The origin of Dark Matter

(Particle Dark Matter and its production)

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1. Dark Matter as particle
2. Creation of Dark Matter in the Early Universe
3. Candidates of Dark Matter in particle physics models
4. Cosmological constraints
5. Discussion

1. Why Dark Matter?

"Anomalies" observed in large astrophysical systems without dark matter, with sizes ranging from galactic to cosmological scales

- Galactic rotational curves
- Mass of galaxy cluster from Gravitational lensing
- Bullet cluster
- Acoustic peak in Cosmic microwave Background (CMB)
- Power spectrum of matter perturbation
- .....

→ The existence of a large amount of unseen dark matter

* All the evidences has gravitational origin in astrophysical and cosmological observation.

Modification of Gravity?

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Massive Compact Halo Objects?
(MACHOs)

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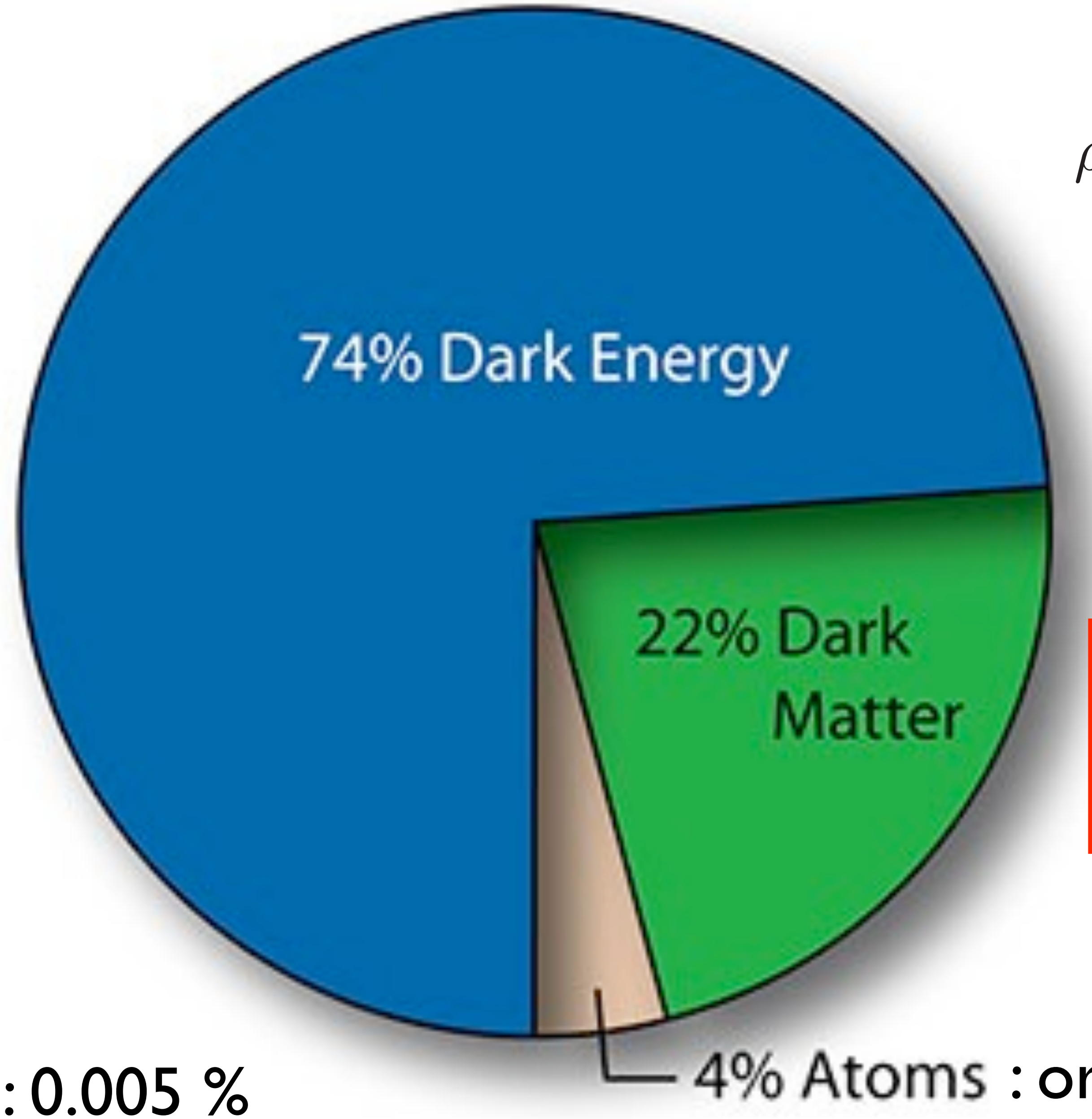
Massive Compact Halo Objects?
(MACHOs)

Dark Matter as non-baryonic particles!

Composition of Universe

$$\rho_c = 3H_0^2 M_P^2 = 1.88 \times 10^{-29} \mathrm{g\,cm}^{-3}$$



: ordinary baryonic matters

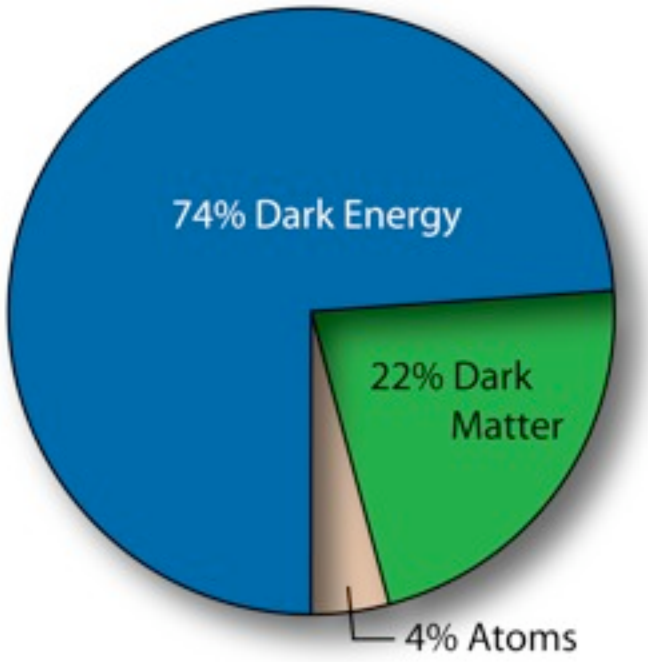
$$\Omega_{DM} = \frac{\rho_{DM}}{\rho_c} \sim 0.22$$

[Komatsu et al., 2011]

Radiation : 0.005 %

Neutrinos : less than 5 %

Dark Matter as a particle must (be)



1. exist around galaxies, clusters

➡ stable or lifetime longer than the age of universe

2. neutral : NO electromagnetic interaction

➡ Only upper bounds on the interaction

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

No lower bound down to gravity!

In fact all the evidences are gravitational.

3. 22% of the present energy density of the universe

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

The Standard Model of Particle Physics

: accounted for all the observed particles and interactions based on gauge symmetry

Matters : quarks, leptons

Force carriers : gauge bosons of SM gauge groups

$$SU(3)_C \times SU(2)_L \times U(1)_Y$$

Higgs : the origin of mass and electroweak symmetry breaking

Through these interactions, the particles can have scattering, annihilations and decay to lighter particles.

Dark matter within 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

$$\sum m_\nu < 1.3\,\text{eV} \quad (95\%\,CL)$$

It is too small!

[Komatsu et al., 2011]

The fluctuations are damped smaller than the neutrino free streaming scale

$$\lambda_{FS} \sim 20 \left(\frac{30 \text{ eV}}{m_\nu}\right) \text{ Mpc}$$

It is too hot! top-down structure formation

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

Beyond Standard Model

Dark Matter in the beyond standard model

1. existence : new particles in the beyond Standard Model

   stability : new symmetry to protect decay or it is slightly broken

2. neutral : no electromagnetic charge

   the interactions from weak to gravitational depending on model

3. 22% of universe : relic density of DM from early Universe

4. cold (warm) dark matter : the generation mechanism and intrinsic property of DM

5. cosmological and astrophysical constraints
   : BBN, CMB, stellar evolution, gamma-ray, direct detection, ...

Stability of Dark Matter

Dark Matter is astonishingly stable

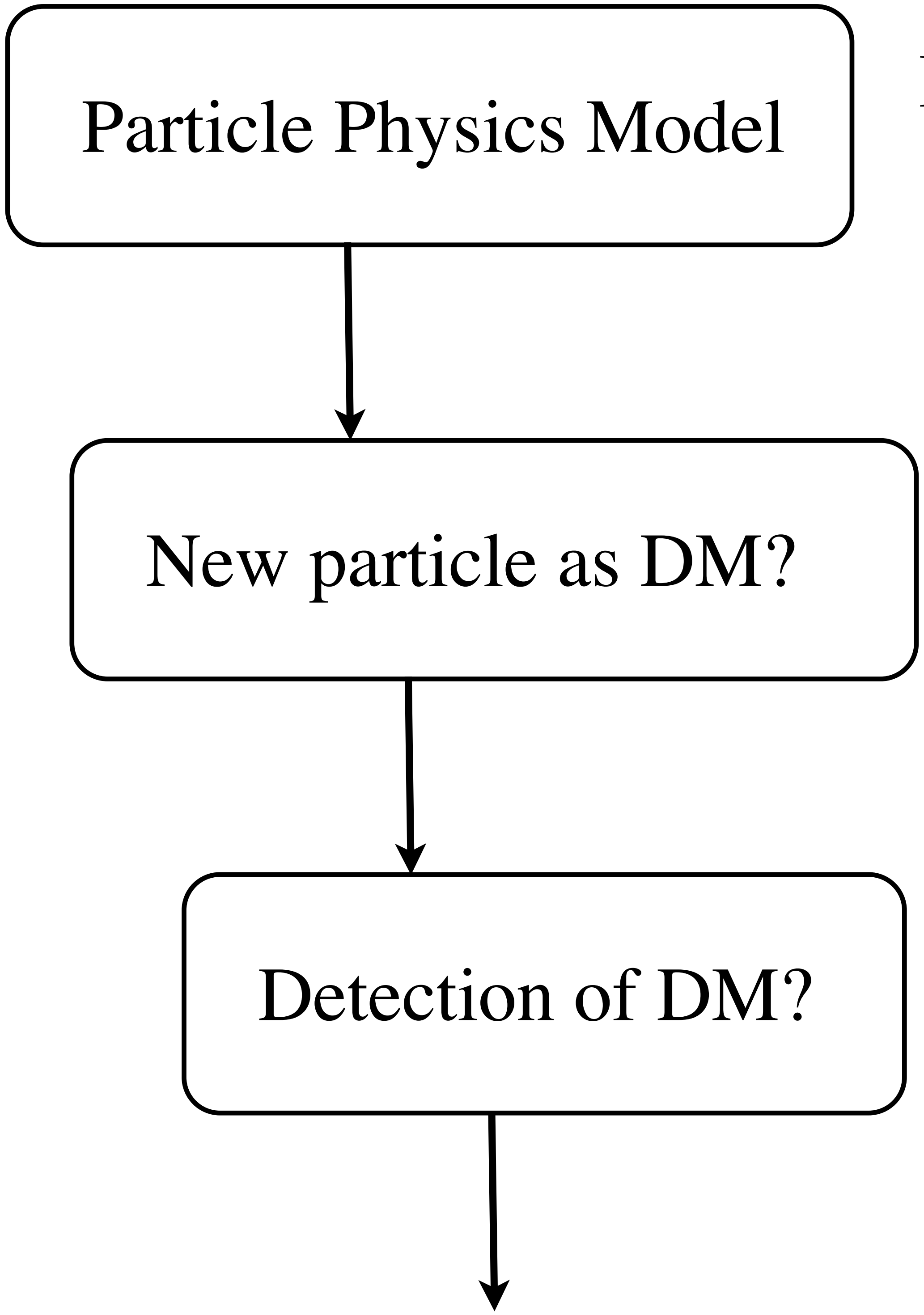
$\tau_{DM} > \tau_{age} \sim 10^{18}\,\mathrm{sec}$ exists in the present Universe

$\tau_{DM} > 10^{26}\,\mathrm{sec}$ not to produce $e^+,\ \bar{p},\ \gamma,\ \ldots$ larger than observed

In many particle physics models, the stability of dark matter is assumed by ad hoc symmetry, e.g. Z_2 symmetry ....

exact symmetry or slightly broken

The origin of the stability is related to the basic structure of the model with specific phenomenology and detectability.



Beyond Standard Model:
motivated to solve problems of SM

Stability : symmetry?
Weak interaction
Relic density

Direct detection
Indirect detection
Collider
Cosmological test

Distinguish among BSM

Dark Matter Candidates

Axions, gravitinos, axinos, WIMPs, Axion-like light bosons, Q-balls, WIMPzillas, Elementary BHs, scalar DM from inert doublet model, sterile neutrinos, light volume moduli, Majorons, Dilatons, Techni-dilatons, ...

WIMPs: Neutralinos, Kaluza-Klein particles, scalar neutrinos,...

Reviews : [Jungman et al., 1996] [Bergstrom, 2000]
[Bertone, Hooper, Silk, 2005]
[Carr et al., 2006]
[Taoso et al., 2008]
[Kusenko, 2009]

Axion

To solve the strong CP problem in the standard model

Chiral U(1) symmetry, Peccei-Quinn symmetry, which anomalous, is spontaneously broken and the pseudo Goldstone boson is the axion.

[KSVZ model, DFSZ model]

$$\mathcal{L} = \frac{g^2}{32\pi^2 f_a} a F^a_{\mu\nu} \tilde{F}^{\mu\nu}_a$$

$$10^9 \text{ GeV} \lesssim f_a \lesssim 10^{12} \text{ GeV}$$

Due to the very weak interactions, the very light axion's lifetime is much longer than the age of the Universe.

$$m_a = \frac{\sqrt{z}}{1+z} \frac{m_\pi f_\pi}{f_a} = 6 \left(\frac{10^6 \text{ GeV}}{f_a} \right) \text{eV} \qquad \tau_a \sim \frac{64\pi}{g^2_{a\gamma\gamma} m_a^3} \simeq 10^{40} \left(\frac{f_a}{10^{10} \text{ GeV}} \right)^5 \text{sec}$$

The cosmic axion can be populated by coherent oscillation due to the initial misalgnment angle as

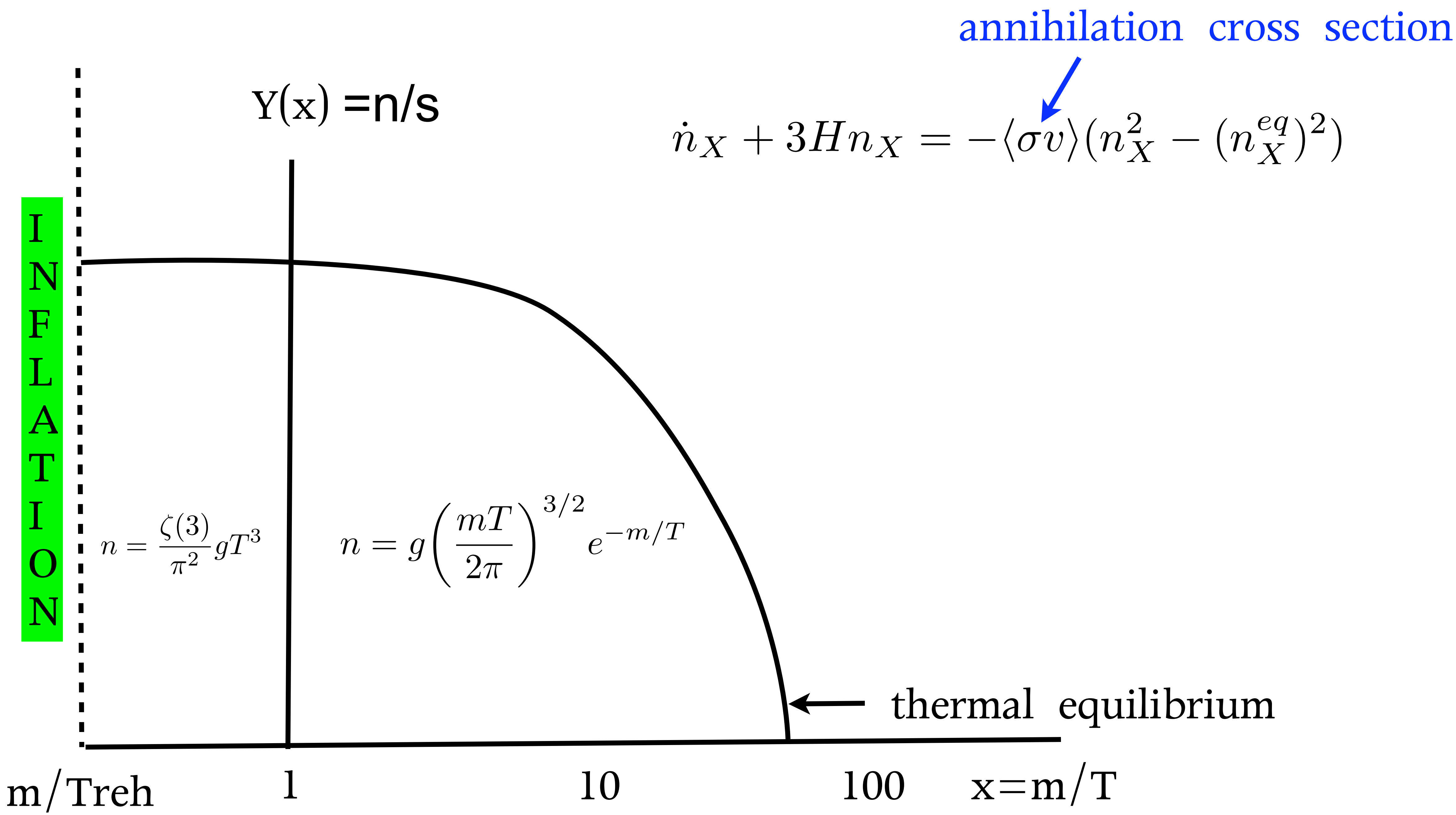
$$\Omega_a h^2 \sim 0.15\, \xi\, f(\Theta_i^2)\, \Theta_i^2 \left(\frac{f_a/N}{10^{12} \text{GeV}} \right)^{7/6}$$

$\xi = \mathcal{O}(1)$ factor

$f(\Theta_i^2)$ anharmonicity

WIMP : Weakly Interacting Massive Particle

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



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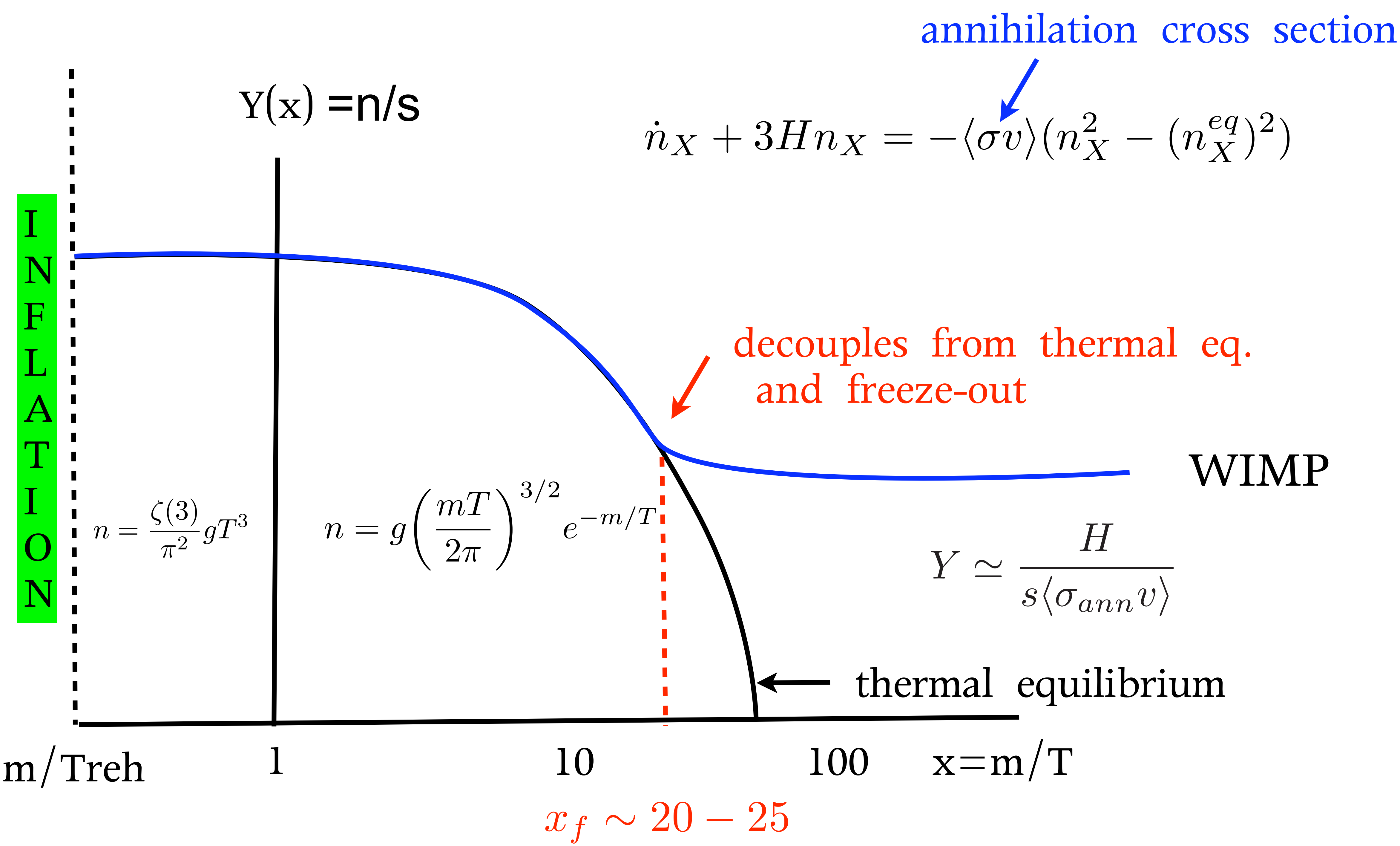

Relic density at present time

$$Y \simeq \frac{H}{s\langle\sigma_{ann}v\rangle}$$

$$\Omega h^2 = \frac{m\,n}{\rho_c} \simeq 0.28\left(\frac{Y}{10^{-11}}\right)\left(\frac{m}{100\ \mathrm{GeV}}\right) \simeq 0.1$$

$$\rho_c = \frac{3H_0^2}{8\pi G} \qquad H_0 = 100\,h\,\mathrm{km\,sec^{-1}\,Mpc^{-1}}$$

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WIMP with $\langle \sigma_{ann} v \rangle \simeq 10^{-10}\ \mathrm{GeV}^{-2} \simeq 10^{-38}\ \mathrm{cm}^2$

gives correct relic density for dark matter.

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

Supersymmetric WIMP

Supersymmetry is a symmetry between bosons and fermions.
It is motivated to solve the theoretical problems such as hierarchy problem and allows gauge coupling unification, electroweak symmetry breaking and dark matter.

TeV scale new particles (SUSY) particles are predicted corresponding to all the SM particles.

R-parity is assumed to protect the decay of proton, which makes the lightest supersymmetric particle (LSP) stable.

LSP can be neutralino, gravitino, axino, scalar neutrino, ...

Neutralino dark matter as WIMP

fermion $\widetilde{\chi}_1^0 = N_{11}\widetilde{B} + N_{12}\widetilde{W} + N_{13}\widetilde{H}_u^0 + N_{14}\widetilde{H}_d^0$

superpartner of $U(1)_Y$ gauge boson, B

$SU(2)_L$ gauge boson, W

Higgs boson, Hu and Hd

EM neutral and stable when it is LSP with R-parity.

100 GeV neutralino can give correct abundance for DM naturally

$$Y_\chi \simeq (1 \sim 10) \times 10^{-12} \left(\frac{m_\chi}{100\,\mathrm{GeV}}\right),$$

It is possible to detect in the direct and indirect experiments.

Gravitino dark matter as E-WIMP (Super-WIMP)

fermion $\widetilde{G}$ ← Graviton
(spin 3/2) superpartner of

EM neutral and stable when it is LSP with R-parity.

Interaction is gravitational suppressed by Planck scale.

Mass can be in the wide range depending on the way of SUSY breaking,

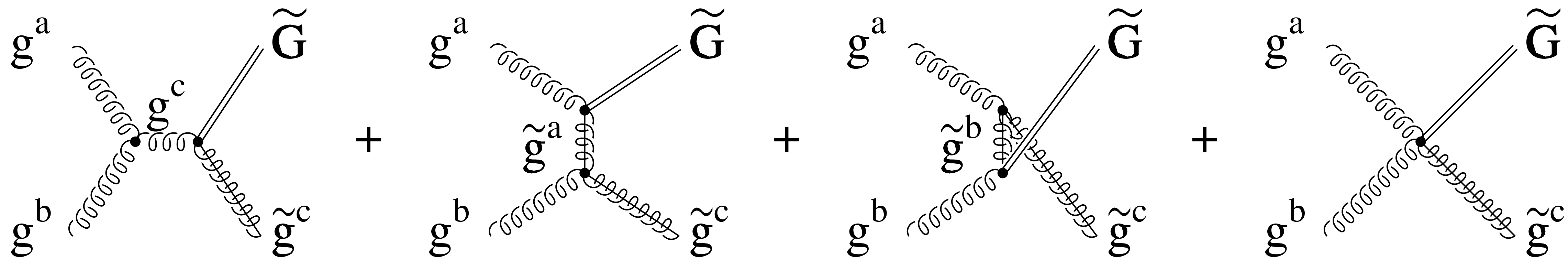
from eV to TeV

Heavy gravitino ~ GeV cannot be in the thermal equilibrium, however they can be produced through the scattering of the thermal particles. That makes the relic abundance depend on the reheating temperature after inflation.

Gravitino dark matter as E-WIMP

- Thermal production : the gravitinos are produced from the 2->2 scatterings after inflation [Ellis, Kim, Nanopoulos 1984]

$$g^a + g^b \to \tilde{g}^c + \widetilde{G}$$

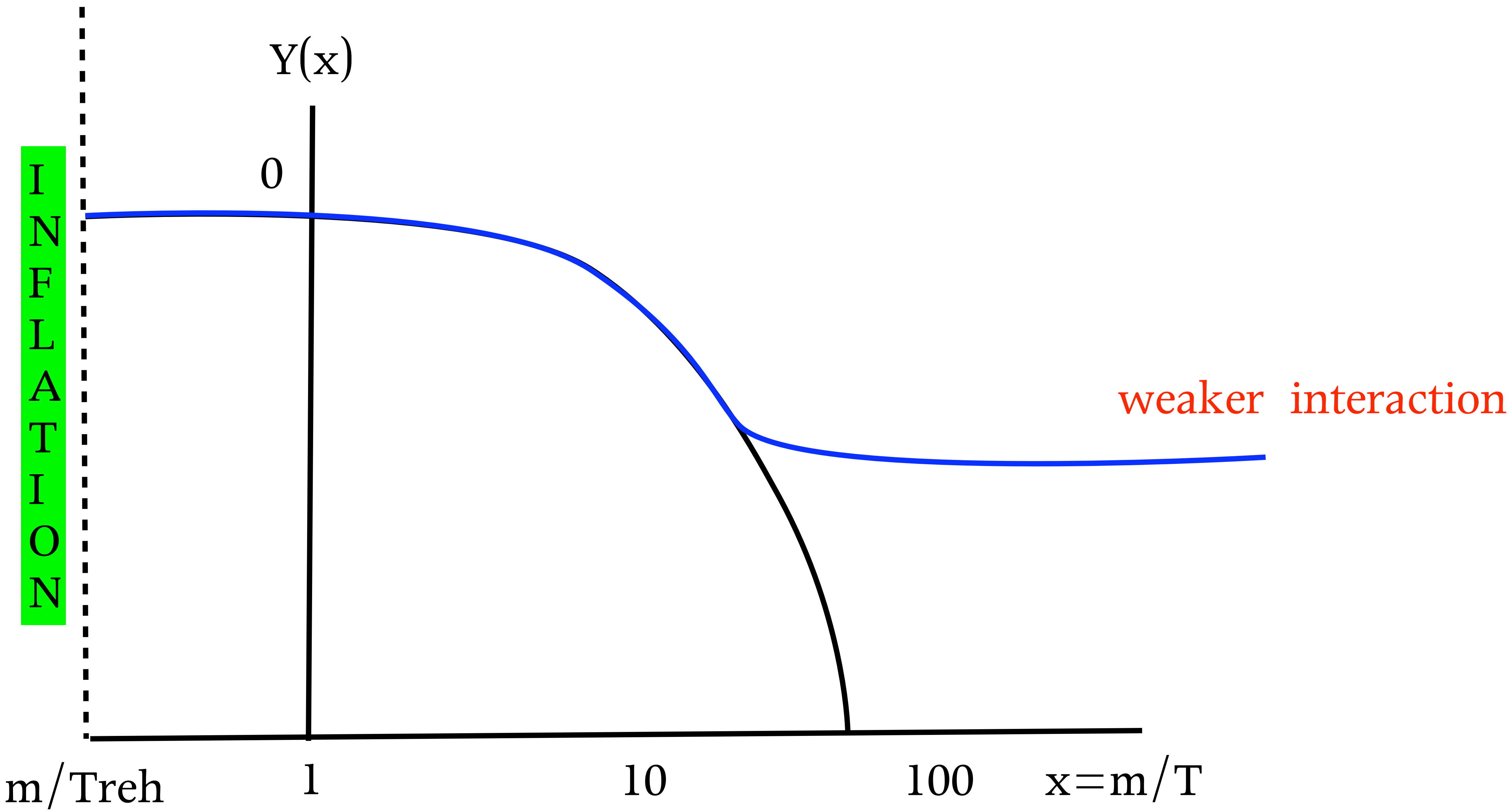


Thermal production is proportional to the reheating temperature

$$\Omega^{TP}_{\widetilde{G}} h^2 \simeq 0.27 \left(\frac{100\,\text{GeV}}{m_{\widetilde{G}}} \right) \left(\frac{m_{\tilde{g}}}{1\,\text{TeV}} \right)^2 \left(\frac{T_{\text{reh}}}{10^{10}\,\text{GeV}} \right)$$

[Bolz, Brandenburg, Buchmuller 2000]

• Thermal production of Dark Matter



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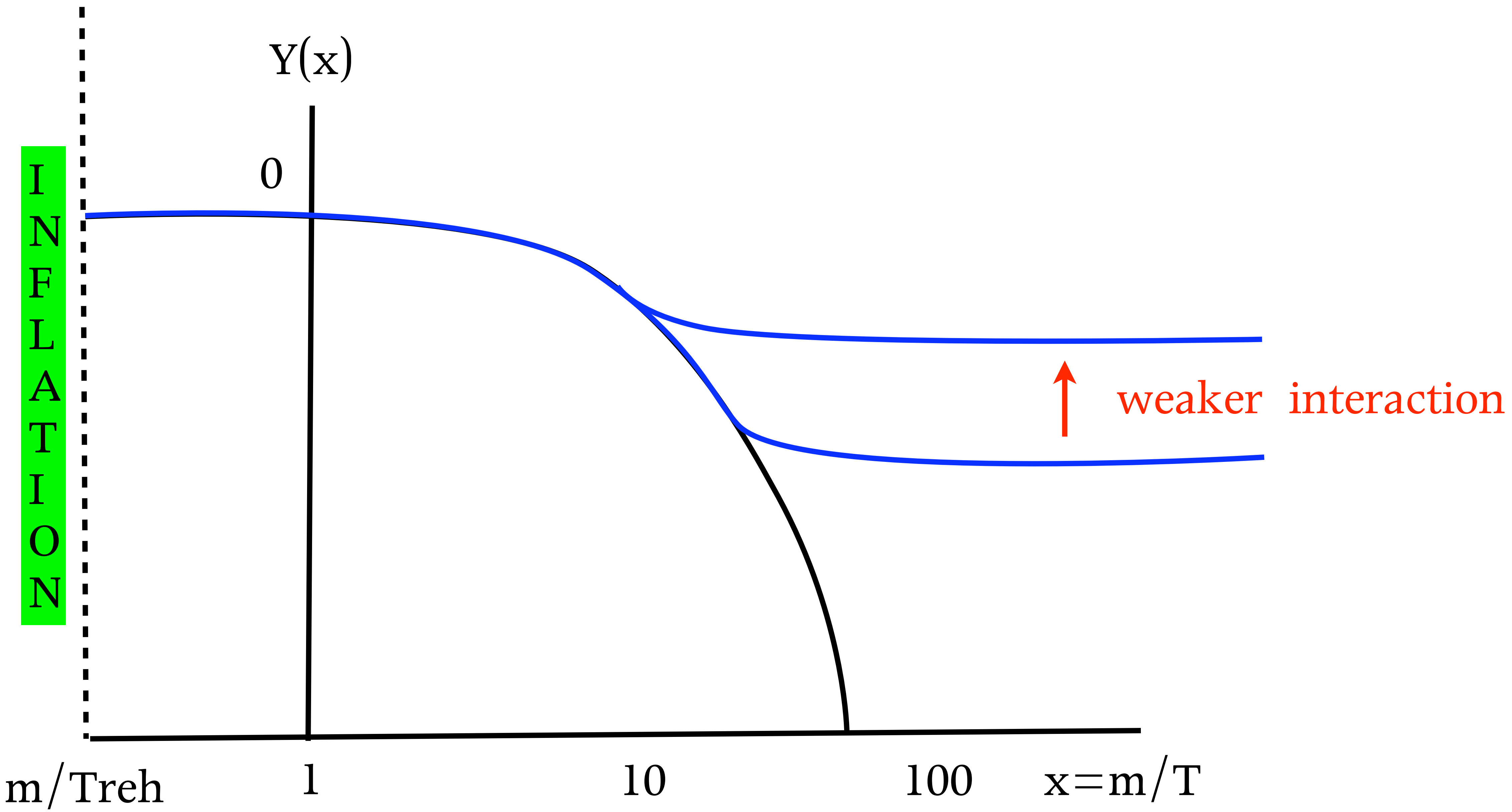

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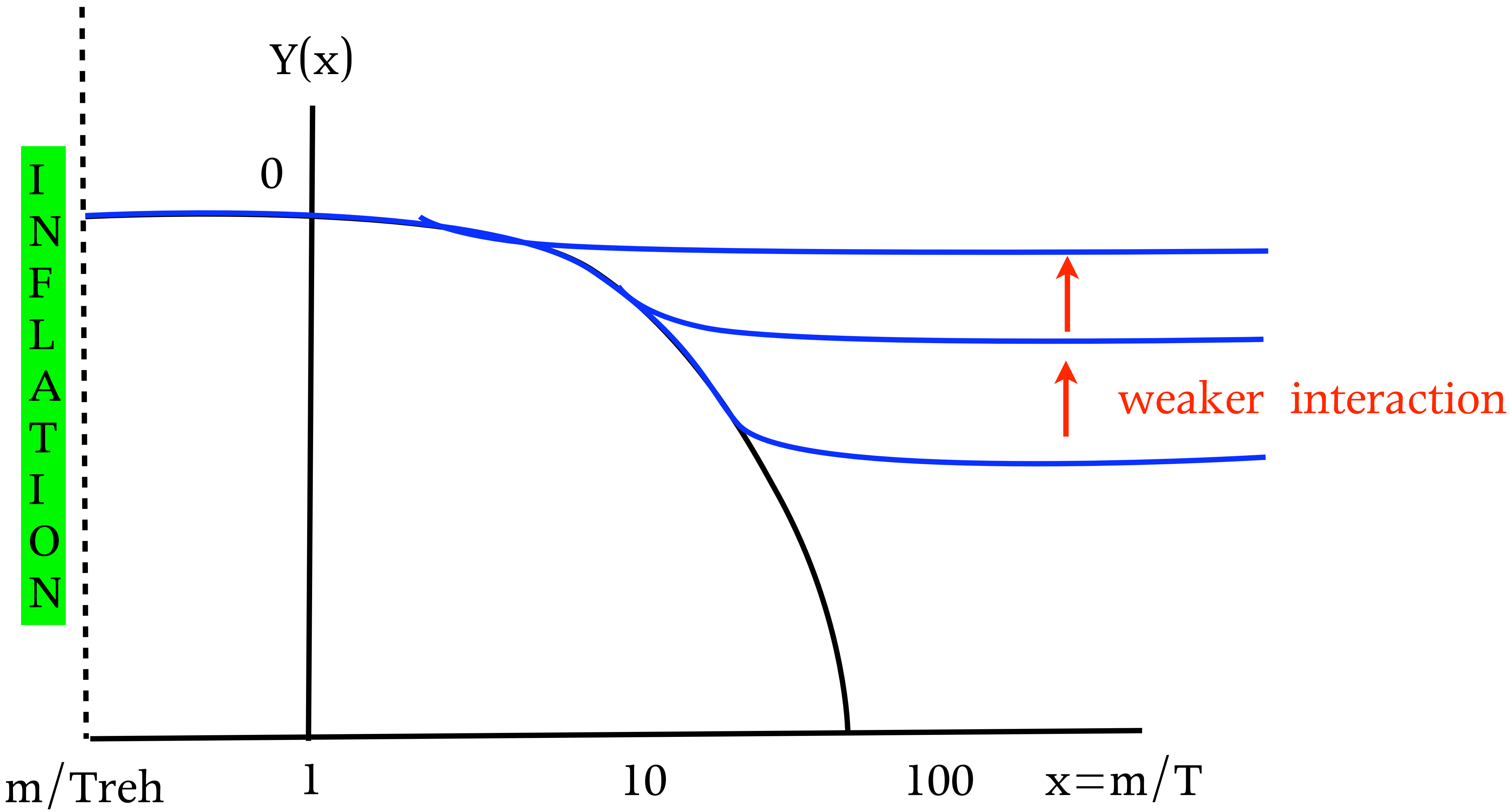

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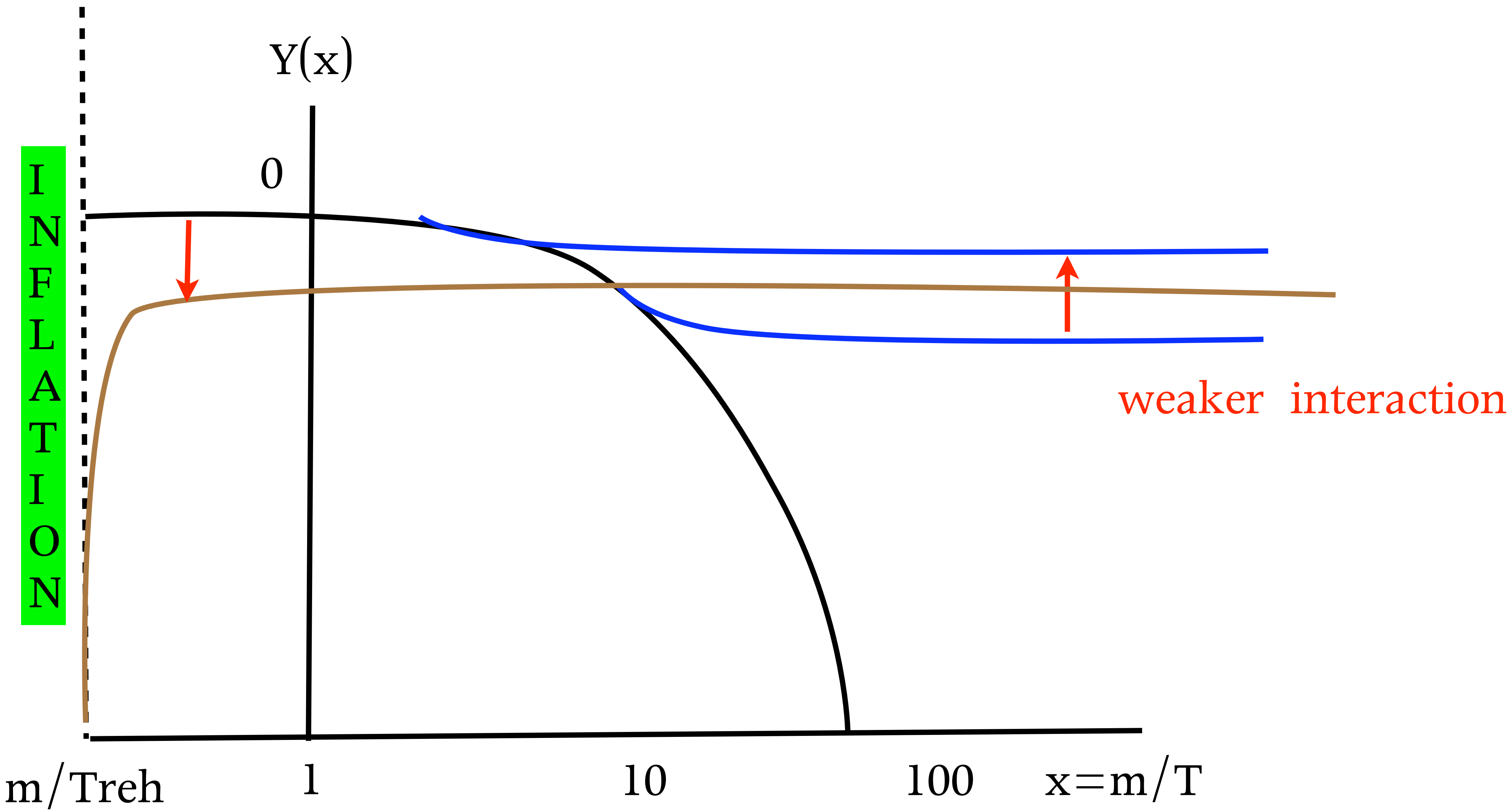

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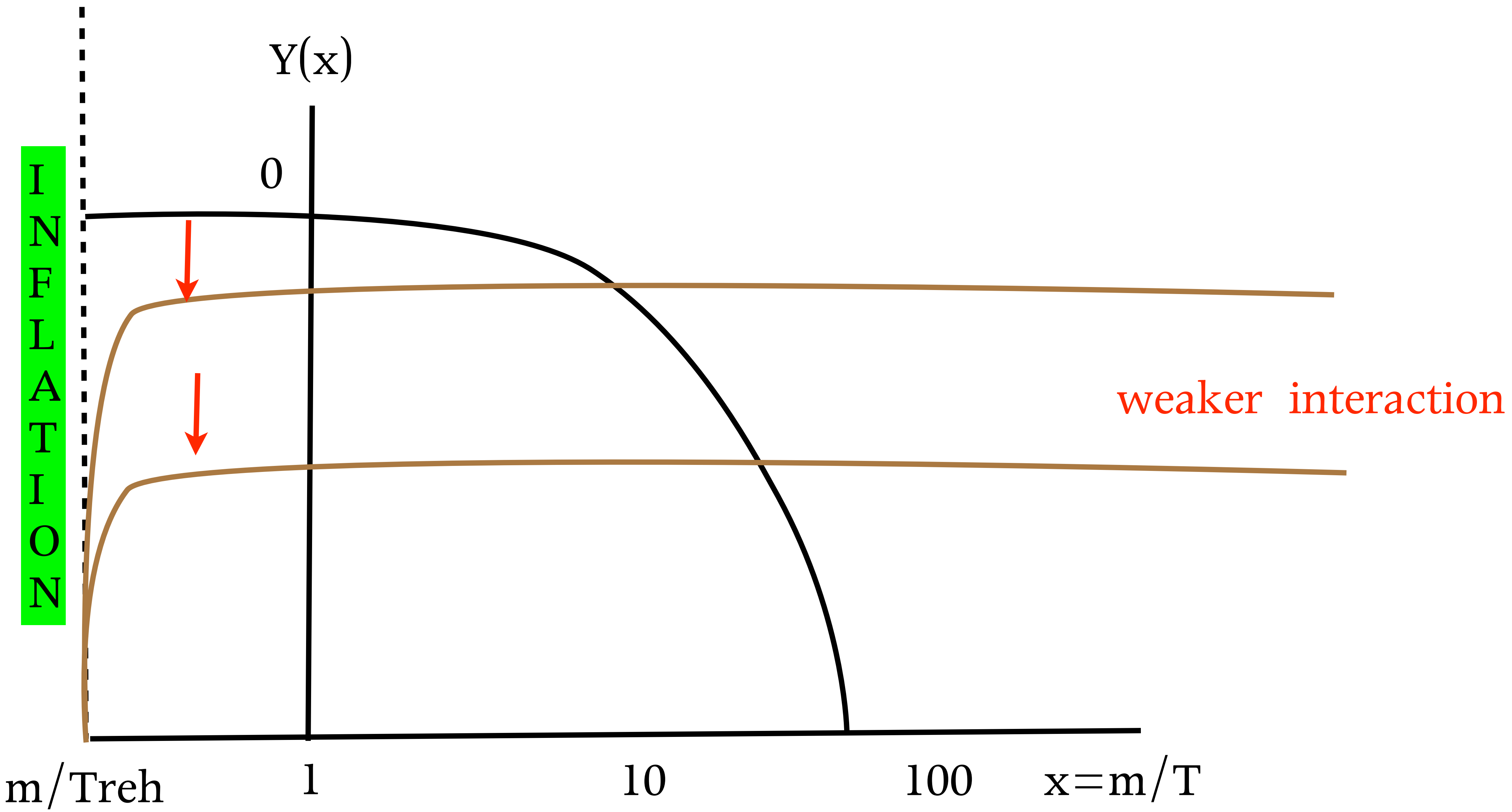

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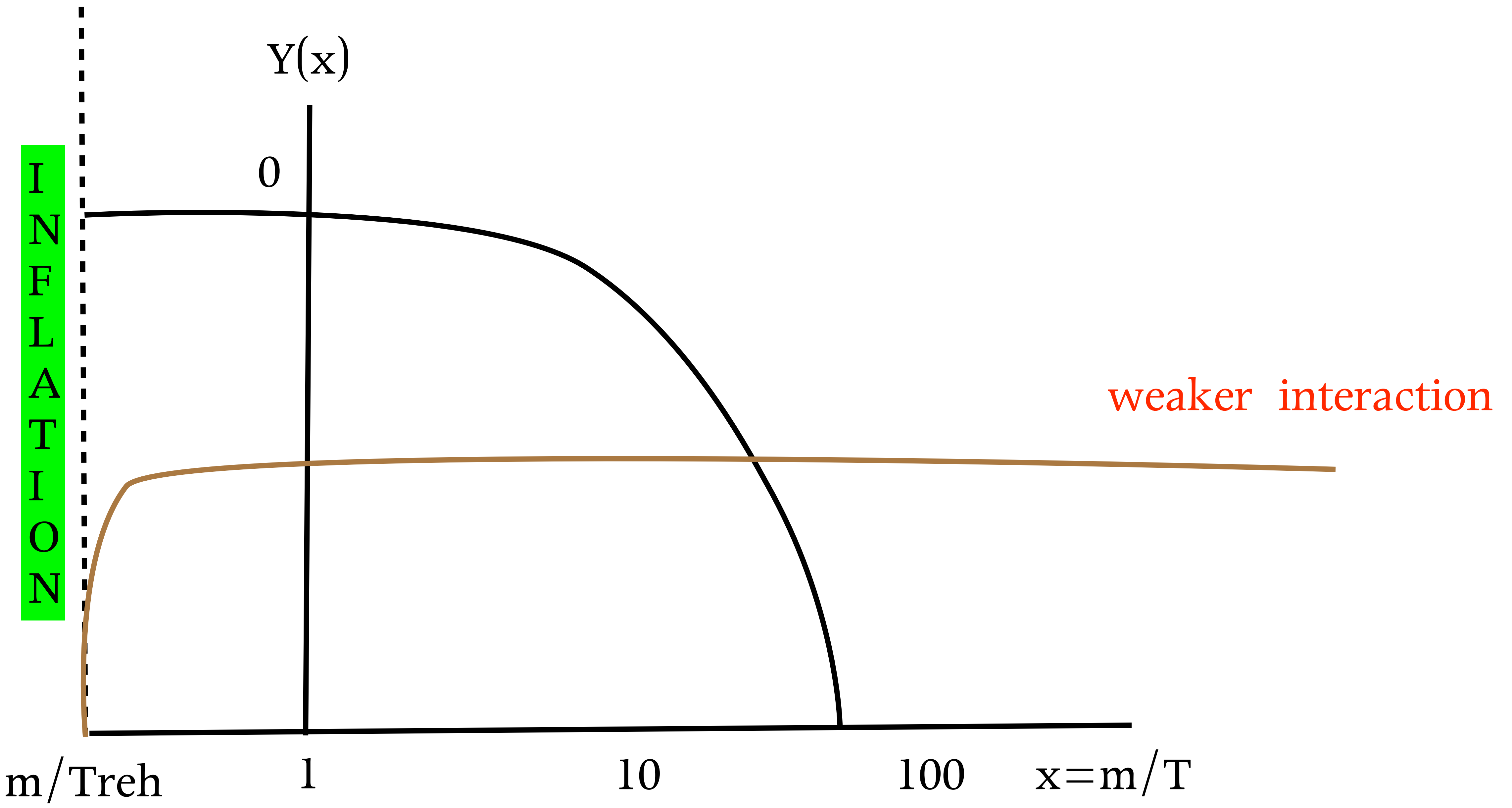

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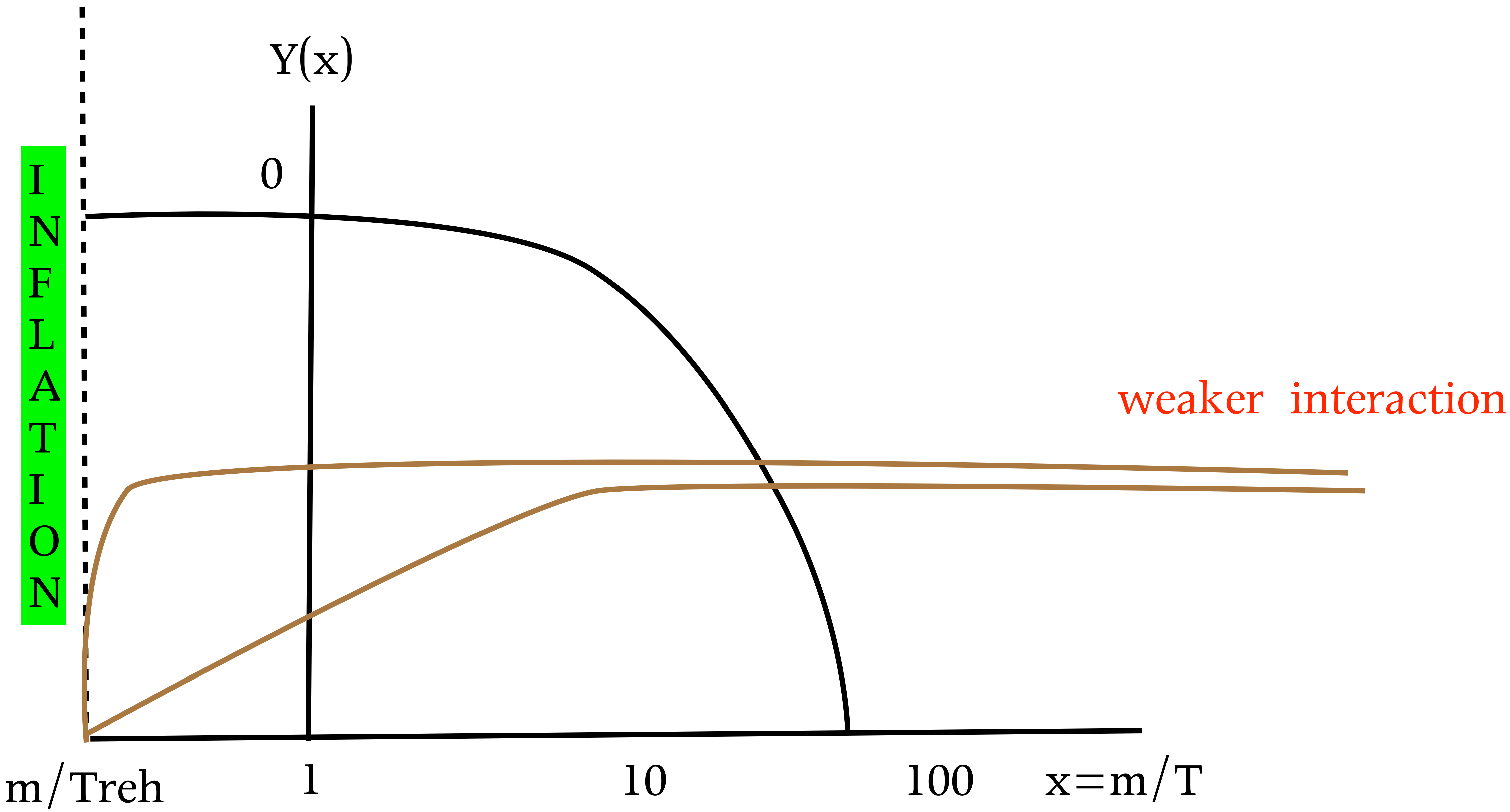

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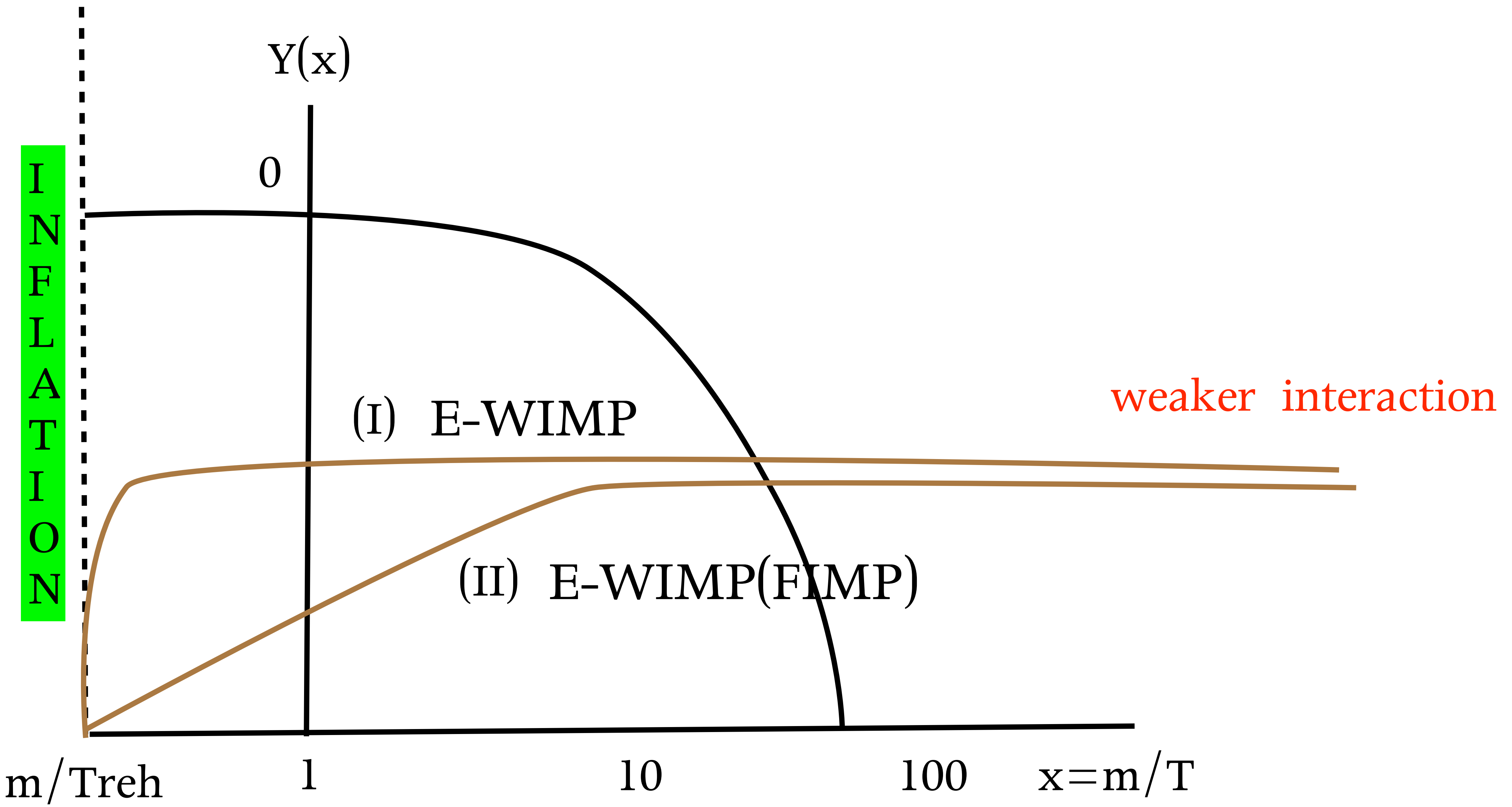
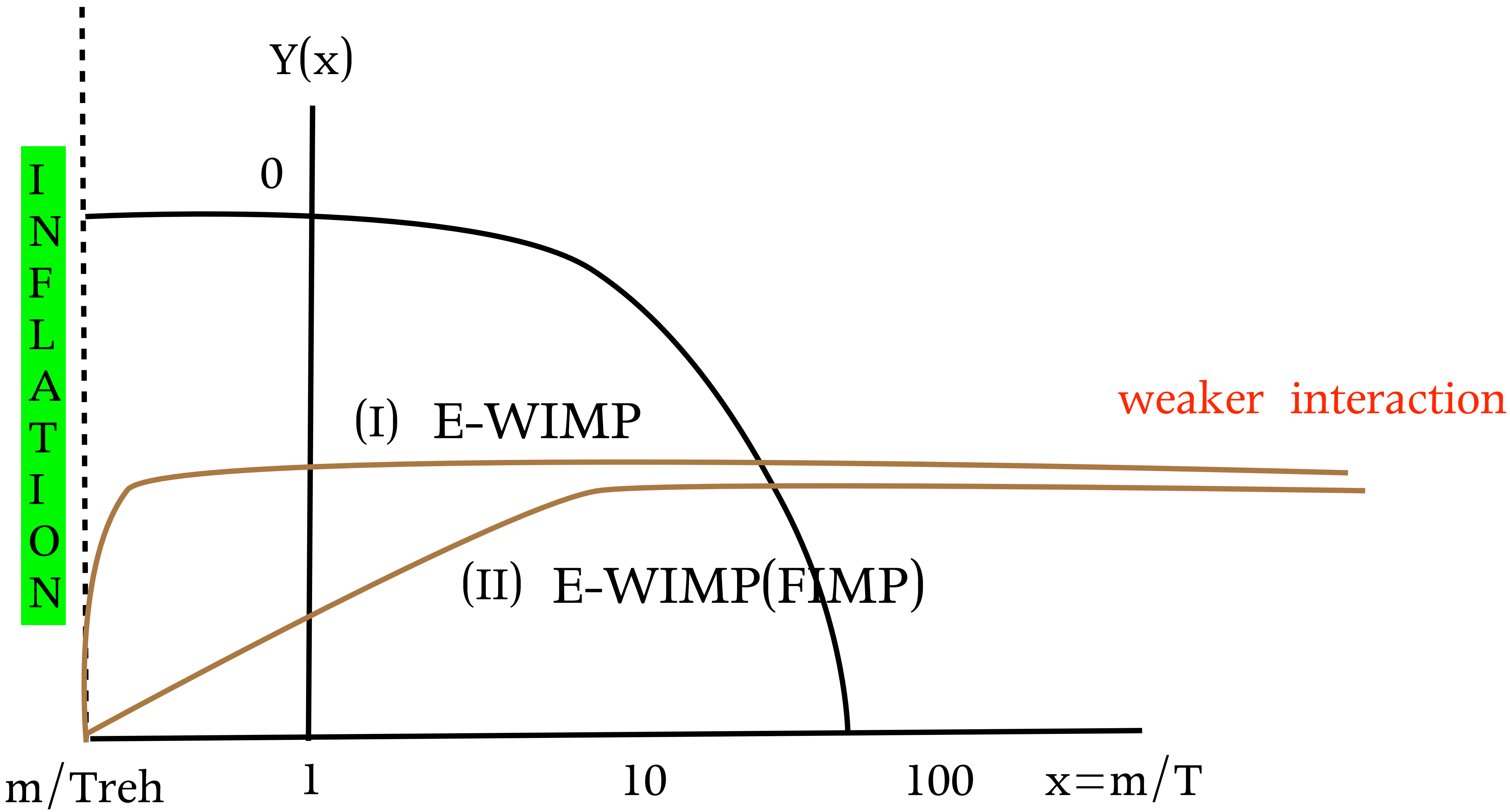


(I) depends on the reheating temperature
and we can get the same amount of abundance for dark matter.

- Thermal production of Dark Matter

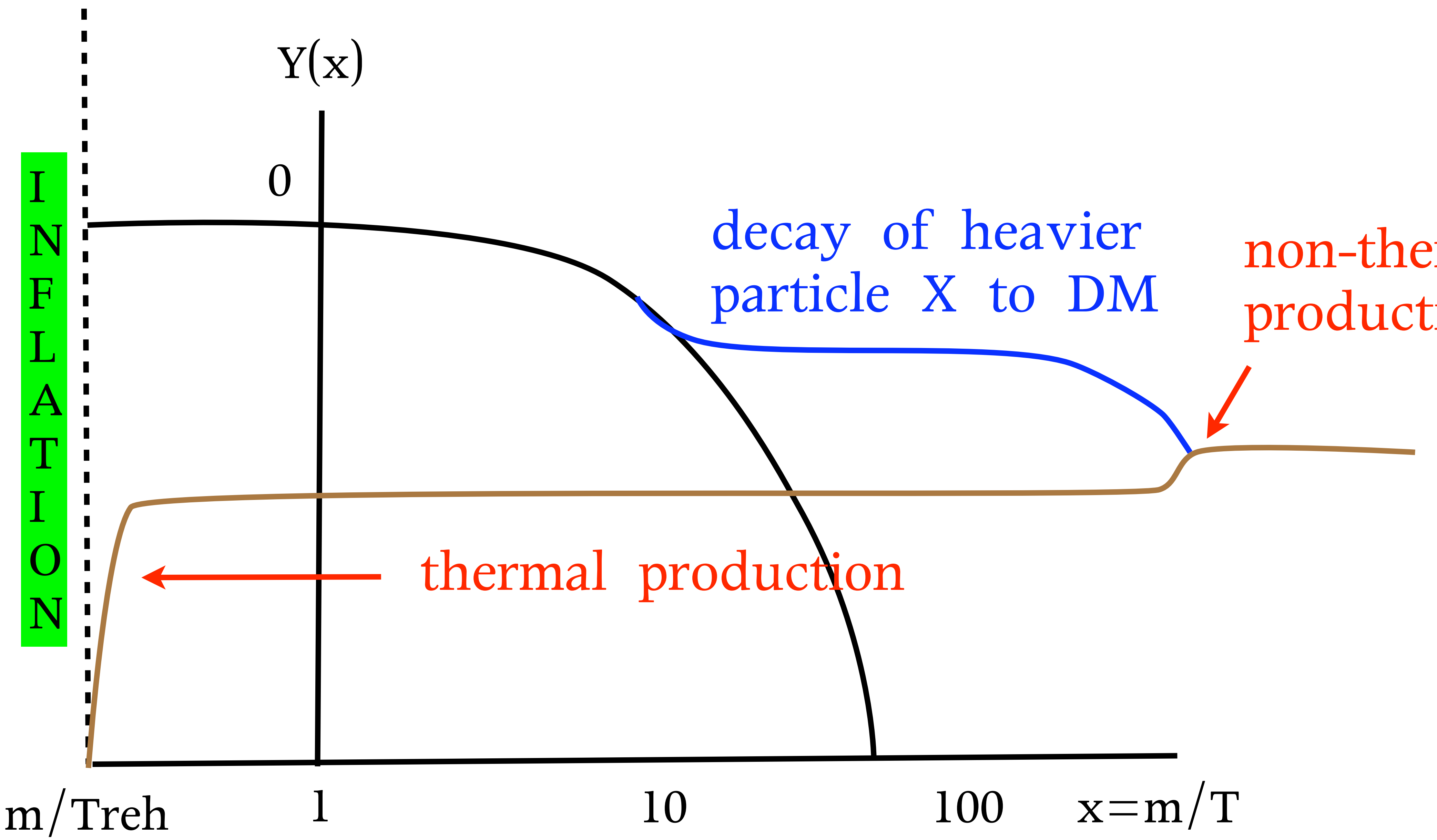


(I) depends on the reheating temperature
and we can get the same amount of abundance for dark matter.

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

- Non-thermal production : all supersymmeric particles decay to NLSP and later NLSP decay to gravitino. By R-parity conservation the number densities of R odd particles are conserved

$$\Omega_{\widetilde{G}}^{NTP} h^2 = \frac{m_{\widetilde{G}}}{m_{NLSP}} \Omega_{NLSP} h^2$$



- Total relic density of gravitino : TP+NTP

$$\Rightarrow \quad \Omega_{\widetilde{G}} h^2 = \Omega_{\widetilde{G}}^{TP} h^2 + \Omega_{\widetilde{G}}^{NTP} h^2$$

$\ast$ Also there are model dependent non-thermal productions (inflaton decay, moduli decay ...)

• Cosmological constraints on Gravitino DM

Due to the very small interactions, the next LSPs decay to Gravitino very late in the early Universe with a cosmic time around

$$\tau_X \sim 1\,\mathrm{sec} - 10^{12}\,\mathrm{sec}$$

This corresponds to the epoch of Big Bang Nucleosynthesis, kinetic decoupling of photns, and the structure formation of small sales.

Cosmological constraints!

NLSP(neutralino, stau ...) decay at 1 sec – 10^{12} sec

m_X

Gravitino E ~ mX/2

$$p_i = \frac{m_X^2 - m_{LSP}^2}{2m_X}$$

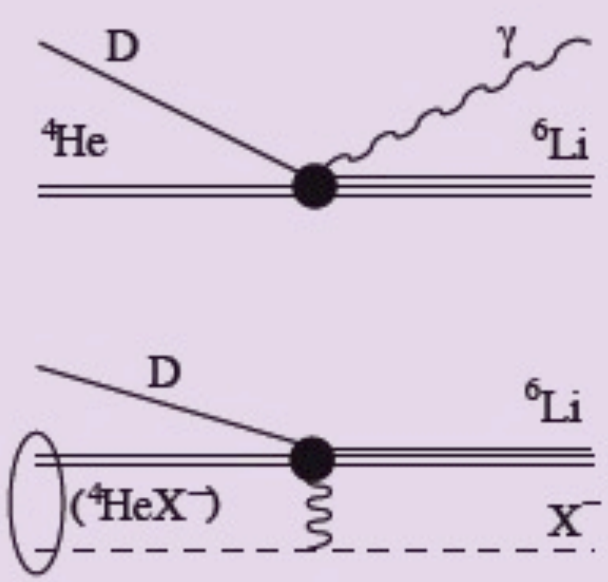
erase small scale perturbation
: affects LSS at small scale

$\gamma, \mathrm{leptons}, q\bar{q}$

E ~ mX/2 : interact with

if negatively charged

Bound with nuclei
: change BBN

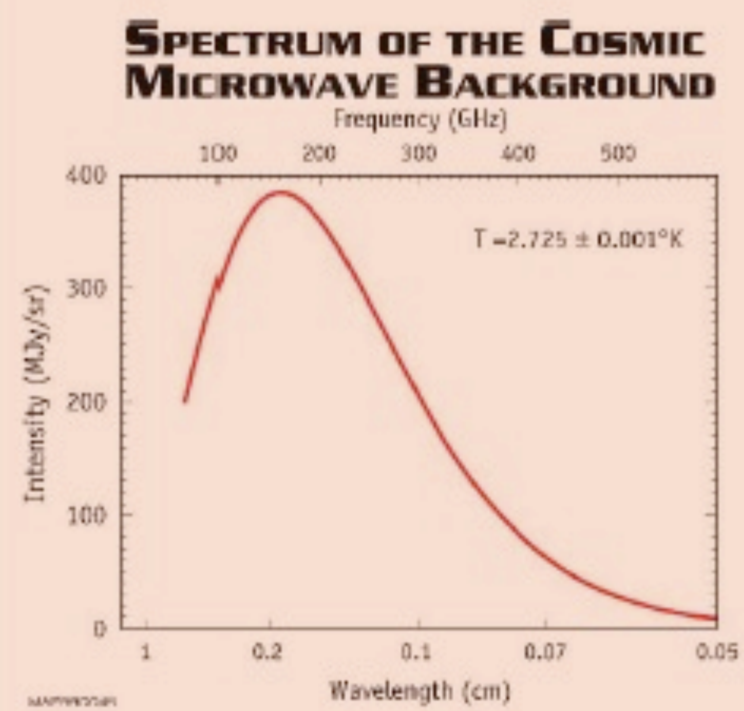


$$Y \equiv \frac{n}{s} \lesssim 10^{-15} - 10^{-14}$$

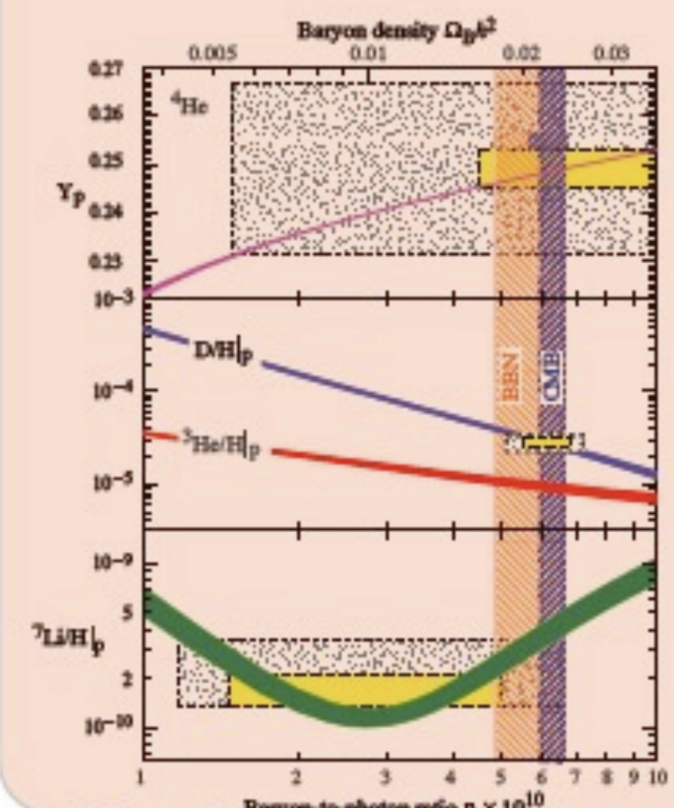
$$\tau_{\tilde{\tau}} \lesssim 5 \times 10^3\ \mathrm{sec}$$

(not always)

Background photons
: CMB distortion

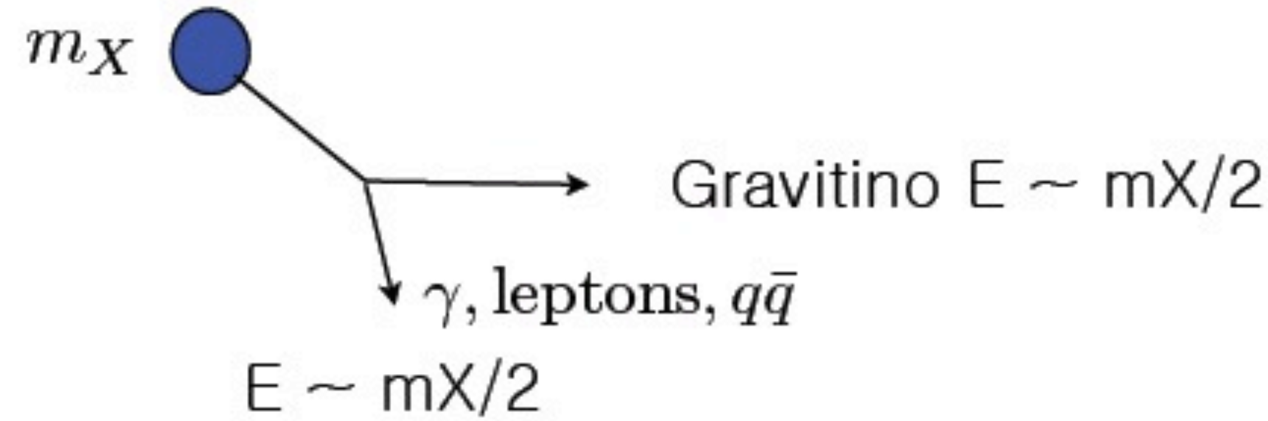


Background nuclei
: BBN disruption



EM and HAD showers

CMB distortion



- $\tau < 10^6\,\mathrm{sec}$

  Additional EM energies are completely thermalized

- $10^6\,\mathrm{sec} < \tau < 4 \times 10^{11} \Omega_b h^2\,\mathrm{sec}$

  Number changing processes are not efficient
  : kinetic equilibrium but not chemical

  ➡ Bose-Einstein distribution with chemical potential

  $$|\mu| < 9 \times 10^{-5} \quad (95\%\mathrm{CL})$$ [Hu et al. '93, Fixen et.al., '96]

- $\tau > 4 \times 10^{11} \Omega_b h^2\,\mathrm{sec}$

  No longer Bose-Einstein sectrum
  : constraints on compton parameter $y \equiv 4\delta\epsilon/\epsilon$

  $$|y| < 1.2 \times 10^{-5} \quad (95\%\mathrm{CL})$$ [Hagiwara et.al., '02]

★ However it is weaker constraint than BBN

[Roskowski et al. '05, Cerdeno et al. 06', et.al., '02]
[Lamon, Durrer '06]

BBN with Gravitino DM

Neutralino NLSP

$$\chi \to \tilde{G} + \gamma$$

$$\chi \to \tilde{G} + Z(h, \gamma^*/Z^*) \to \tilde{G} + q\bar{q}$$

$$B_h \sim 10^{-3}$$

Stau NLSP ★ Catalyzed BBN

$$\tilde{\tau} \to \tilde{G} + \tau$$

$$\tilde{\tau} \to \tilde{G} + \tau + Z(\gamma^*/Z^*) \to \tilde{G} + \tau + q\bar{q}$$

$$\tilde{\tau} \to \tilde{G} + \nu_\tau + W \to \tilde{G} + \nu_\tau + q\bar{q}$$

$$B_h \sim 10^{-5} - 10^{-2}$$

★ High energetic EM and Hadronic showers are generated and interact with nuclei

- n−p conversion by mesons $(t < 100\,\mathrm{s})$: increase of D and He4
- Hadronic dissociation $(100\,\mathrm{sec} - 10^7\,\mathrm{sec})$: increase of D and Li6

$$n + \alpha_{\mathrm{BG}} \to \mathrm{D} + \mathrm{T} \qquad p(n) + \alpha_{\mathrm{BG}} \to \begin{cases} \mathrm{T} + \cdots \\ {}^3\mathrm{He} + \cdots, \end{cases} \qquad \begin{matrix} \mathrm{T} + \alpha_{\mathrm{BG}} \to {}^6\mathrm{Li} + n, \\ {}^3\mathrm{He} + \alpha_{\mathrm{BG}} \to {}^6\mathrm{Li} + p. \end{matrix}$$

- Electromagnetic dissociation $(10^4\,\mathrm{sec} - 10^{12}\,\mathrm{sec})$

$$\gamma + D \to n + p \quad (t \lesssim 10^6\,\mathrm{s}) \qquad \gamma + {}^4He \to n + {}^3He \quad (t \gtrsim 10^6\,\mathrm{s})$$

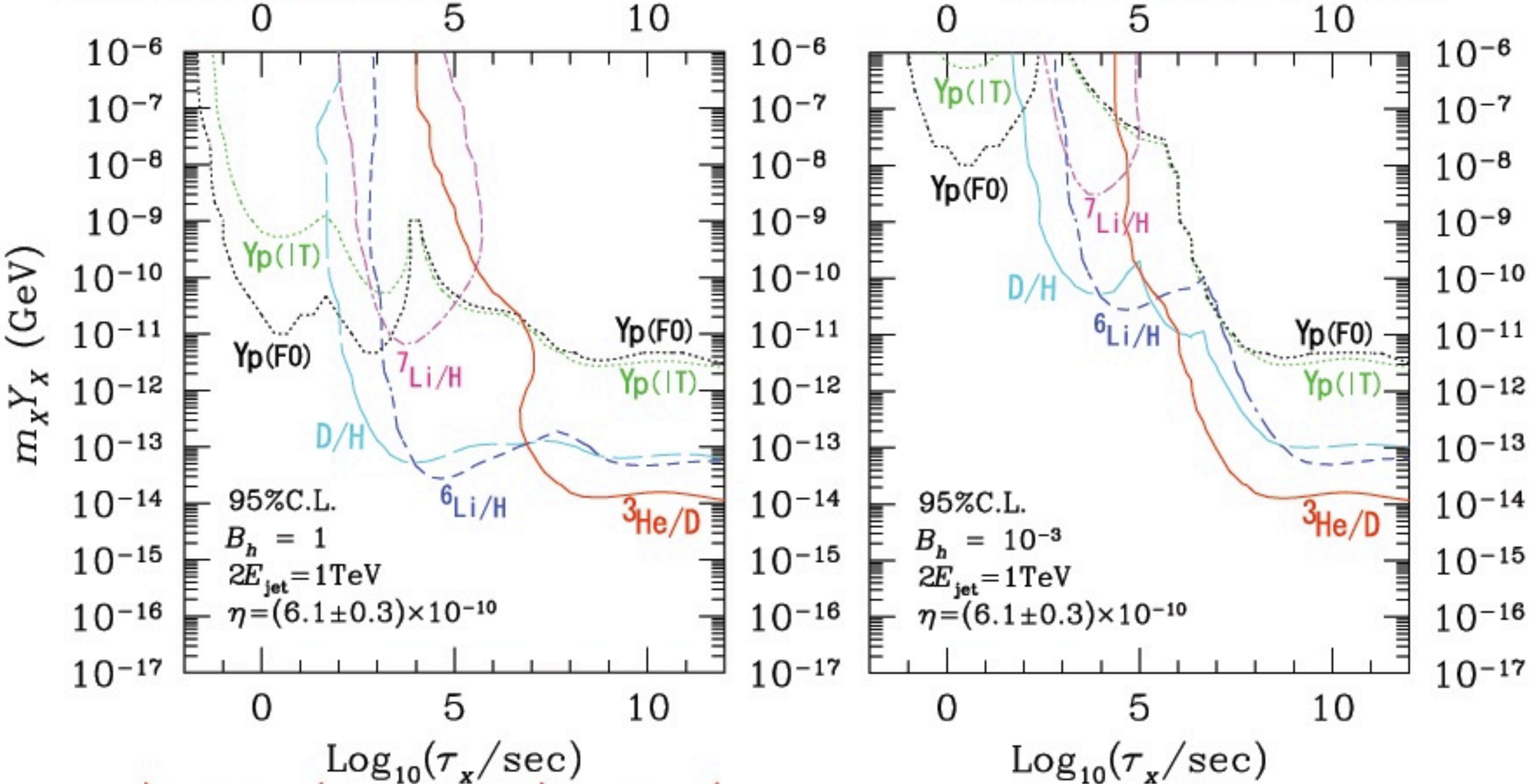
$$\gamma + {}^4He \to p + n + D$$

[Jedamzik 2004]

[Kohri, Kawasaki, Moroi '04]

Neutral particle decay

[Kohri, Kawasaki, Moroi '04]



n−p conversion

EM dissociation

had. dissociation

$$\Omega_X h^2 \simeq 3 \times 10^{-6} \frac{m_X Y_X}{10^{-14}\,\mathrm{GeV}}$$

Hadronic branching ratio is important!

- Charged particle during BBN : Catalyzed BBN

$$\tau(\tilde{\tau} \to \tilde{G}\tau) \simeq 6 \times 10^3 \sec \left(\frac{1\,\mathrm{TeV}}{m_{\tilde{\tau}}}\right)^5 \left(\frac{m_{\tilde{G}}}{100\,\mathrm{GeV}}\right)^2 \left(1 - \frac{m_{\tilde{G}}^2}{m_{\tilde{\tau}}^2}\right)^{-4}$$

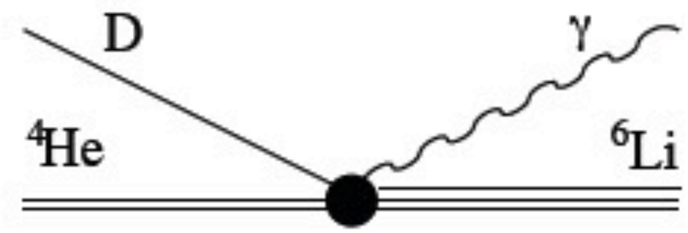
staus still exist during BBN epoch

"The existence of metastable, tau > 10^3 sec, negatively charged EW scale particles (X−) alters the predictions for lithium and other primordial elemental abunances via the formation of bound states with nuclei during BBN"

[M.Pospelov, PRL 2007]

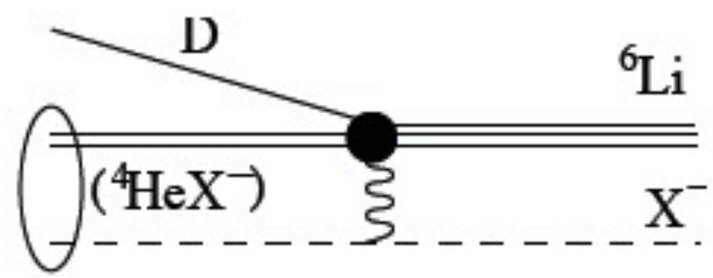
Standard BBN

$$^4\mathrm{He} + \mathrm{D} \to \; ^6\mathrm{Li} + \gamma;$$



Catalyzed BBN

$$(^4\mathrm{He}X^-) + \mathrm{D} \to \; ^6\mathrm{Li} + X^-;$$



requires $Y_X \lesssim 10^{-14}$ for $\tau_X \gtrsim 5 \times 10^3 \sec$

CBBN may dominate had input for $5 \times 10^3 \sec < \tau_X < 10^7 \sec$

Axino dark matter as E-WIMP

fermion $\widetilde{a}$ ← superpartner of — axion
(spin1/2)

EM neutral and stable when it is LSP.

Interaction is suppressed by PQ scale $f_a \sim 10^{10}$ GeV.

Mass can be in the wide range depending on the way of SUSY breaking,

from keV to TeV

Axinos can be produced thermally and also non-thermally.

Axino dark matter production

- Thermal production

1. From thermal scatterings (KSVZ model)

$$\Omega_{\tilde{a}} h^2 \simeq 0.6 \left(\frac{m_{\tilde{a}}}{0.1\,\mathrm{GeV}} \right) \left(\frac{10^{11}\,\mathrm{GeV}}{f_a} \right)^2 \left(\frac{T_\mathrm{R}}{10^4\,\mathrm{GeV}} \right)$$

Reheating temperature dependent!

2. From decays of the thermal particles

$$Y_\mathrm{decay} \simeq \frac{3\zeta(5)\,\bar{g} M_P \Gamma}{4\pi m^2}.$$

Not depend on the reheating temperature

- Non-thermal production

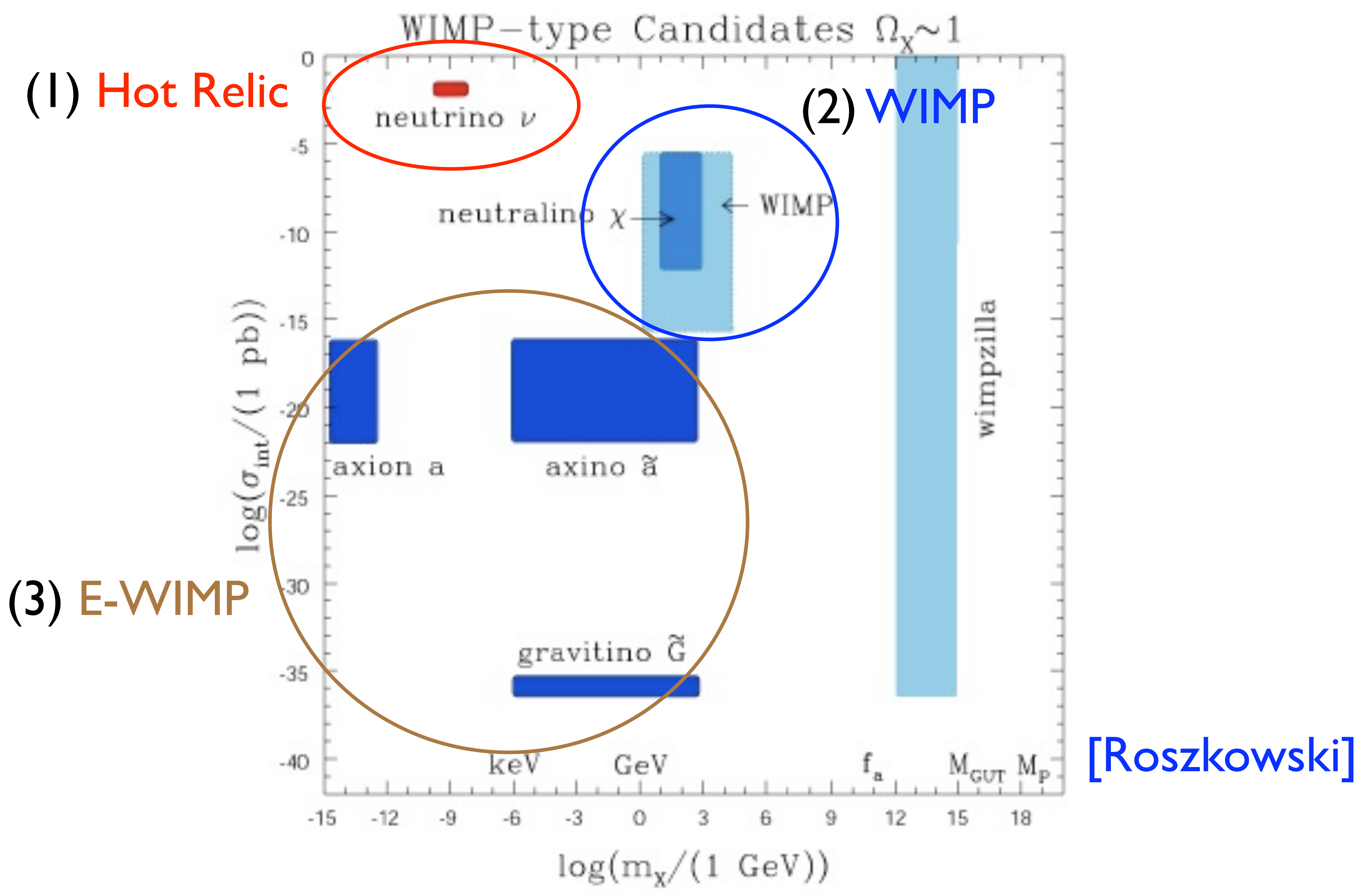
3. From decays of the particles which is out-of-equilibrium

$$\Omega_{\tilde{a}} h^2 = \frac{m_{\tilde{a}}}{m_X} \Omega_X h^2$$

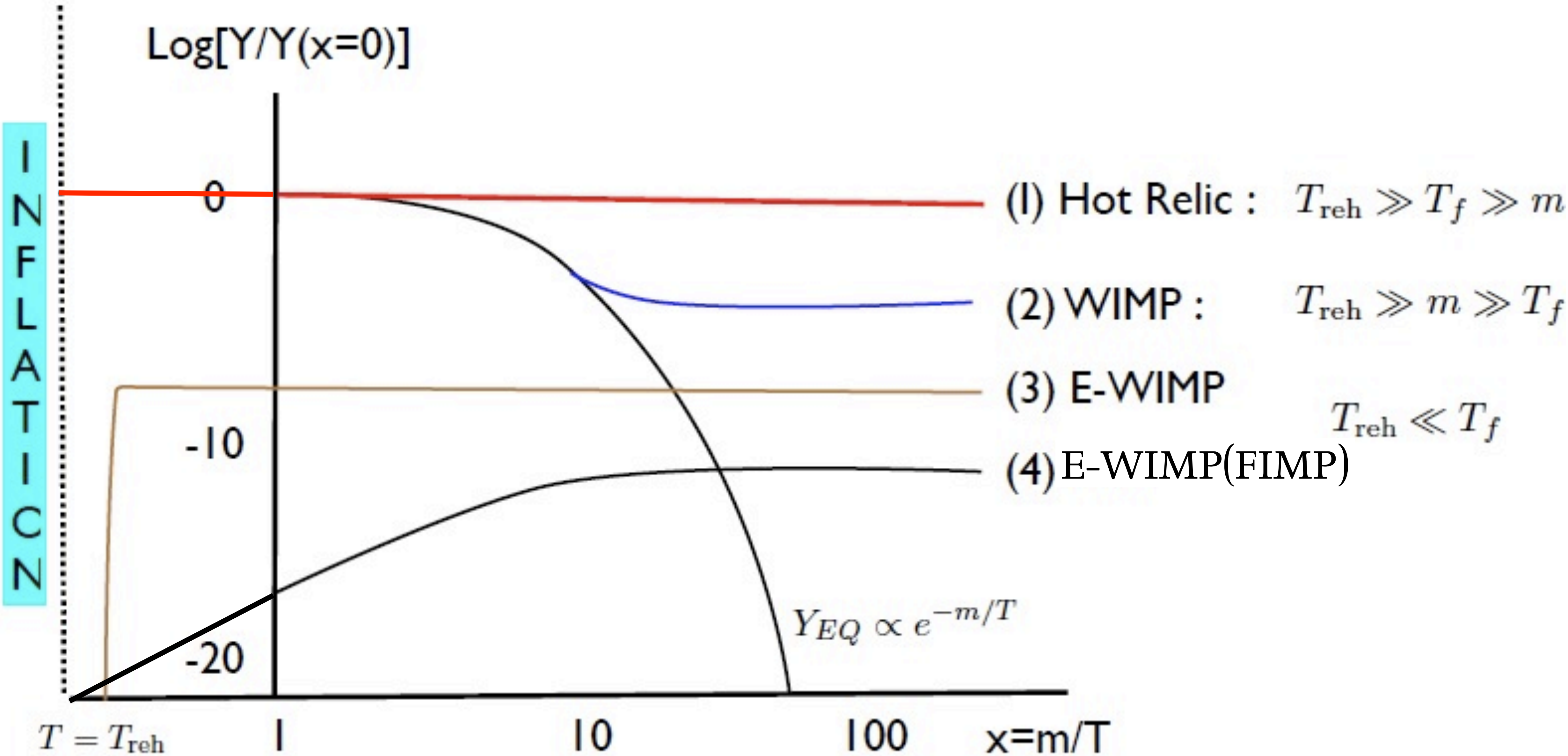
It happens usually before BBN and does not make cosmological problems.

We need to construct theoretical models containing dark matter

by modifying and/or extending the standard model



Thermal production of dark matter



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

n : number density
s : entropy density
EQ : equilibrium

m : mass
T : temperature
Treh : reheating temperature
Tf : freeze-out temperature

Thermally produced particles have a Boltzmann velocity distribution at the moment of production (or freeze-out) and sufficiently cold if the mass is much larger than keV.

KeV thermal relics have velocity dispersion

$$\langle v_{\rm TR} \rangle = \frac{3.151\ T_{\rm TR}(z)}{m_{\rm TR}} = \left(\frac{1+z}{100}\right)\left(\frac{1\ \ {\rm keV}}{m_{\rm TR}}\right)\left(\frac{T_{\rm TR}}{1\ {\rm K}}\right) 8.07\ {\rm km.s}^{-1}$$

[Boyarsky, Iesgourgues, Ruchaiskiy, Viel, 2009]

can be warm and well constrained by Ly alpha.

$$\langle v \rangle < 0.01\ {\rm km}\,(95\%\,CL)$$

corresponding to the lower mass bound $m > 8.1\ {\rm keV}$

For pure WDM

Non-thermally produced particles have a different velocity distribution.

Heavy DM around GeV mass also can be warm.

When DM is produced from the decay of heavy particles,
the free-streaming velocity is gained due to the kinetic energy from the rest mass energy of mother particle

$$p_i = \frac{m_X^2 - m_{DM}^2}{2m_X}$$ initial momentum redshifts with scale factor

gives a present free-streaming velocity (if non-relativistic today)

$$\langle v \rangle = \left(\frac{m_X^2 - m_{DM}^2}{2m_X m_{DM}} \right) \frac{T_0}{T_d} \left(\frac{g_0}{g_d} \right)^{1/2}$$ even though DM is very massive

eg) For gravitino DM produced from the decay of NLSP

$$\langle v \rangle = 0.024 \text{ km/ sec} \left(\frac{g_*(T_d)}{3.36} \right)^{1/4} \left(\frac{m_X}{1 \text{ TeV}} \right)^{-3/2} \left(1 - \frac{m_{DM}^2}{m_X^2} \right)^{-1}$$

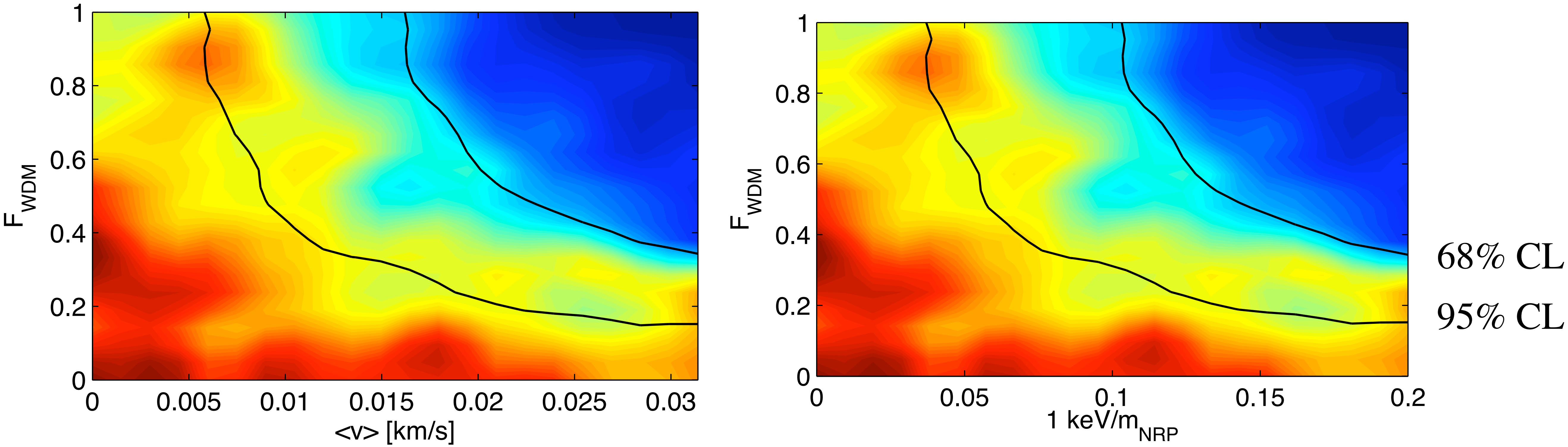
⇨ $m_X > 1.8 \text{ TeV}$ which constrain the models

For pure NTP

Mixed dark matter with thermal + non-thermal production
: cold + warm dark matter

$$F_{\rm WDM} \equiv \frac{\Omega_{\rm WDM}}{\Omega_{\rm CDM} + \Omega_{\rm WDM}}$$

[Boyarsky, lesgourgues, Ruchaiskiy, Viel, 2009]



For mixed model, the WDM is compatible if the composition is less than around 35 % of the total dark matter.

Discussion

1. What is the consistent theory with dark matter?
2. Different predictions for different dark matter models
3. What is the creation mechanism for dark matter?
4. Cold, warm or cold + warm?