INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

Dark Radiation

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@Osaka Univ.

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(IPMU, Univ. of Tokyo)

Nakayama, FT and Yanagida, 1010.5693

1. Introduction

What is the Universe made of ?

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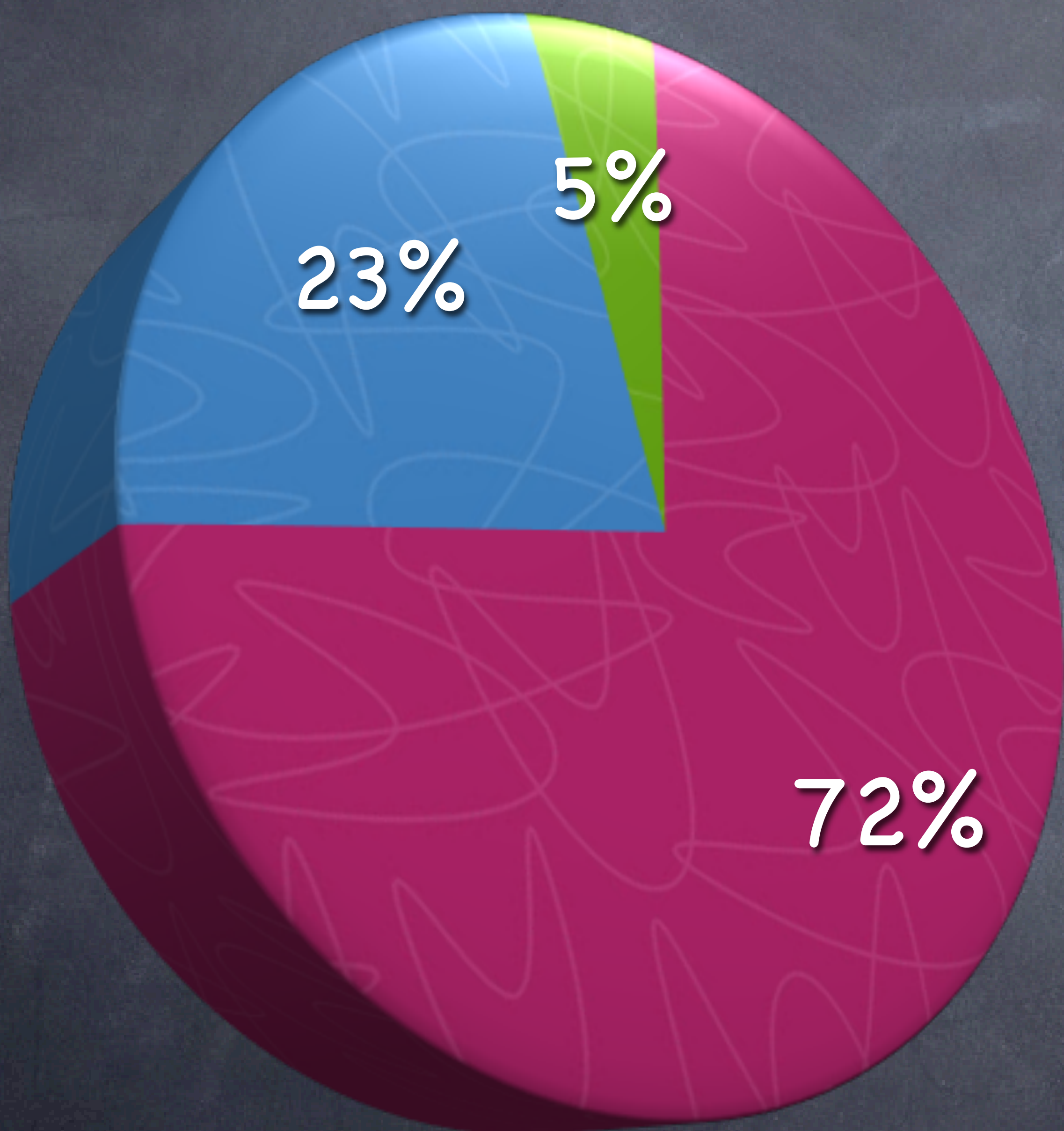

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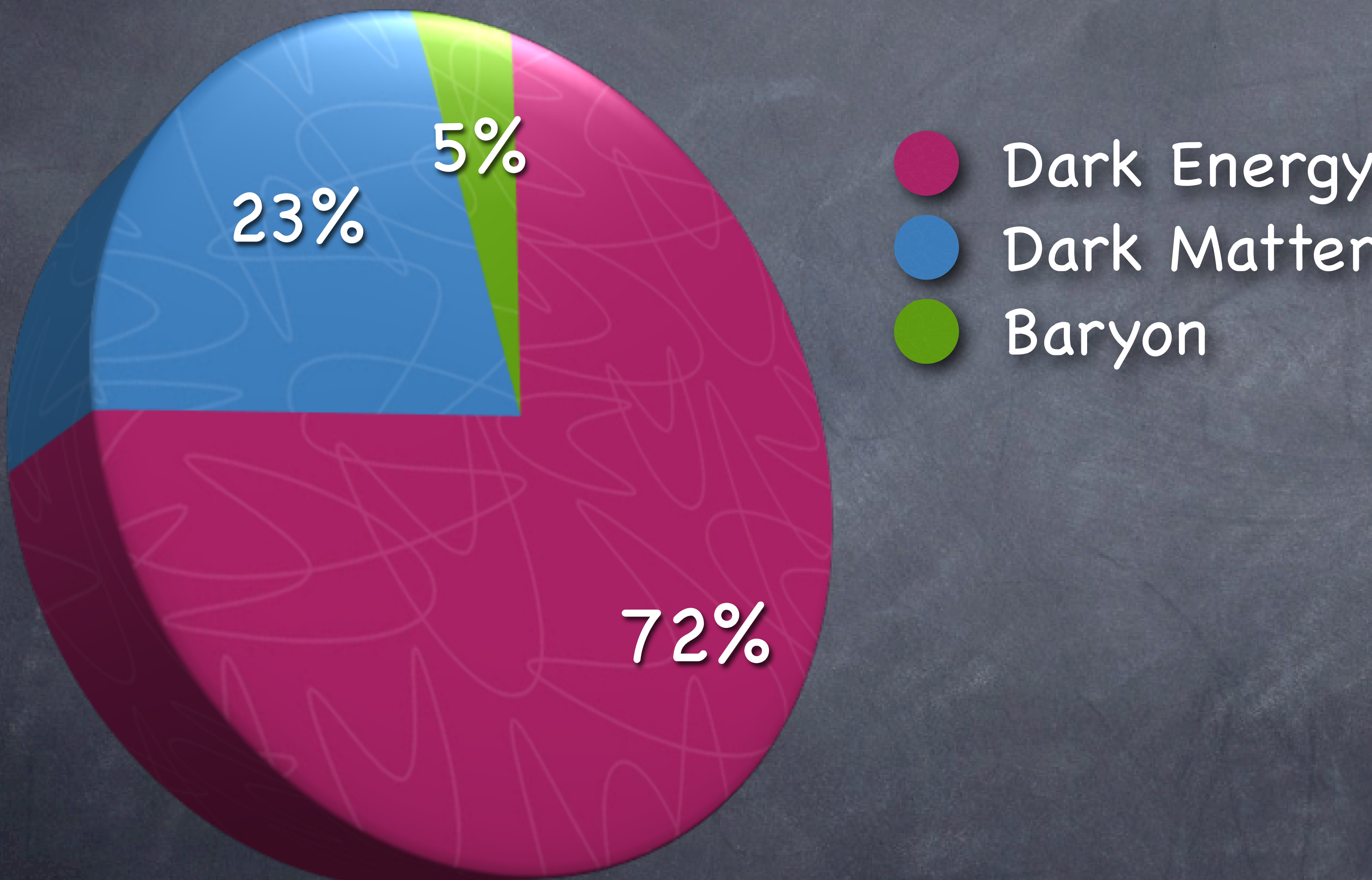

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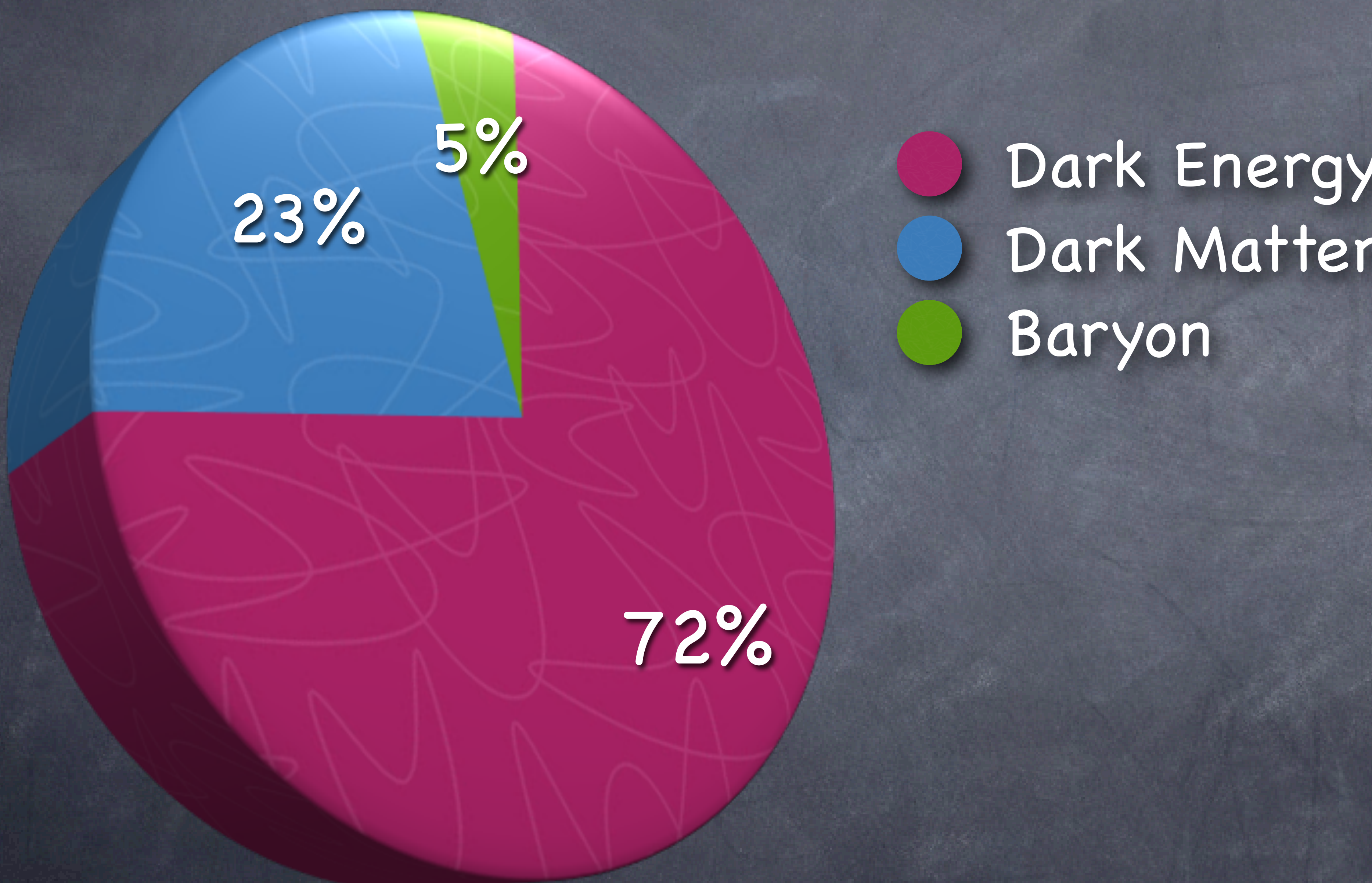
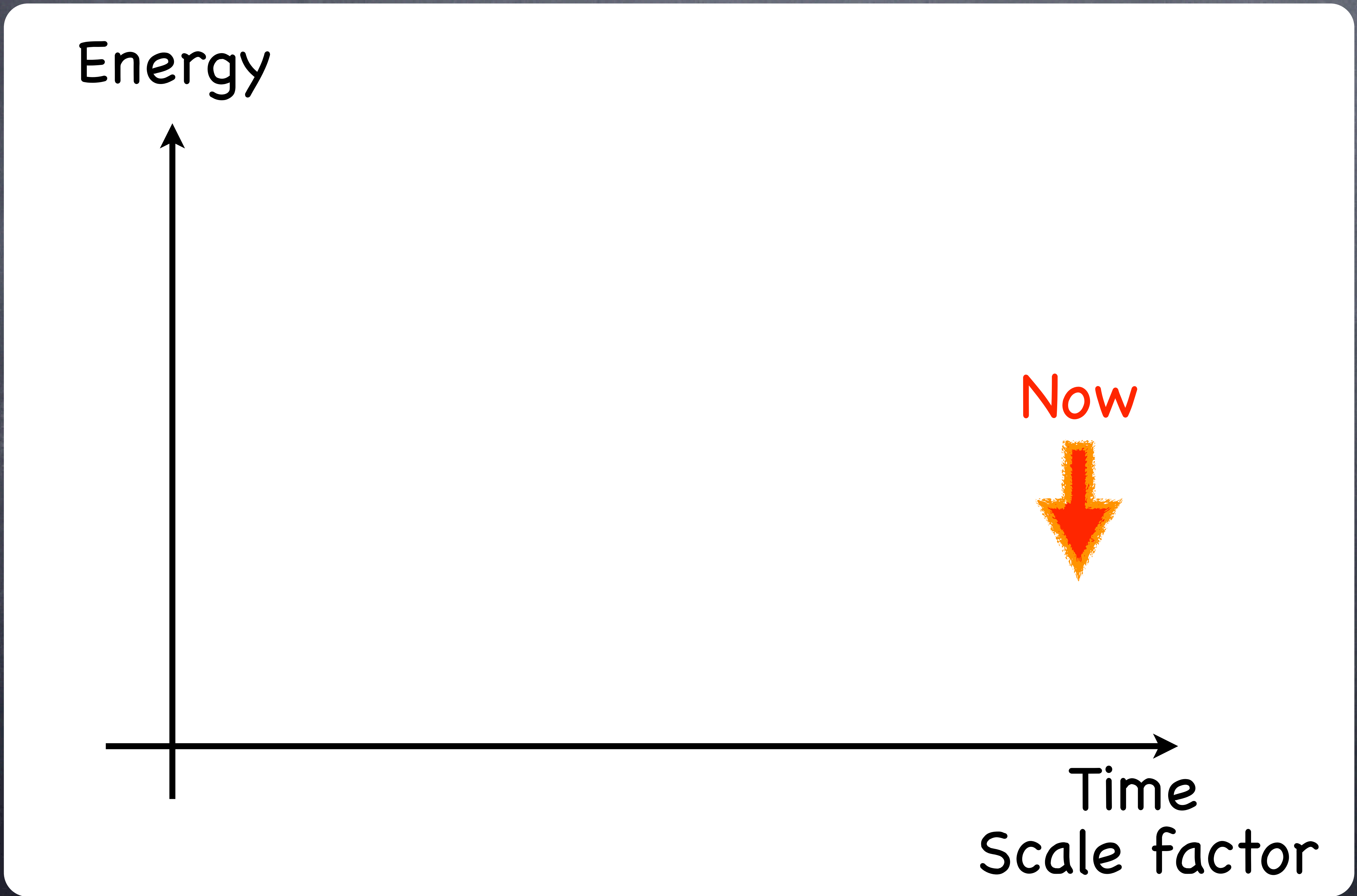


The present Universe is dominated by dark sector.

The fraction of dark energy and dark matter depends on time.



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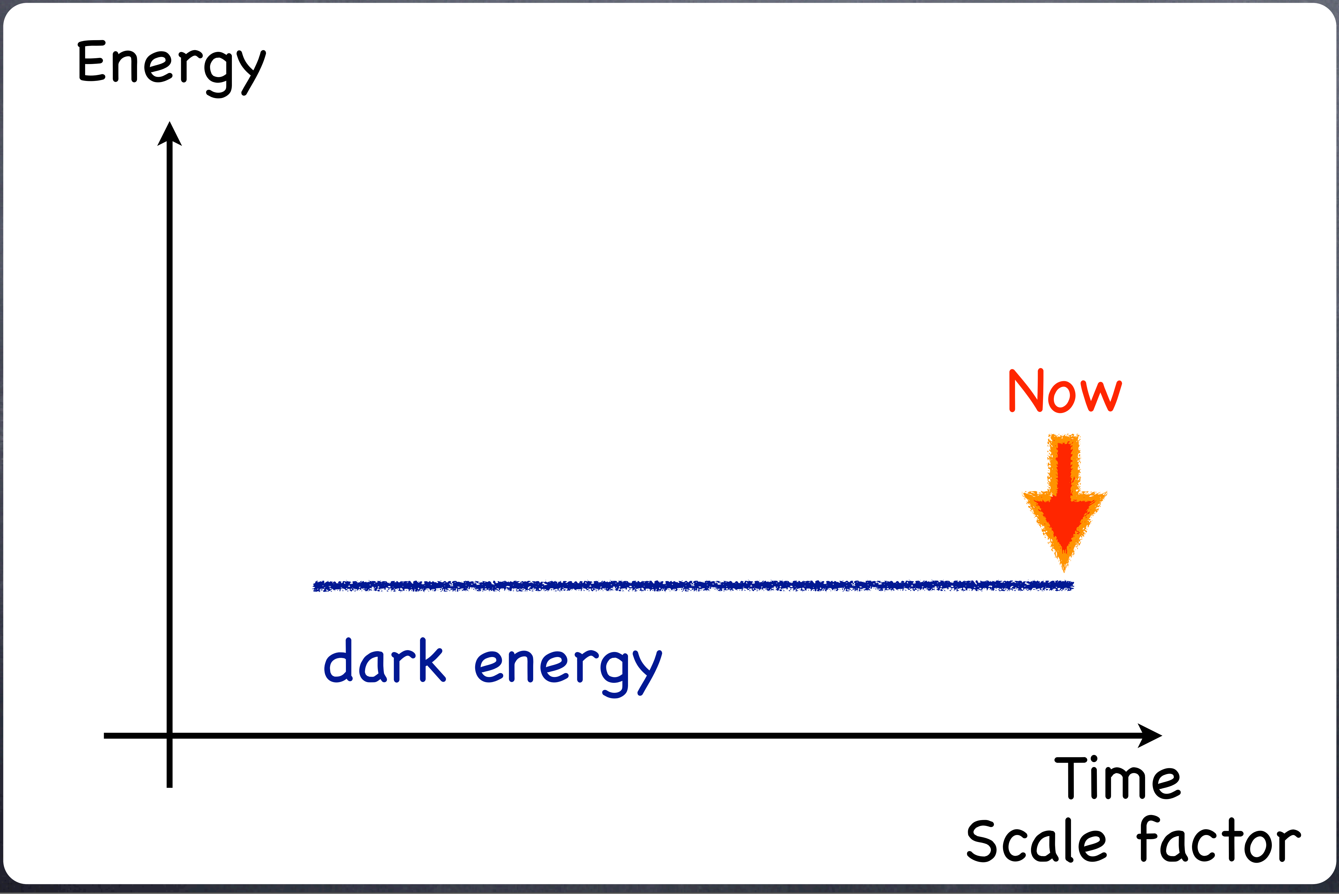

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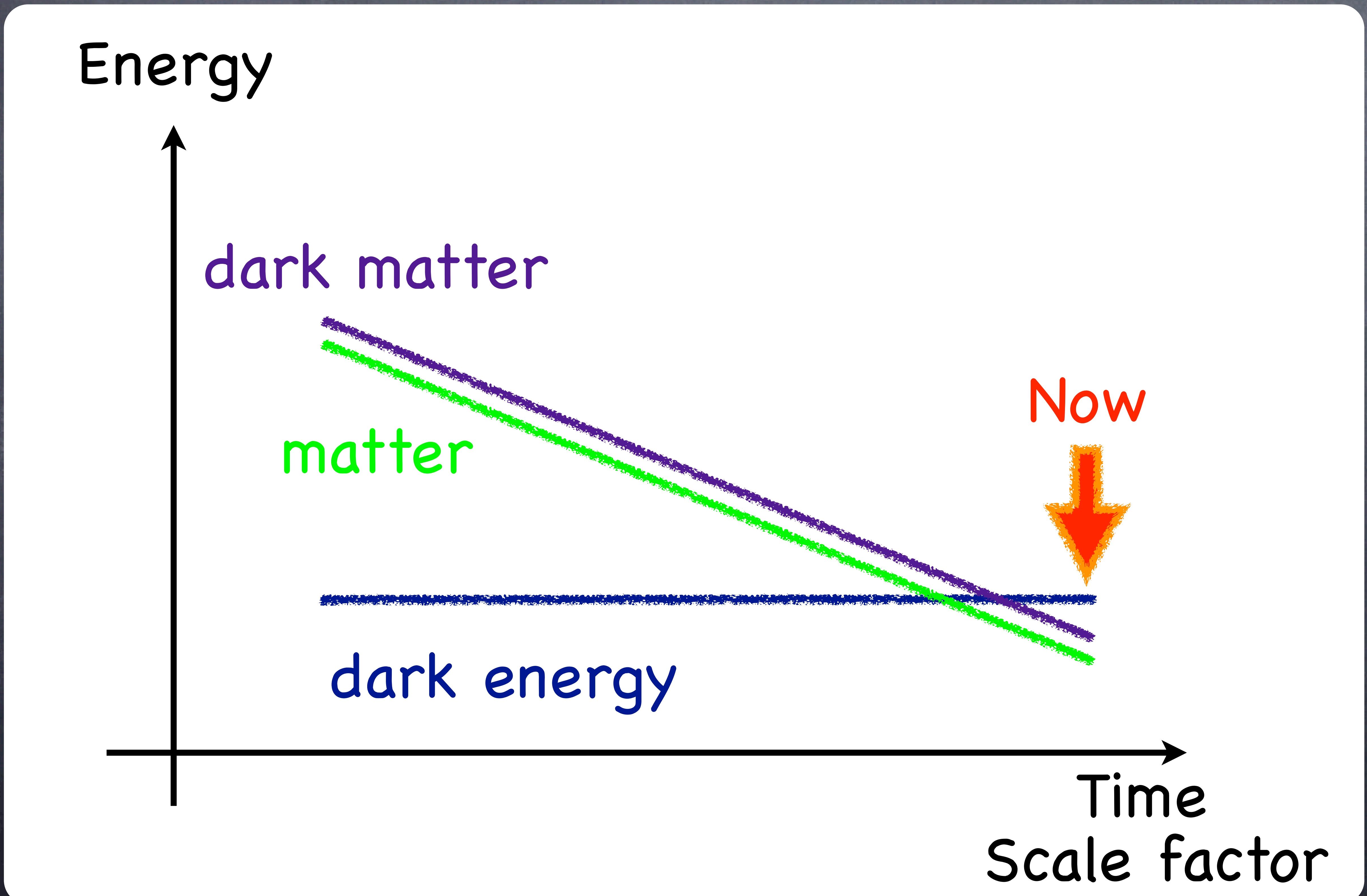

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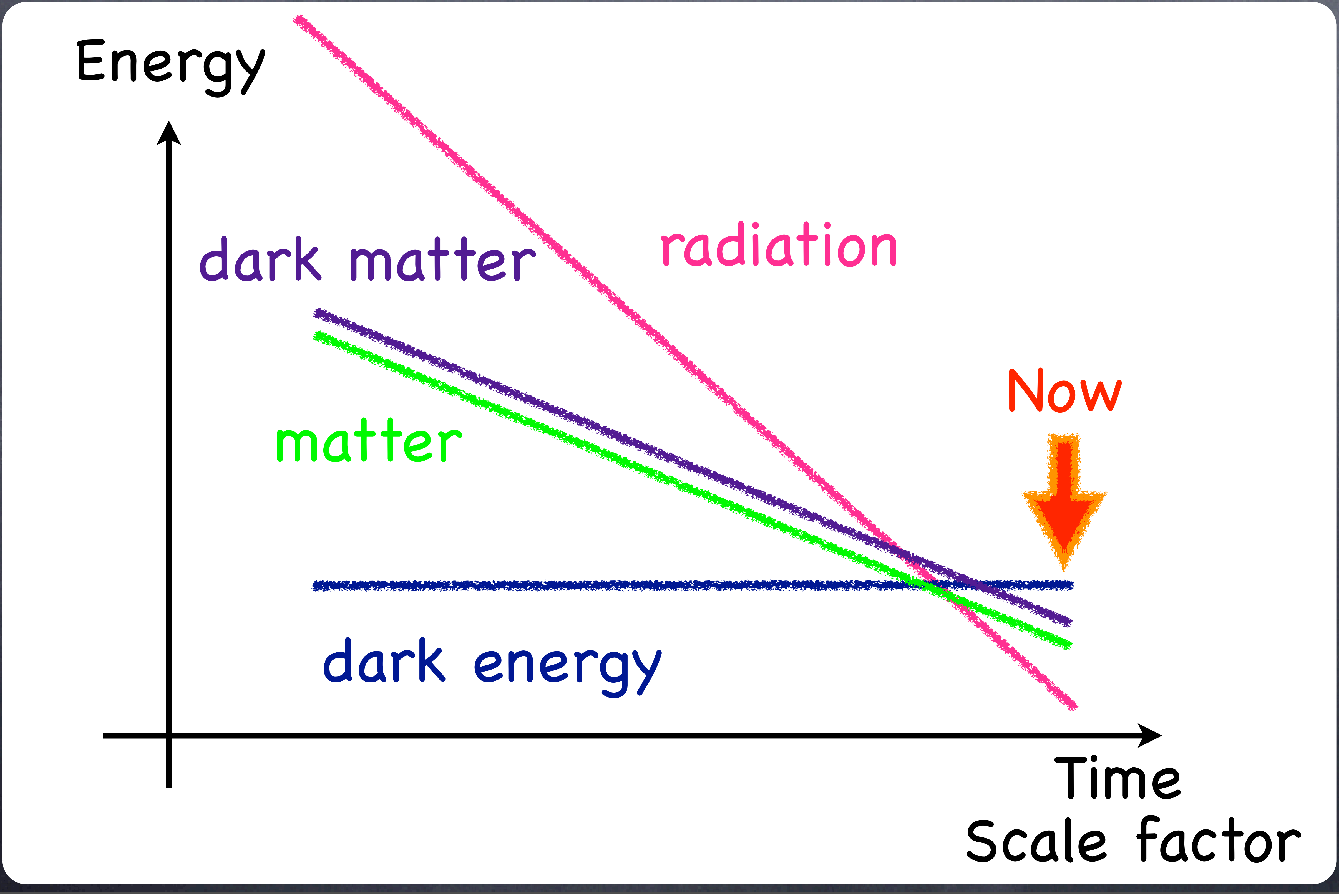

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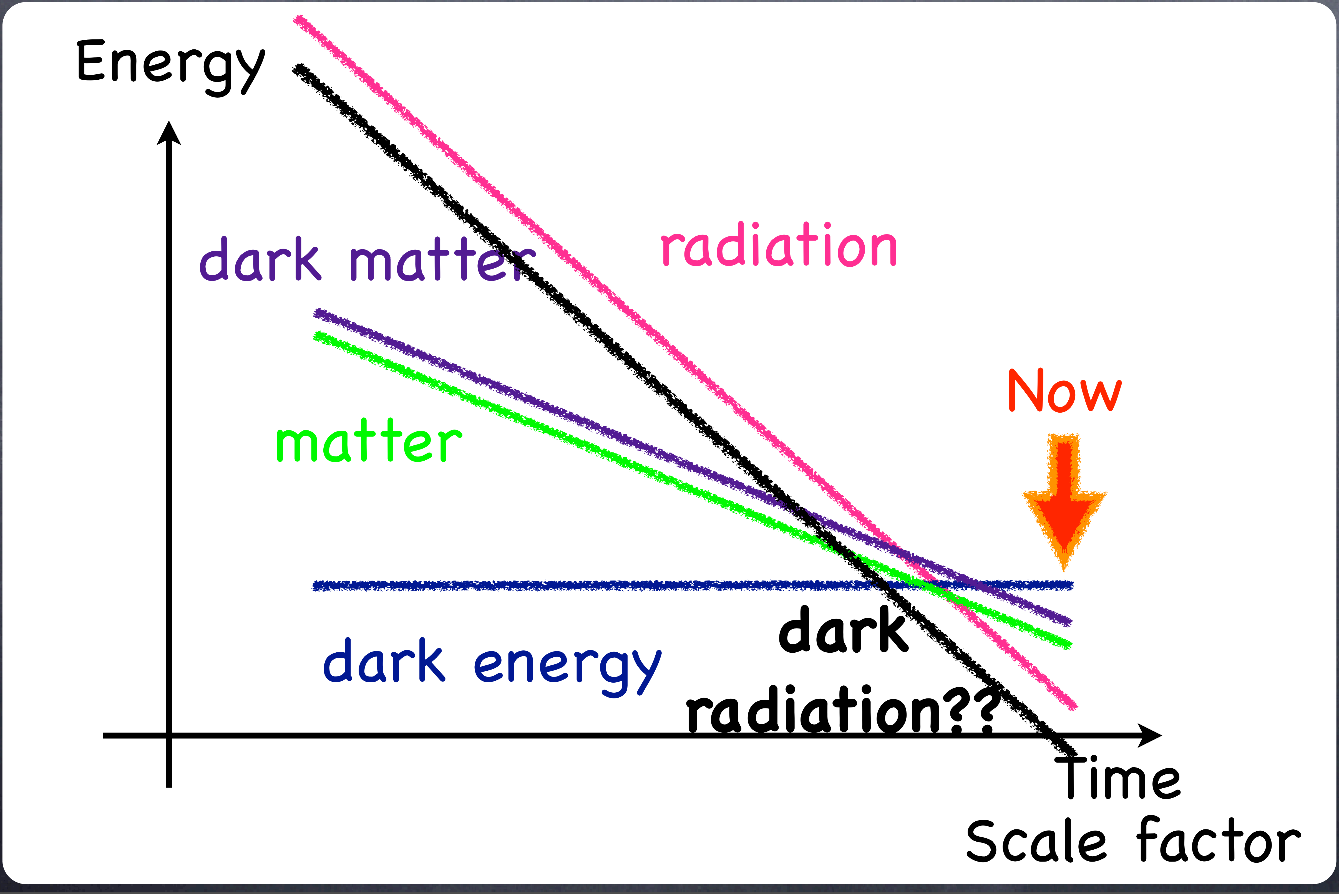

Effective number of light neutrino species

It is conventional to measure the amount of extra radiation in the units of active neutrinos.

$$N_{\rm eff} = N_{\rm eff}^{\rm (std)} + \Delta N_{\rm eff}$$

$$N_{\rm eff}^{\rm (std)} \simeq 3.046$$

The Friedman equation:

$$3H^2 M_P^2 = \rho$$

- The observation of Type Ia SNe revealed the presence of dark energy.
- It is also possible to infer the particle content of the Universe in the past by measuring the helium abundance, cosmic microwave background (CMB) and large-scale structure (LSS).

2. Observations

^{4}He abundance

is sensitive to the expansion rate when the Universe is 1 second old.

Cosmic microwave background radiation

is sensitive to the expansion rate when the Universe is 380,000 years old.

^{4}He abundance

- n-p transformation decouples when

$$\Gamma_{n\leftrightarrow p} = H$$

$$n \leftrightarrow p + e^- + \bar{\nu}_e$$
$$n + \nu_e \leftrightarrow p + e^-$$
$$n + e^+ \leftrightarrow p + \bar{\nu}_e$$

→ n/p ratio is fixed (except for neutron free decay) at T ~1 MeV.

$$\left(\frac{n}{p}\right)_{\rm EQ} = \exp\left(-\frac{Q}{T_*}\right)$$

$$Q = m_n - m_p = 1.293 \mathrm{MeV}$$

→ Almost all neutrons are absorbed in ^{4}He.

If there is extra radiation,

H ↑ Y_p ↑

$$Y_p = \frac{4n_{He}}{4n_{He} + n_H}$$

Two recent results on the helium abundance:

Izotov and Thuan (1001.4440)

$$Y_p = 0.2565 \pm 0.0010\,(\mathrm{stat}) \pm 0.0050\,(\mathrm{syst})$$

$$N_{\mathrm{eff}} = 3.68^{+0.80}_{-0.70} \quad (2\sigma)$$

Aver, Olive and Skillman (1001.5218)

$$Y_p = 0.2561 \pm 0.0108 \quad (68\%\mathrm{CL})$$

For comparison, the std. WMAP value is

$$Y_p = 0.2486 \pm 0.0002 \quad (68\%\mathrm{CL})$$

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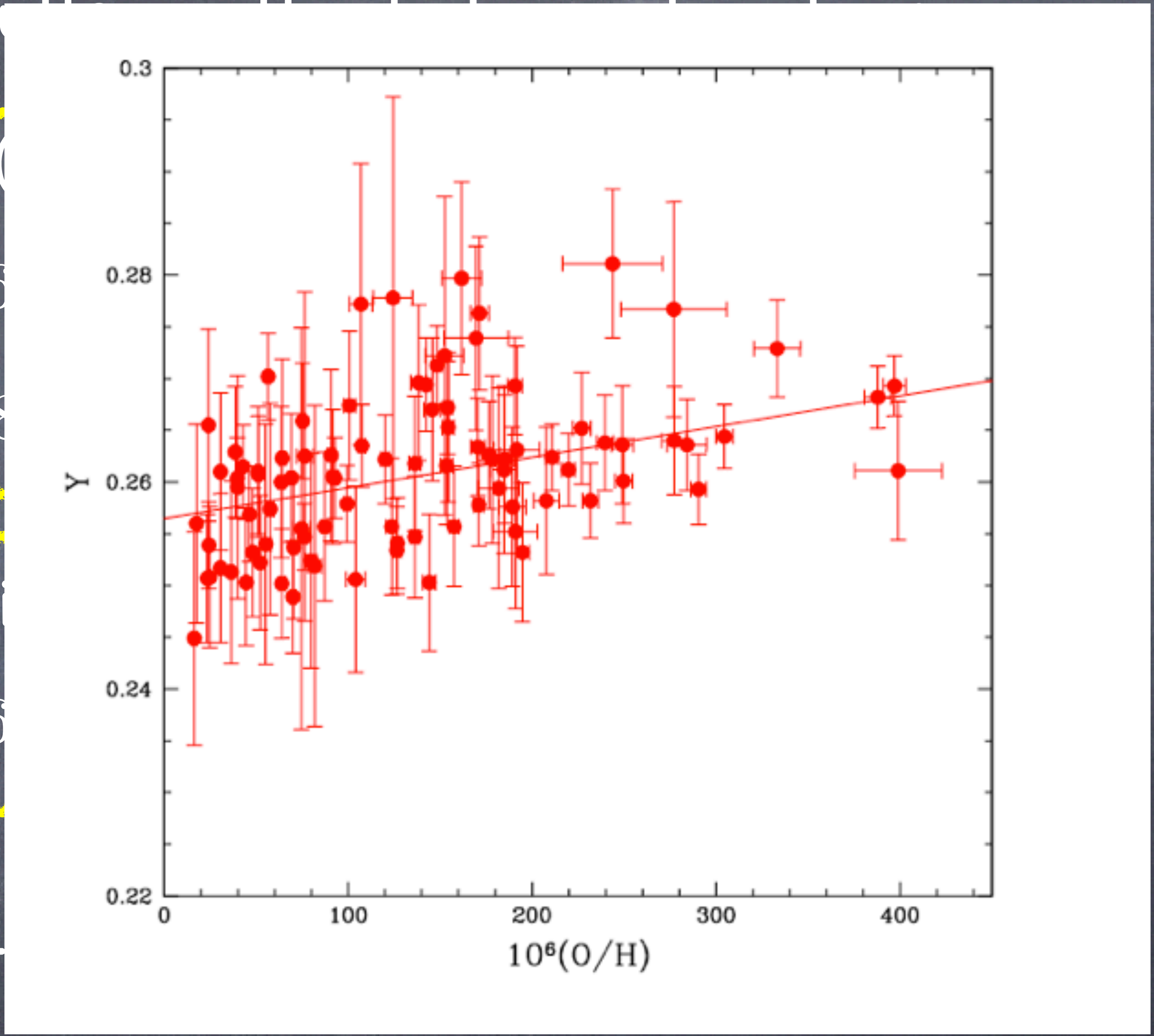

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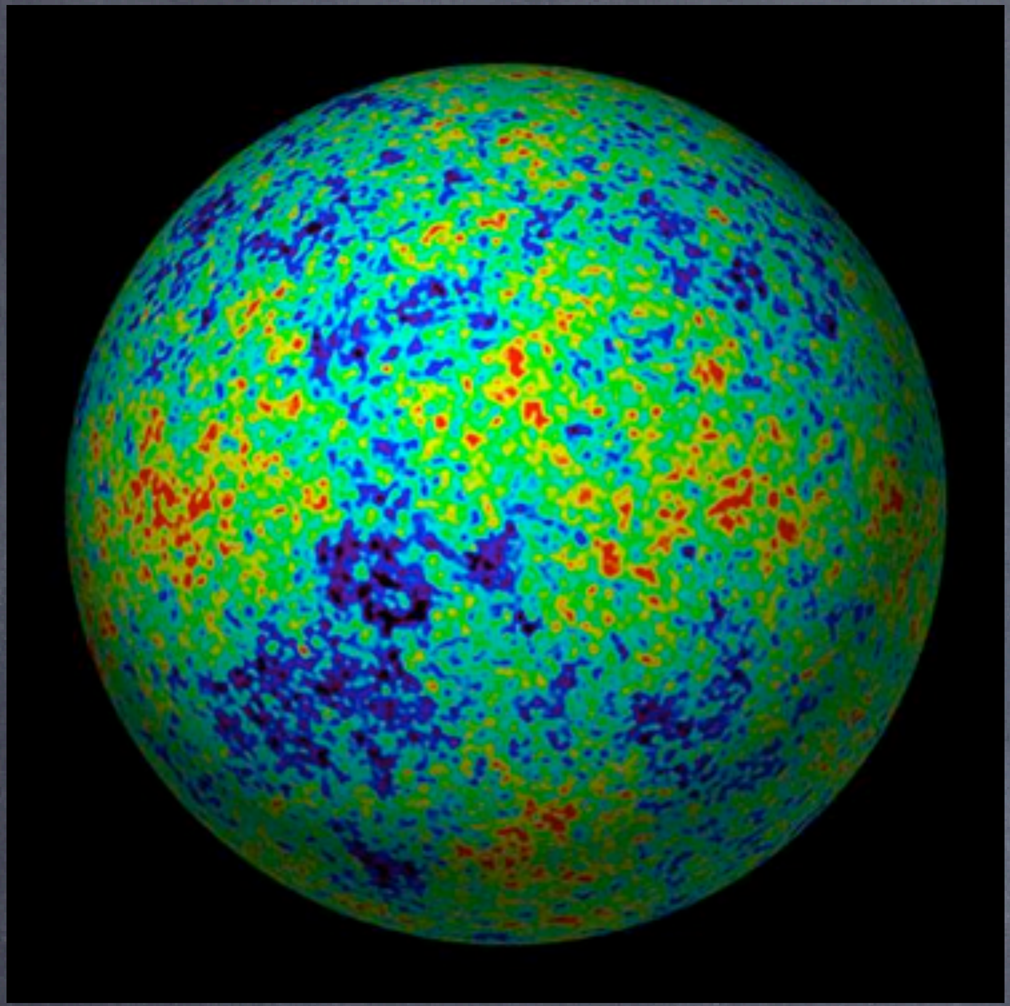
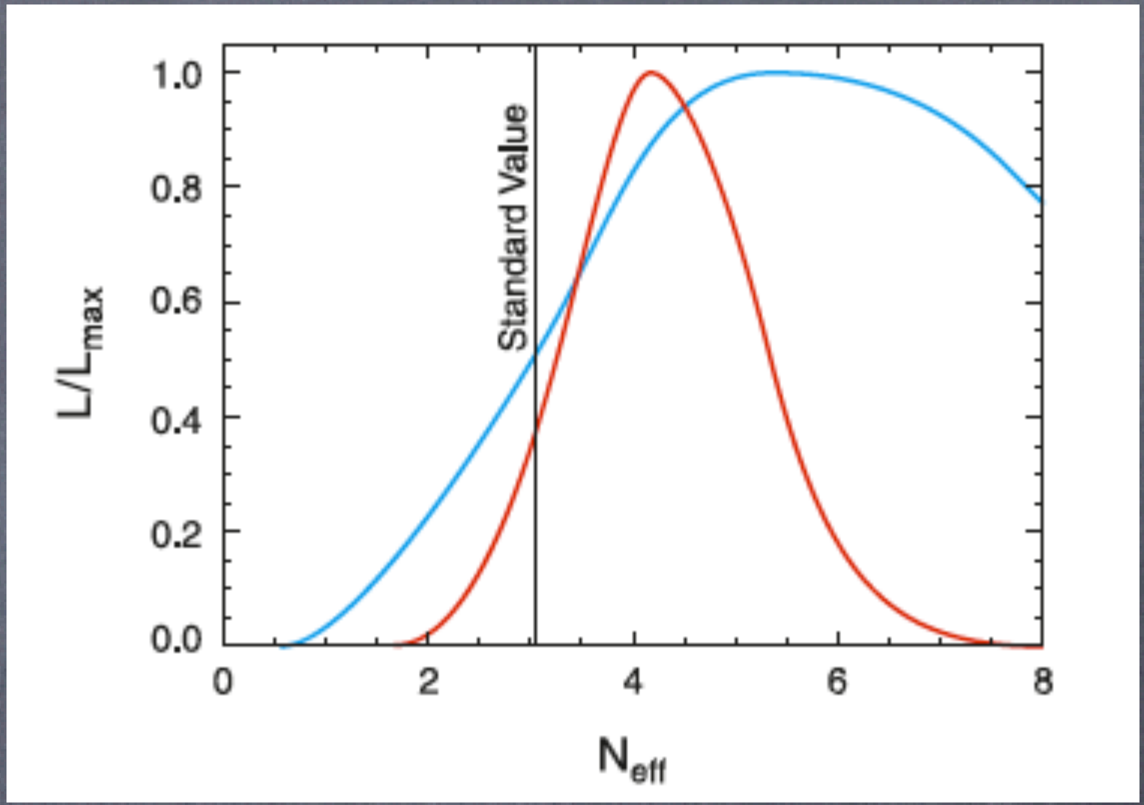
CMB+LSS





- WMAP 7-yr + BAO + H_0 : $N_{\rm eff} = 4.34^{+0.86}_{-0.88}$ (68%CL)

(Komatsu et al, 2010)

- +ACT : $N_{\rm eff} = 4.56 \pm 0.75$ (68%CL) (Dunkley et al, 2010)

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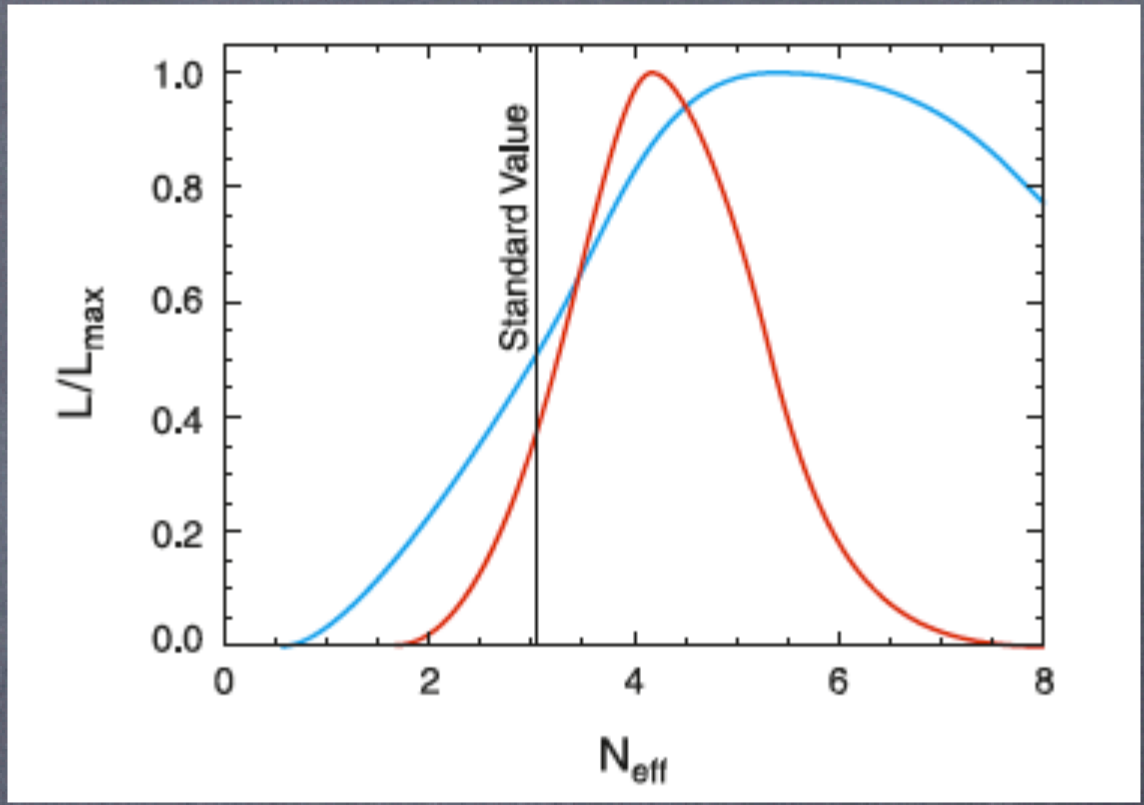

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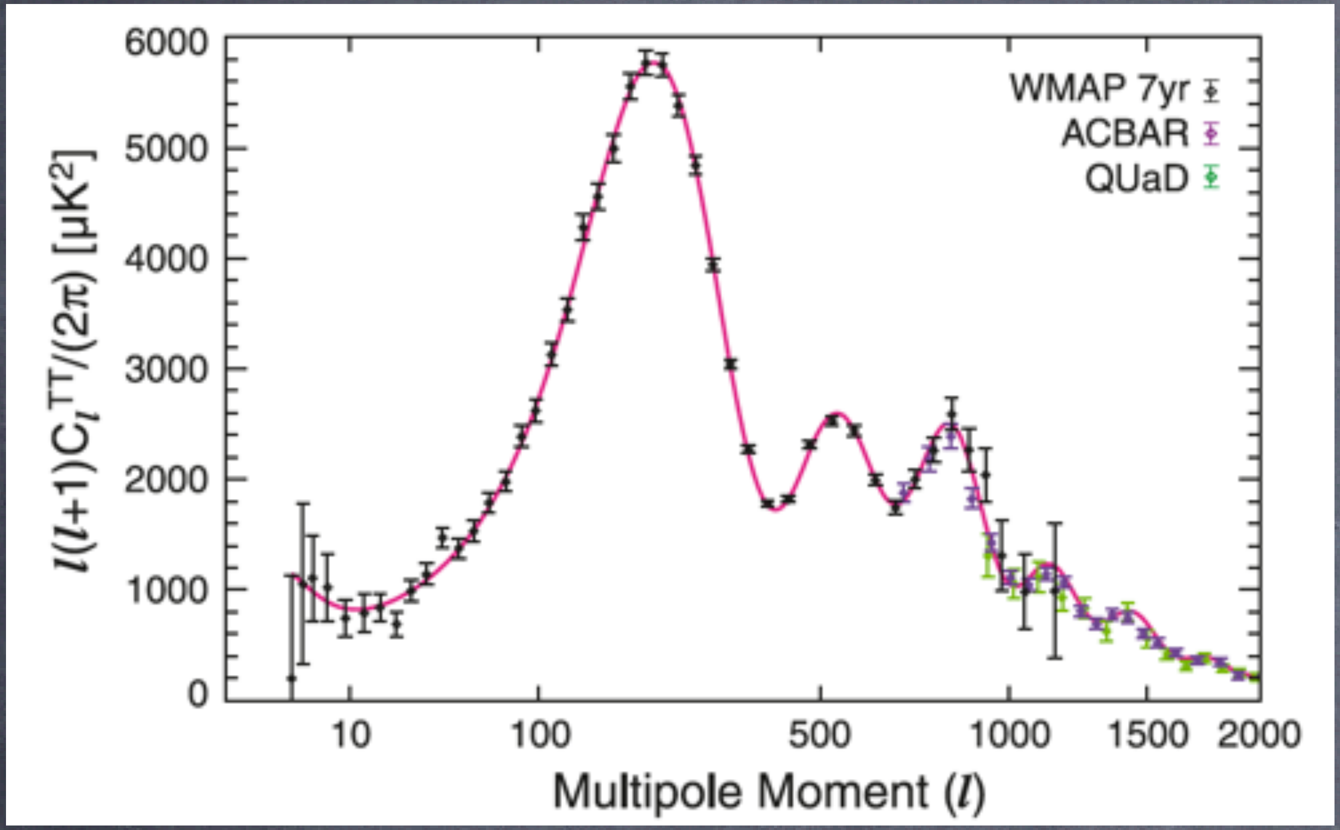

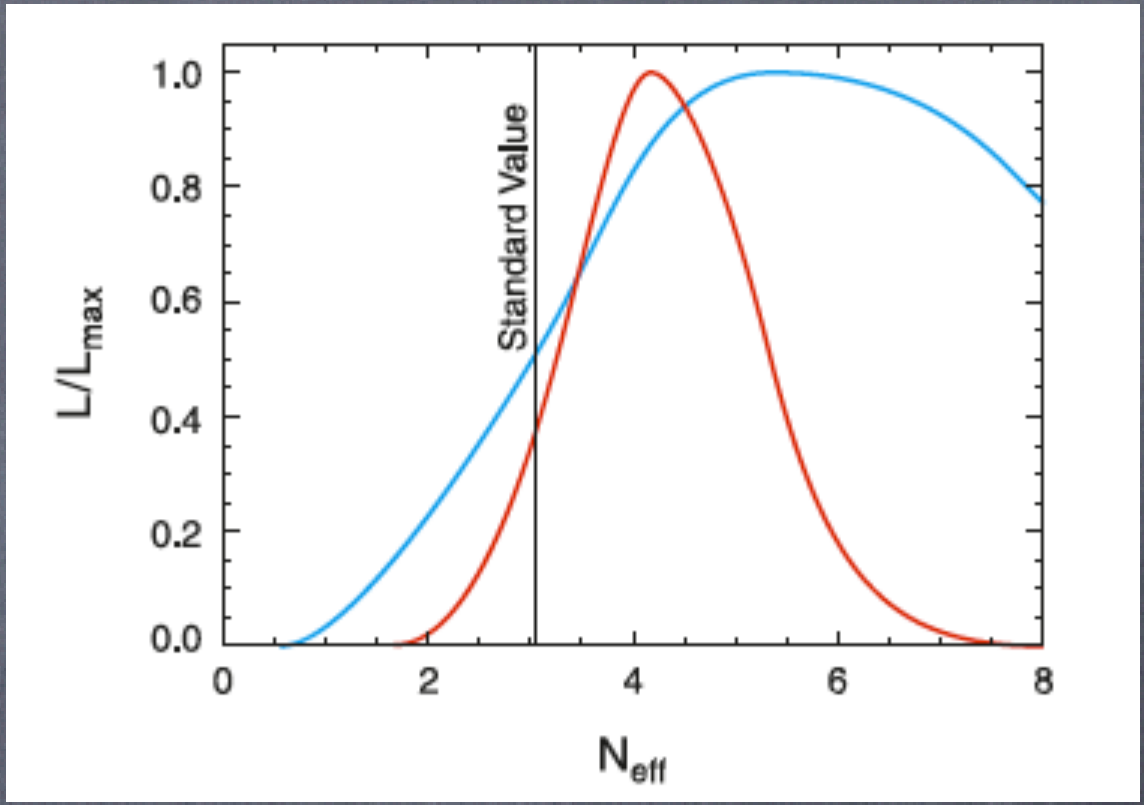

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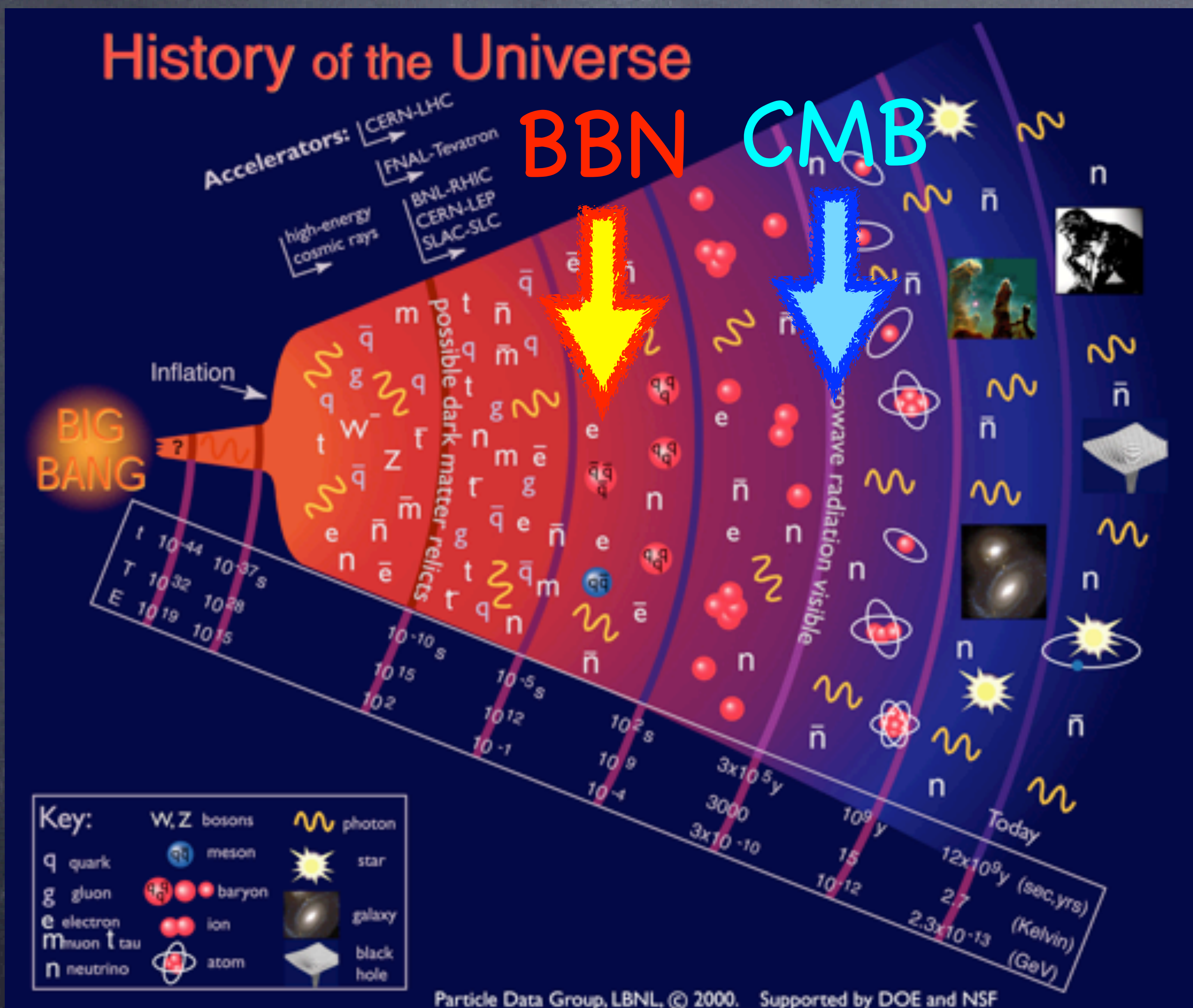
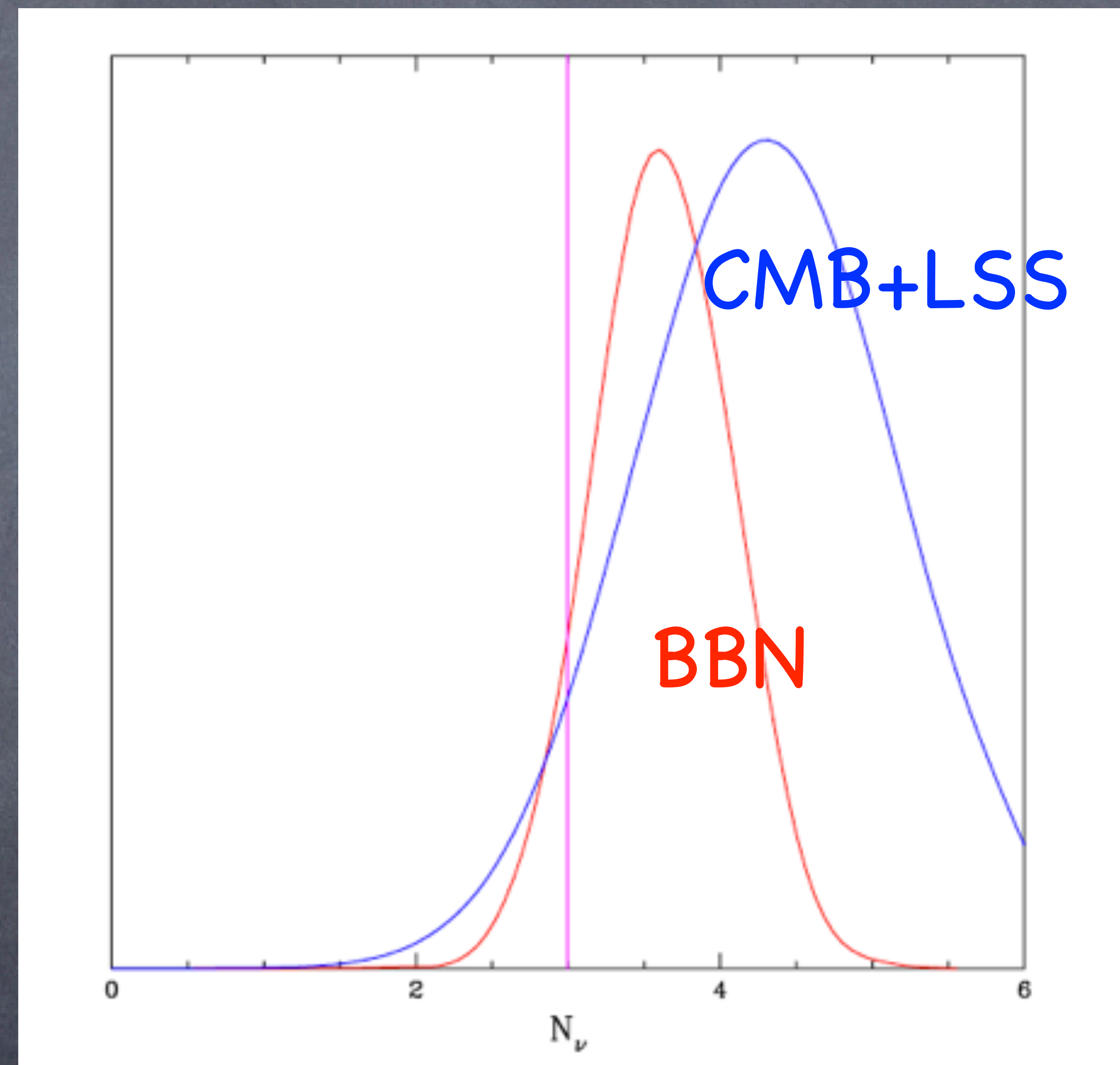
- So, both the helium abundance and CMB/LSS mildly prefer the presence of extra radiation, $\Delta N_{\rm eff} \sim 1$.





(Steigman,1008.4765)

Various possibilities

- Extra radiation: dark radiation or excess in the active neutrinos.
- Modified gravity (e.g. extra dim.)
- Large lepton asymmetry

$$3H^2 M_P^2 = \rho$$

$$n \leftrightarrow p + e^- + \bar{\nu}_e$$
$$n + \nu_e \leftrightarrow p + e^-$$
$$n + e^+ \leftrightarrow p + \bar{\nu}_e$$

- Here we assume that there is indeed extra radiation both at the BBN and CMB epochs, and consider its implications for particle physics.

3. Models

Let us take the observational hint seriously and consider the implications for particle physics.

Assumptions:

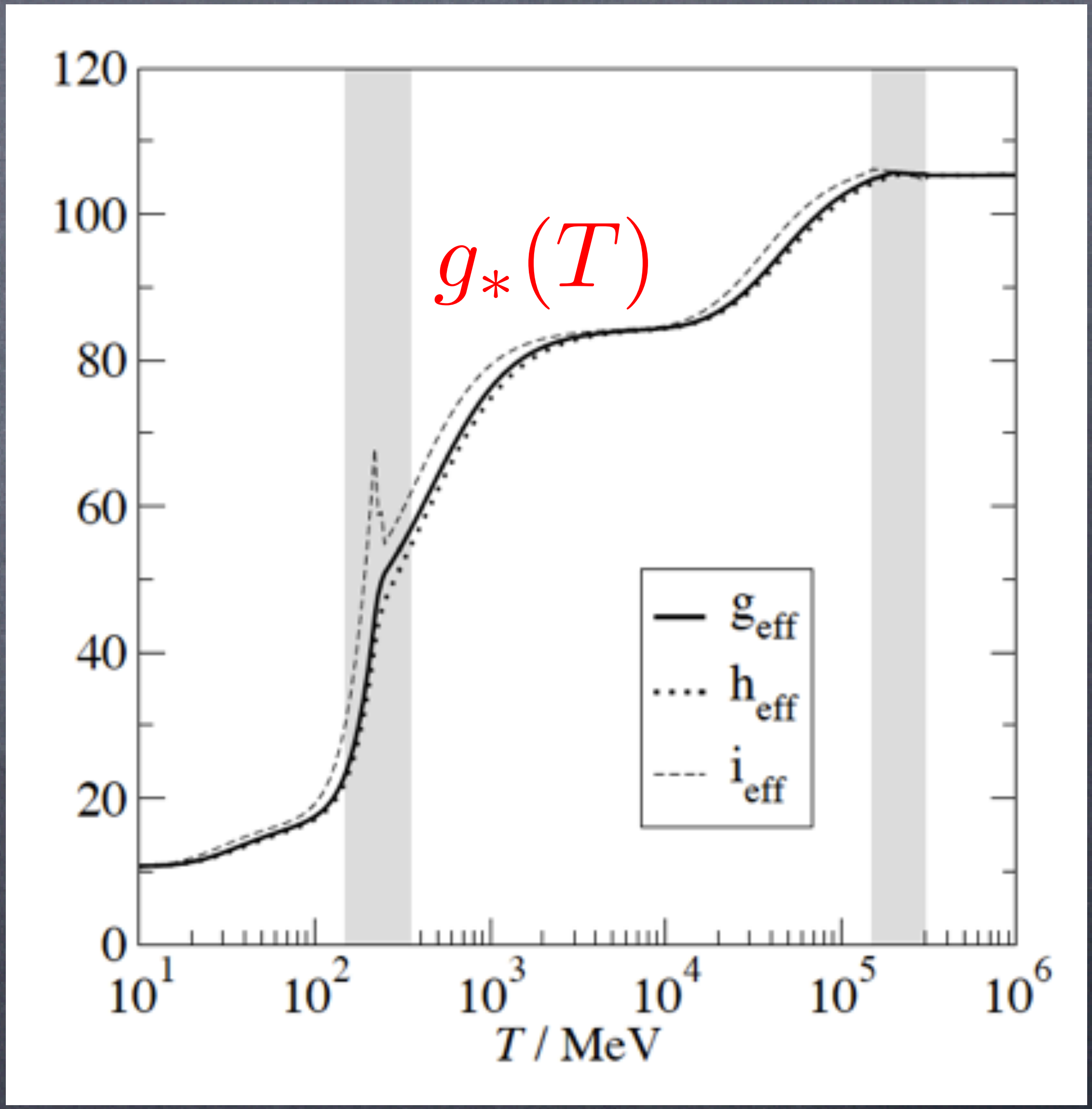
- We assume that the extra radiation is ``dark radiation" made of unknown light and relativistic particles, X_i.
- We also assume that the X_i was once in thermal equilibrium in the early Universe, since some (mild) tuning is necessary to obtain right abundance, otherwise (e.g. non-thermal production).

Light degrees of freedom g_*

$$\Delta N_{\rm eff} = \frac{\rho_X}{\rho_\nu} \sim \left(\frac{T_X}{T_\nu}\right)^4 \sim \left(\frac{g_{*\nu}}{g_{*X}}\right)^{4/3},$$

Broadly speaking, there are 2 cases.

- ~10 particles decoupled (much) before the QCD phase transition.
- one or a few particles that decouple after the QCD phase transition before BBN.



(Laine, Schroeder, `06)

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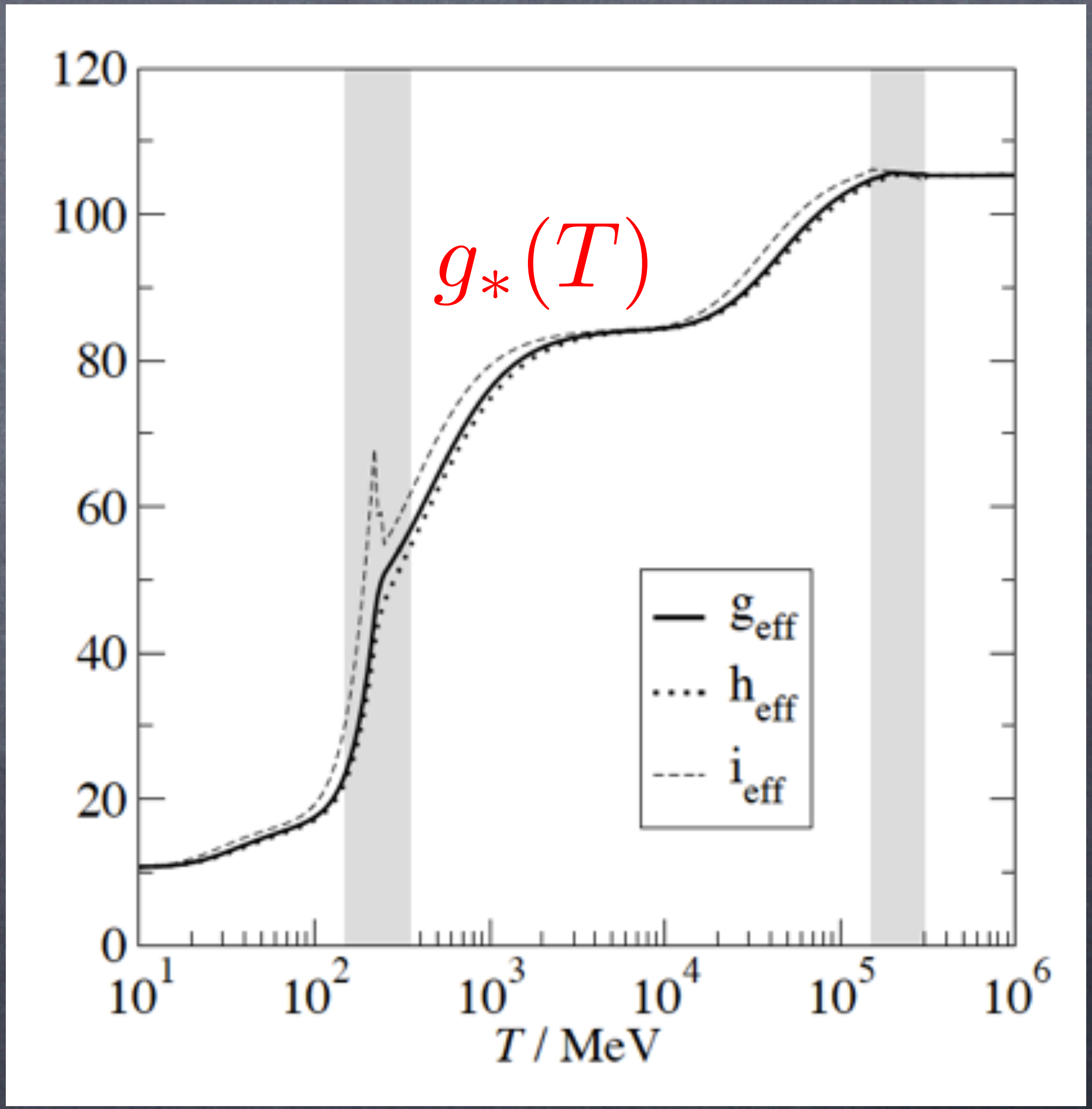

(Laine, Schroeder, `06)

Then the question is why they are so light?

$$m < \mathcal{O}(0.1)\,\mathrm{eV}$$

It is natural to expect that the bare mass is forbidden by symmetry.

1) Gauge symmetry

2) Shift symmetry

3) Chiral symmetry

We consider these cases in turn.

* Here I do not consider the sterile neutrino which mixes with the active neutrinos.

See Melchiorri et al, `08
Hamman et al, `10.

Case 1: Gauge boson

- U(1) hidden photon

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} + \frac{\chi}{2}F_{\mu\nu}B^{\mu\nu} + \frac{1}{2}m_{\gamma'}^2 B_\mu B^\mu,$$

Redefining

$$A'_\mu = (1-\chi^2)^{1/2}A_\mu$$

$$B'_\mu = B_\mu - \chi A_\mu$$

they become canonically normalized, but with a mixing in the mass term:

$$\mathcal{M}^2 = m_{\gamma'}^2 \begin{pmatrix} \chi^2/(1-\chi^2) & \chi/\sqrt{1-\chi^2} \\ \chi/\sqrt{1-\chi^2} & 1 \end{pmatrix}$$

The production rate of the hidden photon is

$$\Gamma(\gamma e \to \gamma' e) \simeq \begin{cases} \chi^2 \left(\frac{m_{\gamma'}}{m_\gamma}\right)^4 \Gamma_{\rm C} & \text{for} \quad m_{\gamma'} \ll m_\gamma \\ \chi^2 \Gamma_{\rm C} & \text{for} \quad m_{\gamma'} \gg m_\gamma \end{cases}$$

where $\Gamma_{\rm C} \sim \alpha_e^2 T$ and $m_{\gamma'} \lesssim 0.1\,{\rm eV}$

The hidden photon is never thermalized before the BBN.

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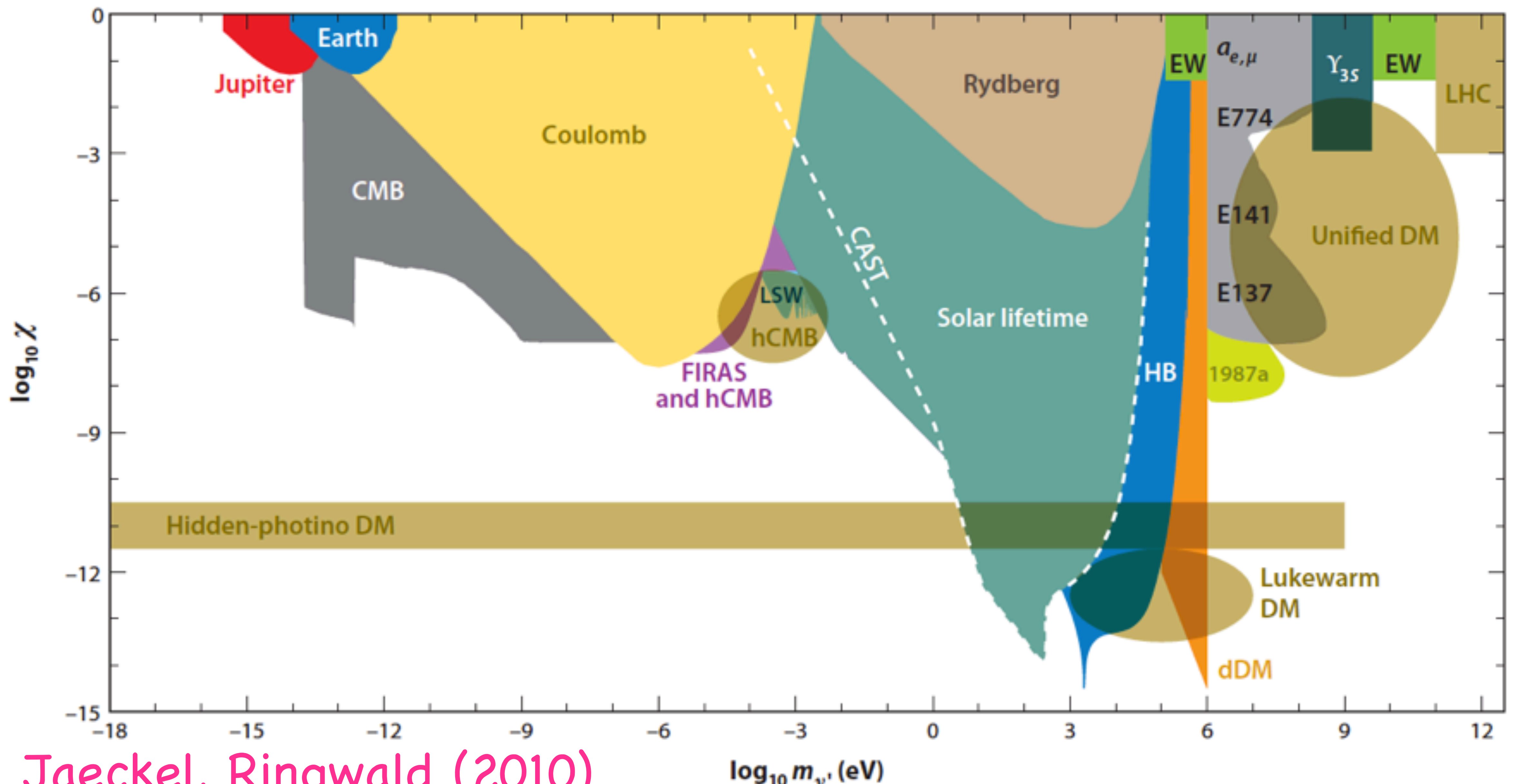

Jaeckel, Ringwald (2010)

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Case 2: Nambu-Goldstone boson

Consider an axion-like particle coupled to the photon:

$$\mathcal{L} = \frac{\alpha_e}{8\pi}\frac{a}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu}.$$

Production rate: $\Gamma(\gamma e \leftrightarrow ae) \sim \langle \sigma v \rangle n_e \sim \frac{\alpha_e^3 T^3}{f_a^2},$

The freeze-out temperature is given by

$$T_f \sim 10\,\mathrm{MeV}\left(\frac{f_a}{10^5\mathrm{GeV}}\right)^2$$

However, the cooling argument using the HB stars gives

$$f_a \gtrsim 10^8\,\mathrm{GeV}$$

Next consider an axion interacting predominantly with the hadrons.

$$\mathcal{L} = \frac{\alpha_s}{8\pi}\frac{a}{f_a}F^a_{\mu\nu}\tilde{F}^{\mu\nu a} + \frac{a}{f_a} i m_q \bar{q}\gamma_5 q.$$

Then, the freeze-out temperature is higher than O(10) MeV, if

$$f_a \gtrsim 10^4\,\mathrm{GeV}$$

The hadronic axion window is

$$3\times 10^5\,\mathrm{GeV} \lesssim f_a \lesssim 2\times 10^6\,\mathrm{GeV}$$

$$3\,\mathrm{eV} \lesssim m_a \lesssim 20\,\mathrm{eV}$$

Axion HDM

However, the window was closed by the recent analysis.

Hannestad, Mirizzi, Raffelt, hep-ph/0504059
Hannestad, Mirizzi, Raffelt, Wong, 1004.0695

Case 3: Chiral fermion

Consider a chiral fermion ψ charged under a new U(1) gauge symmetry, which forbids the mass.

$$\mathcal{L}_{\rm int} = i g_{A\psi\psi} A_H^\mu \bar{\psi}\gamma_\mu \psi + i g_{A\psi\psi} A_H^\mu \bar{f}\gamma_\mu f$$

f : SM fermions

Assuming that the U(1) is spontaneously broken, we have

$$\mathcal{L}_{\rm eff} = \frac{1}{\Lambda^2}(\bar{f}\gamma^\mu f)(\bar{\psi}\gamma_\mu \psi),$$

in the low energy.

$$\Lambda^2 = m_A^2 g_{A\psi\psi}^{-1} g_{Aff}^{-1}$$

Using the production rate,

$$\Gamma(e^+e^- \leftrightarrow \psi\psi) \sim \langle \sigma v \rangle n_e \sim \frac{T^5}{\Lambda^4},$$

the freeze-out temperature is given by

$$T_f \sim 100\,\mathrm{MeV}\left(\frac{\Lambda}{6\,\mathrm{TeV}}\right)^{4/3}$$

The star cooling const. can be evaded because the fermion is much more weakly coupled than neutrinos.

The SN limit reads $\Lambda \gtrsim 6\,\mathrm{TeV}$

There is a slight dilution of a factor (2-3), and so a few fermions are needed to realize $\Delta N \sim 1$

Implications

A chiral fermion coupled to the SM fermions with interactions suppressed by TeV scale is a viable candidate for extra rad.

- We need a new gauge symmetry broken at TeV scale.
- A new heavy gauge boson may be produced at the LHC. The strategy is same as the Z' boson search.
  - ✓ With 10 fb^{-1}, 3TeV Z' can be discovered at LHC.

Example of a new U(1)

One candidate is $U(1)_{B-L}$, which naturally appears in the SO(10) GUT. However it should be broken at a high scale to explain the nu mass thru the seesaw mechanism.

We therefore consider

$$SU(5) \times U(1)_\psi \times U(1)_\chi$$

inspired by the E_6-GUT.

$$E_6 \to SO(10) \times U(1)_\psi$$

$$SO(10) \to SU(5) \times U(1)_\chi$$

Matter content

$$\mathbf{27} = \mathbf{16}_1 + \mathbf{10}_{-2} + \mathbf{1}_4$$

$$\mathbf{16} = \mathbf{10} + \bar{\mathbf{5}} + \mathbf{1}$$

$$\mathbf{10} = \mathbf{5} + \bar{\mathbf{5}}$$

	$SO(10) \times U(1)_\psi$	$SU(5) \times U(1)_\psi \times U(1)_\chi$	
Fermion	$\Psi_{\mathbf{16}}(1)$	$\psi^{(\mathrm{SM})}_{\mathbf{10}}(1,1)$ $\psi^{(\mathrm{SM})}_{\bar{\mathbf{5}}}(1,-3)$ $\psi^{(\mathrm{SM})}_{\mathbf{1}}(1,5) = \nu_{\mathrm{R}}$	
	$\Psi_{\mathbf{10}}(-2)$	$\psi^{(10)}_{\mathbf{5}}(-2,-2)$ $\psi^{(10)}_{\bar{\mathbf{5}}}(-2,2)$	
	$\Psi_{\mathbf{1}}(4)$	$\psi_{\mathbf{1}}(4,0)$	→ Dark rad.
Boson	$\Phi_{\mathbf{16}}(1)$	$\phi^{(16)}_{\mathbf{10}}(1,1)$ $\phi^{(16)}_{\bar{\mathbf{5}}}(1,-3)$ $\phi^{(16)}_{\mathbf{1}}(1,5)$	
	$\Phi_{\mathbf{10}}(-2)$	$\phi_{\mathbf{5}}(-2,-2) \supset$ SM Higgs $\phi_{\bar{\mathbf{5}}}(-2,2) \supset$ SM Higgs	
	$\Phi_{\mathbf{1}}(4)$	$\phi_{\mathbf{1}}(4,0) = \phi_X$	→ Breaks U(1)

The right-handed neutrino acquires a mass from

$$\Phi_{\overline{\mathbf{126}}}\Psi_{\mathbf{16}}\Psi_{\mathbf{16}}$$

if the singlet component of $\Phi_{\overline{\mathbf{126}}}$ develops a vev.

The vev leaves the following U(1) unbroken:

$$U(1)_X \equiv 5U(1)_\psi - U(1)_\chi$$

$SO(10) \times U(1)_\psi$	$SU(5) \times U(1)_\psi \times U(1)_\chi$
$\Psi_{\mathbf{16}}(1)$	$\psi_{\mathbf{10}}^{(\mathrm{SM})}(1,1)$ $\psi_{\bar{\mathbf{5}}}^{(\mathrm{SM})}(1,-3)$ $\psi_{\mathbf{1}}^{(\mathrm{SM})}(1,5) = \nu_{\mathrm{R}}$
$\Psi_{\mathbf{10}}(-2)$	$\psi_{\mathbf{5}}^{(10)}(-2,-2)$ $\psi_{\bar{\mathbf{5}}}^{(10)}(-2,2)$
$\Psi_{\mathbf{1}}(4)$	$\psi_{\mathbf{1}}(4,0)$

The ψ_1 remains massless if $U(1)_X$ is unbroken.

Assuming that $U(1)_X$ is broken by $\langle\phi_X\rangle = \xi$,
ψ_1 acquires a mass from

$$\mathcal{L} = \frac{\phi_X^* \phi_X^* \psi_{\mathbf{1}} \psi_{\mathbf{1}}}{M} + \mathrm{h.c.},$$

The mass m is given by

$$m \sim \frac{\xi^2}{M} \sim 10^{-3}\,\mathrm{eV},$$

for $\xi = 1\,\mathrm{TeV}$ and $M = M_P$

Comments

If there is ψ_1 in each generation, we would have $\Delta N_{\rm eff} = 3$. $\Delta N_{\rm eff} = 1$ can be achieved by slightly increasing ξ.

The colored fermion $\Psi_{\bf 10}^{\rm (color)}$ is long-lived. Cosmological problem can be avoided if

1. Low reheating
2. Mix with SM quarks via $Z_{2(B-L)}$ breaking
3. SUSY

Conclusions

- If there is indeed extra radiation $\Delta N_{\rm eff} \sim 1$ as suggested by the recent observation, a chiral fermion is a plausible candidate.
- Interestingly the U(1) gauge boson should be at TeV scale, and may be within the reach of collider experiments such as the LHC (Z-prime search)
- One example for such a light chiral fermion is a SU(5) singlet fermion Ψ_1 in the **27** rep. of E_6.