Non-neutralino Dark Matter

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Contents

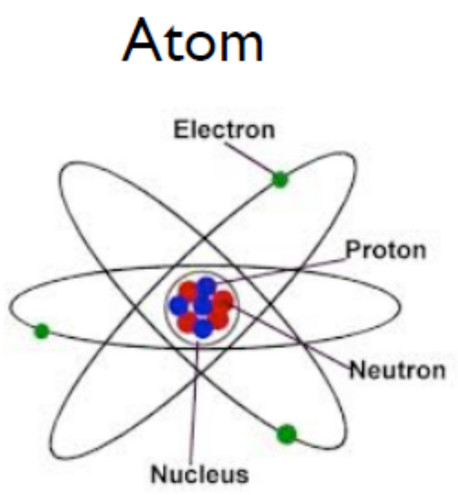
Dark Matter properties

- Observe matters in the Universe

  - With light

    The atoms and molecules can absorb and emit light. We can detect them directly with telescope.

    → Visible matter

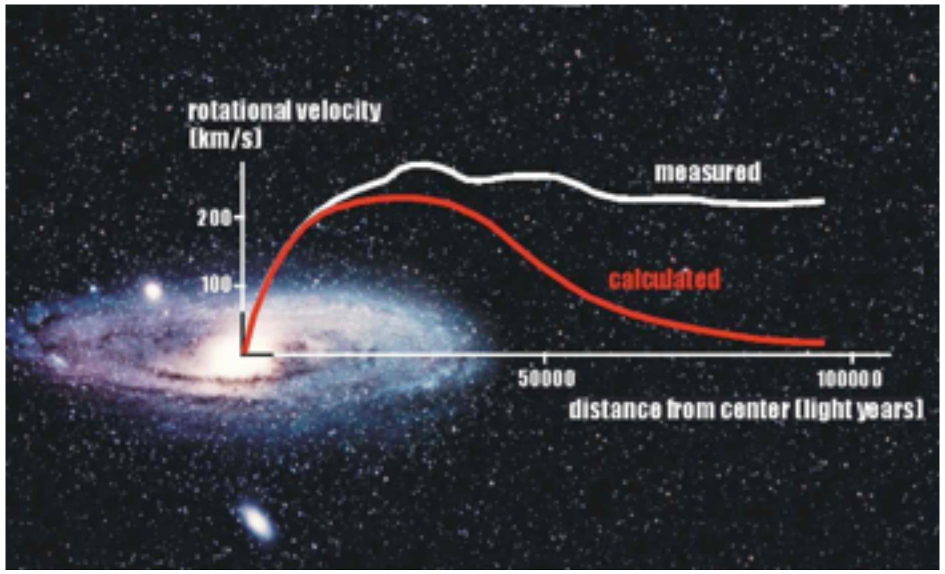


  - With gravity

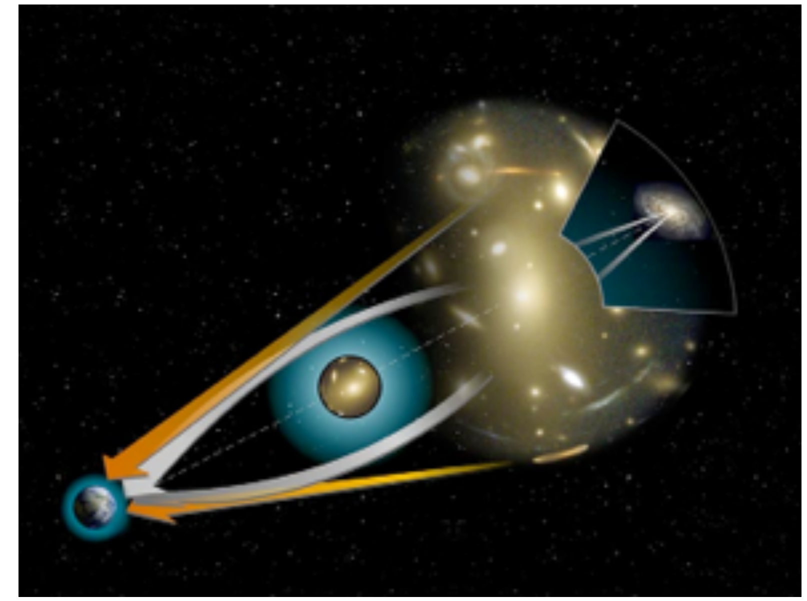
    All forms of mater and energy cause gravity and affected by gravity. With dynamics of the objects or the gravitational lensing, we can detect them indirectly.

    → Gravitational matter

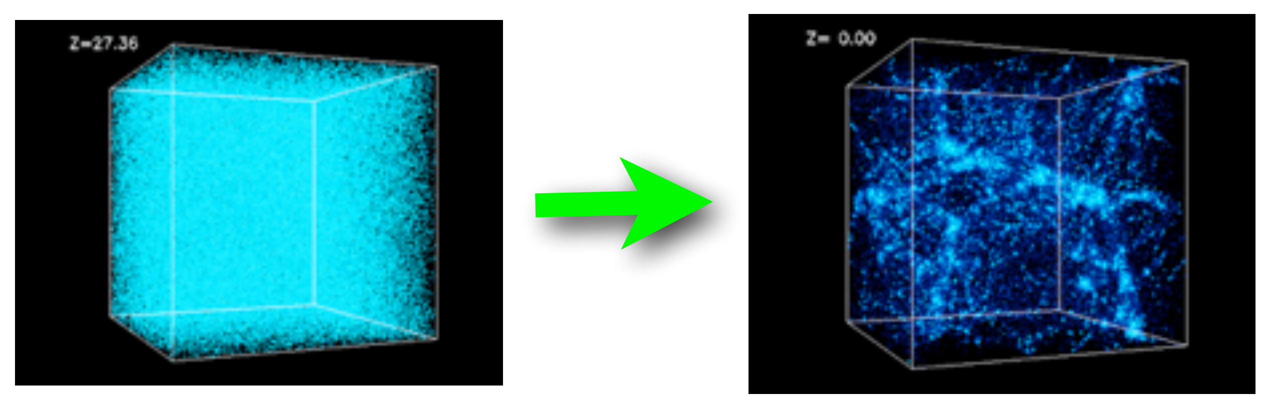
Anomalies between the visible matter and the gravitational matter



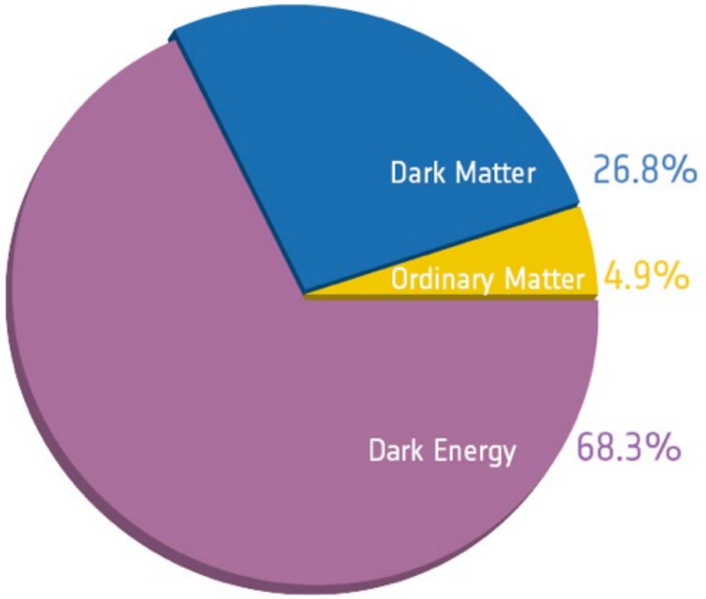
Galaxy rotational curve


Gravitational lensing

The bullet cluster



Structure formation



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

➡ Only upper bounds on the self 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. 25% of the present energy density of the universe

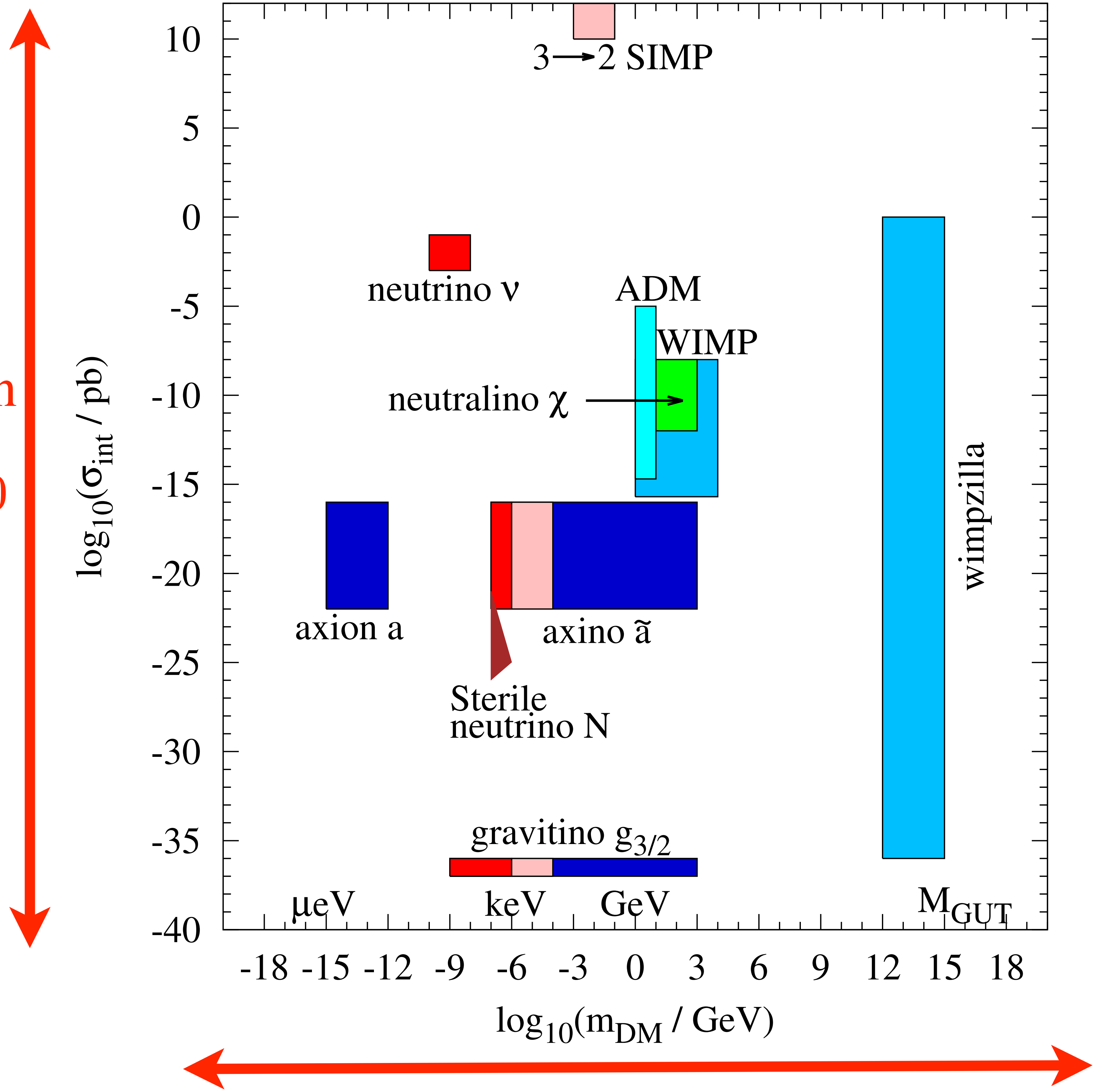
4. cold (or warm) : non-relativistic to seed the structure formation

What is Dark Matter?

No candidate in Standard Model!

Interaction

10^{40}



Mass 10^{40}

Relic density of (non-relativistic) dark matter

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

$$\simeq 0.1$$

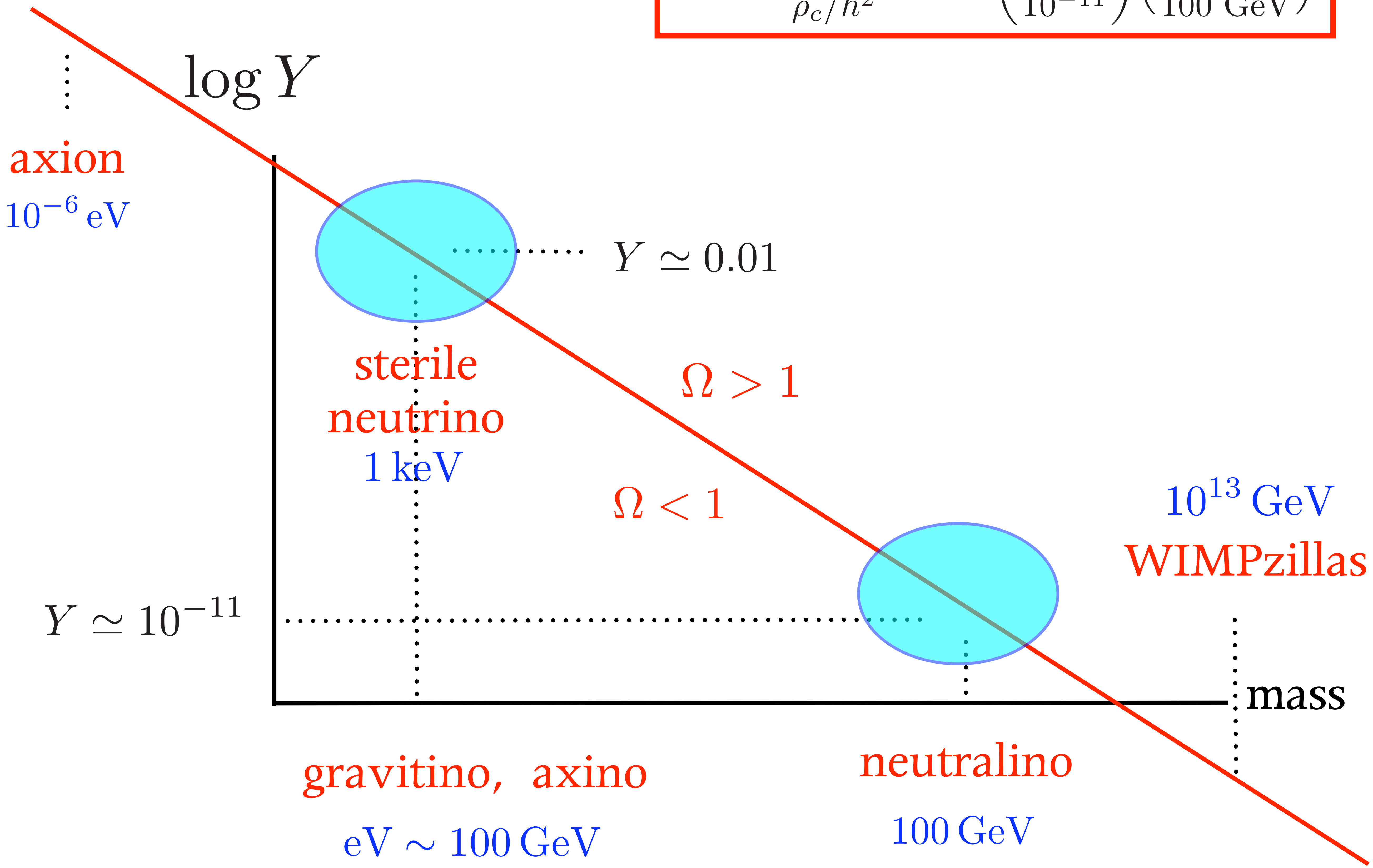
Abundance: $Y \equiv \frac{n}{s}$ Entropy density: $s = \frac{2\pi^2}{45} g_{*s} T^3$

Critical density: $\rho_c \equiv \frac{3H^2}{8\pi G}$

Abundance, Y, is constant after freeze-out.

Relic density of dark matter

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



Production of Dark Matter

Misalignment mechanism

Freeze-out from thermal equilibrium

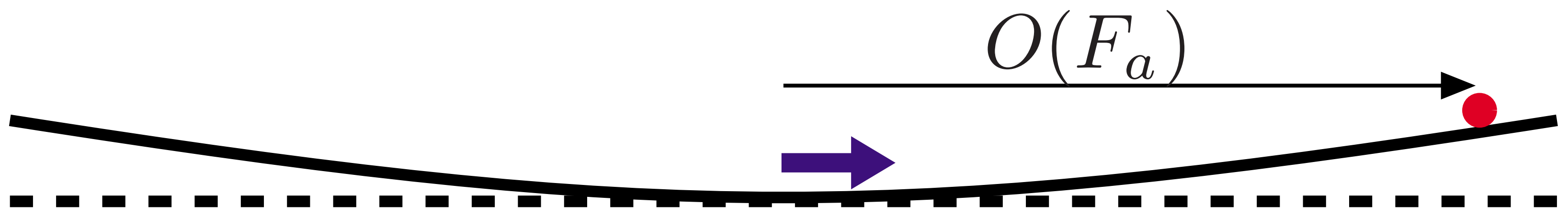
Decay from heavy particles

Scatterings and decays of thermal particles

Asymmetry determines the relic density

Axion : Misalignment mechanism

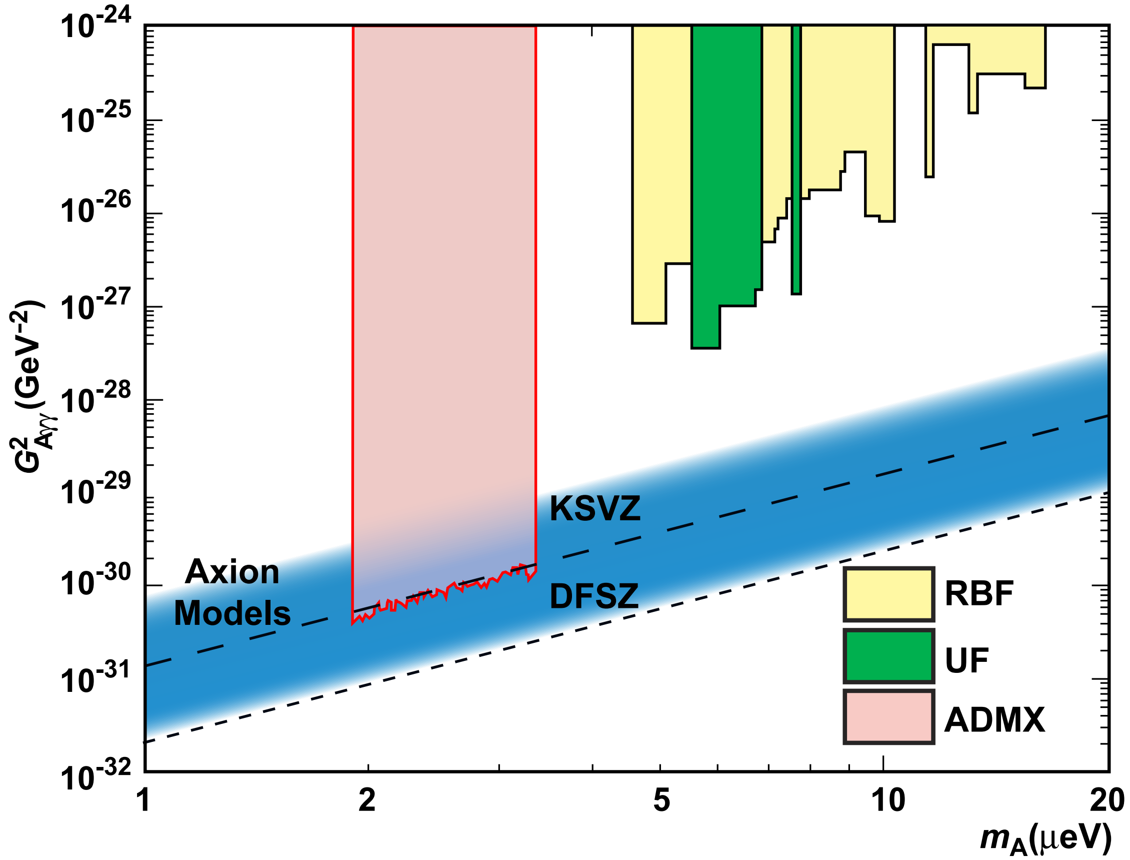
Oscillating scalar field behaves like non-relativistic matter.



[Kim, Carosi]

Axion detection

using $\mathcal{L}_{a\gamma\gamma} = \left(\frac{\alpha_{\rm em} c_{a\gamma\gamma}}{2\pi F_a}\right) a\mathbf{E}\cdot\mathbf{B}$,

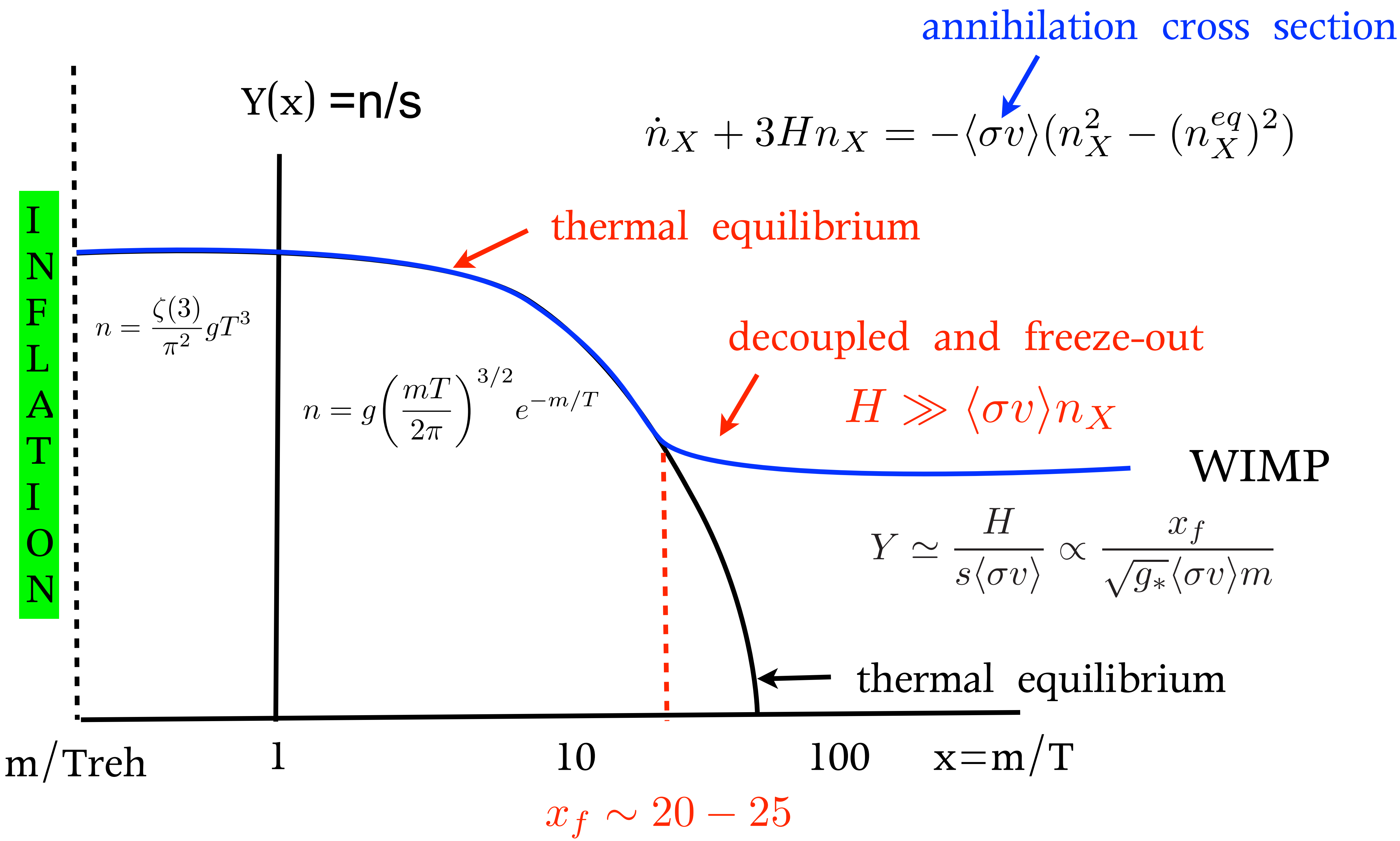


[PDG2013]

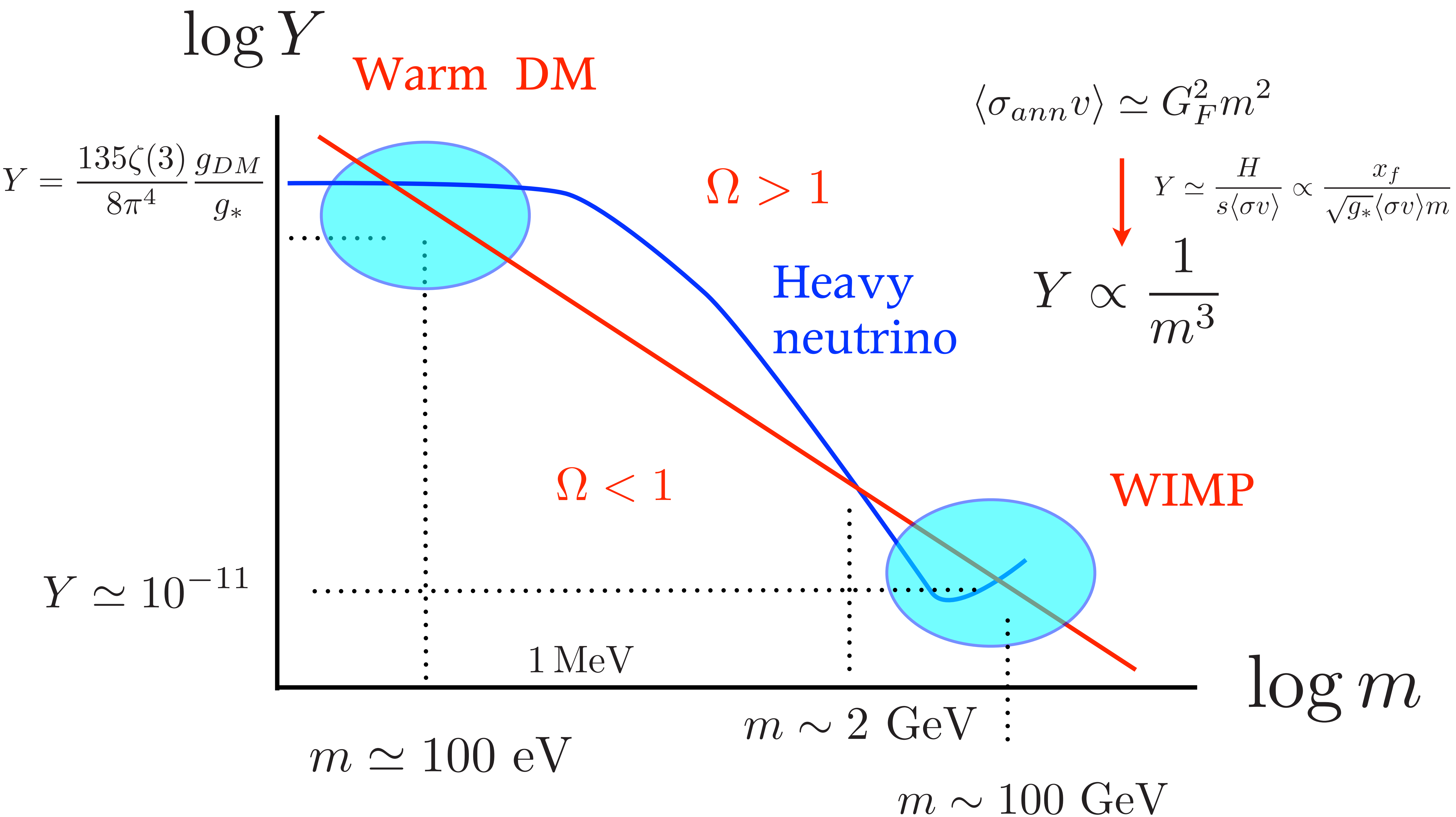
WIMP : Weakly Interacting Massive Particle

[B. W. Lee and S. Weinberg, PRL 1977]

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



Relic density : weakly interacting particles



* Lee-Weinberg bound : $m \gtrsim 2$ GeV for heavy neutrinos not to overclose

WIMP : Weakly Interacting Massive Particle

- Neutralino
- scalar neutrino
- RH neutrino
- minimal DM
- Kaluza-Klein DM

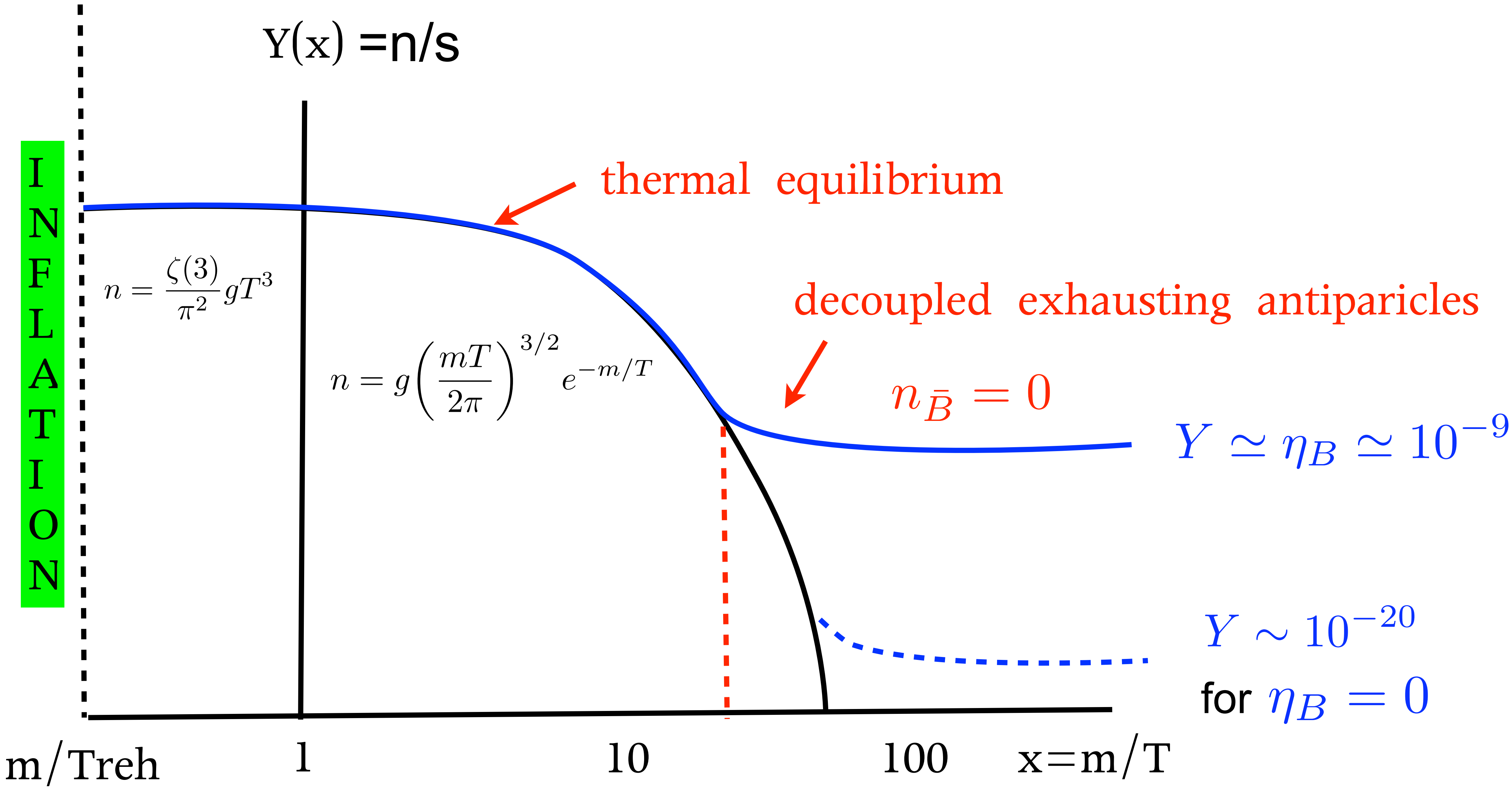
and so on ……

: freeze-out of the thermal eq. when non-relativistic

Asymmetric dark matter: Complex DM with asymmetry

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.

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

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

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

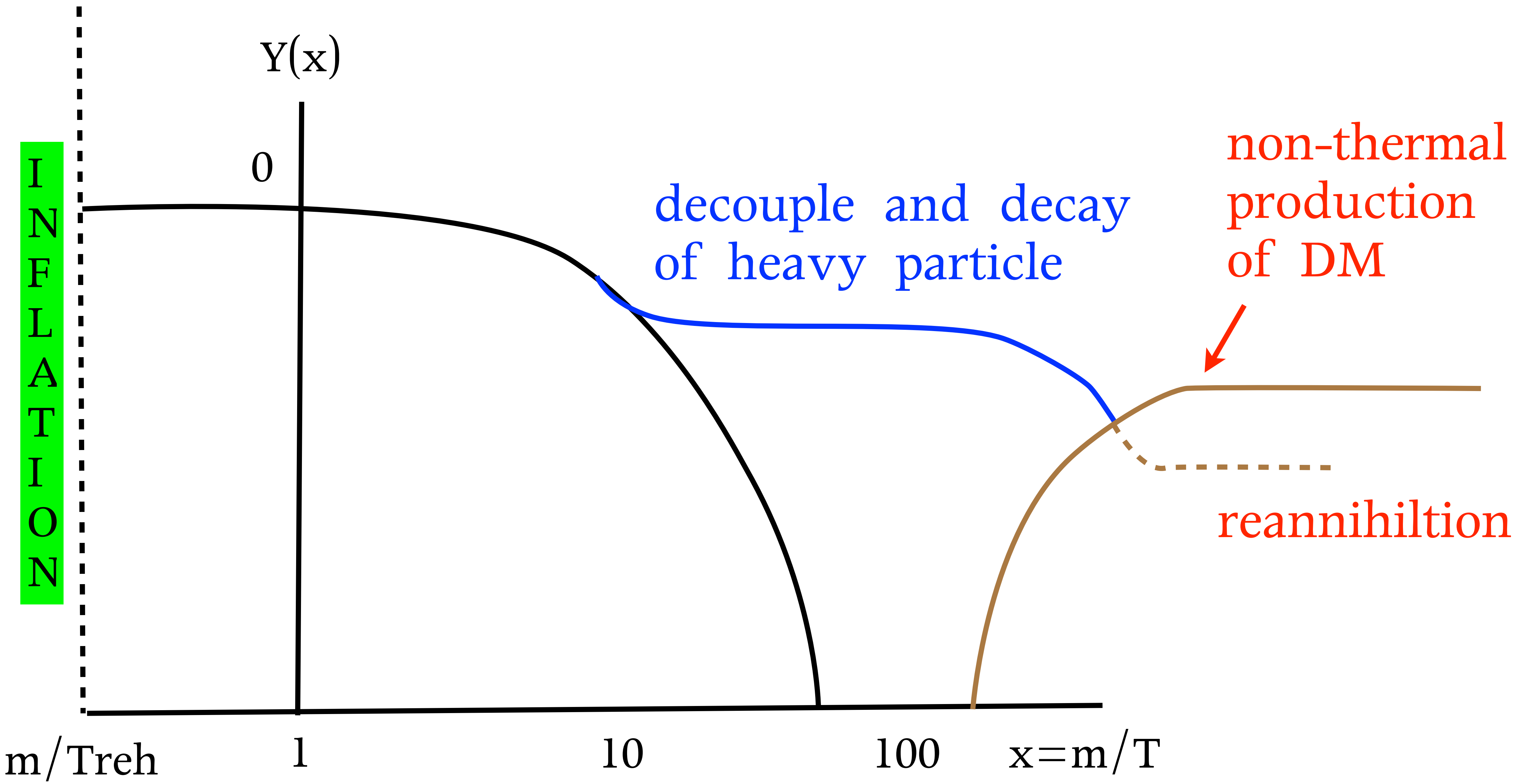
Stable Technibaryon [Nussinov, 1985]

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

$$\Omega_{\rm DM} = \frac{m_{\rm DM}}{m_X}\Omega_X$$

Gravitinos, axinos,....

With additional annihilation of DM from decay of heavy particles

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

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]

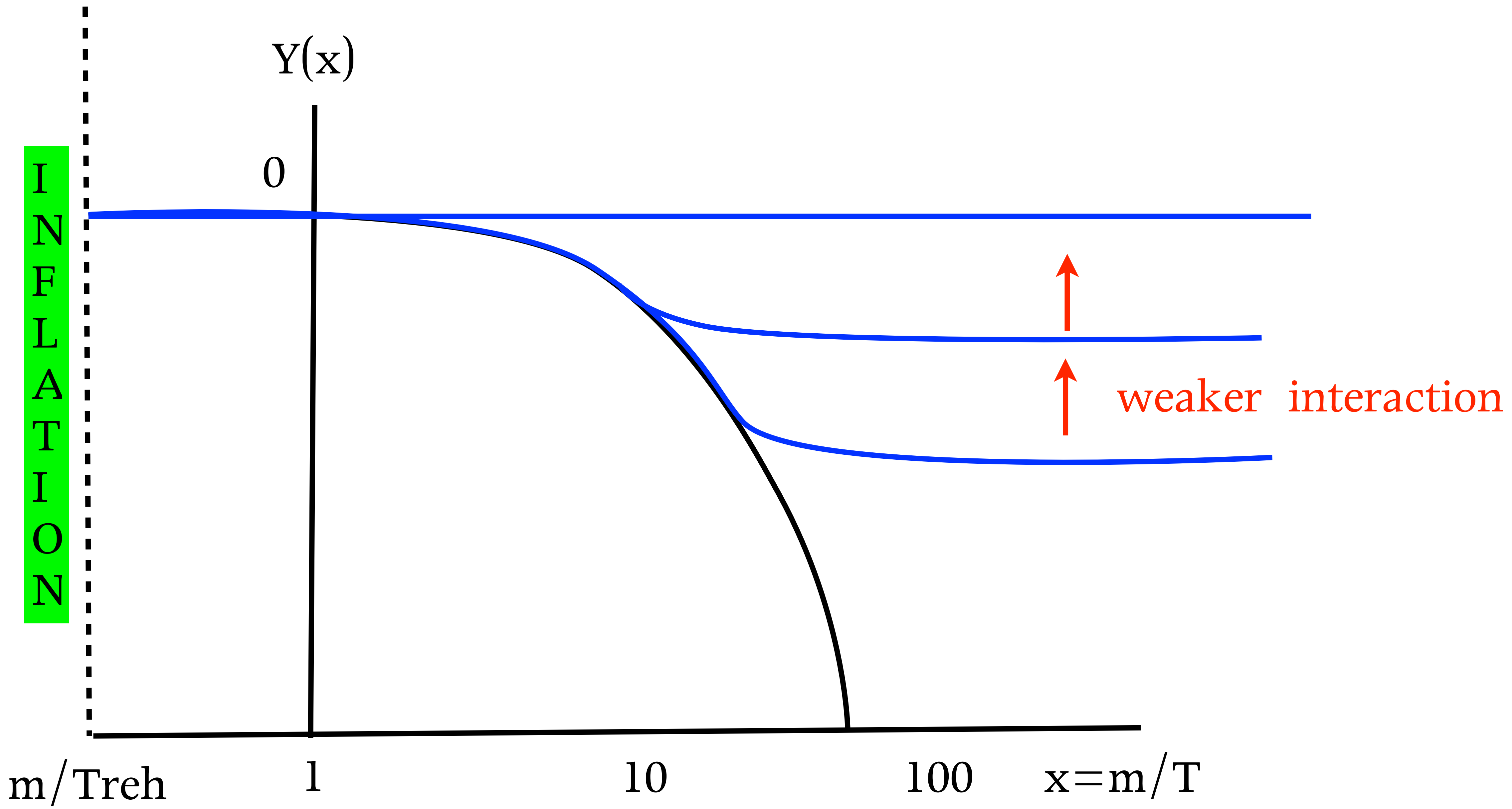
Neutralino DM from heavy axino decay [KYChoi, Kim, Lee, Seto, 2008]

[Baer, Lessa, Rajagopalan, Streethawong, 2011]

.....

More weakly interacting particles?

More weakly ineracting with a given mass

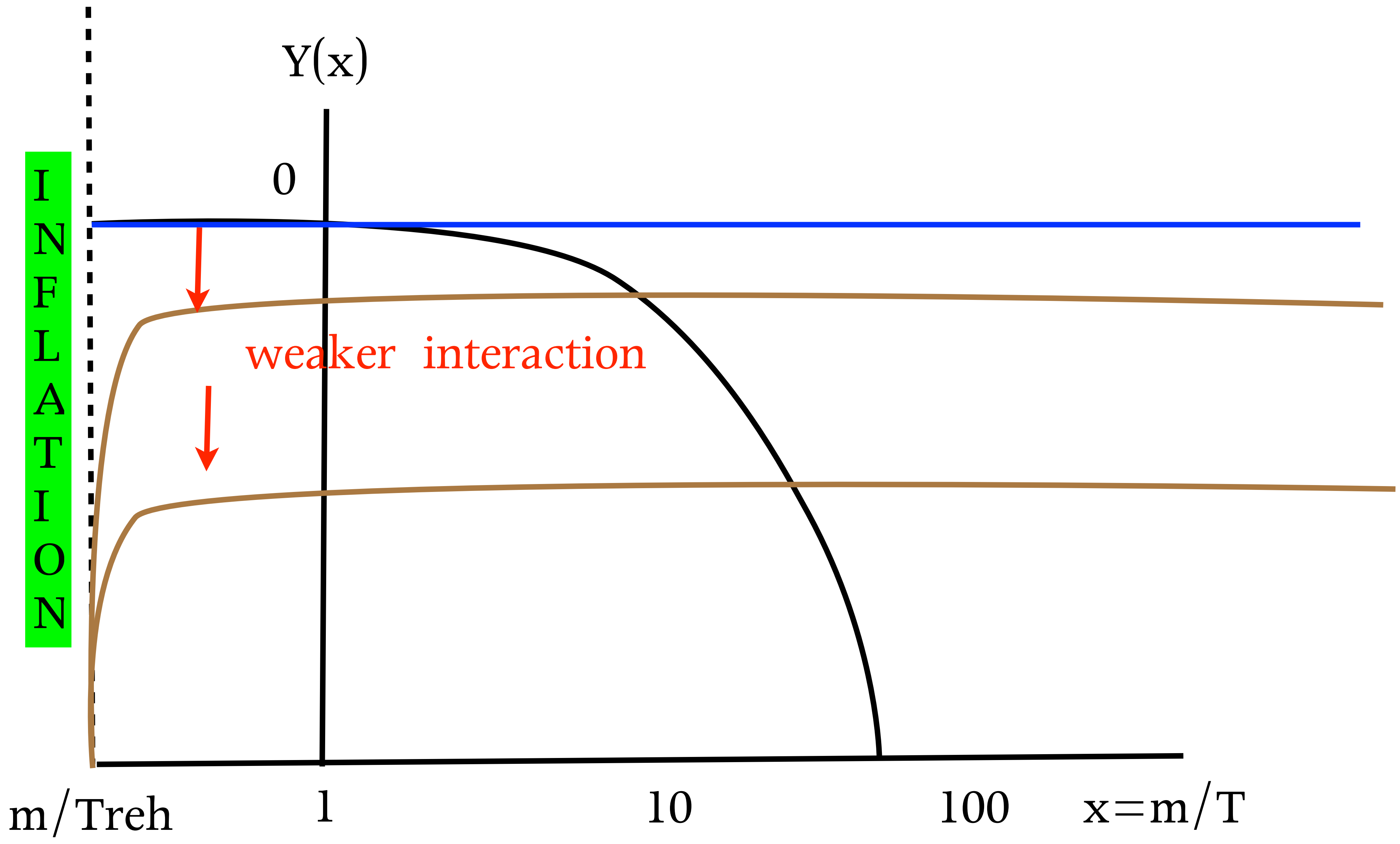


Inflation

Primordial particles are diluted during inflation and reproduced after inflation during reheating and start standard Big Bag cosmology with reheating temperature.

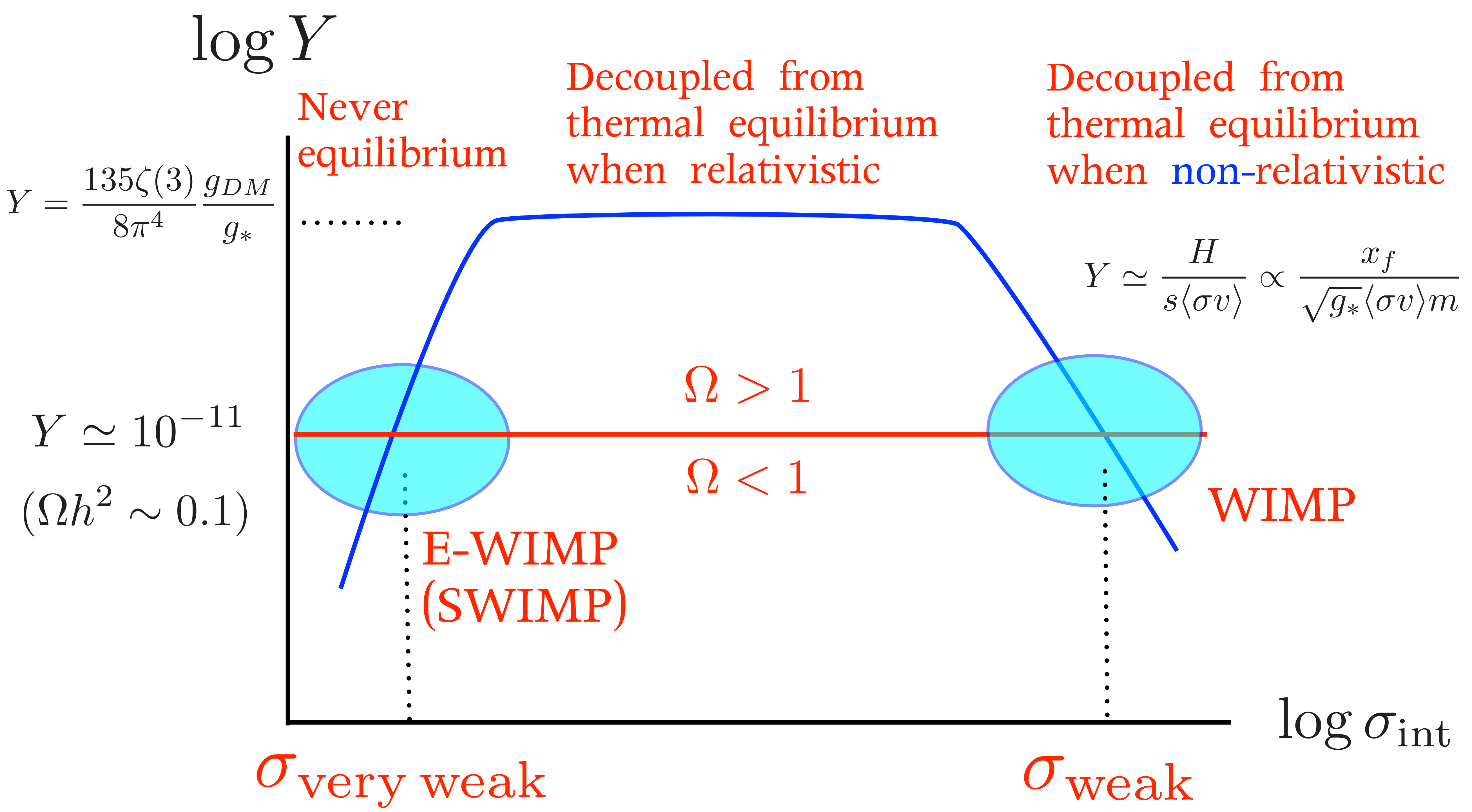
Not all the produced particles can reach the thermal equilibrium: Supermassive or extremely weakly interacting particles ....

More weakly interacting with a given mass



Relic density of massive particles

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



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

For example,

	Gravitino	Axino
	$M_P \sim 10^{18}\,\mathrm{GeV}$	$f_a \sim 10^{11}\,\mathrm{GeV}$

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

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

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

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

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

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

No dependence on the reheating temperature.

Gravitino Dark Matter

Couplings suppressed by Planck scale

Thermal production and non-thermal production:

- Dependence on the reheating temperature
- Late decay of NLSP : constraints from BBN and CMB

$$T_{\rm reh} < \text{a few} \times 10^7 \text{ GeV} \quad (\lesssim 3 \times 10^8 \text{ GeV})$$

with stau NLSP

Axino Dark Matter

Strong CP problem with SUSY

Axino

axion

SUSY

axino

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

$$10^9\,\mathrm{GeV} \lesssim f_a \lesssim 10^{12}\,\mathrm{GeV}$$

$$6 \times 10^{-3}\,\mathrm{eV} \gtrsim m_a \gtrsim 6 \times 10^{-6}\,\mathrm{eV}$$

Stellar energy-loss limit

[Raffelt '06, PDG review '07]

Cosmic axion population

$$\Omega_a h^2 \simeq 0.3 \left(\frac{f_a}{10^{12}\,\mathrm{GeV}} \right)^{7/6}$$

$$m_a = \frac{\sqrt{z}}{1+z} \frac{m_\pi f_\pi}{f_a} = 6 \left(\frac{10^6\,\mathrm{GeV}}{f_a} \right) \mathrm{eV}$$

$$z = \frac{m_u}{m_d} = 0.3 - 0.6$$

$$\Phi_a = (s + ia, \tilde{a})$$

$$W_{PQ} = \frac{g^2}{16\sqrt{2}\pi^2 f_a} \Phi_a W^\alpha W_\alpha$$

- Axino mass

  : strongly model dependent

  -> free parameter

- Axino couplings

  : determined by axion models, suppressed by PQ scale, f_a

- Freeze-out temperature :

$$T_f = 10^9\,\mathrm{GeV} \left(\frac{f_a}{10^{11}\,\mathrm{GeV}} \right)^2 \left(\frac{\alpha_S}{0.1} \right)^{-3}$$

Axion and Axino models

KSVZ

[Kim 1979] [Shifman, Veinstein, Zakharov 1980]

$$W_{\rm KSVZ} = W_{\rm PQ} + f_Q Q_L \overline{Q}_R S_1$$

$Q_L,\ \bar{Q}_R$ are heavy quarks

$$m_Q = f_A V_a$$

SM fields are not charged under $U(1)_{PQ}$

DFSZ

[Dine, Fischler, Srednicki 1981] [Zhitnitskii 1980]

$$W_{\rm DFSZ} = W_{\rm PQ} + \frac{f_s}{M_{\rm P}} S_1^2 H_d H_u$$

$H_d,\ H_u$ are Higgs multiplets

$$\frac{f_s}{M_P} V_a^2 = \mu \qquad \text{mu-term}$$

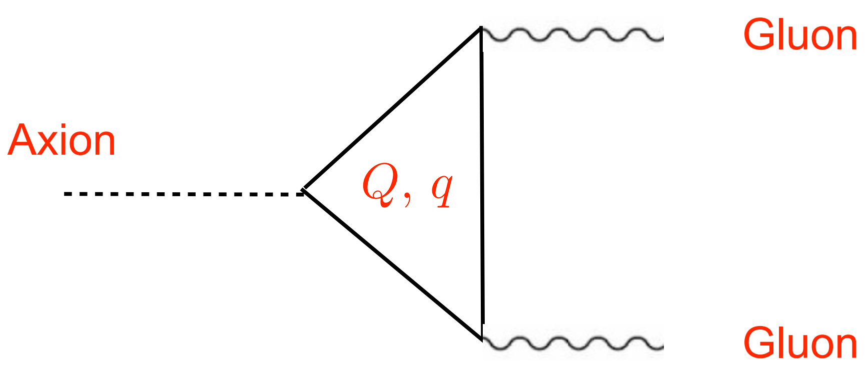
SM fields are charged under $U(1)_{PQ}$

Peccei-Quinn symmetry breaking

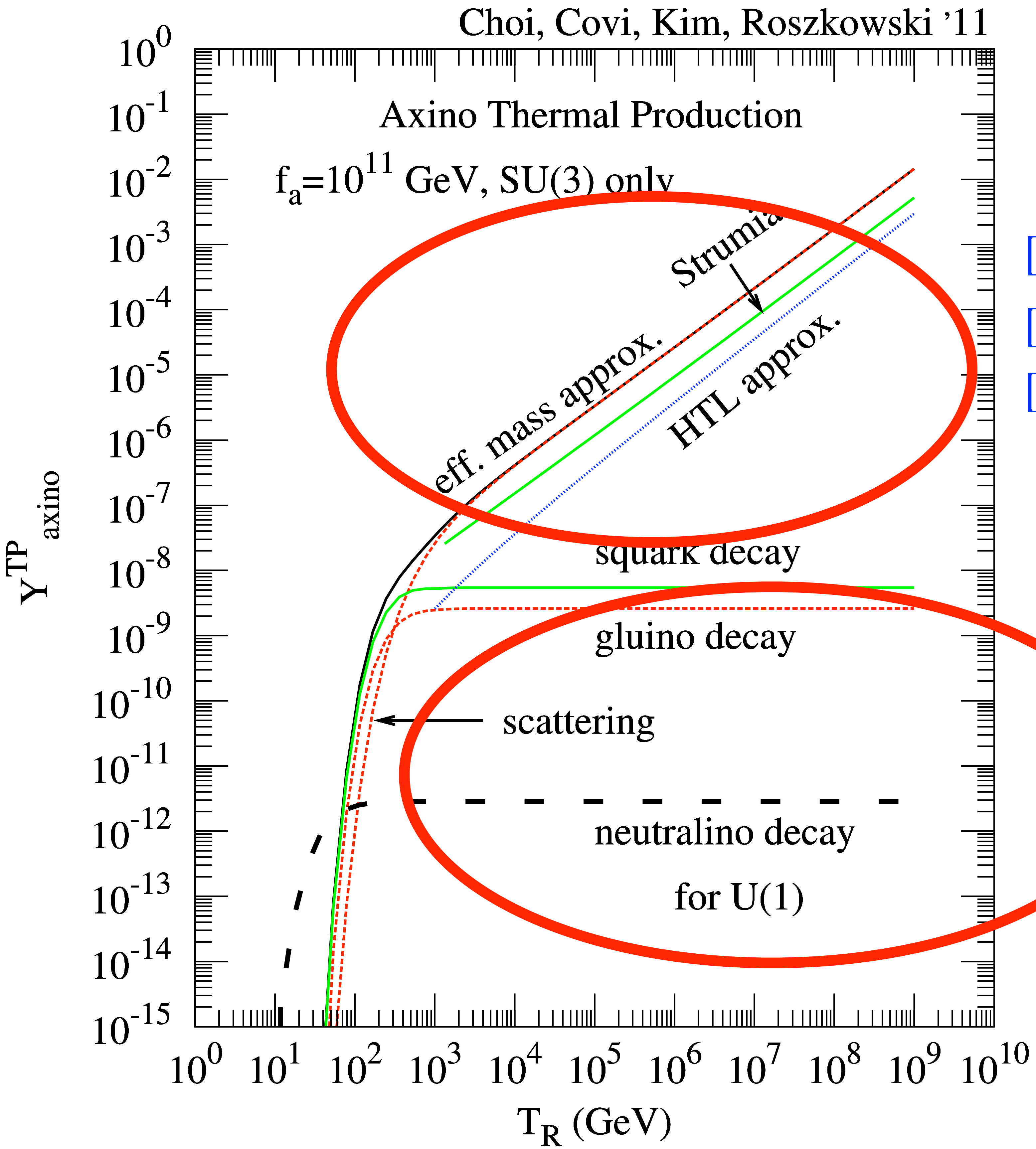
$$W_{\rm PQ} = f_Z Z(S_1 S_2 - V_a^2),$$

$$\langle S_1 \rangle = \langle S_2 \rangle = V_a$$

At low-energy,



Axino thermal production



from anomaly interactions
: depend on Treh,
independent on axino mass

[KYC, Covi, Kim, Roszkowki, 2011]

[Brandenberger, Steffen, 2004]

[Strumia, 2010]

nearly equal but factor 5-10 differences

from Yukawa interactions
: constant for high Treh

[Covi, Kim, Kim, Roszkowski, 2001]

[KYC, Covi, Kim, Roszkowki, 2011]

Axino non-thermal production

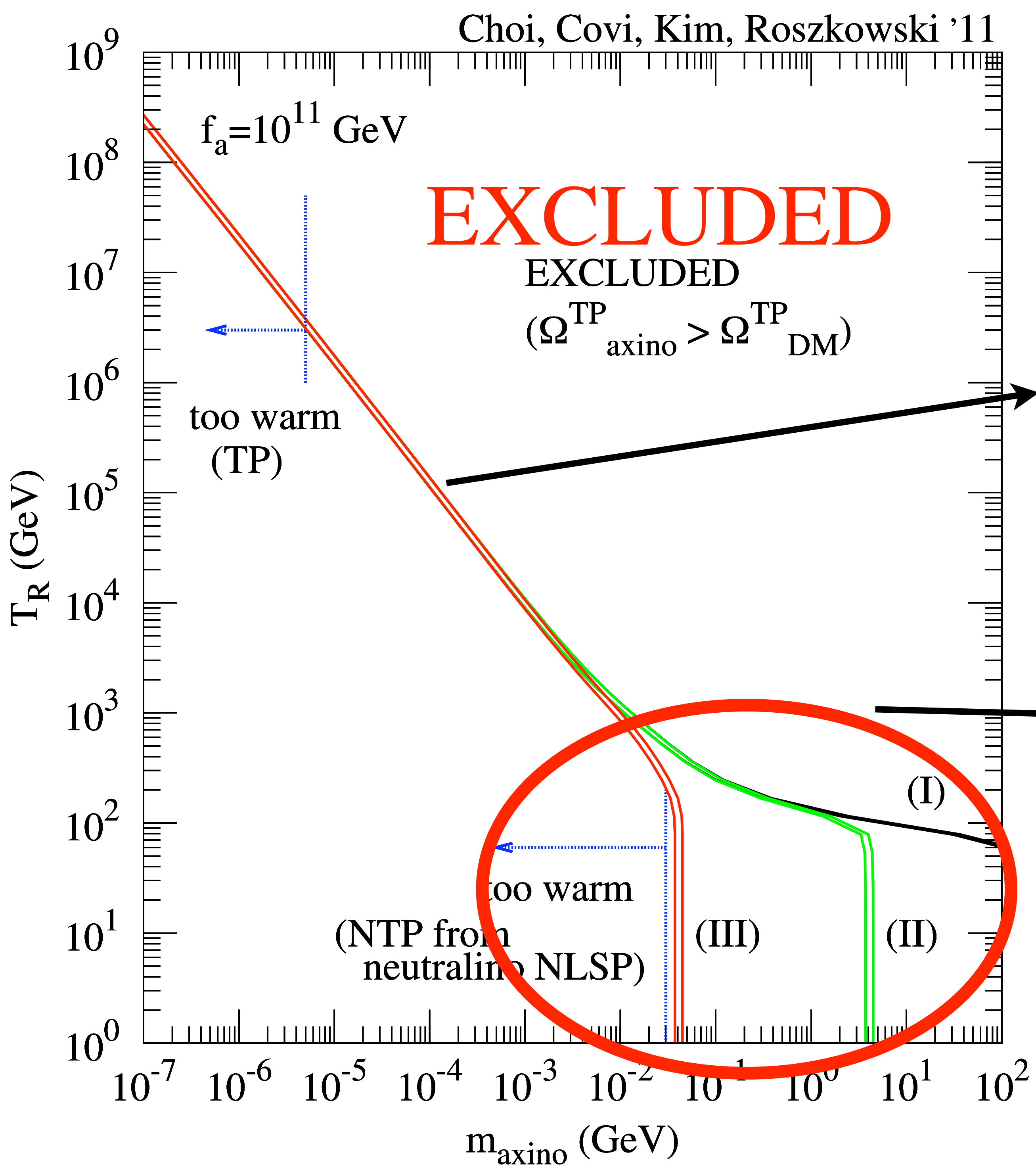
NLSPs decouple from the thermal equilibrium and decay to axino. By R-parity conservation, the number density of R-odd particles are conserved

$$\Omega_{\tilde{a}}^{NTP} h^2 = \frac{m_{\tilde{a}}}{m_{NLSP}} \Omega_{NLSP} h^2$$

- Total relic density of gravitino : TP + NTP

$$\Rightarrow \quad \Omega_{\tilde{a}} h^2 = \Omega_{\tilde{a}}^{TP} h^2 + \Omega_{\tilde{a}}^{NTP} h^2$$

Upper bound on Treh

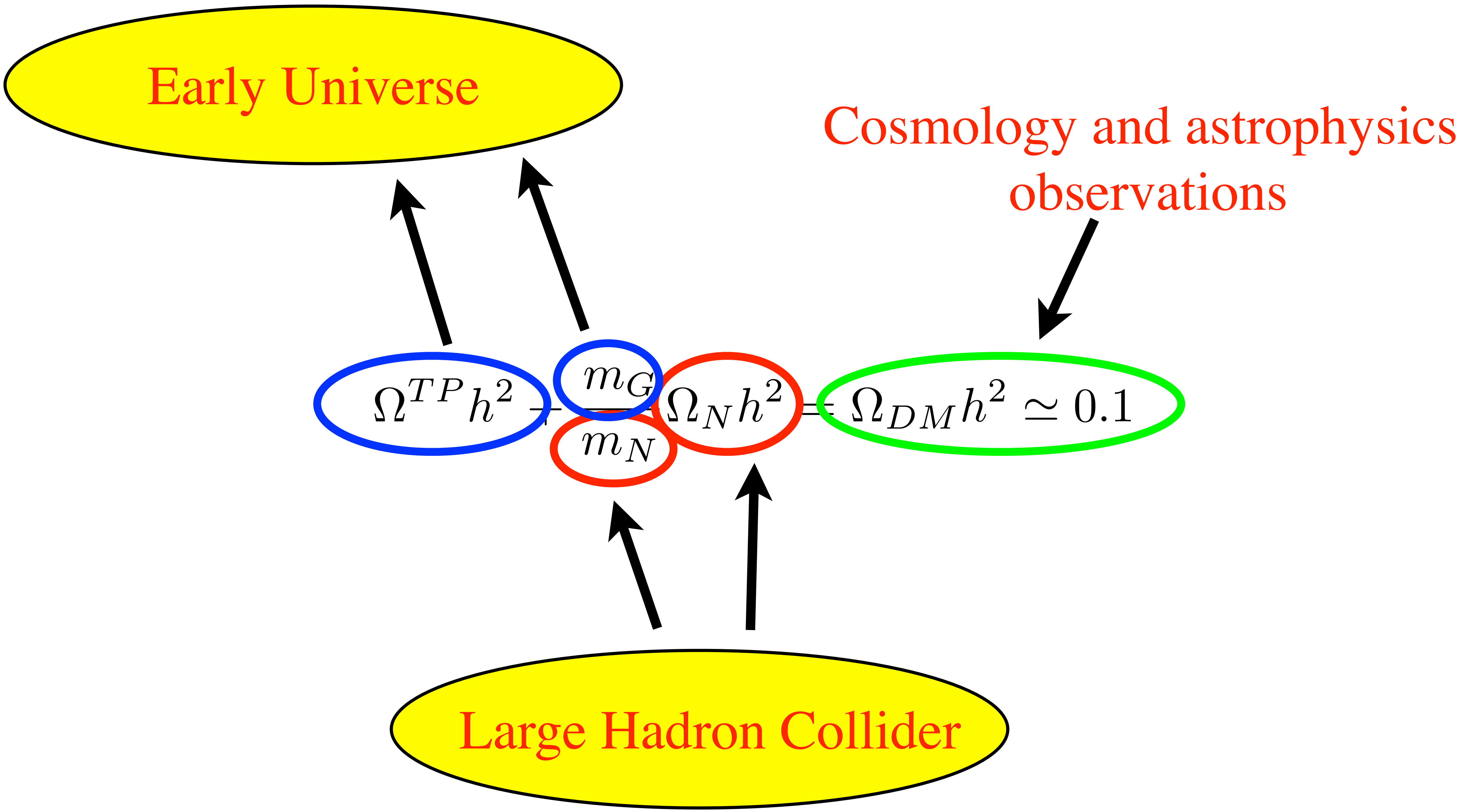


Upper bound on Treh

Axino cold dark matter

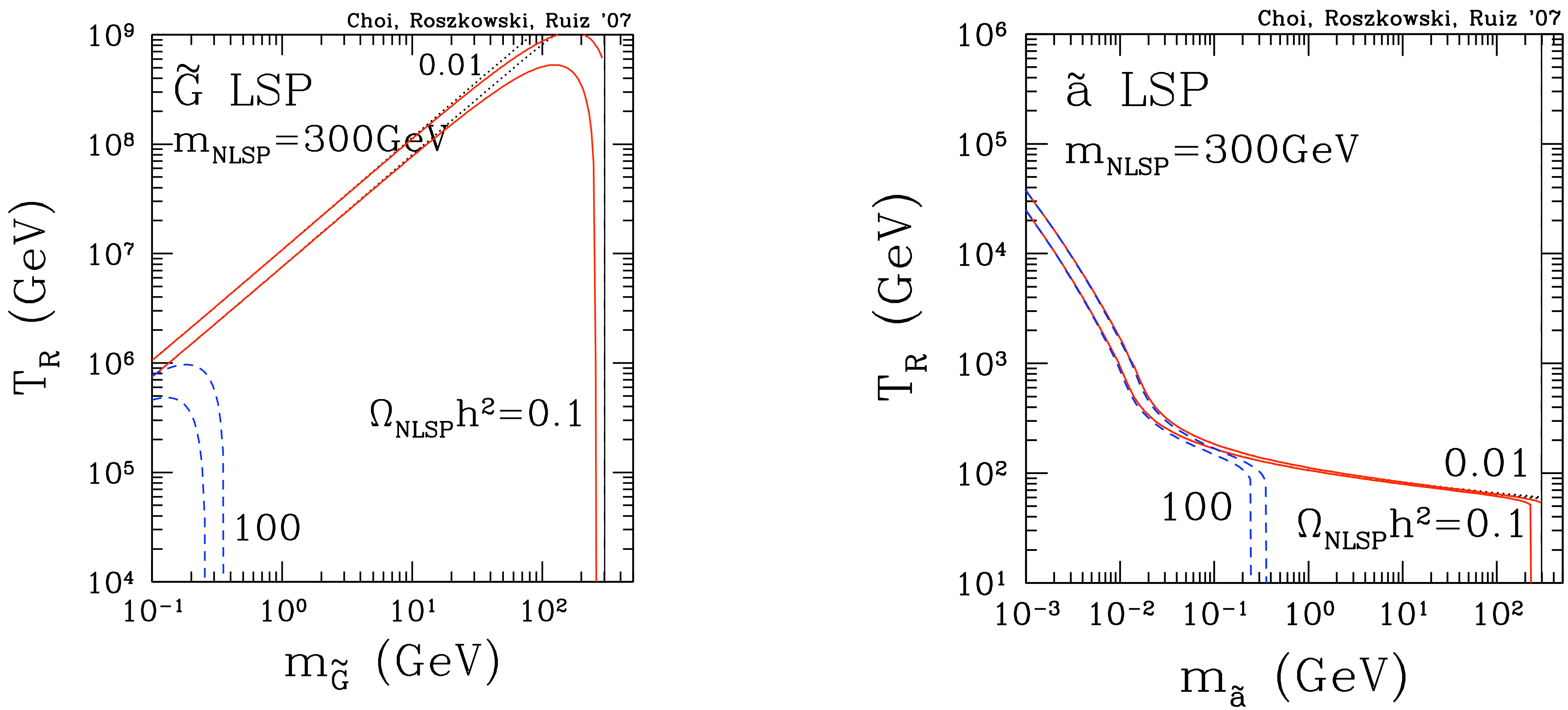
[Covi, Kim, Roszkowki, 1999]

Gravitino Dark Matter measures early Universe from LHC



- Reheating temperature from collider measurements

[KYC, Roszkowski, Ruiz de Austri, 2007]



- $m_{\rm NLSP}$ and $\Omega_{NLPS}h^2$ give relation between $T_{\rm reh}$ and $m_{\widetilde{G}}$
- Upper bound on the gravitino mass and the reheating temperature
- For stau NLSP, considering BBN

$$m_{\widetilde{\tau}} = 300\,{\rm GeV} \quad \Rightarrow \quad m_{\widetilde{G}} \lesssim 2\,{\rm GeV},\ T_{\rm reh} \lesssim 9\times 10^6\,{\rm GeV}$$

$$m_{\widetilde{\tau}} = 1\,{\rm TeV} \quad \Rightarrow \quad m_{\widetilde{G}} \lesssim 40\,{\rm GeV},\ T_{\rm reh} \lesssim 4\times 10^8\,{\rm GeV}$$

- confirmed later with different parameterization by [Steffen 2008] [Endo, Hamaguchi, Nakaji 2010]

Summary

- We need dark matter from the cosmological and astrophysical observations.

- Many candidates for dark matter

: WIMPs, Asymmetric dark matter, DM from Non-thermal production, E-WIMPs or Super WIMPs, Coherently oscillating scalar field, ...

- Axions are produced by misalignment mechanism

- In supersymmetric models, gravitinos or axinos are well-motivated candidates for dark matter and have many implications in cosmology and colliders.

- Dar matter searches to identify the identity of dark matter.