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

AAPCOS, SINP Kolkata

January 27, 2023

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

with Alam, Bastero-Gil, Raghavendra (forthcoming)

From data ONLY

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

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

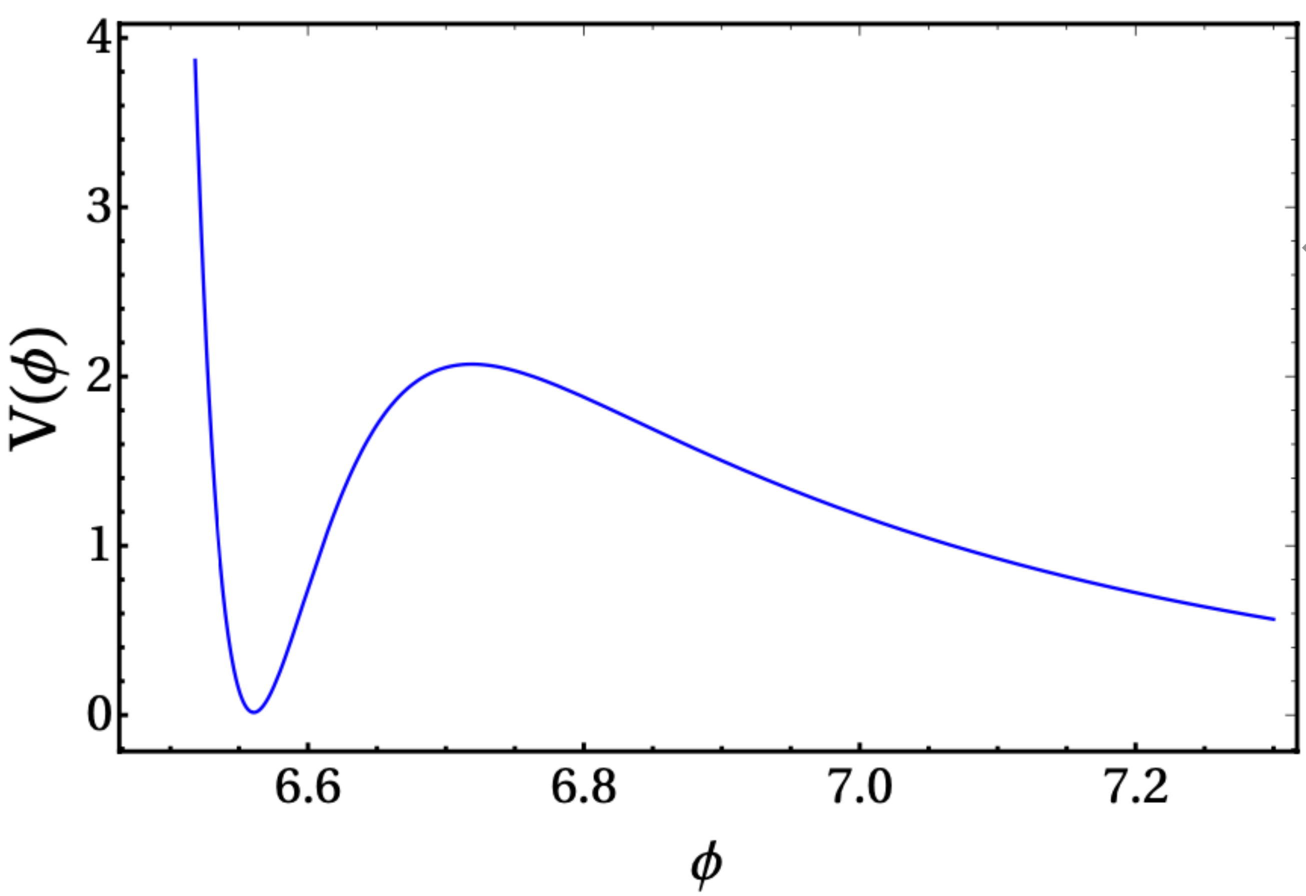
- Coherent super-Hubble perturbations (.. due to inflation ??)
- Dark matter .. gravitational collapse
- Recent cosmic acceleration (dynamical or CC or gravity modifications ??)

Moduli

- 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



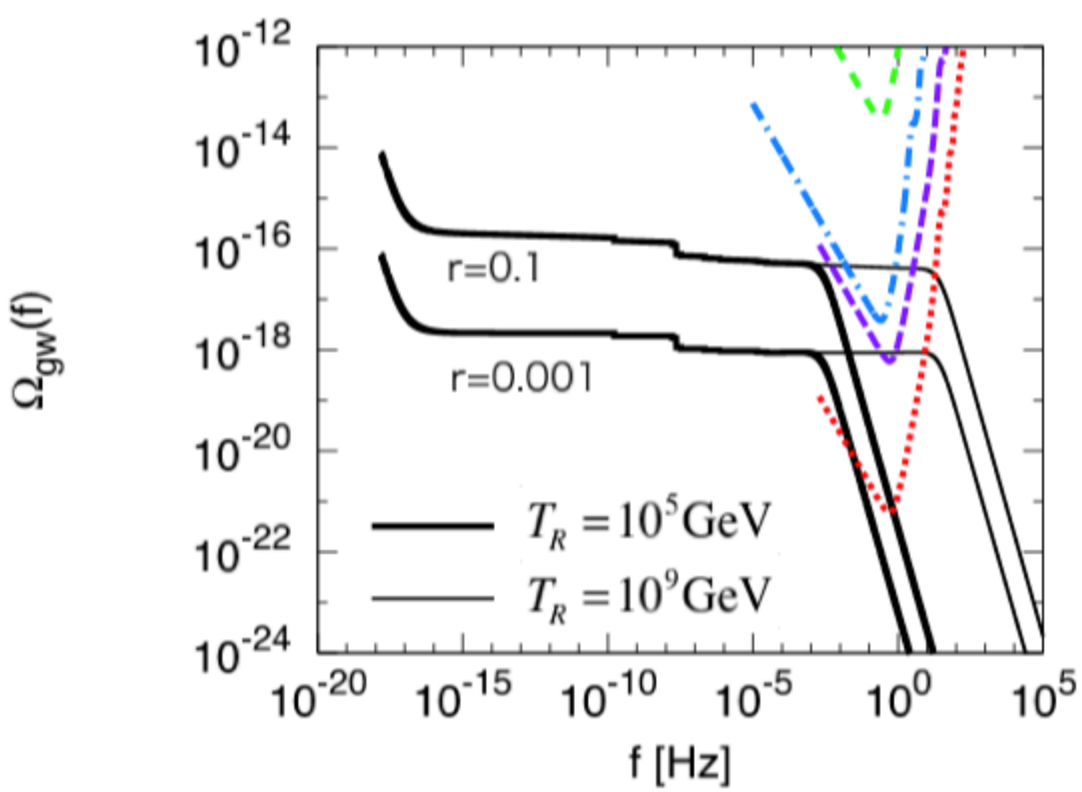
Kachru, Kallosh, Linde, Trivedi

- Moduli oscillations change the thermal history of the Universe: Non-standard thermal history - Early Matter Domination (EMD)

Review: Kane, Sinha, Watson (2015)

Notorious to probe

- 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

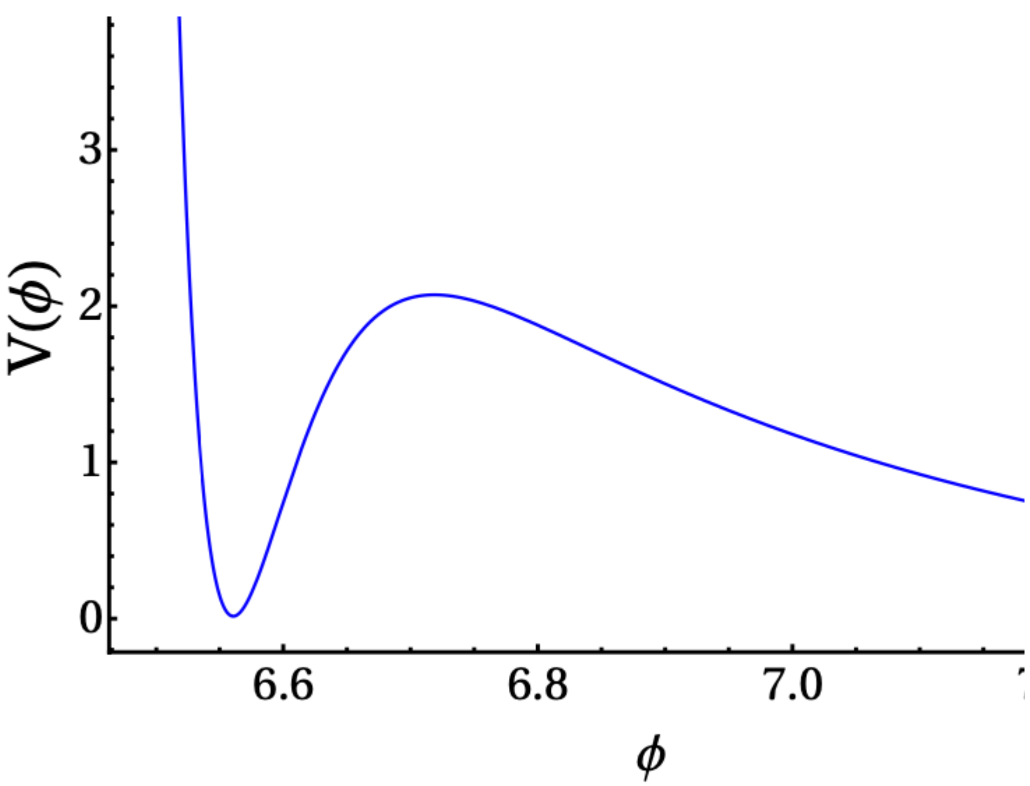
20 MeV

Decays by today

30 TeV

Decays by BBN

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



$$n_\sigma/s \lesssim 10^{-12} \implies \phi_{\rm init} \lesssim 10^{-10} M_P$$

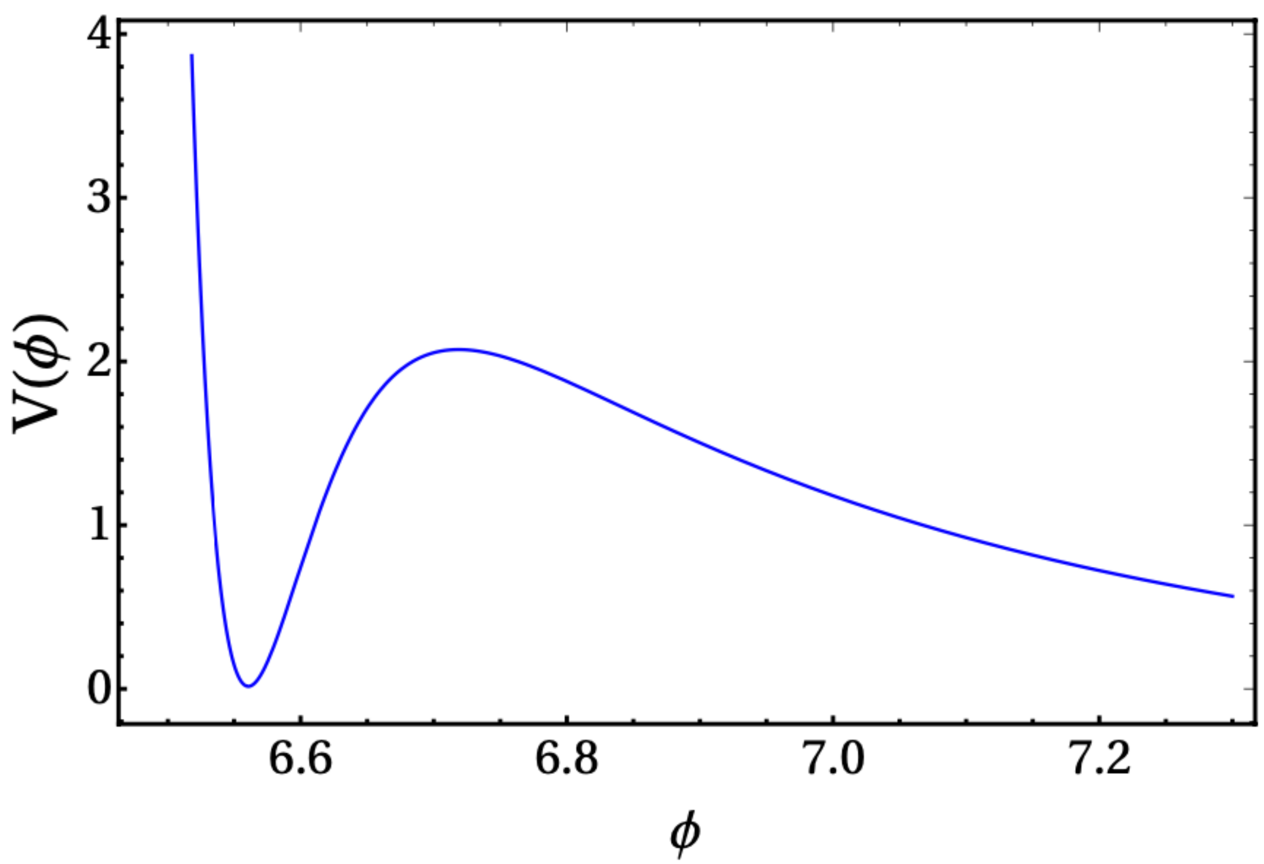
Kawasaki, Kohri and T. Moroi

Thermal or non-thermal productions

Giudice, Tkachev, Riotto

Moduli Problem

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



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

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

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

Cicoli, K.D, Maharana, Quevedo

Classical vacuum misalignment

Also quantum fluctuations

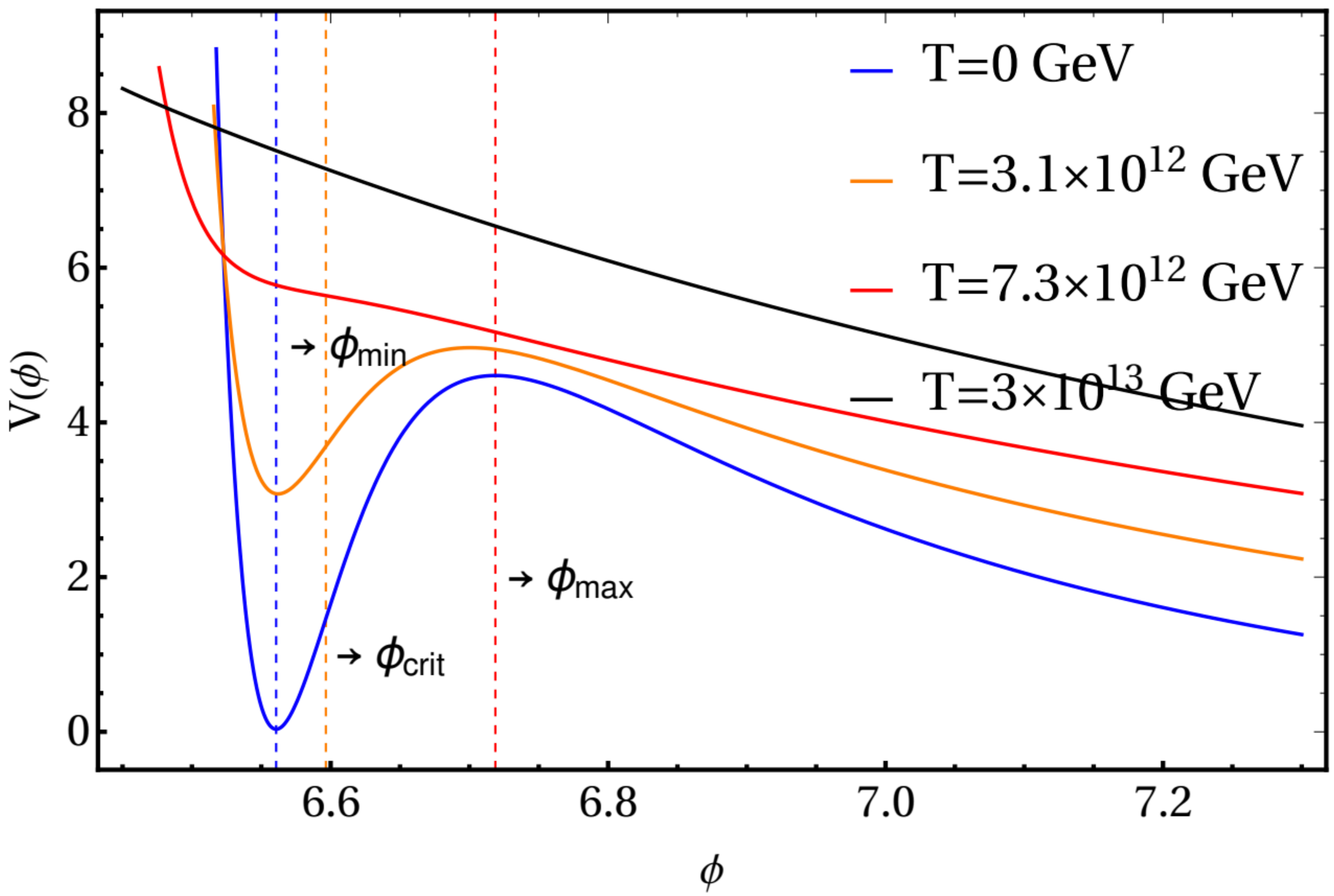
$$H_{\text{inf}} \lesssim m_{3/2}$$

Kallosh & Linde

Antusch, K.D, Halter

Moduli + Thermal Bath

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

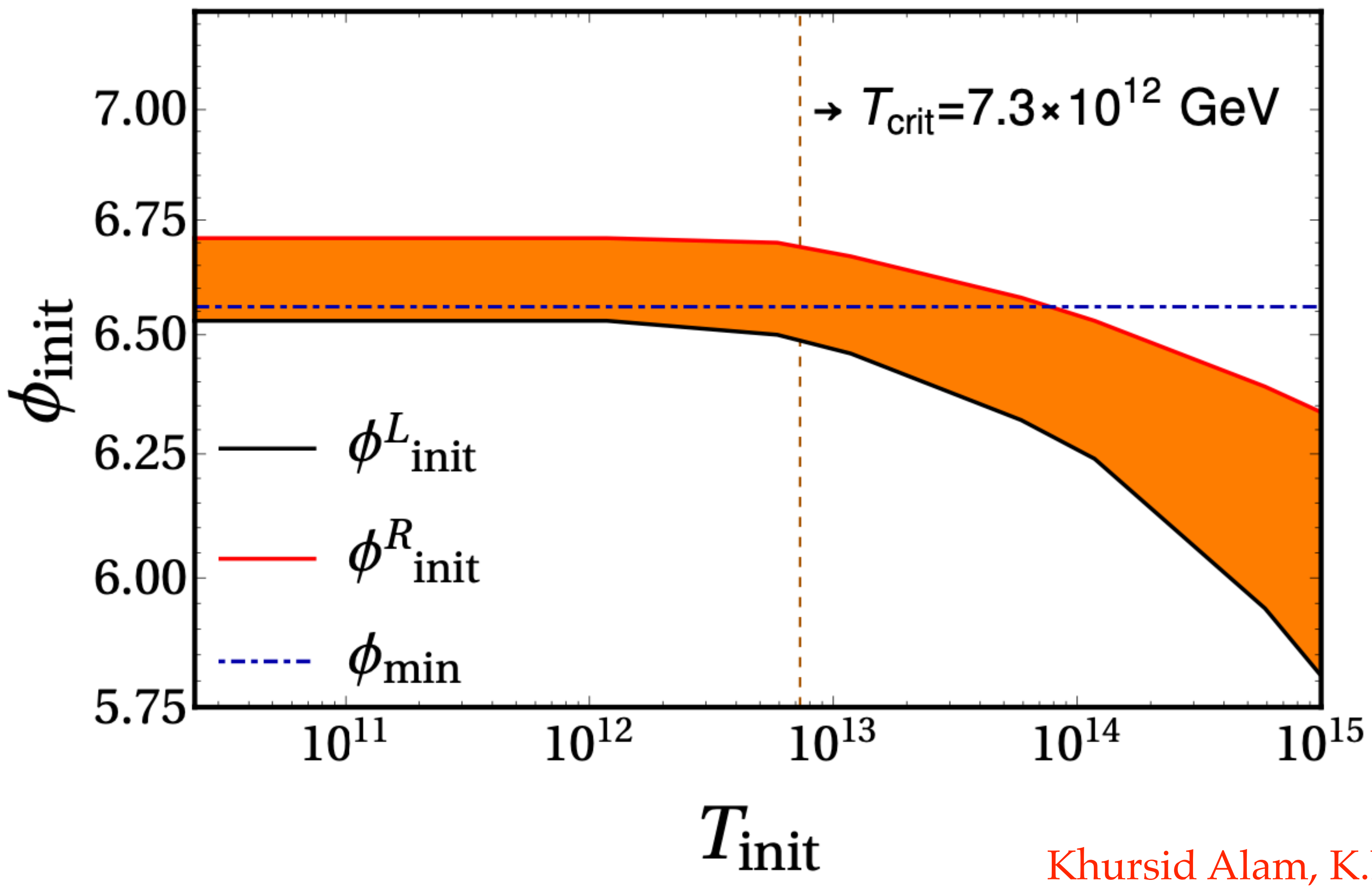


Buchmuller, Yamaguchi, Lebedev, Ratz

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

Upper limit on reheating temperature

Dynamics of Moduli



Khursid Alam, K.D

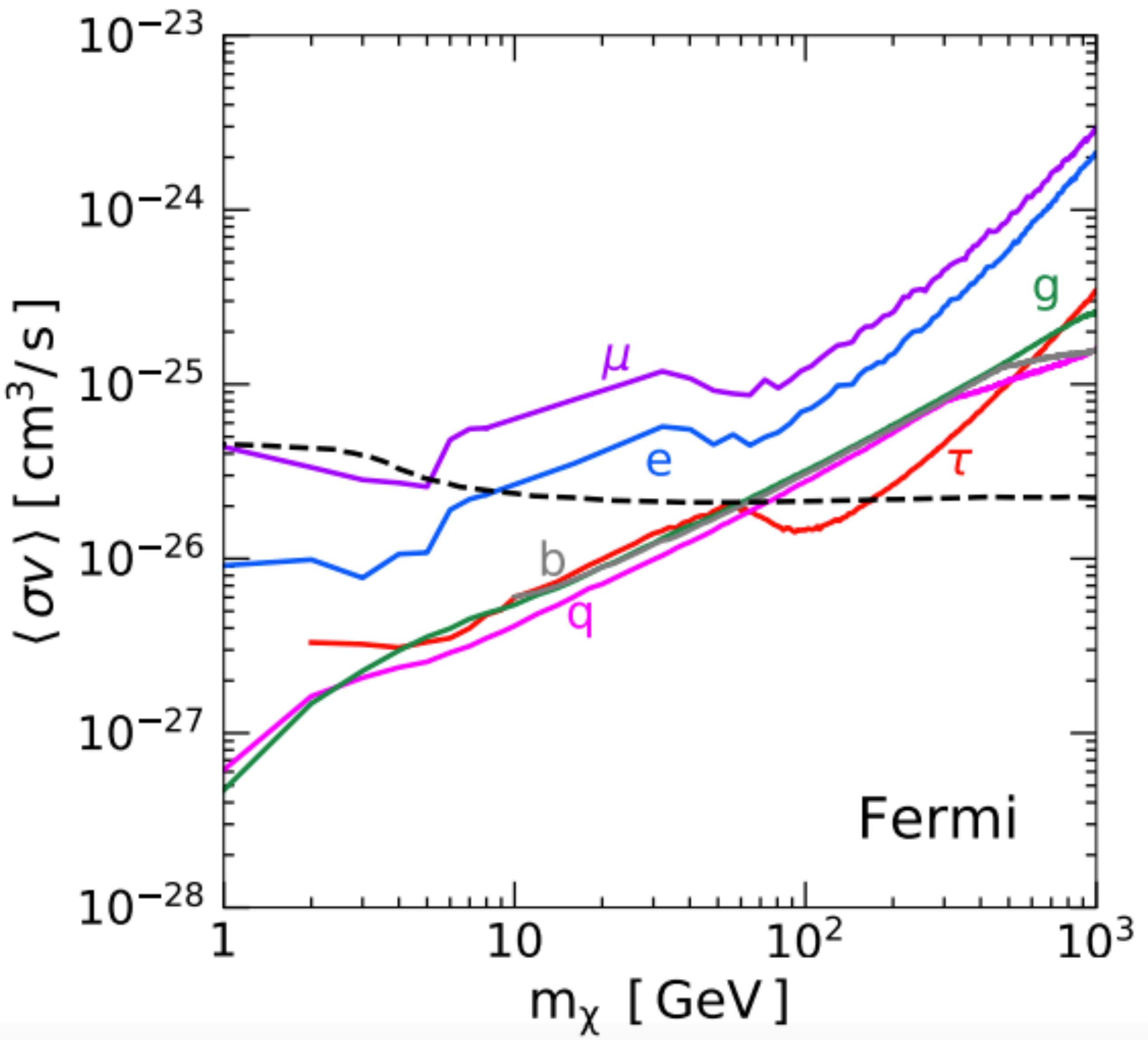
Relating with CMB

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



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

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

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

See also K.D, Ghosh, Kar, Mukhopadhyaya (2022)

Leane, Slatyer, Beacom, Ng (1805.10305)

Freeze-out during EMD

Giudice, Kolb, Riotto; Erickcek

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

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

- 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

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

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

Decay at the end of EMD

Gelmini, Gondolo;

Allahverdi, B. Dutta, Sinha

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

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

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

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

Independent from annihilation cross-section

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

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

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

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

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

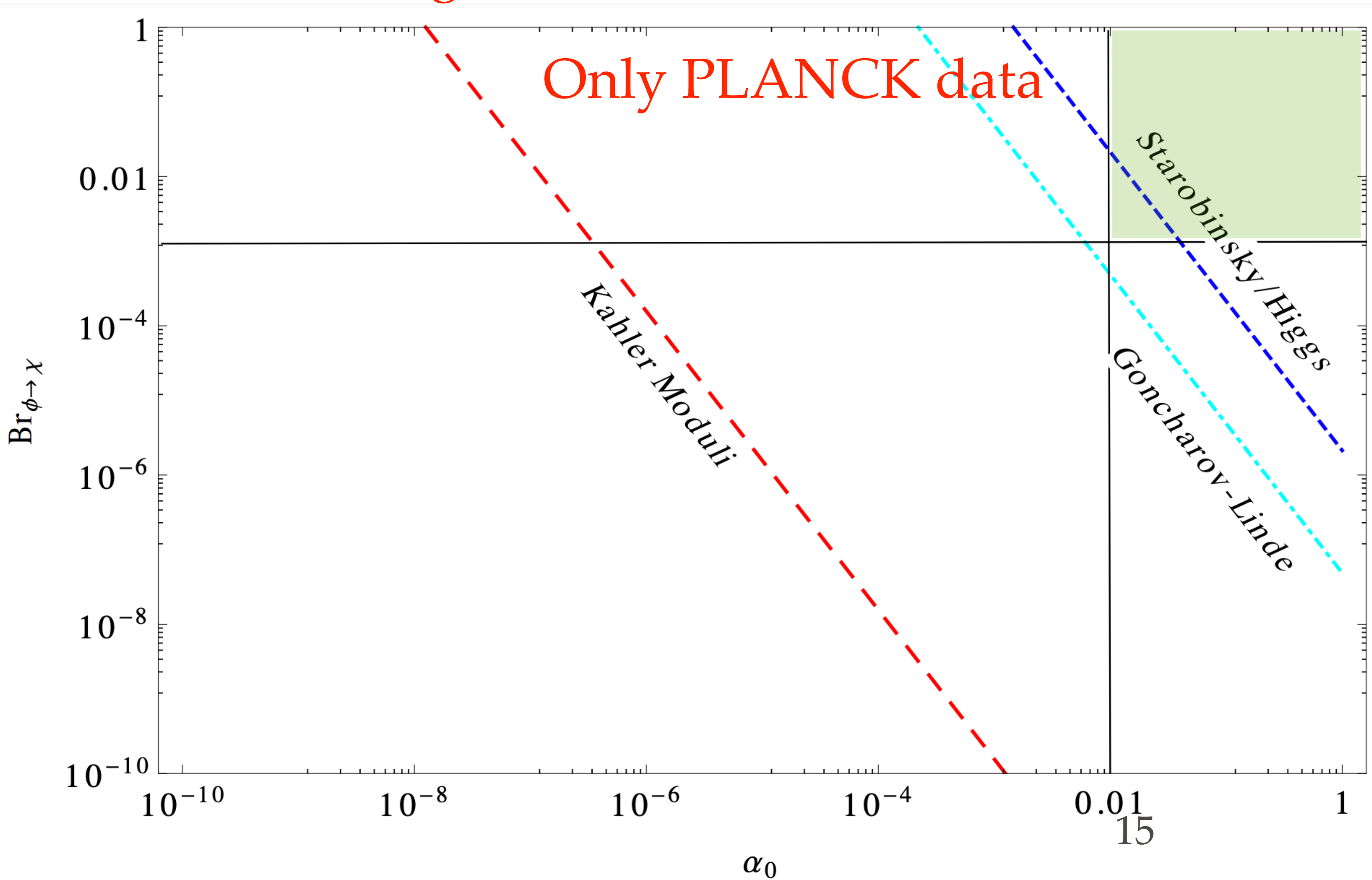
Bound

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

DM abundance

CMB

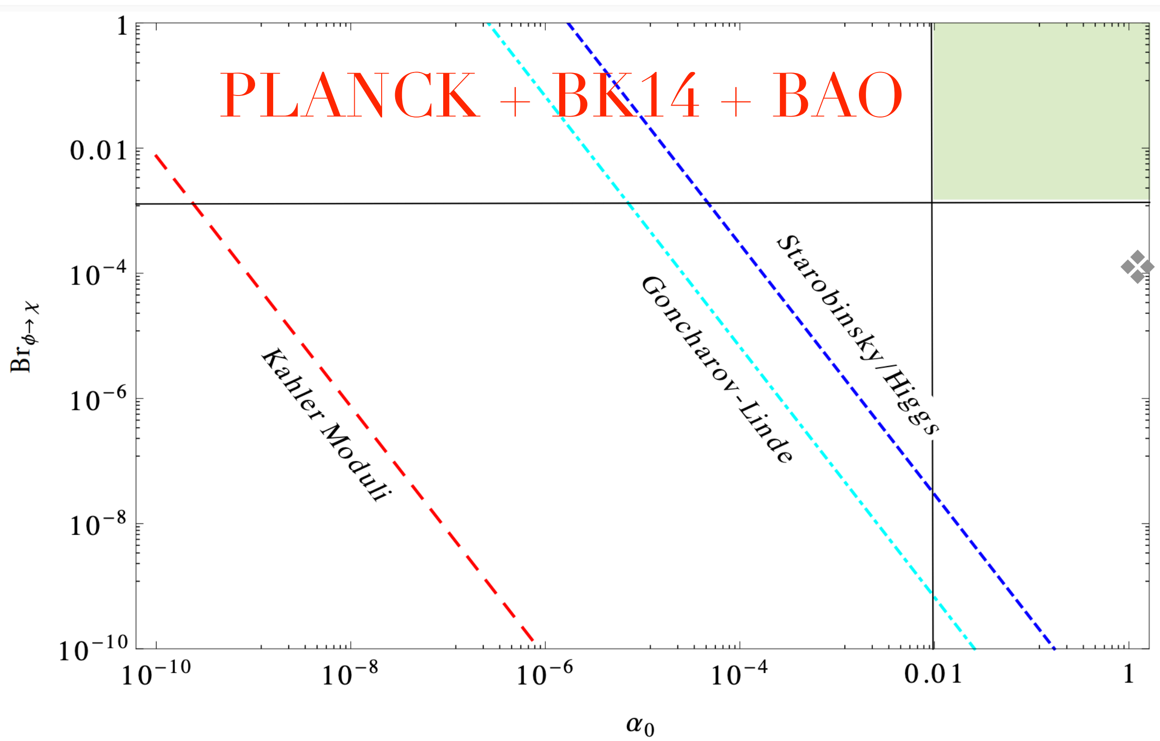
right of each line is disallowed



- 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

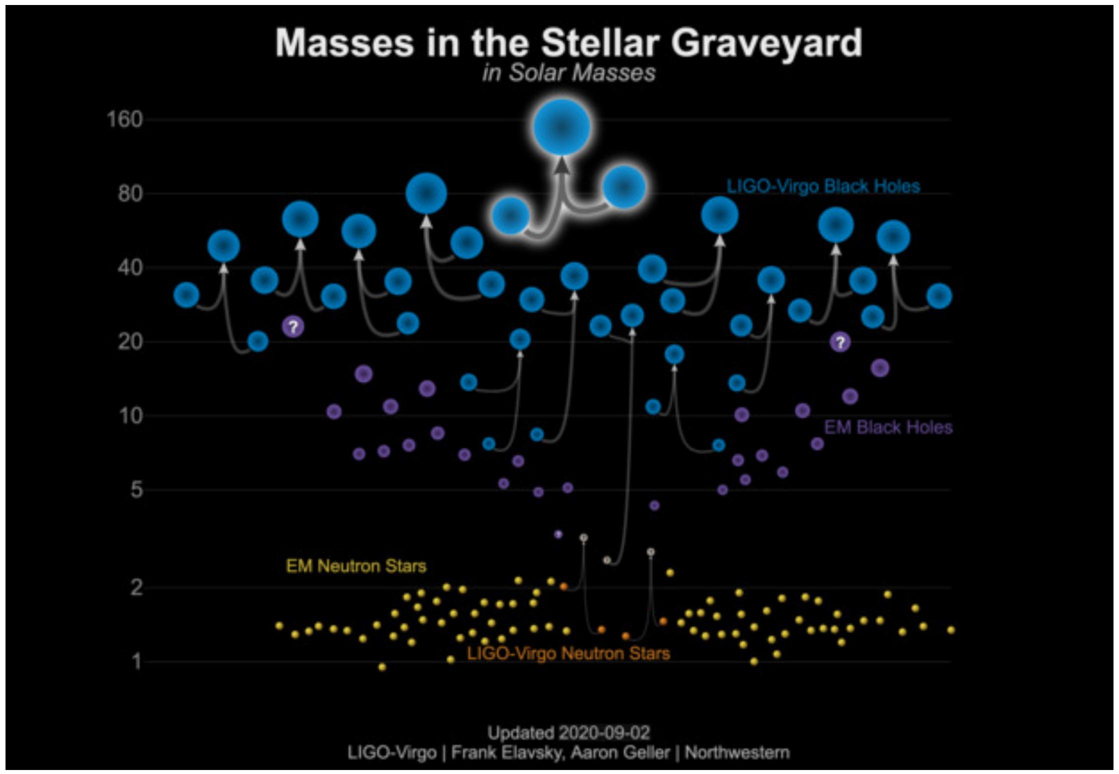
EMD epoch from moduli oscillations is ruled out?

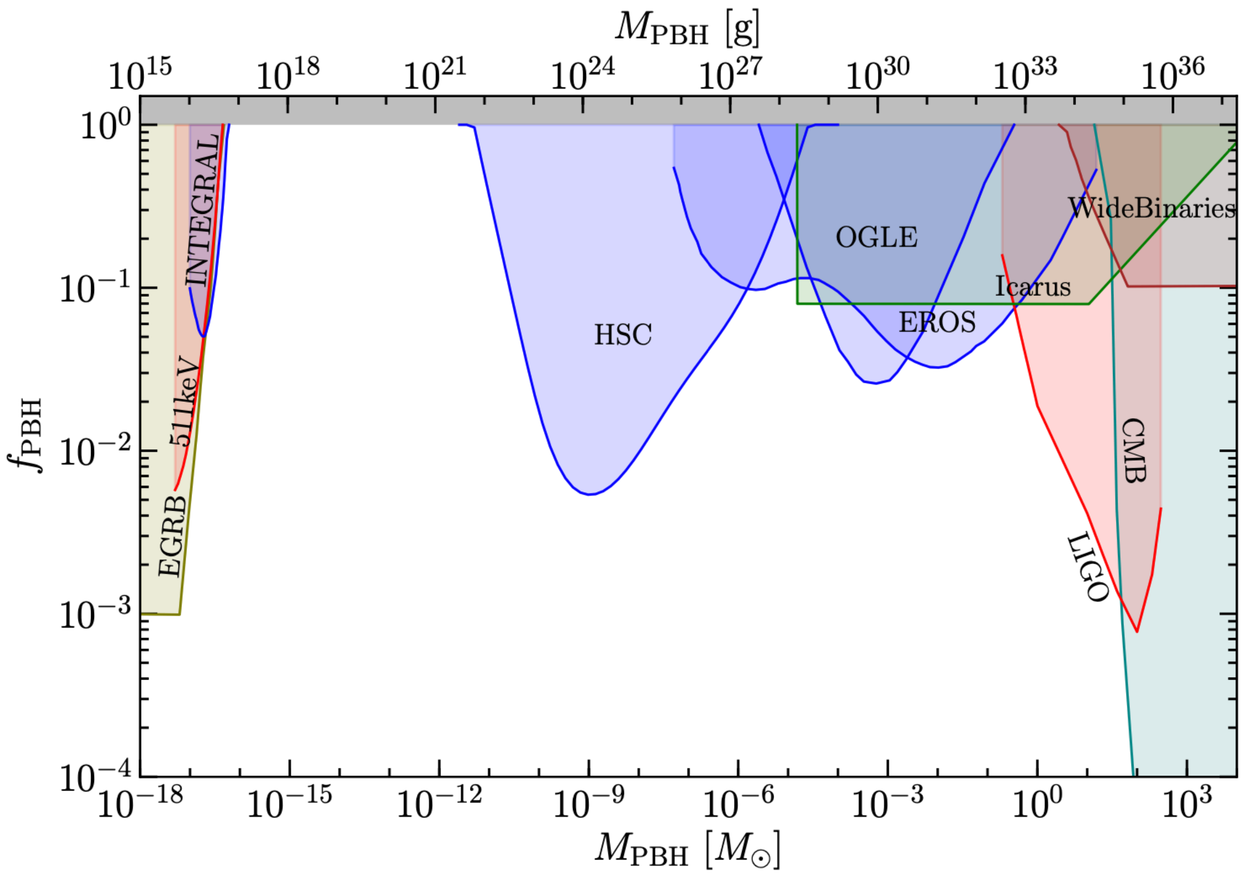
- When EMD field is a visible sector field: allowed

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

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

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

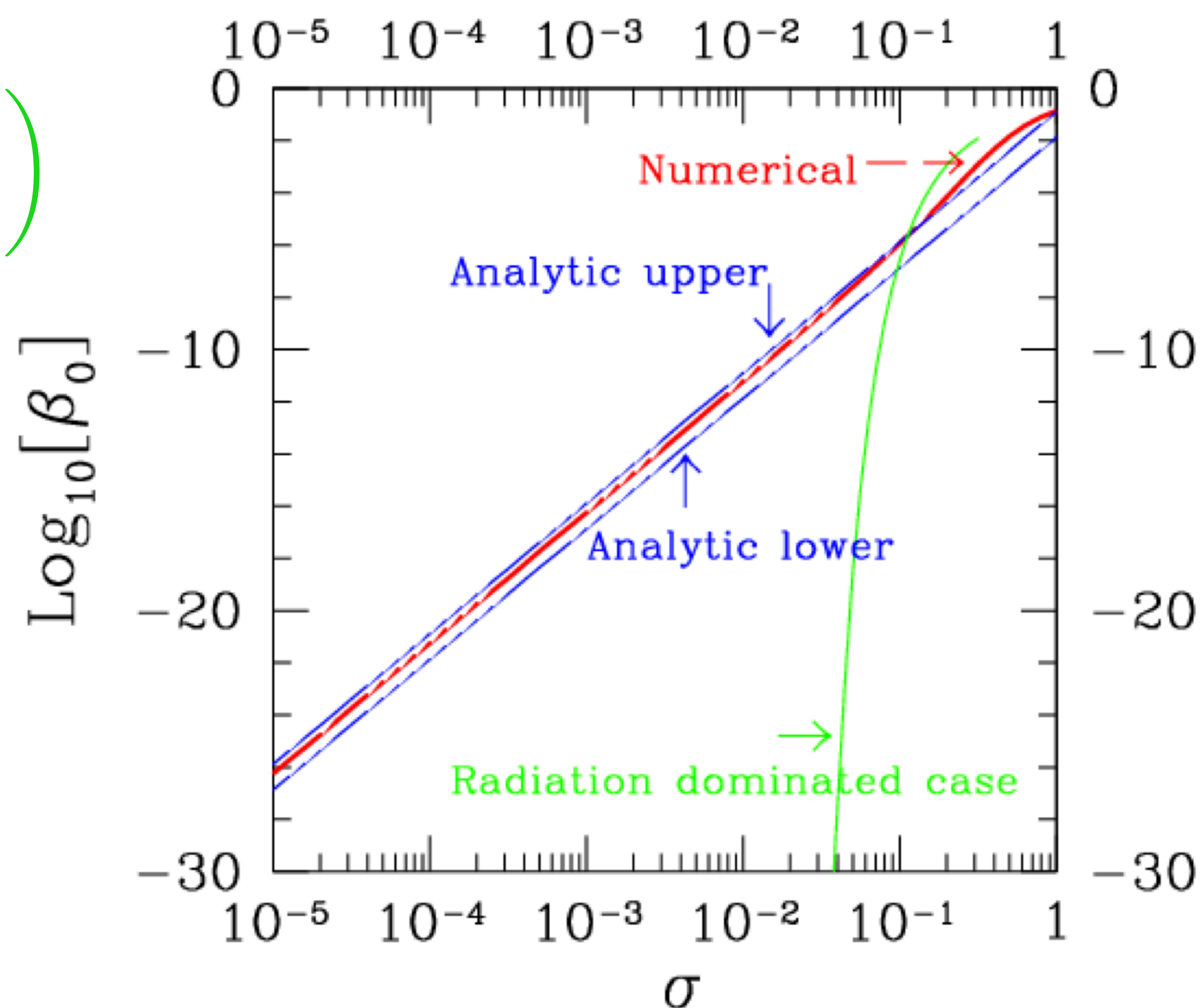
Solar Mass PBH During EMD

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

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

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



Harada et.al (1609.01588)

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

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

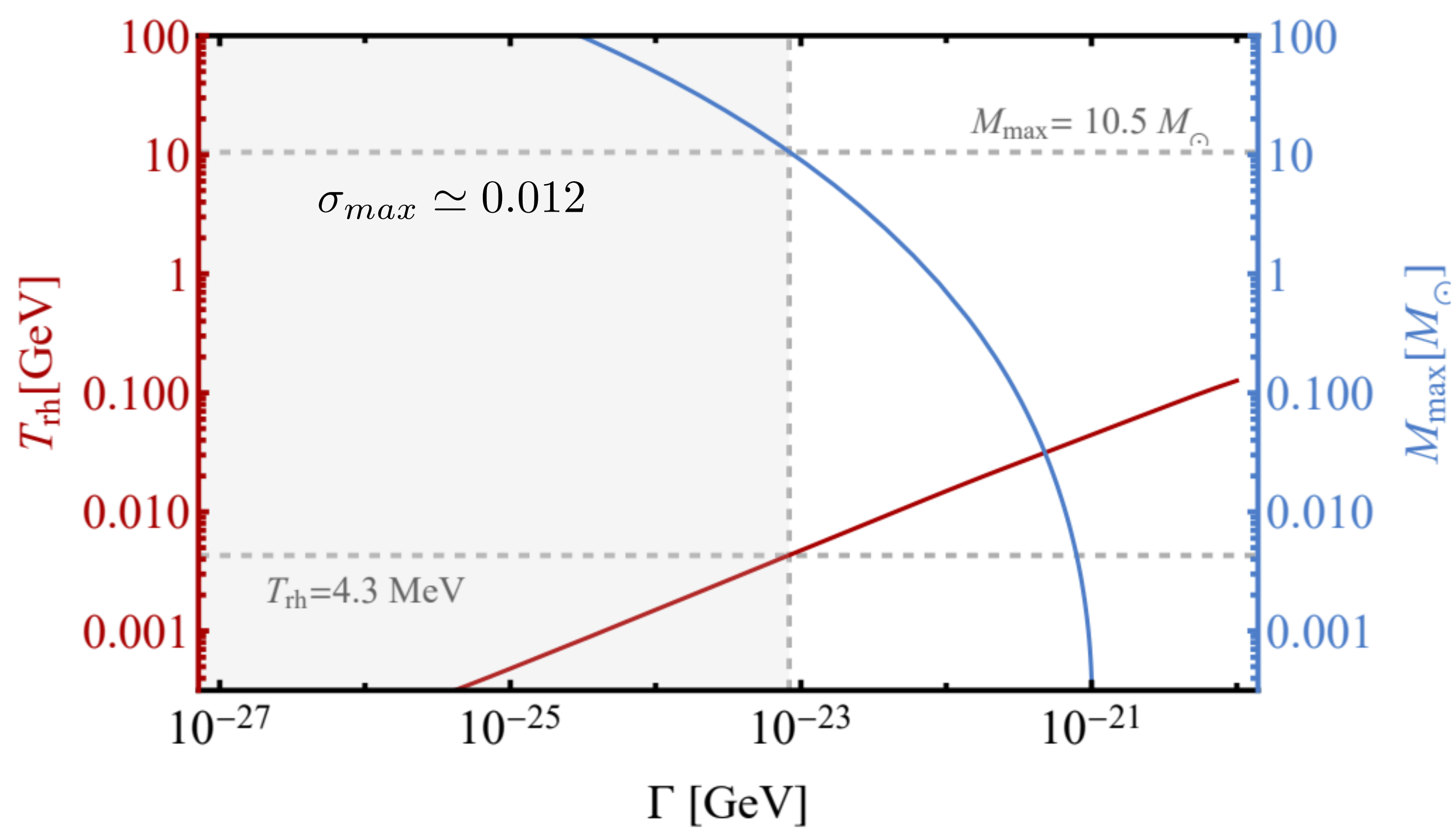
Collapse During EMD

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

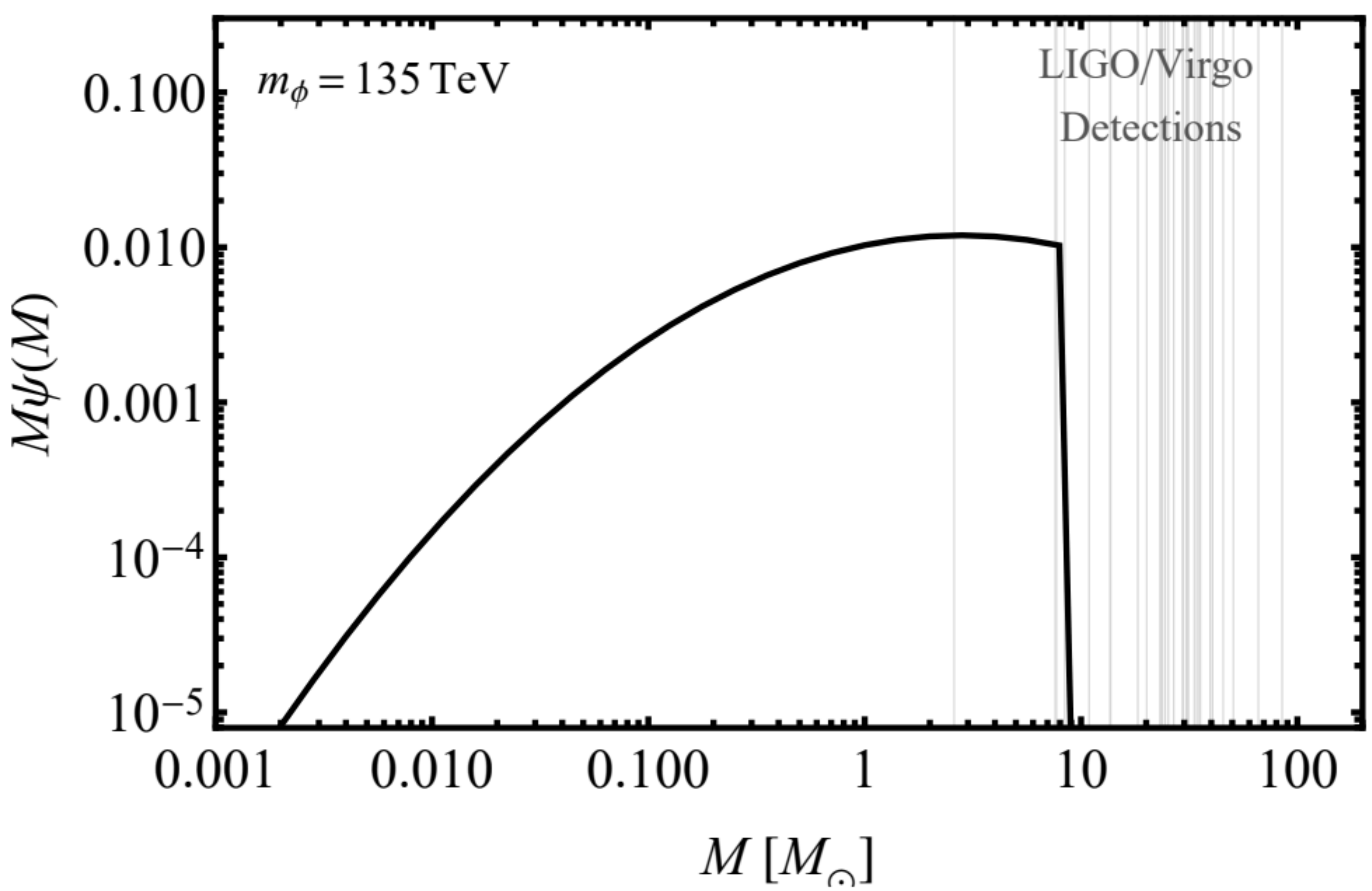
Mass Functions

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

pre-EMD epoch

EMD epoch

post-EMD epoch

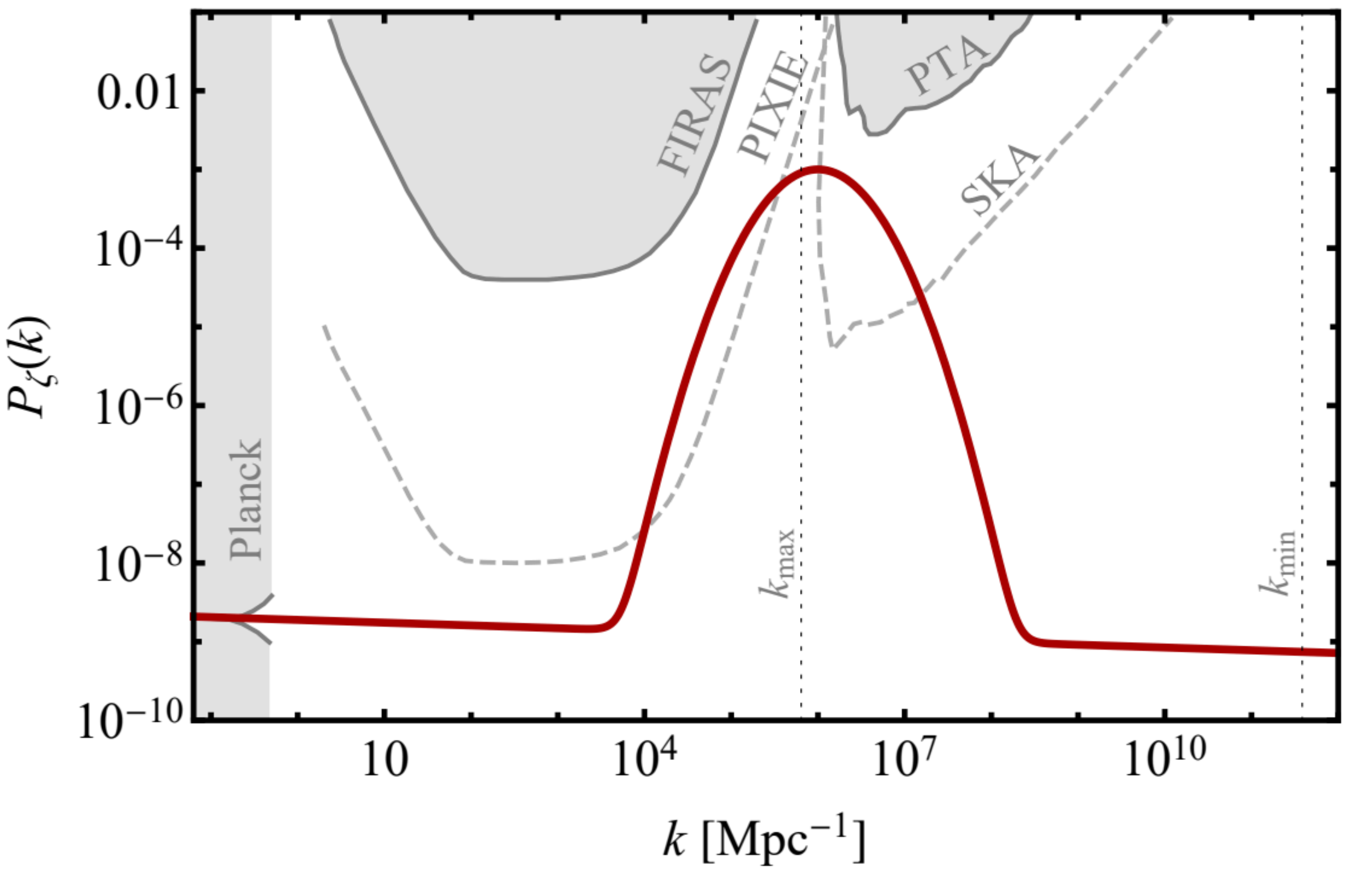


$$M_{\rm min} = M_{max} \left(\frac{m_\phi M_{\rm Pl}}{4\sqrt{\pi}\phi_0^2}\right)^{1/2}$$

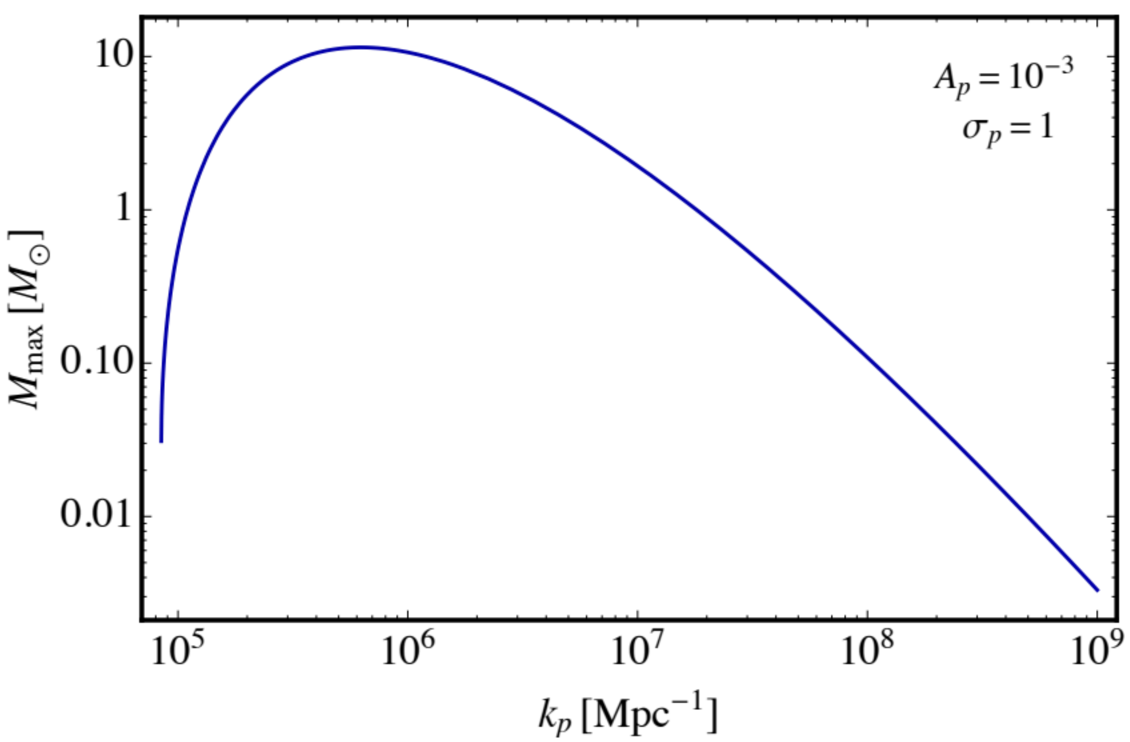
Only a few LIGO-Virgo events can be explained

Primordial Spectrum

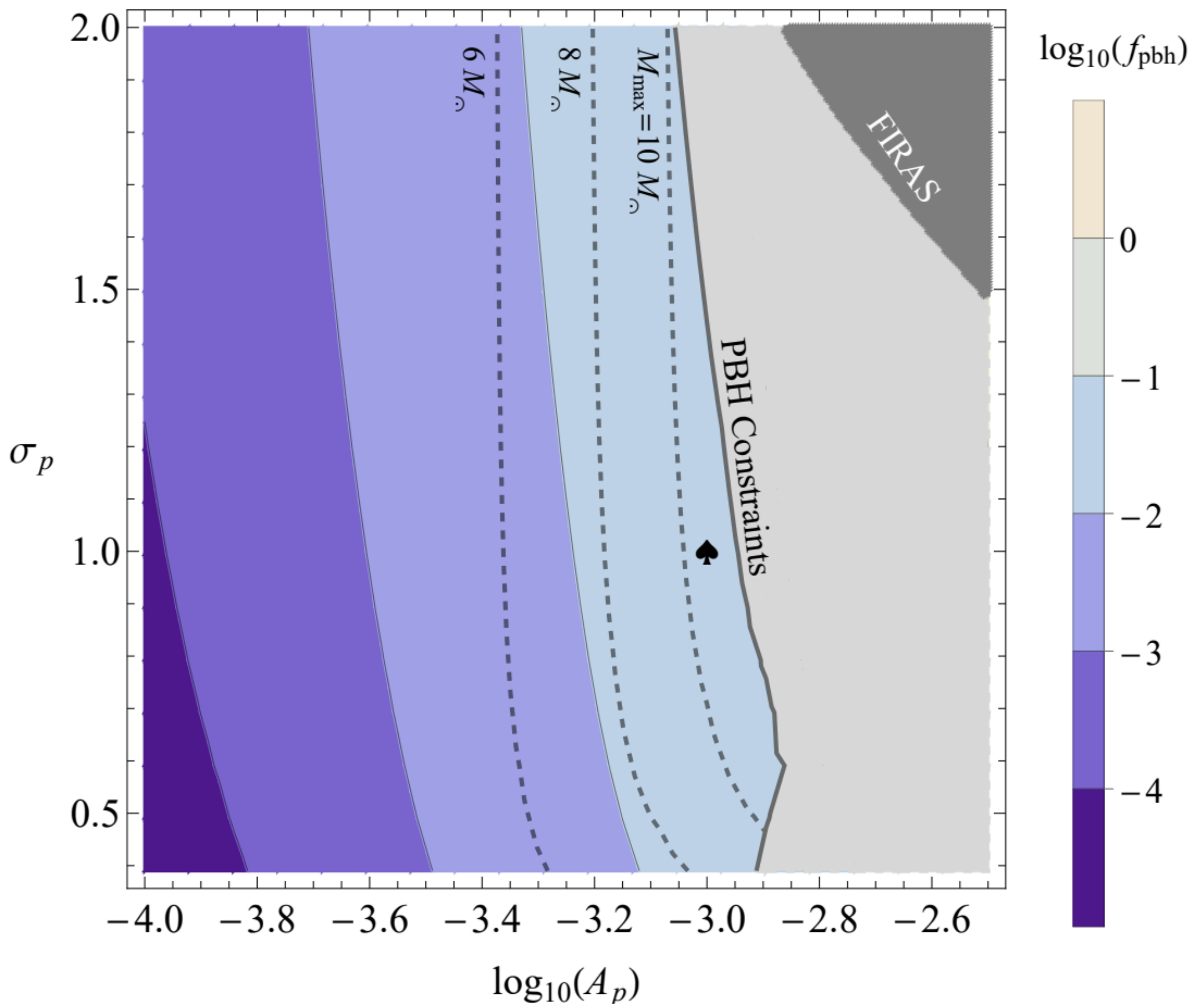
$$P_\zeta(k) = A_s \left(\frac{k}{k_*}\right)^{n_s-1} + A_p \exp\left[-\frac{(N_k - N_p)^2}{2\sigma_p^2}\right]$$

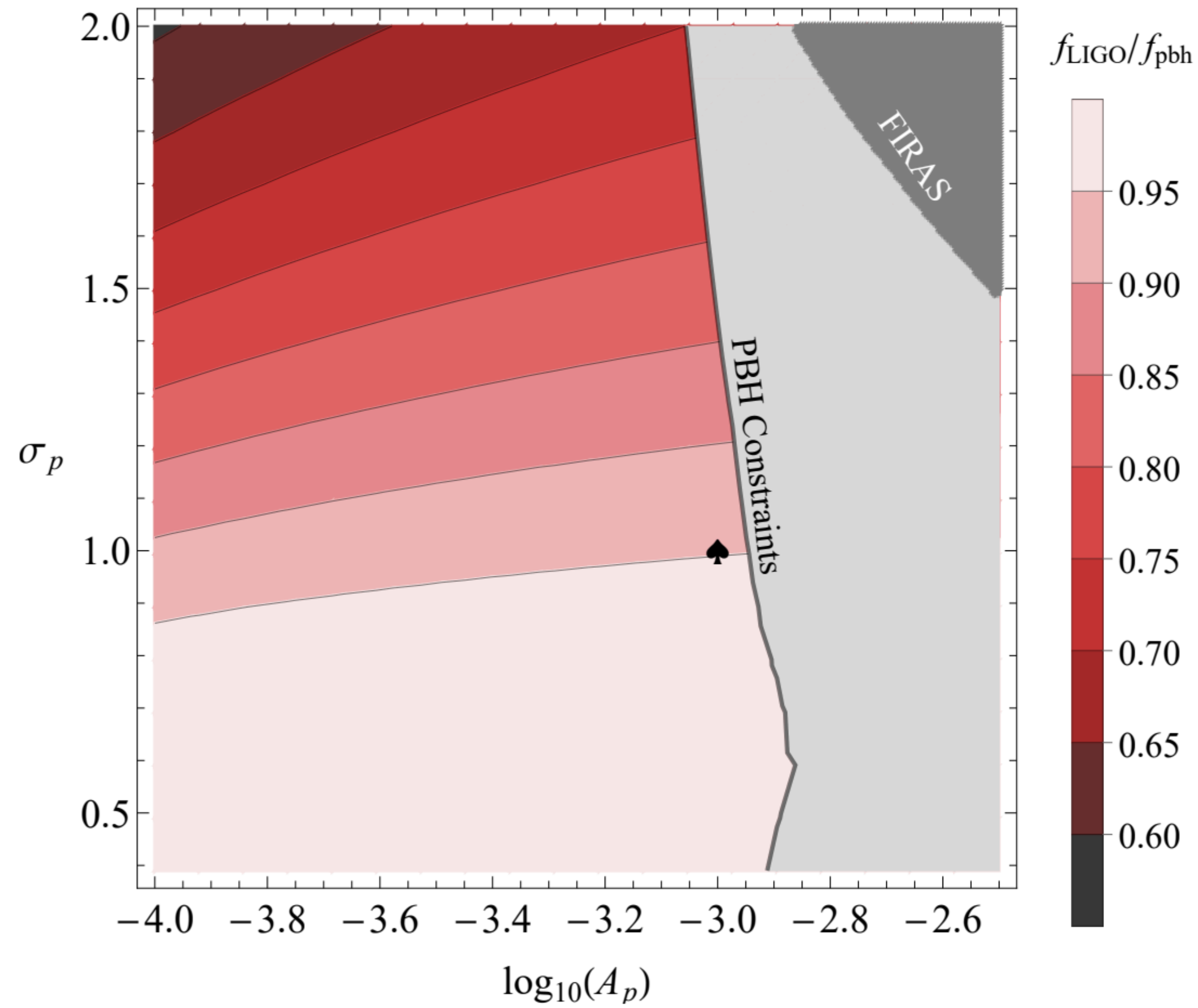


$A_p = 10^{-3}, \sigma_p = 1 \quad k_p = 10^6\,\mathrm{Mpc}^{-1}$



Parameter Constraints





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

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

Implications

- 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.

Non-thermal Production

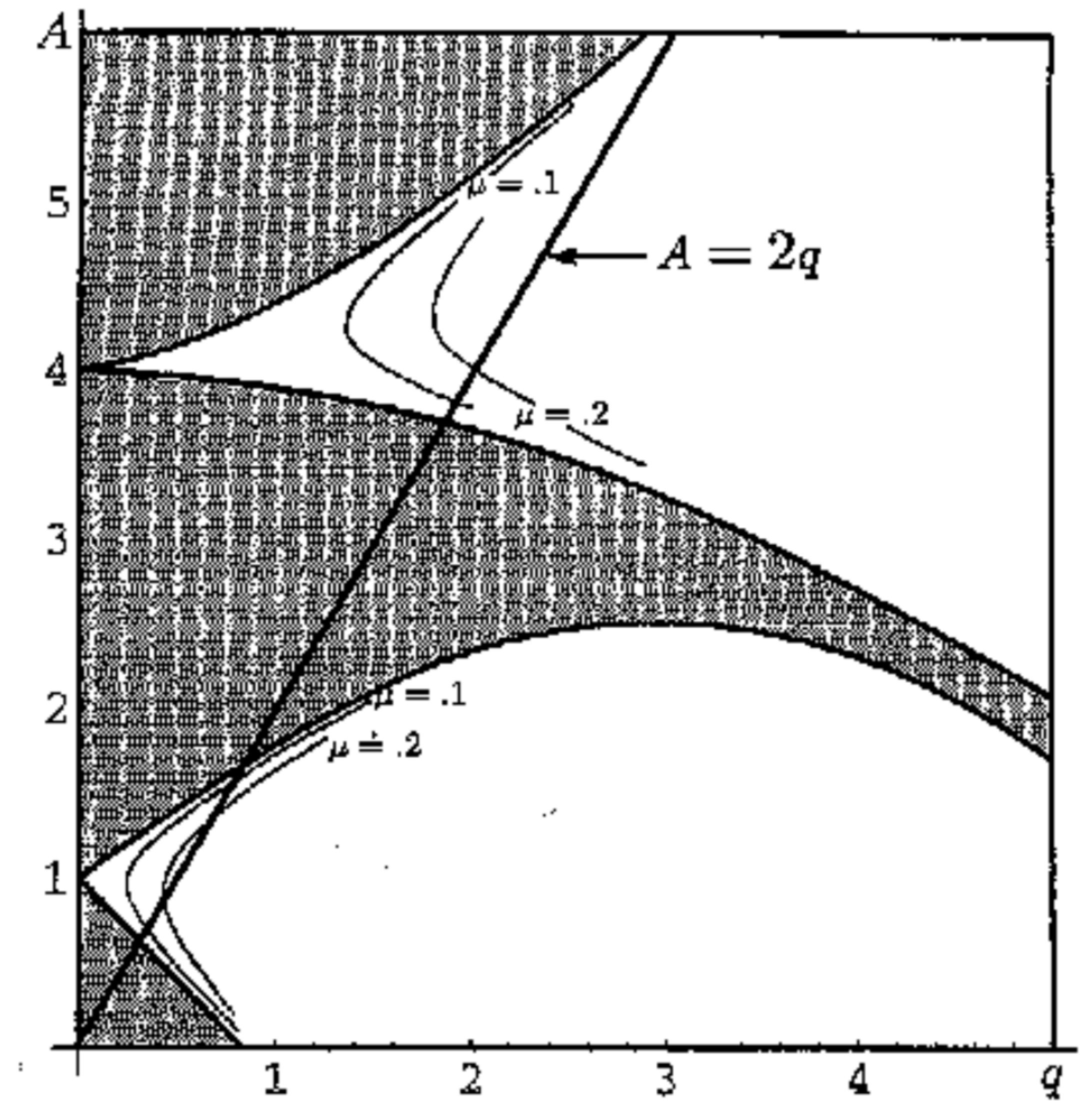
$$\mathcal{L}_{\rm int} = -\frac{1}{2} g^2 \chi^2 \phi^2$$

$$\hat{\chi}(t, \mathbf{x}) = \frac{1}{(2\pi)^{3/2}} \int d^3k \left(\chi_k^*(t) \hat{a}_k e^{i\mathbf{kx}} + \chi_k(t) \hat{a}_k^\dagger e^{-i\mathbf{kx}} \right)$$

$$\ddot{\chi}_k + \left(k^2 + m_\chi^2 + g^2 \Phi^2 \sin^2(mt)\right) \chi_k = 0$$

$$\chi_k'' + (A_k - 2q \cos 2z)\chi_k = 0 \qquad z = mt$$

$$A_k = \frac{k^2 + m_\chi^2}{m^2} + 2q \qquad q = \frac{g^2 \Phi^2}{4m^2}$$



Kofman, Linde, Starobinsky

Non-thermal moduli production

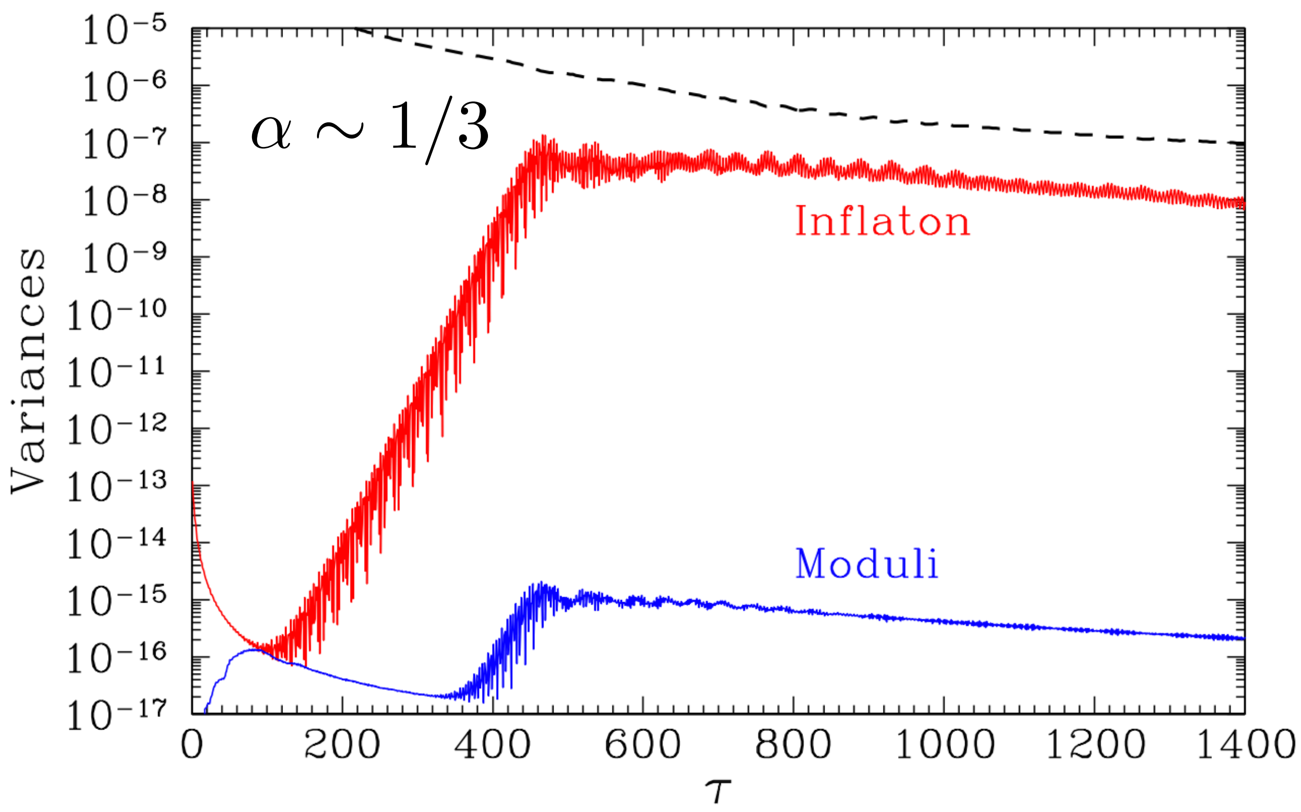
$$V(\phi) = V_0\, f^p(x)\,, \quad x = \tanh\left(\frac{\phi}{\sqrt{6\alpha}}\right)$$

Attractor models

Bottom of the potential

$$V(\phi) \simeq V_0 \left(\frac{\phi}{\sqrt{6\alpha}}\right)^p \qquad m_\phi^2 = \frac{V_0 p(p-1)}{6\alpha M_{\rm Pl}^2}\left(\frac{\phi}{\sqrt{6\alpha}}\right)^{p-2}$$

$$V(\phi,\sigma) = V_0 \left(\frac{\phi}{\sqrt{6\alpha}}\right)^4 \left[1 + c\frac{\sigma}{M_{\rm Pl}}\right]$$



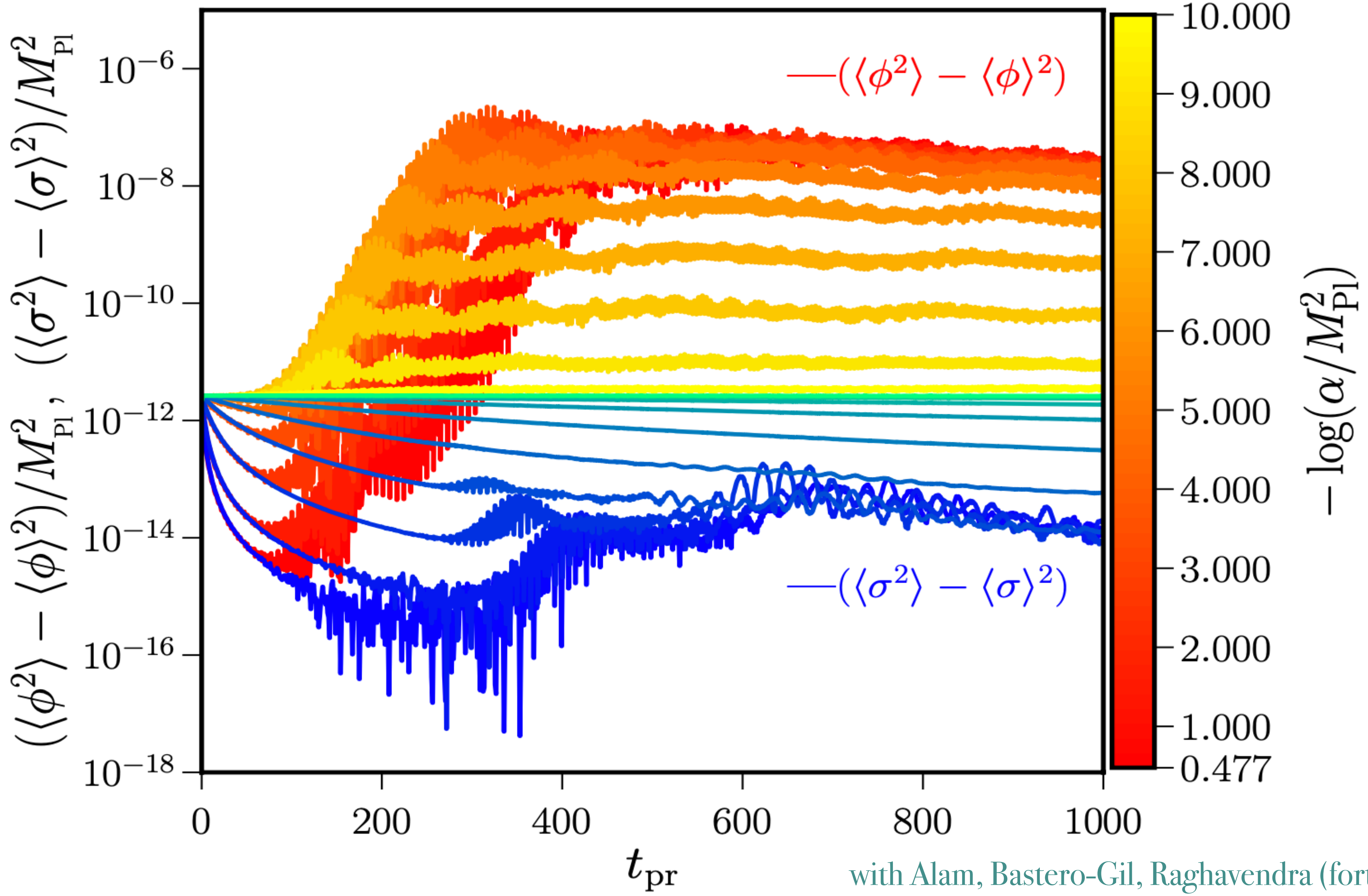
$$\frac{n_\Phi}{s} \sim 10^{-6} c^2 \left(\frac{10^{-13}}{\lambda}\right)^{1/4} \left(\frac{\phi_0^2(t_r)}{10^{-6} M_{\rm Pl}^2}\right)\left(\frac{\langle\phi^2\rangle}{10^{-7} M_{\rm Pl}^2}\right)$$

$$n_\Phi/s \lesssim 10^{-12}$$

Kawasaki, Kohri and T. Moroi

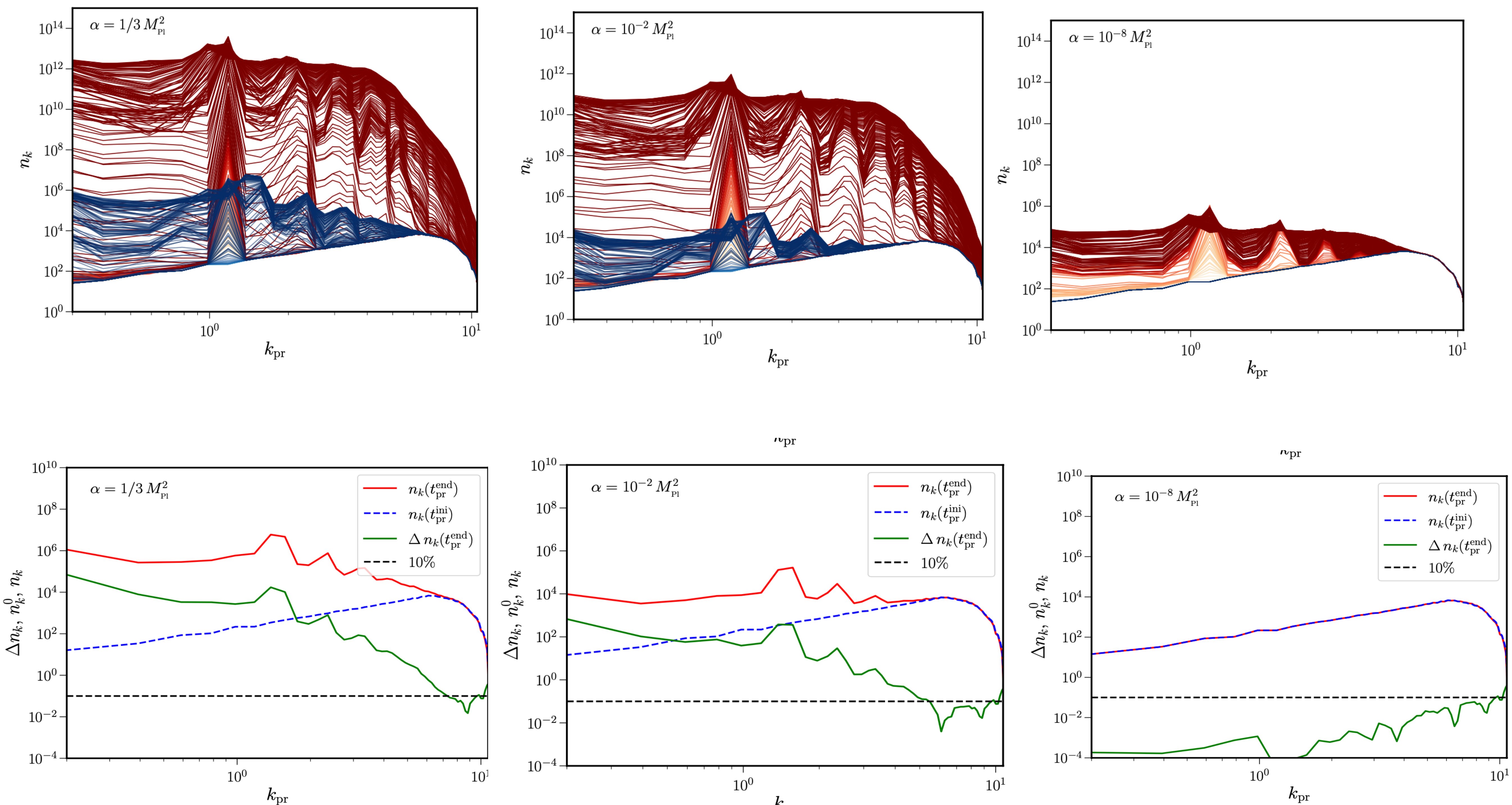
Giudice, Riotto, Tkachev

Moduli production



with Alam, Bastero-Gil, Raghavendra (forthcoming)

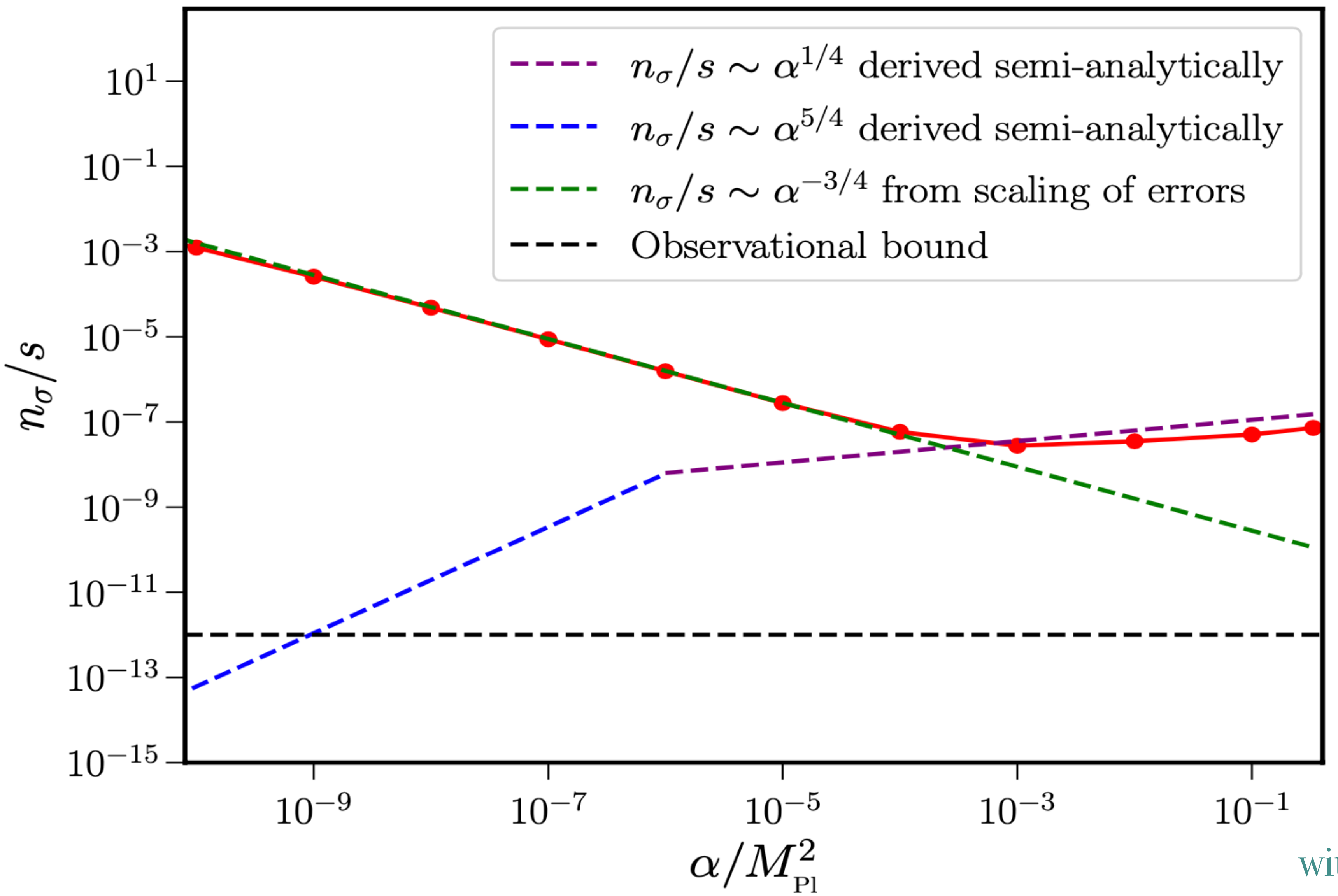
Mode-occupancy



Estimation of n/s

Semi-analytical estimate

$$\frac{n_\sigma}{s} \simeq 1.52\times 10^{-7}\left(\frac{c}{1}\right)^2\left(\frac{140}{a(t_r)}\right)^2\left(\frac{\mathcal{P}_S}{2.1\times 10^{-9}}\right)^{-1/4}\left(\frac{\alpha}{(1/3)M_{\rm Pl}^2}\right)^{1/4}\frac{\langle\delta\phi^2(t_r)\rangle}{10^{-8}\,m_{\rm Pl}^2}$$



Conclusion: Small values of \alpha suppresses non-thermal moduli production!

Low scale inflation with small r

with Alam, Bastero-Gil, Raghavendra (forthcoming)

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: (1) Effects of reheating - See Khursid's talk for the details (2) Correlating with CMB observables (3) Primordial black holes productions (4) Non-thermal moduli productions (forthcoming).

Other topics:

Non-Planckian DM momentum distribution from moduli decay.

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