Workshop on gravity and cosmology
for young researchers@YITP

1st.Mar, 2017

Cosmological constraints on Lorentz symmetry violation

宇宙論的観測を用いたLorentz対称性の破れの検証

Shun Arai (Nagoya University C-lab, M2)

Shun Arai, S.Sibiryakov and Y.Urakawa in prep.

Shun Arai, D.Nitta and H.Tashiro Phys. Rev. D 94, 124048

What's the Lorentz symmetry ?

Electro-Magnetism Newton mechanics

Special Relativity

"The whole Galileo-Newton system thus sank to the level of a first approximation, becoming progressively less exact as the velocities concerned approached that of light."

By Hendrik Lorentz

A.Einstein(1879-1955)

まず、イントロです。Lorentz対称性というのはA.Einsteinにより提唱された特

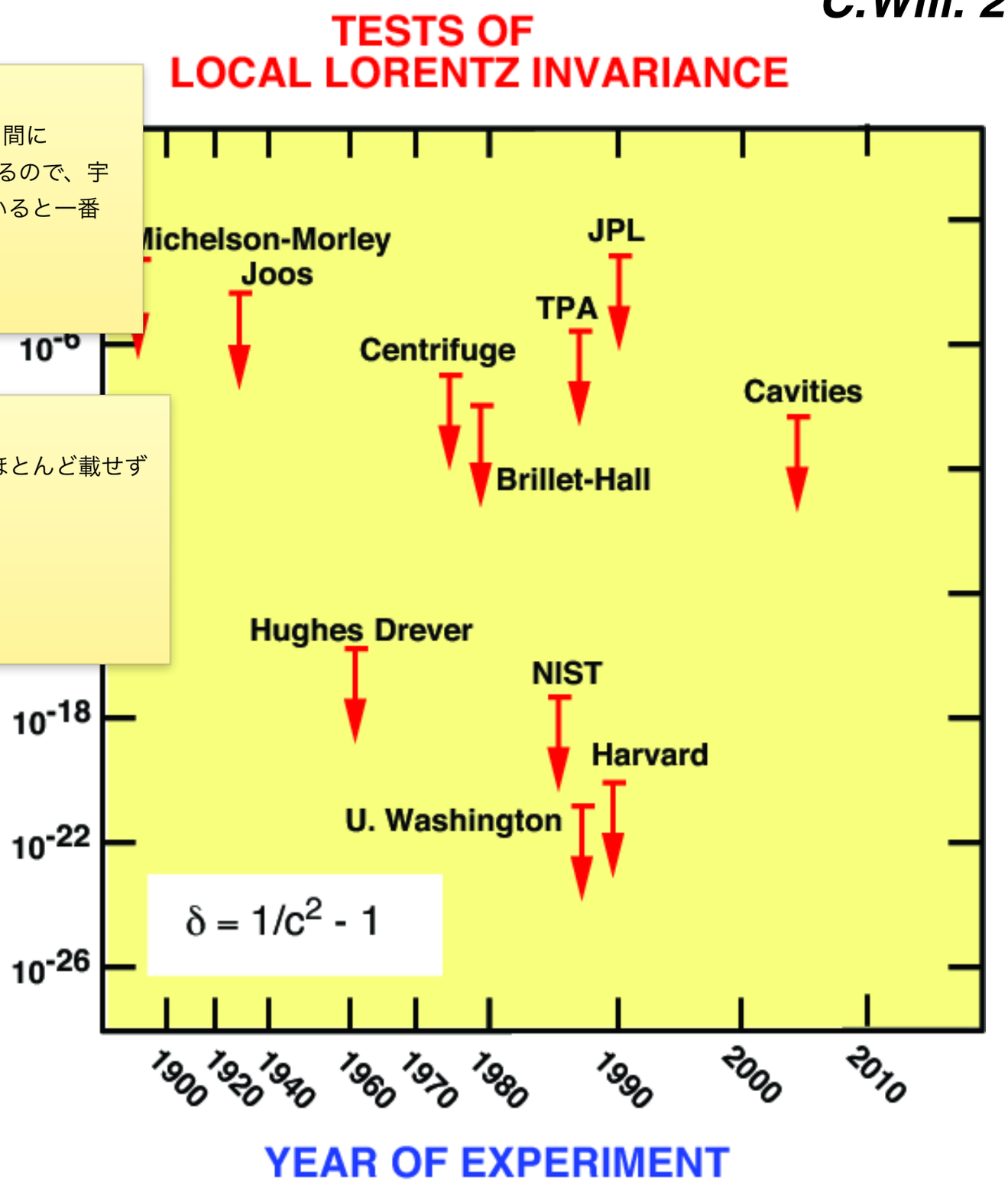
Lorentz symmetry

GR **QFT** **String theory**

Observational constraints for Lorentz symmetry ❶

宇宙論的な距離を飛んでくる間に shapiro 遅延効果は大きくなるので、宇宙論的距離にあるGRBを用いると一番強い制限になる。

今回の発表では、数式をほとんど載せずに説明してみる。



Observational constraints for Lorentz symmetry ❷

- Interferometers ***Michealson - Morley, 1887***
- GZK Cut-off ***HiRes Collaboration et al. 20***
- ***V. A. Kostelecky et al. 2011*** ***J.Ellis et al.2013***
- GRB ***V.Vasileiou et al. 2013*** $E_{\rm LV} > 10^{12}{\rm GeV}$

  The strongest constraint for photon
- Binary pulsars, GW ***K. Yagi et al. 2013*** ***D. Bias et al. 2016***

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Constraints for high energy scale

Constraints for gravity sector

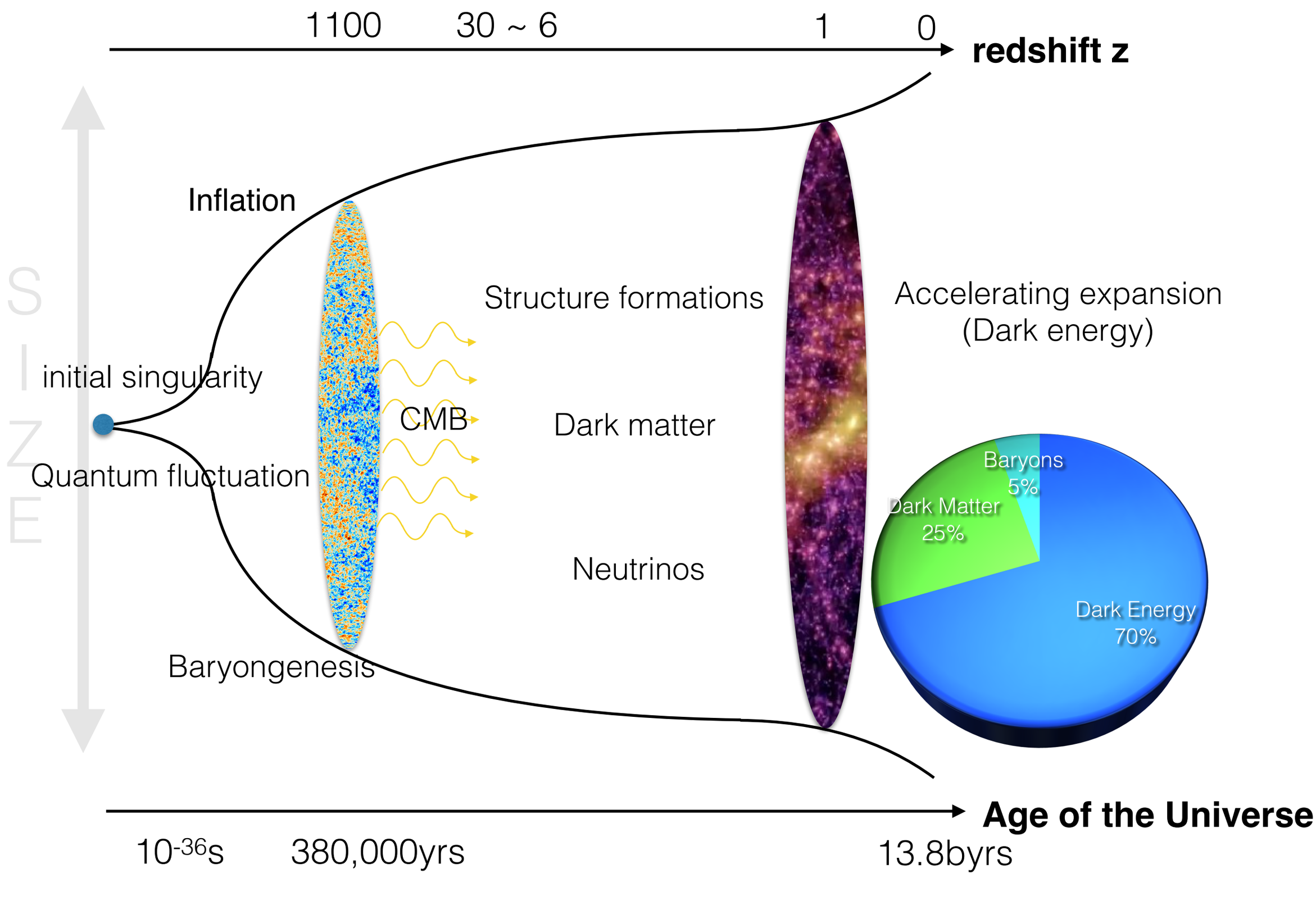
Theoretical predictions of Lorentz Violation (LV)

- Renormalization of gravity ***P. Horava, 2009 J. Barvinski et al. 2015***
- Renormalization & unitarity in LV ***T. Fujimori et al. 2015***
- Renormalization group in LV ***R. Iengo et al. 2009***
- extension of NG theorem ***H.Watanabe and H. Murayama, 2012,2014***

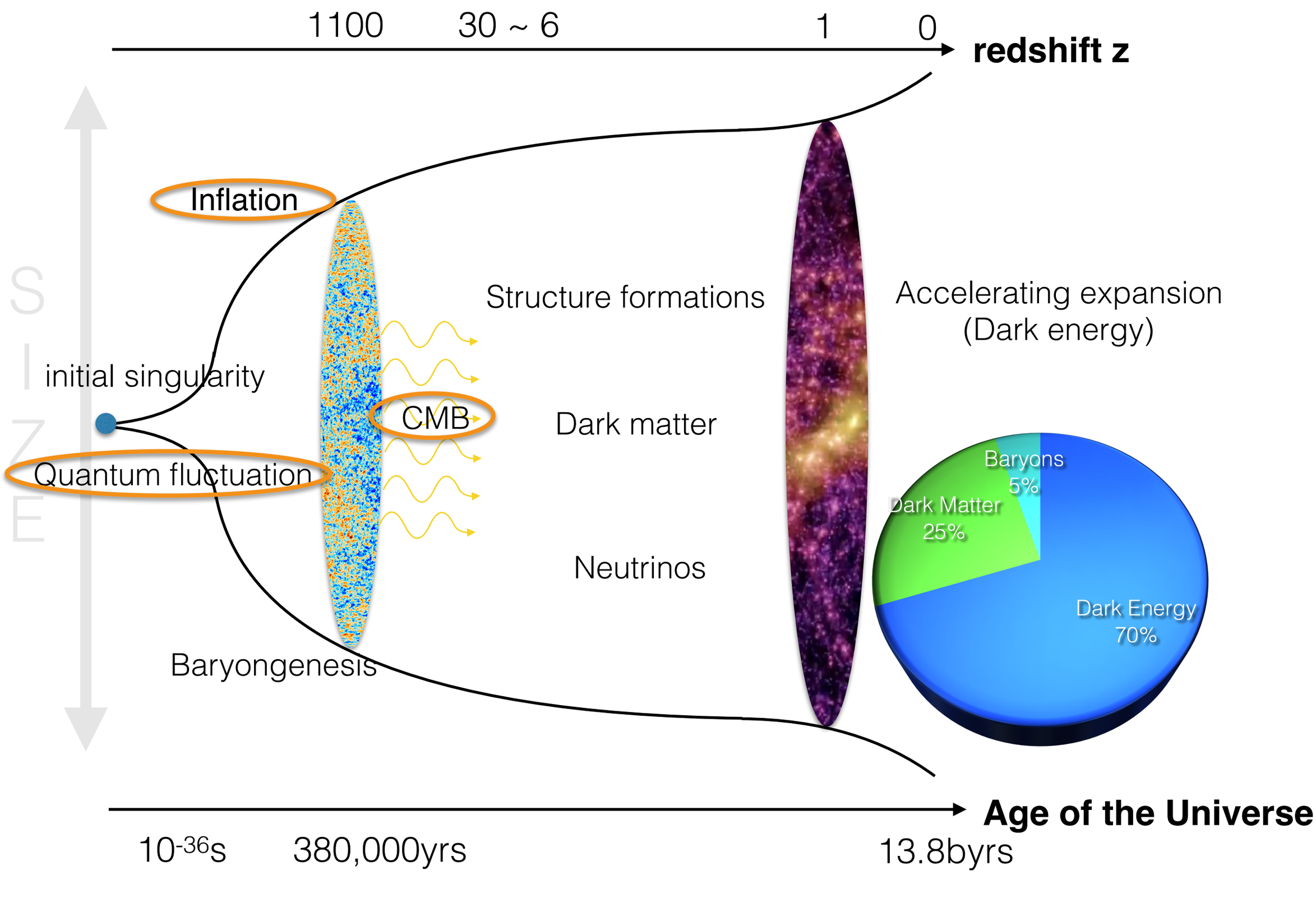
etc…

Phenomena induced by LV are diverse and sometimes non trivial.

Modern Cosmology



Modern Cosmology



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SA, S.Sibiryakov and Y.Urakawa in prep.

2. Late-time constraints on LV with CMB distortions

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3. Summary

これはAmazing factです。今まで知られていなかったことが明らかとなったため

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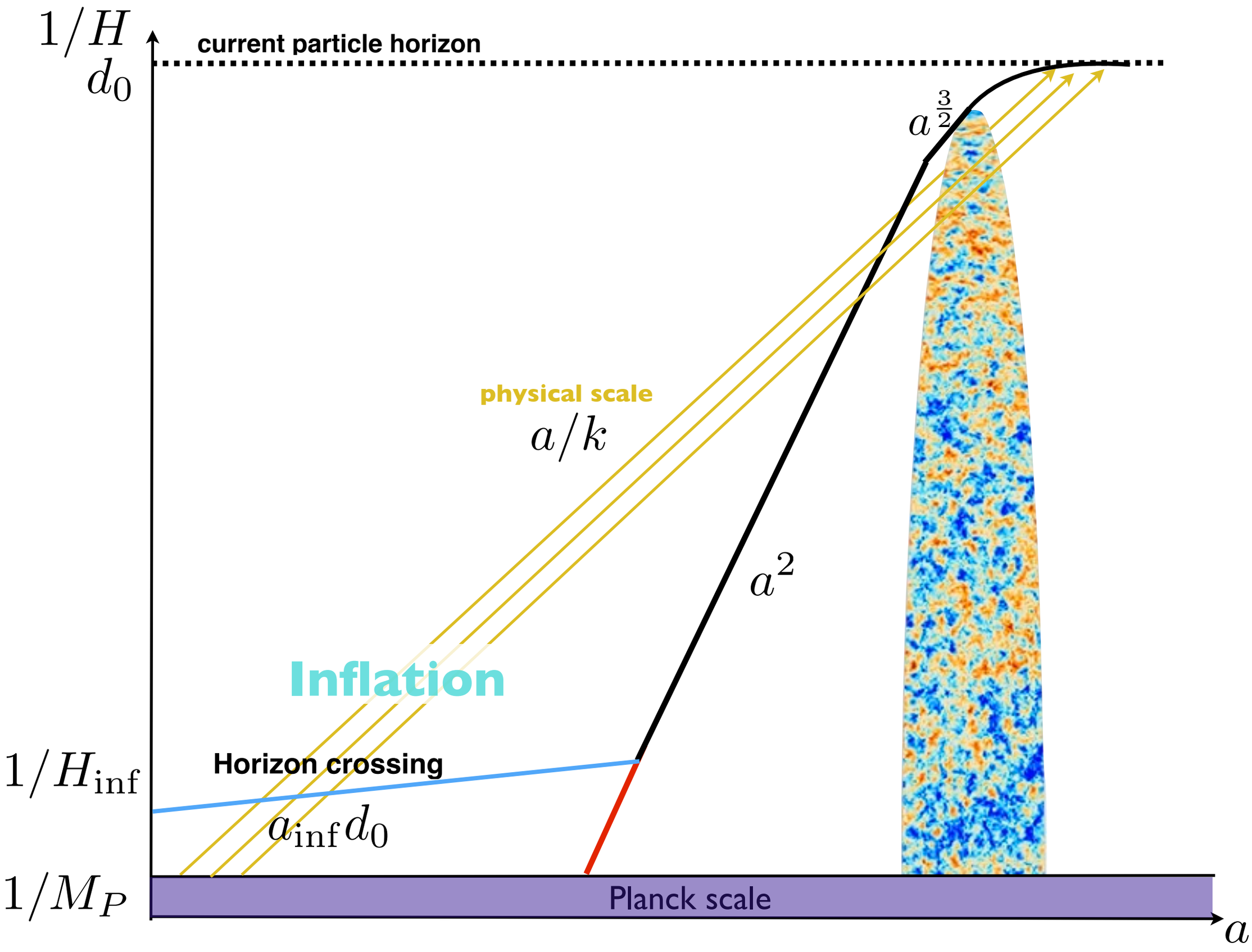
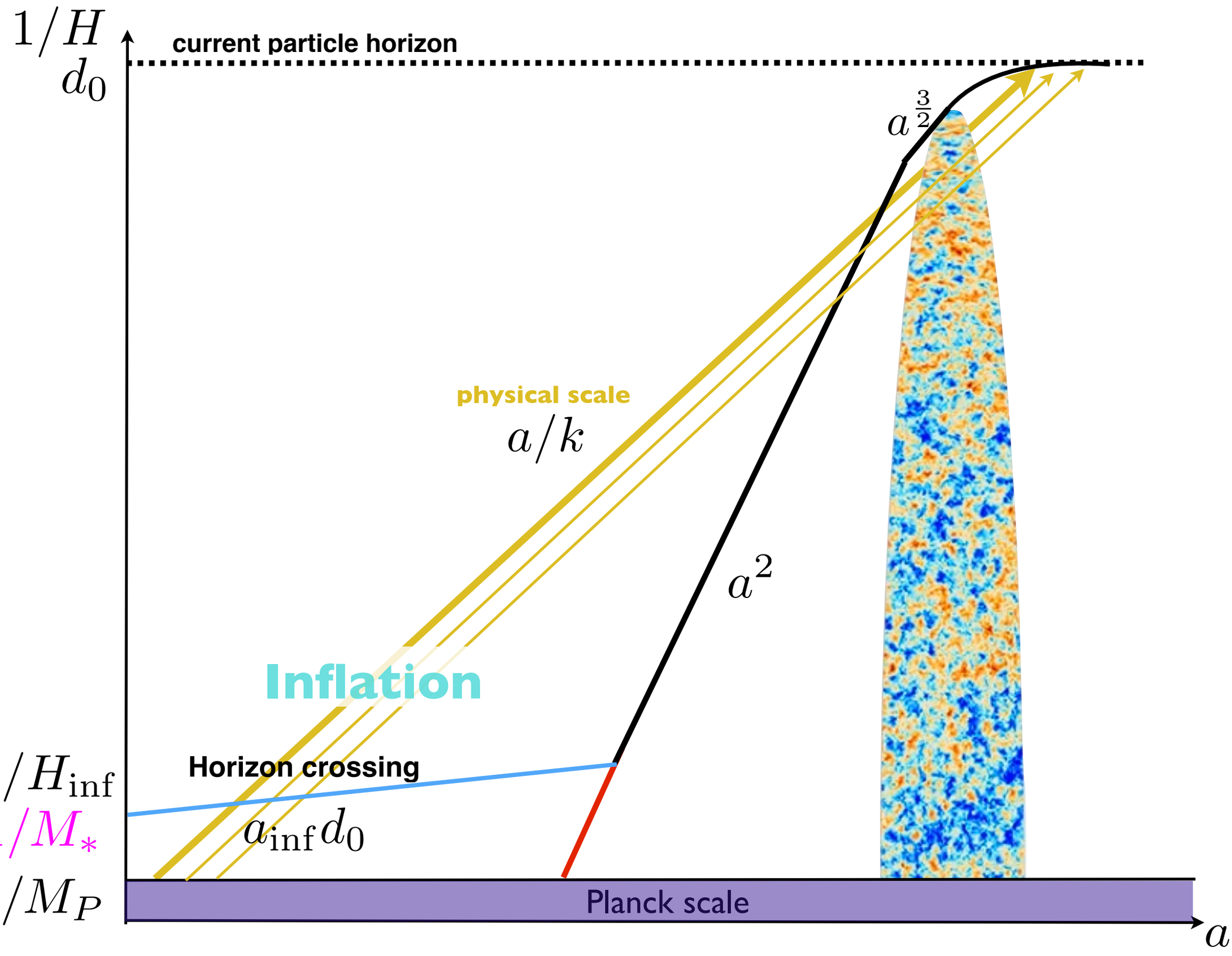

$1/H$
d_0
current particle horizon
$a^{\frac{3}{2}}$
physical scale
a/k
a^2
Inflation
$1/H_{\rm inf}$
Horizon crossing
$a_{\rm inf} d_0$
$1/M_P$
Planck scale
a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Horava Lifshitz Gravity (HL gravity)

Renormalizable theory of gravity ***P. Horava, 2009*** ***J. Barvinski et al. 2015***

anisotropic scaling $t \to b^z t,\ \mathbf{x} \to b\mathbf{x}$

time foliation diffeomorphism $t \to \tilde{t} = \tilde{t}(t),\ \mathbf{x} \to \tilde{\mathbf{x}} = \tilde{\mathbf{x}}(t, \mathbf{x})$

~~**local Lorentz symmetry**~~

2 time derivatives

2z spatial derivatives

no ghost & power counting renormalizable

$E > M_*$

M_* LV energy scale

$M_* = \sqrt{\alpha} M_P$

2 tensors + 1 scalar

new d.o.f ; scalar graviton $\mathcal{R}$

HL gravity + (single) scalar field inflation

$\mathcal{R},\ h_{ij}$ $\phi(t) + \varphi$

、くりこみ可能な重力理論という
話を進める。そしてBack Upに
counting renormalizabilityについ
ライドを入れる。

Renormalizability of Horava gravity

$$t \to b^z t, \ \mathbf{x} \to b\mathbf{x}$$

If a scalar field with scaling $\phi \to b^{-s}\phi$, we can calculate s with invariance of the canonical kinetic term

$$\int dt d^3x \frac{\dot{\phi}^2}{2} \Rightarrow s = \frac{3-z}{2}$$

Remark

the case spatial dimension is D

$$s = \frac{D-z}{2}$$

The n-th order interaction term behaves as

$$\int dt d^3x \phi^n \propto E^{-(z+3-ns)/z}$$

If $z \geq 3$, power counting renormalizable.

From now on, we mainly focus on the case $z = 3$

Types of Horava Lifshitz gravity

In addition to the power-counting renormalizability, there are 2 different types of spacetime in HL gravity:

- **Projectable version:** $N = N(t)$

  - continuous connection to GR

⚠ **IR instability** ⟷ **strong coupling** ***(D.Blas et al. 2010)***

- **Non projectable version:** $N = N(t, x)$

  - Additional terms are possible $\alpha a_i a^i \;\; a_i = \partial_i \ln N$

  - No ghost and IR instability

→ **Non projectable version** is the only healthy LV theory of gravity so far ***(D.Blas et al. 2010)***

Behavior of Scalar graviton

$$h_{ij} = e^{2\mathcal{R}}\delta_{ij}$$

- **4d Diff theory**

Lagrangian is invariant under a dilatation and shift transformation

$$\mathbf{x} \to e^{s}\mathbf{x}, \mathcal{R} \to \mathcal{R} - s \longrightarrow m_{\mathcal{R}} = 0$$

- **HL gravity**

- Projectable version:

simply the same as a system of 2 light Lifshitz scalars with their interactions

- Non projectable version:

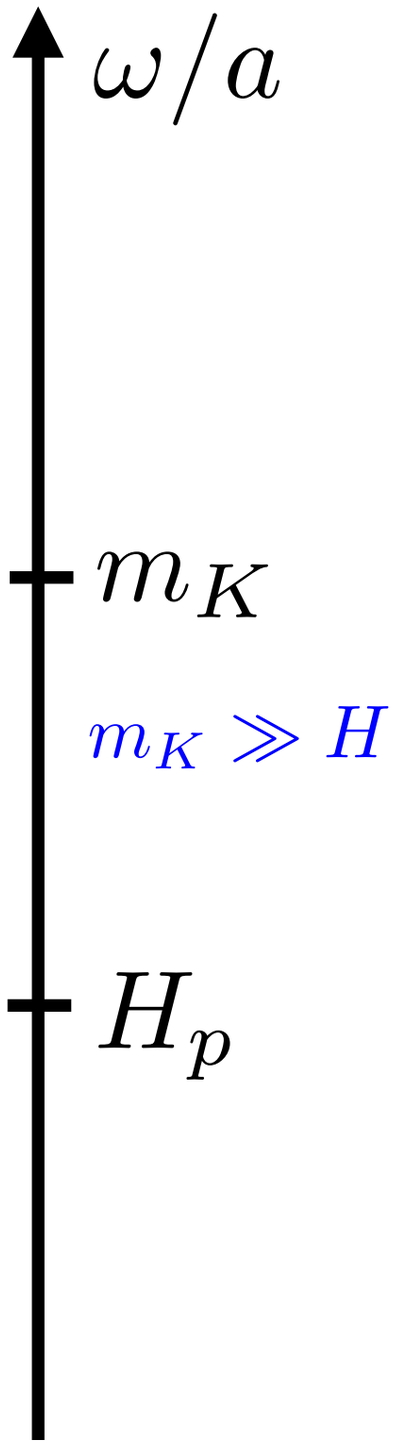
mass term appears because of non canonical kinetic term

$$\mathcal{L}_{\mathcal{R}} \sim a^2\left(X\mathcal{R}'^2 - a^2 m_K^2 X\mathcal{R}^2\right) \qquad X \equiv \left(\frac{p}{aH}\right)^2\left(\frac{p}{aM_*}\right)^{2(z-1)}$$

$$m_K = \mathcal{O}\left(\frac{H}{\sqrt{\alpha}}\right) \gg H$$

In the non projectable version, massive scalar graviton gets decoupled from inflaton before Hubble crossing.

EFT picture of the primordial scalar perturbations (non-projectable version)



EFT picture of the primordial scalar perturbations (non-projectable version)

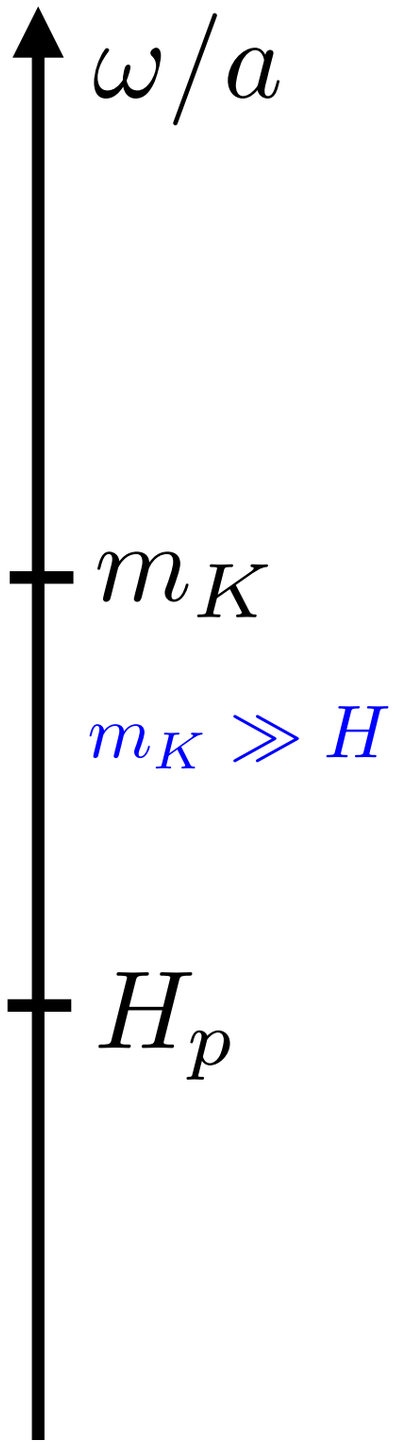
$\mathcal{R},\ \varphi$

decoupled

$$\mathcal{R} = \frac{1}{a\sqrt{2\omega_{\mathcal{R}}}} e^{-i\int d\eta \omega_{\mathcal{R}}}$$

$$\varphi = \frac{1}{a\sqrt{2\omega_{\varphi}}} e^{-i\int d\eta \omega_{\varphi}}$$

coupled



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coupled

ω/a

m_K

$m_K \gg H$

Horizon crossing

H_p

$\zeta,$ **Khronon** $\quad \zeta = \mathcal{R} - \frac{H}{\dot{\phi}}\varphi$

coupled

sub planckにとっていたら必ず
m_KがHよりも大きくなる。

decoupled

ζ

Adiabatic

conserved in time

$$\mathcal{P}_\zeta \propto \frac{1}{\varepsilon_1}\left(\frac{H}{M_P}\right)^{3/z-1}$$

Isocurvature(Khronon)

but purely gauge mode of time foliation

Scalar to tensor ratio & consistency relation

P. Creminelli et al. Phys.Rev.Lett 113, 231301(2014)

$$S_{\gamma\gamma} = \frac{M_P^2}{8}\int d^4x a^3 c_T^{-2}\left[\dot{\gamma}_{ij}^2 - c_T^2\frac{(\partial_k\gamma_{ij})^2}{a^2}\right]$$

- disformal transformation

$$g_{\mu\nu} \mapsto g_{\mu\nu} + (1 - c_T^2(t))n_\mu n_\nu$$

- conformal transformation

$$g_{\mu\nu} \mapsto c_T^{-1}(t) g_{\mu\nu}$$

$$\tilde{c}_s = c_T^{-1}$$

$$\mathcal{L} = \tilde{a}^3 M_P^2 |\dot{\tilde{H}}| c_T^2\left[\dot{\tilde{\pi}}^2 - c_T^{-2}\frac{(\partial_i\tilde{\pi})^2}{\tilde{a}^2} - (1 - c_T^{-2})\dot{\tilde{\pi}}\frac{(\partial_i\tilde{\pi})^2}{\tilde{a}^2}\right]$$

$$\tilde{t} = \int dt c_T^{1/2}(t) \quad \tilde{a} = c_T^{-1/2} a(t)$$

- power spectrum of tensor fluctuation

$$\langle\gamma_{\mathbf{p}}\gamma_{\mathbf{p}'}\rangle = (2\pi)^3\delta(\mathbf{p}+\mathbf{p}')\frac{1}{2p^3}\left(\frac{\tilde{H}}{M_P}\right)^2$$

$$n_t = -\frac{r}{8c_s}$$

\varepsilon > 0 も仮定しているか。

Cosmological Observables of LV inflation

power spectrum of primordial gravitational wave

$$P_t = \left(\frac{H_{\rm inf}}{2\pi}\right)^2 \propto \left(\frac{k}{k_*}\right)^{-n_t}$$

この話をするためには、インフレーションの導入スライドが必要

tensor to scalar ratio

$$r \equiv \frac{P_t}{P_s}$$

4d Diffs and NEC

4 dimensional general covariance = 4d Diffs
Null Energy Condition = NEC

$$n_t = -\frac{r}{8c_s} < 0, \qquad \textit{P. Creminelli et al. (2014)}$$

HL gravity (~~4d Diffs~~) + NEC

$$n_t = 0 \ (z = 3)$$

it is a direct evidence of LV in the early universe.

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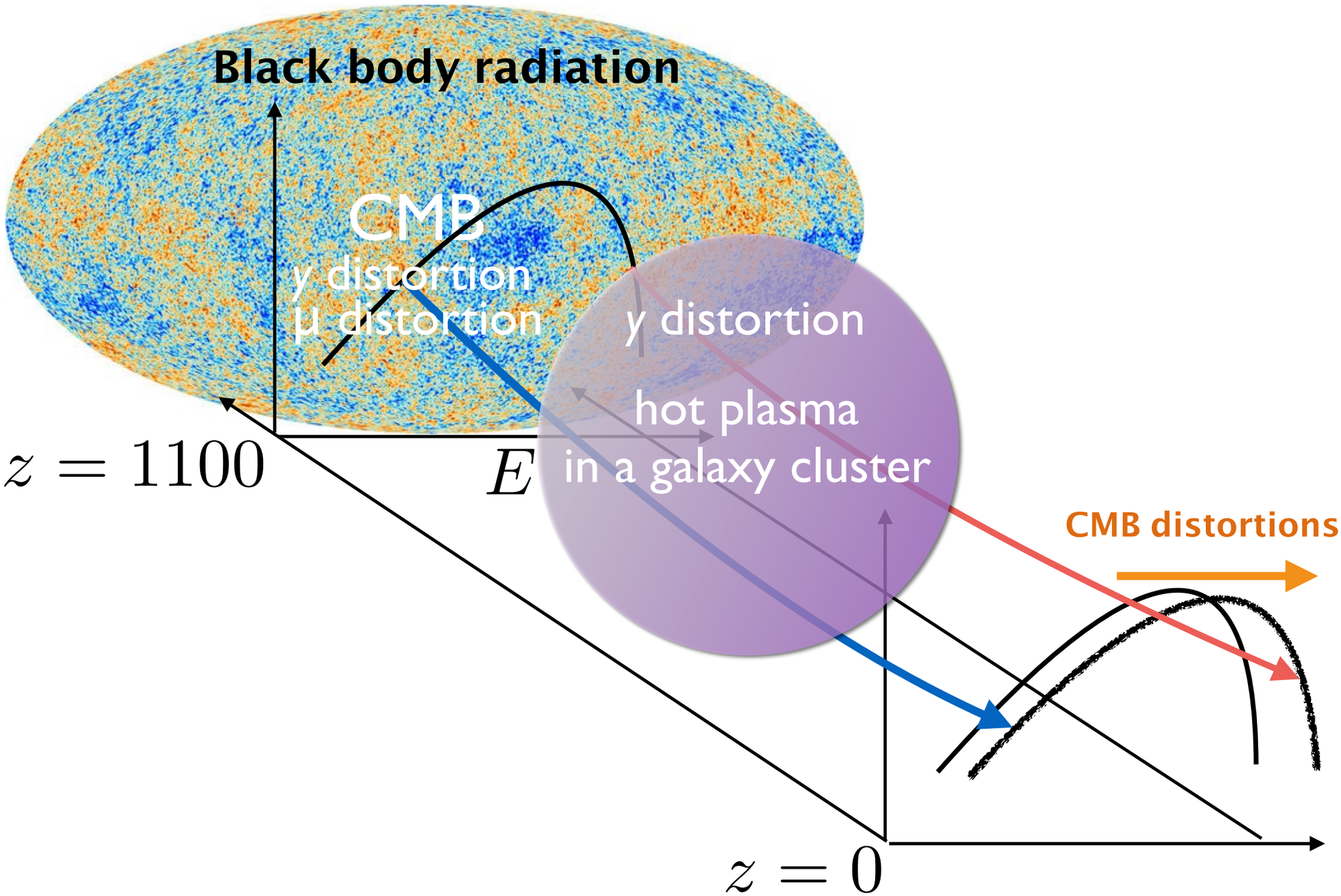
CMB spectral distortions



Science of CMB distortions

- primordial fluctuations at a small scale
- primordial magnetic field
- the nature of dark matter
- high energy physics

Science of CMB distortions

- primordial fluctuations at a small scale
- primordial magnetic field
- the nature of dark matter
- high energy physics
- Test of the General Relativity

Energy dependent metric

$$ds^2 = -dt^2 + \frac{a^2}{g^2(E)}\delta_{ij}dx^i dx^j$$ ※On a static fluid frame

- **Boltzmann equation for a photon**

$$\frac{\partial n_E}{\partial t} - \frac{\dot{a}}{a}E\left(1 - \frac{d\log g}{d\log E}\right)^{-1}\frac{\partial n_E}{\partial E} = 0$$

usual redshift evolution　Modification of a redshift evolution

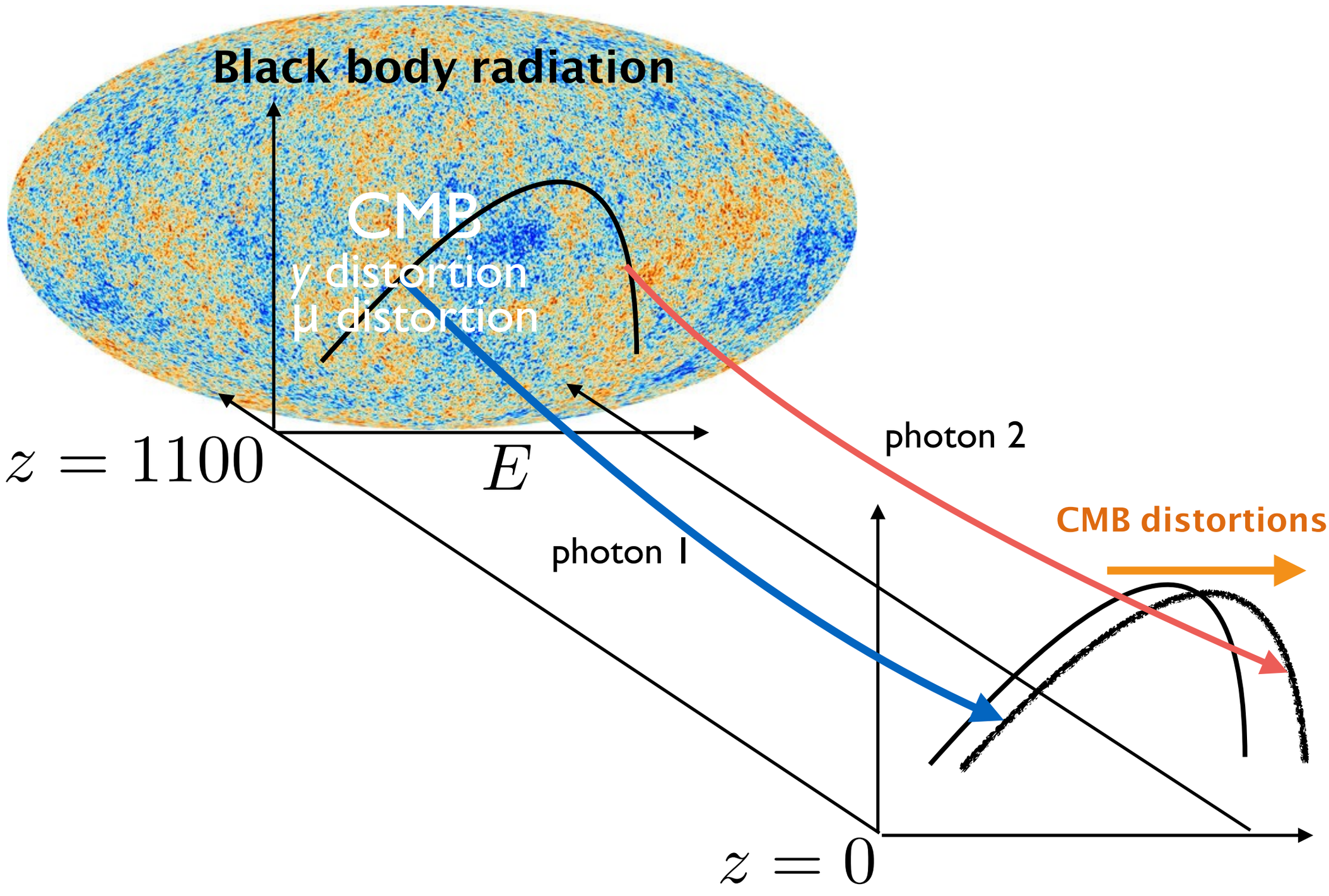
Spectral distortions after recombination

In general *y* distortion and μdistortion

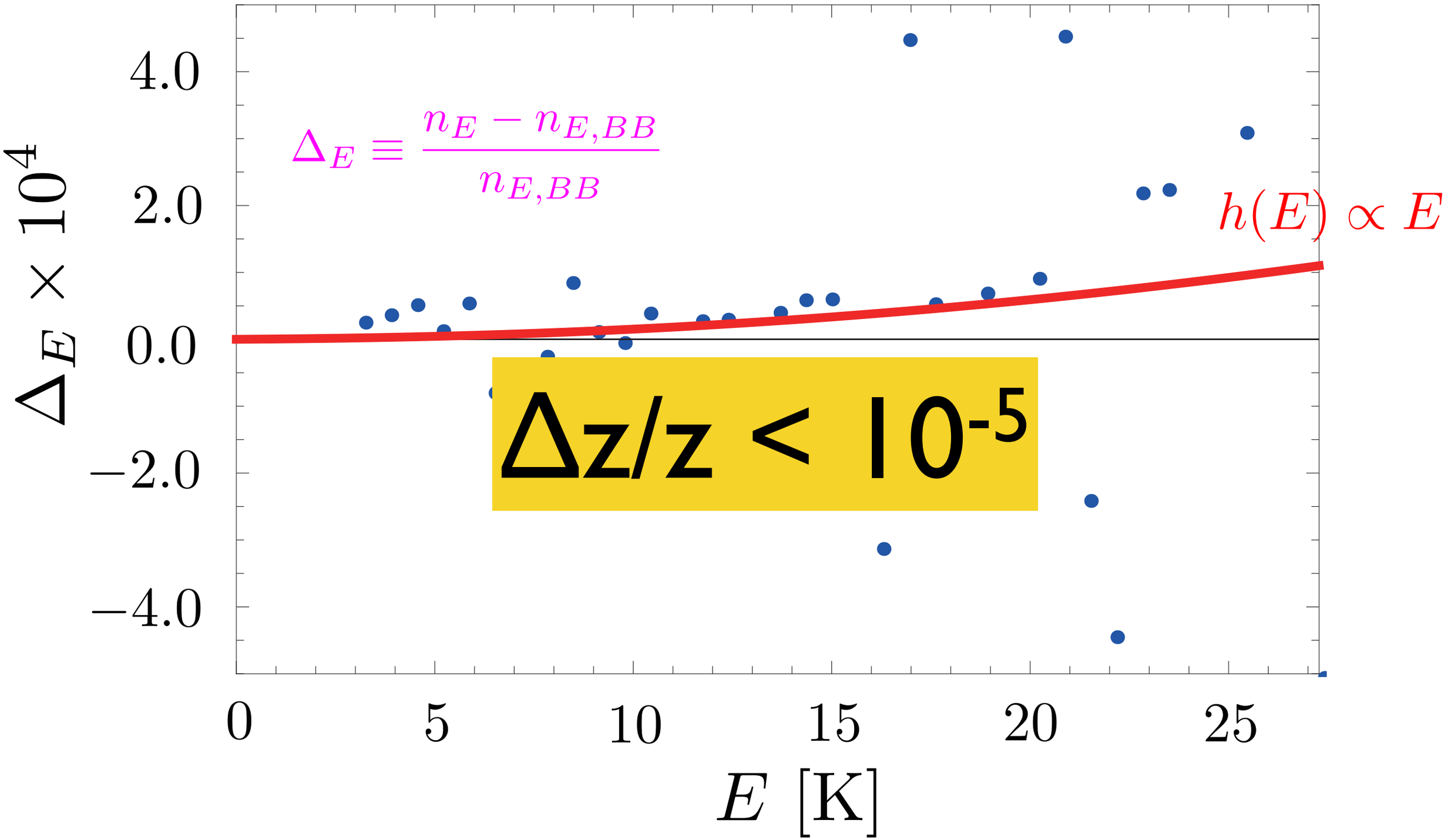
$$g \simeq 1 + h(E), h(E) \ll 1$$

CMBの温度揺らぎによる黒体放射を歪める効果は2次のオーダーにあるので、摂動の1次を今回考

CMB spectral distortions w LV



Constraints w COBE/FIRAS



青点はCOBE/FIRASの黒体放射からのずれ

これはAmazing factです。今まで知られていなかったことが明らかとなったため

Summary

Inflation in a spacetime described by Horava Lifshitz gravity, an extra d.o.f in the gravity sector, scalar graviton get interactive with inflaton fluctuation. However, scalar graviton become massive at sub-horizon scale and inflaton fluctuation get decoupled at horizon crossing time, and finally **only the adiabatic perturbation is left as a primordial density fluctuation.**

Primordial gravitational waves could provide us for a smoking gun of the Lorentz invariance in the context of Horava Lifshitz gravity.

If the Einstein Equivalence Principle is broken, redshift evolution of a photon propagating after recombination is modified with energy dependence of the photon. This modification make **CMB distortions, which enables us to constrain local Lorentz symmetry from observation.**

Thank you for your attention:-)

Space Shuttle Discovery re-entry