# Naturally large tensor-to-scalar ratio in inflation


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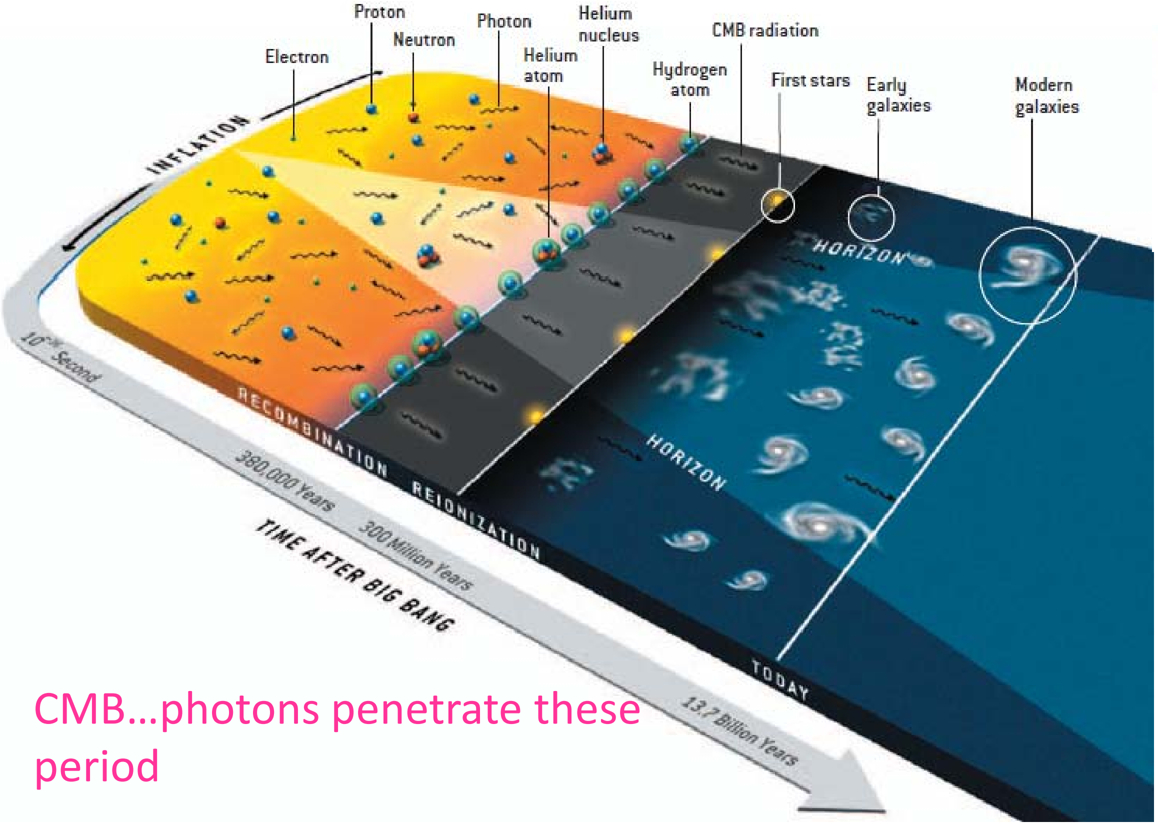
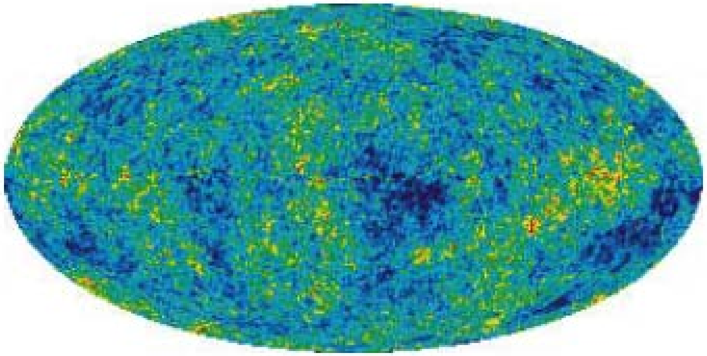
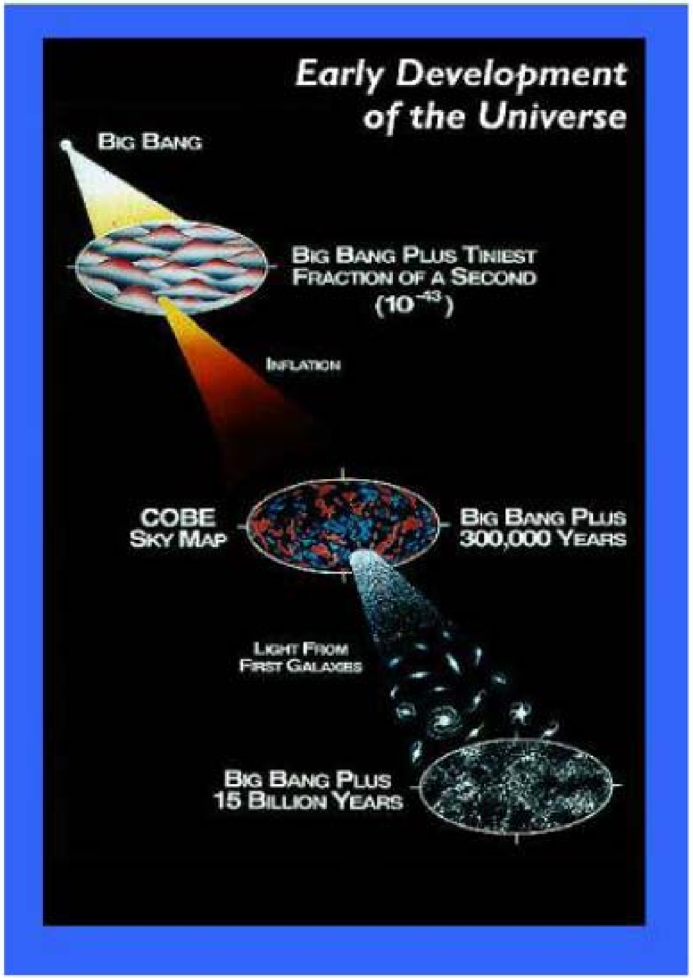
$2^{nd}$ International workshop on Particle Physics and Cosmology after Higss and Planck

# history of Universe



CMB…photons penetrate these period

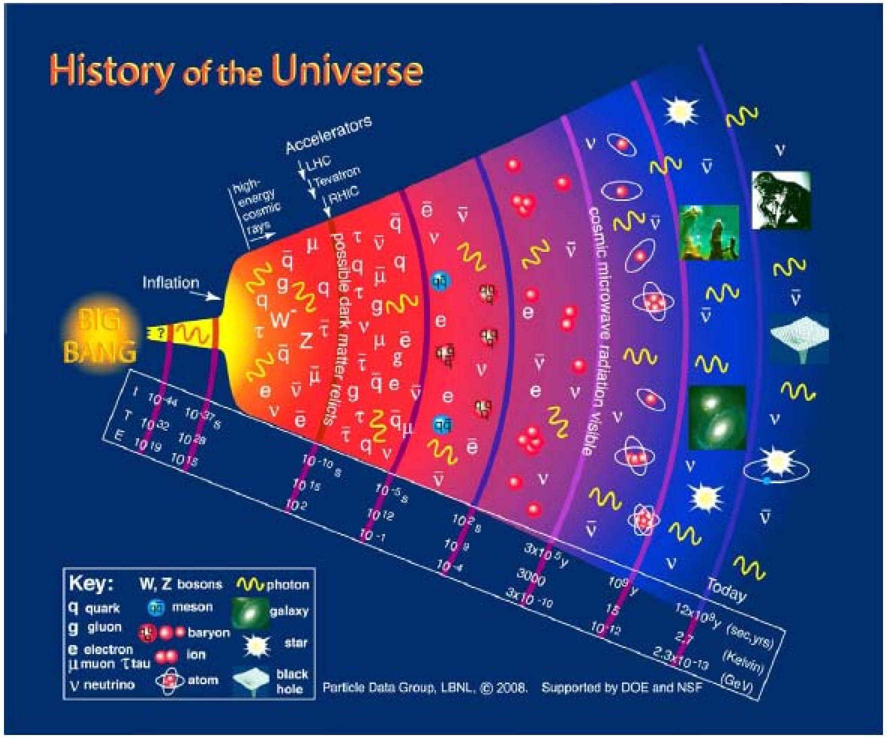



Large angular scale…matter imhomogeneities generate gravitational redshifts

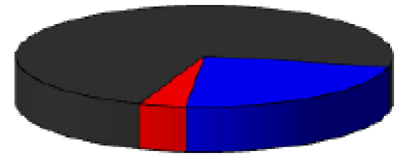
Small angular scale…acoustic oscillations in plasma on generate Doppler shifts

Thomson scatterings with electrons generate polarization

Big Bang

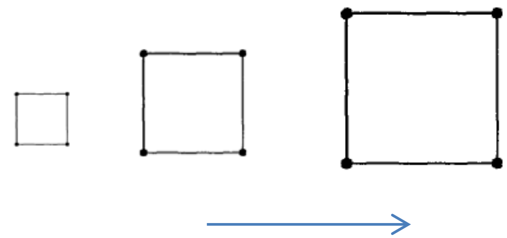



Dark Energy 70%

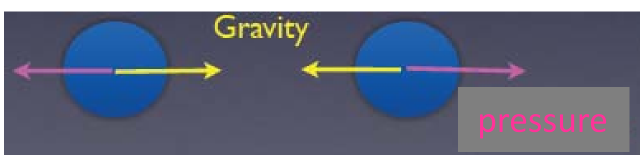


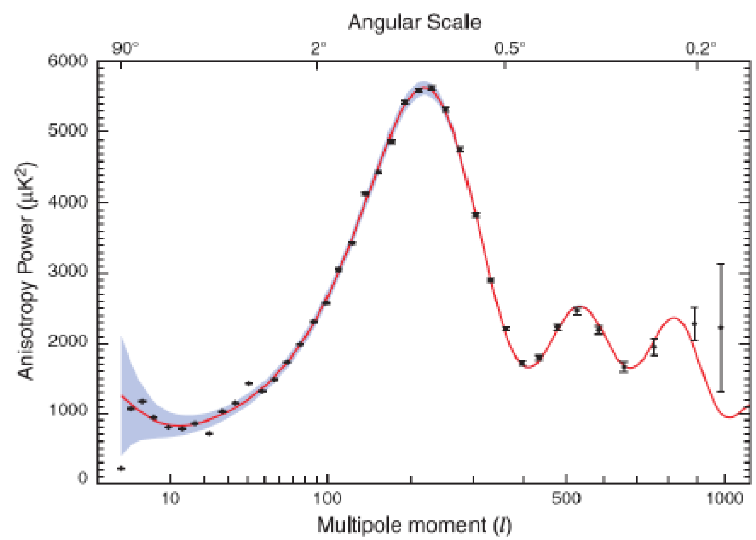
Baryonic Matter 5%

Cold Dark Matter 25%

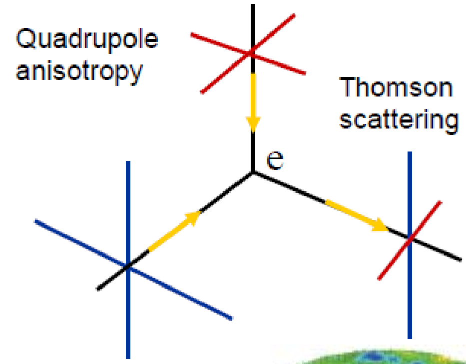



Two forces compete



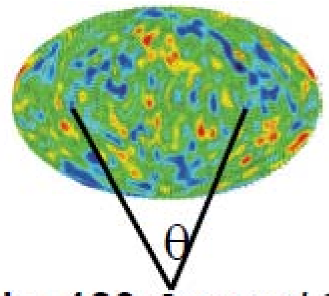



# polarization




Thomson scatterings with electrons generate polarization

Decompose CMB sky into spherical harmonics




l = 180 degrees/ θ

$$T(\theta,\varphi) = \Sigma_{lm}\ a_{lm}\, Y_{lm}(\theta,\varphi)$$

$$(Q - iU)(\theta,\varphi) = \Sigma_{lm}\ a_{2,lm}\ {}_{2}Y_{lm}(\theta,\varphi)$$

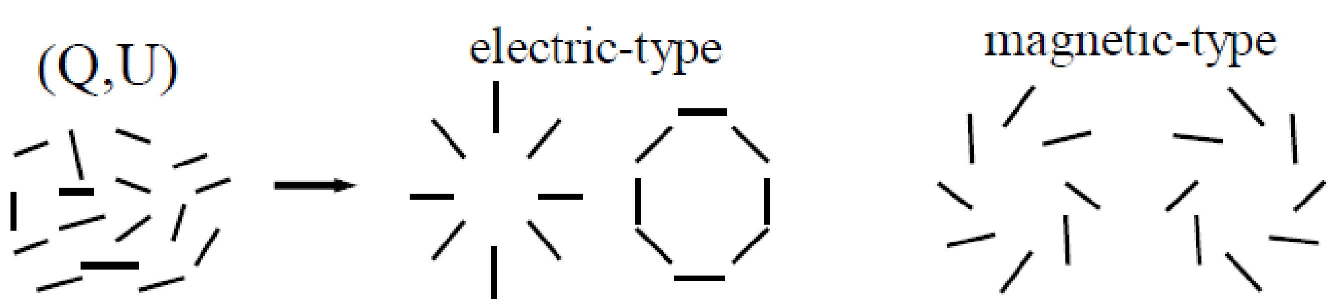
$$(Q + iU)(\theta,\varphi) = \Sigma_{lm}\ a_{-2,lm}\ {}_{-2}Y_{lm}(\theta,\varphi)$$

$C^T_l = \Sigma_m (a^*_{lm}\, a_{lm})$ anisotropy power spectrum

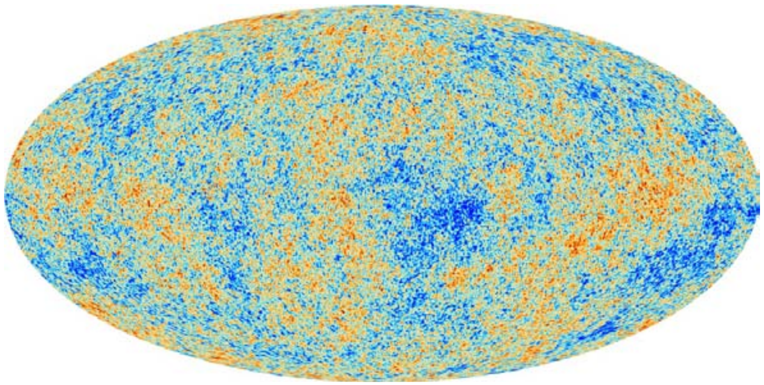
$C^E_l = \Sigma_m (a^*_{2,lm}\, a_{2,lm} + a^*_{2,lm}\, a_{-2,lm})$ E-polarization power spectrum

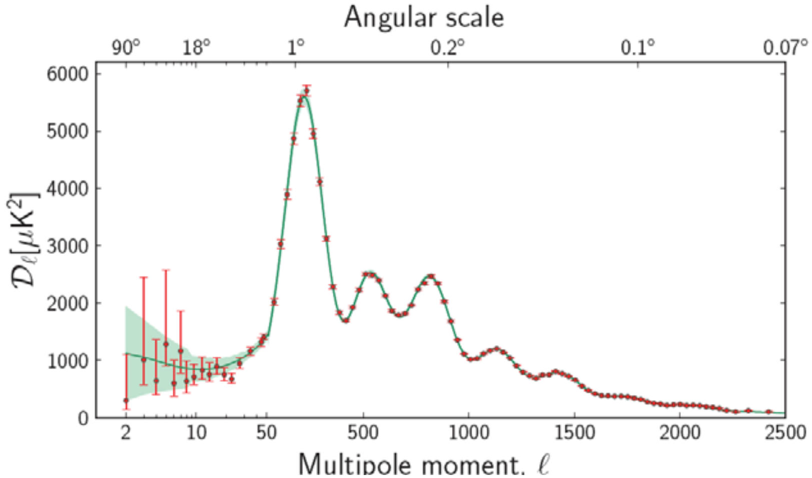
$C^B_l = \Sigma_m (a^*_{2,lm}\, a_{2,lm} - a^*_{2,lm}\, a_{-2,lm})$ B-polarization power spectrum

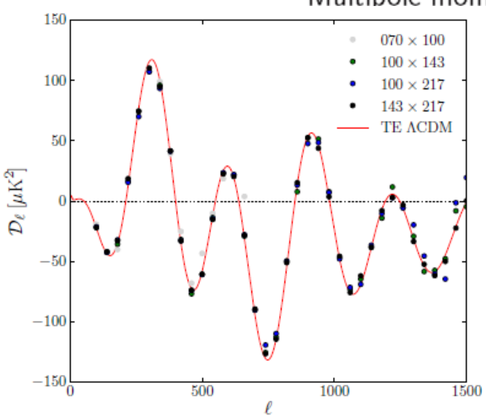
$C^{TE}_l = -\Sigma_m (a^*_{lm}\, a_{2,lm})$ TE correlation power spectrum

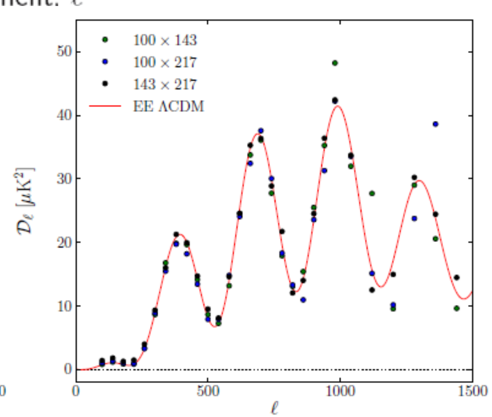


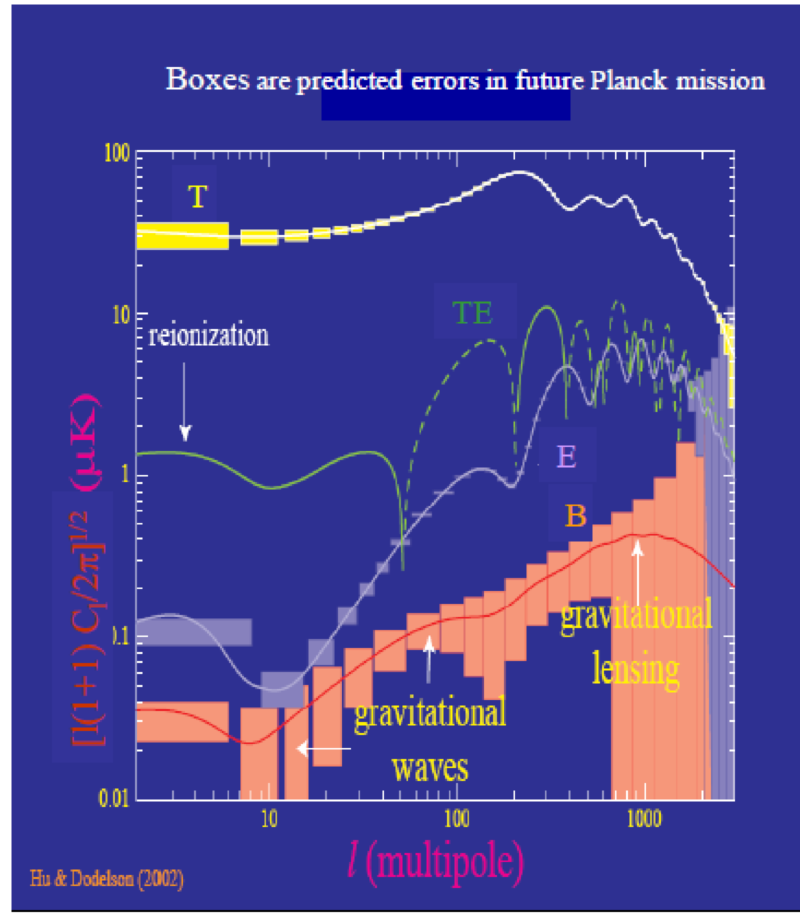
CMB data…Planck



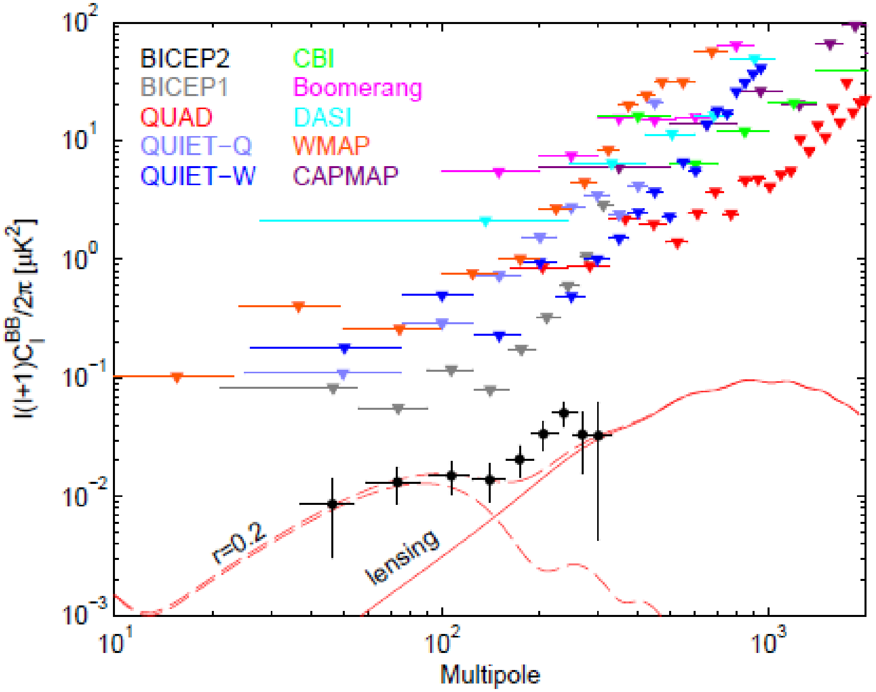


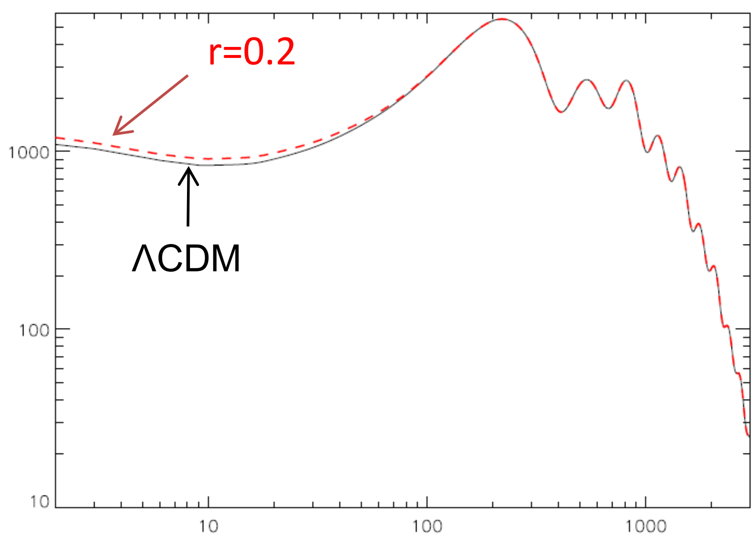



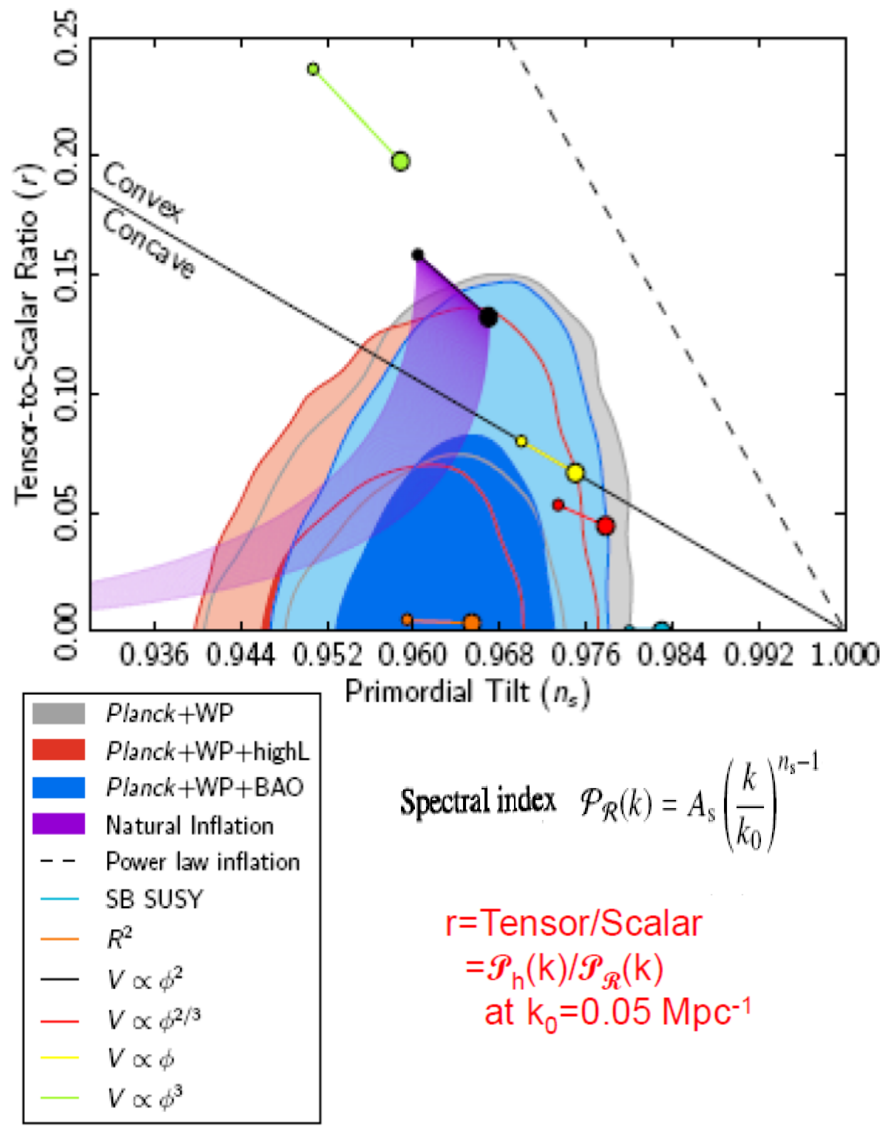



BICEP2



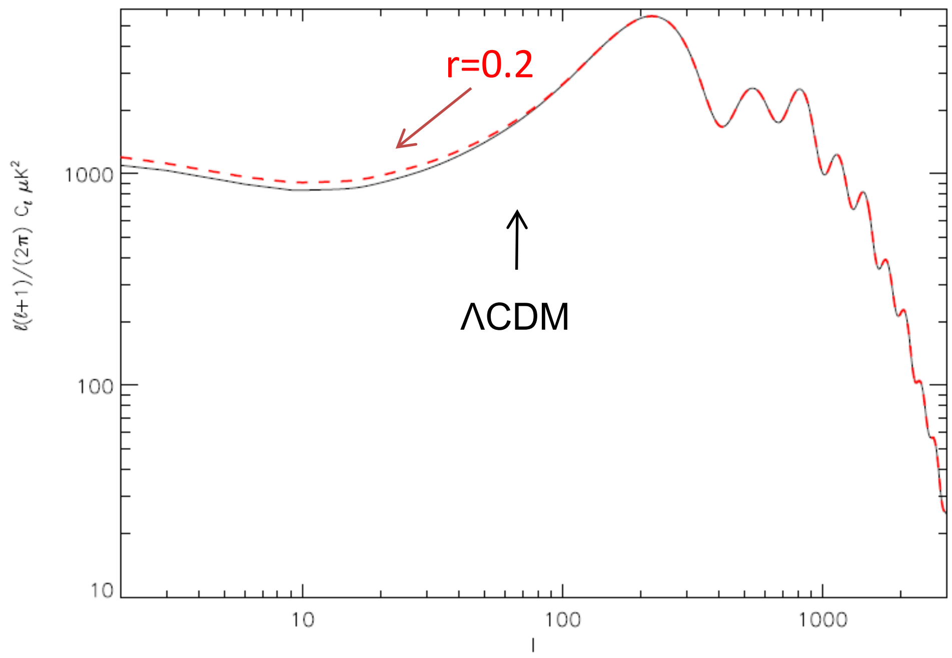




**Tensor/Scalar Ratio and Spectral Index 2013**
**$n_s$=0.9675 and r < 0.11 (95% CL)**




Spectral index $\mathcal{P}_{\mathcal{R}}(k) = A_s \left(\frac{k}{k_0}\right)^{n_s-1}$

r=Tensor/Scalar
$=\mathcal{P}_h(k)/\mathcal{P}_{\mathcal{R}}(k)$
at $k_0$=0.05 $Mpc^{-1}$

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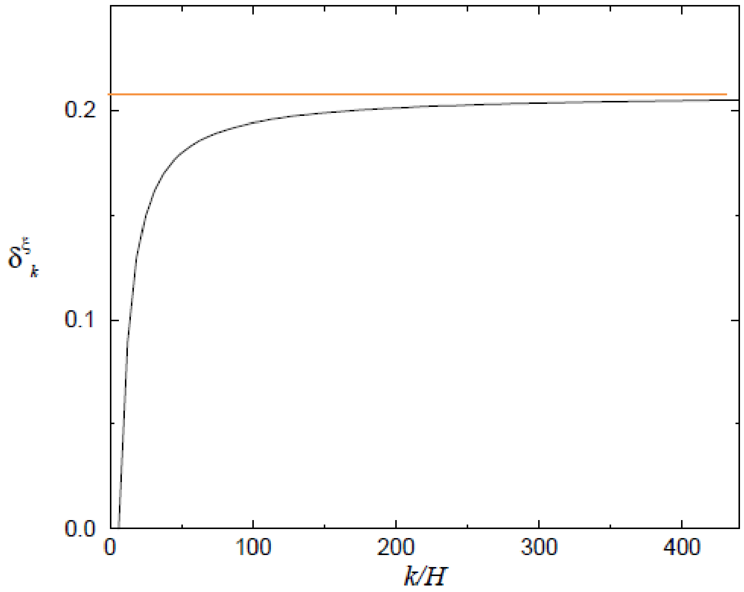
Motivation : the suppression of scalar mode at large scale compensates for the increasing of tensor mode contribution.

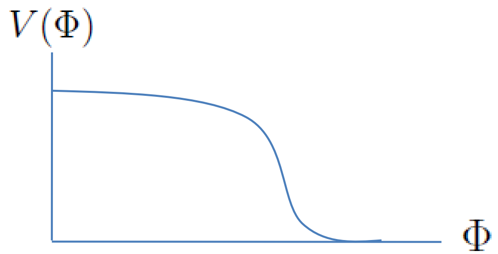
$$P_k = \frac{k^3}{4\pi} \mid \varphi_k(t) \mid^2$$



Noise model

- Flat potential

Slow rolling potential

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$$\mathcal{L} = \frac{1}{2}g^{\mu\nu}\partial_\mu\phi\,\partial_\nu\phi + \frac{1}{2}g^{\mu\nu}\partial_\mu\sigma\,\partial_\nu\sigma - V(\phi) - \frac{m_\sigma^2}{2}\sigma^2 - \frac{g^2}{2}\phi^2\sigma^2$$

- Steep potential

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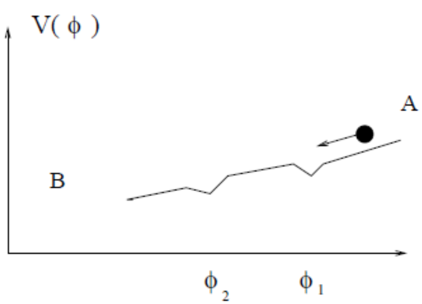
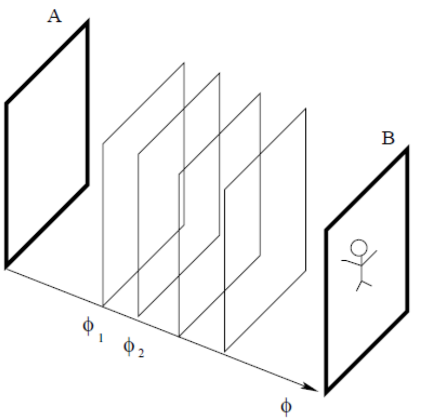
$$\mathcal{L} = \frac{1}{2}g^{\mu\nu}\partial_\mu\Phi\,\partial_\nu\Phi + \frac{1}{2}g^{\mu\nu}\partial_\mu\chi\,\partial_\nu\chi - V(\Phi) - \frac{g^2}{2}(\Phi-\Phi_0)^2\chi^2$$

Trapped inflation , potential is too steep for slow roll

JHEP 0405:030,2004 Kofman et al

Phys.Rev.D80:063533,2009 Green et al



# method

In-in formalism , trace out another scalar field and then obtain the semiclassical Langevin equation

Ann. Phys. 24, 118(1963)
Feynman and Vernon

$$\ddot{\phi} + 2aH\dot{\phi} - \nabla^2\phi + a^2\left[V'(\phi) + g^2\langle\sigma^2\rangle\phi\right] - g^4a^2\phi\int \mathrm{d}^4x' a^4(\eta') \times\theta(\eta-\eta')\,\mathrm{i}\,G_{-}(x,x')\phi^2(x') = g^2a^2\,\phi\,\xi + \xi_{\mathrm{w}}$$

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$$G_{\pm}(x,x') = \langle\sigma(x)\sigma(x')\rangle^2 \pm \langle\sigma(x')\sigma(x)\rangle^2$$

$$P[\xi] = \exp\left\{-\tfrac{1}{2}\int \mathrm{d}^4x\int \mathrm{d}^4x'\,\xi(x)\,G_{+}^{-1}(x,x')\,\xi(x')\right\}$$

$$\langle\xi(x)\xi(x')\rangle = G_{+}(x,x')$$

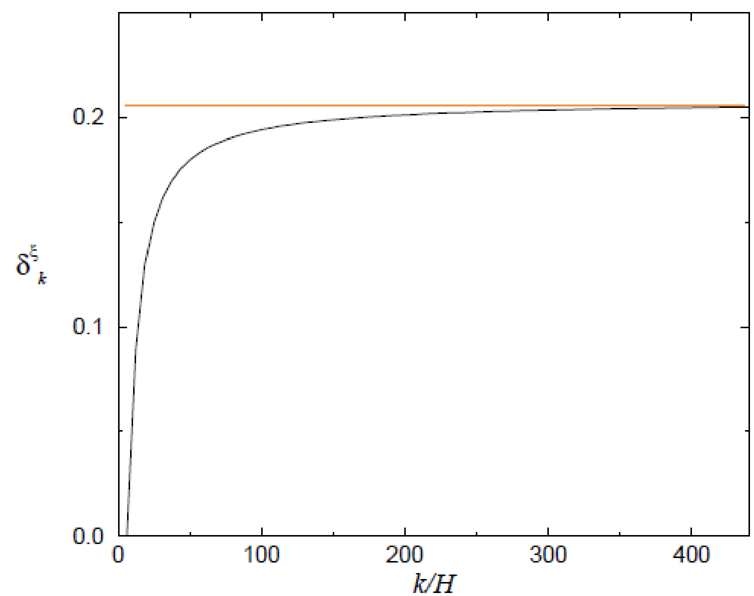
$$\phi(\eta,\mathrm{x}) = \bar{\phi}(\eta) + \varphi(\eta,\mathrm{x})$$

mean fluctuations

$$\ddot{\bar{\phi}} + 2aH\dot{\bar{\phi}} + a^2\left[V'(\bar{\phi}) + g^2\langle\sigma^2\rangle\bar{\phi}\right] = 0$$

$$\ddot{\varphi} + 2aH\dot{\varphi} - \nabla^2\varphi + a^2m^2_{\varphi\mathrm{eff}}\varphi = g^2a^2\bar{\phi}\,\xi$$

$$\langle\varphi_{\mathbf{k}}(\eta)\varphi^*_{\mathbf{k}'}(\eta)\rangle = \frac{2\pi^2}{k^3}\Delta^{\xi}_{k}(\eta)\delta(\mathbf{k}-\mathbf{k}')$$



# Effect on large scale CMB (Model fitting)

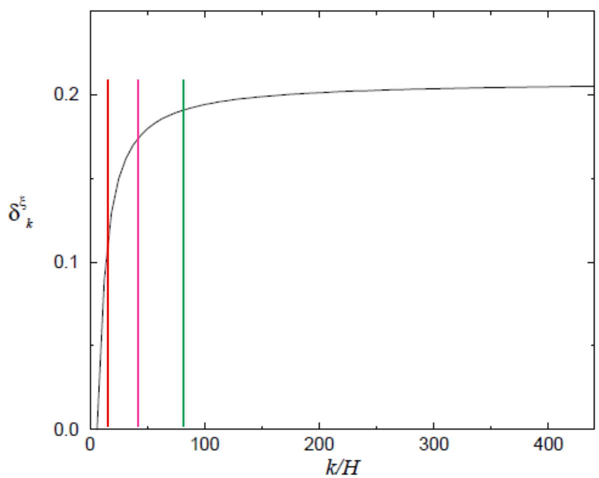
Fits BICEP2 ratio $P^T/P^S_{\Lambda CDM} = 0.2$

$$P^S = P^S_{\Lambda CDM}\frac{1+r'\Delta^{\xi}_k/\Delta^q_k}{1+r'}$$

Scalar power spectrum :
quantum fluctuation+ noise contribution

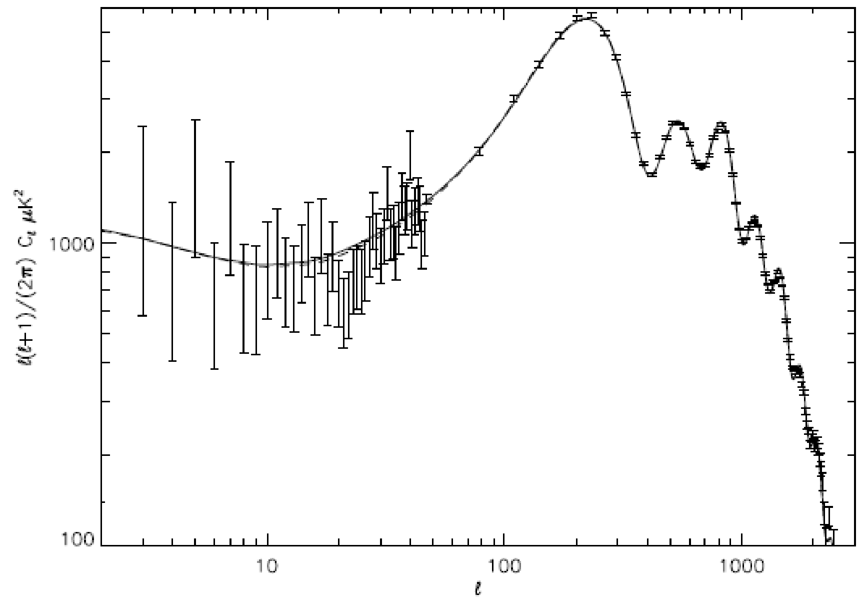
$k/H$ Corresponds to $0.05\mathrm{Mpc}^{-1}$

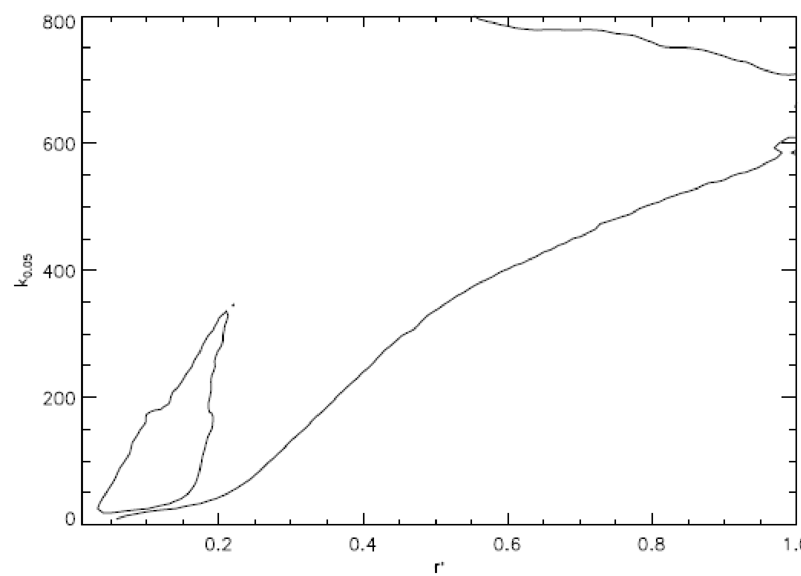
treat it as a free parameter $k_{0.05}$




use best-fit values of cosmological parameters for Planck $\Lambda$CDM model

using $P^S$ and $P^T$ we compute CMB $TT$ power spectra
$r' = 0.1$ and $k_{0.05} = 33$



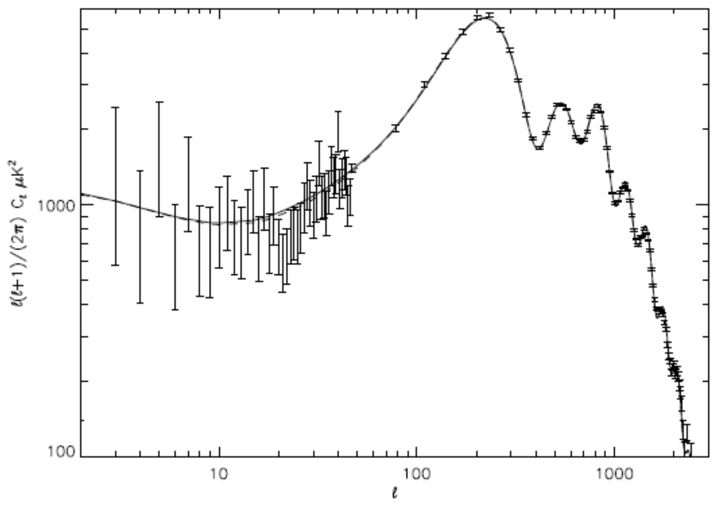
result

Maximum likelihood value at

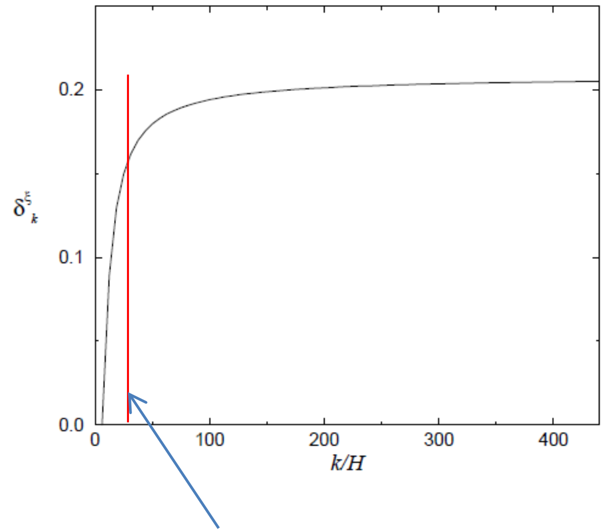
$r' = 0.1$ and $k_{0.05} = 33$

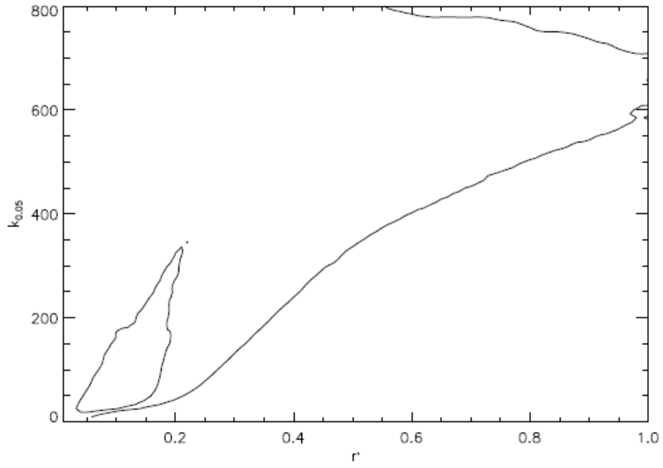
almost overlap with $P^S_{\Lambda CDM}$

our $P^S$ + r=0.2 tensor contribution




Large scale power suppression due to color noise can be make up by the tensor contribution




The duration of inflation is about 60 e-folds

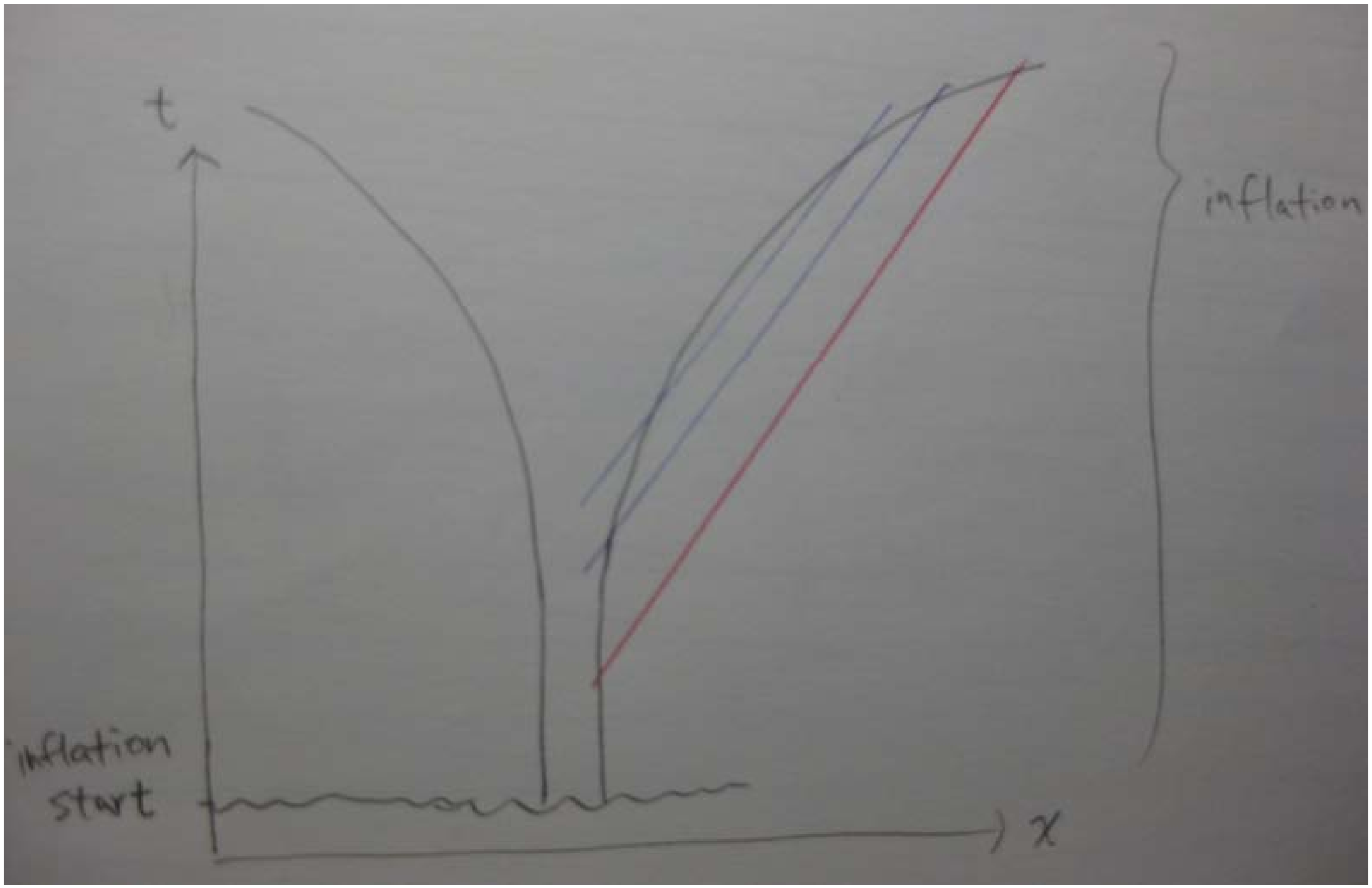
Noise model can naturally explain BICEP2 data

More work

r=0.1

Once BICEP2 data is ruled out or if the future data prefers r=0.1

Thank you for listening !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x
inflation
inflation
start