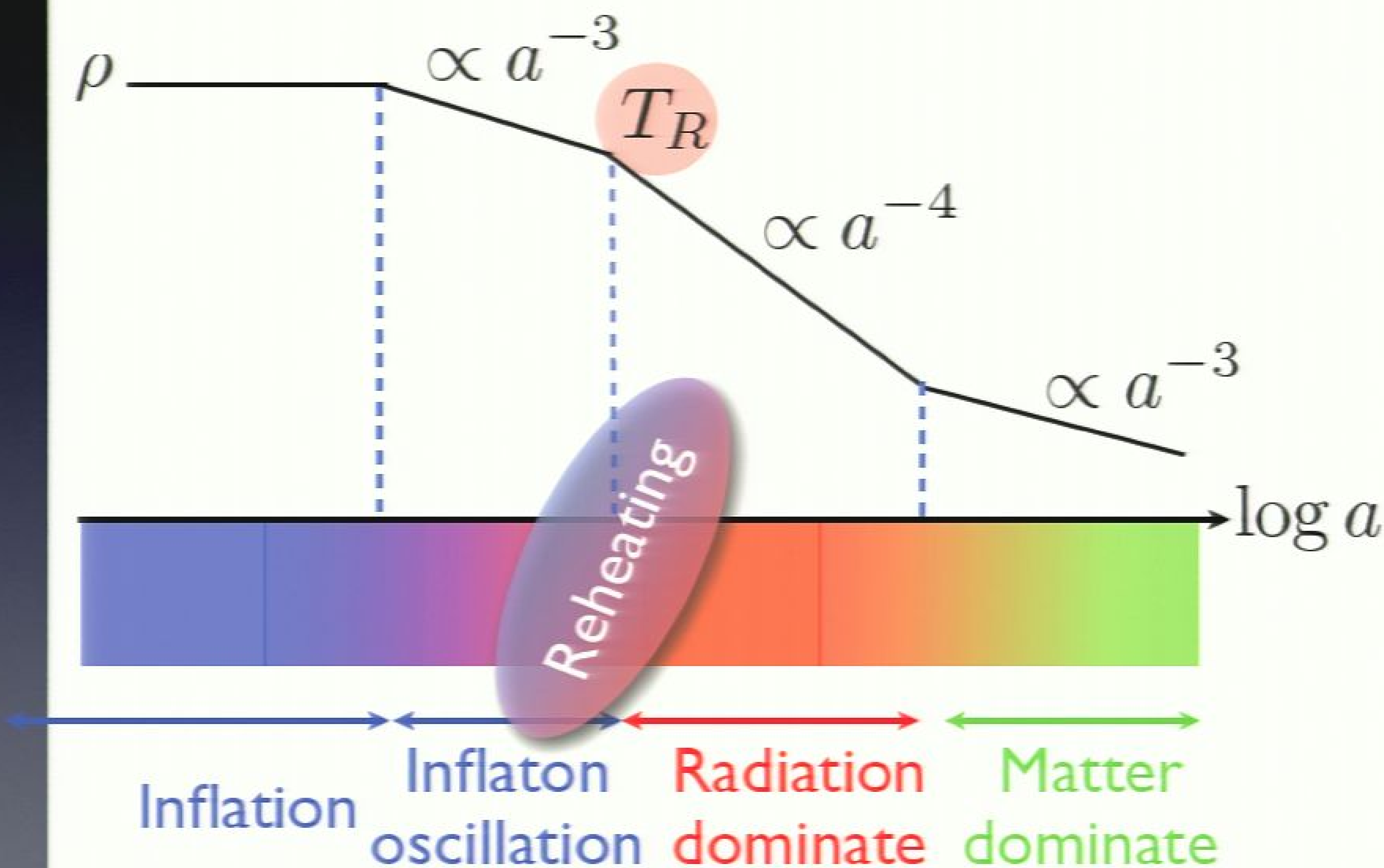
Title: Gravitational wave background as a probe of reheating temperature of the Universe

Date: Jun 06, 2008 12:00 PM

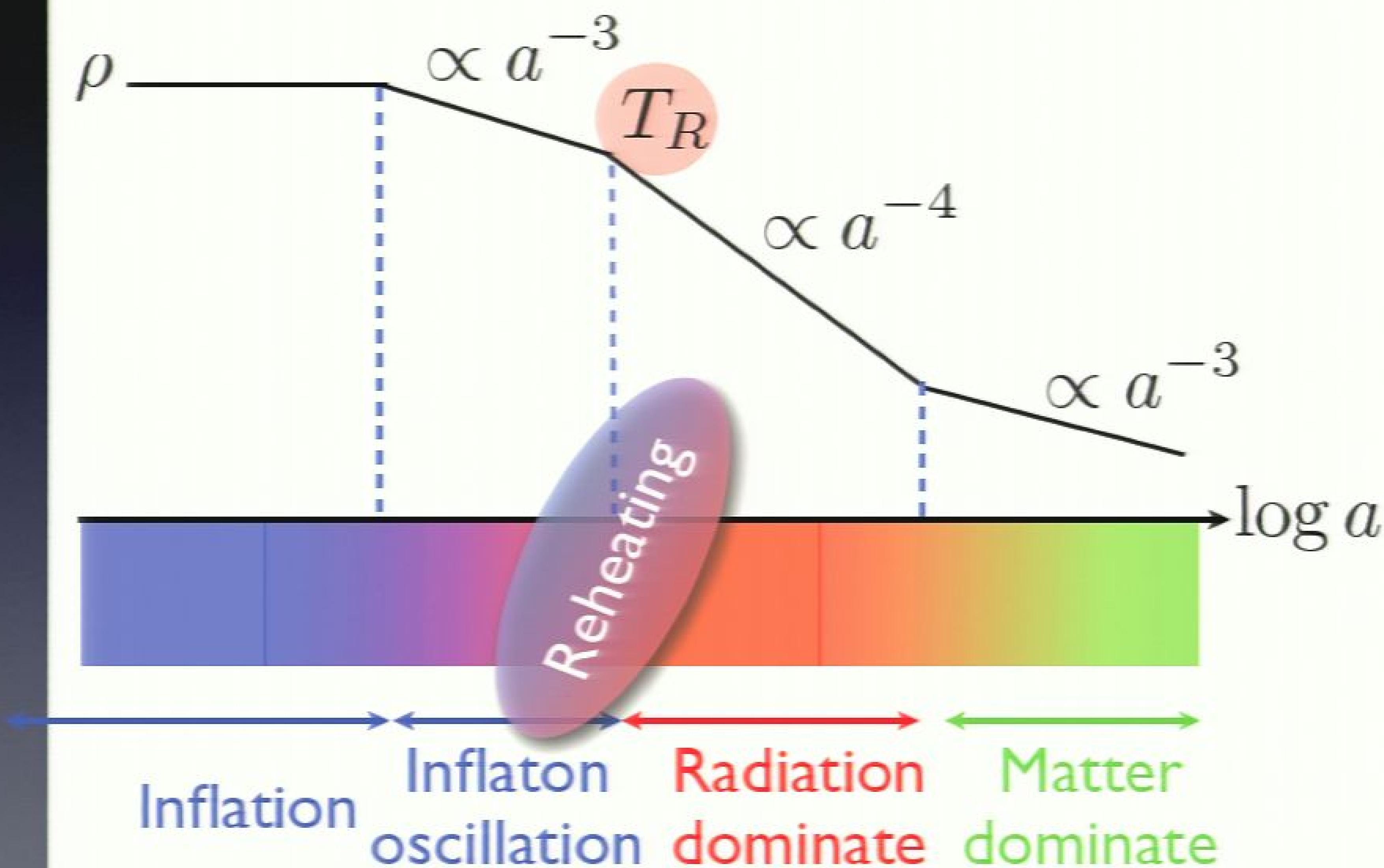
URL: http://pirsa.org/08060186

Abstract: \'Thermal history of the universe after big-bang nucleosynthesis (BBN) is well understood both theoretically and observationally, and recent cosmological observations also begin to reveal the inflationary dynamics. However, the epoch between inflation and BBN is scarcely known. In this work we show that the detection of the stochastic gravitational wave background around 1Hz provides useful information about thermal history well before BBN. In particular, the reheating temperature of the universe may be determined by future space-based laser interferometer experiments such as DECIGO and/or BBO if it is around 10^{6-9} GeV, depending on the tensor-to-scalar ratio r and dilution factor F.\'

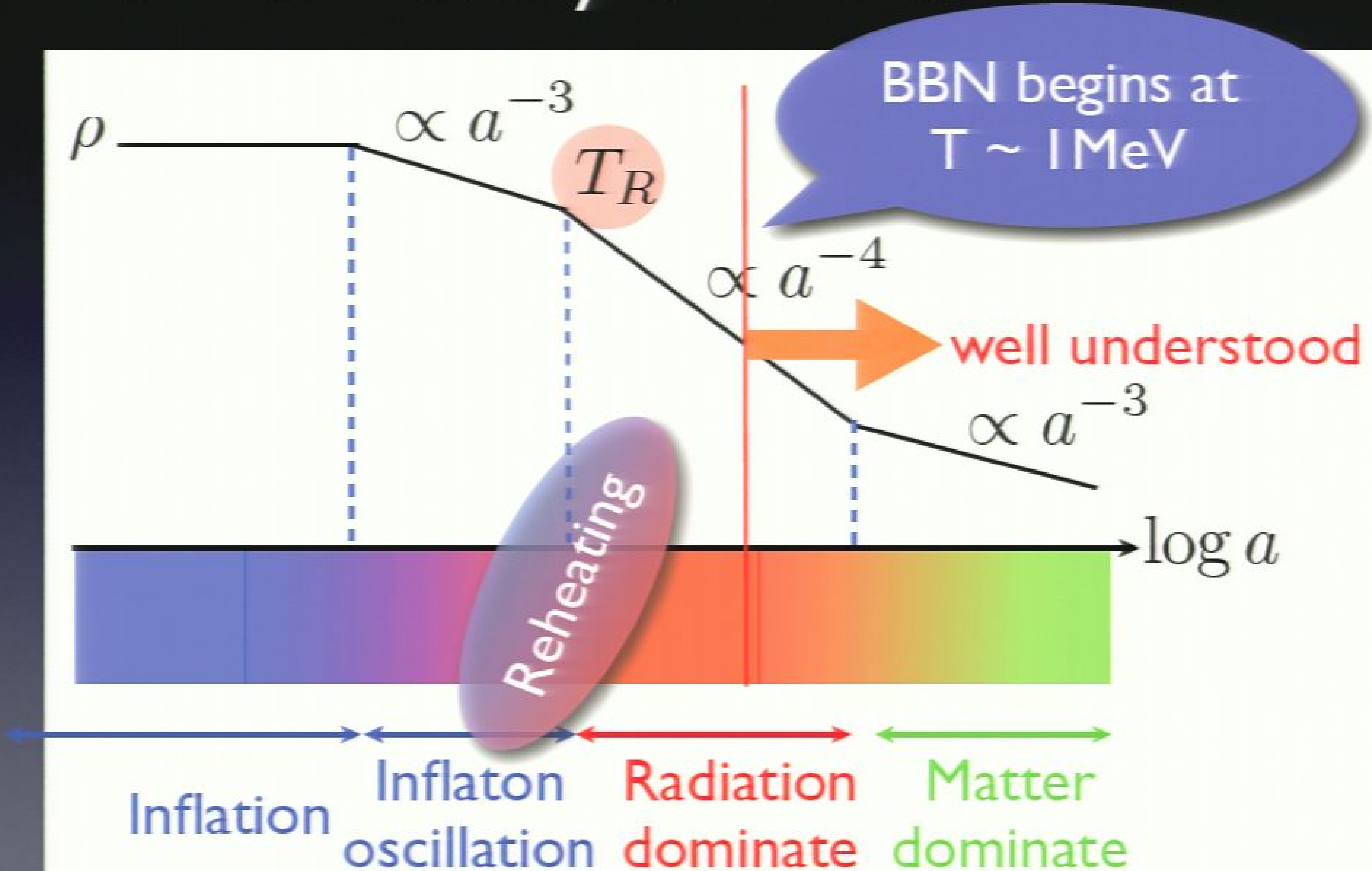
Thermal history of the Universe



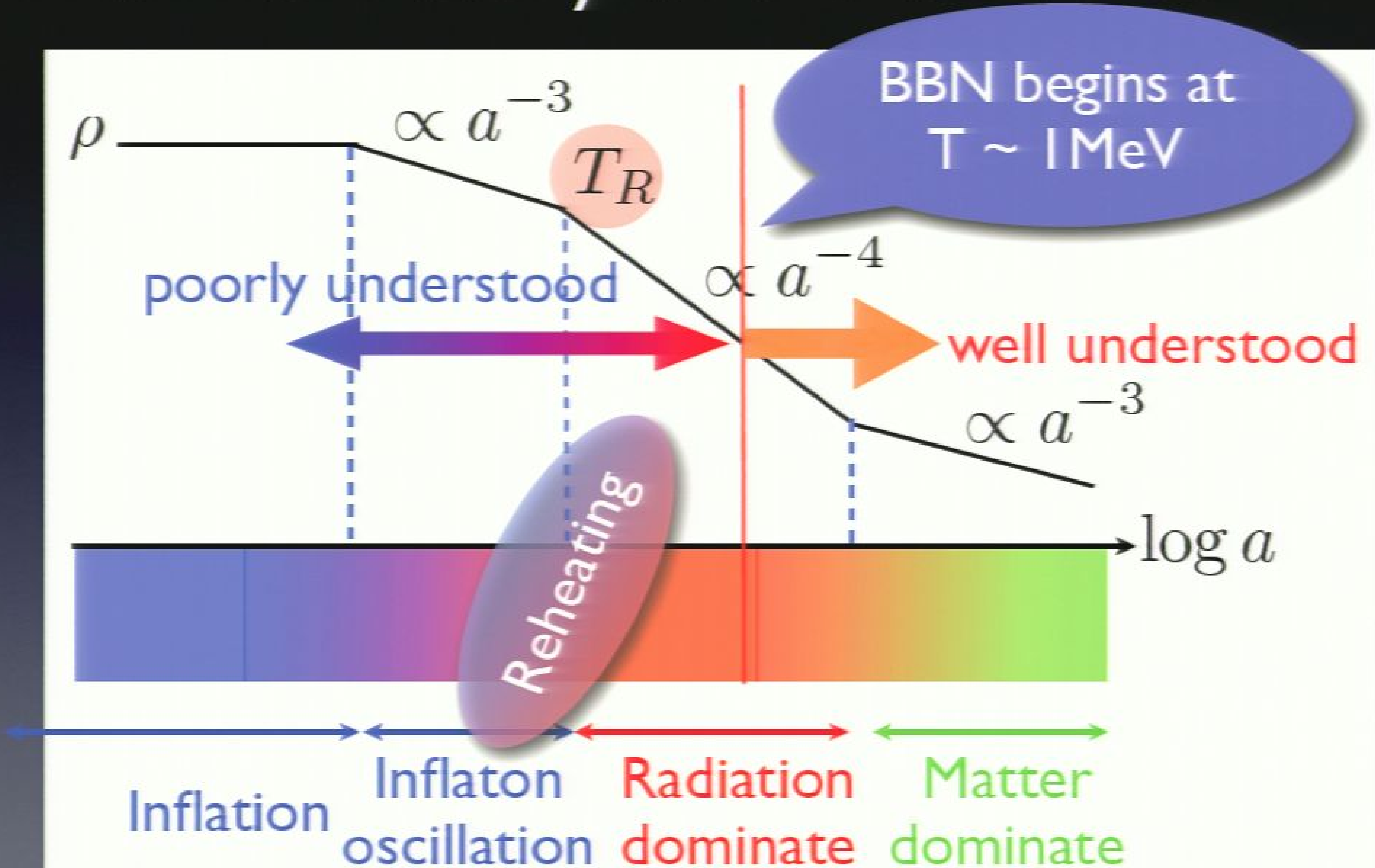
Thermal history of the Universe

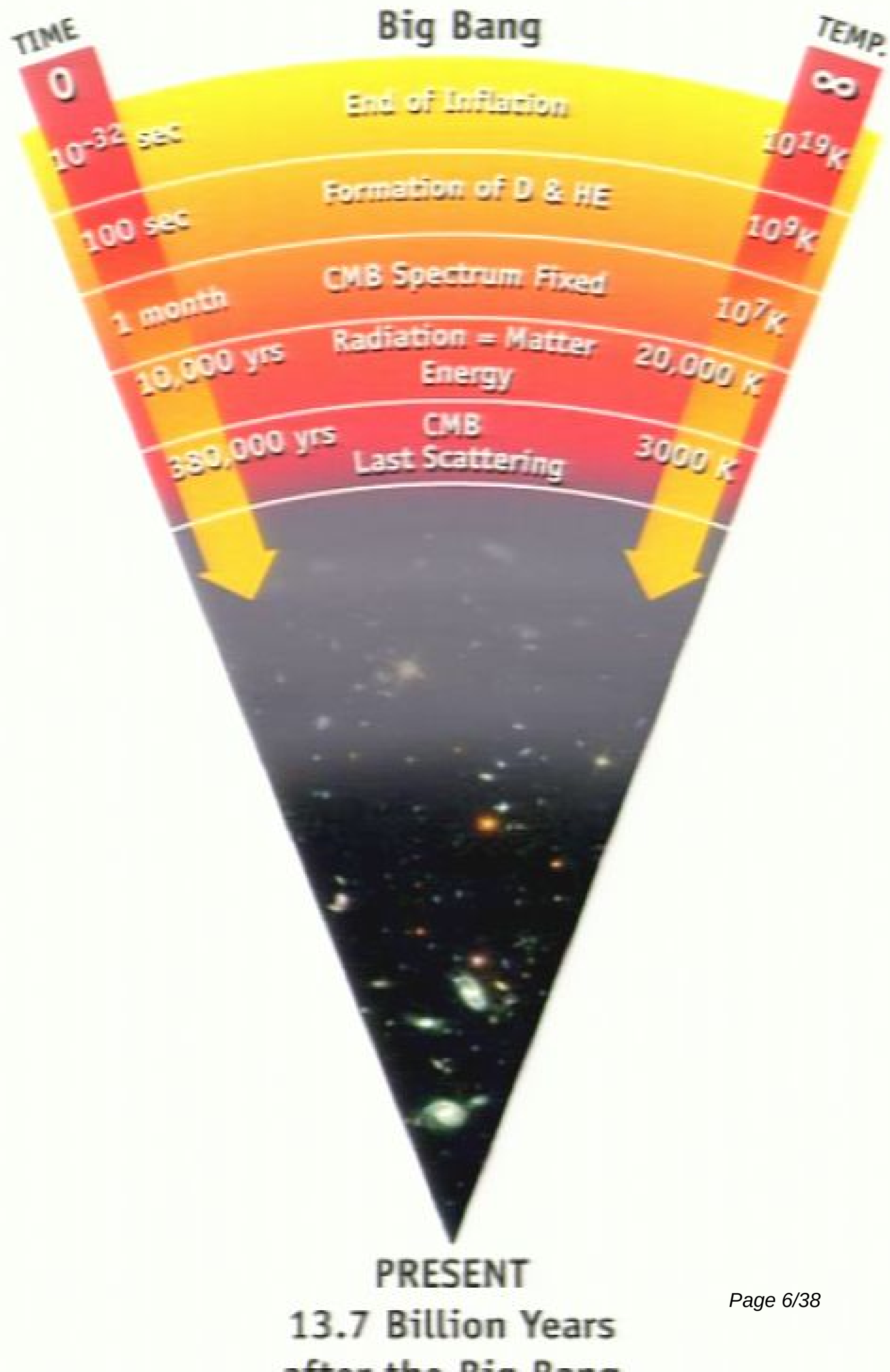


Thermal history of the Universe

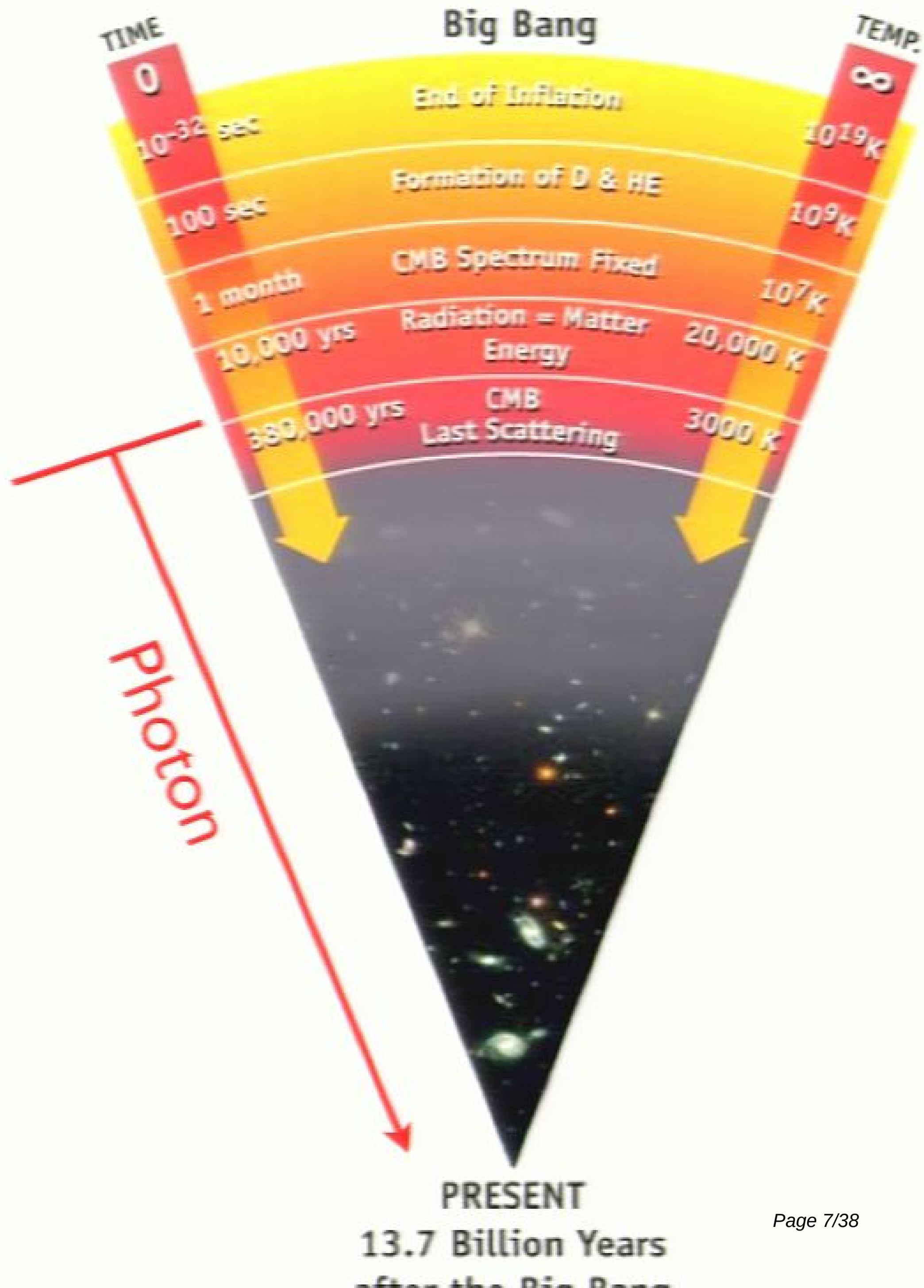


Thermal history of the Universe

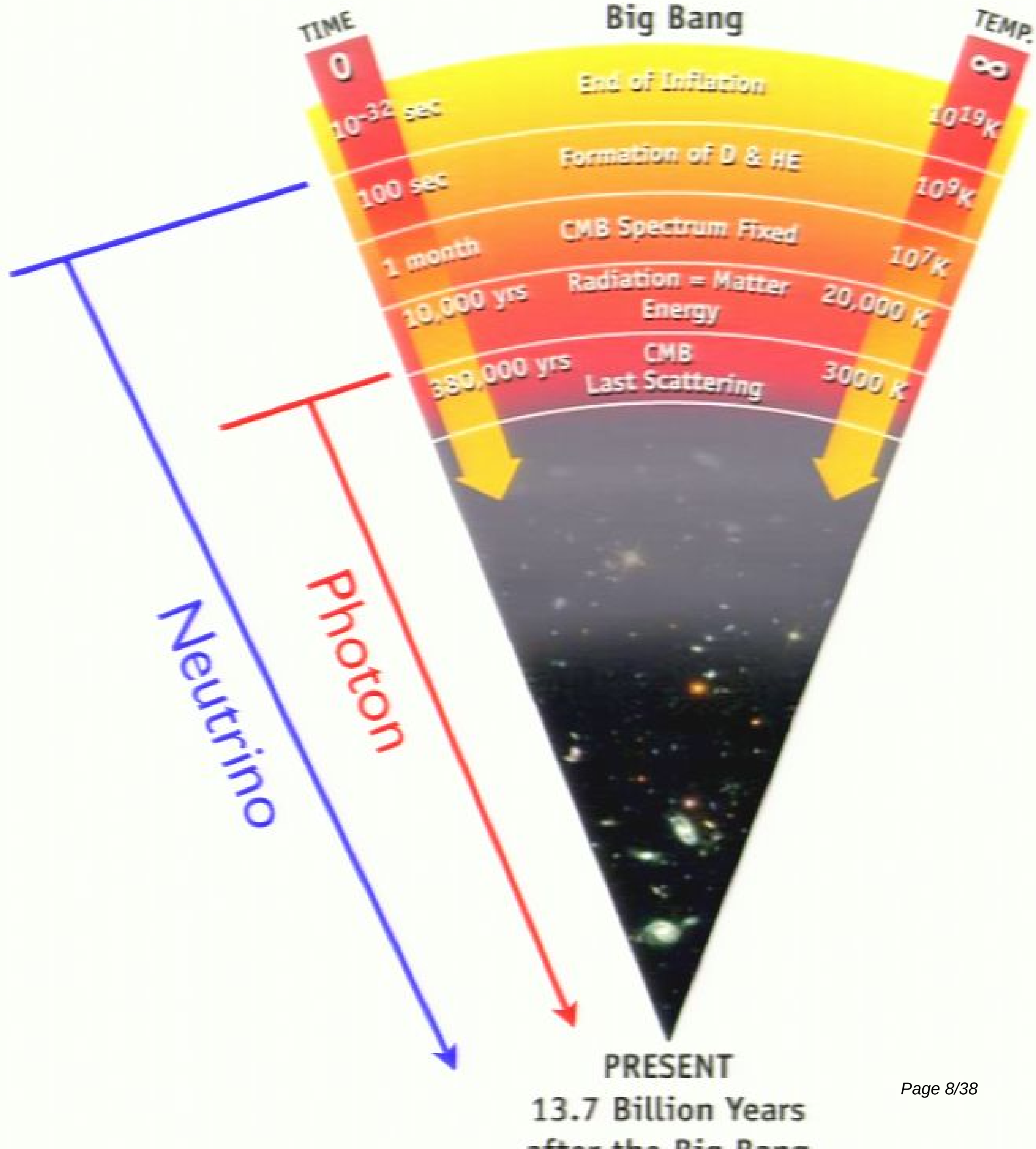




TIME
Big Bang
TEMP.
0
∞
End of Inflation
10^-32 sec
10^19 K
Formation of D & HE
100 sec
10^9 K
CMB Spectrum Fixed
1 month
10^7 K
Radiation = Matter Energy
10,000 yrs
20,000 K
CMB Last Scattering
380,000 yrs
3000 K
PRESENT
13.7 Billion Years



TIME
Big Bang
TEMP.
0
∞
End of Inflation
10-32 sec
1019K
Formation of D & HE
100 sec
109K
CMB Spectrum Fixed
1 month
107K
Radiation = Matter Energy
10,000 yrs
20,000 K
CMB Last Scattering
380,000 yrs
3000 K
Photon
PRESENT
13.7 Billion Years



TIME
Big Bang
TEMP.
0
∞
End of Inflation
10^-32 sec
10^19 K
Formation of D & HE
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CMB Spectrum Fixed
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Radiation = Matter Energy
10,000 yrs
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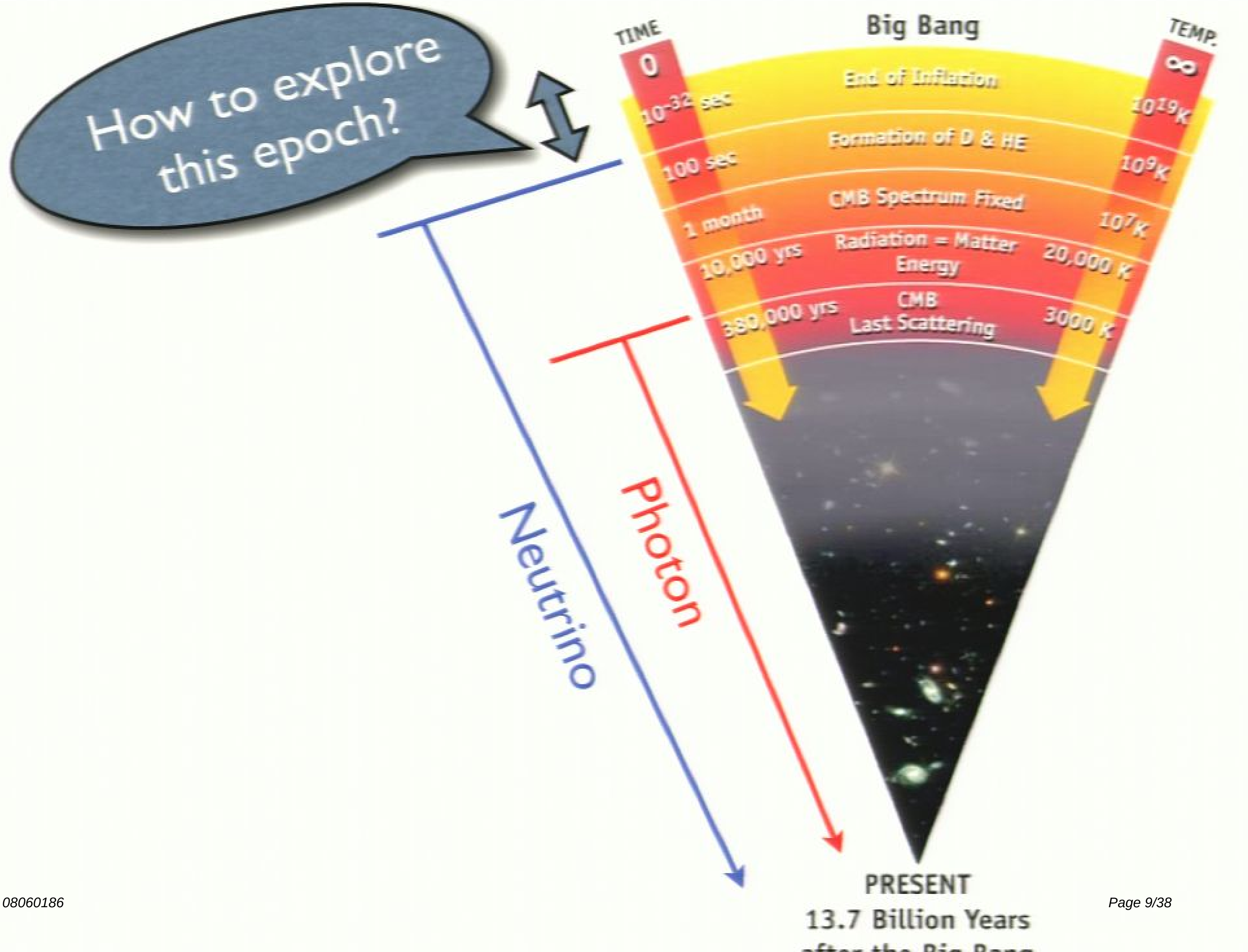
CMB Last Scattering
380,000 yrs
3000 K
Neutrino
Photon
PRESENT
13.7 Billion Years


How to explore this epoch?
TIME
Big Bang
TEMP.
0
∞
End of Inflation
10^{-32} sec
10^{19}K
Formation of D & HE
100 sec
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PRESENT
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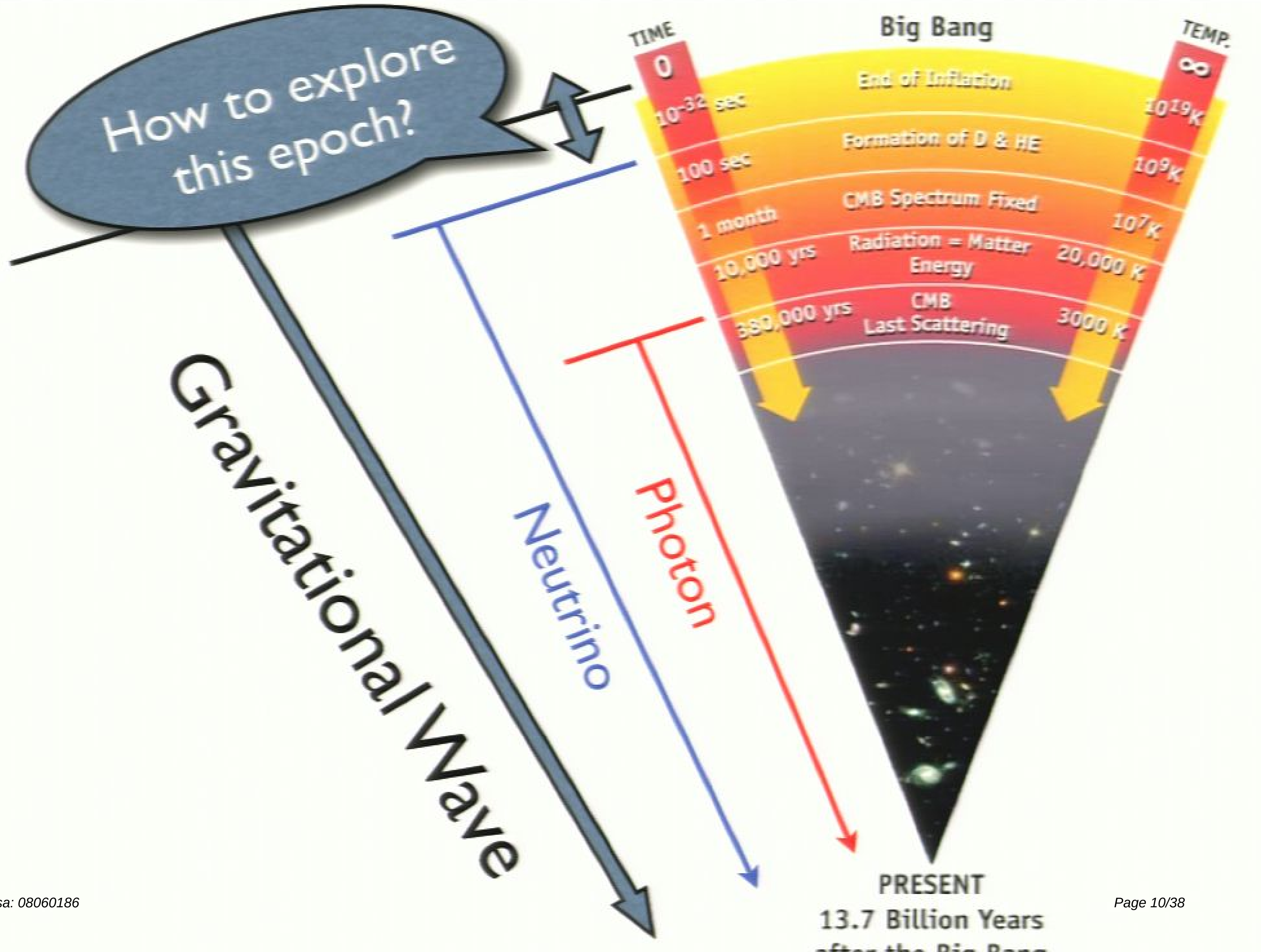
How to explore this epoch?
Big Bang
TIME
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Radiation = Matter Energy
10,000 yrs
20,000 K
CMB Last Scattering
380,000 yrs
3000 K
Gravitational Wave
Neutrino
Photon
PRESENT
13.7 Billion Years

Why determining TR is important ?

- Cosmological point of view

It connects thermal history of the Universe between inflation and BBN

- Particle physics point of view

Some particle physics model can be favored, constrained or excluded.

SUSY → Gravitino Problem

Baryogenesis

Constraints on TR

Inflationary Gravitational Wave Background

Generation of Gravitational Waves

Metric perturbation (tensor part)

$$ds^2 = a^2(t)[-d\tau^2 + (\delta_{ij} + 2h_{ij})dx^i dx^j]$$

$$h_{ij} = \frac{1}{M_P} \sum_{\lambda=+,-} \int \frac{d^3k}{(2\pi)^{3/2}} h_k^\lambda(t) e^{i\mathbf{kx}} e_{ij}^\lambda$$

Same as massless field

Quantization

$$\langle h_k^\lambda h_{k'}^{\lambda'} \rangle = \frac{H_{\rm inf}^2}{2k^3} \delta^3(k-k')\delta^{\lambda\lambda'}$$

during inflation

Dimensionless power spectrum $\Delta_h^2(k) = 64\pi G \left(\frac{H_{\rm inf}}{2\pi} \right)^2$

Tensor-to-scalar ratio : $r = \frac{\Delta_h^2}{\Delta_{\mathcal{R}}^2} = 16\epsilon$

Evolution of GW

$$\ddot{h}_k^\lambda + 3H\dot{h}_k^\lambda + \frac{k^2}{a^2}h_k^\lambda = 0$$

→ Outside the horizon : $h_k^\lambda = \mathrm{const.}$

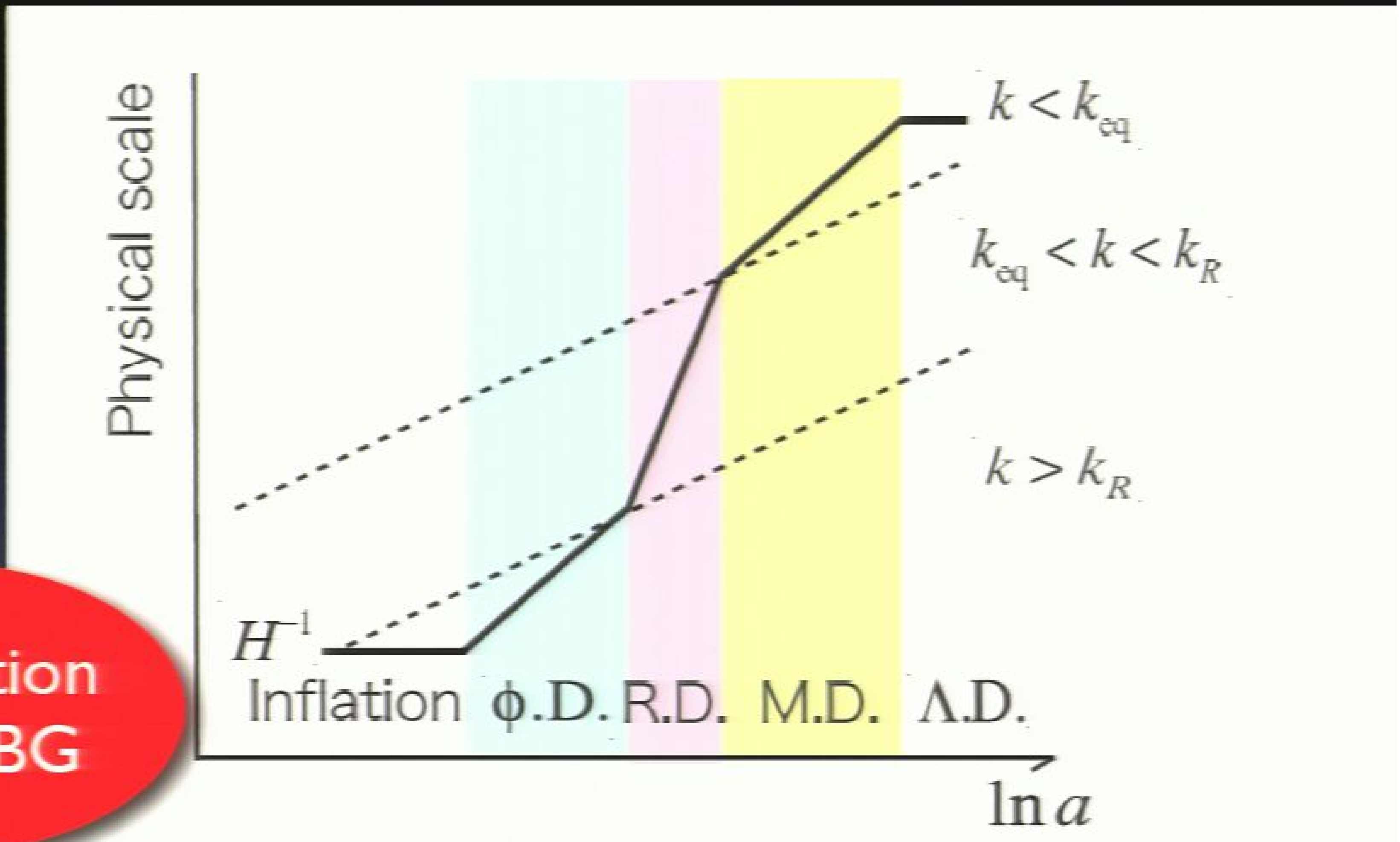
Inside the horizon : $h_k^\lambda \propto a^{-1}$

$$\frac{d\rho_{\rm gw}}{d\ln k} = \sum_\lambda \frac{1}{32\pi G} k^2 |h_k^\lambda|^2 \left(\frac{a_{\rm in}(k)}{a_0}\right)^2 \quad \begin{array}{l} \propto k^{-4} \ \text{ for } \ k < k_{\rm eq} \\ \propto k^{-2} \ \text{ for } \ k > k_{\rm eq} \end{array}$$

$$\Omega_{\rm gw}(k) = \frac{1}{\rho_c}\frac{d\rho_{\rm gw}}{d\ln k} \quad \begin{array}{l} \propto k^{-2} \ \text{ for } \ k < k_{\rm eq} \\ \propto \mathrm{const} \ \text{ for } \ k > k_{\rm eq} \end{array}$$

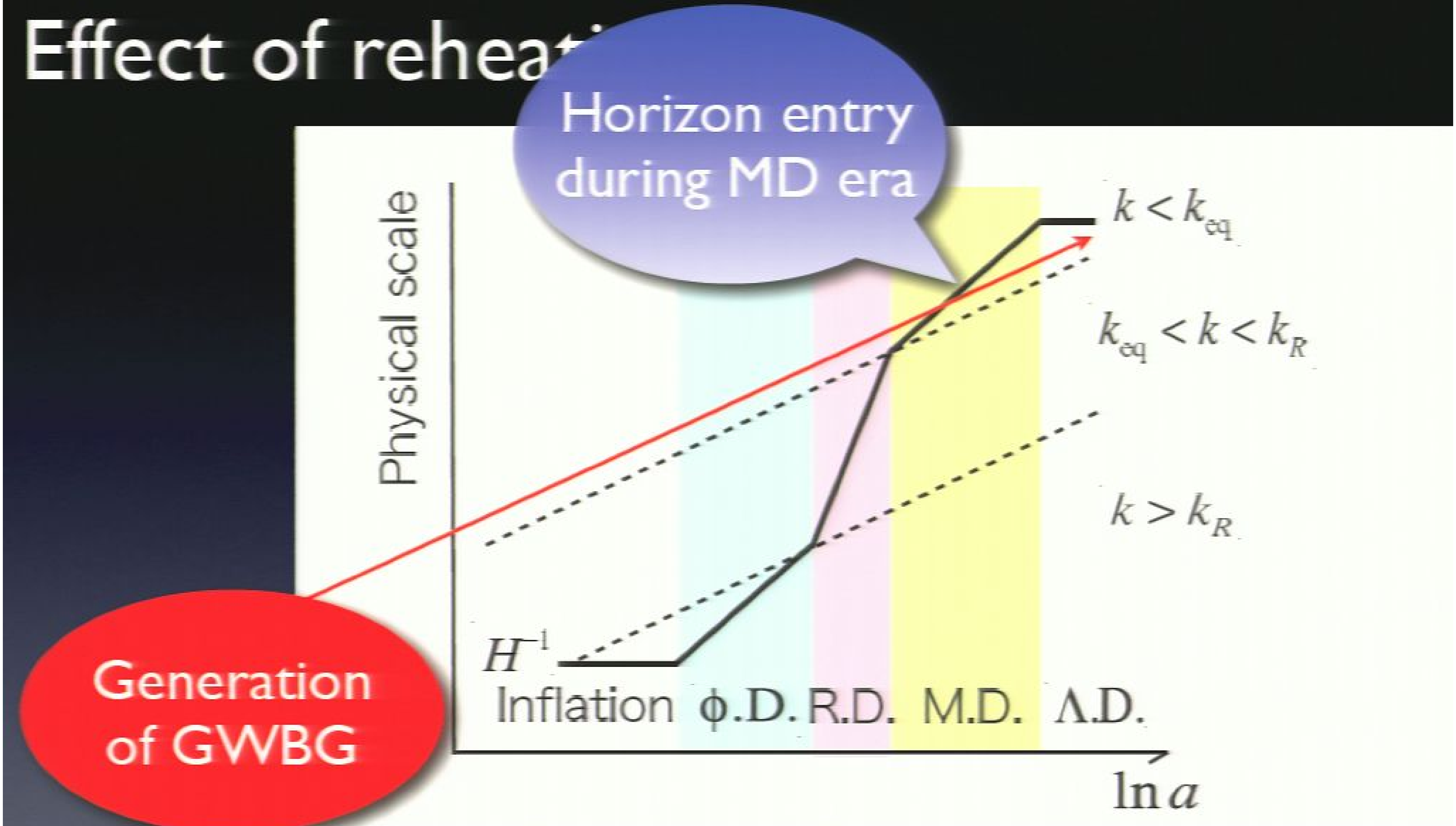
Thermal history is imprinted in the GWB spectrum

Effect of reheating

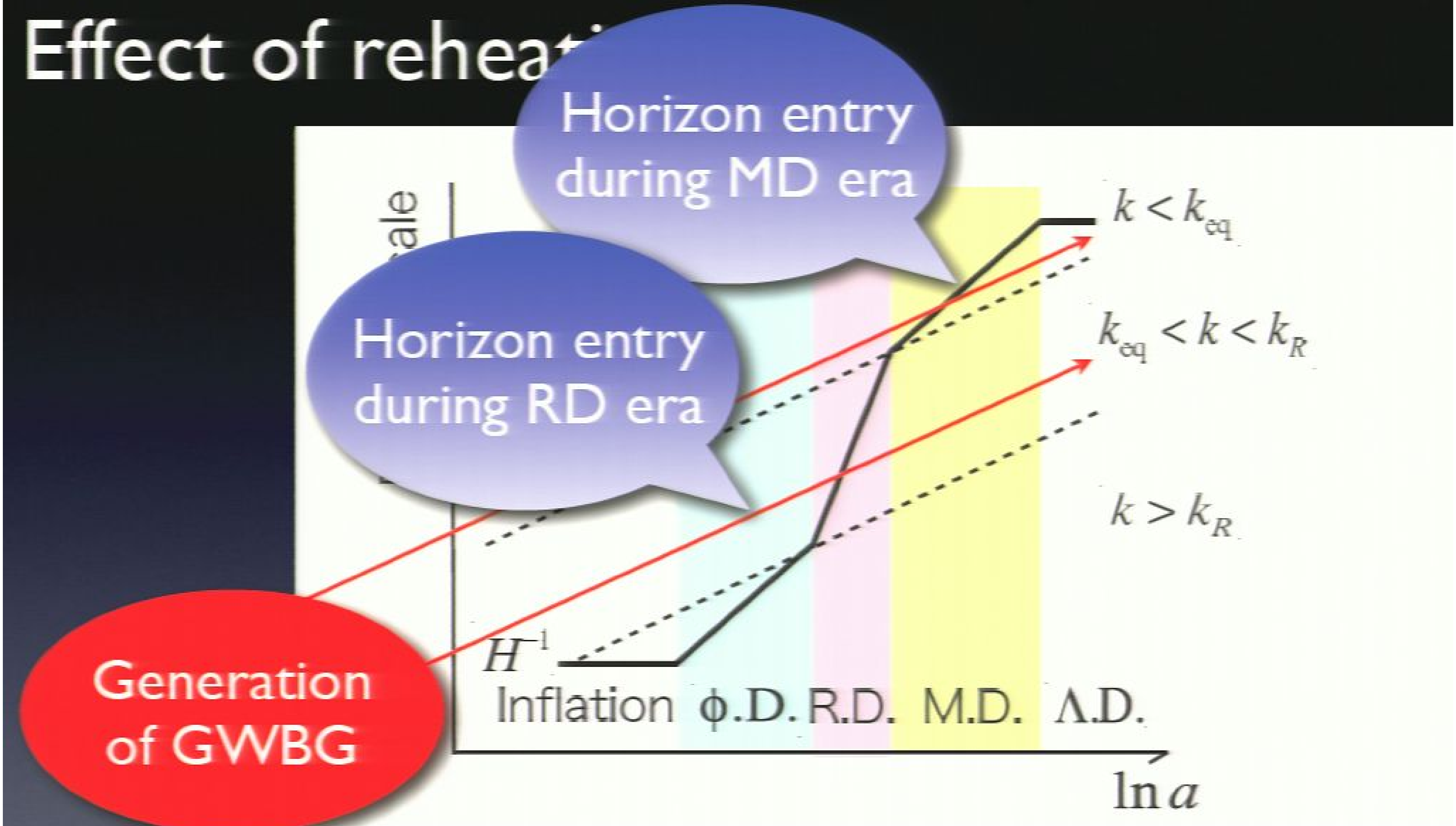


Generation of GWBG

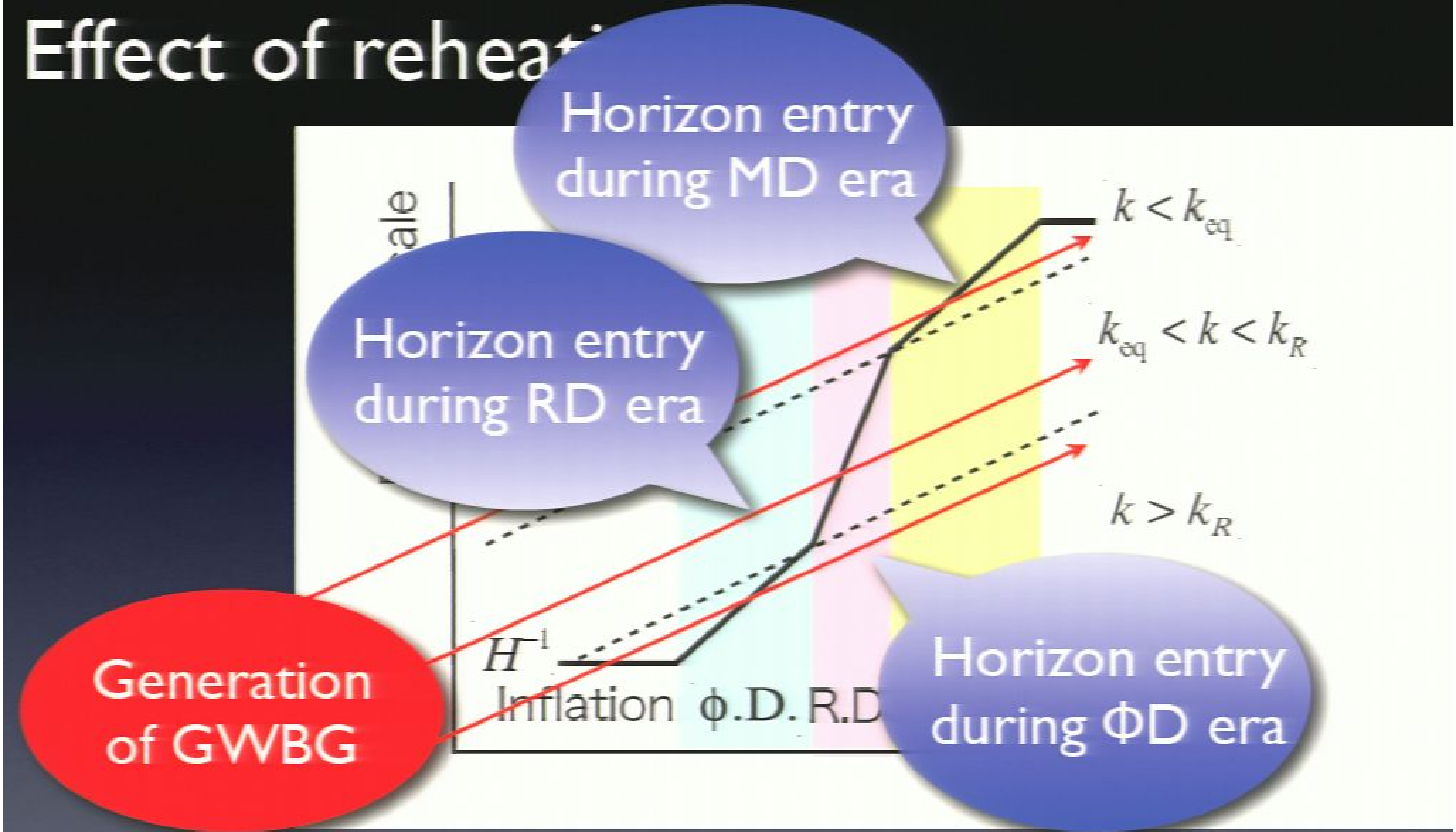
Effect of reheat



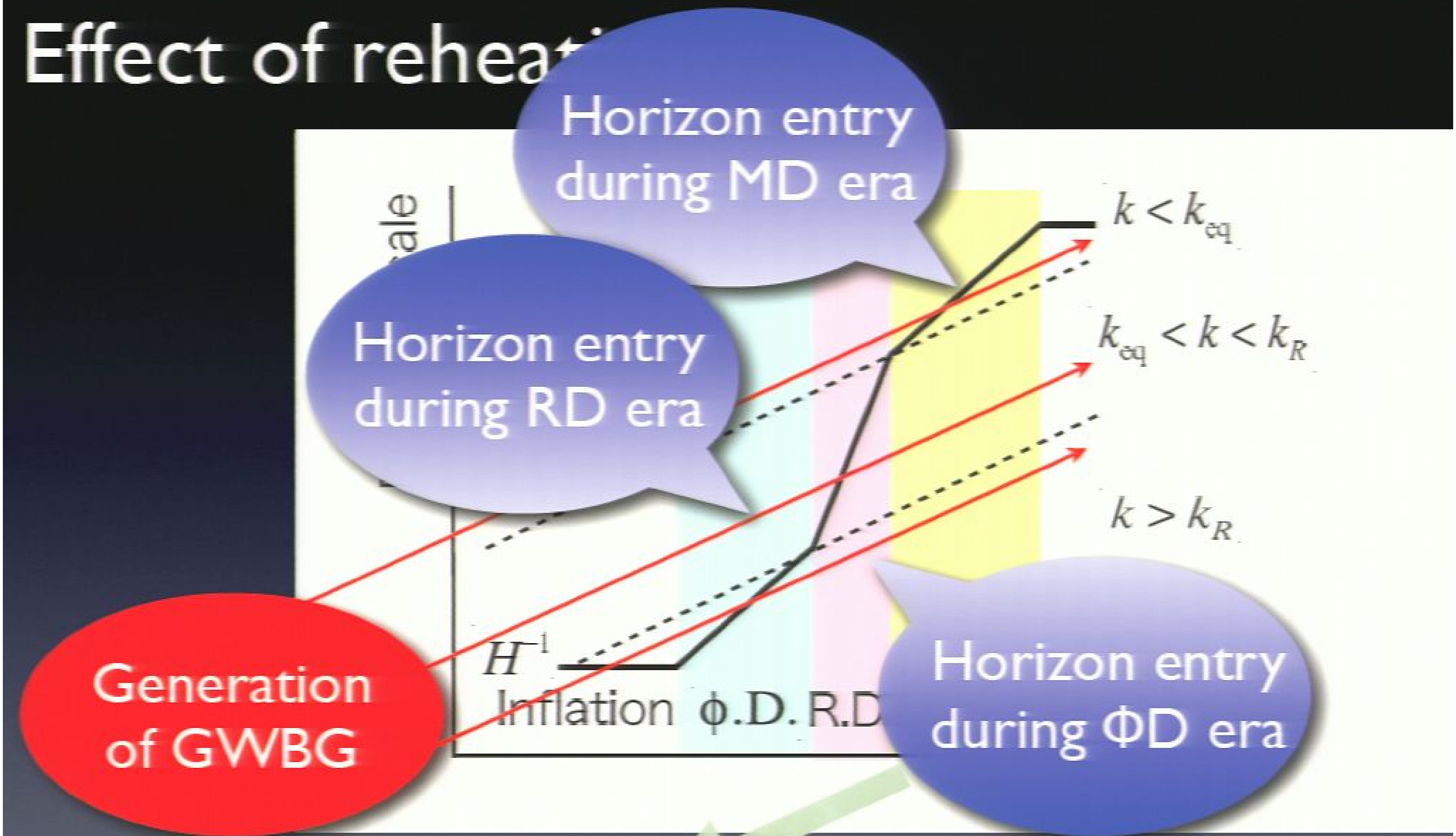
Effect of reheat



Effect of reheati



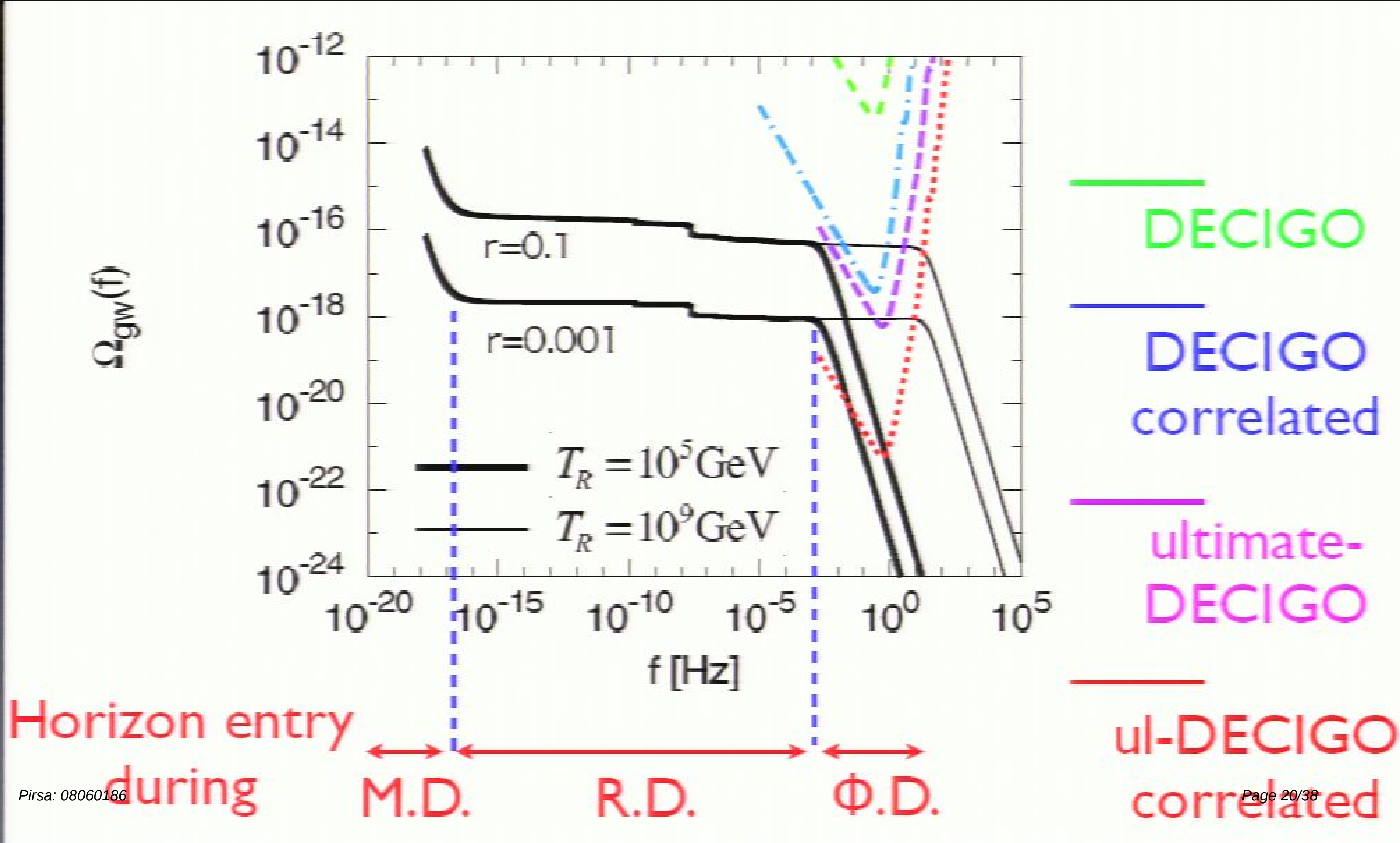
Effect of reheati



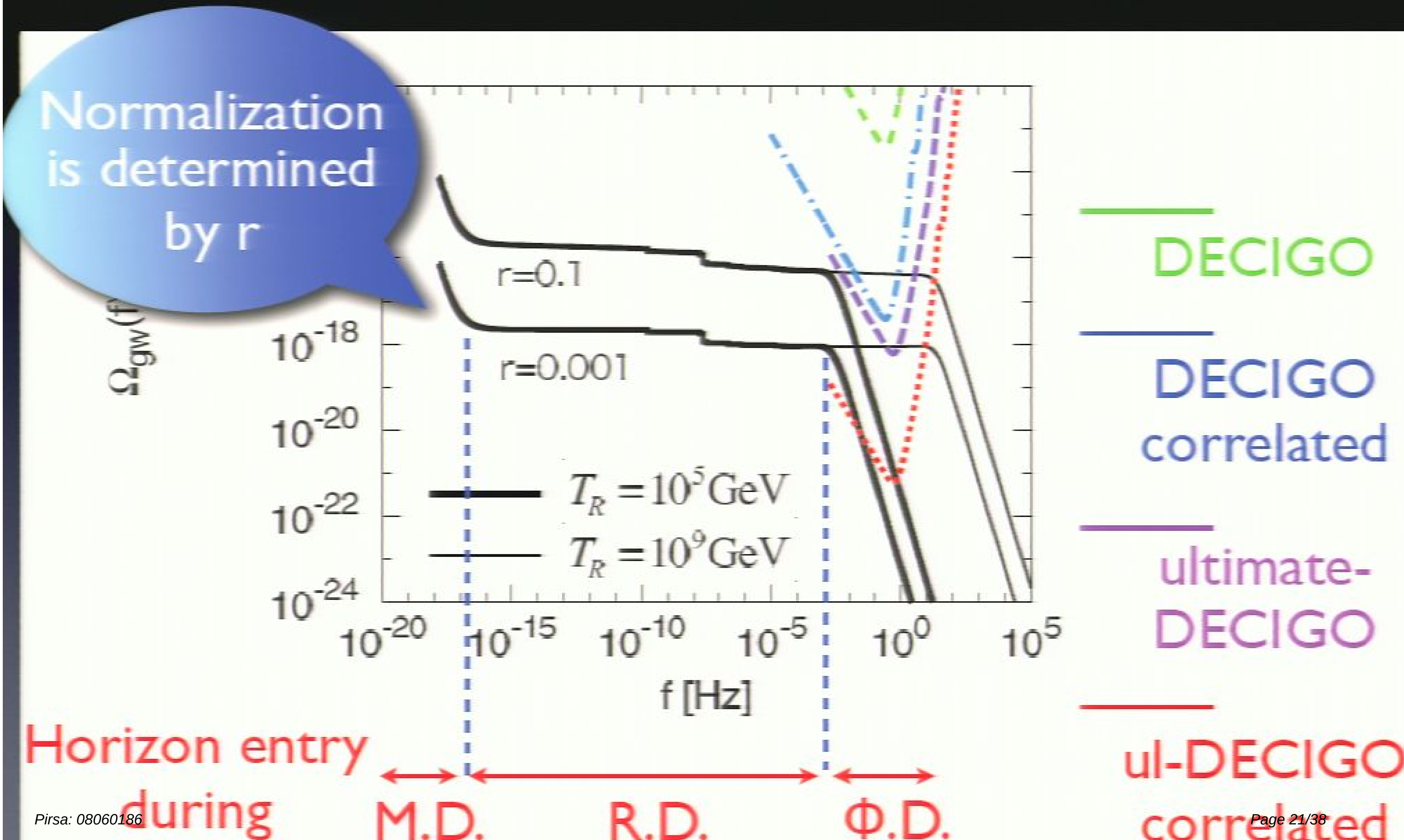
Extra suppression to GW spectrum for this mode

$$f > f_R = 0.026\text{Hz}\left(\frac{T_R}{10^6\text{GeV}}\right)$$

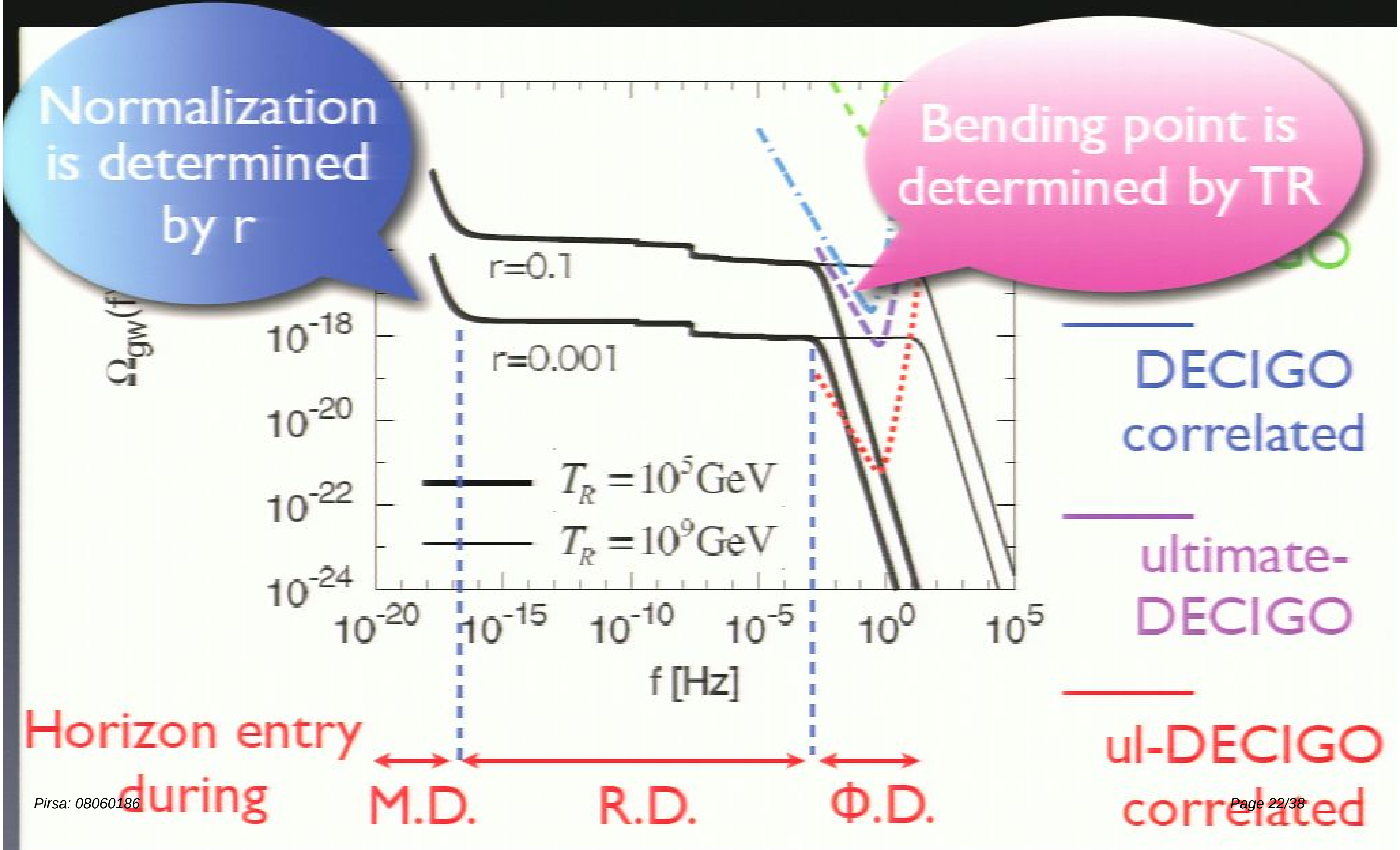
Gravitational Wave Spectrum



Gravitational Wave Spectrum



Gravitational Wave Spectrum

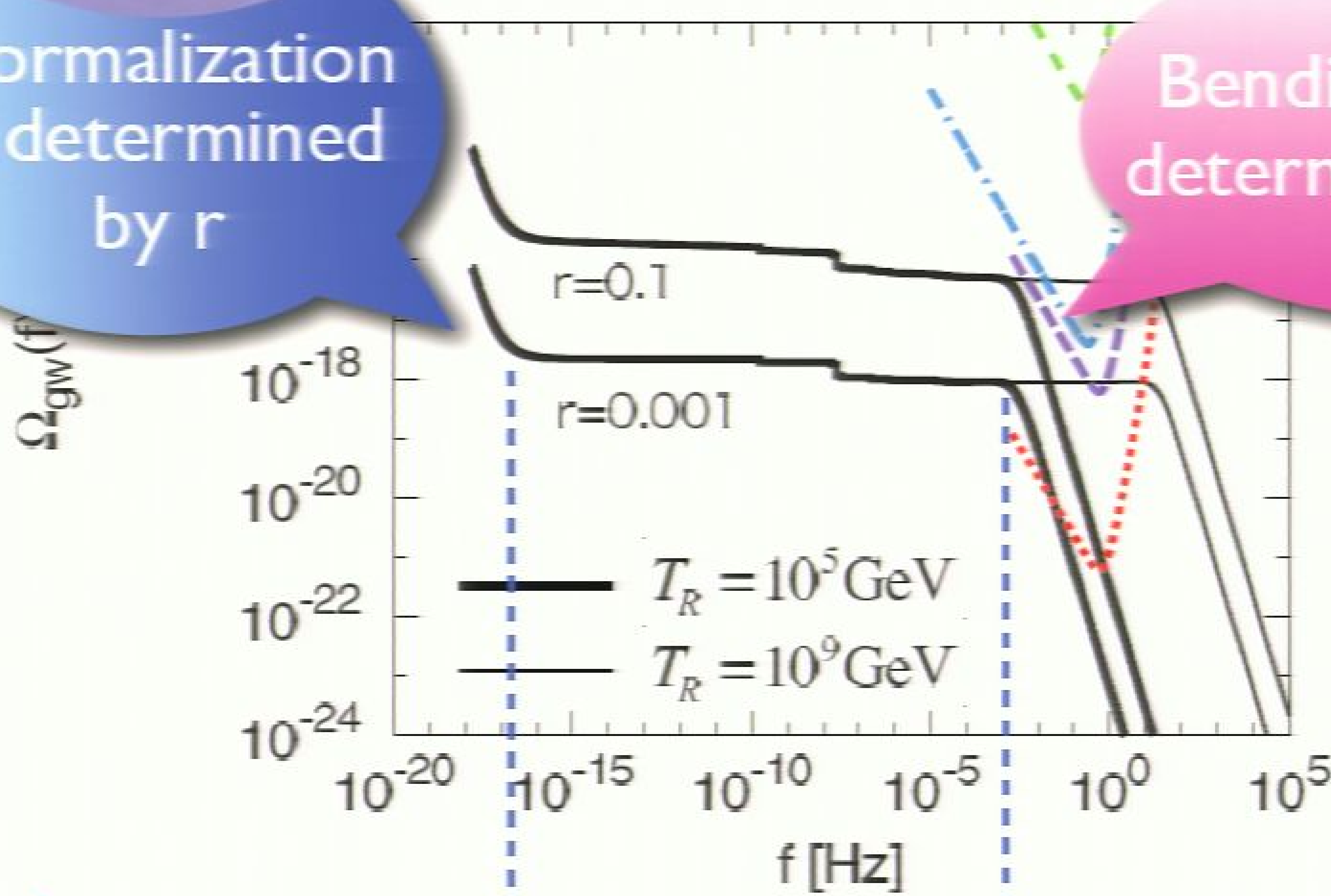


G… ional Wave Spectrum

CMB polarization

Normalization is determined by r

Bending point is determined by TR



DECIGO correlated

ultimate-DECIGO

ul-DECIGO correlated

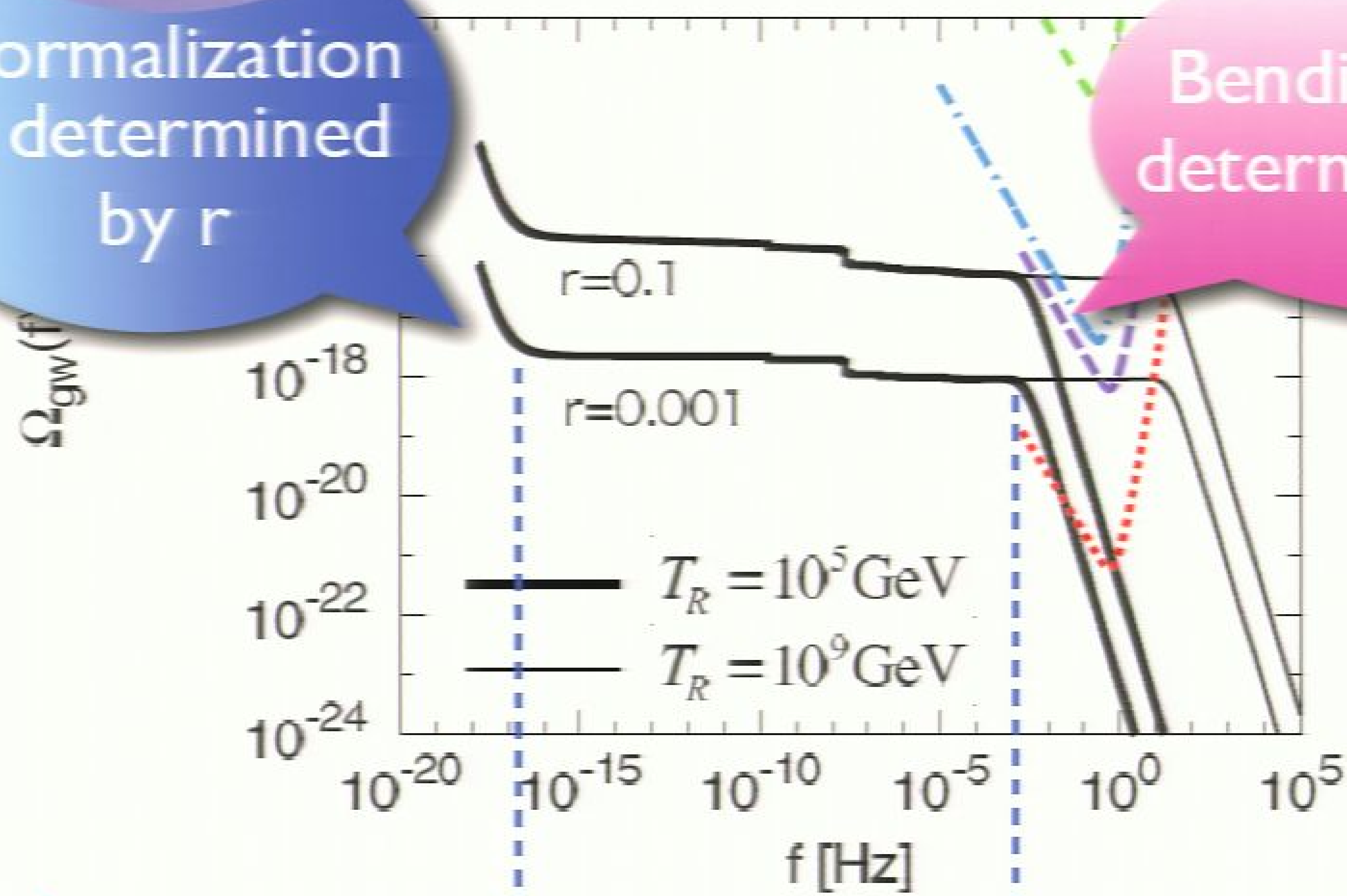
Horizon entry during M.D. R.D. Φ.D.

G ional Wave Spectrum

CMB polarization

Normalization is determined by r

Bending point is determined by TR



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Horizon entry during M.D. R.D. Φ.D.

Astrophysical foreground

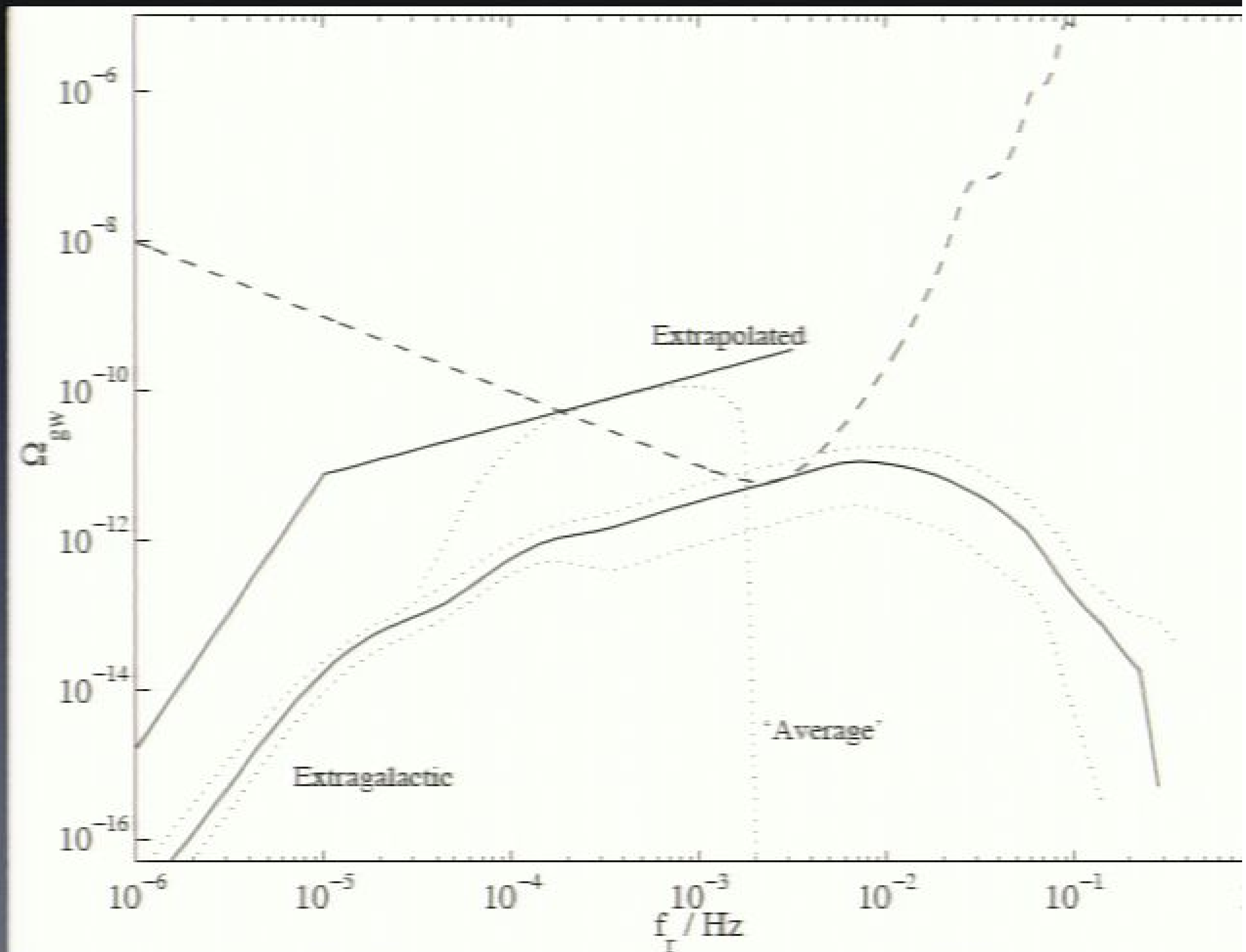
White Dwarf binary

Merger of WD binary

→ Gravitational Waves

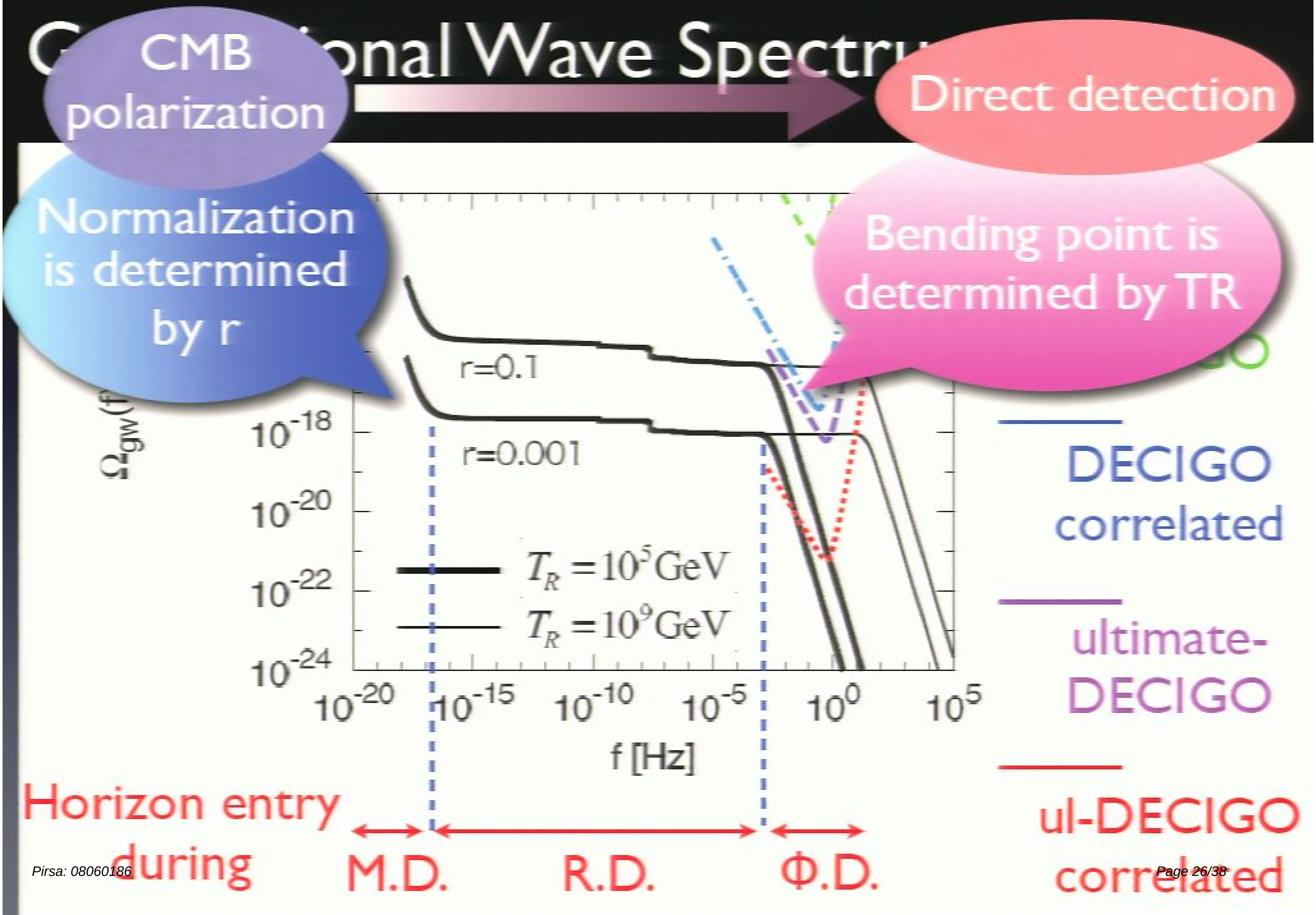
Completely stochastic

→ Cannot be removed.



Farmer and Phinney (03)

G…ional Wave Spectr…



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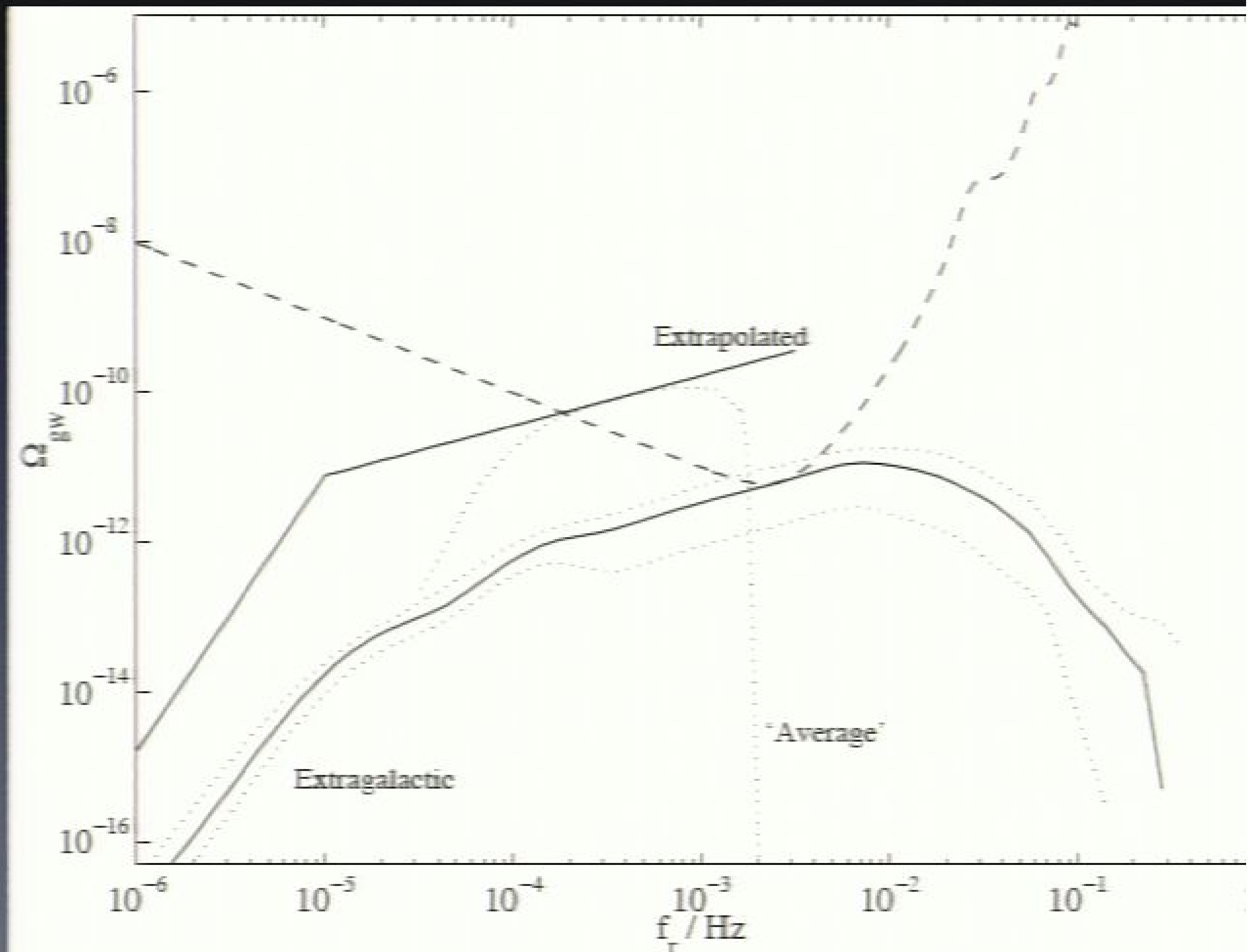
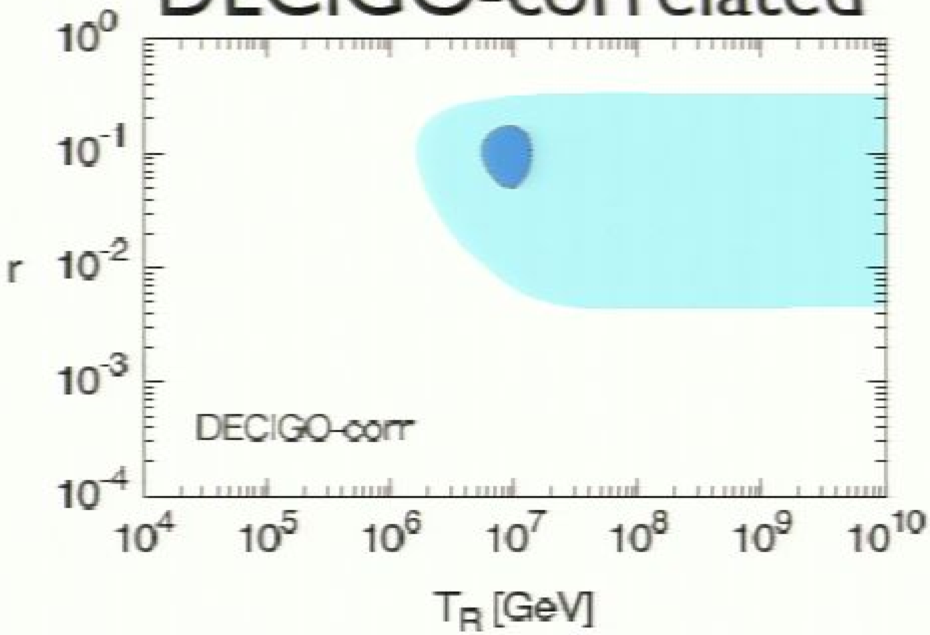
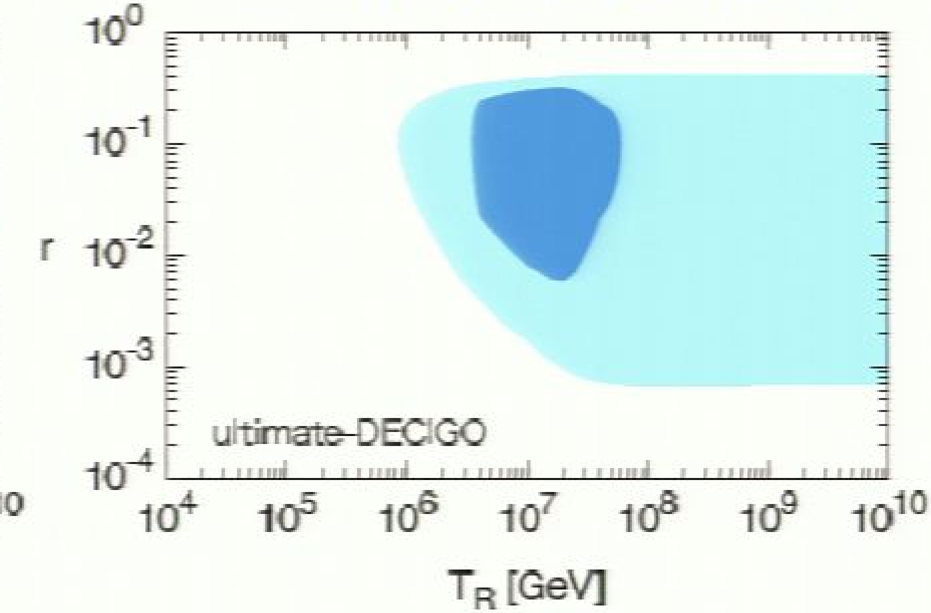


Farmer and Phinney (03)

DECIGO-correlated



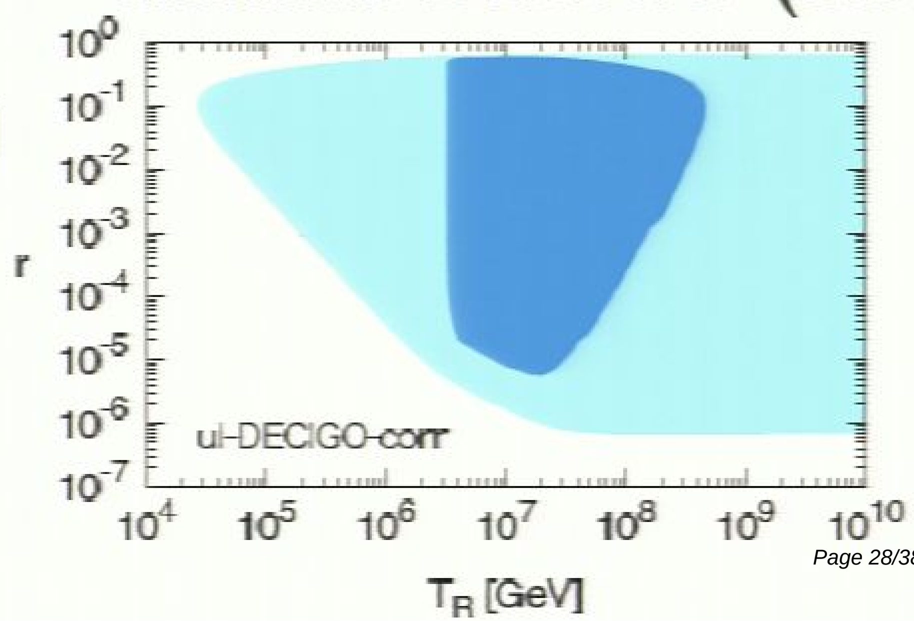
ultimate-DECIGO



GW can be detected

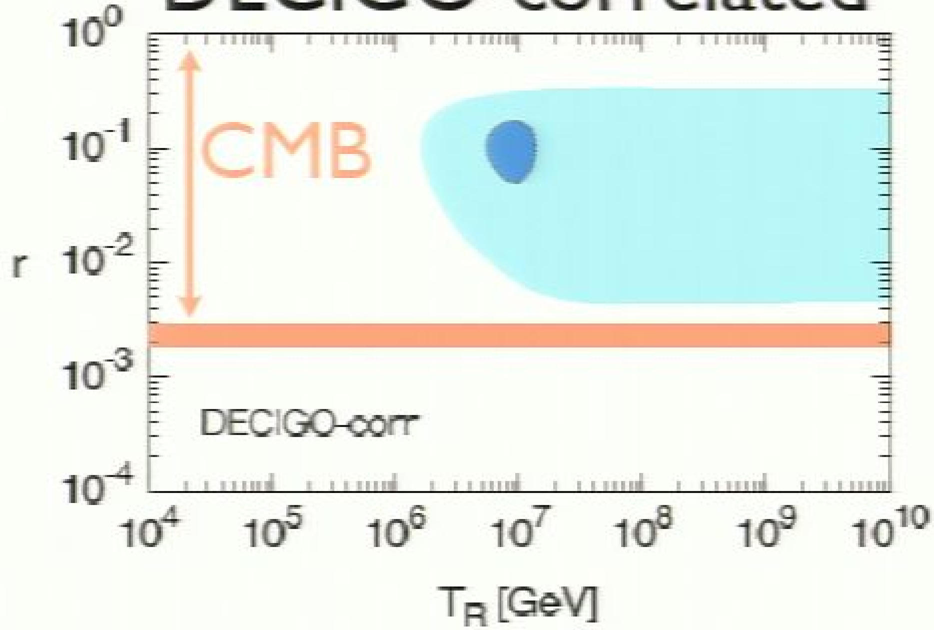
TR can be determined

ultimate-DECIGO (corr)

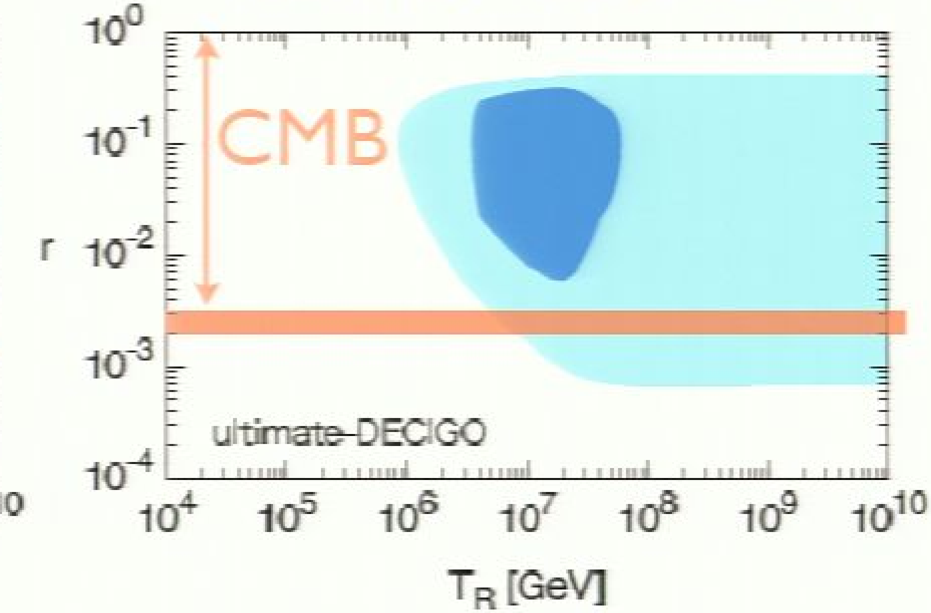


Future observations can determine or constrain TR

DECIGO-correlated



ultimate-DECIGO



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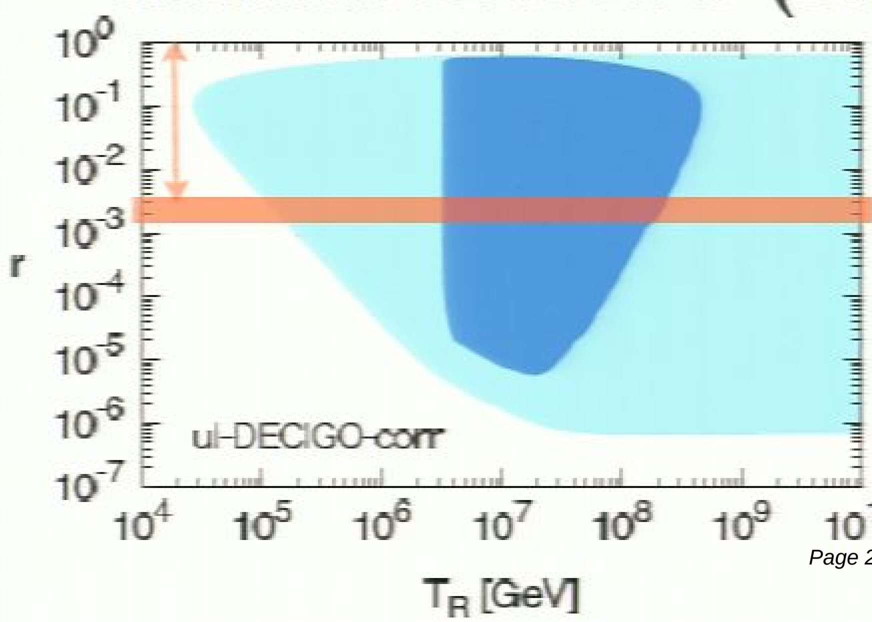


Implications on Particle Physics

Gravitino Problem

Khlopov, Linde (84), Ellis, Kim, Nanopoulos (84), Moroi, Murayama, Yamaguchi (93), Bolz, Brandenburg, Buchmuller (01), Kawasaki, Kohri, Moroi (05), Pradler, Steffen (07)

- Unstable gravitino

Gravitino lifetime $\sim C \frac{M_P^2}{m_{3/2}^3} \gtrsim 1 \text{ sec} \quad \text{for} \quad m_{3/2} \lesssim 10\text{TeV}$

→ Affect BBN

Photo-dissociation
Hadro-dissociation
p-n conversion

- Stable gravitino → Overclosure bound

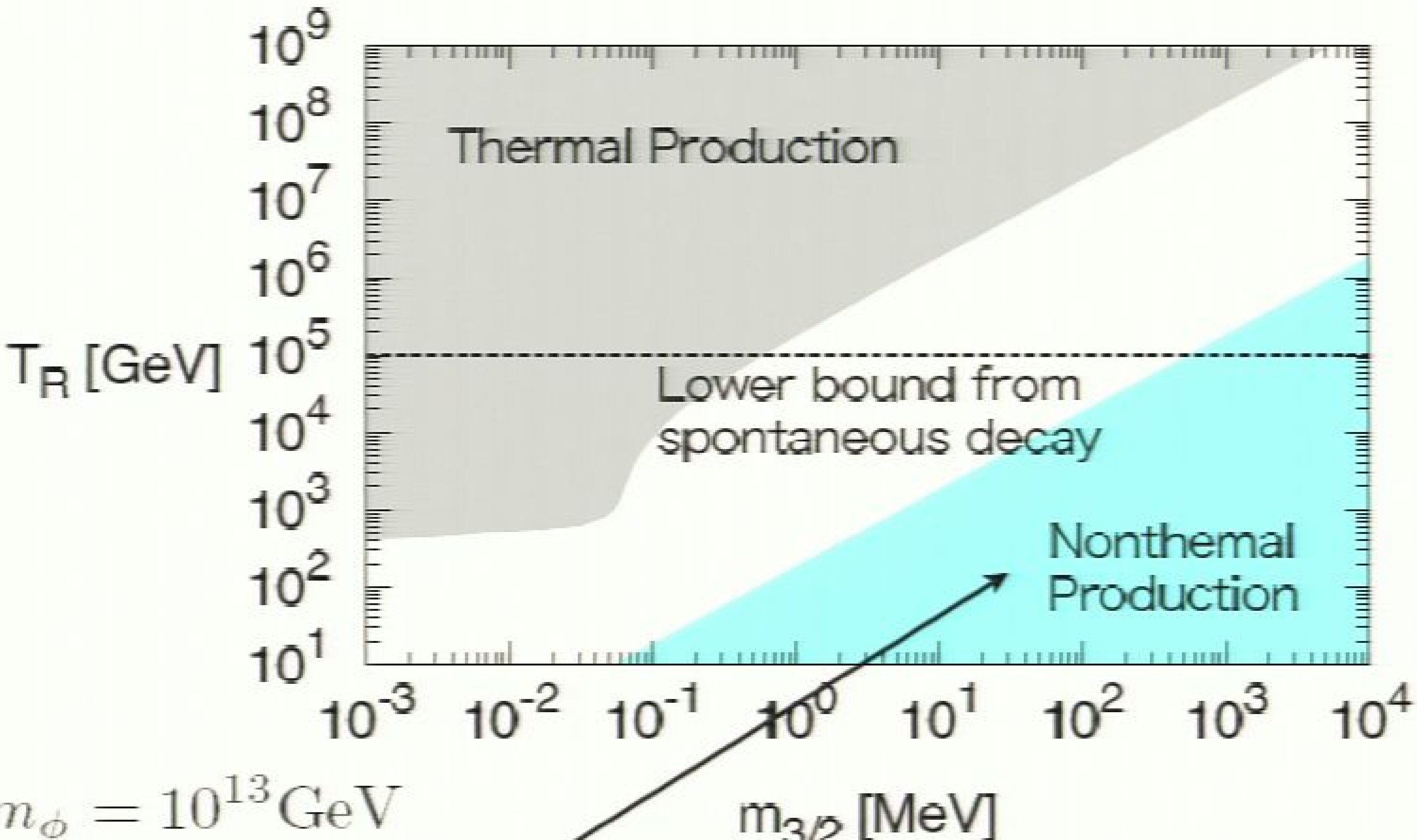
Thermal Production

From scattering of particles in thermal bath

$$Y_{3/2} \sim 2 \times 10^{-12} \left(1 + \frac{m_{\tilde{g}}^2}{3m_{3/2}^2}\right)\left(\frac{T_R}{10^{10}\text{GeV}}\right). \qquad \propto T_R$$

→ Upper bound on TR

Stable Gravitino



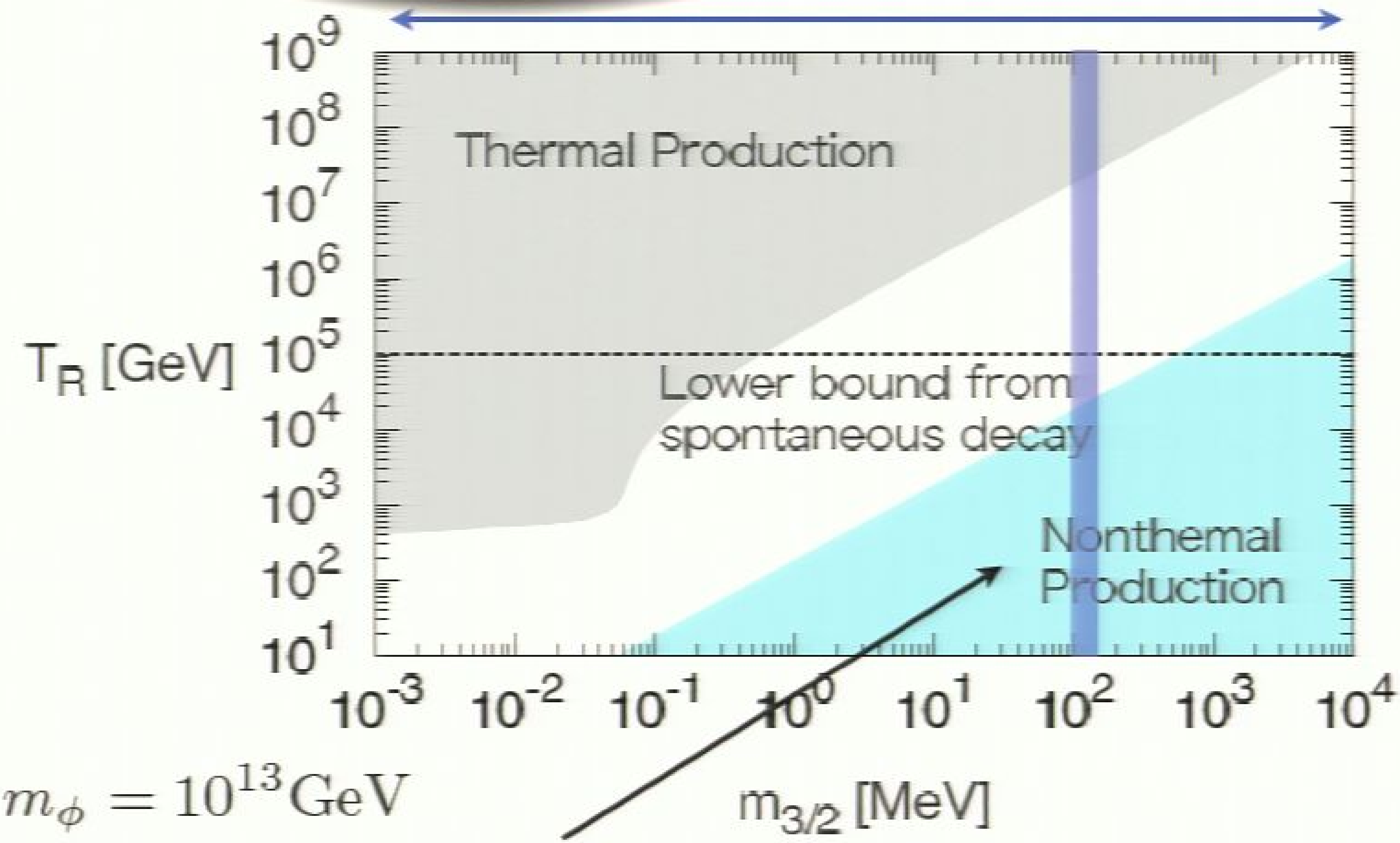
$m_\phi = 10^{13}\mathrm{GeV}$

$\langle\phi\rangle = 10^{15}\mathrm{GeV}$ Inflaton decay

Kawasaki, Takahashi, Yanagida(07)

Stab…

May be determined from accelerator experiments



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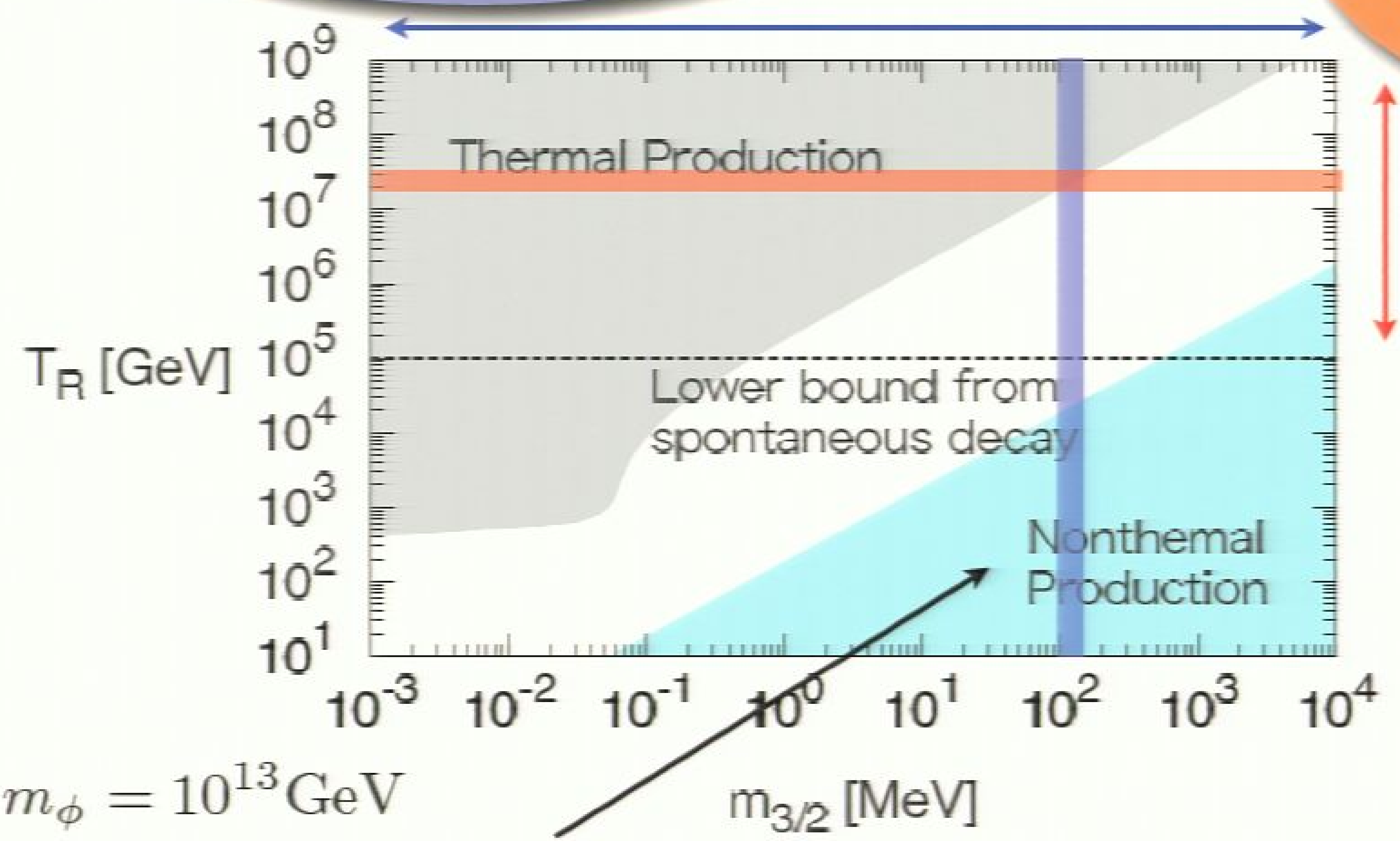
Inflaton decay

Kawasaki, Takahashi, Yanagida(07)

Sta[...]



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Inflaton decay

Kawasaki, Takahashi, Yanagida(07)

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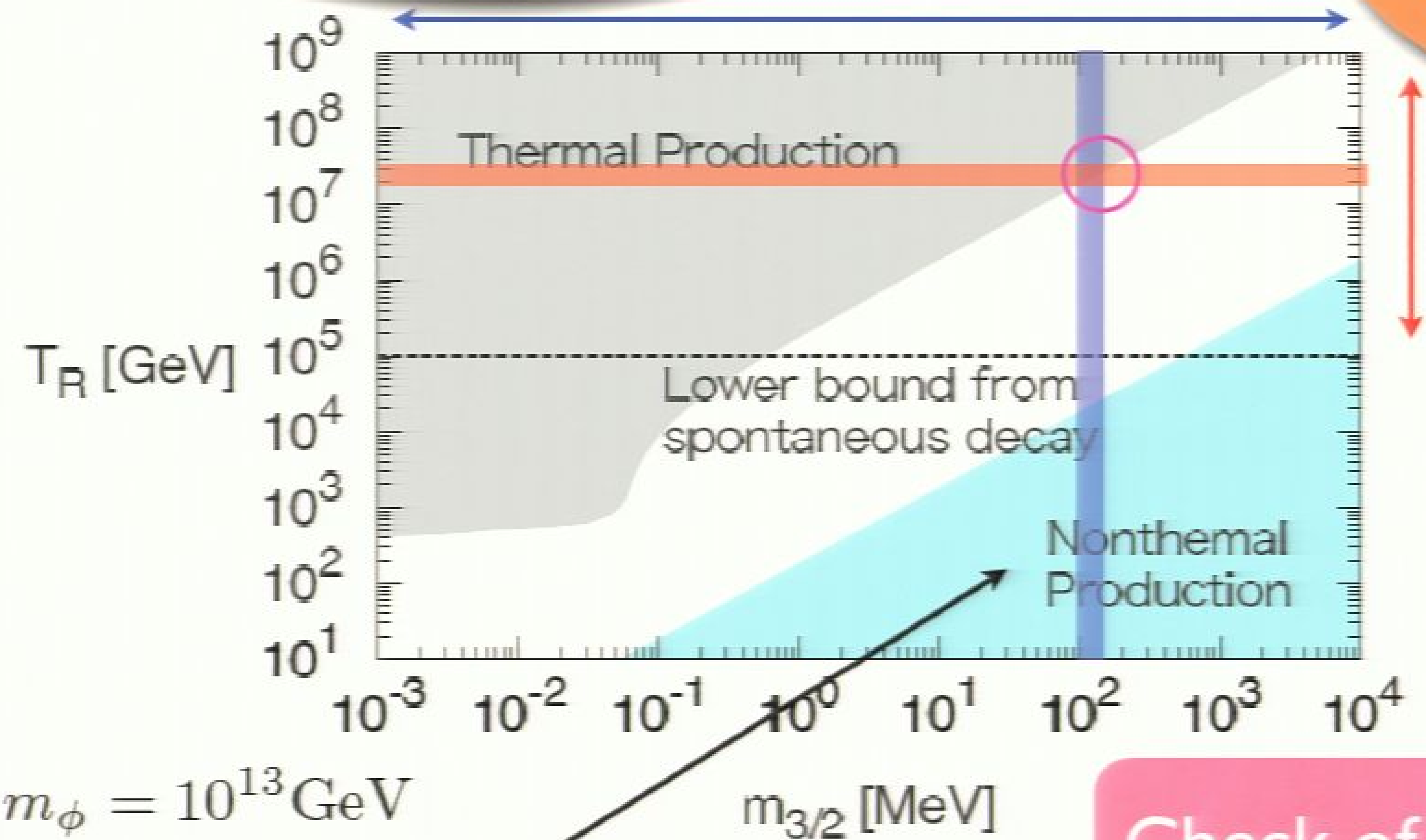
May be determined from accelerator experiments

Accesible with future GW experiment



$m_\phi = 10^{13}\mathrm{GeV}$

$\langle\phi\rangle = 10^{15}\mathrm{GeV}$

Inflaton decay

Check of the gravitino dark metter scenario

Kawasaki, Takahashi, Yanagida(07)

Summary

- Gravitational wave background provides a way to determine reheating temperature of the Universe.

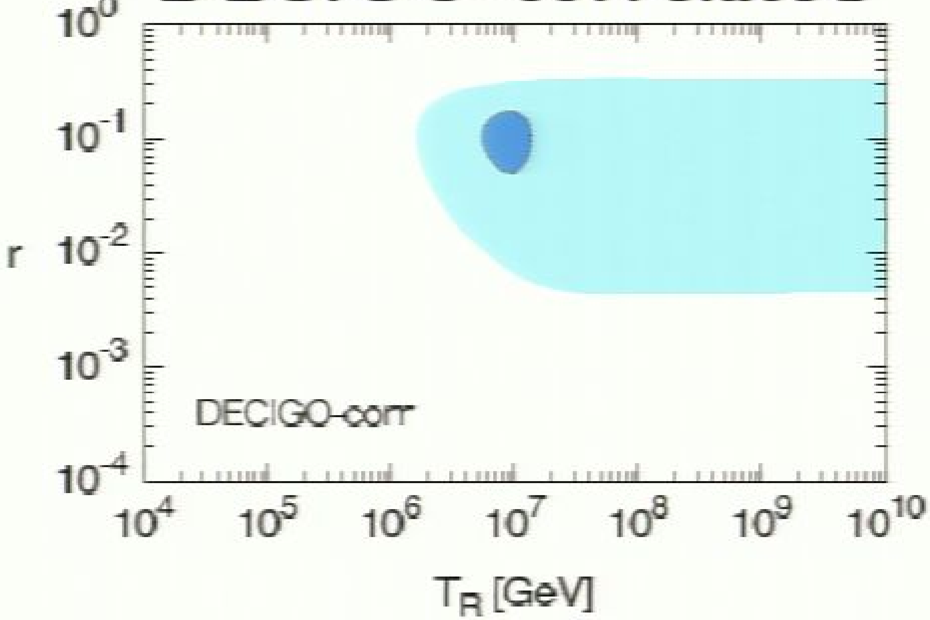
CMB Polarization : $r \gtrsim 10^{-3}$

→ DECIGO/BBO can determine/constrain T

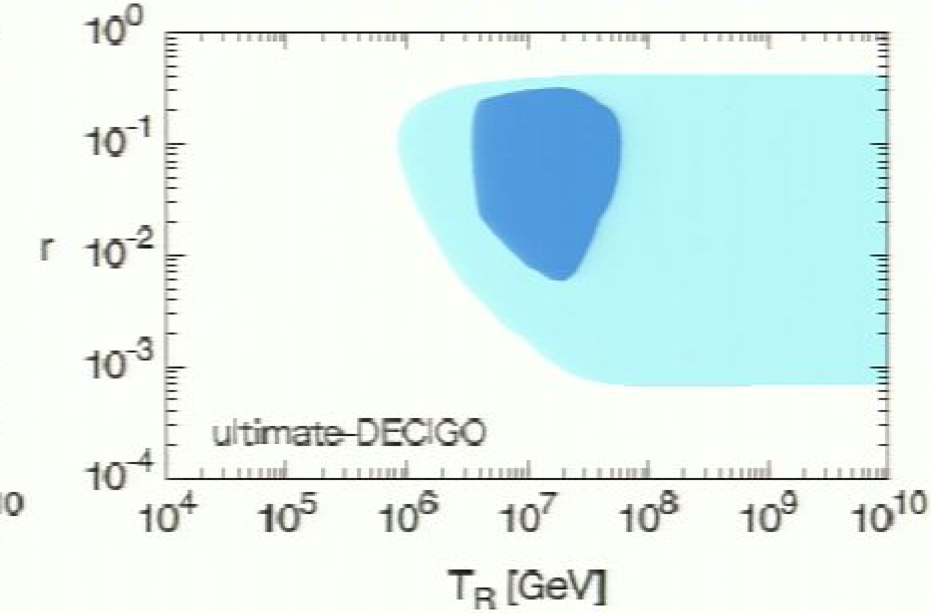
$T_R \gtrsim 10^7 \mathrm{GeV}$ / $T_R \lesssim 10^7 \mathrm{GeV}$

- Together with accelerator experiments, some particle physics (SUSY) models will be favored/constrained.

DECIGO-correlated



ultimate-DECIGO



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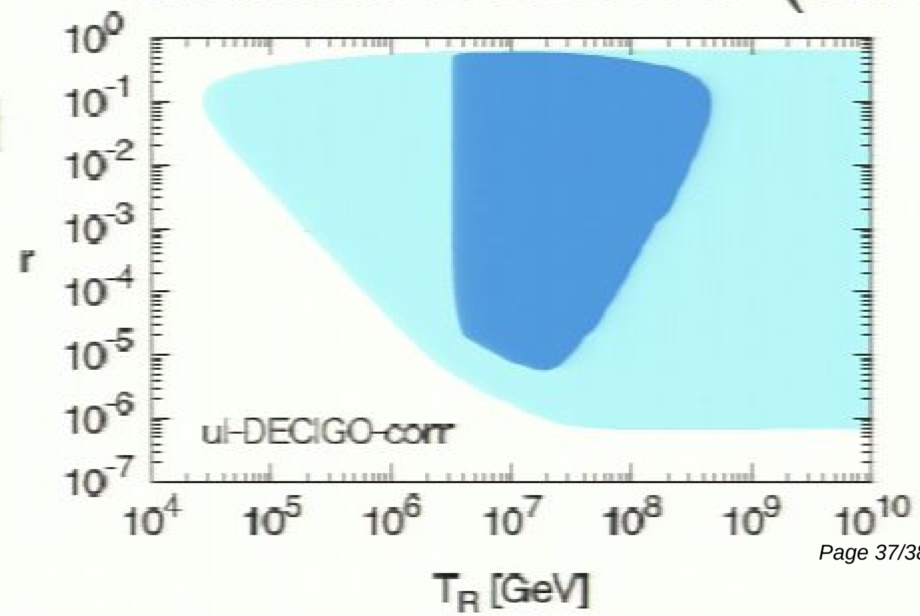
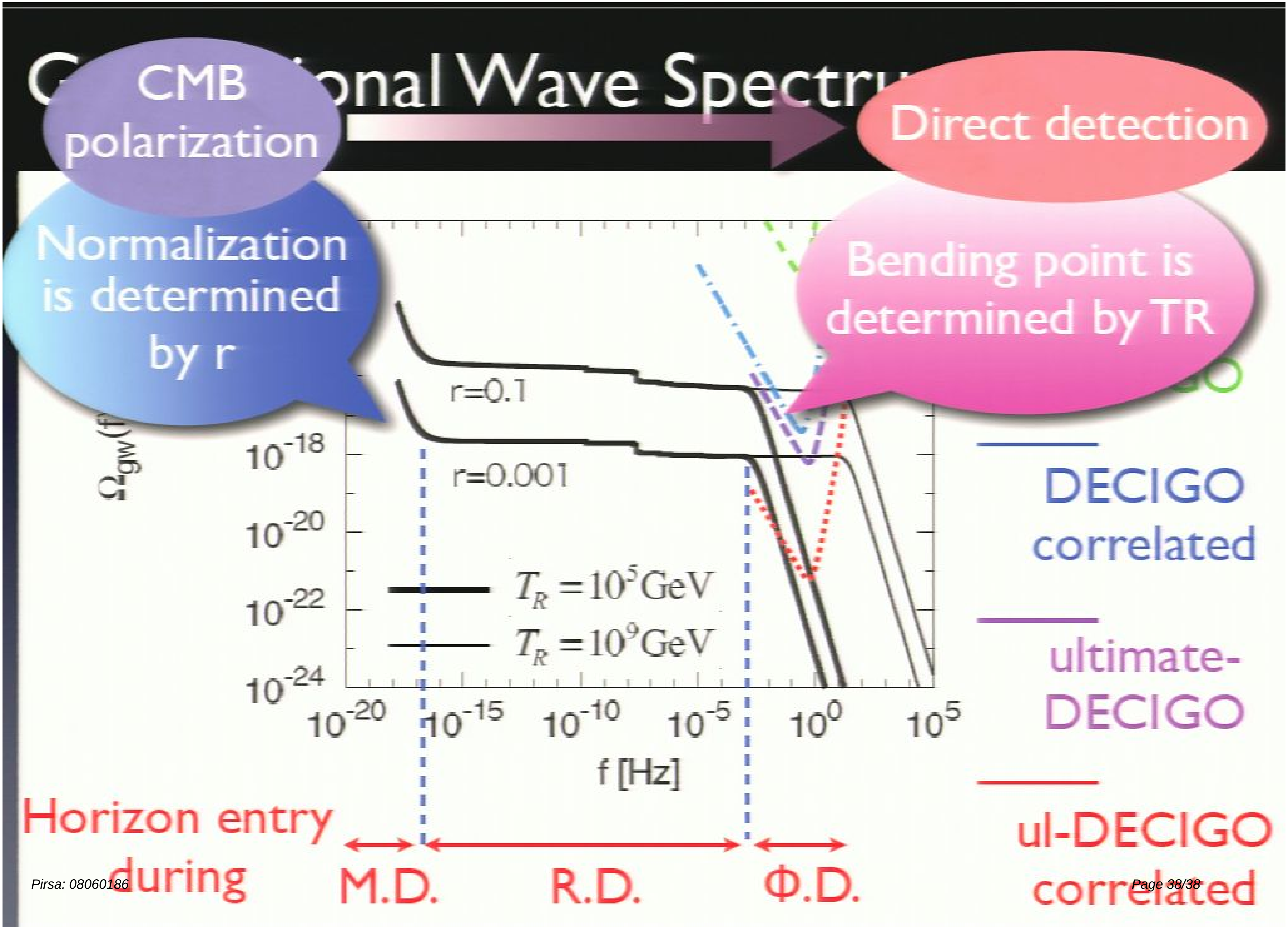
ultimate-DECIGO (corr)



Future observations can determine or constrain TR



CMB polarization
Direct detection
Normalization is determined by r
Bending point is determined by TR
r=0.1
r=0.001
$\Omega_{gw}(f)$
10^{-18}
10^{-20}
10^{-22}
10^{-24}
$T_R = 10^5$GeV
$T_R = 10^9$GeV
10^{-20} 10^{-15} 10^{-10} 10^{-5} 10^{0} 10^{5}
f [Hz]
DECIGO correlated
ultimate-DECIGO
ul-DECIGO correlated
Horizon entry during
M.D.
R.D.
Φ.D.