TURNING IN THE LANDSCAPE: A NEW MECHANISM TO GENERATE PBH

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Based on arXiv 2004.03221
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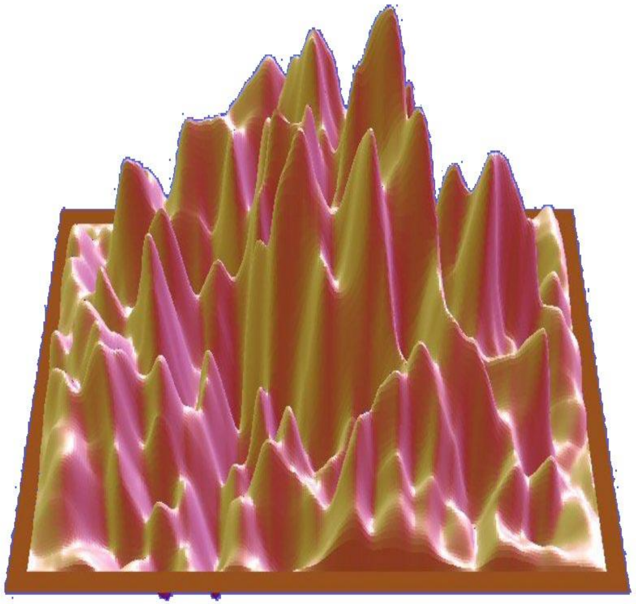
PLAN

- INFLATION IN NON-GEODESIC MOTION
- TRANSIENT INSTABILITY
- MECHANISM
- ANALYTICAL UNDERSTANDING
- POTENTIAL UNIQUE SIGNATURES

TURNING IN THE LANDSCAPE



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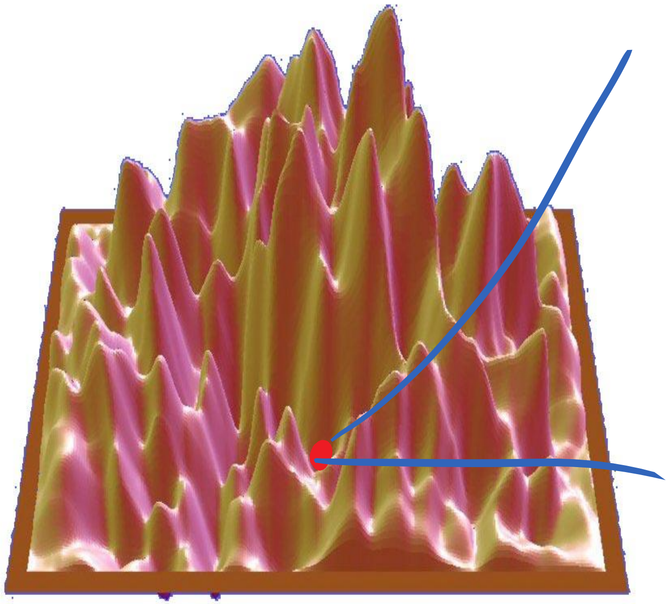

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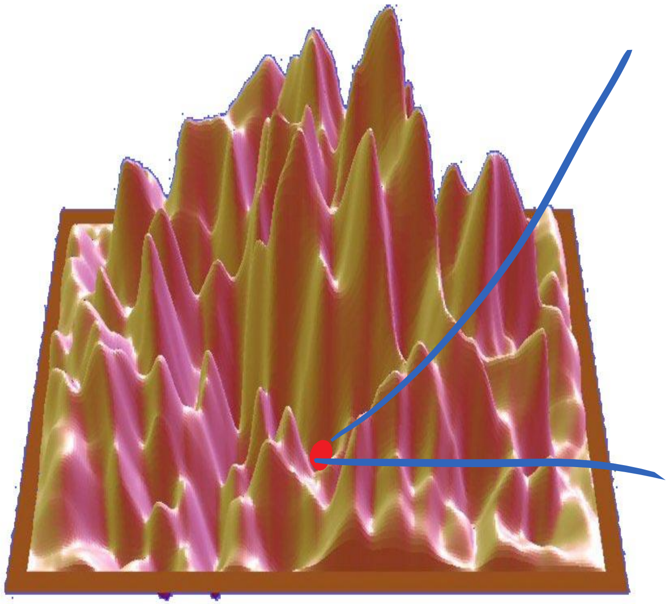

GENERIC/MODEL-INDEPENDENT, POSSIBLE ADVANTAGES , UNIQUE SIGNATURES?

INFLATION IN NON-GEODESIC MOTION

$$S = \int d^4x\sqrt{-g}\left[\frac{M_{\rm Pl}^2}{2}\,R - \frac{1}{2}\,G_{IJ}\partial^\mu\phi^I\partial_\mu\phi^J - V(\phi)\right]$$

EOM = $\mathcal{D}_t\dot{\phi}^I + 3H\dot{\phi}^I + G^{IJ}V_{,J} = 0$

$$\downarrow$$

$$\ddot{\phi}^I + \Gamma^I_{JK}\dot{\phi}^J\dot{\phi}^K$$

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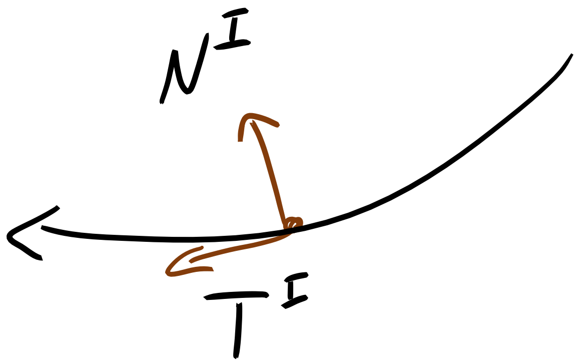


Def. $\dot{\sigma} \equiv \sqrt{G_{IJ}\dot{\phi}^I\dot{\phi}^J}$, $\quad \mathcal{T}^I \equiv \dot{\phi}^I/\dot{\sigma}$, $\quad \mathcal{N}^I \perp \mathcal{T}^I$

INFLATION IN NON-GEODESIC MOTION

$$N^I \text{ (EOM)} \longrightarrow D_t T^I = \eta_\perp H N^I \qquad \eta_\perp = -\frac{V_N}{H\dot{\sigma}}$$

INFLATION IN NON-GEODESIC MOTION

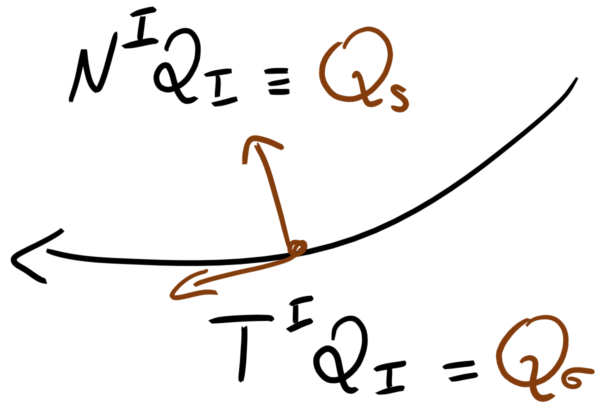
$$N^I(\text{EoM}) \longrightarrow D_t T^I = \eta_\perp H N^I \qquad \eta_\perp = -\frac{V_N}{H\dot{\sigma}}$$

$\eta_\perp = 0 \Longrightarrow$ GEODESIC MOTION , $D_t T^I = 0$

$\eta_\perp \gg 1 \Longrightarrow$ STRONGLY NON-GEODESIC

MULTI-FIELD PERTURBATIONS

$$\boxed{\begin{aligned} \delta\phi^I &= Q_s \mathcal{N}^I \\ g_{IJ} &= a^2 e^{2\zeta}\delta_{IJ} \end{aligned}}$$



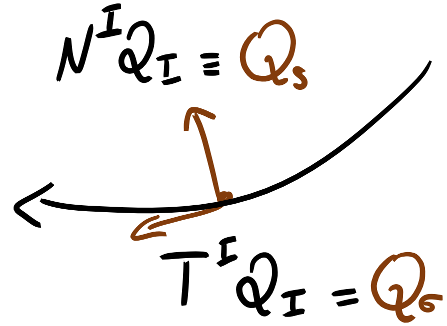
$$\mathcal{L}^{(2)} = a^3 \left[M_{\rm Pl}^2 \epsilon \left(\dot{\zeta}^2 - \frac{(\partial\zeta)^2}{a^2} \right) + 2\dot{\sigma}\underline{\eta_\perp}\dot{\zeta} Q_s \right.$$
$$\left. + \frac{1}{2}\left(\dot{Q_s}^{\,2} - \frac{(\partial Q_s)^2}{a^2} - \underline{m_s^2} Q_s^2 \right) \right],$$

MULTI-FIELD PERTURBATIONS

- EOM ENTROPIC FLUCTUATION

$$\ddot{Q}_s + 3H\dot{Q}_s + \left(\frac{k^2}{a^2} + m_s^2\right) Q_s = -\alpha \eta_\perp \dot{\zeta}$$

$$V_{;ss} + \epsilon R_{\rm fs} H^2 M_{\rm pl}^2 - \eta_\perp^2 H^2$$



MULTI-FIELD PERTURBATIONS

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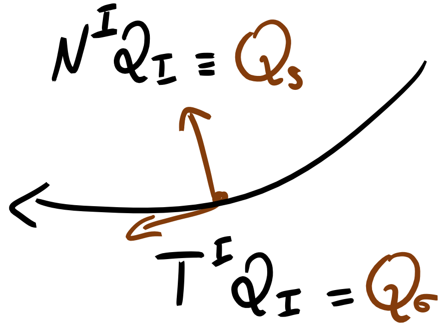
$$\ddot{Q}_s + 3H\dot{Q}_s + \left(\frac{k^2}{a^2} + m_s^2\right) Q_s = -\alpha\eta_\perp\dot{\zeta}$$

$$m_s^2 = V_{;ss} + \epsilon R_{\rm fs} H^2 M_{\rm pl}^2 - \eta_\perp^2 H^2$$



- N.B. $\eta_\perp^2 \gg 1$ " $\Longrightarrow$ " $m_s^2 < 0$; $|m_s| \gg H$

MULTI-FIELD PERTURBATIONS

$$m_s^2 < 0 \quad \not\Rightarrow \quad \text{UNSTABLE BKG}$$

MULTI-FIELD PERTURBATIONS

$$m_s^2 < 0 \quad \not\Longrightarrow \quad \text{UNSTABLE BKG}$$

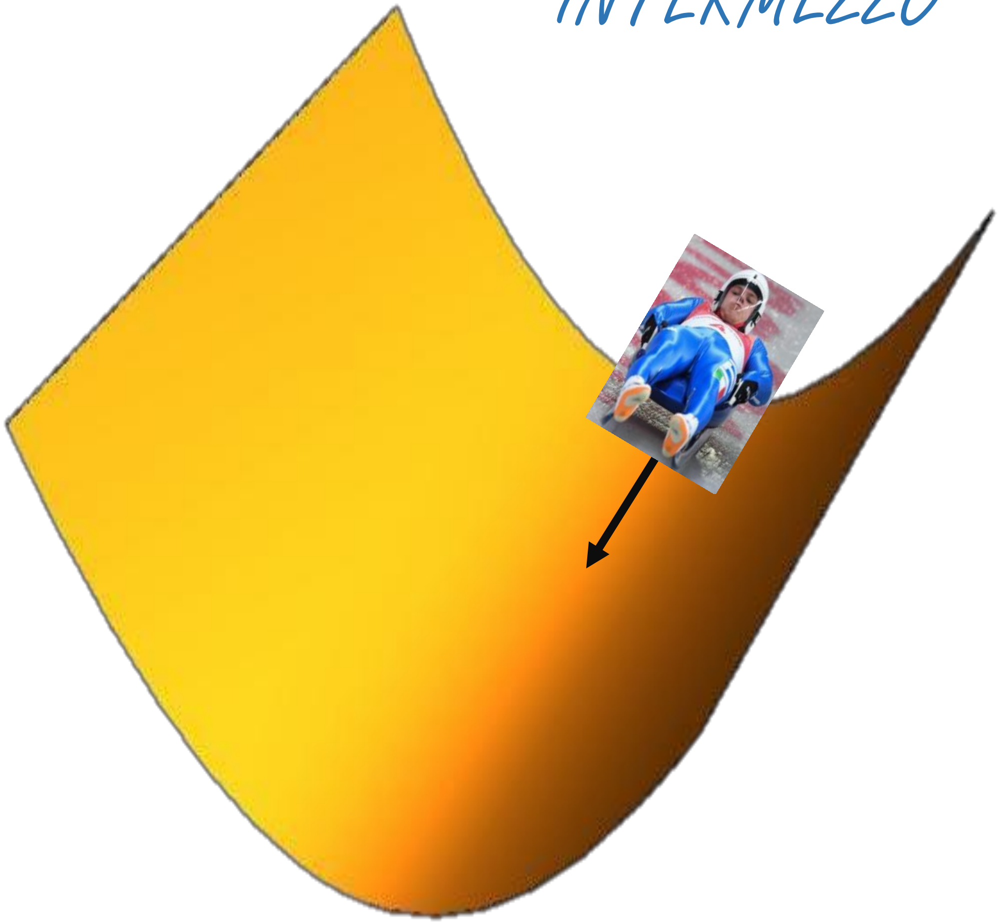
- SUPER-HUBBLE $k/a \ll H$

$$\dot{\zeta} = (2H^2/\dot{\sigma})\eta_\perp Q_s \longrightarrow \text{EOM}[Q_s]$$

$$\Longrightarrow \qquad \ddot{Q}_s + 3H\dot{Q}_s + \left(\frac{k^2}{a^2} + m_{\rm s,eff}^2\right) Q_s = 0$$

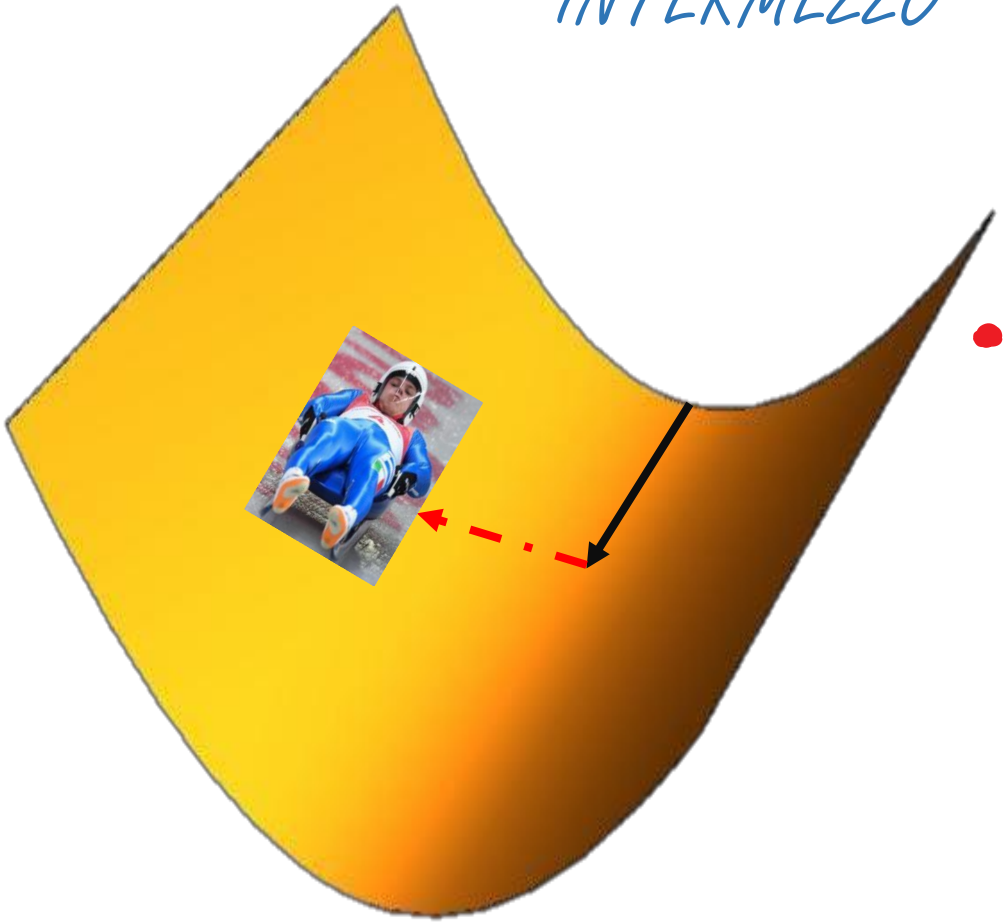
$$m_{\rm s,eff}^2 = \underbrace{V_{;ss} + \epsilon R_{\rm fs} H^2 M_{\rm pl}^2 - \eta_\perp^2 H^2}_{m_s^2 < 0} + 4H^2\eta_\perp^2$$

INTERMEZZO



$$m^2_{s,\mathrm{EFF}} = V_{ss} + \varepsilon R_{sf} H^2 \mathcal{R}^2_{Pl} > 0$$

INTERMEZZO

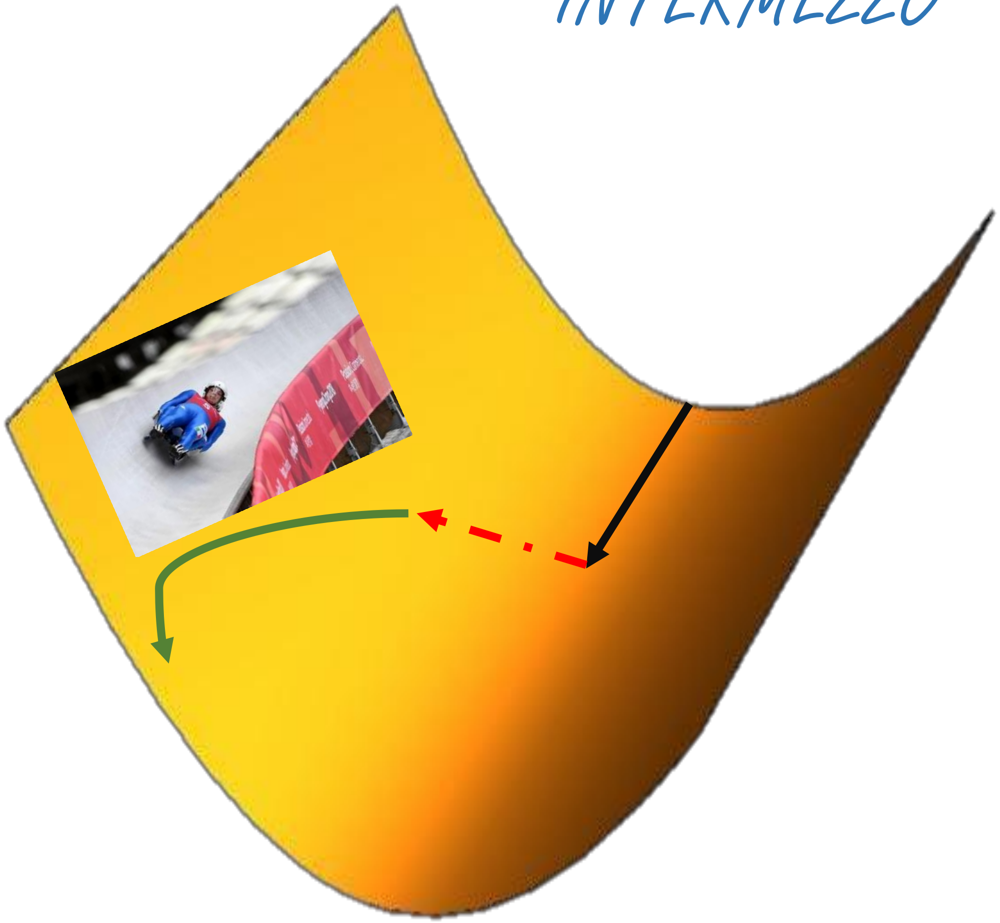


- **GEOMETRICAL DESTABILIZATION**

  S. Renaux-Petel & K. Turzinsky '15

$$m^2_{s,\mathrm{EFF}} = V_{ss} + \varepsilon R_{sf} H^2 \eta_{pe}^2 < 0$$

INTERMEZZO



- SIDETRACKED
  S. Garcia Saenz, S. Renaux-Petel & J. Ronayne '18
  HYPERINFLATION
  A. Brown '17
  D. Marsh & T. Bjorkmo '19
  ANGULAR INFLATION
  P. Christodoulidis, D. Roest, E. Sfakianakis
  ....

$$m^2_{s,\mathrm{EFF}} = \underbrace{V_{ss} + \varepsilon R_{sf} H^2 M_{Pl}^2 - H^2 \eta_\perp^2}_{m_s^2 < 0} + 4 H^2 \eta_\perp^2 > 0$$

INTERMEZZO 2

TOP-DOWN

NEGATIVE CURVATURE IN FIELD SPACE, e.g. α-attractors

$\Longrightarrow$ NEW ATTRACTORS

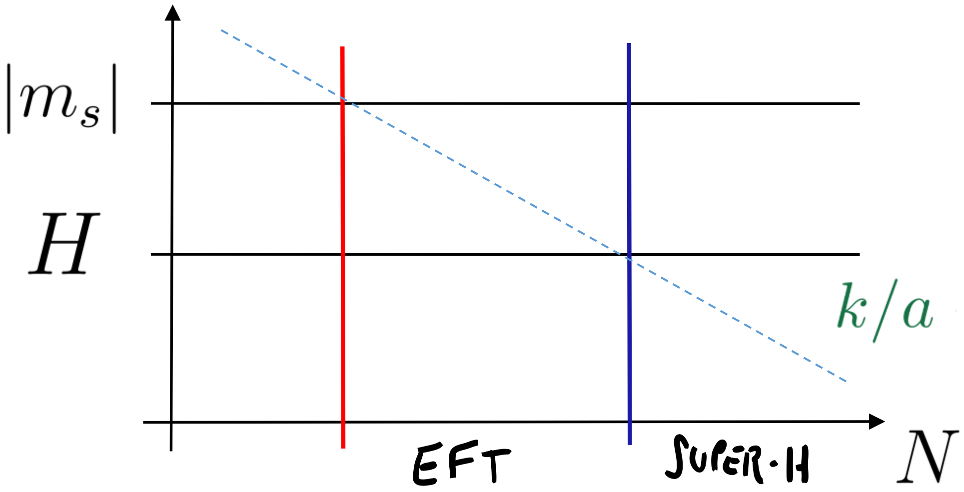
SIDETRACKED, HYPERINFLATION, ANGULAR INFLATION .....
S. Garcia Saenz, S. Renaux-Petel & J. Ronayne '18, A. Brown '17, D. Marsh & T. Bjorkmo '19. P. Christodoulidis, D. Roest, E. Sfakianakis
......

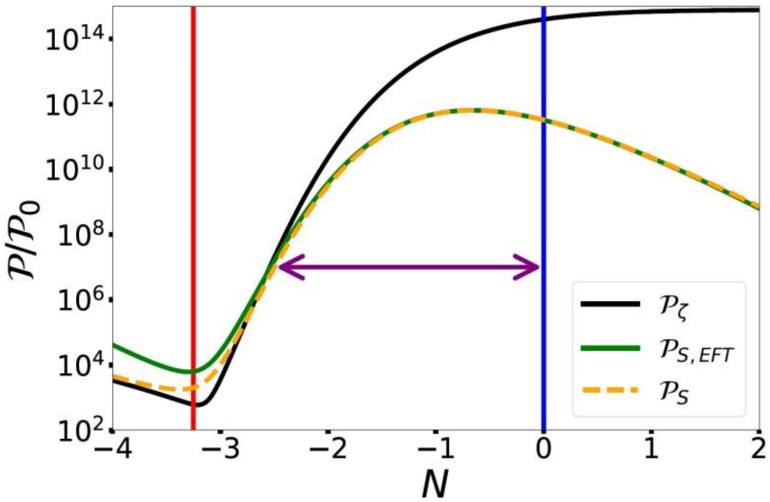
UV EMBEDDINGS & INFLATION.

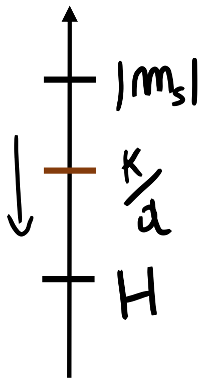
$\rightarrow$ SWAMPLAND CONJECTURES $\leftarrow$ REQUIRE MULTI-FIELD INFLATION WITH LARGE BENDING
A. Achucarro & G. Palma '18

η - PROBLEM $\leftarrow$ REQUIRE INFLATING ON STEEP POTENTIALS

TRANSIENT INSTABILITY

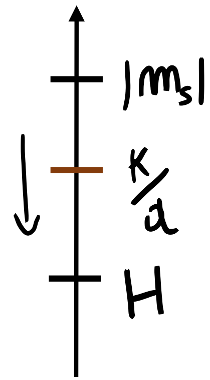






SINGLE FIELD EFFECTIVE FIELD THEORY

- INTEGRATING OUT THE ENTROPIC MODE $|m_s^2| \gg \dfrac{k^2}{a^2}$



$$Q_s^{\rm EFT} = -\frac{(2\dot\sigma)\eta_\perp}{m_s^2}\dot\zeta \longrightarrow \mathcal{S}_2^{\rm EFT}[\zeta] = \int d\tau d^3x \epsilon a^2 \left[\frac{(\zeta')^2}{c_s^2} - (\partial_i\zeta)^2\right]$$

- $$\frac{1}{c_s^2} = 1 + \frac{4H^2\eta_\perp^2}{m_s^2}$$

A. Achucarro et al. '11

SINGLE FIELD EFFECTIVE FIELD THEORY

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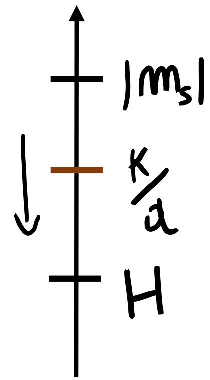


$$Q_s^{\mathrm{EFT}} = -\frac{(2\dot{\sigma})\eta_\perp}{m_s^2}\dot{\zeta} \longrightarrow \mathcal{S}_2^{\mathrm{EFT}}[\zeta] = \int d\tau d^3x \epsilon a^2 \left[\frac{(\zeta')^2}{c_s^2} - (\partial_i\zeta)^2\right]$$

- $$\frac{1}{c_s^2} = 1 + \frac{4H^2\eta_\perp^2}{m_s^2} = \frac{m_{s,\mathrm{eff}}^2}{m_s^2}$$

$\Longleftarrow$ Stable Background

" $\Longleftarrow$ " $\eta_\perp^2 \gg 1$

A. Achucarro et al. '11

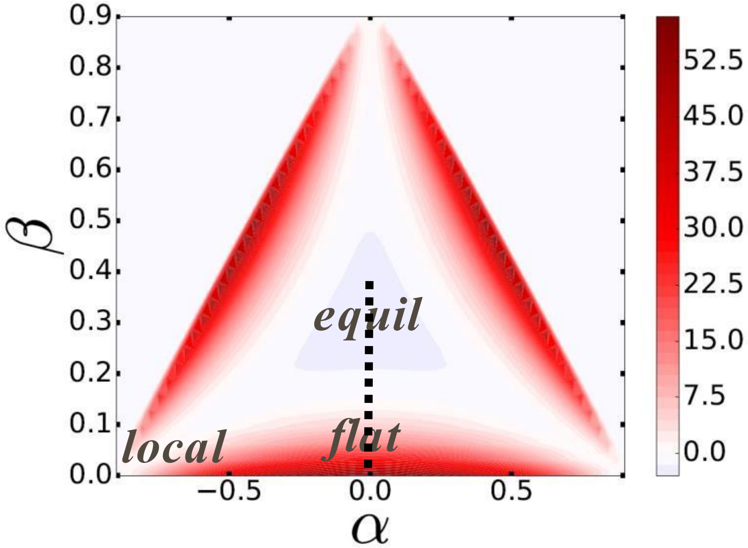
$\Longrightarrow$ $c_s^2 < 0$ EFT WITH IMAGINARY SPEED OF SOUND

S. Garcia Saenz, S. Renaux-Petel '18
J.F., S. Garcia Saenz, L.Pinol, ,
S.Renaux-Petel , J.Ronayne '19

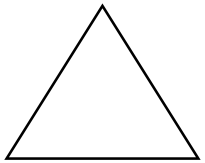
HYPER NON-GAUSSIANITIES

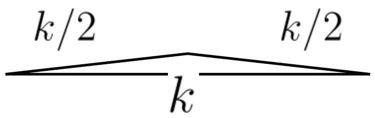
J.F., S. Garcia Saenz, L.Pinol, , S.Renaux-Petel , J.Ronayne PRL '19

Full Bispectrum $\langle \zeta_{k_1} \zeta_{k_2} \zeta_{k_3} \rangle$



$f_{NL}^{\mathrm{eq}} = -2.0\,,\qquad f_{NL}^{\mathrm{flat}} = 53.8$





- ENHANCEMENT FOR PARTICULAR FLATTEN CONFIGURATIONS

  e.g. $k_1 + k_2 - k_3 \to 0$

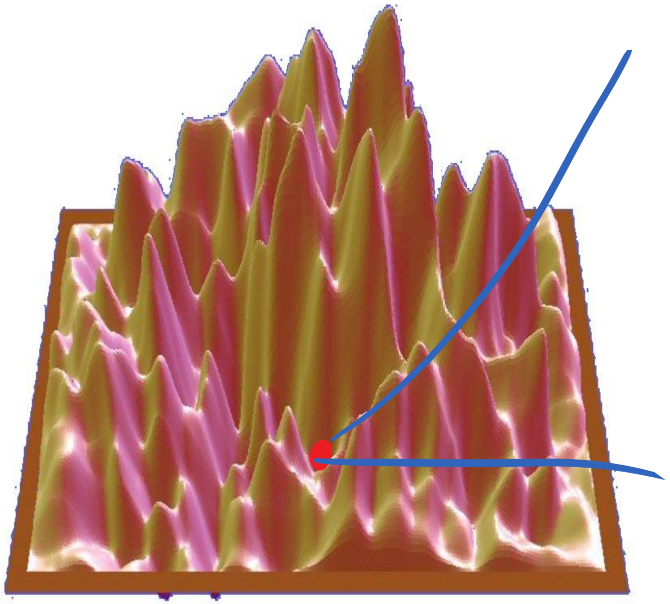
- MATCHING / EFT THAT ALLOWS to SHOW
  - PERTURBATIVE CONTROL
  - HIERARCHICAL ENHANCMENT OF THE N-POINT CORRELATION FUNCTIONS

See also:

T.Bjorkmo, D.Marsh, R. Ferreira '19

R.Ferreria '20

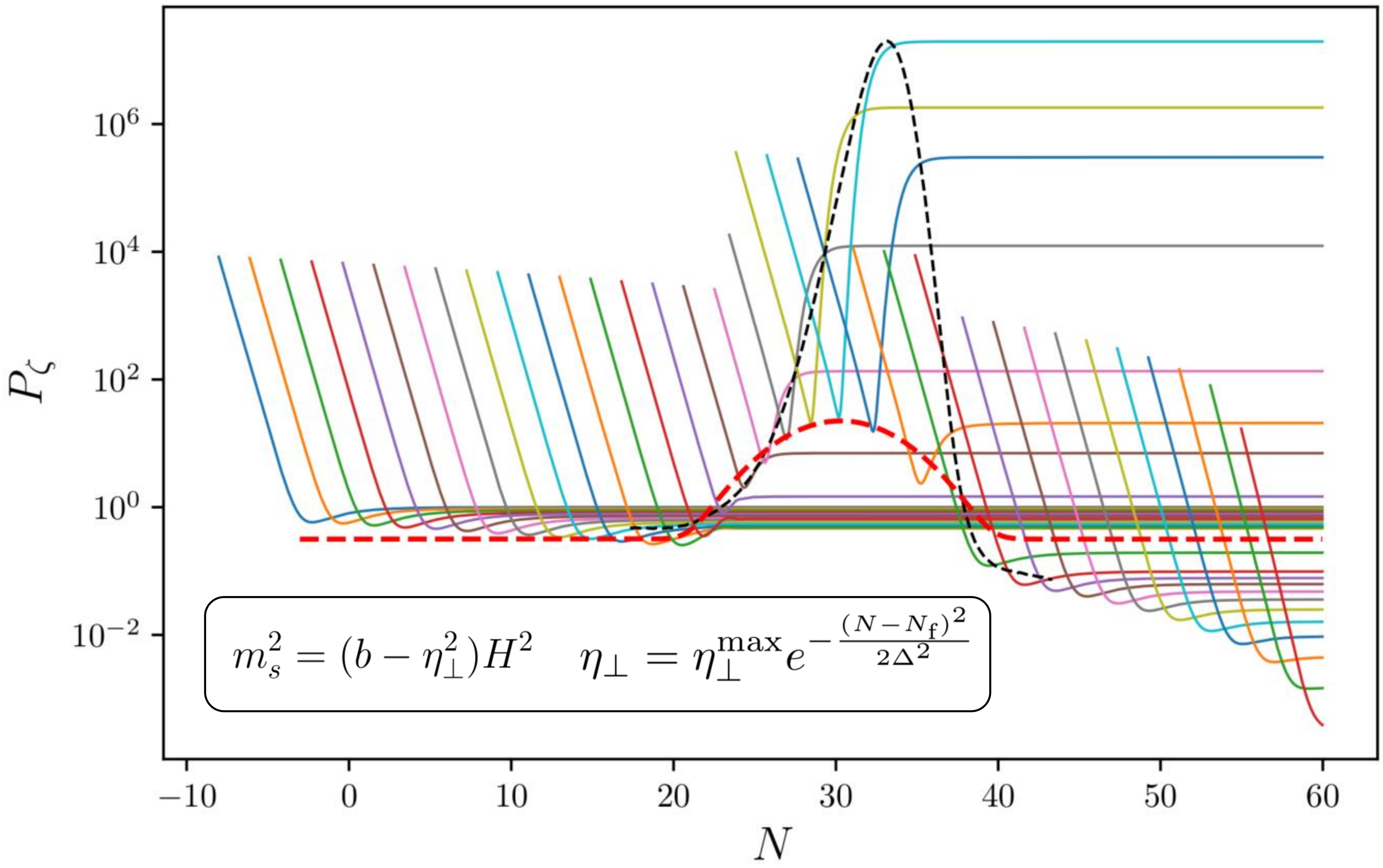
TURNING IN THE LANDSCAPE



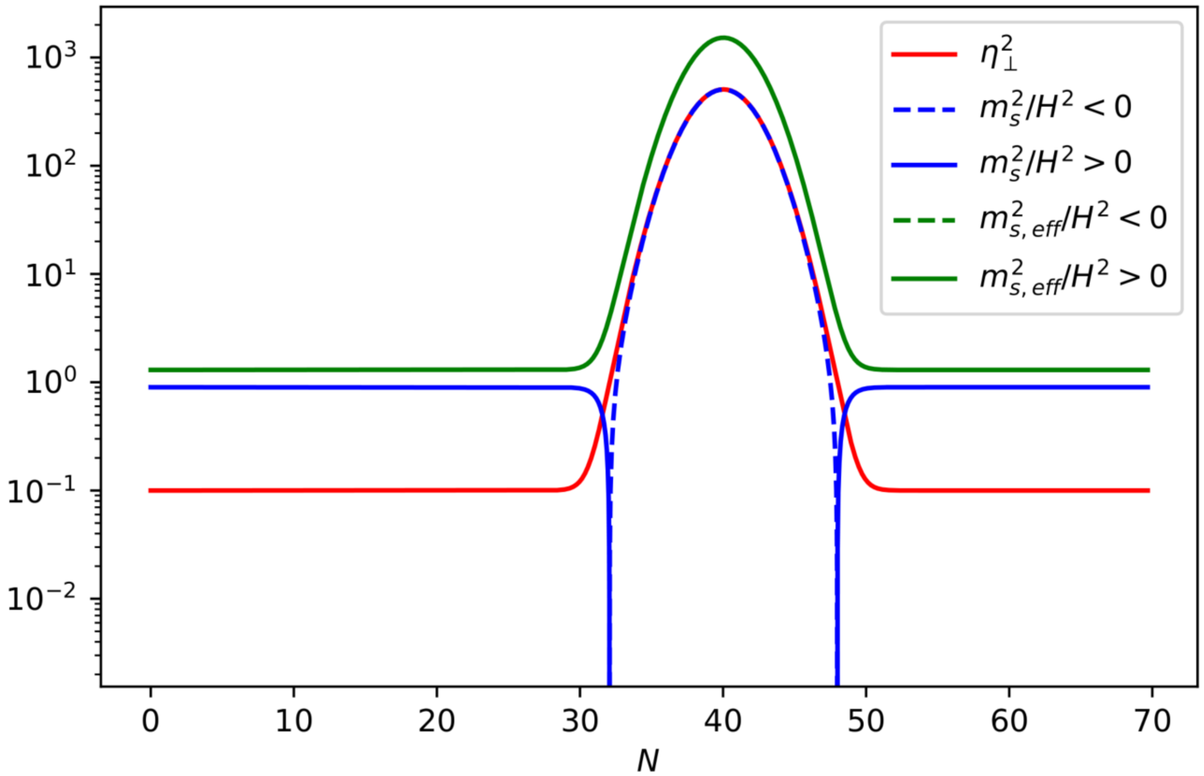
MODEL-INDEPENDENT TREATMENT

$$\eta_\perp(N), \quad m_s(N), \quad H(N)$$

TURNING IN THE LANDSCAPE



PBH & STABLE BACKGROUND



$$\eta_\perp = \eta_\perp^{\max} e^{-\frac{(N-N_\mathrm{f})^2}{2\Delta^2}}$$

$$m_s^2 = (b - \eta_\perp^2)H^2$$

NO NEED FOR A WATERFALL PHASE

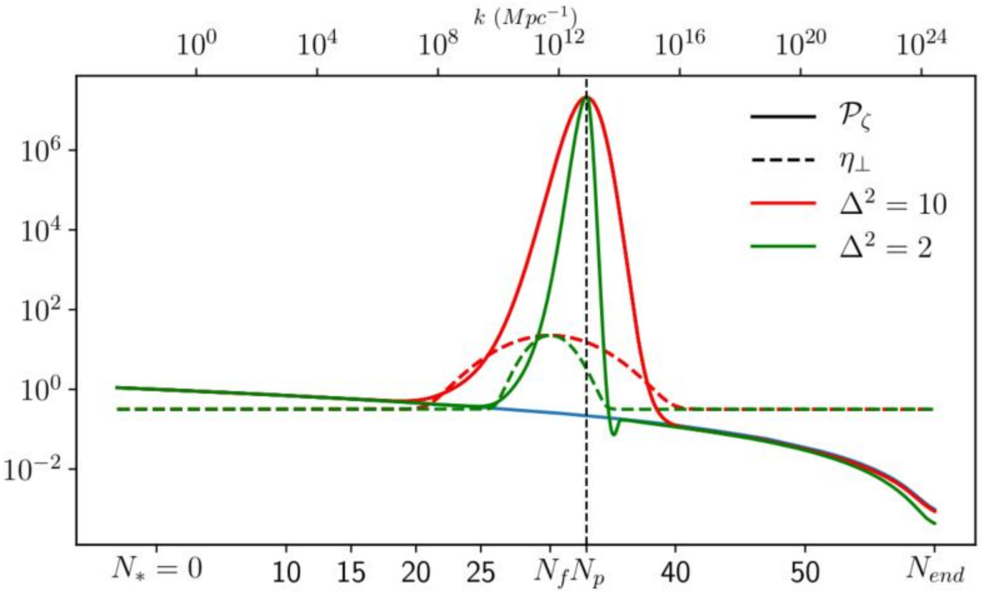
J. Garcia-Bellido, A. D. Linde, and D. Wands '96

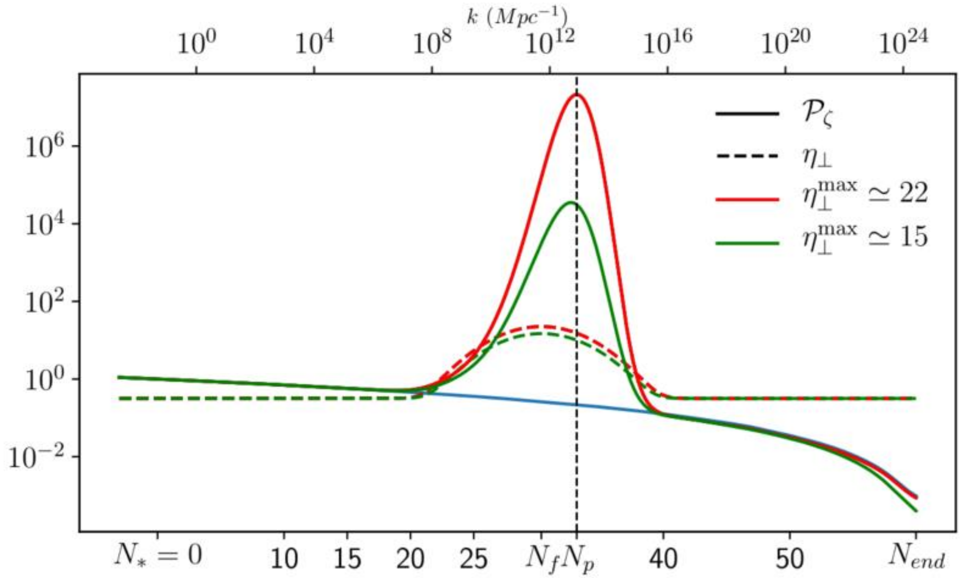
S.Clesse, J.Garcia-Bellido '15

NO NEED FOR USR and/or STOCHASTIC TREATMENT

Many in this Workshop..

TURNING IN THE LANDSCAPE





$$\eta_\perp = \eta_\perp^{\max} e^{-\frac{(N-N_f)^2}{2\Delta^2}}$$

PEAK

- POSITION/HEIGHT
- SHAPE
- GROWTH OF $\mathcal{P}_\zeta$

ANALYTICAL UNDERSTANDING

S. Garcia-Saenz and S. Renaux-Petel, '18
JF et al. '19

EFT

T. Bjorkmo, R. Z. Ferreira, and M. C. D. Marsh '19

WKB

$$\mathcal{P} = \mathcal{P}_0 e^{2\,x}, \qquad x = \frac{\pi}{2}\left(2 - \sqrt{3+\xi}\right)\eta_\perp \qquad m_s^2/H^2 = \xi\eta_\perp^2 - \eta_\perp^2$$

ANALYTICAL UNDERSTANDING

S. Garcia-Saenz and S. Renaux-Petel, '18
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EFT

T. Bjorkmo, R. Z. Ferreira, and M. C. D. Marsh '19 WKB

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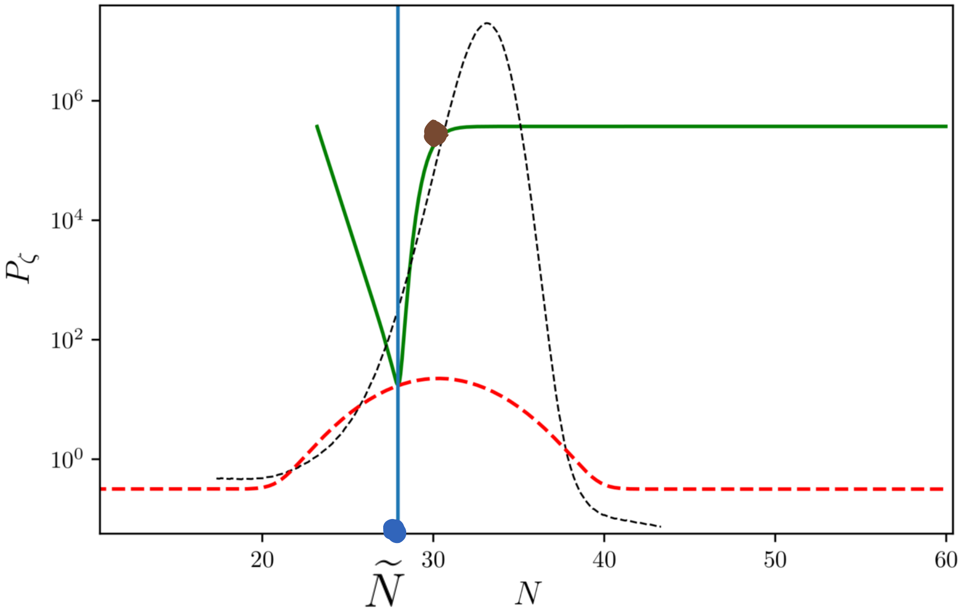

- $\widetilde{N}$: $\quad \dfrac{k}{a(\widetilde{N})} = |m_s(\widetilde{N})|$
- $\bar{N}$: $\quad \dfrac{k|c_s|}{a(\bar{N})} = H(\bar{N})$

ANALYTICAL UNDERSTANDING

S. Garcia-Saenz and S. Renaux-Petel, '18
JF et al. '19
EFT

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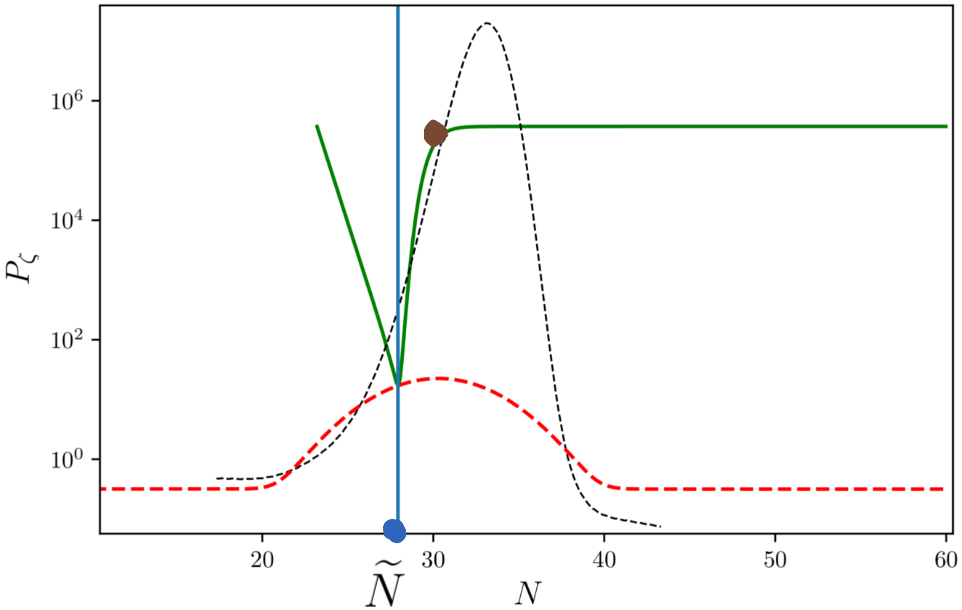
WKB

$$\mathcal{P} = \mathcal{P}_0 e^{2x}\Big|_{\widetilde{N}_k}, \qquad x = \frac{\pi}{2}\left(2 - \sqrt{3+\xi}\right)\eta_\perp \qquad m_s^2/H^2 = \xi\eta_\perp^2 - \eta_\perp^2$$



$$\widetilde{N}: \quad \frac{k}{a(\widetilde{N})} = |m_s(\widetilde{N})|$$

$$\bar{N}: \quad \frac{k|c_s|}{a(\bar{N})} = H(\bar{N})$$

$x \simeq \mathrm{const}$ if

$$(\bar{N} - N_f)^2 - (\widetilde{N} - N_f)^2 \lesssim 2\Delta^2.$$

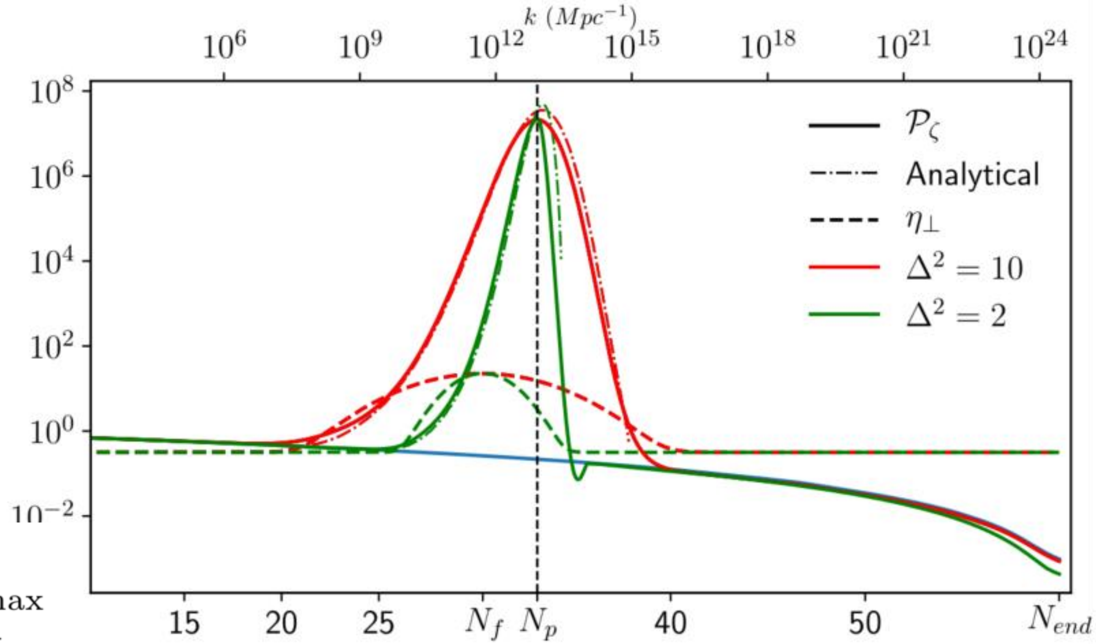
PEAK: HEIGHT & LOCATION

$$\mathcal{P}(k) = \mathcal{P}_0(k) e^{2\,x}|_{\widetilde{N}_k} \qquad \widetilde{N} : \quad \frac{k}{a(\widetilde{N})} = |m_s(\widetilde{N})|$$

$$x \propto \eta_\perp$$

PEAK AT $\widetilde{N}_{k_p} = N_f$

- $$\gamma \equiv \ln\left(\frac{\mathcal{P}}{\mathcal{P}_0}\right)\Big|_{\text{peak}}$$
$$= \pi(2 - \sqrt{3 + b/(\eta_\perp^{\max})^2}) \cdot \eta_\perp^{\max}$$



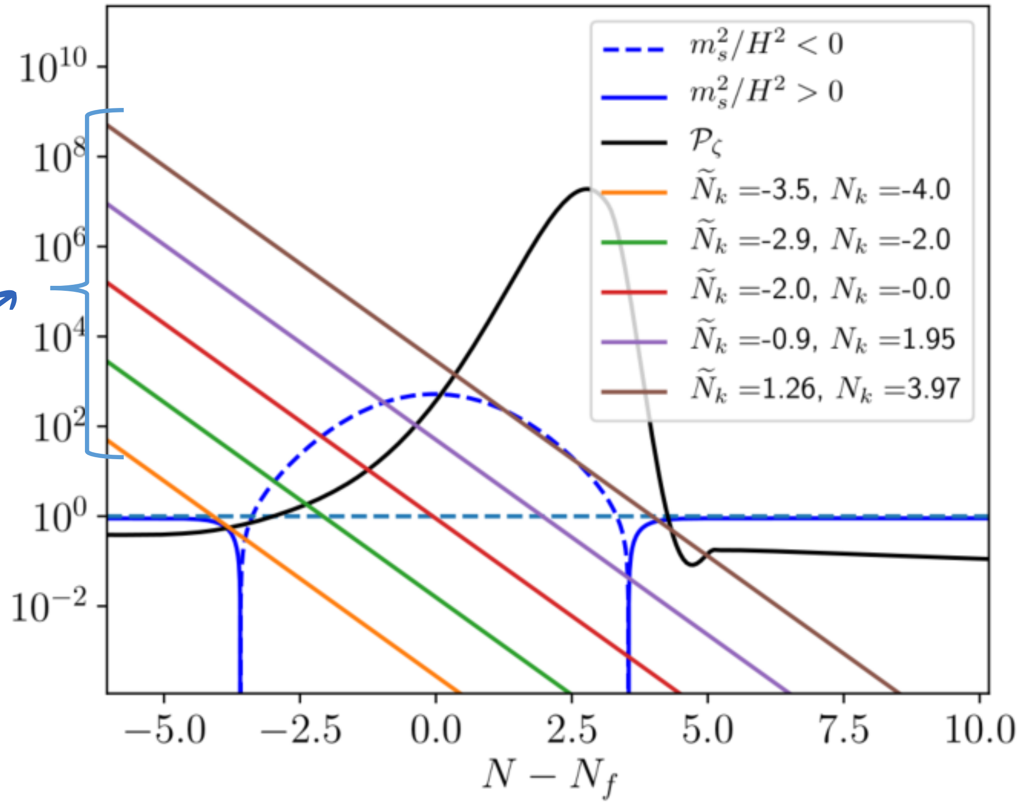
- $$N_p \simeq N_f + \ln \eta_\perp^{\max} = N_f + \ln(\gamma/c)$$

SYMMETRIC $\eta_\perp^2 \Longrightarrow$ ASYMETRIC PEAK

MODE ENHANCED IF

$$\frac{k}{a(\widetilde{N})} = |m_s(\widetilde{N})| \quad \text{while} \quad m_s^2 < 0$$

$$y_k(N) = 2\ln(k/aH)$$
$$= -2N + 2\ln(k/H)$$



SYMMETRIC $\eta_\perp^2 \Longrightarrow$ ASYMETRIC PEAK

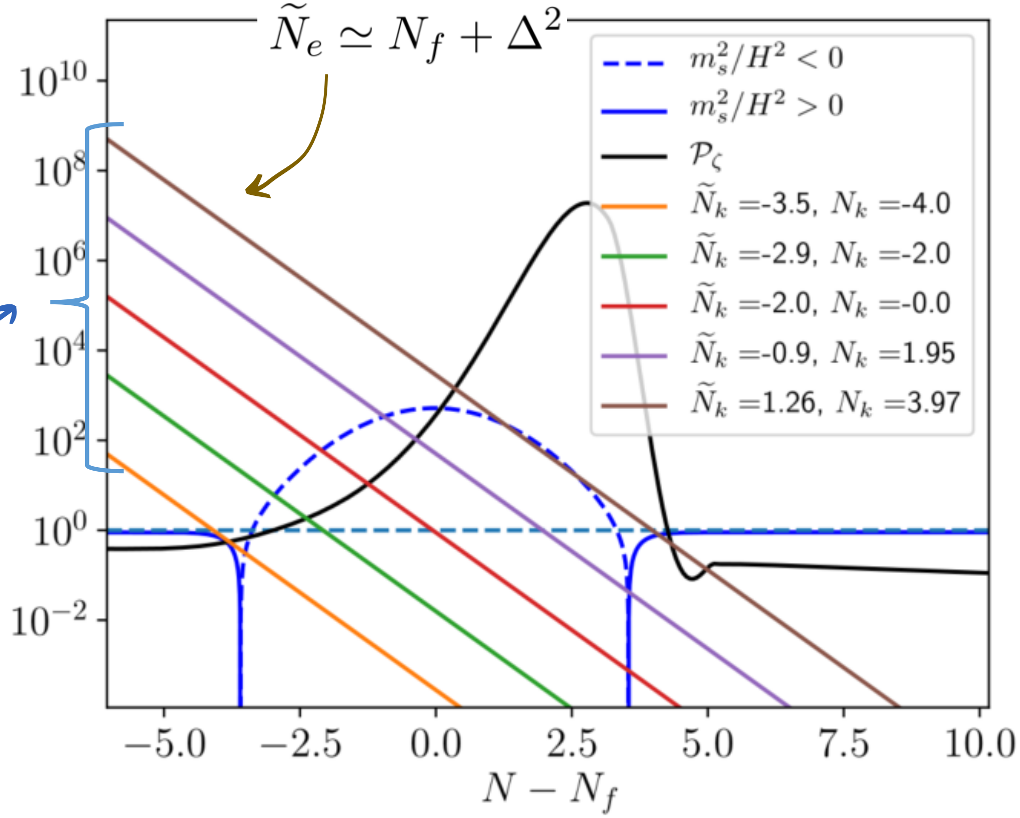
MODE ENHANCED IF

$$\frac{k}{a(\widetilde{N})} = |m_s(\widetilde{N})| \quad \text{while} \quad m_s^2 < 0$$

$$y_k(N) = 2\ln(k/aH)$$
$$= -2N + 2\ln(k/H)$$

LAST MODE ENHANCED

$\widetilde{N}_e \simeq N_f + \Delta^2$



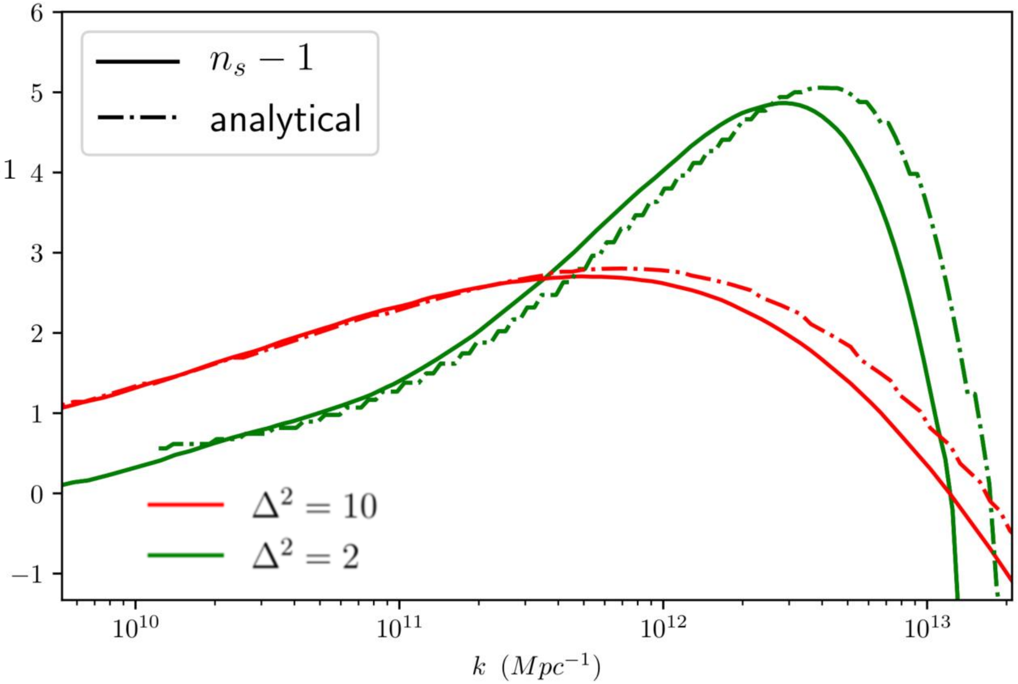
GROWTH OF THE POWER SPECTRUM

- $\mathcal{P}(k) = \mathcal{P}_0(k)e^{2\,x}|_{\widetilde{N}_k}$

$$(n_s - 1) - (n_s - 1)_0 = 2\frac{dx}{d\widetilde{N}}\frac{d\widetilde{N}}{d\ln k}$$

$$= K\frac{d\ln\eta_\perp}{d\widetilde{N}}\eta_\perp\left(1 + \frac{d\ln\eta_\perp}{d\widetilde{N}}\frac{1}{(1 - b/\eta_\perp^2)}\right)^{-1}$$

$$\simeq K\frac{(\widetilde{N} - N_f)}{(\widetilde{N} - N_f) - \Delta^2}\eta_\perp$$

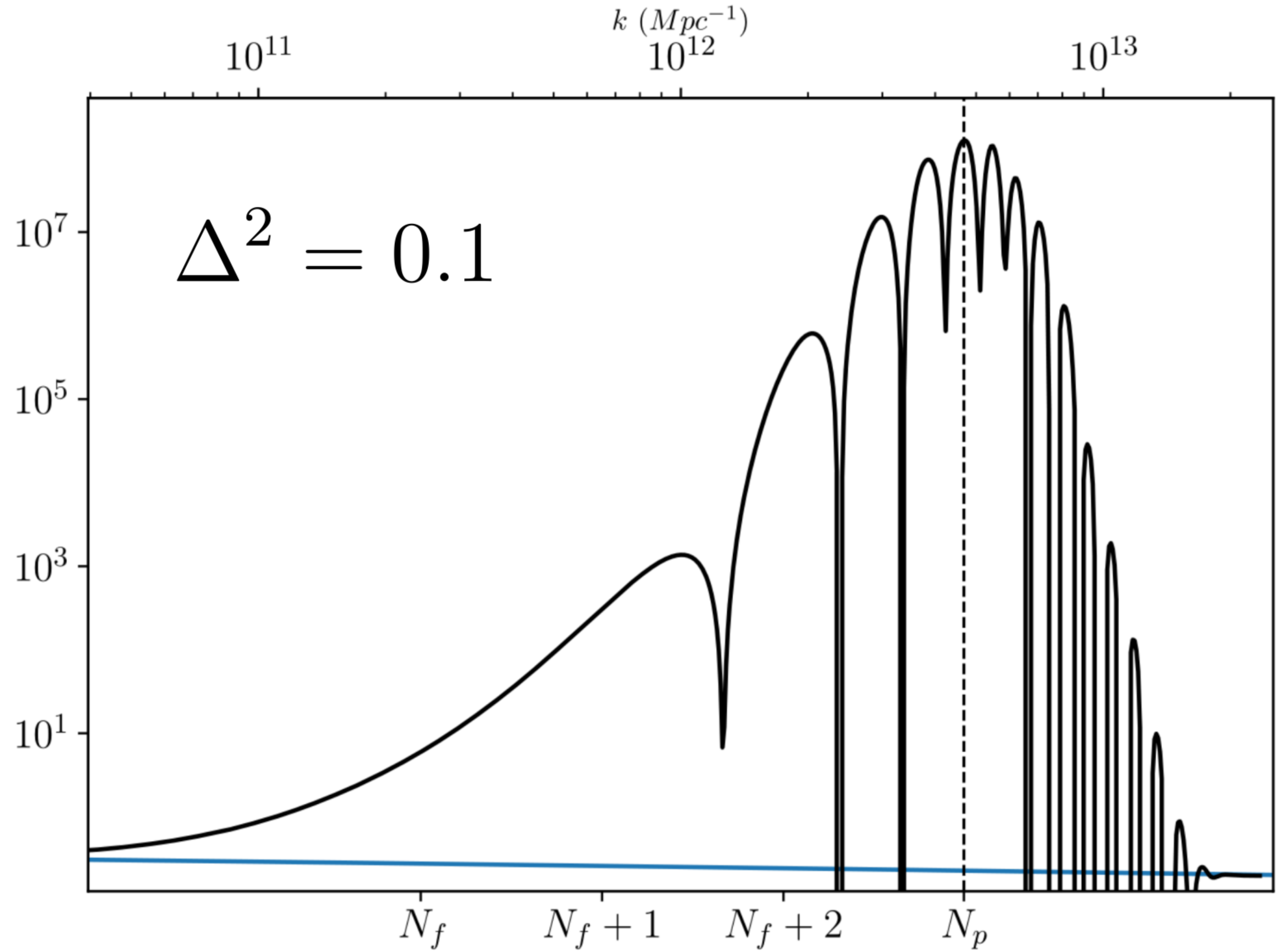


BEYOND SINGLE-FIELD BOUNDS

C. T. Byrnes, P. S. Cole, and S. P. Patil ' '18

P. Carrilho, K. A. Malik, and D. J. Mulryne, '19

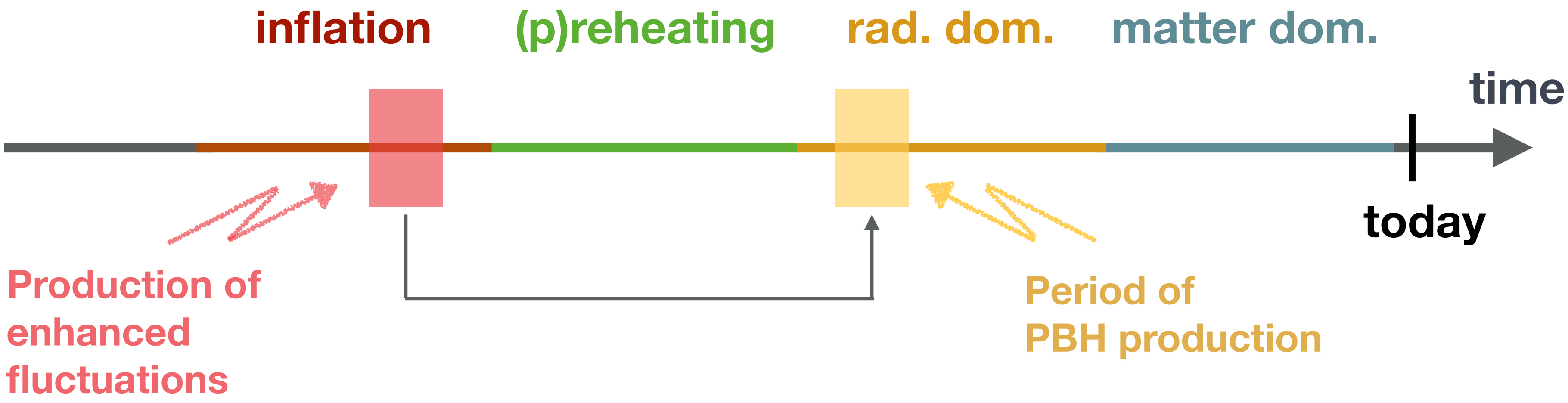
SHARP TURNS



LUKAS WITKOWSKI

PBH formation: short review

Standard picture for PBH formation in inflationary models:



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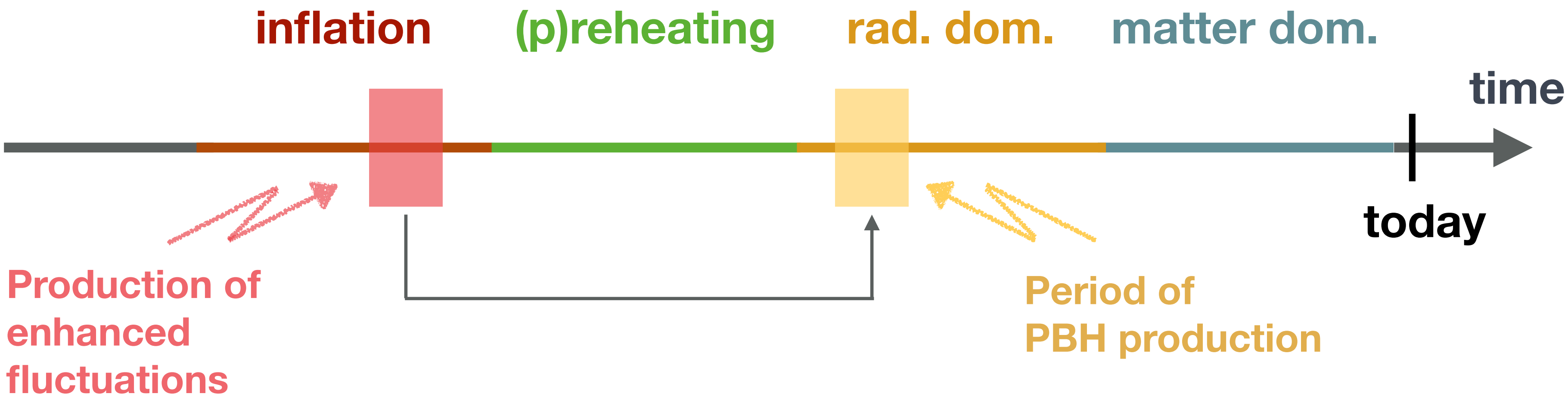

Quantity of interest: energy density in PBHs per logarithmic mass interval as a fraction of the DM energy density today:

Mass function $$f(M) \equiv \frac{1}{\Omega_{\rm CDM}} \frac{d\Omega_{\rm PBH}}{d\ln M}$$

PBH formation: short review

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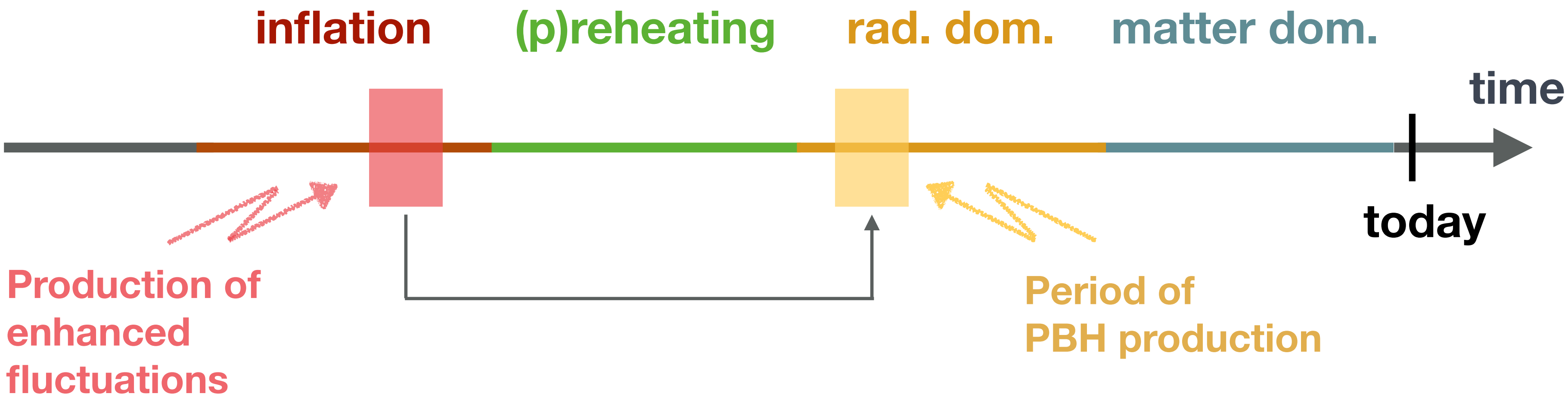

Procedure for computing the mass function $f(M)$:

- Consider a moment during the PBH formation period.
- Calculate the fraction of energy density collapsing into PBHs at that time.
- Apply a redshift factor to relate this to an energy fraction today.
- Sum / integrate over the whole period of PBH formation.

PBH formation: short review

Heuristic: PBH formation upon horizon re-entry of primordial fluctuations that are "sufficiently large".

More precisely: Relevant quantity for PBH formation is the **smoothed density contrast**. [S.Young et al. 1405.7023; S.Young 1905.01230]

Density contrast: $$\delta \equiv \frac{\rho - \bar{\rho}}{\bar{\rho}}\,.$$

This is to be smoothed over the relevant scale, i.e. Horizon scale.

PBH formation if $\delta > \delta_c$ with δ_c the threshold value that is typically determined from numerical studies of collapse.

PBH formation: short review

An important quantity for calculating the PBH abundance is the **probability distribution function** $P_H(\delta)$ for the density contrast at a given time (denoted by the Hubble parameter H).

The energy fraction collapsing into PBHs at a given time is:

$$\beta_H = 2\int_{\delta_c}^{\infty} P_H(\delta)\, d\delta\,.$$

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The energy fraction in PBHs crucially depends on the **tail of the PDF**. ➡ The PBH spectrum is highly sensitive to the detailed statistical properties of the fluctuations.

PBH formation: short review

Dependence of PBH abundance on the detailed statistics of the fluctuations makes PBHs an interesting observable for **primordial non-Gaussianities (NGs)**.

[C.T. Byrnes et al. 1206.4188; S. Young and C.T. Byrnes 1307.4995; G. Franciolini et al. 1801.09415; V. Atal, C. Germani 1811.07857; G. Panagopoulos, E. Silverstein 1906.02827; J.M. Ezquiaga et al. 1912.05399]

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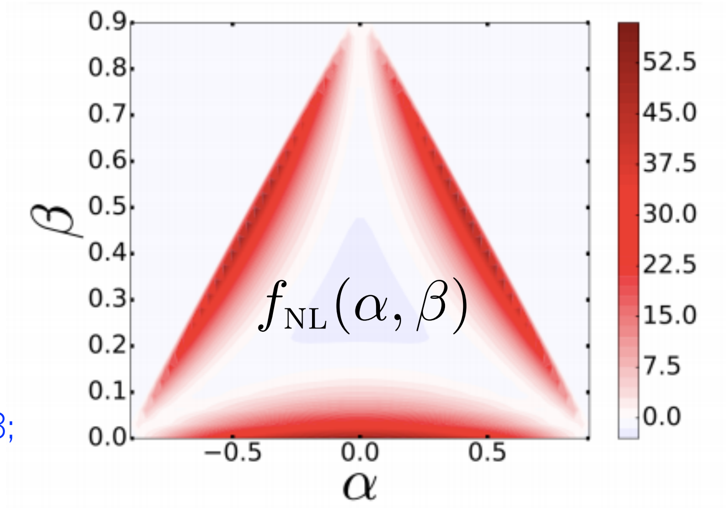
Our model: uses strongly non-geodesic motion that was shown to exhibit a characteristic pattern of NGs, with a bispectrum & higher-order correlation functions enhanced for **flattened** configurations. [S. Garcia-Saenz, S. Renaux-Petel 1805.12563; J. Fumagalli et al. 1902.03221; R. Z. Ferreira 2003.13410]



This unusual pattern of NG may lead to **characteristic features** in the **PBH mass function.**

PBH formation: short review

Caveat: PDF of δ is generically difficult to calculate.

- Knowledge of a number of moments generically not enough.
- Need non-perturbative computational techniques, like the stochastic δN-formalism. [see David Wands', Chris Pattison's and Julien Grain's talks; C. Pattison et al. 1707.00537; J.M. Ezquiaga et al. 1912.05399]

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To proceed: make assumption for the PDF and calculate $f(M)$.

- For simplicity assume **Gaussian statistics**:

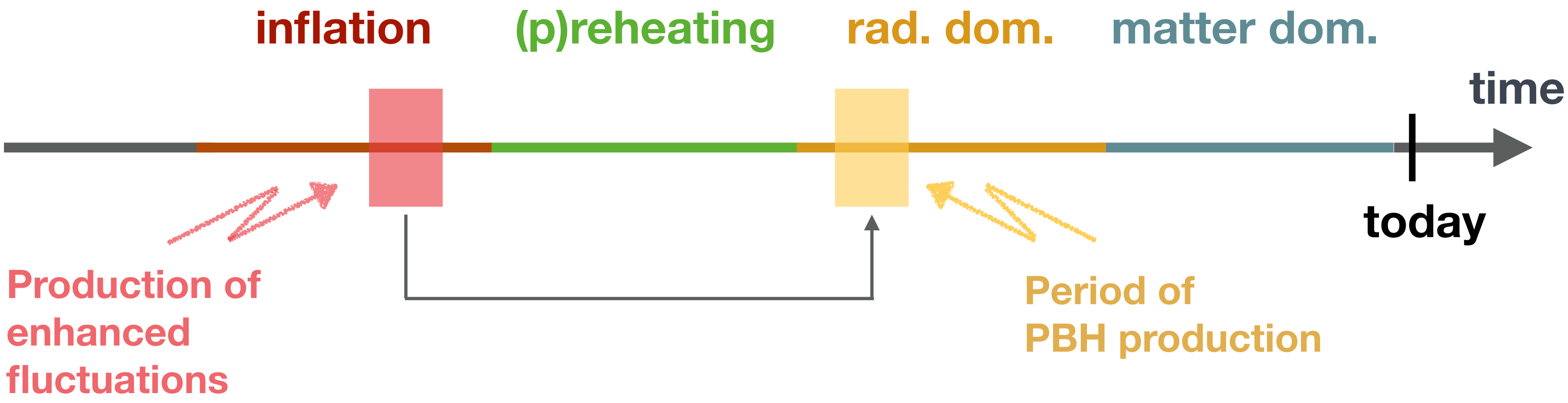
$$P_k(\delta) = \frac{1}{\sqrt{2\pi\,\sigma^2(k)}} \exp\left(- \frac{\delta^2}{2\sigma^2(k)} \right) ,$$

$$\sigma^2(k) = \left(\frac{4}{9}\right)^2 \int_0^\infty \frac{\mathrm{d}q}{q} \, (qk^{-1})^4 \underbrace{e^{-q^2 k^{-2}}}_{\text{smoothing}} \mathcal{P}_\zeta(q)$$

- Results still instructive.

PBH formation: short review

Standard picture for PBH formation in inflationary models:



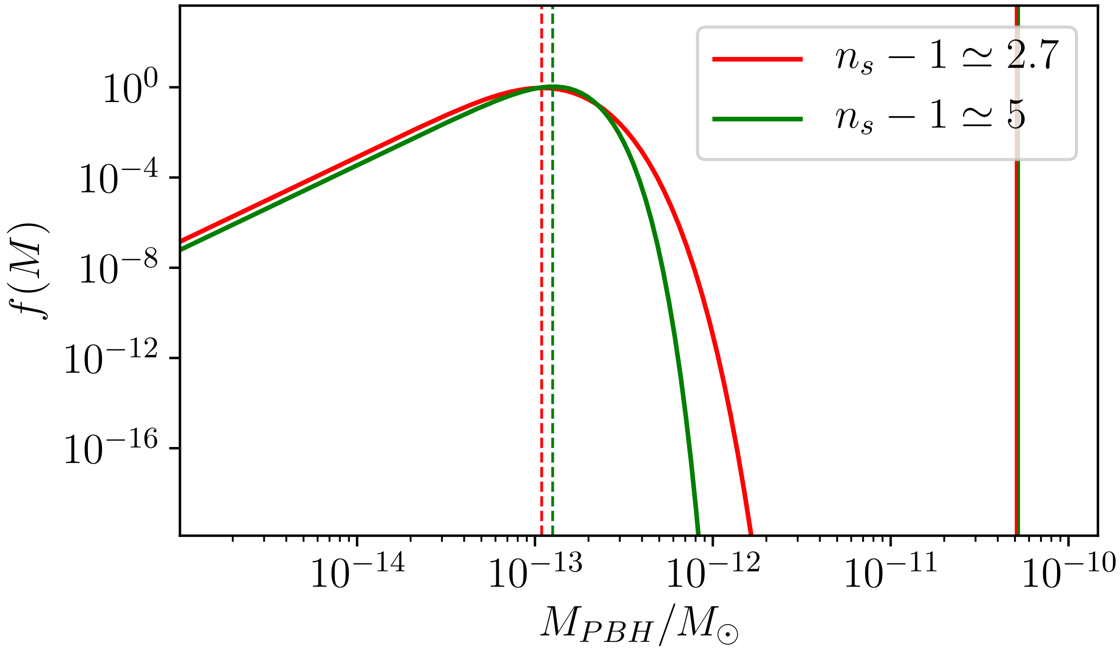
Approximations / omissions in the computation of $f(M)$:

- Assume Gaussian statistics for fluctuations.
- Ignore merger and accretion effects after formation of PBHs.

PBH abundance: results

dashed line:
peak location

solid vertical line:
M_H corresponding
to max. bending



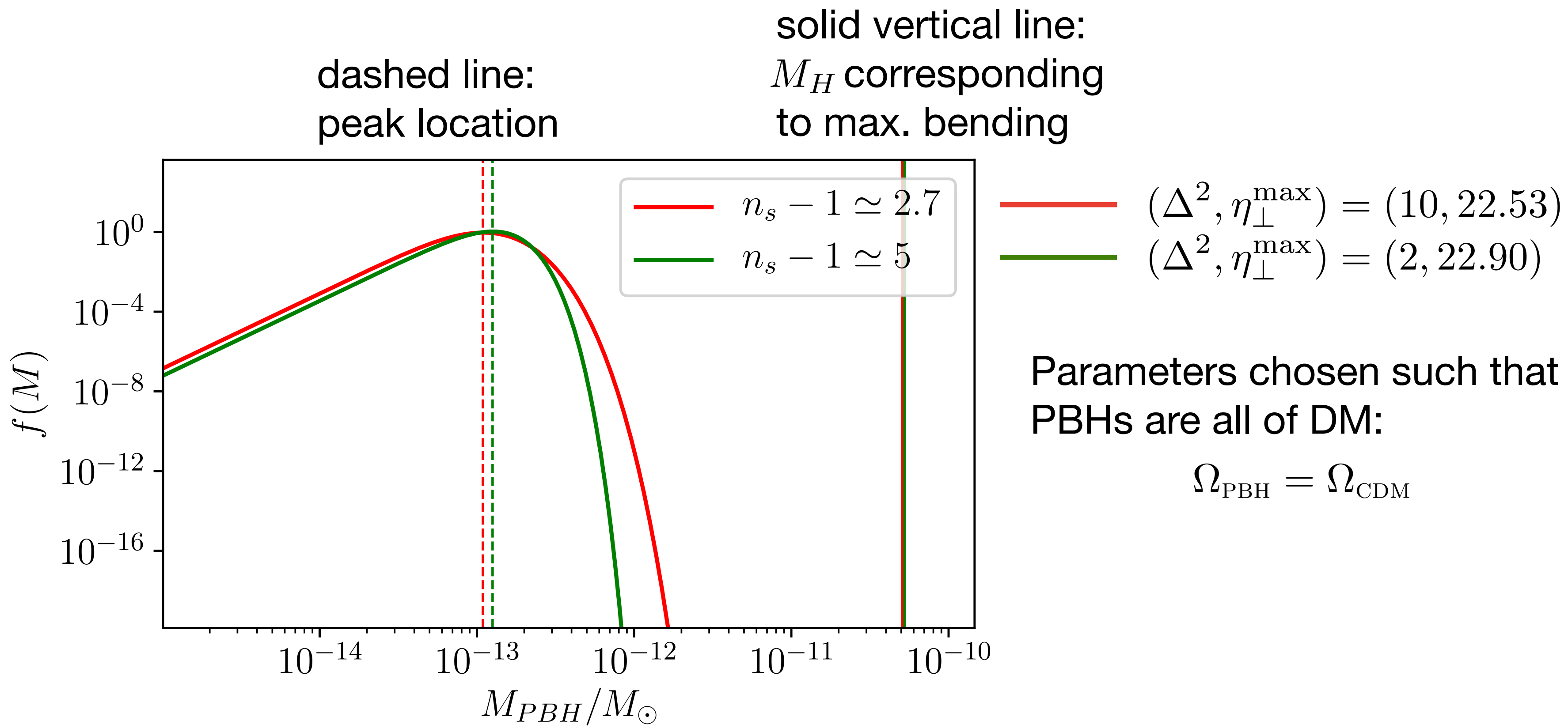
$(\Delta^2, \eta_\perp^{\max}) = (10, 22.53)$

$(\Delta^2, \eta_\perp^{\max}) = (2, 22.90)$

Parameters chosen such that PBHs are all of DM:

$$\Omega_{\rm PBH} = \Omega_{\rm CDM}$$

PBH abundance: results



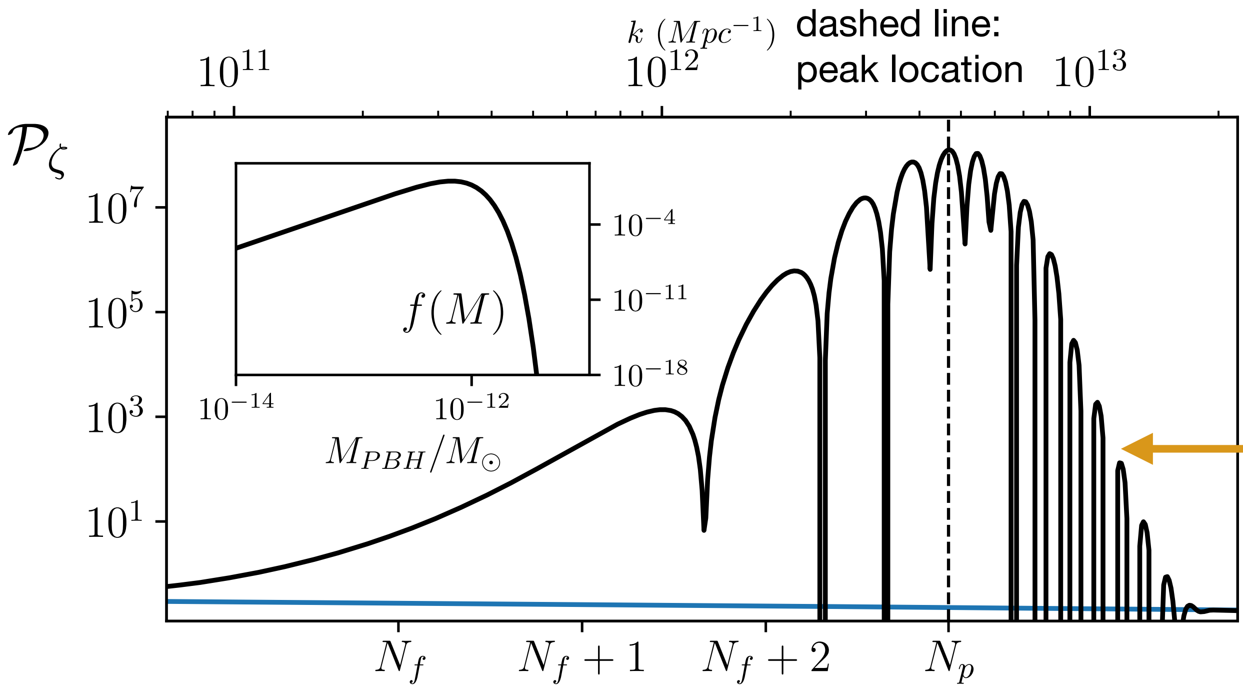
Parameters chosen such that PBHs are all of DM:

$$\Omega_{\text{PBH}} = \Omega_{\text{CDM}}$$

sharper bending → steeper growth of peak in $\mathcal{P}_\zeta(k)$ → narrower peak for $f(M)$

PBH abundance: results

Example with sharper bending $(\Delta^2, \eta_\perp^{\max}) = (0.1, 68)$:



cf. previously:

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Oscillatory pattern in $\mathcal{P}_\zeta$ as a result of sharper bending

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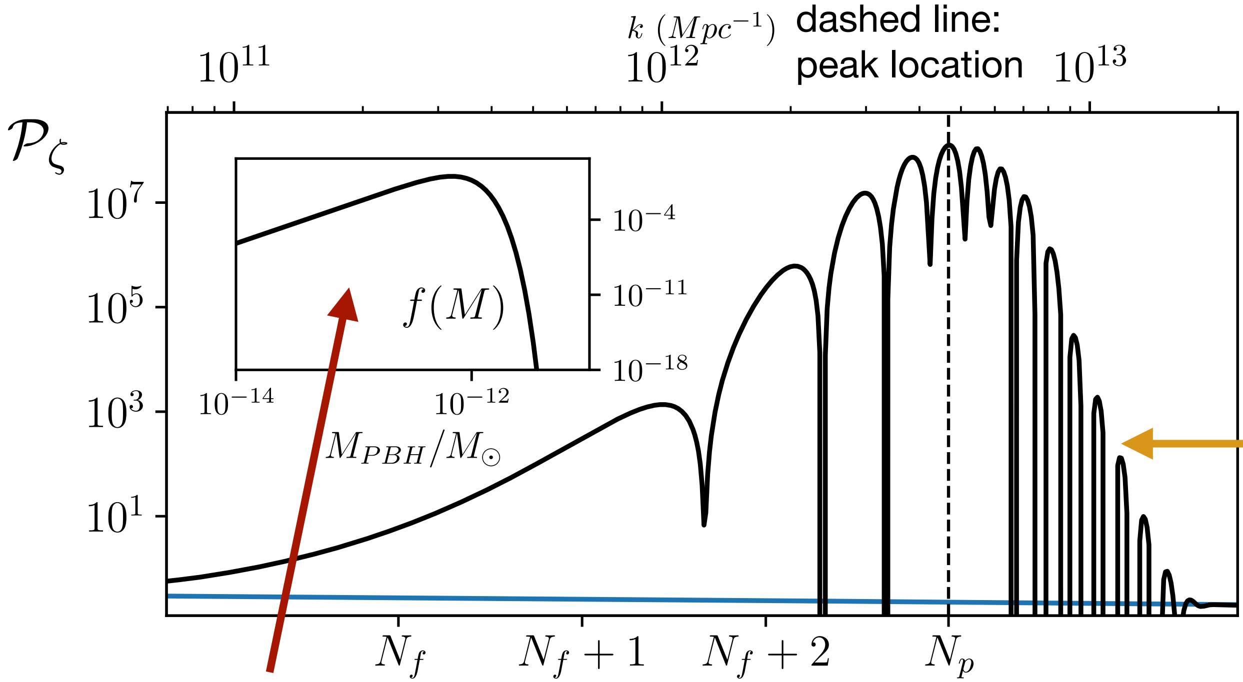

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Oscillatory pattern in $\mathcal{P}_\zeta$ as a result of sharper bending

Oscillations washed out in $f(M)$ as a result of smoothing and the integration over the formation time.

Could this be an artefact of the Gaussian approximation?

Observational Fingerprints

1) Inherent non-Gaussianity with characteristic pattern may lead to unique features in PBH mass function.

2) A potential signal in Gravitational Waves (GWs):

- GWs are sourced during the phase of inflation, but also through **anisotropic stresses during the re-entry** of scalar fluctuations. [S. Mollerach et al. astro-ph/0310711; K.N. Ananda et al. gr-qc/0612013; D. Baumann et al. hep-th/0703290]

- The latter give a contribution to the **stochastic background of GWs**, potentially detectable by LISA and other upcoming GW detectors.

- The **unusual statistical properties** of fluctuations from strongly non-geodesic motion may also leave an imprint in this GW background.

Summary

Phases of strongly non-geodesic motion lead to an enhancement of primordial fluctuations that is sufficient for subsequently producing PBHs with the abundance to be all or a fraction of DM.

The position, amplitude and shape of the peak in $\mathcal{P}_\zeta(k)$ depends on the details of the non-geodesic motion in a precise and quantifiable way.

Potentially unique observational features:

- The **non-Gaussianity** inherent to the mechanism may lead to characteristic **features in the PBH mass spectrum**.
- Also may find a specific pattern in the **stochastic background of GWs**, potentially visible in LISA and other near-future GW observatories.

Extra Slides

PBH formation: mass function

$$f(M) = \frac{2}{\Omega_{\mathrm{CDM}}} \int_{-\infty}^{\infty} \frac{M}{M_H} \underbrace{\sqrt{\frac{M_{\mathrm{eq}}}{M_H}}}_{\text{redshift factor}} \overbrace{P_{M_H}\left(\delta(M, M_H)\right)}^{\text{probability distribution}} \underbrace{\frac{1}{\gamma}\left(\frac{M}{C M_H}\right)^{1/\gamma}}_{\text{from assuming critical collapse}} \overbrace{\mathrm{d}\ln M_H}^{\text{integration over time}}$$

M_H = mass contained in a Hubble volume.

C, γ: parameters describing the collapse, typically taken from numerical simulations. Here: $C = 3.3, \gamma = 0.36$. [see e.g. T. Koike et al., Phys. Rev. Lett. 74, 5170 1995); J.C. Niemeyer, K. Jedamzik, Phys. Rev. Lett. 80, 5481 (1998)]

eq = matter-radiation equality