How *Complex Scalar Field* Dark Matter conspires to facilitate EWBG

Tanja Rindler-Daller

Dep.of Physics & MCTP, U. Michigan, Ann Arbor

Collaborators:

Bohua Li, Paul Shapiro (SFDM: cosmological implications)

Marek Lewicki, James Wells (SFDM: implications for EWBG)

DPF 2015, Ann Arbor, Aug 6th, 2015

Cold DM as an ultralight spin-0 boson

Can have favorable astrophysical features:

Jeans/clustering scale may resolve galactic small-scale structure problems

Appear in BSM theories

Real, pseudoscalars: cold due to vacuum misalignment

- QCD axion
- Axion-like particles

Complex, scalar: cold due to evolution of EOS (dep. on potential)

- Ultralight bosons $m \ll 10^{-6}$ eV

Real ↔ complex SFDM: similar at late times (structure formation),

very different at early times

Genesis of complex SFDM

- (Standard) Inflation gives way to reheating
- Reheating produces SM + DM (ultralight bosons) in thermal EQ
- the latter move readily into their ground state due to their high phase-space density → form BEC
- Ever after described as a complex scalar field ('condensate wave function'), obeying the Klein-Gordon equation in an expanding Universe

Complex SFDM

Complex scalar field $\psi = |\psi|\, e^{i\theta}$

$$\mathscr{L} = \frac{\hbar^2}{2m} g^{\mu\nu}\partial_\mu\psi^*\partial_\nu\psi - V(\psi) \qquad V(\psi) = \frac{1}{2}mc^2|\psi|^2 + \frac{\lambda}{2}|\psi|^4$$

units: $[\mathcal{L}]$ = [eV/cm^3], [ψ] = cm$^{-3/2}$, $\lambda = \hat{\lambda}\frac{\hbar^3}{m^2 c}$

Complex field obeys U(1)-symmetry:

'charge conservation' = conservation of DM abundance

2-body repulsive interactions only

$\lambda \geq 0$ is an energy-independent coupling constant

Fundamental SFDM parameters: m and λ

Equations of motion

Klein-Gordon equation for the scalar field ψ

$$g^{\mu\nu}\partial_\mu\partial_\nu\psi - g^{\mu\nu}\Gamma^{\sigma}{}_{\mu\nu}\partial_\sigma\psi + \frac{m^2c^2}{\hbar^2}\psi + \frac{2\lambda m}{\hbar^2}|\psi|^2\psi = 0$$

Einstein field equations

$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R = \frac{8\pi G}{c^4}T_{\mu\nu}$$

Background evolution of a ΛSFDM universe
(Li,TRD,Shapiro, arXiv:1310.6061)

1) Inflaton-domination:

- (Standard) Inflation
- Reheating (w=0, “CDM-like EOS”)

→ DM bosons form condensate, giving rise to

2) SFDM-domination (w=1, “stiff EOS”):

akin to 'kination': kinetic term due to phase dominates over V

3) SFDM morphes from w=1 to w=1/3 (“radiation-like EOS”): quartic term in V dominates

Radiation-domination (Radiation dominates over SFDM, but SFDM is still relativistic)

4) SFDM morphes from relat. to non-relat. (w=1/3 → w=0 “CDM-like EOS”):

quadratic term in V dominates: **Matter-domination**

5) Λ – domination (assuming cosmological constant)

Background evolution of a ΛSFDM universe

(Li,TRD,Shapiro, arXiv:1310.6061)

Relativistic SFDM changes the expansion history in the early Universe

→ constraints from: a_eq, BBN, primordial GWs, other baryonic processes, ..

Take the same cosmic inventory as the basic ΛCDM model,

except that CDM is replaced by SFDM → ΛSFDM

Cosmological parameters from **Planck results XVI (2013)**:

$$\Omega_m = \Omega_b + \Omega_c$$

$$\Omega_\Lambda = 1 - \Omega_m - \Omega_r$$

assuming SM neutrinos are *massless*

Basic		Derived	
h	0.673	$\Omega_m h^2$	0.14187
$\Omega_b h^2$	0.02207	$\Omega_r h^2$	4.184×10^{-5}
$\Omega_c h^2$	0.1198	$z_{\rm eq}$	3390
$T_{\rm CMB}/{\rm K}$	2.7255	Ω_Λ	0.687

TABLE I. Cosmological parameters. The values in the left column ('Basic') are quoted from the Planck collaboration: central values of the 68% confidence limits for the base ΛCDM model with Planck+WP+highL data, see Table 5 in [5]. We calculate those in the right column ('Derived').

Fiducial SFDM Model

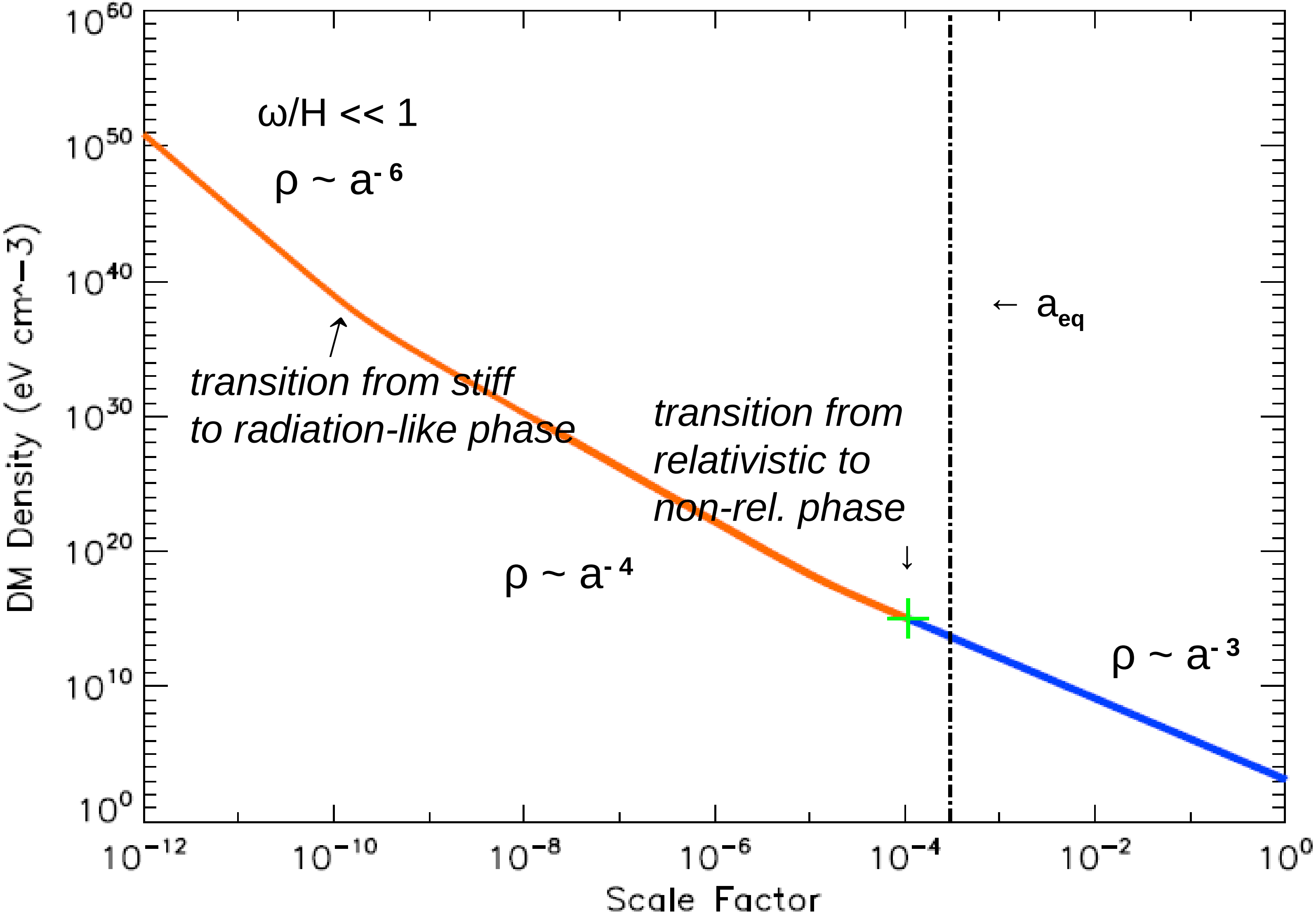
$$(m, \lambda)_{\rm fiducial} = (3 \times 10^{-21}\ {\rm eV/c^2}, 1.8 \times 10^{-59}\ {\rm eV\ cm^3})$$

$$\lambda/(mc^2)^2 = 2 \times 10^{-18}\ {\rm eV^{-1}\ cm^3}$$

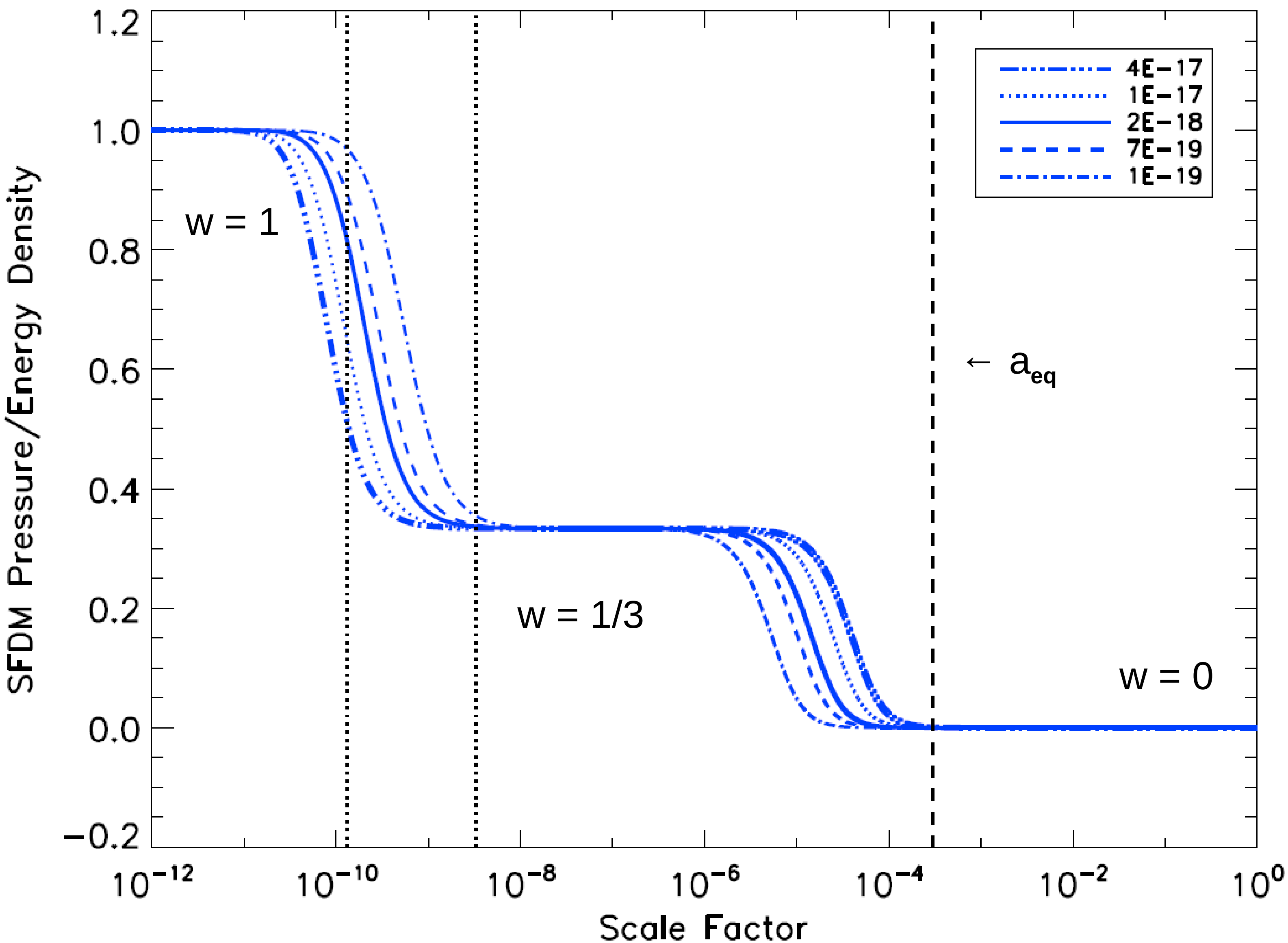
in natural units: $\hat{\lambda}_{\rm fiducial} \simeq 10^{-83}$

for comparison $\hat{\lambda}_{\rm QCDaxion} \simeq 10^{-57}$

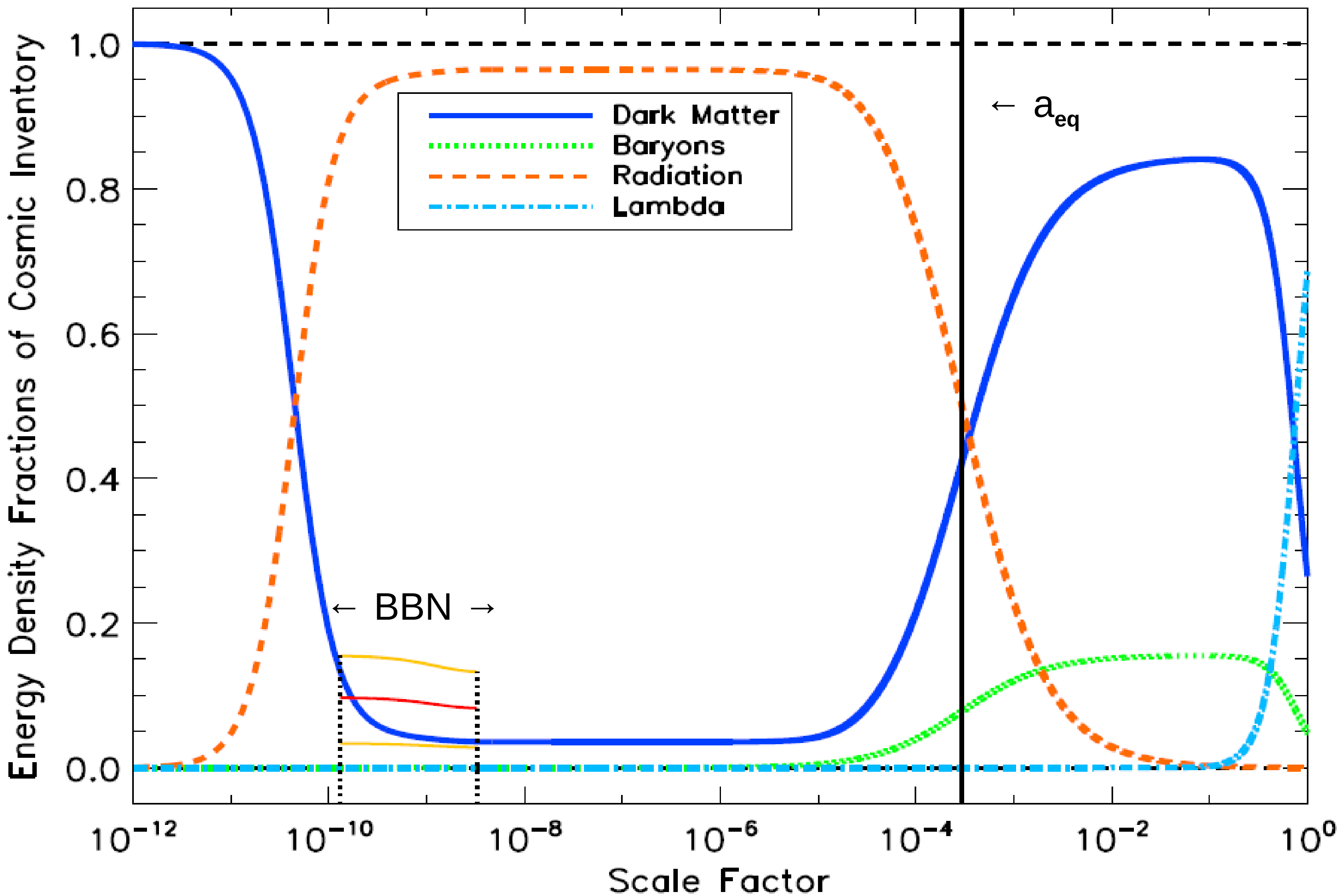
Evolution of SFDM energy density



The larger $\lambda/(mc^2)^2$, the longer lasts the radiation-like phase



Evolution of ΛSFDM universe



We impose a conservative constraint: the N_{eff} during BBN *be all the time* within the **1σ confidence limits** of

$$N_{eff} = 3.71^{+0.47}_{-0.45} \quad \text{or} \quad \Delta N_\nu = 0.66^{+0.47}_{-0.45}$$ (Steigman 2012)

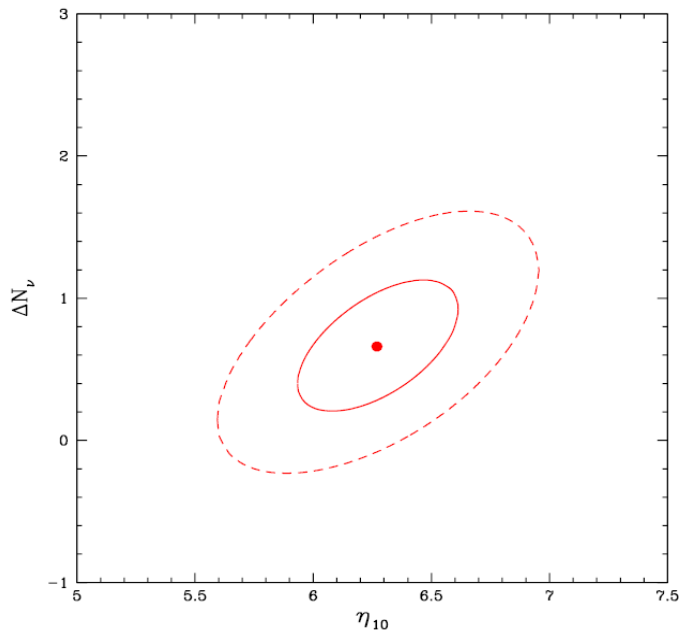
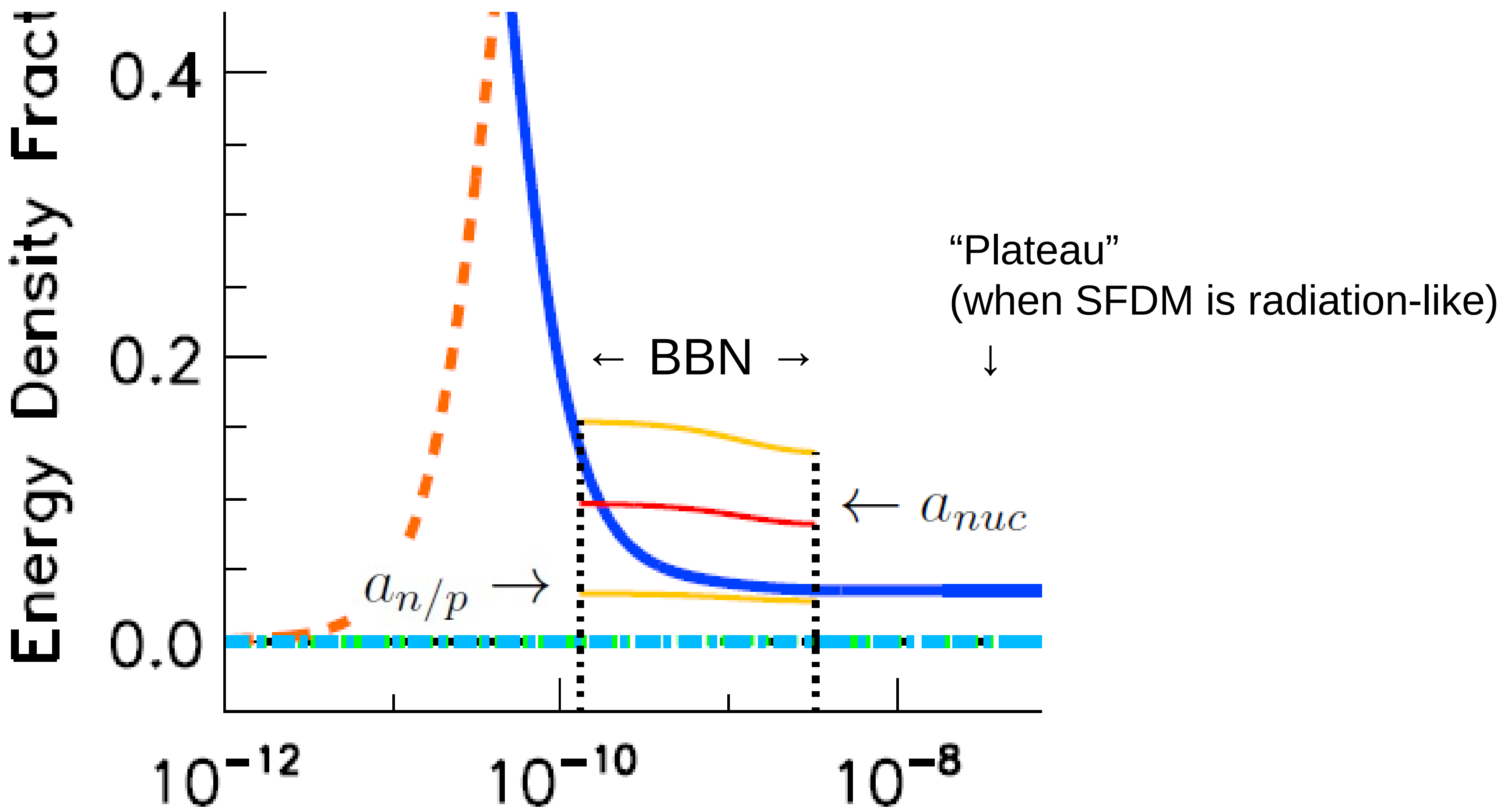


Figure 4: The BBN-inferred 68% (solid) and 95% (dashed) contours in the $\Delta N_\nu - \eta_{10}$ plane derived from D and ^{4}He assuming that $\xi = 0$.

Evolution of ΛSFDM during BBN



Constraints on SFDM from BBN

effective number of relativistic degrees of freedom / neutrinos: N_{eff}

the relation between N_{eff} and Ω_{SFDM} is analytic during the „plateau“ (i.e. during the radiation-like phase) *if* SFDM reaches it before a_{nuc}:

$N_{eff} = 3.71^{+0.47}_{-0.45}$ → $0.028 \leq \Omega_{SFDM,plateau} \leq 0.132$

the higher $\lambda/(mc^2)^2$, the higher the "plateau"

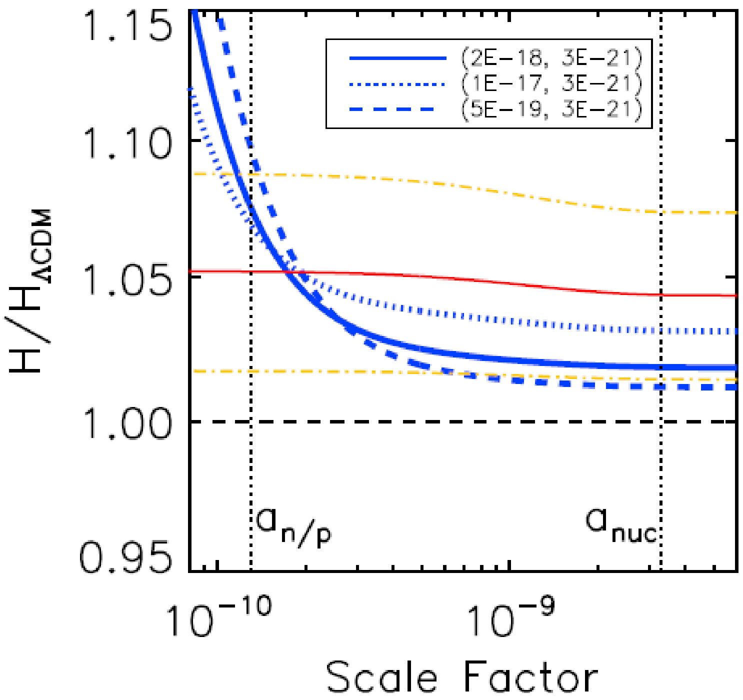
→ *constraint on* $\lambda/(mc^2)^2$

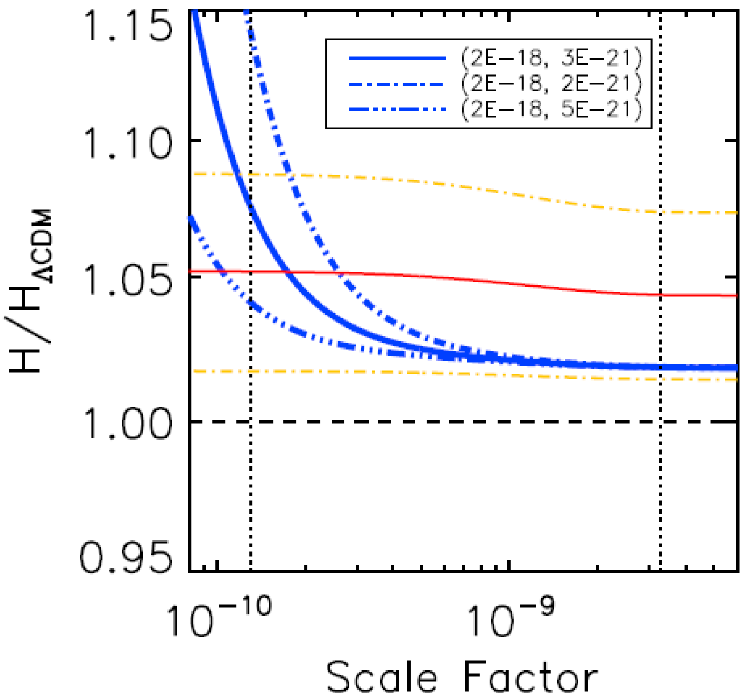
$$9.5\times10^{-19}\,\mathrm{eV}^{-1}\ \mathrm{cm}^3 \leq \lambda/(\mathrm{mc}^2)^2 \leq 1.5\times10^{-16}\,\mathrm{eV}^{-1}\ \mathrm{cm}^3$$

Constraints on SFDM from BBN

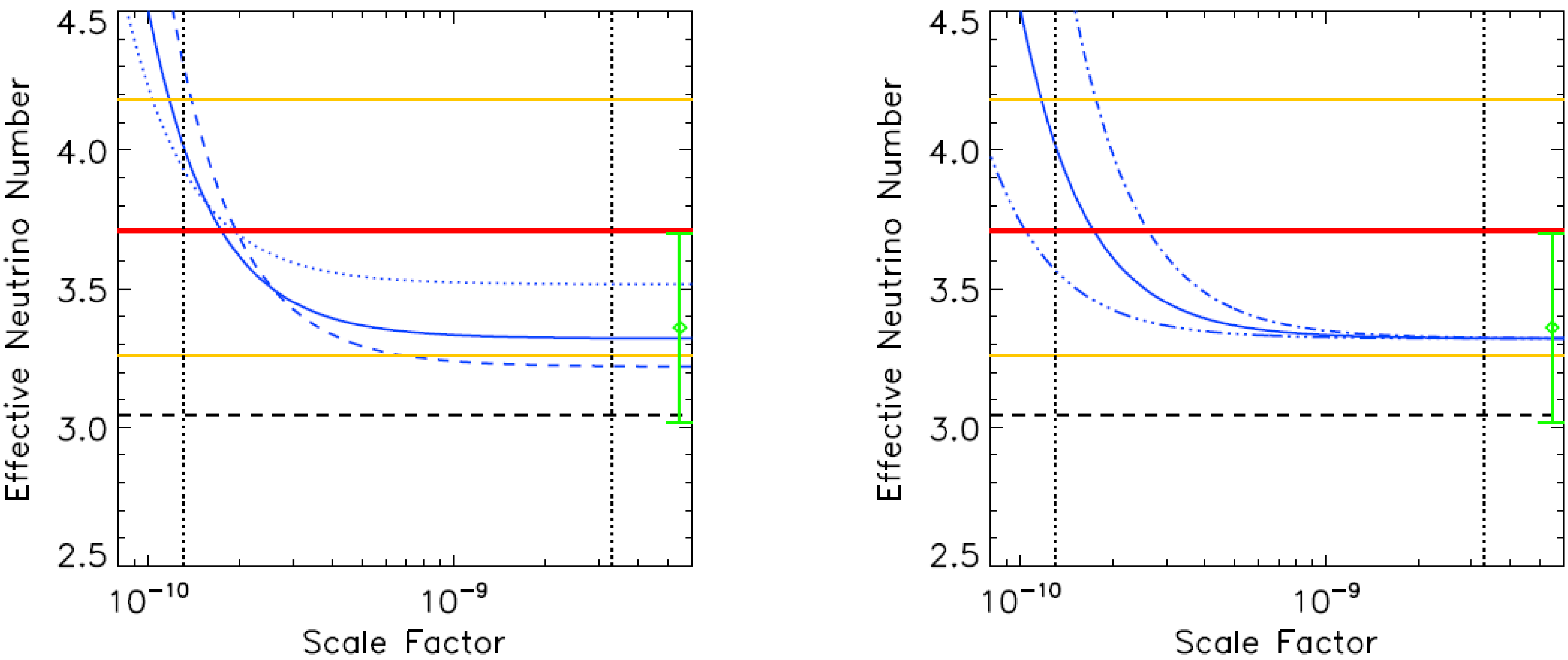
Meanwhile, earlier at $a_{n/p}$, the transition from the stiff to the radiation-like phase may not have finished and the value of **N_{eff} can be higher than at the plateau** – this is a function of *both* $\lambda/(mc^2)^2$ **and** m

→ *constraint on $\lambda/(mc^2)^2$* ***and*** *m*



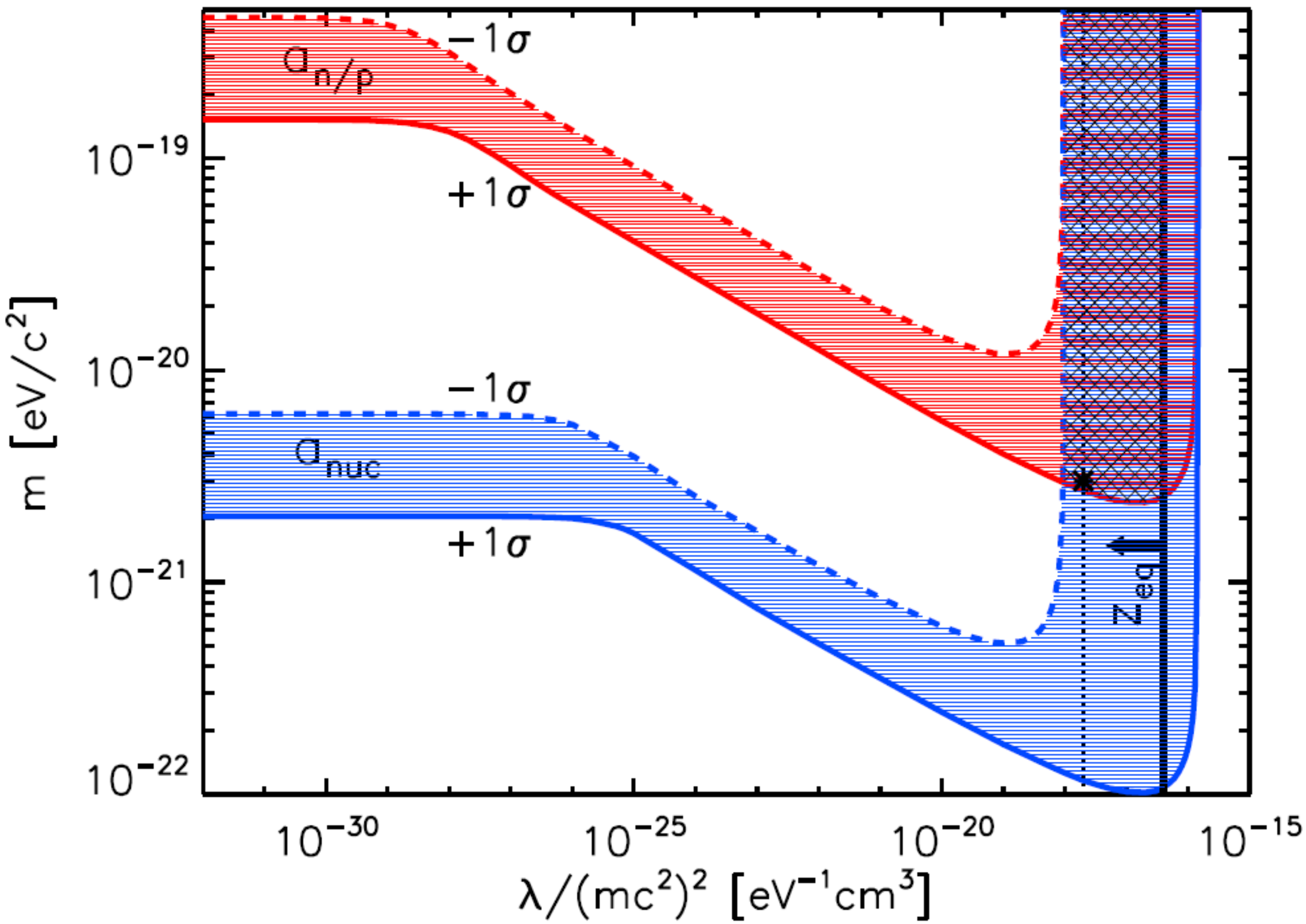


Constraints on SFDM from BBN



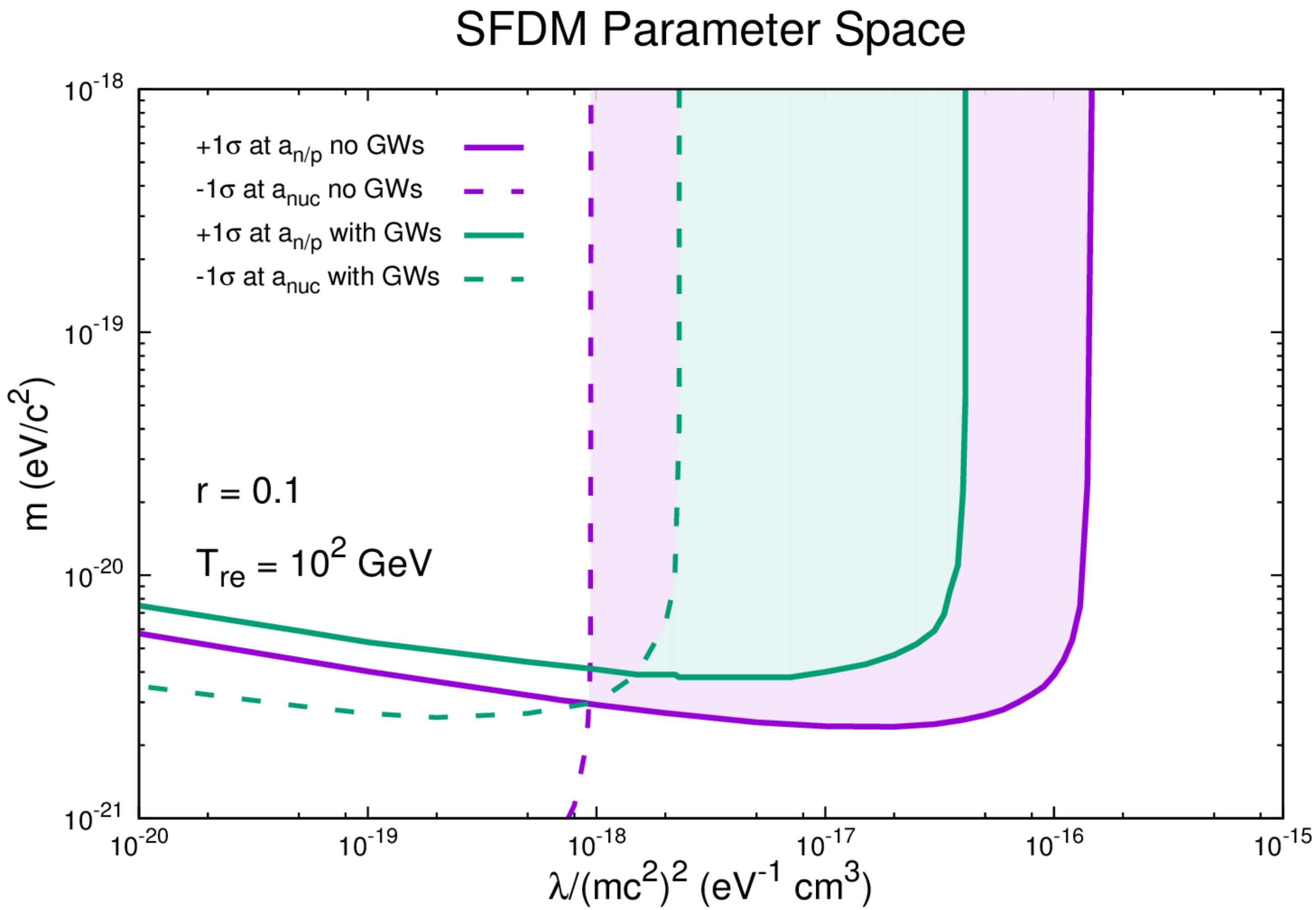
compare: **N_{eff} = 3.36 ± 0.34** (green bar) from CMB alone (Planck+WP+highL)

Allowed parameter space for SFDM from a_eq plus BBN



Allowed parameter space for SFDM from a_eq plus (updated) BBN plus GWs

(Li,TRD,Shapiro,in prep)



Background evolution of a ΛSFDM universe with GWs
(Li,TRD,Shapiro, in prep)

- SFDM is compatible with T_rh higher than the EW scale

- However, higher T_rh implies a higher lower-bound limit on the SFDM particle mass

  e.g. T_rh = 100 GeV → m >~ 3 x 10^{-21} eV

  1 TeV → 3 x 10^{-20} eV

  This is for a given value of r = 0.1. If r < 0.1, the bounds will be relaxed.

- T_rh is mostly a constraint on the SFDM mass m, while it is the N_{eff} during BBN which constrains λ/m^2 most.

Change of exp.history → implications for PTs in early Universe

Criteria for successful EWBG / strong enough 1st order PT:

1) sphalerons be out-of-equilibrium in the broken phase
   → need high enough expan.rate during EW symmetry breaking

2) sufficient CP violation to result in observed amount of baryon asymmetry

Concern ourselves only with 1)

Change of exp.history → implications for PTs in early Universe: Idea exploited before

Joyce 97, Joyce & Prokopec 98:

“Kination” driven by a real, relic scalar field with the desired V

Implies *modified (weaker) bounds* on:

- Sphaleron energy
- Expansion rate
- Ratio of Higgs vev to T_c to be a strong enough 1st order PT

$$\frac{v_c}{T_c} > \left(\frac{v_c}{T_c}\right)_{\Lambda\mathrm{CDM}} - \frac{0.06}{\mathcal{B}} \ln \frac{H_{\Lambda SFDM}}{H_{\Lambda CDM}}$$

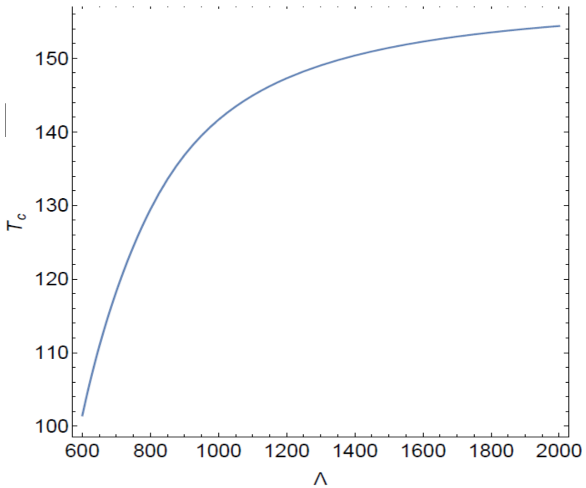
Implication of a ΛSFDM universe on EWBG
(TRD, Lewicki, Wells, in prep)

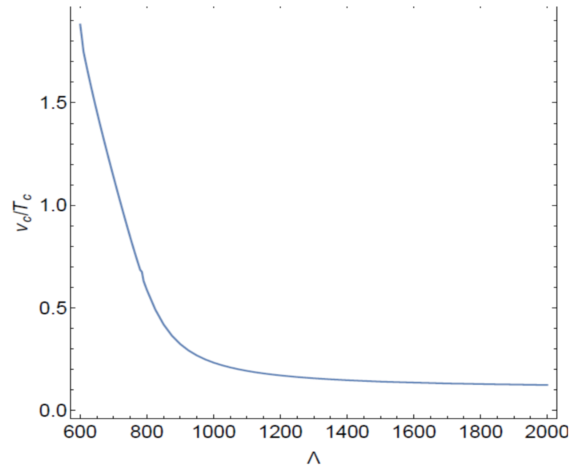
- In our model, it is the *dynamical evolution of Dark Matter (SFDM)* which is responsible for the change in the expansion rate
- Implication for single Higgs doublet (SM EWBG)
- Implication for single Higgs doublet with *modified Higgs self-interactions* (Grojean, Servant, Wells 05; Delaunay, Grojean, Wells 08)

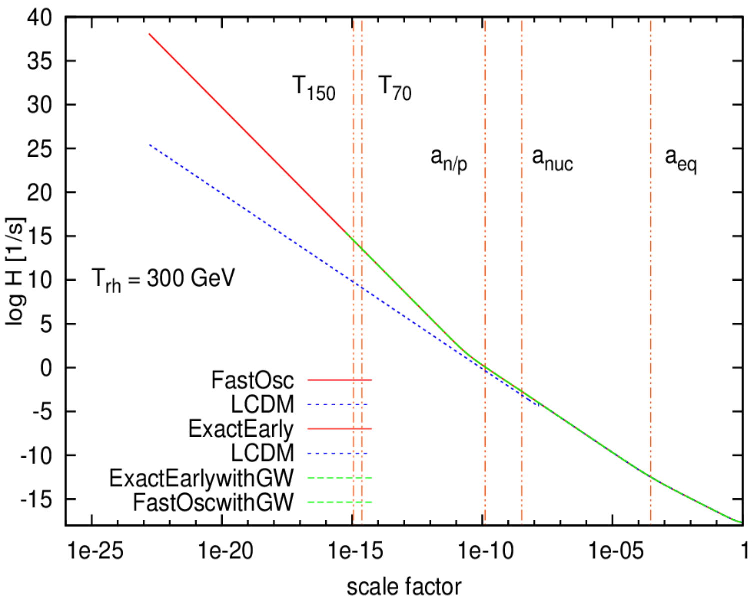
$$V(H) = -\frac{m^2}{2}|H|^2 + \lambda|H|^4 + \frac{1}{\Lambda^2}|H|^6$$

for a Higgs mass of 125 GeV

Implication of a ΛSFDM universe on EWBG
(TRD, Lewicki, Wells, in prep)







Conclusions

- Complex SFDM is a good dark matter candidate so far → but work in progress whether that remains true for structure formation
- We constrained the allowed parameter space severely (compared to previous literature), by considering only the evolution of the background universe
- There remains a semi-infinite stripe in the parameter space which is in accordance with current observations, including parameter sets which are able to resolve the small-scale problems of CDM
- Complex SFDM with self-interaction provides a natural explanation of why N_{eff} during BBN is higher than that inferred from the CMB from Planck data
- Much higher expansion rate due to 'stiff phase' of early SFDM-domination may facilitate baryonic 1st order phase transitions, notably EWBG