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Emergent large-angle, low-frequency CMB anomalies: SU(2) photon physics

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Plan

- **PLANCK and WMAP: TT on large angles**
  - observational situation
  - attempt at explanation

- **ARCADE 2, terrestial surveys of deeply Rayleigh-Jeans CMB**

- **interlude on SU(2) Yang-Mills thermodynamics**
  - action, Euclidean formulation, selfdual gauge fields (calorons), spatial coarse-graining
  - inert thermal ground state and adjoint Higgs mechanism
  - effective coupling, $\hbar$ and caloron action $\Rightarrow$
  - electric-magnetic dual interpr. in $\mathrm{SU(2)_{CMB}}$ for photon *propagation*
  - deconfining-preconfining phase boundary: condensation of unresolved, electric monopoles
  - polarization tensor of massless mode in deconfining, thermal SU(2) YM

- **low-frequency, low-temperature black-body (BB) anomaly**
  - $T_c = T_{\mathrm{CMB}} \sim 2.73$ K (Arcade 2)
  - transverse photons

Plan, cntd.

- **effective theory of anomaly-induced δT**
  - how to do simulations
  - Manton's programme for integral BB anomaly
  - δT depression for $z \leq 1$ in physical (non-comoving), normalized coordinates

- **possible explanation of CMB large-angle anomalies**
  - cold spot
  - suppression of power at large angles
  - hemispherical power and variance asymmetry
  - parity asymmetry

- **vector modes and neutrinos**

some CMB large-angle anomalies: WMAP and Planck

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- dipolar power asymmetry (extends from $l = 2, \cdots, 600$ in blocks of $\Delta l = 100$)
  [Hansen et al. (2009), Ade et al. (2013), etc.]

- low variance (localized on ecliptic North, associated with l=2,3)
  [Monteserin et al. (2008), Cruz et al., (2011), Ade et al. (2013), etc.]

- anomalous alignment of l=2,3 (3°-9°)
  [Tegmark et al. (2003), de Oliveira-Costa et al. (2004), Ade et al. (2013), etc.
  (estimator of axis: maximum of angular momentum dispersion),
  Copi et al. (2004), Schwarz et al. (2004), Bielewicz et al. (2005,2009), Copi et al. (2010), etc.
  (multipole vector decomposition)]

- cold spot (-73μK@4°; -20μK@10°; l,b=207.8°,-56.3°)
  [Viela et al. (2004), Cruz et al. 2005, Rudnick et al. (2007), Ade et al. (2013), etc.]
- hemispherical asymmetry
  (for l=2-40 max. larger power spectrum for hemisphere l,b=237°,-20°)
  [Eriksen et al. (2004), Hansen et al. (2004), Park (2004), Ade et al. (2013), etc.]
- mirror parity violation (plane of max. antisymmetry: l,b=262°,-14°)
  [Finelli et al.(2012); Ben-David et al. (2012), etc.]
- suppression of $\langle TT\rangle(\theta) \equiv C(\theta)$ for $\theta \geq 60^\circ$
  [Spergel et al. (2003), Copi et al. (2004,2007,2009,2010),Ade et al. (2013), etc.]

successful phenomenological attempt at explanation: multiplicative, dipolar modulation model

[Gordon et al. (2005), Eriksen et al. (2007), Hoftuft et al. (2009), Ade et al. (2013)]

$$\vec{d}(\vec{n}) = (1 + A\vec{p}\cdot\vec{n})\vec{s}_{\rm iso} + \vec{n}$$

dipole amplitude   dipole direction   instrumental noise   isotropic CMB sky

maximum likelihood at: $A \sim 0.07;\ \ l_p \sim 220^\circ; b_p \sim -21^\circ$

- robust against change of foreground treatment and experiment (WMAP,Planck)

- comparison with CMB cold spot: $l_{cs} \sim 207.8^\circ; b_{cs} \sim -56.3^\circ$

$$\Rightarrow \angle \vec{p}, \vec{e}_{cs} \sim 36^\circ$$

two more facts on CMB sky:

$$\angle \vec{e}_{\text{mirror antisym}}, \vec{e}_{cs} \sim 42^\circ - 56^\circ ;$$

$$\angle \vec{e}_{\text{hemisph asym}}, \vec{e}_{cs} \sim 42^\circ .$$

CMB at low frequencies: ARCADE 2 and terrestial radio observations

[Fixsen et al. (2009), Haslam et al. (1981), Reich et Reich (1986), Roger et al. (1999), Maeda et al. (1999)]

- strong increase of CMB line temperture below $\nu = 3$ GHz

$$T(\nu) = T_0 + T_R \left(\frac{\nu}{\nu_0}\right)^{\beta}$$

where: $T_0 = 2.725\,\mathrm{K}\,;\ \nu_0 = 1\,\mathrm{GHz}\,;$
$\beta = -2.62 \pm 0.04\,.$

- notice also: radiosurveys of CMB yield line temperatures as:

source	ν[GHz]	T[K]
Roger	0.022	21200 ± 5125
Maeda	0.045	4355 ± 520
Haslam	0.408	16.24 ± 3.4
Reich	1.42	3.213 ± 0.53
Arcade2	3.20	2.792 ± 0.010
Arcade2	3.41	$2.771 \pm 0.009\,.$

Deconfining SU(2) Yang-Mills thermodynamics

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[Herbst et Hofmann (2004), Hofmann (2005,2006), Giacosa et Hofmann (2006), Schwarz et al. (2007), Ludescher et Hofmann (2008), Falquez et al. (2010, 2011), Hofmann (2012)]

- **Euclidean action:**

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

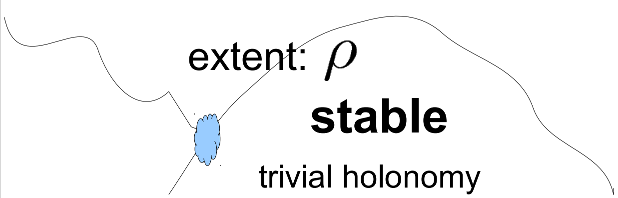
where $F_{\mu\nu} \equiv \partial_\mu A_\nu - \partial_\nu A_\mu - ig[A_\mu, A_\nu]$

- **(anti)selfdual gauge fields:** $\boxed{F_{\mu\nu}[A] = \pm\tilde{F}_{\mu\nu}[A] \;\Rightarrow\; \theta_{\mu\nu}[A] \equiv 0\,.}$

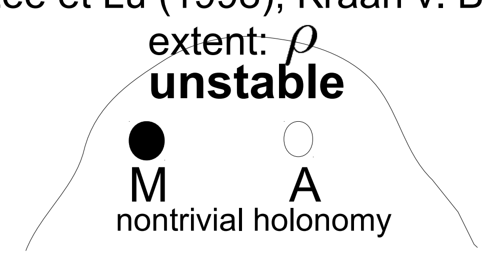
Nontrivial configs. stabilized by winding $S_3 \to SU(2) = S_3$.

- **in particular:** (anti)calorons of winding number unity, localized action density

[Harrington et Shepard (1977)



[Nahm (1981-84), Lee et Lu (1998), Kraan v. Baal (1998), Diakonov 2004]



Deconfining SU(2) YM thermodynamics, cntd.

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- thermal ground state:

- perform spatial coarse-graining over noninteracting (anti)calorons
  → inert adjoint scalar field ϕ , modulus set by T and Λ

constant of integration

- perform spatial coarse-graining over propagating sector
  → same form as fundamental action (pert. renormalizability) for effective gauge field a_μ
  → effective action density

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

- solve e.o.m. for a_μ in background of ϕ: pure gauge
- ground-state pressure and energy density:

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

interacting small-holonomy (anti)calorons

- adjoint Higgs mechanism:

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

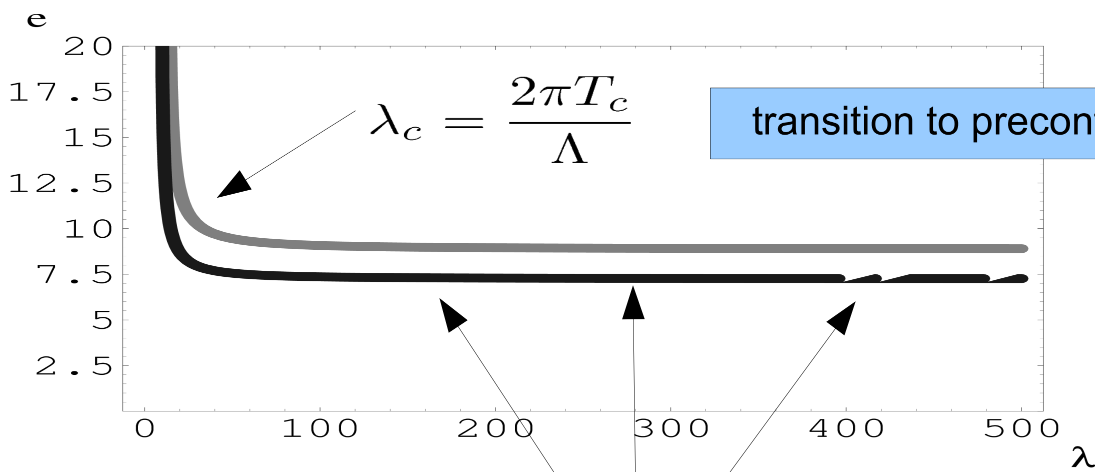
unitary gauge →

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

Deconfining SU(2) YM thermodynamics, cntd.

- propagating sector (free thermal quasiparticles) :

- evolution of effective gauge coupling: e ← thermodynamical consistency



transition to preconfining phase

[Dolan et Jackiw (1974)]

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

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 et Hofmann 2012,
Hofmann (2012,2013)]

Deconfining SU(2) YM thermodynamics, cntd.

- if SU(2) will have to do something with photons 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:

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

But: magnetic coupling in SU(2)

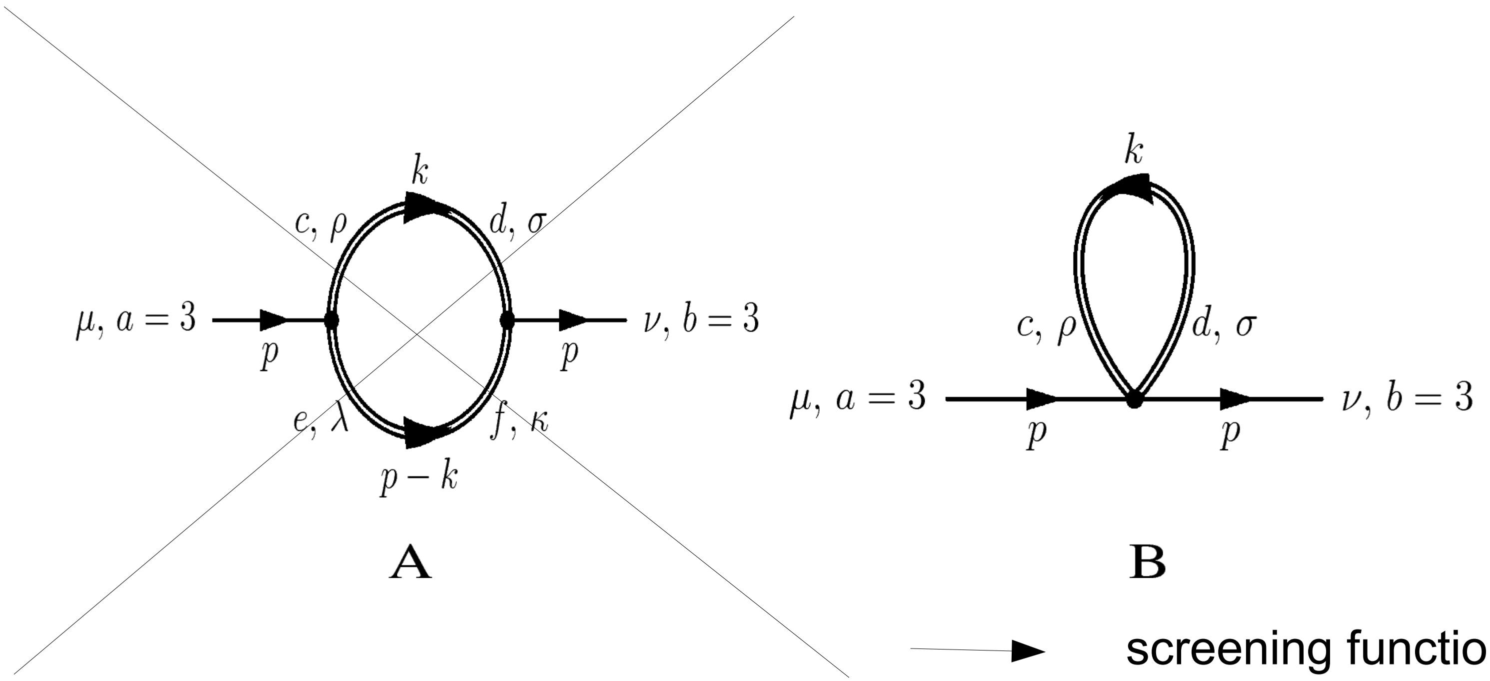
$$\boxed{g = \frac{4\pi}{e}\,.} \longrightarrow$$

In real world: SU(2) is to be interpreted in an **electric-magnetically dual way**.

Deconfining SU(2) YM thermodynamics, cntd.

- radiative corrections
(feeble interaction of vectors with photon):

- thermodynamical quanties: 2-loop/1-loop ($<10^{-3}$), 3-loop/1-loop ($<10^{-7}$)
- polarization tensor of massless mode:

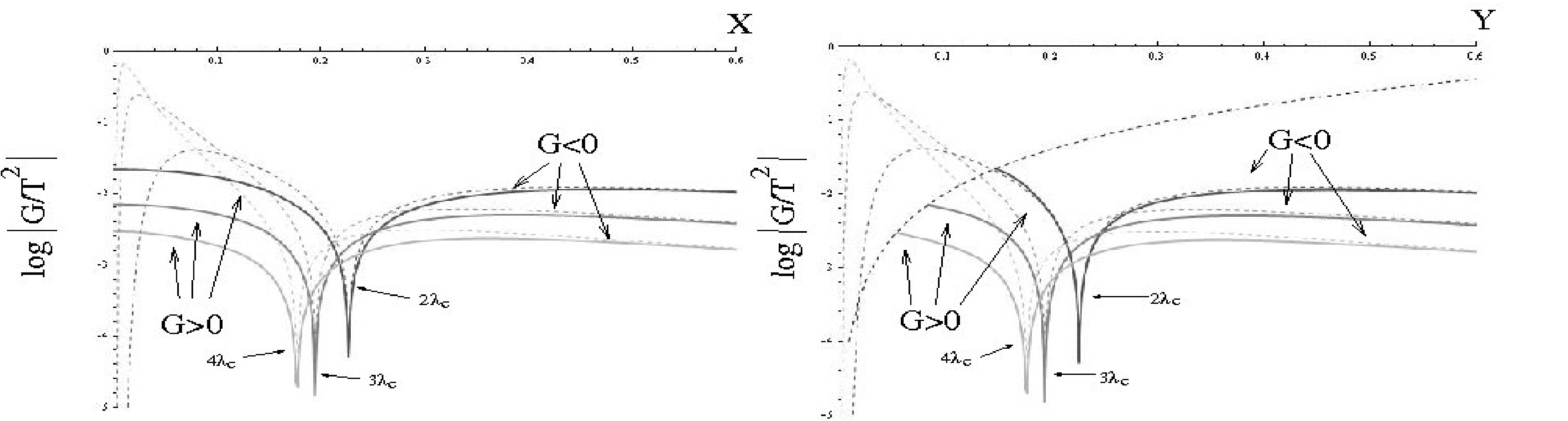


→ screening functions

G, F

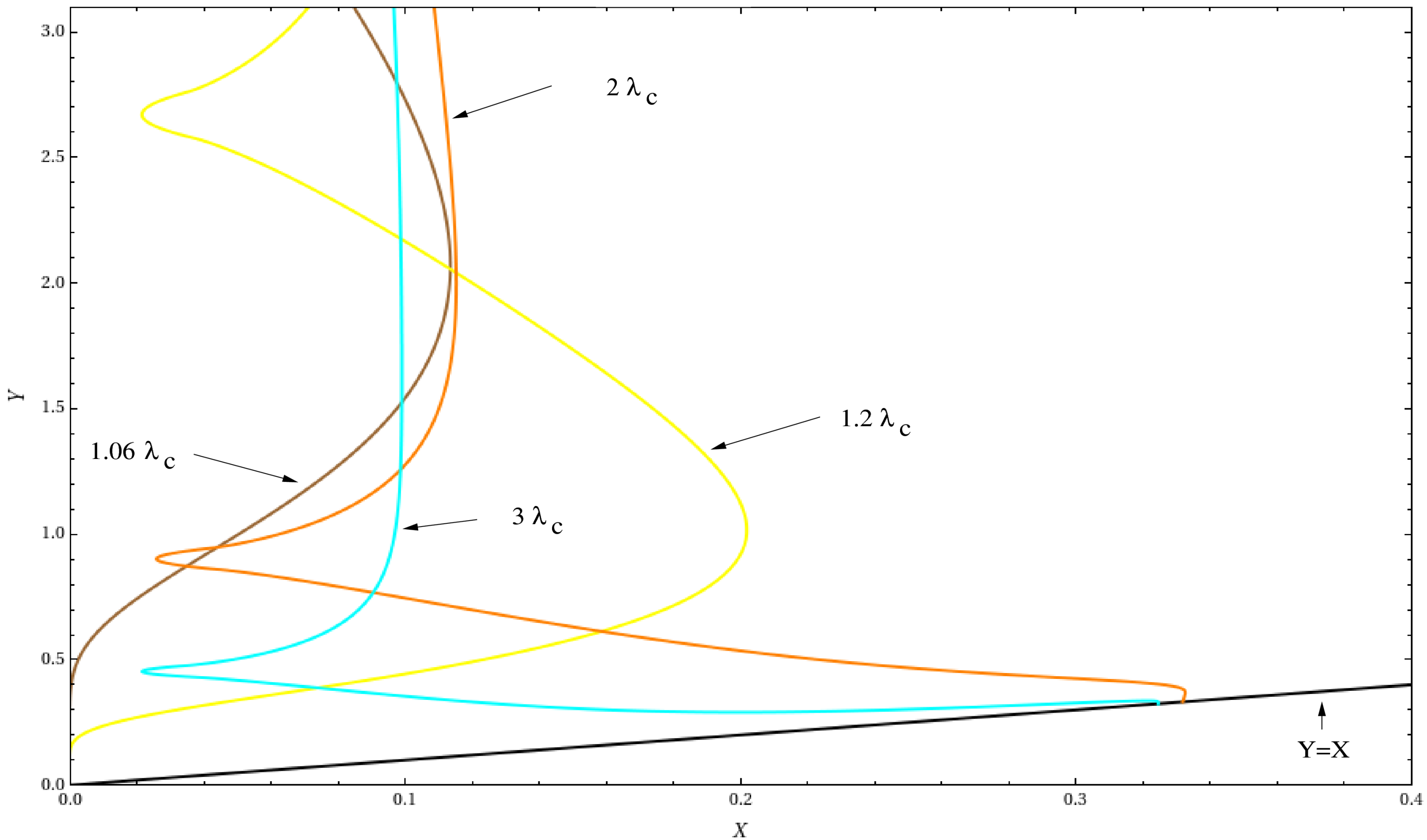
Deconfining SU(2) YM thermodynamics, cntd.

- transverse photons, screening function G :
  [Schwarz et al. (2007), Ludescher et Hofmann (2008)]



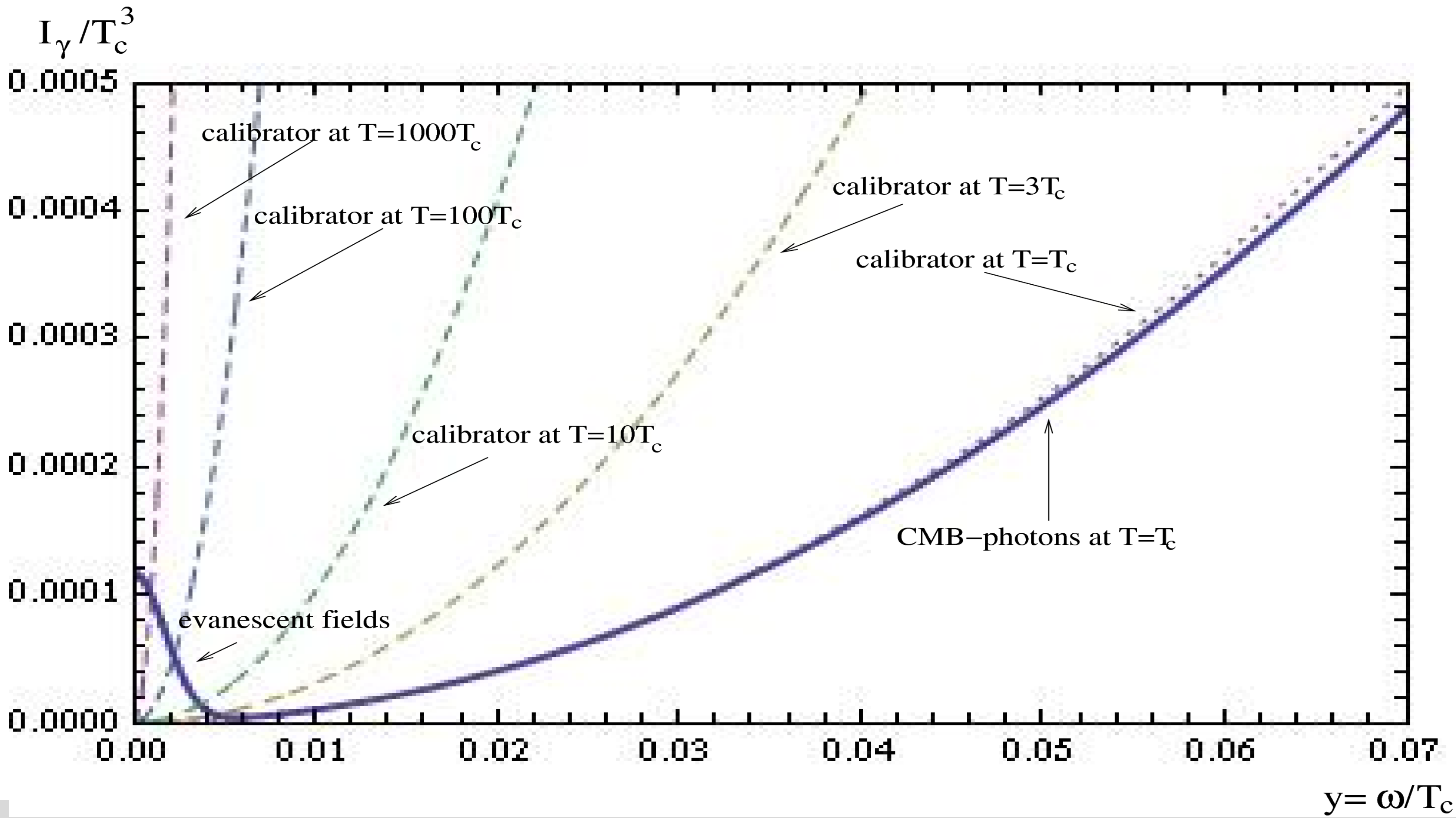
Deconfining SU(2) YM thermodynamics, cntd.

- longitudinal „photons" (purely magnetic), dispersion law :
  [Falquez et al. (2011)]



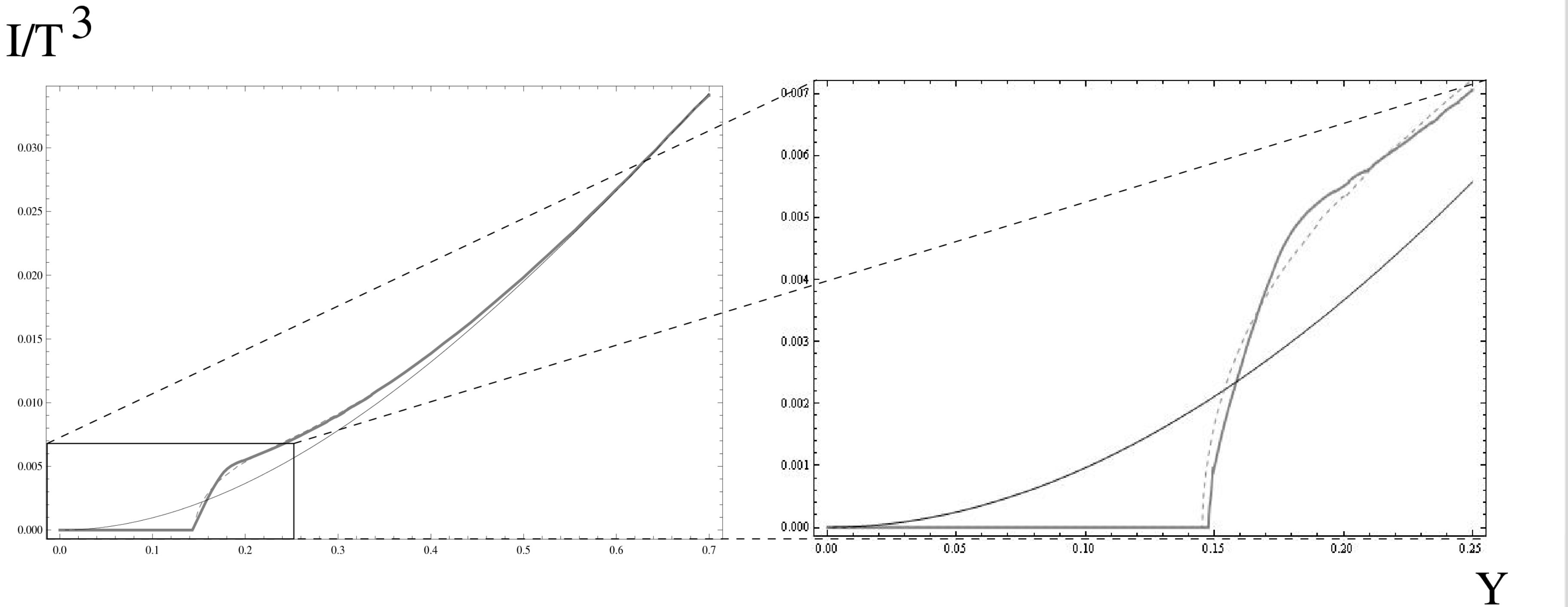
Spectral black-body anomaly

- What is T_c ? $\longrightarrow$ ARCADE 2
- bump interpreted as contribution of evanescent modes ($\omega < m_\gamma$), m_γ photon Meissner mass (condensation of electric monopoles)
- T_c very close to present CMB temperature T_0 $\longrightarrow$ $\mathrm{SU(2)_{CMB}}$
  [Hofmann (2009)]



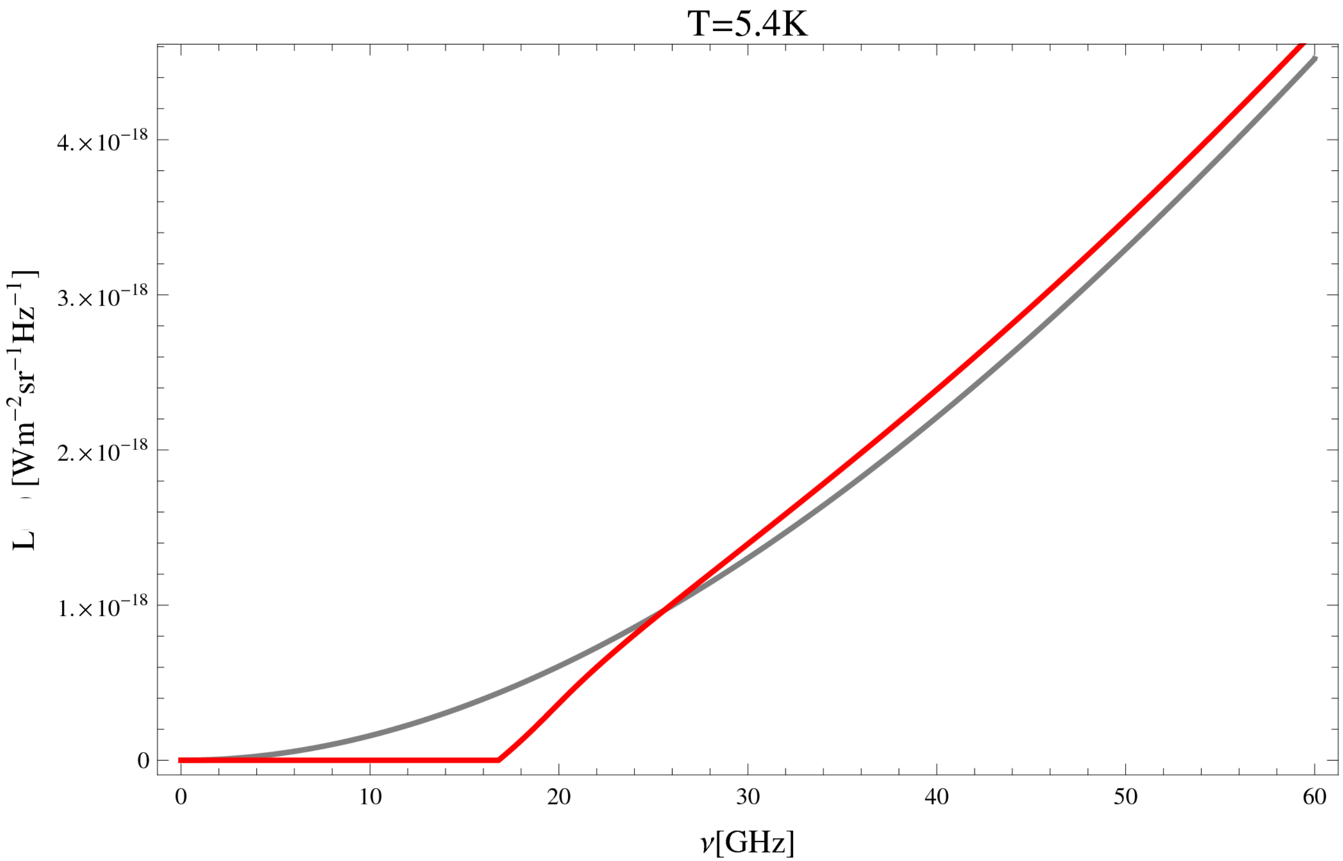
Spectral black-body anomaly

spectral distribution of energy density, $T = 2T_0$



Spectral black-body anomaly

Radiance, $T = 2T_0$



Effective theory of BB anomaly-induced δT in large-angle CMB

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- integral BB anomaly:

- $\delta\rho(T) \equiv \rho_{\mathrm{SU(2)}_{\mathrm{CMB}}} - \rho_{\mathrm{U(1)}}$
- $T = \bar{T}(t) + \delta T(t,\vec{x})$
- **in simulations** bias factor $F(\bar{T},\delta T)$ for δT in phys. voxel volume ΔV :

$F(\bar{T},\delta T) = \frac{P_{\mathrm{SU(2)}}}{P_{\mathrm{U(1)}}}$ where $P = \frac{\exp(-\rho\Delta V/\bar{T})}{\int_{T_0}^{\infty} dT\, \exp(-\rho\Delta V/\bar{T})}$.

- $\delta\rho$ potential for scalar field δT $\longrightarrow$
- **Manton's programme** $\partial_\mu \delta T \partial^\mu \delta T$

introduce kinetic term

action density:

$$\sqrt{-g}\,\mathcal{L}_{\mathrm{CMB}} = \left(\frac{\bar{T}_0}{\bar{T}}\right)^3 \left(k\,\partial_\mu \delta T \partial^\mu \delta T - \delta\rho(T)\right)$$

where k empirically determined normalization

Effective theory, cntd.

- varying action, linearizing e.o.m., and coordinate change

$$\partial_{\tilde{\mu}}\partial^{\tilde{\mu}}\delta T - \frac{3}{\bar{T}}\partial_\tau \bar{T}\,\partial_\tau \delta T + \frac{T_0^2}{kH_0^2}\left[\frac{1}{2}\left.\frac{\mathrm{d}^2\hat{\rho}}{\mathrm{d}T^2}\right|_{T=\bar{T}}\delta T + \frac{1}{2}\left.\frac{\mathrm{d}\hat{\rho}}{\mathrm{d}T}\right|_{T=\bar{T}}\right] = 0\,,$$

where $\delta\rho = T_0^2\,\hat{\rho}$ and ct $\tilde{x}_0 \equiv \tau = H_0\,t\,,\quad \tilde{x}_i = \frac{\mathrm{d}a}{\mathrm{d}t}\,x_i = \frac{x_i}{H^{-1}}a\,.$

(time i.u. of today's age of universe; spatial coordinates i.u. size of actual universe)

- assuming 3D spherical symmetry

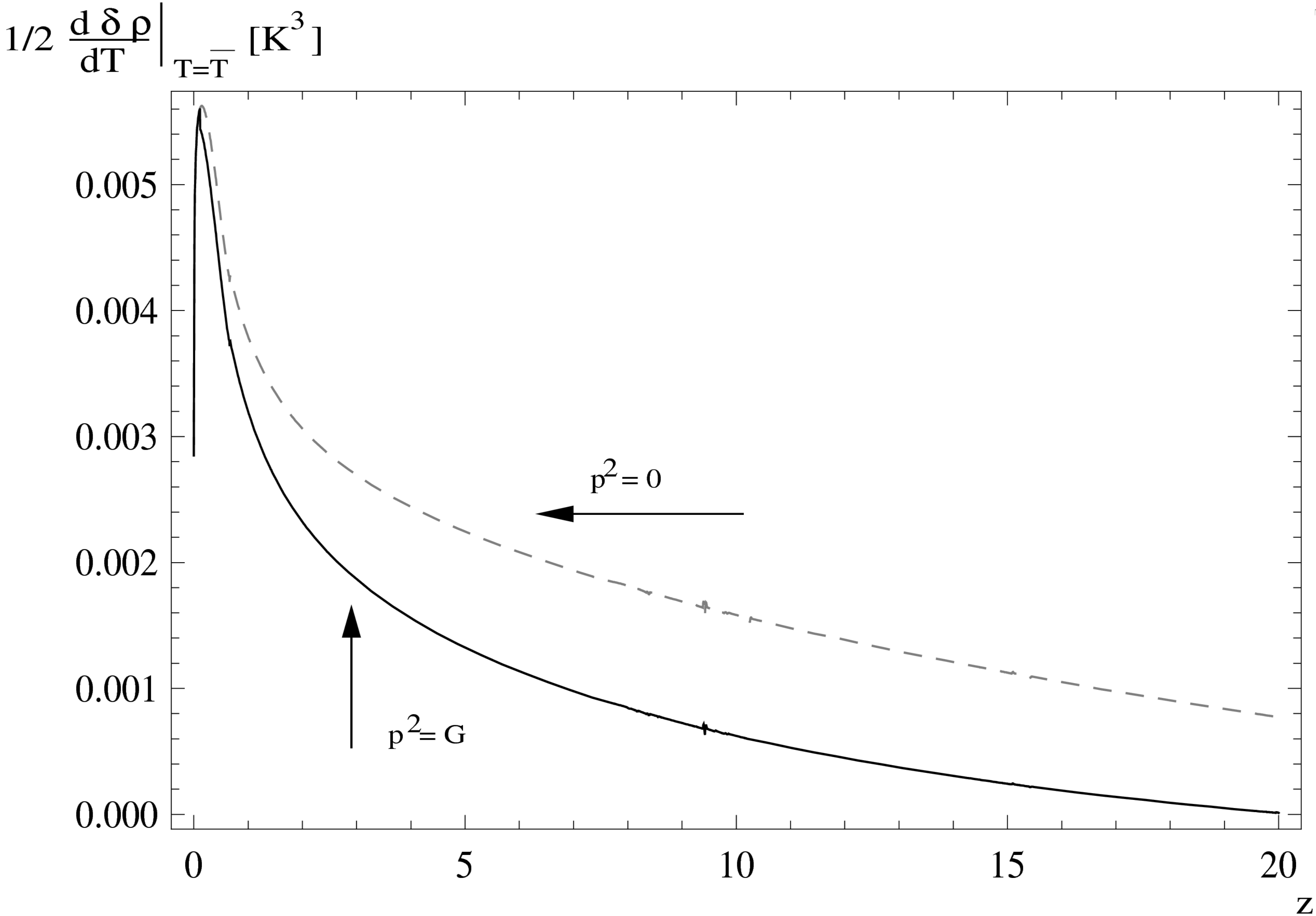
$$0 = \partial_\tau\partial_\tau\delta T - \left(\frac{\mathrm{d}a}{a\,\mathrm{d}\tau}\right)^2\left[\partial_\sigma\partial_\sigma\delta T + \frac{2}{\sigma}\partial_\sigma\delta T\right] - \frac{3}{\bar{T}}\partial_\tau\bar{T}\,\partial_\tau\delta T + \frac{T_0^2}{kH_0^2}\left[\frac{1}{2}\left.\frac{\mathrm{d}^2\hat{\rho}}{\mathrm{d}T^2}\right|_{T=\bar{T}}\delta T + \frac{1}{2}\left.\frac{\mathrm{d}\hat{\rho}}{\mathrm{d}T}\right|_{T=\bar{T}}\right]$$

where

$$\sigma \equiv \sqrt{\tilde{x}_1^2 + \tilde{x}_2^2 + \tilde{x}_3^2}\,.$$

source term

source term:



$1/2 \left.\frac{d\,\delta\rho}{dT}\right|_{T=\bar{T}}$ [K^3]
0.005
0.004
0.003
0.002
0.001
0.000
0
5
10
15
20
z
$p^2 = 0$
$p^2 = G$

δT depression:

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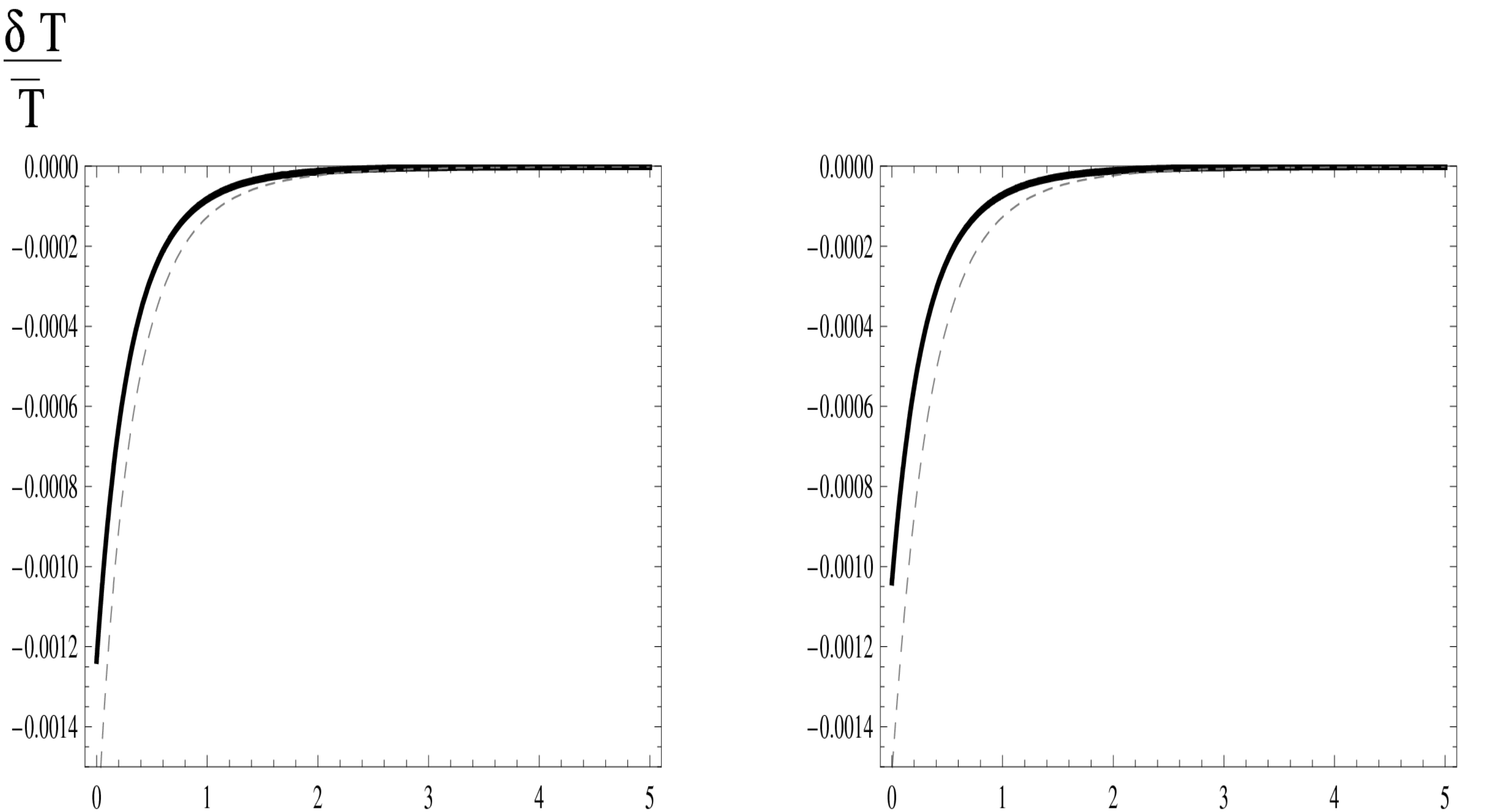
- study evolution in terms of z subject to best-fit ΛCDM

- **initial conditions:** fluctuation of primordial norm., arbitr. width, speed of initial fluctuation **zero** for $z_i > 20$ or so

- **boundary conditions:** extremum at $\sigma = 0$, **zero** at $\sigma = 1$ (causal connection to $\sigma = 0$)

- determine k phenomenologically (mismatch of Local Group motion with motion extracted kinemetically from measured CMB dipole or directly from a large-angle anomaly in dipole subtracted map, later) [Ludescher et Hofmann (2009), Erdogdu et al.(2006)]

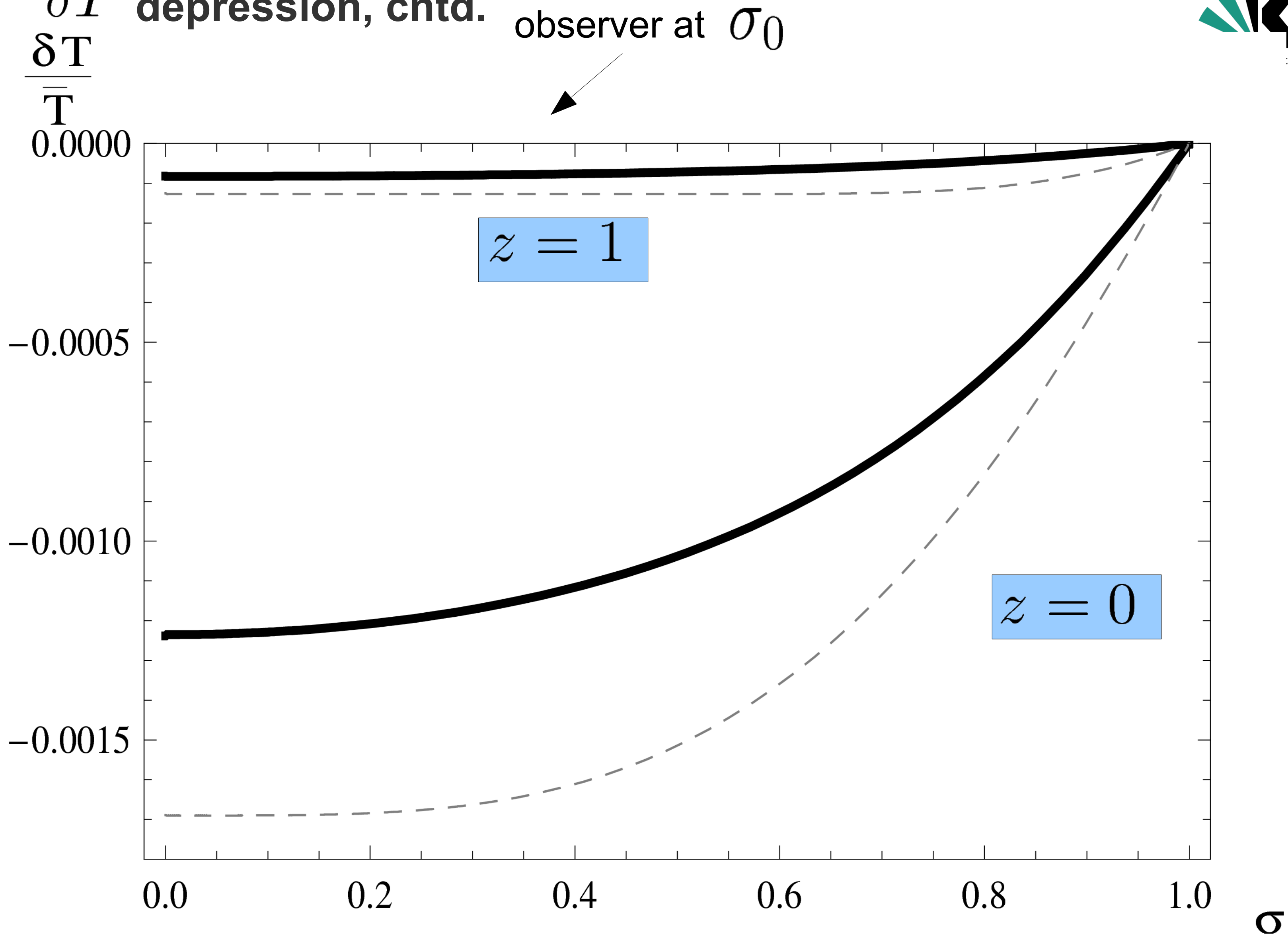
δT depression, cntd.



$\sigma = 0.05$ $\sigma = 0.5$

$(\, k = 0.01868 \, \bar{T}_0^2 / H_0^2 \,)$

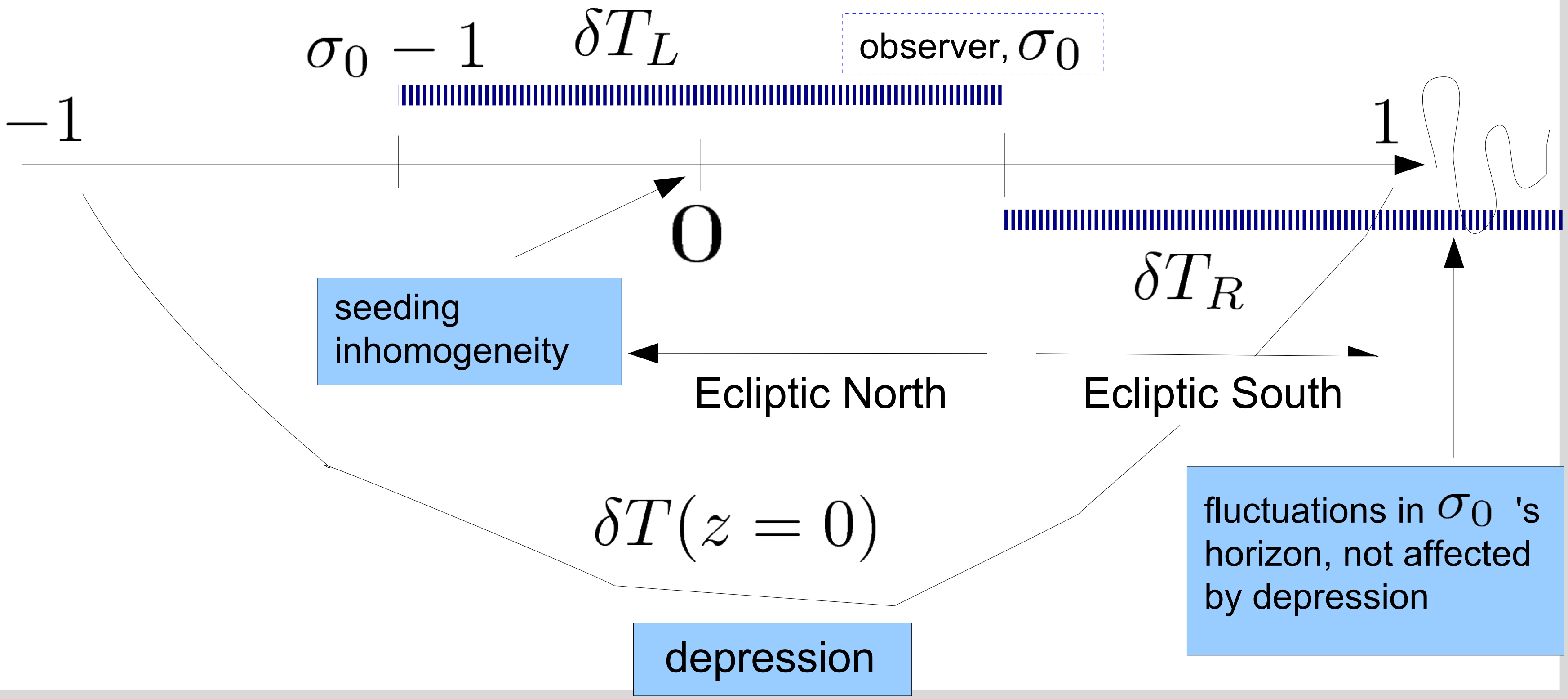
δT depression, cntd.



cntd.

- **CMB cold spot, low variance, power asymmetry:**
  consider:

$$\delta T_L \equiv \int_{\sigma_0}^{1} d\xi\, \delta T(z=0,\xi)\,, \quad \delta T_R \equiv \int_{\sigma_0-1}^{\sigma_0} d\xi\, \delta T(z=0,\xi)$$



cntd.

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now:

- **dynamical contribution in measured (kinematically dominated) CMB dipole** $\longrightarrow$

$$\boxed{|\vec{D}_{dyn}| = \frac{1}{2}\,(\delta T_L - \delta T_R)}$$

- $\boxed{\mathrm{offset} = \frac{1}{2}\,(\delta T_L + \delta T_R)}$ $\longrightarrow$ **cold spot**

- $\longrightarrow$ $\boxed{\vec{d}_{cs}||\vec{e}_{\mathrm{mirror\ antisymm}}}$ $\boxed{\vec{d}_{cs}||\vec{e}_{\mathrm{hemisph\ asymmetry}}}$

recall (Planck observations): $\angle \vec{e}_{\mathrm{mirror\ antisym}}, \vec{e}_{cs} \sim 42^\circ - 56^\circ\,;$ $\angle \vec{e}_{\mathrm{hemisph\ asym}}, \vec{e}_{cs} \sim 42^\circ\,.$

- **variance asymm:**
  North projection longer along profile $\longrightarrow$ less variance,
  South projection includes causally disconnected fluctuations
  $\longrightarrow$ more variance

cntd.

- suppression of TT for $\theta > 60^\circ$

rapid build-up of profile at $z \sim 1$

- alignment of quadrupole and octopule (axis of evil)
~ along gradient to profile, $\vec{\nabla}\delta T|_{z=0,\sigma_0}$ **:**

$$\angle - \vec{e}_{aoe}, \vec{e}_{cs} \sim 49^\circ$$

- dipolar power asymmetry:
Planck: l-binned mean ~ 67 °
concordance -model simulation: l-binned mean ~ 90 ° →

preferred direction over large range of angular resolution after dipole substraction: $\vec{\nabla}\delta T|_{z=0,\sigma_0}$ **or** $\vec{e}_{cs}$

Summary & Outlook

- some oservational facts
- dipolar, multiplicative modulation model
- deconfining SU(2) YMTD
- dual interpretation
- photon propagation described by $\mathrm{SU(2)}_{\mathrm{CMB}}$ rather than U(1)
- some evidence
- black-body anomaly
- effective theory for temperature fluctuations: rapid build-up of profile at z~1
- interpretation of results: accomodation of pot. dipole discrepancy, cold spot, variance and power asymmetries, and mirror antisymmetry preferred direction in the dipole subtracted CMB sky
- relax simplifying assumptions (spherical symmetry, instanteneous line-of-sight integrations) and do more realistic simulations
- BUT YOU CAN DO IT MUCH BETTER! (2-parameter model in simulations: σ_0 and ξ)

Thank you.

CMB large-angle and low frequency anomalies in terms of $\mathrm{SU}(2)_{\mathrm{CMB}}$

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- excess of radiance at low frequencies:

- photon acquires Meissner mass $m_\gamma \sim 0.1\,\mathrm{GHz}$ by coupling to preconfining ground state [Hofmann 2009]
- for $\omega < m_\gamma$: photons become evanescent (standing waves) of Gaussian radiance distribution about zero mean $\longrightarrow$ **line temperature for** $\omega \to 0$:

$$\boxed{T \propto \omega^{-2}.}$$

spectral index

(spectral index of line temperature ~ - 2.6 at $\nu \sim 2\,\mathrm{GHz}$, when lower ν included in fit spectral index increases!) $\longrightarrow$

massive cosmological neutrino equation of state:

Assume: $m_\nu = \xi T$

(neutrino single center-vortex loop of yet another
but now confining-phase SU(2), neutrino mass induced by environment)

[Moosmann,Hofmann 2008]