Karlsruher Institut für Technologie

Particle Dark Matter Candidates

Lisa Biermann | June 17, 2019

HAUPTSEMINAR: FROM THE SMALLEST TO THE LARGEST SCALES

Outline

Particle Dark Matter Production in the Early Universe

. . . about why we need additional non-baryonic matter to describe our universe and how this dark matter must look like.

Matter Content of the Universe

Description of the evolution of the universe by

Friedmann Lemaître Equation

$$\frac{H^2}{H_0^2} = \Omega_r a^{-4} + \Omega_m a^{-3} + \Omega_k a^{-2} + \Omega_\Lambda$$

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- Ω_i: density parameters (today):
  - Ω_r: radiation/relativistic matter density
  - **Ω_m: non-relativistic matter density**
  - Ω_k: curvature density
  - Ω_Λ: vacuum density

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Critical density ρ_c: mediator between expansion and gravitational collapse of the universe:

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Matter relic density

$$\Omega_m = \Omega_b + \Omega_\chi \quad \text{with} \quad \Omega_\chi > \Omega_b$$

- Ω_m: non-relativistic matter density
- Ω_b: non-relativistic baryonic matter density ($\Omega_f \ll \Omega_b$)
- Ω_χ: dark matter density

Matter Content of the Universe

PLANCK results for matter densities:

- **CMB power spectrum**:
  spherical fourier transform of temperature fluctuation map of CMB

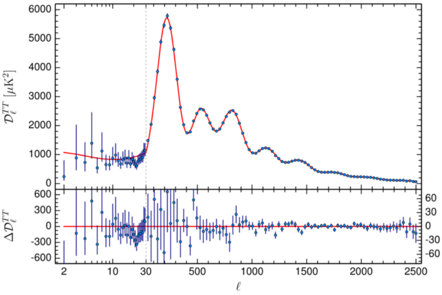

Figure: CMB power spectrum [arXiv:1502.01589]

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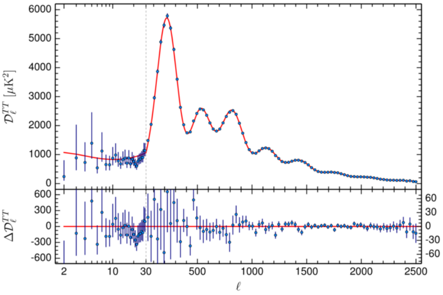

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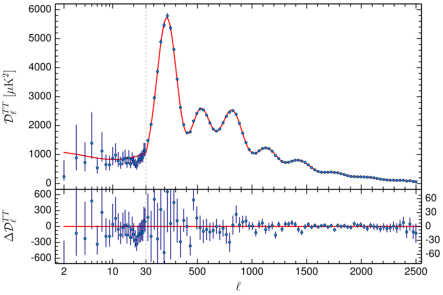
Non-relativistic baryonic matter relic density

$\Omega_b h^2 = 0.022\,25 \pm 0.000\,23$



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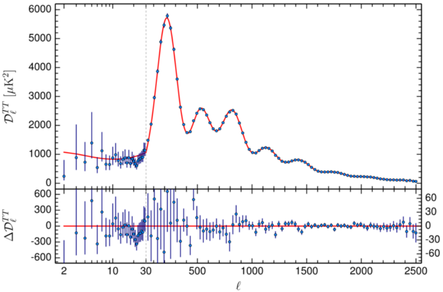

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Non-relativistic baryonic matter relic density

$\Omega_b h^2 = 0.022\,25 \pm 0.000\,23$

- $\Omega_m = 0.308 \pm 0.012$
- $\Omega_\chi = \Omega_m - \Omega_b \rightarrow 25\,\%$ of ρ_c has to be **non-baryonic dark matter**

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Role of Dark Matter in Structure Formation:

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- GR: growth of fluctuations for matter in linear regime ($\delta\rho/\rho \lesssim 1$): $\delta\rho/\rho \sim a$, growth of a to today by factor 10^3
- **problem**: not enough time in baryon-only universe for structures to get to the non-linear regime

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Role of Dark Matter in Structure Formation:
requirement for $\delta\rho/\rho \gg 1$:

- additional particle species decoupled from baryon-photon fluid before CMB decoupling
- creation of gravitational potential wells, $(\delta\rho/\rho)_{\text{DM}} \gg 10^{-4}$ (at CMB decoupling)

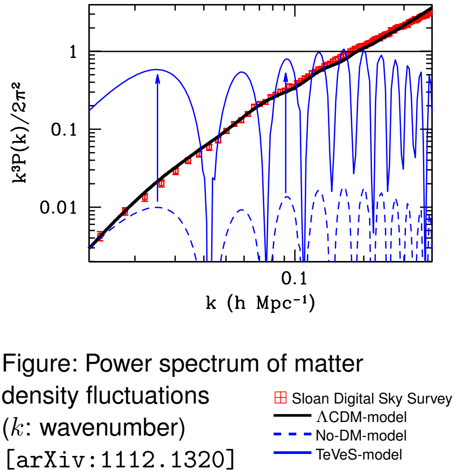

Figure: Power spectrum of matter density fluctuations (k: wavenumber) [arXiv:1112.1320]

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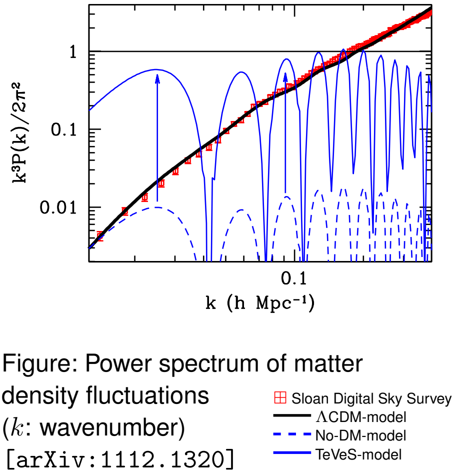
Non-Baryonic Dark Matter stabilizes matter accumulation and enables structure formation

- *"dark"*: sufficient electrical neutrality
- *"cold"*: non-relativistic enough prohibiting free-streaming out of gravitational wells by itself



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3. ***mass***: very broad mass range
   $\rightarrow$ stability of bound systems forbids $m_\chi \gtrsim 10^3\,\mathrm{M}_\odot$
   $\rightarrow$ confinement on galactic scales $\sim$ kpc $\rightarrow \lambda <$ kpc $\rightarrow m_\chi > 10^{-22}\,\mathrm{eV}$
   $\rightarrow$ lower mass bound from *Tremaine-Gunn limit* for fermionic dark matter

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4. ***relic density and distribution***: agreement with observed abundance, explanation of observed density and velocity distribution of galaxies

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principle:

- **at high temperatures:** statistic mechanical thermal equilibrium due to reactions with $\Gamma \gg H(T)$
  $1/\Gamma \sim$ average time between reactions,
  $t_H = 1/H(T) \sim$ Hubble time ($\sim$ measure of age of universe)
- **freeze-out:** $\Gamma(T_{f.o.}) = H(T_{f.o.})$
- **further cooling of universe:** $\Gamma \ll H(T)$, only expansion determines number density (redshift)

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thermal decoupling can describe particle origin in early universe
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hot relics: freeze-out happens in relativistic regime, $T_{f.o.} \gg m$

cold relics: freeze-out in non-relativistic regime, $T_{f.o.} \ll m$

Particle Dark Matter Candidates

. . . how particle dark matter models and particle dark matter candidates do or can look like.

WIMPs

. . . probably the most famous particle dark matter candidate.

The WIMP Miracle

= Weakly Interacting Massive Particle

assumptions:

- thermal creation, freeze-out and expansion of the universe determine the relic density
- non-relativistic at $T_{f.o.}/m_\chi \sim$ few $\times$ GeV $\rightarrow$ stabilization of structure formation

The WIMP Miracle

- thermal equilibrium with SM particles: ($\chi = \bar{\chi}$ possible)

$$\chi\chi \leftrightarrow f\bar{f}$$

- freeze-out-condition

$$\Gamma(T_{f.o.}) = H(T_{f.o.})$$

$$\Gamma(T_{f.o.}) = \sigma_{\chi\chi} v n_{\chi\chi}, \quad n_{\chi\chi} = n_{\text{non-rel}} \propto \frac{m_\chi^3}{x^{3/2}} \exp(-x), \quad x = \frac{m_\chi}{T}$$

$$H(T_{f.o.}) \propto \frac{T_{f.o.}^2}{M_{pl}}$$ radiation dominated epoch

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numerical solution for a cold relic ($x \gg 1$): $\quad 20 \leq x_{f.o.} \leq 50$

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- calculation of relic density:

$$\Omega_\chi = \frac{\rho_\chi}{\rho_c} = \frac{m_\chi n_0}{\rho_c}$$

$$= \frac{m_\chi T_0^3}{\rho_c}\frac{n_0}{T_0^3}, \quad \text{iso-entropic universe} \Leftrightarrow \frac{n}{T^3} = \text{const.}$$

$$= \frac{T_0^3}{\rho_c}x_{f.o.}\left(\frac{n_{f.o.}}{T_{f.o.}^2}\right), \; n_{f.o.} \sim \frac{T_{f.o.}^2}{M_{pl}\sigma}$$

$$= \left(\frac{T_0^3}{\rho_c M_{pl}}\right)\frac{x_{f.o.}}{\sigma}$$

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WIMP miracle: weak interacting cold thermal relic gives measured relic density

- result from calculation with Boltzmann equation:

$$\Omega_\chi h^2 = 0.12\left(\frac{x_{f.o.}}{23}\right)^{3/2}\frac{\sqrt{g_{\text{eff}}}}{10}\left(\frac{35\,\text{GeV}}{m_\chi}\right)^2$$

The WIMP Miracle

How a general WIMP must look like:

- Lee-Weinberg limit: $m_\chi \gtrsim 10\,\mathrm{GeV}$ with assumption $\sigma \sim G_F^2 m_\chi^2$, same constraint also from PLANCK's upper limit on dark matter annihilation cross section

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- coupling to Standard Model to assure annihilation to produce relic density in thermal relic framework

WIMP models

Dark Real Scalar in Higgs Portal Interaction

- renormalizable extension of Higgs potential by a real scalar field S (real scalar field to avoid mixing with SM Higgs boson and the resulting modification of SM Higgs couplings and $W-$ and $Z-$masses)

$$V(\phi) = \mu_H^2 \phi^\dagger \phi + \lambda_H (\phi^\dagger \phi)^2 + \mu_S^2 S^2 + \kappa S^3 + \lambda_S S^4 + \kappa_3 \phi^\dagger \phi S + \lambda_3 \phi^\dagger \phi S^2$$

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- additional global symmetry Z_2-symmetry to prevent $S \to HH$ decays, $S \to -S$, $H \to +H$
- **stable scalar particle** with mass $m_S = \sqrt{2\mu_S^2 - \lambda_3 v_H^2}$
- and **weak coupling to the SM** with $g_{SSH} = -2\lambda_3 v_H$ and $g_{SSHH} = -2\lambda_3$
  $\to$ annihilation via Higgs mediator possible
  $\to$ **viable DM candidate**

WIMP models

Dark Real Scalar in Higgs Portal Interaction

- calculation of **parameter space** for observed relic density: annihilation rate

$$\langle \sigma v \rangle \propto \left(\left(4m_S^2 - m_H^2\right)^2 + m_H^2 \Gamma_H^2 \right)^{-1}$$

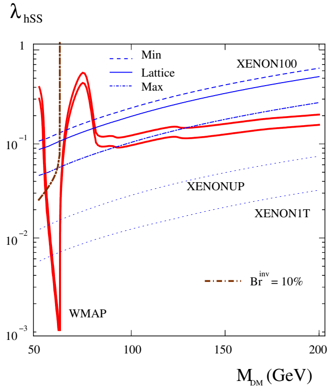

Figure: Parameter space for self-coupling $\lambda_{hSS} \sim \lambda_3$ and scalar mass $M_{DM} = m_S$ [arXiv:1112.3299]

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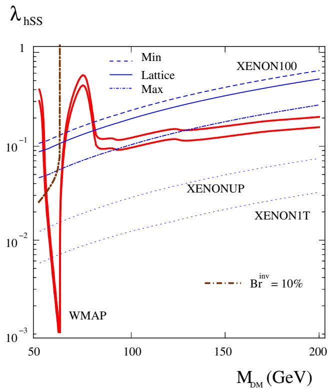

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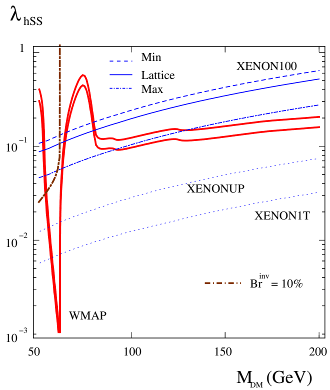

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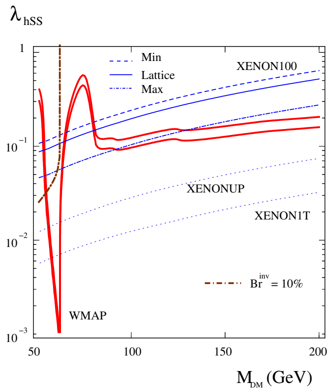
- self-coupling $\lambda_3 \sim 10^{-3}$ for Higgs pole $m_H = 2m_S$
- $m_S \ll m_H$: $\lambda_3 \sim 1$
- $m_S \gg m_H$: annihilation to Higgs pairs via four-point interaction dominates over $s-$channel Higgs propagator contribution
  $\rightarrow$ thresholds at $m_S = m_Z$ and $m_S = m_W$



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Vector Portal Model:

- new massive gauge boson as a mediator of thermal freeze-out production of the dark matter particle
- **or** new massive gauge boson as dark matter itself
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- global symmetries of SM can be extended to anomaly-free gauge symmetries
- example: extension of hypercharge symmetry $U(1)_Y$ by additional $U(1)$ gauge group
- **kinetic mixing** in Lagrangian

$$\mathcal{L}_{\text{gauge}} = -\frac{1}{4}\hat{B}^{\mu\nu}\hat{B}_{\mu\nu} - \frac{s_\chi}{2}\hat{V}^{\mu\nu}\hat{B}_{\mu\nu} - \frac{1}{4}\hat{V}^{\mu\nu}\hat{V}_{\mu\nu}$$

with small mixing parameter $s_\chi = \sin\chi$.

WIMP models

Vector Portal Model:

- resulting physical masses (weak mixing angle ω):

$$m_\gamma^2 = 0,\; m_Z^2 = \hat{m}_Z^2 \left[1 + s_\chi^2 s_\omega^2 \left(1 + \frac{\hat{m}_V^2}{\hat{m}_Z^2}\right)\right],\; m_V^2 = \hat{m}_V^2 \left[1 + s_\chi^2 c_\omega^2\right]$$

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- coupling of V to SM matter
  - for $\frac{\hat{m}_V^2}{\hat{m}_Z^2} \ll 1$: vanishing coupling to $Z-$current in leading $s_\chi-$order

    $\rightarrow V$ is called **hidden photon**

  - for $\frac{\hat{m}_V^2}{\hat{m}_Z^2} \gg 1$: coupling to $Z-$current can be dominating coupling to SM fields

    $\rightarrow V$ is called $Z'-$**boson**

WIMP models

Vector Portal Model with Z' mediator:

- $\Omega \propto \frac{1}{\sigma}$ with $\sigma \propto \frac{m_\chi^2}{(s - m_{Z'}^2)^2 + m_{Z'}^4}$
- range for hot relics: for $m_\chi < 1\,\text{MeV}$, $\Omega_\chi \propto m_\chi$

  $\rightarrow$ **hot relic for** $m_\chi \sim 10\,\text{eV}$

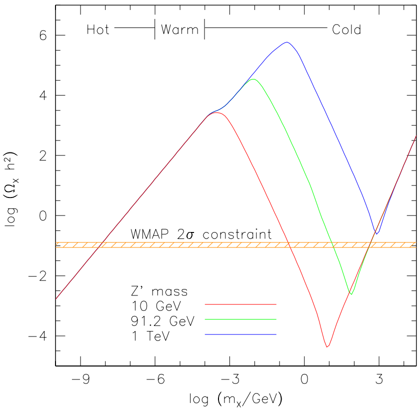

Figure: Relic density as a function of m_χ in Z' mediator model [arXiv:astro-ph/0412170]

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Vector Portal Model with Z' mediator:

- $\Omega \propto \frac{1}{\sigma}$ with $\sigma \propto \frac{m_\chi^2}{(s-m_{Z'}^2)^2+m_{Z'}^4}$
- range for hot relics: for $m_\chi < 1\,\text{MeV}$, $\Omega_\chi \propto m_\chi$

  $\rightarrow$ **hot relic for** $m_\chi \sim 10\,\text{eV}$
- range for cold relics:

  $m_\chi \gg m_{Z'}$: $\Omega_\chi \sim \sigma^{-1} \sim m_\chi^2$

  $m_\chi \ll m_{Z'}$: $\Omega_\chi \sim m_{Z'}^4/m_\chi^2$

  $\rightarrow$ **cold relic for** $m_\chi \sim 1\,\text{TeV}$

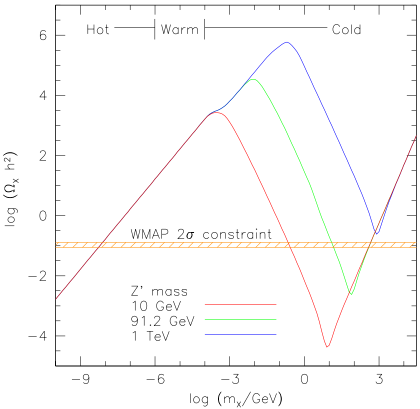

Figure: Relic density as a function of m_χ in Z' mediator model [arXiv:astro-ph/0412170]

WIMP Candidates from Supersymmetry

. . . just a glimpse on supersymmetric realization of WIMPs.

Lightest Neutralino

- couplings in **Minimal Supersymmetric Standard Model (MSSM)** do not ensure baryon (B) and lepton number (L) conservation

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- **neutralinos** are created through mixing of gauginos (bino with mass parameter M_1 and wino with mass parameter M_2) and higgsinos (mass parameter μ)
- lightest neutralino as LSP and DM candidate

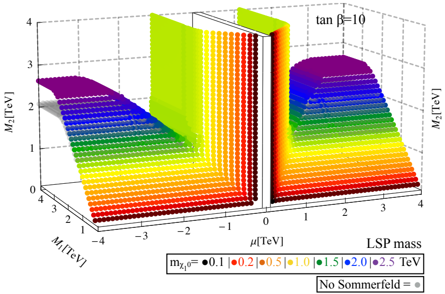

Figure: Parameter space for neutralinos as LSP [arXiv:1510.03460]

Gravitinos

. . . *the first supersymmetric dark matter candidate ever proposed!*

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- Massless gravitinos are described by **(Majorana) Rarita-Schwinger fields** (vector-spinor fields), $\Psi_\mu^a(x)$
- **Super-Higgs Mechanism** introduces a massless Goldstino χ and provides the gravitino with mass $m_{3/2}$
- Interactions with matter via **Majorana super-current** S_μ

Lagrangian for massive Gravitino

$$\mathcal{L} = -\frac{1}{2}\epsilon^{\mu\nu\rho\sigma}\bar{\Psi}_\mu\gamma_5\gamma_\nu\partial_\rho\Psi_\sigma - \frac{m_{3/2}}{4}\bar{\Psi}_\mu\left[\gamma^\mu,\gamma^\nu\right]\Psi_\nu + \frac{1}{2M_{Pl}}\bar{\Psi}_\mu S^\mu$$

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$\rightarrow$ Very weak interactions:

- transverse modes: suppressed by Planck scale
- longitudinal modes: suppressed by supersymmetry-breaking scale $F \propto m_{3/2}^{-1}$

Gravitinos

- assumption: gravitino as stable LSP (= lightest supersymmetric particle)

Gravitinos

- <u>assumption</u>: gravitino as stable LSP (= lightest supersymmetric particle)
- for $m_{3/2}$ below electroweak scale and $s \ll M_{\tilde{\gamma}}^2$:
  pair-annihilation cross section is dominated by two-photon channel over fermion-antifermion channel
  Freeze-out temperature for light gravitinos:

$$T_{f.o.} \sim 450\,\text{GeV} \left(\frac{m_{3/2}}{0.1\,\text{eV}}\right)^{4/5} \left(\frac{100\,\text{GeV}}{M_{\tilde{\gamma}}}\right)^{2/5}$$

Relic density: ($g_*(T)$ is effective number of relativistic degrees of freedom)

$$\Omega_{3/2}h^2 \simeq \frac{m_{3/2}}{\text{keV}} \left(\frac{100}{g_*(T_{f.o.})}\right)$$

$\rightarrow$ potential **hot relics** ($T_{f.o.} \gg m_{3/2}$) with $m_{3/2} \sim 100\,\text{eV}$
$\rightarrow$ in disagreement with Tremaine-Gunn bound (too light)

Gravitinos

- $T_{f.o.} \sim M_s$ for $m_{3/2} \gtrsim 0.02\,\text{eV}$ with M_s mass scale of other SUSY particles
- **single-gravitino processes** possible while other SUSY particles are in thermal equilibrium: (e.g. with gauge boson V and corresponding gaugino $\tilde{\lambda}$)

$$V + \tilde{\lambda} \leftrightarrow V + \tilde{G}, \qquad V + V \leftrightarrow \tilde{\lambda} + \tilde{G}$$

Freeze-out temperature including single-gravitino processes

$$T_{f.o.} \sim 1\,\text{TeV} \left(\frac{m_{3/2}}{1\,\text{keV}}\right)^2 \left(\frac{1\,\text{TeV}}{M_3}\right)^2$$

Gravitinos

- problem: thermalization of gravitinos with $m_{3/2} \gtrsim 1\,\text{keV}$ lead to $\Omega_{3/2}h^2 \gg \Omega_\chi h^2$

Gravitinos

- problem: thermalization of gravitinos with $m_{3/2} \gtrsim 1\,\text{keV}$ lead to $\Omega_{3/2}h^2 \gg \Omega_\chi h^2$
- mechanism to generate heavier gravitinos:
  - example 1: decay of NLSP (next-to-lightest supersymmetric particles) after freeze-out

$$\Omega_{3/2}h^2 = m_{3/2} \cdot \frac{\Omega_{\text{NLSP}} h^2}{m_{\text{NLSP}}}$$

  - example 2: gravitinos are not the LSP
    non-thermal production of LSP's via decay of gravitinos with $m_{3/2} \gg 100\,\text{TeV}$

Axions and ALPs

. . . a particle dark matter candidate with concrete connection to the strong CP problem of QCD.

Axions and ALPs

Strong CP Problem of QCD

Lagrangian of Quantum Chromodynamics (QCD)

$$\mathcal{L}_{\text{QCD}} = -\frac{1}{4} G^a_{\mu\nu} G^{a\mu\nu} + \sum_{j=1}^{n} \left[\bar{q}_j \gamma^\mu i D_\mu q_j - \left(m_j q^\dagger_{Lj} q_{Rj} + h.c. \right) \right] + \frac{\theta g^2 s}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{a\mu\nu} \quad (1)$$

- **Adler-Bell-Jackiw anomaly:** if none of the quark masses vanishes the theta term has to be present
- **strong CP problem:** **theta term** violates CP, T and P-symmetry
  $\bar{\theta} = \theta + arg(\det \mathcal{M})$, chiral pertubation theory:
  $d_n \approx 5 \cdot 10^{-16} \cdot \bar{\theta} \cdot e$cm $\Leftrightarrow d_{n,\text{exp}} <$ few $\cdot 10^{-26} e$cm

$\Rightarrow$ Smallness of θ, $\bar{\theta}$?

Axions and ALPs

Strong CP Problem of QCD

Peccei-Quinn Theory: global $U_{\text{PQ}}(1)$ symmetry

- *explicitly* broken by non-perturbative effects producing theta-term
- *spontaneously* broken at scale $f_a \rightarrow m_a \sim \frac{\Lambda_{\text{QCD}}^2}{f_a}$

$\Rightarrow$ **pseudo-Nambu-Goldstone boson: axion**

$\rightarrow$ ground state of axion potential drives $\bar{\theta} \rightarrow 0$

Axions and ALPs

Constraints and Consequences

- general axion mass range dictated by **PQ-theory**: $m_a \sim \frac{\Lambda^2_{\text{QCD}}}{f_a}$

  $10^{-12}\,\text{eV} \lesssim m_a \lesssim 1\,\text{MeV}$ (for $100\,\text{GeV} < f_a < M_{pl}$)

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- $10\,\text{keV} \lesssim m_a \lesssim 1\,\text{MeV}$ (below e^+e^-–threshold) would lead to $K^+ \to \pi^+ + a$, $J/\Psi \to a + \gamma$, $\Upsilon \to a + \gamma$ (axion would leave detector before decaying into two photons)

  $\rightarrow$ **unobserved decays**

Axions and ALPs

Thermal Production of Hot Axions

axion production and annihilation in early universe mainly through:

$$a + g \leftrightarrow \bar{q} + q \qquad a + g \leftrightarrow g + g$$
$$a + q \leftrightarrow g + q \qquad a + \bar{q} \leftrightarrow g + \bar{q}$$

$$T_{f.o.} \approx 5 \times 10^{11}\,\mathrm{GeV} \left(\frac{f_a}{10^{12}\,\mathrm{GeV}} \right)$$

problem: $\Omega_{\text{th.ax.}} \sim \Omega_\chi \Rightarrow m_a \sim 13\,\mathrm{eV} \Rightarrow \tau_a < \tau_U$

$\Rightarrow$ DM cannot consist only of thermally produced hot axions

Axions and ALPs

Non-thermal Production of Cold Light Dark Matter

toy model: complex scalar field $\phi(t)$ with potential V, metric g

$$\frac{\mathcal{L}}{\sqrt{\text{det}(g)}} = (\partial^\mu \phi^*)(\partial_\mu \phi) - V(\phi) = (\partial^\mu \phi^*)(\partial_\mu \phi) - m_\phi^2 \phi^* \phi$$

- for flat space ($k = 0$): det$(g) = a^6$
- equation of motion:

$$\ddot{\phi}(t) + 3H\dot{\phi}(t) + m_\phi^2 \phi(t) = 0$$

Axions and ALPs

Non-thermal Production of Cold Light Dark Matter

$$\ddot{\phi}(t) + 3H\dot{\phi}(t) + m_\phi^2\phi(t) = 0$$

solution: $\phi(t) = \exp(i\omega t)$, $\omega = \frac{3i}{2}H \pm \sqrt{-\frac{9}{4}H^2 + m_\phi^2}$

3 cases:

- **Early Universe,** $H \gg m_\phi$:
  $\omega_1 = 0, \omega_2 = 3iH, \phi(t) = \phi_1 + \phi_2 \exp(-3Ht)$
  $\Rightarrow$ **misalignment mechanism**: temporal evolution to ϕ_1, not a minimum of $V(\phi)$ (in general)

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- **Late Universe,** $H \ll m_\phi$: $\phi(t) = \phi_3 \exp(\pm i m_\phi t)\exp(-3H/2t)$

Axions and ALPs

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Non-Thermal Production of Cold Axions

... through the **misalignment mechanism:**

- assumption: relaxation of $\bar{\theta} \to 0$ through oscillation
- solution to Lagrange equation of motion for $T \gg \Lambda_{\text{QCD}}$:
  $\bar{\theta} = \bar{\theta}_1 =$ const. $\hat{=}$ misalignment-angle
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$\Rightarrow$ very cold axions with typical velocity $\frac{v_a}{c} \sim 10^{-18}$
$\Rightarrow a \to \gamma\gamma$ gives $\tau_{a\to\gamma\gamma} \approx 2 \times 10^{47}$ years $\gg \tau_U \sim 14 \times 10^9$ years ✓

Axions and ALPs

Generalization

- axion: explanation of strong CP problem and Dark Matter

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Axion-like particle (ALP):

- global $U(1)$ symmetry spontaneously broken by hidden Higgs-type mechanism (symmetry breaking scale v_h)
  $H_h(x) = \frac{1}{\sqrt{2}}\left(v_h + h_h(x)\right)\exp\left(\frac{ia(x)}{v_h}\right)$
  (v_h suppresses ALP-SM interactions)
- $m_a = \frac{\mu^2}{f_a}$, μ is not related to Λ_{QCD}

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$\Rightarrow \mu \approx 100\,\text{eV}$, $m_a \approx 10^{-22}\,\text{eV}$
typical velocity $v \approx 100\,\text{km}/\text{s}$, $\lambda_{\text{de-broglie}} \sim$ galaxy
$\Rightarrow$ **fuzzy dark matter**

Sterile Neutrinos

. . . on the task of simultaneously explaining dark matter and neutrino masses and mixing.

Sterile Neutrinos

possible explanation of neutrino masses and mixing:

n right-handed fermions N_a $(a = 1, \ldots, n)$ which form a singlet under all SM gauge interactions = ***sterile* neutrinos**

See-Saw Lagrangian

$$\mathcal{L} = \mathcal{L}_{SM} + i\bar{N}_a \partial\!\!\!/ N_a - y_{\alpha a} H^\dagger \bar{L}_\alpha N_a - \frac{M_a}{2} \bar{N}_a^c N_a \quad (2)$$

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- mass eigenvalues: $M(\nu_{1,2,3}) \sim \frac{y^2 v^2}{M} \Leftrightarrow m(\nu_a) \sim M$
  $\rightarrow$ lightness of **active neutrinos** due to heaviness of **sterile neutrinos**!
- mixing angle $\theta^2 \sim \frac{y_{\alpha a} v^2}{M^2}$
- scale M can be derived as VEV of a real scalar S associated with the electroweak scale

Sterile Neutrinos

Sterile Neutrinos as Dark Matter Candidate

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- SN lifetime estimation with mixing angle θ and mass m:

$$\Gamma \sim \theta^2 G_F^2 m^5 \quad \Rightarrow \quad \tau \sim 10^{16}\,\mathrm{s}\,\theta^{-2}\left(\frac{m}{\mathrm{keV}}\right)^{-5} \Rightarrow m \ll 1\,\mathrm{keV}/\theta^{2/5}$$

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- decay into three active neutrinos:

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- Fermi statistic constraint: **Tremaine-Gunn bound** $\sim$ decreasing of max. value of phase-space density with time $m \gtrsim 1\,\mathrm{keV}$

Sterile Neutrinos

Production of Sterile Neutrinos

early universe: non-thermal production by oscillations between active and sterile neutrinos

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e.g. mixing only between ν_e and N_1

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Sterile Neutrinos

Production of SN

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Possible model implementation:

νMSM = minimal SM with neutrino masses

- three sterile neutrinos M_1, M_2, M_3
- lightest SN with $M_1 \sim$ keV is dark matter
- $M_2 \simeq M_3 \sim$ GeV with $|M_2 - M_3| \sim 1$ keV lead to dynamical generation (neutrino oscillations) of lepton asymmetry $L \sim B \rightarrow$ explanation of baryon asymmetry

Superheavy Dark Matter

. . . just a short glimpse on more ”exotic” dark matter candidates.

Superheavy Dark Matter

WIMPzillas

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  description of particle production in presence of an intense classical field

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Superheavy Dark Matter

<u>WIMPzillas</u>

- Schrödinger 1939: `"The proper vibrations of the expanding universe"`
  description of particle production in presence of an intense classical field
- non-thermal production mechanism of superheavy particles X in early universe in presence of strong gravitational fields
- most likely just after inflation, at $T = T_*$:

  interaction rate is weak enough $\Leftrightarrow \Gamma_X < H$

  X is never in thermal equilibrium $\Leftrightarrow \left(\frac{200\text{ TeV}}{M_X}\right)^2 \left(\frac{T_*}{M_X}\right) < 1$

- mass estimation for WIMPzillas

$$M_X \gtrsim 200\text{ TeV}$$

Superheavy Dark Matter

Strangelets

- macroscopic objects: quarks clumped together to macroscopic objects (= nuggets)
- $r = 10\,\text{mm} - 10\,\text{cm}$
- $m = 10^9\,\text{g} - 10^{18}\,\text{g} \Leftrightarrow M_X \gtrsim 200\,\text{TeV} = 3.6 \times 10^{-25}\,\text{g}$

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- possible connection to baryogenesis:
  $\rightarrow$ if ratio of nugget to antinugget 2:3 after nugget formation: explanation of baryogenesis without needing a net baryon excess

Kaluza-Klein-, Asymmetric-, Self- and Strongly-Interacting- and Feebly Interacting Dark Matter as well as ELastically DEcoupling Relics

. . . some further particle dark matter interaction and production mechanisms.

Kaluza-Klein Dark Matter in Universal Extra Dimension

assumptions:

- SM fields are allowed to propagate in extra spatial dimension (ED)
- tree-level mass of the n-th Kaluza-Klein excitation of SM field $X^{(n)}$ with SM mass $m^2_{X^{(0)}}$

$$m^2_{X^{(n)}} = \frac{n^2}{R^2} + m^2_{X^{(0)}},$$ assuming ED realized by circle with radius R

- LKP (= lightest Kaluza-Klein particle) as DM candidate:
  - $1/R \lesssim 800\,\text{GeV}$: Kaluza-Klein graviton $G^{(1)}$ (super-WIMP)
  - $1/R \gtrsim 800\,\text{GeV}$: Kaluza-Klein hypercharged gauge boson $B^{(1)}$ (Spin 1 WIMP)

Asymmetric Dark Matter

Is the similarity between Ω_χ and Ω_b just a coincidence, or can they be linked?

$$\frac{\Omega_\chi}{\Omega_b} = \frac{0.12}{0.022} \approx 5.5$$

Ω_b determined by initial asymmetry, $\frac{n_B - n_{\bar{B}}}{n_B} \approx 3 \times 10^{-8}$ (not by thermal freeze-out).

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assumptions:

- link between Ω_χ and Ω_b
- production of DM out of thermal bath and annihilation with DM anti-particles
- at decoupling of DM-baryon-link: relativistic baryons and non-relativistic DM
  $\rightarrow m_\chi \approx 15\, T_{\text{dec}}$, heavy DM $m_\chi \gg m_b$
- observed relic density Ω_χ due to initial asymmetry

Self-Interacting Dark Matter (SIDM)

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- DM candidate classification depending on behavior of co-moving number N and entropy S in region $T \sim m_\chi$

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- DM candidate classification depending on behavior of co-moving number N and entropy S in region $T \sim m_\chi$
- **Hot DM** ($T_{f.o.} \gg m_\chi$): N and S do **not** change
- **Cold DM** ($T_{f.o.} \ll m_\chi$): N and S do change

Self-Interacting Dark Matter (SIDM)

- DM candidate classification depending on behavior of co-moving number N and entropy S in region $T \sim m_\chi$
- **Hot DM** ($T_{f.o.} \gg m_\chi$): N and S do **not** change
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problem: prediction of very light DM $m_\chi \leq 100\,\text{eV} \Leftrightarrow$ large-scale structure constraints

Strongly Interacting Massive Particles (SIMPs)

- SIDM with small coupling to SM thermal bath (thermal equilibrium guaranteed for both sectors)
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  $\to$ combination associated with scale of QCD, $\alpha_{n\to 2} \sim 1$

$$\left(\frac{\Omega_\chi}{0.2}\right) \sim \left(\frac{m_\chi}{35\,\text{MeV}}\right)^{3/2} \left(\frac{x_{f.o.}}{20}\right)^2 \left(\frac{1}{\alpha_{3\to 2}}\right)^{-3/2}$$

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problem: condition for equilibrium is coupling with visible sector

ELastically DEcoupling Relics (ELDERs)

ELDER scheme:

After chemical decoupling from thermal bath: DM is still in

- **kinetic equilibrium** with thermal plasma
- **chemical equilibrium** with itself due to SIMP-like processes $n \to 2$

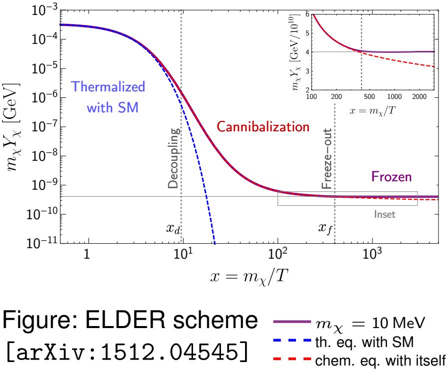

Figure: ELDER scheme [arXiv:1512.04545]

$\Upsilon_\chi = \frac{n_\chi}{s}$ with number density n and entropy density s
$\to \Upsilon_\chi \propto$ co-moving number density in iso-entropic universe ($sa^3 =$ const.)

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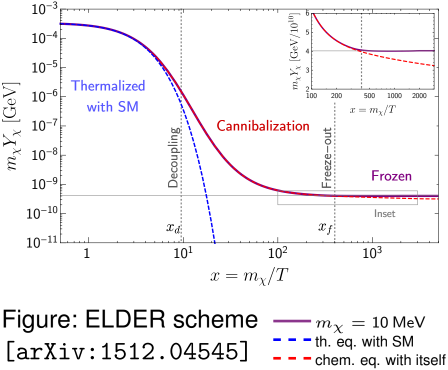

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After freeze-out at x_f:

- case 1: cannibalization processes out of equilibrium, DM is completely frozen
- case 2: self-annihilation induced cannibalization continues after decoupling

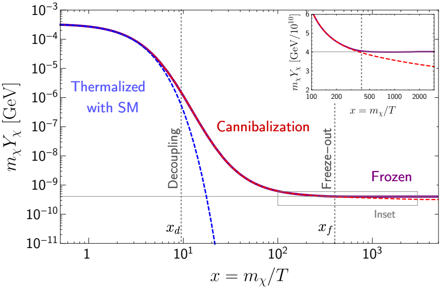

Figure: ELDER scheme [arXiv:1512.04545]

$m_\chi = 10$ MeV
th. eq. with SM
chem. eq. with itself

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FIMPs and LOSPs

Freeze-in mechanism

assumption:

- coupling between SM and DM large enough to reach thermal equilibrium
- SM particles decay and annihilate producing DM
- DM not in thermal equilibrium

$\Rightarrow$ non-thermal **freeze-in** mechanism, e.g. sterile neutrinos

FIMPs and LOSPs

- **FIMP = Feebly-Interacting Massive Particle**
  - zero initial abundance
  - never in thermal equilibrium due to highly suppressed interaction vertex with coupling $\lambda \ll 1$
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  - if LOSP is heavier:
    1. dominant contribution from **freeze-in** with additional small contribution from LOSP freeze-out and decay to **FIMP DM**
    2. dominant contribution from **freeze-out** and decay of LOSP to **FIMP DM**, additional small contribution from freeze-in

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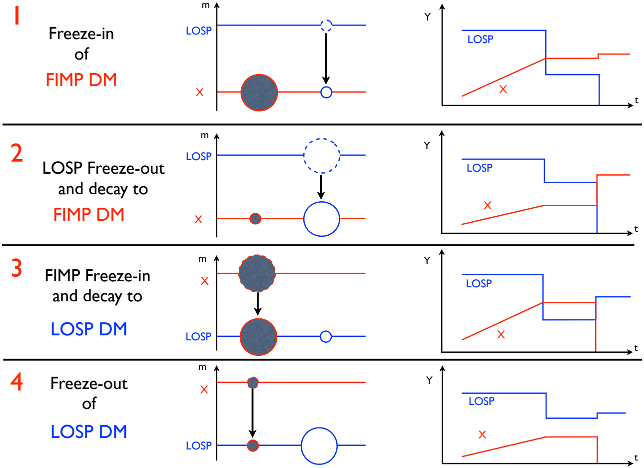
  - participates in $\lambda-$vertex
  - if LOSP is heavier:
    1. dominant contribution from **freeze-in** with additional small contribution from LOSP freeze-out and decay to **FIMP DM**
    2. dominant contribution from **freeze-out** and decay of LOSP to **FIMP DM**, additional small contribution from freeze-in
  - if LOSP is lighter than FIMP:
    1. dominant contribution from **freeze-in** of FIMP which later decays to **LOSP DM**, additional small contribution from LOSP freeze-out
    2. dominant contribution from **freeze-out** of **LOSP DM**, additional small contribution from FIMP freeze-in and decay to LOSP DM

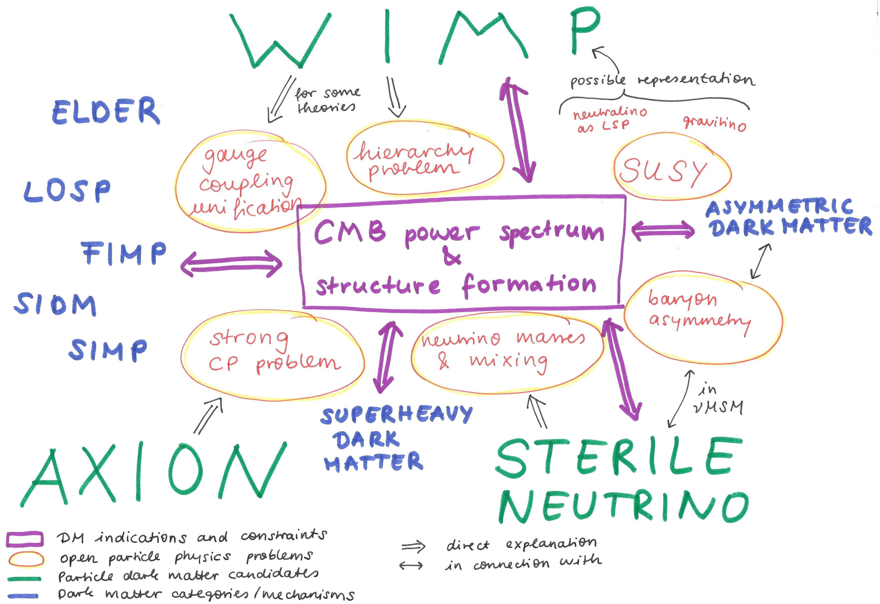
FIMPs and LOSPs



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

Figure: Mechanism of freeze-in and freeze-out for FIMP and LOSP DM [arXiv:0911.1120]

Comparison and Summary



Thanks for Your Attention!

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Pictures

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