Black-body radiation and Yang-Mills thermodynamics

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Universität Karlsruhe (TH)
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outline

- Planck: a heroic deed (h and BB radiation law)
- Einstein and Bohr: putting h into practice (light-quantum and H-atom)
- present experimental (observational) situation: photon physics
- SU(2) YM thermodynamics: de- and preconfining phase
- $\mathrm{SU(2)_{CMB}}$:

  astrophysical and cosmological implications
- summary and outlook

Max Planck (1900,1901):

spectral intensity I of perfect black body from:

1) N randomized resonators
2) entropy S of single resonator as function of its internal energy U
   $\Rightarrow \frac{dS}{dU} = \frac{1}{T}$
3) Boltzmann's definition of total entropy S_N:
   $S_N \equiv k \log W +$ const.
4) implicit: total energy distributed on N resonators in units of a smallest quantum ϵ
5) Wien's displacement law:
   $I = T^5 \frac{c^3}{\nu^2} F\left(\frac{T}{\nu}\right)$.

$$\Rightarrow S = f\left(\frac{U}{\nu}\right) \overset{\text{Boltzmann}}{\Longrightarrow}$$

$$\boxed{\epsilon = h\nu}$$ (h a constant)

$$\Rightarrow U = \frac{h\nu}{\exp[h\nu/(kT)]-1} \Rightarrow$$

$$\boxed{I = \frac{8\pi h\nu^3}{c^3}\frac{1}{\exp[h\nu/(kT)]-1}}$$

Planck’s derivation:

h parametrizes microscopic disorder in single resonator!

Albert Einstein (1905):

photoelectric effect
and quantum of light:

1) electron kicked out of metal
2) kinetic electron energy K:

$$K = h\nu - W$$

Niels Bohr (1913):

discrete transitions and quantization of angular momentum in H-atom:

$$E_1 - E_2 = h\nu,\, L = n\hbar \Rightarrow$$

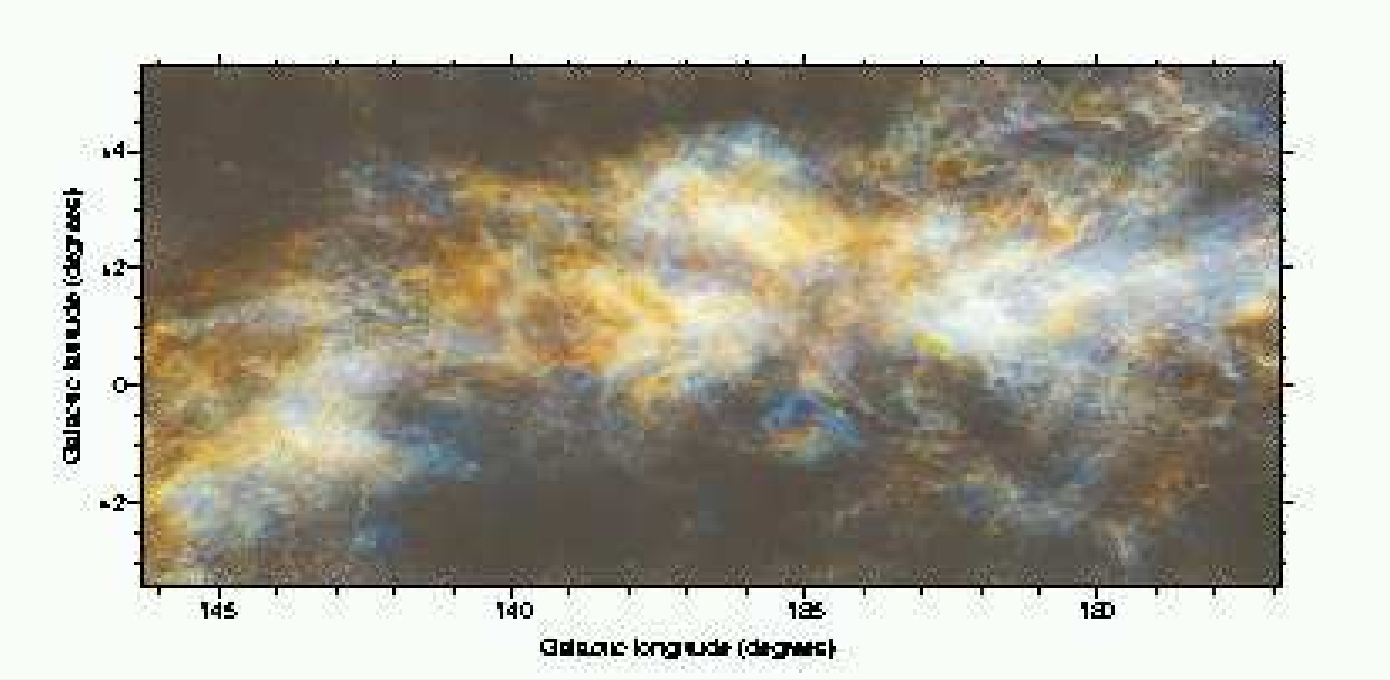
$\Rightarrow$ explanation of Rydberg series

photons: recent experiments

- cold and dilute HI clouds in Milky Way

  [Brunt and Knee, Nature 412, 308 (2001)]

  age: $5 \times 10^7\, y$, temperature: $5\,\mathrm{K}$-$10\,\mathrm{K}$, density: $1\,\mathrm{cm}^{-3}$

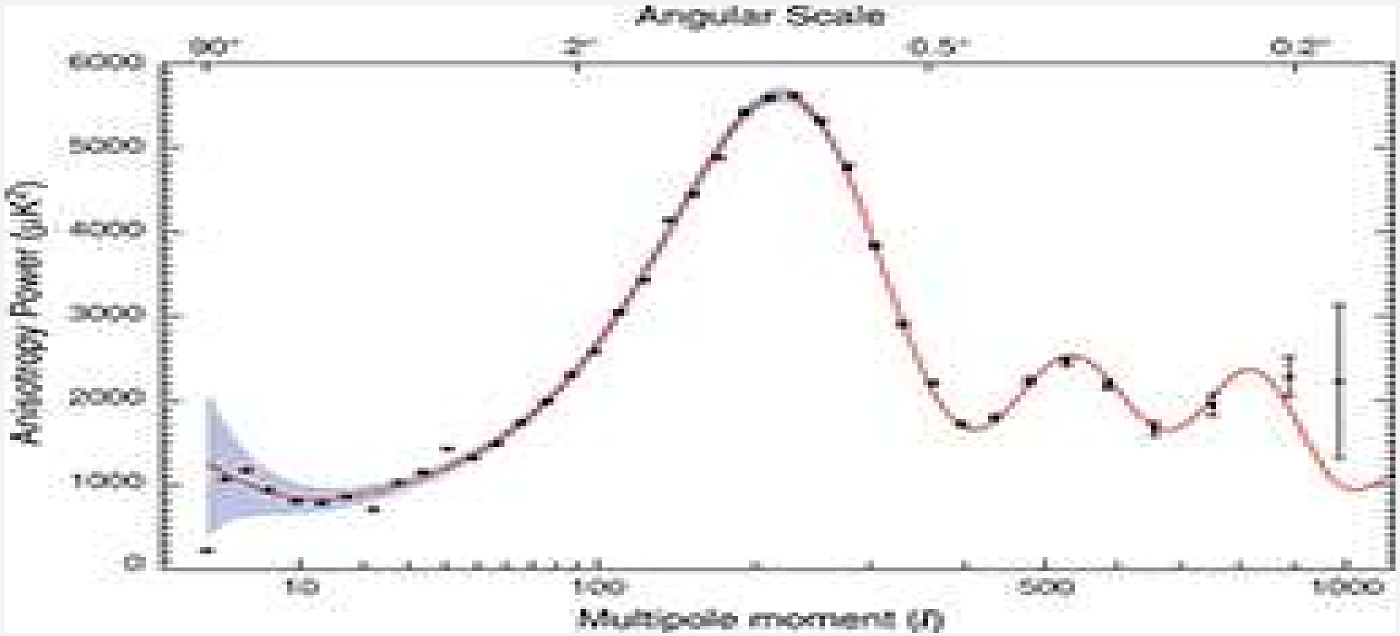


- low multipoles in CMB (WMAP)

  [Copi et al., Phys. Rev. D. 75: 023507 (2007)]

  – strongly suppressed TT correlations for $\theta > 60$ degrees

  – low multipoles statistically correlated



- PVLAS experiment

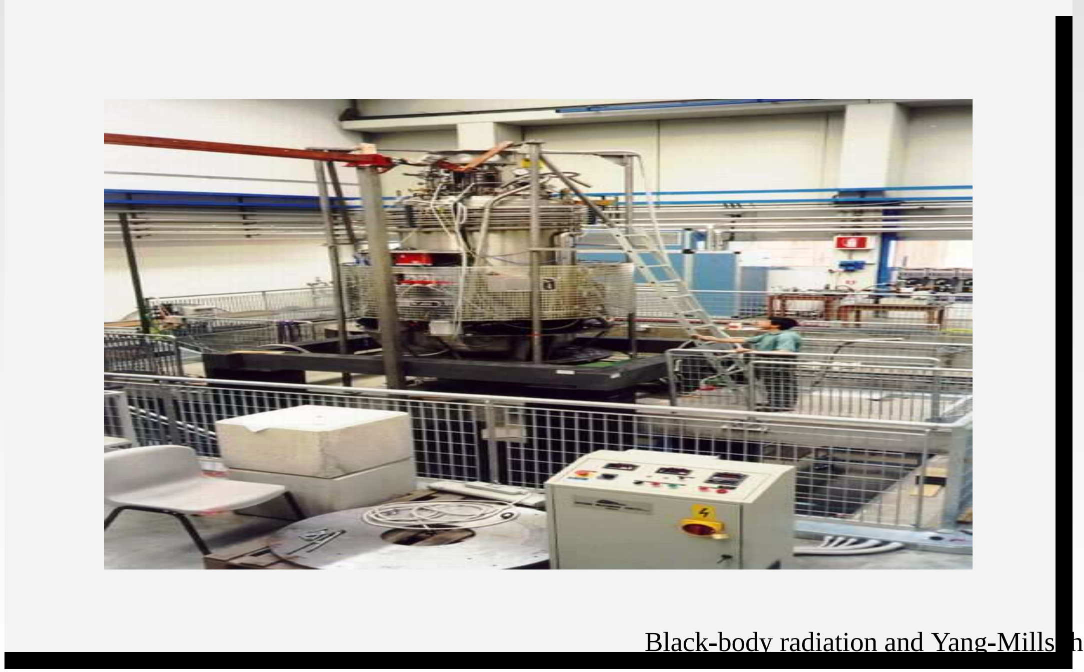
  [E. Zavattini et al., Phys. Rev. Lett. 96, 110406 (2006)]

  – measurement at

  $B = 5.5\,\mathrm{T}$, $\lambda \sim 10^3$ nm (lin. pol. laser)

  – rotation of polarization axis $\sim 10^4$

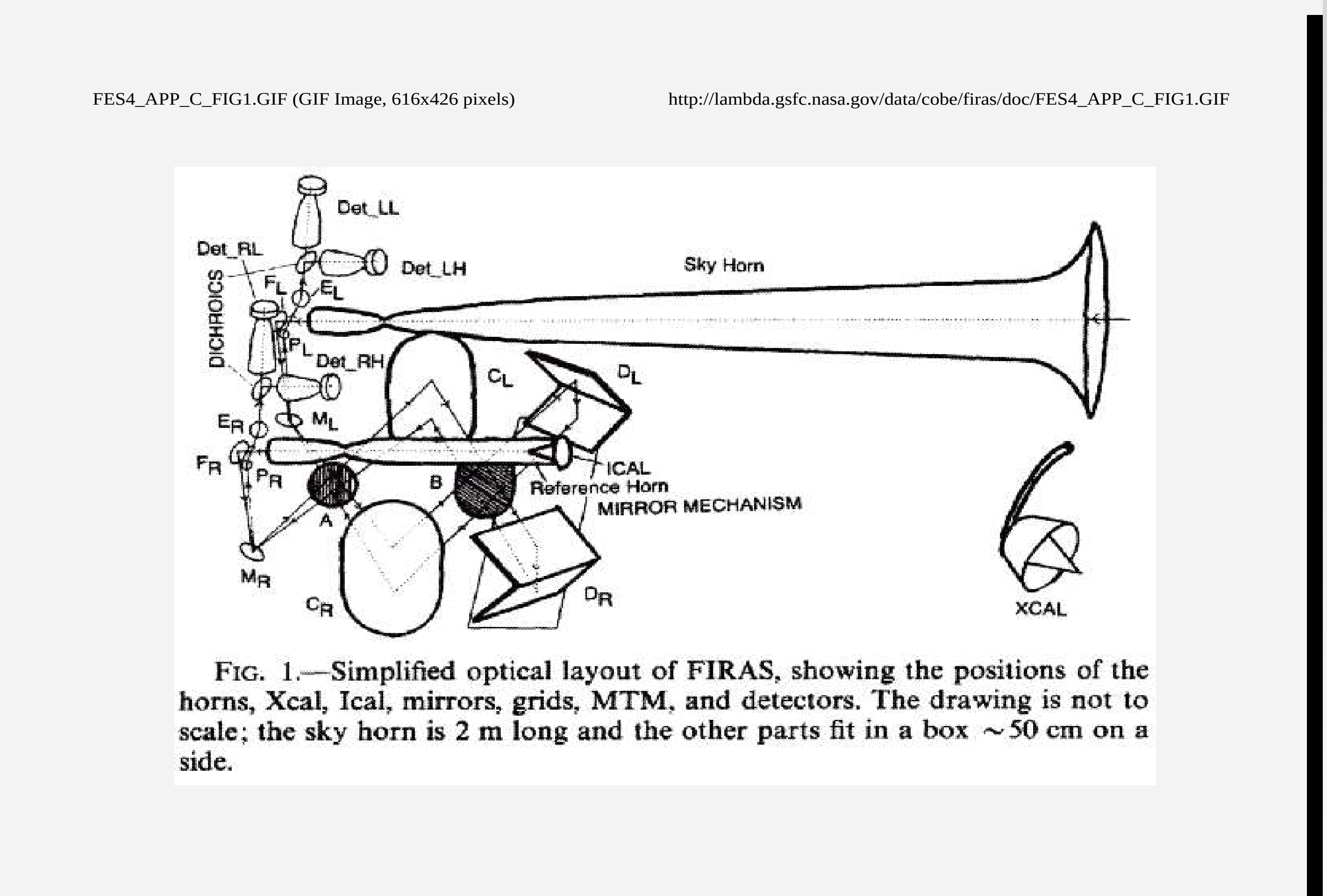
  times larger than QED prediction



- Cobe (FIRAS): temperature calibration

  [Mather et al., APJ 420, 439 (1994)]

  radiation temp. versus calibrator temp.



FES4_APP_C_FIG1.GIF (GIF Image, 616x426 pixels) http://lambda.gsfc.nasa.gov/data/cobe/firas/doc/FES4_APP_C_FIG1.GIF

FIG. 1.—Simplified optical layout of FIRAS, showing the positions of the horns, Xcal, Ical, mirrors, grids, MTM, and detectors. The drawing is not to scale; the sky horn is 2 m long and the other parts fit in a box ~50 cm on a side.

extreme supercooling

(increase of effective number of photon polarizations?)

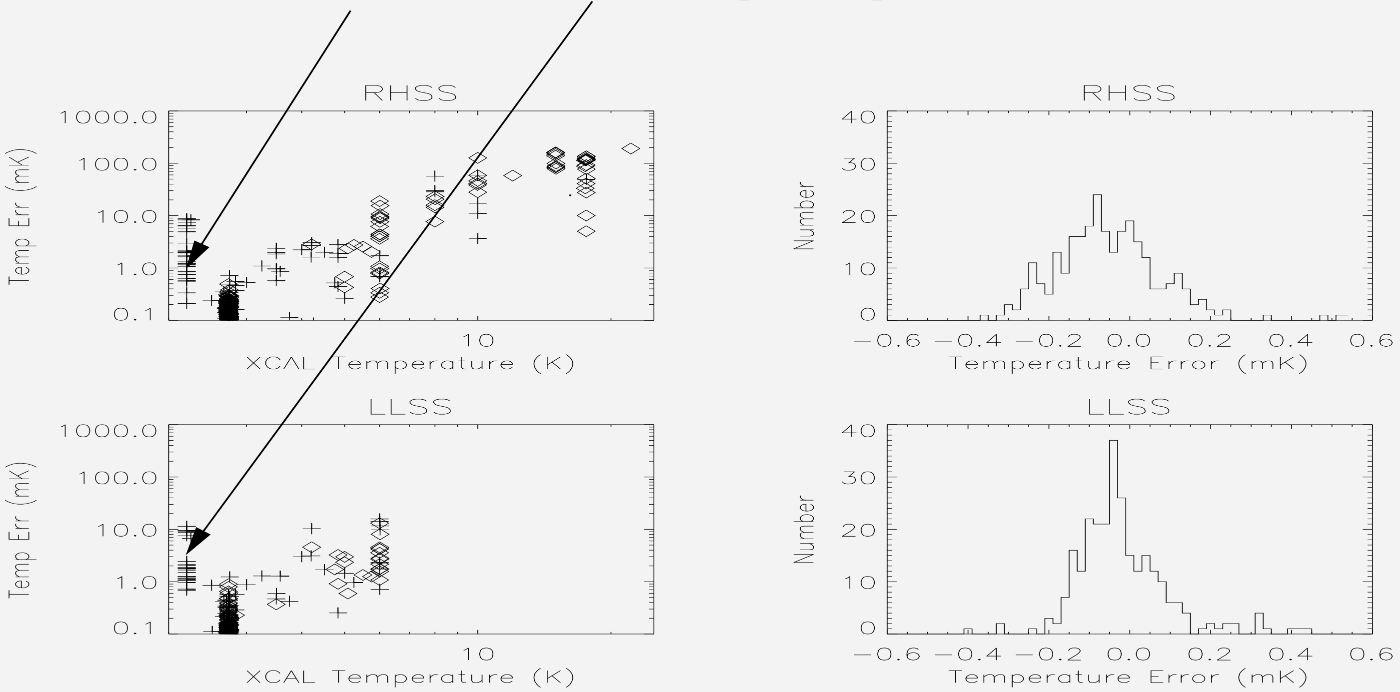


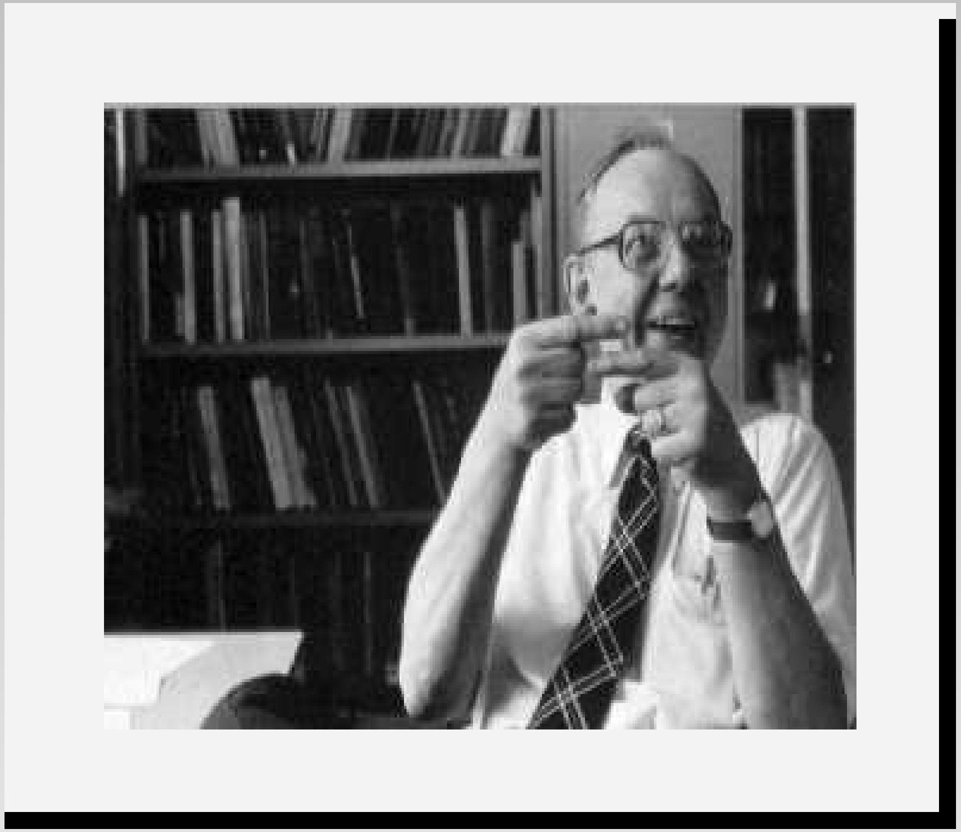
Fig. 5.3.— Photometric XCAL temperature adjustments — The values for RHSS (top plots) and LLSS (bottom plots) calibrations are shown here. The left hand plots are the adjustments (in mK), plotted as a function of XCAL temperature (in K). The symbol + indicates a positive correction, and the symbol ⋄ indicates a negative correction. Temperatures greater than 7K are not used in LLSS. On the right are histograms of temperature adjustments for cold nulls (i.e. all controllables $\sim$2.7K).

What happens when postulating photon PROPAGATION due to SU(2) gauge principle?

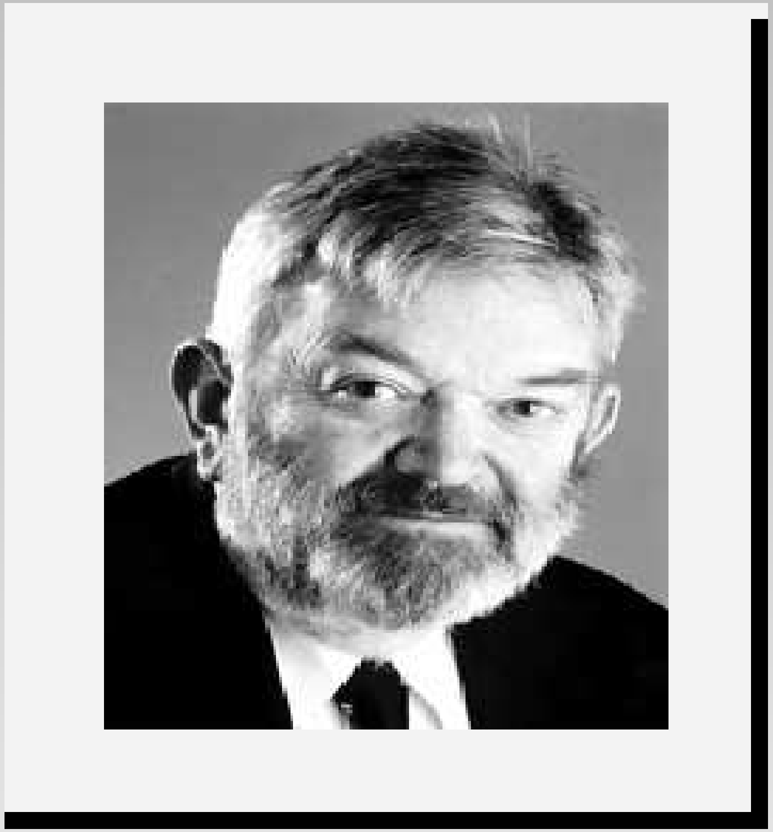
– needs analytical approach to SU(2) Yang-Mills theory

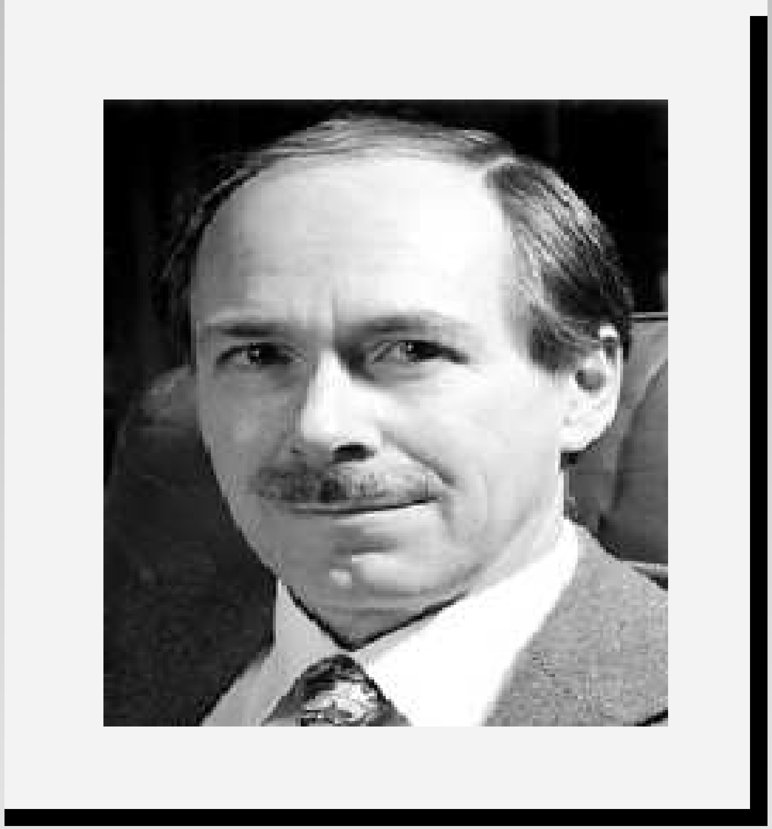
– presently possible thermodynamically
[RH, IJMPA20, 4123 (2005), ...]

– among others relying on work by ...



Formulation of SU(2) gauge theory (1955).





- pert. renormalizability of YM
- magnetic monopole
- selfdual, singular-gauge constructions ⇒
- trivial-holonomy calorons
  [Harrington and Shepard, 1977]
- center-vortex, ’t Hooft loop

- calorons of nontrivial holonomy
  (magnetic dipole constituents, (1983)) ⇒
- explicit construction using Nahm trafo and ADHM

  [Lee and Lu, Kraan and van Baal 1998]

phase diagram: SU(2) YM TD

confining

ground state:

Cooper−pair condensate of single center−vortex loops, pressure precisely zero

excitations:

massless (single) and massive (self−intersecting) center−vortex loops (spin−1/2 fermions)

preconfining

ground state:

condensate of magnetic monopoles, collapsing center−vortex loops, negative pressure

excitations:

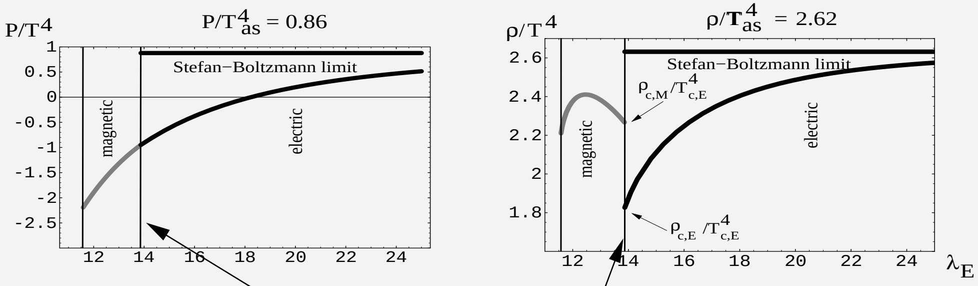
massive dual gauge modes

deconfining

ground state: interacting calorons and anticalorons, negative pressure

excitations: massless and massive gauge modes

power−like approach to Stefan Boltzmann limit



decoupling of V^+, V^-, no (anti) screening

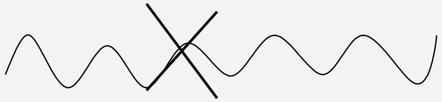
$T_c = 2.73$ K ⟶ $\Lambda \sim 10^{-4}$ eV

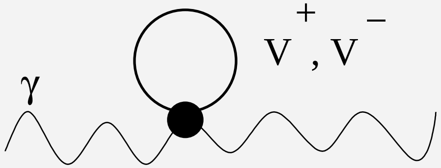
T_c

T

Hagedorn

2nd order like

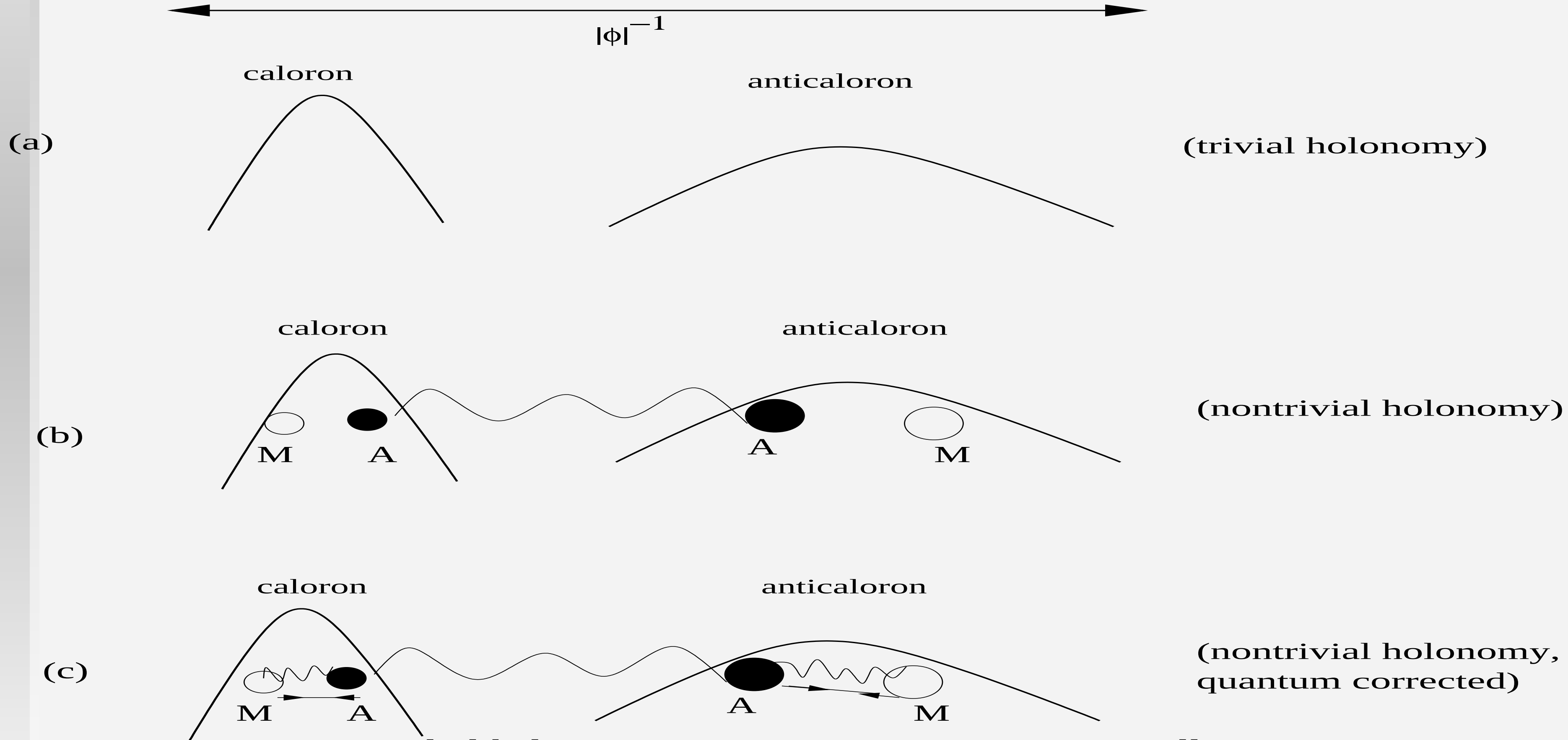




(anti) screening

a thermal ground state:

deconfining phase:



attraction extremely likely => negative pressure macroscopically
repulsion extremely unlikely => isolated and screened magnetic monopoles

technically:

spatial coarse-graining, infinite volume

$\Rightarrow$ phase of emergent adjoint scalar ϕ^a:

$$\hat{\phi}^a(\tau) \sim \sum_{\text{HS (anti)caloron}} \mathrm{tr} \int d^3x \int d\rho \, \frac{\lambda^a}{2} \times$$

$$F_{\mu\nu}\left((\tau,0)\right) \left\{(\tau,0),(\tau,\vec{x})\right\} \times$$

$$F_{\mu\nu}\left((\tau,\vec{x})\right) \left\{(\tau,\vec{x}),(\tau,0)\right\} \,.$$

infinite-volume average saturates at

$$\rho, |\vec{x}| < |\phi|^{-1} = \sqrt{\frac{2\pi T}{\Lambda}}$$

$\Rightarrow$ coarse-graining sufficiently local to include only $|Q| = 1$ (anti)calorons

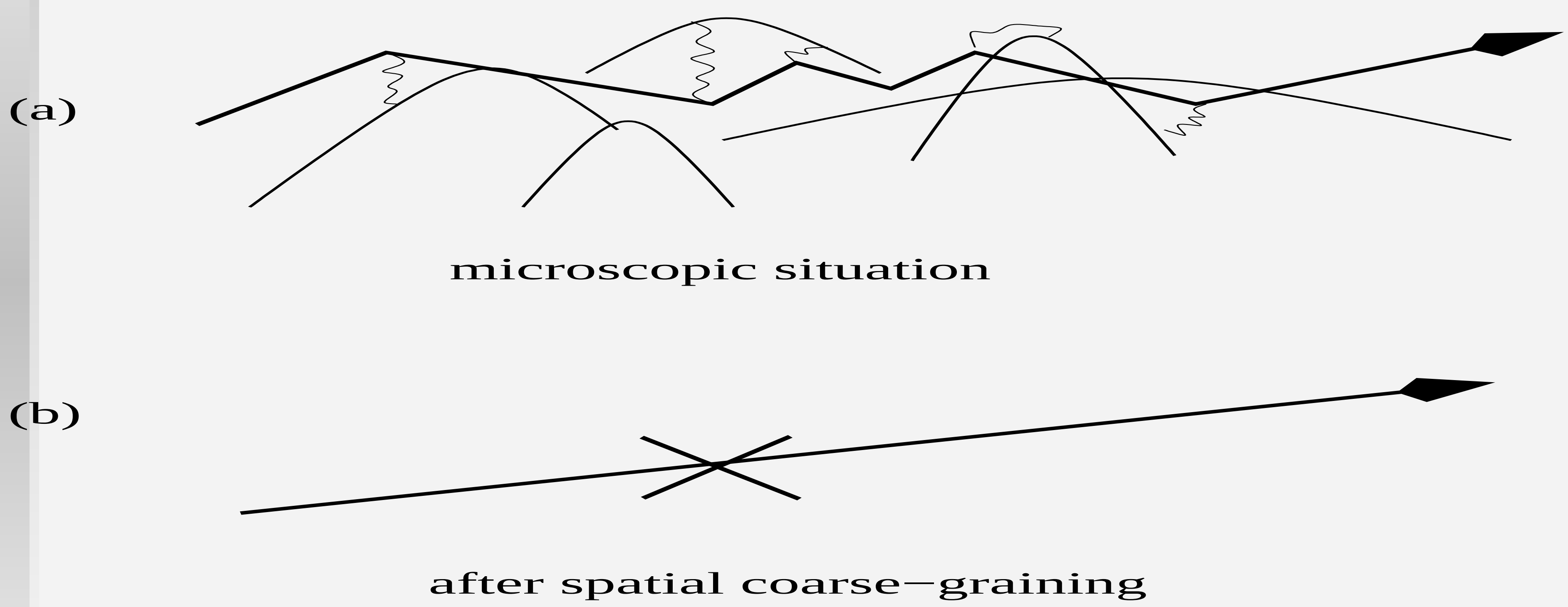
$\Rightarrow$ ground state described by (inert) field ϕ and a $Q = 0$ (coarse-grained) pure-gauge config. $a_\mu^{g.s.}$

$\Rightarrow$ show electric Z_2 degeneracy (Polyakov loop)

$\Rightarrow$ deconfining phase

emergent mass

deconfining phase, adjoint Higgs mechanism:



⇒ T dependent mass for two out of three directions

⇒ quasiparticles on tree level in effective theory

interactions

quantum fluctuations constrained by $|\phi|$:

$\Rightarrow$ two-loop versus one-loop: $\leq 10^{-3}$
[Schwarz, RH, Giacosa, IJMPA22, 1213 (2007)]

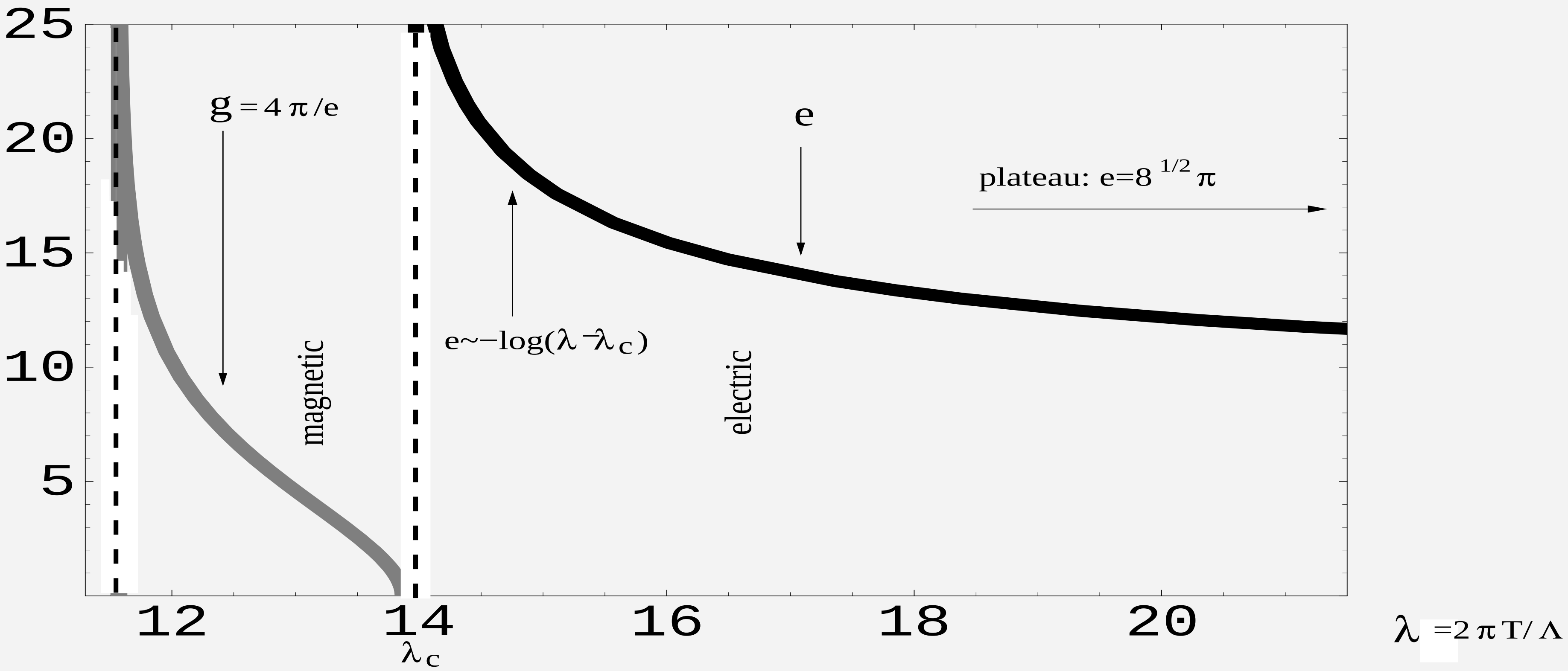
$\Rightarrow$ three-loop versus one-loop: $\leq 10^{-7}$
[Kaviani, RH, arXiv:0704.3326 [th]]

$\Rightarrow$ mod. 1-PI res. rapidly conver. loop expan.
[RH, hep-th/0609033]

$\Rightarrow$ running of effective coupling e **entirely** sufficient at one-loop level

running effective coupling

de - and preconfining phases:

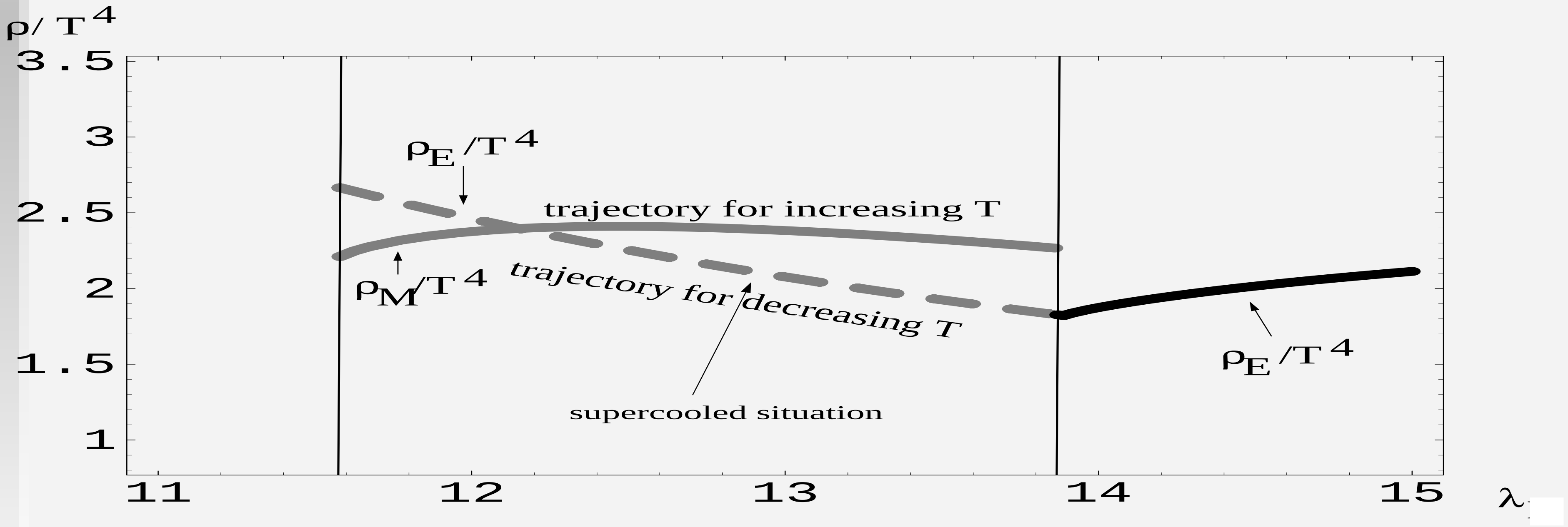


scale of SU(2)$_{\text{CMB}}$:

if photon propagation described by SU(2) YM

$\xRightarrow{\text{COBE,FIRAS}}$ boundary between de- and preconfining phase

$$\Rightarrow \qquad \Lambda_{\text{CMB}} \sim 10^{-4}\,\text{eV}$$



phase transition:

rather independently of cosmological model

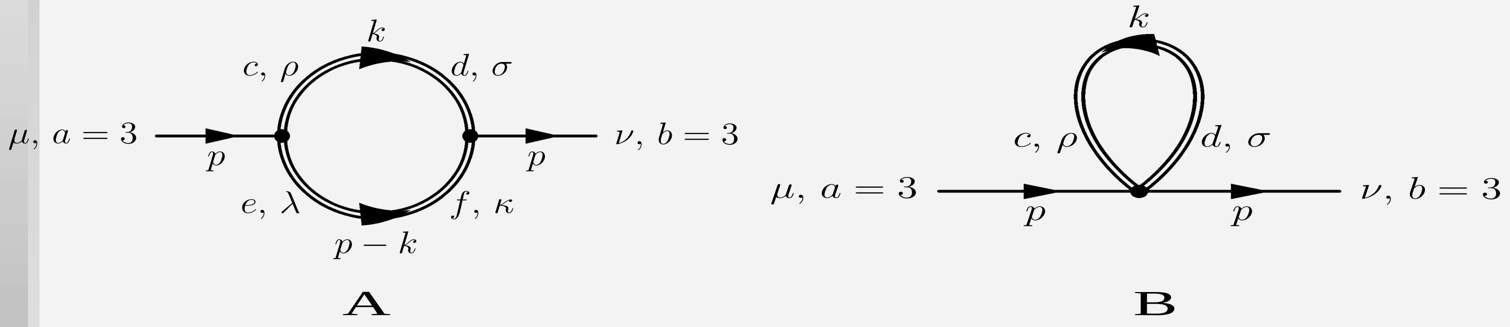
$\xRightarrow{H_0}$ duration $\Delta t_{m_\gamma=0}$ of supercooled situation:

$$\Delta t_{m_\gamma=0} = (2.2 \pm 0.15)\,\mathbf{Gy}$$

[Giacosa and RH, EPJC50, 635 (2007)]

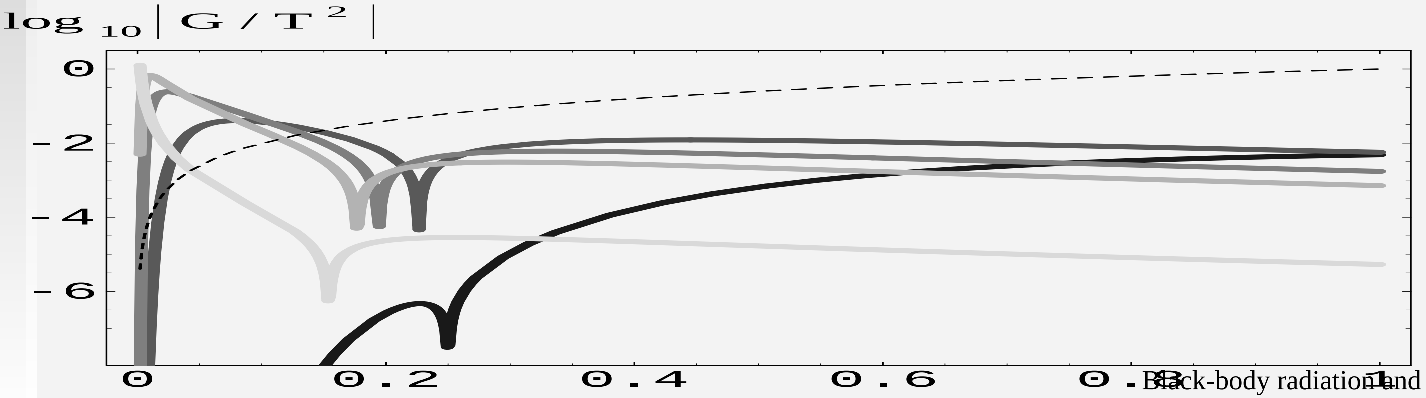
photon screening:

polarization tensor in effective theory:



modification of dispersion law:

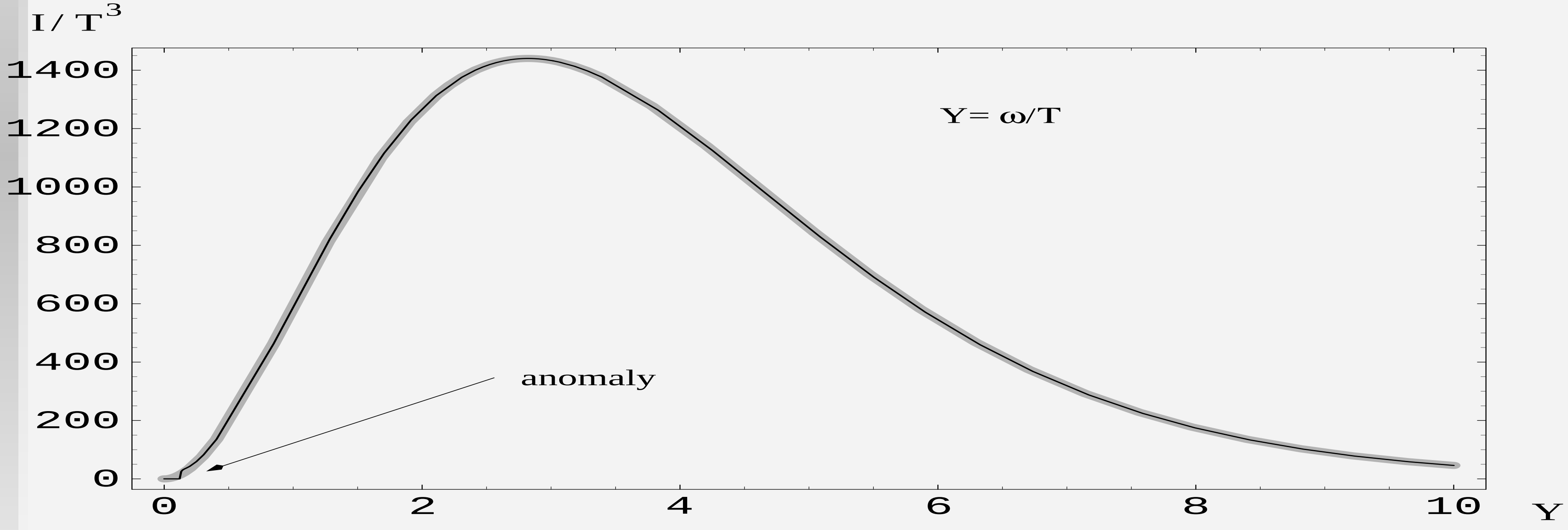
$$\omega^2=\vec{p}^2+G(T,|\vec{p}|)$$



mod. black-body spectrum (1):

[Schwarz, RH, Giacosa; IJMPA, JHEP 2007]

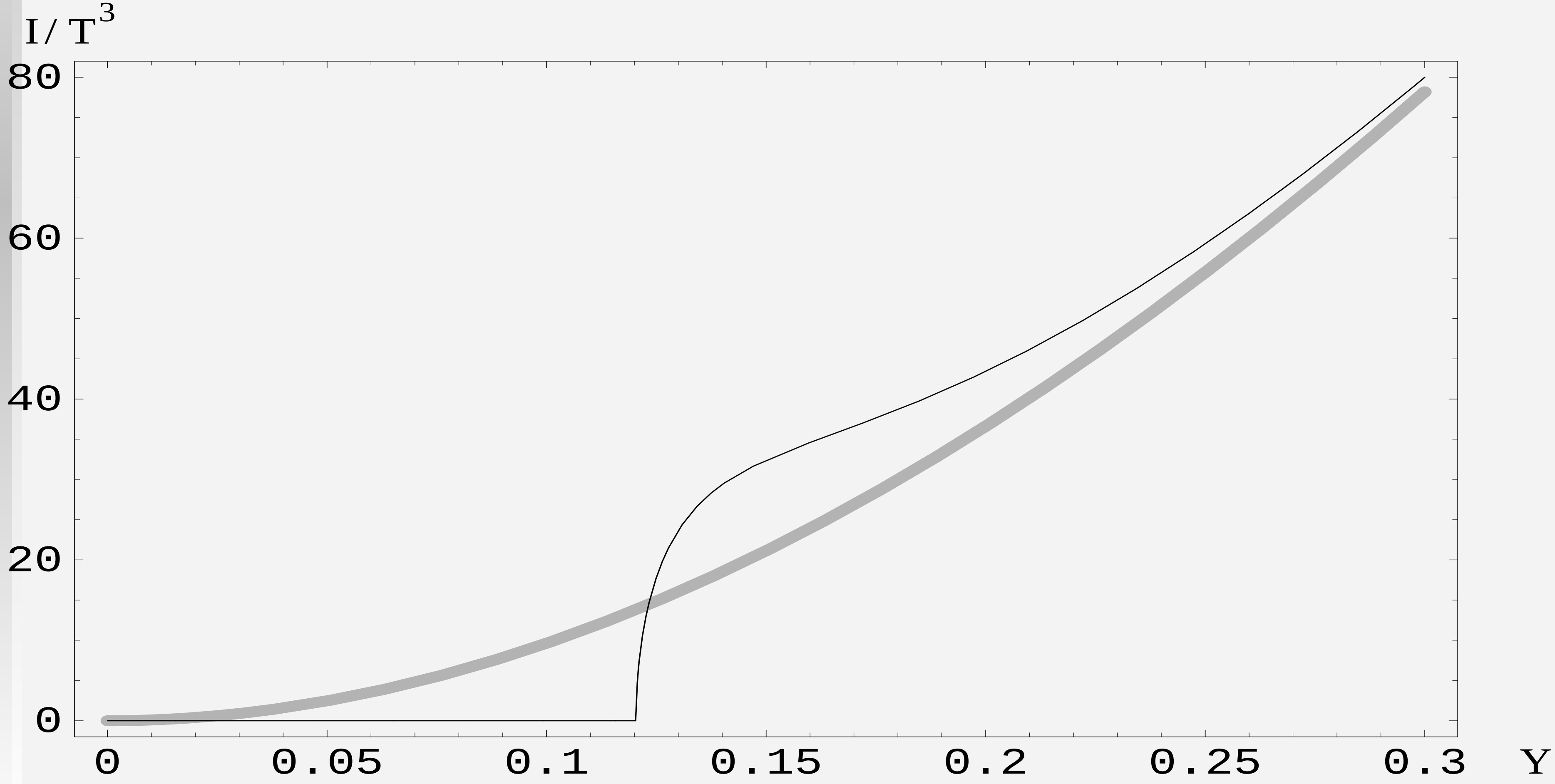
$$(T = 10\,\mathrm{K},\, k_B = \hbar = c = 1)$$



$$I_{\mathrm{SU(2)}} = I_{\mathrm{U(1)}} \times \frac{(\omega - 1/2\frac{d}{d\omega}G)\sqrt{\omega^2 - G}}{\omega^2}\,\theta(\omega - \omega^*)$$

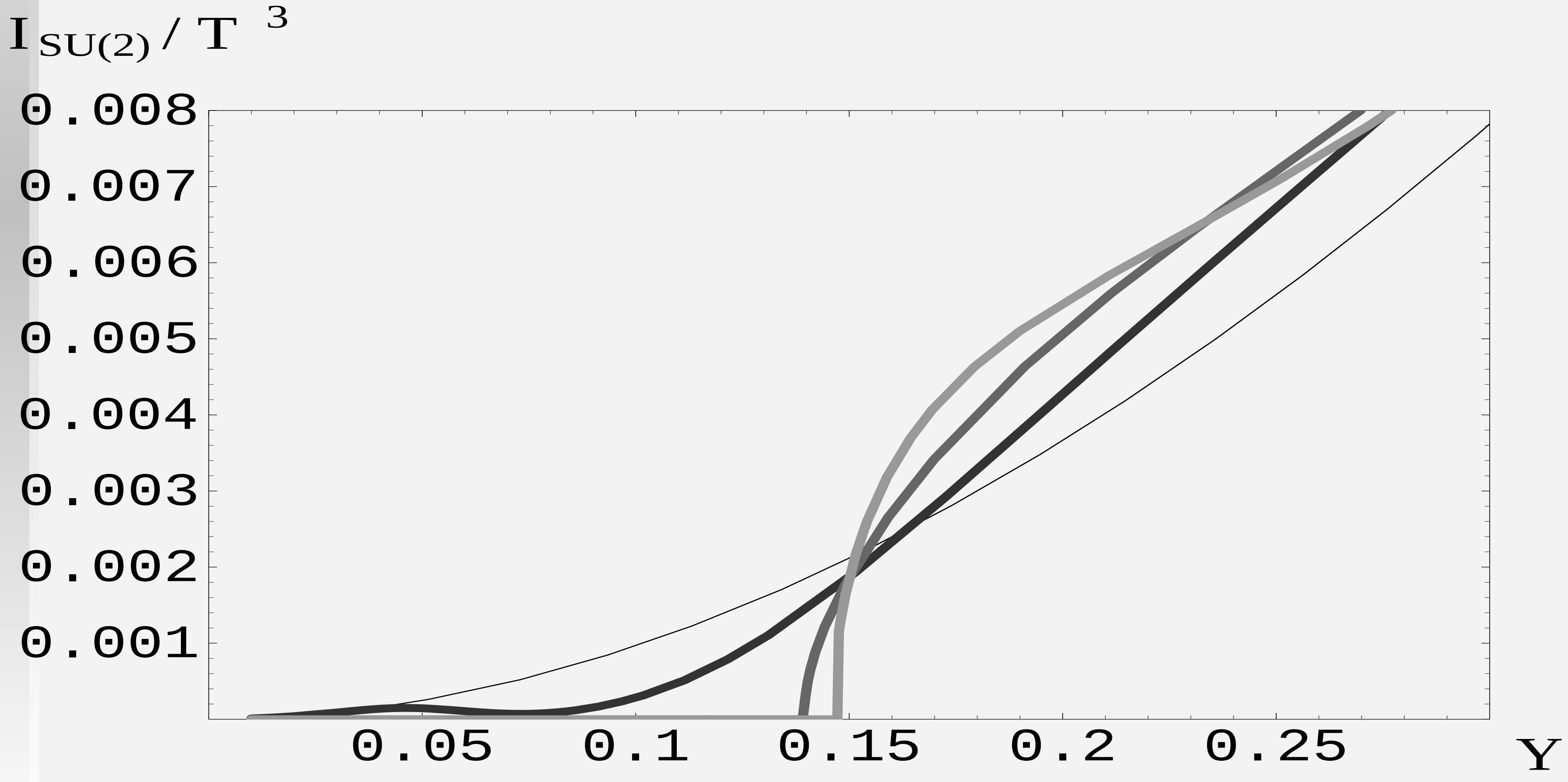
mod. black-body spectrum (2):

($T = 10\,\mathrm{K}$, low frequencies)



mod. black-body spectrum (3):

($T = 4, 5, 6\,\mathrm{K}$, low frequencies)



implications of $\mathrm{SU(2)_{CMB}}$ (1)

cosmologically:

$\Rightarrow$ dynamic contr. to CMB dipole
[Szopa, RH, hep-ph/0703119]

$\Rightarrow$ TT supression at large angles?
[Szopa, RH, work in progress]

$\Rightarrow$ BB nucleosynthesis:
12% enhancement of G_F at $T = 1\,$MeV,
ew SSB by fundamental Higgs?
[Schwarz, RH, Giacosa, JHEP 2007]

astrophysically:

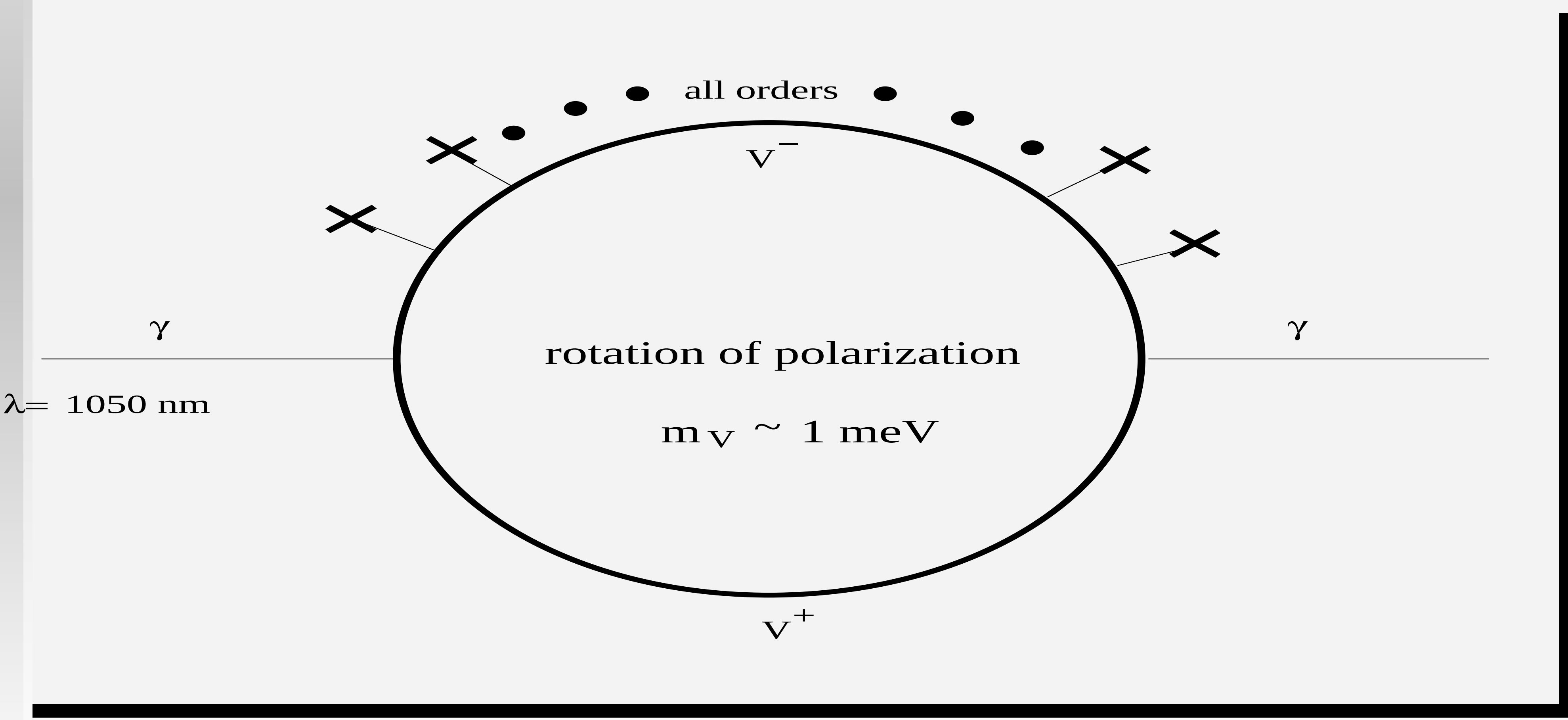
$\Rightarrow$ stability of innergalactic HI clouds

[Brunt, Knee, Nature 2001; Schwarz, RH, Giacosa, JHEP 2007]

implications of $SU(2)_{CMB}$ (2)

”table-top” experiment:

$\Rightarrow$ PVLAS



[Giacosa, RH, work in progress]

summary

- historic situation: microsc. disorder $\leftrightarrow$ $\hbar$
- questions posed by experiment and observation
- deconfining SU(2) YM thermodynamics
- $\mathrm{SU(2)}_{\mathrm{CMB}}$: (anti)screening, BB anomaly
- $\mathrm{SU(2)}_{\mathrm{CMB}}$: implications in nature

Thank you.