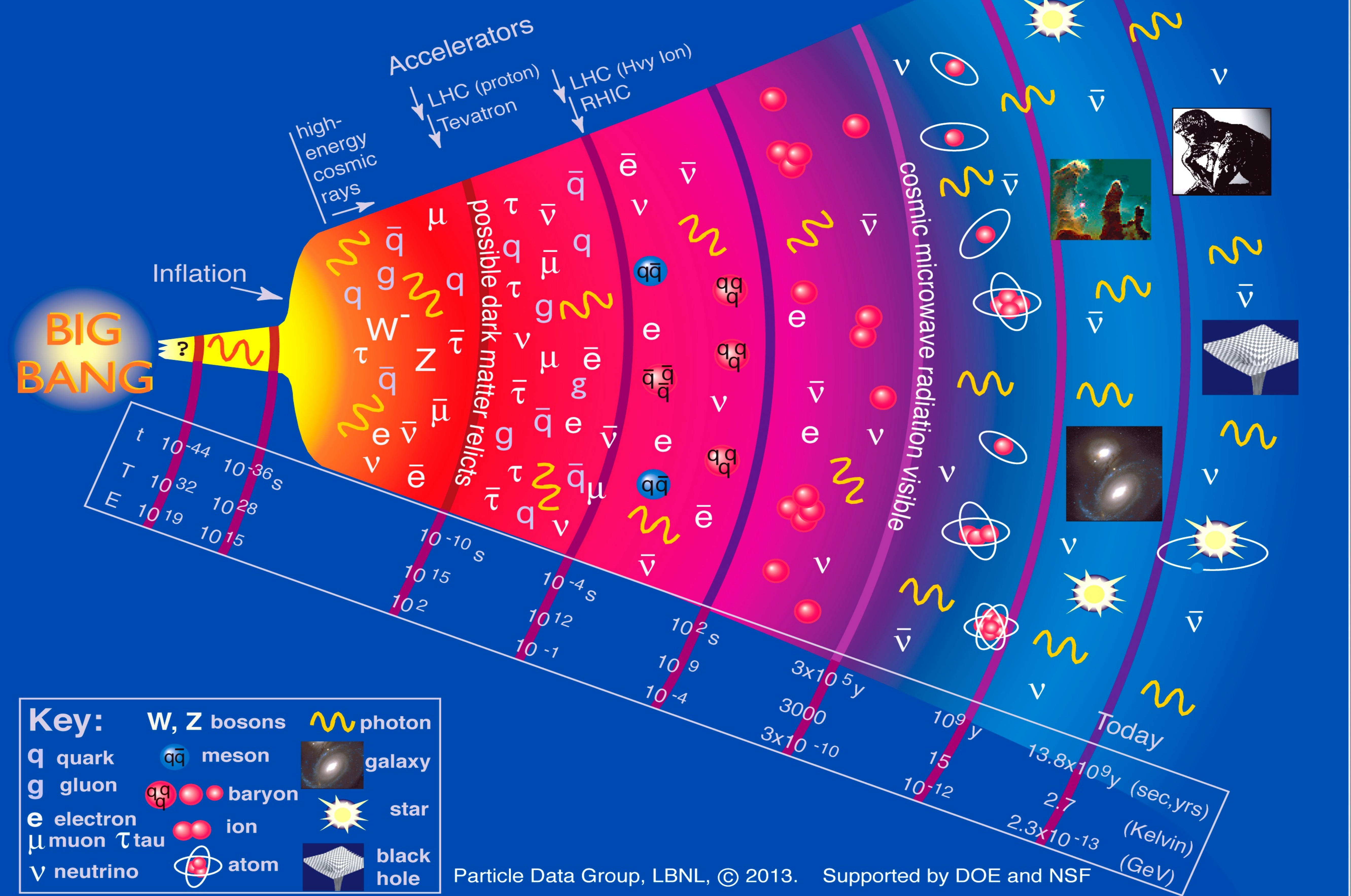
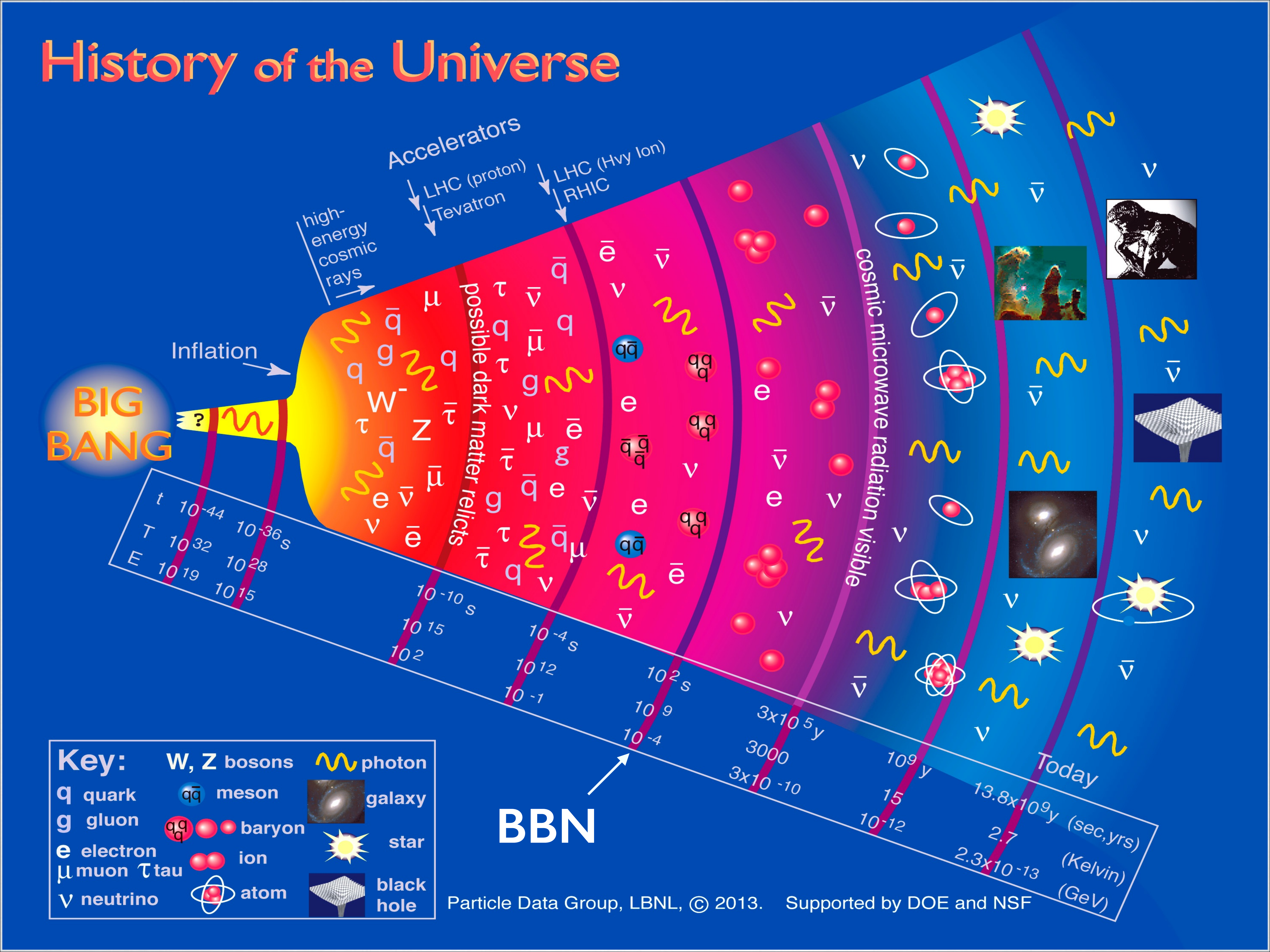
COSMOLOGICAL CONSTRAINTS ON BOSE-EINSTEIN-CONDENSED SCALAR FIELD DARK MATTER

Bohua Li
Department of Astronomy, the University of Texas at Austin
Texas Symposium, Dec 11th, 2013

(with Dr. Tanja Rindler-Daller and Dr. Paul Shapiro)
arXiv: 1310.6061, submitted to PRD

History of the Universe




History of the Universe
BIG BANG
Inflation
high-energy cosmic rays
Accelerators
LHC (proton)
Tevatron
LHC (Hvy Ion)
RHIC
possible dark matter relicts
cosmic microwave radiation visible
t 10^{-44} 10^{-36} s
T 10^{32} 10^{28}
E 10^{19} 10^{15}
10^{-10} s
10^{15}
10^{2}
10^{-4} s
10^{12}
10^{-1}
10^{2} s
10^{9}
10^{-4}
$3x10^{5}$ y
3000
$3x10^{-10}$
10^{9} y
15
10^{-12}
Today
$13.8x10^{9}$ y (sec,yrs)
2.7 (Kelvin)
$2.3x10^{-13}$ (GeV)
BBN
Key:
q quark
g gluon
e electron
μ muon τ tau
ν neutrino
W, Z bosons
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baryon
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photon
galaxy
star
black hole
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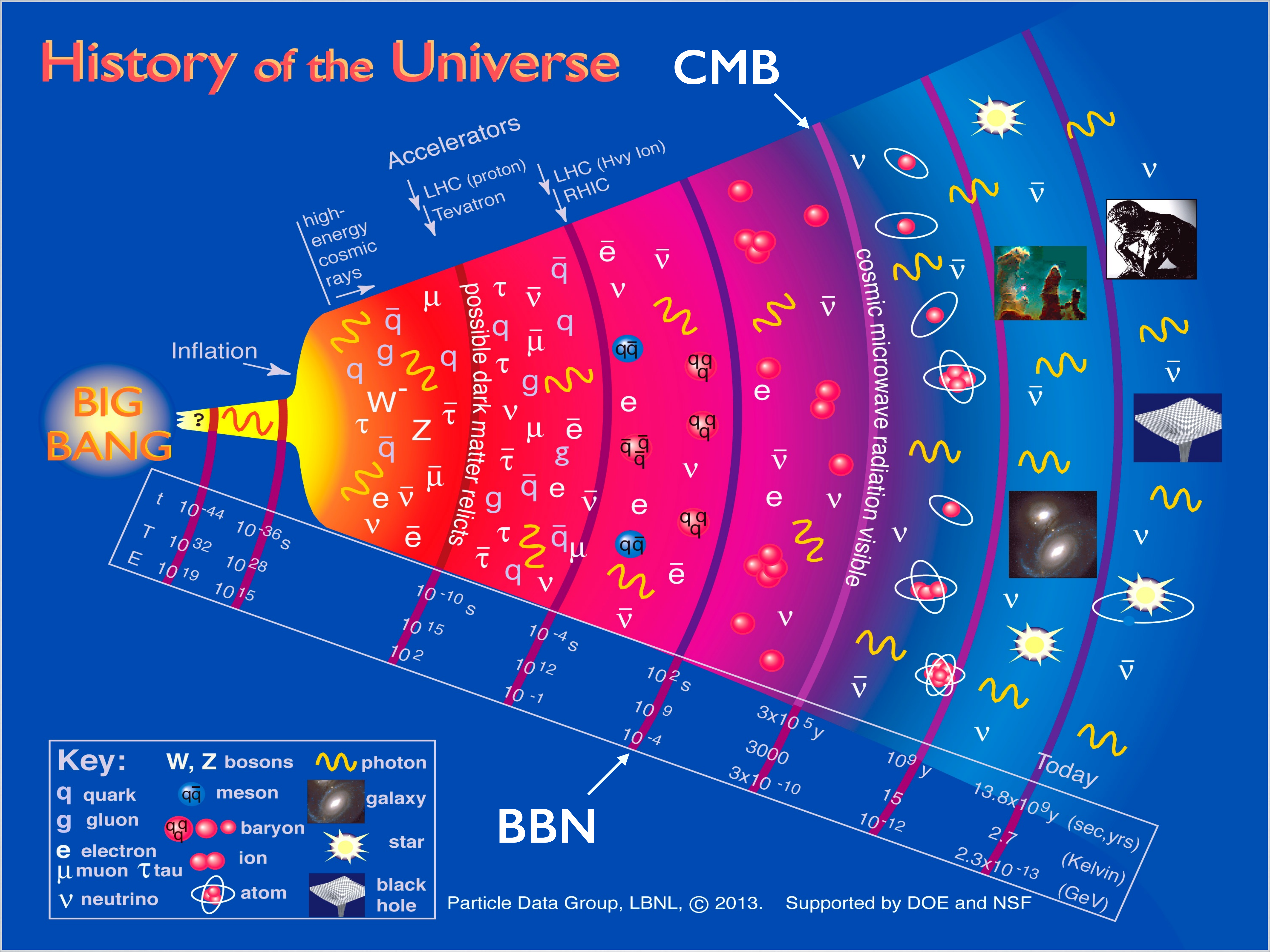

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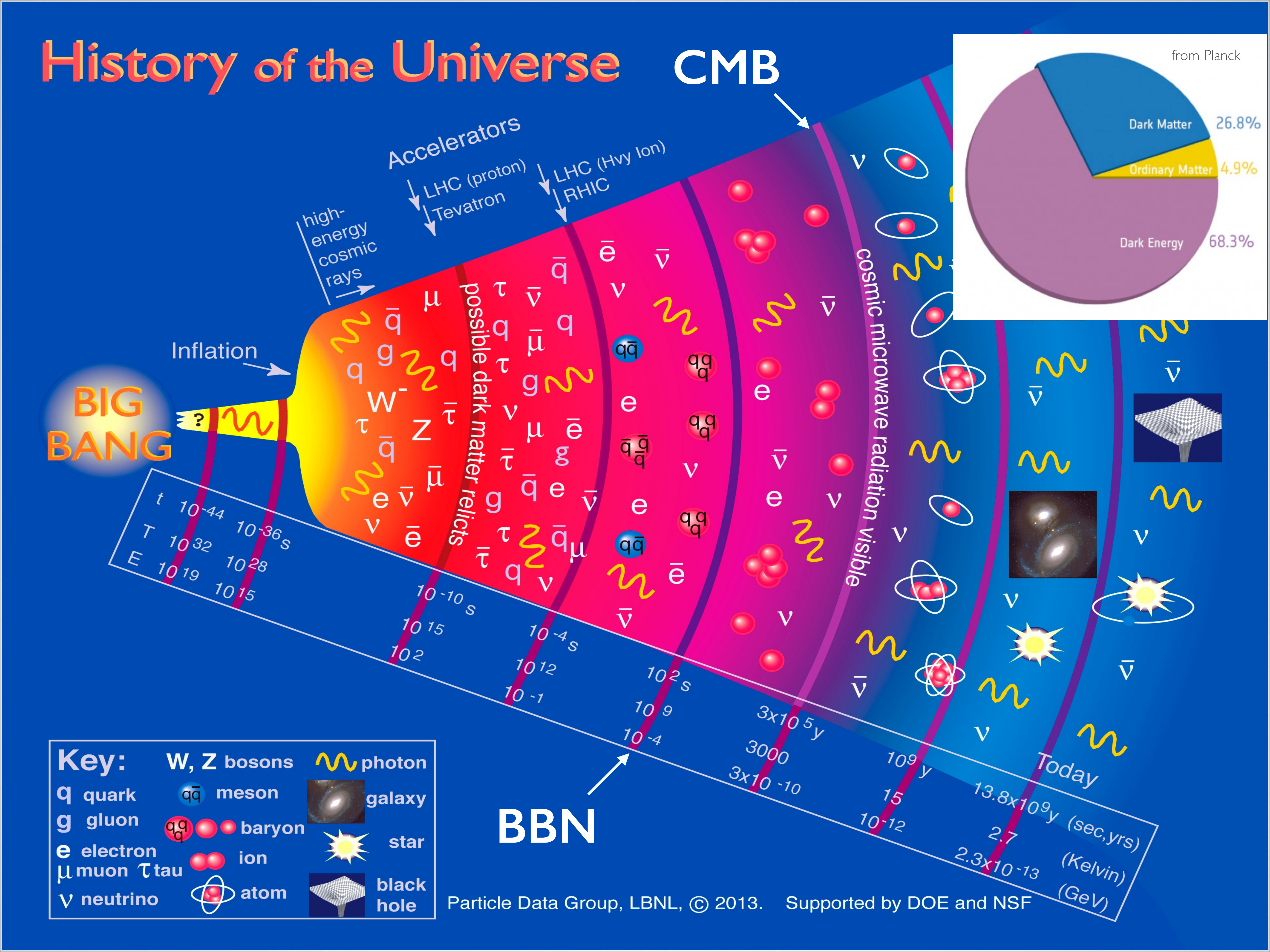
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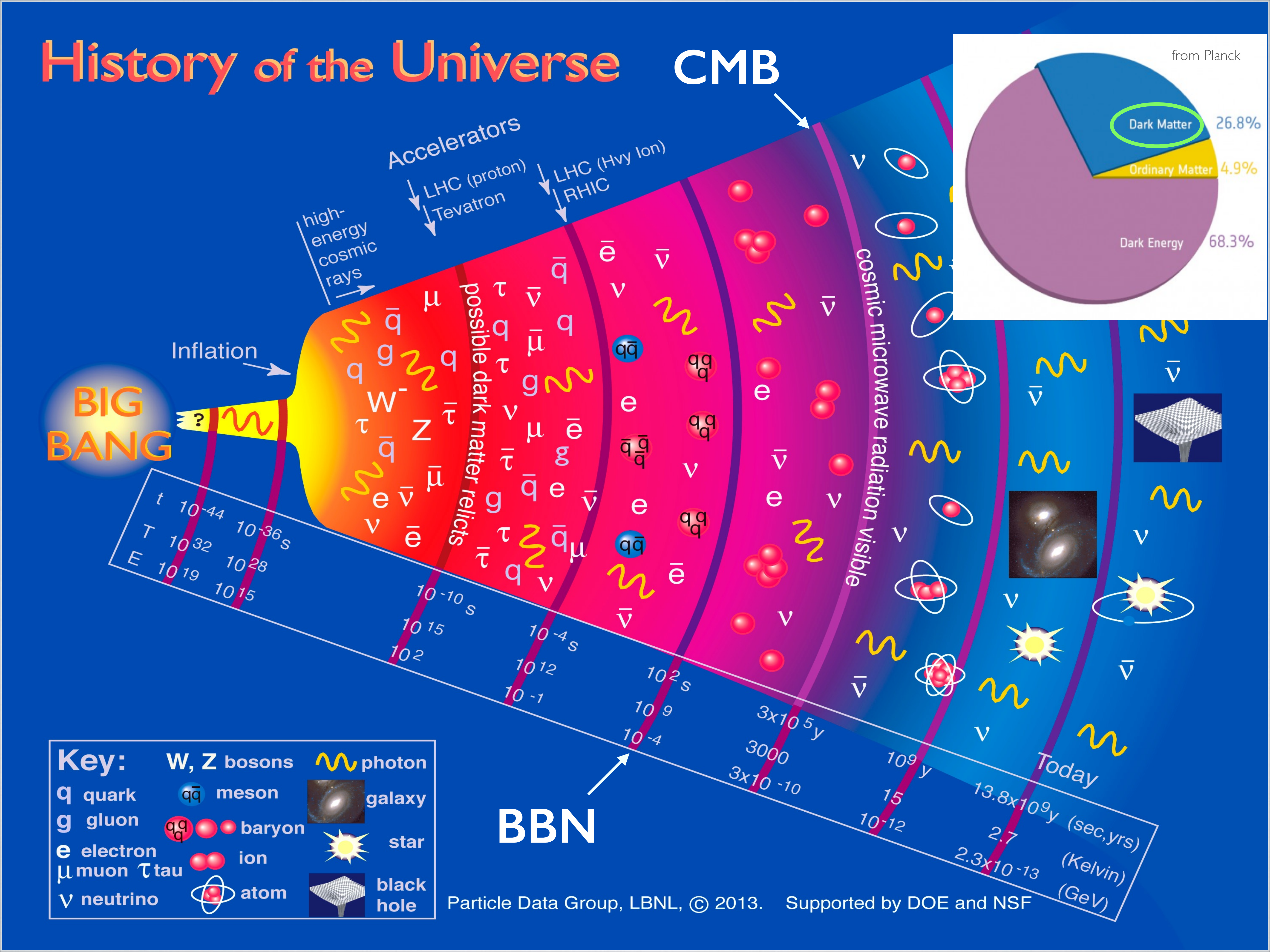

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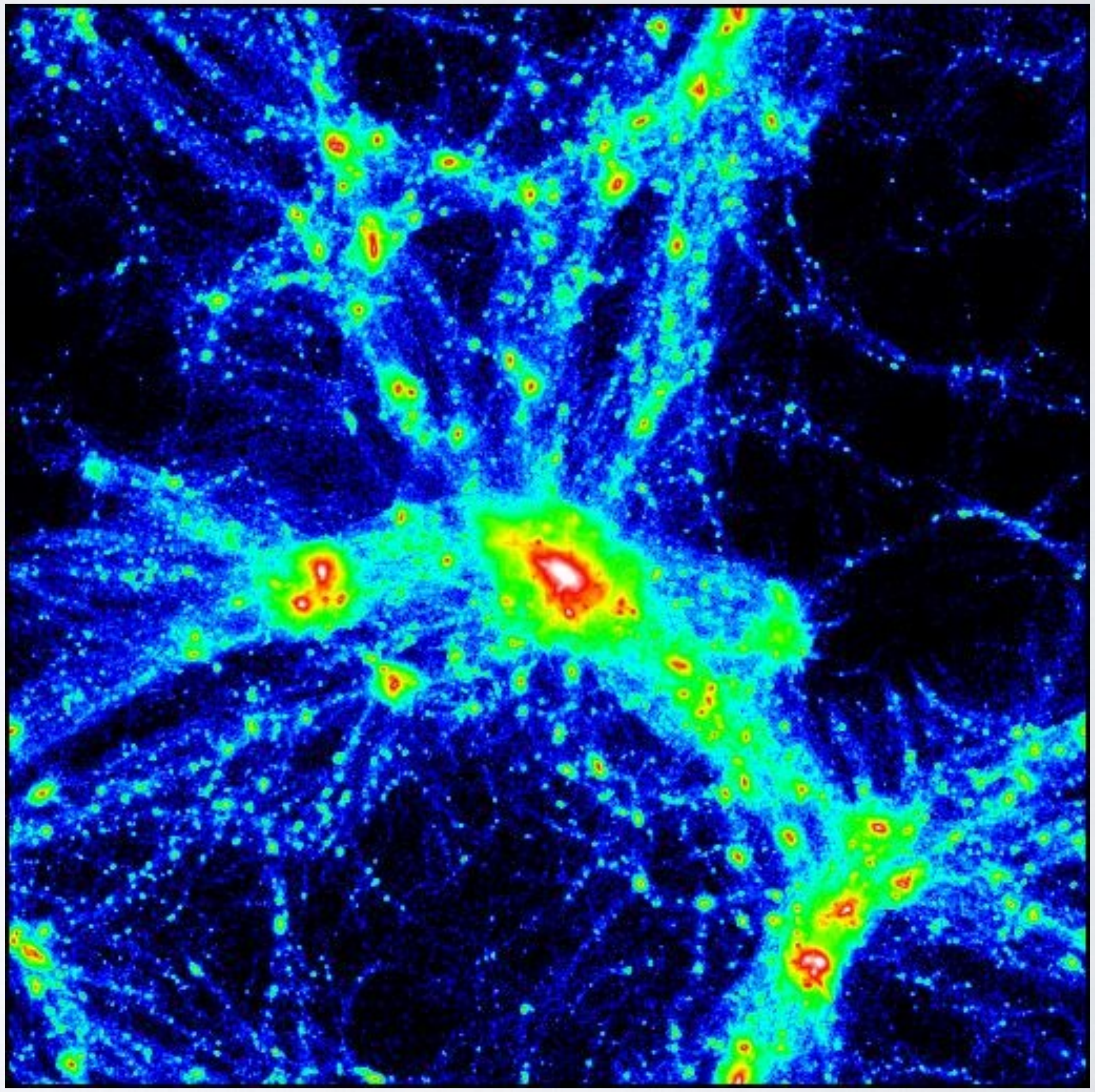
COLD DARK MATTER

- Non-relativistic, pressureless
- Form structure gravitationally
- Beyond Standard Model of particle physics



COLD DARK MATTER

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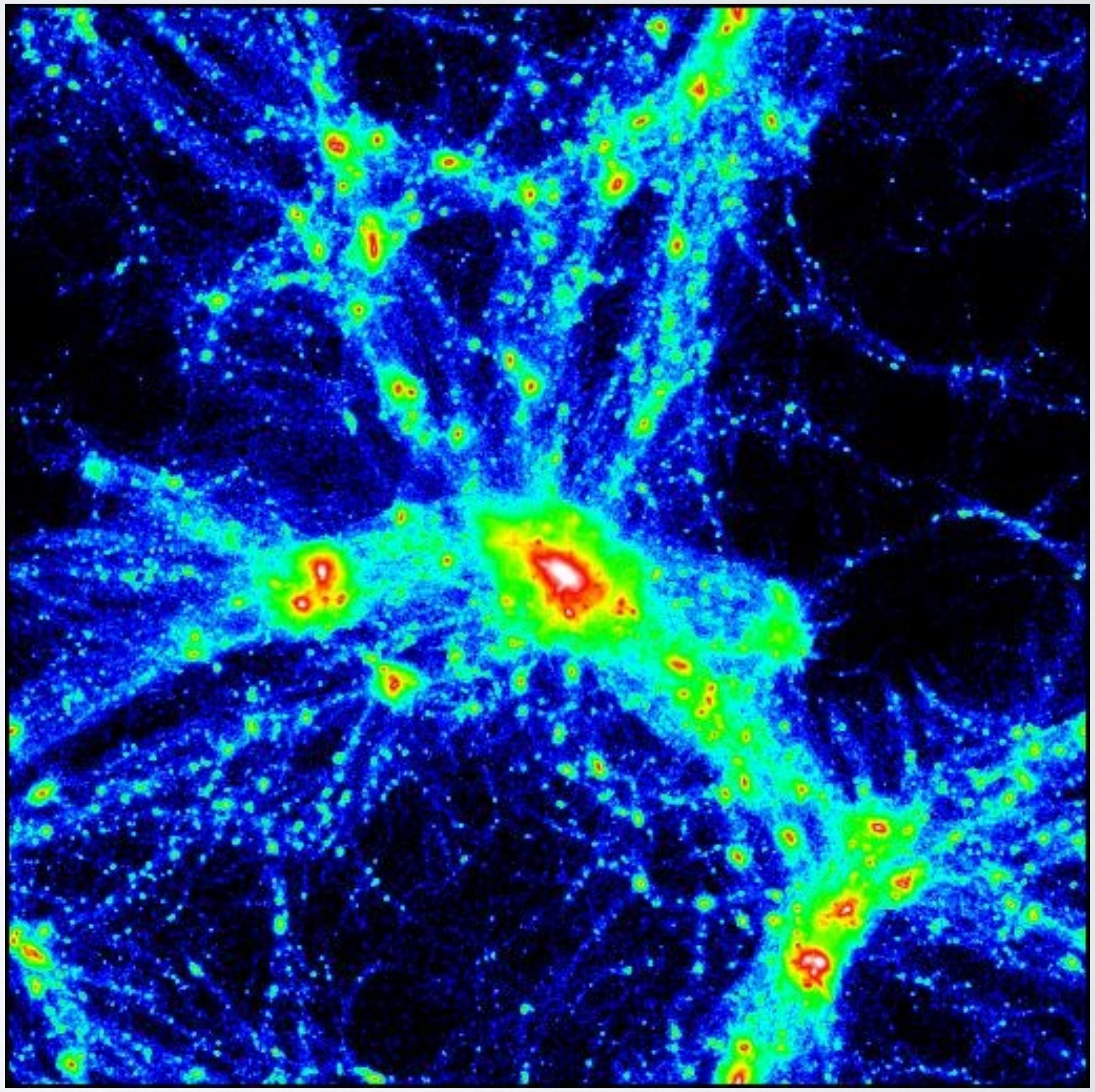
- Candidates:
    - Weakly-interacting massive particles (WIMPs)
    - QCD Axions
    - Condensed ultralight bosons



No positive detections yet from various experiments

COLD DARK MATTER

- Non-relativistic, pressureless
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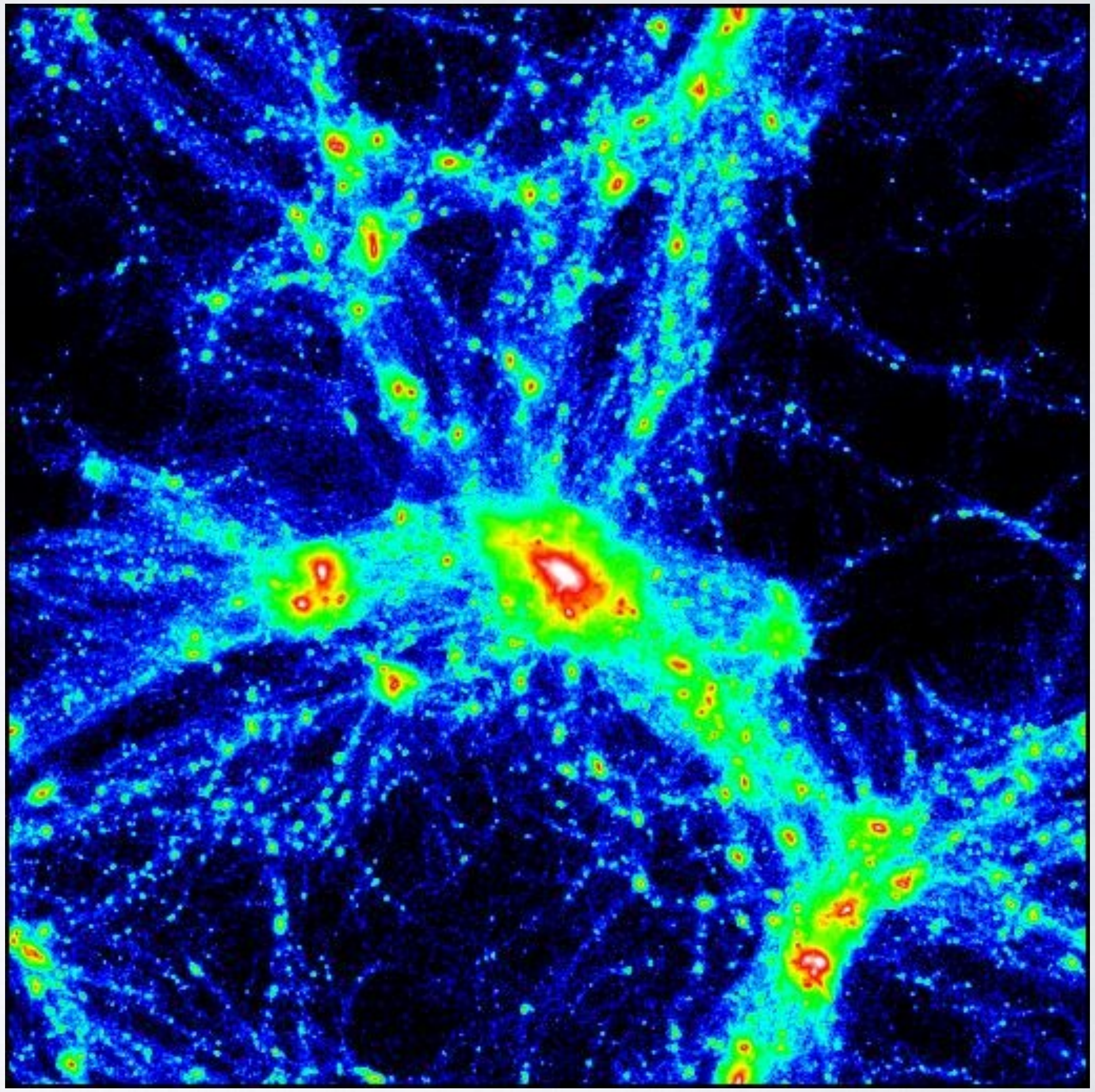
- Beyond Standard Model of particle physics
- Candidates:
  - Weakly-interacting massive particles (WIMPs)
  - QCD Axions
  - Condensed ultralight bosons, described by coherent classical scalar field



BEC SCALAR FIELD DARK MATTER

- Early works
  - Peebles (2000), ApJ Letters, 534, L127
  - Goodman (2000), New Astronomy, 5, 103
  - Hu, Barkana & Gruzinov (2000), Physical Review Letters, 85, 1158

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- Particle origin of spin-0 ultralight bosons
  - String axions

    Arvanitaki et al. (2010), Physical Review D, 81, 123530
  - Gravitationally produced by inflation

    Peebles & Vilenkin (1999), Physical Review D, 60, 103506
  - Gravitational exciton from multidimensional cosmological models

    Günther, Starobinsky & Zhuk et al. (2004), Physical Review D, 69, 044003
  - etc.

BEC SCALAR FIELD DARK MATTER

- Complex scalar field
  - Conserved charge Q due to U(1) symmetry
  - Asymmetric dark matter
  - Richer structure dynamics, e.g., vortex

    Rindler-Daller & Shapiro (2012), MNRAS, 422, 135

$$Q \equiv n - \bar{n}$$

n : number density of bosons

$\bar{n}$: number density of anti-bosons

At later times $Q \approx n$ because anti-bosons are annihilated away

BEC SCALAR FIELD DARK MATTER

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- Tiny mass
  - $m > 10^{-33}\,\mathrm{eV} \sim H_0$

    ↑ required since SFDM should be cold at present

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- Bose-Einstein Condensate if initially $mQ / S \gg 1$

Haber & Weldon (1982), Physical Review D, 25, 502

S : entropy density

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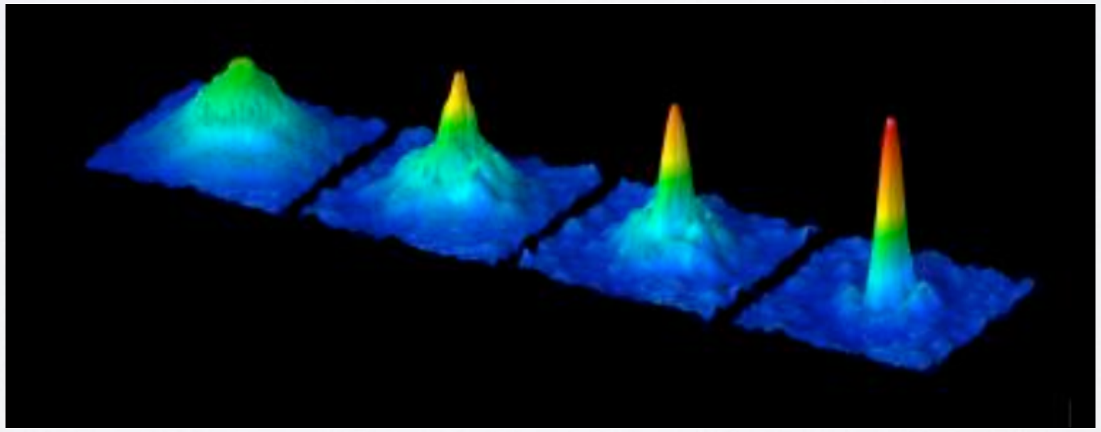

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BEC SCALAR FIELD DARK MATTER

- Formalism from Largrangian

$$\mathscr{L} = \frac{\hbar^2}{2m} g^{\mu\nu} \partial_\mu \psi^* \partial_\nu \psi - V(\psi).$$

$$V(\psi) = \frac{1}{2} m c^2 |\psi|^2 + \frac{\lambda}{2} |\psi|^4.$$

- in SI units, $[\lambda] = \mathrm{eV\ cm^3}$
- Fiducial model:

$$\lambda / (mc^2)^2 = 2 \times 10^{-18}\ \mathrm{eV^{-1} cm^3}$$

$$m = 3 \times 10^{-21}\ \mathrm{eV} / c^2$$

⇐ $\lambda = 1.8 \times 10^{-59}\ \mathrm{eV\ cm^3}$
or dimensionless value
$\hat{\lambda} \sim 10^{-80}$

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Why these values?

Small-scale controversies of collisionless CDM

- Cusp/core problem: *too steep a central density profile of dark matter halos*
- Missing satellites problem: *too many substructures predicted*
- 'Too big to fail': *biggest subhalos have too high circular velocities to hold classical MW satellites*
- etc.

BEC SCALAR FIELD DARK MATTER

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Potentially resolvable through SFDM

SFDM provides minimum clustering scales
- de Broglie wave length l_{deB}
- self-interaction Jeans length $l_{\text{SI}} \propto \sqrt{\lambda / (mc^2)^2}$

HOMOGENEOUS ΛSFDM UNIVERSE

- FRW metric $$ds^2 = c^2 dt^2 - a^2(t)(dx^2 + dy^2 + dz^2)$$

- Friedmann equation

$$H^2(t) \equiv \left(\frac{\mathrm{d}a/\mathrm{d}t}{a}\right)^2 = \frac{8\pi G}{3c^2}\left[\bar{\rho}_r(t) + \bar{\rho}_b(t) + \bar{\rho}_\Lambda(t) + \bar{\rho}_{\mathrm{SFDM}}(t)\right],$$

Radiation: $\bar{\rho}_r = \bar{\rho}_{r,0}/a^4$
(photons+3 SM neutrinos)
Baryons: $\bar{\rho}_b = \bar{\rho}_{b,0}/a^3$
Cosmological constant: $\bar{\rho}_\Lambda = \bar{\rho}_{\Lambda,0}$

present-day cosmological parameters from Planck

Basic		Derived	
h	0.673	$\Omega_m h^2$	0.14187
$\Omega_b h^2$	0.02207	$\Omega_r h^2$	4.184×10^{-5}
$\Omega_c h^2$	0.1198	z_{eq}	3390
$T_{\mathrm{CMB}}/\mathrm{K}$	2.7255	Ω_Λ	0.687

EVOLUTION OF HOMOGENEOUS SFDM

- Ideal fluid

$$\bar{\rho} = T^0{}_0 = \frac{\hbar^2}{2mc^2}|\partial_t\psi|^2 + \frac{1}{2}mc^2|\psi|^2 + \frac{1}{2}\lambda|\psi|^4,$$
$$\bar{p} = -T^i{}_i = \frac{\hbar^2}{2mc^2}|\partial_t\psi|^2 - \frac{1}{2}mc^2|\psi|^2 - \frac{1}{2}\lambda|\psi|^4.$$

- Klein-Gordon equation

$$\frac{\hbar^2}{2mc^2}\partial_t^2\psi + \frac{\hbar^2}{2mc^2}\frac{3\mathrm{d}a/\mathrm{d}t}{a}\partial_t\psi + \frac{1}{2}mc^2\psi + \lambda|\psi|^2\psi = 0$$

SFDM EVOLUTIONARY PHASES

- Fast-oscillation regime ($\omega / H \gg 1$)

Define: $\psi = |\psi| e^{i\theta}$

$\omega \equiv \partial_t \theta$

SFDM EVOLUTIONARY PHASES

- Fast-oscillation regime $(\omega / H \gg 1)$

  - temporal averaging approximation

Define: $\psi = |\psi| e^{i\theta}$ $\omega \equiv \partial_t \theta$

Turner (1983), Physical Review D, 28, 1243
Peebles & Vilenkin (1999), Physical Review D, 60, 103506

$$\langle \bar{\rho} \rangle = mc^2 \langle |\psi|^2 \rangle + \frac{3}{2} \lambda \langle |\psi|^4 \rangle$$
$$\approx mc^2 \langle |\psi|^2 \rangle + \frac{3}{2} \lambda \langle |\psi|^2 \rangle^2,$$
$$\langle \bar{p} \rangle = \frac{1}{2} \lambda \langle |\psi|^4 \rangle \approx \frac{1}{2} \lambda \langle |\psi|^2 \rangle^2.$$

-Equation of state

$$\langle \bar{p} \rangle = \frac{m^2 c^4}{18\lambda} \left(\sqrt{1 + \frac{6\lambda \langle \bar{\rho} \rangle}{m^2 c^4}} - 1 \right)^2$$

or

$$\langle \bar{w} \rangle \equiv \frac{\langle \bar{p} \rangle}{\langle \bar{\rho} \rangle} = \frac{1}{3} \left[\frac{1}{1 + \frac{2mc^2}{3\lambda \langle |\psi|^2 \rangle}} \right]$$

Colpi, Shapiro & Wasserman (1986), Physical Review Letters, 57, 2485
Matos & Arturo Ureña-López (2001), Physical Review D, 63, 063506

SFDM EVOLUTIONARY PHASES

- Fast-oscillation regime $\left(\omega / H \gg 1\right)$

$$\langle\bar{\rho}\rangle = mc^2\langle|\psi|^2\rangle + \frac{3}{2}\lambda\langle|\psi|^4\rangle$$
$$\approx mc^2\langle|\psi|^2\rangle + \frac{3}{2}\lambda\langle|\psi|^2\rangle^2,$$
$$\langle\bar{p}\rangle = \frac{1}{2}\lambda\langle|\psi|^4\rangle \approx \frac{1}{2}\lambda\langle|\psi|^2\rangle^2.$$

- CDM-like phase: non-relativistic

$$\tfrac{3}{2}\lambda\langle|\psi|^2\rangle^2 \ll mc^2\langle|\psi|^2\rangle$$

$$\left\langle\overline{w}\right\rangle \equiv \left\langle\overline{p}\right\rangle / \left\langle\overline{\rho}\right\rangle = 0 \qquad \left\langle\overline{\rho}\right\rangle \propto a^{-3}$$

SFDM EVOLUTIONARY PHASES

- Fast-oscillation regime $(\omega / H \gg 1)$

$$\langle\bar{\rho}\rangle = mc^2\langle|\psi|^2\rangle + \frac{3}{2}\lambda\langle|\psi|^4\rangle \approx mc^2\langle|\psi|^2\rangle + \frac{3}{2}\lambda\langle|\psi|^2\rangle^2,$$

$$\langle\bar{p}\rangle = \frac{1}{2}\lambda\langle|\psi|^4\rangle \approx \frac{1}{2}\lambda\langle|\psi|^2\rangle^2.$$

- Radiation-like phase: relativistic

$$\frac{3}{2}\lambda\langle|\psi|^2\rangle^2 \gg mc^2\langle|\psi|^2\rangle$$

$$\langle\overline{w}\rangle = 1/3 \qquad \langle\overline{\rho}\rangle \propto a^{-4}$$

SFDM EVOLUTIONARY PHASES

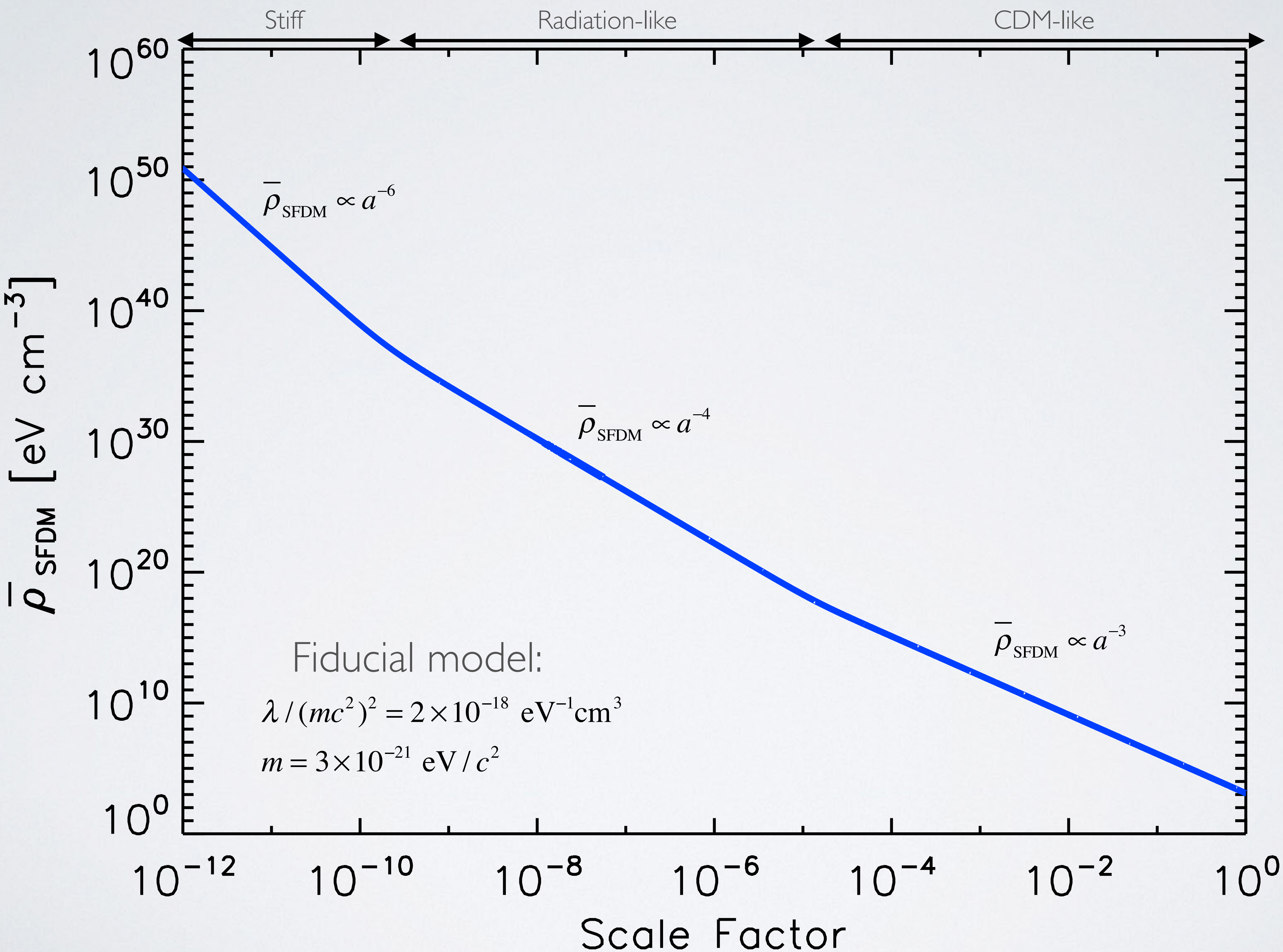
- Slow-oscillation regime $(\omega / H \ll 1)$

$$\bar{p} \approx \bar{\rho} \approx \frac{\hbar^2}{2mc^2}|\partial_t \psi|^2.$$

- Stiff phase: relativistic

$$\overline{w} = 1 \qquad \overline{\rho} \propto a^{-6}$$

SOLUTION: ΛSFDM EVOLUTION



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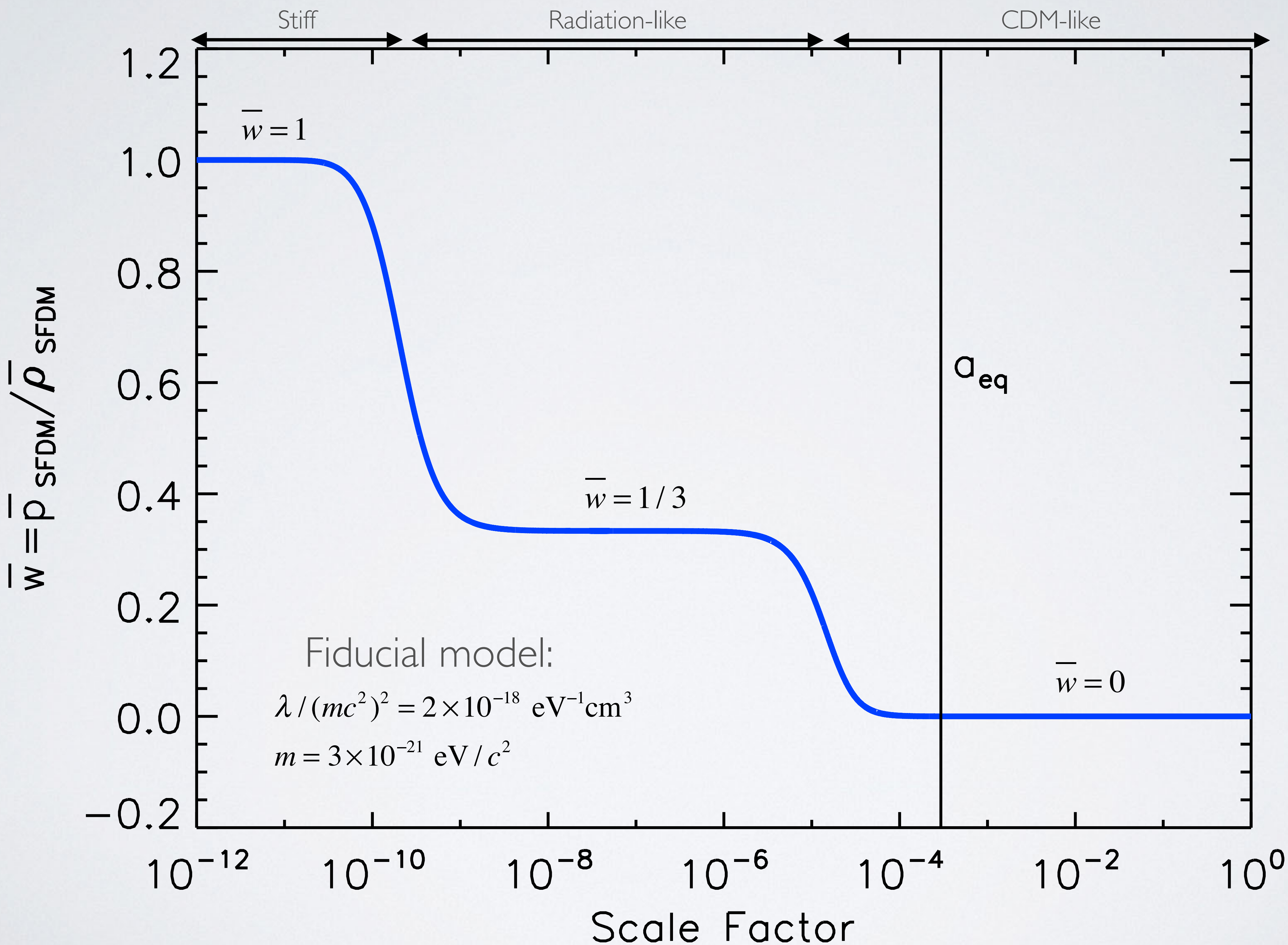

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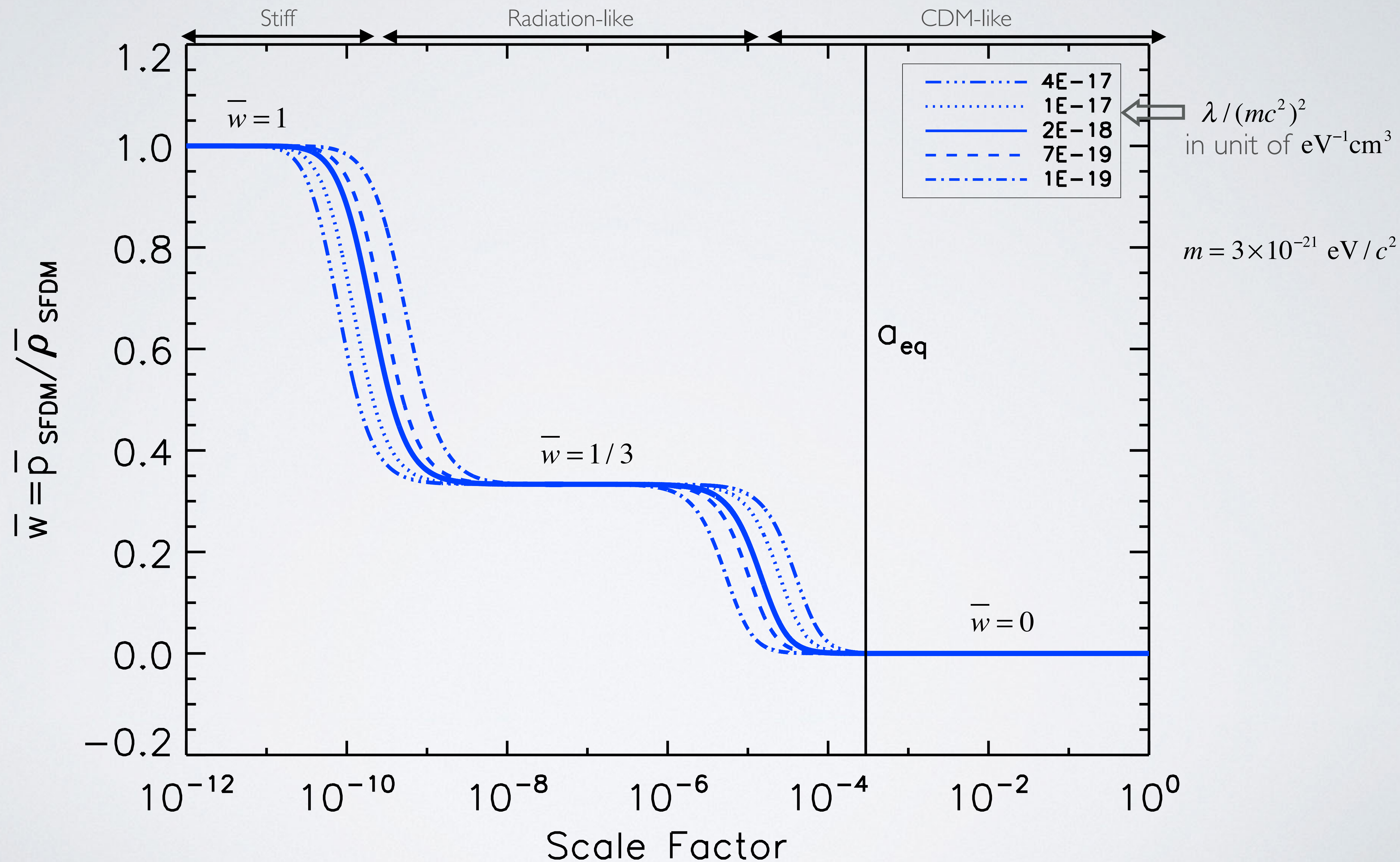

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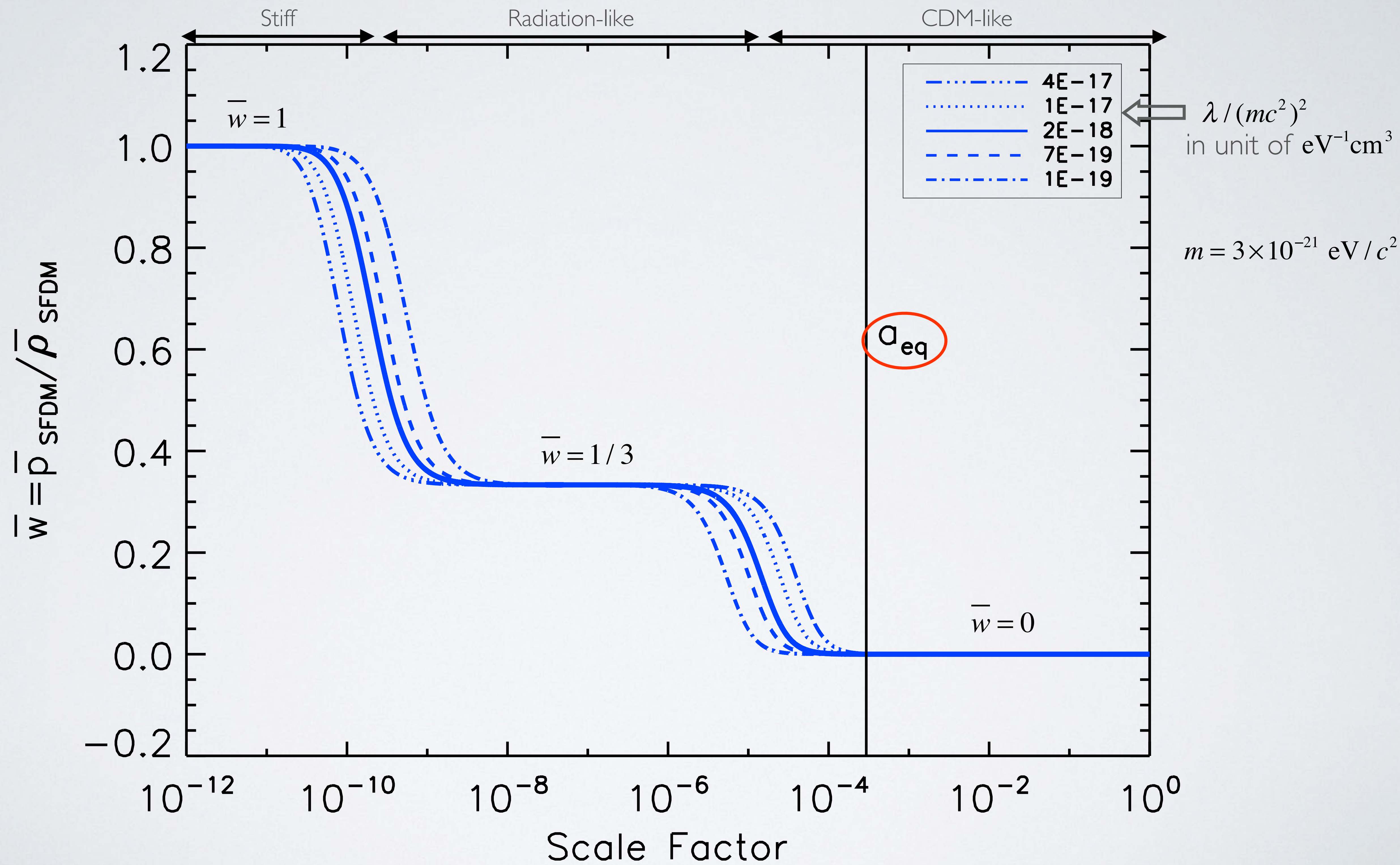

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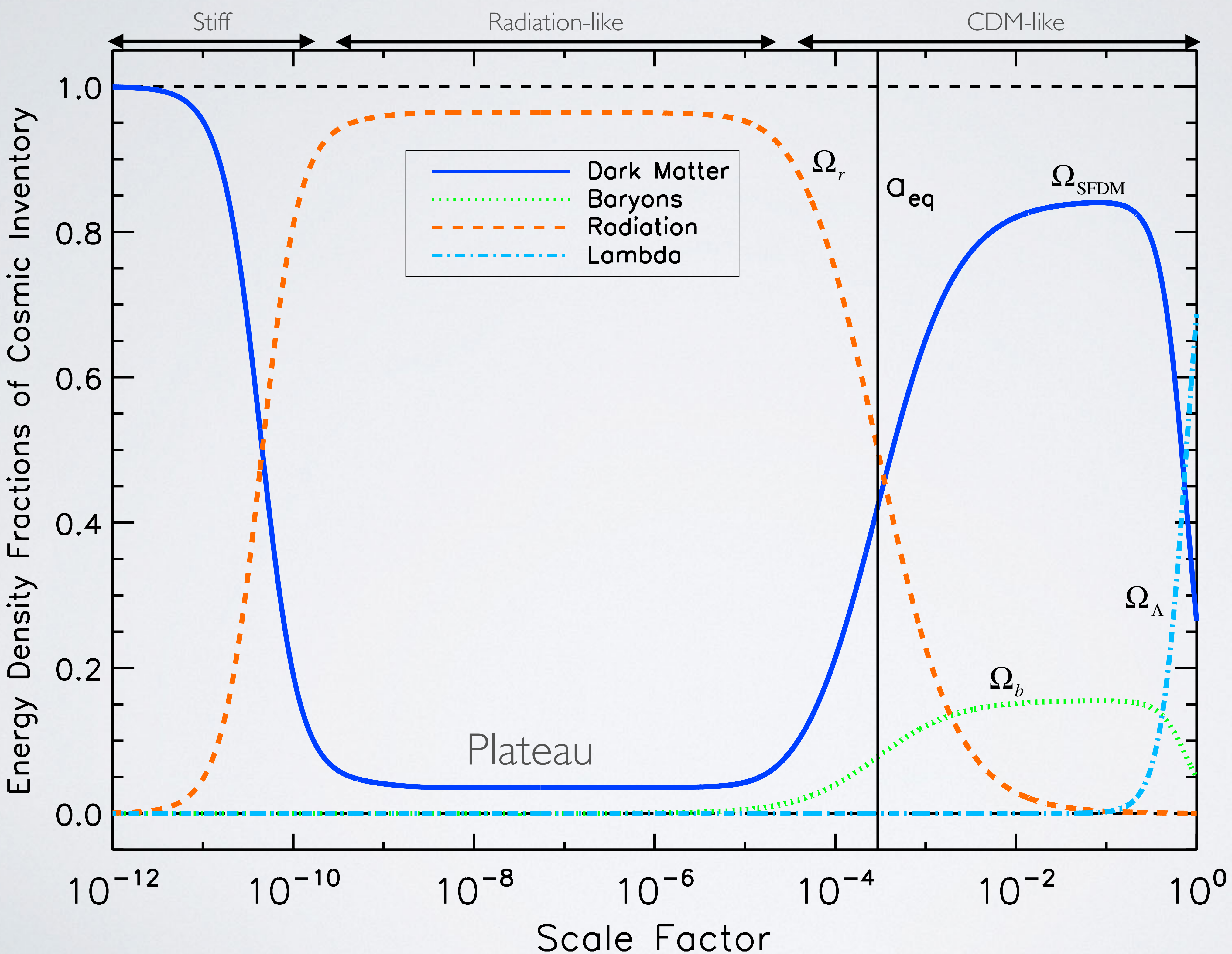

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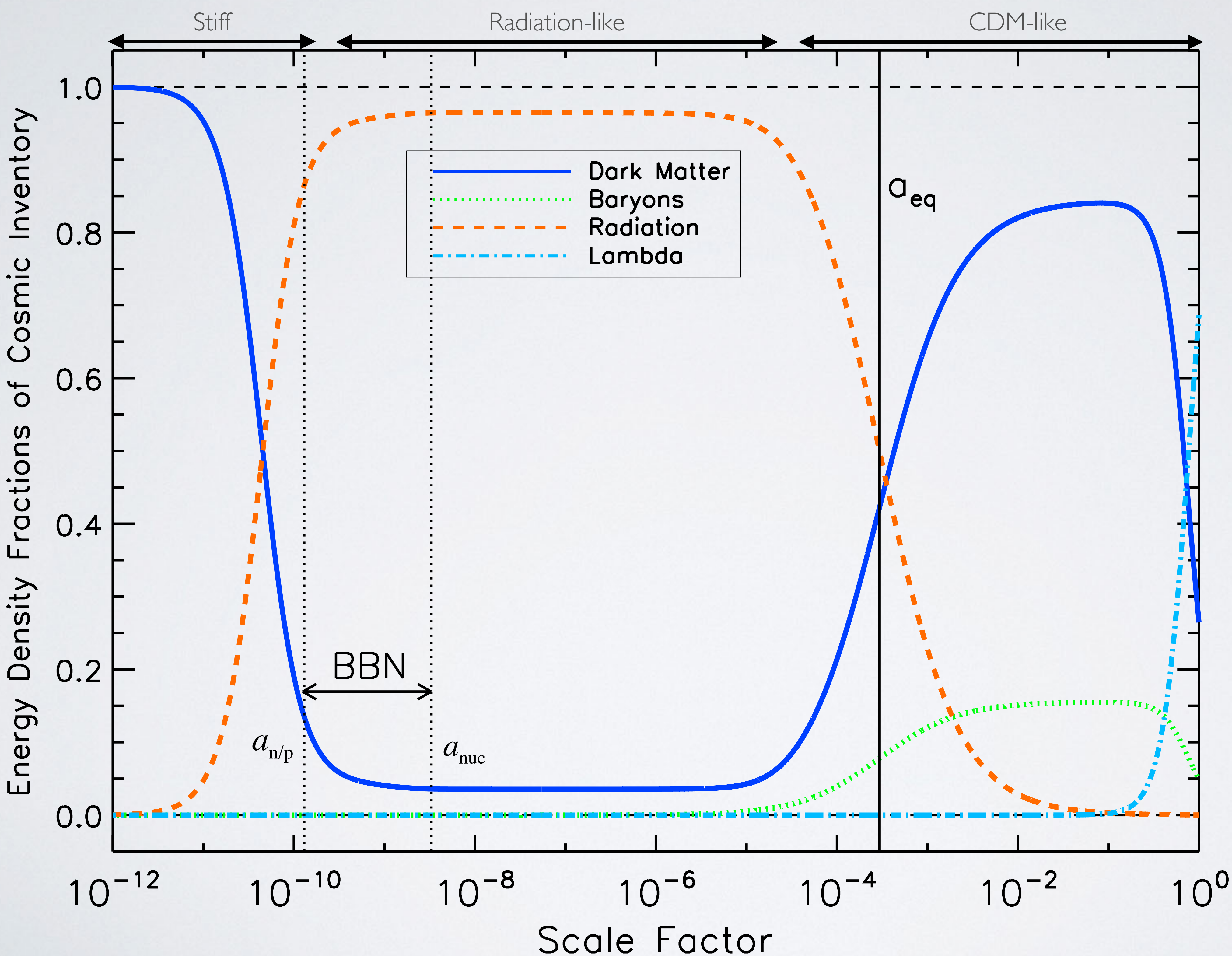

$a_{n/p}$: the epoch at which the neutron to proton ratio freezes out

a_{nuc} : the epoch at which light nuclei production occurs

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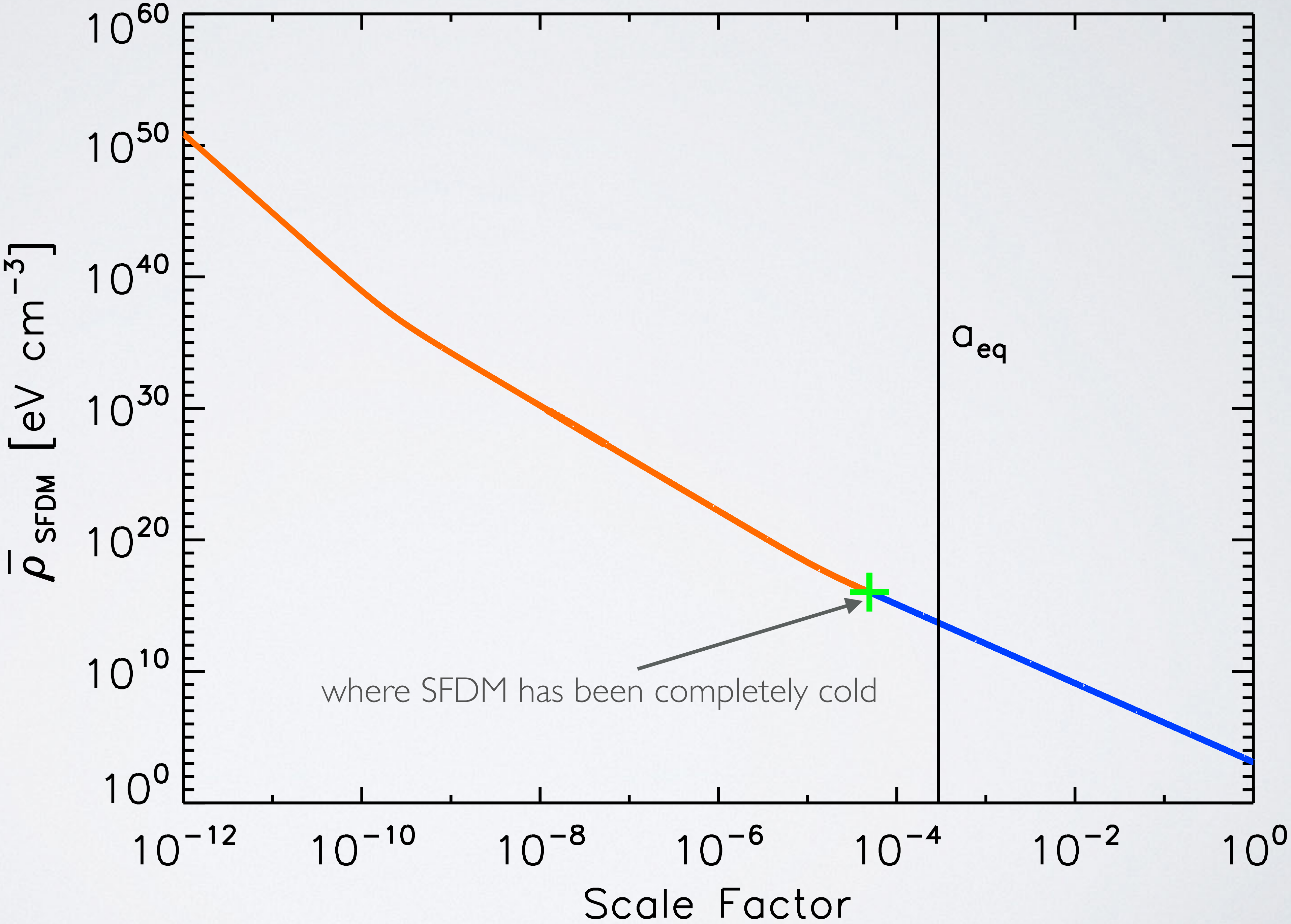
CONSTRAINTS

- From z_{eq}

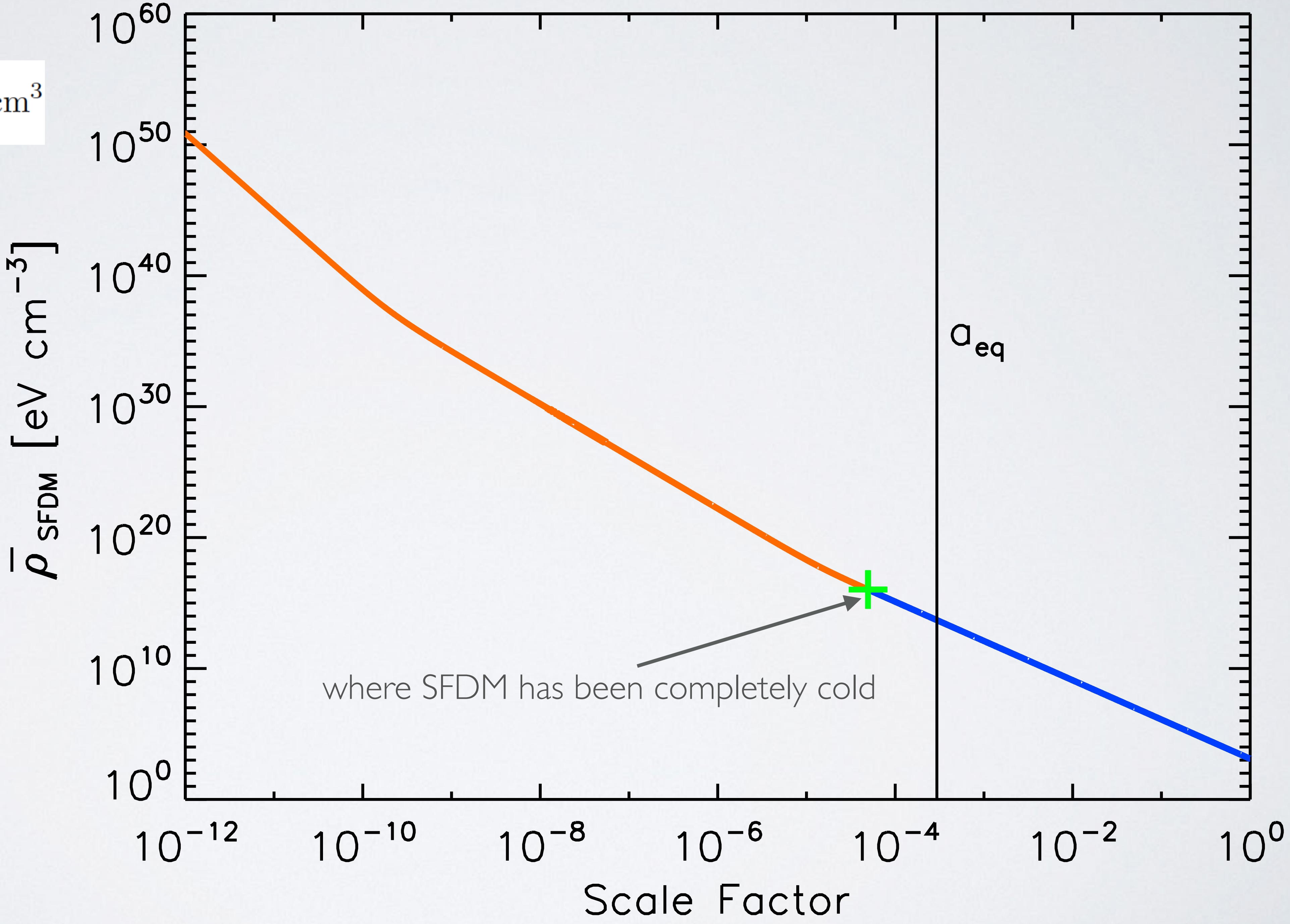
$$1 + z_{\rm eq} \equiv \frac{1}{a_{\rm eq}} = \frac{\Omega_b h^2 + \Omega_c h^2}{\Omega_r h^2}$$



CONSTRAINTS

- From z_{eq}

$$\frac{\lambda}{(mc^2)^2} \leq 4 \times 10^{-17}\ \mathrm{eV}^{-1}\ \mathrm{cm}^3$$



CONSTRAINTS

- From N_{eff} : the effective number of neutrino species

Relativistic SFDM

⇩

Expansion rate (N_{eff})

⇩

Primordial light element abundances ([He], [D], …)

$$\frac{\Delta N_{\rm eff}}{N_{\rm eff,standard}} = \frac{\bar{\rho}_{\rm SFDM}}{\bar{\rho}_\nu},$$

$$N_{\rm eff,standard} = 3.046$$

accounts for 3 SM neutrinos

$$\Delta N_{\rm eff} \equiv N_{\rm eff} - N_{\rm eff,standard}$$

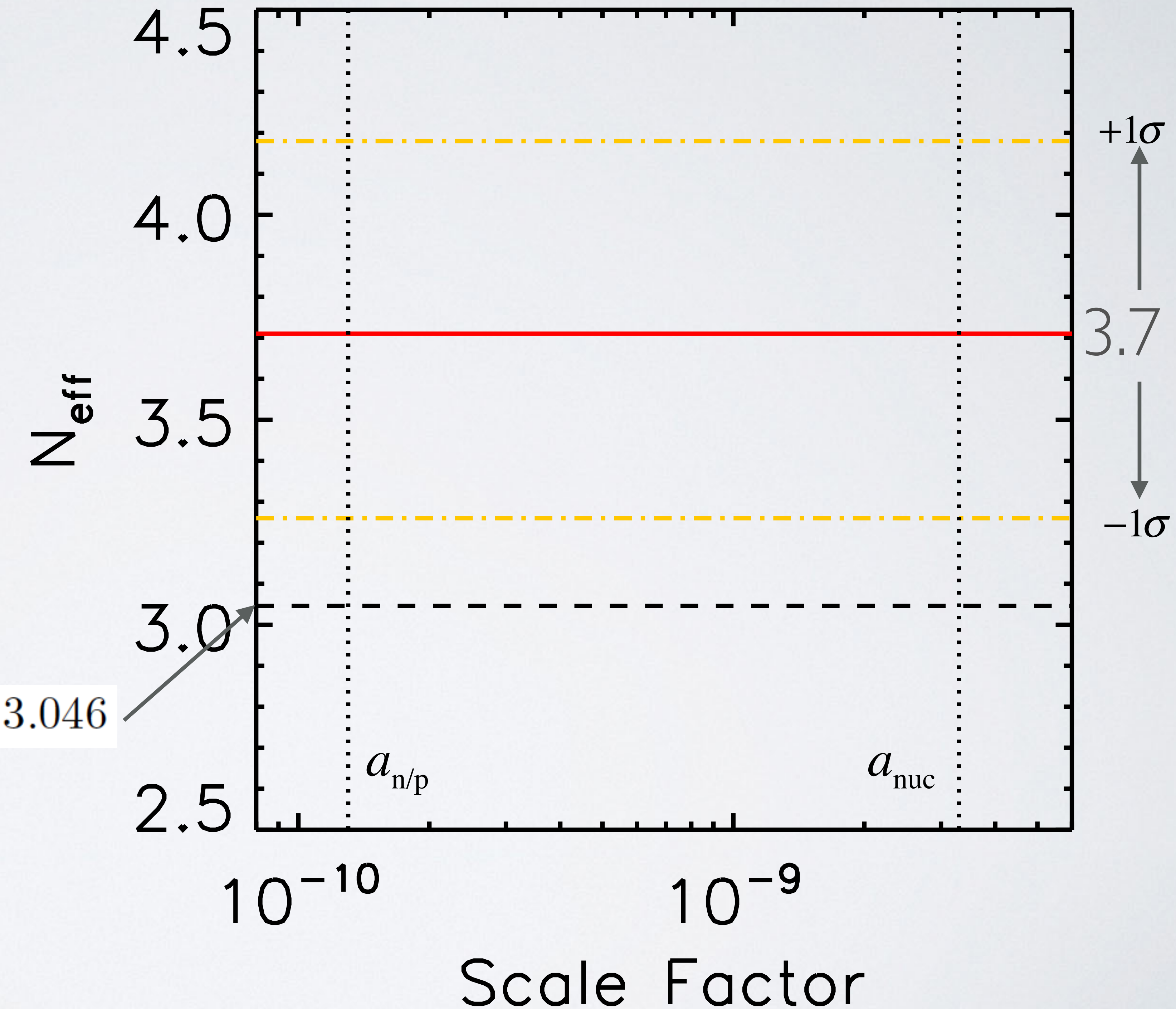
CONSTRAINTS

- From N_{eff}

$$N_{\rm eff} = 3.71^{+0.47}_{-0.45}$$

Steigman (2012), arXiv:1208.0032

$$N_{\rm eff,standard} = 3.046$$



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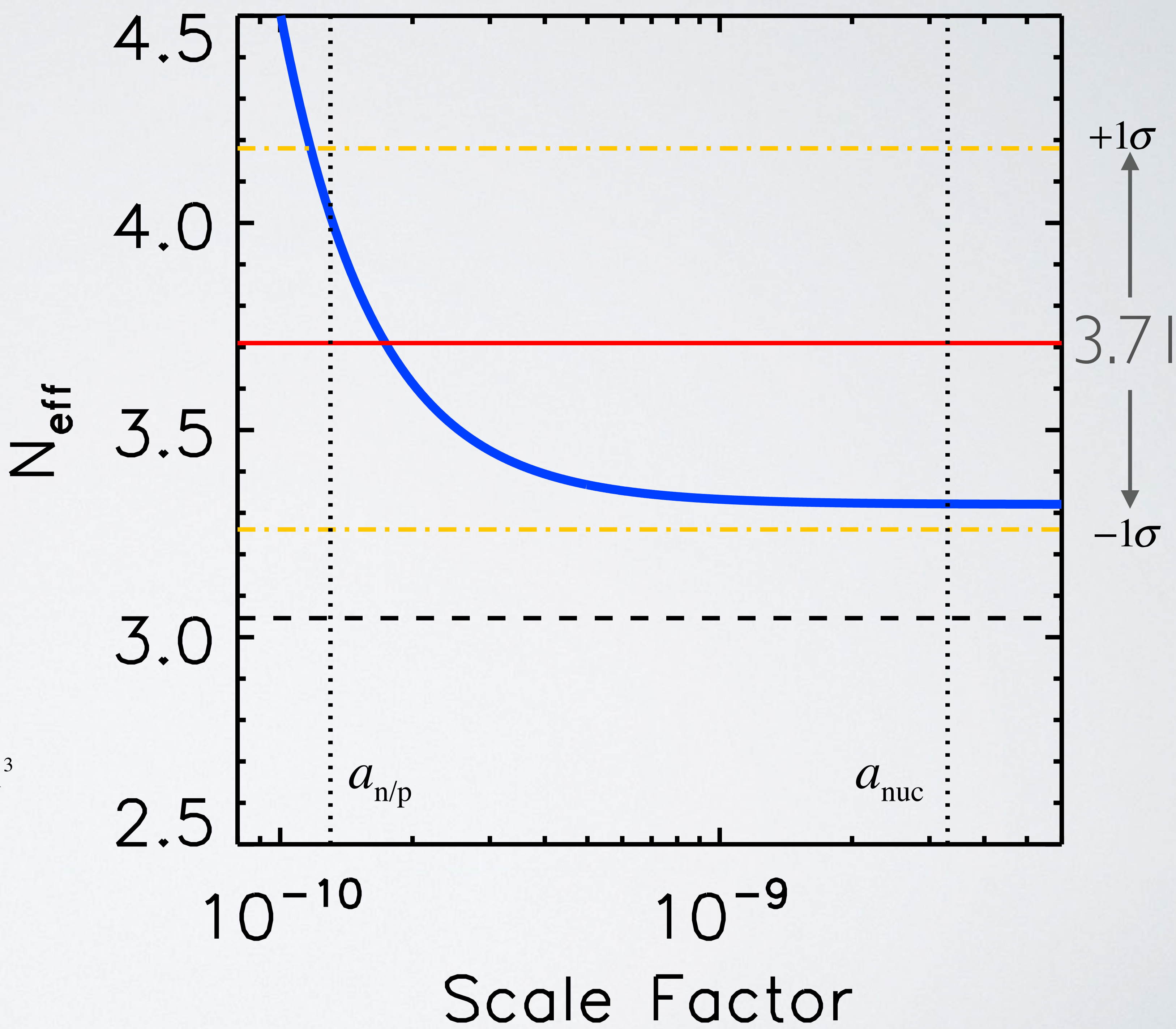

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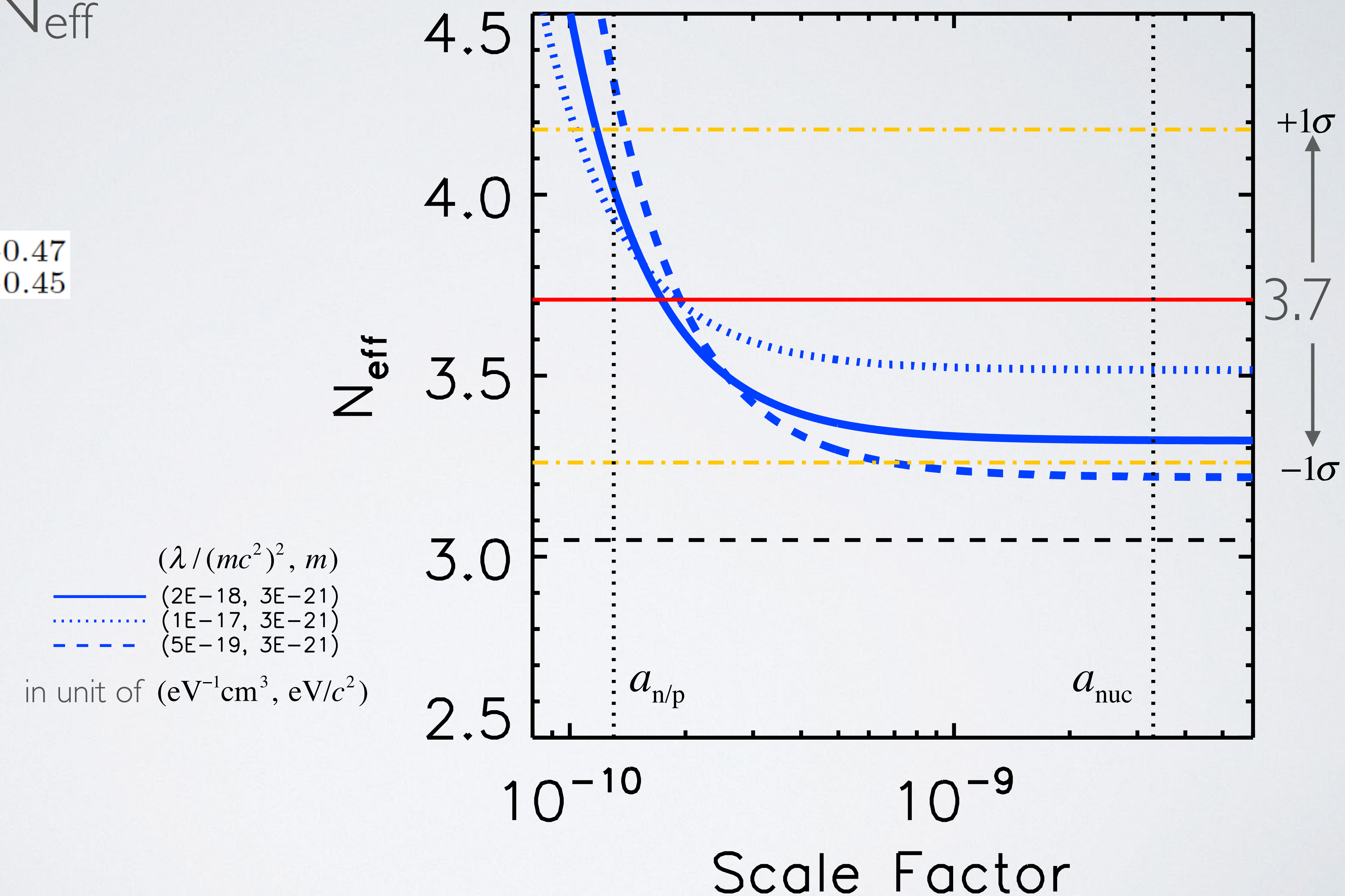
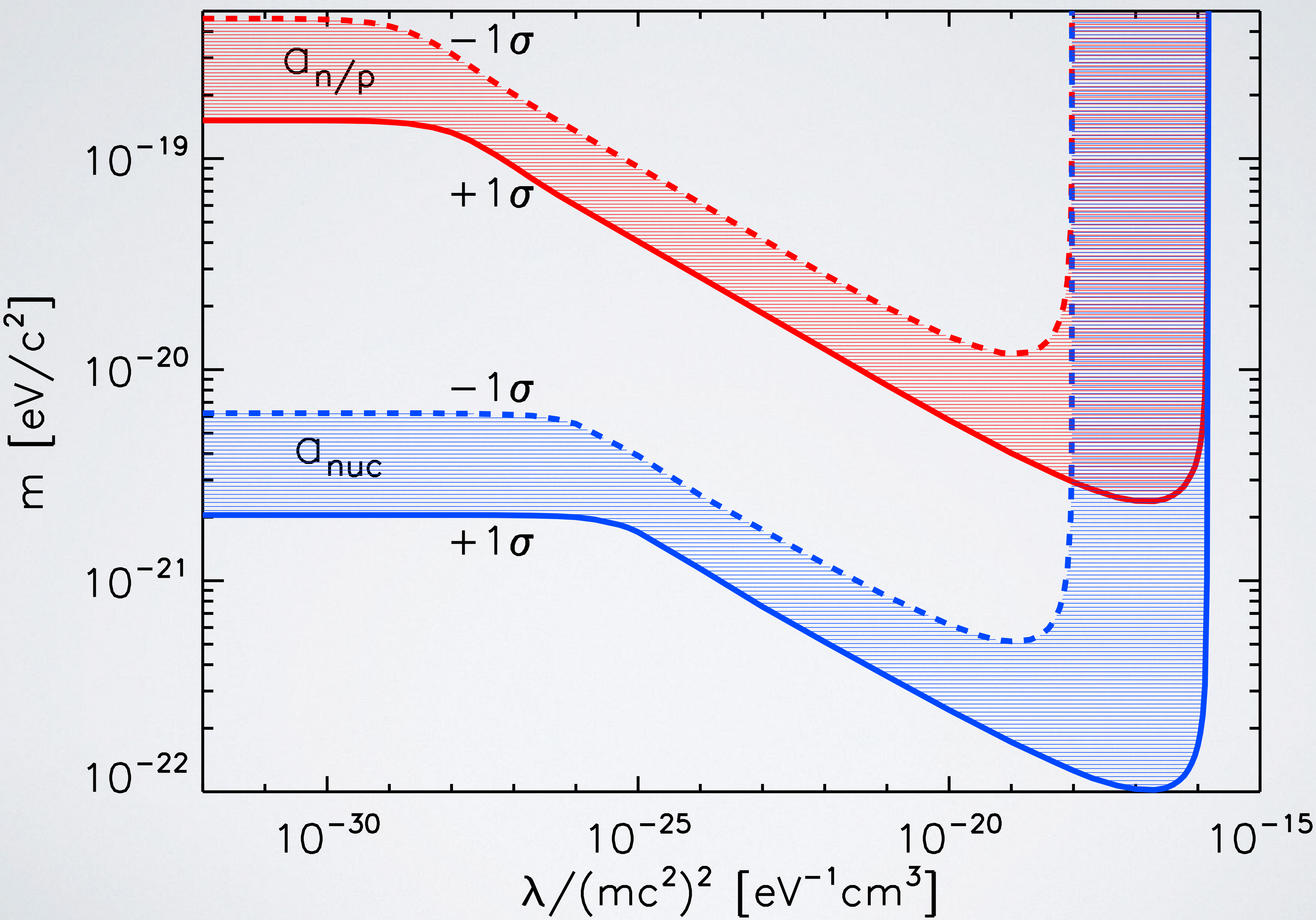


RESULT: PARTICLE PARAMETER SPACE



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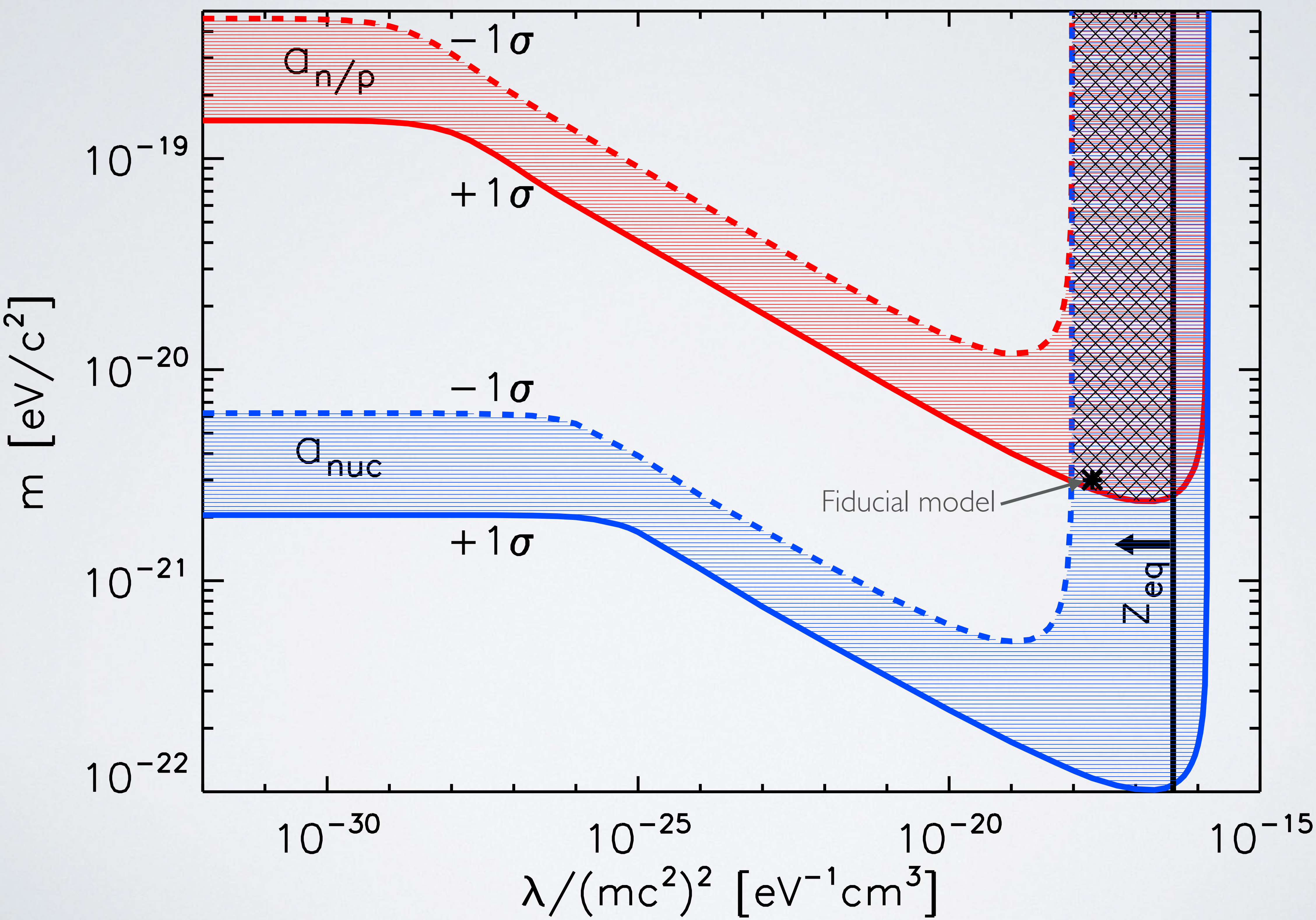
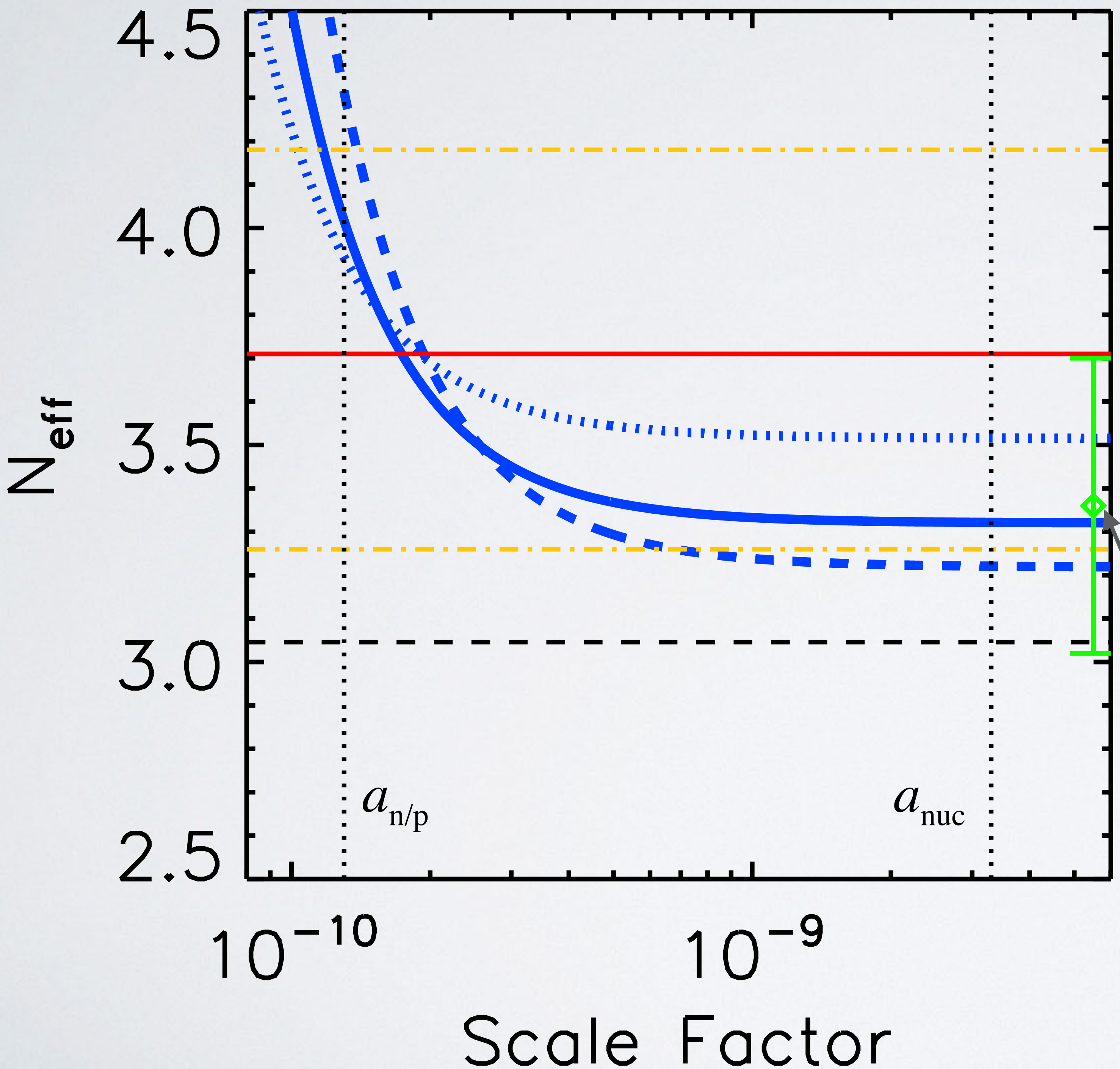


N_{EFF} FROM BBN VS. N_{EFF} FROM CMB



$N_{\rm eff} = 3.71^{+0.47}_{-0.45}$

from BBN

$N_{\rm eff} = 3.36 \pm 0.34$

from Planck

Probing the redshift range from

$z_{entry} \sim 10^5$ to $z_{rec} \sim 1100$

FUTURE WORK

- Find the exact constraint on the SFDM particle parameters from N_{eff} during BBN, by calculating primordial abundances of the light elements using a BBN code

- Calculate the growth of structures with SFDM
    - Linear: mass function, power spectrum, CMB
    - Non-linear: halo formation