QCD-driven Warm Inflation: The Big Bang as an open quantum system

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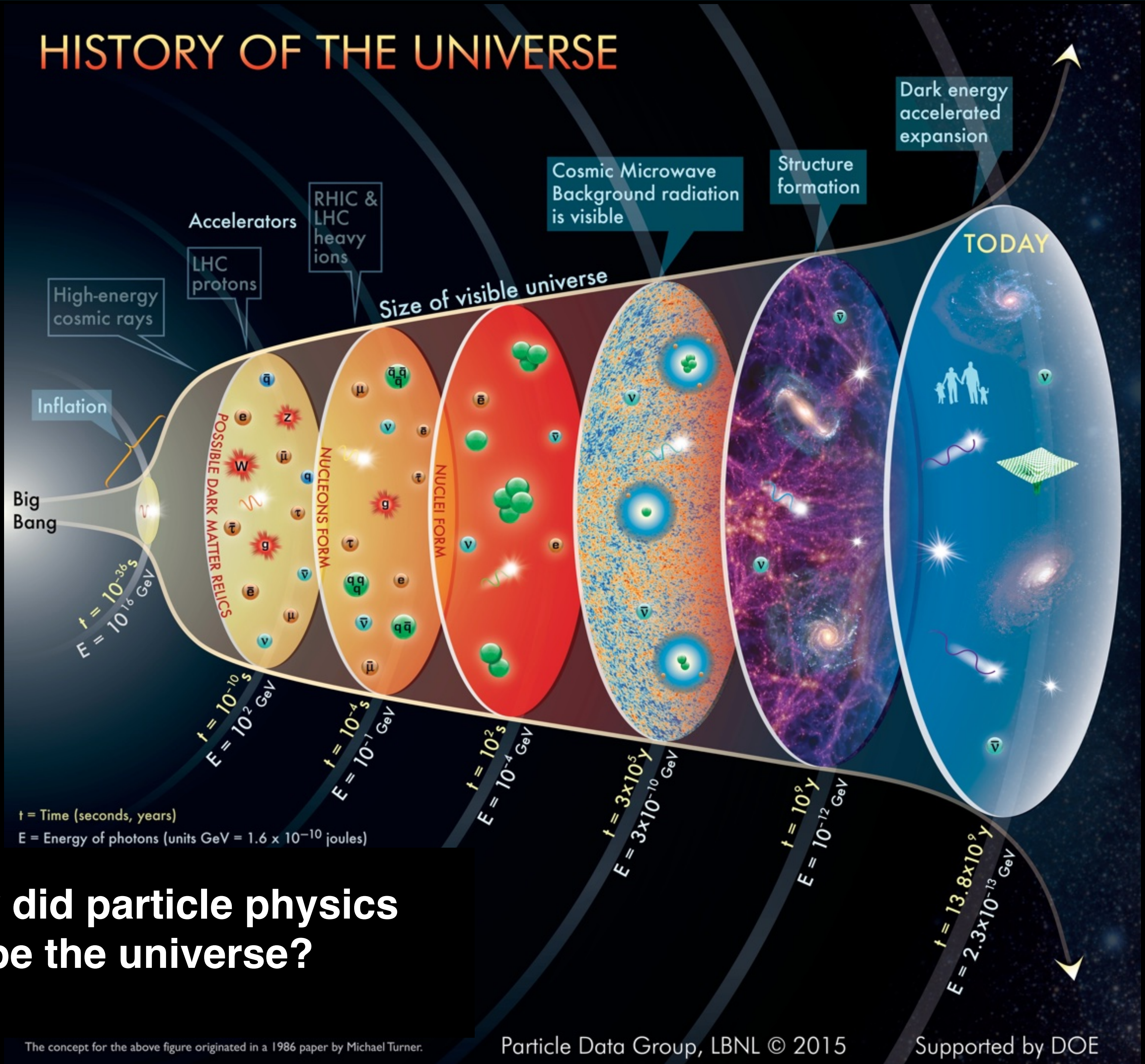
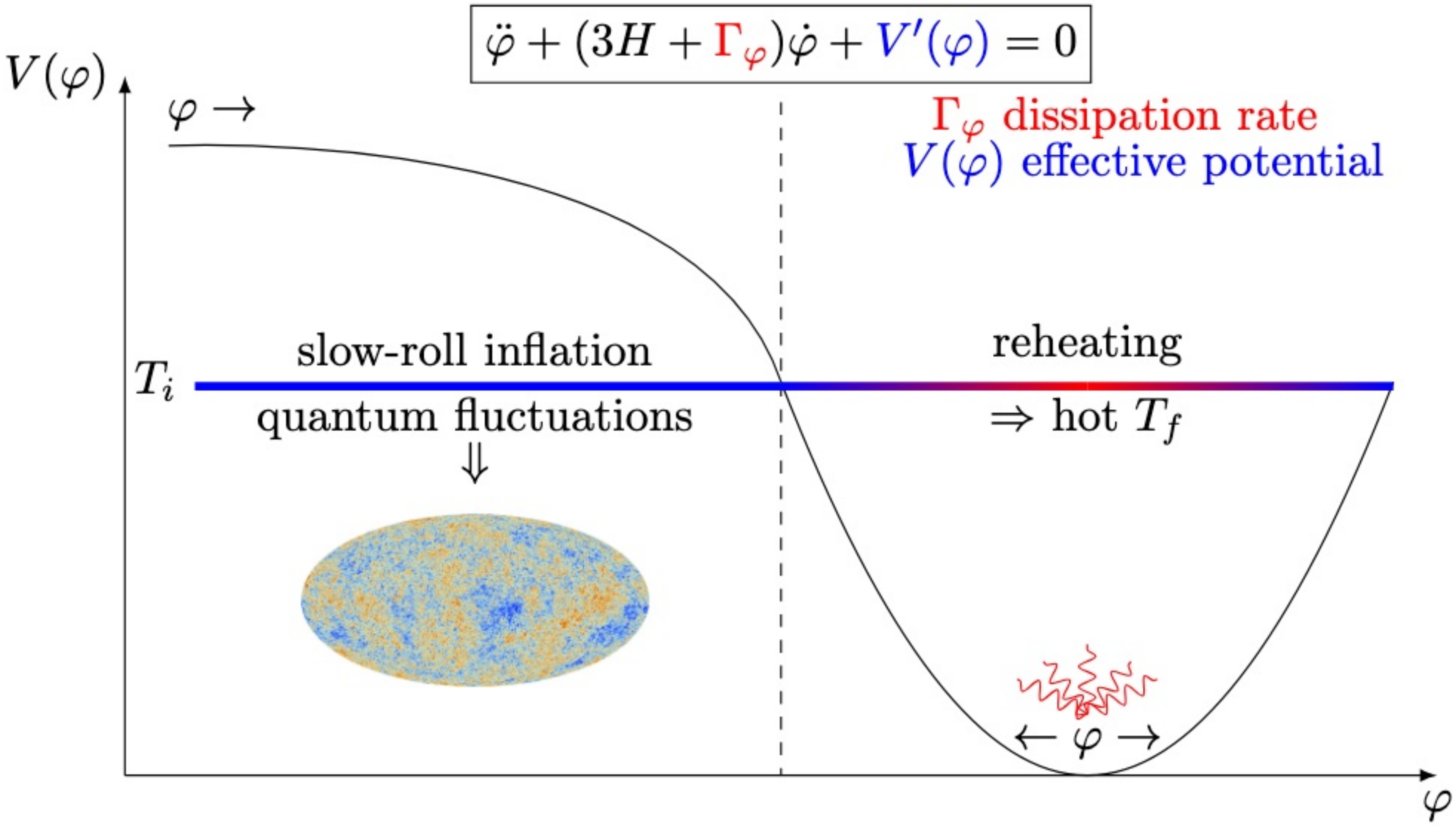
Open Quantum Systems: Dissipation and Decoherence from Subatomic to Cosmic Scales
16.04.2026, MITP, Mainz, Germany

[based on work in collaboration with Kim Berghaus and Sebastian Zell arXiv:2503.18829]



How did particle physics shape the universe?

Inflation and Reheating

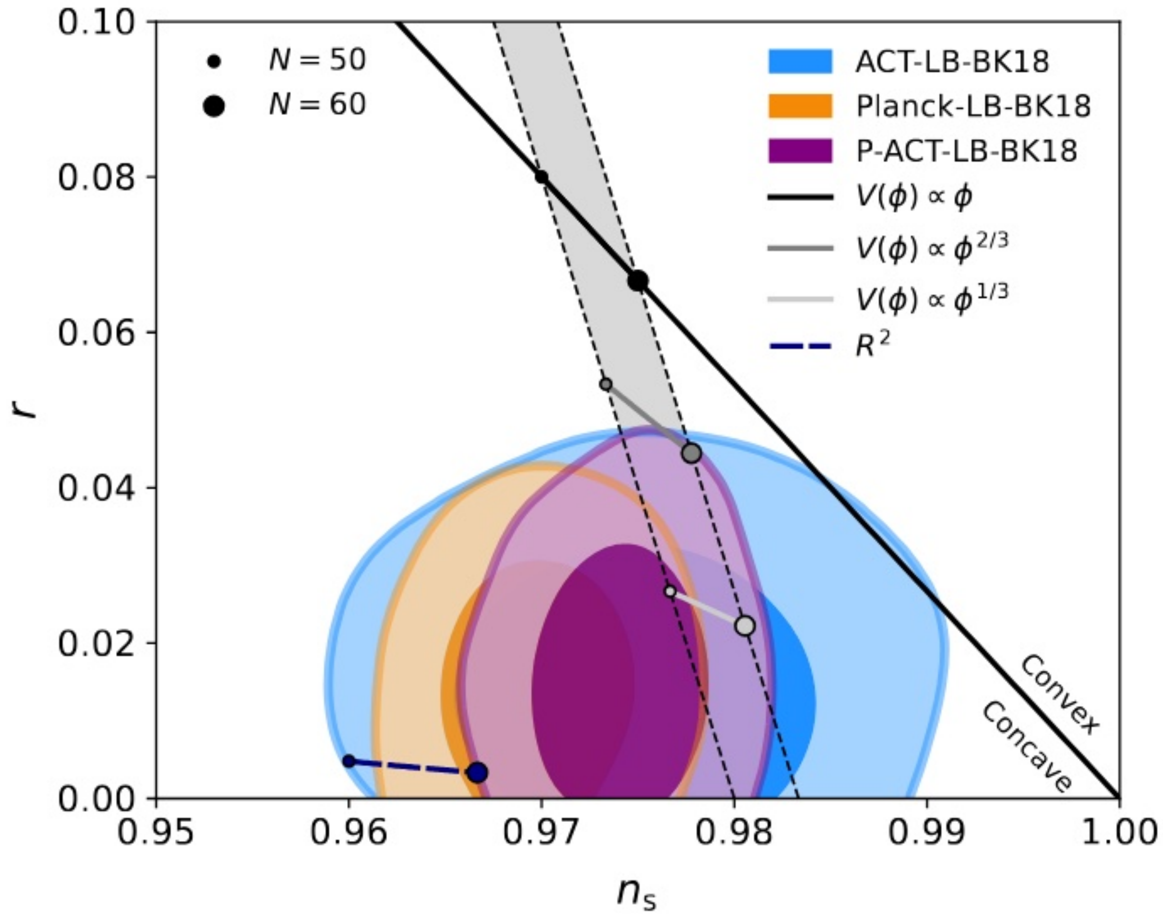


[image: Gilles Buldgen]

Challenges in Standard (cold) Inflation

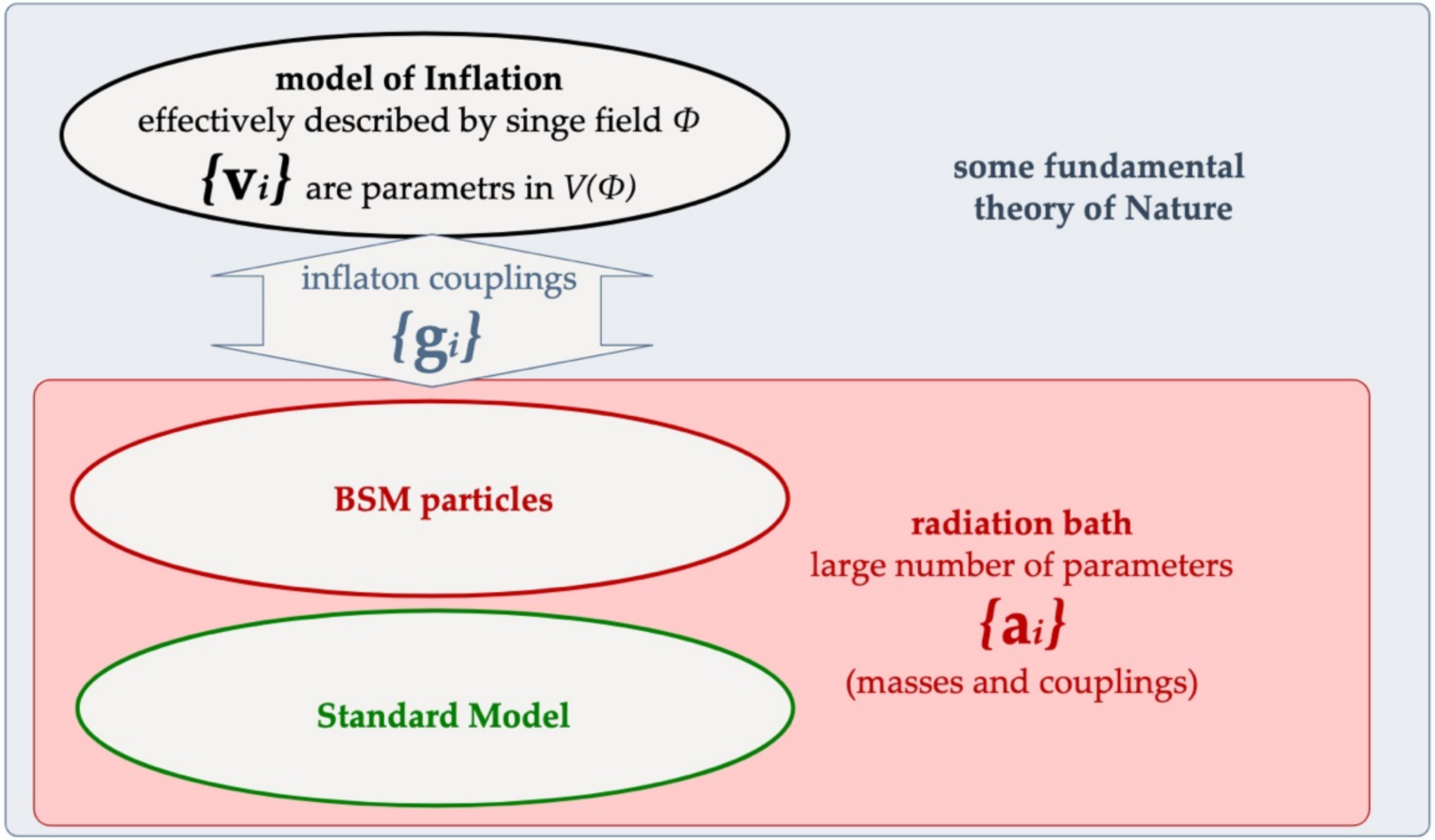
- Initial conditions
- Flatness of the potential
- Trans-Planckian field values
- Simplest potentials do not work
- Uncertainty due to reheating
- Connection to known physics unclear
- Lack of testability

[disclaimer: list and priorities are subjective]



[ACT 2503.14454]

Reheating and connection to known 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}

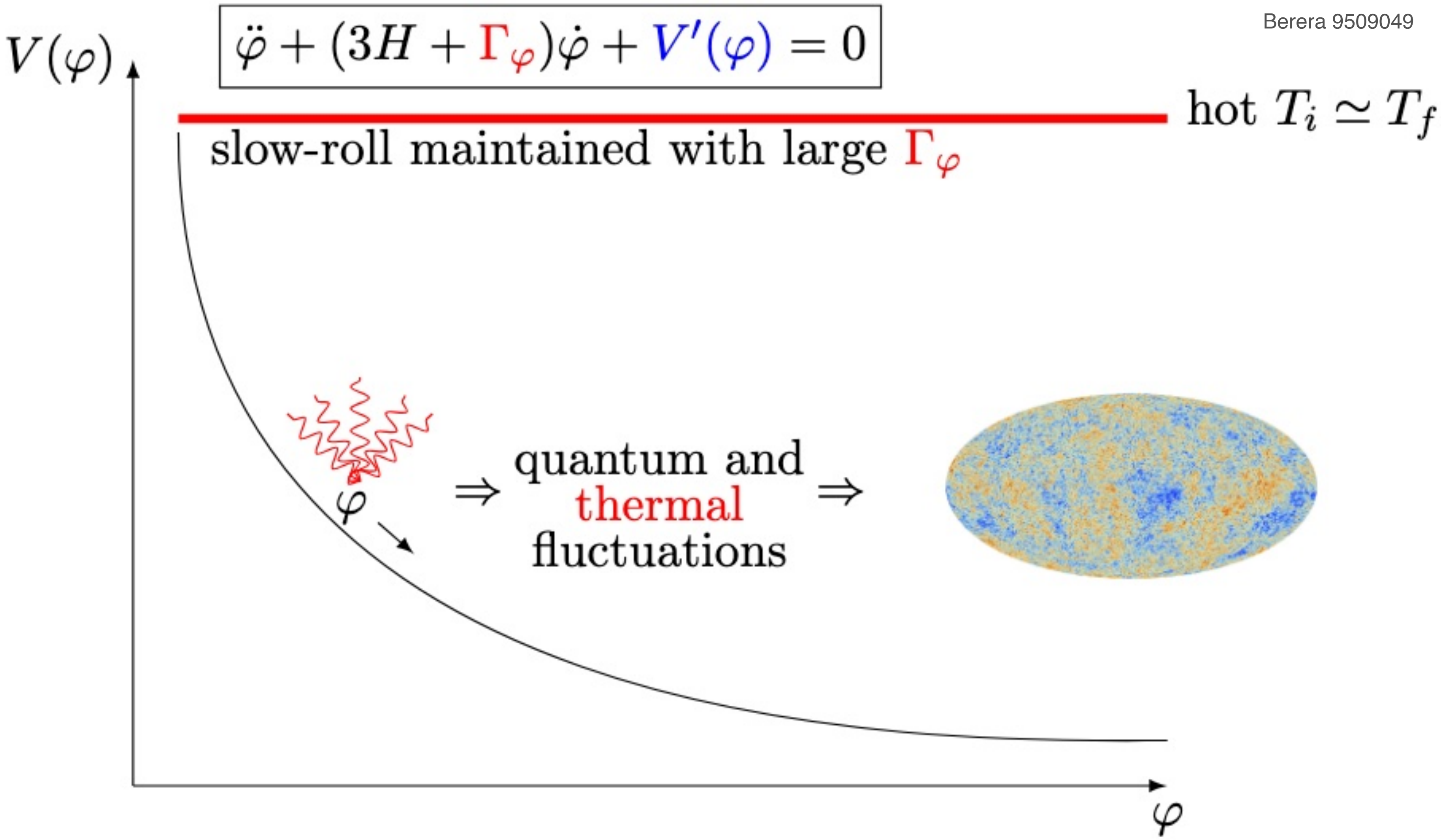
  Martin/Ringeval/Vennin 1410.7958, …
  MaD/Ming 2208.07609, …

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

  MaD 1903.09599, MaD/Ming/Oldengott 2303.13503, …

Warm Inflation

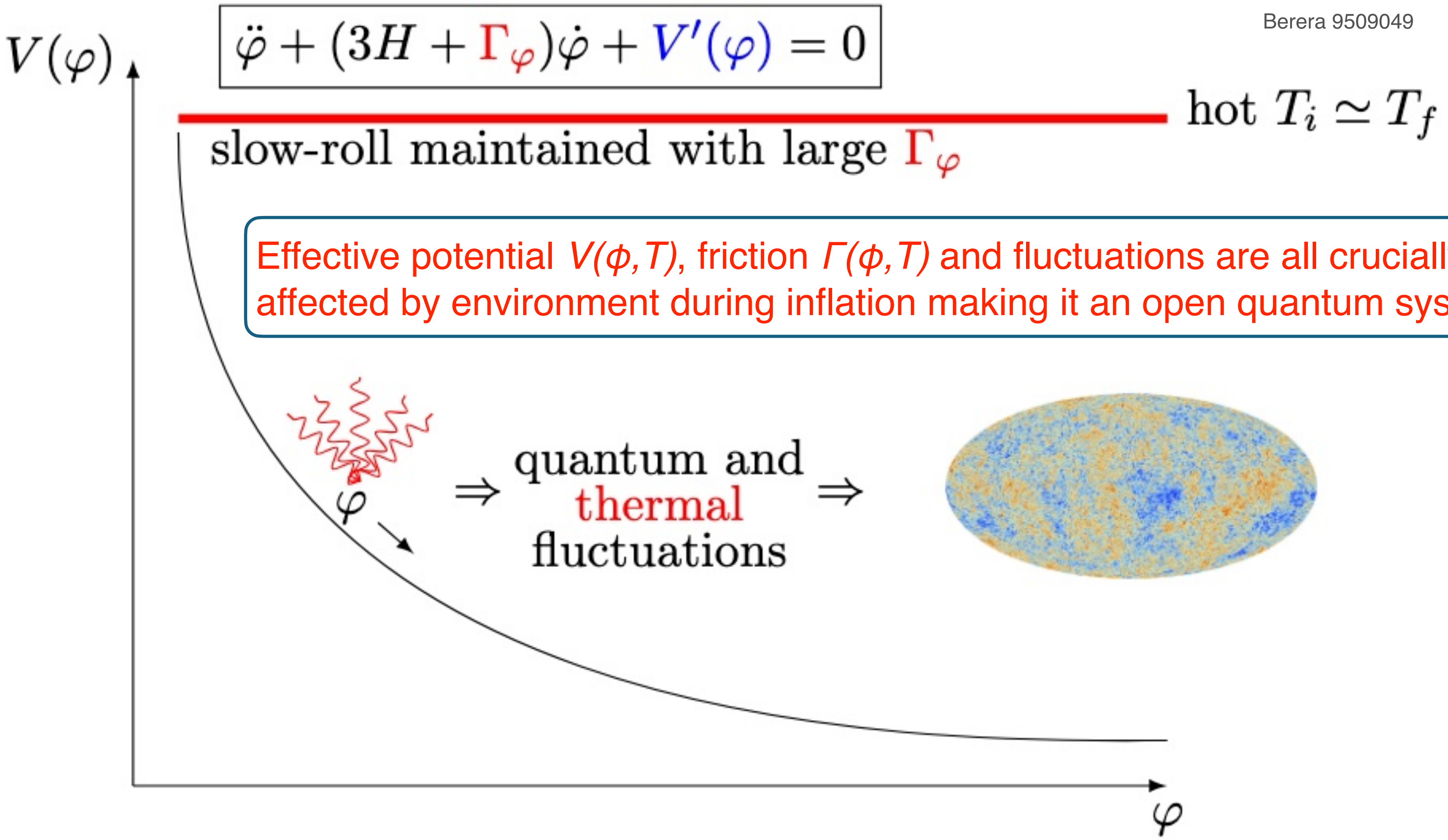
Berera 9509049



[image: Gilles Buldgen]

Warm Inflation

Berera 9509049



Effective potential *V(ϕ,T)*, friction *Γ(ϕ,T)* and fluctuations are all crucially affected by environment during inflation making it an open quantum system

[image: Gilles Buldgen]

Quantitative Description

- Full information about quantum statistical system contained in von Neumann density operator, with equation of motion

$$\dot{\varrho} = -\mathrm{i}[H, \varrho]$$

- Equivalently: consider infinite tower of n-point functions with expectation values

$$\langle \ldots \rangle = \mathrm{Tr}(\varrho \ldots)$$

- in practice usually one- and two-point functions are sufficient (bound state need four-point function)One point function ("condensate") ~ classical field

$$\varphi(x) \equiv \langle \Phi(x) \rangle$$

$$\Delta^{>}(x_1, x_2) = \langle \Phi(x_1)\Phi(x_2) \rangle - \varphi(x_1)\varphi(x_2)$$

$$\Delta^{<}(x_1, x_2) = \langle \Phi(x_2)\Phi(x_1) \rangle - \varphi(x_1)\varphi(x_2)$$

- Expressing all observables in terms of correlation functions avoids semi-classical assumptions or reference to asymptotic states
- Equations of motion obtained from 2PI effective action in the Schwinger-Keldysh formalism (e.g. Kadanoff-Baym equations); usually non-Markovian and not suitable for parameter scans
- Obtain effective quantum kinetic equations suitable for numerics in a series of controlled approximations adapted to the problem under consideration (gradient expansion in Wigner space, loop truncation, quasiparticle approximation…)

e.g. **Inflation**: Ai/MaD/Glavan/Hajer 2108.00254, Buldgen/MaD/Kang/Mun 1912.02772, **Baryogengesis**: Garbrecht 1812.02651, **Neutrino decoupling**: Bennet et al 2012.02726, MaD et al 2402.18481

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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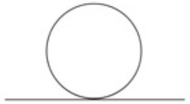
Flatness of the potential problem

- Thermal bath modifies both potential and dissipation coefficient

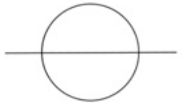
$$\ddot{\phi} + (3H + \Gamma)\dot{\phi} + V'(\phi) = 0$$

- The two are related, similar to dispersive and dissipative part of refractive index
- Come from real and imaginary parts of same Feynman diagrams. Example: $V(\phi) = \lambda\phi^4$

$$\delta V \propto \lambda T$$



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



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

Yokokama/Linde 9809409

Sphaleron Heating

- 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

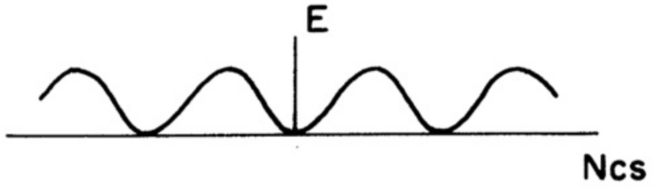
Laine/Procacci 2102.09913

- 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

McLarren/Mottola/Shaposhnikov 91

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

The Problem of Light Fermions

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

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

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

$$\begin{aligned}\ddot{\phi} + 3H\dot{\phi} + V' &= -\Gamma_{\rm sph}\left(\dot{\phi} + 2N_f f\mu_A\right)\\ \dot{\mu}_A + 3H\mu_A &= -\frac{6f\Gamma_{\rm sph}}{N_cT^2}\left(\dot{\phi} + 2N_f f\mu_A\right)\end{aligned}$$

- 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 McLarren/Mottola/Shaposhnikov 91
- Since SM fermions are light, it was concluded that SM gauge interactions cannot sustain warm inflation

Berghaus/Graham/Kaplan 1910.07525

Ways Out

MaD/Zell 2312.13739

Chirality violating interactions: example Yukawa coupling *y*

- Mediates chirality violating interactions at rate $\gamma_{\rm ch} \sim y^2 T$
  restores sphaleron heating if $|y| \gtrsim (\alpha N_c)^{5/2}$

- May generate fermion mass *m* by spontaneous symmetry breaking, yielding $\gamma_{\rm ch} \sim N_c \alpha m^2/T$
  Restores sphaleron heating if $|y_\varphi \langle\varphi\rangle| \gtrsim (\alpha N_c)^2 T$, i.e., as *m* depends on "Higgs" field value

  If inflaton itself plays that role, avoiding corrections to *V(ϕ)* negligible for $|y_\varphi T| \lesssim \sqrt{|V''(\langle\varphi\rangle)|}$

Another sphaleron: Suppose fermions are charged under another SU(N') w/o coupling to *ϕ*

- Restores sphaleron heating if $\tilde{\alpha}\tilde{N}_c \gtrsim \alpha N_c$

Spectators: SU(N) charged fermions have no (total) chirality violating interactions, but efficiently interact with sector that does.

- Examples: baryogengesis, generation of primordial helical magnetic fields

Hubble dilution of μ_A: This is unavoidable, no further extensions of SM needed

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

Berghaus/MaD/Zell 2503.18829

Warm Inflation with the SM

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

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

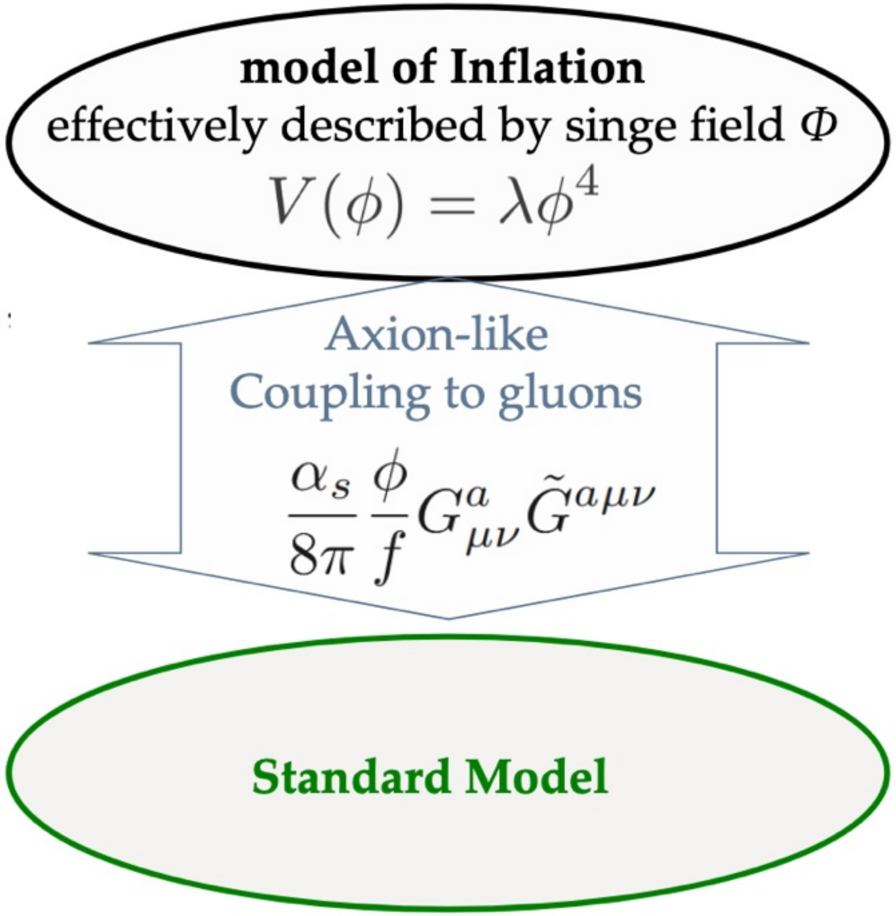
into the set of effective equations of motion

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

- 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

Simple Example : Quartic Potential



- For fixed *V(ϕ)* 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 *f* is fixed in terms of λ 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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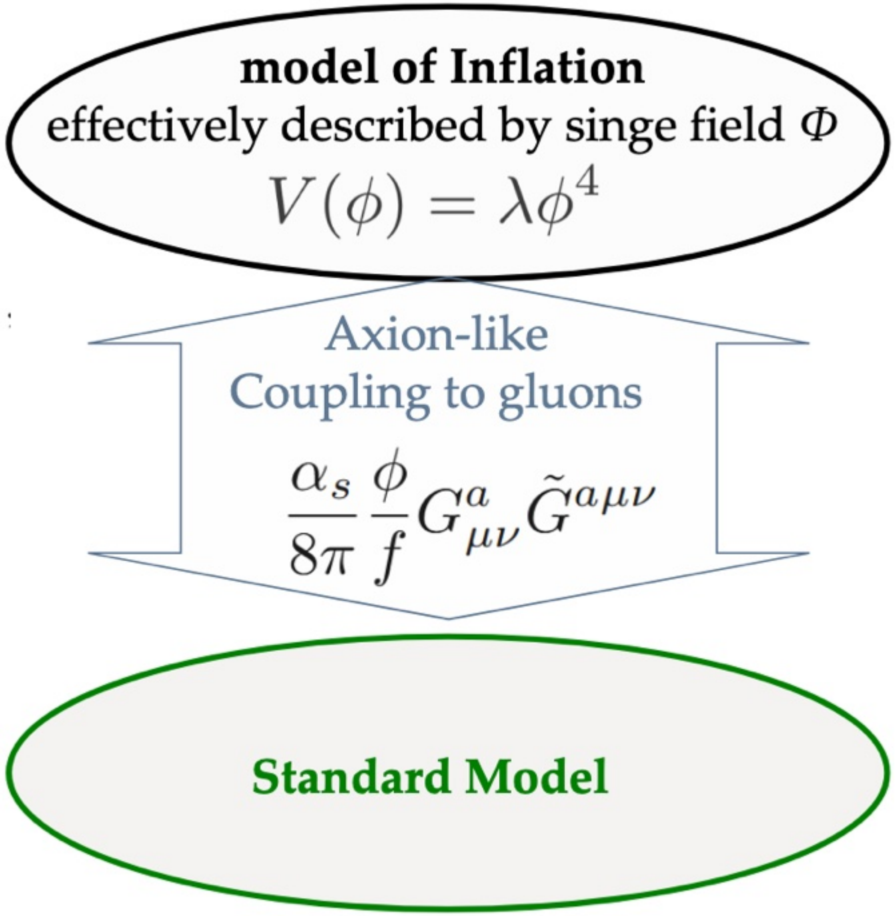

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Berghaus/MaD/Zell 2503.18829

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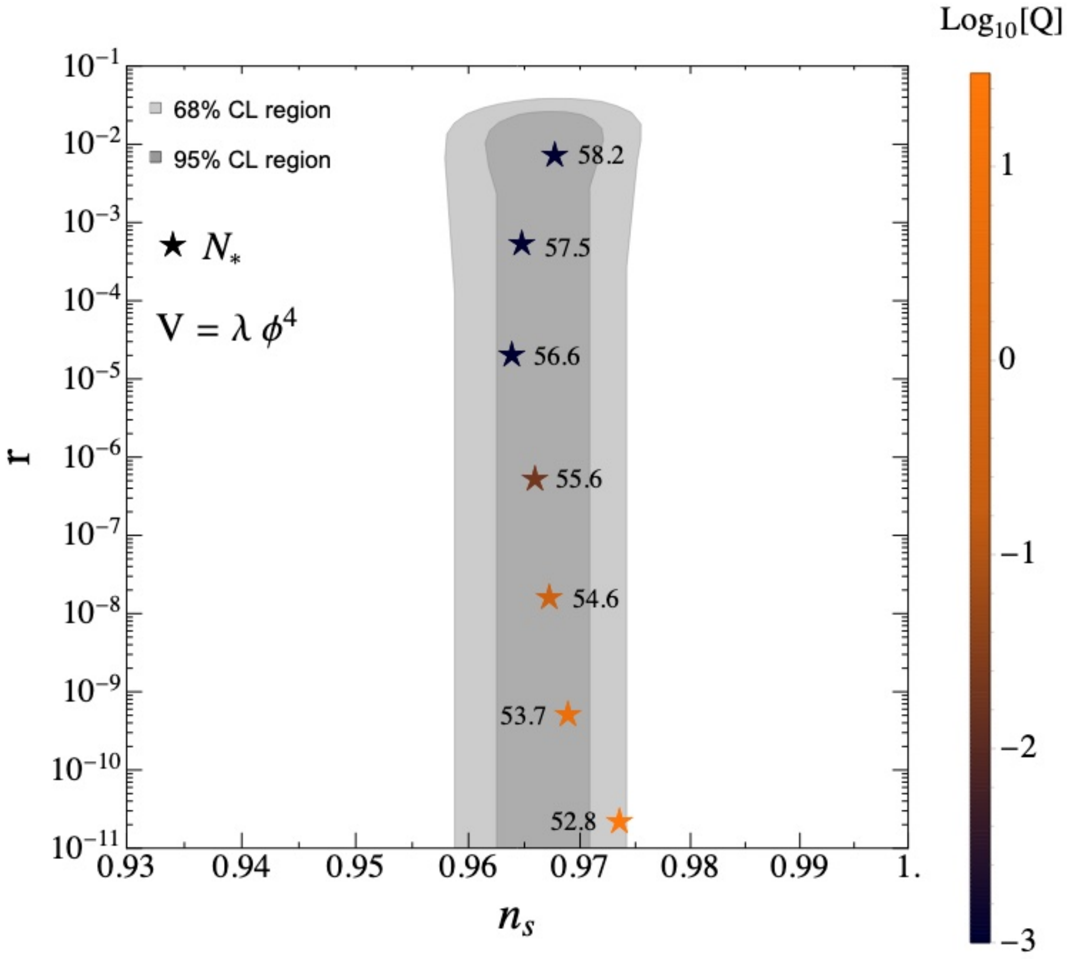


Berghaus/MaD/Zell 2503.18829

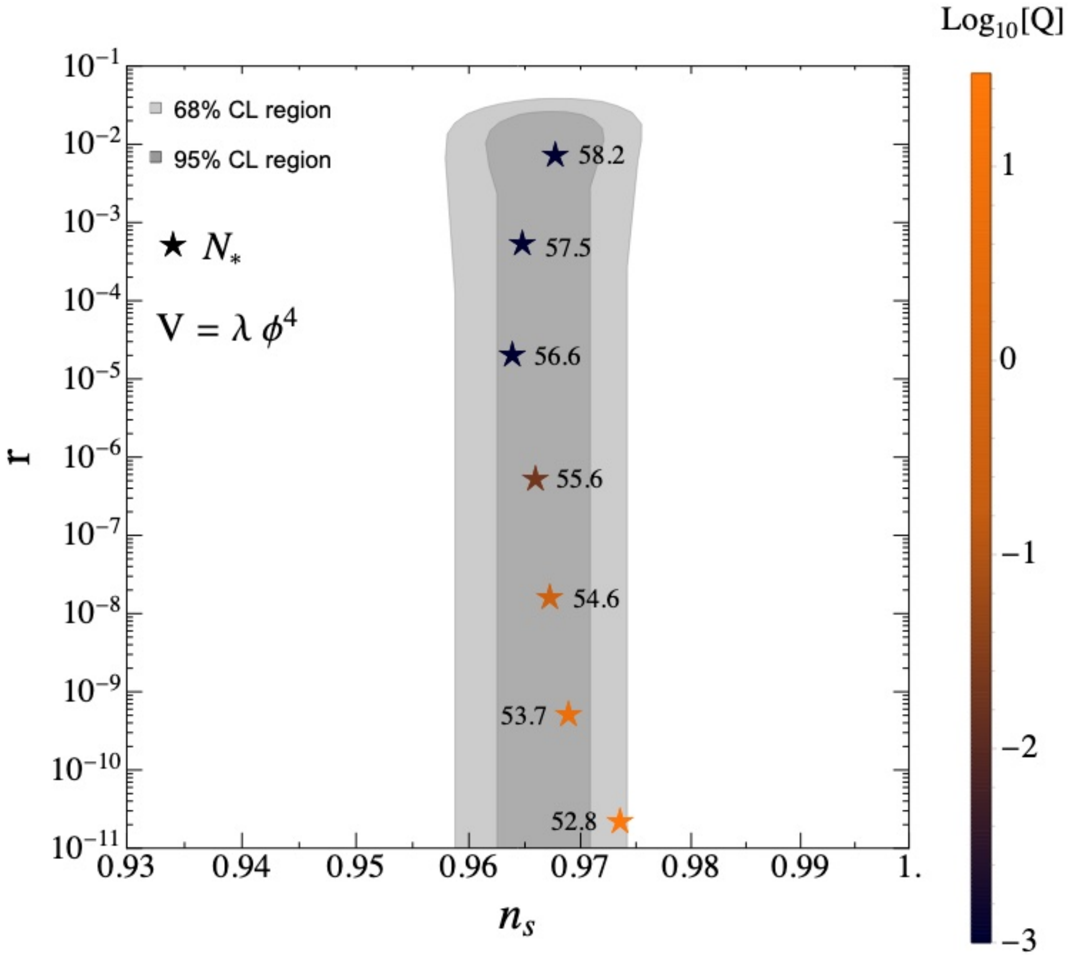
- CMB predictions for warm inflation are less established from first principles than for standard inflation
- We compared several approaches

  Mirbabayi/Gruzinov 2205.13227 [our results use this one]
  Ramos/Rodrigues 2504.20943
  Laine/Procacci/Rogelj 2507.12849

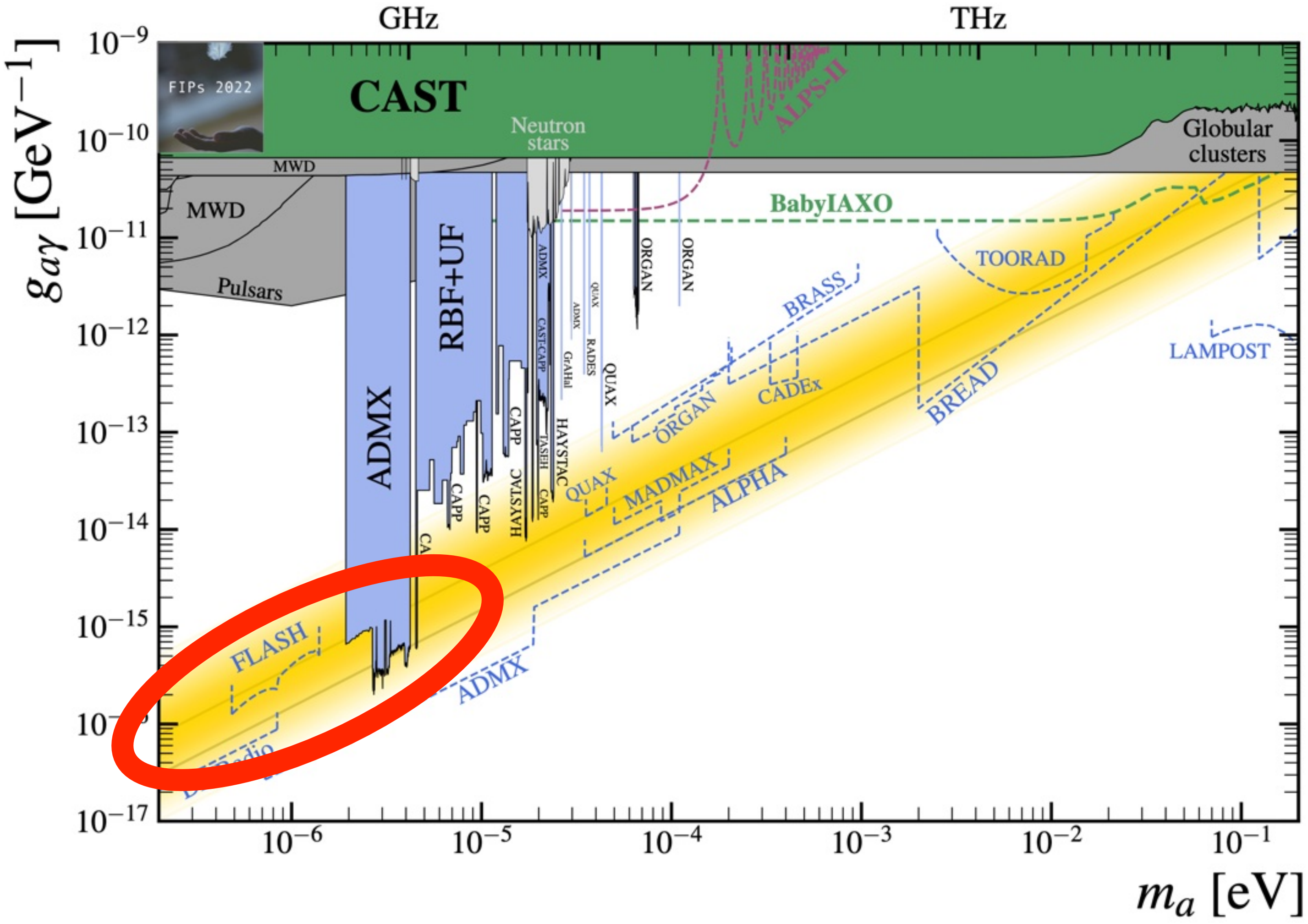
- Differences are smaller than Planck+BK 2σ error bars on *ns*, but will matter for future observations

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}

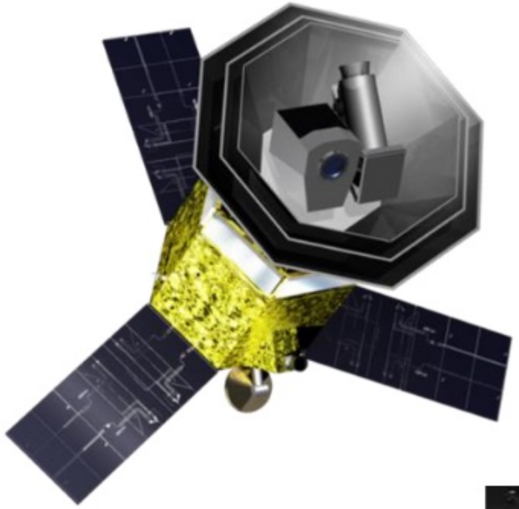
Simple Example : Quartic Potential

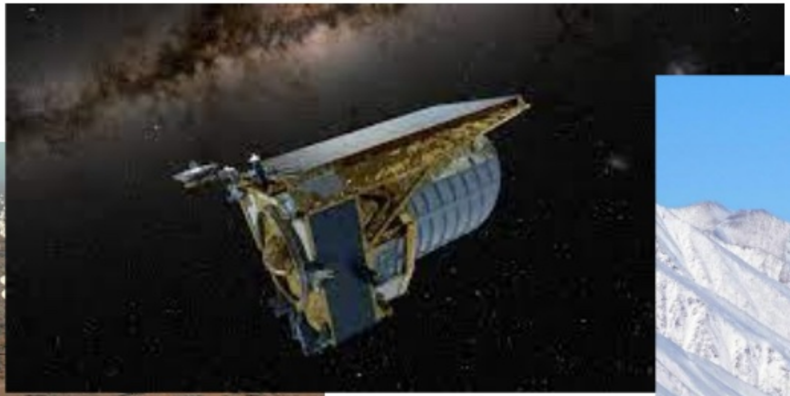


Berghaus/MaD/Zell 2503.18829

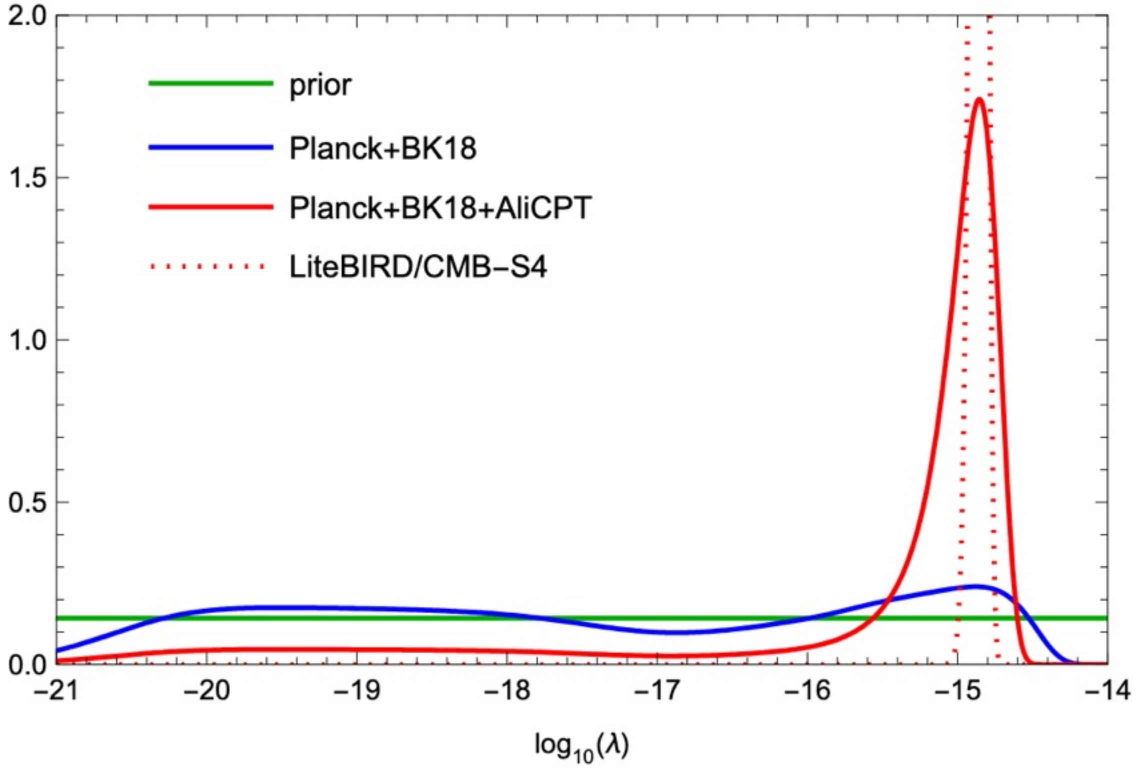


Observations





Simple Example : Quartic Potential

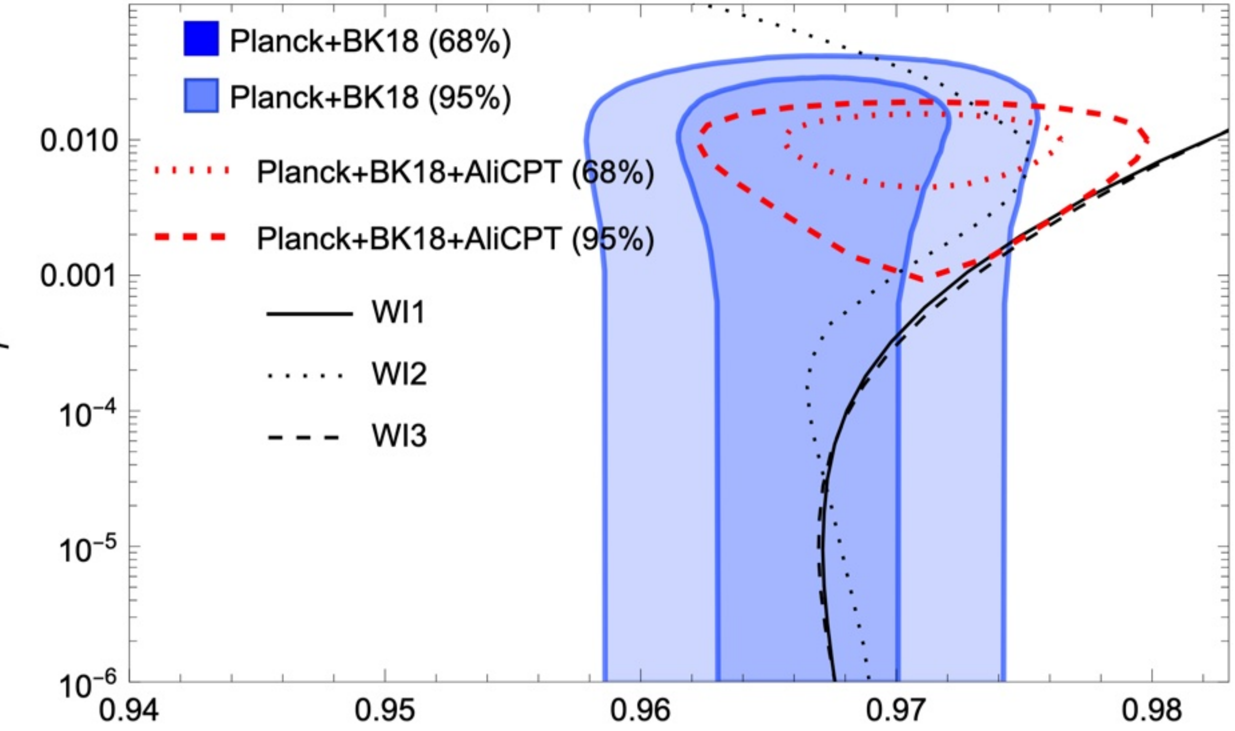


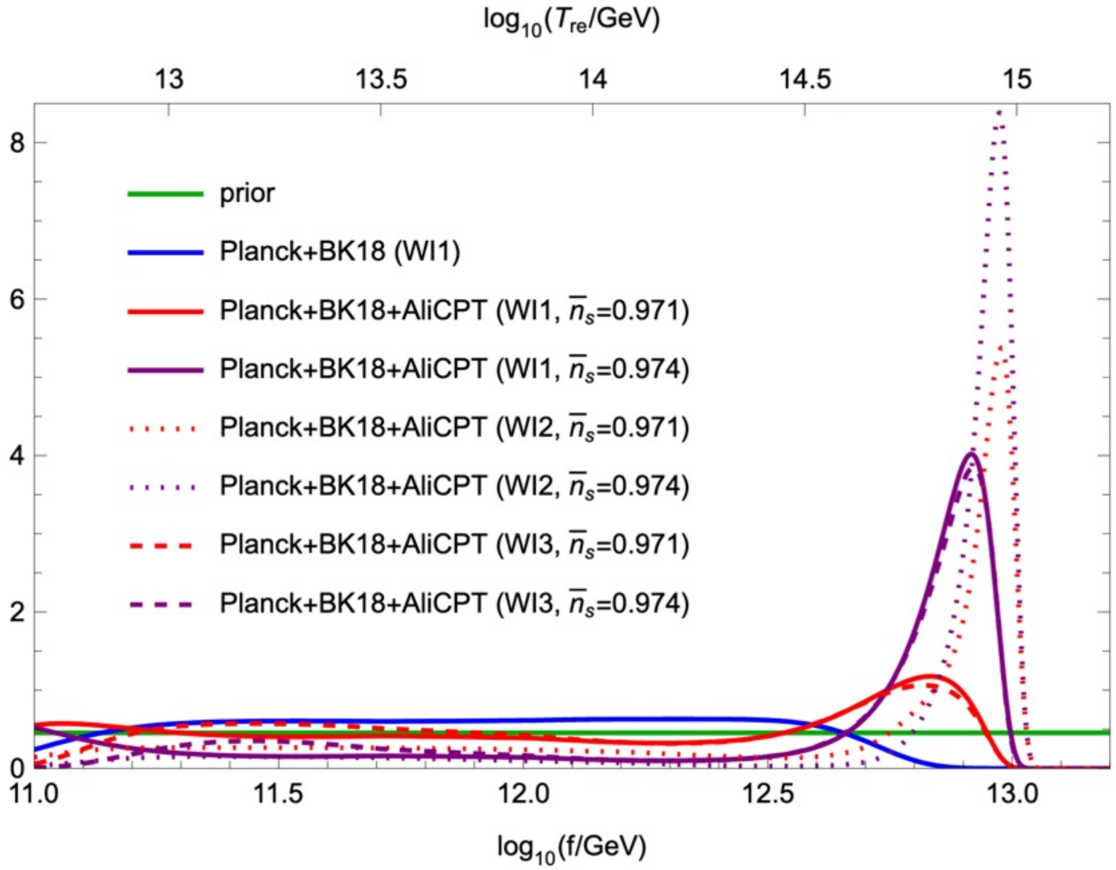
- LiteBIRD's sensitivity to *r* would make them ideal to probe warm inflation

- Given the current status of these missions, we assess what can be done with AliCPT with 19 detector modules (σ_r = 0.0037 for a fiducial value r = 0.01)

- LiteBIRD could determine the order of magnitude of λ,
  AliCPT could measure λ with a larger error

Fluctuation & Dissipation





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

pheno plots:
Liu/Ming/MaD/Li 2503.21207

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**