Lectures on Particle Cosmology

Pre-SUSY School 2016

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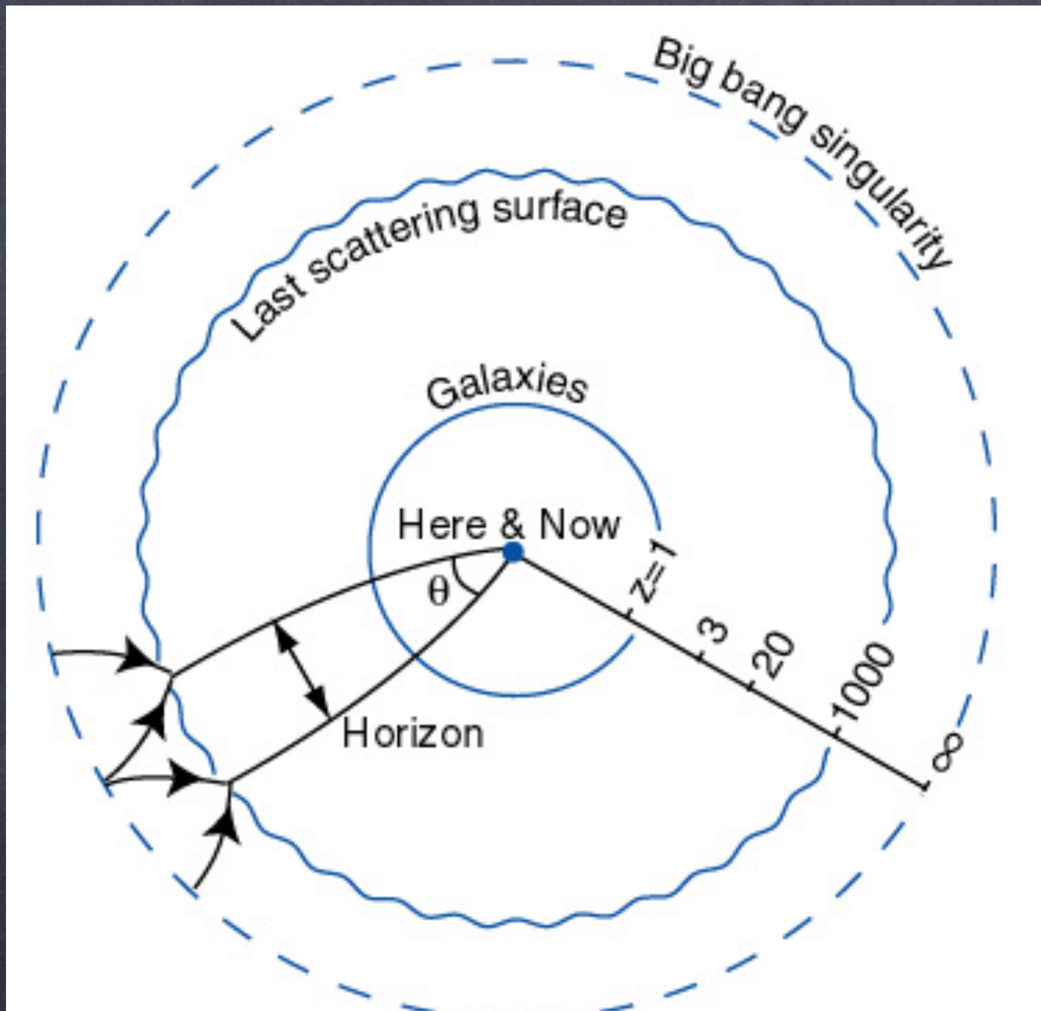
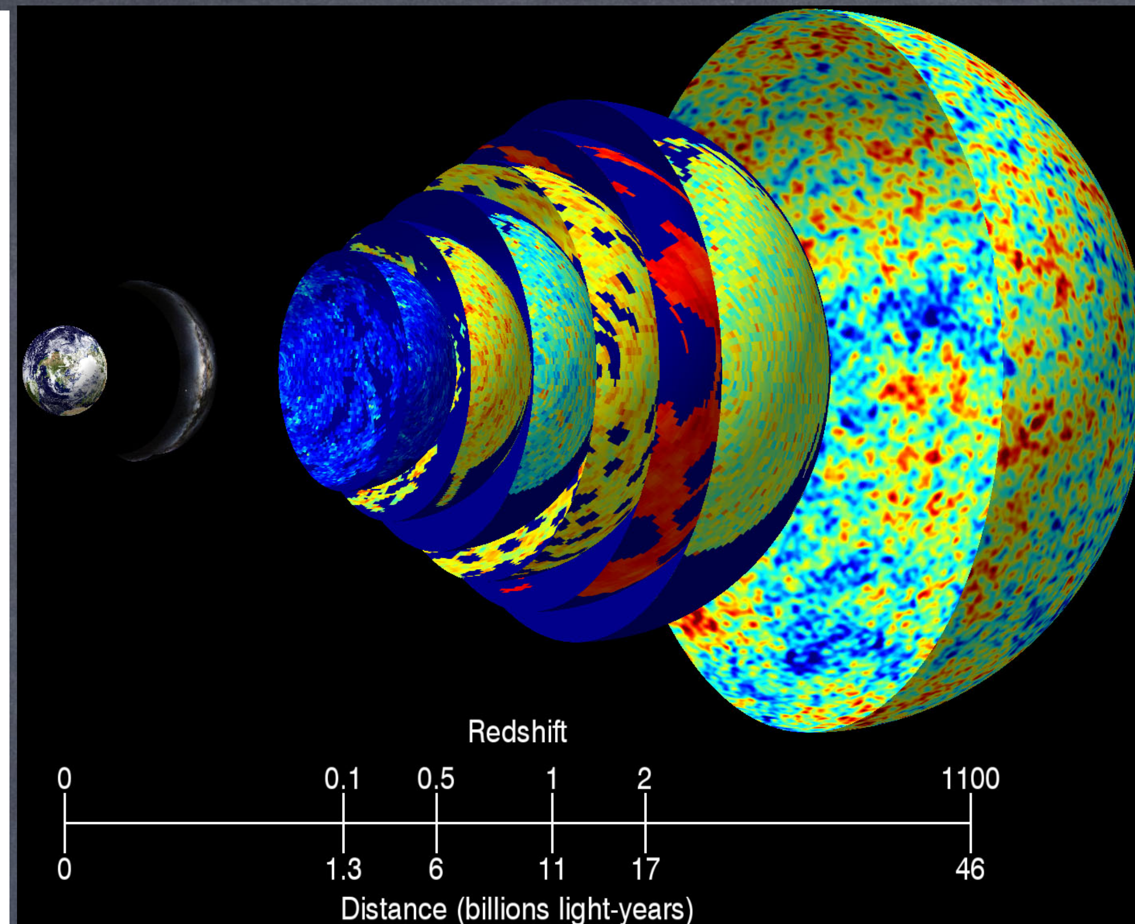
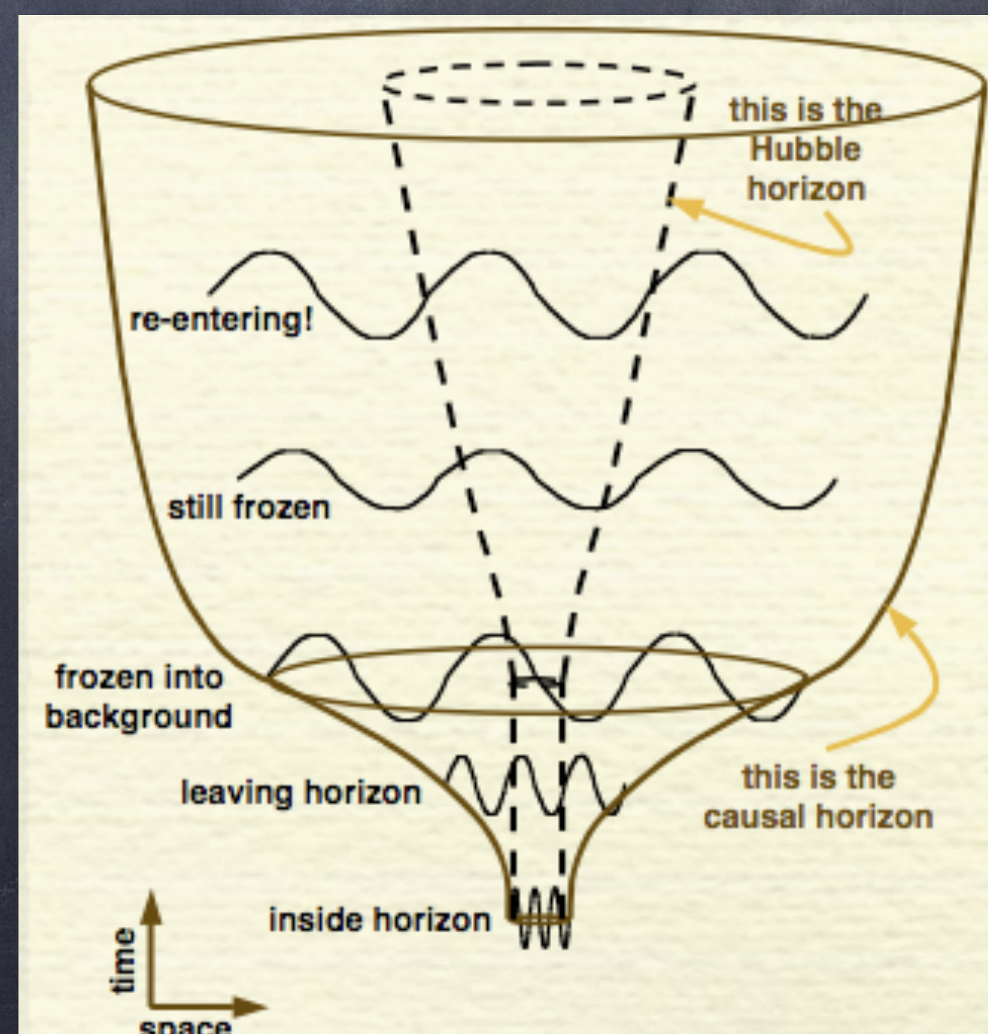
Observations

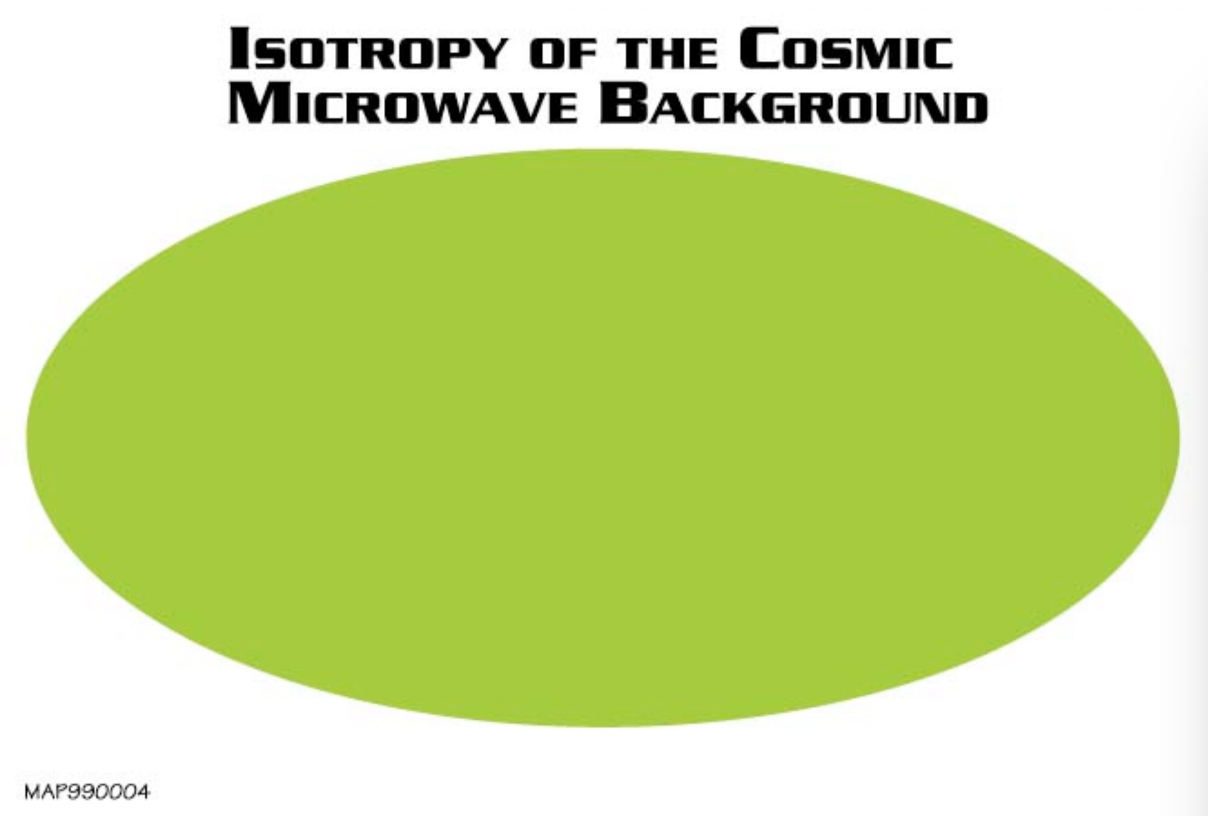


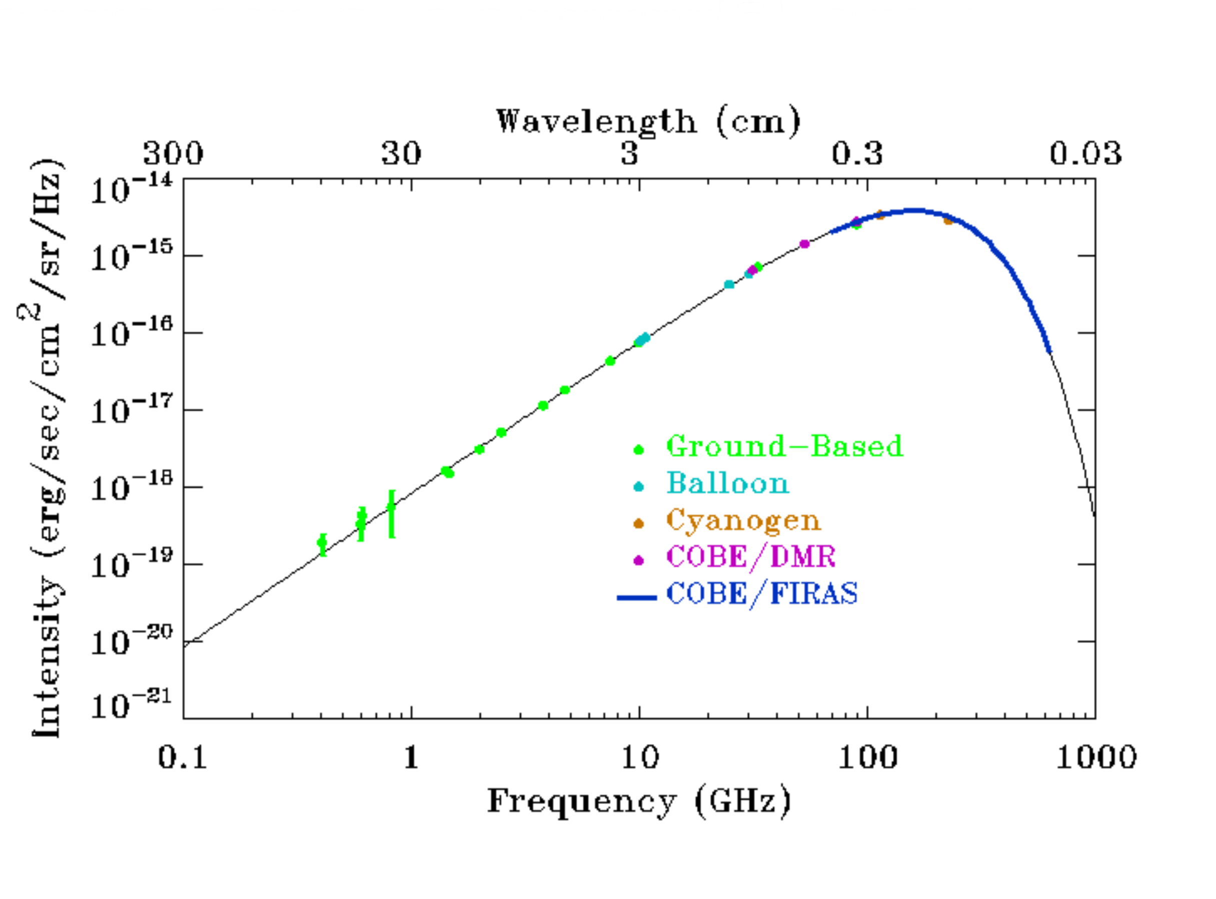


Fluctuations on scales larger than the Hubble radius at the surface of last scattering



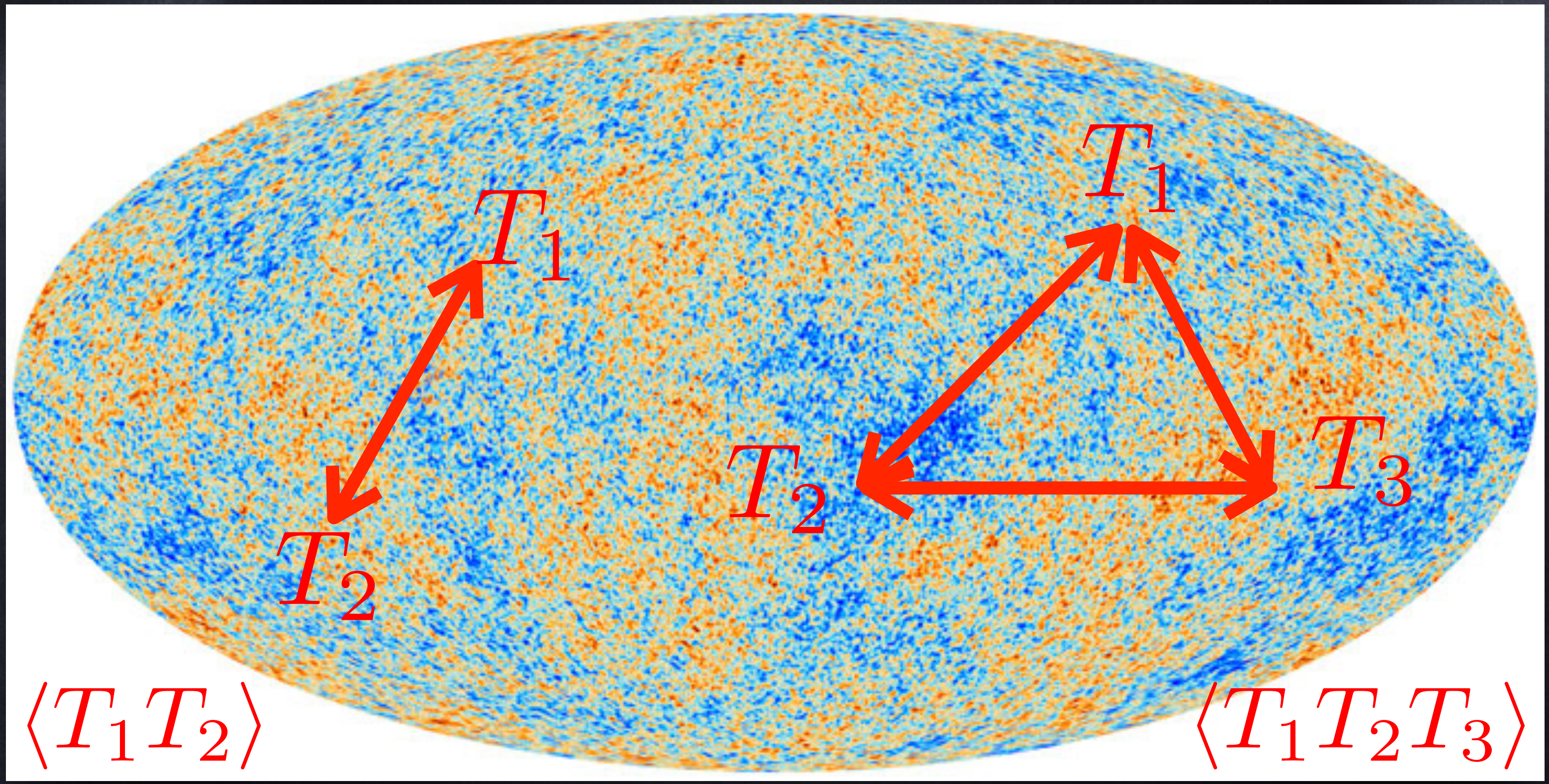
What Observations are telling us?



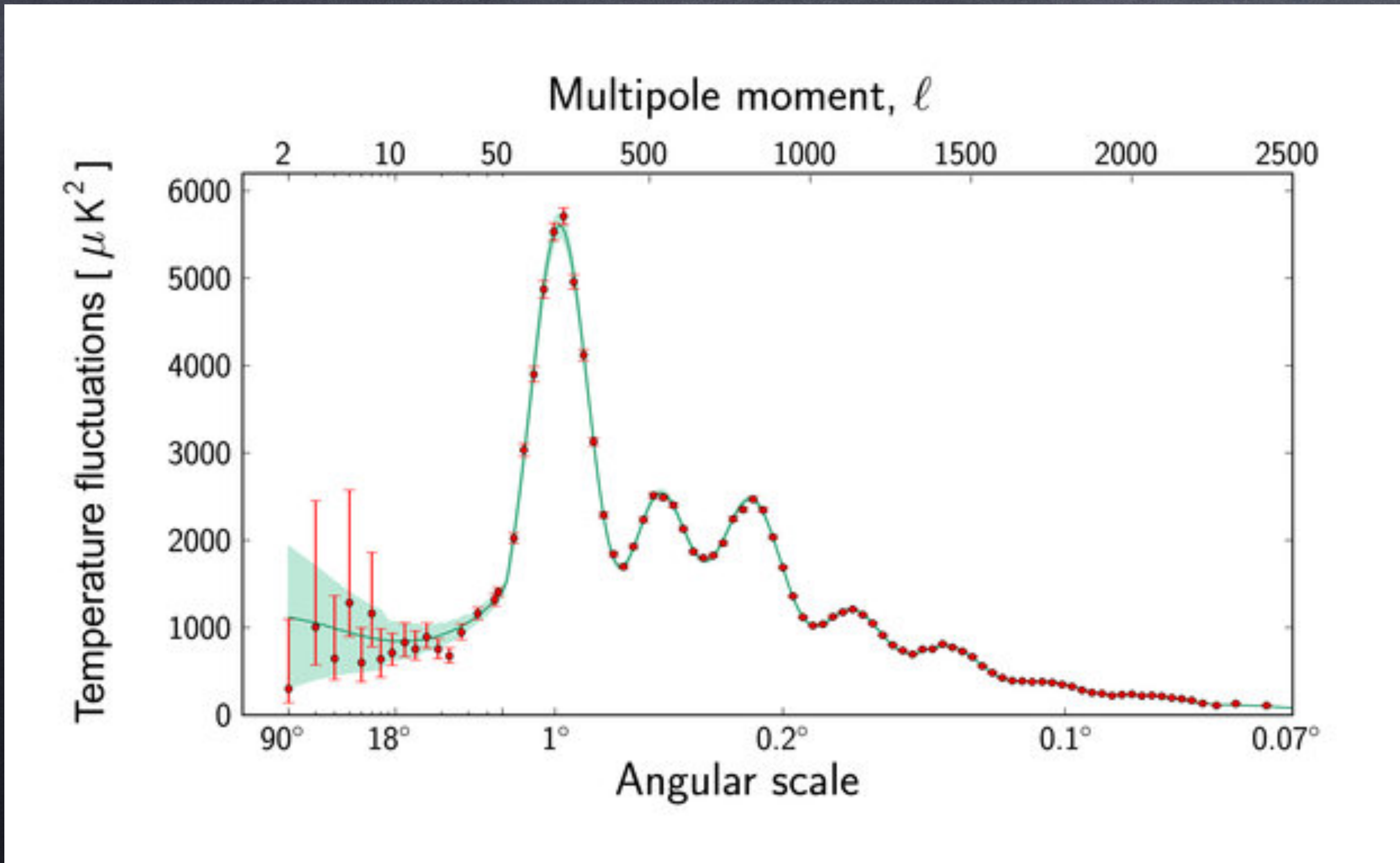


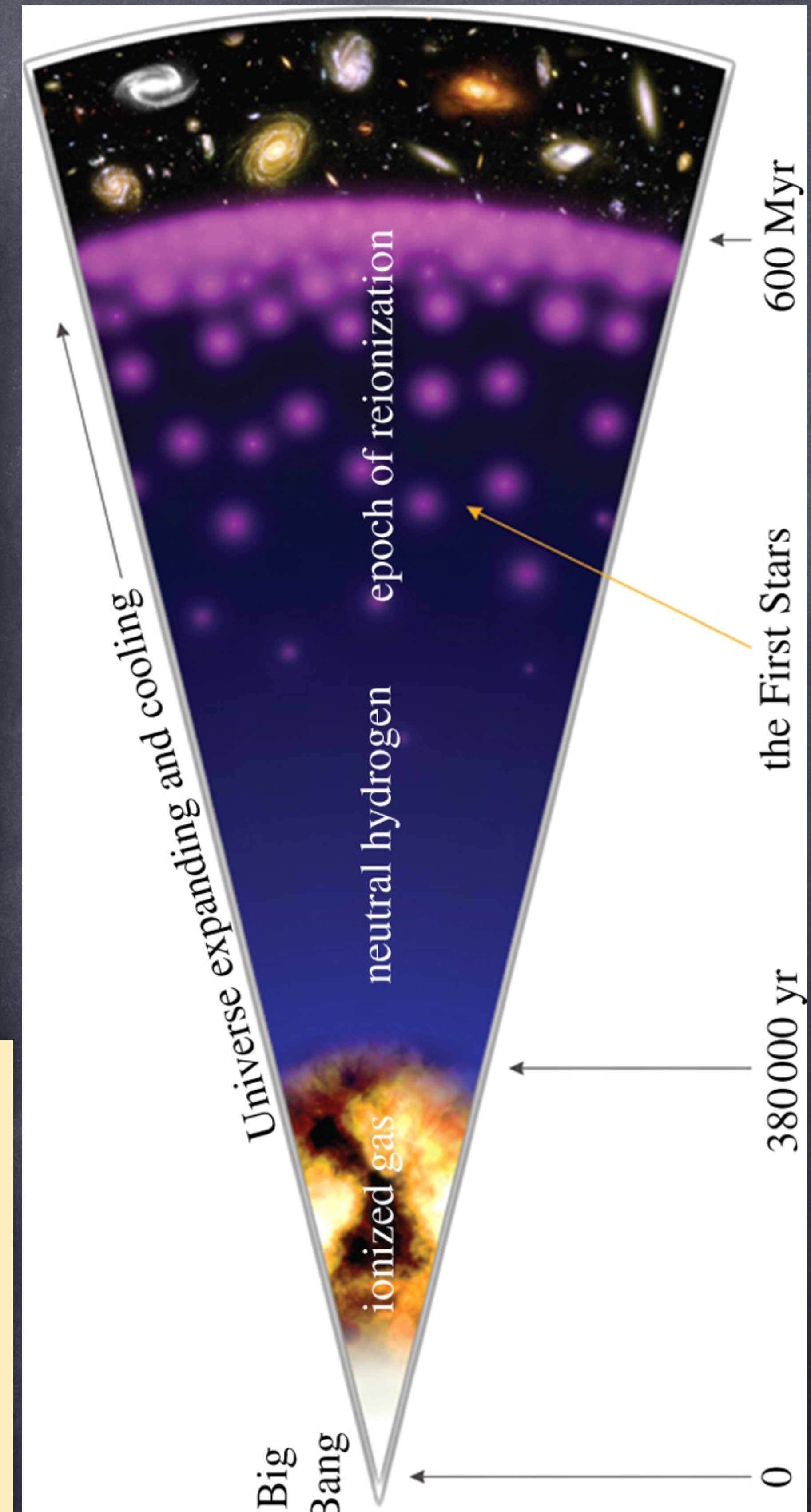
$$\frac{\Delta T}{T} = 4.6 \times 10^{-5}$$

Perturbations are Gaussian



Angular Power Spectrum





(1) Baryon density

(2) Dark Matter density

(3) Dark Energy density

(4) Amplitude 4.6×10^{-5}

(5) Tilt: $n_s = 0.96$

(6) Reionization Optical depth

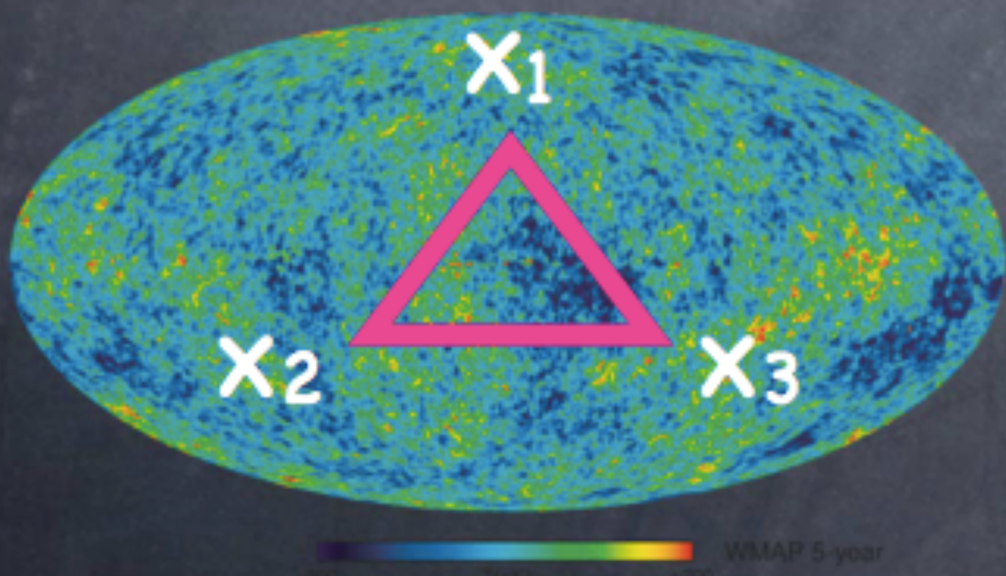
6 Model Parameters

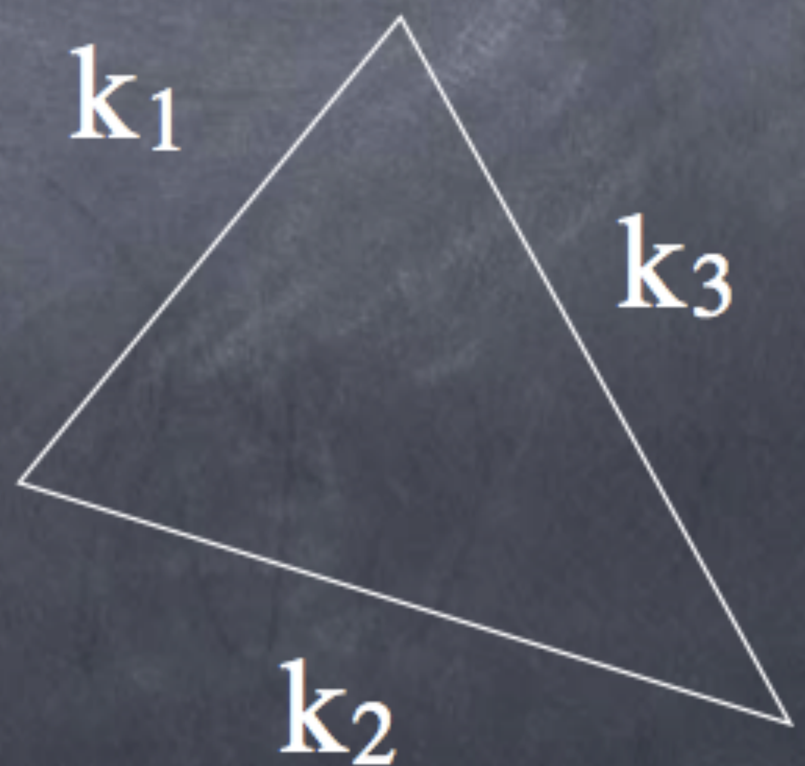
	Planck (CMB+lensing)		*Planck*+WP+highL+BAO	
Parameter	Best fit	68 % limits	Best fit	68 % limits
$\Omega_b h^2$	0.022242	0.02217 ± 0.00033	0.022161	0.02214 ± 0.00024
$\Omega_c h^2$	0.11805	0.1186 ± 0.0031	0.11889	0.1187 ± 0.0017
$100\theta_{MC}$	1.04150	1.04141 ± 0.00067	1.04148	$\boxed{1.04147 \pm 0.00056}$
τ	0.0949	0.089 ± 0.032	0.0952	0.092 ± 0.013
n_s	0.9675	0.9635 ± 0.0094	0.9611	$\boxed{0.9608 \pm 0.0054}$
$\ln(10^{10} A_s)$	3.098	3.085 ± 0.057	3.0973	3.091 ± 0.025

$$P_s \sim 3 \times 10^{-10} \left(\frac{k}{k_0}\right)^{n_s - 1} \qquad k_0 = 0.04\ \mathbf{Mpc}^{-1}$$

Non-Gaussianity

$$\Phi(x) = \Phi_G(x) - f_{NL}\Phi_G(x)^2$$

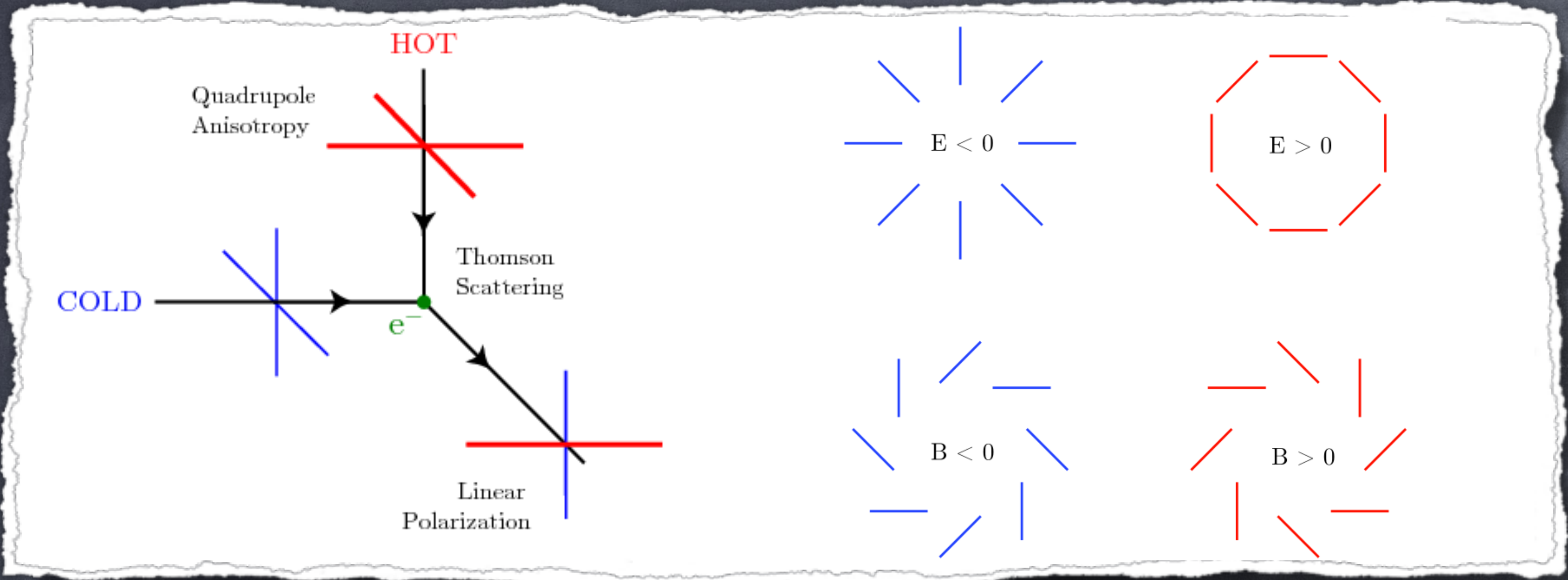




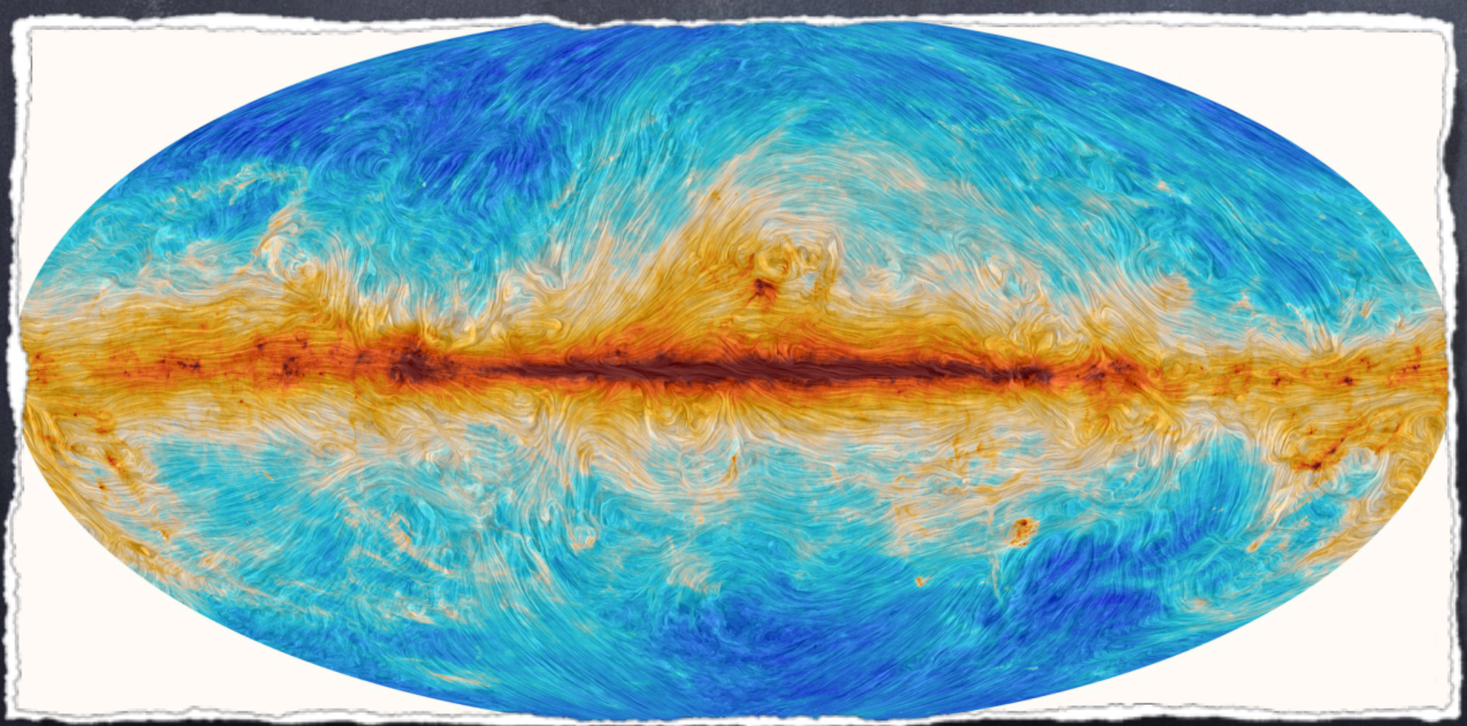
$$f_{NL} = 2.7 \pm 5.8$$

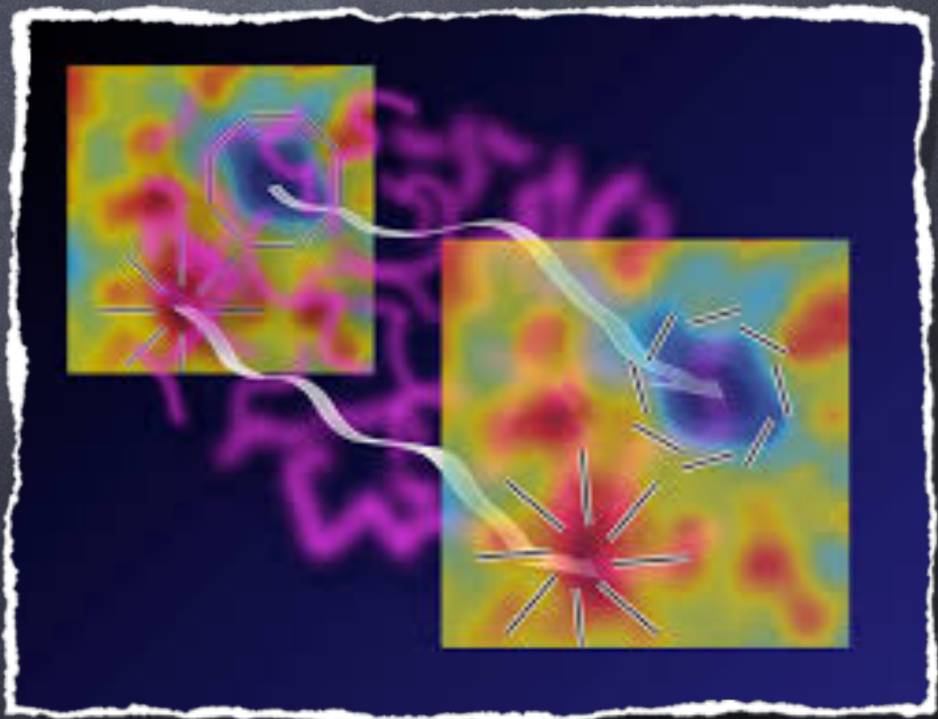
Fluctuations are Primarily Gaussian

E-mode & B-mode Polarisations



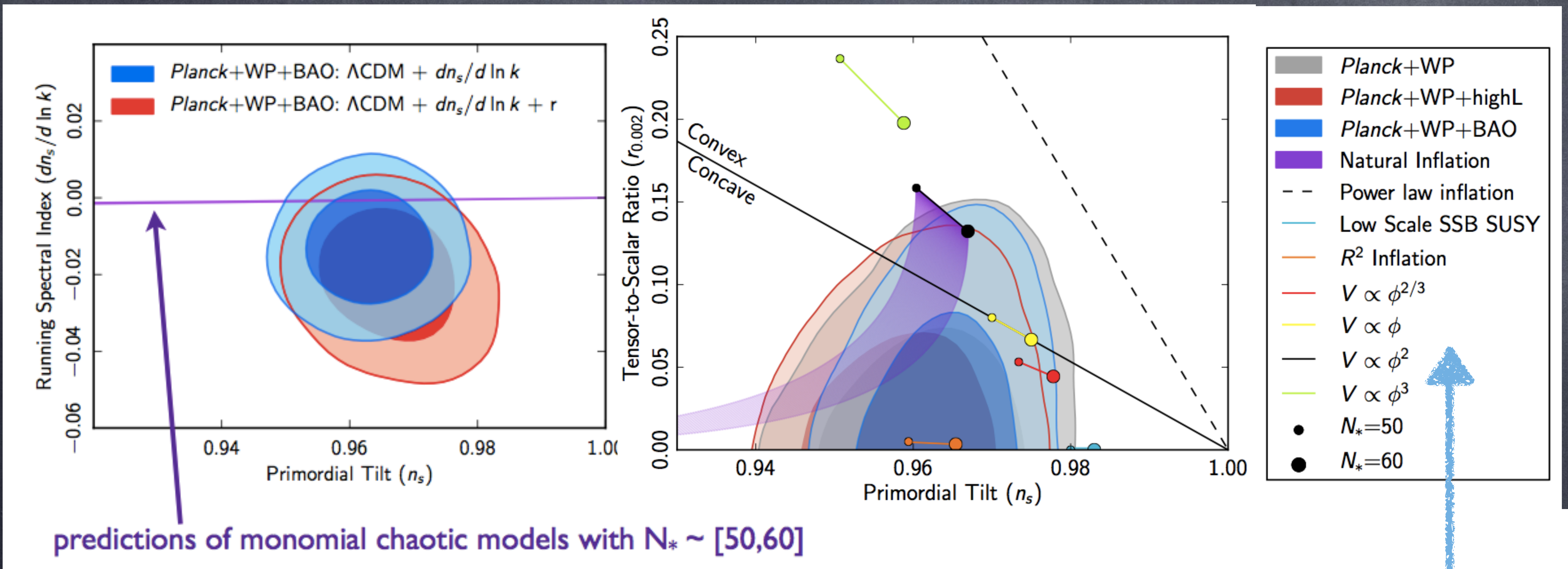
A pure E mode turns into B mode if we turn all polarisation vector by 45 degrees





No primordial B-modes detected so far

Summary Plot for Theorists from Planck



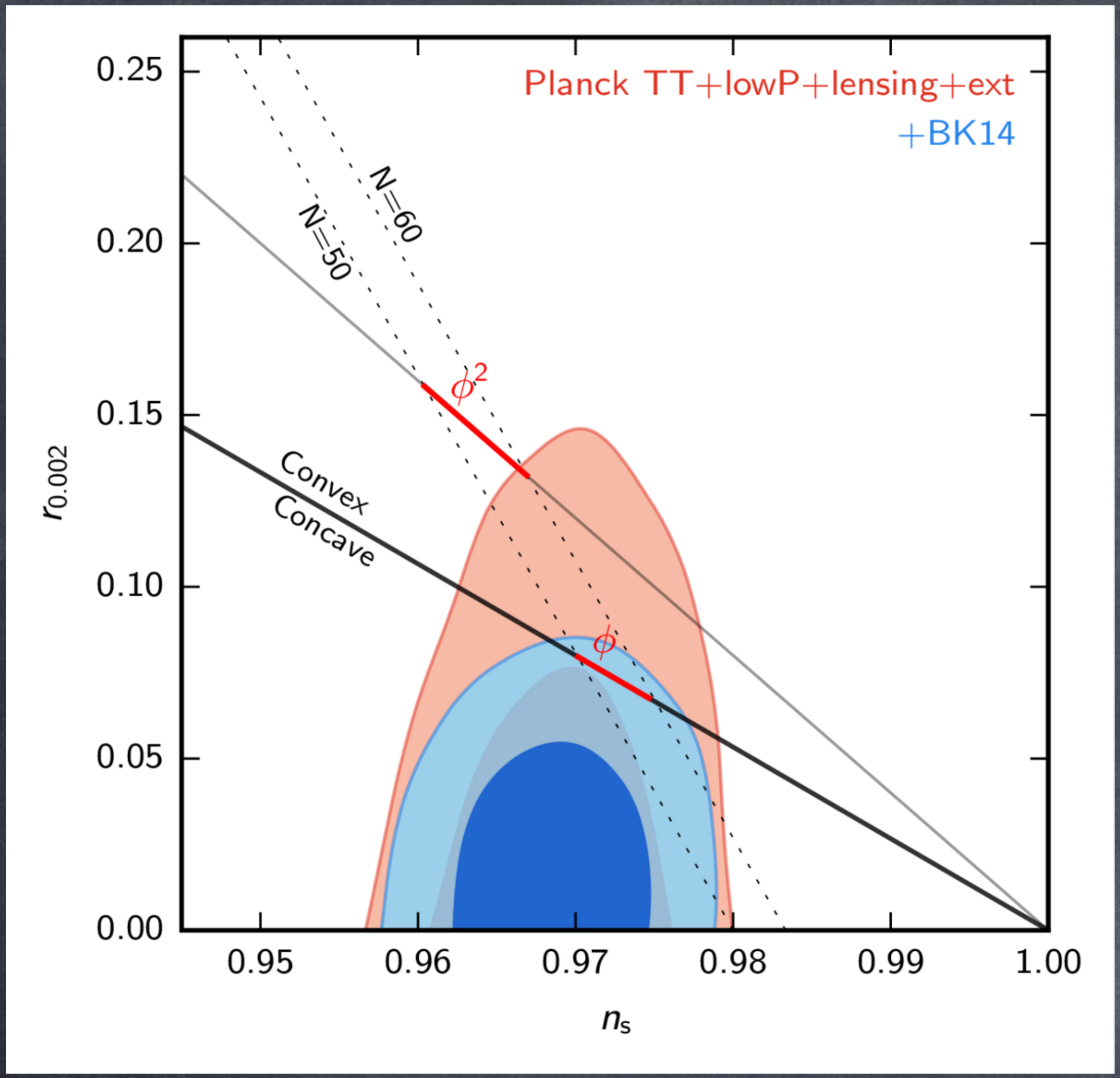
$$n_s = 0.959 \pm 0.007 \qquad r_{0.02} < 0.11 \ (95\% \ CL) \qquad \frac{dn_s}{d\ln k} = -0.015 \pm 0.009$$

$$S = \int d^4x \sqrt{g}\left[M_p^2 R + \alpha R^2\right] \qquad \alpha \sim 10^{10}$$

$$r = \frac{12}{N_e^2} = 3(n_s - 1)^2$$

Bench mark points -
No real physics

Super-Planckian VEVs



$$r(k_*) \equiv \frac{\mathcal{P}_T(k_*)}{\mathcal{P}_\zeta(k_*)}$$

$$\mathcal{P}_T = \frac{2H_{inf}^2}{\pi^2 M_p^2} \approx \frac{2V_{inf}}{3\pi M_p^4} \sim 4.2 \times 10^{-10}$$

$$r = 16\epsilon \leq 0.003 \left(\frac{50}{N}\right)^2 \left(\frac{\Delta\phi}{M_p}\right)^2$$

$$r \sim 0.1,\ N \sim 60,\ \Delta\phi \geq 48 M_p$$

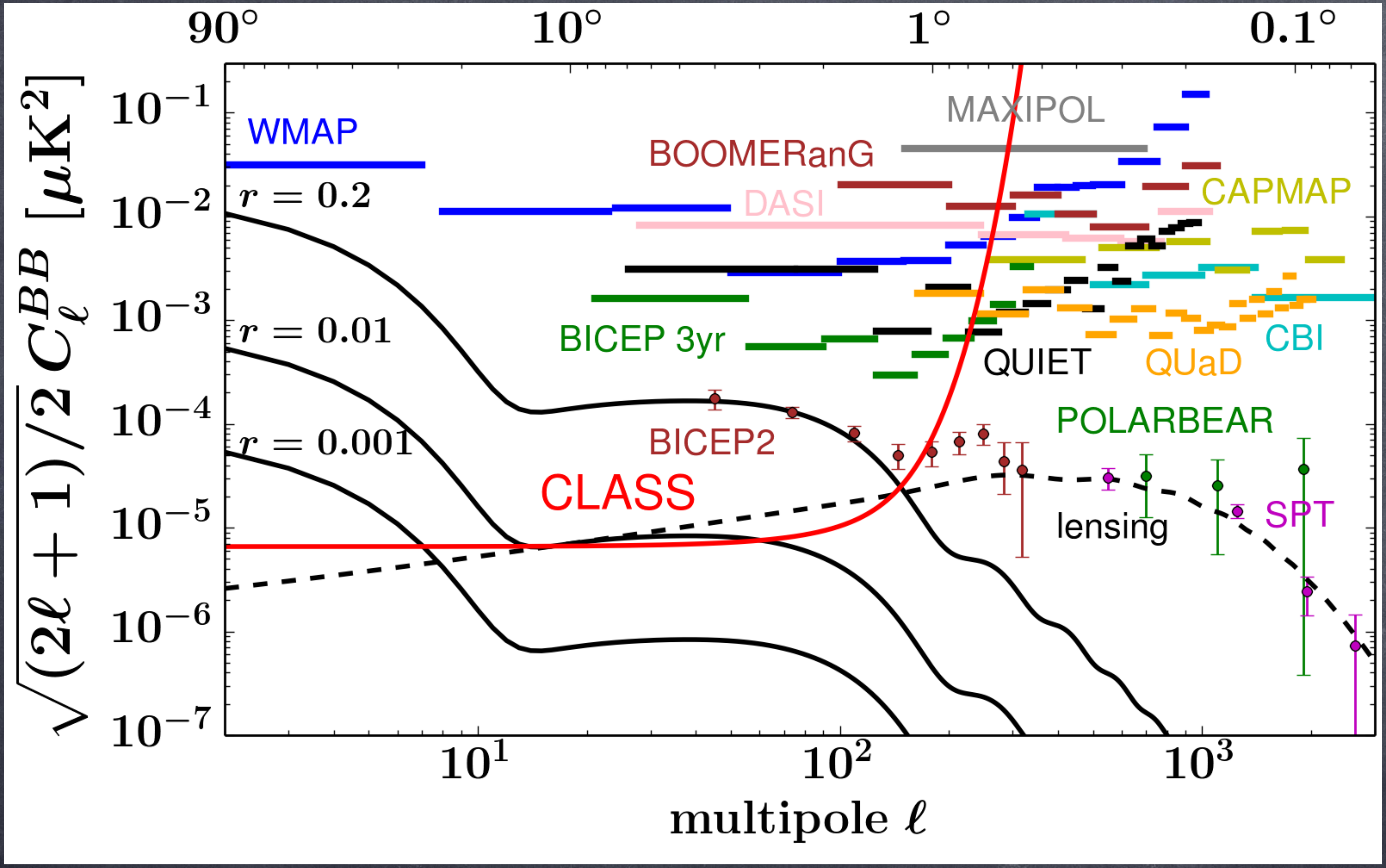
Starobinsky Inflation:

$$S = \int d^4x \sqrt{g}\left[M_p^2 R + \alpha R^2\right]$$

$$r = \frac{12}{N_e^2} = 3(n_s - 1)^2 \qquad r \sim 10^{-3}$$

Bicep+Planck jont analysis: 1510.09217

Immediate Future for CMB: B modes



$$f_{\rm NL}^{h\zeta\zeta} \equiv \langle h\zeta\zeta\rangle / (P_\zeta^{3/2} P_h^{1/2})$$

Tensor to scalar ratio: $r \equiv P_h(k_*)/P_\zeta(k_*)$

Non-Gaussianity: $f_{\rm NL} \propto \langle\zeta\zeta\zeta\rangle / P_\zeta^2(k)$

Challenges for Inflation

Many many models of inflation...

how many can really yield the Universe we see?

Perhaps NONE!

Some people like to do Bayesian fit to the data:

There is no Physics in such analysis: Priors

- assisted brane inflation
- anomaly-induced inflation
- assisted inflation
- assisted chaotic inflation
- B-inflation
- boundary inflation
- brane inflation
- brane-assisted inflation
- brane gas inflation
- brane-antibrane inflation
- braneworld inflation
- Brans-Dicke chaotic inflation
- Brans-Dicke inflation
- bulky brane inflation
- chaotic inflation
- chaotic hybrid inflation
- chaotic new inflation
- Chromo-Natural Inflation
- D-brane inflation
- D-term inflation
- dilaton-driven inflation
- dilaton-driven brane inflation
- double inflation
- double D-term inflation
- dual inflation
- dynamical inflation
- dynamical SUSY inflation
- S-dimensional assisted inflatior
- eternal inflation
- extended inflation
- extended open inflation
- extended warm inflation
- extra dimensional inflation
- Roulette inflation
- curvature inflation
- Natural inflation
- Warm natural inflation
- Super inflation
- Super natural inflation
- Thermal inflation
- Discrete inflation
- Polarcap inflation
- Open inflation
- Topological inflation
- Multiple inflation
- Warm inflation
- Stochastic inflation
- Generalised assisted inflation
- Self-sustained inflation
- Graduated inflation
- Local inflation
- Singular inflation
- Slinky inflation
- Locked inflation
- Elastic inflation
- Mixed inflation
- Phantom inflation
- Non-commutative inflation
- Tachyonic inflation
- Tsunami inflation
- Lambda inflation
- Steep inflation
- Oscillating inflation
- Mutated hybrid inflation
- Inhomogeneous inflation
- higher-curvature inflation
- hybrid inflation
- Hyper-extended inflation
- induced gravity inflation
- intermediate inflation
- inverted hybrid inflation
- Power-law inflation
- K-inflation
- Super symmetric inflation
- F-term inflation
- F-term hybrid inflation
- false-vacuum inflation
- false-vacuum chaotic inflation
- fast-roll inflation
- first-order inflation
- gauged inflation
- Ghost inflation
- Hagedorn inflation

Inflation Models are summarised

A.M & Rocher, Phys. Rept. (2011), Particle Physics Models of Inflation & Curvaton, 1001.0993

Visible Sector

BSM but not far from SM

$\phi \sim SU(3) \times SU(2) \times U(1)$

$\phi \sim SU(3) \times SU(2) \times U(1) \times U(1)'$

MSSM Flat directions as an inflaton (predictive thermal history)

SM Higgs inflation

$$\mathcal{L} \sim R + \xi R H^2$$

(predictive thermal history)

Hybrid inflation

$$V \sim \phi^2 (H^2 - v^2)$$

Higgs need not be SM, could be GUT

Hidden Sector

SM gauge singlets, String theory inspired models driven by open string moduli

Open Closed String

Brane/anti-brane inflation

Gravity Sector (universal)

$$\mathcal{L} \sim M_p^2 R + 10^{10} R^2$$

Broad classes of Inflation

A.M & Rocher, Phys. Rept. (2011), Particle Physics Models of Inflation & Curvaton, 1001.0993

High Scale Inflation

$$\Delta\phi \geq M_p, \quad \phi_{CMB} \geq M_p$$

Chaotic $V \sim \phi^n$

Natural/Monodromy

$$V \sim \Lambda^4(1+\cos(\phi/f))$$

Topological

$$V \sim \frac{\lambda}{4}(\phi^2-\eta^2)^2$$

Higgs

$$V \sim \frac{\lambda M_p^4}{4\xi^2}(1-e^{-2\phi/\sqrt{6}M_p})$$

Starobinsky

$$\mathcal{L} \sim M_p^2 R + 10^{10} R^2$$

Intermediate Scale Inflation

$$\Delta\phi \leq M_p, \quad \phi_{CMB} \leq M_p$$

Assisted/N-flation

$$V \sim \sum_i \phi_i^n$$

Hybrid/Mutated

$$V(\phi,\psi) = \frac{1}{2}m^2\phi^2 + \frac{\lambda}{4}\left(\psi^2 - M^2\right)^2 + \frac{\lambda'}{2}\phi^2\psi^2$$

$$V_{pq}(\phi,\psi) = M^4\left[1-\left(\frac{\psi}{m}\right)^p\right]^2 + \lambda\phi^2\psi^q$$

MSSM/Inflection

$$V \sim V_0 + (\phi-\phi_0)V'(\phi) + (\phi-\phi_0)^3 V''' + \cdots$$

Low Scale Inflation

$$\Delta\phi \ll M_p, \quad \phi_{CMB} \ll M_p$$

Thermal

$$V \sim g^2T^2\phi^2 + \lambda(\phi^2-\eta^2)^2$$

Fundamental Aspects of Inflation

There are many assumptions we make, which are not so easy to justify …

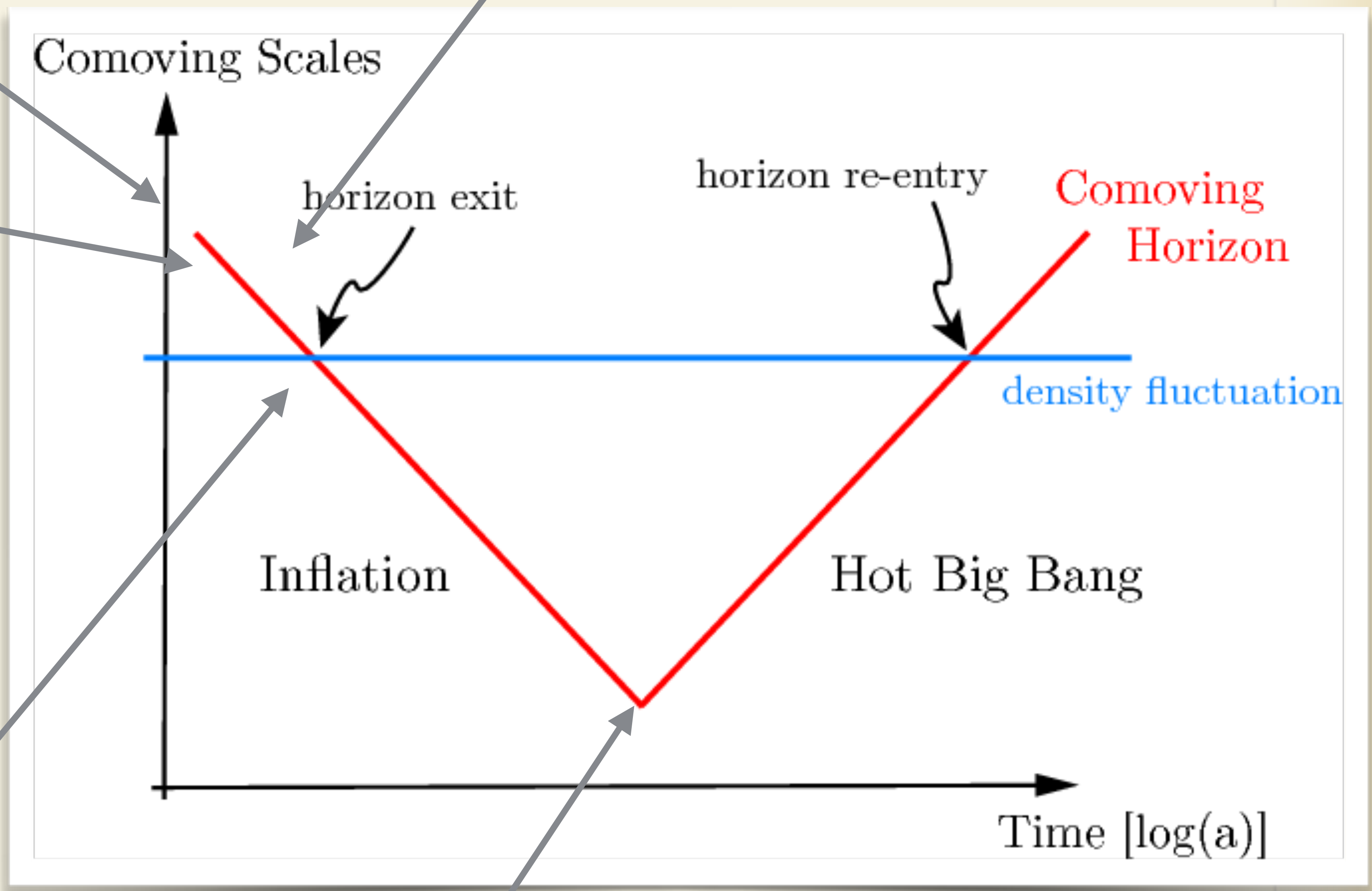
Questions & Assumptions:

within my causal patch

Why Inflationary patch is homogeneous & isotropic ?

Is there a dynamical attractor solution?

Whether EFT is valid close to the cut-off too ?



Assuming Validity of EFT produces data, i.e. slow roll inflation

How do we produce the SM dof ?

Validity of Effective Field Theory

$M_p \sim 10^{18}$ GeV

M_s

$H_{inf} \leq 10^{13}$ GeV

	Single UV scale	Multiple scales
	$\rho_{inf} \leq M_p^4$	$\rho_{inf} \leq M_s^2 M_p^2$
Momentum transfer	$\leq M_p$	$\leq M_s$

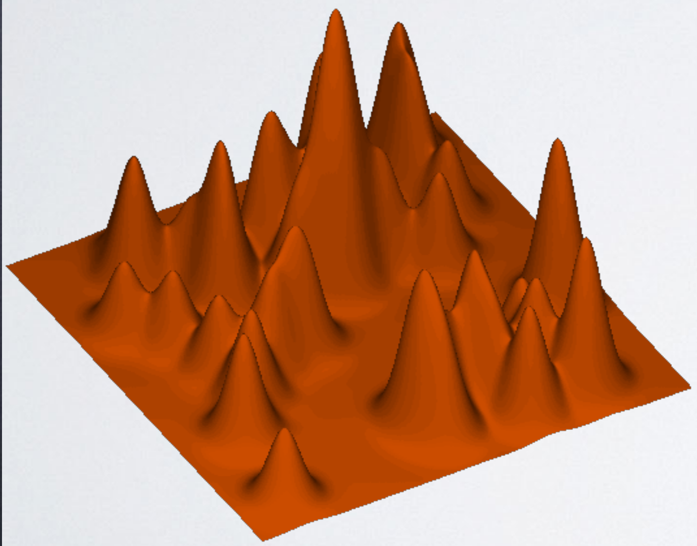
Super-Planckian VEVs

Virtual Blackhole and break-down of Semi-Classicality during inflation

QUANTUM CORRECTIONS: SEA OF BLACK HOLES!

$$V \sim \sum_i^N g_i \phi \bar{\psi}_i \psi_i \,, \qquad V \sim \sum_i^N g_i' \phi F^i_{\mu\nu} F^{i\ \mu\nu}$$

$$g_i,\ g_i' \sim \mathcal{O}(1), \quad \langle\phi\rangle \sim \mathcal{O}(1-10) M_p$$



$$m_{\psi,\ A_\mu} \sim g\langle\phi\rangle \sim 10 g M_p$$

Inflaton coupled to a "sea of Planckian Black holes"

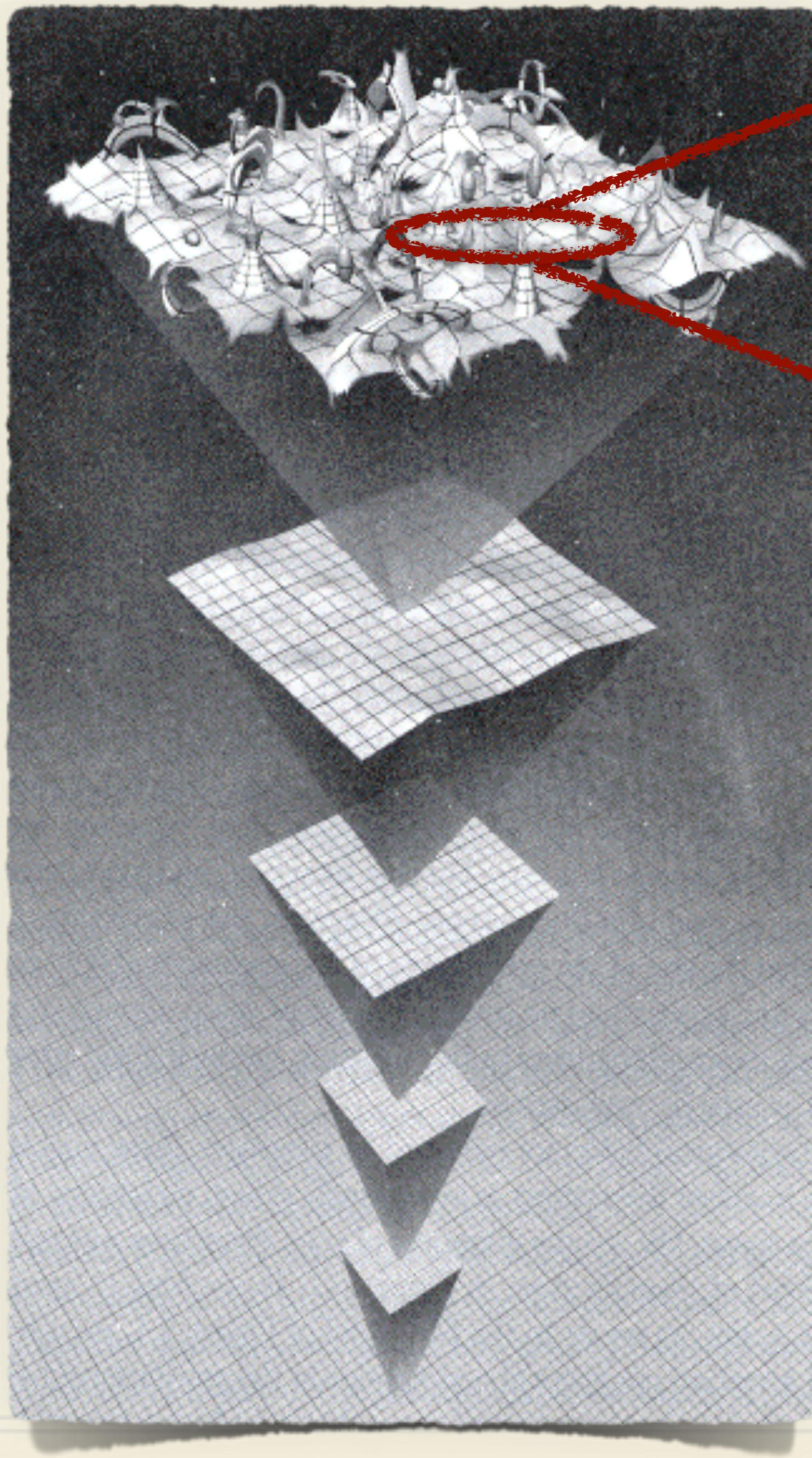
$$(N m_\psi)^4 \sim (N g \langle\phi\rangle)^4 \leq 10^{64}\ \mathrm{GeV})^4$$

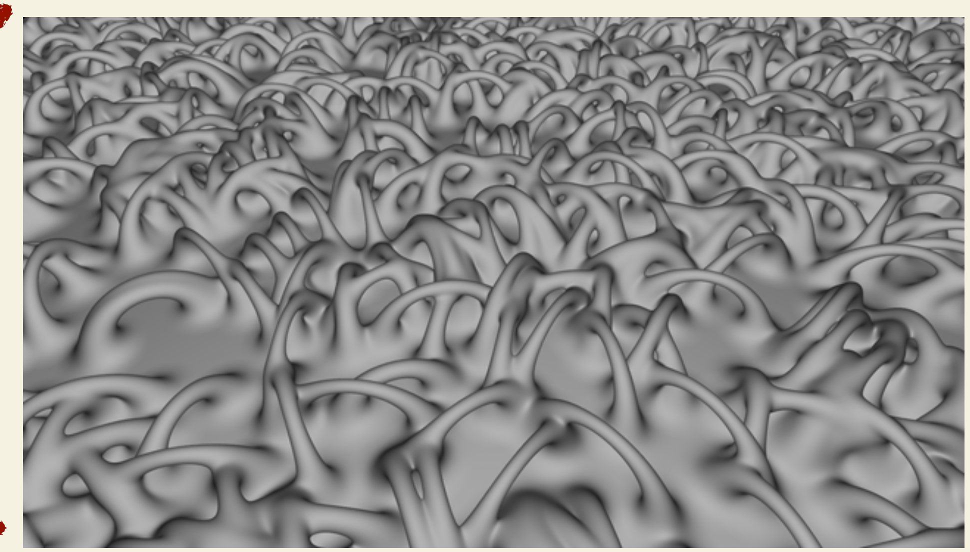
$$N g \leq 10^{-3}$$

Such an inhomogeneous Universe cannot be inflated !

Inflation requires initial condition

M_p





M

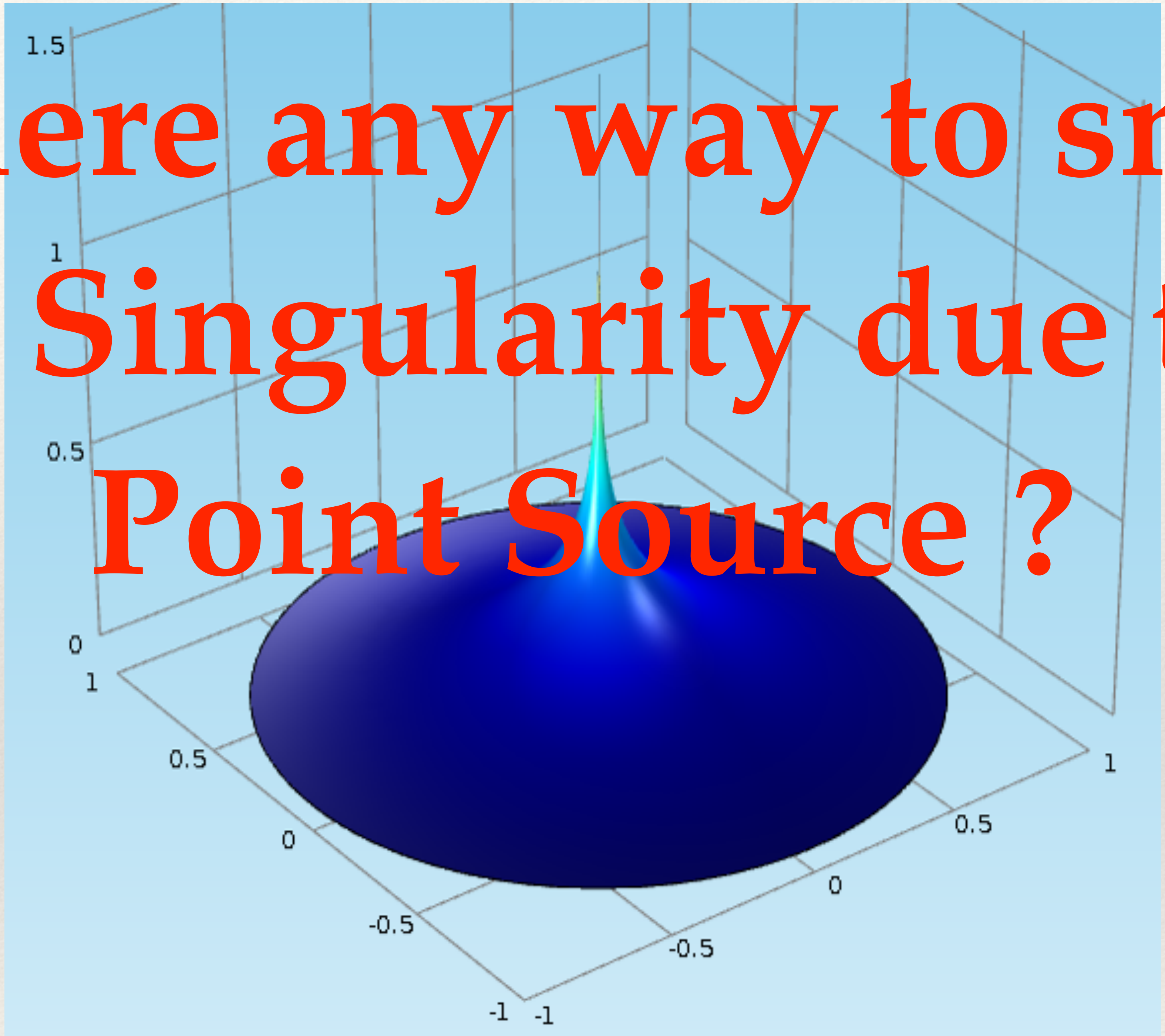
Inflationary scale

$H_{inf} \leq 10^{13}$ GeV

What ever mechanism smoothens the spacetime

Holds the key for a successful inflation

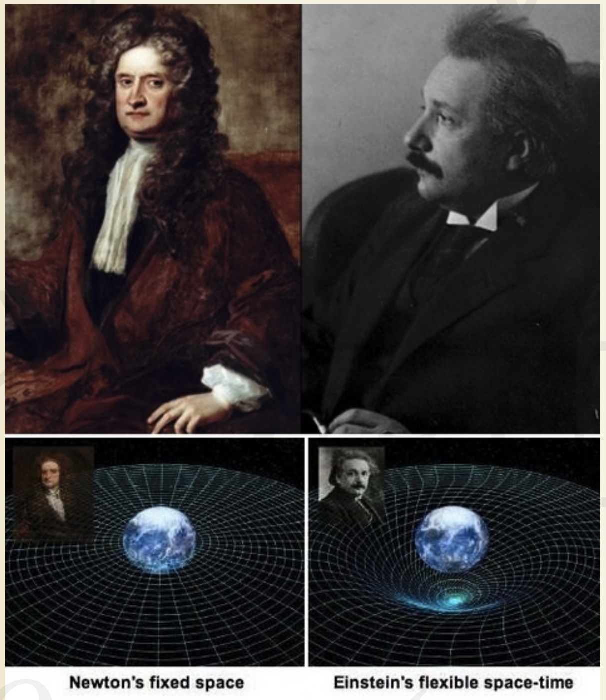
Einstein Gravity



Is there any way to smear the Singularity due to a Point Source ?

$$ds^2 = \left(1 - \frac{2Gm}{r}\right) dt^2 - \frac{dr^2}{\left(1 - \frac{2Gm}{r}\right)}$$

UV Modification of Gravity



UV is Pathological,

IR Part is Safe

$$S = \int \sqrt{-g}d^4x \left(\frac{R}{16\pi G} + \cdots \right)$$

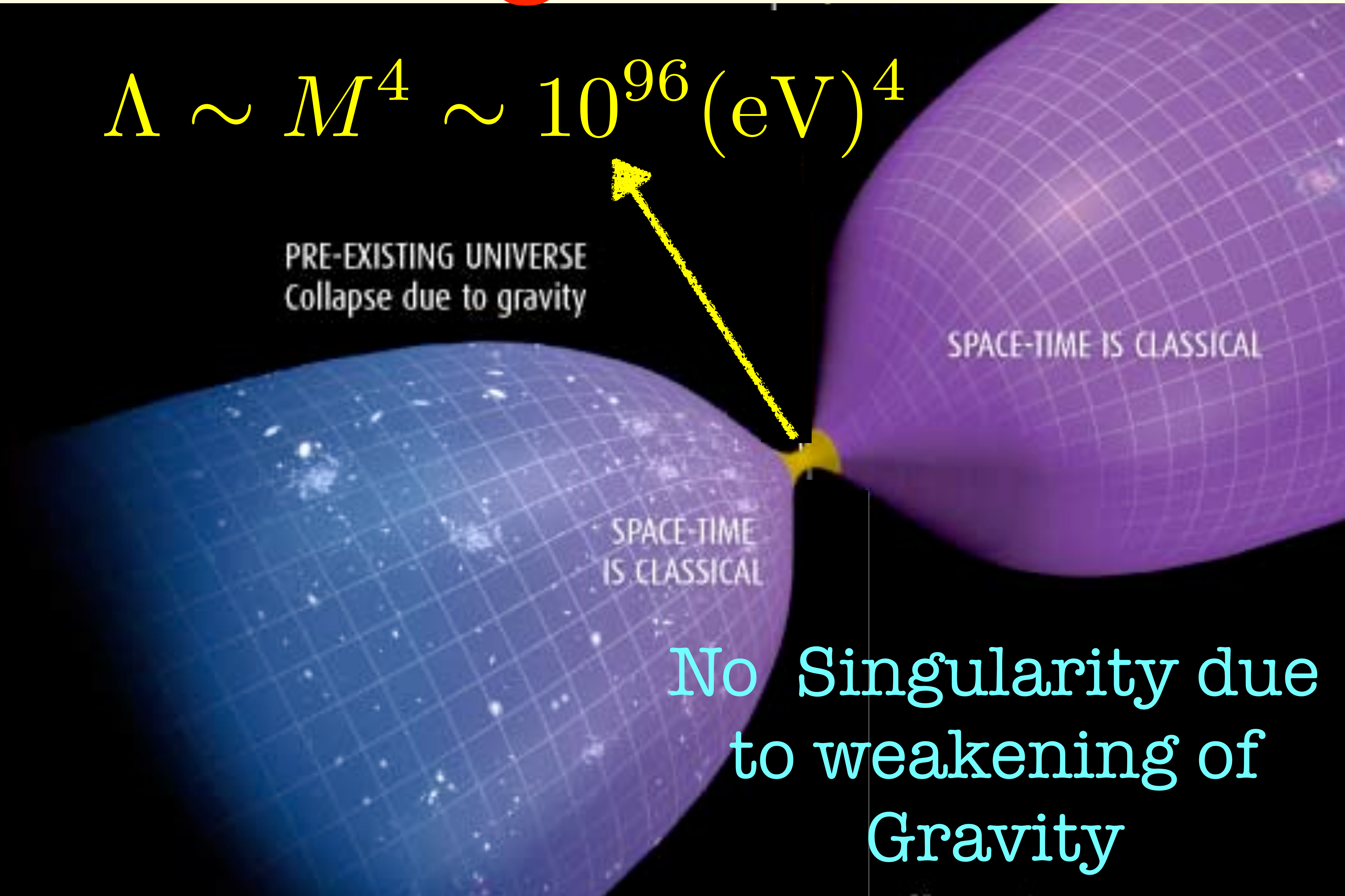
You need to weaken Gravity such that at small spatial scales and at small times spacetime does not collapse to form blackholes !

$$\big\downarrow$$

$$S = \int \sqrt{-g}d^4x \left(\frac{R}{16\pi G} \right)$$

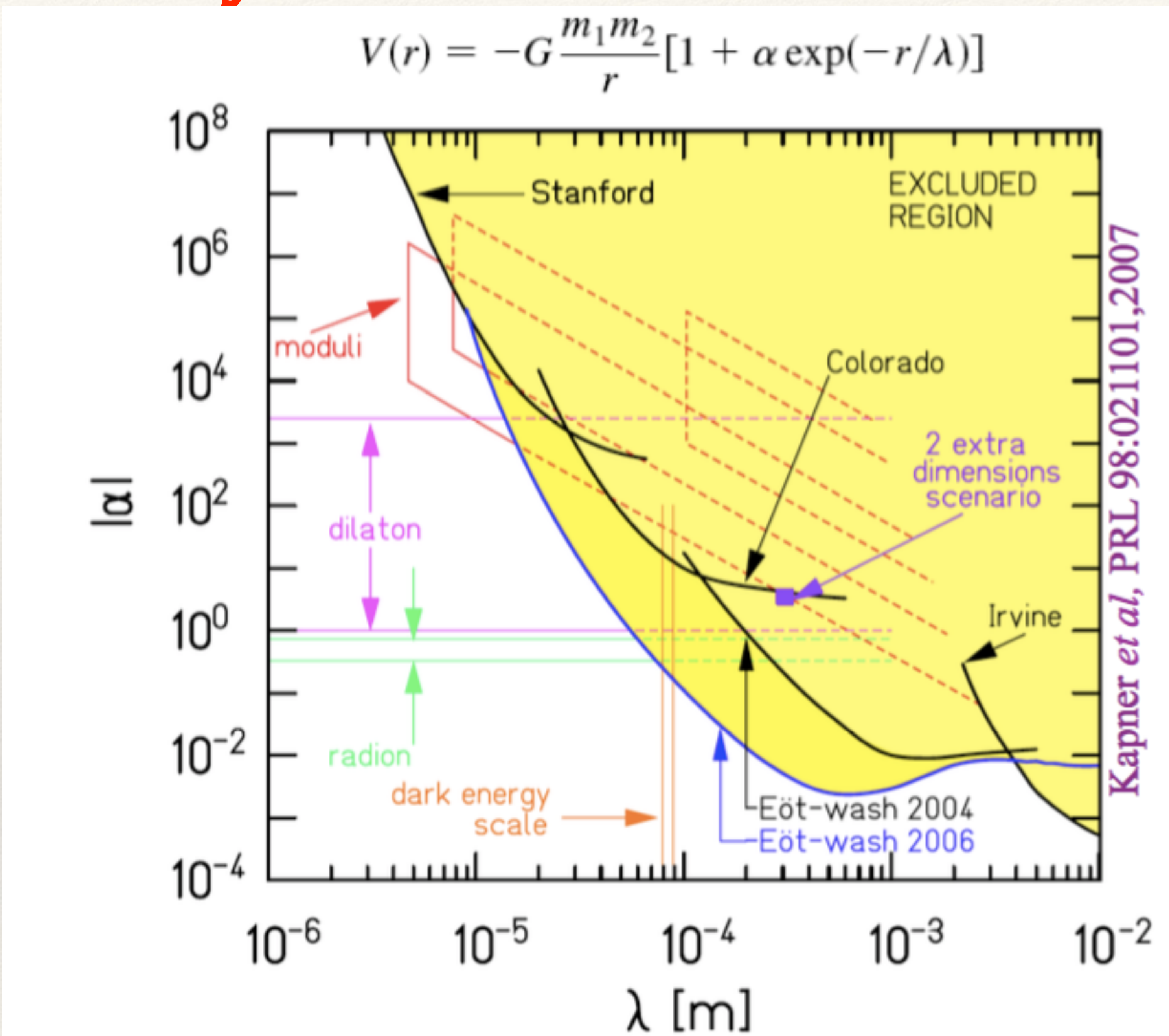
Big Bounce

$$\Lambda \sim M^4 \sim 10^{96} (\mathrm{eV})^4$$



No Singularity due to weakening of Gravity

Energy Ladder :
Very Little do we know about Gravity



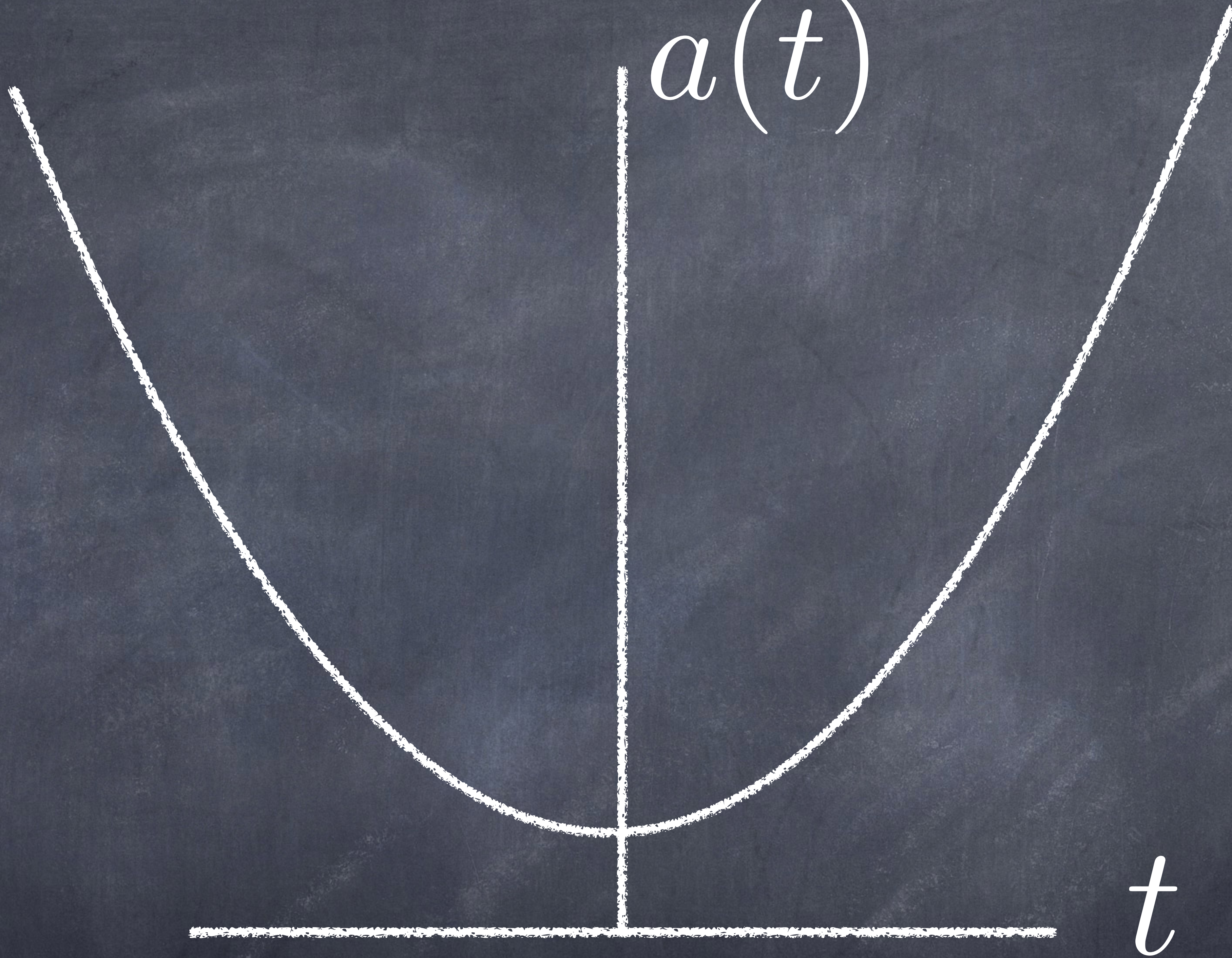
$(10^{27}\ \mathrm{eV})^4$

$(10^{-2}\ \mathrm{eV})^4$

$(10^{-3}\ \mathrm{eV})^4$

No departure from Newtonian Gravity up to

$10^{-5}\ \mathrm{m} \sim 100\ (\mathrm{eV})^{-1}$ or, $M \sim 10^{-2}\ \mathrm{eV}$



At the bounce point universe ought to be Inflating

$$S = \int d^4x \sqrt{g} \left[M_p^2 R + \alpha R^2 \right]$$

Could this do a job?

It can give rise to inflation,
but it cannot explain the Non-Singular
Bounce

4th Derivative Gravity & Power Counting renormalizability

$$I = \int d^4x \sqrt{g}\left[\lambda_0 + k\,R + a\,R_{\mu\nu}R^{\mu\nu} - \tfrac{1}{3}(b+a)R^2\right]$$

$$D \propto \frac{1}{k^4 + Ak^2} = \frac{1}{A}\left(\frac{1}{k^2} - \frac{1}{k^2+A}\right)$$

Massive Spin-0 & Massive Spin-2 (Ghost) Stelle (1977)

Utiyama, De Witt (1961), Stelle (1977)

Modification of Einstein's GR

Modification of Graviton Propagator

Extra propagating degree of freedom

Challenge: to get rid of the extra dof

Ghosts

Higher Order Derivative Theory Generically Carry Ghosts (-ve Risidue) with real "m"(No-Tachyon)

$$S = \int d^4x\ \phi\Box(\Box + m^2)\phi \Rightarrow \Box(\Box + m^2)\phi = 0$$

$$\Delta(p^2) = \frac{1}{p^2(p^2+m^2)} \sim \frac{1}{p^2} - \frac{1}{(p^2+m^2)}$$

Propagator with first order poles

Ghosts cannot be cured order by order, finite terms in perturbative expansion will always lead to Ghosts !!

$$\Box e^{-\Box}\phi = 0$$

No extra states other than the original dof.

Moffat (1991), Tomboulis (1997), Tseytlin (1997), Siegel (2003), Biswas, Grisaru, Siegel (2004), Biswas, Mazumdar, Siegel (2006)

Consistent Covariant Quadratic Theories of Gravity with Stable Constant Curvature Backgrounds

“Perturbative Unitarity”

“Ghost Free”

“Tachyon Free”

“Correct degrees of freedom in Graviton Propagator”

Spin-2

&

Spin-0

components of a Graviton Propagator

UV completion of Starobinsky Inflation

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

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

(1) GR
(2) Weyl Gravity
(3) F(R) Gravity
(4) Gauss-Bonnet Gravity
(5) Ghost free Gravity

Biswas, Mazumdar, Siegel, JCAP, 2006,

Biswas, Gerwick, Koivisto, Mazumdar, PRL. (2012)

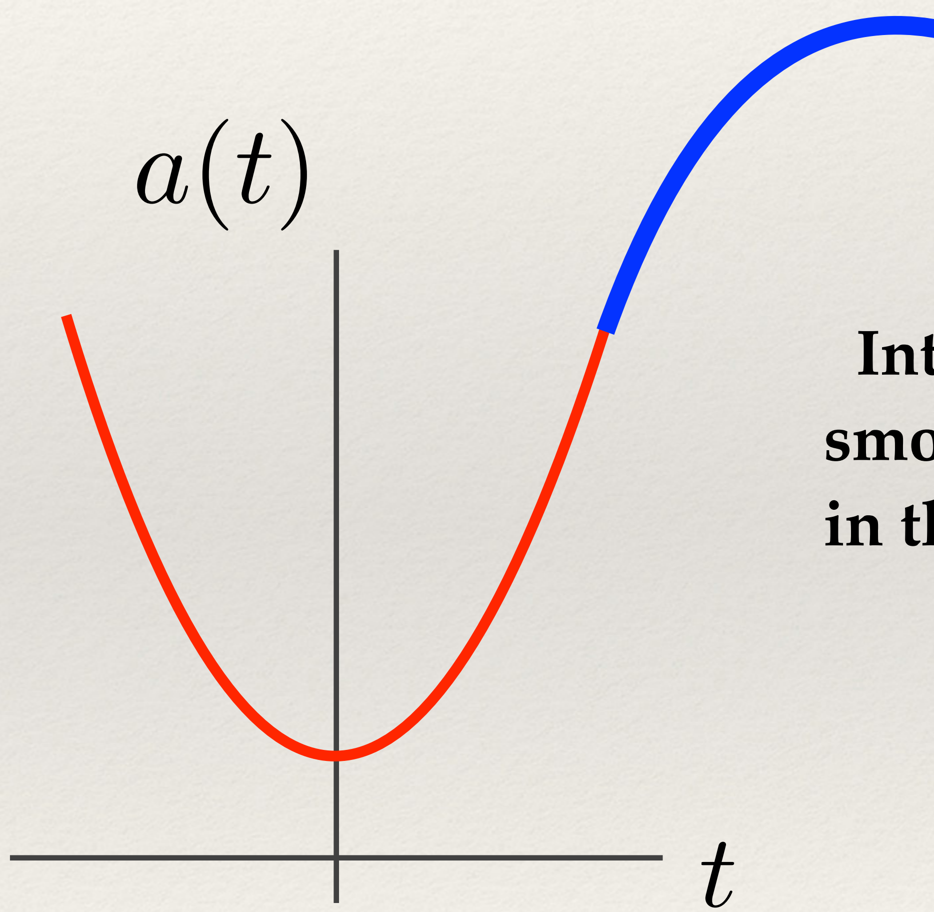
Chialva, Mazumdar, 2013,

Koshelev, Modesto, Rachwal, Starobinsky, 2016

Nonlocal Gravity & Cosmological Singularity

$$S = \int d^4x \sqrt{-g}\left[\frac{R}{2} + R\left[\frac{e^{\frac{-\Box}{M^2}} - 1}{\Box}\right] R + \Lambda\right]$$

$$a(t) = a_0 \cosh\left(\sqrt{\frac{\Lambda}{6M_{pl}^2}}\, t\right)$$



Interesting smoking gun in the Planck data !

Cosmological Constant at Bounce

$$M \sim \Lambda^{1/4}$$

Biswas, AM, PRD (2014)

"Einstein Gravity Does Not Permit Such Solution"

Non-local action

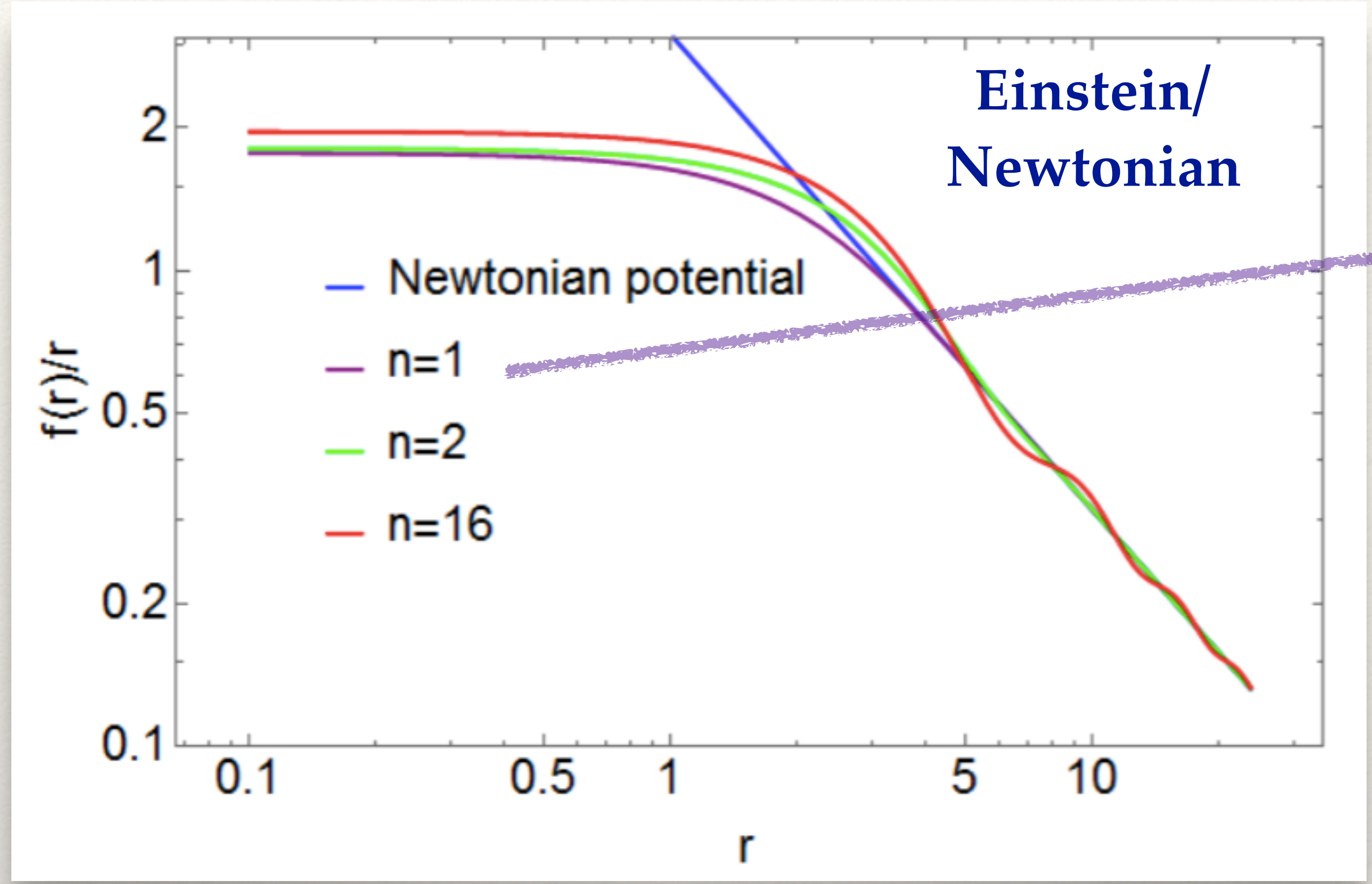
$$S = \int d^4x \, \sqrt{-g} \left[\frac{R}{2} + R \left[\frac{e^{\frac{-\Box}{M^2}} - 1}{\Box} \right] R - 2R_{\mu\nu} \left[\frac{e^{-\frac{\Box}{M^2}} - 1}{\Box} \right] R^{\mu\nu} \right]$$

$$ds^2 = -(1 - 2\Phi)dt^2 + (1 + 2\Psi)dr^2$$

$$\Phi = \Psi = \frac{Gm}{r} \mathbf{erf} \left(\frac{rM}{2} \right)$$

Biswas, Gerwick, Koivisto, Mazumdar, Phys. Rev. Lett. (2012)
(gr-qc/1110.5249)

Resolution of Singularity at short distances

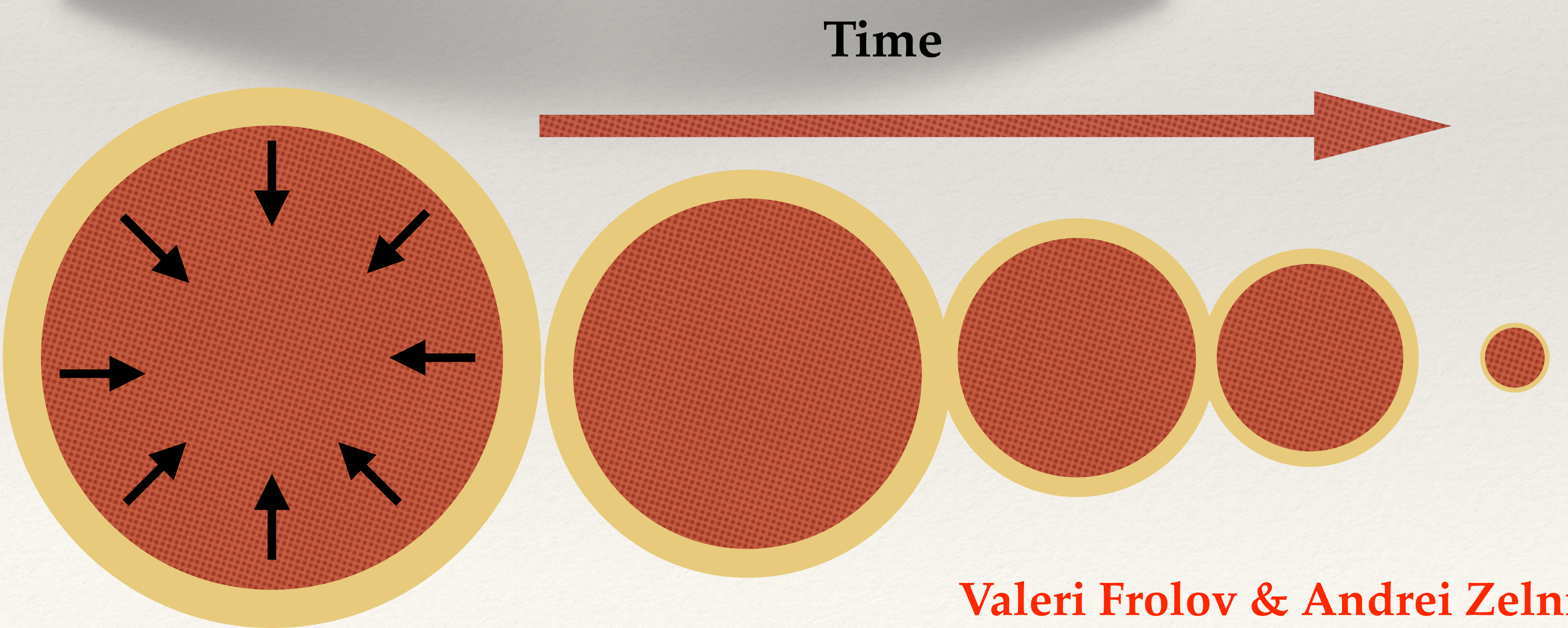


$$\Phi(r) = \Psi(r) = \frac{Gm}{r}\mathbf{erf}\left(\frac{rM}{2}\right)$$

$$mM \ll M_p^2 \implies m \ll M_p$$

Current Bound : M > 0.01 eV

Edholm, Koshelev, Mazumdar (2016)



A lump of matter without horizon and without singularity

Valeri Frolov & Andrei Zelnikov (2015)

SM Higgs as an Inflaton

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

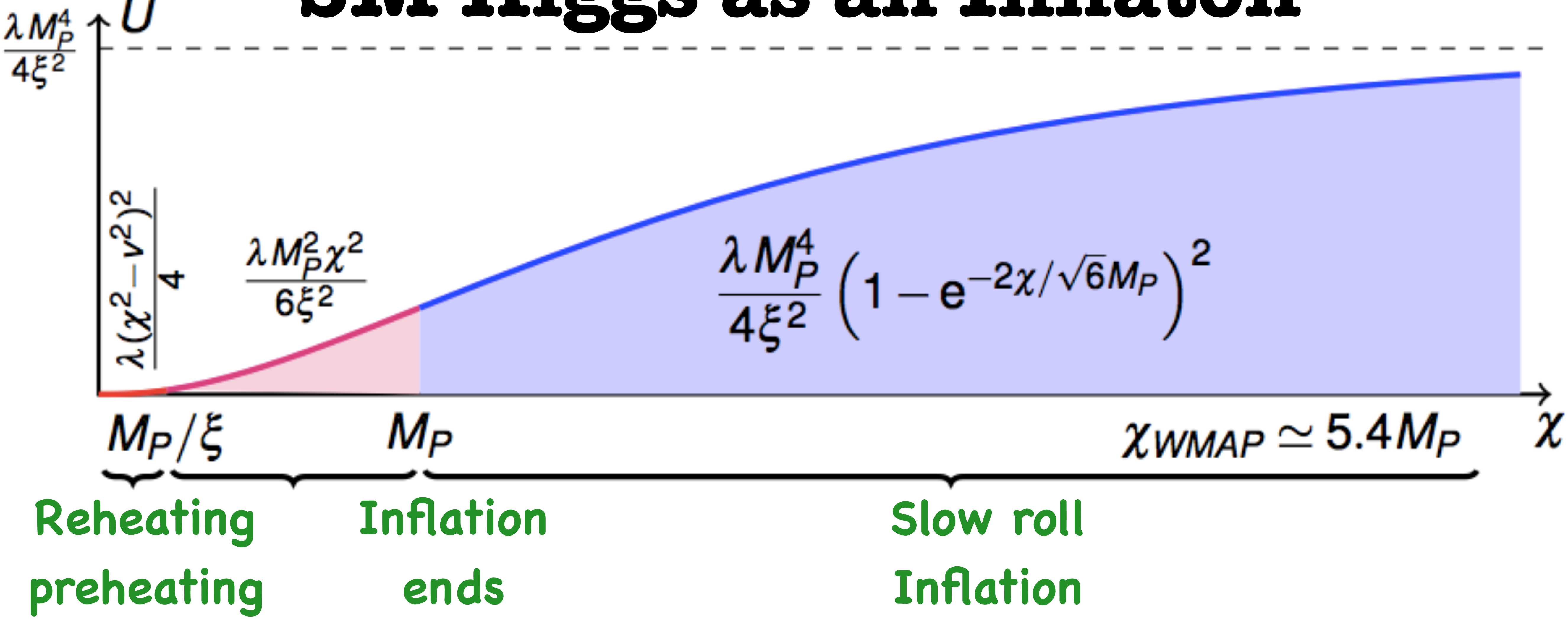
$$\hat{g}_{\mu\nu} = \Omega^2 g_{\mu\nu}\,, \qquad \Omega^2 \equiv 1 + \frac{\xi h^2}{M_P^2}$$

Redefinition of the Higgs field to get canonical kinetic term

$$\frac{d\chi}{dh} = \sqrt{\frac{\Omega^2 + 6\xi^2 h^2/M_P^2}{\Omega^4}} \implies \begin{cases} h \simeq \chi & \text{for } h < M_P/\xi \\ \Omega^2 \simeq \exp\left(\frac{2\chi}{\sqrt{6}M_P}\right) & \text{for } h > M_P/\xi \end{cases}$$

$$S_E = \int d^4x\sqrt{-\hat{g}}\left\{-\frac{M_P^2}{2}\hat{R} + \frac{\partial_\mu\chi\partial^\mu\chi}{2} - \frac{\lambda}{4}\frac{h(\chi)^4}{\Omega(\chi)^4}\right\}$$

SM Higgs as an Inflaton



spectral index	$n \simeq 1 - \frac{8(4N+9)}{(4N+3)^2} \simeq 0.97$
tensor/scalar ratio	$r \simeq \frac{192}{(4N+3)^2} \simeq 0.0033$

$$\delta T/T \sim 10^{-5} \quad \Longrightarrow \quad \frac{\xi}{\sqrt{\lambda}} \simeq 47000$$

Reheating temperature $M_P/\xi < T_{\text{reheating}} < M_P/\sqrt{\xi}$

Effective field theory is invalid

[FB, Magnin, Sibiryakov, Shaposhnikov'11]

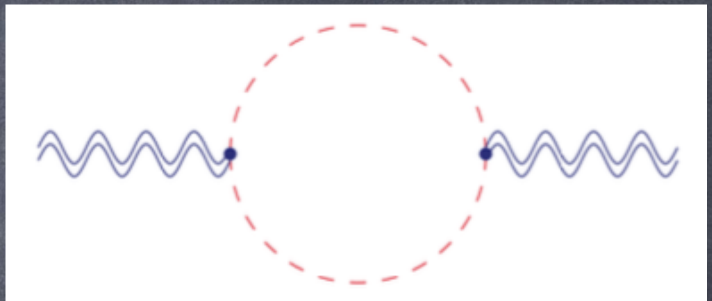
SM Higgs - Starobinsky Model of Inflation

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

$$\delta T/T \sim 10^{-5} \quad \Longrightarrow \quad \frac{\xi}{\sqrt{\lambda}} \simeq 47000$$

$$S = \int d^4x\sqrt{-g}\left[-\left(\frac{M_p^2}{2} + \xi H^2\right)R + \alpha R^2\right]$$

$$|\alpha| \geq \frac{\xi^2}{8\pi^2}$$

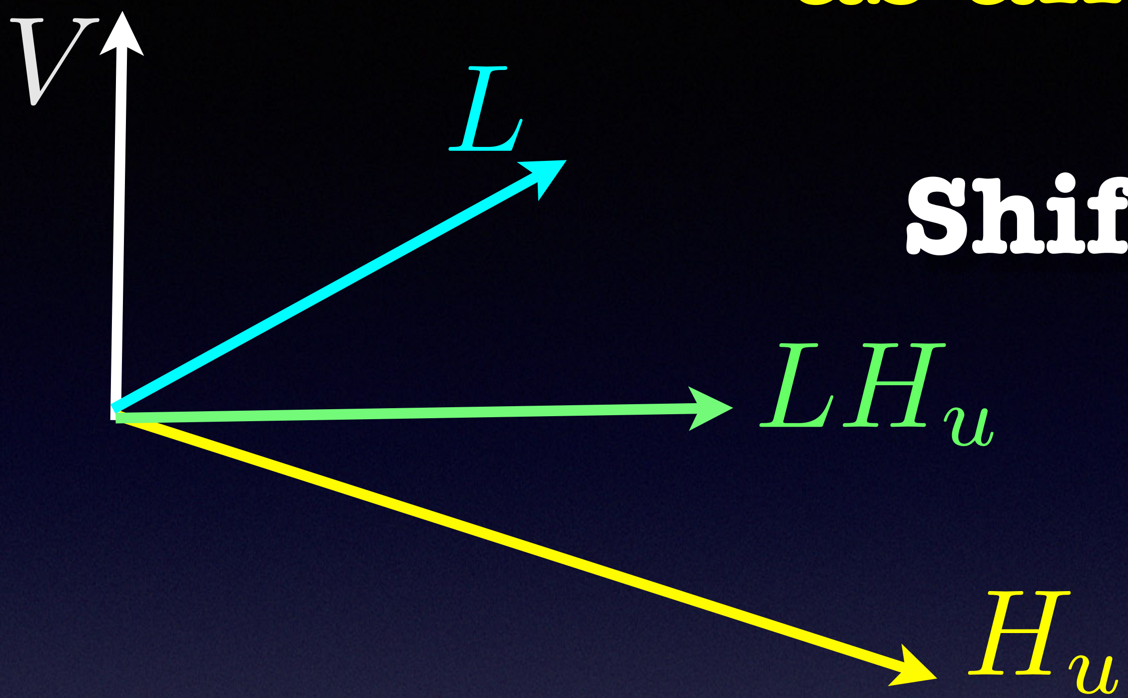


Inflation is driven by Starobinsky scalar and not by Higgs

SUSY Based Models

SUSY+ Gravity = SUGRA Based Models

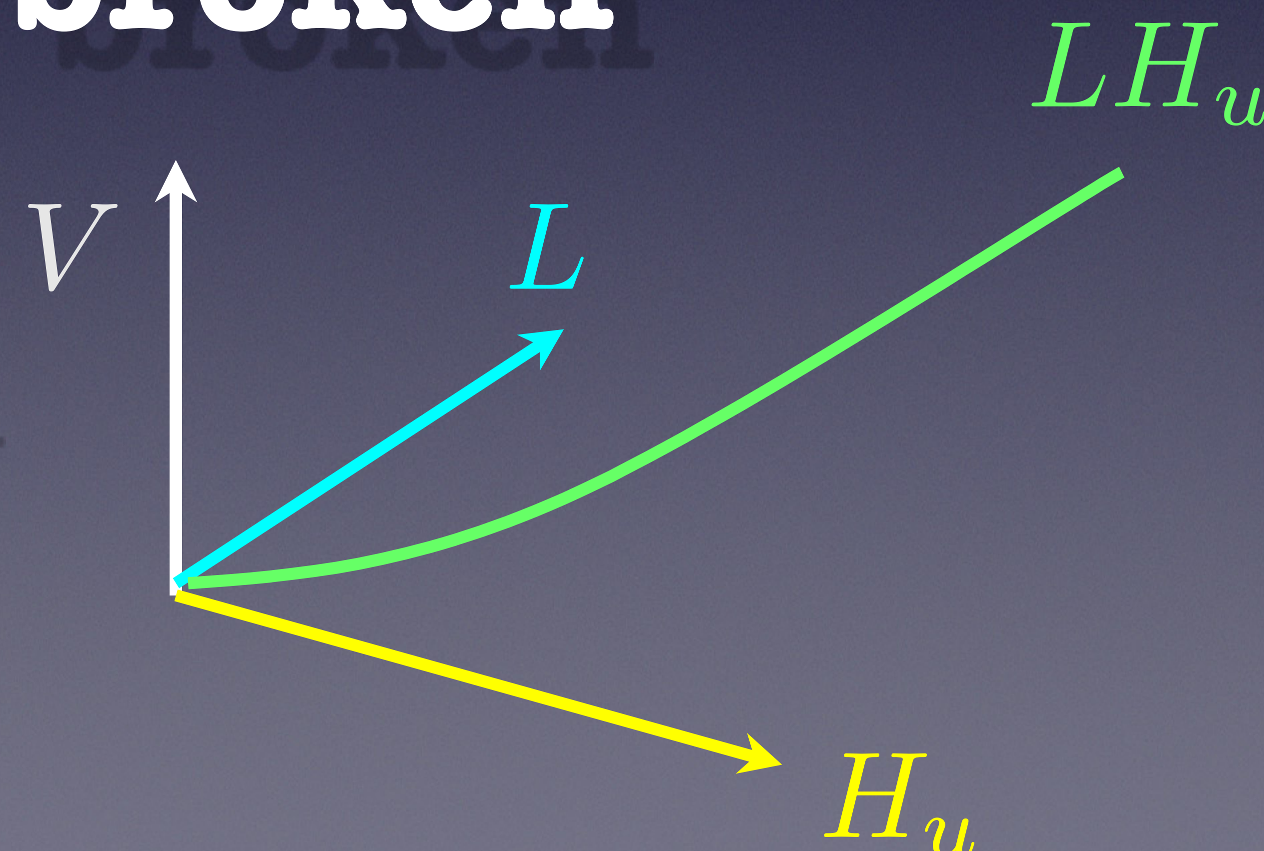
SUSY Flat direction as an Inflaton



Shift symmetry

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	√

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

$u_1d_2d_3$ $\quad d_2^\beta=\frac{1}{\sqrt{3}}\phi \quad u_1^\alpha=\frac{1}{\sqrt{3}}\phi \quad d_3^\gamma=\frac{1}{\sqrt{3}}\phi$

$L_1L_2e_3$ $\quad L_1^a=\frac{1}{\sqrt{3}}\begin{pmatrix}0\\ \phi\end{pmatrix} \quad L_2^b=\frac{1}{\sqrt{3}}\begin{pmatrix}\phi\\ 0\end{pmatrix} \quad e_3=\frac{1}{\sqrt{3}}\phi$

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

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

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

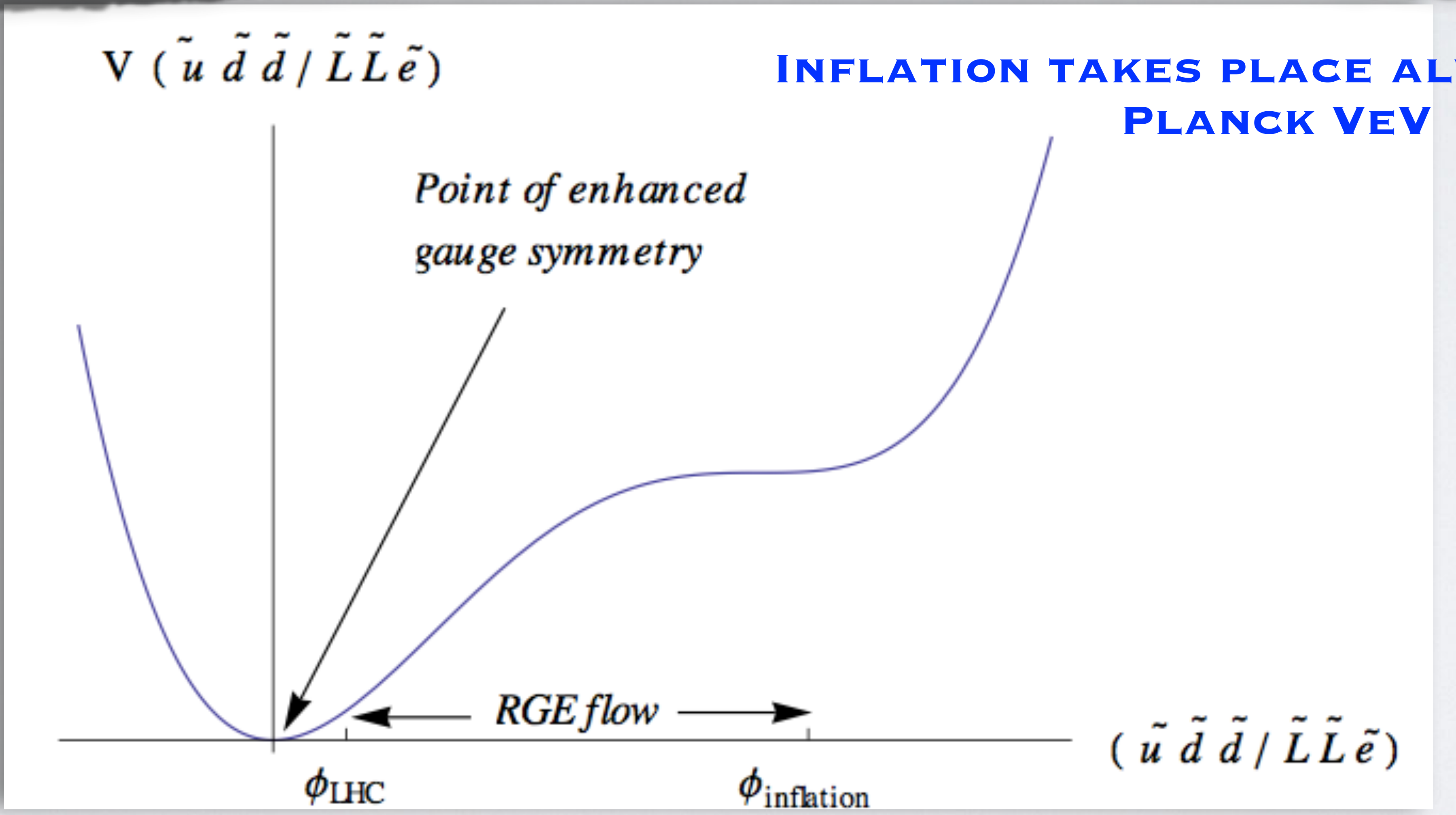
Allahverdi, Enqvist, Bellido, AM, (PRL, 2006), (JCAP, 2007), Allahverdi, Kusenko, AM, JCAP (2007), Allahverdi, Dutta, AM (PRL 2007), Chatterjee, AM, JCAP (2011)

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

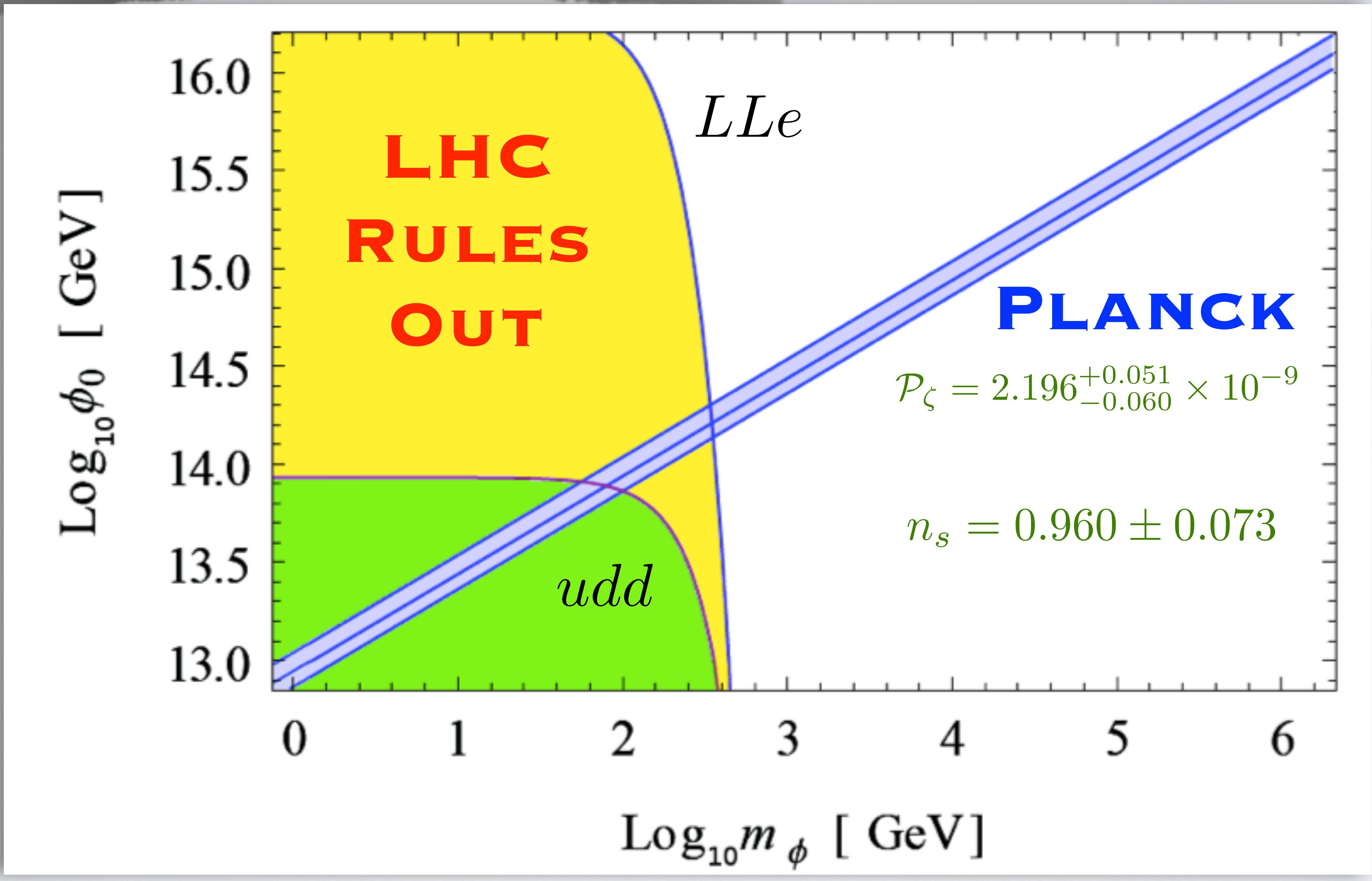


Allahverdi, Enqvist, Garcia-Bellido, AM, PRL (2006), JCAP (2006), Allahverdi, Kusenko AM, JCAP (2006), Allahverdi, Dutta, AM, PRL (2007)

LHC & PLANCK JOINT CONSTRAINTS ON INFLATONS

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

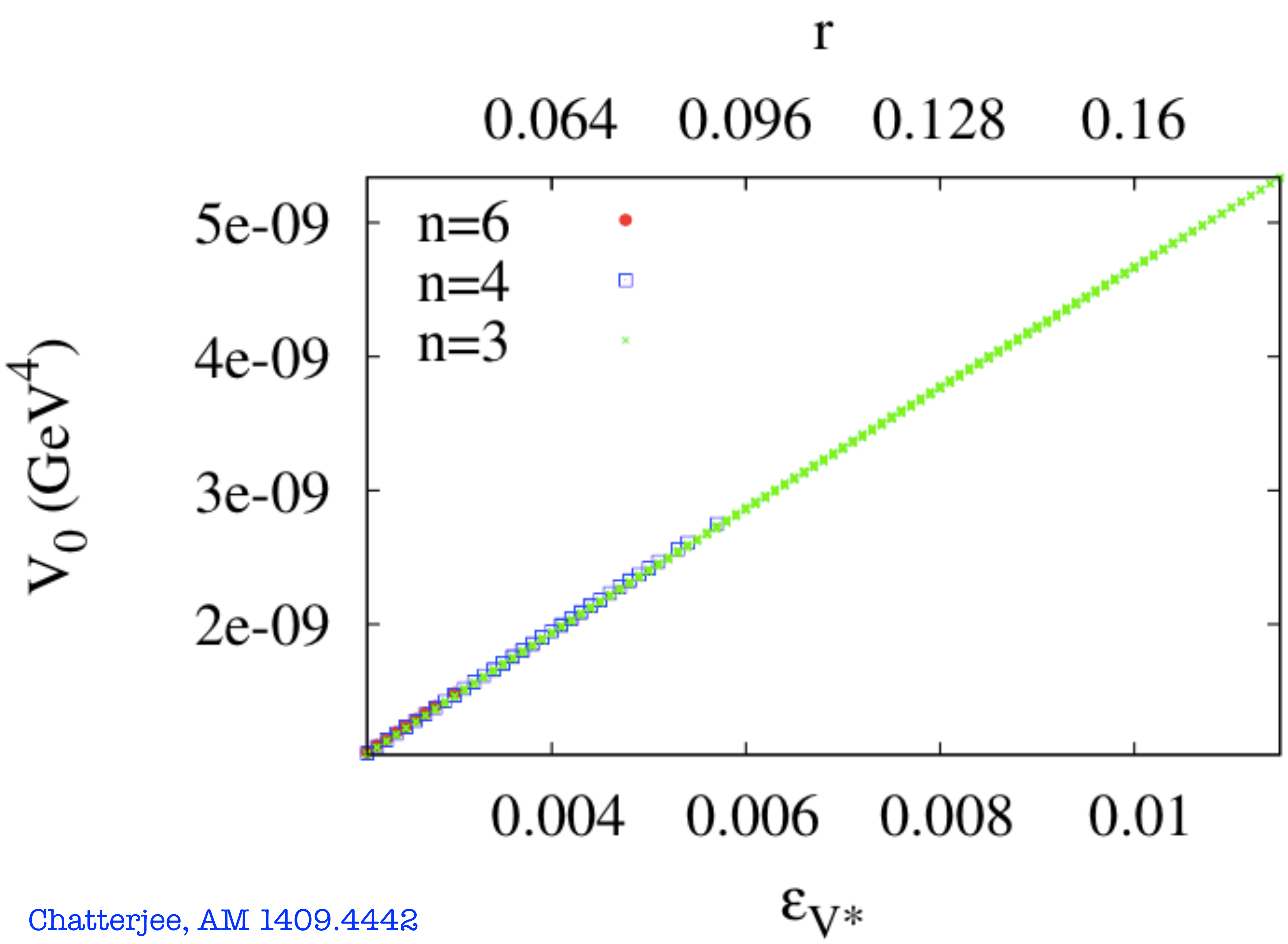
RENORMALIZATION GROUP EQUATIONS CAN RELATE LHC SCALE TO INFLATIONARY SCALE



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

Largest r for sub-Planckian Inflation?

$$V(\phi) = V_0 + c_H H^2\phi^2 - a_H H\lambda_n\phi^n + \lambda_n^2\phi^{2n-2}$$
$$= V_0 + A\phi^2 - B\phi^n + C\phi^{2n-2}.$$



Chatterjee, AM 1409.4442

$n = 3$

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

$n = 4$

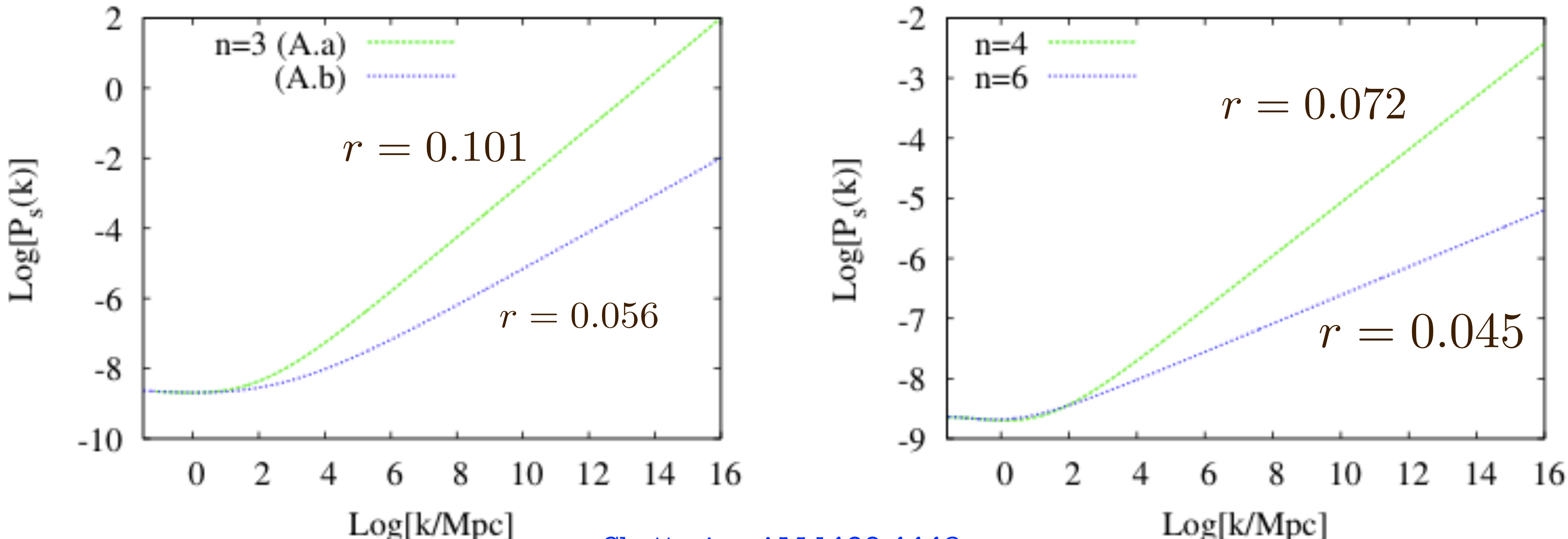
$$\phi = \frac{H_u + H_d}{\sqrt{2}}$$

$n = 6$

$$\phi = \frac{\widetilde{u} + \widetilde{d} + \widetilde{d}}{\sqrt{3}}$$

$$\phi = \frac{\widetilde{L} + \widetilde{L} + \widetilde{e}}{\sqrt{3}}$$

Largest r for sub-Planckian Inflation?



Chatterjee, AM 1409.4442

	n	V_0	A	B	C	r
(A.a)	3	3.010×10^{-9}	5.114×10^{-10}	3.126×10^{-10}	7.075×10^{-11}	0.101
(A.b)	3	1.710×10^{-9}	2.061×10^{-10}	1.165×10^{-10}	2.248×10^{-11}	0.056
(B)	4	2.184×10^{-9}	2.238×10^{-10}	8.301×10^{-11}	1.778×10^{-11}	0.072
(C)	6	1.388×10^{-9}	7.884×10^{-11}	1.096×10^{-11}	1.712×10^{-12}	0.045

It would be hard to make: r> 0.1 for sub-Planckian

Recap of SUSY and SUGRA Potential

$$V = \sum_i |F_i|^2 + \frac{1}{2}\sum_a g_a^2 D^a D^a \qquad V = e^{K(\phi_i,\phi^{*i})/M_P^2}\left[\left(K^{-1}\right)_i^j F_i F^j - 3\frac{|W|^2}{M_P^2}\right] + \frac{g^2}{2}\mathrm{Re} f_{ab}^{-1}\hat{D}^a\hat{D}^b$$

$$F_i \equiv \frac{\partial W}{\partial \phi_i}, \quad D^a = \phi^\dagger T^a \phi\ , \qquad F^i = W^i + K^i\frac{W}{M_{\rm Pl}^2}, \qquad \hat{D}^a = -K^i (T^a)_i^j \phi_j + \xi^a .$$

Fayet-Iliopoulos contribution ξ^a to the D-term, and $\hat{D}^a = D^a/g^a$;

$K^i \equiv \partial K/\partial \phi_i \qquad K_i^j = (K^{-1})_i^j = \delta_i^j)$

Scalar kinetic term:

$$\frac{\partial^2 K}{\partial \phi_i \partial \phi_j^*} D_\mu \phi_i D^\mu \phi_j^*$$

$$K = \phi_i \phi^{*i} + (k_k^{ij}\phi_i\phi_j\phi^{*k} + c.c.)/M_P$$

Gauge kinetic term:

$$\frac{1}{4}(\mathrm{Re} f_{ab}) F^a_{\mu\nu} F_a^{\mu\nu}$$

$$f_{ab} = \delta_{ab}(1/g_a^2 + f_a^i \phi_i/M_P + \cdots)$$

Gravitino mass:

$$m_{3/2}^2 = \frac{\langle K_j^i F_i F^{*j}\rangle}{3M_P^2} = e^{\langle K\rangle/M_P^2}\frac{|\langle W\rangle|^2}{M_P^4}$$

SUGRA-eta Problem

$$K = \int d^4\theta \frac{1}{M_{\rm P}^2}(I^\dagger I)(\phi^\dagger \phi) \qquad \mathcal{L} = \frac{\rho_I}{M_{\rm P}^2}\phi^\dagger\phi = 3H_I^2\phi^\dagger\phi$$

$$m_\phi^2 = \left(2 + \frac{F_I^* F_I}{V(I)}\right) H^2$$

Inflation requires : $m_\phi^2 \ll H_I^2$

$$W = \lambda \frac{\Phi^n}{M_P^{n-3}}$$

$$W = M^2 I,$$

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

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Particle physics models of inflation and curvaton scenarios

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ABSTRACT

We review the particle theory origin of inflation and curvaton mechanisms for generating large scale structures and the observed temperature anisotropy in the cosmic microwave background (CMB) radiation. Since inflaton or curvaton energy density creates all matter, it is important to understand the process of reheating and preheating into the relevant degrees of freedom required for the success of Big Bang Nucleosynthesis. We discuss two distinct classes of models, one where inflaton and curvaton belong to the hidden sector, which are coupled to the Standard Model gauge sector very weakly. There is another class of models of inflaton and curvaton, which are embedded within Minimal Supersymmetric Standard Model (MSSM) gauge group and beyond, and whose origins lie within *gauge invariant* combinations of supersymmetric quarks and leptons. Their masses and couplings are all well motivated from low energy physics, therefore such models provide us with a unique opportunity that they can be verified/falsified by the CMB data and also by the future collider and non-collider based experiments. We then briefly discuss the stringy origin of inflation, alternative cosmological scenarios, and bouncing universes.

Contents

Reheating in Inflationary Cosmology: Theory and Applications

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Key Words

inflationary universe, reheating, early universe cosmology, preheating, parametric resonance

Abstract

Reheating is an important part of inflationary cosmology. It describes the production of Standard Model particles after the phase of accelerated expansion. We review the reheating process with a focus on an in-depth discussion of the preheating stage, which is characterized by exponential particle production due to a parametric resonance or tachyonic instability. We give a brief overview of the thermalization process after preheating and end with a survey of some applications to supersymmetric theories and to other issues in cosmology, such as baryogenesis, dark matter, and metric preheating.

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