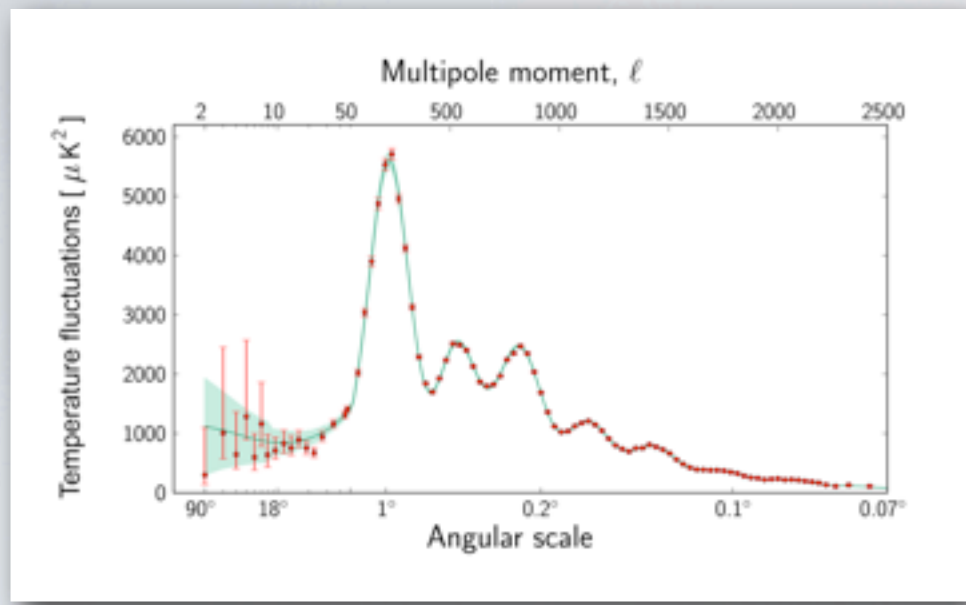
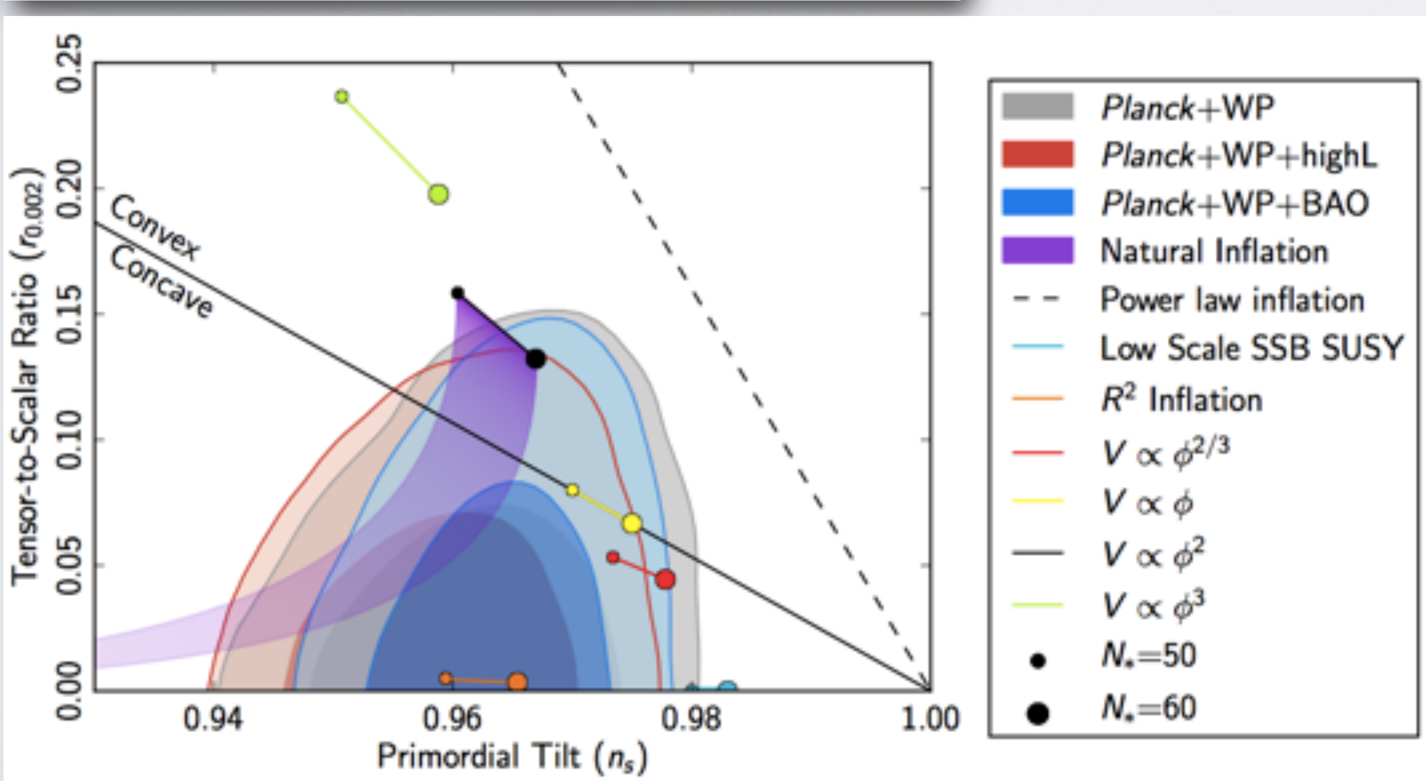
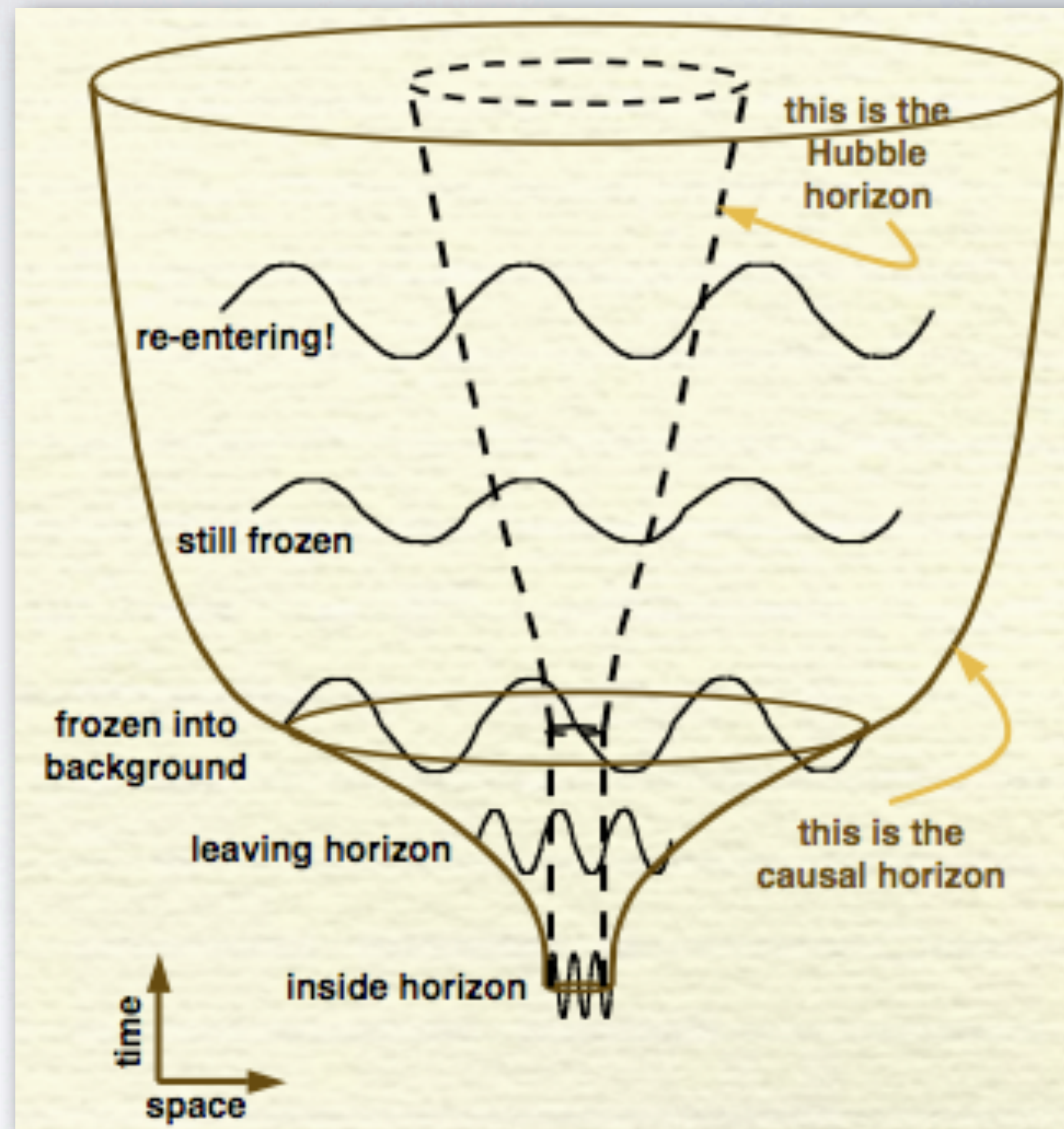
ORIGIN OF INFLATION

ANUPAM MAZUMDAR LANCASTER UNIVERSITY



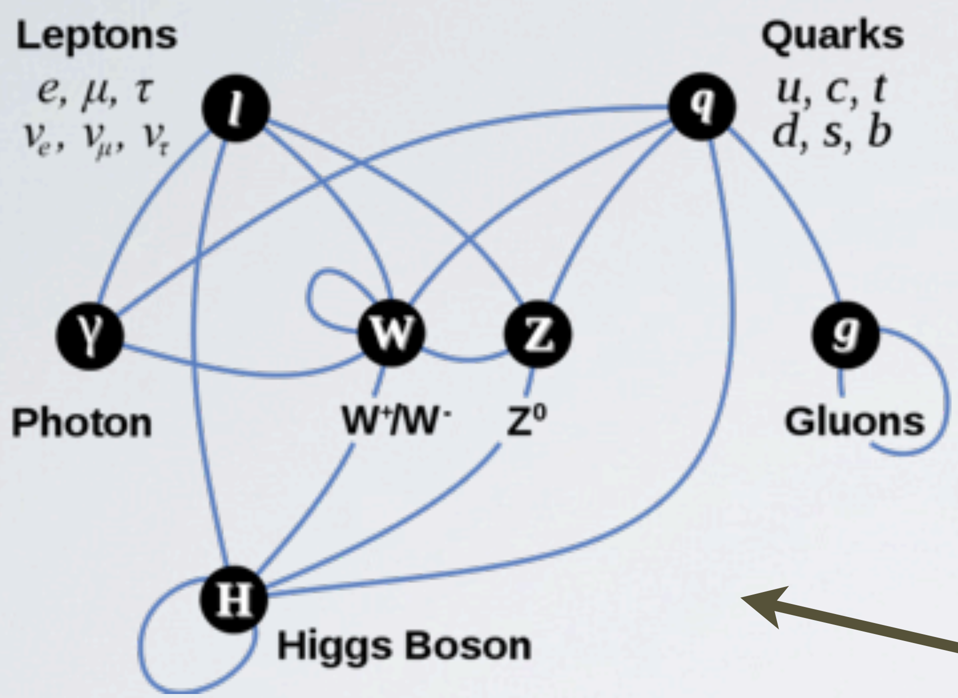




We mostly Concentrate on CMB

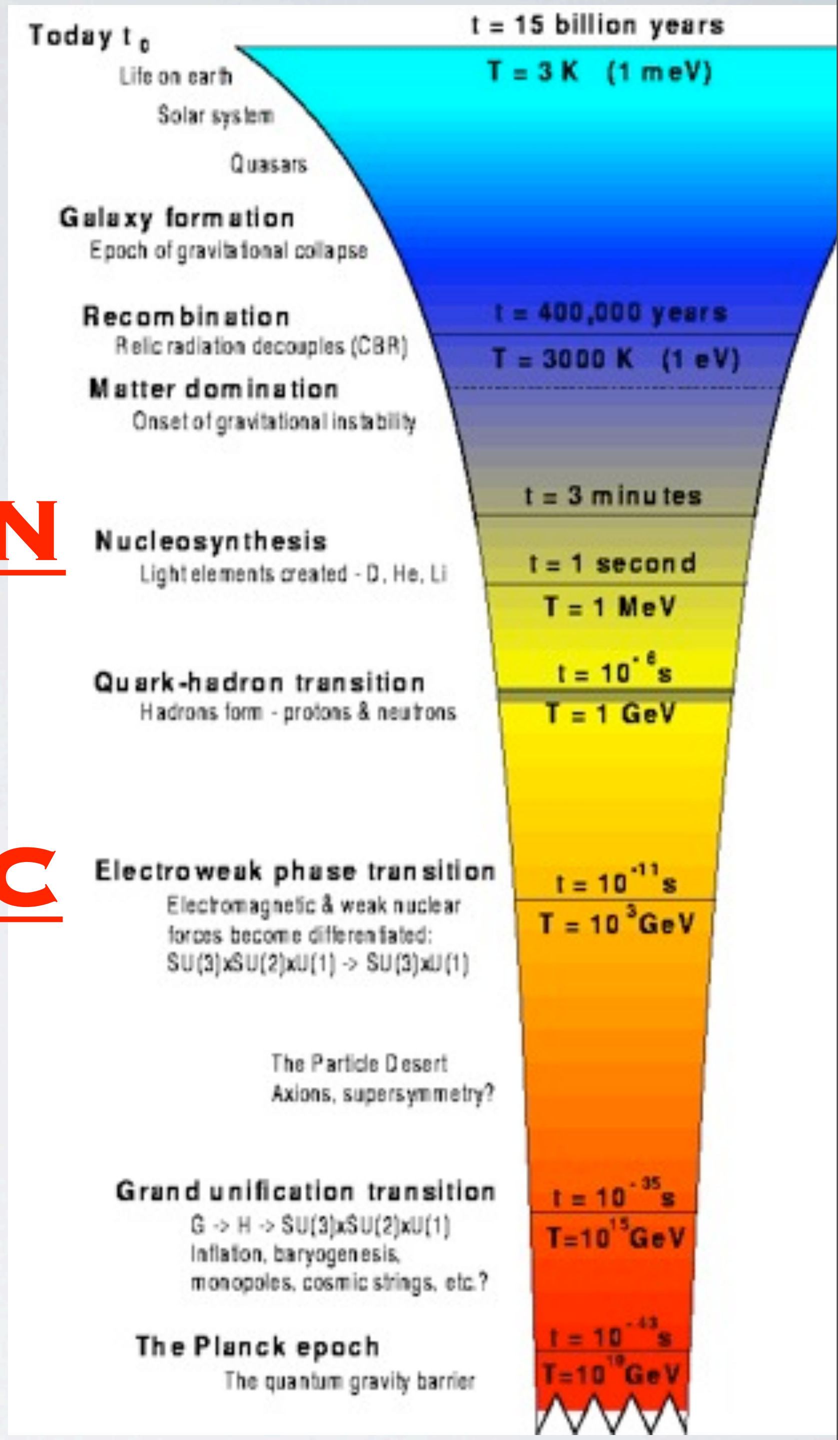
99% of INFLATION papers are HALF complete!!

Confusions/Conclusions



BBN

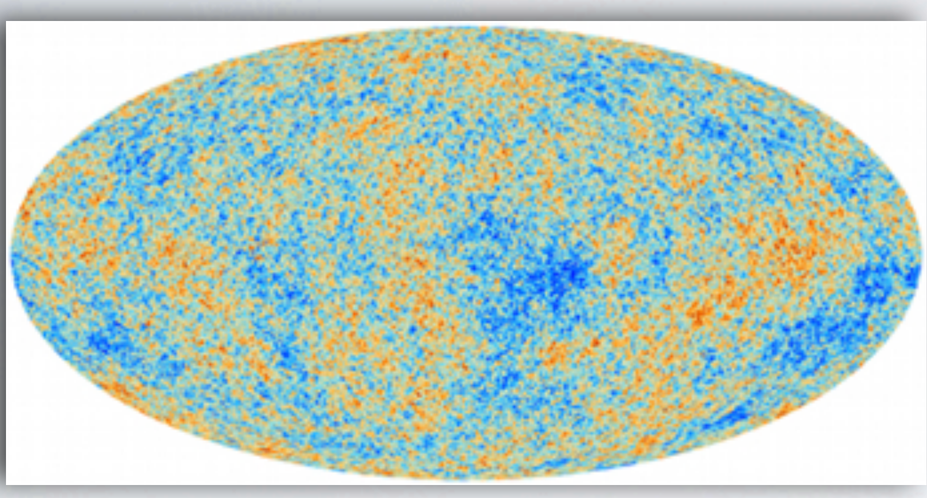
LHC



- Inflaton can not be an arbitrary field
- Quantifying the Reheat Temperature
- Sub-Planckian VEV inflationary models can generate large tensor-to-scalar ratio

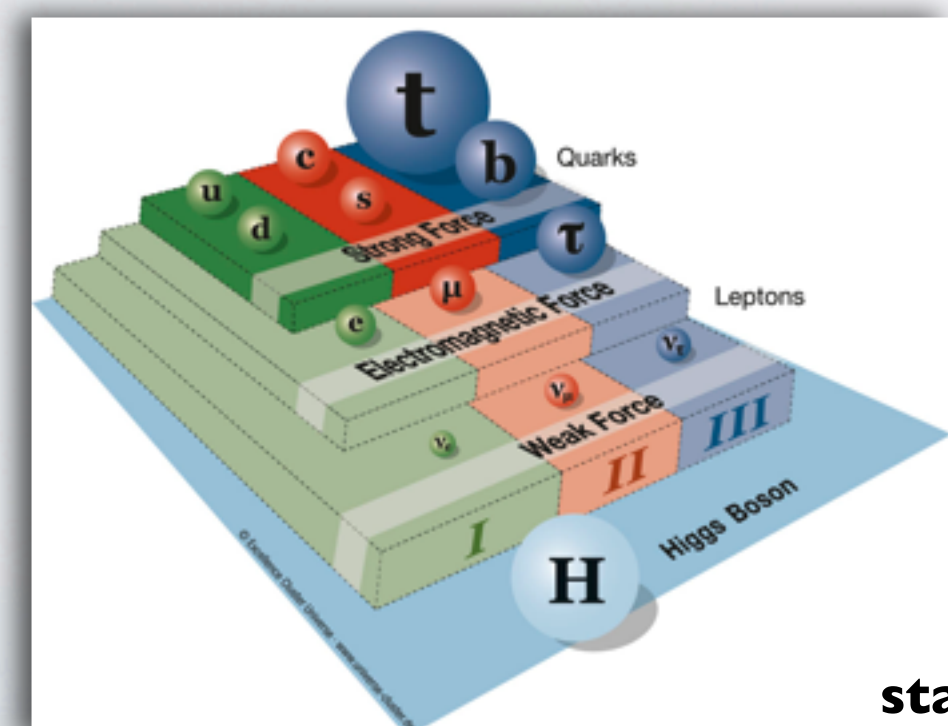
Confusion-1

CMB Perturbations



Einstein's Gravity +
Equation of State,
No modification of GR is required at Low Energies

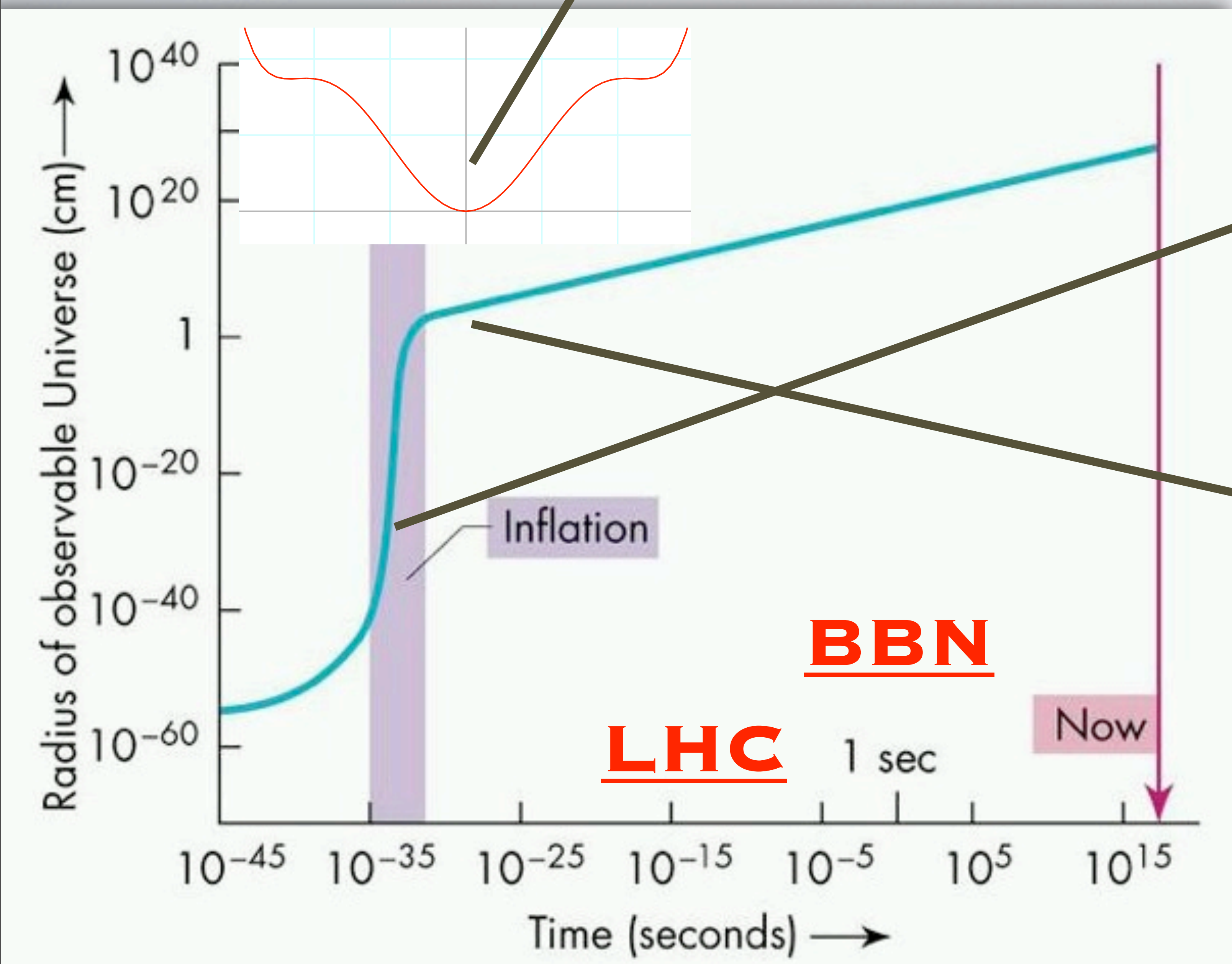
INFLATION DILUTES ALL MATTER !!

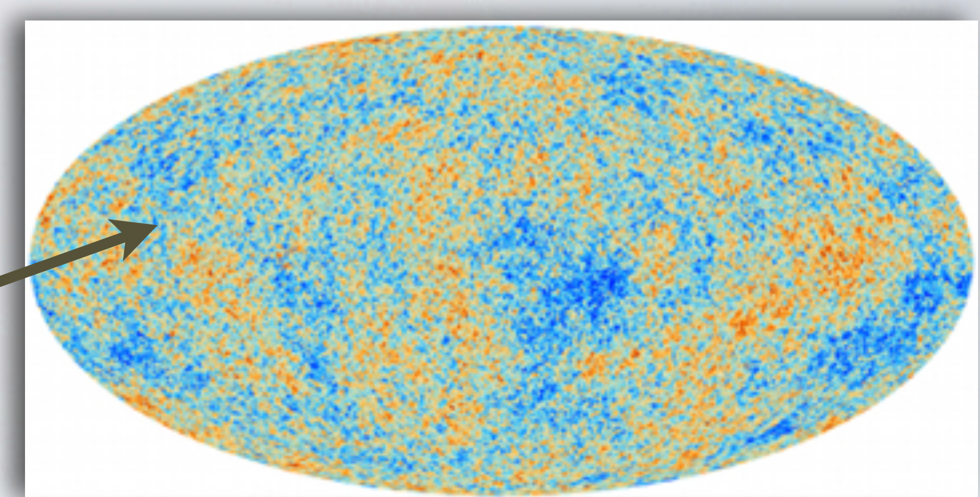


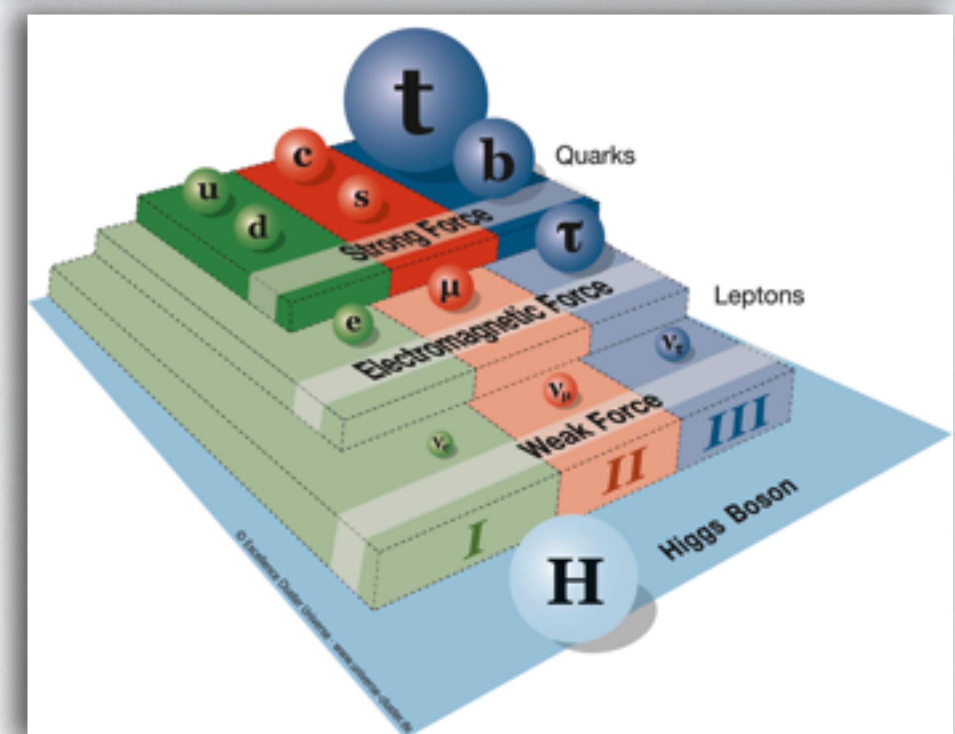
You must explain the relevant DOF.
&
NOT Just the equation of State

99% of INFLATION papers are happy with an equation of state argument for reheating, whether they are SM or some other radiation -- who cares? (its part of assumption !!)

The Inflaton Vacuum cannot be arbitrary: it must know our existence!





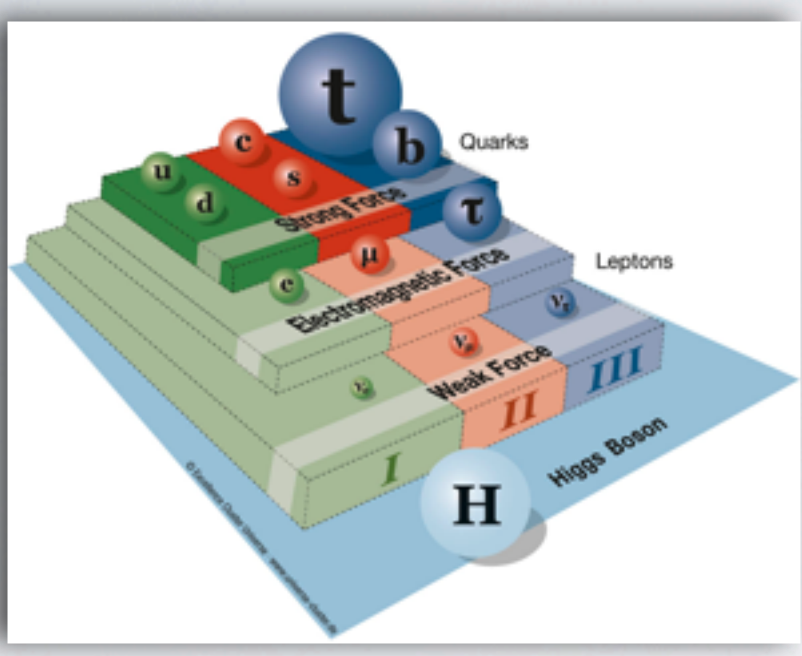


NO Hidden Radiation - ONLY Standard Model DOF

A.M & Rocher, Phys. Rept. (2011), Particle Physics Models of Inflation & Curvaton

Standard Model Higgs

The last 50-60 e-foldings of inflation must happen in a visible sector



The action ? validity of EFT ?

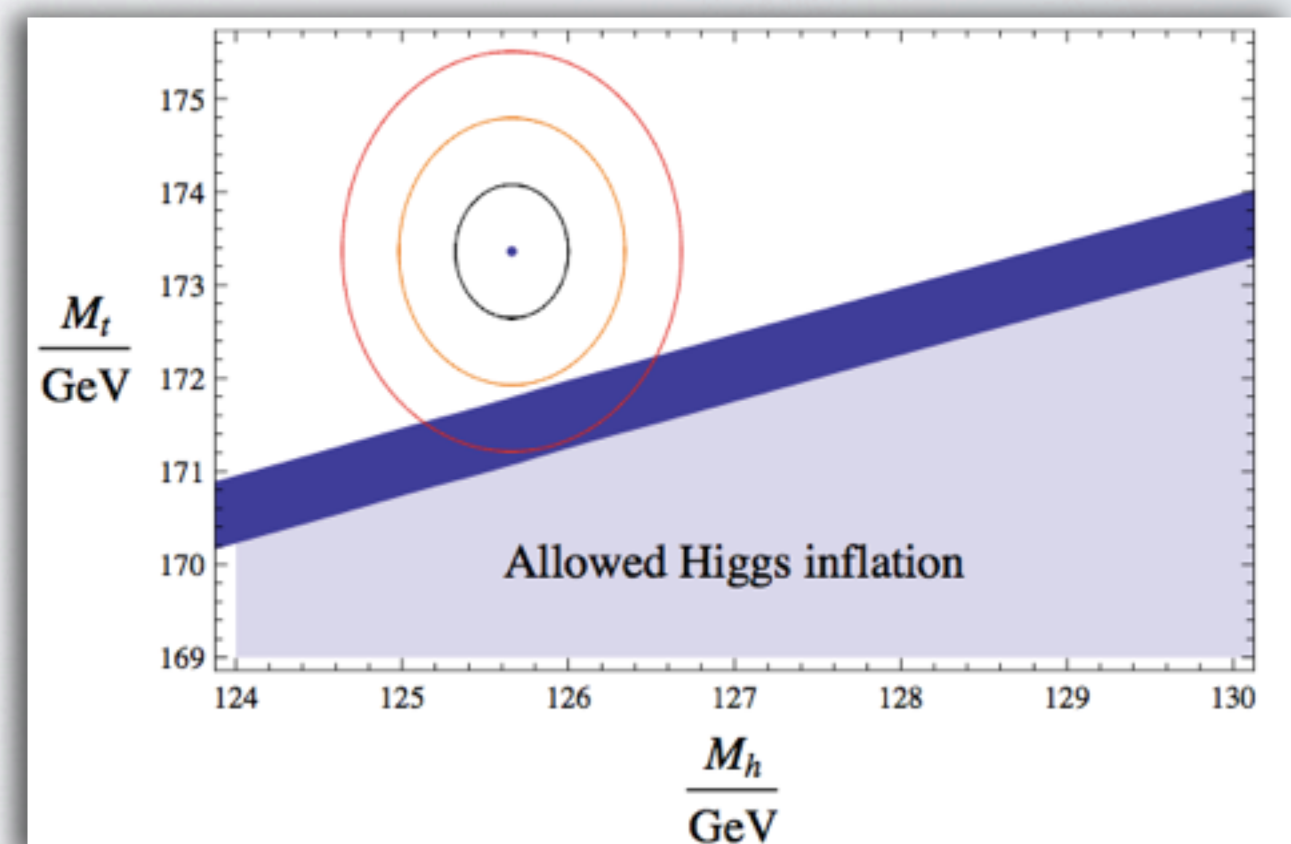
$$S_J = \int d^4x\sqrt{-g}\left\{\frac{M^2+\xi h^2}{2}R + \frac{1}{2}\partial_\mu h \partial^\mu h - \frac{\lambda}{4}\left(h^2-v^2\right)^2\right\}$$

$$\xi \simeq 5\times 10^4\sqrt{\lambda}$$

Embedding higgs inflation in sugra does not help

introduces more unknown parameters

MSSM higgses with D-flat direction can overcome these issues



Starobinsky $R + R^2$ It is utterly INCOMPLETE !

$$S_q = \int d^4x\sqrt{-g}[RF_1(\Box)R + RF_2(\Box)\nabla_\mu\nabla_\nu R^{\mu\nu} + R_{\mu\nu}F_3(\Box)R^{\mu\nu} + R^\nu_\mu F_4(\Box)\nabla_\nu\nabla_\lambda R^{\mu\lambda}$$
$$+ R^{\lambda\sigma}F_5(\Box)\nabla_\mu\nabla_\sigma\nabla_\nu\nabla_\lambda R^{\mu\nu} + RF_6(\Box)\nabla_\mu\nabla_\nu\nabla_\lambda\nabla_\sigma R^{\mu\nu\lambda\sigma} + R_{\mu\lambda}F_7(\Box)\nabla_\nu\nabla_\sigma R^{\mu\nu\lambda\sigma}$$
$$+ R^\rho_\lambda F_8(\Box)\nabla_\mu\nabla_\sigma\nabla_\nu\nabla_\rho R^{\mu\nu\lambda\sigma} + R^{\mu_1\nu_1}F_9(\Box)\nabla_{\mu_1}\nabla_{\nu_1}\nabla_\mu\nabla_\nu\nabla_\lambda\nabla_\sigma R^{\mu\nu\lambda\sigma}$$
$$+ R_{\mu\nu\lambda\sigma}F_{10}(\Box)R^{\mu\nu\lambda\sigma} + R^\rho_{\mu\nu\lambda}F_{11}(\Box)\nabla_\rho\nabla_\sigma R^{\mu\nu\lambda\sigma} + R_{\mu\rho_1\nu\sigma_1}F_{12}(\Box)\nabla^{\rho_1}\nabla^{\sigma_1}\nabla_\rho\nabla_\sigma R^{\mu\rho\nu\sigma}$$
$$+ R_\mu^{\nu_1\rho_1\sigma_1}F_{13}(\Box)\nabla_{\rho_1}\nabla_{\sigma_1}\nabla_{\nu_1}\nabla_\nu\nabla_\rho\nabla_\sigma R^{\mu\nu\lambda\sigma} + R^{\mu_1\nu_1\rho_1\sigma_1}F_{14}(\Box)\nabla_{\rho_1}\nabla_{\sigma_1}\nabla_{\nu_1}\nabla_{\mu_1}\nabla_\mu\nabla_\nu\nabla_\rho\nabla_\sigma R^{\mu\nu\lambda\sigma}]$$

Gravity Invokes ∞ Higher Order Corrections

$$S = \int d^4x\sqrt{-g}\left[R + R\mathcal{F}_1(\Box)R + R_{\mu\nu}\mathcal{F}_2(\Box)R^{\mu\nu} + R_{\mu\nu\alpha\beta}\mathcal{F}_3(\Box)R^{\mu\nu\alpha\beta}\right]$$

$$\mathcal{F}_i(\Box) = \sum_n^\infty a_n\Box^n \qquad \Delta\mathcal{L} = \sqrt{-g}\,(\alpha R^2 + \beta R^2_{\mu\nu} + \gamma R^2_{\alpha\beta\mu\nu})$$

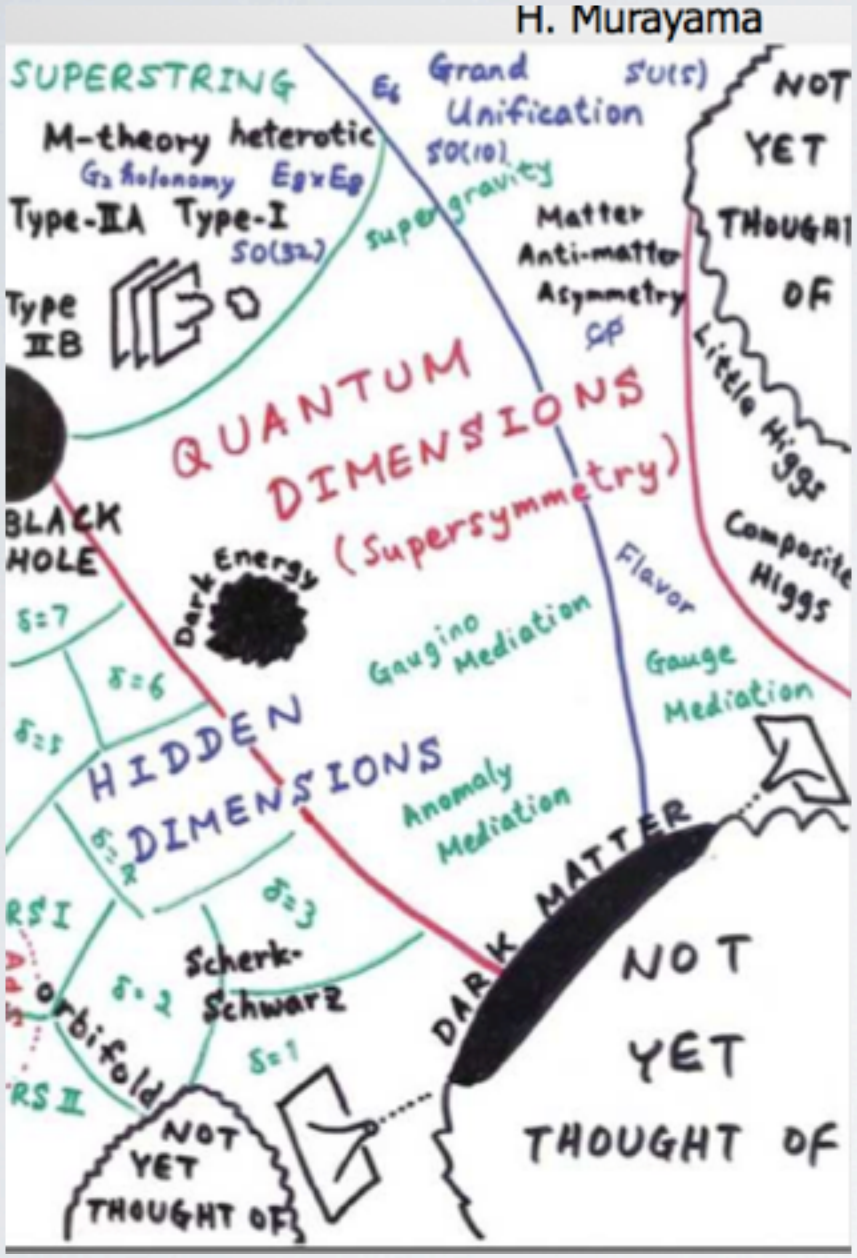
$$2\mathcal{F}_1(\Box) + \mathcal{F}_2(\Box) + 2\mathcal{F}_3(\Box) = 0$$

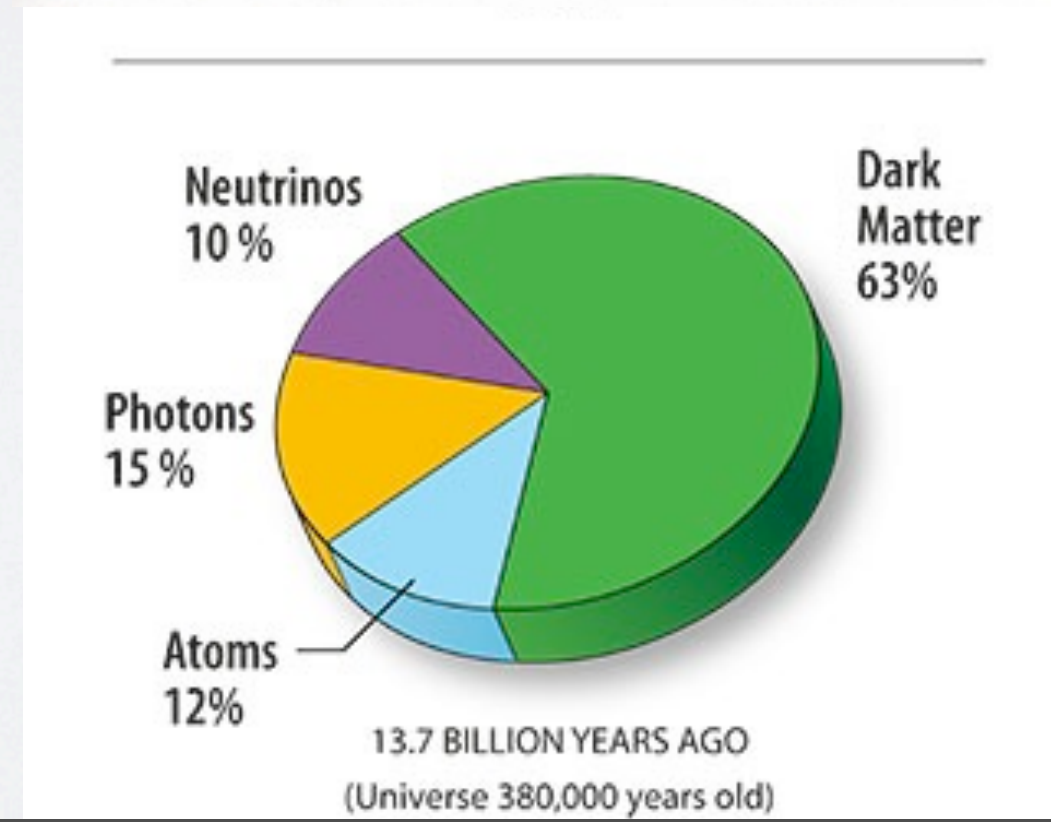
Classical Gravity becomes WEAK in the UV

(Asymptotic Freedom)

Biswas, Gerwick, Koivisto & AM, Phys. Rev. Lett. (2012)

BESIDES... GRAVITY/SUPERGRAVITY YOU NEED TO INVOKE THE BSM





THIS IS WHAT NATURE CARES FOR !!

Singlet Inflaton has no preference:

Billion Hidden Sectors vs. 1 SM

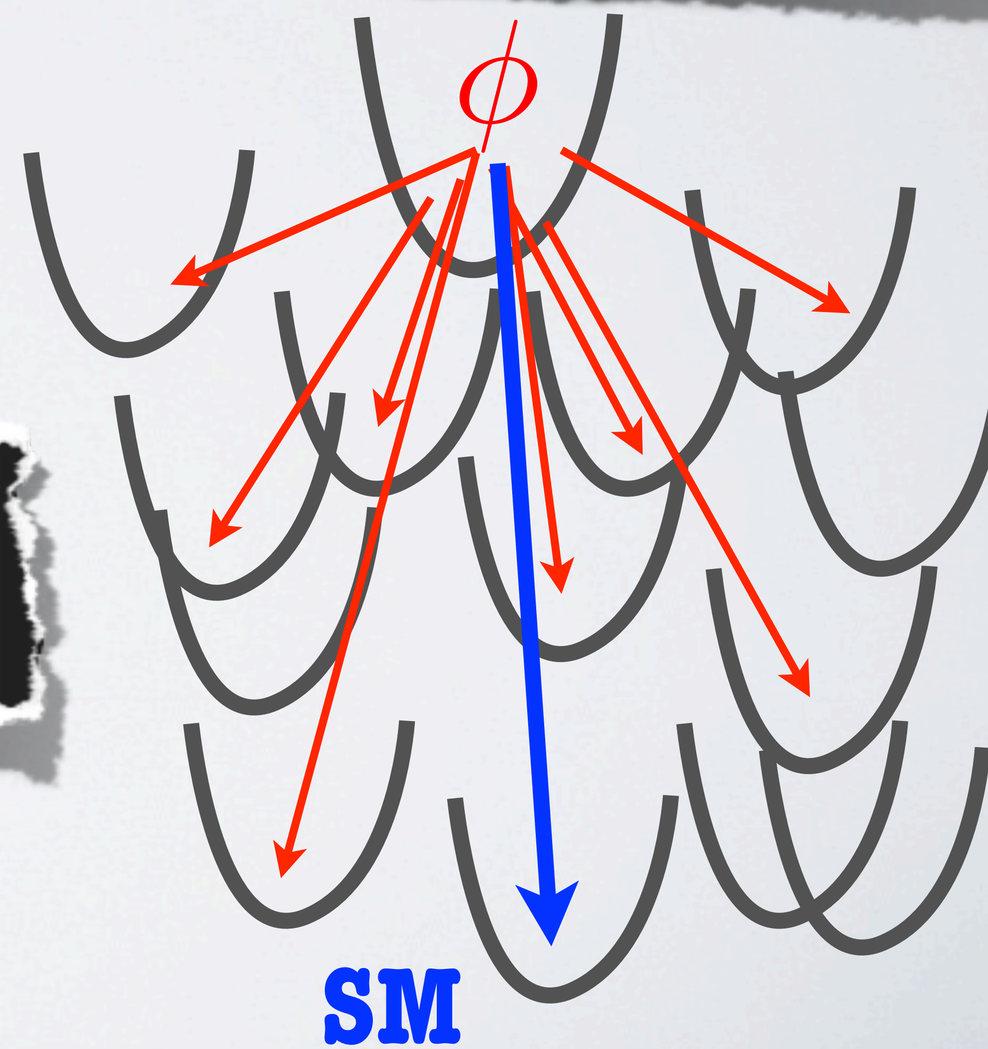
Standard Model $g^2\phi^2 H^2, \quad \frac{\phi}{M_*}(Hq_L)q_R\ , \quad \frac{\phi}{M_*}\tilde{F}F$

Hidden Sector $\phi^2 \sum_i^{N_{Hidden}} g_i^2\chi_i^2, \quad \phi \sum_i^{N_{Hidden}} h_i\bar{\psi}_i\psi_i, \quad \frac{\phi}{M_*}\sum_i^{N_{Hidden}} \tilde{G}_i G_i$

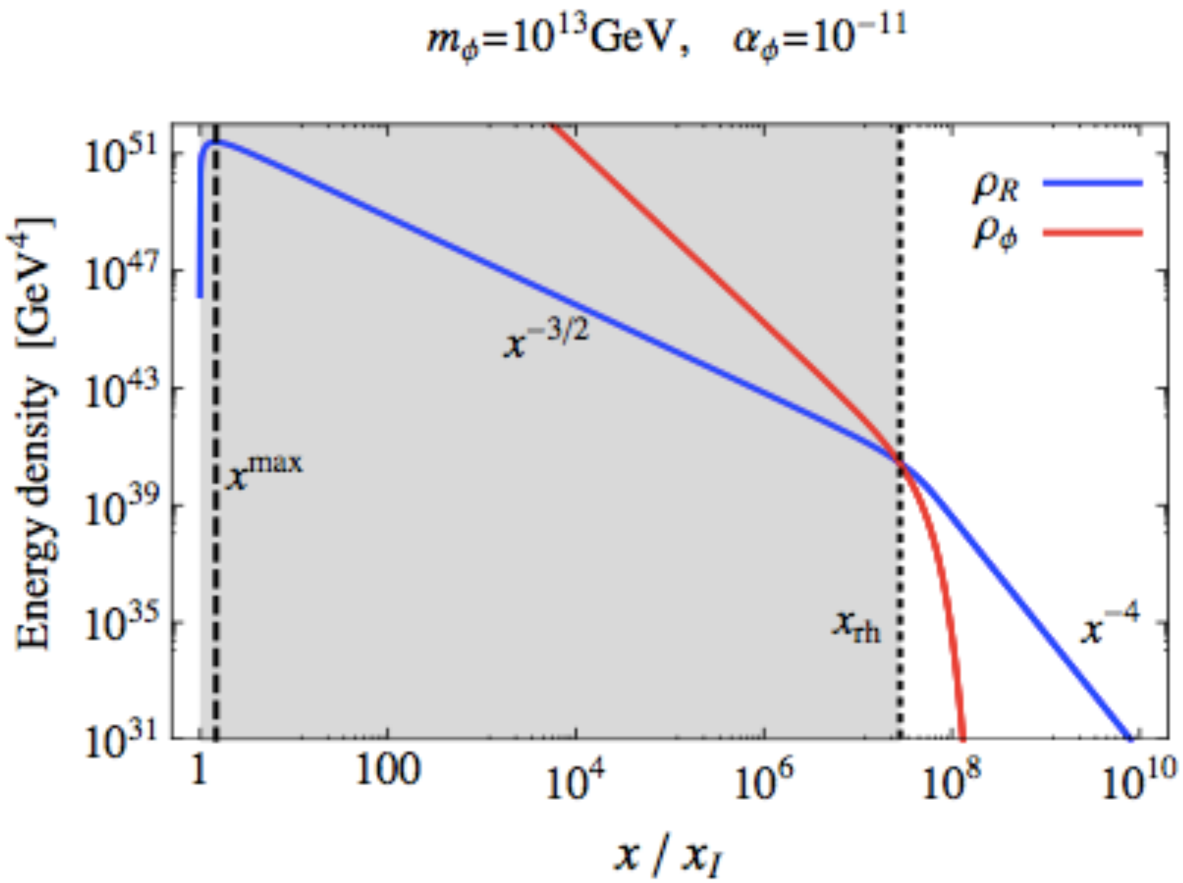
$N_{Hidden},\ h_i,\ g_i$???

$$\Omega_X h^2 \approx 10^{17}\left(\frac{T_R}{10^9\ GeV}\right)\frac{\rho_X}{\rho_{inf}}$$

Over abundant dark matter from Direct Inflaton decay!!



When does the notion of temperature makes sense after Inflation ?

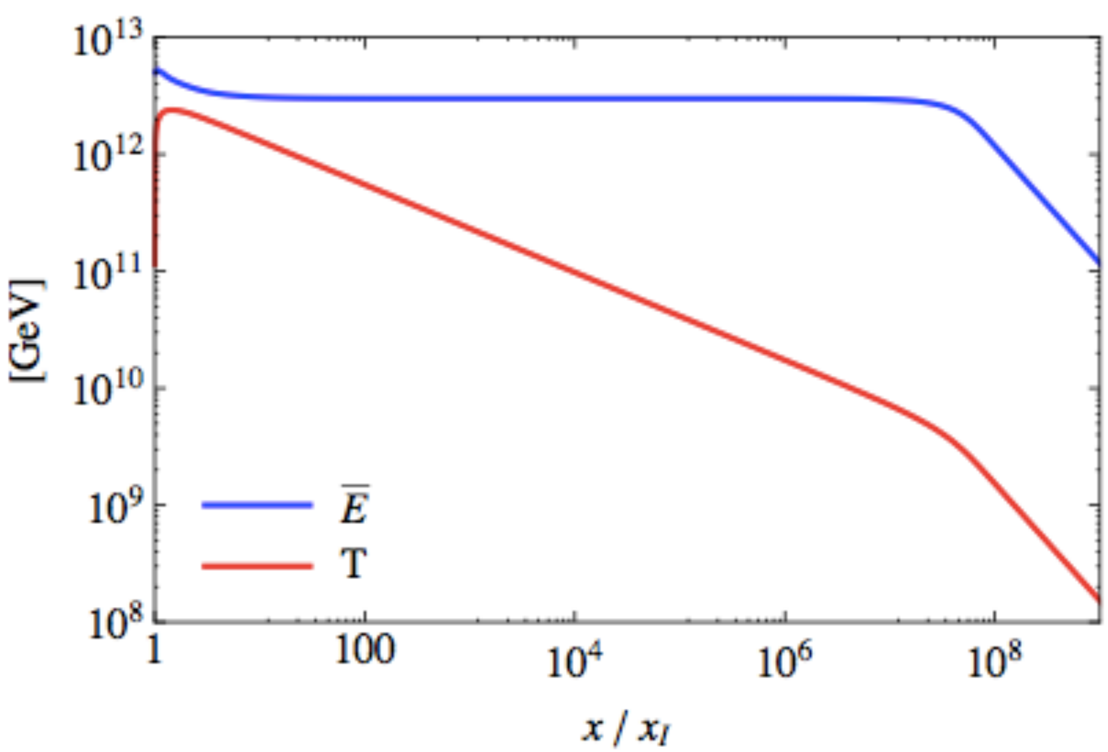


Standard Reheat temperature since 1980s

$$T(t) = \left[\frac{30}{\pi^2}\rho_R(t)/g_*(t)\right]^{1/4} \qquad T_{rh} = \left(\frac{90}{8\pi^3 g_*}\right)^{1/4}\sqrt{\Gamma_\phi M_P}$$

$$T_{\max} \simeq \left[\frac{1.57}{\pi^3 g_*}\right]^{1/4}\sqrt{M_P}\,(\Gamma_\phi H_I)^{1/4}$$

This assumes thermalization is achieved instantly at the time of radiation domination

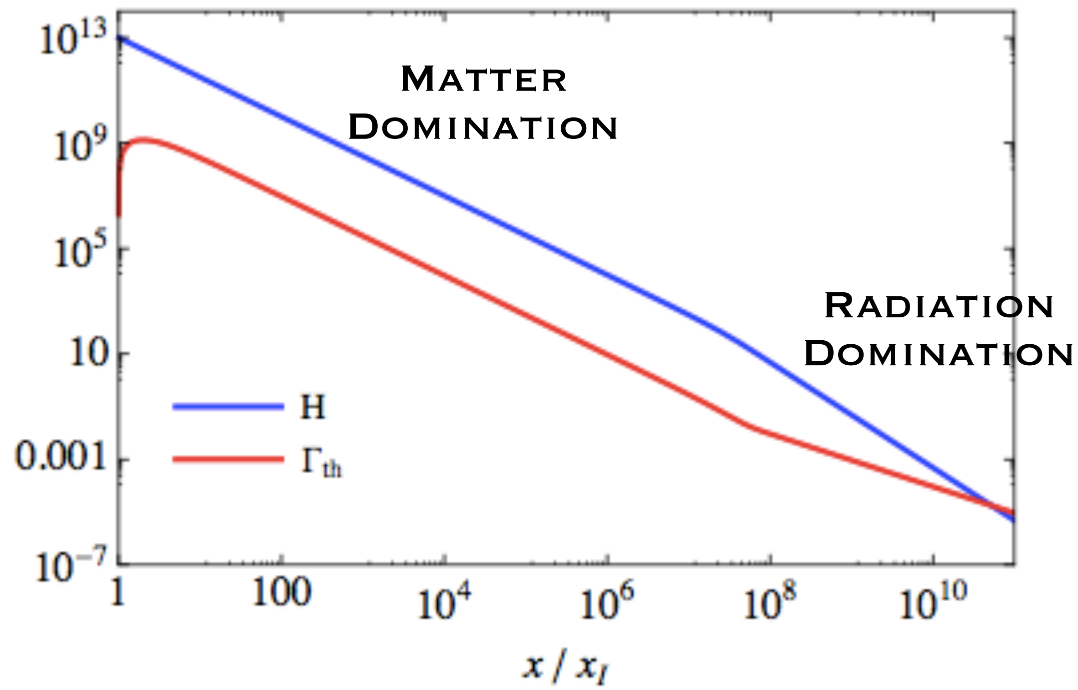


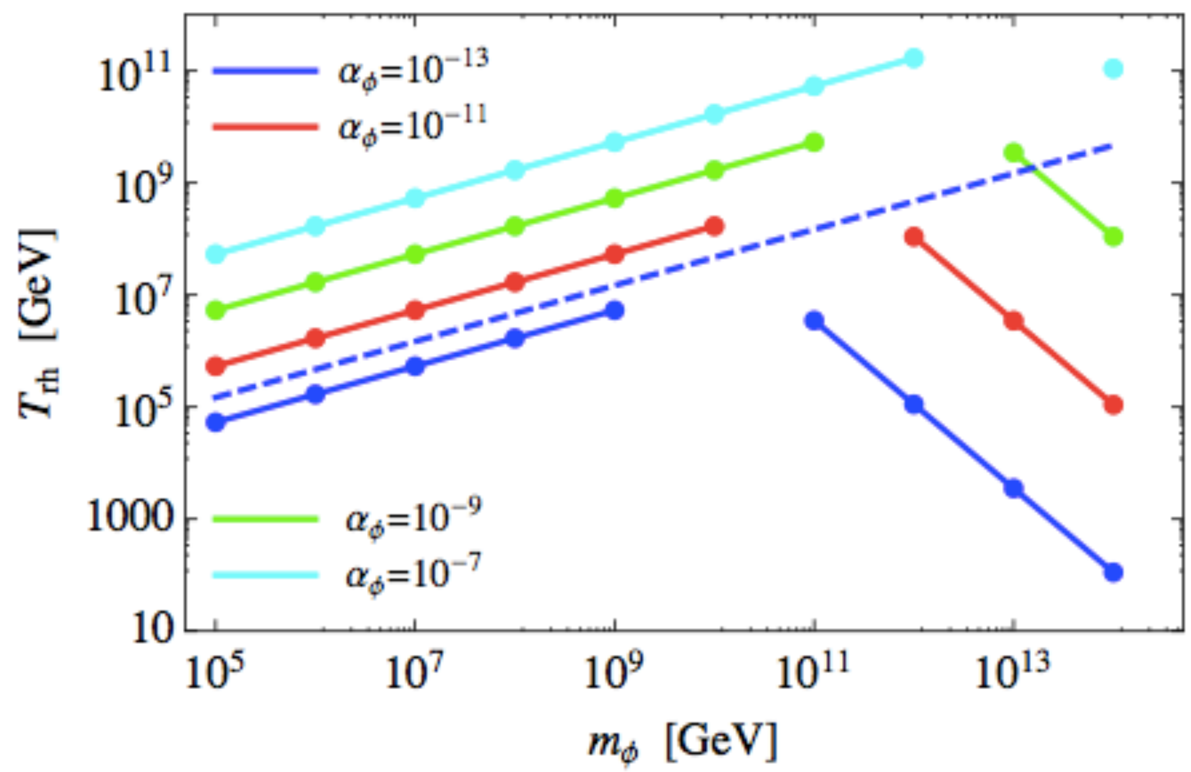
How Good the assumption of instant thermalization is?

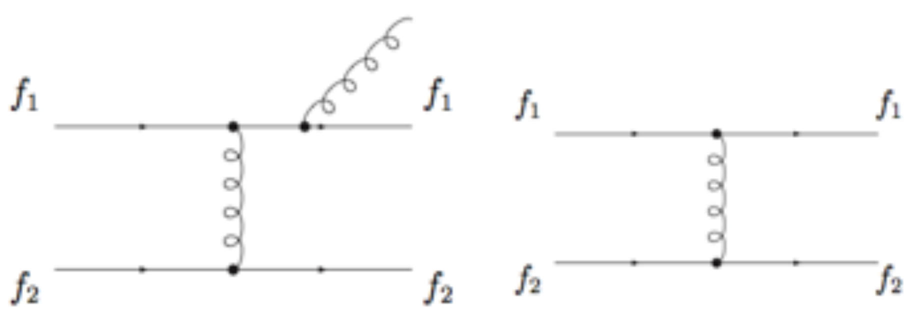
Wednesday, 23 October 13

Quantifying Reheat Temperature

Standard estimation of reheat temperature is wrong







$$\sigma \sim \frac{\alpha_s^3}{p(t)^2} \log\left(\frac{m_\phi^2}{p(t)^2}\right)$$

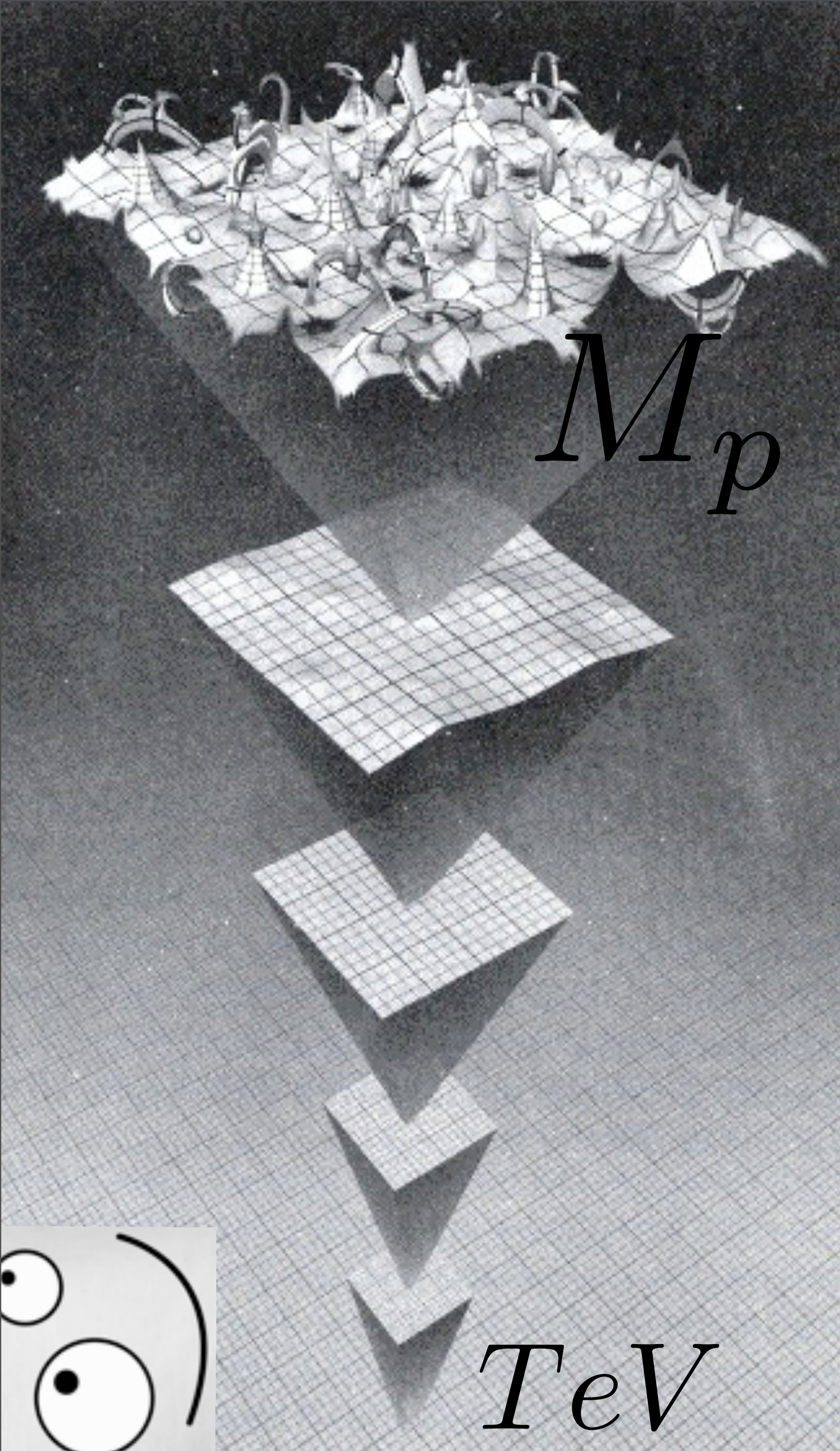
Instant thermalization

$$T_{rh}(x_{th} \ll x_{rd}) \approx \frac{0.6}{g_*^{1/4}} \sqrt{\alpha_\phi\, m_\phi\, M_P}$$

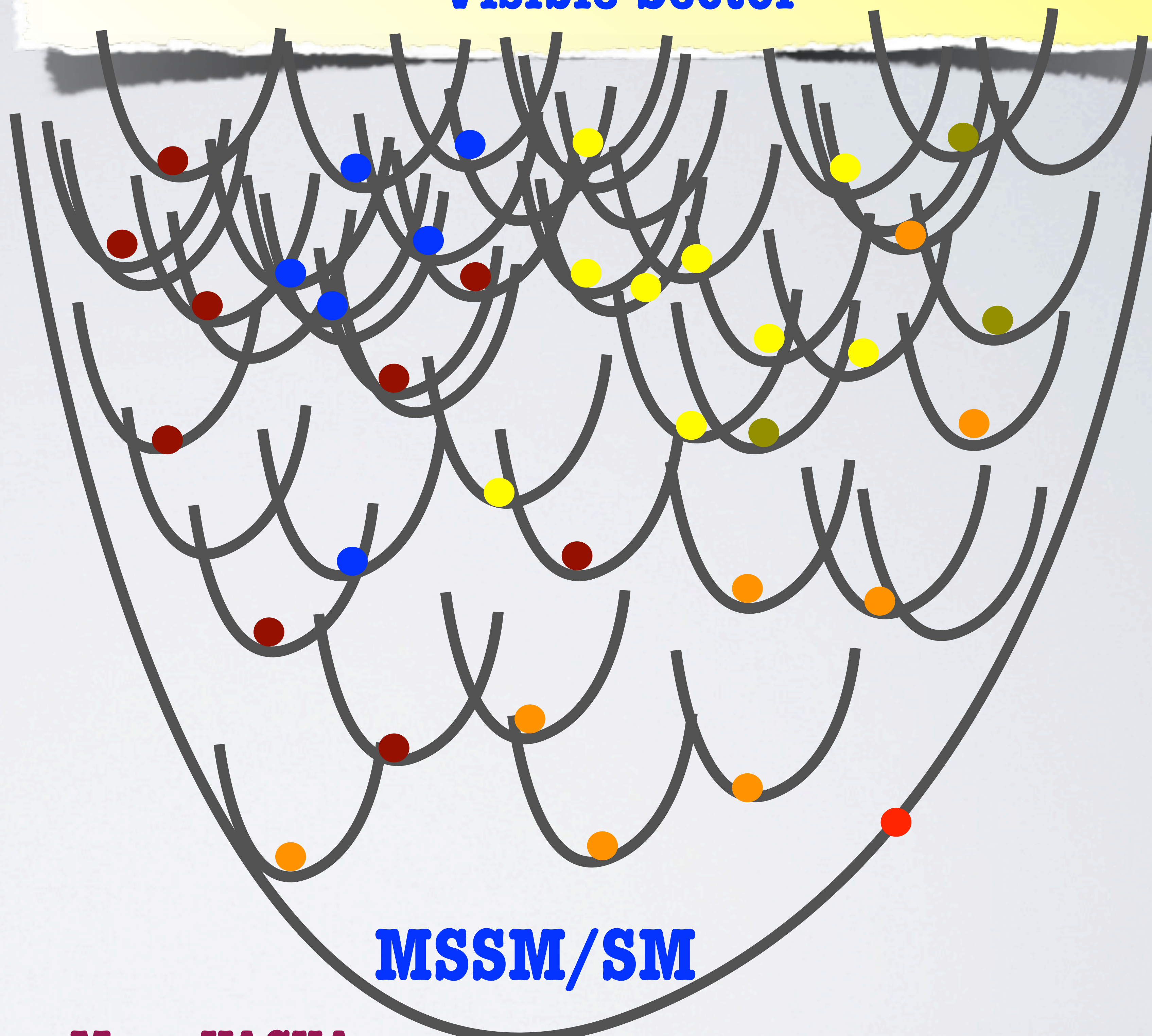
Delayed thermalization

$$T_{rh}(x_{th} \gg x_{rd}) \approx \frac{0.7\, \alpha_s^3\, \alpha_\phi^{3/2} M_P^{5/2}}{g_*^{1/4} m_\phi^{3/2}}$$

AM+Zaldivar, 1310.5143



Last 50-60 e-folds MUST happen within a Visible Sector

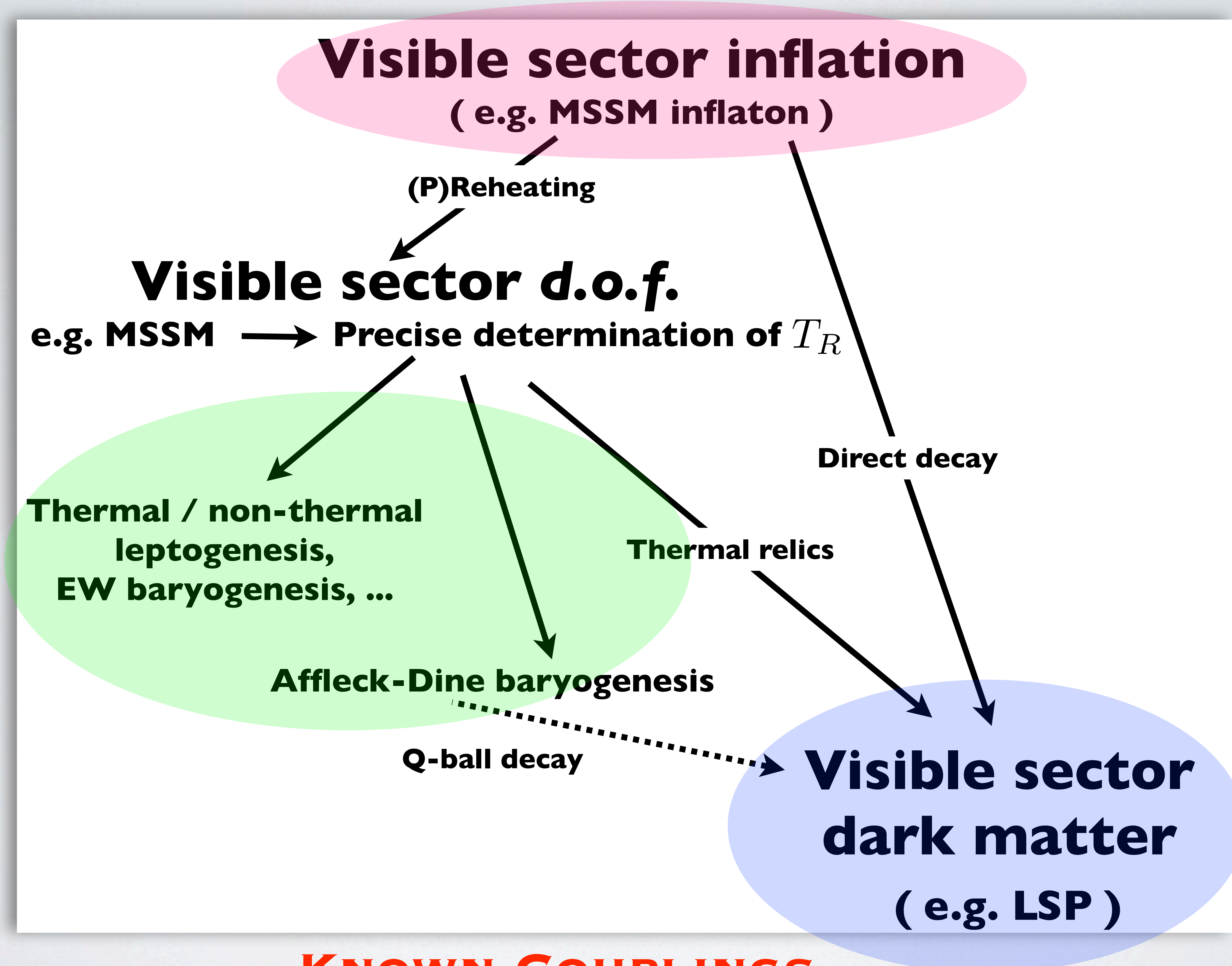


Inflation can happen in Many Many VACUA,

BUT the Lightest states are naturally displaced from their minimum

The lightest states are presumably MSSM/SM

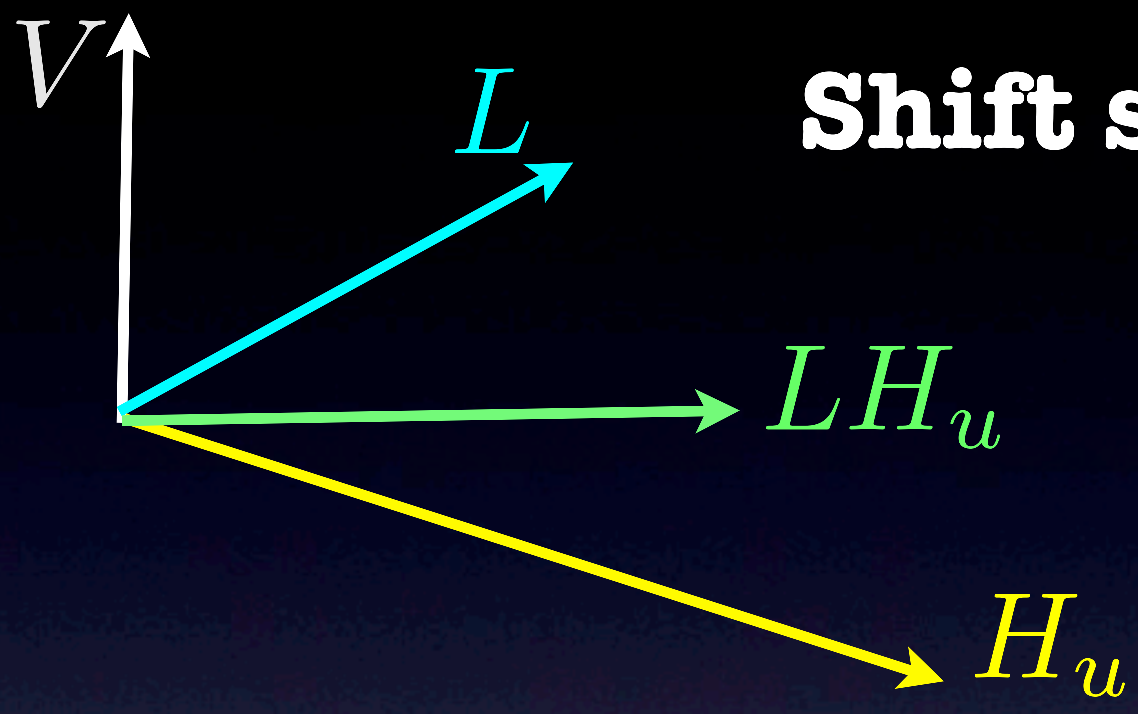
WHY MSSM ? PREDICTIVE POWER



KNOWN COUPLINGS

SUSY BREAKING SCALE IS THE MAIN UNCERTAINTY

SUSY Flat directions

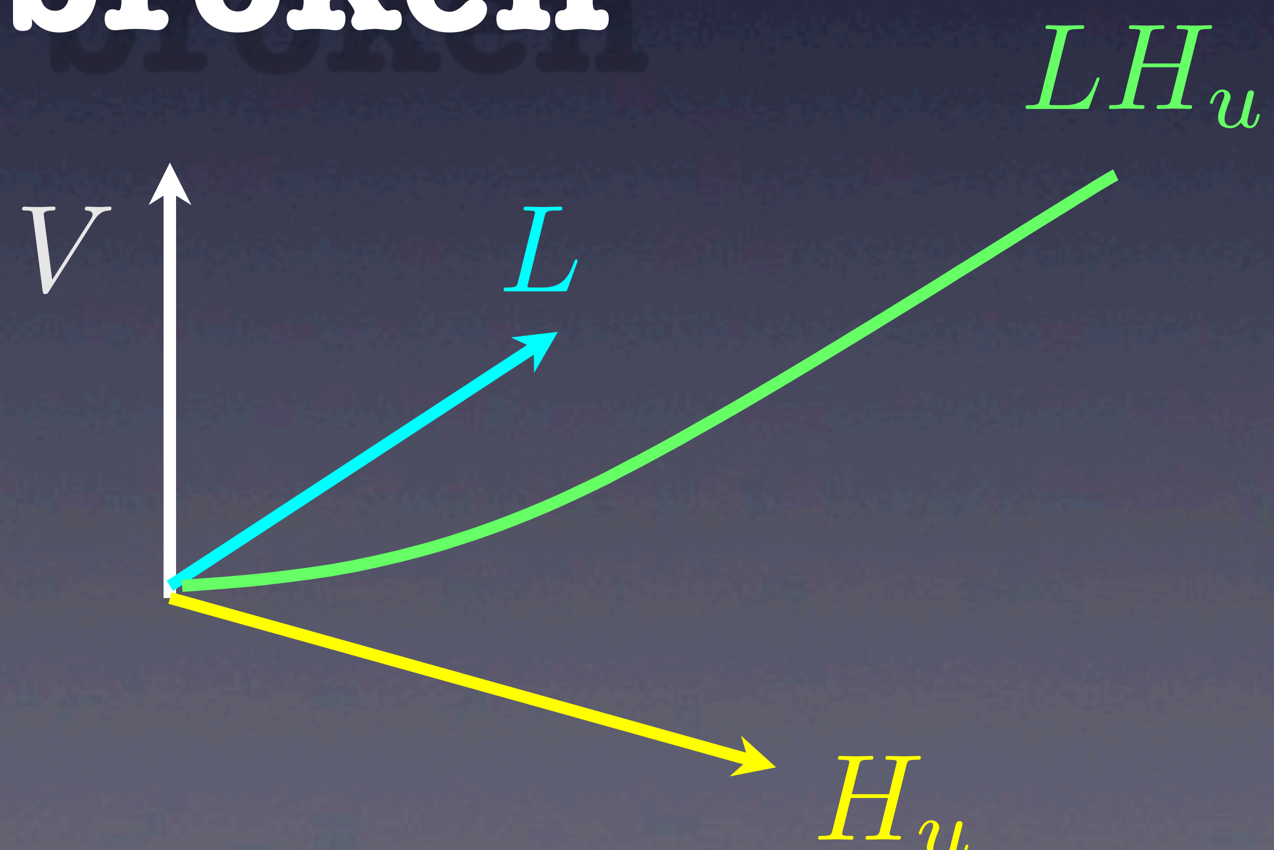


Shift symmetry

as a Gauge Invariant operator minimises the Potential

SUSY is broken

Shift symmetry is broken



Enqvist, Mazumdar, Phys. Rept. (2004)

Gauge invariant Inflatons

	B−L	Always lifted by W_{renorm}?
LH_u	−1	
H_uH_d	0	
udd	−1	
LLe	−1	
QdL	−1	
QuH_u	0	√
QdH_d	0	√
LH_de	0	√
QQQL	0	
QuQd	0	
QuLe	0	
uude	0	
$QQQH_d$	1	√
QuH_de	1	√
dddLL	−3	
uuuee	1	
QuQue	1	
QQQQu	1	
$dddLH_d$	−2	√
$uudQdH_u$	−1	√
$(QQQ)_4LLH_u$	−1	√
$(QQQ)_4LH_uH_d$	0	√
$(QQQ)_4H_uH_dH_d$	1	√
$(QQQ)_4LLLe$	−1	
uudQdQd	−1	
$(QQQ)_4LLH_de$	0	√
$(QQQ)_4LH_dH_de$	1	√
$(QQQ)_4H_dH_dH_de$	2	√

$$SU(3) \times SU(2)_l \times U(1)_Y$$

$u_1 d_2 d_3$ $$d_2^\beta = \frac{1}{\sqrt{3}}\phi \qquad u_1^\alpha = \frac{1}{\sqrt{3}}\phi \qquad d_3^\gamma = \frac{1}{\sqrt{3}}\phi$$

$L_1 L_2 e_3$ $$L_1^a = \frac{1}{\sqrt{3}}\begin{pmatrix}0\\ \phi\end{pmatrix} \qquad L_2^b = \frac{1}{\sqrt{3}}\begin{pmatrix}\phi\\ 0\end{pmatrix} \qquad e_3 = \frac{1}{\sqrt{3}}\phi$$

$H_u H_d$ $$H_u = \frac{1}{\sqrt{2}}\begin{pmatrix}\phi\\ 0\end{pmatrix} \qquad H_d = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ \phi\end{pmatrix}$$

$$SU(3) \times SU(2)_l \times U(1)_Y \times U(1)_{B-L}$$

$N H_u L$ $$N = \frac{1}{\sqrt{3}}\phi \qquad H_u = \frac{1}{\sqrt{3}}\begin{pmatrix}0\\ \phi\end{pmatrix} \qquad L = \frac{1}{\sqrt{3}}\begin{pmatrix}\phi\\ 0\end{pmatrix}$$

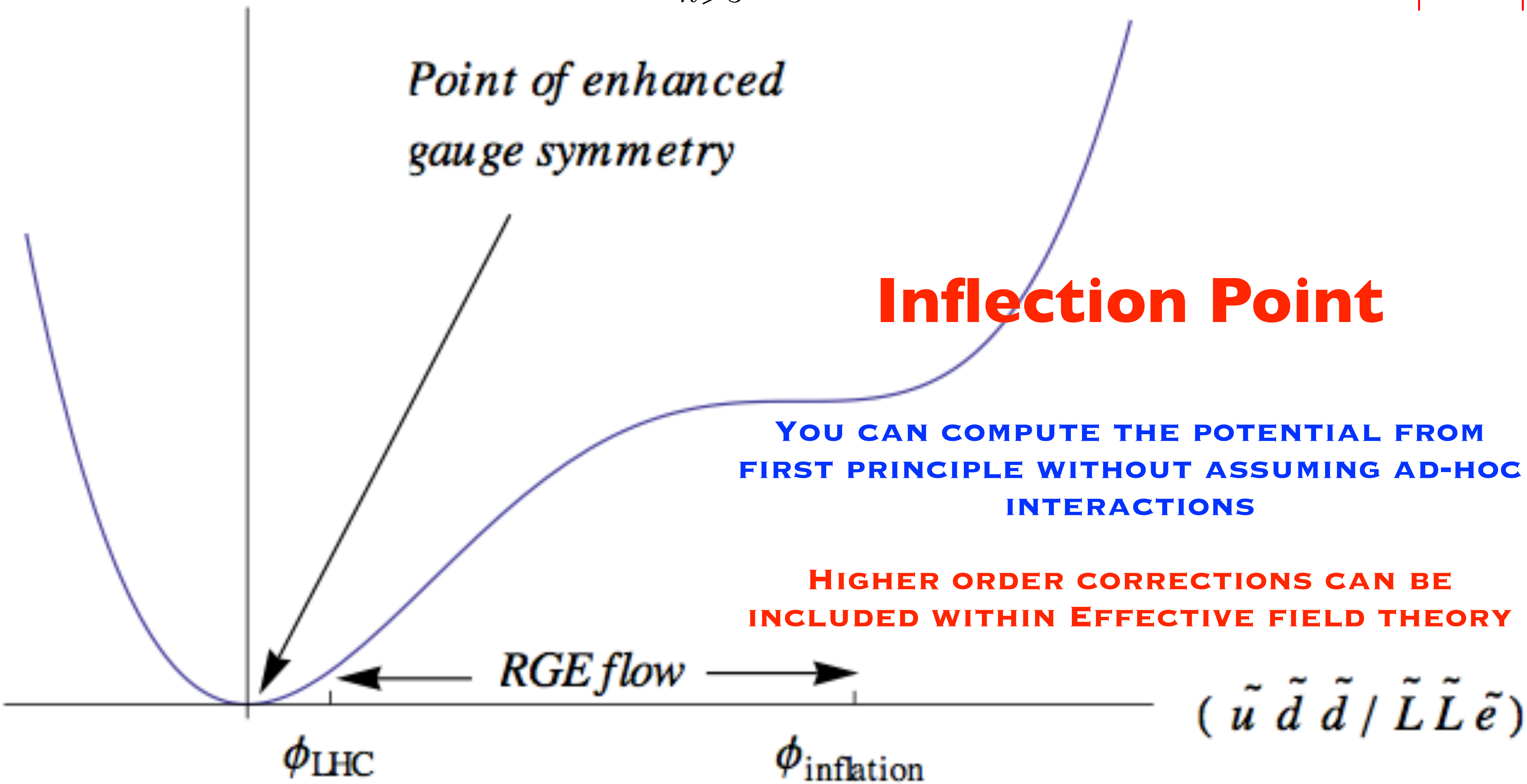
Allahverdi, Enqvist, Bellido, AM, (PRL, 2006), (JCAP, 2007), Allahverdi, Kusenko, AM, JCAP (2007), Allahverdi, Dutta, AM (PRL 2007), Chatterjee, AM, JCAP (2011)

MSSM Inflaton Potential

V $(\tilde{u}\,\tilde{d}\,\tilde{d}\,/\,\tilde{L}\,\tilde{L}\,\tilde{e})$

$$W \sim \lambda \sum_{n>3} \frac{\Phi^n}{M_p^{n-3}}$$

$$V = \text{Soft SUSY terms} + \left|\frac{\partial W}{\partial \Phi}\right|^2$$



Inflection Point

You can compute the potential from first principle without assuming ad-hoc interactions

Higher order corrections can be included within Effective field theory

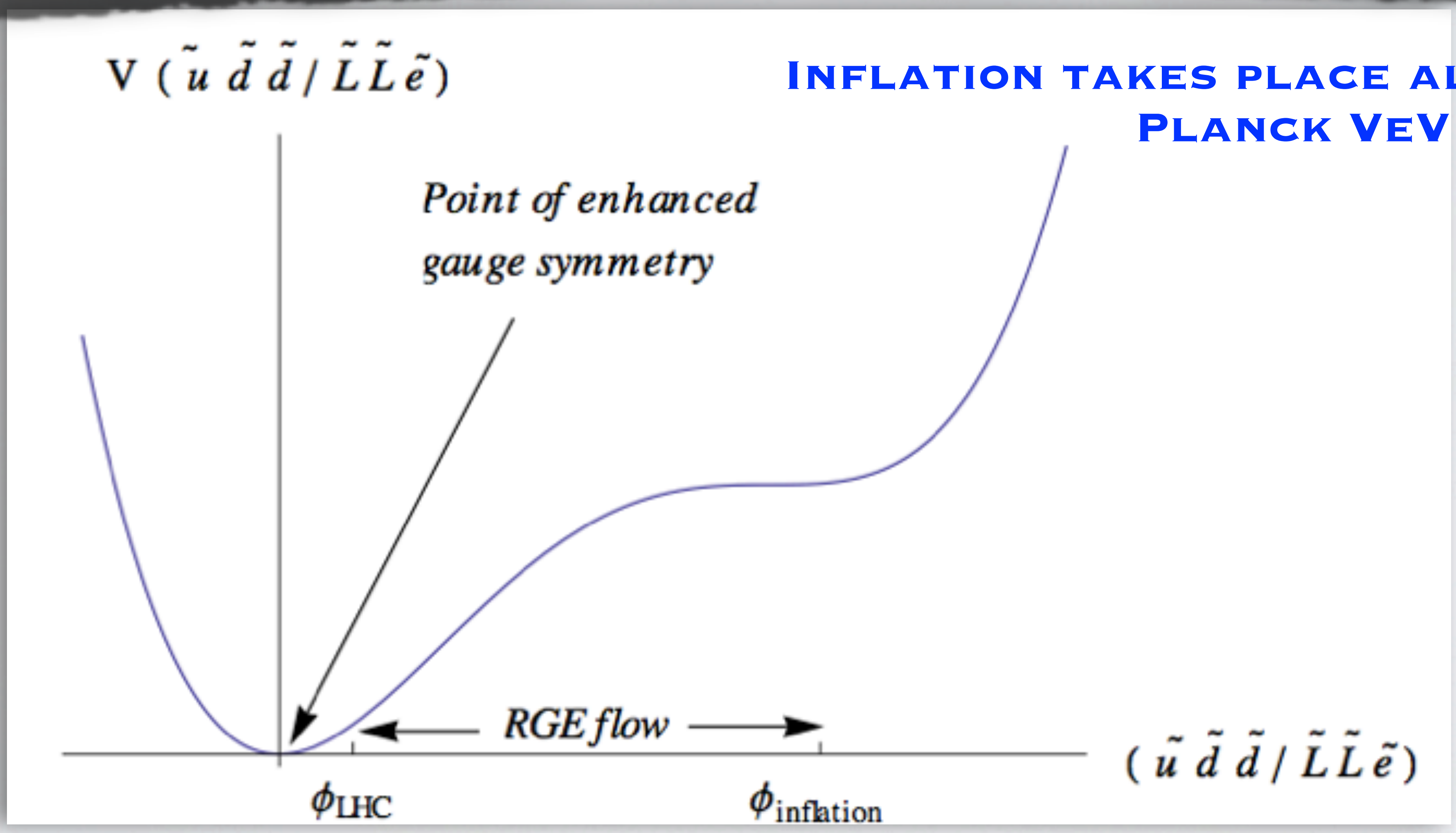
Potentials are constructed by small perturbations around the Enhanced Gauge Symmetry Point

Allahverdi, Enqvist, Garcia-Bellido, AM, PRL (2006), JCAP (2006)

Constructing a Potential at the lowest order

$$V(|\phi|) = \frac{1}{2}m^2|\phi|^2 - \frac{Ah}{3}\phi^3 + h^2|\phi|^4 \quad (n=3)$$

$$V(|\phi|) = \frac{1}{2}m^2|\phi|^2 - \frac{A\lambda}{6}\frac{\phi^6}{M_p^3} + \lambda^2\frac{|\phi|^{10}}{M_p^6} \quad (n=6)$$



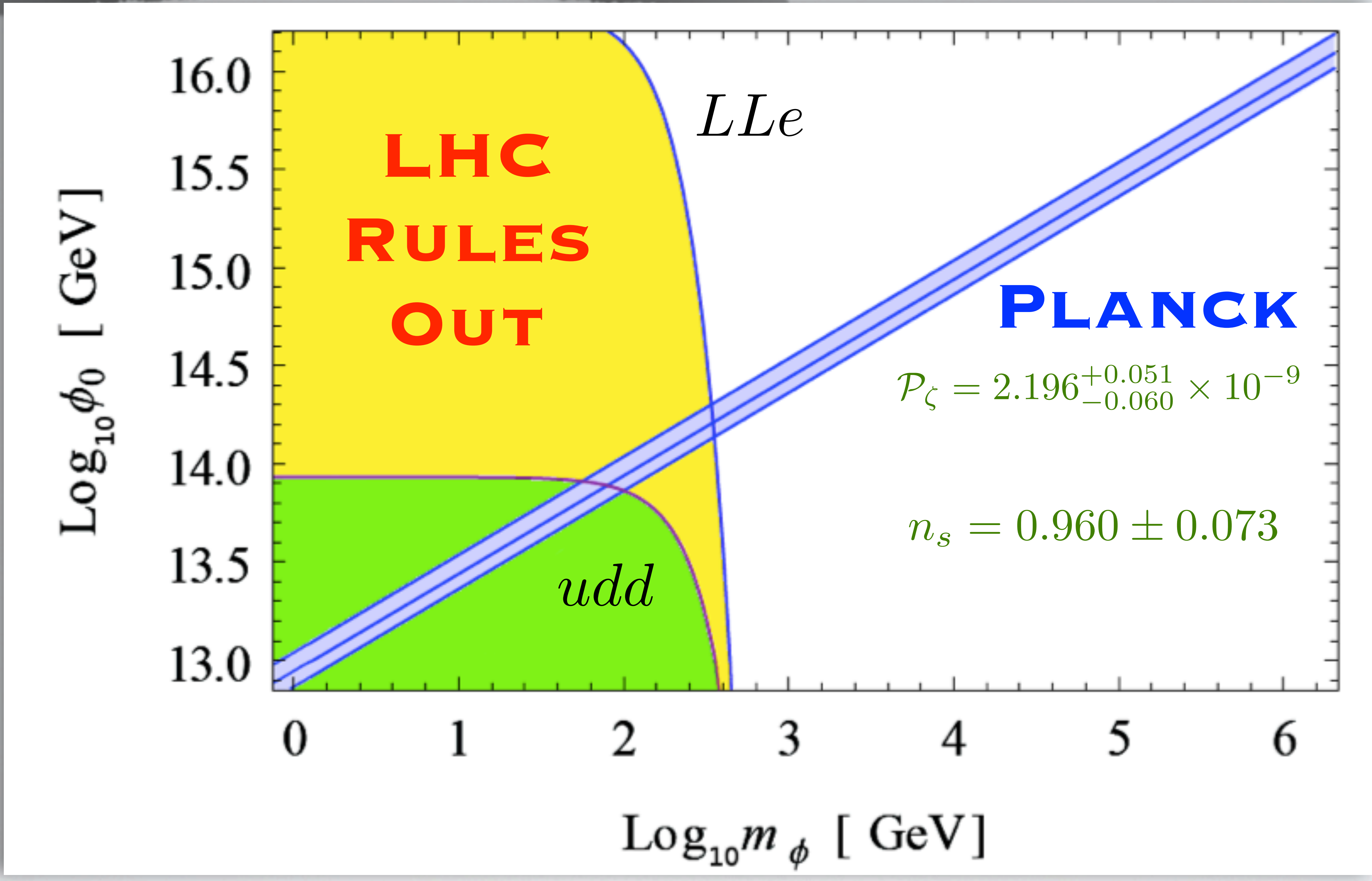
Inflation takes place always Below Planck VeV

Allahverdi, Enqvist, Garcia-Bellido, AM, PRL (2006), JCAP (2006), Bueno-Sanchez, Dimopoulos, Lyth, JCAP (2006), Allahverdi, Kusenko AM, JCAP (2006), Allahverdi, Dutta, AM, PRL (2007)

LHC & PLANCK JOINT CONSTRAINTS ON INFLATONS

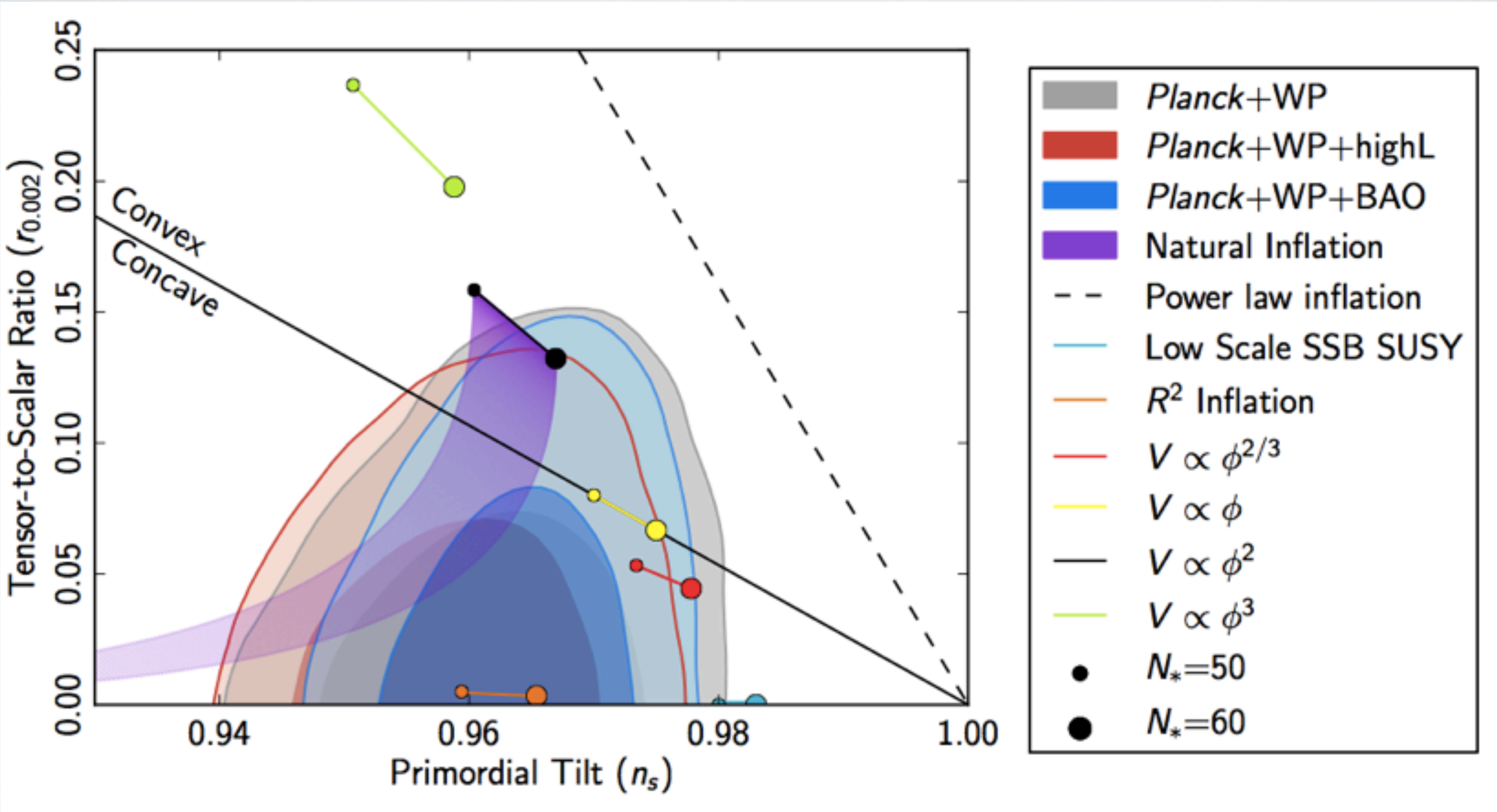
$$W = \lambda \frac{(LLe)(LLe)}{M_p^3} \quad \text{or} \quad \lambda \frac{(udd)(udd)}{M_p^3}$$

RENORMALIZATION GROUP EQUATIONS CAN RELATE LHC SCALE TO INFLATIONARY SCALE

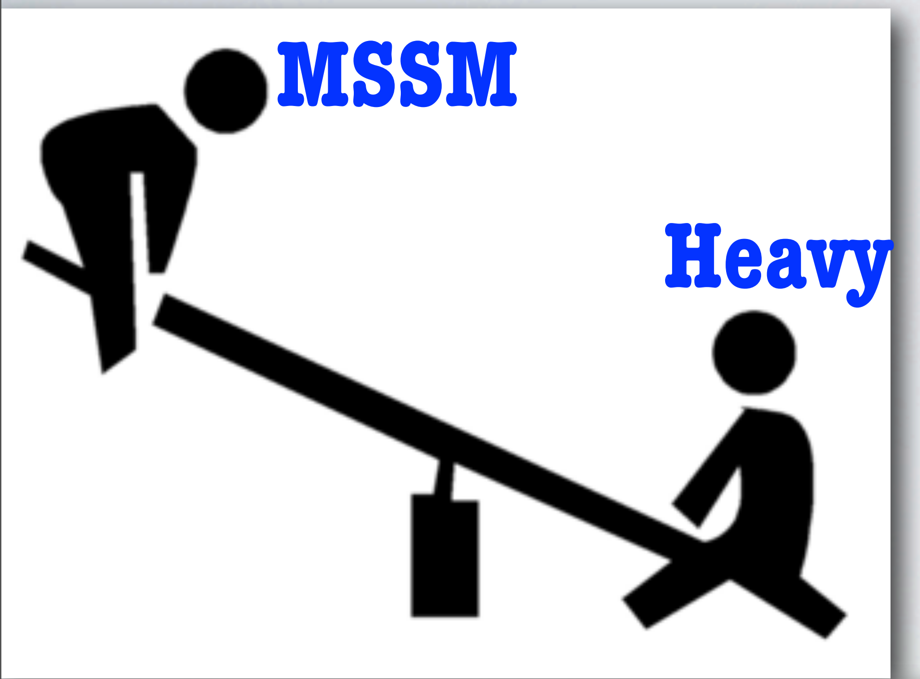


BOEHM, DASILVA, AM & PUKARTAS, PRD (2012), WANG, PUKARTAS & AM, JCAP (2013)

Can MSSM inflation produce large tensor to scalar ratio?

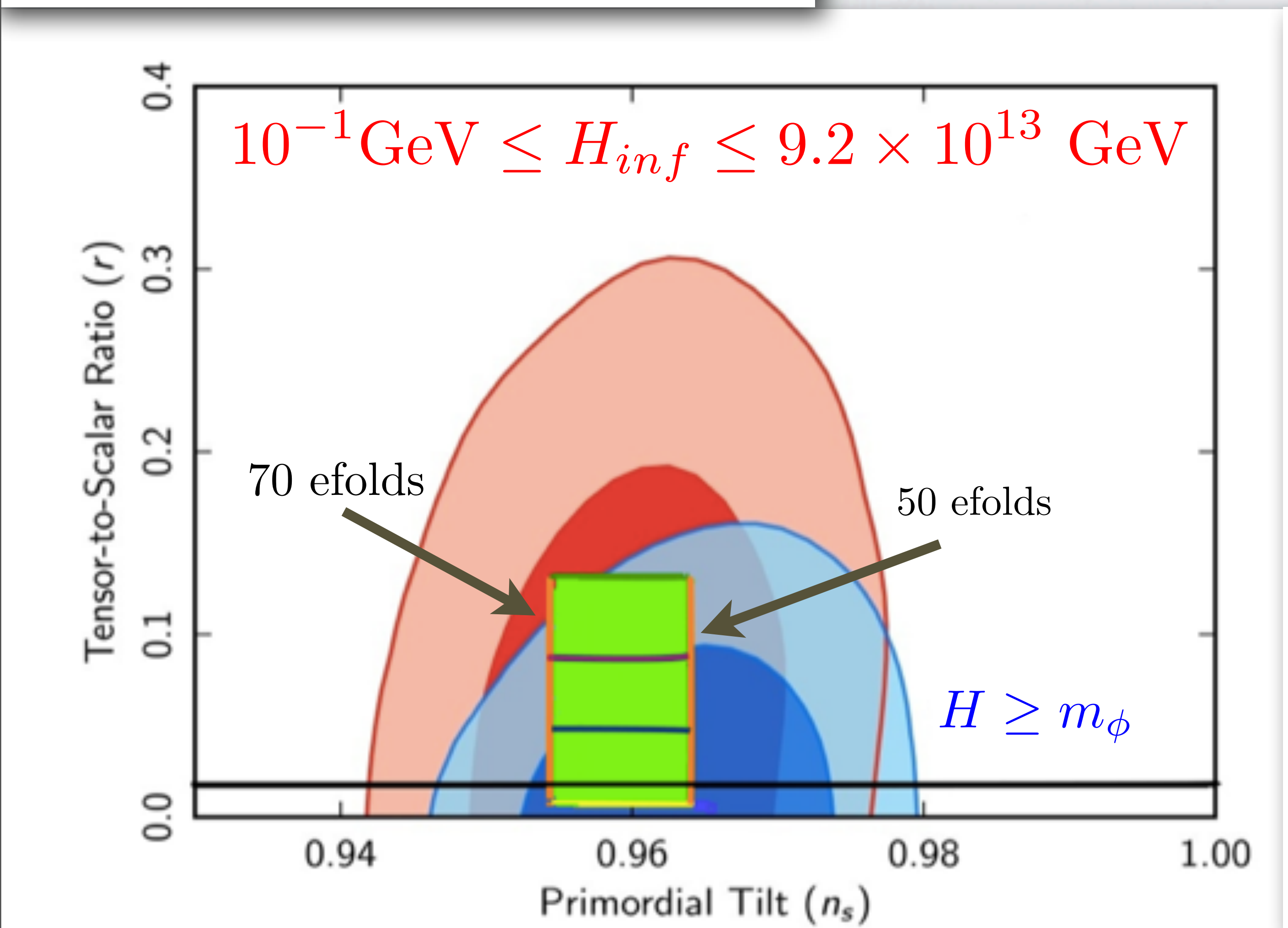


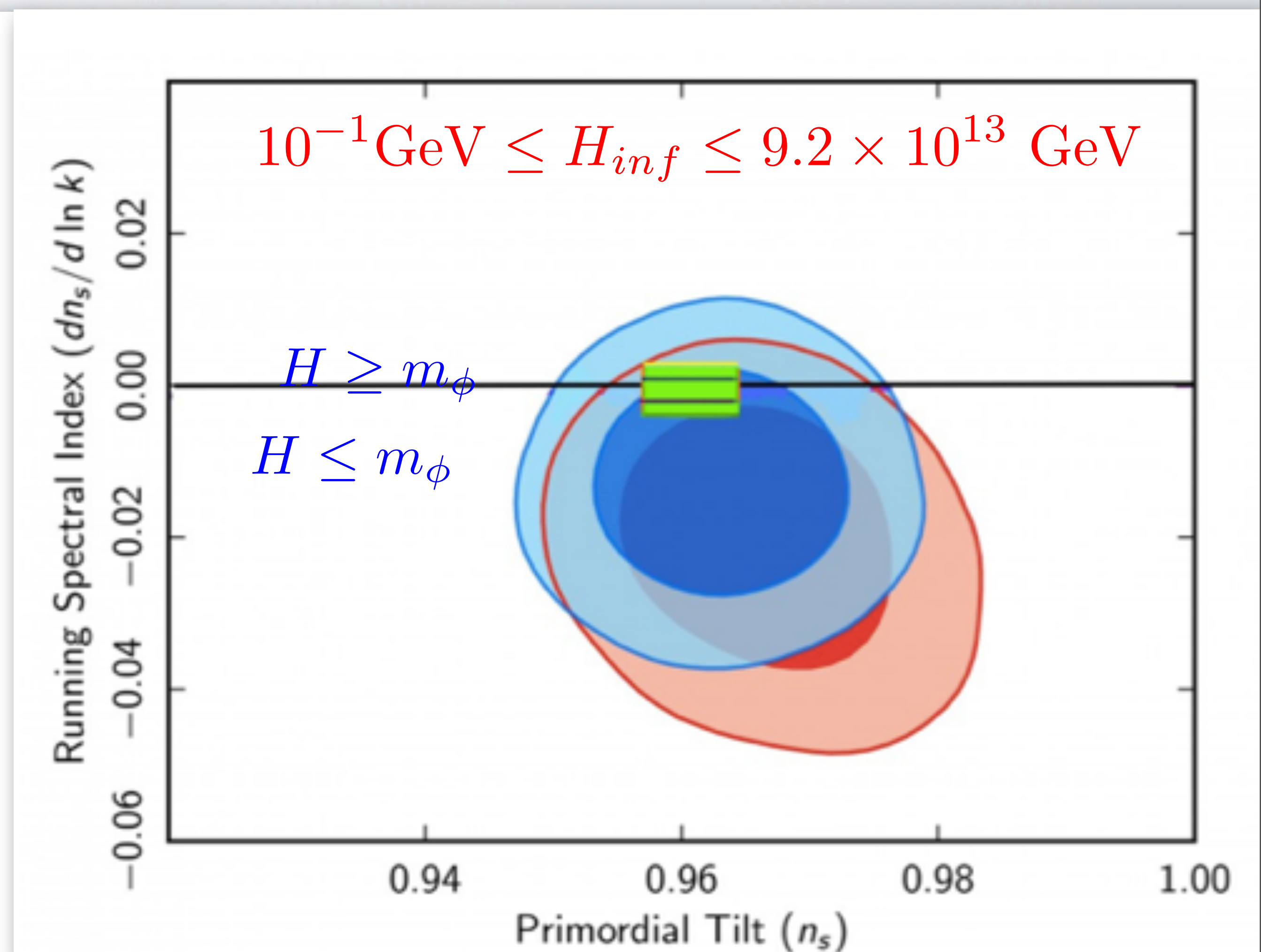
N=1 SUGRA & MSSM Inflation



$$V(\phi) = V_c + \frac{c_H H^2}{2}|\phi|^2 - \frac{a_H H}{n M_P^{n-3}}\phi^n + \frac{|\phi|^{2(n-1)}}{M_P^{2(n-3)}}$$

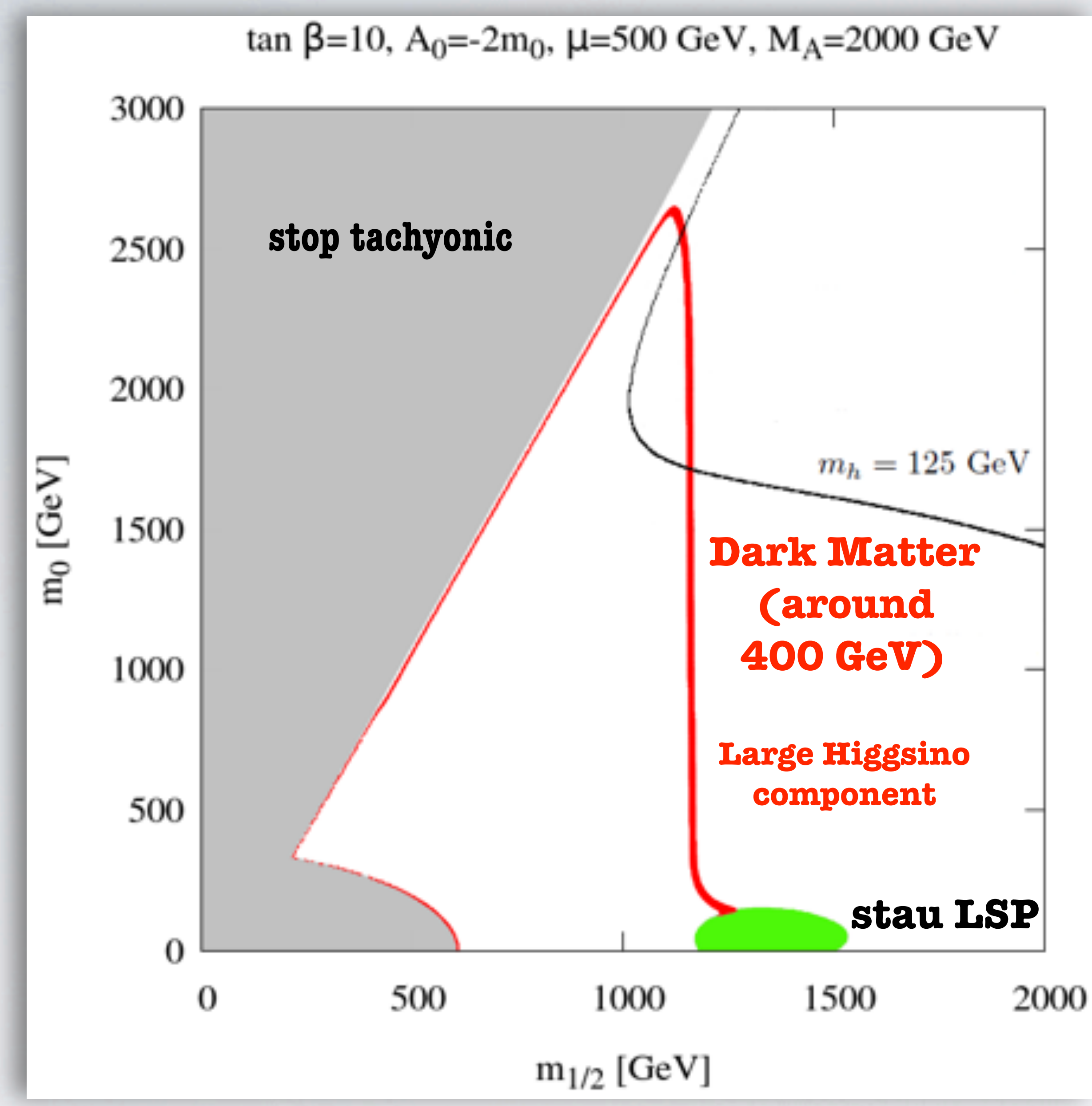
$$H \geq m_\phi$$

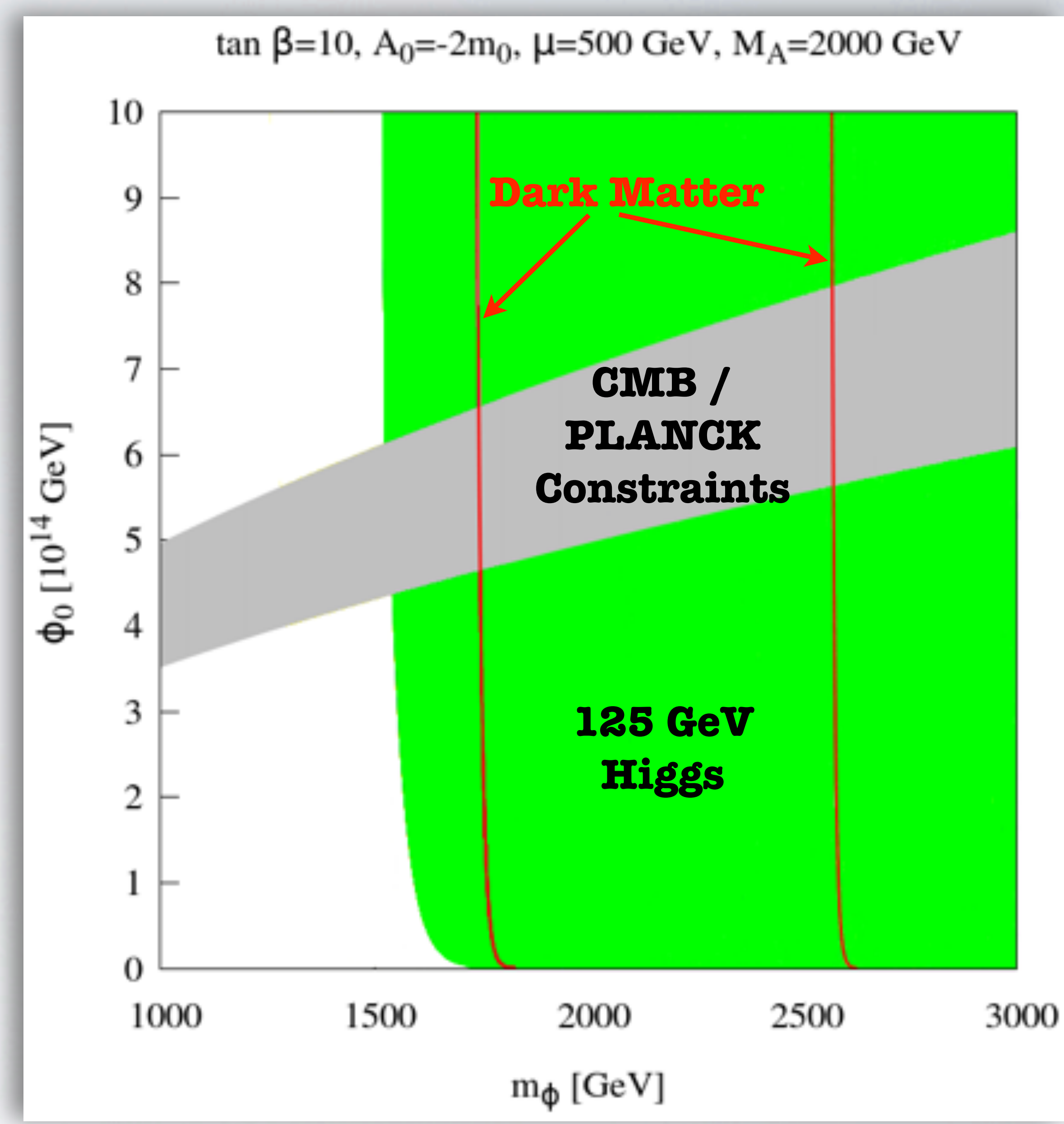




Choudhury, AM, Pal, JCAP (2013)

Correlation between CMB + Dark mater



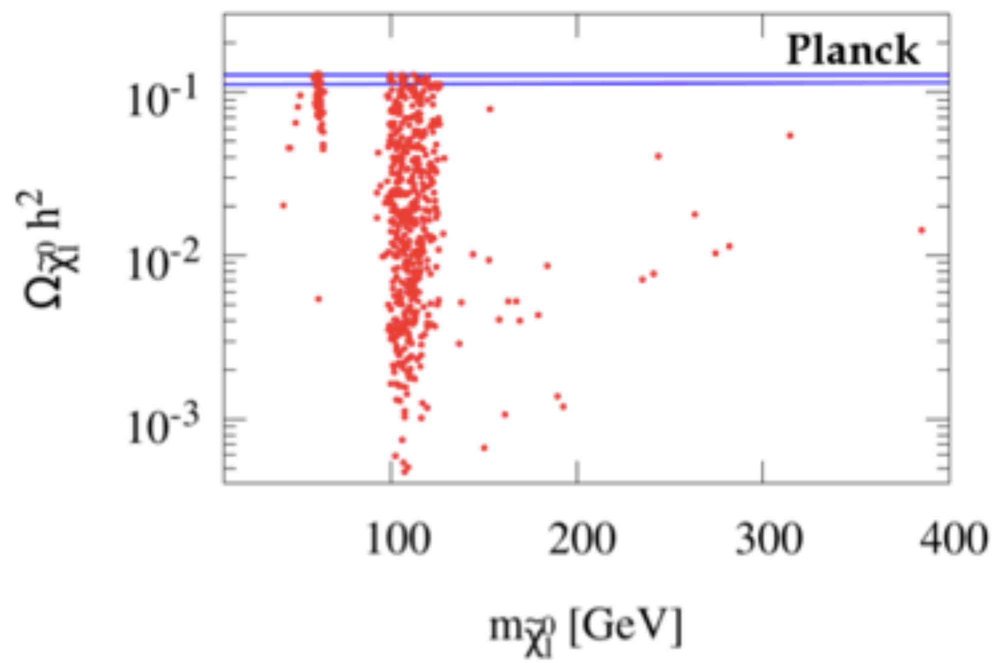


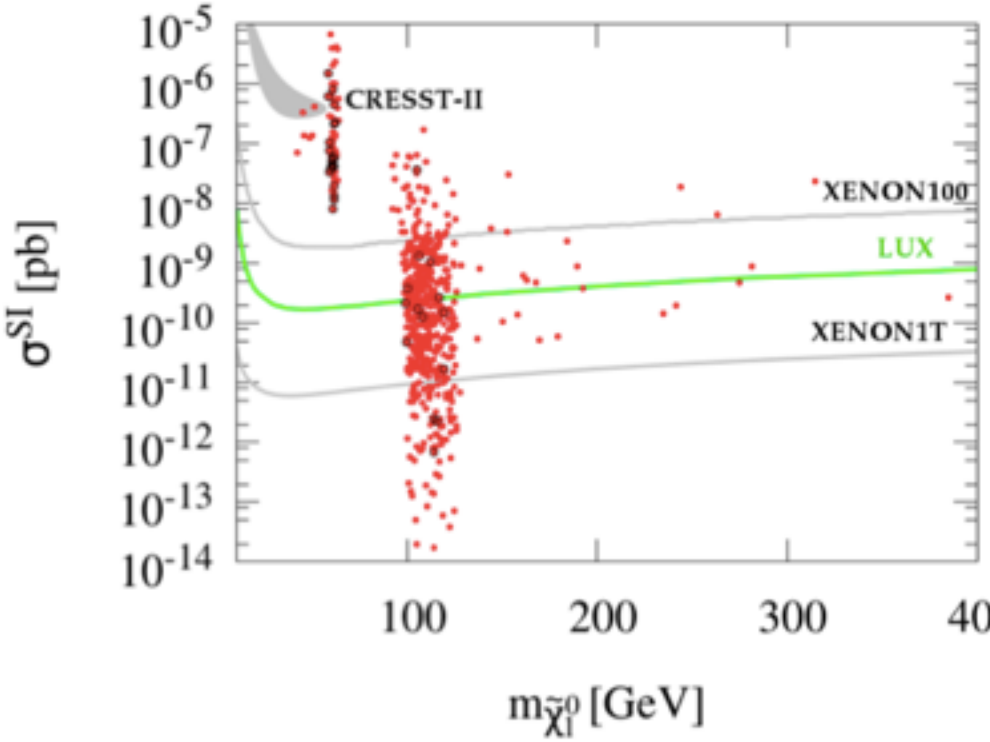
Higgs Mass +Dark matter constraint + CMB for udd Inflaton

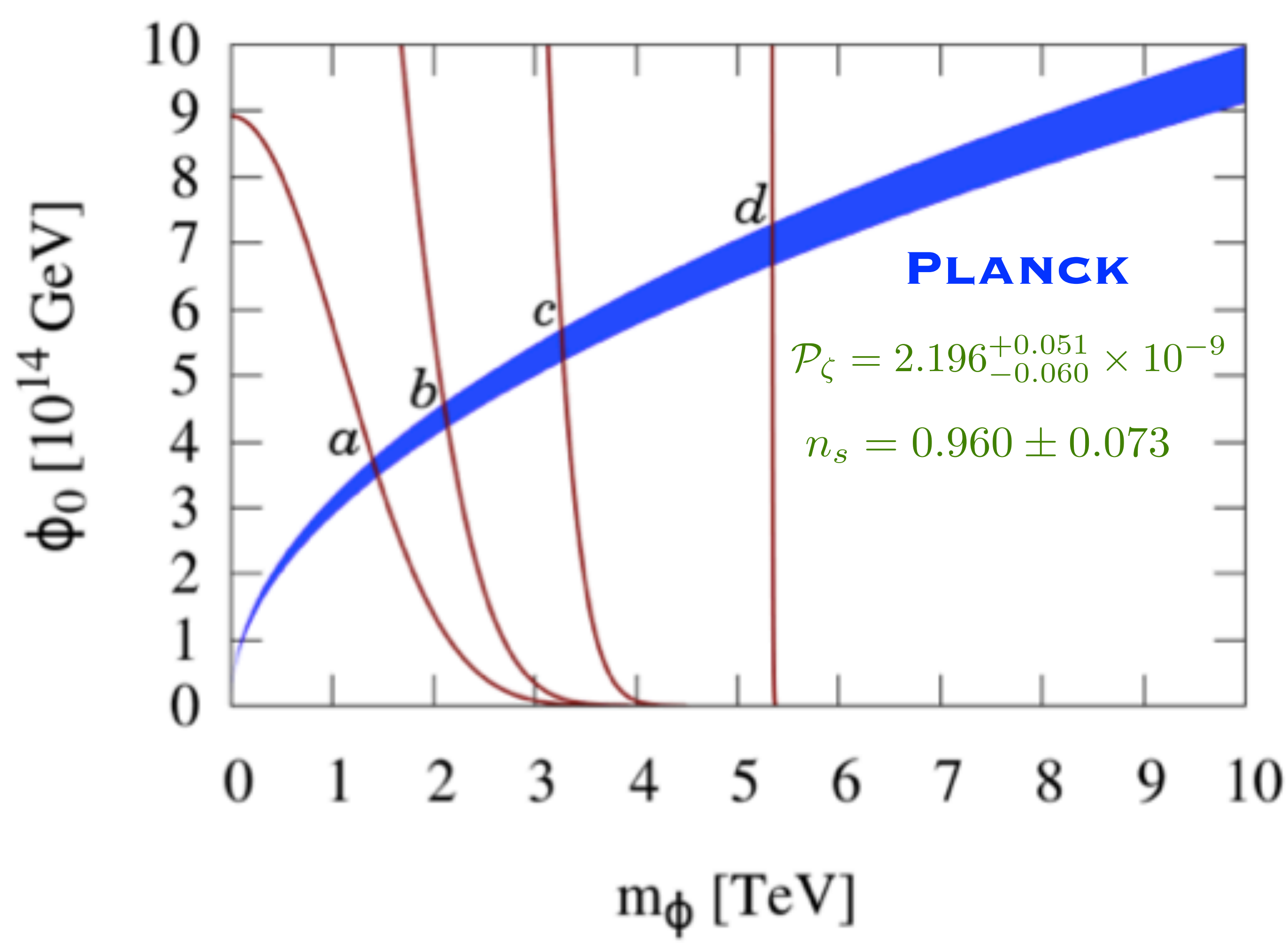
Boehm, DaSilva, AM & Pukartas, PRD (2012), Wang, Pukartas & AM JCAP (2013) (hep-ph/1303.535)

ONE MORE BSM ... NMSSM

NMSSM: can invoke successful electroweak baryogenesis via 1st order phase transition







Higgs Mass constraint
Dark matter constraint
1st order phase transition
Inflationary constraint for udd inflaton

Balasz+AM+ Pukartas + White 1309.5091

LAST 50-60 E-FOLDS MUST HAPPEN WITHIN A VISIBLE SECTOR

	$\mathcal{P}_\zeta$	$\mathcal{P}_\zeta \propto k^{n_s-1}$	$r = \frac{\mathcal{P}_T}{\mathcal{P}_\zeta}$	Hidden Radiation	UV completion	Dark Matter Abundance
Pure Gravity +SM	✓	✓	✓	✓	**Required**	**No prediction**
String Theory	✓	✓	✓	**No prediction**	**Required**	**No prediction**
Higgs Inflation	✓	✓	✓	**NO** ✓	**Required but Quantum Gravity**	**Extra Physics**
Visible Sector, i.e.MSSM	✓	✓	✓	**NO** ✓	**Required but within Matter sector** ✓	✓

Stringy inflation is still helpful but not during last 50-60 e-folds...

$R + R^2$ Gravity is utterly incomplete : requires higher derivative terms

Confusion-3

Large Tensor to Scalar Ratio can be obtained by Sub-Planckian VEV Inflation

$$\frac{3}{25}\sqrt{\frac{r(k_\star)}{0.12}}\left|\left\{\frac{3}{400}\left(\frac{r(k_\star)}{0.12}\right)-\frac{\eta_V(k_\star)}{2}-\frac{1}{2}-\left(8\mathcal{C}_E+\frac{14}{3}\right)\epsilon_V^2(k_\star)-\frac{\eta_V^2(k_\star)}{6}-\frac{\xi_V^2(k_\star)}{8}+\frac{5\eta_V(k_\star)\epsilon_V(k_\star)}{12}-\frac{\sigma_V^3(k_\star)}{24}+\cdots\right\}\right|\approx\frac{|\Delta\phi|}{M_p}$$

Inflection Point Inflation

Ben-Dayan, R. Brustein, JCAP (2009),

Hotchkiss, AM, Seshadri, JCAP (2012)

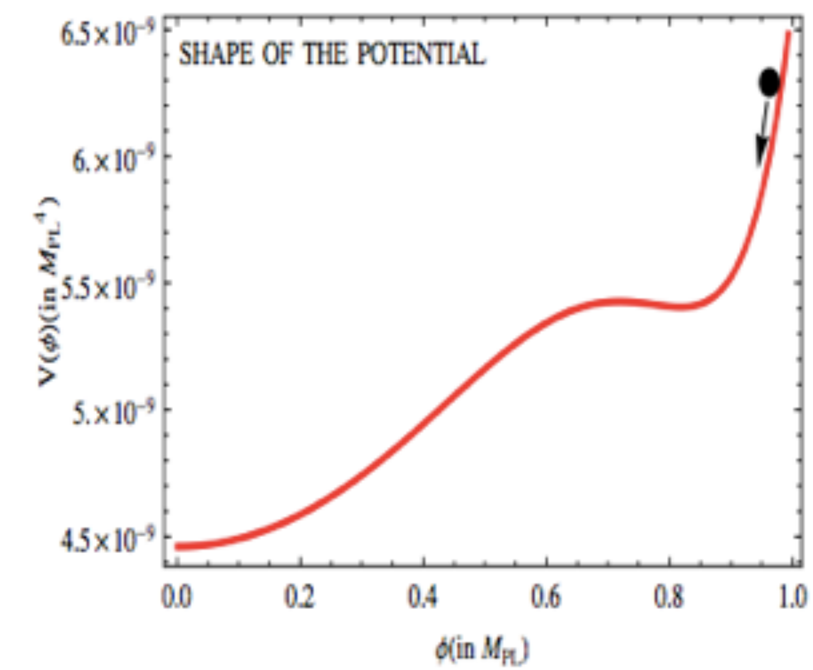
Choudhury, AM, Pal, JCAP (2013), Choudhury, AM, 1306.4496

An accurate bound on tensor-to-scalar ratio and the scale of inflation

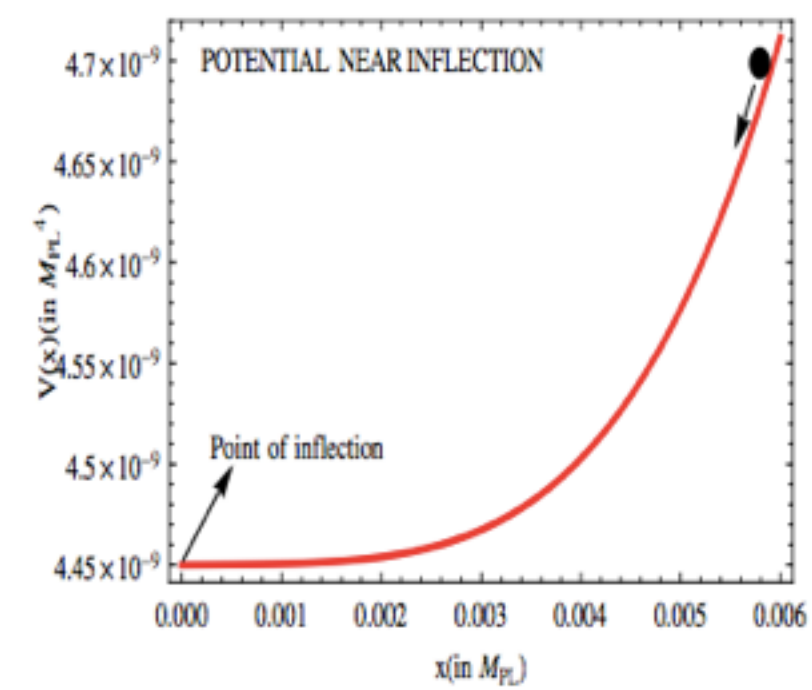
Sayantan Choudhury [1] and Anupam Mazumdar[2]

[1] *Physics and Applied Mathematics Unit, Indian Statistical Institute, 203 B.T. Road, Kolkata 700 108, INDIA and*
[2] *Consortium for Fundamental Physics, Physics Department, Lancaster University, LA1 4YB, UK*

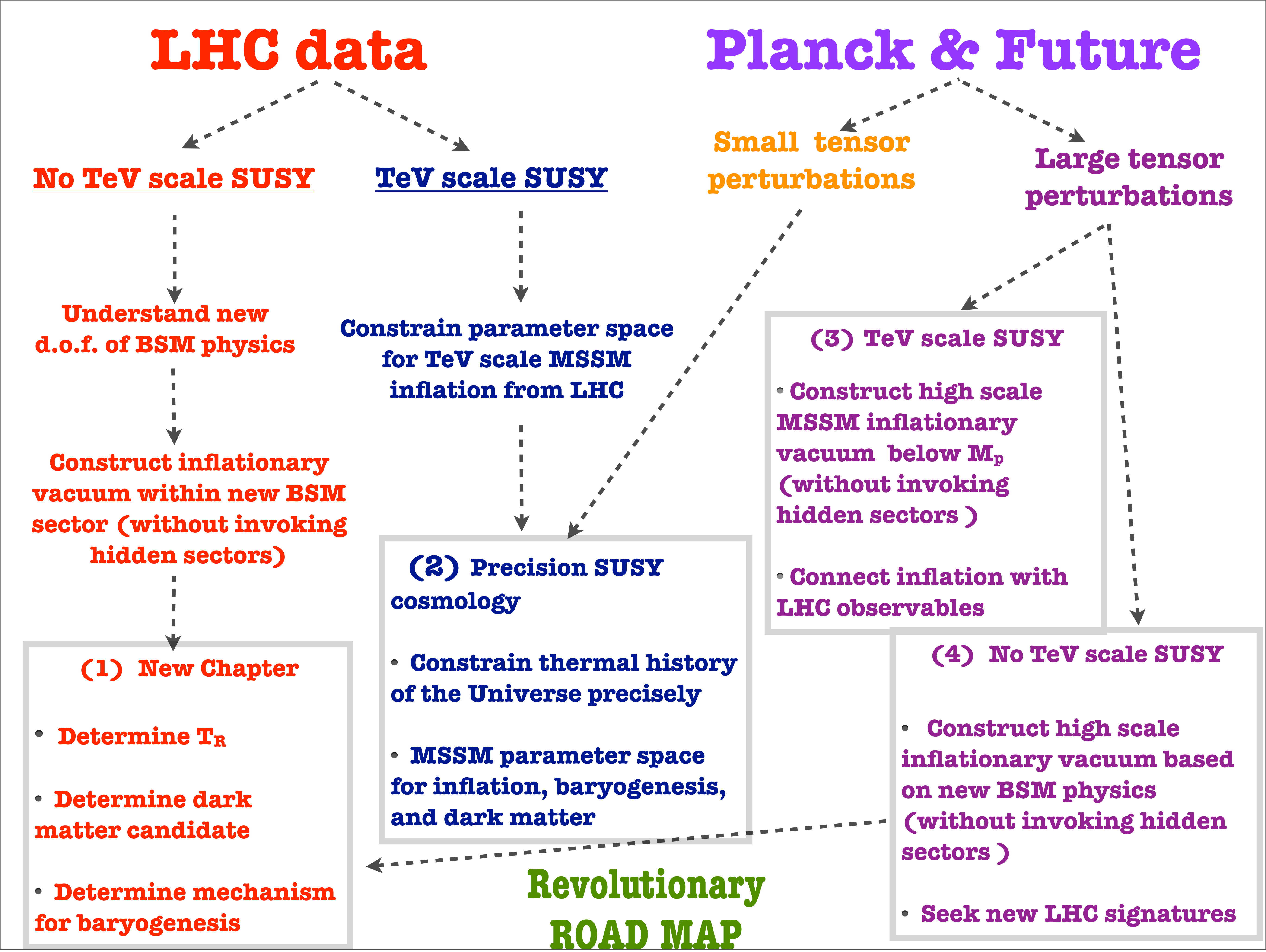
In this paper we provide an accurate bound on tensor-to-scalar ratio (r) for class of models where inflation always occurs below the Planck scale, and the field displacement during inflation remains sub-Planckian.



(a) Shape of the potential. Note the existence of a flat plateau below the Planck scale.



(b) The blow up picture of the potential near the inflection point. Here $x=\phi-\phi_0$, where ϕ_0 is the inflection-point.


LHC data
Planck & Future
No TeV scale SUSY
TeV scale SUSY
Small tensor perturbations
Large tensor perturbations
Understand new d.o.f. of BSM physics
Constrain parameter space for TeV scale MSSM inflation from LHC
(3) TeV scale SUSY
• Construct high scale MSSM inflationary vacuum below M_p (without invoking hidden sectors)
• Connect inflation with LHC observables
Construct inflationary vacuum within new BSM sector (without invoking hidden sectors)
(2) Precision SUSY cosmology
• Constrain thermal history of the Universe precisely
• MSSM parameter space for inflation, baryogenesis, and dark matter
(1) New Chapter
• Determine T_R
• Determine dark matter candidate
• Determine mechanism for baryogenesis
(4) No TeV scale SUSY
• Construct high scale inflationary vacuum based on new BSM physics (without invoking hidden sectors)
• Seek new LHC signatures
Revolutionary ROAD MAP

Extra Slides

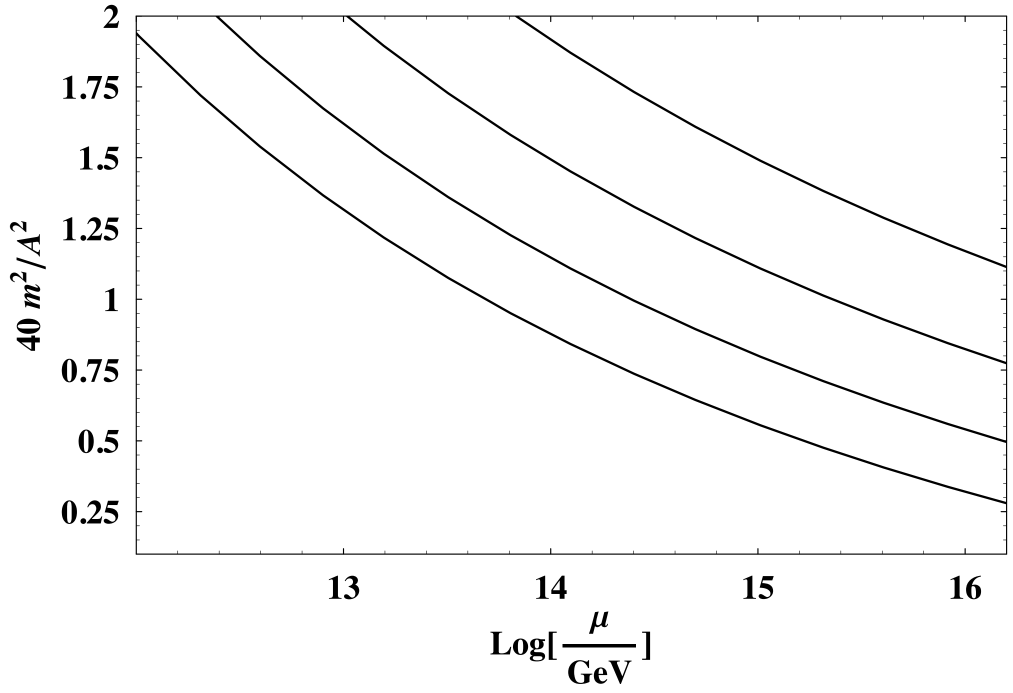


FIG. 2: The ratio $(40m_\phi^2/A^2)$ as a function of $\mathrm{Log}[\frac{\mu}{\mathrm{GeV}}]$ in the case of *udd* flat direction. The curves are for M_{GUT} boundary values m_ϕ= 150, 200, 250, 300 GeV (respectively from left to right), and $A = 1.6$ TeV.

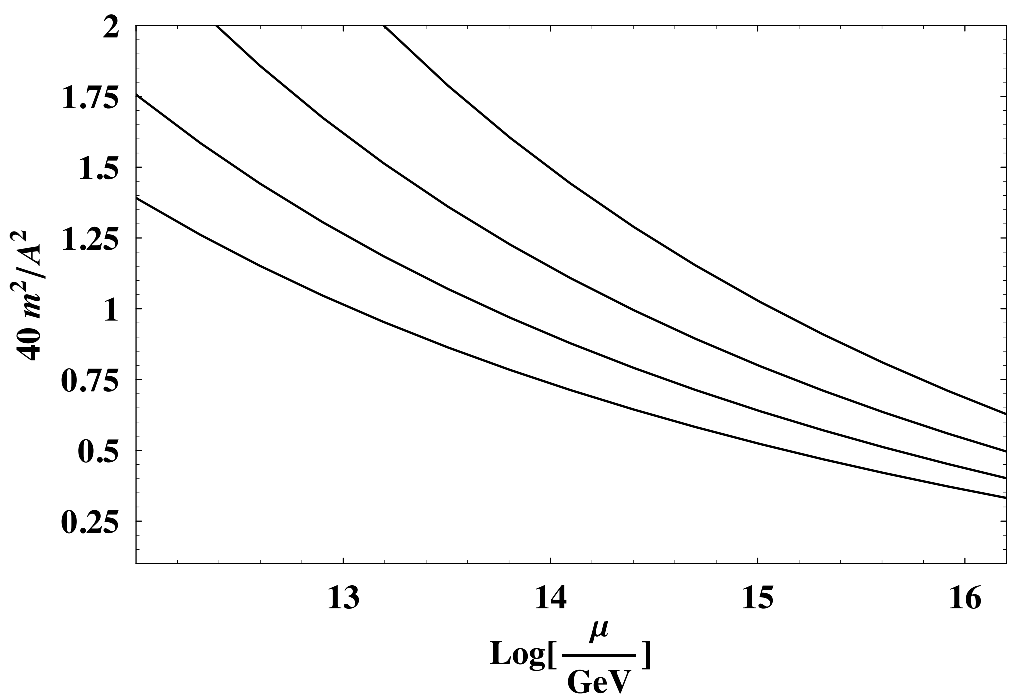


FIG. 3: The ratio $(40m_\phi^2/A^2)$ as a function of $\mathrm{Log}[\frac{\mu}{\mathrm{GeV}}]$ in the case of *udd* flat direction. The curves are for M_{GUT} boundary values A_{udd}=1.6, 1.8, 2.0, 2.2 TeV (respectively from top to bottom), and $m_\phi = 400$ GeV.

Is there a Fine - Tuning ?

$$m_\phi(\phi_0),\ A(\phi_0)$$

RG - Equations

$$m_\phi(100\ \mathrm{GeV}),\ A(100\ \mathrm{GeV})$$

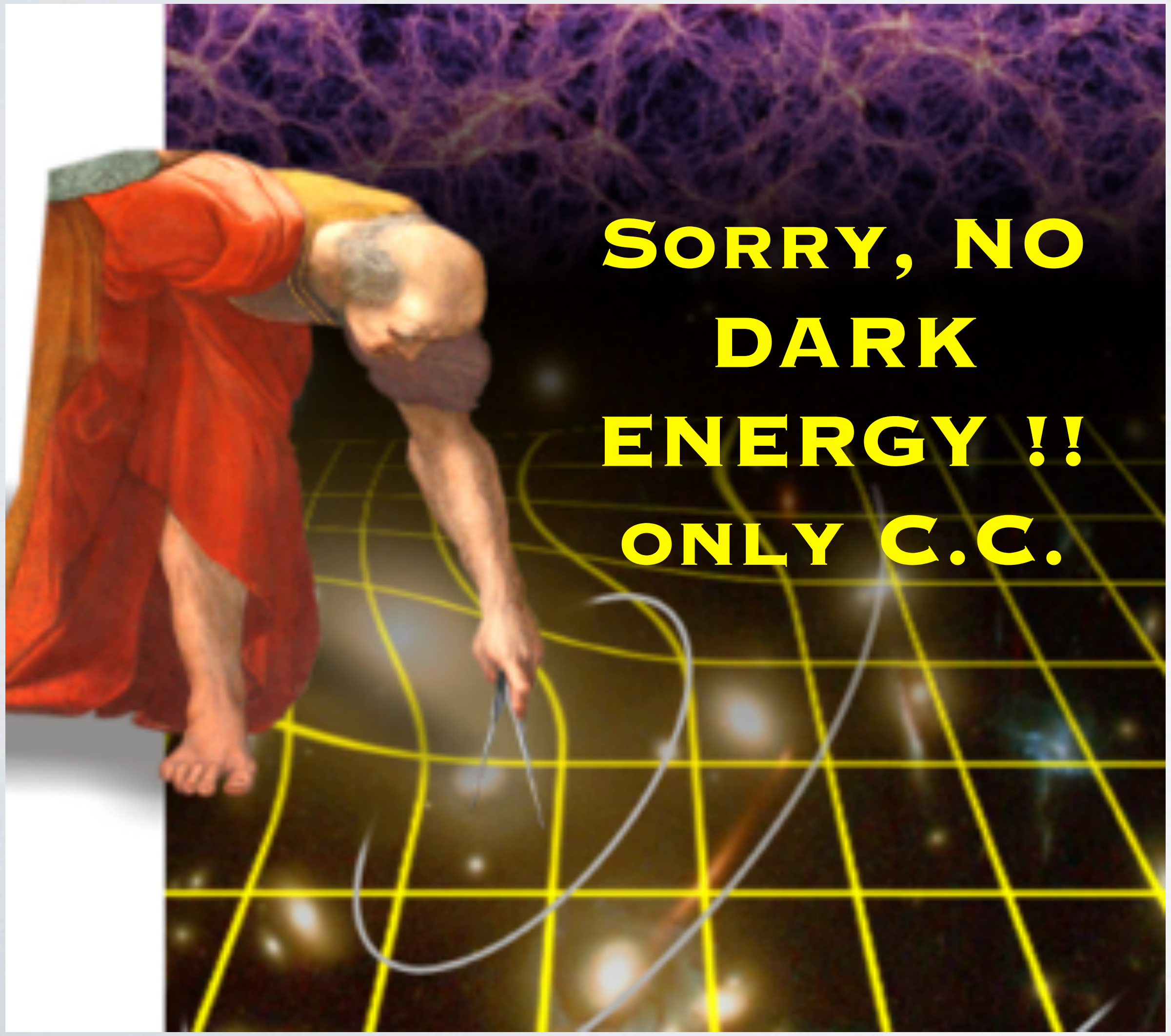
Predictions from 10^{500} vacua

Excess Dark Matter

Excess Gravitinos

Excess Dark radiation

No Solution to Singularity problem



(1) Setting up the initial condition for a visible sector inflation

$$V = V_{Landscape} + V_{MSSM}$$

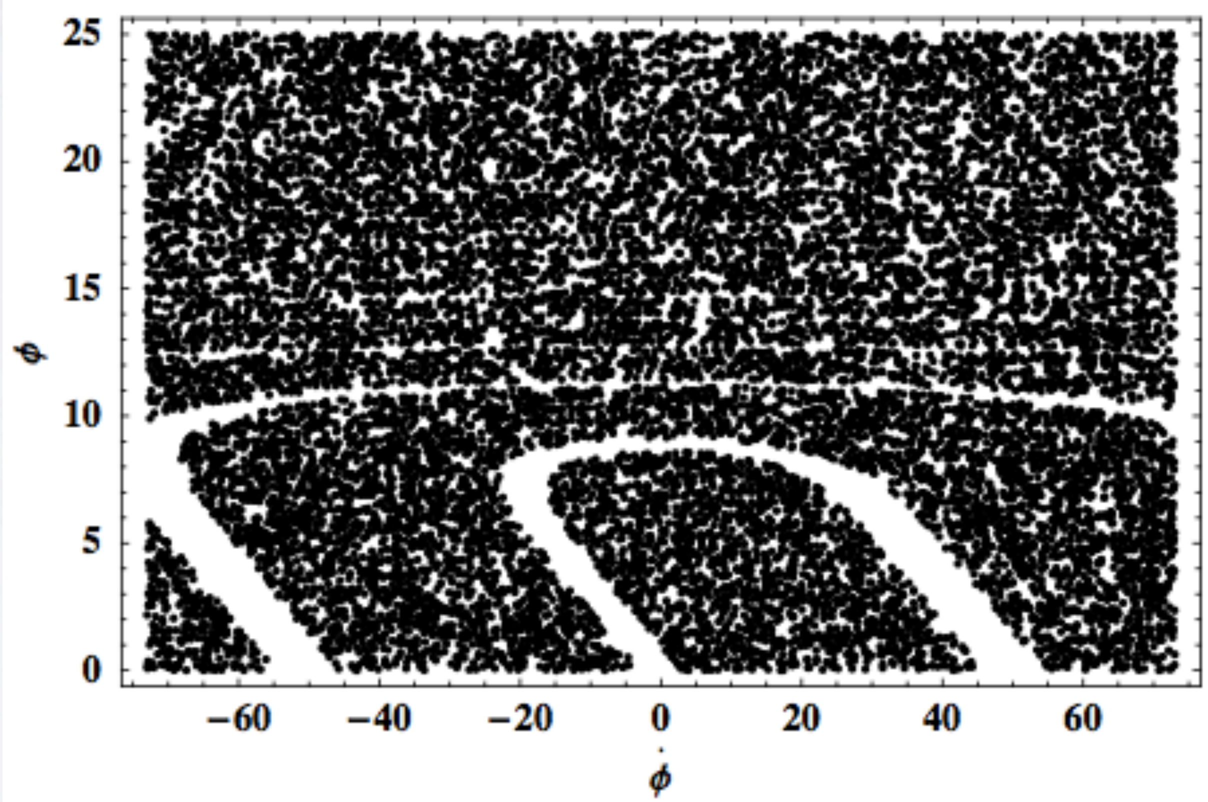


FIG. 5: Same as in Fig. (4) for $H_{\rm false} = 10^3 m_\phi$.

(2) Cosmological constant

How about Cosmological Singularity Problem?

String theory is immature to tackle this problem: one requires close string field theory

$$S_q = \int d^4x\sqrt{-g}[RF_1(\Box)R + RF_2(\Box)\nabla_\mu\nabla_\nu R^{\mu\nu} + R_{\mu\nu}F_3(\Box)R^{\mu\nu} + R^\nu_\mu F_4(\Box)\nabla_\nu\nabla_\lambda R^{\mu\lambda}$$
$$+ R^{\lambda\sigma}F_5(\Box)\nabla_\mu\nabla_\sigma\nabla_\nu\nabla_\lambda R^{\mu\nu} + RF_6(\Box)\nabla_\mu\nabla_\nu\nabla_\lambda\nabla_\sigma R^{\mu\nu\lambda\sigma} + R_{\mu\lambda}F_7(\Box)\nabla_\nu\nabla_\sigma R^{\mu\nu\lambda\sigma}$$
$$+ R^\rho_\lambda F_8(\Box)\nabla_\mu\nabla_\sigma\nabla_\nu\nabla_\rho R^{\mu\nu\lambda\sigma} + R^{\mu_1\nu_1}F_9(\Box)\nabla_{\mu_1}\nabla_{\nu_1}\nabla_\mu\nabla_\nu\nabla_\lambda\nabla_\sigma R^{\mu\nu\lambda\sigma}$$
$$+ R_{\mu\nu\lambda\sigma}F_{10}(\Box)R^{\mu\nu\lambda\sigma} + R^\rho_{\mu\nu\lambda}F_{11}(\Box)\nabla_\rho\nabla_\sigma R^{\mu\nu\lambda\sigma} + R_{\mu\rho_1\nu\sigma_1}F_{12}(\Box)\nabla^{\rho_1}\nabla^{\sigma_1}\nabla_\rho\nabla_\sigma R^{\mu\rho\nu\sigma}$$
$$+ R_\mu^{\nu_1\rho_1\sigma_1}F_{13}(\Box)\nabla_{\rho_1}\nabla_{\sigma_1}\nabla_{\nu_1}\nabla_\nu\nabla_\rho\nabla_\sigma R^{\mu\nu\lambda\sigma} + R^{\mu_1\nu_1\rho_1\sigma_1}F_{14}(\Box)\nabla_{\rho_1}\nabla_{\sigma_1}\nabla_{\nu_1}\nabla_{\mu_1}\nabla_\mu\nabla_\nu\nabla_\rho\nabla_\sigma R^{\mu\nu\lambda\sigma}]$$

Gravity Invokes ∞ Higher Order Corrections

$$S = \int d^4x\sqrt{-g}\left[R + R\mathcal{F}_1(\Box)R + R_{\mu\nu}\mathcal{F}_2(\Box)R^{\mu\nu} + R_{\mu\nu\alpha\beta}\mathcal{F}_3(\Box)R^{\mu\nu\alpha\beta}\right]$$

$$\mathcal{F}_i(\Box) = \sum_n^\infty a_n\Box^n$$

$$\Delta\mathcal{L} = \sqrt{-g}\left(\alpha R^2 + \beta R^2_{\mu\nu} + \gamma R^2_{\alpha\beta\mu\nu}\right)$$

$$2\mathcal{F}_1(\Box) + \mathcal{F}_2(\Box) + 2\mathcal{F}_3(\Box) = 0$$

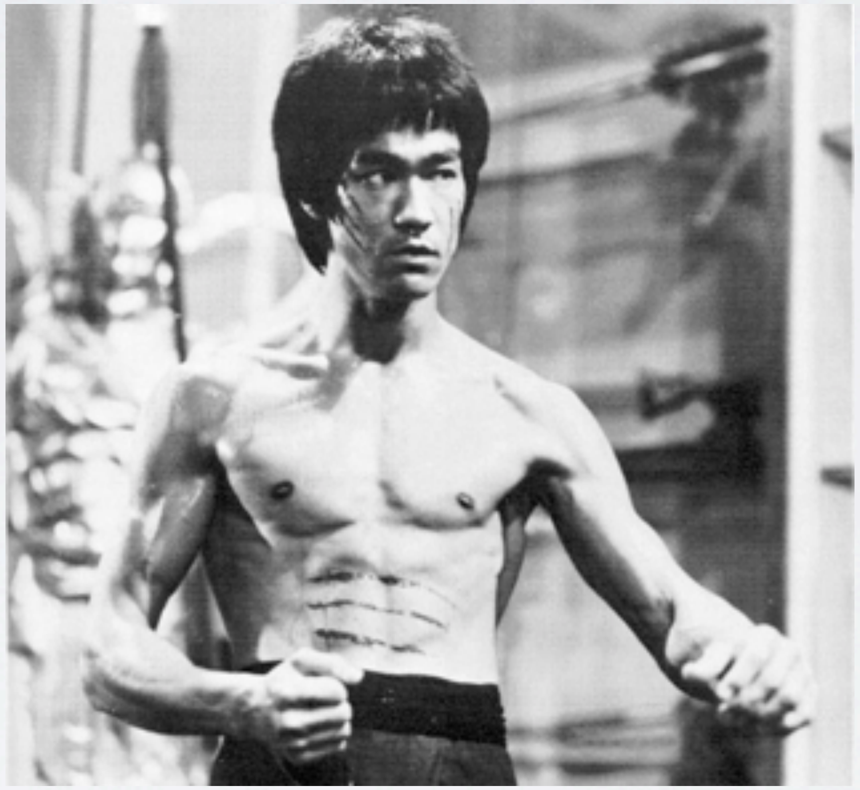
Classical Gravity becomes WEAK in the UV

Biswas, Gerwick, Koivisto & AM, Phys. Rev. Lett.

SUSY SCALE COULD BE HIGHER THAN TEV !!

UNDERSTANDING FINE TUNING IS IMPORTANT

IT CAN ONLY BE ADDRESSED WITHIN A CONTEXT

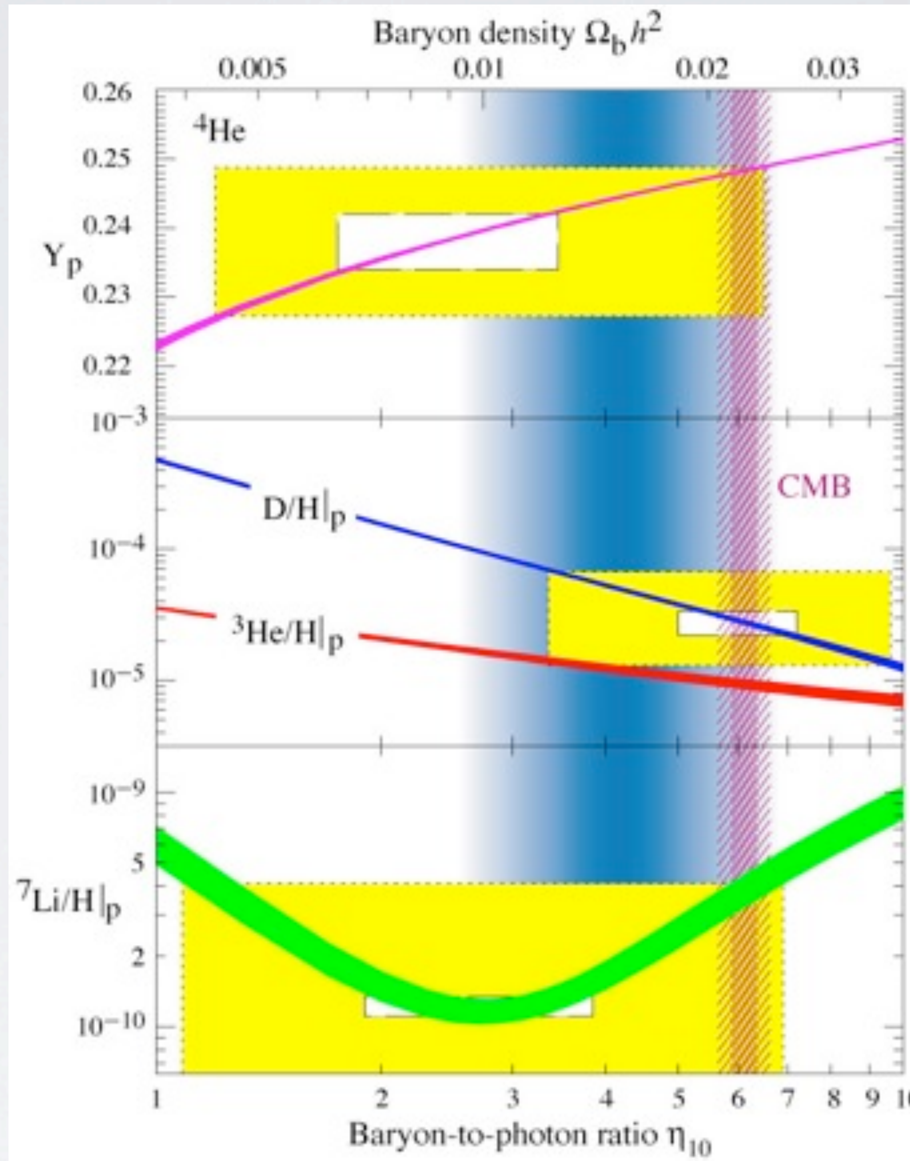


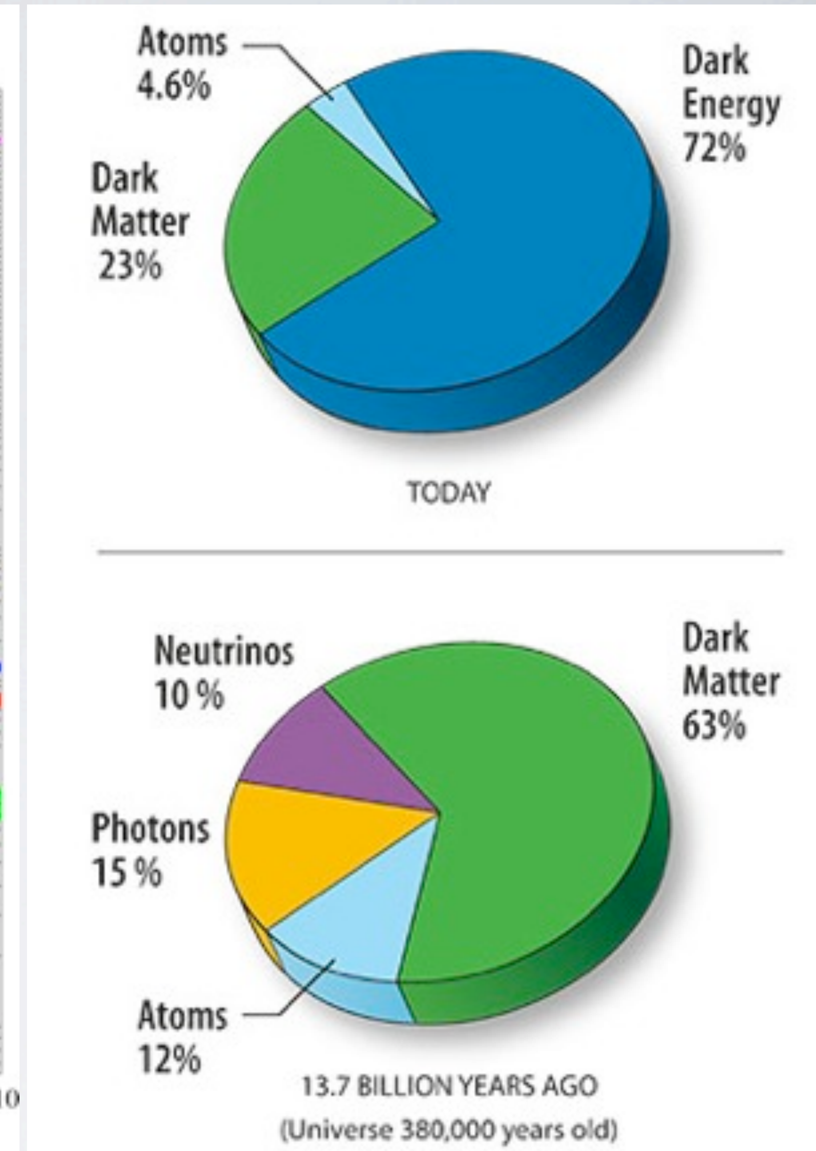
$$10^{-11}\ for\ neutrino\ mass\ and\ 10^{-44}\ for\ C.C$$

NATURE IS FINE TUNED

FOUR REASONS WHY INFLATION MUST END IN A <u>VISIBLE SECTOR</u>

- Big Bang Nucleosynthesis
- Baryonic Asymmetry
- Observed Dark Matter Abundance
- dark radiation





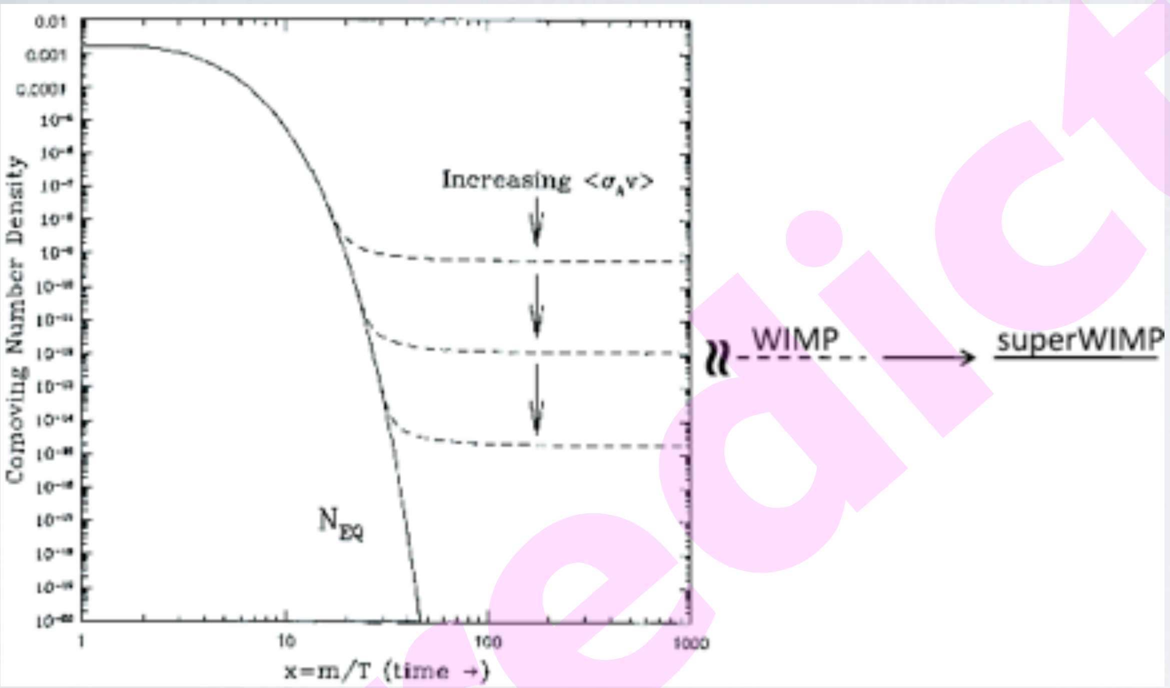
$$\Omega_X h^2 \approx 10^{17} \left(\frac{T_R}{10^9\ GeV} \right) \frac{\rho_X}{\rho_{inf}}$$

Hidden sector Inflation can easily <u>Overproduce</u> any Dark long lived sector

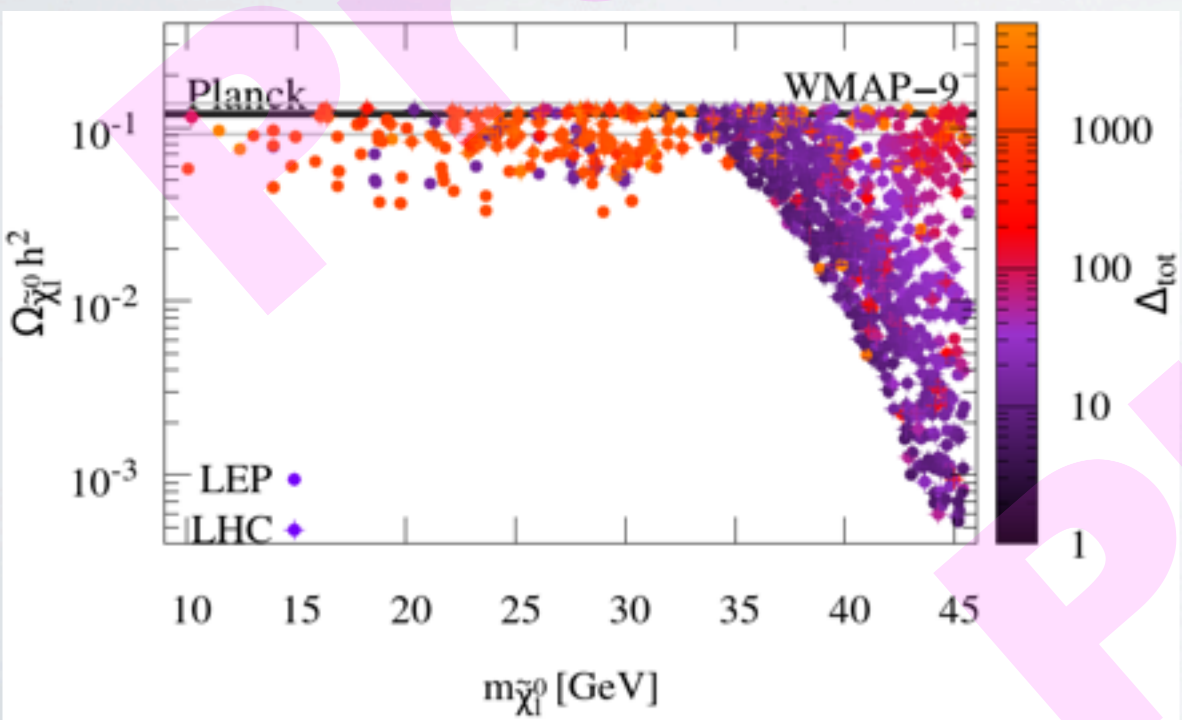
YOU REALLY NEED TO SUPPRESS THE BRANCHING RATIO

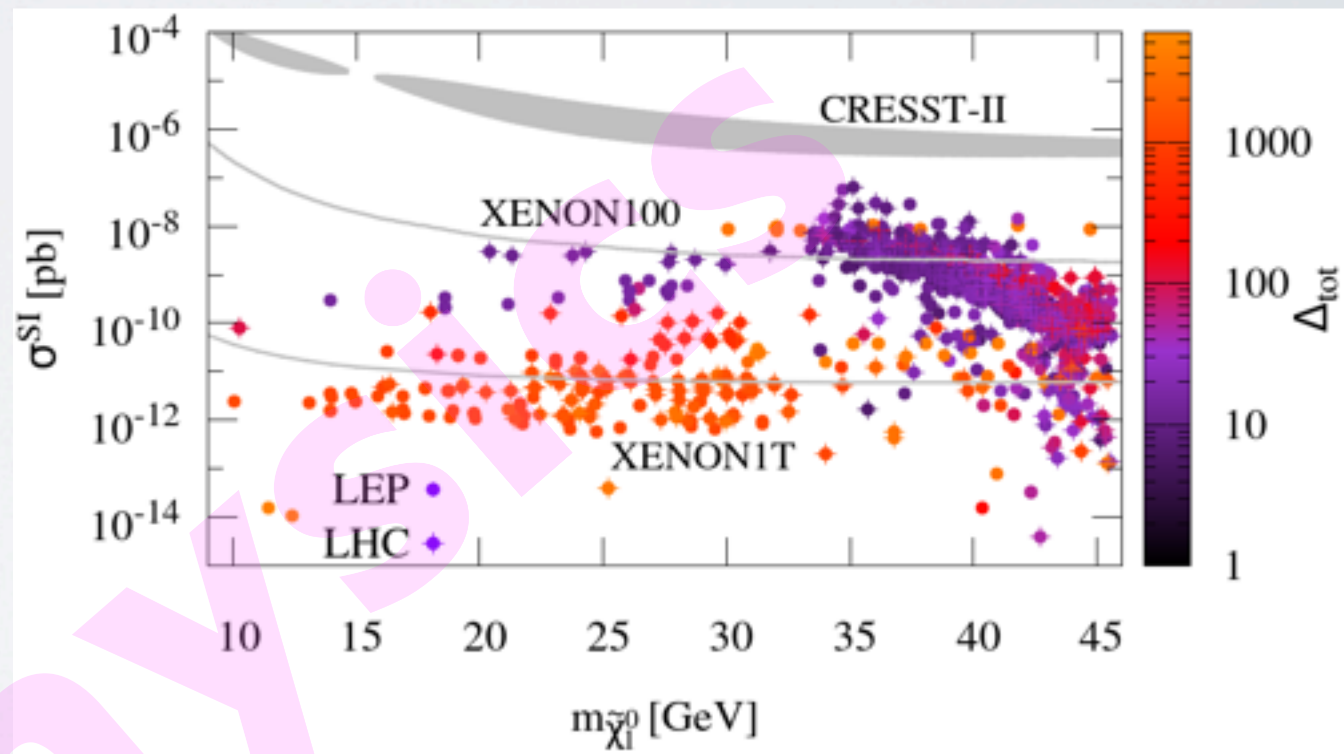
What about Dark Matter ?

Concrete predictions can be made ONLY for a WIMP scenario
--> Particle Physics Embedding (BSM Physics)



$$\Omega h^2 \approx \frac{3\times 10^{-27}\mathrm{cm}^2/\mathrm{s}}{\langle \sigma_{ann} v\rangle}$$

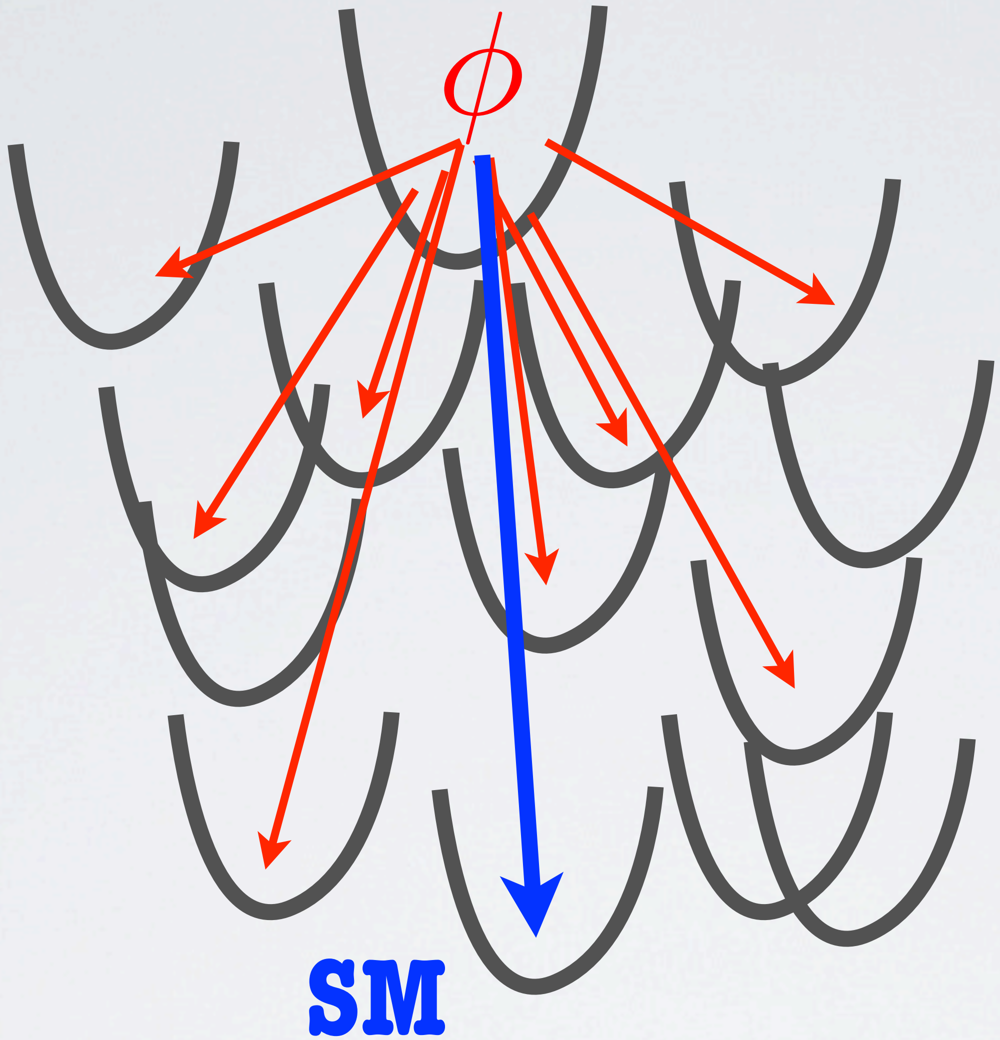




Latest Status on light Neutralino Dark Matter

Boehm, Dev, AM, Pukartas

Perhaps we can NEVER make it predictive

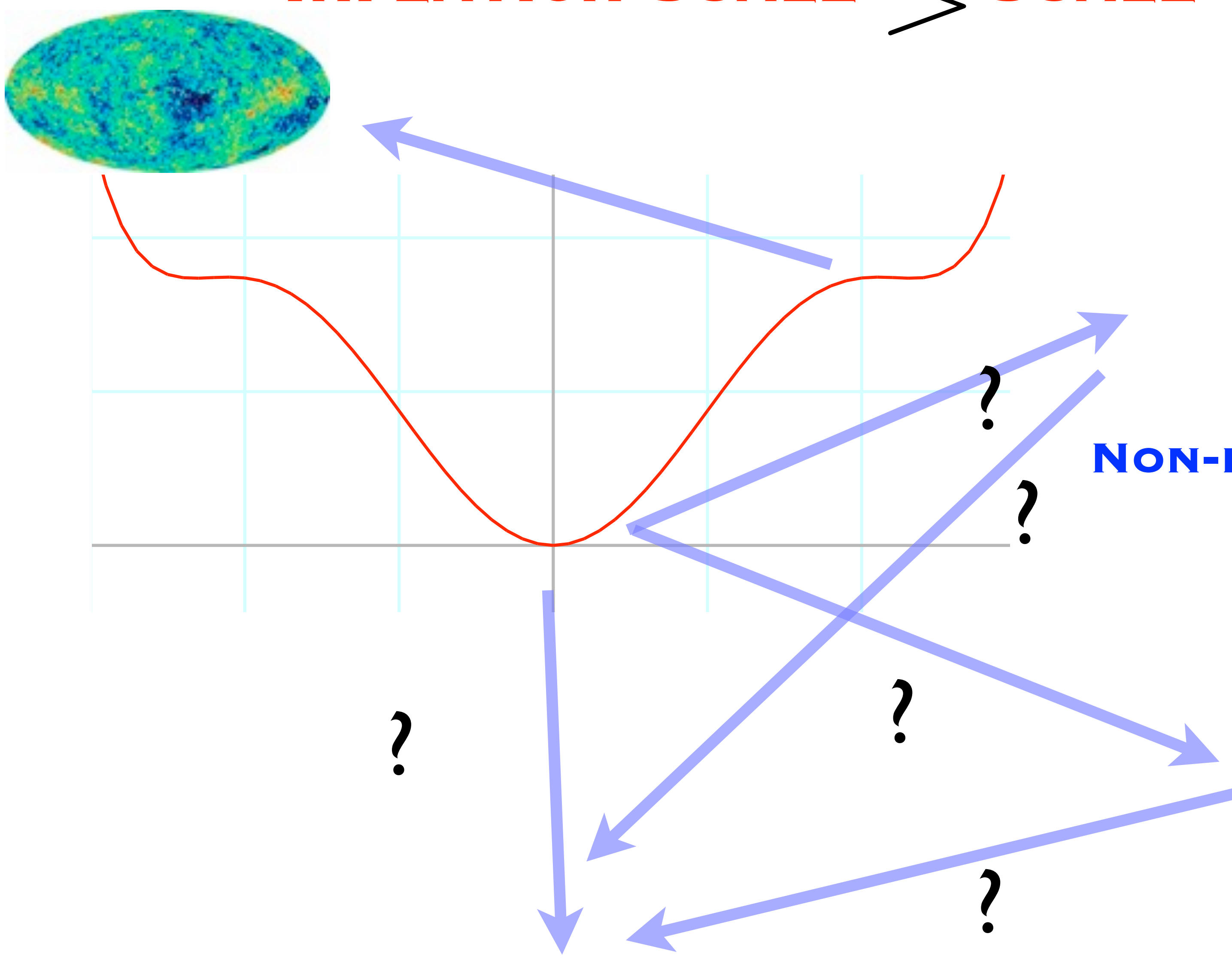


One has to know all the HIDDEN sectors, then they are NO longer HIDDEN any more!!

Jumbled Route for a singlet/hidden inflaton

Inflation Scale $\lessgtr$ Scale of Hidden sector

$10^{18}\ GeV$



Hidden Sectors ?

Non-perturbative, preheating

Hidden sector must not harbor dark sector

Hidden Sectors ?

$10^{3}\ GeV$

Observable Sector

We need to know how the Hidden sectors are coupled to the Observable sector

Top-down & Bottom-up approach

Cicoli, AM, JCAP(2010), PRD (2010)

Even if the origin of Inflaton comes from SUSY S(10)

$$
\begin{aligned}
SO(10) &\xrightarrow{M_G} SU(4)_c \times SU(2)_L \times SU(2)_R \\
&\xrightarrow{M_X} SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L} \\
&\xrightarrow{M_{B-L}} SU(3)_c \times SU(2)_L \times U(1)_Y \\
&\xrightarrow{m_W} SU(3)_c \times U(1)_{em}.
\end{aligned}
$$

There are many scalars - naturally their masses/ VEVs are all at the GUT scale !!

None of them can be made technically light to be an inflaton

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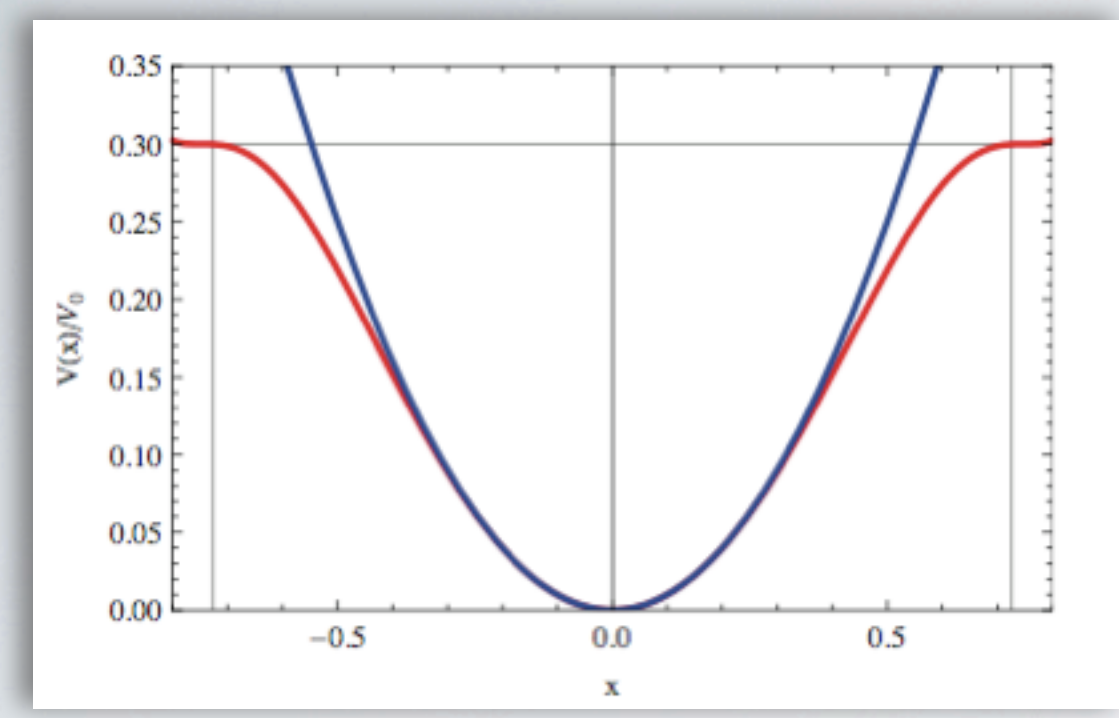
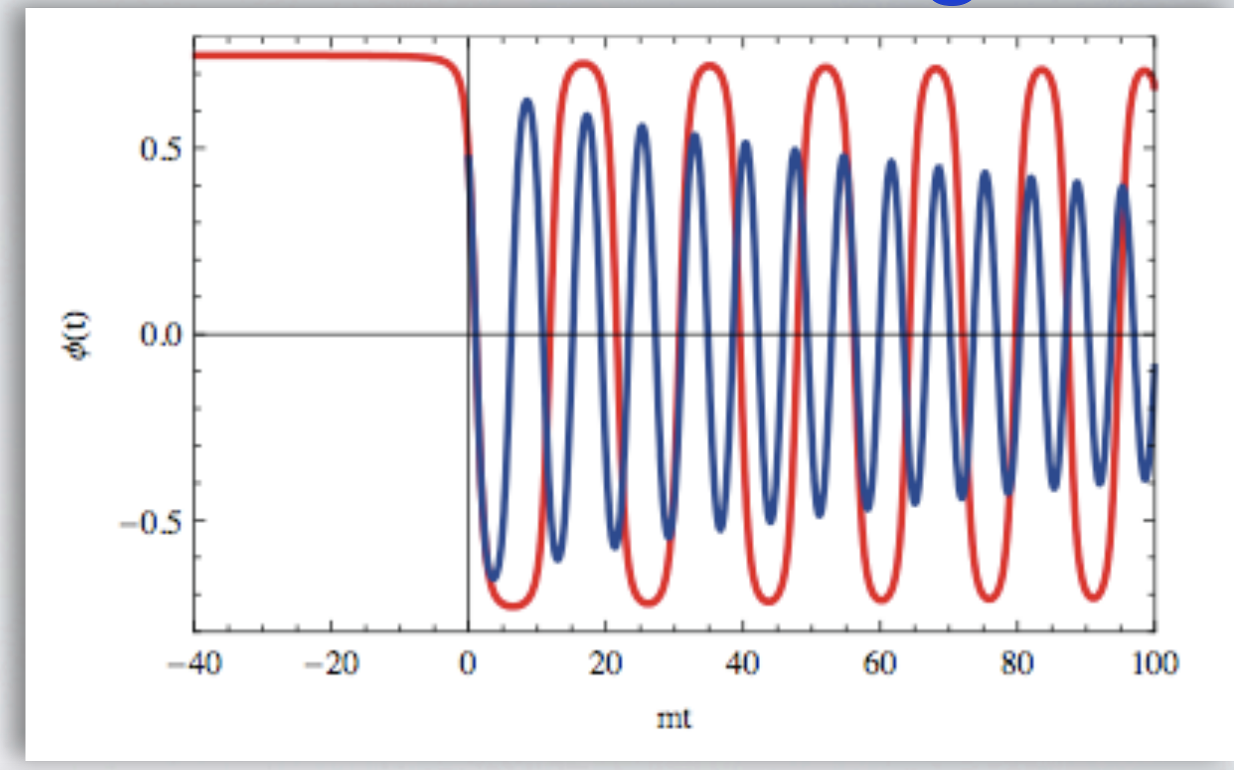
Particle physics models of inflation and curvaton scenarios

Anupam Mazumdar[a,b,*], Jonathan Rocher[c]

MSSM dof Via Instant Preheating



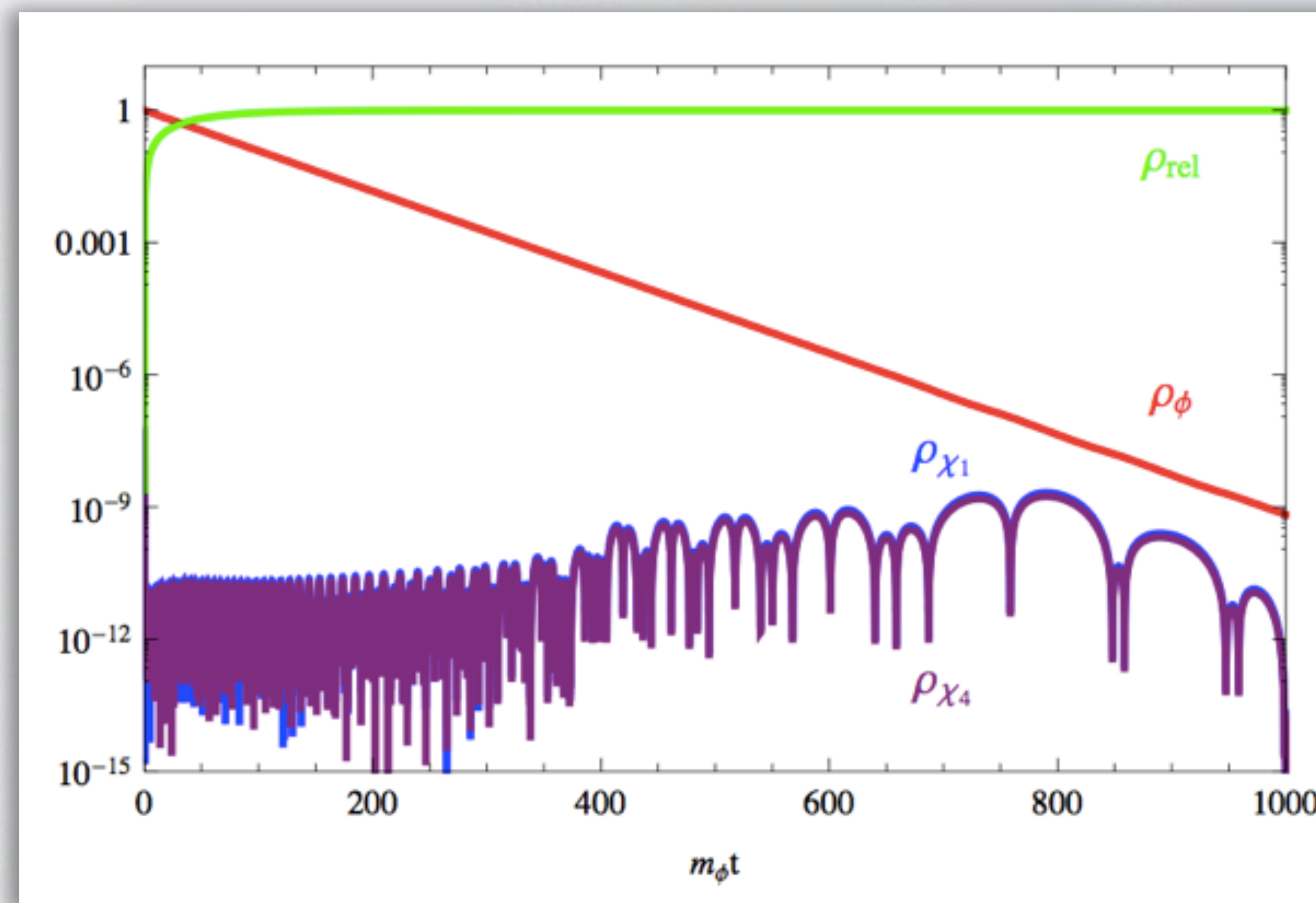


$$V = \frac{1}{2}m^2\phi^2 - A\frac{\phi^6}{M_P^3} + \frac{\phi^{10}}{M_P^4}$$

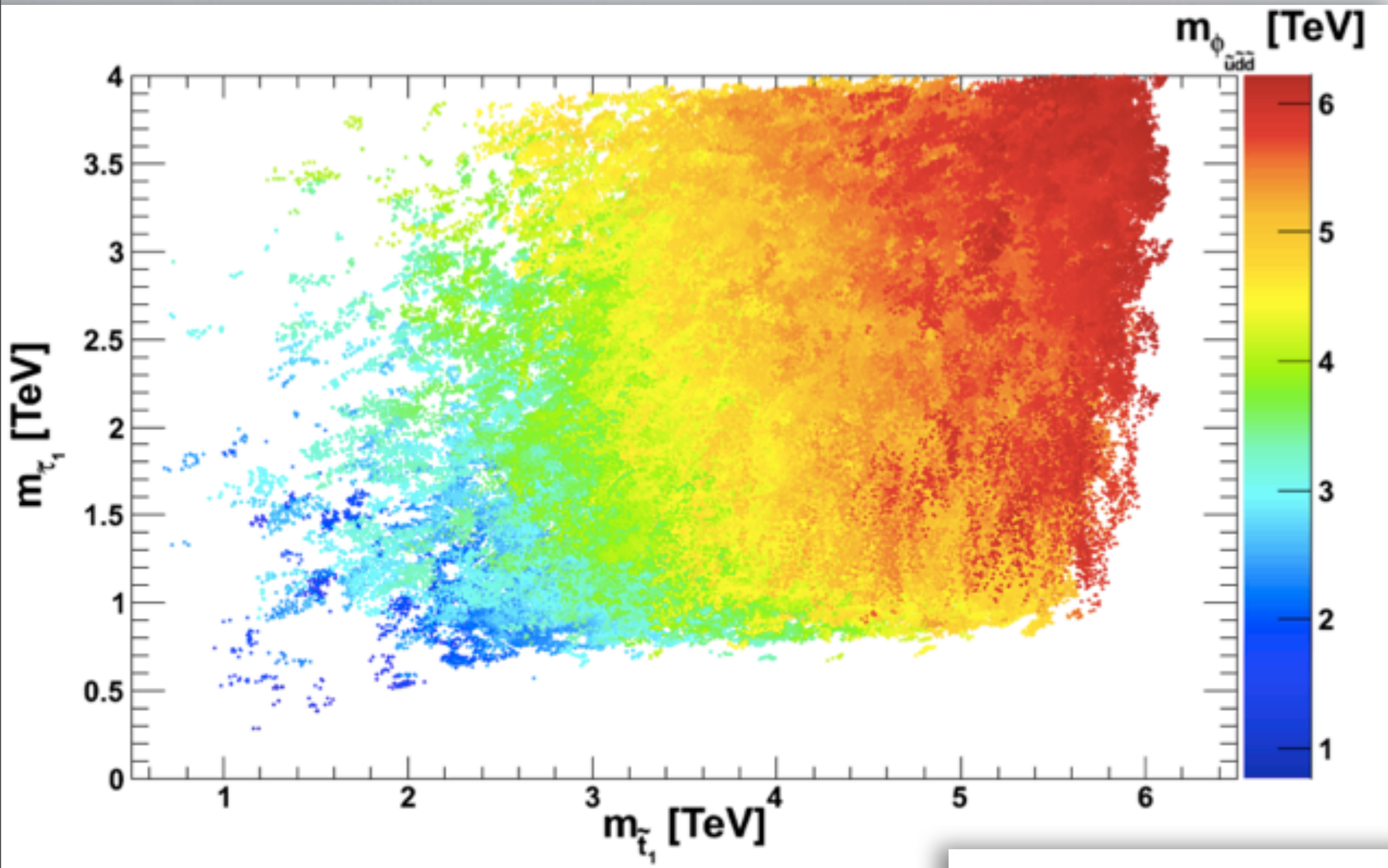
$$\frac{\rho_{rel}}{\rho_\phi} \sim 10\% \text{ (per crossing)}$$

$$T_{rh} = \left(\frac{30}{\pi^2 g_*}\right)^{1/4} \rho_\phi^{1/4}$$

$$\sim 3 \times 10^8 \text{ GeV (for } m_\phi \sim 1 \text{ TeV)}$$

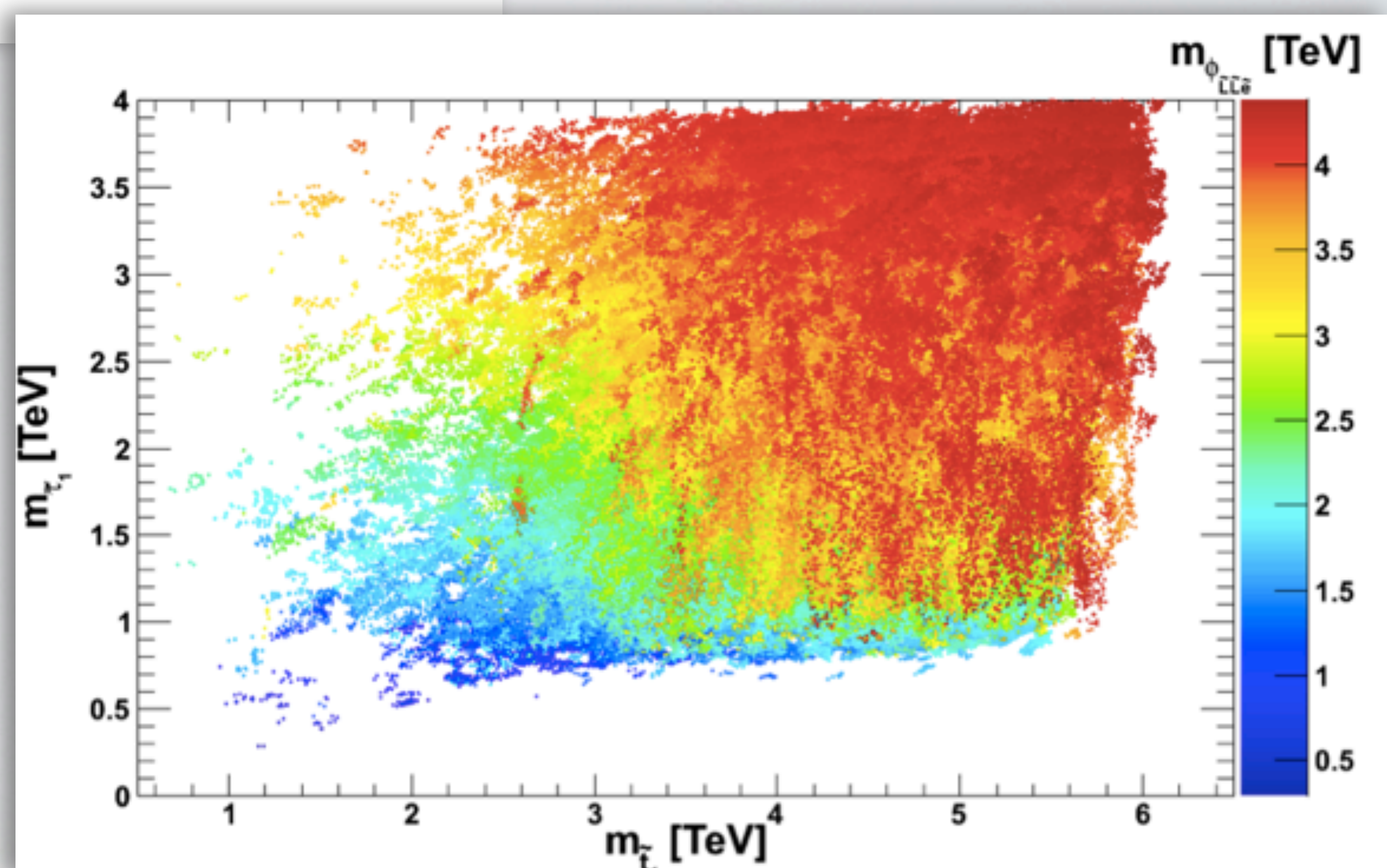


Allahverdi, Ferrantelli, Garcia-Bellido & AM PRD (2011)



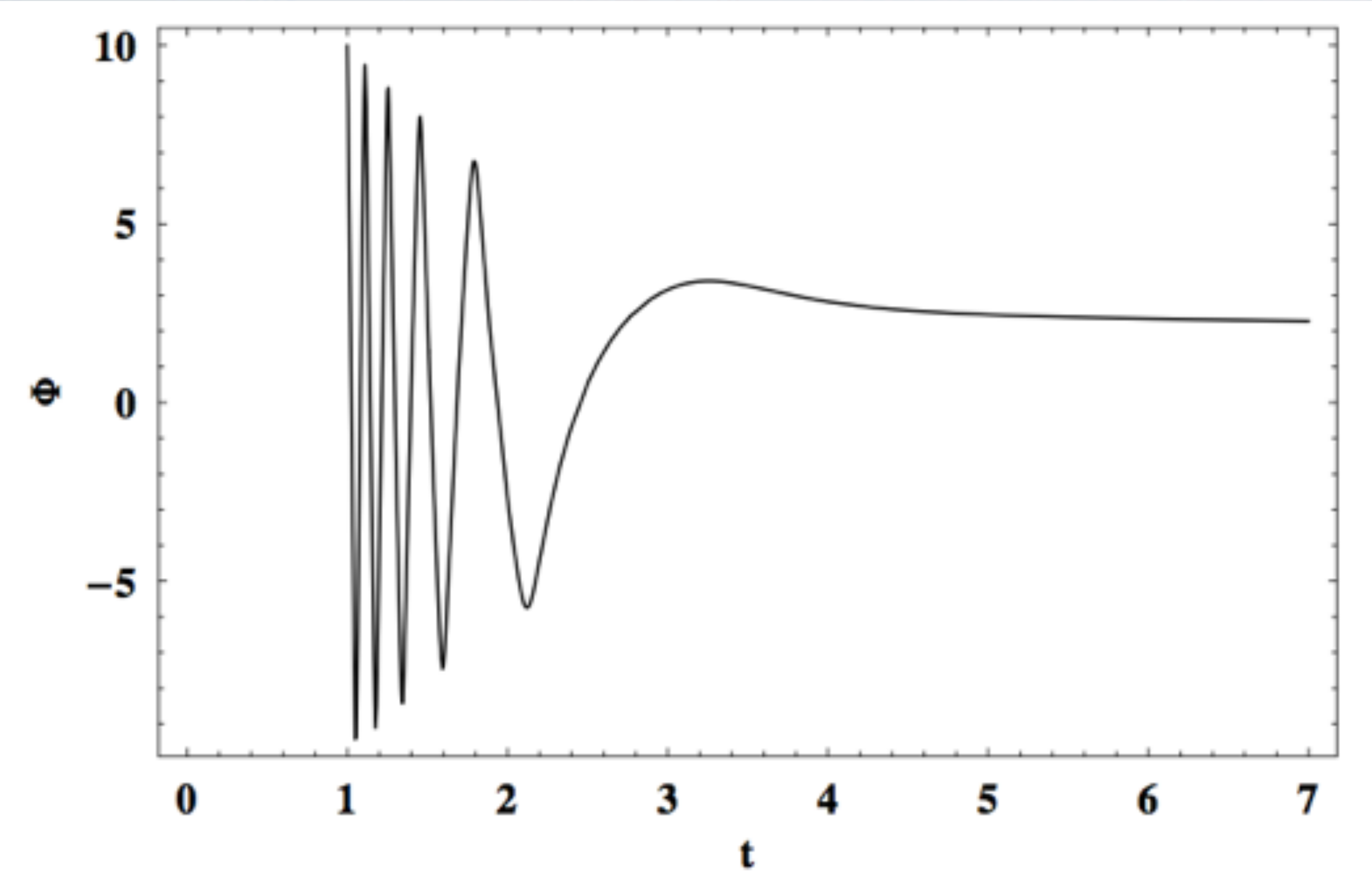
Scanning NUHM-2 scenario

Correlation between Inflaton, Stau & lightest Stop



Boehm, DaSilva, AM & Pukartas, PRD (2012),

Attraction Towards Inflection Point



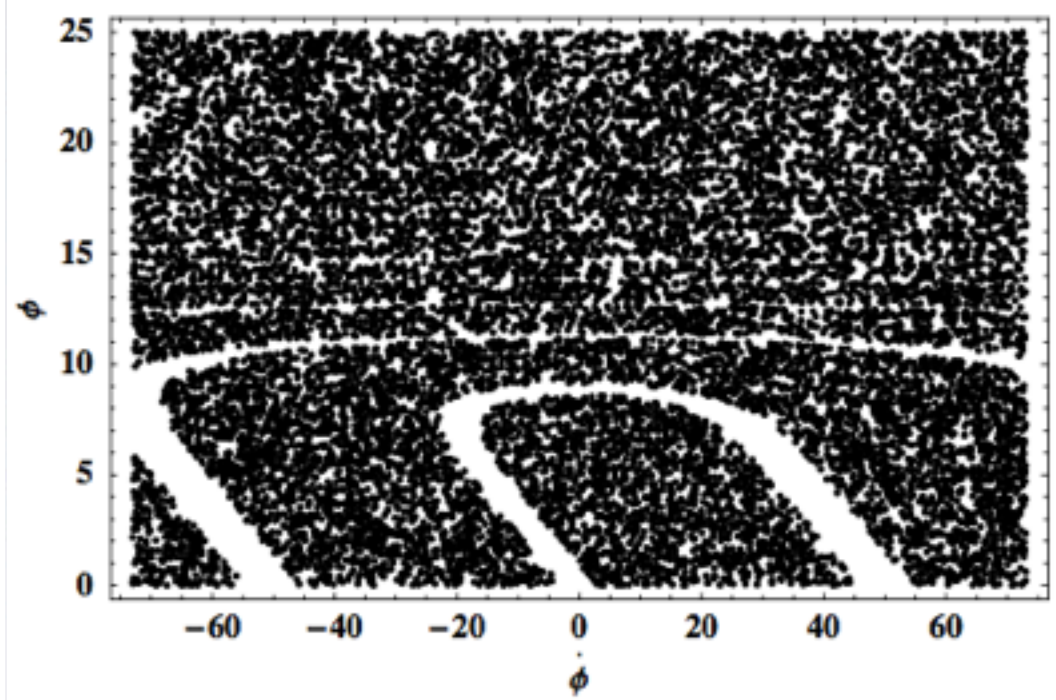


FIG. 5: Same as in Fig. (4) for $H_{\rm false} = 10^3 m_\phi$.

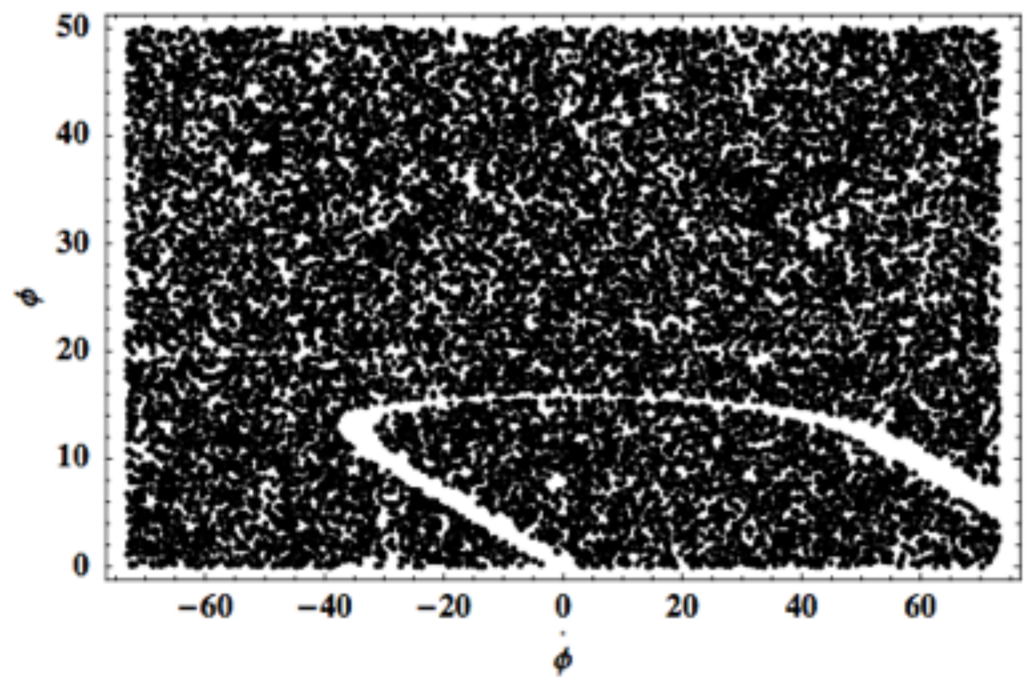


FIG. 6: Same as in Fig. (4) for $H_{\rm false} = 10^4 m_\phi$.

$$V = V_{Landscape} + V_{MSSM}$$

Allahverdi, Dutta & AM, Phys. Rev. D (2008)

Bench-Mark Points for Visible Sector Models of Inflation & Curvaton

Planck Constraints (1σ)	MSSM inflation	MSSM Curvaton
Tensor-to-scalar ratio $r < 0.11$ (95% CL) [4]	★Negligible, ✓	Negligible, ✓
$10^9 P_\zeta = 2.196^{+0.051}_{-0.060}$ [2]	✓	✓
$n_s = 0.9603 \pm 0.073$ [2]	✓	✓
$dn_s/d\ln k = -0.0134 \pm 0.0090$ [4]	$\lesssim -0.002$, ✓	✓
$f_{\rm NL}^{local} = 2.7 \pm 5.8$ [3]	< 1, ✓	Constrained, ✓
$f_{\rm NL}^{equil} = -42 \pm 75$ [3]	< 1, ✓	Constrained, ✓
$f_{\rm NL}^{orth} = -25 \pm 39$ [3]	< 1, ✓	Constrained, ✓
Relativistic *dof* [2]	only SM	only SM

★ $r < 0.11$

With Hubble-Induced SUGRA Corrections

Inflection Point for Inflaton

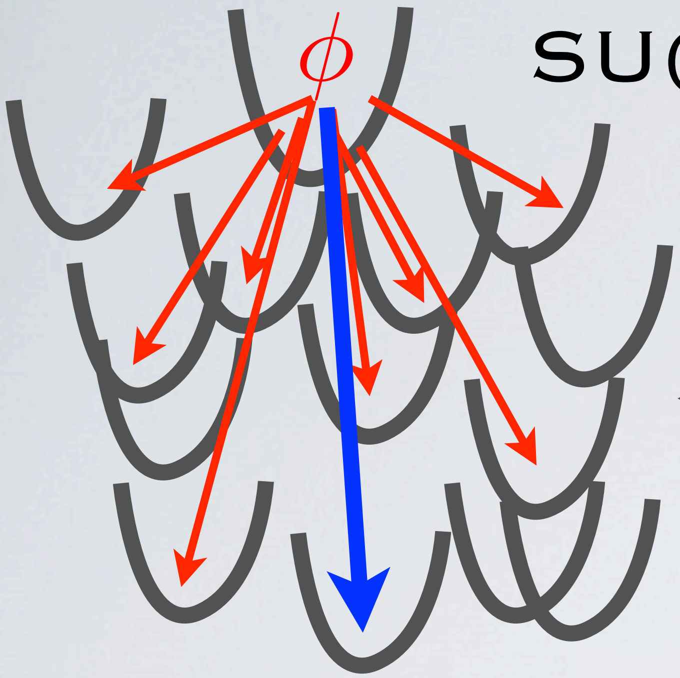
Saddle Point for Both Inflaton & Curvaton

Conclusions

Last 50-60 e-folds of Inflation MUST be embedded within a VISIBLE sector

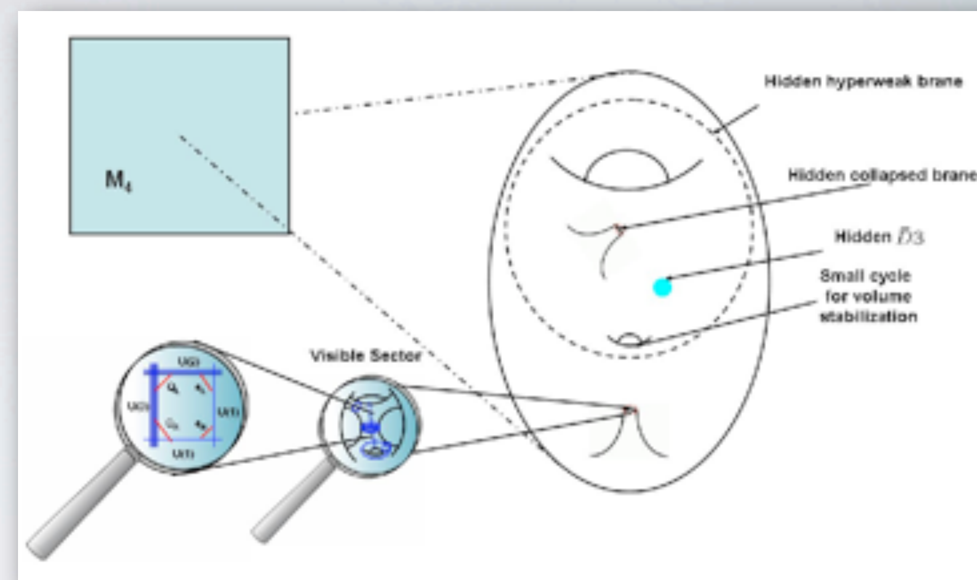
Discovery of B-modes will not only test the Inflationary paradigm but will also test the structure of Space-Time and perhaps the nature of Quantum Gravity itself

Last 50-60 e-folds of Inflation



SU(5),SO(10), E6,...

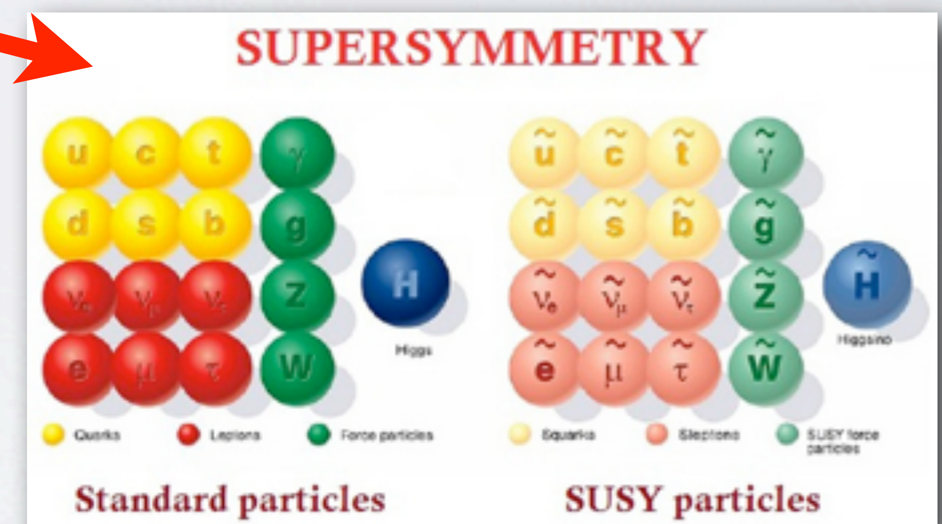
Too many hidden sectors / moduli

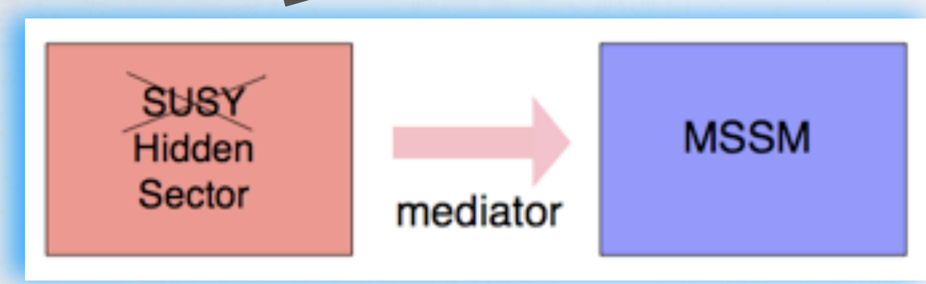


SM/MSSM

Inflaton

Most predictive



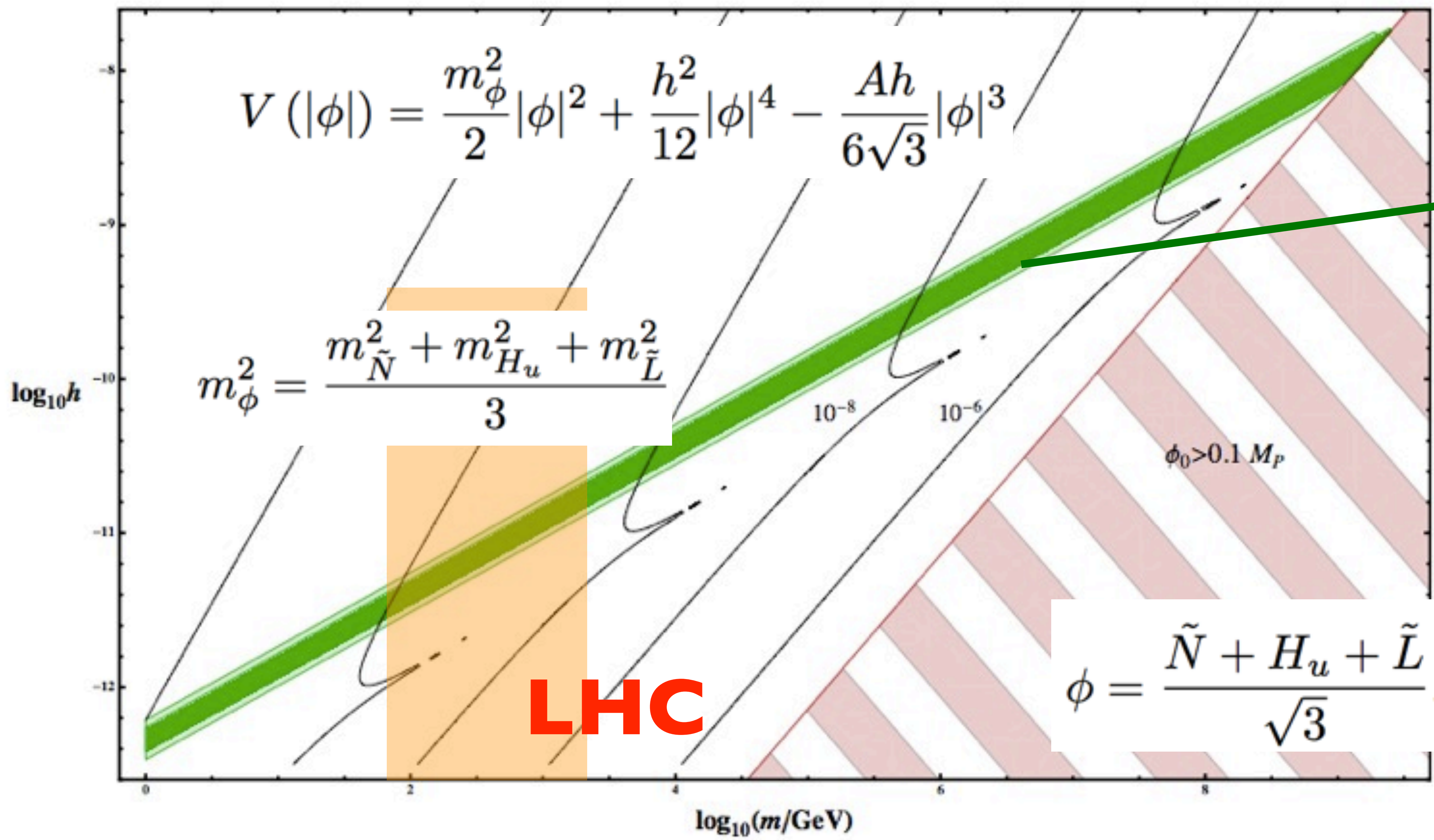


Cicoli, AM: show explicitly hidden sectors are populated more than MSSM/visible in string compactification

JCAP(2010), PRD (2011)

Avoid any hidden state : inflate with a minimal content of matter of a visible sector

Renormalizable Potential from a Visible Sector



$$V\left(|\phi|\right) = \frac{m_\phi^2}{2}|\phi|^2 + \frac{h^2}{12}|\phi|^4 - \frac{Ah}{6\sqrt{3}}|\phi|^3$$

$$m_\phi^2 = \frac{m_{\tilde{N}}^2 + m_{H_u}^2 + m_{\tilde{L}}^2}{3}$$

$$\phi = \frac{\tilde{N} + H_u + \tilde{L}}{\sqrt{3}}$$

$$\mathcal{P}_\zeta = 2.196^{+0.051}_{-0.060} \times 10^{-9}$$

$$n_s = 0.960 \pm 0.073$$

Allahverdi, Kusenko & AM, JCAP (2006)

Hotchkiss, AM & Nadathur, JCAP (2011)

Inflaton is a D-flat direction of MSSM*U(1), i.e. $SU(3) \times S(2)_L \times U(1)_Y \times U(1)_{B-L}$

$$W \supset h\mathbf{N}\mathbf{H}_u\mathbf{L}.$$

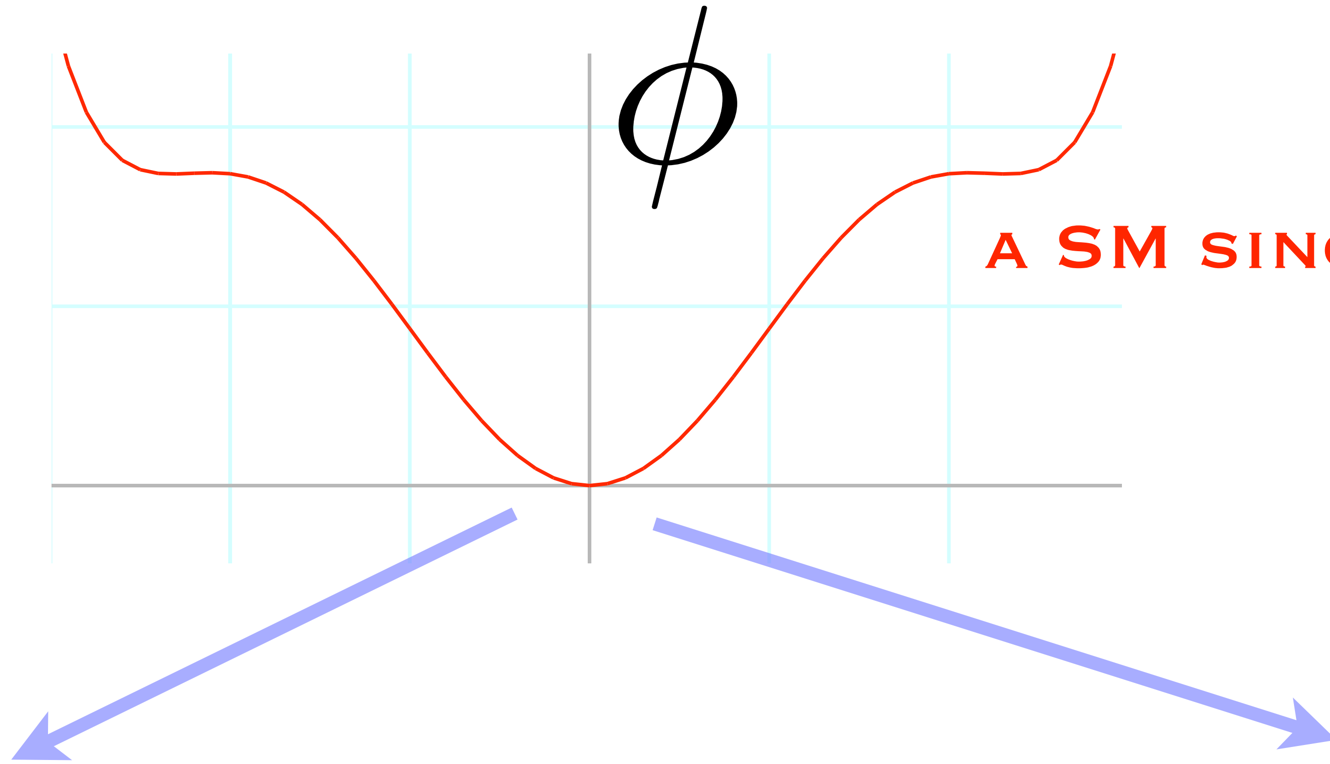
$$m_\nu \sim h\langle H_u\rangle \sim 0.1eV$$

Inflaton decays into MSSM dof + LSP (dark matter candidate)

Allahverdi, Dutta & AM, Phys.Rev.Lett. (2007)

Singlet /Hidden sector inflation & Branching ratio?

$10^{18}\ GeV$



A SM singlet Inflation

Observable Sector | **Hidden Sector**

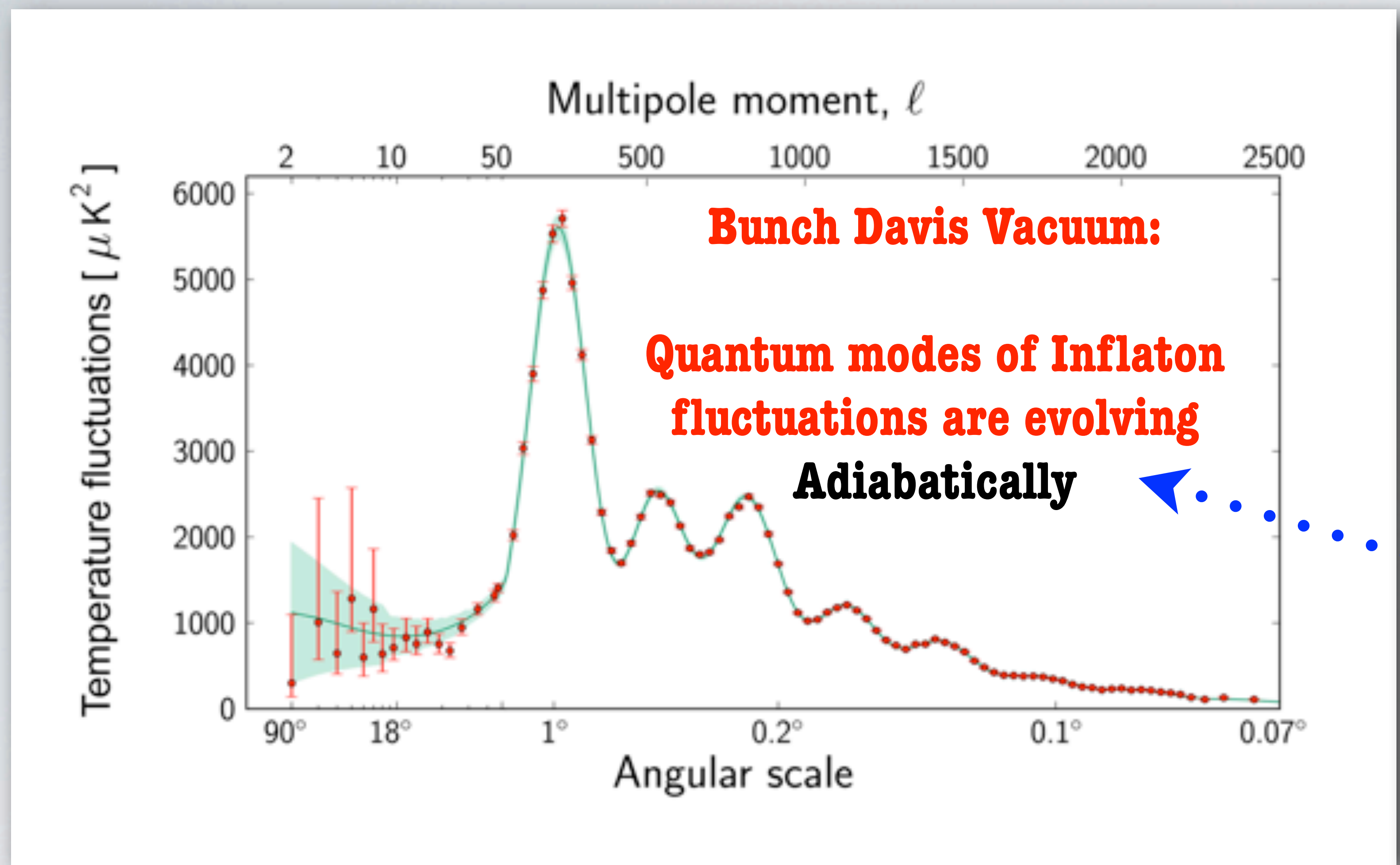
$10^{3}\ GeV$

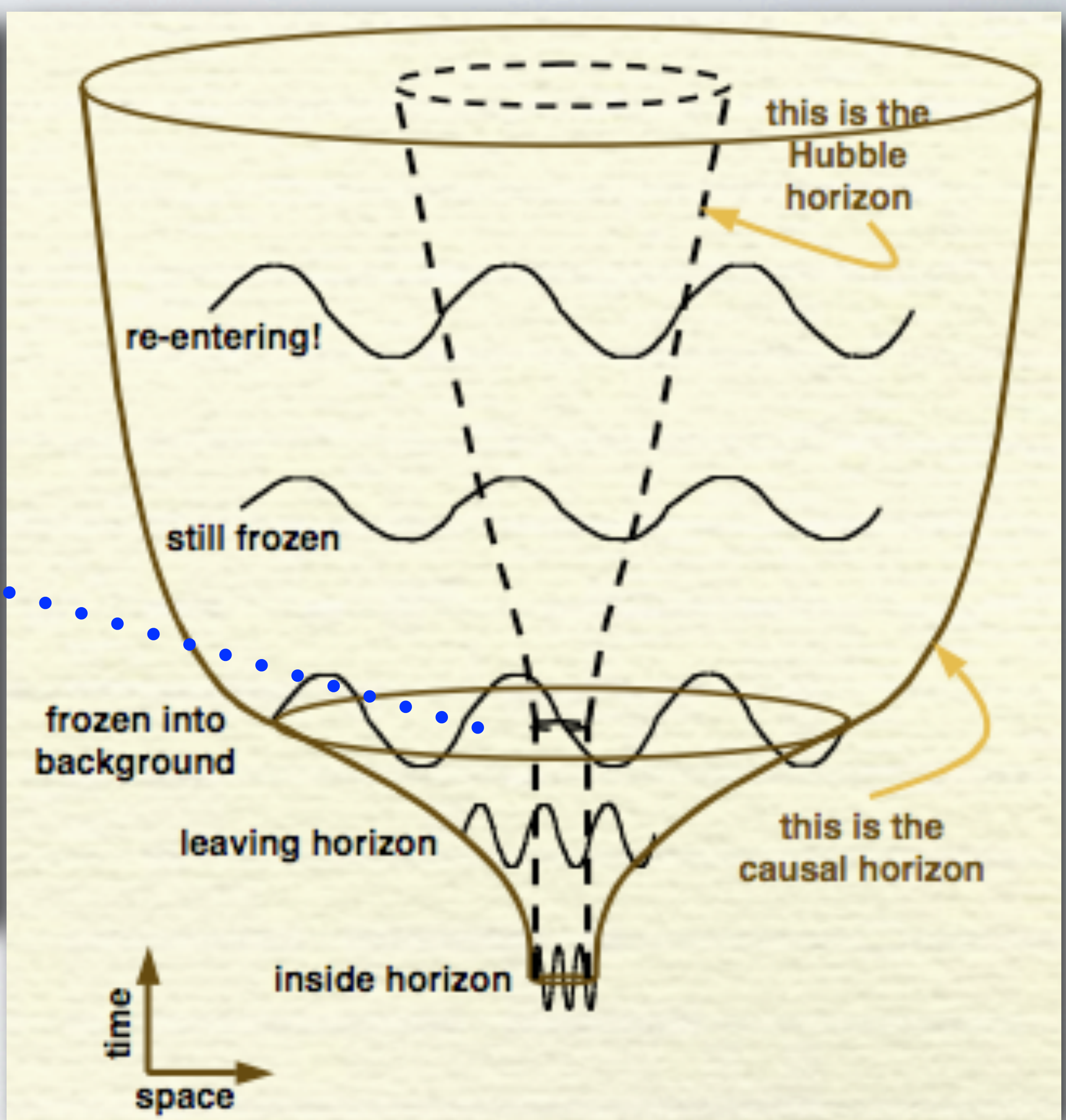
Hidden sectors always exist Beyond the SM

How do we make sure that inflaton excites the SM quarks and leptons ?

Mazumdar & Rocher, 1001.0993 Phys. Rept. (2010)

Inflation + Adiabatic Vacuum





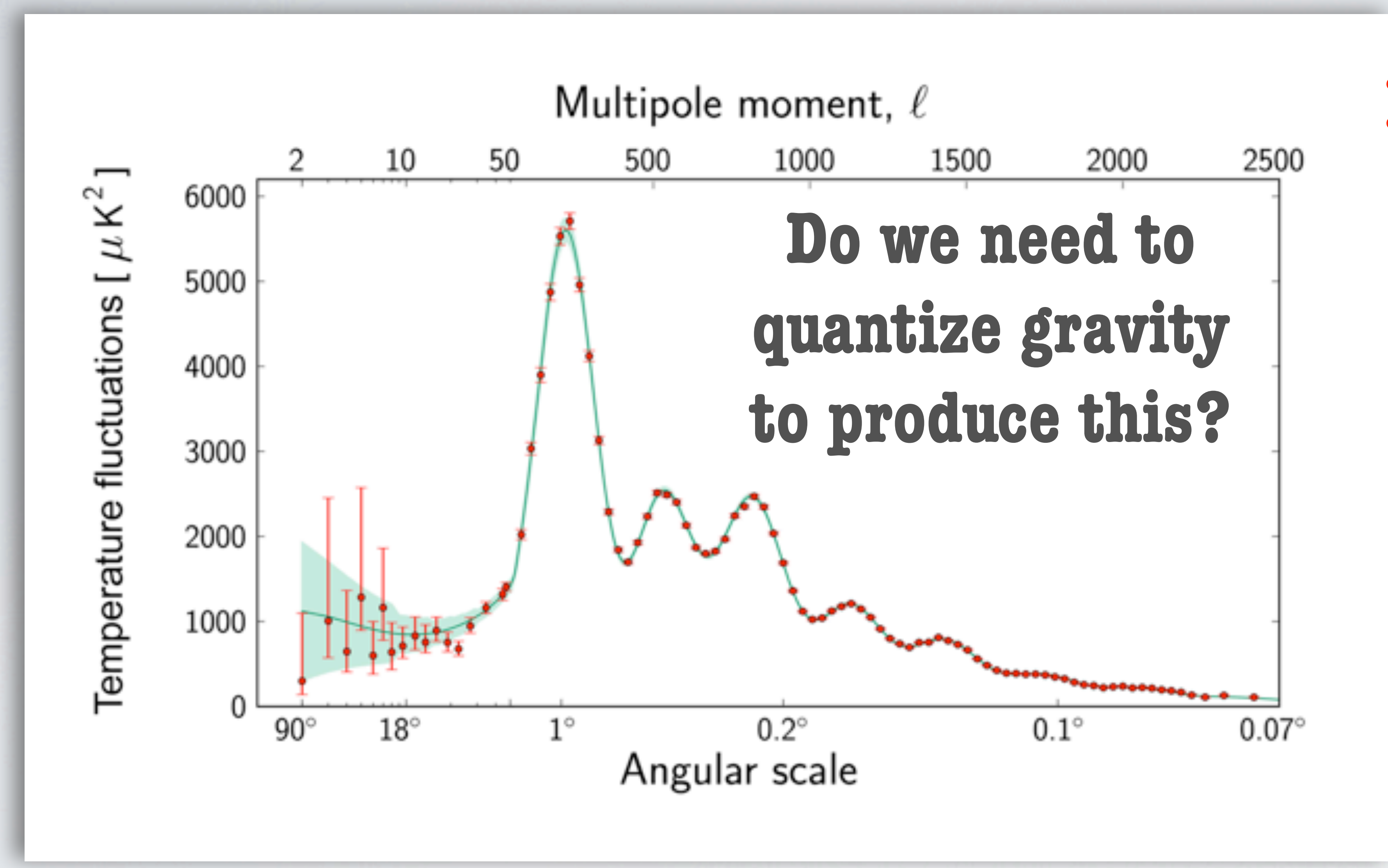
17 e-foldings

Why is Quantum Gravity so kind towards us?

What is the CMB telling us about the Nature of Gravity in UV?

Some Issues about Inflation

Quantization of Space Time



May be gravity remains classical forever

or

Gravity becomes Asymptotically Free in the UV

Biswas, Gerwick, Koivisto & AM, Phys. Rev. Lett. (2012)

Would we ever see B-mode of Polarization ?

Never: If Gravity is treated Classically

Ashoorioon, Dev & AM (1211.4678)

Note: B-modes do not require super-Planckian Inflaton VEVs such as Chaotic Inflation

Inflection Point Inflation can do so with VeVs below the cut-off

Hotchkiss, AM & Nadathur, JCAP (2012)

Ever Changing models of Inflation

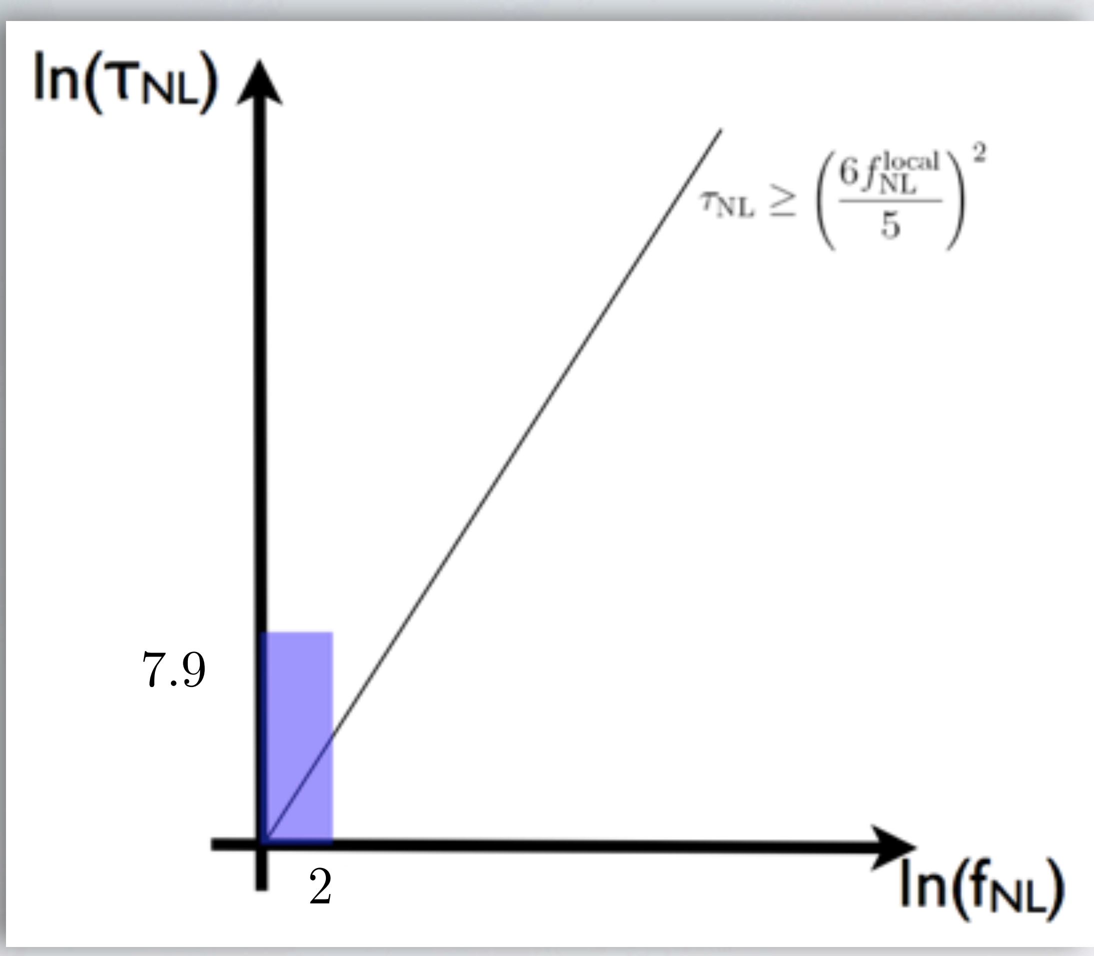
1980 R*R, OLD, NEW, CHAOTIC, EXTENDED, SOFT, BRANS-DICKE, SUSY, SUGRA, THERMAL, EXPONENTIAL, DOUBLE, ...

1990 HYBRID, MUTATED HYBRID, INVERTED HYBRID, F-TERM, D-TERM, K-TERM, TOPOLOGICAL, ASSISTED, ...

2000 N-FLATION, BRANE, BRANE-CHAOTIC/HYBRID, TACHYONIC, DBI, RACE-TRACK, HILL-TOP, FAST-ROLL, P-TERM, F+D-TERM, EXTENDED-HIGGS, CYCLIC, Kahler, Non-Kahler, Sweese Cheese, D3/D7, ...

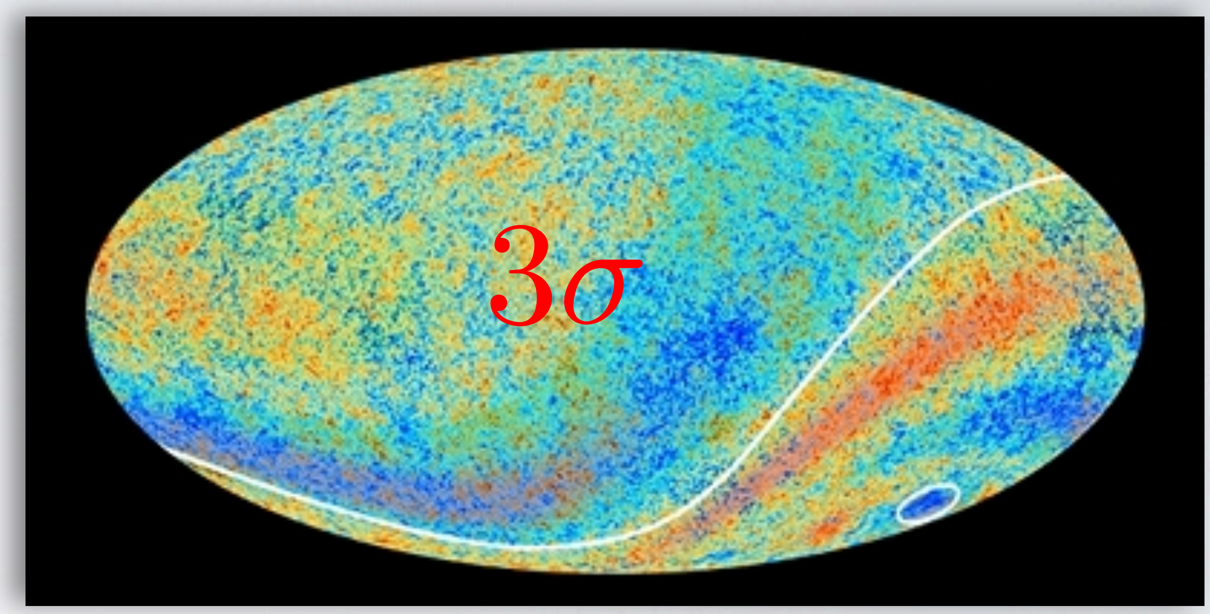
None of these models can actually work !!

Planck Data: Good Agreements



It is consistent with a SINGLE Inflaton

No need for exotic models, except



$$\mathcal{P}_\zeta(k,r) = \mathcal{P}_\zeta(k)[1 + 2A\vec{p}\cdot\vec{r}/r_{ls}] \qquad A = \frac{\Delta\mathcal{P}_\zeta}{\mathcal{P}_\zeta} = 0.072 \pm 0.022 \ (\ell < 64)$$

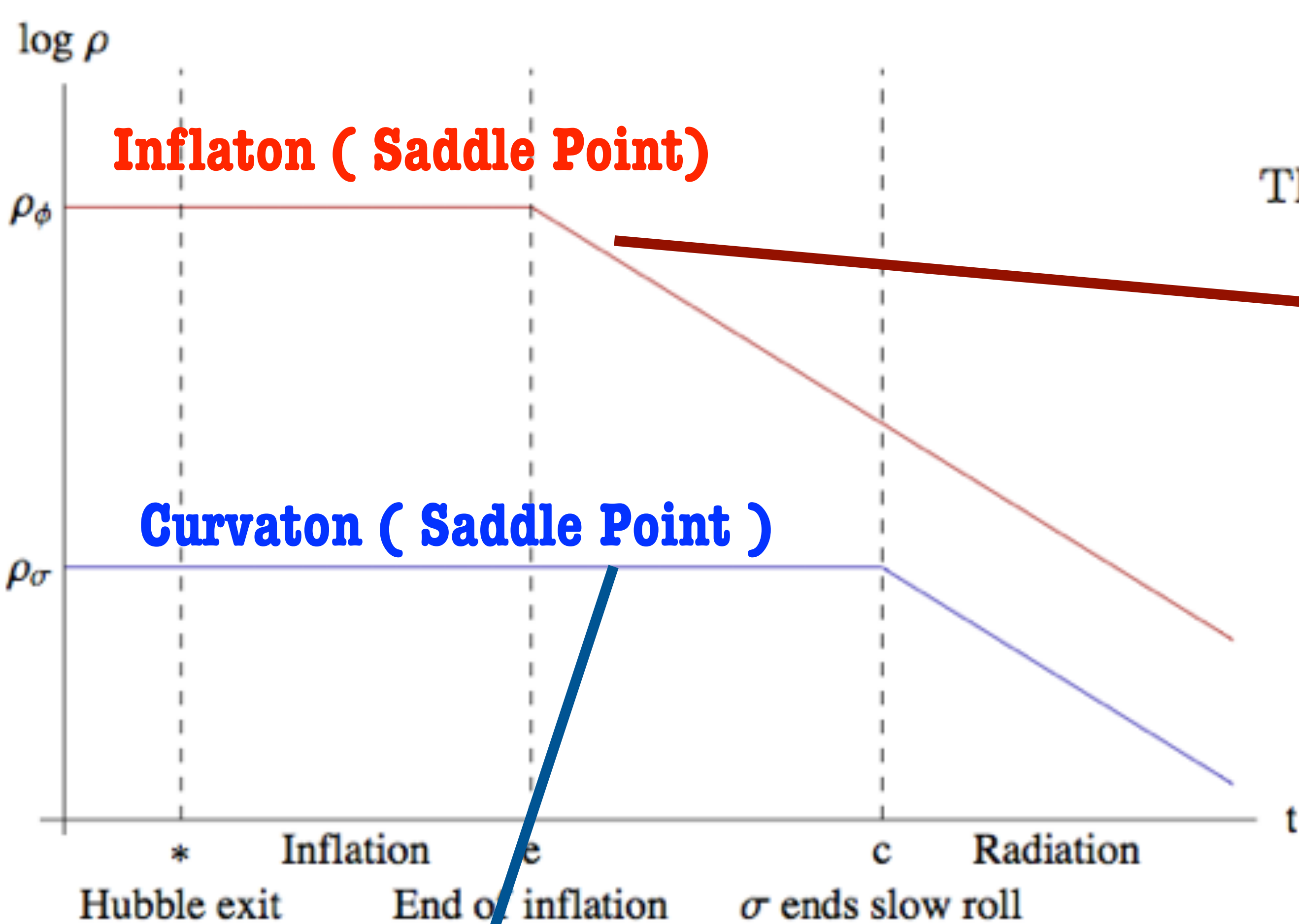
$$A \propto f_{NL} \qquad \Phi = \Phi_g + f_{NL}\Phi_g^2 + (\tau_{NL} + g_{NL})\Phi_g^3 + \cdots$$

More than one sources of Non-Gaussianity

$$+f_{NL} \quad \& \quad -f_{NL} \qquad |A| \leq \sqrt{\tau_{NL}} \qquad \tau_{NL} < 2800 \ (\ @\ 95\%)$$

Wang, AM (2013), 1304.6399

Curvaton & Inflaton from MSSM



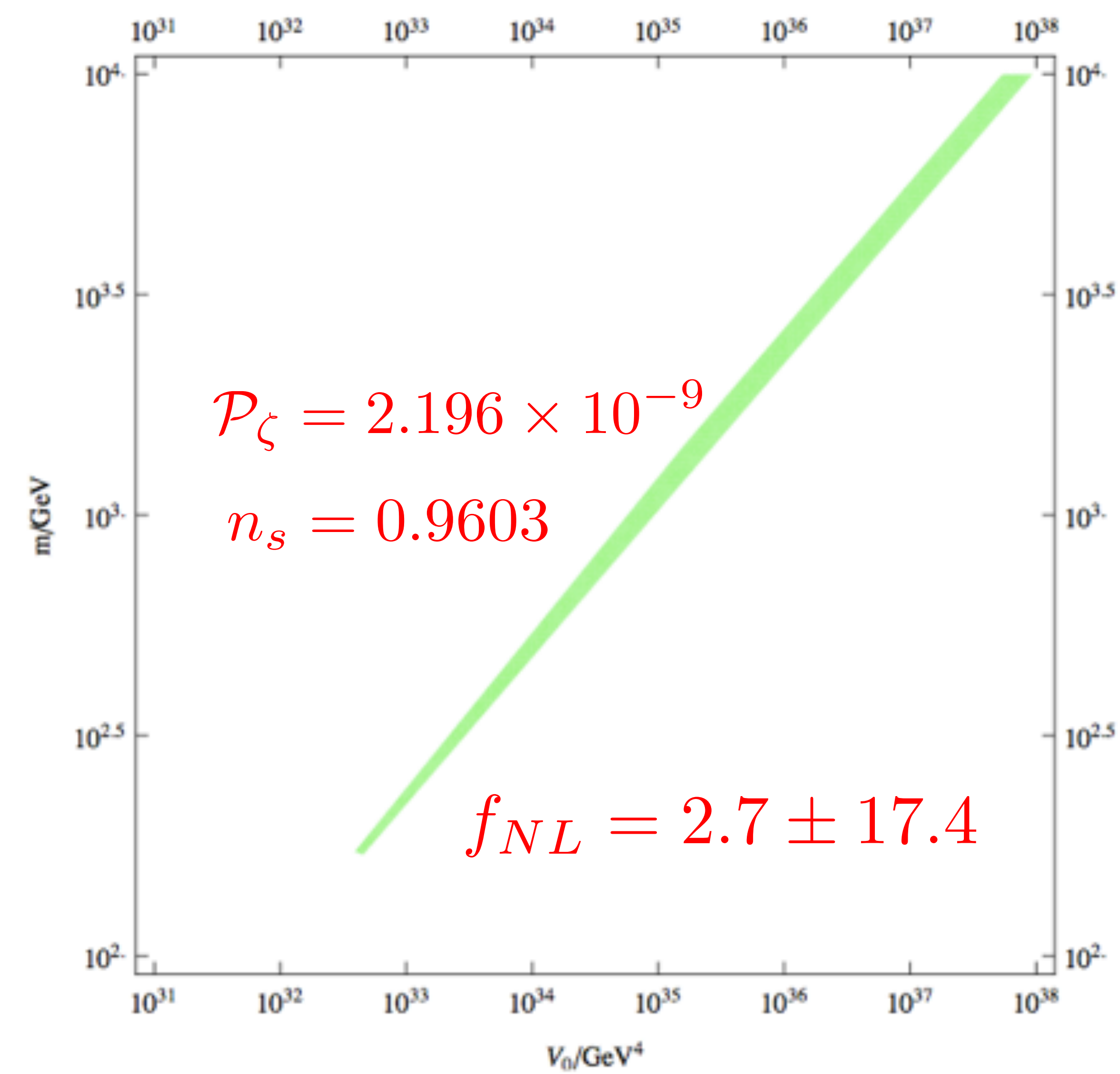
$$W = \sum_{m\geq 2} \frac{\lambda_m}{3m} \frac{\Phi^{3m}}{M_*^{3m-3}} .$$

The potential at lowest order would be:

$$\phi = \frac{\widetilde{u} + \widetilde{d} + \widetilde{d}}{\sqrt{3}} \qquad V(\phi) = \left| \lambda_2 \frac{\phi^5}{M_*^3} + \lambda_3 \frac{\phi^8}{M_*^6} + \lambda_4 \frac{\phi^{11}}{M_*^9} + \cdots \right|^2$$

$$\sigma = \frac{(\widetilde{L} + \widetilde{L} + \widetilde{e})}{\sqrt{3}} , \qquad m_\sigma^2 = \frac{m_{\widetilde{L}}^2 + m_{\widetilde{L}}^2 + m_{\widetilde{e}}^2}{3}$$

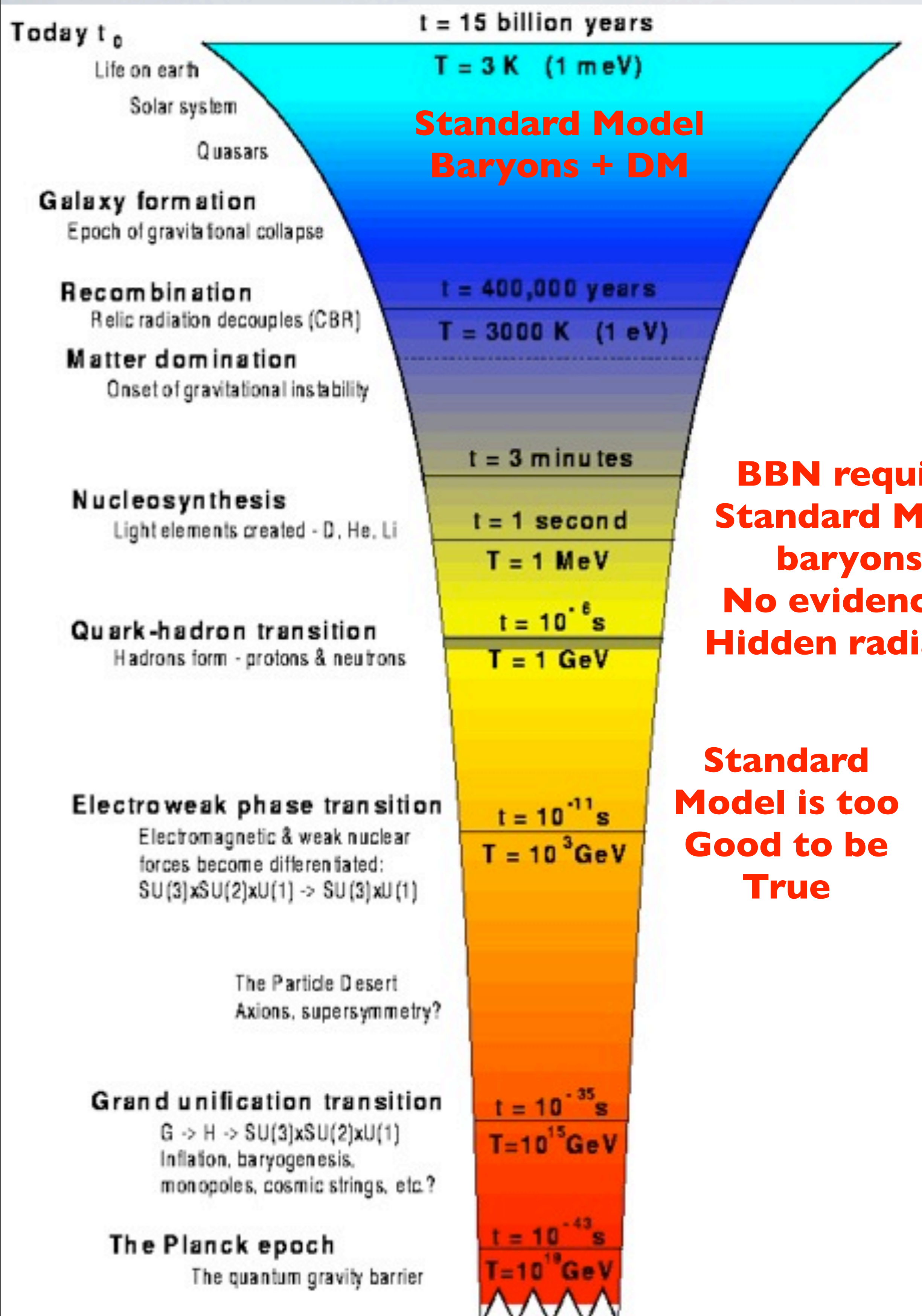
$$U(\sigma) = \frac{1}{2} m_\sigma^2 |\sigma|^2 - \frac{A\lambda}{6} \frac{\sigma^6}{M_*^3} + \lambda^2 \frac{|\sigma|^{10}}{M_*^6}$$



NO Iso-Curvature Perturbations

AM & Nadathur, Phys. Rev. Lett. (2012), Wang, Pukartas & AM, (hep-ph/1303.535)

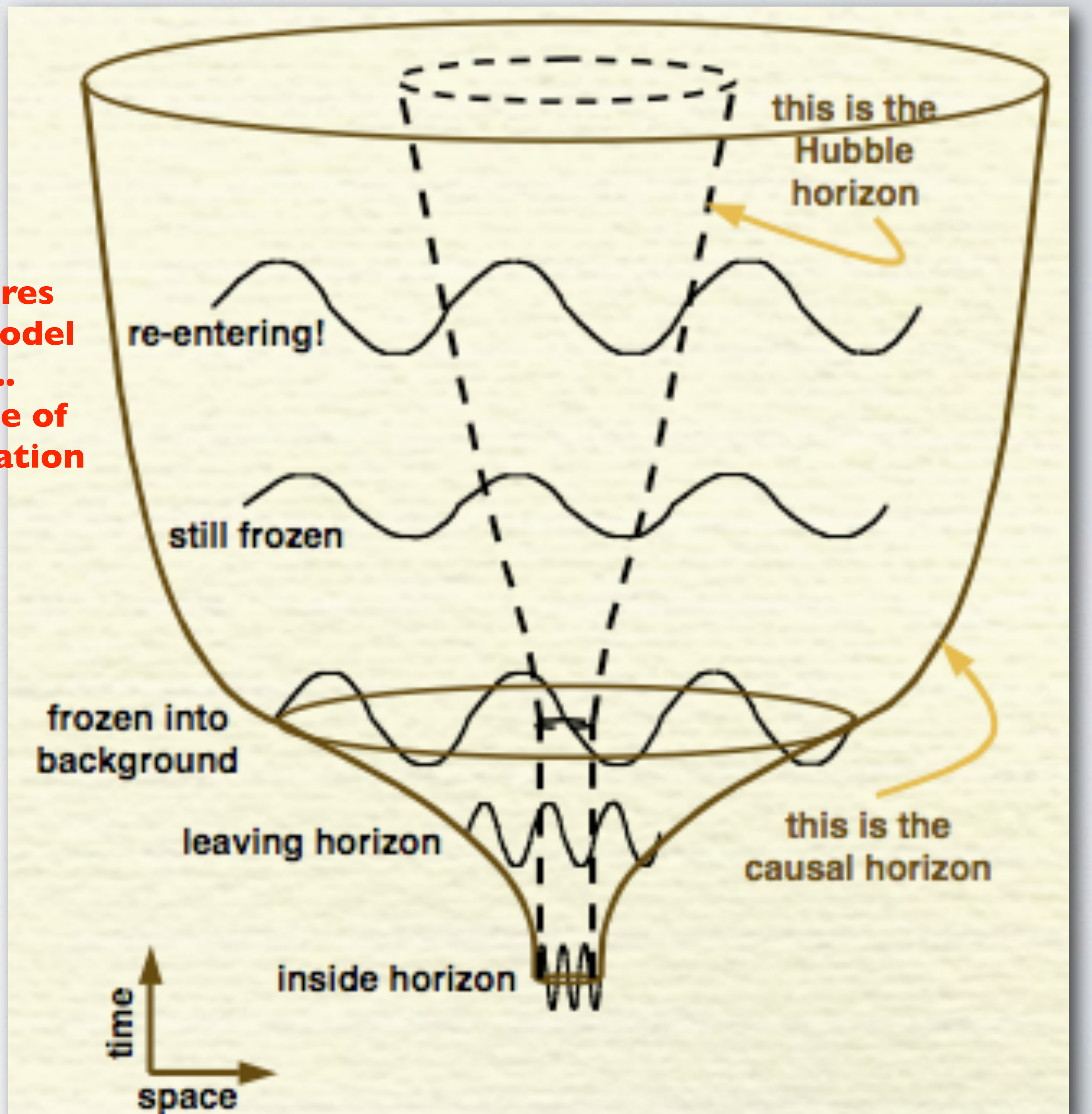
EXPLAINING OUR UNIVERSE



BBN requires Standard Model baryons..
No evidence of Hidden radiation

Standard Model is too Good to be True

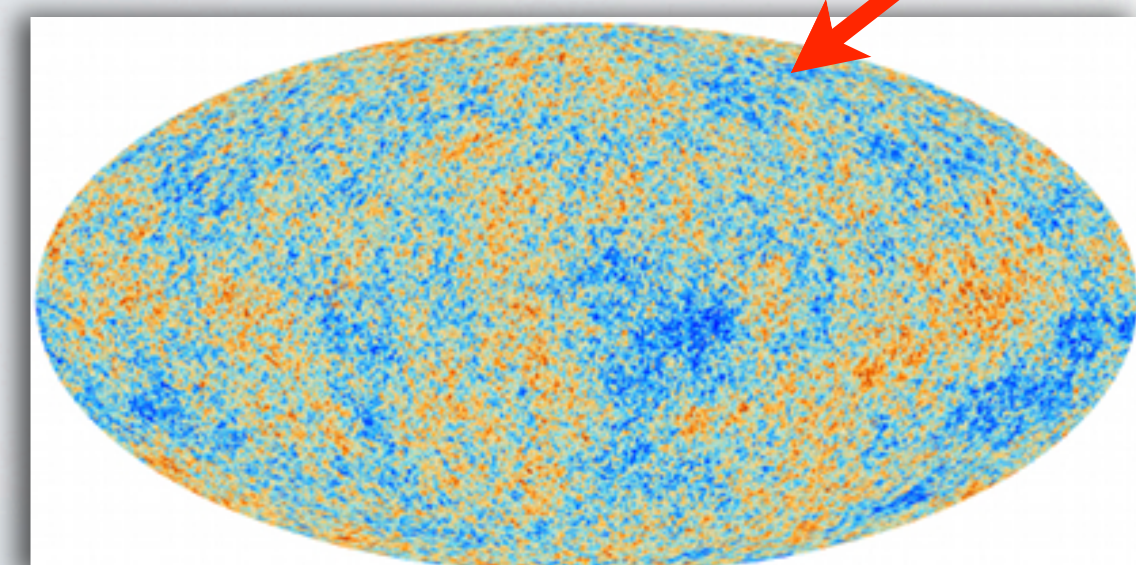
ALMOST SCALE INVARIANCE
GAUSSIAN PERTURBATIONS



MODEL INDEPENDENT ANALYSIS IS NICE TO DESCRIBE CMB, E.G. NON-GAUSSIANITY, ANOMALIES, FEATURES, ETC.

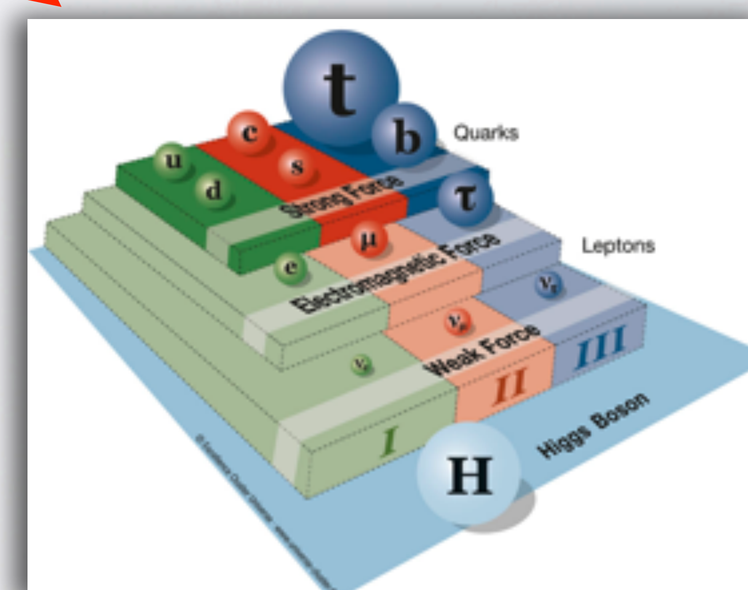
BUT YOU NEED TO EMBED THE INFLATON INTERACTIONS IN A PROPER CONTEXT - DON'T FORGET THAT YOU NEED TO EXCITE THE SM DOF

Inflaton Interactions



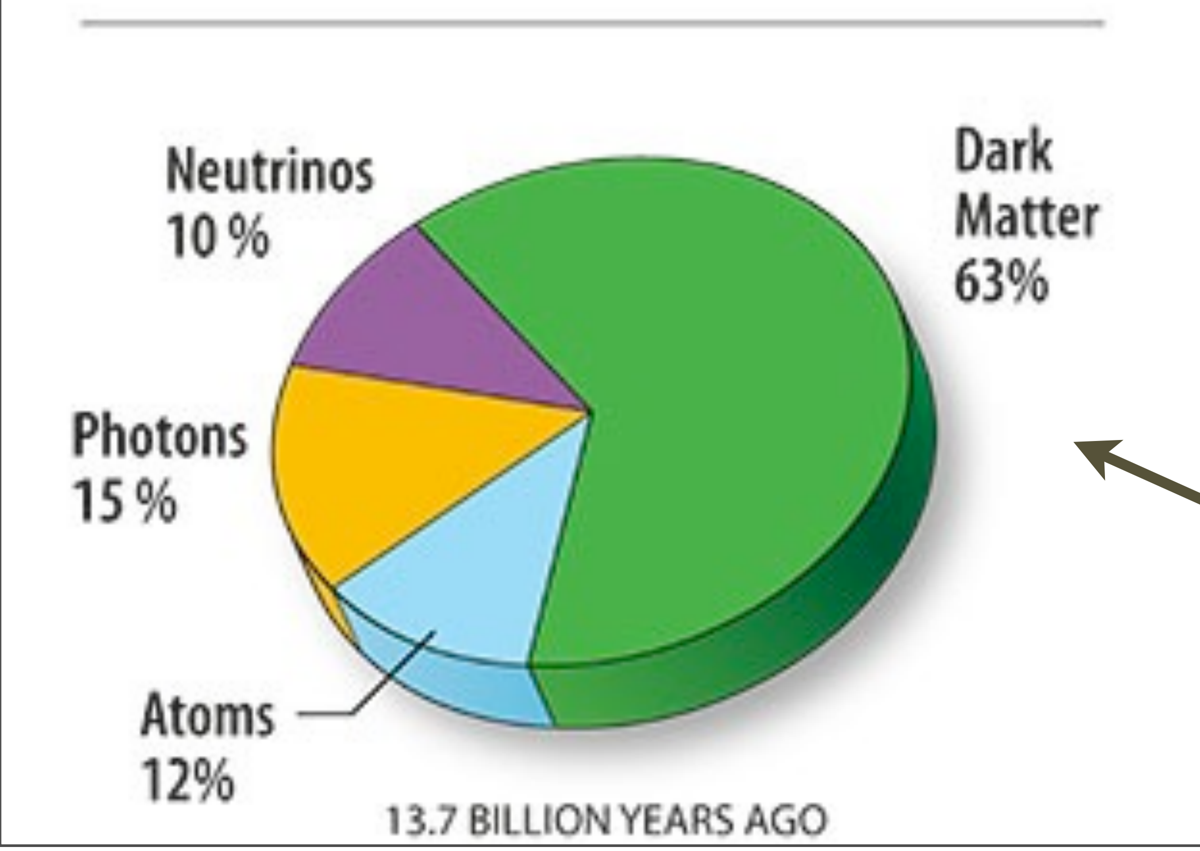
NON-GAUSSIANITY, MAGNETIC FIELD, ETC..

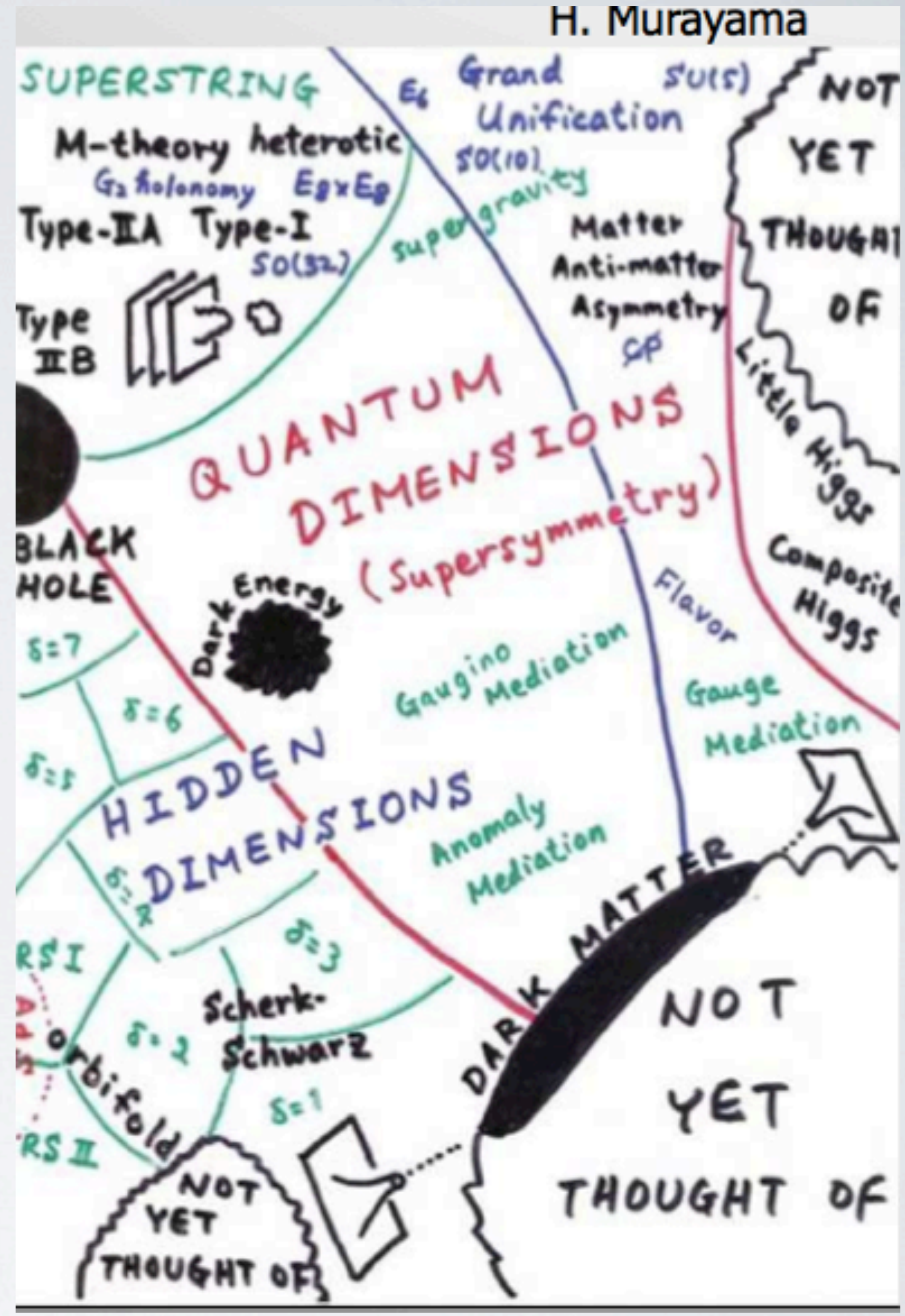
EFT APPROACH MUST TAKE THIS INTO ACCOUNT



E.G. CHIRALITY

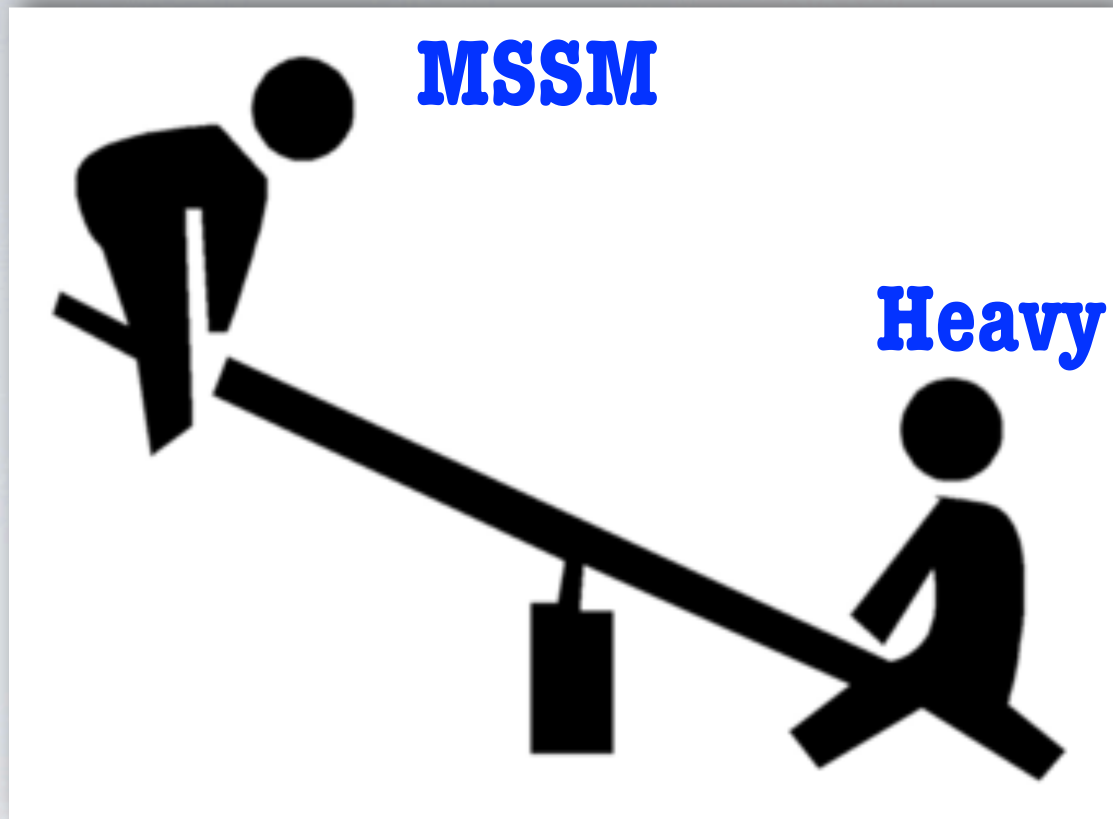
Beyond the Standard Model





But this is what Nature Cares for !!

Confusion -2: Effective Field Theory For Inflation



$$K = I^\dagger I + \phi^\dagger \phi + \delta K,$$

$$\delta K = f(\phi^\dagger \phi, I^\dagger I)\,,\ f(I^\dagger \phi\phi)\,,\ f(I^\dagger I^\dagger \phi\phi)\,,\ f(I\phi^\dagger \phi)$$

$$W = W_{MSSM} + W_{Heavy}$$

$$W(\phi) = \lambda \frac{\Phi^n}{M_{pl}^{n-3}} \qquad W(I) = M_s I^2$$

$$K = \phi^\dagger \phi + I^\dagger I + \frac{a}{M_{Pl}^2} \phi^\dagger \phi I^\dagger I$$

$$\mathcal{L}_{Kin} = K_{ij^*}(\partial_\mu \Phi^i)(\partial^\mu \Phi^{j^*}) = \left(1 + \frac{a|I|^2}{M_{Pl}^2}\right)(\partial_\mu \phi)(\partial^\mu \phi^\dagger) + \frac{a}{M_{Pl}^2}\{\phi^\dagger I(\partial_\mu \phi)(\partial^\mu I^\dagger) + \phi I^\dagger(\partial_\mu I)(\partial^\mu \phi^\dagger)\} + \left(1 + \frac{a|\phi|^2}{M_{Pl}^2}\right)(\partial_\mu I)(\partial^\mu I^\dagger).$$

$$V(\phi) \approx \begin{cases} V_0 + \left(m_\phi^2 + 3(1-a)H^2\right)|\phi|^2 - \frac{A\phi^n}{nM_{Pl}^{n-3}} + \lambda^2 \frac{|\phi|^{2(n-1)}}{M_{Pl}^{2(n-3)}} & \text{for } |I| << M_{Pl} \\ V_0 + \left(m_\phi^2 + 3(1+a^2)H^2\right)|\phi|^2 - \left\{A\frac{\phi^n}{nM_{Pl}^{n-3}} + \left[\left((1+a)^2 - \frac{4}{n} - \frac{2a}{n}\right)\frac{\lambda M \phi^n}{M_{Pl}^{n-3}} + h.c.\right]\right\} + \lambda^2 \frac{|\phi|^{2(n-1)}}{M_{Pl}^{2(n-3)}} & \text{for } |I| \sim M_{Pl}. \end{cases}$$

Mostly papers play an arbitrary game here - break global/local invariance, introduce ghosts & spurious states, etc.