SCALAR SINGLET DARK MATTER EFFECTS ON HIGGS BOSON DRIVEN INFLATION

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OUTLINE

- **Introduce large non-minimal coupling of Higgs-doublet to Ricci scalar curvature; allows identification of standard model Higgs field as inflaton**

- **Model non-baryonic dark matter as standard model singlet hermitian scalar field**

- **Construct renormalization group improved effective potential for Higgs-inflaton scalar including effects of scalar dark matter**

- **Analyze slow roll inflation cosmological constraints on Higgs boson-scalar dark matter parameter space**

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Higgs Field as Inflaton

- Slow roll cosmological inflation generally implemented by inclusion of additional, independent inflaton degree of freedom.

- Identification of standard model Higgs boson as inflaton stymied by required flatness of the inflaton potential as dictated by size of observed density fluctuations, i.e. necessitates far too small a quartic self coupling for the inflaton to be identified with Higgs scalar.

- Include non-minimal coupling of Higgs doublet $H = \frac{1}{\sqrt{2}} \begin{pmatrix} \chi^+ \\ (v+h) + \chi^0 \end{pmatrix}$ to the gravitational Ricci scalar curvature R

$$\Gamma_{\xi - SM} = \int d^4x \sqrt{-g}[\Lambda + \frac{1}{2}m_{Pl}^2 R + (D_\mu H)^\dagger g^{\mu\nu} D_\nu H - \lambda(H^\dagger H - \frac{v^2}{2})^2 + \xi R(H^\dagger H - \frac{v^2}{2}) + ...]$$

- During inflationary phase physical Higgs-inflaton field has large expectation value: $h \sim m_{Pl}/\sqrt{\xi} >> v$

- Eliminate h dependence in non-minimal coupling by rescaling metric tensor $g_{\mu\nu} \rightarrow (1 + \frac{1}{2}\frac{\xi h^2}{m_{Pl}^2}) g_{\mu\nu}$

- Resultant Higgs field classical potential $\frac{\lambda h^4}{4} \frac{1}{(1 + \frac{\xi h^2}{2m_{Pl}^2})^2} \sim \frac{\lambda m_{Pl}^4}{\xi^2}$ is flat for $\frac{\xi h^2}{m_{Pl}^2} >> 1$

- Can accommodate observed amplitude of density fluctuations with $\xi \sim 10^3 - 10^4$

- Identification of Higgs boson as inflaton is viable

- Inclusion of radiative corrections provides cosmologically acceptable range of Higgs boson masses.

Scalar Singlet Dark Matter

- Existence of non-baryonic dark matter requires additional degrees of freedom beyond those appearing in the standard model.

- Minimal extension of standard model which accounts for primordial abundance of dark matter is by inclusion of singlet hermitian scalar field S

- Standard model including non-minimal coupling plus singlet dark matter

$$\Gamma_{\xi-SM-DM} = \Gamma_{\xi-SM} + \int d^4x\sqrt{-g}[\frac{1}{2}\partial_\mu S g^{\mu\nu}\partial_\nu S - \frac{1}{2}m_S^2 S^2 - \frac{\lambda_S}{4}S^4 - \kappa S^2(H^\dagger H - \frac{v^2}{2}) + \frac{1}{2}\xi_S R S^2]$$

- Scalar odd under unbroken Z_2 symmetry: insures its stability

- For m_S away from $m_h/2$, either heavier or lighter, identification of S with dark matter favors $\kappa > \mathcal{O}(0.1)$ and is insensitive to λ_S

- Potential invisible decay mode of Higgs boson to scalar pairs;

rate comparable to standard model Higgs total decay rate for $\kappa > \mathcal{O}(0.1)$

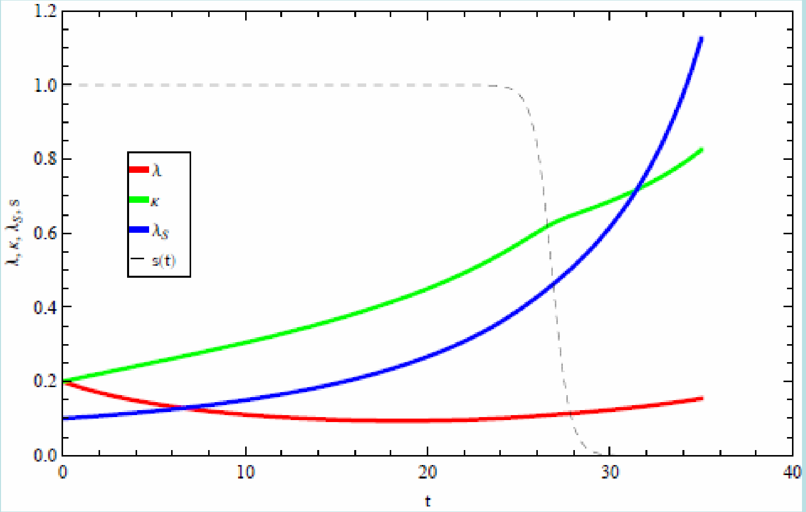
Action modified by inclusion of radiative corrections

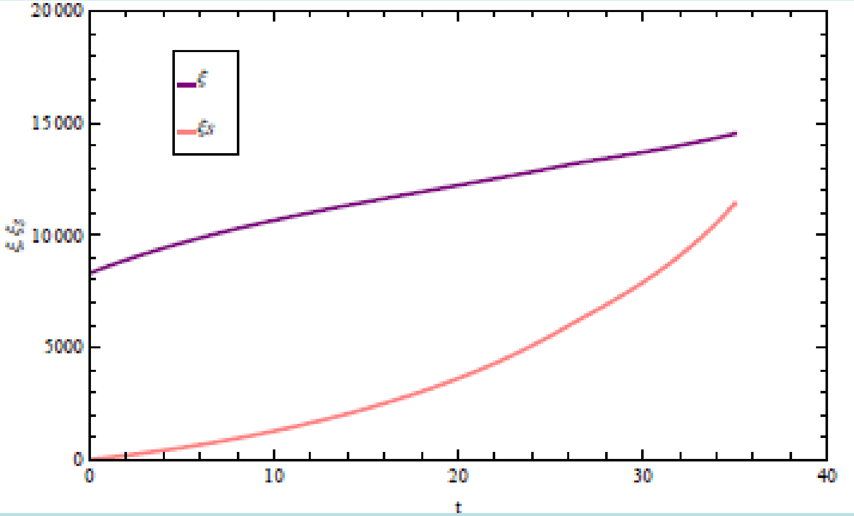
- Mixing of Higgs field with gravity leads to non-canonical Higgs field propagator $1/p^2 \to s(h)/p^2$ with modification factor $s(h) = \frac{1+\xi h^2/m_{Pl}^2}{1+(1+6\xi)\xi h^2/m_{Pl}^2}$
- Note that $s(h) \to 1$ when $\frac{\xi h^2}{m_{Pl}^2} << 1$ while $s(h) \to \frac{1}{6\xi}$ when $\frac{\xi h^2}{m_{Pl}^2} >> 1$
- Internal Higgs field propagation suppressed for large inflationary backgrounds $\frac{\xi h^2}{m_{Pl}^2} >> 1$ and large ξ
- Renormalization group functions and improved effective action can be computed using modified propagator for physical Higgs field.
- Cosmological quantities can most readily calculated in the Einstein frame where non-minimal coupling of h is transformed away
- Einstein frame effective potential for Higgs-inflaton: $V_E = \frac{m_{Pl}^4}{4}\frac{\lambda(t)}{\xi^2(t)}\frac{\psi^4(t)}{\left(1+\psi^2(t)\right)^2}$

where $\psi^2(t) = \xi(t) e^{-\int_0^t dt' 2\gamma(t')} e^{2t} m_t^2/m_{Pl}^2$; $\gamma(t)$ Higgs field anomalous dimension

Characteristic one-loop running of couplings

Scaling variable $t = ln(h/m_t)$

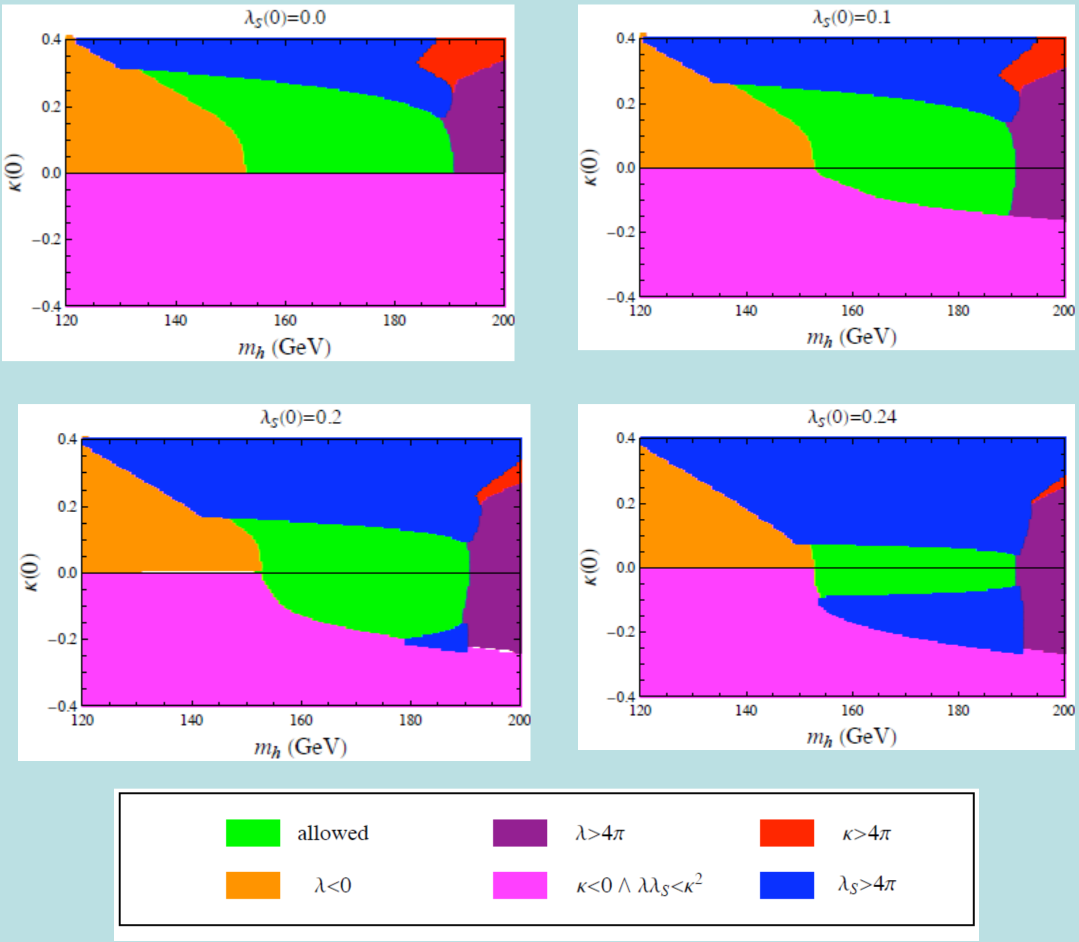




Running couplings where $\kappa(0) = 0.2\ ;\ \xi(0) = 8314.6\ ;\ \xi_S(0) = 0$

Onset of inflation occurs at $t_i = 35$ while exit of inflation is at $t_f = 32.7$

One loop triviality and vacuum stability bounds including the Higgs propagator modification factor



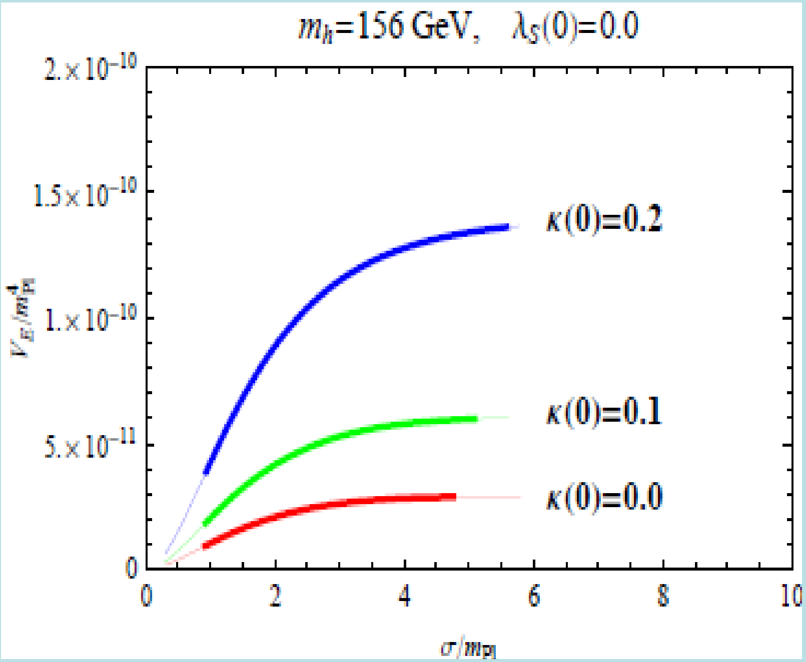
The constraints apply to the scale $t = 34.5$ which is typical of the onset of inflation.

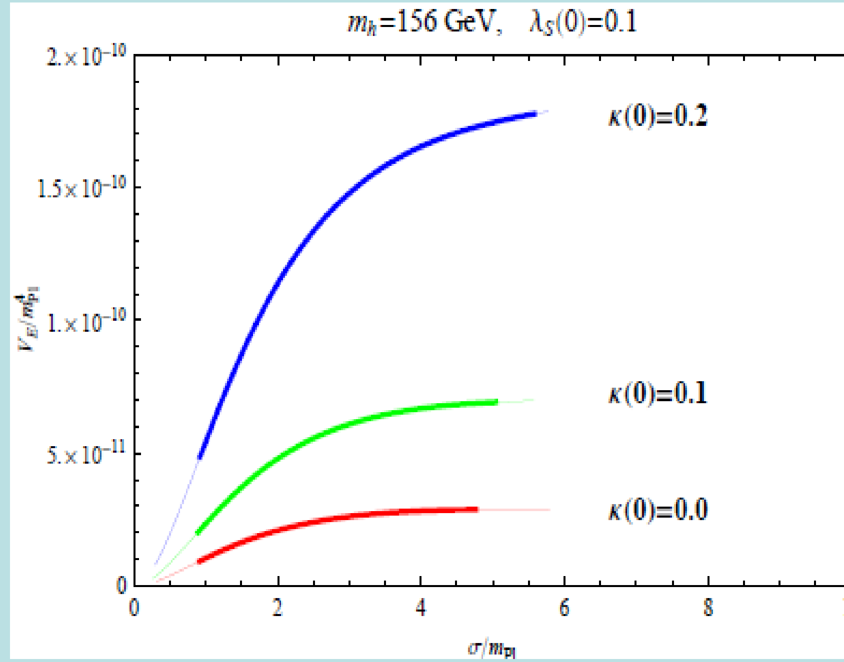
Here we have chosen the initial non-minimal coupling $\xi(0) = 10^4$

Larger $\kappa(0)$ values allow for a smaller allowed m_h

The allowed parameter space vanishes for $\lambda_S(0) > 0.25$

Higgs-inflaton effective potential





Einstein frame renormalization group improved effective potential as function of canonically normalized Higgs-inflaton field σ defined as

$$\left(\frac{d\sigma}{dh}\right)^2 = \frac{e^{-2\int_0^t dt'\gamma(t')}(1+\psi^2(t)) + \frac{3}{2}\frac{m_{Pl}^2}{m_t^2}e^{-2t}\left(\frac{d\psi^2(t)}{dt}\right)^2}{(1+\psi^2(t))^2}$$

with $t = ln(h/m_t)$

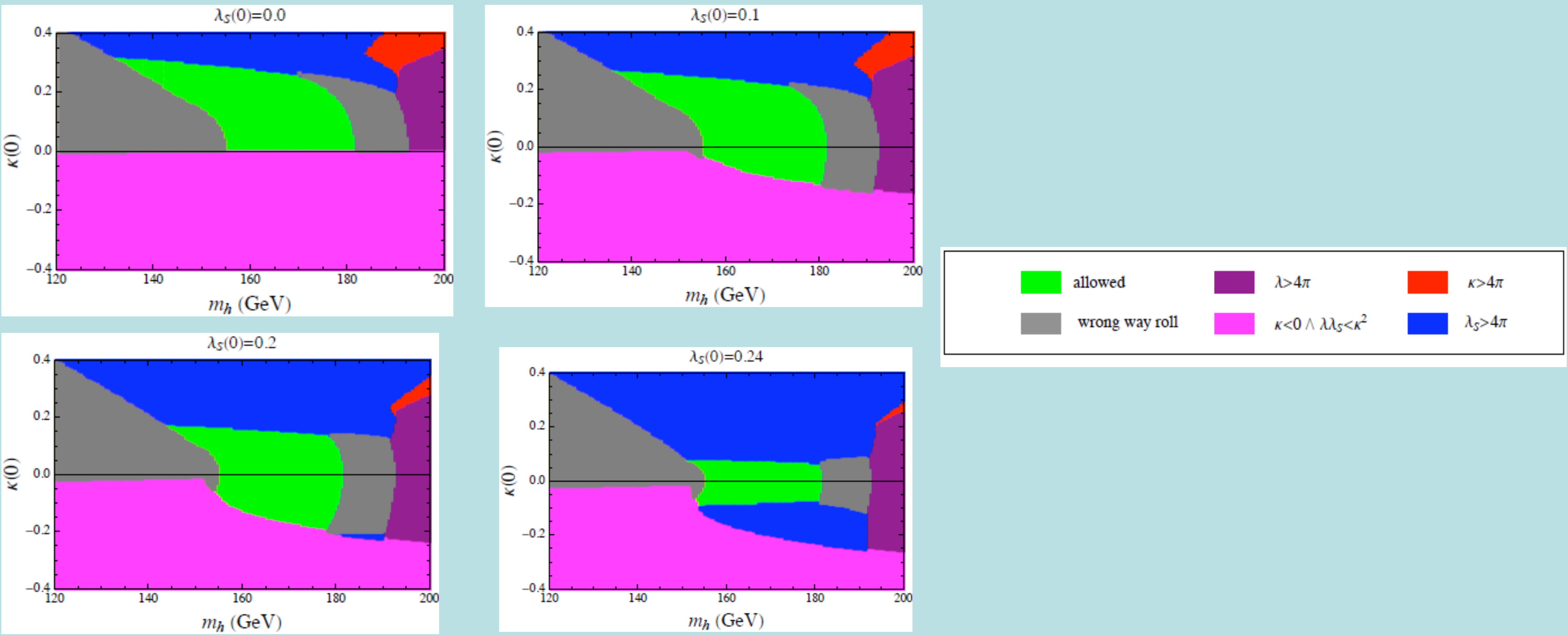
Magnitude and shape varies with strength of Higgs-dark matter coupling κ and dark matter self coupling λ_S .

The thickened portion of the curves corresponds to the 60 e-folds of inflation.

Continuing to larger values σ/m_{Pl} , the one loop effective potential exhibits maximum at some point.

Prevent wrong way rolling

- One-loop effective potential exhibits a maximum at a certain t value.
- Must insure that onset of inflation occurs at t_i less than this value or else rolling occurs the wrong way toward Planck mass and beyond.
- Thus there is region of parameter space allowed by triviality and vacuum stability bounds which is ruled out by wrong way rolling condition



Wrong way rolling constraint applied up to $t = 34.5$ .Result displayed is for $\xi(0) = 10^4$, $\xi_S(0) = 0$
Larger values of $\kappa(0)$ allow for smaller Higgs boson masses.
Allowed parameter space disappears for $\kappa(0) > 0.3$ and $\lambda_S(0) > 0.25$

Slow roll cosmological parameters

Measured cosmological quantities provide additional restriction on allowed model parameter space

- **The various cosmological parameters governing the slow roll inflation secured in terms of derivatives of the effective potential with respect to the physical Higgs field evaluated during the inflationary phase when it has a large expectation value.**

- **Slow roll inflationary parameters**

$$\epsilon = \frac{1}{2}m_{Pl}^2\left(\frac{1}{V_E}\frac{dV_E}{d\sigma}\right)^2$$
$$\eta = m_{Pl}^2\frac{1}{V_E}\frac{d^2V_E}{d\sigma^2}$$
$$\zeta^2 = m_{Pl}^4\frac{1}{V_E}\frac{d^3V_E}{d\sigma^3}\frac{1}{V_E}\frac{dV_E}{d\sigma}$$

Spectrum of density fluctuations: k space

$$P_s(k) = \Delta_{\mathcal{R}}^2\left(\frac{k}{k^*}\right)^{n_s(k)-1}$$

Amplitude of density perturbations

$$\Delta_{\mathcal{R}}^2 = \frac{V_E}{24\pi^2 m_{Pl}^4\epsilon}|_{k^*}$$

combination of WMAP5, BAO and SN data:

$$\Delta_{\mathcal{R}}^2 = (2.445 \pm 0.096) \times 10^{-9} \text{ at } k^* = 0.002 \text{ Mpc}^{-1}$$

- **Slow roll inflation predicts the spectral index , its running and the tensor to scalar ratio,**

$$n_s = 1 - 6\epsilon + 2\eta$$
$$\alpha = dn_s/d\ln k = -24\epsilon^2 + 16\epsilon\eta - 2\zeta^2$$
$$r = 16\epsilon$$

- **WMAP5, BAO and SN:** $n_s = 0.960 \pm 0.013$; $\alpha = -0.028 \pm 0.020$; $r < 0.22$ (95% CL)

Calculational procedure

- Solve RGE with experimental inputs for $m_t = 171.2\ GeV$ $\alpha_1(0) = 0.01027$ $\alpha_2(0) = 0.03344$ $\alpha_3(0) = 0.10864$

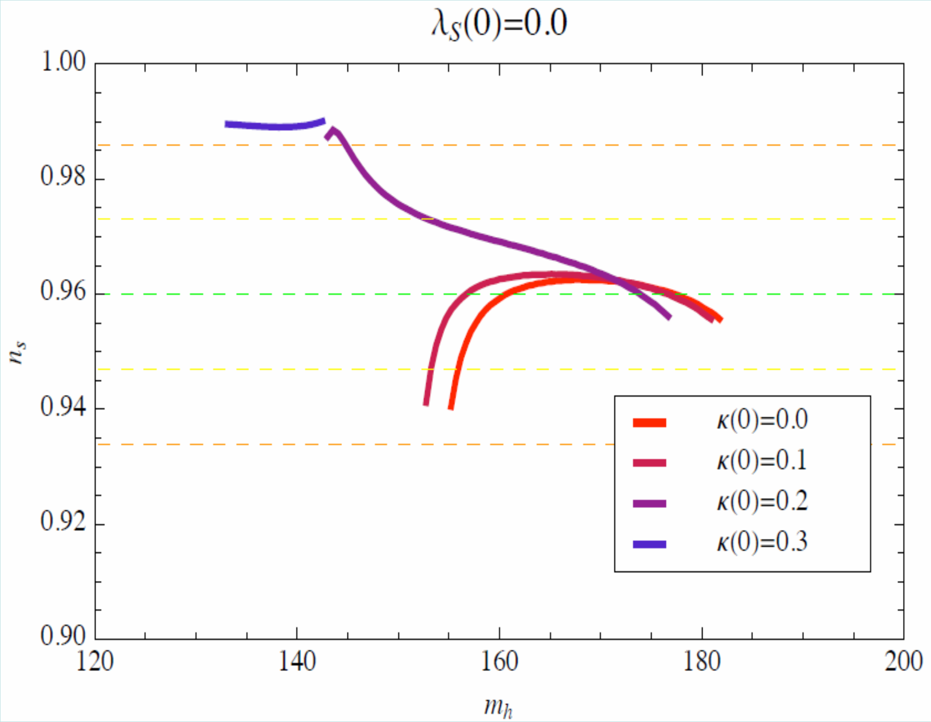
  and using various values for $m_h = \sqrt{2\lambda(0)}v\ ;\ \kappa(0)\ ;\ \lambda_S(0)\ ;\ \xi_S(0)$

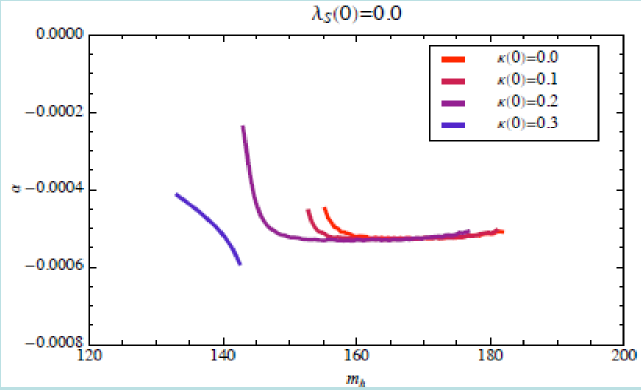
- Measured value of Δ_R^2 fixes $\xi(t_i)$ where t_i is onset of inflation
- Exit of inflation t_f fixed by $\epsilon(t_f) = 1$
- Number of e-folds of inflation between t_i and t_f is $N_e(t_i) = \frac{1}{\sqrt{2}m_{Pl}} \int_{\sigma_i}^{\sigma_f} \frac{d\sigma'}{\sqrt{\epsilon(\sigma')}}$

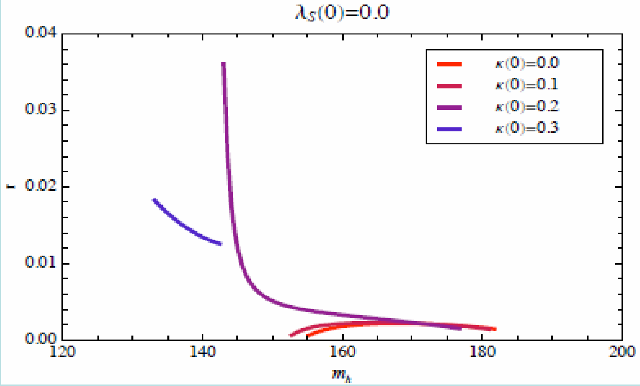
  which is taken as 60 and thus fixes t_i

- Compute the various cosmological parameters which are evaluated at the determined value of the onset of inflation t_i

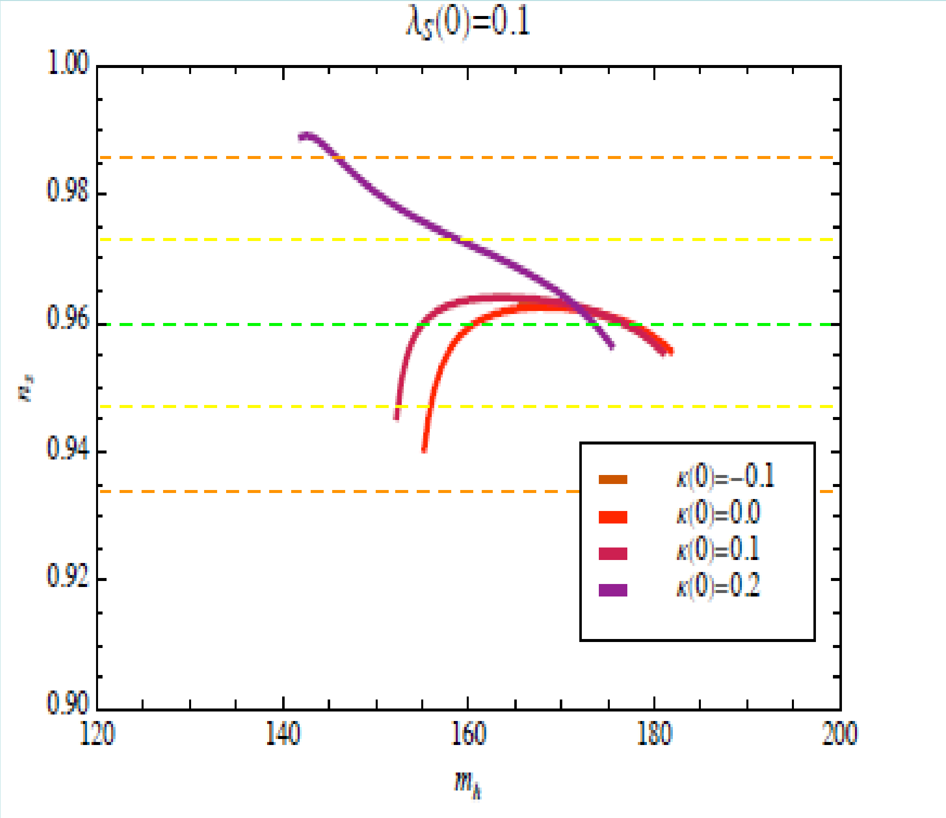
Cosmological restriction of parameter space

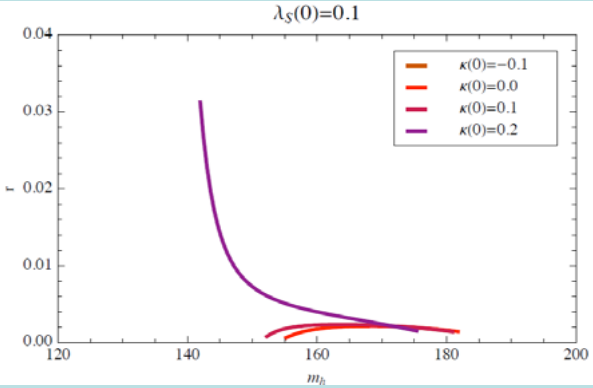


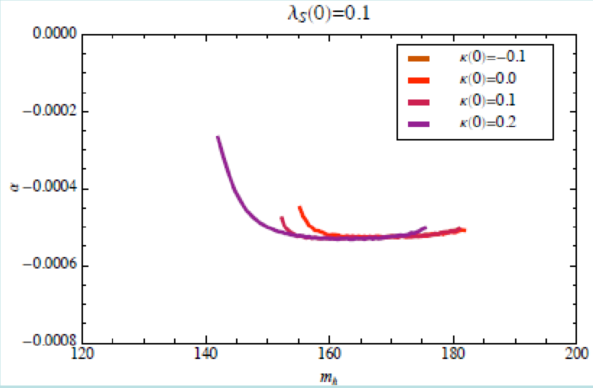




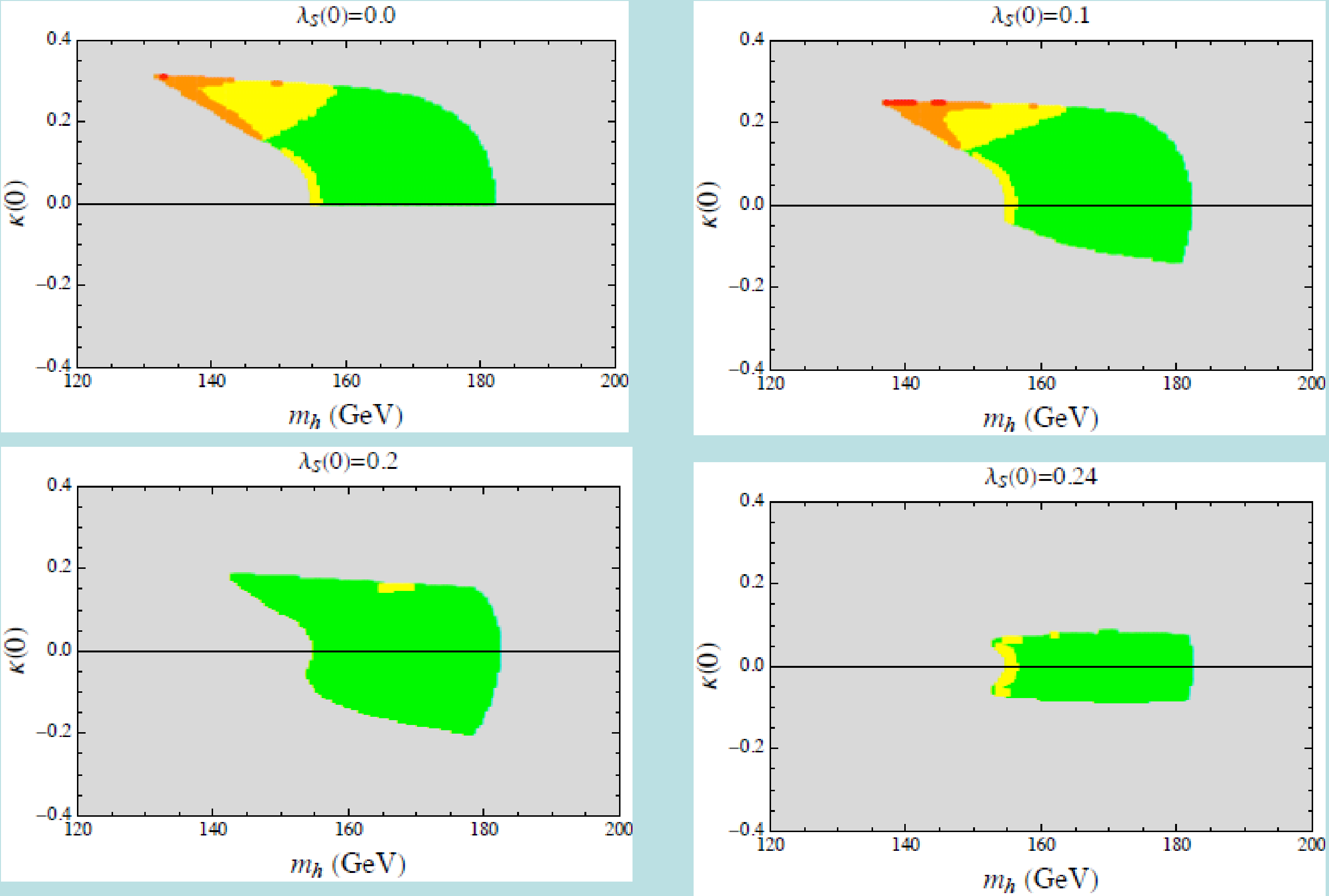
Spectral index, n_s , its running and tensor to scalar ratio as function of Higgs boson mass for various values of the Higgs-dark matter coupling $\kappa(0)$ with vanishing initial singlet self coupling. The green line is the central value $n_s = 0.960$ of measured spectral index. The yellow line is one standard deviation from the central value and the orange line is two standard deviations Curves for α and r lie well below experimental limits. Larger values of $\kappa(0)$ allow for smaller Higgs boson masses.







Spectral index, n_s , its running and tensor to scalar ration as function of Higgs mass for various values Higgs-dark matter coupling $\kappa(0)$ with initial dark matter self coupling $\lambda_S(0) = 0.1$. The green line is the central value $n_s = 0.960$, the yellow line is one standard deviation from the central value and the orange line is two standard deviations. Curves for α and r lie well below experimental limits. Larger values of $\kappa(0)$ allow for smaller Higgs boson masses.



Parameter space constraints arising from spectral index.
Gray area excluded by triviality, vacuum stability and wrong way rolling constraints.
Green regions corresponds to model prediction within one standard deviation of central value $n_s = 0.960$
Yellow regions correspond to model predictions between one and two standard deviations of central value.
Orange regions correspond to model predictions between two and three standard deviations of central value.
Red regions correspond to model predictions of more than three standard deviations from central value.
Allowed parameter space vanishes for $\lambda_S(0) > 0.25$.

Conclusions

- Minimally extended standard model to include a dark matter singlet scalar and a large non-minimal coupling coupling of the Higgs doublet to the Ricci scalar curvature.

- Parameter space includes Higgs boson mass, Higgs boson-dark matter coupling and singlet scalar self coupling and mass.

- In addition to triviality and vacuum stability bounds, parameter space further constrained by slow roll inflation. Must insure inflaton rolls toward origin and not the Planck scale (wrong way roll constraint). Spectral index provides most stringent constraint on remainder of parameter space.

- Larger couplings of the Higgs boson to the dark matter scalar, which are preferred by dark matter abundance calculations, lead to a lower allowed range of Higgs boson masses. For this range of masses, agreement with spectral index measurements between 1-3 standard deviations above current central value.

- For a range of Higgs boson masses which are attainable at the LHC, the model including scalar singlet dark matter is consistent with accelerator limits and the cosmological constraints of slow roll inflation with the Higgs scalar serving as the inflaton.

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Scalar singlet dark matter

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Observational data

G. Hinshaw *et al.* [WMAP Collaboration], Astrophys. J. Suppl. **180**, 225 (2009) [arXiv:0803.0732 [astro-ph]].

Work reported on here

The standard model Higgs boson-inflaton and dark matter, T.E. Clark, B. Liu, S.T. Love and T. ter Veldhuis, arXiv:0906.5595 [hep-ph]

• One loop renormalization group beta functions including Higgs field suppression factor

$$
\begin{aligned}
(4\pi)^2\frac{dg_1}{dt} &= g_1^3\left(\frac{81+s(t)}{12}\right)\\
(4\pi)^2\frac{dg_2}{dt} &= -g_2^3\left(\frac{39-s(t)}{12}\right)\\
(4\pi)^2\frac{dg_3}{dt} &= -7g_3^3\\
(4\pi)^2\frac{dy_t}{dt} &= y_t\left(\left(\frac{23}{6}+\frac{2}{3}s(t)\right)y_t^2-8g_3^2-\frac{17}{12}g_1^2-\frac{9}{4}g_2^2\right)\\
(4\pi)^2\frac{d\lambda}{dt} &= \left((6+18s^2(t))\lambda^2-6y_t^4+\frac{3}{8}\left(2g_2^4+(g_1^2+g_2^2)^2\right)+12y_t^2\lambda-3g_1^2\lambda-9g_2^2\lambda+2\kappa^2\right)\\
(4\pi)^2\frac{d\kappa}{dt} &= \kappa\left(8s(t)\kappa+6(1+s^2(t))\lambda+6\lambda_S+6y_t^2-\frac{3}{2}g_1^2-\frac{9}{2}g_2^2\right)\\
(4\pi)^2\frac{d\lambda_S}{dt} &= 18\ \lambda_S^2+(6+2s^2(t))\ \kappa^2\\
(4\pi)^2\frac{d\xi}{dt} &= \left(\xi+\frac{1}{6}\right)\left(6(1+s^2(t))\lambda+6y_t^2-\frac{3}{2}g_1^2-\frac{9}{2}g_2^2\right)+\left(\xi_S+\frac{1}{6}\right)\ 2\kappa\\
(4\pi)^2\frac{d\xi_S}{dt} &= \left(\xi_S+\frac{1}{6}\right)\ 6\lambda_S+\left(\xi+\frac{1}{6}\right)(6+2s^2(t))\ \kappa
\end{aligned}
$$

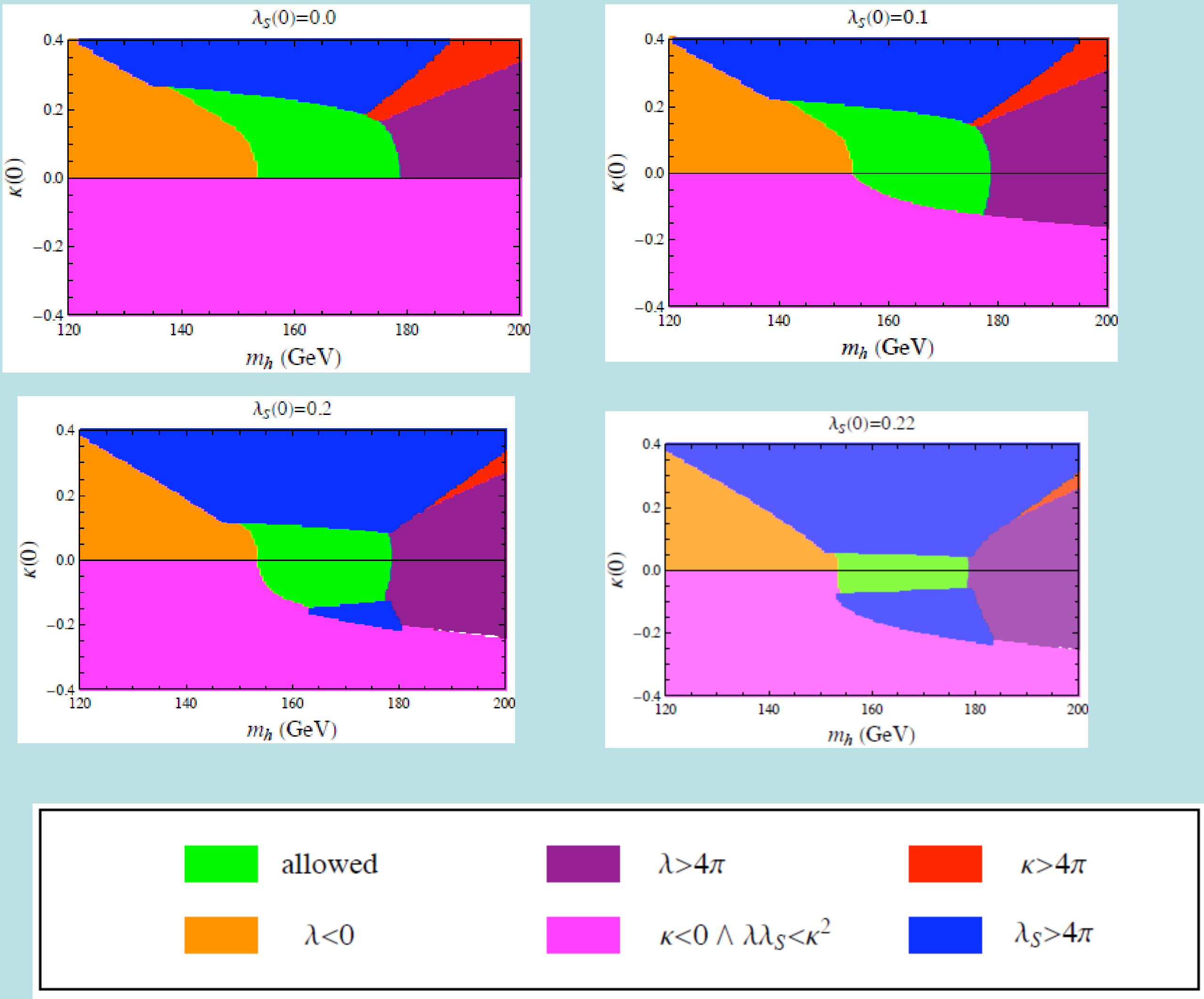
where

$$
s(t)=\frac{1+\xi(t)m_t^2e^{2t}/m_{Pl}^2}{1+(1+6\xi(t))\ \xi(t)m_t^2e^{2t}/m_{Pl}^2}
$$

• One loop Higgs field anomalous dimension (Landau gauge)

$$
(4\pi)^2\gamma=3y_t^2-\frac{3}{4}g_1^2-\frac{9}{4}g_2^2
$$

One loop triviality and vacuum stability bounds: no modification on Higgs boson propagator



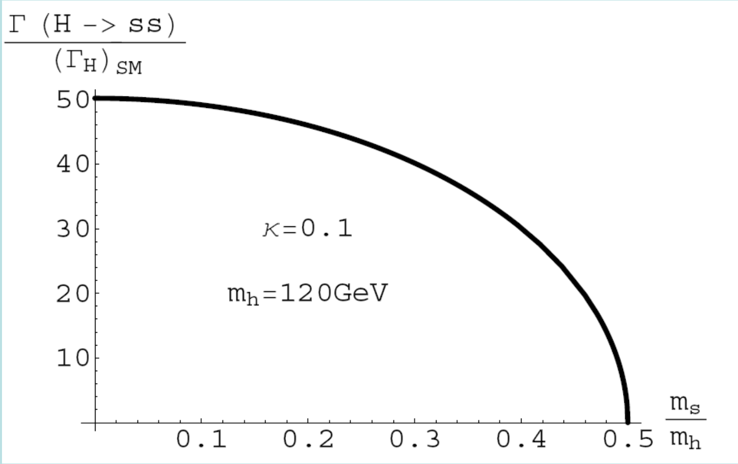
Allowed parameter space vanishes for $\lambda_S(0) > 0.23$

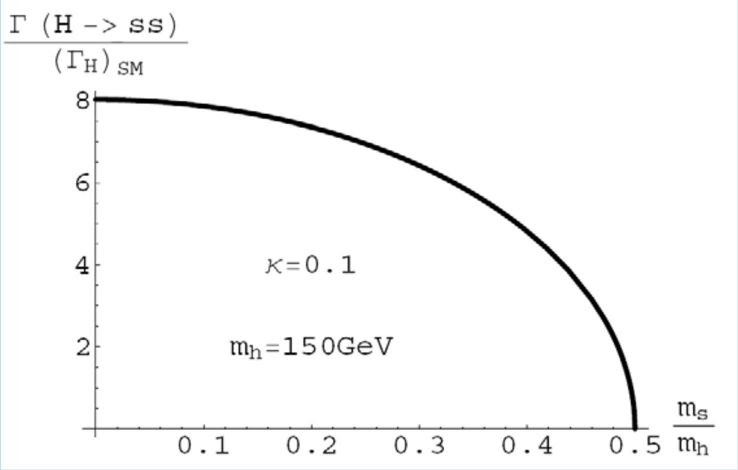
Singlet scalar is stable

Decay of Higgs boson into singlet scalar pairs

Appears as invisible Higgs boson decay

$$\Gamma(H \to SS) = \frac{\kappa^2 v^2}{8\pi m_h}\sqrt{1 - \frac{4m_S^2}{m_h^2}}$$





Decay rate comparable to standard model total decay rate