DARK MODELS:
Production mechanisms
Indirect searches

Jose A. R. Cembranos

Contents

- **PRODUCTION MECHANISMS**
- **INDIRECT DETECTION**

WIMPs

Weakly Interacting Massive Particles

- Thermal production by the freeze-out mechanism.

- Cold Dark Matter

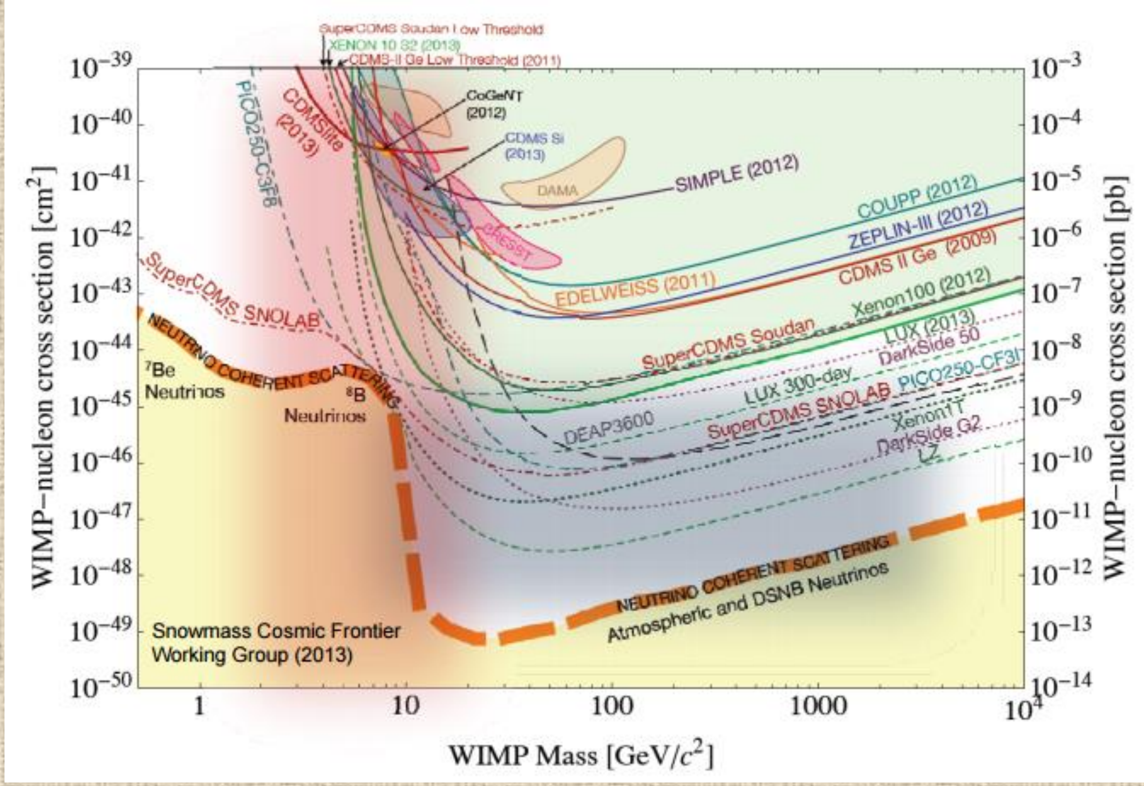
WIMP experimental constraints

Numerous experimental searches have not found evidence of WIMPs.

Direct searches

There are important constraints for light WIMPs:

$$m_{WIMP} \geq 100 \quad GeV$$



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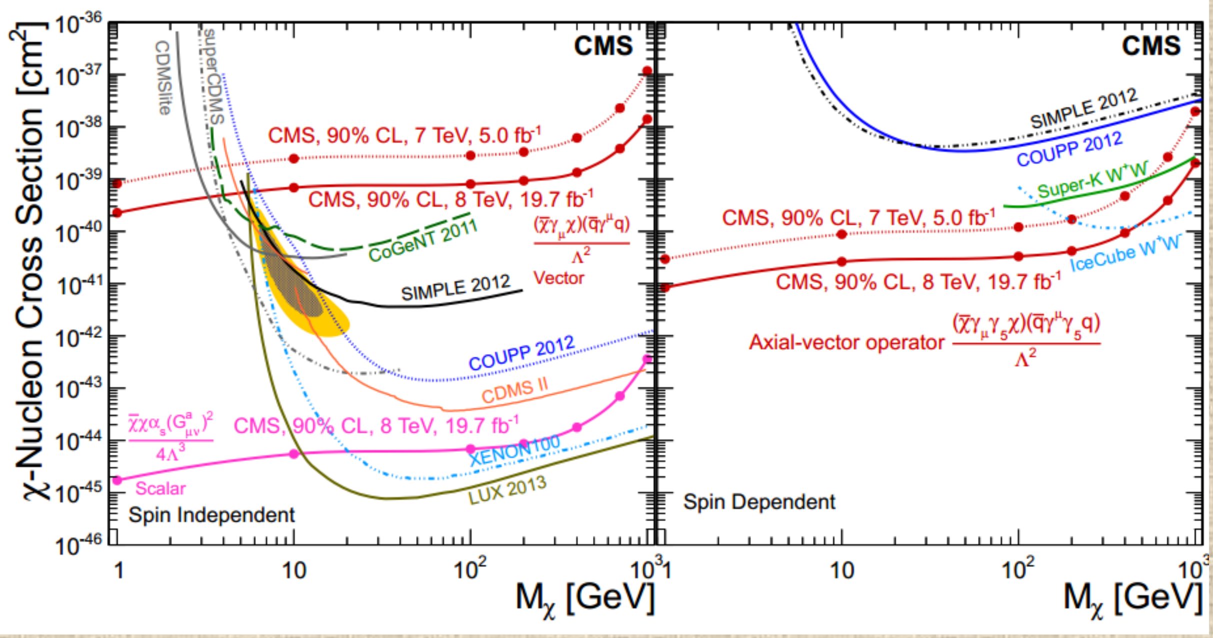

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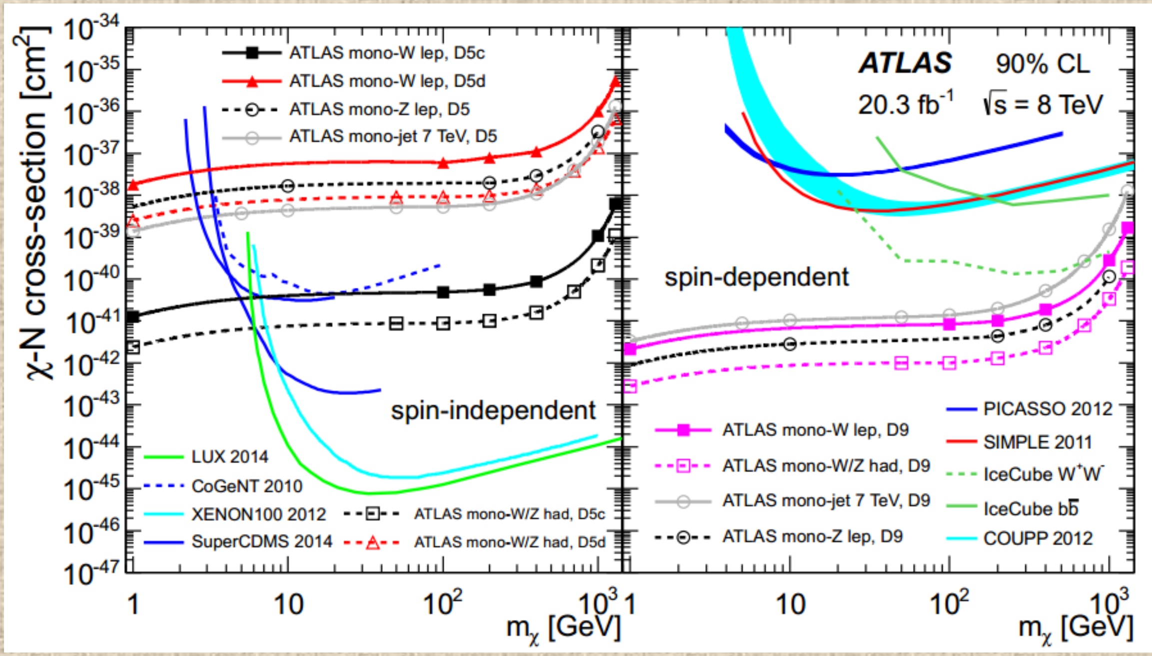

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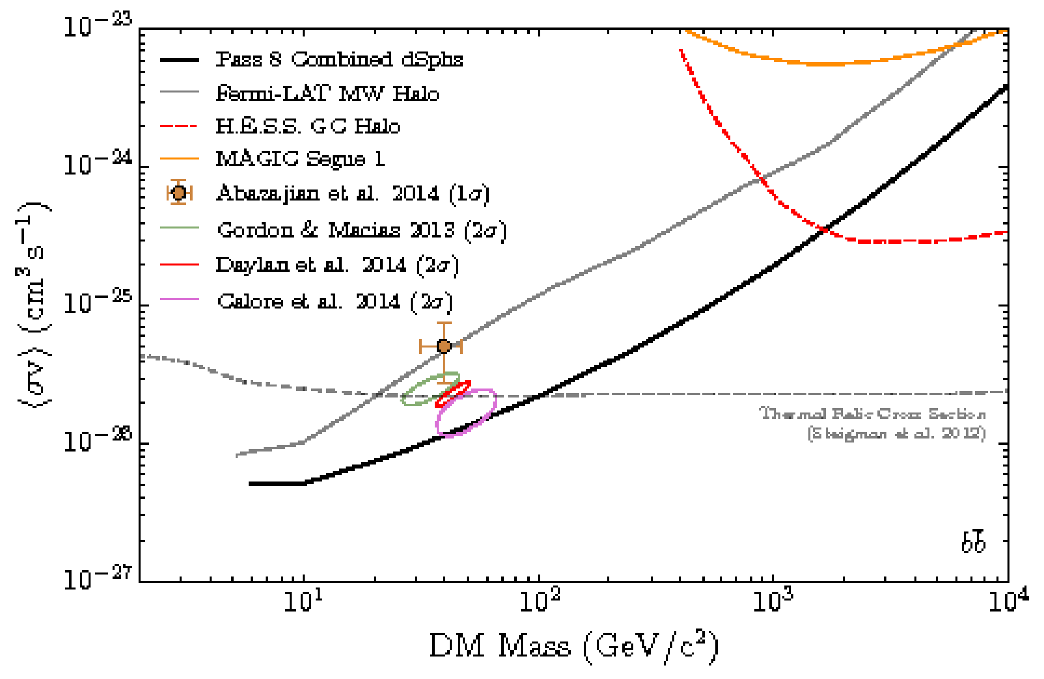

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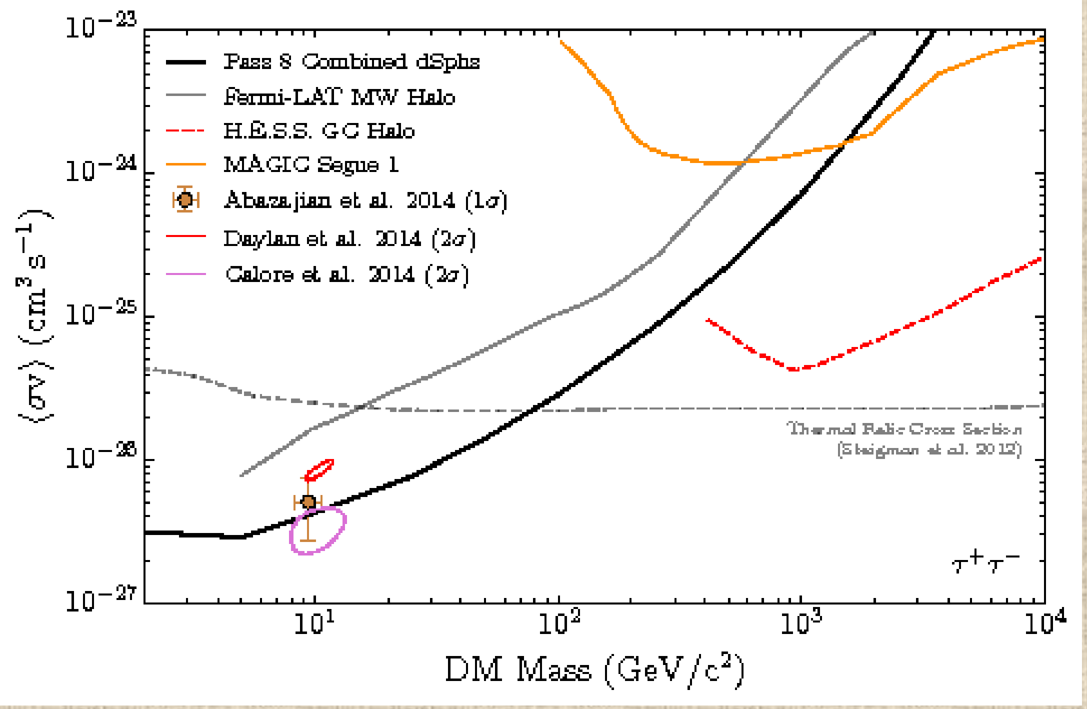


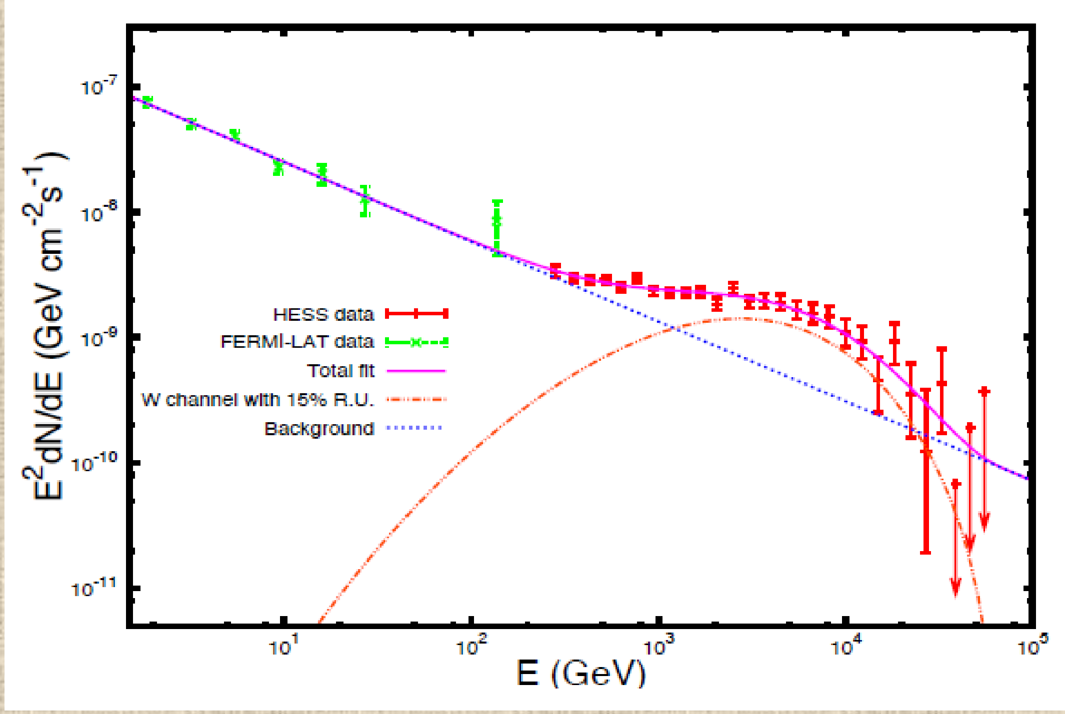
Prospects for heavy WIMPs

Unitarity arguments limit the WIMP mass to:

$$m_{WIMP} \leq 100 \quad TeV$$

Gamma rays

The search of heavy WIMPs is effectively restricted to indirect searches



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Positrons

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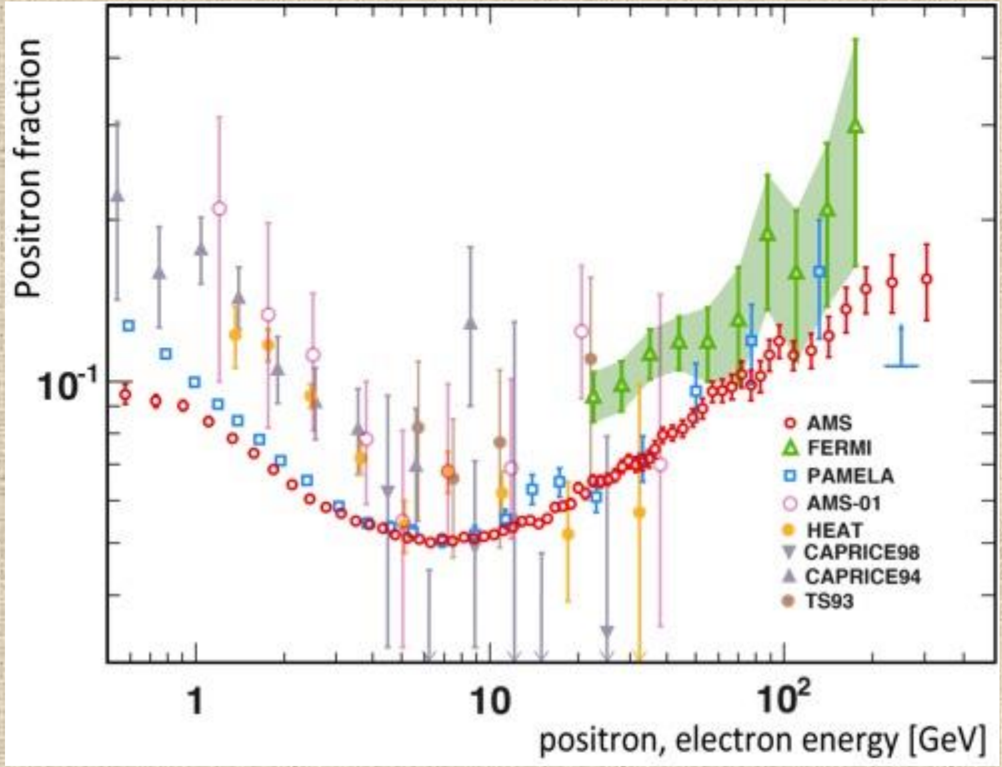

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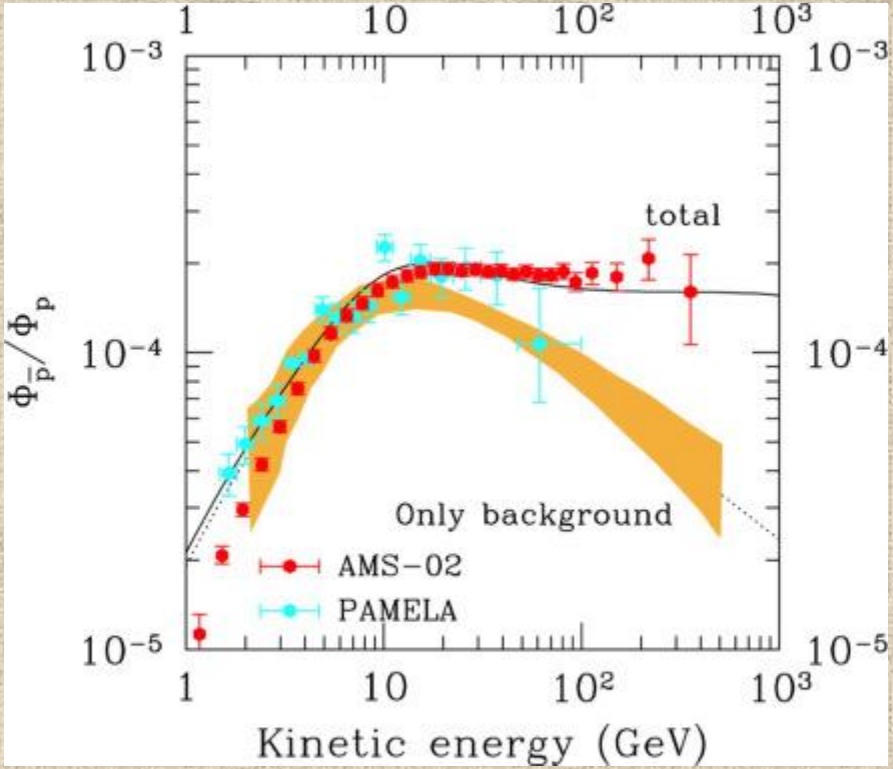

Prospects for heavy WIMPs

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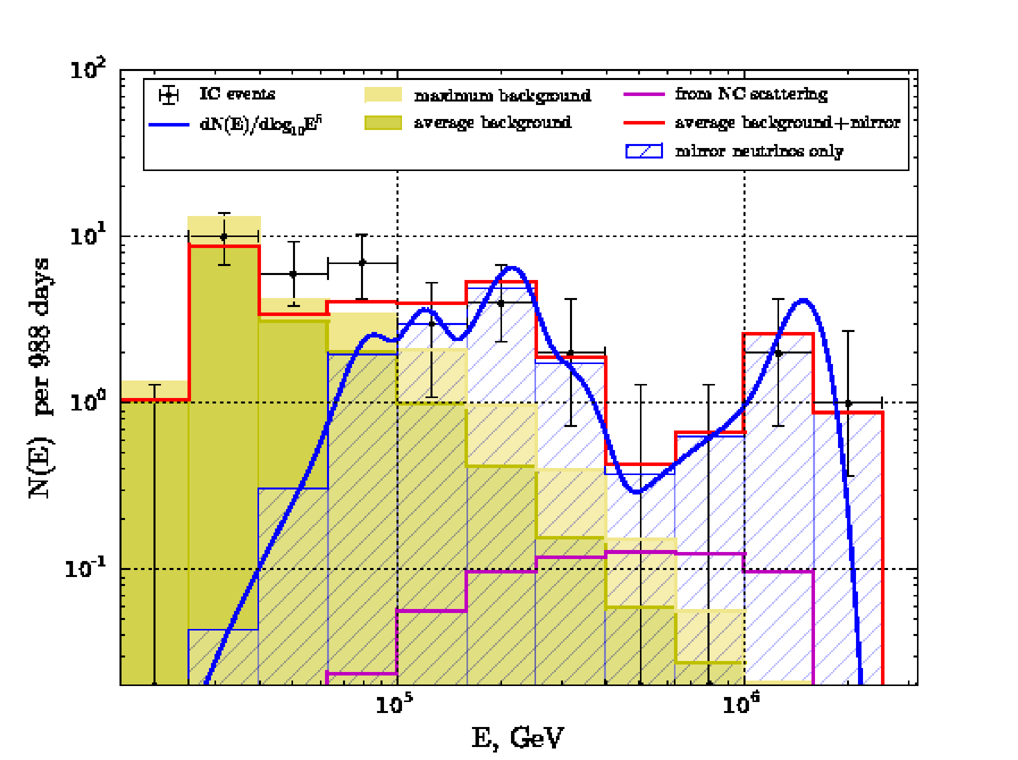
Neutrinos

The search of heavy WIMPs is effectively restricted to indirect searches



WIMP alternatives

Weakly Interacting Massive Particles

- **Thermal production by the freeze-out mechanism**

- **Cold Dark Matter**

WIMP alternatives

Weakly Interacting Massive Particles

- **Thermal production by the freeze-out mechanism**

Alternatives:

- **Freeze-in mechanism**
- **Decays of other particles**
- **Gravitational production**
- **Misalignment mechanism**
- **Spontaneous symmetry breaking**
- **Asymmetric DM**
- **…**

WIMP Relic Density

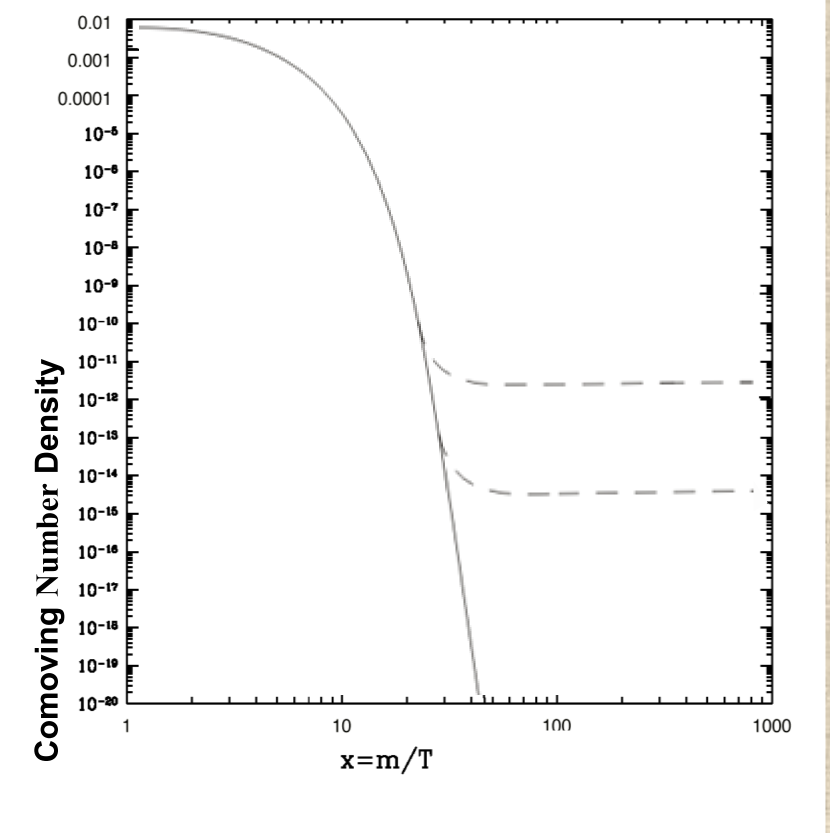
The evolution of the number density follow the Boltzmann equation:

$$dn_{WIMP}/dt = -3Hn_{WIMP} - <\sigma_A v>[(n_{WIMP})^2 - (n_{WIMP}^{eq})^2]$$

Thermal equilibrium density:

$$n_{DM}^{eq} = g/(2\pi)^3 \int f(p)\, d^3p$$

When $\Gamma = <\sigma_A v>\, n_{DM} < H$, the DM is frozen out.



WIMP Relic Density

The evolution of the number density follow the Boltzmann equation:

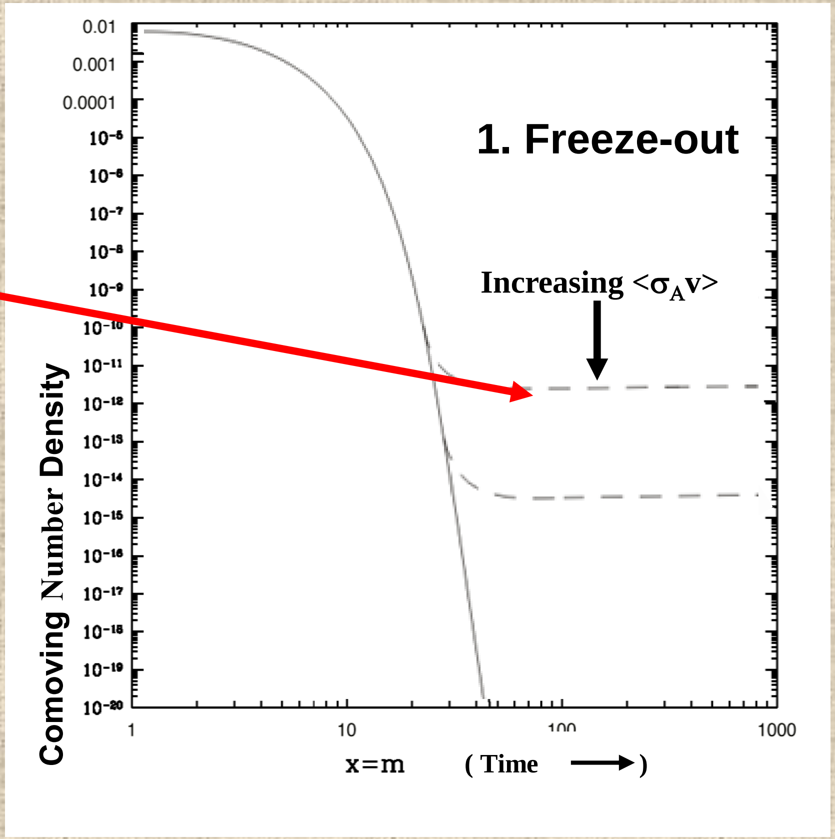
$$dn_{WIMP}/dt = -3Hn_{WIMP} - \langle \sigma_A v \rangle [(n_{WIMP})^2 - (n_{WIMP}^{eq})^2]$$

WIMP relic density:

$$\Omega_{WIMP}\, h^2 \propto 1/\langle \sigma_A v_{WIMP} \rangle$$

$$T_{\text{Freeze out}} \sim m_{WIMP} / 20$$

$$\langle \sigma_A v \rangle \approx 3 \cdot 10^{-26} \quad cm^3 s^{-1}$$



Freeze-in Relic Density

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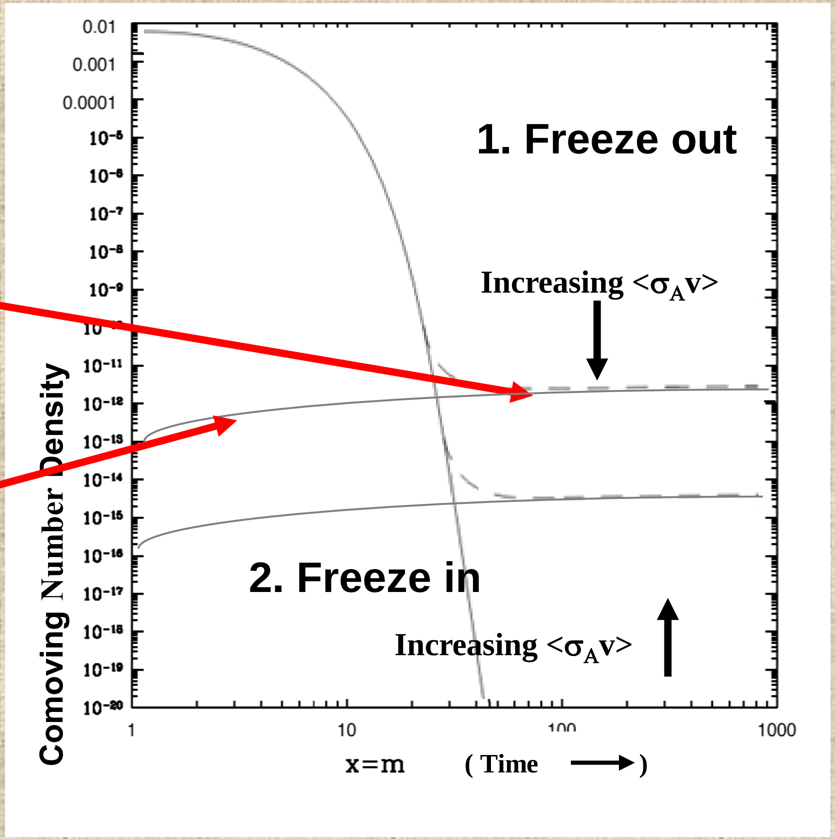
WIMP relic density:

$$\Omega_{WIMP}\, h^2 \propto m_{WIMP} / \langle \sigma_A v_{WIMP} \rangle$$

$$T_{Freeze\ out} \sim m_{WIMP} / 20$$

Freeze-in relic density:

$$\Omega_{FI}\, h^2 \propto \langle \sigma_A v_{DMI} \rangle$$



Freeze-in Relic Density

By assuming the standard inflation scenario:

- The energy density is dominated by the inflaton:

$$\left(\frac{H}{H_R}\right)^2 = \left(\frac{T}{T_R}\right)^8 = \left(\frac{a}{a_R}\right)^{-3}$$

- The abundance can be computed from the Boltzmann equation:

$$\Omega_0 h^2 \simeq \frac{s_0 g^2 x_R^{-7}}{36\pi^6 H_0^2 M_{\rm pl}} \left(\frac{90}{g_*}\right)^{\frac{3}{2}} \mathcal{F}(x_{\rm max})\,,$$

$$\mathcal{F}(y) \simeq \frac{\Gamma(9-j,2y)}{2^{9-j}} c_j \simeq \begin{cases} \frac{(8-j)!}{2^{9-j}} c_j\,, & y \ll 3\,; \\ \frac{y^{8-j}}{2e^{2y}} c_j\,, & y \gg 3\,. \end{cases}$$

Decays of other particles

The evolution of the number density follow the Boltzmann equation:

$$dn_{WIMP}/dt = -3Hn_{WIMP} - <\sigma_A v>[(n_{WIMP})^2 - (n_{WIMP}^{eq})^2]$$

WIMP relic density:

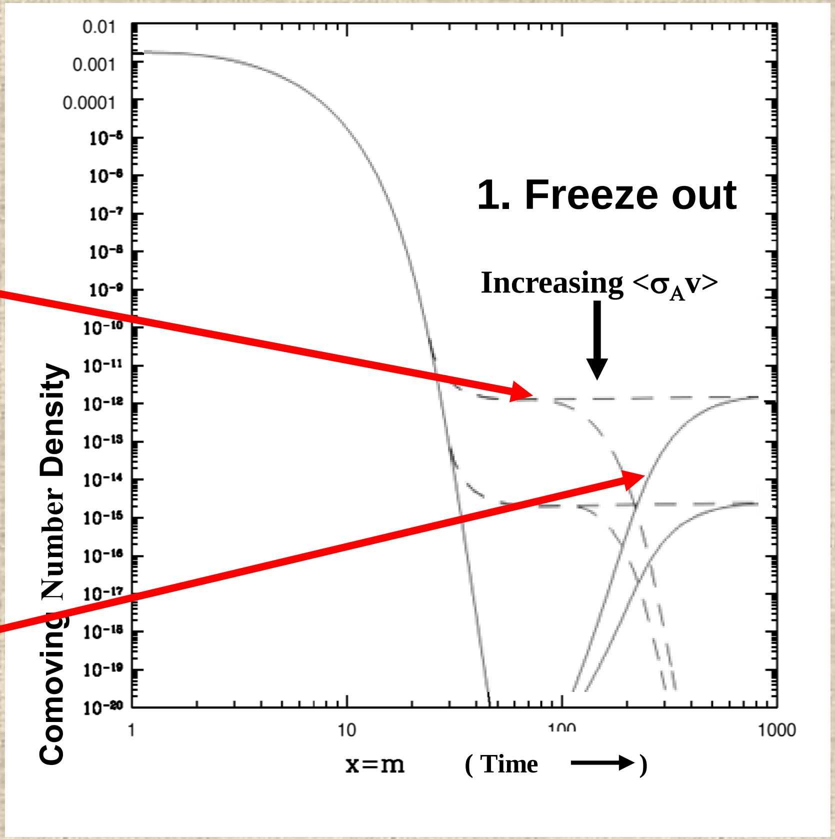
$$\Omega_{WIMP} h^2 \propto 1/\langle\sigma_A v_{WIMP}\rangle$$

$$T_{Freeze\ out} \sim m_{WIMP} / 20$$

SWIMP relic density:

$$\Omega_{SWIMP} h^2 = \Omega_{WIMP} h^2\, m_{SWIMP} / m_{WIMP}$$

$$\propto 1/\langle\sigma_A v_{WIMP}\rangle\, (m_{SWIMP} / m_{WIMP})$$



Gravitational decays

Planck scale suppressed decay:

$$\tau \simeq \frac{3\pi}{b}\frac{M_P^2}{(\Delta m)^3} \simeq \frac{3.57\times 10^{22}\ \mathrm{s}}{b}\left[\frac{\mathrm{MeV}}{\Delta m}\right]^3$$

with:

$b = 10\cos^2\theta_W/3 \simeq 2.54$	$B^1 \to G^1\gamma$
$b = 2\cos^2\theta_W \simeq 1.52$	$G^1 \to B^1\gamma$
$b = 2\lvert\boldsymbol{N}_{11}\rvert^2$	$\chi \to \tilde{G}\gamma$
$b = \lvert\boldsymbol{N}_{11}\rvert^2$	$\tilde{G} \to \chi\gamma$

$$\chi = \boldsymbol{N}_{11}(-i\tilde{\gamma}) + \boldsymbol{N}_{12}(-i\tilde{Z}) + \boldsymbol{N}_{13}\tilde{H}_u + \boldsymbol{N}_{14}\tilde{H}_d$$

In mUED, life-times longer than the age of the Universe are associated to : $795\ \mathrm{GeV} < R^{-1} < 820\ \mathrm{GeV}$

Gravitational production

Particles are generically produced by a temporal depending geometry

- The number density is related to Bogoliubov coefficients β_k

$$n = \frac{1}{2\pi^2 a^3} \int dk\, k^2 \left|\beta_k\right|^2$$

- Scalar mode wave functions in large k region:

$$\ddot{\phi}_k + 3H\dot{\phi}_k + \omega_k^2(a)\phi_k = 0$$

- WKB approximation:

$$\phi_k = \frac{1}{\sqrt{2\omega_k a^3}} \left(\alpha_{k,0} e^{-i\int \omega_k\, dt} + \beta_{k,0} e^{+i\int \omega_k\, dt} \right)$$

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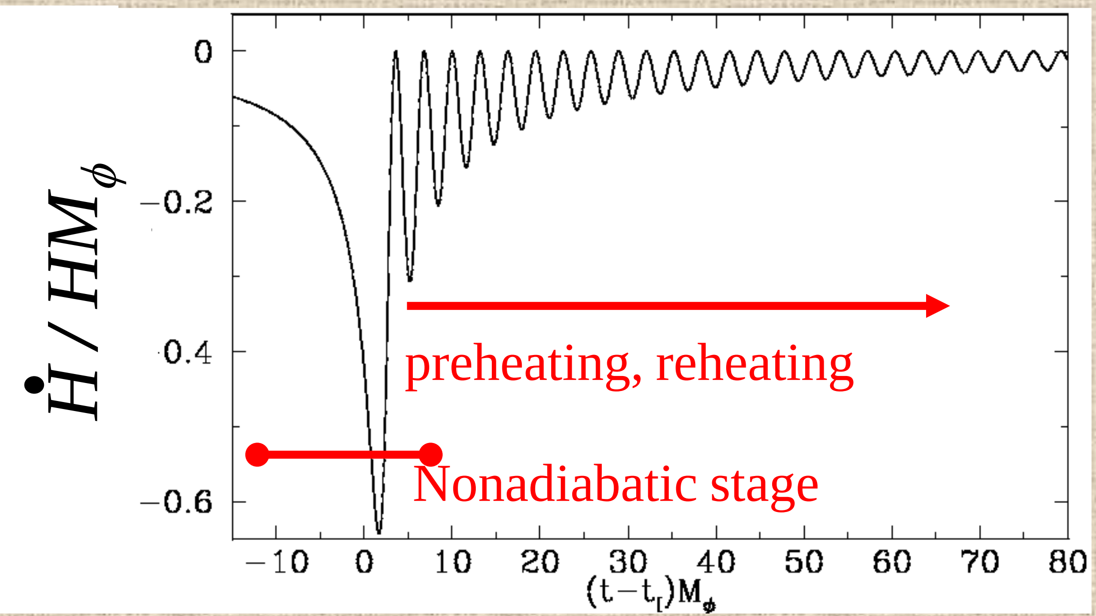
Chaotic inflation, conformal coupling



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$$n = \frac{1}{2\pi^2 a^3}\int dk\, k^2 \left|\beta_k\right|^2$$

- Scaling of the DM density related to radiation:

$$\frac{\rho(t_0)}{\rho_R(t_0)} = \frac{\rho(t_{\mathrm{RH}})}{\rho_R(t_{\mathrm{RH}})}\left(\frac{T_{\mathrm{RH}}}{T_0}\right)$$

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$$\frac{\rho(t_{\rm RH})}{\rho_R(t_{\rm RH})} \approx \frac{8\pi}{3} \frac{\rho(t_e)}{M_{Pl}^2 H^2(t_e)}$$

Gravitational production

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- The number density is related to Bogoliubov coefficients β_k

$$n = \frac{1}{2\pi^2 a^3}\int dk\, k^2 \left|\beta_k\right|^2$$

- Abundance: $\Omega \equiv \rho(t_0)/\rho_c(t_0)$ $\leftarrow$ $\rho_c(t_0) = 3H_0^2 M_{Pl}^2/8\pi$

$$\Omega h^2 \approx \Omega_R h^2 \frac{8\pi}{3}\left(\frac{T_{\rm RH}}{T_0}\right)\frac{n(t_e)m}{M_{Pl}^2 H^2(t_e)}$$

Gravitational production

Particles are generically produced by a temporal depending geometry

- The number density is related to Bogoliubov coefficients β_k

$$n = \frac{1}{2\pi^2 a^3}\int dk\, k^2 |\beta_k|^2$$

$$|\beta_k|^2 \approx \frac{\pi^2}{9}\exp\left(-4\frac{(k/a_{\rm eff}(r))^2 + m^2}{m\sqrt{H_{\rm eff}^2(r) + R_{\rm eff}(r)/6}}\right)$$

- Abundance:

$$\Omega h^2 \approx \Omega_R h^2 \frac{8\pi}{3}\left(\frac{T_{\rm RH}}{T_0}\right)\frac{n(t_e)m}{M_{Pl}^2 H^2(t_e)}$$

Gravitational production

Particles are generically produced by a temporal depending geometry

- The number density is related to Bogoliubov coefficients β_k

$$n = \frac{1}{2\pi^2 a^3}\int dk\, k^2 \left|\beta_k\right|^2$$

- Abundance:

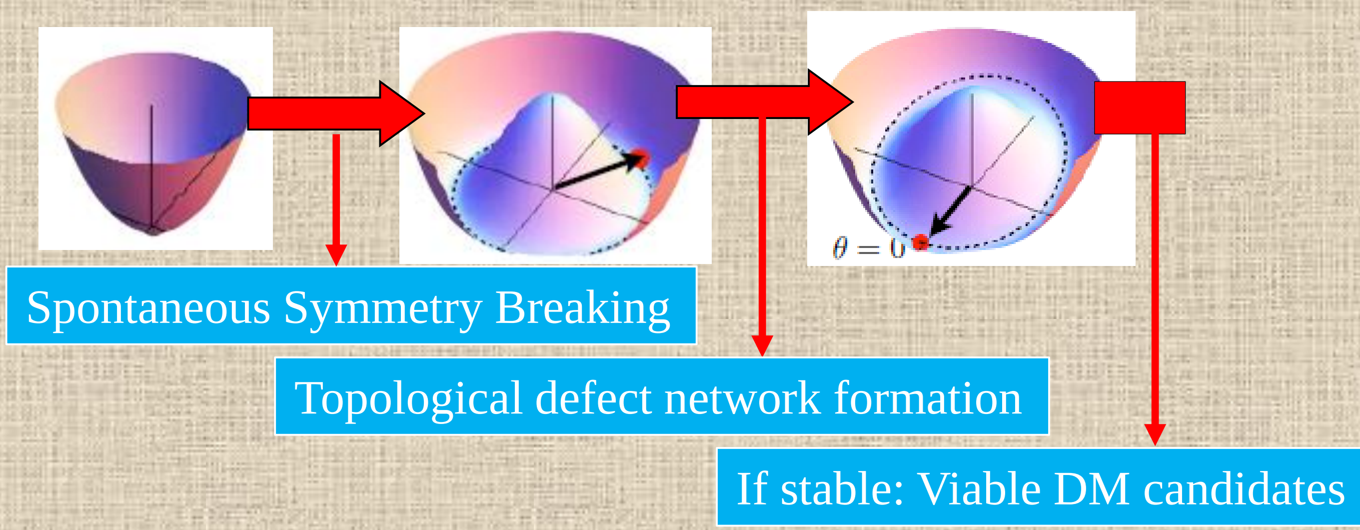
$$\Omega_X h^2 \approx \left(\frac{M_X}{10^{11}\,\mathrm{GeV}}\right)^2 \frac{T_{RH}}{10^9\,\mathrm{GeV}} \left(\frac{M_X}{H_e}\right)^{1/2} \exp\left(-2M_X/H_e\right)$$

→ Supermassive DM: Mx > 10^9 GeV

Chung, Crotty, Kolb, Riotto, arXiv:hep-ph/0104100

Relic Density from symmetry breaking

- **Non-topological and topological solitons are generically formed:**
  - Strings: Non trivial first homotopy group
  - Monopoles: Non trivial second homotopy group
  - Skyrmions: Non trivial third homotopy group



Particle defects: Monopoles

- **Kibble-Zurek mechanism:**
  - Correlation lenght
  - Relaxation time

$$\begin{cases} \xi = \xi_0 |\epsilon|^{-\nu} \\ \tau = \tau_0 |\epsilon|^{-\mu} \end{cases} \qquad \epsilon \equiv \frac{T_c - T}{T_c}.$$

$$\Omega_M h^2 \sim 2 \cdot 10^{12} \left(\frac{1.97 \cdot 10^{-12}}{x_c} \right)^{\frac{3\nu}{\mu+1}} \left(\frac{m_M}{\mathrm{PeV}} \right)^{\frac{3\nu}{\mu+1}+1} \qquad x_c = m_M / T_c$$

  - Landau-Ginzburg: $$\Omega_M h^2 \sim \frac{2.30}{x_c} \left(\frac{m_M}{\mathrm{PeV}} \right)^2$$
  - Fiducial model: $$\Omega_M h^2 \sim \frac{1.9 \cdot 10^{-2}}{x_c^{6/5}} \left(\frac{m_M}{\mathrm{PeV}} \right)^{\frac{11}{5}}$$

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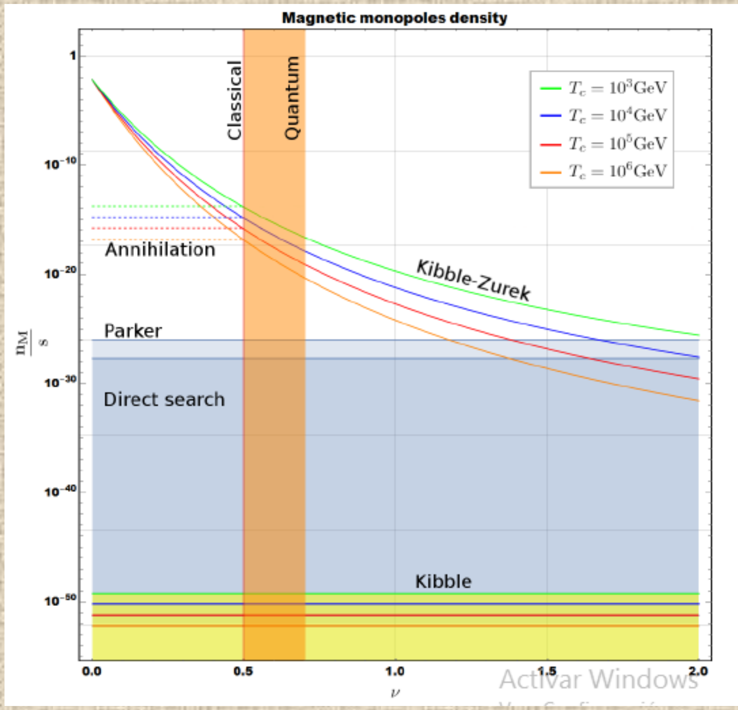

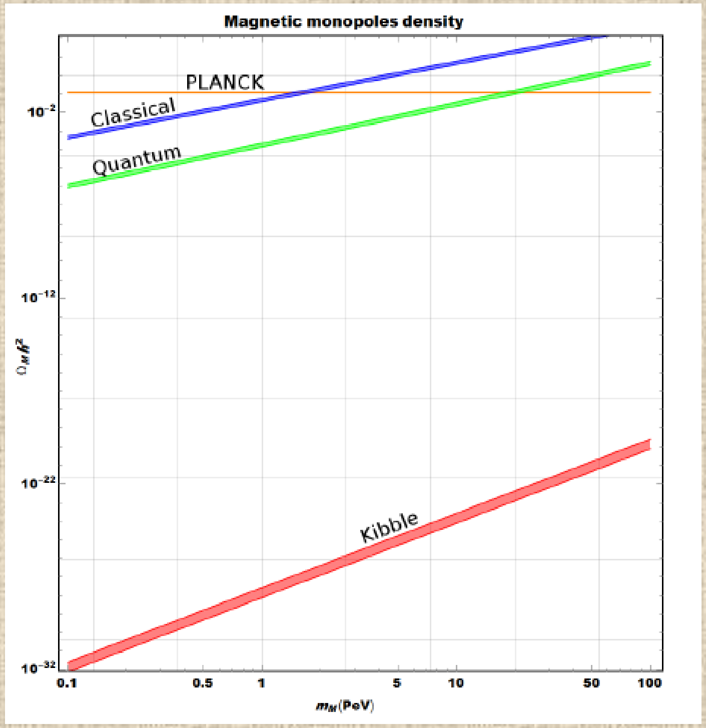

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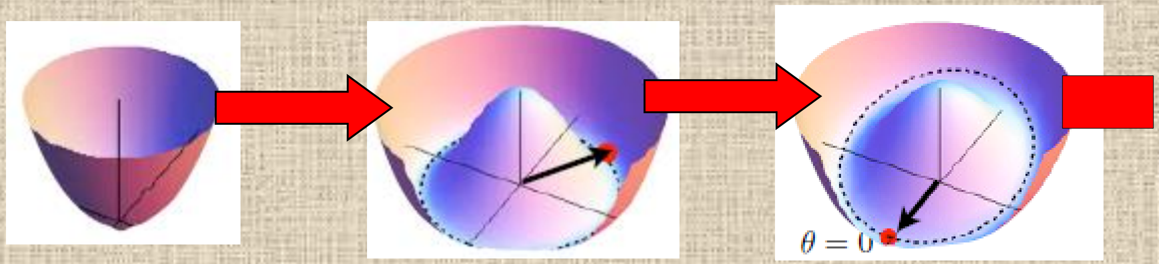


- **Monopoles:**

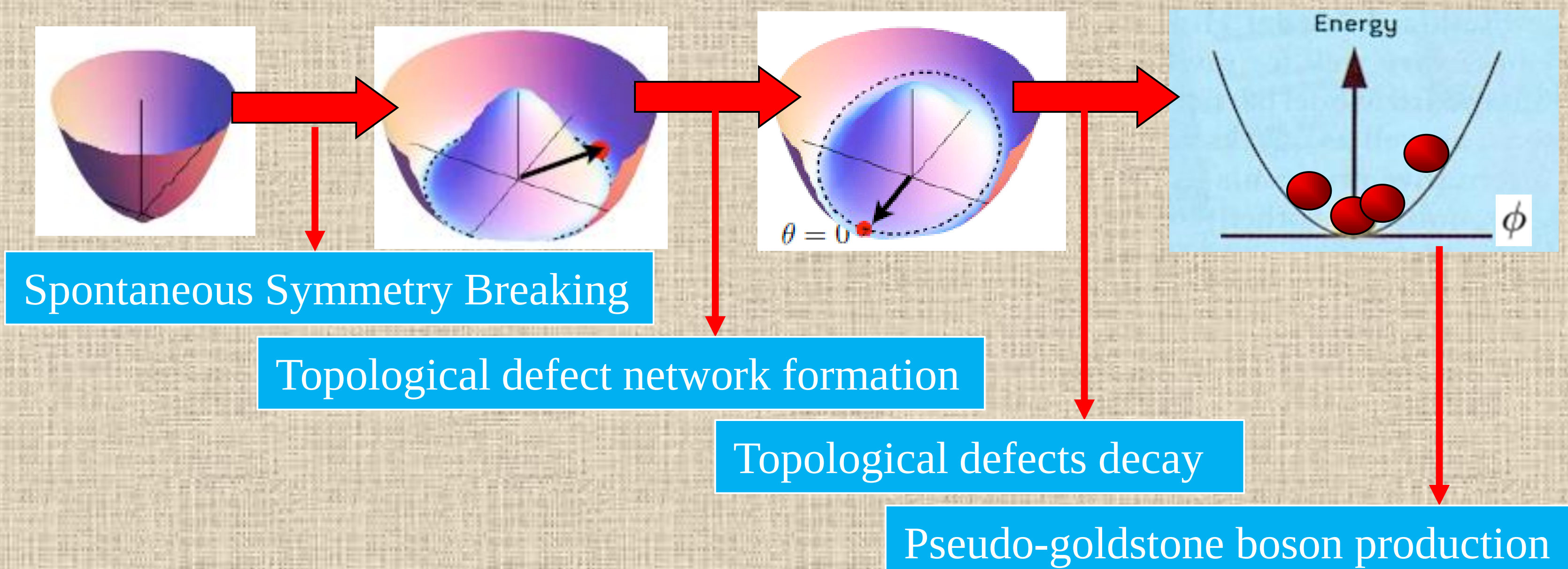
$$\Omega_{PD} h^2 \approx 1.5 \times 10^9 \left(\frac{x_c T_c}{1\text{TeV}}\right) \left(\frac{30 T_c}{M_{pl}}\right)^{\frac{3\nu}{1+\nu}}$$

$$T_C \approx 10^6 \quad GeV$$

Murayama and Shu, arXiv:0905.1720v1

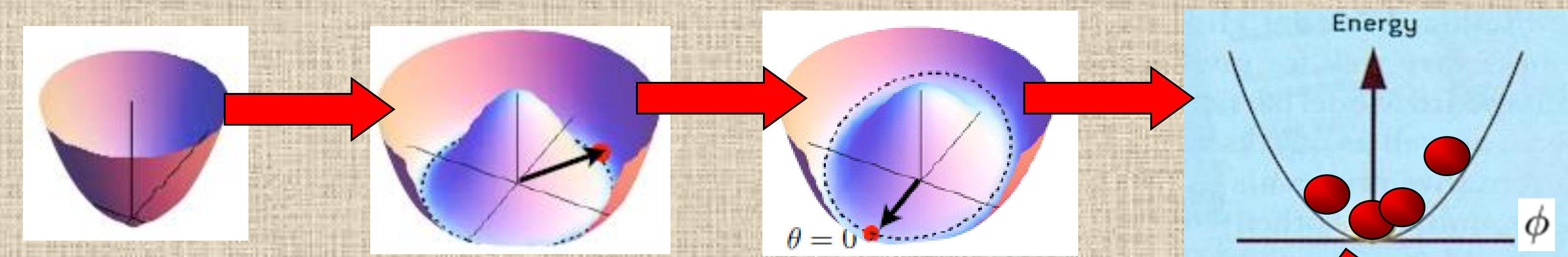
Relic Density from symmetry breaking

- **Non-topological and topological solitons are generically formed:**
  - Strings: Non trivial first homotopy group
  - Monopoles: Non trivial second homotopy group
  - Textures or skyrmions: Non trivial third homotopy group



Relic Density from symmetry breaking

- **Topological defects are generically formed depending on the symmetry pattern:**
  - Strings: Non trivial first homotopy group
  - Monopoles: Non trivial second homotopy group
  - Textures or skyrmions: Non trivial third homotopy group



Cold DM Abundance:

$$\Omega_\phi h^2 \simeq 0.15 \left[\frac{m_s}{1\,\mathrm{eV}}\right]^{\frac{1}{2}} \left[\frac{\phi_1}{10^{12}\,\mathrm{GeV}}\right]^2 \left[\frac{1}{(\gamma_{s1}\, g_{s1})^4}\right]^{\frac{1}{4}} S$$

Relic Density from Misalignments

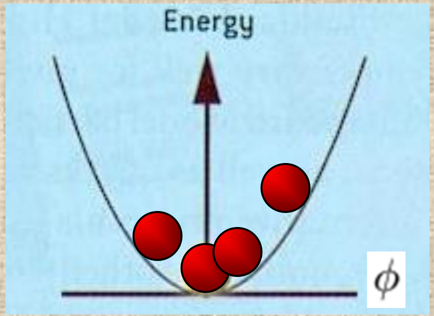
- Bosonic particles may have important abundance due to initial displacements.

- Misalignment mechanism
  - For $H(T) >> m_s$ → $\phi = \phi_1$
  - For $3H(T) \leq m_s$ → ϕ oscillates around the minimum of its potential. These oscillations correspond to a zero-momentum condensate.

$$T_1 \simeq 15.5\,\mathrm{TeV} \left[\frac{m_s}{1\,\mathrm{eV}}\right]^{\frac{1}{2}} \left[\frac{100}{g_{e\,1}}\right]^{\frac{1}{4}}$$

Cold DM Abundance:

$$\Omega_\phi h^2 \simeq 0.86 \left[\frac{m_s}{1\,\mathrm{eV}}\right]^{\frac{1}{2}} \left[\frac{\phi_1}{10^{12}\,\mathrm{GeV}}\right]^2 \left[\frac{100\, g_{e\,1}^3}{(\gamma_{s1}\, g_{s1})^4}\right]^{\frac{1}{4}}$$



Cembranos, PRL102:141301 (2009)

Axions

- **In QCD, the CP violating phase is physical:**

$$\theta = \theta_{\mathrm{QCD}} + \delta$$

Axions

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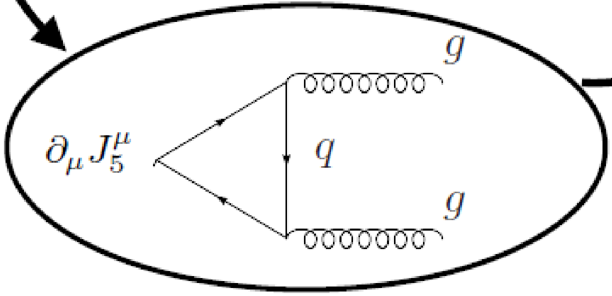
$$\theta = \theta_{\mathrm{QCD}} + \delta$$

$$\mathcal{L}_{\mathrm{SM}} \in -\bar{q}_L \begin{pmatrix} m_u e^{i\delta} & 0 & \dots \\ 0 & m_d e^{i\delta} & \dots \\ 0 & 0 & \dots \end{pmatrix} \begin{pmatrix} u \\ d \\ \dots \end{pmatrix}_R - \frac{\alpha_s}{8\pi} G\widetilde{G}\, \theta_{\mathrm{QCD}}$$



Axions

- **In QCD, the CP violating phase is physical:**

$$\theta = \theta_{\rm QCD} + \delta$$

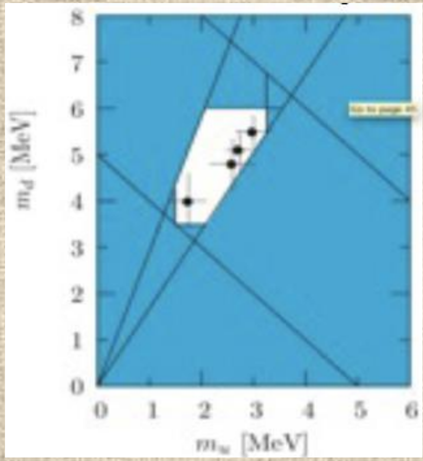
  - Electric Dipole Moment of the Neutron:

$$d_n \sim \theta \times \mathcal{O}(10^{-2})[e\,\mathrm{fm}]$$
$$d_n^{\rm exp} < 3 \times 10^{-13}[e\,\mathrm{fm}]$$

  - Strong CP problem: $\theta < 10^{-10}$

Strong-CP Problem

- **Solutions:**
  - The presence of a massless quark:



  - Introducing a new axial U(1) symmetry:
    - Spontaneusly broken → Nambu-Goldstone boson
    - The theta parameter becomes dynamical: $\theta \to a/f_a$

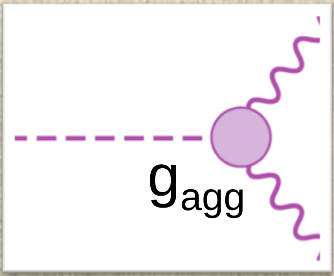
Axion

    - The new U(1) is explicitly broken by QCD radiative effects:

→ pseudo-Nambu-Goldstone boson

Strong-CP Problem

The QCD-axion is predicted by the Pecci-Quinn solution to the strong-CP problem. Many other theories beyond the SM predicts light pseudo-scalars very weakly coupled to SM particles.



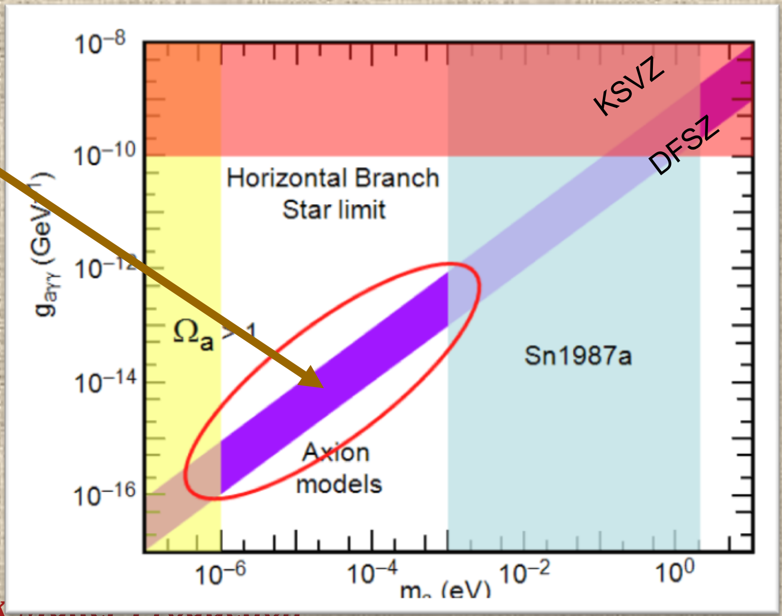
The main phenomenology and signatures comes from the two photon coupling (Primakov effect):

1.- SuperWIMP scenario:

Axions

SuperWIMP signatures:

a. Indirect detection
a.1. Axion solar flux
b. Star and SN cooling
c. Laser experiments



G. Carosi et al [ADMX] (2010)

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Asymmetric DM

The abundance of DM may be related to a different number of DM particles versus DM antiparticles.

- **A Dark global symmetry can be postulated associated with a dark baryonic number:**
  - **B_V is broken, whereas B_D is not.**
  - **B_D is broken, whereas B_V is not.**
  - **B_V and B_D are both broken.**
  - **A linear combination of B_V and B_D can be broken: X**
- **Different possibilities for production:**

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K. Petraki and R.R. Volkas, arXiv:1305.4939v3 [hep-ph]

Asymmetric DM

The abundance of DM may be related to a different number of DM particles versus DM antiparticles.

- **A Dark global symmetry can be postulated associated with a dark baryonic number:**
- **Different possibilities for production:**
  - **Asymmetric freeze-out**
  - **Asummetric freeze-in**
  - **Violating X and CP Decaying DM**
  - **Coherent bosonic background violating X and CP (Affleck-Dine mechanism)**
  - **First order phase transition (X is violated through sphalerons)**
  - **Spontaneous genesis (CPT violation)**

K. Petraki and R.R. Volkas, arXiv:1305.4939v3 [hep-ph]

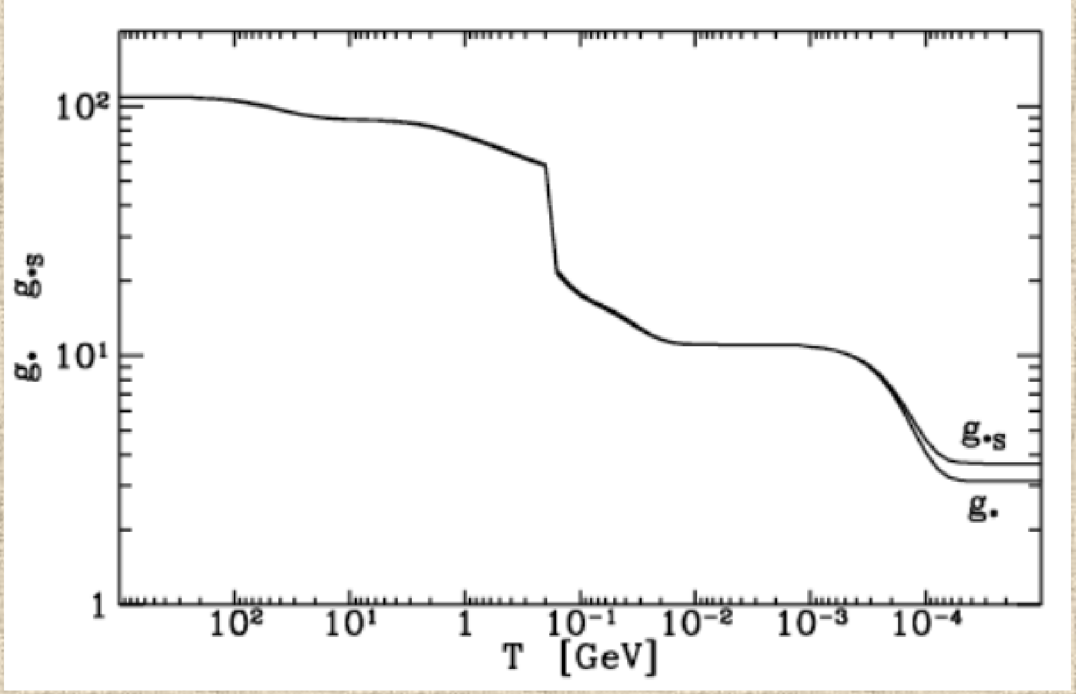
Conclusions

We have discussed about different DM production mechanisms:

- Freeze-out mechanism
- Freeze-in mechanism
- Decays of other particles
- Gravitational production
- Misalignment mechanism
- Spontaneous symmetry breaking
- Asymmetric DM

Fundamentals of Cosmology

Effective number of relativistic degrees of freedom:
From 106.75 to 3.36 (energy) or 3.91 (entropy)



$$\rho_b = \frac{\pi^2}{30} g T^4 \; ,$$

$$\rho_f = \frac{7}{8}\frac{\pi^2}{30} g T^4 \; .$$