QCD-driven Warm Inflation
A testable mechanism to set the Hot Big Bang initial conditions

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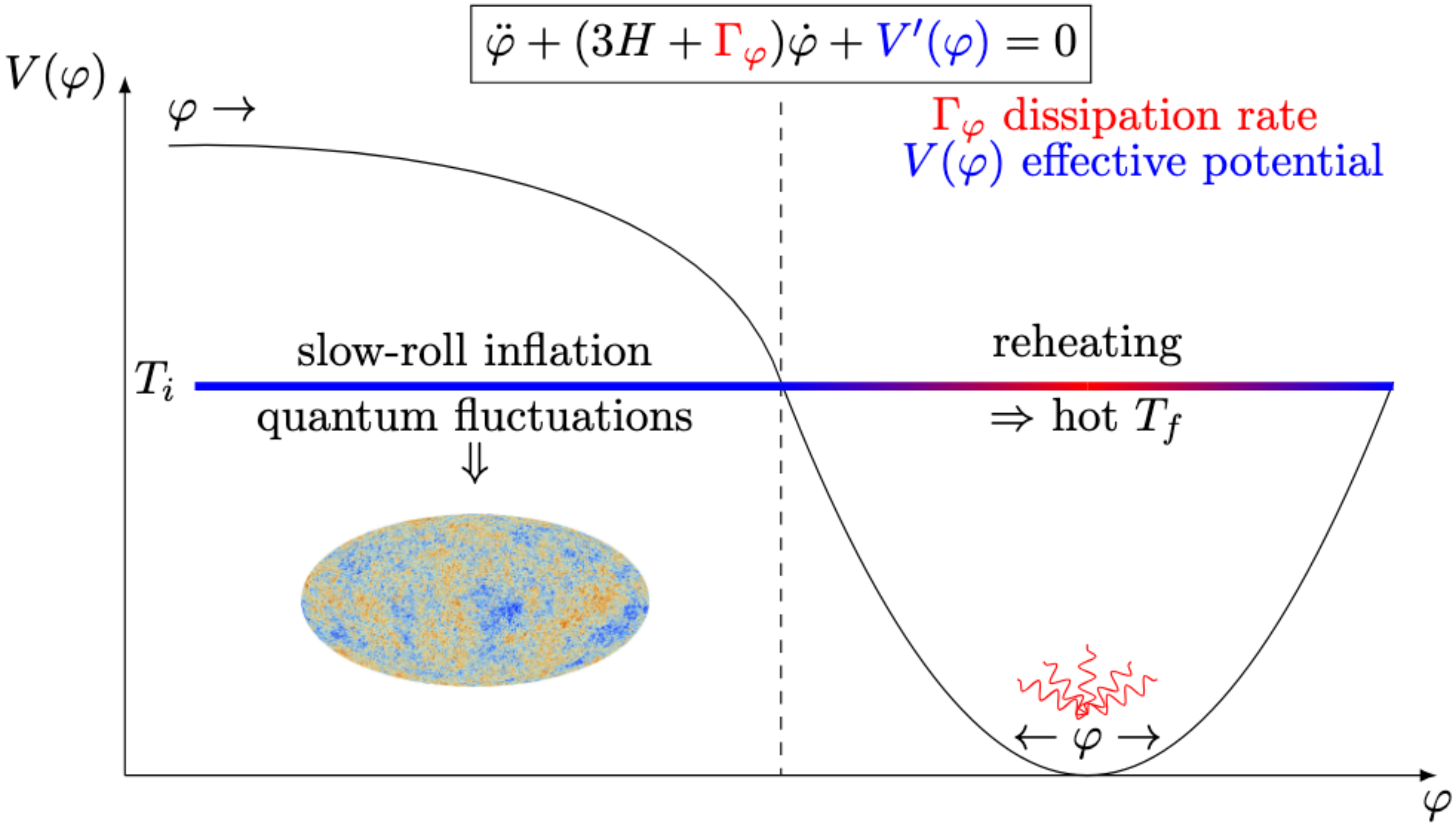
17.09.2026
Particle Physics in the Early Universe, Paris, France

[based on work in collaboration with Kim Berghaus, Lei Ming, Isabel Oldengott and Sebastian Zell]

Inflation and Reheating

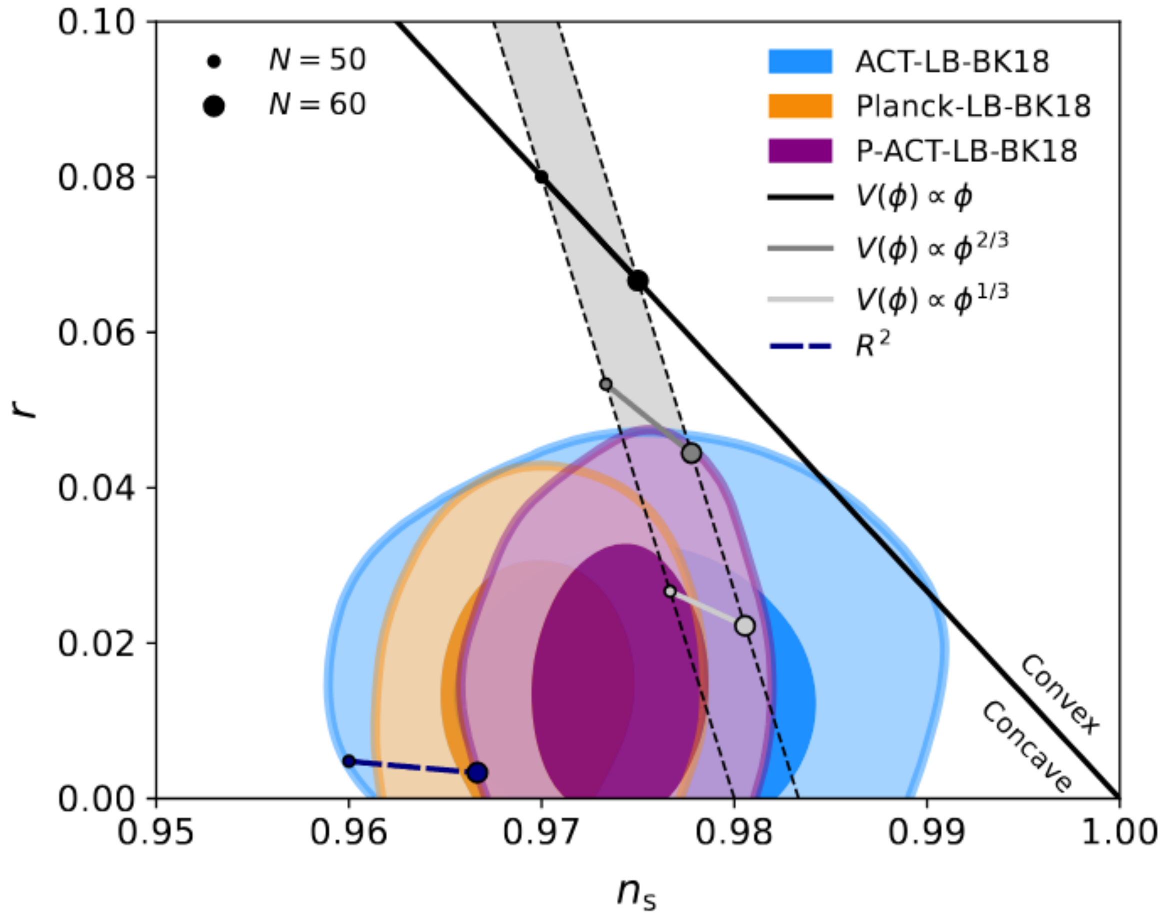


[image: Gilles Buldgen]

Challenges in Standard (cold) Inflation

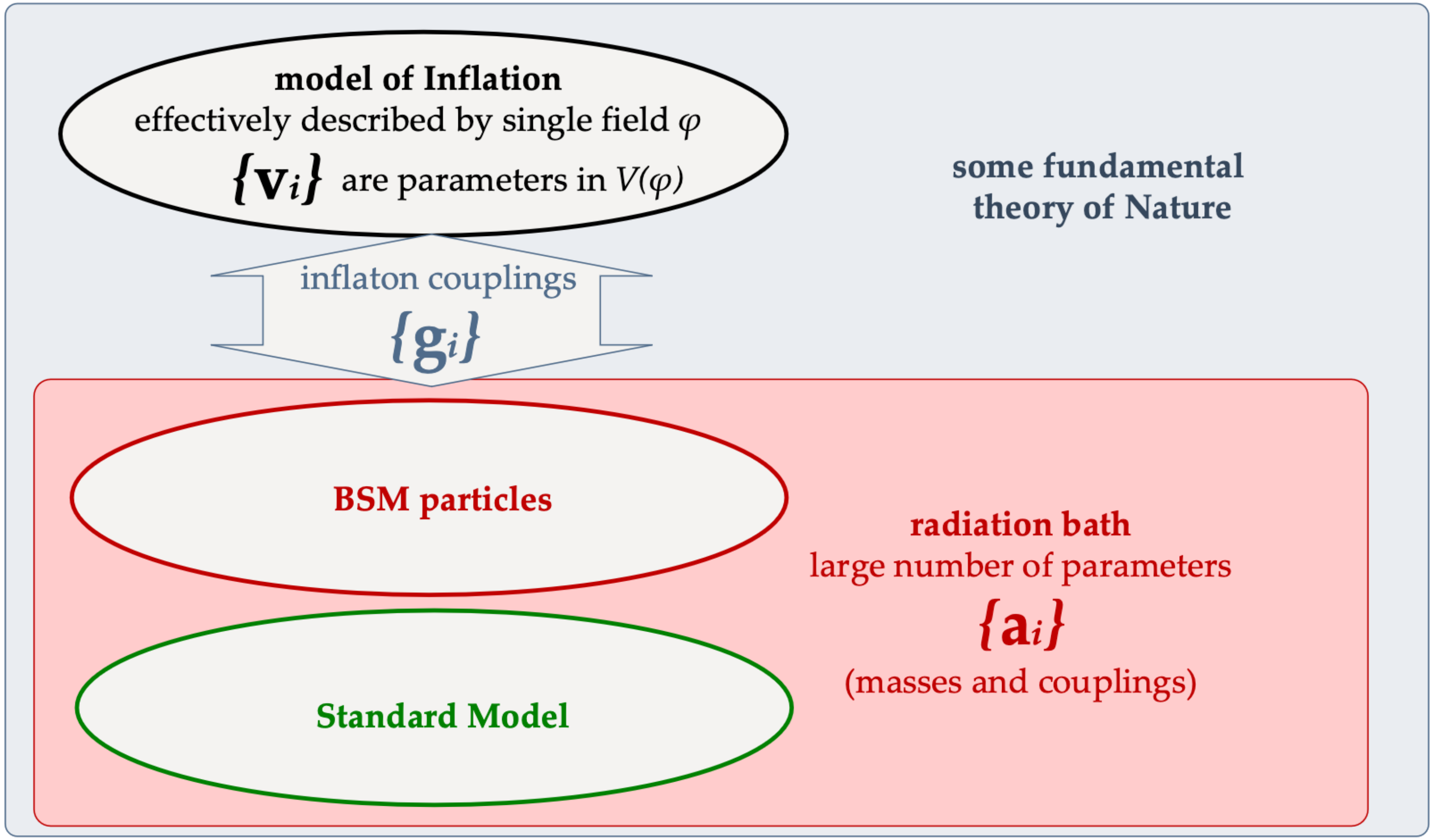
- Initial conditions
- Flatness of the potential
- Trans-Planckian field values
- Simplest potentials do not work
- Uncertainty due to reheating
- Connection to known physics unclear
- Lack of testability

[disclaimer: list and priorities are subjective]



[ACT 2503.14454]

Connecting Inflation to Particle Physics



- Reheating leaves observable imprint in cosmological perturbations due to redshifting

  Martin/Ringeval 1004.5525., Adshead et al 1007.3748, Easther/Peiris 1112.0326, ...

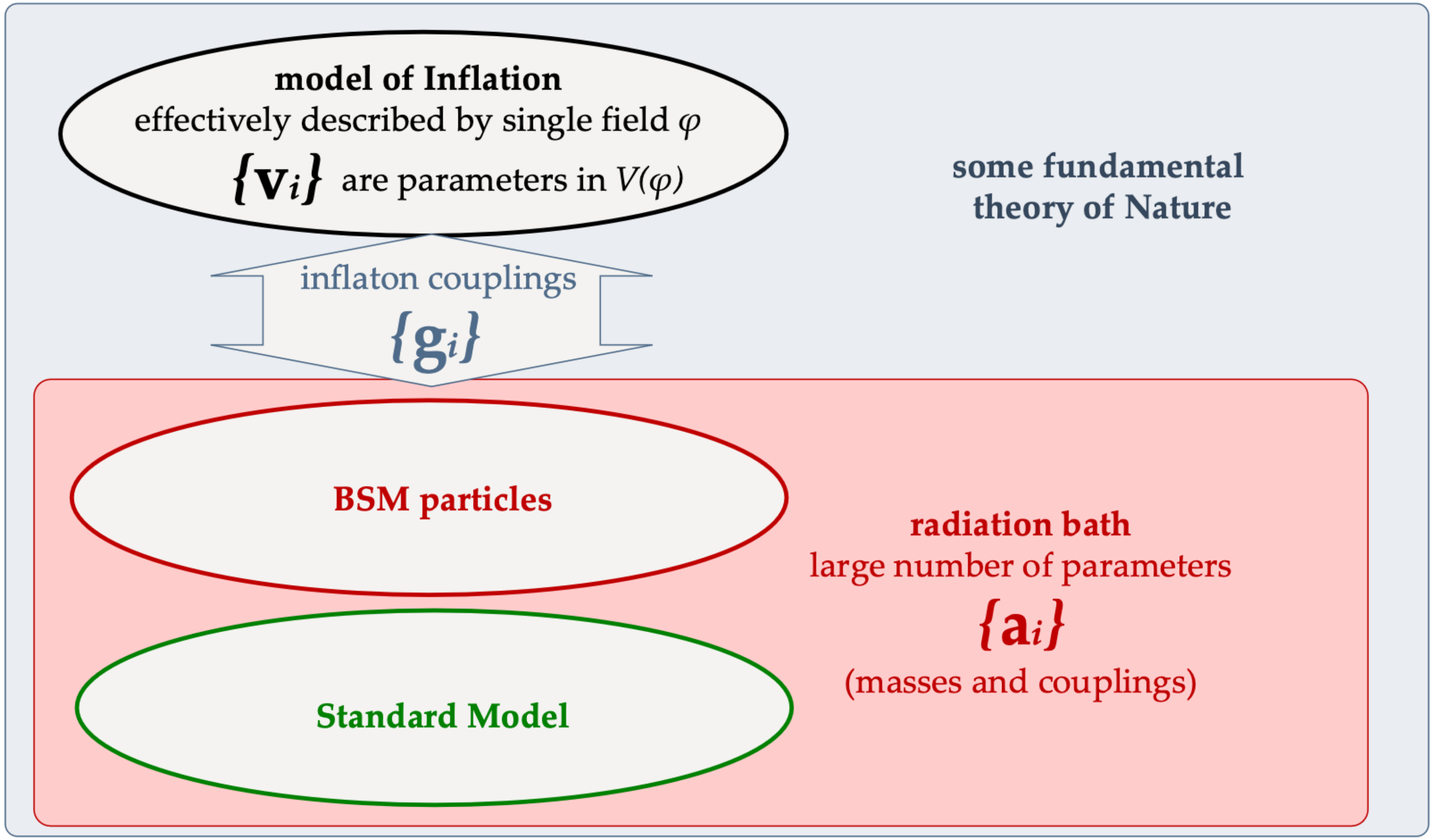
- Next-generation observations can for the first time measure T_{re}

  Martin/Ringeval/Vennin 1410.7958, …
  MaD/Ming 2208.07609, …

- Translation into constraints on fundamental (particle) physics parameters tricky

  MaD 1511.03280, MaD 1903.09599, …

Testability of Inflation



- **1) Model inference problem**: Predictions are usually not unique to a specific model, e.g., even if we knew the values of $\{A_s, n_s, r\}$ with arbitrarily small errors, there would be a large set of $V(\phi)$ consistent with each choice.
- **2) Parameter inference problem**: Even for a given shape of $V(\phi)$ it is often not possible to measure all microphysical parameters.

Exceptions:

Starobinsky inflation
Starobinsky 1980

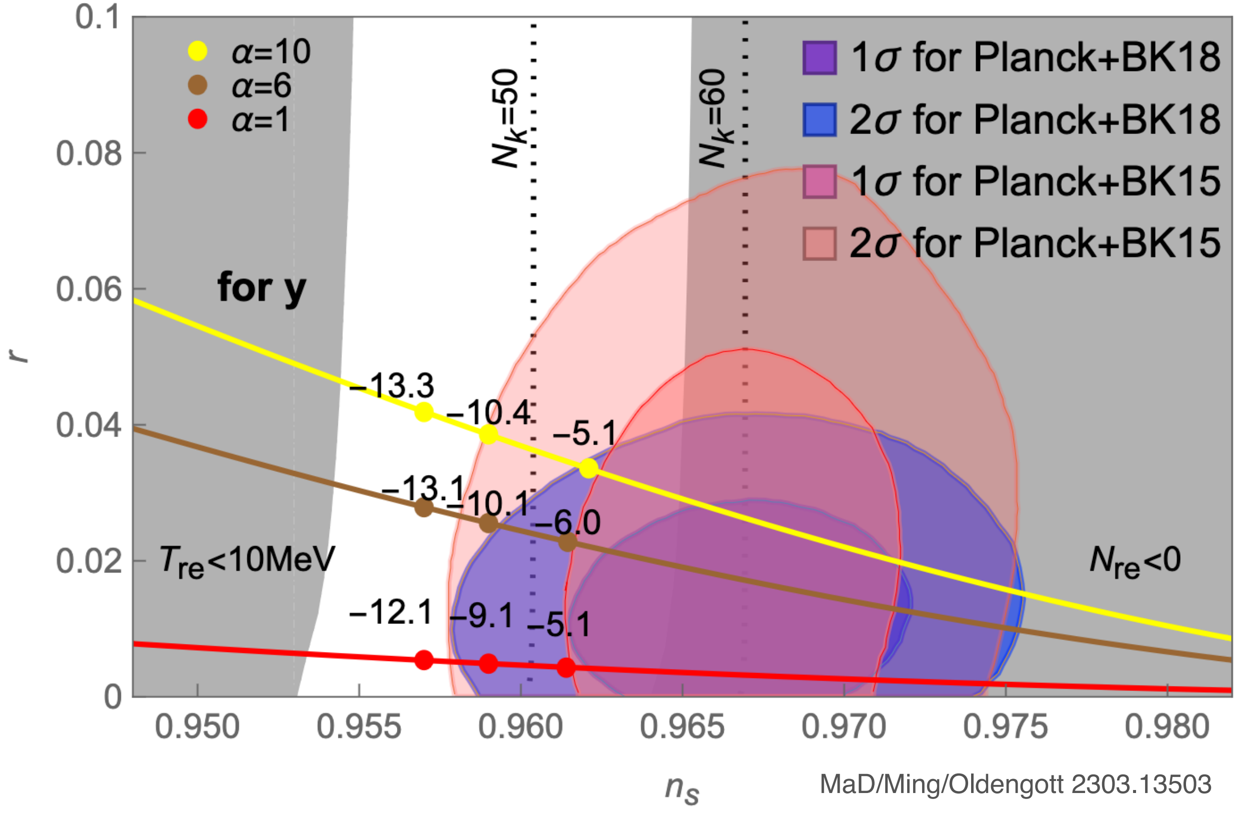
Higgs inflation
Bezrukov/Shaposhnikov 0710.3755

QCD driven Warm inflation
Berghaus/MaD/Zell 2503.18829

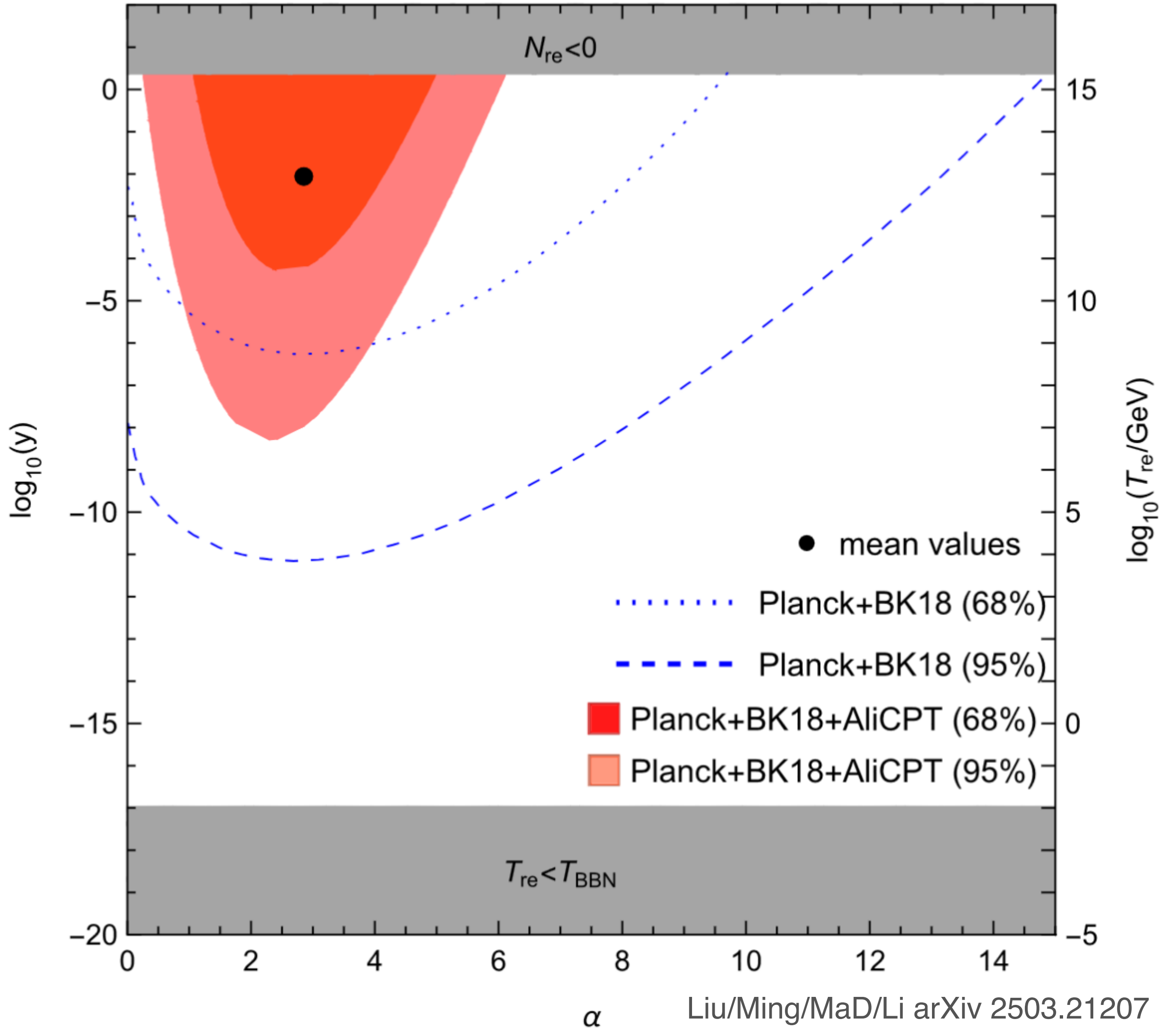
Example: α-attractor Model T

$$\mathcal{V}(\varphi) = M^4 \tanh^{2n}\left(\frac{\varphi}{\sqrt{6\alpha}M_{pl}}\right)$$

Carrasco/Kallosh/Linde



MaD/Ming/Oldengott 2303.13503



Liu/Ming/MaD/Li arXiv 2503.21207

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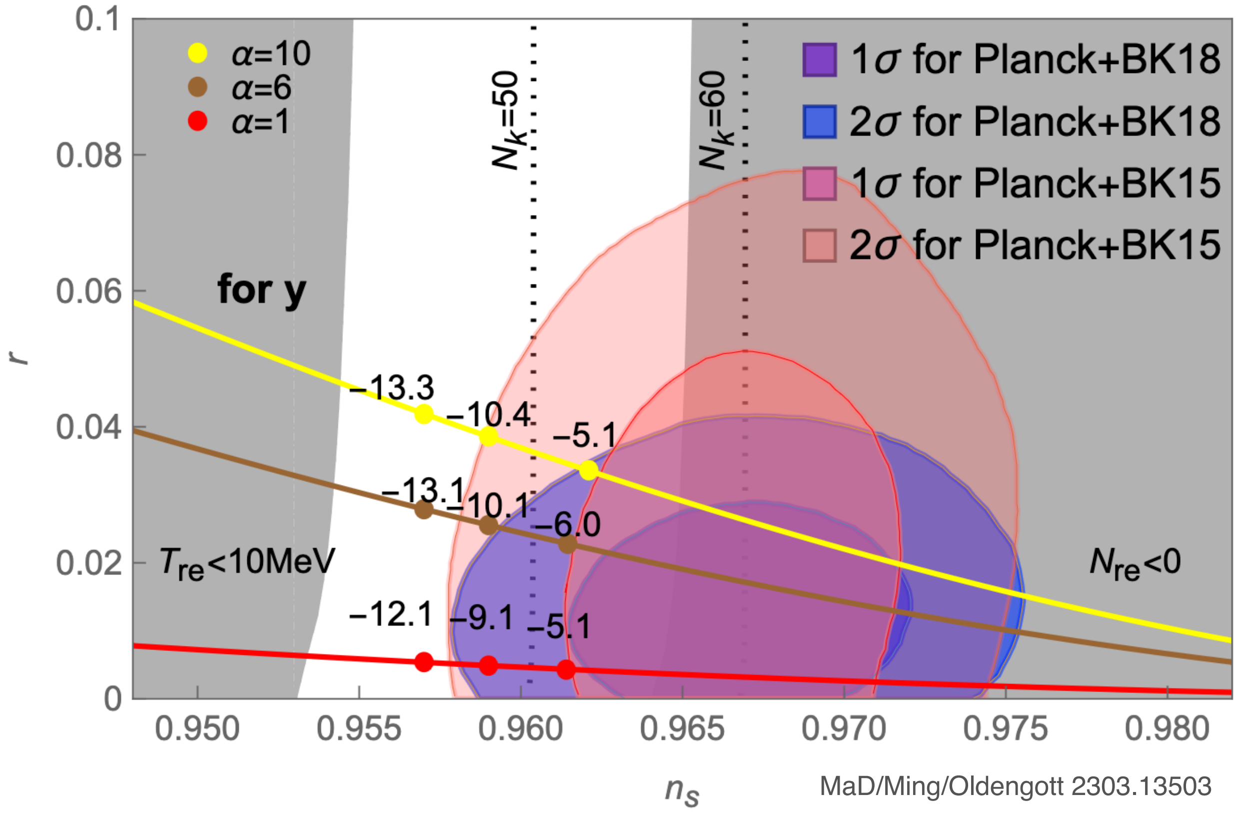

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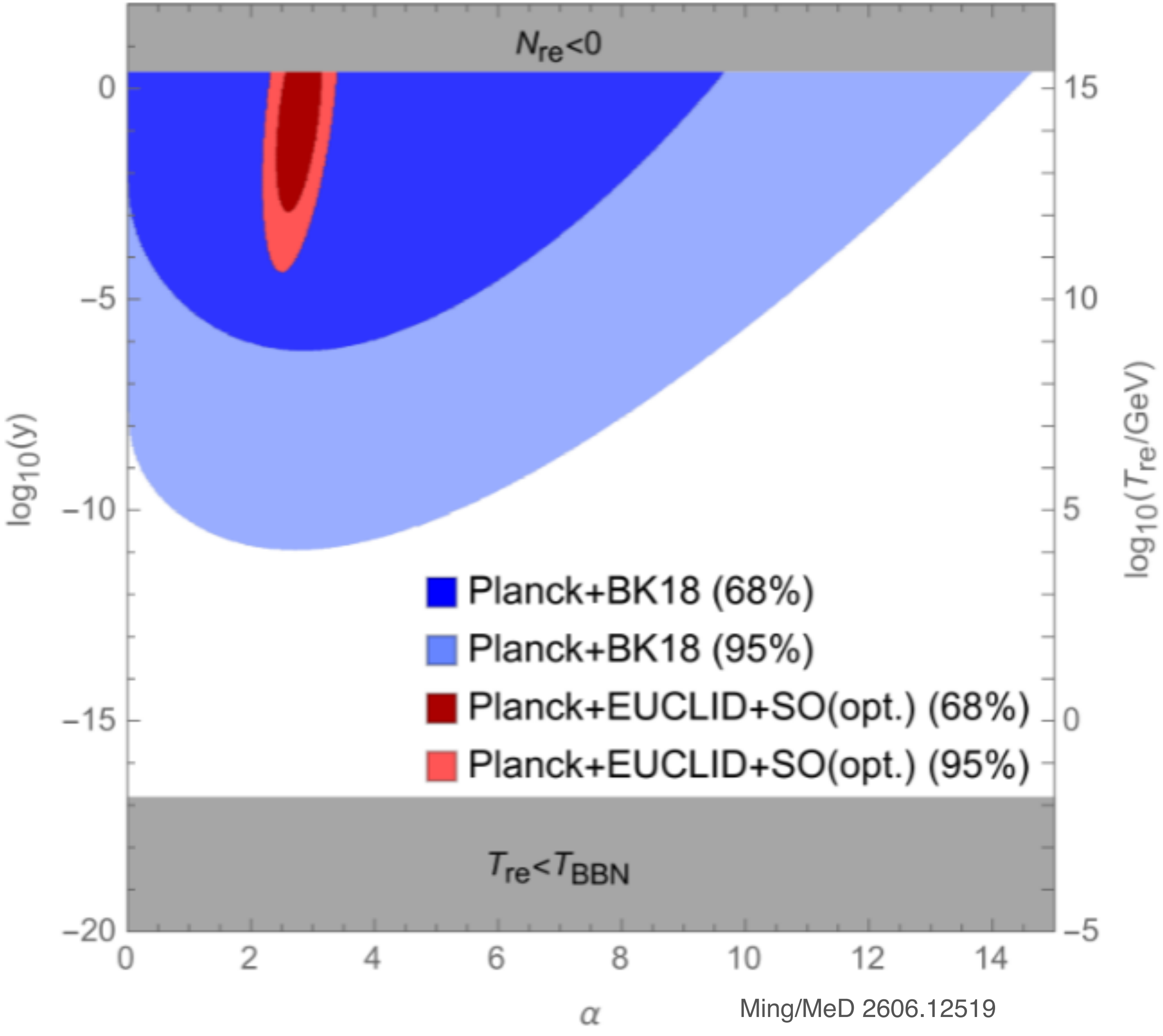


Ming/MeD 2606.12519

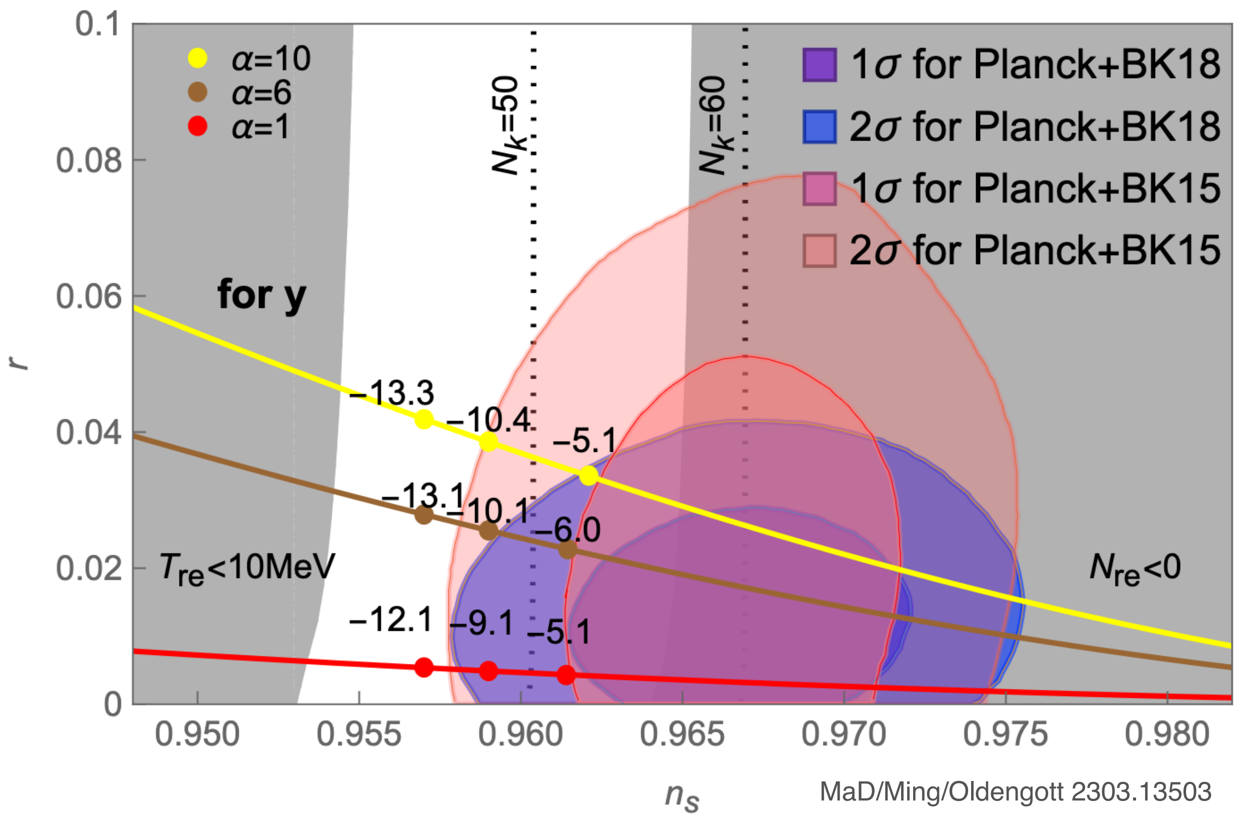
Example: α-attractor Model T

$$\mathcal{V}(\varphi) = M^4 \tanh^{2n}\left(\frac{\varphi}{\sqrt{6\alpha}M_{pl}}\right)$$

Carrasco/Kallosh/Linde

Feedback introduces $\{a_i\}$ dependence unless $y \ll \left(3\pi^2 r A_s\right)^{j/2}$

MaD 1903.09599



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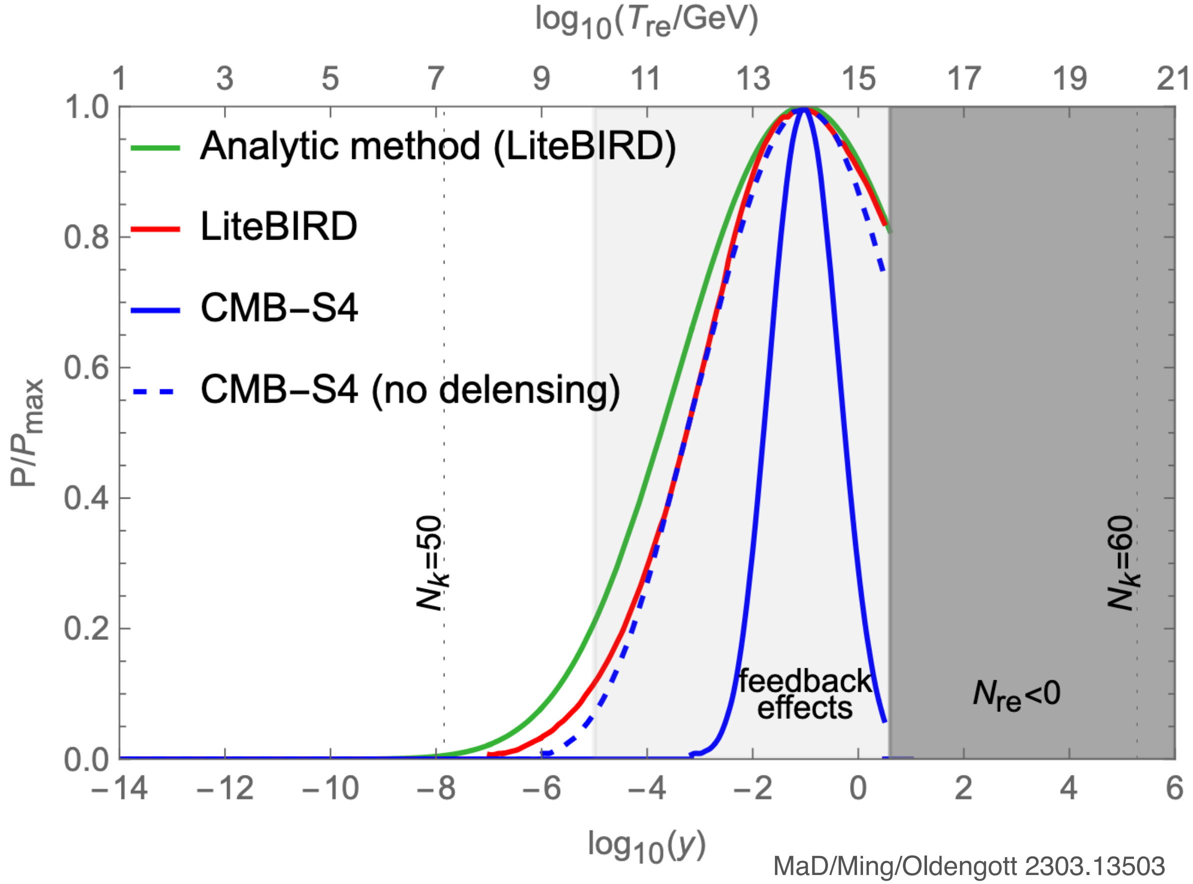
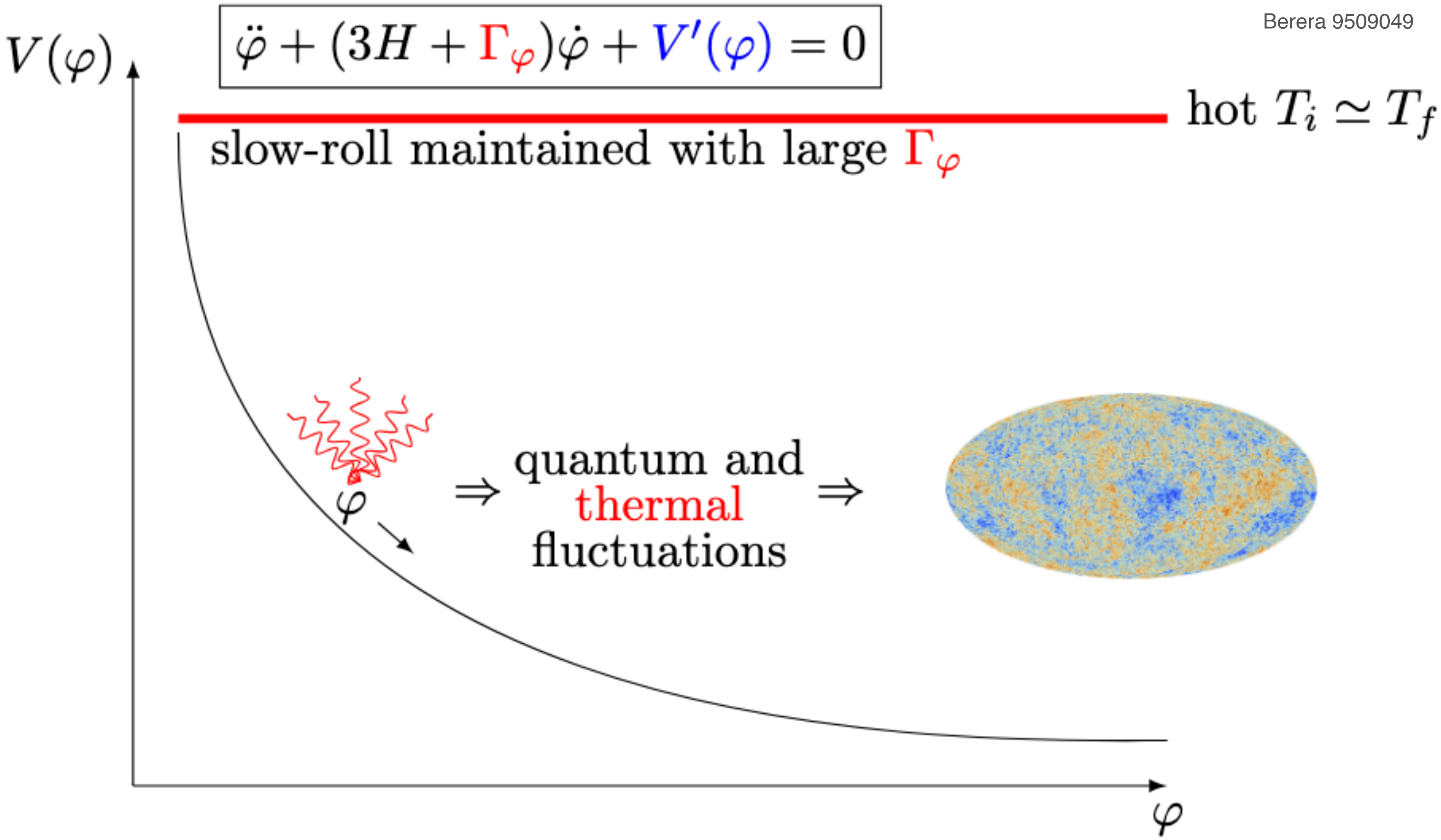


MaD/Ming/Oldengott 2303.13503

Warm Inflation

Berera 9509049



[image: Gilles Buldgen]

Regimes of Warm Inflation

Coupled equations for inflaton and radiation

$$\begin{aligned} \ddot{\phi} + (3H + \Gamma)\dot{\phi} + V' &= 0 \\ \dot{\rho}_R + 4H\rho_R &= \Gamma\dot{\phi}^2 \end{aligned}$$

Stationary solution

$$\frac{\pi^2}{30} g_* T^4 \approx \frac{\Gamma}{4H} \left(\frac{V'}{(3H + \Gamma)} \right)^2$$

$$Q = \frac{\Gamma}{3H}$$

***Q > 1* : Strong regime** - Dissipation dominates slow-roll dynamics, thermal fluctuations dominate scalar cosmological perturbations

***Q < 1* : Weak regime** - Standard Hubble friction dominates slow-roll dynamics, but thermal fluctuations still contribute to scalar cosmological perturbations

Modified slow roll parameters:

$$\epsilon_V \equiv \frac{M_{\rm pl}^2}{2(1+Q)} \left(\frac{V'}{V} \right)^2, \quad \eta_V \equiv \frac{M_{\rm pl}^2}{(1+Q)} \frac{V''}{V}$$

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Flatness of the potential problem

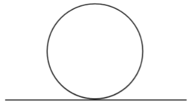
- Thermal bath modifies both potential and dissipation coefficient

$$\ddot{\phi} + (3H + \Gamma)\dot{\phi} + V'(\phi) = 0$$

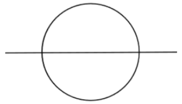
- The two are related, similar to dispersive and dissipative part of refractive index

- Come from real and imaginary parts of same Feynman diagrams. Example: $V(\phi) = \lambda\phi^4$

$$\delta V \propto \lambda T^2$$



$$\Gamma \propto \lambda^2 T$$



- Makes it very difficult to get sizable Γ without spoiling flatness of $V(\phi)$

Yokokama/Linde 9809409

Sphaleron Heating

- Problem may be avoided is *V(ϕ)* is protected by a shift symmetry

Bastero-Gil/Berera/Ramos/Rosa 1604.08838 Berghaus/Graham/Kaplan 1910.07525

- Let us consider the Lagrangian

$$\mathcal{L} = \frac{1}{2}\partial^\mu \phi \partial_\mu \phi - V(\phi) - \frac{\alpha_s}{8\pi}\frac{\phi}{f} G^a_{\mu\nu}\tilde{G}^{a\mu\nu}$$

- If yields the equation of motion

$$\ddot{\phi} + 3H\dot{\phi} + V' = -\frac{\alpha_s}{8\pi f}\langle G^a_{\mu\nu}\tilde{G}^{a\mu\nu}\rangle$$

- Expectation value on the RHS is quantum-statistical, and can be evaluated in different regimes

Laine/Procacci 2102.09913

- For a slowly evolving scalar it receives a non-perturbative correction from sphaleron transitions that does not yield a correction to *V(ϕ)* because the axion-like coupling is shift symmetric

McLerran/Mottola/Shaposhnikov 91

The Problem of Light Fermions

- If gauge fields couple to fermions, sphalerons also modify fermion numbers
- This induces a coupling to the axial current

$$\frac{\alpha}{8\pi f}\langle G^a_{\mu\nu}\tilde{G}^{a\mu\nu}\rangle = \Gamma_{\rm sph}\left(\dot\phi + \frac{6 f j^0_A}{N_c T^2}\right)$$

- Effectively couples equations for inflaton field and axial chemical potentials μ_A

$$\begin{aligned}\ddot\phi + 3H\dot\phi + V' &= -\Gamma_{\rm sph}\left(\dot\phi + 2N_f f\mu_A\right)\\ \dot\mu_A + 3H\mu_A &= -\frac{6f\Gamma_{\rm sph}}{N_c T^2}\left(\dot\phi + 2N_f f\mu_A\right)\end{aligned}$$

- In absence of any other fermion number violating processes, this renders friction inefficient
- For massive fermions chirality flips that erase μ_A can prevent this conclusion McLerran/Mottola/Shaposhnikov 91
- Since SM fermions are light, it was concluded that SM gauge interactions cannot sustain warm inflation

Berghaus/Graham/Kaplan 1910.07525

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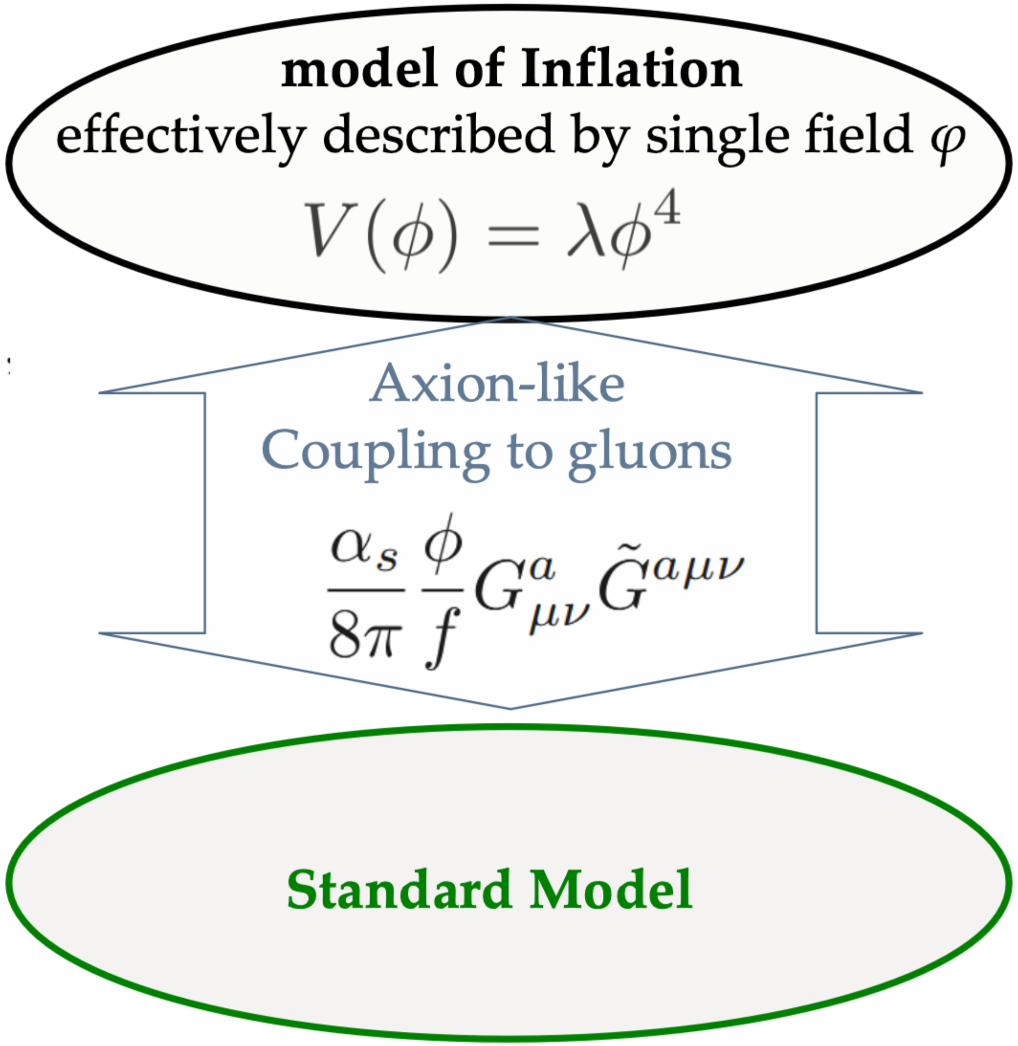
- Hubble expansion alone turns out to be sufficient to make QCD-driven warm inflation possible!

MaD/Zell 2312.13739

Berghaus/MaD/Zell 2503.18829

Simple Example : Quartic Potential



- For fixed $V(\phi)$ the model is "complete": No uncertainty regarding reheating, entire cosmic history can be computed
- In practice Γ is only known during slow roll and near the potential minimum

e.g. D'Eramo/Hajkarim/Yun 2108.05371, Laine/Procacci 2102.09913

- For a quartic potential λ is fixed in terms of f by measured A_s (effectively a single parameter model)

- For a quartic potential, simple estimates indicate that
  - transition to radiation domination is fast
  - ϕ cannot simultaneously drive inflation and solve the strong CP-problem
  - contribution to DM density is small

Berghaus/MaD/Zell 2503.18829

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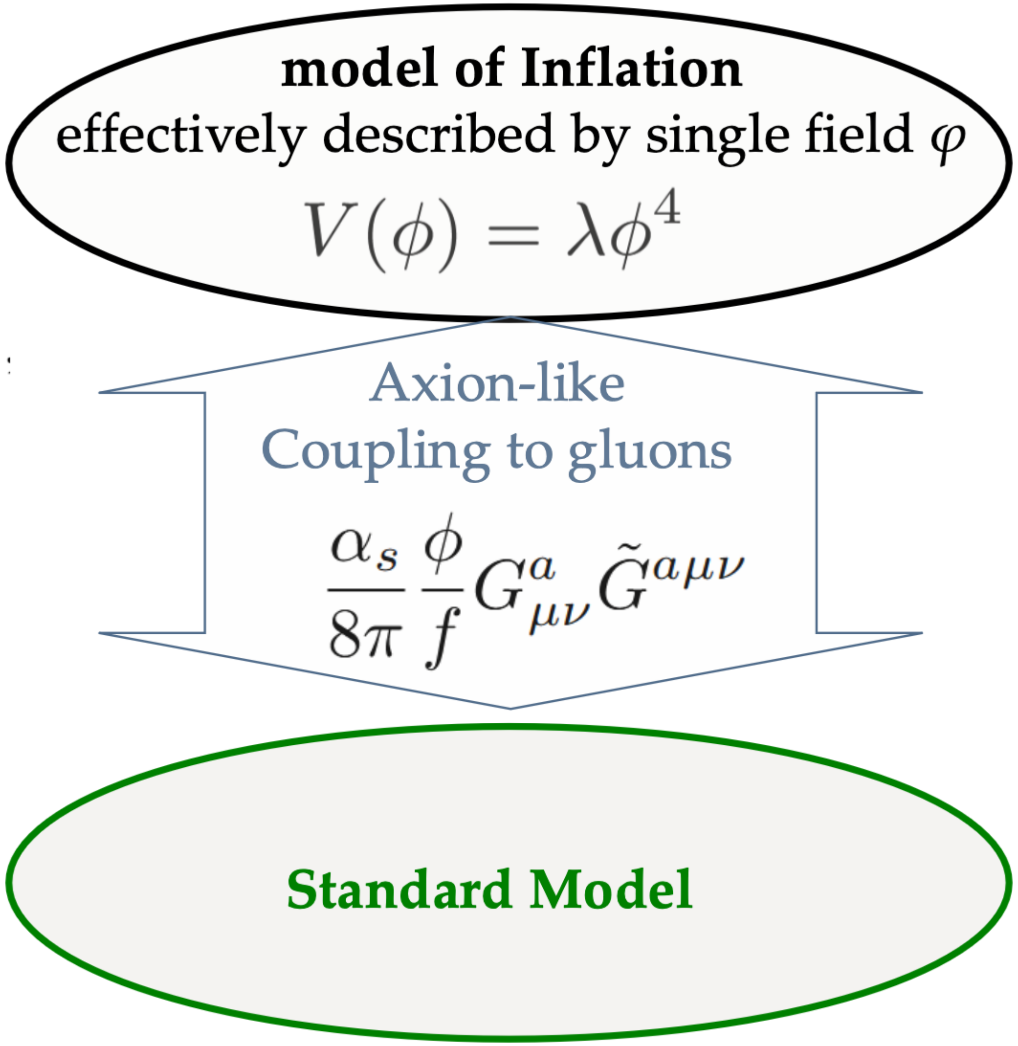

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Berghaus/MaD/Zell 2503.18829

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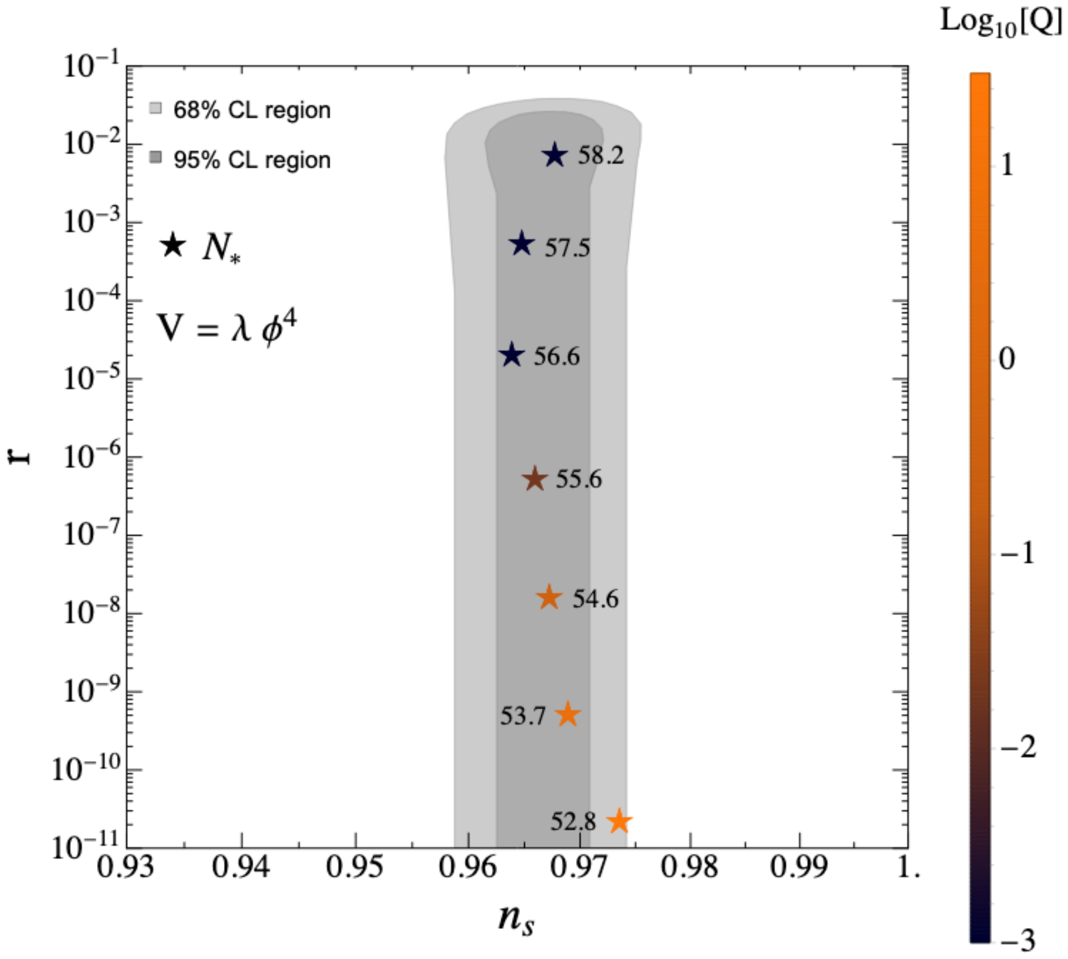


Berghaus/MaD/Zell 2503.18829

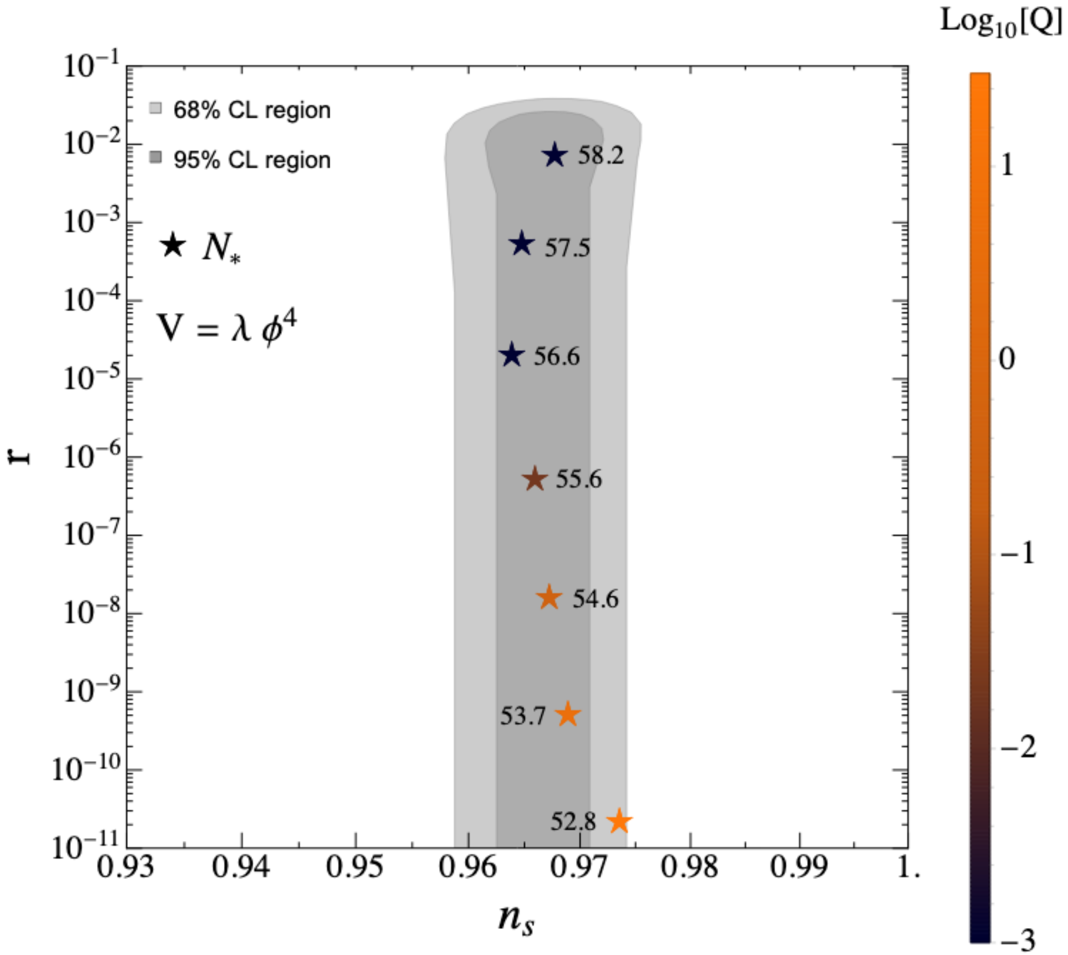
- CMB predictions for warm inflation are less established from first principles than for standard inflation
- We compared several approaches

  Mirbabayi/Gruzinov 2205.13227
  Berghaus/MaD/Zell 2503.18829
  Ramos/Rodrigues 2504.20943
  Laine/Procacci/Rogelj 2507.12849

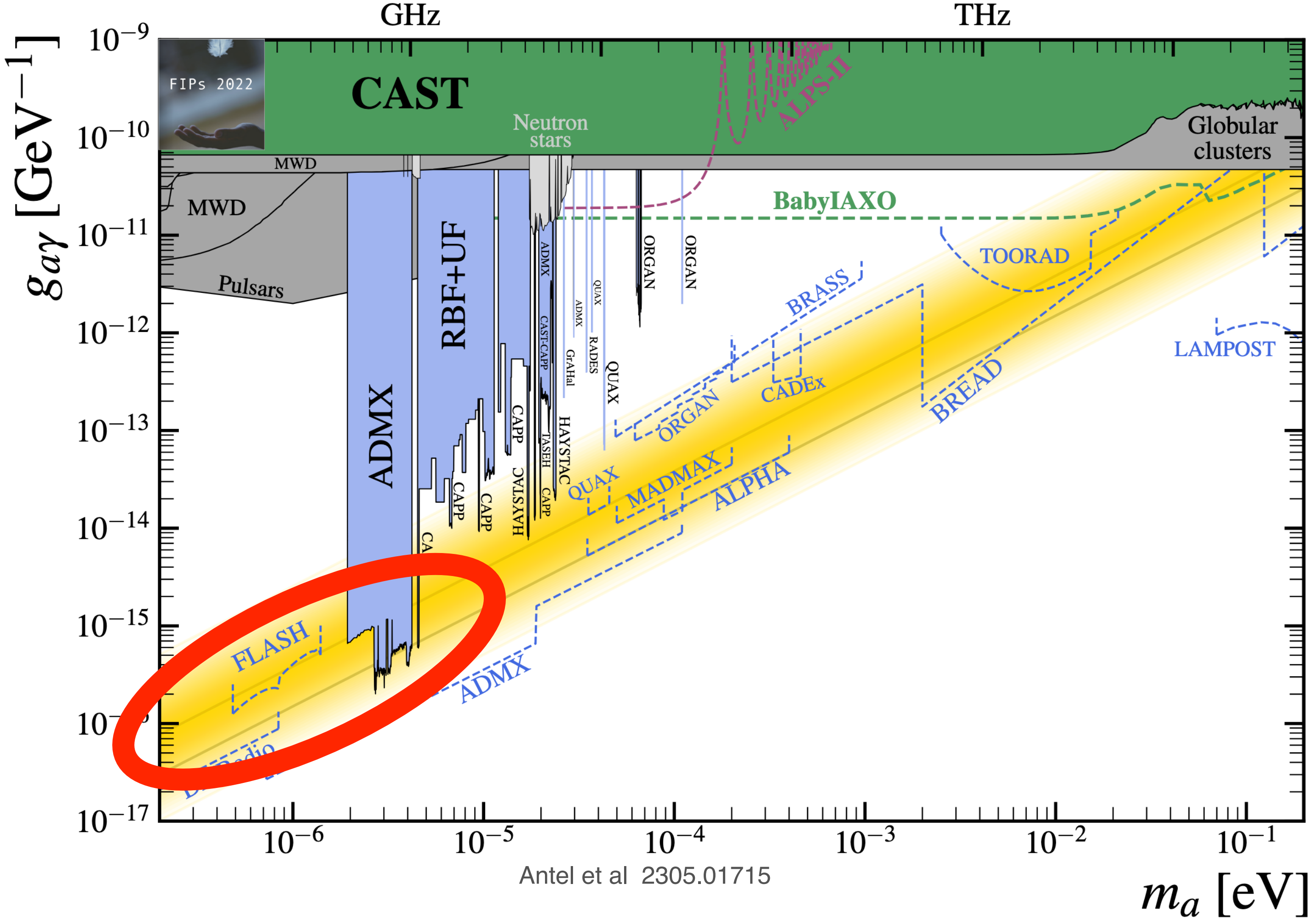
- Differences are smaller than Planck+BK 2σ error bars on n_s, but will matter for future observations

λ	$\frac{\phi_*}{M_{\rm pl}}$	f [10^{12} GeV]	T [10^{12} GeV]	α_s	T/H	$\frac{2N_f N_c^4 \alpha_s^5 T}{\sqrt{\lambda\phi_*^4/3M_{\rm pl}^2}}$	$T/\Lambda_{\rm cutoff}$	N_*	Q	n_s	r
10^{-21}	5.02	0.146	8.75	0.0269	7820	8.99×10^{-2}	0.064	52.8	14.9	0.9736	2.15×10^{-11}
10^{-20}	6.19	0.264	19.1	0.0263	3551	3.63×10^{-2}	0.076	53.7	9.22	0.9689	4.96×10^{-10}
10^{-19}	8.22	0.518	44.1	0.0257	1474	1.34×10^{-2}	0.087	54.6	4.78	0.9672	1.54×10^{-8}
10^{-18}	11.1	1.05	101	0.0251	582	4.69×10^{-3}	0.0966	55.6	2.19	0.9657	5.18×10^{-7}
10^{-17}	15.6	2.30	219	0.0246	202	1.46×10^{-3}	0.093	56.6	0.661	0.9639	2.02×10^{-5}
10^{-16}	20.0	4.95	329	0.0243	59.0	4.03×10^{-4}	0.064	57.5	0.0892	0.9648	5.36×10^{-4}
10^{-15}	21.4	8.69	383	0.0242	18.9	1.27×10^{-4}	0.042	58.2	0.0123	0.9677	7.02×10^{-3}

Simple Example : Quartic Potential

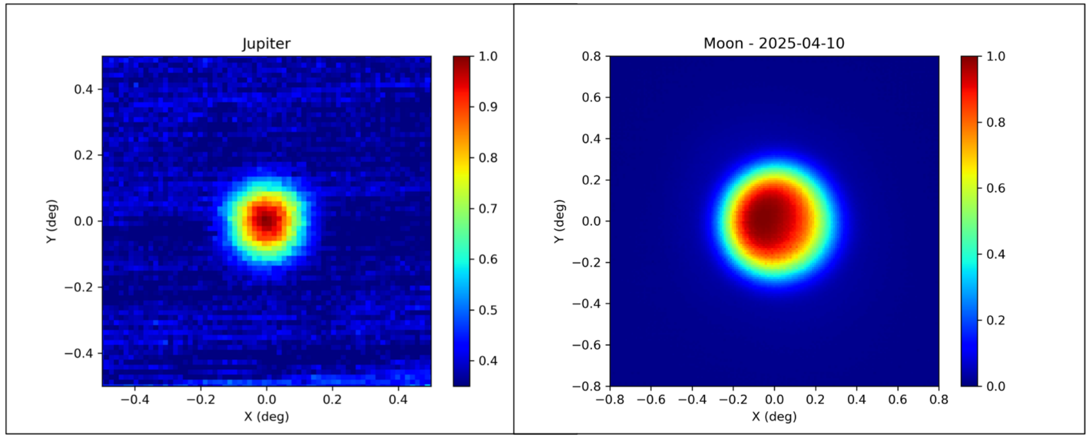


Berghaus/MaD/Zell 2503.18829



Antel et al 2305.01715

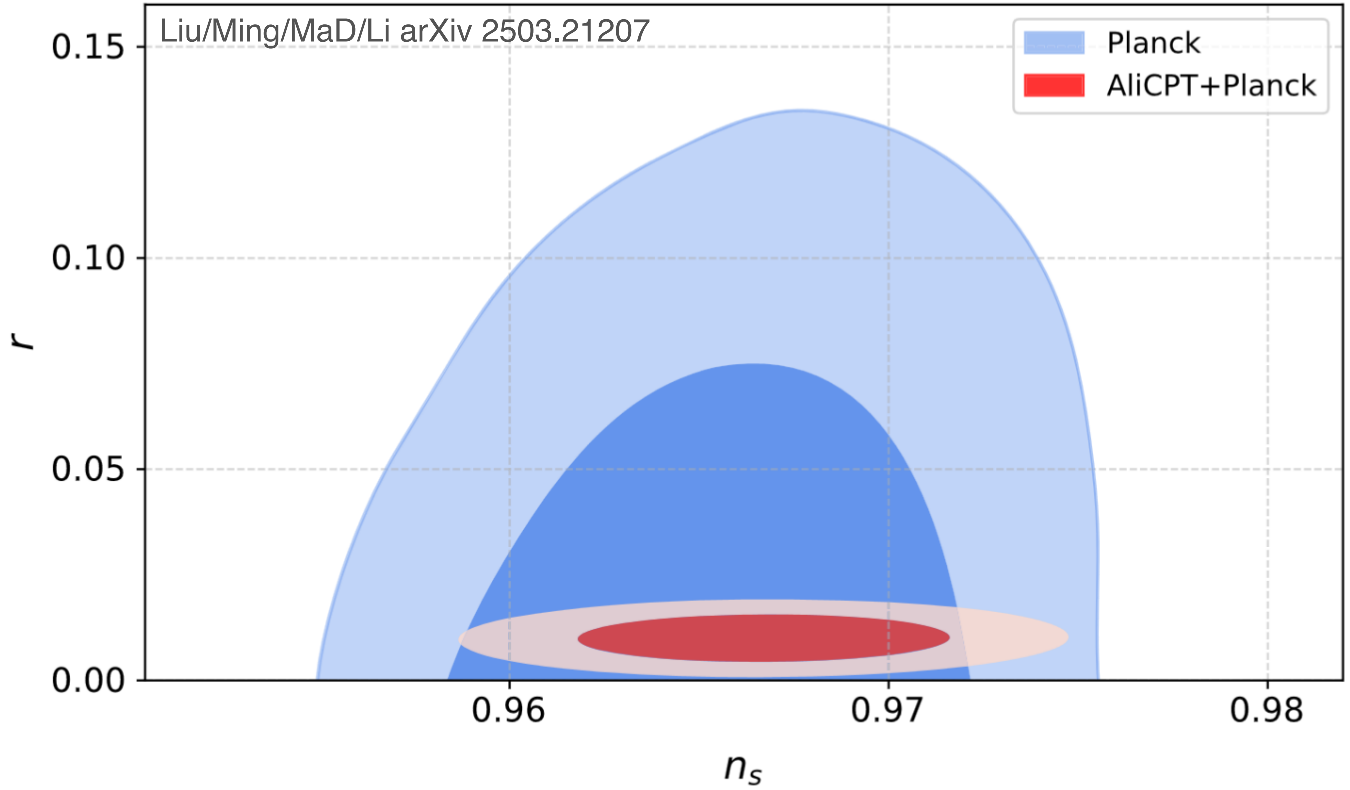
AliCPT-1 Observatory

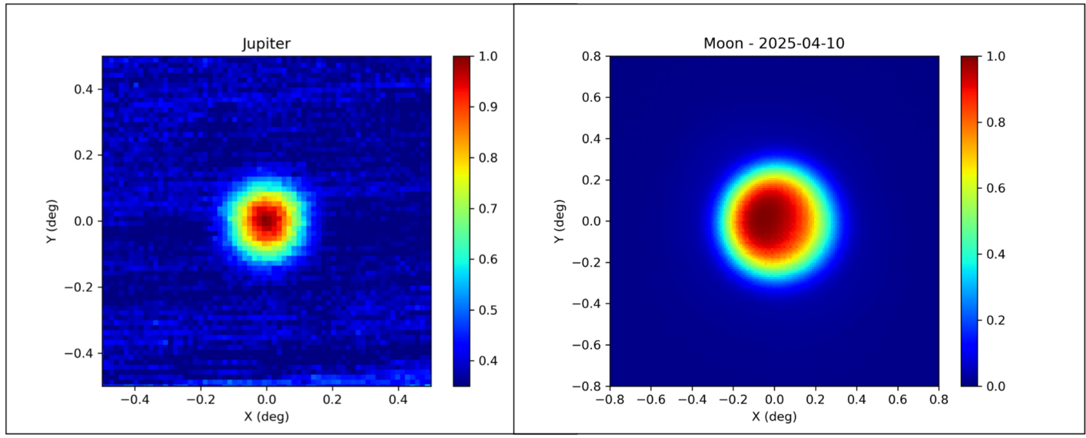


[image credit Hong Li and AliCPT collaboration]

- Located at 5250m altitude
- Construction started 2017, first light 2025
- Location: Tibet, China

AliCPT-1 Observatory





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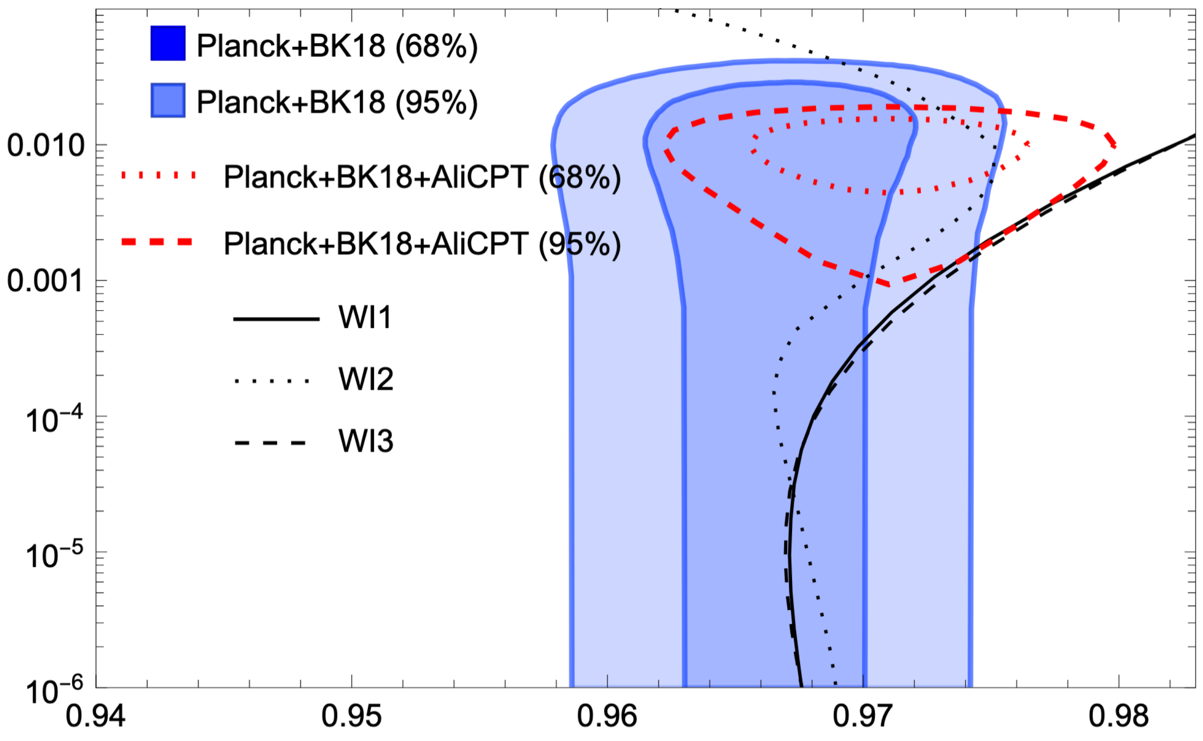
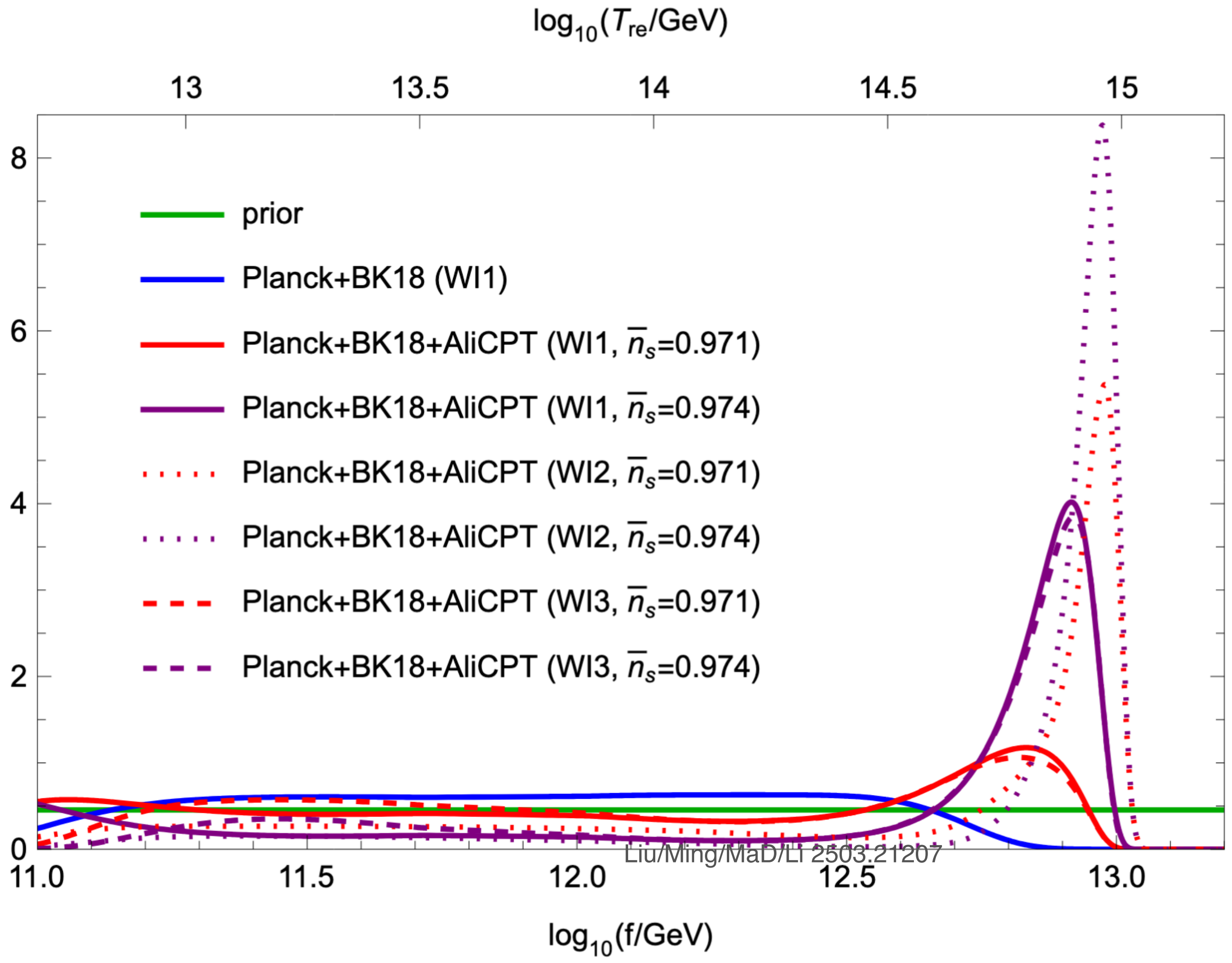
Theory Uncertainties

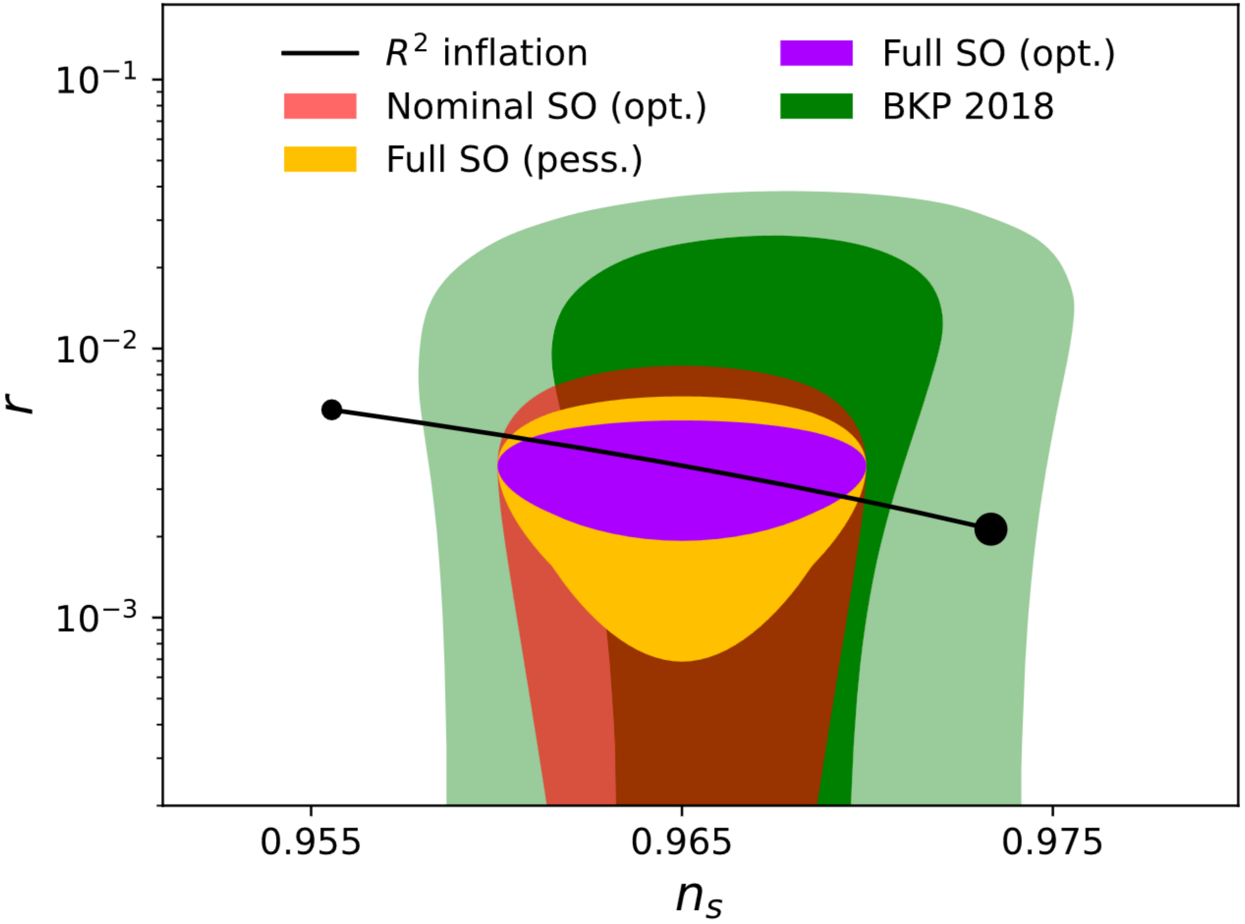


Fluctuation computations:
WI1: Berghaus/MaD/Zell 2503.18829
WI2: Ramos/Rodrigues 2504.20943
WI3: Laine/Procacci/Rogelj 2507.12849



Liu/Ming/Drewes/Li arXiv 2503.21207

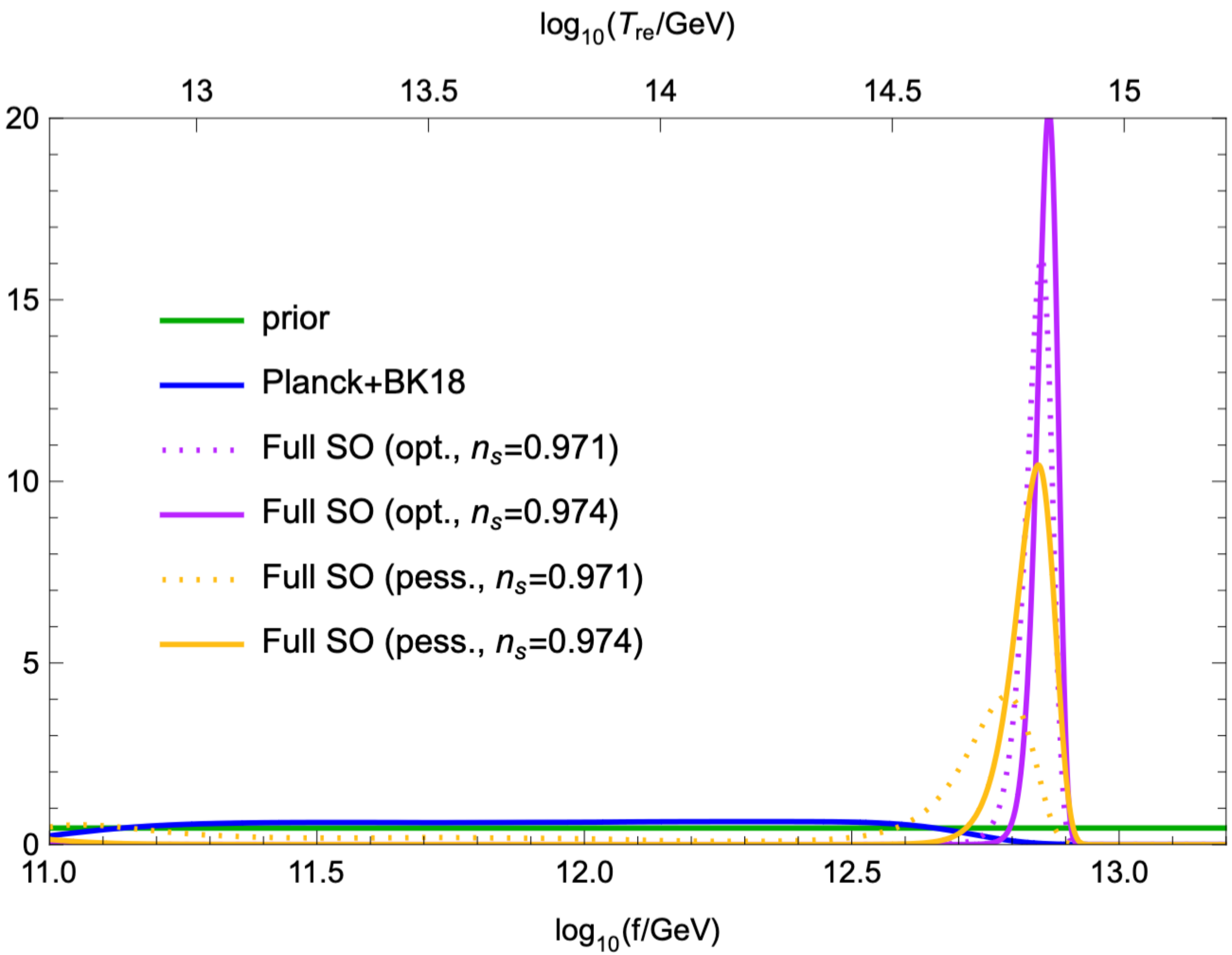
Expanded Simons Observatory



SO collaboration 2512.15833

- Located at 5200m altitude
- Already taking data, to be expanded by 3 SATs
- Location: Atacama desert, Chile

Expanded Simons Observatory



Ming/MaD 2606.12519

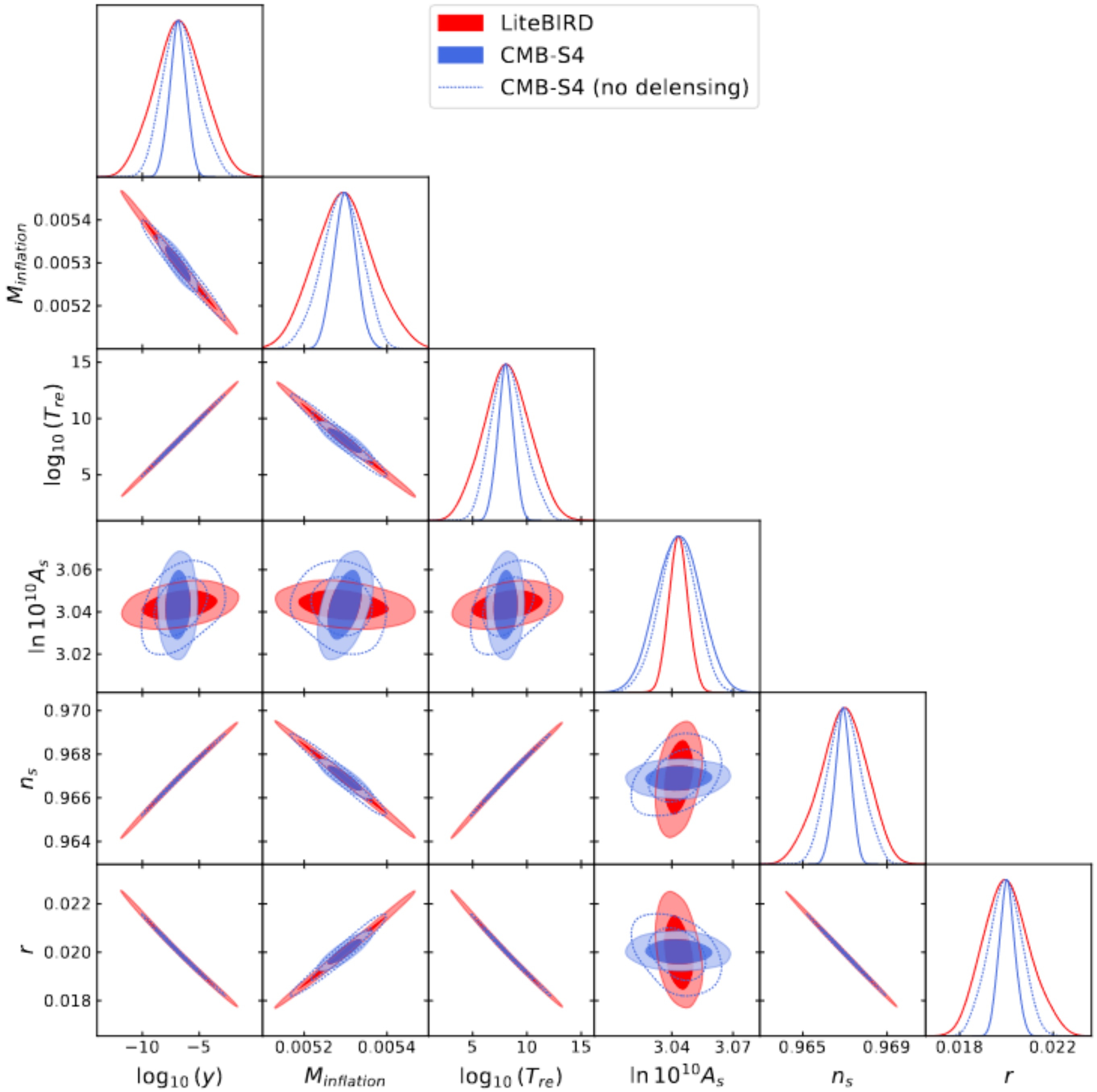
benchmark	$\log_{10}(f/\mathrm{GeV})$	$\mathrm{MAP}_{\mathbf{x}}$	$\mathrm{FWHM}_{\mathbf{x}}$	mass	$\log_{10}\frac{T_{\mathrm{re}}}{\mathrm{GeV}}$
SO(pess.)C	12.36 ± 0.62	12.79	0.15	49%	14.17 ± 0.60
SO(opt.)C	12.84 ± 0.04	12.85	0.06	73%	14.56 ± 0.03
SO(pess.)D	12.81 ± 0.21	12.85	0.09	72%	14.53 ± 0.20
SO(opt.)D	12.86 ± 0.02	12.87	0.05	74%	14.57 ± 0.01

- For optimistic noise modeling a measurement of log(*f*) at the sub-percent level seems feasible
- Even for pessimistic modeling a precision at the percent level seems possible!
- This enables precise predictions for axion searches
- Additional probe: trispectrum Mirbabayi Gruzinov 2205.13227

Summary and Conclusion

- Warm inflation is an interesting alternative to the standard inflationary paradigm
- Thermal bath is maintained during inflation, cosmic inflation is an open quantum system; background evolution driven by dissipation, perturbations caused by fluctuations
- Implementing warm inflation in realistic particle physics models in notoriously difficult; an axion-like inflaton is a promising candidate
- We showed that this can be done with SM gauge interactions (axion-like coupling to gluons), implying that the inflaton may be found in axion-searches
- Monomial quartic potential can fit CMB data

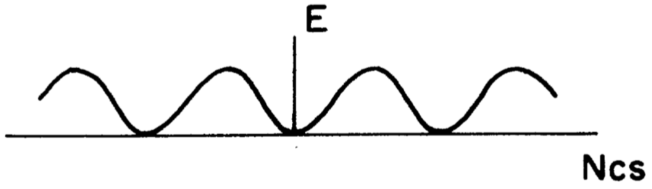
Backup



MaD/Ming/Oldengott 2303.13503

Sphaleron Heating

- Non-Abelian gauge theory has infinitely many vacua, related by large gauge transformations



- At high temperature jumps between them via sphalerons occur randomly due to thermal fluctuations

- Coupling the system to an axion $\frac{\alpha}{8\pi}\frac{\phi}{f}G^a_{\mu\nu}\tilde{G}^{a\mu\nu}$ introduces a preferred direction,

  leading to a net transfer of energy to the thermal bath, effectively described by a dissipation coefficient

$$\frac{\alpha}{8\pi f}\langle G^a_{\mu\nu}\tilde{G}^{a\mu\nu}\rangle \equiv \Gamma_{\rm sph}\dot{\phi}$$

McLarren/Mottola/Shaposhnikov 91

$$\Gamma_{\rm sph} \simeq (\alpha N_c)^5 \frac{T^3}{2f^2}$$

Moore/Tassler 1011.1167

- Shift symmetry protects *V(ϕ)* from receiving correction at this order, making this an ideal candidate for a microphysical mechanism that can drive warm inflation

Berghaus/Graham/Kaplan 1910.07525

Warm Inflation with the SM

- Hubble dilution of μ_A can be included by introducing the effective dissipation coefficient

$$\begin{aligned}\Gamma_{\text{eff}} &= \Gamma_{\text{sph}} \Big/ \left(1 + \frac{\Gamma_{\text{sph}}}{3H}\frac{N_f}{N_c}\frac{12f^2}{T^2}\right) \\ &= N_c^5 \alpha_s^5 \frac{T^3}{2f^2} \Big/ \left(1 + \frac{2N_f N_c^4 \alpha_s^5 T}{\sqrt{V(\phi)/(3M_{\text{pl}}^2)}}\right)\end{aligned}$$

into the set of effective equations of motion

$$\begin{aligned}\ddot{\phi} + 3H\dot{\phi} + V' &= -\Gamma_{\text{eff}}\dot{\phi} \\ \dot{\rho}_R + 4H\rho_R &= \Gamma_{\text{eff}}\dot{\phi}^2\end{aligned}$$

- This general framework permits QCD-driven warm inflation!
- The inflaton ϕ contributes to the Dark Matter density and can be targeted by axion-searches
- Phenomenological viability depends on the choice of $V(\phi)$

Berghaus/MaD/Zell 2503.18829