007]

(i) perform spatial coarse graining over Euclidean time dependence of single HS caloron and anticaloron to **render this time dependence** a **„choice of gauge“** for **phase of an adjoint and inert scalar field** ϕ

(ii) find e.o.m.s (1st **and** 2nd order) for ϕ

(iii) from (ii) find e.o.m. for $V(\phi)$ $\longrightarrow$ **densely packed (anti)caloron centers**

(iv) complete action density for „dynamics“ of ϕ by appeal to **inertness**, **gauge invariance,** and **perturbative renormalizability of k=0 part**

['t Hooft 1972, 't Hooft & Veltman 1973]

– Solve (2nd order) e.o.m. for **curvature-free configuration** a_μ^{gs}

$\longrightarrow$ **overlapping (anti)caloron peripheries**

Deconfining thermal ground-state estimate

Inert and adjoint scalar field from HS (anti)caloron centers:

– family of phases

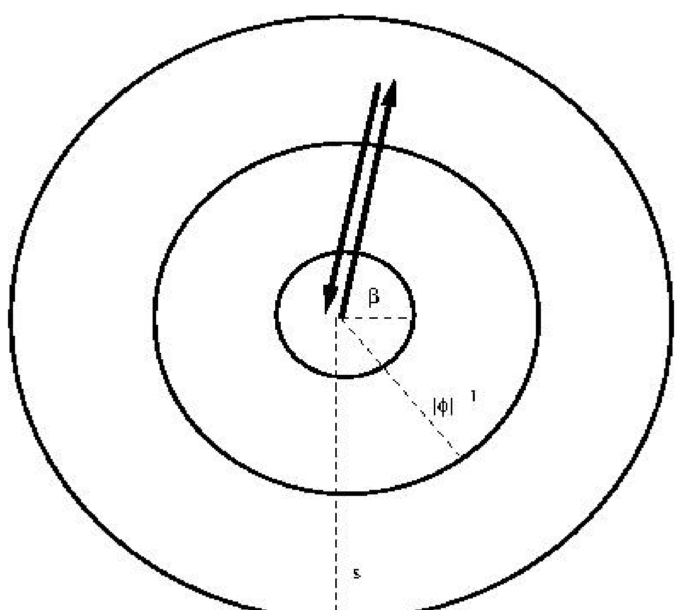
$$\{\hat{\phi}^a\} \equiv \sum_{C,A} \mathrm{tr}\int d^3x \int d\rho\, t^a\, F_{\mu\nu}(\tau,\vec{0})\,\{(\tau,\vec{0}),(\tau,\vec{x})\} \times\; F_{\mu\nu}(\tau,\vec{x})\{(\tau,\vec{x}),(\tau,\vec{0})\},$$

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

3D space

unique definition:

- no higher n points
- no higher k
- no curvature of lines
- no shiftability of base point



Deconfining thermal ground-state estimate

– leads to: $\{\hat{\phi}^a\}$ as kernel of **uniquely determined differential operator**

$$\mathcal{D} \equiv \partial_\tau^2 + \left(\frac{2\pi}{\beta}\right)^2$$

(harmonic oscillator)

– but: $\mathcal{D}$ exhibits **explicit** β **dependence** which must not be there;
→ absorb β dependence into **potential** $V(\phi)$

– consistency of Euler-Lagrange (2nd order) and Bogolomoln'yi-Prasad-Sommerfield (BPS, 1st order) e.o.m.s yields:

$$\frac{\partial V(|\phi|^2)}{\partial |\phi|^2} = -\frac{V(|\phi|^2)}{|\phi|^2}$$

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

$$|\phi| = \sqrt{\frac{\Lambda^3\beta}{2\pi}}$$

Yang-Mills scale

Deconfining thermal ground-state estimate

full effective action density, ground-state solution:

– inertness of ϕ , renormalizability, gauge invariance:

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

$$(\ G_{\mu\nu} = \partial_\mu a_\nu - \partial_\nu a_\mu - ie[a_\mu, a_\nu] \equiv G^a_{\mu\nu}\, t_a\,, \quad D_\mu\phi = \partial_\mu\phi - ie[a_\mu,\phi]\,.\ )$$

effective coupling

– Euler-Lagrange for a_μ : $\boxed{D_\mu G_{\mu\nu} = ie[\phi, D_\nu\phi]}$

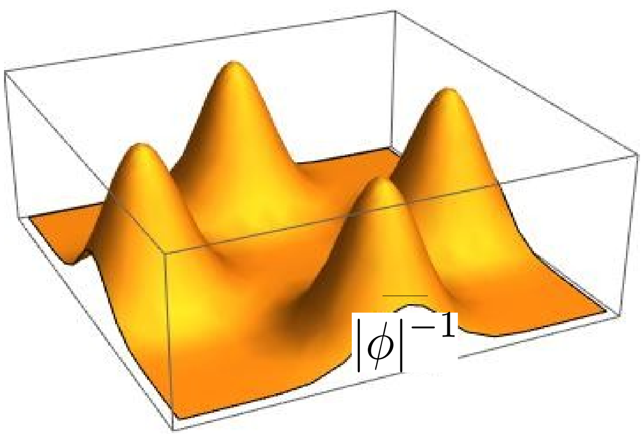
pure-gauge solution:

$$\boxed{a^{\rm gs}_\mu = \mp\delta_{\mu4}\frac{2\pi}{e\beta}\,t_3} \quad (D_\nu\phi \equiv G_{\mu\nu} \equiv 0) \longrightarrow \boxed{P_{gs} = -\rho_{gs} = -4\pi\Lambda^3 T\,.}$$

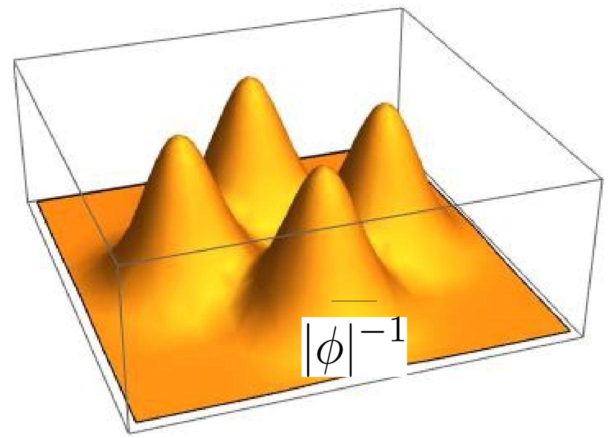
Overlapping, small and transient-holonomy (anti)calorons implying collapsing monopole-antimonopole pairs.

Deconfining thermal ground-state estimate

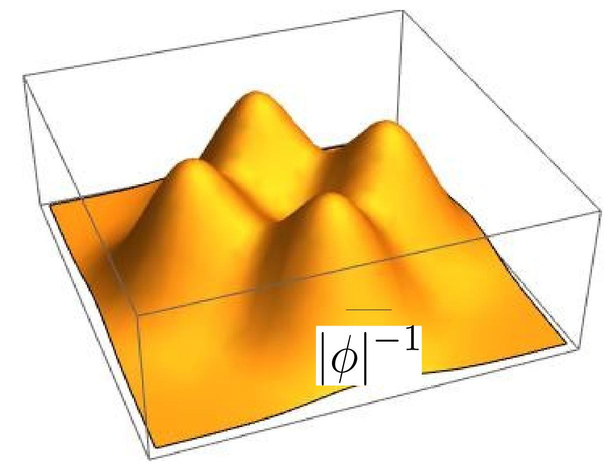
– **interpretation** of ground-state estimate $\phi, a_\mu^{\rm gs}$:



isolated (anti)caloron centers



(anti)caloron centers with **some overlap in peripheries**



densely packed (anti)caloron centers with overlapping peripheries

$a_\mu^{\rm gs}$ describes the **collective overlap of all peripheries at a given center** when **centers** are **densely packed.**

This is **not yet the entire truth** since there are **packing voids** and slight **overlaps** of **centers** → **effective radiative corrections**, later.

Deconfining thermal ground-state estimate

- nature of excitations

electric/magnetic dipole density:

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

classical external electric (or magnetic, selfduality!) field strength squared to match ground-state energy density:

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

$$\rightarrow \quad \boxed{\epsilon_0[Q(\mathrm{Vm}^{-1})] \equiv \frac{|\mathbf{D}_e|}{\overline{|\mathbf{E}_e|}} = \frac{9}{32\pi^2}\frac{\Lambda[\mathrm{m}^{-1}]}{\Lambda[\mathrm{eV}]}(\xi Q)^2 \neq f(T)}$$

similarly for μ_0

→ **speed of light** independent of intensity and, because of **Doppler, independent of Lorentz frame**

Deconfining thermal ground-state estimate

But:

$$\boxed{\overline{|\mathbf{E}|_e}^4 \nu \ll 8\Lambda^9} \qquad (*)$$

(ν frequency of a monochromatic wave, back to natural units)

$\Rightarrow$ for **thermal ground state** to be excited in a **wavelike** way (electromagnetic spectrum) **Yang-Mills scale** Λ must be sufficiently **large**.

$\Rightarrow$ in a thermodynamical situation, however, Λ must be **small** to **avoid ultraviolet catastrophe** in BB radiation.

$\rightarrow$ If nature indeed makes use of the SU(2) **thermal ground state** to **progagate em disturbances** then at least **two** such **theories** are required, subject to a **thermalization dependent mixing angle for their Cartan subalgebras**.

Deconfining thermodynamics

– go to entirely fixed and physical unitary-Coulomb gauge: $\boxed{\phi^a = \delta^{a3}|\phi|\,, \quad \partial_i a_i^3 = 0\,.}$

→ mass spectrum (adjoint Higgs mechanism) :

$$\boxed{m_{1,2} = 2e|\phi| \equiv m\,, \quad m_3 = 0\,.}$$

yet undetermined

off-Cartan massive vector modes,
thermal quasi-particle fluctuations

Cartan massless „photons“

– to draw same **Legendre trafos** from **effective** as from **fundamental partition function** one demands for pressure P :

$$\boxed{\frac{\partial P}{\partial m} = 0}$$

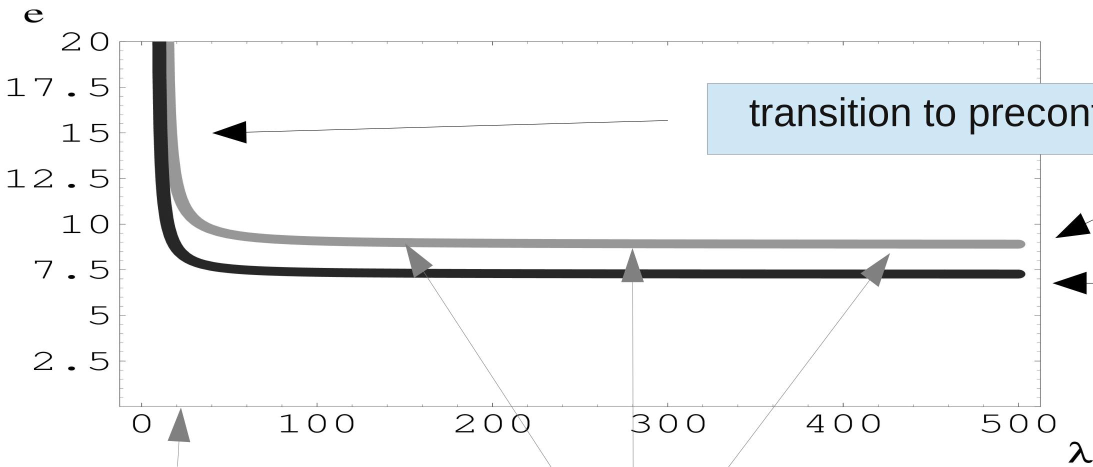
(on one-loop thermodynamical selfconsistency)

Corrections from higher loops (hopefully) well under control.

evolution equation for coupling e →

Deconfining thermodynamics

effective gauge coupling



transition to preconfining phase

SU(2)

SU(3)

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

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

$$e = \sqrt{8}\pi$$

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

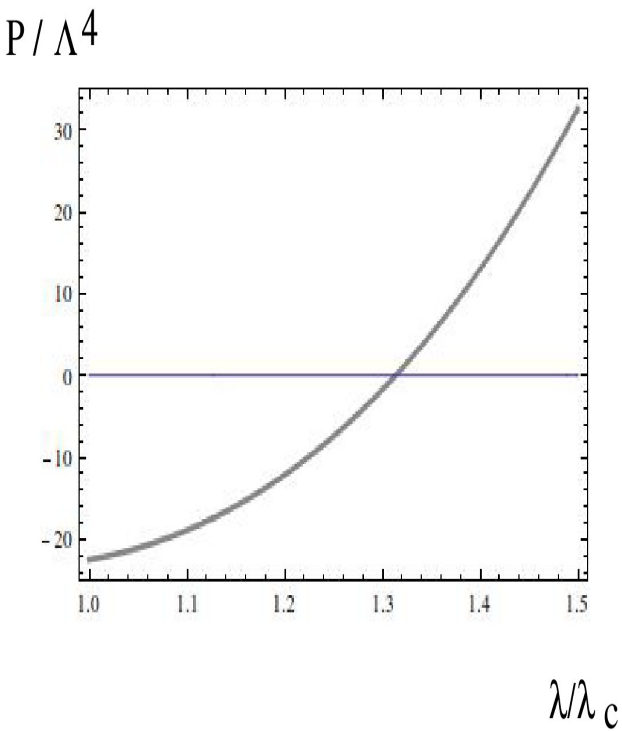
- restore $\hbar$

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

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

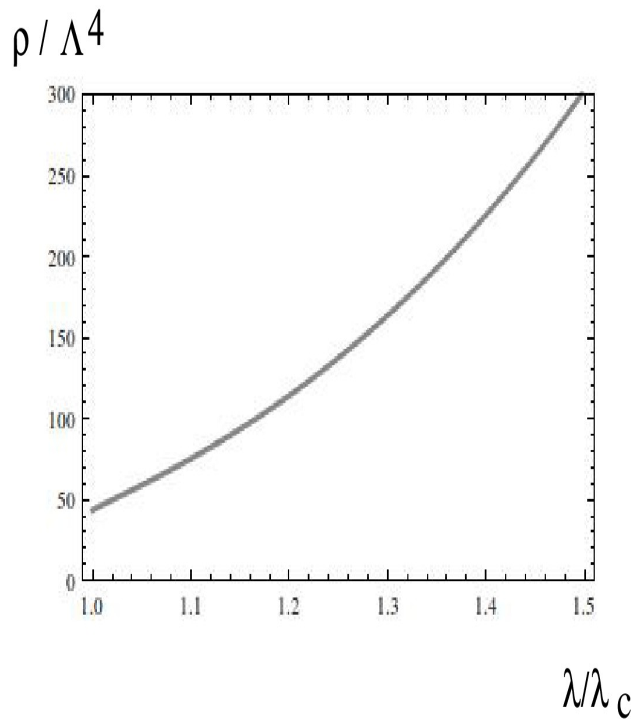
$$S_{C/A} = \hbar\,.$$

Deconfining thermodynamics: pressure and energy density



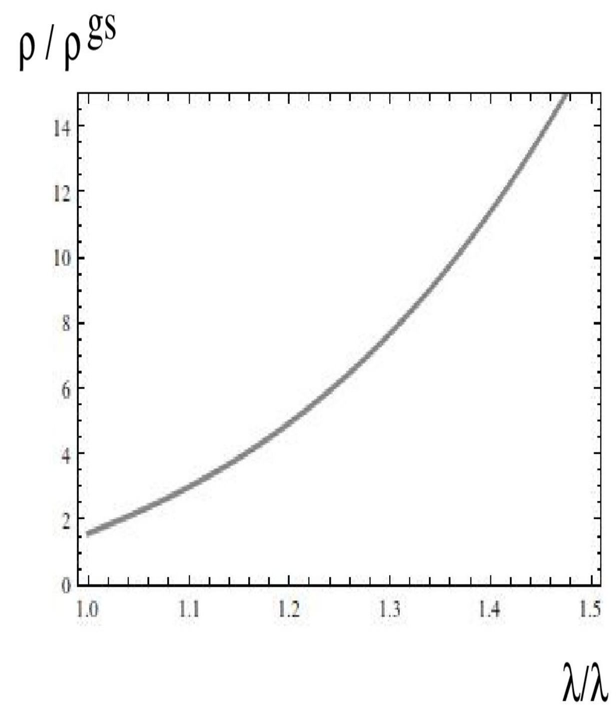
(a)

total pressure



(b)

total energy density



(c)

energy densities:
total vs. ground state

Deconfining thermodynamics: radiative corrections

A (anti)caloron center **localises Planck's quantum of action** $\hbar$.

Such centers therefore must be interpreted as effective **vertex induces** (scattering of a_μ -fields) or as **originators** of **all massive** fluctuations or **high-frequency massless** fluctuations

$\longrightarrow$ real-time **Feynman rules in unitary-Coulomb gauge.**

(completely fixed gauge)

To not resolve a center in 2-2 scattering, momentum transfer in all Mandelstam variables s, t, u is bounded by $|\phi|^2$.

To not resolve a center in 2-1 scattering, off-shellness of massless mode is bounded by $|\phi|^2$.

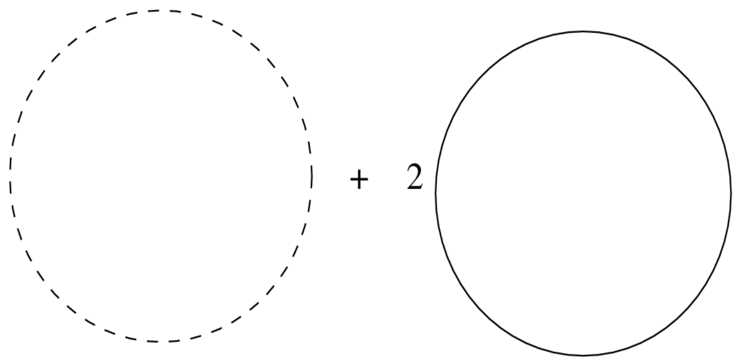
$\longrightarrow$ Radiative corrections are **infrared** (masses) and **ultraviolet** (bounds on momenta transfers) **finite**.

Deconfining thermodynamics: radiative corrections

– loop expansion of pressure:

[RH 2005]

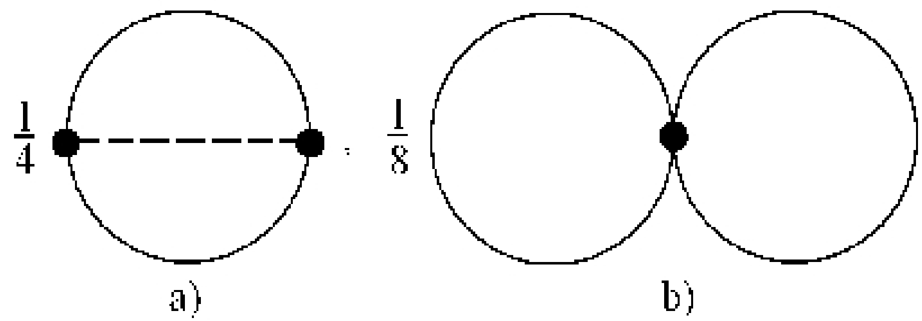
$O(1)$



+

[Schwarz, Giacosa, RH 2007]

$O(10^{-2})$

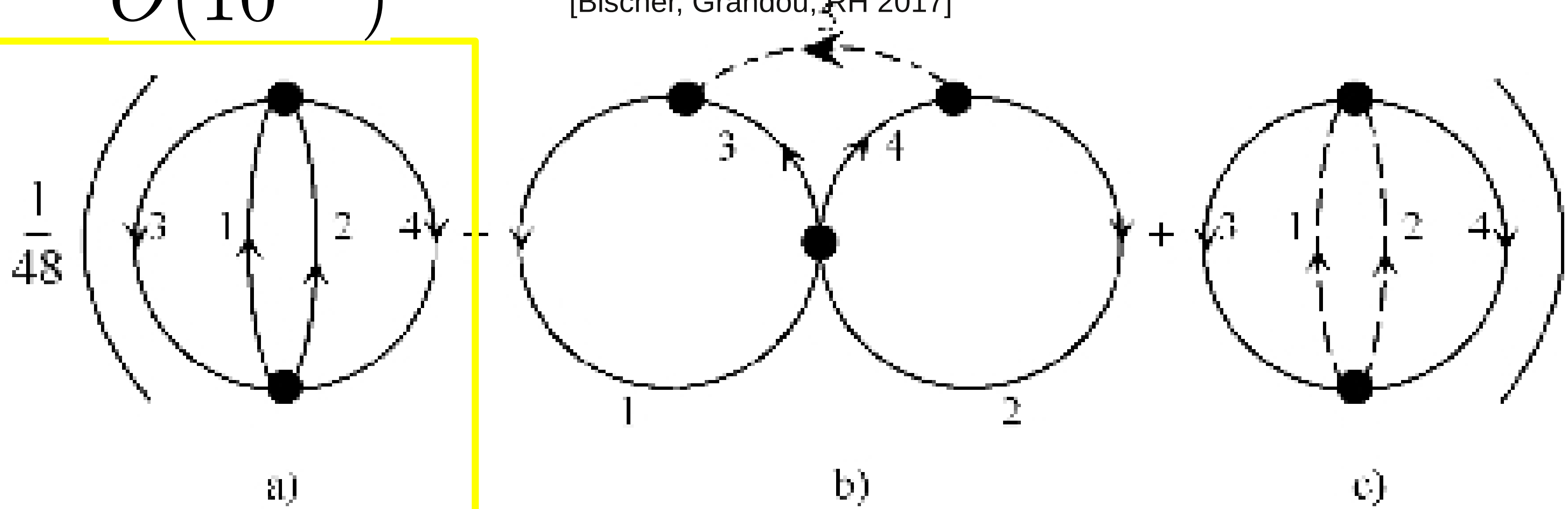


+ one more diagram

$O(10^{-5})$

[Bischer, Grandou, RH 2017]

+

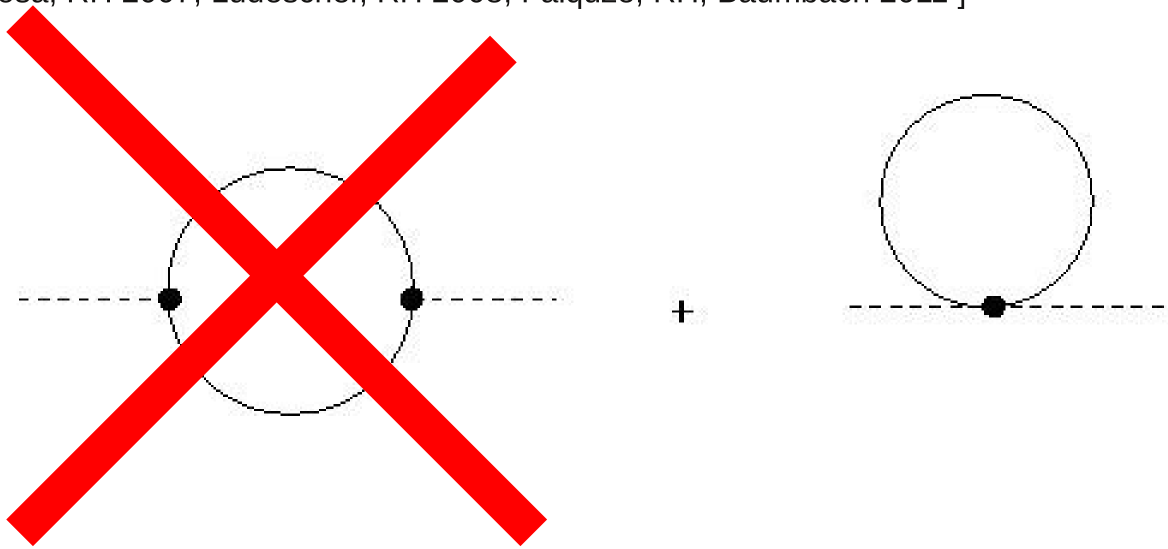


(subject to resummation)

Deconfining thermodynamics: radiative corrections

– polarisation tensor of massless mode

[Schwarz, Giacosa, RH 2007; Ludescher, RH 2008; Falquze, RH, Baumbach 2011]



→ **gap equations** for **transverse** and **longitudinal** screening functions G and F

→ upon resummation: **radiatively corrected/invoked dispersion laws**

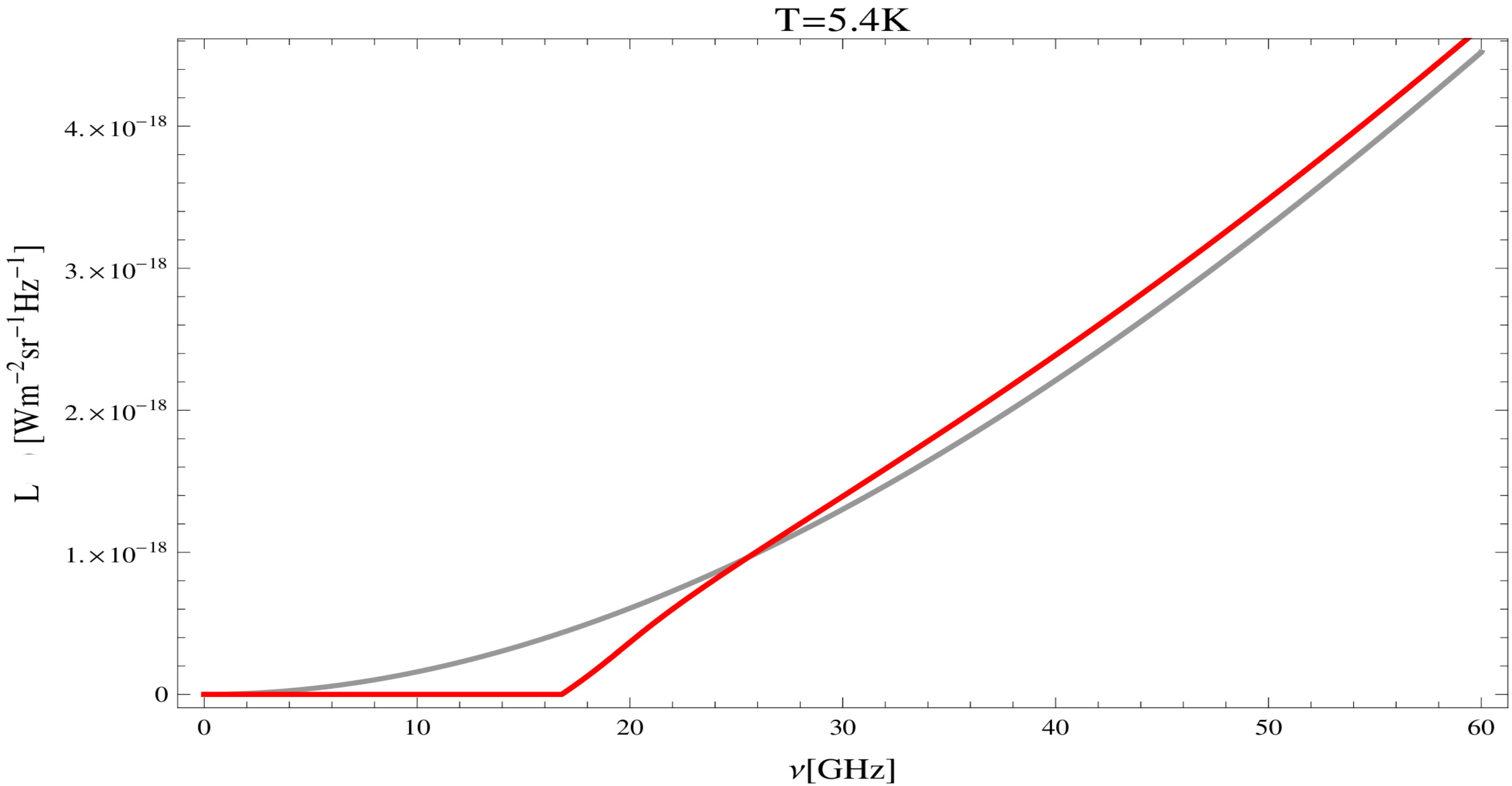
$$\boxed{\omega_T^2 = \vec{p}^2 + G}$$

$$\boxed{\omega_L^2 = \vec{p}^2 + F}$$

Deconfining thermodynamics: radiative corrections, BB anomaly

Transverse modes:

[Falquez, RH, Baumbach 2011]



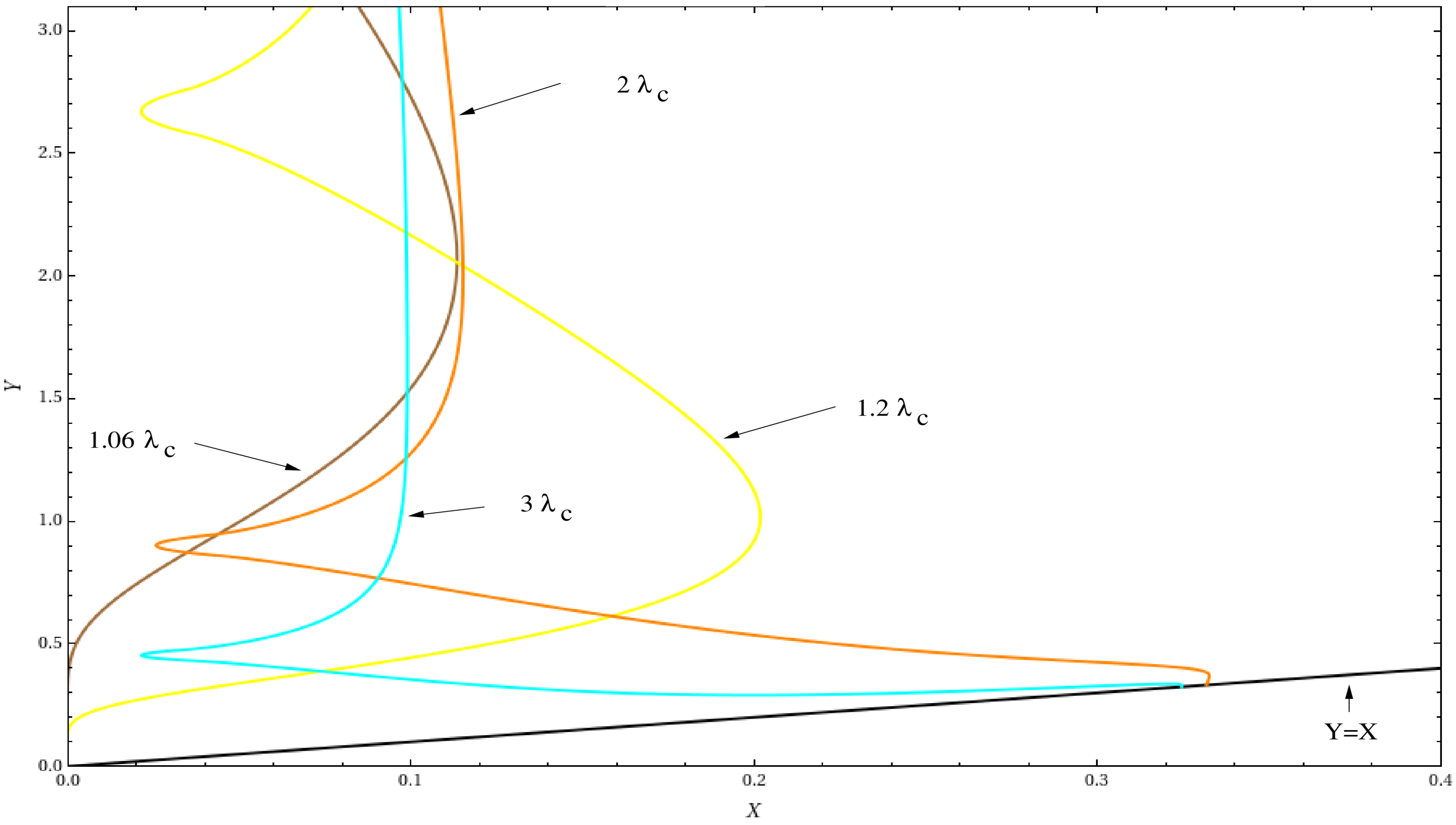
(Yang-Mills scale or T_c fixed by CMB observation at low frequencies, later)

Deconfining thermodynamics: radiative corrections

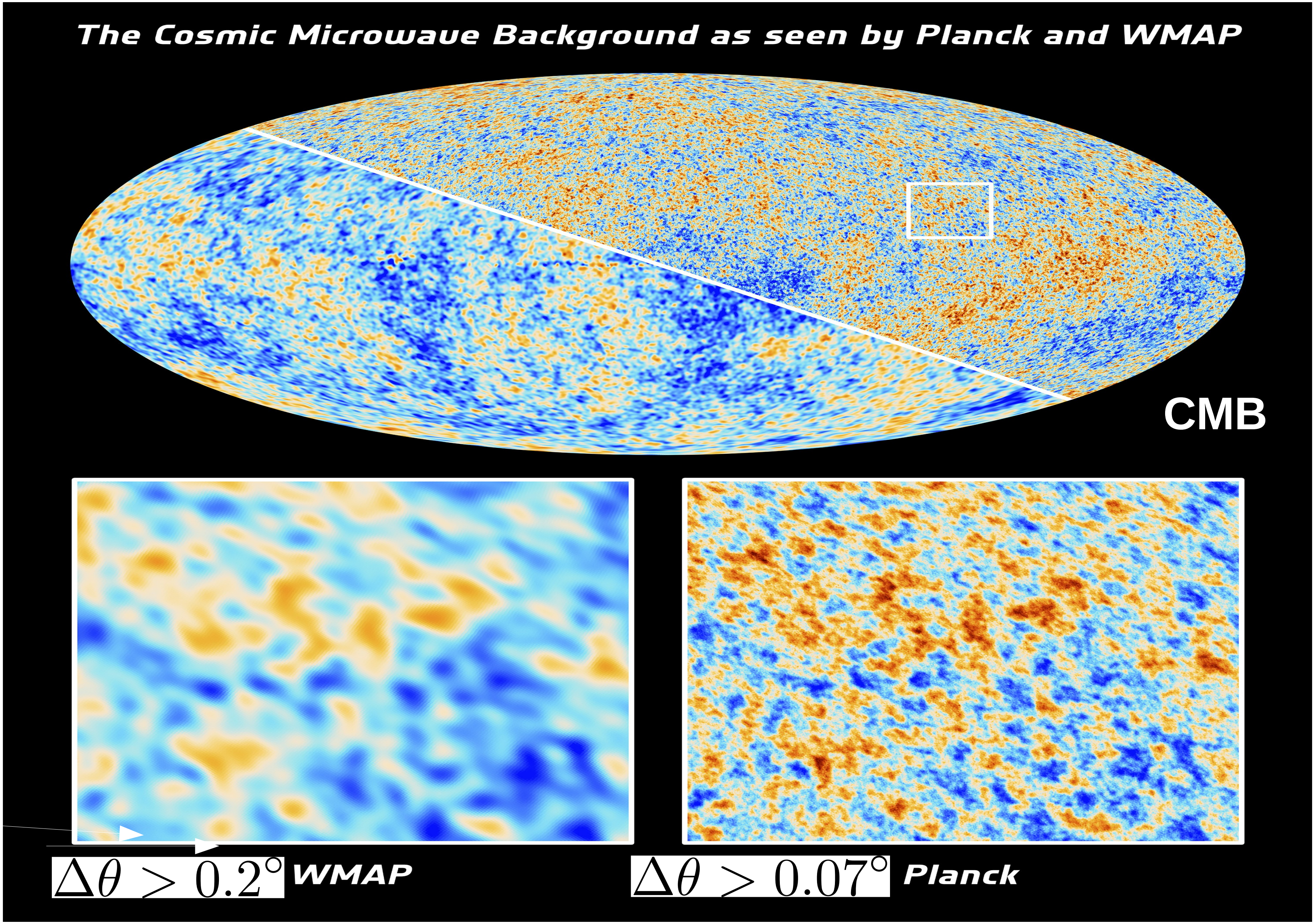
Longitudinal modes:

[Falquez, RH, Baumbach 2012]

various low-momentum branches,
physics implications: later



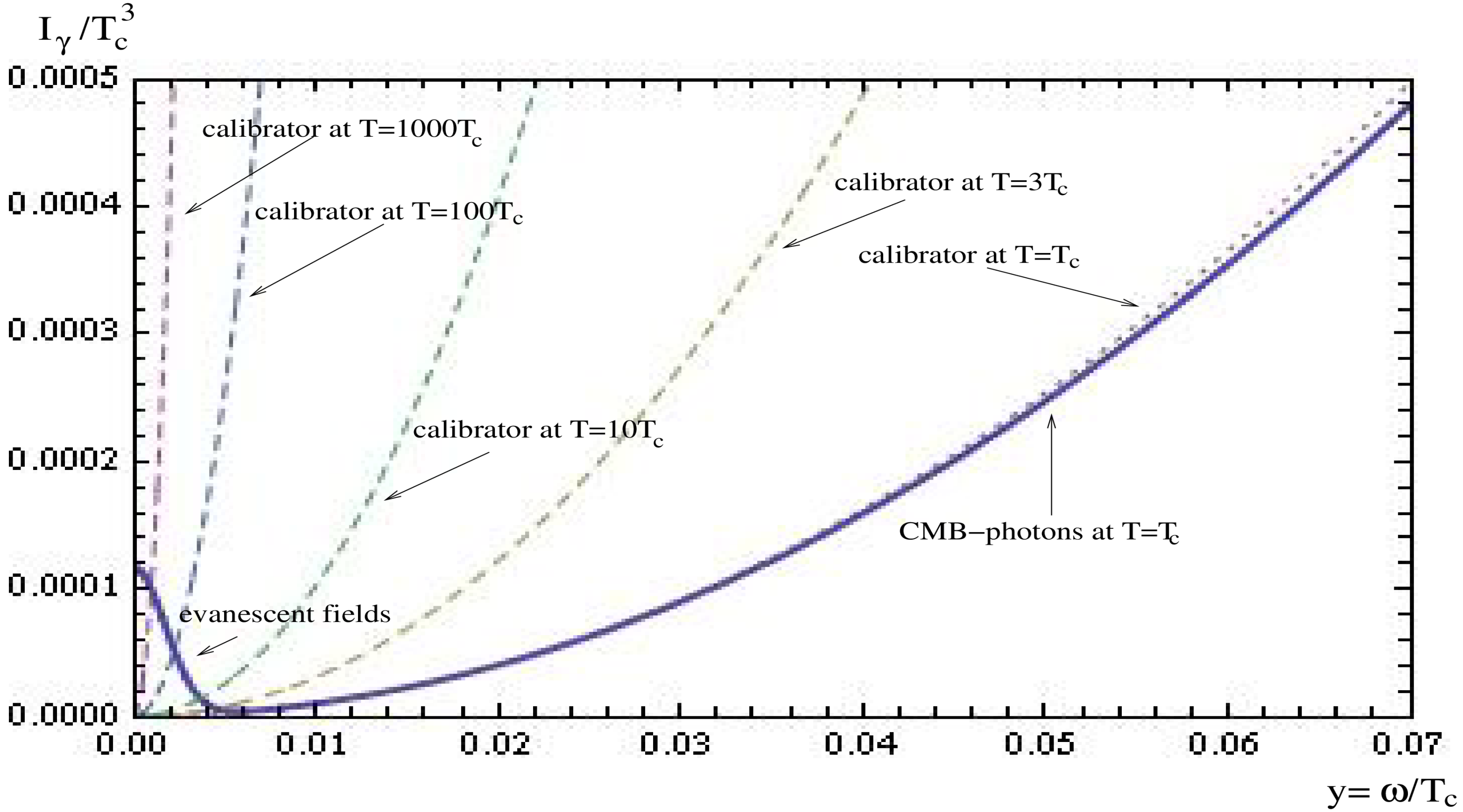
Observational situation after WMAP and PLANCK



Low-temperature photon gases: Fixation of Yang-Mills scale

– low-frequency CMB radiance spectrum

[terrest. observations 1981-1999; Arcade2 2009]

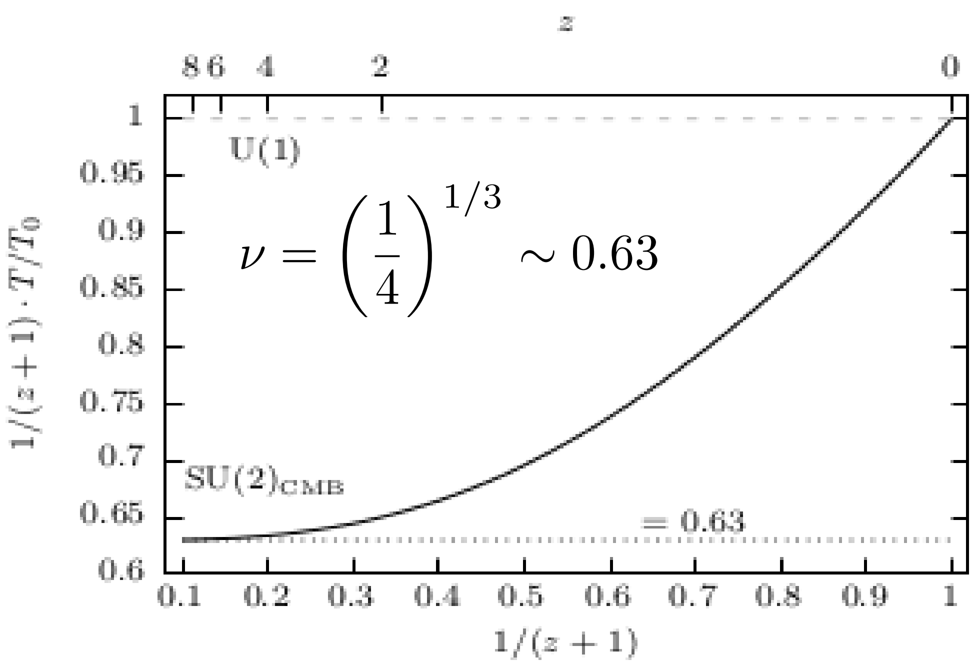


– interpretation as onset of deconfining-preconfining phase transition through **Meissner mass** $\longrightarrow$ **evanescence of low-frequency waves ;** **sharply** fixes [RH 2009]

$$\boxed{T_c = T_0 = 2.725\,\mathrm{K} \quad \Rightarrow \Lambda = \frac{2\pi T_c}{13.87} \sim 10^{-4}\,\mathrm{eV}} \longrightarrow \boxed{\mathrm{SU}(2)_{\mathrm{CMB}}}$$

R. Hofmann

CMB: temperature (T)-redshift (z) relation



follows from energy conservation in FLRW universe upon deconfining-phase SU(2) equation of state $P = P(\rho)$: [RH (2015)]

$$\boxed{\frac{d\rho}{da} = -\frac{3}{a}(P+\rho)}$$

immediate consequences:

- **discrepancy** addressed between **re-ionisation redshifts** as extracted from

  (i) fit to **TT angular power spectrum** of CMB [Planck coll. 2013, 2015]

  (ii) **Gunn-Peterson trough** in high-z quasar spectra [Becker et al 2001]

→ **modification of high-z cosmological model**, possible explanation of discrepancy in H_0 from $\Lambda\mathrm{CDM}$ fits to CMB power spectra and local observation, later

[Planck coll . 2013,2015; Riess et al 2016; HoliCow 2016]

CMB: temperature (T)-redshift (z) relation: 3D Ising exponent

[Hahn & RH (2017)]

$$\frac{d\rho}{da} = -\frac{3}{a}(P+\rho)$$

exact solution: :

$$a = \exp\left(-\frac{1}{3}\log\frac{s(T)}{s(T_0)}\right)$$

where S denotes entropy density

asymptotic solution:

$$a = \left(\frac{1}{4}\right)^{\frac{1}{3}}\frac{T_0}{T} \qquad \left(\frac{T}{T_0} \gg 1\right)$$ (*)

deduces from two points of scale invariance in phase diagram: $T = T_0$; $T = \infty$

Note that:

$$\left(\frac{1}{4}\right)^{\frac{1}{3}} = 0.629960(5)$$

→ Deviates from numerically determined exponent of 3D Ising [Kos et al (2016)]
(same univ. class like SU(2) YMTD concerning dec.-prec. transition)
for correlation length l by only 0.001 % ! [Svetitsky & Yaffe (1983)]

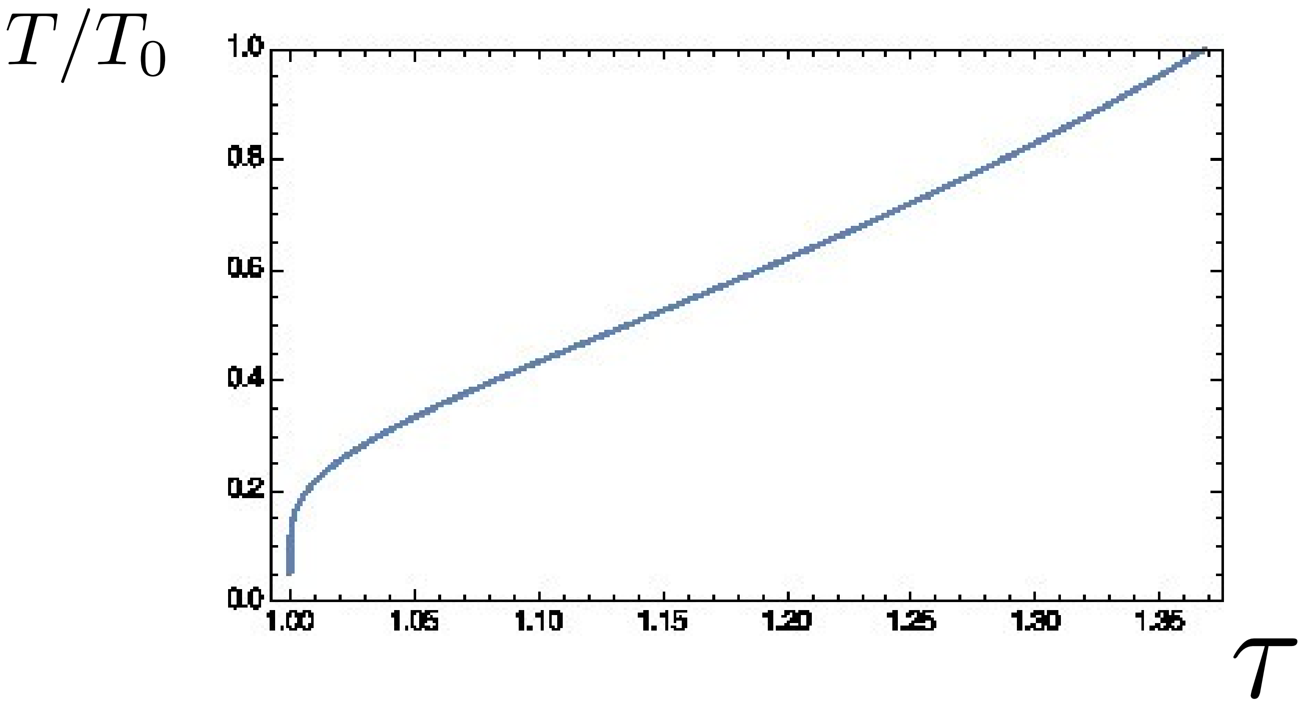
Why?

– continuing (*) down to $T = 0$ →
T fictitious temperature in SU(2) YMTD

– consider map to from T/T_0 to physical Ising temperature θ

$$\frac{T}{T_0} = -\frac{1}{\log(\tau - 1)} \qquad \left(\tau \equiv \frac{\theta}{\theta_c}\right)$$ (**)

CMB: temperature (T)-redshift (z) relation: 3D Ising exponent



– exponentiation of (*) under consideration of (**) yields

$$\boxed{\exp(a) = (\tau - 1)^{-\left(\frac{1}{4}\right)^{\frac{1}{3}}}} \longrightarrow$$

– interpretation of $\exp(a)$ as l/l_0 (system size a where l_0 a suitable reference length)

High-z cosmological model

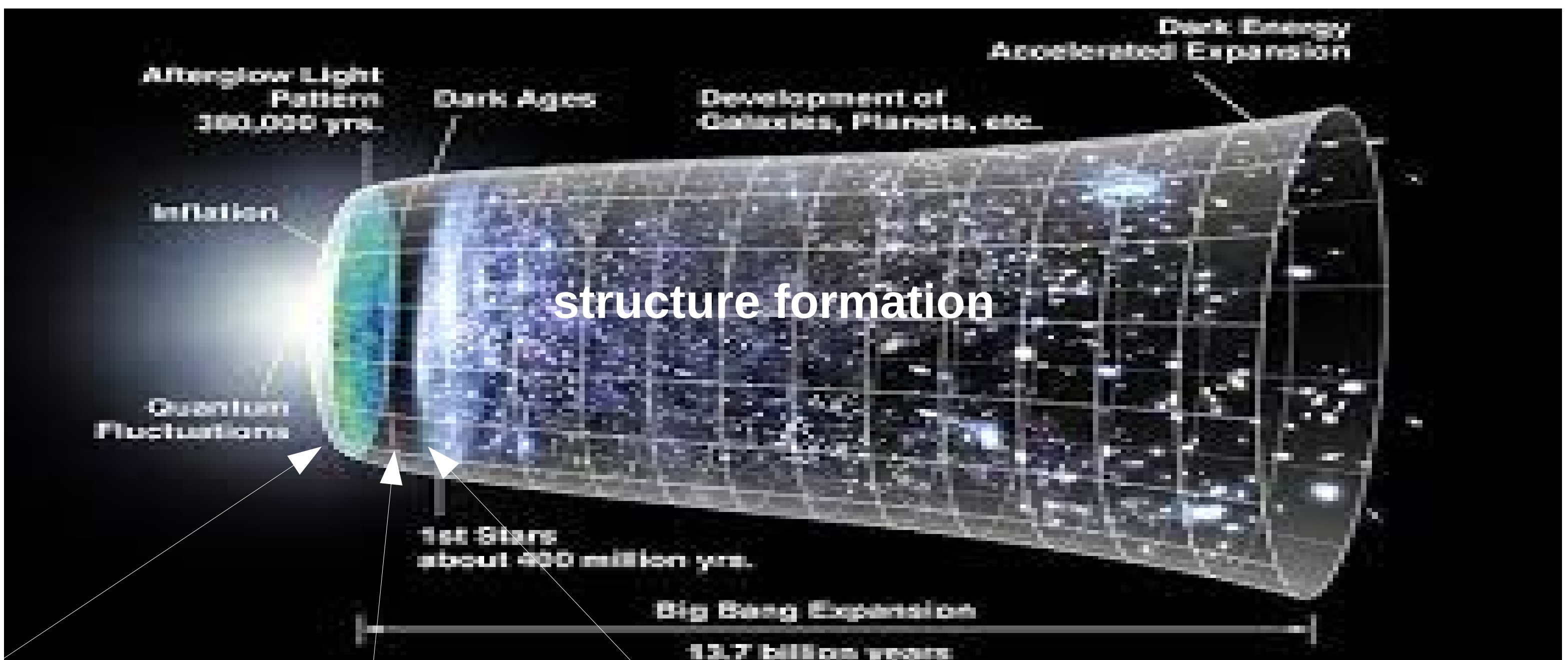
– re-combination z_* at a $\sim 1/0.63$ times higher redshift compared to $\Lambda\mathrm{CDM}$

→ reduced **dark matter** at z_* [Hahn, RH 2017; Hahn, RH, Kramer 2018]

→ predicts (comov) sound horizon (at baryon drag) such that H_0 **in agreement with local observation, later**

→ **But:** requires interpolation to low-z $\Lambda\mathrm{CDM}$ [Bernal et al 2016; Riess et al 2018; Bonvin et al 2016]

(de-percolation of Planck-scale axion vortices)



re-combination de-percolation re-ionisation

$\mathrm{SU}(2)_{\mathrm{CMB}}$ and a Planck-scale axion (PSA): dark sector

– **ultralight pseudo-scalar field** φ first proposed by **Frieman et al. 1995** and revived by **Wilczek et al 2004** to serve as quintessence

[Peccei, Sola ,Wetterich 1987; Wetterich 1988; Peebles, Ratra 1988]

– **conceptual underpinning:** radiative protection of a rather strongly determined potential arising from an explicit, quantum-anomaly induced breaking (topological charge!) of a dynamically broken global U(1) symmetry

[Adler,Bardeen,Bell,Jackiw1969; Fujikawa 1979;Peccei, Quinn 1977]

– **dynamical breaking (Peccei-Quinn scale):**
Planckian physics in a de Sitter spacetime $\longrightarrow$ PQ scale: $\boxed{M_P \sim 10^{19}\,\mathrm{GeV}}$

[Giacosa, Neubert, RH 2008]

explicit breaking:
deconfining thermal ground states of Yang-Mills theories

– **on cosmological scales**, only presently **deconfining YM theory:** $\mathrm{SU}(2)_{\mathrm{CMB}}$

$\longrightarrow$ **axion mass:**

$$\boxed{m_a = \frac{\Lambda^2_{\mathrm{CMB}}}{M_P} \sim 10^{-36}\,\mathrm{eV} \sim H_0}$$

$\mathrm{SU(2)_{CMB}}$ and PSA: percolated and depercolated PSA vortices

–transitions from deconfining to confining phases in SU(2) YM are **highly nonthermal** (Hagedorn)

[RH 2007]

$\longrightarrow$ U(1) phase φ may wind around S_1 $\longrightarrow$ **PSA vortices**

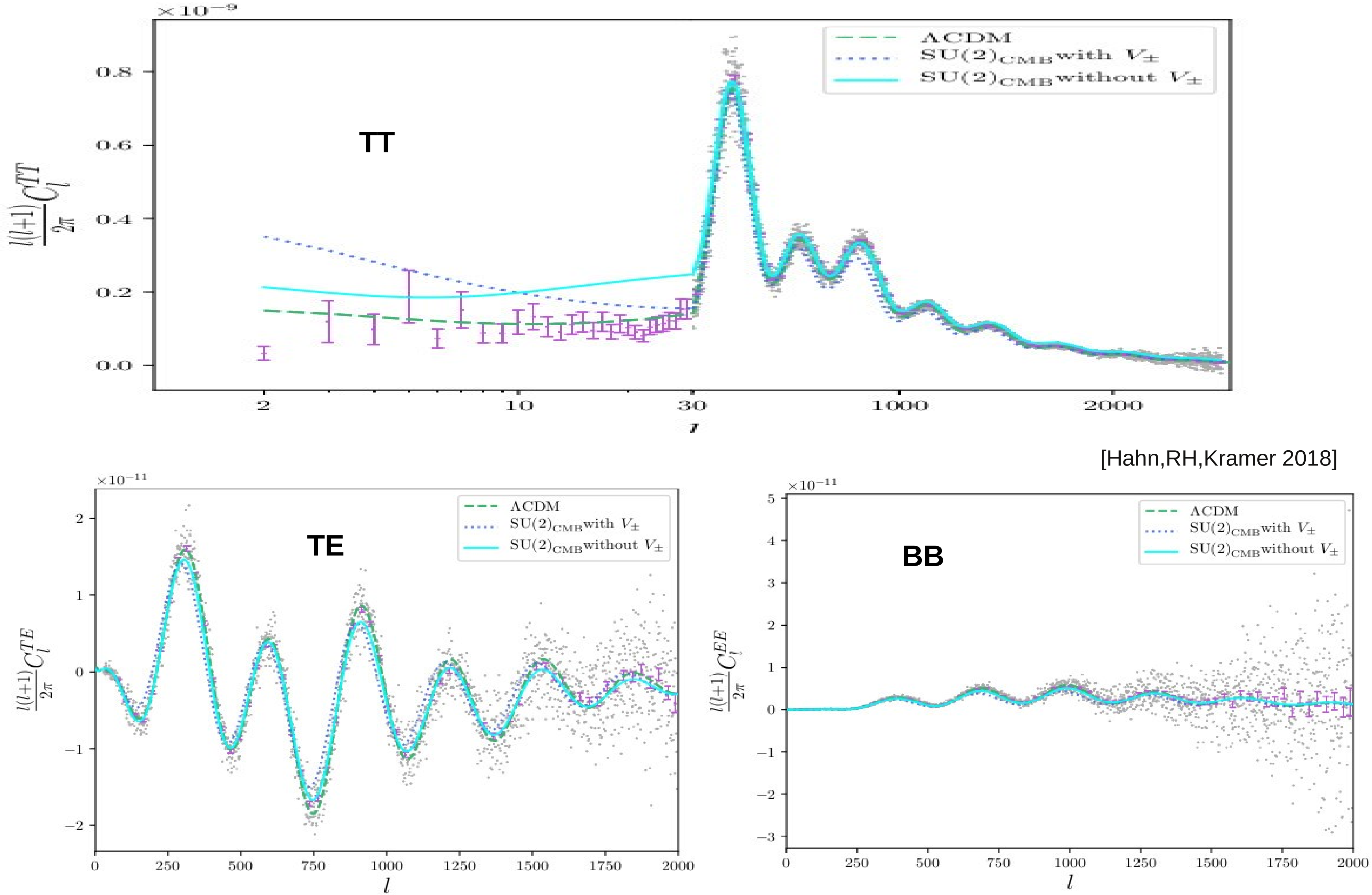
– PSA percolate in **Berezinski-Kosterlitz-Thouless** transition subsequent to **Hagedorn** (not unreasonable to assume **DE e.o.s. for percolate**)

– de-percolation at some redshift z_p , DE e.o.s. transforms into DM e.o.s.

$$\hat{\rho}_{\mathrm{DS}} = \hat{\rho}_{\Lambda} + \hat{\rho}_{\mathrm{CDM},0} \cdot \begin{cases} (z+1)^3 & (z < z_p) \\ (z_p+1)^3 & (z \geq z_p) \end{cases}$$

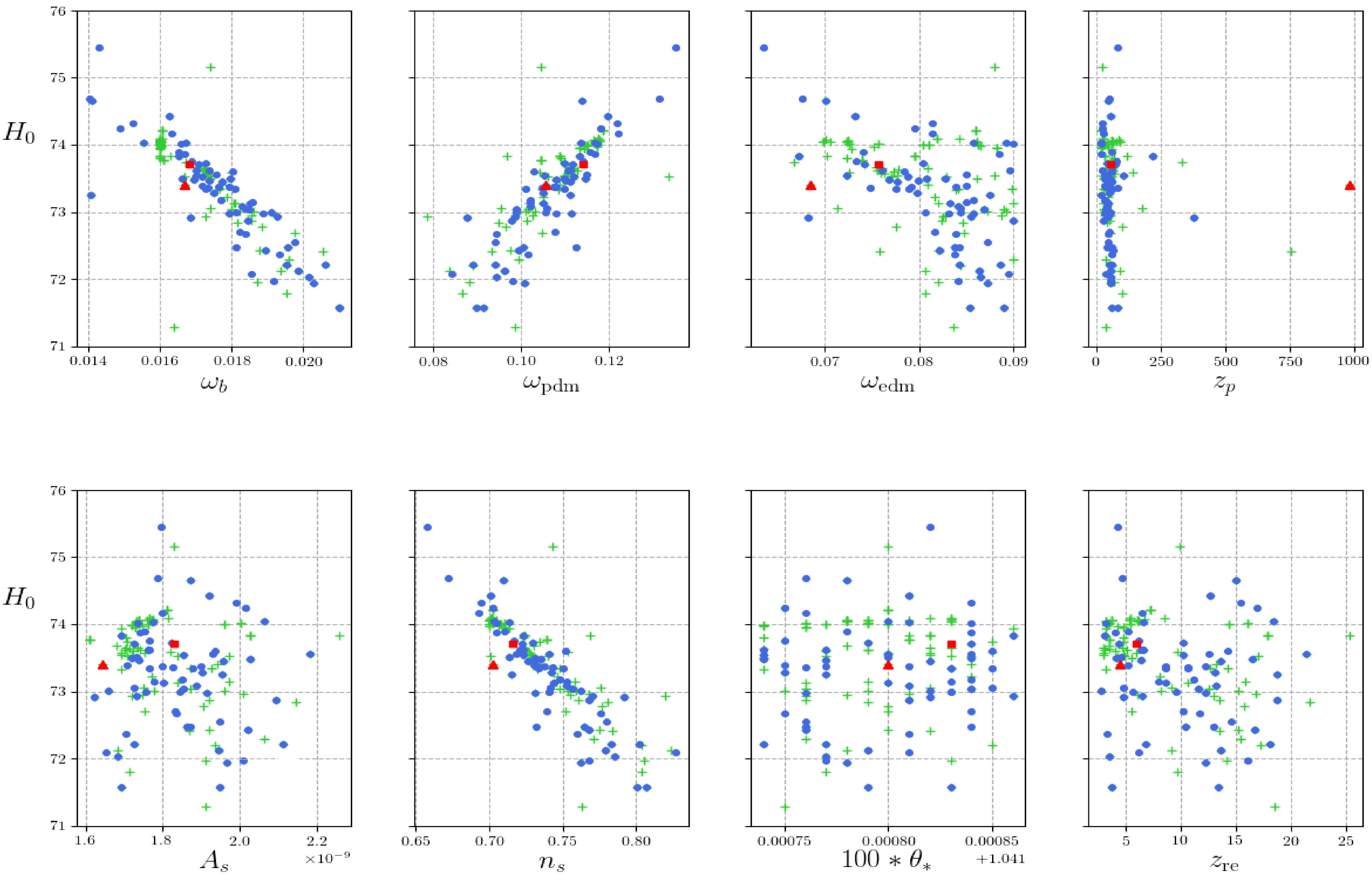
(interpolation of high-z model to $\Lambda\mathrm{CDM}$)

$\mathrm{SU}(2)_{\mathrm{CMB}}$ and PSA: fits to angular power spectra



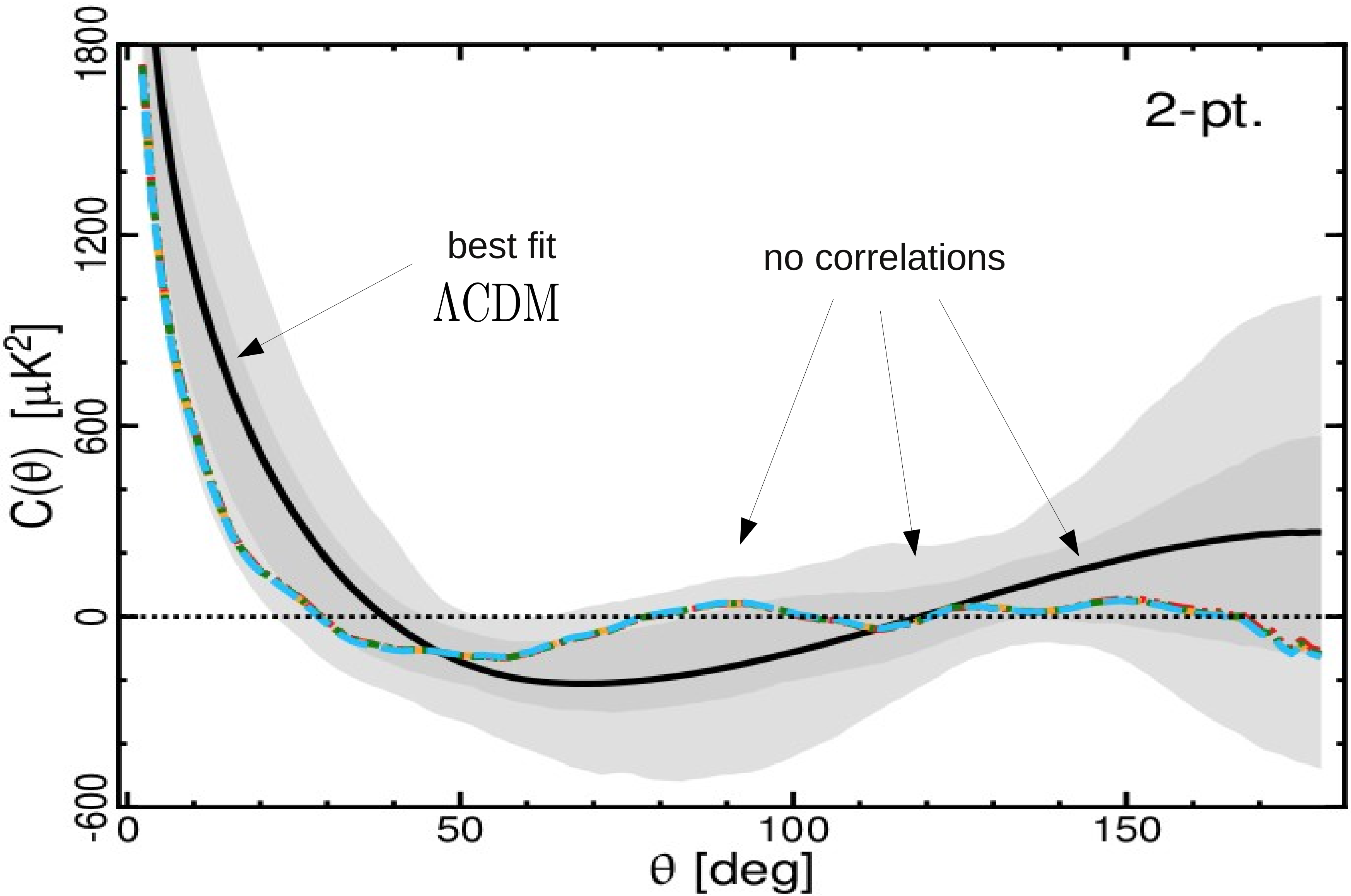
[Hahn,RH,Kramer 2018]

$\mathrm{SU}(2)_{\mathrm{CMB}}$ and PSA: H_0 and r_{re}



$\mathrm{SU}(2)_{\mathrm{CMB}}$ and thermal photon dispersion law: CMB at large angles

– TT correlation function $C(\theta)$ (PLANCK) [courtesy: Schwarz, Copi, Huterer, Starkman 2015]



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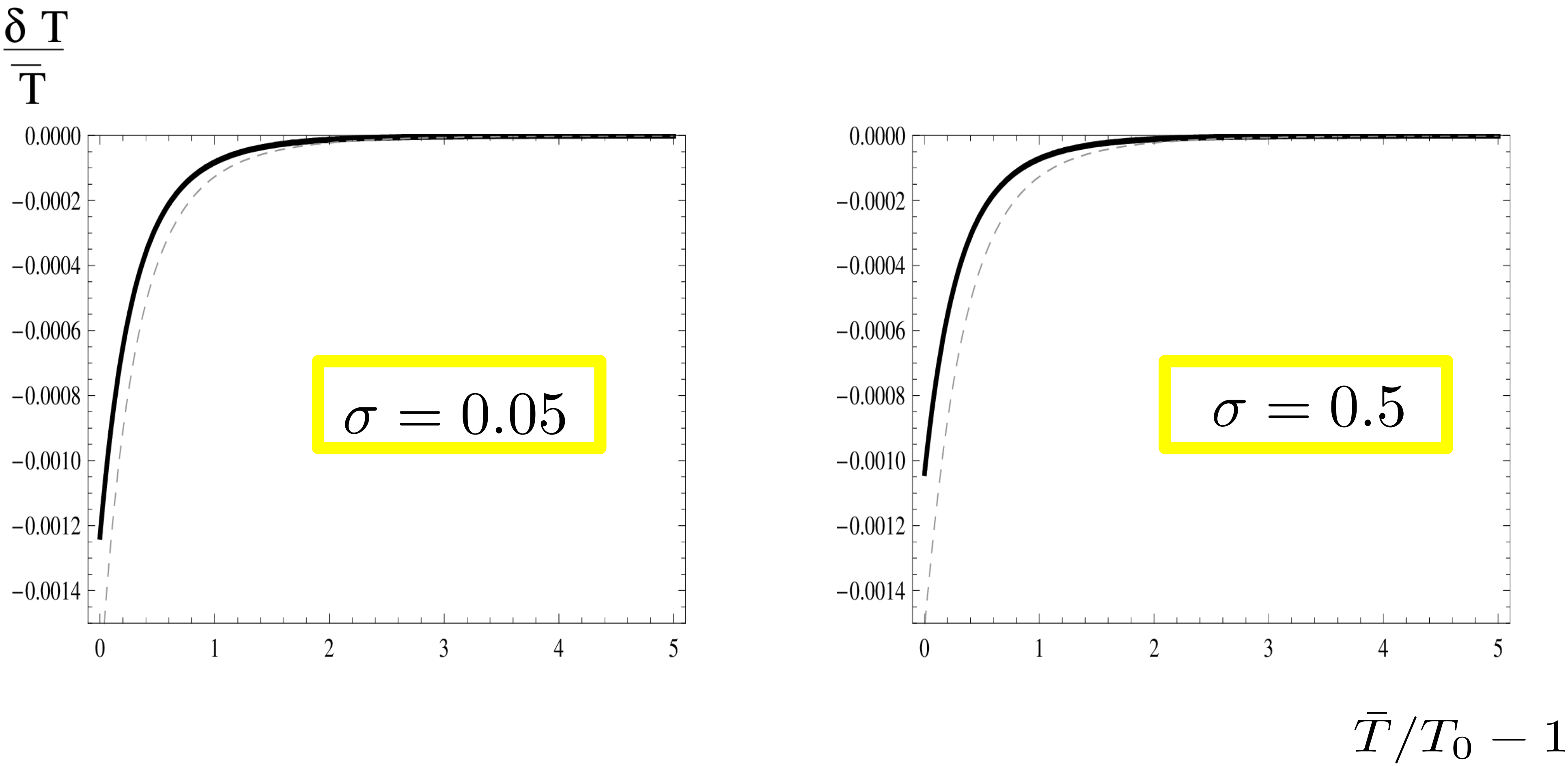


→ **at around z~1:** rapid formation of temperature depression

[Szopa, RH 2007; Ludescher, RH, 2008]

Summary:

- nonabelian gauge principle: group **SU(2)**
- (anti)selfdual gauge fields, stable and unstable **(anti)calorons**

- sketch of **a priori estimate**
- properties of stable (anti)calorons
- ground-state permittivity and permeability
- excitations: waves vs. particles

- evolution of **coupling**
- **pressure and energy density**

- **loop expansion** of pressure
- **polarisation tensor**

- applications to CMB: $\mathrm{SU}(2)_{\mathrm{CMB}}$
  fixation of Yang-Mills scale; T-z relation; 3D Ising exponent;
  re-visiting the cosmological model at high-z;
  low-z induction of large-angle anomalies

Acknowledgements: **extremely helpful theoretical physics or mathematics or observation**

… and many, many more.

important practical support and/or guidance/collaboration

… amongst many others.

Collaborators

Ulrich Herbst
Francesco Giacosa
Markus Schwarz
Jochen Rohrer
Josef Ludescher
Jochen Keller
Carlos Falquez

Michal Szopa
Matthias Neubert
Dariush Kaviani
Nucu Stamatescu
Sebastian Scheffler
Niko Krasowski

Julian Moosmann
Steffen Hahn
Ingolf Bischer
Thierry Grandou
Daniel Kramer
Philip Matthias

Thank you!

Low-temperature photon gases: electric-magnetically dual interpretations of $\mathrm{U}(1) \subset \mathrm{SU}(2)$

– 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

$$\boxed{\alpha = \frac{Q^2}{4\pi\hbar}\,,}$$

– for α to be unitless:

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

But: magnetic coupling in SU(2)

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

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

$\mathrm{SU(2)_{CMB}}$ and a Planck-scale axion (PSA): dark sector

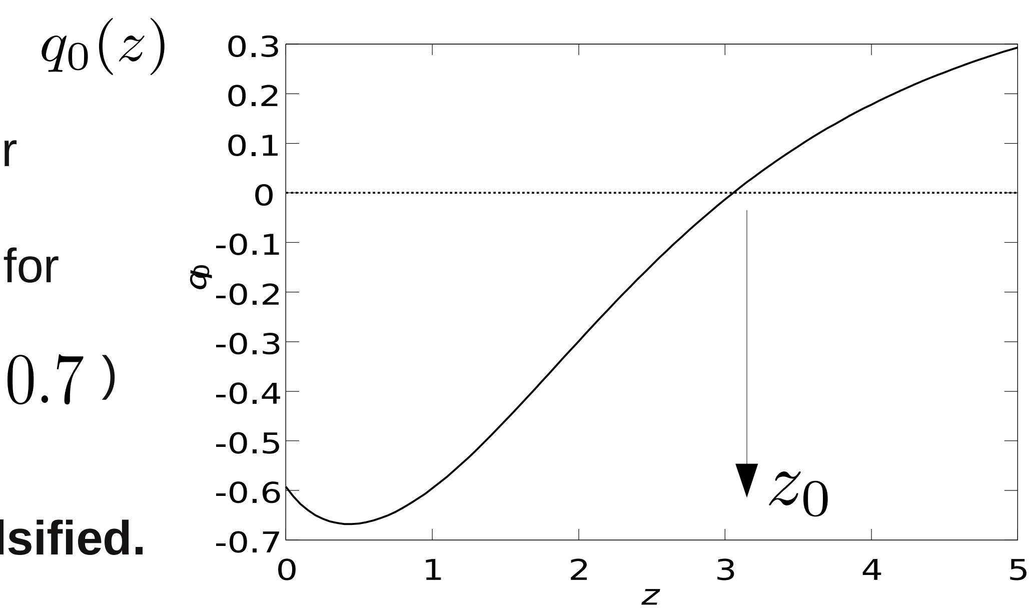
– **interesting coincidence:** $m_a \sim H_0$

(in view of $\boxed{\ddot{\varphi} + 3H\dot{\varphi} + \frac{\mathrm{d}}{\mathrm{d}\varphi}V(\varphi) \sim \ddot{\varphi} + 3H\dot{\varphi} + m_a^2\varphi = 0}$)

energy density in **damped oscillations** (DM eos) **comparable** to potential energy density (DE eos)
Notice: in $\Lambda\mathrm{CDM}$ $\boxed{\Omega_\Lambda = 0.7 \sim \Omega_{\mathrm{DM},0} = 0.25}$

However: deacceleration parameter

Universe accelerates **too early** for **viable structure formation** ($z_0 > 3$ as opposed to $z_0 \sim 0.7$)



Homogeneously oscillating PSA field falsified.

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– to address these in $\mathrm{SU}(2)_{\mathrm{CMB}}$ **CMB Boltzmann hierarchies** plus **evolution of curvature perturbations** subject to new cosmological model with modified T-z relation must be solved
[under investigation]

– **first-shot approach:**

treat T as a scalar field, introduce kinetic term, and take potential from integrated BB anomaly $\longrightarrow$ e.o.m. (spherical symm. + linear fluct.)

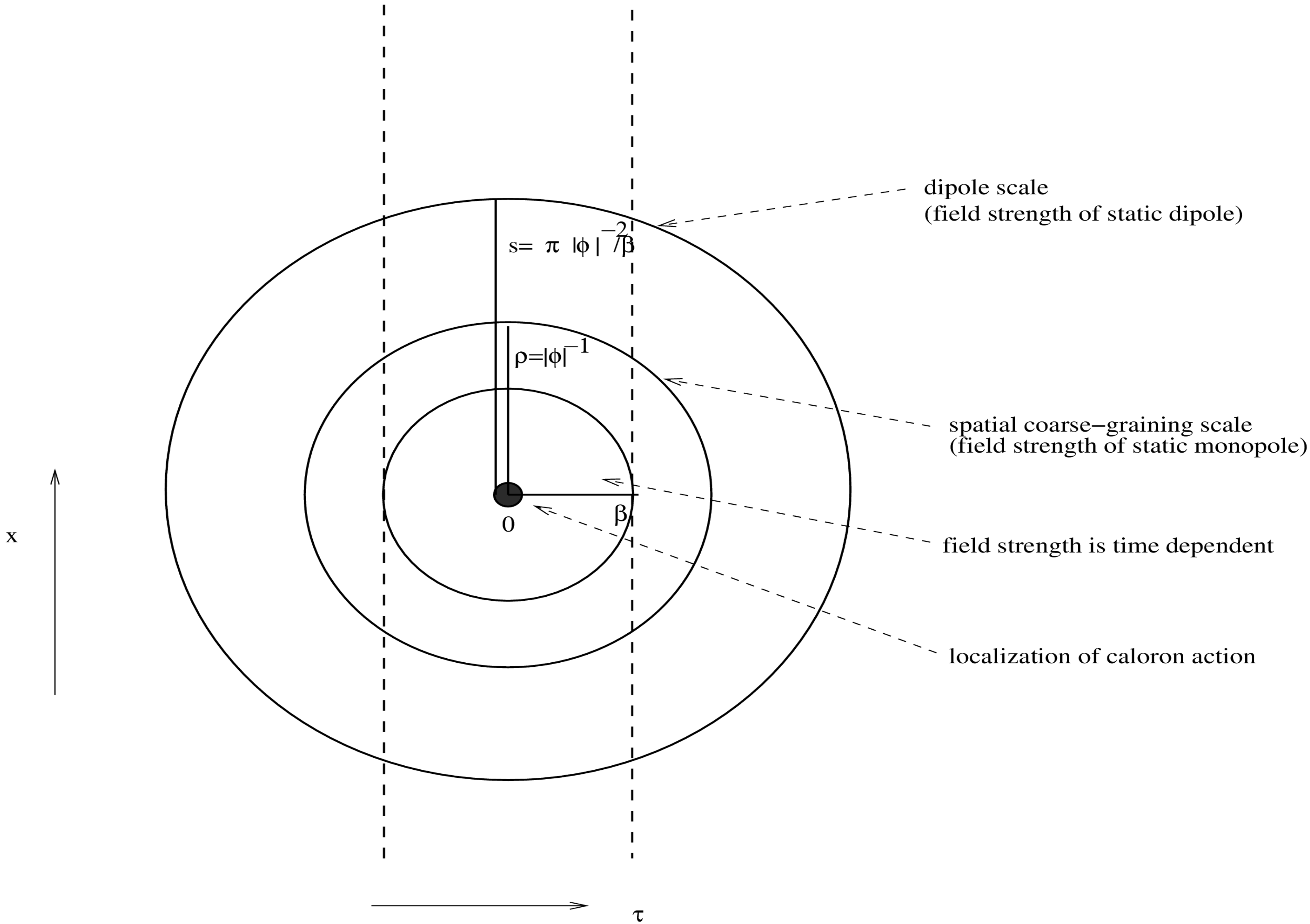
$$0=\partial_\tau\partial_\tau\delta T-\left(\frac{\mathrm{d}a}{a\,\mathrm{d}\tau}\right)^2\left[\partial_\sigma\partial_\sigma\delta T+\frac{2}{\sigma}\,\partial_\sigma\delta T\right]-\frac{3}{\bar{T}}\,\partial_\tau\bar{T}\,\partial_\tau\delta T+\frac{\bar{T}_0^2}{kH_0^2}\left[\frac{1}{2}\,\frac{\mathrm{d}^2\hat{\rho}}{\mathrm{d}T^2}\bigg|_{T=\bar{T}}\delta T+\frac{1}{2}\,\frac{\mathrm{d}\hat{\rho}}{\mathrm{d}T}\bigg|_{T=\bar{T}}\right]$$

to be determined from Doppler inferred discrepancy between measured and predicted dipole

[Szopa, RH 2007; Ludescher, RH 2009]

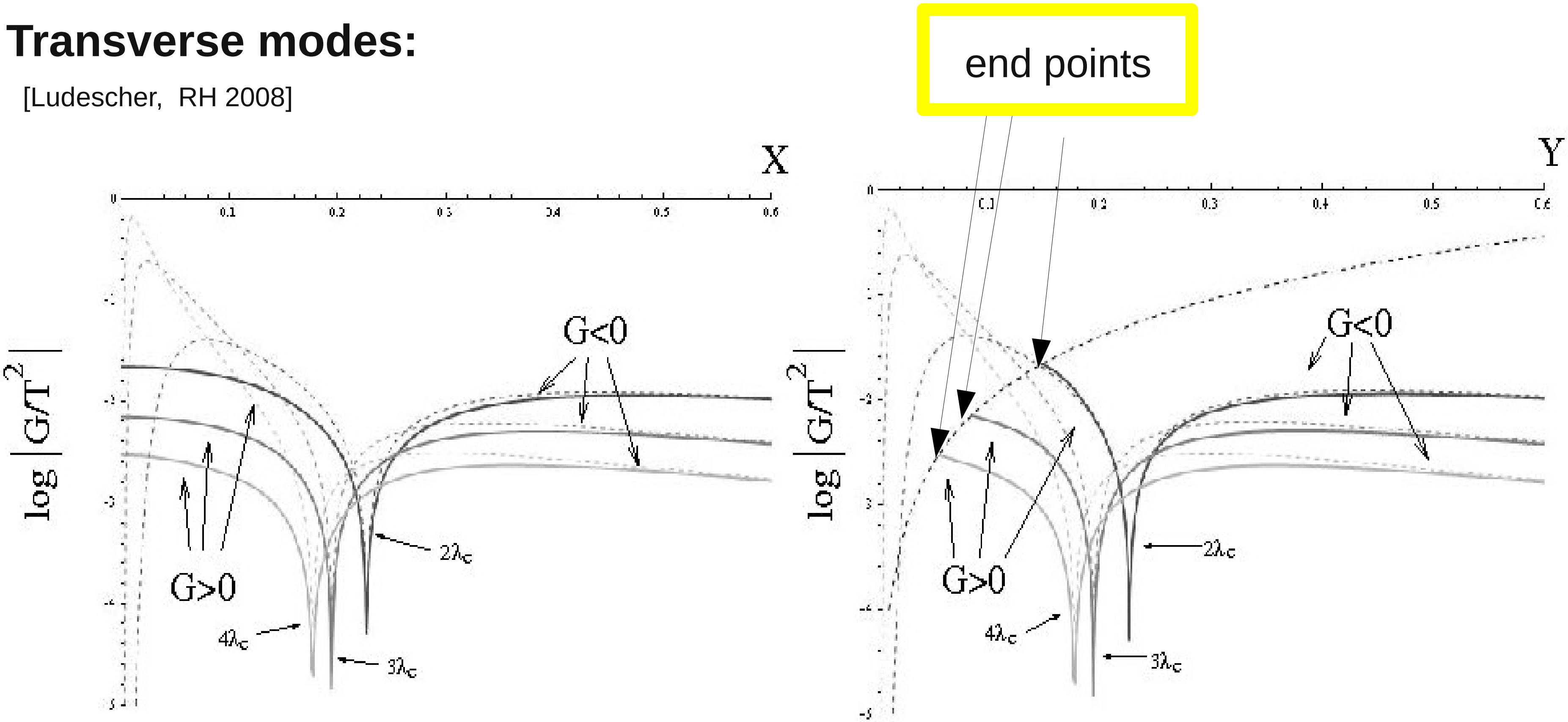
Deconfining thermal ground-state estimate

Anatomy of (stable) HS caloron:



Transverse modes:

[Ludescher, RH 2008]



→ **modified spectral radiance in black-body (BB) radiation**