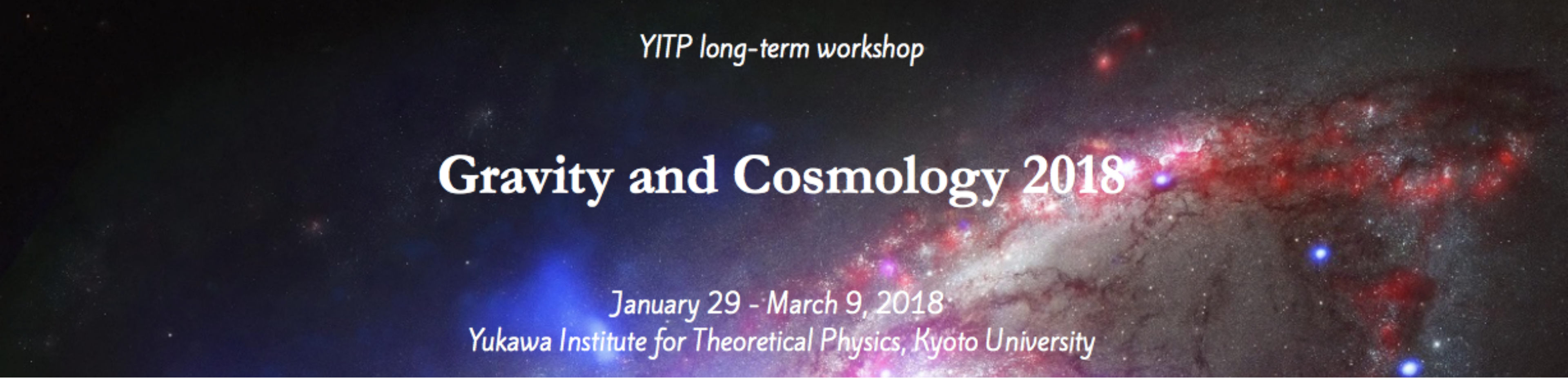

Seeing stochastic inflation

David Wands

Institute of Cosmology and Gravitation, University of Portsmouth

work with

Rob Hardwick, Chris Pattison, Vincent Vennin, Hooshyar Assadullahi

Chris Byrnes, Hassan Firouzjahi, Mahdiyar Noorbala & Jesus Torrado

ICG Portsmouth

UNIVERSITY OF PORTSMOUTH

27th February 2018


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Three applications of stochastic inflation

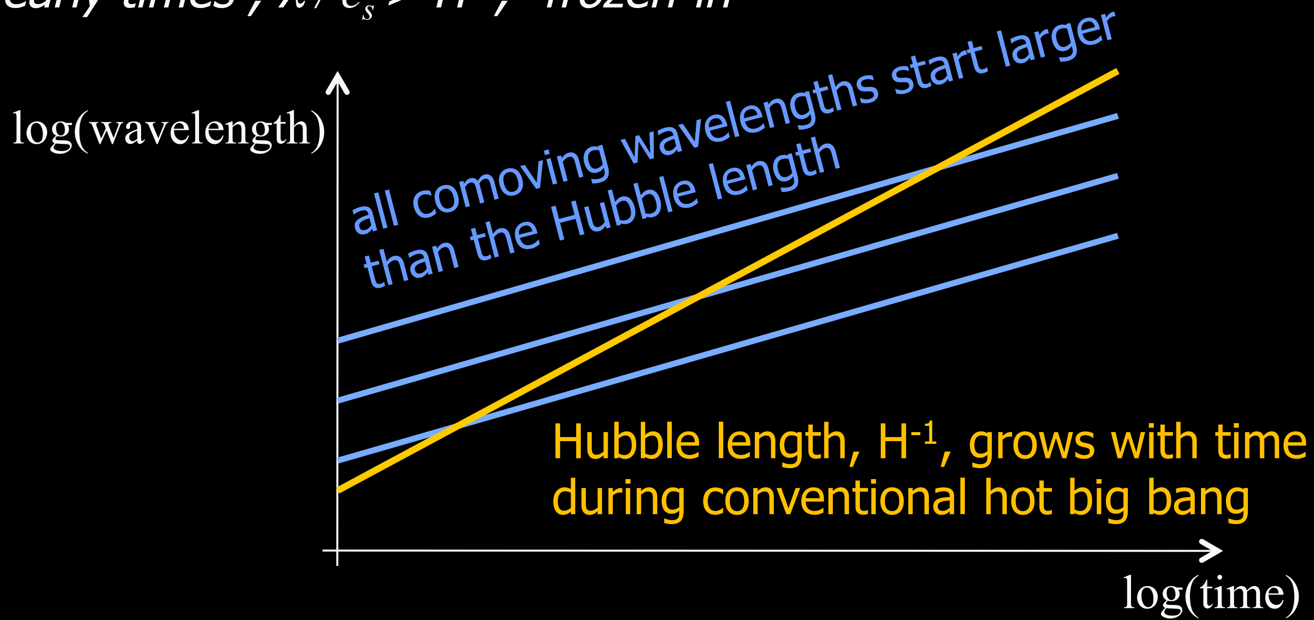
1. Primordial density perturbations can be sensitive to **Planck scale physics**
   - *Assasdullahi, Firouzjahi, Noorbala, Vennin & Wands (2016)*
2. Stochastic approach gives **full probability distribution function for density perturbations** needed, e.g., for **primordial black hole** abundance
   - *Pattison, Assadullahi, Vennin & Wands (2017)*
3. Bayesian **model comparison sensitive to stochastic distribution** of multiple fields
   - *Torrado, Byrnes, Hardwick, Vennin & Wands (2017)*

Inflation = origin of super-Hubble structure

$$\delta\ddot{\rho} + 3H\delta\dot{\rho} + (c_S / \lambda)^2 \delta\rho = 0$$

Characteristic timescales for density waves with fixed comoving wavelength

- *small-scales = late times,* $\lambda / c_s < H^{-1}$ *, under-damped oscillator*
- *large-scales = early times ,* $\lambda / c_s > H^{-1}$*, "frozen-in"*



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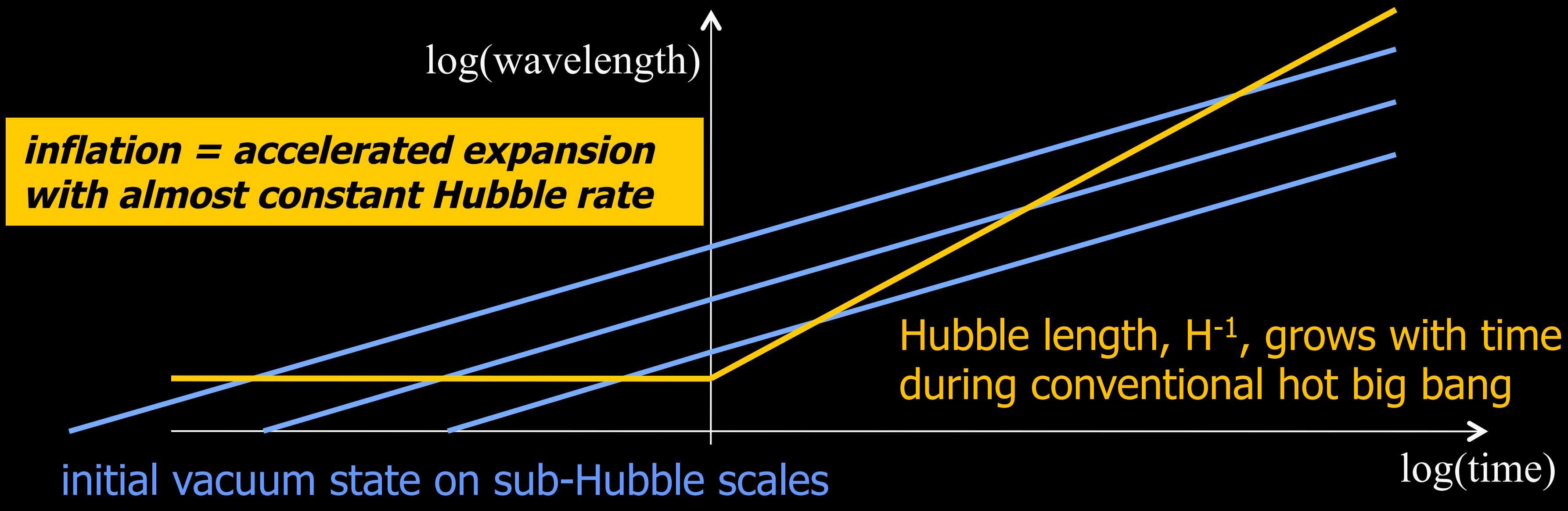
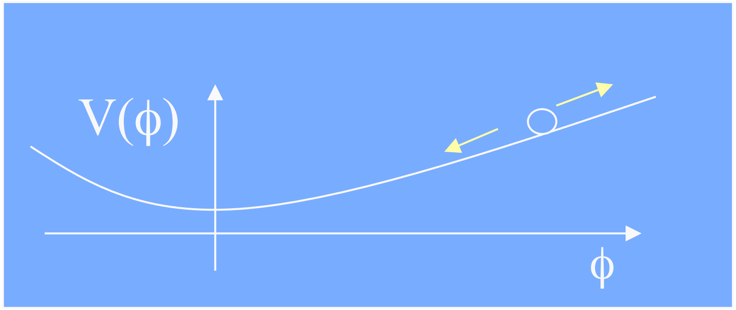


vacuum fluctuations



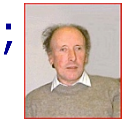
$$\delta\ddot{\varphi} + 3H\delta\dot{\varphi} + \frac{k^2}{a^2}\delta\varphi = 0$$

- *sub-Hubble/underdamped zero-point oscillations:* $\delta\phi_k \approx \frac{e^{-ik\eta}}{\sqrt{2k}}$
- *super-Hubble/overdamped perturbations in squeezed state:*

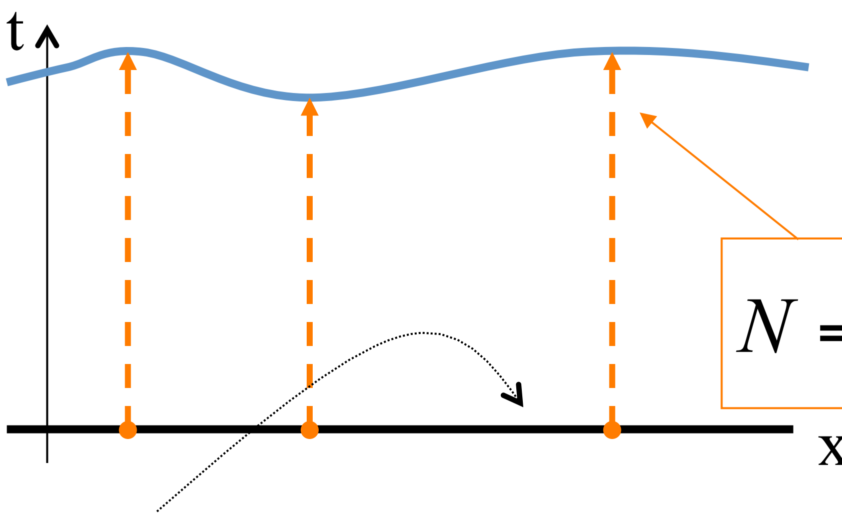
$$\left\langle \delta\phi^2 \right\rangle_{k=aH} \approx \frac{4\pi k^3 \left|\delta\phi_k{}^2\right|}{(2\pi)^3} = \left(\frac{H}{2\pi}\right)^2$$

  - *sub-Hubble vacuum fluctuations are constantly crossing the Hubble scale (k=aH) into the coarse-grained super-Hubble field*

δN formalism for primordial density perturbations

 Starobinsky '85;  Sasaki & Stewart '96;  Lyth & Rodriguez '05

after inflation: **curvature perturbation ζ on uniform-density hypersurface**



$$N = \int_{initial}^{final} H\, dt$$

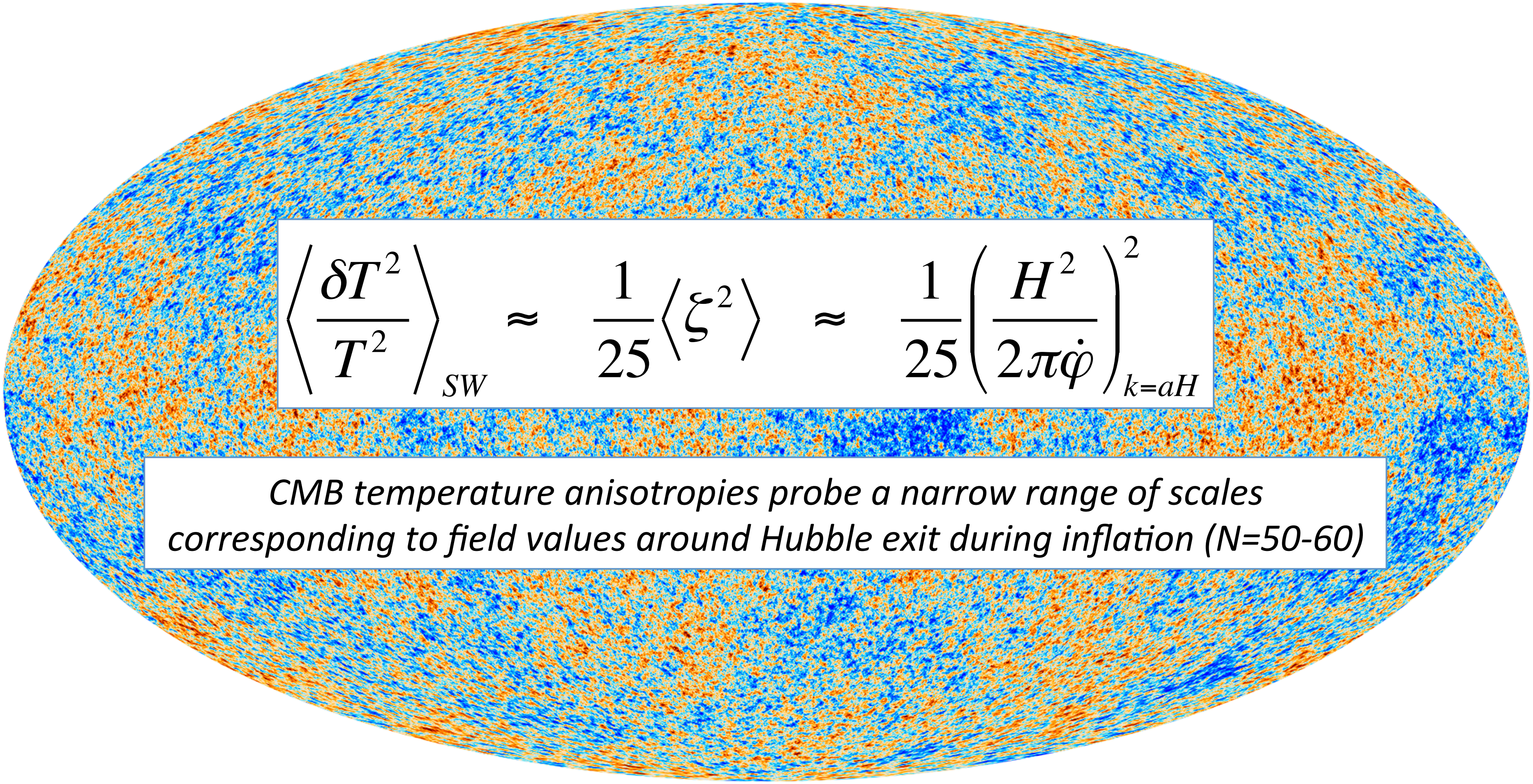
during inflation: **field perturbations $\phi(x,t_i)$ on initial spatially-flat hypersurface**

on super-Hubble scales, evolve as **"separate universes"** (neglect spatial gradients):

$$\zeta = N(\phi_{initial}) - \bar{N} \approx \sum_I \frac{\partial N}{\partial \phi_I} \delta\phi_I$$

Seeing vacuum fluctuations

Planck collaboration 2015



$$\left\langle \frac{\delta T^2}{T^2} \right\rangle_{SW} \approx \frac{1}{25}\left\langle \zeta^2 \right\rangle \approx \frac{1}{25}\left(\frac{H^2}{2\pi\dot{\varphi}} \right)^2_{k=aH}$$

CMB temperature anisotropies probe a narrow range of scales corresponding to field values around Hubble exit during inflation (N=50-60)

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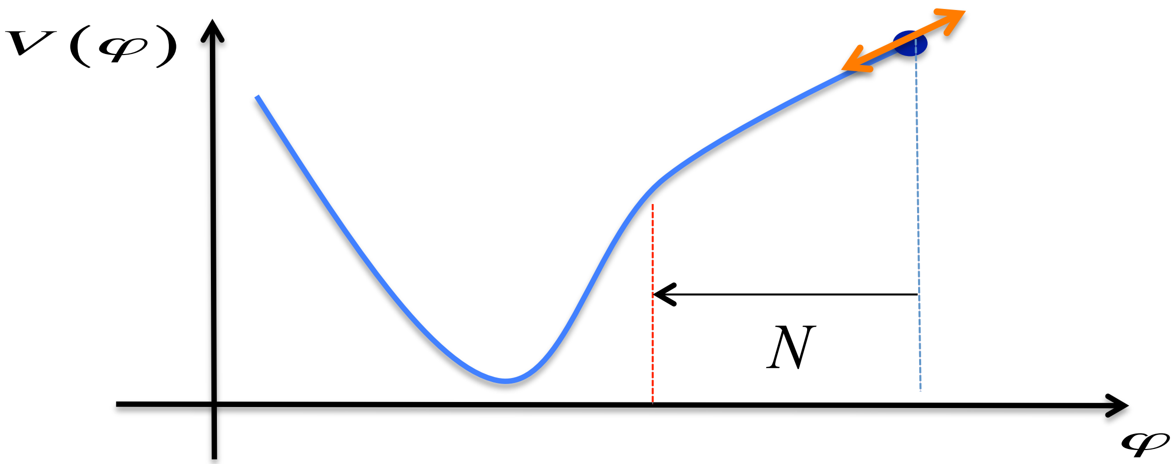
Stochastic inflation

Starobinsky (1986)

- Quantum fluctuations swept up to super-Hubble scales give stochastic kick, $\xi(N)$, to coarse-grained (k<aH) field

$$\frac{d\varphi}{dN} = -\frac{V'}{3H^2} + \frac{H}{2\pi}\xi(N)$$

- Number of e-folds to the end of inflation, $\mathcal{N}$, from a given field value, φ, becomes a stochastic variable



Stochastic $\mathcal{N}$ Vennin & Starobinsky (2015)

$$\frac{\partial\phi}{\partial N}+\frac{V'}{3H^2}=\frac{H}{2\pi}\xi \longleftrightarrow \frac{\partial}{\partial N}P(\phi,N)=\frac{\partial}{\partial\phi}\left[\frac{V'}{3H^2}P(\phi,N)\right]+\frac{\partial^2}{\partial\phi^2}\left[\frac{H^2}{8\pi^2}P(\phi,N)\right]$$

$$=-\mathcal{L}_{\mathrm{FP}}\cdot P(\phi,N)$$

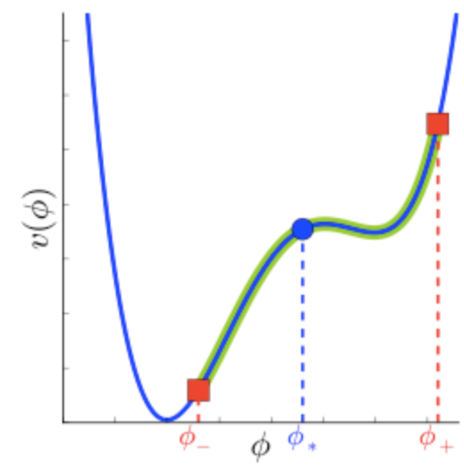
Langevin equation

Fokker-Planck equation

First Passage Time: Louis Bachelier, 1900 $\mathcal{L}_{\mathrm{FP}}^{\dagger}\cdot\langle\mathcal{N}\rangle(\phi_*)=1$

$$\langle\mathcal{N}\rangle'' v-\langle\mathcal{N}\rangle'\frac{v'}{v}=-1 \quad \text{where} \quad v=V/(24\pi^2M_{\mathrm{Pl}}^4)$$

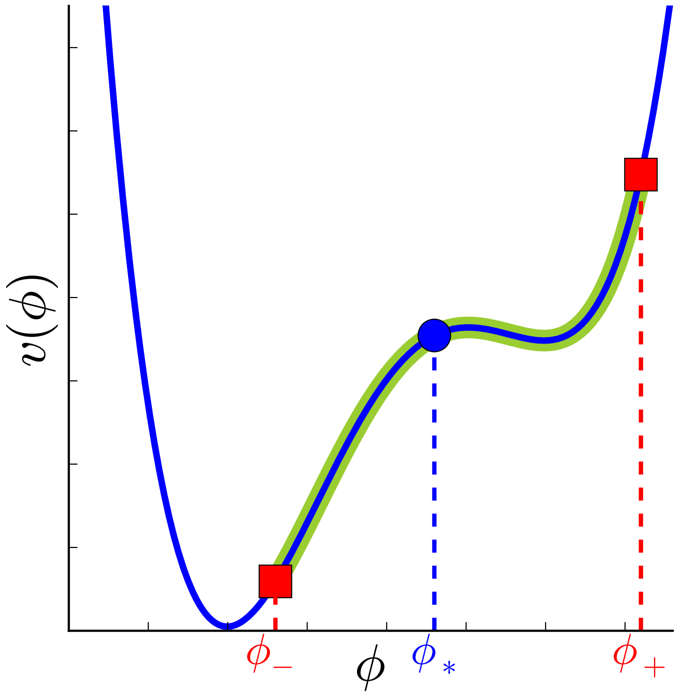
$$\langle\mathcal{N}\rangle=\int_{\phi_{\mathrm{end}}}^{\phi_*}\frac{\mathrm{d}x}{M_{\mathrm{Pl}}}\int_x^{\bar\phi}\frac{\mathrm{d}y}{M_{\mathrm{Pl}}}\frac{1}{v(y)}\exp\left[\frac{1}{v(y)}-\frac{1}{v(x)}\right]$$



Stochastic δN

Vennin & Starobinsky (2015)

see also Enqvist et al (2008);
Fujita, Kawasaki, Tada & Takesako (2013, 2014)



$$\langle \mathcal{N} \rangle = \int_{\phi_-}^{\phi_*} \frac{\mathrm{d}x}{M_{\mathrm{Pl}}} \int_{x}^{\phi_+} \frac{\mathrm{d}y}{M_{\mathrm{Pl}}} \frac{e^{\frac{1}{v(y)} - \frac{1}{v(x)}}}{v(y)}$$

where dimensionless potential : $v(\phi) \equiv \dfrac{V(\phi)}{24\pi^2 M_{\mathrm{Pl}}^4}$

$$\zeta = \mathcal{N} - \langle \mathcal{N} \rangle$$

- integration domain covers the entire field space

Saddle Point Approximation

$$\langle \mathcal{N} \rangle = \int_{\phi_{\mathrm{end}}}^{\phi_*} \frac{\mathrm{d}x}{M_{\mathrm{Pl}}} \int_x^{\bar{\phi}} \frac{\mathrm{d}y}{M_{\mathrm{Pl}}} \frac{1}{v(y)} \exp\left[\frac{1}{v(y)} - \frac{1}{v(x)}\right]$$

$$\left| 2v - \frac{v'' v^2}{v'^2} \right| \ll 1$$

$$\langle \mathcal{N} \rangle \simeq \int_{\phi_{\mathrm{end}}}^{\phi_*} \frac{\mathrm{d}x}{M_{\mathrm{Pl}}^2} \frac{v(x)}{v'(x)} \left[1 + v(x) - \frac{v''(x)\, v^2(x)}{v'^2(x)} + \cdots\right]$$

Classical result

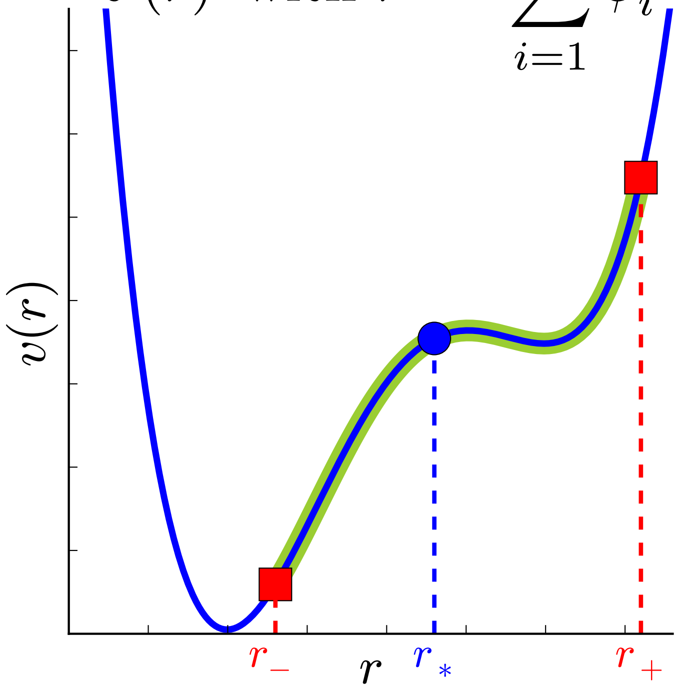
First order correction

Vennin & Starobinsky (2016)

Infinite inflation and number of fields (D)

Vennin, Assadullahi, Firouzjahi, Noorbala & Wands (2016)

$v(r)$ with $r^2 = \sum_{i=1}^{D} \phi_i^2$



$$\langle \mathcal{N} \rangle = \int_{r_-}^{r_*} \frac{\mathrm{d}x}{M_{\mathrm{Pl}}} \int_{x}^{r_+} \frac{\mathrm{d}y}{M_{\mathrm{Pl}}} \frac{e^{\frac{1}{v(y)} - \frac{1}{v(x)}}}{v(y)} \left(\frac{y}{x}\right)^{D-1}$$

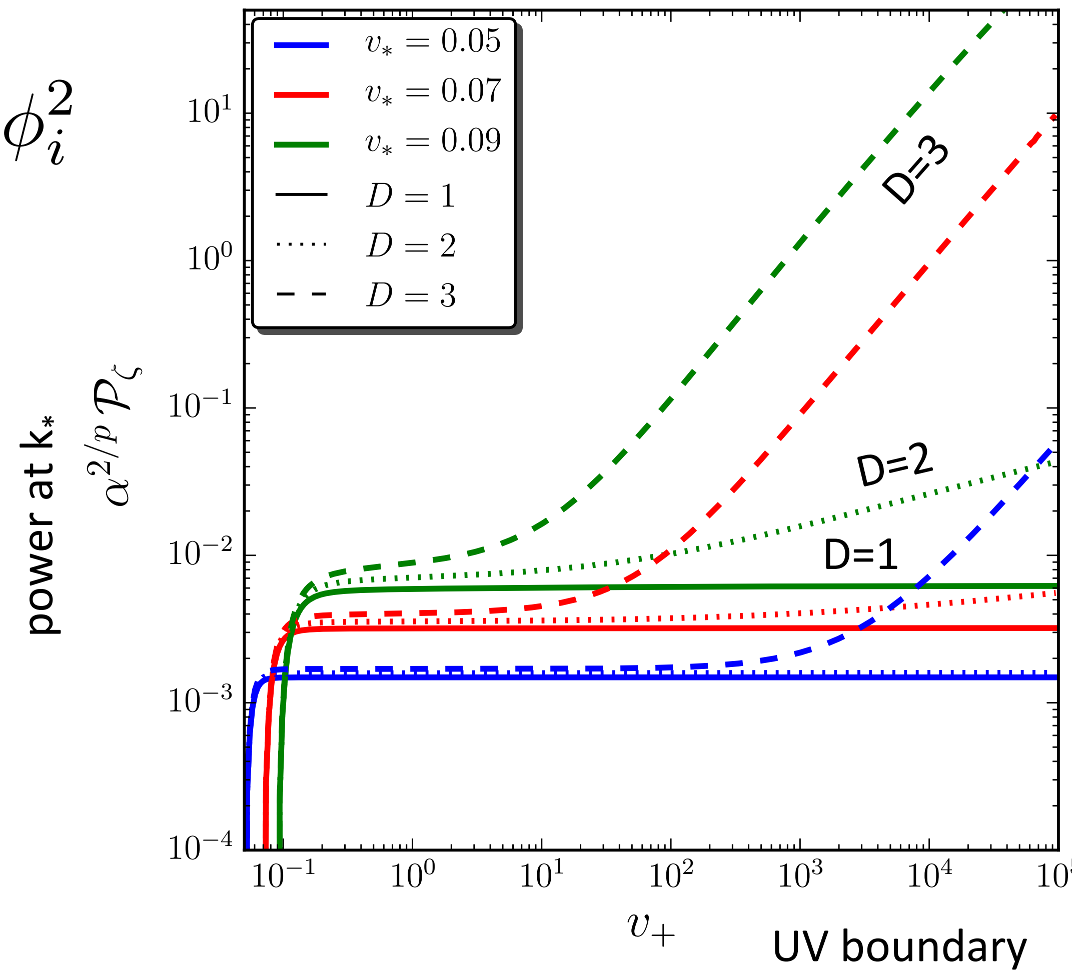
- integration domain covers the entire field space
- what if $r_+ \to \infty$? $\quad v(r) \propto r^p \quad \longrightarrow \quad \langle \mathcal{N} \rangle = \infty$ if $p \leq D$

Stochastic δ$\mathcal{N}$

Vennin, Assadullahi, Firouzjahi, Noorbala & Wands (2016)

D>2 requires UV regularisation (boundary) at $v_+ \sim \mathrm{M_{Pl}}$

$$v \propto \sum_{i=1}^{D} \phi_i^2$$



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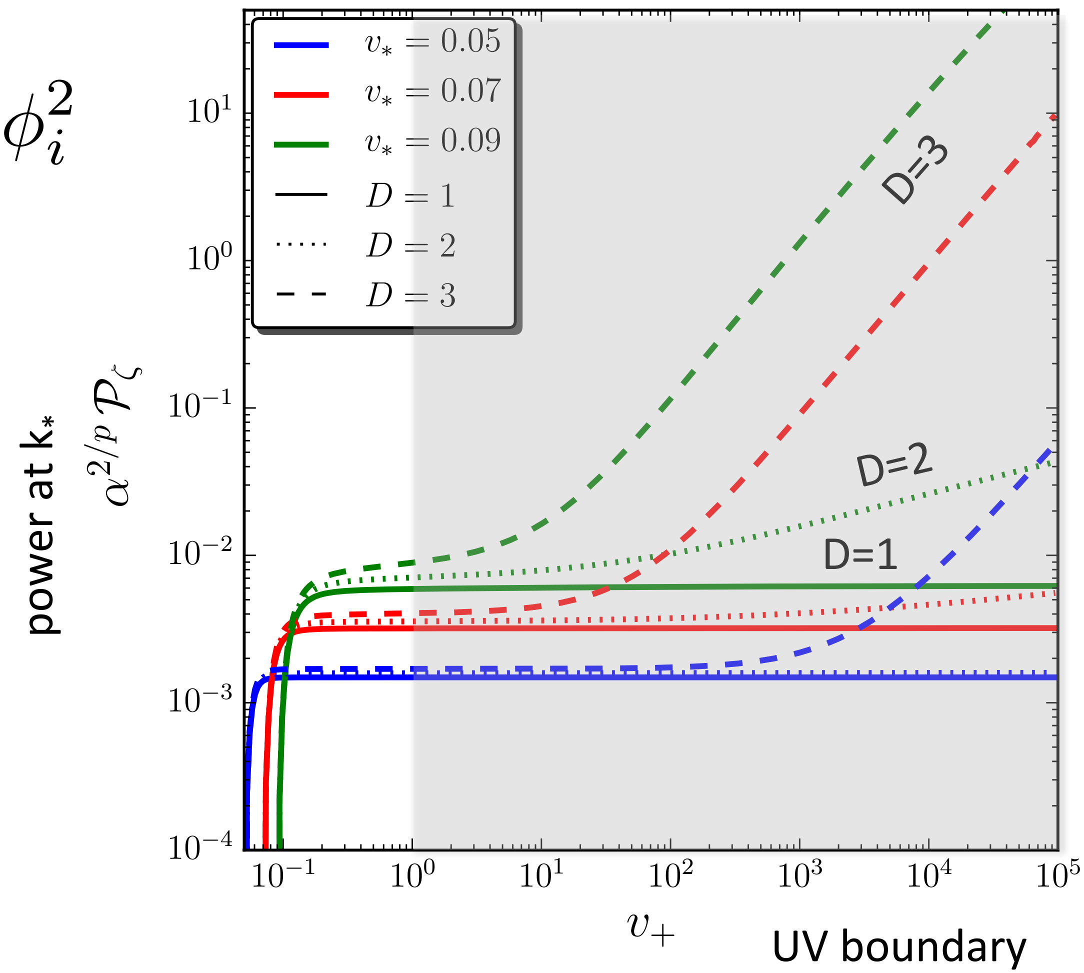

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Primordial black holes from inflation

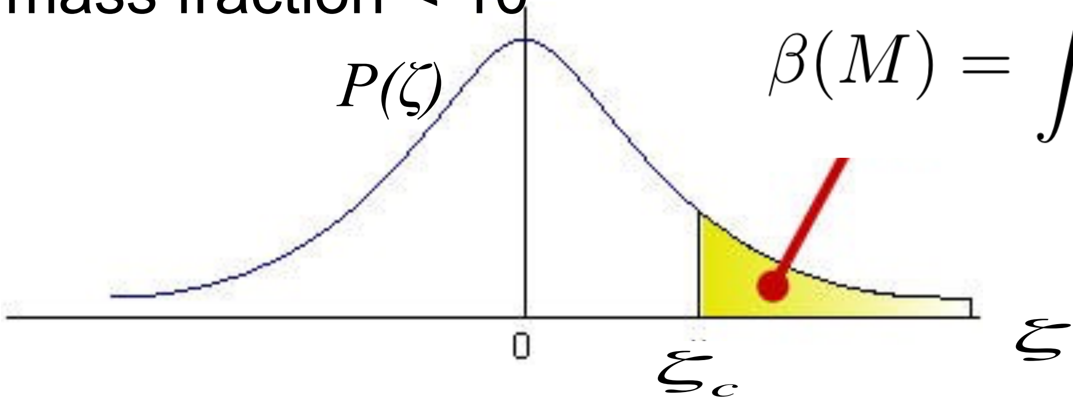
- primordial density perturbations when modes re-enter Hubble-scale after inflation

$$\left.\frac{\delta\rho}{\rho}\right|_{k=aH} \sim \zeta$$

- rare fluctuations exceeding critical value, $\zeta > \zeta_c \sim 1$, collapse to form black holes

- $\beta(M)$ = mass fraction < 10^{-8}

$$\beta(M) = \int_{\zeta_c}^{\infty} P(\zeta) d\zeta$$



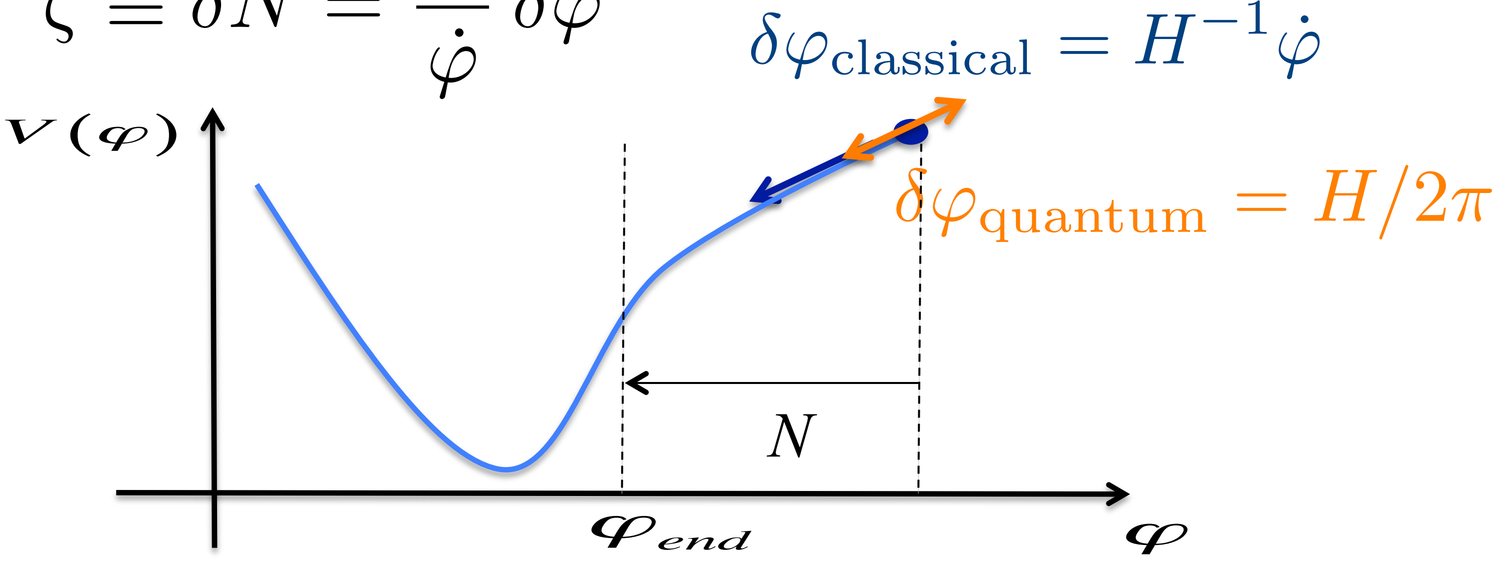
Classical vs quantum inflation

- **Classical** slow-roll inflates universe

$$N = \int H\, dt = \int \frac{H}{\dot{\varphi}}\, d\varphi$$

- **Quantum** field fluctuations lead to primordial metric perturbations

$$\zeta \equiv \delta N = \frac{H}{\dot{\varphi}}\, \delta\varphi$$



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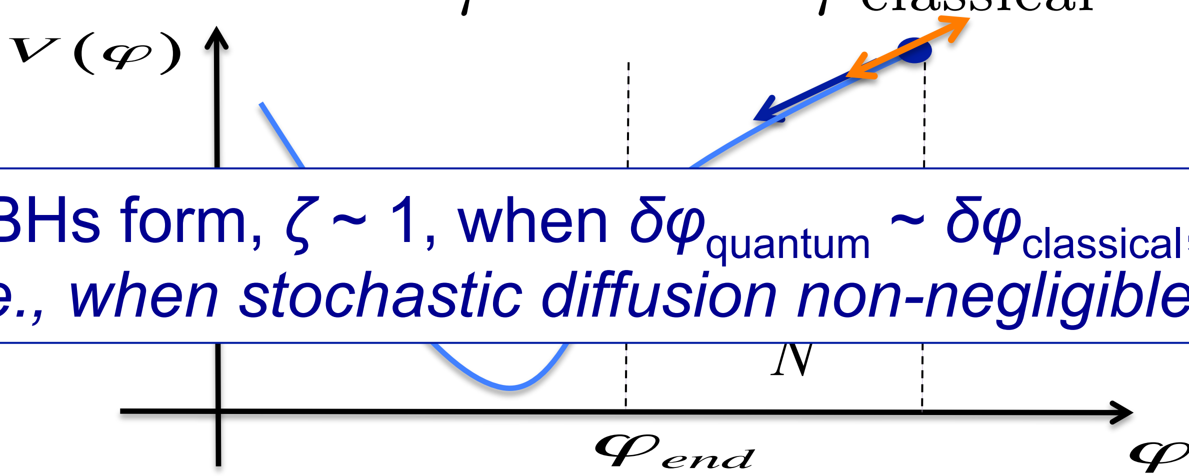
- **Quantum** field fluctuations lead to primordial metric perturbations

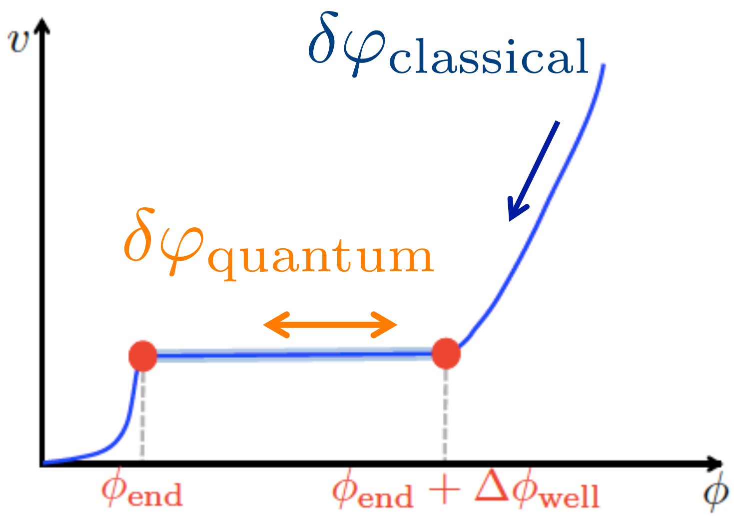
$$\zeta \equiv \delta N = \frac{H}{\dot{\varphi}}\, \delta\varphi = \frac{\delta\varphi_{\mathrm{quantum}}}{\delta\varphi_{\mathrm{classical}}}$$



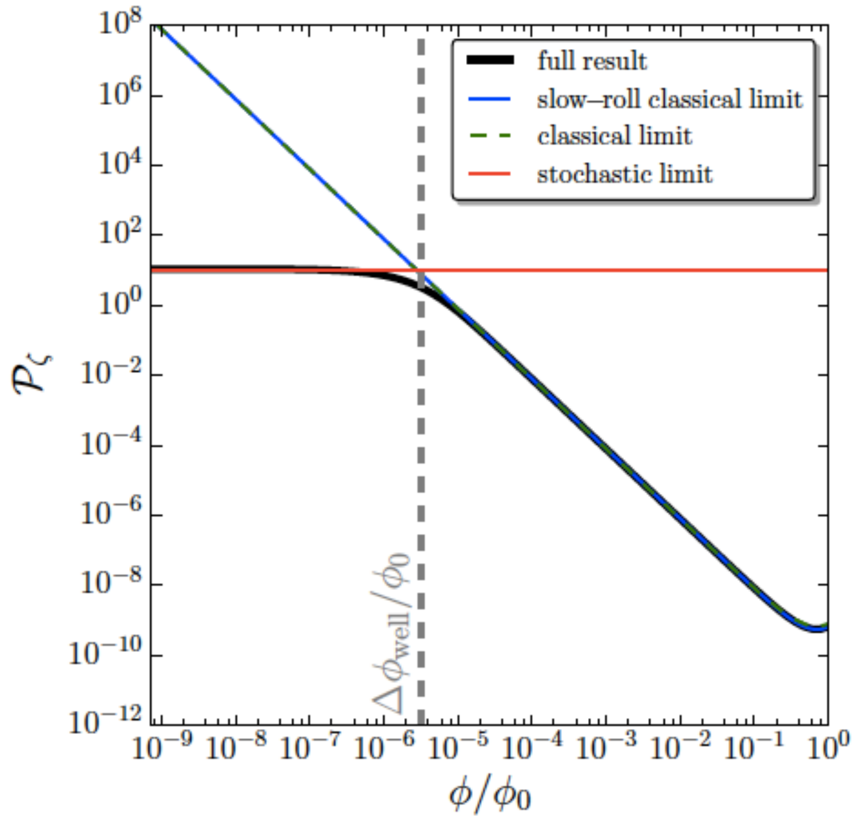
PBHs form, $\zeta \sim 1$, when $\delta\varphi_{\mathrm{quantum}} \sim \delta\varphi_{\mathrm{classical}}$,
i.e., when stochastic diffusion non-negligible

Plateau at end of inflation Pattison et al (2017)

- large deviations from classical δN when quantum diffusion dominates over classical drift near end of inflation: $\phi < \phi_{\rm end} + \Delta\phi_{\rm well}$



$$v = v_0 \left[1 + \left(\frac{\phi}{\phi_0} \right)^p \right]$$



Full PDF for *δN* Pattison et al (2017)

- number of e-folds is a stochastic variable, $\mathcal{N}(\phi)$

$$\zeta = \mathcal{N} - \langle \mathcal{N} \rangle$$

- define characteristic function (includes all the moments)

$$\chi_{\mathcal{N}}(t,\varphi) = \langle e^{it\mathcal{N}(\varphi)} \rangle = \int e^{it\mathcal{N}(\varphi)}\, P(\mathcal{N},\varphi)\, d\mathcal{N}$$

- obeys differential equation

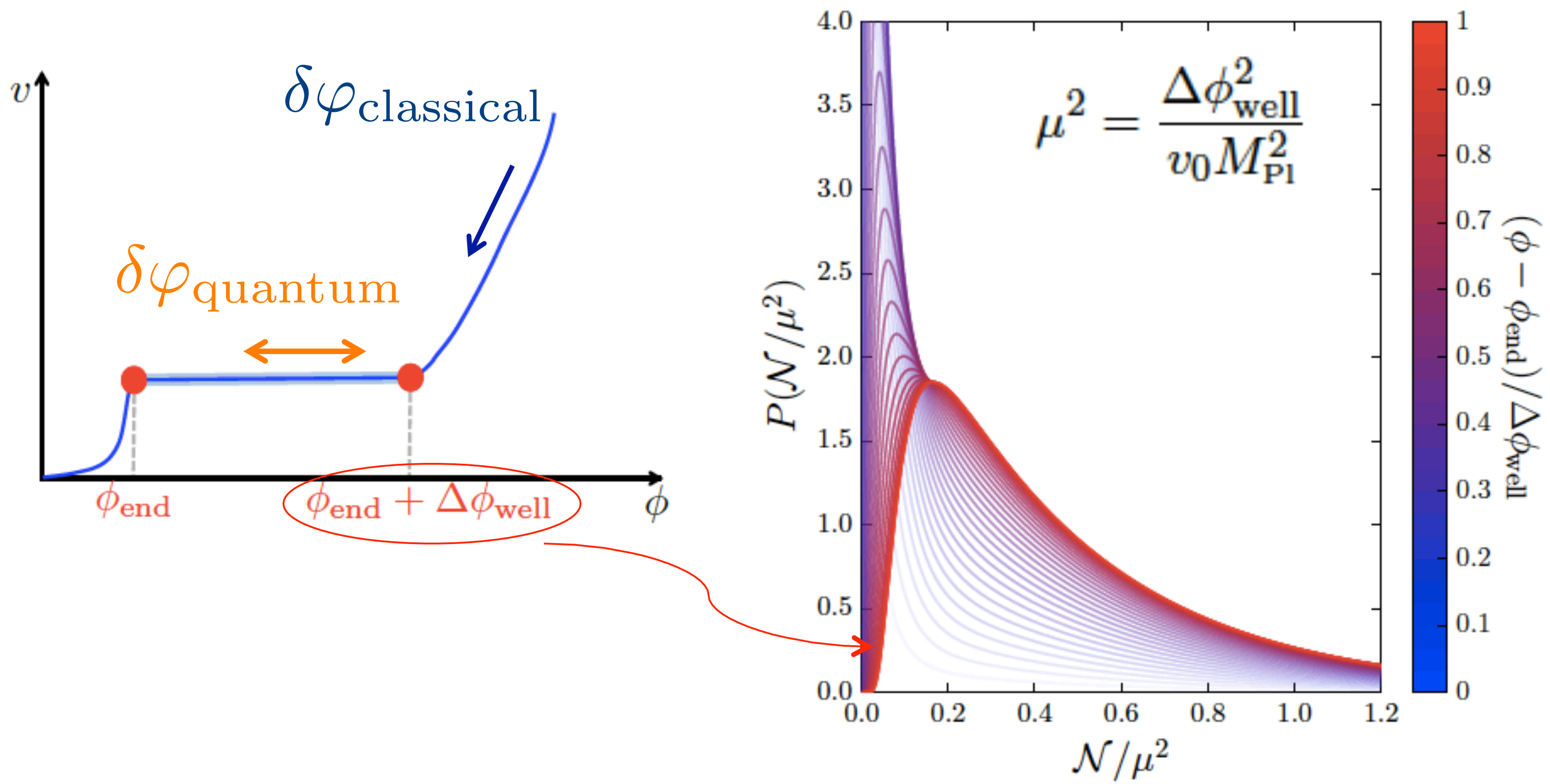
$$\left(\frac{\partial^2}{\partial \phi^2} - \frac{v'}{v^2}\frac{\partial}{\partial \phi} + \frac{it}{v M_{\rm Pl}^2} \right) \chi_{\mathcal{N}}(t,\phi) = 0$$

- inverse Fourier transform gives full probability distribution

$$P(\mathcal{N},\varphi) = \frac{1}{2\pi} \int_{-\infty}^{\infty} e^{-it\mathcal{N}}\, \chi_{\mathcal{N}}(t,\varphi)\, dt$$

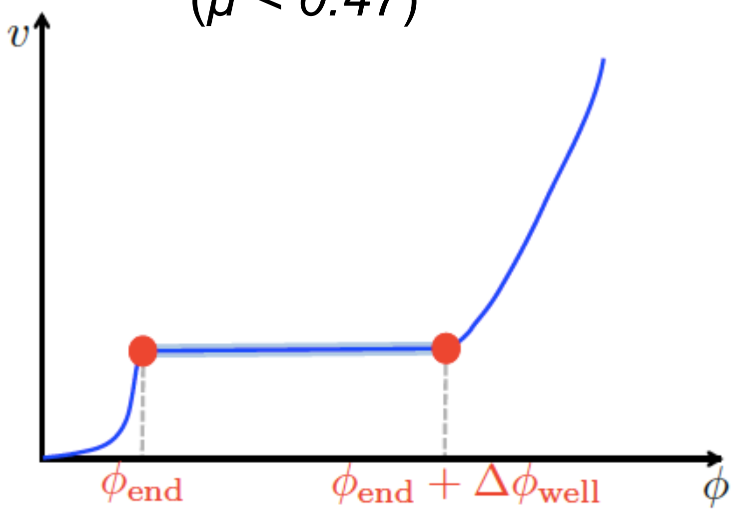
Plateau at end of inflation Pattison et al (2017)

- large deviations from classical δN when quantum diffusion dominates over classical drift -> non-Gaussian probability distribution

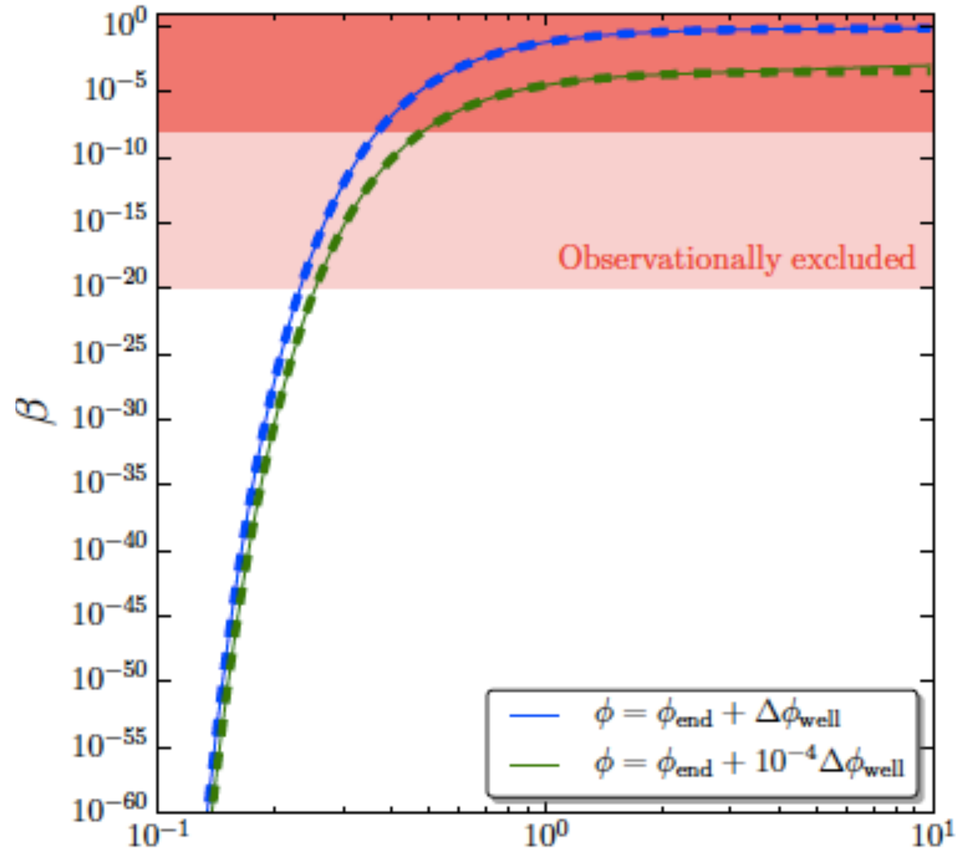


Plateau at end of inflation Pattison et al (2017)

- require number of e-folds in quantum diffusion dominated regime N < 1
  ($\mu < 0.47$)



mass fraction of primordial black holes



$$\mu^2 = \frac{\Delta\phi_{\rm well}^2}{v_0 M_{\rm Pl}^2}$$

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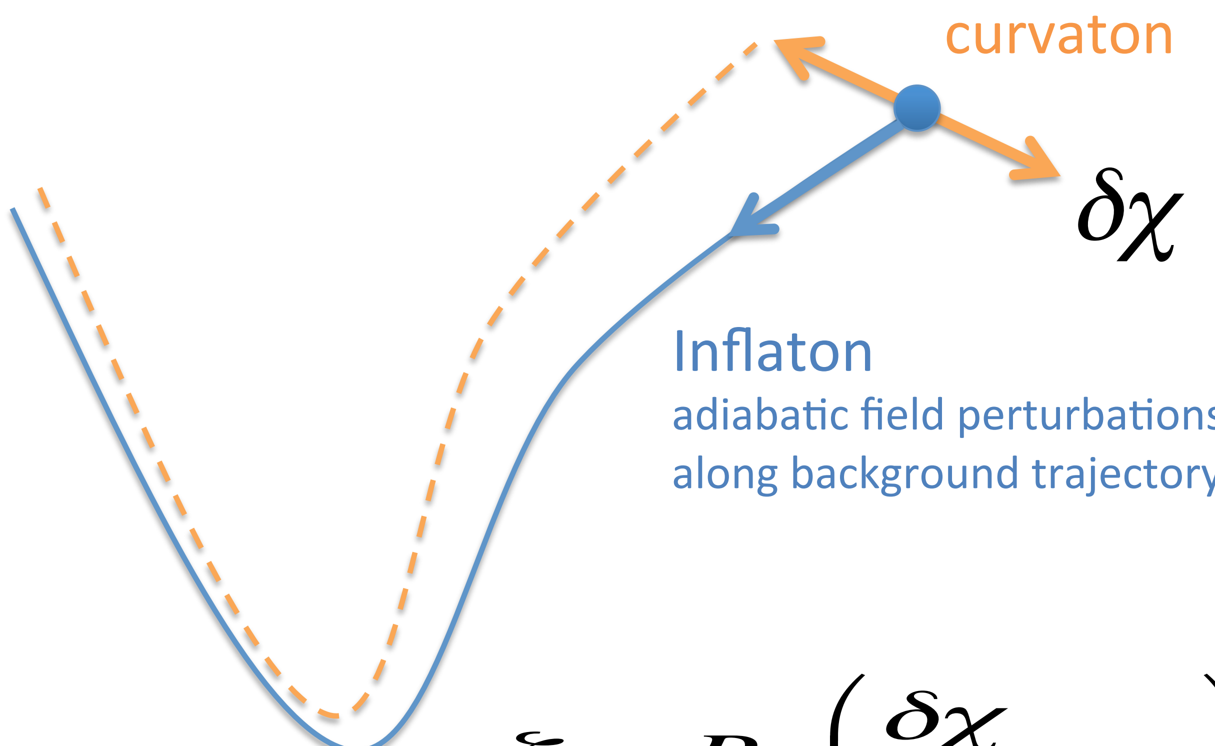
what is the origin of primordial density perturbations?



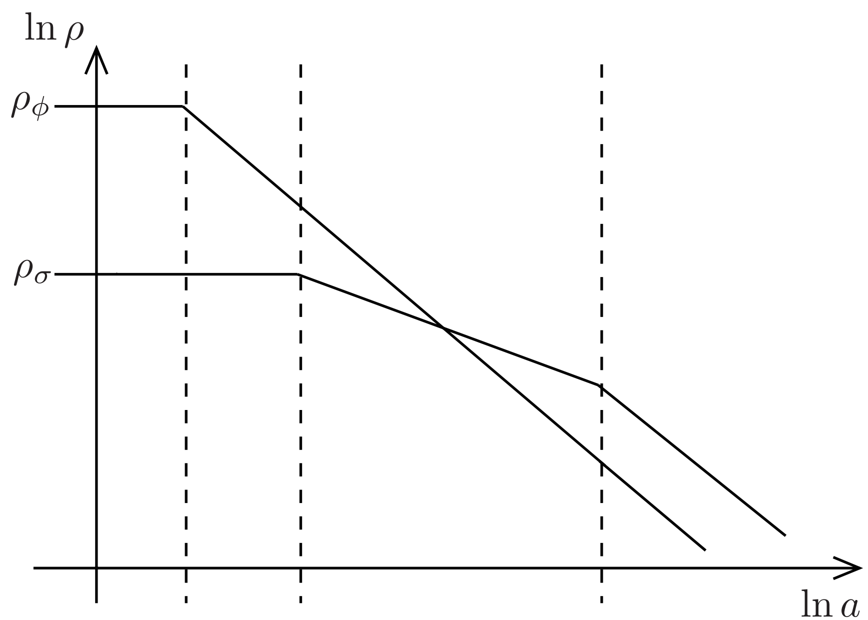
$$\zeta \sim R_{\chi}\left(\frac{\delta\chi}{\chi} + \ldots\right)$$

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

Inflaton models + curvaton field, χ

Curvaton scenarios with quadratic potential $V(\phi,\chi) = U(\phi) + m_\chi^{\,2}\chi^2 / 2$

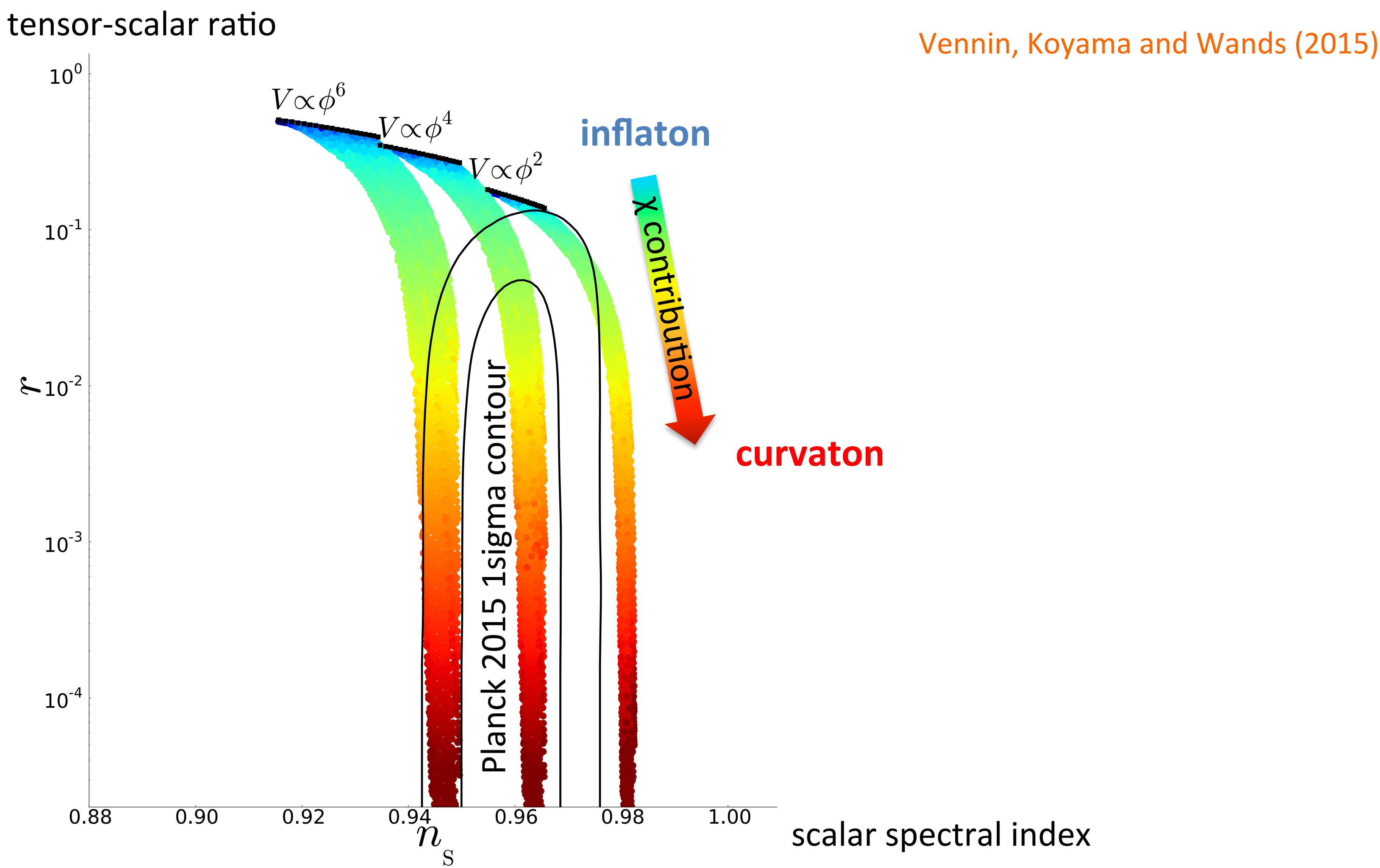
Linde and Mukhanov, 1997
Enqvist and Sloth, 2001
Lyth and Wands, 2001
Moroi and Takahashi, 2001
Langlois and Vernizzi, 2004



more reheating parameters: $\Gamma_\phi \;\rightarrow\; \Gamma_\phi\,,\; \Gamma_\chi\,,\; m_\chi\,,\; \chi_{\rm end}$

primordial perturbations directly dependent on reheating
(not just through the expansion N_*)

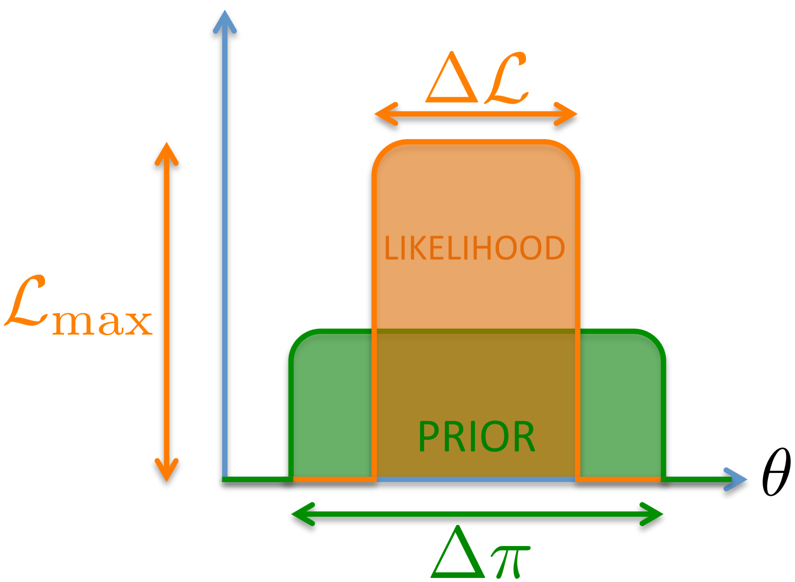
large-field inflaton (LFI) plus quadratic curvaton, χ



Bayesian Approach

to model comparison

Bayesian evidence: Integral of the likelihood over parameter prior



$$\mathcal{E}\left(\mathcal{M}\right) = \mathcal{L}_{\max} \frac{\Delta\mathcal{L}}{\Delta\pi}$$

Compromise between quality of fit and simplicity

Bayes factor = ratio of evidence

$$B_{ij} = E\,(M_i) \,/\, E\,(M_j)$$

Jeffreys scale

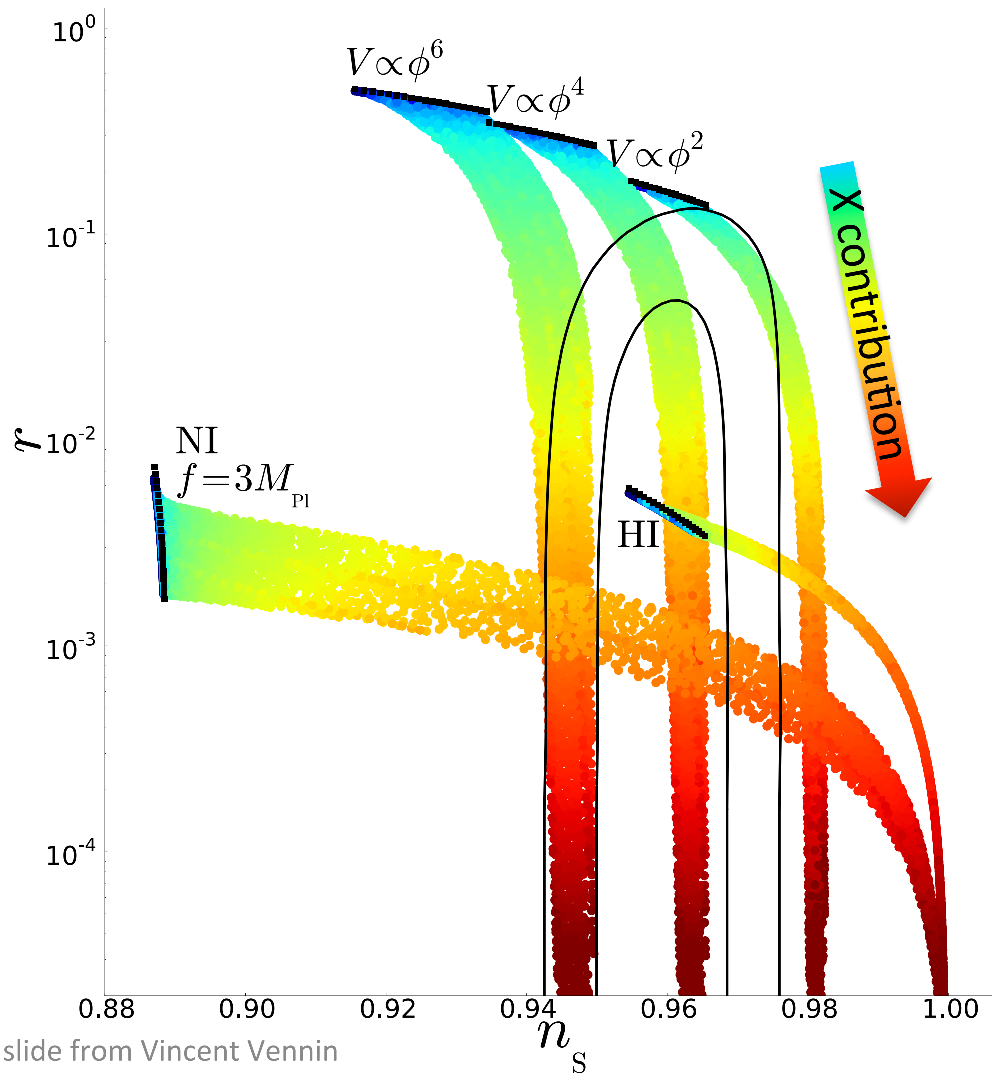
- Strong evidence $\ln(B_{ij}) > 5$
- Moderate evidence $\ln(B_{ij}) > 2.5$
- Weak evidence $\ln(B_{ij}) > 1$
- Inconclusive $\ln(B_{ij}) < 1$

slide from Vincent Vennin

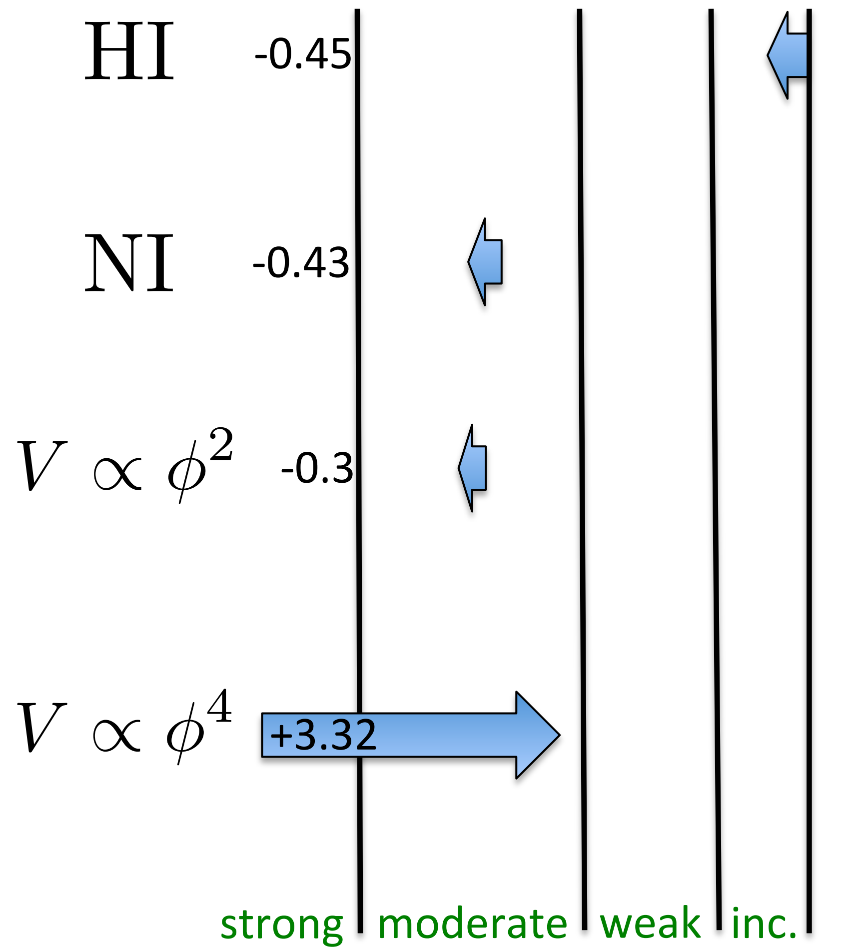
Inflaton models plus weakly-coupled scalar field, χ

Vennin, Koyama and Wands (2015)

CASE # 5



Bayesian evidence, averaging over all cases:



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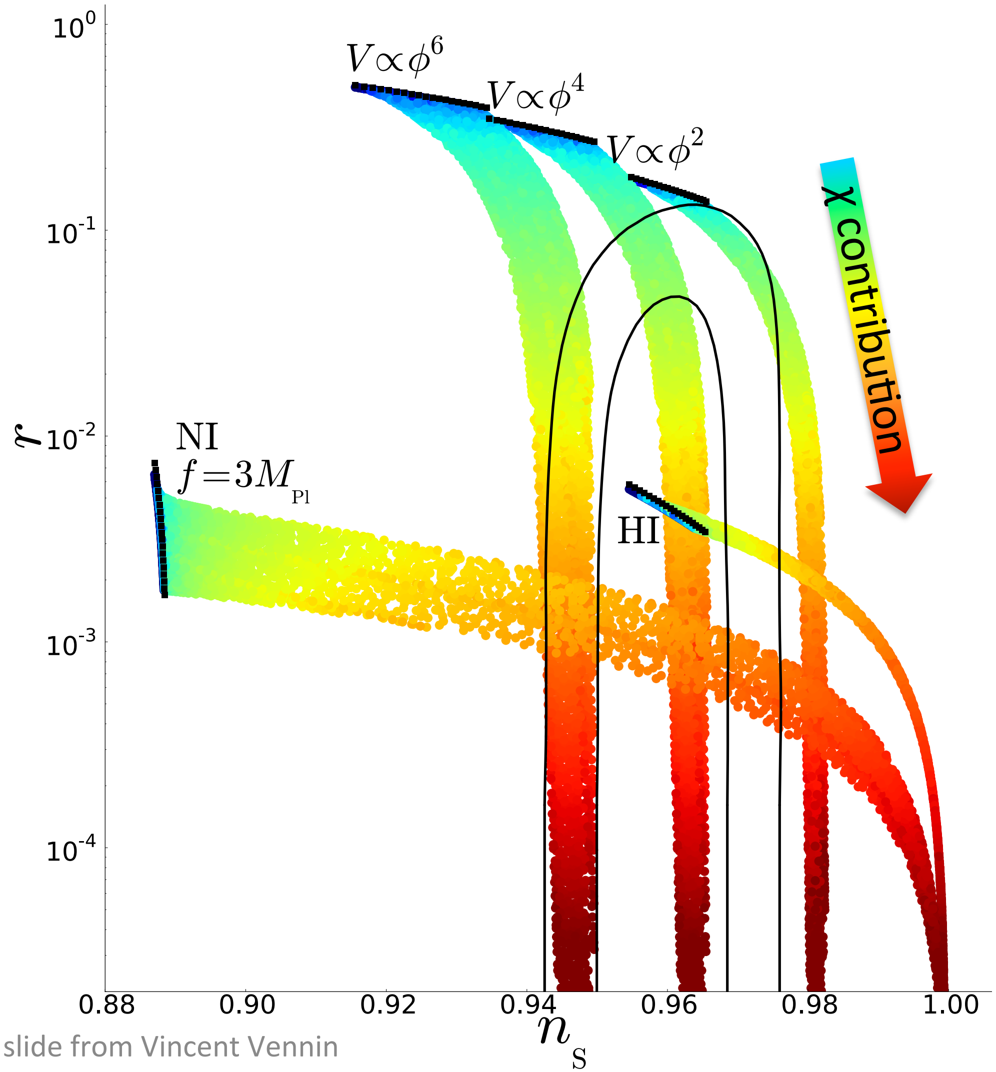

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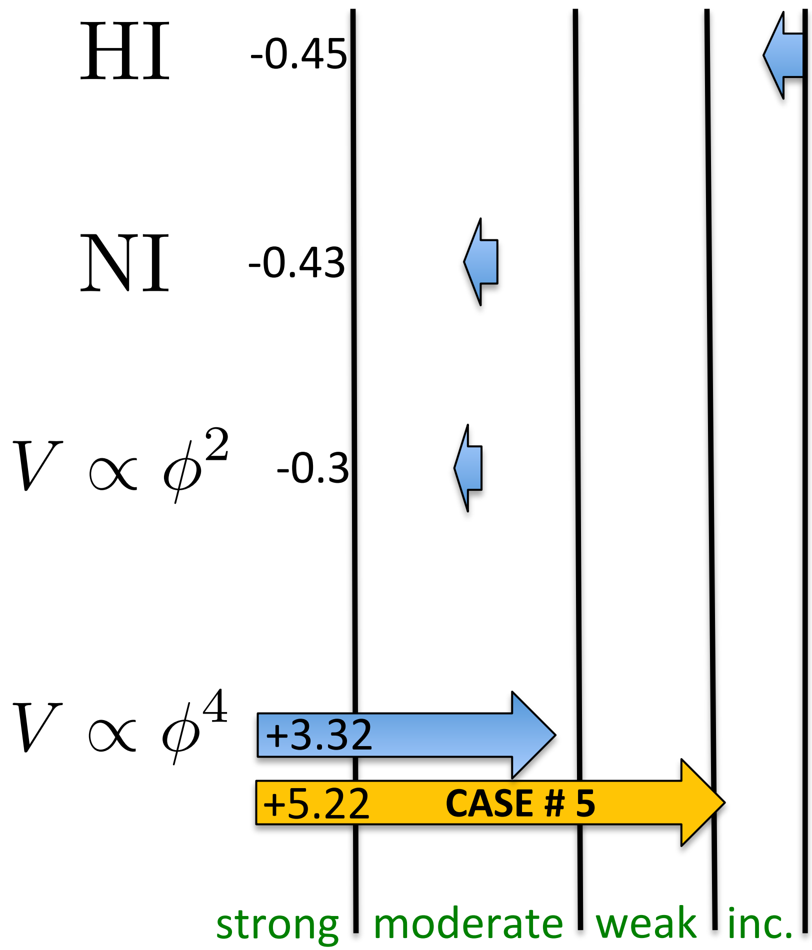
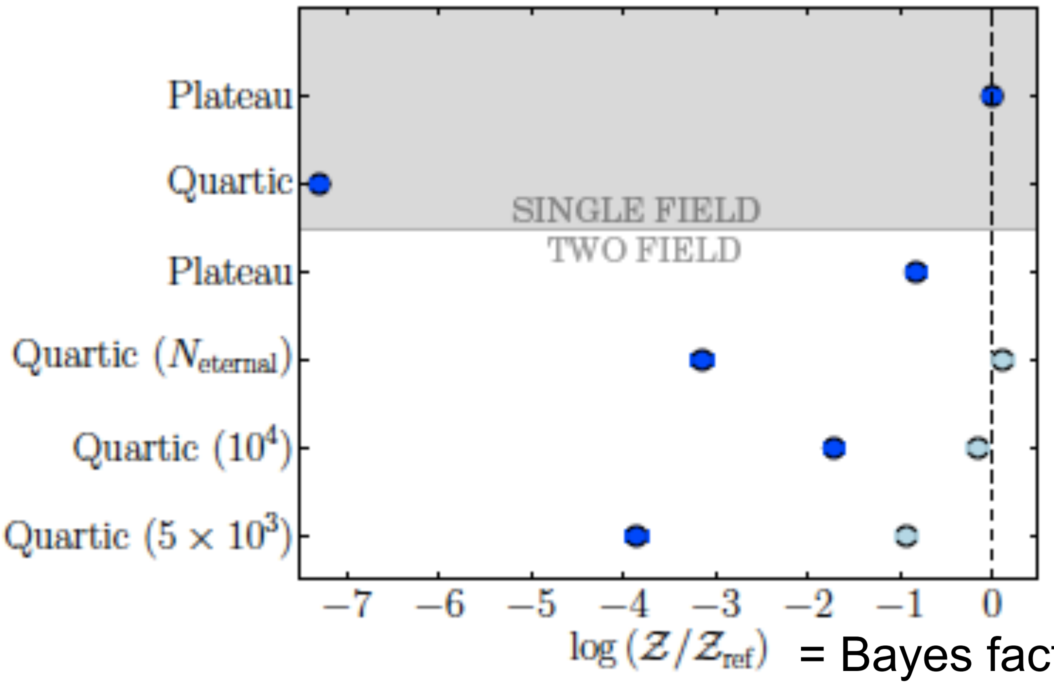


slide from Vincent Vennin

evidence depends on theory priors

- Stochastic evolution can predict statistical distribution of curvaton field value during inflation
- Weakly-coupled curvaton does not reach the stationary distribution during large-field inflation
- Curvaton variance grows with the duration of inflation

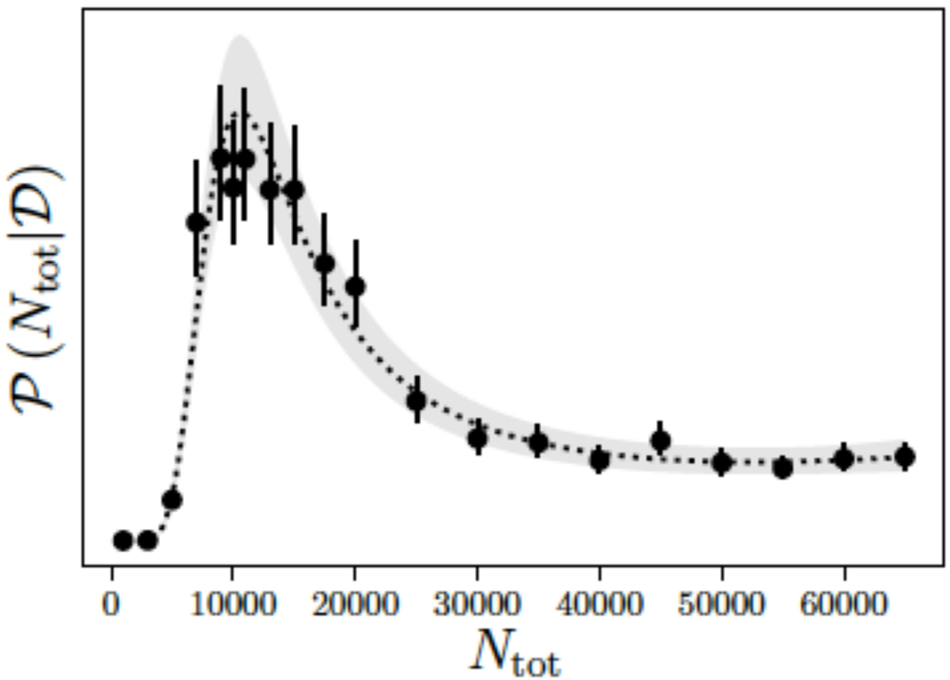


= Bayes factor

Observing the duration of inflation

Torrado, Byrnes, Hardwick, Vennin & Wands (2017)

- Curvaton variance grows with duration of inflation
- Observational data can be used to infer likelihood ("observe") the duration of inflation in the curvaton scenario…



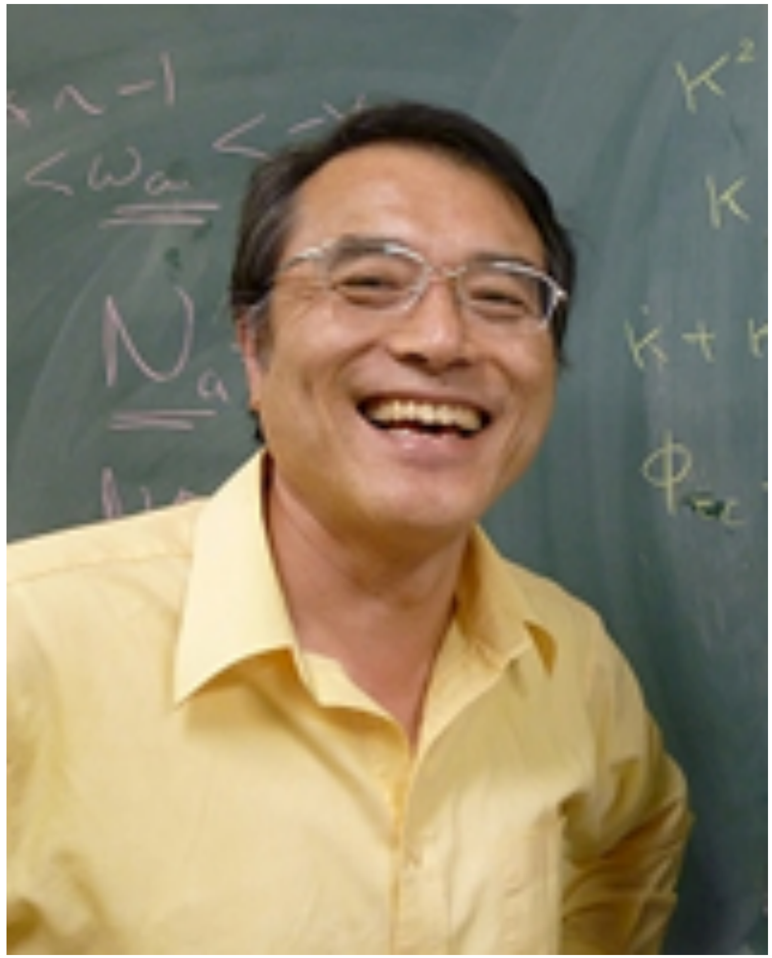
stochastic inflation has observational implications

- (not just our place in the eternally inflating multiverse and all that…)

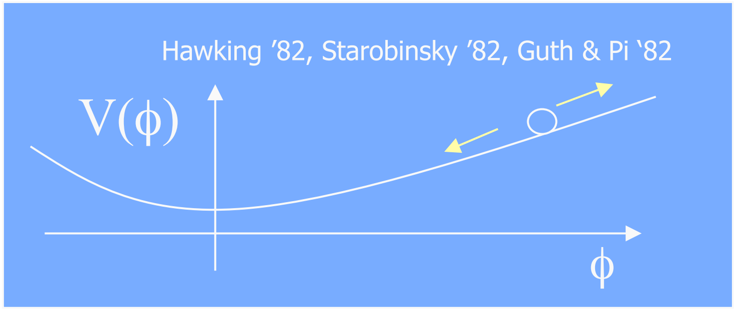
- Density perturbations beyond the perturbative approach
  - Stochastic δN formalism
    - Enqvist et al (2008); Fujita et al (2013, 2014); Vennin & Starobinsky (2015)
  - Infinite inflation requires UV cut-off
    - *Assadullahi, Firouzjahi, Noorbala, Vennin & Wands, arXiv:1604.04502*
  - Quantum diffusion and PBHs from inflation
    - *Pattison, Vennin, Assasdullahi & Wands, arXiv:1707.00537*

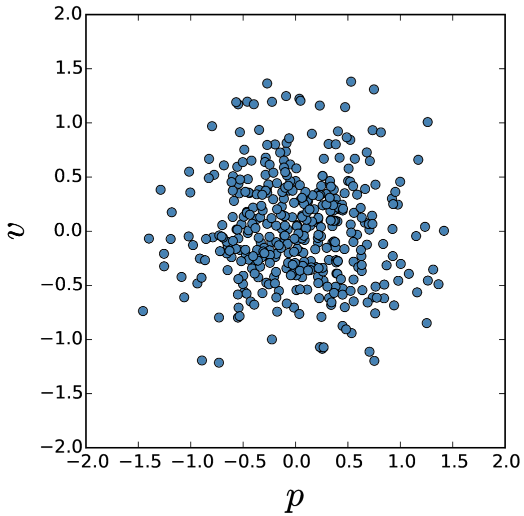
- Probability distributions for field values in inflation
  - The stochastic spectator
    - *Hardwick, Vennin, Byrnes, Torrado & Wands, arXiv:1701.06473*
  - Theoretical priors for Bayesian model comparison
    - *Torrado, Byrnes, Hardwick, Vennin & Wands, arXiv:1712.05364*

best wishes to Sasaki-san!



vacuum fluctuations





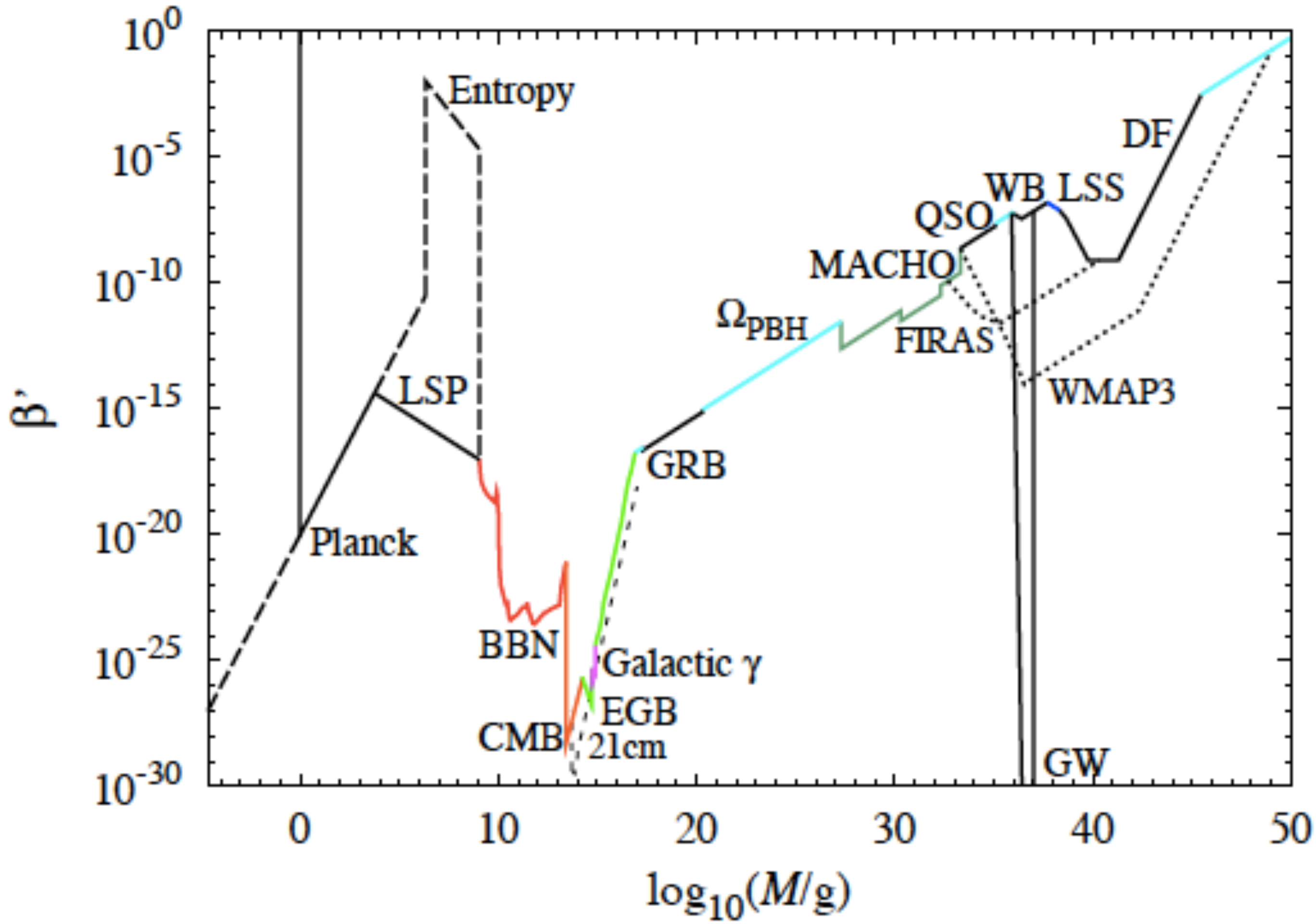
- *phase-space evolution (animation c/o Vincent Vennin)*
- *small-scale/underdamped zero-point oscillations:* $\delta\phi_k \approx \frac{e^{-ik\eta}}{\sqrt{2k}}$
- *large-scale/overdamped perturbations in squeezed state:*

$$\left\langle \delta\phi^2 \right\rangle_{k=aH} \approx \frac{4\pi k^3 \left|\delta\phi_k^{\ 2}\right|}{(2\pi)^3} = \left(\frac{H}{2\pi}\right)^2$$

Primordial black holes from inflation

e.g., Carr, Kohri, Sendouda & Yokoyama (2009)

- $\beta(M)$ = mass fraction



summary

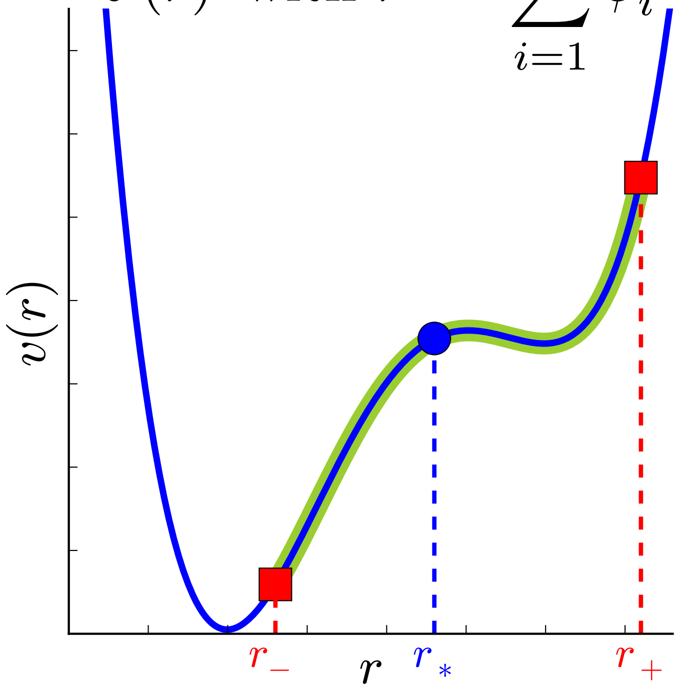
- Stochastic δN needed to calculate primordial density perturbations beyond perturbative approach
- We constructed full probability distribution function
  - solve for characteristic function, then Fourier transform
  - calculated abundance of primordial black holes produced in simple plateau models
    - e.g., running-mass model of inflation
- ***Primordial Black Hole bounds require $N < 1$ in quantum diffusion regime***

further work:

- alternative PBH models
  - transient non-slow-roll backgrounds, e.g., inflection point inflation (e.g., Garcia-Bellido & Ruiz, Germani & Prokopec, Motohashi & Hu 2017)
- explore nature of non-Gaussianity beyond leading order (classical) δN
  - corrections to tail of distribution even close to classical limit?
  - understand consistency of non-Gaussian pdf with absence of correlation between large and small physical scales in single-clock inflation (e.g., Pajer, Schmidt & Zaldarriaga 2013)

Large-Field Exploration & Number of Fields

$$v\,(r) \;\; \text{with } r^2 = \sum_{i=1}^{D} \phi_i^2$$



$$\langle \mathcal{N} \rangle = \int_{r_-}^{r_*} \frac{\mathrm{d}x}{M_{\mathrm{Pl}}} \int_{x}^{r_+} \frac{\mathrm{d}y}{M_{\mathrm{Pl}}} \frac{e^{\frac{1}{v(y)} - \frac{1}{v(x)}}}{v(y)} \left(\frac{y}{x}\right)^{D-1}$$

$$p_+ = \frac{\displaystyle\int_{r_-}^{r_*} x^{1-D} e^{-\frac{1}{v(x)}} \mathrm{d}x}{\displaystyle\int_{r_-}^{r_+} x^{1-D} e^{-\frac{1}{v(x)}} \mathrm{d}x}$$

- integration domain covers the entire field space
- what if $r_+ \to \infty$? $\quad v(r) \propto r^p \quad \longrightarrow \quad \langle \mathcal{N} \rangle = \infty$ if $p \leq D$

  $p_+ > 0$ if $D > 2$

Classical Limit

$$\mathcal{P}_\zeta\left(\phi_*\right) = 2\left\{\int_{\phi_*}^{\bar{\phi}} \frac{\mathrm{d}x}{M_\mathrm{Pl}} \frac{1}{v\left(x\right)} \exp\left[\frac{1}{v\left(x\right)} - \frac{1}{v\left(\phi_*\right)}\right]\right\}^{-1} \times$$
$$\int_{\phi_*}^{\bar{\phi}} \frac{\mathrm{d}x}{M_\mathrm{Pl}} \left\{\int_{x}^{\bar{\phi}} \frac{\mathrm{d}y}{M_\mathrm{Pl}} \frac{1}{v\left(y\right)} \exp\left[\frac{1}{v\left(y\right)} - \frac{1}{v\left(x\right)}\right]\right\}^{2} \exp\left[\frac{1}{v\left(x\right)} - \frac{1}{v\left(\phi_*\right)}\right]$$

Saddle Point Approximation $\quad \left|2v - \frac{v'' v^2}{v'^2}\right| \ll 1$

$$\mathcal{P}_\zeta\left(\phi_*\right) \simeq \frac{2}{M_\mathrm{Pl}^2} \frac{v^3\left(\phi_*\right)}{v'^2\left(\phi_*\right)} \left[1 + 5v\left(\phi_*\right) - 4\frac{v^2\left(\phi_*\right) v''\left(\phi_*\right)}{v'^2\left(\phi_*\right)} + \cdots\right]$$

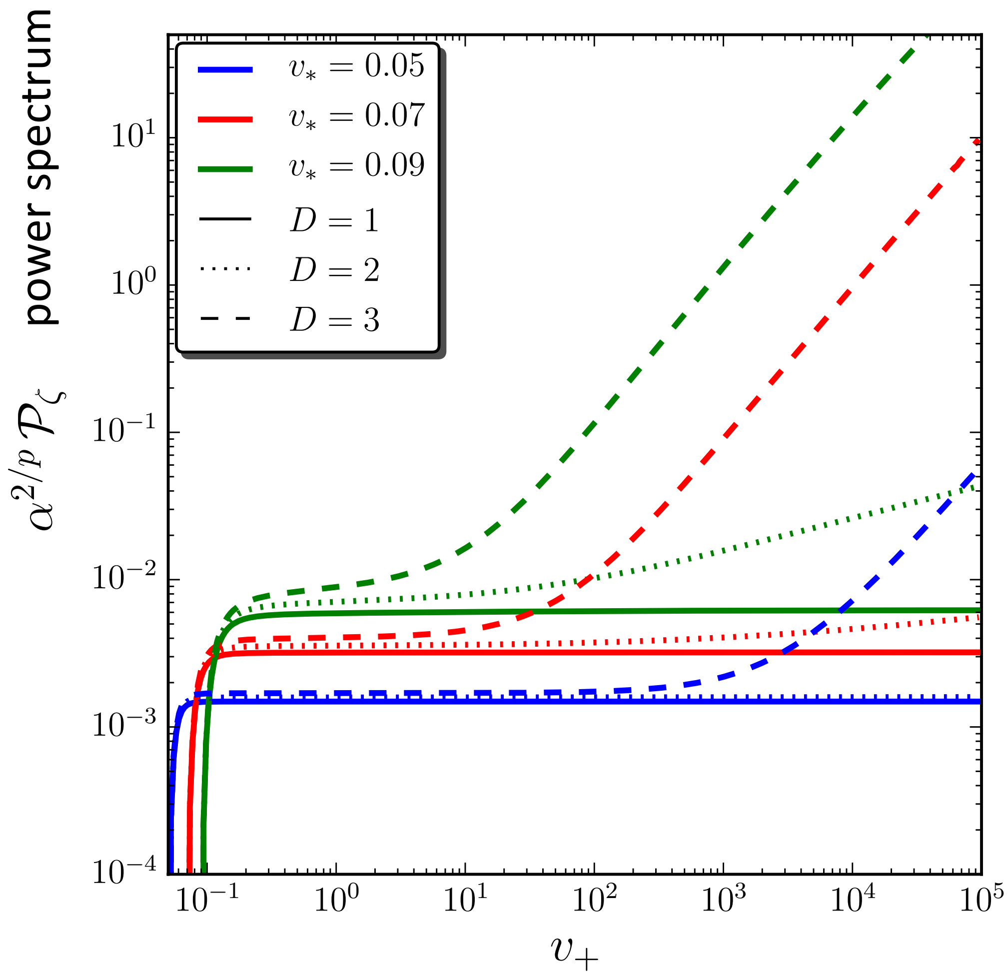
Classical result

First order correction

Stochastic $\delta\mathcal{N}$

D>2 requires UV regularisation (boundary) at some v_+

$v \propto r^2$



Monomial Potentials:

$$v_* \ll v_+ \ll e^{\frac{\mathcal{O}(1)}{v_*}}$$

$$D = 2,\ p = 3:$$

$$v_+ \ll 10^{3{,}474{,}355{,}825}$$

Plateau Potentials

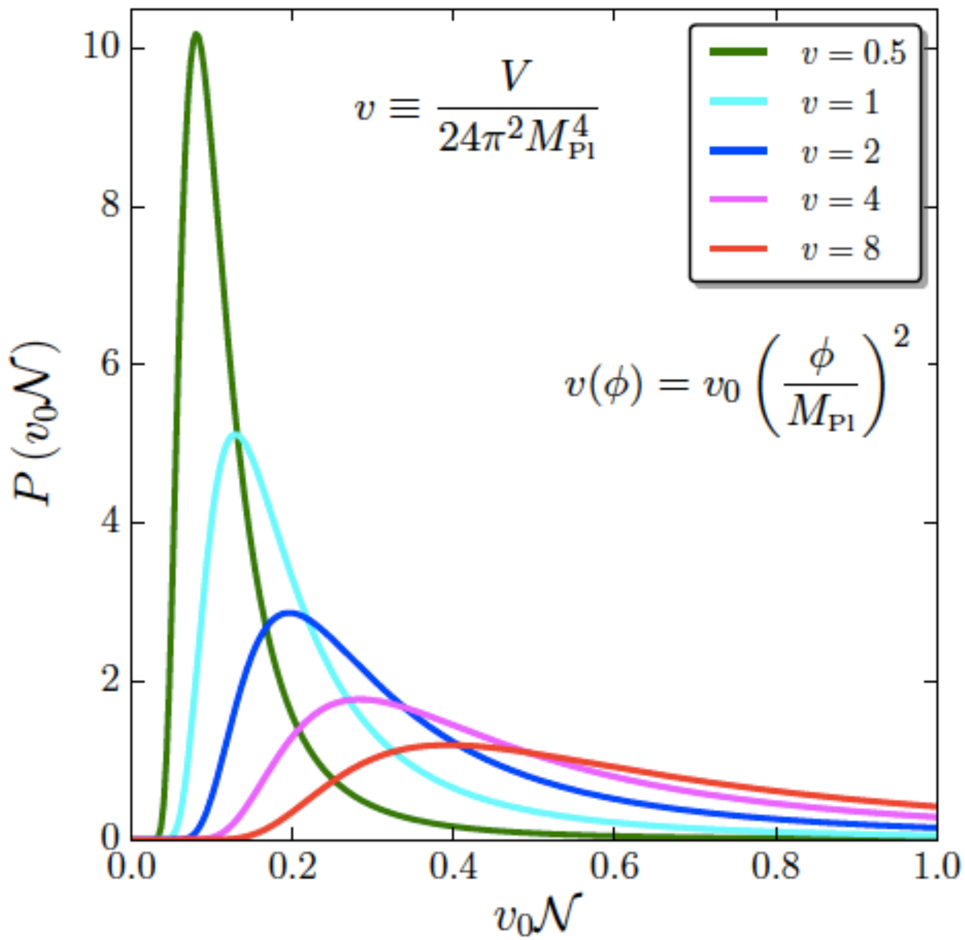
$$r \ll r_+ \ll e^{\mathcal{O}(1)\left(\frac{1}{v_*} - \frac{1}{v_\infty}\right)}$$

$$D = 1,\ \text{Starobinsky:}$$

$$r_+ \ll 10^{6{,}166{,}453{,}090} M_{\rm Pl}$$

Large-field inflation Pattison et al (2017)

- large deviations from classical δN close to Planck energies
  - -> non-Gaussian probability distribution



Stochastic δN

- number of e-folds is a stochastic variable, $\mathcal{N}(\phi)$

$$\zeta = \mathcal{N} - \langle \mathcal{N} \rangle$$

- moments obey an iterative relation (Vennin & Starobinsky 2015)

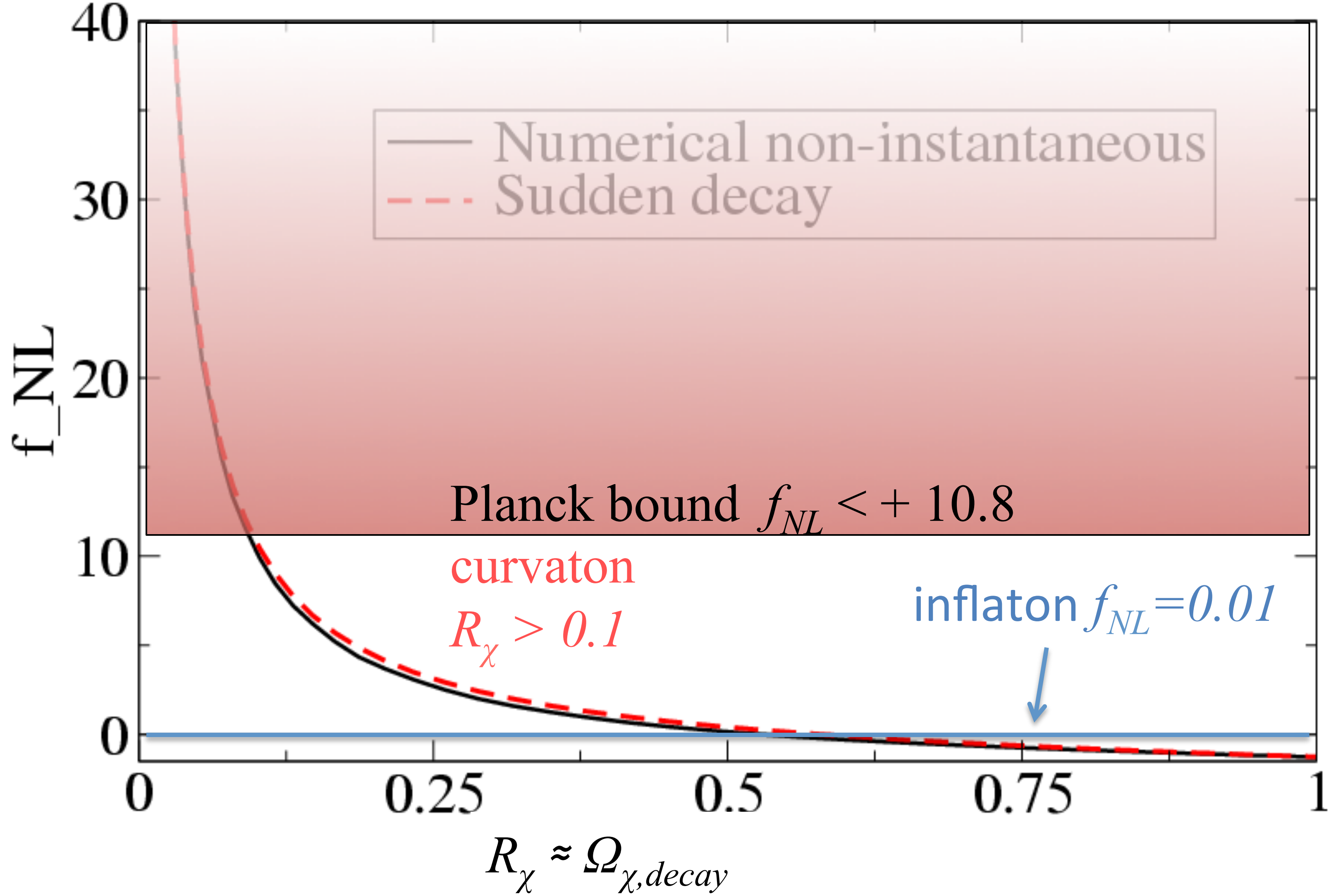
$$f_n \equiv \langle \mathcal{N}^n \rangle$$

$$\Rightarrow f_n'' - \frac{v'}{v^2} f_n' = -\frac{n}{v M_P^2} f_{n-1}$$

- …but PBHs require full probability distribution function

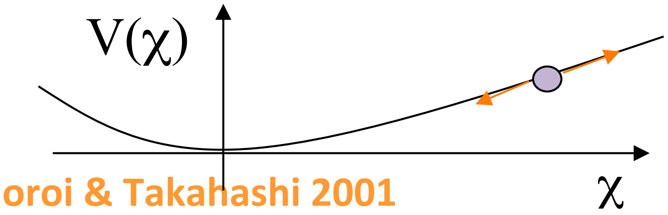
non-linearity parameter for quadratic curvaton

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



curvaton scenario:

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



curvaton χ = weakly-coupled, late-decaying scalar field

- light field (m<H) 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

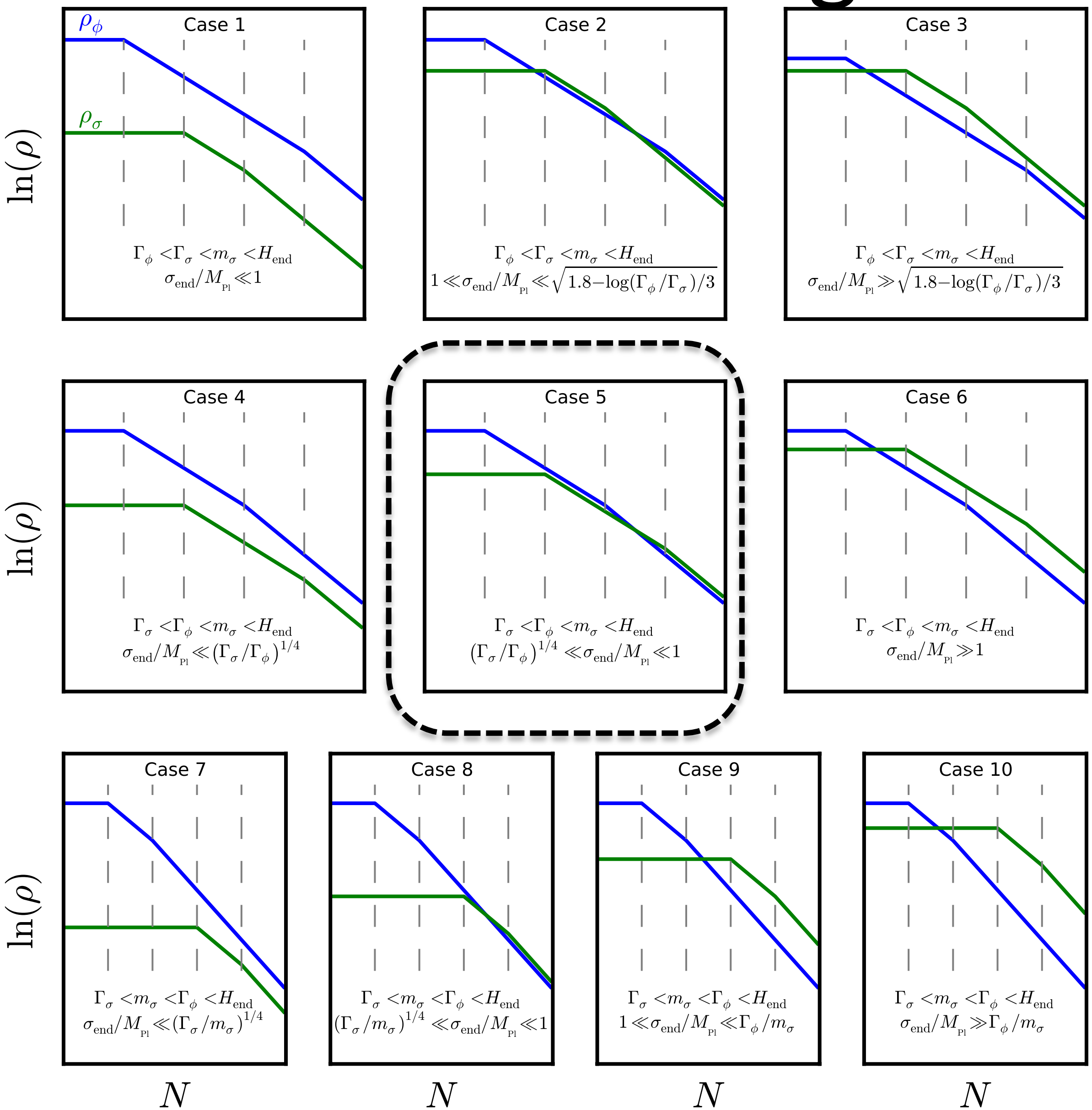
$$\zeta_\chi \approx \frac{1}{3}\frac{\delta\rho_\chi}{\rho_\chi} \approx \frac{1}{3}\left(\frac{2\chi\delta\chi + \delta\chi^2}{\chi^2}\right)$$

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

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

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

10 curvaton reheating scenarios



Vennin, Koyama and Wands (2015)

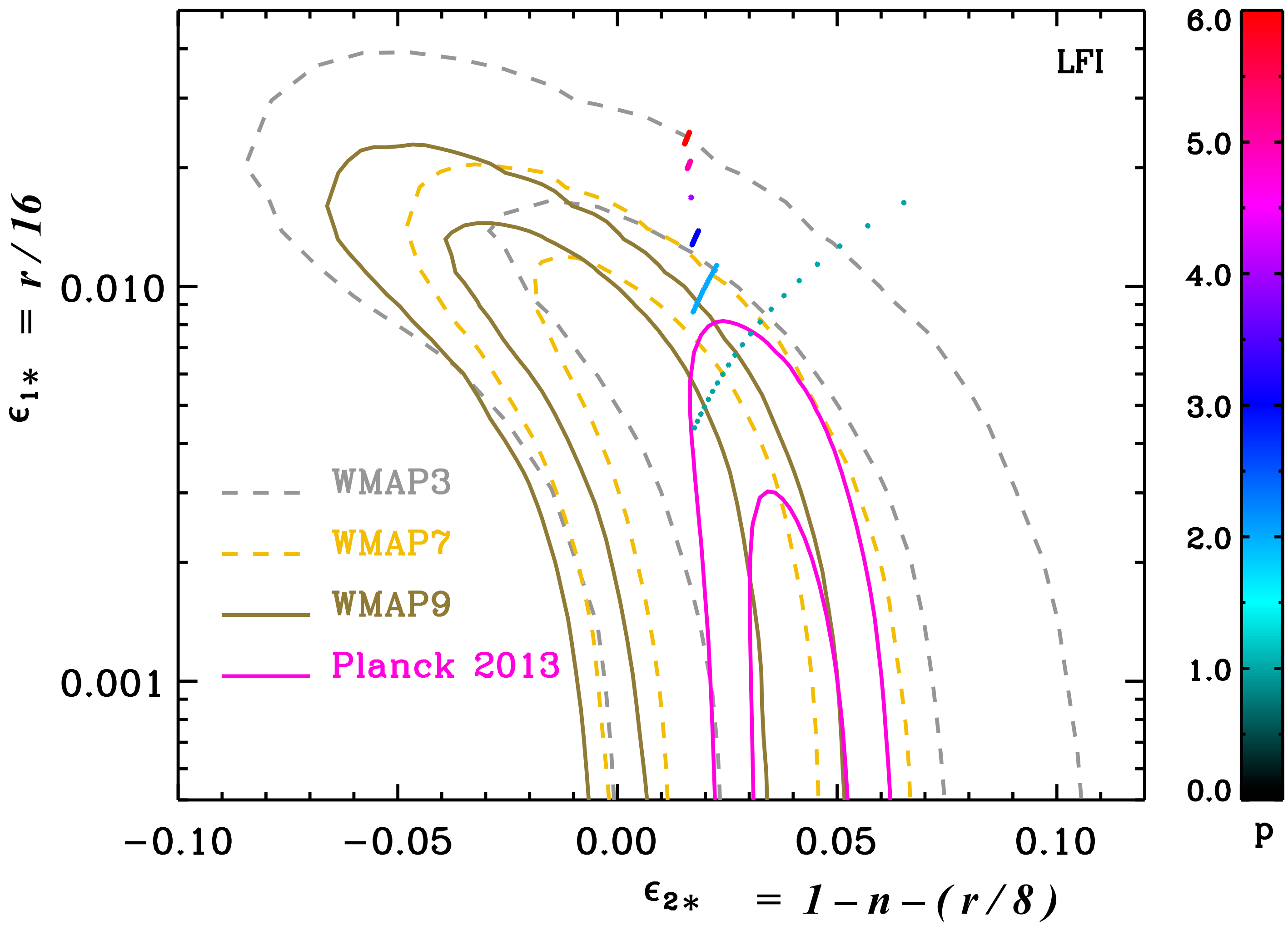
after inflaton slow-roll ends

Case 5:

i. Curvaton become heavy
ii. Inflaton decays
iii. Curvaton dominates
iv. Curvaton decays

Inflaton model predictions and Observations

Inflaton example: « large field inflation » $V(\phi) = M^4 \left(\frac{\phi}{M_{\rm Pl}}\right)^p$



LFI+curvaton vs Higgs inflation

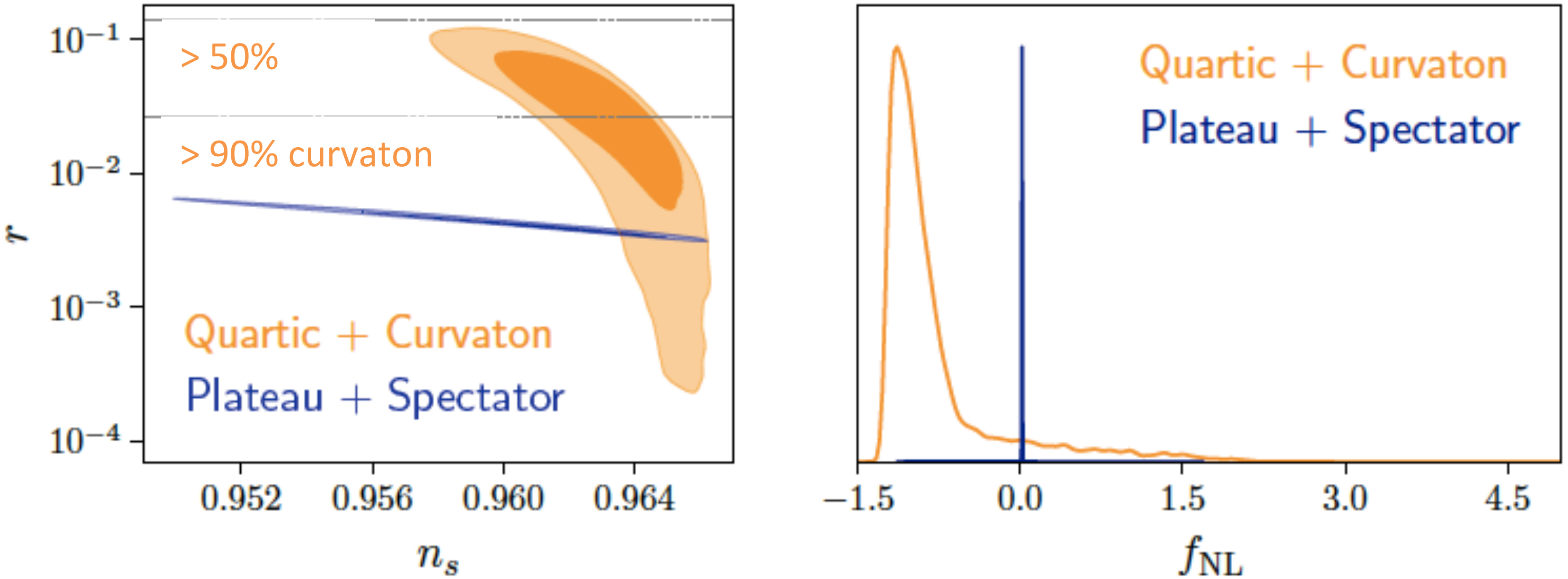


FIG. 2: Marginal posterior distributions over the key observables from inflation for plateau-like inflation (blue, darker) and quartic inflation (orange, clearer) with a spectator field. In the quartic case, the posterior fraction below the lower (upper) dotted line has more than 90% (50%) of primordial density perturbations generated by the curvaton field. Post-2020 CMB experiments would likely distinguish between or rule out both scenarios in terms of $n_{\rm s}$ and r. In combination with LSS data, the typical value of $f_{\rm NL} = -5/4$ associated with the curvaton scenario could also be distinguished in the future from $f_{\rm NL} \sim \mathcal{O}(10^{-2})$ in the inflaton scenario.