Inflating the Universe With Light Dark Sector and Conformal Invariance

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June 2021 PATRAS, TRIESTE

Outline of the talk:

- Ultraviolat (UV) and Infrared (IR)physics is connected via RGE.
- Complementarity between Lab and Cosmic observables.
- Inflation and Scalar Field Models of Inflation.
- Particle Models: Higgs Inflation
- Particle Model: Creating an Inflection-point
  - Creating an Inflection-point via RGE.
  - Complementary Probes via CMB & Light Dark Sector Experiments.
- Various model-building: dark matter, neutrinos & conformal models.
- Conclusion

Inflation: Motivations

- Cosmic Inflation, characterised as quasi-de Sitter expansion is invoked to solve the problems of Big Bang Cosmology:
  - Horizon Problem.
  - Flatness Problem.
  - Origin of Primordial density fluctuations seen in CMB.
  - Monopole problem.
  - Others...
- Slow-roll Inflation:
  - A scalar field inflaton rolling down a potential.
  - This potential needs to be flat from CMB constraints.

Planck 2018 and Constraints

Constraints on scalar and tensor perturbations from the PLANCK satellite

Observational constraints :

$$\begin{cases} \Delta_\zeta(k_0) = 2.137^{+0.063}_{-0.061} \times 10^{-9}, \\ n_s = 0.968 \pm 0.006, \\ r < 0.11, \\ k_0 = 0.002\text{Mpc}^{-1}. \end{cases}$$

(TT+lowP+lensing)

Theoretical predictions :

$$\begin{cases} \Delta_\zeta(k) \simeq \frac{1}{8\pi^2\epsilon}\left(\frac{H}{M_G}\right)^2, \\ n_s - 1 = \frac{d\ln\Delta_\zeta(k)}{d\ln k} \simeq -2\epsilon - 2\eta, \\ \Delta_h(k) \simeq \frac{2}{\pi^2}\left(\frac{H}{M_G}\right)^2, \quad n_T = \frac{d\ln\Delta_h(k)}{d\ln k} \simeq -2\epsilon, \\ r \equiv \frac{\Delta_h(k)}{\Delta_\zeta(k)} \simeq 16\epsilon (= -8n_T). \end{cases}$$

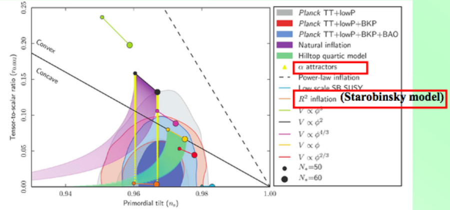


Fig. 54. Marginalized joint 68 % and 95 % CL regions for n_s and $r_{0.002}$ from *Planck* alone and in combination with its cross-correlation with BICEP2/Keck Array and/or BAO data compared with the theoretical predictions of selected inflationary models.

Attractor models like Starobinsky model fit the data well.

Planck 2015 results. XX

Scalar Field with Slow-roll

Single Scalar Field: Slow Roll Inflation Scenario

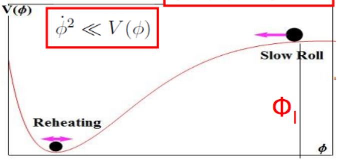
- **Slow Roll Inflation**

Slow Roll $\{\epsilon,\ |\eta|,\ \zeta^2\} \ll 1$

$$\epsilon(\phi) = \frac{M_P^2}{2}\left(\frac{V'}{V}\right)^2$$

$$\eta(\phi) = M_P^2\left(\frac{V''}{V}\right)$$

$$\zeta^2(\phi) = M_P^4\left(\frac{V'V'''}{V^2}\right)$$



- **e-folds:**

$$N = \frac{1}{M_P^2}\int_{\phi_E}^{\phi_I}\left(\frac{V}{V'}\right)\mathrm{d}\phi$$

$N \simeq 60$ To solve the horizon problem

- **Observables**

$$r = 16\epsilon$$

$$n_s = 1 - 6\epsilon + 2\eta$$

$$\alpha = \frac{\mathrm{d}n_s}{\mathrm{d}\ln k} = 16\epsilon - 24\epsilon^2 - 2\zeta$$

$$\Delta_{\mathcal{R}}^2 = \frac{1}{24\pi^2}\frac{1}{M_P^4}\frac{V}{\epsilon}\Big|_{k_0=0.002\ \mathrm{Mpc}^{-1}}$$

Planck 2015 Measurements

$$r \leq 0.11$$

$$n_s \simeq 0.9655 \pm 0.0062$$

$$\alpha = -0.0057 \pm 0.0071$$

$$\Delta_{\mathcal{R}}^2 = 2.195 \times 10^{-9}$$

Non-minimally Coupled Inflaton

Non-minimal Quartic Inflation: simple & successful scenario

Action in Jordan Frame

See, for example,
NO, Rehman & Shafi, PRD 82 (2010) 04352

$$\mathcal{S}_J = \int d^4x\sqrt{-g}\left[-\frac{1}{2}f(\phi)\mathcal{R} + \frac{1}{2}g^{\mu\nu}\left(\partial_\mu\phi\right)\left(\partial_\nu\phi\right) - V_J(\phi)\right],$$

- Non-minimal gravitational coupling

$f(\phi) = (1+\xi\phi^2)$ with a real parameter $\xi > 0$,

- Quartic coupling dominates during inflation

$$V_J(\phi) = \frac{1}{4}\lambda\phi^4$$

3

ϕ can be the Standard Model Higgs field or any other scalar field.
Slides (N Okada).

- Only one free parameter ξ decides the scenario.
- CMB can be satisfied as long as $\xi \geq O(10^{-2})$.
- No direct sensitivity to particle model-building and laboratory observables as any scalar with such a potential can be the inflaton.

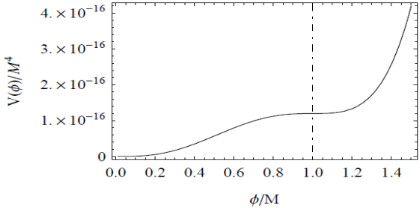
Q: Can we have a scenario be one-to-correspondence between particle properties like coupling & mass and CMB values ? Or else, lots of degeneracies in cosmology. In the similar spirit as DM relic density, or the baryon asymmetry particle physics models ?

Inflection-point Inflation

- Inflection-point Inflation is a small-field ($\phi_I \leq M_{pl}$) inflationary scenario where the scalar field potential is expanded around a point-of-ínflection M in its plane.
- Conditions for inflection-point: $V'(\phi_I) \simeq 0..$ $V''(\phi_I) \simeq 0..$

- Potential expansion around the inflection-point

$$V(\phi) \simeq V_0 + V_1(\phi - M) + \frac{V_2}{2}(\phi - M)^2 + \frac{V_3}{6}(\phi - M)^3$$



M = ϕ_I

Idea is to make the cubic term dominate in the potential !

Inflection-point Analysis for PLANCK Data

$U(1)_{B\text{-}L}$ Model

- Minimal Gauged B-L(Baryon-Lepton) Extension of Standard Model
  - Gauge Anomaly Free: 3 generation of right handed Neutrinos (N_i).
  - B-L Higgs Field : Breaks B-L gauge symmetry.
  - B-L Symmetry Breaking: Generates Z' boson mass and Majorana mass for N_i.

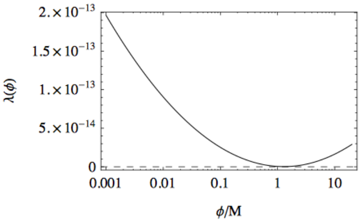
$$\mathcal{L} \supset -\frac{1}{2}\sum_{i=1}^{3} Y \varphi \overline{N^c} N + \text{h.c.}$$

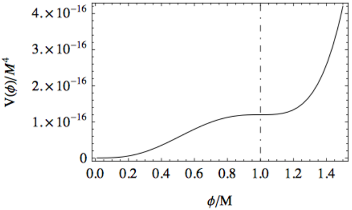
	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)_{B-L}$
q_L^i	3	2	$+1/6$	$+1/3$
u_R^i	3	1	$+2/3$	$+1/3$
d_R^i	3	1	$-1/3$	$+1/3$
ℓ_L^i	1	2	$-1/2$	-1
NR^i	1	1	0	-1
e_R^i	1	1	-1	-1
H	1	2	$-1/2$	0
φ	1	1	0	$+2$

  - See-Saw Mechanism
  - Mass Spectrum : $m_{NR} = \frac{1}{\sqrt{2}} Y_N v_{BL},\ m_{Z'} = 2 g v_{BL},\ m_\phi^2 = 2\lambda v_{BL}^2$

Inflection-point Analysis for PLANCK Data

As the quartic reaches the very small value to satisfy the CMB constraint, due the inflection-point conditions imposed from the Yukawa and gauge coupling cancelling each other, the flattened inflationary potential is generated.





- Gauge coupling and Yukawa coupling cancel each other and creates the inflection-point.
- Logarithimic-corrected RGE-improved Higgs potential responsible for cosmic inflation.
- Laboratory phenomenology for the particle model becomes very predictive.

Ghoshal (2021).

Inflection-point Analysis for PLANCK Data

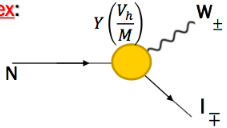
Collider Z' Phenomenology

- Z' boson direct search : $pp \to Z' + X \to \ell^+ \ell^- + X$

- Heavy Neutrino search via displaced vertex:

$$Z' \to N\ N$$

$$N \to W^{\pm} + l^{\mp}$$



The partial decay width of heavy neutrinos is suppressed by See-Saw mechanism.

$$\Gamma_N \sim Y^2 \left(\frac{V_h}{M}\right)^2 M \sim \frac{m_D{}^2}{M} \sim m_\nu$$

- Kinematic Constraint:

$$m_{Z'}{}^2 > 4\, m_N{}^2$$

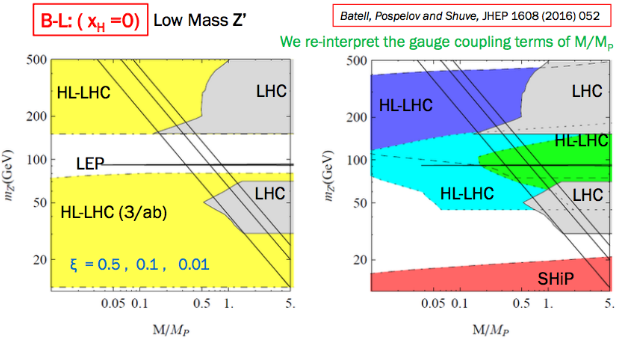
Non-degenerate Yukawa

$$Y_2 = Y_3$$
$$m_{Z'}/m_{N^1} = 3$$
$$\frac{m_{N^{2,3}}}{m_{Z'}} \simeq 0.929$$

Batell, Pospelov and Shuve, JHEP 1608 (2016) 052

Raut slides [Pheno (2017)]

Inflection-point Analysis for PLANCK Data



Raut (2016)

- Constraints on the parameter space from current and future colliders.
- Diagonal lines are for re-heating temperatures 1 MeV for mixing various angles ξ. The region on the right is ruled out due to BBN constraints.
- Inflection-point scale M and Higgs vev are the free parameter of the model; rest are all related via RGE running.

Conclusions:

- UV is connected to the IR via the RGE.
- Complementary probes of BSM models via light dark sector experimental searches and CMB.
- SM Higgs cannot be play such a role as the gauge coupling is too high. But can be done in any dark BSM $U(1)_X$ or $SU(N)_X$ sector.
- For Type-I seesaw neutrino models we showed the collider and CMB complementarity, for freeze-in dark matter.
- Next we are constructing conformal models where radiative symmetry-breaking generates EW scale and Seesaw scale in the IR via Coleman-Weinberg and achieve inflection-point inflation in the UV via RGE.
- Next we are also constructing gauged-free extensions where inflection point is achieved. In this case actual light inflaton hunt is possible via light scalar decay searches. *Old idea by Berzukov & Gorbunov*.
- Plethora of particle physics model-building directions possible now involving dark sector and CMB, now that we have one-to-one correspondence between particle property and CMB.

Generic Inflection-point Condition for SU(N) Theory:

Gauge-Yukawa-Higgs Theory:

$$\beta_g = -\kappa\, g^3 \left(\frac{11}{3} N_c - \frac{1}{6} - \frac{2n_f}{3} \right) ,$$

$$\beta_{\mathbf{Y}} = \kappa \left(\frac{3}{2} \mathbf{Y}\mathbf{Y}^\dagger\mathbf{Y} + \mathbf{Y}\mathrm{tr}(\mathbf{Y}^\dagger\mathbf{Y}) - 3\frac{N_c^2-1}{2N_c} g^2\,\mathbf{Y} \right) ,$$

$$\beta_\lambda = \kappa \left(\frac{3(N_c-1)(N_c^2+2N_c-2)}{4N_c^2} g^4 - 2\,\mathrm{tr}(\mathbf{Y}^\dagger\mathbf{Y}\,\mathbf{Y}^\dagger\mathbf{Y}) - \frac{6(N_c^2-1)}{N_c} \lambda\, g^2 + 4\,\lambda\,\mathrm{tr}(\mathbf{Y}^\dagger\mathbf{Y}) + 4\,(N_c+4)\,\lambda^2 \right) ,$$

$$Y^4 = \frac{3(N_c-1)(N_c^2+2N_c-2)}{8N_c^2} g^4 \,.$$

Thank You