# Particle Candidates for Dark Matter

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1st September, COSMO2017

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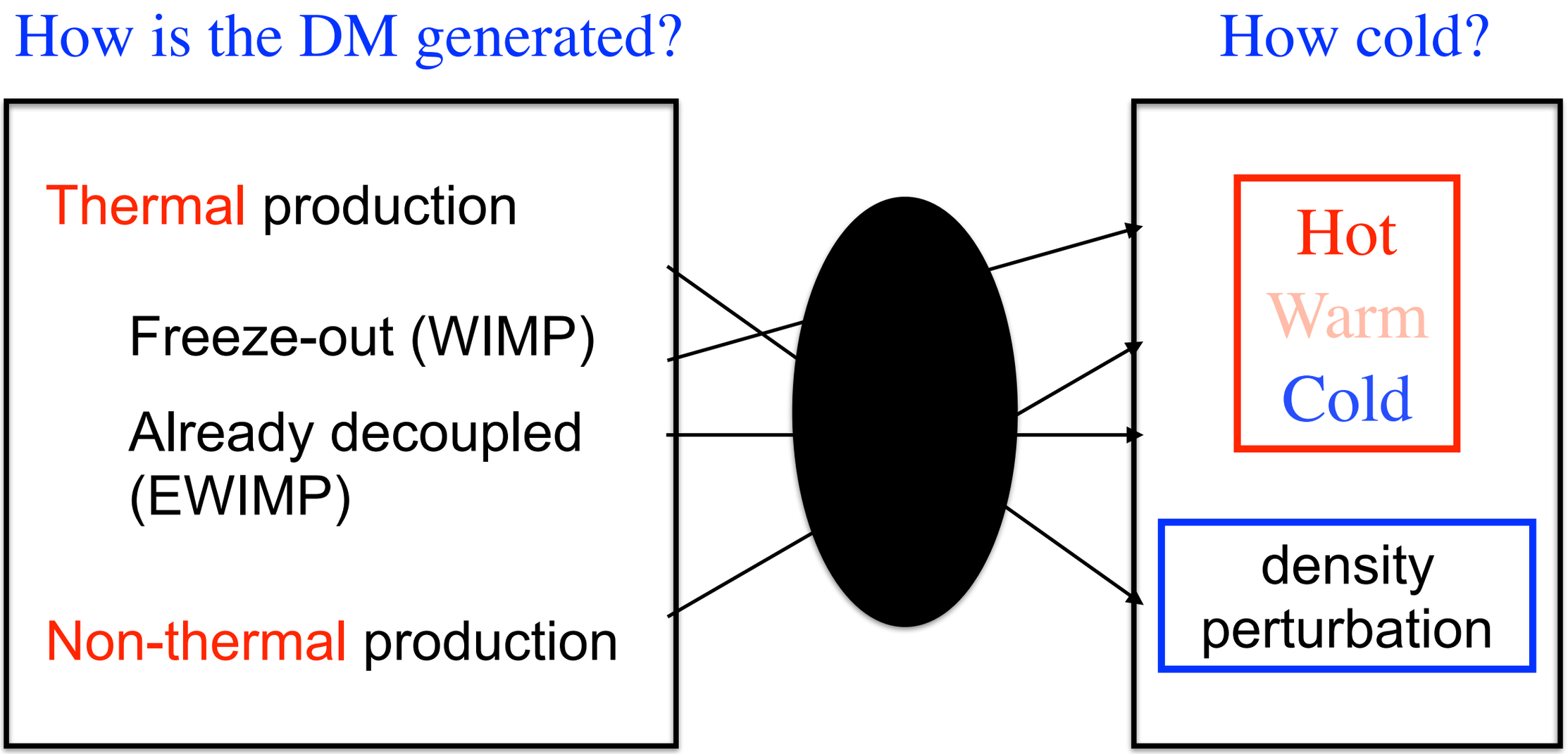
- Particle candidates for dark matter



# Evidences for dark matter

In 1933, F. Zwicky first discovered Dark Matter in the velocity dispersion of galaxies in the COMA cluster.

The discrepancies between visible matter and gravitational matter in different scales.

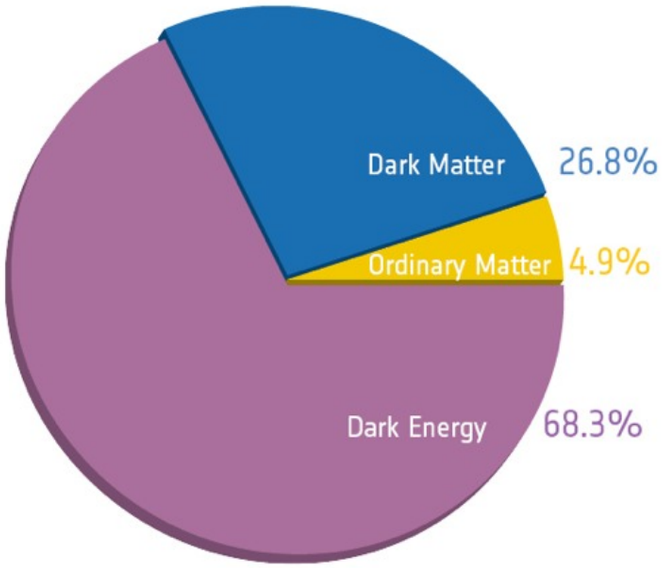
- Galactic scales : rotation curves of galaxies

- Galaxy cluster scales : distribution of velocities, gravitational lensing, profile of X-ray emission, Bullet cluster

- Cosmological scales : acoustic peaks of CMB, large scale structure formation

All of these observations can be explained by a single component of dark matter.

# Dark Matter as a particle must




1. have existed from early Universe up to now and located around galaxies, clusters

➡ be stable or lifetime longer than the age of universe

2. be neutral : NO electromagnetic interaction

➡ Only upper bounds on the self interaction [Harvey et al., 1503.07675]

$\sigma/m < 0.47\ \mathrm{cm}^2/\mathrm{g}$ at 95% CL from cluster collisions

No lower bound down to gravity!

In fact all the evidences are gravitational.

3. 27% of the present energy density of the universe

$$\Omega_{\mathrm{DM}}\, h^2 = 0.1186(20)$$ [Planck 2015]

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

# Dark matter candidate in the Standard Model?

**Massive Neutrinos** Relic density from thermal freeze-out

$$\Omega_\nu h^2 = \frac{\sum_i m_{\nu_i}}{93.14\ \mathrm{eV}} < 0.015$$ It is too small!

from $\sum m_\nu < 1.3\,\mathrm{eV} \quad (95\%\,CL)$ [Komatsu et al., 2011]

The large free streaming scale disturb the clustering of galaxies

$$\lambda_{FS} \sim 20 \left(\frac{30\ \mathrm{eV}}{m_\nu}\right)\ \mathrm{Mpc}$$ It is too hot!

**Primordial Black Holes**

[G.Smoot's talk]
[M.Sasaki's talk]

Non luminous baryons if formed before BBN and would not violate the ordinary baryon abundance

$$\Omega_b\, h^2 = 0.02226(23)$$

Primordial Black Holes as Dark Matter [Carr et al 2016]
[Florian Kuhnel's talk ]

# Candidates of dark matter
# beyond Standard Model

Strong CP problem : axion

Neutrino sector : sterile neutrino, RH neutrino, Majoron

Technicolor : Techni-baryon, Techni-dilaton

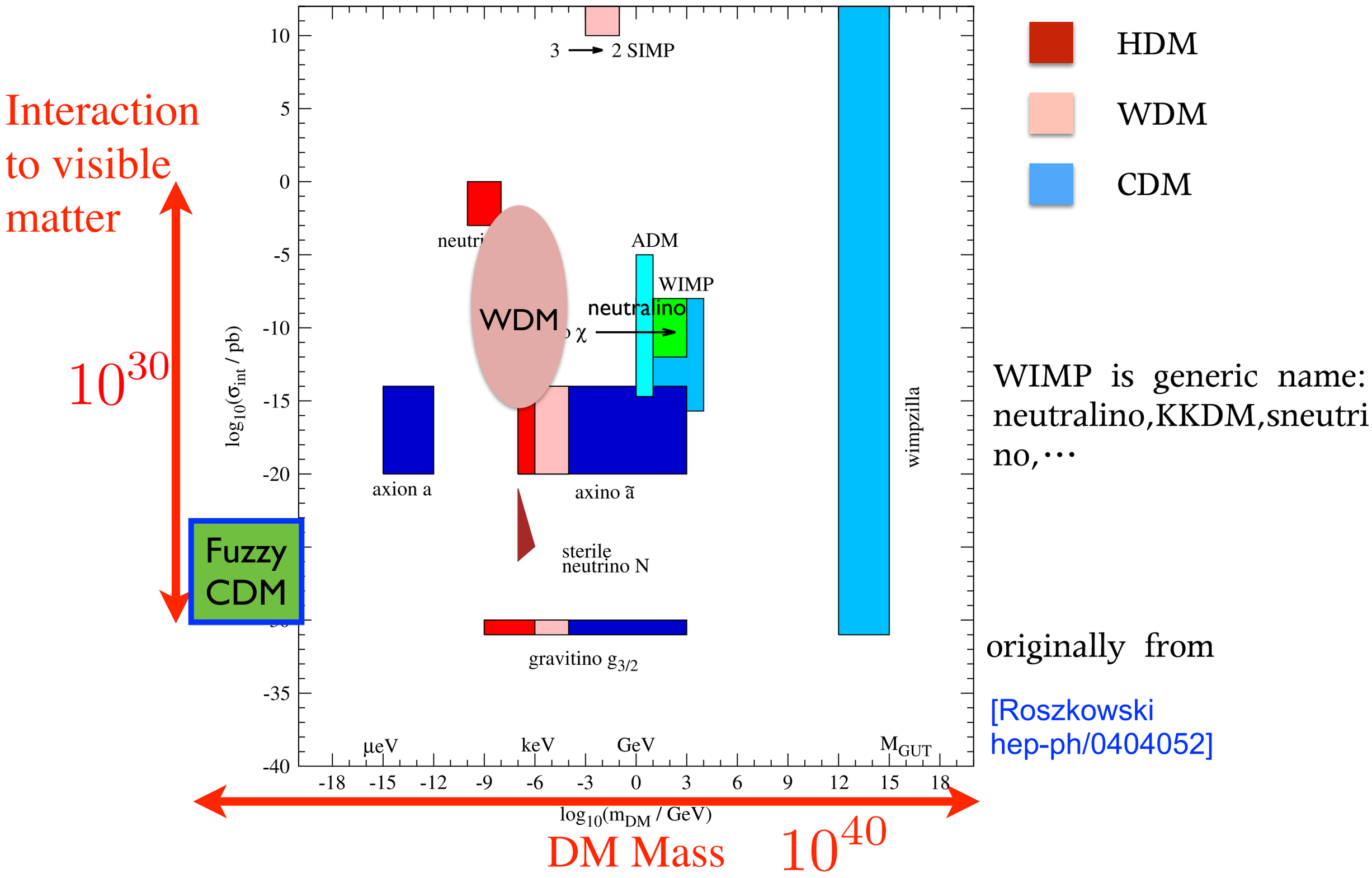
Supersymmetry : neutralino, gravitino, axino, scalar neutrino

Extra dimension : Kaluza-Klein particle

and WIMPzillas, primordial Black-Hole, dilaton

Fuzzy CDM, minimal DM, Maverick DM, Asymmetric DM, Hidden sector DM, SIDM, Mirror DM, Composite DM, Fermionc DM,

and more ....



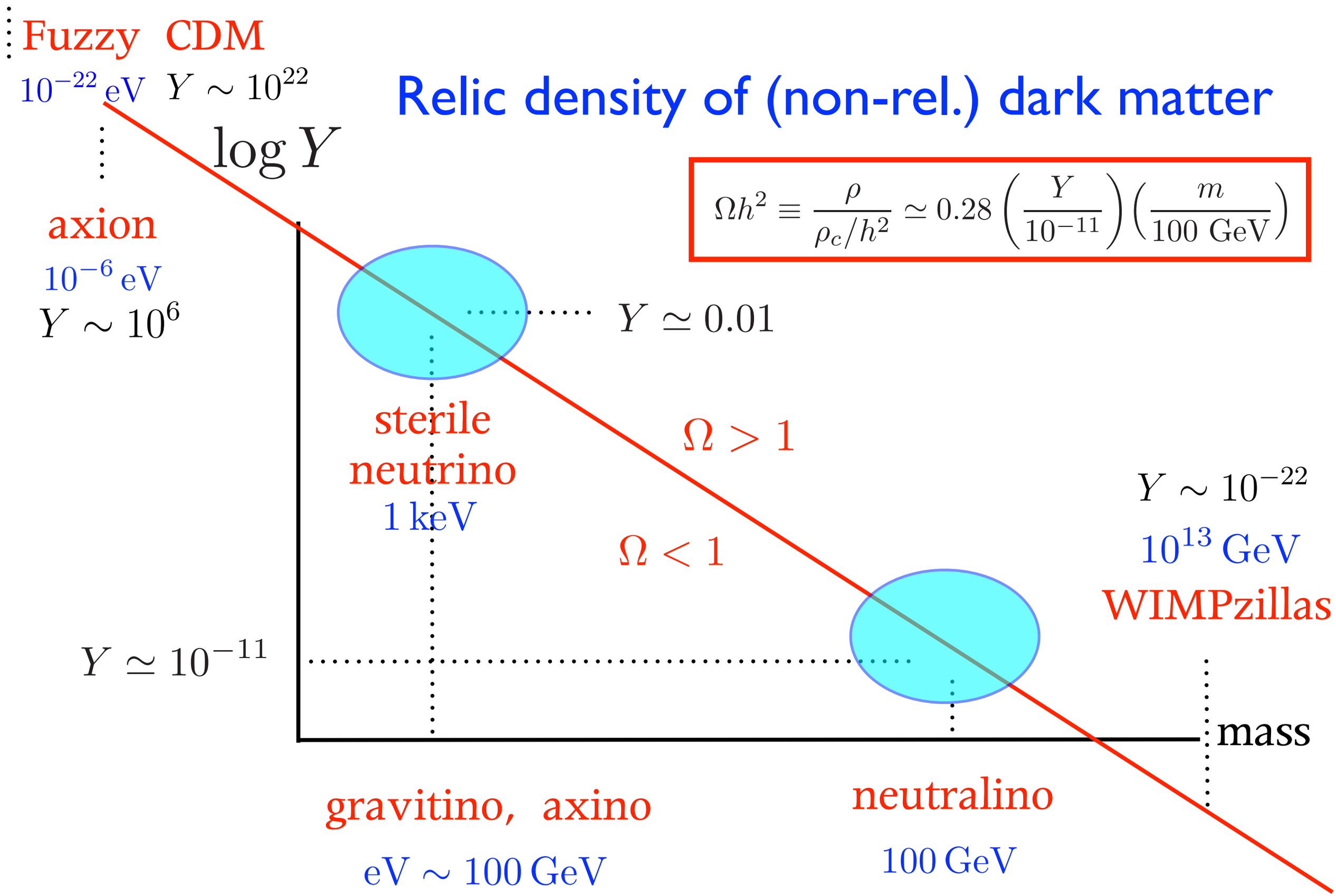

WIMP is generic name: neutralino,KKDM,sneutrino,⋯

originally from

[Roszkowski hep-ph/0404052]

# Relic density of (non-rel.) dark matter

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



# The evolution of the number density (Boltzmann equation)

$$\frac{dn_X}{dt} + 3Hn_X = g_X \int C[f_X] \frac{d^3p}{(2\pi)^3}$$

Freeze-out can happen in the expanding Universe.

$$\boxed{n_X \propto a^{-3}}$$

$T \ll T_f$

out of equilibrium

or

$$\boxed{n_X = n_{eq}}$$

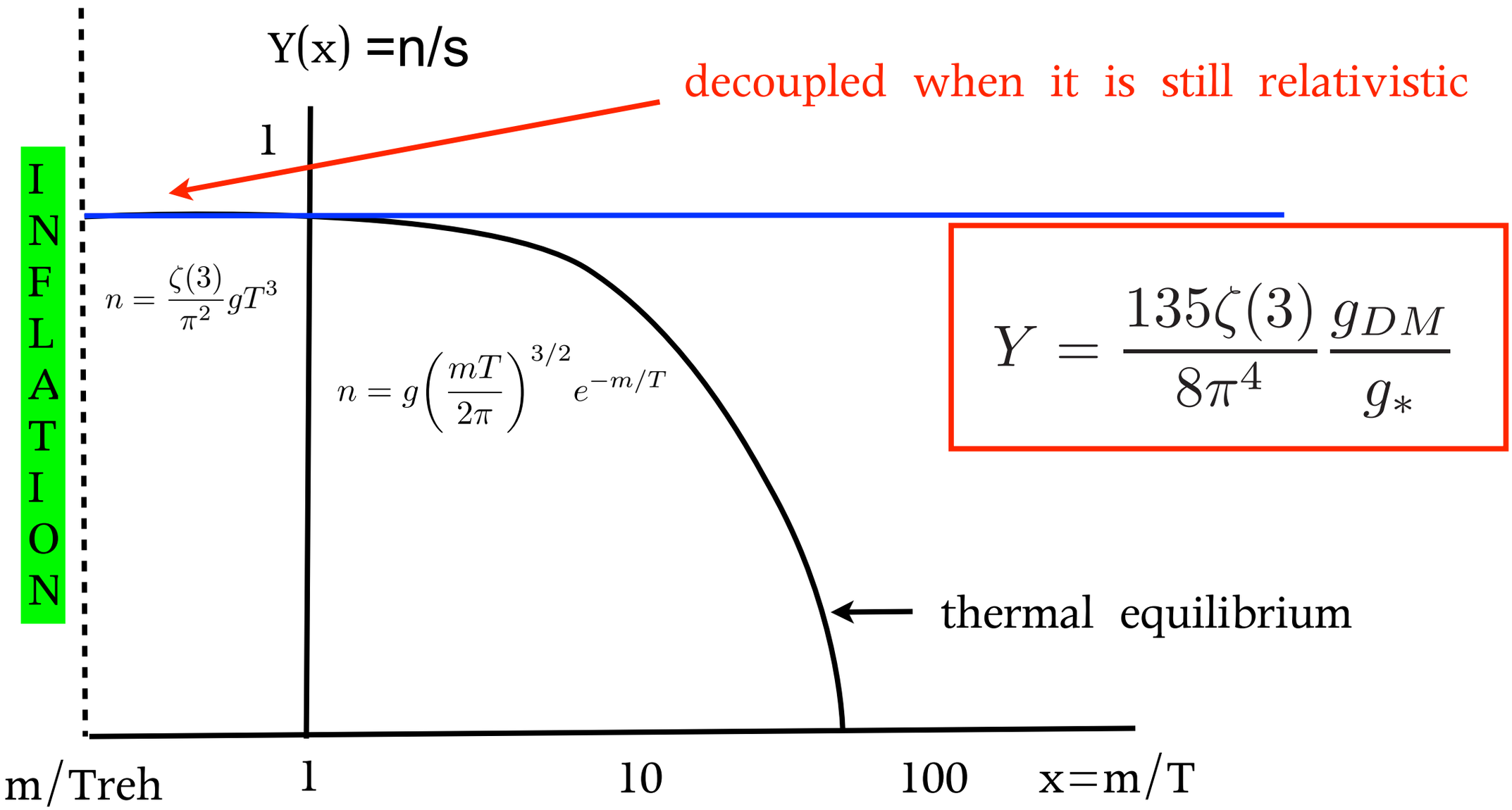
$T \gg T_f$

in equilibrium

$T_f$: freeze-out temperature

# Hot relics: Weakly Interacting Light Particle $T_f > m$

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



**Warm dark matter:** They become non-relativistic when $T \lesssim m$

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

Light gravitinos [Pagels, Primack, 1982]

Light axinos [Rajagopal, Turner, Wilczek, 1990]

Sterile neutrinos [Dodelson, Widrow, 1994] [Shi, Fuller, 1999]

Warm dark matter may solve small scale problems of CDM but can make problems due to the cutoff of the small scale power spectrum

$$m \gtrsim 5.3\,{\rm keV}\ (2\sigma\ {\rm CL})$$ Lyman $\alpha$ flux-power spectrum

[Irsic, Viel, Haehnelt, et.al, 2017]

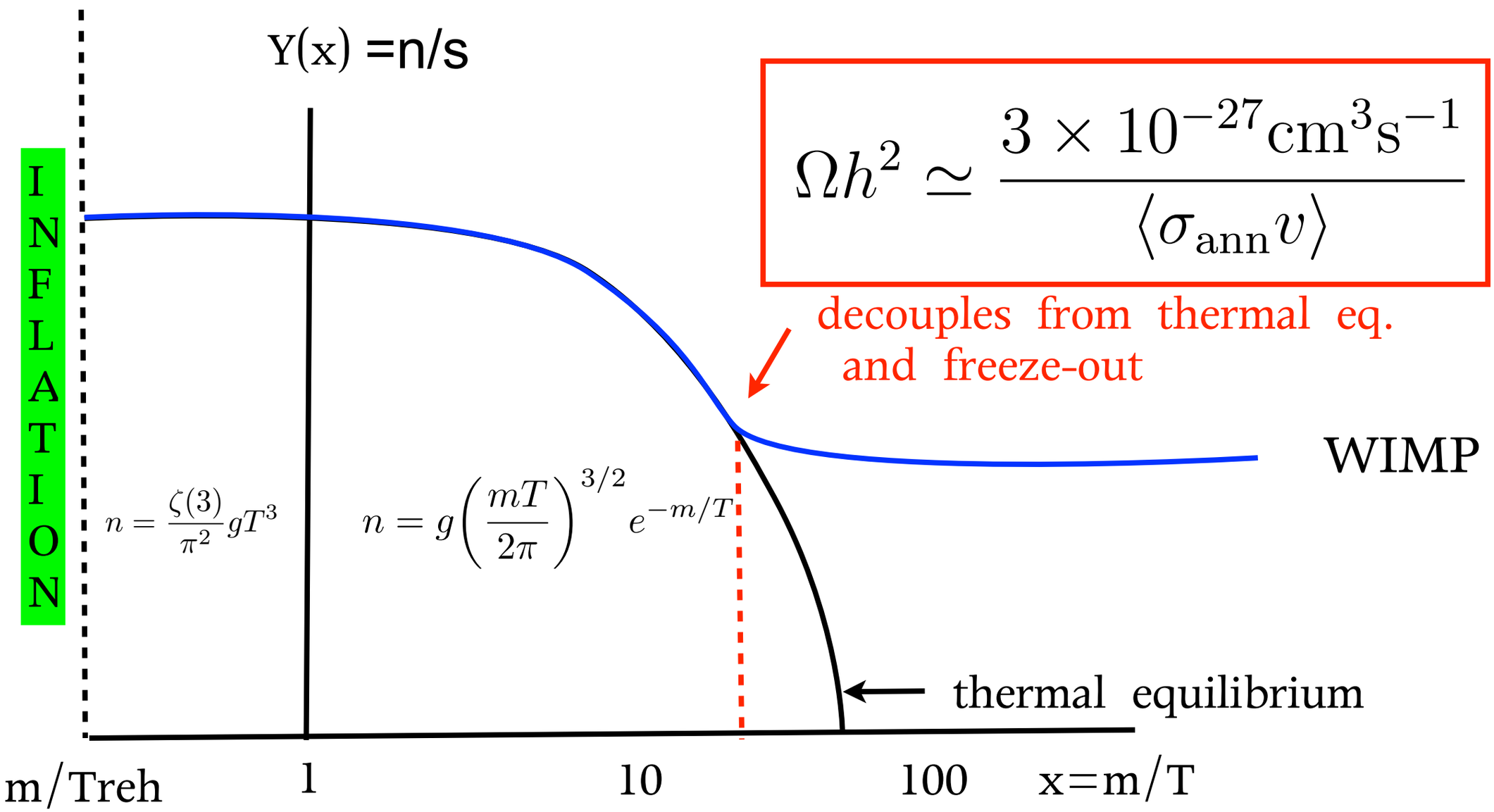
Possible tension between relic density and the structure formation.

$$g_* \sim 5000\,?$$

# WIMP : Weakly Interacting Massive Particle

$$T_f < m$$

Initially the particles are in the thermal equilibrium and decoupled when it is non-relativistic: Boltzmann suppression



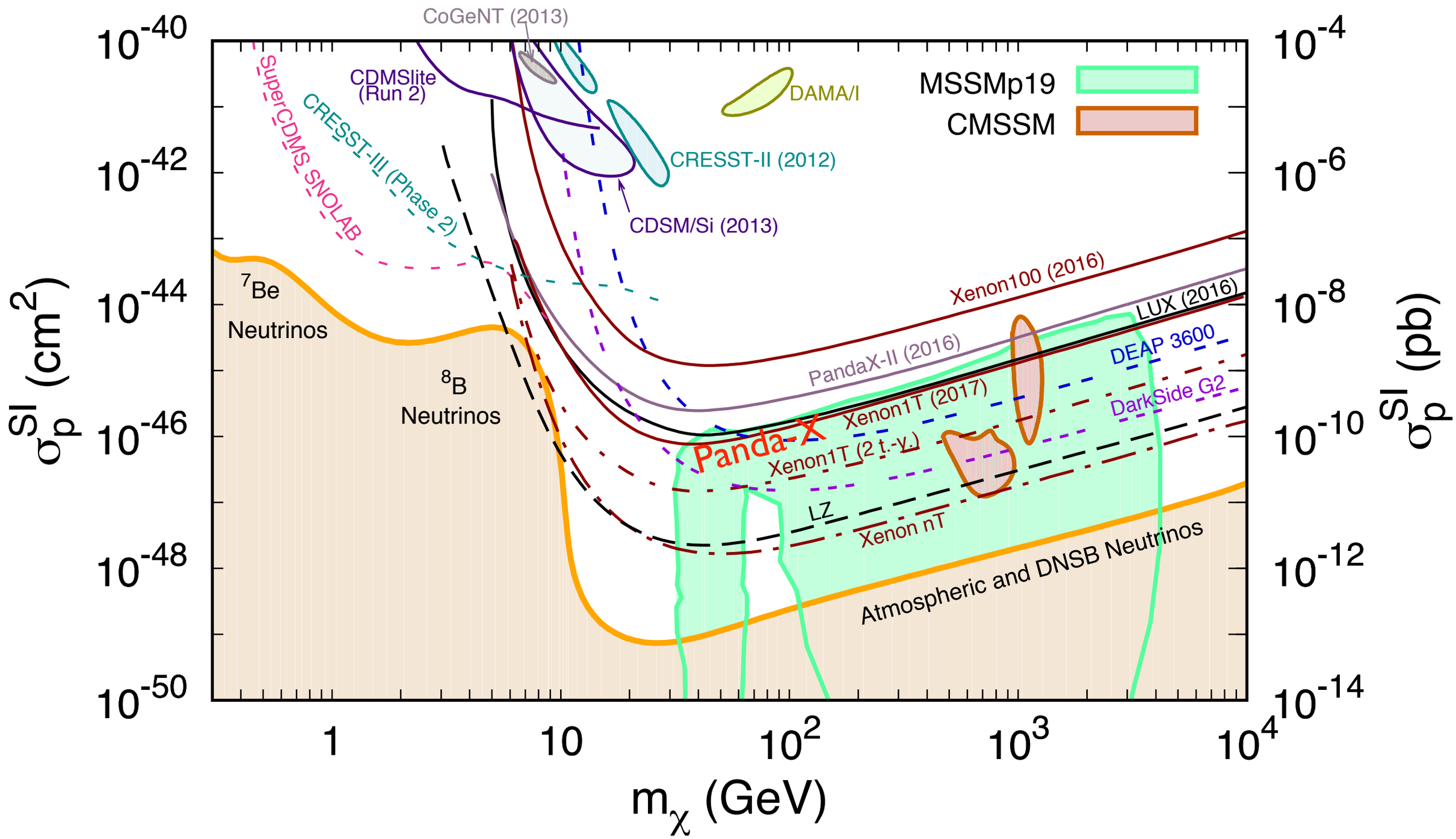

$$\Omega h^2 \simeq \frac{3 \times 10^{-27} \mathrm{cm}^3 \mathrm{s}^{-1}}{\langle \sigma_{\mathrm{ann}} v \rangle}$$

decouples from thermal eq. and freeze-out

$$x_f \sim 20 - 25$$

# WIMP direct detection

**1707.06277 DM review**



# The 125 GeV Higgs boson and TeV SUSY

**In SUSY Higgs mass is a calculated quantity**

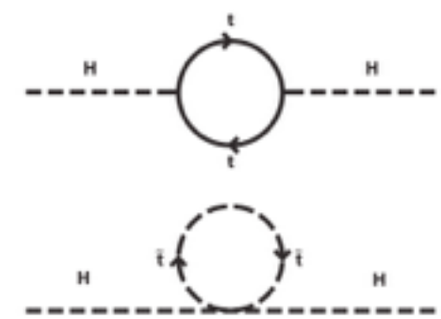
➢ **1 loop correction**

1302.5956

$$\Delta m_h^2 = \frac{3m_t^4}{4\pi^2 v^2}\left[\ln\left(\frac{M_{\rm SUSY}^2}{m_t^2}\right) + \frac{X_t^2}{M_{\rm SUSY}^2}\left(1 - \frac{X_t^2}{12M_{\rm SUSY}^2}\right)\right]$$

$$X_t = A_t - \mu\cot\beta$$

$$M_{\rm SUSY} \equiv \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$$

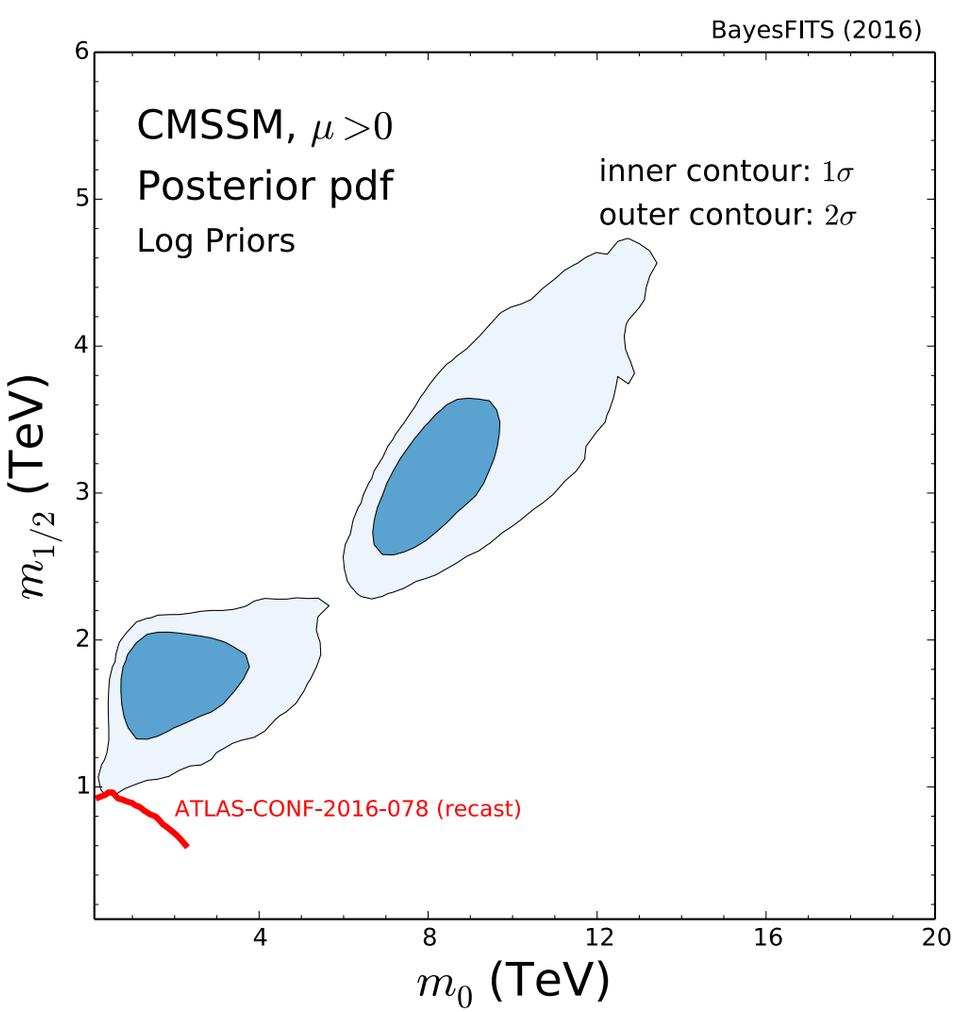


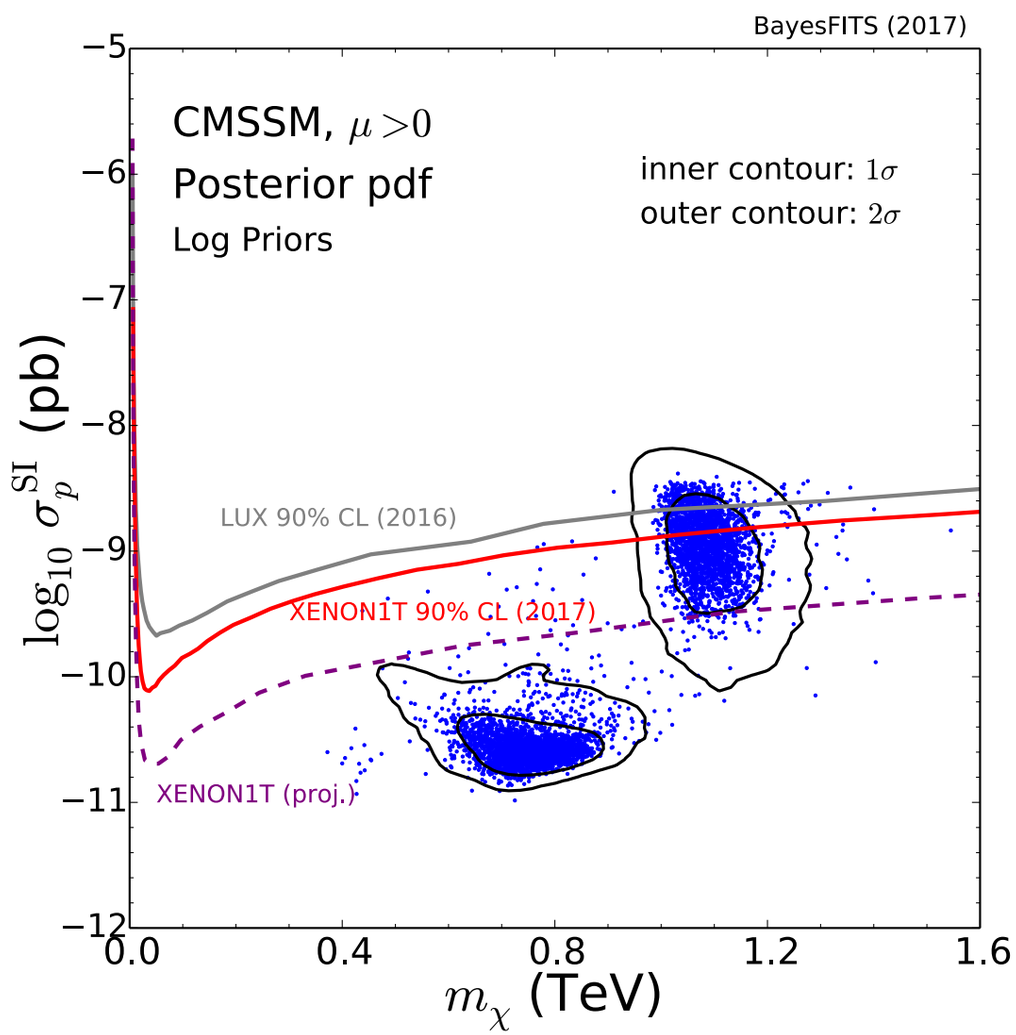

**125 GeV Higgs -> multi-TeV SUSY**

**Consistent with stringent lower limit on superpartner masses**

# 1 TeV Higgsino DM and direct detection

Updated from [Kowalska, Roszkowski, Sessolo 2013] [Roszkowski, Sessolo, Williams 2014]




**~1TeV higgsino DM: exciting prospects for 1 tonne detectors**

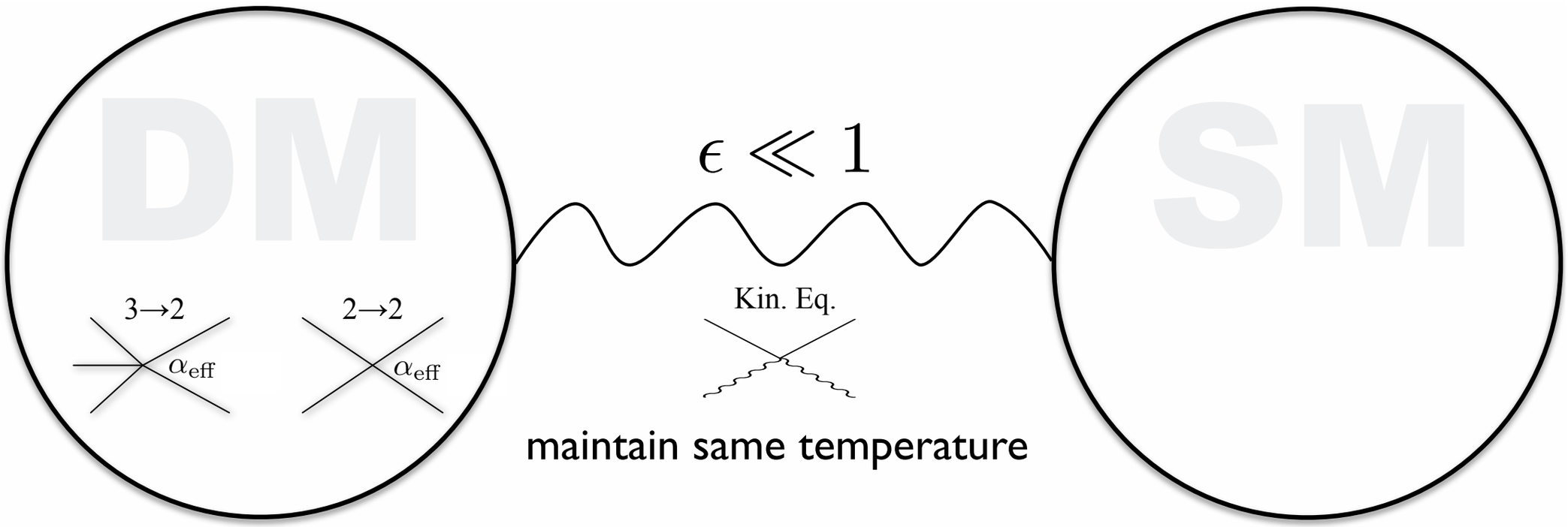
**Robust solution present in a broad class of unified SUSY models**

[Indirect Detection by C.Weniger]

# SIMP dark matter

[Carson, Machacek, Hall 1992]
[Hochberg et al 2014]
[HML et al, 2015, 2016, 2017]

## (Strongly Interacting Massive Particle)




[Ayuki Kamada'stalk]

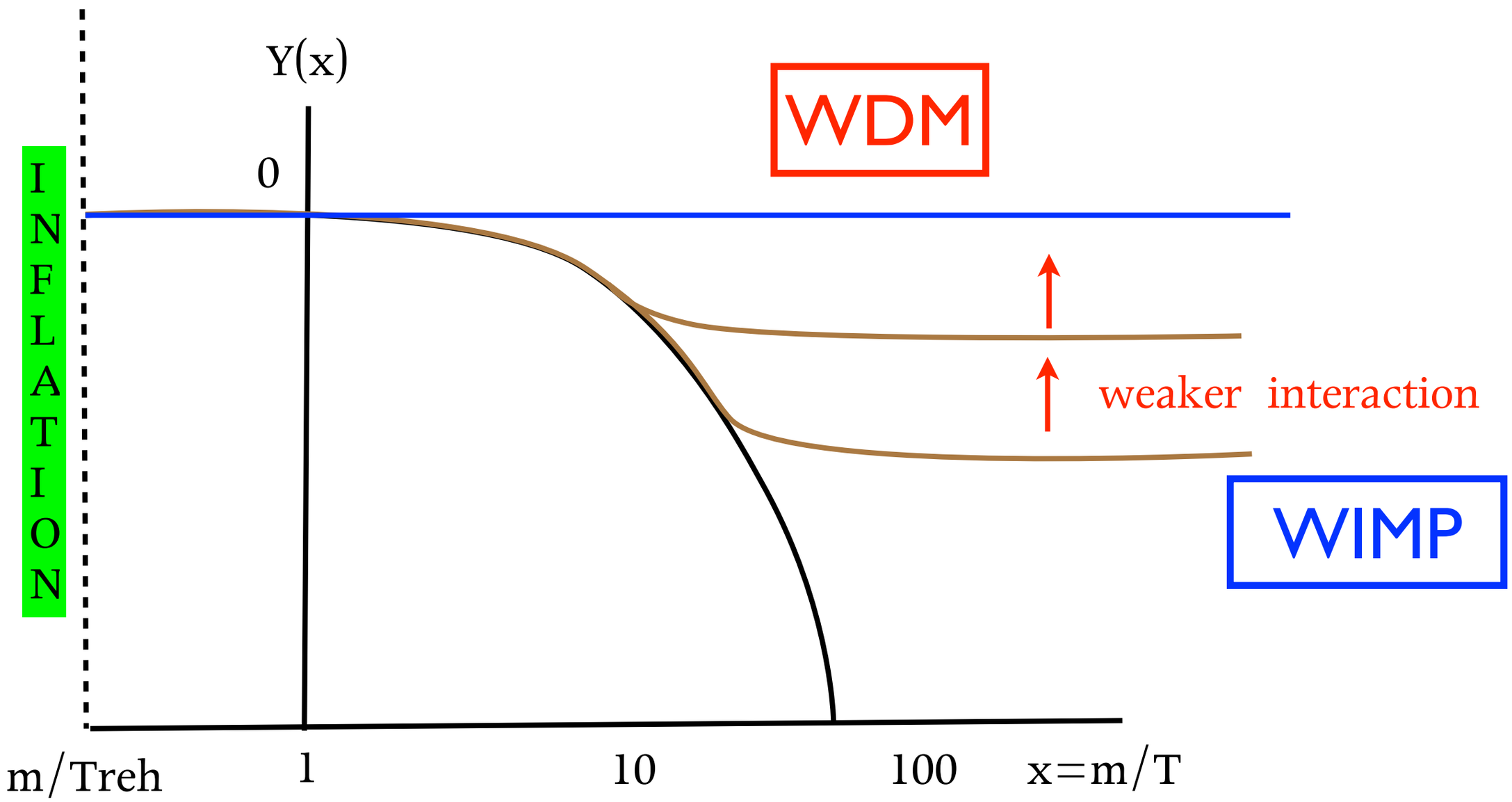
3 → 2 process determines freeze-out rather than 2 → 2

address the small scale structure problem of CDM

Simple realisation with pion of Wess-Zumino-Witten tem.

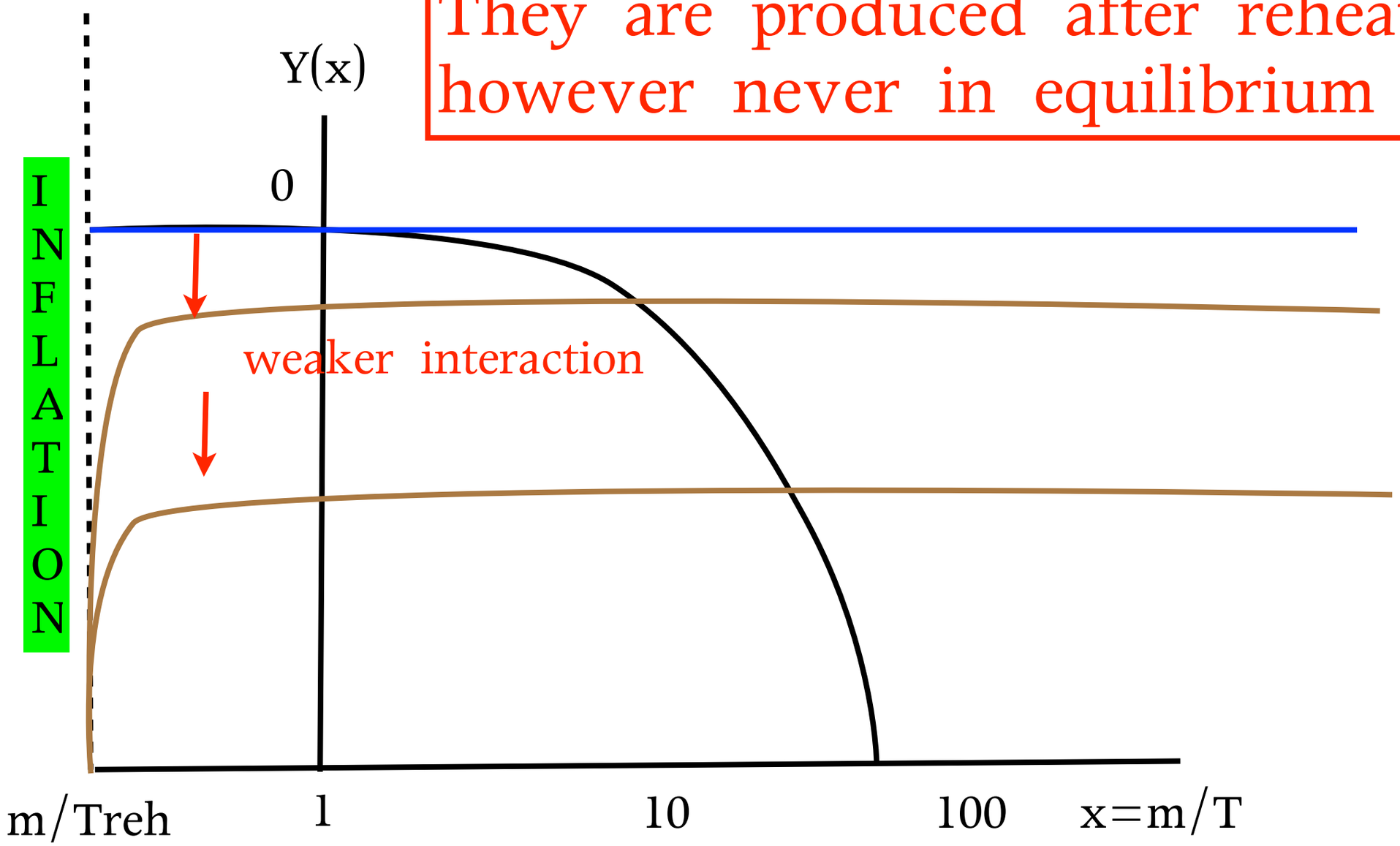
[Hochberg et al 2014]

# More weakly interacting for a given mass

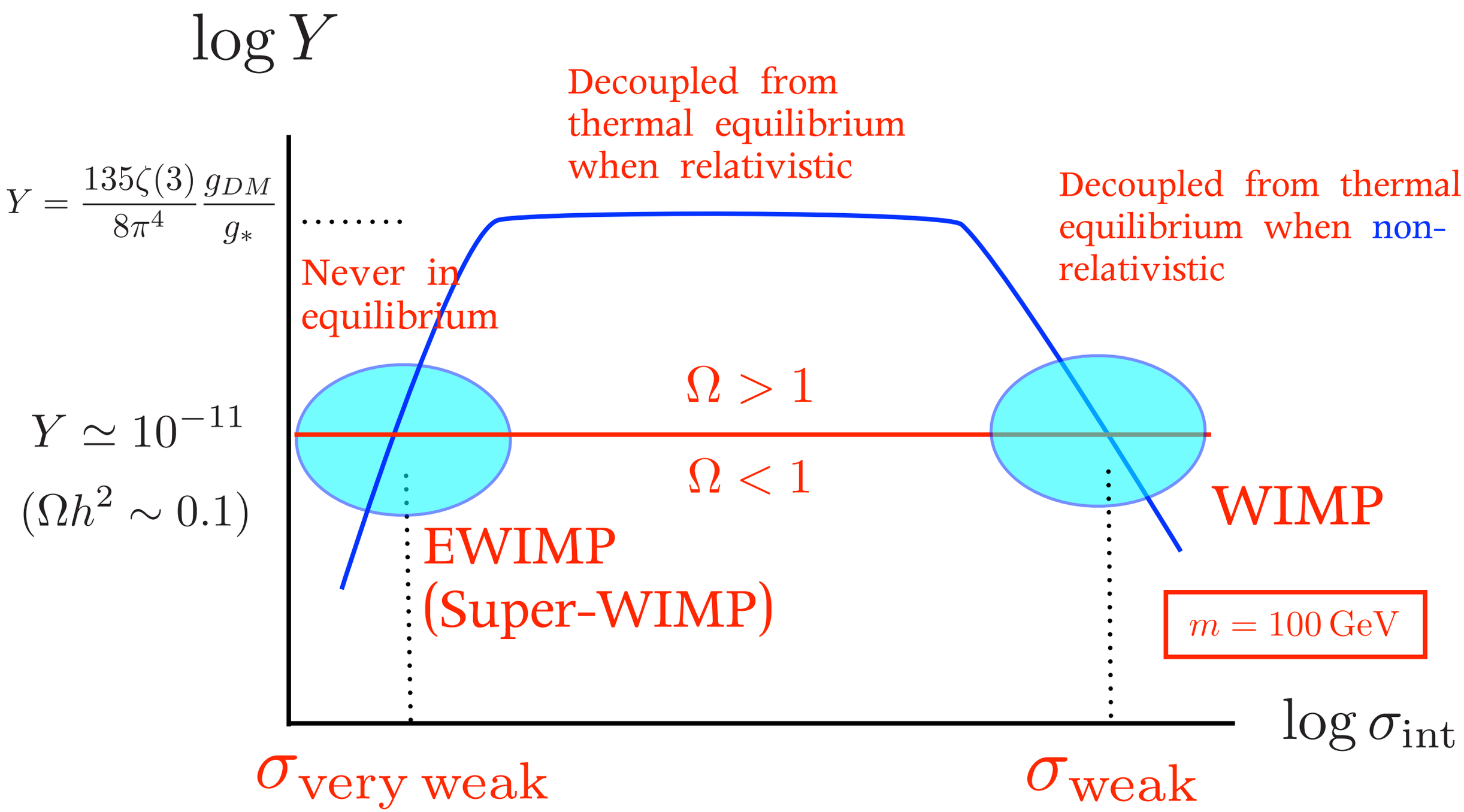


# Extremely weakly interacting particles (EWIMP)

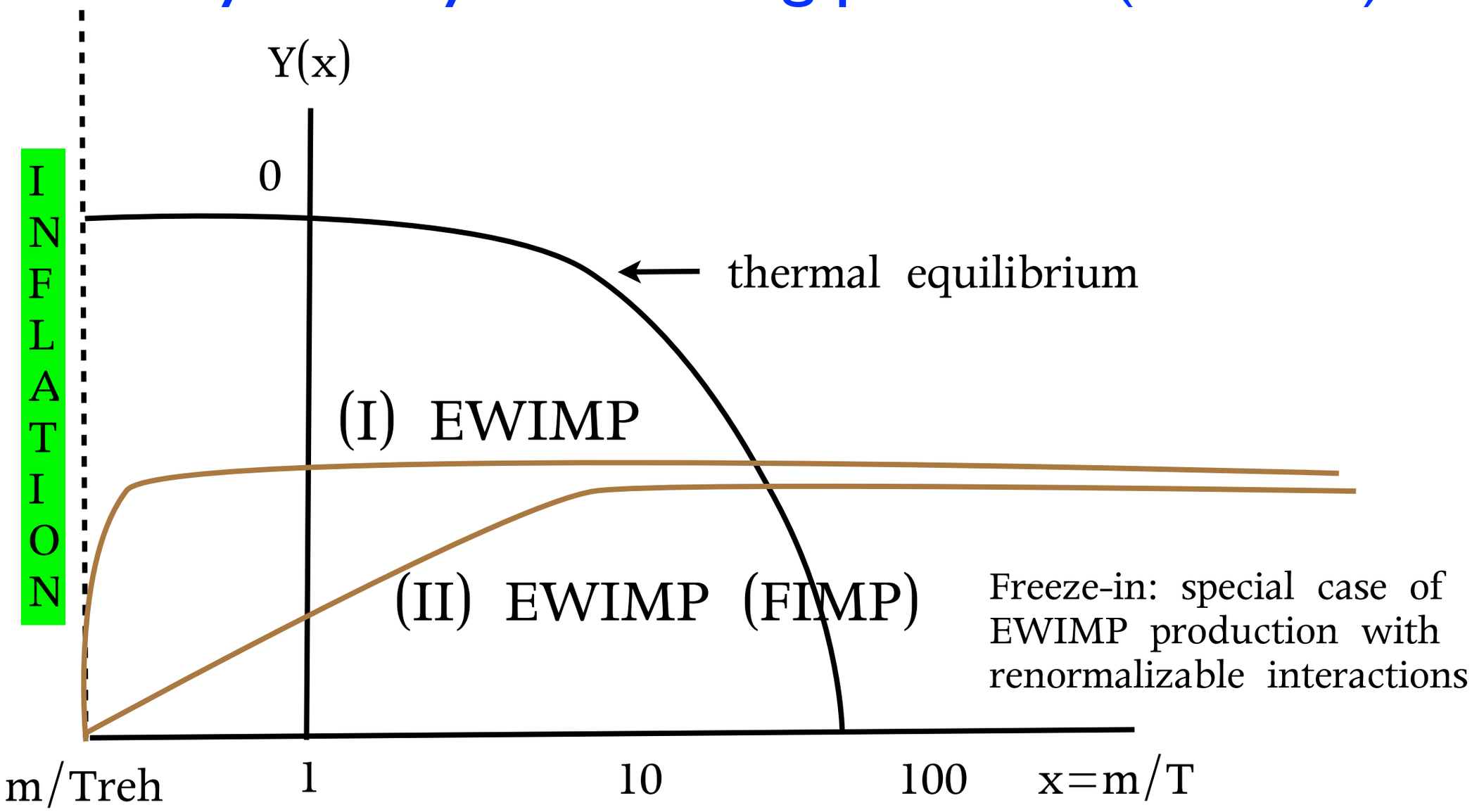
They are produced after reheating, however never in equilibrium



# Relic density of massive particles for a GeV scale mass



# Extremely weakly interacting particles (EWIMP)




(I) depends on the reheating temperature: produced at high temperature

(II) no dependence on the reheating temperature: produced at low temperature

# Abundance of EWIMP

in the process of self-annihilation with the type $X + X \to 3 + 4$

$$\frac{dn_X}{dt} = -3Hn_X - \langle \sigma_{\rm ann} v \rangle (\cancel{n_X^2} - n_{\rm eq}^2).$$

The EWIMP density can be ignored

$$\rightarrow \quad \boxed{\frac{dY}{dT} = \frac{\langle \sigma v \rangle n_{\rm eq}^2(T)}{s(T)H(T)T} \sim M_P \langle \sigma v \rangle}$$

and we can integrate

# (I) EWIMP depends on the reheating temperature

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

For example,

**Gravitino**

$$M_P \sim 10^{18}\,\mathrm{GeV}$$

[Bolz,Brandenburg, Buchmuller 2001]
[Fradler, Steffen 2007]
[Rychkov, Strum 2007]

**Axino**

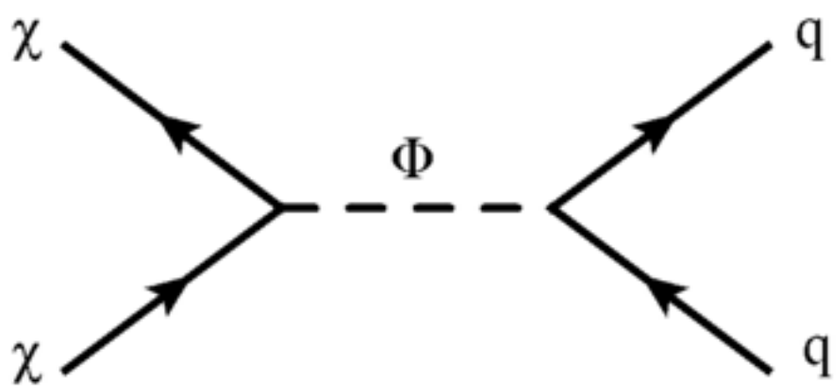
$$f_a \sim 10^{11}\,\mathrm{GeV}$$

[Covi,Kim,Roszkowski 1999]
[Covi,Kim,Kim,Roszkowski 2001]
[Brandenburg, Steffen 2004] [Strumia 2010]
[Choi,Covi,Kim,Roszkowski 2012]

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

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

# (I) EWIMP depends on the reheating temperature




For heavy mediator, $\langle \sigma v \rangle \sim \frac{T^2}{M^4}$ ➡ $Y \propto T_R^3$

For DM heavier than the reheating temperature

$\langle \sigma v \rangle \sim \frac{T^6}{M^8}$ ➡ $Y \propto T_R^7$ [Benakli et al 1701.06574]
[Dudas et al 1704.03008]

## (II) EWIMP does not depend on the reheating temperature

RH sneutrino or axino with small Yukawa couplings

can be produced via scatterings of thermal particles.

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

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

Most of them are produced at low temperature.

$$\Omega h^2 \simeq 0.1 \left( \frac{y}{10^{-11}} \right)^2$$

## (II) EWIMP does not depend on the reheating temperature

DM can be produced via decay of thermal particles

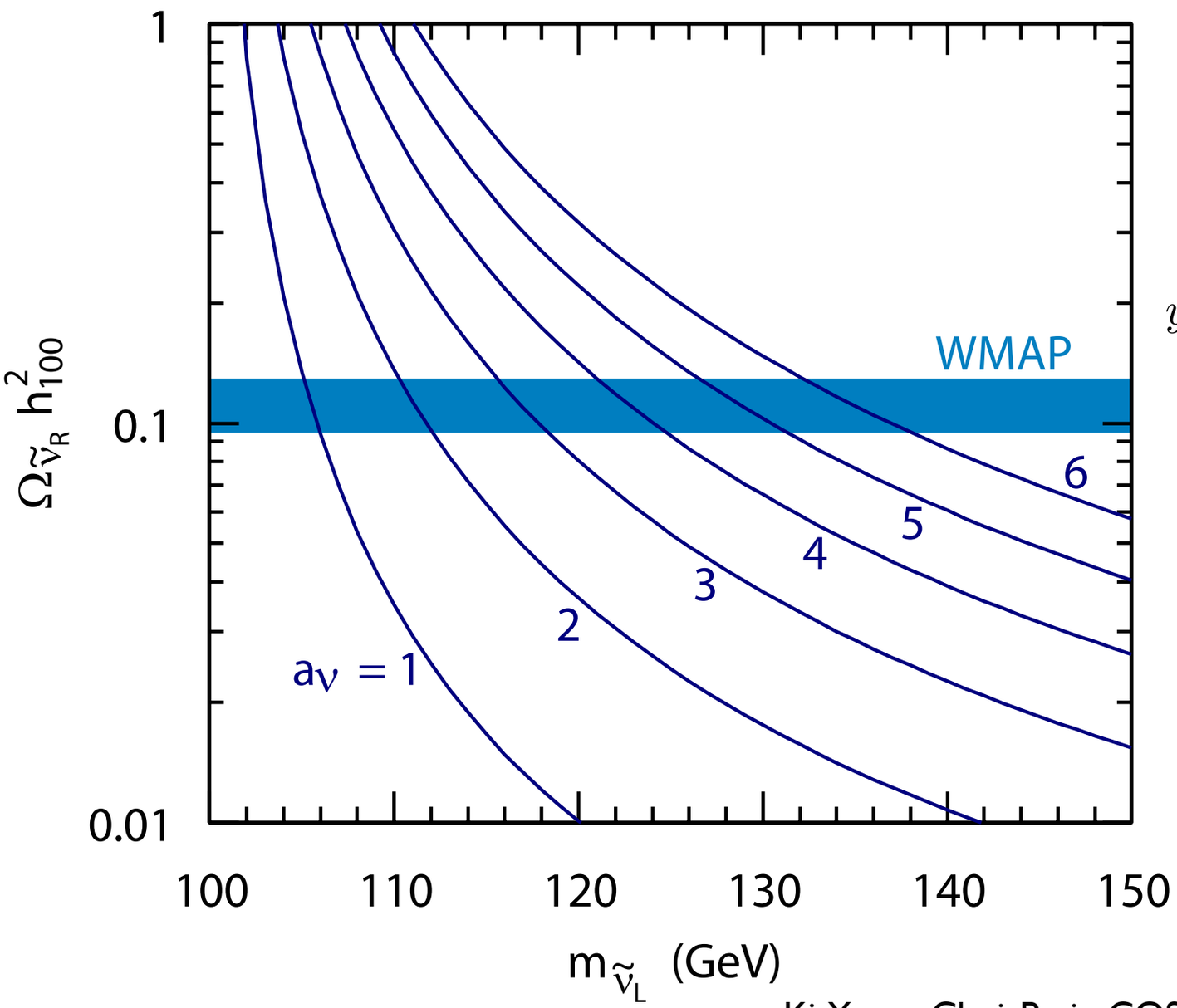
with decay rate $\Gamma$ and mass $M$

$$\Rightarrow \quad Y(T_0) = \int_{T_0}^{T_{\rm reh}} \frac{\Gamma_{\rm int} n_{eq}}{s(T)H(T)T} dT \simeq \frac{405\sqrt{10}\zeta(5) M_P}{8\pi^4 g_*^{3/2}} \frac{\Gamma}{M^2}$$

# RH sneutrino as CDM

[Asaka, Ishiwata, Moroi 2005]

RH sneutrino of purely Dirac type neutrino mass

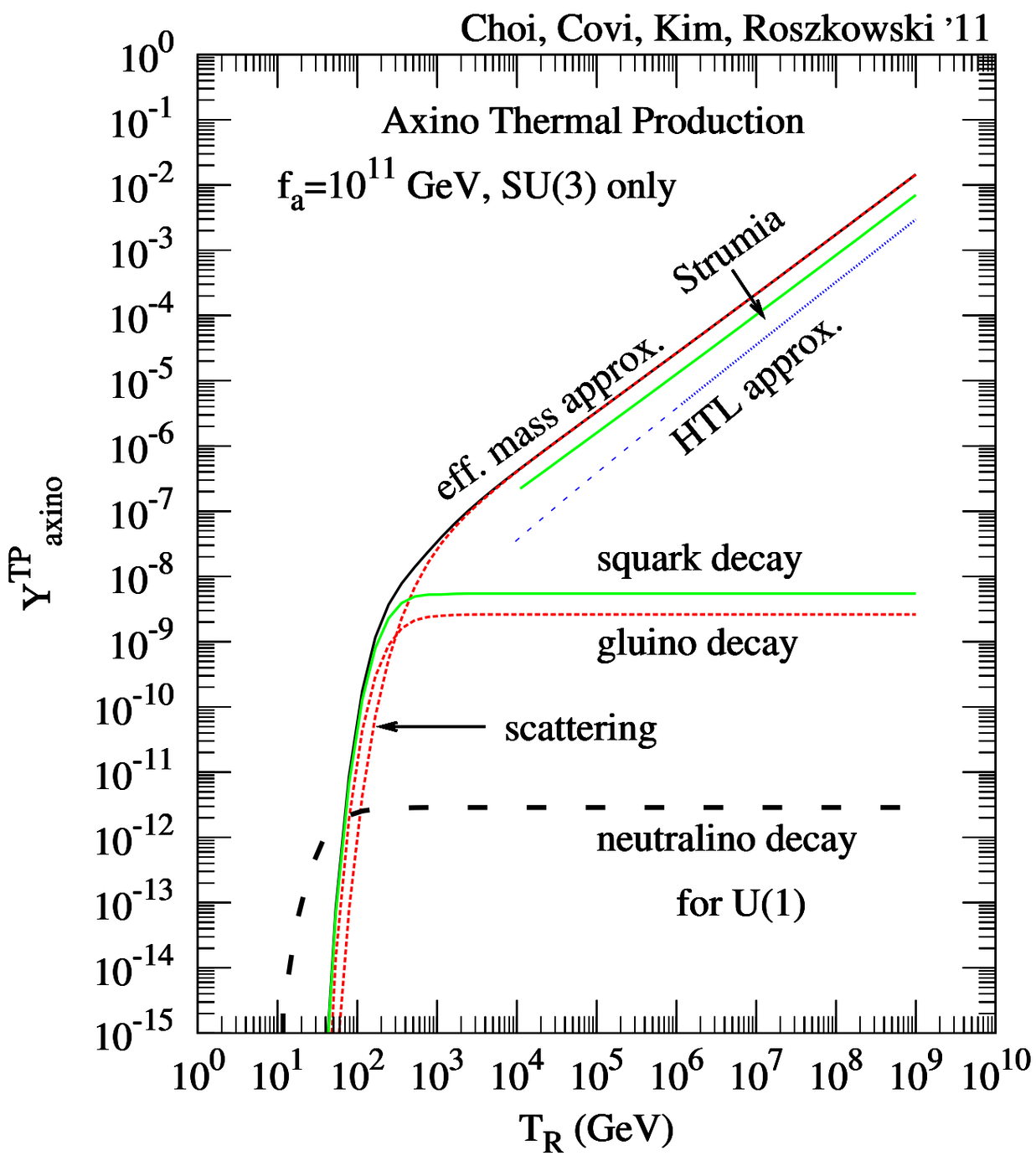



with small Yukawa coupling

$$y_\nu \sin\beta = 3.0 \times 10^{-13} \times \left( \frac{m_\nu^2}{2.8 \times 10^{-3}\ \mathrm{eV}^2} \right)^{1/2}$$

RH sneutrinos are never thermalised, but effectively produced by decays of various superparticles.

# Axino Thermal Production




[Covi,Kim,Roszkowski 1999]

[Covi,Kim,Kim,Roszkowski 2001]

[Choi,Covi,Kim,Roszkowski 2012]

for KSVZ axino

(I) EWIMP

: reheating temperature dependent

(II) EWIMP (FIMP)

: generated at low temperature

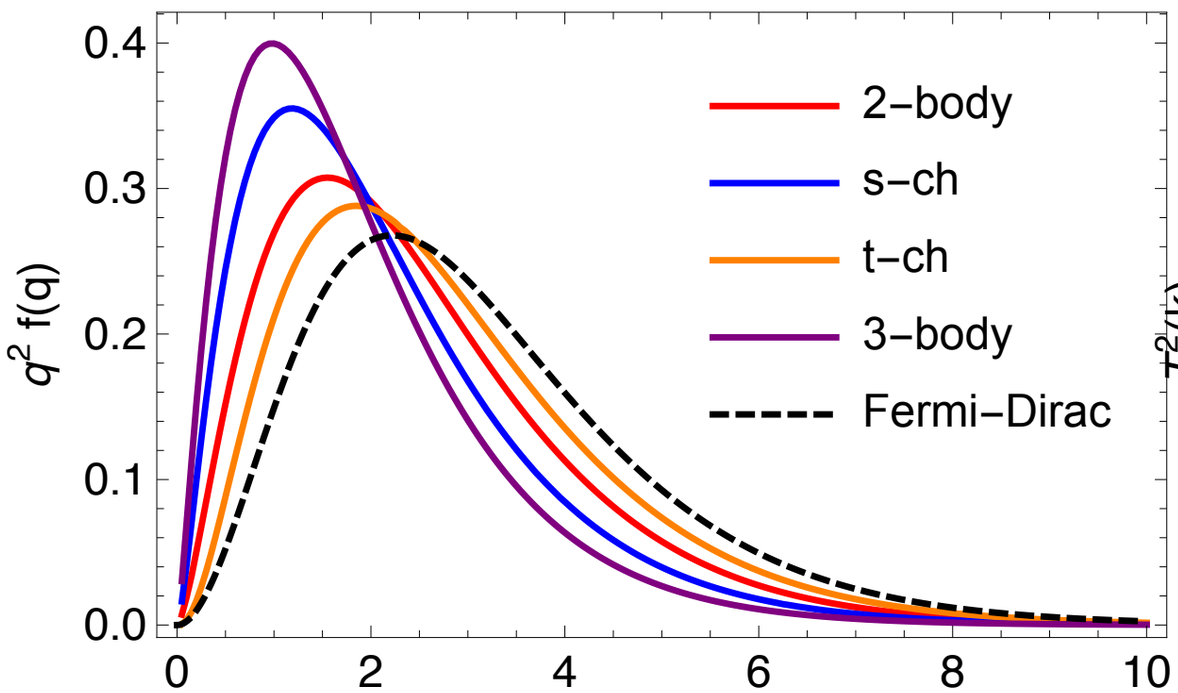
DFSZ axino [Bae, Choi, Im 2011]

# Axino as WDM

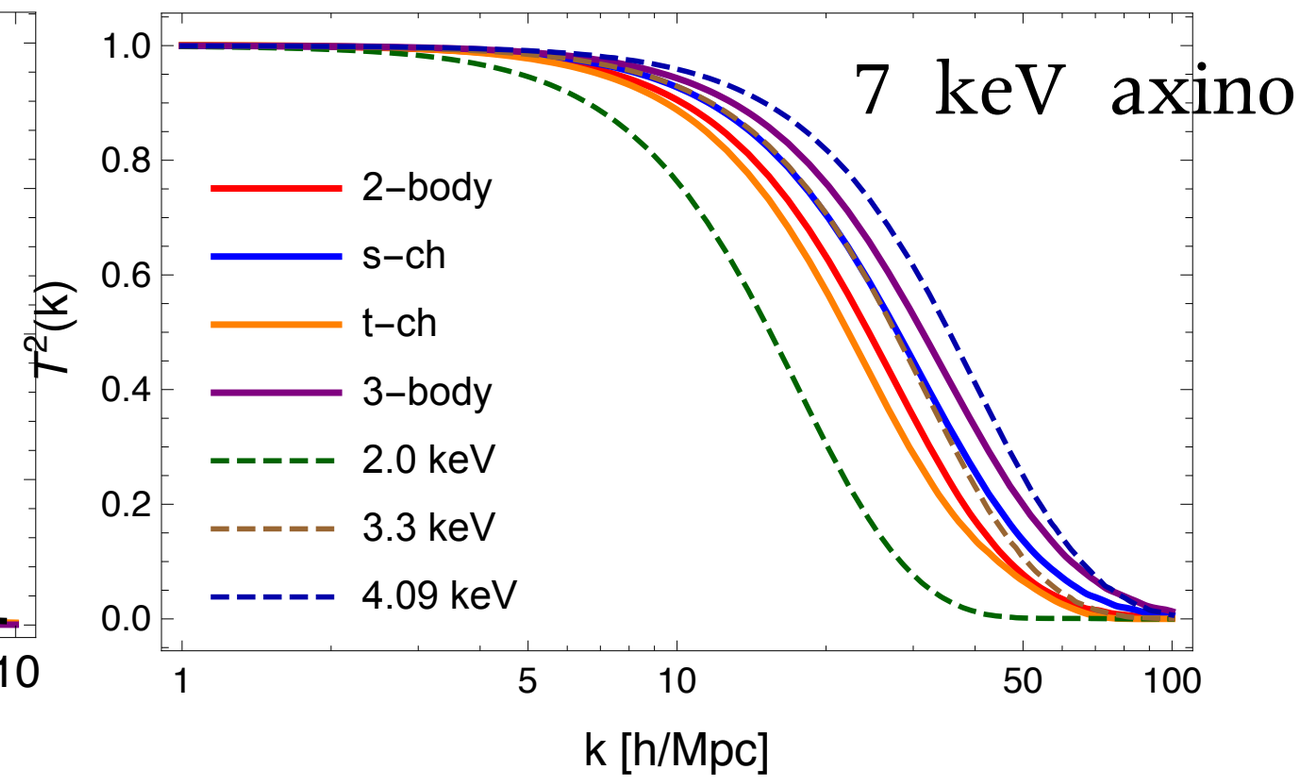
DFSZ axino

[Bae, Kamada, Liew, Yanagi, 1707.06418]

Phase space distribution




Linear matter power spectrum

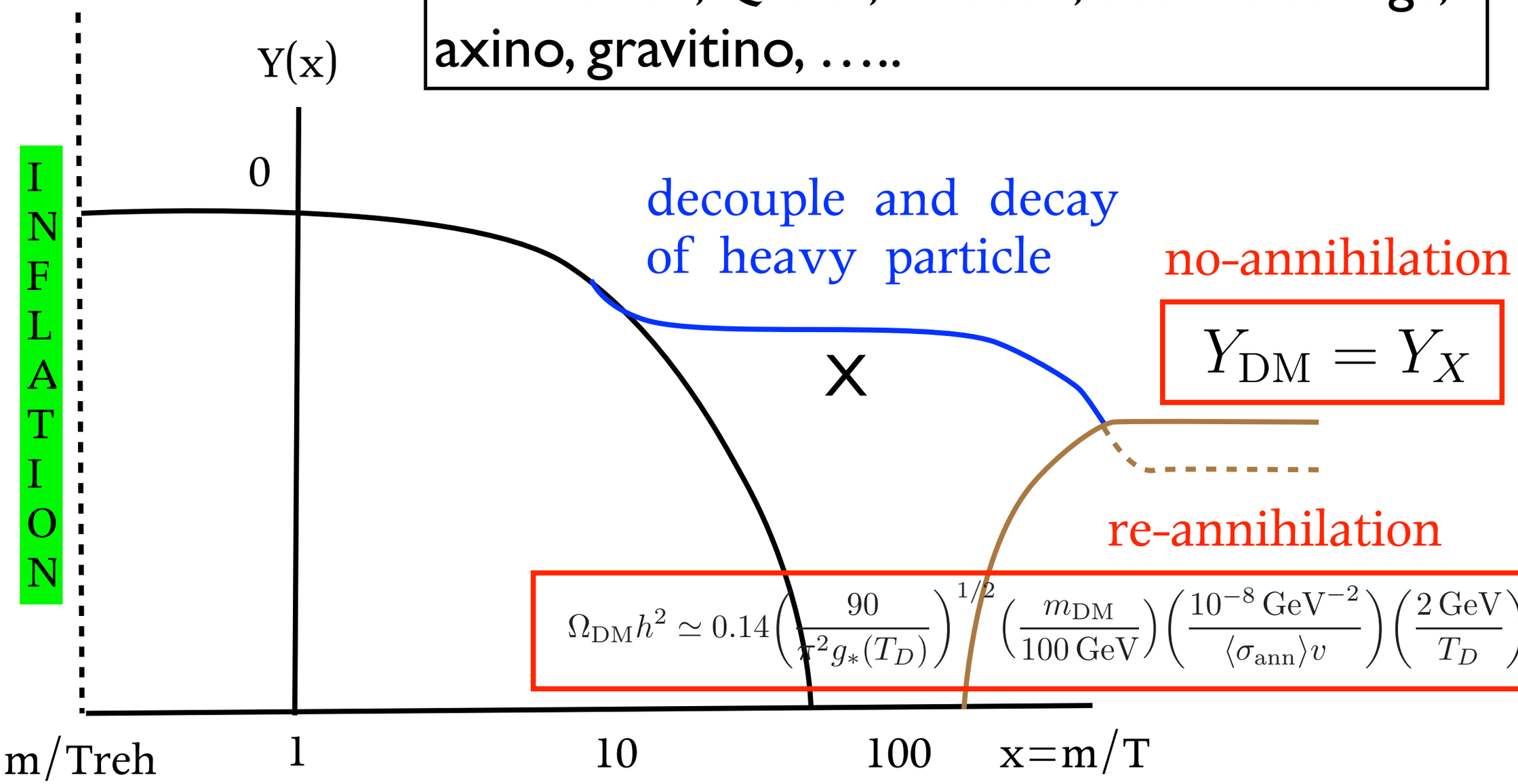



Axino is colder than ordinary WDM.

[K. Yanagi's poster]

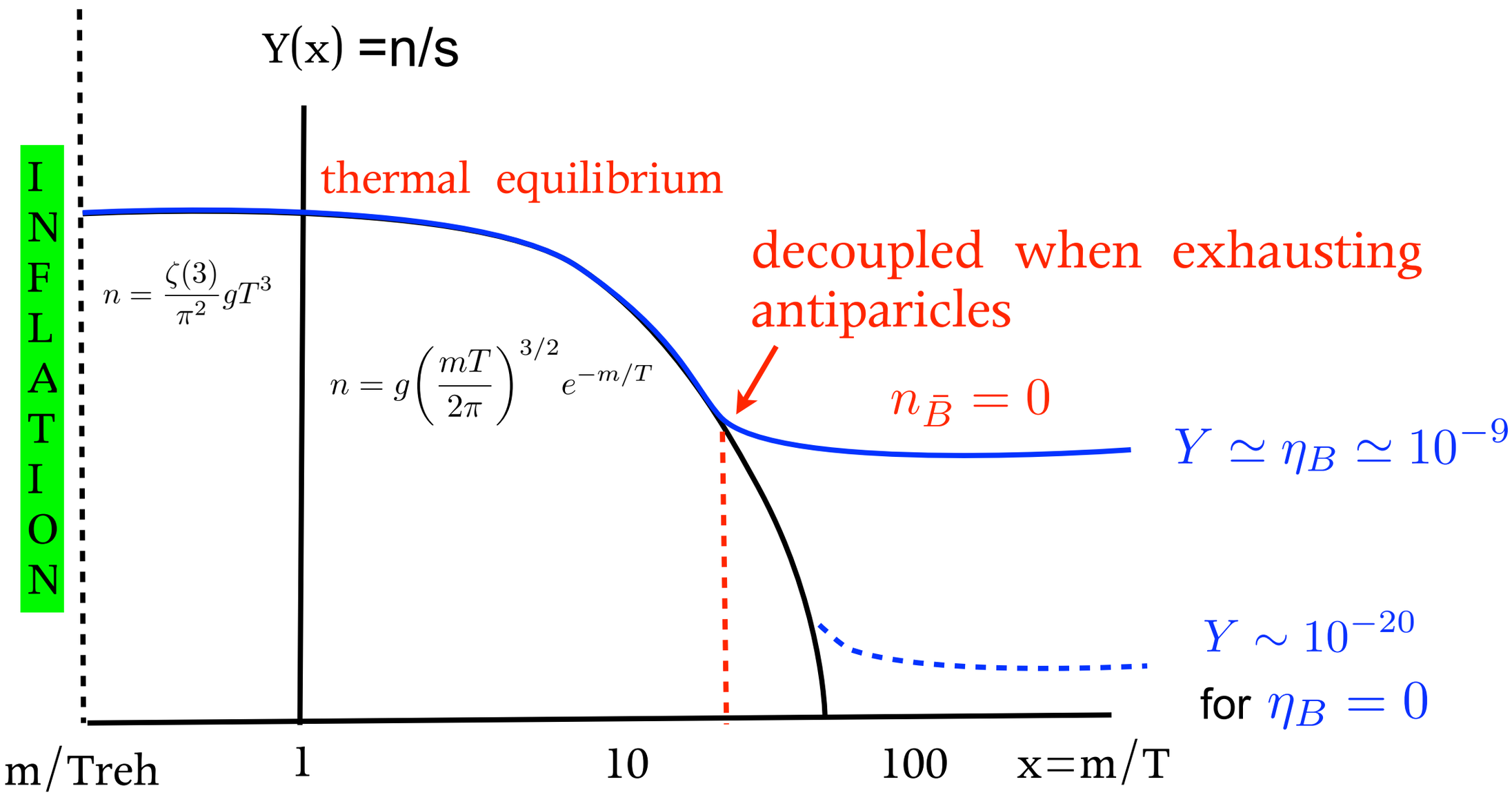
# Non-thermal production: from decay of heavy particles

X= moduli, Q-ball, inflaton, cosmic strings, axino, gravitino, …..



# Asymmetric dark matter
## freeze-out with particle-antiparticle asymmetry

*Baryons decouple from thermal equilibrium much earlier than without asymmetry



# Asymmetric dark matter of GeV mass

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, $\eta_{\rm DM} = \eta_B$

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

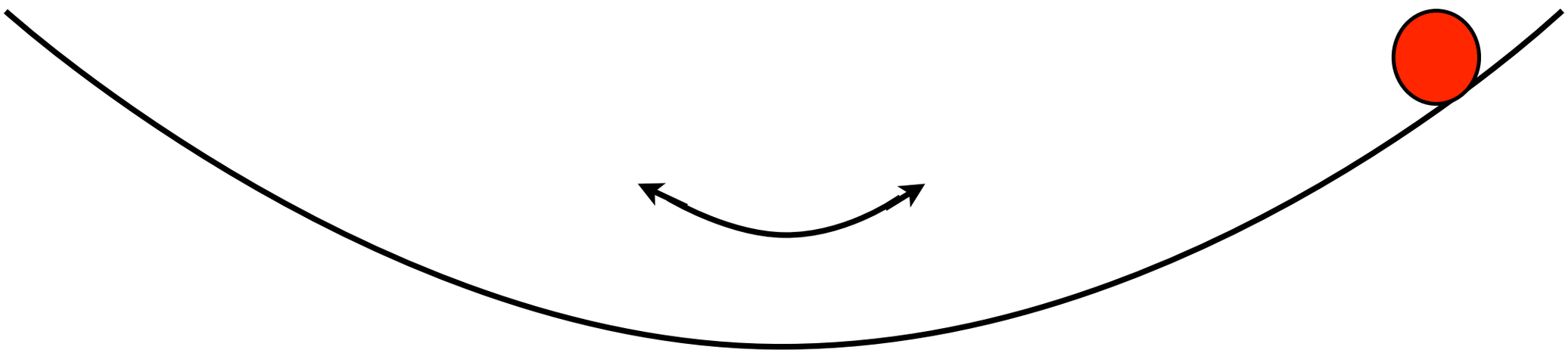
Stable Technibaryon [Nussinov, 1985]

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: Bosonic Coherent Motion (BCM)



The oscillating scalar fields in the quadratic potential behaves like cold dark matter (zero pressure fluid) in the zeroth, linear, 2nd order and even fully non-linear order in the super-Jeans scale.

[Khlopov 1985, Nambu, Sasaki 1990, Ratra 1991, Hwang 1997, Sikivie, Yang 2009, Hwang, Noh 2009 ] [Noh, Hwang, Park, 1707.08568]

Example : axion, fuzzy CDM, ALP

[Jose Cembranos's Talk]
[Alma Gonzalez's Talk]

# DM during early Matter Domination

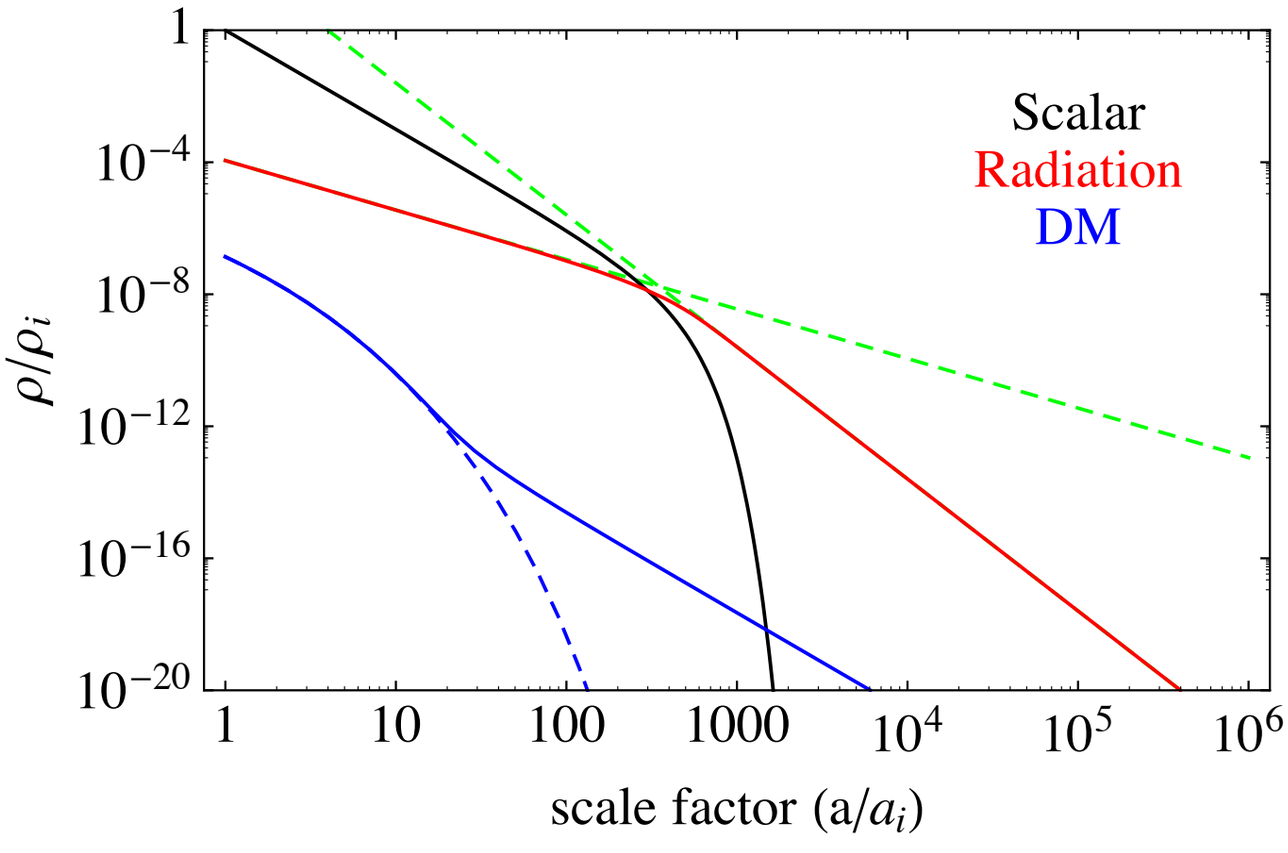
- Creation of isocurvature perturbation
- Low bound on reheating temperature
- Quasi-decoupled state and free-streaming scale

# Early Matter Domination (eMD) and Low Reheating Temperature

The Universe is dominated by heavy particles (early matter domination) and reheated (radiation domination) by the decay of them. It happens for:

- Inflaton oscillation
- Thermal inflation
- Curvaton domination
- Heavy axino and saxion
- Moduli
- .....

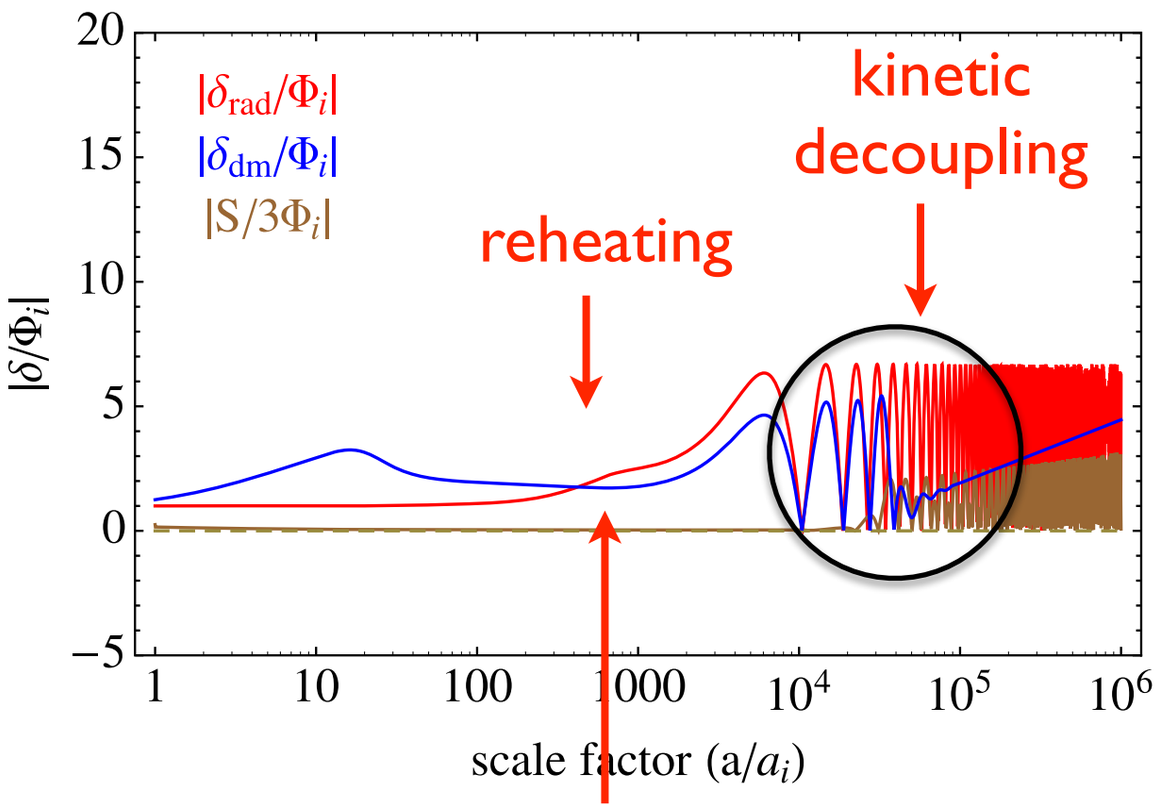
$$T_{\rm reh} \simeq \left(\frac{90}{\pi^2 g_*}\right)^{1/4} \sqrt{\Gamma M_P}$$

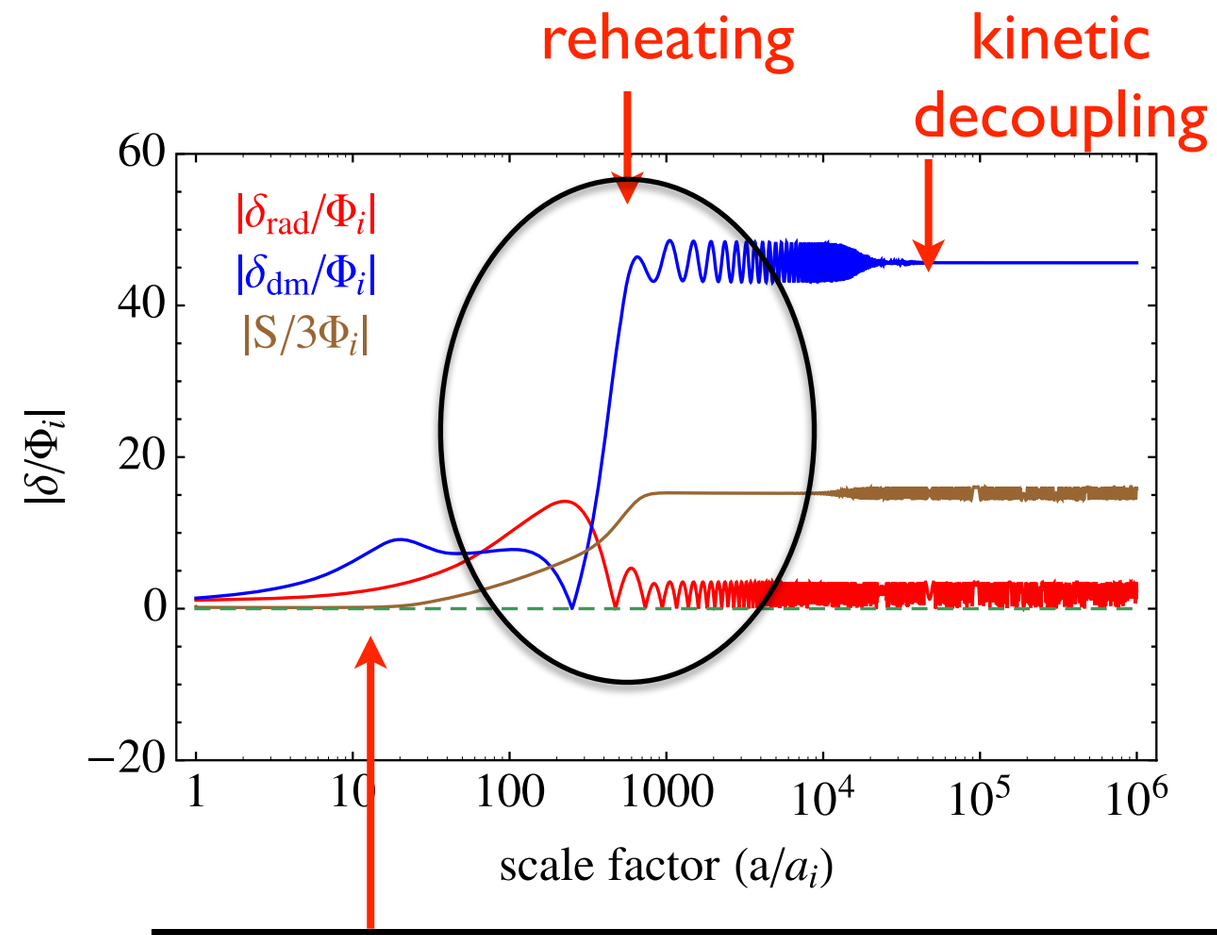


Kinetic decoupling scale of WIMP $\overset{?}{=}$ the smallest scale of the structure formation?

# 1. Creation of Isocurvature Perturbation

[KYChoi, Gong, Shin 2015]




Horizon entry after reheating

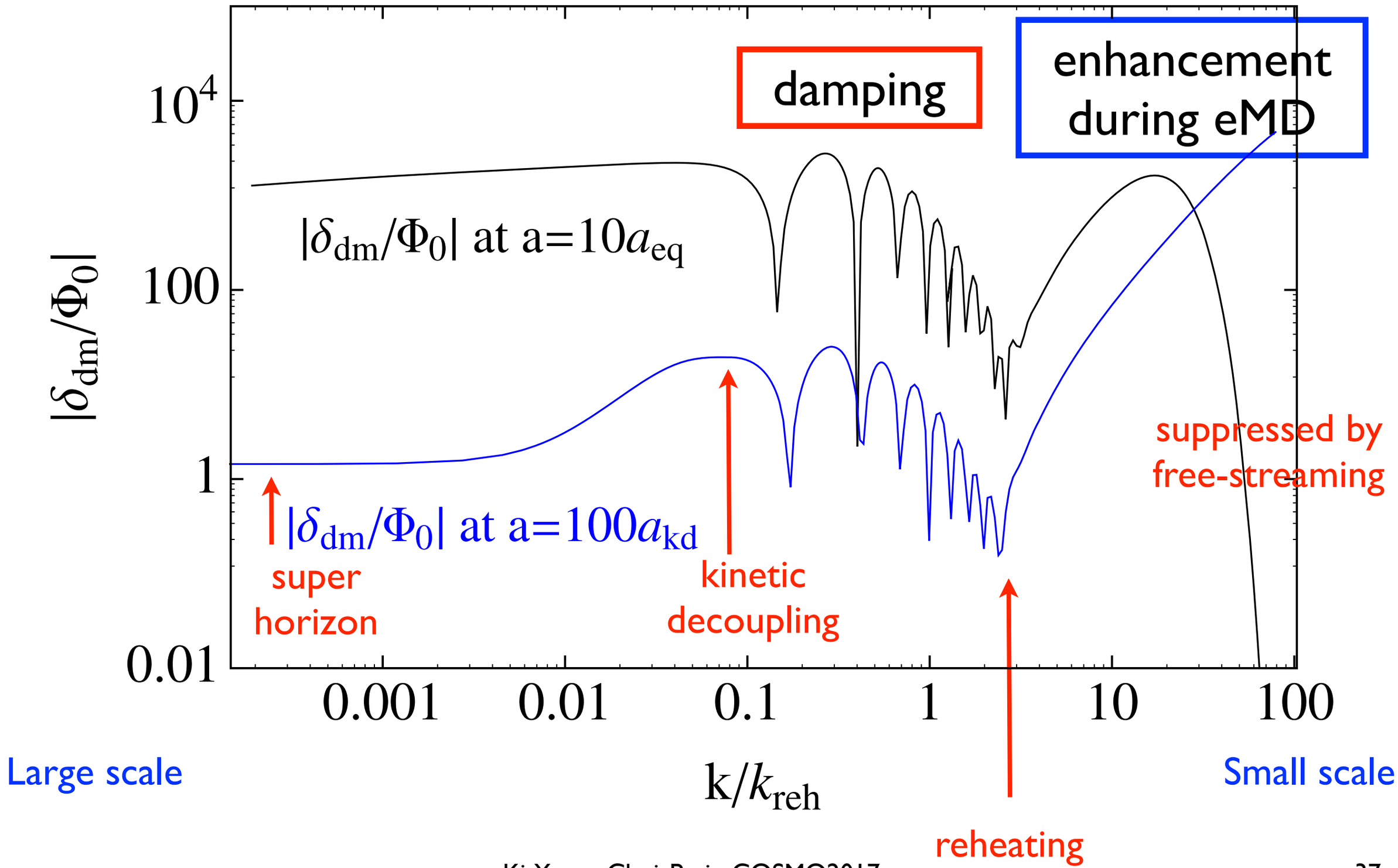
Damping erases the perturbations.

Horizon entry during early MD before reheating

Enhancement and No damping.

# Damping and Enhancement of Density Perturbation

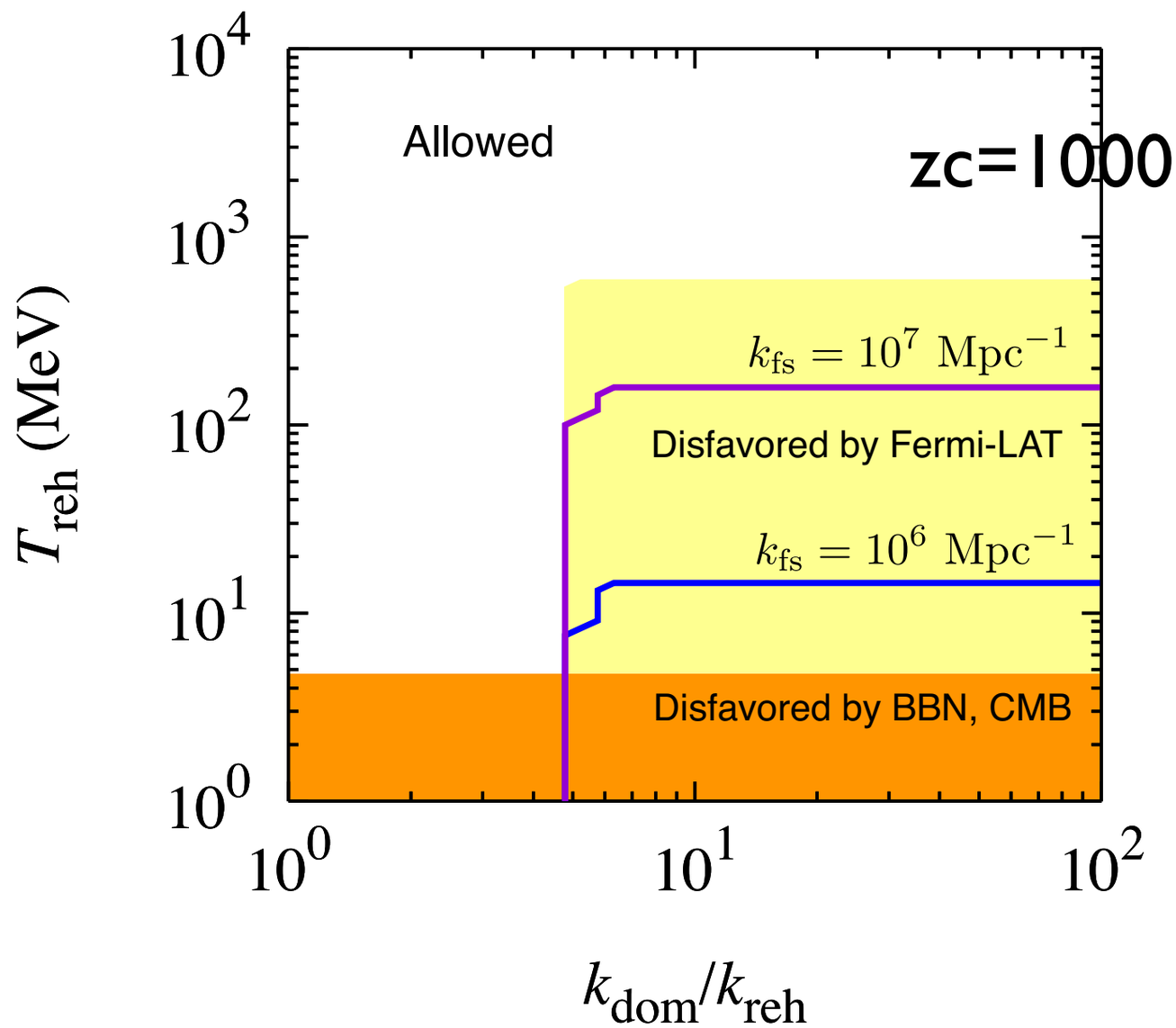
[KYChoi, Gong, Shin 2015]



# 2. Low-bound on reheating temperature with dark matter

# 2. Low bound on Treh with WIMP DM of UCMHs

UCMH production from the large perturbation




[Smoot's talk]

UCMH constraint by Fermi-LAT from annihilation of WIMP DM.

$$T_R \gtrsim 10 - 100\,{\rm MeV}$$

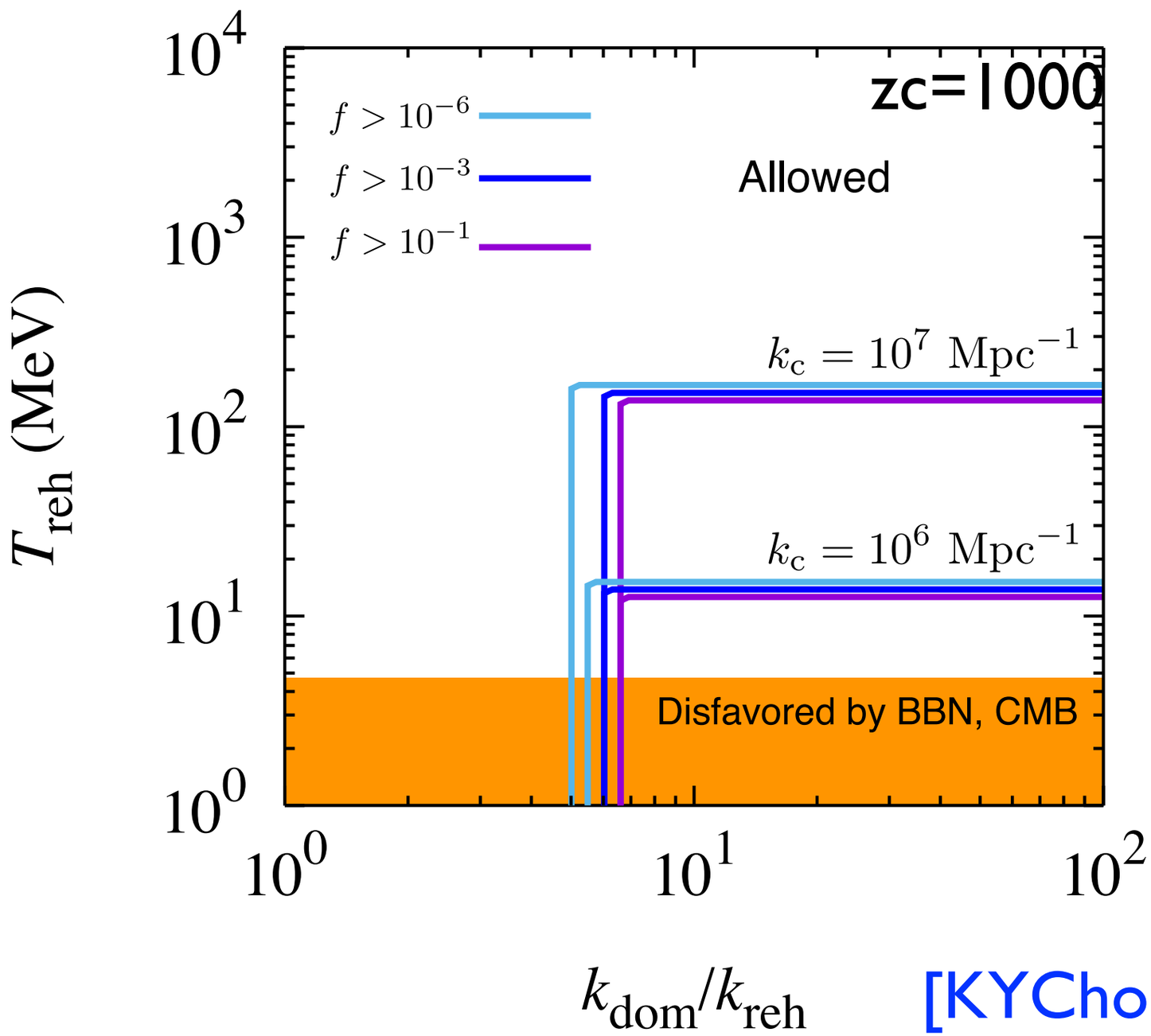
[KYChoi, Tomo Takahashi, 2017]

cf) $T_{\rm reh} \gtrsim 4.7\,{\rm MeV}$ BBN+CMB

[Kwasaki, Kohri, Sugiyama, 1999, 2000]
[Salas et al 2015]

$k_{\rm 1MeV} = 10^4\,{\rm Mpc}^{-1}$

# Future Low bound on Treh with non-WIMP DM




Future gravitational observations: lensing, pulsar timing

at the scale of

$k_c$

$$T_R \gtrsim 10 - 100\,\mathrm{MeV}$$

[KYChoi, Tomo Takahashi, 2017]

## 3. The decoupled non-relativistic particle

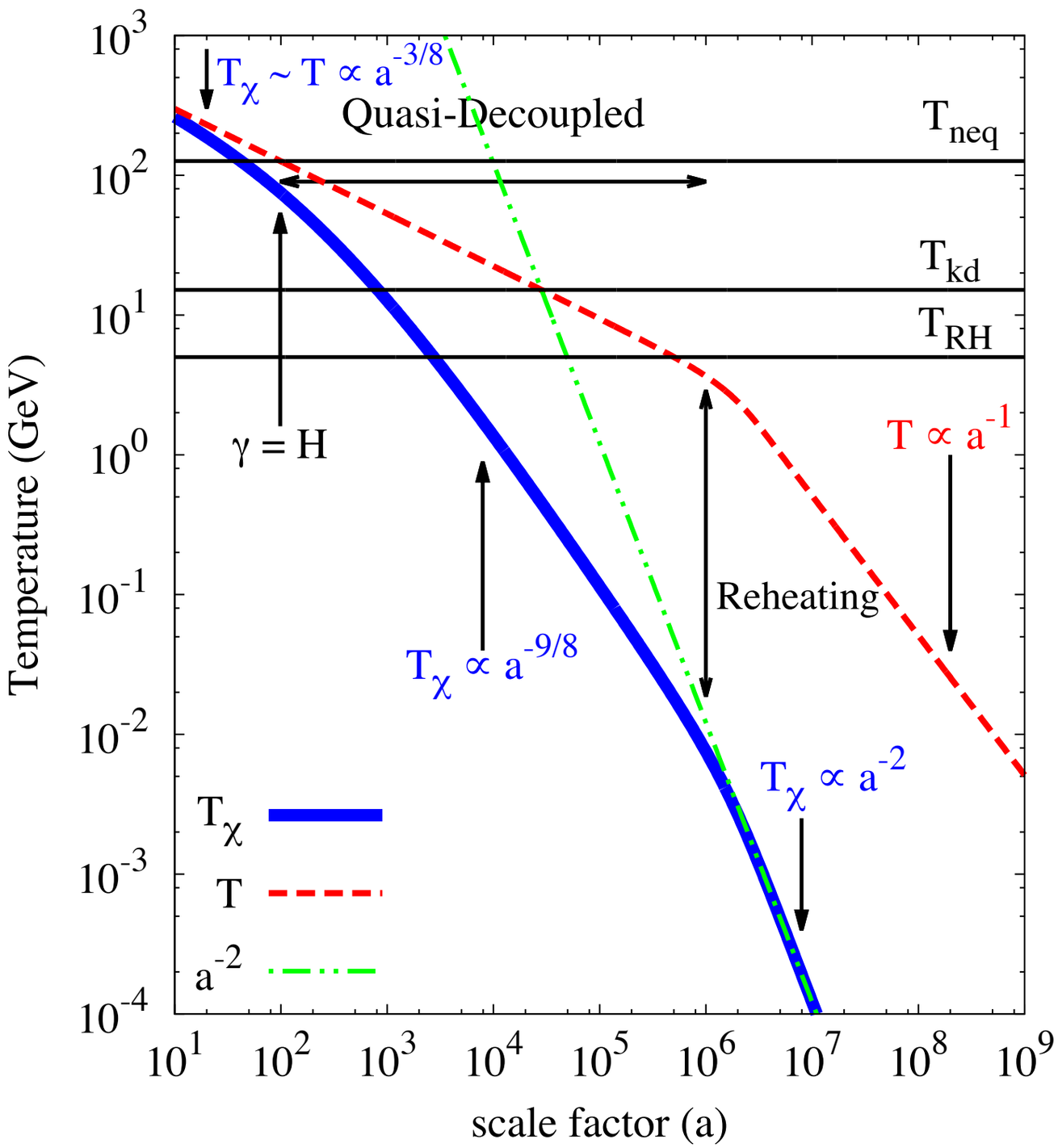
$$T_\chi(a) \propto a^{-2}$$

at lower temperature?

$$a\,\frac{dT_\chi}{da} + 2\,T_\chi(a)\left[1 + \frac{\gamma(a)}{H(a)}\right] = 2\,\frac{\gamma(a)}{H(a)}\,T(a).$$

# 3. Quasi-decoupled state during eMD

[Waldstein, Erickcek, Ilie, 2016]




During eMD, DM is not fully decoupled. Instead it enters in the quasi-decoupled state, which temperature is between the fully decoupled and plasma state.

Change of free-streaming scale

$$\lambda_{\rm fs} = \int_{a_{\rm neq}}^{a_0} da \, \frac{v_\chi(a)}{a^2 H(a)}$$

# Summary

- Particle candidates for dark matter:
  : the simplest and effective candidate for dark matter motivated by theory, data, or curiosity
- DM production is connected to the evolution of structures
  : mass and interactions determine the properties
  - Freeze-out of equilibrium: HDM, WDM, WIMP,…
  - Already decoupled : gravitino, axino, RH sneutrino,…
- Non-thermal production
  - heavy particle decay, ADM, BCM, PBH,….
- Dark Matter with the early Matter-Domination
  - Isocurvature perturbation of WIMP: no damping during kinetic decoupling
  - Low-bound on the reheating temperature: constraints from UCMH
  - quasi-decoupled state: free-streaming scale,…

# Merci Beaucoup

# 1. Creation of Isocurvature Perturbation

After chemical decoupling and before reheating during scalar-domination:

Dark matter and radiation are still kinetically coupled: $\theta_m \approx \theta_r$.

$$\dot{\delta}_m \approx -\frac{\theta_r}{a},$$

$$\dot{\delta}_r \approx -\frac{4}{3}\frac{\theta_r}{a} + \frac{\Gamma_\phi \rho_\phi}{\rho_r}(\delta_\phi - \delta_r),$$

Radiation is still produced from decay of the dominating scalar, however dark matter is not produced any more.

The difference in the number density creates the isocurvature perturbation between dark matter and radiation.

[KYChoi, Gong, Shin 2015]

$$S(t_{\rm reh}) \approx -\frac{3}{4}\int_{t_i}^{t_{\rm reh}} dt \frac{\Gamma_\phi \rho_\phi \delta_\phi}{\rho_r} \approx \frac{5}{4}\Phi_i \left(\frac{k}{k_{\rm reh}}\right)^2.$$