Dark Matter and Early Universe

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Based on arXiv:1807.00554 [hep-ph], with J. Ellis, F. Mahmoudi and G. Robbins

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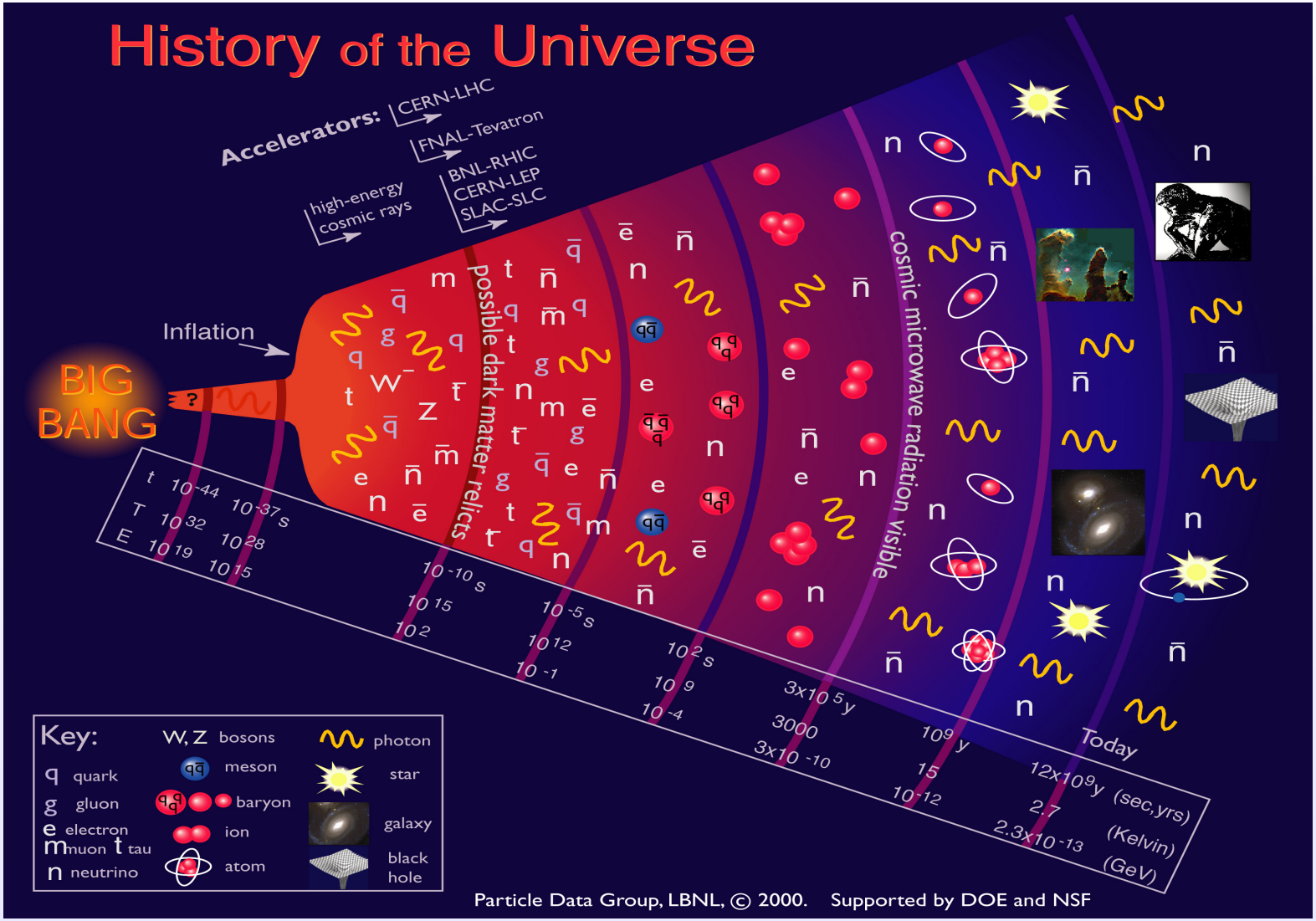
History of the Universe
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
t 10-44 10-37 s
T 1032 1028
E 1019 1015
10-10 s
1015
102
10-5 s
1012
10-1
102 s
109
10-4
3x105 y
3000
3x10-10
109 y
15
10-12
Today
12x109 y (sec,yrs)
2.7 (Kelvin)
2.3x10-13 (GeV)
Key:
q quark
g gluon
e electron
m muon t tau
n neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

What happened before recombination?

- Quantum gravity? Branes? Other gravitation theories?
- Inflation
- Topological defects (cosmic strings, magnetic monopoles, domain walls, ...)?
- Primordial Black Holes?
- Leptogenesis
- Baryogenesis
- Particle-antiparticle asymmetry
- QCD-dominated plasma
- Relic particle freeze-out/in
- Big-Bang nucleosynthesis
- ...

Big-Bang nucleosynthesis (BBN) is the oldest epoch which leads to direct observations.

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 lower temperature, suppressed interactions with the thermal bath
- Annihilation/co-annihilation of relic particles down to freeze-out temperature ($\sim 10 - 100$ GeV)
- Out-of-equilibrium description through Boltzmann equations
- Good 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.

Minimal Supersymmetric extension of the Standard Model (MSSM)

- More than 100 free parameters
- Provided R-parity is conserved, SUSY particles produced in pairs
- The lightest supersymmetric particle is stable
- 4 neutralinos and 2 charginos: supersymmetric partners of the Higgs ($h, H, A, H^{\pm}$) and vector bosons ($\gamma, Z, W^{\pm}$)
- The lightest neutralino is a suitable dark matter candidate

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

- Mixed state of bino/wino/higgsino (photino/zino/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

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Relic density: standard calculation

In the Standard Model of Cosmology:

- before and at nucleosynthesis time, the expansion is dominated by radiation
$$H^2 = 8\pi G/3 \times \rho_{\text{rad}}$$
- the evolution of the number density of all supersymmetric particles follows the Boltzmann equation
$$\frac{dn}{dt} = -3Hn - \langle \sigma_{\text{eff}} v \rangle (n^2 - n_{\text{eq}}^2)$$
- the time and temperature are related through the adiabaticity condition:
$$\frac{ds_{\text{rad}}}{dt} = -3Hs_{\text{rad}}$$

Thermal average of effective cross section ($K_{1,2}$: modified Bessel functions):

$$\langle \sigma_{\text{eff}} v \rangle = \frac{\int_0^\infty dp_{\text{eff}}\, p_{\text{eff}}^2\, W_{\text{eff}}\, K_1\left(\frac{\sqrt{s}}{T}\right)}{m_1^4\, T \left[\sum_i \frac{g_i}{g_\chi} \frac{m_i^2}{m_\chi^2} K_2\left(\frac{m_\chi}{T}\right)\right]^2}$$

where: (ij: coannihilating SUSY particles / kl: SM outgoing particles)

$$\frac{dW_{\text{eff}}}{d\cos\theta} = \sum_{ijkl} \frac{p_{ij}\, p_{kl}}{32\pi\, p_{\text{eff}}\, S_{kl} \sqrt{s}} \sum_{\text{helicities}} \left| \sum_{\text{diagrams}} \mathcal{M}(ij \to kl) \right|^2$$

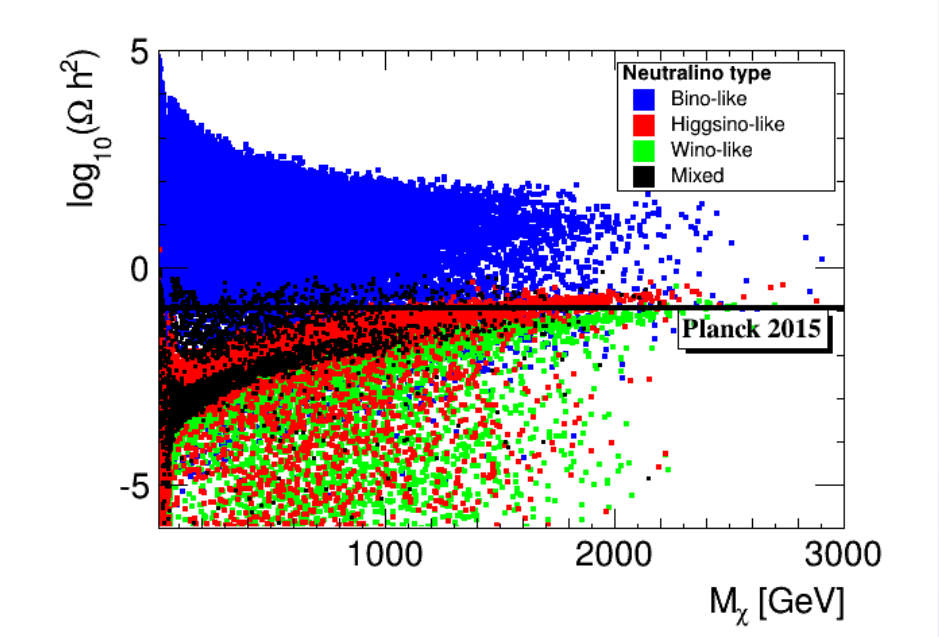
Neutralino relic density

The relic density is then obtained: (Today: $T_0 = 2.725$ K)

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

Very precise measurements of cold dark matter density by Planck (+ others) (2015):

$$\Omega_c h^2(T_0) = 0.1188 \pm 0.0010$$



AA, M. Boudaud, F. Mahmoudi, G. Robbins, arXiv:1707.00426

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

Caveat!

Many unobservable phenomena could have happened during the pre-BBN era.

Relic density: alternative cosmological scenarios

For example, the expansion rate can be modified:

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

The entropy content of the Universe can also be altered!

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

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

And relics can be generated non-thermally:

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

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

Relic density: decaying scalar field

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

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

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

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

Decay width related to the reheating temperature T_{RH}:

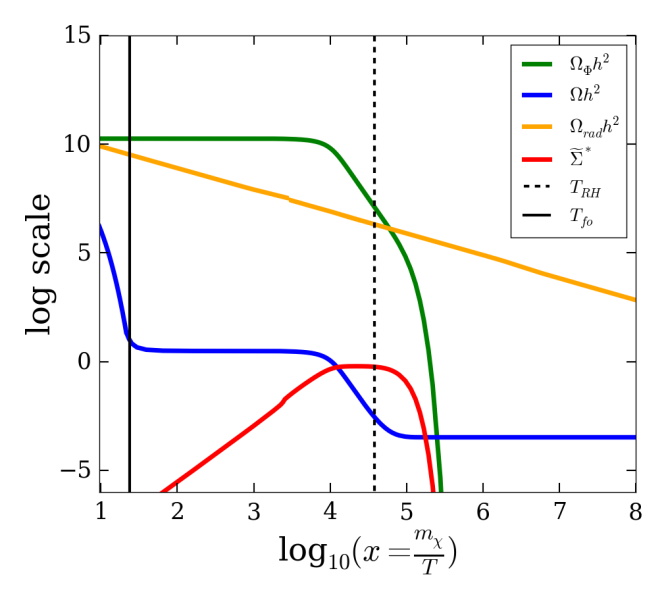
$$\Gamma_\phi = \sqrt{\frac{4\pi^3 g_{eff}(T_{RH})}{45}}\frac{T_{RH}^2}{M_P}$$

Important parameters:

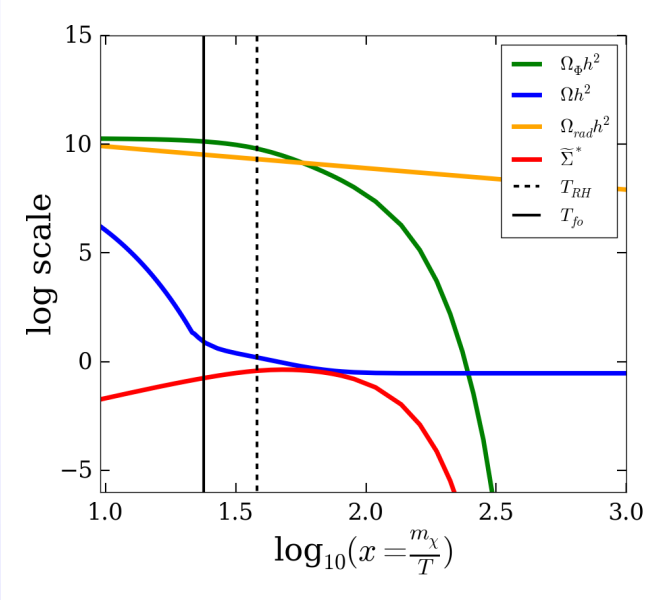
$$\eta = b\left(\frac{1\ \text{GeV}}{m_\phi}\right) \qquad \kappa_\phi = \frac{\rho_\phi(T_{init})}{\rho_\gamma(T_{init})}$$

Relic density: decaying scalar field

Evolution of the scalar field density, neutralino 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 neutralinos ($\eta = 0$)



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



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

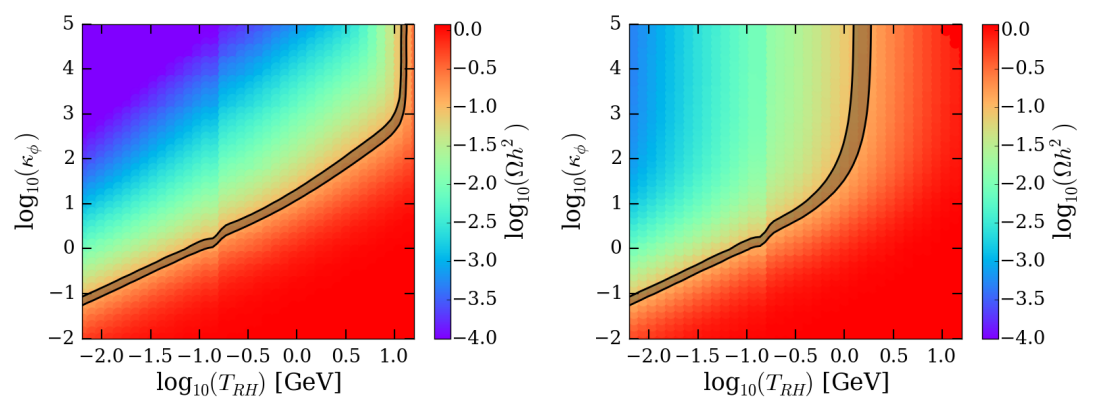
Complex interplay between expansion rate and entropy injection...

In absence of non-thermal neutralino prodcution, results in a decrease of the relic density

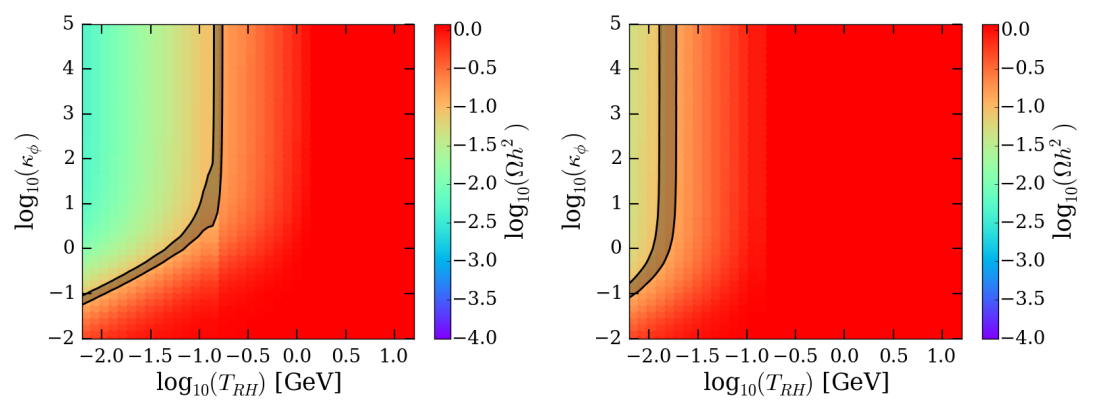
Relic density: decaying scalar field

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

$$\Omega_{\rm standard} h^2 = 1.27 \qquad \text{to be compared to} \qquad \Omega_{\rm Planck} h^2 = 0.1188 \pm 0.0010$$



(c) $\eta = 0$ (d) $\eta = 10^{-12}$



(e) $\eta = 10^{-11}$ (f) $\eta = 10^{-10}$

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

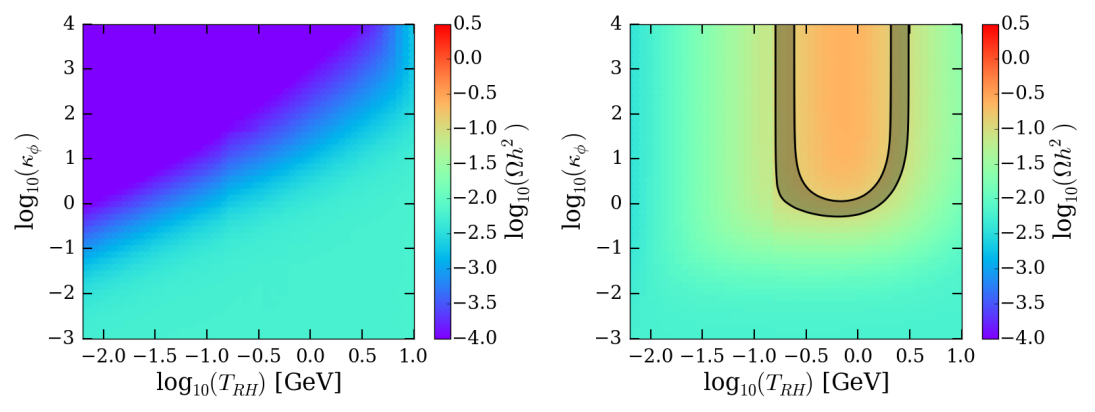
The whole parameter region is compatible with Big-Bang nucleosynthesis constraints

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

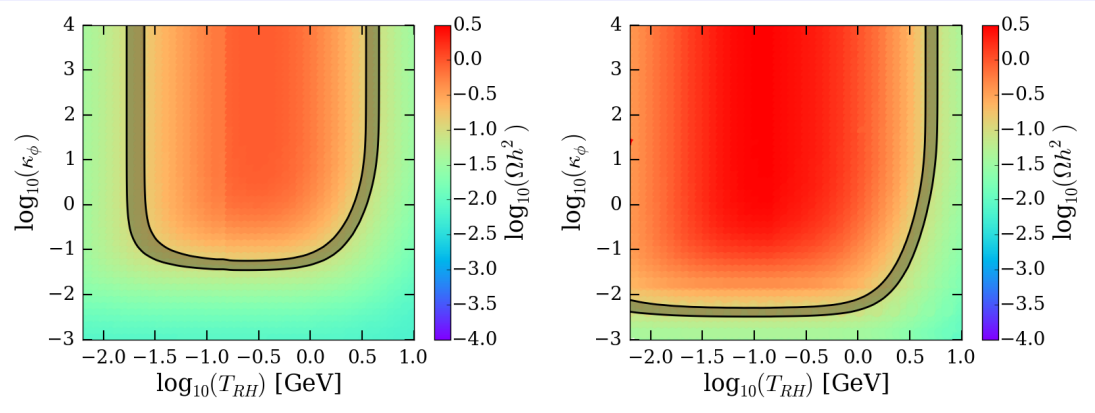
Relic density: decaying scalar field

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 $\Omega_{\rm Planck} h^2 = 0.1188 \pm 0.0010$



(g) $\eta = 0$ (h) $\eta = 10^{-11}$



(i) $\eta = 10^{-10}$ (j) $\eta = 10^{-9}$

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

Conclusions

- Decaying scalar fields can increase or decrease relic density by orders of magnitude
- Cosmological quintessence can increase 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

Advertisement

- `SuperIso Relic v4`: calculation of DM observables – arXiv:1806.11489 [hep-ph]

  http://superiso.in2p3.fr/relic/ → G. Robbins' talk tomorrow at 6:45pm!
- `AlterBBN v2`: calculation of BBN observables – arXiv:1806.11095 [astro-ph.CO]

  https://alterbbn.hepforge.org/
- Open sources and user-friendly codes
- Flexible cosmological scenario implementation

Backup

Relic density: quintessence

Quintessence: cosmological scalar field giving a dynamical explanation for dark energy

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

Klein-Gordon equation:

$$\begin{aligned} \frac{d\rho_\phi}{dt} &= -3H(\rho_\phi + P_\phi) \\ P_\phi &= \frac{1}{2}\dot{\phi}^2 - V(\phi) \\ \rho_\phi &= \frac{1}{2}\dot{\phi}^2 + V(\phi) \end{aligned}$$

Many possibilities for the potential, e.g. $V(\phi) = \alpha_1 \exp(-\beta_1\phi) + \alpha_2 \exp(-\beta_2\phi)$

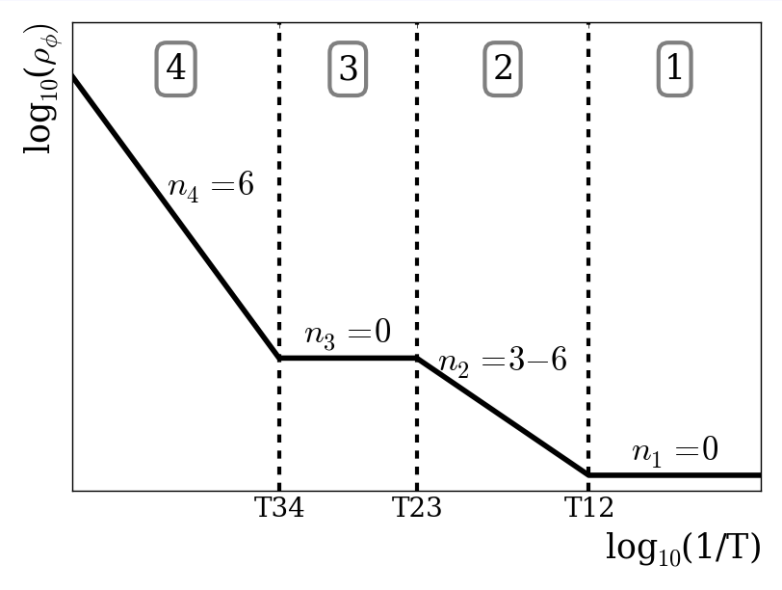
Today: $V(\phi) \gg \dot{\phi}^2 \Longleftrightarrow P_\phi \approx -\rho_\phi \Longleftrightarrow \rho_\phi \propto T^0$

In the very early Universe: $\dot{\phi}^2 \gg V(\phi) \Longleftrightarrow P_\phi \approx +\rho_\phi \Longleftrightarrow \rho_\phi \propto T^6$

Different possibilities in intermediate times, depending on the choice of the potential and values of the potential parameters.

Relic density: quintessence

We checked that full quintessence evolution can be parametrised in the following way:



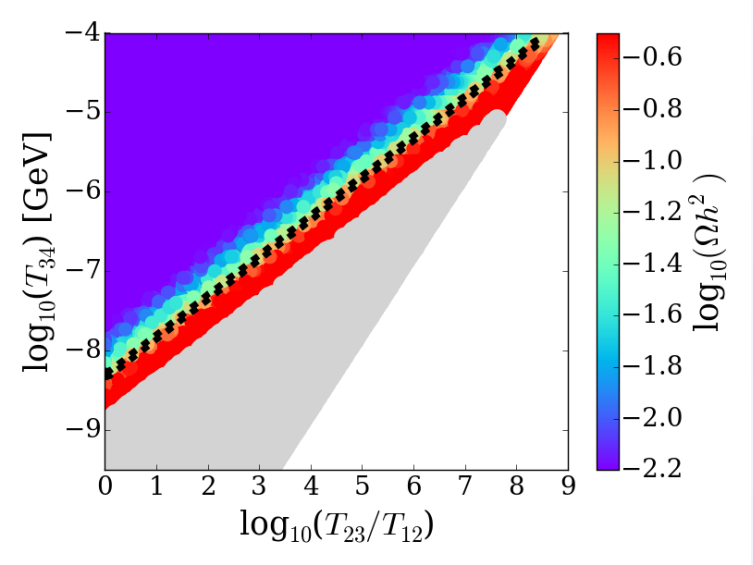
Here $\rho_\phi \propto T^n$, where n can be modified at different times

Since quintessence can only add an energy density to the Friedmann equation and therefore accelerate the expansion, the relic density can only be increased in this scenario

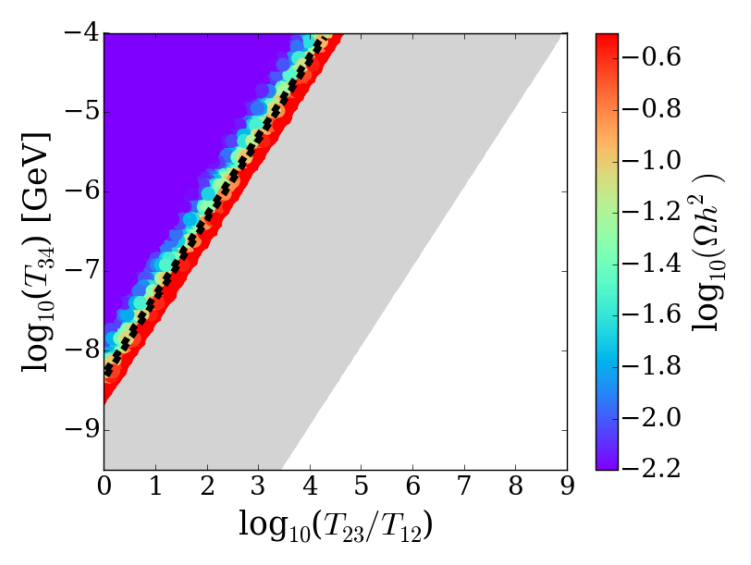
Relic density: quintessence

We consider a point with too small relic density:

$$\Omega_{\rm standard} h^2 = 5.9 \times 10^{-3} \qquad \text{to be compared to} \qquad \Omega_{\rm Planck} h^2 = 0.1188 \pm 0.0010$$



(k) $n_2 = 3$



(l) $n_2 = 6$

Grey regions excluded by Big-Bang nucleosynthesis constraints

Dashed lines corresponds to the Planck value

The relic density can be increased by 2–3 orders of magnitude by the presence of quintessence

However, neutralinos with a standard relic density $\lesssim 3 \times 10^{-4}$ can not be restored because of BBN constraints