Complementarity Probes between Sky and the Lab via RGE: Gravitational Waves, Higgs Inflation and Light Dark Sector

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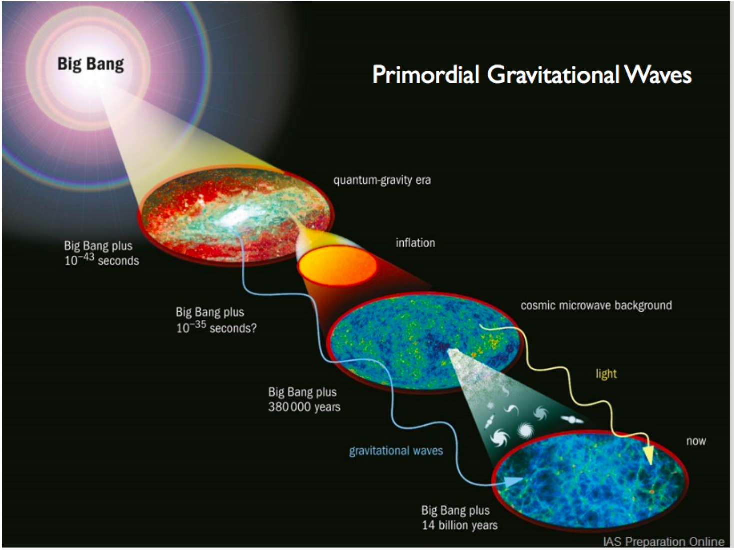
Outline of the talk:

- Ultraviolat (UV) and Infrared (IR)physics is connected via RGE flow.
- 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

History of the Universe



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 :

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

(TT+lowP+lensing)

Theoretical predictions :

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

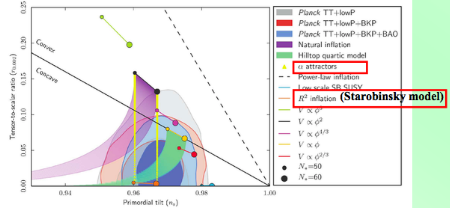


Fig. 54. Marginalized joint 68 % and 95 % CL regions for n_s and $r_{0.002}$ from *Planck* alone and in combination with its cross-correlation with BICEP2/Keck Array and/or BAO data compared with the theoretical predictions of selected inflationary models.

Attractor models like Starobinsky model fit the data well.

Planck 2015 results. XX

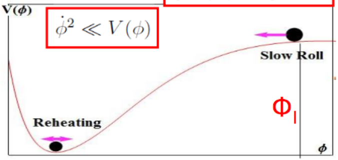
Scalar Field with Slow-roll

Single Scalar Field: Slow Roll Inflation Scenario

- **Slow Roll Inflation**

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

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



- **e-folds:** $$N = \frac{1}{M_P^2}\int_{\phi_E}^{\phi_I}\left(\frac{V}{V'}\right)d\phi$$

$N \simeq 60$

To solve the horizon problem

- **Observables**

$$r = 16\epsilon$$
$$n_s = 1 - 6\epsilon + 2\eta$$
$$\alpha = \frac{dn_s}{d\ln k} = 16\epsilon - 24\epsilon^2 - 2\zeta$$
$$\Delta_{\mathcal{R}}^2 = \frac{1}{24\pi^2}\frac{1}{M_P^4}\frac{V}{\epsilon}\Big|_{k_0=0.002\ \mathrm{Mpc}^{-1}}$$

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).

Non-minimally Coupled Higgs Inflaton

Non-minimal Quartic Inflation: simple & successful scenario

Action in Jordan Frame

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NO, Rehman & Shafi, PRD 82 (2010) 04352

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

Quartic Higgs Inflation

Inflationary Predictions VS Planck 2018 results

ξ	ϕ_0/M_p	ϕ_e/M_p	n_s	r	$\alpha(10^{-4})$	λ
0	22.1	2.83	0.951	0.262	-8.06	1.43×10^{-13}
0.00333	22.00	2.79	0.961	0.1	-7.03	3.79×10^{-13}
0.00642	21.85	2.76	0.963	0.064	-7.50	3.79×10^{-13}
0.0689	18.9	2.30	0.967	0.01	-5.44	6.69×10^{-12}
1	8.52	1.00	0.968	0.00346	-5.25	4.62×10^{-10}
10	2.89	0.337	0.968	0.00301	-5.24	4.01×10^{-8}

- 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.

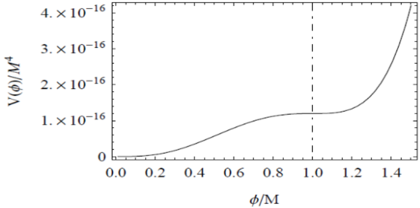
Q: Can we have a scenario be one-to-correspondence between particle properties like coupling & mass and CMB values ? Or else, lots of degeneracies in cosmology. In the similar spirit as DM relic density, or the baryon asymmetry particle physics models ?

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**

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



$M = \phi_I$

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

Inflection-point Analysis for PLANCK Data

- **Summary** of Inflection-point inflation analysis:

Constraint on Potential to satisfy Planck 2015 inflationary measurements

$$\frac{V_1}{M^3} \simeq 1961 \left(\frac{M}{M_P}\right)^3 \left(\frac{V_0}{M^4}\right)^{3/2},$$
$$\frac{V_2}{M^2} \simeq -1.725 \times 10^{-2} \left(\frac{M}{M_P}\right)^2 \left(\frac{V0}{M^4}\right)$$
$$\frac{V_3}{M} \simeq 6.989 \times 10^{-7} \left(\frac{M}{M_P}\right) V_0^{1/2}$$

$M = \phi_I$

N = 60 ; n_s = 0.9655

r = 0.11 ; $\Delta_R^2 = 2.195 * 10^{-9}$

Free Parameters:

V_0 , M

- **Model-independent Prediction** for the Running of the Spectral Index

$$\alpha \simeq -2\zeta^2(M) = -\,2.742 \times 10^{-3} \left(\frac{60}{N}\right)^2$$

Planck 2015

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

- The future experiments can reduce the error to ±0.002.

(*Abazajian et. al. , arXiv:1309.5381*)

- Hence this prediction can be tested in the future.

BSM Model

With such an analysis in hand, let us now ask the following:

- We stick to quartic potential (only re-normalizable term in QFT sense).
- Can the SM Higgs play such a role ?
- Can in any BSM Higgs motivated from neutrino, dark matter, axion or flavor models play such a role ?
- Will there be complementarity between CMB & Laboratory observables ?

We start with a very generic $U(1)_X$ quartic Higgs potenial.

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.

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

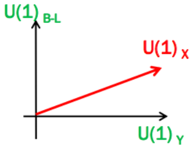
	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)_{B-L}$
q_L^i	3	2	$+1/6$	$+1/3$
u_R^i	3	1	$+2/3$	$+1/3$
d_R^i	3	1	$-1/3$	$+1/3$
ℓ_L^i	1	2	$-1/2$	-1
NR^i	1	1	0	-1
e_R^i	1	1	-1	-1
H	1	2	$-1/2$	0
φ	1	1	0	$+2$

- 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

$U(1)_X$ Model $SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_X$

- Generalization of the minimal B-L model.
- $U(1)_X$ is defined as a linear combination of $U(1)_Y$ and $U(1)_{B-L}$.



	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)_X = Q_Y x_H + Q_{B-L} x_\Phi$
q_L^i	3	2	1/6	$(1/6)x_H + (1/3)x_\Phi$
u_R^i	3	1	2/3	$(2/3)x_H + (1/3)x_\Phi$
d_R^i	3	1	−1/3	$(-1/3)x_H + (1/3)x_\Phi$
ℓ_L^i	1	2	−1/2	$(-1/2)x_H - x_\Phi$
e_R^i	1	1	−1	$(-1)x_H - x_\Phi$
H	1	2	−1/2	$(-1/2)x_H$
N_R^i	1	1	0	$-x_\Phi$
Φ	1	1	0	$+2x_\Phi$

Parameterization

$x_\Phi = 1$

x_H (Free)

B-L limit: $x_H = 0$

$U(1)_Y$ limit: $x_H \rightarrow \infty$

Inflection-point Analysis for PLANCK Data

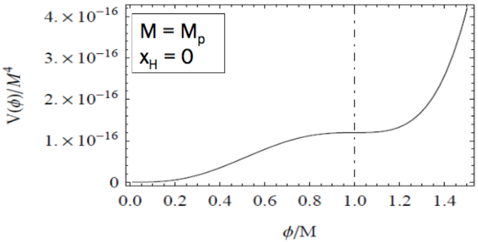
$U(1)_X$ Higgs/Inflaton Potential

- RG improved $U(1)_X$ Higgs/Inflaton potential: $V(\phi) = \frac{1}{4}\,\lambda_\Phi(\phi)\,\phi^4$

Constraint on $U(1)_X$ couplings for a successful inflection-point inflation

$$\lambda_\Phi(M) \simeq 4.770 \times 10^{-16} \left(\frac{M}{M_P}\right)^2, \qquad \boxed{Y(M) \simeq 32^{1/4} g_X(M)}$$

$$g_X(M, x_H) \simeq \frac{1.511 \times 10^{-2}}{(93 + 256 x_H + 164 x_H{}^2)^{1/6}} \left(\frac{M}{M_P}\right)^{1/3}.$$



Free Parameters:

x_H , M

Expanding the potential:

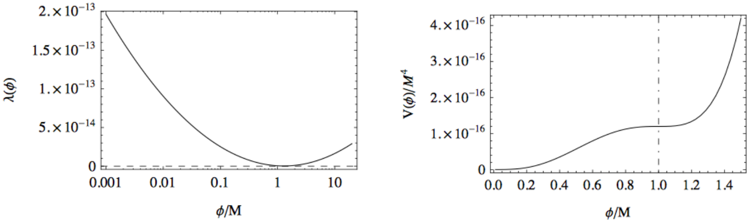
$$\frac{V_1}{M^3} = \frac{1}{4}(4\lambda_\phi + \beta_{\lambda_\phi}),$$
$$\frac{V_2}{M^2} = \frac{1}{4}(12\lambda_\phi + 7\beta_{\lambda_\phi} + M\beta'_{\lambda_\phi}),$$
$$\frac{V_3}{M} = \frac{1}{4}(24\lambda_\phi + 26\beta_{\lambda_\phi} + 10M\beta'_{\lambda_\phi} + M^2\beta''_{\lambda_\phi}),$$

$$\beta_\lambda = \frac{1}{16\pi^2}\left(20\lambda^2 - (48g^2 - 6Y^2)\lambda + 96g^4 - 3Y^4\right)$$

- Simplified assumptions taken: Yukawa degenracy.
- Gauge coupling and Yukawa coupling cancel each other and creates the inflection-point.
- Gauge and Yukawa couplings themselves do not run so much.
- Logarithimic-corrected RGE-improved Higgs potential responsible for cosmic inflation.

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.



- Inflation basically imposes boundary conditions on particle physics model.
- Similar to the MPP principle (Nielsen & Froggart) for the Higgs.
- Small gauge coupling required. Cannot be done with the SM Higgs. But any dark sector works.
- Laboratory phenomenology for the particle model becomes very predictive.

Ghoshal (2021).

Inflection-point Analysis for PLANCK Data

Constraint on Low Energy Observables

- Low Energy Observables evaluated at VEV

Inflection-point condition leads to a relation between low energy observables!

$$Y \equiv Y_1 = Y_2 = Y_3$$

$$\frac{m_N}{m_{Z'}} \simeq 0.84, \qquad (m_{Z'} > m_N)$$

$$\frac{m_\phi}{m_{Z'}} \simeq 2.911 \times 10^{-6} \left(\frac{M}{M_P}\right)^{2/3} \left(87 + 256 x_H + 164 x_H^2\right)^{1/6} \ln\left[2 g_X \frac{M}{m_{Z'}}\right].$$

$$g_X(M, x_H)$$

- Free Parameters

x_H, M, $m_{Z'}$

Raut slides (2016)

Inflection-point Analysis for PLANCK Data

Decay of Inflaton and Reheating

- Φ decays into the SM particle
- Themalization of decay products recreates Standard Big Bang Scenario.

Reheating Temperature

$$T_R \simeq 0.55 \left(\frac{100}{g_*}\right)^{1/4} \sqrt{\Gamma_\phi M_P}$$

BBN Constraint
T_R > 1 MeV

- Inflaton being very light, it can only decay through SM Higgs coupling

$$V = \lambda_H \left(H^\dagger H - \frac{v_h^2}{2}\right)^2 + \lambda_\Phi \left(\Phi^\dagger \Phi - \frac{v_X^2}{2}\right)^2 + \lambda_{\rm mix} \left(H^\dagger H - \frac{v_h^2}{2}\right)\left(\Phi^\dagger \Phi - \frac{v_X^2}{2}\right)$$

$$\Gamma_\phi(m_\phi, \xi) \simeq \theta^2 \, \Gamma_h(m_\phi)$$

$$m_\phi(x_H, M, m_{Z'})$$

$$\lambda_{mix} = \left(\frac{m_H^2}{v_H \; v_X}\right)\theta$$

Additional Constraint

$$\theta^2 = \left(\frac{m_\phi}{m_H}\right)^2 \xi$$

$$\xi < 1$$

- Free Parameters: ξ, X_H, M, $m_{Z'}$

Raut slides (2016)

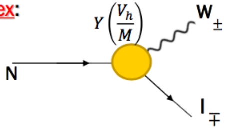
Inflection-point Analysis for PLANCK Data

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

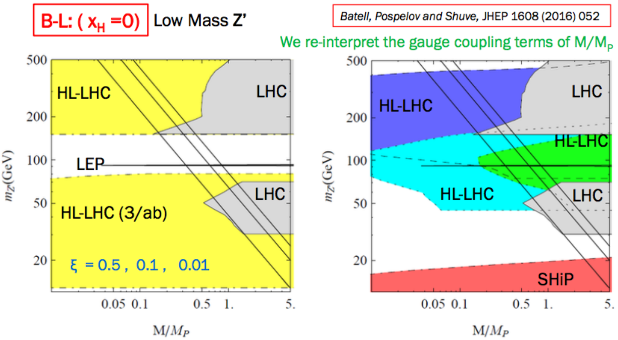
$Y_2 = Y_3$

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

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

Raut slides [Pheno (2017)]

Inflection-point Analysis for PLANCK Data



- 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.

Dark Matter

What about Dark Matter candidate ?

- Condition for inflection-point dictates gauge coupling to be very very small.
- Freeze-in Z'-portal dark matter.

Model Content:

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)_{B-L}$
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
N_R^i	**1**	**1**	0	-1
e_R^i	**1**	**1**	-1	-1
H	**1**	**2**	$-1/2$	0
φ	**1**	**1**	0	$+2$
ζ	**1**	**1**	0	Q

ζ is a dark vector-like fermion is the dark matter candidate.

$$\mathcal{L}_{Z_{BL}} = y_l \bar{L}\tilde{H}N + g_{BL}\,(Z_{BL})_\mu \left[\sum_f (B-L)_f \bar{f}\gamma^\mu f + Q_\zeta \bar{\zeta}\gamma^\mu \zeta\right]$$

Ghoshal (2021)

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d_R^i	**3**	**1**	$-1/3$	$+1/3$
ℓ_L^i	**1**	**2**	$-1/2$	-1
N_R^i	**1**	**1**	0	-1
e_R^i	**1**	**1**	-1	-1
H	**1**	**2**	$-1/2$	0
φ	**1**	**1**	0	$+2$
ζ	**1**	**1**	0	Q

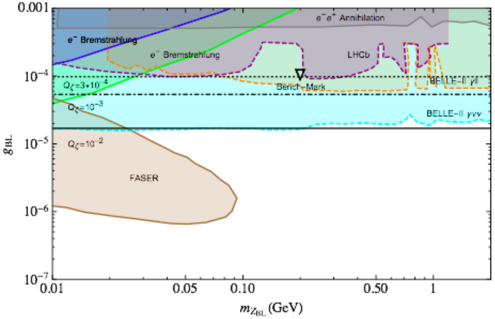
$$\mathcal{L}_{Z_{BL}} = y_l \bar{L}\tilde{H}N + g_{BL}\,(Z_{BL})_\mu \left[\sum_f (B-L)_f \bar{f}\gamma^\mu f + Q_\zeta \bar{\zeta}\gamma^\mu \zeta\right]$$

Dark Matter

Dark Matter Relic Density:

$$\sigma(\bar{\zeta}\zeta \to f\bar{f})\,v \simeq \frac{37}{36\pi s}(Q_\zeta g_{BL})^2 g_{BL}^2,$$
$$\sigma(\bar{\zeta}\zeta \to Z_{BL}Z_{BL})\,v \simeq \frac{(Q_\zeta g_{BL})^4}{4\pi s}\left(\ln\left[\frac{s}{m_\zeta^2}\right]-1\right),$$

Collider Searches:



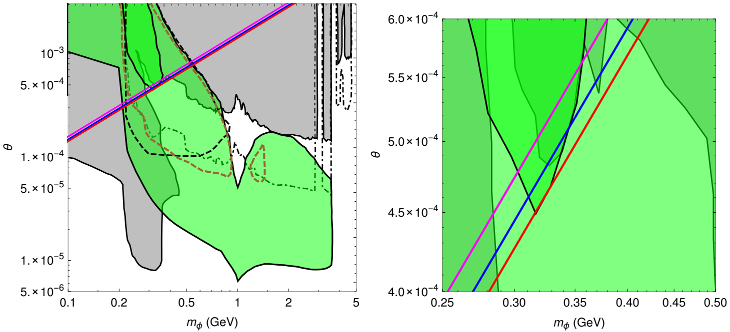
Inflaton Hunt

Inflaton Hunt (no gauge extension: SM + sterile neutrinos)

$$\beta_{\lambda_\phi} = \frac{1}{16\pi^2}\left(12\lambda_\phi y^2 - 6y^4 + 8\lambda_{H\phi}^2 + 20\lambda_\phi^2\right),$$

$$\theta = \frac{1}{2}\tan^{-1}\left(\frac{2\lambda_{H\phi} m_\phi v_h}{\sqrt{2\lambda_\phi}\left(m_h^2 - m_\phi^2\right)}\right)$$

Long Lived Particle Searches:



Conformal Model

We want to construct a conformal model where no scales are present at the tree-level. In the IR, Seesaw Scale and EW Scale is generated via Coleman-Weinberg. Inflection-point Inflation happens in the UV. All determined by the RGE.

$$\mathcal{V}(H,\phi) = \lambda_H |H|^4 - \lambda_{H\phi} |H|^2 |\phi|^2 + \lambda_\phi |\phi|^4.$$

Conformal Model

The Model Content:

The B-L Extended Model

Field	Group	Coupling
Z_{BL}	$U(1)_{B-L}$	g_{BL}

TABLE I. New gauge sector of the model

Field	Spin	$U(1)_{B-L}$
ϕ	0	2
$\psi_{L,R}$	$\frac{1}{2}$	-1
N_R^i	$\frac{1}{2}$	-1

TABLE II. New scalars and fermions in the model.

$$\mathcal{V}(H,\phi) = \lambda_H |H|^4 - \lambda_{H\phi} |H|^2 |\phi|^2 + \lambda_\phi |\phi|^4.$$

Conformal Model: RGE

RGE:

$$\phi\frac{d\lambda_\phi}{d\phi}=\frac{1}{16\pi^2}\left(20\lambda_\phi^2+96g_{BL}^4-\sum_j Y_j^{low\ 4}+\lambda_\phi\left(2\sum_j Y_j^{low\ 2}-48g_{BL}^2\right)\right),$$

$$\phi\frac{dg_{BL}}{d\phi}=\frac{1}{16\pi^2}\left(12+\frac{4}{3}\right)g_{BL}^3,$$

$$\phi\frac{dY_i^{low}}{d\phi}=\frac{1}{16\pi^2}\left(6g_{BL}^2Y_i^{low}+Y_i^{low}\left(\frac{1}{2}\left(\sum_j Y_j^{low\ 2}+y_L^2+y_R^2\right)-12g_{BL}^2+Y_i^{low\ 2}\right)\right),$$

$$\phi\frac{dy_L}{d\phi}=\frac{1}{16\pi^2}\left(6g_{BL}^2y_L+y_L\left(\frac{1}{2}\left(\sum_j Y_j^{low\ 2}+y_L^2+y_R^2\right)-12g_{BL}^2+y_L^2\right)\right),$$

$$\phi\frac{dy_R}{d\phi}=\frac{1}{16\pi^2}\left(6g_{BL}^2y_R+y_R\left(\frac{1}{2}\left(\sum_j Y_j^{low\ 2}+y_L^2+y_R^2\right)-12g_{BL}^2+y_R^2\right)\right),$$

$$\phi\frac{d\lambda_\phi}{d\phi}=\frac{1}{16\pi^2}\left(20\lambda_\phi^2+96g_{BL}^4-\left(\sum_j Y_j^{low\ 4}+y_L^4+y_R^4\right)+\lambda_\phi\left(2\sum_j Y_j^{low\ 2}+2y_L^2+2y_R^2-48g_{BL}^2\right)\right)(14)$$

Conformal Model

RGE:

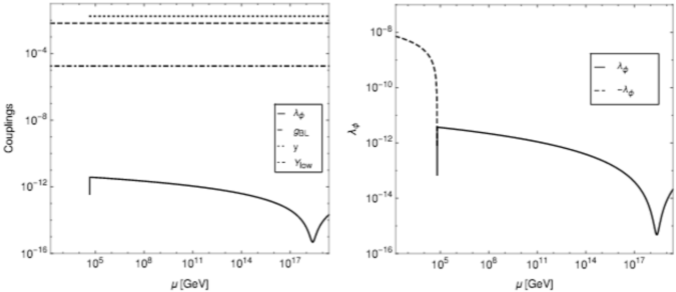


FIG. 2. ***Left Panel:*** *RG running of all the couplings for the benchmark point (M = 1 M_P, $\mu_T = 44.85$ TeV) against μ.* ***Right Panel:*** *RG running of λ_ϕ against μ. Note the abrupt drop of λ_ϕ to negative value at the threshold. We have chosen negligible $Y^{low} = 10^{-3}y$ for this work.*

Conformal Model

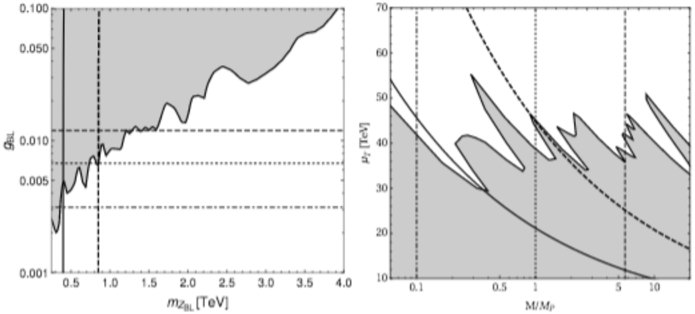


FIG. 4. ***Left Panel:*** *The diagonal jagged solid line is the upper bound on the B-L gauge coupling as a function of Z_{BL} mass, from the ATLAS final result [84] (ATLAS-CONF-2019-001). The horizontal lines correspond to the inflection-point scale $M = 5.67\ M_P$ (dashed), M_P (dotted) and $0.1\ M_P$ (dot-dashed) respectively* [6]*. This corresponds to $m_{Z_{BL}}$ lower bounds to be 1.64 TeV, 850 GeV and 360 GeV, respectively. The vertical solid line and the vertical thick dashed line correspond to $m_{Z_{BL}} = 3 \times 133$ and 850 GeV respectively, the lower limit for theoretical consistency*

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.
- We showed 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.
- We showed how to construct 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:

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

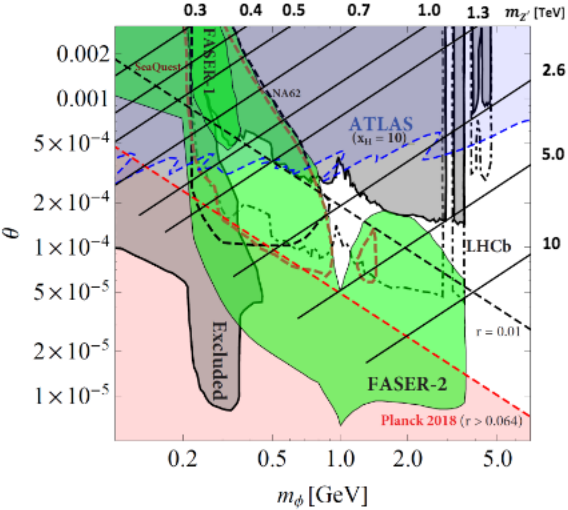
$$\beta_{\mathbf{Y}} = \kappa \left(\frac{3}{2} \mathbf{Y}\,\mathbf{Y}^\dagger \mathbf{Y} + \mathbf{Y}\mathrm{tr}(\mathbf{Y}^\dagger \mathbf{Y}) - 3\frac{N_c^2 - 1}{2N_c} g^2\, \mathbf{Y} \right) ,$$

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

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

Names of experiments

Dark Matter Relic Density:



Thank You