Implications of Planck for Fundamental Physics
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# Curvaton model for origin of structure *after Planck*

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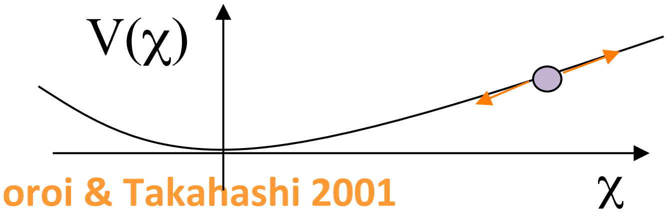
# outline

- Curvaton
  - non-adiabatic model for origin of structure
  - smoking gun for non-adiabatic models
    - Non-Gaussianity
    - Isocurvature perturbations
- Planck parameter constraints
  - power spectrum
  - bispectrum
  - anomalies
- Conclusions

# curvaton scenario:

Linde & Mukhanov 1997; Enqvist & Sloth, Lyth & Wands, Moroi & Takahashi 2001




curvaton $\chi$ = weakly-coupled, late-decaying scalar field

- light field during inflation acquires an almost scale-invariant, ***Gaussian distribution of field fluctuations*** on large scales
- **quadratic energy density** for free field, $\rho_\chi = m^2\chi^2/2$
- spectrum of initially isocurvature density perturbations

$$\zeta_\chi \approx \frac{1}{3}\frac{\delta\rho_\chi}{\rho_\chi} \approx \frac{1}{3}\left(\frac{2\chi\delta\chi + \delta\chi^2}{\chi^2}\right)$$

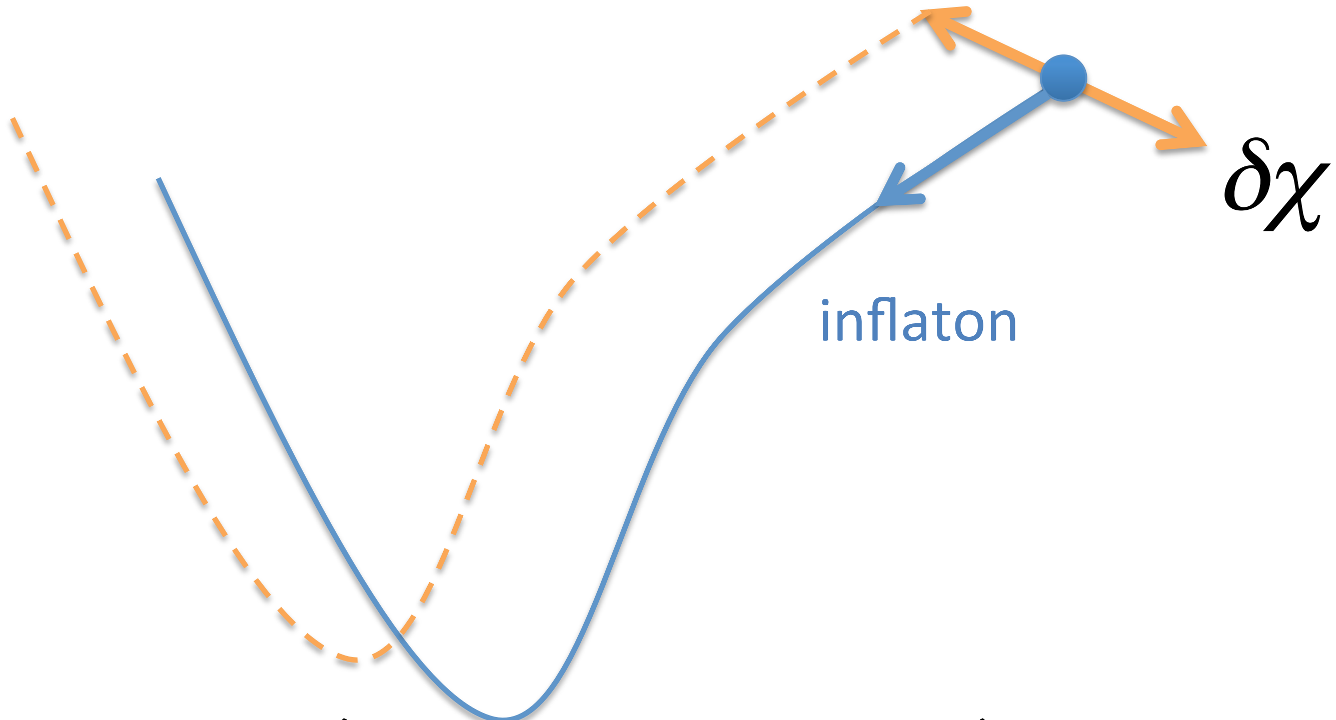
- **transferred to radiation when curvaton decays** after inflation with some **efficiency,** $0 < R_\chi < 1$, where $R_\chi \approx \Omega_{\chi,decay}$

$$\zeta = R_\chi \zeta_\chi \approx \frac{R_\chi}{3}\left(2\frac{\delta\chi}{\chi} + \frac{\delta\chi^2}{\chi^2}\right)$$

$$= \zeta_G + \frac{3}{4R_\chi}\zeta_G^2 \quad \Rightarrow \quad f_{NL} = 5/4R_\chi$$

# non-adiabatic field fluctuations

see also multi-field inflation, modulated reheating, inhomogeneous end of inflation…



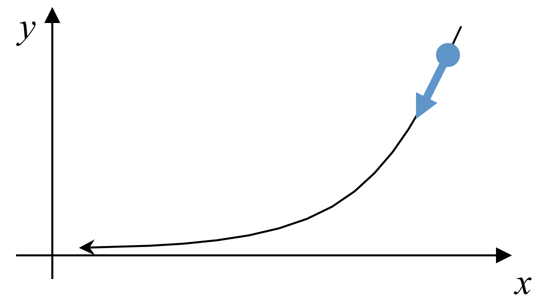

$$\zeta \sim R_\chi \left( \frac{\delta\chi}{\chi} + \frac{\delta\chi^2}{\chi^2} + \ldots \right)$$

# Cosmological perturbations on large scales

- **adiabatic perturbations** *e.g.,* $\delta\left(\frac{n_\gamma}{n_B}\right) \propto \frac{\delta n_\gamma}{n_\gamma} - \frac{\delta n_B}{n_B} = 0$
  - *perturb along the background trajectory*

$$\frac{\delta x}{\dot{x}} = \frac{\delta y}{\dot{y}} = \delta t$$

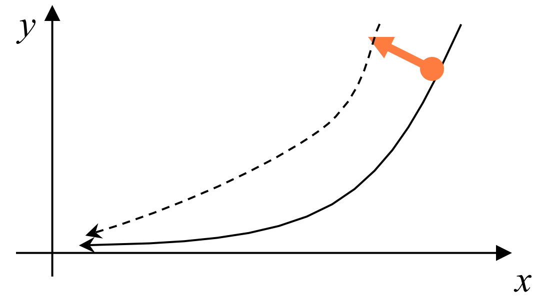
  - ***adiabatic perturbations stay adiabatic***




- **entropy perturbations**
  - *perturb off the background trajectory*

$$\frac{\delta x}{\dot{x}} \neq \frac{\delta y}{\dot{y}}$$

  - *e.g., baryon-photon **isocurvature** perturbation*




***(non-linear) evolution of curvature perturbation on large scales***

# Distinctive predictions

- Local non-Gaussianity requires non-adiabatic field fluctuations during inflation

# simplest quadratic curvaton: $V=m^2\chi^2/2$

- *first-order perturbations*

$$\zeta = R_\chi \, \zeta_\chi \qquad \text{where} \qquad R_\chi = \left[\frac{3\Omega_\chi}{4-\Omega_\chi}\right]_{\text{decay}} \leq 1$$

- *second-order perturbations*

$$\Rightarrow \quad f_{NL} = \frac{5}{4R_\chi} - \frac{5}{3} - \frac{5R_\chi}{6} \quad \geq -\frac{5}{4}$$

- *third-order perturbations*

$$\Rightarrow \quad g_{NL} = -\frac{25}{6R_\chi}\left[1 - \frac{R_\chi}{18} - \frac{10R_\chi^2}{9} - \frac{R_\chi^3}{3}\right] \quad \leq \frac{9}{2}$$

- *Predictions of the simplest quadratic curvaton model:*
  - *for $R_\chi \approx 1$*

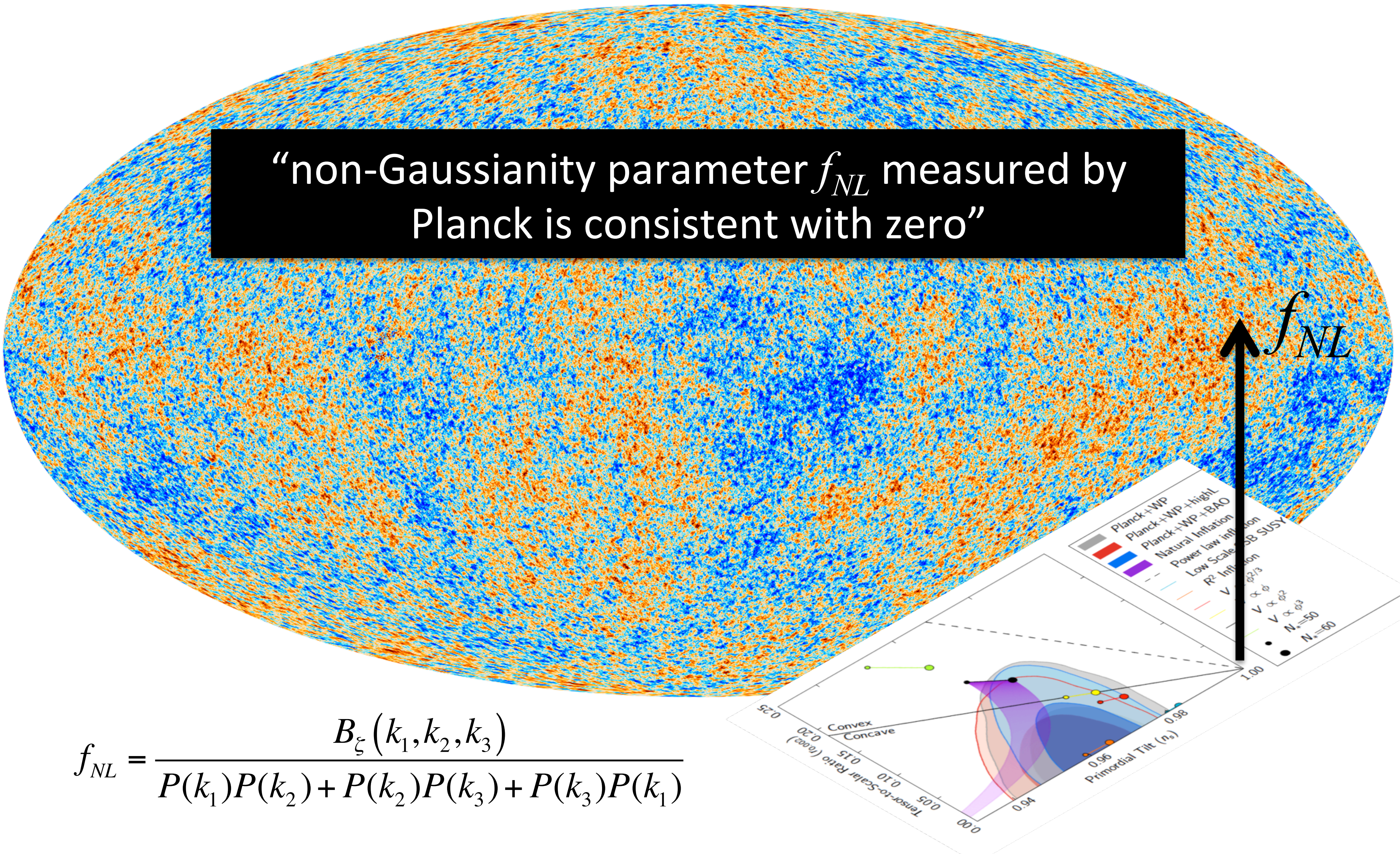
$$f_{NL} = -\frac{5}{4} \quad , \quad g_{NL} = \frac{9}{2}$$

  - *for $R_\chi << 1$*

$$f_{NL} = \frac{5}{4R_\chi} >> 1 \quad , \quad \tau_{NL} = \frac{36}{25} f_{NL}^2 >> \quad g_{NL} = -\frac{10}{3} f_{NL}$$

single source consistency relation

# Planck - new standard model of primordial cosmology




“non-Gaussianity parameter $f_{NL}$ measured by Planck is consistent with zero”

$$f_{NL} = \frac{B_\zeta(k_1, k_2, k_3)}{P(k_1)P(k_2) + P(k_2)P(k_3) + P(k_3)P(k_1)}$$

# Constraints on local non-Gaussianity

- WMAP9 constraints using estimators based on optimal templates:
  - Local:

    $-3 < f_{NL} < 77$ (95% CL) Bennett et al 2012

    $-5.6 < g_{NL} / 10^5 < 8.6$ Ferguson et al; Smidt et al 2010

- LSS constraints on local nG from galaxy power spectrum:
  - Local:

    $-37 < f_{NL} < 20$ (95% CL) Giannantonio et al 2013

    $-4.5 < g_{NL} / 10^5 < 1.6$ [cross-correlating SDSS+NVSS]

- Planck constraints (Ade et al March 2013)
  - Local: $f_{NL} = 2.7 \pm 5.8$ (68% CL)

# Constraints on local non-Gaussianity

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  - Local:

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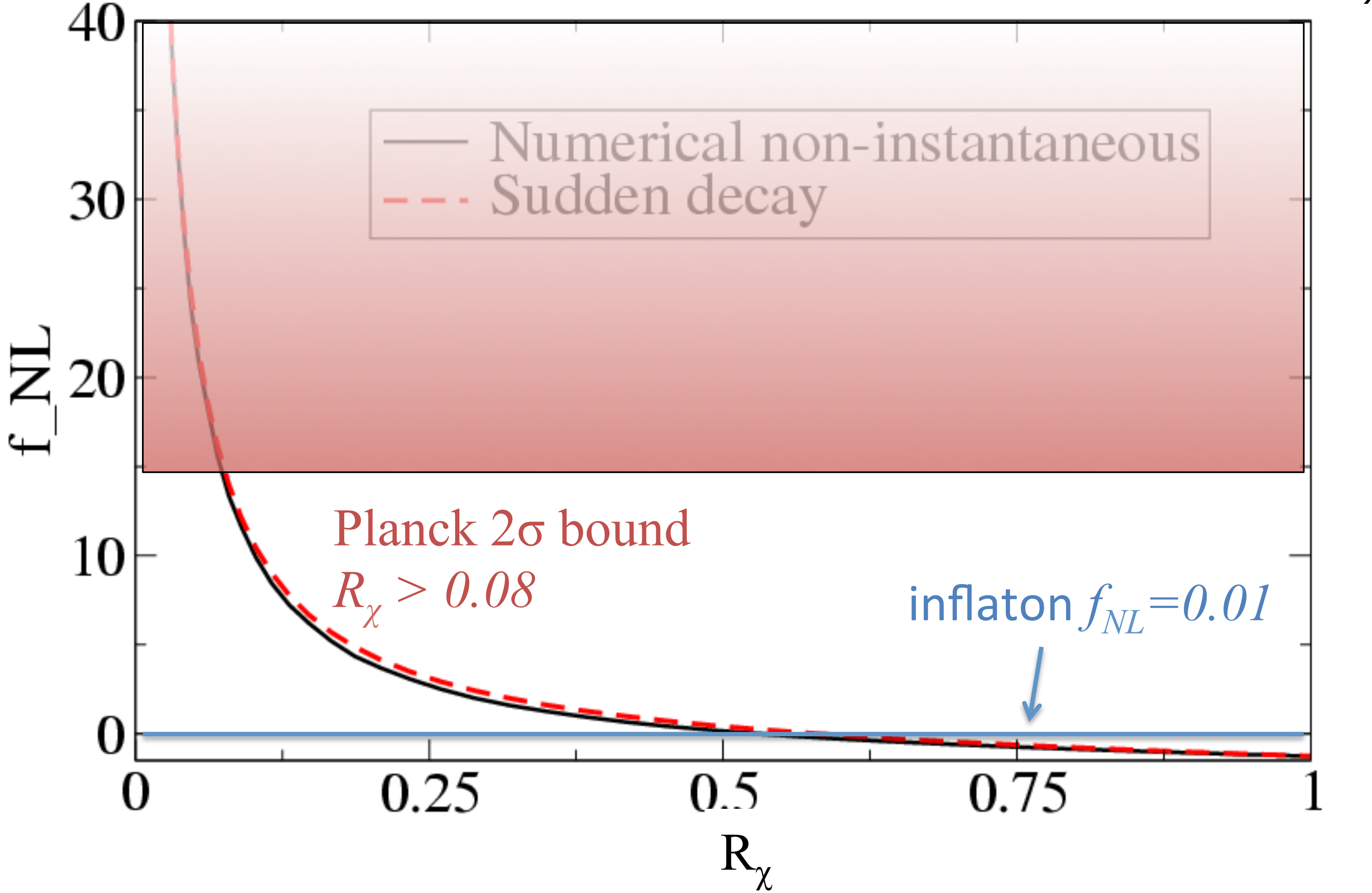
- Planck constraints (Ade et al March 2013)
  - Local: $-9.8 < f_{NL} < 14.3$ (95% CL)

# Quadratic curvaton non-linearity parameter

Sasaki, Valiviita & Wands (2006)
see also Malik & Lyth (2006)



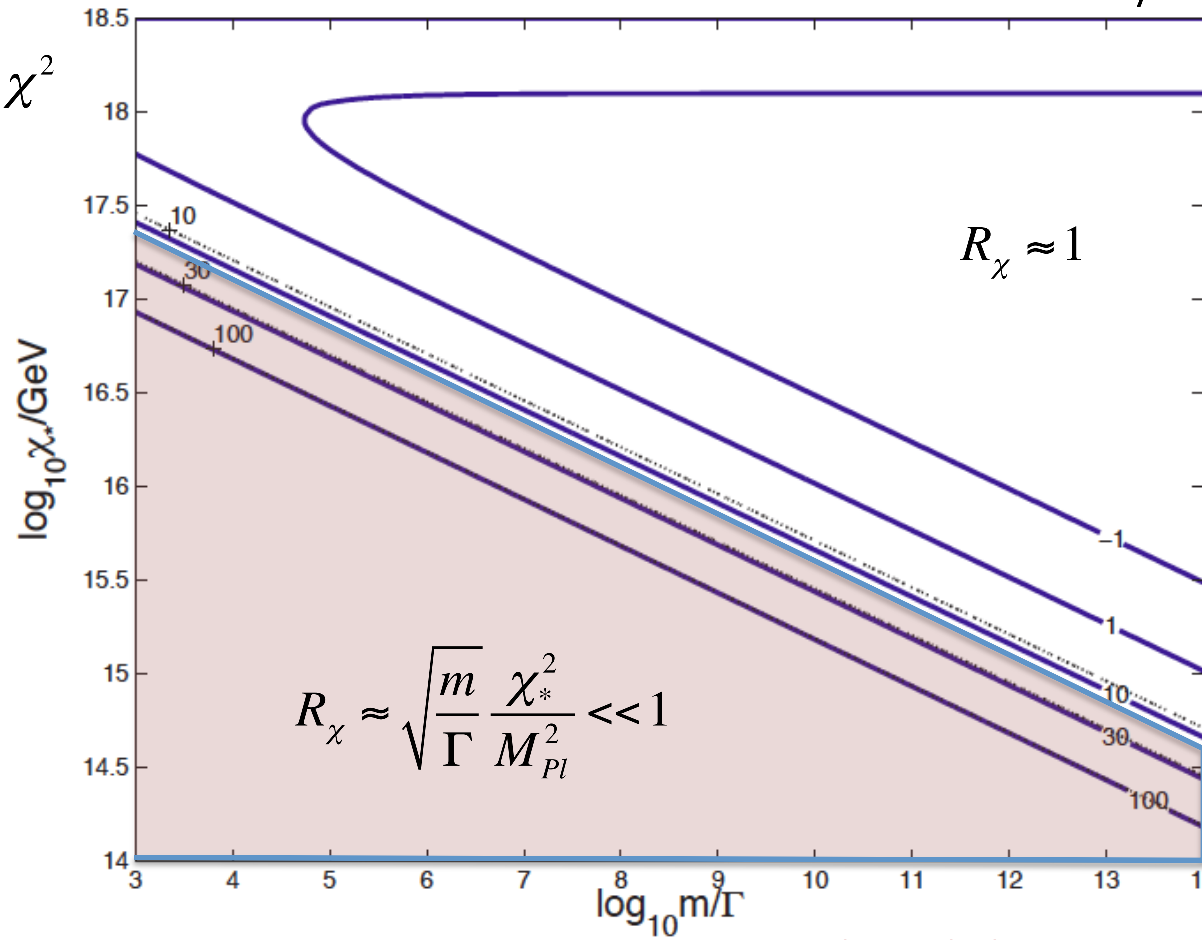
# Distinctive predictions

- Local non-Gaussianity requires non-adiabatic field fluctuations during inflation
  - *absence of evidence is not evidence of absence!*
- Curvaton model can produce almost Gaussian primordial perturbations, $|f_{NL}|\sim 1$
  - constraints on fNL do give important constraints on curvaton models

# $f_{NL}$ bounds on quadratic curvaton

Fonseca & Wands (2011)
see also Nakayama et al (2010)

$$V(\chi) = \frac{1}{2} m^2 \chi^2$$




$$R_\chi \approx 1$$

$$R_\chi \approx \sqrt{\frac{m}{\Gamma}} \frac{\chi_*^2}{M_{Pl}^2} << 1$$

Planck bounds $f_{NL}$

# Primordial power spectrum constraints

- Inflaton

$$P_\zeta \approx \frac{1}{8\pi^2\varepsilon}\left(\frac{H_*}{M_{Pl}}\right)^2$$

tilt: $n-1 = -6\varepsilon + 2\eta_\varphi$

$$P_T \approx \frac{2}{\pi^2}\left(\frac{H_*}{M_{Pl}}\right)^2$$

tensor-scalar ratio: $r_T = 16\varepsilon$

- Curvaton

$$P_\zeta \approx \frac{R_\chi^2}{9\pi^2}\left(\frac{H_*}{\langle\chi_*\rangle}\right)^2$$

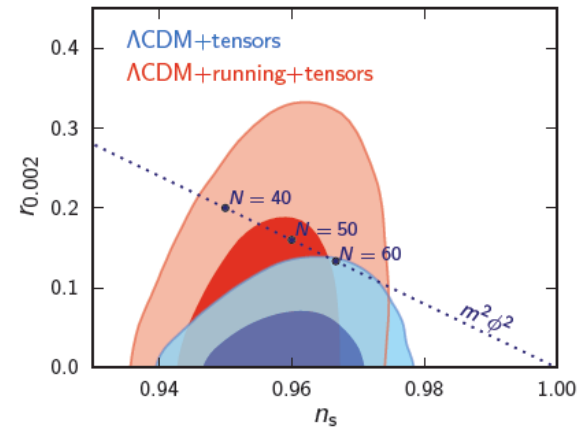
tilt: $n-1 = -2\varepsilon + 2\eta_\chi$

$$P_T \approx \frac{2}{\pi^2}\left(\frac{H_*}{M_{Pl}}\right)^2$$

tensor-scalar: $r_T = 18\langle\chi_*\rangle^2 / R_\chi^2 M_{Pl}^2 << 16\varepsilon$

slow roll parameters $\varepsilon = -\dot{H}/H^2$ , $\eta_i = m_i^2 / 3H^2$

- Planck 2013:
  - $n = 0.9624 \pm 0.0075$
  - $r_T < 0.012$



# Different perspectives

Inflaton viewpoint

- Tensor-scalar ratio bounds $\varepsilon < 0.01$
- Scalar tilt n=0.96 then favours $\eta_\varphi < 0$
  - E.g., axion e.g., axion $V(\varphi)=\Lambda^4(1-\cos(\varphi/f))$

Curvaton viewpoint

- Tensor-scalar ratio bounds $H_{inf}$ *(model-independent)*, not $\varepsilon$
- Scalar-tilt either
  - Large-field inflation: $\varepsilon \approx 0.02$ and $\eta_\chi \approx 0$
    - e.g., $\lambda\varphi^4$ (with N≈60) or $m^2\varphi^2$ (with N≈30 and late entropy from curvaton decay)
  - Small-field with $\eta_\chi < 0$ and $\varepsilon << 0.02$
    - e.g., axion $V(\chi)=\Lambda^4(1-\cos(\chi/f))$

# Mixed inflaton+curvaton

$$P_\zeta \approx \frac{1}{8\pi^2(1-w_\chi)\varepsilon}\left(\frac{H_*}{M_{Pl}}\right)^2 \quad \text{where} \quad w_\chi = \frac{8\varepsilon R^2 M_{Pl}^2}{8\varepsilon R^2 M_{Pl}^2 + 9\chi_*^2}$$

tilt: $n-1 = -(6-4w_\chi)\varepsilon + 2(1-w_\chi)\eta_\varphi + 2w_\chi\eta_\chi$

$$P_T \approx \frac{2}{\pi^2}\left(\frac{H_*}{M_{Pl}}\right)^2$$

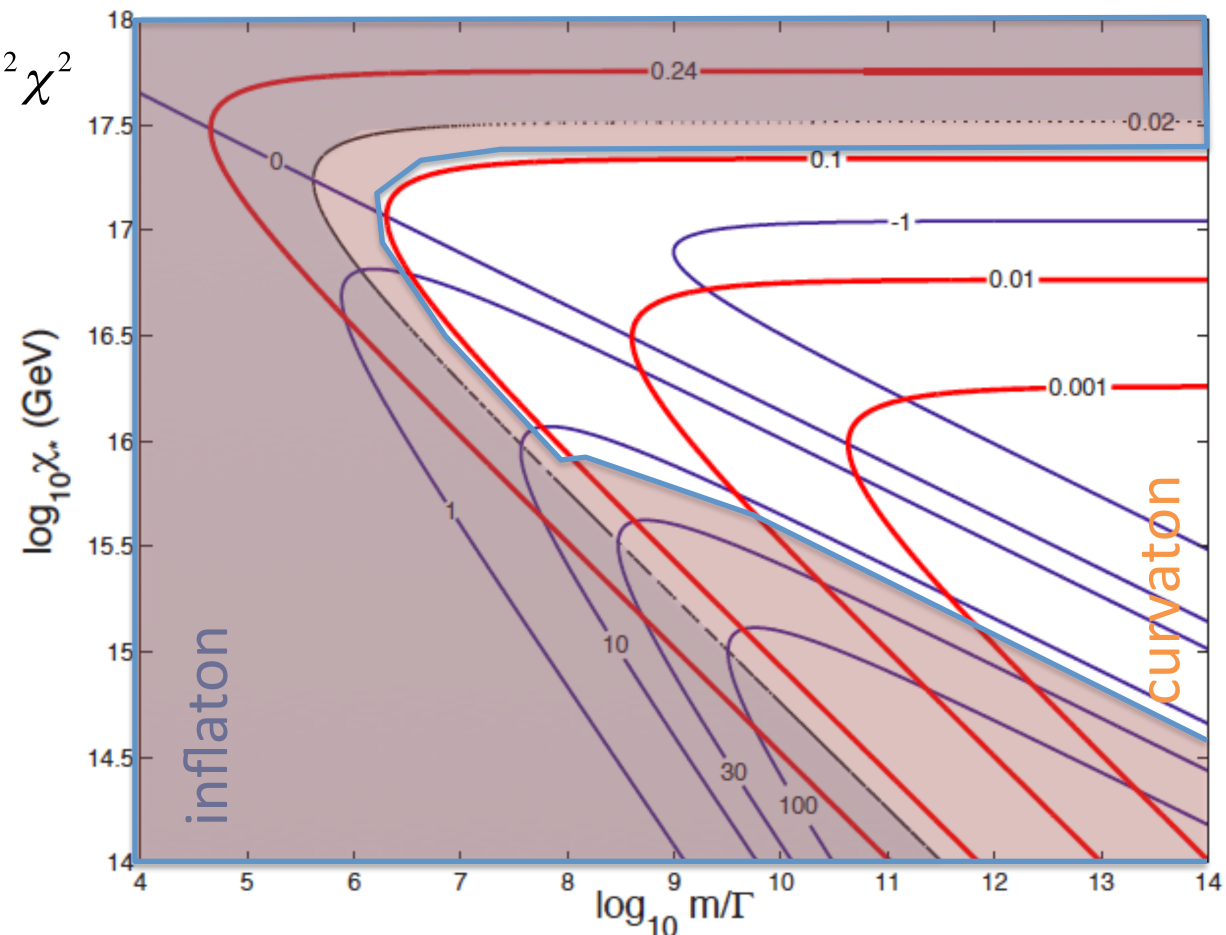
tensor-scalar ratio: $r_T = 16(1-w_\chi)\varepsilon \le 16\varepsilon$

slow roll parameters $\varepsilon = -\dot{H}/H^2$ , $\eta_i = m_i^2/3H^2$

# $f_{NL}$ + $r_T$ quadratic curvaton + inflaton: ε=0.02

Fonseca & Wands (2012)

$$V(\chi)=\frac{1}{2}m^2\chi^2$$

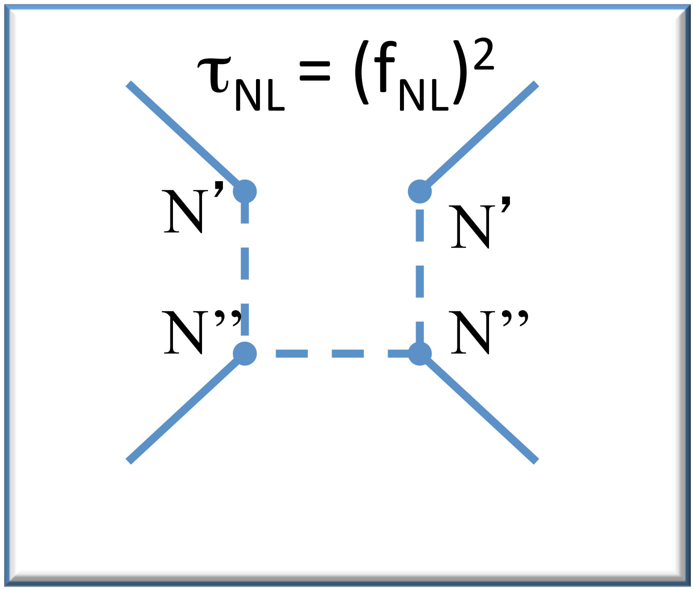


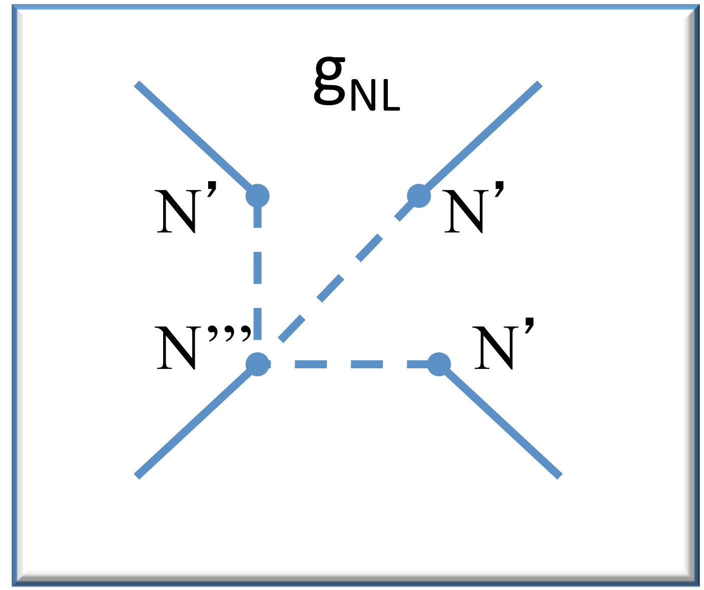

$$f_{NL}\approx\frac{5}{4R_\chi}w_\chi^2$$

Planck bounds $f_{NL}$ and $r_T$

# local trispectrum has 2 terms at leading order

$$\zeta = \zeta_1 + \frac{3}{5} f_{NL} \zeta_1^2 + \frac{9}{25} g_{NL} \zeta_1^3 + \cdots$$



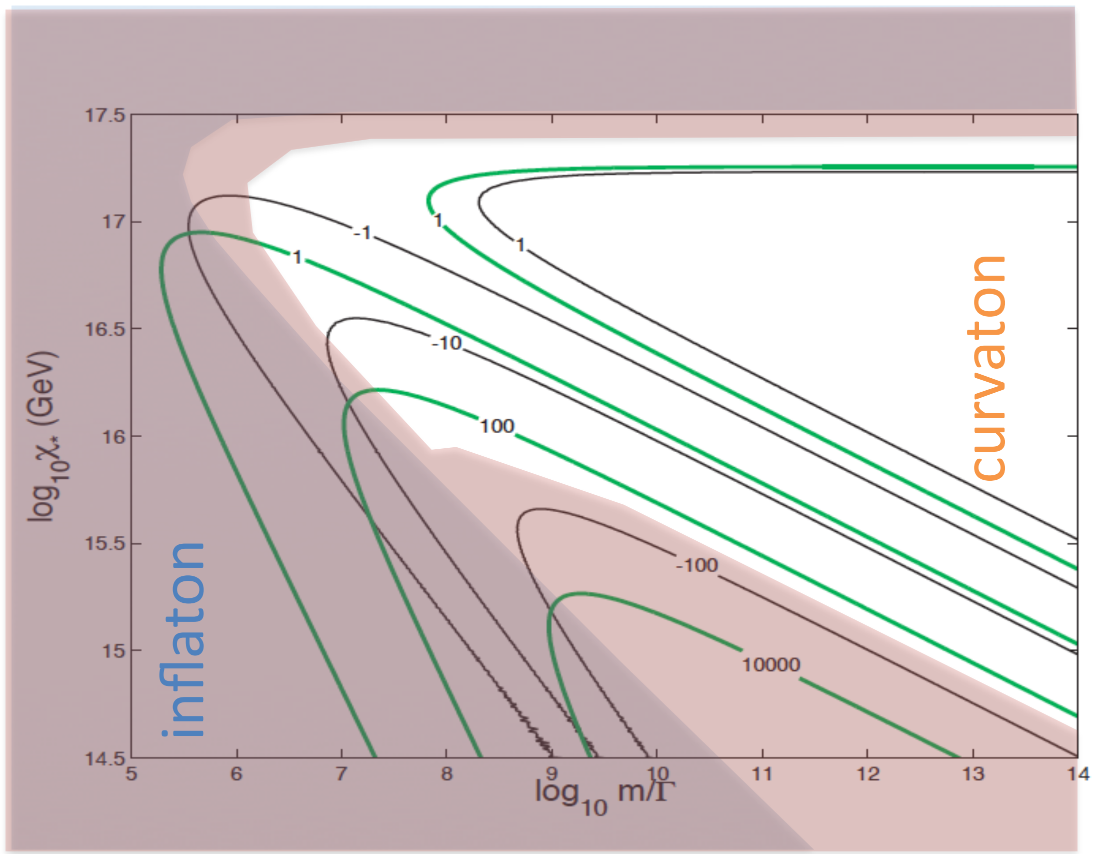




- can distinguish by different momentum dependence
- multi-source consistency relation: $\tau_{NL} \geq (f_{NL})^2$

# $g_{NL}$ + $\tau_{NL}$ quadratic curvaton + inflaton: ε=0.02

Fonseca & Wands (2012)

$$V(\chi) = \frac{1}{2} m^2 \chi^2$$




$$\tau_{NL} \approx \frac{f_{NL}^2}{w_\chi}$$

$$g_{NL} \approx f_{NL} w_\chi$$

Planck bounds $f_{NL}$ and $r_T$

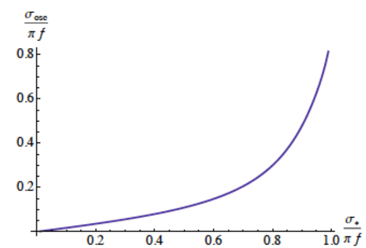
# self-interacting curvaton

Enqvist & Nurmi (2005)
Huang (2008)
Enqvist et al (2009)
...

$$V(\chi) = \frac{1}{2}m^2\chi^2 \pm m^2\frac{\chi^4}{f^2} + \dots$$

assume curvaton is **Gaussian at Hubble exit** during inflation, but allow for **non-linear evolution** on large scales before oscillating about quadratic minimum

$$\chi_{osc} = g(\chi_*) \quad \Rightarrow \quad \chi_{osc} = g + g'\delta\chi + \frac{1}{2}g''(\delta\chi)^2 + \dots$$

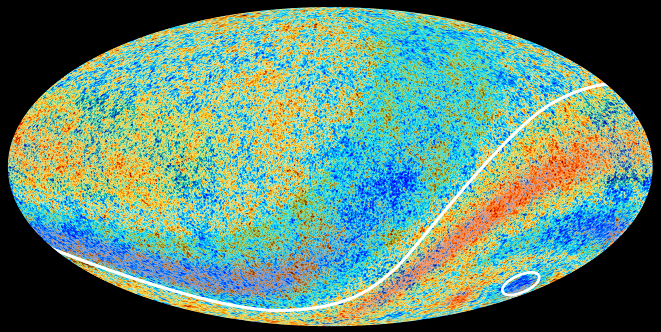



e.g. **axion curvaton**: n=0.96 => $m^2=-0.06H_*^2$ => **"hill-top" curvaton**: g">0

Kawasaki, Kobayashi & Takahashi (2012)

$$f_{NL} = \frac{5}{4R_\chi}\left(\frac{g''g}{g'^2}\right) \quad , \quad \tau_{NL} = \frac{36}{25}f_{NL}^2 \quad \sim \quad g_{NL} = \frac{27}{4R_\chi^2}\left(\frac{g''g}{g'^2} + \frac{g'''g^2}{3g'^3}\right)$$

# asymmetries in the data:



**Hemispherical power asymmetry**

- Dipole modulation?

$$\zeta = \zeta_G + \frac{3}{5} f_{NL} \left( \zeta_G^2 - \left\langle \zeta_G^2 \right\rangle \right) + \ldots$$

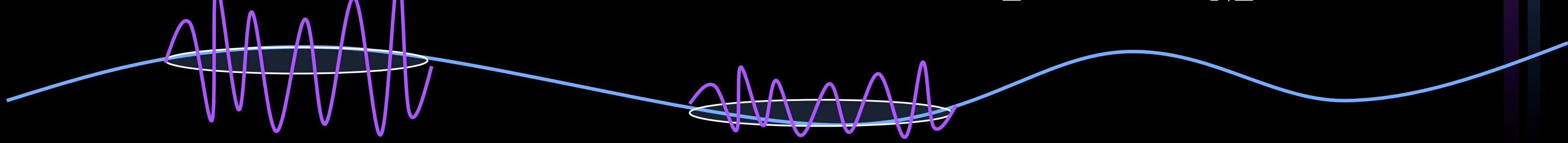
short+long wavelength split: $\zeta_G = \zeta_S + \zeta_L$

$$\Rightarrow \quad \zeta = \left( \zeta_S + \zeta_L \right) + \frac{3}{5} f_{NL} \left( \zeta_S^2 + 2\zeta_S \zeta_L + \zeta_L^2 - \left\langle \zeta_S^2 + \zeta_L^2 \right\rangle \right) + \ldots$$

$$\Rightarrow \quad \tilde{\zeta} = \left( 1 + \frac{6}{5} f_{NL} \zeta_L \right) \zeta_S + \frac{3}{5} f_{NL} \left( \zeta_S^2 - \left\langle \zeta_S^2 \right\rangle \right) + \ldots$$

i.e., long-wavelength modulation $\tilde{\zeta} = \left( 1 + A_L \right) \zeta_S$ where $A_L = \frac{6}{5} f_{NL} \zeta_L$

- Grishchuk-Zeldovich effect (Lyth 2013): $A_L < 0.01\, f_{NL}$



# Conclusions:

- ***Curvaton*** provides a simple non-adiabatic model for origin of structure
  - Local non-Gaussianity ($|f_{NL}|>1$) requires non-adiabatic model
  - but, non-adiabatic model does *not* require significant non-Gaussianity
  - Tensor-scalar ratio bounds inflation energy scale, not $\varepsilon$
- ***Quadratic curvaton well-described by simplest local $f_{NL}$***
  - *$n \approx 0.96$ requires large-field inflation, $\varepsilon \approx 0.02$*
- ***Many variants***
  - *self-interactions ($\tau_{NL}$ and $g_{NL}$ still small)*
  - *curvaton+inflaton ($\tau_{NL}$ could be large, scale-dependent $f_{NL}$)*
- ***Many potential observables:***
  - *trispectrum, isocurvature (bi)spectra, large-scale power modulation…*