A Generalized Method of Constraining Warm Inflation with CMB Data

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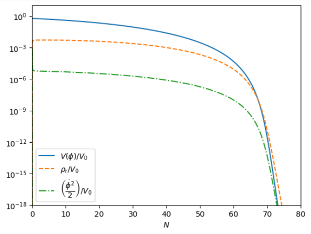
Outline

- Motivation for Warm Inflation.
- Dynamics of Warm Inflation.
- Observational Signatures.
- Challenges & Methodology.
- Advantages & Results.
- Conclusions.

Motivation

- Inflation provides a solution to the fine-tuning problems associated with hot Big Bang cosmology.
- Warm Inflation (WI) differs from cold Inflation (CI) by allowing radiation to co-exist with the inflaton field.
- Features:
  - Resolves reheating issues naturally.
  - Broader range of viable potentials due to added dissipative friction.



Reheating occurs naturally in Warm Inflation.

Cold vs Warm Inflation

Cold Inflation (CI):

- Inflaton decoupled from other fields.
- Relies only on quantum fluctuations.
- Radiation only emerges after reheating.

Warm Inflation (WI):

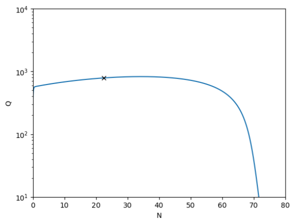
- The inflaton interacts with the radiation bath.
- Includes thermal and quantum fluctuations.
- Radiation coexists with inflaton during inflation.

Dynamics of Warm Inflation

- Inflaton's equation of motion:

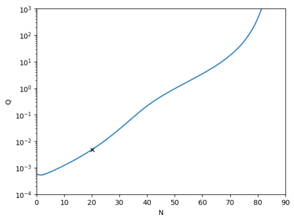
$$\ddot{\phi} + (3H + \Upsilon)\dot{\phi} + V_{,\phi}(\phi) = 0$$

- Two friction terms:
  - Hubble friction: $3H\dot{\phi}$
  - Dissipative friction: $\Upsilon\dot{\phi}$
- Regimes:
  - Weak dissipative ($\Upsilon \ll 3H$).
  - Strong dissipative ($\Upsilon \gg 3H$).



Strong dissipative regime.

$Q = \Upsilon/3H$.



Weak dissipative regime.

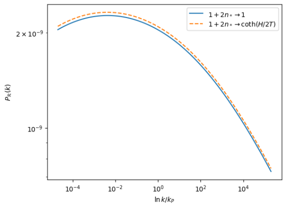
$Q = \Upsilon/3H$.

Observational Signatures

- WI modifies the scalar power spectrum:

$$\mathcal{P}_{\mathcal{R}(\mathrm{WI})}(k_*) = \mathcal{P}_{\mathcal{R}(\mathrm{CI})}(k_*) \left[1 + 2n_* + \frac{T_*}{H_*} \frac{2\sqrt{3}\pi Q_*}{\sqrt{3 + 4\pi Q_*}}\right] G(Q_*)$$

- Key differences:
    - Includes a thermal distribution term n_*.
    - Growth factor $G(Q_*)$ depends on dissipative coefficient (Υ) *(G.Montefalcone et al JCAP01(2024)032), G. S. Rodrigues et al arXiv:2504.17760*.
- The tensor power spectrum remains unchanged: $\mathcal{P}_T \propto H^2$



Observational Signatures: Warm vs Cold Inflation

- **Tensor-to-Scalar Ratio r:**
  - CI: $r \gtrsim 10^{-3}$
  - WI: $r \ll 10^{-4}$ (with strong dissipation)
- **Running & Running-of-Running (n_s', n_s''):**
  - CI: Negligible or negative runnings
  - WI: Non-negligible but still within current CMB limits
- **Non-Gaussianity:**
  - CI: Nearly Gaussian bispectrum
  - WI: Distinct non-Gaussian signatures due to thermal noise
- **Small-Scale Power & PBHs:**
  - CI: Needs special features for PBH formation
  - WI: Naturally enhances small-scale power and PBH formation

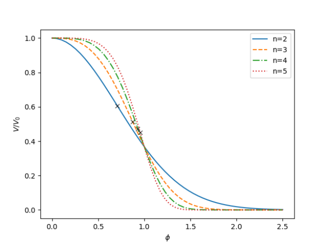
Key Strategy: Combining future constraints on r, n_s', and n_s'' and bispectrum shape to test WI vs CI.

Steep Potentials in WI

- Steep potentials (e.g., $V(\phi) \propto e^{-\alpha\phi^n}$) *(S. Das et al Phys. Rev. D 102, 103522)* are viable in WI.
- Slow-roll condition modified:

$$\epsilon_H = \frac{\epsilon_V}{(1+Q)} \ .$$

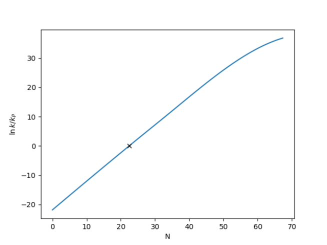
- Strong dissipative regime $(Q \gg 1)$ allows steep potentials while maintaining slow-roll.



Steep potential: $V_0 e^{-\alpha(\phi/M_{Pl})^n}$

Challenges and Methodology

- Incorporating WI spectra into cosmological codes:
  - Complex dependence on comoving wavenumber k.
  - Not possible to solve analytically for nontrivial forms of $V(\phi)$ and Υ.
- Generalized method developed to express spectra as functions of k, enabling analysis via `CAMB` and `Cobaya`.



Relation between the number of e-folds N and the comoving wavenumber k.

Methodology for Constraining Warm Inflation (Part 1)

Goal: Constrain Warm Inflation (WI) models with CMB data.

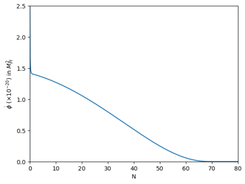
Steps:

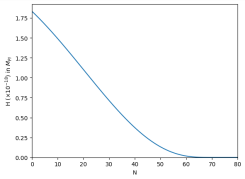
- Solve background equations numerically:

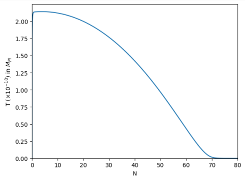
$$\ddot{\phi} + (3H + \Upsilon)\dot{\phi} + V_{,\phi}(\phi) = 0$$

$$\dot{\rho_r} + 4H\rho_r = \Upsilon\dot{\phi}^2$$

- Use e-folds N as the temporal variable.
- Link N to k by specifying pivot scale k_P exit.







Methodology for Constraining Warm Inflation (Part 2)

Steps:

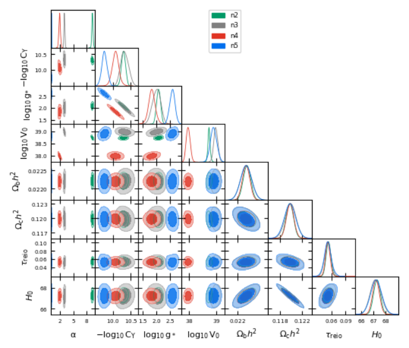
- **Parameterize Spectrum:**
  - Include the thermal distribution term (n) and $G(Q)$ that accounts for dissipative effects on perturbations.
  - Express the scalar power spectrum $\mathcal{P}_{\mathcal{R}}(k)$ as a function of k.
- **Compare with CMB Data:**
  - Compare the model predictions with observational data from CMB datasets.
  - Perform MCMC analysis with `CAMB`/`CLASS` and `Cobaya`.
- **Constrain Parameters:**
  - Derive bounds for WI model parameters.

Advantages of the Methodology

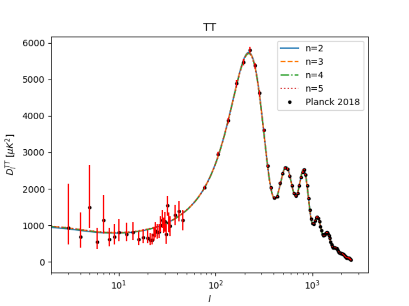
- **Previous Approaches:**
  - Relied on analytical solutions with specific potentials and dissipative coefficients.
  - Depended on Slow-Roll approximations.
  - Lacked a unified pipeline for incorporating WI spectra into cosmological codes for parameter inference.
- **This Methodology:**
  - Generalizes WI power spectra to accommodate arbitrary potentials and dissipative coefficients.
  - Eliminates the need for Slow-Roll approximations.
  - Provides a streamlined approach to incorporating WI spectra within cosmology codes (`CAMB` and `Cobaya`).

Results

- The results from the analysis show the constraints on model parameters from CMB Data *(Planck 2018)*.



Parameter dependences.



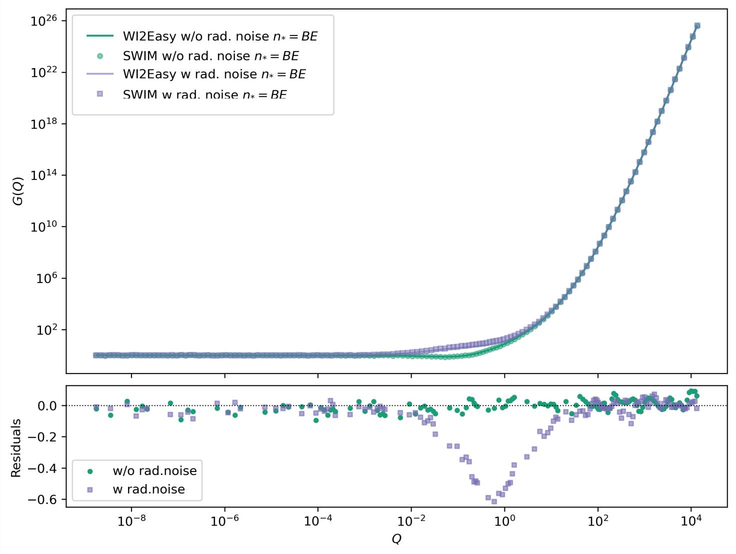
CMB angular spectrum using best-fit values from the analysis.

Conclusion

- Generalized Methodology applicable to nontrivial WI models.
- Easy to incorporate into cosmological codes for parameter inference.
- Can be extended to incorporate beyond Slow-Roll dynamics.

Thank You for Your Attention!

Appendix



WI2Easy w/o rad. noise $n_* = BE$
SWIM w/o rad. noise $n_* = BE$
WI2Easy w rad. noise $n_* = BE$
SWIM w rad. noise $n_* = BE$
$G(Q)$
10^{26}
10^{22}
10^{18}
10^{14}
10^{10}
10^{6}
10^{2}
Residuals
0.0
−0.2
−0.4
−0.6
w/o rad.noise
w rad.noise
10^{-8}
10^{-6}
10^{-4}
10^{-2}
10^{0}
10^{2}
10^{4}
Q