Just enough inflation: power spectrum modifications on large scales

[1407.1048]

Francisco Gil Pedro

DESY

in collaboration with:
Michele Cicoli, Bhaskar Dutta,
Sean Downes, and Alexander Westphal

Outline:

- Observational hints
- The standard inflationary picture
- The spectrum of slow-roll inflation
- Pre-inflation and the power spectrum
- Degeneracy in power loss
- Summary

Francisco Gil Pedro, Trieste, 8 July 2014

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Observational hints

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Planck 2013 results. XV. CMB power spectra and likelihood

Planck Collaboration: P. A. R. Ade[89], N. Aghanim[62], C. Armitage-Caplan[94], M. Arnaud[76], M. Ashdown[73,6], F. Atrio-Barandela[19], J. Aumont[62], C. Baccigalupi[88], A. J. Banday[97,10], R. B. Barreiro[70], J. G. Bartlett[1,71], E. Battaner[98], K. Benabed[63,96], A. Benoît[60], A. Benoit-Lévy[26,63,96], J.-P. Bernard[10], M. Bersanelli[36,52], P. Bielewicz[97,10,88], J. Bobin[76], J. J. Bock[71,11], A. Bonaldi[72], L. Bonavera[70], J. R. Bond[9], J. Borrill[14,91], F. R. Bouchet[63,96⋆], F. Boulanger[62], M. Bridges[73,6,66], M. Bucher[1], C. Burigana[51,34], R. C. Butler[51], E. Calabrese[94], J.-F. Cardoso[77,1,63], A. Catalano[78,75], A. Challinor[66,73,12], A. Chamballu[76,16,62], L.-Y Chiang[65], H. C. Chiang[28,7], P. R. Christensen[84,40], S. Church[93], D. L. Clements[58], S. Colombi[63,96], L. P. L. Colombo[25,71], C. Combet[78], F. Couchot[74], A. Coulais[75], B. P. Crill[71,85], A. Curto[6,70], F. Cuttaia[51], L. Danese[88], R. D. Davies[72], R. J. Davis[72], P. de Bernardis[35], A. de Rosa[51], G. de Zotti[48,88], J. Delabrouille[1], J.-M. Delouis[63,96], F.-X. Désert[55], C. Dickinson[72], J. M. Diego[70], H. Dole[62,61], S. Donzelli[52], O. Doré[71,11], M. Douspis[62], J. Dunkley[94], X. Dupac[43], G. Efstathiou[66], F. Elsner[63,96], T. A. Enßlin[81], H. K. Eriksen[68], F. Finelli[51,53], O. Forni[97,10], M. Frailis[50], A. A. Fraisse[28], E. Franceschi[51], T. C. Gaier[71], S. Galeotta[50], S. Galli[63], K. Ganga[1], M. Giard[97,10], G. Giardino[44], Y. Giraud-Héraud[1], E. Gjerløw[68], J. González-Nuevo[70,88], K. M. Górski[71,100], S. Gratton[73,66], A. Gregorio[37,50], A. Gruppuso[51], J. E. Gudmundsson[28], F. K. Hansen[68], D. Hanson[82,71,9], D. Harrison[66,73], G. Helou[11], S. Henrot-Versillé[74], C. Hernández-Monteagudo[13,81], D. Herranz[70], S. R. Hildebrandt[11], E. Hivon[63,96], M. Hobson[6], W. A. Holmes[71], A. Hornstrup[17], W. Hovest[81], K. M. Huffenberger[99], G. Hurier[62,78], T. R. Jaffe[97,10], A. H. Jaffe[58], J. Jewell[71], W. C. Jones[28], M. Juvela[27], E. Keihänen[27], R. Keskitalo[23,14], K. Kiiveri[27,47], T. S. Kisner[80], R. Kneissl[42,8], J. Knoche[81], L. Knox[30], M. Kunz[18,62,3], H. Kurki-Suonio[27,47], G. Lagache[62], A. Lähteenmäki[2,47], J.-M. Lamarre[75], A. Lasenby[6,73], M. Lattanzi[34], R. J. Laureijs[44], C. R. Lawrence[71], M. Le Jeune[1], S. Leach[88], J. P. Leahy[72], R. Leonardi[43], J. León-Tavares[45,2], J. Lesgourgues[95,87], M. Liguori[33], P. B. Lilje[68], V. Lindholm[27,47], M. Linden-Vørnle[17], M. López-Caniego[70], P. M. Lubin[31], J. F. Macías-Pérez[78], B. Maffei[72], D. Maino[36,52], N. Mandolesi[51,5,34], D. Marinucci[39], M. Maris[50], D. J. Marshall[76], P. G. Martin[9], E. Martínez-González[70], S. Masi[35], S. Matarrese[33], F. Matthai[81], P. Mazzotta[38], P. R. Meinhold[31], A. Melchiorri[35,54], L. Mendes[43], E. Menegoni[35], A. Mennella[36,52], M. Migliaccio[66,73], M. Millea[30], S. Mitra[57,71], M.-A. Miville-Deschênes[62,9], D. Molinari[51], A. Moneti[63], L. Montier[97,10], G. Morgante[51], D. Mortlock[58], A. Moss[90], D. Munshi[89], P. Naselsky[84,40], F. Nati[35], P. Natoli[34,4,51], C. B. Netterfield[21], H. U. Nørgaard-Nielsen[17], F. Noviello[72], D. Novikov[58], I. Novikov[84], I. J. O'Dwyer[71], F. Orieux[63], S. Osborne[93], C. A. Oxborrow[17], F. Paci[88], L. Pagano[35,54], F. Pajot[62], R. Paladini[59], D. Paoletti[51,53], B. Partridge[46], F. Pasian[50], G. Patanchon[1], P. Paykari[76], O. Perdereau[74], L. Perotto[78], F. Perrotta[88], F. Piacentini[35], M. Piat[1], E. Pierpaoli[25], D. Pietrobon[71], S. Plaszczynski[74], E. Pointecouteau[97,10], G. Polenta[4,49], N. Ponthieu[62,55], L. Popa[64], T. Poutanen[47,27,2], G. W. Pratt[76], G. Prézeau[11,71], S. Prunet[63,96], J.-L. Puget[62], J. P. Rachen[22,81], A. Rahlin[28], R. Rebolo[69,15,41], M. Reinecke[81], M. Remazeilles[62,1], C. Renault[78], S. Ricciardi[51], T. Riller[81], C. Ringeval[67,63,96], I. Ristorcelli[97,10], G. Rocha[71,11], C. Rosset[1], G. Roudier[1,75,71], M. Rowan-Robinson[58], J. A. Rubiño-Martín[69,41], B. Rusholme[59], M. Sandri[51], L. Sanselme[78], D. Santos[78], G. Savini[86], D. Scott[24], M. D. Seiffert[71,11], E. P. S. Shellard[12], L. D. Spencer[89], J.-L. Starck[76], V. Stolyarov[6,73,92], R. Stompor[1], R. Sudiwala[89], F. Sureau[76], D. Sutton[66,73], A.-S. Suur-Uski[27,47], J.-F. Sygnet[63], J. A. Tauber[44], D. Tavagnacco[50,37], L. Terenzi[51], L. Toffolatti[20,70], M. Tomasi[52], M. Tristram[74], M. Tucci[18,74], J. Tuovinen[83], M. Türler[56], L. Valenziano[51], J. Valiviita[47,27,68], B. Van Tent[79], J. Varis[83], P. Vielva[70], F. Villa[51], N. Vittorio[38], L. A. Wade[71], B. D. Wandelt[63,96,32], I. K. Wehus[71], M. White[29], S. D. M. White[81], D. Yvon[16], A. Zacchei[50], and A. Zonca[31]

(Affiliations can be found after the references)

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Abstract

This paper presents the *Planck* likelihood, a complete statistical description of the two-point correlation function of the CMB temperature fluctuations that accounts for all known relevant uncertainties, both instrumental and astrophysical in nature. We use this likelihood to derive our best estimate of the CMB angular power spectrum from *Planck* over three decades in multipole moment, ℓ, covering $2 \le \ell \le 2500$. The main source of error at $\ell \lesssim 1500$ is cosmic variance. Uncertainties in small-scale foreground modelling and instrumental noise dominate the error budget at higher ℓs. For $\ell < 50$, our likelihood exploits all *Planck* frequency channels from 30 to 353 GHz, separating the cosmological CMB signal from diffuse Galactic foregrounds through a physically motivated Bayesian component separation technique. At $\ell \ge 50$, we employ a correlated Gaussian likelihood approximation based on a fine-grained set of angular cross-spectra derived from multiple detector combinations between the 100, 143, and 217 GHz frequency channels, marginalizing over power spectrum foreground templates. We validate our likelihood through an extensive suite of consistency tests, and assess the impact of residual foreground and instrumental uncertainties on the final cosmological parameters. We find good internal agreement among the high-ℓ cross-spectra with residuals below a few μK^2 at $\ell \lesssim 1000$, in agreement with estimated calibration uncertainties. We compare our results with foreground-cleaned CMB maps derived from all *Planck* frequencies, as well as with cross-spectra derived from the 70 GHz *Planck* map, and find broad agreement in terms of spectrum residuals and cosmological parameters. We further show that the best-fit ΛCDM cosmology is in excellent agreement with preliminary *Planck EE* and *TE* polarisation spectra. We find that the standard ΛCDM cosmology is well constrained by *Planck* from the measurements at $\ell \lesssim 1500$. One specific example is the spectral index of scalar perturbations, for which we report a $5.4\,\sigma$ deviation from scale invariance, $n_s \neq 1$. Increasing the multipole range beyond $\ell \simeq 1500$ does not increase our accuracy for the ΛCDM parameters, but instead allows us to study extensions beyond the standard model. We find no indication of significant departures from the ΛCDM framework. Finally, we report a tension between the *Planck* best-fit ΛCDM model and the low-ℓ spectrum in the form of a power deficit of 5–10% at $\ell \lesssim 40$, with a statistical significance of 2.5–3 σ. Without a theoretically motivated model for this power deficit, we do not elaborate further on its cosmological implications, but note that this is our most puzzling finding in an otherwise remarkably consistent dataset.

Key words. Cosmology: cosmic background radiation – Surveys – Methods: data analysis

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Observational hints

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arXiv:1303.5075v2 [astro-ph.CO] 25 Mar 2013

DESY

Observational hints

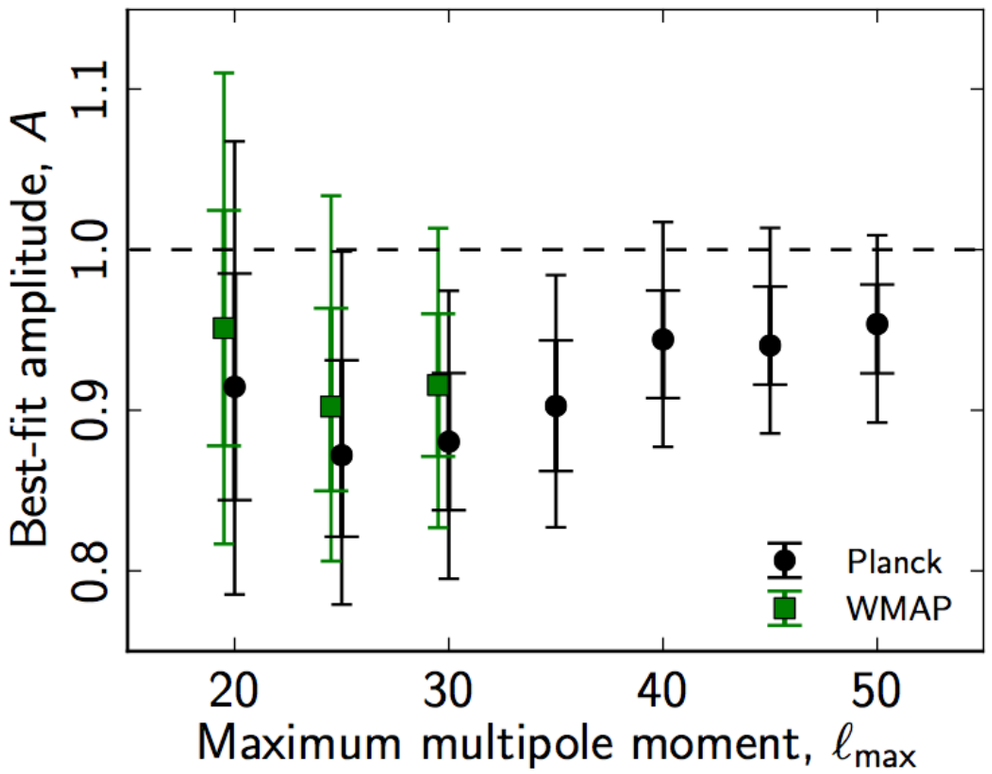


Figure 39. Power spectrum amplitude, q, relative to the best-fit *Planck* model as a function of ℓ_{max}, as measured by the low-ℓ *Planck* and *WMAP* temperature likelihoods, respectively. Error bars indicate 68 and 95% confidence regions.

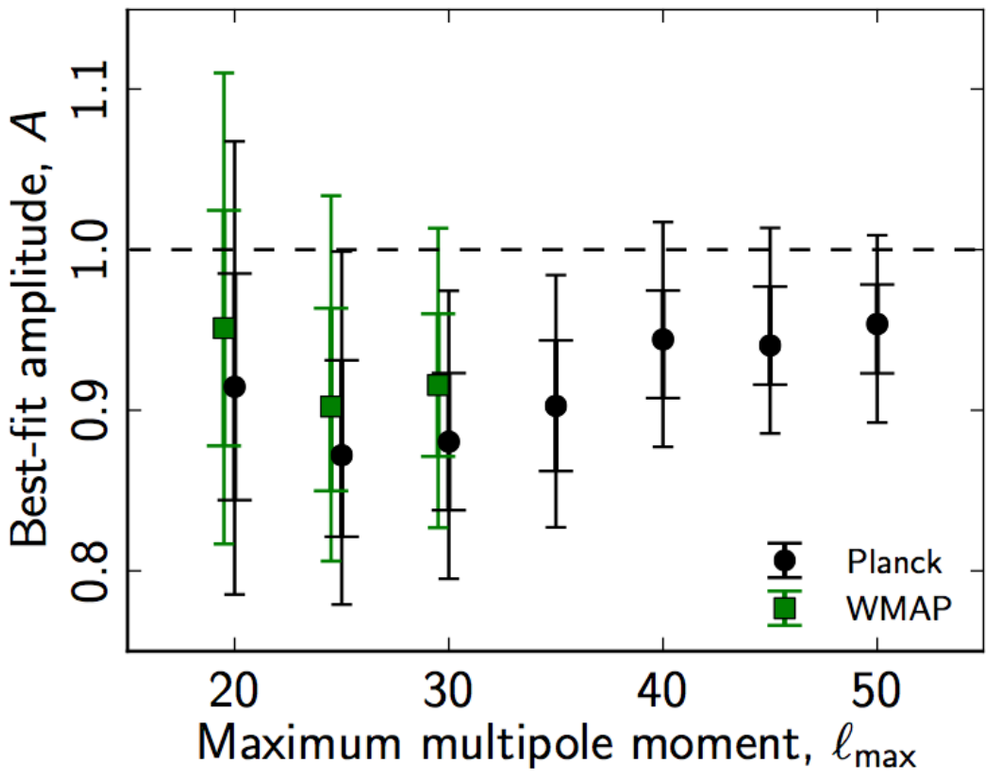
$$\mathcal{P}_{\mathcal{R}}(k) = \mathcal{P}_0(k)\left\{1 - \exp\left[-\left(\frac{k}{k_c}\right)^{\lambda_c}\right]\right\}.$$

Model	$-2\Delta \ln \mathcal{L}_{max}$	$\ln B_{0X}$	Parameter	Best fit value
Wiggles	-9.0	1.5	α_w	0.0294
			ω	28.90
			φ	0.075 π
Step-inflation	-11.7	0.3	$\mathcal{A}_f$	0.102
			$\ln(\eta_f/\mathrm{Mpc})$	8.214
			$\ln x_d$	4.47
Cutoff	-2.9	0.3	$\ln(k_c/\mathrm{Mpc}^{-1})$	−8.493
			λ_c	0.474

Table 11. Improvement in fit and logarithm of the Bayes factor with respect to power law ΛCDM and best fit parameter values for the wiggles, step-inflation, and cutoff models. The larger $\ln B_{0X}$, the greater the preference for a featureless power law spectrum.

DESY

Observational hints



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Tensor modes contribute to TT spectrum on large scales

<u>large r increases:</u>
-significance of power loss
-level of power loss

Francisco Gil Pedro, Trieste, 8 July 2014

DESY

Cosmic variance

We only have one sky

Measurements on largest scales are statistically limited

[Planck XV]

Cosmic variance

CV is the simplest explanation for low-ℓ anomaly

CV can be decreased using LSS data

[1309.4060]

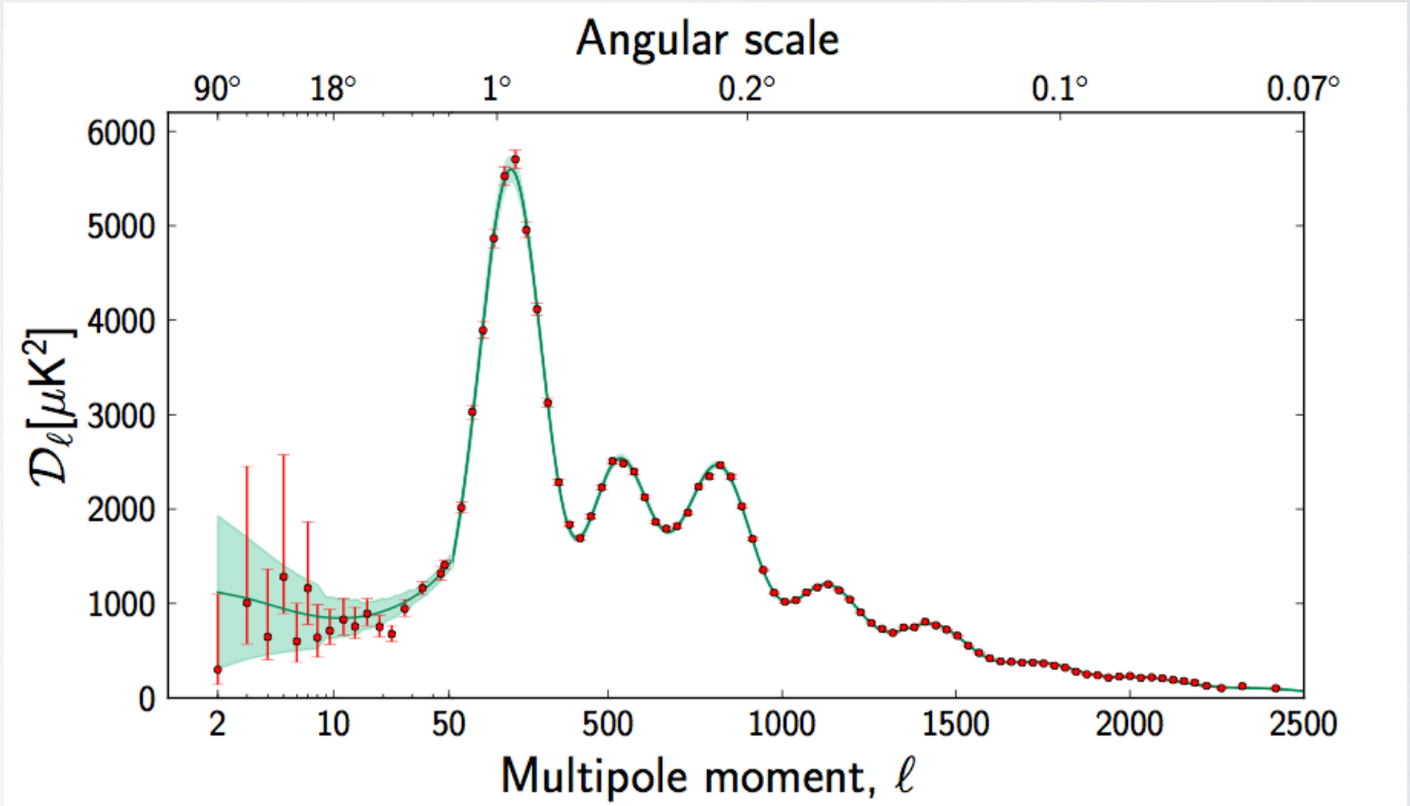
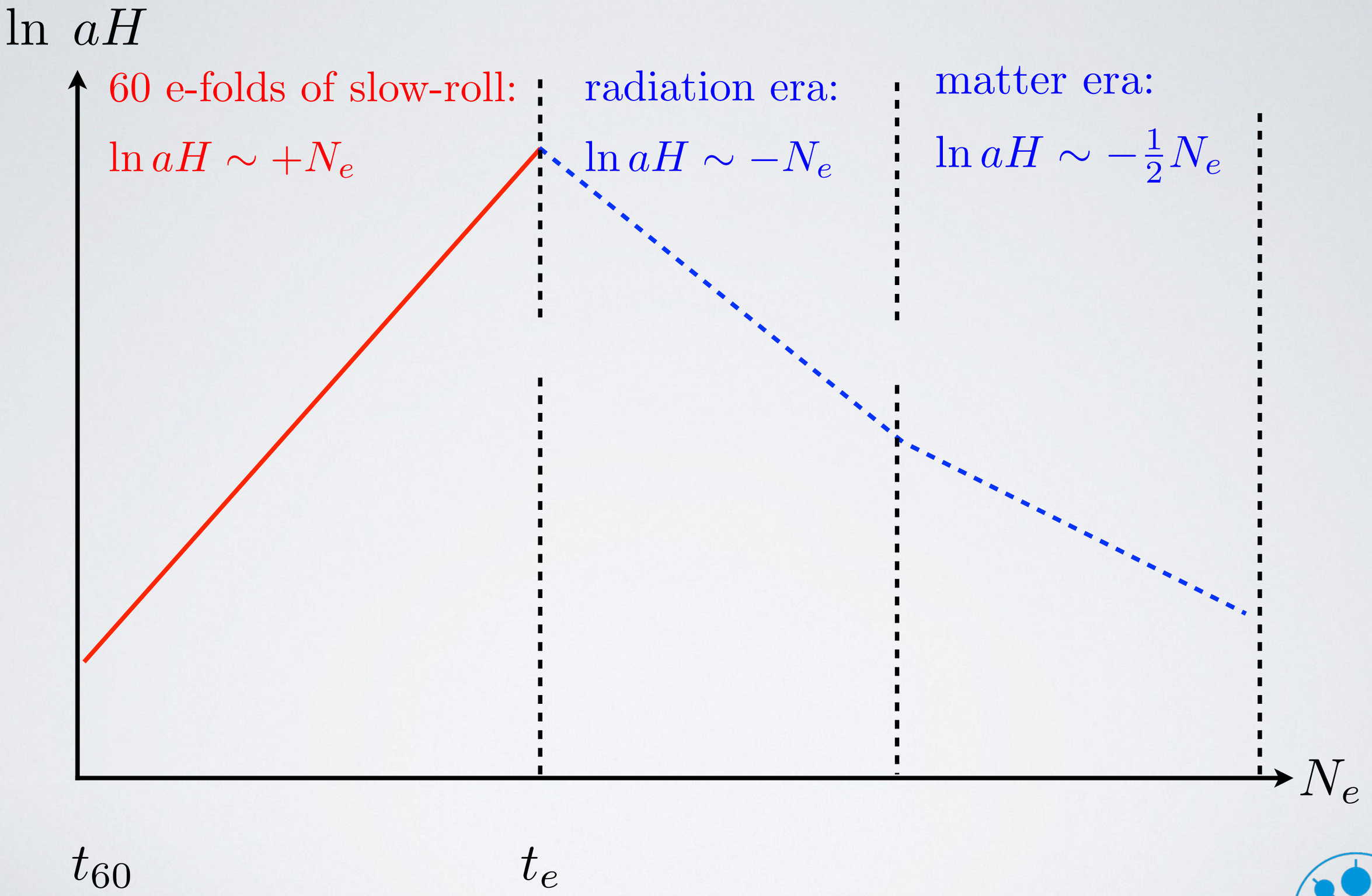


Figure 37. The 2013 *Planck* CMB temperature angular power spectrum. The error bars include cosmic variance, whose magnitude is indicated by the green shaded area around the best fit model. The low-ℓ values are plotted at 2, 3, 4, 5, 6, 7, 8, 9.5, 11.5, 13.5, 16, 19, 22.5, 27, 34.5, and 44.5.

DESY

The standard picture



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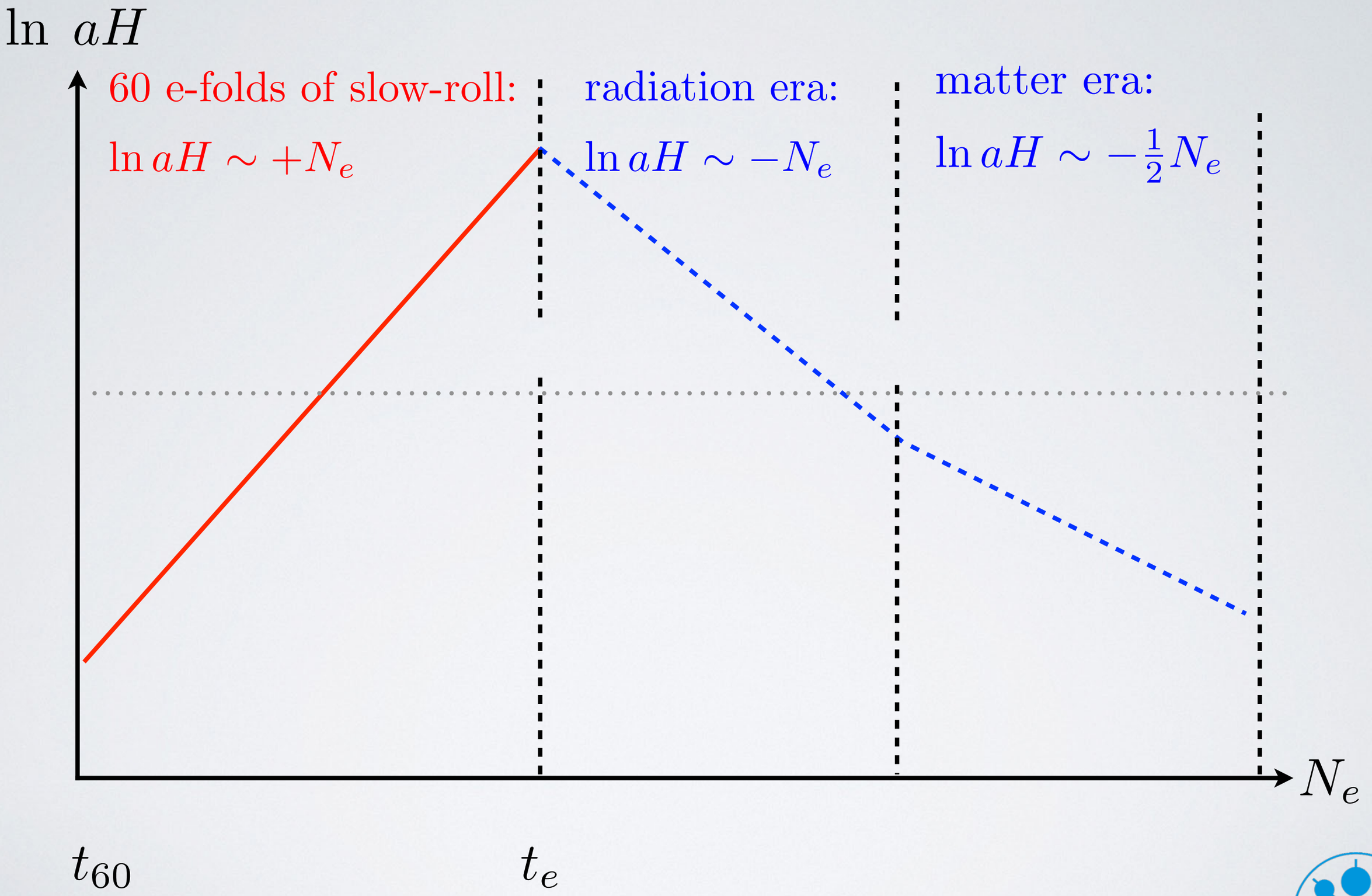

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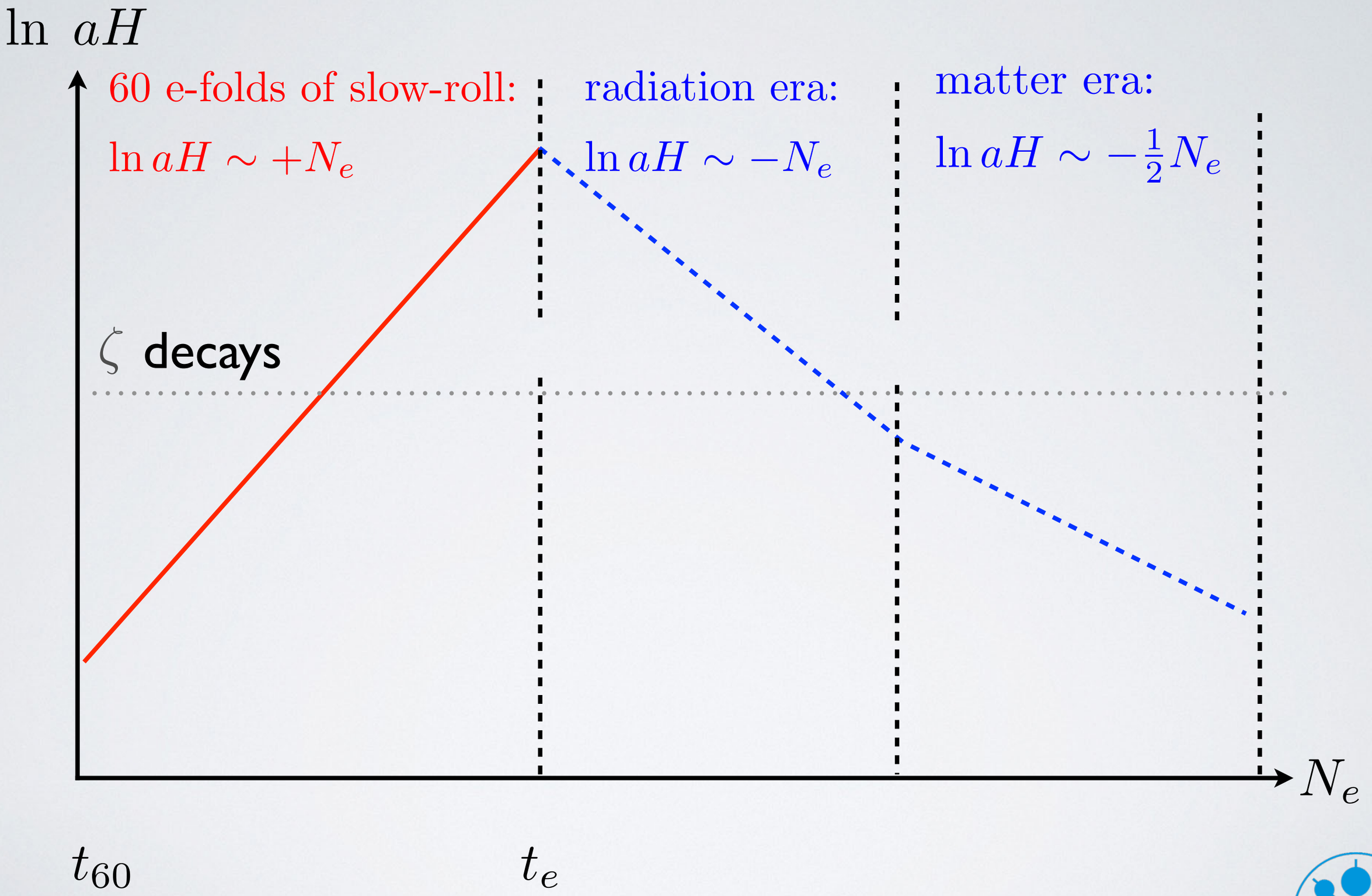

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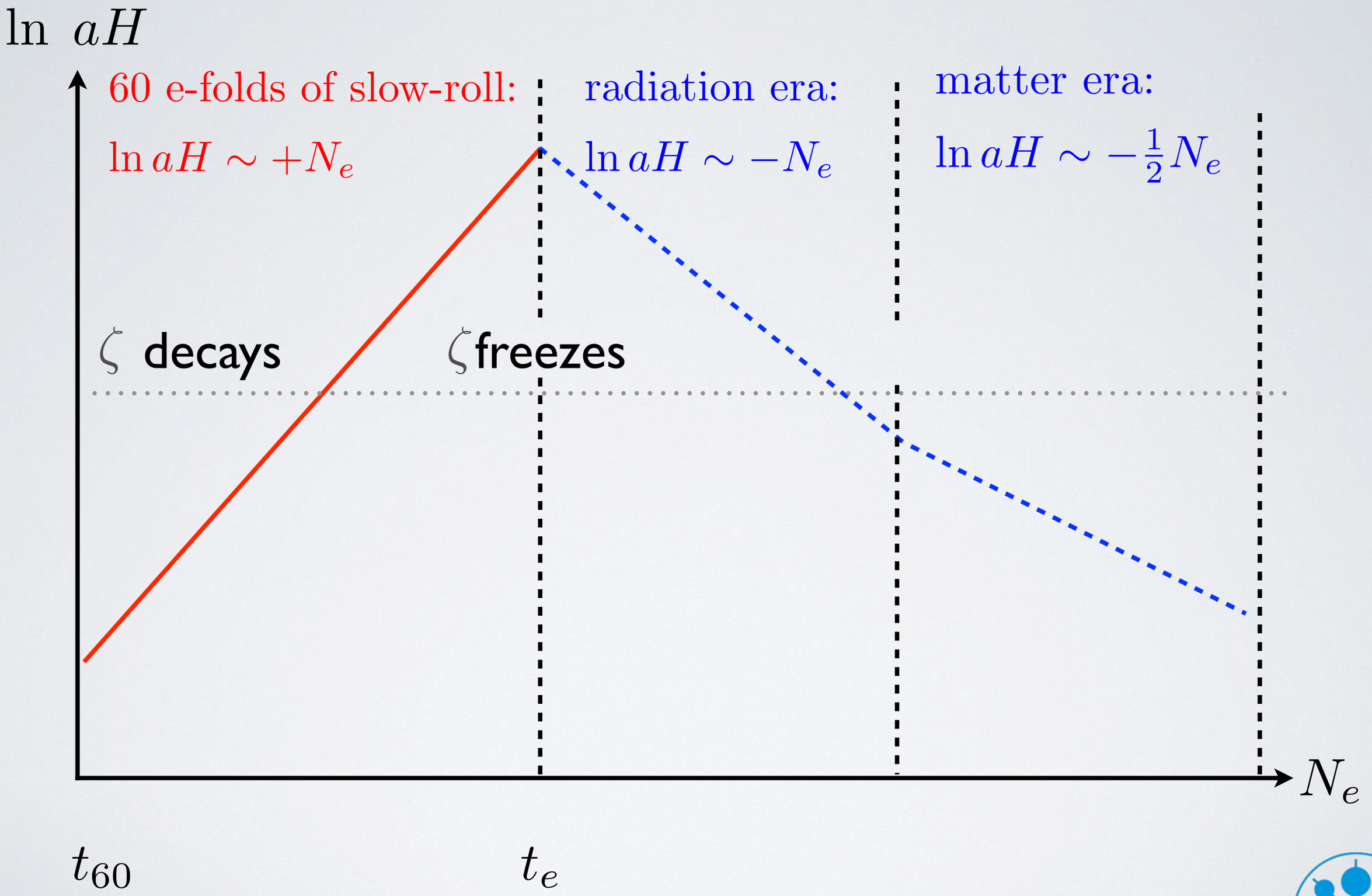

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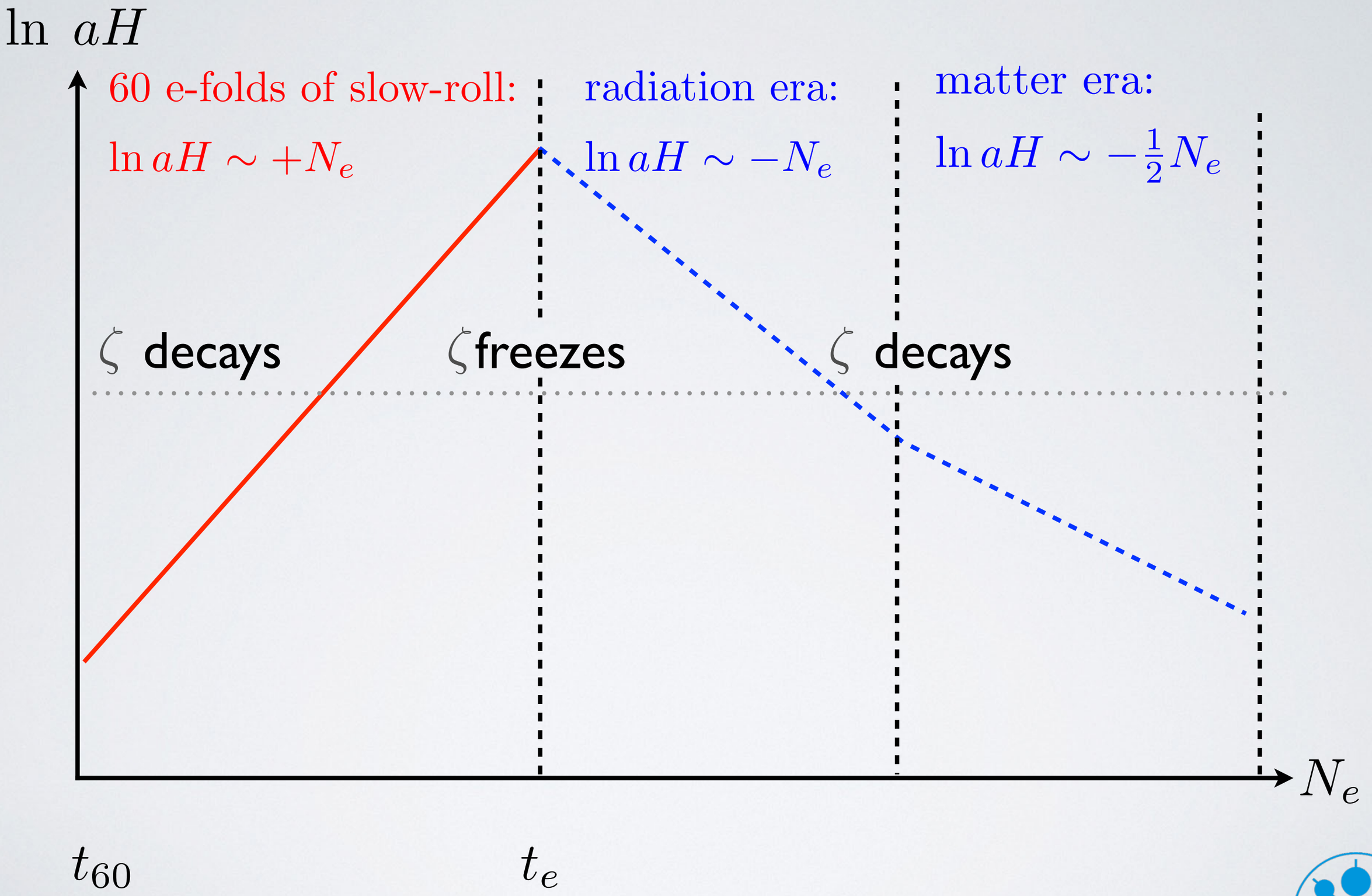

DESY

The Mukhanov-Sasaki Equation

curvature perturbation: ζ $\quad u \equiv \zeta\, z \quad$ with $\quad z \equiv a\sqrt{2\epsilon_H}$

$$u'' + \left(k^2 - \frac{z''}{z}\right) u = 0$$

Useful to use efolds as 'time' coordinate

Assume background of the form: $\quad aH \sim e^{\xi N}$

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$$u_{\alpha\alpha} + \xi\, u_\alpha + \left\{\left(\frac{k}{aH}\right)^2 - (1+\xi)\right\} u = 0$$

DESY

The Mukhanov-Sasaki Equation

Behaviour of curvature pert. depends on $L_{hor} \equiv H^{-1}$

during inflation:

$k > a\,H \leftrightarrow \lambda_{phys} < H^{-1}$ **inside** horizon, ζ **decays**

$k < a\,H \leftrightarrow \lambda_{phys} > H^{-1}$ **outside** horizon, ζ **freezes**

Francisco Gil Pedro, Trieste, 8 July 2014

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$$u = C^{(1)} \frac{1}{\sqrt{\xi a H}} H_\nu^{(1)} \left(\frac{k}{\xi a H} \right) + C^{(2)} \frac{1}{\sqrt{\xi a H}} H_\nu^{(2)} \left(\frac{k}{\xi a H} \right)$$

$C^{(1)}, C^{(2)}$ set by ics

$$\nu = \left| \frac{2+\xi}{2\xi} \right|$$

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The spectrum of slow-roll inflation

Francisco Gil Pedro, Trieste, 8 July 2014

The spectrum of slow-roll inflation

deep inside horizon $\lambda_{phys} \ll H^{-1}$ modes do not feel curvature

Francisco Gil Pedro, Trieste, 8 July 2014

The spectrum of slow-roll inflation

deep inside horizon $\lambda_{phys} \ll H^{-1}$ modes do not feel curvature

flat space mode functions

$$C^{(1)} = \sqrt{\pi/2}$$

$$C^{(2)} = 0$$

$$u = \frac{\sqrt{\pi/2}}{\sqrt{aH}} H_\nu^{(1)} \left(\frac{k}{aH} \right)$$

$$\nu = \frac{3}{2} + \epsilon_H + \frac{1}{2}\eta_H$$

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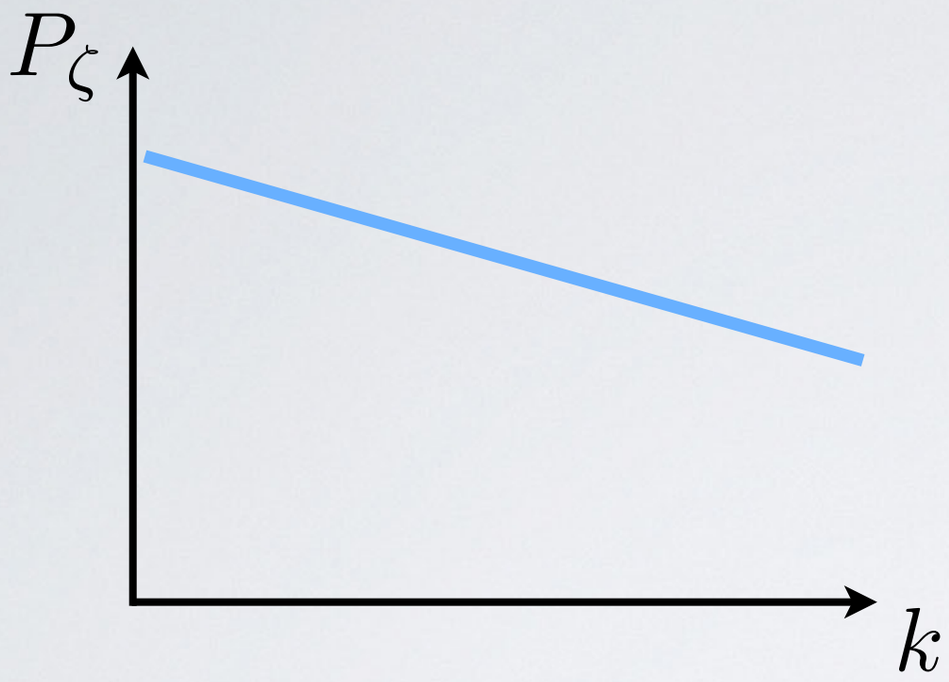
$$P_k \equiv k^3 \left| \frac{u}{z} \right|^2 \sim \frac{H^2}{\epsilon_H} k^{3-2\nu}$$

DESY

The spectrum of slow-roll inflation



Planck XXII:

$$n_s = 0.9603 \pm 0.0073$$

$$\ln(10^{10} A_s) = 3.089^{+0.024}_{-0.027}$$

$$P_k = A_s \left(\frac{k}{k_*}\right)^{n_s - 1}$$

$$k_* = 0.002 \text{ Mpc}^{-1}$$

Scale invariance is excluded by more than 5 σ

DESY

Pre-inflation and the power spectrum

?? What if inflation was short ??

Francisco Gil Pedro, Trieste, 8 July 2014

Pre-inflation and the power spectrum

?? What if inflation was short ??

Freivogel et al. 2007
McAllister et al. 2013

theoretically well motivated:

$$P(N_e) \sim \left(\frac{1}{N_e}\right)^{\alpha} \qquad \alpha > 0$$

Pre-inflation and the power spectrum

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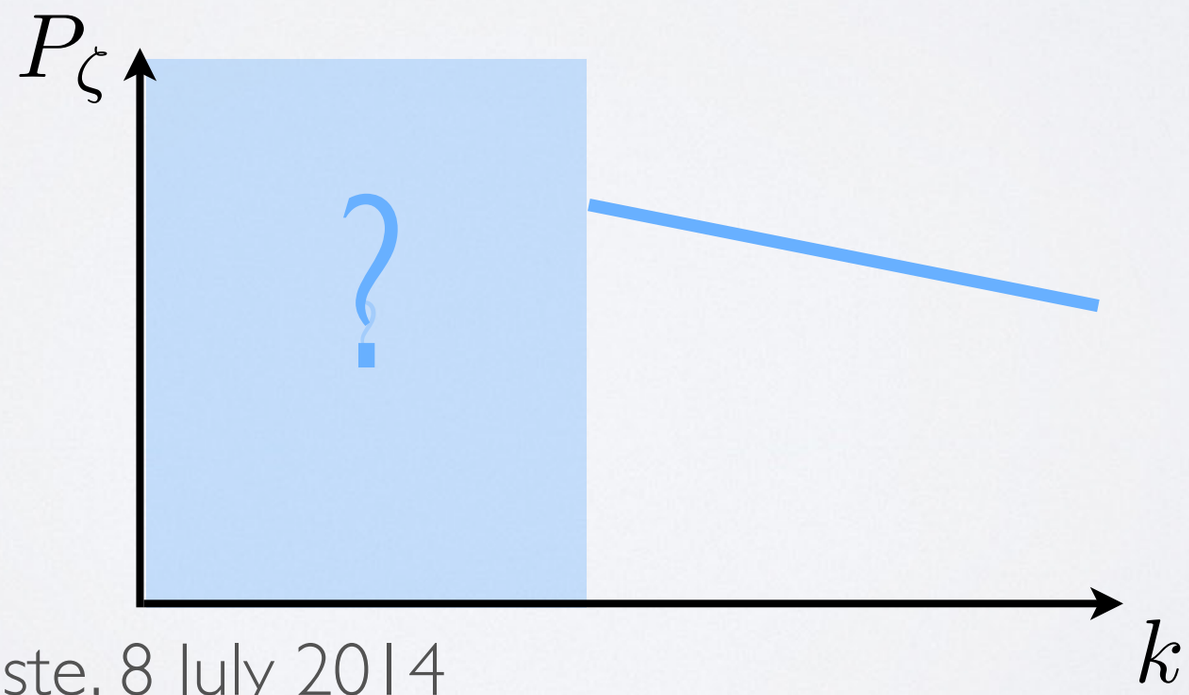
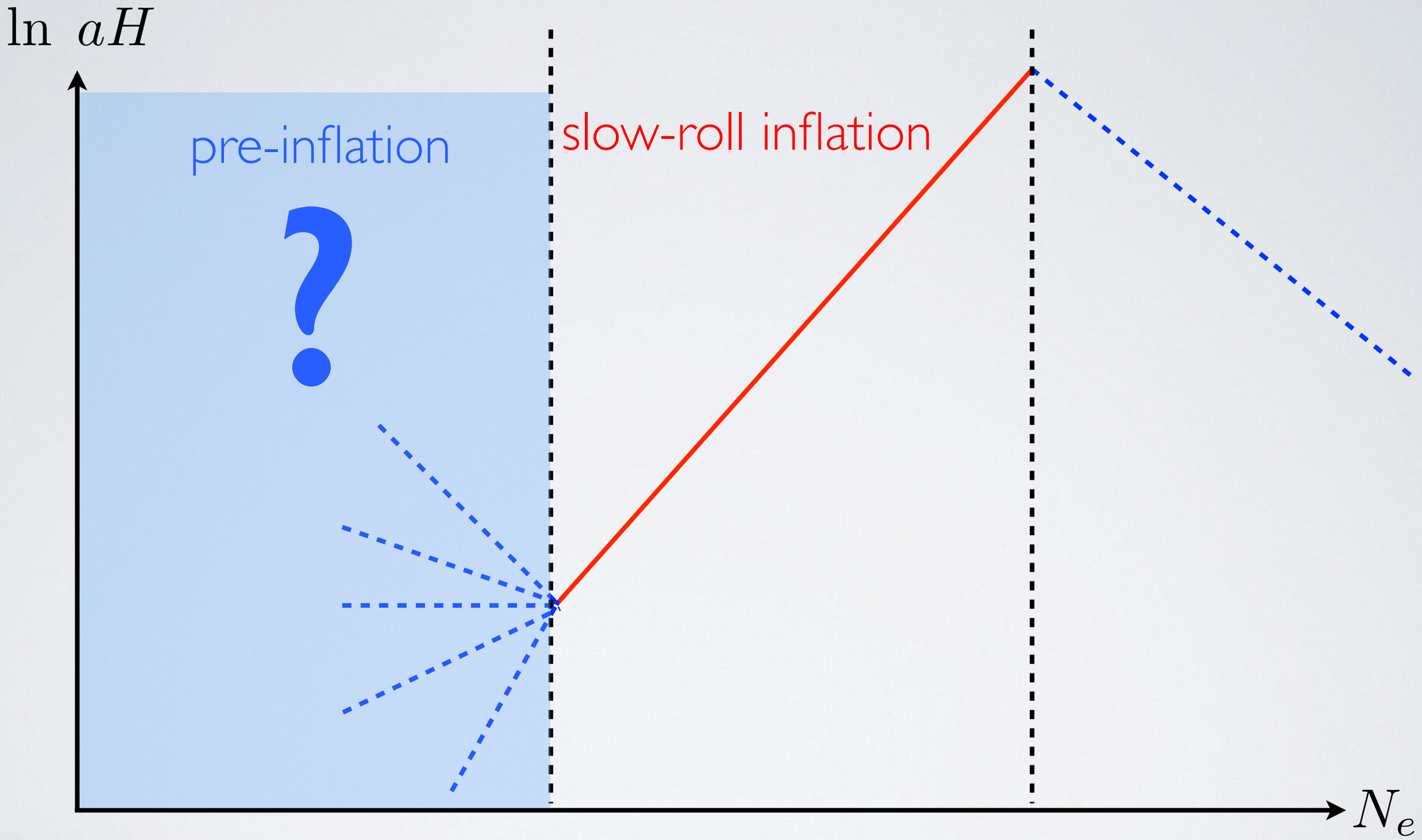
Can this leave an imprint on the power spectrum?

Modifies large scale part of spectrum



DESY

Pre-inflation and the power spectrum



DESY

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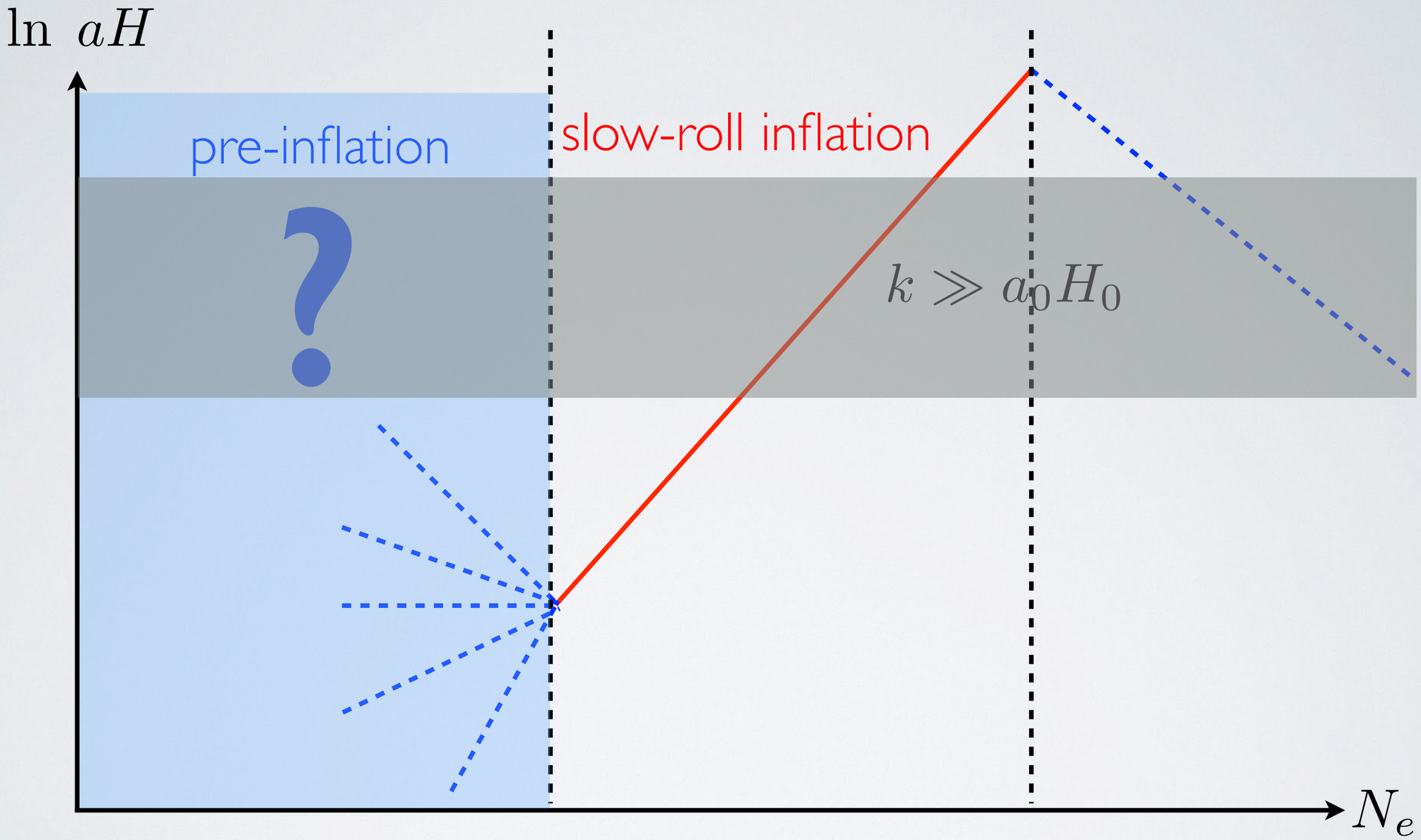
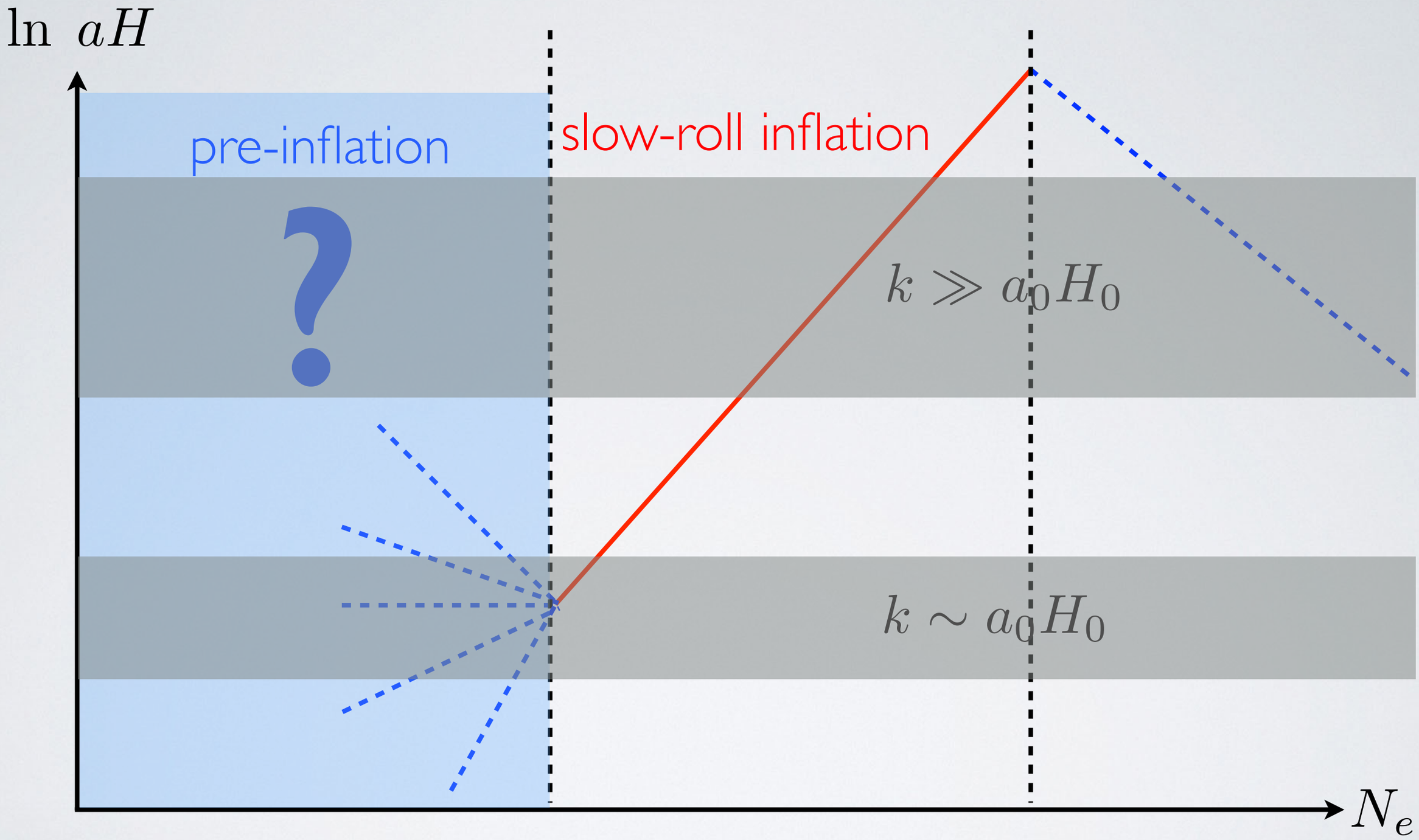


DESY

Pre-inflation and the power spectrum



DESY

What pre-inflation?

- Fast-roll $\xi = -2$ *Contaldi et al. 2003*
- Super inflation $\xi = 2$ *Liu et al. 2013*
- Climbing scalars *Sagnotti et al. 2012/14*
- Radiation domination $\xi = -1$ *Nicholson&Contaldi 2007*, *Kinney&Powell 2008*
- Matter domination $\xi = -1/2$
- Curvature domination $\xi = 0$ Linde et al. 1998,…,2011

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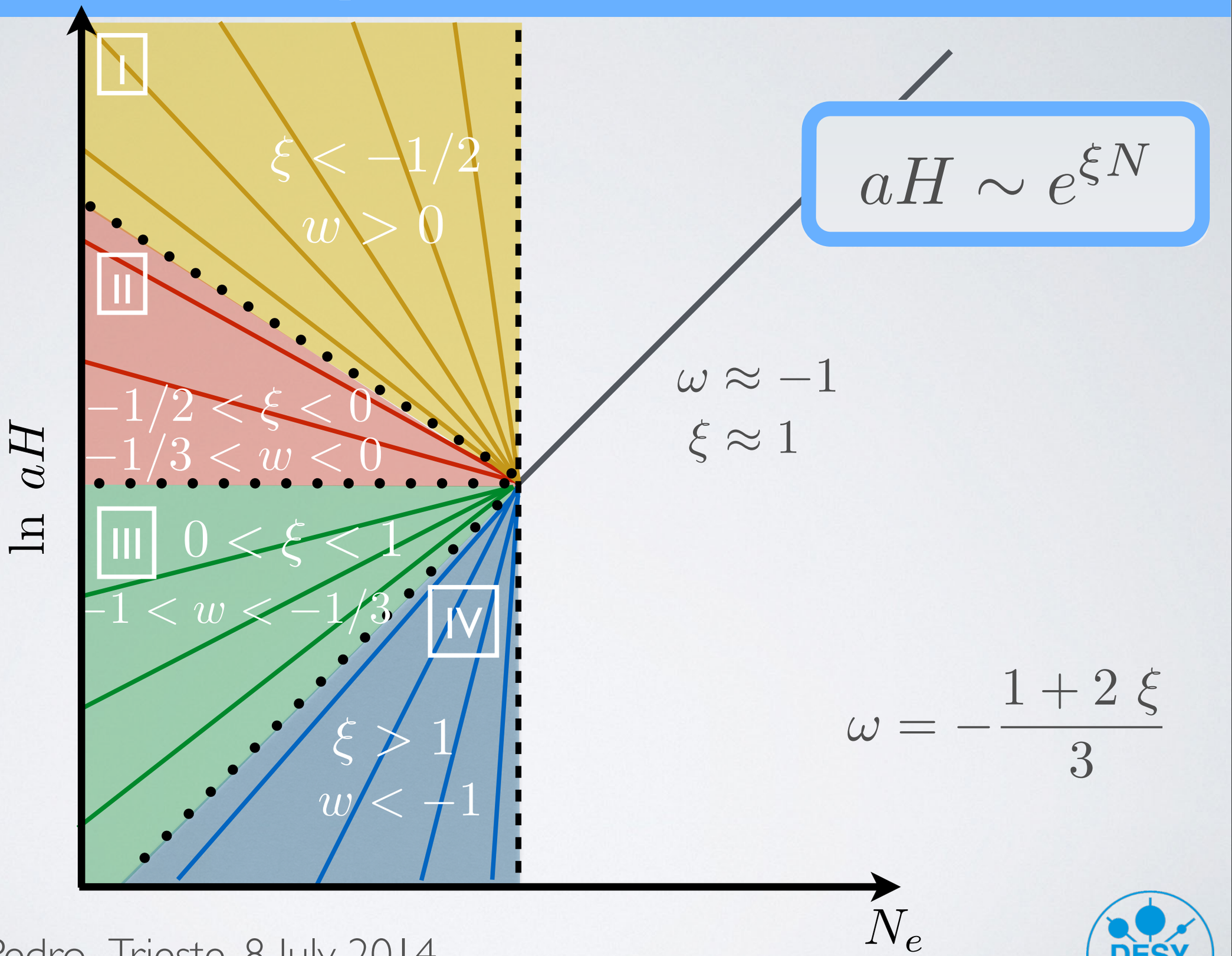
What similarities and what differences?

DESY

What pre-inflation?



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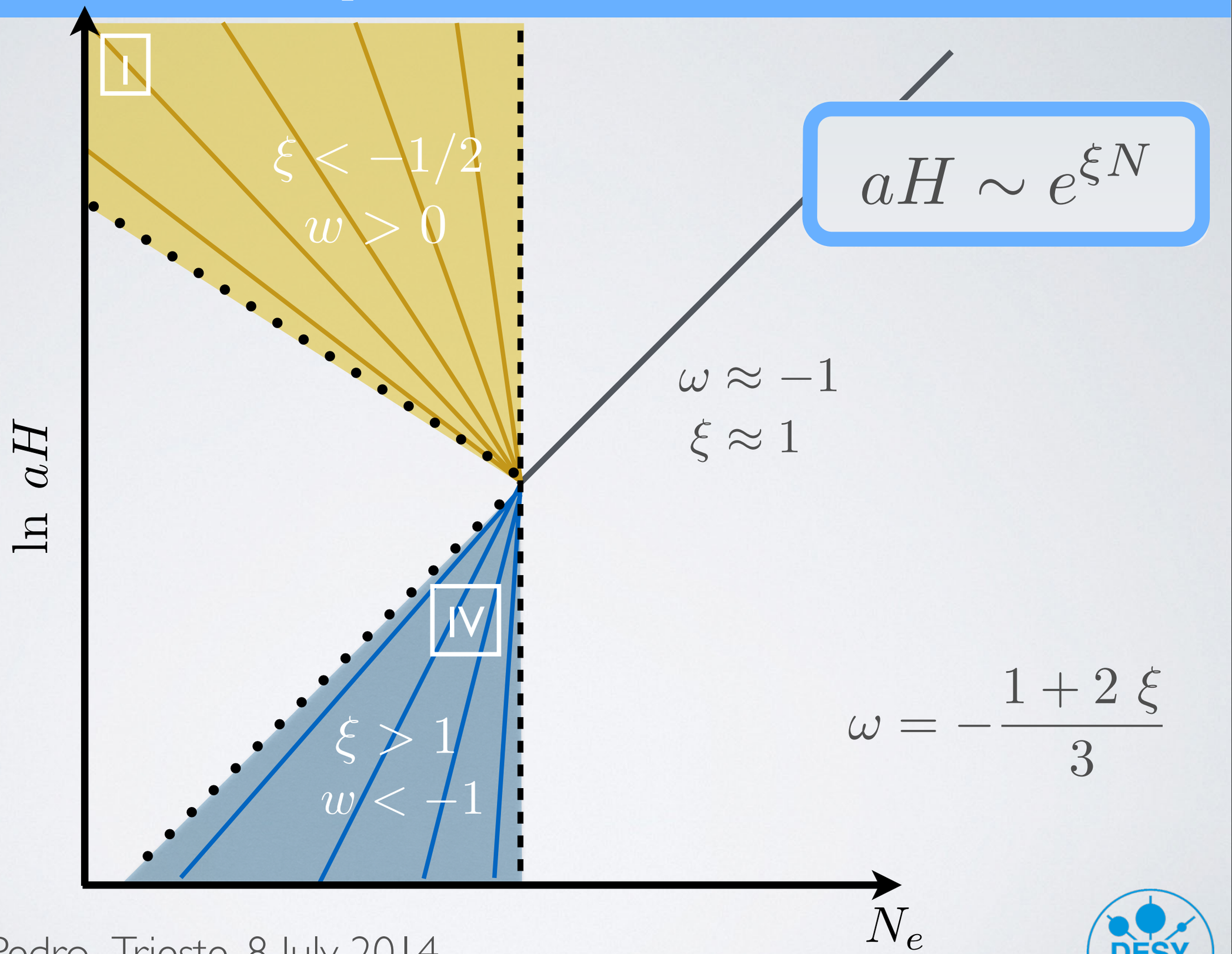


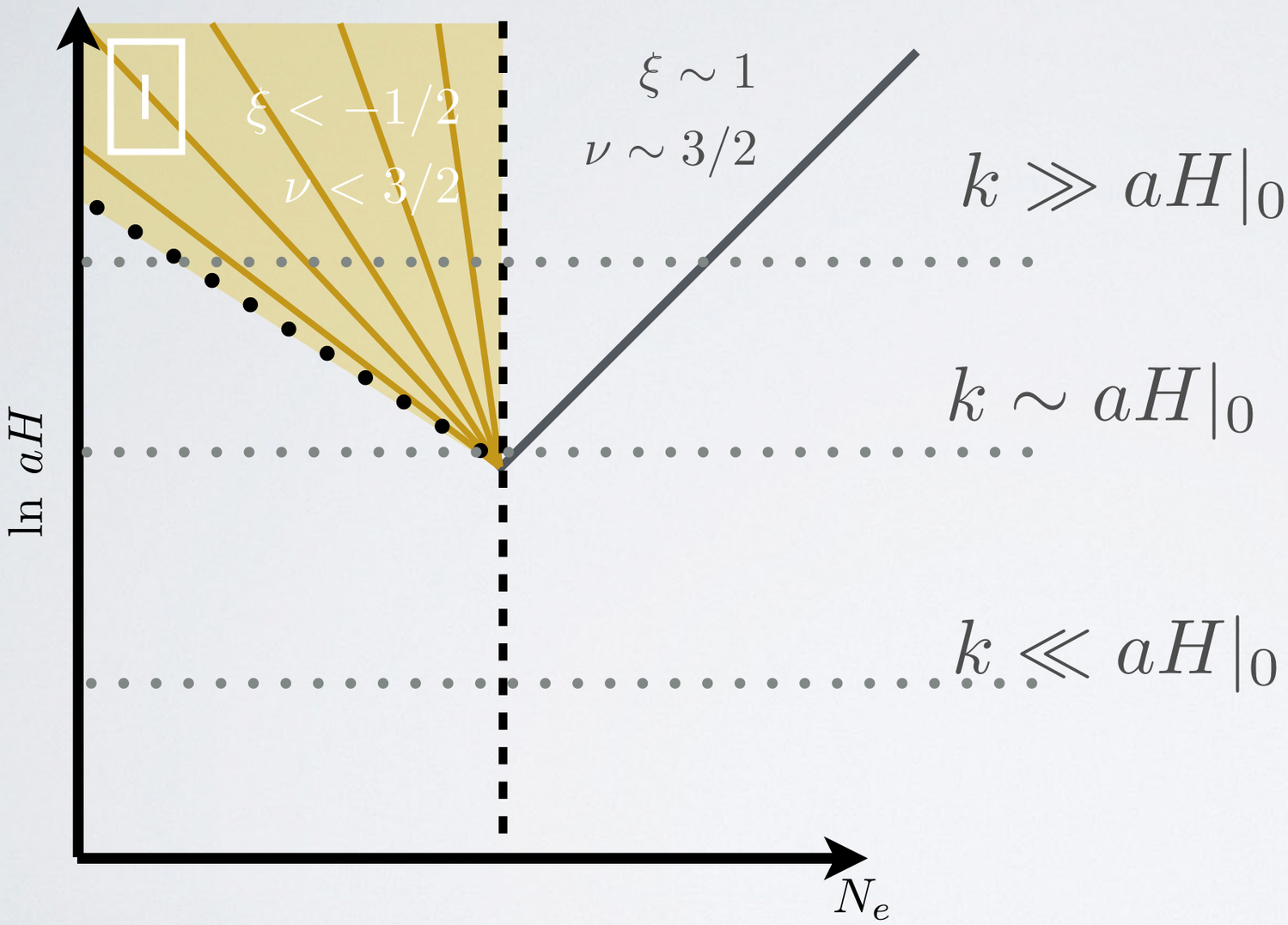
$$\omega = -\frac{1+2\,\xi}{3}$$

DESY

Type I backgrounds

Decelerated expansion: H decreases

Large scale spectrum from superhorizon modes



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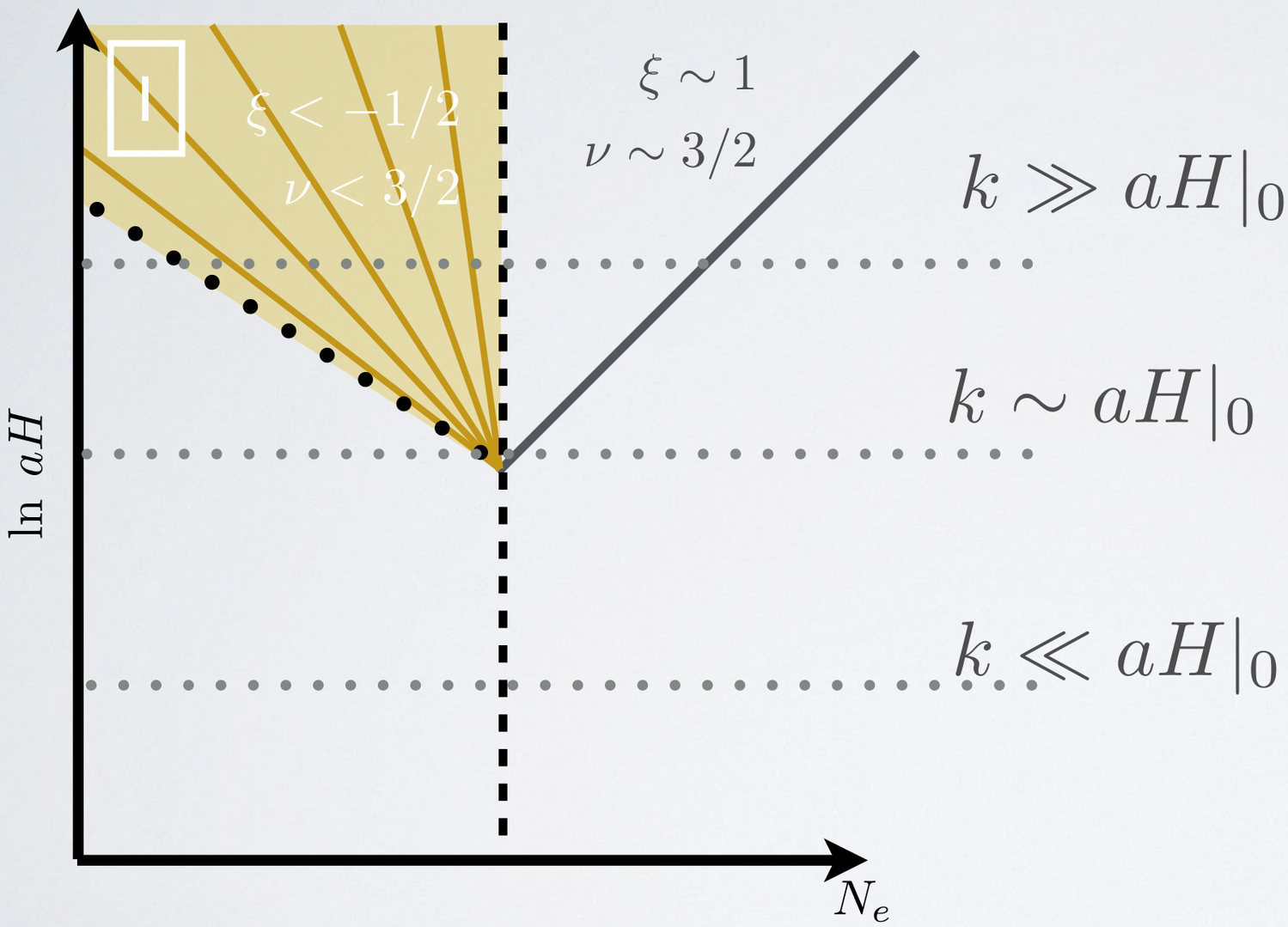
large scales set by pre-inflationary vacuum



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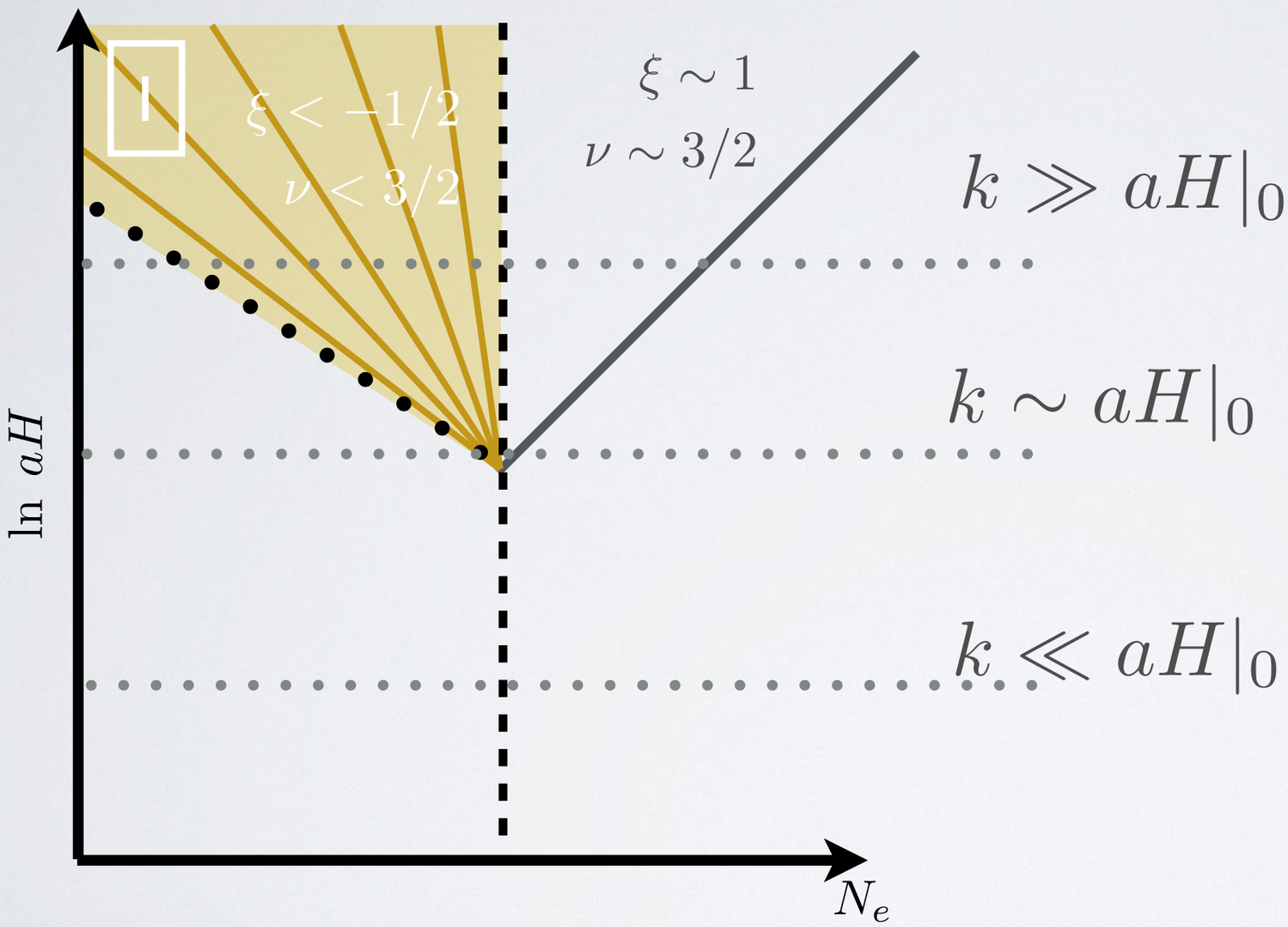

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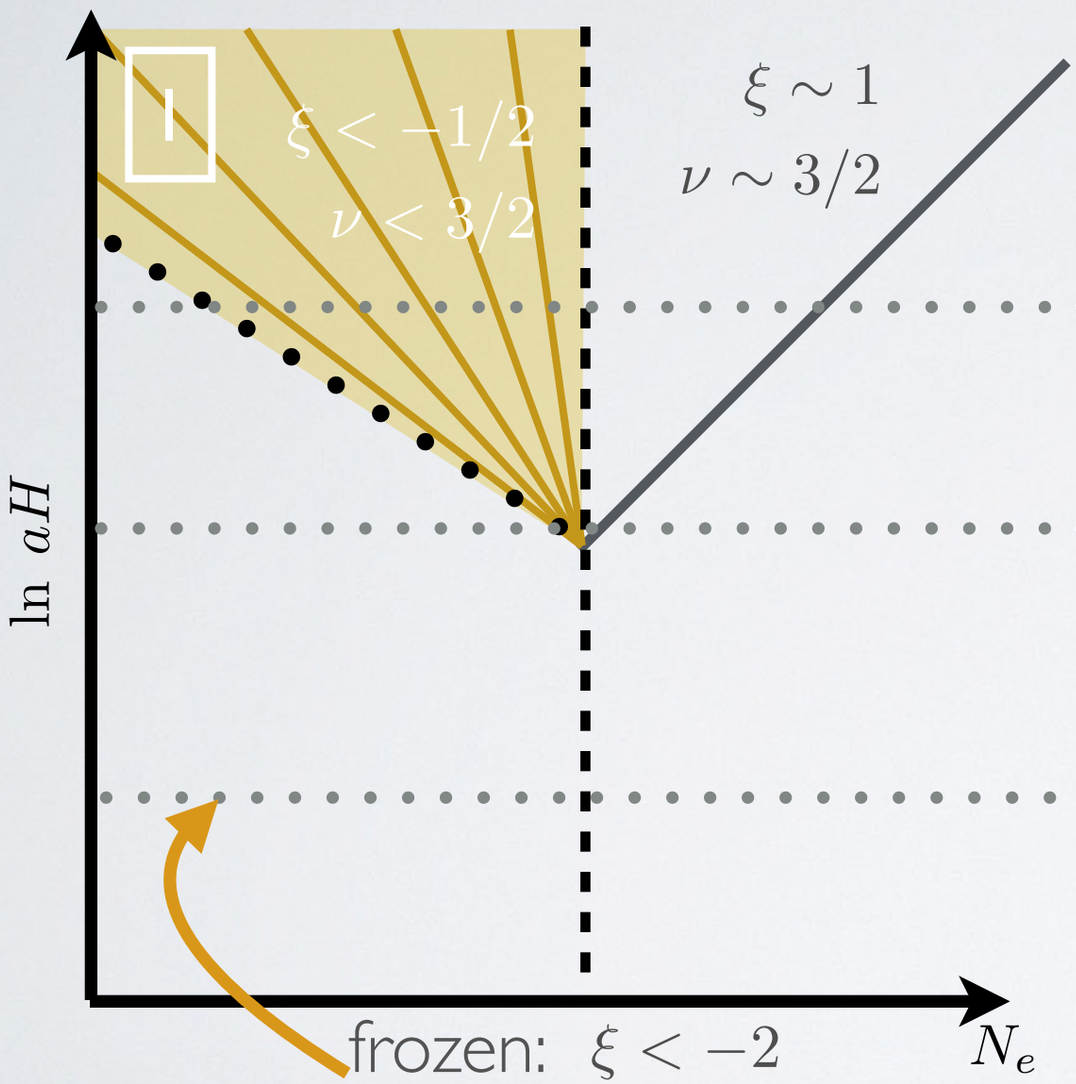

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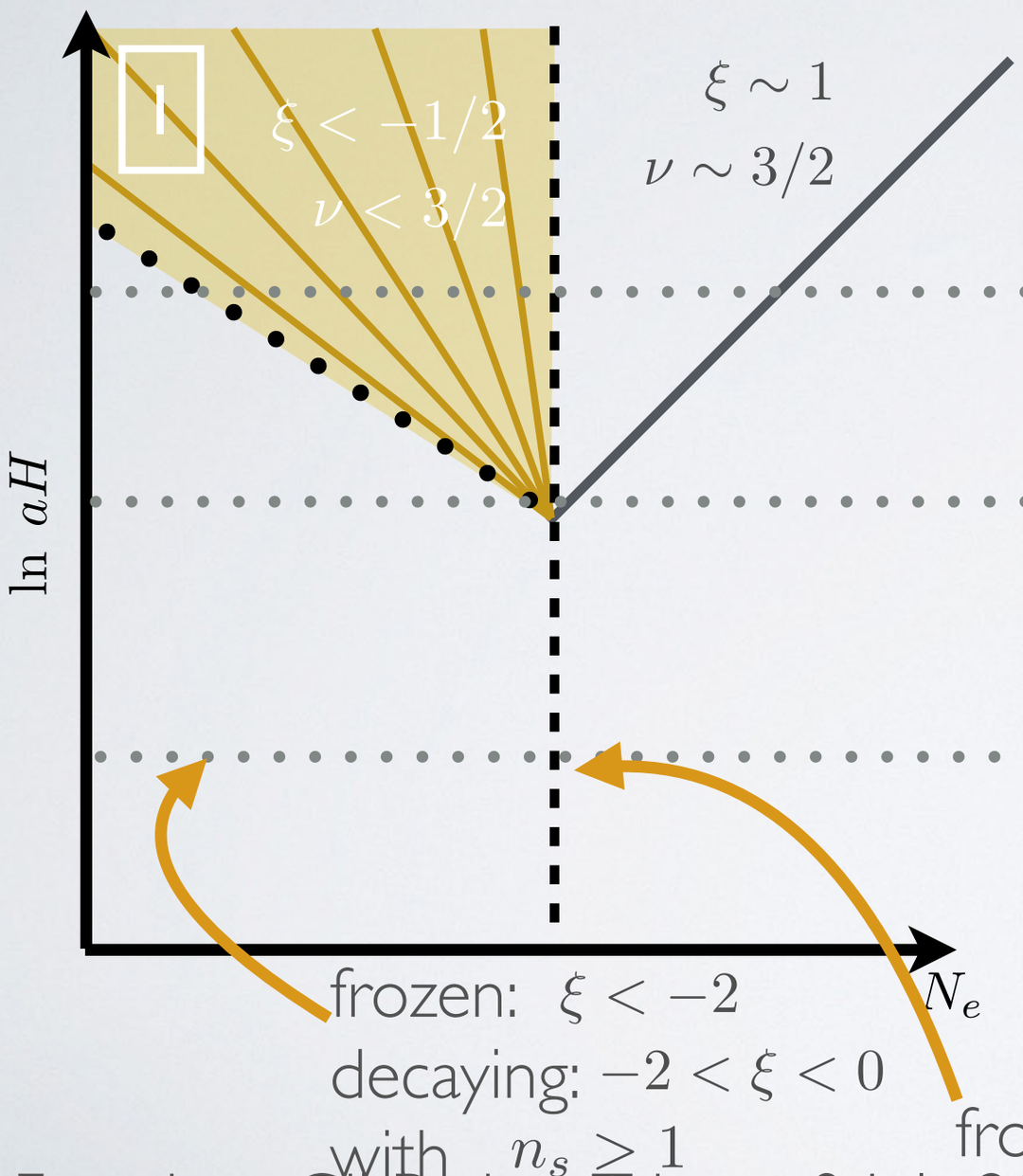

$$k \gg aH|_0 \quad \rightarrow P_k \sim \frac{H^2_{inf}}{\epsilon_H}$$

$$k \sim aH|_0$$

$$k \ll aH|_0$$

DESY

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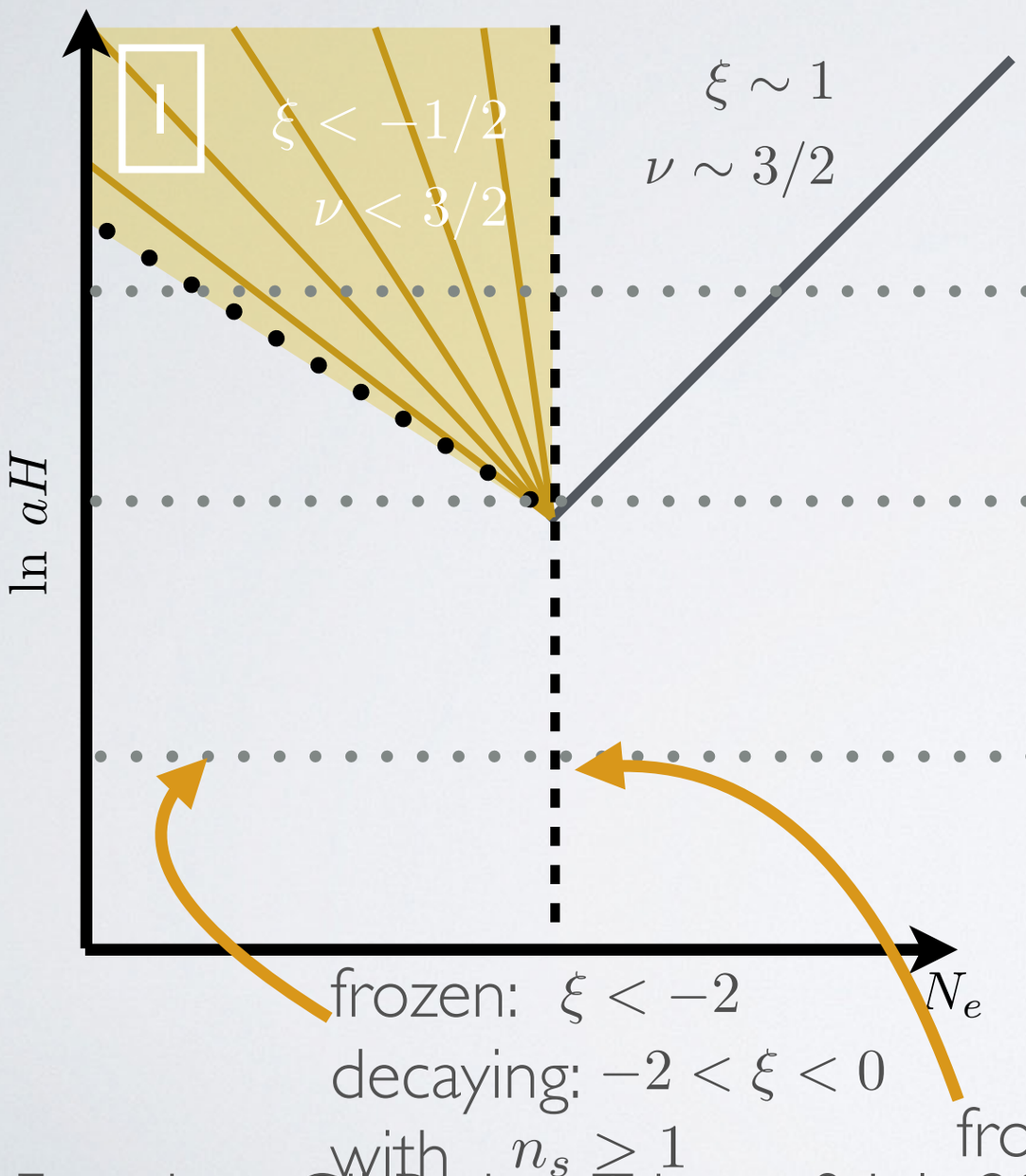

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$$k \sim aH|_0$$

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deep IR behaviour determined by n_s :

DESY

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Decelerated expansion: H decreases

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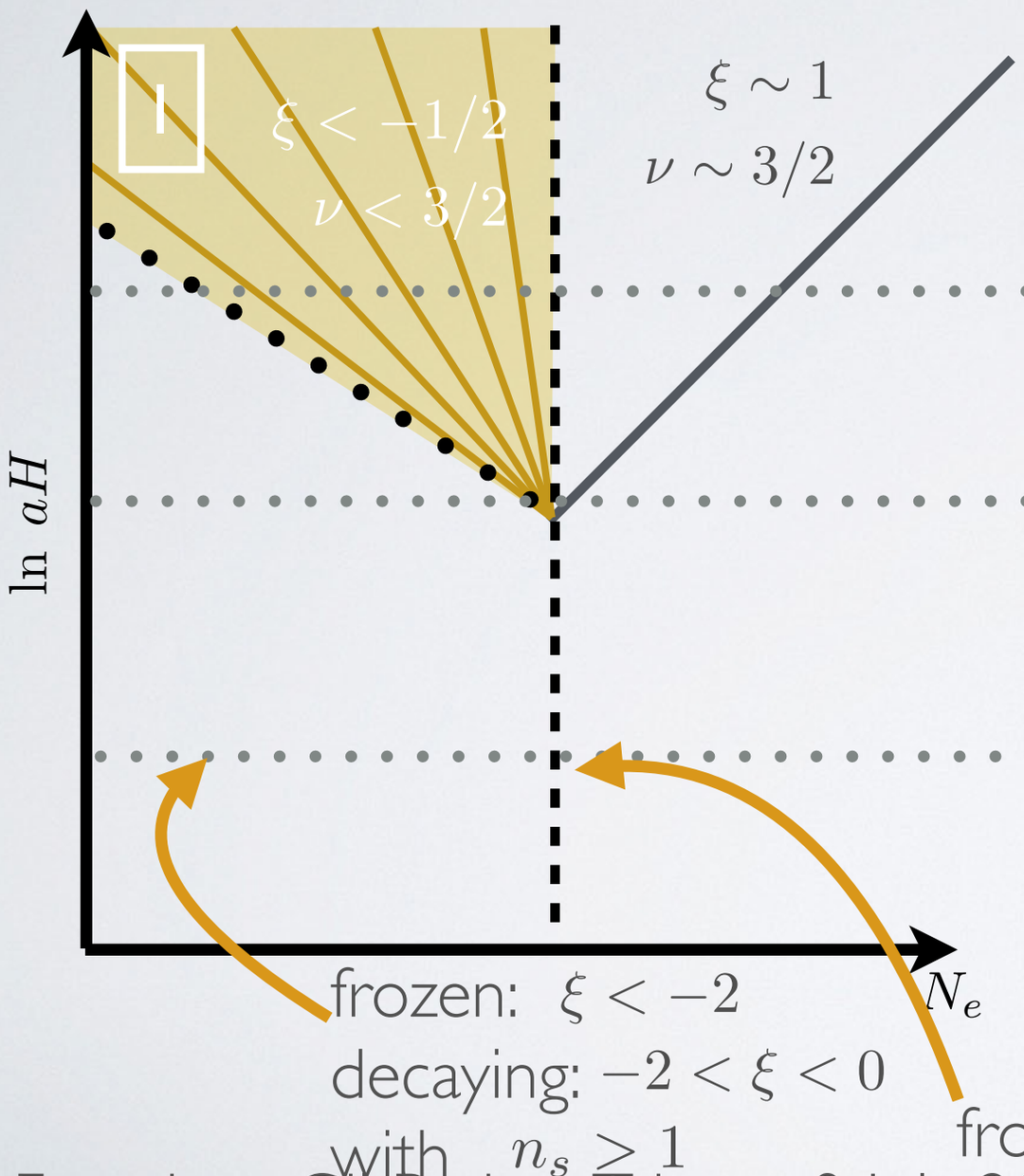
large scales set by pre-inflationary vacuum



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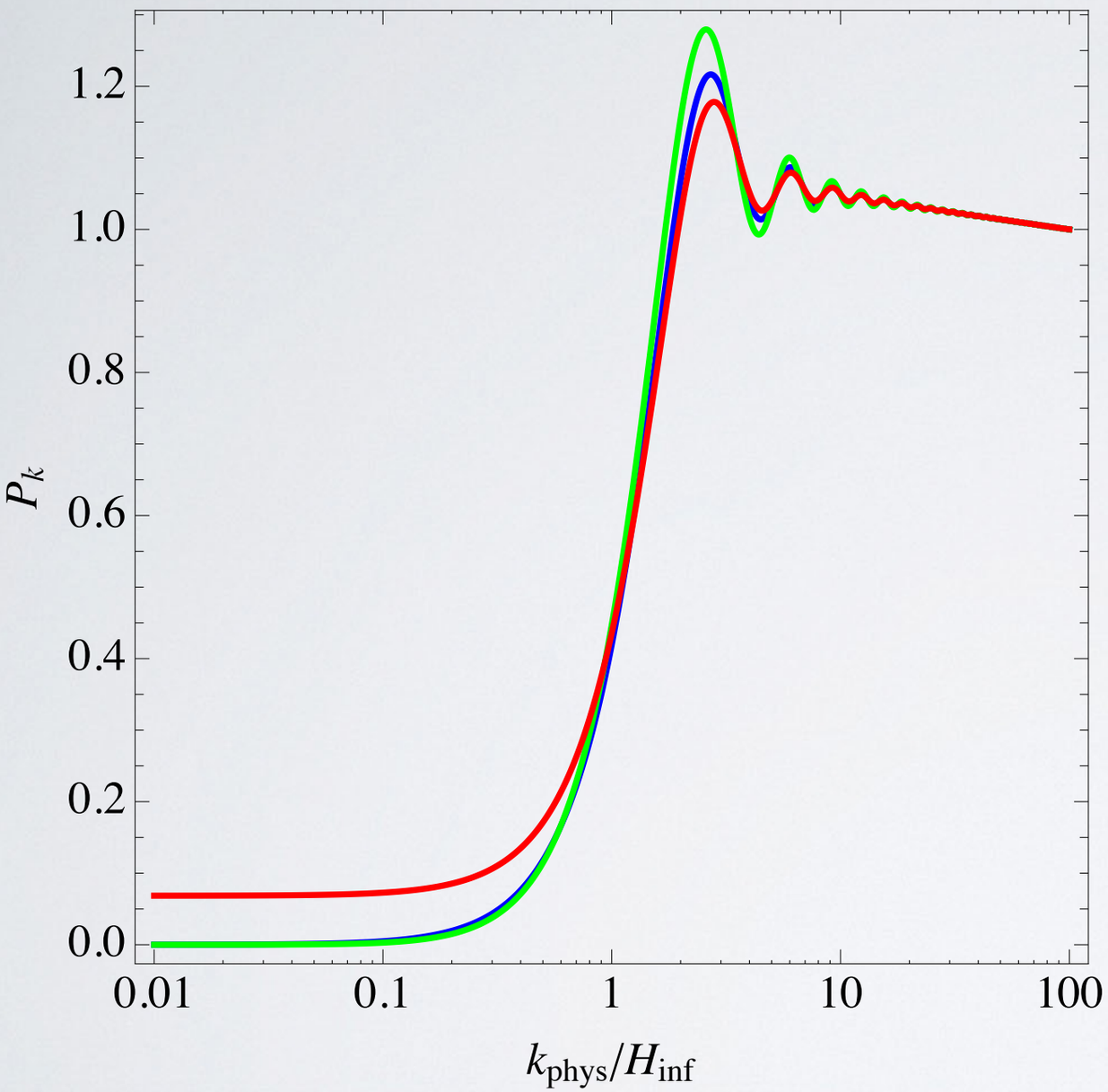
deep IR behaviour determined by n_s :

IR power suppression

Type I backgrounds



		background:
red	$\xi = -1/2$	matter
green	$\xi = -2$	fast-roll
blue	$\xi = -1$	radiation

Same broad features

Different peak amplitude

Different low-k fall-off

We see what we put in:

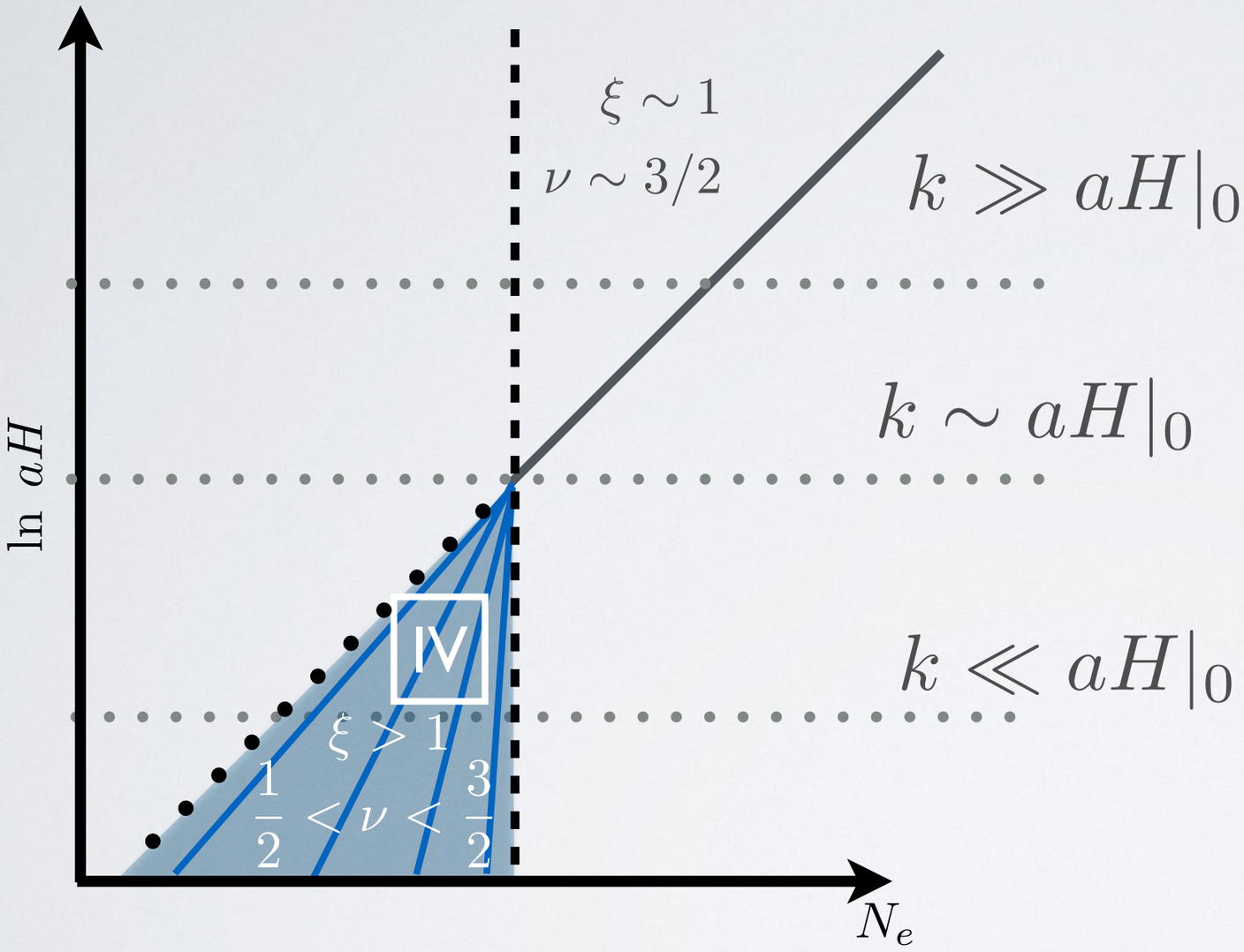
choice of ICs determines power on large scales

DESY

Type IV backgrounds

Accelerated expansion: H is growing $\quad H \propto e^{(\xi-1)N_e}$

Large scale spectrum from pre-inf. subhorizon modes



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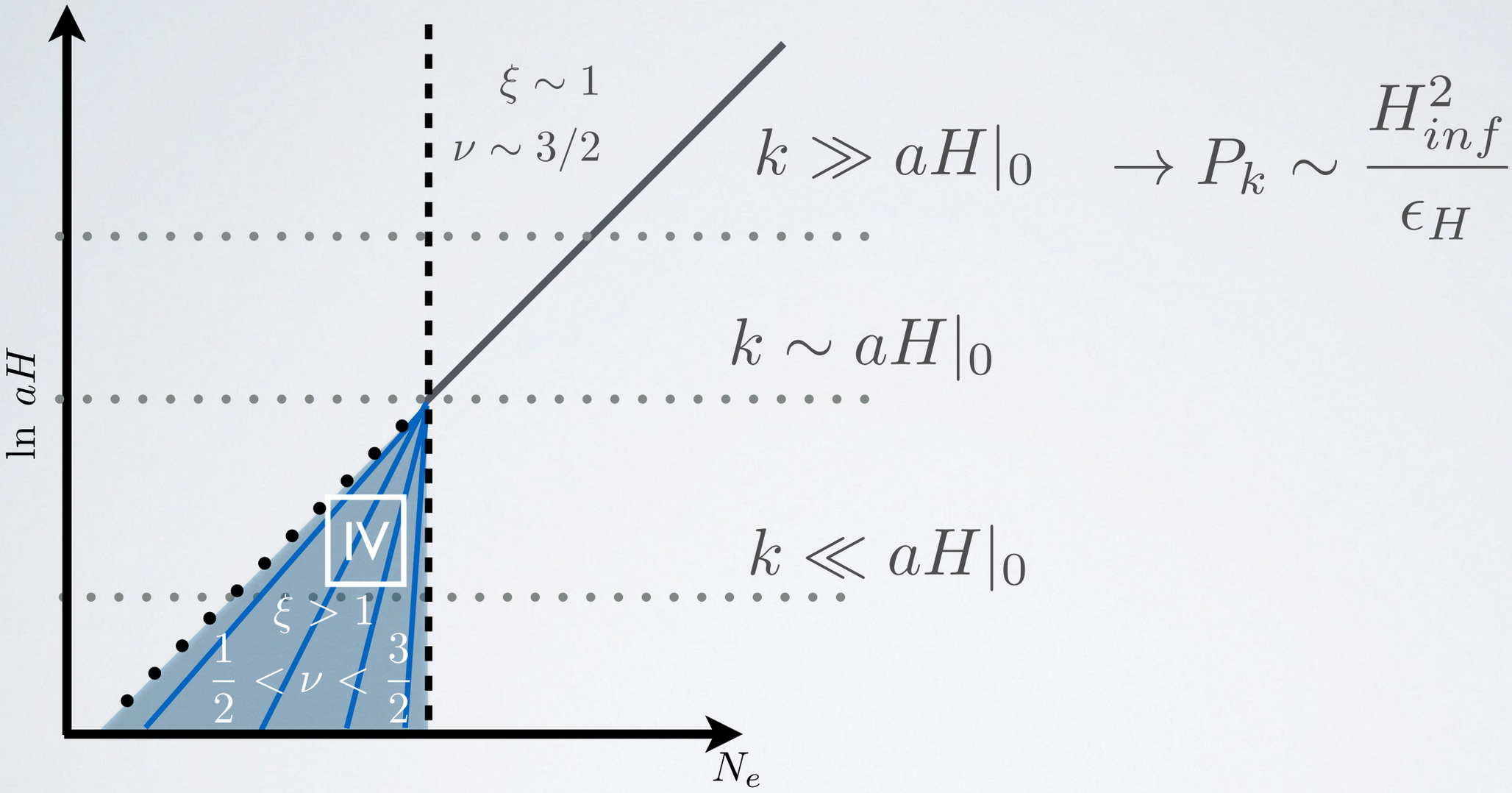

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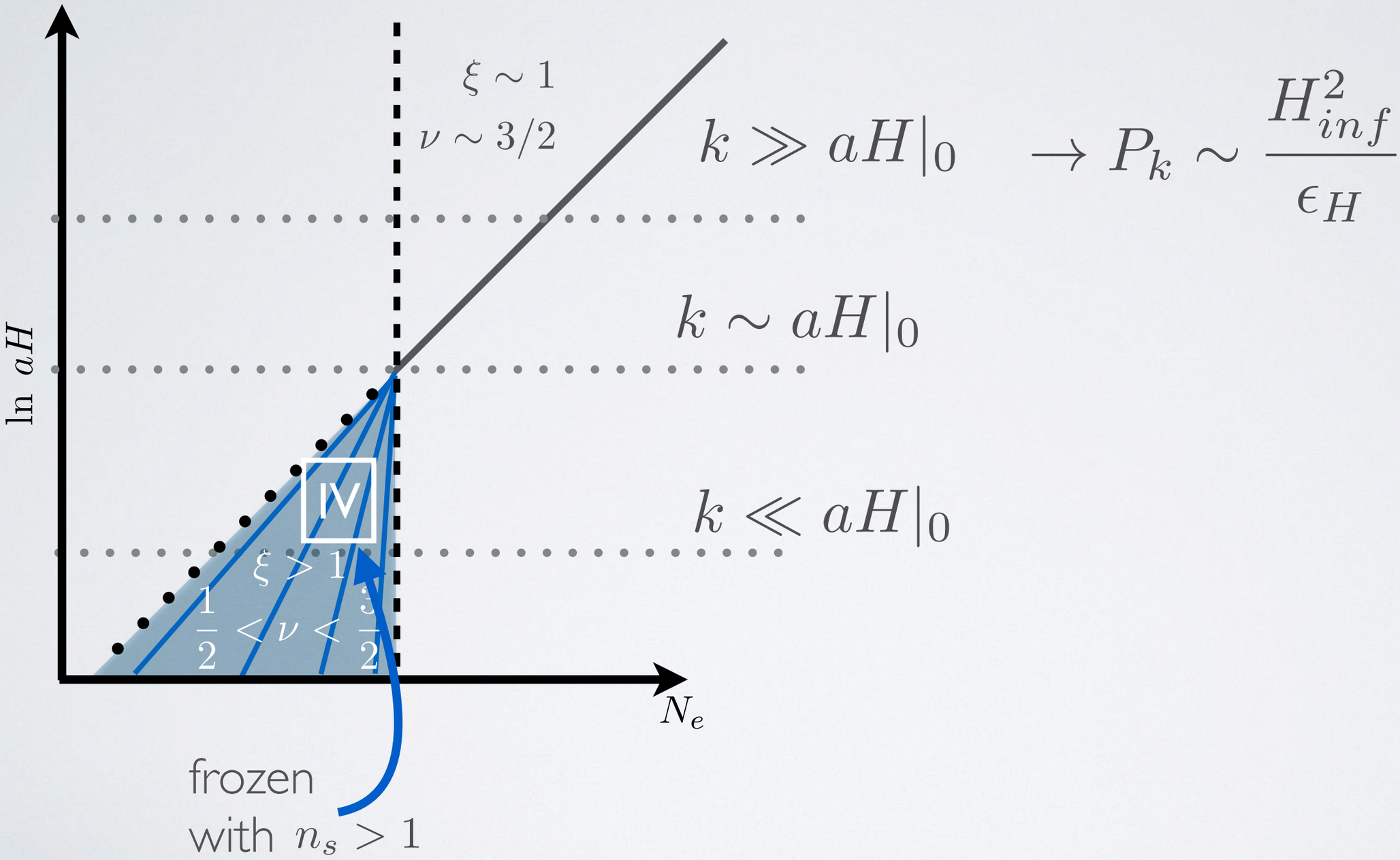

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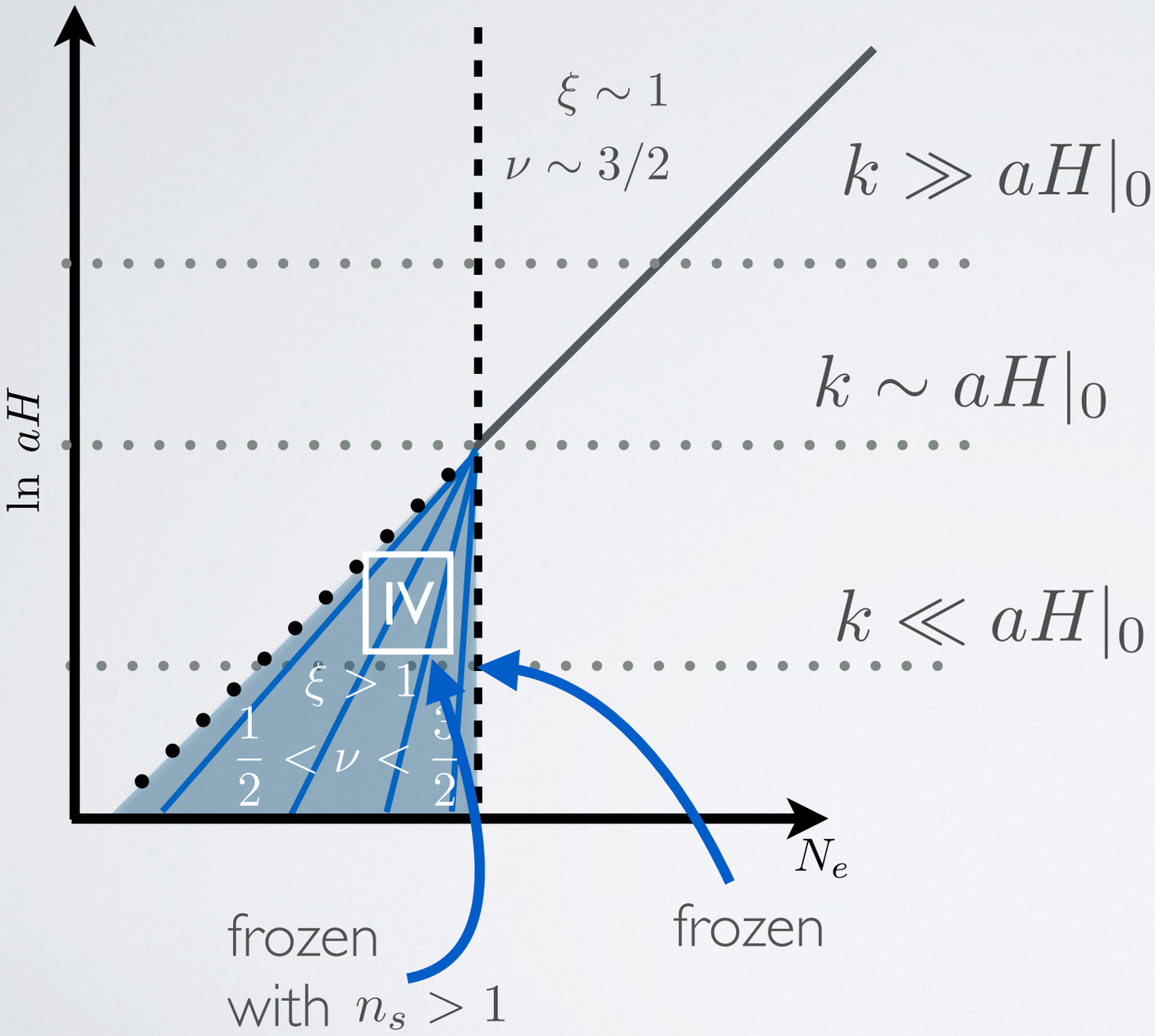

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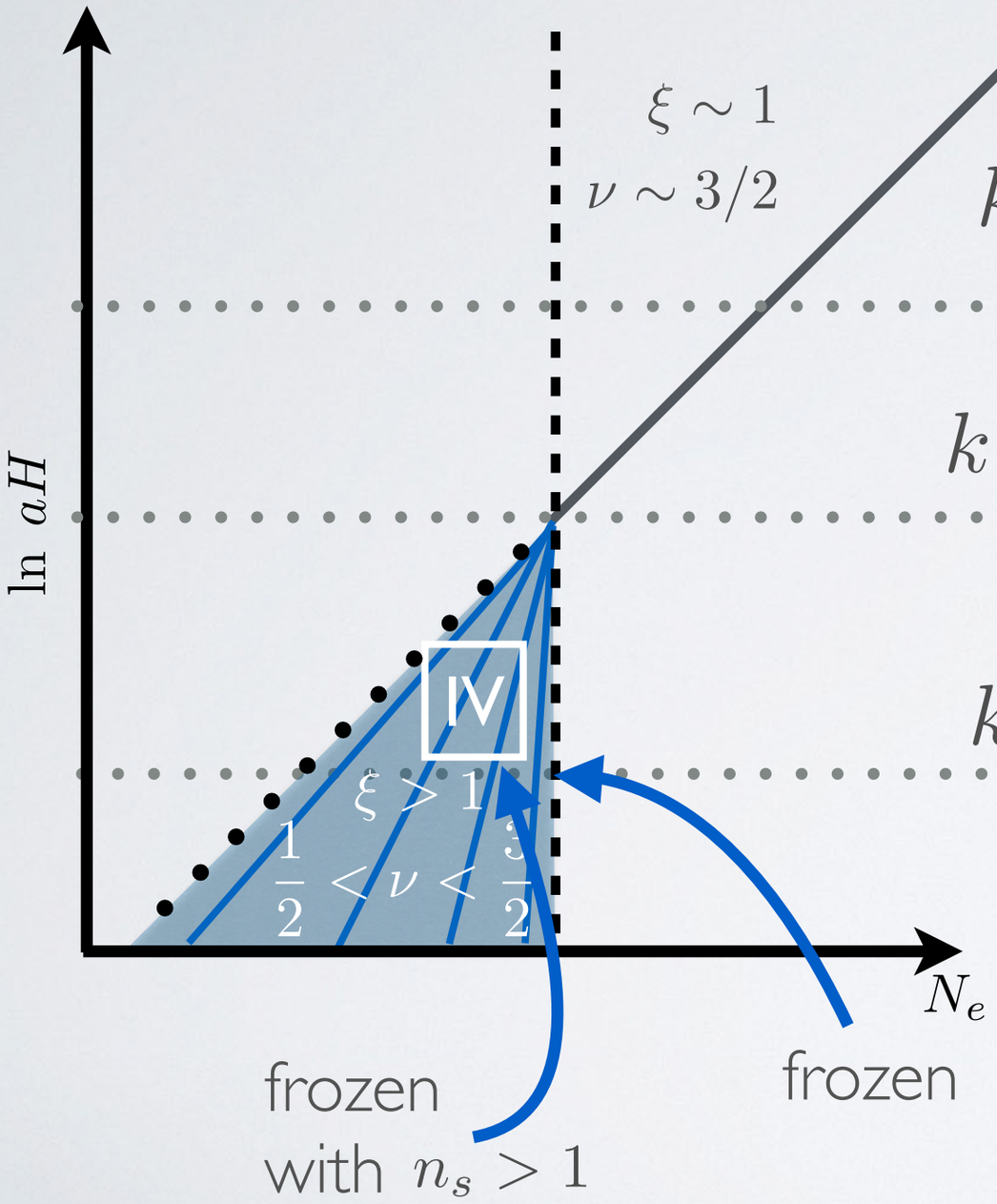

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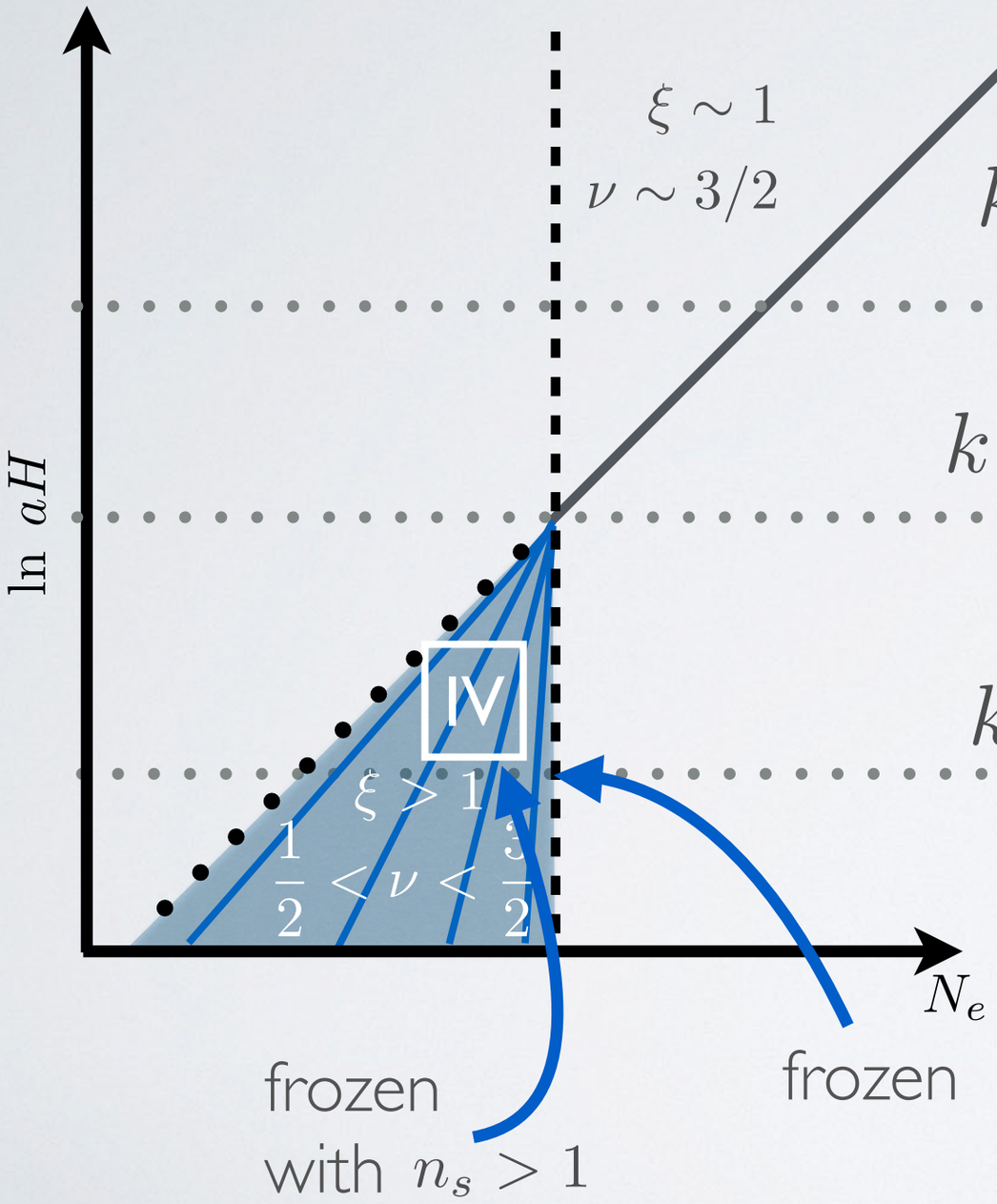
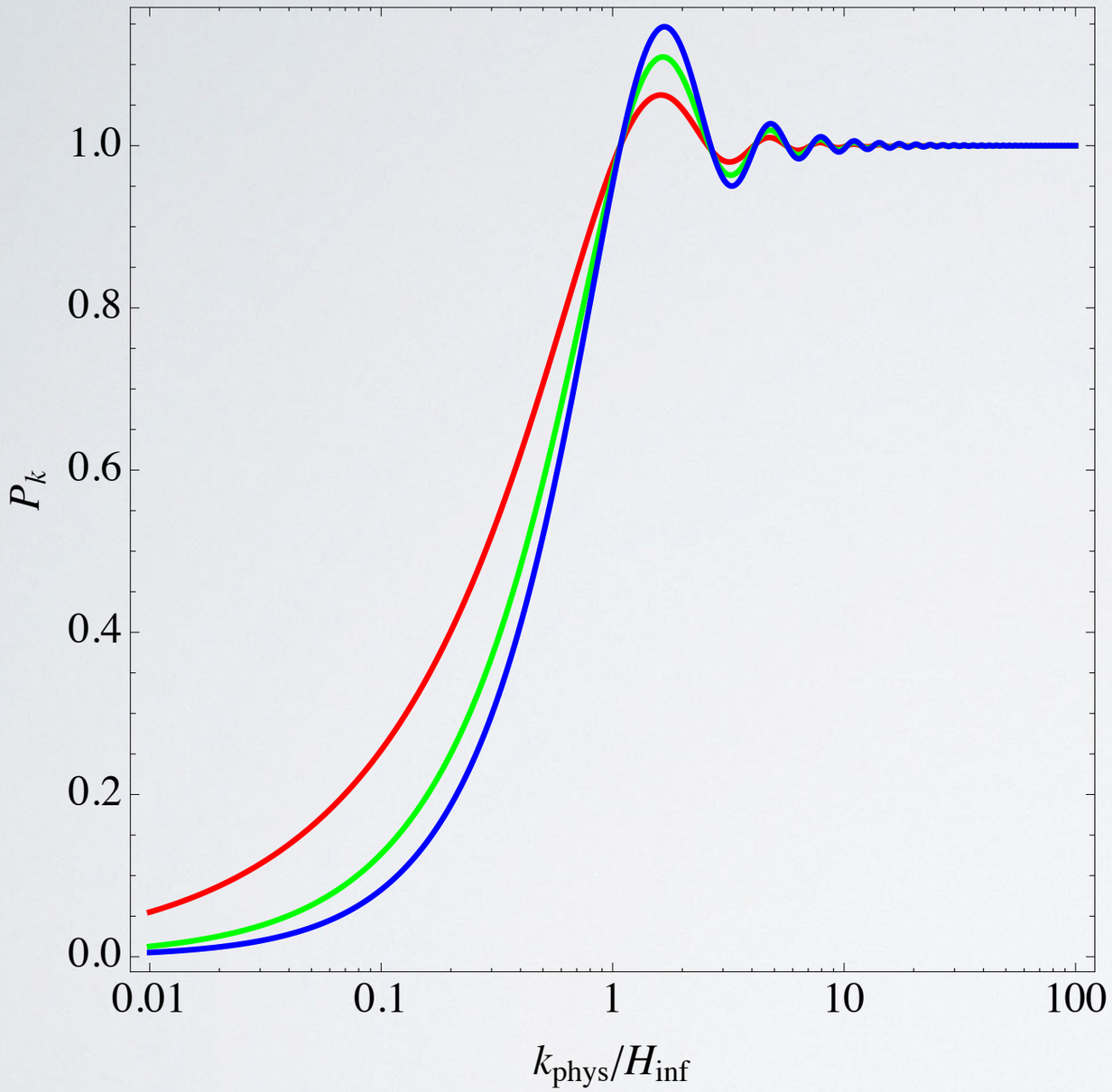


Low power on large scales

DESY

Type IV backgrounds



background:

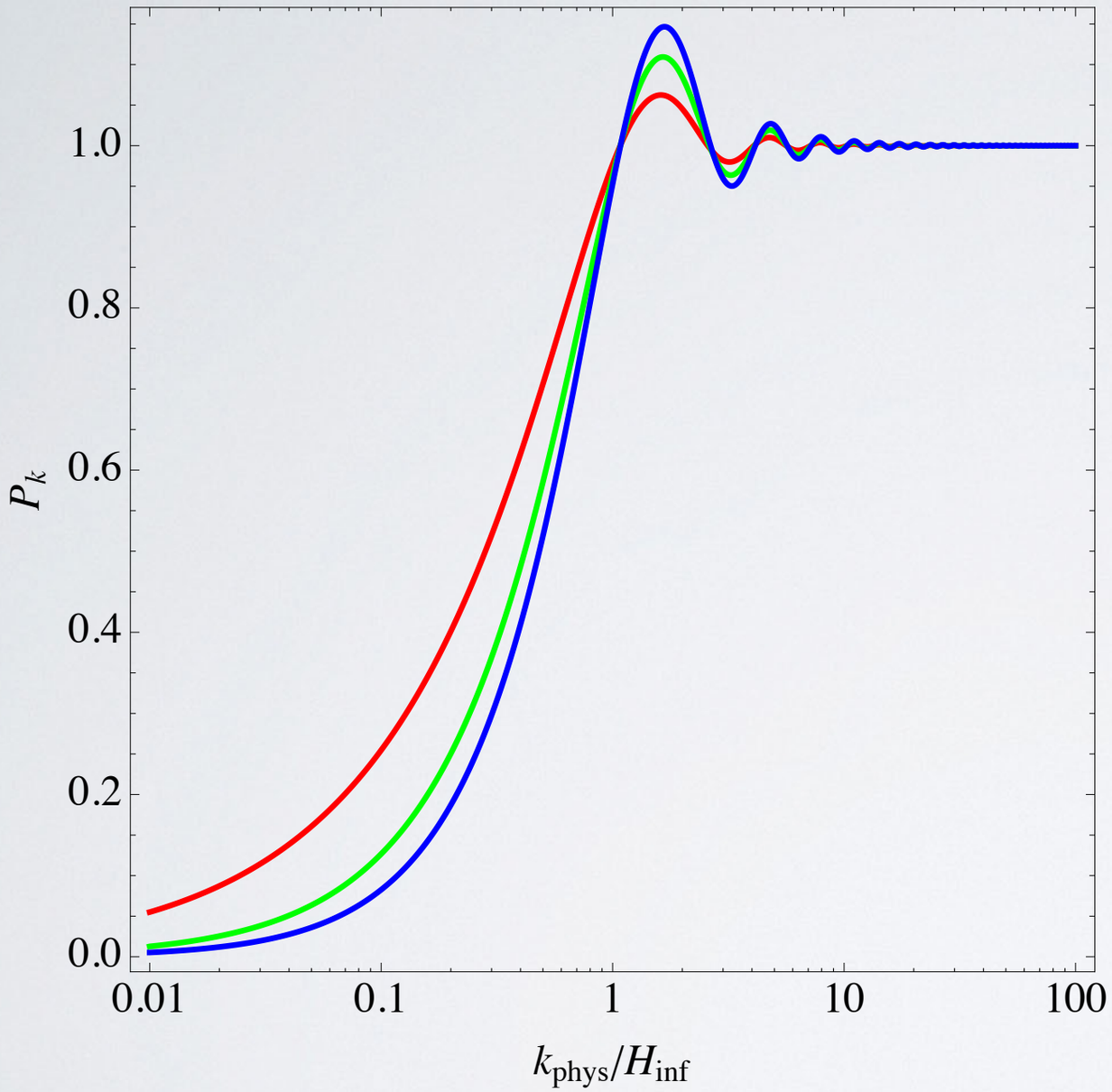
red $\xi = 3/2$

green $\xi = 2$ super-inflation

blue $\xi = 5/2$

DESY

Type IV backgrounds



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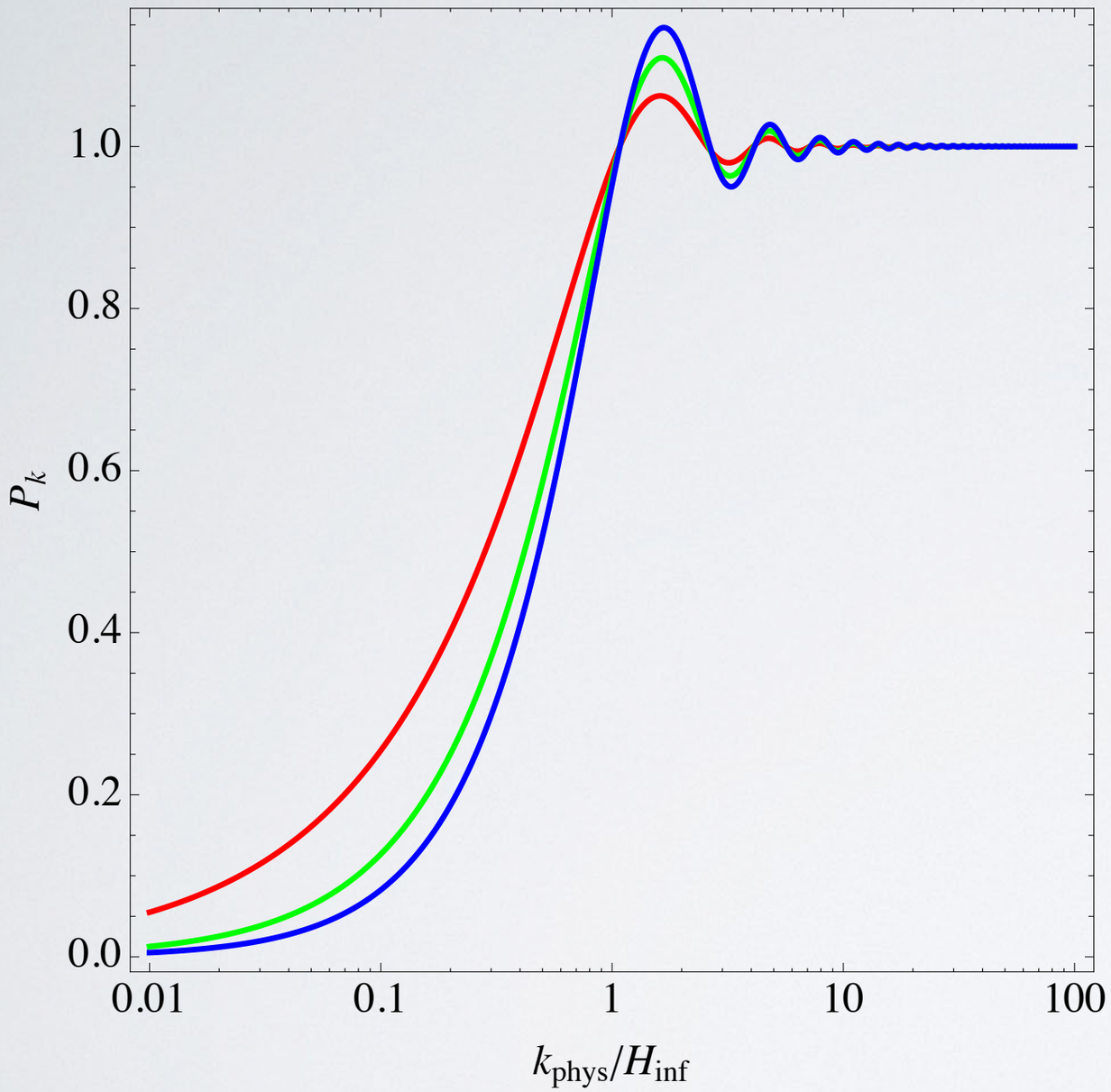

background:

red $\xi = 3/2$

green $\xi = 2$ super-inflation

blue $\xi = 5/2$

Same broad features

Different peak amplitude

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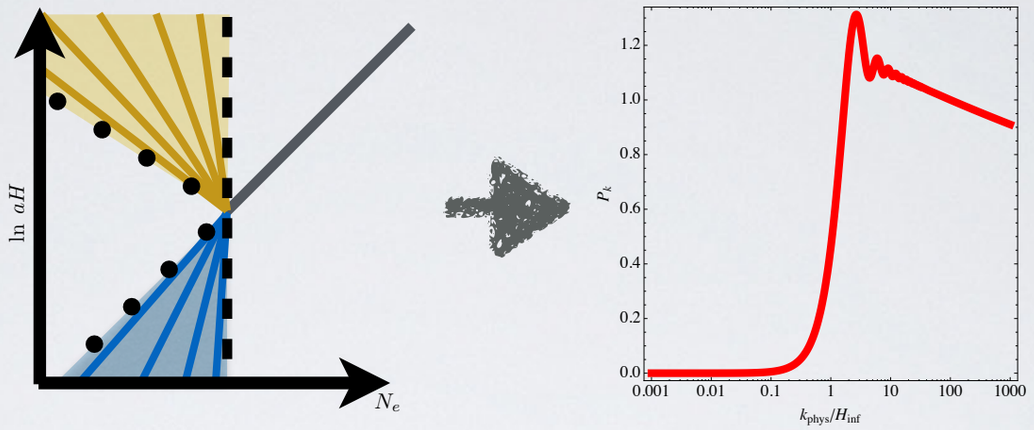
More robust than Type I:
Insensitive to choice of ICs

DESY

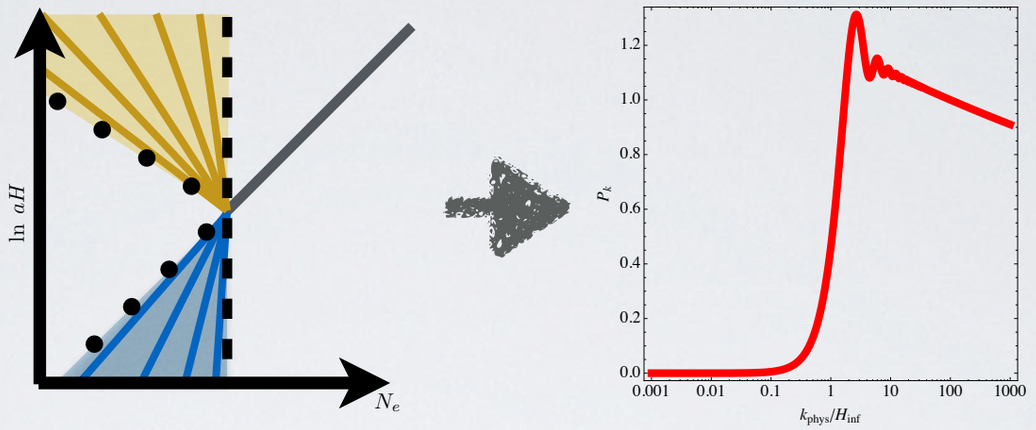
Pre-inflation and power loss



Degeneracy: one-parameter family of primordial spectra

DESY

Pre-inflation and power loss



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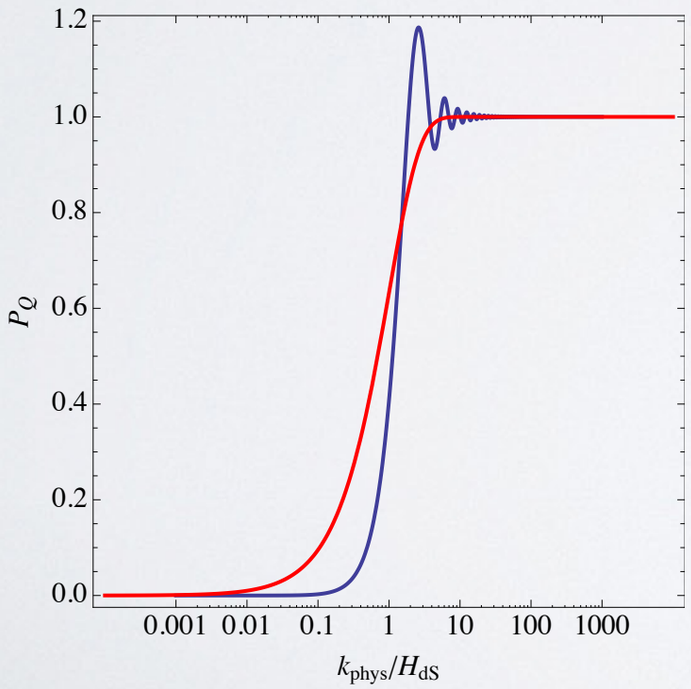


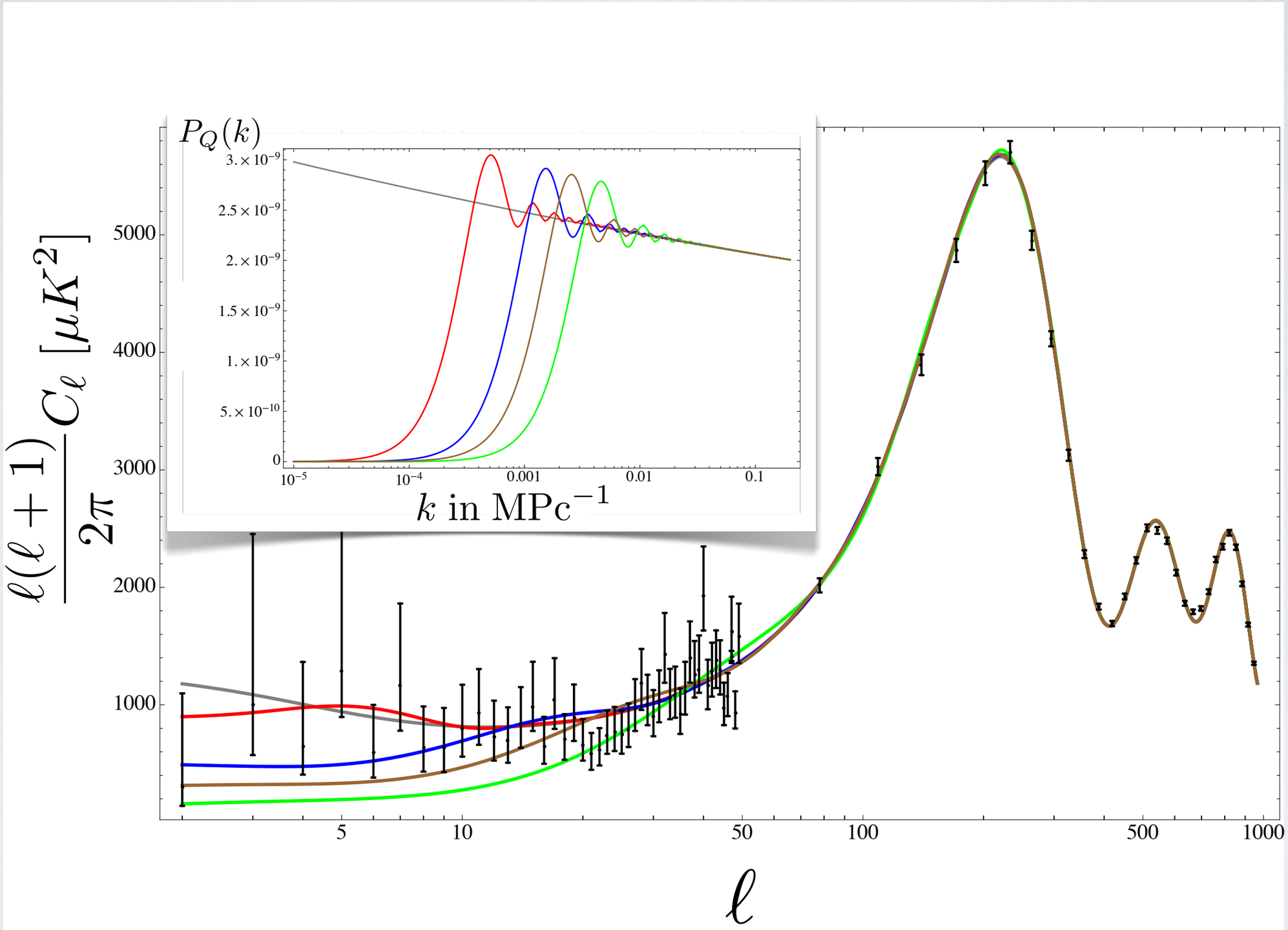
Interesting hints:

[1311.1599] & [1402.1418]

claim these spectra are better fits than simpler monotonic parametrization

DESY

TT Power spectrum



DESY

Summary

- Persistent hints from COBE / WMAP / PLANCK
- Short inflation modifies large scale/low- ℓ power spectrum
- Different ways to reduce power
- Degeneracy/universality in power loss
- Better understanding requires fit to the data
- We might be seeing pre-inflationary phase

Thank you

[1407.1048]

Francisco Gil Pedro, Trieste, 8 July 2014

DESY