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Moduli Dynamics at the End of Inflation: A Few Phenomenological Implications

Centre for Strings, Gravitation and Cosmology,
IIT Chennai
October 28, 2022

arXiv:2208.00427 (JCAP)
with Khursid Alam

arXiv:2101.02234 (JCAP)
with Sukannya Bhattacharya and Anirban Das
&
arXiv:1808.02659 (JCAP)
with Rouzbeh Allahverdi and Anshuman Maharana

From data ONLY

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

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

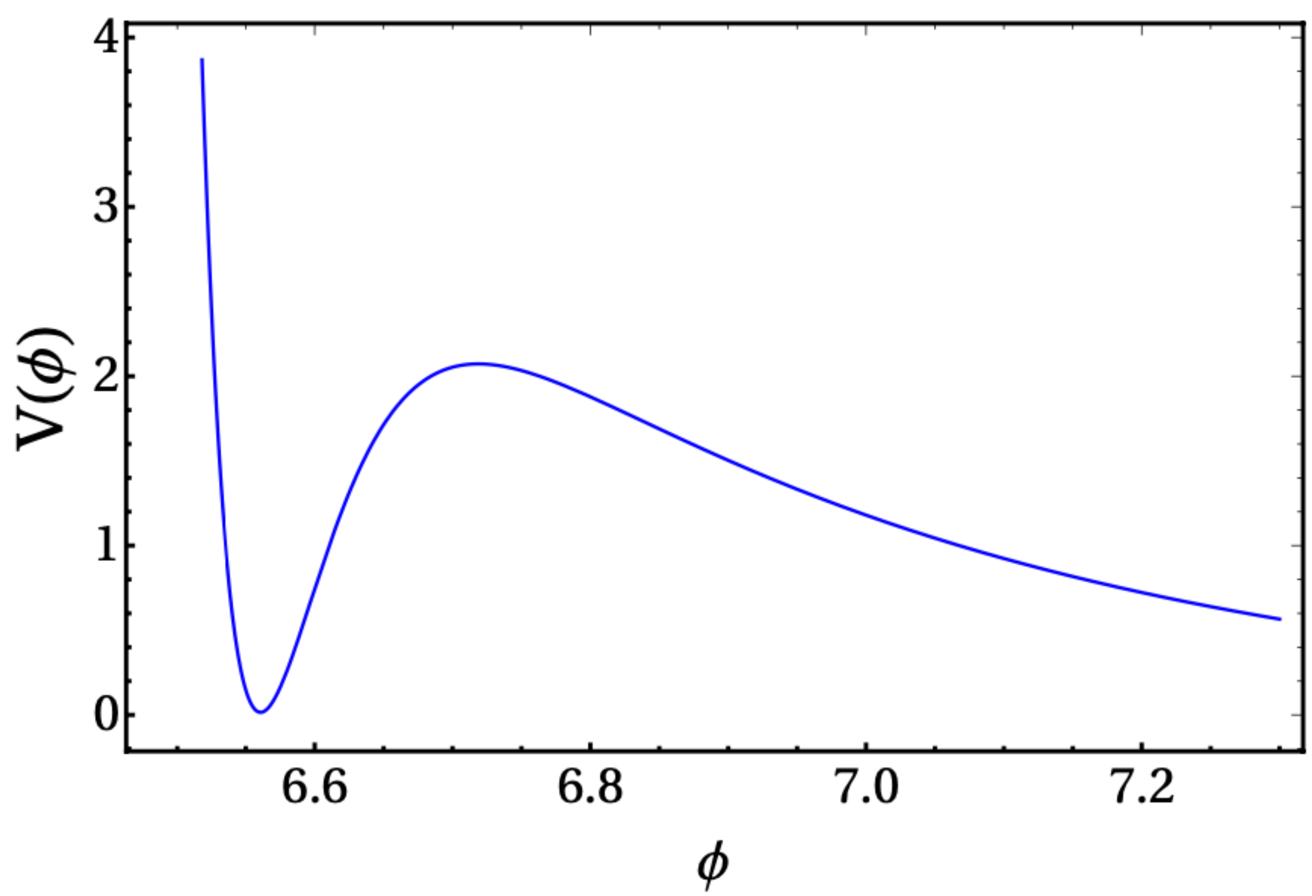
- Coherent super-Hubble perturbations (.. due to inflation)
- Dark matter .. gravitational collapse

Moduli Potential

- BSM: Several gravitationally coupled scalar fields ϕ or σ

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

- Crucial to stabilise those fields to be consistent with low energy observations



Kachru, Kallosh, Linde, Trivedi

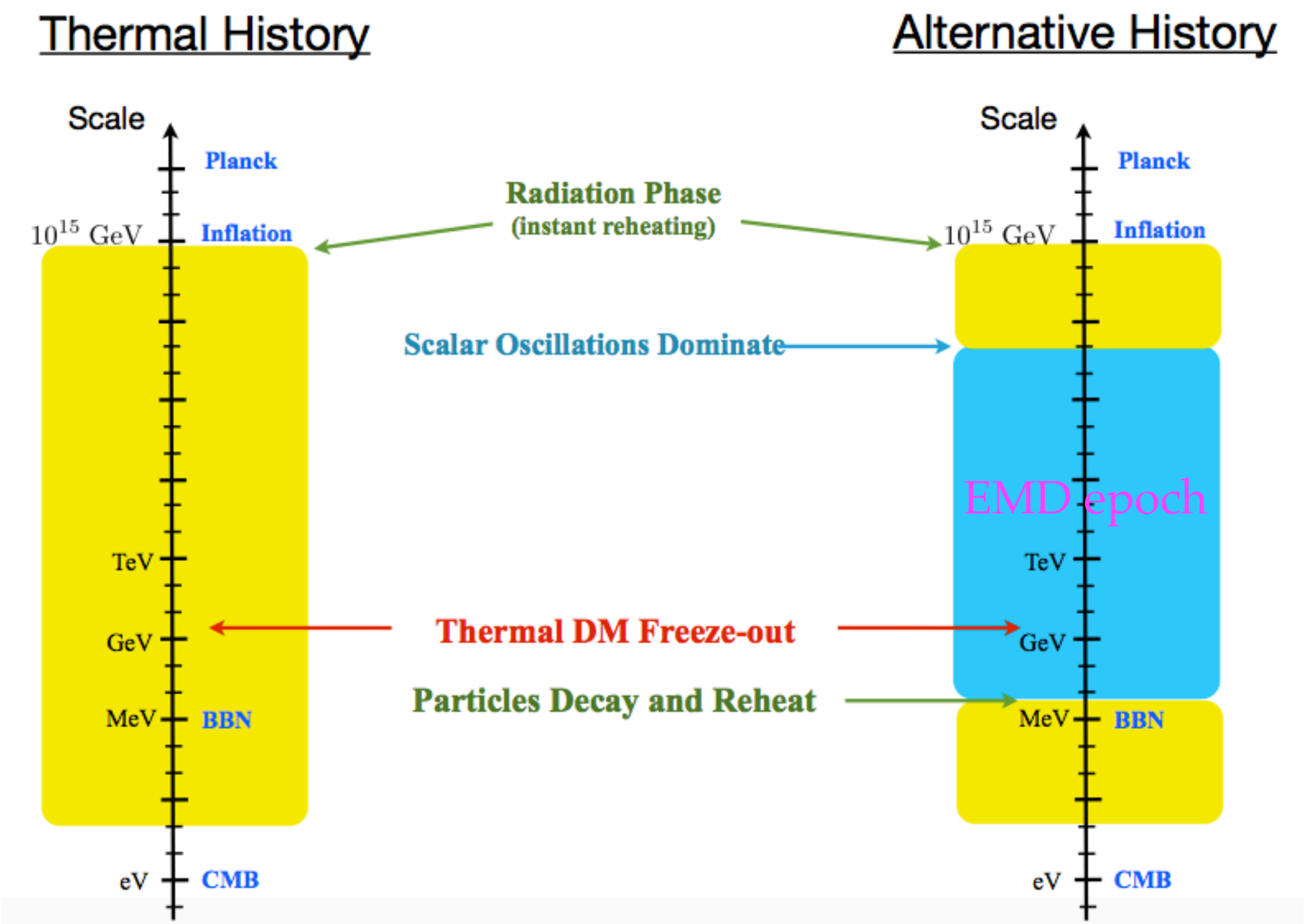
Non-standard Thermal History

Kane, Sinha, Watson (2015)

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

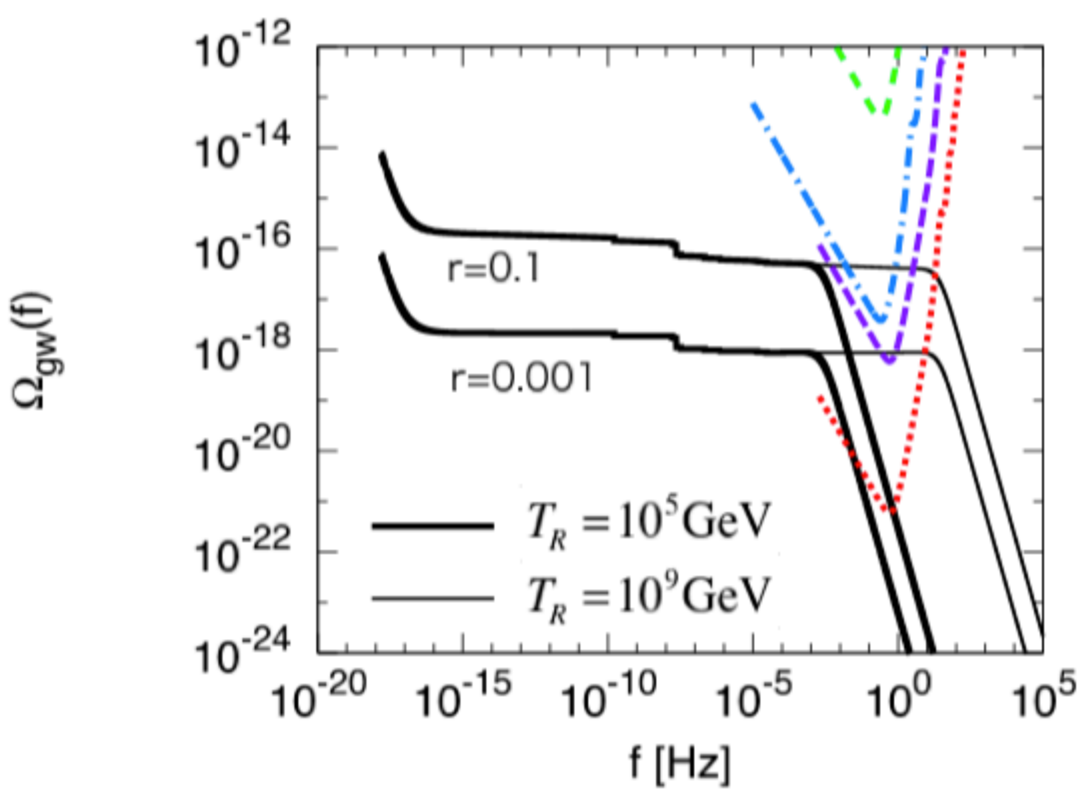
$$T_R \sim \mathcal{O}(\text{GeV})$$

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



EMD Epoch: Why Important?

- BBN corresponds to 1 pc scales - extremely non-linear scale today
- Primordial gravity wave signals gets further suppressed due to Early Matter Dominated (EMD) epoch



Nakayama, Saito, Suwa, Yokoyama

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

Moduli Problem

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

10^{-26} eV

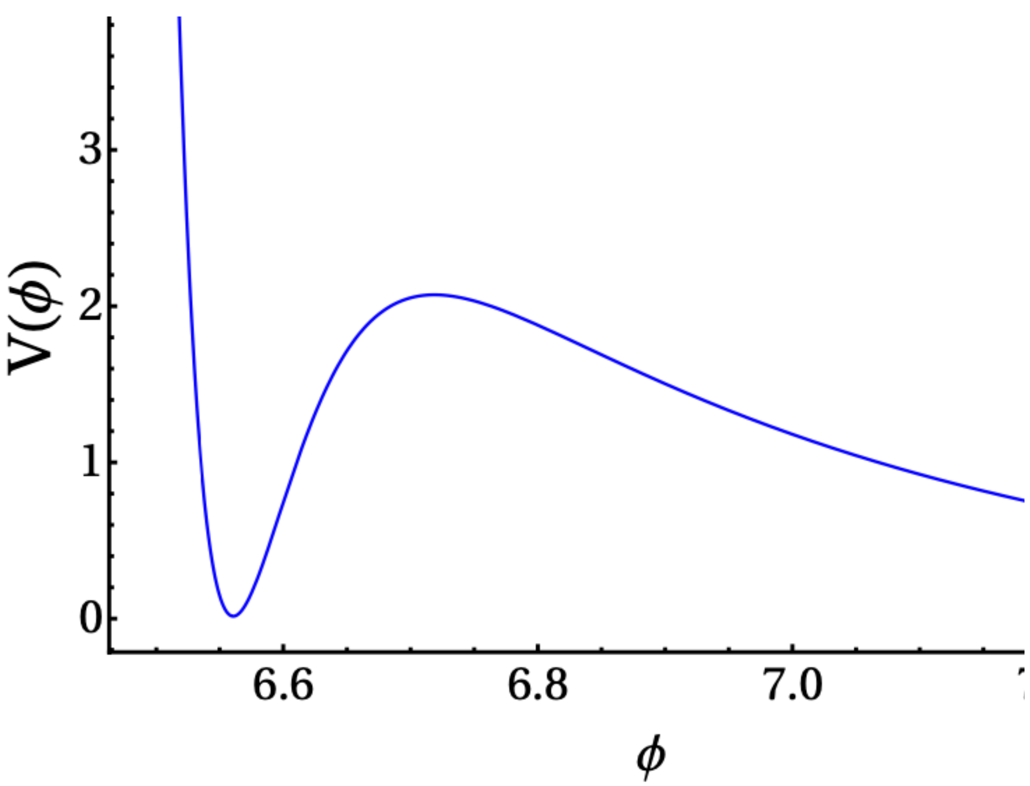
20 MeV

Decays by today

30 TeV

Decays by BBN

OK → Over-closes ← → Problem for BBN ← OK

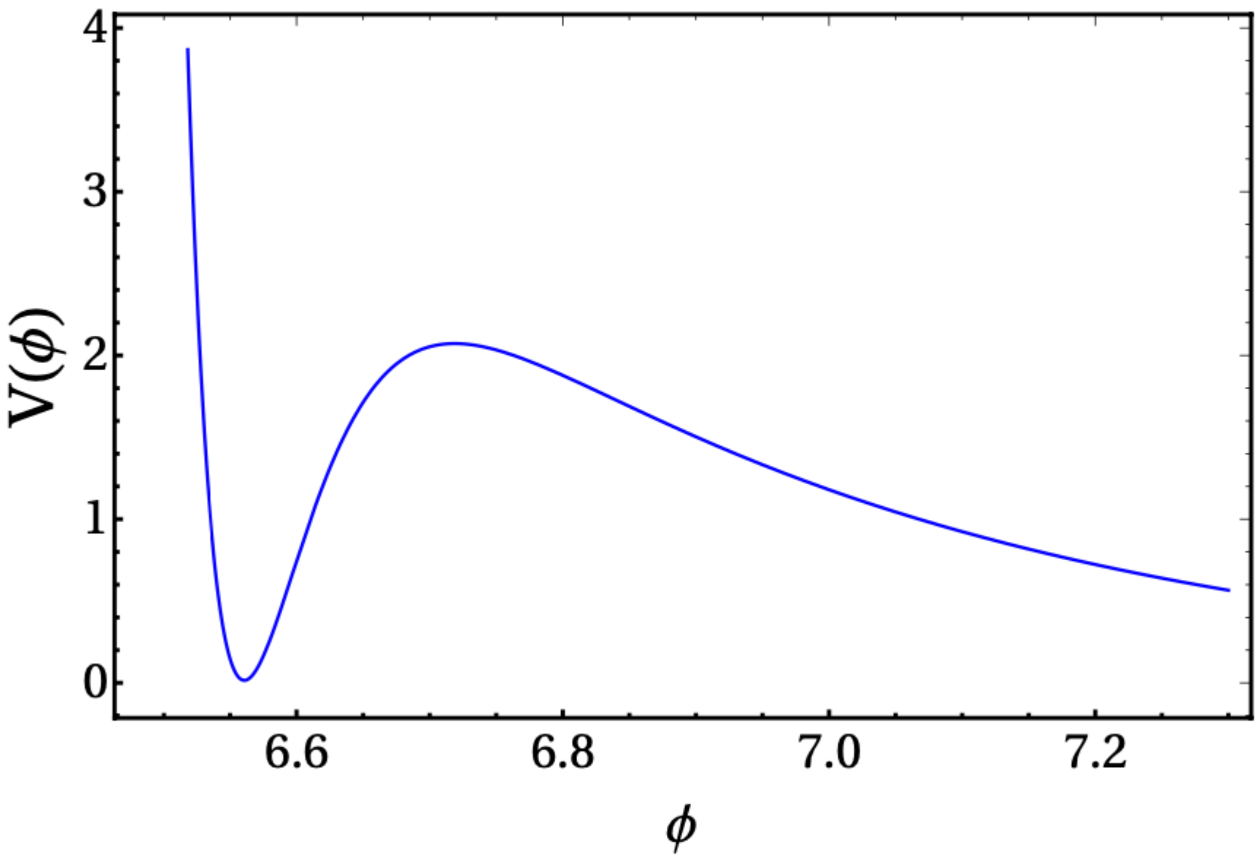


$$\frac{\rho_\phi}{s} \lesssim 10^{-14}\ \text{GeV} \implies \phi_{\text{init}} \lesssim 10^{-10} M_P$$

Kawasaki, Kohri and T. Moroi

Moduli Problem

- Finite barrier height
- Possibility of overshooting R. Brustein and P.J. Steinhardt



$$V_{\rm total} = V_0(\sigma) + V_{\rm inf}(\varphi, \sigma)$$

$$V_{\rm inf}(\varphi, \sigma) = V(\varphi)/\sigma^n$$

$$\phi_{ini} \sim \mathcal{O}(0.1)$$

Cicoli, K.D, Maharana, Quevedo

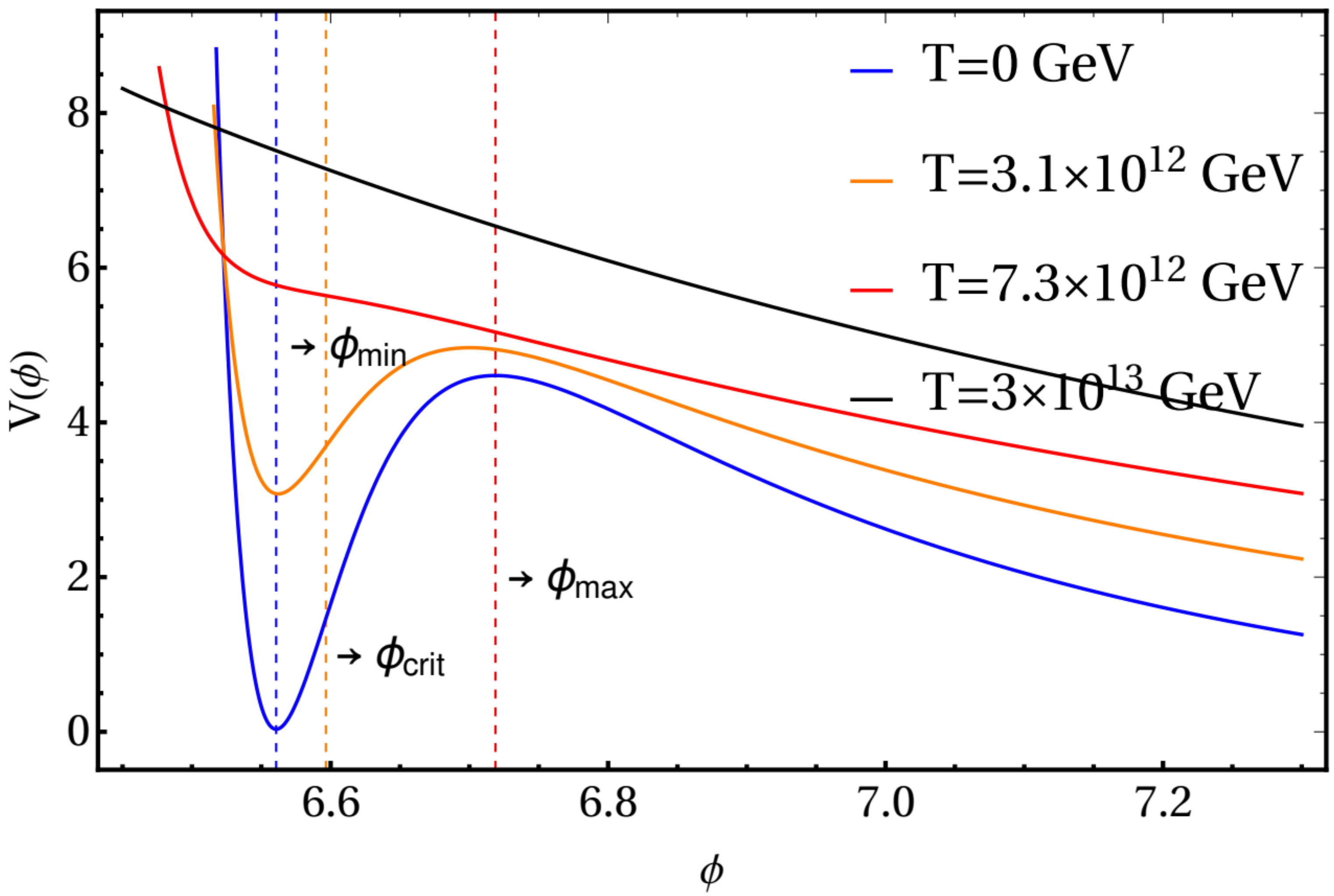
Classical vacuum misalignment

Also quantum fluctuations

$$H_{\rm inf} \lesssim m_{3/2}$$ Kallosh & Linde

Moduli + Thermal Bath

$$V_{\text{total}} = V_{\text{KKLT}}(\sigma) + V_T(\sigma), \text{where}, V_T = T^4\left(a_0 + \frac{a_2}{\sigma}\right)$$



Buchmuller, Yamaguchi, Lebedev, Ratz

$$T_{\text{crit}} \sim c\sqrt{m_{3/2}M_p}$$

Upper limit on reheating temperature

Dynamics of Moduli

$$\ddot{\sigma} + 3H\dot{\sigma} - \frac{\dot{\sigma}^2}{\sigma} + \frac{2\sigma^2}{3} V'_{\rm total}(\sigma, \rho_r) = 0$$

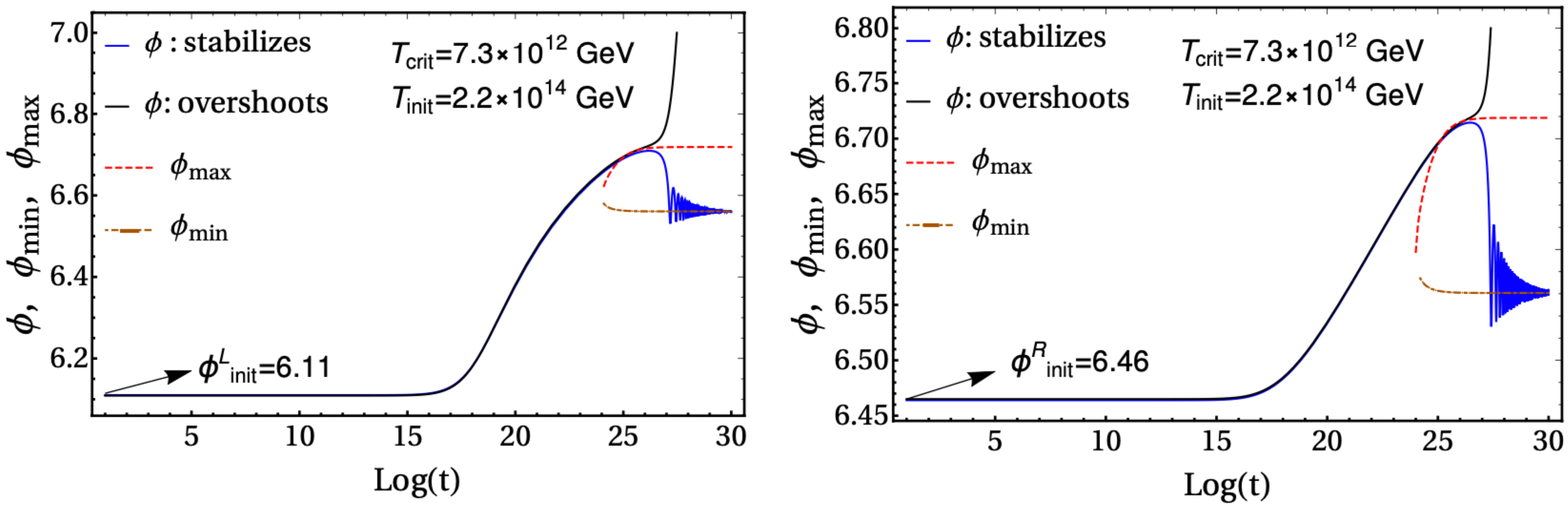
$$\dot{\rho}_r + 4H\rho_r = 0,$$

$$3M_p^2 H^2 = \frac{3}{4}\left(\frac{\dot{\sigma}}{\sigma}\right)^2 + \rho_r + V(\sigma),\ \text{H= Hubble parameter}$$

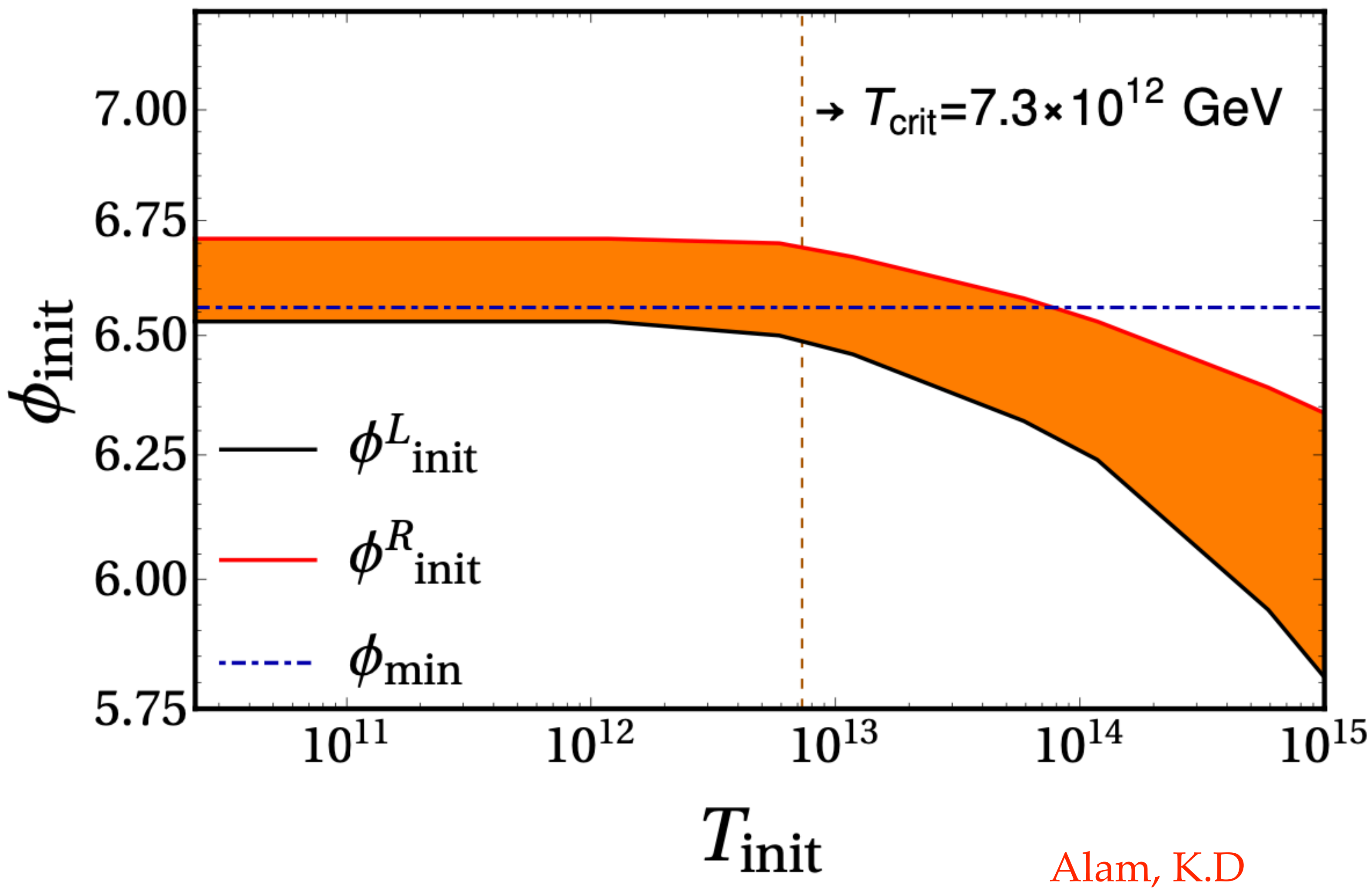
Barreiro, Carlos, Copeland, Nunes

Alam, K.D

$$T_{\rm init} > T_{\rm crit}$$



Dynamics of Moduli

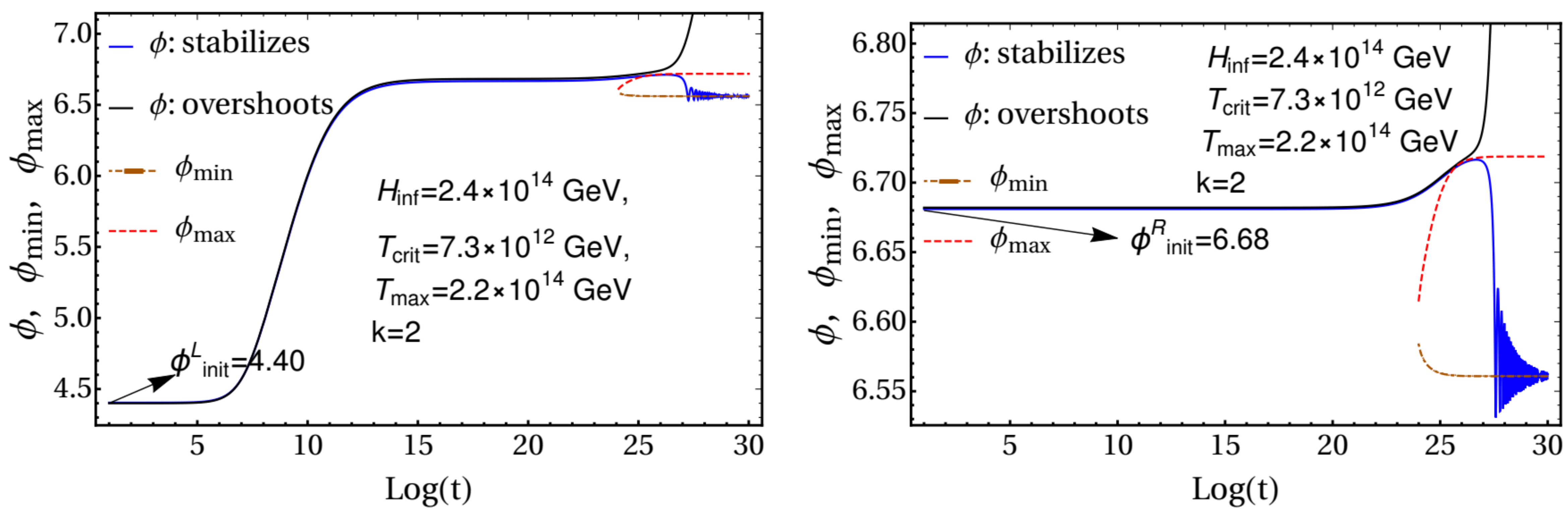


Alam, K.D

Effects of Reheating

$$\ddot{\sigma} + 3H\dot{\sigma} - \frac{\dot{\sigma}^2}{\sigma} + \frac{2\sigma^2}{3} V'_{\text{total}}(\sigma, \rho_r) = 0$$
$$\dot{\rho_\varphi} + 3(1+\omega_\varphi)H\rho_\varphi + \Gamma_\varphi(1+\omega_\varphi)\rho_\varphi = 0$$
$$\dot{\rho}_r + 4H\rho_r - (1+\omega_\varphi)\Gamma_\varphi\rho_\varphi = 0$$
$$3M_p^2H^2 = \frac{3}{4}\left(\frac{\dot{\sigma}}{\sigma}\right)^2 + \rho_\varphi + \rho_r + V_0(\sigma)$$

Field range is further larger than the previous case



Conclusion: I

$$\phi_{\rm init} \lesssim \begin{cases} 10^{-6} M_p & \text{for } t_{\rm osc} < t_R\,, \\ 10^{-10} M_p & \text{for } t_{\rm osc} > t_R\,. \end{cases}$$

Avoid BBN bound

$$\phi_{\rm init} \lesssim \mathcal{O}(0.1 - 0.01)$$

Avoid overshooting

- For heavy moduli, dynamics & reheating effects relax the initial conditions
- For light moduli BBN bound more stringent, and thus useful

PART II

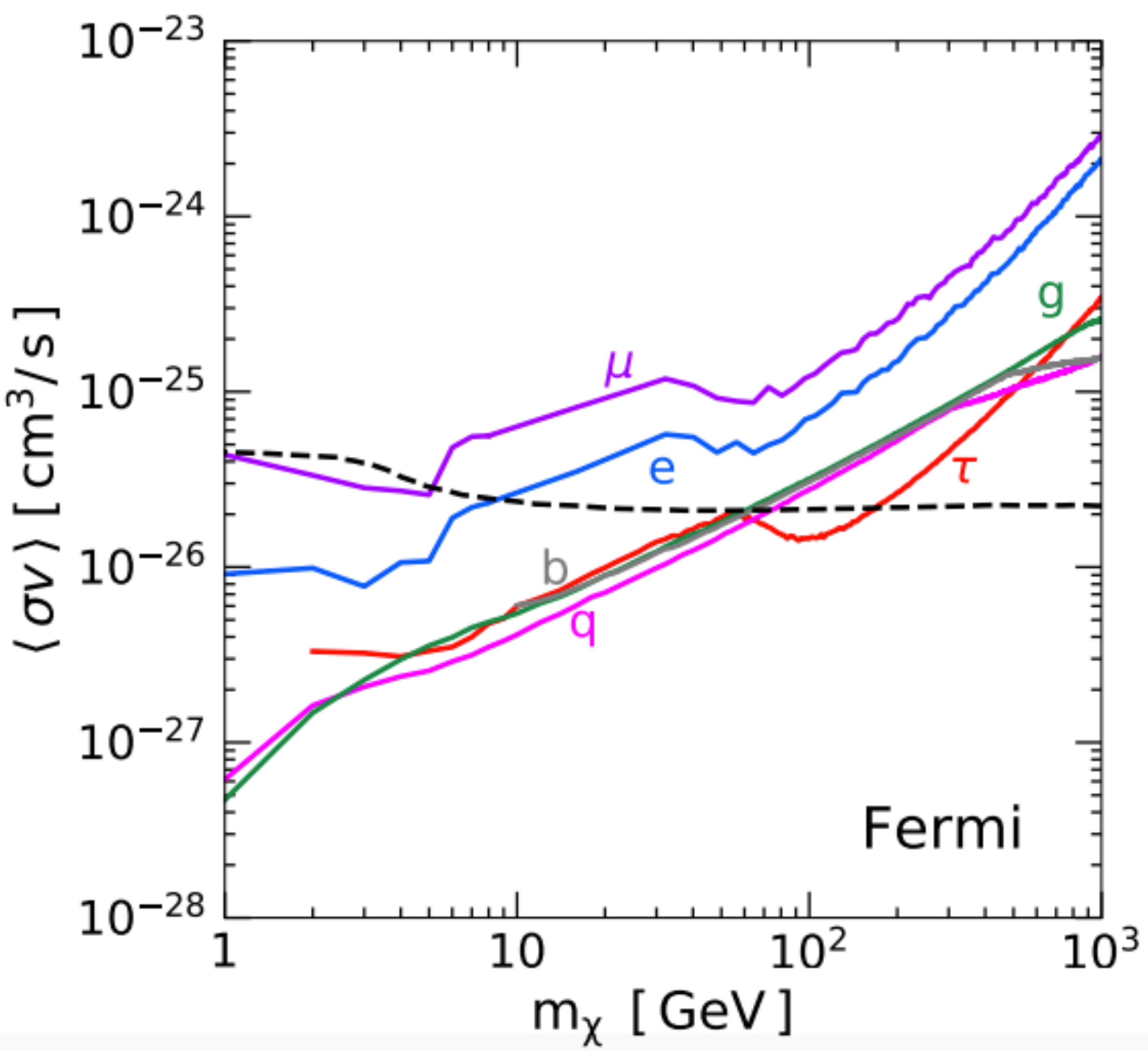
Key Points (arXiv:1808.02659)

Allahverdi, K.D, Maharana

- 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 produced by moduli fields.

Indirect Observations

CMB + FERMI + AMS



Leane, Slatyer, Beacom, Ng (1805.10305)

$$\Omega_{DM} h^2 \sim 0.1 \frac{3 \times 10^{-26} \ cm^3 \ s^{-1}}{\langle \sigma v \rangle}$$

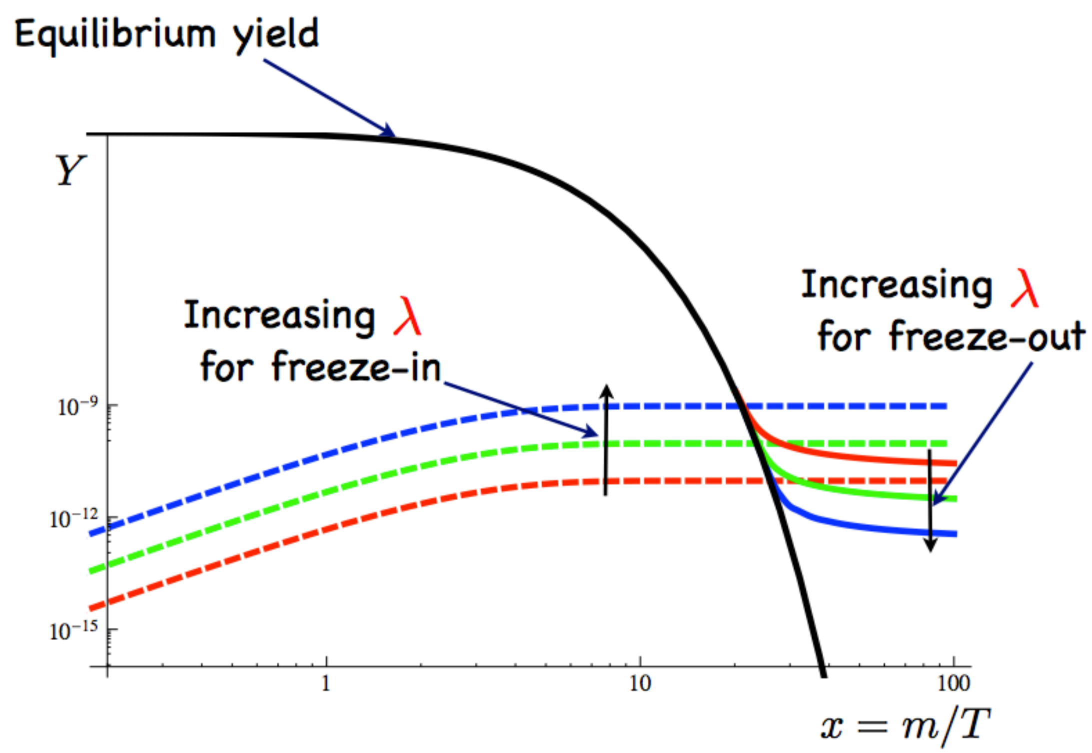
$$T_f = m_\chi / 20$$ WIMP miracle

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

See also K.D, Ghosh, Kar, Mukhopadhyaya (forthcoming)

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

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

Dynamics of EMD

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

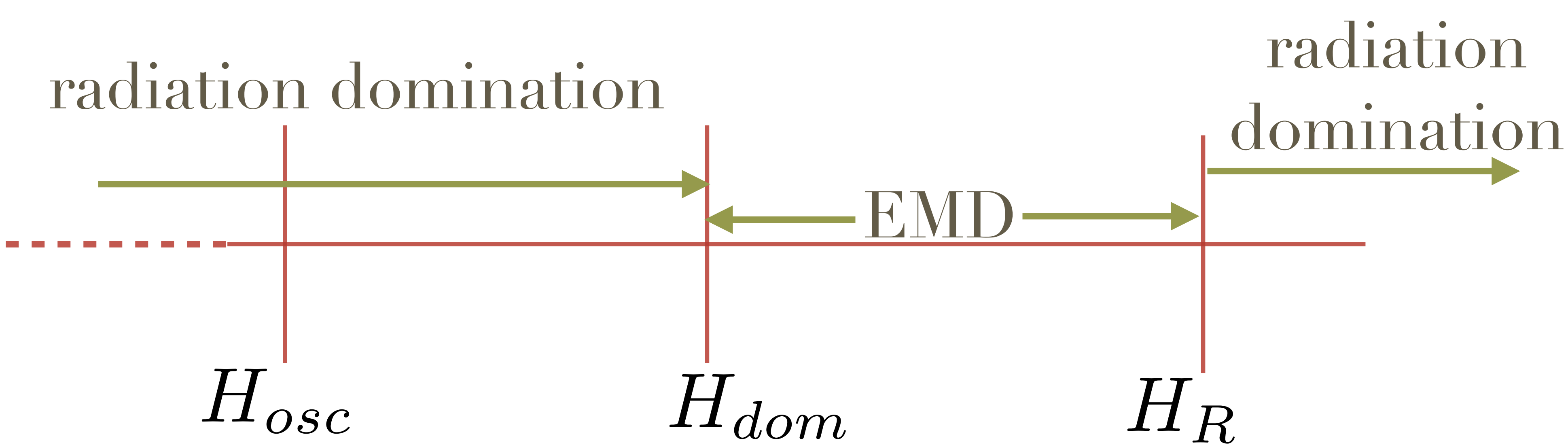
$$\alpha_0 \simeq (\phi_0/M_{Pl})^2 = Y^2$$

- 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, B. Dutta, Sinha

$$\left(\frac{n_\chi}{s}\right)_{dec} = \left(\frac{n_\chi}{s}\right)_{obs}$$

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

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

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

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

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

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

Connecting to CMB

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

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

Liddle, Leach

K.D, Maharana

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

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

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

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

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

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	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

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

DM abundance

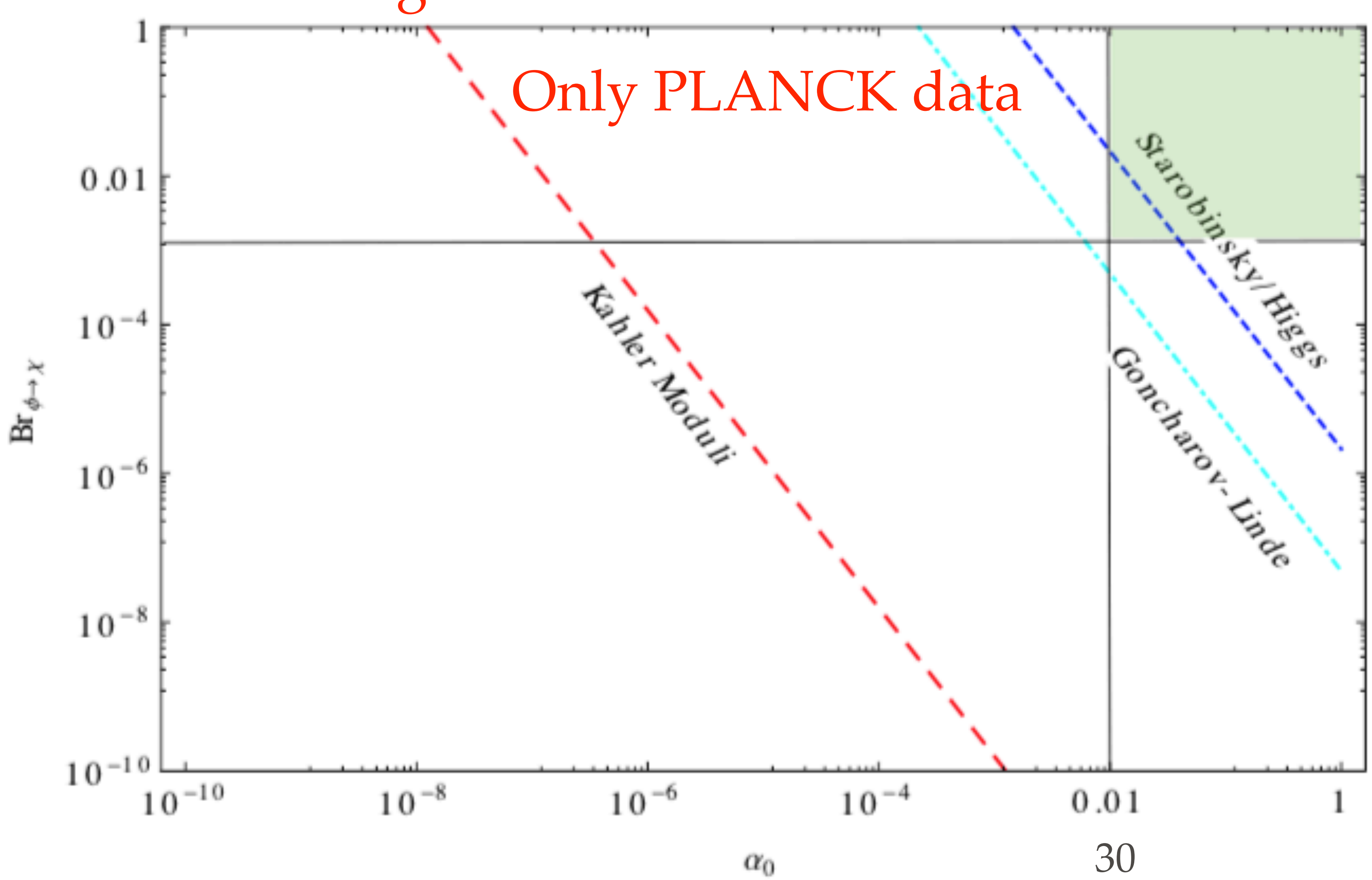
CMB

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

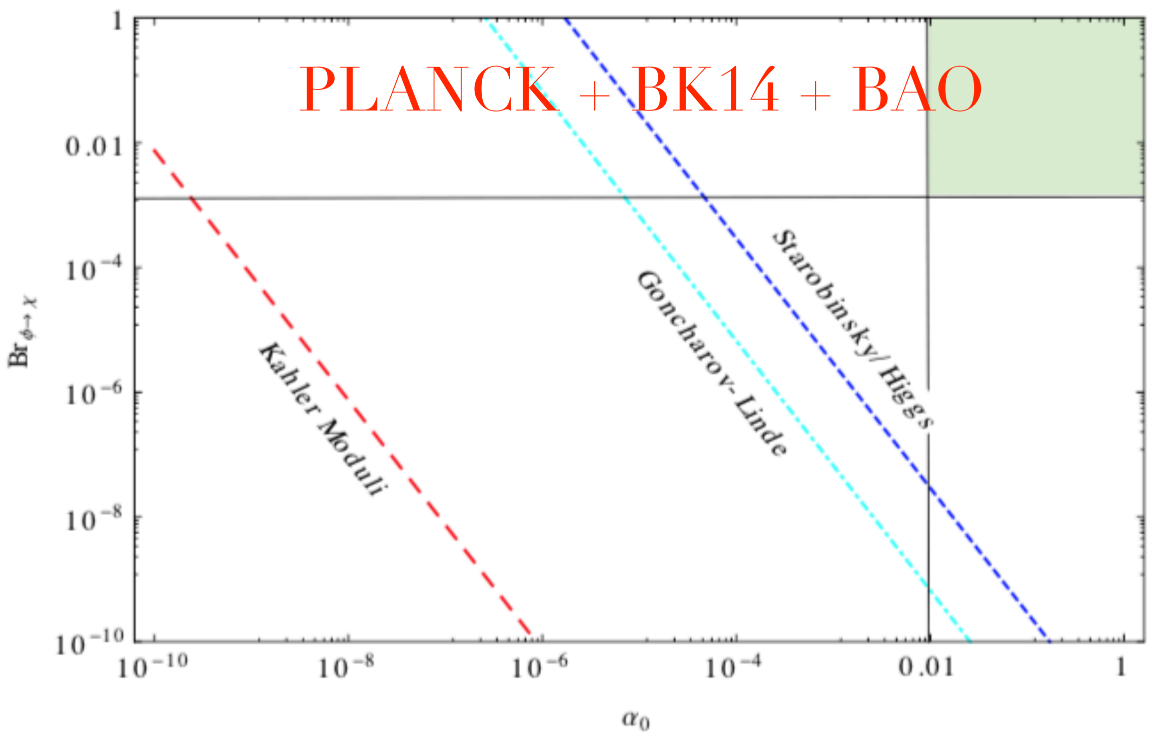
right of each line is disallowed



- More inputs of reheating, particle physics models will make the bound stronger

Implications

right of each line is disallowed



- Models with $r \lesssim \mathcal{O}(0.01)$ strong constraints

- When EMD field is a moduli

  $\varphi_0 \gtrsim \mathcal{O}(0.1)$ Dine, Randall, Thomas Dvali

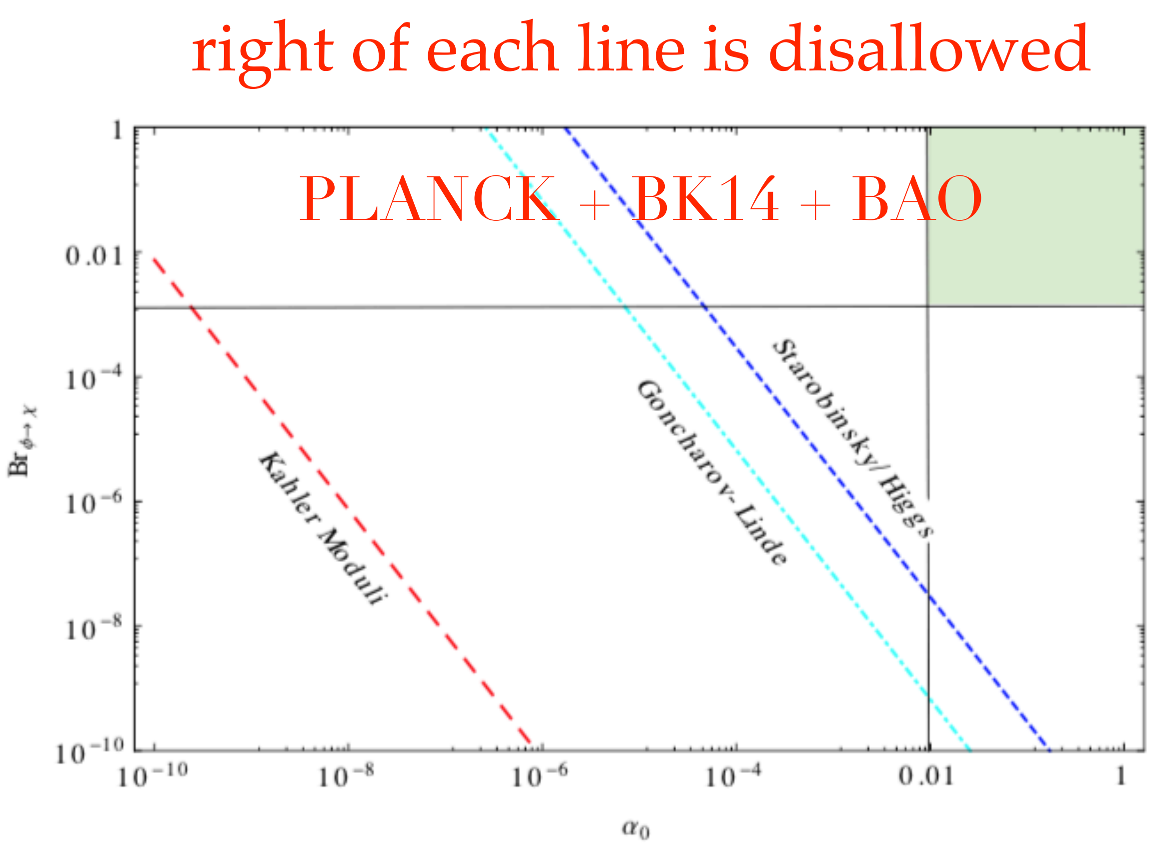
  Cicoli, K.D, Maharana, Quevedo

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

  Allahverdi, B. Dutta, Sinha

EMD epoch from moduli oscillations is (possibly)ruled out!

Implications



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EMD epoch from moduli oscillations is ruled out!

- When EMD field is a visible sector field: allowed

Enqvist, McDonald $\alpha_0 \ll 1 \quad \text{and/or} \quad \mathrm{Br}_{\phi\to\chi} \ll 10^{-3}$ Allahverdi, B. Dutta, Sinha

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

Comments

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

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

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

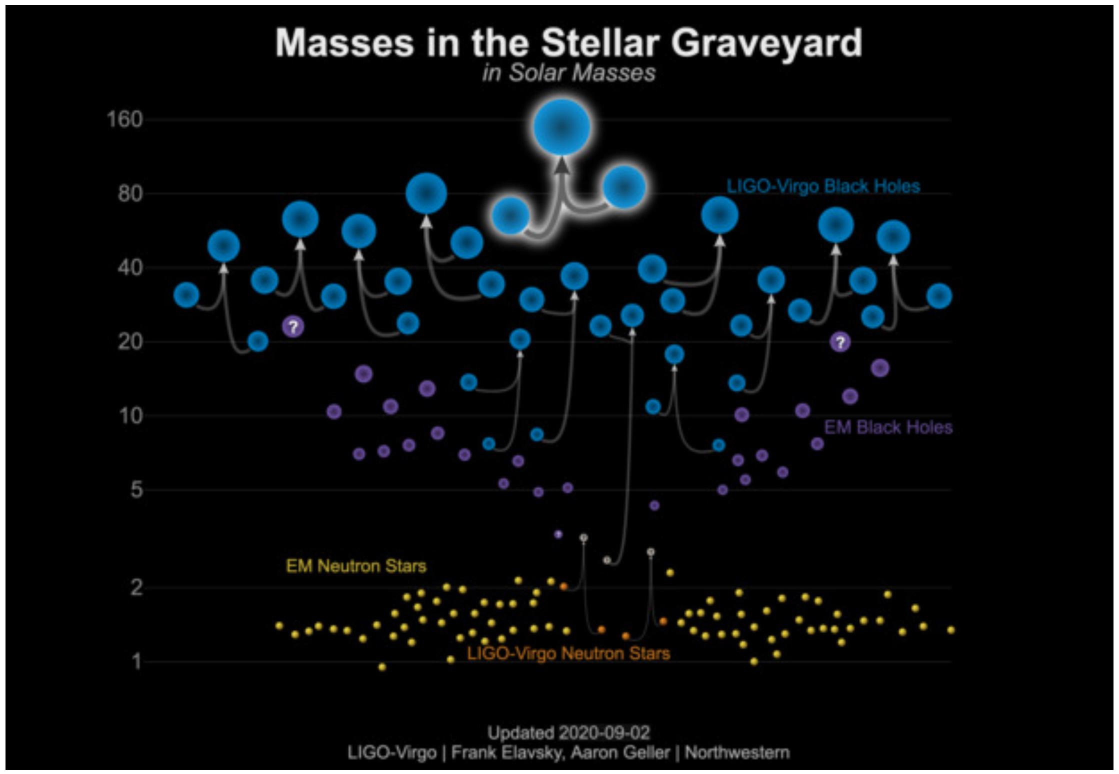
- More inputs from reheating will strengthen the bound
- Future CMB experiments are expected to shrink the error bar on the spectral index by a factor of ~ 2!

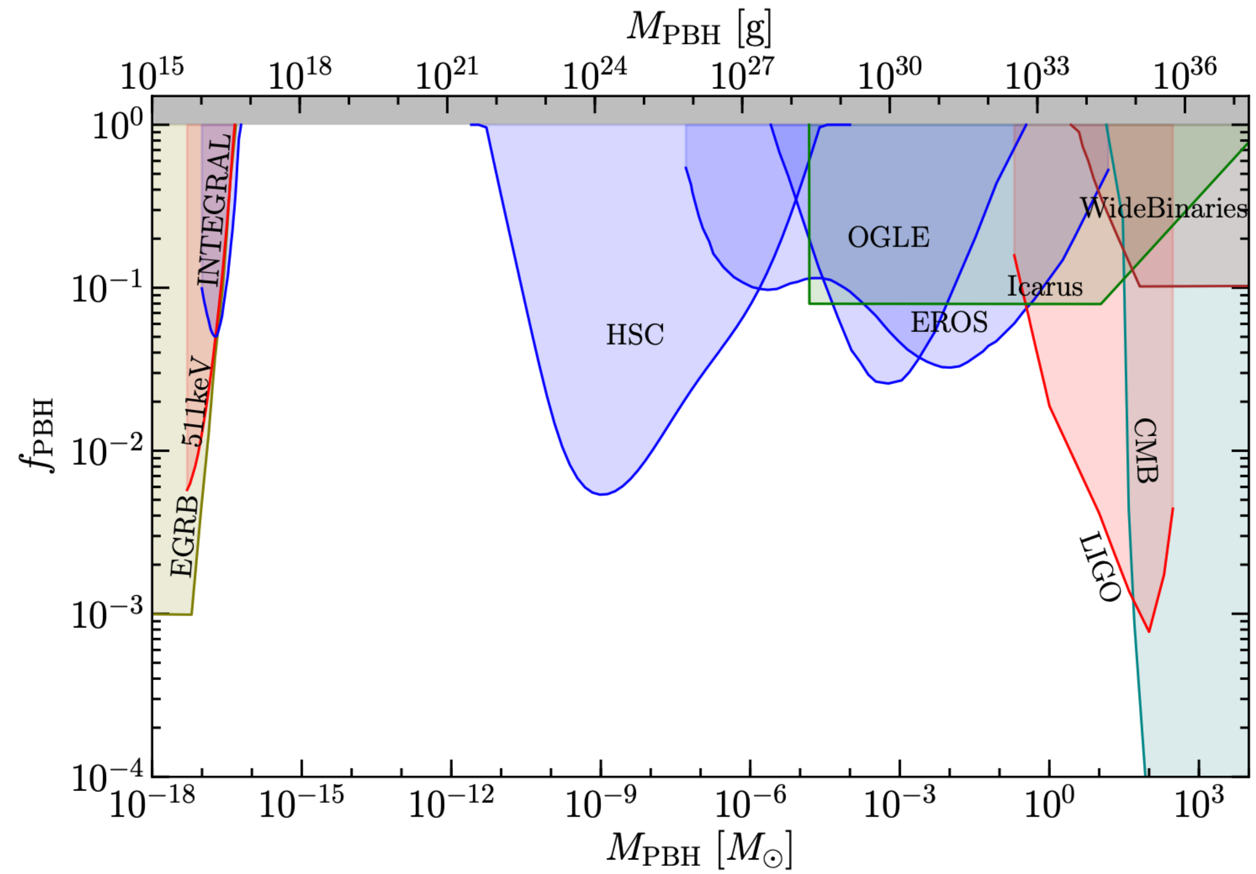
Conclusion - Part II

- 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.

PART III

Primordial Black Hole





- Large fluctuations collapse at the horizon re-entry

Hawking & Carr 1974

$$M = \gamma M_H = \gamma \frac{4\pi M_{Pl}^2}{H}$$

- Can form DM (a fraction) and probe small scale fluctuations

Solar Mass PBH During EMD

arXiv:2101.02234 - JCAP
with Sukannya Bhattacharya and Anirban Das

- Mass - Scale relation varies with background equation of state parameter
- Critical condition for collapse is different

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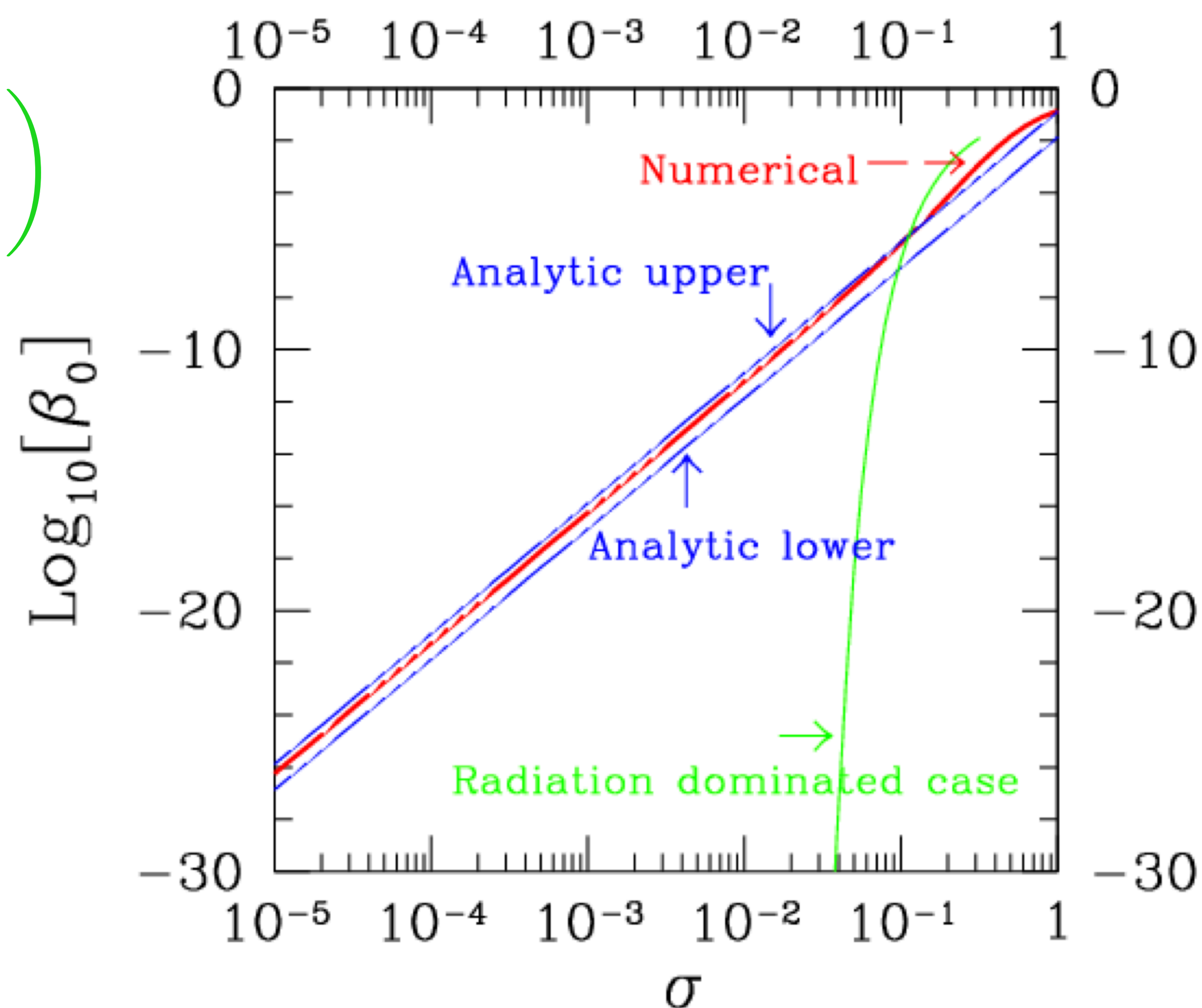
$$\beta_{RD}(M) = \int_{\delta_c}^{\infty} (d\delta)\ P(\delta) = \text{erfc}\left(\frac{\delta_c}{\sqrt{2}\sigma(M)}\right)$$

$$\beta_{MD}(M) \simeq 0.056\sigma^5(M)$$



Harada et.al (1609.01588)

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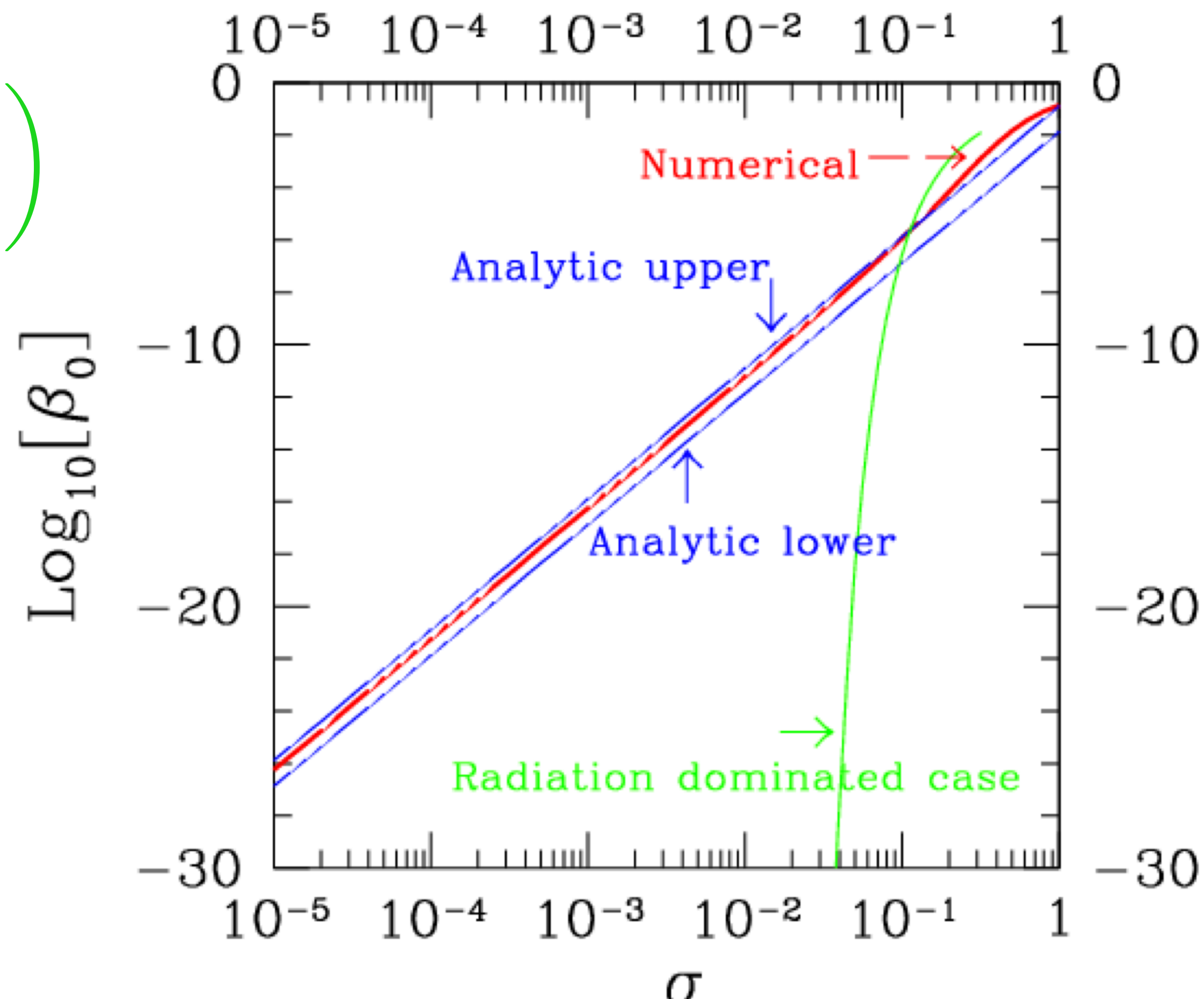
- Mass - Scale relation varies with background equation of state parameter
- Critical condition for collapse is different

$$\beta_{RD}(M) = \int_{\delta_c}^{\infty} (d\delta)\ P(\delta) = \mathrm{erfc}\left(\frac{\delta_c}{\sqrt{2}\sigma(M)}\right)$$

$$\beta_{MD}(M) \simeq 0.056\sigma^5(M)$$

- Mass function $\psi(M) = \frac{1}{M}\frac{\rho_{\mathrm{PBH}}}{\rho_{\mathrm{DM}}}$

$$f_{PBH} = \int dM \psi(M)$$



Harada et.al (1609.01588)

Collapse During EMD

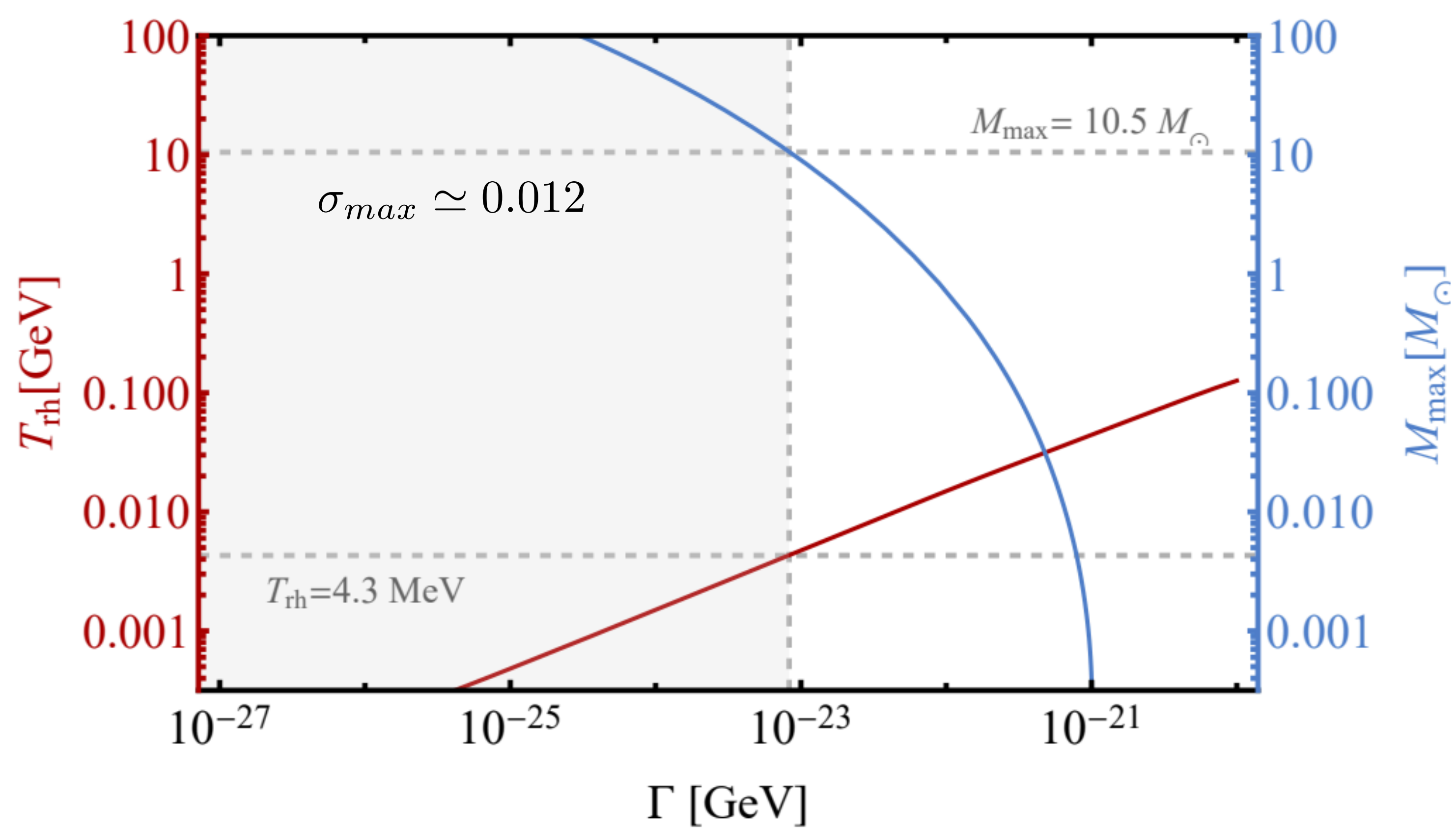
- Density fluctuations grow linearly with scale factor during EMD

$$M = \frac{4\pi M_{\rm Pl}^2}{H_{\rm hor}} = \frac{4\pi M_{\rm Pl}^2}{H_c}\sigma^{3/2}$$

$$M_{\rm max} = \frac{4\pi M_{Pl}^2}{H_{max}} = \frac{4\pi M_{Pl}^2}{H_{\rm rh}}\sigma_{\rm max}^{3/2} = \frac{4\pi M_{Pl}^2}{\Gamma}\sigma_{\rm max}^{3/2} = M_{rh}\sigma_{\rm max}^{3/2}$$

$$\sigma_{\rm max}^2 \simeq (2/5)^2 P_\zeta(k_{\rm max})$$

- Fixes mass $m_\phi \sim 135\text{TeV}$



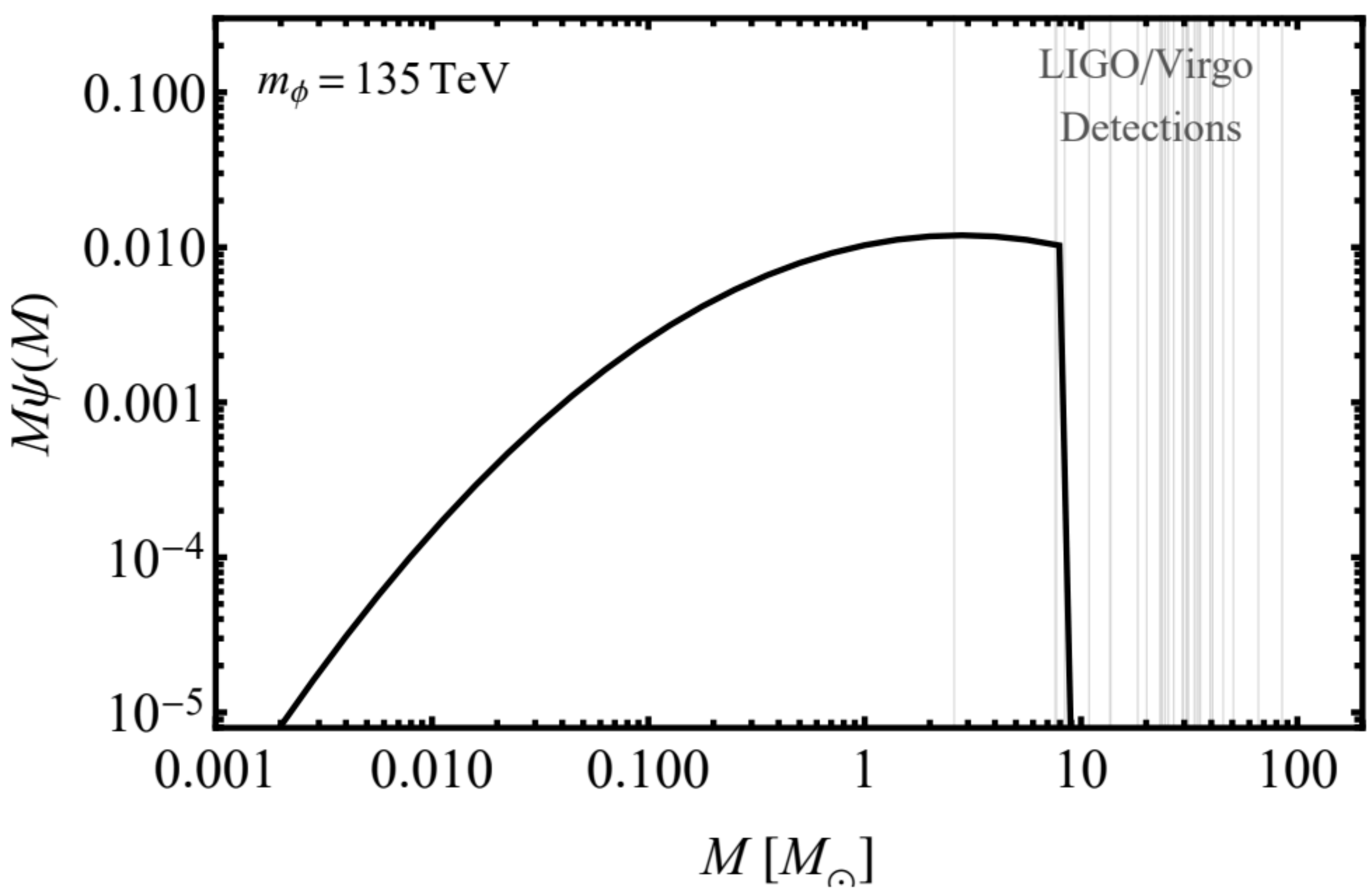
Mass Functions

$$\psi(M) = \begin{cases} 2.6 \times 10^{8} \left(\frac{M_\odot}{M}\right)^{1/2} \left(\frac{m_\phi M_{\rm Pl}}{\phi_0^2}\right)^{1/3} \frac{\beta_{\rm RD}(M)}{M}, & M < M_{\rm min}, \\ 5.2 \times 10^{26} \left(\frac{m_\phi}{M_{\rm Pl}}\right)^{3/2} \frac{\beta_{\rm MD}(M)}{M}, & M_{\rm min} \le M \le M_{\rm max}, \\ 5 \times 10^{8} \left(\frac{M_\odot}{M}\right)^{1/2} \frac{\beta_{\rm RD}(M)}{M}, & M > M_{\rm max}. \end{cases}$$

pre-EMD epoch

EMD epoch

post-EMD epoch

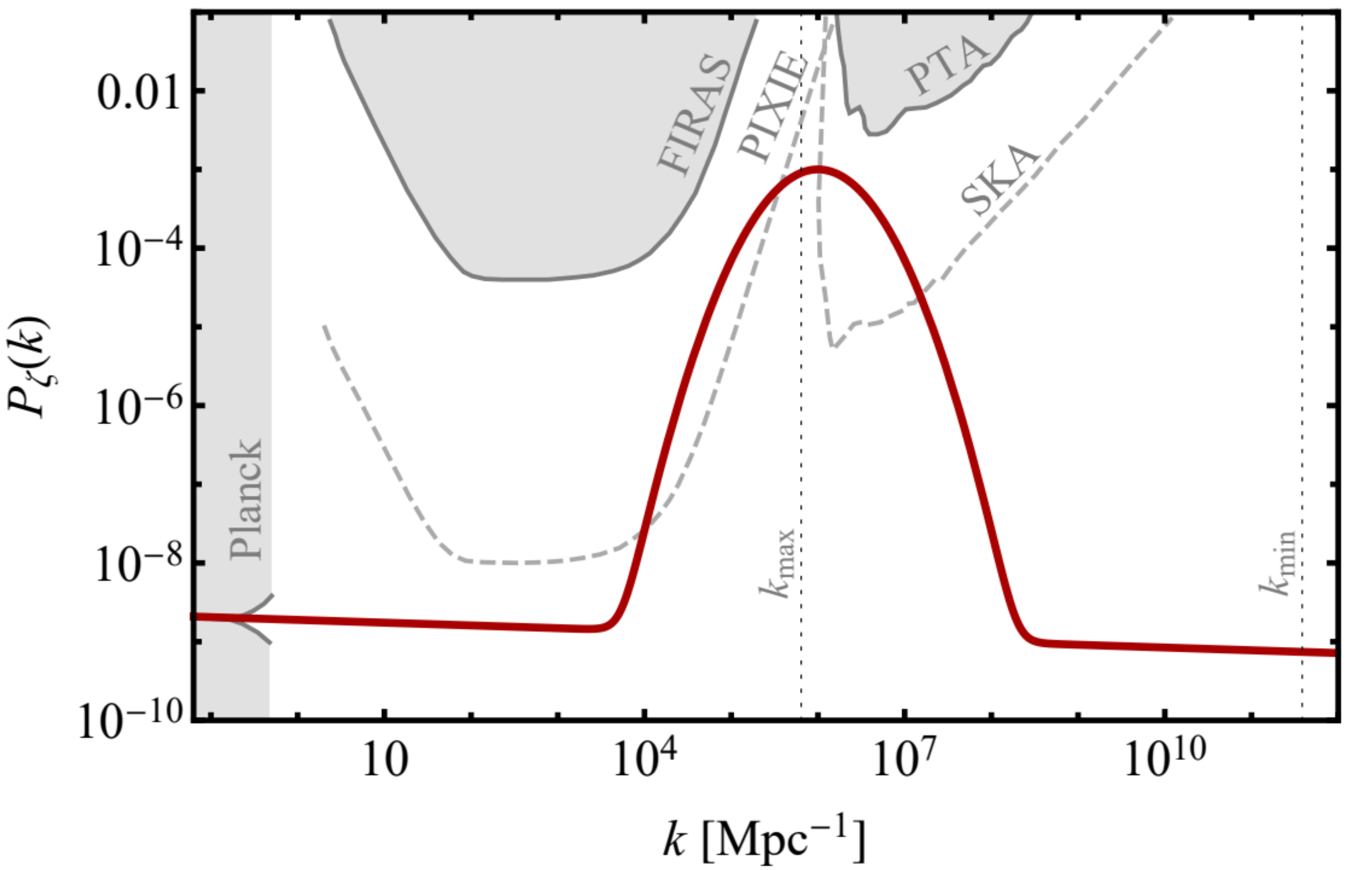


$$M_{\rm min} = M_{max} \left(\frac{m_\phi M_{\rm Pl}}{4\sqrt{\pi}\phi_0^2}\right)^{1/2}$$

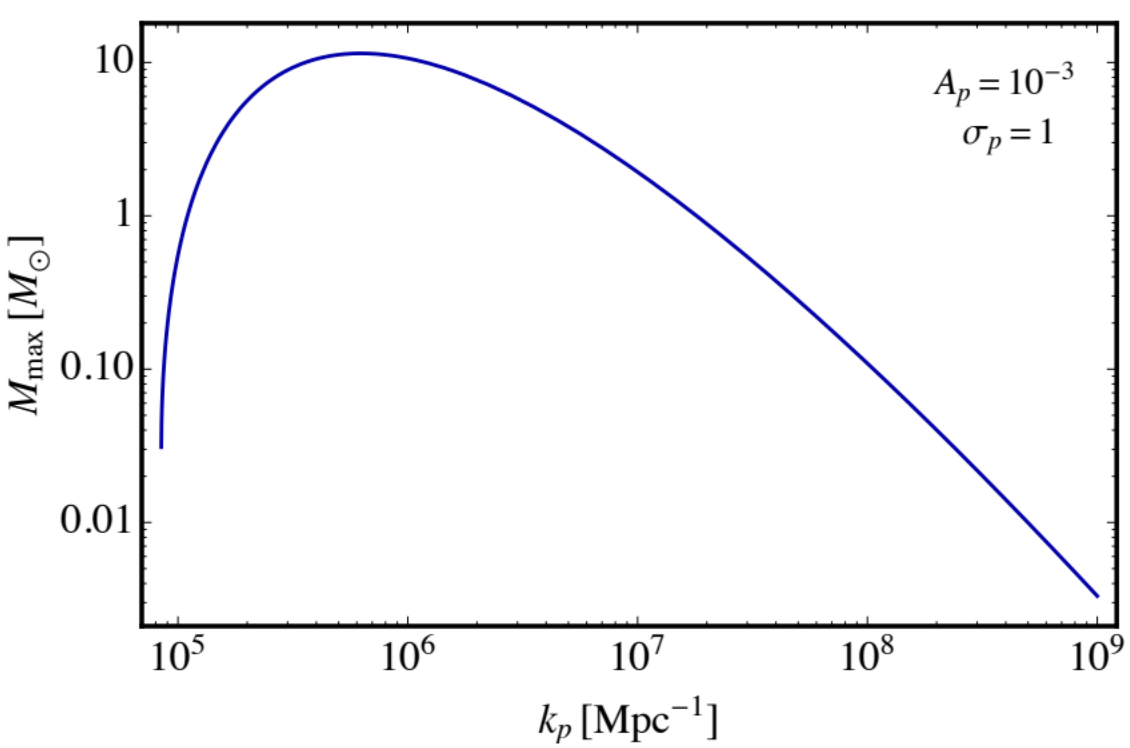
Only a few LIGO-Virgo events can be explained

Primordial Spectrum

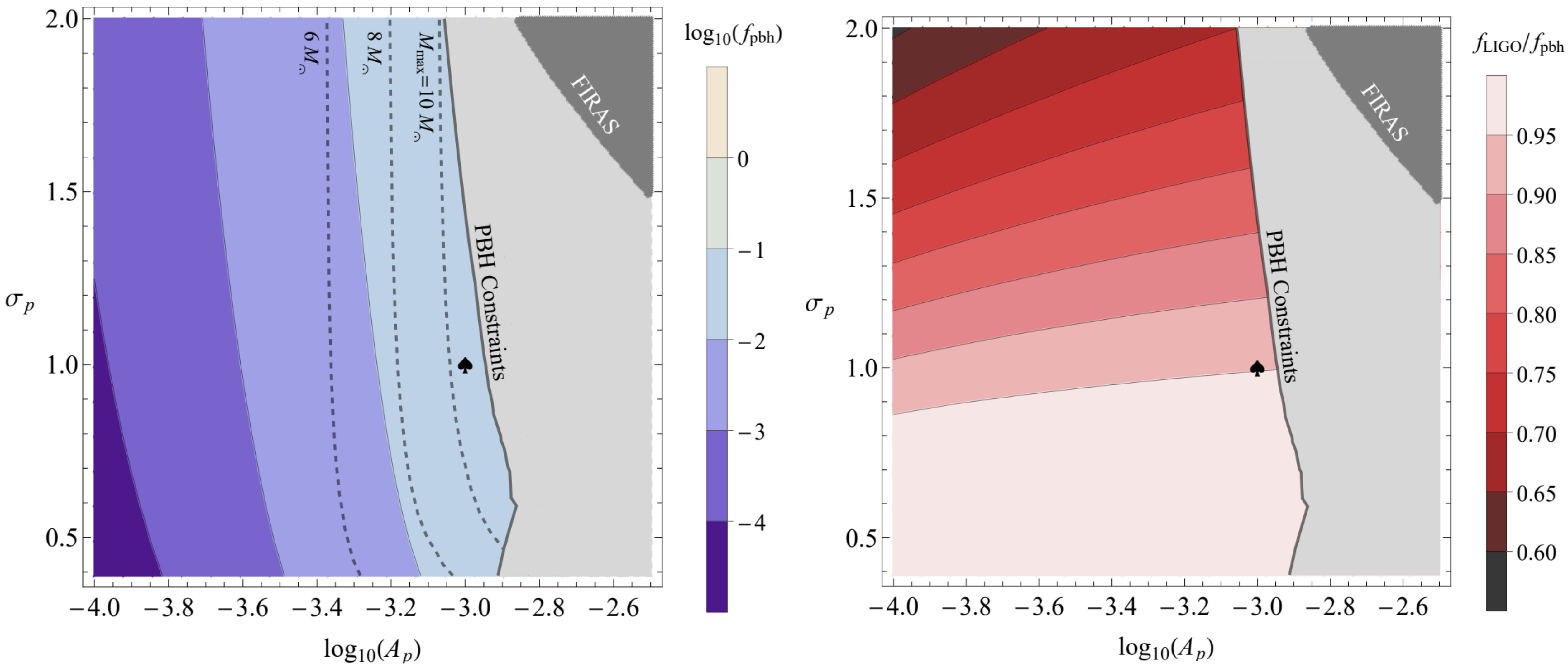
$$P_\zeta(k) = A_s\left(\frac{k}{k_*}\right)^{n_s-1} + A_p \exp\left[-\frac{(N_k - N_p)^2}{2\sigma_p^2}\right]$$



$A_p = 10^{-3}, \sigma_p = 1 \quad k_p = 10^6\,\mathrm{Mpc}^{-1}$



Parameter Constraints



Only 4% of the DM comes from PBH, the rest may come from other DM produced from moduli

$$f_{\rm LIGO} = \int_{0.1\,M_\odot}^{300\,M_\odot} \psi(M)dM$$

Conclusion: Part III

- Production of PBHs in the EMD epoch is different than the RD epoch.

- In the most optimistic case, EMD epoch can produce PBH of the maximum of 10 solar mass. Thus it CAN NOT potentially explain all the events observed by LIGO-VIRGO.

- In this case, only a few percent of DM may come from PBH, and the rest of DM must come from other sources - see paper for more details.

Final Remarks

- Understanding pre-BBN physics is crucial
- Knowing this epoch is related to other unsolved puzzle: (1) Baryon number generations, (2) CMB predictions etc
- We talked about two issues: (1) Effects of reheating (2) Correlating with CMB observables (3) Primordial black holes productions

Other topics:

Non-Planckian DM momentum distribution from moduli decay.

arXiv: 2009.05987 (Bhattacharya, Das, K. D, Gangopadhyay, Mahanta, Maharana)

Non-thermal moduli production during preheating.

Alam, Bastero-Gil, K.D, Raghavendra (forthcoming)