Title: Testing Quantum Mechanics in the Early Universe

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Abstract: <p>Hidden-variables theories account for quantum mechanics in terms of a particular 'equilibrium' distribution of underlying parameters corresponding to the Born rule. In the most well-studied example, the pilot-wave theory of de Broglie and Bohm, it is well established that the Born rule may be understood to arise from a process of dynamical relaxation. This 'quantum relaxation' may have taken place in the very early universe and could have left imprints on the cosmic microwave background (CMB). Such imprints amount to signatures of the decay of early violations of the Born rule. In this colloquium we summarise recent progress in making detailed predictions and in comparing them with the reported large-scale anomalies in the CMB data.</p>

Testing quantum mechanics in the early universe

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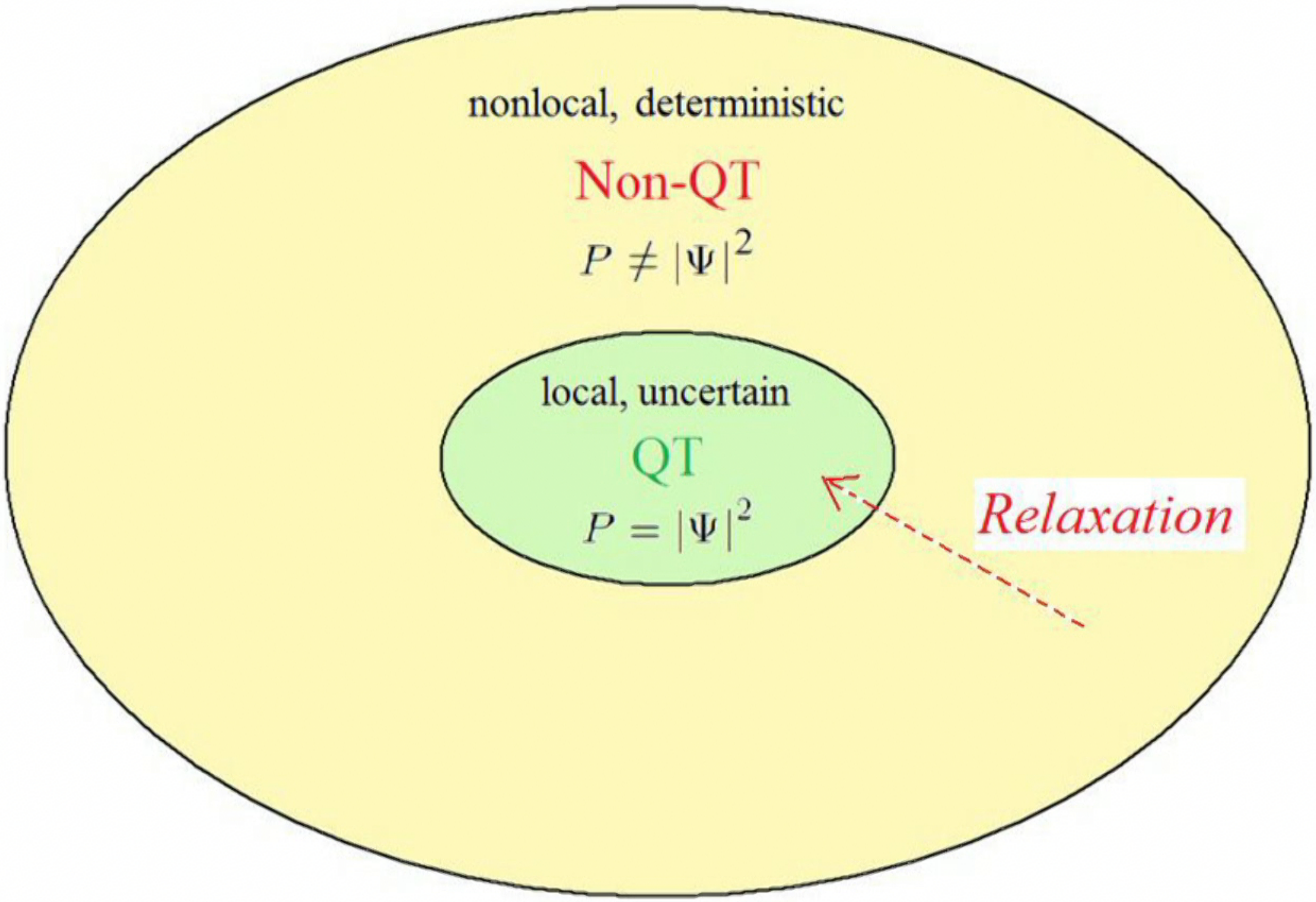
A. Valentini, Inflationary cosmology as a probe of primordial quantum mechanics, Phys. Rev. D **82**, 063513 (2010)

S. Colin and A. Valentini, Mechanism for the suppression of quantum noise at large scales on expanding space, Phys. Rev. D **88**, 103515 (2013)

S. Colin and A. Valentini, Primordial quantum nonequilibrium and large-scale cosmic anomalies, Phys. Rev. D **92**, 043520 (2015)

S. Vitenti, A. Valentini and P. Peter, forthcoming (data analysis)

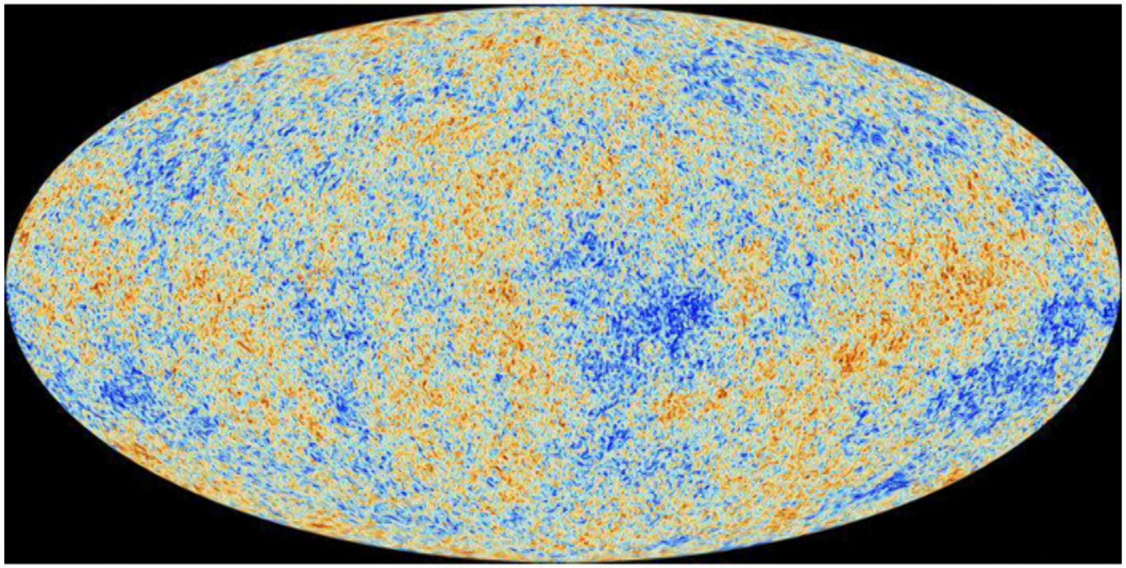
Quantum theory is a special case of a much wider physics



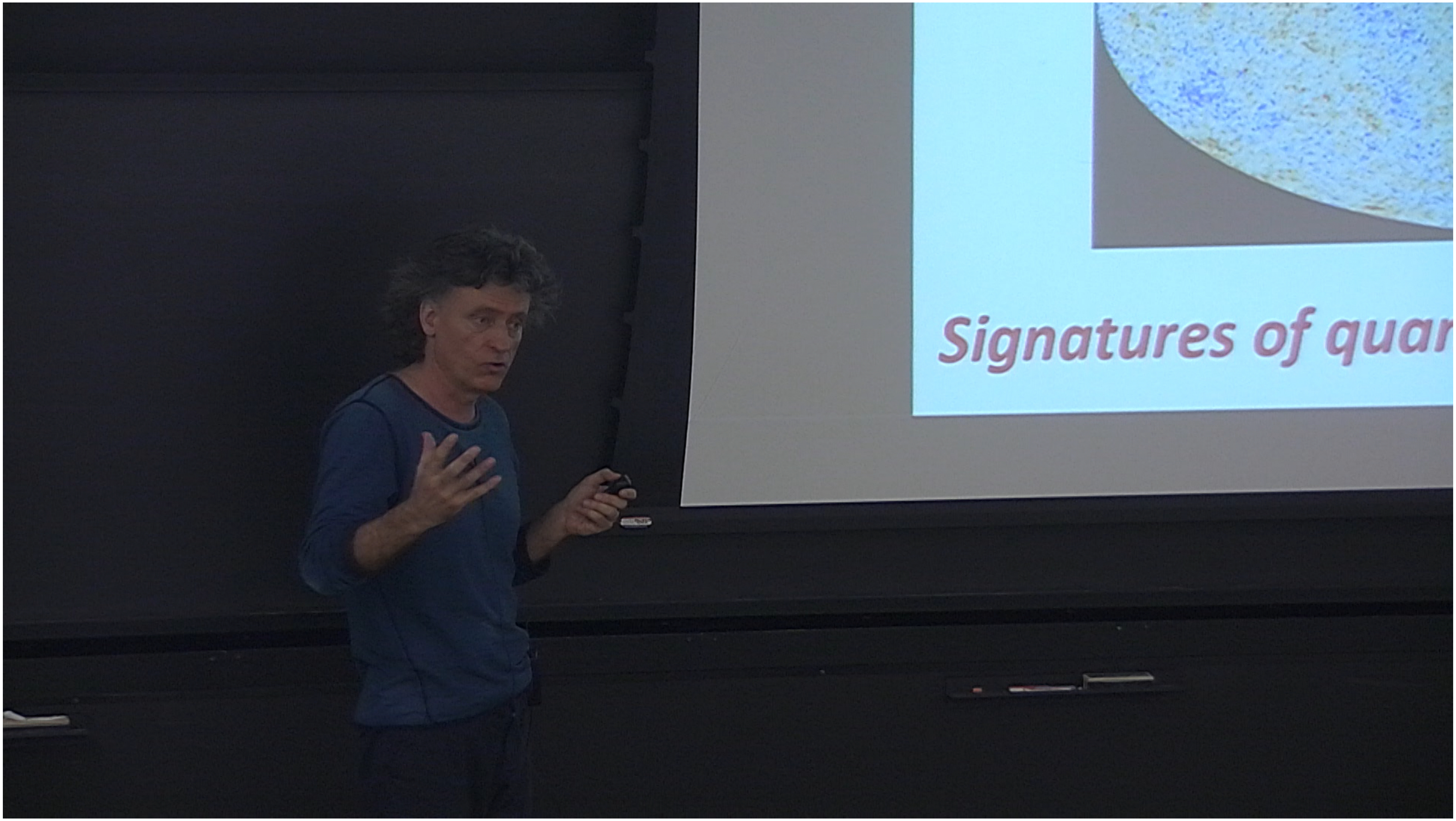
(Valentini 1991, 1992)

Quantum noise is a relic of the big bang

CMB anisotropies are ultimately generated by early quantum noise (inflationary vacuum)



Signatures of quantum relaxation in the CMB?


Signatures of quar

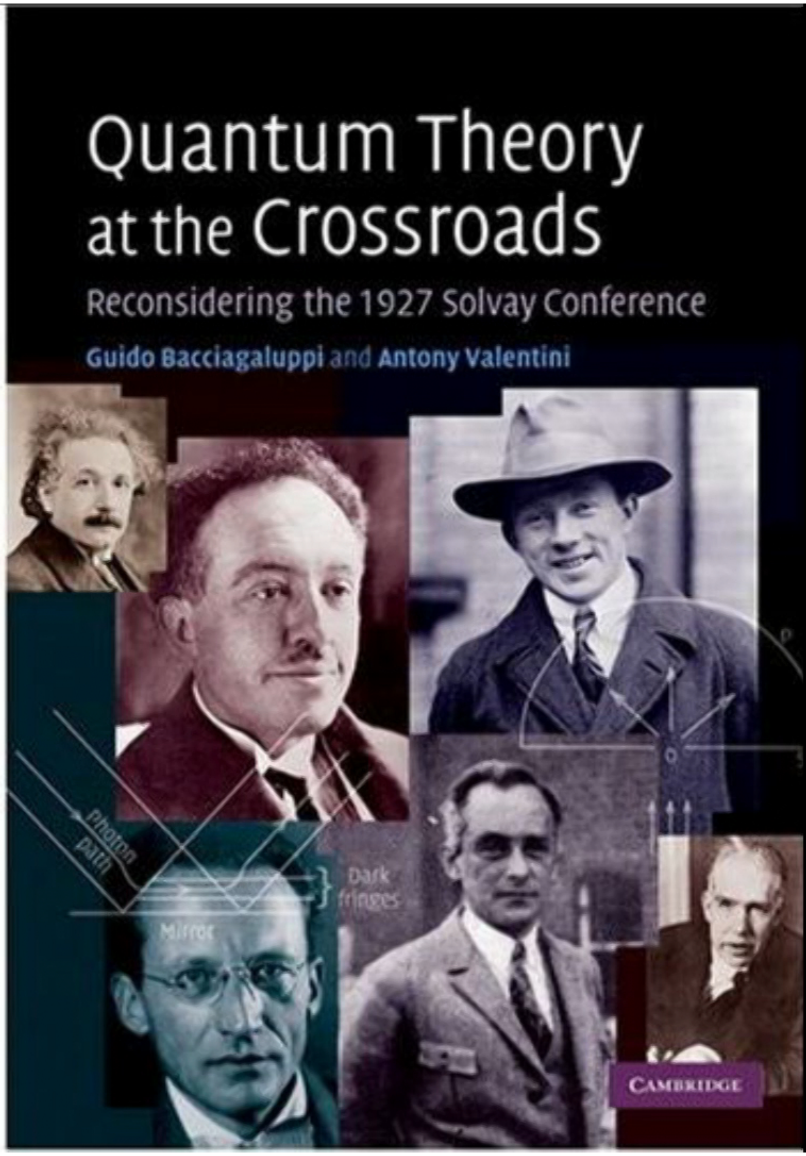
The 1927 Solvay Conference

Three theories extensively discussed.
No consensus reached.

G. Bacciagaluppi and A. Valentini, *Quantum Theory at the Crossroads* (Cambridge University Press, 2009) [quant-ph/0609184]

De Broglie's largely-unknown but major contributions:

1923—27: de Broglie developed a new, non-Newtonian form of dynamics

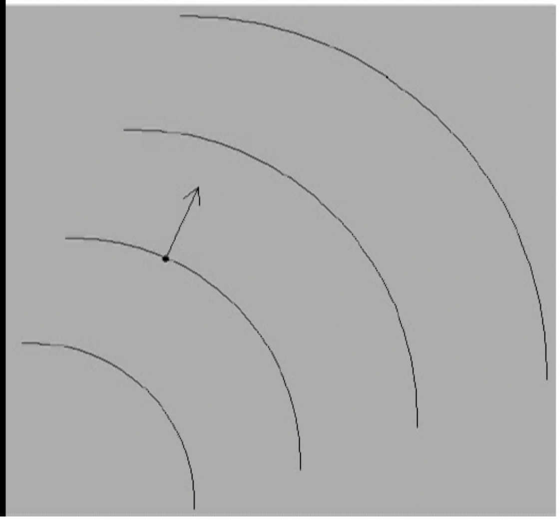


De Broglie's Pilot-Wave Dynamics (1927)

$$i\frac{\partial \Psi}{\partial t} = \sum_{i=1}^{N} -\frac{1}{2m_i}\nabla_i^2 \Psi + V\Psi$$

$$(\ \Psi = |\Psi|\, e^{iS}\ ) \qquad m_i \frac{d\mathbf{x}_i}{dt} = \nabla_i S$$

(cf. WKB, but for *any* wave function)



(Generalise: configuration $q(t)$)

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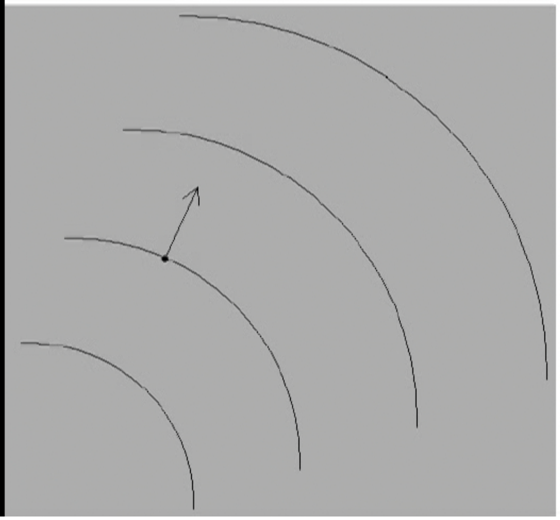


(Generalise: configuration $q(t)$)

Get QM if *assume* initial Born-rule distribution, $P = |\Psi|^2$ (preserved in time by the dynamics)

(shown fully by Bohm in 1952)

System with configuration $q(t)$ and wave function(al) $\psi(q,t)$

$$i\frac{\partial \psi}{\partial t} = \hat{H}\psi$$

$$\frac{dq}{dt} = \frac{j}{|\psi|^2}$$

These equations define a *pilot-wave dynamics* for any system whose Hamiltonian $\hat{H}$ is given by a differential operator (Struyve and Valentini 2009)

where $j = j[\psi] = j(q,t)$ is the Schrödinger current

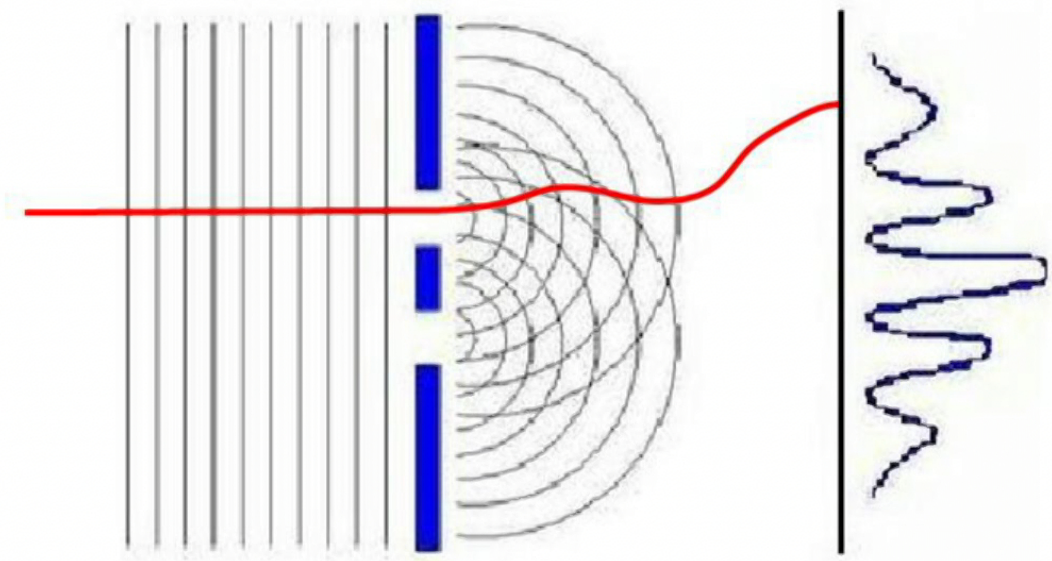
[Requires an underlying preferred foliation with time function *t*
Valid in any globally-hyperbolic spacetime (Valentini 2004)]

By construction $\rho(q,t)$ will obey

$$\frac{\partial \rho}{\partial t} + \partial_q \cdot (\rho v) = 0 \qquad \frac{dq}{dt} = v$$

and $\rho(q,t) = |\psi(q,t)|^2$ is preserved in time (Born rule).

Example of one particle



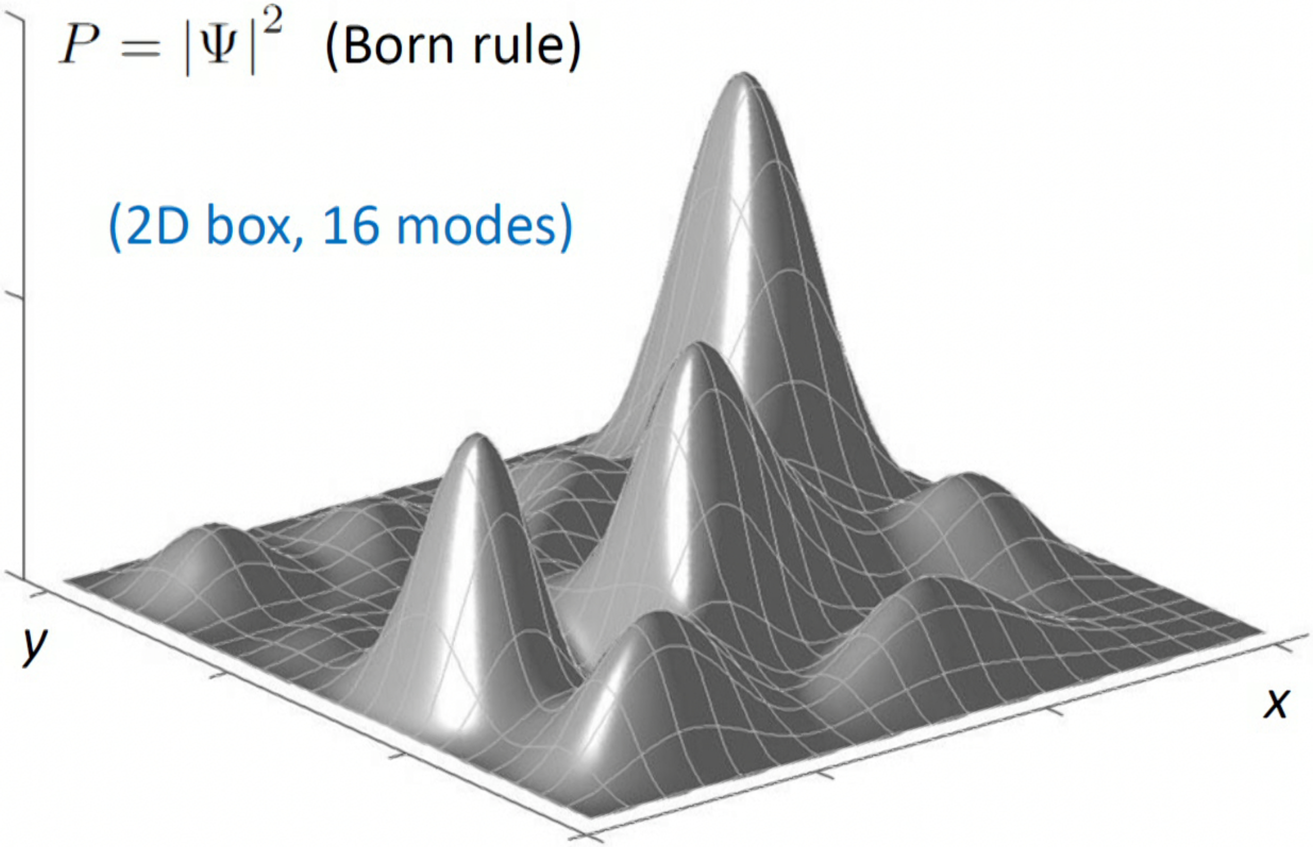
In agreement with experiment
if assume initial $P = |\Psi|^2$

Disagrees with experiment for initial $P \neq |\Psi|^2$

Quantum theory = special case of a wider physics

BUT: *experimentally* quantum dof's are always found to have the "quantum equilibrium" distribution:

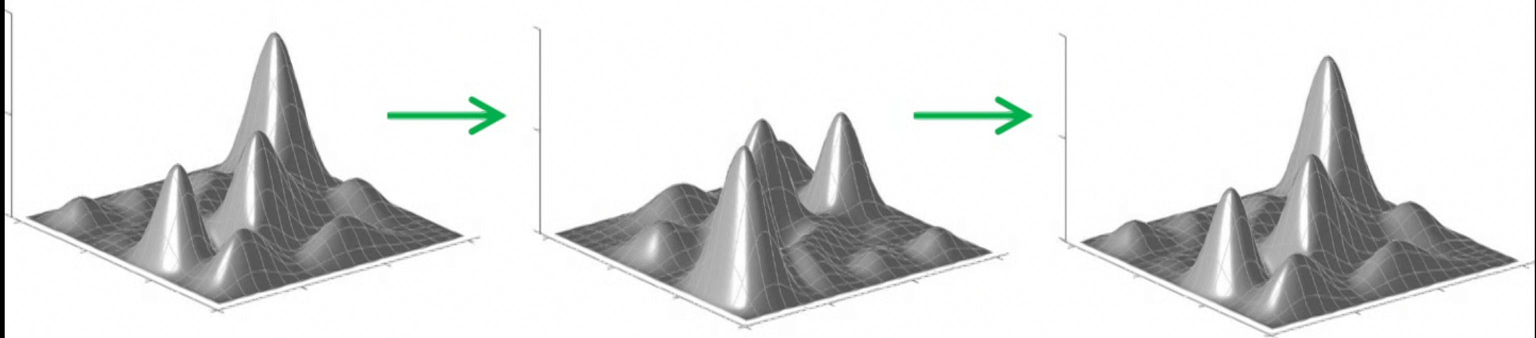
$P = |\Psi|^2$ (Born rule)



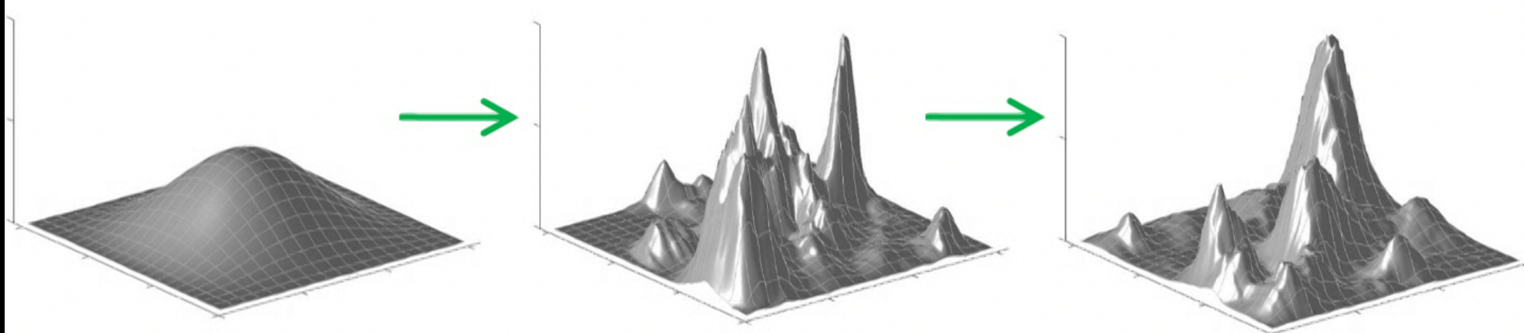
Why?

Quantum relaxation (cf. thermal relaxation)

Equilibrium ($P = |\Psi|^2$) changes with time



Non-equilibrium ($P \neq |\Psi|^2$) relaxes to equilibrium



(Valentini and Westman, Proc. Roy. Soc. A 2005)

Quantify relaxation with a coarse-grained *H*-function

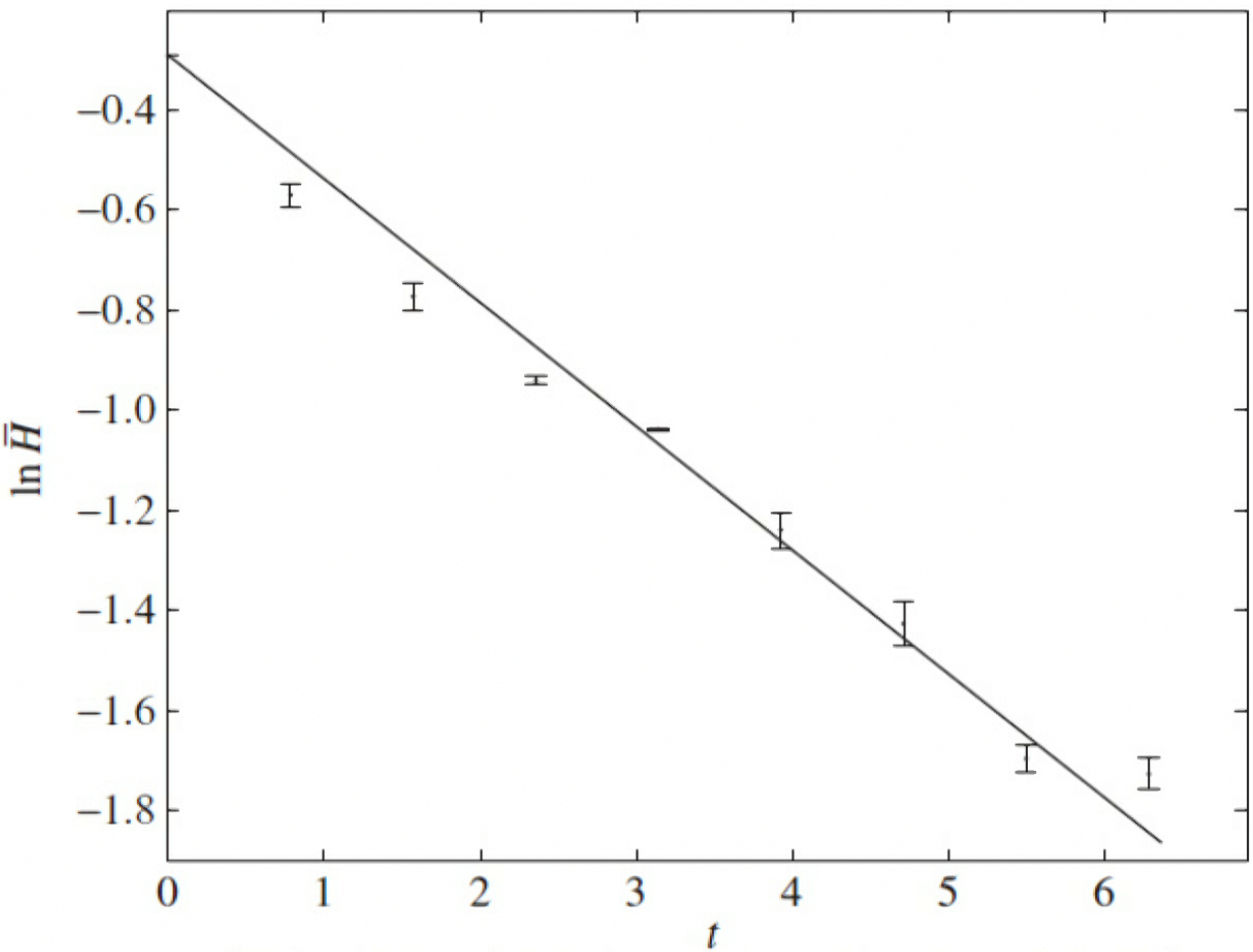
$$\bar{H} = \int \mathrm{d}q \, \bar{\rho} \ln(\bar{\rho}/\overline{|\psi|^2}),$$ (minus the relative entropy)

Obeys the *H*-theorem (Valentini 1991, 1992)

$$\bar{H}(t) \leqslant \bar{H}(0)$$ (cf. classical analogue)

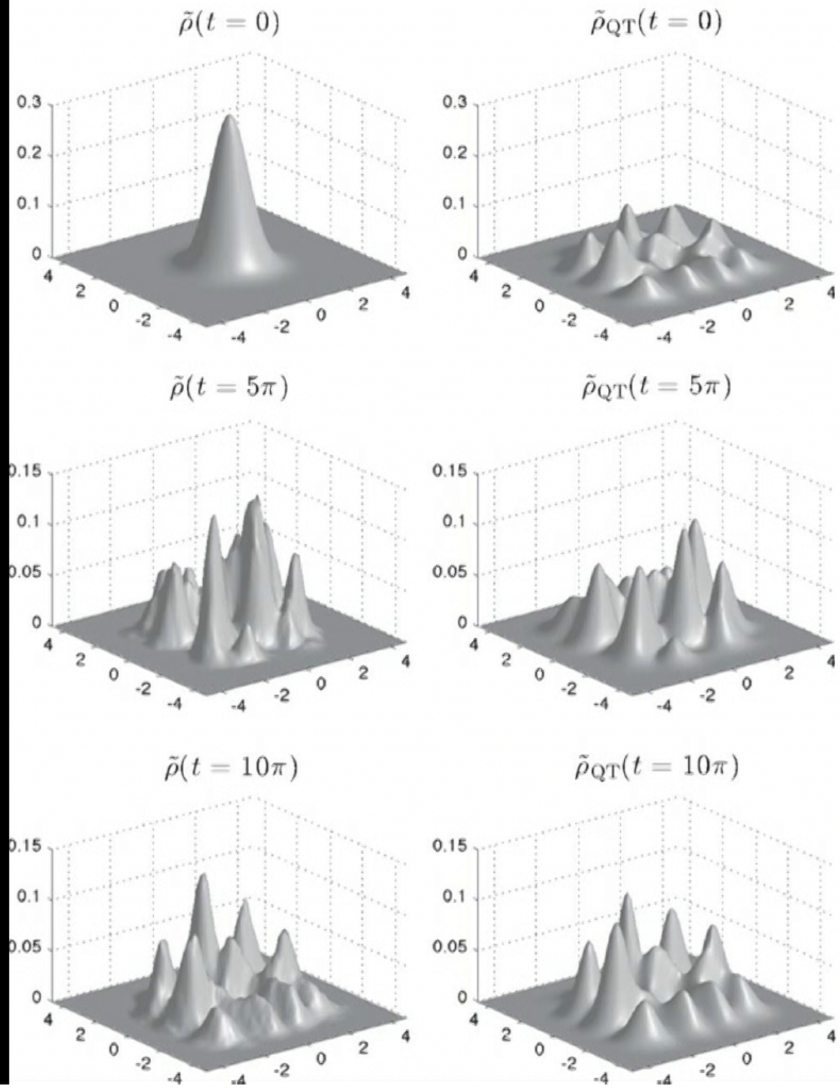
assuming no initial fine-grained structure in ρ and $|\psi|^2$

Simulations show *exponential decay* of *H*-function

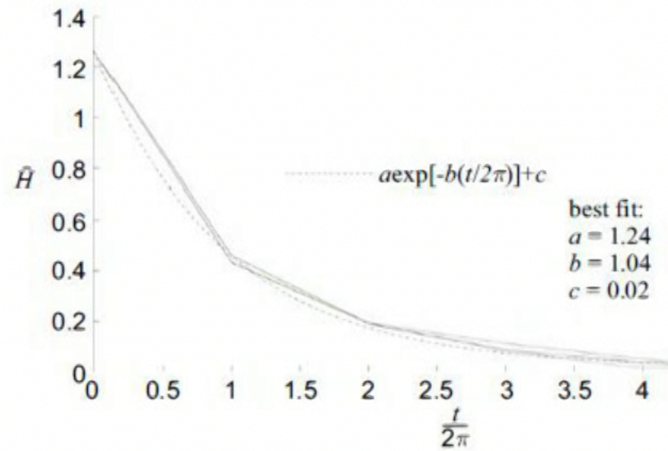


(Valentini and Westman, Proc. Roy. Soc. A 2005)

Confirmed and extended by many independent simulations



2D oscillator, 25 modes in superposition (Abraham, Colin and Valentini, J. Phys. A 2014)



Relaxation is faster for larger numbers of modes.

Very crudely: timescale is of order the timescale for wave function evolution.

The Born probability rule $P = |\Psi|^2$ is not a law of nature; it holds only because we are stuck in "equilibrium".

And we are stuck in "equilibrium" because everything we can see has a long and violent astrophysical history.

When did quantum relaxation happen?

Presumably, a long time ago, in the very early universe, soon after the big bang.

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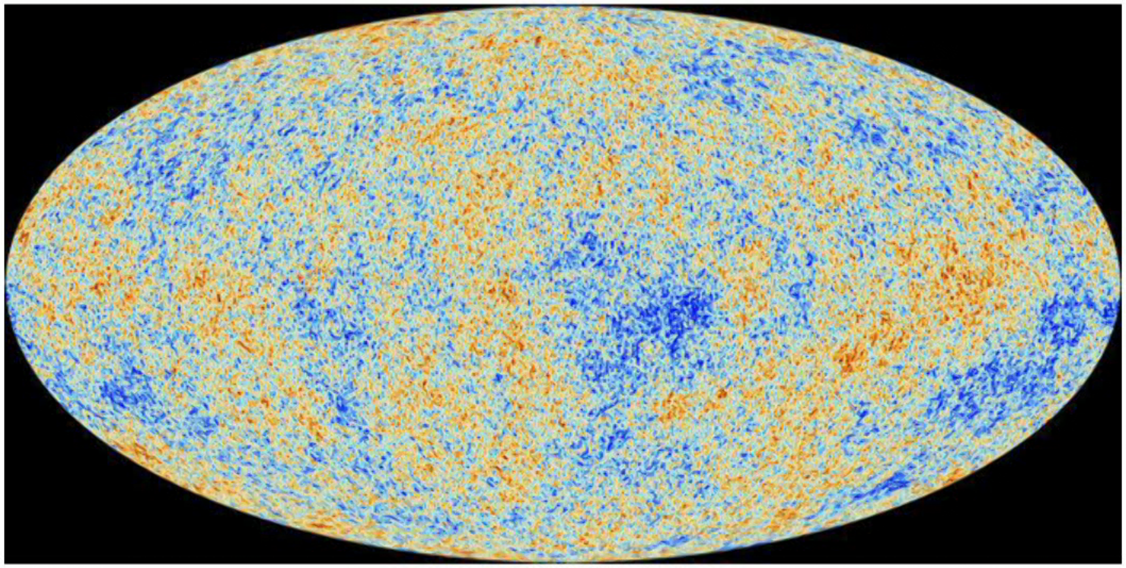


Signatures of quantum relaxation in the CMB?

Physical wavelengths

$$d\tau^2 = dt^2 - a^2 d\mathbf{x}^2$$

E.g. $a \propto t^{1/2}$ (radiation-dominated)

coordinate distance $|d\mathbf{x}|$

corresponds to a physical distance $a(t)|d\mathbf{x}|$

($a_0 = 1 \text{ today}$)

Physical wavelengths are given by $\lambda_{\text{phys}} = a(t)\lambda$

where $\lambda = 2\pi/k$ is the proper wavelength today

('comoving' wavelength)

The Hubble radius

Hubble parameter $H \equiv \dot{a}/a$

measures the rate of spatial expansion

Hubble radius H^{-1}

E.g. $a \propto t^{1/2}$

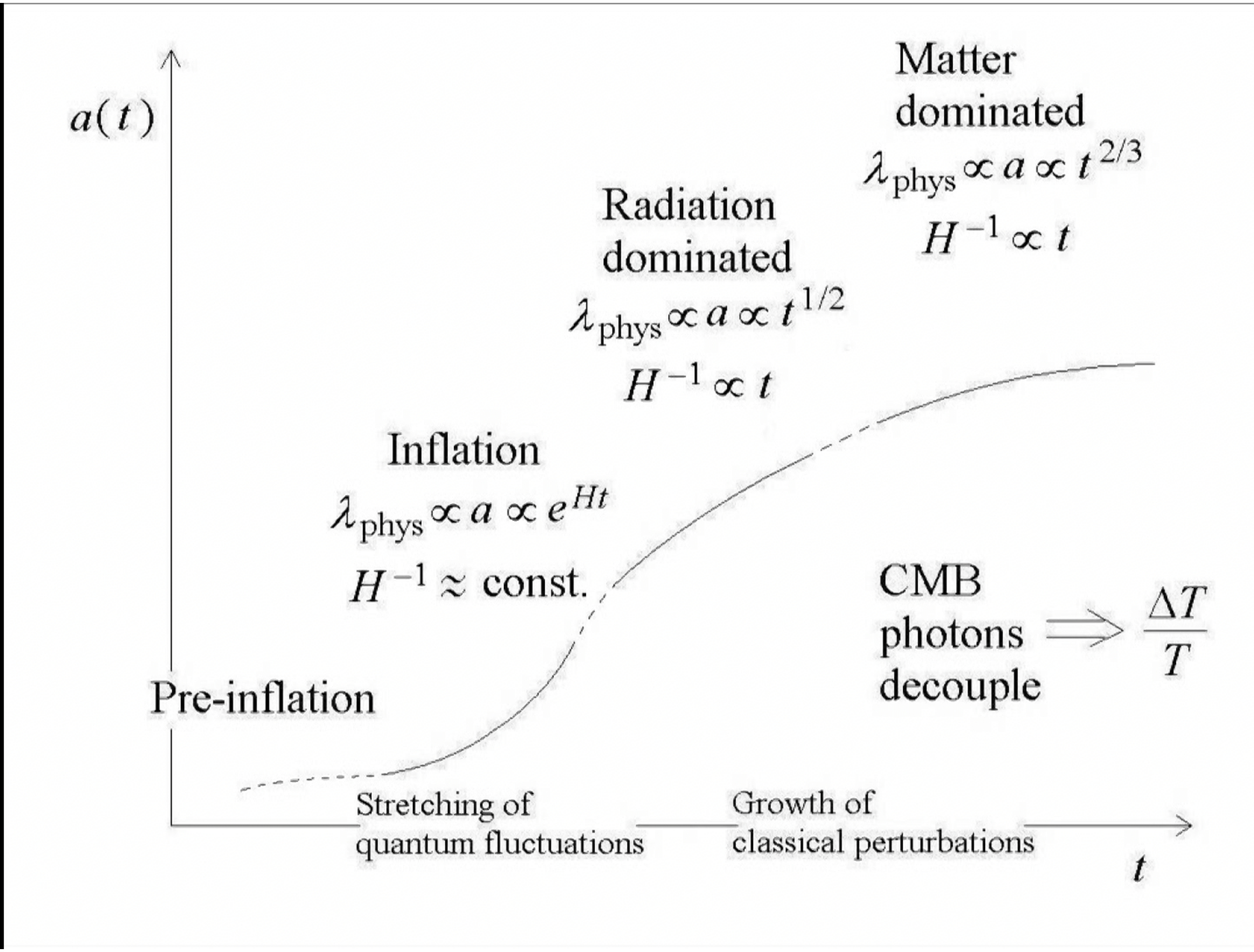
$H^{-1} = 2t$

is a characteristic lengthscale (or time, with $c = 1$)

Short-wavelength limit, $\lambda_{\rm phys} << H^{-1}$ (Minkowski)

Long-wavelength limit, $\lambda_{\rm phys} >> H^{-1}$

(classical perturbations 'freeze')


$a(t)$
Matter dominated
$\lambda_{\rm phys} \propto a \propto t^{2/3}$
$H^{-1} \propto t$
Radiation dominated
$\lambda_{\rm phys} \propto a \propto t^{1/2}$
$H^{-1} \propto t$
Inflation
$\lambda_{\rm phys} \propto a \propto e^{Ht}$
$H^{-1} \approx$ const.
CMB photons decouple $\Longrightarrow \frac{\Delta T}{T}$
Pre-inflation
Stretching of quantum fluctuations
Growth of classical perturbations
t

Corrections to Inflationary Predictions for the CMB

inflation perturbation ϕ $\longrightarrow$ curvature perturbation $\mathcal{R}_{\mathbf{k}}$

curvature perturbation $\mathcal{R}_{\mathbf{k}}$ $\longrightarrow$ temperature anisotropy a_{lm}

$$\mathcal{R}_{\mathbf{k}} = -\left[\frac{H}{\dot{\phi}_0}\phi_{\mathbf{k}}\right]_{t=t_*(k)}$$

$$a_{lm} = \frac{i^l}{2\pi^2}\int d^3\mathbf{k}\ \mathcal{T}(k,l)\mathcal{R}_{\mathbf{k}}Y_{lm}(\hat{\mathbf{k}})$$

(transfer function)

$$\frac{\Delta T(\theta,\phi)}{\bar{T}} = \sum_{l=2}^{\infty}\sum_{m=-l}^{+l} a_{lm}Y_{lm}(\theta,\phi)$$

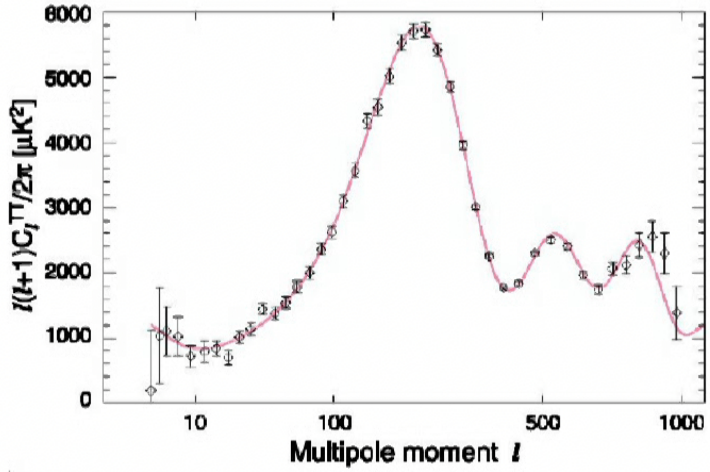
(Angular brackets: average over a "theoretical ensemble")

Angular power spectrum $C_l \equiv \left\langle |a_{lm}|^2 \right\rangle$
(independent of *m*)

$$C_l = \frac{1}{2\pi^2}\int_0^\infty \frac{dk}{k}\, \mathcal{T}^2(k,l)\mathcal{P}_\mathcal{R}(k)$$

(depends on the primordial *probability* distribution)

$$\mathcal{P}_\mathcal{R}(k) \equiv \frac{4\pi k^3}{V}\left\langle |\mathcal{R}_\mathbf{k}|^2 \right\rangle$$



$$\mathcal{R}_\mathbf{k} = -\left[\frac{H}{\dot\phi_0}\phi_\mathbf{k}\right]_{t=t_*(k)} \qquad \left\langle |\phi_\mathbf{k}|^2 \right\rangle_{\rm QT} = \frac{V}{2(2\pi)^3}\frac{H^2}{k^3}$$

(quantum theory)

How can we probe probabilities with only one sky?

Statistical isotropy $P[T(\theta - \delta\theta, \phi - \delta\phi)] = P[T(\theta, \phi)]$

$$\Rightarrow \quad \langle a^*_{l'm'} a_{lm} \rangle = \delta_{ll'}\, \delta_{mm'}\, C_l$$

Deduce that $\left\langle |a_{lm}|^2 \right\rangle$ is independent of *m*

Measured statistic (for *one* sky)

$$C_l^{\text{sky}} \equiv \frac{1}{2l+1} \sum_{m=-l}^{+l} |a_{lm}|^2 \qquad\qquad \left\langle C_l^{\text{sky}} \right\rangle = C_l$$

is unbiased estimate of $C_l \equiv \left\langle |a_{lm}|^2 \right\rangle$ (for ensemble)

If *l* is not too small, will probably find $C_l^{\text{sky}} \approx C_l$

(Cosmic variance $\frac{\Delta C_l^{\text{sky}}}{C_l} = \sqrt{\frac{2}{2l+1}}$)

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Quantum non-equilibrium

-- No quantum relaxation during inflation
(Bunch-Davies dynamics is too simple: AV, PRD 2010)

-- "You get out what you put in at the beginning"

$$\langle|\phi_{\mathbf{k}}|^2\rangle = \langle|\phi_{\mathbf{k}}|^2\rangle_{\mathrm{QT}}\,\xi(k) \qquad \mathcal{R}_{\mathbf{k}} = -\left[\frac{H}{\dot{\phi}_0}\phi_{\mathbf{k}}\right]_{t=t_*(k)}$$

$$\mathcal{P}_{\mathcal{R}}(k) = \mathcal{P}_{\mathcal{R}}^{\mathrm{QT}}(k)\xi(k)$$

Can set empirical limits on $\xi(k)$ (Valentini 2010)

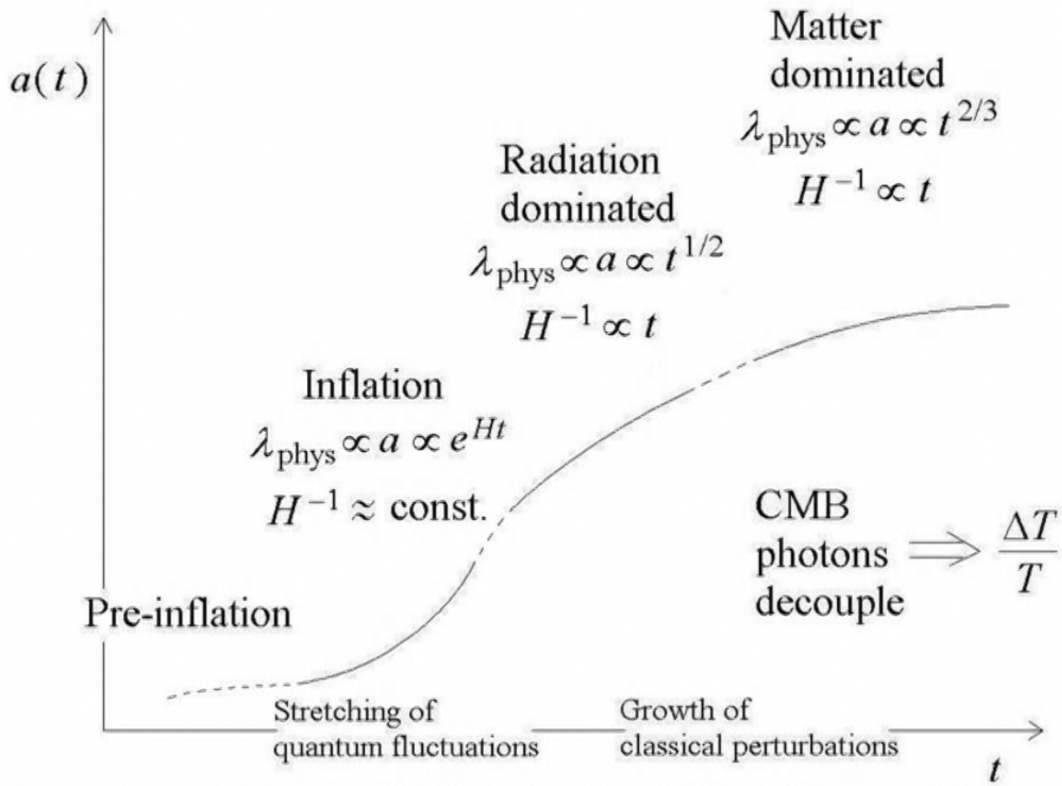
$$|S_{\mathrm{hv}}(k)| \lesssim 10^{-2}$$

close to $k_0 = 0.002\ \mathrm{Mpc}^{-1}$

Can we *predict* something about $\xi(k)$?

One possible strategy:

- Consider a pre-inflationary (radiation-dominated) era
- Derive constraints on relic non-equilibrium from that era



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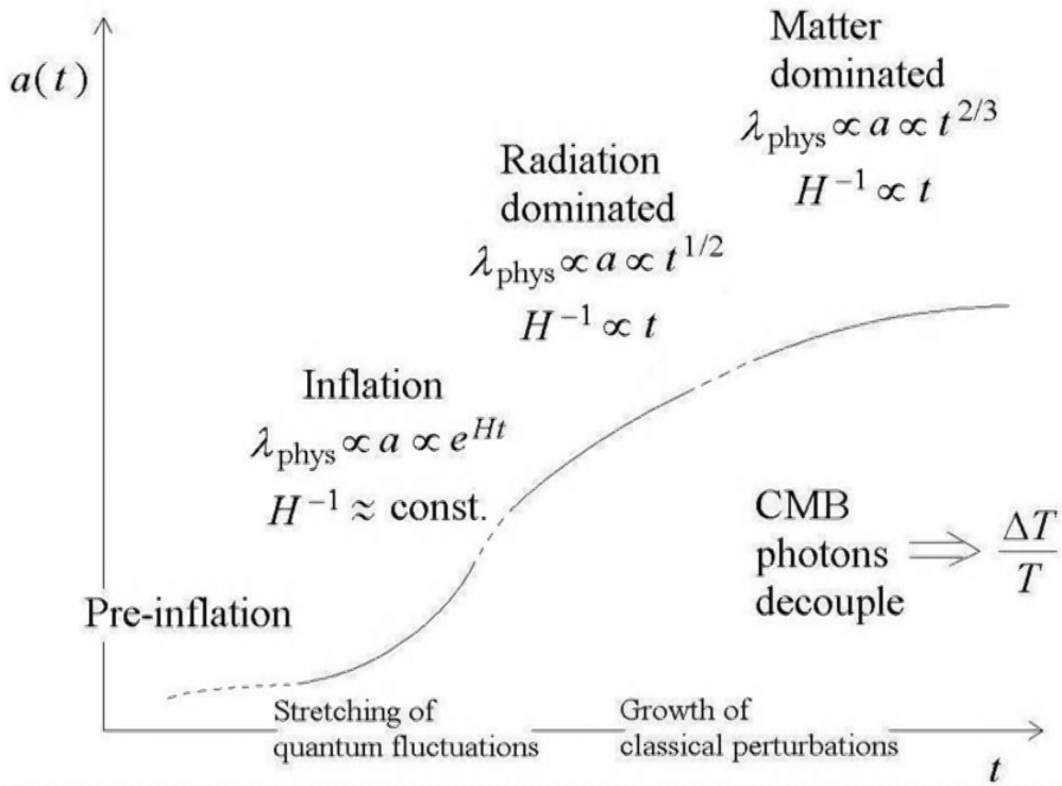


Pilot-wave field theory on expanding space

Flat metric $d\tau^2 = dt^2 - a^2 d\mathbf{x}^2$

$H \equiv \dot{a}/a$ is the Hubble parameter

physical wavelengths $\lambda_{\text{phys}} = a(t)\lambda$, where $\lambda = 2\pi/k$ is a comoving wavelength

free (minimally-coupled) massless scalar field ϕ

Hamiltonian density $\mathcal{H} = \frac{1}{2}\frac{\pi^2}{a^3} + \frac{1}{2}a(\nabla\phi)^2$

Fourier components $\phi_{\mathbf{k}} = \frac{\sqrt{V}}{(2\pi)^{3/2}}(q_{\mathbf{k}1} + iq_{\mathbf{k}2})$

Hamiltonian $H = \int d^3\mathbf{x}\, \mathcal{H}$ becomes $H = \sum_{\mathbf{k}r} H_{\mathbf{k}r}$

with $H_{\mathbf{k}r} = \frac{1}{2a^3}\pi_{\mathbf{k}r}^2 + \frac{1}{2}ak^2 q_{\mathbf{k}r}^2$

Schrödinger equation for $\Psi = \Psi[q_{\mathbf{k}r}, t]$ is

$$i\frac{\partial \Psi}{\partial t} = \sum_{\mathbf{k}r} \left(-\frac{1}{2a^3}\frac{\partial^2}{\partial q_{\mathbf{k}r}^2} + \frac{1}{2}ak^2 q_{\mathbf{k}r}^2 \right) \Psi$$

and the de Broglie velocities

$$\frac{dq_{\mathbf{k}r}}{dt} = \frac{1}{a^3}\frac{\partial S}{\partial q_{\mathbf{k}r}}$$

initial distribution $P[q_{\mathbf{k}r}, t_i]$,

time evolution $P[q_{\mathbf{k}r}, t]$ will be determined by

$$\frac{\partial P}{\partial t} + \sum_{\mathbf{k}r} \frac{\partial}{\partial q_{\mathbf{k}r}} \left(P \frac{1}{a^3}\frac{\partial S}{\partial q_{\mathbf{k}r}} \right) = 0$$

THE MODEL (one mode)

$$i\frac{\partial\psi}{\partial t} = \sum_{r=1,\ 2}\left(-\frac{1}{2m}\partial_r^2 + \frac{1}{2}m\omega^2 q_r^2\right)\psi$$

$$\dot{q}_r = \frac{1}{m}\,\mathrm{Im}\,\frac{\partial_r\psi}{\psi}$$ [= (1/*m*)grad *S*]

$$\frac{\partial\rho}{\partial t} + \sum_{r=1,\ 2}\partial_r\left(\rho\frac{1}{m}\,\mathrm{Im}\,\frac{\partial_r\psi}{\psi}\right) = 0$$

$$m = a^3\ , \quad \omega = k/a$$

All of our results come simply from the standard quantum-mechanical equation

$$\frac{\partial \rho}{\partial t} + \sum_{r=1,\ 2} \partial_r \left(\rho \frac{1}{m} \operatorname{Im} \frac{\partial_r \psi}{\psi} \right) = 0$$

The only change is in the initial conditions.

We assume that at the initial time the width of $\rho(q_1, q_2, t_i)$ *is smaller than the width of* $|\psi(q_1, q_2, t_i)|^2$

(impossible in standard quantum mechanics)

STRATEGY

Apply to a pre-inflationary era (rad.-dom. $a \propto t^{1/2}$).

Find large-scale "squeezing" of the Born rule for a spectator scalar field (suppression of relaxation at long wavelengths, $\xi(k) < 1$)

Assume that similar "squeezing" of the Born rule is imprinted on the inflationary spectrum (pending a model of the transition, future work).

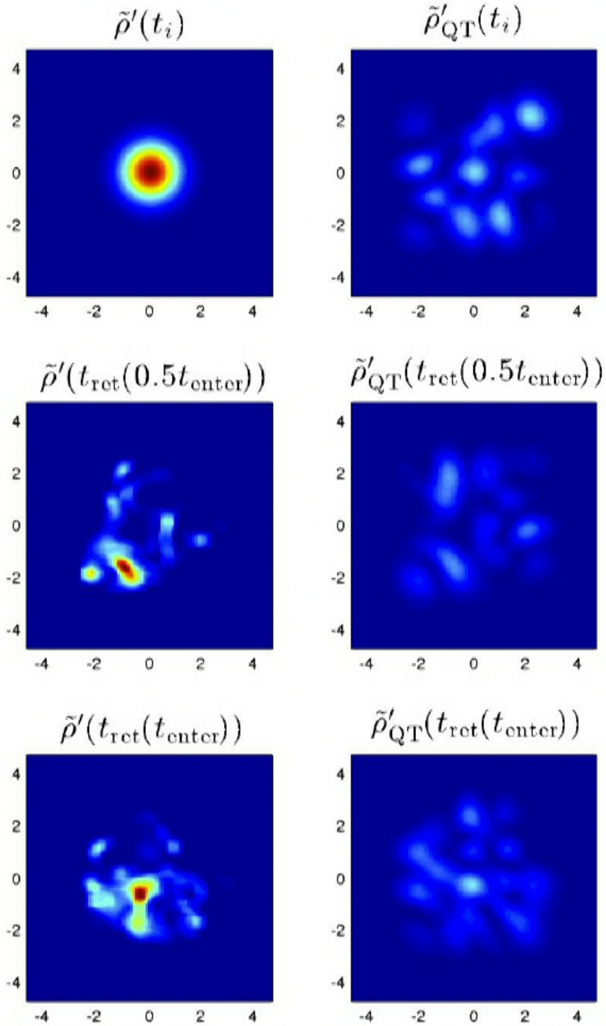
Suppression of quantum relaxation at super-Hubble wavelengths
(Colin and Valentini, Phys. Rev. D 2013)

Superposition of M=25 energy states, random initial phases

$$\psi(q_1, q_2, t_i) = \frac{1}{\sqrt{M}} \sum_{n_1=0}^{\sqrt{M}-1} \sum_{n_2=0}^{\sqrt{M}-1} e^{i\theta_{n_1 n_2}} \Phi_{n_1}(q_1) \Phi_{n_2}(q_2)$$

Initial non-equilibrium = a 'ground-state' Gaussian

Mode begins outside Hubble radius, evolve until time t_{enter}



expanding space

We are simply evolving this equation

$$\frac{\partial \rho}{\partial t} + \sum_{r=1,\ 2} \partial_r \left(\rho \frac{1}{m} \,\mathrm{Im}\, \frac{\partial_r \psi}{\psi} \right) = 0$$

forwards in time.

Right column: equilibrium initial conditions

$$\rho(q_1, q_2, t_i) = |\psi(q_1, q_2, t_i)|^2$$

Left column: nonequilibrium initial conditions

$$\rho(q_1, q_2, t_i) \neq |\psi(q_1, q_2, t_i)|^2$$

(assume subquantum width)

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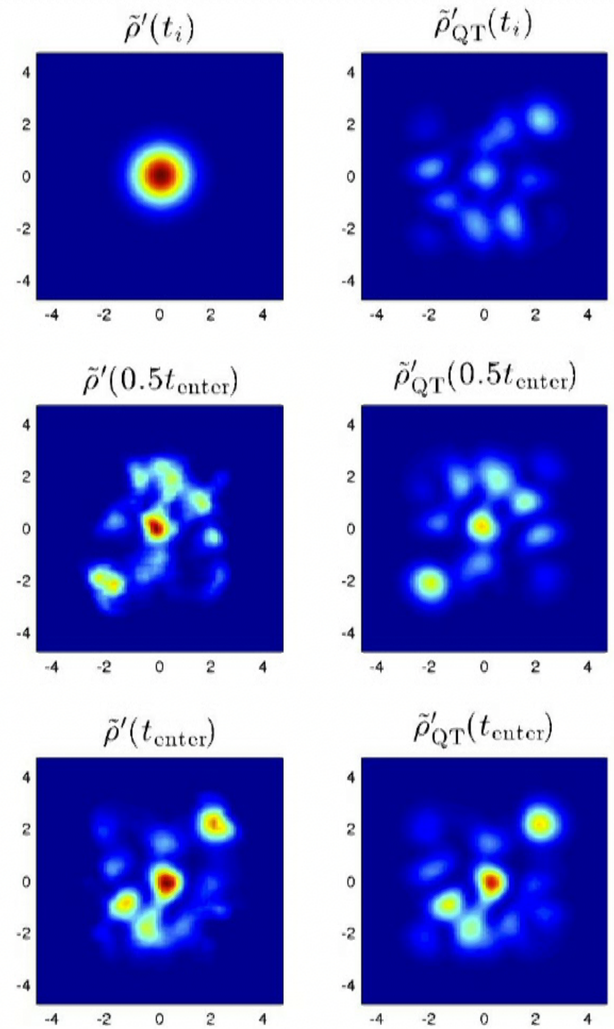
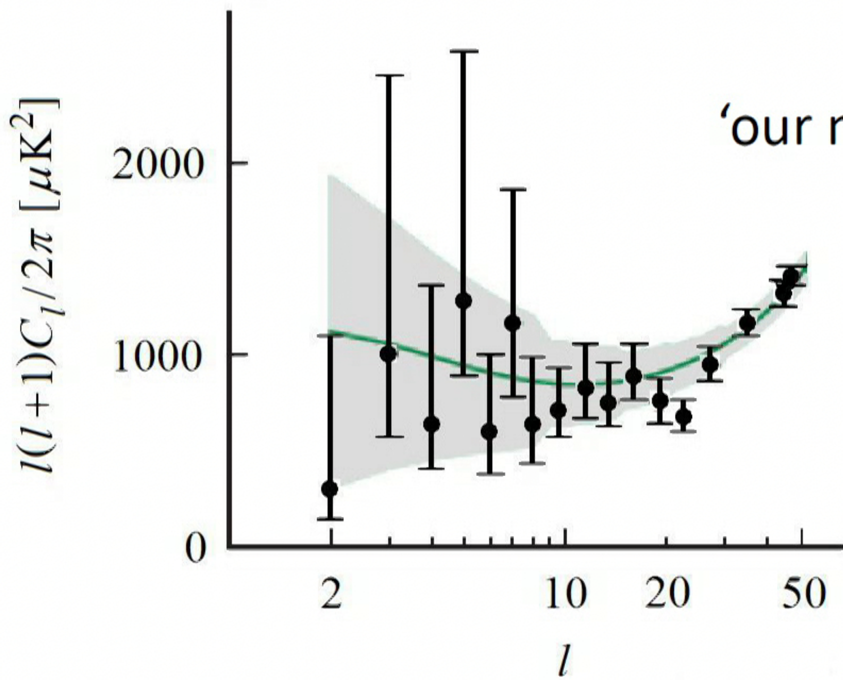


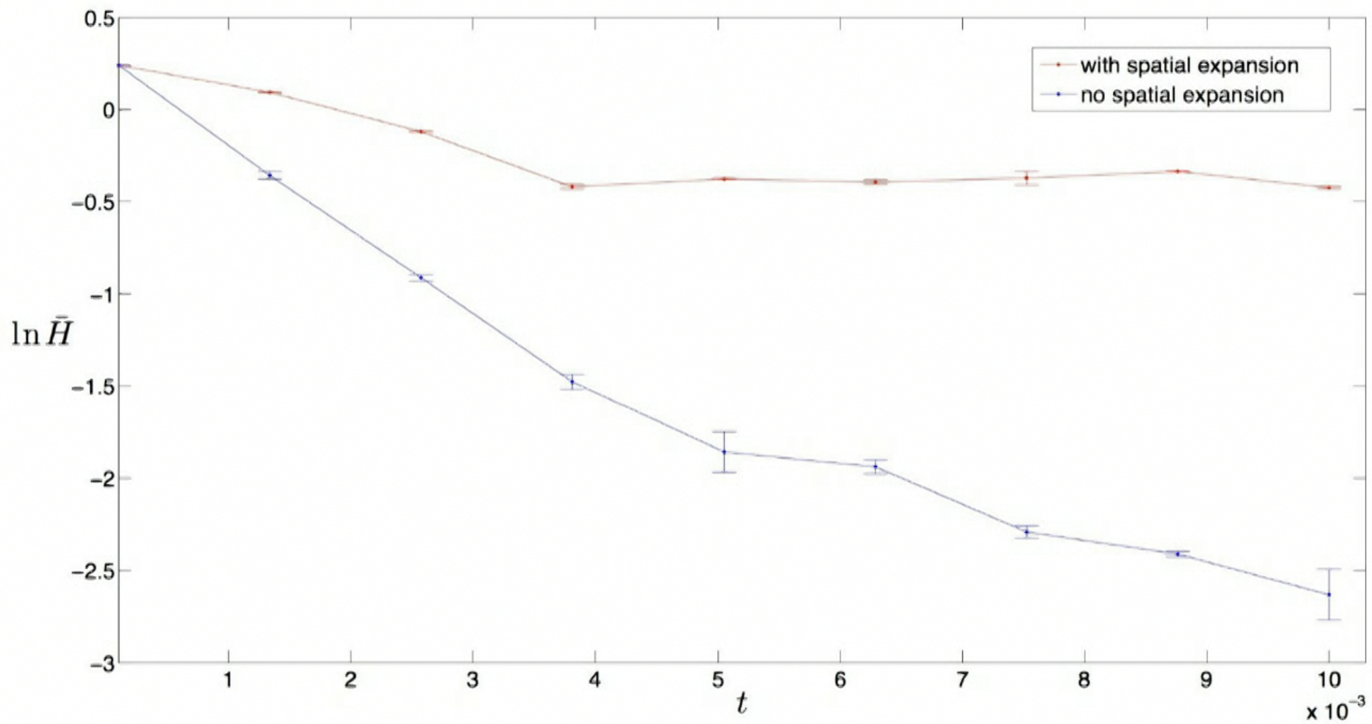
no expanding space

Planck 2013 results. XV. CMB power spectra and likelihood

f a power deficit of 5–10% at $\ell \lesssim 40$, with a statistical significance of 2.5–3 σ.



‘our most puzzling finding’



Suppression of quantum noise at large scales on expanding space

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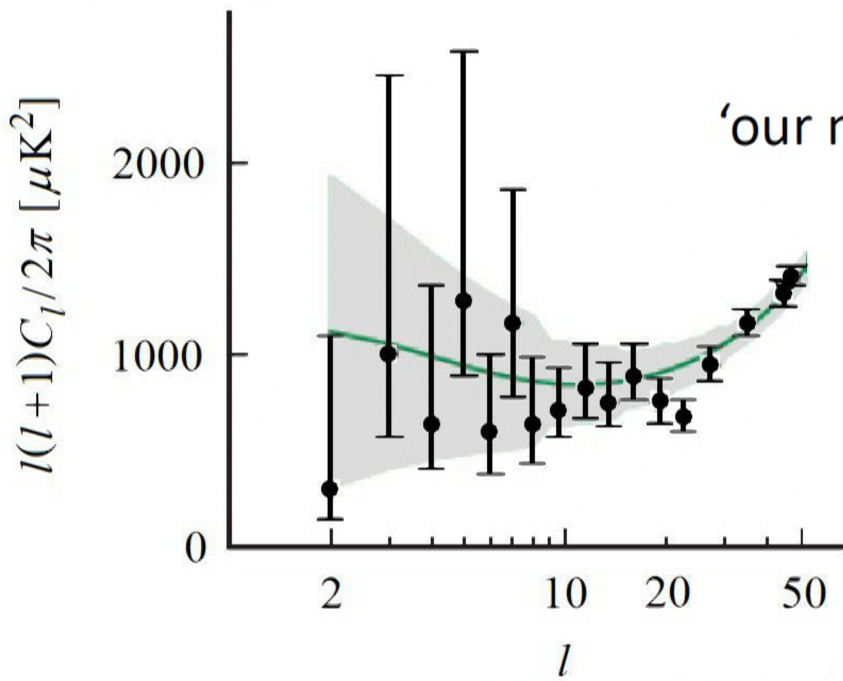


'our most puzzling finding'

Write

$$\langle |\phi_{\mathbf{k}}|^2 \rangle = \langle |\phi_{\mathbf{k}}|^2 \rangle_{\mathrm{QT}} \, \xi(k)$$

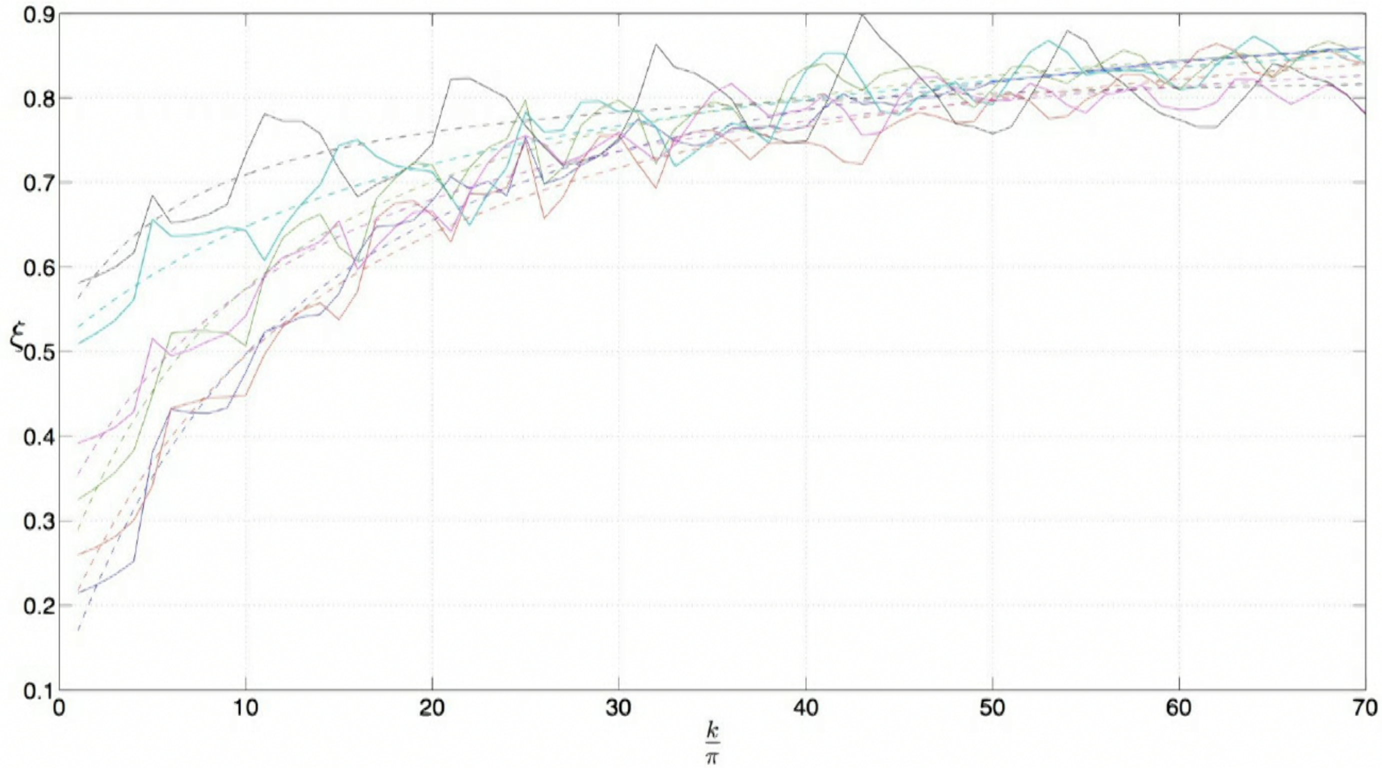
The function $\xi(k)$ measures the *power deficit* at the end of pre-inflation ("squeezed" Born rule)

Expect $\xi(k)$ to be smaller (< 1) for smaller *k* (longer wavelengths, less relaxation).

Expect $\xi(k)$ to approach 1 for large *k* (shorter wavelengths, more relaxation)

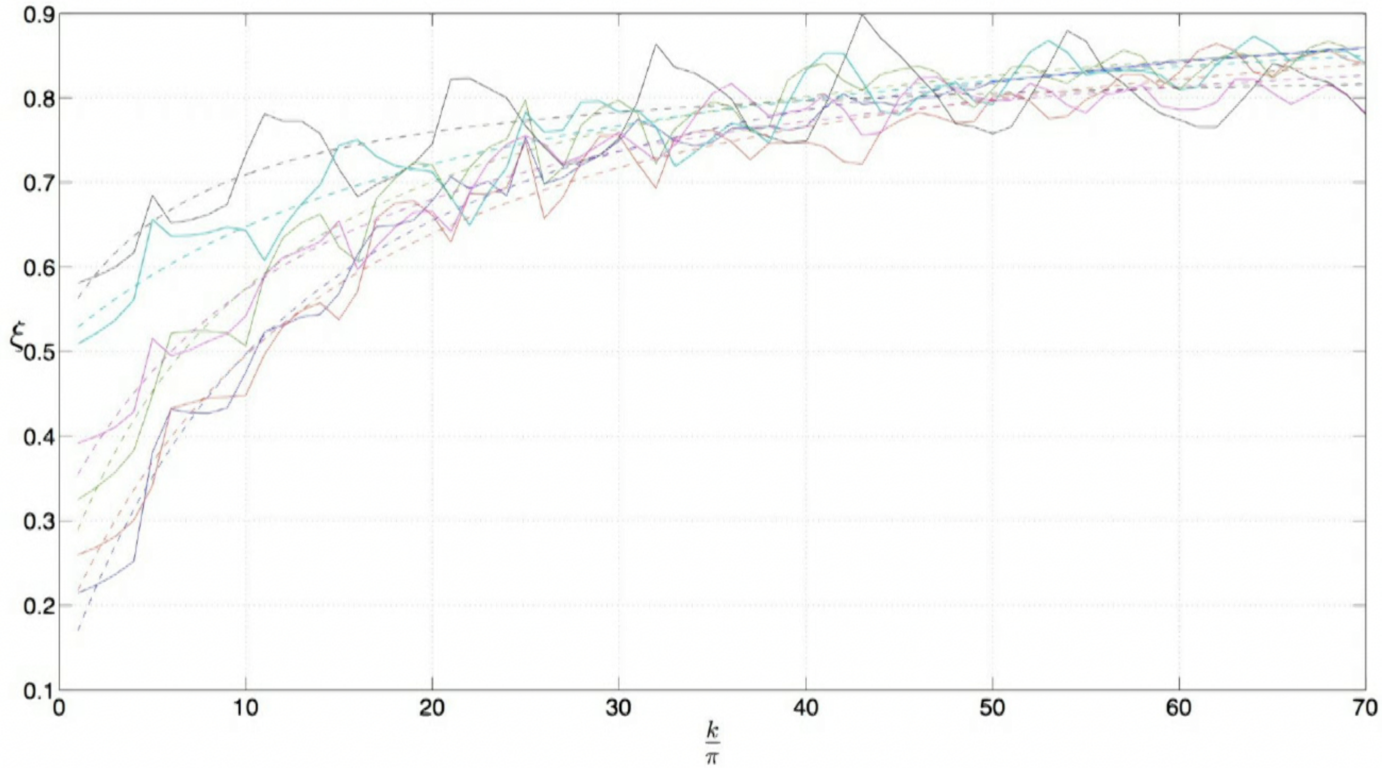
Repeat the above simulation for varying *k* , plot the results as a function of *k*
(Colin and Valentini, Phys. Rev. D 2015)

Results for M = 4, 6, 9, 12, 16, 25 modes (fixed time interval)



Signatures of early quantum relaxation

Results for M = 4, 6, 9, 12, 16, 25 modes (fixed time interval)



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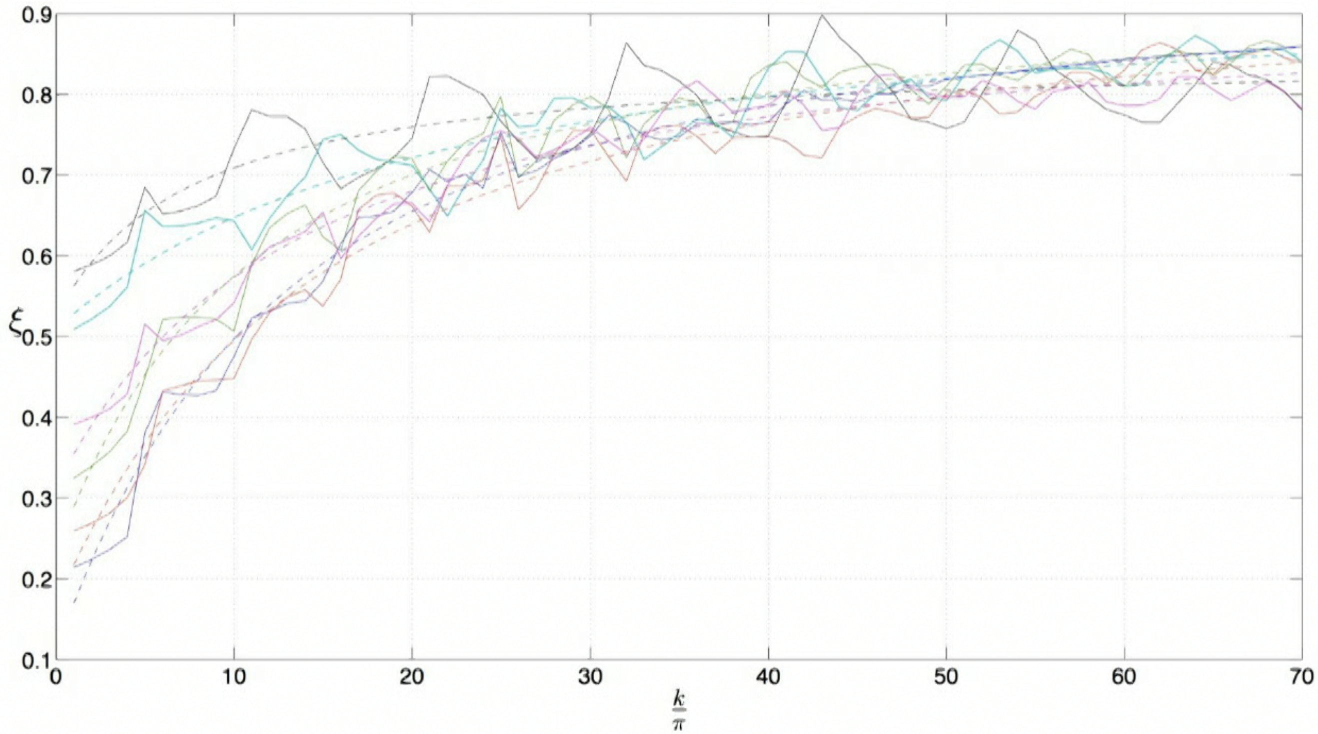


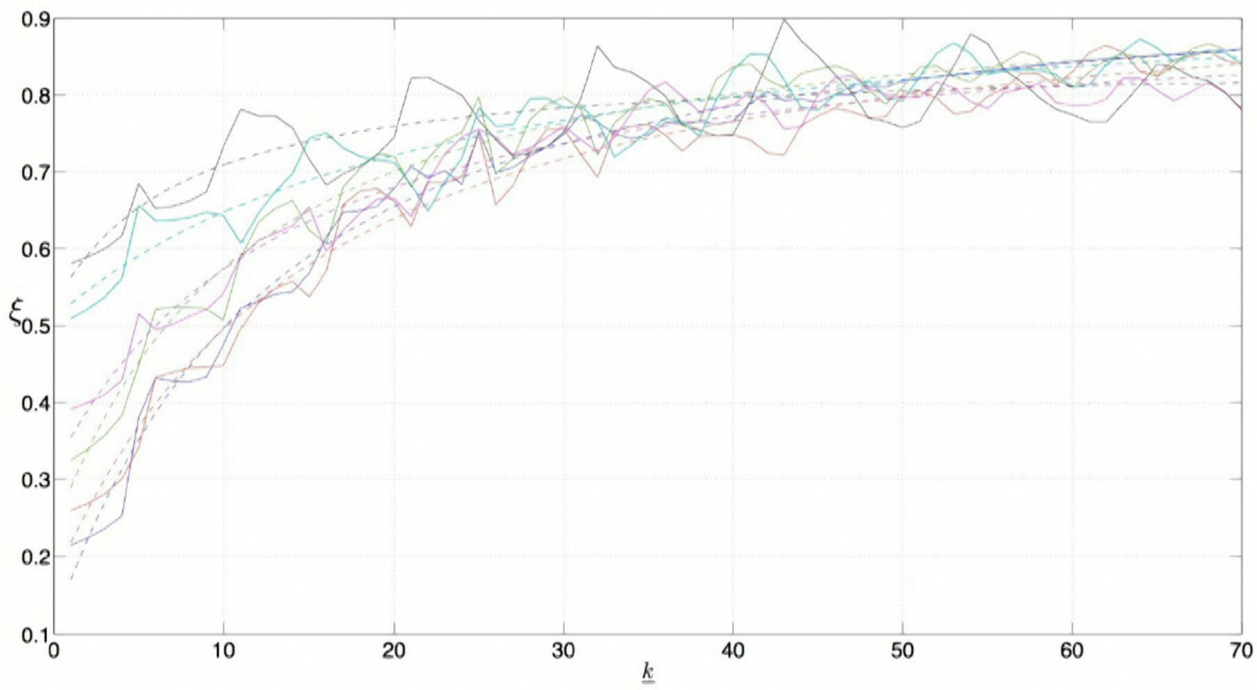
$$\xi(k) = \tan^{-1}(c_1(k/\pi) + c_2) - (\pi/2) + c_3$$

c_1, c_2 and c_3 are free parameters

First approximation: ignore oscillations in $\xi(k)$

We have derived a "squeezed Born rule" for a spectator scalar field at the end of a pre-inflationary era.

Assume a similar correction to the Born rule in the Bunch-Davies vacuum (pending model of transition), with the Born rule "squeezed" by the same factor $\xi(k)$.



Predicted *shape* for the CMB power deficit

$$\mathcal{R}_{\mathbf{k}} = -\left[\frac{H}{\dot{\phi}_0}\phi_{\mathbf{k}}\right]_{t=t_*(k)}$$ (ϕ is now the inflaton perturbation)

$$\left\langle |\phi_{\mathbf{k}}|^2 \right\rangle = \left\langle |\phi_{\mathbf{k}}|^2 \right\rangle_{\mathrm{QT}} \xi(k)$$

$$\mathcal{P}_{\mathcal{R}}(k) = \mathcal{P}_{\mathcal{R}}^{\mathrm{QT}}(k)\xi(k)$$

$$\xi(k) = \tan^{-1}(c_1(k/\pi) + c_2) - (\pi/2) + c_3$$

(S. Colin and A. Valentini, Phys. Rev. D **92**, 043520 (2015))

NOTE

Cannot predict lengthscale at which power deficit

$$\xi(k) = \tan^{-1}(c_1(k/\pi) + c_2) - (\pi/2) + c_3$$

will set in, since measured c_1 will be rescaled by inflationary expansion (depends on unknown number of e-folds)

Can predict the "shape" but not the "location"

Three-parameter model of the power deficit

$$\mathcal{P}_{\mathcal{R}}(k) = \mathcal{P}_{\mathcal{R}}^{\mathrm{QT}}(k)\xi(k)$$

$$\xi(k) = \tan^{-1}(c_1(k/\pi) + c_2) - (\pi/2) + c_3$$

(really 2 parameters: c_1, c_2, c_3 depend on the *number M of modes* and on the *time interval* in pre-inflation)

Data analysis (with S. Vitenti and P. Peter):
-- use NumCosmo to explore the best fit
-- results are mixed, no simple conclusion

GENERAL METHOD

Calculate

Prob(Data, given Model)

for varying values of the parameters c_1, c_2, c_3

This is the "likelihood" of the model:

L(Model, given Data)

(as a function of c_1, c_2, c_3)

Repeat for our model and for other models (e.g. exponential cutoff instead of inverse-tangent)

A better model has a higher probability of generating the data we see

(Use Likelihood Ratio Statistic to compare models)

Results from fitting to cosmological data (CMB + other)

-- results for temperature data only: similar to Planck analysis (above 2σ) for both models of deficit

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-- BUT: significance disappears when add CMB polarization data

Perhaps the low power is not really there?
(deficit in temperature spectrum is a statistical fluke)

Nonequilibrium tensor modes?

-- tensor perturbations can contribute significantly to the polarization spectrum (neglected in our fits, set $r \approx 0$)

-- different degrees of freedom are expected to have different nonequilibrium distributions (AV, PRD 2010)

-- $\xi(k) = \tan^{-1}(c_1(k/\pi) + c_2) - (\pi/2) + c_3$ for scalar part

$\xi'(k) = \tan^{-1}(c'_1(k/\pi) + c'_2) - (\pi/2) + c'_3$ for tensor part

-- explains degradation of fit when add polarization data?

-- possibly: need to rerun all fits with $\xi(k)$ *and* $\xi'(k)$ (6 parameters, anything could happen…)

FURTHER WORK (brief)

Unlikely we can draw convincing conclusions by modeling the large-scale power deficit alone

Need to consider more detailed predictions:

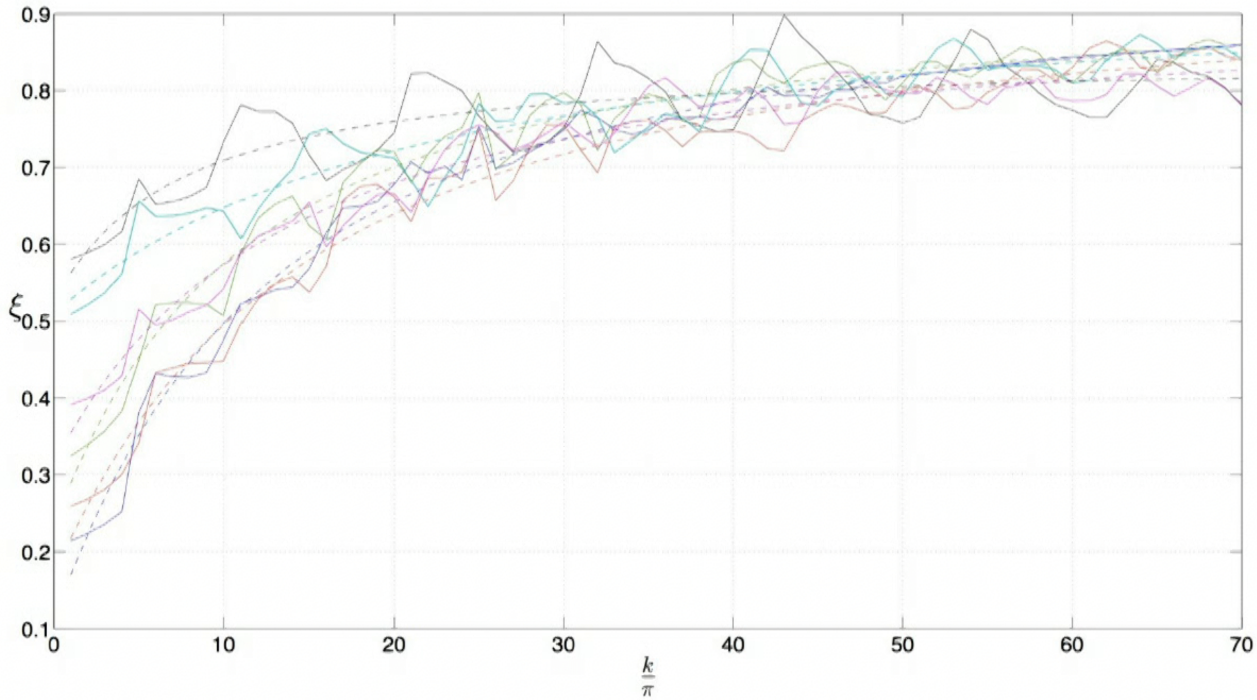
-- oscillations

-- statistical anisotropy

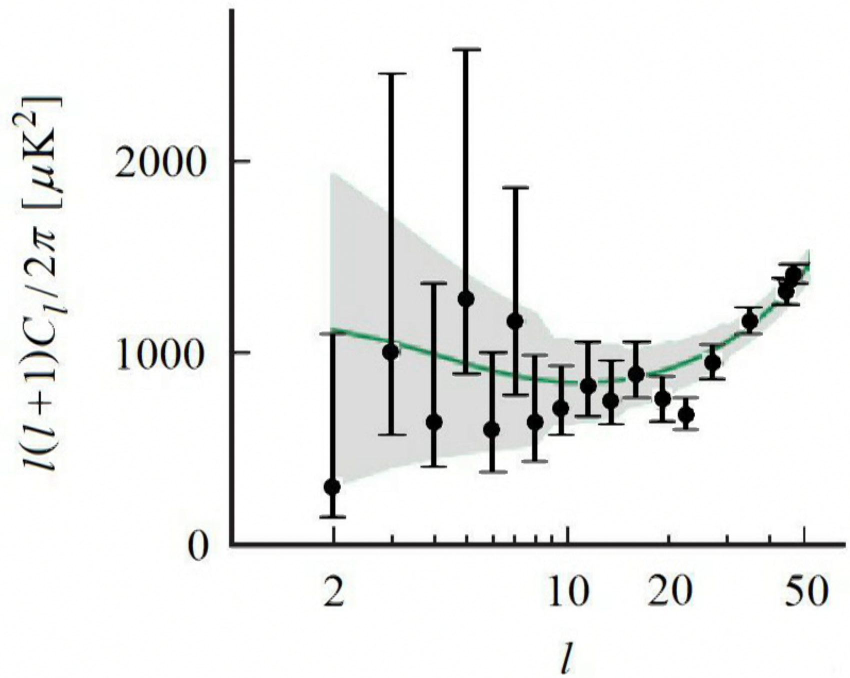
Made progress with predictions but no data fitting yet...

OSCILLATIONS

Quantum relaxation predicts large-scale oscillations in $\xi(k)$



Does the CMB data contain large-scale oscillations?



(work in progress with A. Kandhadai)

STATISTICAL ANISOTROPY

Statistical isotropy ⟹ $\langle a^*_{l'm'} a_{lm} \rangle = \delta_{ll'}\,\delta_{mm'}\,C_l$

Planck data: evidence for correlations at low *l*

$\langle a^*_{l'm'} a_{lm} \rangle \neq 0$ for $l', m' \neq l, m$

Breaking the Born rule in the Bunch-Davies vacuum will generically break statistical isotropy:

-- “squeezing” factor ξ can depend on **k**

-- have studied a model where the parameters c_1, c_2, c_3 depend weakly on **k** (Valentini 2015)

-- predictions for scaling of *l*-(*l*+1) correlations with *l* (among other)

Planck 2013 results. XXIII. Isotropy and statistics of the CMB

pected. However, it should be clear that the evidence for some of the large-angular scale anomalies is significant indeed, yet few physically compelling models have been proposed to account for them, and none so far that provide a common origin. The dipole

We have proposed a mechanism for a common origin

Quantum relaxation naturally predicts both low power and statistical anisotropy at large scales

Data analysis so far:

- consistent with the data (as well as standard model)
- no clear positive or negative evidence (yet)