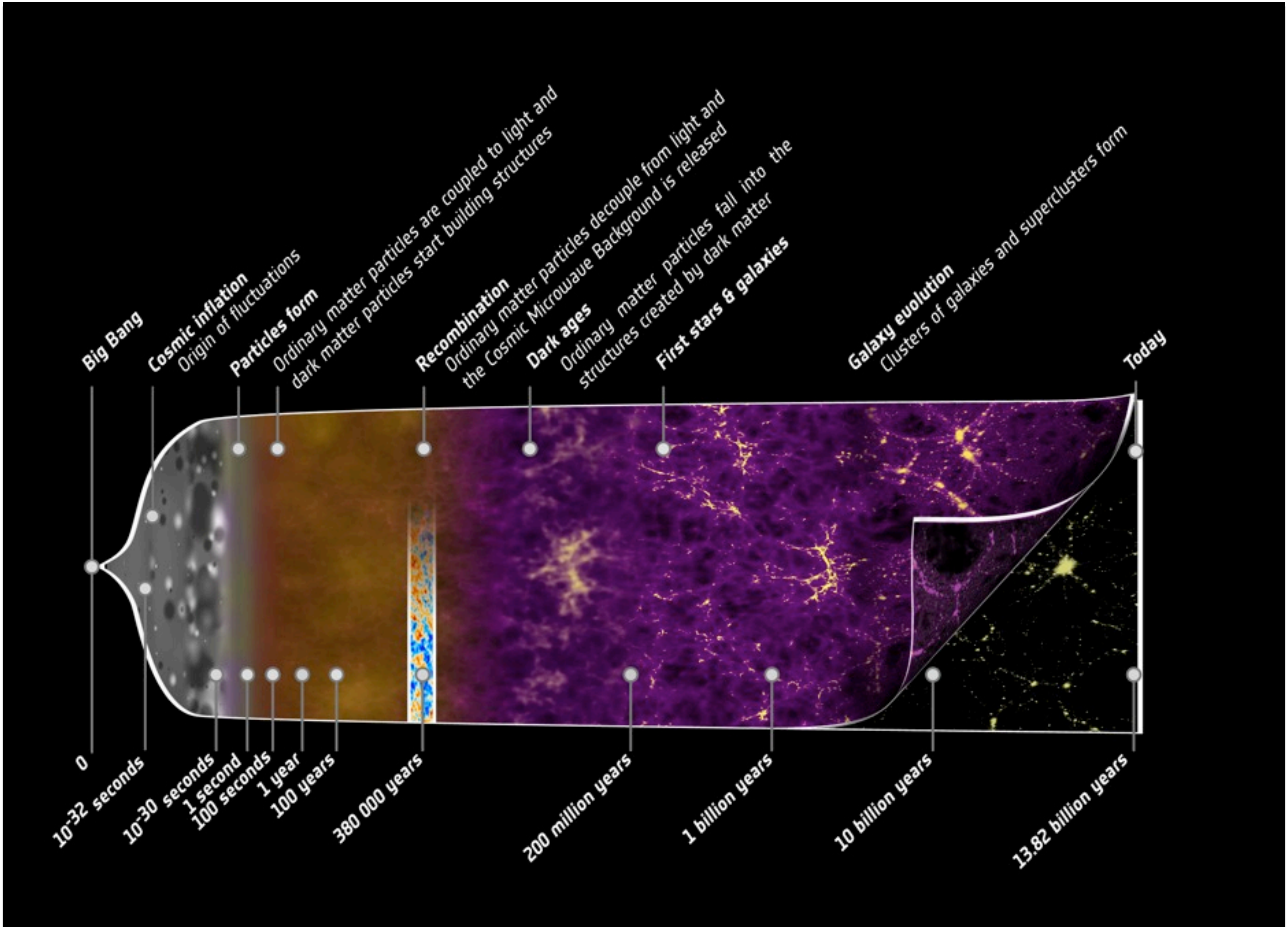
Spectator mechanism and the CMB modulation

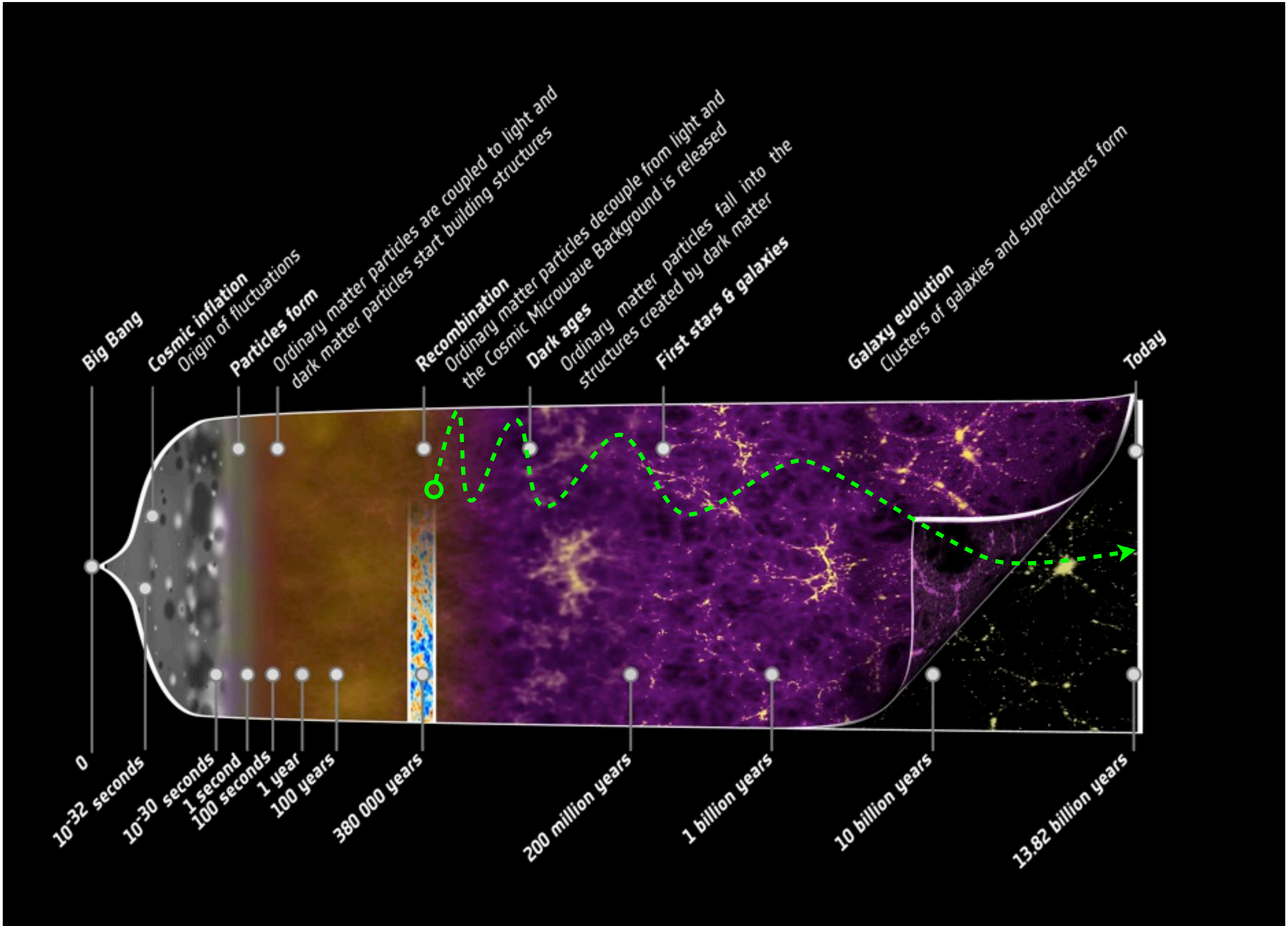
Lingfei Wang
Lancaster University

Based on [1306.5736], PRD 88 023512,
JCAP 1307 019, JCAP 1305 012, PRD 87 083501

21 October, 2013


Big Bang
Cosmic inflation
Origin of fluctuations
Particles form
Ordinary matter particles are coupled to light and dark matter particles start building structures
Recombination
Ordinary matter particles decouple from light and the Cosmic Microwave Background is released
Dark ages
Ordinary matter particles fall into the structures created by dark matter
First stars & galaxies
Galaxy evolution
Clusters of galaxies and superclusters form
Today
0
10^-32 seconds
10^-30 seconds
1 second
100 seconds
1 year
100 years
380 000 years
200 million years
1 billion years
10 billion years
13.82 billion years

[ESA/Planck]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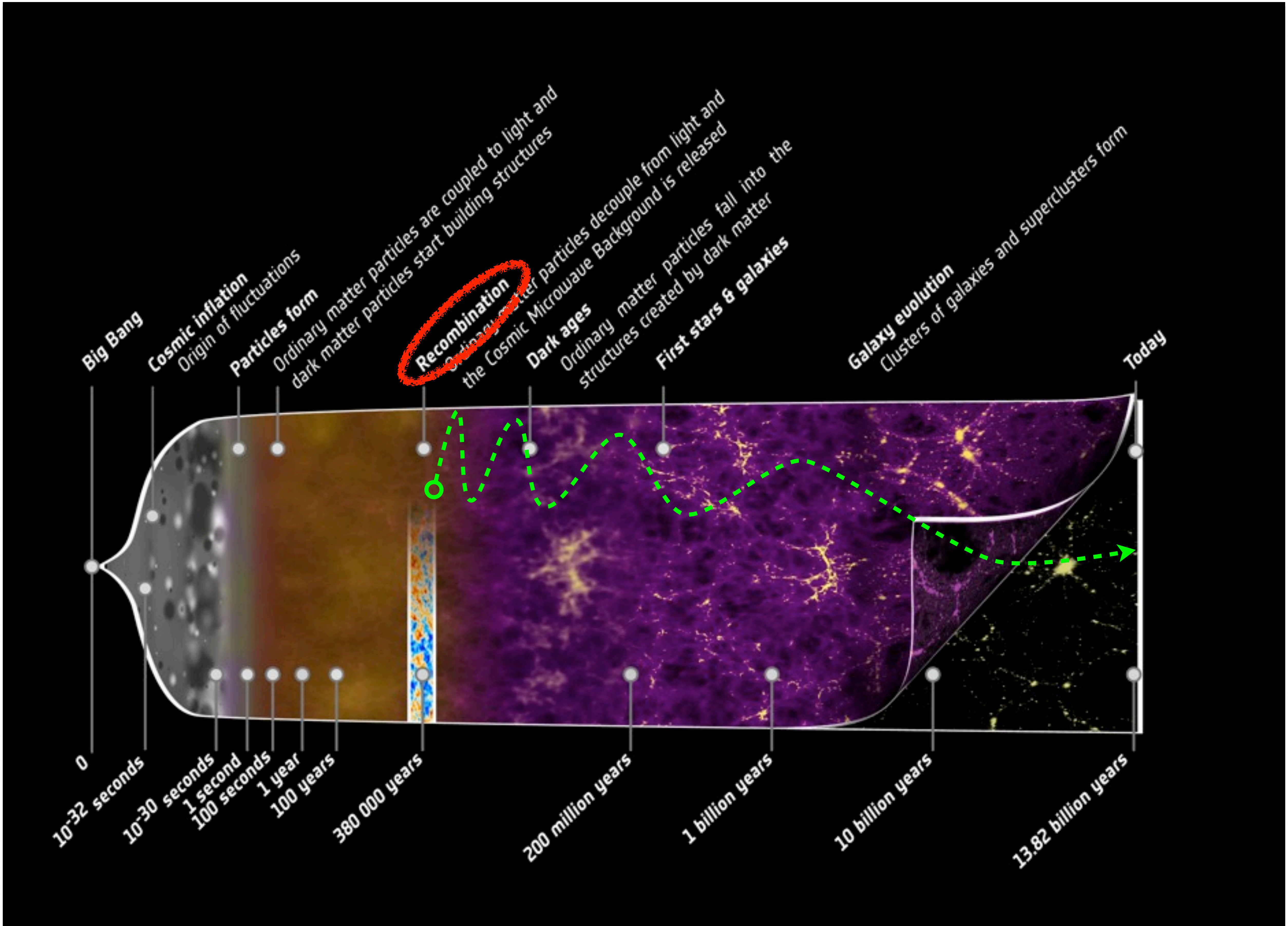
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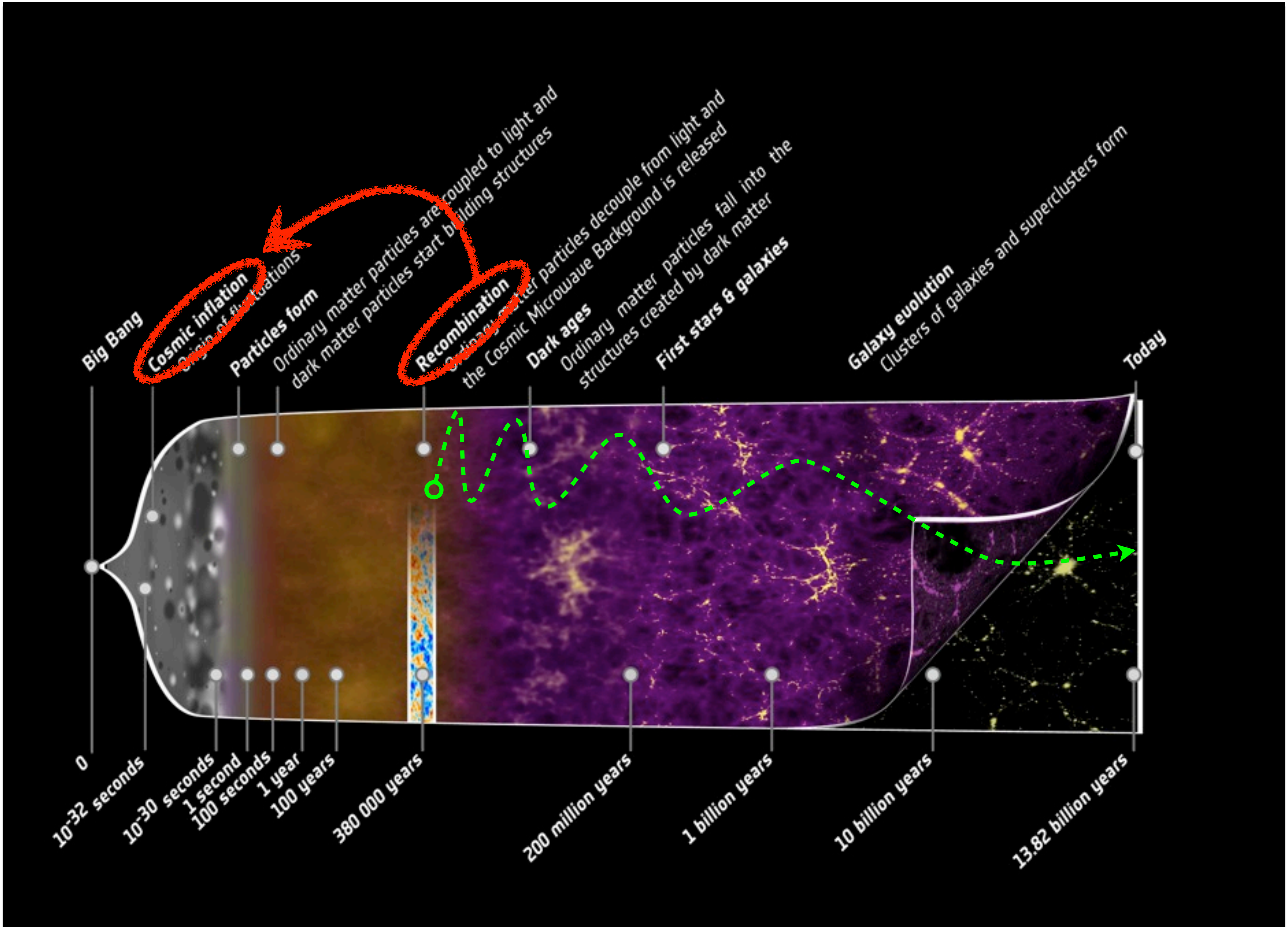

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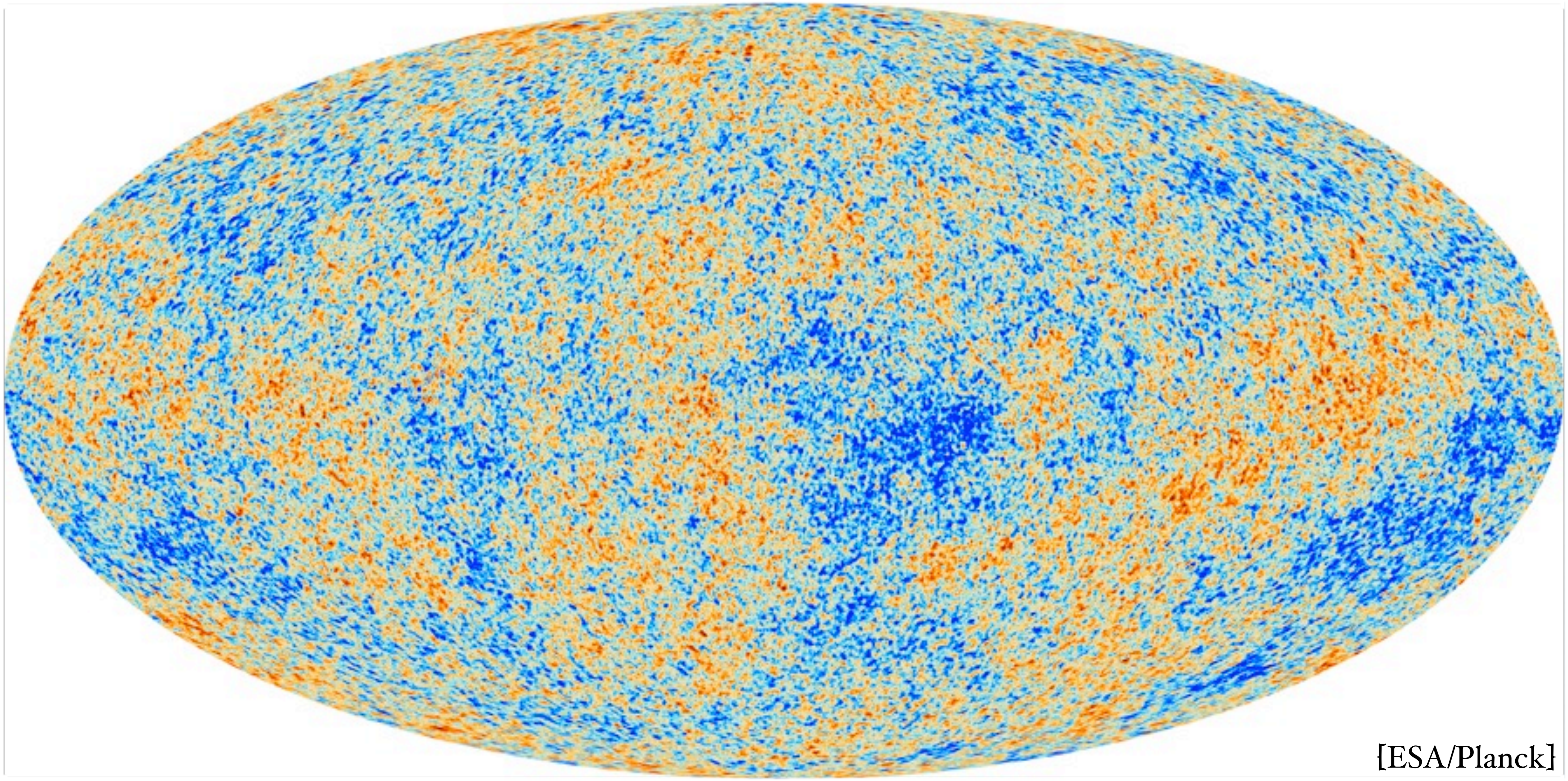
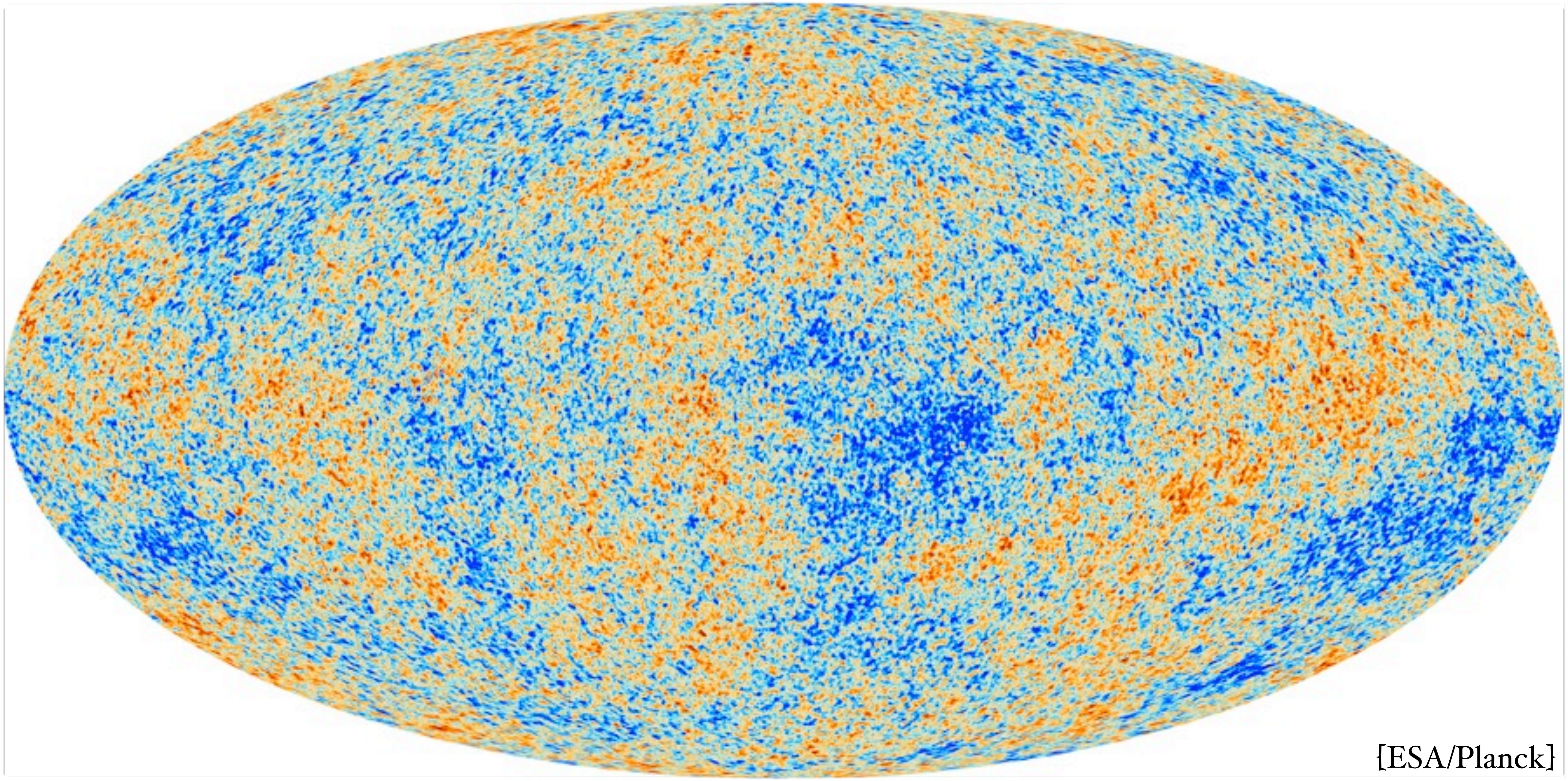
CMB anisotropy



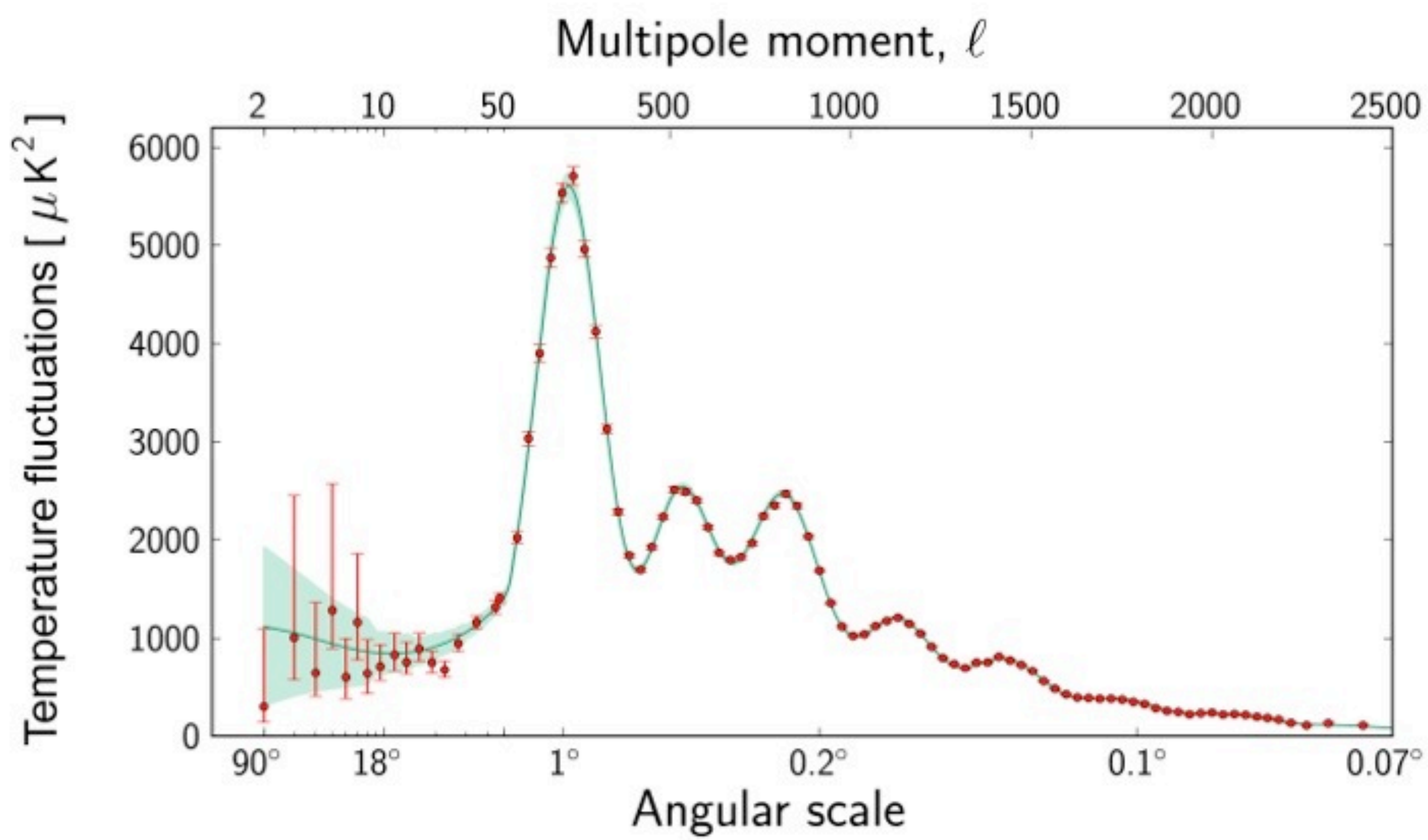
{ESA/Planck}



$$\Delta T(\hat{\mathbf{n}}) = \sum_{lm} a_{lm} Y_{lm}(\hat{\mathbf{n}})$$

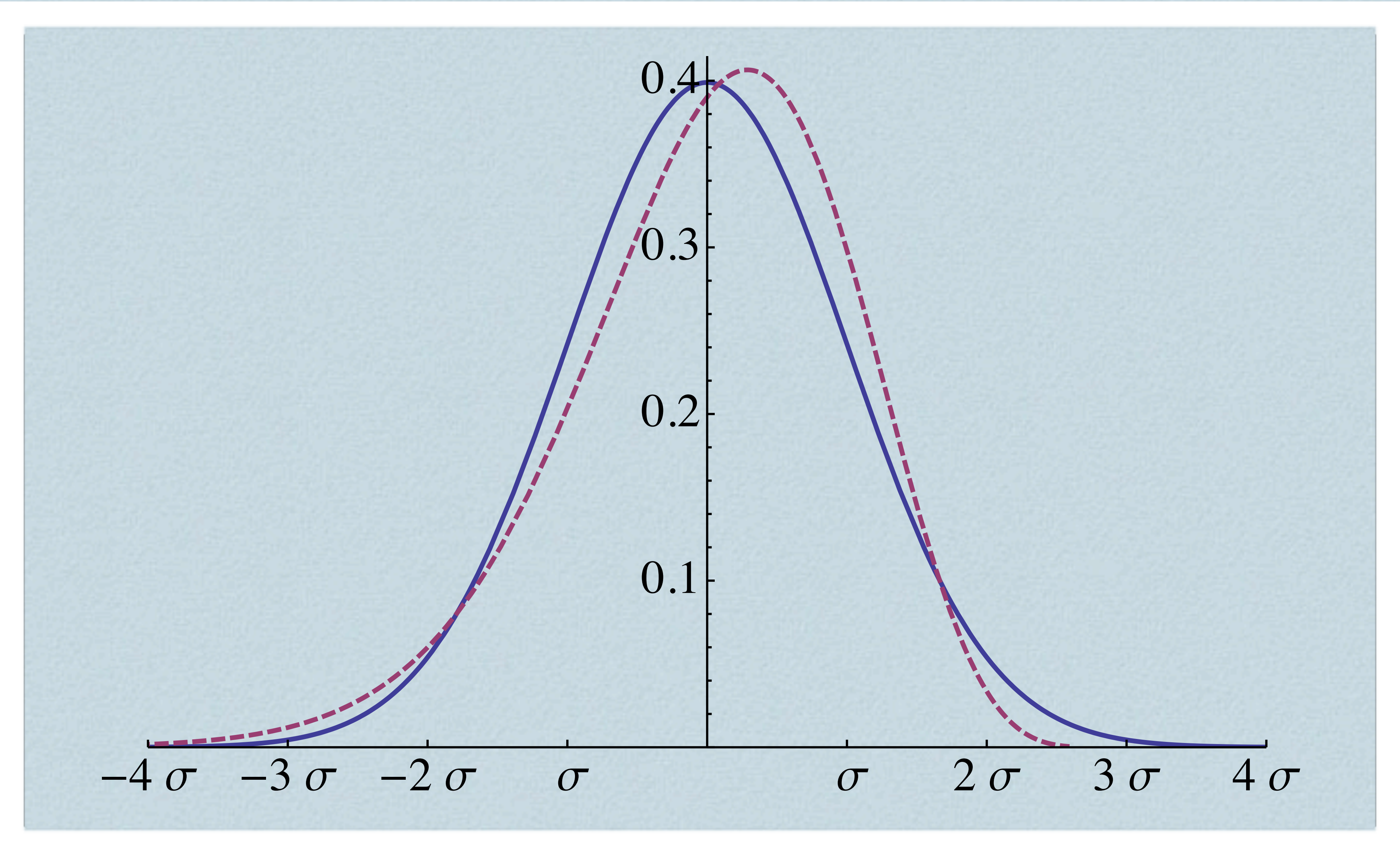
$$\langle a^*_{lm} a_{l'm'} \rangle = C_l \delta_{ll'} \delta_{mm'}$$

CMB anisotropy



[ESA/Planck]

CMB non-Gaussianity



CMB non-Gaussianity

- Temperature fluctuations $\Delta T(\hat{\mathbf{n}}) = \sum_{lm} a_{lm} Y_{lm}(\hat{\mathbf{n}})$
- Angular bispectrum

$$\langle a_{l_1 m_1} a_{l_2 m_2} a_{l_3 m_3} \rangle = \begin{pmatrix} l_1 & l_2 & l_3 \\ m_1 & m_2 & m_3 \end{pmatrix} B_{l_1 l_2 l_3}$$

  - Post-inflation: ISW effect, etc
  - Inflation: primordial bispectrum (e.g. local $f_{\rm NL}$)

$$\langle \Phi(\mathbf{k}_1) \Phi(\mathbf{k}_2) \Phi(\mathbf{k}_3) \rangle = (2\pi)^3 \delta^3(\mathbf{k}_1 + \mathbf{k}_3 + \mathbf{k}_3) B(k_1, k_2, k_3)$$

Hu 01, Bartolo et al 04, [1303.5084]

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- Trispectrum $\tau_{\rm NL}$ $\langle a_{l_1 m_1} a_{l_2 m_2} a_{l_3 m_3} a_{l_4 m_4} \rangle, \ \ldots$

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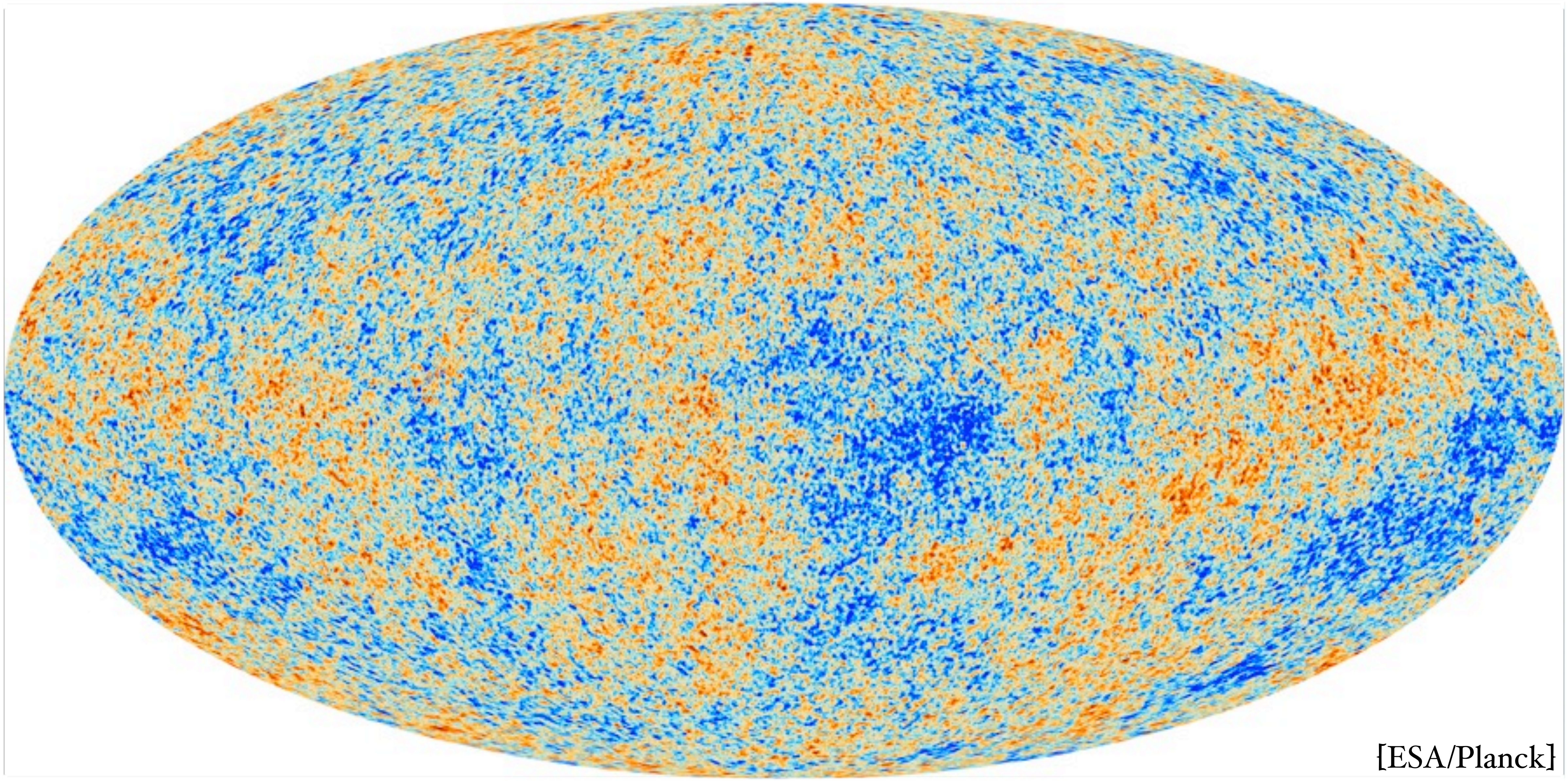
- Trispectrum $\tau_{\rm NL} < 2800$ $\langle a_{l_1 m_1} a_{l_2 m_2} a_{l_3 m_3} a_{l_4 m_4} \rangle, \ \ldots$

Hu 01, Bartolo et al 04, [1303.5084]

CMB dipole asymmetry



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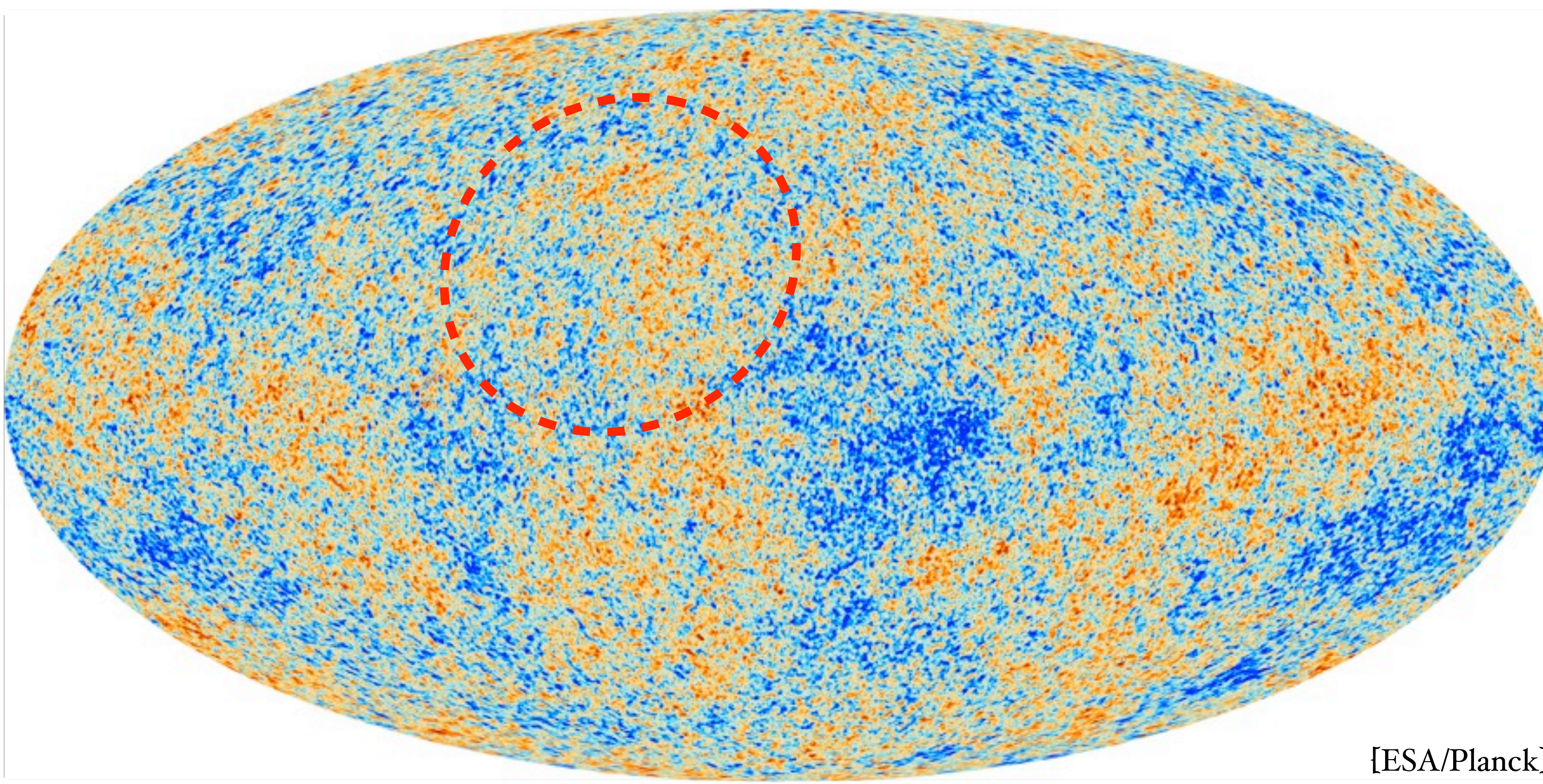

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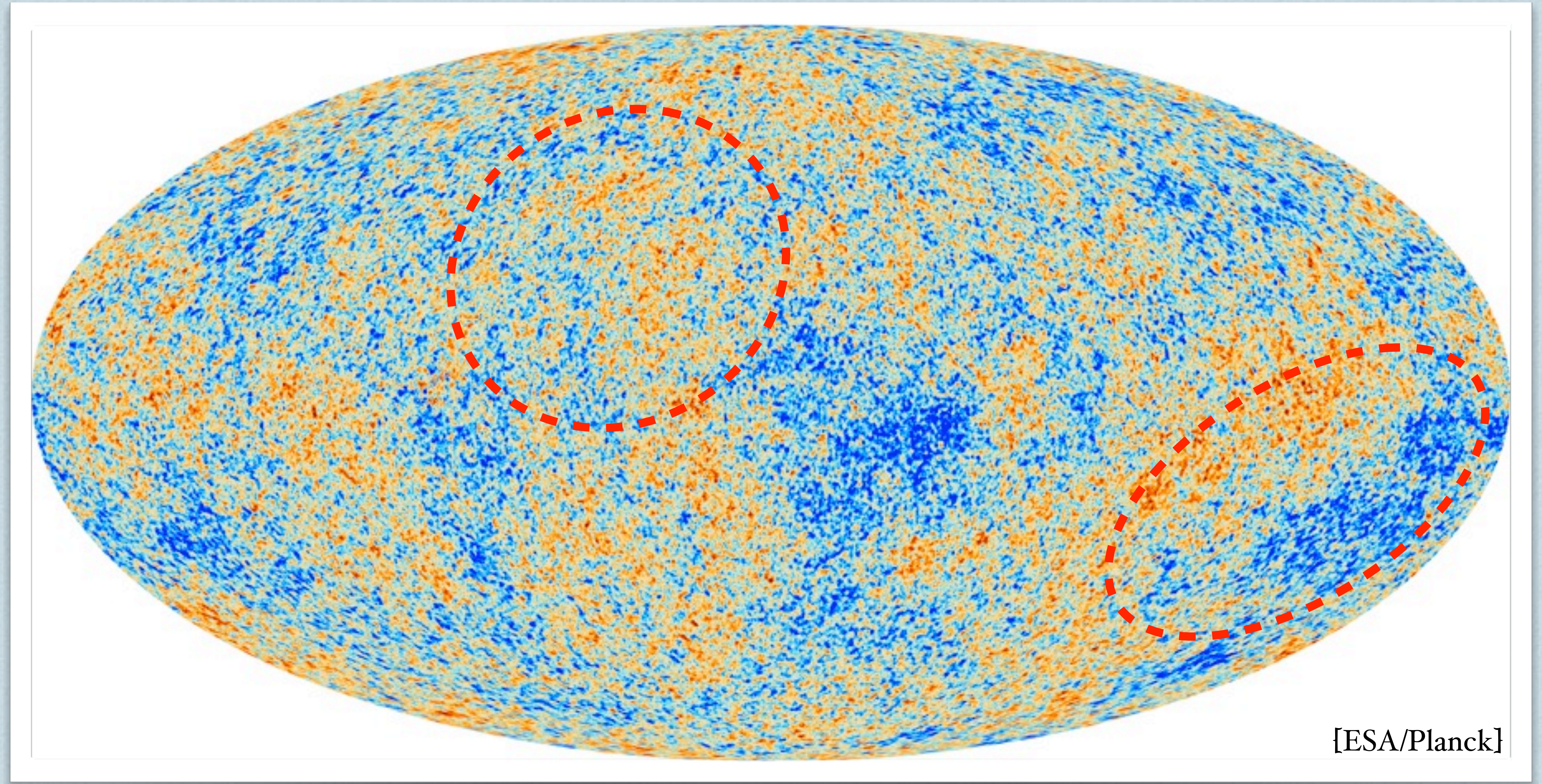

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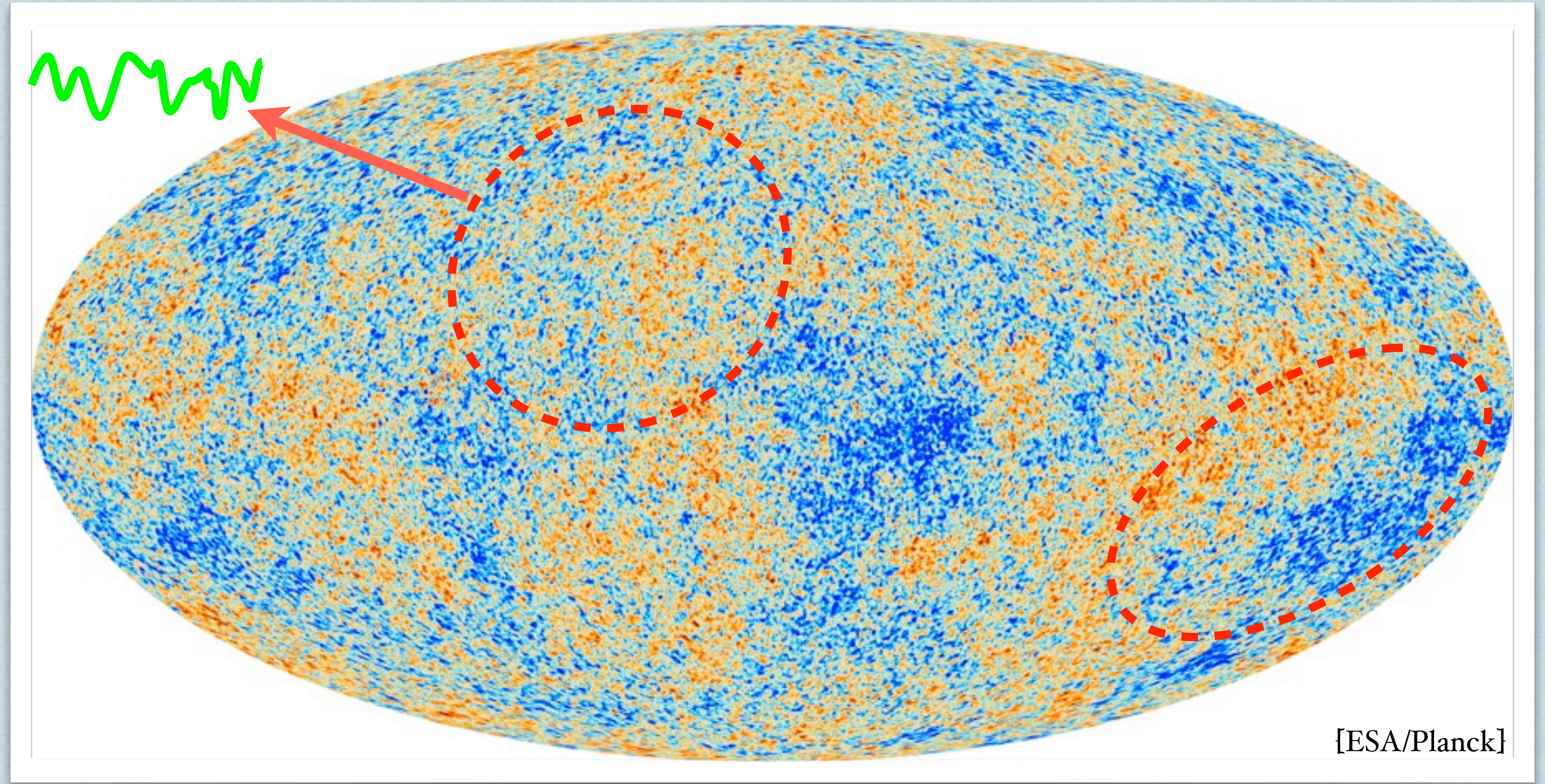

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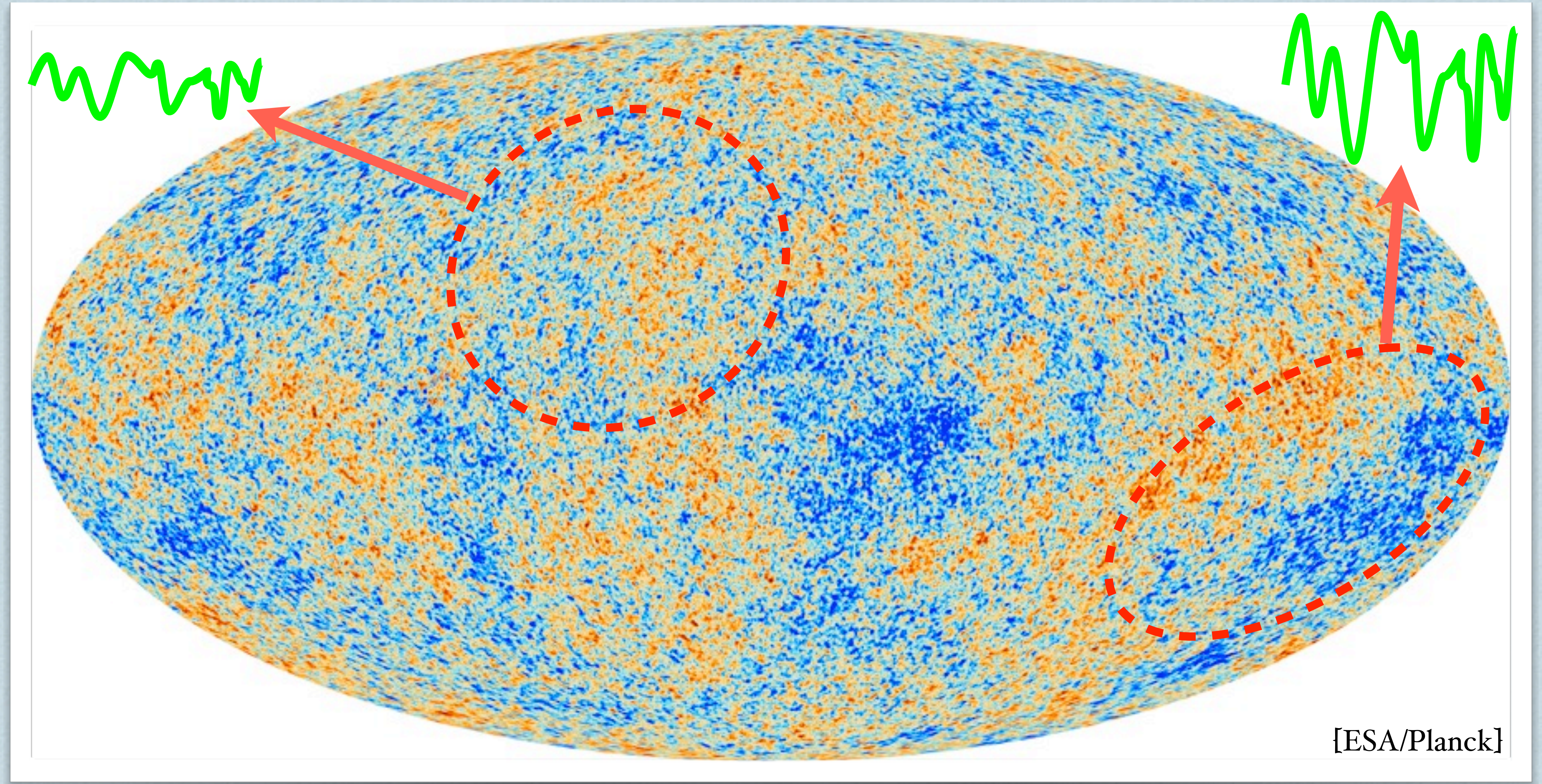

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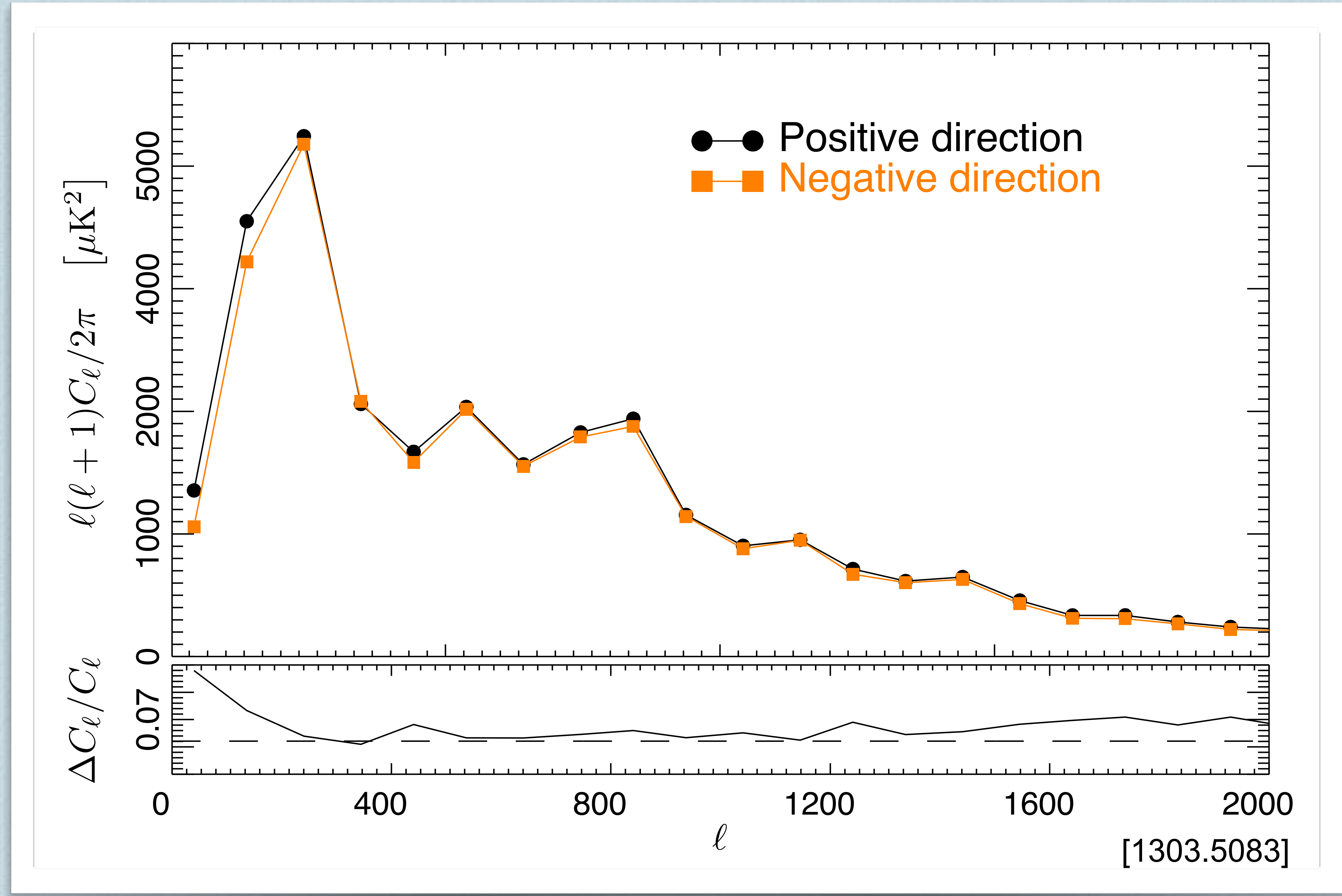

Erickcek et al 08, Dai et al 13, Lyth 13, Wang & Mazumdar 13

Isocurvature perturbations

- CMB temperature perturbations ΔT
- Other perturbations $\Delta \rho_{\mathrm{CDM}}$ $\Delta \rho_{\nu}$

[1303.5082]

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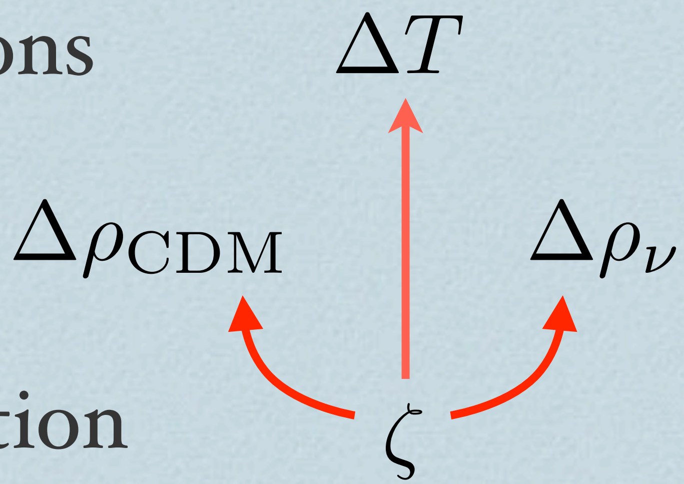

[1303.5082]

Isocurvature perturbations

- CMB temperature perturbations
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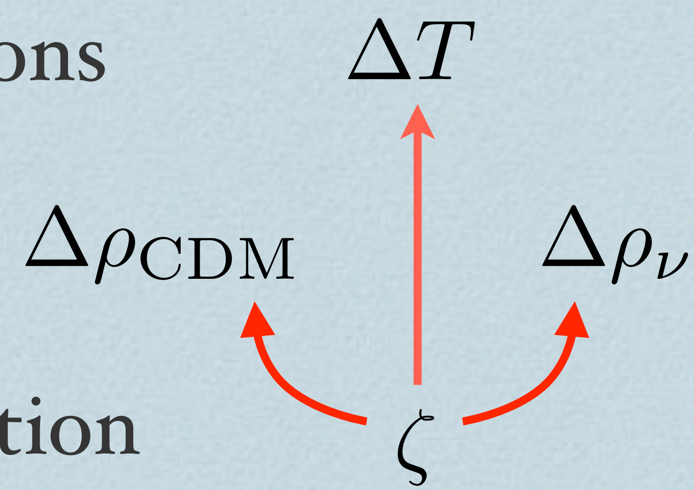
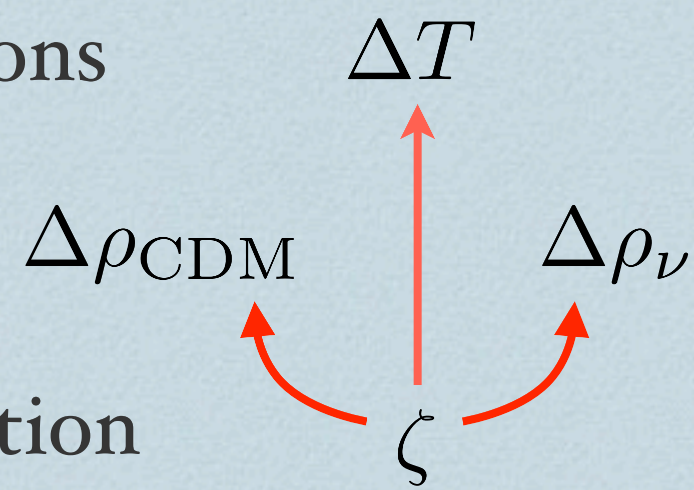
- Isocurvature: more than one degree of freedom during inflation



[1303.5082]

Isocurvature perturbations

- CMB temperature perturbations
- Other perturbations
- Adiabatic: curvature perturbation
- Isocurvature: more than one degree of freedom during inflation
- Constrain multi-field inflation



[1303.5082]

Inflation checklist

- CMB power spectrum $P_\zeta = 2.196 \times 10^{-9}$
  - Spectral index $n_s = 0.9603 \pm 0.0073$

[1303.5082], [1303.5083], [1303.5084]

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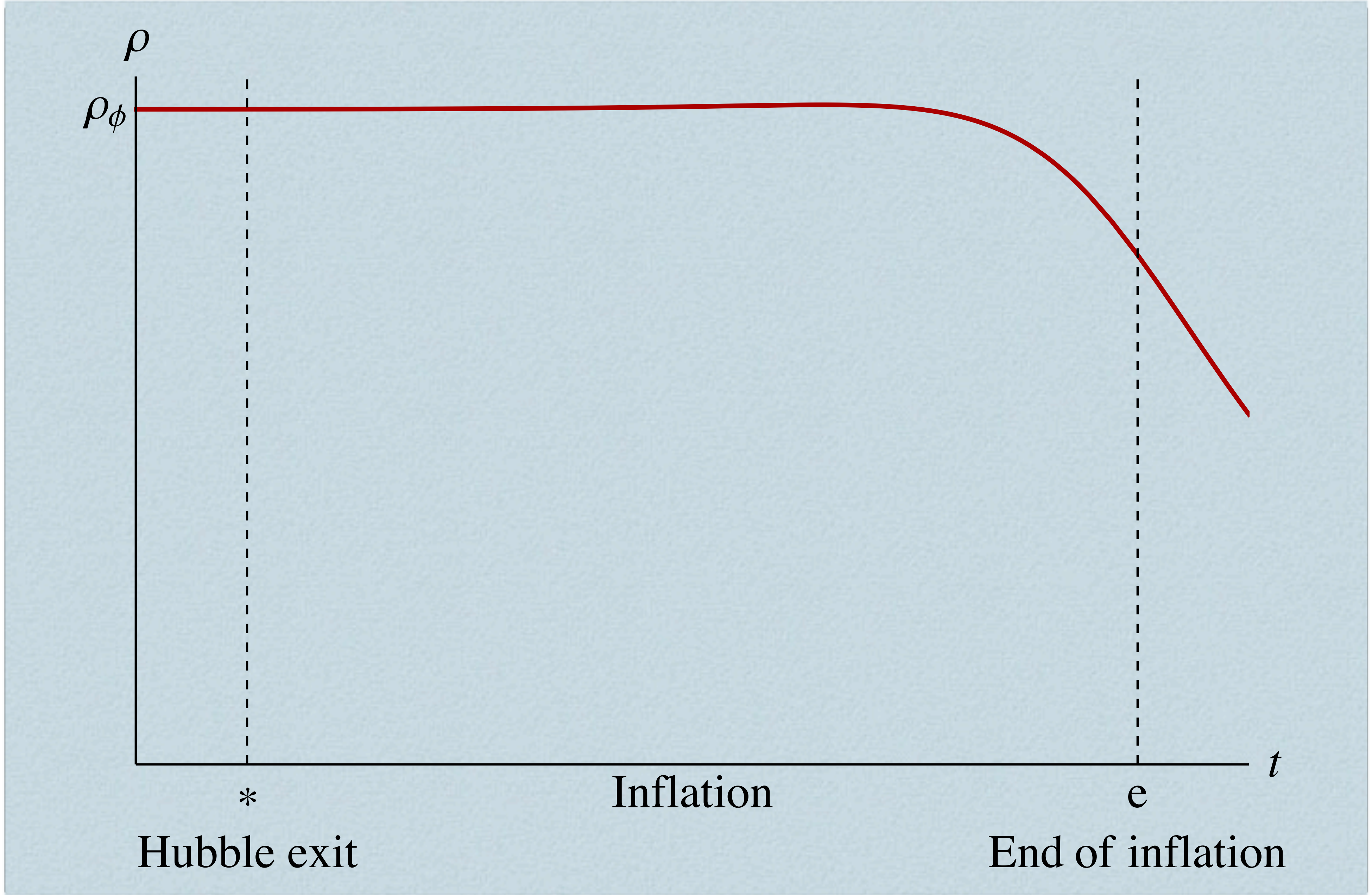
Standard Model Lagrangian Density

$$-\frac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \frac{1}{4}g_s^2 f^{abc}f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu +$$
$$\frac{1}{2} i g_s^2 (\bar{q}^\sigma_i \gamma^\mu q^\sigma_j) g^a_\mu + \bar{G}^a \partial^2 G^a + g_s f^{abc}\partial_\mu \bar{G}^a G^b g^c_\mu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu -$$
$$M^2 W^+_\mu W^-_\mu - \frac{1}{2} \partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \frac{1}{2c_w^2} M^2 Z^0_\mu Z^0_\mu - \frac{1}{2} \partial_\mu A_\nu \partial_\mu A_\nu - \frac{1}{2} \partial_\mu H \partial_\mu H -$$
$$\frac{1}{2} m_h^2 H^2 - \partial_\mu\phi^+\partial_\mu\phi^- - M^2\phi^+\phi^- - \frac{1}{2}\partial_\mu\phi^0\partial_\mu\phi^0 - \frac{1}{2c_w^2} M\phi^0\phi^0 - \beta_h[\frac{2M^2}{g^2} +$$
$$\frac{2M}{g}H + \frac{1}{2}(H^2+\phi^0\phi^0+2\phi^+\phi^-)] + \frac{2M^4}{g^2}\alpha_h - igc_w[\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu -$$
$$W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu\partial_\nu W^-_\mu -$$
$$W^-_\nu\partial_\nu W^+_\mu)] - igs_w[\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu(W^+_\mu\partial_\nu W^-_\mu -$$
$$W^-_\mu\partial_\nu W^+_\mu) + A_\mu(W^+_\nu\partial_\nu W^-_\mu - W^-_\nu\partial_\nu W^+_\mu)] - \frac{1}{2} g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu +$$
$$\frac{1}{2} g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2c_w^2(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) +$$
$$g^2 s_w^2(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w[A_\mu Z^0_\nu(W^+_\mu W^-_\nu -$$
$$W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha[H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-] -$$
$$\frac{1}{8} g^2\alpha_h[H^4+(\phi^0)^4+4(\phi^+\phi^-)^2+4(\phi^0)^2\phi^+\phi^-+4H^2\phi^+\phi^-+2(\phi^0)^2H^2] -$$
$$gMW^+_\mu W^-_\mu H - \frac{1}{2} g\frac{M}{c_w^2} Z^0_\mu Z^0_\mu H - \frac{1}{2} ig[W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) -$$
$$W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)] + \frac{1}{2} g[W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) - W^-_\mu(H\partial_\mu\phi^+ -$$
$$\phi^+\partial_\mu H)] + \frac{1}{2} g\frac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) - ig\frac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) +$$
$$igs_wMA_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) - ig\frac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) +$$
$$igs_wA_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \frac{1}{4} g^2 W^+_\mu W^-_\mu[H^2+(\phi^0)^2+2\phi^+\phi^-] -$$
$$\frac{1}{4} g^2\frac{1}{c_w^2}Z^0_\mu Z^0_\mu[H^2+(\phi^0)^2+2(2s_w^2-1)^2\phi^+\phi^-] - \frac{1}{2} g^2\frac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- +$$
$$W^-_\mu\phi^+) - \frac{1}{2} ig^2\frac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \frac{1}{2} g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- +$$
$$W^-_\mu\phi^+) + \frac{1}{2} ig^2 s_w A_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\frac{s_w}{c_w}(2c_w^2-1)Z^0_\mu A_\mu\phi^+\phi^- -$$
$$g^1 s_w^2 A_\mu A_\mu\phi^+\phi^- - \bar{e}^\lambda(\gamma\partial+m_e^\lambda)e^\lambda - \bar\nu^\lambda\gamma\partial\nu^\lambda - \bar u^\lambda_j(\gamma\partial+m_u^\lambda)u^\lambda_j - \bar d^\lambda_j(\gamma\partial+$$
$$m_d^\lambda)d^\lambda_j + igs_wA_\mu[-(\bar e^\lambda\gamma e^\lambda) + \frac{2}{3}(\bar u^\lambda_j\gamma u^\lambda_j) - \frac{1}{3}(\bar d^\lambda_j\gamma d^\lambda_j)] + \frac{ig}{4c_w}Z^0_\mu[(\bar\nu^\lambda\gamma^\mu(1+$$
$$\gamma^5)\nu^\lambda) + (\bar e^\lambda\gamma^\mu(4s_w^2-1-\gamma^5)e^\lambda) + (\bar u^\lambda_j\gamma^\mu(\frac{4}{3} s_w^2-1-\gamma^5)u^\lambda_j) +$$
$$(\bar d^\lambda_j\gamma^\mu(1-\frac{8}{3} s_w^2-\gamma^5)d^\lambda_j)] + \frac{ig}{2\sqrt2}W^+_\mu[(\bar\nu^\lambda\gamma^\mu(1+\gamma^5)e^\lambda) + (\bar u^\lambda_j\gamma^\mu(1+$$
$$\gamma^5)C_{\lambda\kappa}d^\kappa_j)] + \frac{ig}{2\sqrt2}W^-_\mu[(\bar e^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar d^\kappa_j C^\dagger_{\lambda\kappa}\gamma^\mu(1+\gamma^5)u^\lambda_j)] +$$
$$\frac{ig}{2\sqrt2}\frac{m_e^\lambda}{M}[-\phi^+(\bar\nu^\lambda(1-\gamma^5)e^\lambda) + \phi^-(\bar e^\lambda(1+\gamma^5)\nu^\lambda)] - \frac{g}{2}\frac{m_e^\lambda}{M}[H(\bar e^\lambda e^\lambda) +$$
$$i\phi^0(\bar e^\lambda\gamma^5 e^\lambda)] + \frac{ig}{2M\sqrt2}\phi^+[-m_d^\kappa(\bar u^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) + m_u^\lambda(\bar u^\lambda_j C_{\lambda\kappa}(1+$$
$$\gamma^5)d^\kappa_j] + \frac{ig}{2M\sqrt2}\phi^-[m_d^\lambda(\bar d^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m_u^\kappa(\bar d^\lambda_j C^\dagger_{\lambda\kappa}(1-\gamma^5)u^\kappa_j] -$$
$$\frac{g}{2}\frac{m_u^\lambda}{M}H(\bar u^\lambda_j u^\lambda_j) - \frac{g}{2}\frac{m_d^\lambda}{M}H(\bar d^\lambda_j d^\lambda_j) + \frac{ig}{2}\frac{m_u^\lambda}{M}\phi^0(\bar u^\lambda_j\gamma^5 u^\lambda_j) - \frac{ig}{2}\frac{m_d^\lambda}{M}\phi^0(\bar d^\lambda_j\gamma^5 d^\lambda_j) +$$
$$\bar X^+(\partial^2-M^2)X^+ + \bar X^-(\partial^2-M^2)X^- + \bar X^0(\partial^2-\frac{M^2}{c_w^2})X^0 + \bar Y\partial^2 Y +$$
$$igc_wW^+_\mu(\partial_\mu\bar X^0X^- - \partial_\mu\bar X^+X^0) + igs_wW^+_\mu(\partial_\mu\bar YX^- - \partial_\mu\bar X^+Y) +$$
$$igc_wW^-_\mu(\partial_\mu\bar X^-X^0 - \partial_\mu\bar X^0X^+) + igs_wW^-_\mu(\partial_\mu\bar X^-Y - \partial_\mu\bar YX^+) +$$
$$igc_wZ^0_\mu(\partial_\mu\bar X^+X^+ - \partial_\mu\bar X^-X^-) + igs_wA_\mu(\partial_\mu\bar X^+X^+ - \partial_\mu\bar X^-X^-) -$$
$$\frac{1}{2} gM[\bar X^+X^+H + \bar X^-X^-H + \frac{1}{c_w^2}\bar X^0X^0H] + \frac{1-2c_w^2}{2c_w}igM[\bar X^+X^0\phi^+ -$$
$$\bar X^-X^0\phi^-] + \frac{1}{2c_w}igM[\bar X^0X^-\phi^+ - \bar X^0X^+\phi^-] + igMs_w[\bar X^0X^-\phi^+ -$$
$$\bar X^0X^+\phi^-] + \frac{1}{2} igM[\bar X^+X^+\phi^0 - \bar X^-X^-\phi^0]$$

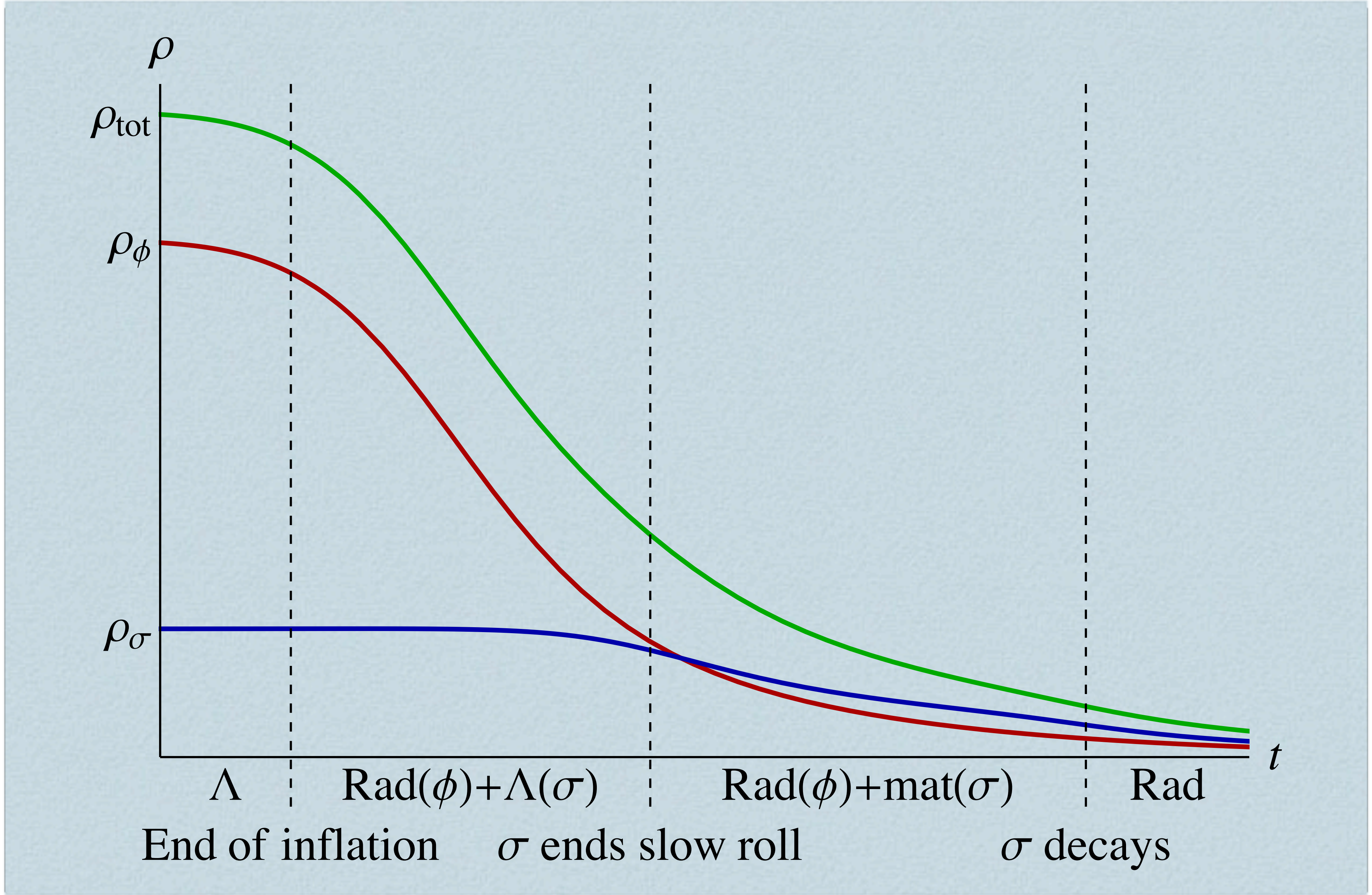
Standard Model Lagrangian Density

$$-\frac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \frac{1}{4}g_s^2 f^{abc} f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu +$$
$$\frac{1}{2}ig_s^2(\bar{q}^\sigma_i \gamma^\mu q^\sigma_j) g^a_\mu + \bar{G}^a \partial^2 G^a + g_s f^{abc}\partial_\mu \bar{G}^a G^b g^c_\mu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu -$$
$$M^2 W^+_\mu W^-_\mu - \frac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \frac{1}{2c_w^2} M^2 Z^0_\mu Z^0_\mu - \frac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \frac{1}{2}\partial_\mu H \partial_\mu H -$$
$$\frac{1}{2}m_h^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - M^2 \phi^+ \phi^- - \frac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \frac{1}{2c_w^2} M \phi^0 \phi^0 - \beta_h[\frac{2M^2}{g^2} +$$
$$\frac{2M}{g}H + \frac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)] + \frac{2M^4}{g^2}\alpha_h - igc_w[\partial_\nu Z^0_\mu (W^+_\mu W^-_\nu -$$
$$W^+_\nu W^-_\mu) - Z^0_\nu (W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu (W^+_\nu \partial_\nu W^-_\mu -$$
$$W^-_\nu \partial_\nu W^+_\mu)] - igs_w[\partial_\nu A_\mu (W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu (W^+_\mu \partial_\nu W^-_\mu -$$
$$W^-_\mu \partial_\nu W^+_\mu) + A_\mu (W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)] - \frac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu +$$
$$\frac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c_w^2 (Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) +$$
$$g^2 s_w^2 (A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w [A_\mu Z^0_\nu (W^+_\mu W^-_\nu -$$
$$W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha[H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-] -$$
$$\frac{1}{8}g^2\alpha_h[H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2H^2] -$$
$$gMW^+_\mu W^-_\mu H - \frac{1}{2}g\frac{M}{c_w^2} Z^0_\mu Z^0_\mu H - \frac{1}{2}ig[W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) -$$
$$W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)] + \frac{1}{2}g[W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) - W^-_\mu(H\partial_\mu\phi^+ -$$
$$\phi^+\partial_\mu H)] + \frac{1}{2}g\frac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) - ig\frac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) +$$
$$igs_w MA_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) - ig\frac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) +$$
$$igs_w A_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \frac{1}{4}g^2 W^+_\mu W^-_\mu[H^2 + (\phi^0)^2 + 2\phi^+\phi^-] -$$
$$\frac{1}{8}g^2\frac{1}{c_w^2}Z^0_\mu Z^0_\mu[H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2\phi^+\phi^-] - \frac{1}{2}g^2\frac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- +$$
$$W^-_\mu\phi^+) - \frac{1}{2}ig^2\frac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \frac{1}{2}g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- +$$
$$W^-_\mu\phi^+) + \frac{1}{2}ig^2 s_w A_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\frac{s_w}{c_w}(2c_w^2 - 1)Z^0_\mu A_\mu\phi^+\phi^- -$$
$$g^2 s_w^2 A_\mu A_\mu\phi^+\phi^- - \bar{e}^\lambda(\gamma\partial + m_e^\lambda)e^\lambda - \bar{\nu}^\lambda\gamma\partial\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial + m_u^\lambda)u^\lambda_j - \bar{d}^\lambda_j(\gamma\partial +$$
$$m_d^\lambda)d^\lambda_j + igs_w A_\mu[-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \frac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) - \frac{1}{3}(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)] + \frac{ig}{4c_w}Z^0_\mu[(\bar{\nu}^\lambda\gamma^\mu(1 +$$
$$\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s_w^2 - 1 - \gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(\frac{4}{3}s_w^2 - 1 - \gamma^5)u^\lambda_j) +$$
$$(\bar{d}^\lambda_j\gamma^\mu(1 - \frac{8}{3}s_w^2 - \gamma^5)d^\lambda_j)] + \frac{ig}{2\sqrt{2}}W^+_\mu[(\bar{\nu}^\lambda\gamma^\mu(1 + \gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(1 +$$
$$\gamma^5)C_{\lambda\kappa}d^\kappa_j)] + \frac{ig}{2\sqrt{2}}W^-_\mu[(\bar{e}^\lambda\gamma^\mu(1 + \gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\lambda\kappa}\gamma^\mu(1 + \gamma^5)u^\lambda_j)] +$$
$$\frac{ig}{2\sqrt{2}}\frac{m_e^\lambda}{M}[-\phi^+(\bar{\nu}^\lambda(1 - \gamma^5)e^\lambda) + \phi^-(\bar{e}^\lambda(1 + \gamma^5)\nu^\lambda)] - \frac{g}{2}\frac{m_e^\lambda}{M}[H(\bar{e}^\lambda e^\lambda) +$$
$$i\phi^0(\bar{e}^\lambda\gamma^5 e^\lambda)] + \frac{ig}{2M\sqrt{2}}\phi^+[-m_d^\kappa(\bar{u}^\lambda_j C_{\lambda\kappa}(1 - \gamma^5)d^\kappa_j) + m_u^\lambda(\bar{u}^\lambda_j C_{\lambda\kappa}(1 +$$
$$\gamma^5)d^\kappa_j] + \frac{ig}{2M\sqrt{2}}\phi^-[m_d^\lambda(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1 + \gamma^5)u^\kappa_j) - m_u^\kappa(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1 - \gamma^5)u^\kappa_j] -$$
$$\frac{g}{2}\frac{m_u^\lambda}{M}H(\bar{u}^\lambda_j u^\lambda_j) - \frac{g}{2}\frac{m_d^\lambda}{M}H(\bar{d}^\lambda_j d^\lambda_j) + \frac{ig}{2}\frac{m_u^\lambda}{M}\phi^0(\bar{u}^\lambda_j\gamma^5 u^\lambda_j) - \frac{ig}{2}\frac{m_d^\lambda}{M}\phi^0(\bar{d}^\lambda_j\gamma^5 d^\lambda_j) +$$
$$\bar{X}^+(\partial^2 - M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2 - \frac{M^2}{c_w^2})X^0 + \bar{Y}\partial^2 Y +$$
$$igc_w W^+_\mu(\partial_\mu\bar{X}^0 X^- - \partial_\mu\bar{X}^+ X^0) + igs_w W^+_\mu(\partial_\mu\bar{Y}X^- - \partial_\mu\bar{X}^+ Y) +$$
$$igc_w W^-_\mu(\partial_\mu\bar{X}^- X^0 - \partial_\mu\bar{X}^0 X^+) + igs_w W^-_\mu(\partial_\mu\bar{X}^- Y - \partial_\mu\bar{Y}X^+) +$$
$$igc_w Z^0_\mu(\partial_\mu\bar{X}^+ X^+ - \partial_\mu\bar{X}^- X^-) + igs_w A_\mu(\partial_\mu\bar{X}^+ X^+ - \partial_\mu\bar{X}^- X^-) -$$
$$\frac{1}{2}gM[\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{c_w^2}\bar{X}^0 X^0 H] + \frac{1-2c_w^2}{2c_w}igM[\bar{X}^+ X^0\phi^+ -$$
$$\bar{X}^- X^0\phi^-] + \frac{1}{2c_w}igM[\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-] + igMs_w[\bar{X}^0 X^-\phi^+ -$$
$$\bar{X}^0 X^+\phi^-] + \frac{1}{2}igM[\bar{X}^+ X^+\phi^0 - \bar{X}^- X^-\phi^0]$$

Single-field slow roll inflation

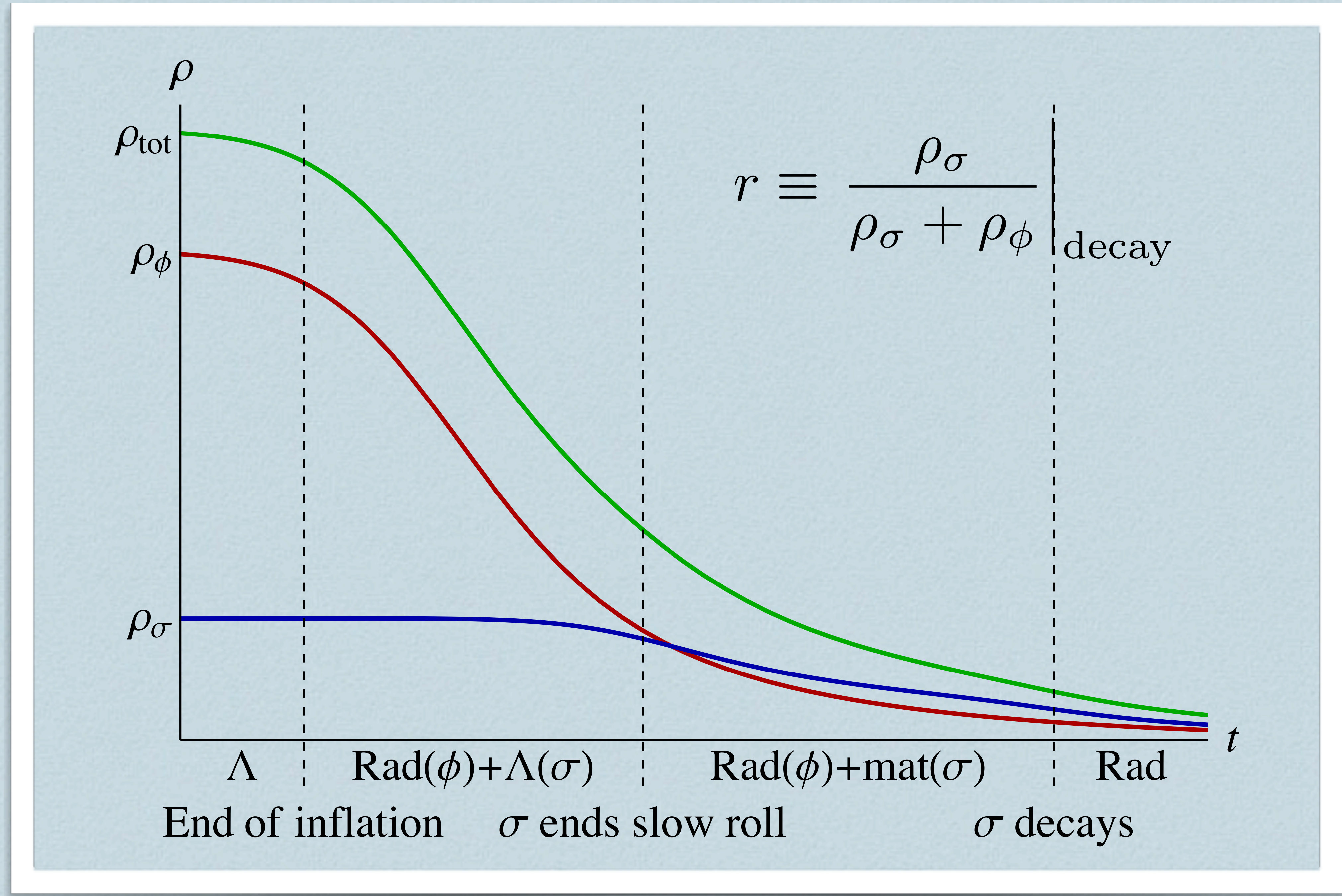


Curvaton



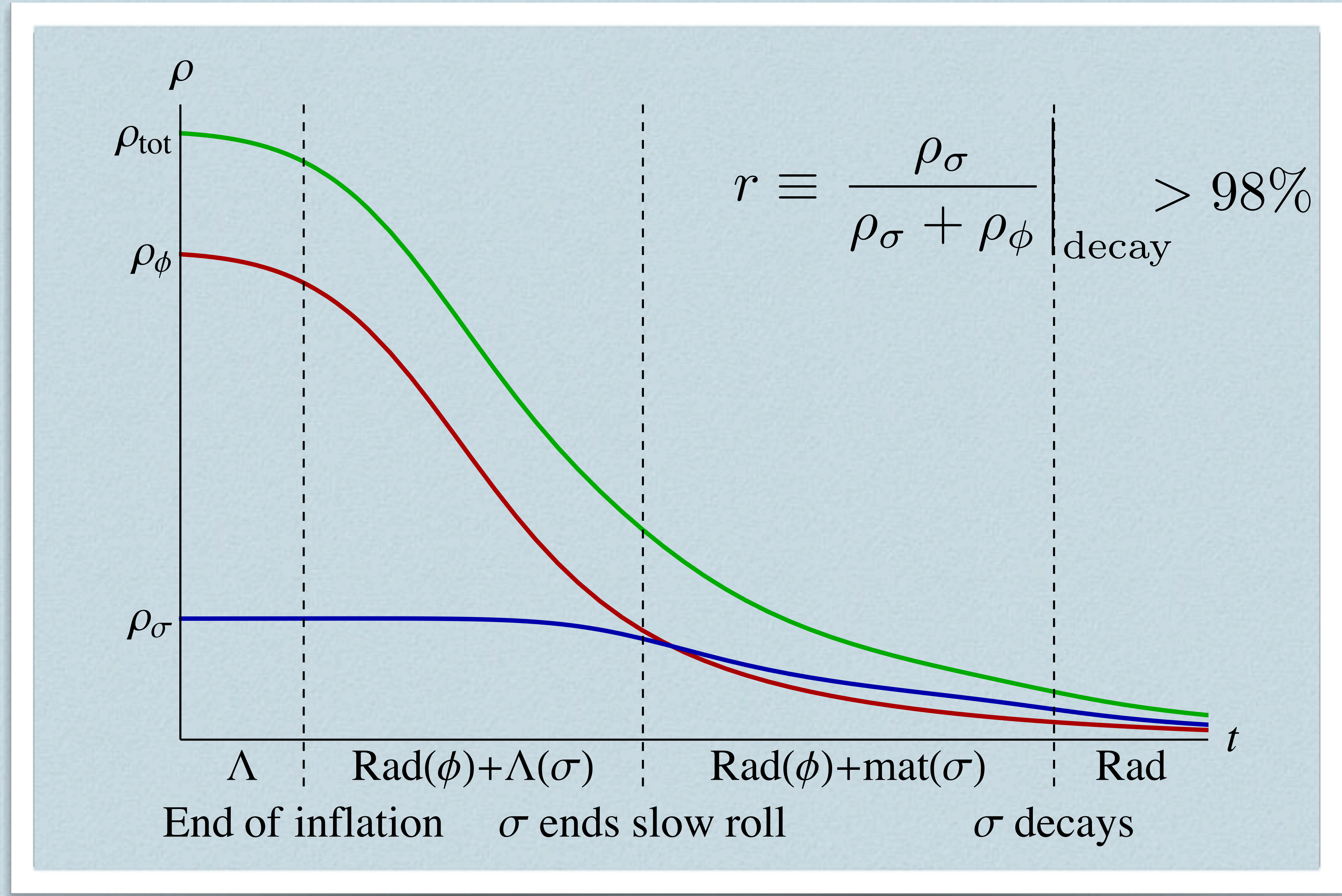
Lyth & Wands 01, Lyth et al 02, Lyth & Rodriguez 05, [1303.5082]

Curvaton



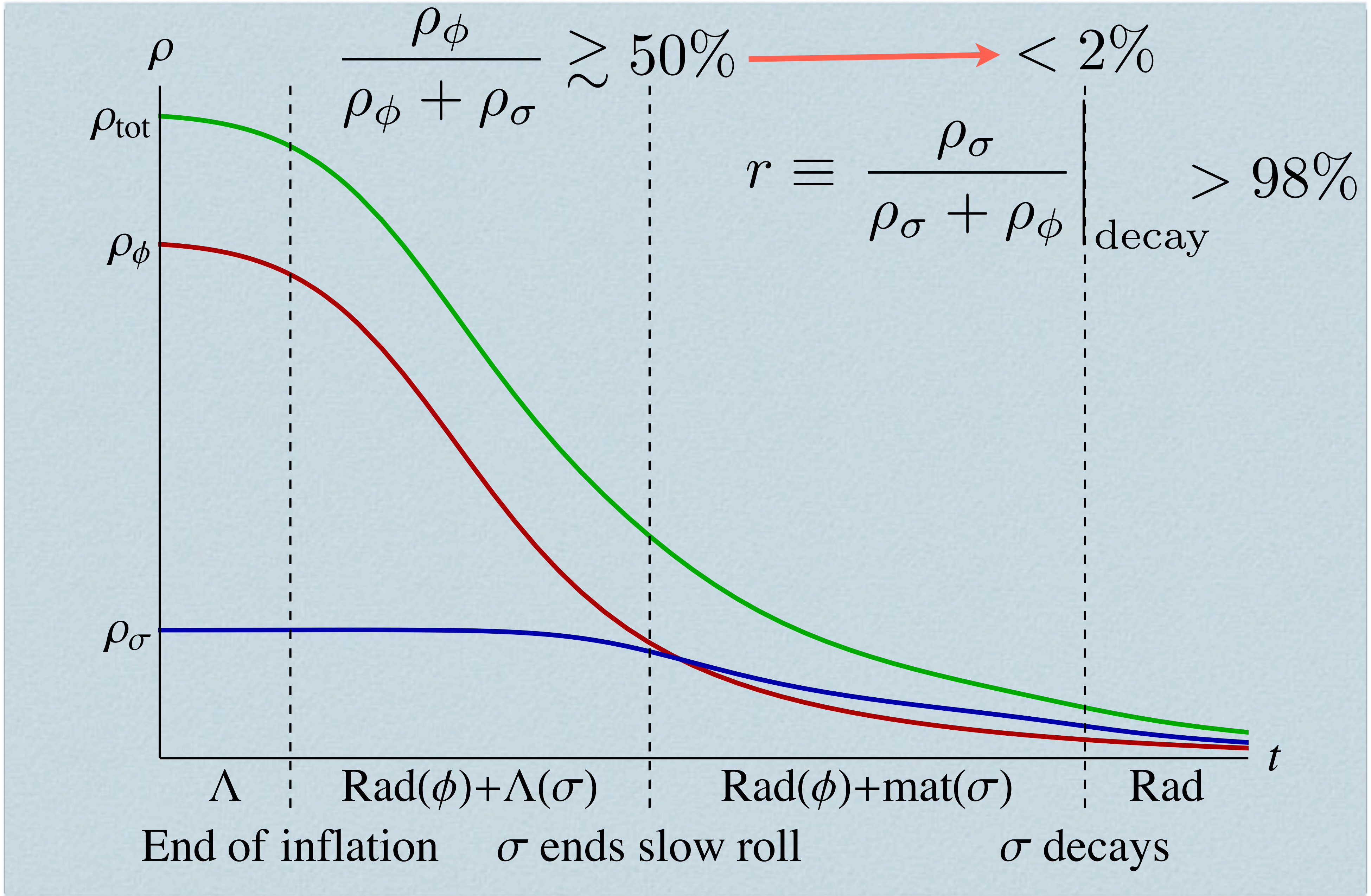
Lyth & Wands 01, Lyth et al 02, Lyth & Rodriguez 05, [1303.5082]

Curvaton



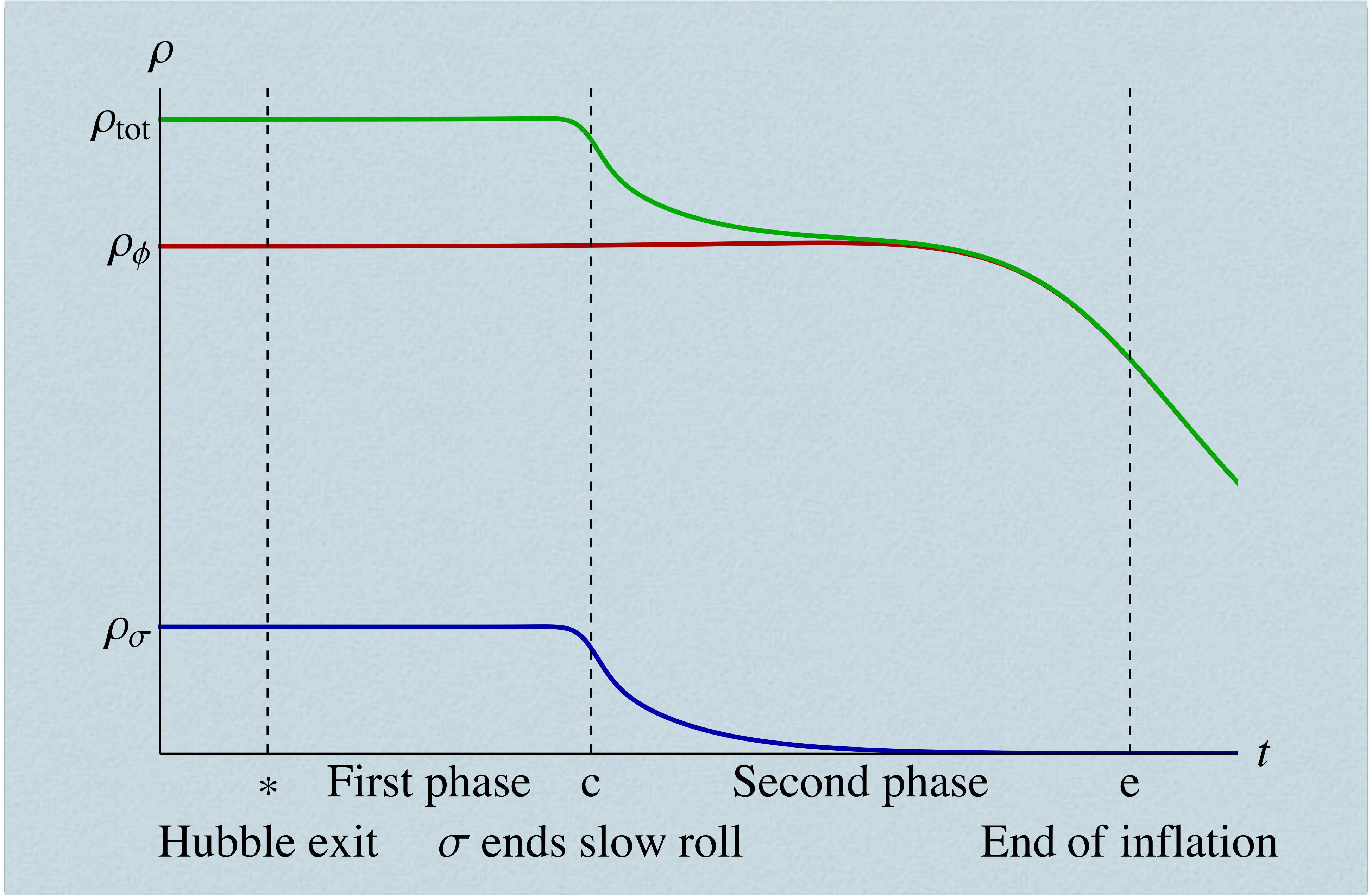
Lyth & Wands 01, Lyth et al 02, Lyth & Rodriguez 05, [1303.5082]

Curvaton



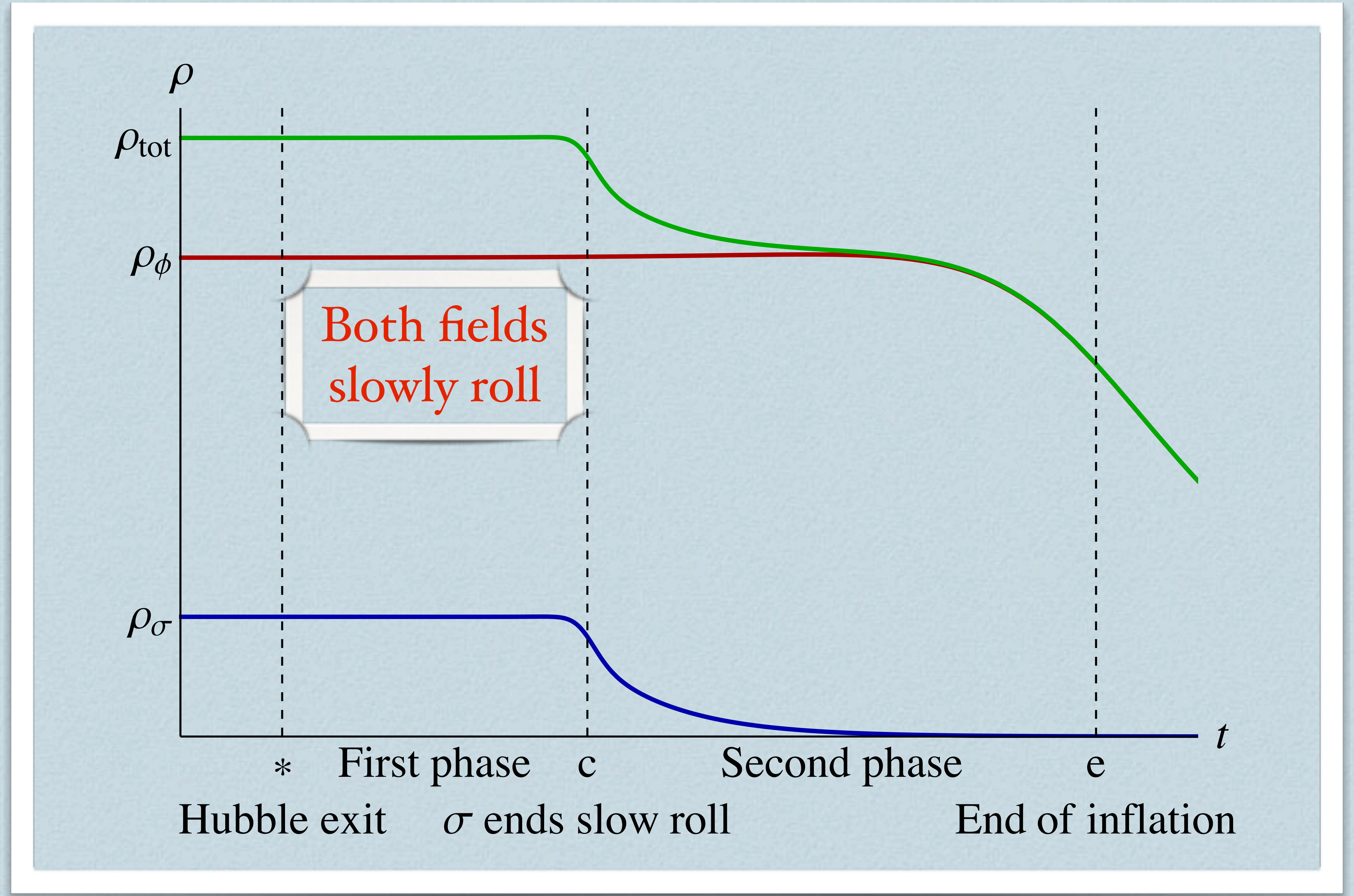
Lyth & Wands 01, Lyth et al 02, Lyth & Rodriguez 05, [1303.5082]

Spectator



Mazumdar & Wang 12, Wang & Mazumdar 13

Spectator



Mazumdar & Wang 12, Wang & Mazumdar 13

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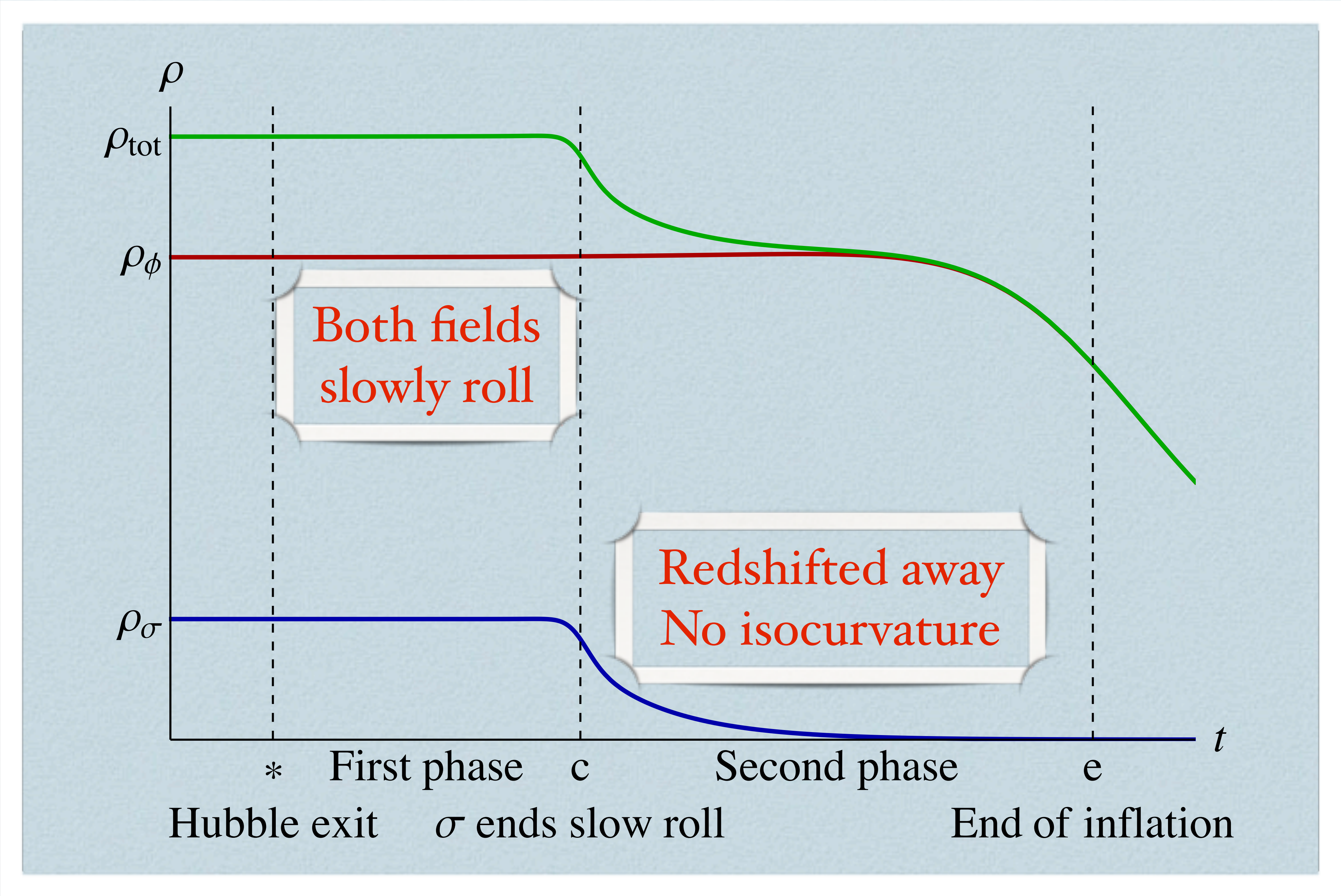

Mazumdar & Wang 12, Wang & Mazumdar 13

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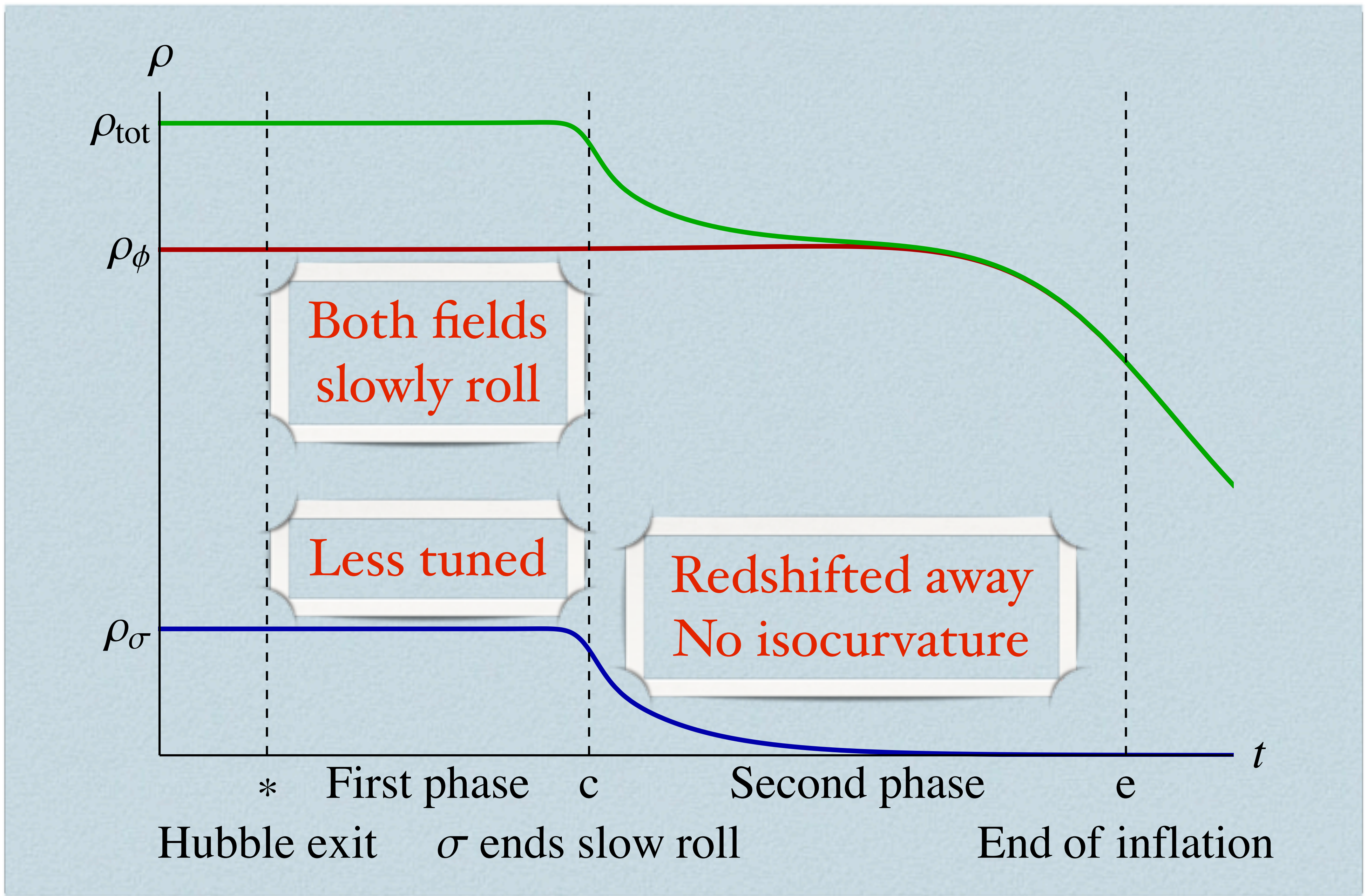
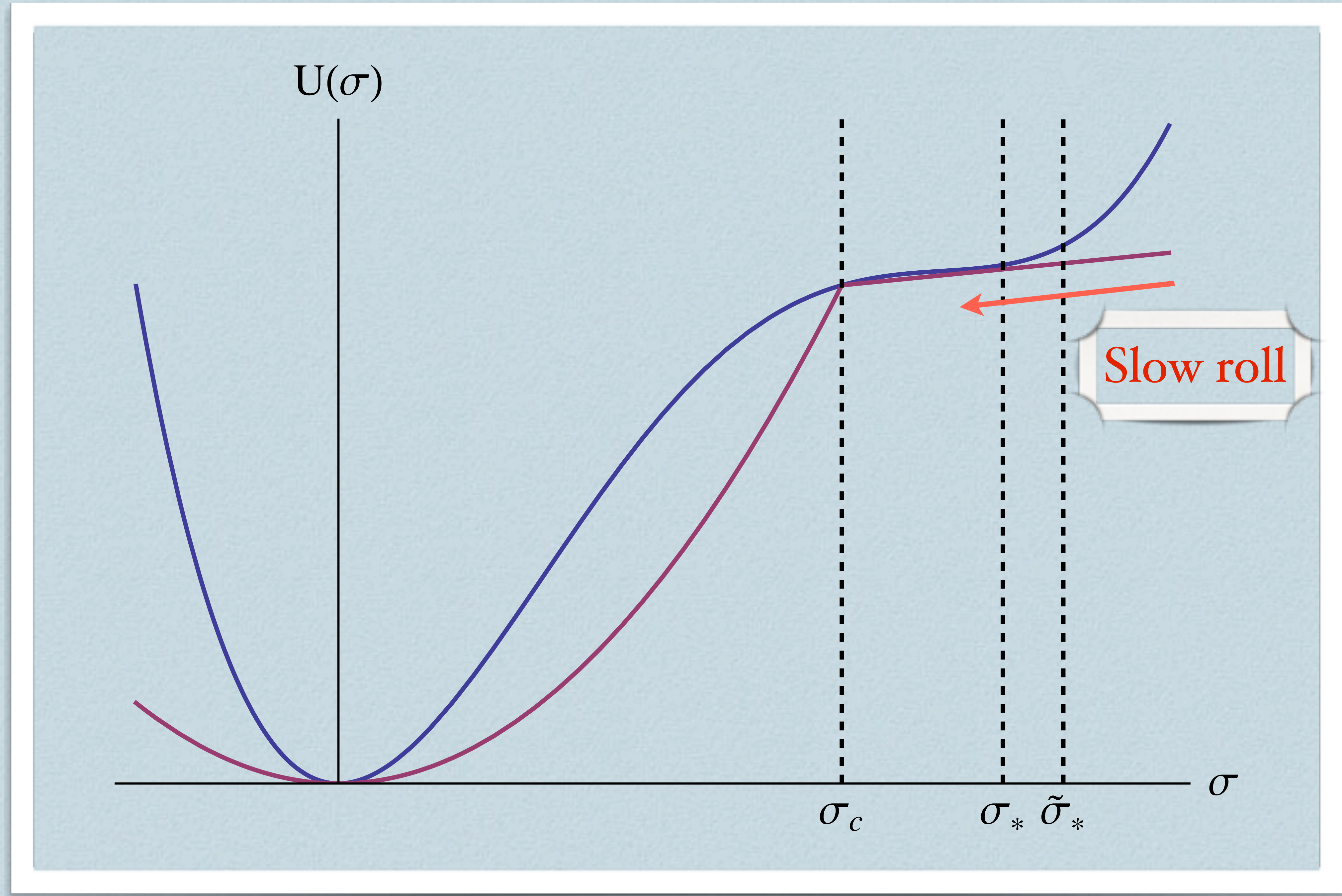


Mazumdar & Wang 12, Wang & Mazumdar 13

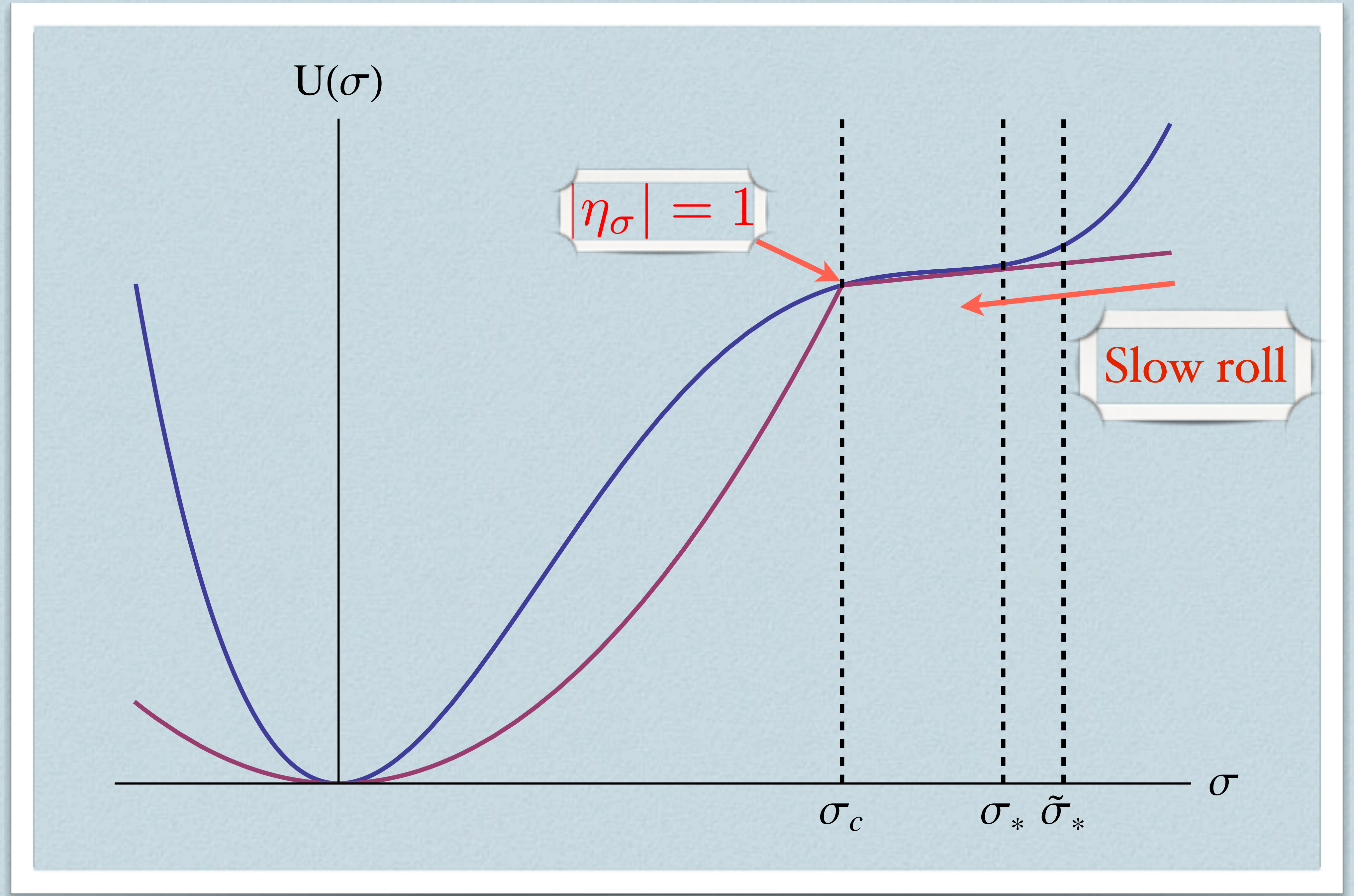
A spectator should:

- Not affect inflation dynamics when perturbed/removed
    - Subdominate the energy density
    - Not couple to the inflaton(s) (except minimally by gravity)
- Dominate (or contribute significant) curvature perturbations
- End slow roll during inflation, after the Hubble exit of the relevant scales

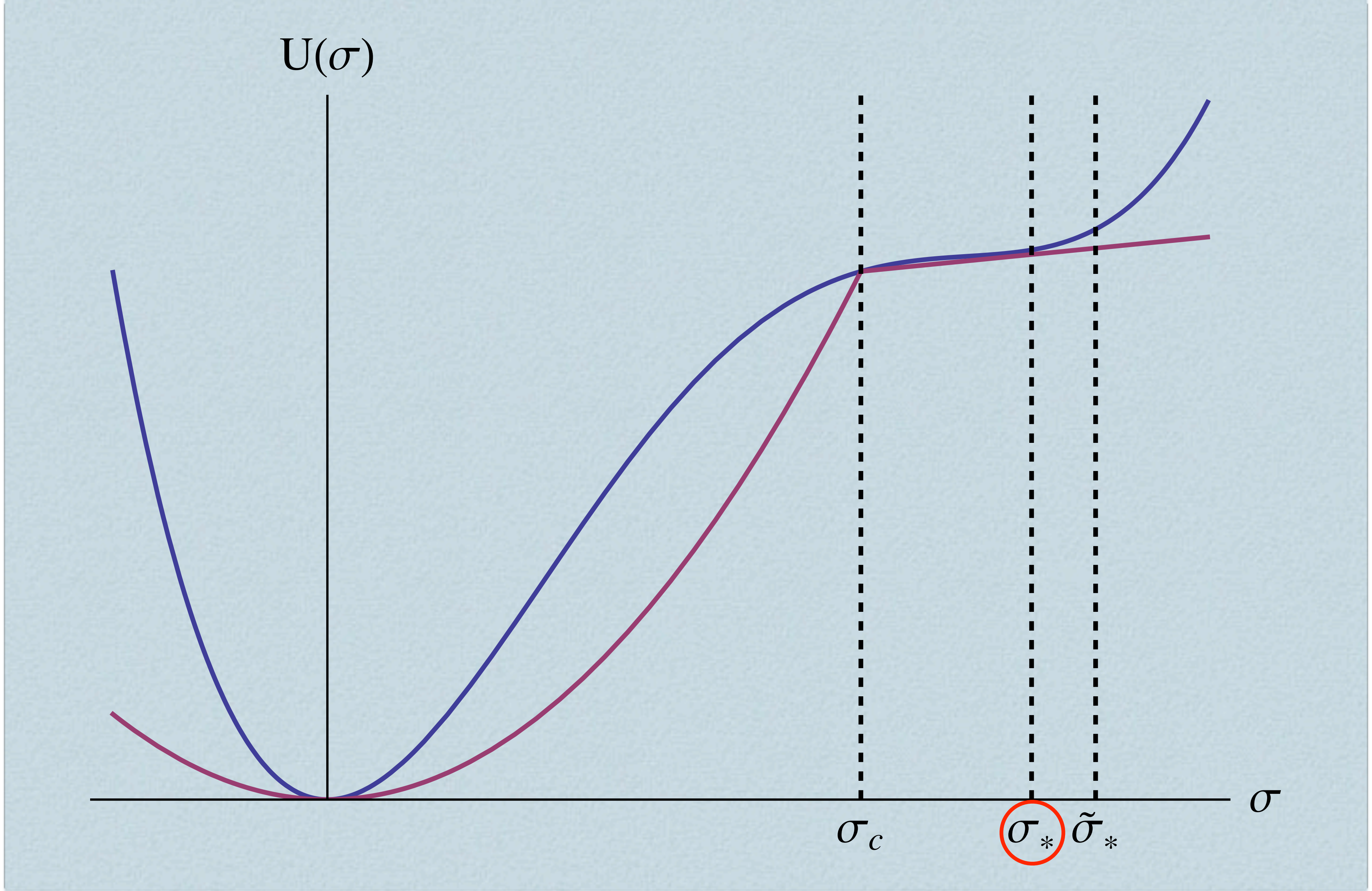
Typical potential



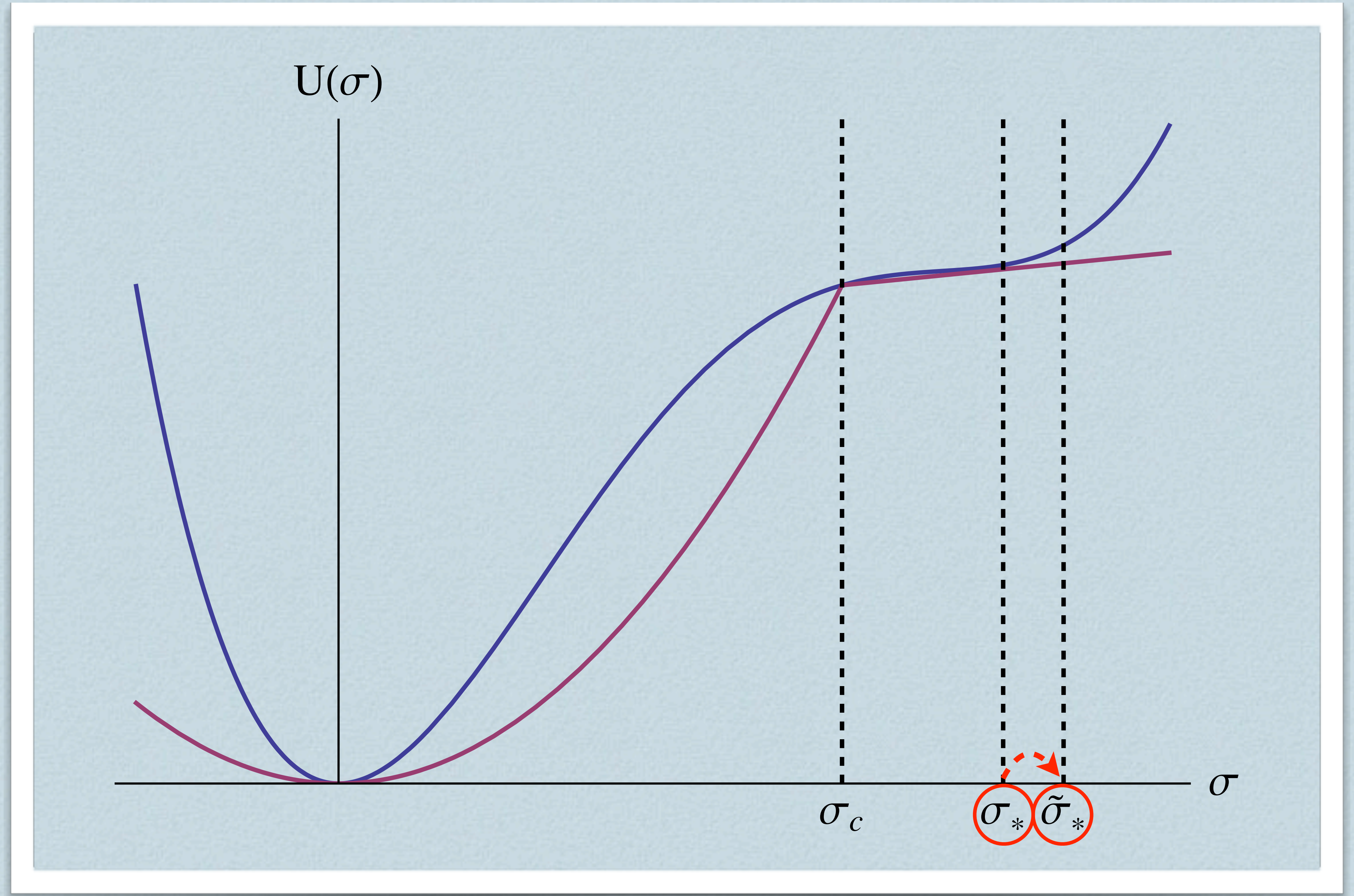
Typical potential



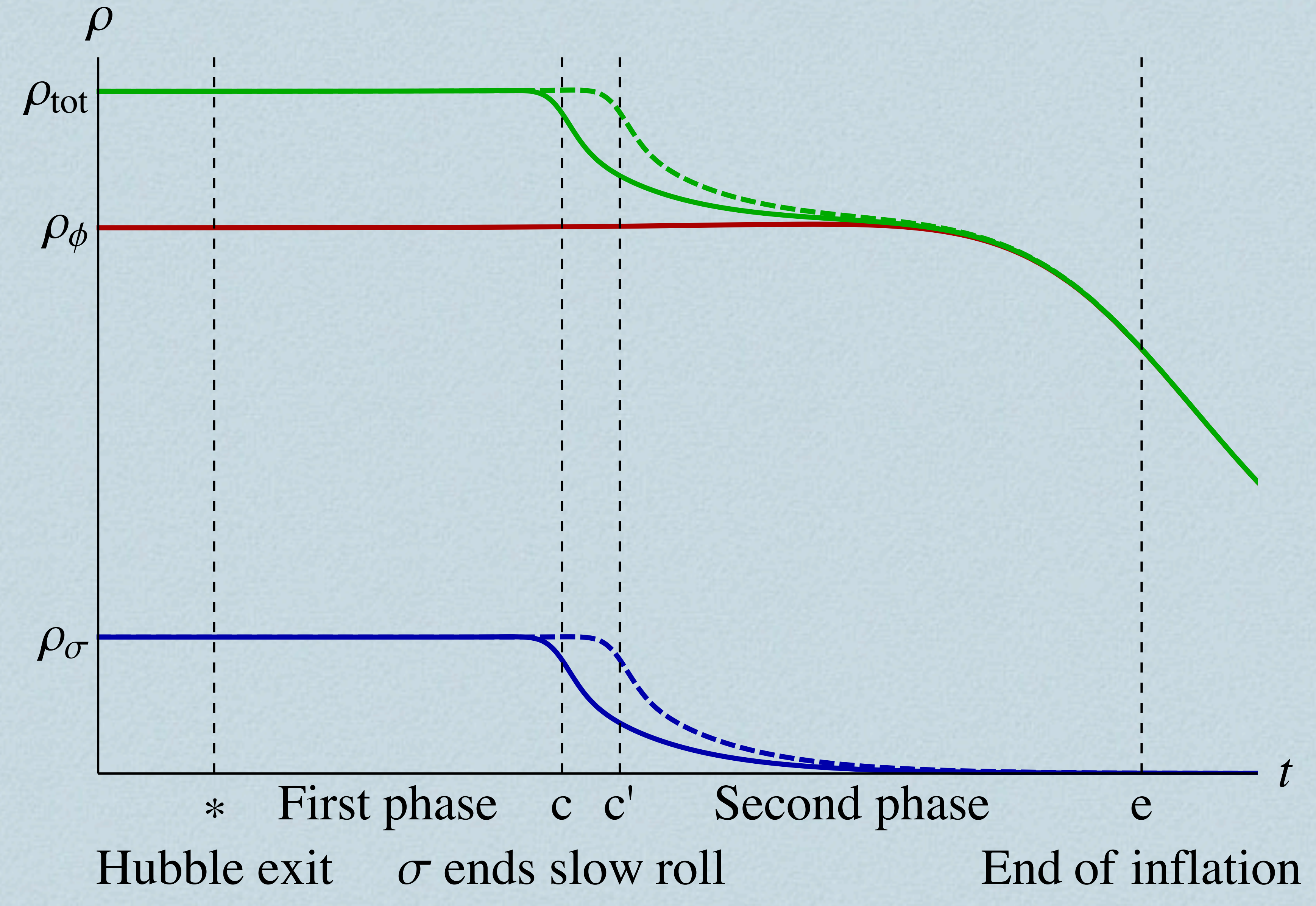
Typical potential



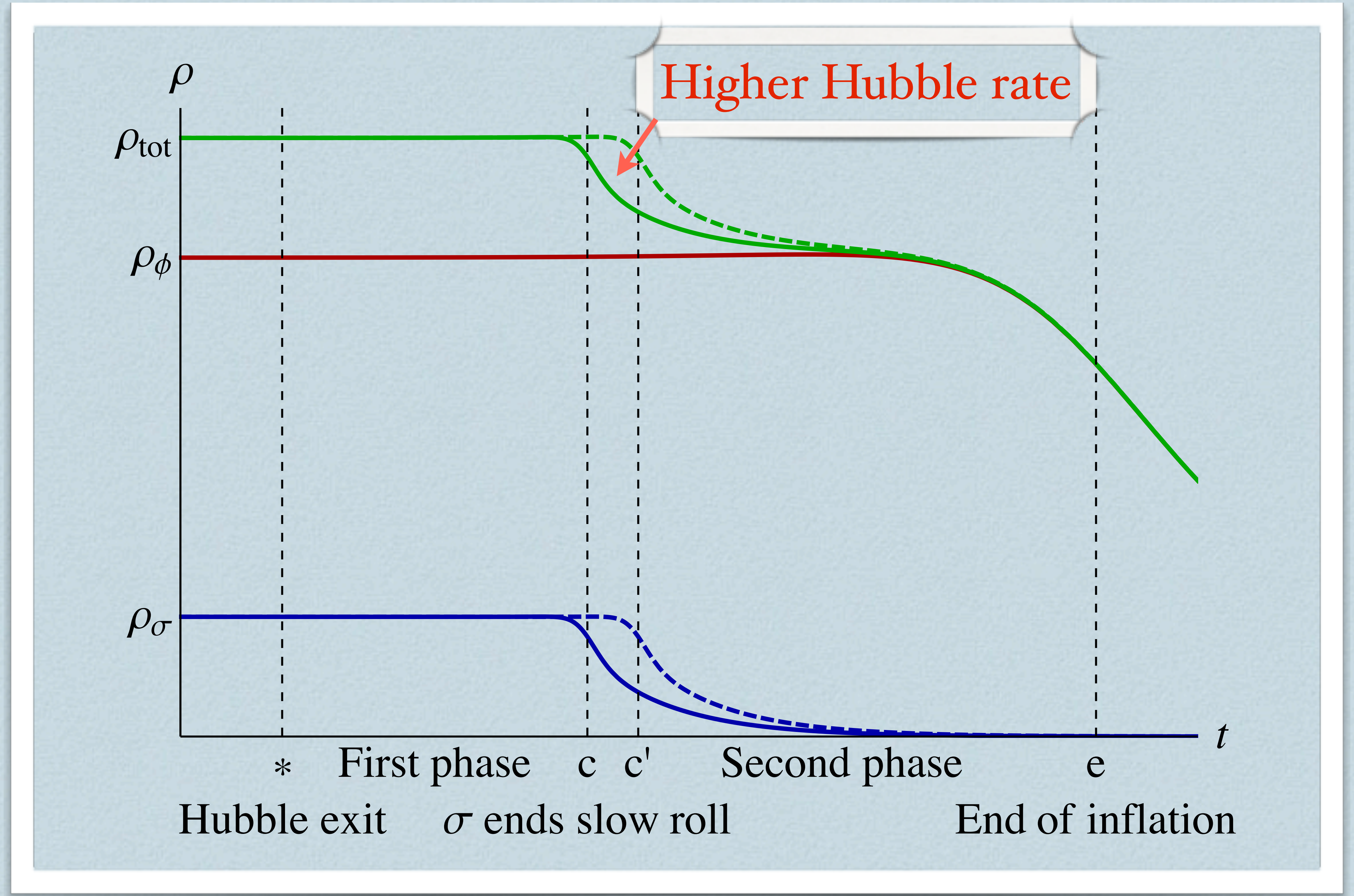
Typical potential



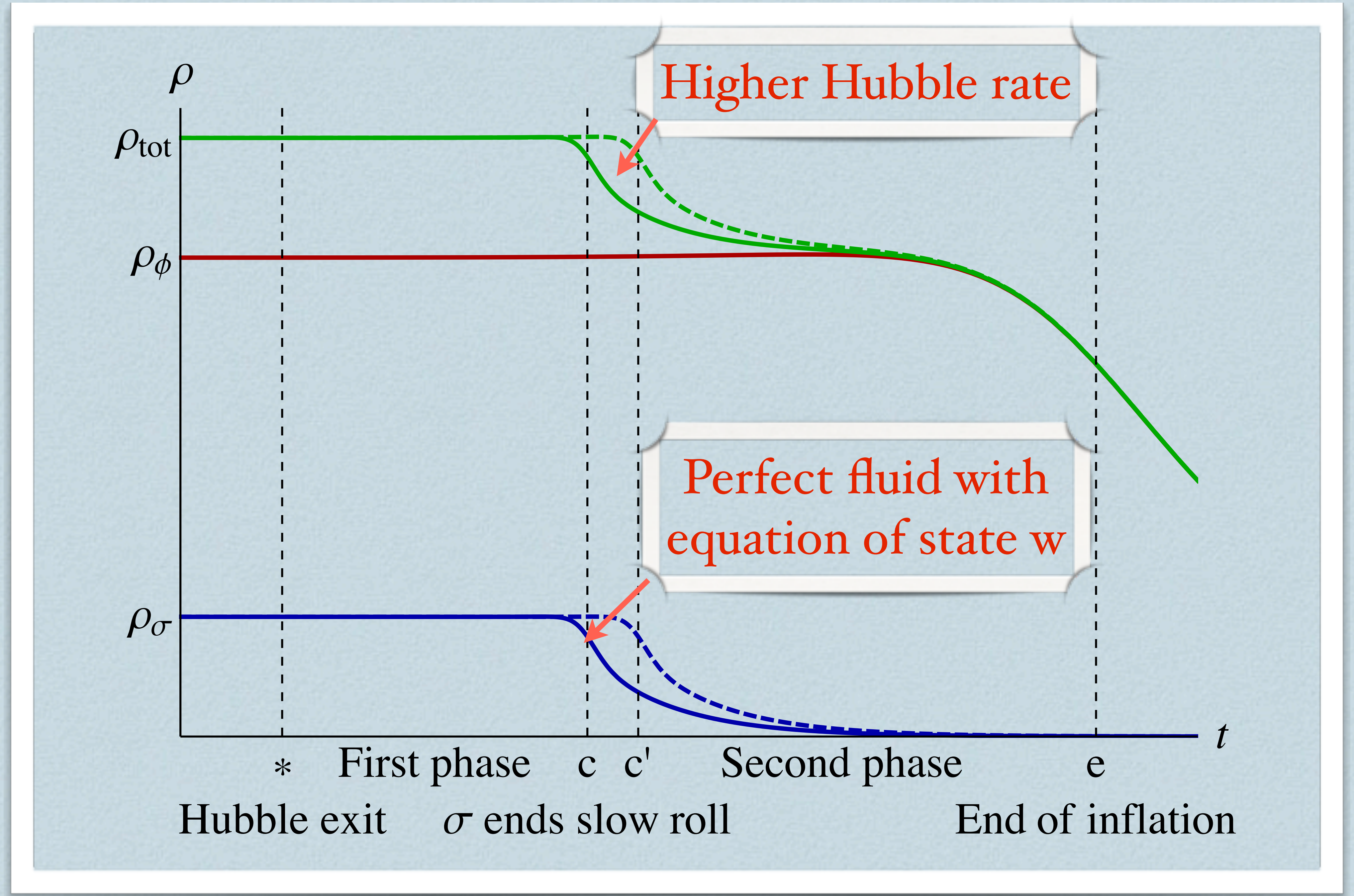
Shifting boundary



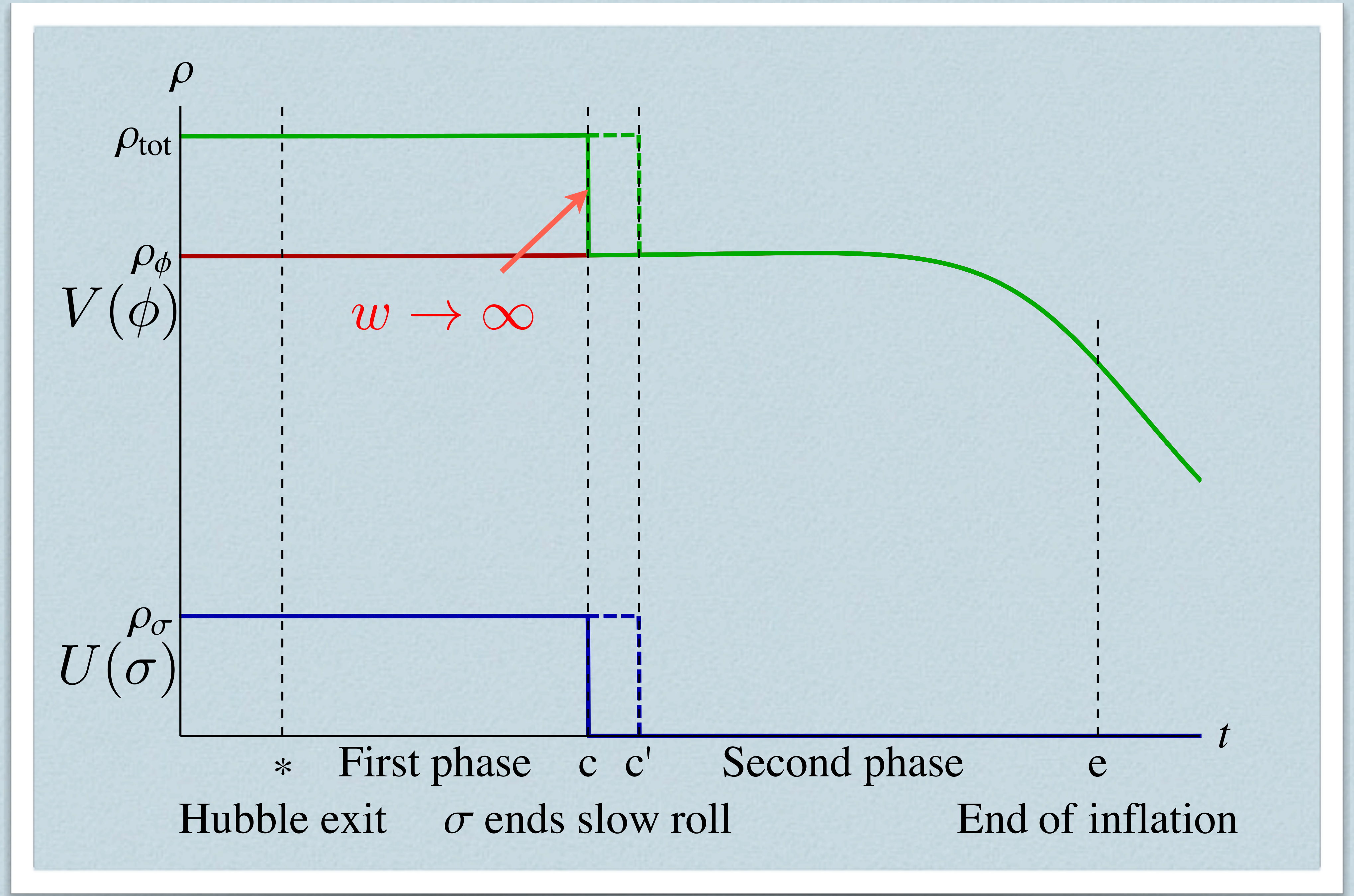
Shifting boundary



Shifting boundary



Approximated boundary



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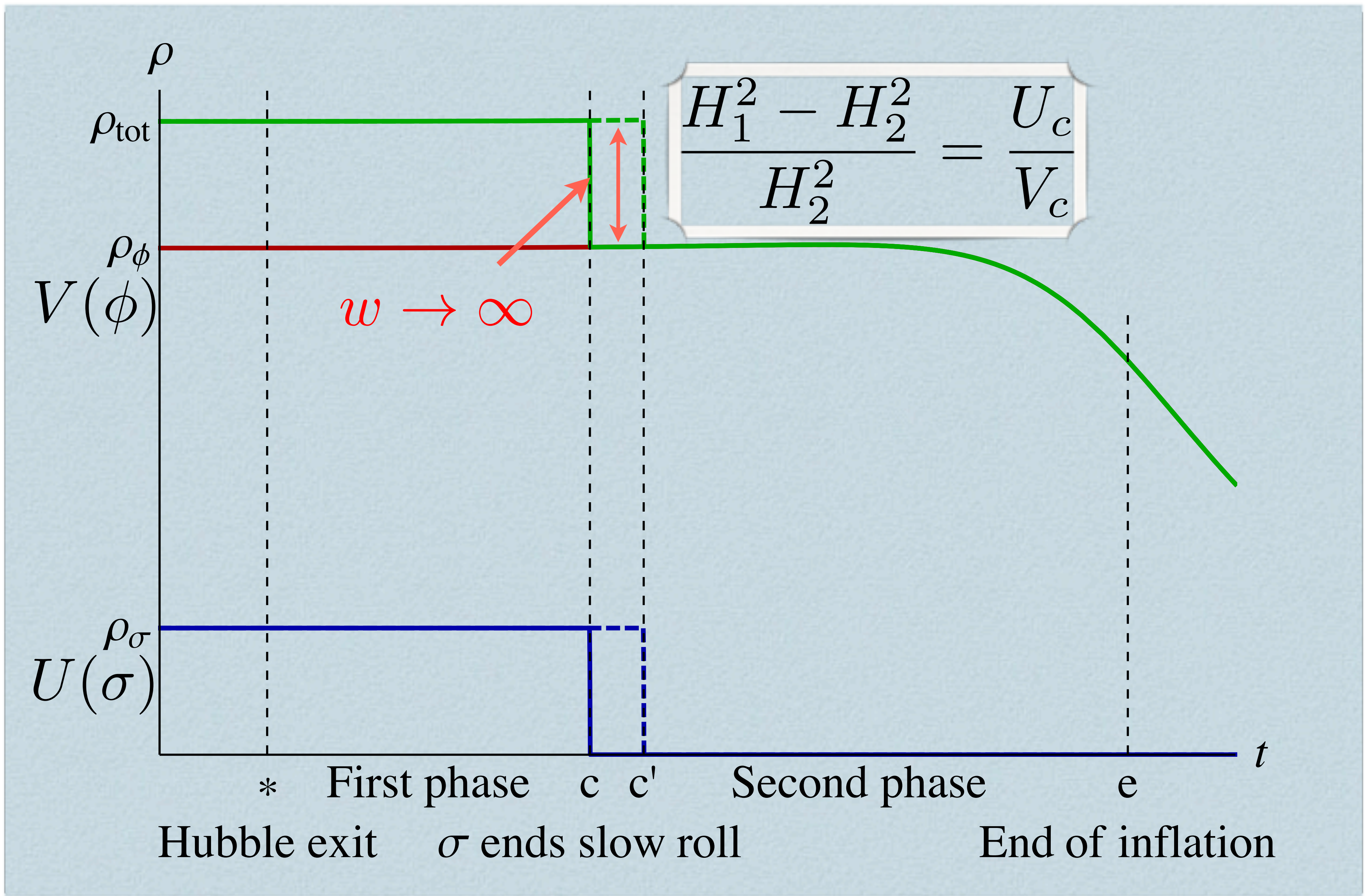

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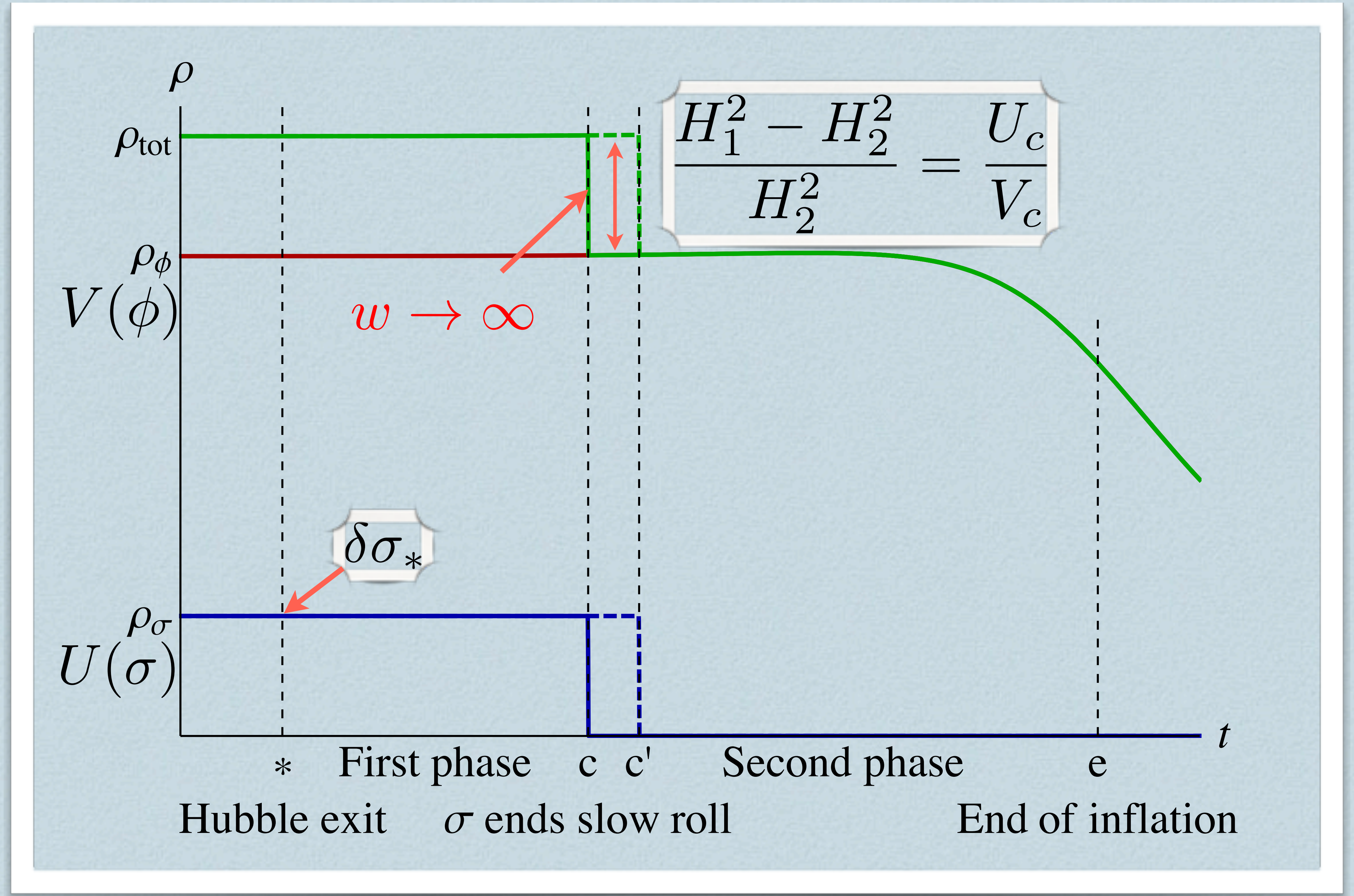
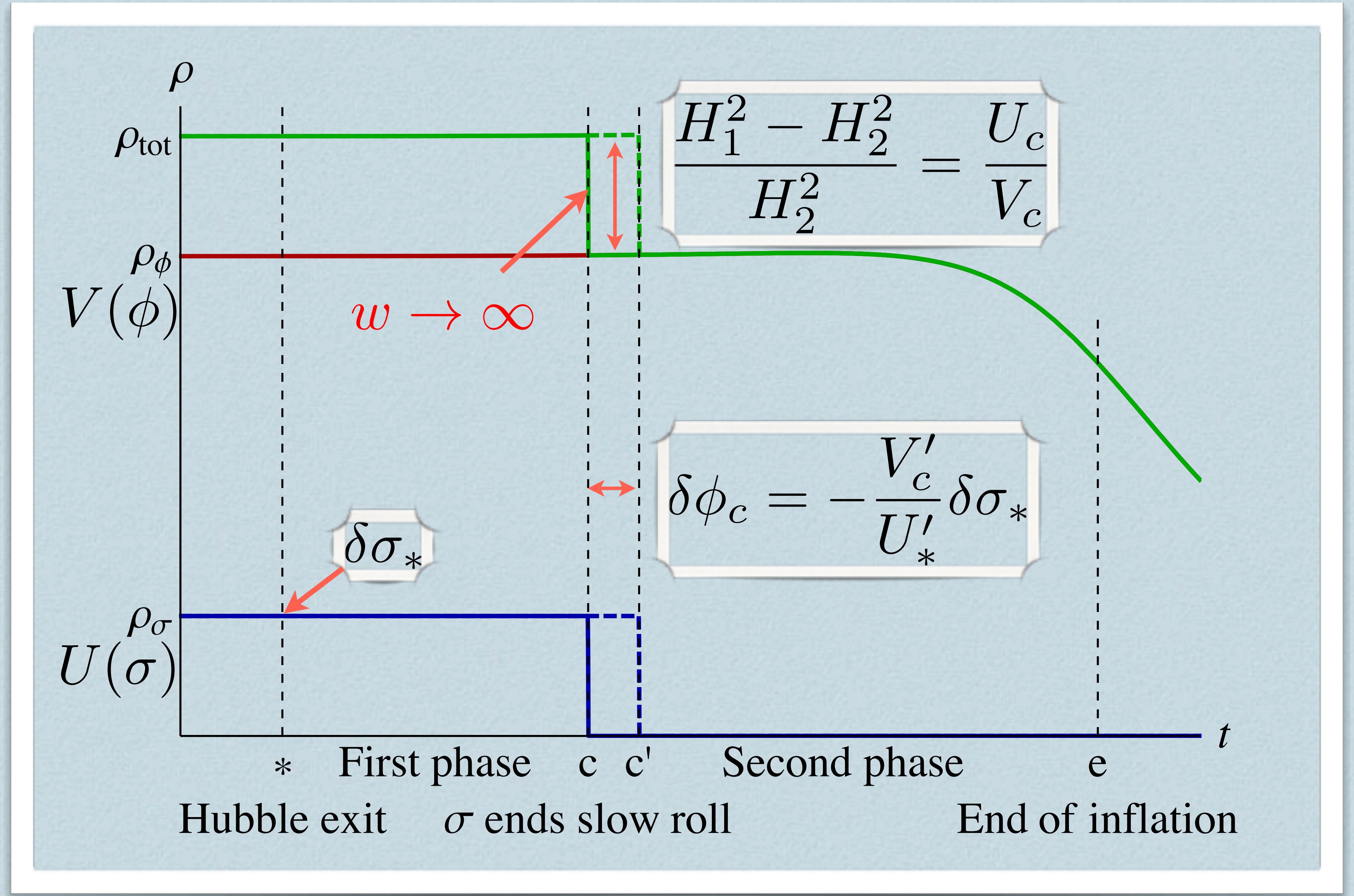


Approximated boundary



Power spectrum

$$V_{\text{tot}} = V(\phi) + U(\sigma)$$

$$\delta N = N_\sigma \delta\sigma_* \qquad N_\sigma = \frac{8\pi U_*}{M_p^2 U'_*}\Big(1 + \mathcal{O}(\epsilon) + \mathcal{O}(\eta)\Big)$$

$$\epsilon_\phi \equiv \frac{M_p^2 V'^2}{16\pi(U+V)^2} \qquad \eta_\sigma \equiv \frac{M_p^2 U''}{8\pi(U+V)}$$

Mazumdar & Wang 12, Wang & Mazumdar 13

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Mazumdar & Wang 12, Wang & Mazumdar 13

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Not suppressed by a low energy density $U_* \to 0$

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Mazumdar & Wang 12, Wang & Mazumdar 13

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Mazumdar & Wang 12, Wang & Mazumdar 13

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Not suppressed by a low energy density $U_* \to 0$

$$N_\phi = \frac{8\pi V_*}{M_p^2 V'_*}$$

Spectator produces significant perturbations when its potential is relatively flatter: $\frac{U'_*}{U_*} \lesssim \frac{V'_*}{V_*}$

Mazumdar & Wang 12, Wang & Mazumdar 13

Non-Gaussianity

$$\delta N = N_\sigma \delta\sigma_* + \frac{1}{2} N_{\sigma\sigma} \delta\sigma_*^2 \qquad N_{\sigma\sigma} \equiv \frac{\partial N_\sigma}{\partial \sigma_*}$$

Mazumdar & Wang 12, Wang & Mazumdar 13

Non-Gaussianity

$$\delta N = N_\sigma \delta\sigma_* + \frac{1}{2} N_{\sigma\sigma} \delta\sigma_*^2 \qquad N_{\sigma\sigma} \equiv \frac{\partial N_\sigma}{\partial \sigma_*}$$

$$f_{\rm NL} = \frac{5}{6}\frac{N_{\sigma\sigma}}{N_\sigma^2} = \frac{10\epsilon_{\phi c}(2\epsilon_{\phi c} - \eta_{\phi c})}{9(1+w)r} - \frac{5\eta_{\sigma *}}{6r} + \cdots$$

Mazumdar & Wang 12, Wang & Mazumdar 13

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$$r \equiv \frac{U_c}{U_c + V_c} \ll 1$$

Mazumdar & Wang 12, Wang & Mazumdar 13

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Mazumdar & Wang 12, Wang & Mazumdar 13

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$$r \equiv \frac{U_c}{U_c + V_c} \ll 1$$

Curvaton: $f_{NL} \sim \frac{1}{r}$

Mazumdar & Wang 12, Wang & Mazumdar 13

Non-Gaussianity

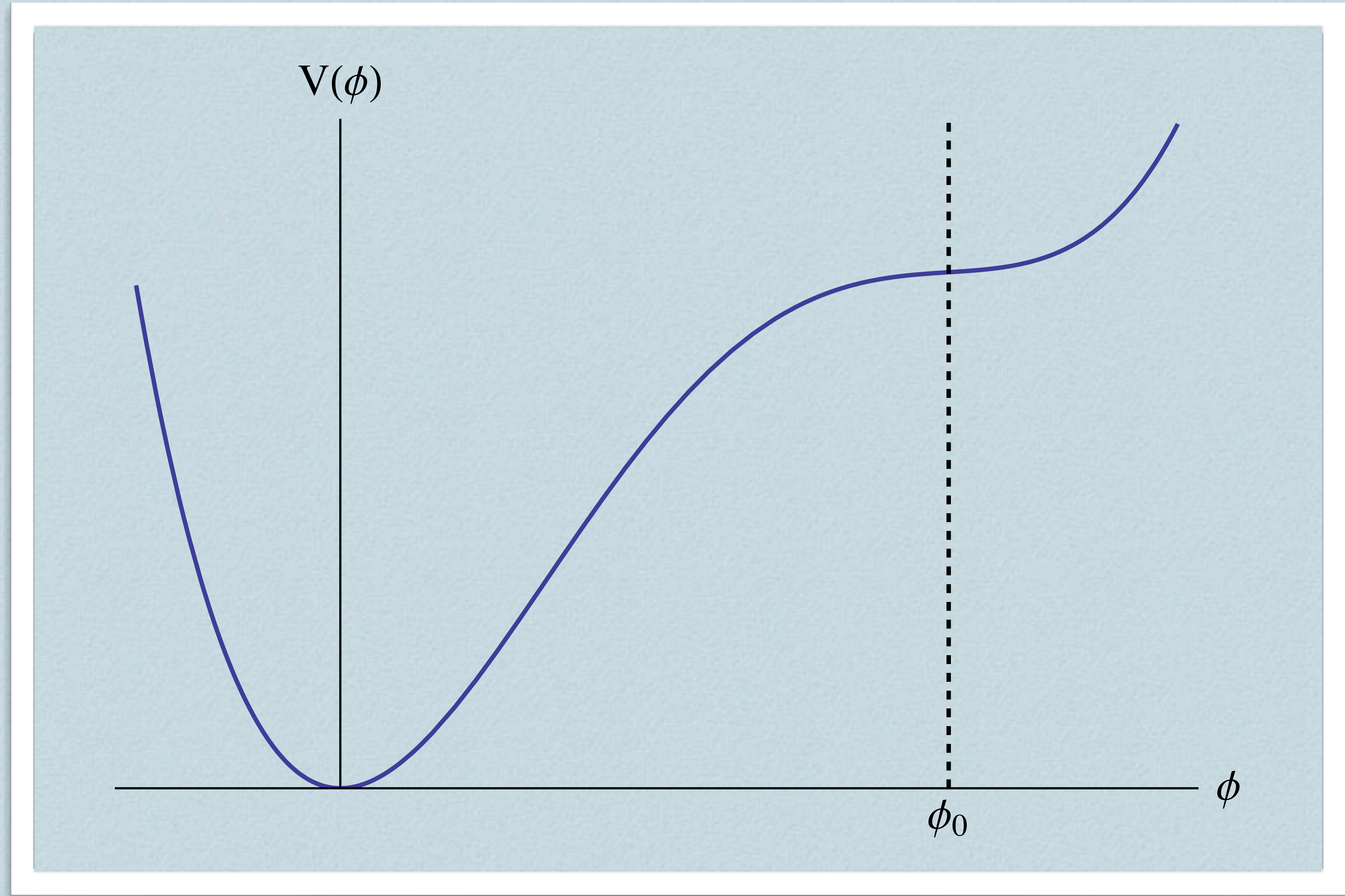
$$\delta N = N_\sigma \delta\sigma_* + \frac{1}{2} N_{\sigma\sigma} \delta\sigma_*^2 \qquad N_{\sigma\sigma} \equiv \frac{\partial N_\sigma}{\partial \sigma_*}$$

$$f_{\rm NL} = \frac{5}{6}\frac{N_{\sigma\sigma}}{N_\sigma^2} = \frac{10\epsilon_{\phi c}(2\epsilon_{\phi c} - \eta_{\phi c})}{9(1+w)r} - \frac{5\eta_{\sigma *}}{6r} + \cdots \qquad \ll 1$$

Smaller non-Gaussianity than Curvaton: $f_{NL} \sim \dfrac{1}{r}$

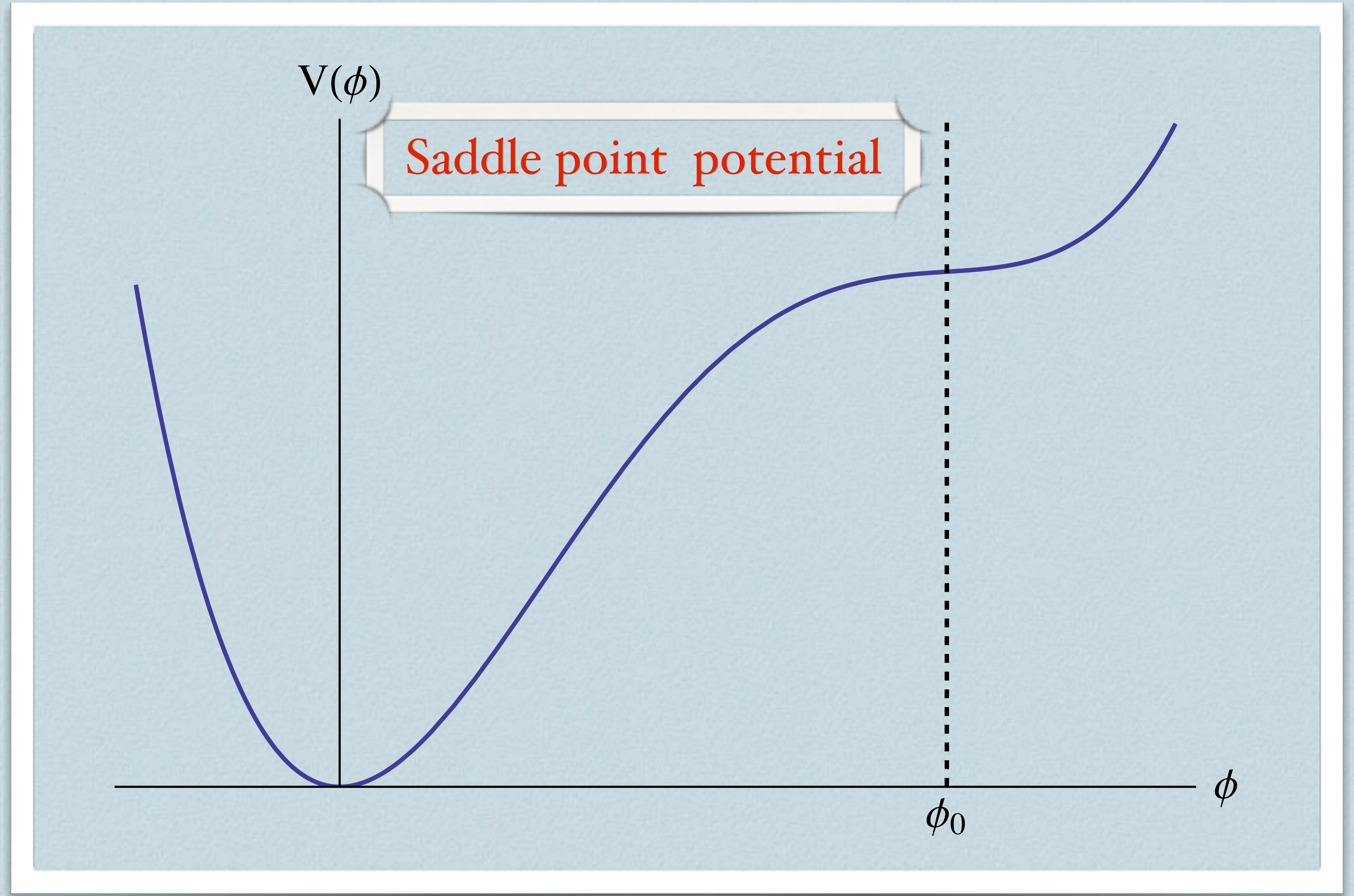
Mazumdar & Wang 12, Wang & Mazumdar 13

MSSM flat direction inflaton



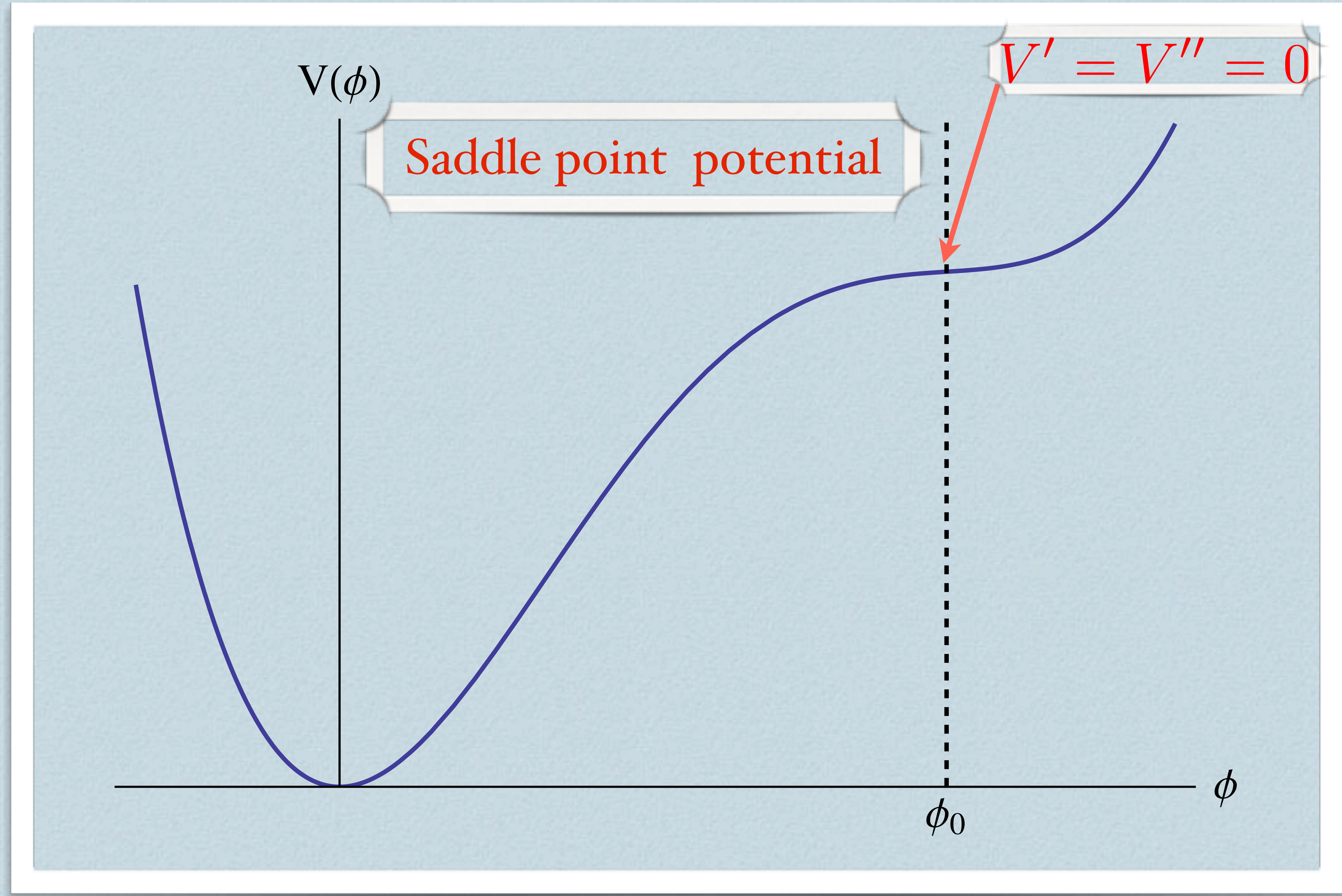
Allahverdi et al 06, Allahverdi et al 06, Wang et al 13

MSSM flat direction inflaton



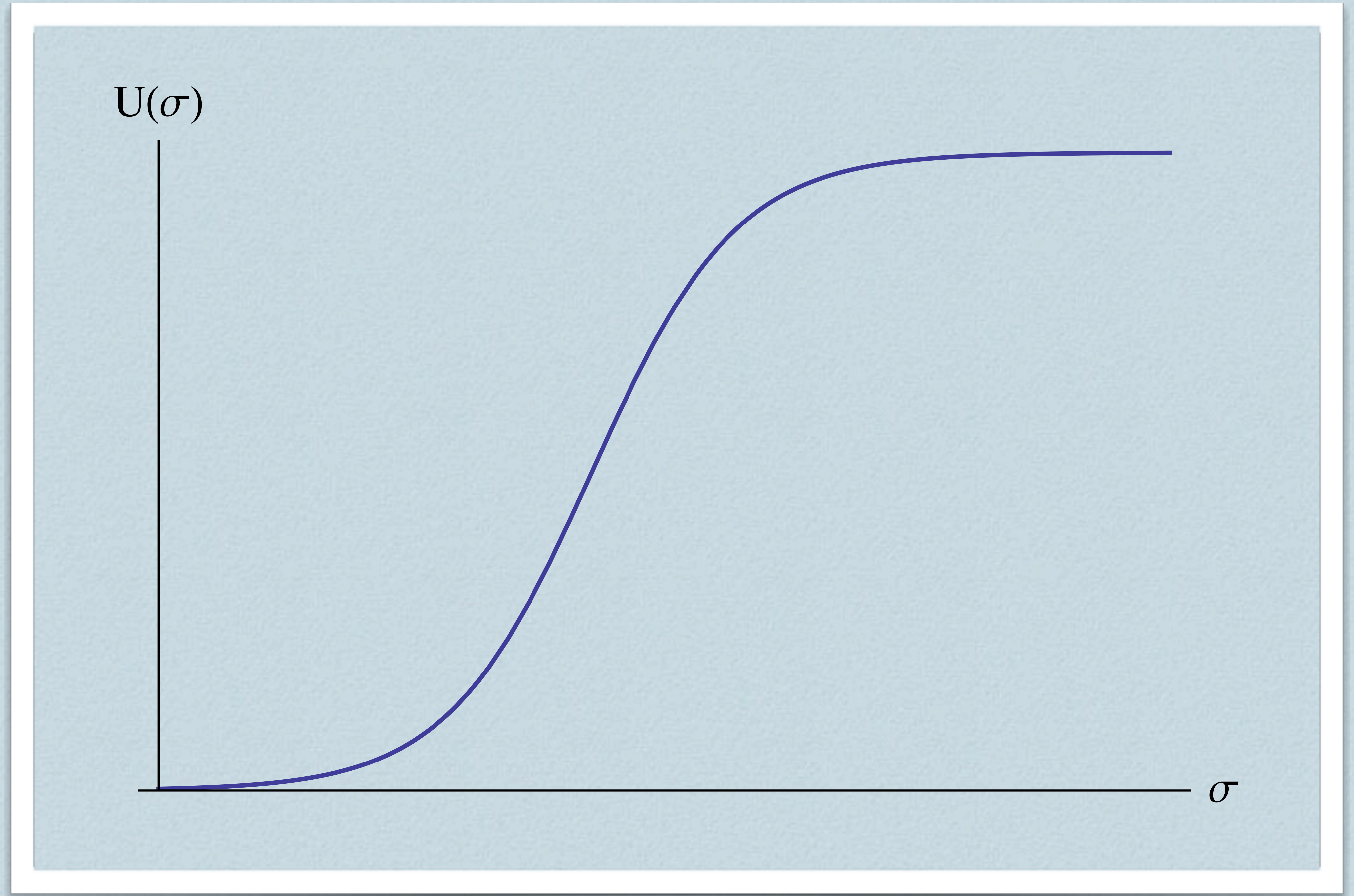
Allahverdi et al 06, Allahverdi et al 06, Wang et al 13

MSSM flat direction inflaton



Allahverdi et al 06, Allahverdi et al 06, Wang et al 13

Hyperbolic tangent spectator



Major results

$$V(\phi) = \frac{1}{2}m^2|\phi|^2 - \frac{2mh}{3\sqrt{3}}\phi^3 + \frac{h^2}{12}|\phi|^4$$

$$U(\sigma) = \frac{U_0}{2}\left(1 + \tanh\frac{\sigma}{\sigma_0}\right)$$

Wang et al 13

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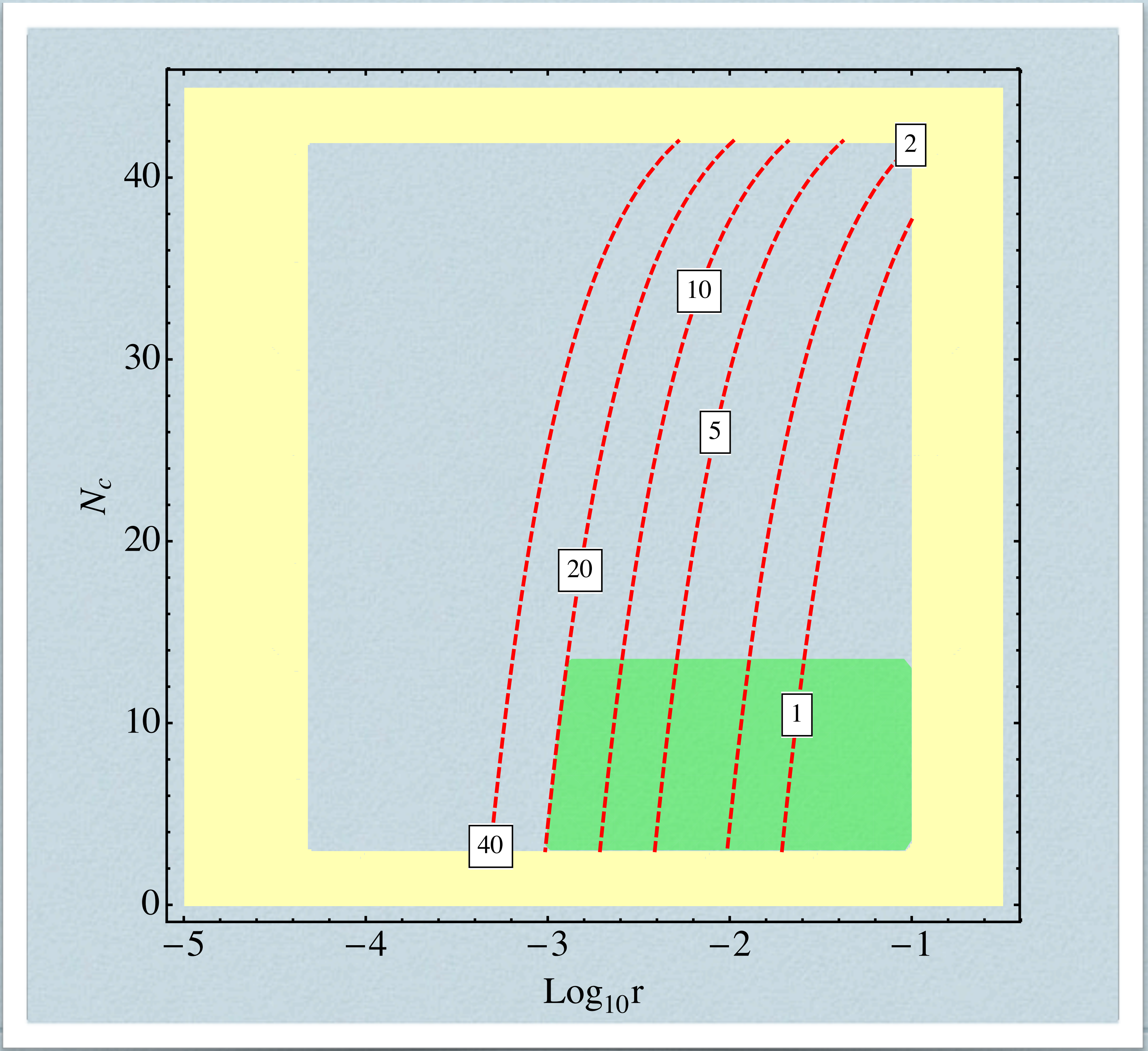
$$n_s - 1 = -\frac{2}{N_* - N_c + 1}$$

$$f_{NL} = \frac{5}{6(N_* - N_c + 1)r}$$

Wang et al 13

Parameter space



Wang et al 13

Is spectator too rare/unnatural?

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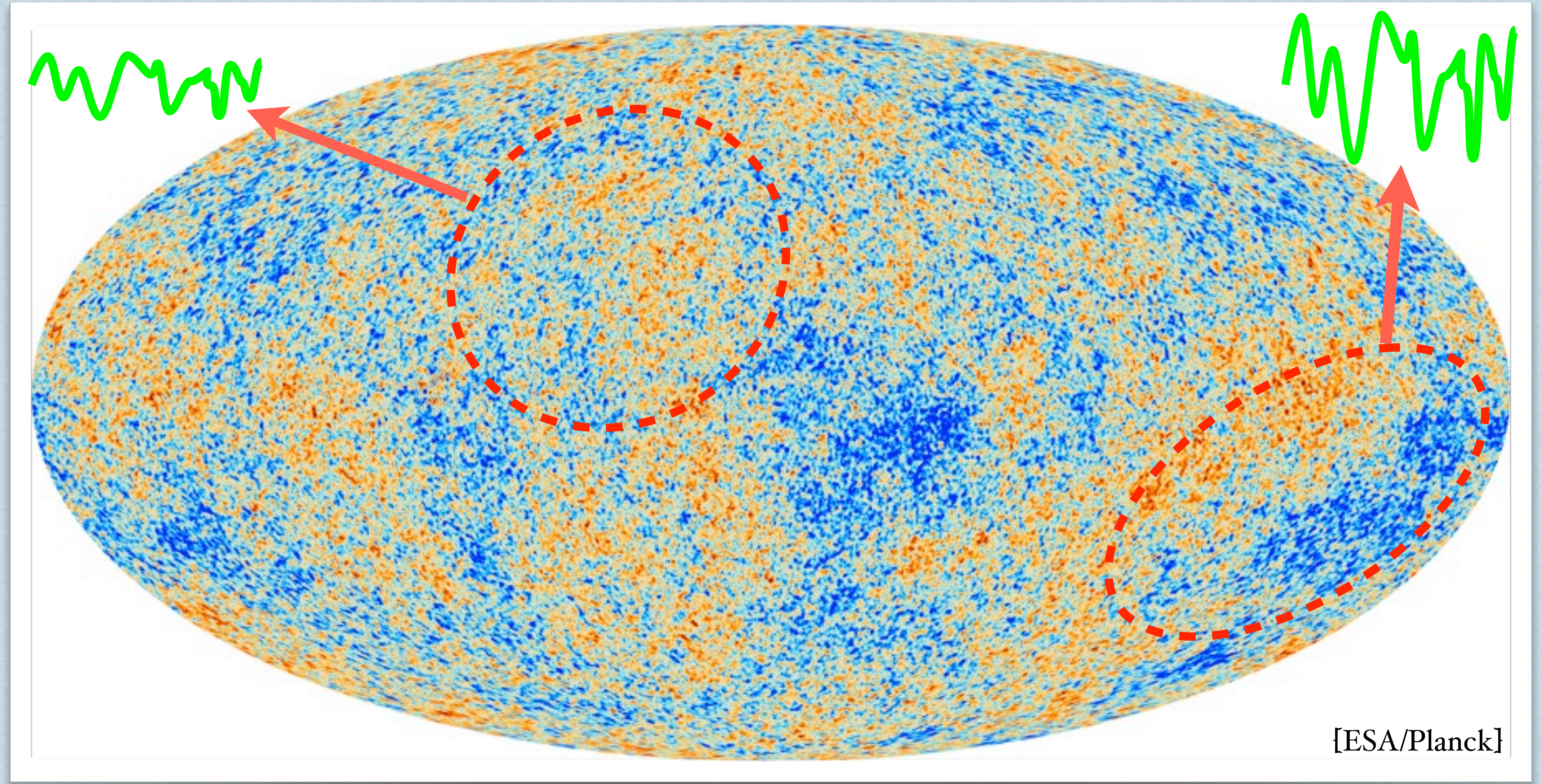
CMB dipole asymmetry



CMB dipole asymmetry

- Phenomenological model: $\Delta T(\hat{\mathbf{n}}) = (1 + A\,\hat{\mathbf{p}}\cdot\hat{\mathbf{n}})\Delta T_{\rm iso}(\hat{\mathbf{n}})$
- Planck result: $A = 0.07 \pm 0.02$

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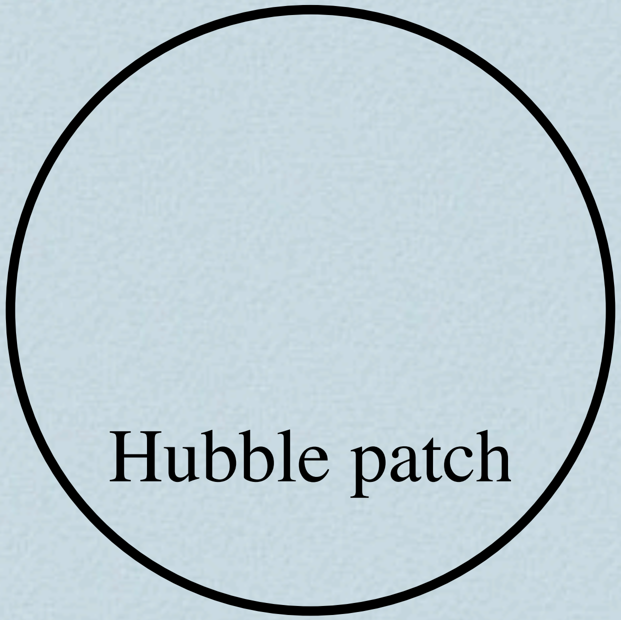

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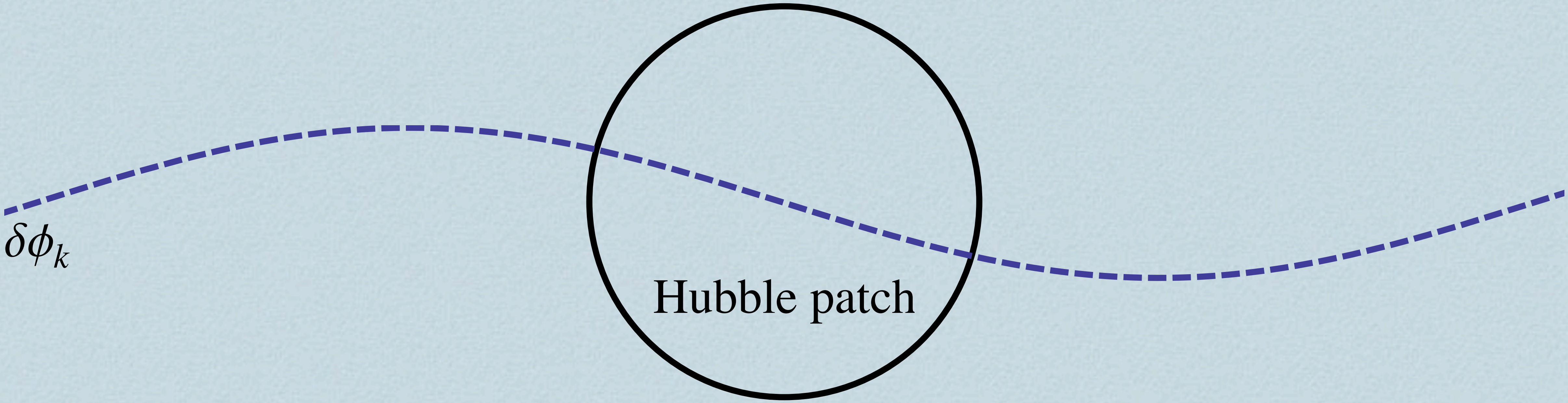

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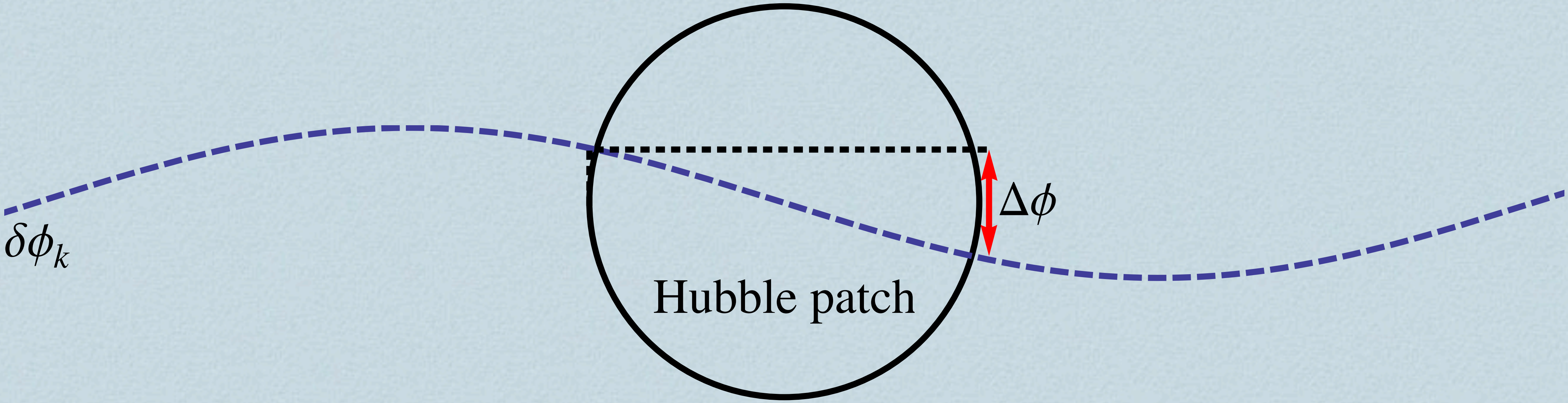

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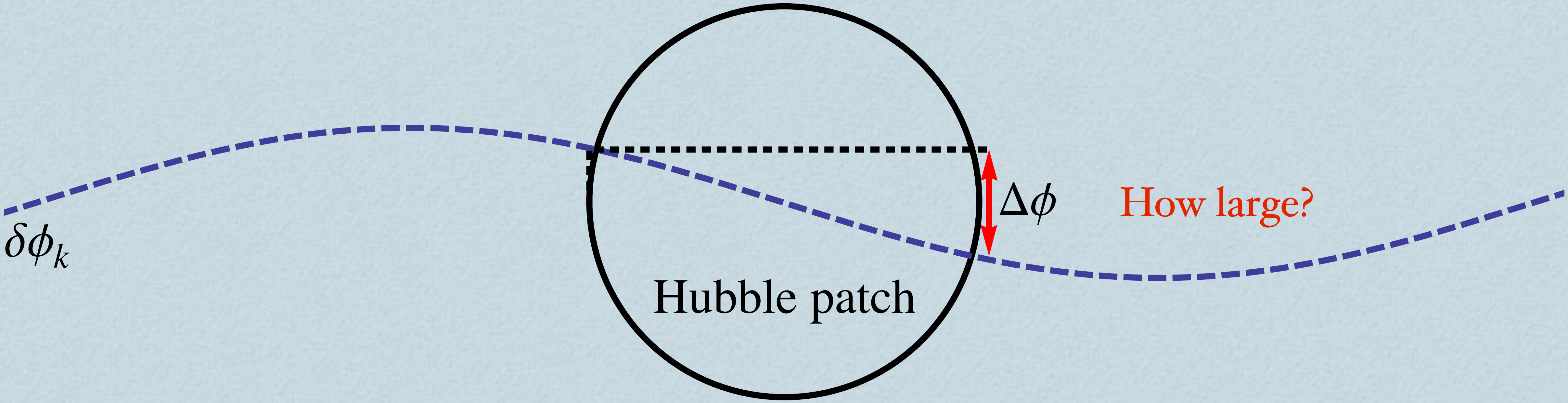

Eriksen et al 03, Eriksen et al 07, [1303.5083]

Non-Gaussianity dependence

- Dependence on primordial local non-Gaussianity
  - Single perturbation source:

Lyth 13, Wang & Mazumdar 13

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$$A = \frac{3}{5}\frac{|\Delta\sigma|}{\sqrt{P_{\delta\sigma_*}}}\,|f_{\rm NL}|\,\sqrt{P_\zeta}$$

Lyth 13, Wang & Mazumdar 13

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σ generates curvature perturbations
and gains very large scale perturbations

Lyth 13, Wang & Mazumdar 13

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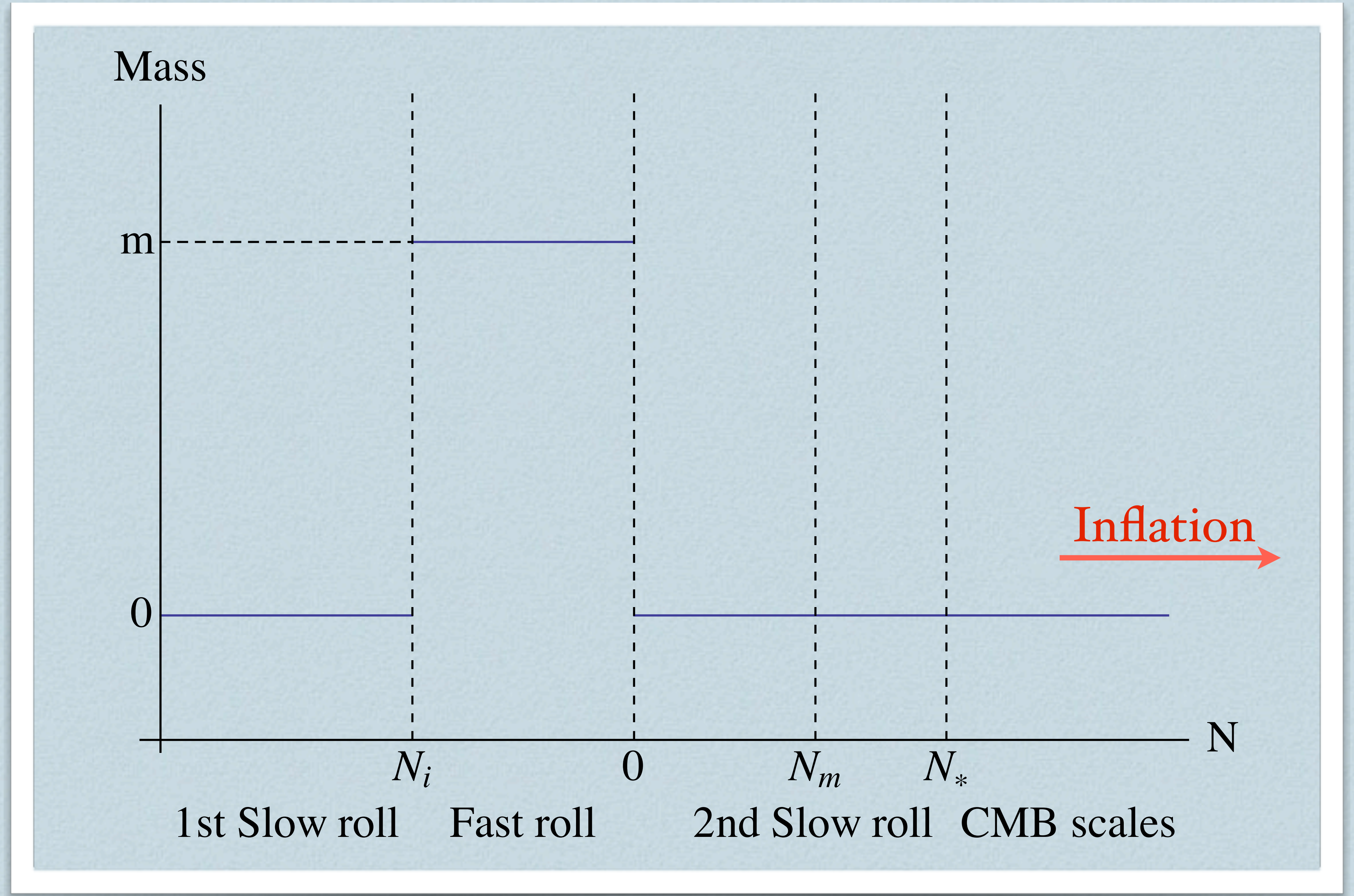
- Scale invariant spectrum $\frac{|\Delta\sigma|}{\sqrt{P_{\delta\sigma_*}}} \lesssim 2$ must be violated

Lyth 13, Wang & Mazumdar 13

Tachyonic fast roll enhancement



(Fast roll for the field, not inflation)

Mazumdar & Wang 13

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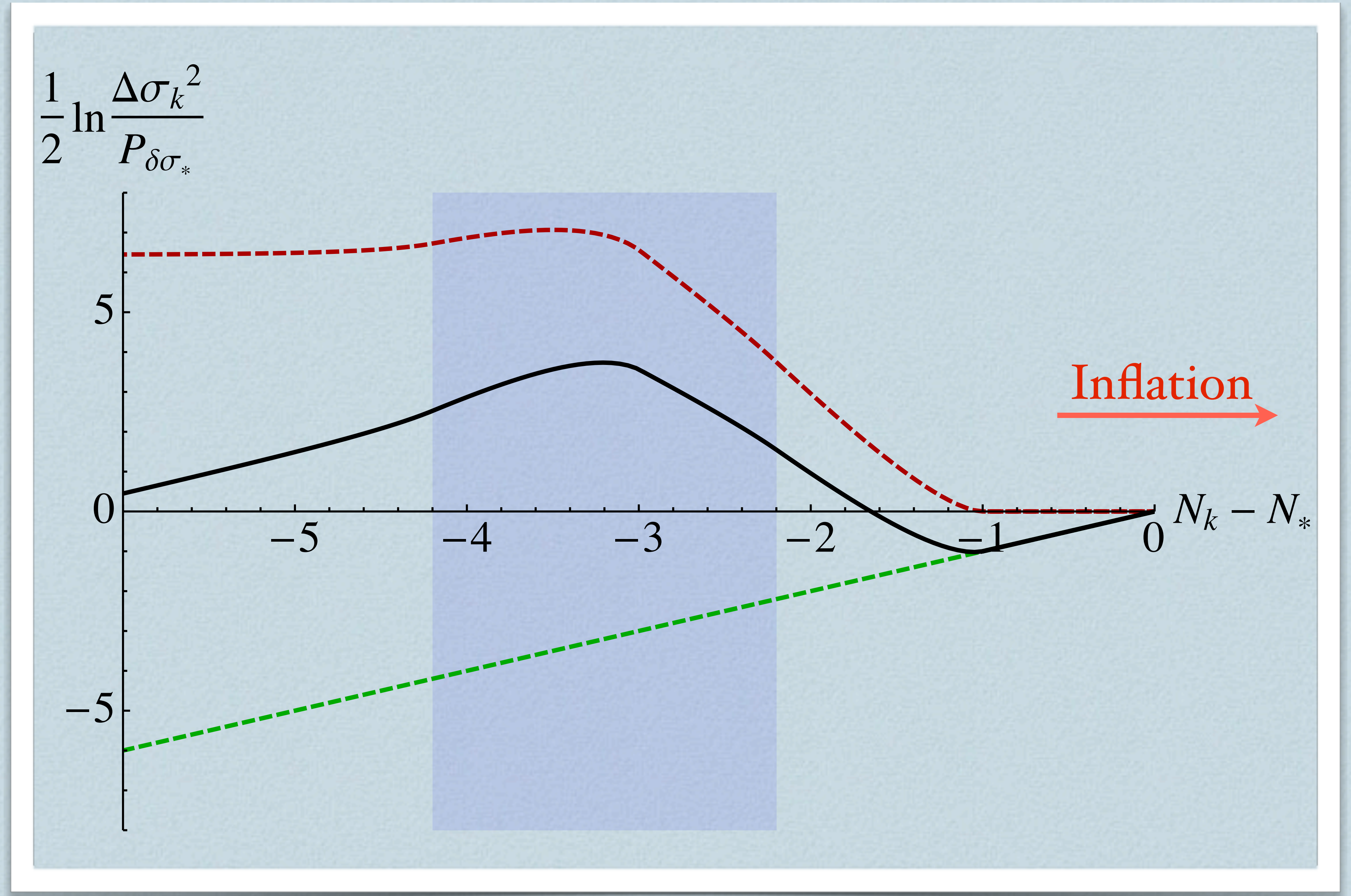

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Mazumdar & Wang 13

Tachyonic fast roll enhancement

$$m^2 = (e^{2N_m} - 1)2H^2 \qquad N_m = 1.4$$

Mazumdar & Wang 13

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Mazumdar & Wang 13

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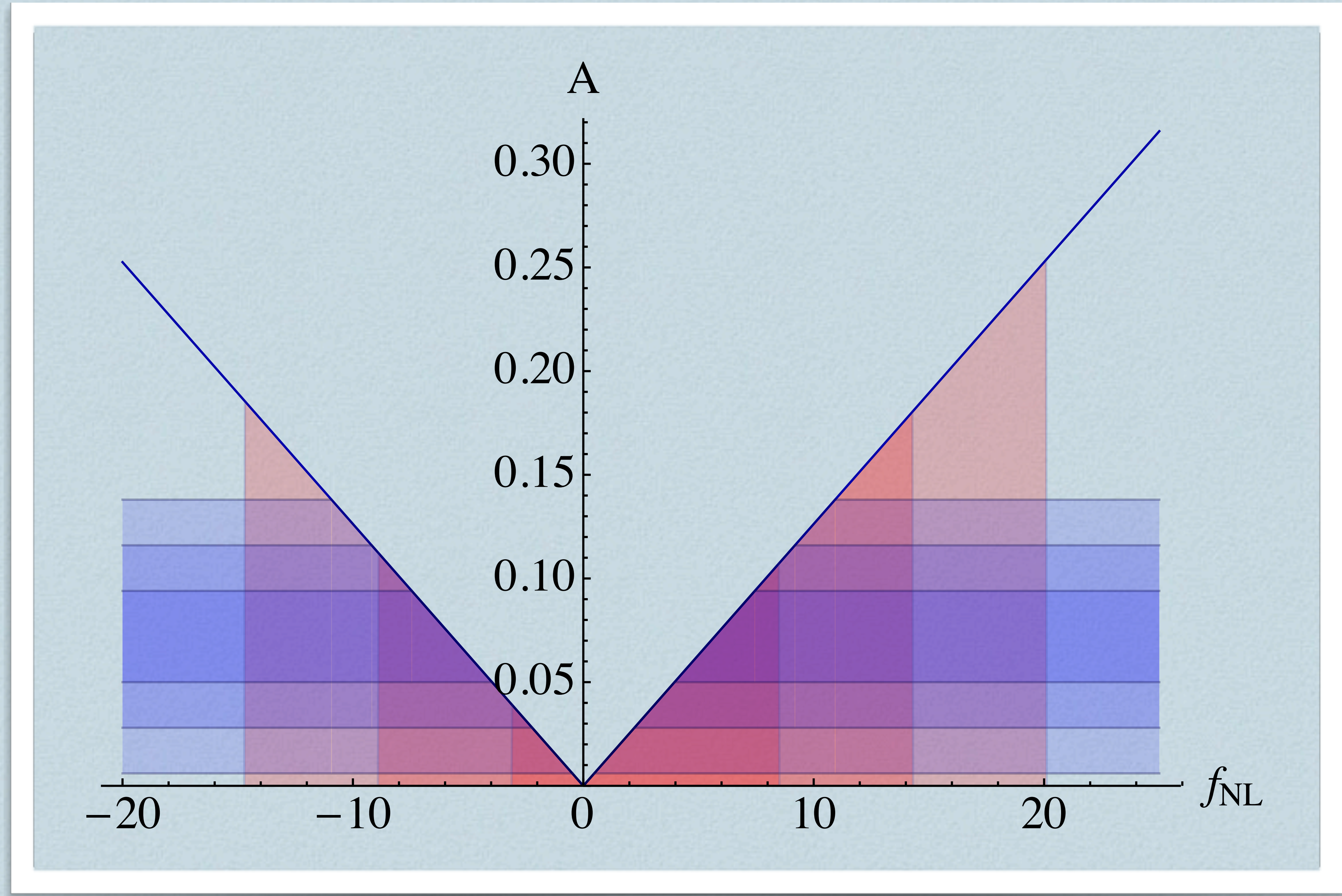
- ✓ No dipole asymmetry from small scales
- ✓ No excessive quadrupoles and octupoles

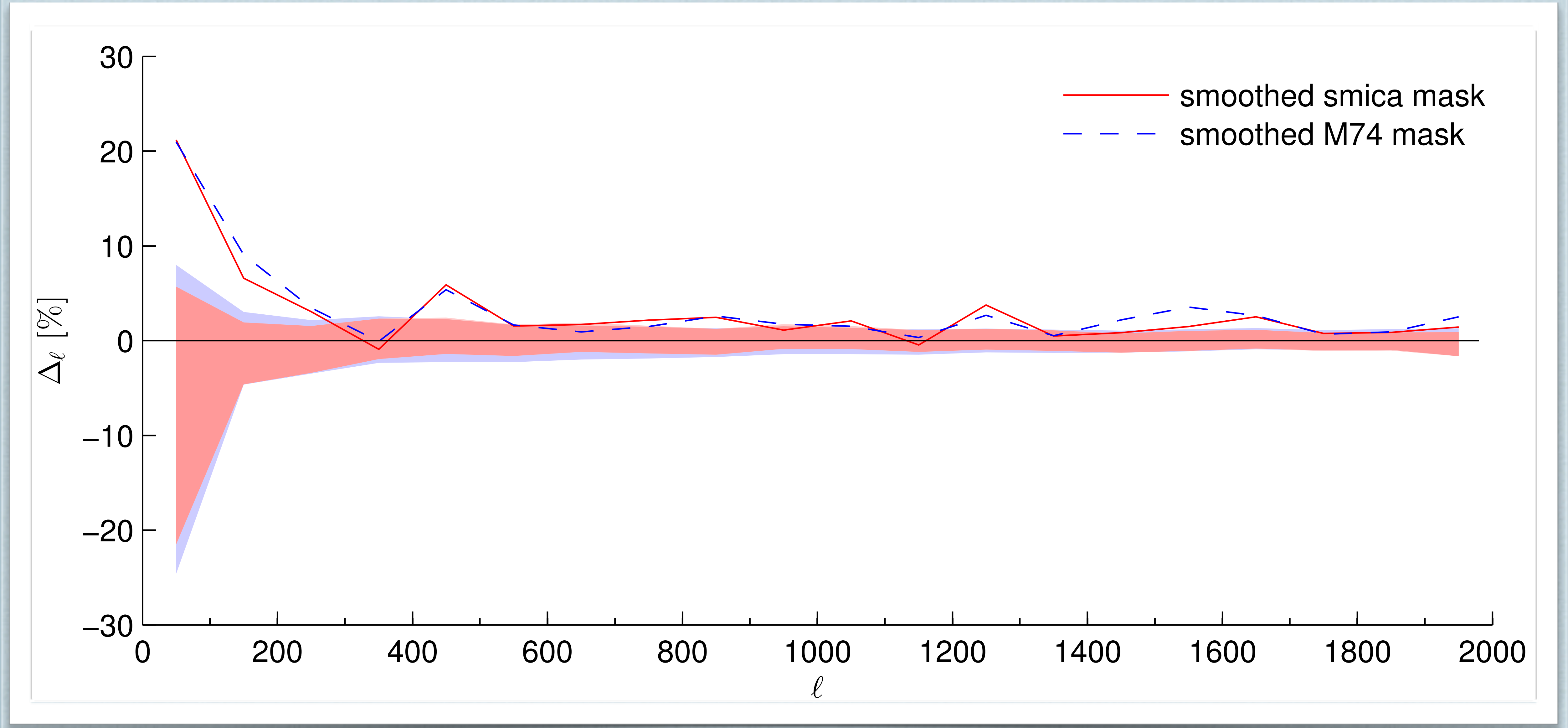
Mazumdar & Wang 13

Parameter space for fast roll



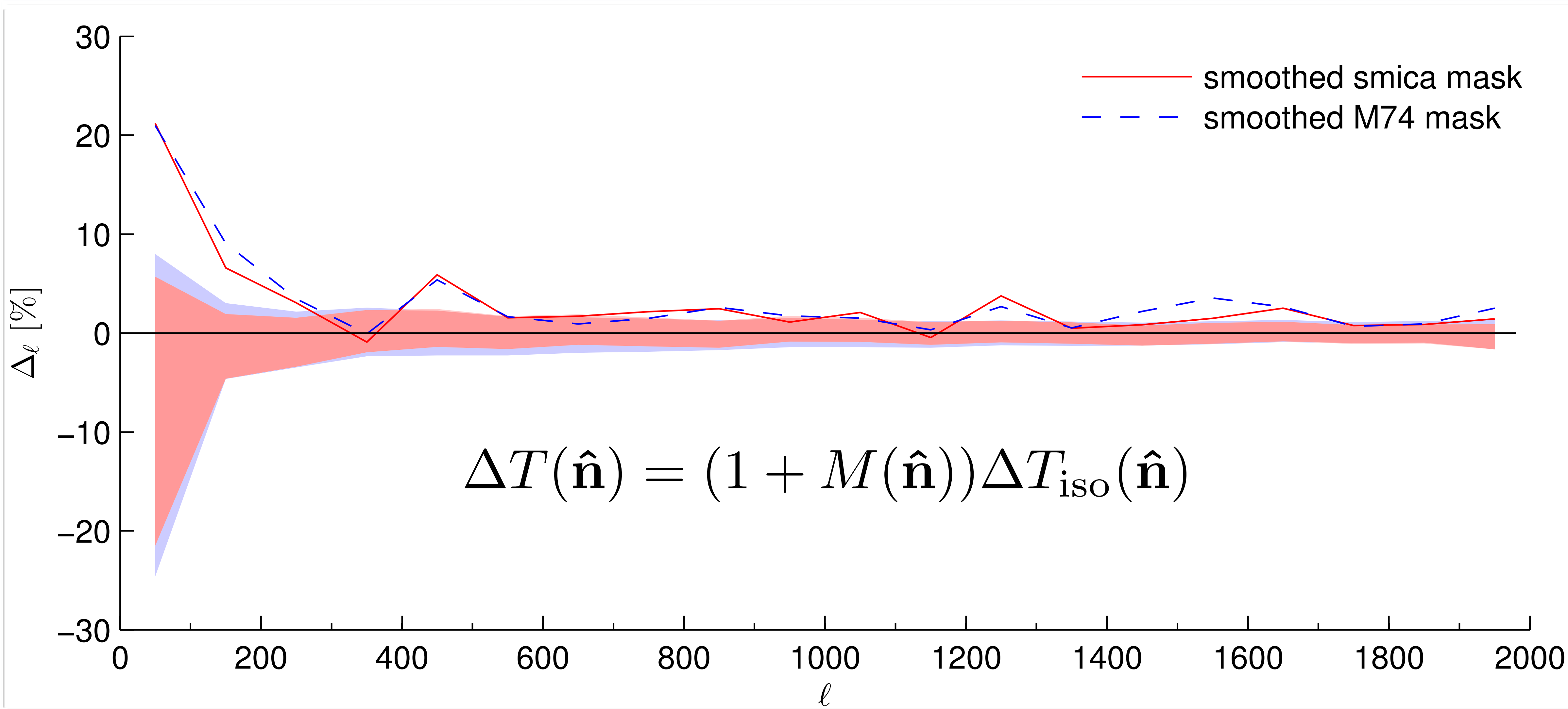
Mazumdar & Wang 13

Scale dependence



Flender & Hotchkiss 13

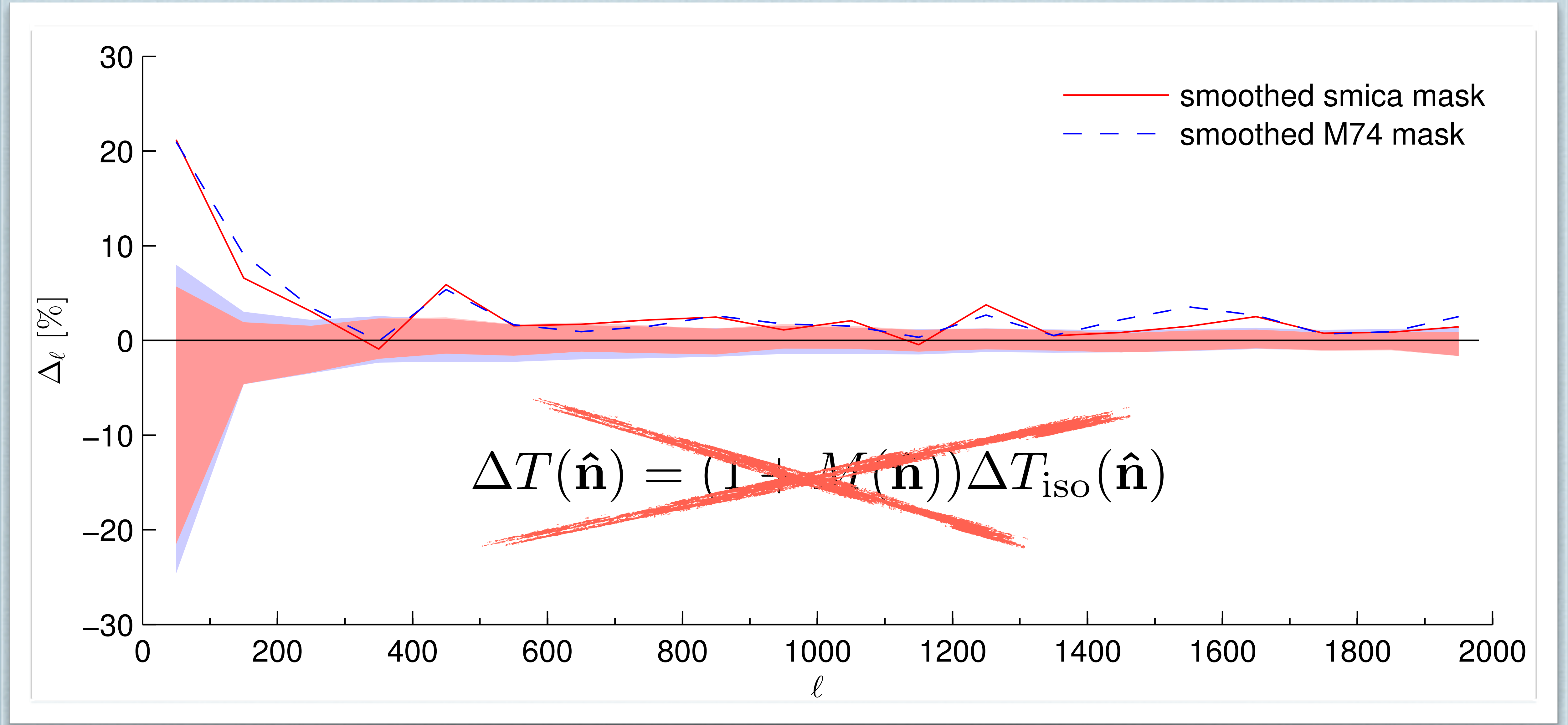
Scale dependence



$$\Delta T(\hat{\mathbf{n}}) = (1 + M(\hat{\mathbf{n}}))\Delta T_{\rm iso}(\hat{\mathbf{n}})$$

Flender & Hotchkiss 13

Scale dependence



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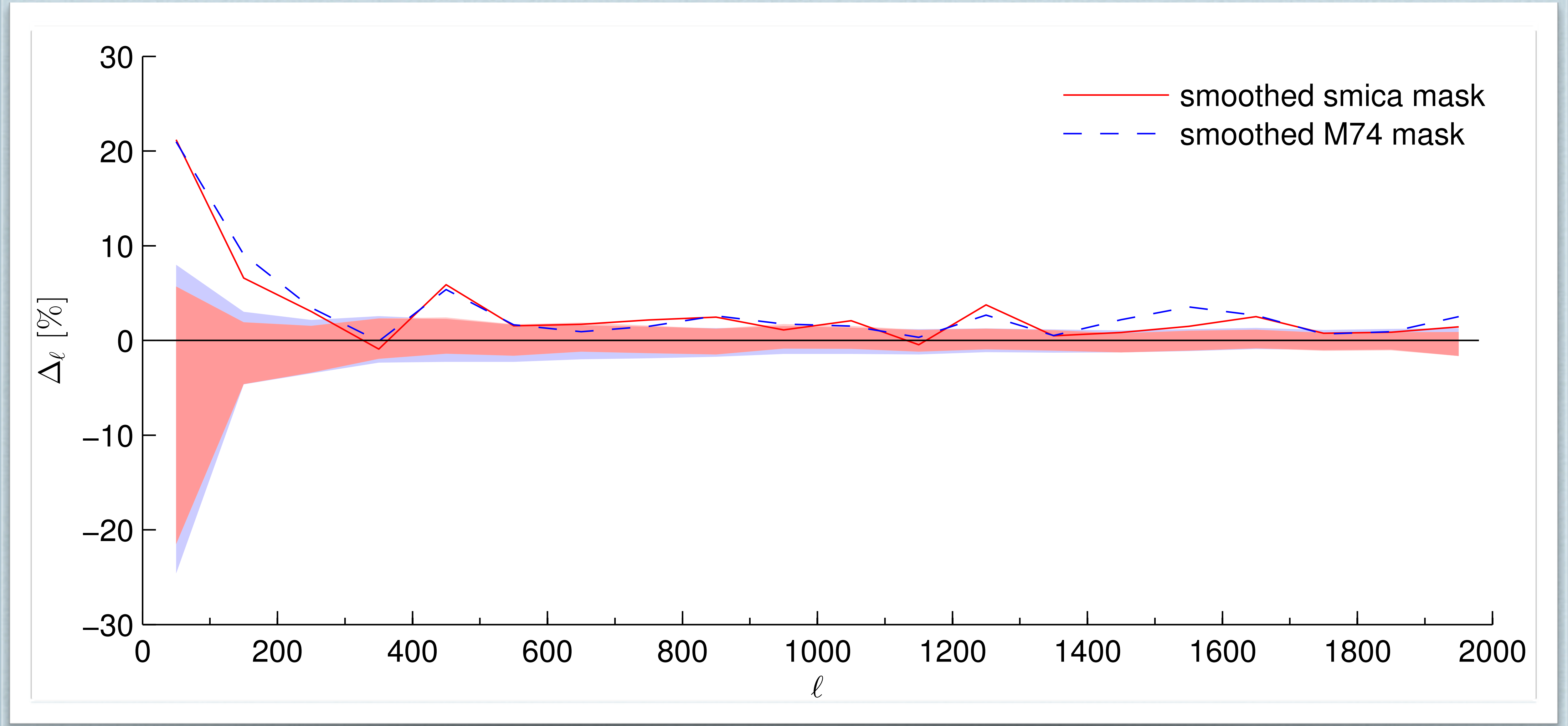

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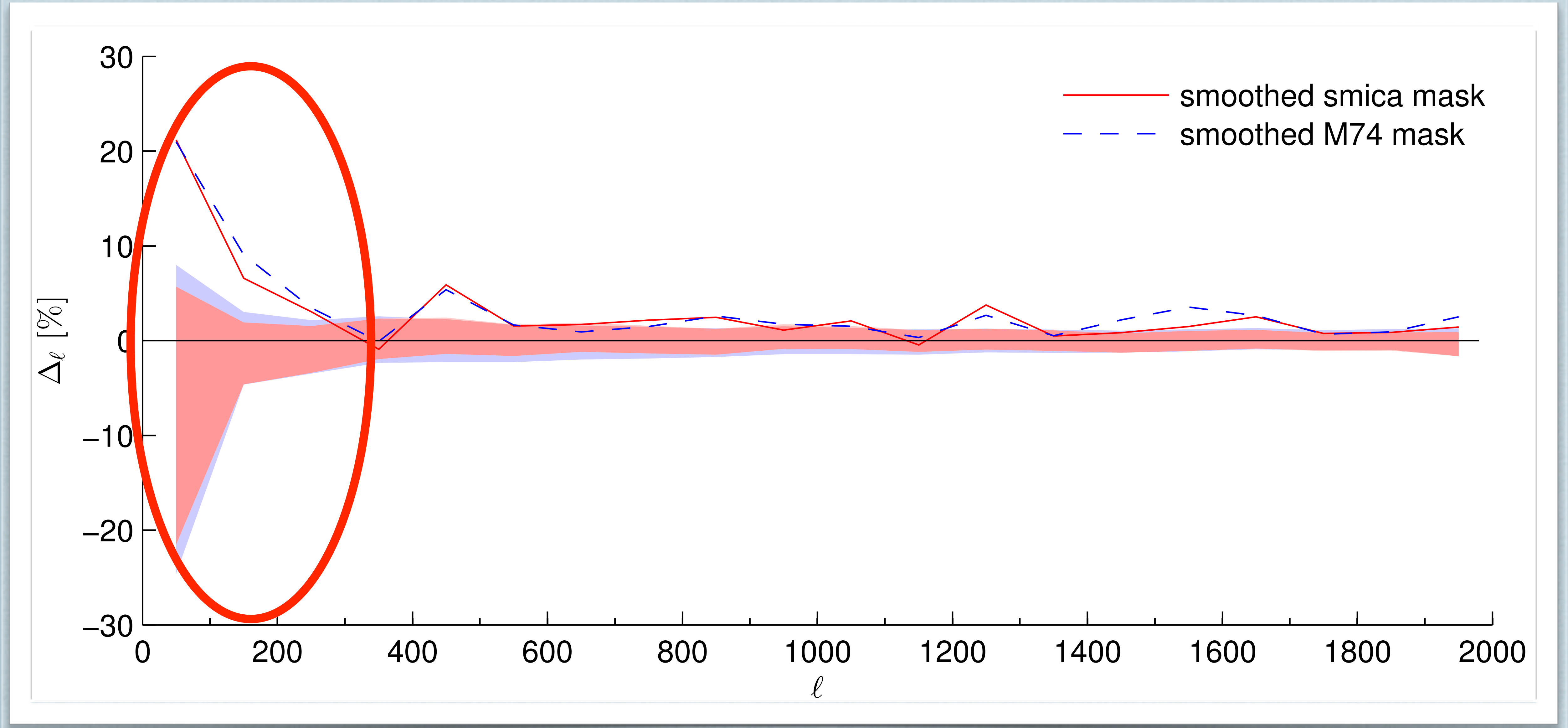
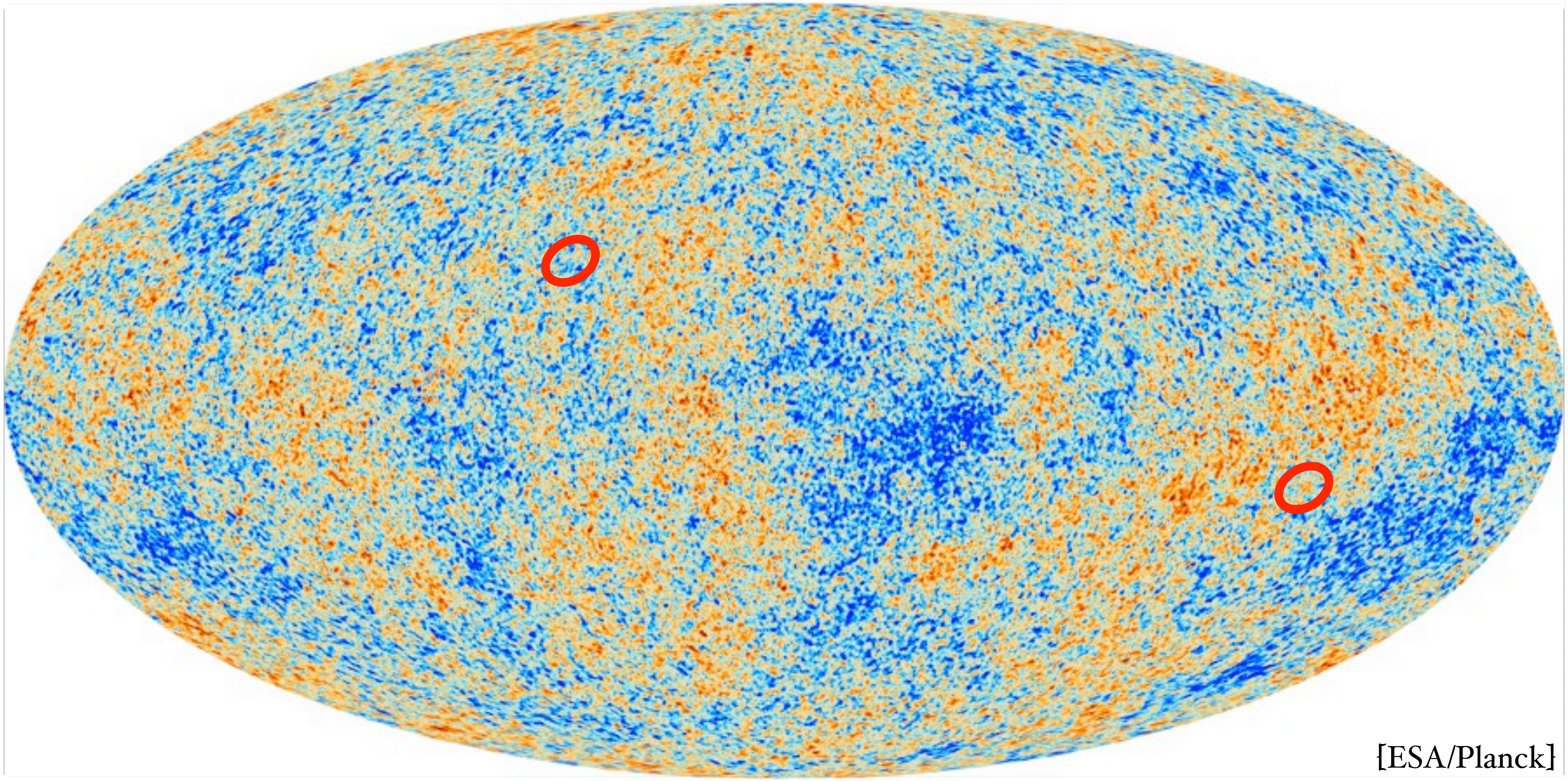


Flender & Hotchkiss 13

How significant?


[ESA/Planck]

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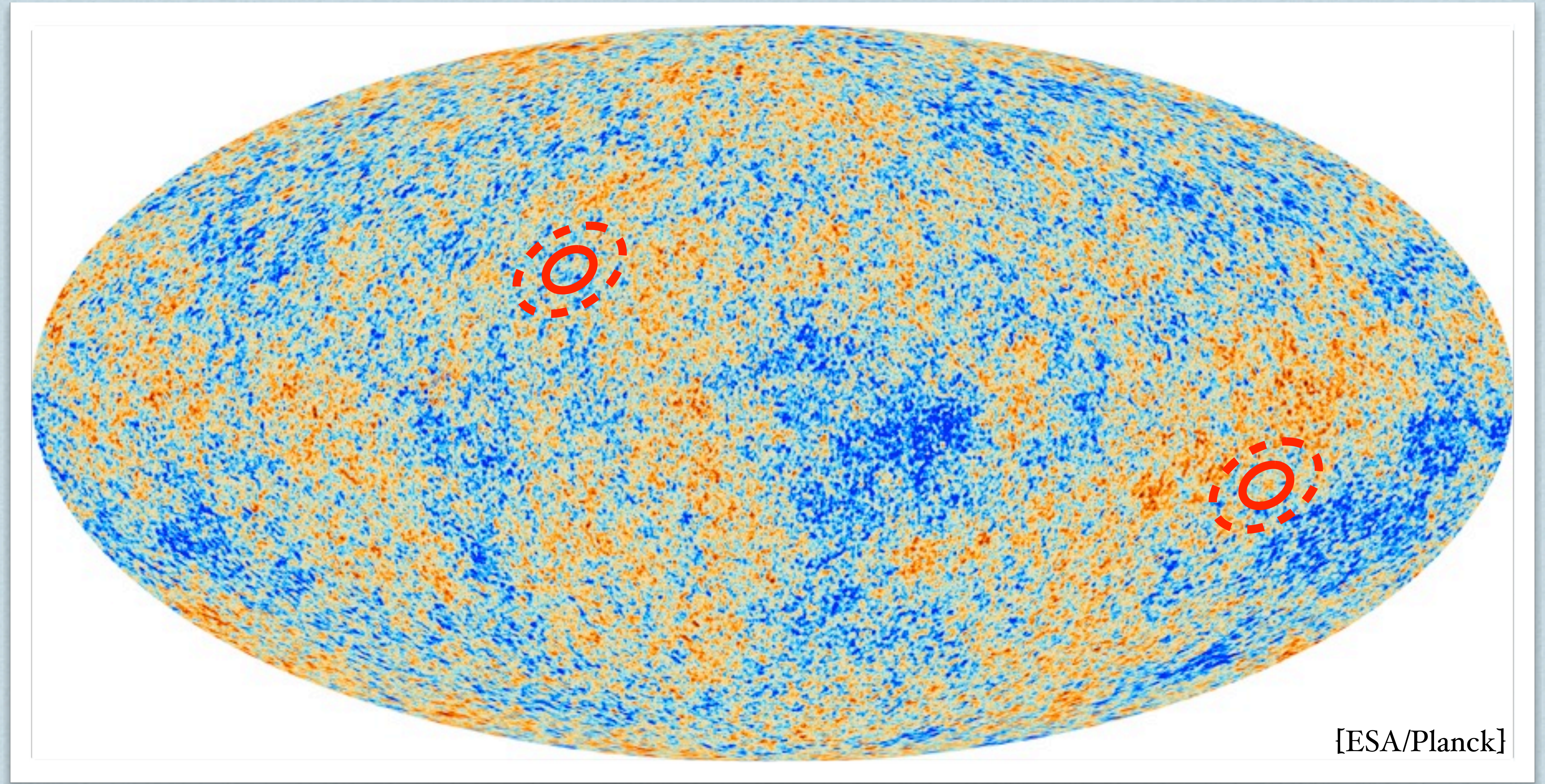
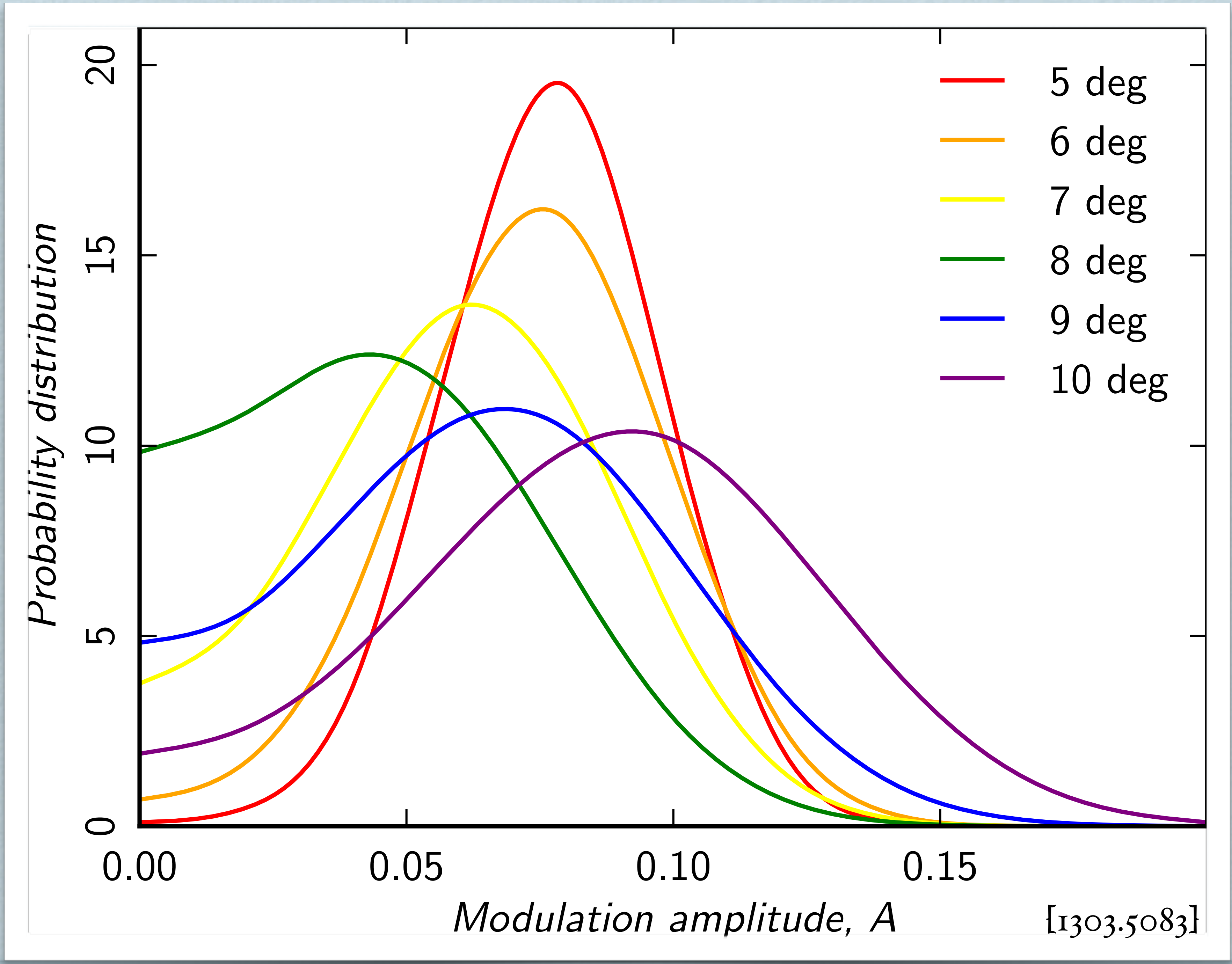


Not so significant?



Over estimate

$$\Delta T(\hat{\mathbf{n}}) = (1 + A\,\hat{\mathbf{p}} \cdot \hat{\mathbf{n}})\Delta T_{\mathrm{iso}}(\hat{\mathbf{n}})$$

In progress

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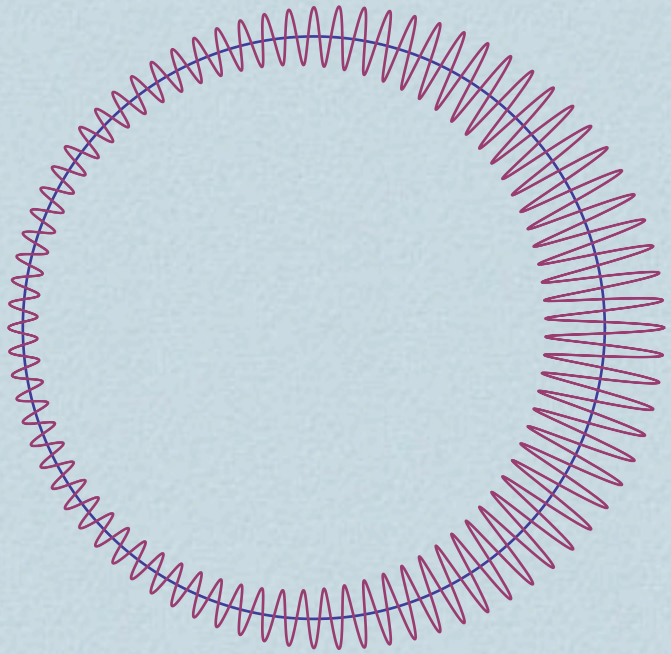

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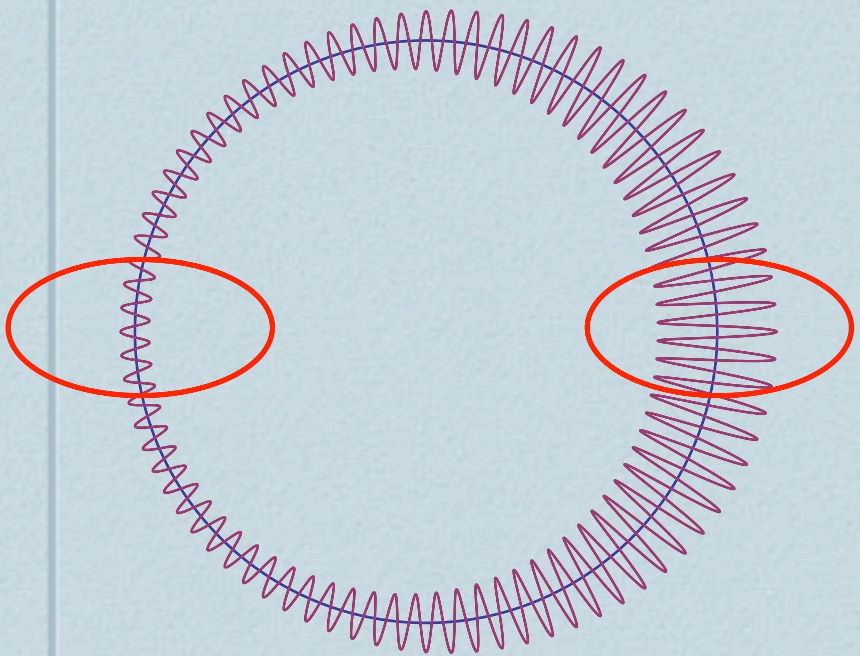

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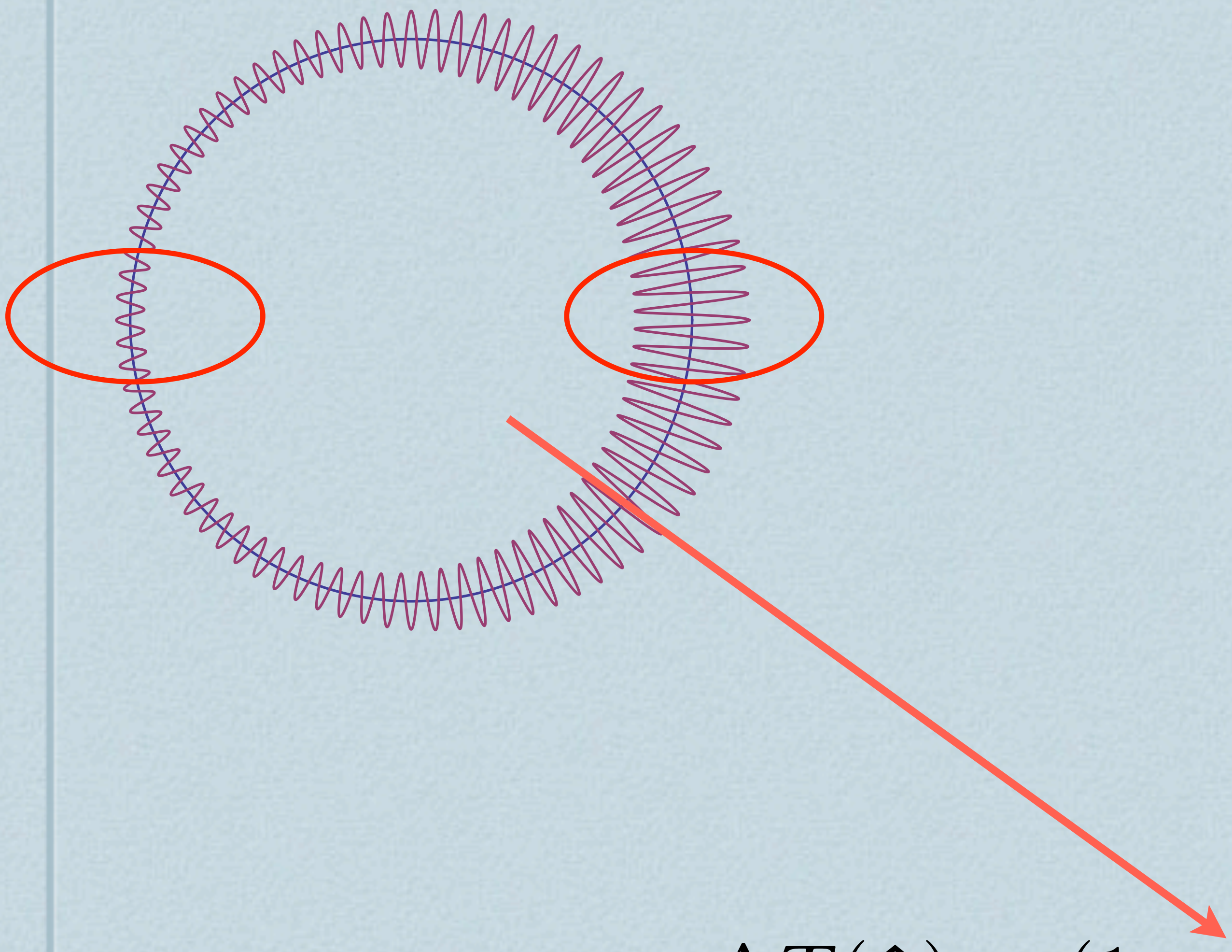

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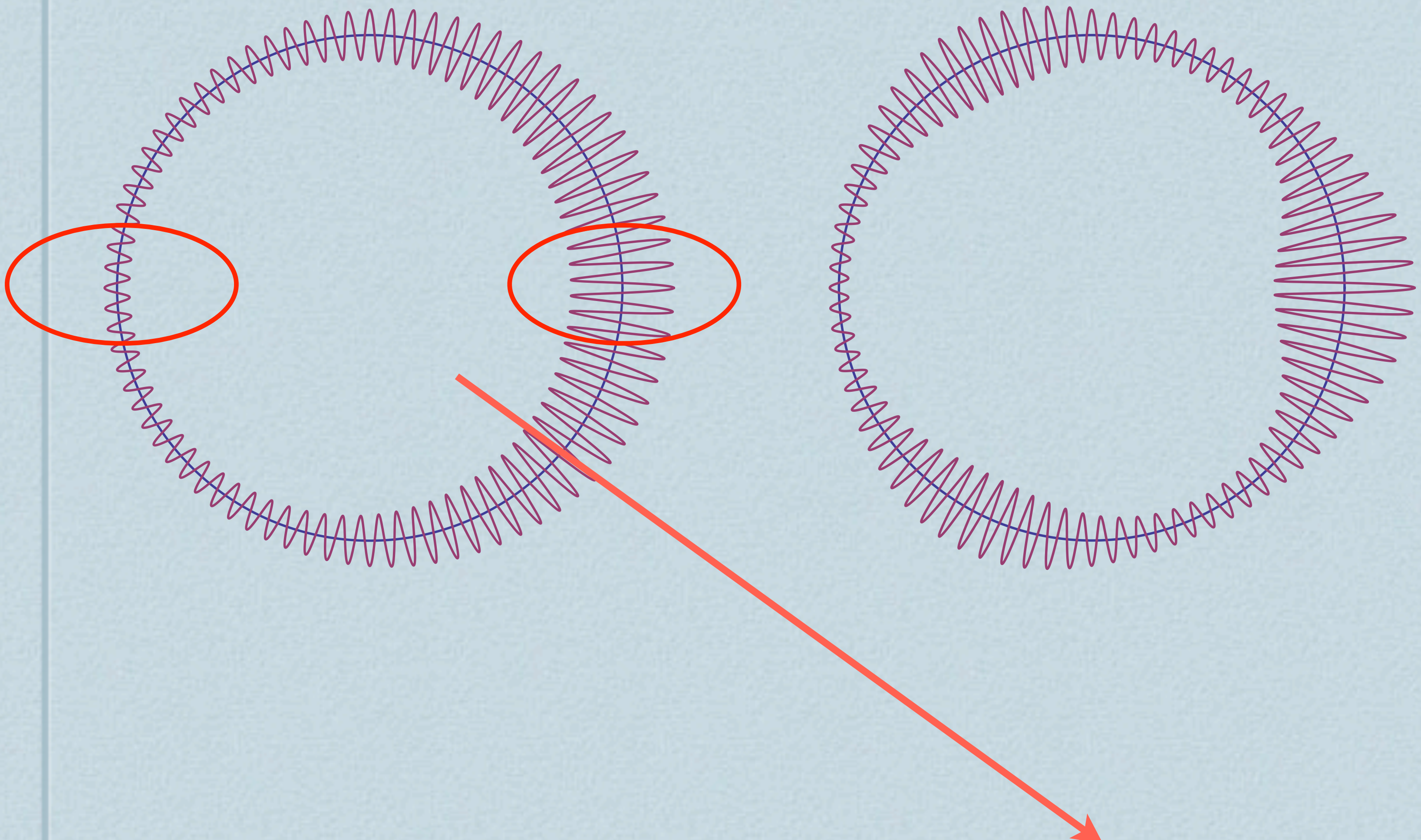

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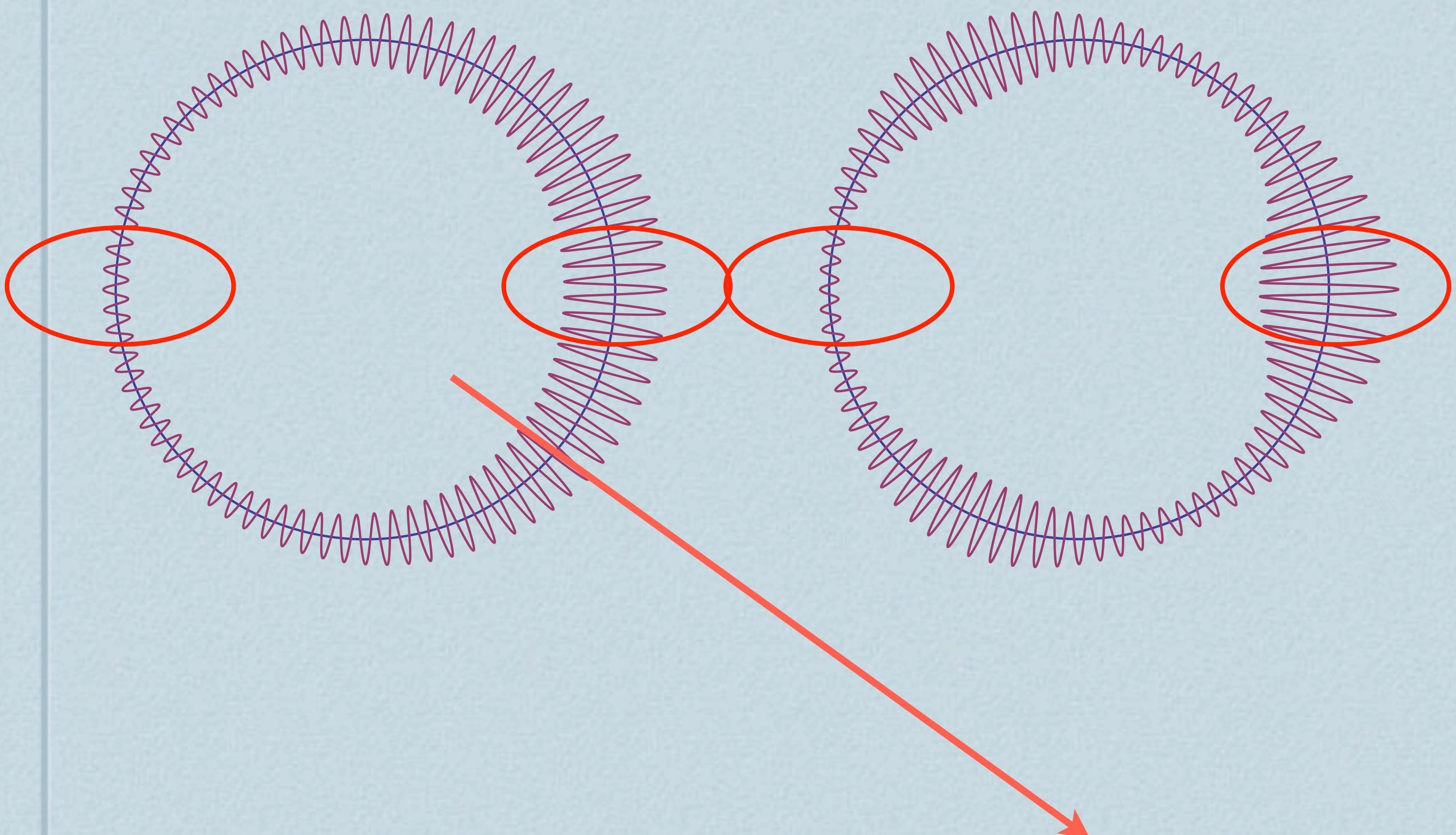

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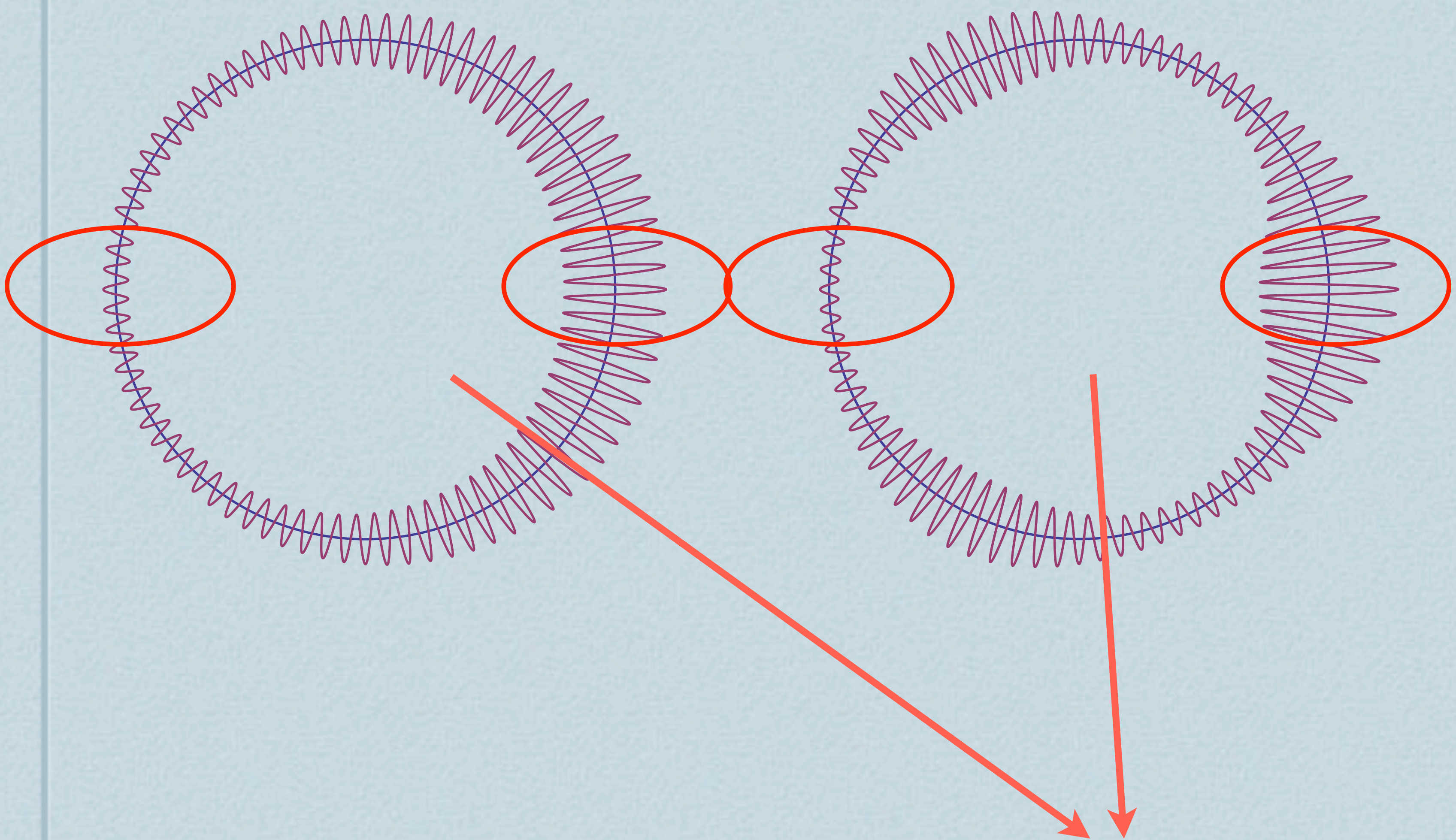

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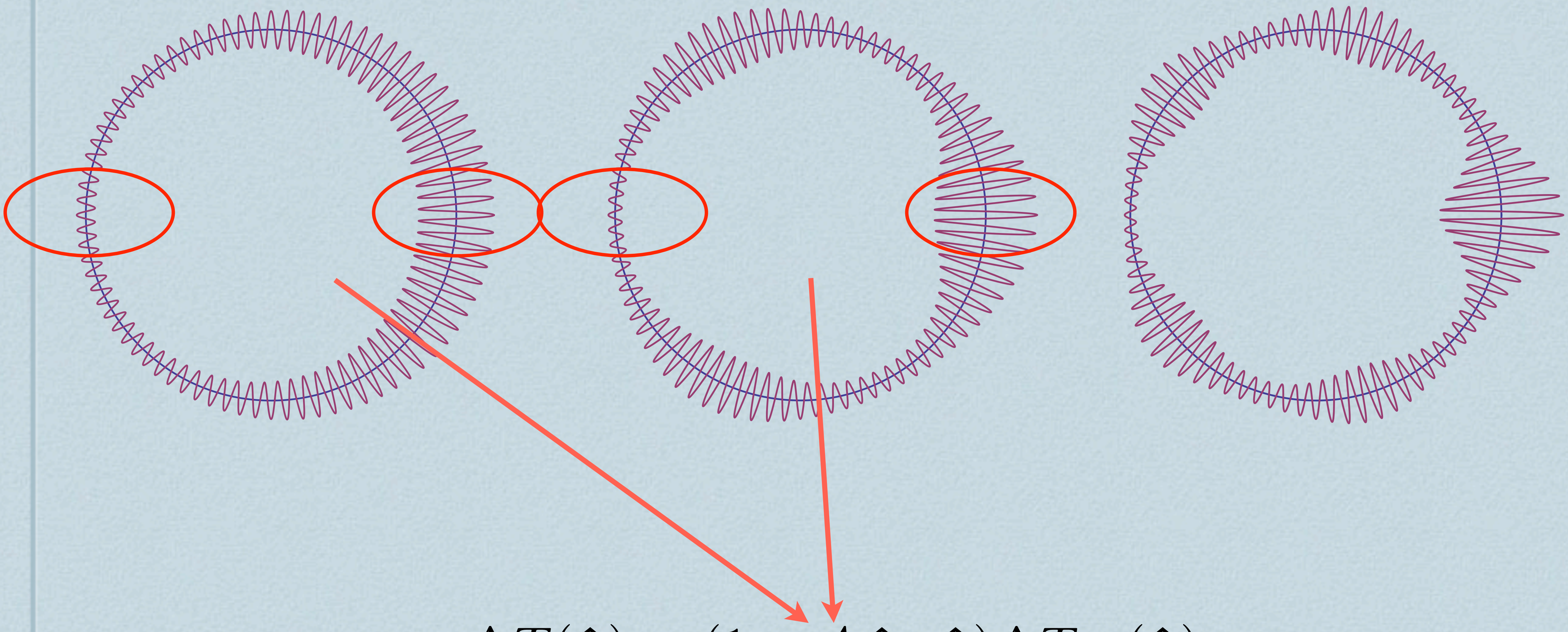

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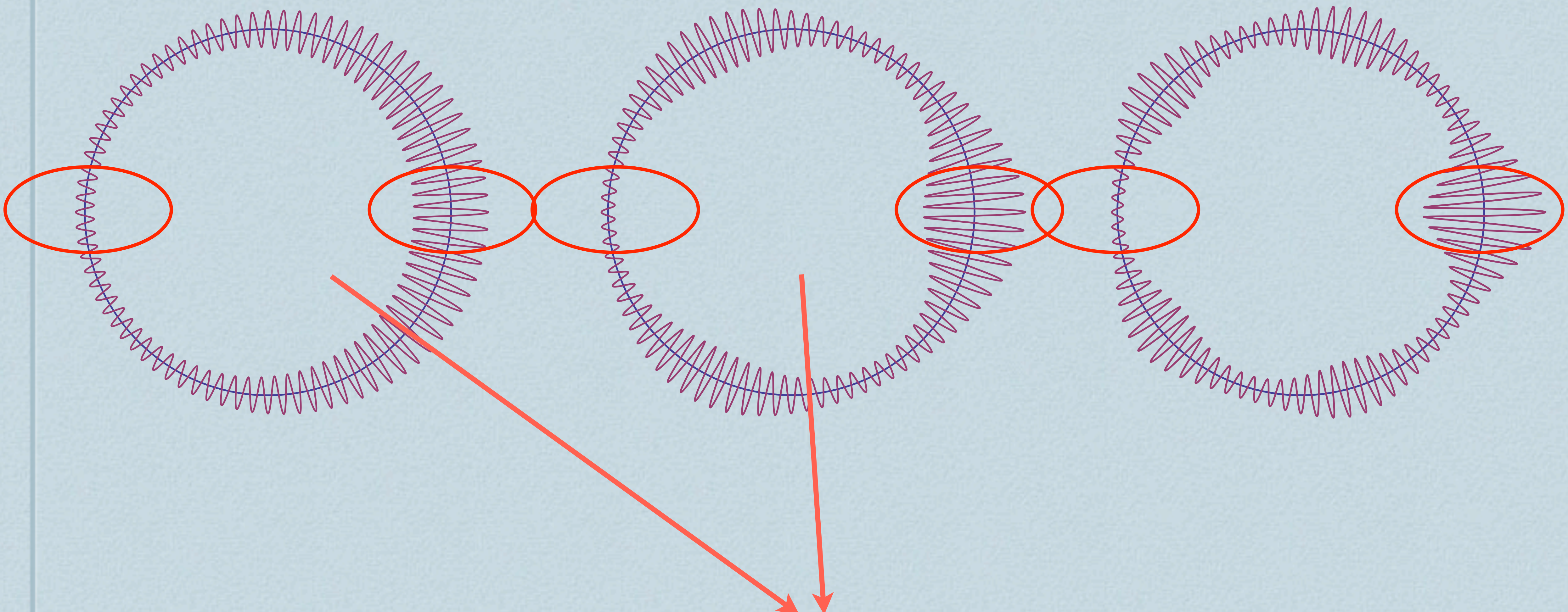

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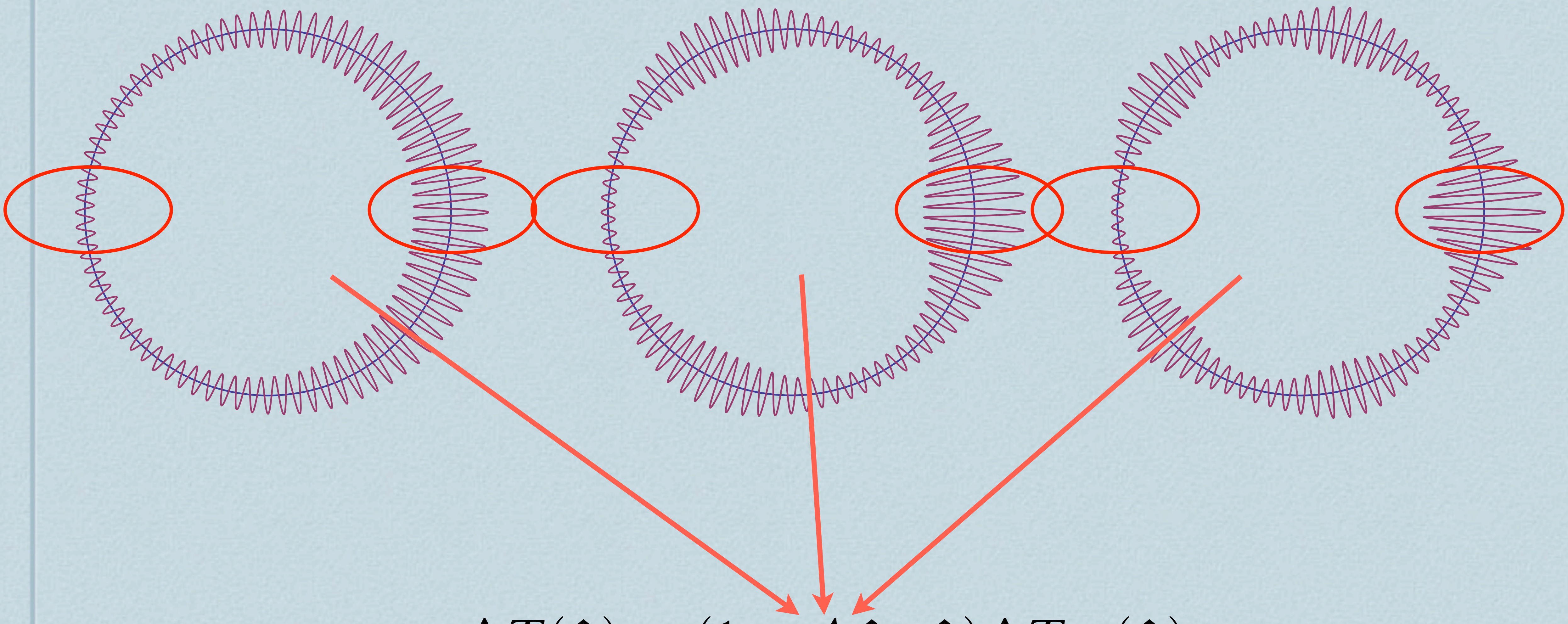

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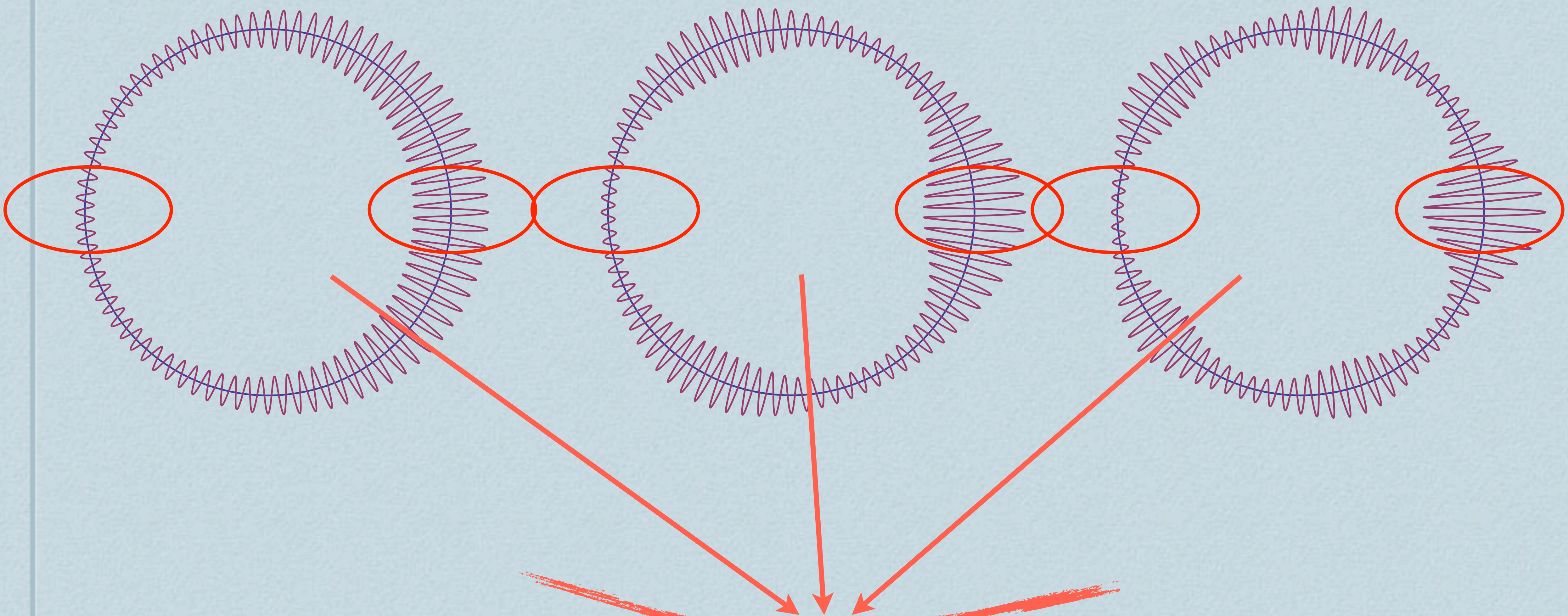

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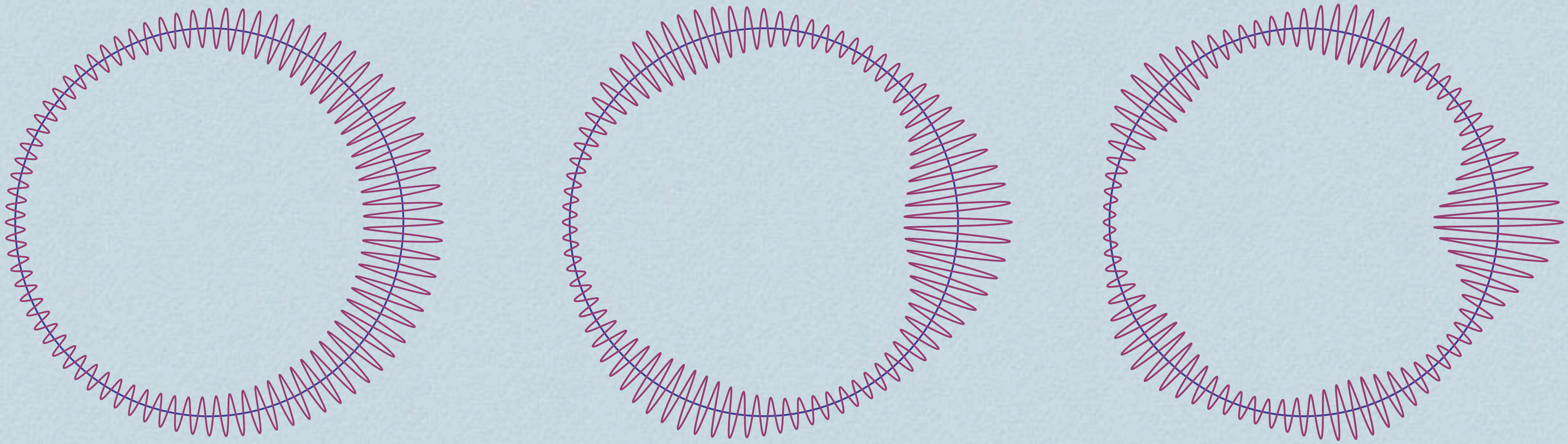
In progress

Other multipoles



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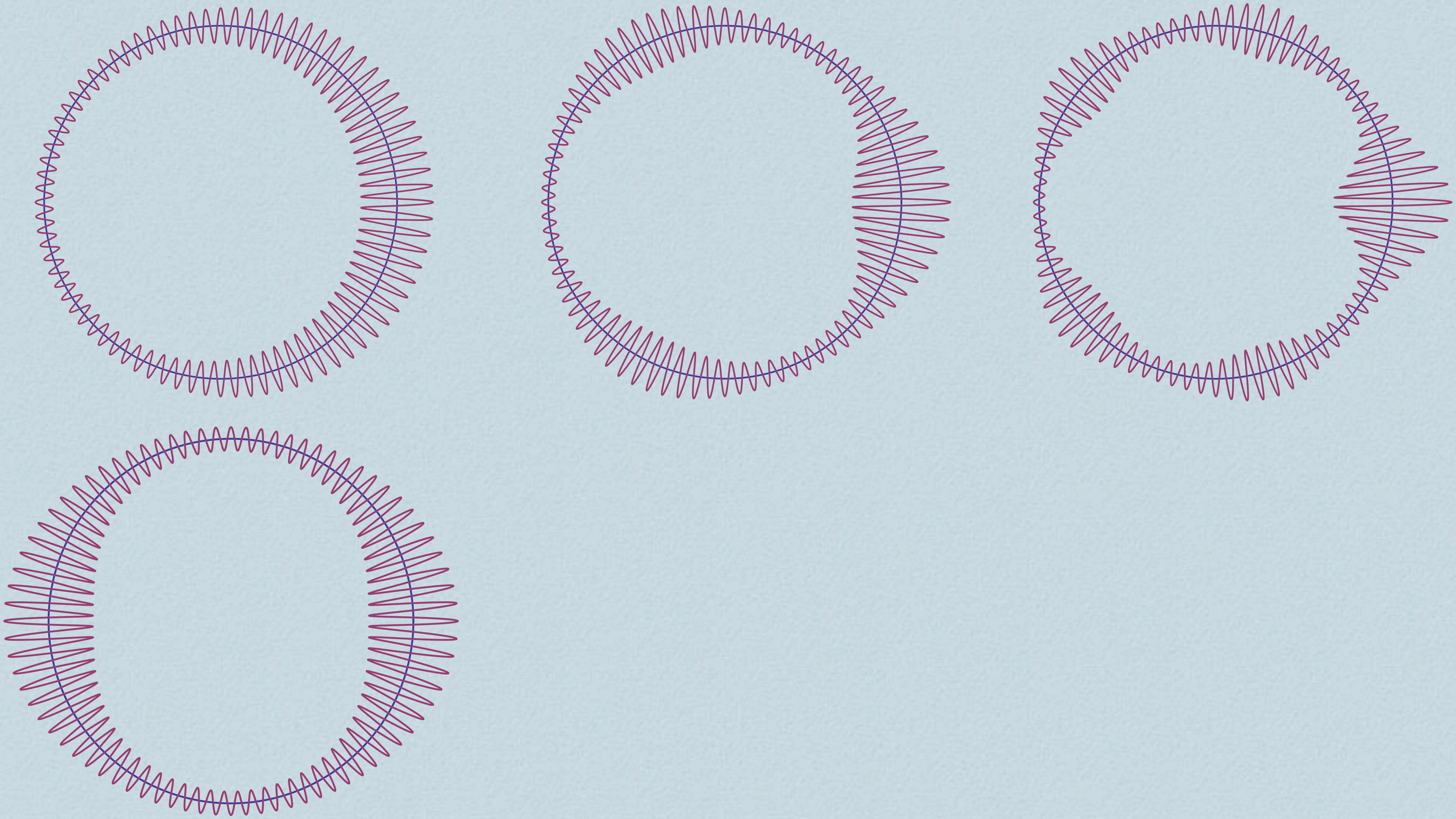

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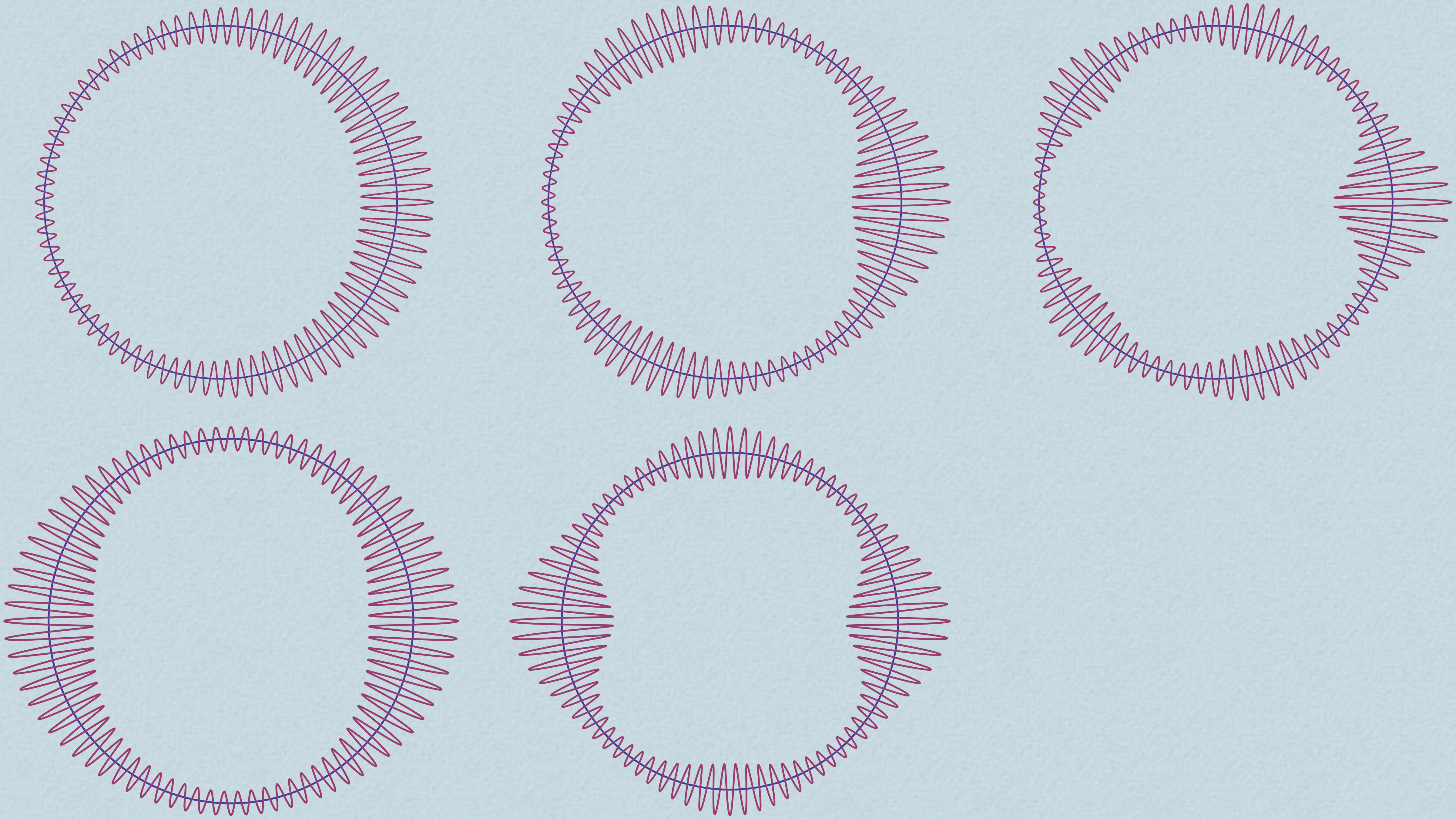

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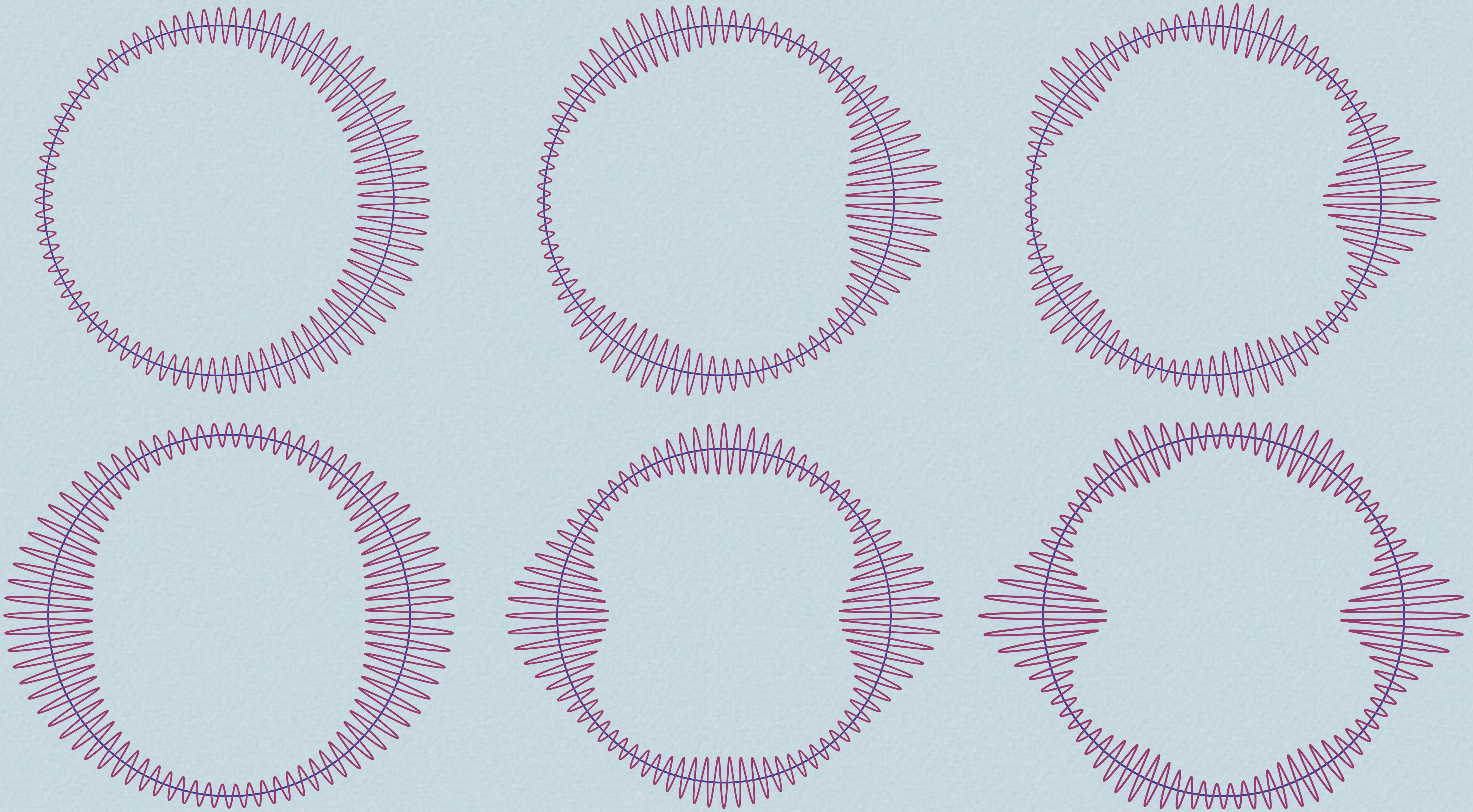
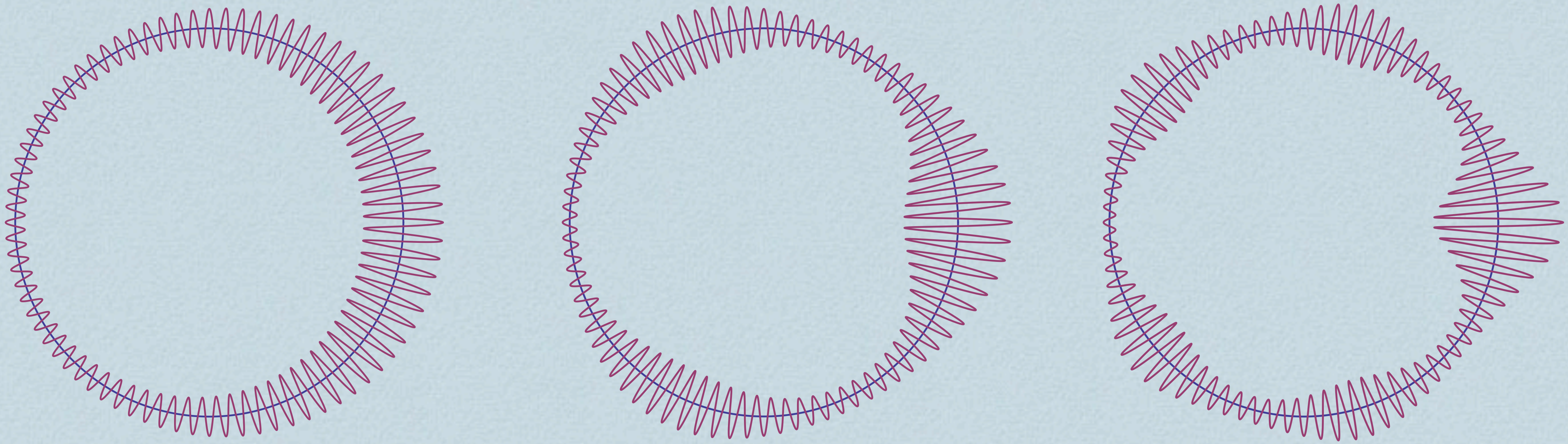


In progress

CMB power multipole



In progress

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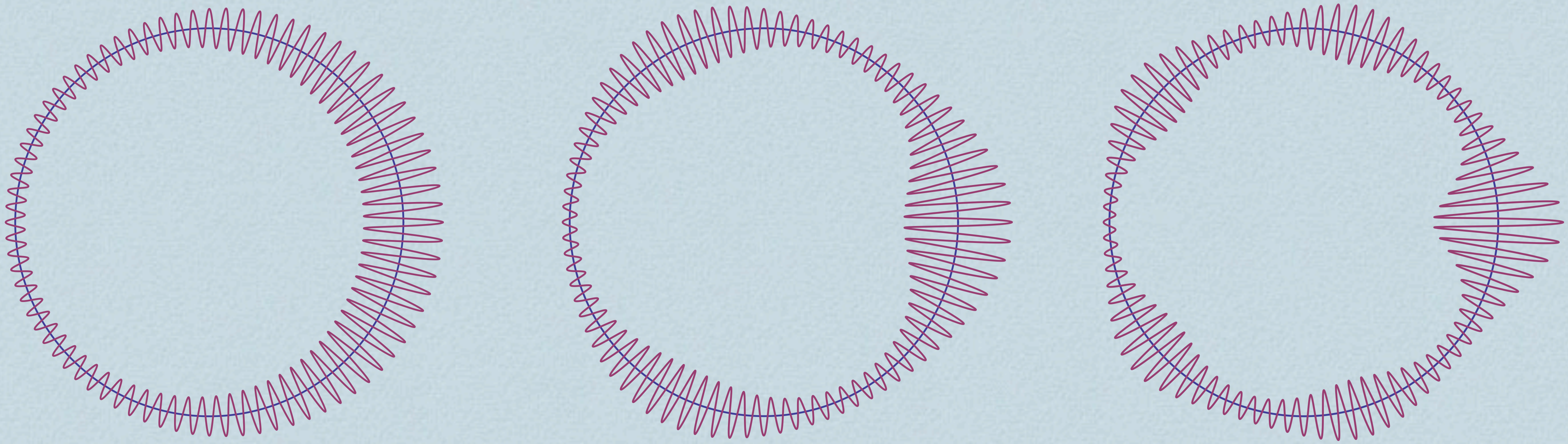

$$\Delta T(\hat{\mathbf{n}}) = \sum_{lm} a_{lm} Y_{lm}(\hat{\mathbf{n}})$$

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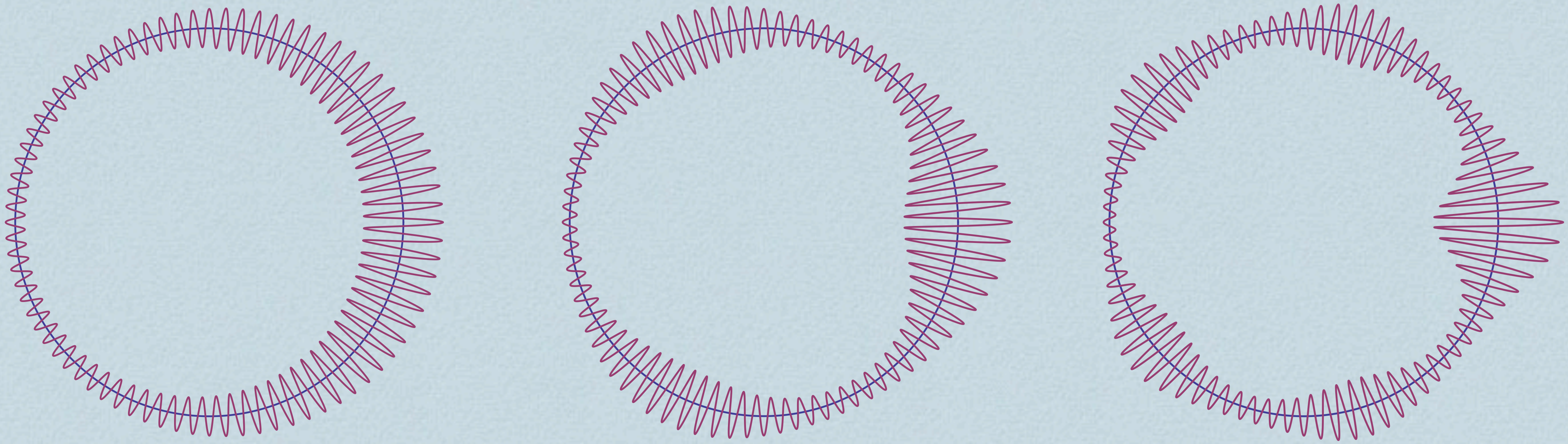

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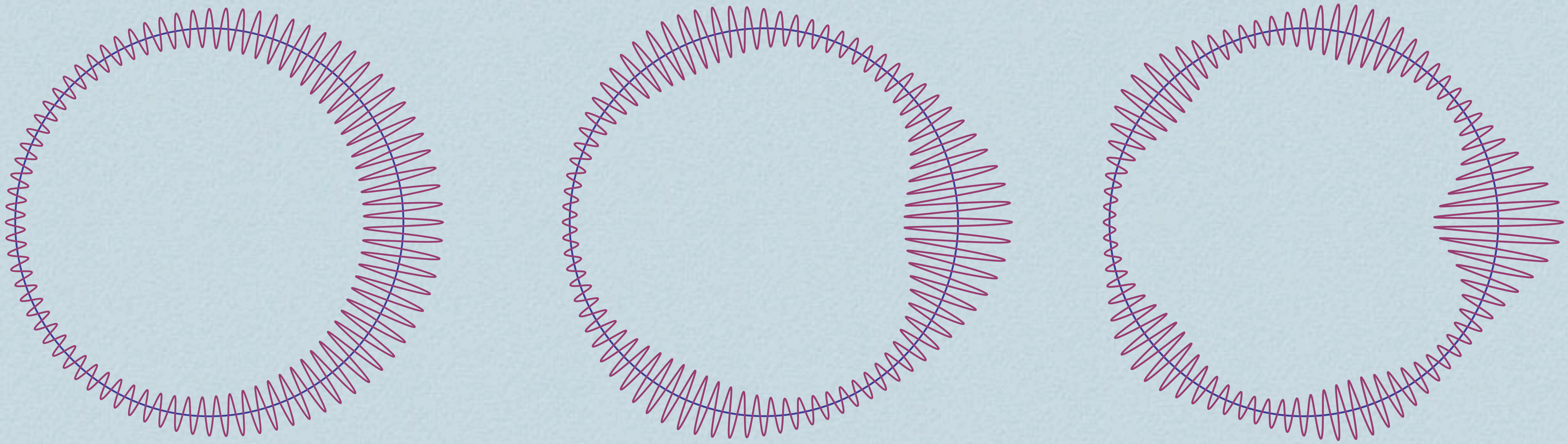
CMB power multipole



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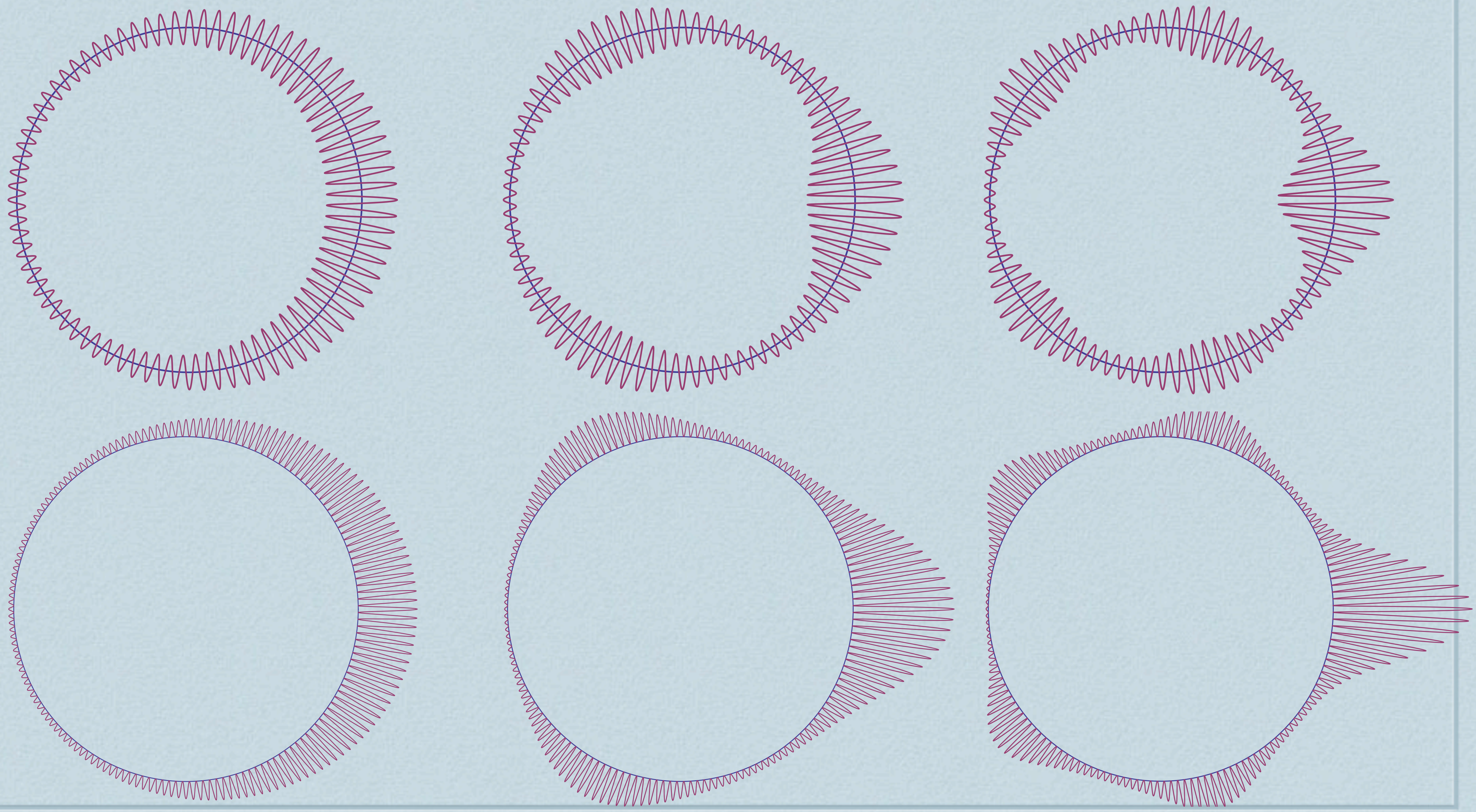
$$\langle a_{lm}^{(2)*} a_{l'm'}^{(2)} \rangle = C_l^{(2,2)} \delta_{ll'} \delta_{mm'}$$

In progress

CMB power multipole



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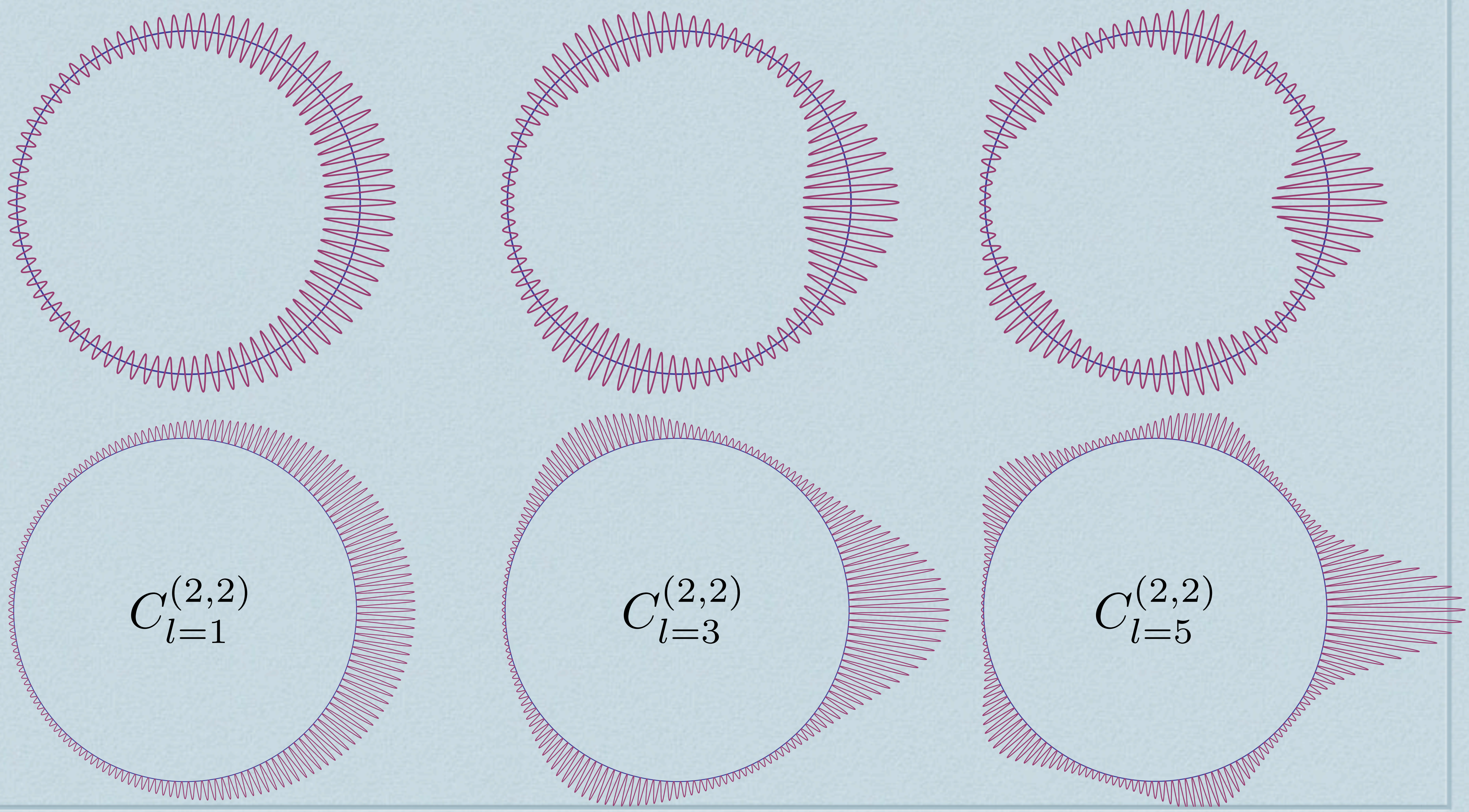

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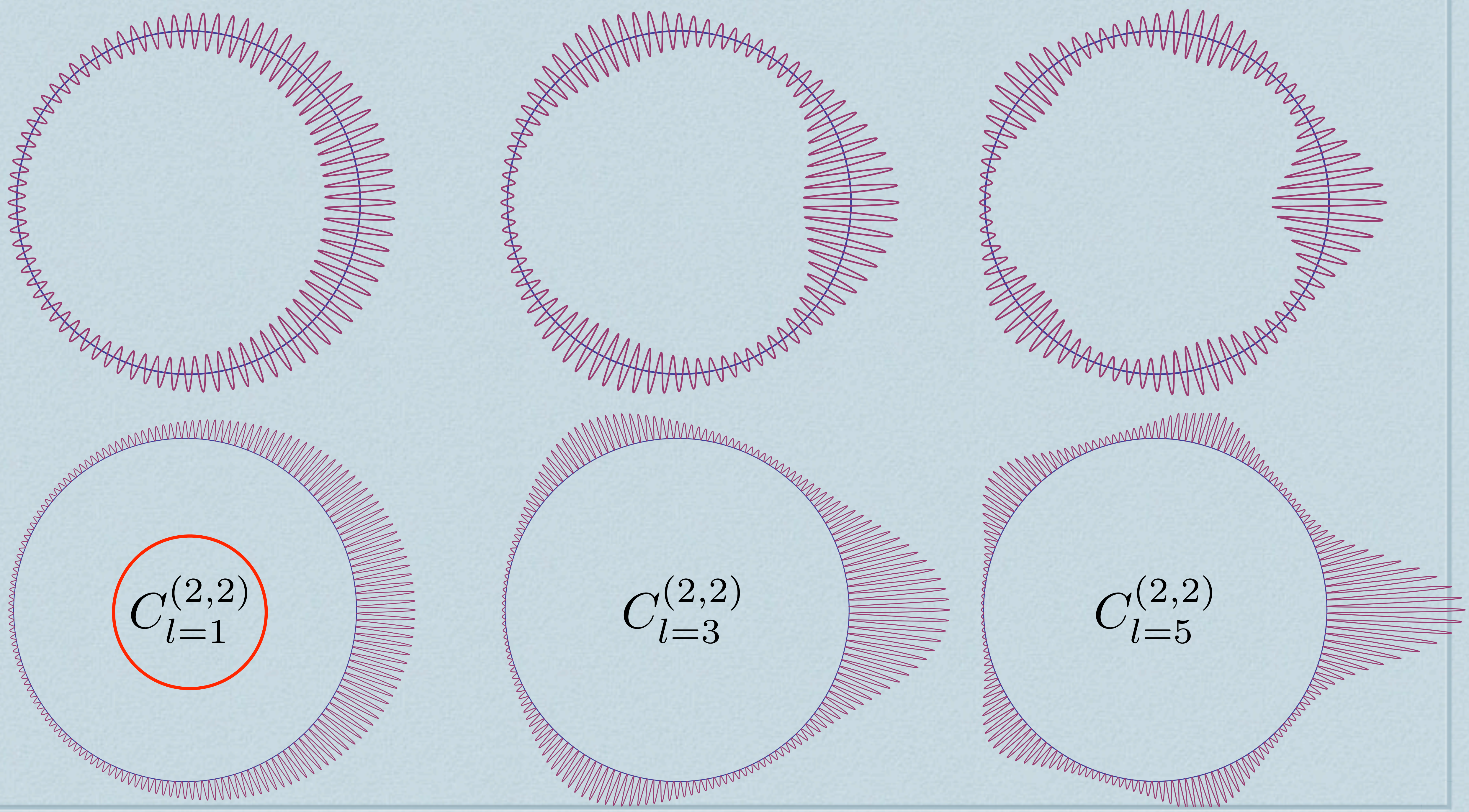
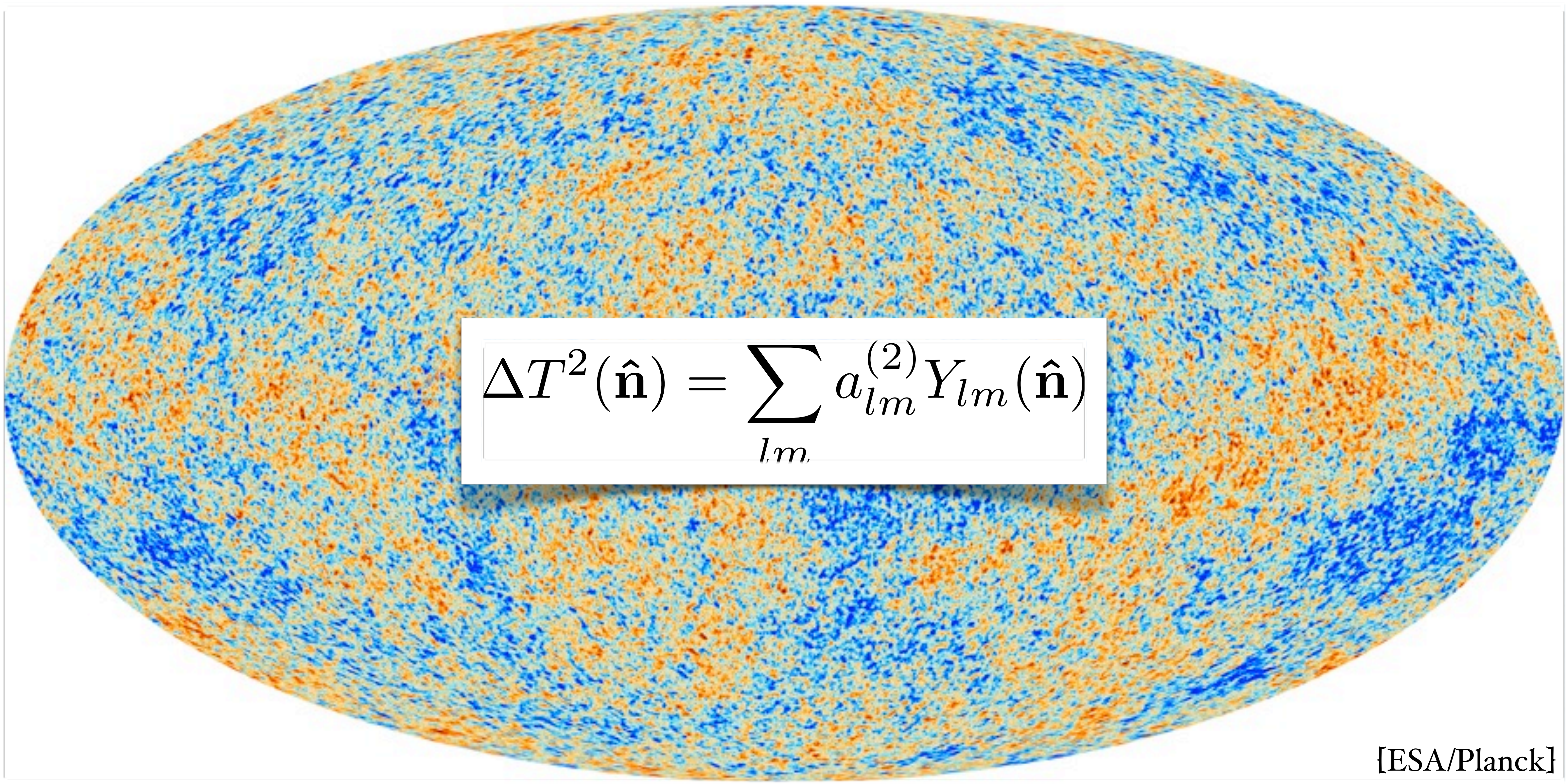


In progress

Measurable



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{ESA/Planck}

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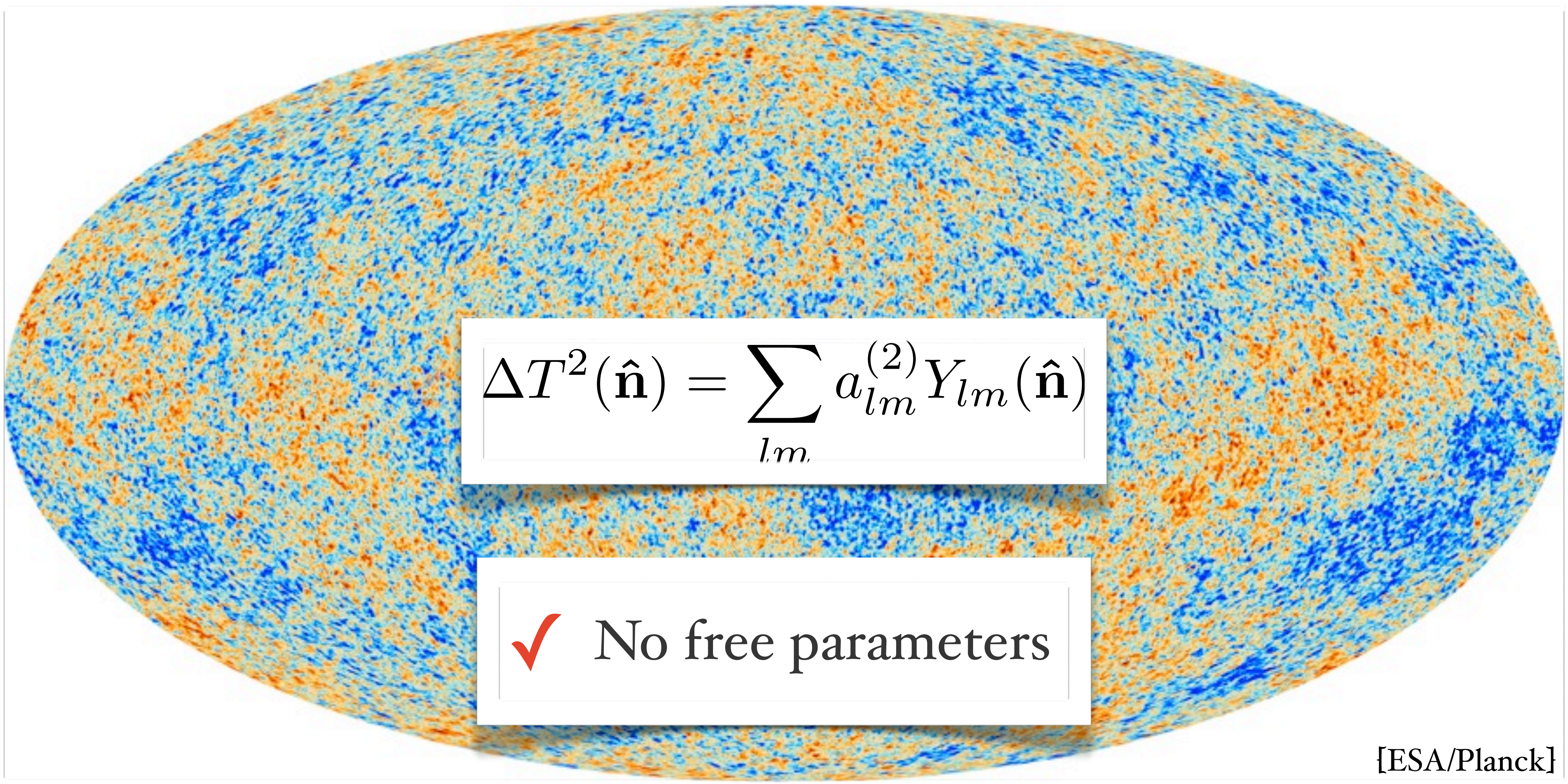

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✓ No free parameters

Calculable

- For Gaussian perturbations

$$C_l^{(2,2)} = \sum_{l_1 l_2} \frac{(2l_1+1)(2l_2+1)}{4\pi} P_{l_1 l_2 l} C_{l_1} C_{l_2}$$

$$P_{l_1 l_2 l} \equiv (-1)^{l_1+l_2+l} \int_{-1}^{1} P_{l_1}(x) P_{l_2}(x) P_l(x) \mathrm{d}x$$

$P_l(x)$: Legendre polynomials

In progress

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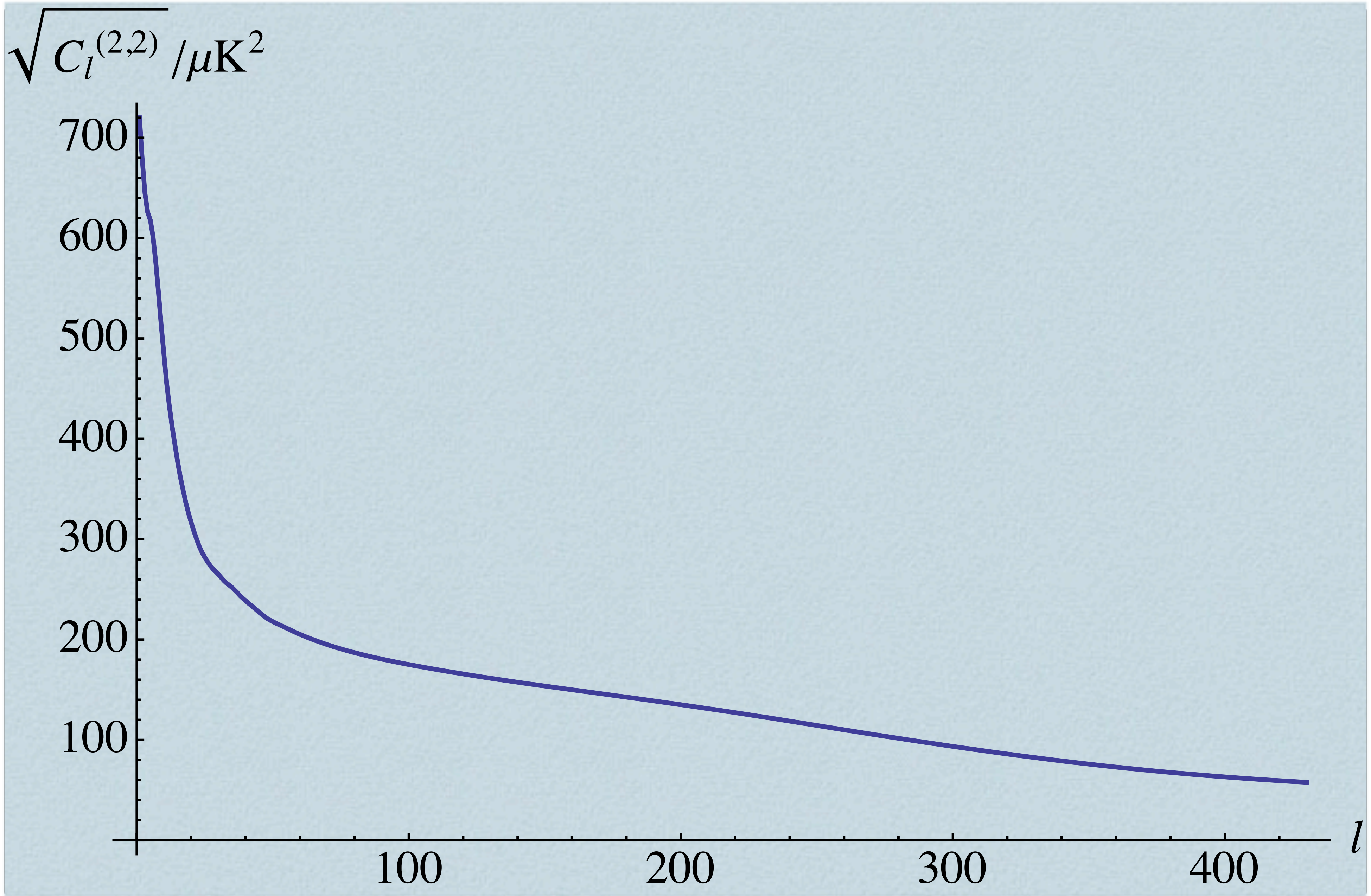
$P_l(x)$: Legendre polynomials

- Power dipole

$$C_1^{(2,2)} = \sum_l \frac{l+1}{\pi} C_l C_{l+1}$$

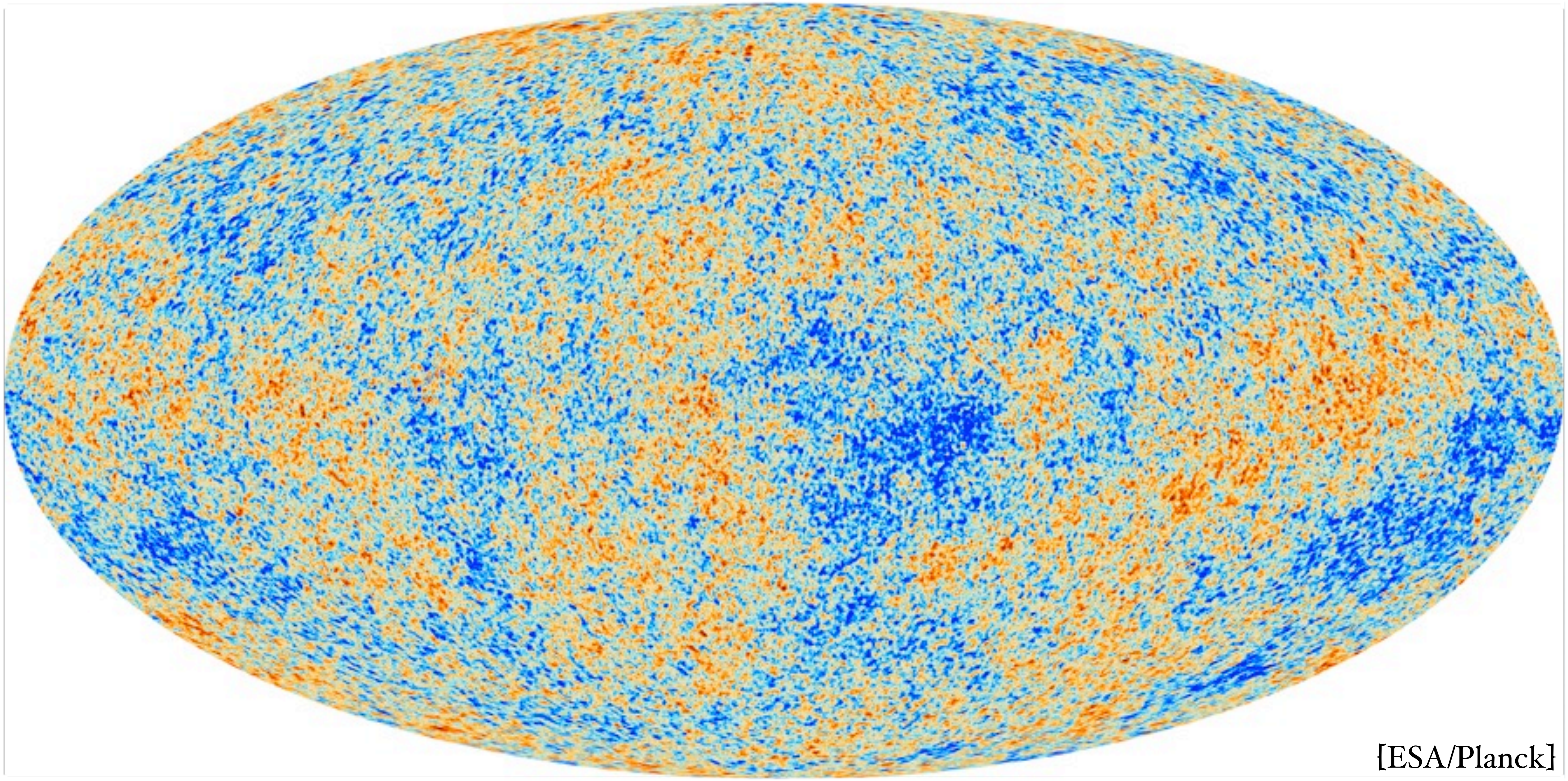
In progress

Gaussian perturbations

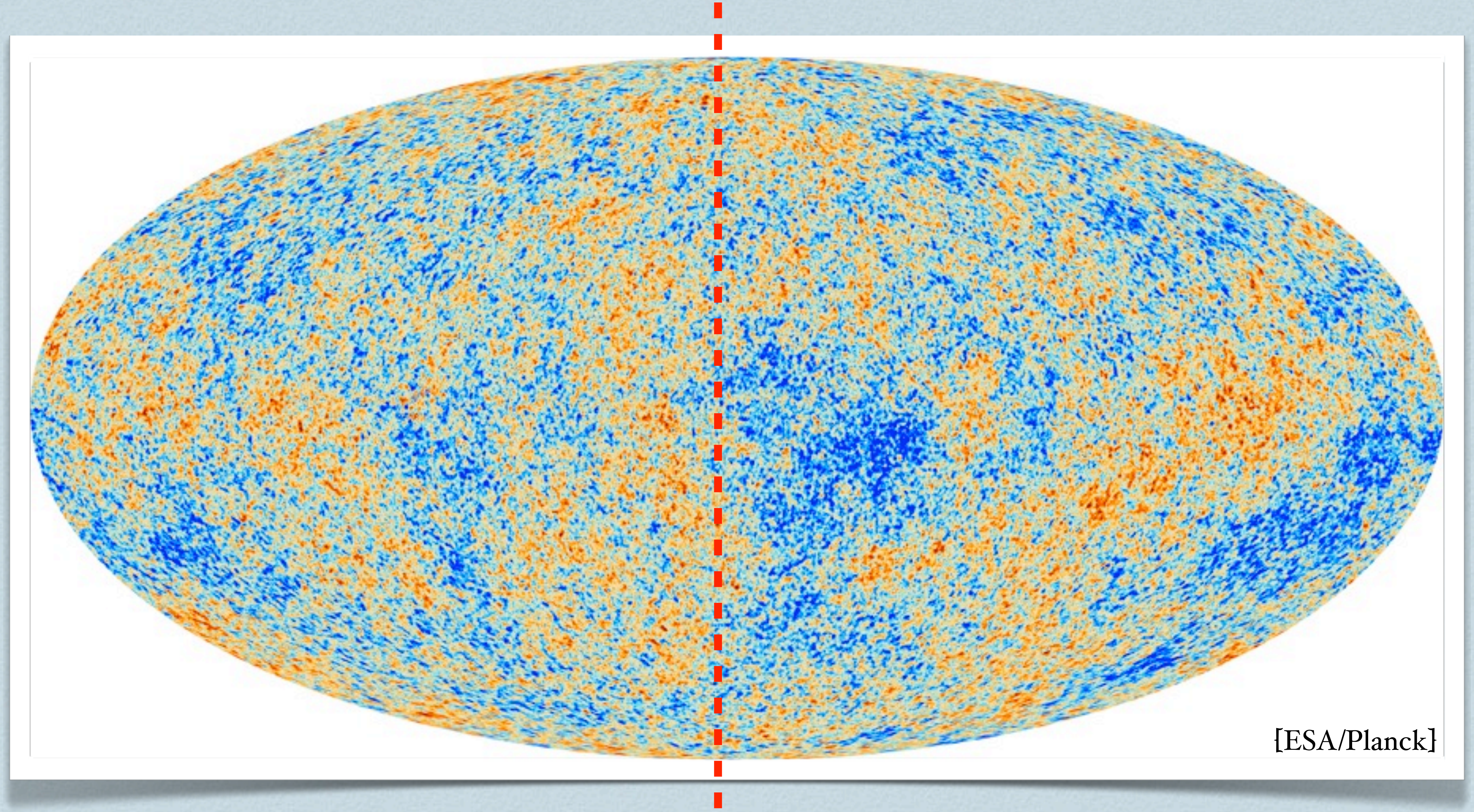


In progress

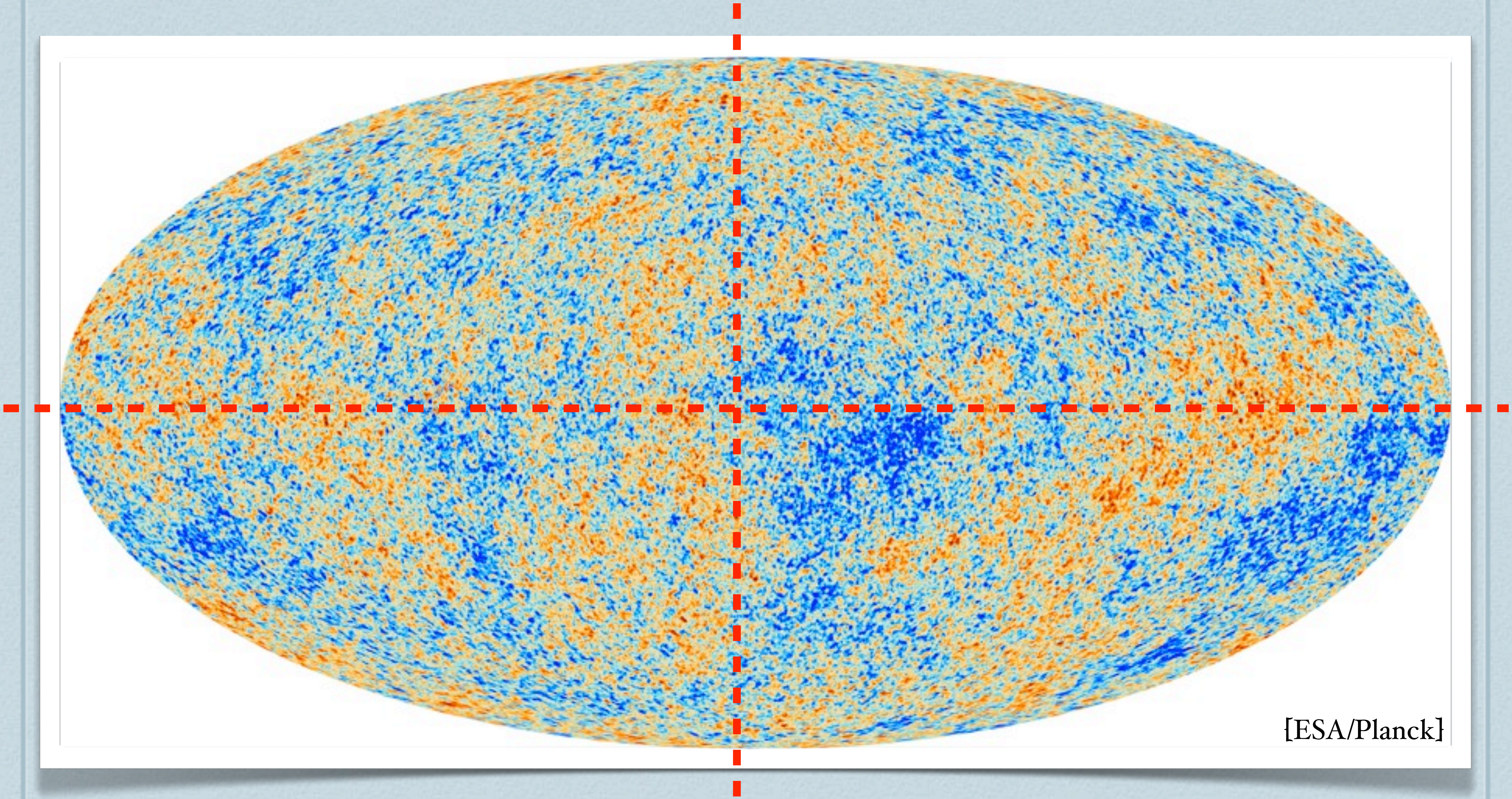
Natural modulation



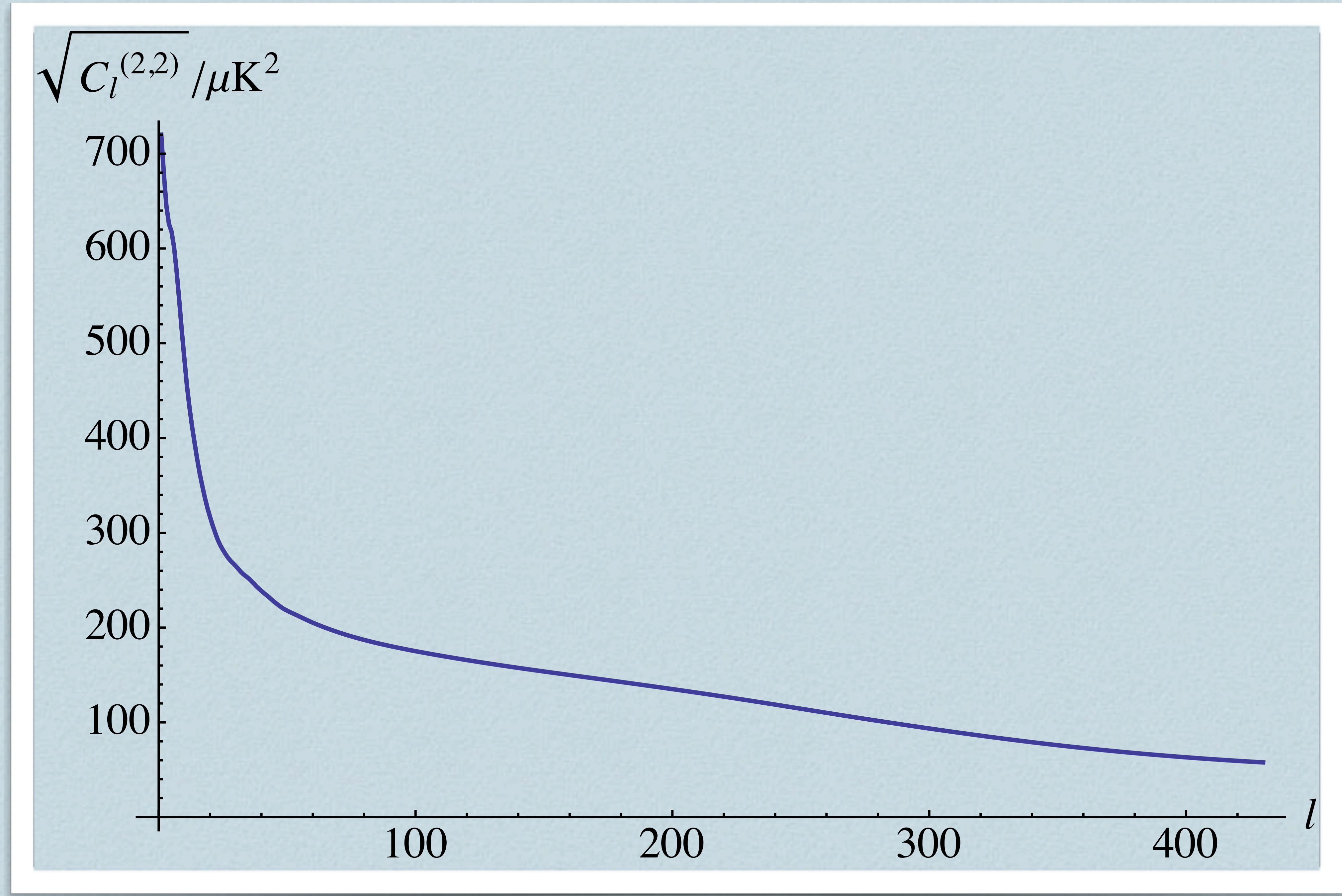
Natural modulation



Natural modulation



Gaussian perturbations



In progress

Calculable

- For non-Gaussian perturbations

$$\Delta C_l^{(2,2)} = \sum_{l_1 \ldots l_4} \frac{\sqrt{\prod_{n=1}^{4} (-1)^{l_n} (2l_n + 1)}}{8\pi(2l+1)} \sqrt{P_{l_1 l_2 l} P_{l_3 l_4 l}}\, T^{l_1 l_2}_{l_3 l_4}(l)$$

Hu 01, In progress

Calculable

- For non-Gaussian perturbations

$$\Delta C_l^{(2,2)} = \frac{1}{2l+1} \sum_{l_1 \ldots l_4} F_{l_1 l_2 l_3 l_4} T^{l_1 l_2}_{l_3 l_4}(l)$$

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Hu 01, In progress

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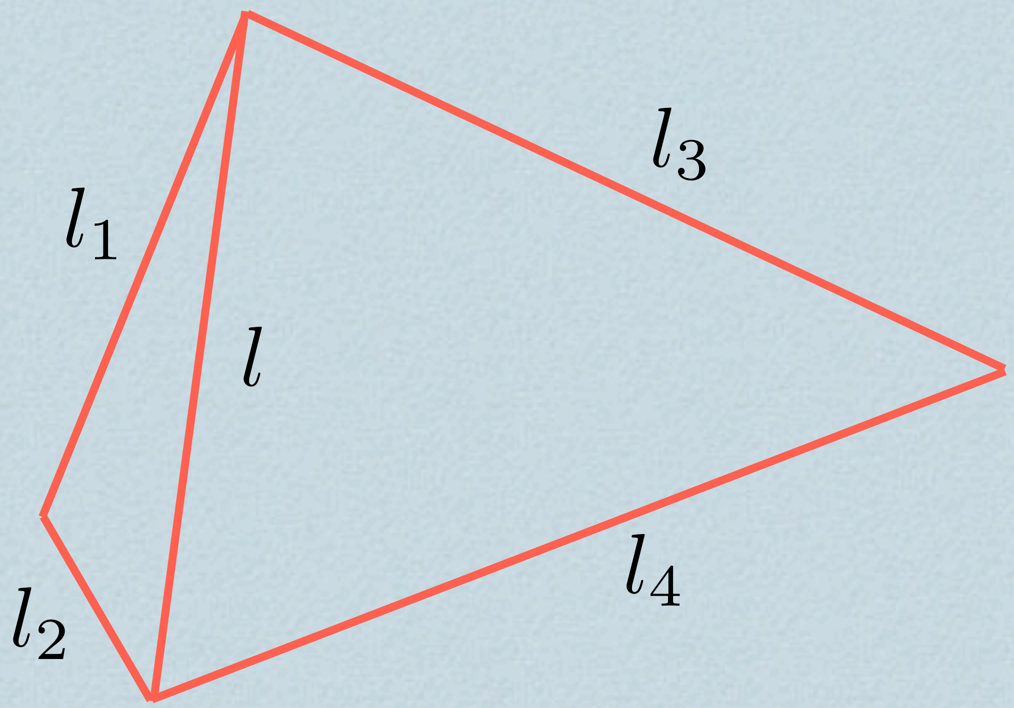

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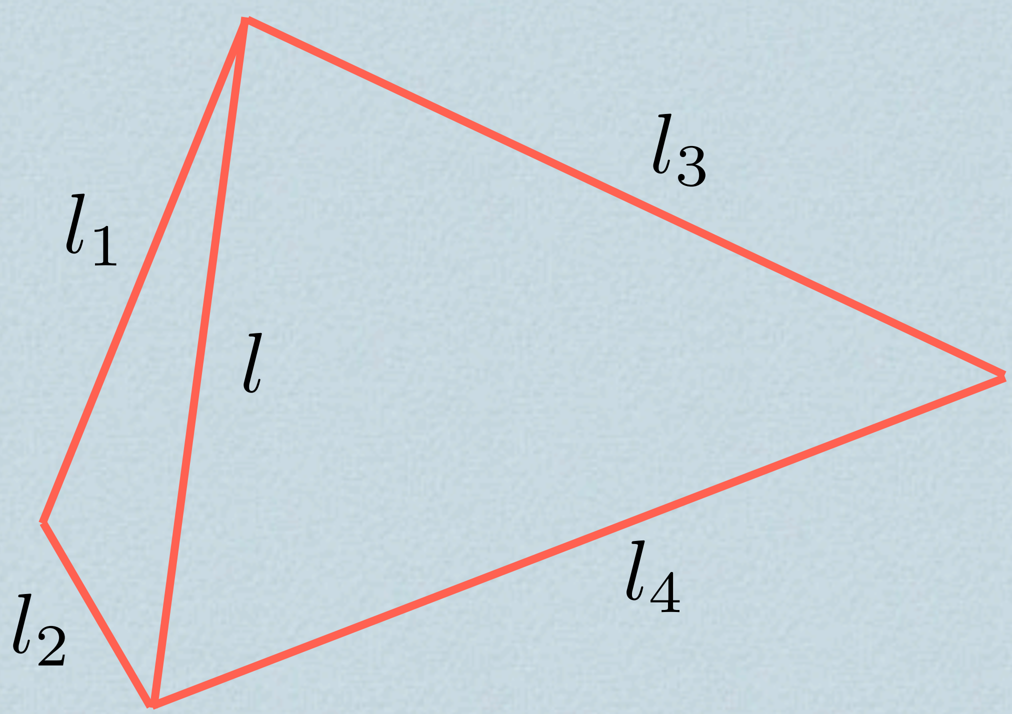

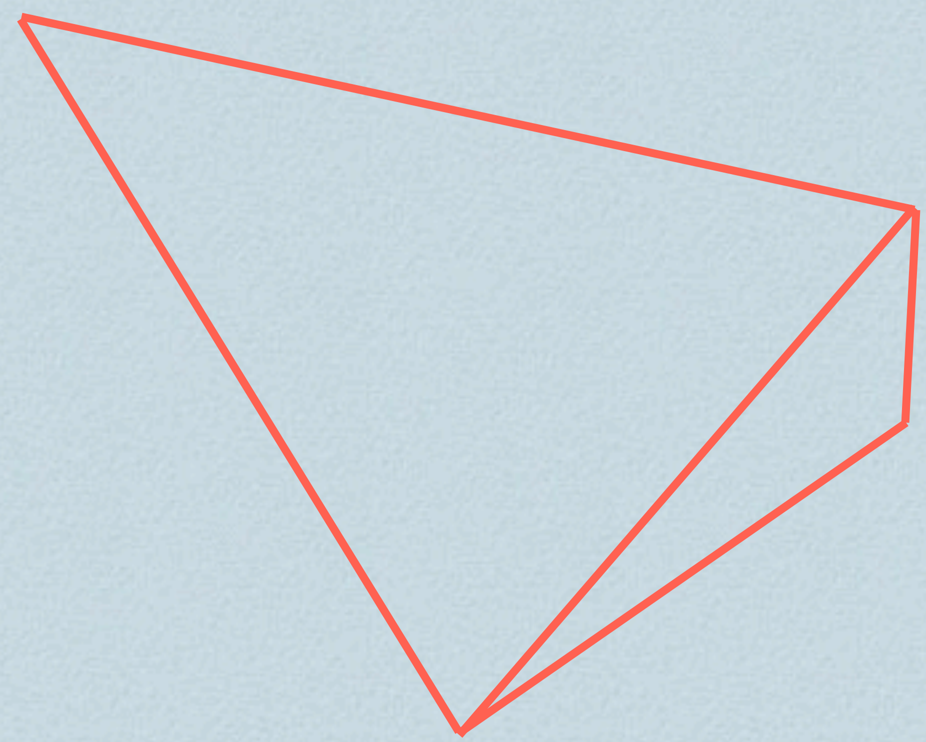

Hu 01, In progress

Calculable

- For non-Gaussian perturbations

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$$\langle \Phi(\mathbf{k}_1) \Phi(\mathbf{k}_2) \Phi(\mathbf{k}_3) \Phi(\mathbf{k}_4) \rangle$$

- Fully determined by primordial cosmology

In progress

Calculable

- For non-Gaussian perturbations

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$\tau_{\rm NL}$ $g_{\rm NL}$

- Fully determined by primordial cosmology

In progress

Calculable

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$\tau_{\rm NL}$ $\quad$ $g_{\rm NL}$

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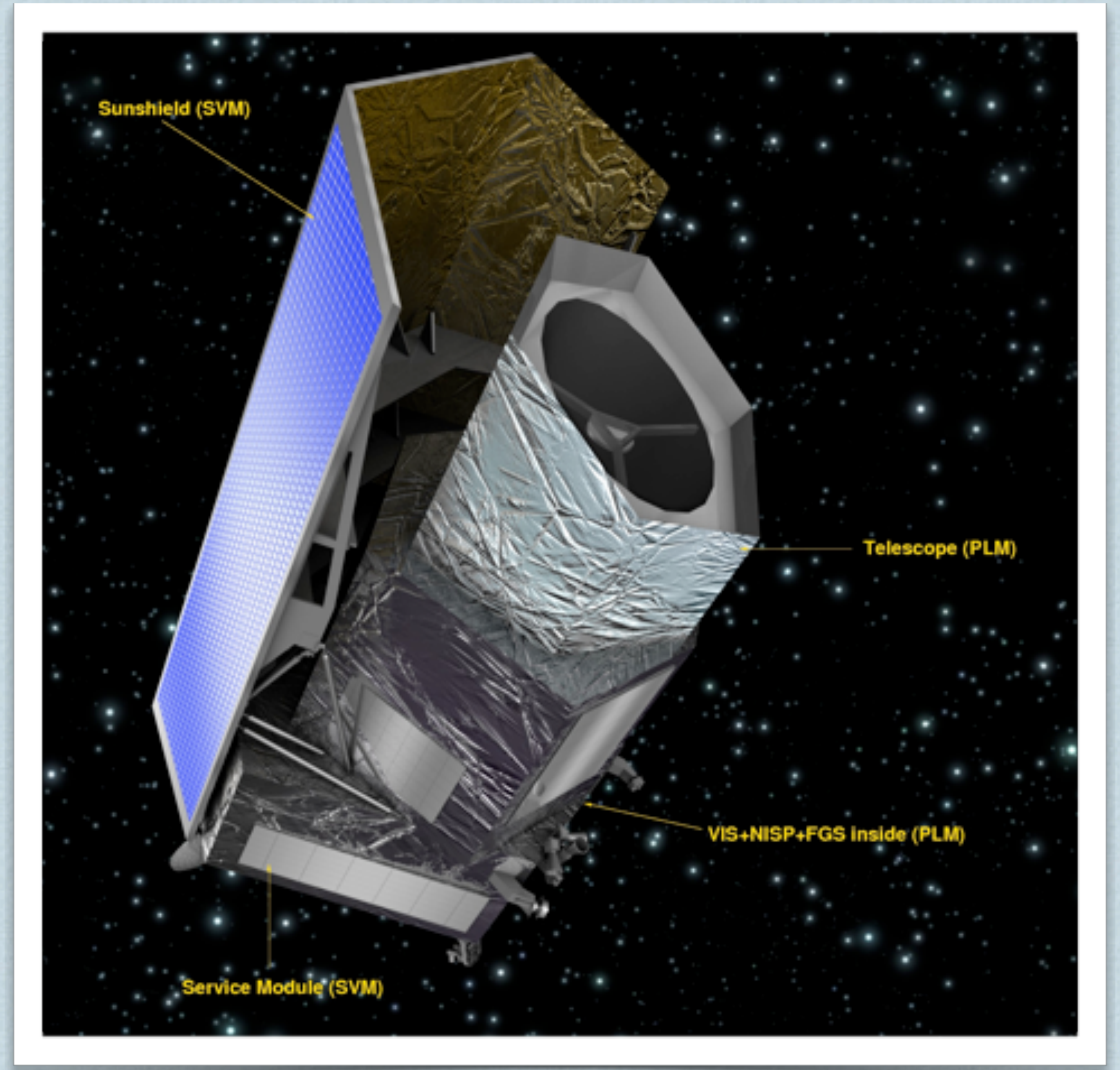
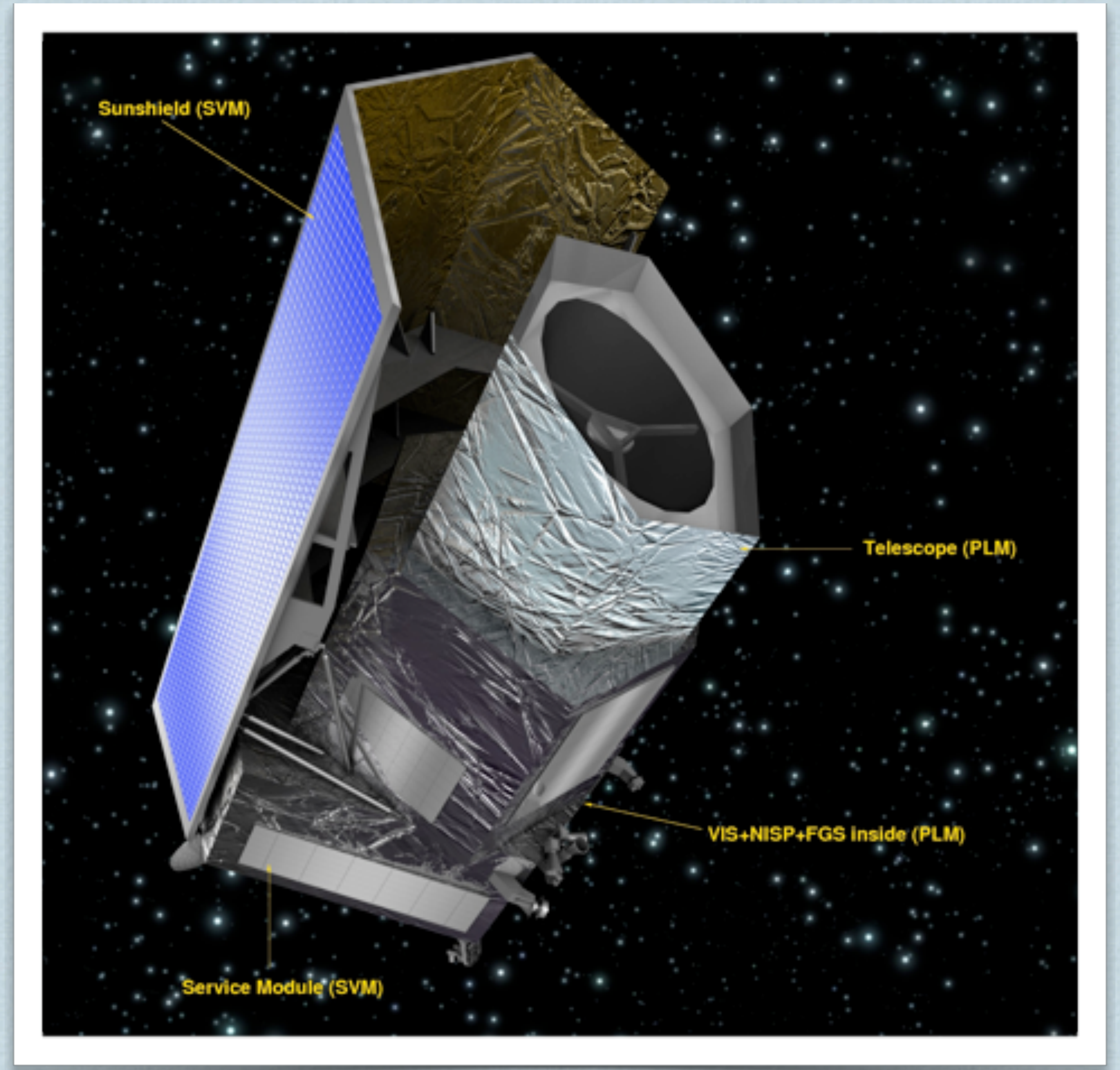
In progress

LSS power multipoles

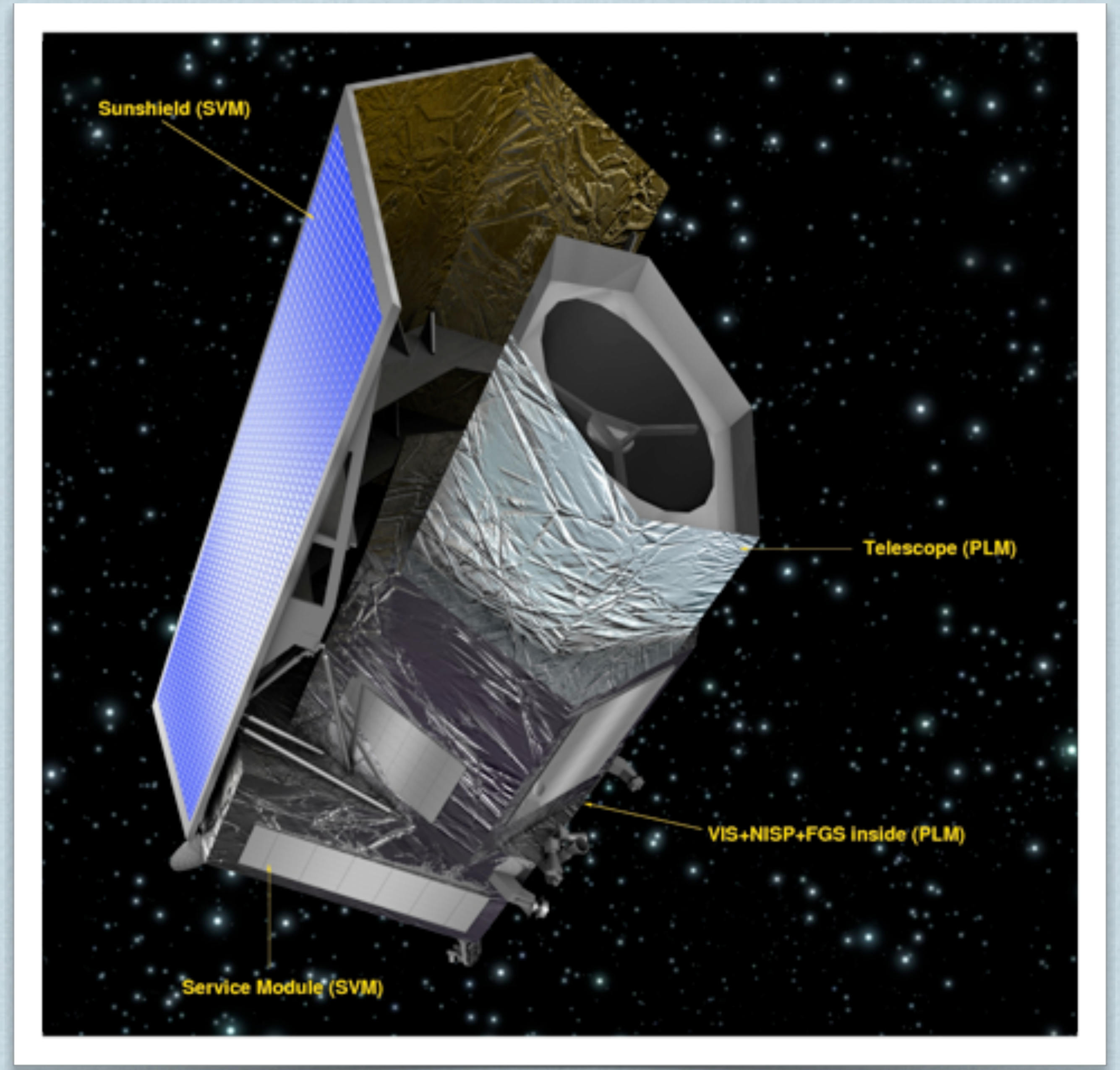


LSS power multipoles



$$\Delta T(\hat{\mathbf{n}}) = \sum_{lm} a_{lm} Y_{lm}(\hat{\mathbf{n}})$$

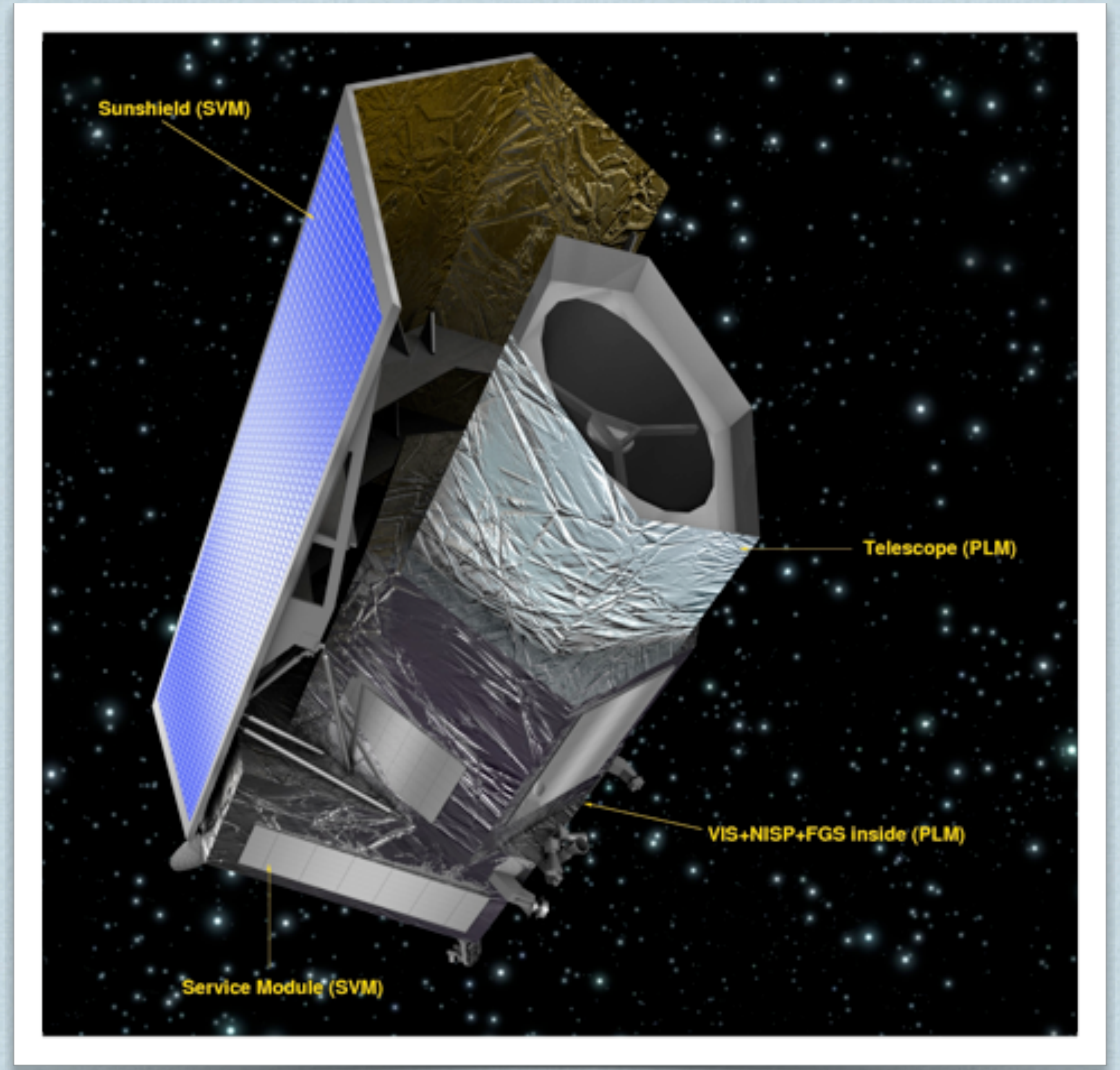
LSS power multipoles



$$\Delta T(\hat{\mathbf{n}}) = \sum_{lm} a_{lm} Y_{lm}(\hat{\mathbf{n}})$$

$$\delta(\mathbf{x}) = \int d^3\mathbf{x} e^{i\mathbf{k}\cdot\mathbf{x}} \delta(\mathbf{k})$$

LSS power multipoles



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- Possible measurement in the near future

Summary

- Spectator is an alternative to the curvaton scenario
  - It generates smaller non-Gaussianity, negligible isocurvature perturbations, and less tuning
- Example model shows good agreement with Planck
- CMB asymmetry is explained with a fast roll spectator
- Power multipoles is an alternative approach to dipole asymmetry
  - It has no free parameter and is determined by primordial cosmology

Based on [1306.5736], PRD 88 023512,
JCAP 1307 019, JCAP 1305 012, PRD 87 083501