Quantum-to-classical transition of the primordial perturbations

Andreas Albrecht (QMAP/UC Davis)

At

ICTS Physics of the Early Universe Online Precursor

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My Big Picture Agenda:

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We've been "doing physics for many thousands of years" and only discovered quantum 100 years ago

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My goal is to equip you for your own path of discovery

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Cosmic inflation is both OVER and UNDER rated as a solution to these problems

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"Many worlds" or "Everett"

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I) Some key elements of quantum physics

- Quantum coherence
- Quantum entanglement
- Quantum Darwinism
- Wavefunction as a classically evolving distribution

II) The actual Universe

- Discuss the roles of the above phenomena

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I) Some key elements of quantum physics

Quantum coherence

- The state of quantum system is described by a "wavefunction" which assigned a quantum amplitude to each element of a basis which spans the full Hilbert space:

$$|\psi\rangle = \sum_i \alpha_i |i\rangle$$

- If $|\psi_1\rangle$ and $|\psi_2\rangle$ are possible states of the system, then so is

$$|\psi\rangle = a_1|\psi_1\rangle + a_2|\psi_2\rangle$$

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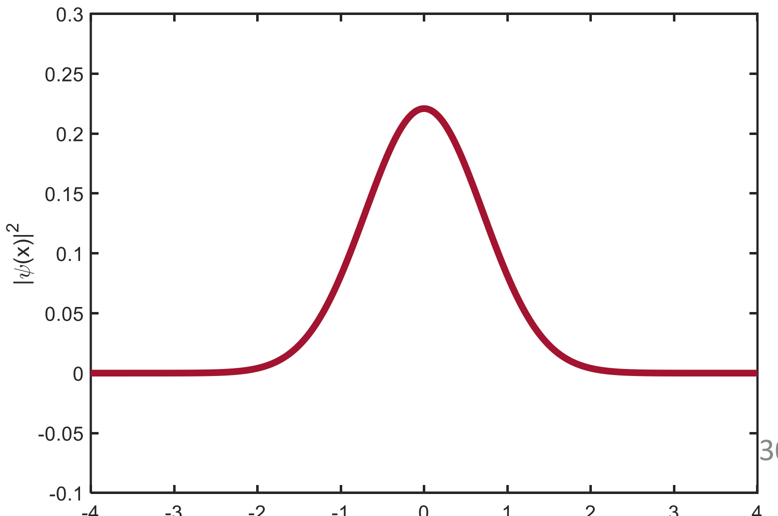
Quantum coherence

- The "coherence" of a quantum state only means something in relation to what measurement you are going to make.
- If $\psi(x)$ corresponds to classical wavepacket, and you only ever expect to measure the particle in a wavepacket basis, then the particle simply moves from here to there, and there is no particular meaning to "quantum coherence".
- Even though the expression $\psi(x)$ technically gives the amplitudes representing the wavepacket as a *coherent superposition* of eigenstates of $\hat{X}$



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The "relativity of quantum coherence"

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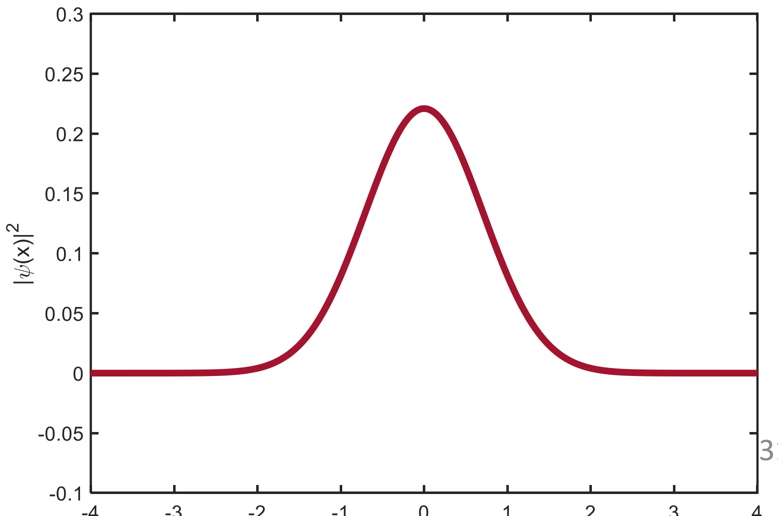

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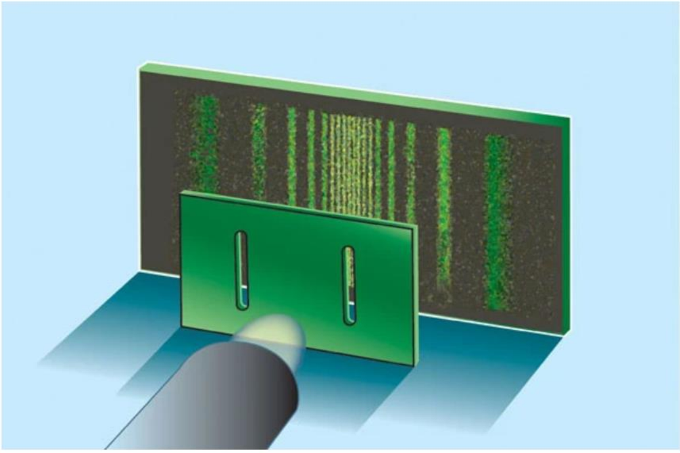
- The double slit experiment is a striking example of quantum coherence because there is a large discrepancy between the diffracted quantum state of the particle and the localized basis in which the screen makes the measurement.



https://www.nature.com/articles/35089156/figures/1

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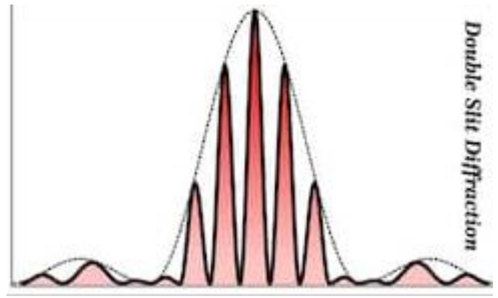
- The double slit experiment is a striking example of quantum coherence because there is a large discrepancy between the diffracted quantum state of the particle and the localized basis in which the screen makes the measurement.

- If instead of a screen making localized measurements, you had an apparatus that could measure the particle in a "double slit state", the narrative would be much more mundane, and the concept of "quantum coherence" would not be needed.



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A very quantum phenomenon (can know "everything about the whole, but nothing about the parts")

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As with the topic of coherence, the degree things "look quantum" depends on the questions you ask

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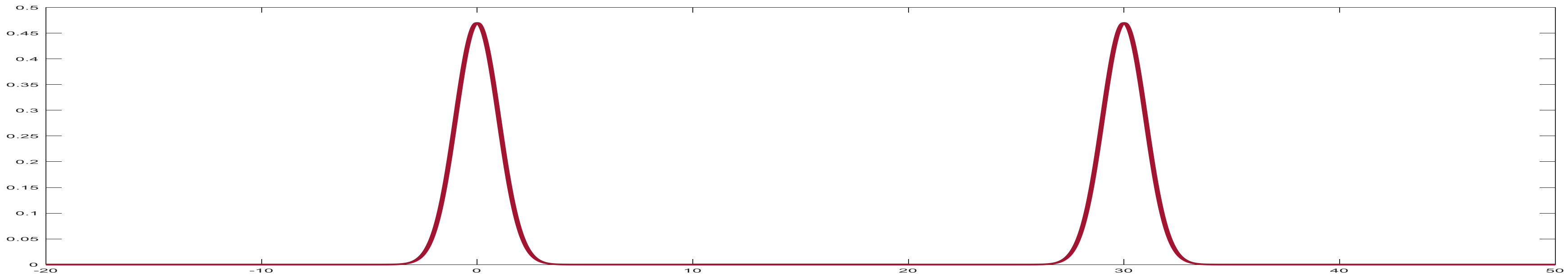
Interactions can create entanglement $\quad |\psi\rangle_{tot} = |\psi\rangle_b |\psi\rangle_\gamma$

Pure state before collision

$|\psi\rangle_\gamma =$

$|\psi\rangle_b =$



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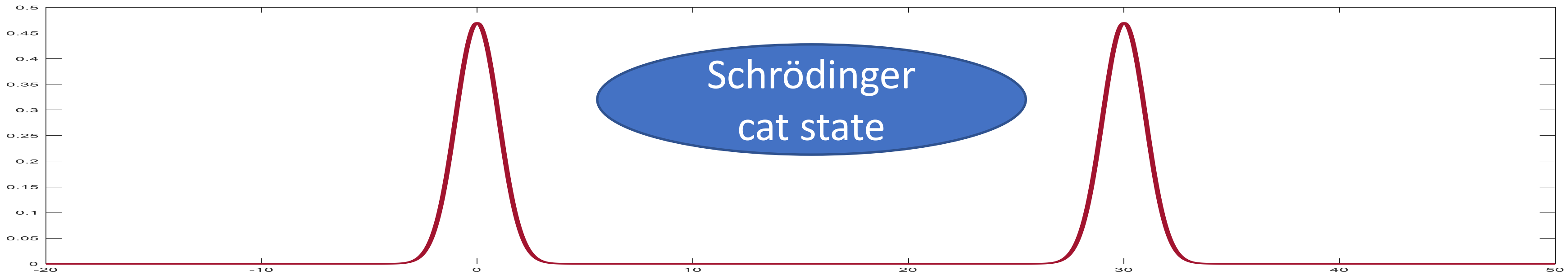

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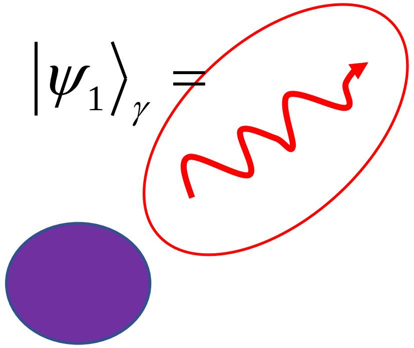

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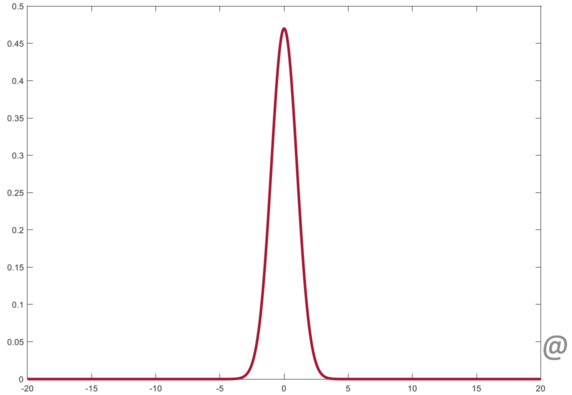

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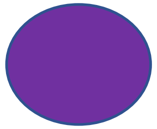

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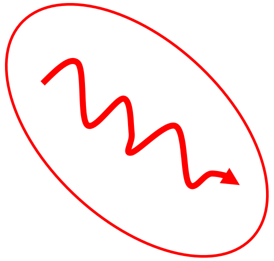

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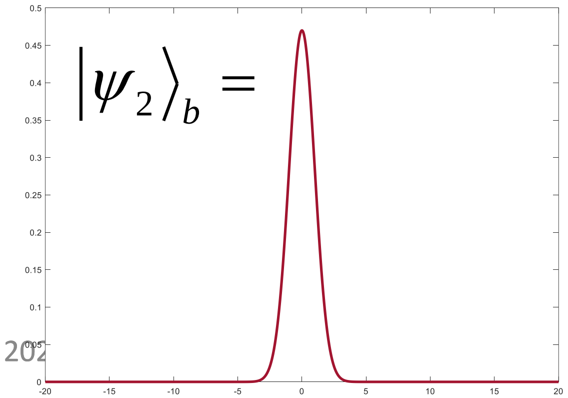

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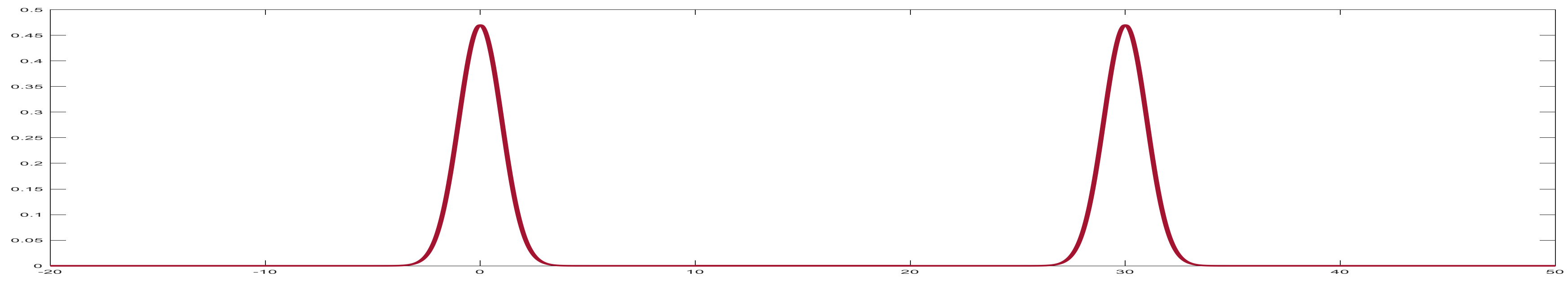

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Entangled state after collision

In the example of the photon striking the ball, the Schrödinger cat initial state evolved into a <u>classical mixture of localized packets</u>, thanks to the *locality of the interactions and the locality of the photon state*

(need ${}_b\left\langle {}_i\psi \middle| \psi_j \right\rangle_b \approx \delta_{ij}$ which is natural for ball separation much greater than that photo coherence length)

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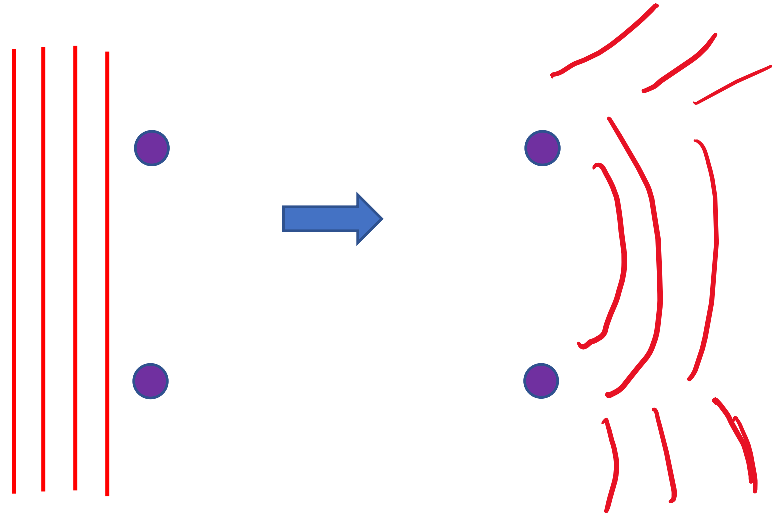

One could imagine probing the “Schrödinger cat” nature of the initial ball state with a coherent plane wave, suitably measure after the collision.

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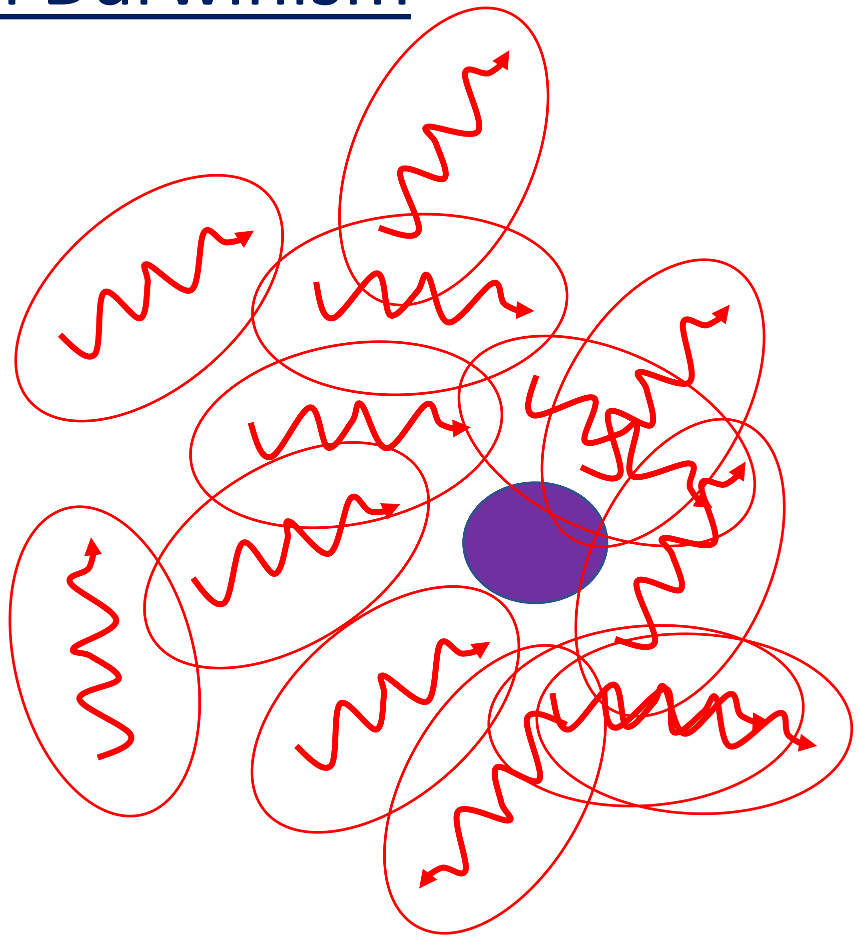

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Zurek 2009 https://arxiv.org/abs/0903.5082

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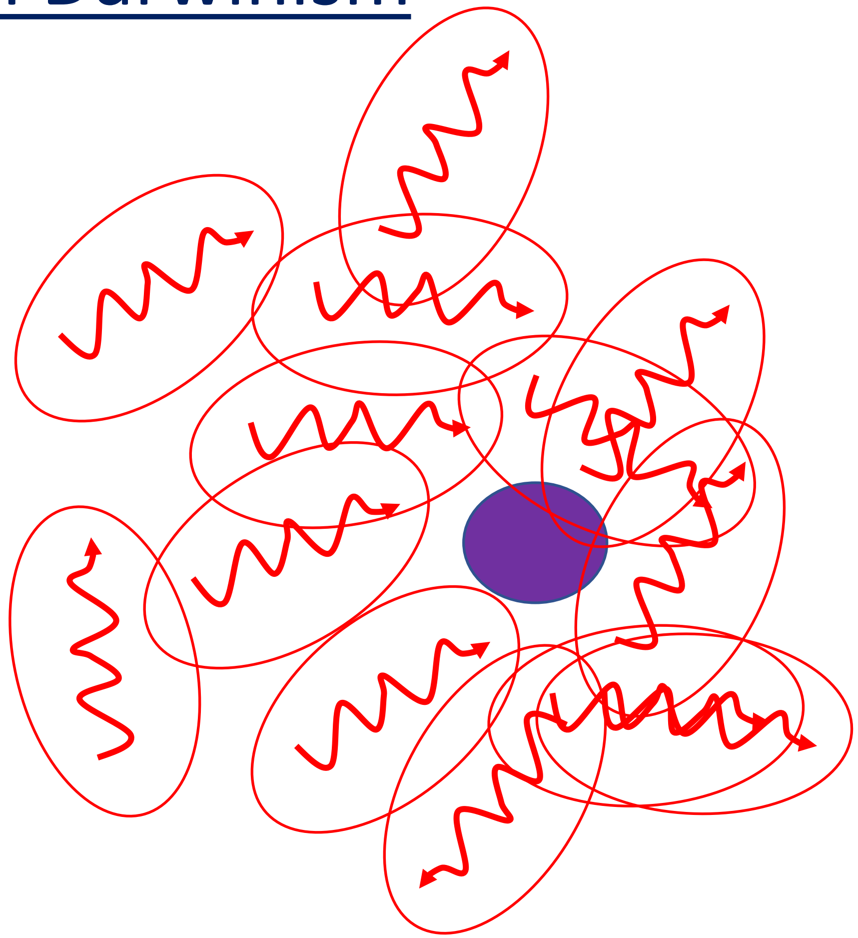

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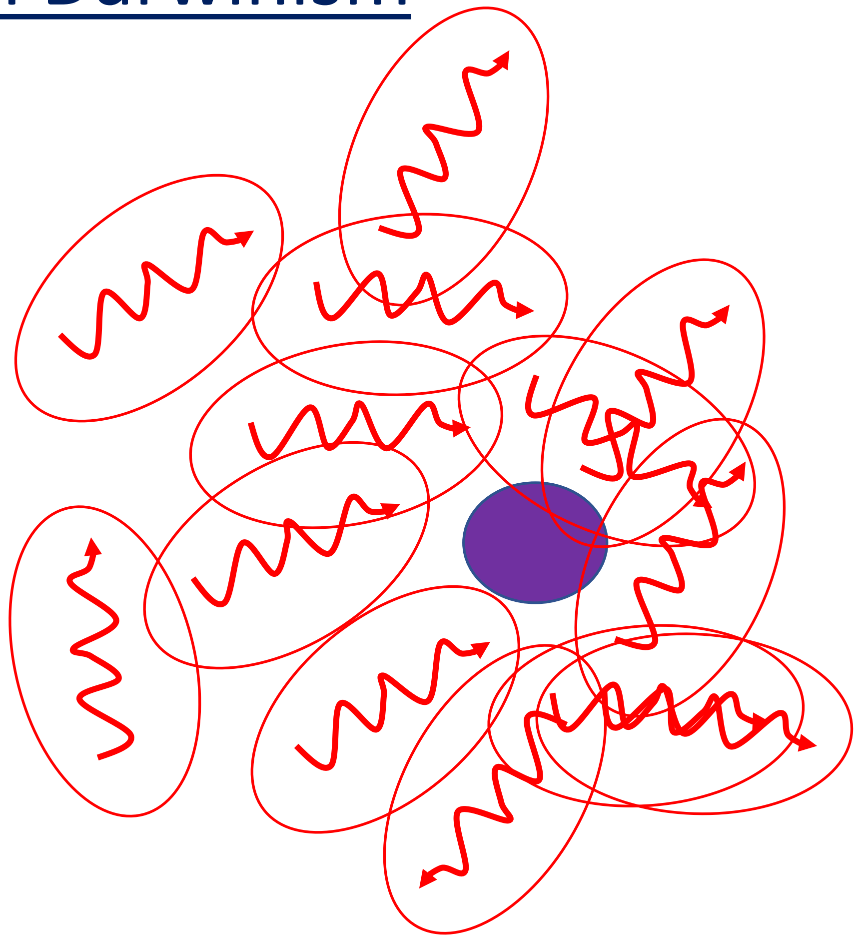

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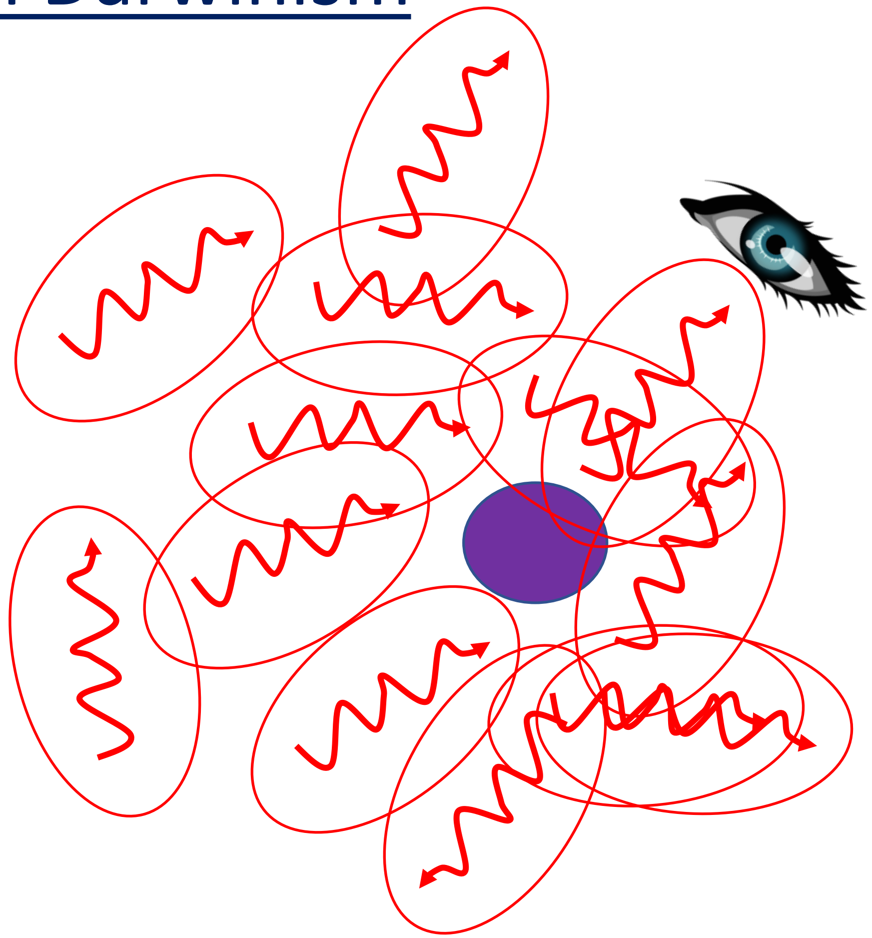

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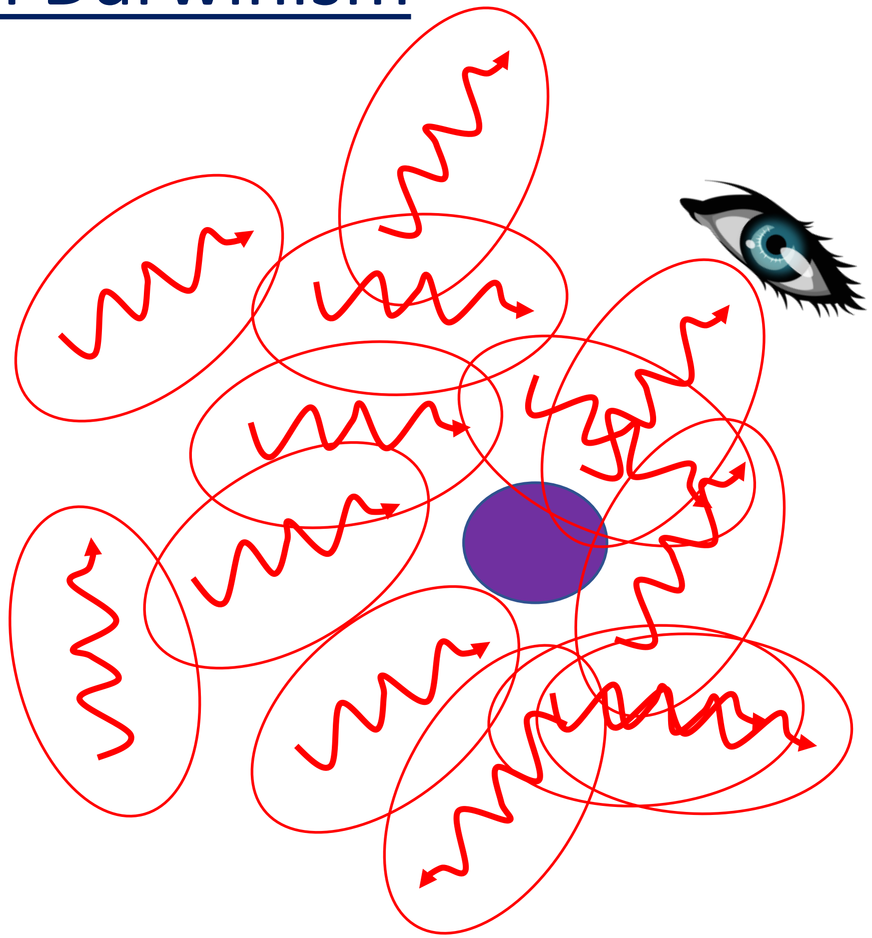

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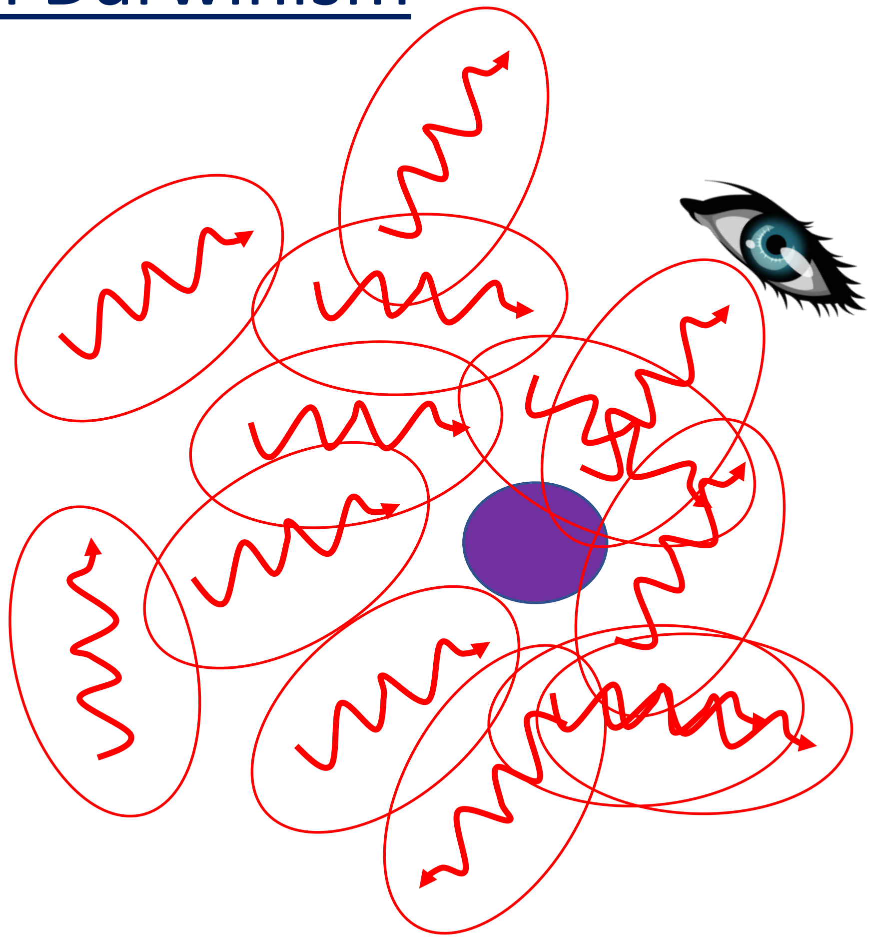

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Which states are "prepared"

In what basis you make measurements

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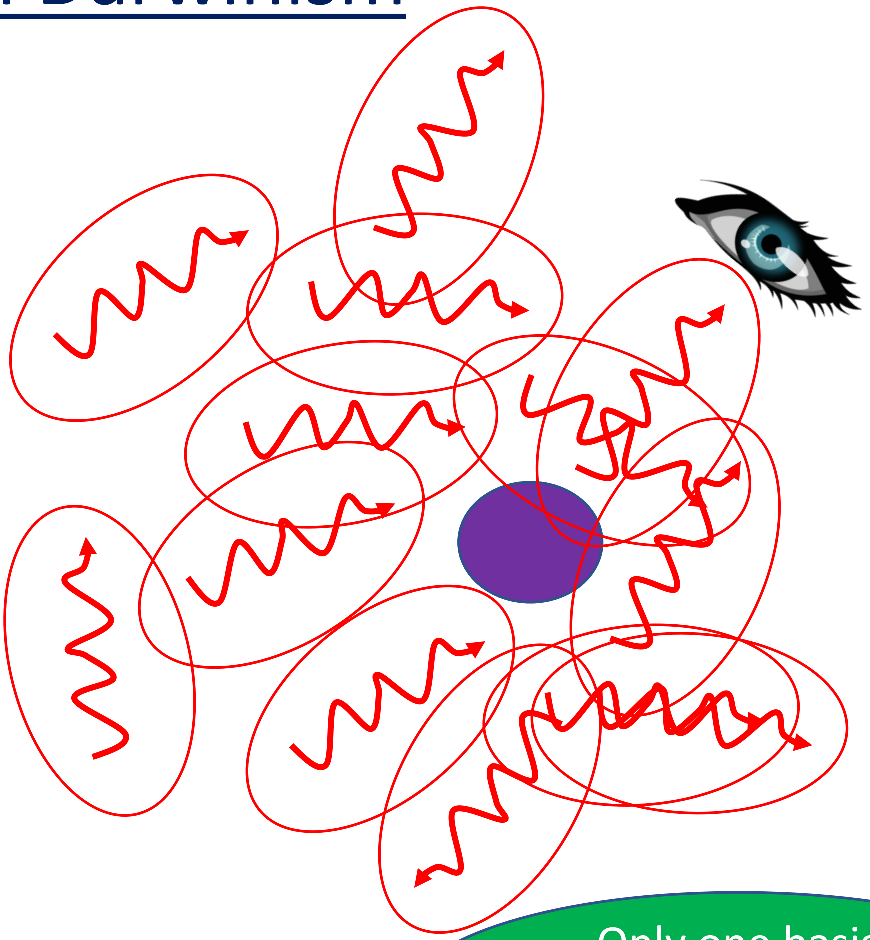

- The actual macroscopic world is awash in localized photon (and air) wavepackets
- If you try to introduce a Schrodinger cat state, the environment will “get there first” and decohere it into a classical mixture of wavepacket states
- In the real macroscopic world, this phenomenon is simply unavoidable (e.g. blackbody radiation from the walls of the lab)
- Furthermore, you “measure” the object simply by sampling a small part of the environment
- The “relativity of coherence” is not a meaningful feature of the macroscopic world. The environment makes all the choices for you.

Only one basis “survives” the action of the environment

Which states are “prepared”

In what basis you make measurements

Zurek 2009 https://arxiv.org/abs/0903.5082

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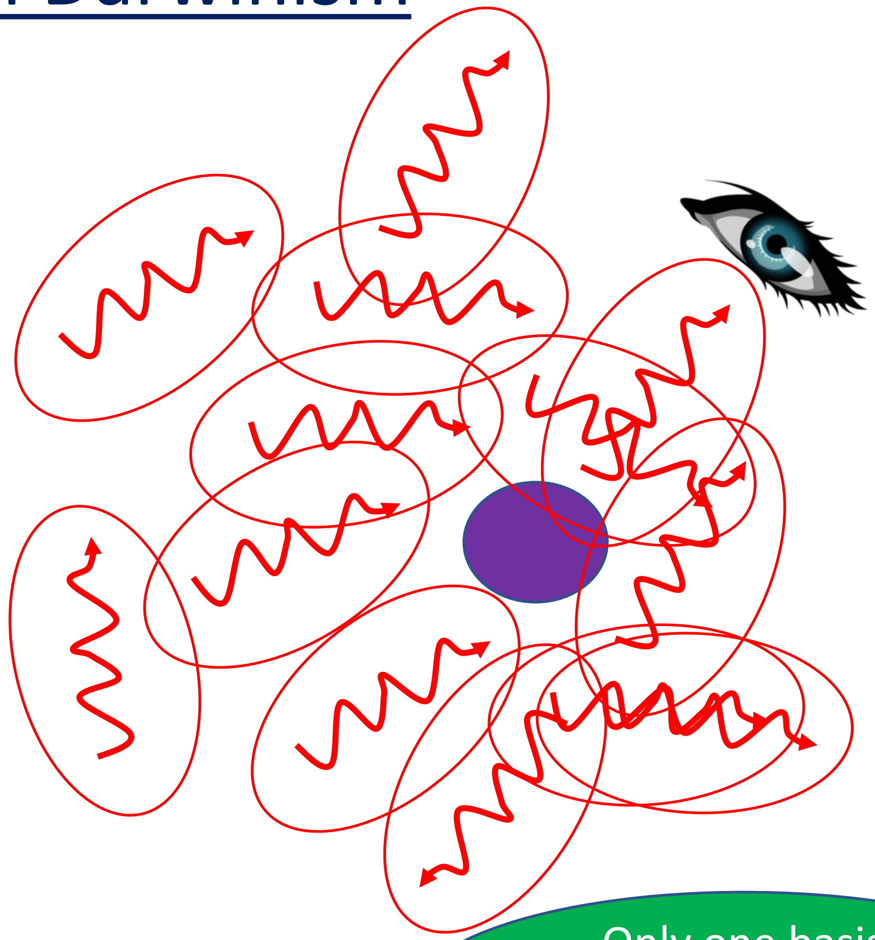

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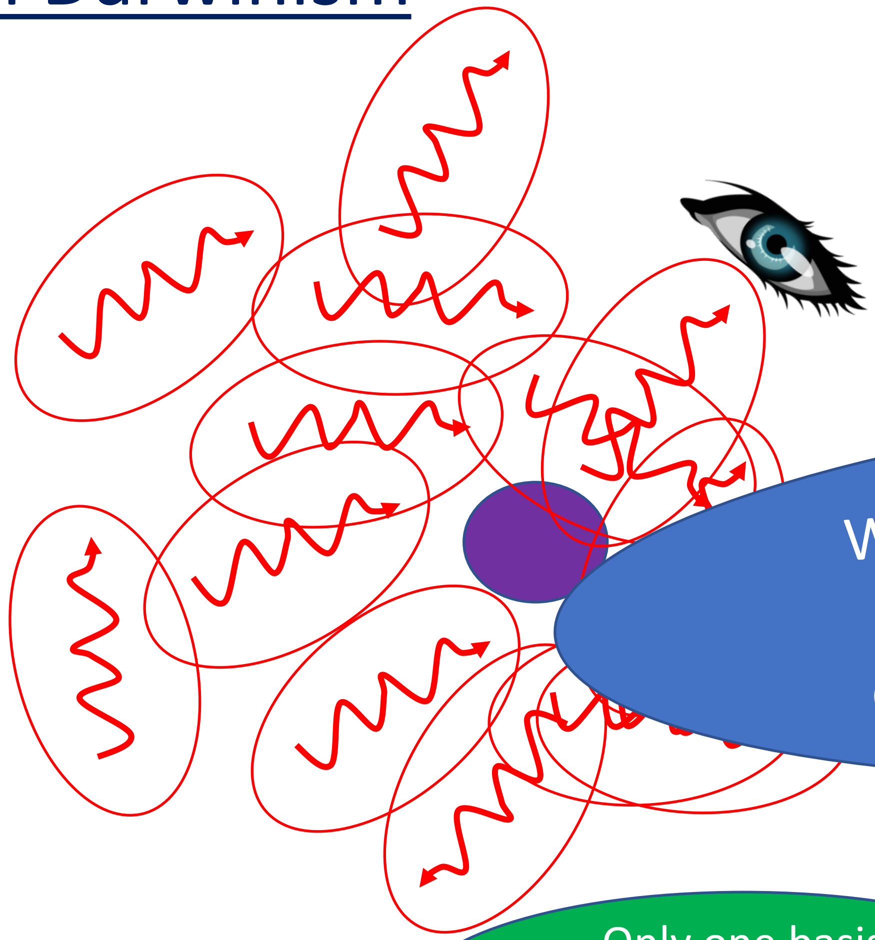

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We've been "doing physics for many thousands of years" and only discovered quantum 100 years ago

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I) Some key elements of quantum physics

- Quantum coherence
- Quantum entanglement
- Quantum Darwinism 🡐
- Wavefunction as a classically evolving distribution

II) The actual Universe

- Discuss the roles of the above phenomena

III) Some examples

IV) Conclusions

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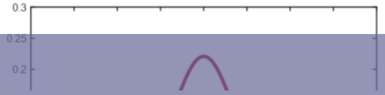

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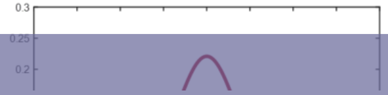

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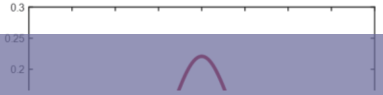

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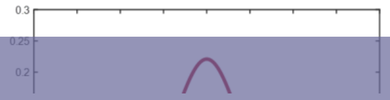

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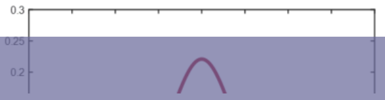

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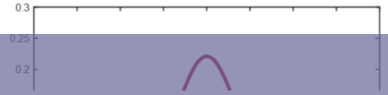

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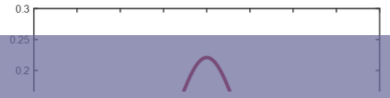

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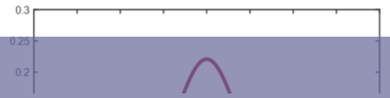

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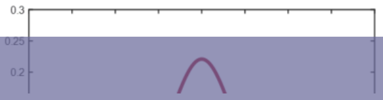

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This is where quantum Darwinism can play a role

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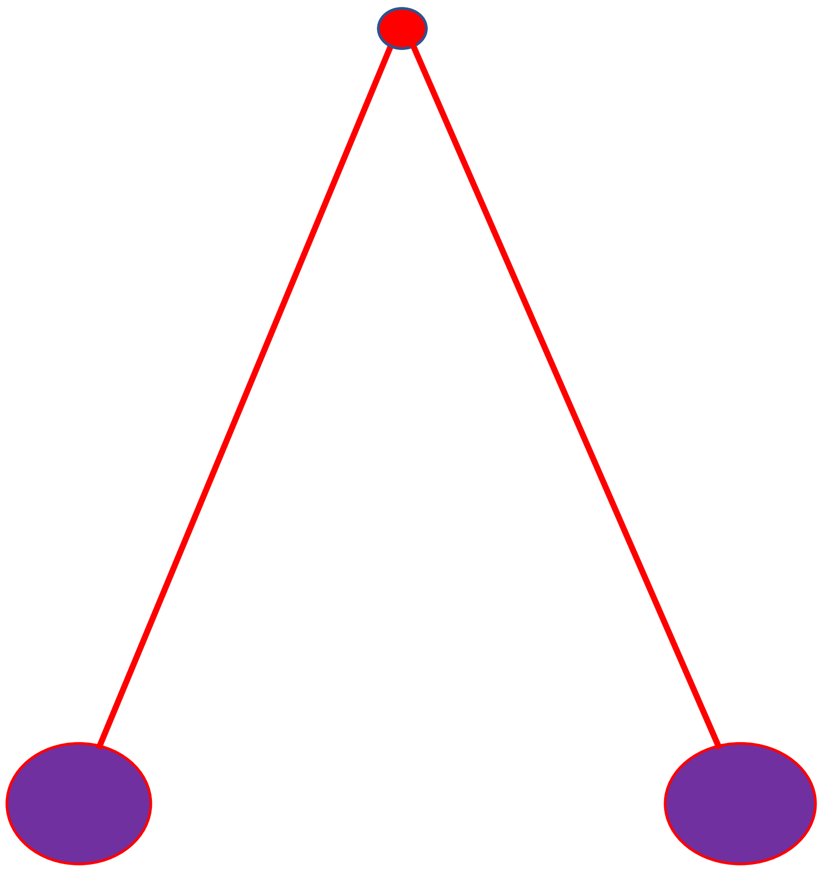

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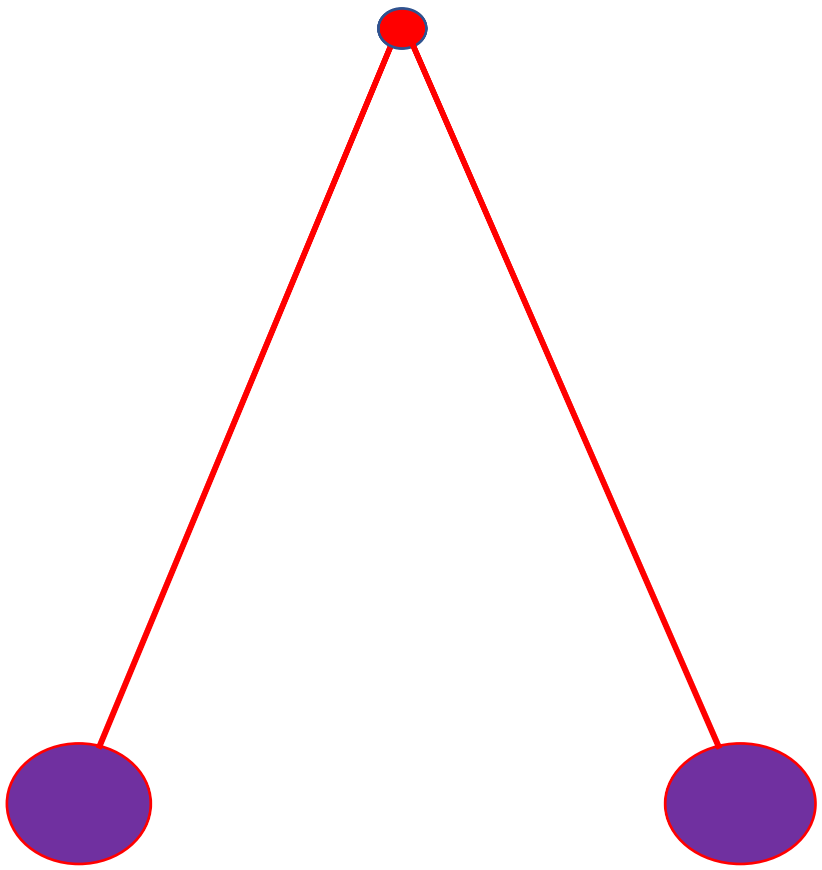

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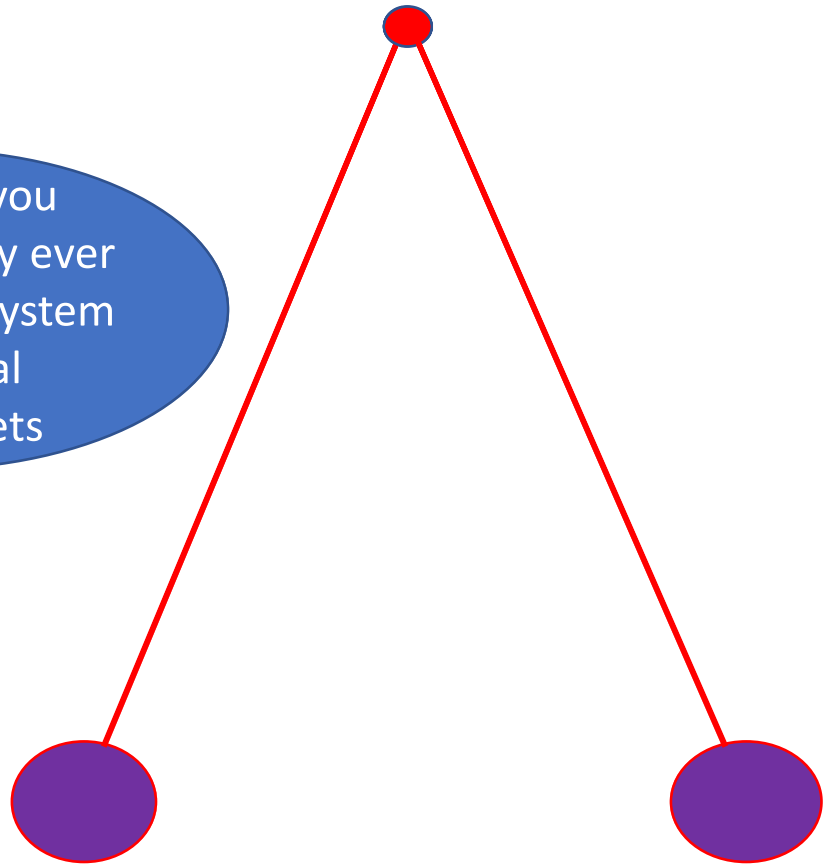

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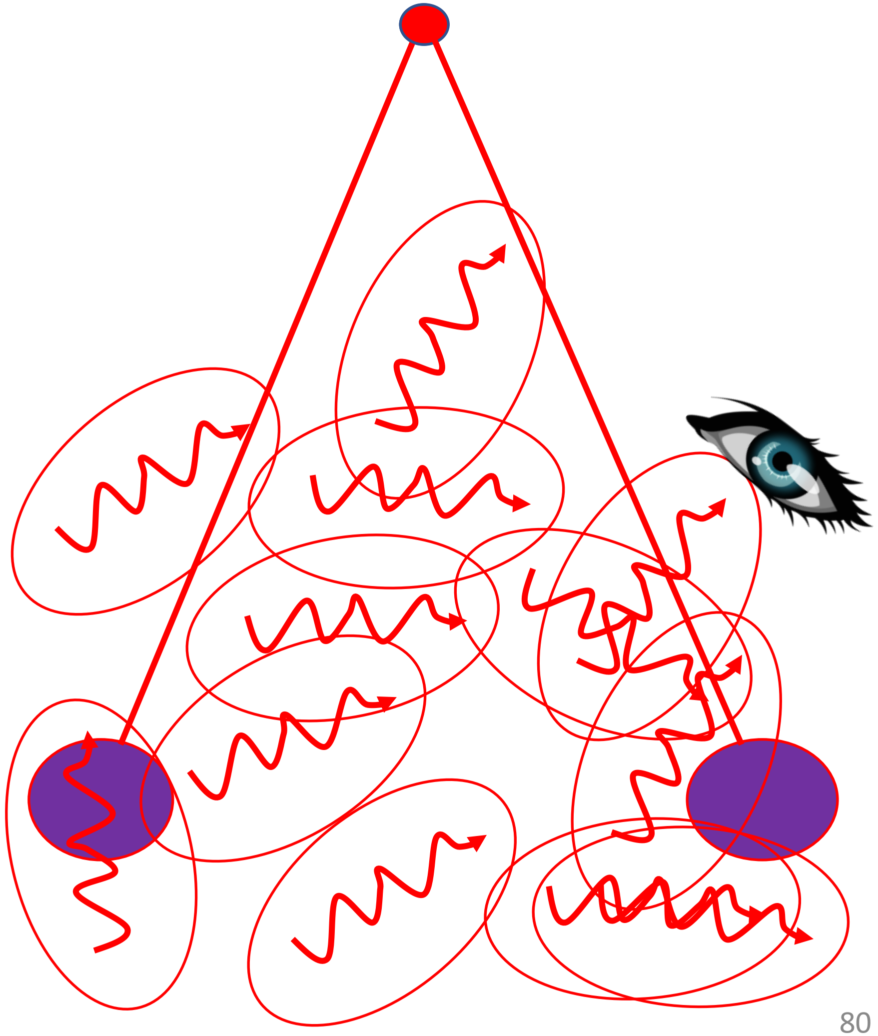

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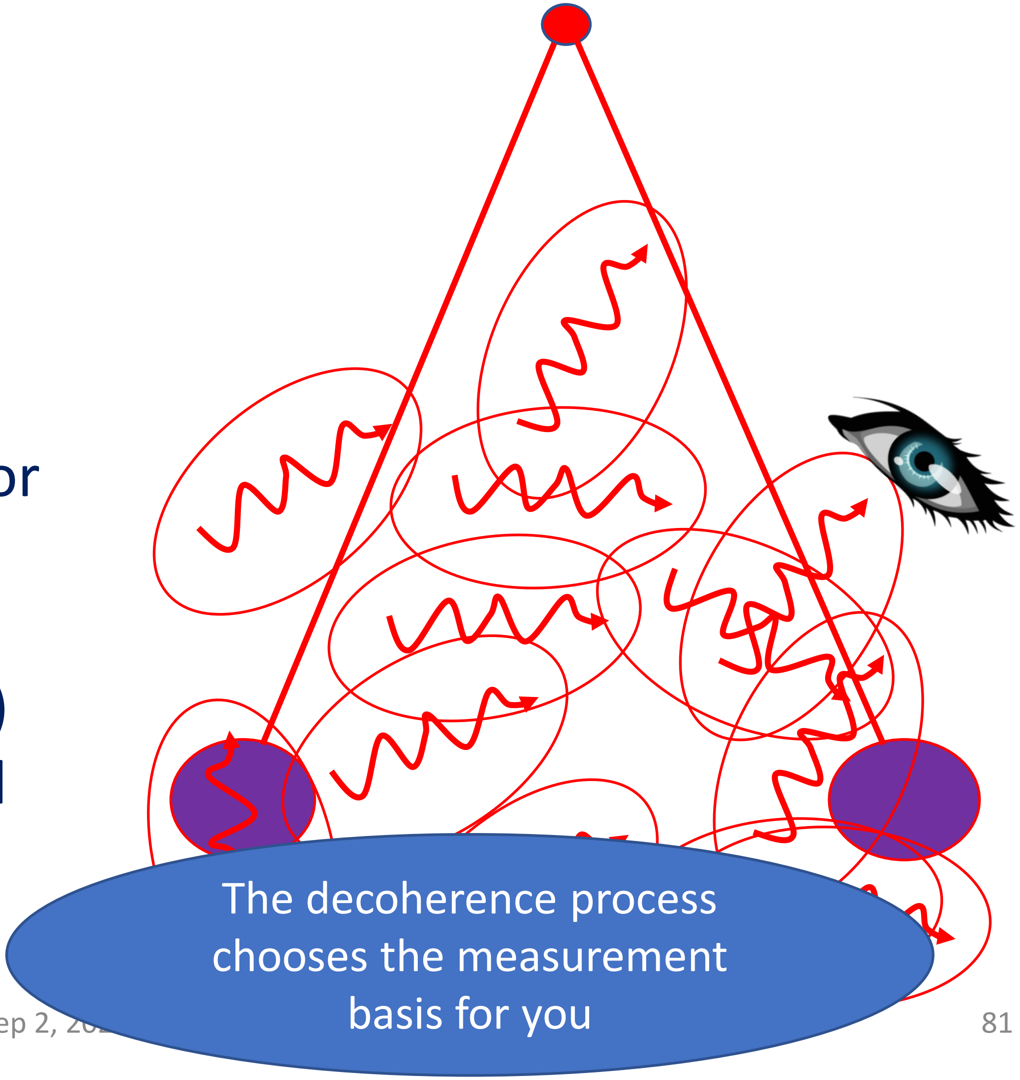

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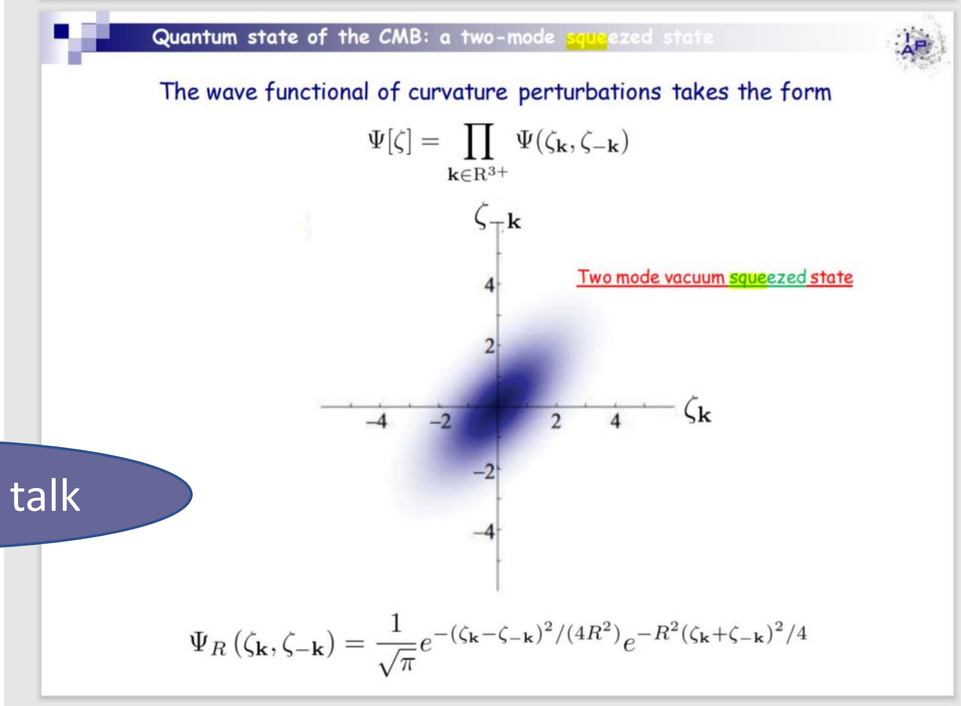

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Inflation and squeezed quantum states

ALBRECHT, FERREIRA, JOYCE, AND PROKOPEC 50

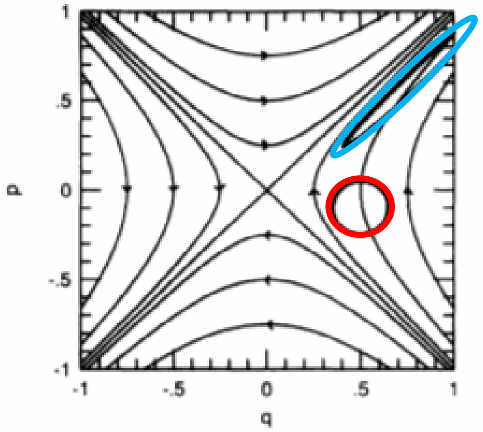

FIG. 1. Phase space trajectories for a classical upside-down harmonic oscillator. The presence of one growing and one decaying solution produces a "squeezing" effect even at the classical level. The circular region shown evolves with time into the squeezed shape above it.

https://arxiv.org/abs/astro-ph/9303001

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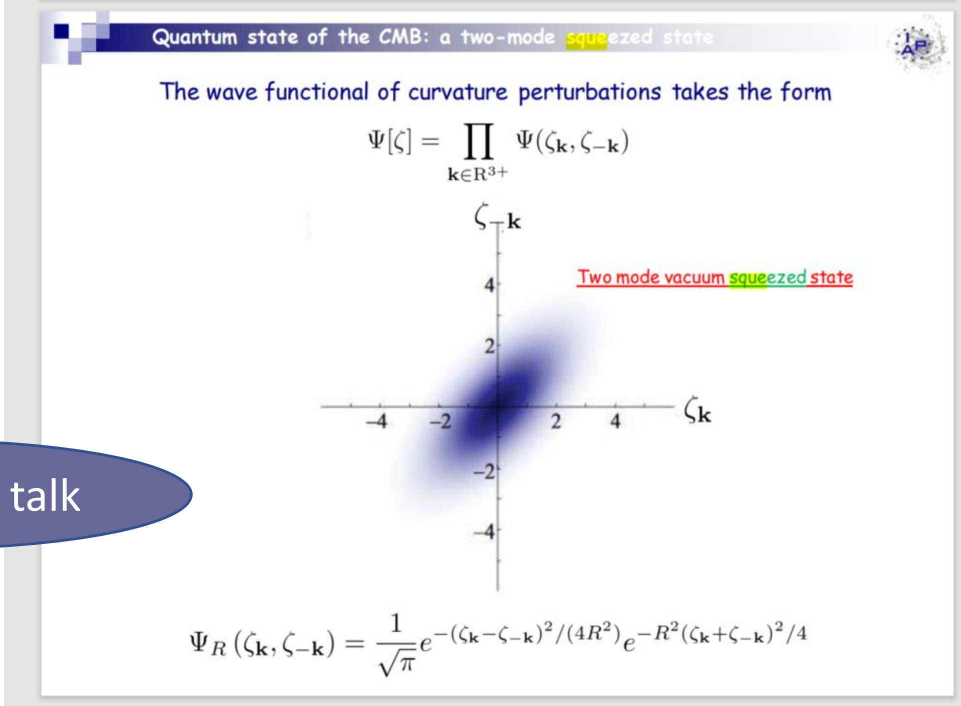

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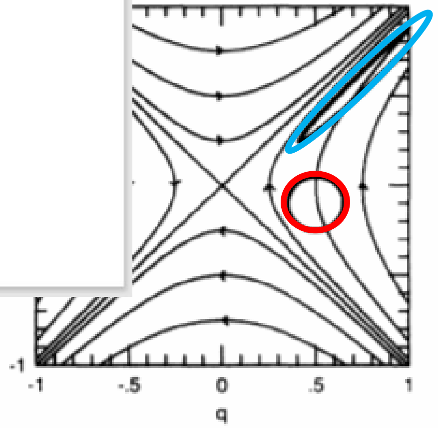

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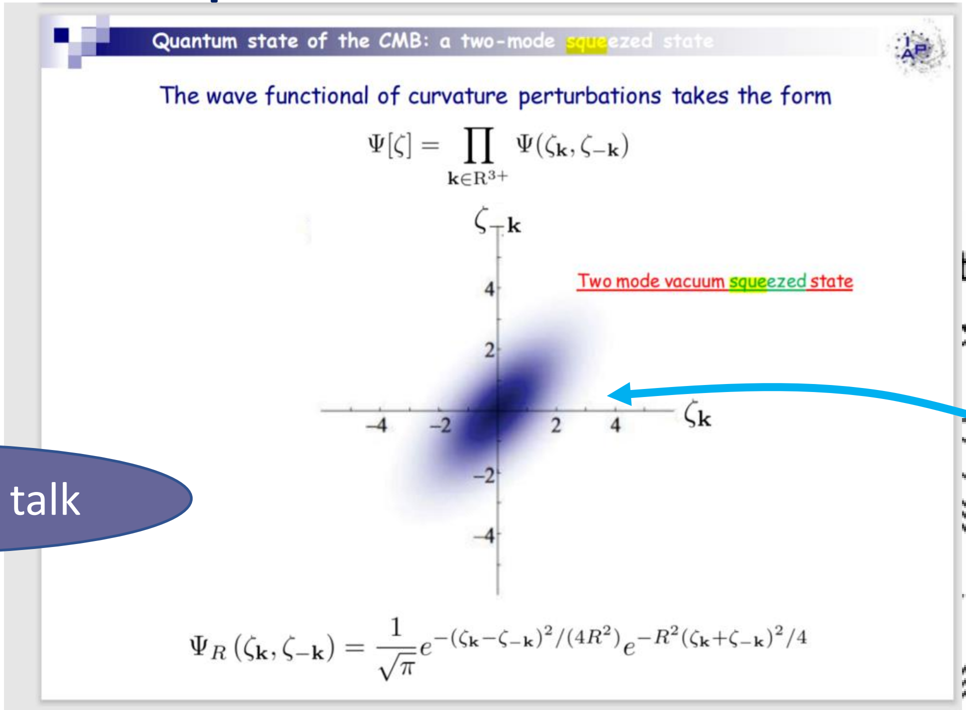

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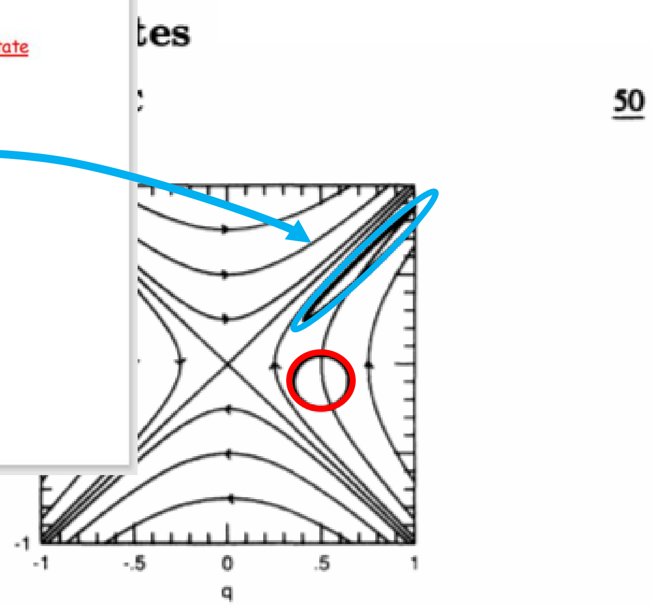

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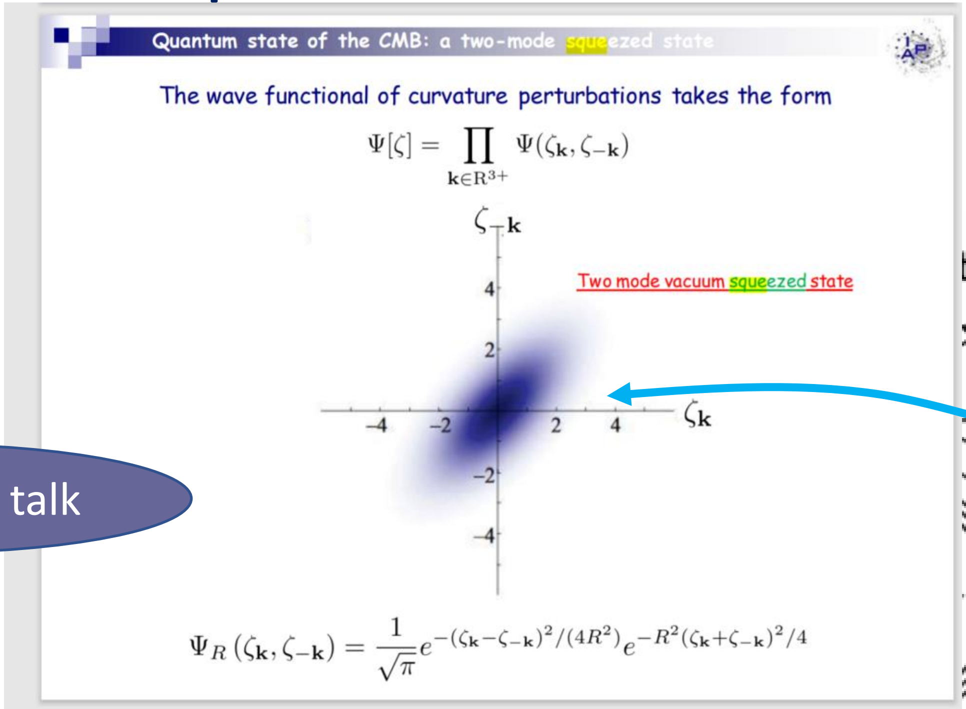

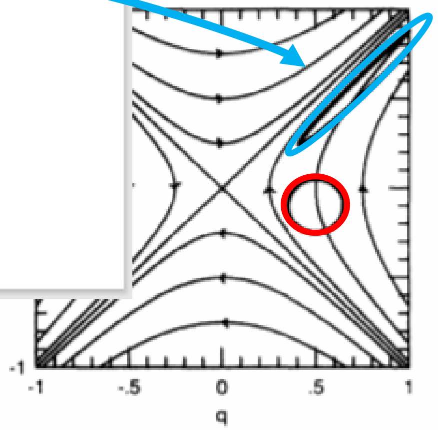

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See D. Wands talk

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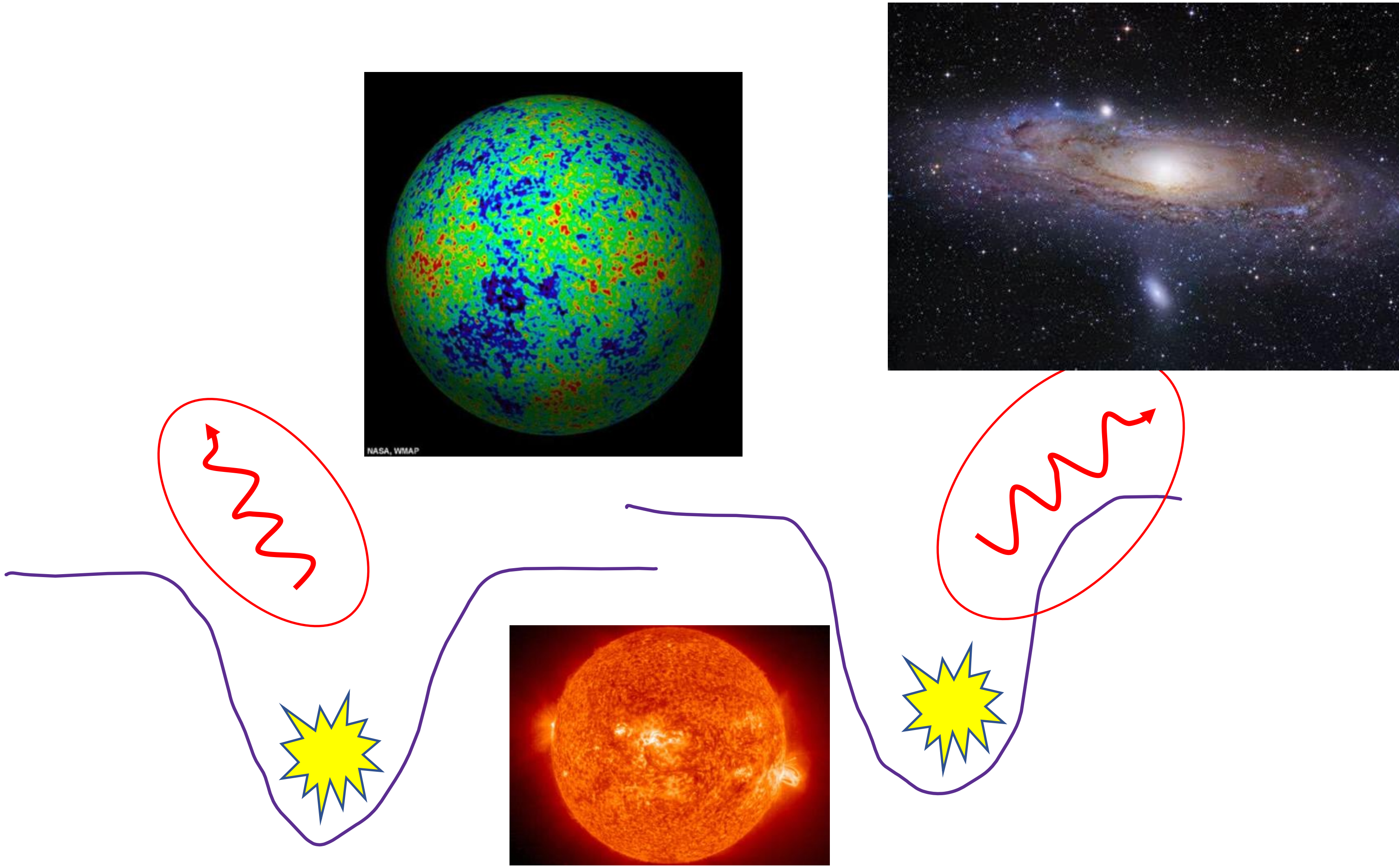
And, there are a relentless array of *local* interactions that will cause decoherence:

- Particles produced during reheating
- The CMB
- Cosmic dust
- Starlight



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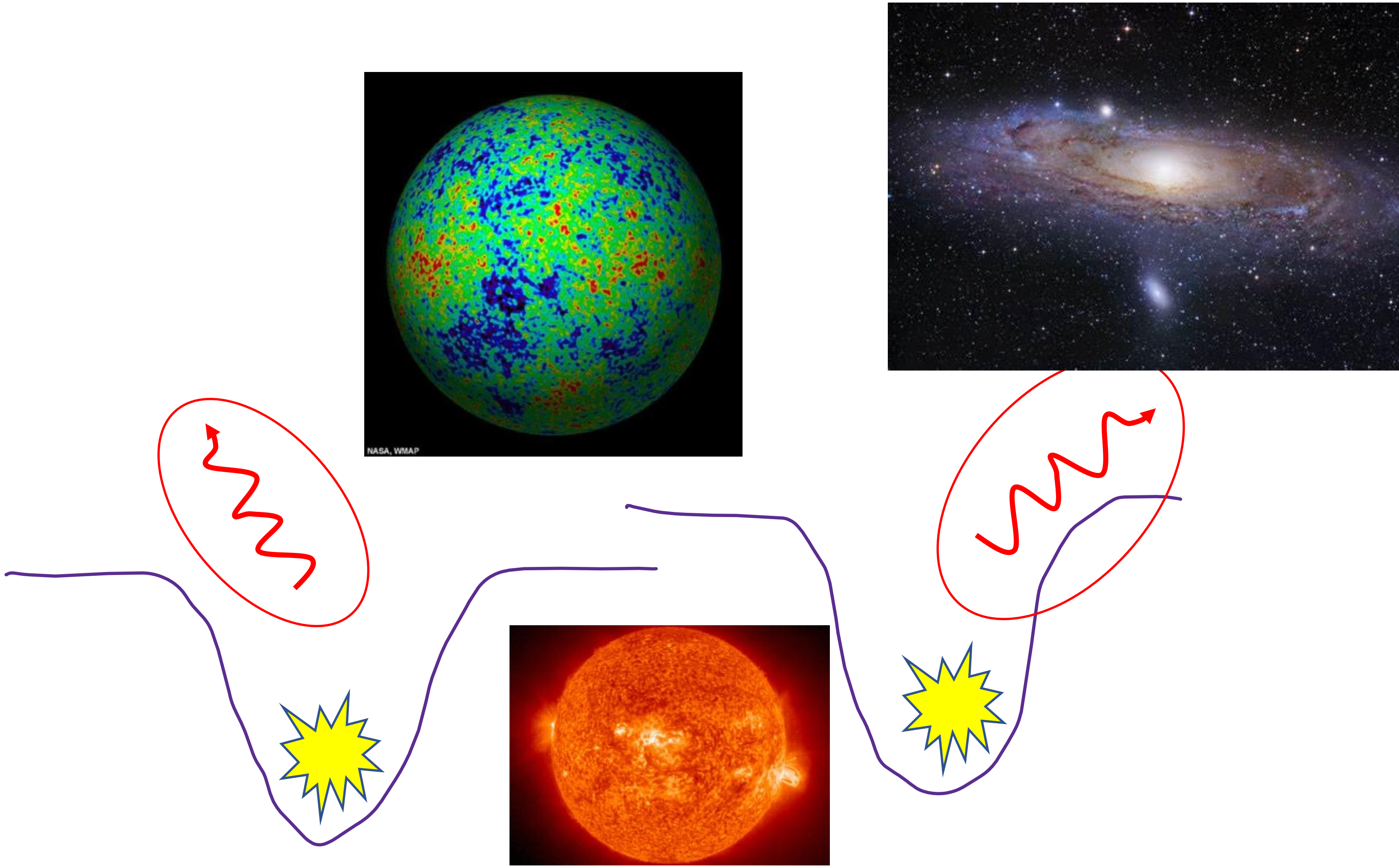
“One photon will do it”



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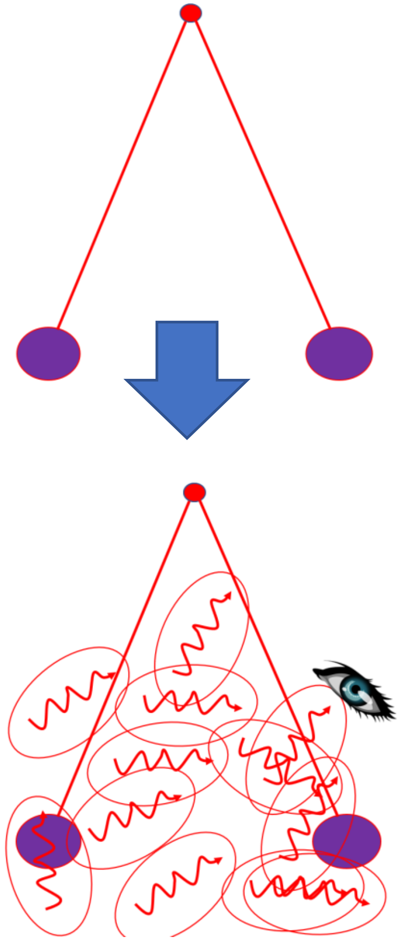

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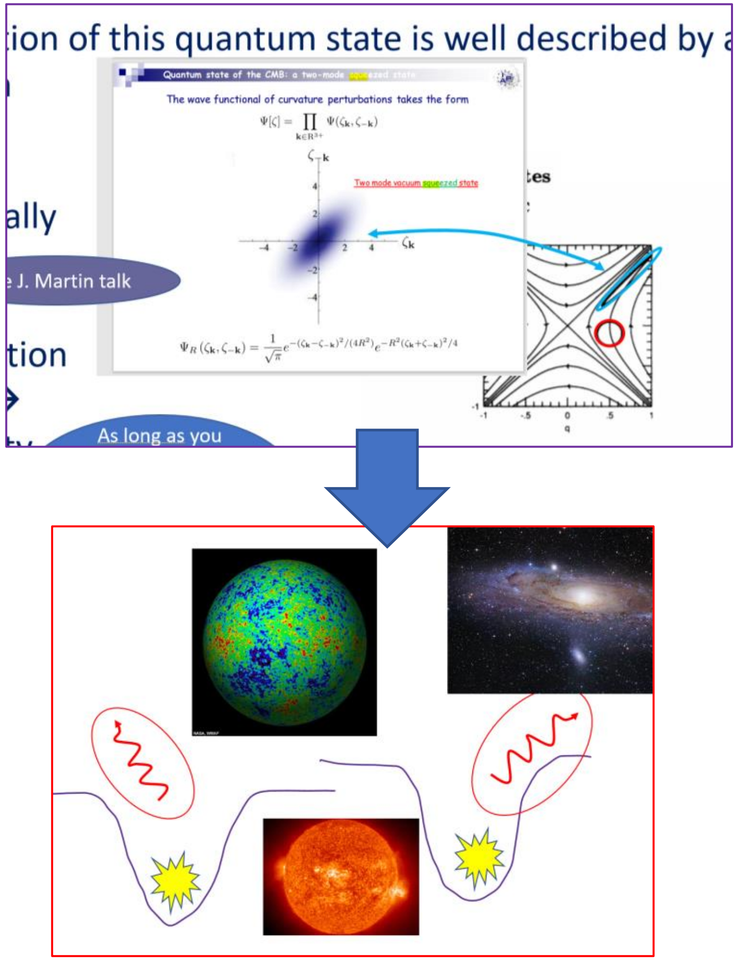

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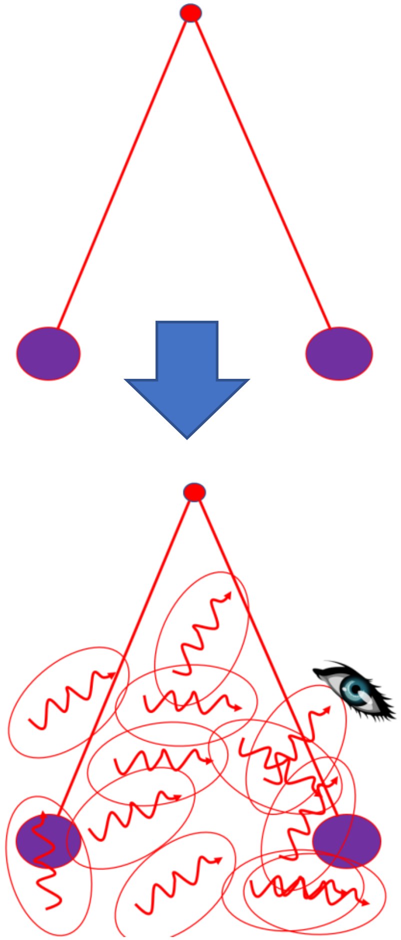

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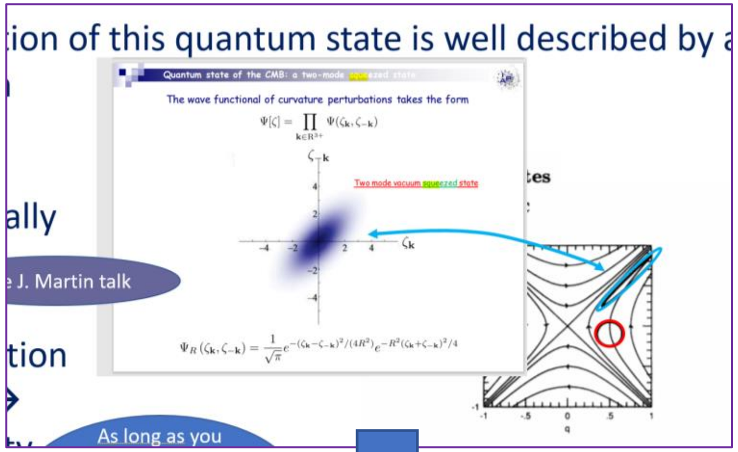

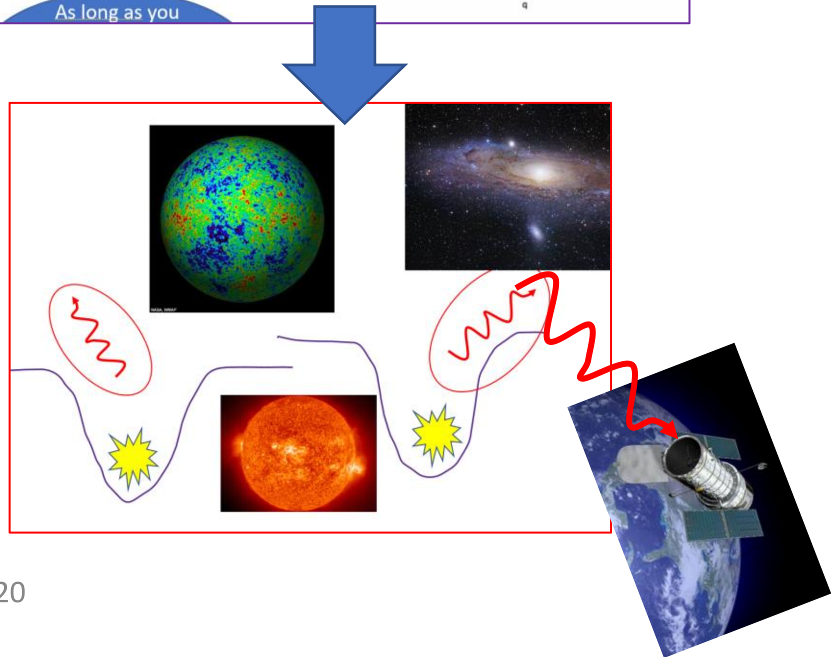

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- In popular theories perturbations are made from an "exotic quantum state" (the QFT vacuum)
- You would think this gives opportunities to reveal interesting quantum phenomena in the early universe
- However, classically equivalent early evolution, plus a vast array of subsequent decoherence processes seems to be working against you.

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- Maldacena 2015 https://arxiv.org/abs/1508.01082 (Constructs an *extremely exotic* inflation model specially designed to give observable quantum effects.)

- Quantum Entanglement in Cosmology workshop (IPMU May 2019) https://indico.ipmu.jp/event/300/overview

- J. Martin talk here and at IPMU workshop

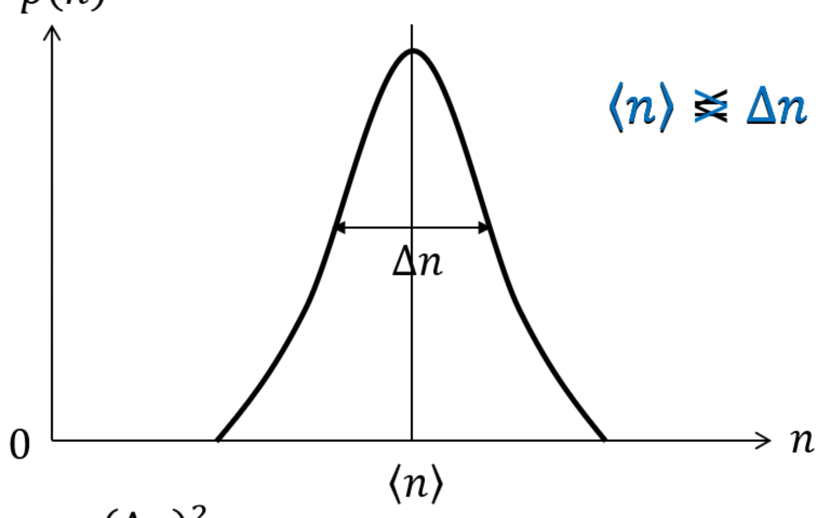
- Kanno et al *Noise and decoherence induced by gravitons* https://arxiv.org/abs/2007.09838

- Parikh et al https://arxiv.org/abs/2005.07211 (with story)

How to characterize nonclassicality?

S. Kanno @ IPMU 2019
https://indico.ipmu.jp/event/300/overview

Qunatum optics: Count photon numbers in a given state



$\langle n \rangle \lesseqgtr \Delta n$

Fano factor: $F = \dfrac{(\Delta n)^2}{\langle n \rangle} \lesseqgtr 1$

Distribution of photons in classical theory is always super-Poissonian and $F > 1$

⬇ contraposition

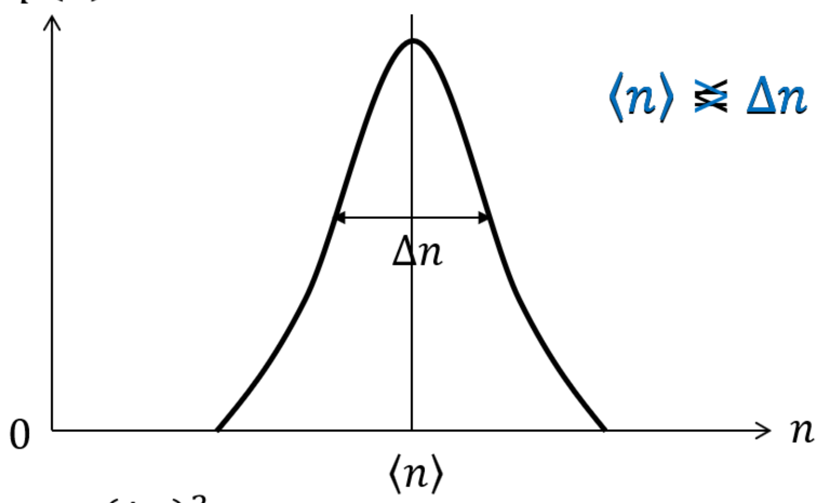
Sub-Poissonian distribution or $F < 1$ must be a signature of nonclassicality

4

How to characterize nonclassicality?

S. Kanno @ IPMU 2019
https://indico.ipmu.jp/event/300/overview

Qunatum optics: Count photon numbers in a given state



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Kanno: Let's apply this test to primordial gravitons

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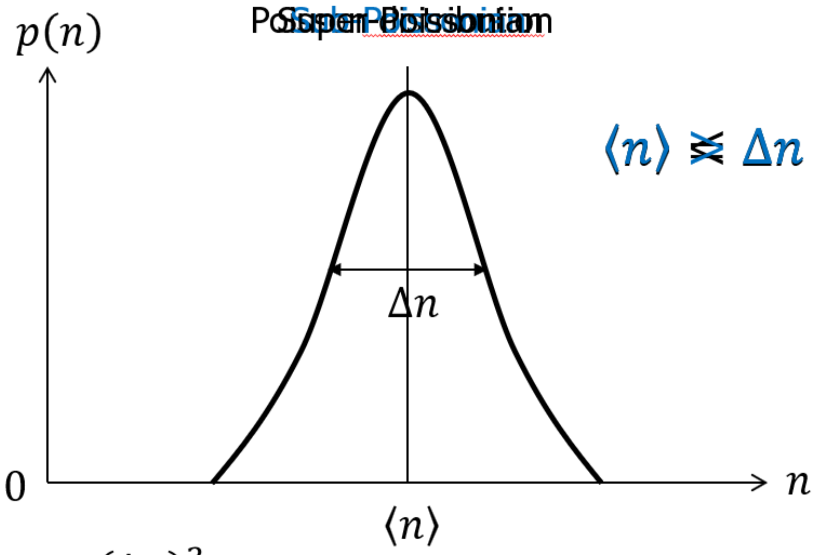

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AA: How do you count individual gravitons?

How to characterize nonclassicality?

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Qu

Inflation and squeezed quantum states

ALBRECHT, FERREIRA, JOYCE, AND PROKOPEC

https://arxiv.org/abs/astro-ph/9303001

fies the WKB criterion for classicality. This is equivalent to the WKB classicality at late times in an inverted harmonic oscillator studied by Guth and Pi in Ref. [11]. The point of this section is to explain that the apparently very quantum mechanical squeezed state is in fact classical in the sense with which cosmologists are familiar. That the truly quantum mechanical features of these states which are probed, for example, in quantum optics might have cosmological implications is a fascinating claim but one which has no substance at present. In Sec. VIII we sum-

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D

contraposition

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contraposition

Sub-Poissonian distribution or $F<1$ must be a signature

The "relativity of quantum coherence"

How to characterize nonclassicality?

The properties of the noise – its amplitude, power spectrum, etc – are calculable and depend on the state. We find that for the vacuum state or a coherent state, the fluctuations in the arm length are extremely small and almost certainly undetectable, as foreseen by Dyson. But for thermal states – such as from cosmology or evaporating black holes – the noise is significantly enhanced. Most favorably, if the gravitational field is in a squeezed state, as predicted by some inflationary models, the fluctuations in the arm length can be enhanced by an exponential of the squeezing parameter, and are potentially detectable.

$(\Delta n)^2$

Detection of this fundamental noise would constitute direct evidence for the quantization of gravity and the existence of gravitons.

↓ contraposition

Sub-Poissonian distribution or $F<1$ must be a signature of nonclassicality

4

Parikh et al: Don't need to measure individual gravitons, just look at noise in (future) gravity wave detectors. https://arxiv.org/abs/2005.07211

OUTLINE

I) Some key elements of quantum physics

- Quantum coherence
- Quantum entanglement
- Quantum Darwinism
- Wavefunction as a classically evolving distribution

II) The actual Universe

- Discuss the roles of the above phenomena

III) Some examples ←

IV) Conclusions

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- In popular theories perturbations are made from an "exotic quantum state" (the QFT vacuum)
- You would think this gives opportunities to reveal interesting quantum phenomena in the early universe
- However, classically equivalent early evolution, plus a vast array of subsequent decoherence processes seems to be working against you.

IV) Conclusions

- In popular theories perturbations are made from an “exotic quantum state” (the QFT vacuum)
- You would think this gives opportunities to reveal interesting quantum phenomena in the early universe
- H … ay

The universe works hard to hide its quantum nature, but also we are not so good at seeking it out

My goal is to equip you for your own path of discovery

I’ll give examples of new ideas that were just published this year