Reconstructing early Universe properties with dark matter

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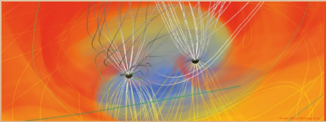
Thanks to Alex Arbey, John Ellis and Glenn Robbins



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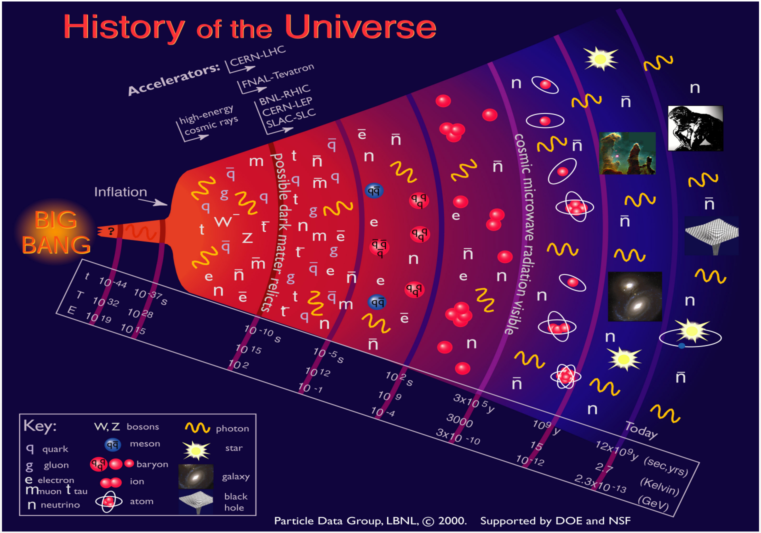

Recombination (and emission of cosmic microwave background) constitutes a limit between the dark times and the observable Universe

What happened during the dark times before recombination?

T

- How to describe the beginning of the Universe ($\sim$ Planck energy)?
  Quantum gravity? Brane theories? Other gravitation theories?
- What did drive **inflation** in the early Universe? When did it end?
- Do/did **topological defects** (magnetic monopoles, domain walls, ...) exist?
- Do/did **primordial black holes** exist?
- What did happen during **leptogenesis**?
- What did happen during **baryogenesis**?
- Where does the **particle-antiparticle asymmetry** come from?
- Did the **relic particle freeze-out** happen, how and when?
- Do we fully understand the properties of the **QCD-dominated plasma**?
- Do we fully understand **Big-Bang nucleosynthesis**?

Hypothesis: dark matter (DM) made of thermal relics.

Thermal relics

- Stable, massive and weakly interacting particles
- Particles in thermal equilibrium in the early Universe
- At the freeze-out temperature ($\sim 10 - 100$ GeV), suppressed interactions with the thermal bath
- After freeze-out, annihilation/co-annihilation of relic particles
- Out-of-equilibrium description of relic density through Boltzmann equations
- Particle physics candidates should have the observed cold dark matter density
- Standard particle physics candidates are in reach of the LHC and dark matter detection experiments

For illustrative purposes: dark matter composed of the MSSM lightest neutralinos.

Phenomenological MSSM (pMSSM)

- The most general MSSM scenario with R-parity and minimal flavour violation
- No universality assumption
- 19 independent parameters (20 with the gravitino mass)
- If the neutralino is the lightest supersymmetric particle (thus stable), it can constitute dark matter

Lightest neutralino $\tilde{\chi}_1^0 \equiv \chi$

- Mixed state of bino/wino/higgsino
- if mostly bino, very weakly interacting
- if mostly wino, accompanied by one chargino close in mass
- if mostly higgsino, accompanied by one chargino and another neutralino close in mass
- if mixed, more strongly interacting

Example of thermal relic: the MSSM neutralino

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In the Standard Model of Cosmology:

- before and at nucleosynthesis time, the expansion is dominated by radiation

$$H^2 = 8\pi G/3 \times \rho_{\rm rad}$$

- the evolution of the number density of all BSM particles follows the Boltzmann equation

$$\frac{dn}{dt} = -3Hn - \langle\sigma_{\rm eff} v\rangle(n^2 - n^2_{\rm eq})$$

$\langle\sigma_{\rm eff} v\rangle$: thermal average of effective cross section

related to the amplitudes of (co-)annihilations of BSM particles into SM particles

- the time and temperature are related through the adiabaticity condition:

$$\frac{ds_{\rm rad}}{dt} = -3Hs_{\rm rad}$$

with $s_{\rm rad} \propto h_{eff}(T)\, T^3$ (h_{eff}: radiation entropy degrees of freedom)

The differential equations are solved from an initial temperature T_{init} down to the present temperature $T_0 = 2.725$ K

The relic density is then obtained:

$$\Omega_\chi h^2(T_0) \equiv 2.755 \times 10^{-8} \frac{\rho_\chi(T_0)}{s_{rad}(T_0)} \qquad \text{with} \;\; \rho_\chi = m_\chi \, n(T_0)$$

Very precise measurements of cold dark matter density by Planck (+ others) (2018):

$$\Omega_c h^2(T_0) = 0.120 \pm 0.001$$

The Planck results lead to very strong constraints on BSM parameters.

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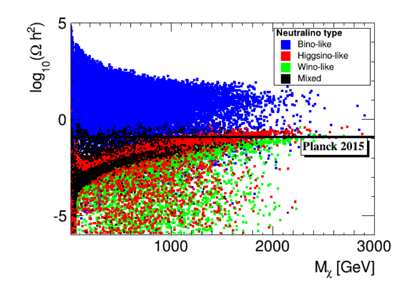

A. Arbey, M. Boudaud, FM, G. Robbins, JHEP 1711 (2017) 132

Possible solutions with a large range of masses

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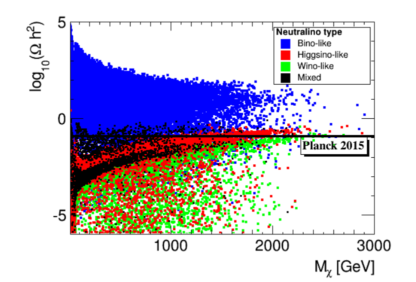
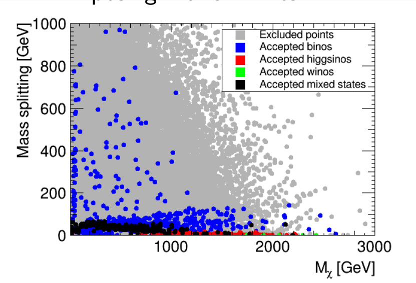


imposing Planck limits



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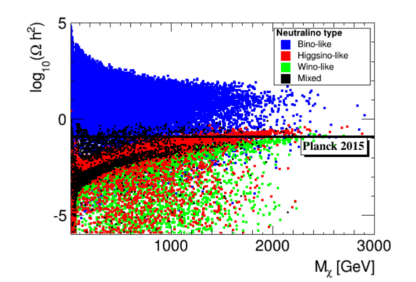
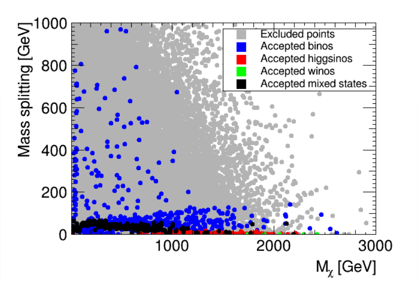




Theoretical limitations: uncertainties

- QCD equations of state: $\sim$5%
- Sommerfeld enhancement (non-perturbative): $\sim$5–50%
- Higher order corrections: $\sim$5–30%
- Multi-component dark matter: lower limit not applicable?
- Early Universe dominated by a dark component: lower limit not applicable?
- Entropy injection in early Universe: Planck limits not applicable?

Let's do the opposite:

particle physics $\rightarrow$ cosmology

Particle physics scenarios

$\Downarrow$

Calculation of dark matter observables in different cosmological scenarios

$\Downarrow$

Constraints on cosmological models and phenomena in the dark times...

In alternative cosmological scenarios, the expansion rate can be modified:

$$H^2 = 8\pi G/3 \times (\rho_{\rm rad} + \rho_D)$$

The entropy content of the Universe can also be altered!

$$\frac{ds_{\rm rad}}{dt} = -3Hs_{\rm rad} + \Sigma_D$$

$\Rightarrow$ Modified relation between time, expansion rate and temperature!

And relics can be generated non-thermally:

$$\frac{dn}{dt} = -3Hn - \langle \sigma_{\rm eff} v \rangle (n^2 - n_{\rm eq}^2) + N_D$$

ρ_D, Σ_D and N_D are model-dependent...

Relic density: example of decaying scalar field

Scenario with a pressureless decaying scalar field (e.g. modulus, late inflaton, dilaton, ...) of energy density ρ_ϕ:

$$H^2 = 8\pi G/3\,(\rho_{rad} + \rho_\phi)$$

We define the scalar field decay width Γ_ϕ, with a large branching fraction to radiation and a (tiny) branching ratio b to WIMPs:

$$\begin{aligned}
\frac{d\rho_\phi}{dt} &= -3H\rho_\phi - \Gamma_\phi\rho_\phi \\
\frac{ds_{rad}}{dt} &= -3Hs_{rad} + \frac{\Gamma_\phi\rho_\phi}{T} \\
\frac{dn}{dt} &= -3Hn - \langle\sigma_{\rm eff} v\rangle\left(n^2 - n_{eq}^2\right) + \frac{b}{m_\phi}\Gamma_\phi\rho_\phi
\end{aligned}$$

Reheating temperature T_{RH} (at which the scalar field is mostly decayed) defined by:

$$\Gamma_\phi = \sqrt{\frac{4\pi^3 g_{eff}(T_{RH})}{45}}\,\frac{T_{RH}^2}{M_P}$$

Non-thermal production parameter:

$$\eta = b\left(\frac{1\ \mathrm{GeV}}{m_\phi}\right)$$

Initial (relative) scalar field density:

$$\kappa_\phi = \frac{\rho_\phi(T_{init})}{\rho_\gamma(T_{init})}$$

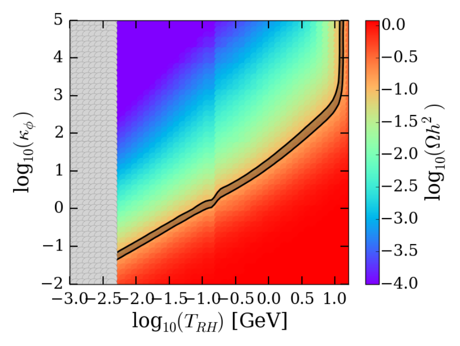
A. Arbey, J. Ellis, FM, G. Robbins, JHEP 1810 (2018) 132

Relic density: decaying scalar field vs. Big-Bang nucleosynthesis

Value of the relic density as a function of T_{RH} and κ_ϕ for a pMSSM example point with $\Omega_{\rm standard} h^2 = 1.27$, in absence of non-thermal production ($\eta = 0$)

Relic density: decaying scalar field vs. Big-Bang nucleosynthesis

Value of the relic density as a function of T_{RH} and κ_ϕ for a pMSSM example point with $\Omega_{\rm standard} h^2 = 1.27$, in absence of non-thermal production ($\eta = 0$)

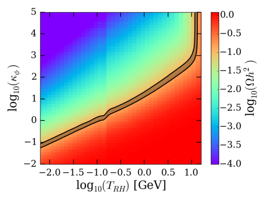


The gray region is excluded by Big-Bang nucleosynthesis constraints, which imposes $T_{RH} > 6$ MeV

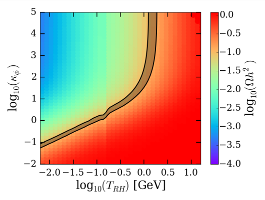
The dark strip is compatible with Planck results

We consider a point with **too large relic density** (pMSSM point with bino-like neutralino):

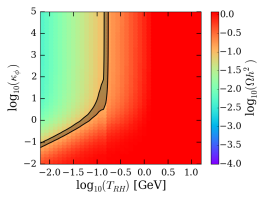
$$\Omega_{\rm standard} h^2 = 1.27 \qquad \text{to be compared to} \qquad \Omega_{\rm Planck} h^2 = 0.120 \pm 0.001$$



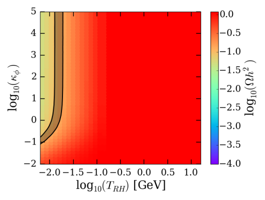
$\eta = 0$



$\eta = 10^{-12}$



$\eta = 10^{-11}$



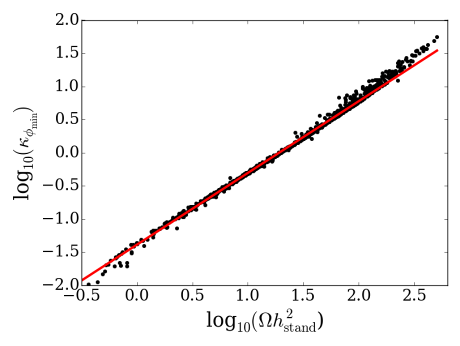
$\eta = 10^{-10}$

The dark region corresponds to the Planck value $\pm 10\%$ theoretical uncertainty.

The whole parameter region is compatible with Big-Bang nucleosynthesis constraints.

The relic density can be easily decreased by 3–4 orders of magnitude for any values of η.

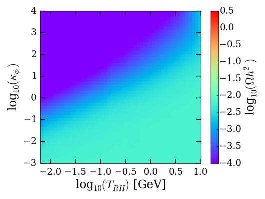
Minimal value of κ_ϕ to obtain the observed relic density as a function of original relic density $\Omega_{\rm standard} h^2$ for a sample of pMSSM points, with $T_{RH} = 6$ MeV (limit of BBN), $T_{init} = 40$ GeV and in absence of non-thermal production ($\eta = 0$)



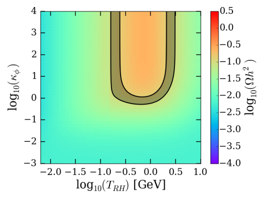
This sets constraints on the primordial Universe...

We consider a point with **too small relic density** (pMSSM point with higgsino-like neutralino):

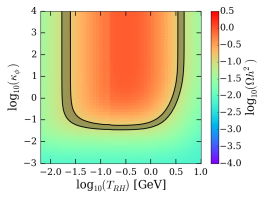
$\Omega_{\rm standard} h^2 = 5.9 \times 10^{-3}$ to be compared to $\Omega_{\rm Planck} h^2 = 0.120 \pm 0.001$



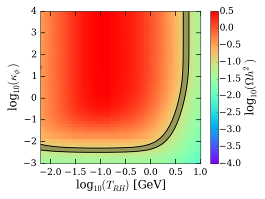
$\eta = 0$



$\eta = 10^{-11}$



$\eta = 10^{-10}$



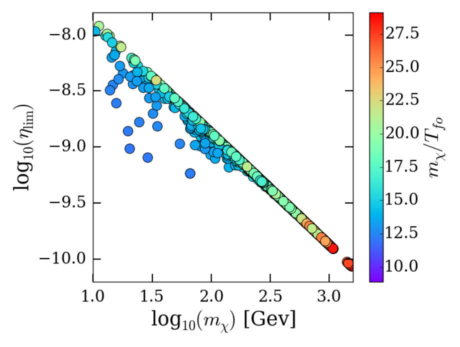
$\eta = 10^{-9}$

The dark region corresponds to the Planck value $\pm 10\%$ theoretical uncertainty.

The whole parameter region is compatible with Big-Bang nucleosynthesis constraints.

The relic density is decreased in absence of η, but can be easily increased by 2–3 orders of magnitude for tiny values of η.

Maximal value of non-thermal production parameter η to obtain the observed relic density as a function of the neutralino mass and freeze-out temperature for a sample of pMSSM points, with $T_{init} = 40$ GeV



This sets constraints on the primordial Universe...

Conclusions

- Decaying scalar fields can increase or decrease relic density by orders of magnitude
- It is not possible to exclude a new physics scenario using only relic density constraints
- Relic density constraints can simultaneously set limits on BOTH a new physics model AND a cosmological scenario
- If new particles are discovered, relic density will provide constraints on the early Universe properties at $T \sim$ GeV–TeV

Commercial

- `SuperIso Relic v4`: calculation of DM observables in SUSY – arXiv:1806.11489

  http://superiso.in2p3.fr/relic/
- `aSuperIsoDM`: calculation of DM observables in generic DM scenarios – SOON!
- `AlterBBN v2`: calculation of BBN observables – arXiv:1806.11095 [astro-ph.CO]

  https://alterbbn.hepforge.org/
- Open source codes
- Careful treatment of uncertainties, and flexible cosmological scenarios

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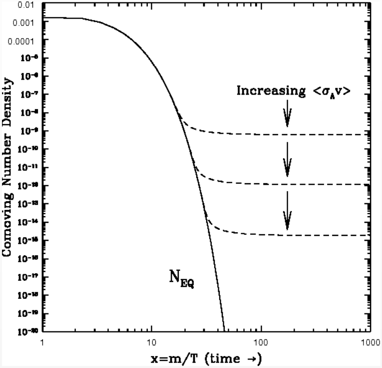
Backup

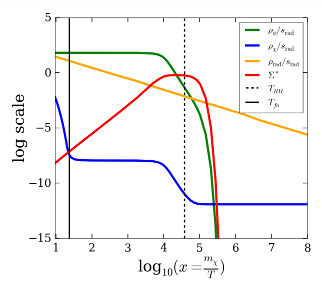
Dark matter density normalised to radiation entropy density as a function of m_χ/T.



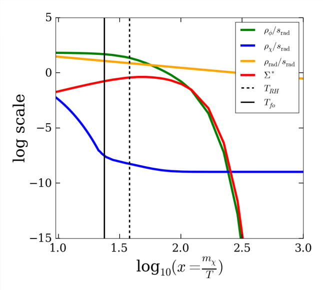
D. Hooper, TASI lecture 2008

The moment at which the dark matter density leaves the equilibrium density is called freeze-out.

Evolution of the scalar field density, WIMP density and entropy injection $\tilde{\Sigma}^* \equiv \frac{\Gamma_\phi \rho_\phi}{3HTs_{rad}}$ as a function of $x = m_\chi / T$, in absence of non-thermal production of WIMPs ($\eta = 0$)



$T_{RH} = 0.01$ GeV, $\kappa_\phi^{init} = 100$, $T_{init} = 40$ GeV

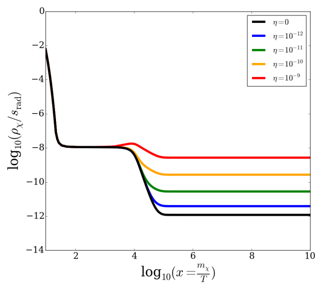


$T_{RH} = 10$ GeV, $\kappa_\phi^{init} = 100$, $T_{init} = 40$ GeV

Complex interplay between expansion rate and entropy injection...

In absence of non-thermal WIMP production, results in a decrease of the relic density

Evolution of the WIMP density as a function of $x = m_\chi / T$ in presence of non-thermal production of WIMPs



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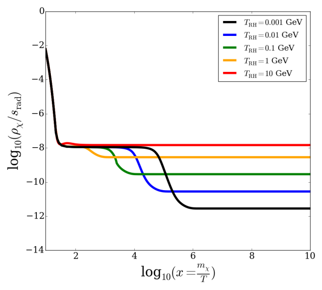

$\eta = 10^{-\mathbf{11}}$, $\kappa_\phi^{init} = 100$, , $T_{init} = 40$ GeV

Standard scenario can be strongly modified by the non-thermal production of WIMPs.