Koushik Dutta

Theory Division, Saha Institute of Nuclear Physics, Kolkaka

Constraining non-thermal Dark Matter by CMB

(arXiv:1808.02659)

with Rouzbeh Allahverdi and Anshuman Maharana

Physics Department
Indian Institute of Technology, Bombay

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Key Points (arXiv:1808.02659)

- Early matter domination (EMD) is observationally allowed
- Dark matter (DM) can be produced non-thermally
- Correct DM abundance puts a lower bound on the duration of EMD
- Inflationary scalar spectral index puts an upper bound on the duration of EMD
- A large class of inflation models ($r < 0.01$) are not compatible** with EMD

Plan

- Key points of Inflation, and DM production
- EMD history of the Universe
- DM production during EMD
- Relating to inflationary observables
- Constraints on models

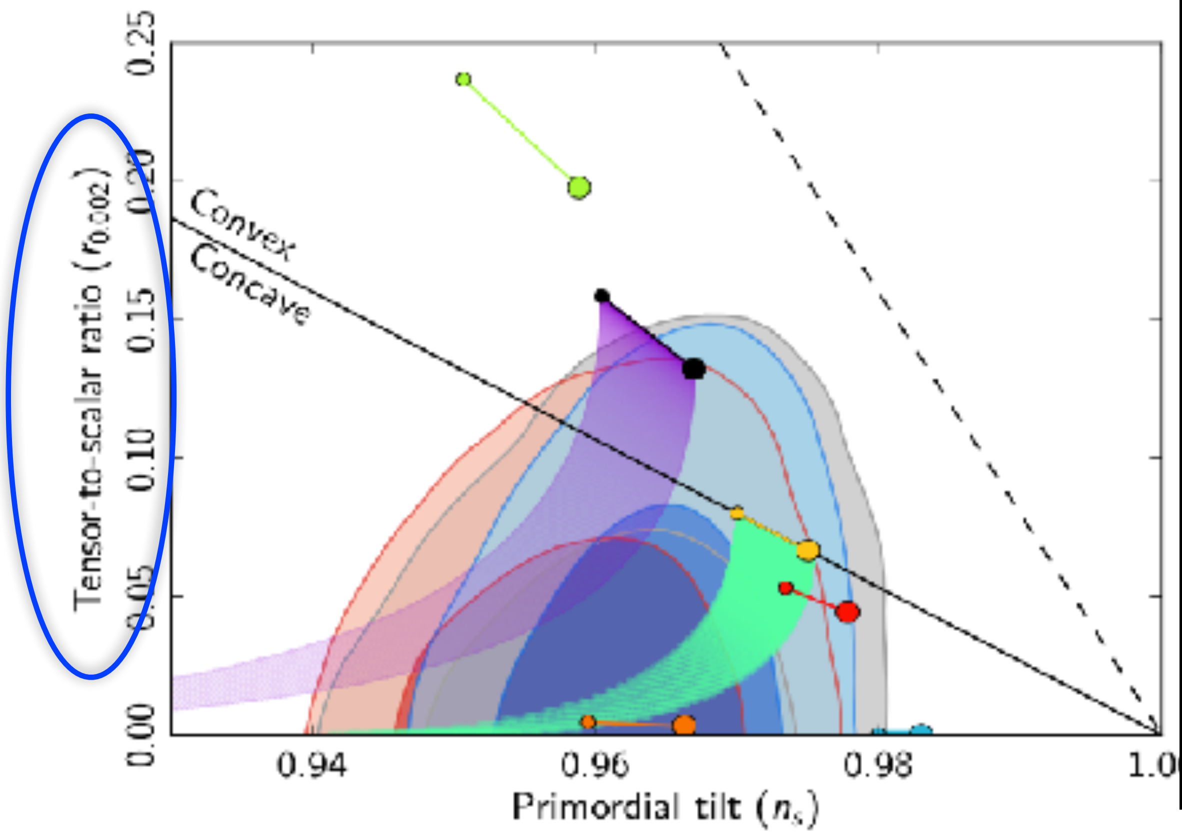
From data ONLY

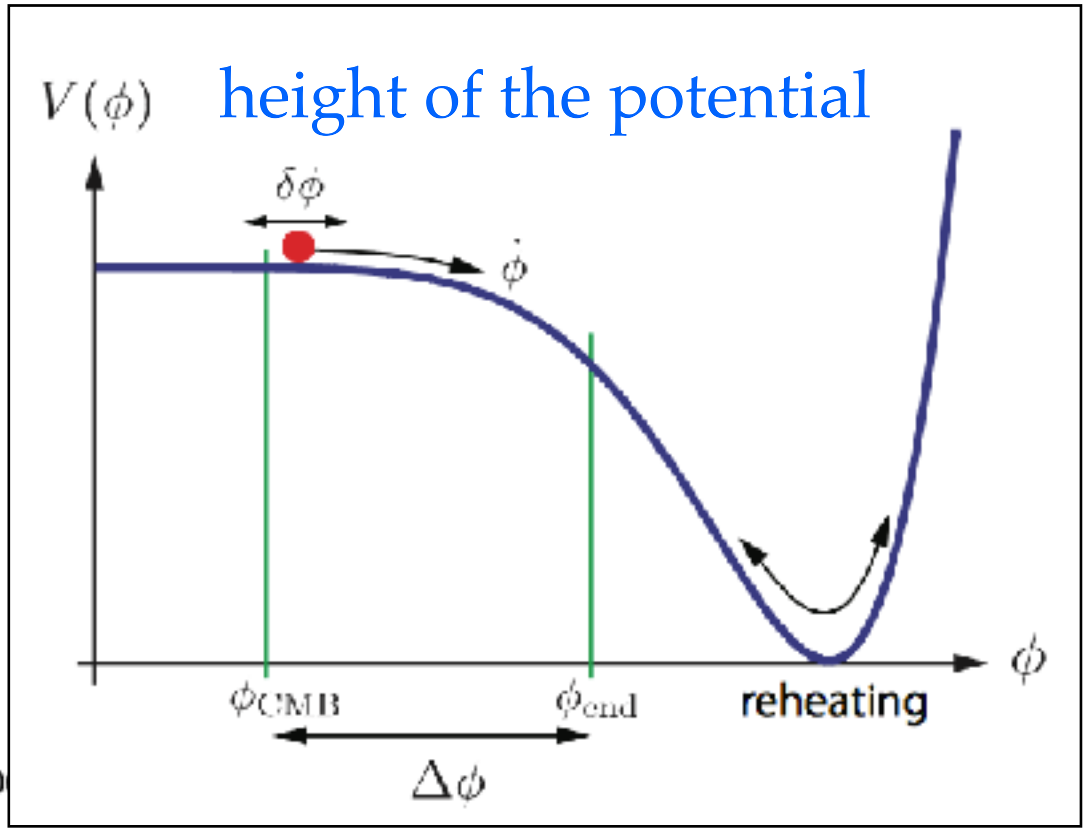
- At the time of BBN, the Universe was radiation dominated
- The existence of primordial spectrum

$$\Delta^2_{\mathcal{R}}(k) = A_s (k/k_*)^{n_s - 1}$$

- Coherent super-Hubble perturbations (.. due to inflation)
- Dark matter .. gravitational collapse

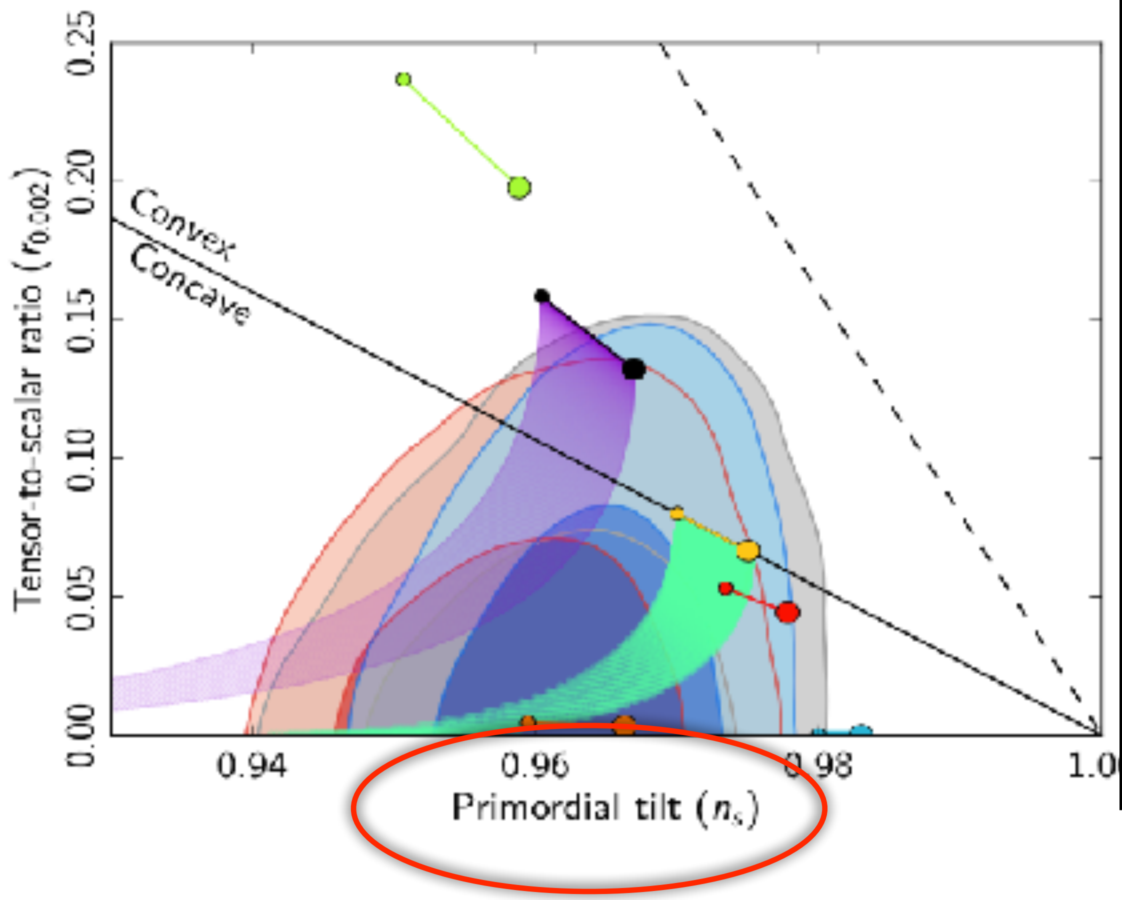
Inflation Observables

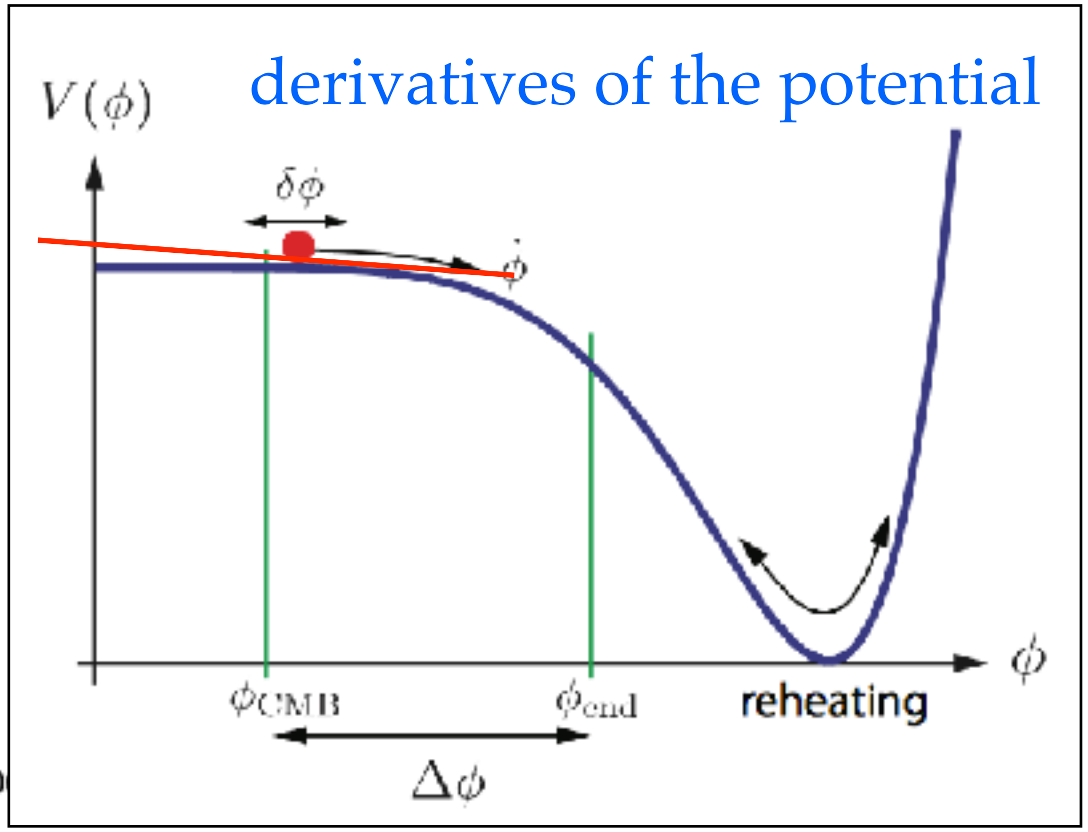




$$V^{1/4} \sim \left(\frac{r}{0.01}\right)^{1/4} 10^{16}\ GeV$$

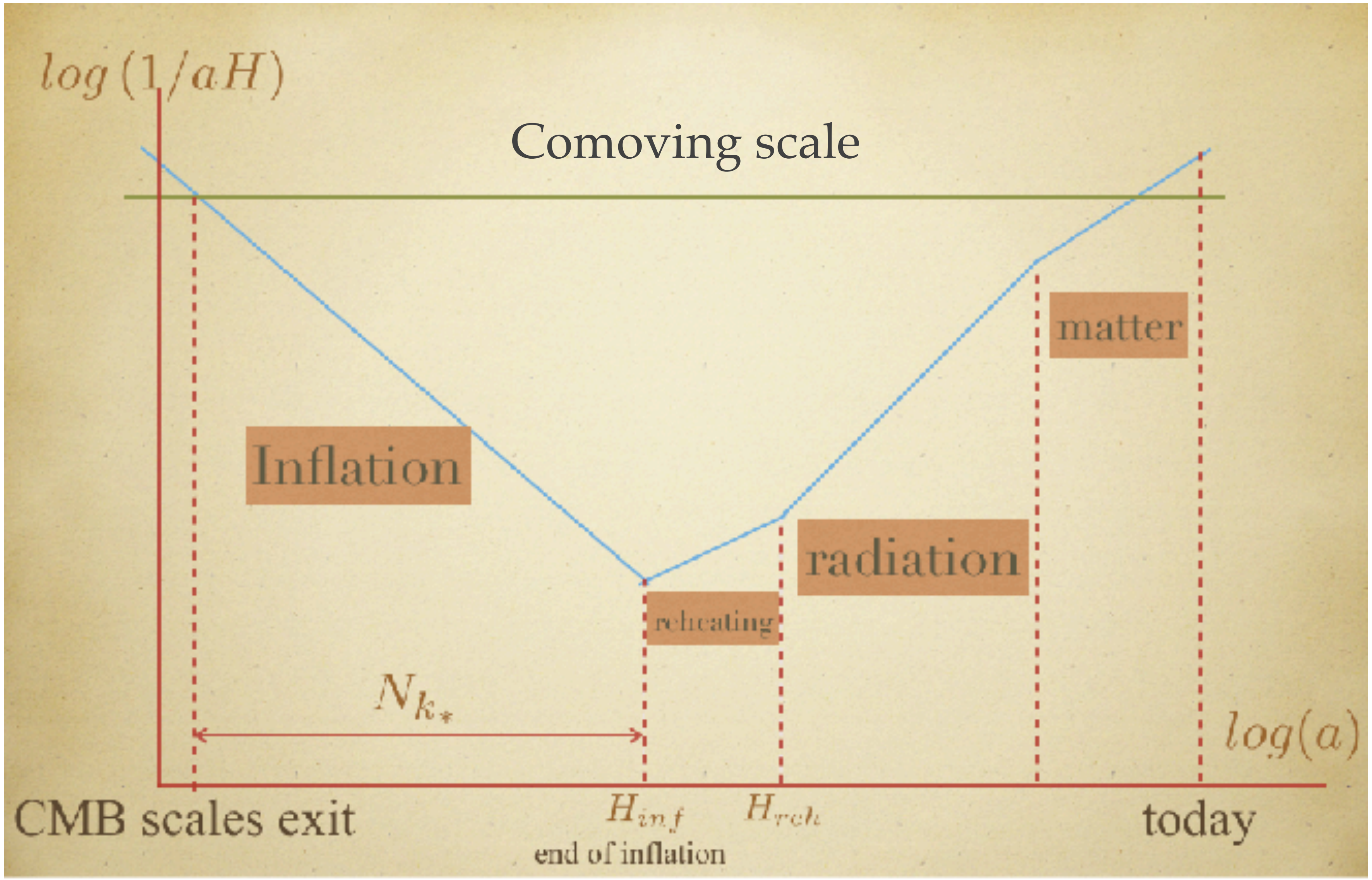
Inflation Observables





$$n_s = 1 - 6\epsilon + 2\eta$$

Thermal History



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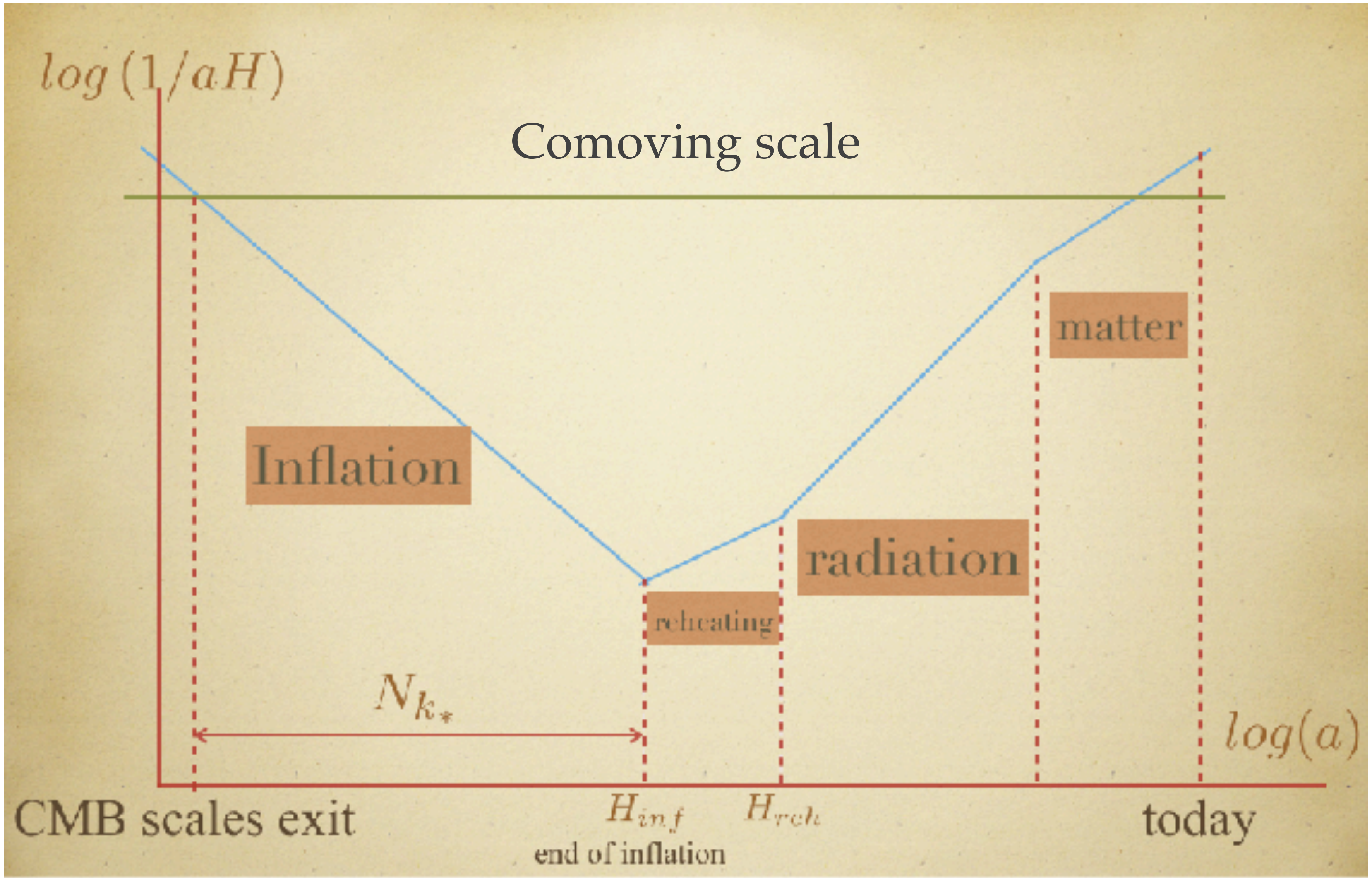


$$N_{k_*} \sim 57.3 + \frac{1}{4} ln(r) - \Delta N_{reh}$$

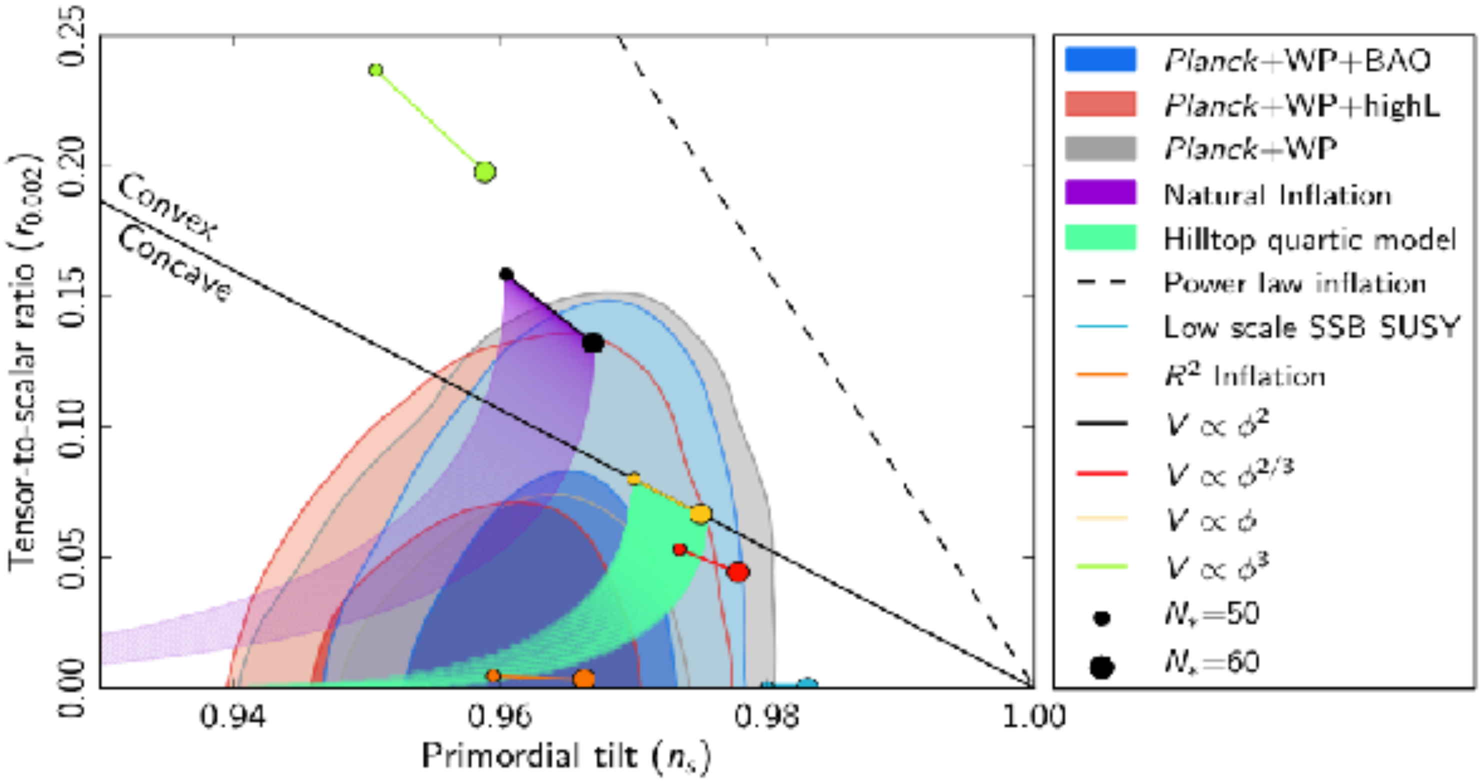
$$\Delta N_{reh} \equiv \frac{1 - 3w_{reh}}{6(1 + w_{reh})} log\left(\frac{H_{inf}}{H_{reh}}\right)$$

Liddle, Leach (2003)

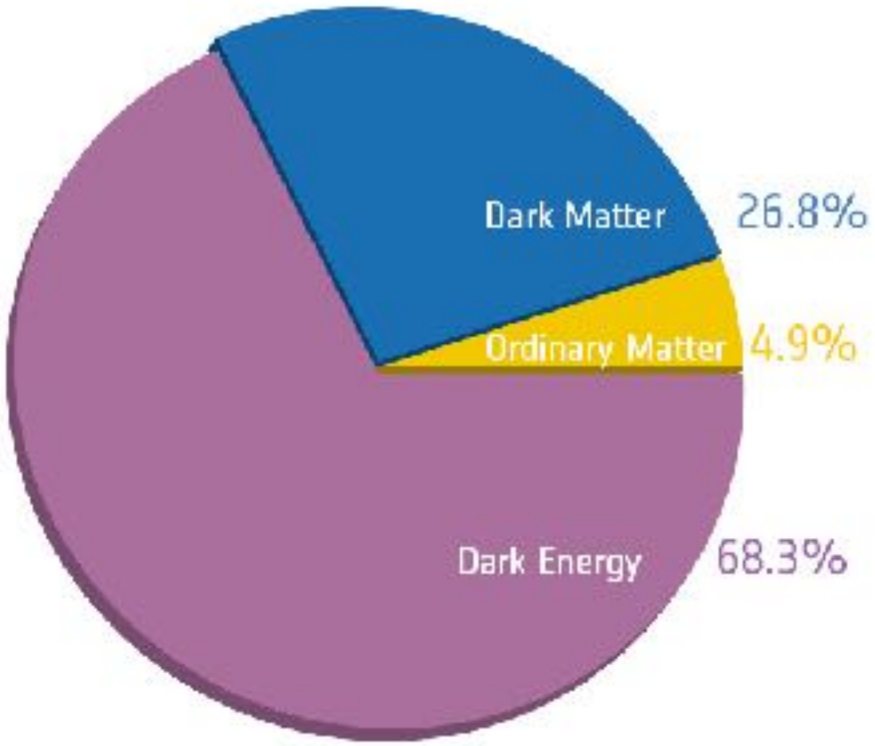
Making Predictions

- Compute observables in terms of N_{k_*} and see whether it fits for $N_{k_*} = 50$ and 60 ('theoretical prior')

$$V(\chi) = \frac{1}{2}m^2\chi^2 \qquad n_s - 1 = -\frac{2}{N_{k_*}} \qquad r = 8/N_{k_*}$$



Dark Matter Production



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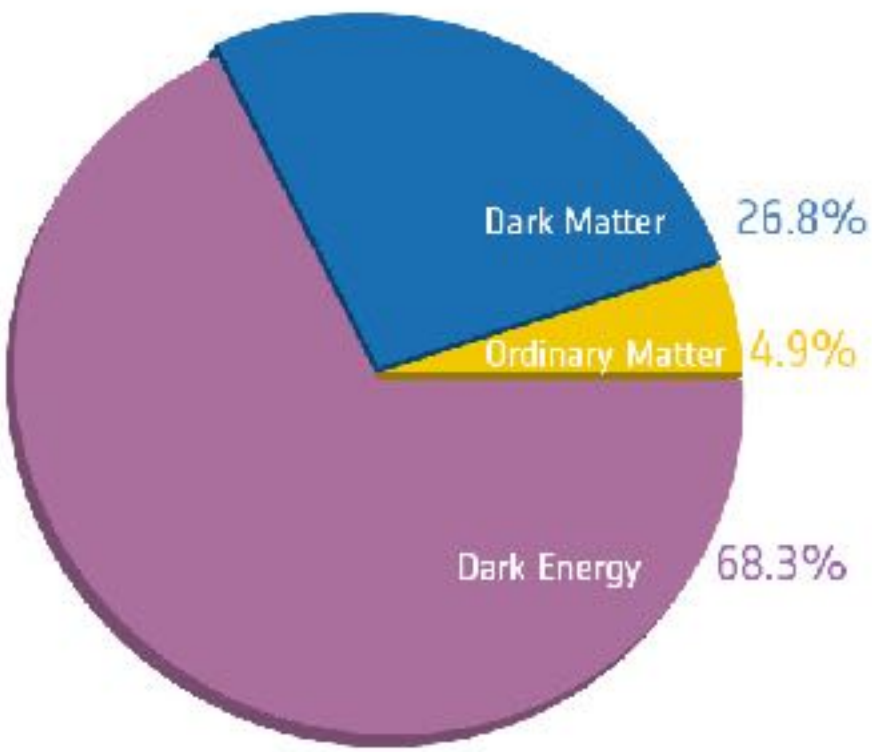
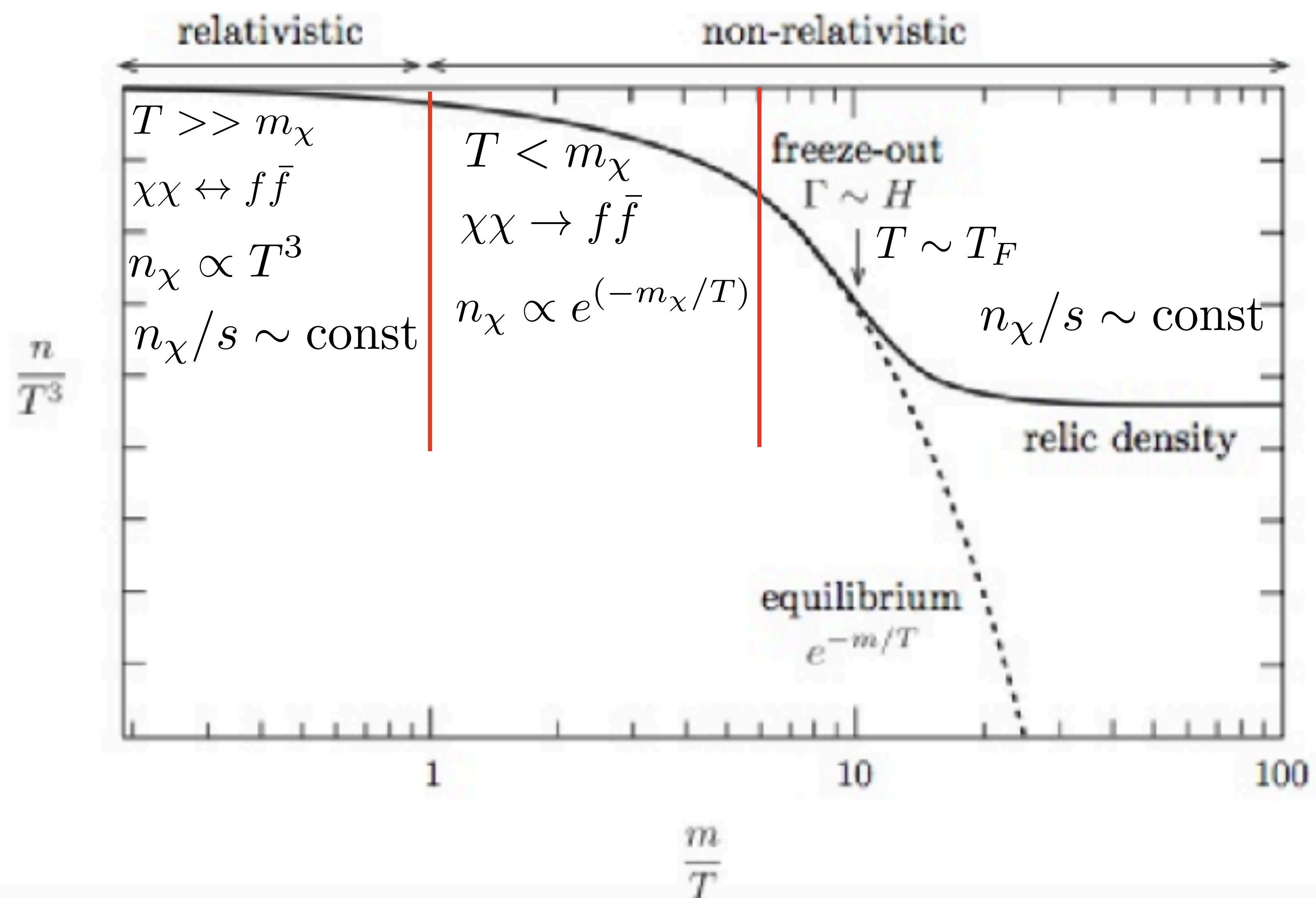


Thermal Freeze-Out



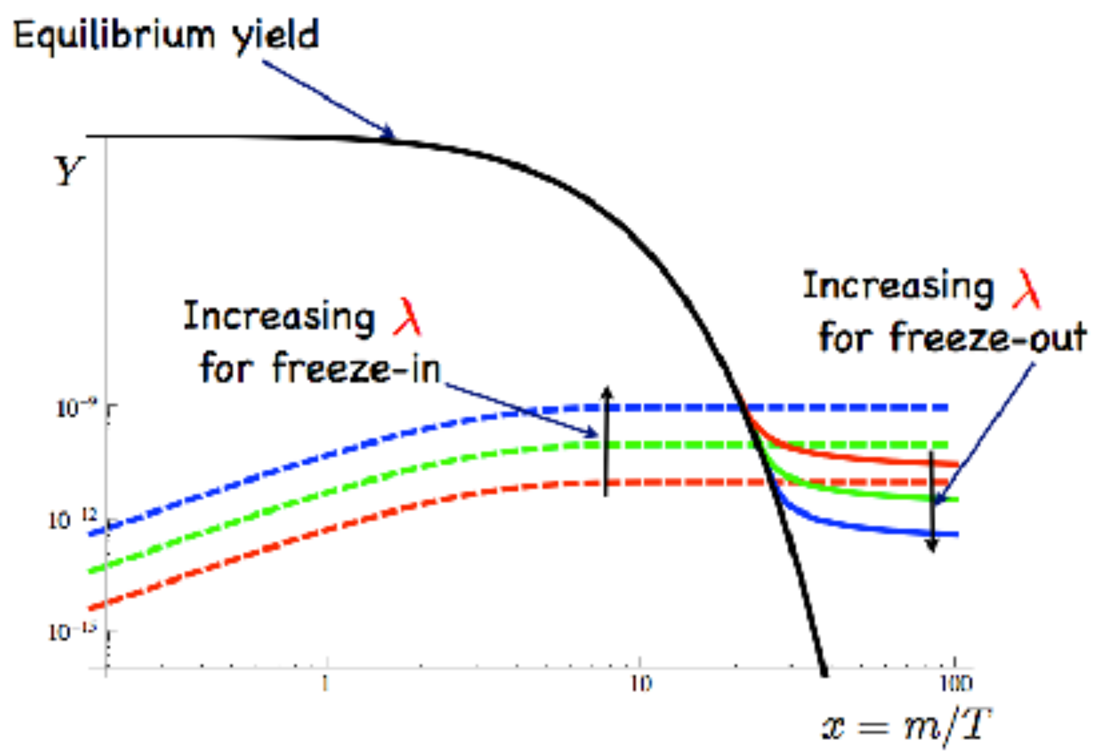
$$\Gamma = n_{DM}\langle\sigma v\rangle < H$$

$$\Omega_{DM}h^2 \sim 0.1\frac{3\times 10^{-26}\ cm^3\ s^{-1}}{\langle\sigma v\rangle} \qquad T_f = m_\chi/20$$

WIMP miracle

Dark Matter Production

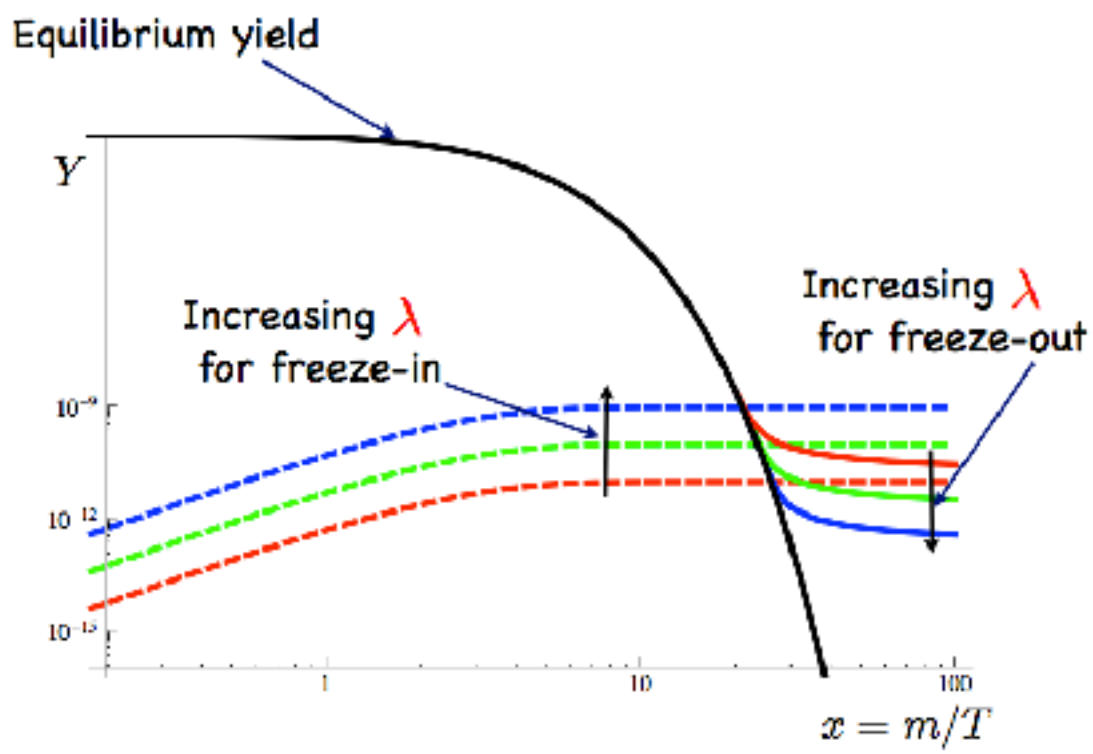
Thermal Freeze-In: DM particles never in thermal equilibrium



Produced from annihilation of SM particles

Dark Matter Production

Thermal Freeze-In: DM particles never in thermal equilibrium



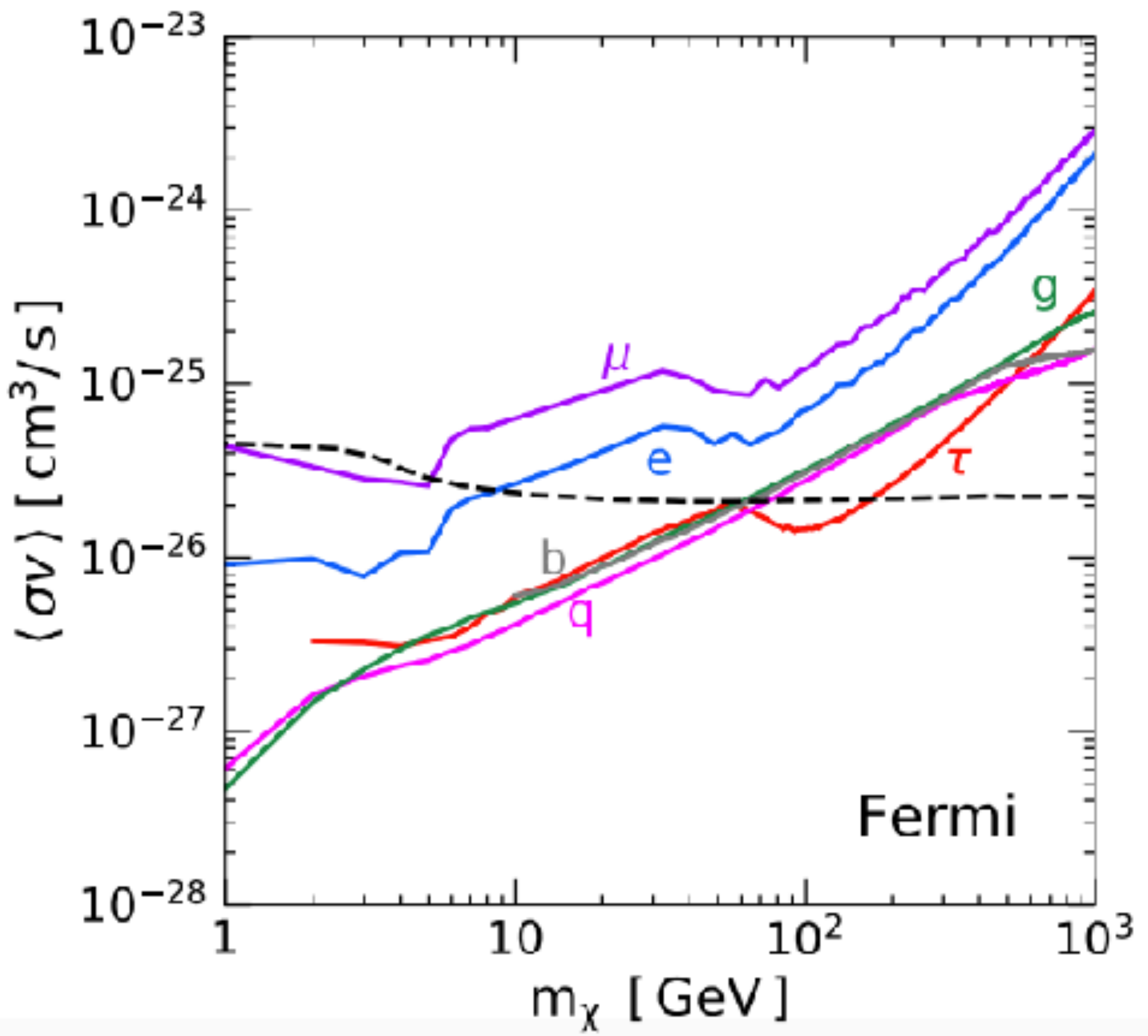
Produced from annihilation of SM particles

Decays: DM is produced from decay of parent particle, and remains non-thermal

$$\left(\frac{n_\chi}{s}\right)_{dec} = \frac{3T_R}{4m_\phi} Br_{\phi\to\chi}$$

Indirect Observations

CMB + FERMI + AMS



Leane, Slatyer, Beacom, Ng (1805.10305)

'Freeze-out' in RD universe leads to overproduction of DM

Moduli Dynamics & EMD

- Moduli arise naturally in SUSY/String models - massive and long lived

$$\Gamma_\varphi = \frac{c}{2\pi}\frac{m_\varphi^3}{M_{Pl}^2} \qquad \text{typically with } c \sim 0.1 - 1$$

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$$\mathcal{L} \supset -\frac{1}{2}m^2\varphi^2 - \frac{1}{2}H^2(\varphi - \hat{\varphi})^2 - V_{inf}(\chi) \qquad m_\varphi << H_{inf}$$

- Displaced during inflation: $Y = \varphi_0/M_{Pl} \sim 1$

Dine, Randall, Thomas

Dvali

Antusch, K.D, Halter

Cicoli, K.D, Maharana, Quevedo

- Start oscillating when $H \sim m_\varphi$
- Decay and reheats the Universe $T_R \sim \left(\frac{m_\varphi}{50 \text{ TeV}}\right)^{3/2} 3 \text{ MeV}$
- BBN requires $T_R > 3$ MeV ➡ $m_\varphi > 50$ TeV **BBN bound**

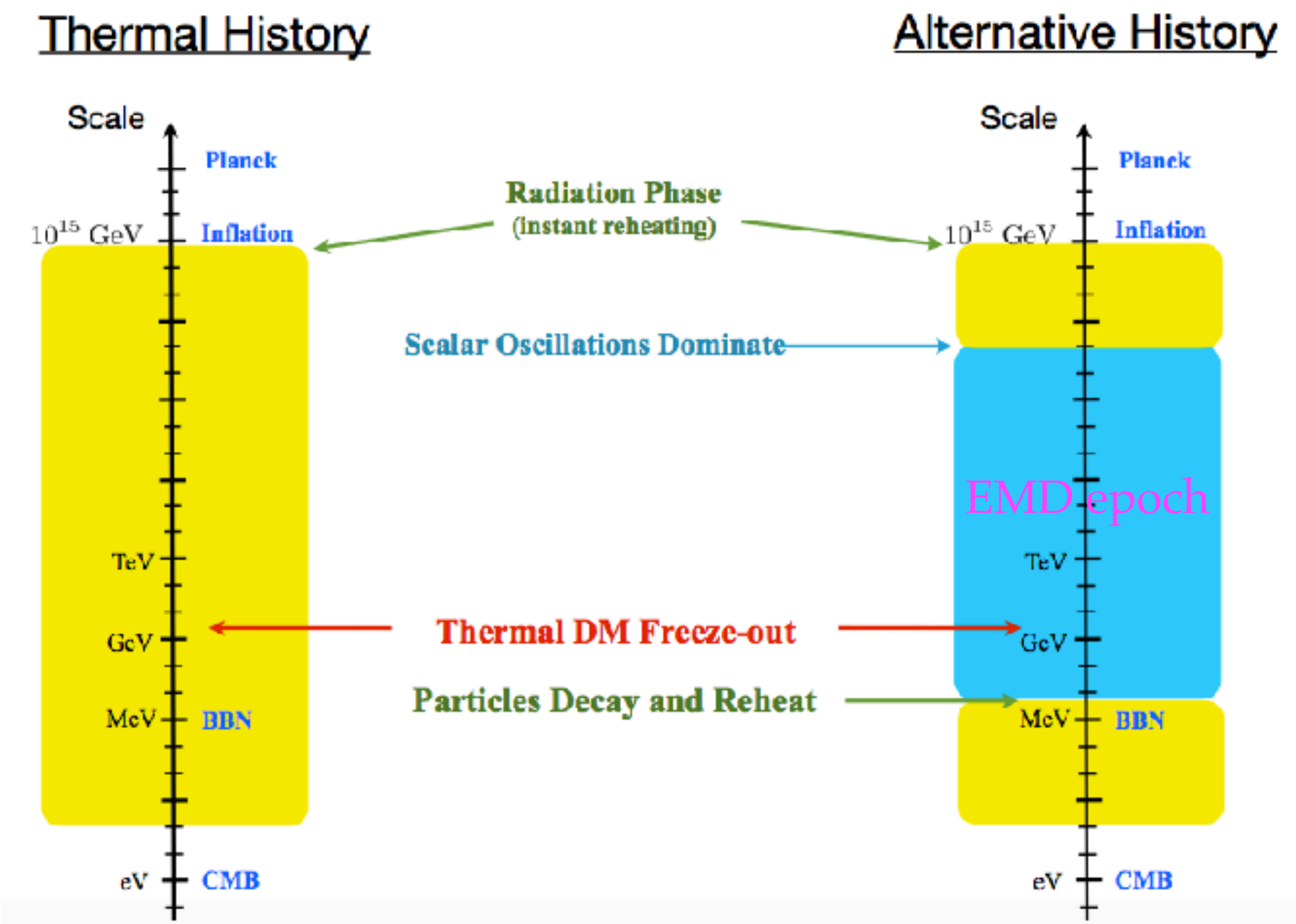
Non-standard Thermal History

Kane, Sinha, Watson (2015)

$$m_\varphi \sim 10^3 \text{ TeV}$$

$$T_R \sim \mathcal{O}(\text{GeV})$$

- Moduli oscillations change the thermal history of the Universe
- All preexisting DM or baryon asymmetry are washed away!



Dynamics of EMD

- The field starts to oscillate when $H \sim m_\varphi \simeq H_{osc}$
- Fractional energy density at the onset of oscillations

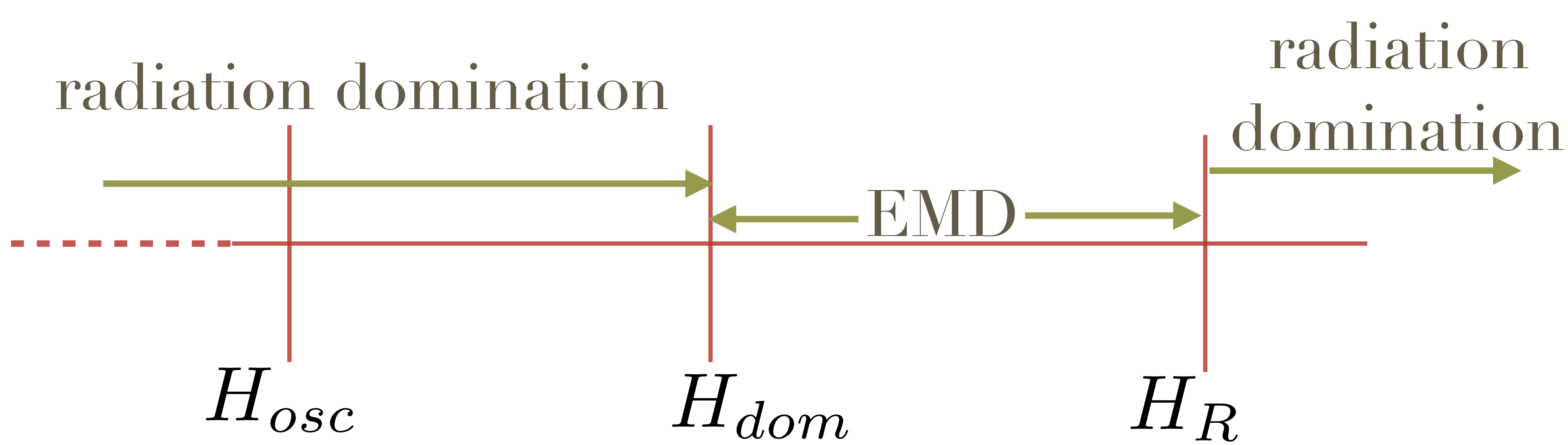
$$\alpha_0 \simeq (\phi_0/M_{Pl})^2 = Y^2$$

- As oscillations behaves like matter

$$\alpha(t) \propto a(t) \propto H^{-1/2}$$

- EMD starts when $\alpha(t) \simeq 1$

$$H_{dom} \simeq \alpha_0^2 m_\varphi$$



Decay during EMD

- Decay of oscillations happens when $H \simeq \Gamma_\varphi = H_R$
- After thermalisation RD universe $T_R \simeq \left(\frac{90}{\pi^2 g_{*,R}}\right)^{1/4} \sqrt{\Gamma_\varphi M_{Pl}}$

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Decay is a continuous process where subdominant radiation component grow continuously

- Instantaneous temperature of decay products

Giudice, Kolb, Riotto; Erickcek

$$T = \left(\frac{6\sqrt{g_{*,R}}}{5 g_*}\right)^{1/4} \left(\frac{30}{\pi^2}\right)^{1/8} \left(H T_R^2 M_{Pl}\right)^{1/4}$$

- During EMD for $H >> \Gamma_\varphi$, we have $T >> T_R$

DM production from thermal processes (freeze-out/in) possible during EMD

$$m_\chi/25 \lesssim T_f \lesssim m_\chi/5$$

Freeze-out during EMD

Giudice, Kolb, Riotto; Erickcek

$$\Omega_\chi h^2 \simeq 1.6 \times 10^{-4} \frac{\sqrt{g_{*,\mathrm{R}}}}{g_{*,\mathrm{f}}} \left(\frac{m_\chi/T_\mathrm{f}}{15}\right)^4 \left(\frac{150}{m_\chi/T_\mathrm{R}}\right)^3 \times \left(\frac{3\times 10^{-26}\ \mathrm{cm}^3\ \mathrm{s}^{-1}}{\langle\sigma_\mathrm{ann} v\rangle_\mathrm{f}}\right)$$

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- Observational constraint (PLANCK): $\Omega_\chi h^2 < 0.120$

$$\frac{H_\mathrm{f}}{H_\mathrm{R}} \gtrsim 4\times 10^{-2} \left(g_{*,\mathrm{R}}\ \ g_{*,\mathrm{f}}\right)^{-1/3} \left(\frac{m_\chi}{T_\mathrm{f}}\right)^{4/3} \times \left(\frac{3\times 10^{-26}\ \mathrm{cm}^3\ \mathrm{s}^{-1}}{\langle\sigma_\mathrm{ann} v\rangle_\mathrm{f}}\right)^{4/3}$$

- Using $H_\mathrm{dom} > H_\mathrm{f}$ and $m_\chi \gtrsim 5T_\mathrm{f}$

$$\frac{H_\mathrm{dom}}{H_\mathrm{R}} \gtrsim 4\times 10^{-2} \left(g_{*,\mathrm{R}}\ g_{*,\mathrm{f}}\right)^{-1/3} \times \left(\frac{3\times 10^{-26}\ \mathrm{cm}^3\ \mathrm{s}^{-1}}{\langle\sigma_\mathrm{ann} v\rangle_\mathrm{f}}\right)^{4/3}$$

Freeze-in during EMD

Giudice, Kolb, Riotto; Erickcek

$$\Omega_\chi h^2 \simeq 0.062 \frac{g_{*,\mathrm{R}}^{3/2}}{g_*^3(m_\chi/4)} \left(\frac{150}{m_\chi/T_\mathrm{R}}\right)^5 \left(\frac{T_\mathrm{R}}{5\ \mathrm{GeV}}\right)^2 \times \left(\frac{\langle\sigma_\mathrm{ann} v\rangle_\mathrm{f}}{10^{-36}\ \mathrm{cm}^3\ \mathrm{s}^{-1}}\right)$$

$$\frac{H_\mathrm{dom}}{H_\mathrm{R}} \gtrsim 4\times 10^3 \left(g_{*,\mathrm{R}}\ g_*^5(m_\chi/4)\right)^{-1/7} \times \left(\frac{\langle\sigma_\mathrm{ann} v\rangle_\mathrm{f}}{10^{-36}\ \mathrm{cm}^3\ \mathrm{s}^{-1}}\right)^{4/7}$$

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Decay at the end of EMD

Gelmini, Gondolo; Allahverdi, Dutta, Sinha

$$\left(\frac{n_\chi}{s}\right)_{dec} = \left(\frac{n_\chi}{s}\right)_{obs} \Rightarrow \frac{3T_\mathrm{R}}{4m_\phi}\mathrm{Br}_{\phi\to\chi} \simeq 5\times 10^{-10}\left(\frac{1\ \mathrm{GeV}}{m_\chi}\right)$$

$$H_{dom} \simeq \alpha_0^2 m_\varphi$$

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

$$\frac{H_\mathrm{dom}}{H_\mathrm{R}} \gtrsim 10^{10}\left(\frac{90}{\pi^2 g_{*,\mathrm{R}}}\right)^{1/2}\left(\frac{M_\mathrm{P}}{1\ \mathrm{GeV}}\right)\ \alpha_0^2\ \mathrm{Br}_{\phi\to\chi}$$

Independent from annihilation cross-section

Comments

- For smaller annihilation cross-section, we need enough dilution: Lower bound on the duration of EMD

- This bound can be more robust if we know more about $T_R, m_\chi, \langle\sigma_{ann}v\rangle$

- Freeze-out/in bound depends mostly on DM parameters, whereas decay depends on the EMD driving scalar field

- (Decay+Freeze-out) or (Decay+ Freeze-in) must be satisfied simultaneously.

- Strongest constraint comes from decay process abundance

$$\frac{H_{\rm dom}}{H_{\rm R}} \gtrsim 10^{10} \left(\frac{90}{\pi^2 g_{*,\rm R}}\right)^{1/2} \left(\frac{M_{\rm P}}{1\ {\rm GeV}}\right)\ \alpha_0^2\ {\rm Br}_{\phi\to\chi}$$

EMD and Inflation

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

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

Liddle, Leach

K.D, Maharana

$$\Delta N_{EMD} \equiv \frac{1}{6}\left(\frac{H_{dom}}{H_R}\right)$$

Implications for inflation models:

$$N_{inf} = \left(55 - \frac{1}{3} ln\left(\frac{\sqrt{16\pi} M_{pl} Y^2}{m_\varphi}\right)\right) \pm 5$$

Das, K.D, Maharana

Cicoli, K.D, Maharana, Quevedo

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Liddle, Leach K.D, Maharana

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

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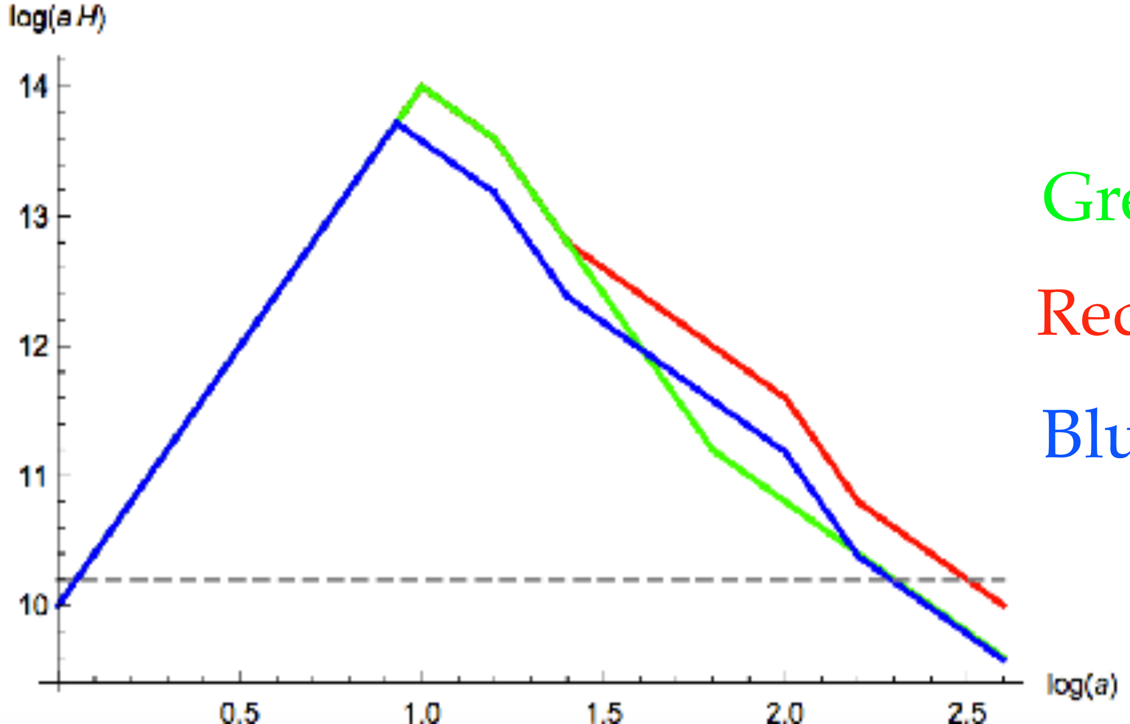

Green: thermal history

Red: non-thermal wrong history

Blue: non-thermal correct history

Connecting to CMB

$$N_{k_*} \sim 57.3 + \frac{1}{4} ln(r) - \Delta N_{reh} - \Delta N_{EMD} \qquad \Delta N_{reh} \equiv \frac{1 - 3w_{reh}}{6(1 + w_{reh})} log\left(\frac{H_{inf}}{H_{reh}}\right)$$

$$\Delta N_{reh} > 0 \qquad\qquad 0 \leq w_{re} \leq 1/3$$

$$\Delta N_{EMD} \lesssim 57.3 - N_{k_*} + \frac{1}{4} ln\ r$$

Connecting to CMB

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Inflationary observables $\quad n_s \simeq 1 - \frac{a}{N_{k_*}} \quad , \quad r \simeq \frac{b}{N_{k_*}^c}$

Class I models

$$a = c \quad \text{and} \quad b \sim \mathcal{O}(10)$$

Starobinsky, Higgs inflation with a =2, b~12

$$r \lesssim \mathcal{O}(0.01)$$

Class II models

$$b = 8(a-1) \quad \text{and} \quad c = 1$$

$$V(\varphi) \propto \varphi^{2(a-1)}$$

$$r \sim \mathcal{O}(0.1)$$

Connecting to CMB

Observations: $n_s^{min} \leq n_s \leq n_s^{max}$

$$N_{k_*}^{\rm min} = \frac{a}{1 - n_s^{\rm min}} \quad , \quad N_{k_*}^{\rm max} = \frac{a}{1 - n_s^{\rm max}}$$

$$\Delta N_{\rm EMD} \lesssim 57.3 - N_{k_*}^{\rm min} + \frac{1}{4} \ln r(N_{k_*}^{\rm min})$$

Connecting to CMB

Observations: $n_s^{min} \leq n_s \leq n_s^{max}$

$$N_{k_*}^{\min} = \frac{a}{1 - n_s^{\min}} \quad , \quad N_{k_*}^{\max} = \frac{a}{1 - n_s^{\max}}$$

$$\Delta N_{\text{EMD}} \lesssim 57.3 - N_{k_*}^{\min} + \frac{1}{4} \ln r(N_{k_*}^{\min})$$

	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

Bound

$$10^{10}\left(\frac{90}{\pi^2 g_{*,R}}\right)^{1/2}\left(\frac{M_{Pl}}{1GeV}\right)\alpha_0^2 Br_{\varphi\to\chi} < \left(\frac{H_{dom}}{H_R}\right) < 6(57.3 - N_{k_*}^{\min} + \frac{1}{4}\ \mathrm{ln} r(N_{k_*}^{\min}))$$

DM abundance

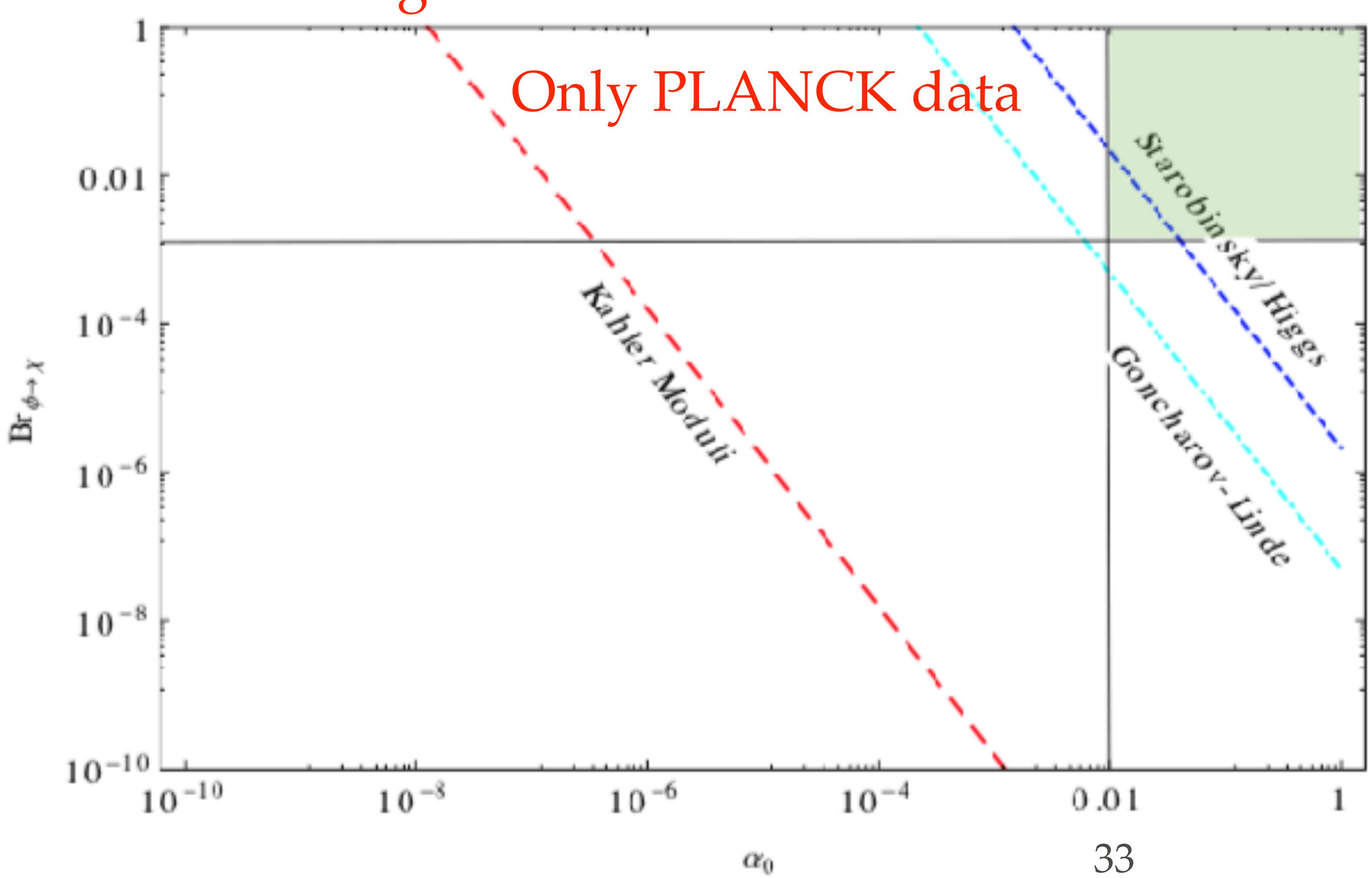
CMB

Bound

$$10^{10}\left(\frac{90}{\pi^2 g_{*,R}}\right)^{1/2}\left(\frac{M_{Pl}}{1GeV}\right)\alpha_0^2 Br_{\varphi\to\chi} < \left(\frac{H_{dom}}{H_R}\right) < 6(57.3 - N_{k_*}^{\min} + \frac{1}{4}\ln r(N_{k_*}^{\min}))$$

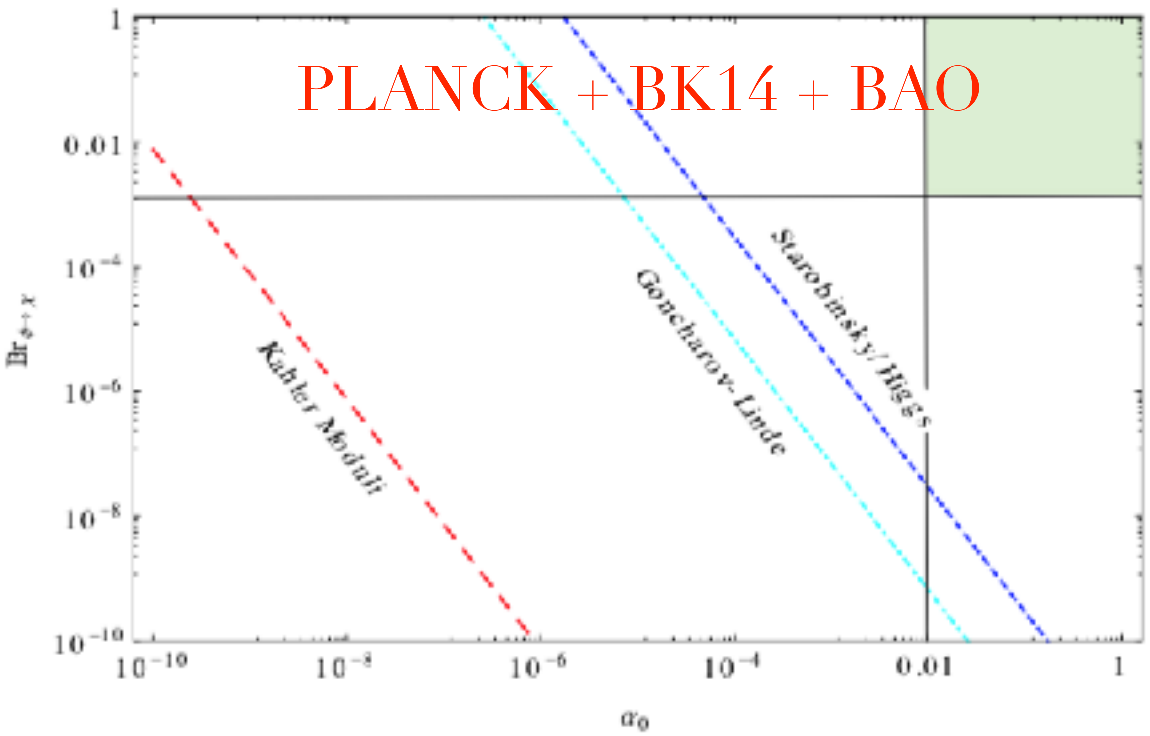
DM abundance CMB

right of each line is disallowed



- The bound is conservative and model independent
- More inputs of reheating, particle physics models will make the bound stronger

Implications



- Models with $r \lesssim \mathcal{O}(0.01)$ strong constraints
- When EMD field is a moduli

$$\varphi_0 \gtrsim \mathcal{O}(0.1)$$

$$\mathcal{O}(10^{-3}) \lesssim \mathrm{Br}_{\phi\to\chi} \lesssim \mathcal{O}(1)$$

EMD epoch from moduli oscillations is ruled out!

- When EMD field is visible sector field: allowed

$$\alpha_0 \ll 1 \quad \text{and/or} \quad \mathrm{Br}_{\phi\to\chi} \ll 10^{-3}$$

- For future experiments, freeze-out/in contributions might be important $\alpha_0^2\, \mathrm{Br}_{\varphi\to\chi} \lesssim 10^{-25}$

Comments

$$N_{k_*} \sim 57.3 + \frac{1}{4} ln(r) - \Delta N_{reh} - \Delta N_{EMD} \qquad \Delta N_{reh} \equiv \frac{1 - 3w_{reh}}{6(1 + w_{reh})} log\left(\frac{H_{inf}}{H_{reh}}\right)$$

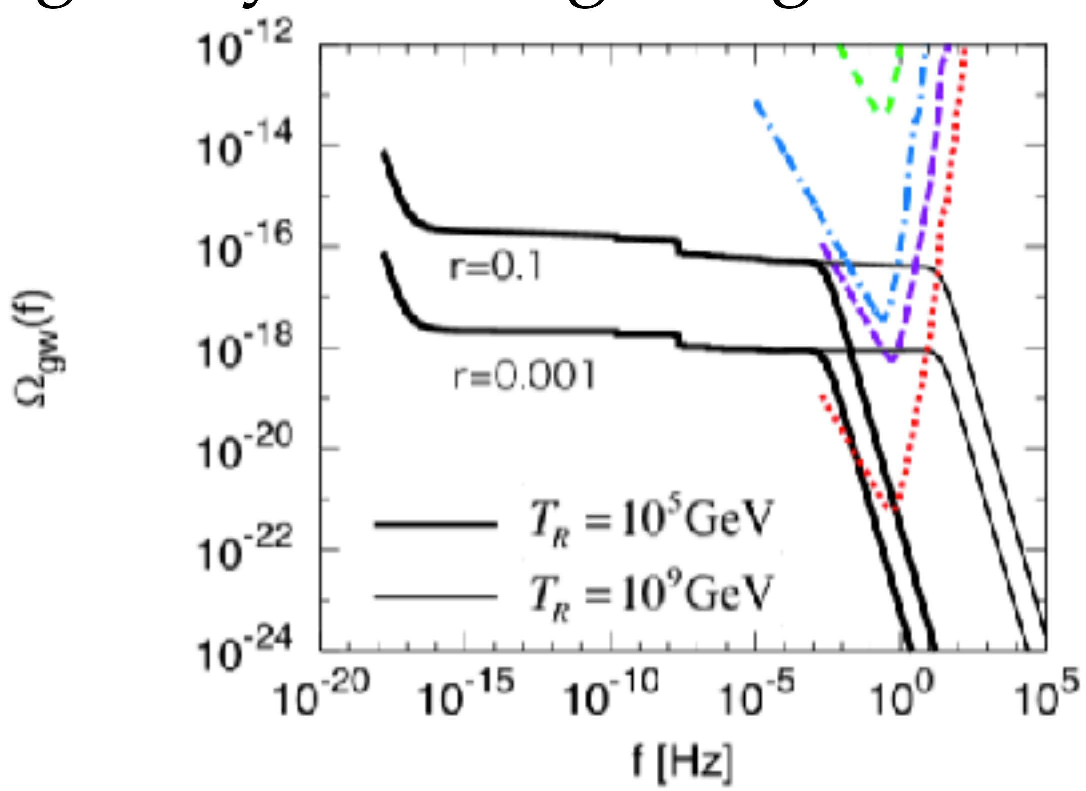
$$\Delta N_{reh} > 0 \qquad 0 \leq w_{re} \leq 1/3$$

$$\Delta N_{EMD} \lesssim 57.3 - N_{k_*} + \frac{1}{4} ln\ r$$

- More inputs from reheating will strengthen the bound
- Future CMB experiments are expected to shrink the error bar on the spectral index by a factor of ~ 2!
- In extension of $\Lambda\text{CDM} + r$ model the constraints are going to be weaker!

Why Important?

- BBN corresponds to 1 pc scales - extremely non-linear scale today
- Primordial gravity wave signals gets further suppressed due to EMD



Nakayama, Saito, Suwa, Yokoyama

- Other than particle physics inputs, (probably) correlating with CMB observables is the only way!

Conclusion

- Viability of non-thermal DM from a period of EMD in light of CMB data
- We focussed on $\langle \sigma_{\rm ann} v \rangle_{\rm f} < 3 \times 10^{-26} {\rm cm}^3 s^{-1}$
- Lower bound on the duration of EMD from DM abundance, and upper bound from CMB observables
- Models with $r \lesssim \mathcal{O}(0.01)$ disfavours non-thermal SUSY DM from a modulus-driven EMD.

Thank you!