Anthropic Bound on Dark Radiation

June 6 2019

43rd Johns Hopkins Workshop@IPMU

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Based on FT, Masaki Yamada 1904.12864

What is dark radiation?

Dark radiation (DR) = Extra relativistic degrees of freedom

Candidates for DR:

massless or ultralight particles

e.g. NG bosons, chiral fermions, and gauge bosons.

Abundance of DR:

$$N_{\rm eff} \quad \textbf{or} \quad \Delta N_{\rm eff} = N_{\rm eff} - 3.046$$

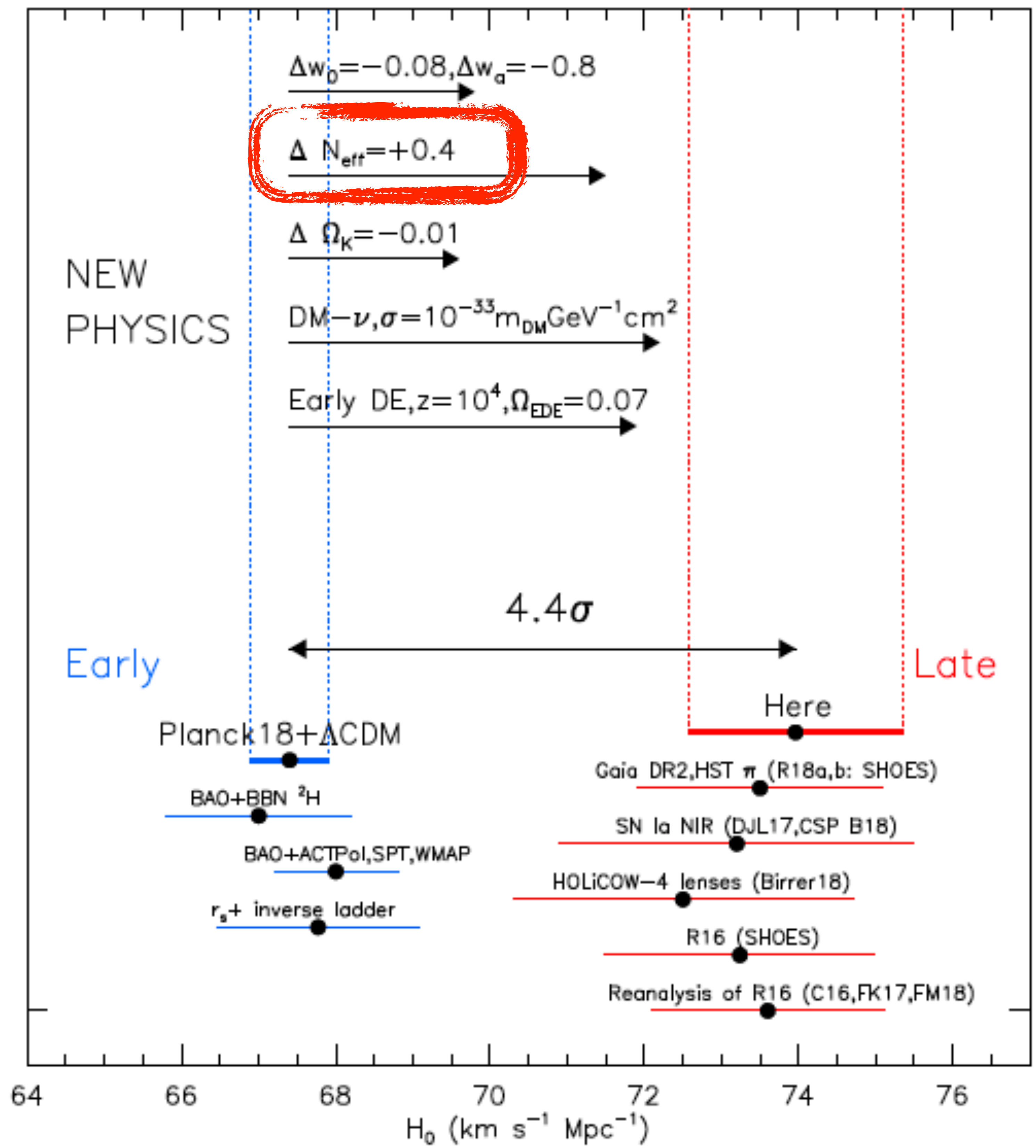
$$N_{\rm eff} = 3.27 \pm 0.15$$

(Planck 2018)
TT,TE,EE+lowE
+lensing+BAO+R18

A hint for DR?

There is a tension in the estimate of H_0 btw the early and late Universe.

DR with $\Delta N_{eff} = 0.4$ can relax the H_0 tension.



Riess et al, 1903.07603

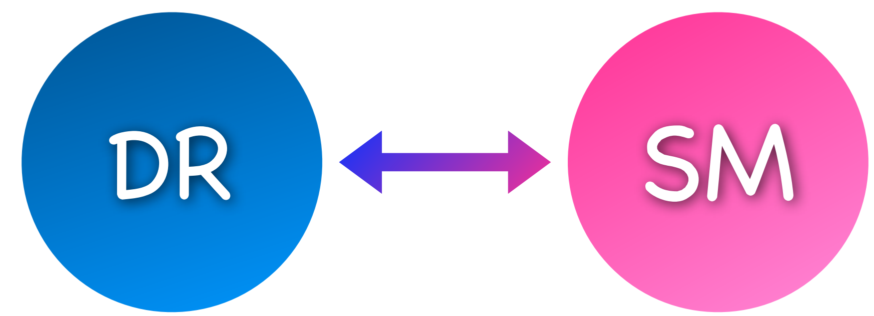
How is DR produced?

• Thermal production

Nakayama, FT, Yanagida (2010)

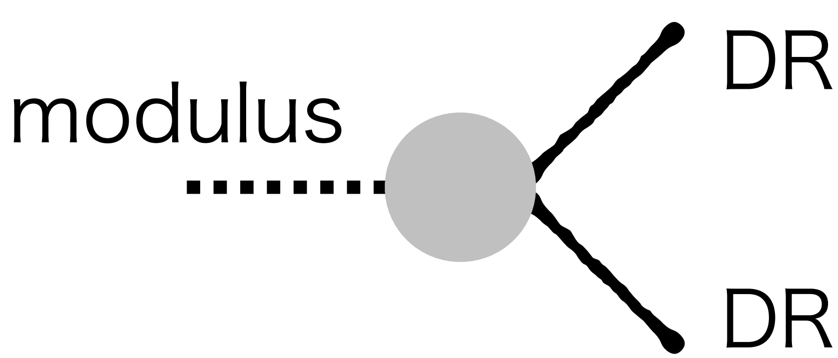
DR is once in thermal equilibrium with the SM particles, and decoupled at a certain point.

$$\Delta N_{\rm eff} = \left(\frac{4}{7}N_{\rm NGB} + N_f + \frac{8}{7}N_g\right)\left(\frac{g_{*\nu}}{g_{*\rm dec}}\right)^{4/3}$$



• Non-thermal production

DR is non-thermally produced by heavy particle decays. DR is often overproduced.



E. J. Chun and A. Lukas `95, Lyth and Stewart `96, K. Choi, E. J. Chun and J. E. Kim `96, Ichikawa et al `07, Hasenkamp `11, Menestrina and Scherrer `11, K-S. Jeong and FT, K. Choi, K.-Y. Choi and C. S. Shin `12, Cicoli, Conlon and Quevedo `12, Higaki FT `12, and many others.

DR in the landscape

If DR is ubiquitous in the landscape, and if it is copiously produced in the early Universe, the typical $N_{\rm eff}$ will be >> 1.

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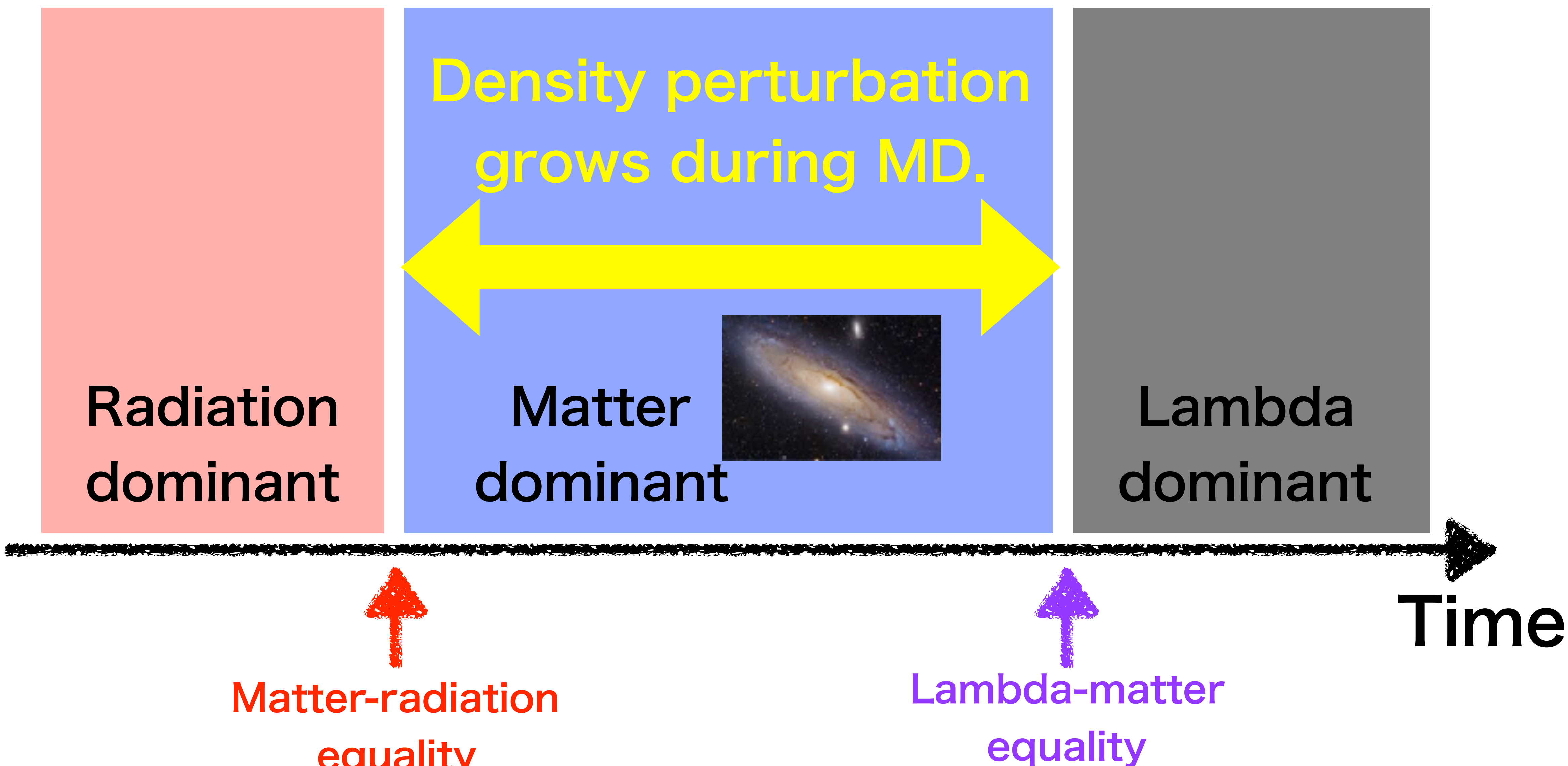
If DR is ubiquitous in the landscape, and if it is copiously produced in the early Universe, the typical $N_{\rm eff}$ will be >> 1.

There must be a reason to suppress DR.
Here let us study the anthropic reasoning.

Anthropic argument for Λ

S. Weinberg `87, P. Davies and S. Unwin `81, J. D. Barrow `82,
A. Linde `87, J. D. Barrow and F. J. Tipler `88,

The anthropic argument seems successful to explain the observed value of Λ.



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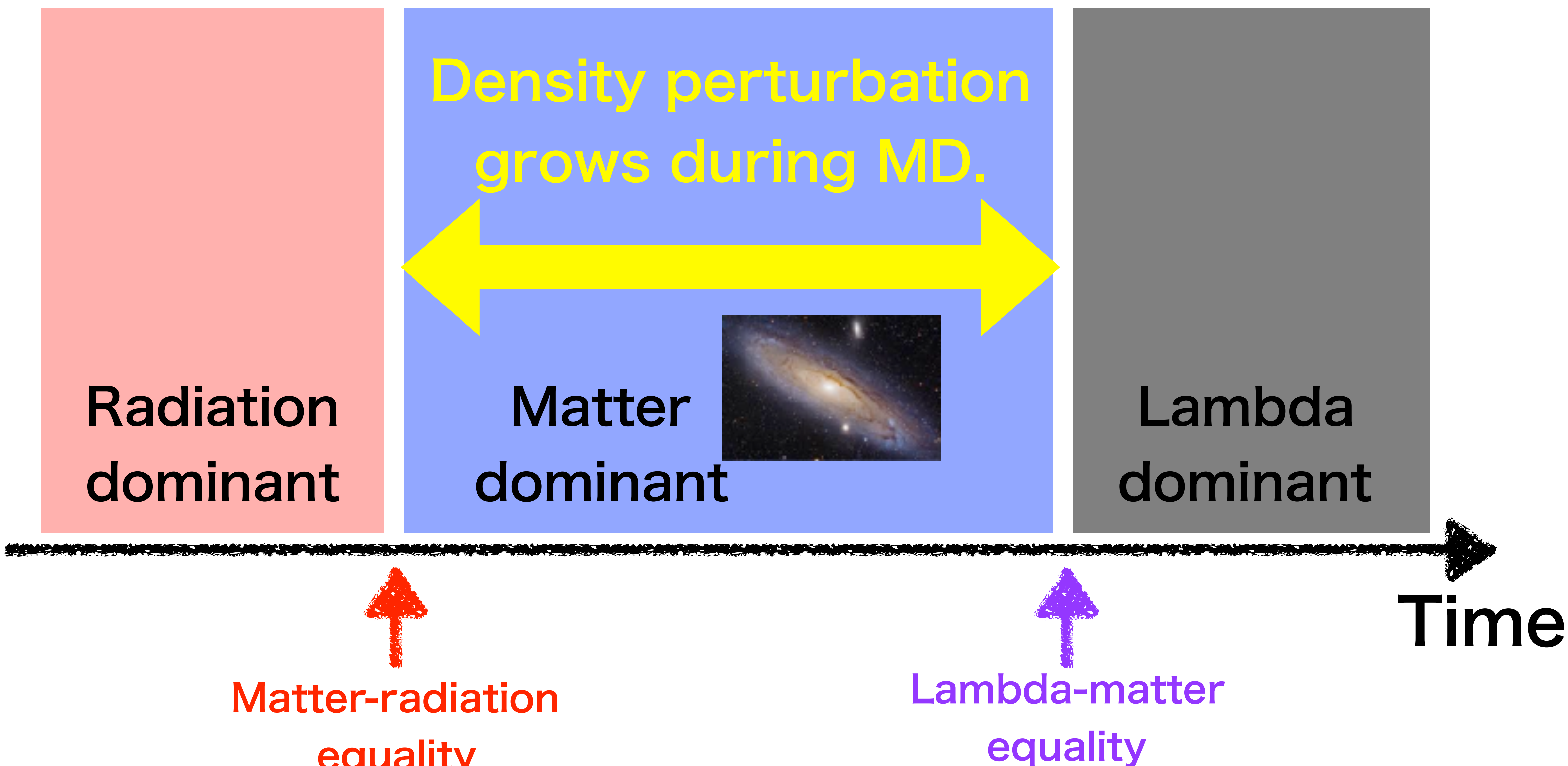

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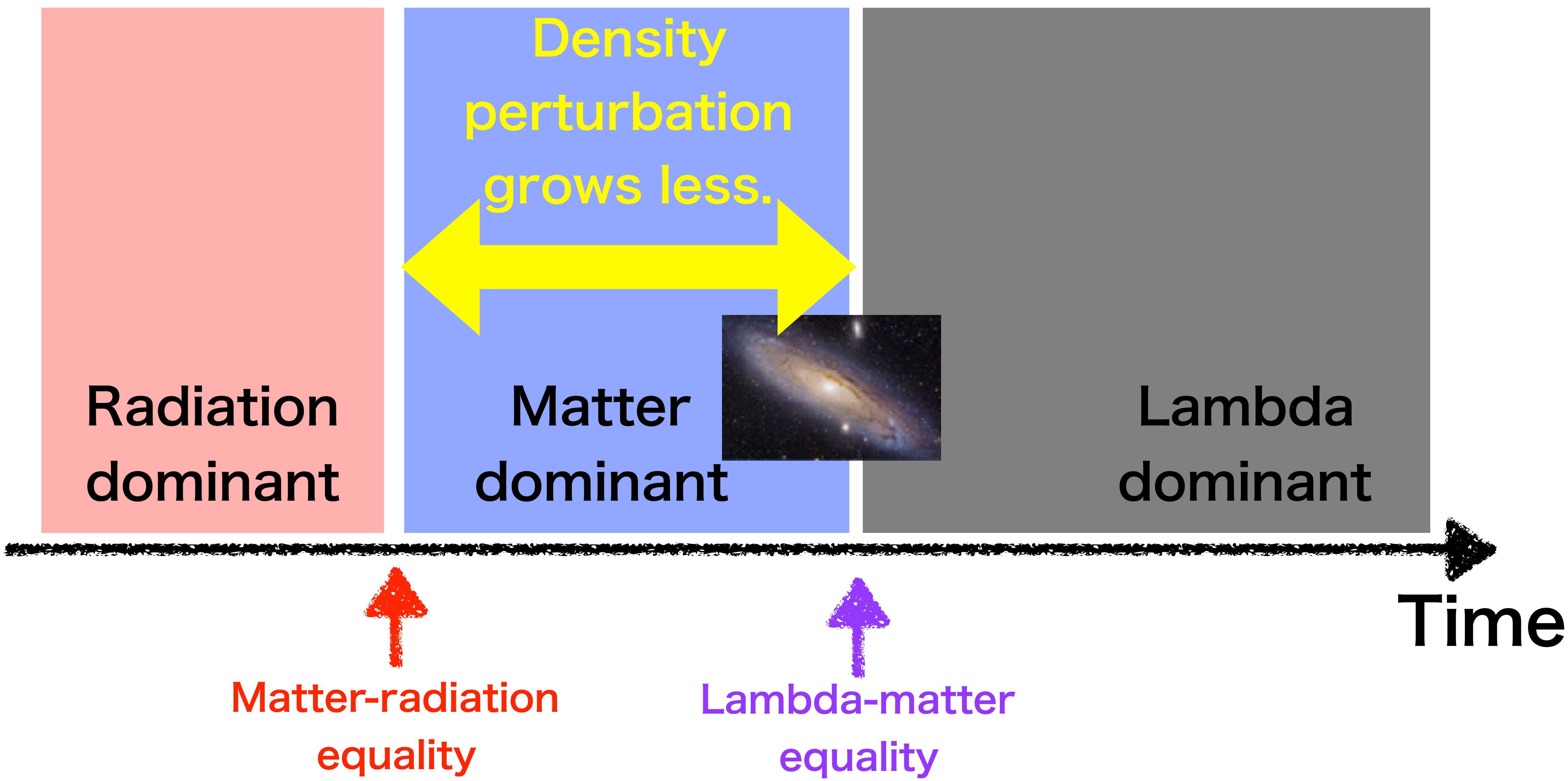

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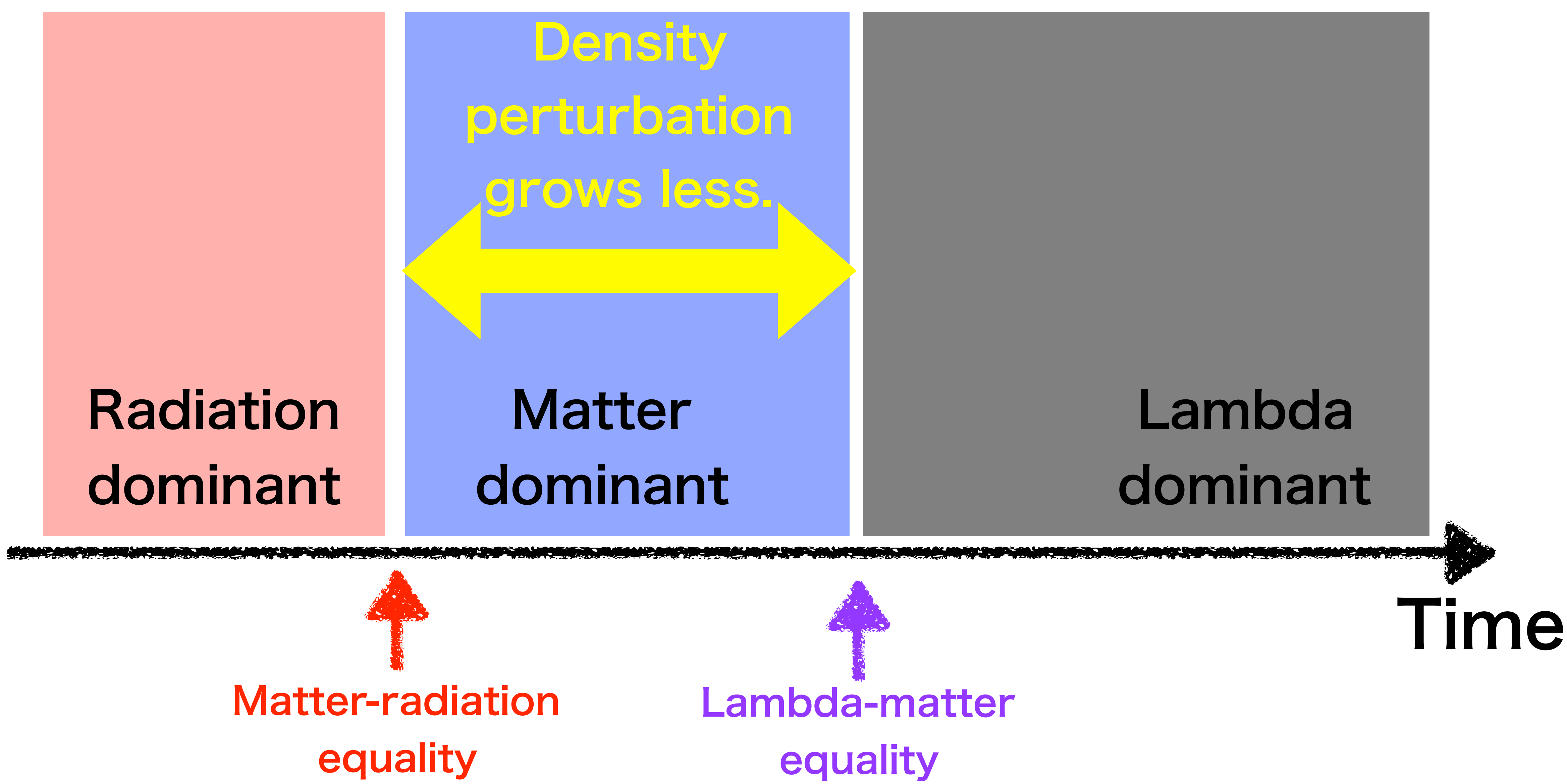

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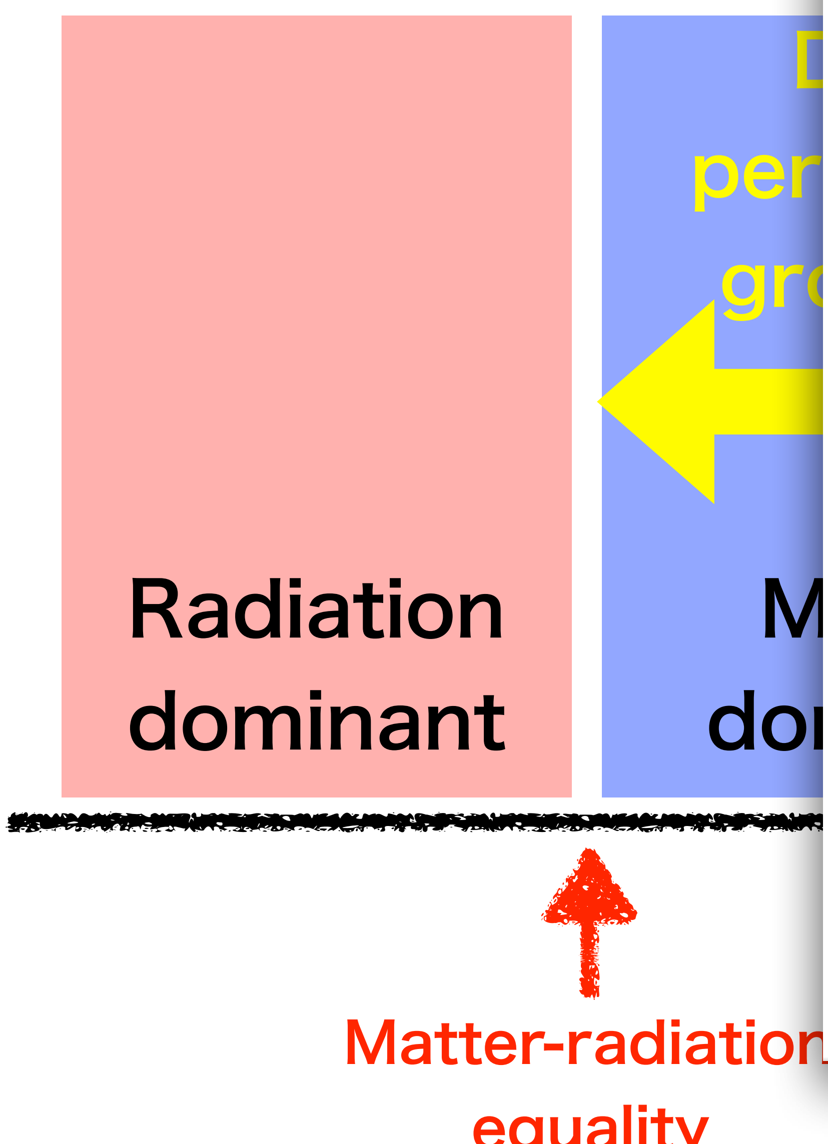


TABLE 1

PROBABILITY THAT A RANDOM ASTRONOMER WOULD OBSERVE A VACUUM ENERGY DENSITY AS SMALL AS THE VALUE ρ_V^* IN OUR SUBUNIVERSE[a] FOR VARIOUS VALUES OF ρ_V^*

		$R_G = 1$ Mpc		$R_G = 2$ Mpc	
λ_0	ρ_V^*/ρ_0	σ	$\mathscr{P}(\leq \rho_V^*)$	σ	$\mathscr{P}(\leq \rho_V^*)$
0.1	0.11	0.0067	0.0005	0.0042	0.0019
0.2	0.25	0.0063	0.0013	0.0040	0.0045
0.3	0.43	0.0059	0.0025	0.0038	0.0084
0.4	0.67	0.0054	0.0049	0.0036	0.015
0.5	1.00	0.0048	0.0097	0.0032	0.027
0.6	1.50	0.0041	0.021	0.0029	0.054
0.7	2.33	0.0033	0.054	0.0024	0.12
0.8	4.00	0.0023	0.19	0.0017	0.35
0.9	9.00	0.0011	0.90	0.0008	0.98

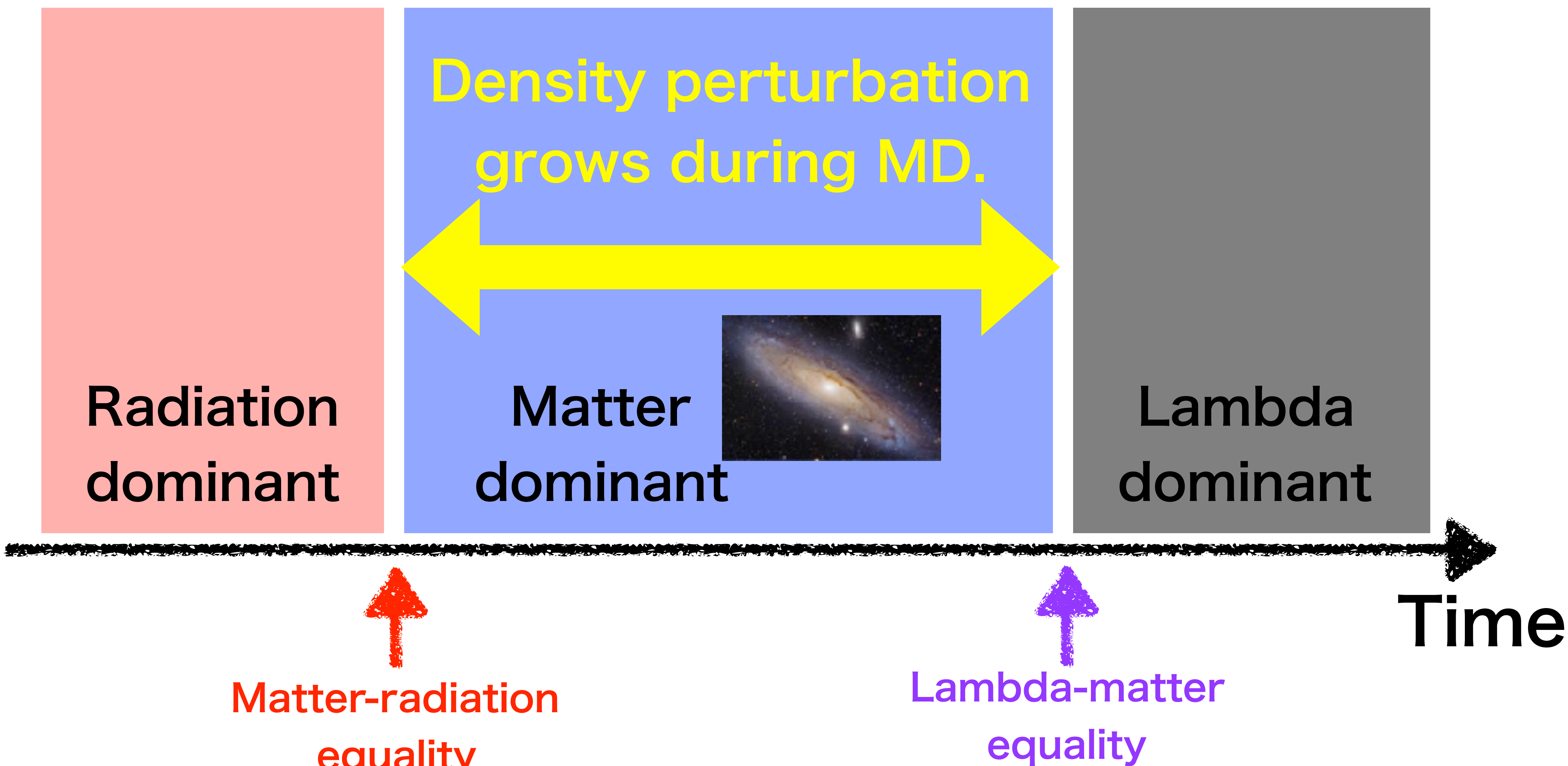
[a] For $s = 1$, $H_0 = 70$ km s^{-1} Mpc^{-1} and $n = 1$.

Martel, Shapiro, Weinberg `98

Anthropic argument for $N_{\rm eff}$

FT and M. Yamada, 1904.12864

If $N_{\rm eff}$ were larger, there would be less time for the density perturbation to grow.



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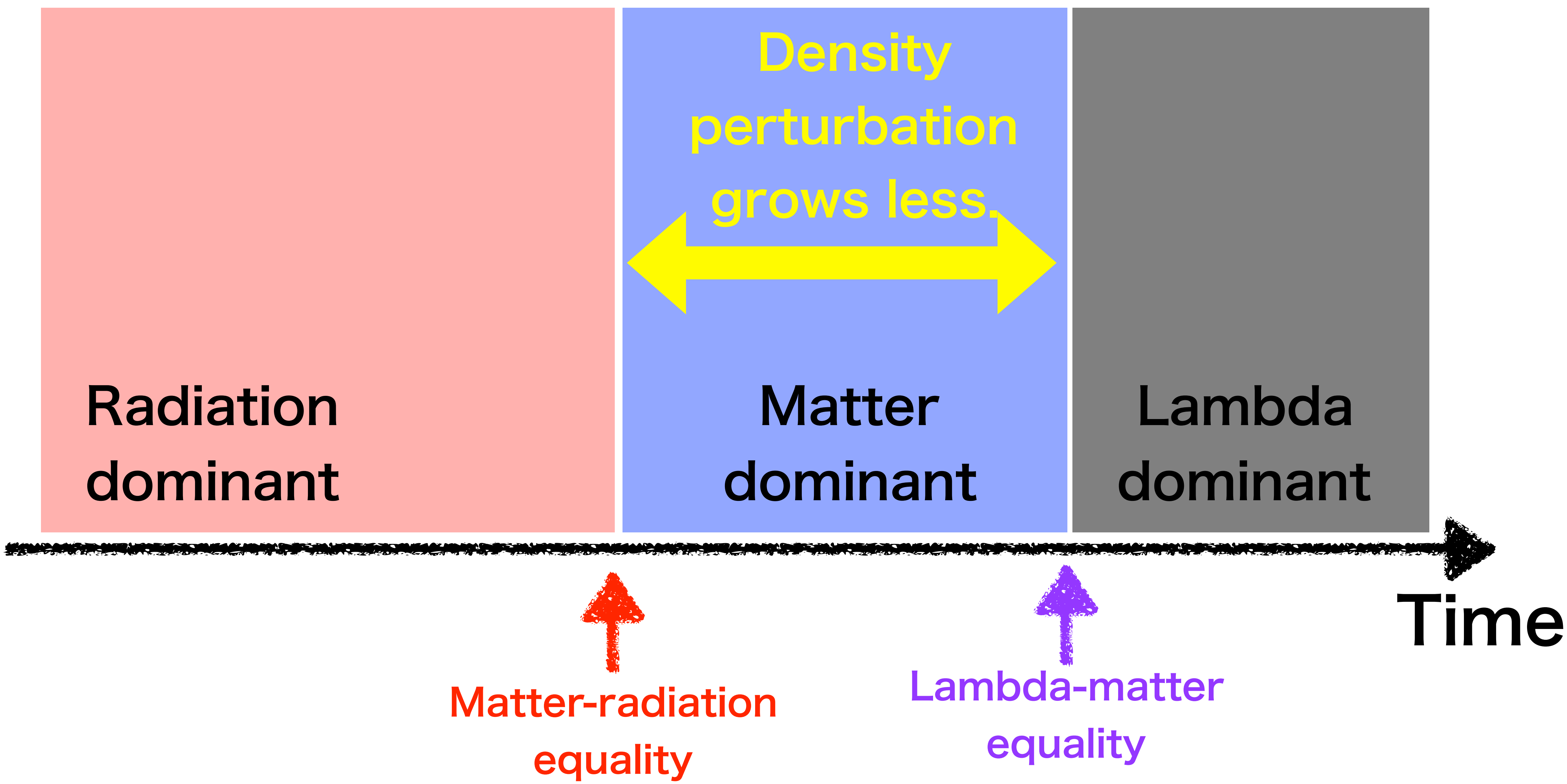

Anthropic argument for $N_{\rm eff}$

$$P_{\rm obs}(\Delta N_{\rm eff}) \propto P_{\rm prior}(\Delta N_{\rm eff})$$

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$$P_{\rm obs}(\Delta N_{\rm eff}) \propto P_{\rm prior}(\Delta N_{\rm eff}) \times A_{\rm obs}(\Delta N_{\rm eff})$$

Mean number of astronomers in a universe with $\Delta N_{\rm eff}$

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Mean number of astronomers in a universe with $\Delta N_{\rm eff}$

No observers

$\Delta N_{\rm eff} \gg 1$

$\Delta N_{\rm eff} < 1$

Anthropic argument for $N_{\rm eff}$

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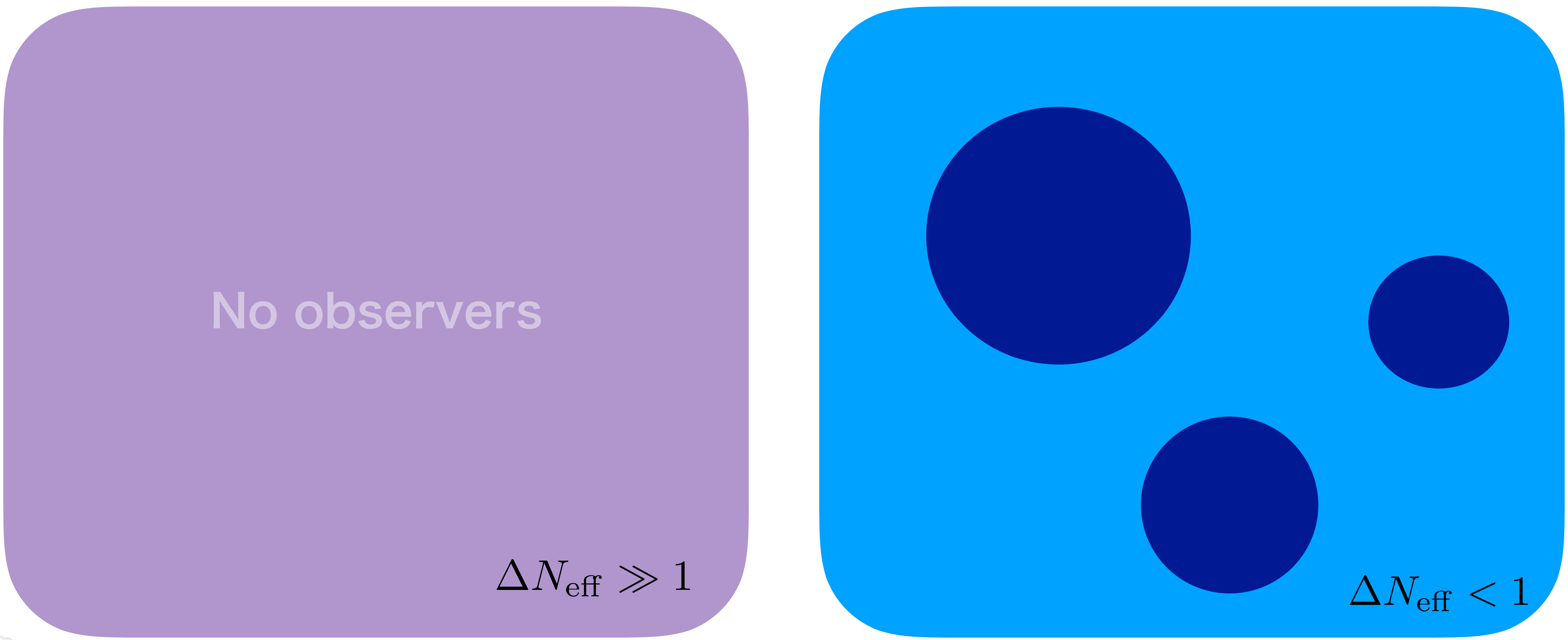

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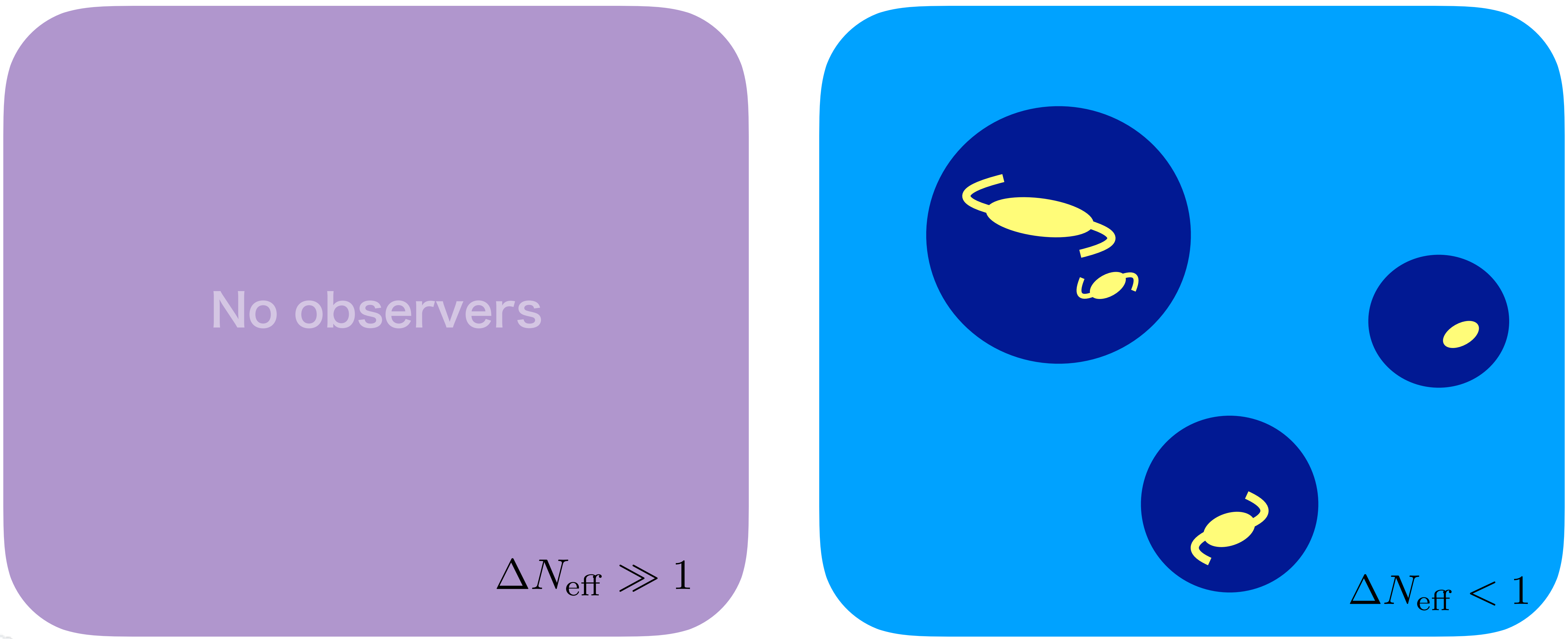

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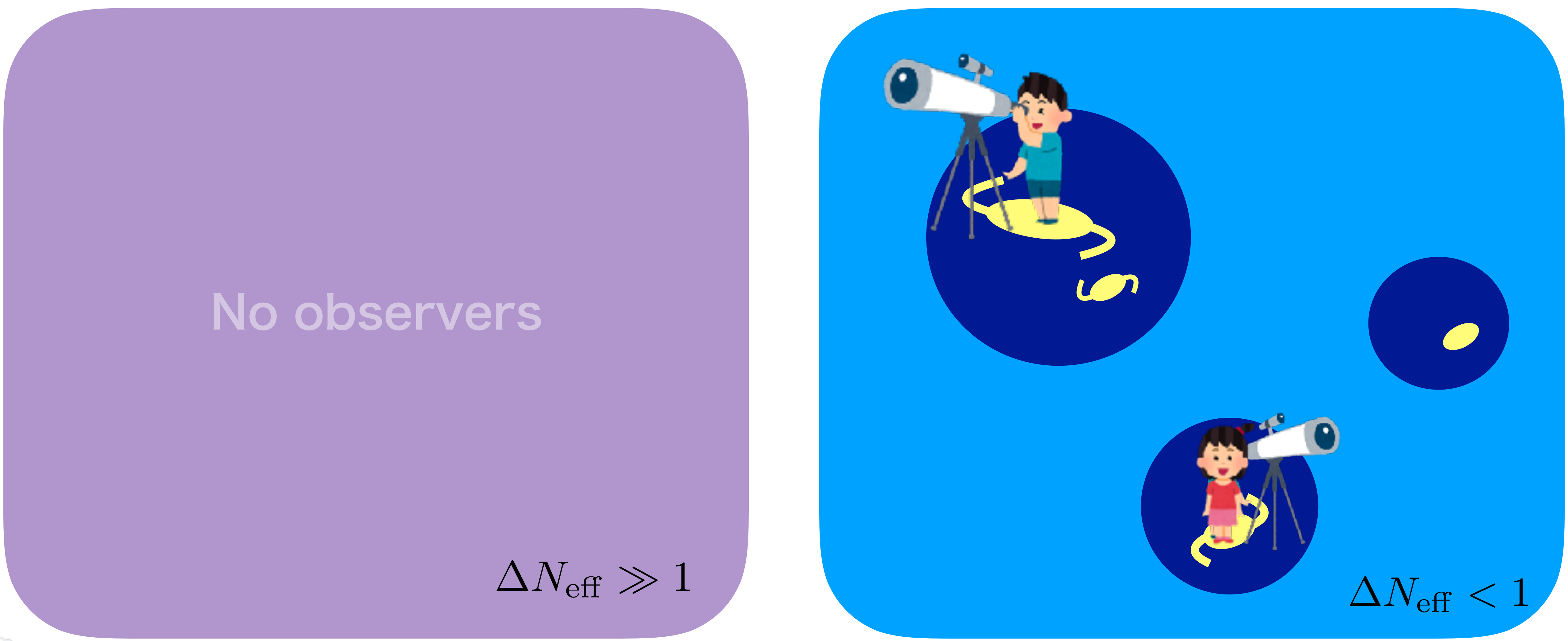

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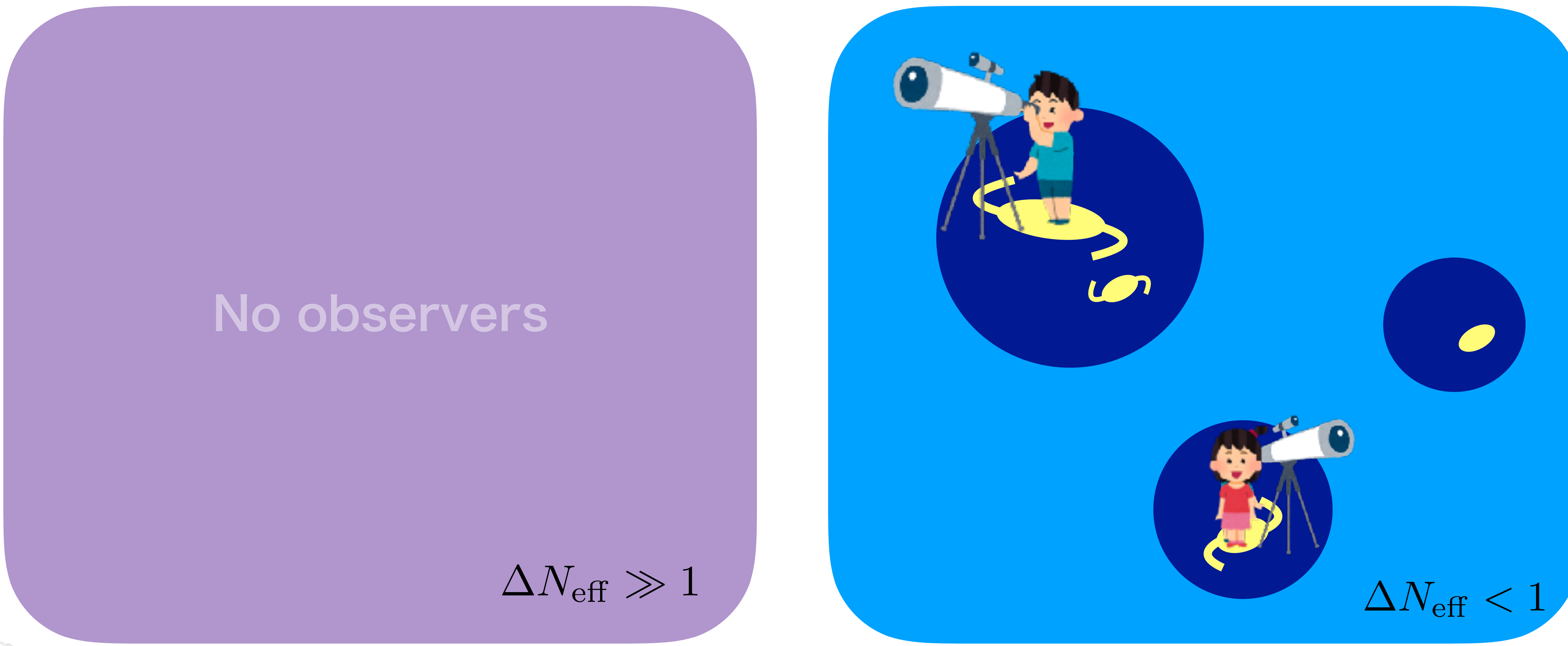
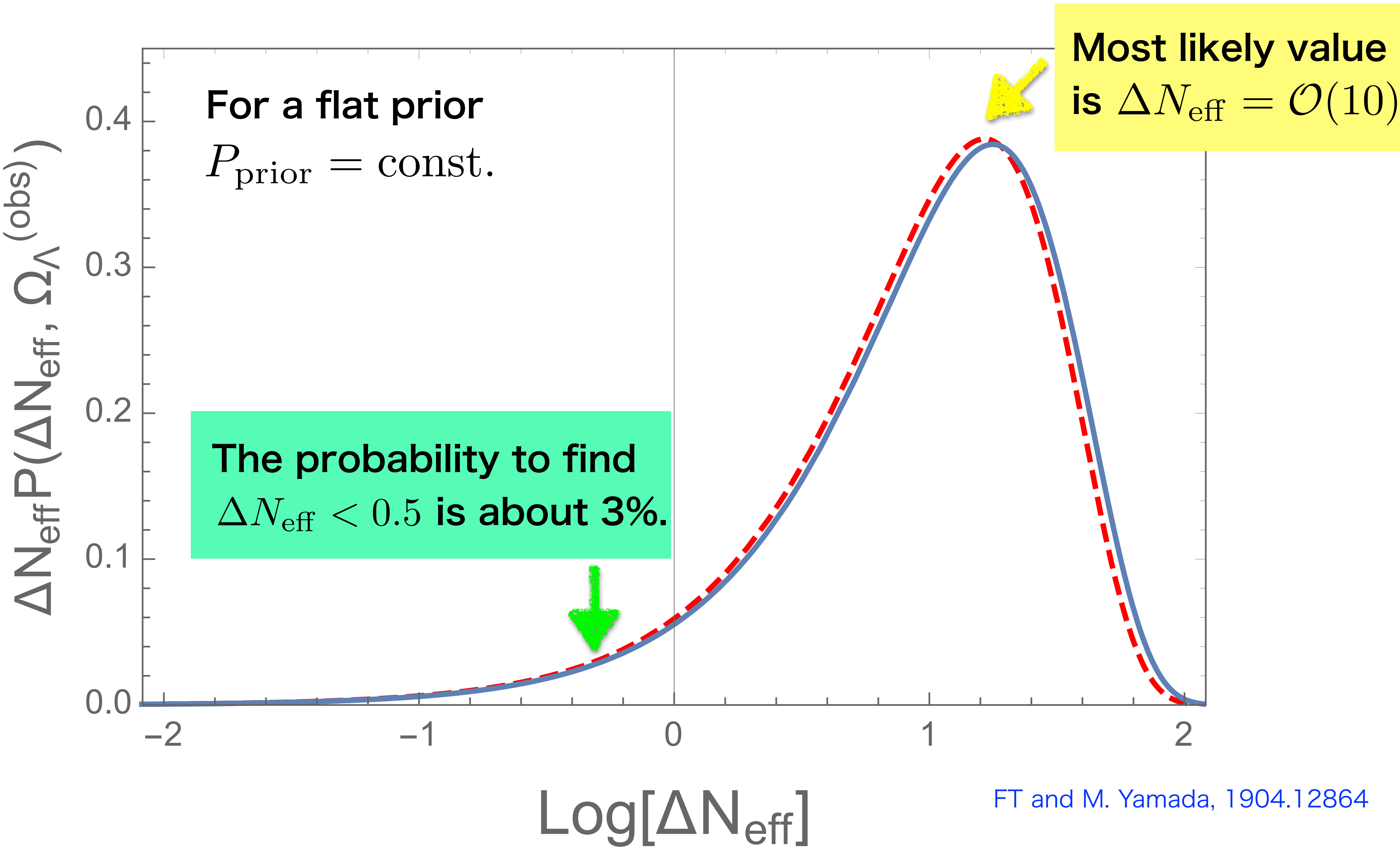
Mean number of astronomers in a universe with $\Delta N_{\rm eff}$

$A_{\rm obs}(\Delta N_{\rm eff}) \propto F(\Delta N_{\rm eff}, M > M_G)$: Fraction of matter that collapses into a galaxy with mass > M_G.



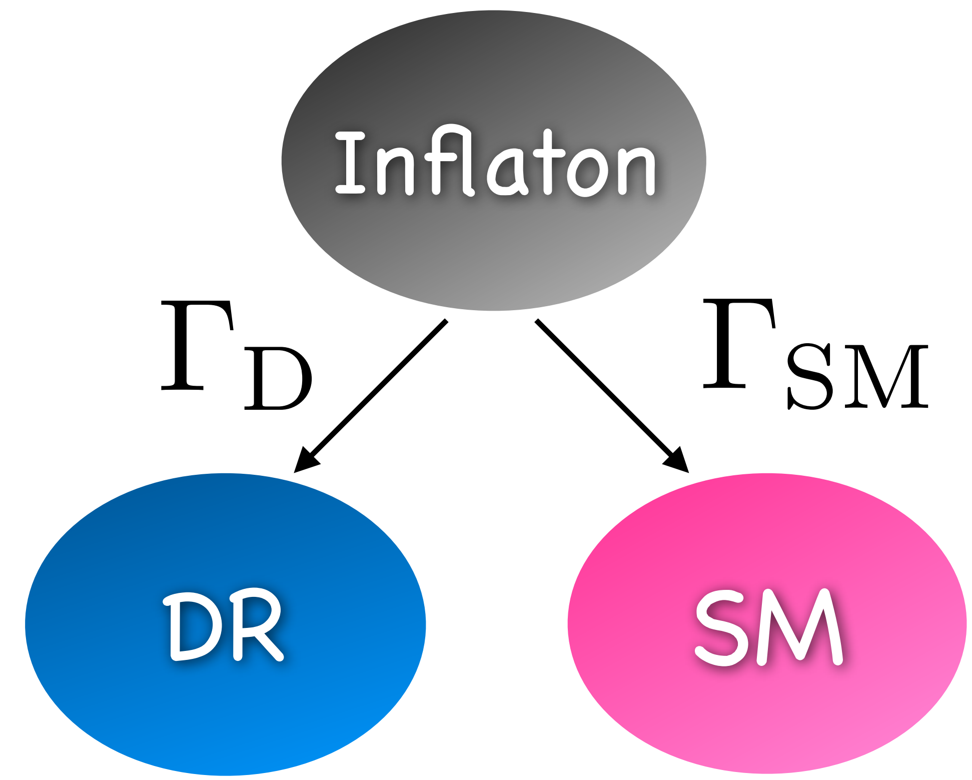
Anthropic argument for N_{eff}



FT and M. Yamada, 1904.12864

Implications for reheating

Suppose that DR is produced by the inflaton decay.



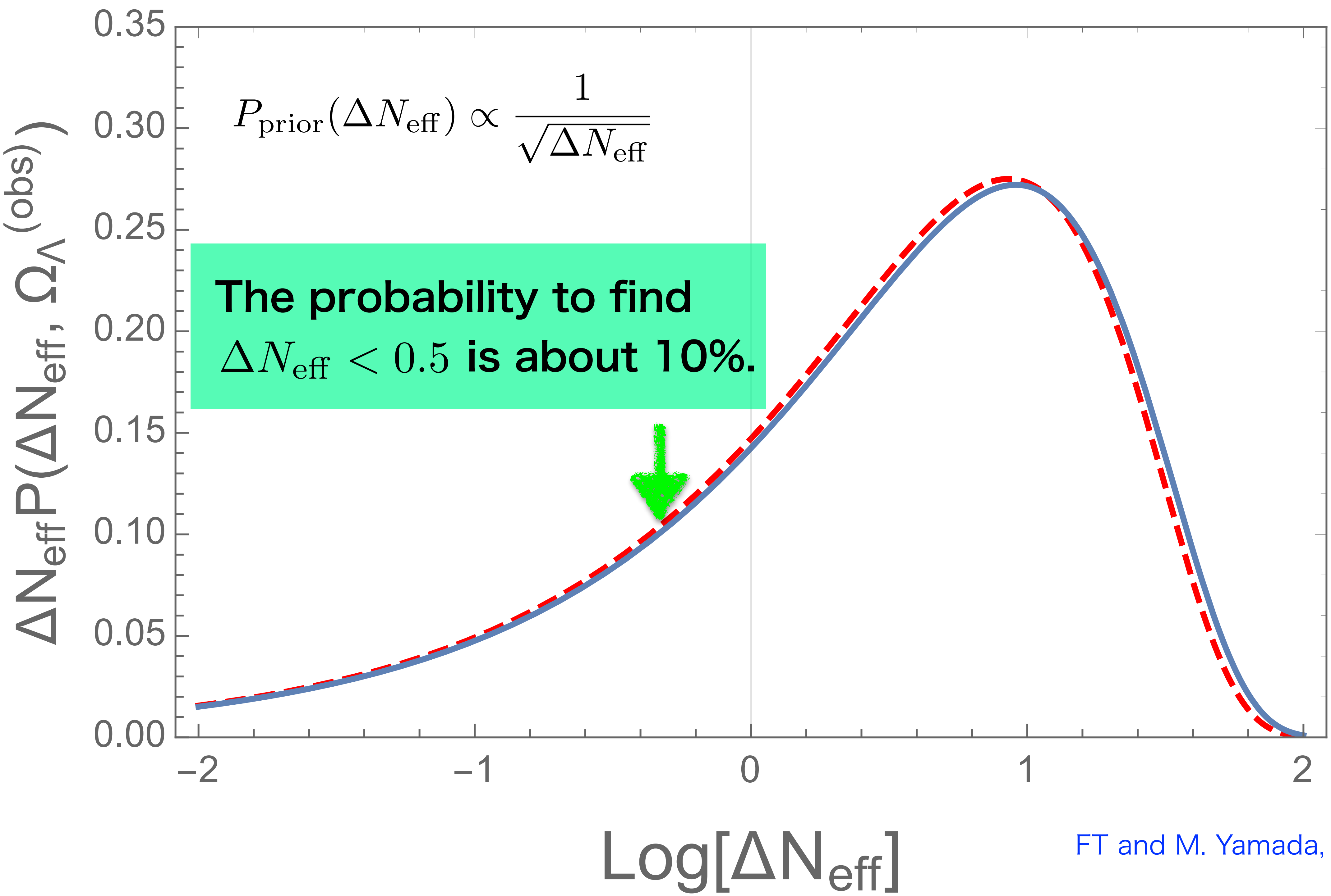
$$\Delta N_{\rm eff} = \frac{43}{7}\left(\frac{43/4}{g_*}\right)^{1/3}\frac{\Gamma_D}{\Gamma_{\rm SM}},$$

$\Gamma_D \propto c^2$ $\quad$ c : the inflaton coupling to DR

If c takes a random value with a flat distribution, the prior distribution of DR is peaked at zero:

$$P_{\rm prior}(\Delta N_{\rm eff}) \propto \frac{1}{\sqrt{\Delta N_{\rm eff}}}$$

Implications for reheating



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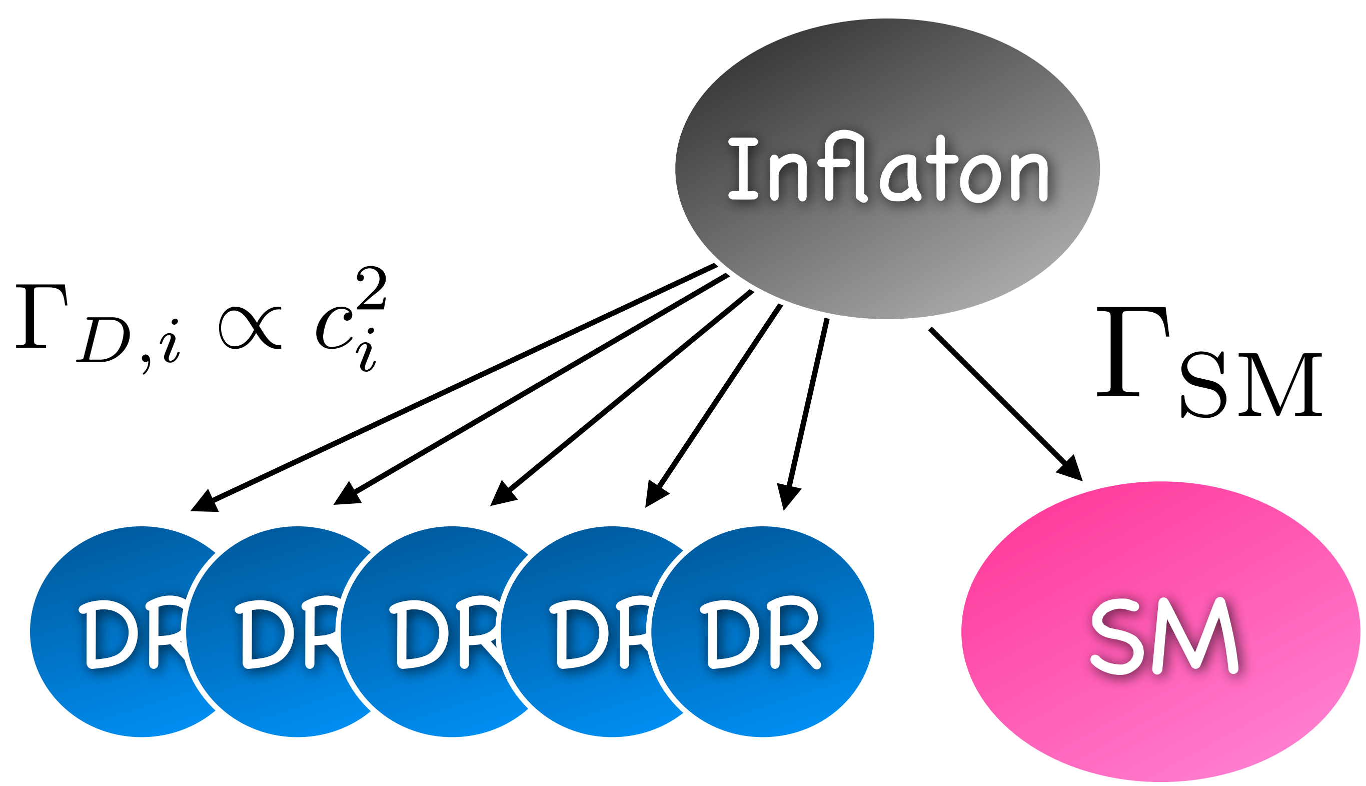
Implications for reheating

On the other hand, if there are many decay channels to DR, and if each coupling varies, the DR prior dist. is peaked at larger values.



If this is the case, the anthropic argument fails to explain the current upper bound on $\Delta N_{\rm eff}$.

Summary

- We found that, for a flat prior distribution, the probability of finding $\Delta N_{\rm eff} < 0.5$ is about 3%, which is not unlikely.

- If correct, DR close to the current upper bound will be discovered soon.

- The prior distribution is model-dependent.

  ✤ If DR is produced by the inflaton decay through the coupling that randomly varies with a flat distribution, the probability of $\Delta N_{\rm eff} < 0.5$ is about 10%.

Back-ups

PHYSICS TODAY

DOI:10.1063/PT.5.010310

17 Apr 2015 in Commentary & Reviews

One million physicists

Economic development could dramatically boost the number of physicists worldwide.

Last week, in the context of a discussion about *Physics Today*'s potential global reach, a question was posed: How many physicists are there on Earth?

. . . .

For the 34 countries that make up 80% of the world's population, I derived a high estimate of 772 000 and a low estimate of 297 000. Renormalizing for 100% of the population yields 964 000 and 372 000. The world might not have a million physicists, but that's the right order of magnitude.

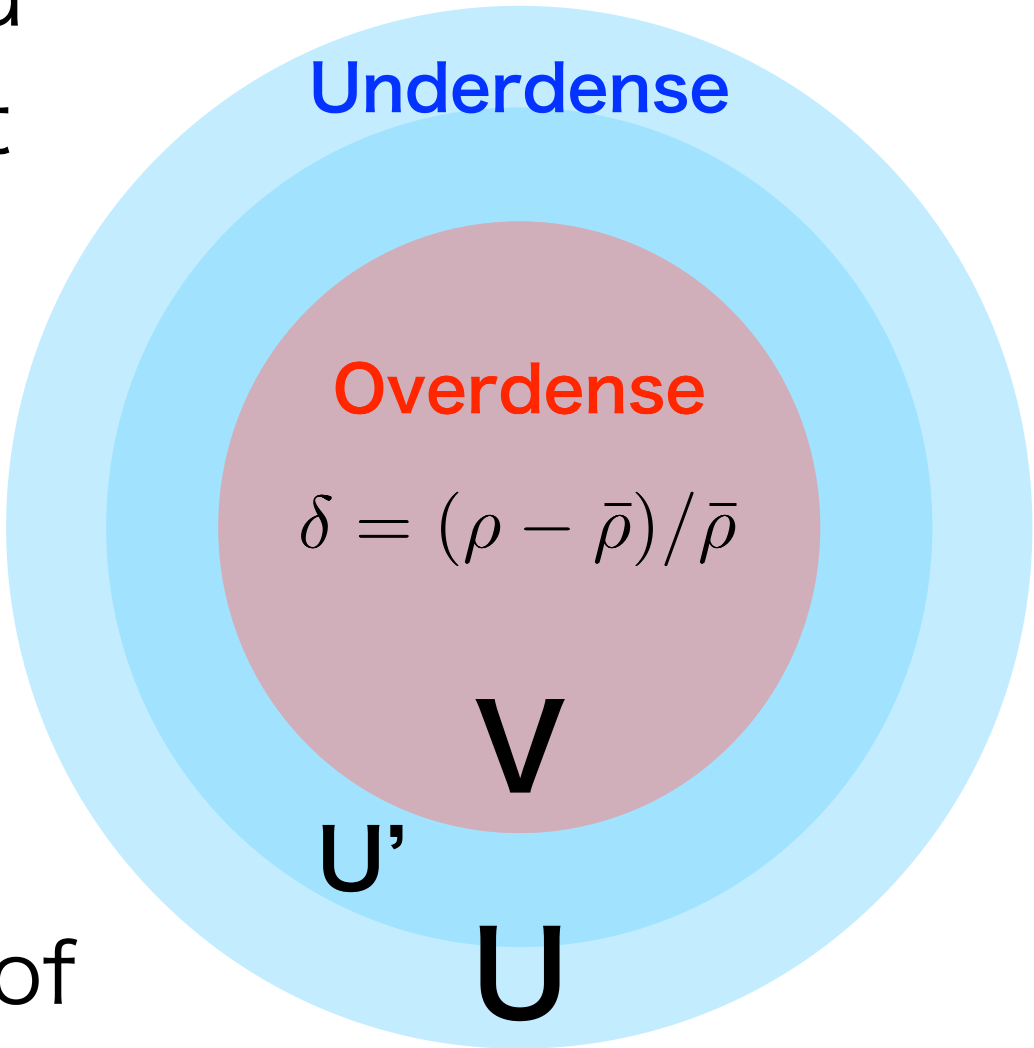
https://physicstoday.scitation.org/do/10.1063/PT.5.010310/full/

Spherical collapse model

Weinberg `87, Martel, Shapiro, and Weinberg `98

The overdense region V is surrounded by the underdense region U such that the mass fluctuation in V+U vanishes.

If $\delta \geq \left(\frac{729\rho_\Lambda}{500\bar{\rho}_m}\right)^{\frac{1}{3}}$, the V+U' region undergoes gravitational collapse.



In this overdense region, the fraction of the matter that collapses is given by

$$\mathcal{F}(\delta) = \frac{V}{U}\delta\frac{1+\delta_c}{\delta_c + \frac{V}{U}\delta} \qquad \delta_c \equiv \left(\frac{729\rho_\Lambda}{500\bar{\rho}_m}\right)^{\frac{1}{3}}$$

Spherical collapse model

Weinberg `87, Martel, Shapiro, and Weinberg `98

So, the mean fraction of matter that gravitationally collapses is

$$F = \int_{\delta_c}^{\infty} d\delta \left(\sqrt{\frac{2}{\pi\sigma^2}} e^{-\frac{\delta^2}{2\sigma^2}} \right) \mathcal{F}(\delta)$$

Gaussian distribution

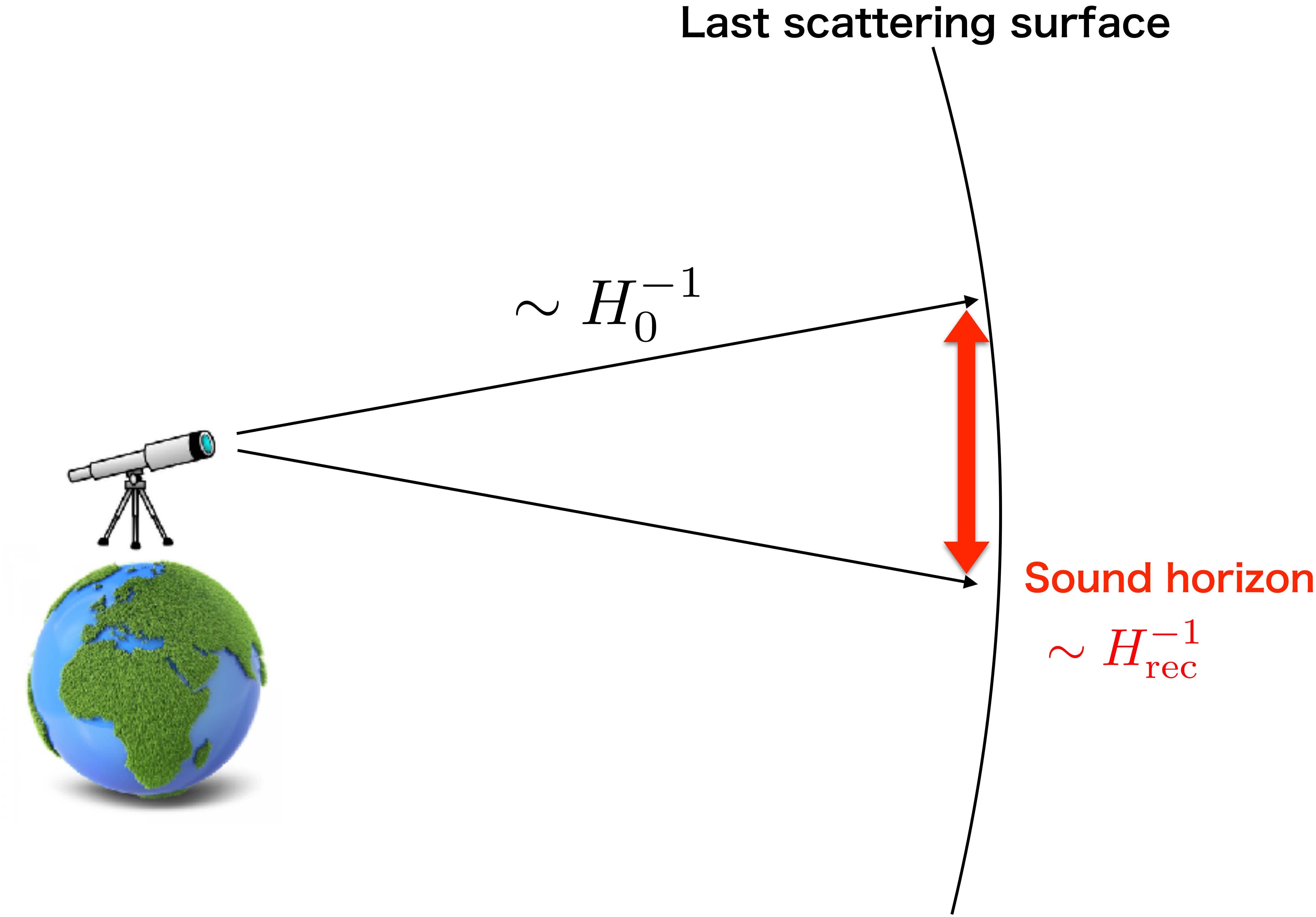
The variance depends on the primordial density perturbations, growth factor, transfer function, and the smoothing scale.

$$\sigma^2 = \frac{1}{2\pi^2} \int_0^{\infty} dk\, k^2 P_\delta(k) W^2(kR)$$

Window function

$$P_\delta(k) = \frac{8\pi^2}{25} \frac{k}{\Omega_m^2 H_0^4} \mathcal{P}_\zeta(k) T^2(k) D(a)^2$$

DR and CMB



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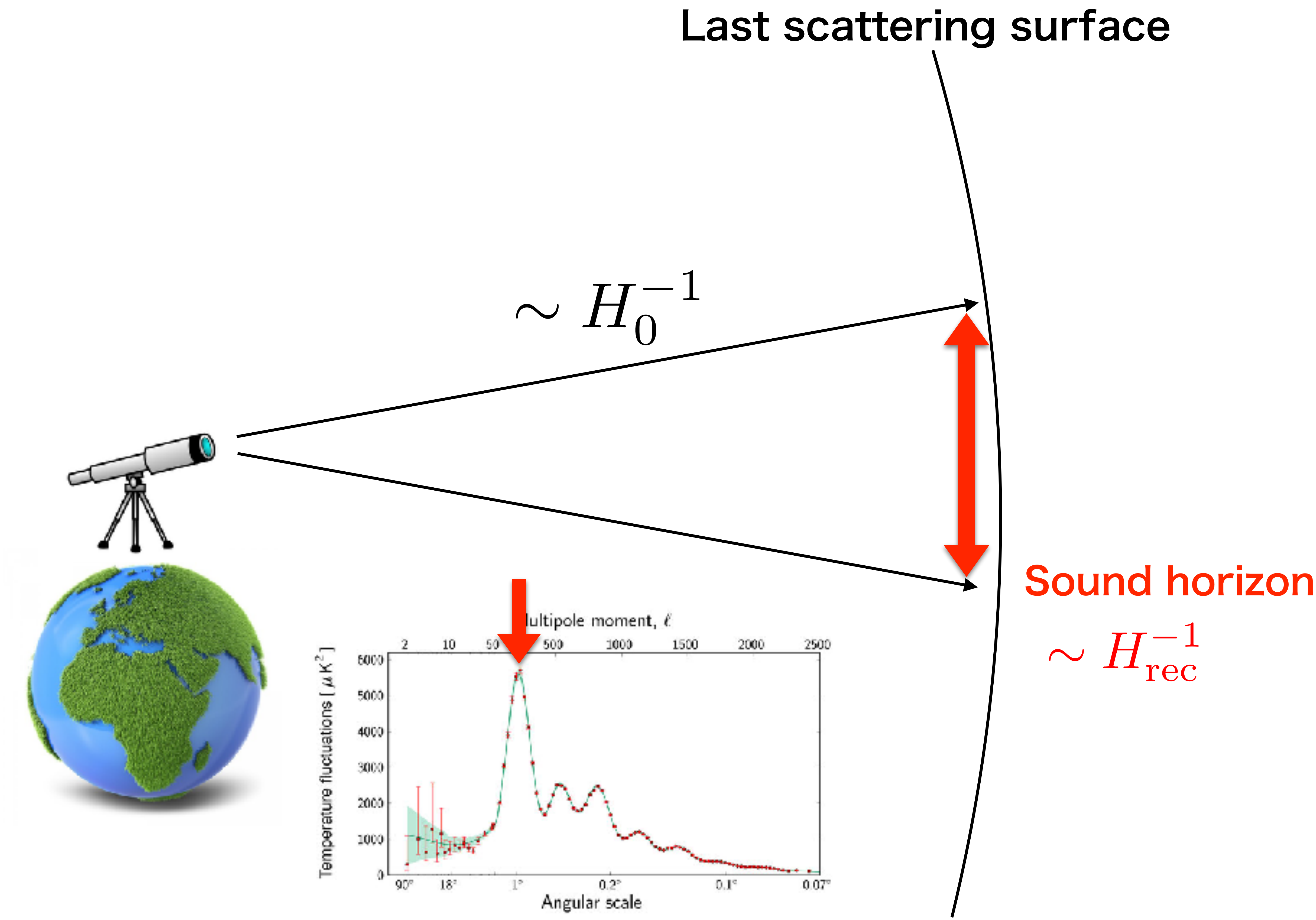
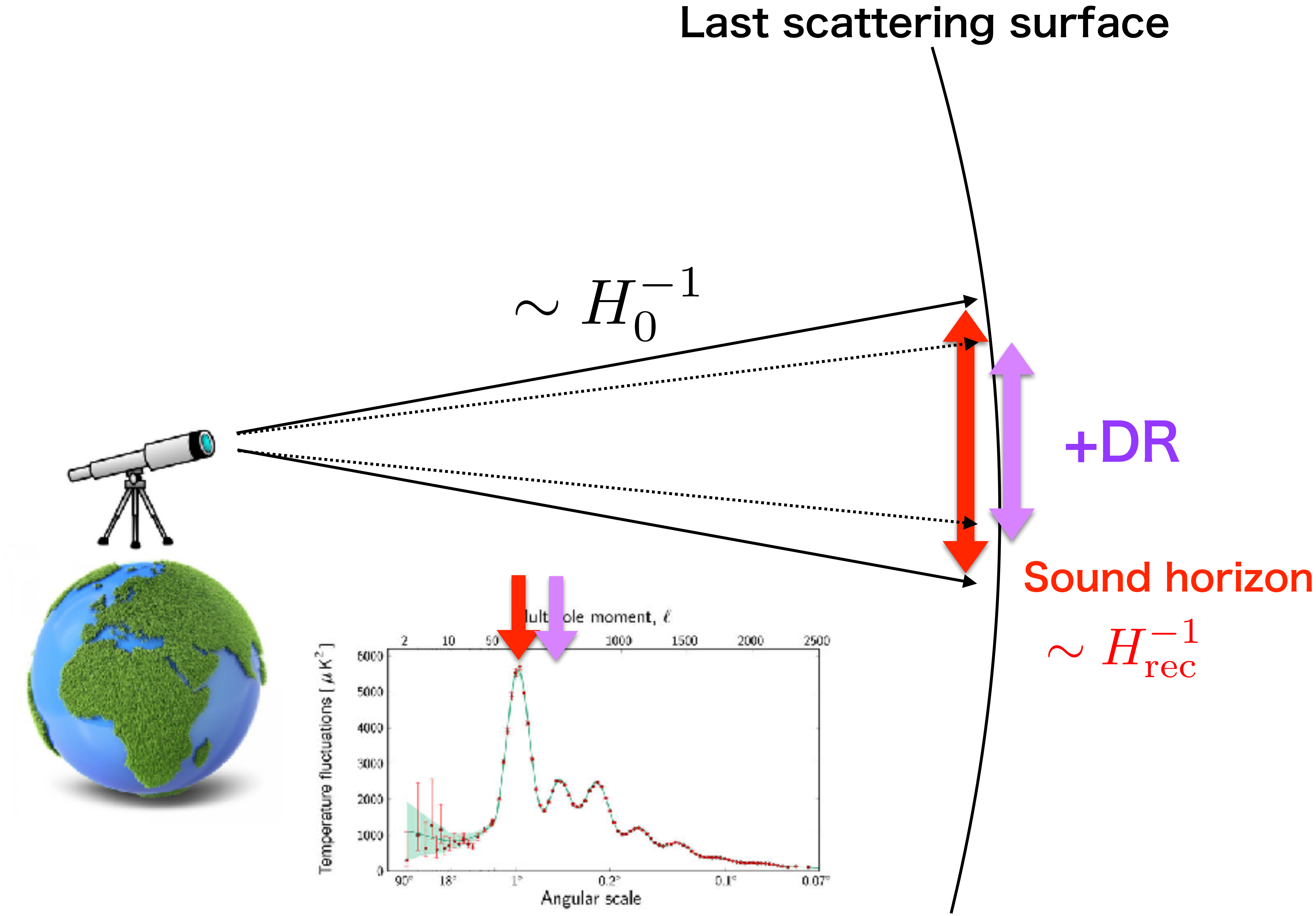

Last scattering surface
$\sim H_0^{-1}$
Sound horizon
$\sim H_{\rm rec}^{-1}$
ultipole moment, ℓ
Temperature fluctuations [μK^2]
Angular scale

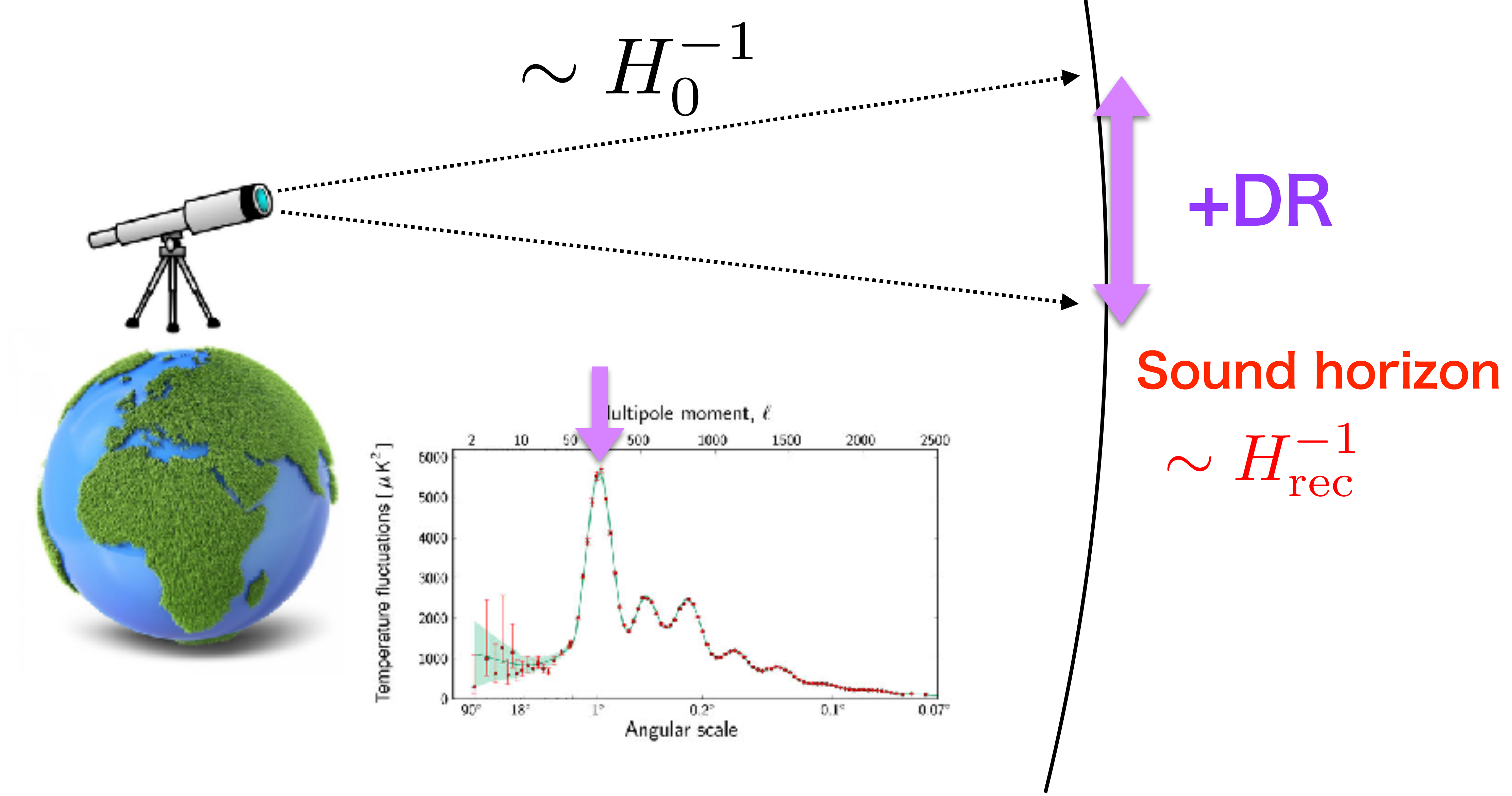
DR and CMB


Last scattering surface
$\sim H_0^{-1}$
+DR
Sound horizon
$\sim H_{\rm rec}^{-1}$
Temperature fluctuations [μK^2]
Angular scale

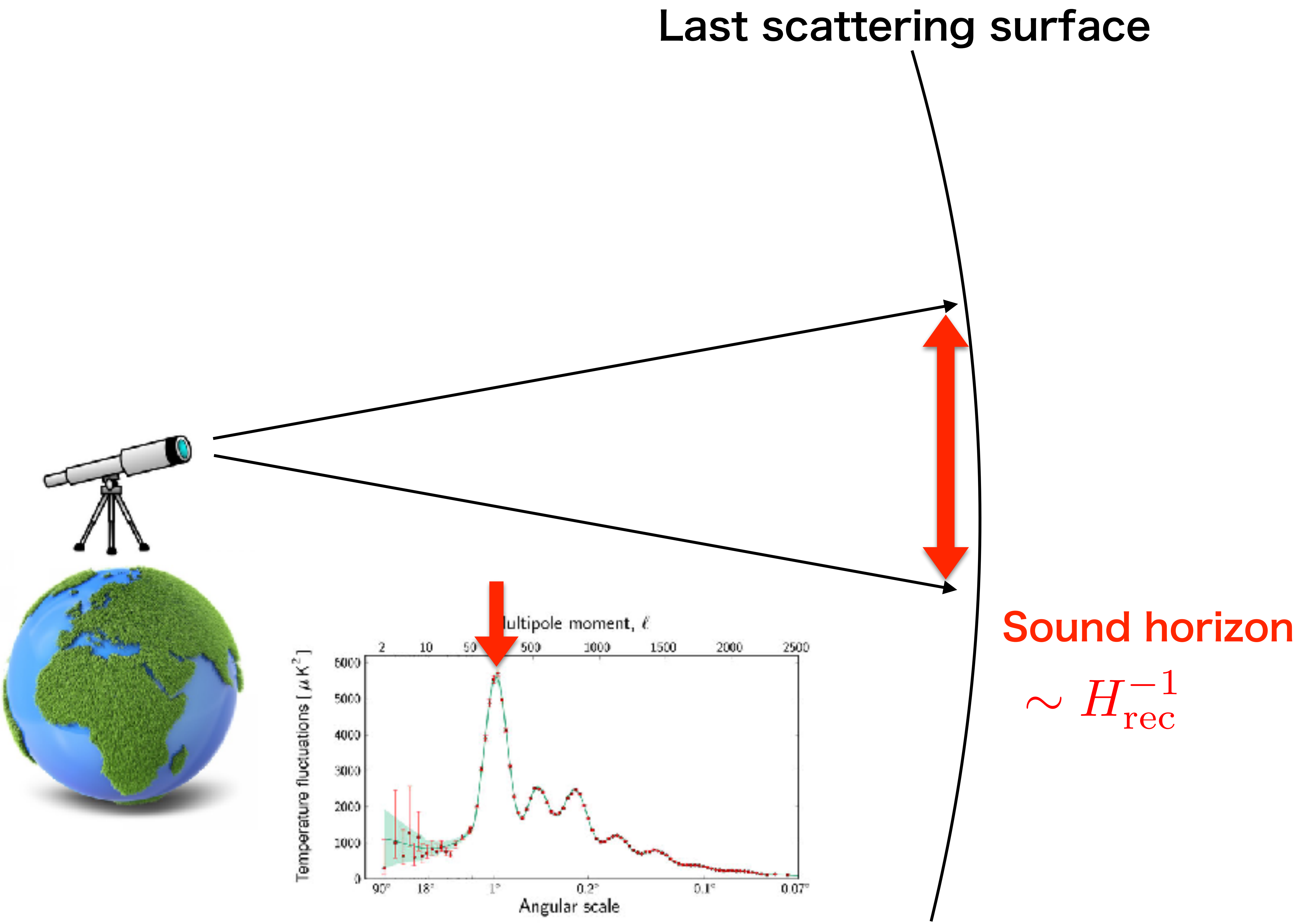
DR and CMB

The effect of DR on the sound horizon can be compensated by increasing H_0.

Last scattering surface

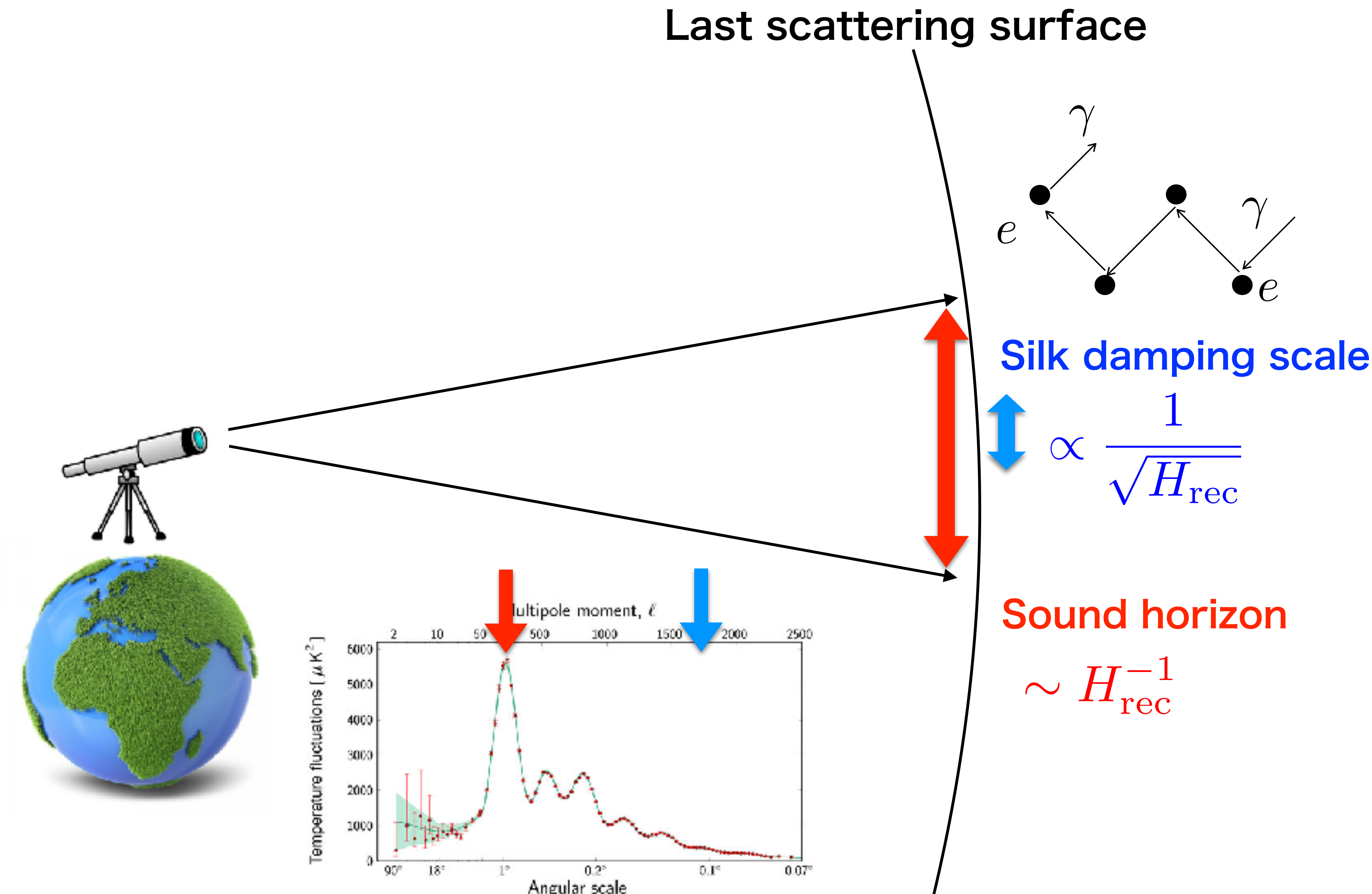


DR and CMB



Last scattering surface
Sound horizon
$\sim H_{\rm rec}^{-1}$
ultipole moment, ℓ
2 10 50 500 1000 1500 2000 2500
Temperature fluctuations [μK^2]
6000 5000 4000 3000 2000 1000 0
90° 18° 1° 0.2° 0.1° 0.07°
Angular scale

DR and CMB



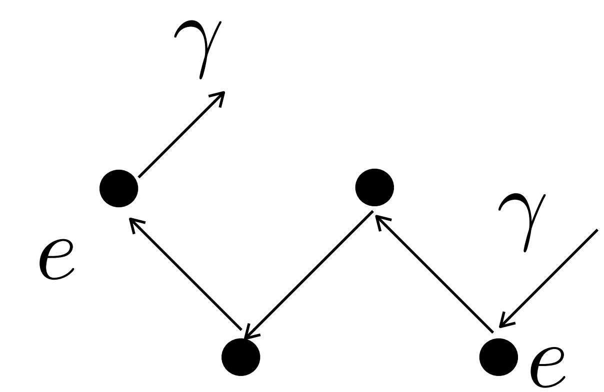
Last scattering surface
γ
e
γ
e
Silk damping scale
$\propto \frac{1}{\sqrt{H_{\rm rec}}}$
Sound horizon
$\sim H_{\rm rec}^{-1}$
Multipole moment, ℓ
Temperature fluctuations [μK^2]
Angular scale

DR and CMB

Last scattering surface

The Silk damping scale becomes relatively larger, suppressing fluctuations at larger ℓ.

$$\frac{d_{\rm SD}}{d_{\rm SH}} \propto \sqrt{H_{\rm rec}}$$



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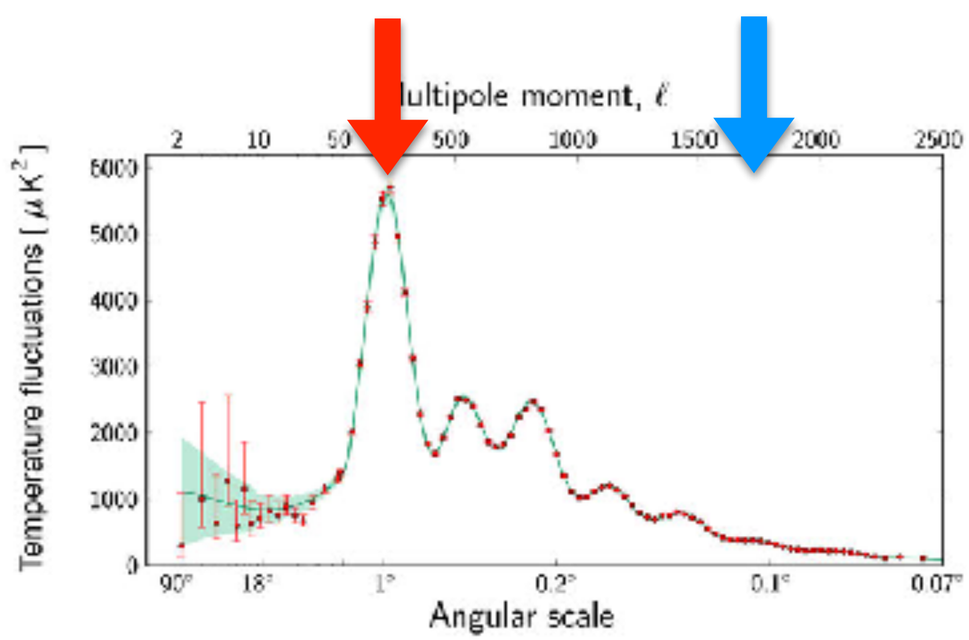
Sound horizon

$$\sim H_{\rm rec}^{-1}$$



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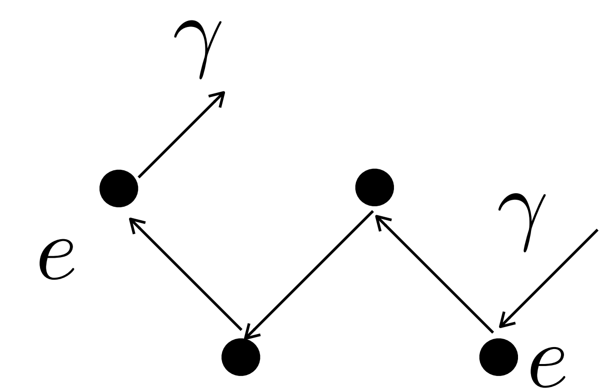

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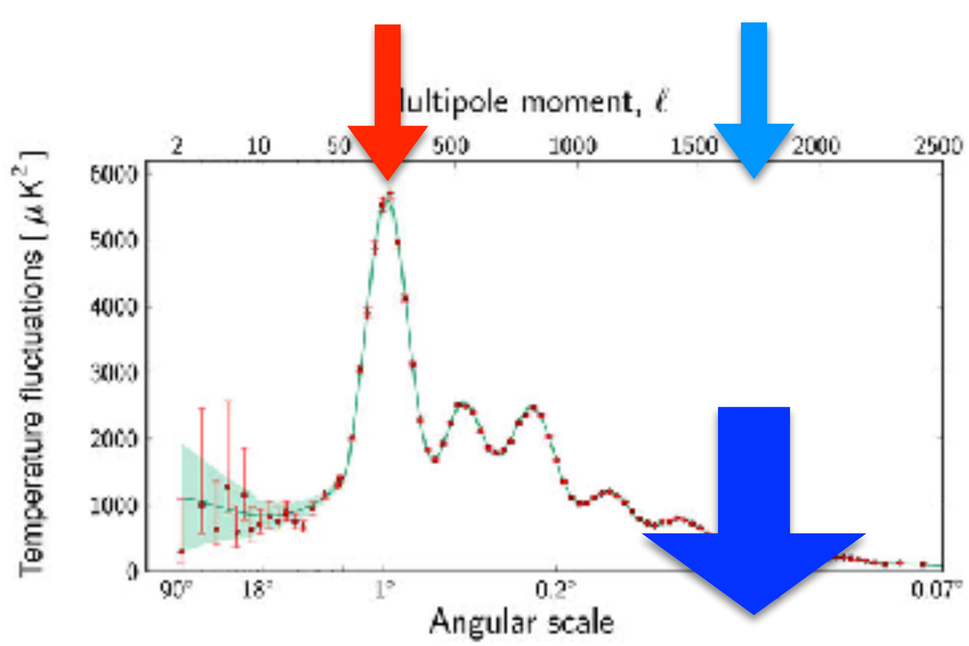
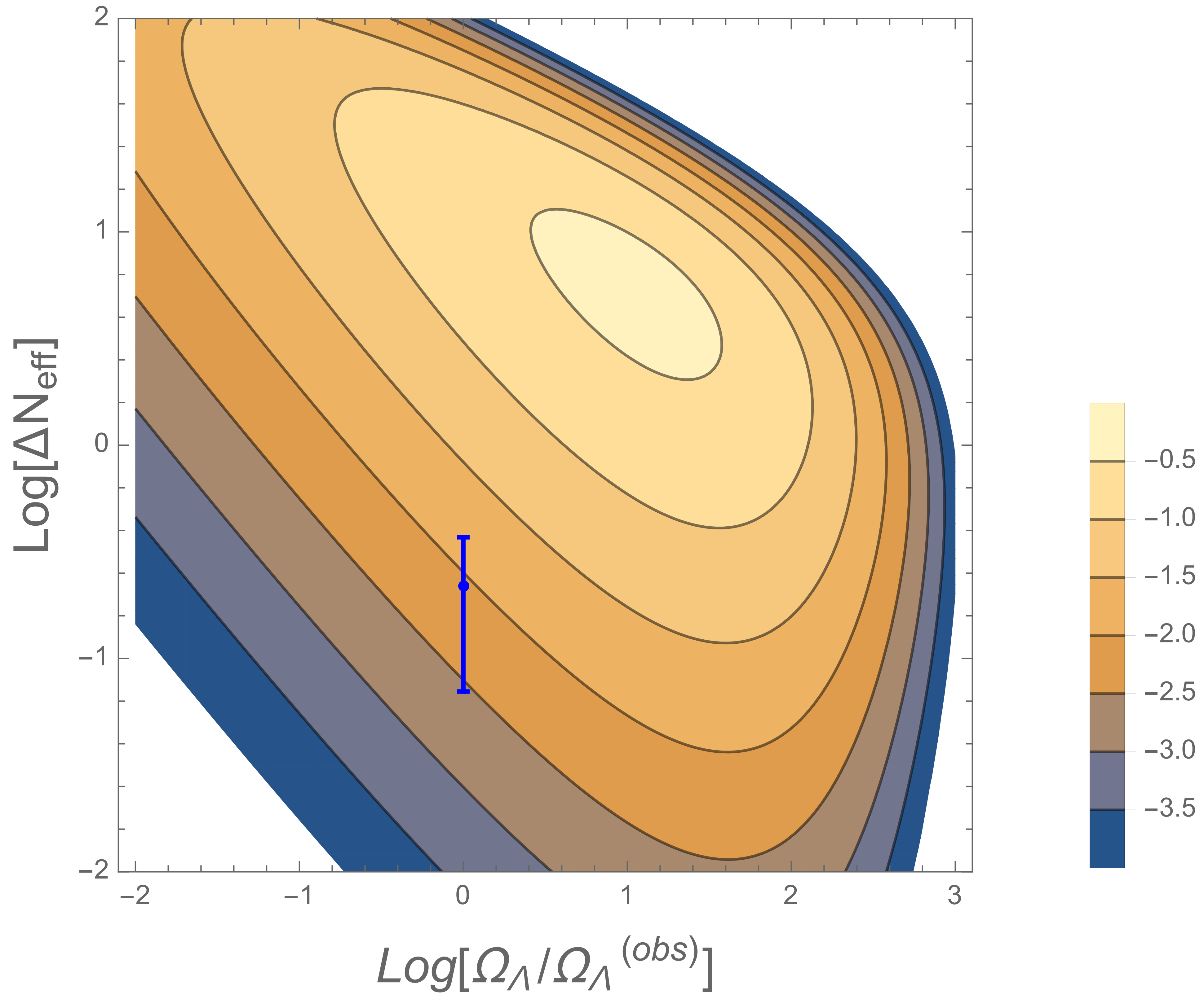
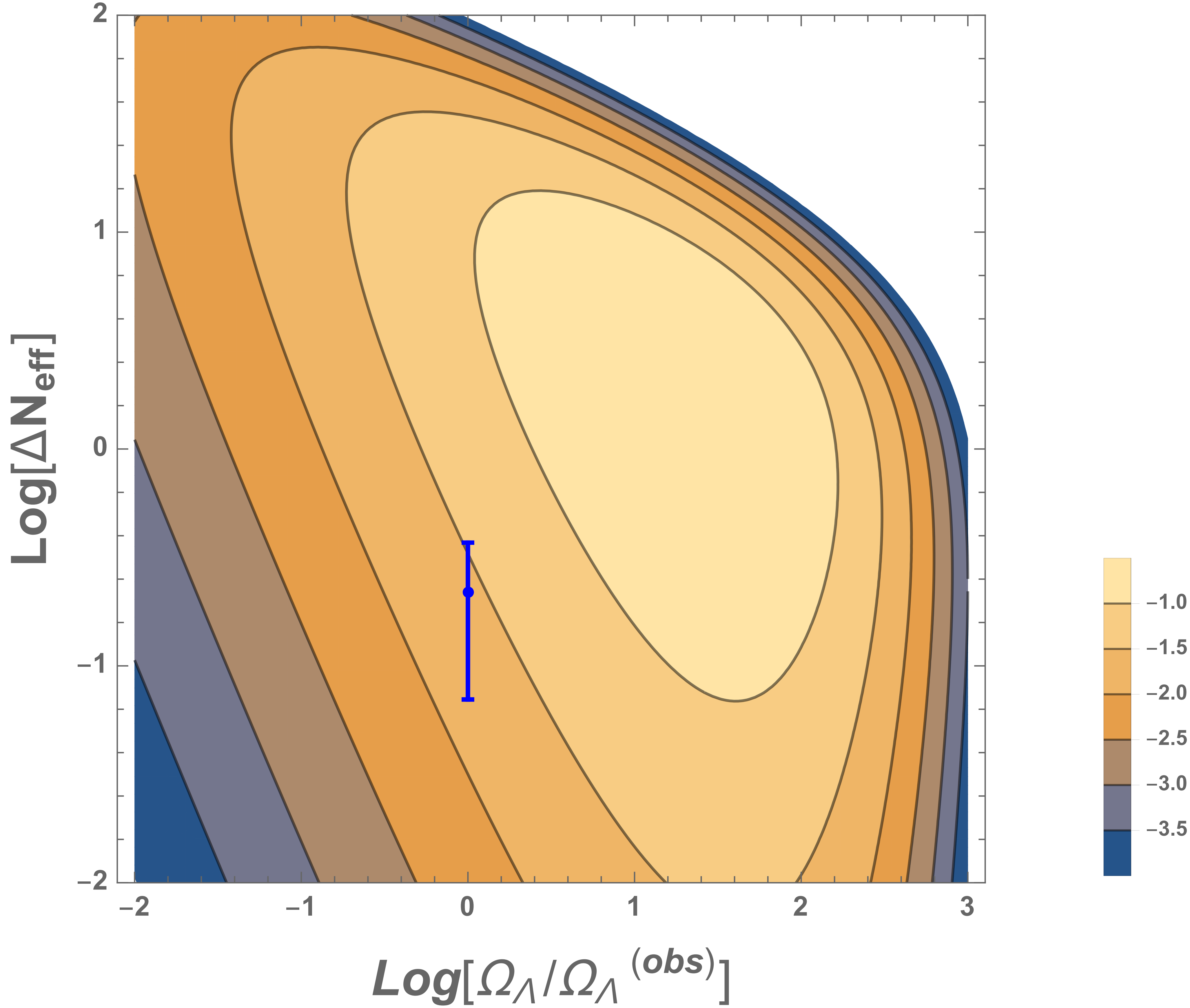




Log[ΔN_eff]
Log[Ω_Λ/Ω_Λ^(obs)]
−0.5
−1.0
−1.5
−2.0
−2.5
−3.0
−3.5



2
1
0
−1
−2
−2
−1
0
1
2
3
Log[ΔN_eff]
Log[Ω_Λ/Ω_Λ^(obs)]
−1.0
−1.5
−2.0
−2.5
−3.0
−3.5