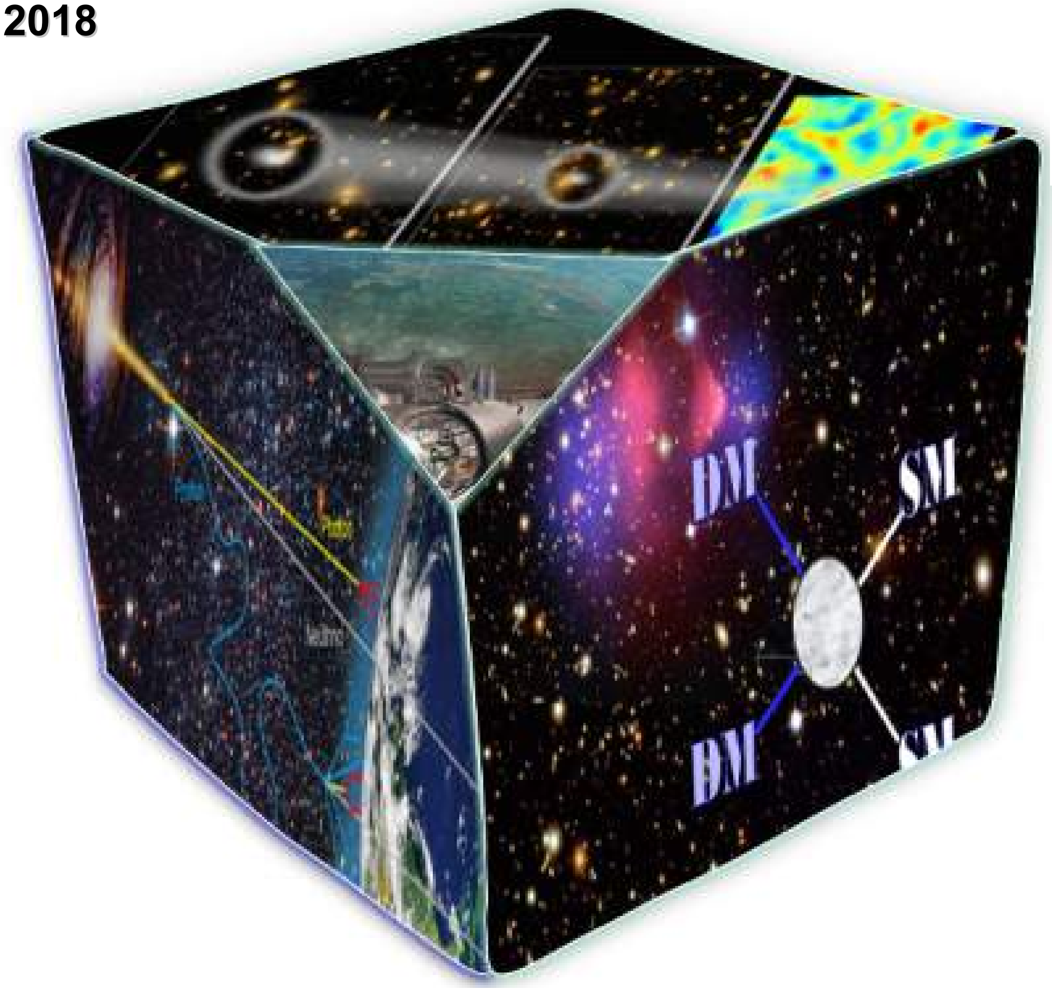
Dark Matter & Neutrino School – ICTP-SAIFR
July 23-27, 2018



Cosmological Production of Dark Matter

Farinaldo Queiroz

International Institute of Physics
&
ICTP-SAIFR

Outline

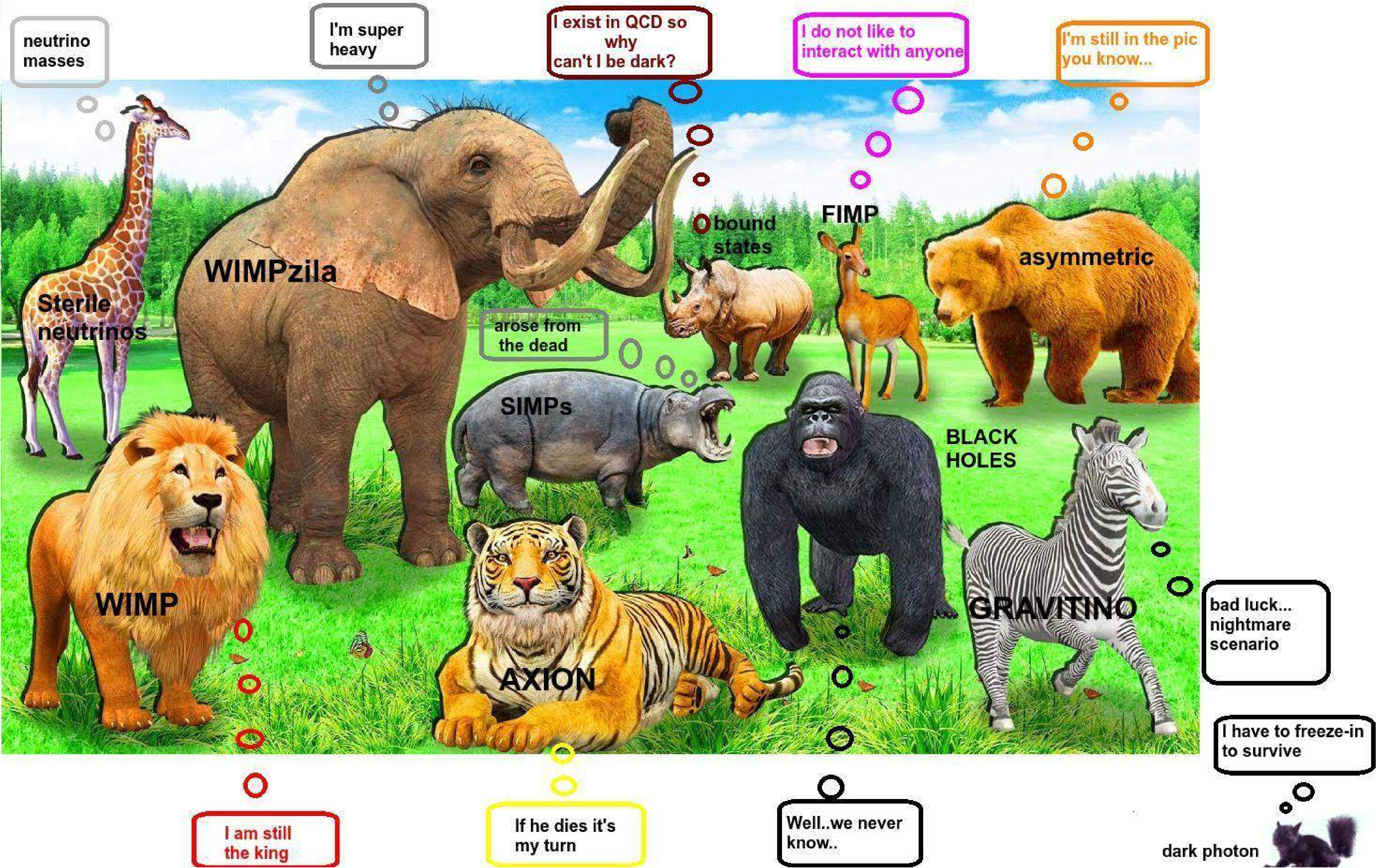
1. Introduction

- *Cold and hot thermal relic*
- *How heavy/light can a dark matter particle be?*
- *WIMP miracle*

2. Production Mechanisms

- ***Thermal freeze-out***
  - *Annihilation 2 $\leftrightarrow$ 2 Processes*
  - *Resonances*
  - *Threshold*
  - *Co-annihilation*
  - *Semi-annihilation*
- ***Non-thermal freeze-in***
  - *FIMP Miracle*
  - *Late time decays*
- ***Asymmetric production***
  - *Matter-dark matter coincidence*
  - *Matter-antimatter*
- ***Modified cosmological history***
  - *Late time decays*

ZOO OF DARK MATTER CANDIDATES

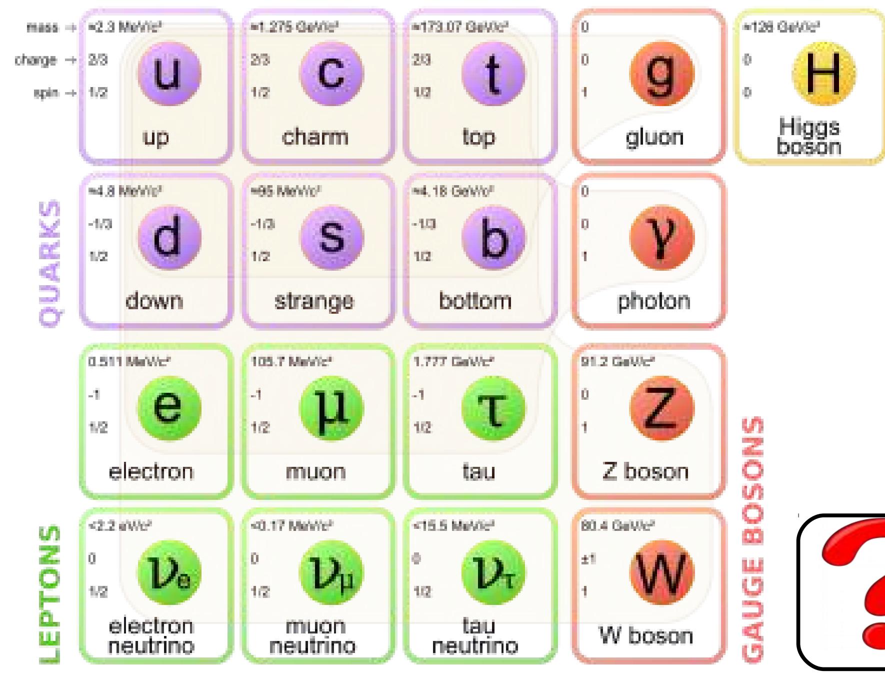


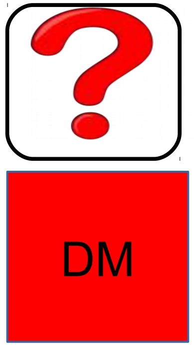
Our current knowledge of elementary particles is summarized by the so-called Standard Model

It includes all the known elementary particles

It correctly predicts their interactions

Does it account for all there is?





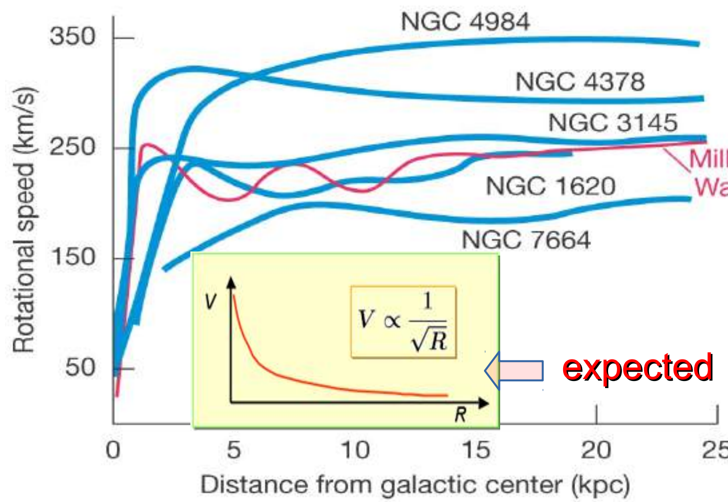
No! There is Dark Matter!

...The need for Dark Matter...

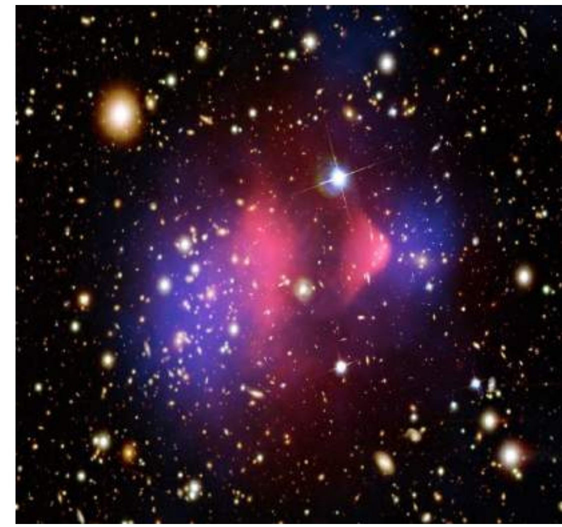
F. S. Queiroz, *1605.08788*

In 1933 Fritz Zwick used the virial theorem to infer the existence of unseen matter in the Coma galaxy cluster

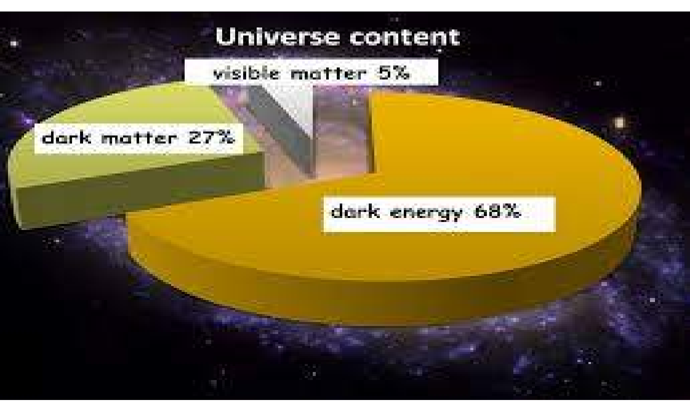
In 1970s Vera Rubin+, established the existence of dark matter in galaxies by studying galaxy rotation curves

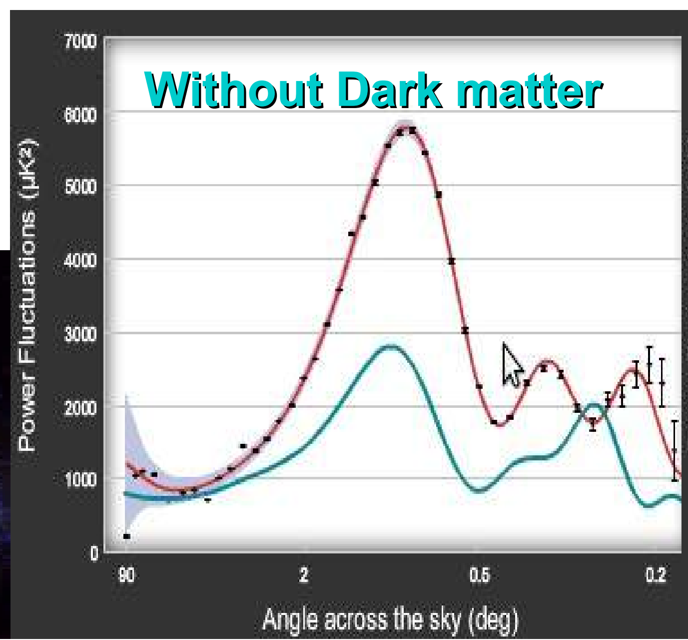


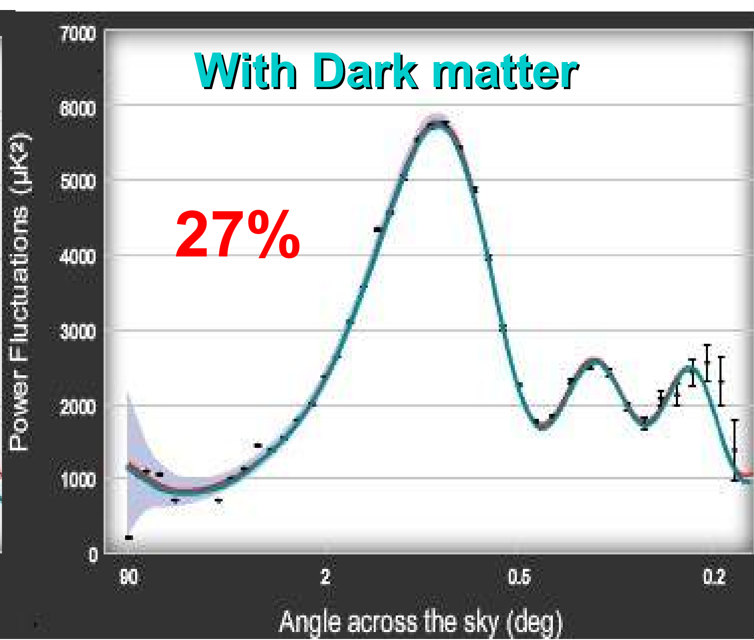
In 2003 the observation of the bullet cluster by Maxim Markevitch+



COBE (1990s), WMAP (2000s), PLANCK (2013) confirmed the existence of dark matter using CMB data





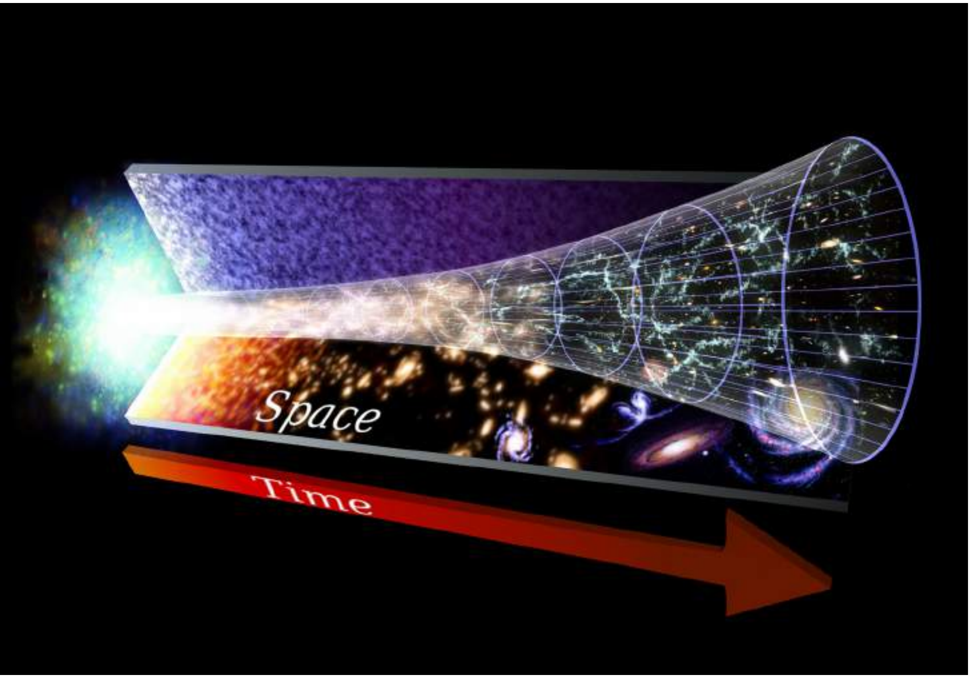


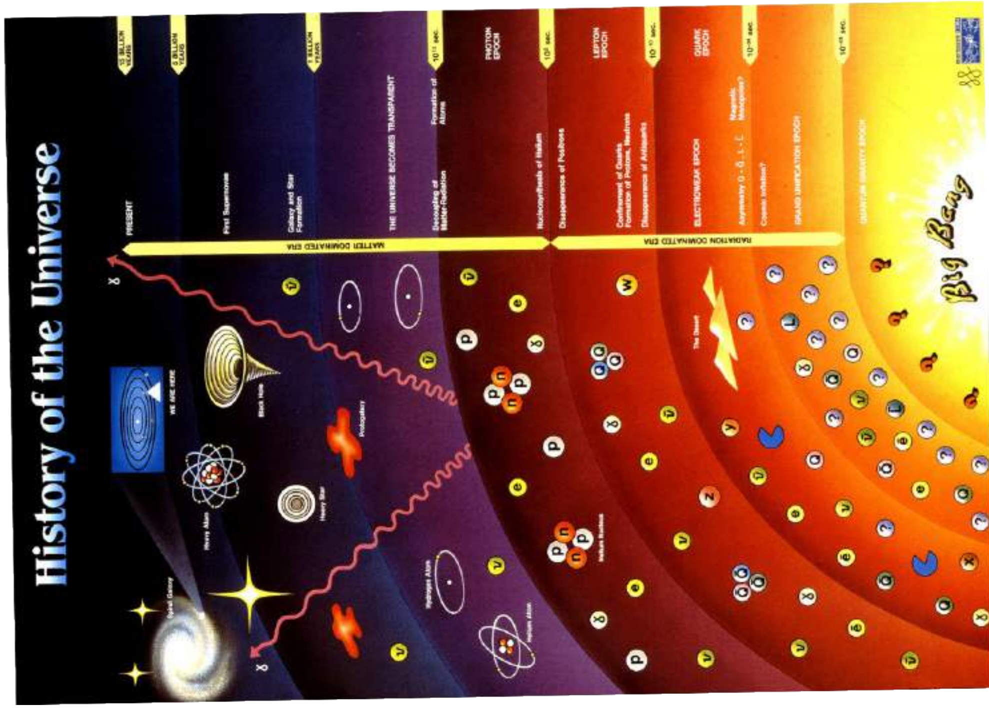
Cold and hot thermal relic: thermal decoupling

Numbers to remember

$$\rho_{crit} = \frac{3H_0^2}{8\pi G_N} \simeq 10^{-29} g/cm^3 \longrightarrow \rho_{crit} = 10^{-6} GeV/cm^3$$

$$\rho_{DM} = \Omega_{DM}\rho_{crit} \simeq \rho_{crit} \longrightarrow \rho_{\odot} = \Omega_{DM}\rho_{crit} \simeq 0.3\rho_{crit}$$





$$\Gamma = n\sigma v$$

BBN- Thermal Production

$p + e^- \longleftrightarrow n + \nu$

$n + e^+ \longleftrightarrow p + \bar{\nu}$

neutron:proton ratio in thermal equilibrium

$n \longrightarrow p + e^- + \bar{\nu}$

$p + n \longleftrightarrow d + \gamma$

$d + n \longrightarrow H^3 + \gamma$

$H^3 + p \longrightarrow He^4 + \gamma$

$d + p \longrightarrow He^3 + \gamma$

$He^3 + n \longrightarrow He^4 + \gamma$

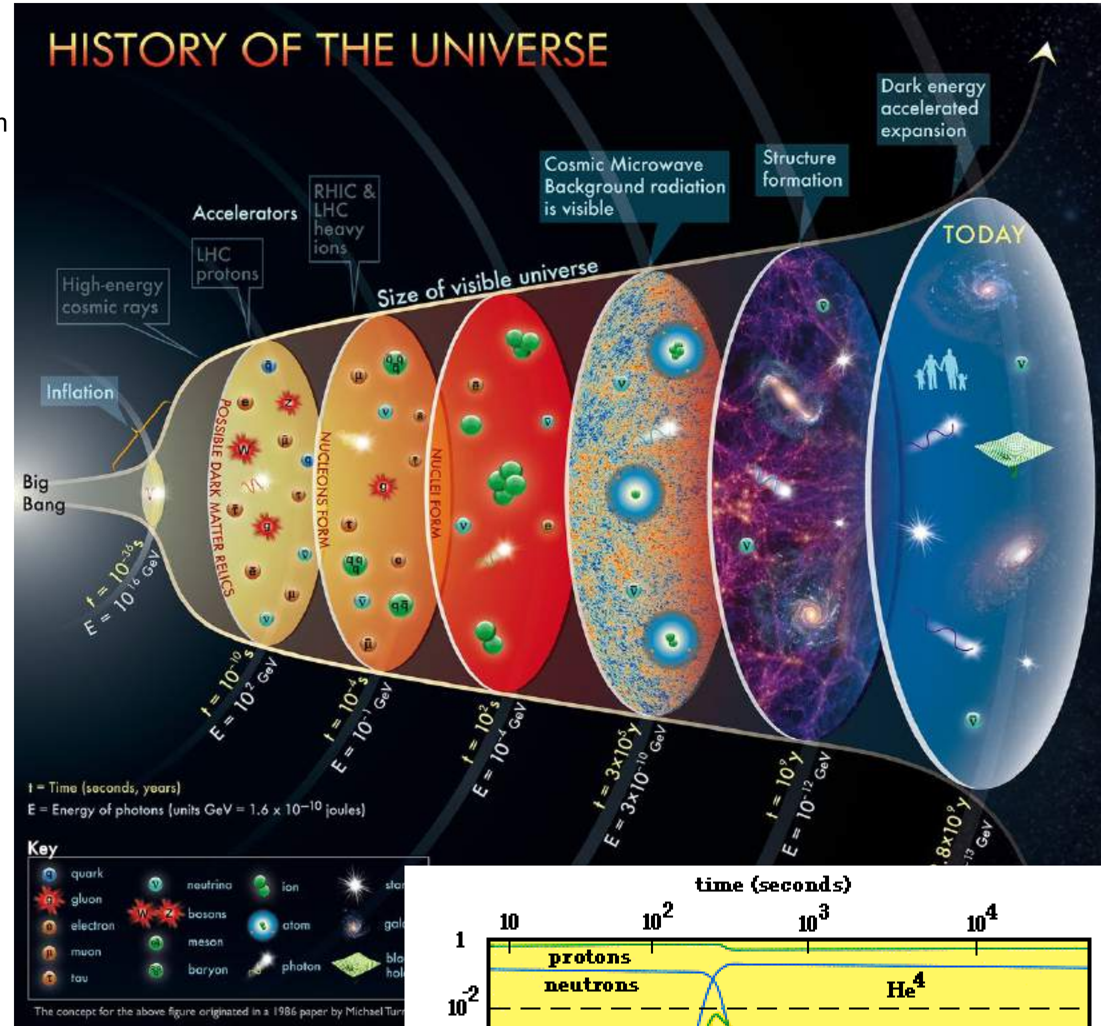
$d + d \longrightarrow He^3 + n$

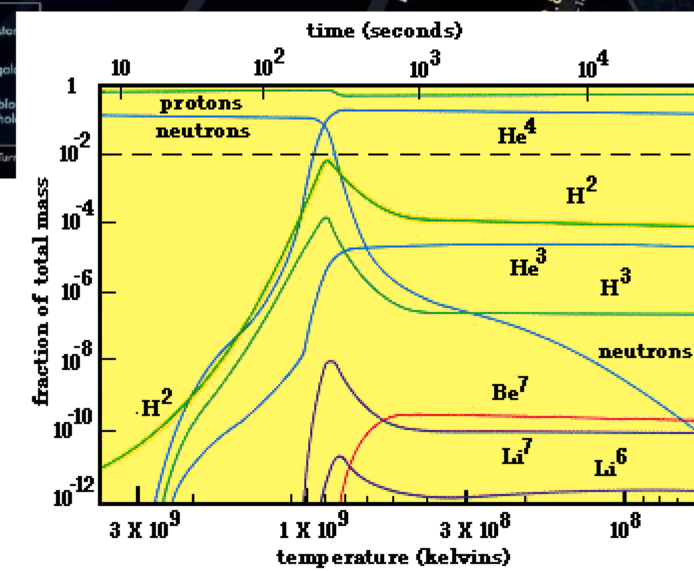
$d + d \longrightarrow H^3 + p$

$H^3 + d \longrightarrow He^4 + n$

$He^3 + d \longrightarrow He^4 + p$

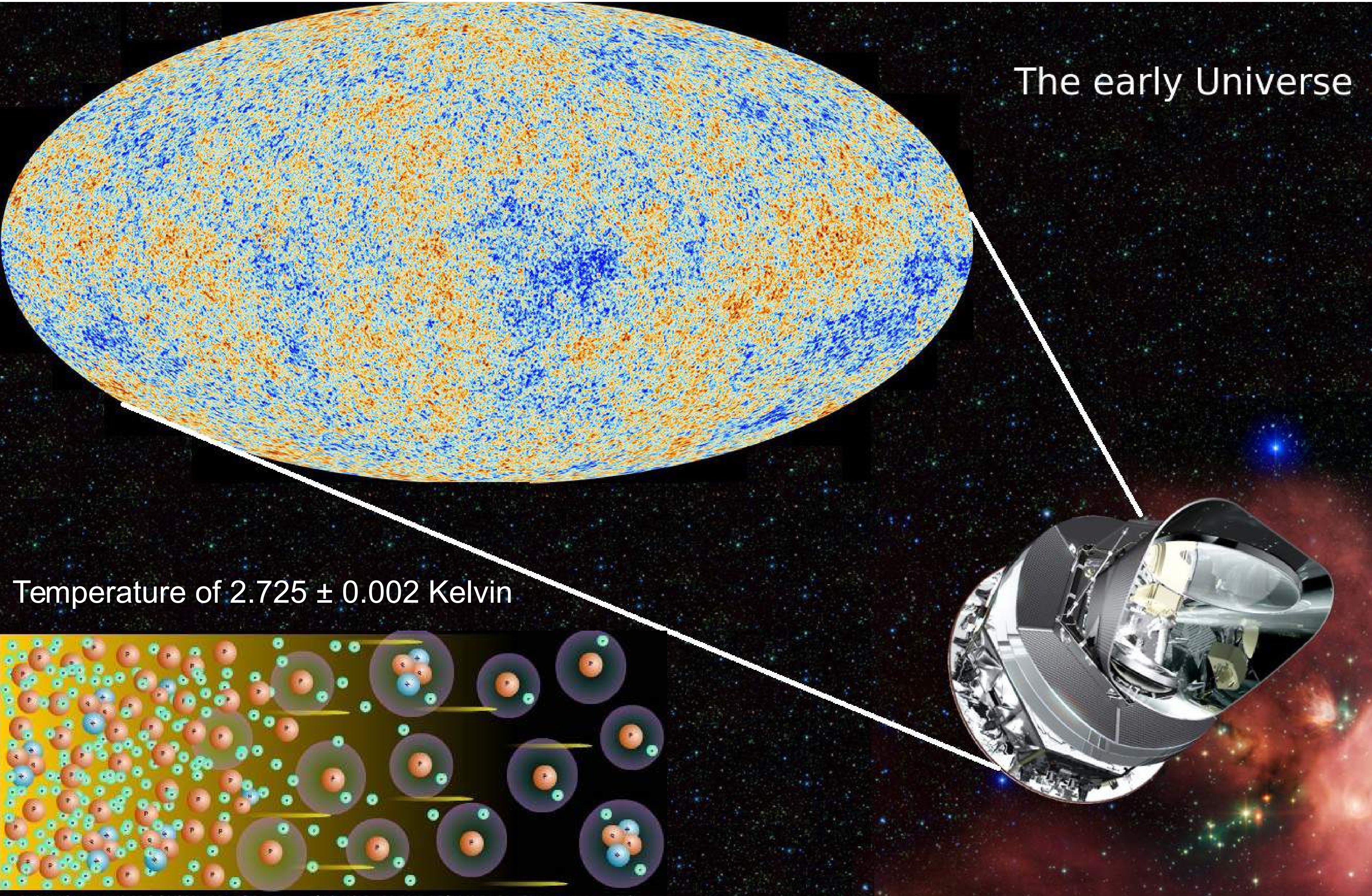
$d + d \longrightarrow He^4 + \gamma$

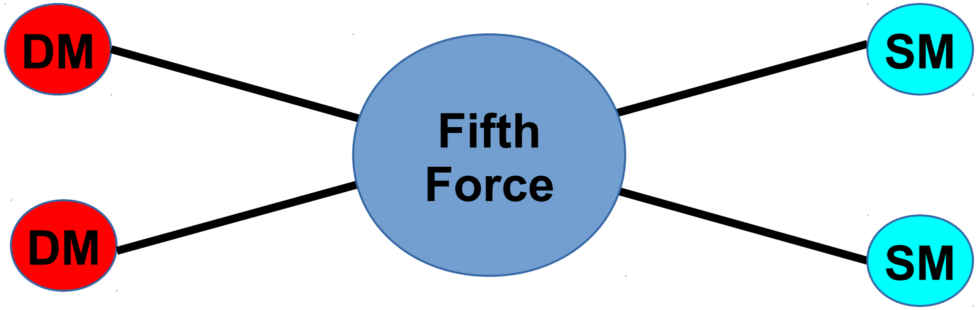




The temperature is slightly less than the neutron-proton mass difference these weak reactions become slower than the expansion rate of the Universe, and the neutron:proton ratio freezes out at about 1:6.

Thermal Photons - CMB





Evidence for Dark Matter

+

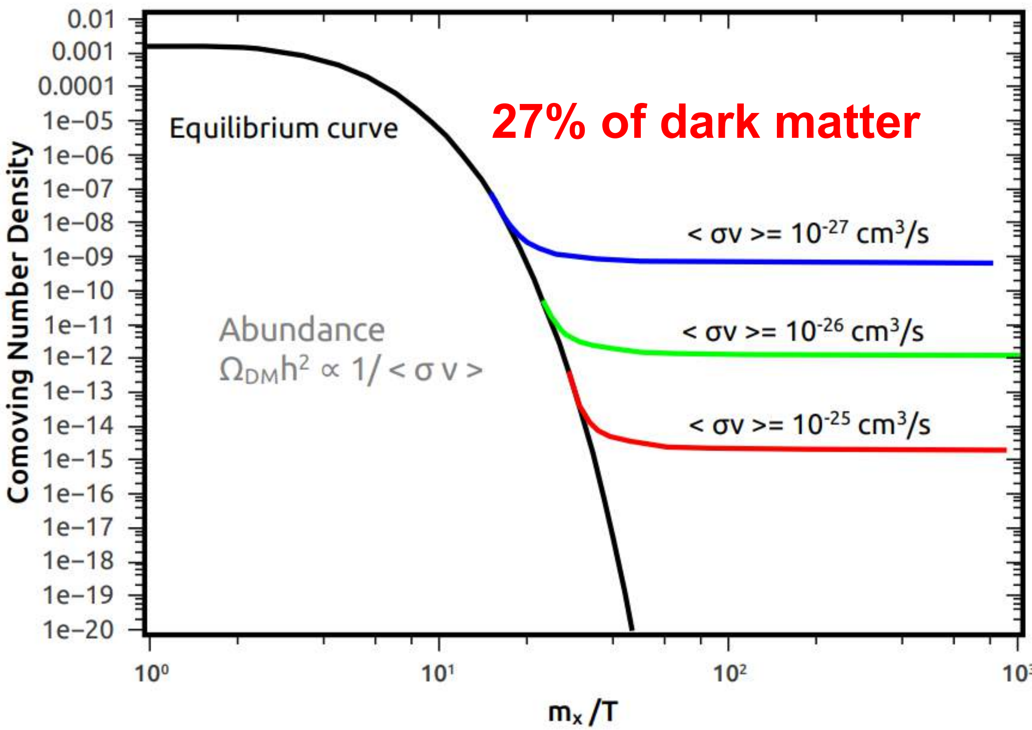
Thermal Equilibrium - BBN

+

Thermal Equilibrium - CMB

↓

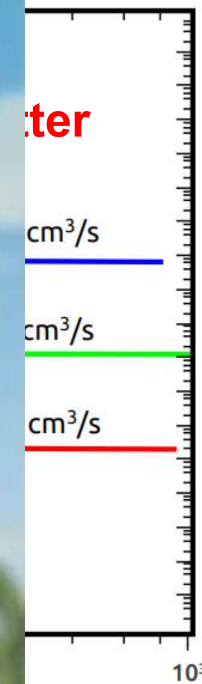
Thermal Production of Dark Matter



Arxiv: 1703.07364

Very good guess

Evidence for Dark Matter



Very good guess

Cold and hot thermal relic: thermal decoupling

Hot Relic

Interaction Rate x Expansion Rate

$$\Gamma = n\sigma v \qquad H^2 = \frac{8\pi G_N}{3}\rho$$

For T > 1eV

$$\rho = \rho_{rad} = \frac{\pi^2}{30} g T^4$$

Expansion Rate

$$H \sim T^2/M_p$$

Reduced Planck Mass

$$M_p = 1/\sqrt{8\pi G_N} = 2.435 \times 10^{18} GeV$$

Decoupling condition

$$n(T_\nu)\sigma(T_\nu) = H(T_\nu)$$

$$n_{rel} \sim T^3, m \ll T$$

$$T_\nu^3 G_F^2 T_\nu^2 = T_\nu^2/M_p$$

Neutrino decoupling temperature →

$$T_\nu = (G_F^2 M_P)^{-1/3} \sim 1 MeV$$

Cold and hot thermal relic: thermal decoupling

Interaction Rate x Expansion Rate

$$\Gamma = n\sigma v \qquad H^2 = \frac{8\pi G_N}{3}\rho$$

For T > 1eV

$$\rho = \rho_{rad} = \frac{\pi^2}{30} g T^4$$

Expansion Rate

$$H \sim T^2/M_p$$

Hot Relic

Reduced Planck Mass

$$M_p = 1/\sqrt{8\pi G_N} = 2.435 \times 10^{18} GeV$$

Decoupling condition

$$n(T_\nu)\sigma(T_\nu) = H(T_\nu)$$

$$n_{rel} \sim T^3, m \ll T$$

$$T_\nu^3 G_F^2 T_\nu^2 = T_\nu^2/M_p$$

Neutrino decoupling temperature →

$$T_\nu = (G_F^2 M_P)^{-1/3} \sim 1MeV$$

Cold and hot thermal relic: thermal decoupling

Hot Relic

Abundance of a hot relic

$$Y_{freeze-out} = \frac{n(T)}{s(T)} = \frac{\rho_\nu(T_\nu)}{m_\nu s(T_\nu)}$$

entropy density = s

For T > 1eV

$$\rho = \rho_{rad} = \frac{\pi^2}{30} g T^4$$

Expansion Rate

$$H \sim T^2/M_p$$

Reduced Planck Mass

$$M_p = 1/\sqrt{8\pi G_N} = 2.435 \times 10^{18} GeV$$

Iso-entropic universe → $s.a^3 = constant$

$$n_{rel} \sim T^3, m \ll T$$

Abundance of neutrinos → $\Omega_\nu h^2 \simeq \frac{m_\nu}{92eV}$

read S. Dodelson Book- “section about neutrinos”

Cold and hot thermal relic: thermal decoupling

Cold Relic

Interaction Rate x Expansion Rate

$$\Gamma = H$$

Expansion Rate

$$H \sim T^2/M_p$$

$$n_{f.o.} \simeq \frac{T_{f.o}^2}{M_p \sigma}$$

$$n_{non-rel} \sim (mT)^{3/2} \exp^{m/T}, m \gg T$$

$$x = m_\chi / T.$$

Cold relic condition $x \gg 1$

Decoupling condition: $\frac{m_\chi^3}{x^{3/2}} \exp^{-x} = \frac{m_\chi^2}{x^2 M_p \sigma}$ $\longrightarrow$ $\sqrt{x} \exp^{-x} = \frac{1}{m_\chi M_p \sigma}$

Assuming

$\sigma \sim G_F^2 m_\chi^2 \quad m_\chi = 100 GeV$ $\Rightarrow$ $\sqrt{x} \exp^{-x} \sim 10^{-14}$

Cold and hot thermal relic: thermal decoupling

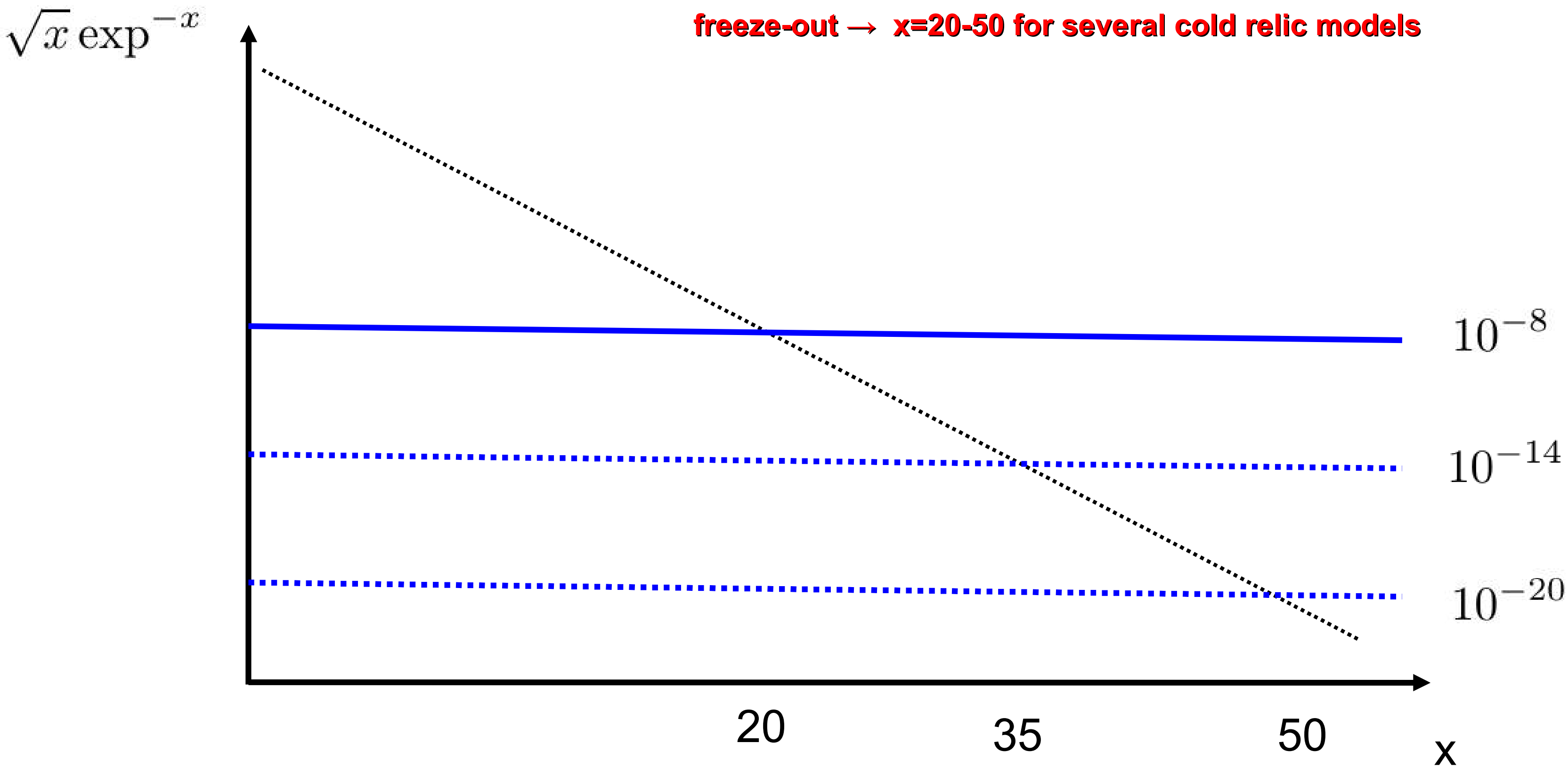
Cold Relic

Assuming

$$\sigma \sim G_F^2 m_\chi^2 \quad m_\chi = 100 GeV$$

$$\sqrt{x}\exp^{-x} \sim 10^{-14}$$

freeze-out → x=20-50 for several cold relic models



Cold and hot thermal relic: thermal decoupling

Cold Relic

$$\frac{n_0}{T_0^3} \simeq \frac{n_{f.o}}{T_{f.o}^3}$$

Going back to the relic density

$$\Omega_\chi = \frac{m_\chi n_\chi (T = T_0)}{\rho_c} = \frac{m_\chi T_0^3}{\rho_c} \frac{n_0}{T_0^3}$$

$$\Omega_\chi = \frac{m_\chi T_0^3}{\rho_c} \frac{n_{f.o}}{T_{f.o}^3} = \frac{T_0^3}{\rho_c} x_{f.o} \left(\frac{n_{f.o}}{T_{f.o}^2} \right) = \frac{T_0^3}{\rho_c M_p} \frac{x_{f.o}}{\sigma}$$

Cold relic abundance:

$$\frac{\Omega_\chi}{0.2} \simeq \frac{x_{f.o}}{20} \left(\frac{10^{-8} GeV^{-2}}{\sigma} \right)$$

Changing units

$$\sigma v \sim 10^{-8} GeV^{-2} \times 10^{10} cm/s \;\rightarrow\; \sigma v \sim 3 \times 10^{-26} cm^3/s$$

let's see if we can find a similar cross section in nature

Modified cosmological history

Cold and hot thermal relic: thermal decoupling

Cold Relic

$$\frac{n_0}{T_0^3} \simeq \frac{n_{f.o}}{T_{f.o}^3}$$

Going back to the relic density

$$\Omega_\chi = \frac{m_\chi n_\chi(T = T_0)}{\rho_c} = \frac{m_\chi T_0^3}{\rho_c}\frac{n_0}{T_0^3}$$

$$\Omega_\chi = \frac{m_\chi T_0^3}{\rho_c}\frac{n_{f.o}}{T_{f.o}^3} = \frac{T_0^3}{\rho_c} x_{f.o}\left(\frac{n_{f.o}}{T_{f.o}^2}\right) = \frac{T_0^3}{\rho_c M_p}\frac{x_{f.o}}{\sigma}$$

Cold relic abundance:

$$\frac{\Omega_\chi}{0.2} \simeq \frac{x_{f.o}}{20}\left(\frac{10^{-8} GeV^{-2}}{\sigma}\right)$$

Changing units

$$\sigma v \sim 10^{-8} GeV^{-2} \times 10^{10} cm/s \quad \longrightarrow \quad \sigma v \sim 3 \times 10^{-26} cm^3/s$$

let's see if we can find a similar cross section in nature

$$\sigma_{EW} \sim G_F^2 E^2 \sim G_F^2 T^2 \sim G_F^2 \left(\frac{m_\chi}{x}\right)^2 \sim G_F^2 \left(\frac{m_\chi}{20}\right)^2 \sim 10^{-8} GeV^{-2}$$

WEAK SCALE!

Read arxiv:0803.4196

How light/heavy can a thermal relic be?

Lower Limit

Decoupling condition: $\sqrt{x}\,\exp^{-x} = \frac{1}{m_\chi\, M_p\, \sigma}$

Cold relic condition: $x \gg 1$

$\Rightarrow m_\chi\, M_p\, \sigma \gg 1$

remember $\sigma \sim 10^{-8} GeV^{-2}$ $\Rightarrow$ $m_\chi \gg 0.1 eV$ *

* *There are bounds from structure formation m > KeV*

Upper Limit

Write pair-annihilation cross section in partial waves and use the optical theorem

$$\sigma < \frac{4\pi}{m_\chi^2} \Rightarrow \frac{\Omega_\chi}{0.3} > 10^{-8} GeV^{-2} \frac{m_\chi^2}{4\pi} \Rightarrow m_\chi < 100\, TeV$$

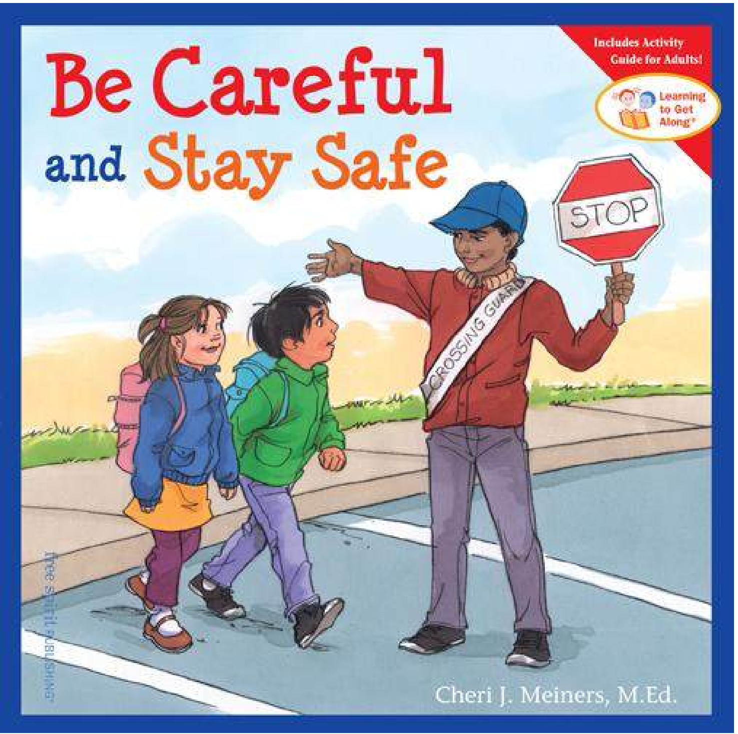
Read K. Griest, PRL 1990

How light/heavy can a thermal relic be?

Is that all? **NO!**

We have assumed an iso-entropic universe. If entropy is injected after the thermal relic has frozen-out the abundance can change!

$$s \to \gamma s \qquad \Omega_\chi \to \Omega_\chi / \gamma$$



Overabundance thermal relic can be diluted to the right relic density, but….

Be careful

The entropy injection has to occur before BBN

Thermal freeze-out

Boltzmann Equation $\hat{L}[f] = \hat{C}[f]$

$$f \equiv f(p, x, t)$$

$$\int L[f] g \frac{d^3p}{(2\pi)^3} = \frac{dn}{dt} + 3H.n \qquad \int C[f] \frac{d^3p}{(2\pi)^3} = - < \sigma v > (n_1 n_2 - n_1^{eq} n_2^{eq})$$

$$v \equiv \frac{\sqrt{(p1.p2)^2 - m_1^2 m_2^2}}{E_1 E_2}$$

$$\dot{n} + 3Hn =< \sigma v > (n_{eq}^2 - n^2)$$

$$< \sigma v >= \frac{\int \sigma v \exp^{-E_1/T} \exp^{-E_2/T} d^3p_1 d^3p_2}{\int \exp^{-E_1/T} \exp^{-E_2/T} d^3p_1 d^3p_2}$$

defining $Y = n/s$

$$\frac{x}{Y_{eq}} \frac{dY}{dx} = -\frac{\Gamma}{H} \left[\left(\frac{Y}{Y_{eq}} \right)^2 - 1 \right]$$

Boltzmann Equation

Outline

1. Introduction

- *Cold and hot thermal relic*
- *How heavy/light can a dark matter particle be?*
- *WIMP miracle*

2. Production Mechanisms

Thermal freeze-out

- *Annihilation 2 ↔ 2 Processes*
- *Resonances*
- *Threshold*
- *Co-annihilation*
- *Semi-annihilation*

Non-thermal freeze-in

- *FIMP Miracle*
- *Late time decays*

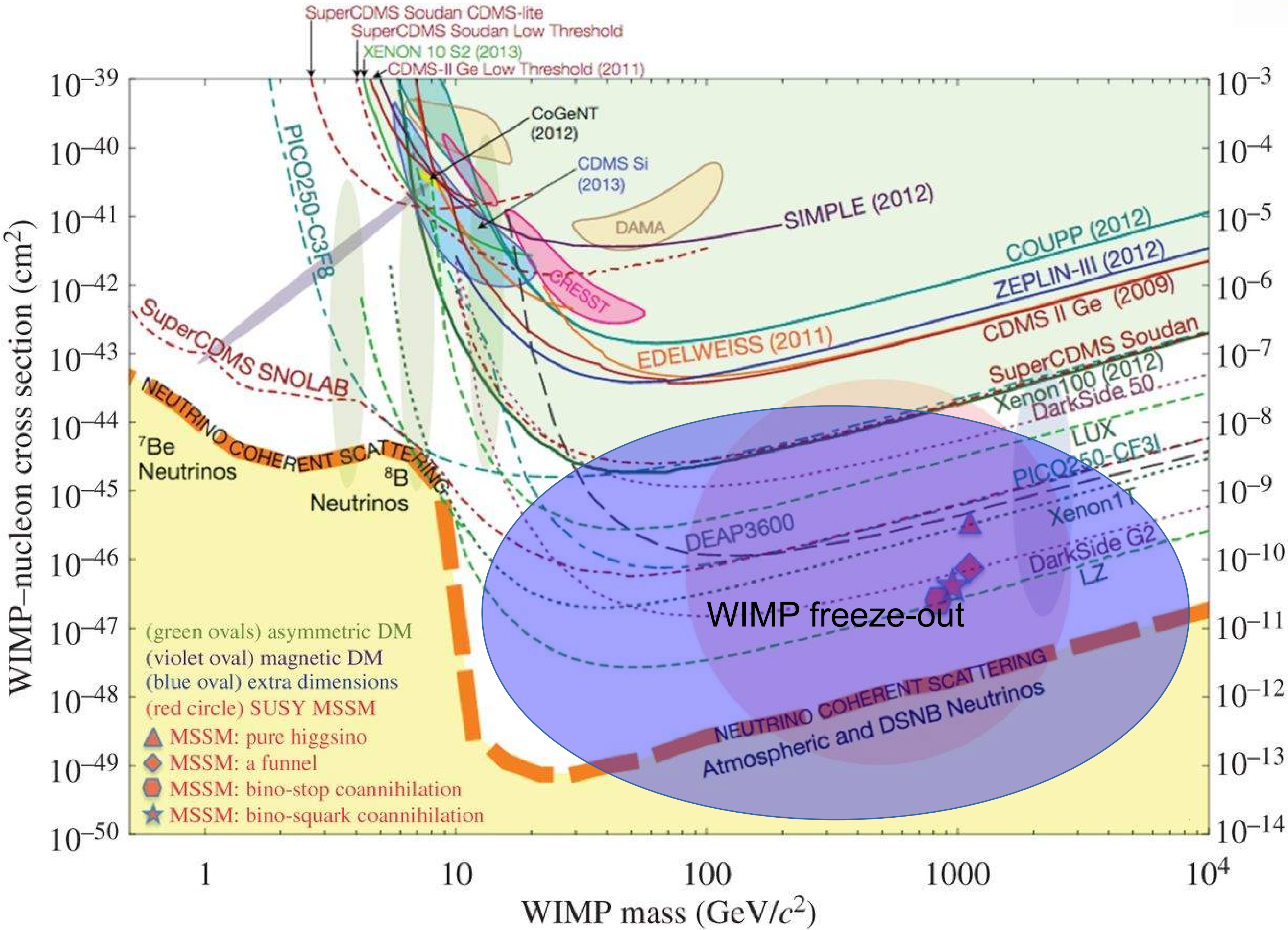
Asymmetric production

- *Matter-dark matter coincidence*
- *Matter-antimatter*

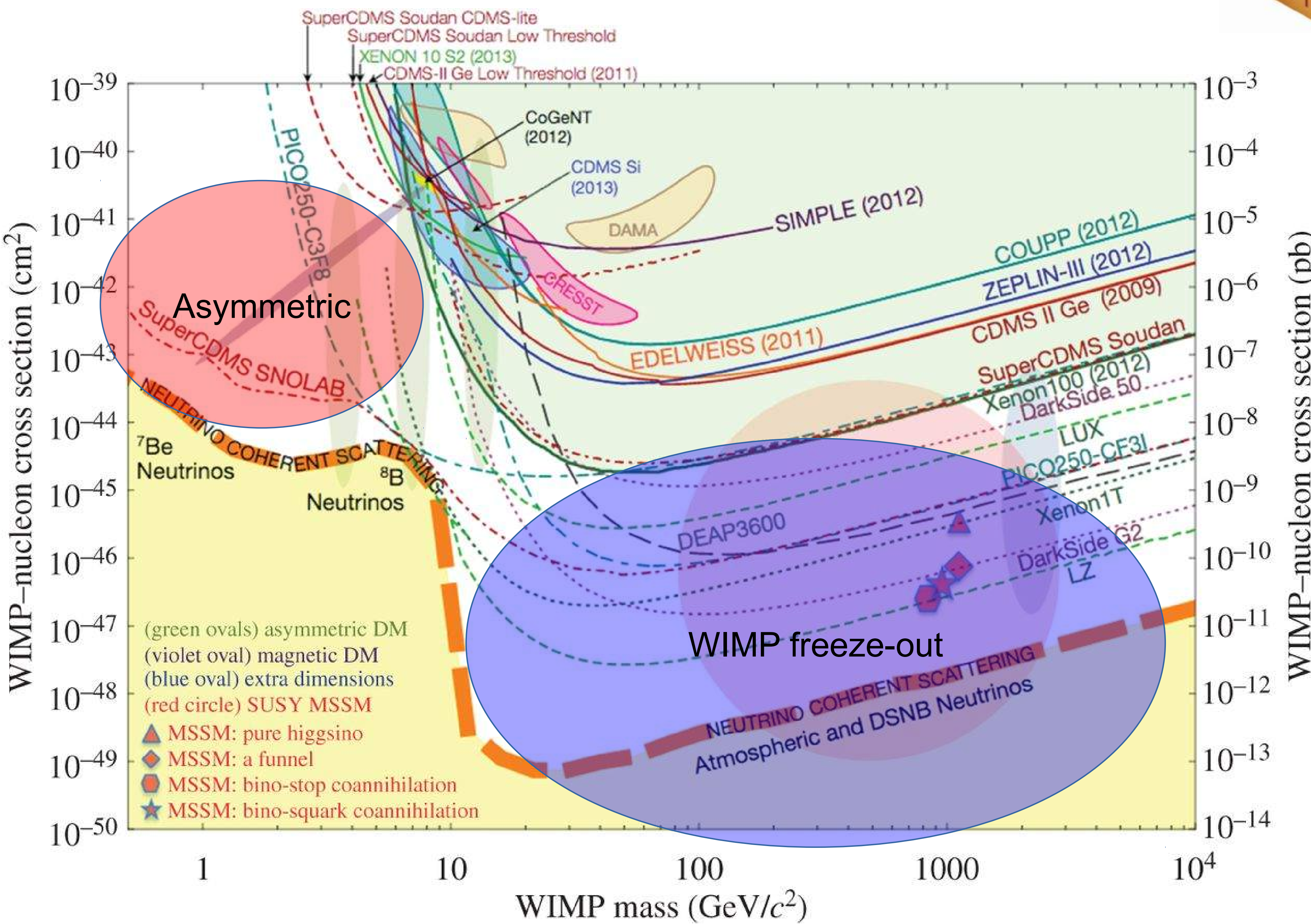
Modified cosmological history

- *Late time decays*

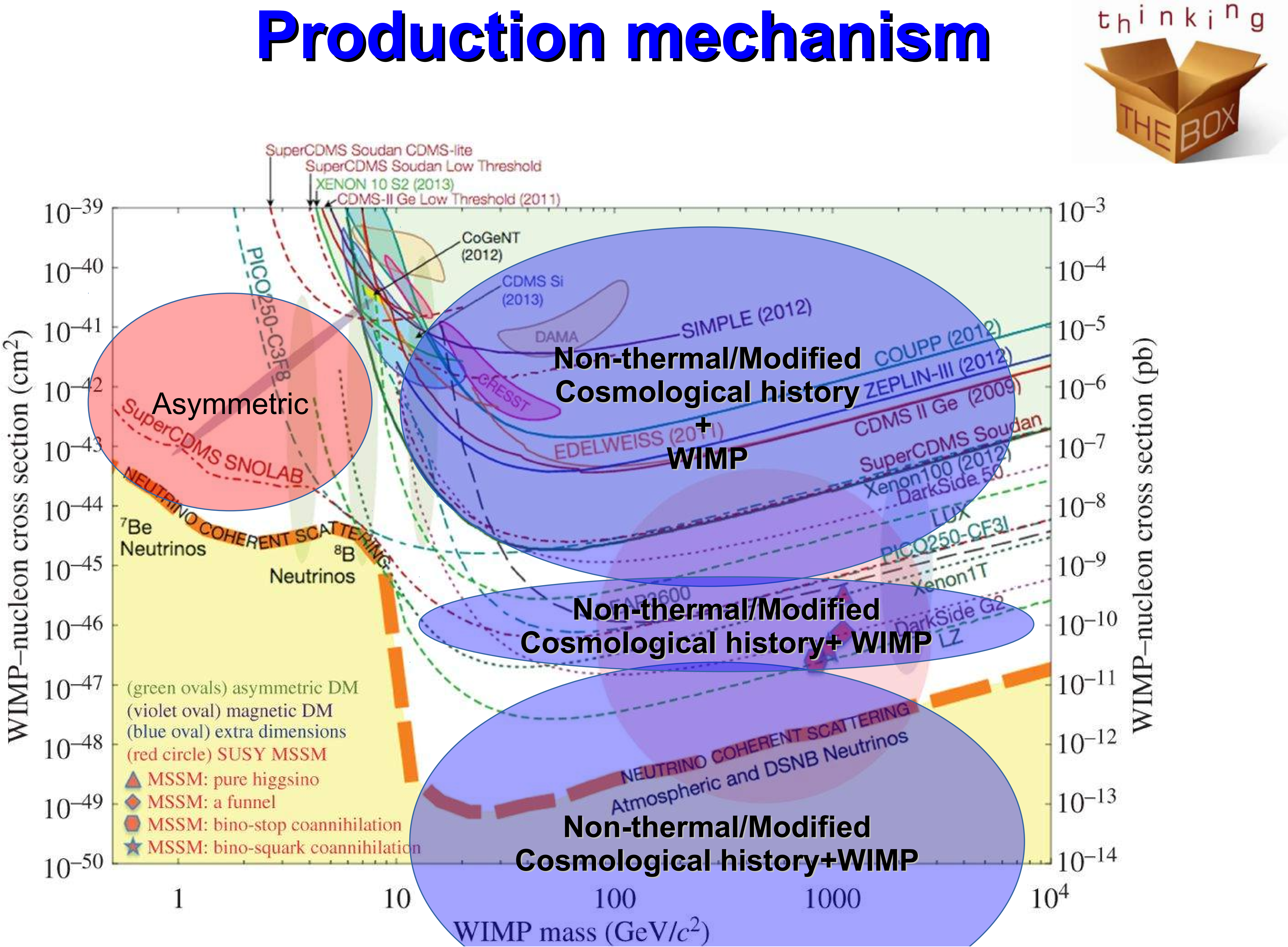
Production mechanism



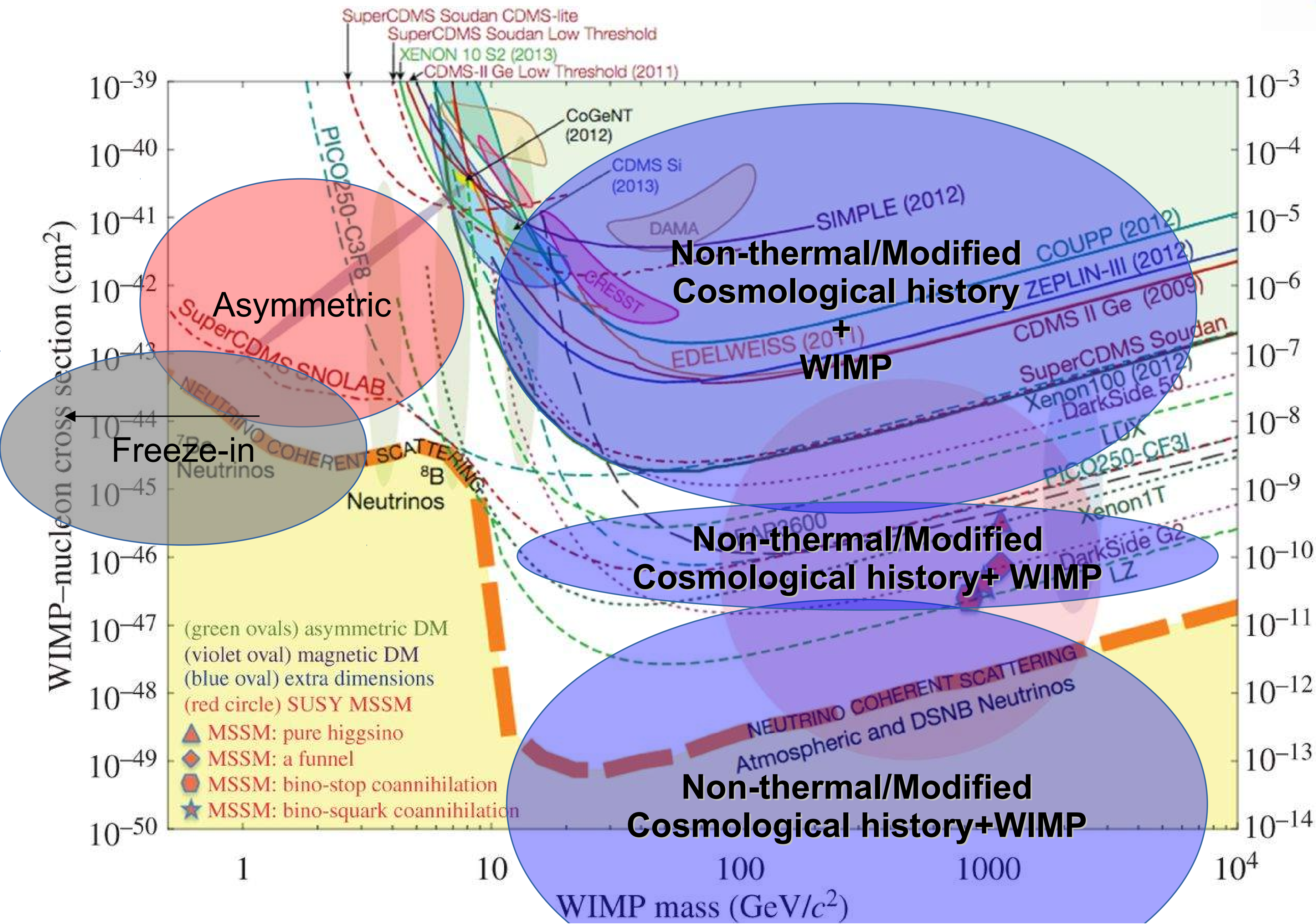
Production mechanism



Production mechanism



Production mechanism



Production mechanism

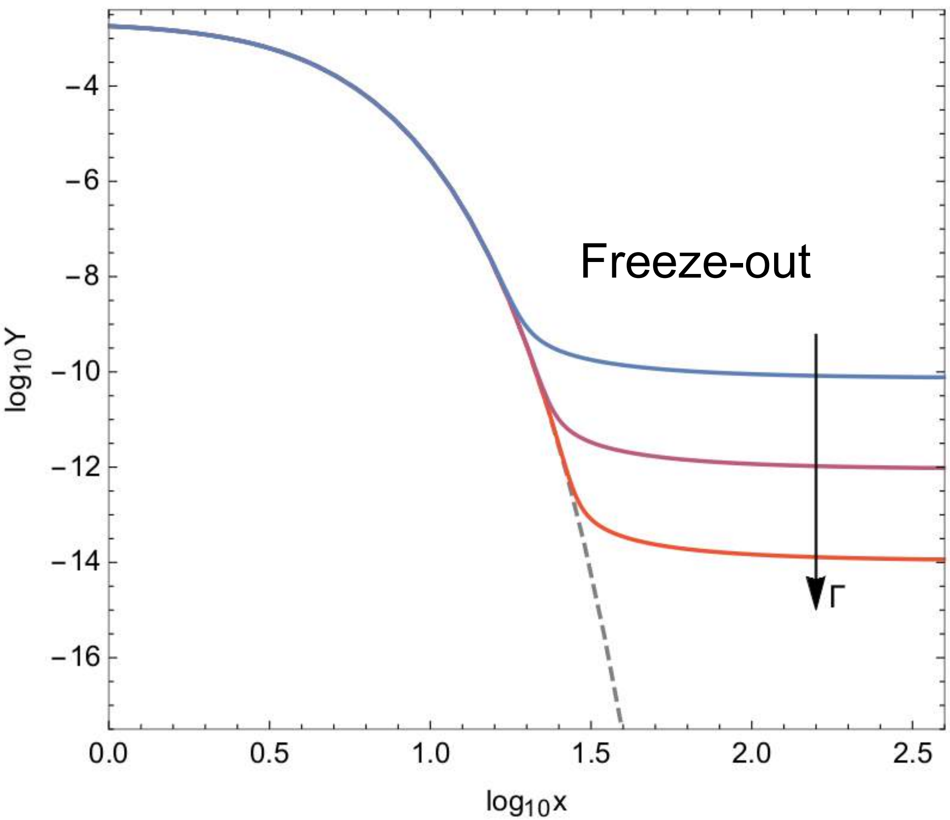
Thermal freeze-out

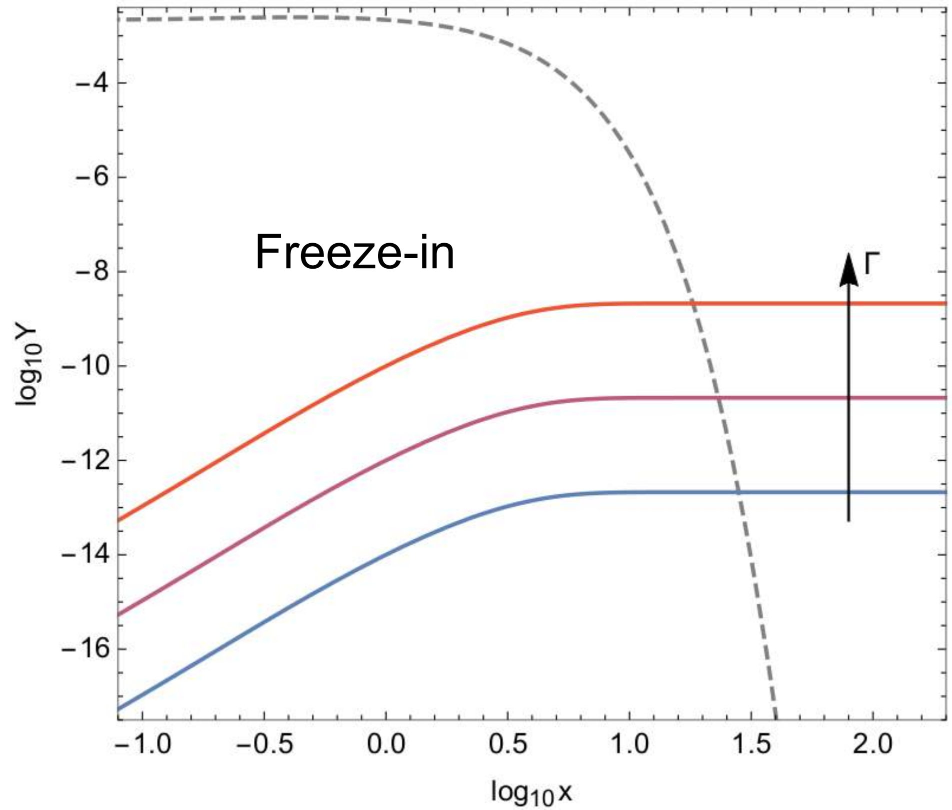
- *Annihilation 2 ↔ 2 Processes*
- *Resonances*
- *Threshold*
- *Co-annihilation*
- *Semi-annihilation*

Production mechanism

Non-thermal freeze-in

The coupling between the visible sector and DM particles is very small





Modified Cosmological History

Consider a scalar field Lagrangian

$$\rho_\phi = \frac{1}{2}\left(\frac{d\phi}{dt}\right)^2 + V(\phi) \qquad P_\phi = \frac{1}{2}\left(\frac{d\phi}{dt}\right)^2 - V(\phi)$$

$$V(\phi) = M_p^4 \exp^{-\lambda_\phi/M_p}$$

There's no WIMP miracle here!

Change in the expansion rate

$$H \sim \frac{T^2}{M_p}\frac{T}{T_{dec}}$$

$$\frac{\Omega_\chi^\phi}{\Omega_\chi} \sim \frac{T_{f.o}}{T_{dec}} \sim \frac{m_\chi}{20}\frac{1}{T_{BBN}} \sim 10^4 \frac{m_\chi}{100GeV}$$

With a modified expansion history the connection to weak scale might be lost!

Modified Cosmological History

Pandora's box

With a modified expansion history the connection to weak scale might be lost!