Constraining Non-thermal Dark Matter by CMB

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Outline:

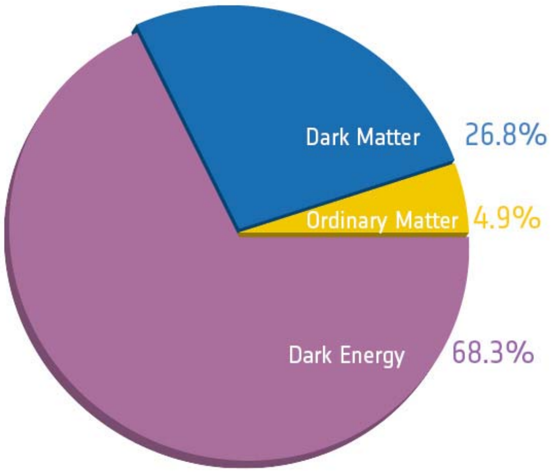
- Introduction
- Non-thermal DM from early matter domination
- Connection to CMB
- Results
- Conclusion and Outlook

Based on:

R.A., K. Dutta, A. Maharana JCAP 1810, 038 (2018)

Introduction:

The present universe according to observations:



BSM needed to explain 95% of the universe.

Important questions about DM:

What is the nature of DM?

How did it acquire its relic abundance?

Profound consequences for:

Particle Physics (BSM)

Cosmology (thermal history)

Focus of this talk is on the second question

Thermal DM:

Starting in a RD universe at $T >> m_\chi$:

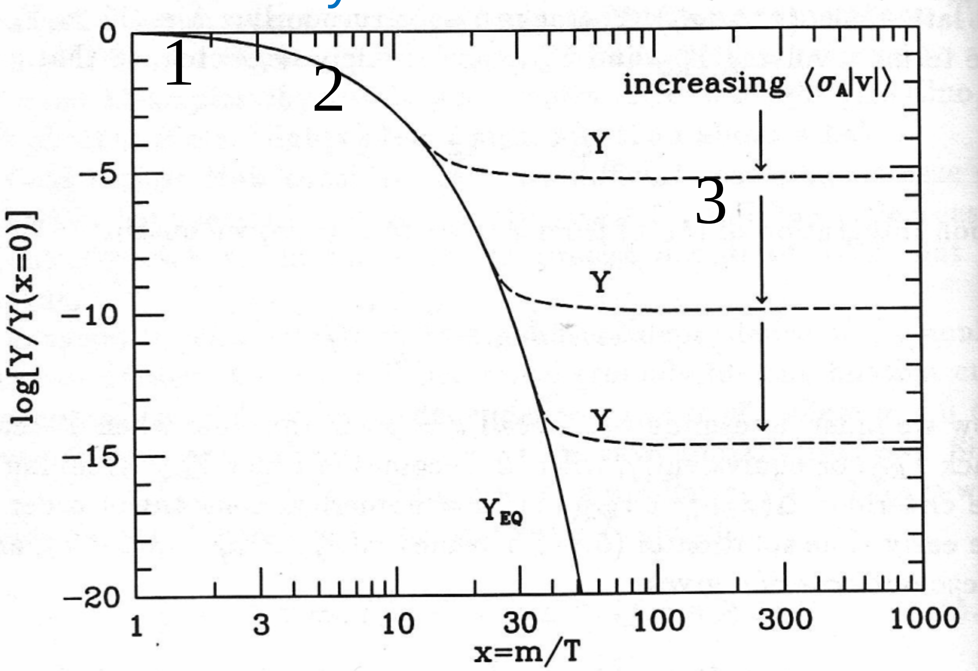
1) $T >> m_\chi$: $\chi\chi \leftrightarrow f\bar{f},\ldots \Rightarrow n_\chi \propto T^3$, $n_\chi / s = const$

2) $T < m_\chi$: $\chi\chi \rightarrow f\bar{f},\ldots \Rightarrow n_\chi \propto \exp(-m_\chi / T)$

3) $T \approx T_f$: $freeze-out \Rightarrow n_\chi / s = const$

$$\Omega_\chi h^2 \approx 10^{-1} \Rightarrow \boxed{<\sigma_{ann} v>_f = 3\times 10^{-26}\ cm^3 s^{-1}}$$

"The Early Universe" Kolb & Turner



WIMP miracle:

$$<\sigma_{ann} v>_f = \frac{\alpha_\chi^2}{m_\chi^2}$$

$$\alpha_\chi \sim O(10^{-2}),\ m_\chi \sim 10-10^3\ GeV$$

$$\Omega_\chi h^2 \sim 10^{-3} - 1 \qquad \boxed{t_f \lesssim 10^{-7}\ s}$$

In principle, thermal DM is a very attractive scenario:
- Predictive
- Robust

However:
- Nominal annihilation rate increasingly scrutinized by experiments

More importantly:
- Freeze-out during RD is an assumption

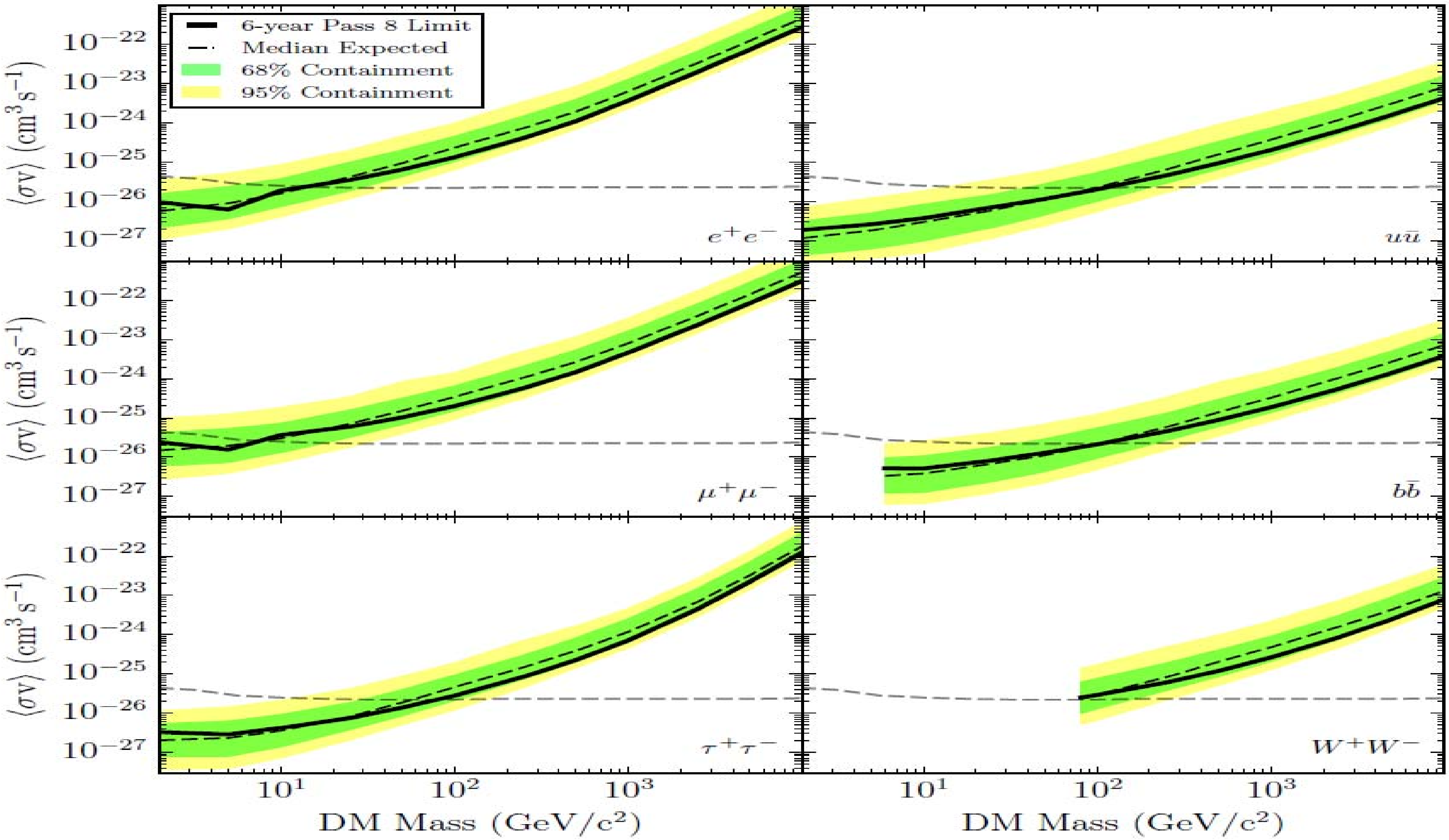
In fact, in a well-motivated class of particle physics models a RD universe is established much later than the freeze-out.

DM would a probe of the thermal history well before BBN, and discriminate the early universe models, after a discovery is made.

Studying alternatives to thermal DM is therefore well motivated.

Indirect detection experiments

Fermi Collaboration PRL 115, 231301 (2015)



For DM masses < *20 GeV*:

$$<\sigma_{ann} v>_f \; < 3\times 10^{-26}\; cm^3 s^{-1}$$

(assuming S wave 2→2 annihilation)

R. Leanne, T. Slatyer, J. Beacom, K. Ng PRD 98, 023016 (2018)

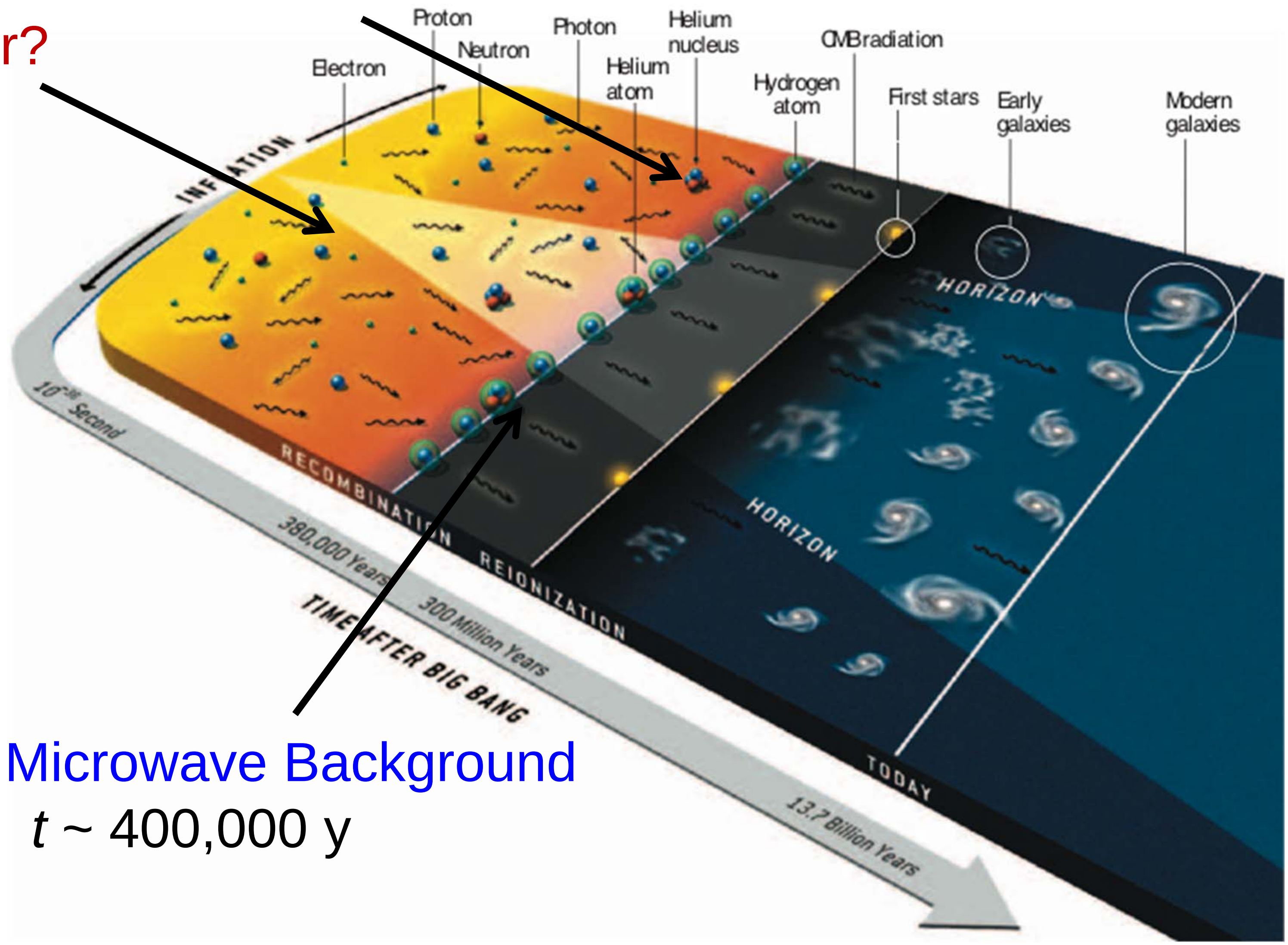
Current observational probes of the early universe

Big Bang Nucleosynthesis

t ~ *1* s

Dark Matter?

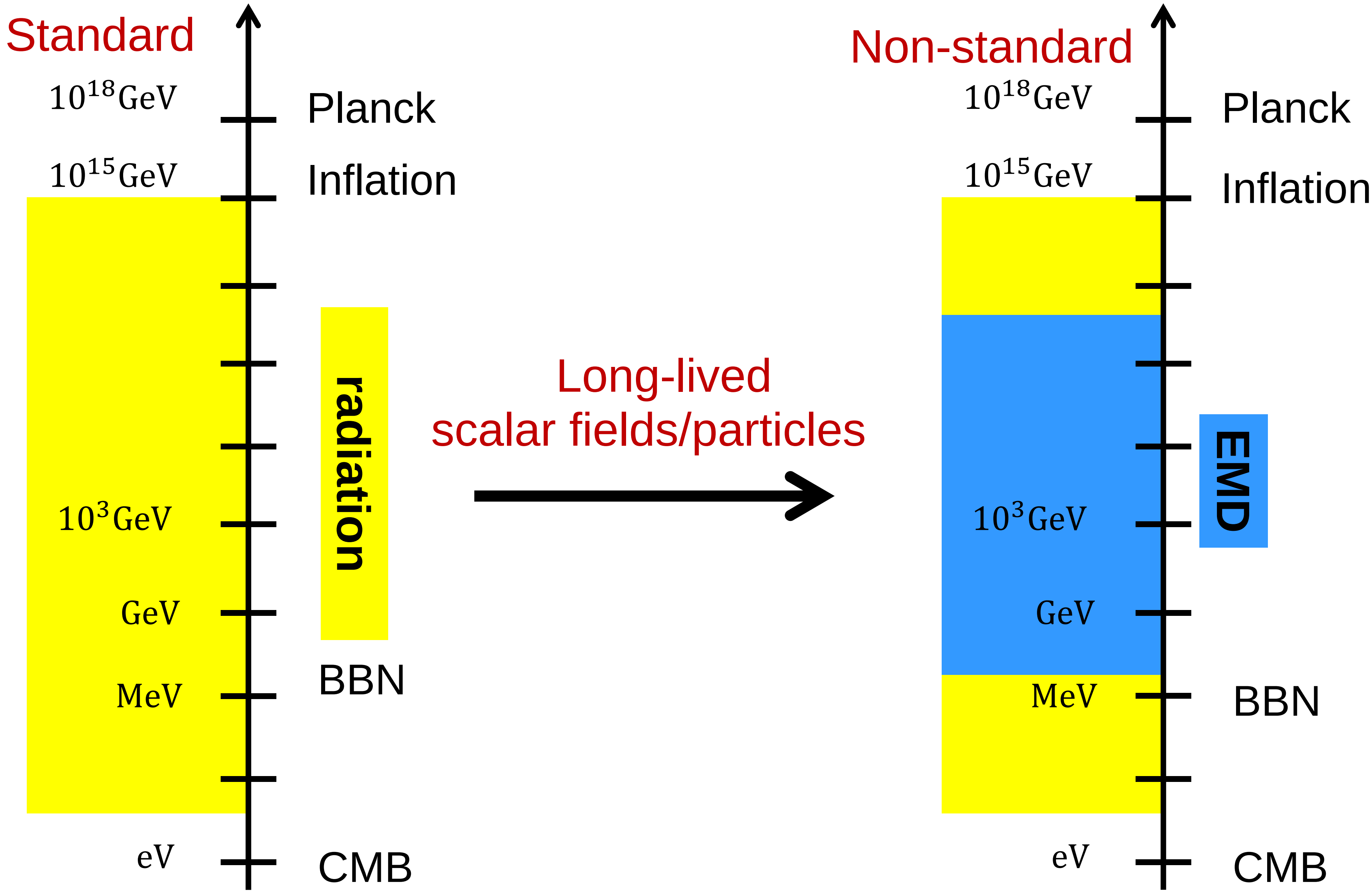
t << 1 s



Cosmic Microwave Background

t ~ 400,000 y

Standard thermal history altered in well-motivated models



G. Kane, K. Sinha, S. Watson IJMPD 8, 1530022 (2015)

Non-thermal DM from Early Matter Domination:

Consider a scalar field ϕ with mass m_ϕ and decay width Γ_ϕ .

Modulus fields in string theory are natural candidates for ϕ:

$$\Gamma_\phi \sim \frac{m_\phi^3}{M_P^2}$$

Dynamics in the early universe:

$H \gg m_\phi$: Displacement from the minimum during inflation

$H \simeq m_\phi$: Start of oscillations about the minimum

$\Gamma_\phi \ll H \lesssim m_\phi$: Oscillations dominate the universe

$H \simeq \Gamma_\phi$: Oscillations decay and form a RD universe $T_R \sim (\Gamma_\phi M_P)^{1/2}$

$$\dot{\rho}_\phi + 3H\rho_\phi = -\Gamma_\phi \rho_\phi$$
$$\dot{\rho}_r + 4H\rho_r = +\Gamma_\phi \rho_\phi$$
$$H^2 = \frac{\rho_\phi + \rho_r}{3M_P^2} \qquad \rho_r = \frac{\pi^2}{30} g_* T^4$$

$$\dot{n}_\chi + 3Hn_\chi = <\sigma_{ann} v>_f \left(n_{\chi,eq}^2 - n_\chi^2\right) + Br_\chi \Gamma_\phi n_\phi$$

Br_χ: number of DM quanta produced per decay of ϕ quanta

Decay can yield the correct abundance for small & large $<\sigma v>_f$.

M. Kawasaki, T. Moroi, T. Yanagida PLB 370, 52 (1996)
T. Moroi, L. Randall NPB 570, 455 (2000)
G. Gelmini, P. Gondolo PRD 74, 023510 (2006)
B. Acharya, G. Kane, S. Watson, P. Kumar PRD 80, 083529 (2009)
R.A., B. Dutta, K. Sinha PRD 83, 083502 (2011)

Correct abundance from thermal processes only for small $<\sigma v>_f$.

D. Chung, E. Kolb, A. Riotto PRD 60, 063504 (1999)
G. Giudice, E. Kolb, A. Riotto PRD 64, 043512 (2001)
A. Erickcek PRD 92, 103505 (2015)

We focus on <u>small</u> $<\sigma v>_f$.

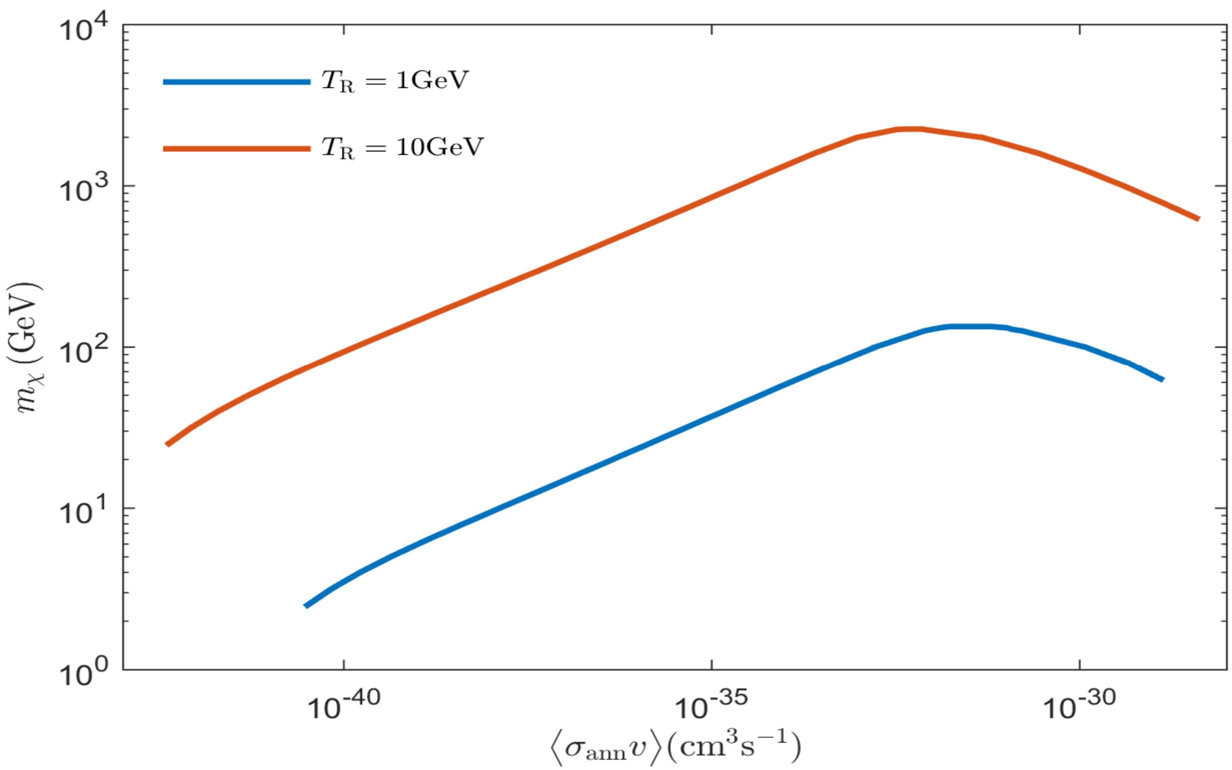
Freeze-out production:

$$\Omega_\chi h^2 \sim 1.6 \times 10^{-4} \left(\frac{m_\chi/T_f}{15}\right)^4 \left(\frac{150}{m_\chi/T_R}\right)^3 \left(\frac{3\times 10^{-26}\mathrm{cm}^3\mathrm{s}^{-1}}{<\sigma v>_f}\right)$$

Freeze-in production:

$$\Omega_\chi h^2 \sim 0.062 \left(\frac{150}{m_\chi/T_R}\right)^5 \left(\frac{T_R}{5\ \mathrm{GeV}}\right)^2 \left(\frac{<\sigma v>_f}{3\times 10^{-26}\mathrm{cm}^3\mathrm{s}^{-1}}\right)$$

A. Erickcek PRD 92, 103505 (2015)



R.A., J. Osinski
PRD 99, 083517 (2019)

Direct production from ϕ decay:

$$\frac{n_\chi}{s} = \frac{3T_R}{4m_\phi}\, Br_\chi$$

$$\boxed{\Omega_\chi h^2 \sim 2 \times 10^8\, Br_\chi \,\frac{T_R}{m_\phi} \left(\frac{m_\chi}{1\ GeV}\right)}$$

Note that the annihilation rate drops out of the expression for relic abundance.

However, in general, the RH side provides an upper bound on the relic abundance for large annihilation rate.

Residual annihilation can be efficient at the end of the decay when $< \sigma v >_f > 3 \times 10^{-26}\ cm^3\ s^{-1}$, which will lower the number of DM particles produced by from decay.

Connection to CMB:

For small annihilation rate, freeze-out/in & production from decay make up the entire DM relic abundance.

Each source should contribute less than the observed abundance.

In the EMD scenario, we have:

$$T_R < T_f \lesssim \frac{m_\chi}{5}$$

$H_0 \lesssim m_\phi$ H_0: Hubble rate at the onset of EMD

Useful parametrization:

$$H_0 = \alpha_0^2 m_\phi$$

In case of coherent oscillations of ϕ :

$$\alpha_0 \simeq \left(\frac{\phi_0}{m_\phi}\right)^2$$

ϕ_0: Initial amplitude of oscillations

We can find an absolute lower bound on the duration of EMD.

R.A., K. Dutta, A. Maharana JCAP 1810, 038 (2018)

From direct production alone, we have:

$$\frac{H_0}{H_R} \gtrsim 10^{10} \left(\frac{90}{\pi^2 g_{*,R}}\right)^{1/2} \left(\frac{M_P}{1\ GeV}\right) \alpha_0^2\, Br_\chi$$

From freeze-out, we get:

$$\frac{H_0}{H_R} \gtrsim 4 \times 10^{-2} (g_{*,R}\ g_{*,f})^{-1/3} \left(\frac{3 \times 10^{-26}\ cm^3\ s^{-1}}{< \sigma_{ann}\, v >_f}\right)^{4/3}$$

In case of freeze-in, we have:

$$\frac{H_0}{H_R} \gtrsim 4 \times 10^{3} (g_{*,R}\ g_*(m_\chi/4))^{-1/7} \left(\frac{< \sigma_{ann}\, v >_f}{3 \times 10^{-26}\ cm^3\ s^{-1}}\right)^{4/7}$$

Typically, direct production provides the tightest limit.

Effect on the number of e-foldings for cosmological perturbations relevant for CMB observations:

$$N_{k_*} \approx 57.3 + \frac{1}{4}\ln(r) - \Delta N_{reh} - \Delta N_{EMD}$$

$$\Delta N_{reh} = \frac{1 - 3w_{reh}}{6(1 + w_{reh})}\, ln\left(\frac{H_{inf}}{H_{reh}}\right)$$

$$\Delta N_{EMD} = \frac{1}{6}\, ln\left(\frac{H_0}{H_R}\right) > 0$$

$$w_{reh} \le \frac{1}{3} \Longrightarrow \Delta N_{k_*} \ge \Delta N_{EMD}$$

$$ln\left(\frac{H_0}{H_R}\right) \lesssim 344 - 6N_{k_*}^{min} + \frac{3}{2}\ln\left(r\left(N_{k_*}^{min}\right)\right)$$

The duration of EMD affects the inflationary observables, namely the scalar spectral index and the tensor-to-scalar ratio:

$$n_s = 1 - \frac{a}{N_{k_*}} \qquad\qquad r = \frac{b}{N_{k_*}^c}$$

Lets consider two universality classes of single field models.
D. Roest JCAP 1401, 007 (2014)

- Class I: $a = c\,, b \sim O(10)$

Prototypical models are Starobinsky inflation and Higgs inflation.

Typically have a small tensor-to-scalar ratio $r \lesssim O(0.01)$.

- Class II: $b = 8(a-1), c = 1$

Includes large field models such as the axion monodromy model.

Have a sizeable tensor-to-scalar ratio $r \sim O(0.1)$.

Results:

We have chosen a handful of inflationary models consistent with the latest Planck results.

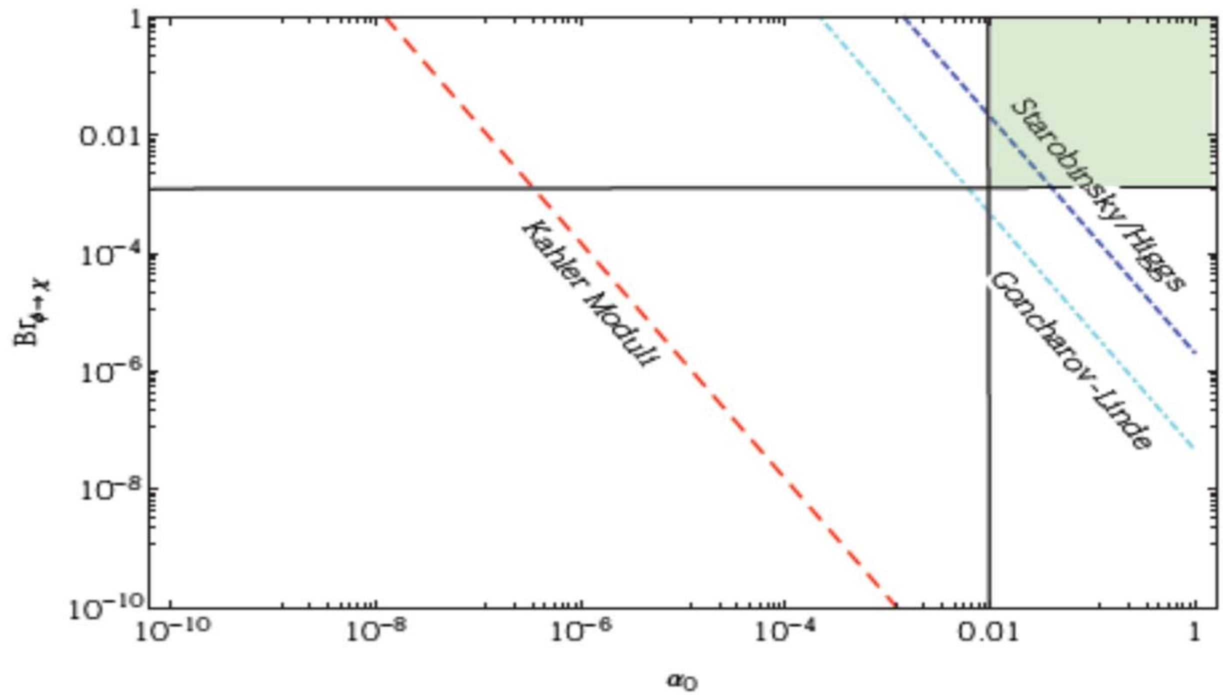
Planck 2σ : $n_s = 0.9659 \pm 0.0082$

Planck+BK14+BAO 2σ : $n_s = 0.9670 \pm 0.0074$

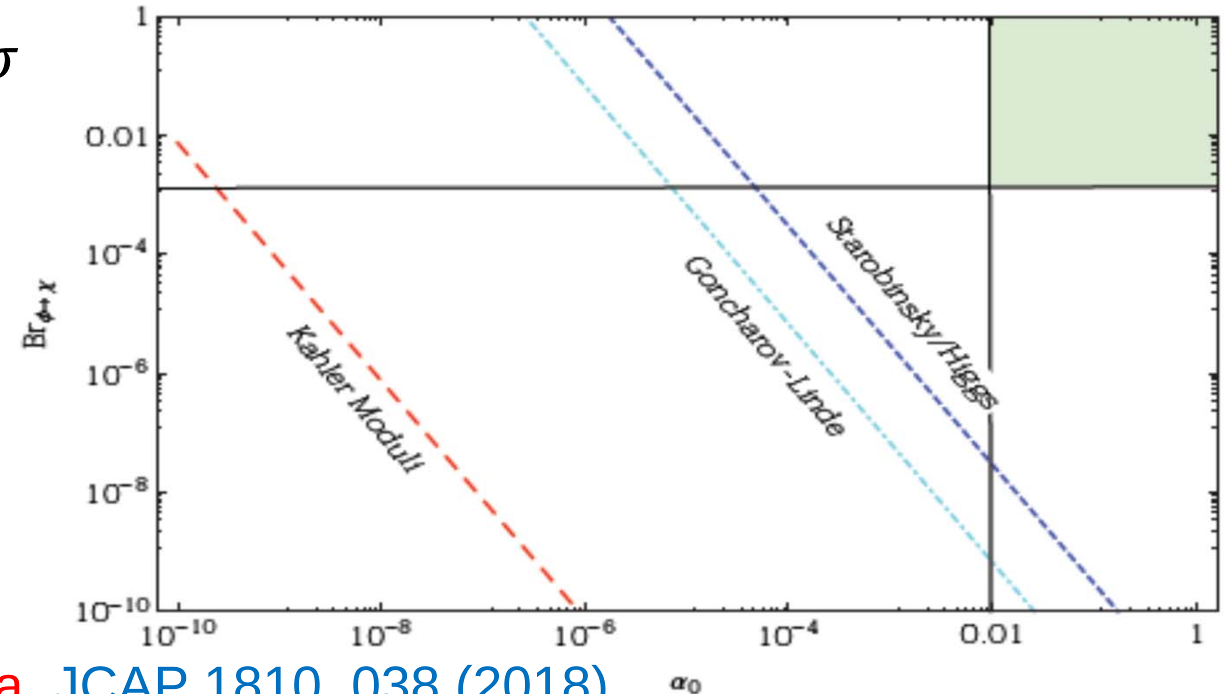
	PLANCK18			PLANCK18 + BK14 + BAO		
Inflation Models	$N_{k_*}^{min}$	$r(N_{k_*}^{min})$	ΔN_{EMD}^{up}	$N_{k_*}^{min}$	$r(N_{k_*}^{min})$	ΔN_{EMD}^{up}
$V(\phi) \sim \phi^{4/3}$	39.4	0.13	17.4	41.2	0.13	15.5
$V(\phi) \sim \phi$	35.5	0.11	21.3	37.1	0.11	19.6
Starobinsky/Higgs Inflation	47.3	0.0054	8.7	49.5	0.0049	6.5
Kähler Moduli Inflation	47.3	9.46×10^{-10}	4.8	49.5	8.24×10^{-10}	2.57
Goncharov-Linde Model $(\alpha = 1/9)$	47.1	0.00059	8.1	49.3	0.00054	5.8

R.A., K. Dutta, A. Maharana JCAP 1810, 038 (2018)

Planck 2σ



Planck+BK14+BAO 2σ



R.A., K. Dutta, A. Maharana JCAP 1810, 038 (2018)

EMD driven by moduli typically predicts:

$\alpha_0 \gtrsim O(0.01)$

For LSP DM, in this scenario, we expect:

$Br_\chi \gtrsim O(10^{-3})$

The lower bound comes from three-body decay to gauginos.

R.A., B. Dutta, K. Sinha PRD 83, 083502 (2011)
R.A., M. Cicoli, B. Dutta, K. Sinha PRD 88, 095015 (2013)

SUSY DM from modulus decay disfavored in models with small r .

The situation relaxed for extensions of LCDM, e.g., with $\Delta N_{eff} \neq 0$.

In explicit models, modulus decay also generates some DR. However, it may not be easy to have non-thermal DM along with a small amount of DR.

R.A., M. Cicoli, B. Dutta, K. Sinha JCAP 1410, 002 (2014)

Conclusion and Outlook:

- An epoch of EMD is typical in a well-motivated class of models
- EMD provides a framework for non-thermal production of DM
- For small annihilation rate duration of EMD bounded from below
- CMB constraints typically limit length of EMD from above
- Models with small r may disfavor SUSY DM from moduli decay
- Future data from CMB S4 can set even stronger constraints
- Modest amount of DR can relax the tension
- Warrants further study of models for non-thermal DM+DR
- Interesting to include information from primordial gravity waves