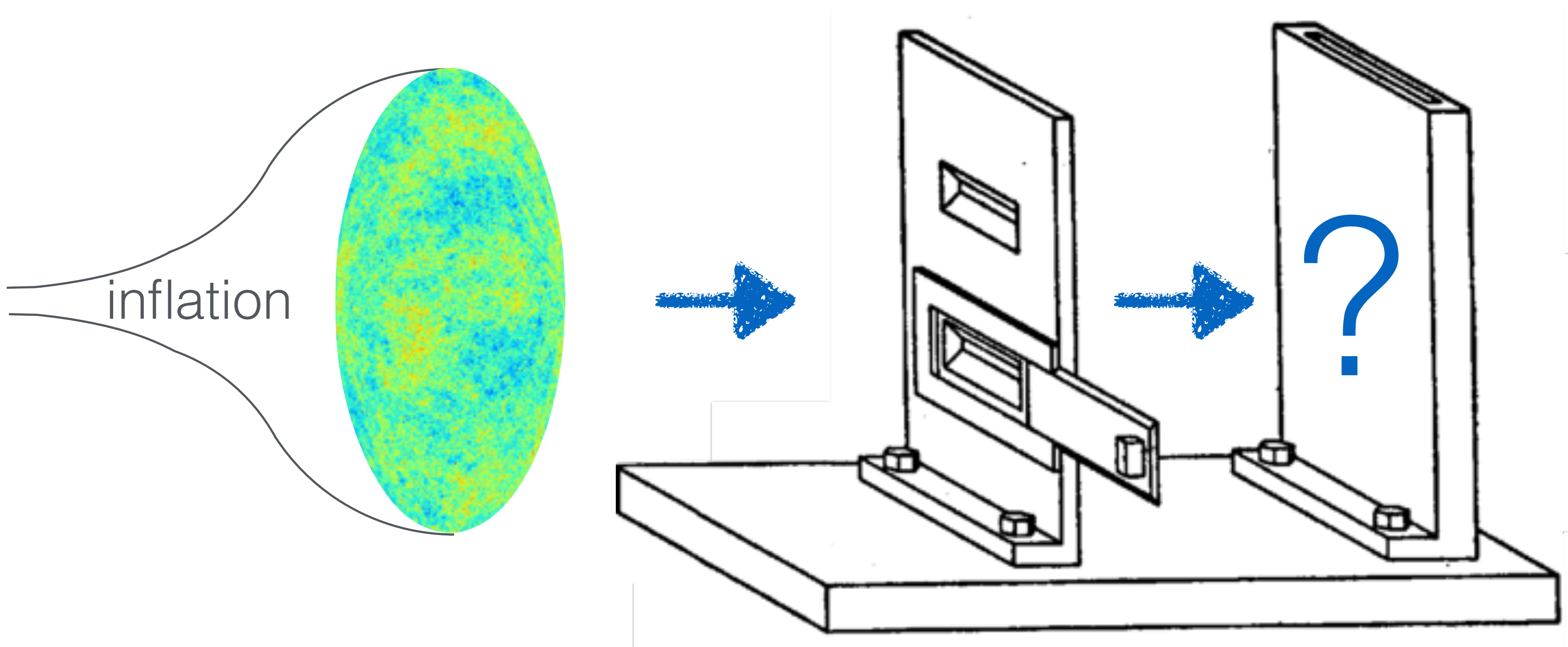
Cosmic Inflation and Quantum Mechanics II: Applications



Vincent Vennin

Workshop Quantum Foundations

New frontiers in testing quantum mechanics from underground to space

Laboratori Nazionali di Frascati, 1st December 2017

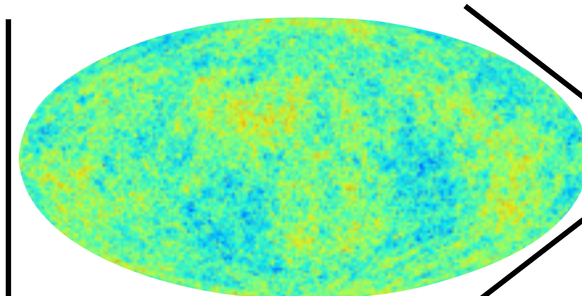
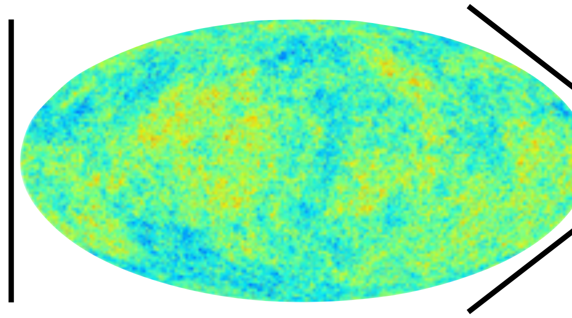
Quantum Mechanics and Cosmology: Open Issues

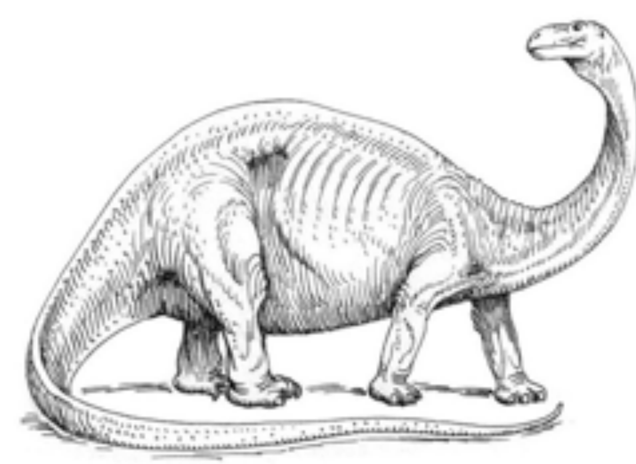
from Jerome Martin’s talk:

- Quantum-to-classical transition of cosmological fluctuations
- Role of decoherence
- Quantum measurement problem
- Signature of the quantum origins of cosmological structures

(exacerbated) Quantum Measurement Problem in Cosmology

e.g. Sudarsky (2009)

$|\mathrm{CMB}\rangle = \Big|$  $\Big\rangle$ + $\Big|$  $\Big\rangle + \dots$



$|\uparrow\rangle + |\downarrow\rangle \longrightarrow |\uparrow\rangle$ → need to break unitarity

Spontaneous collapse model

Ghirardi, Rimini, Weber (1985), Pearle (1989), Bassi, Ghirard (2003), etc

$$\mathrm{d}|\Psi\rangle = -i\hat{H}\,|\Psi\rangle\mathrm{d}t + \sqrt{\gamma}\left(\hat{C} - \langle\hat{C}\rangle\right)\mathrm{d}W_t\,|\Psi\rangle - \frac{\gamma}{2}\left(\hat{C} - \langle\hat{C}\rangle\right)^2\mathrm{d}t\,|\Psi\rangle$$

standard   non linear and stochastic

- non-linear, to break the superposition principle
- stochastic, to produce random outcomes

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$$\mathrm{d}|\Psi\rangle = -i\frac{\hat{p}^2}{2m}|\Psi\rangle \mathrm{d}t + \sqrt{\gamma}\Big(\hat{x} - \langle\hat{x}\rangle\Big)\mathrm{d}W_t\,|\Psi\rangle - \frac{\gamma}{2}\Big(\hat{x} - \langle\hat{x}\rangle\Big)^2\mathrm{d}t\,|\Psi\rangle$$

standard　　non linear and stochastic

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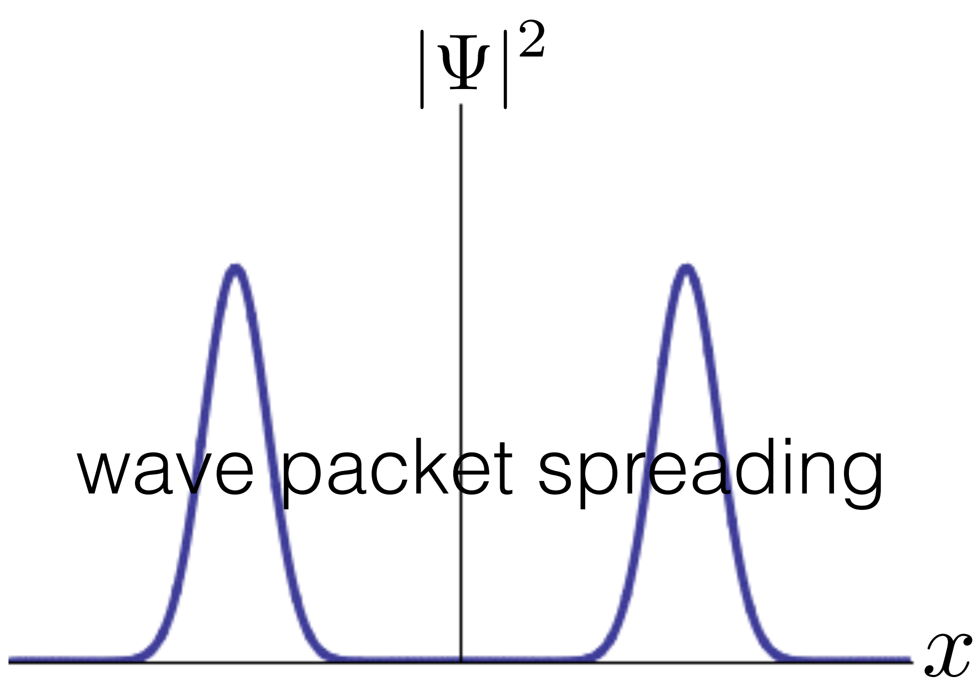
Example: Free particle



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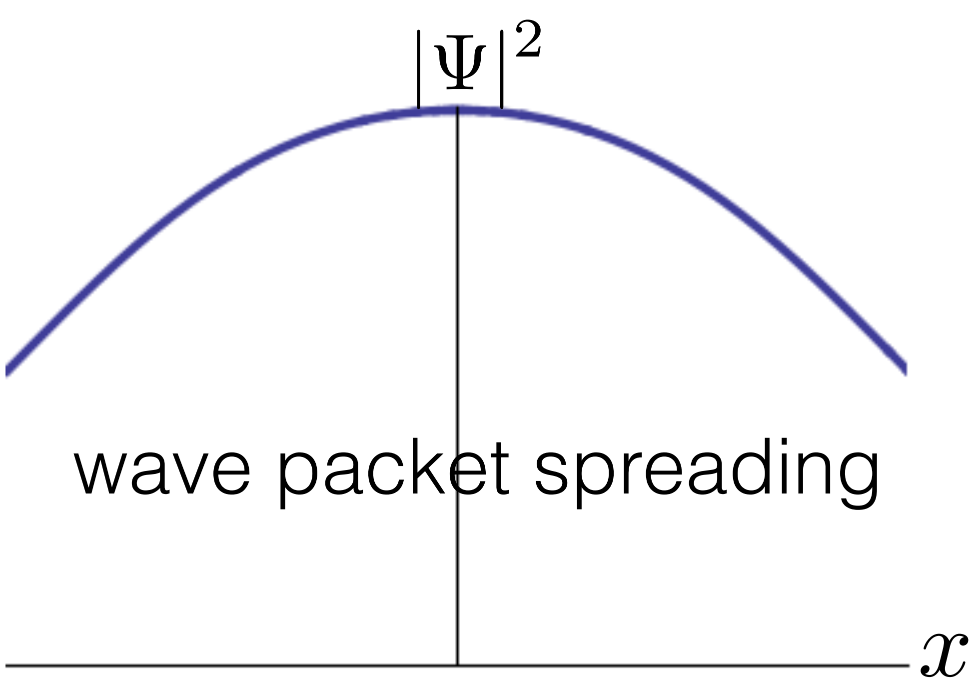

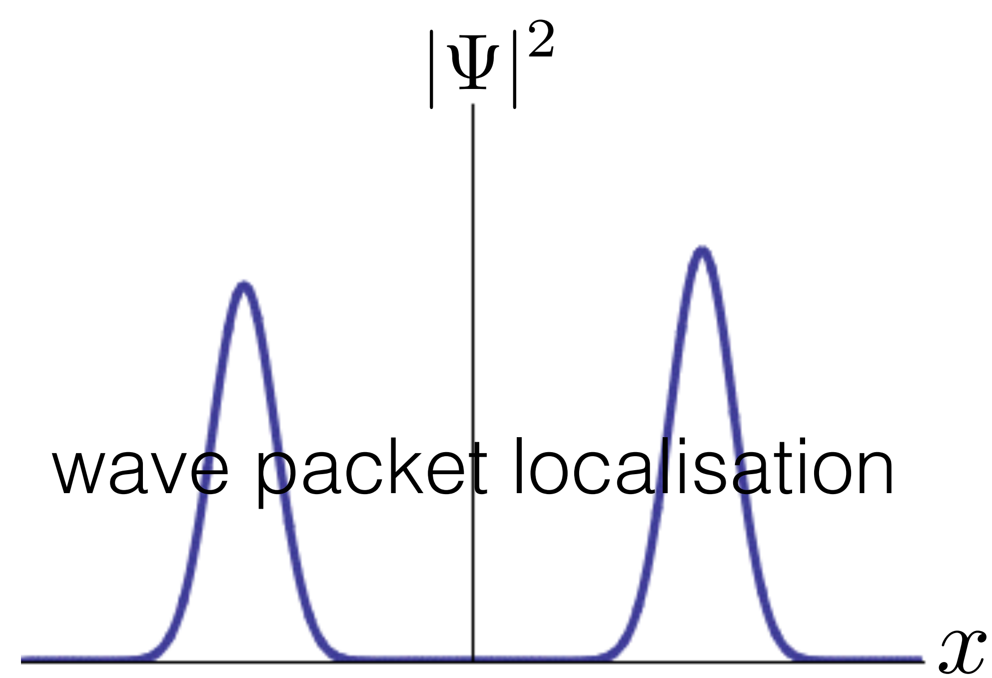

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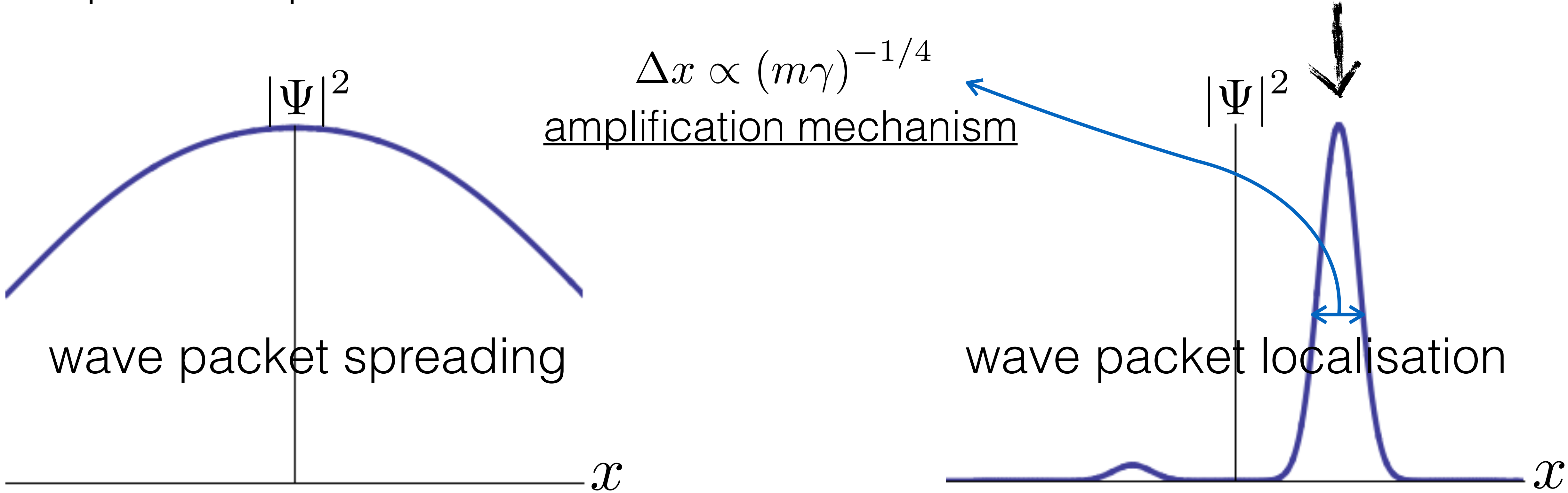
Example: Free particle

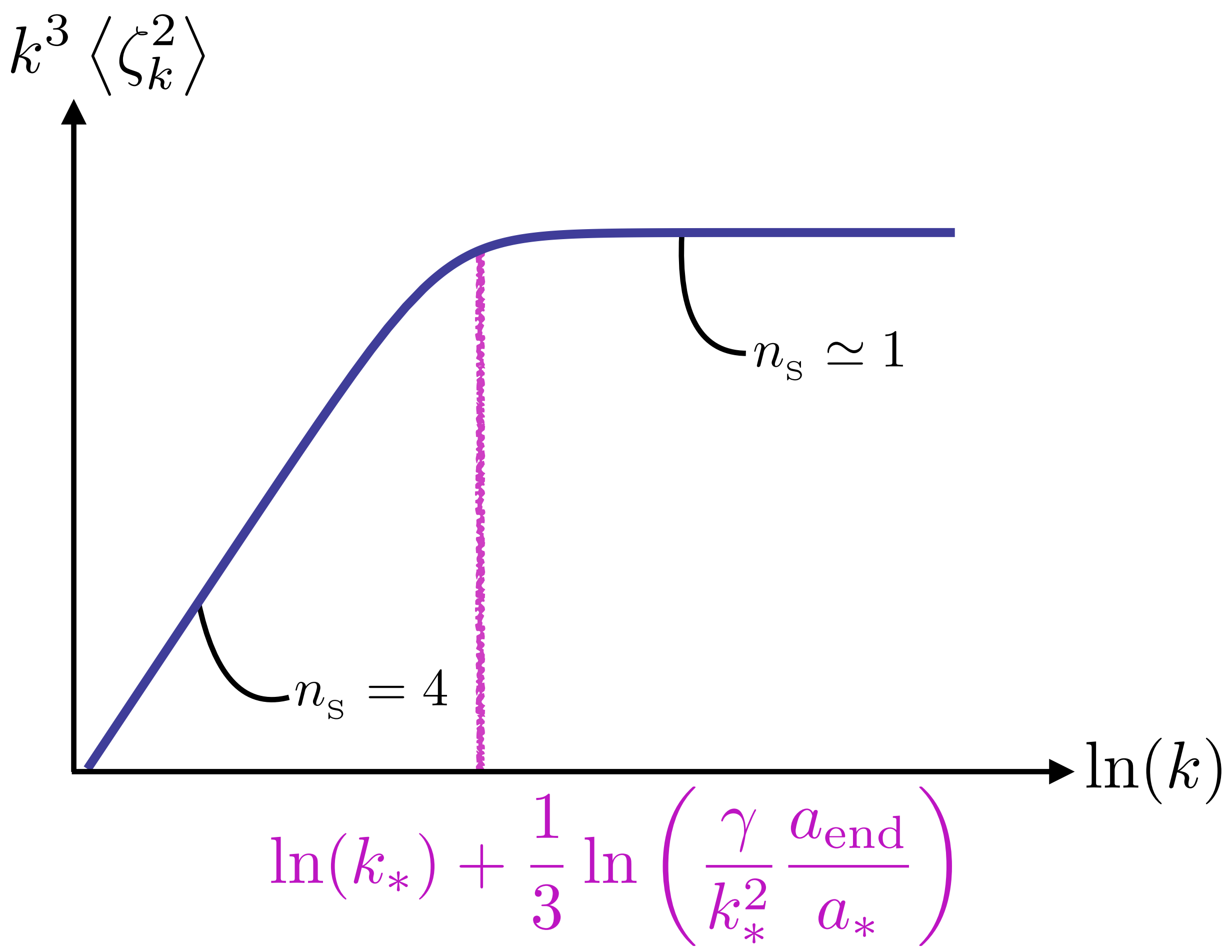
selection according to Born rules



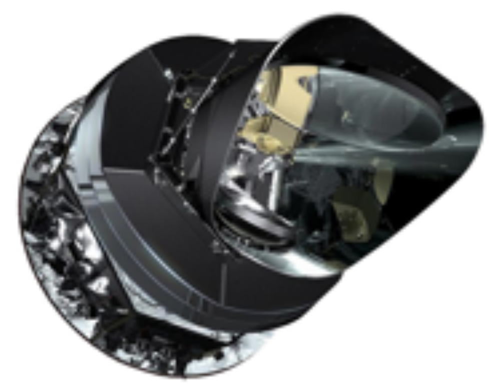
Collapsing the wave function of cosmological fluctuations $\zeta \propto \delta T/T$

Martin, Vennin, Peter (2012)

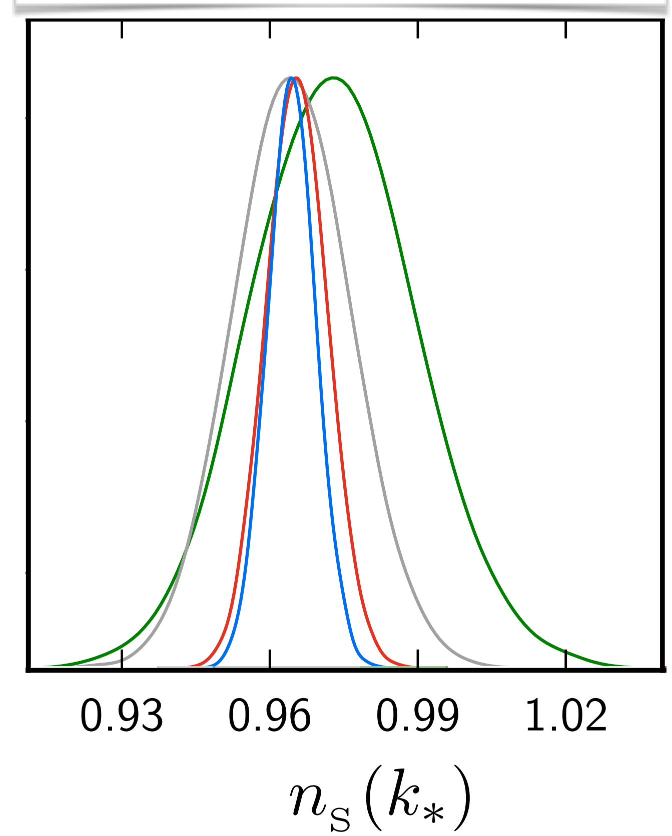
$$\mathrm{d}|\Psi\rangle = -i\hat{H}_{\mathrm{cosmo}}\,|\Psi\rangle\mathrm{d}t + \sqrt{\gamma}\left(\hat{\zeta} - \langle\hat{\zeta}\rangle\right)\mathrm{d}W_t\,|\Psi\rangle - \frac{\gamma}{2}\left(\hat{\zeta} - \langle\hat{\zeta}\rangle\right)^2\mathrm{d}t\,|\Psi\rangle$$



$$\frac{\gamma_*}{k_*^2} \ll \frac{a_*}{a_{\mathrm{end}}} \sim 10^{-50}$$


Planck satellite

Planck collaboration 2015



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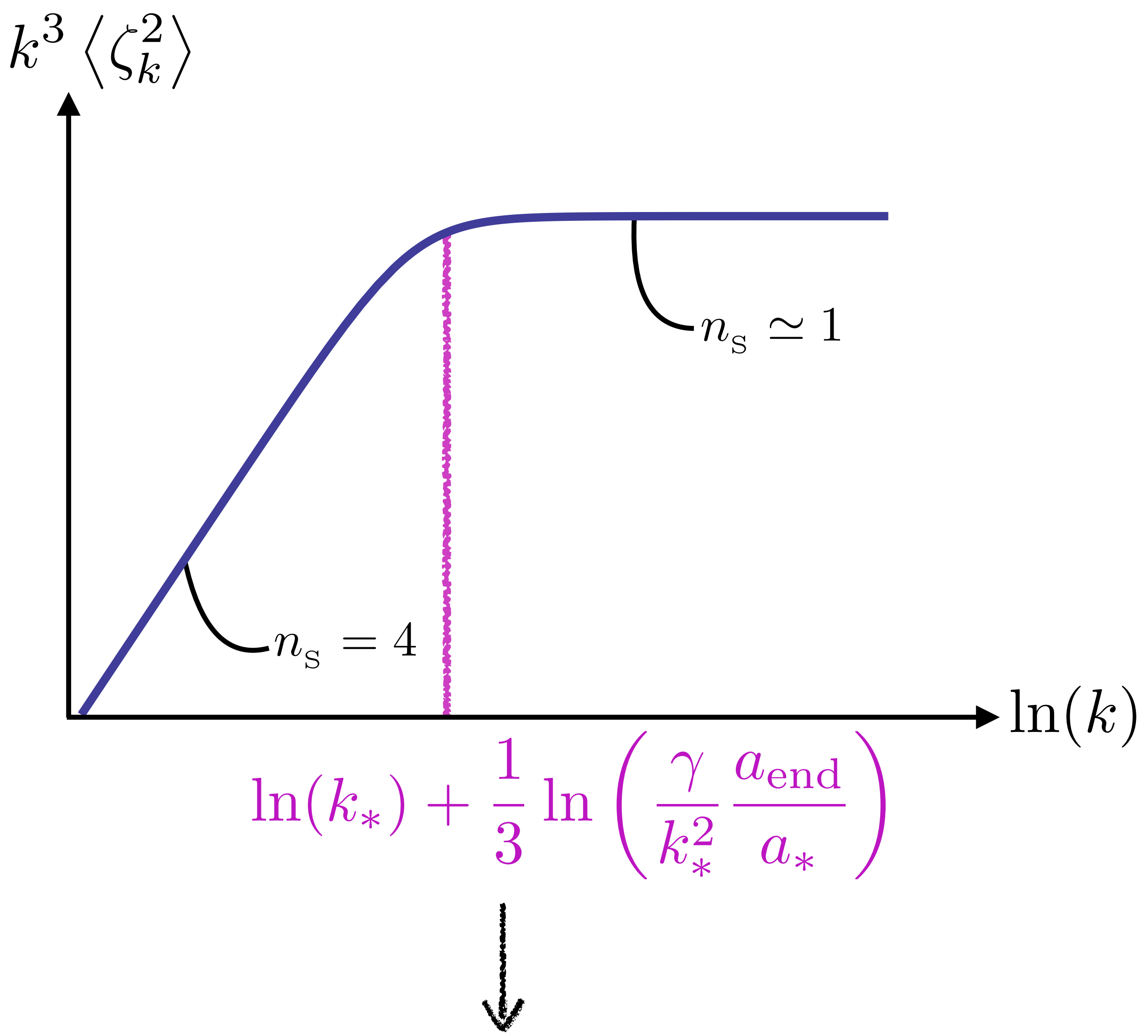

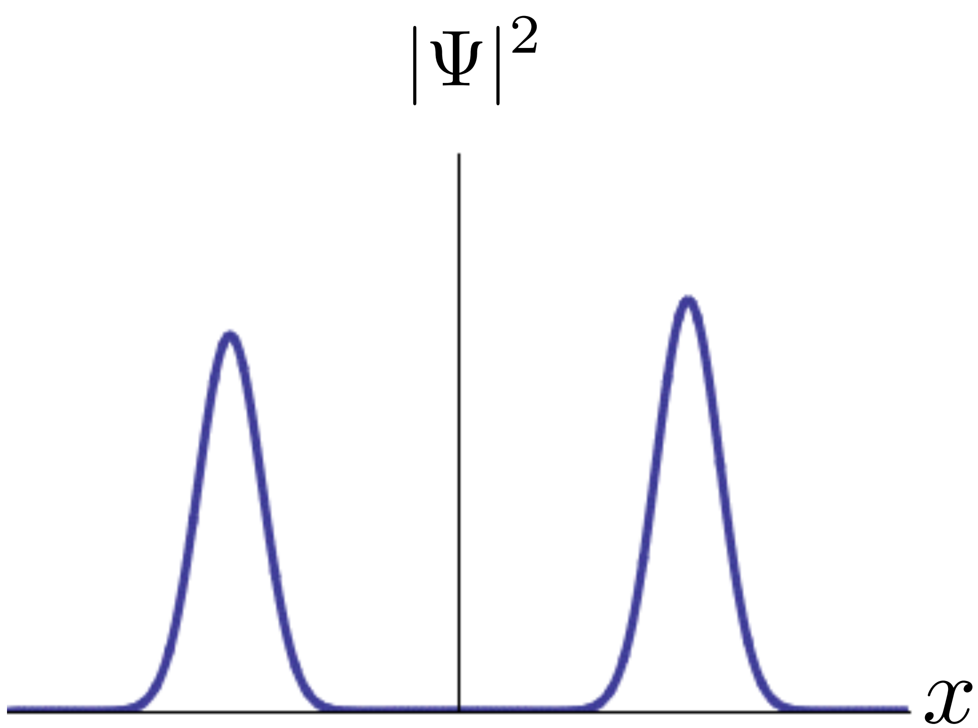

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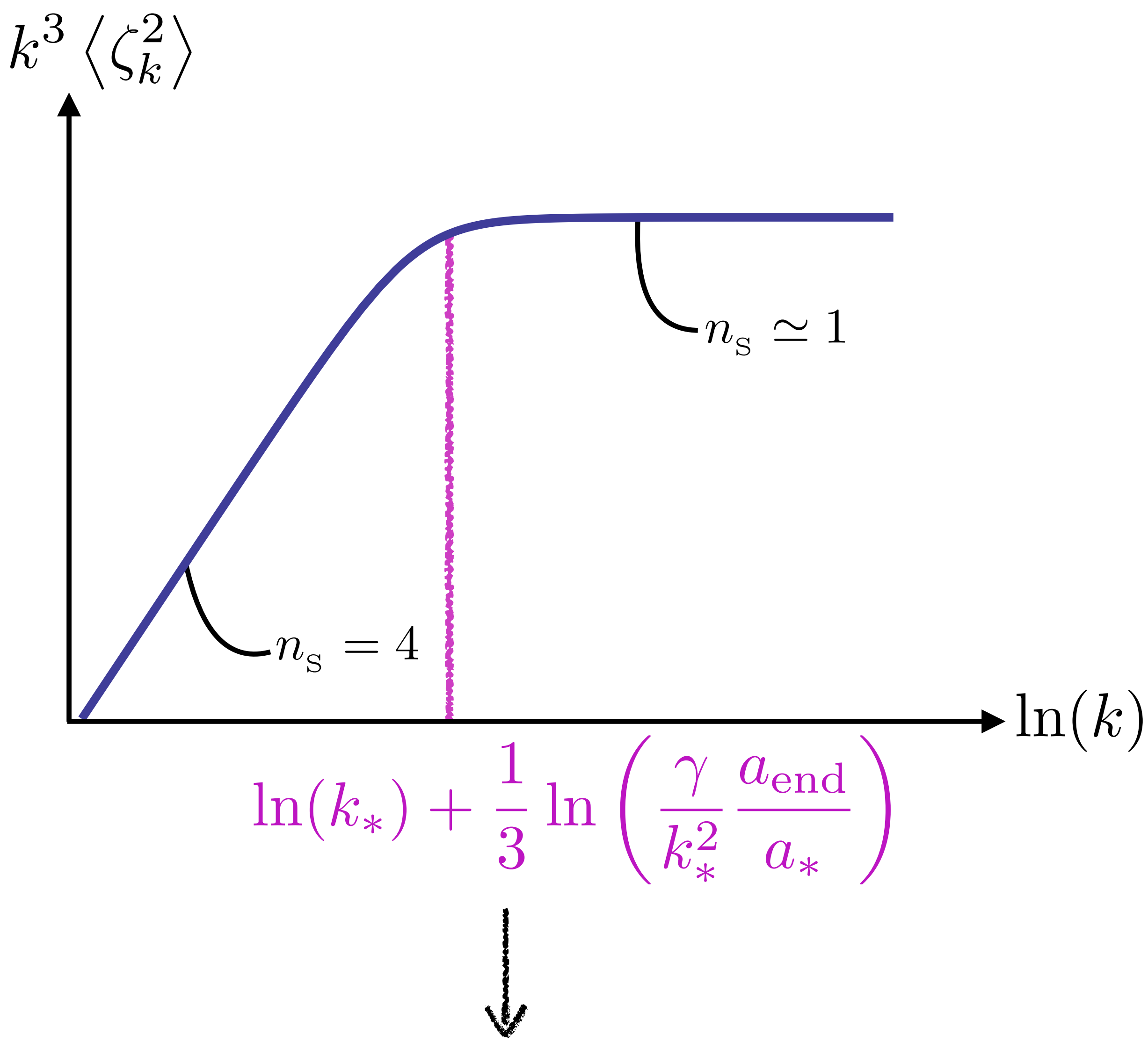

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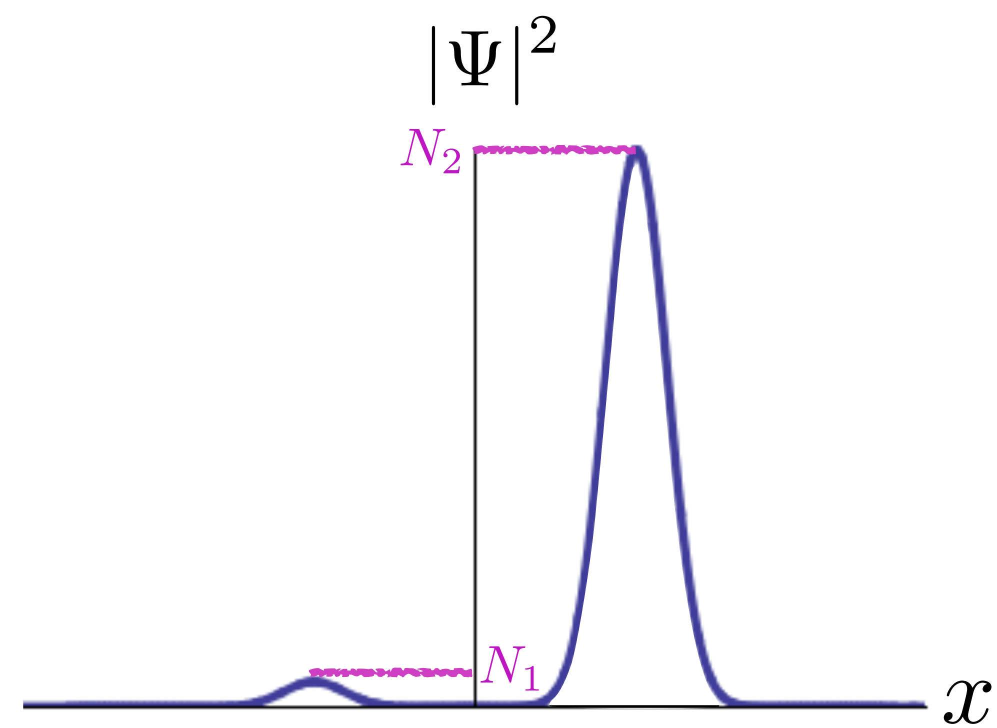

$$\Gamma = \ln\left(\frac{N_2}{N_1}\right)$$

Collapsing the wave function of cosmological fluctuations $\zeta \propto \delta T/T$

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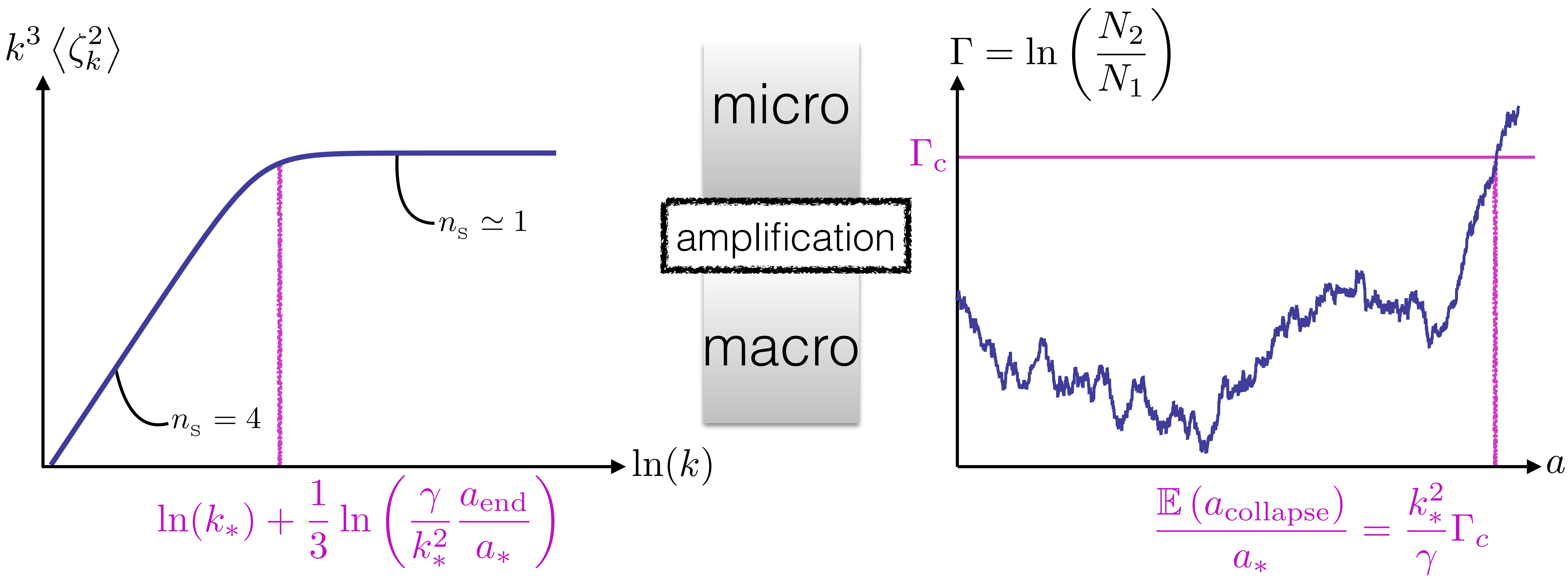

$$\frac{\gamma_*}{k_*^2} \ll \frac{a_*}{a_\mathrm{end}} \sim 10^{-50}$$

contradiction

$$\frac{\gamma_*}{k_*^2} > \frac{a_*}{a_\mathrm{end}}$$

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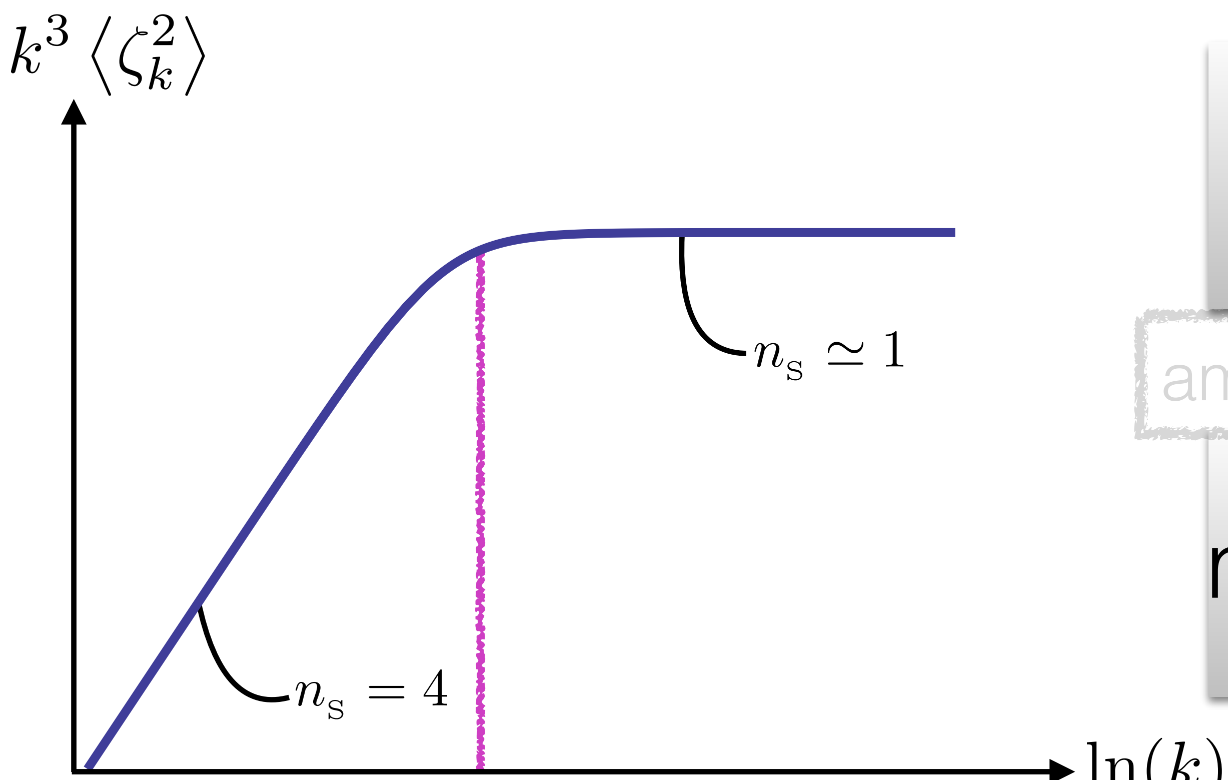
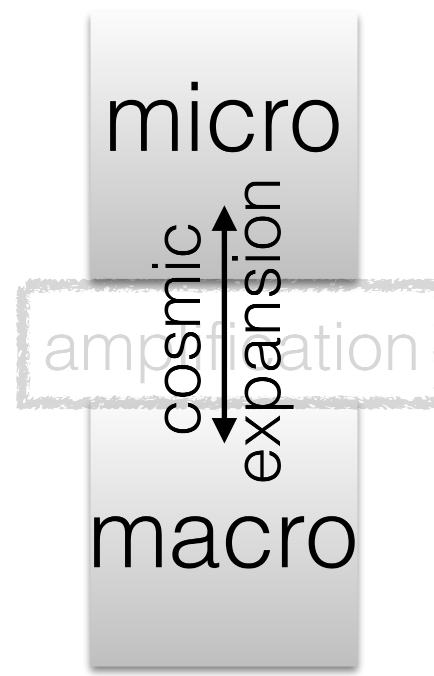
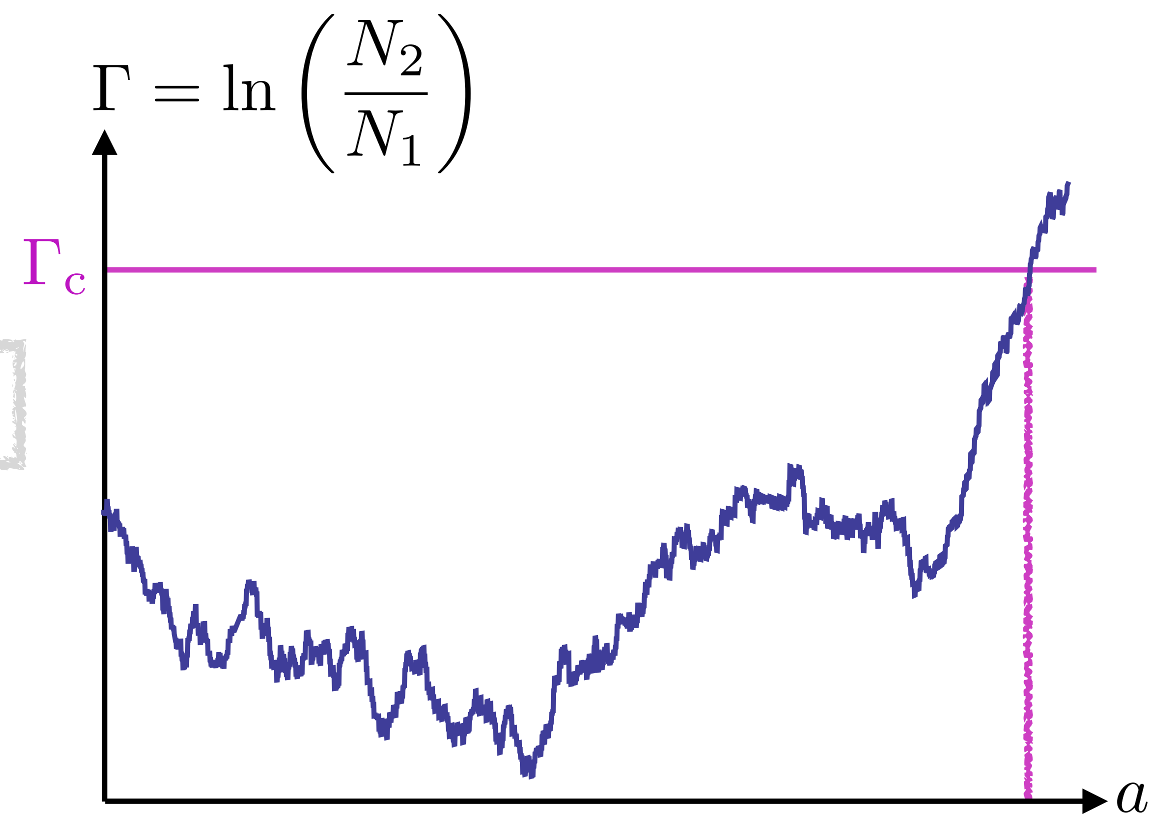


$$\ln(k_*) + \frac{1}{3}\ln\left(\frac{\gamma}{k_*^2}\frac{a_{\mathrm{end}}}{a_*}\right)$$





$$\frac{\mathbb{E}\left(a_{\mathrm{collapse}}\right)}{a_*} = \frac{k_*^2}{\gamma}\Gamma_c$$

$$\frac{\gamma_*}{k_*^2} \ll \frac{a_*}{a_{\mathrm{end}}} \sim 10^{-50}$$

contradiction

$$\frac{\gamma_*}{k_*^2} > \frac{a_*}{a_{\mathrm{end}}}$$

Quantum Mechanics and Cosmology: Open Issues

from Jerome Martin’s talk:

- Quantum to classical transition of cosmological fluctuations
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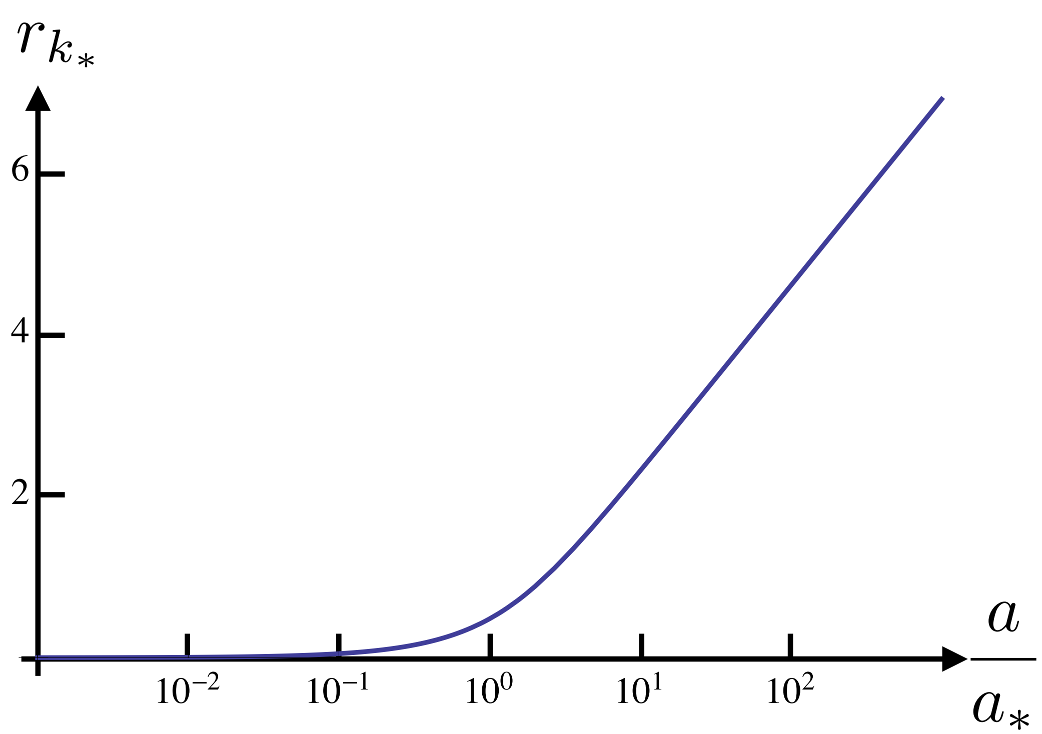
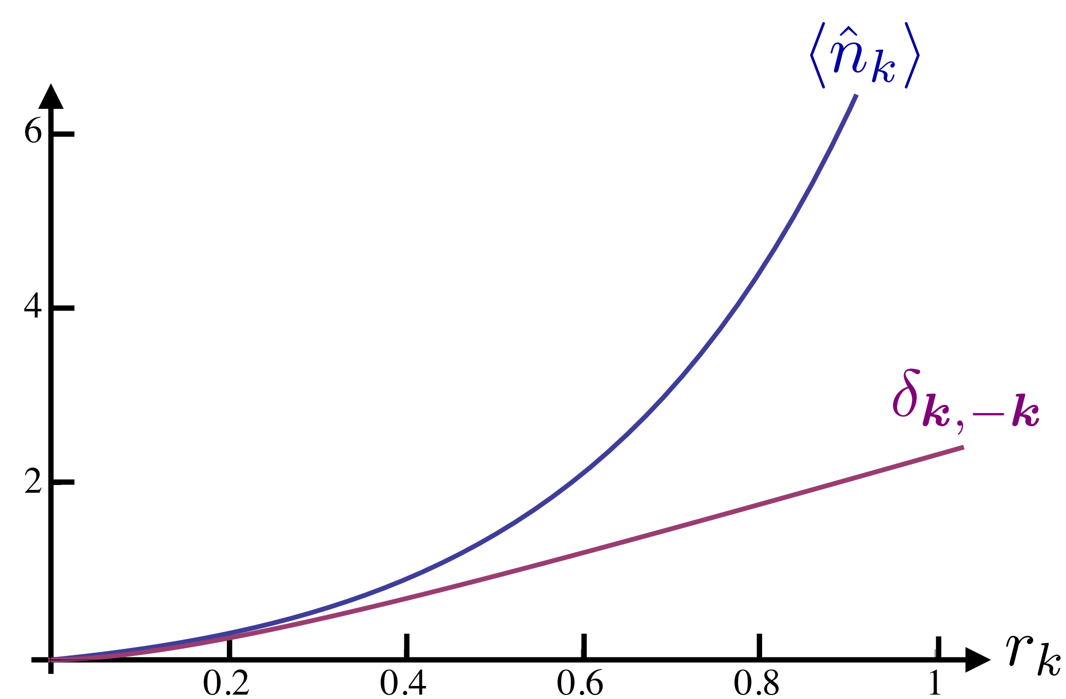
- Signature of the quantum origins of cosmological structures

Signature of the quantum origins of cosmological structures

$$|\Psi_{\rm CMB}\rangle = \bigotimes_{\boldsymbol{k}\in\mathbb{R}^{3+}} |\Psi_{\boldsymbol{k}}\rangle \qquad \text{with} \qquad |\Psi_{\boldsymbol{k}}\rangle = \frac{1}{\cosh r_k}\sum_{n=0}^{\infty} e^{2in\varphi_k}(-1)^n \tanh^n r_k |n_{\boldsymbol{k}}, n_{-\boldsymbol{k}}\rangle$$

similar to $|\uparrow,\uparrow\rangle + |\downarrow,\downarrow\rangle$ $\longrightarrow$ can violate Bell inequalities ?





Martin, Vennin (2016)

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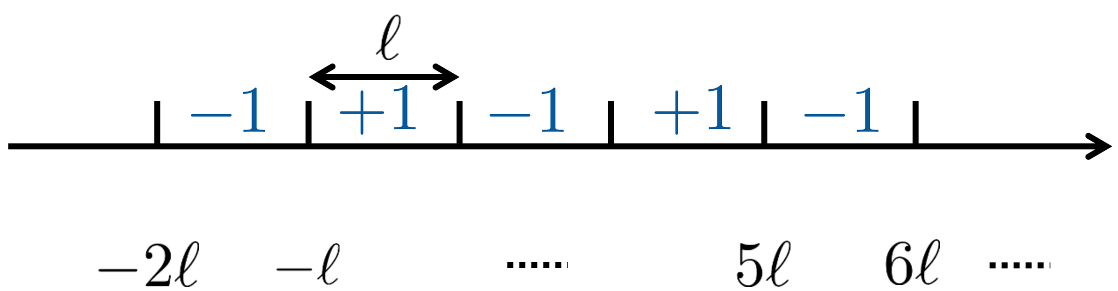
Spin operators for continuous variables

Larsson (2004)



$$\hat{S}_z(\ell) = \sum_{n=-\infty}^{\infty} (-1)^n \int_{n\ell}^{(n+1)\ell} \mathrm{d}\zeta_{\mathbf{k}} |\zeta_{\mathbf{k}}\rangle\langle\zeta_{\mathbf{k}}|$$

completed with

$$\hat{S}_{\pm}(\ell) = \pm \sum_{n=-\infty}^{\infty} \int_{2n\ell}^{(2n\pm1)\ell} \mathrm{d}\zeta_{\boldsymbol{k}}\, |\zeta_{\boldsymbol{k}}\rangle\, \langle\zeta_{\boldsymbol{k}} \pm \ell|$$

obey spin algebra!

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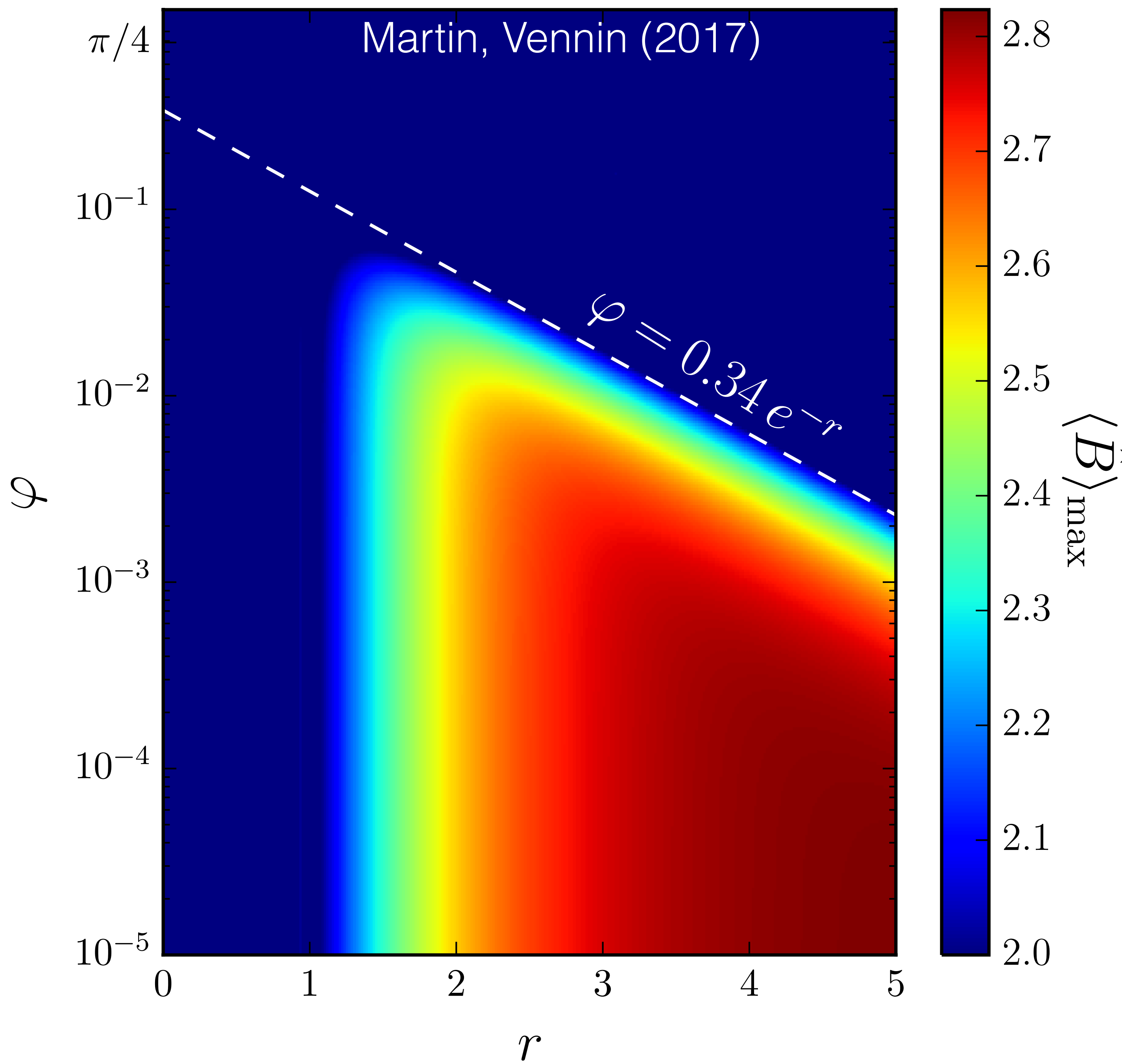

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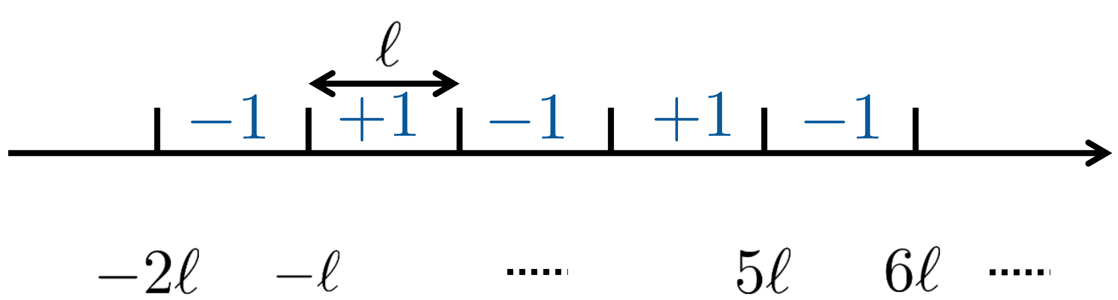

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requires to access phase information

↓

conjugated momentum $\zeta_{\boldsymbol{k}}'$

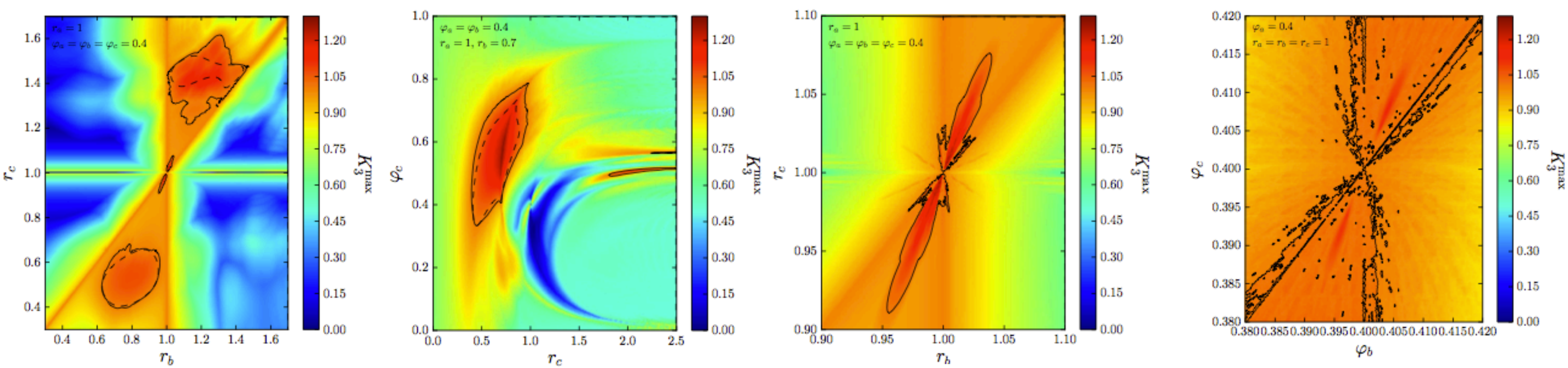
↓

decaying mode

Legget-Garg inequalities

“temporal Bell inequalities”

Rely on measuring a single spin component at different times



can be violated for two-mode squeezed states!

Martin, Vennin (2017)

Conclusions

The early Universe is an interesting playground to push quantum mechanics and its foundational issues to unexplored regimes (energies, times, distances) and setups (lack of external observer)

This relies on seeding cosmological structures with quantum fluctuations. This part of the scenario can be tested in principle, but hard in practice!