Dark Matter
and the signatures

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Fundamental particles

Standard Model

Higgs

BOSONS

Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W$^-$	80.39	−1
W$^+$ W bosons	80.39	+1
Z^0 Z boson	91.188	0

Strong (color) spin =1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

FERMIONS
matter constituents
spin = 1/2, 3/2, 5/2, …

Leptons spin =1/2

Flavor	Mass GeV/c^2	Electric charge
ν_L lightest neutrino*	$(0-0.13)\times10^{-9}$	0
e electron	0.000511	−1
ν_M middle neutrino*	$(0.009-0.13)\times10^{-9}$	0
μ muon	0.106	−1
ν_H heaviest neutrino*	$(0.04-0.14)\times10^{-9}$	0
τ tau	1.777	−1

Quarks spin =1/2

| Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.002	2/3
d down	0.005	−1/3
c charm	1.3	2/3
s strange	0.1	−1/3
t top	173	2/3
b bottom	4.2	−1/3

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Standard Model

+

Dark Matter

We know the existence by gravity,
though invisible with EM interactions.

Contents

- Why do we need Dark Matter?

  - Dark Matter in the early Universe

  - Dark Matter in the present Universe

- What is Dark Matter?

  - Candidates of Dark Matter

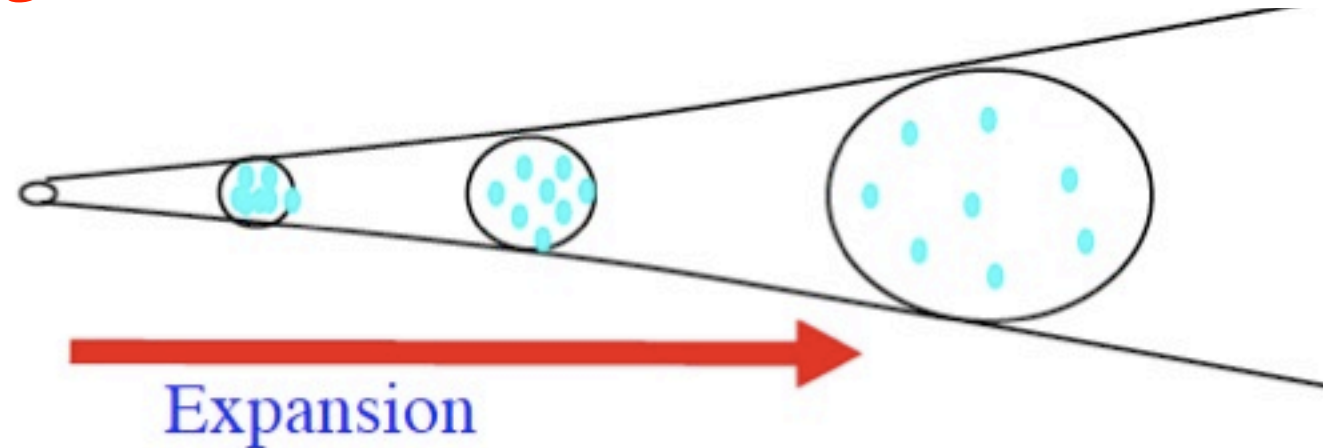- How can we identify it?

  - Signatures of Dark Matter

Dark Matter
in the early Universe

- Matter dominated Universe

- CMB temperature perturbation

- Large scale structure formation

Interactions

Expanding Universe

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In the expanding Universe

Expansion
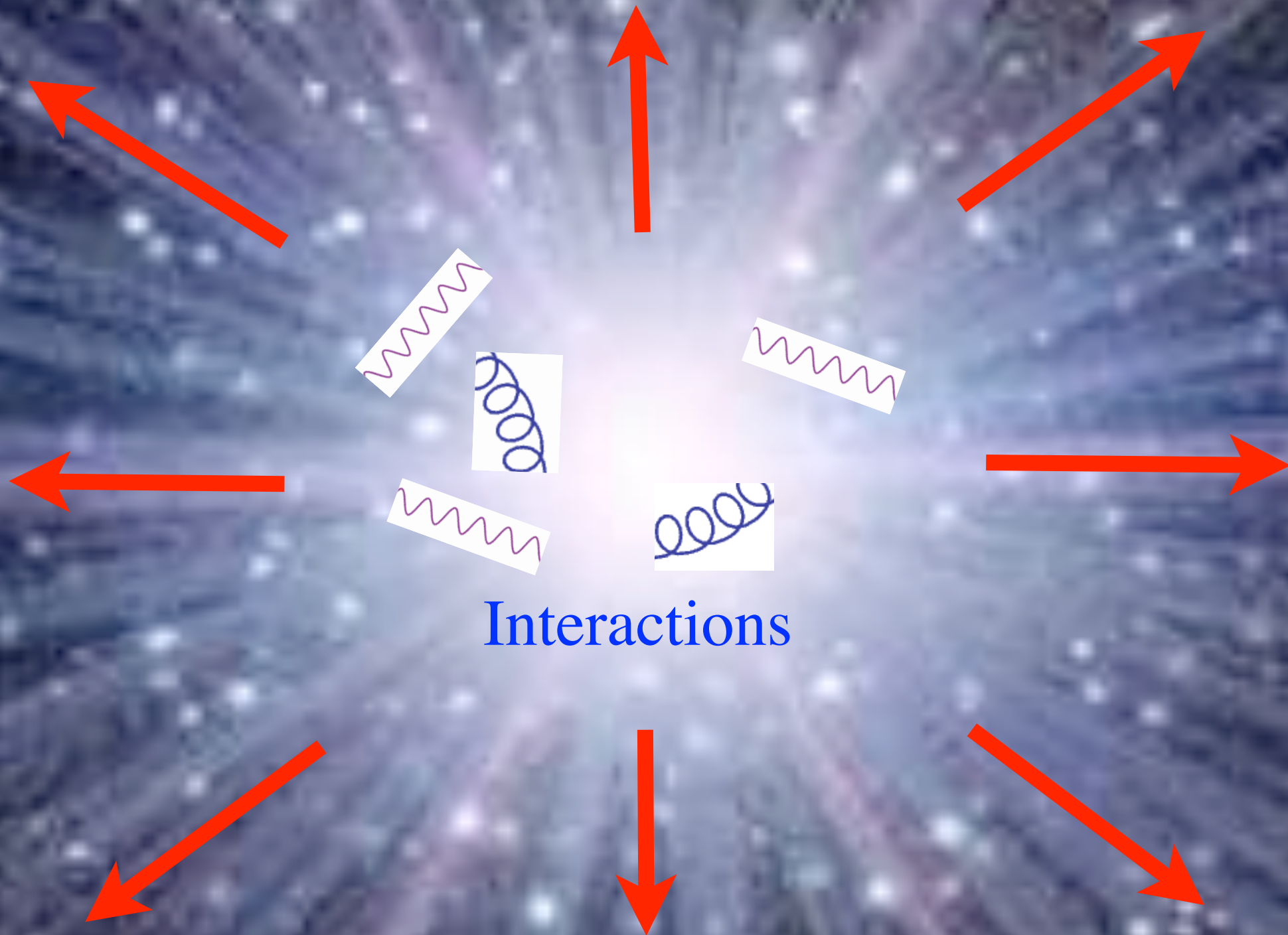
1. The number density decreases. $n(t) \propto \dfrac{1}{R^3(t)}$

2. The momentum is redshifted. $P(t) \propto \dfrac{1}{R(t)}$

Relativistic matter $\quad \rho_r(t) \sim E(t) n(t) \propto R(t)^{-4}$

$$P(t) \propto \frac{1}{R(t)} \qquad n(t) \propto \frac{1}{R^3(t)}$$

Non-Relativistic matter $\quad \rho_m \sim M\, n(t) \propto R(t)^{-3}$

$$P(t) \propto \frac{1}{R(t)}$$

$k = +1 \qquad k = 0$

$$= R(t) \times \qquad \frac{\sin^{-1} r_1}{k = +1} \quad \frac{\sinh^{-1} r_1}{k = 0} \quad k =$$

Present energy density

Relativistic matter : photons in the CMB

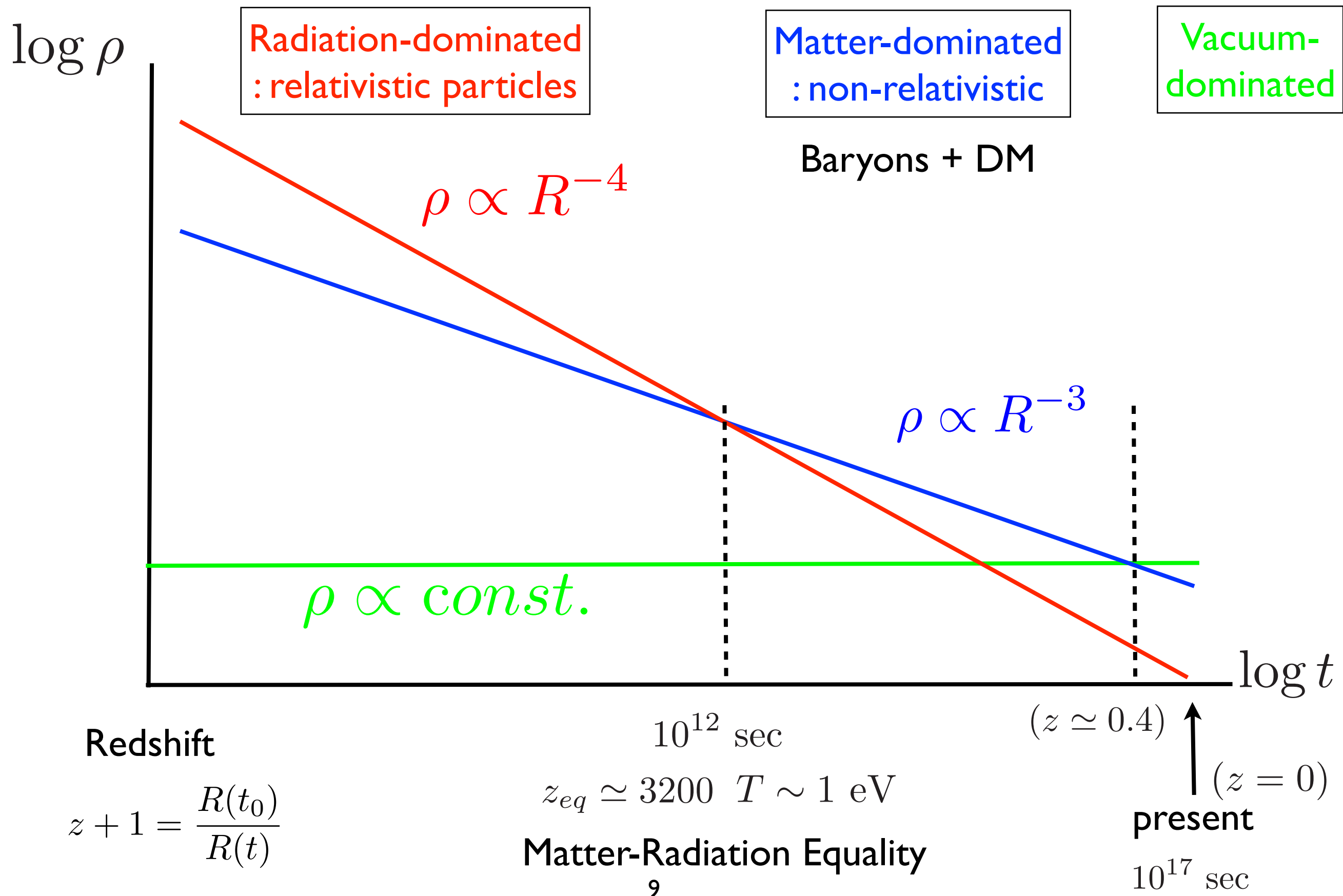Planck distribution with $T_0 = 2.7\,\mathrm{K}$

$$\Rightarrow \quad \rho_{\gamma,0} = 4.8 \times 10^{-34}\,\mathrm{gram\,cm^{-3}}$$

Non-Relativistic matter : Galaxy and clusters

$$\Rightarrow \quad \rho_{m,0} \sim 10^{-30}\,\mathrm{gram\,cm^{-3}}$$

Ratio $\quad \dfrac{\rho_{m,0}}{\rho_{\gamma,0}} \sim 2 \times 10^3$

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• Dark Matter dominated Universe

$\log \rho$

Radiation-dominated
: relativistic particles

Matter-dominated
: non-relativistic

Vacuum-dominated

Baryons + DM

$\rho \propto R^{-4}$

$\rho \propto R^{-3}$

$\rho \propto const.$

$\log t$

$(z \simeq 0.4)$

10^{12} sec

Redshift

$z + 1 = \dfrac{R(t_0)}{R(t)}$

$z_{eq} \simeq 3200 \quad T \sim 1$ eV

Matter-Radiation Equality

$(z = 0)$

present

10^{17} sec

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1. Dark matter and baryons energy begins to dominate the Universe from the cosmic age around $10^{12}\,\sec$.

- Evolution of states in the Universe

atom, molecule
neucleus
electron

Very Cold   Structure formation

Galaxy
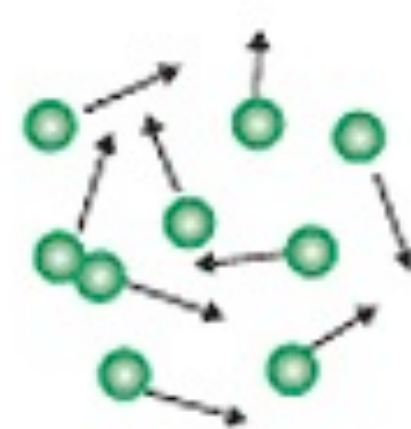
Recombination,
photon decoupling
: CMB

Gas

Very Hot

Matter-dom.
―――――――
Radiation-dom.

| photons, Quarks, gluons, electrons.. |

| protons, neutrons, electrons, photons |

thermal equilibrium ⟶
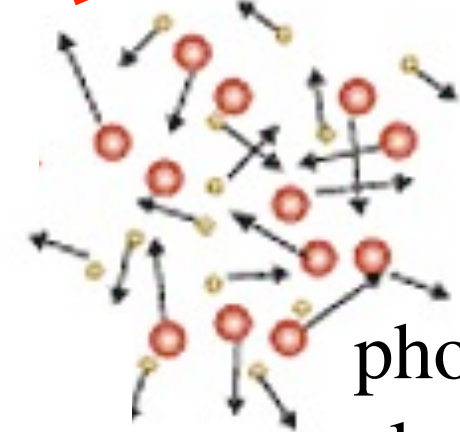
⟶   ⟶   photons,
electrons,
light nuclei

Quark-hadron transition   BBN

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- **Recombination of nuclei and electrons and photon decoupling** (cosmic age 380,000 years)

Proton, Electron

Photon

Hydrogen atom

a   Before recombination   b   After recombination
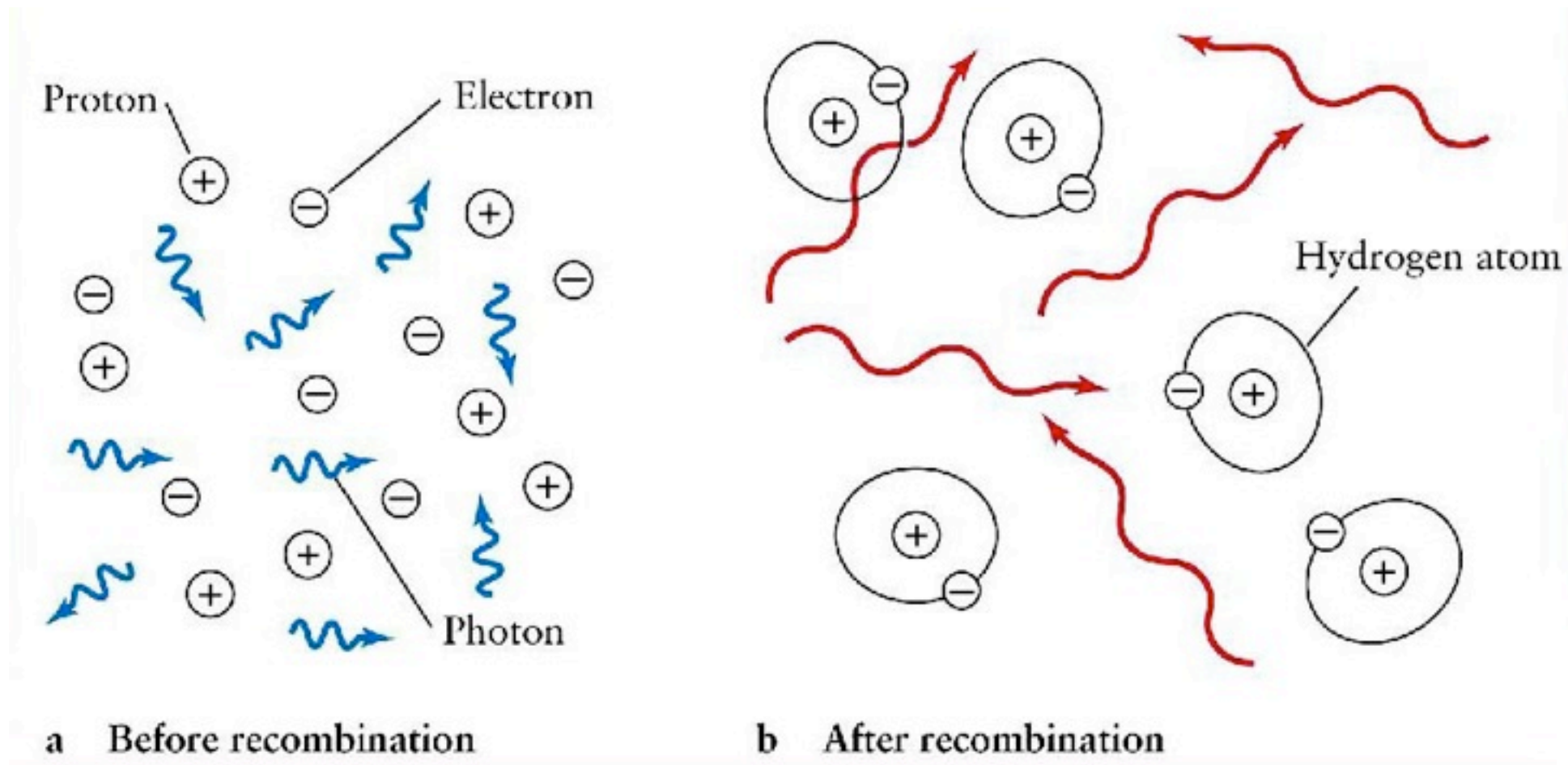
Binding energy of hydrogen atom and electron is 13.6 eV
: cosmic temperature is around 3000 K ~ eV
The free photons can move freely to us from the decoupling and around us.

- ## Recombination of nuclei and electrons and photon decoupling (cosmic age 380,000 years)
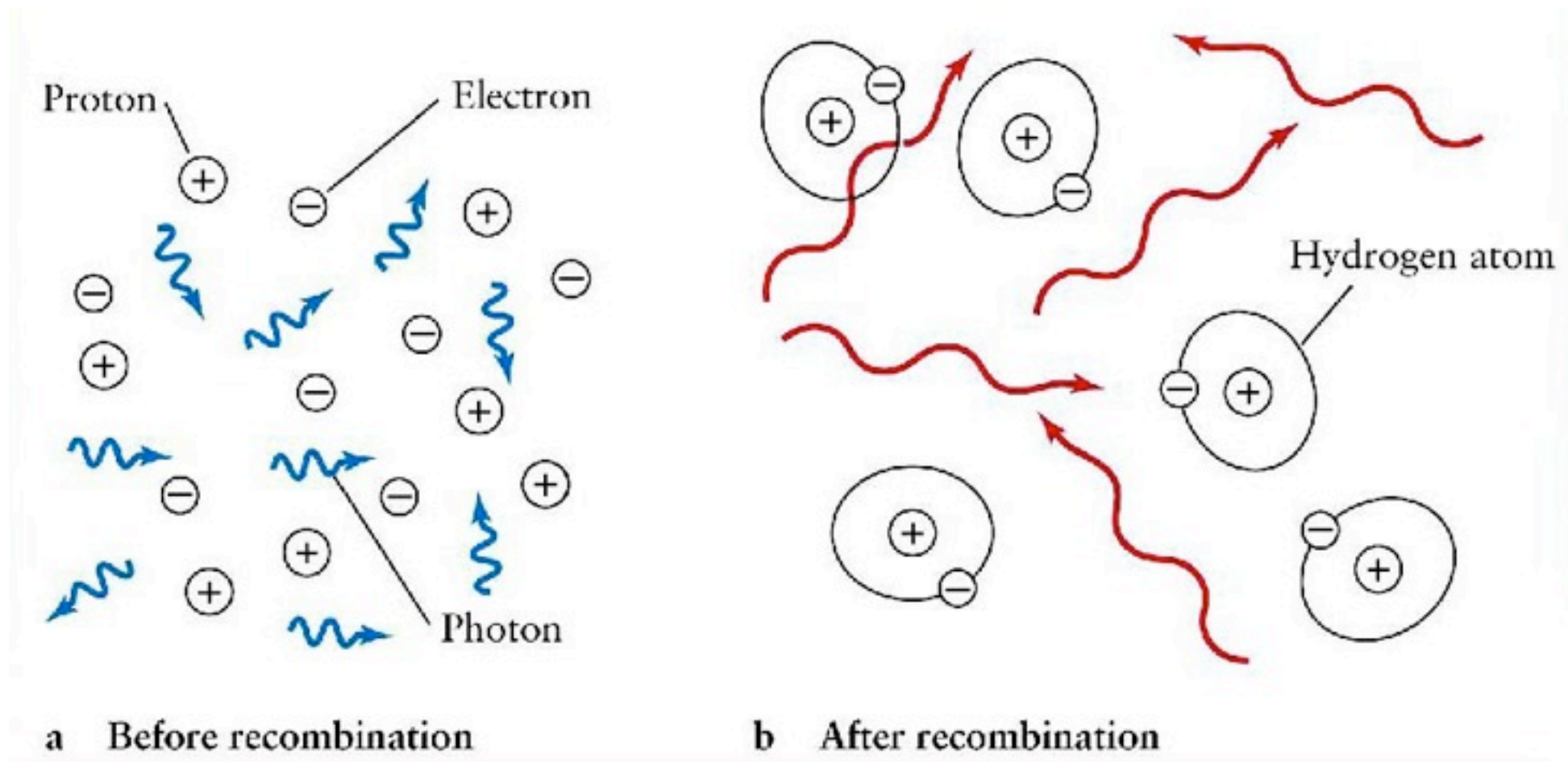
Proton Electron

Photon

a Before recombination

Hydrogen atom

b After recombination

Binding energy of hydrogen atom and electron is 13.6 eV
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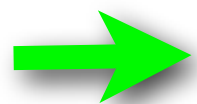
→ **Cosmic Microwave Background**

: The temperature decreased due to the cosmic expansion and now
it is around 2.7 K (Alpher and Herman predicted in 1948)

The European Space Agency's *Planck* satellite.

New results from Planck

Planck was launched on 14 May 2009

9 bands (30 - 857 GHz)

Angular resolution ~ 7 arcminutes

accuracy around 10^{-6} in temperature fluctuation

21st March, 2013 first release of data

15.5 months data

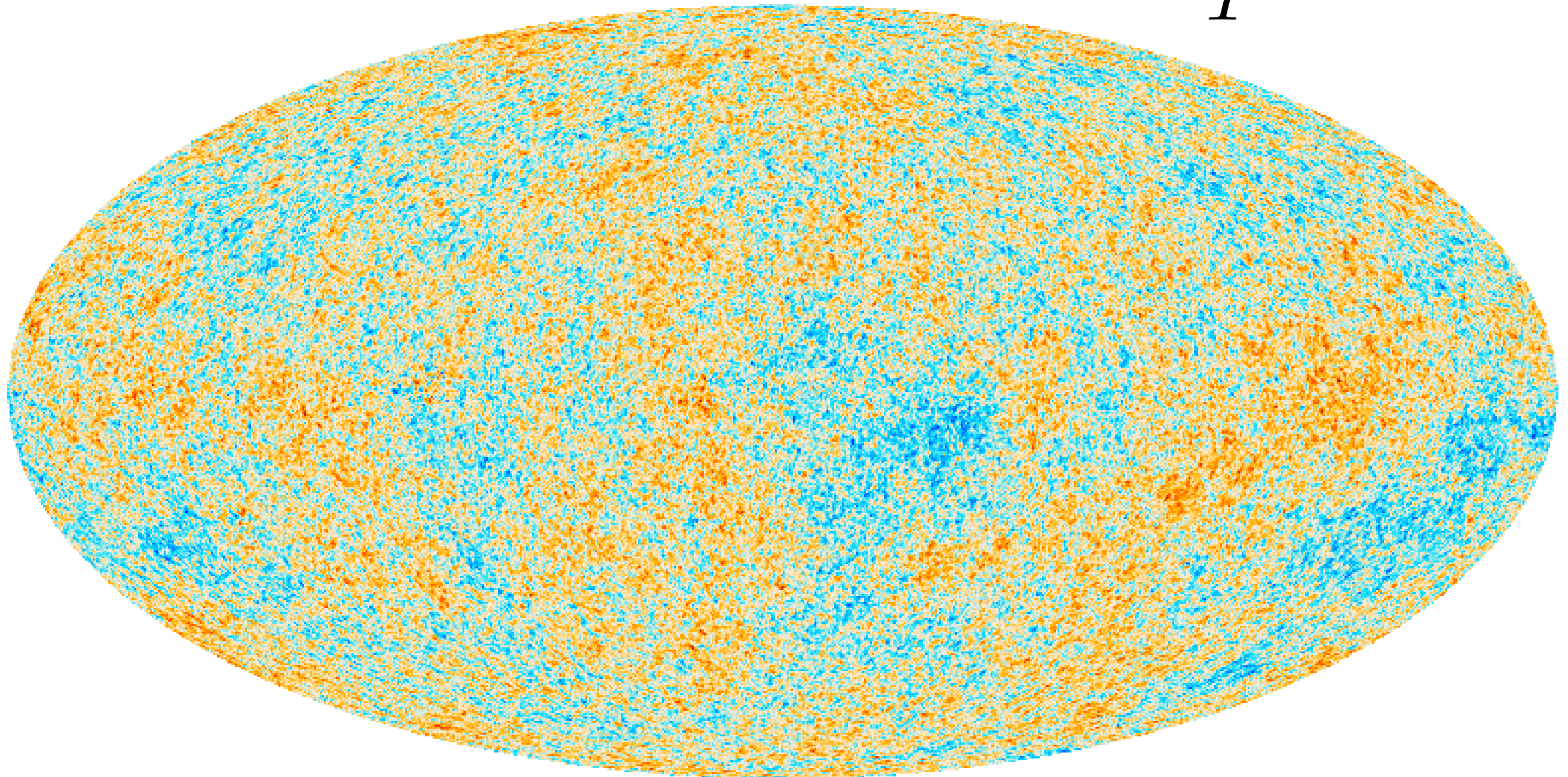Temperature data only (Polarization next year)

29 papers at

http://www.sciops.esa.int/index.php?project=PLANCK&page=Planck_Published_Papers

In 2014, full temperature and polarization date will be released

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$T_0 \simeq 2.725\,\mathrm{K}$

$$\frac{\delta T}{T} \sim 10^{-5}$$

-500 $500\ \mu\mathrm{K}_{\mathrm{CMB}}$

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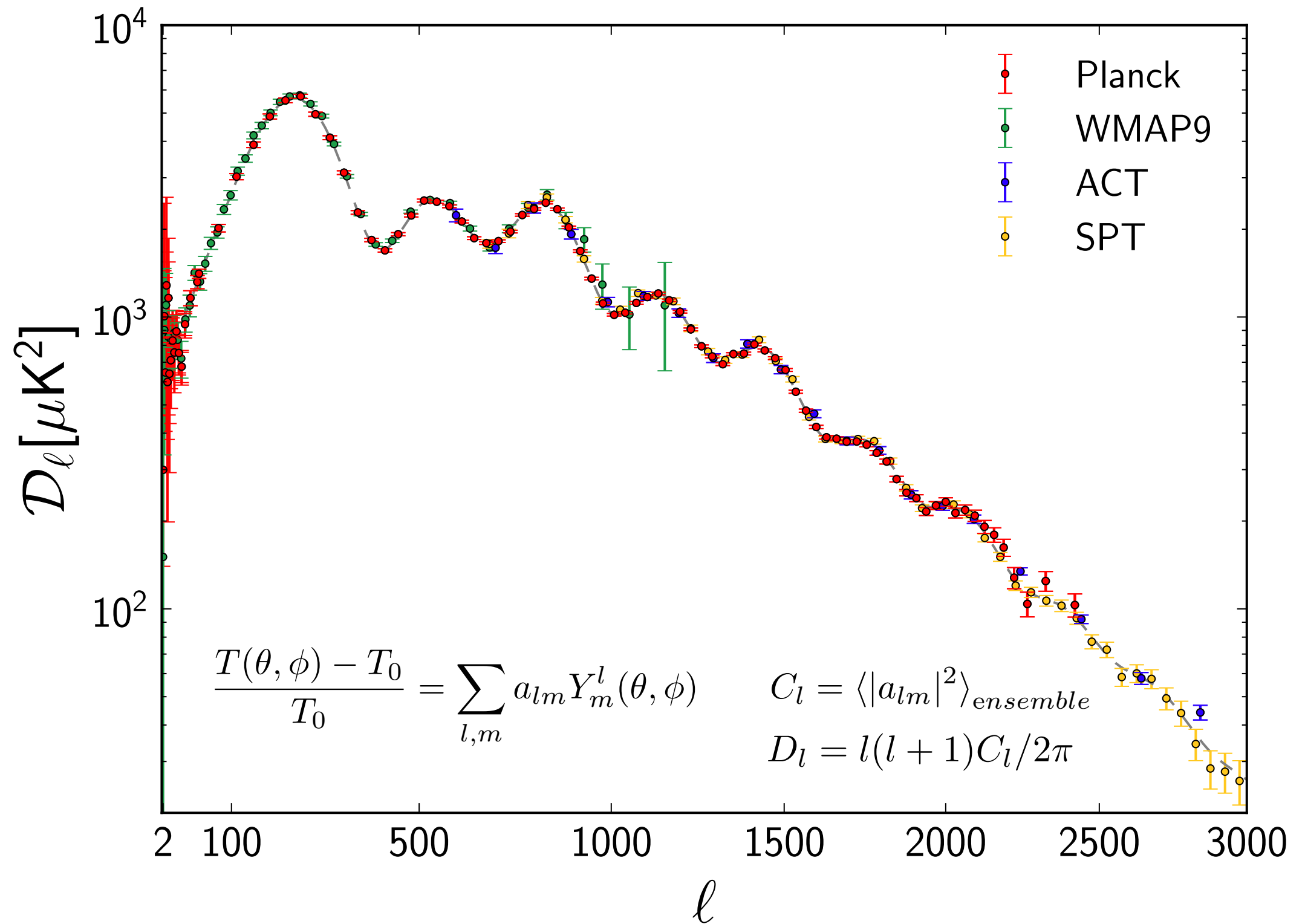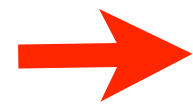# • Dark Matter in the CMB temperature perturbation

Fig. 25. Measured angular power spectra of *Planck*, WMAP9, ACT, and SPT. The model plotted is *Planck*'s best-fit model including *Planck* temperature, WMAP polarization, ACT, and SPT (the model is labelled [Planck+WP+HighL] in Planck Collaboration XVI (2013)). Error bars include cosmic variance. The horizontal axis is $\ell^{0.8}$.

- **Dark Matter in the CMB temperature perturbation**
  (ΛCDM + power law spectrum)

The positions of the peaks depends on the expansion
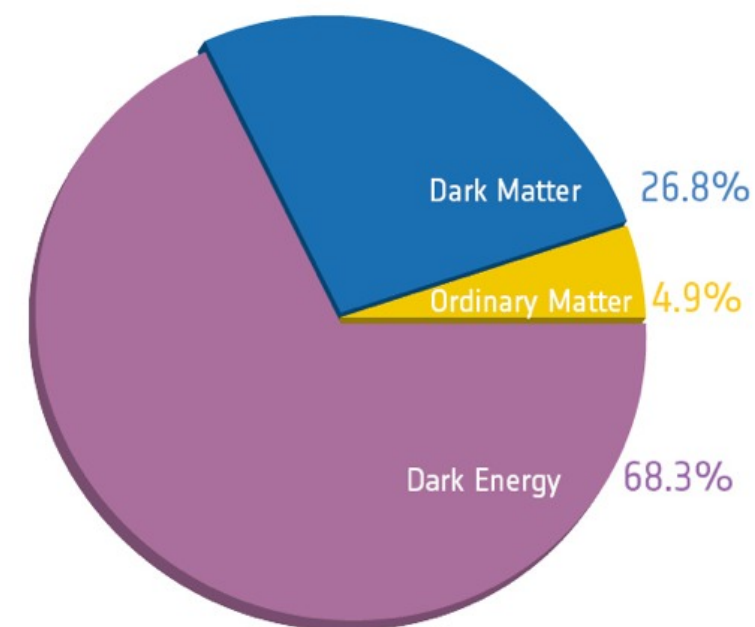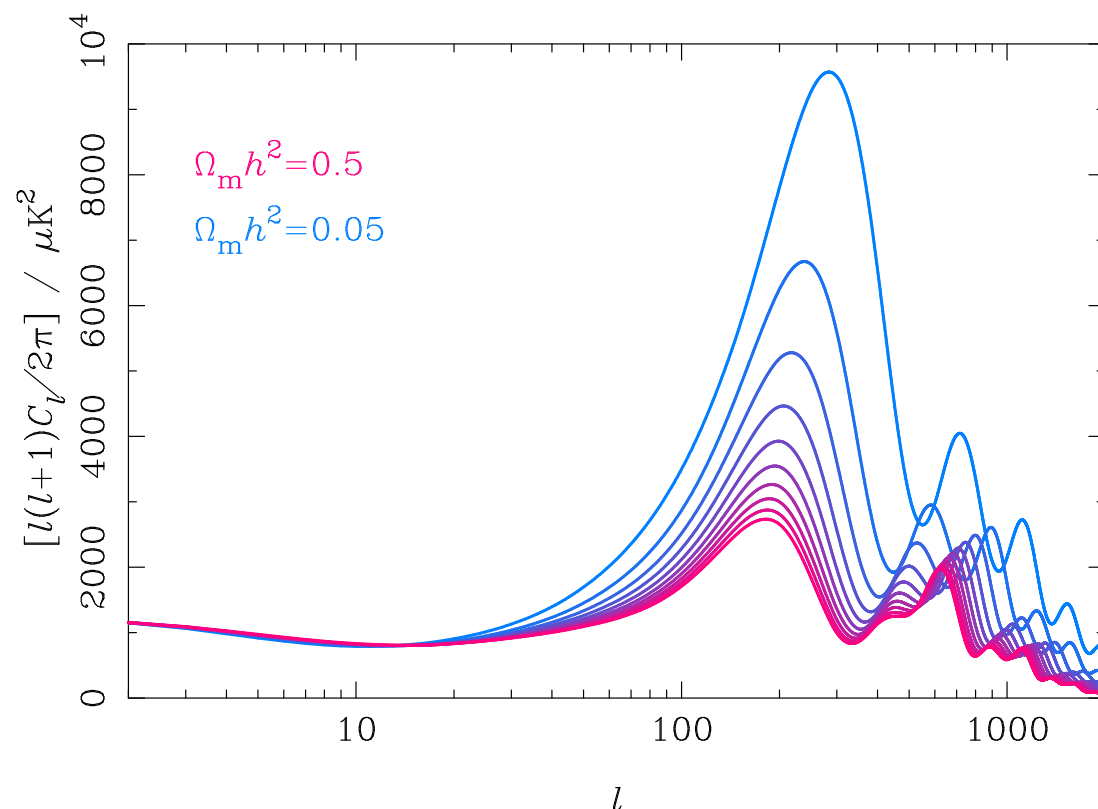history after last scattering → Energy density of Matter, DE

The gravitational potential is dominated by DM at the last scattering moment since it is the matter-dominated epoch. The amplitude is strongly depends on the density perturbation of Dark Matter.
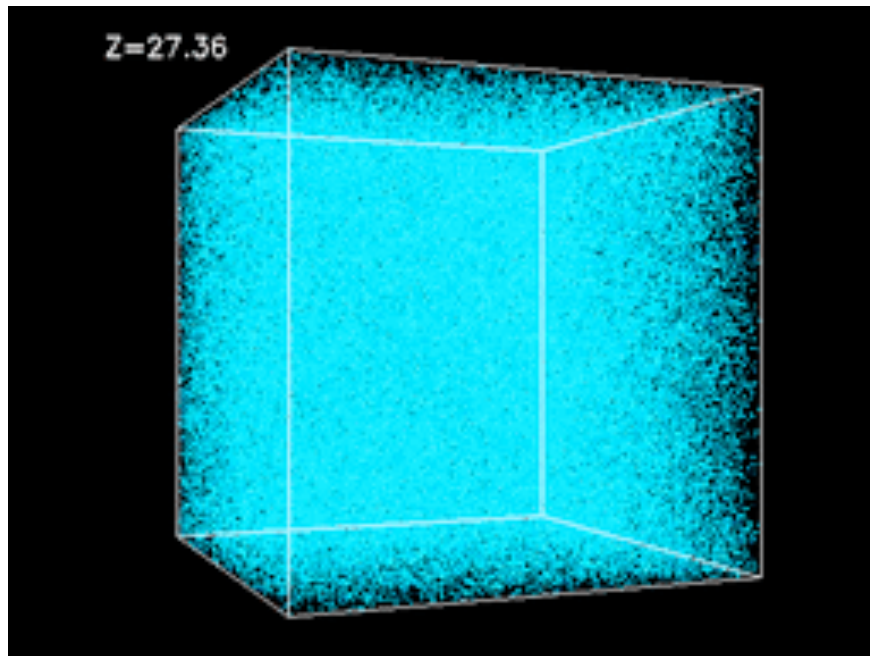
→ Density perturbation of DM, radiation, baryon

2. Dark matter density and its perturbation affected the CMB temperature anisotropies.

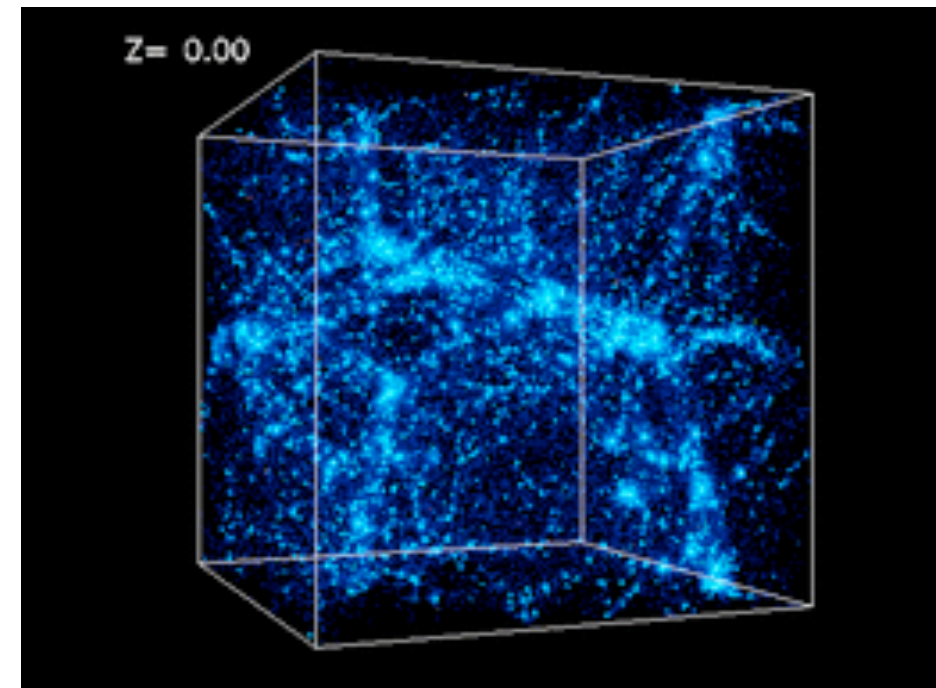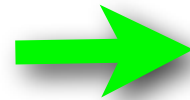- Dark Matter for the Large scale structure formation

Early Universe

Present Universe

Homogeneous, isotropic

Inhomogeneous, anisotropic

$$\frac{\delta\rho}{\rho} \sim 10^{-5}$$

By gravitational attraction

$$\frac{\delta\rho}{\rho} \gtrsim 1$$

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- Linear growth of the perturbation

The growth of the primordial density perturbation in the expanding universe depends on the scale, type of matter and background matter.

Outside horizon : density perturbation $\frac{\delta\rho}{\rho}$ is constant
with adiabatic condition $p = p(\rho)$

Inside horizon : density perturbation grows

$$z_{eq} \simeq 3200$$

| $\frac{\delta\rho}{\rho} \propto$	Radiation dom.	Matter dom.
Non-Rel. matter	$\log a \propto \log t$	$a \propto t^{2/3}$
Rel. matter	oscillating	oscillating

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Baryon for the structure formation without dark matter ? NO!

Baryons are tightly coupled to the photons before recombination and thus their perturbation cannot grow. After recombination, they can grow linearly but up to around 1000 times from 0.0001. It is 0.1 and still in the linear. They cannot make the non-linear structures as we can observe now.

We need new kind of matter which is non-relativistic and decoupled from photons even earlier than recombination to make sufficient grow of the density perturbations. That is Dark Matter and its perturbation grows logarythmically even during the radiation-dominated era before recombination. After recombination baryons are decoupled from radiation and catch up with the DM perturbations. Then the perturbations of both components grow togetehr.

If the DM constitutes about 30 % of the present critical density, then the small initial perturbations explain well the observed large-scale structures seen today.

We need Dark Matter.
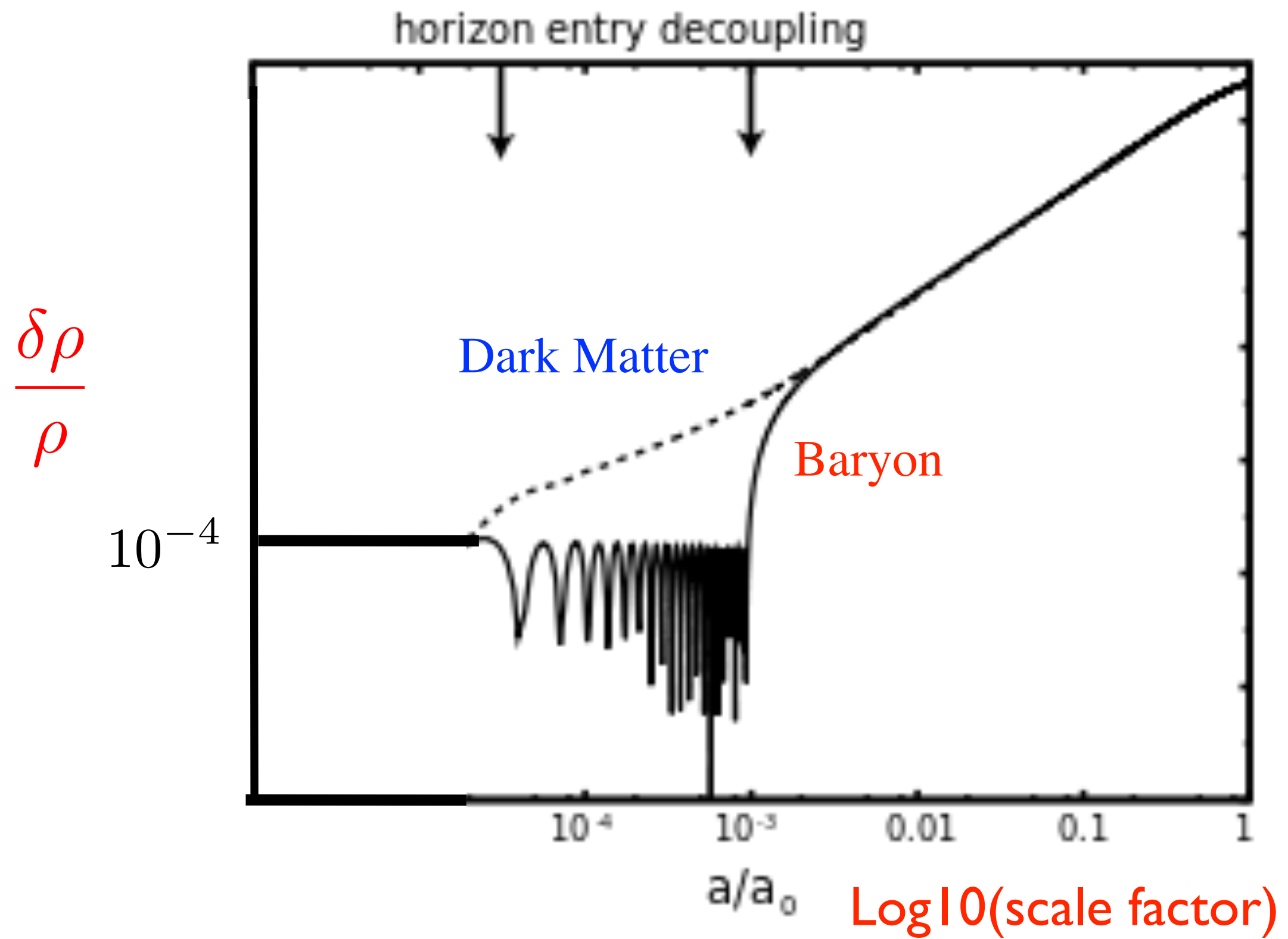
3. Dark matter density perturbation seeded the structure formation of the large scale structures such as galaxies, clusters of galaxies, etc.

- ## Cold Dark Matter

  The free streaming (collision-less damping, Landau damping) of dark matter from dense regions to under-dense regions smoothes out inhomogeneities for the smaller than the free streaming length scale.
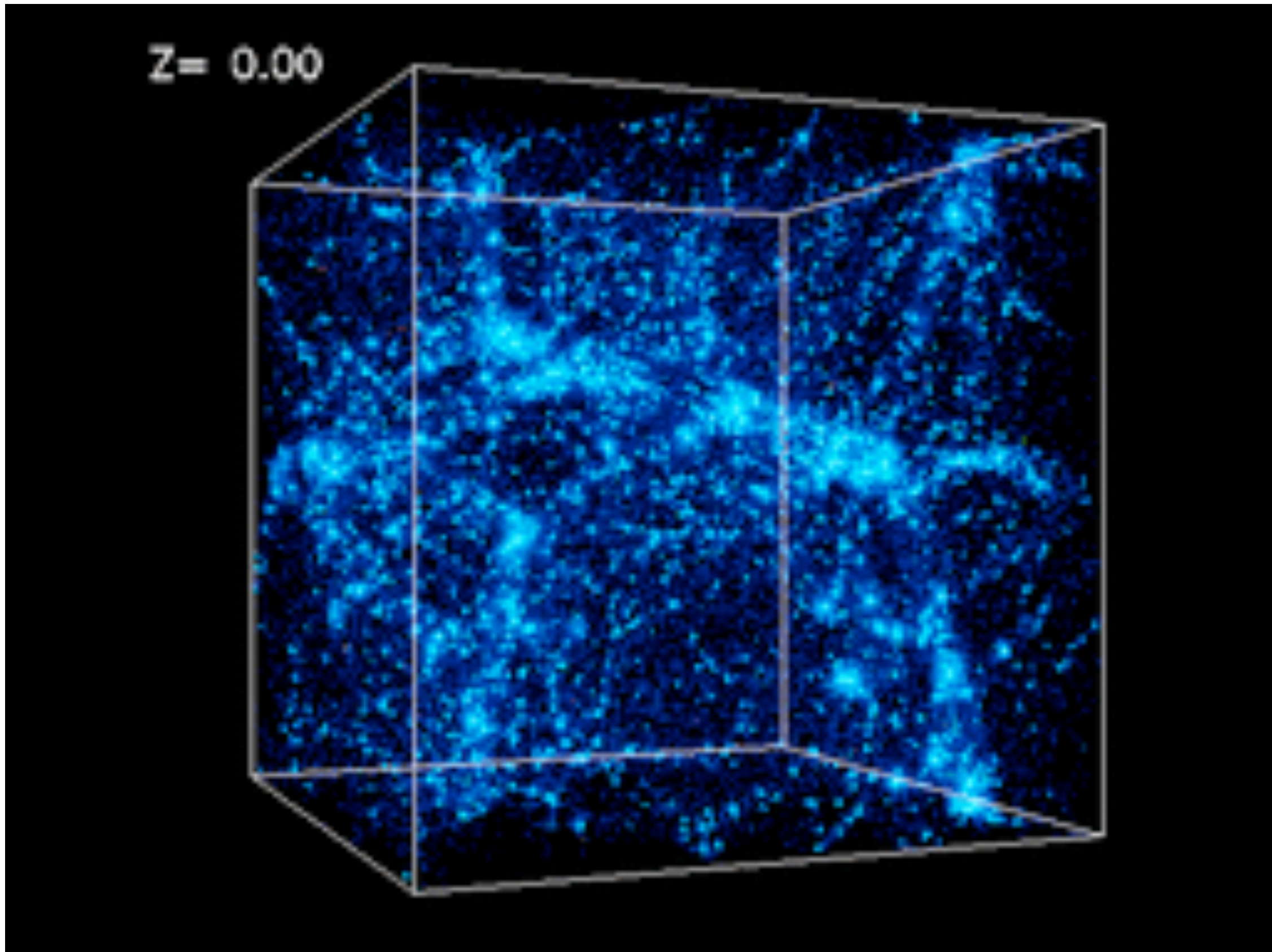
  $$\lambda_f = \int_{t_i}^{t} \frac{v(t')}{R(t')} dt'.$$

  For eV neutrinos, it corresponds to around 600 Mpc. Then Galaxy cannot form. It is hot dark matter.

  For structure formation it must be cold dark matter $\quad \lambda_f \ll 1\mathrm{Mpc}$
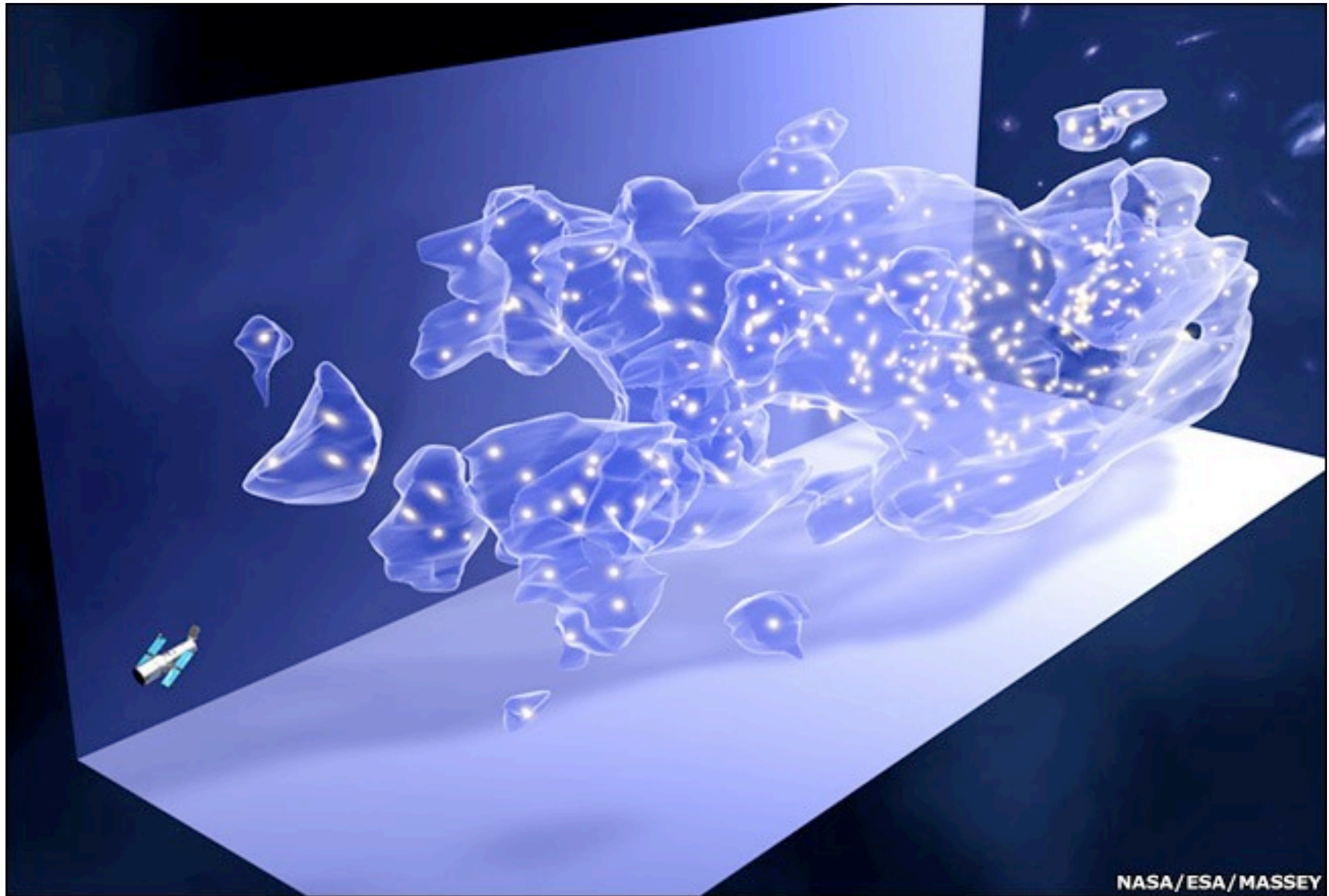
  We call warm dark matter for $\lambda_f \sim 1\mathrm{Mpc}$

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- Dark Matter distribution in the Universe and galaxies in it.

Dark Matter in the present Universe

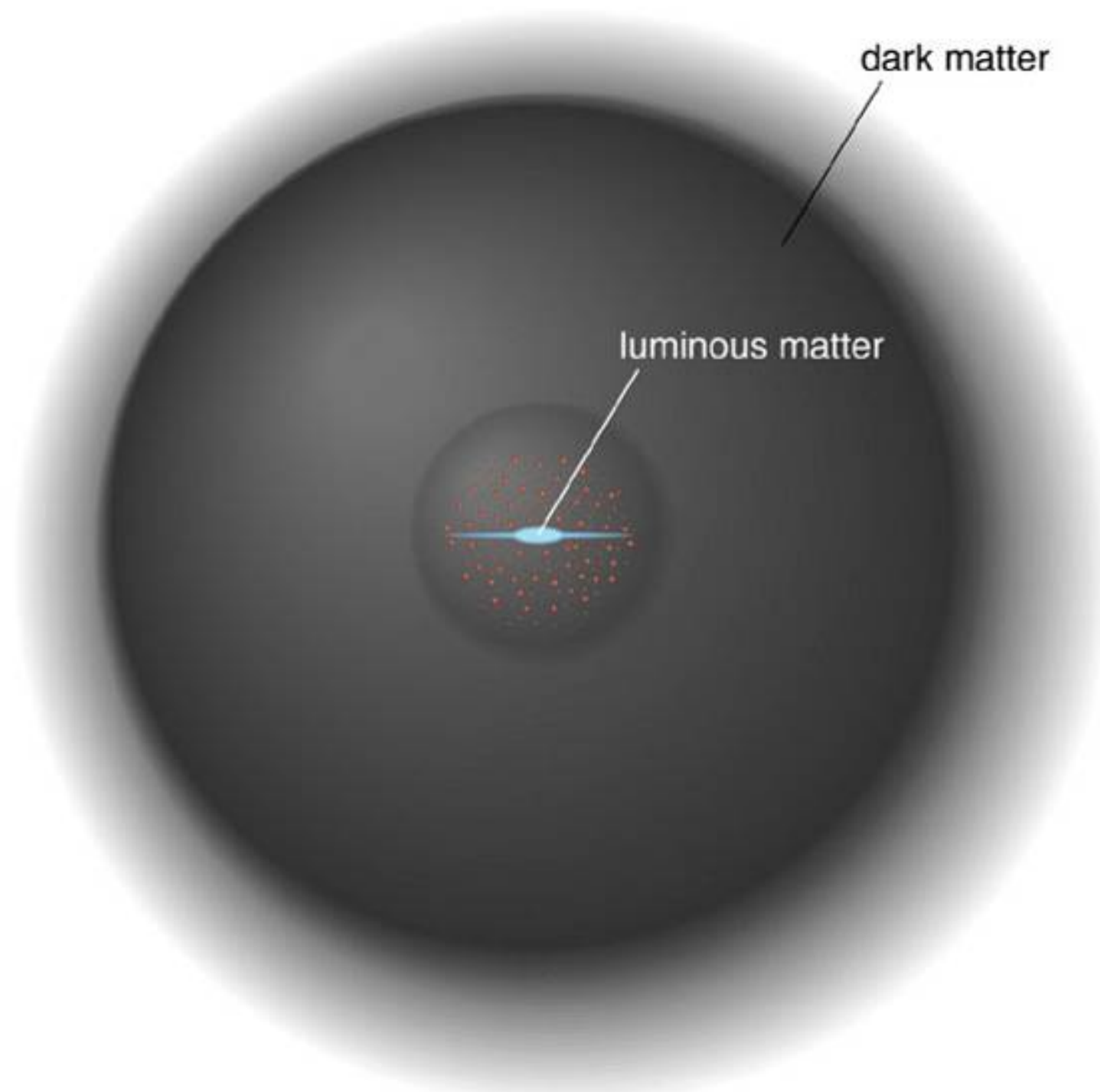- Rotation curve of spiral galaxies

- Gravitational lensing

- Velocity dispersions of galaxies in the cluster

- Bullet cluster

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Hubble's map: Dark matter may be invisible but it accounts for most of the Universe's mass. Its gravitational attraction acts as a template, pulling normal matter - the stars in their galaxy groupings into the large-scale structures we can see through telescopes.

- Image of Dark Matter around Milky Way

- How can we measure the density of DM in the galaxy?
: Rotational curve in the spiral galaxy

NGC2403

NGC2841

NGC1560

NGC2903

NGC3198

Milky Way

NGC6503

NGC7331
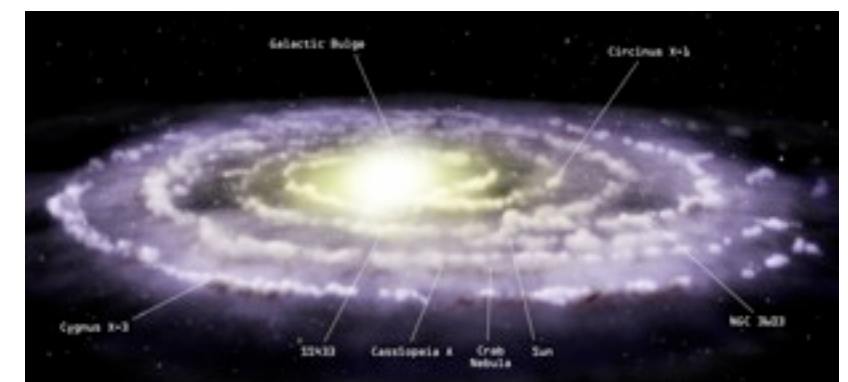
- Rotation curve of spiral galaxy
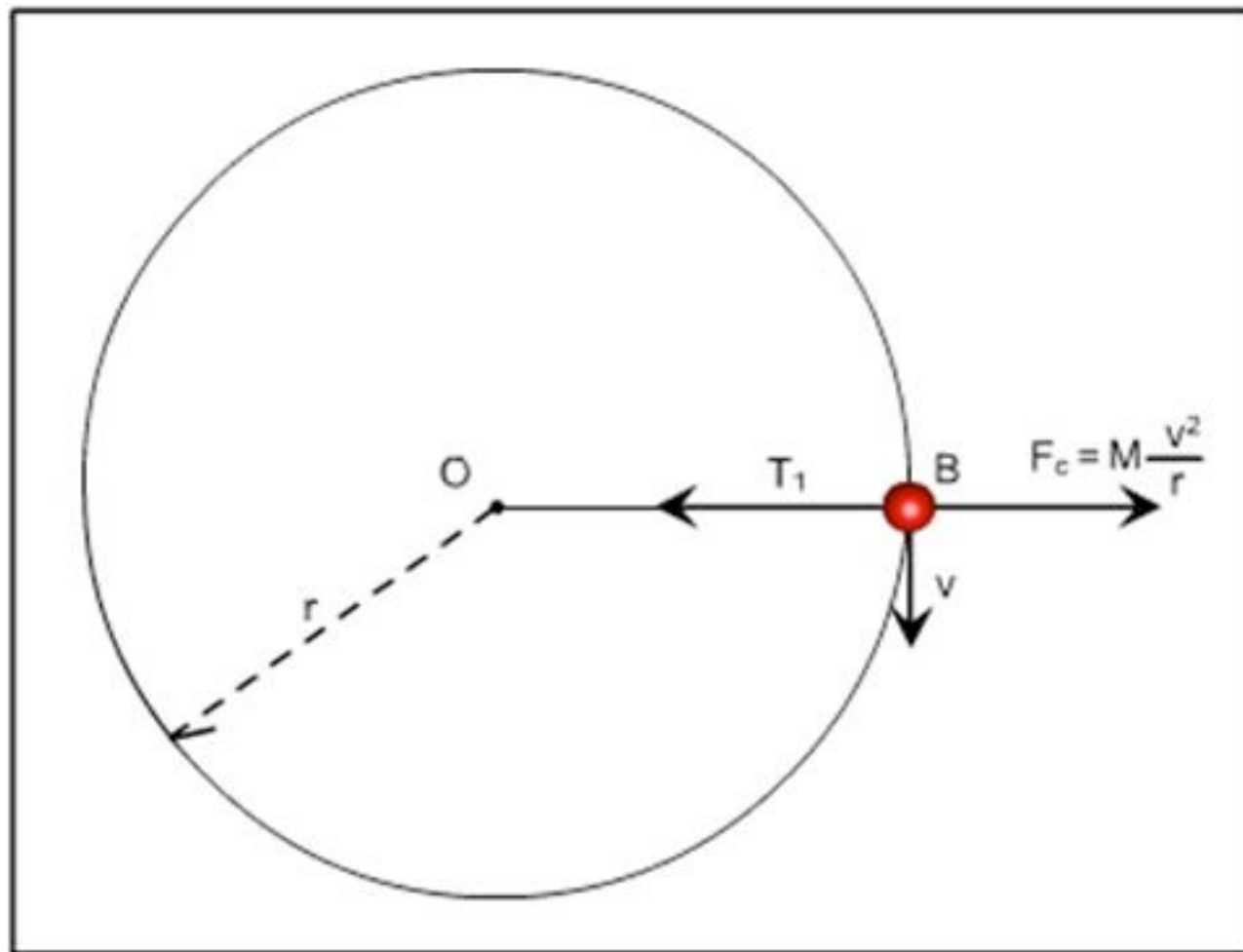
$$\frac{GMm}{r^2} = \frac{mv^2}{r}$$

$$v \propto \sqrt{\frac{GM}{r}}$$

M : mass inside the radius of beyond optical disc

$v = \text{const.}$ requires that $M = 4\pi \int_0^r \rho(r')r'^2 dr \propto r$

or $\rho(r) \propto \dfrac{1}{r^2}$

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- Rotation curve of spiral galaxy

rotational velocity [km/s]

$v \sim$ const.

measured

200

calculated

100

$v \propto \dfrac{1}{\sqrt{R}}$

50000

100000

distance from center (light years)

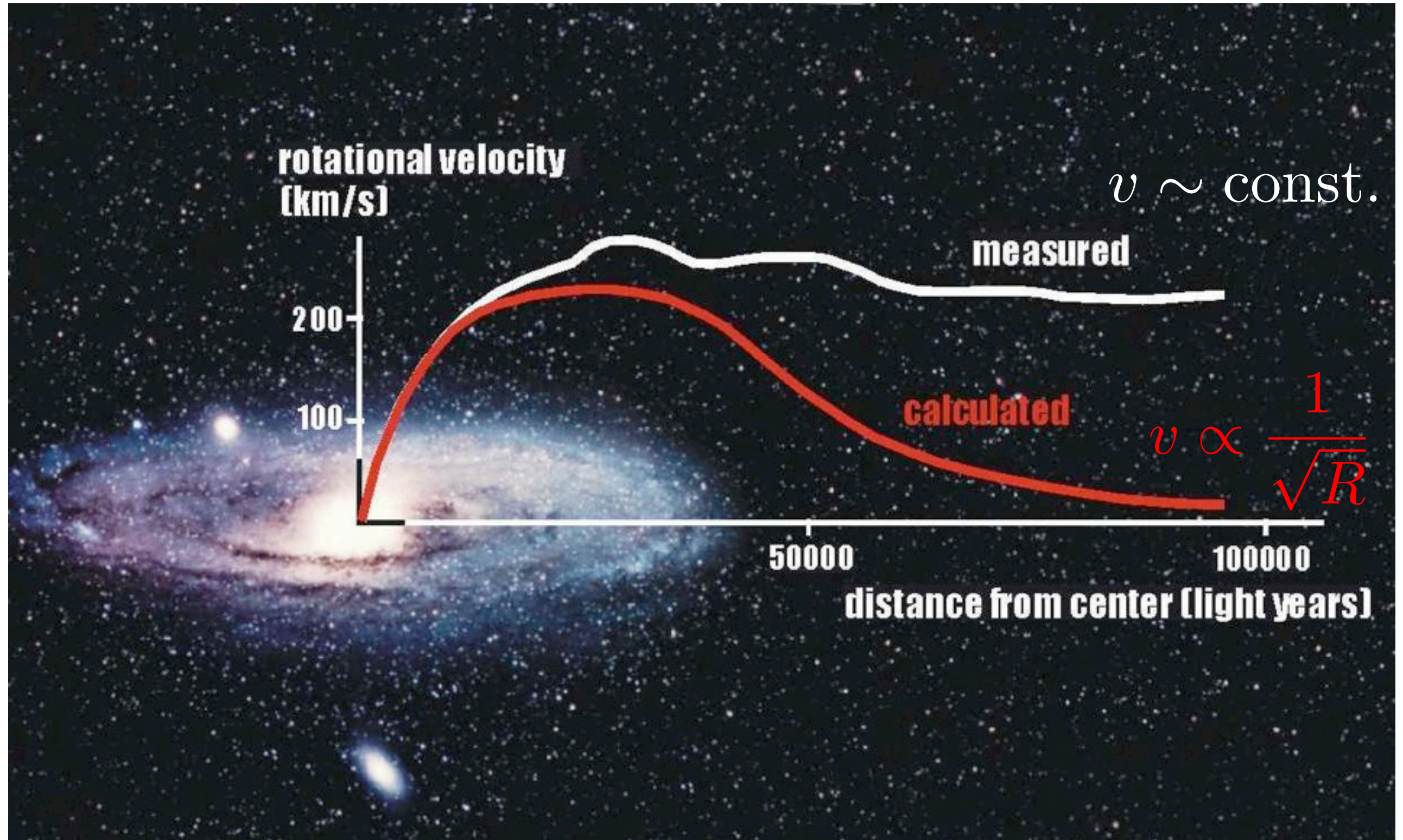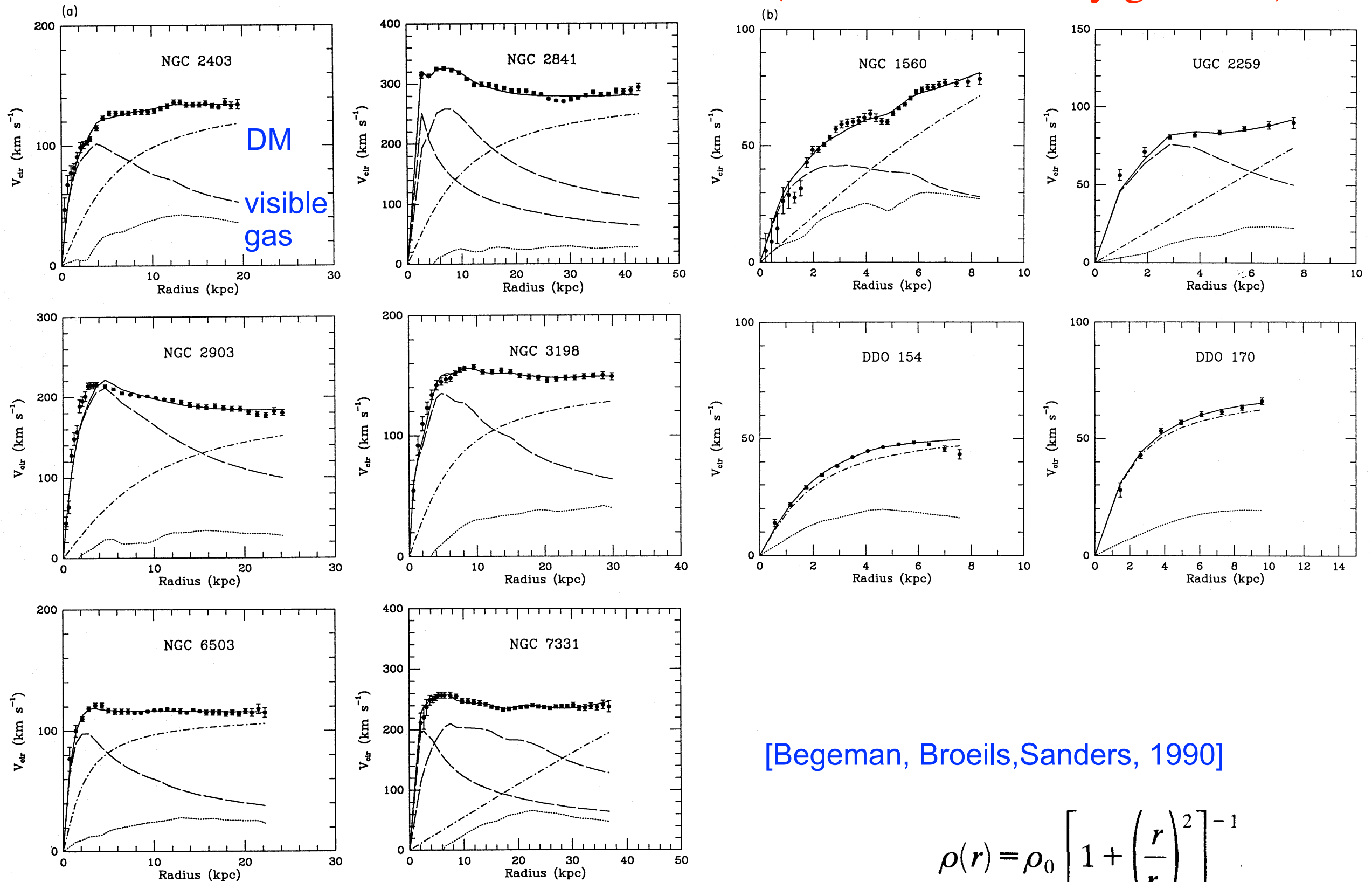(Lower luminosity galaxies)

DM

visible

gas

[Begeman, Broeils, Sanders, 1990]

$$\rho(r) = \rho_0 \left[1 + \left(\frac{r}{r_c} \right)^2 \right]^{-1}$$

Figure 1. Three-parameter dark-halo fits (solid curves) to the rotation curves of sample galaxies. The rotation curves of the individual components are also shown: the dashed curves are for the visible components, the dotted curves for the gas, and the dash-dot curves for the dark halo. The fitting parameters are the mass-to-light ratio of the disc (M/L), the halo core radius (r_c), and the halo asymptotic circular velocity (V_h). The galaxies from the sample of Begeman are shown in (a) and the lower luminosity galaxies in (b). Best-fit values for the free parameters are given in columns 2, 3 and 4 of Table 2.

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• Dark Matter around Sun in the Milky Way
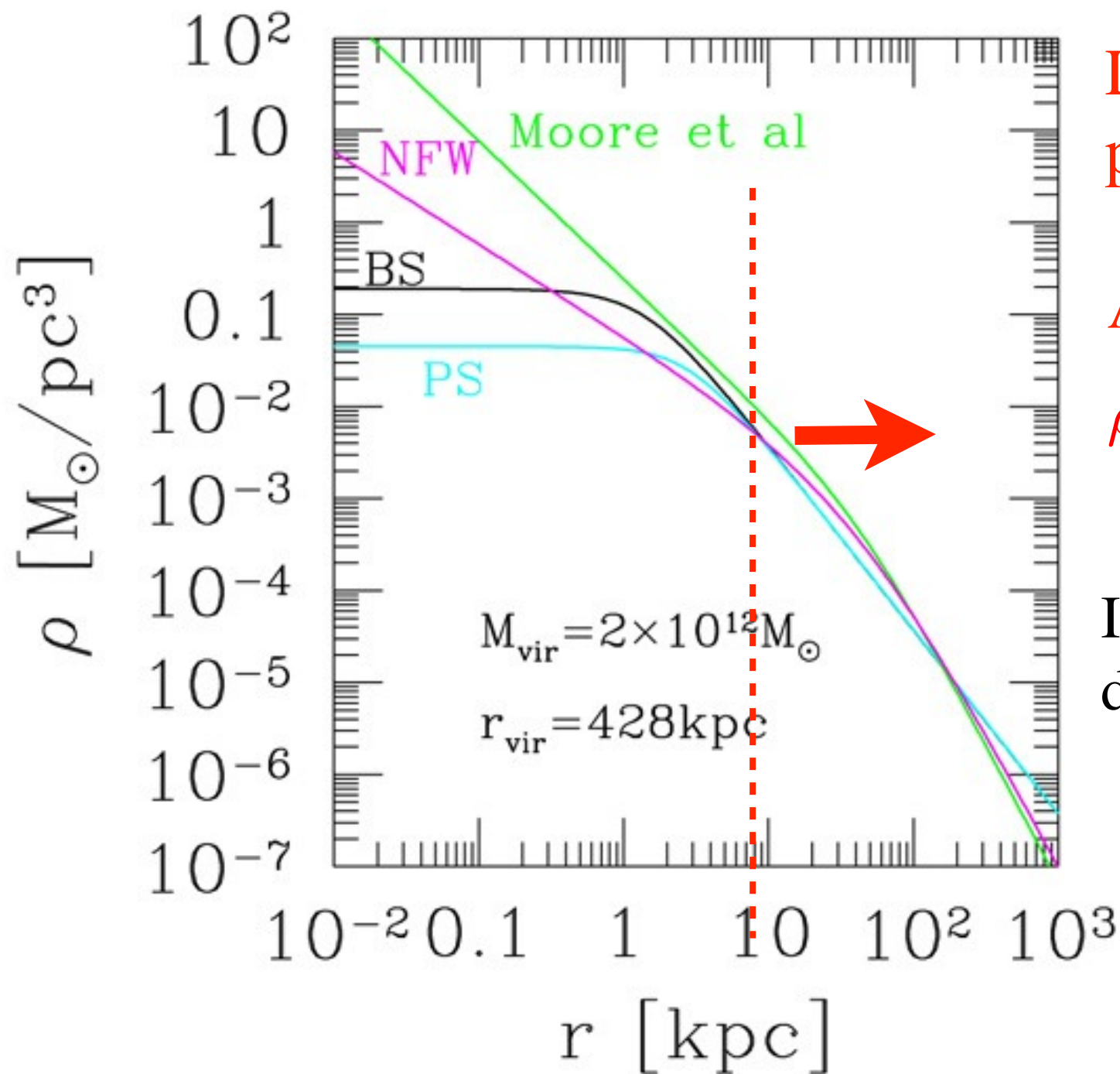
Large uncertainty in the inner part of galaxies.

Around Sun

$$\rho_\odot \simeq 0.3 \pm 0.1 \, \mathrm{GeV \, cm^{-3}}$$

$$\sim 5 \times 10^{-25} \, \mathrm{gram/cm^3}$$

Important for direct and indirect detection

Number density

$$n = \frac{\rho}{M_{\mathrm{dm}}} \sim \frac{0.3}{\mathrm{cm^3}} \left(\frac{1 \, \mathrm{GeV}}{M_{\mathrm{dm}}} \right)$$

Air density at sea level

$$\rho_{\mathrm{air}} \sim 10^{-3} \, \mathrm{gram/cm^3}$$

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4. Dark matter density is small locally but exists in the large scales. Thus they dominate the matter density in the Universe and the cumulative gravitational attraction affects the dynamics of the galaxy.

• DM in the cluster

First hints of dark matter from the velocity dispersion of galaxies in the Coma cluster. [Zwicky, 1933]

Virial Theorem $\quad \overline{\epsilon}_k = -\frac{1}{2}\overline{\epsilon}_p,$

radius R of about one million light-years (equal to 10^{24} cm) and contains 800 individual nebulae with a mass of each corresponding to 10^9 solar masses. The mass M of the whole system is therefore

$$M \sim 800 \times 10^9 \times 2 \times 10^{33} = 1.6 \times 10^{45} \text{ g}.$$

the total potential energy Ω:

$$\Omega = -\frac{3}{5}\Gamma\frac{M^2}{R} \quad \text{or} \quad \overline{\varepsilon}_p = \Omega/M \sim -64 \times 10^{12} \text{ cm}^2\text{s}^{-2}$$

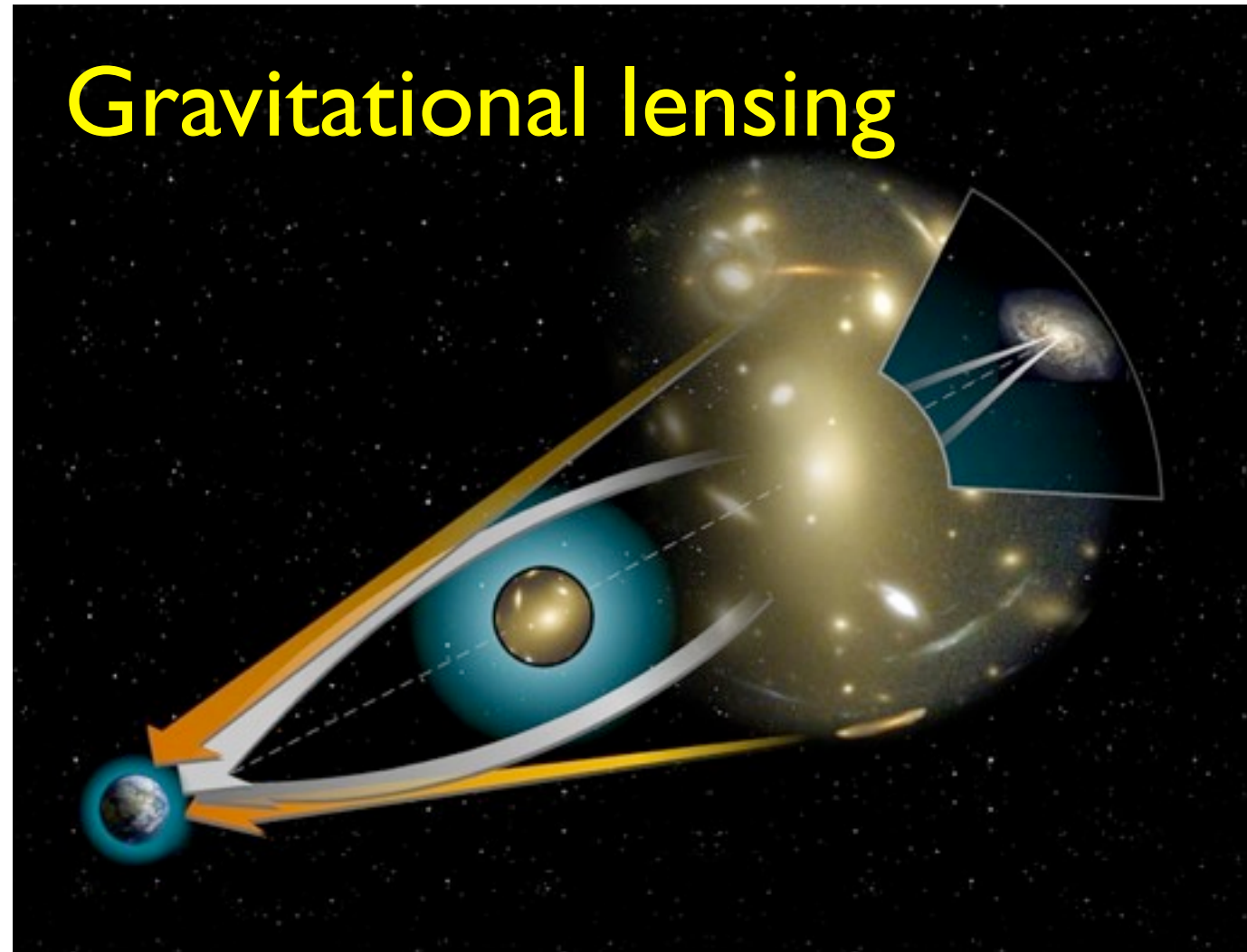$$\Gamma = \text{Gravitational constant}$$

and then

$$\overline{\varepsilon}_k = \overline{v^2}/2 \sim -\overline{\varepsilon}_p/2 = 32 \times 10^{12} \text{ cm}^2\text{s}^{-2}$$

$$\left(\overline{v^2}\right)^{1/2} = 80 \text{ km/s}. \quad \ll 1000\,\text{km}/\sec$$

Therefore the average density should be at least 100 times larger than that from the observations of luminous matter.

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- Gravitational lensing

Einstein: All forms of matter and energy cause gravity, and are affected by gravity. By observing how light is deflected, we can detect gravitational fields, and the distribution of matters.

The difference between the mass from the gravitational lensing and the luminous matter gives the dark matter distribution.

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- Bullet cluster Two colliding clusters of galaxies [Clowe et.al, 2006]
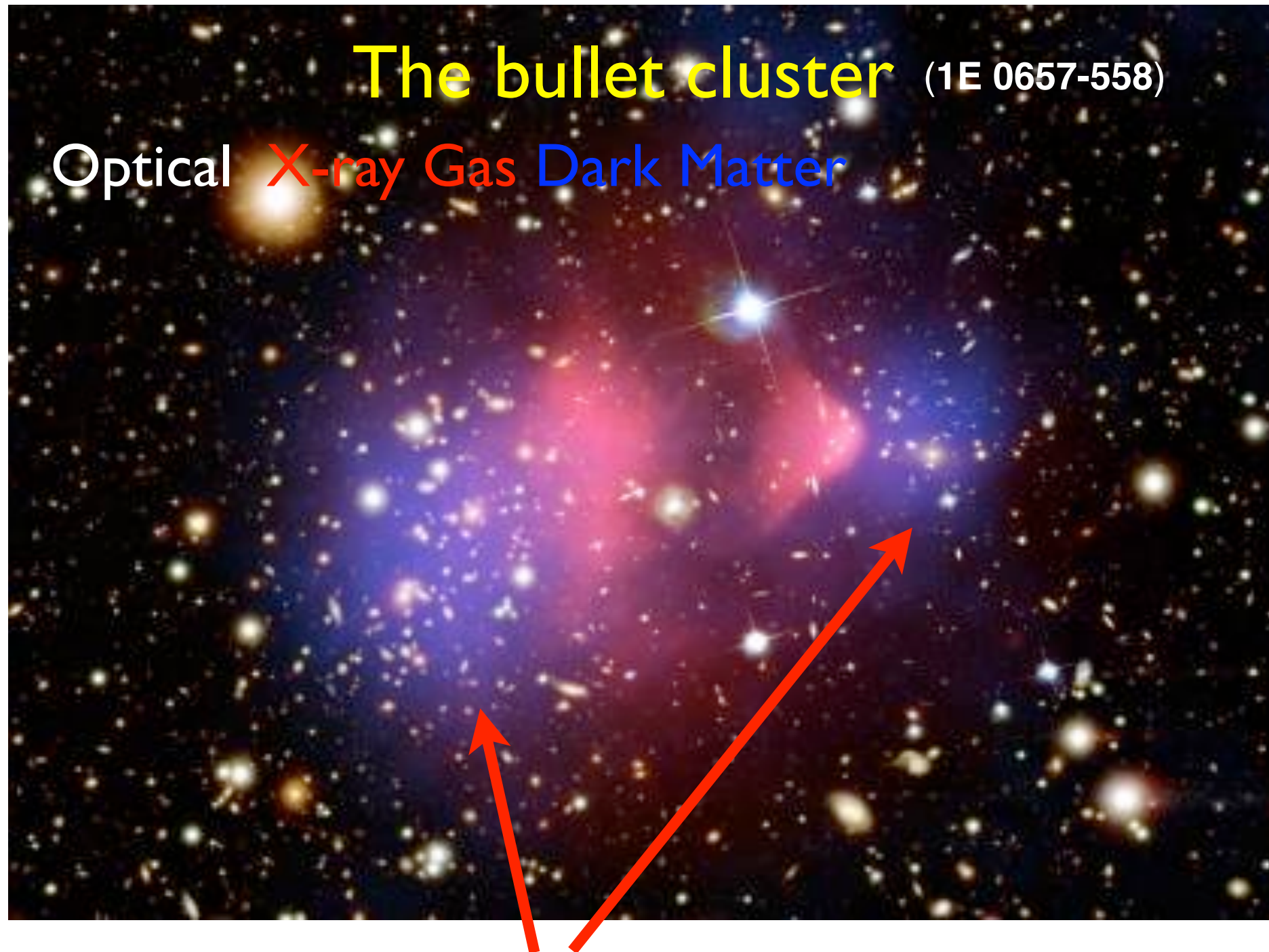
Gravitational potential is located in a Dark Matter (blue)
other than the ordinary matter (red)

The Merging clusters give upper bound on the self interaction of dark matter itself.

Maruša Bradač

Challenge

Bullet   A520   Baby Bullet   Musket Ball   Pandora's   SIDM

$\sigma/m < 0.7 \text{ cm}^2\text{g}^{-1}$ $\sigma/m < 4 \text{ cm}^2\text{g}^{-1}$ $\sigma/m < 3 \text{ cm}^2\text{g}^{-1}$
Randall et al. 2008   Bradač et al. 2008   Merten et al. 2011

$\sigma/m < 3 \text{ cm}^2\text{g}^{-1}$ $\sigma/m < 7 \text{ cm}^2\text{g}^{-1}$

Clowe et al. 2012   Dawson et al. 2012

* Will we ever do better?
$$\sigma/m \lesssim 10^{-24} \text{ cm}^2/\text{GeV}$$

* $\sigma/m < 0.05 \text{ cm}^2\text{g}^{-1}$ will be effectively the same as CDM in terms of observables of structure (halo profiles, shapes, substructure

5. Dark matter show their existence in the cluster scales by gravitational interaction.

What is Dark Matter?

- Dark Matter properties
- Production of Dark Matter

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Dark Matter as a particle must (be)
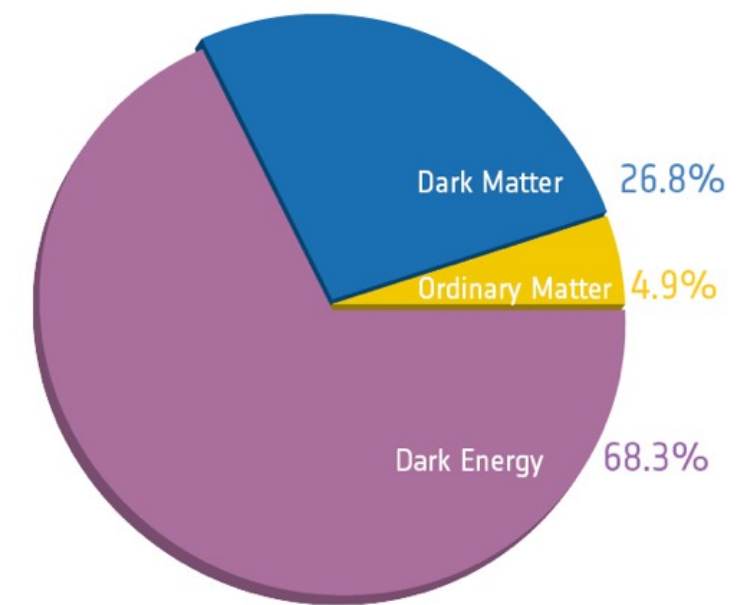
1. have existed from early Universe up to now and located around galaxies, clusters

➡ stable or lifetime longer than the age of universe

2. neutral : NO electromagnetic interaction

Wednesday, June 5, 13

➡ Only upper bounds on the self interaction

$$\sigma/m \lesssim 10^{-24} \ \mathrm{cm}^2/\mathrm{GeV} \quad \text{from bullet cluster}$$

No lower bound down to gravity!

In fact all the evidences are gravitational.

3. 25% of the present energy density of the universe

4. cold (or warm) : non-relativistic to seed the structure formation

Dark matter candidate in the Standard Model?

The only EM neutral and stable particles, neutrino, was a candidate for hot dark matter.

Neutrinos decouple from a relativistic thermal bath at T~ 1 MeV in the early Universe with a relic density today as

$$\Omega_\nu h^2 = \frac{\sum_i m_{\nu_i}}{90 \text{ eV}}$$

With observational constraints

$$\sum m_\nu < 1.3 \, \text{eV} \quad (95\% \, CL) \qquad \text{It is too small!}$$

[Komatsu et al., 2011]

The fluctuations are damped smaller than the neutrino free streaming scale

$$\lambda_{FS} \sim 20 \left(\frac{30 \text{ eV}}{m_\nu} \right) \text{ Mpc} \qquad \text{It is too hot!} \quad \text{top-down structure formation}$$

The standard theory of structure formation prefers to cold dark matter.

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- Candidates of dark matter

    : Motivated from beyond Standard Model

Strong CP problem : axion

Neutrino sector : sterile neutrino, RH neutrino, Majoron
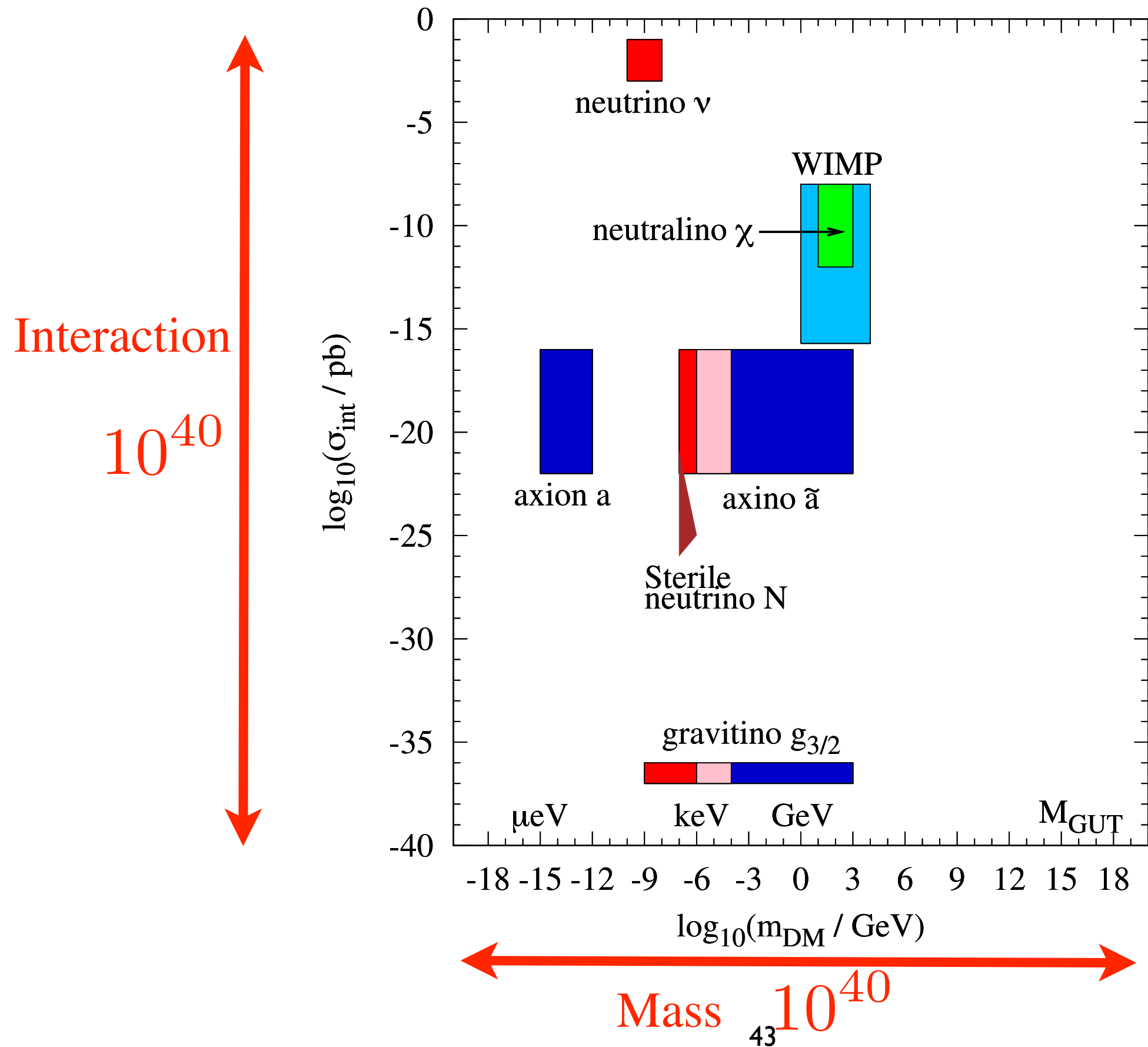
Technicolor : Techni-baryon, Techni-dilaton

Supersymmetry : neutralino, gravitino, axino, scalar neurino

Extra dimension : Kaluza-Klein particle

and WIMPzillas, Balck-Holes, light volume moduli, dilaton

and more ....

- Candidates of dark matter beyond Standard Model

Interaction 10^{40}

Mass 10^{40}

Dark Matter in a theory

0. existence : beyond Standard Model, introducing new particles

1. stability : new symmetry to protect decay (or it is slightly broken)

   kinematically forbidden / suppressed

2. neutral : EM charge singlet

3. weakly interacting or much weaker down to gravitational interaction

4. 22% of universe : relic density of DM from early Universe

5. cold dark matter : related to the generation mechanism of DM

Dark Matter in a theory

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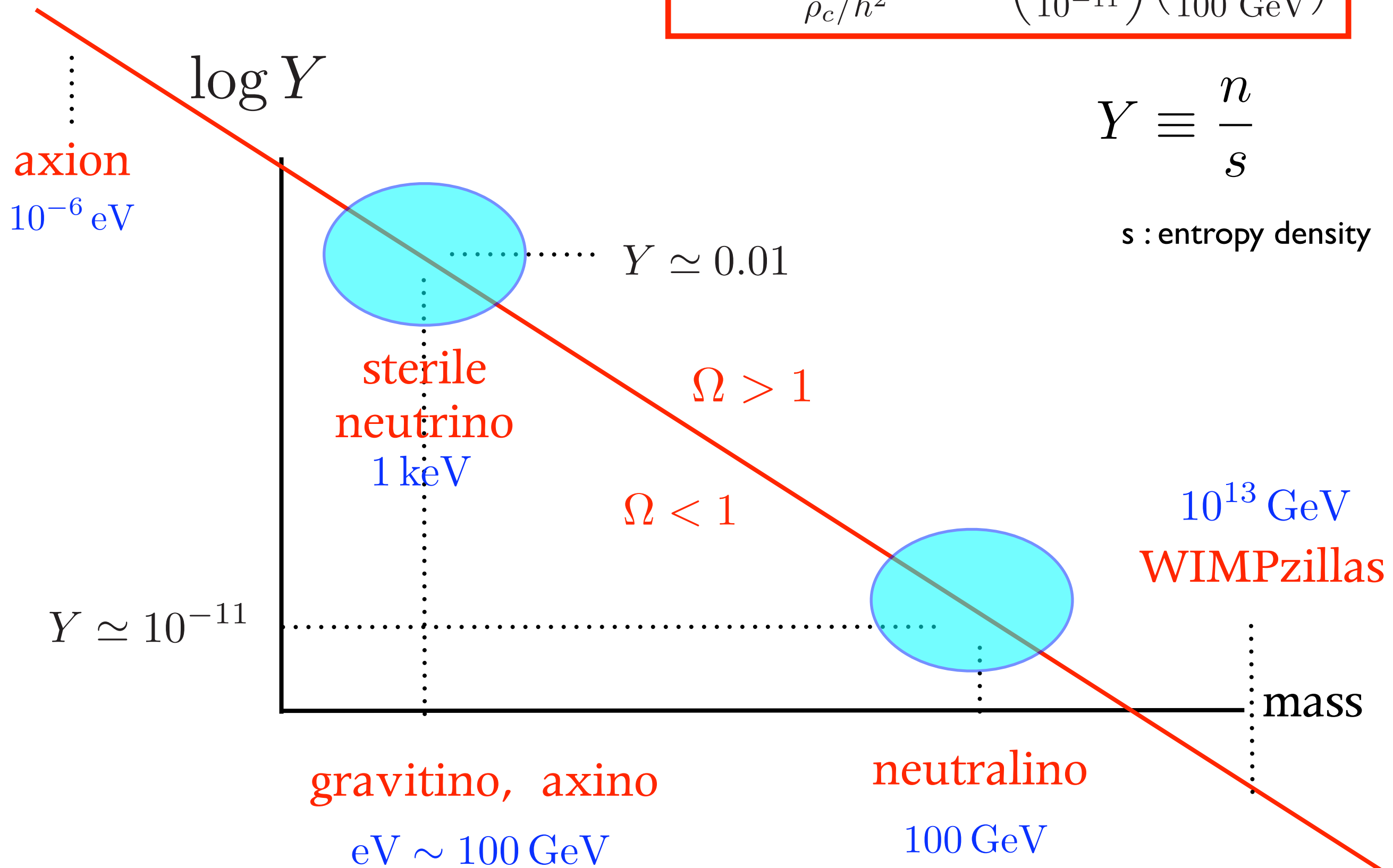
The relic density of dark matter

$$\Omega_{\mathrm{DM}} \simeq 0.26$$

Relic density of dark matter

$$\Omega h^2 \equiv \frac{\rho}{\rho_c/h^2} \simeq 0.28 \left(\frac{Y}{10^{-11}}\right)\left(\frac{m}{100\ \text{GeV}}\right)$$

$\log Y$

$Y \equiv \dfrac{n}{s}$

s : entropy density

axion

$10^{-6}\ \text{eV}$

$Y \simeq 0.01$

sterile
neutrino

$1\ \text{keV}$

$\Omega > 1$

$\Omega < 1$

$10^{13}\ \text{GeV}$

WIMPzillas

$Y \simeq 10^{-11}$

mass

gravitino, axino

$\text{eV} \sim 100\ \text{GeV}$

neutralino

$100\ \text{GeV}$

- How the DM are generated? : Production mechanism

Thermal production

    Freeze-out from thermal equilibrium
        : WIMP, Asymmetric DM

    Already decoupled
        : E-WIMP (Super WIMP), FIMP

Non-thermal production

        : Oscillating DM or produced by decays of unstable objects

- How much cold? : Hot, Warm or Cold

Free streaming length of the dark matter

- Expanding Universe and decoupling

In the non-Expanding Universe and thermal equilibrium

After enough long time much larger than the interaction time, the system leads to the thermal equilibrium (chemical and kinetic).

$$t \gtrsim t_{\mathrm{int}} \simeq (n v \sigma)^{-1}$$

In the expanding Universe and decoupling

The expansion is faster than the interaction, the particles cannot maintain the equilibrium and decoupled from the thermal plasma.

equilibrium $\quad n v \sigma > H$

decoupling $\quad n v \sigma < H$

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- Expanding Universe and decoupling

$$n v \sigma > H$$

Particles in thermal equilibrium, FD and BE distribution

In the relativistic limit (at high temperature), $(m \ll T)$,

$$\rho \propto T^4 \qquad n \propto T^3 \qquad \longrightarrow \qquad Y \equiv \frac{n}{s} = \text{const.}$$

$$s(t) R(t)^3 = \text{const.} \quad \text{in an iso-entropic Universe}$$

$$\longrightarrow s \propto R^{-3} \propto T^3$$

In the non-relativistic limit (at low temperature), $m \gg T$

$$\rho = mn \quad n = g \left(\frac{mT}{2\pi} \right)^{3/2} e^{-(m-\mu)/T} \quad \text{Boltzmann dist.}$$

$$\longrightarrow Y \propto e^{-m/T}$$

$$Y \equiv \frac{n}{s}$$

Y(x)/Y(x0)

1

$$n = \frac{\zeta(3)}{\pi^2} g T^3$$

$$n = g\left(\frac{mT}{2\pi}\right)^{3/2} e^{-m/T}$$

relativistic   non-relativistic   ← thermal equilibrium

m/Treh   1   10   100   x=m/T

time

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Particles after decoupled from thermal bath

Relativistic matter $\qquad \rho_r \sim E(t)\,n(t) \propto R(t)^{-4}$

Non-Relativistic matter $\quad \rho_m \sim M\,n(t) \propto R(t)^{-3}$

$$\Longrightarrow \qquad Y \equiv \frac{n}{s} = \text{const.}$$

Comoving abundance Y is conserved after decoupling.

Example : neutrinos

$$n \sim T^3 \qquad v = c \qquad \sigma \sim G_F^2 E^2 \sim G_F^2 T^2 \qquad H \sim \frac{T^2}{M_P}$$

Therefore $\quad n v \sigma = H \quad$ gives

$$T_f \sim (G_F^2 M_P)^{-1/3} \simeq (10^{-10} \times 10^{18})^{-1/3} \sim 1 \text{ MeV} \quad \gg m_\nu$$

The neutrinos decouple when they are fully relativistic.
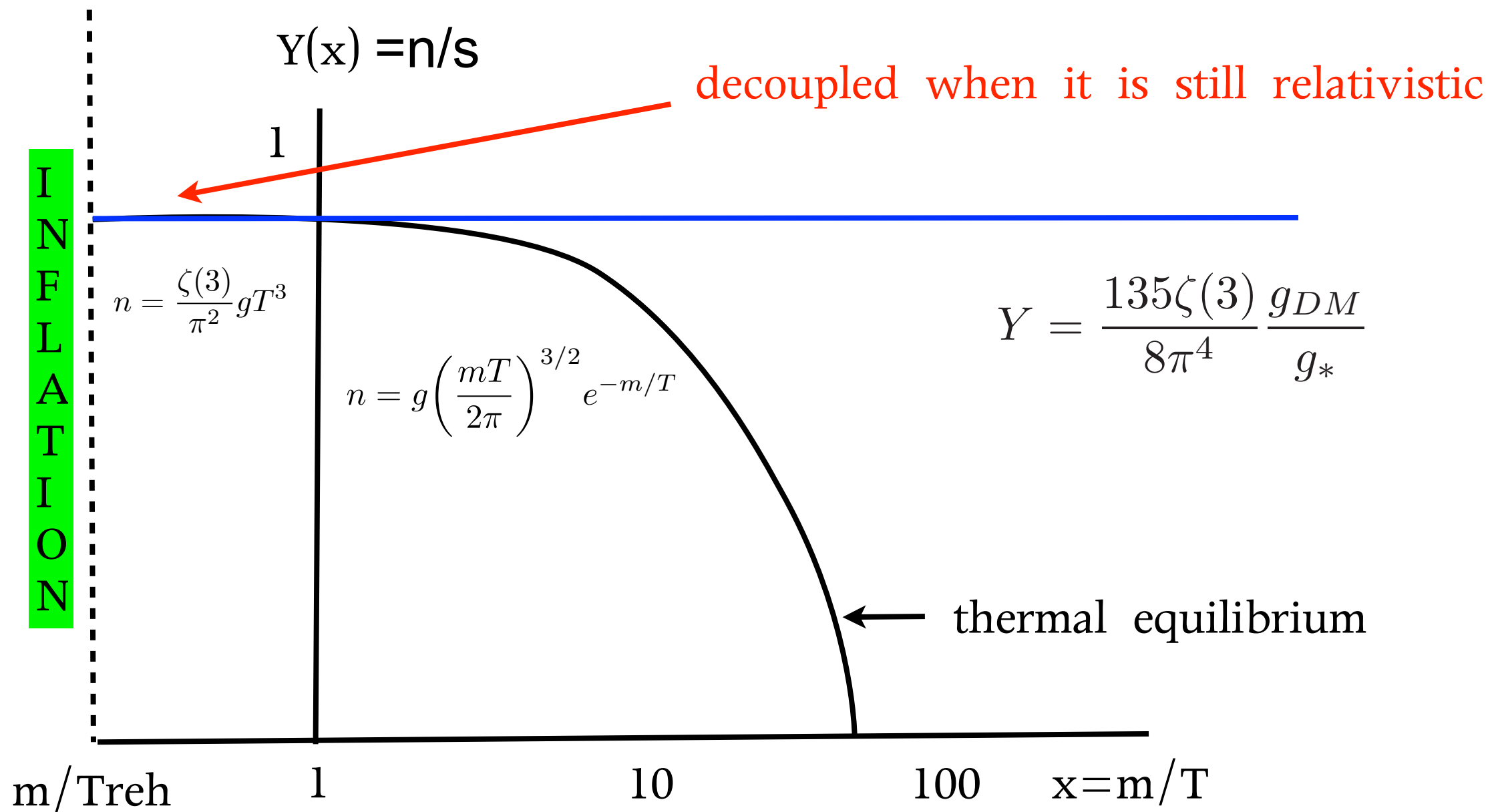
The comoving abundance is

$$Y(T_0) = Y(T_f) = \frac{3\zeta(3)gT^3}{4\pi^2} / \frac{2\pi^2 g_* T^3}{45} = \frac{135\zeta(3)g}{8\pi^4 g_*} \sim 0.1$$

Therefore the present relic density is

$$\boxed{\Omega_\nu h^2 = \frac{\sum_i m_{\nu_i}}{90 \text{ eV}}}$$

Hot relics: Weakly Interacting Light Particle

Initially the particles are in the thermal equilibrium and decoupled when it is relativistic in the expanding Universe.

Warm dark matter:

$$\Omega h^2 = \frac{\rho}{\rho_c} h^2 = mY \frac{sh^2}{\rho_c} = 2.8 \times \left(\frac{Y}{10^{-8}}\right)\left(\frac{m}{\text{GeV}}\right)$$

$$\Omega_{\text{WDM}} h^2 \simeq \left(\frac{m}{1\,\text{keV}}\right)\left(\frac{106.75}{g_*}\right)$$

Light gravitinos [Pagels, Primack, 1982]

Sterile neurinos [Dodelson, Widrow, 1994]

Warm dark matter can erase small scale fluctuations,

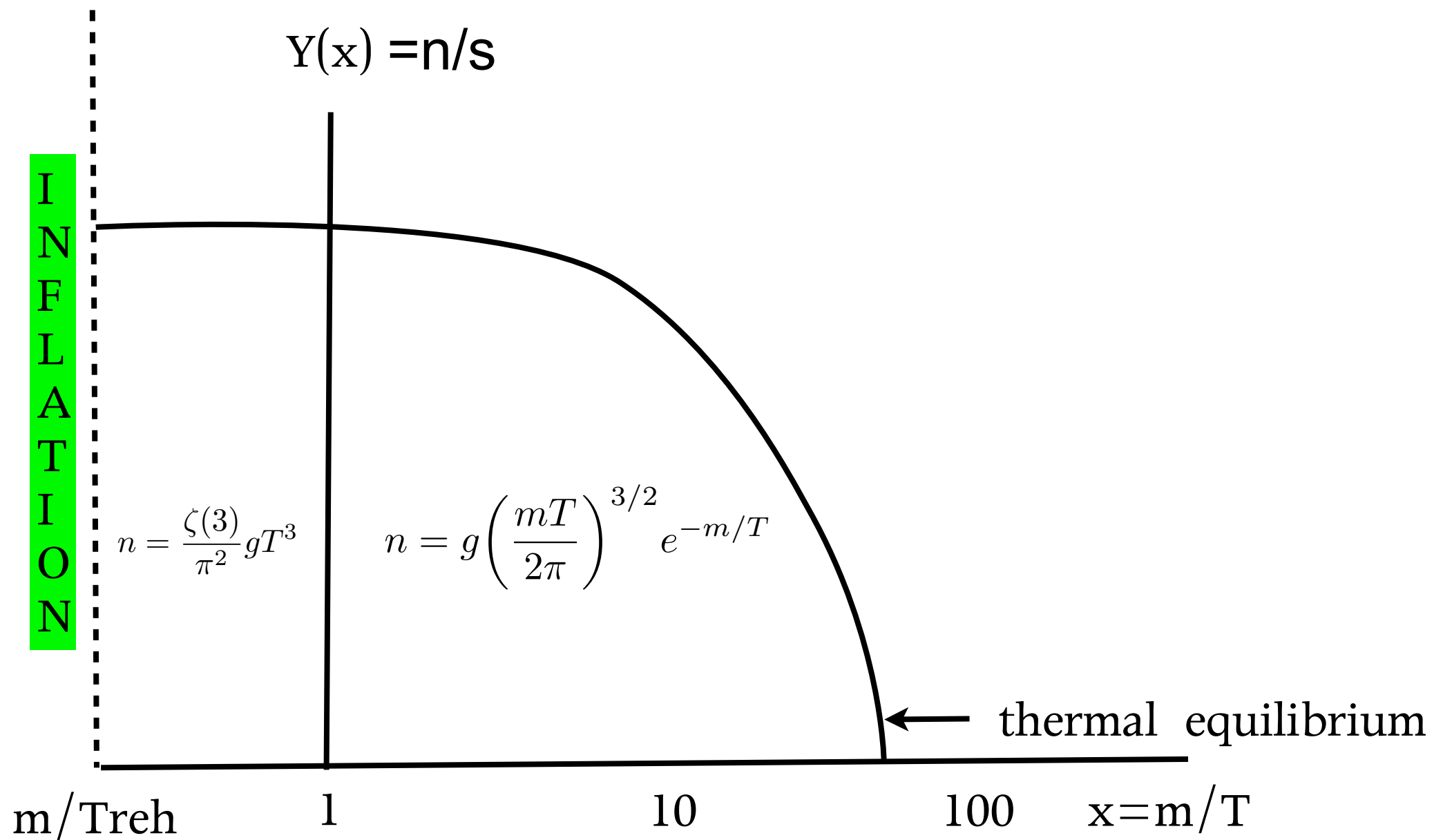$$m \gtrsim 1\,\text{keV}$$

[Seljak, Makarov, McDonald, Trac, 2008]

[Boyarsky, Lesgourgues, Ruchayskiy, Viel, 2009]

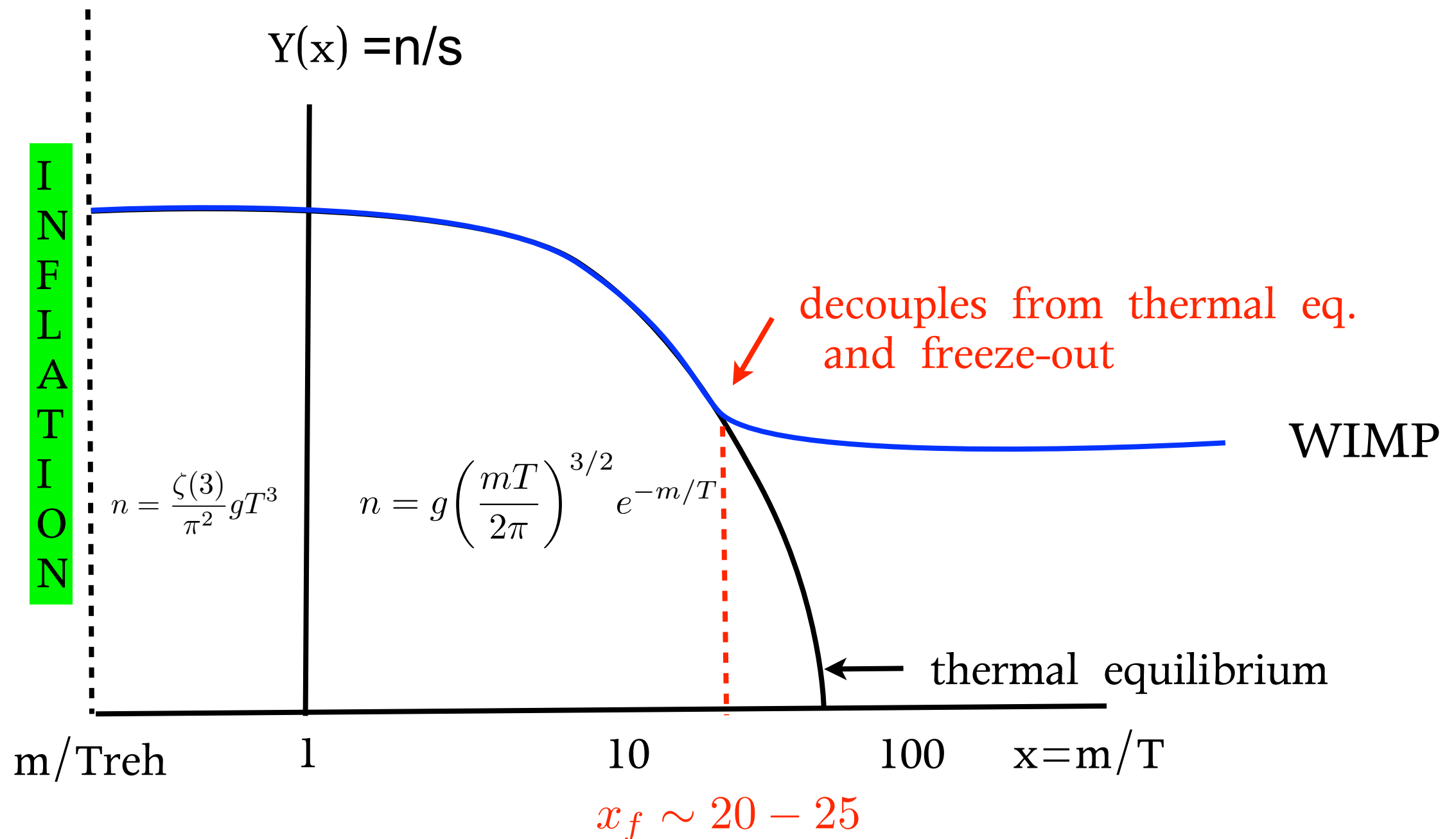Possible tension between relic density and the structure formation.

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WIMP : Weakly Interacting Massive Particle

Initially the particles are in the thermal equilibrium and decoupled when it is non-relativistic in the expanding Universe.

WIMP : Weakly Interacting Massive Particle

Initially the particles are in the thermal equilibrium and decoupled when it is non-relativistic in the expanding Universe.

Y(x) =n/s

INFLATION

$$n = \frac{\zeta(3)}{\pi^2} g T^3$$

$$n = g \left(\frac{mT}{2\pi} \right)^{3/2} e^{-m/T}$$

decouples from thermal eq. and freeze-out

WIMP

thermal equilibrium

m/Treh   1   10   100   x=m/T

$$x_f \sim 20 - 25$$

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WIMP : freeze-out temperature

$$3Hn_{eq} \simeq \langle \sigma_{ann} v \rangle n_{eq}^2$$

$$H = \sqrt{\frac{8\pi G}{3}\rho} = \sqrt{\frac{8\pi G}{3}\frac{\pi^2}{30}g_* T^4}$$

$$n = g\left(\frac{mT}{2\pi}\right)^{3/2} e^{-m/T}$$

$$x_f \equiv \frac{m}{T_f} = \log\left[\frac{\langle \sigma v \rangle g_x (mT/(2\pi))^{3/2}}{3\sqrt{\frac{8\pi G}{3}\frac{\pi^2}{30}g_* T^4}}\right] \simeq 20 - 25$$

WIMP : Relic density

$$Y \simeq \left. \frac{n_X}{s} \right|_{T_f} \simeq \frac{3H}{s\langle \sigma v \rangle} \sim \frac{1}{\langle \sigma v \rangle M_P T_f} \simeq \frac{x_f}{\langle \sigma v \rangle M_P m_X}$$

$$\Omega h^2 = 2.8 \left(\frac{Y}{10^{-8}} \right) \left(\frac{m}{\mathrm{GeV}} \right)$$

$$\simeq \frac{2.5 \times 10^{-10}\,\mathrm{GeV}}{\langle \sigma_{\mathrm{ann}} v \rangle} \simeq \frac{3 \times 10^{-27}\,\mathrm{cm}^3\,\mathrm{sec}^{-1}}{\langle \sigma_{\mathrm{ann}} v \rangle}$$

[Benjamin W. Lee and Steven Weinberg, PRL 1977]

WIMP with EW cross section $\quad \langle \sigma_{\mathrm{ann}} v \rangle \sim \dfrac{\alpha^2}{(300\,\mathrm{GeV})^2} \sim 10^{-9}\,\mathrm{GeV}^{-2}$
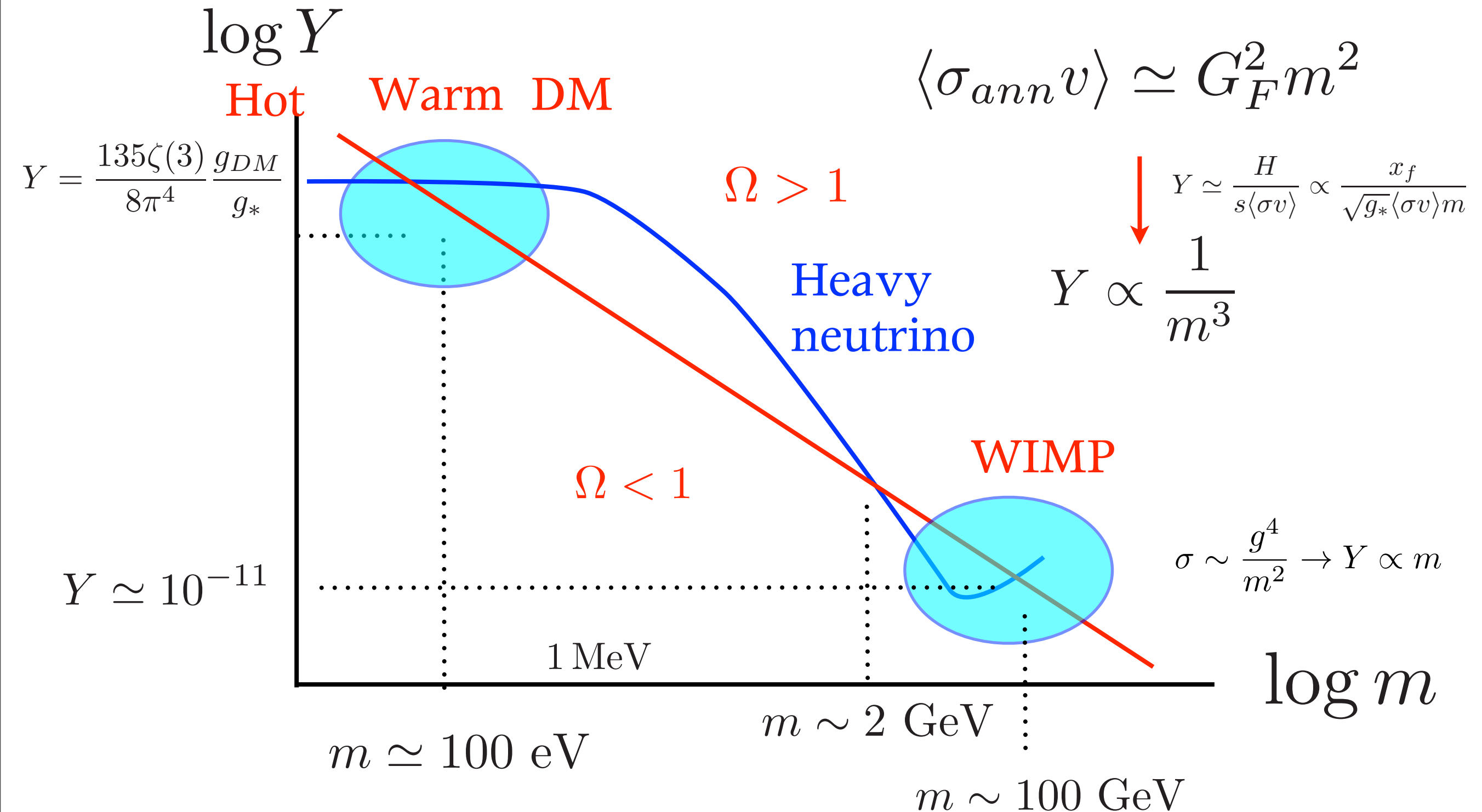
gives correct relic density for dark matter.

Relic density : weakly interacting particles

$$\langle \sigma_{ann} v \rangle \simeq G_F^2 m^2$$

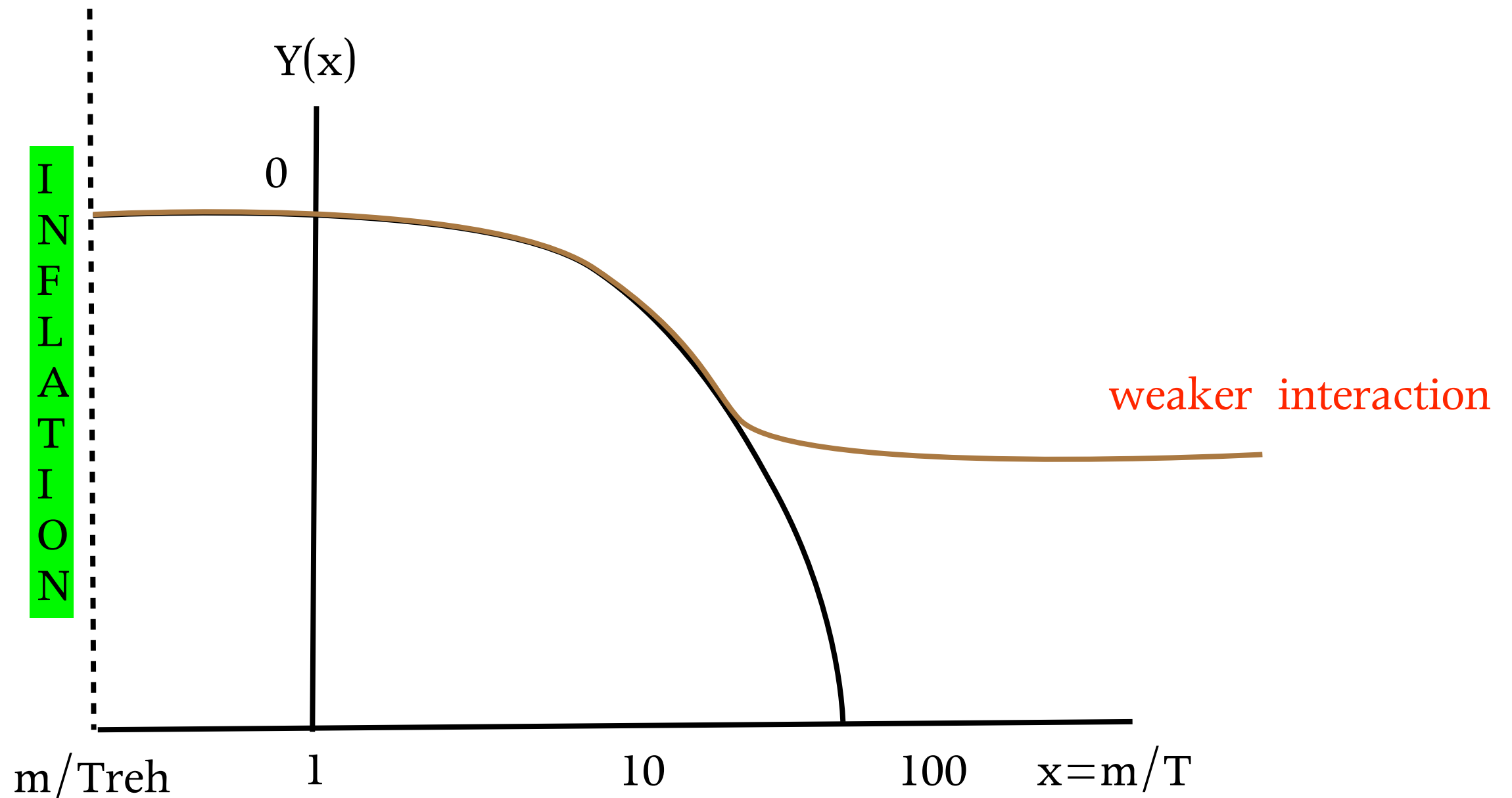$$Y = \frac{135\zeta(3)}{8\pi^4} \frac{g_{DM}}{g_*}$$

$$Y \simeq \frac{H}{s\langle\sigma v\rangle} \propto \frac{x_f}{\sqrt{g_*}\langle\sigma v\rangle m}$$

$$Y \propto \frac{1}{m^3}$$

Heavy neutrino

$$Y \simeq 10^{-11}$$

$$\sigma \sim \frac{g^4}{m^2} \rightarrow Y \propto m$$

$1\,\mathrm{MeV}$

$\log m$

$m \simeq 100\,\mathrm{eV}$

$m \sim 2\,\mathrm{GeV}$

$m \sim 100\,\mathrm{GeV}$

$\log Y$

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Relic density : weakly interacting particles

$$\langle \sigma_{ann} v \rangle \simeq G_F^2 m^2$$

$\log Y$

Hot   Warm DM

$$Y = \frac{135\zeta(3)}{8\pi^4}\frac{g_{DM}}{g_*}$$

$\Omega > 1$

$$Y \simeq \frac{H}{s\langle \sigma v \rangle} \propto \frac{x_f}{\sqrt{g_*}\langle \sigma v \rangle m}$$

Heavy
neutrino

$$Y \propto \frac{1}{m^3}$$

$\Omega < 1$

WIMP

$$Y \simeq 10^{-11}$$

$$\sigma \sim \frac{g^4}{m^2} \to Y \propto m$$

$1\,\mathrm{MeV}$

$\log m$

$m \sim 2\,\mathrm{GeV}$

$m \simeq 100\,\mathrm{eV}$

$m \sim 100\,\mathrm{GeV}$
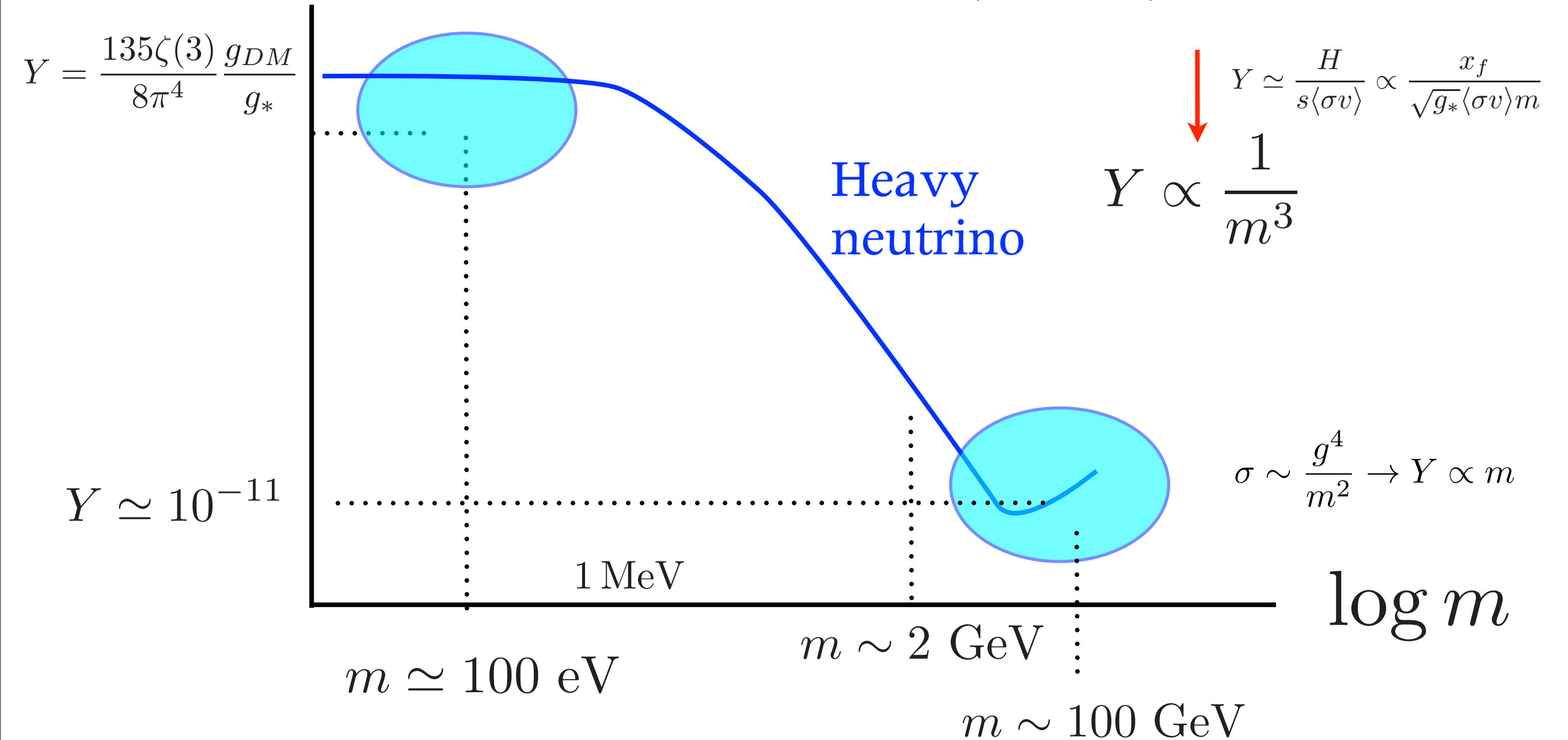
* Lee-Weinberg bound : $m \gtrsim 2\,\mathrm{GeV}$ for heavy neutrinos not to overclose
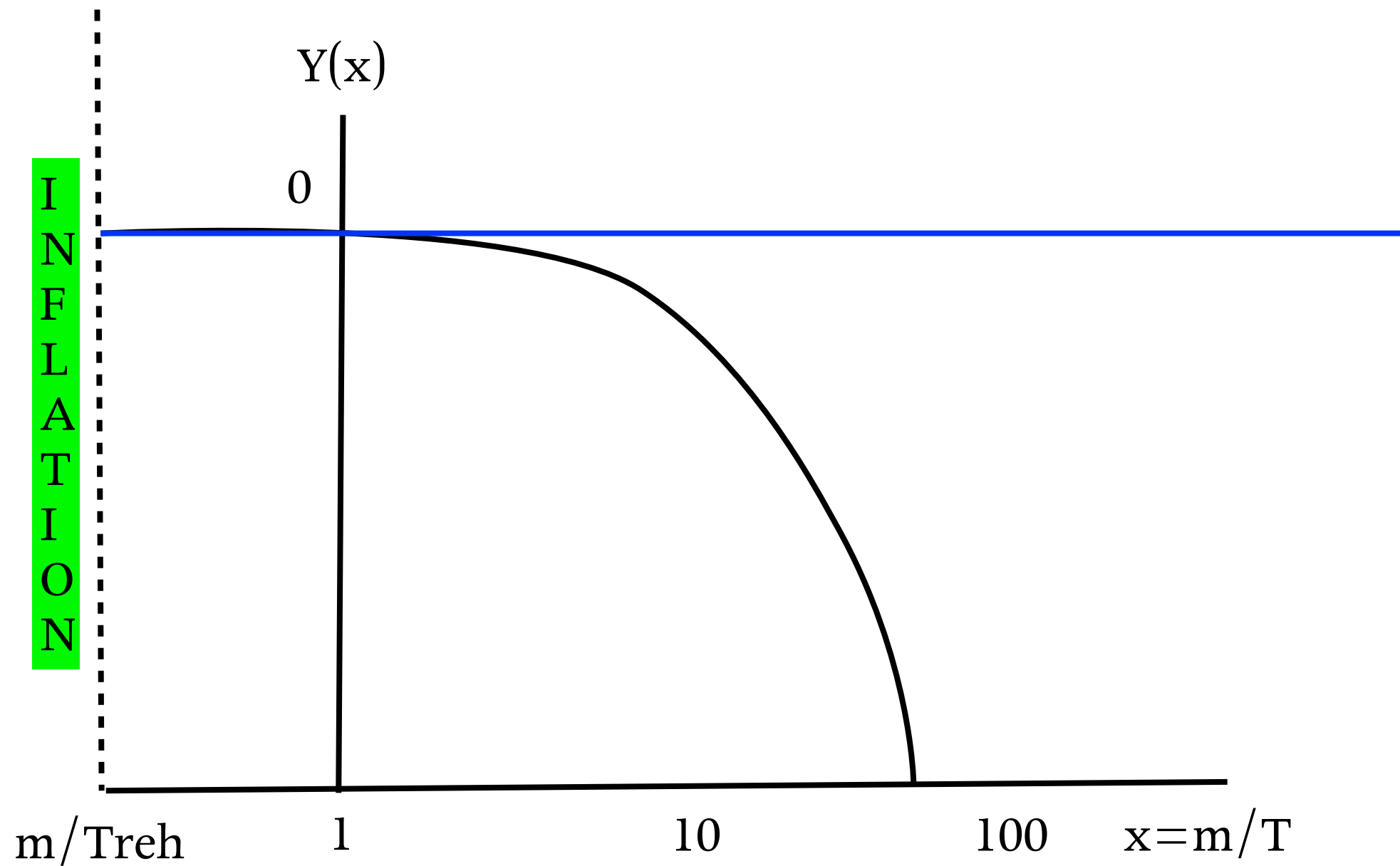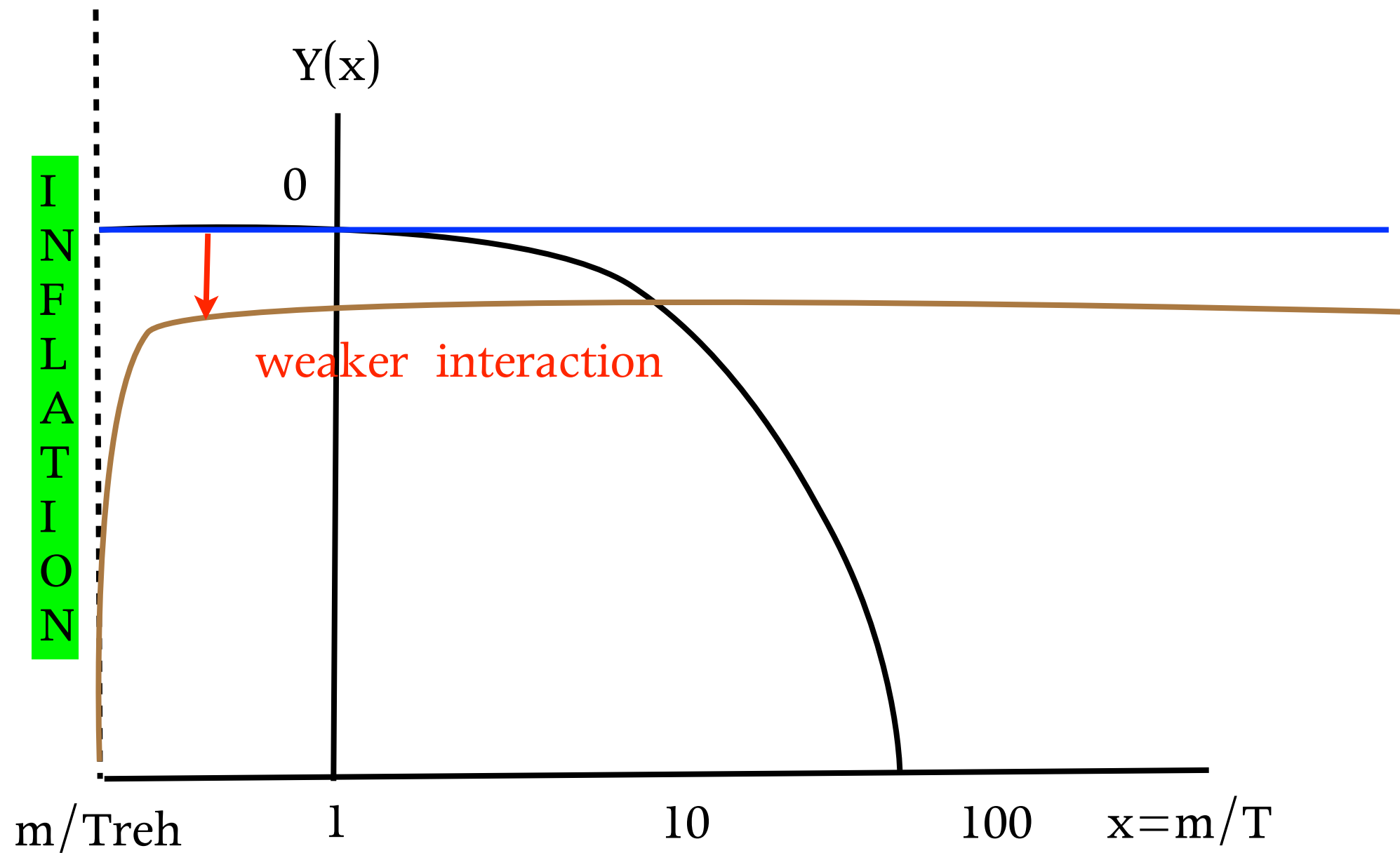
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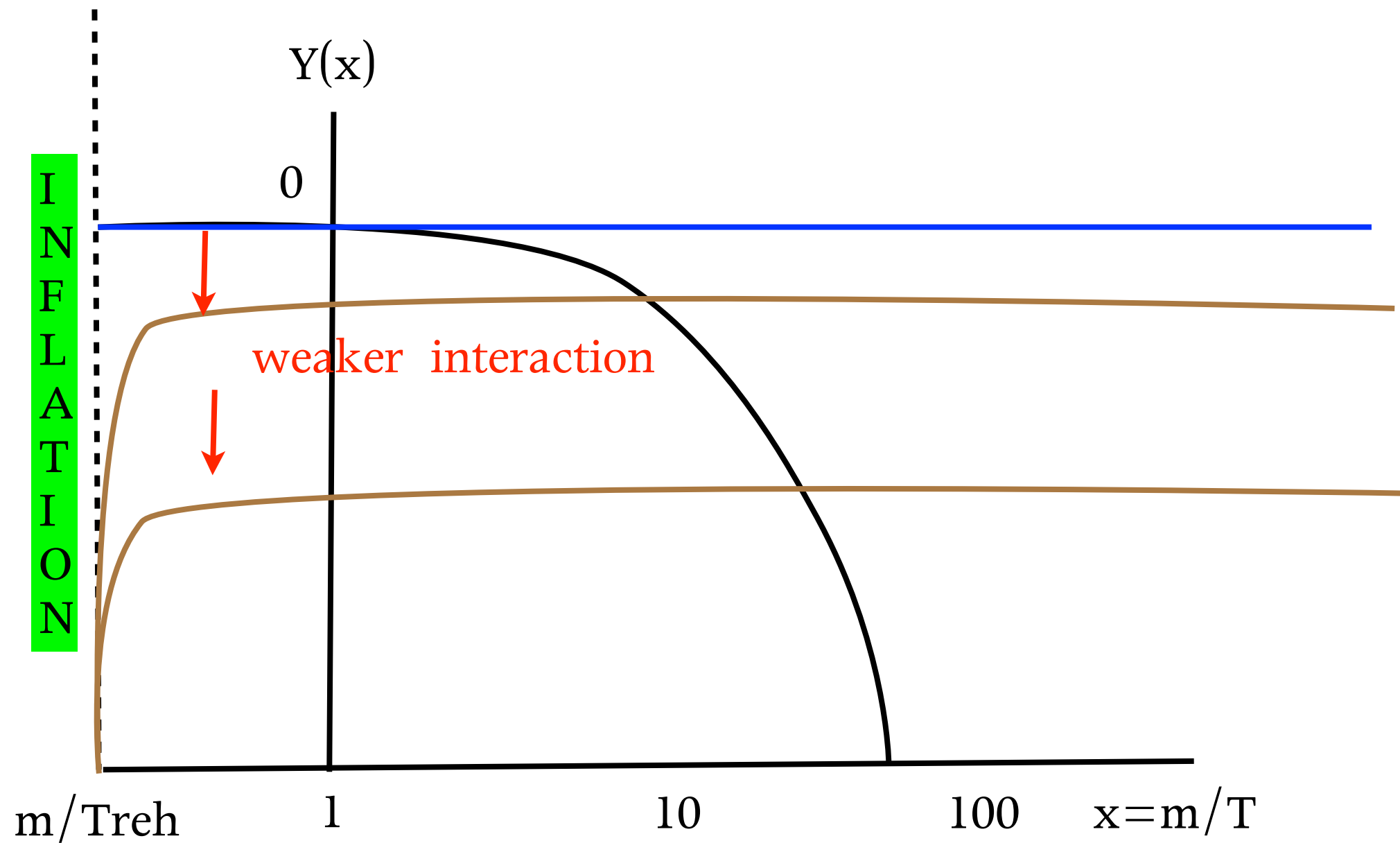# More weakly interacting for a given mass

More weakly interacting for a given mass

More weakly interacting for a given mass

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More weakly interacting for a given mass

More weakly interacting for a given mass

More weakly interacting for a given mass

weaker interaction

Y(x)

0

INFLATION

m/Treh   1   10   100   x=m/T

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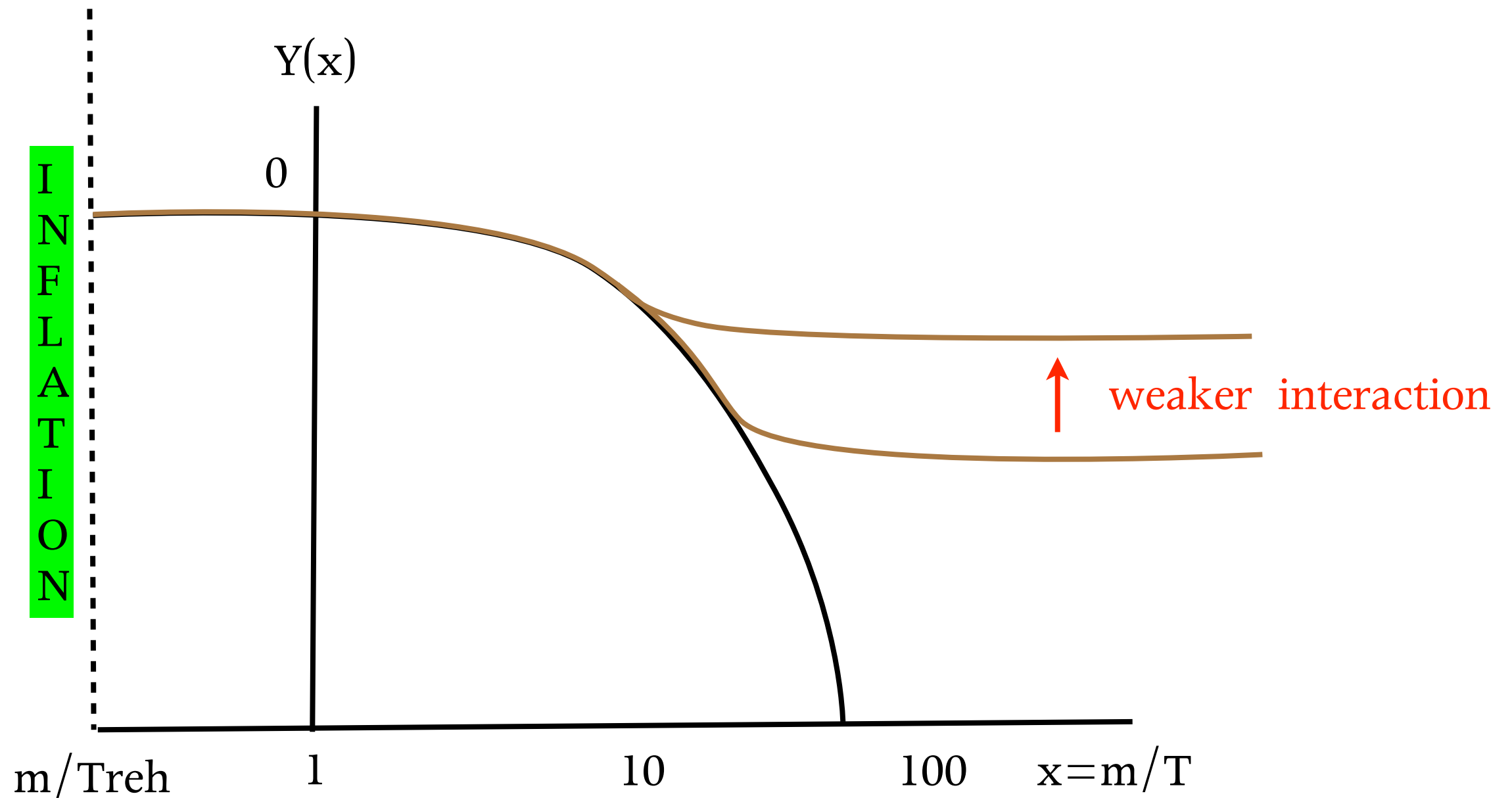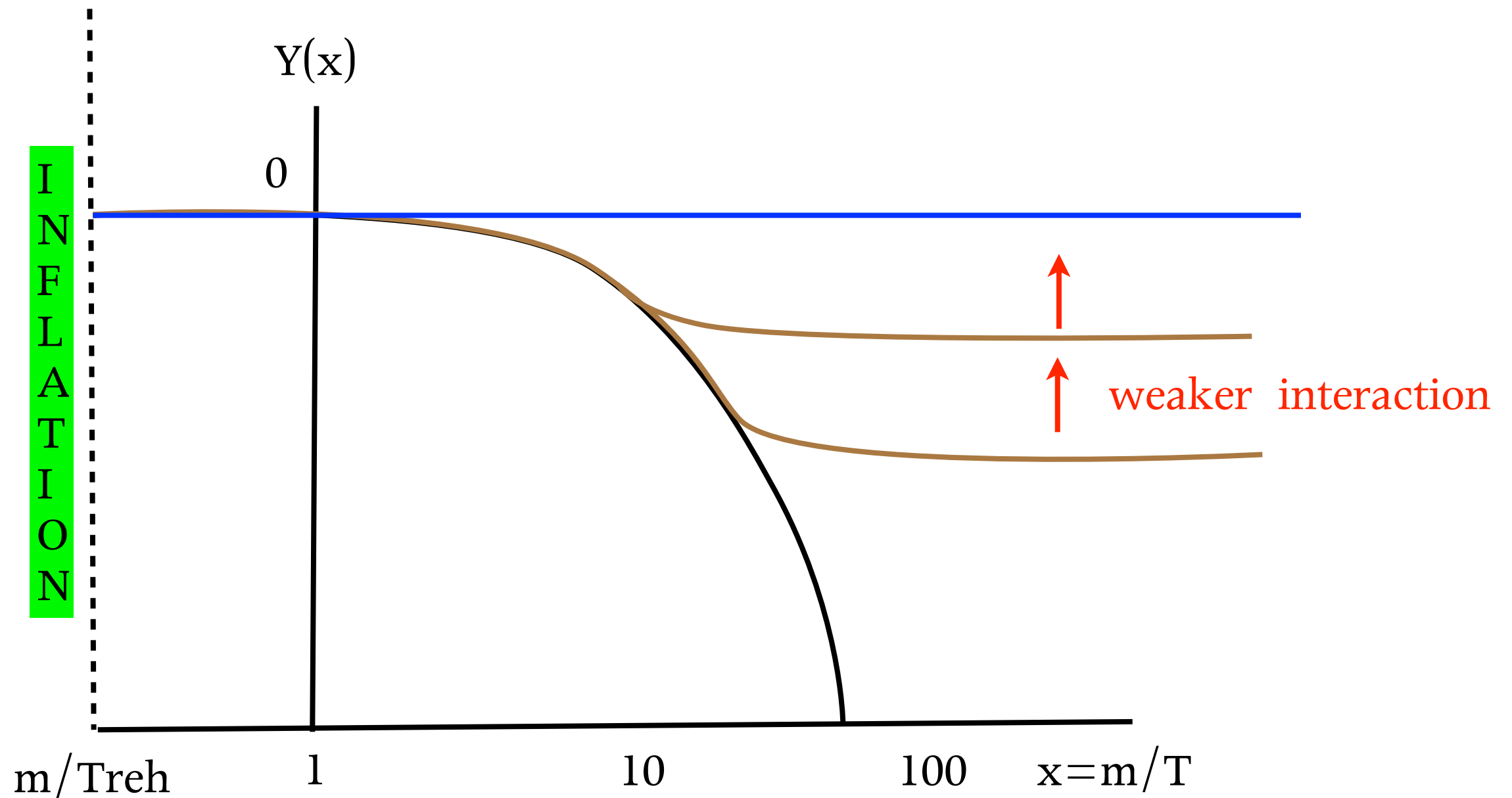
Relic density of massive particles for a given mass

$m = 100\,\mathrm{GeV}$

$\log Y$

Never equilibrium

Decoupled from thermal equilibrium when relativistic

Decoupled from thermal equilibrium when non-relativistic

$Y = \dfrac{135\zeta(3)}{8\pi^4}\dfrac{g_{DM}}{g_*}$

$Y \simeq \dfrac{H}{s\langle\sigma v\rangle} \propto \dfrac{x_f}{\sqrt{g_*}\langle\sigma v\rangle m}$

$\Omega > 1$

$Y \simeq 10^{-11}$

$\Omega < 1$

$(\Omega h^2 \sim 0.1)$

WIMP

E-WIMP (Super-WIMP)

$\log \sigma_{\mathrm{int}}$

$\sigma_{\text{very weak}}$

σ_{weak}

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Tuesday, August 20, 13

Extremely (Super-) weakly interacting massive particles
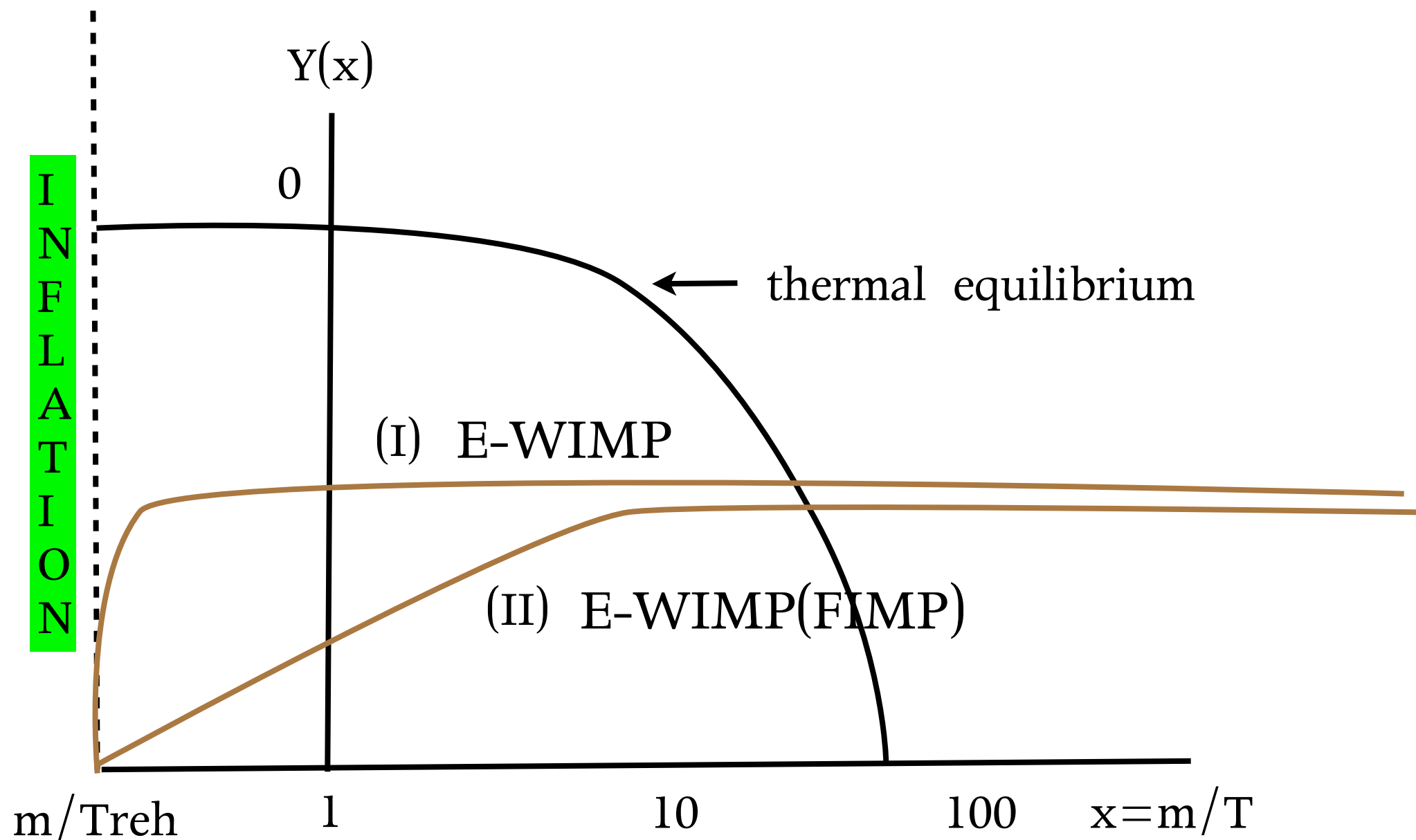
(I) depends on the reheating temperature
and we can get the same amount of abundance for dark matter.

(II) does not depend on the reheating temperature and we can get the same amount of abundance for dark matter.

(I) depends on the reheating temperature
and we can get the same amount of abundance for dark matter.

For example,   Gravitino   Axino

$$M_P \sim 10^{18}\ \mathrm{GeV} \qquad f_a \sim 10^{11}\ \mathrm{GeV}$$

They are decoupled already from the thermal plasma,
however can be produced from thermal scatterings or decays

$$\sigma \sim \frac{1}{M_P^2}, \quad \frac{1}{f_a^2}$$

$$Y(T_0) = \int_{T_0}^{T_{\mathrm{reh}}} \frac{\langle \sigma v \rangle n_{eq}^2}{s(T)H(T)T} dT \propto M_P \frac{T_{\mathrm{reh}}}{M_P^2}, \quad M_P \frac{T_{\mathrm{reh}}}{f_a^2}$$

Relic Abundance $\propto$ Reheating Temperature T_{reh}

(II) does not depend on the reheating temperature and we can get the same amount of abundance for dark matter.

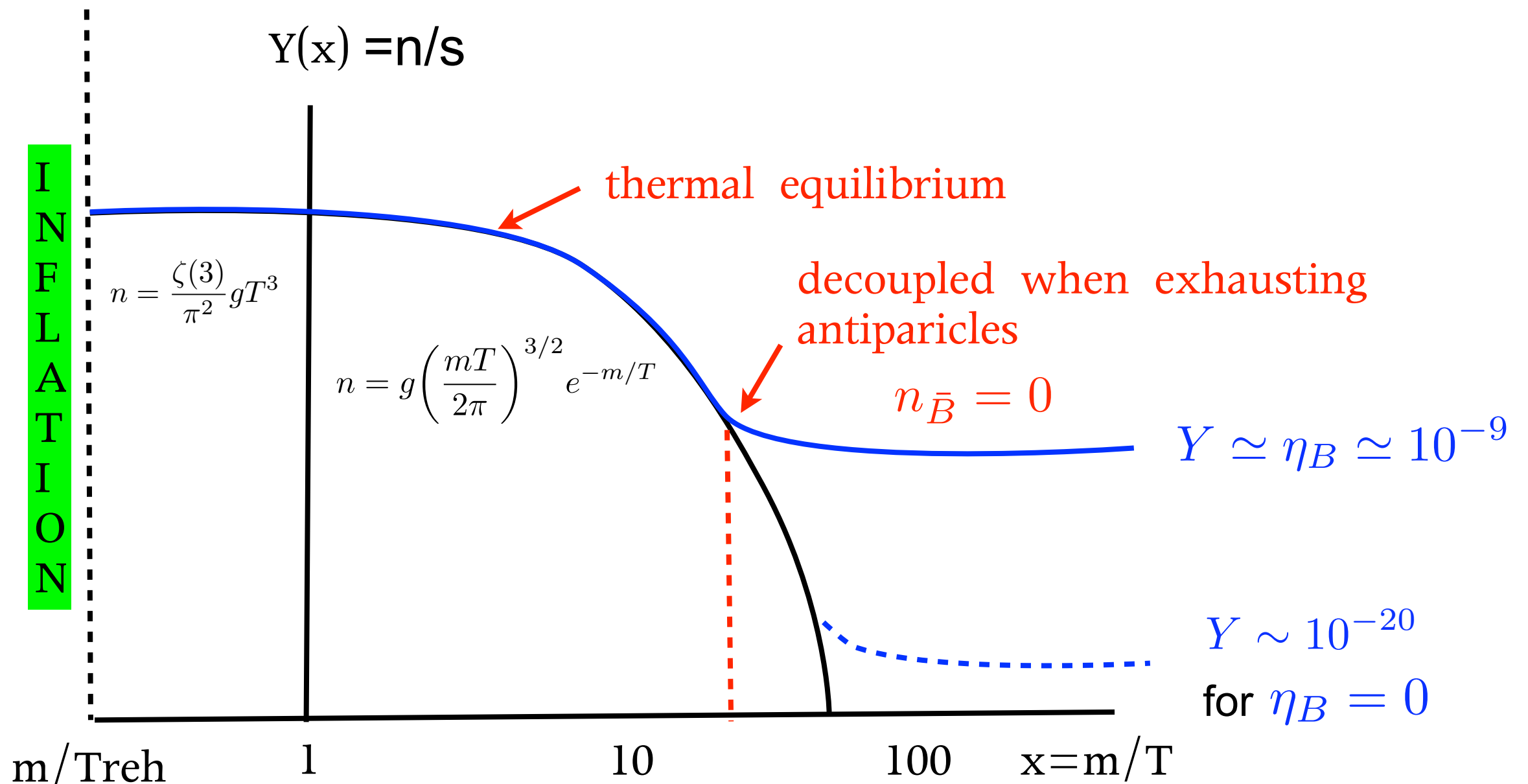For example, Axino can be produced via the Yukawa interactions

$$\sigma \sim \frac{m_{soft}^2}{f_a^2} \frac{1}{s} \qquad \text{with} \qquad s \propto T^2$$

$$\Longrightarrow \quad Y(T_0) = \int_{T_0}^{T_{\text{reh}}} \frac{\langle \sigma v \rangle n_{eq}^2}{s(T) H(T) T} dT \propto \frac{m_{soft}^2}{f_a^2} \frac{1}{T} \bigg|_{T \sim m_{soft}}$$

No dependence on the reheating temperature.

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Asymmetric dark matter:
decouple due to the particle-antiparticle asymmetry

*Baryons decouple from thermal equilibrium much earlier than without asymmetry

Asymmetric dark matter

The abundance Y of dark matter is determined from the asymmtry.

$$Y_{\mathrm{DM}} = \eta_{\mathrm{DM}} \equiv \frac{n_{\mathrm{DM}} - n_{\mathrm{anti\,DM}}}{s}$$

For the same origin of asymmetry for baryons and DM, $\eta_{\mathrm{DM}} = \eta_B$

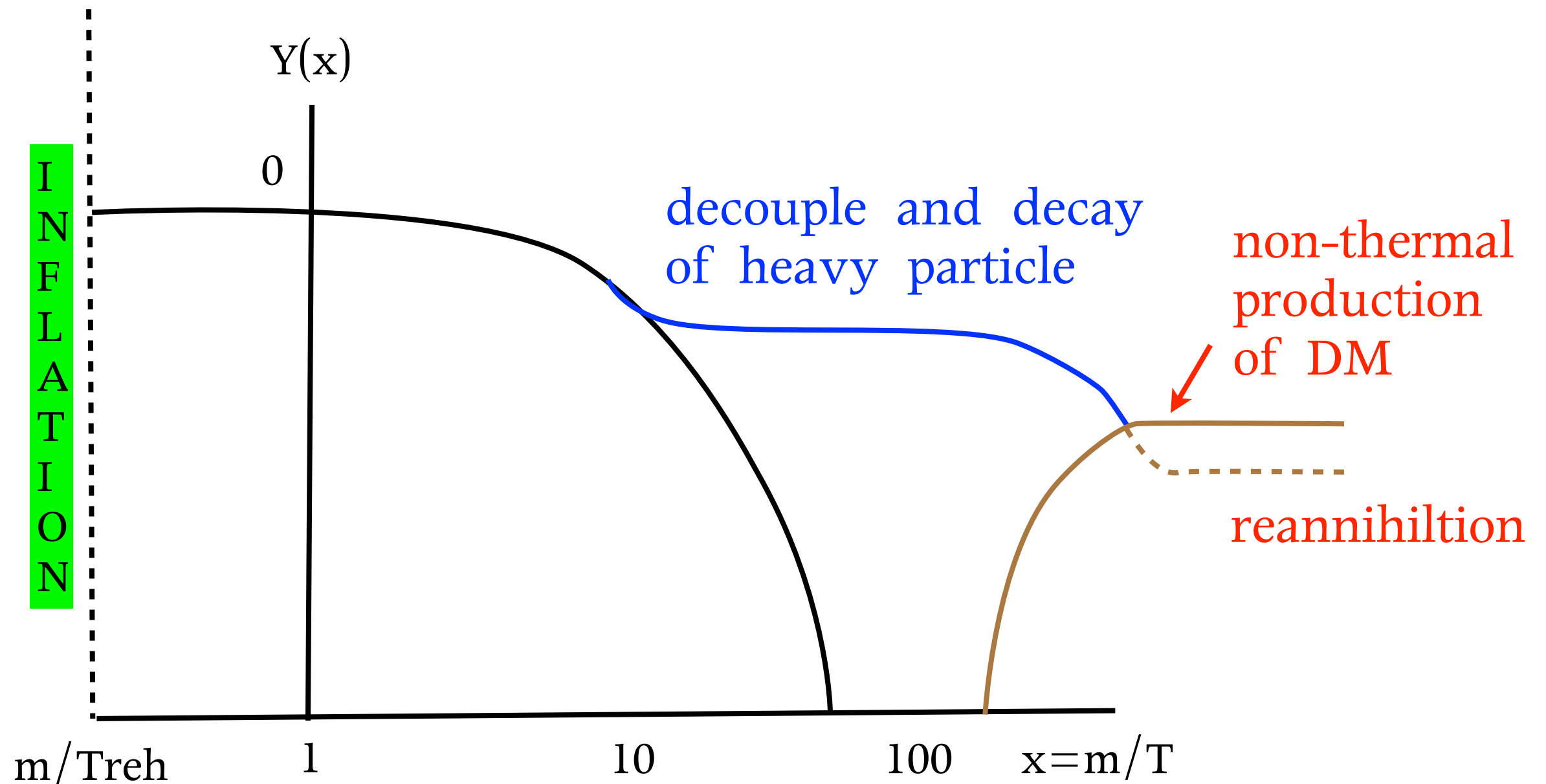$$m_{\mathrm{DM}} \simeq \frac{\Omega_{\mathrm{DM}}}{\Omega_B} m_B \simeq 5 \ \mathrm{GeV}$$

Stable Technibaryon [Nussinov, 1985]

Asymmetric dark matter [Kaplan, Luty, Zurek, 2009]

Asymmetric WIMP [Graesser, Shoemaker, Vecchi, 2011; Iminniyaz, Drees, Chen, 2011]

Mirror baryons as dark matter [review in Ciacelluti, 2011]

Non-thermal production: from decay of heavy particles

Dark matter from the decay of heavy particles

With no more annihilation of DM such as gravitino, axino DM

$$\Omega_{\mathrm{DM}} = \frac{m_{\mathrm{DM}}}{m_X} \Omega_X \qquad \text{Gravitinos, axinos,....}$$

With additional annihilation of DM from decay of heavy particles

$$\Omega_{\mathrm{DM}} h^2 \simeq 0.14 \left(\frac{90}{\pi^2 g_*(T_D)} \right)^{1/2} \left(\frac{m_{\mathrm{DM}}}{100\,\mathrm{GeV}} \right) \left(\frac{10^{-8}\,\mathrm{GeV}^{-2}}{\langle \sigma_{\mathrm{ann}} \rangle v} \right) \left(\frac{2\,\mathrm{GeV}}{T_D} \right)$$

Higgsino and wino DM from Q-ball decay in Affleck-Dine baryogeensis
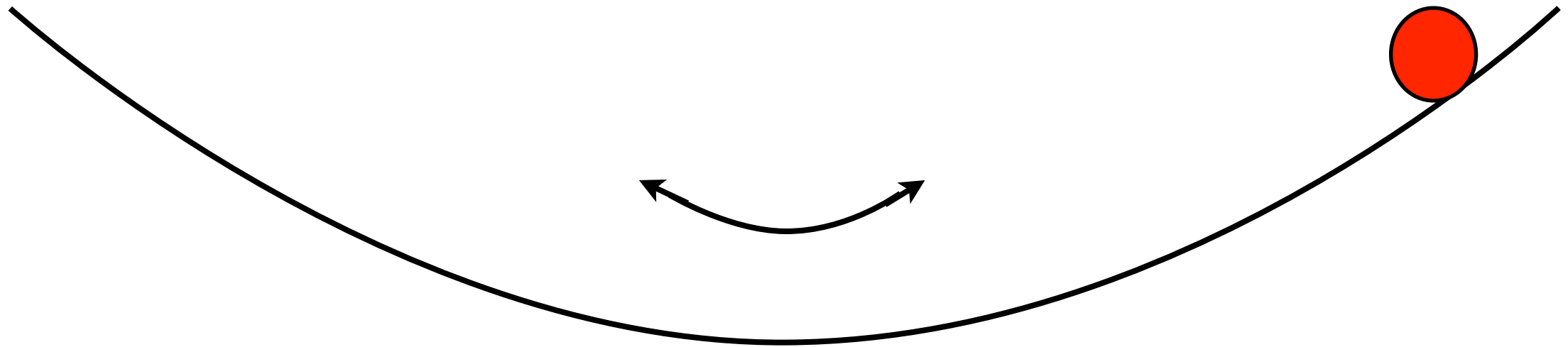[Fujii, Hamaguchi, 2002; Seto 2006;]

Neutralino DM from Polonyi field decay [Nakamura, Yamaguchi, 2007]
Neutralino DM from heavy axino decay [KYChoi, Kim, Lee, Seto, 2008]

[Baer, Lessa, Rajagopalan, Streethawong, 2011]

.....

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Non-thermal production: Misalignment mechanism

The oscillating scalar fields behaves like cold dark matter.

Example : axion