Origin of probabilities and their application to the multiverse

Andreas Albrecht
UC Davis

2015: THE SPACETIME ODYSSEY CONTINUES
Stockholm
June 4, 2015

AA & D. Phillips (PRD Dec 2014) http://arxiv.org/abs/1212.0953

Origin of probabilities and their application to the multiverse

Andreas Albrecht
UC Davis

2015: THE SPACETIME ODYSSEY CONTINUES
Stockholm
June 4, 2015

AA & D. Phillips (PRD Dec 2014)

Thank you Katie!!!

Origin of probabilities and their application to the multiverse

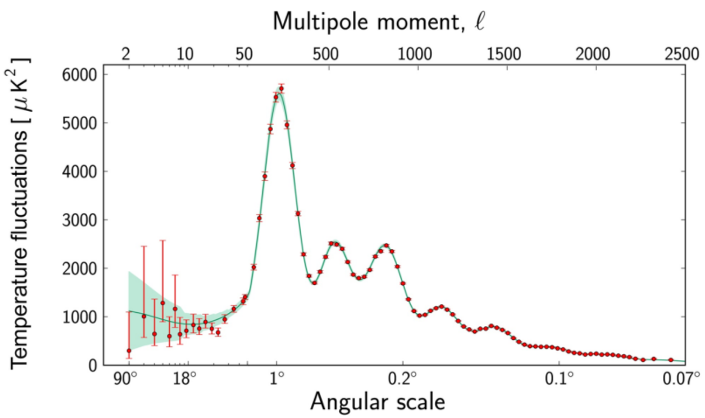
Andreas Albrecht
UC Davis

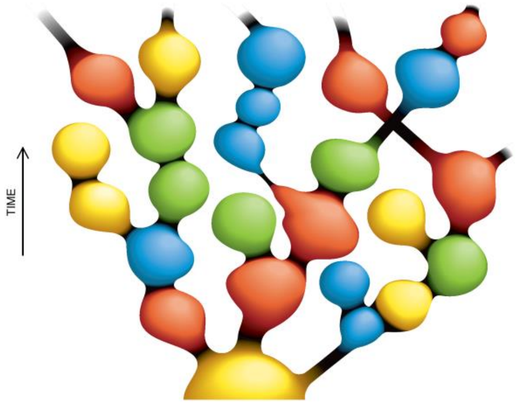
2015: THE SPACETIME ODYSSEY CONTINUES
Stockholm
June 4, 2015

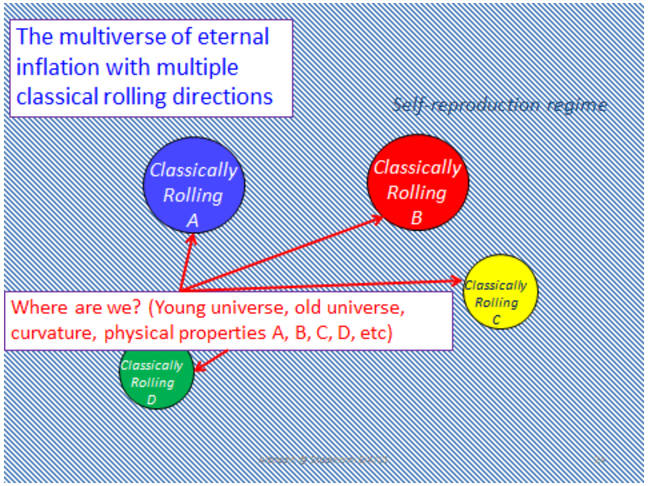
AA & D. Phillips (PRD Dec 2014)

Cosmic Inflation:

Consumers & Producers

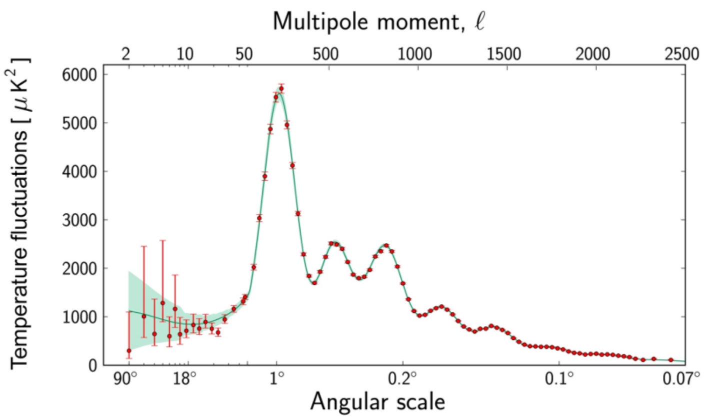


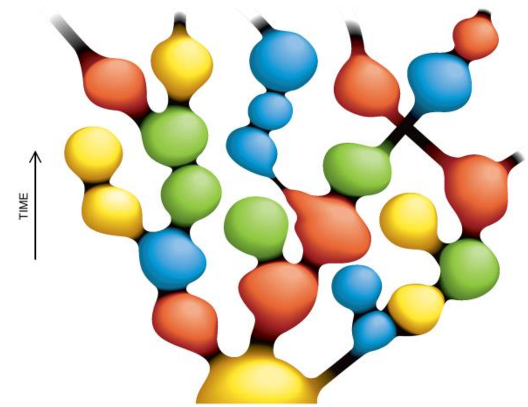


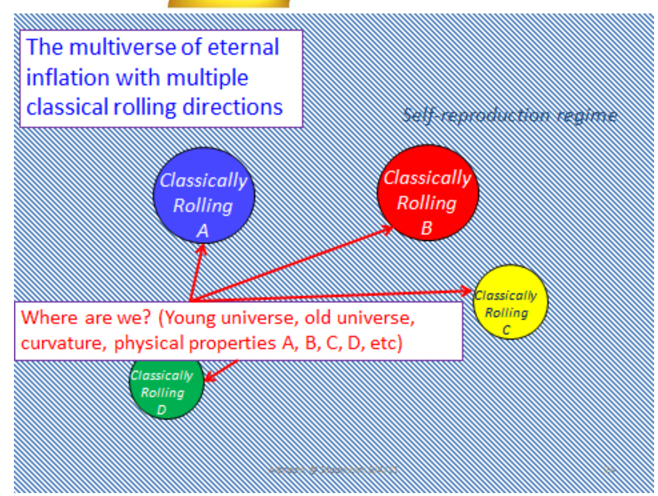


Cosmic Inflation:

Consumers & Producers

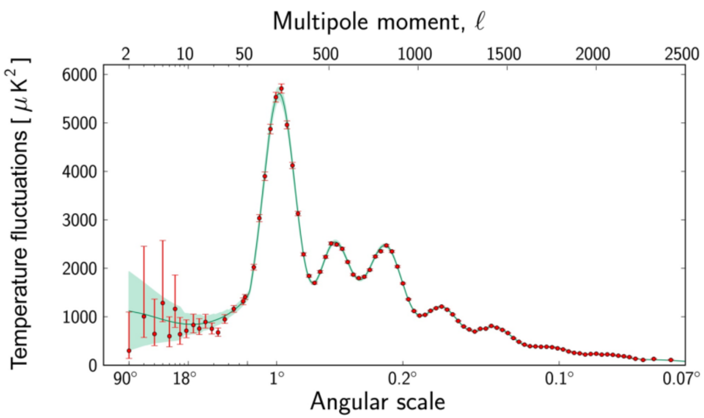


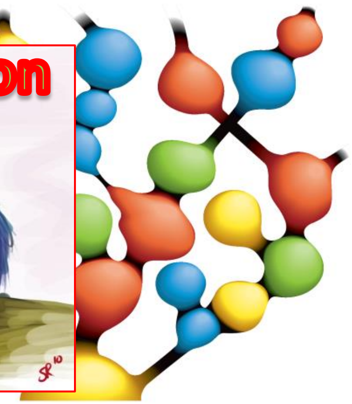


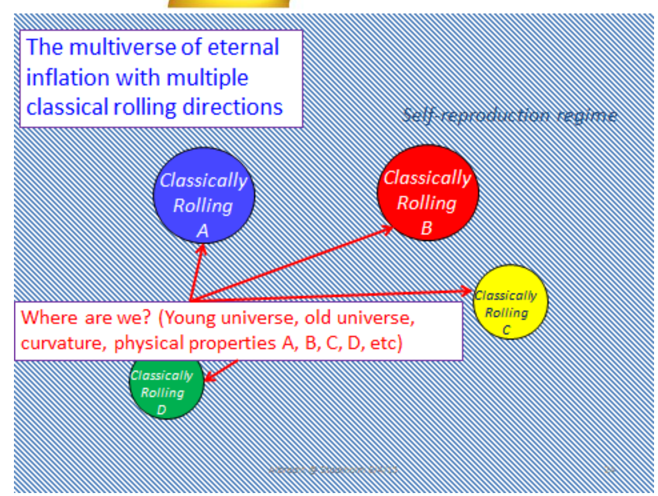


Cosmic Inflation:

Consumers & Producers



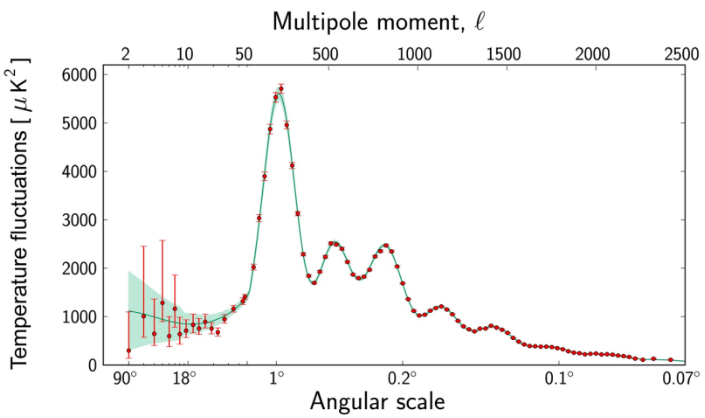


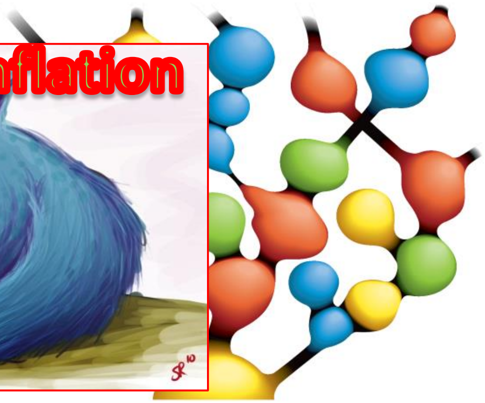


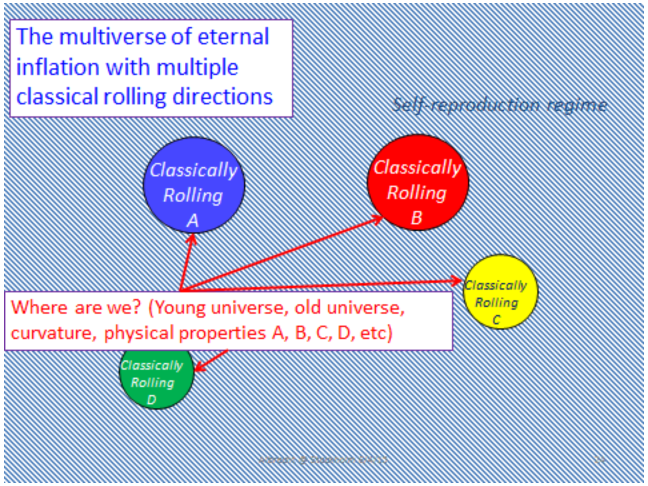
(Blue Monster by Simon Richards)

Cosmic Inflation:

Consumers & Producers



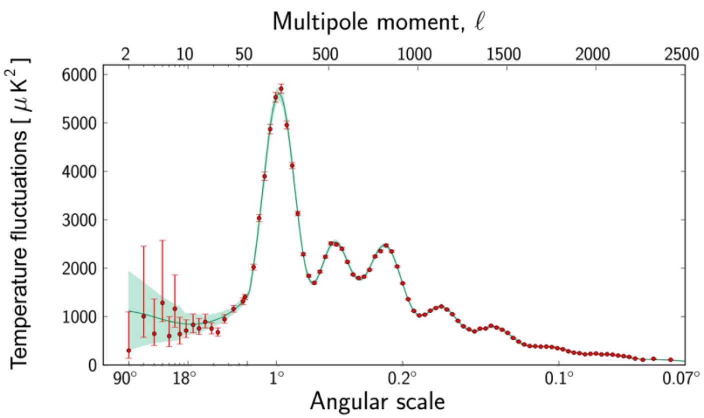


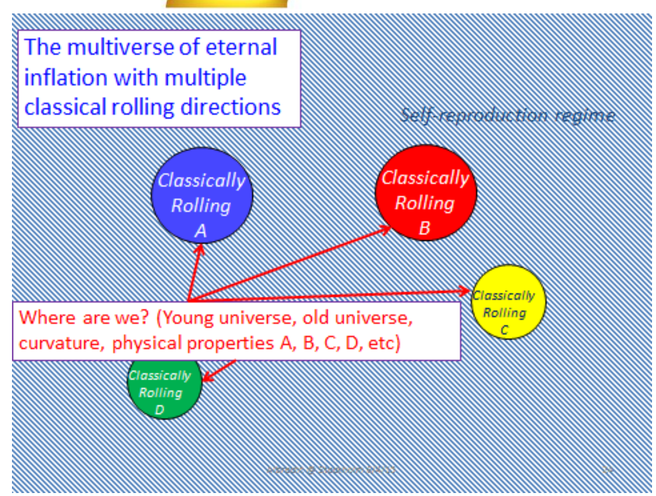


(Blue Monster by Simon Richards)

Cosmic Inflation:

Consumers & Producers



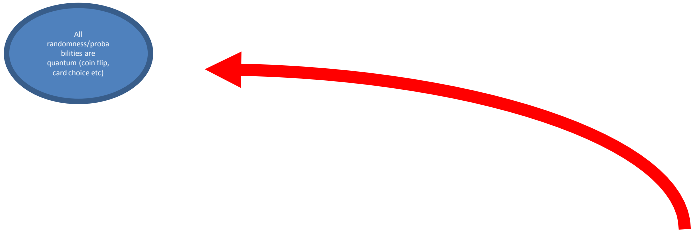


[(Blue Monster by Simon Richards)]

My history with this topic

AA: All randomness/ probabilities are quantum (coin flip, card choice etc)

My history with this topic

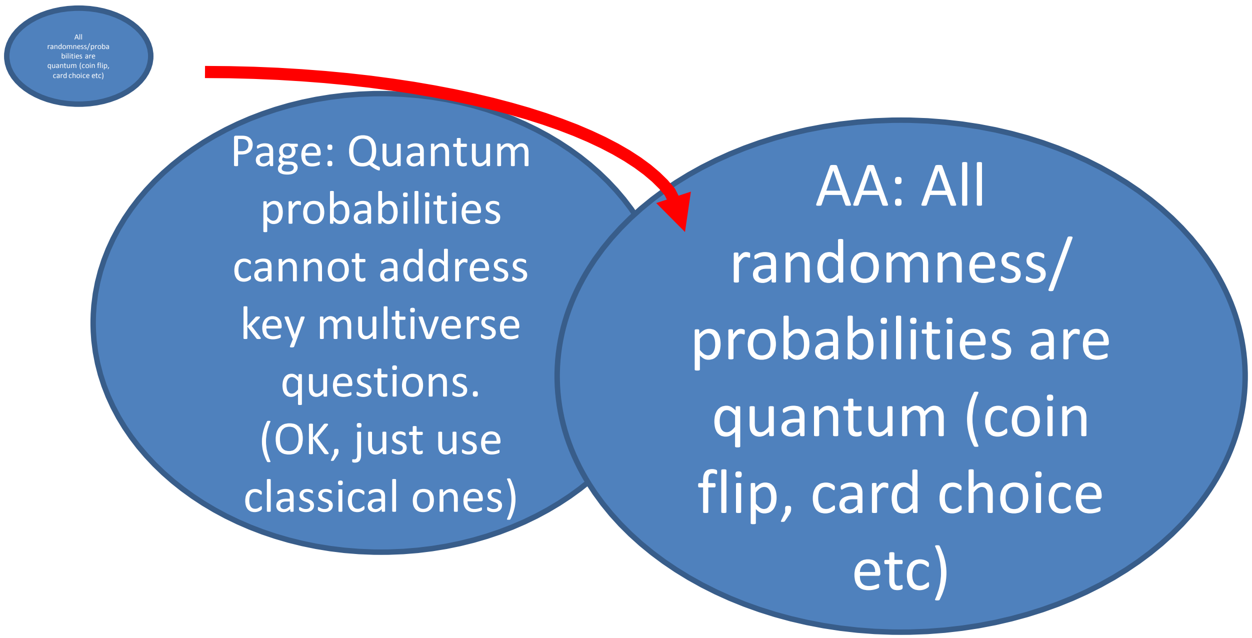


My history with this topic

All randomness/probabilities are quantum (coin flip, card choice etc)

Page: Quantum probabilities cannot address key multiverse questions. (OK, just use classical ones)

My history with this topic



My history with this topic

All randomness/probabilities are quantum (coin flip, card choice etc)

Page: Quantum probabilities cannot address key multiverse questions.
(OK, just use classical ones)

AA: All randomness/ probabilities are quantum (coin flip, card choice etc)

Hartle, Srednicki, Aguirre, Tegmark, …

My history with this topic

All randomness/probabilities are quantum (coin flip, card choice etc)

Page: Quantum probabilities cannot address key multiverse questions. (OK, just use classical ones)

AA: All randomness/ probabilities are quantum (coin flip, card choice etc)

AA: A deeper problem than the measure problems for the multiverse

My history with this topic

All randomness/probabilities are quantum (coin flip, card choice etc)

Page: Quantum probabilities cannot address key multiverse questions.
(OK, just use classical ones)

AA: All randomness/probabilities are quantum (coin flip, card choice etc)

AA: A deeper problem than the measure problems for …ltiverse

A potential issue even for finite models

My history with this topic

All randomness/probabilities are quantum (coin flip, card choice etc)

Page: Quantum probabilities cannot address key multiverse questions. (OK, just use classical ones)

AA: All randomness/ probabilities are quantum (coin flip, card choice etc)

AA: Write paper explaining this with Phillips

AA: A deep problem than the measure problems for the multiverse

My history with this topic

All randomness/probabilities are quantum (coin flip, card choice etc)

Page: Quantum probabilities cannot address key multiverse questions.
(OK, just use classical ones)

AA: All randomness/ probabilities are quantum (coin flip, card choice etc)

AA: A deep problem than the measure problems for the multiverse

AA: Write paper ...ining this ... Phillips

AA: This is fundamentally about giving permission to dismiss certain probability questions (the non quantum ones) as "ill posed".

My history with this topic

All randomness/probabilities are quantum (coin flip, card choice etc)

Page: Quantum probabilities cannot address key multiverse questions. (OK, just use classical ones)

AA: All randomness/ probabilities are quantum (coin flip, card choice etc)

AA: A deep problem than the measure problems for the multiverse

AA: This is fundamentally about giving permiss… dismiss certain pr… questions (th… quantum ones… posed".

Perhaps this type of discipline can help resolve the measure problems of the multiverse/eternal inflation

My history with this topic

All randomness/probabilities are quantum (coin flip, card choice etc)

Page: Quantum probabilities cannot address key multiverse questions.
(OK, just use classical ones)

AA: All randomness/ probabilities are quantum (coin flip, card choice etc)

AA: A deep problem than the measure problems for the multiverse

X ?

AA: This is fundamentally about giving permiss dismiss certain pr questions (th quantum ones posed".

Perhaps this type of discipline can help resolve the measure problems of the multiverse/eternal inflation

My history with this topic

All randomness/probabilities are quantum (coin flip, card choice etc)

Page: Quantum probabilities cannot address key multiverse questions. (OK, just use classical ones)

AA: All randomness/ probabilities are quantum (coin flip, card choice etc)

AA: A deep problem than the measure problems for the multiverse

?

AA: This is fundamentally about giving permiss dismiss certain pr questions (th quantum ones posed".

Apparently this type of discipline can ~~help~~ resolve the measure problems of the multiverse/eternal inflation

Outline

1) Quantum vs non-quantum probabilities (toy model/multiverse)

2) Everyday probabilities

3) Be careful about counting!

4) Implications for multiverse/eternal inflation

Outline

1) Quantum vs non-quantum probabilities (toy model/multiverse)
2) Everyday probabilities
3) Be careful about counting!
4) Implications for multiverse/eternal inflation

Outline

1) Quantum vs non-quantum probabilities (toy model/multiverse)
2) Everyday probabilities
3) Be careful about counting!
4) Implications for multiverse/eternal inflation

NB: Very different subject from "make probabilities precise" in "Stanford sense".

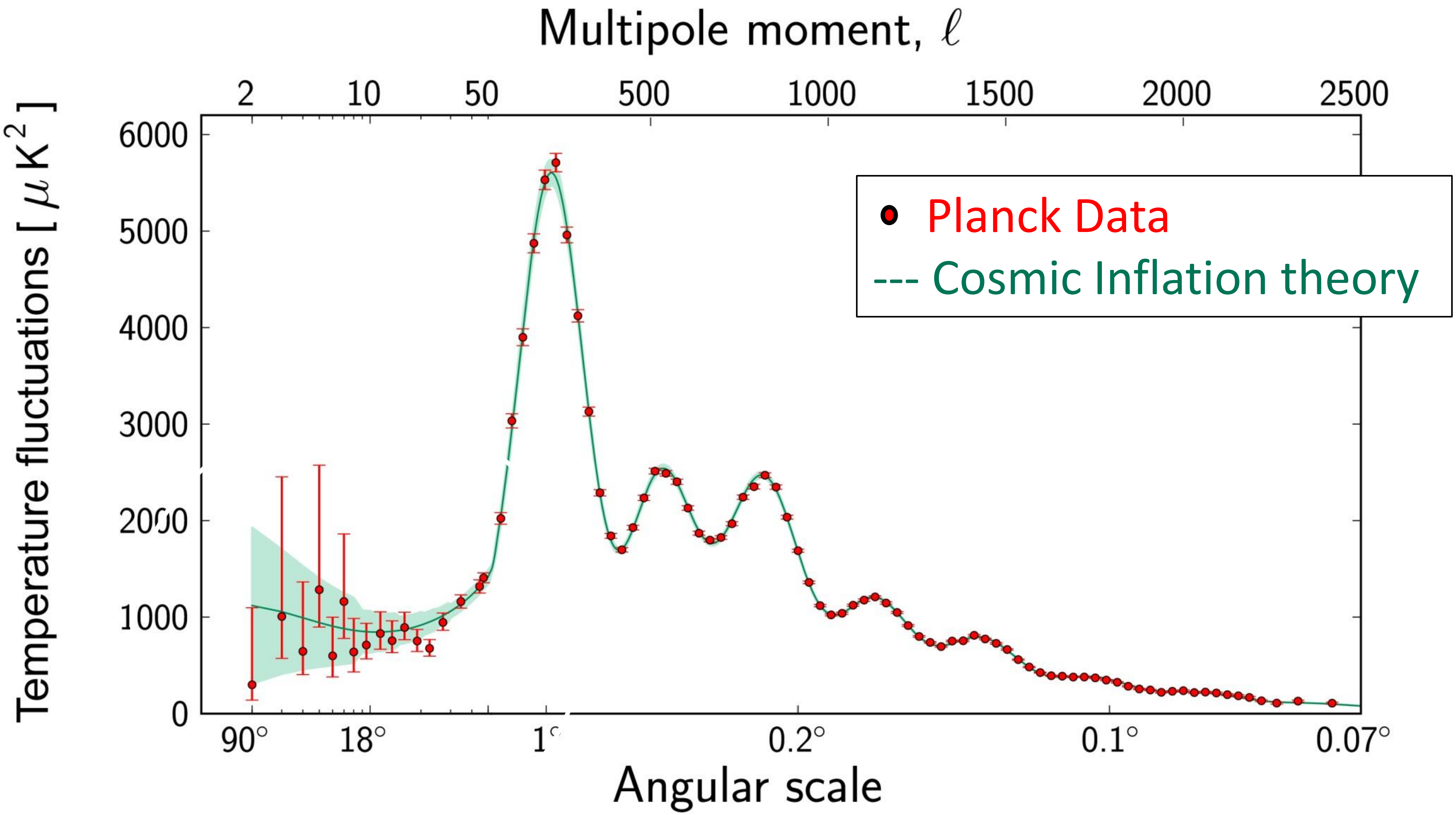
Outline

1) Quantum vs non-quantum probabilities (toy model/multiverse)

2) Everyday probabilities

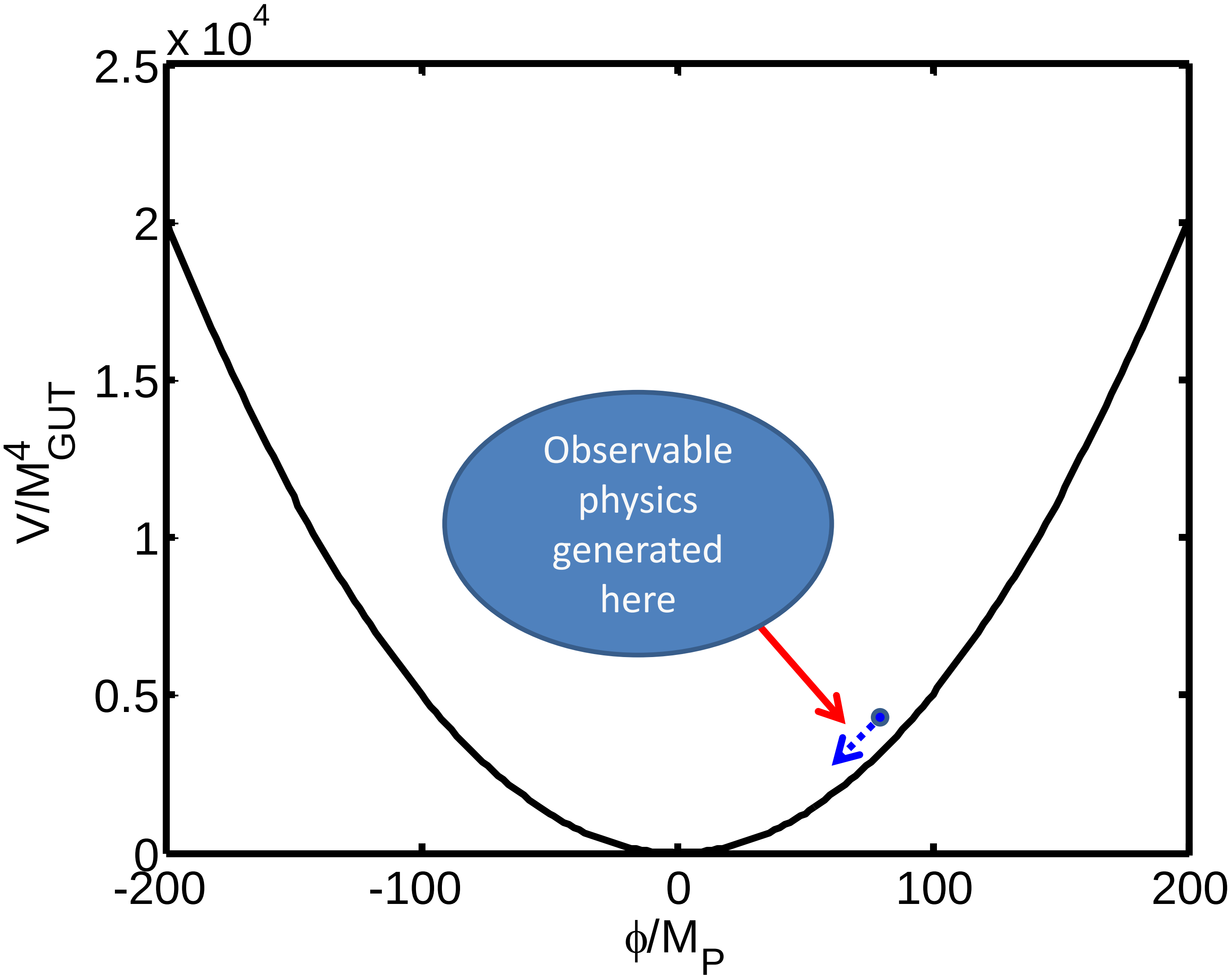
3) Be careful about counting!

4) Implications for multiverse/eternal inflation

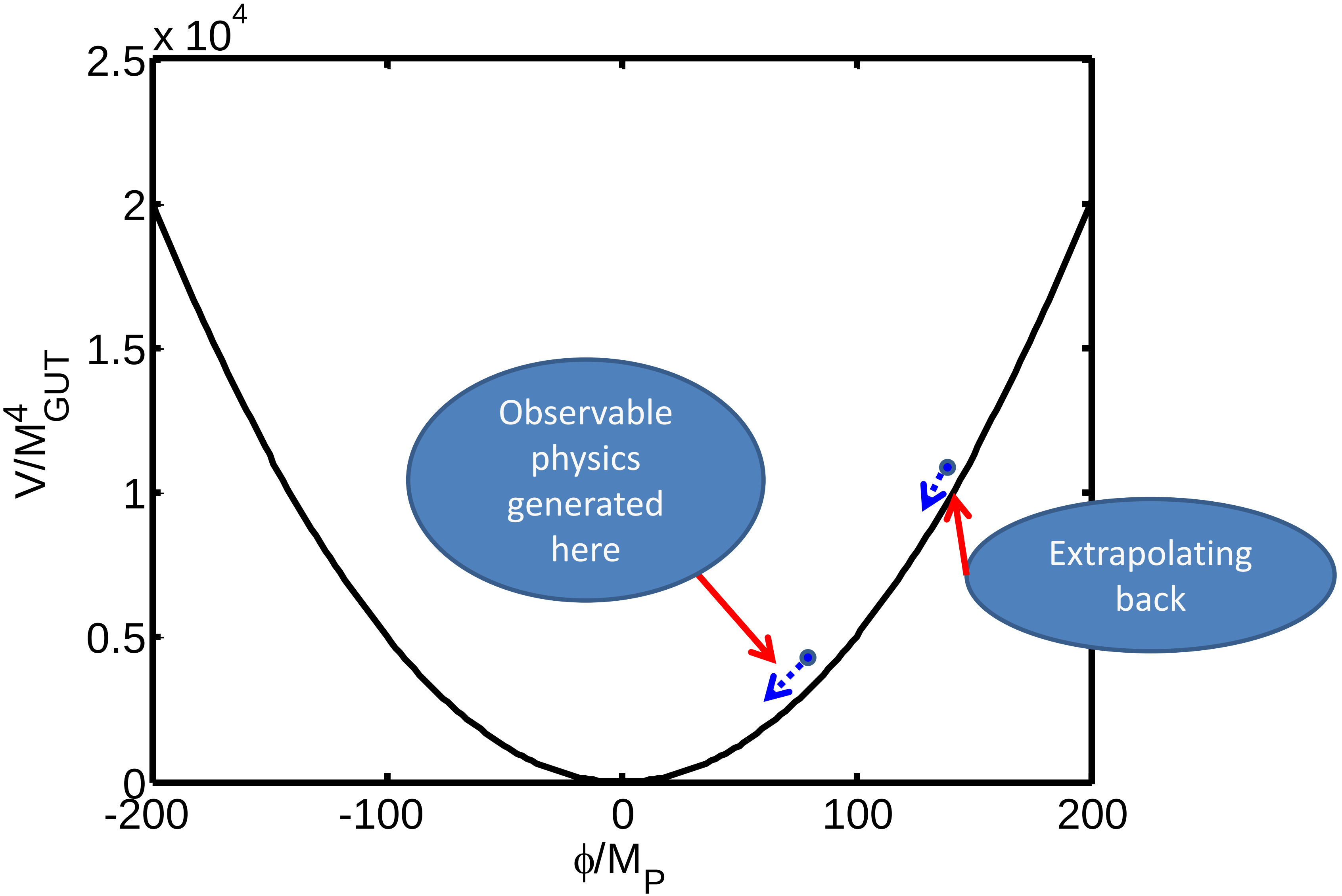


Multipole moment, ℓ
2
10
50
500
1000
1500
2000
2500
Temperature fluctuations [μK^2]
6000
5000
4000
3000
2000
1000
0
90°
18°
1°
0.2°
0.1°
0.07°
Angular scale
Planck Data
--- Cosmic Inflation theory

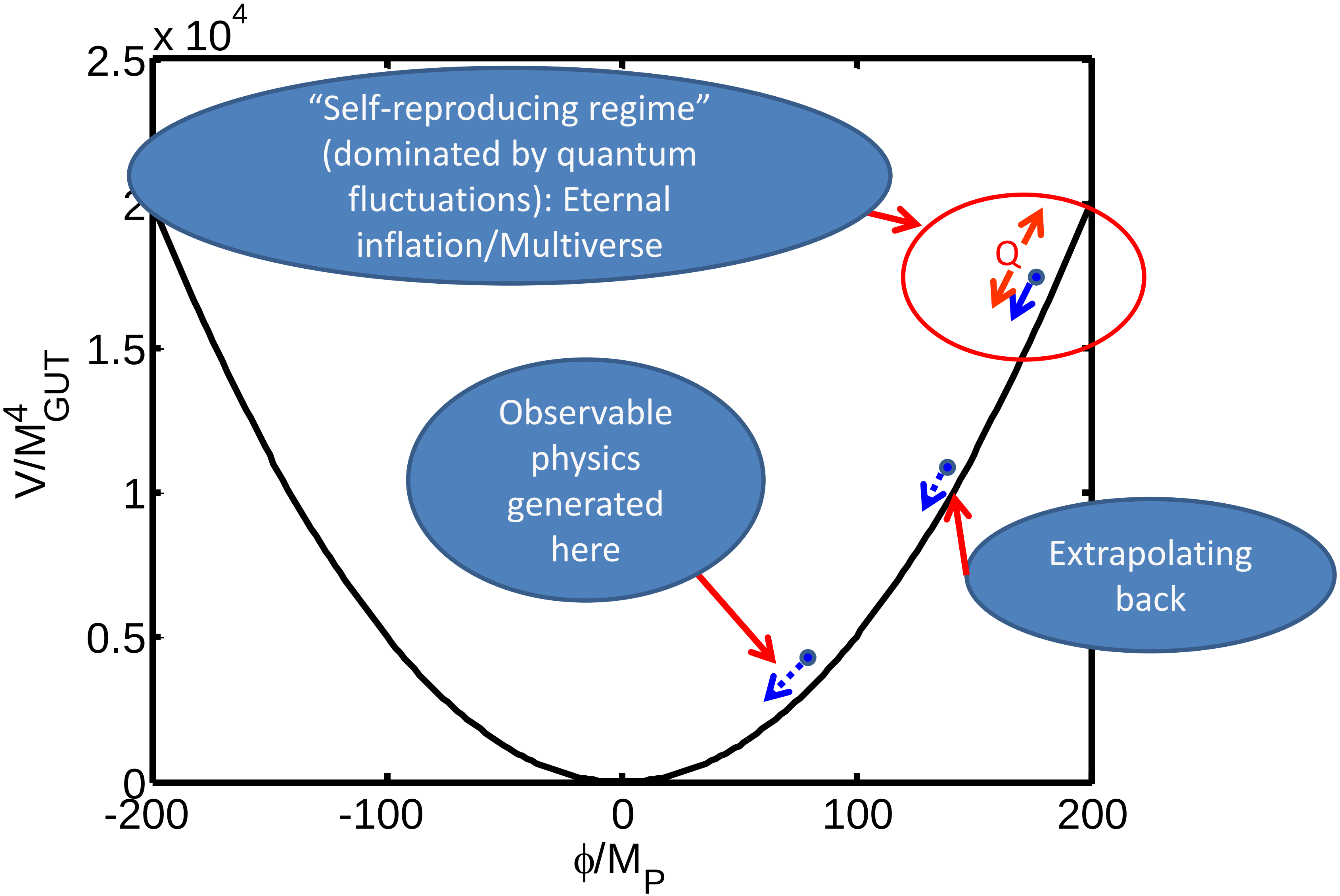
Slow rolling of inflaton



Slow rolling of inflaton

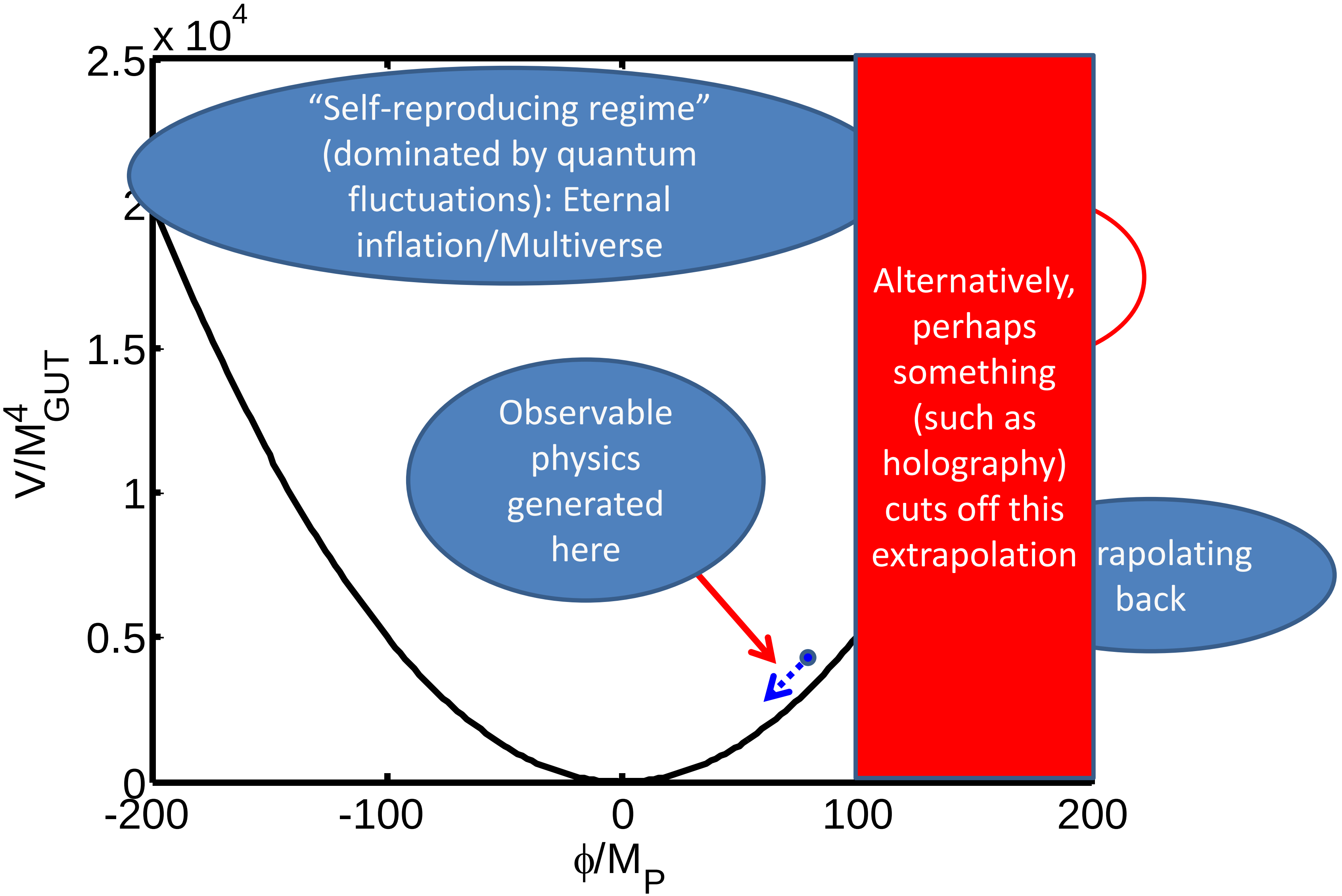


Slow rolling of inflaton



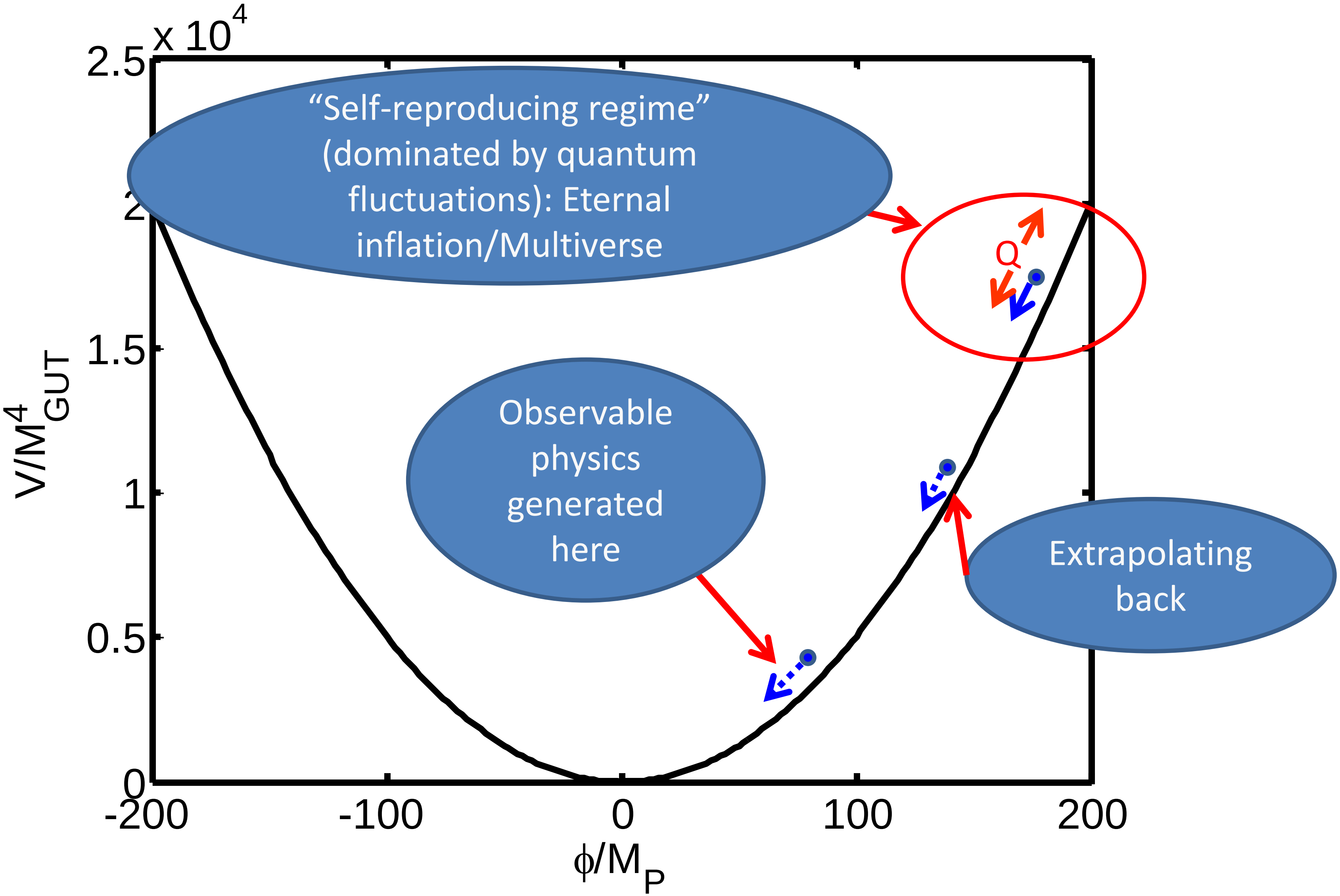
Steinhardt 1982, Linde 1982, Vilenkin 1983, and (then) many others

Slow rolling of inflaton



Steinhardt 1982, Linde 1982, Vilenkin 1983, and (then) many others

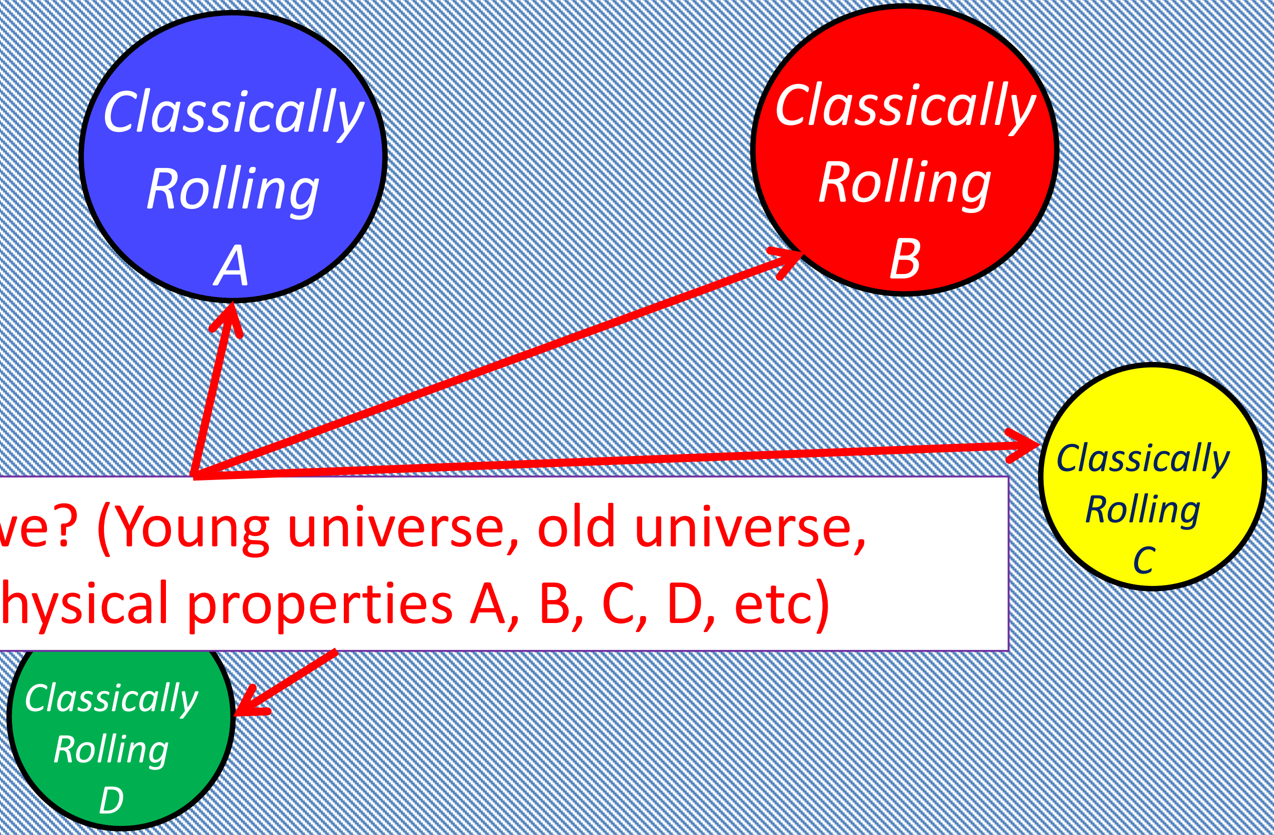
Slow rolling of inflaton



Steinhardt 1982, Linde 1982, Vilenkin 1983, and (then) many others

The multiverse of eternal inflation with multiple classical rolling directions

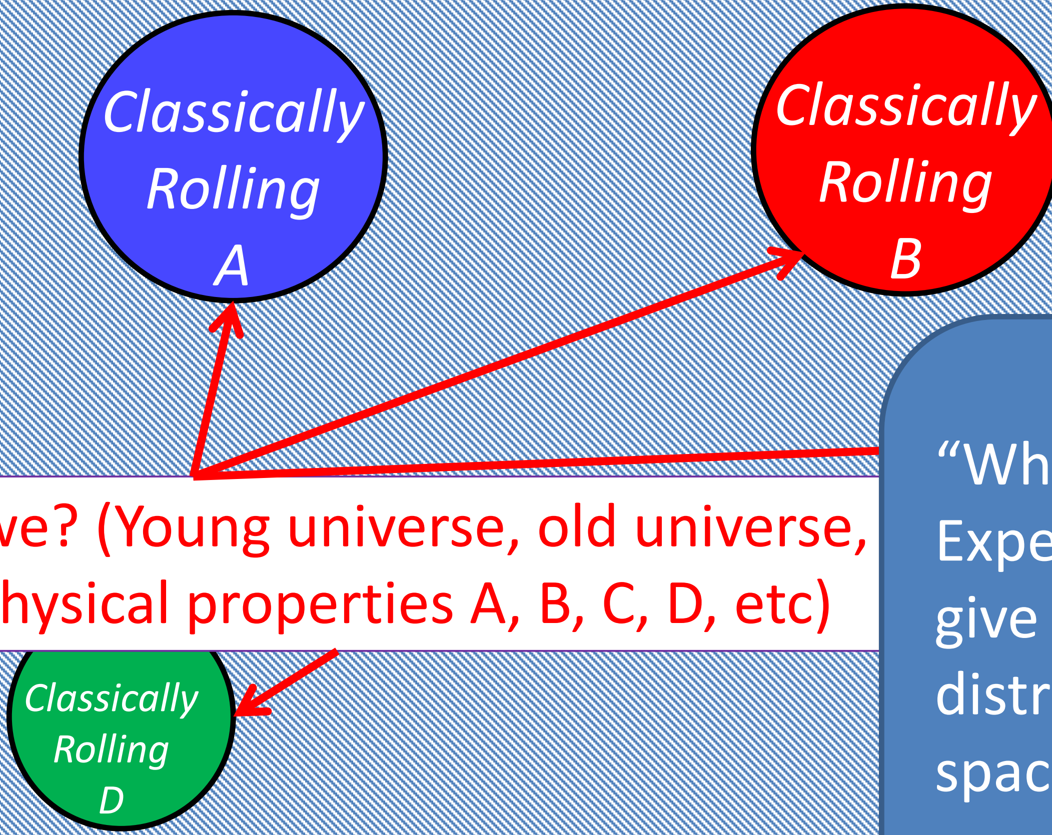
Self-reproduction regime



Where are we? (Young universe, old universe, curvature, physical properties A, B, C, D, etc)

The multiverse of eternal inflation with multiple classical rolling directions

Self-reproduction regime

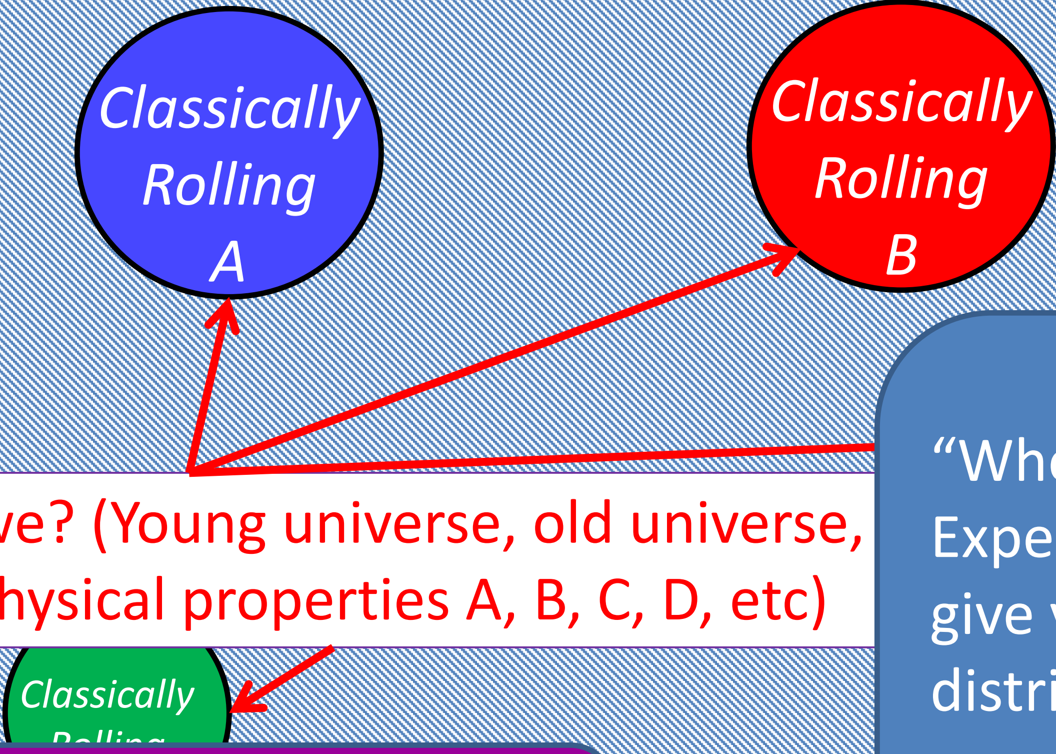


Where are we? (Young universe, old universe, curvature, physical properties A, B, C, D, etc)

"Where are we?" → Expect the theory to give you a probability distribution in this space… hopefully with some sharp predictions

The multiverse of eternal inflation with multiple classical rolling directions

Self-reproduction regime



Where are we? (Young universe, old universe, curvature, physical properties A, B, C, D, etc)

"Anything that can happen will happen infinitely many times" (A. Guth)

"Where are we?"→ Expect the theory to give you a probability distribution in this space… hopefully with some sharp predictions

The multiverse of eternal inflation with multiple classical rolling direct

String theory landscape even more complicated (e.g. many types of eternal inflation)

Classically Rolling A

Rolling B

Where are we? (Young universe, old universe, curvature, physical properties A, B, C, D, etc)

Classically

"Where are we?" → Expect the theory to give you a probability distribution in this space… hopefully with some sharp predictions

"Anything that can happen will happen infinitely many times" (A. Guth)

The multiverse of eternal inflation with multiple classical rolling direct

String theory landscape even more complicated (e.g. many types of eternal inflation)

Rolling
B

Where are we? (Young universe, old universe, curvature, physical properties A, B, C, D, etc)

Classically

"Where are we?" → Expect the theory to give you a probability distribution in this space… hopefully with some sharp predictions

"Anything that can happen will happen infinitely many times" (A. Guth)

Quantum vs Non-Quantum probabilities

Non-Quantum probabilities in a toy model:

$$U = A \otimes B$$

$$A : \left\{ |1\rangle^A, |2\rangle^A \right\} \qquad B : \left\{ |1\rangle^B, |2\rangle^B \right\}$$

$$U : \left\{ |11\rangle, |12\rangle, |21\rangle, |22\rangle \right\} \qquad |ij\rangle \equiv |i\rangle^A |j\rangle^B$$

Page, 2009; These slides follow AA & Phillips 2014

Quantum vs Non-Quantum probabilities

Non-Quantum probabilities in a toy model:

$$U = A \otimes B \qquad A:\left\{|1\rangle^A, |2\rangle^A\right\} \qquad B:\left\{|1\rangle^B, |2\rangle^B\right\}$$

$$U:\left\{|11\rangle, |12\rangle, |21\rangle, |22\rangle\right\} \qquad |ij\rangle \equiv |i\rangle^A |j\rangle^B$$

Possible Measurements ←→ Projection operators:

Measure *A* only: $\hat{P}_i^A = \left(|i\rangle^{A\,A}\langle i|\right) \otimes \mathbf{1}^B = \left[|i1\rangle\langle i1| + |i2\rangle\langle i2|\right]$

Measure *B* only: $\hat{P}_i^B = \left(|i\rangle^{B\,B}\langle i|\right) \otimes \mathbf{1}^A = \left[|1i\rangle\langle 1i| + |2i\rangle\langle 2i|\right]$

Measure entire *U*: $\hat{P}_{ij} \equiv |ij\rangle\langle ij|$

Quantum

Non-Quan

$$U = A$$

$^{A}|j\rangle^{B}$

BUT: It is impossible to construct a projection operator for the case where you do not know whether it is A or B that is being measured.

Possible Measurements ←→ Projection operators:

Measure *A* only: $\hat{P}_i^A = \left(|i\rangle^{A\;A}\langle i|\right) \otimes \mathbf{1}^B = \left[|i1\rangle\langle i1| + |i2\rangle\langle i2|\right]$

Measure *B* only: $\hat{P}_i^B = \left(|i\rangle^{B\;B}\langle i|\right) \otimes \mathbf{1}^A = \left[|1i\rangle\langle 1i| + |2i\rangle\langle 2i|\right]$

Measure entire *U*: $\hat{P}_{ij} \equiv |ij\rangle\langle ij|$

Quantum

Non-Quan

$U = A$

BUT: It is impossible to construct a projection operator for the case where you do not know whether it is A or B that is being measured.

Could Write

$$\hat{P}_i = p_A \hat{P}_i^A + p_B \hat{P}_i^B$$

$^A \left| j \right\rangle^B$

Possible Measurements ←→ Projection operators:

Measure *A* only: $\hat{P}_i^A = \left(\left| i \right\rangle^{A\;A} \left\langle i \right| \right) \otimes \mathbf{1}^B = \left[\left| i1 \right\rangle \left\langle i1 \right| + \left| i2 \right\rangle \left\langle i2 \right| \right]$

Measure *B* only: $\hat{P}_i^B = \left(\left| i \right\rangle^{B\;B} \left\langle i \right| \right) \otimes \mathbf{1}^A = \left[\left| 1i \right\rangle \left\langle 1i \right| + \left| 2i \right\rangle \left\langle 2i \right| \right]$

Measure entire *U*: $\hat{P}_{ij} \equiv \left| ij \right\rangle \left\langle ij \right|$

Quantum

BUT: It is impossible to construct a projection operator for the case where you do not know whether it is A or B that is being measured.

Non-Quan

Classical Probabilities to measure A, B

Could Write

$$U = A($$

$$\hat{P}_i = p_A \hat{P}_i^A + p_B \hat{P}_i^B$$

$$^{A}|j\rangle^{B}$$

Possible Measurements ←→ Projection operators:

Measure *A* only: $\hat{P}_i^A = \left(|i\rangle^{A\ A}\langle i|\right) \otimes \mathbf{1}^B = \left[|i1\rangle\langle i1| + |i2\rangle\langle i2|\right]$

Measure *B* only: $\hat{P}_i^B = \left(|i\rangle^{B\ B}\langle i|\right) \otimes \mathbf{1}^A = \left[|1i\rangle\langle 1i| + |2i\rangle\langle 2i|\right]$

Measure entire *U*: $\hat{P}_{ij} \equiv |ij\rangle\langle ij|$

Quantum

Non-Quan

$U = A$

BUT: It is impossible to construct a projection operator for the case where you do not know whether it is A or B that is being measured.

Could Write

$$\hat{P}_i = p_A \hat{P}_i^A + p_B \hat{P}_i^B$$

$$\hat{P}_i \hat{P}_j \neq \delta_{ij} \hat{P}_j$$

Classical Probabilities to measure A, B

$^A|j\rangle^B$

Does not represent a quantum measurement

ments ↔ Projection operators:

$$\hat{P}_i^A = \left(|i\rangle^{A\,A}\langle i|\right) \otimes \mathbf{1}^B = \left[|i1\rangle\langle i1| + |i2\rangle\langle i2|\right]$$

$$\hat{P}_i^B = \left(|i\rangle^{B\,B}\langle i|\right) \otimes \mathbf{1}^A = \left[|1i\rangle\langle 1i| + |2i\rangle\langle 2i|\right]$$

M... y:

Measure entire *U*: $\hat{P}_{ij} \equiv |ij\rangle\langle ij|$

Quantum

Non-Quan

$U = A$

BUT: It is impossible to construct a projection operator for the case where you do not know whether it is A or B that is being measured.

Could Write

$$\hat{P}_i = p_A \hat{P}_i^A + p_B \hat{P}_i^B$$

$$\hat{P}_i \hat{P}_j \neq \delta_{ij} \hat{P}_j$$

Classical Probabilities to measure A, B

$^A |j\rangle^B$

Does not represent a quantum measurement

ments ←→ P

$\hat{P}_i^A = \left(|i\rangle^A \right.$

$\hat{P}_i^B = \left(|i\rangle^B \right.$

Page: The multiverse requires this (are you in pocket universe A or B?)

M... y:

Measure entire *U*: $\hat{P}_{ij} \equiv |ij\rangle\langle ij|$

Quantum

BUT: It is impossible to construct a projection operator for the case where you do not know whether it is A or B that is being measured.

Classical Probabilities to measure A, B

Non-Quan

Could Write

$U = A$

$$\hat{P}_i = p_A \hat{P}_i^A + p_B \hat{P}_i^B$$

$$\hat{P}_i \hat{P}_j \neq \delta_{ij} \hat{P}_j$$

$^A |j\rangle^B$

Does not represent a quantum measurement

ments ↔ P

Page: The multiverse requires this (are you in pocket universe A or B?)

$$\hat{P}_i^A = \left(|i\rangle^A \right.$$

$$\hat{P}_i^B = \left(|i\rangle^B \right.$$

Measure entire *U*: $\hat{P}_{ij} \equiv |ij\rangle\langle ij|$

- All everyday probabilities are quantum probabilities

AA & D. Phillips 2014

- All everyday probabilities are quantum probabilities

Our *only* experiences with successful practical applications of probabilities are with quantum probabilities

AA & D. Phillips 2014

- All everyday probabilities are quantum probabilities

- One should not use ideas from everyday probabilities to justify probabilities that have been proven to have no quantum origin

AA & D. Phillips 2014

- All everyday probabilities are quantum probabilities

- One should not use ideas from everyday probabilities to justify probabilities that have been proven to have no quantum origin

A problem for many multiverse theories

AA & D. Phillips 2014

- All everyday probabilities are quantum probabilities

- One should not use ideas from everyday probabilities to justify probabilities that have been proven to have no quantum origin

A problem for many multiverse theories (as practiced)

AA & D. Phillips 2014

Quantum

Non-Quan

$U = A$

BUT: It is impossible to construct a projection operator for the case where you do not know whether it is A or B that is being measured.

Could Write

$$\hat{P}_i = p_A \hat{P}_i^A + p_B \hat{P}_i^B$$

$$\hat{P}_i \hat{P}_j \neq \delta_{ij} \hat{P}_j$$

Classical Probabilities to measure A, B

$^A|j\rangle^B$

Does not represent a quantum measurement

ments ←→ P

$$\hat{P}_i^A = \left(|i\rangle^A\right.$$

$$\hat{P}_i^B = \left(|i\rangle^B\right.$$

Page: The multiverse requires this (are you in pocket universe A or B?)

Measure entire U:

$$\hat{P}_{ij} \equiv |ij\rangle\langle ij|$$

Quantum

Non-Quan

$U = A($

BUT: It is impossible to construct a projection operator for the case where you do not know whether it is A or B that is being measured.

Could Write

$$\hat{P}_i = p_A \hat{P}_i^A + p_B \hat{P}_i^B$$

$$\hat{P}_i \hat{P}_j \neq \delta_{ij} \hat{P}_j$$

Classical Probabilities to measure A, B

Where do these come from anyway?

Does not represent a quantum measurement

...ments ←→ P...

$\hat{P}_i^A = \left(|i\rangle^A\right.$

$\hat{P}_i^B = \left(|i\rangle^B\right.$

Page: The multiverse requires this (are you in pocket universe A or B?)

M... ...y:

Measure entire *U*: $\hat{P}_{ij} \equiv |ij\rangle\langle ij|$

Outline

1) Quantum vs non-quantum probabilities (toy model/multiverse)
2) Everyday probabilities
3) Be careful about counting!
4) Implications for multiverse/eternal inflation

Outline

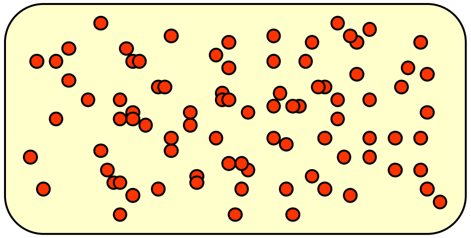
1) Quantum vs non-quantum probabilities (toy model/multiverse)

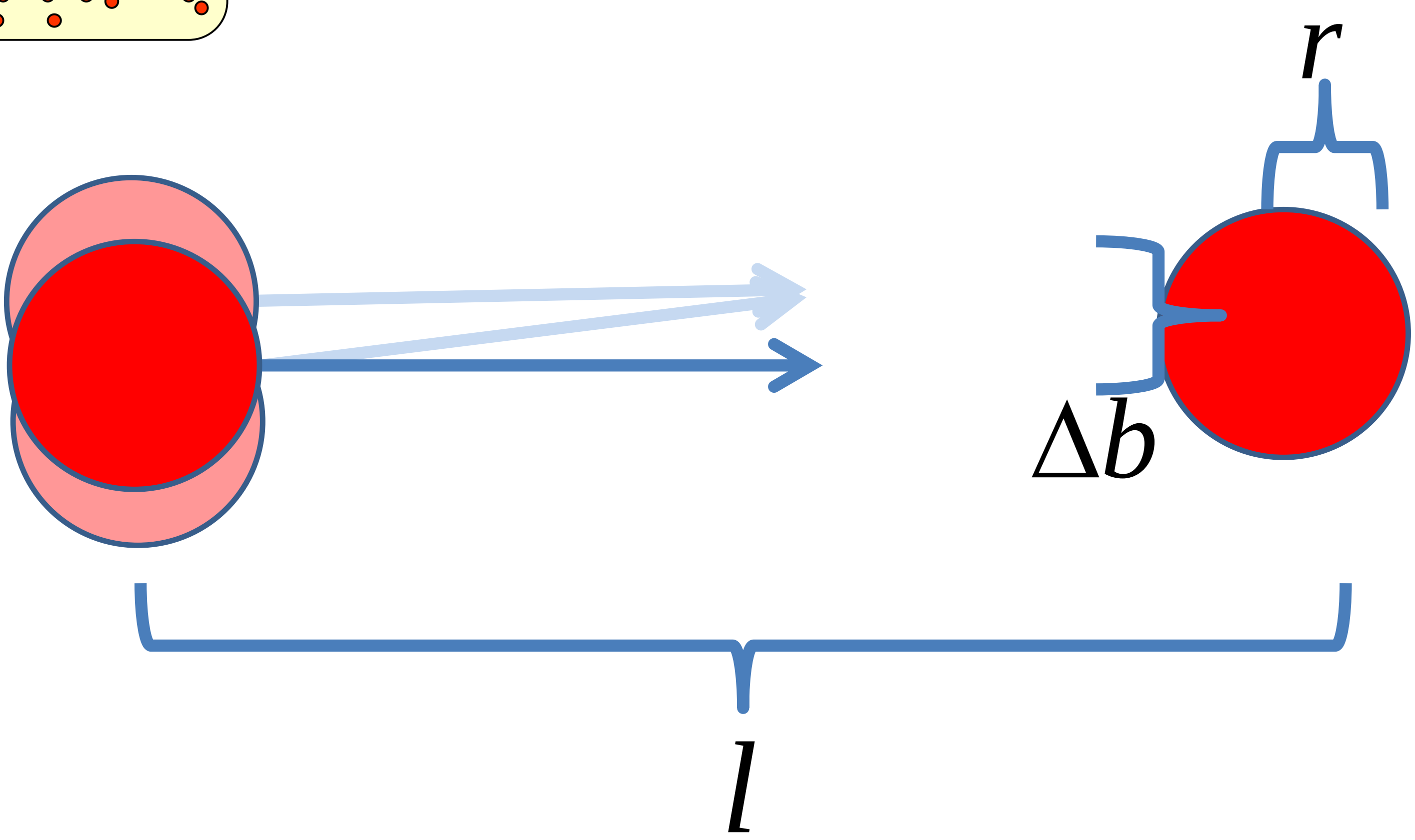
2) Everyday probabilities

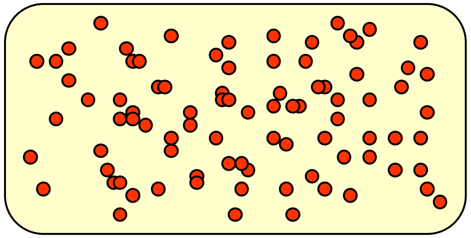
3) Be careful about counting!

4) Implications for multiverse/eternal inflation

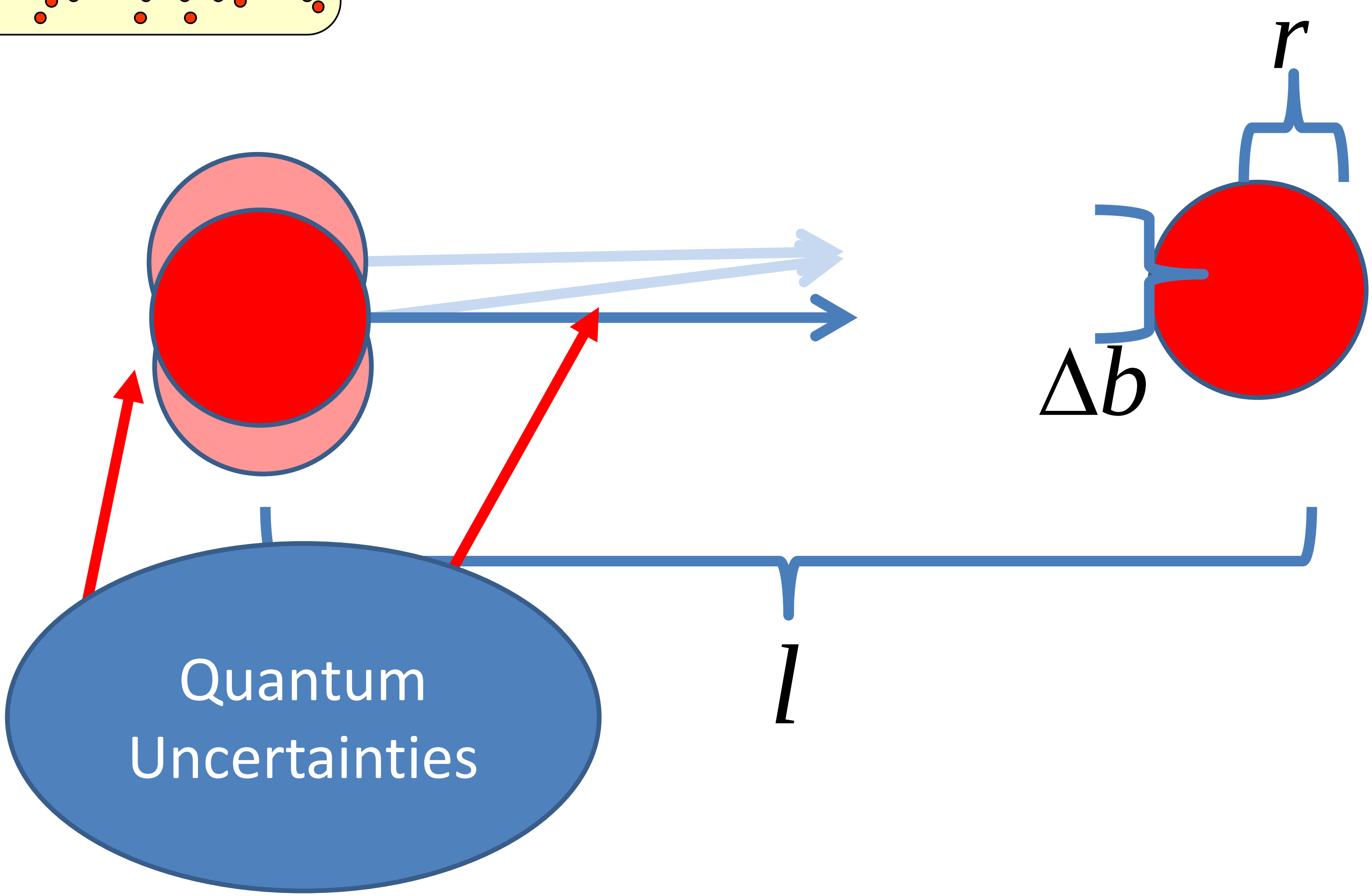
Quantum effects in a billiard gas

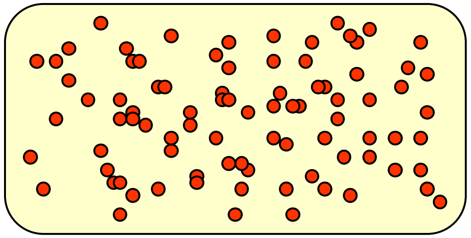




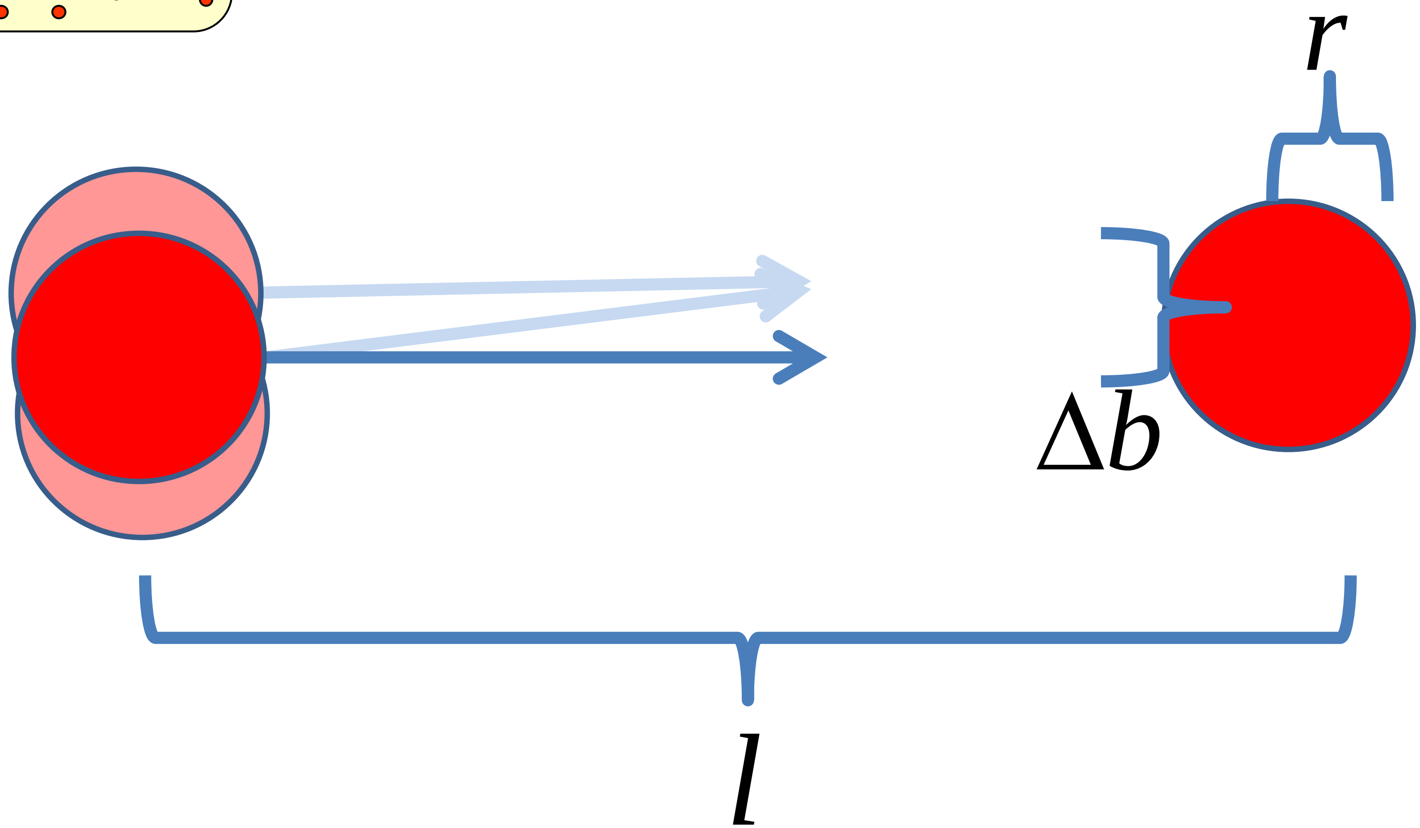


Quantum effects in a billiard gas

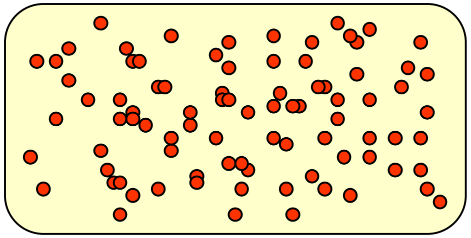




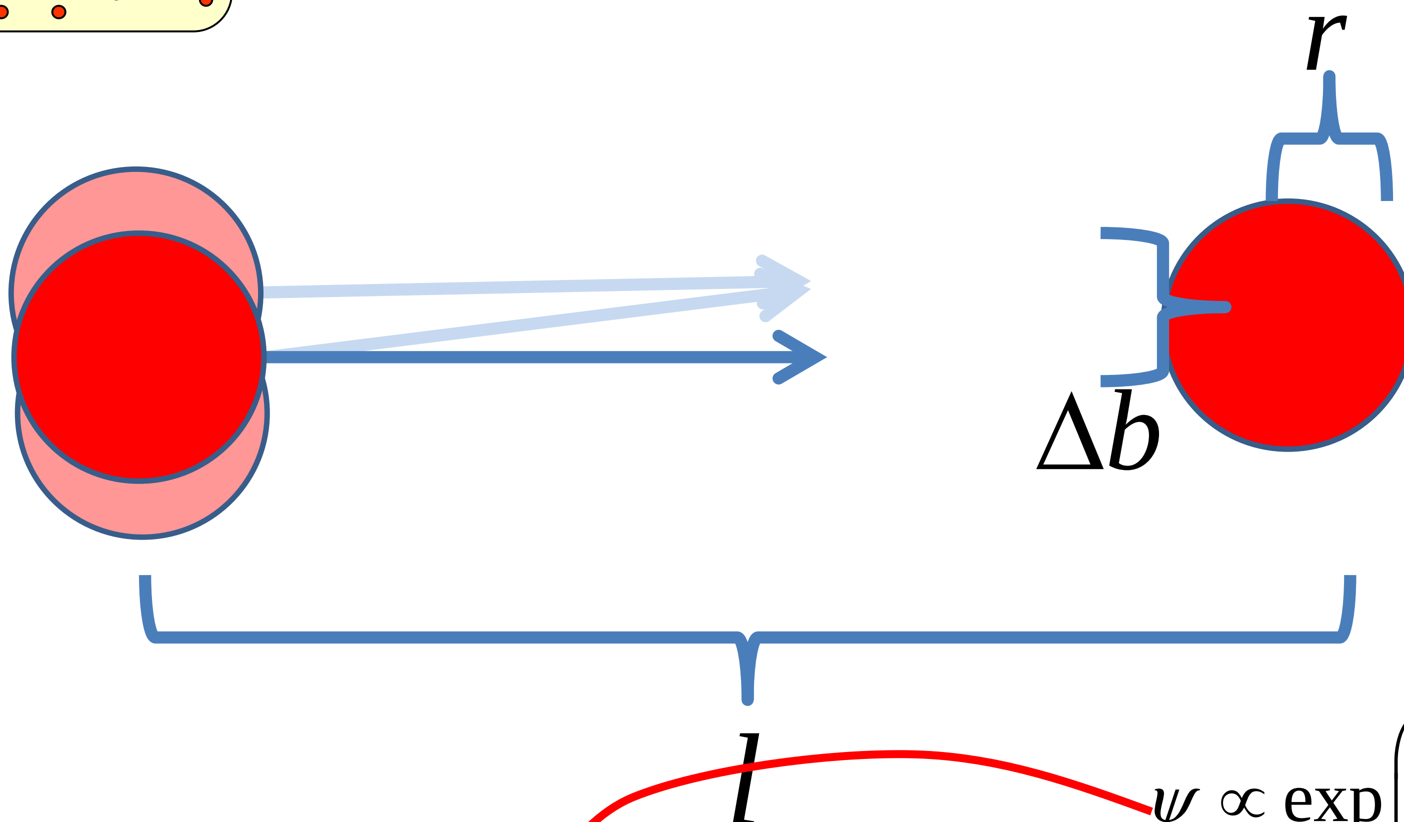
Quantum effects in a billiard gas



$$\Delta b = \delta x_{\perp} + \frac{\delta p_{\perp}}{m} \Delta t$$

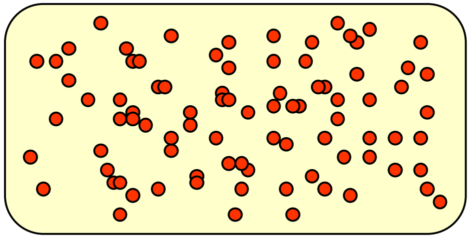


Quantum effects in a billiard gas

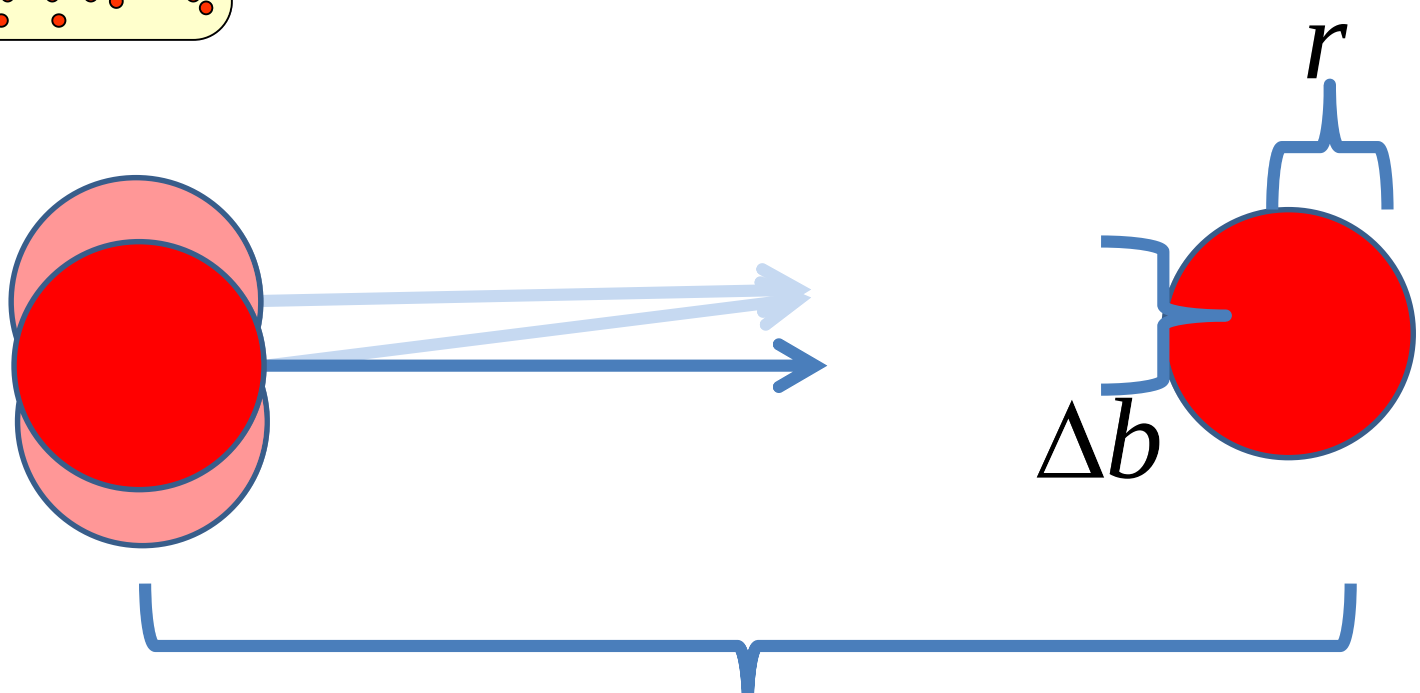


$$\psi \propto \exp\left(\frac{-x^2}{2a^2}\right)$$

$$\Delta b = \delta x_\perp + \frac{\delta p_\perp}{m}\Delta t = \sqrt{2}\left(a + \frac{\hbar}{2a}\frac{l}{m\bar{v}}\right)$$



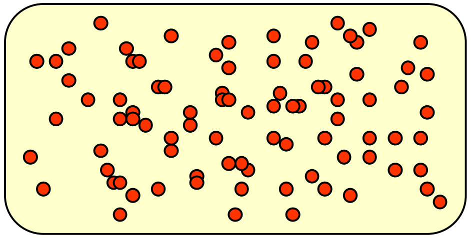
Quantum effects in a billiard gas



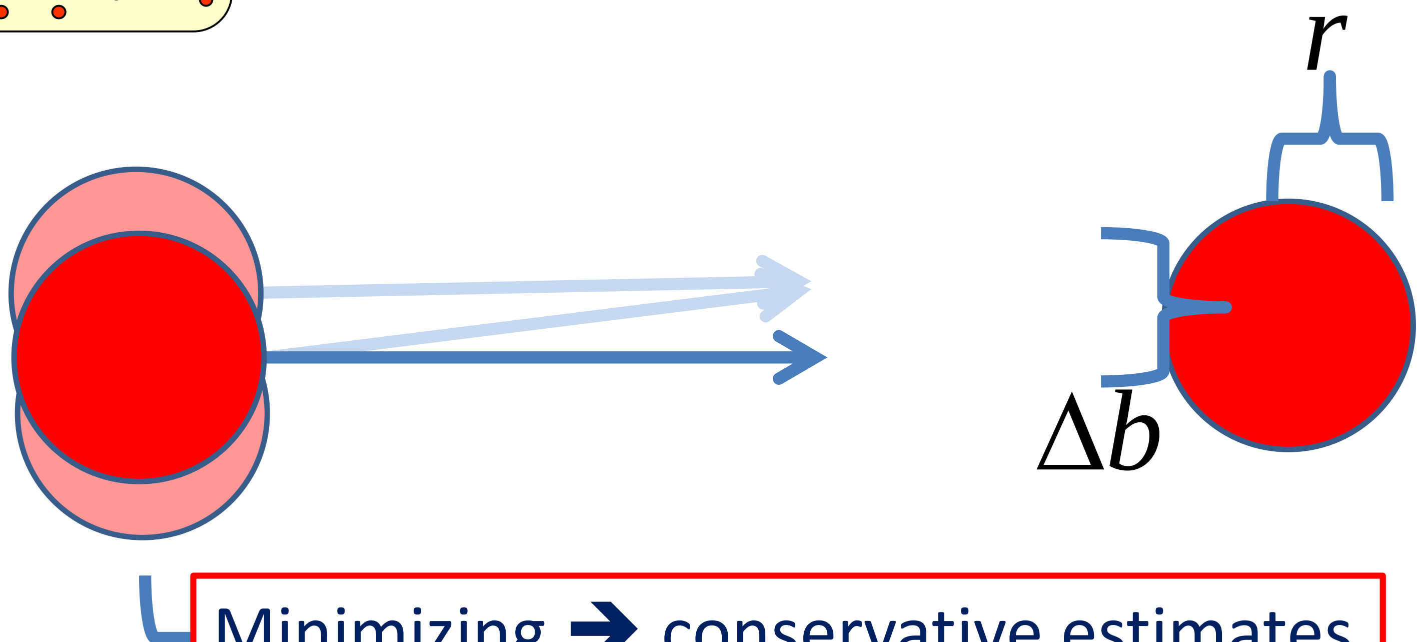
$$\Delta b = \delta x_{\perp} + \frac{\delta p_{\perp}}{m}\Delta t = \sqrt{2}\left(a + \frac{\hbar}{2a}\frac{l}{m\bar{v}}\right)$$

$$\psi \propto \exp\left(\frac{-x^2}{2a^2}\right)$$

$$\xrightarrow{\min} 2^{3/2}\left(\frac{\hbar l}{2m\bar{v}}\right) \equiv \sqrt{l\lambda\!\!\!^{-}_{dB}/2}$$



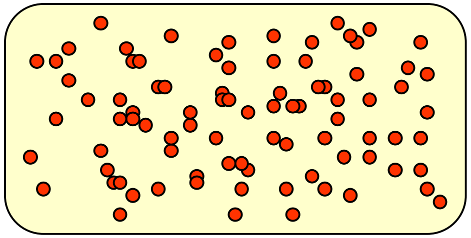
Quantum effects in a billiard gas



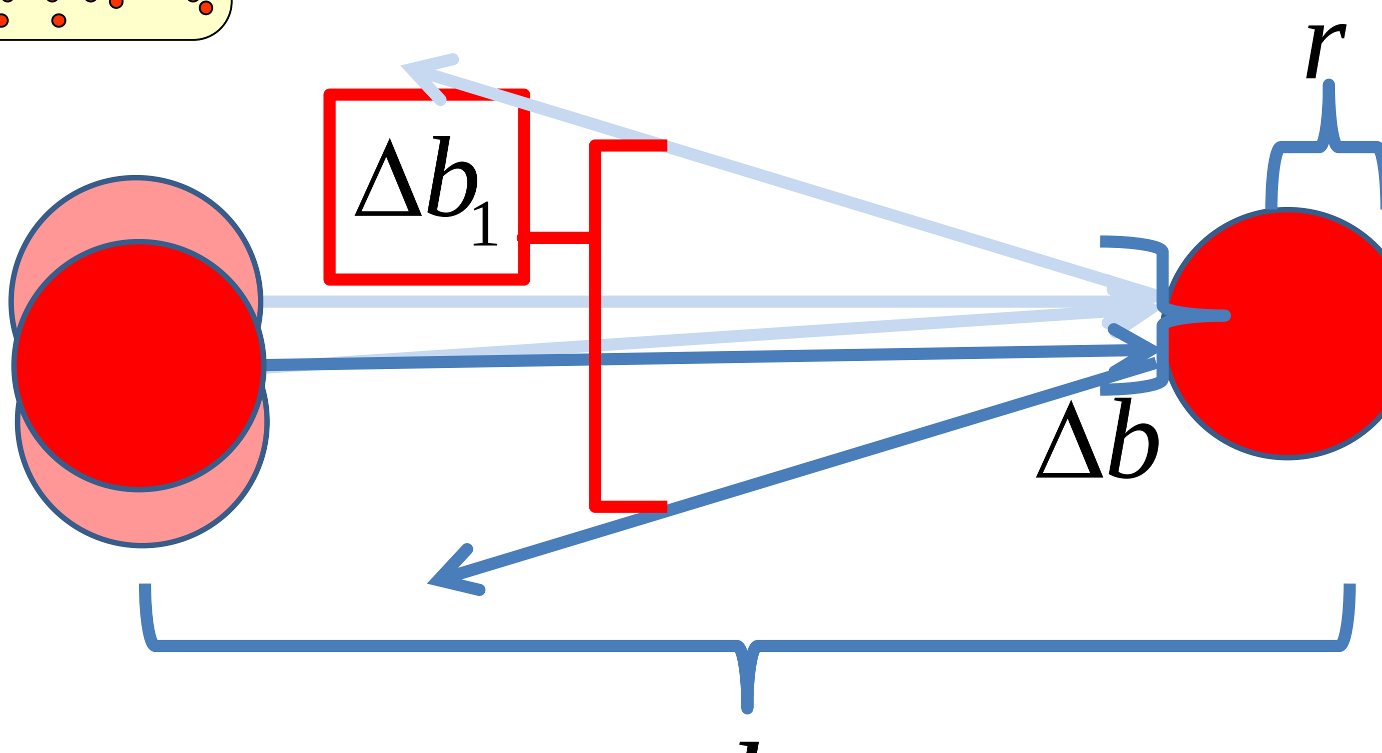
Minimizing ➔ conservative estimates for my purposes (also motivated by decoherence in some cases)

$$\Delta b = \delta x_{\perp} \quad \ldots \quad m \quad \ldots \quad 2a^2 m v \quad \ldots \quad \left(\frac{-x^2}{2a^2}\right)$$

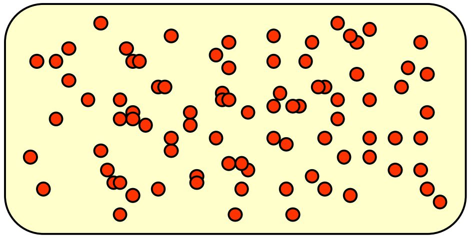
$$\xrightarrow{\min} 2^{3/2}\left(\frac{\hbar l}{2m\bar{v}}\right) \equiv \sqrt{l \lambda\!\!\!^{-}_{dB} / 2}$$



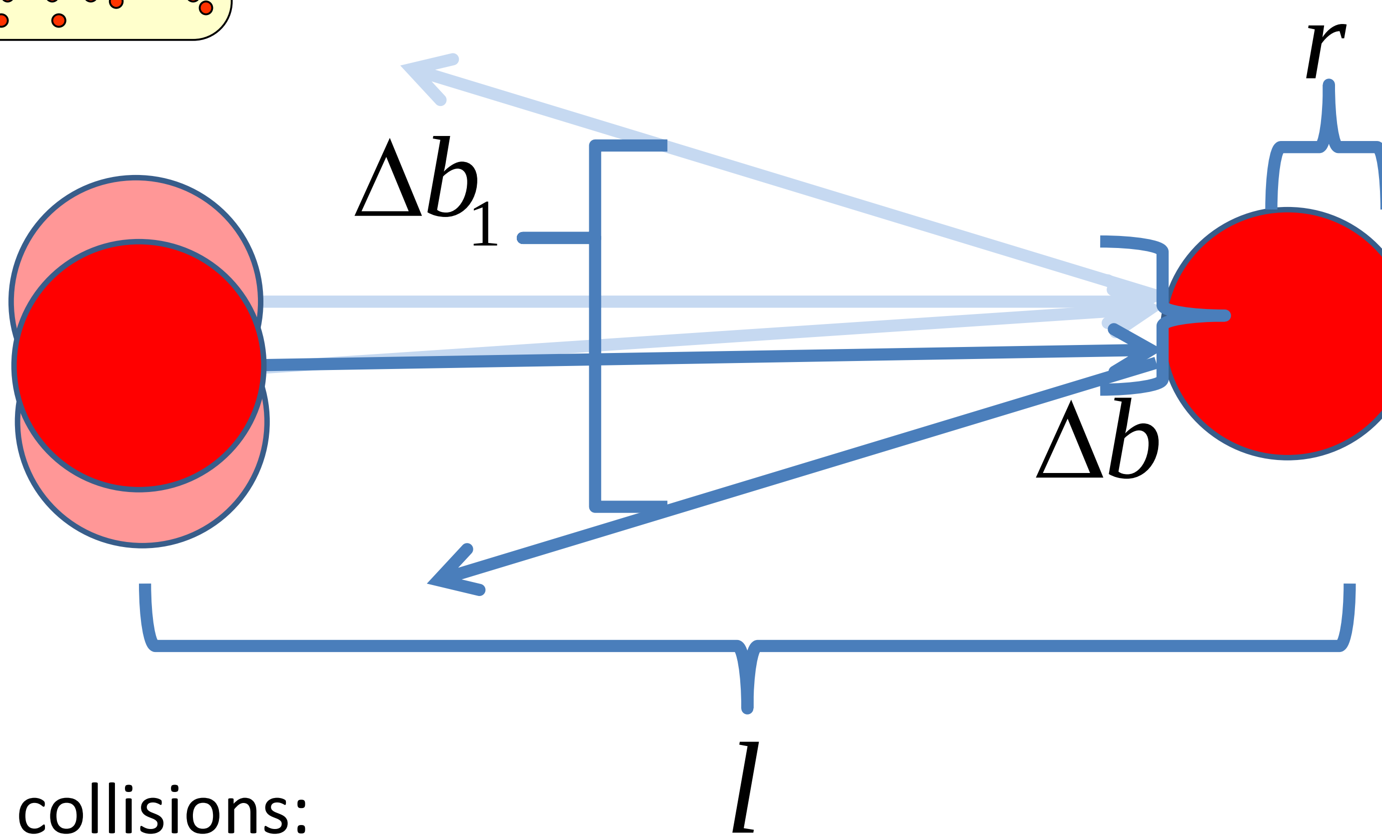
Quantum effects in a billiard gas



Subsequent collisions amplify the initial uncertainty (treat later collisions classically ➔ additional conservatism)

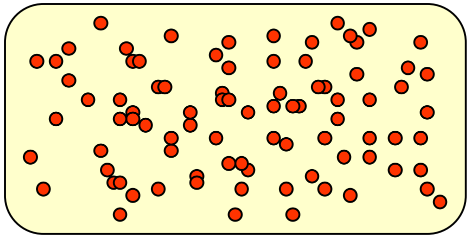


Quantum effects in a billiard gas

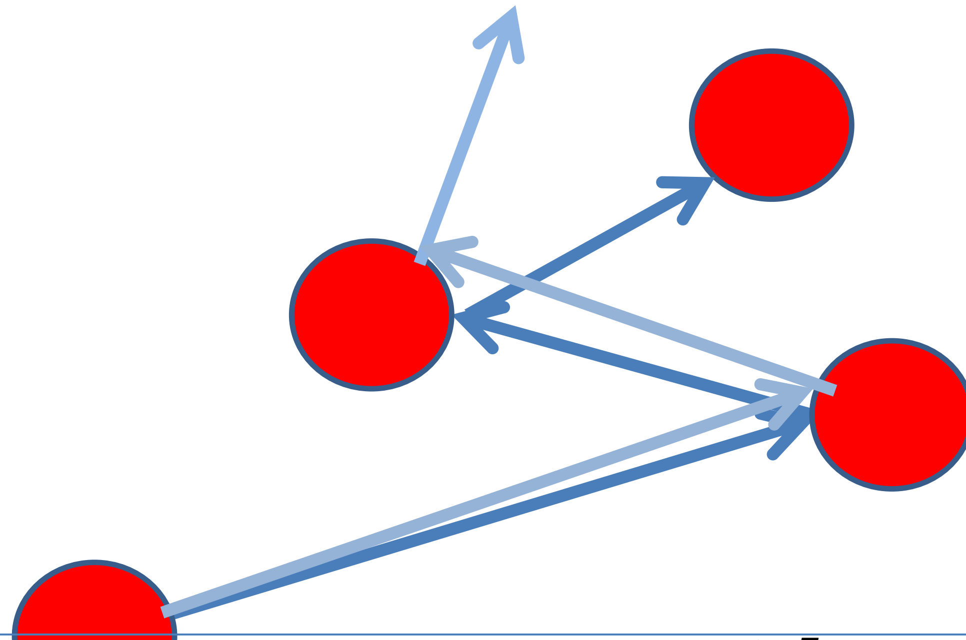


After *n* collisions:

$$\Delta b_n = \Delta b\left(1 + 2l/r\right)^n$$



Quantum effects in a billiard gas



n_Q is the number of collisions so that $\Delta b_{n_Q} = r$

(full quantum uncertainty as to which is the next collision)

$$n_Q = -\frac{\log\left(\frac{\Delta b}{r}\right)}{\log\left(1+\frac{2l}{r}\right)}$$

n_Q for a number of physical systems

(all units MKS)

	r	l	m	$\bar{v}$	λ_{dB}	Δb	n_Q
Air							
Water							
Billiards							
Bumper Car							

n_Q for a number of physical systems

(all units MKS)

	r	l	m	$\bar{v}$	$\lambda\!\!\!^{-}_{dB}$	Δb	n_Q
Air							
Water							
Billiards							
Bumper Car	1	2	150	0.5	1.4×10^{-36}	3.4×10^{-18}	25

n_Q for a number of physical systems

(all units MKS)

	r	l	m	$\bar{v}$	λ_{dB}	Δb	n_Q
Air							
Water							
Billiards	0.029	1	0.16	1	6.6×10^{-34}	5.1×10^{-17}	8
Bumper Car	1	2	150	0.5	1.4×10^{-36}	3.4×10^{-18}	25

n_Q for a number of physical systems

(all units MKS)

	r	l	m	$\bar{v}$	$\lambda\!\!\!^{-}_{dB}$	Δb	n_Q
Air							
Water	3.0×10^{-10}	5.4×10^{-10}	3×10^{-26}	460	7.6×10^{-12}	1.3×10^{-10}	0.6
Billiards	0.029	1	0.16	1	6.6×10^{-34}	5.1×10^{-17}	8
Bumper Car	1	2	150	0.5	1.4×10^{-36}	3.4×10^{-18}	25

n_Q for a number of physical systems

(all units MKS)

	r	l	m	$\bar{v}$	$\bar{\lambda}_{dB}$	Δb	n_Q
Air	1.6×10^{-10}	3.4×10^{-7}	4.7×10^{-26}	360	6.2×10^{-12}	2.9×10^{-9}	-0.3
Water	3.0×10^{-10}	5.4×10^{-10}	3×10^{-26}	460	7.6×10^{-12}	1.3×10^{-10}	0.6
Billiards	0.029	1	0.16	1	6.6×10^{-34}	5.1×10^{-17}	8
Bumper Car	1	2	150	0.5	1.4×10^{-36}	3.4×10^{-18}	25

n_Q for a number of physical systems

(all units MKS)

	r	l	m	$\bar{v}$	$\lambda\!\!\!^{-}_{dB}$	Δb	n_Q
Air	1.6×10^{-10}	3.4×10^{-7}	4.7×10^{-26}	360	6.2×10^{-12}	2.9×10^{-9}	-0.3
Water	3.0×10^{-10}	5.4×10^{-10}	3×10^{-26}	460	7.6×10^{-12}	1.3×10^{-10}	0.6
Billiards	0.029	1	0.16	1	6.6×10^{-34}	5.1	
Bumper Car	1	2	150	0.5	1.4×10^{-36}	3.	

Quantum at every collision



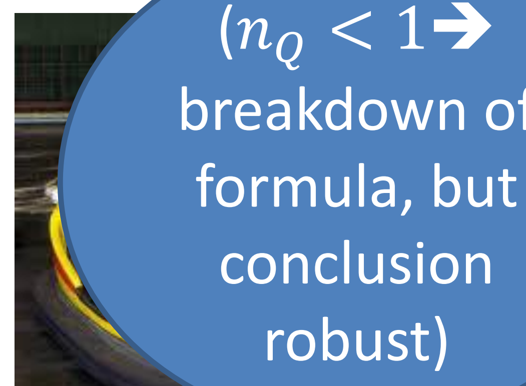

n_Q for a number of physical systems

(all units MKS)

	r	l	m	$\bar{v}$	$\bar{\lambda}_{dB}$	Δb	n_Q
Air	1.6×10^{-10}	3.4×10^{-7}	4.7×10^{-26}	360	6.2×10^{-12}	2.9×10^{-9}	-0.3
Water	3.0×10^{-10}	5.4×10^{-10}	3×10^{-26}	460	7.6×10^{-12}	1.3×10^{-10}	0.6
Billiards	0.029	1	0.16	1	6.6×10^{-34}	5.1	
Bumper Car	1	2	150	0.5	1.4×10^{-36}	3.	

Quantum at every collision

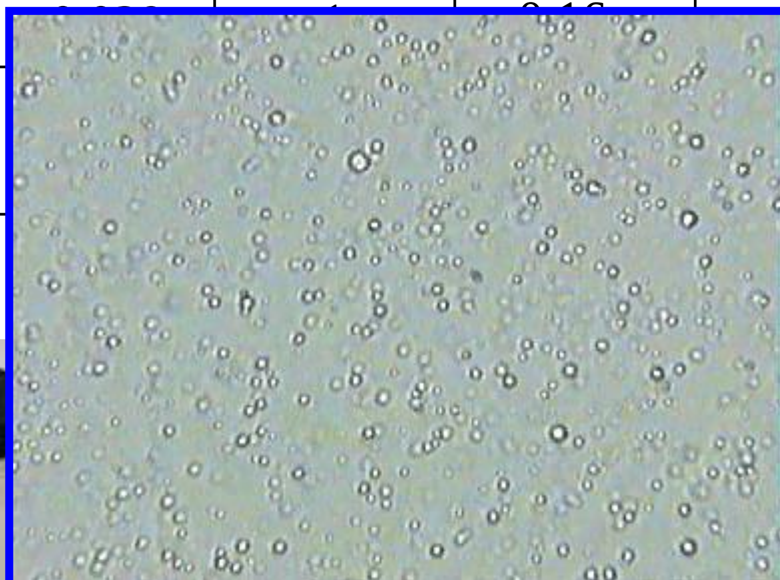
($n_Q < 1$ → breakdown of formula, but conclusion robust)



n_Q for a number of physical systems

(all units MKS)

	r	l	m	$\bar{v}$	$\lambda\!\!\!^{-}_{dB}$	Δb	n_Q
Air	1.6×10^{-10}	3.4×10^{-7}	4.7×10^{-26}	360	6.2×10^{-12}	2.9×10^{-9}	-0.3
Water	3.0×10^{-10}	5.4×10^{-10}	3×10^{-26}	460	7.6×10^{-12}	1.3×10^{-1}[illegible]	0.6
Billiards	[illegible]	[illegible]	[illegible]	1	6.6×10^{-34}	5.1[illegible]	[illegible]
Bumper Car	[illegible]	[illegible]	[illegible]	.5	1[illegible]	[illegible]	[illegible]



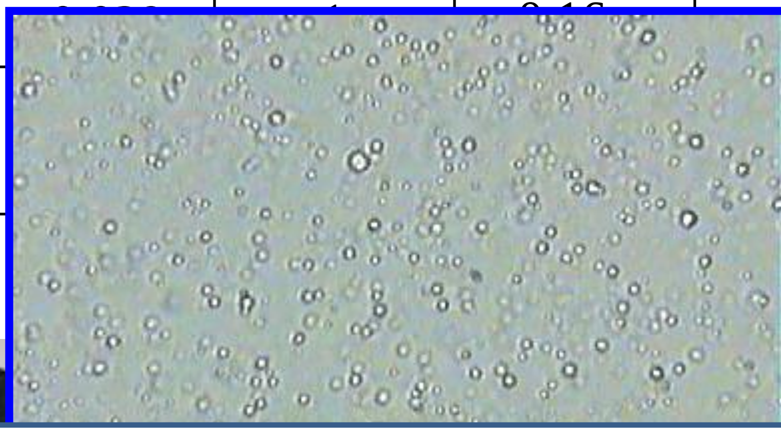
Quantum at every collision

Every Brownian Motion is a "Schrödinger Cat"

n_Q for a number of physical systems

(all units MKS)

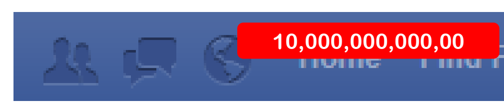
	r	l	m	$\bar{v}$	λ_{dB}	Δb	n_Q
Air	1.6×10^{-10}	3.4×10^{-7}	4.7×10^{-26}	360	6.2×10^{-12}	2.9×10^{-9}	-0.3
Water	3.0×10^{-10}	5.4×10^{-10}	3×10^{-26}	460	7.6×10^{-12}	1.3×10^{-10}	0.6
Billiards	[illegible]	[illegible]	[illegible]	[illegible]	6.6×10^{-34}	5.[illegible]	[illegible]
Bumper Car	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]



Quantum at every [illegible]llision

Every Brownian Motion is a "Schrödinger

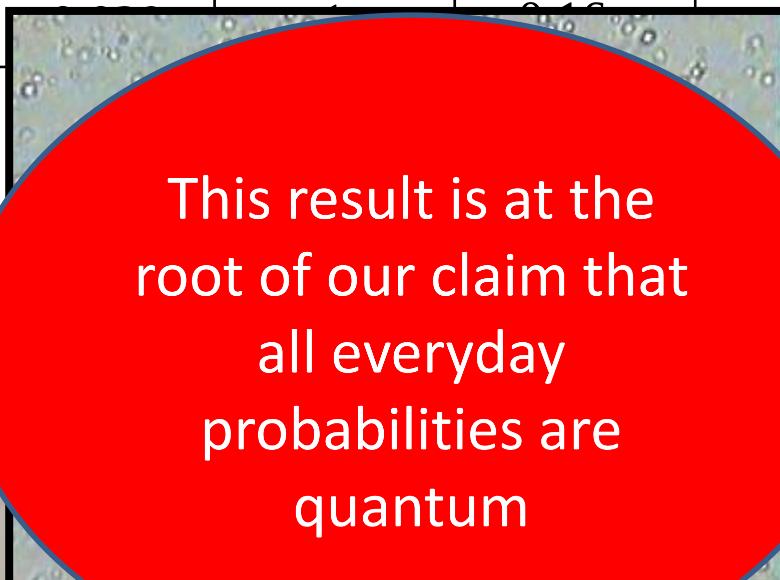
(independent of "interpretation")



n_Q for a number of physical systems

(all units MKS)

	r	l	m	$\bar{v}$	λ_{dB}	Δb	n_Q
Air	1.6×10^{-10}	3.4×10^{-7}	4.7×10^{-26}	360	6.2×10^{-12}	2.9×10^{-9}	-0.3
Water	3.0×10^{-10}	5.4×10^{-10}	3×10^{-26}	460	7.6×10^{-12}	1.3×10^{-10}	0.6
Billiards	[illegible]	[illegible]	[illegible]	1	6.6×10^{-34}	5.1 [illegible]	[illegible]
Bumper Car	[illegible]	[illegible]	[illegible]	.5	1 [illegible]	[illegible]	[illegible]

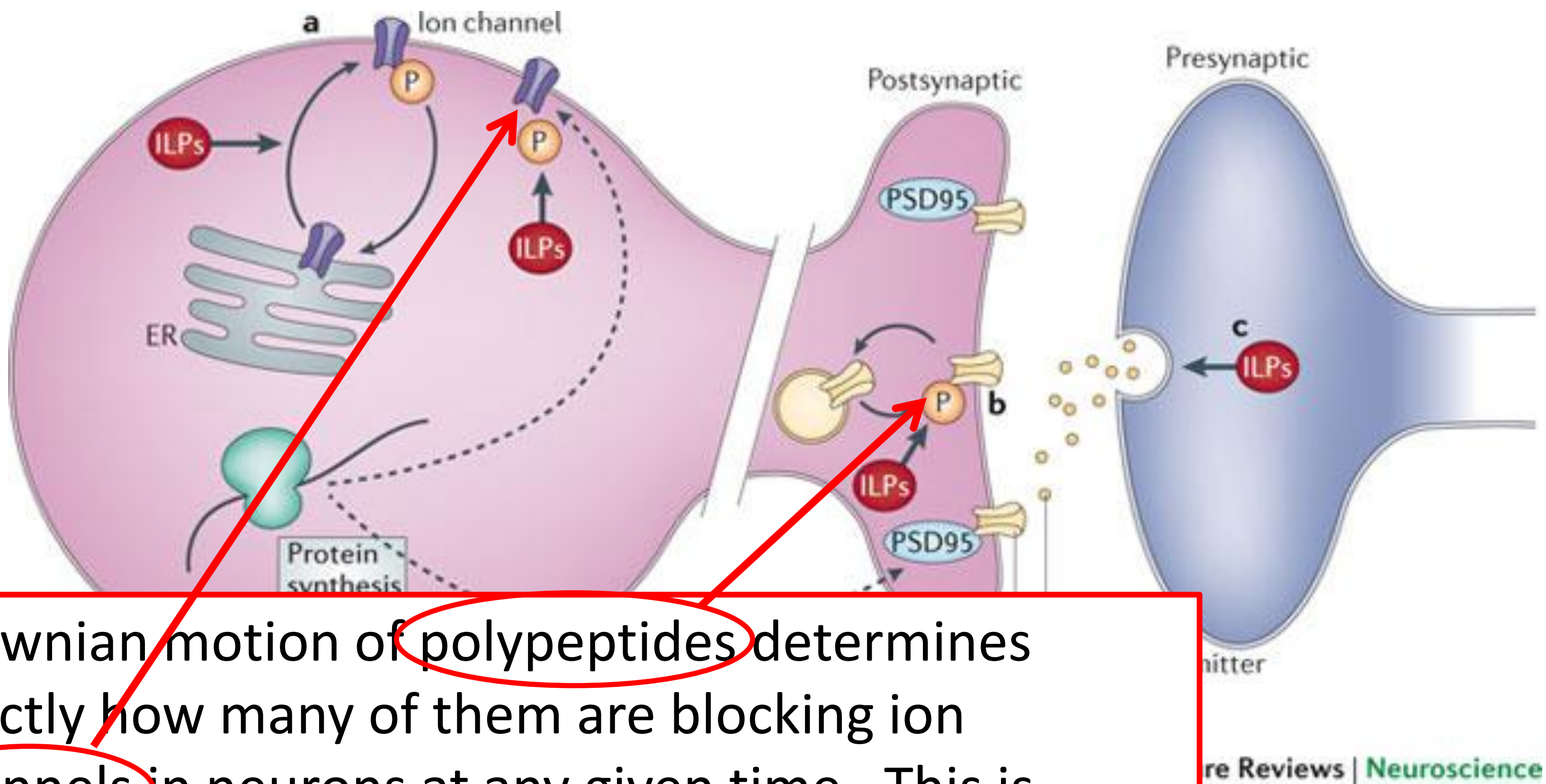


This result is at the root of our claim that all everyday probabilities are quantum

Every Brownian Motion is a "Schrödinger Cat"

Quantum at every ...llision

An important role for Brownian motion: Uncertainty in neuron transmission times



Brownian motion of polypeptides determines exactly how many of them are blocking ion channels in neurons at any given time. This is believed to be the dominant source of *neuron transmission time uncertainties* $\delta t_n \approx 1ms$

Image from http://www.nature.com/nrn/journal/v13/n4/full/nrn3209.html

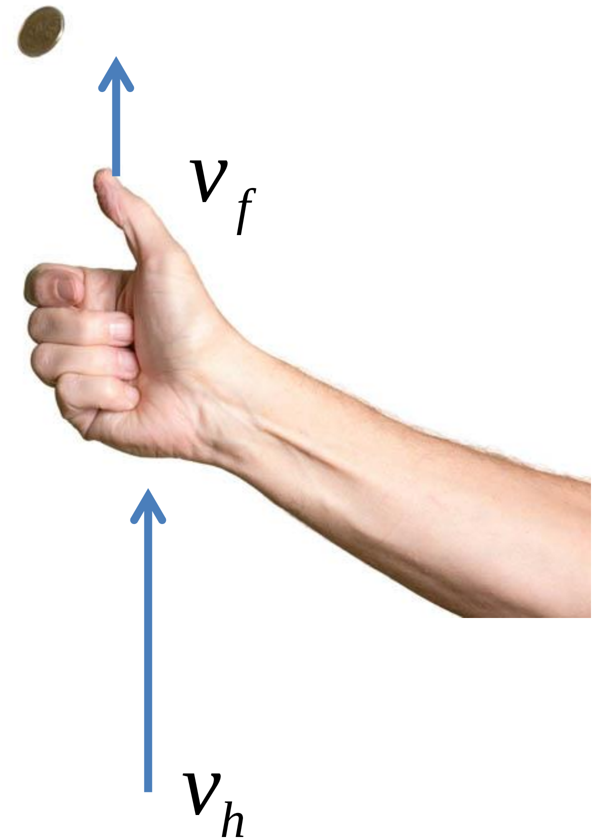
Analysis of coin flip

$$\delta t_f = \delta t_n \times \left(\frac{v_h}{v_h + v_f} \right)$$

$$\delta t_t = \sqrt{2}\,\delta t_f$$

$$f = \frac{4 v_f}{\pi d}$$

$$\delta N = f\,\delta t_t = 0.5$$



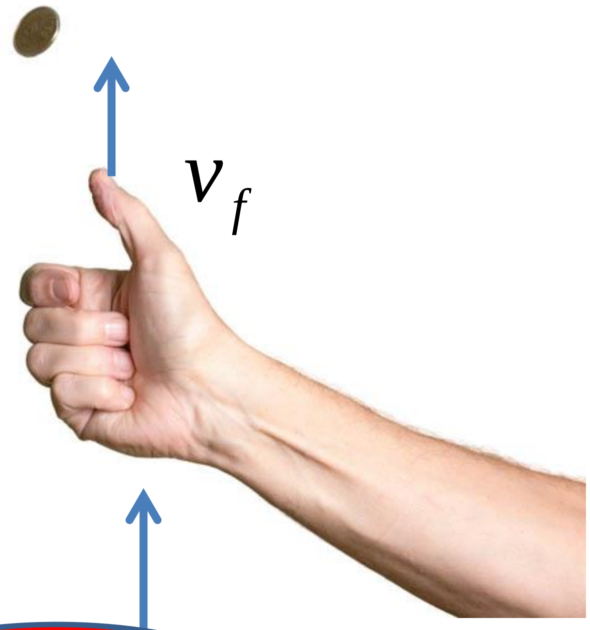
Coin diameter $= d$

Using:

$\delta t_n \approx 1ms$ $\quad$ $v_h = v_f = 5m/s$

$d = 0.01m$

Analysis of coin flip



$$\delta t_f = \delta t_n \times \left(\frac{v_h}{v_h + v_f} \right)$$

$$\delta t_t = \sqrt{2}\,\delta t_f$$

$$f = \frac{4v_f}{\pi d}$$

$$\delta N = f\,\delta t_t = 0.5$$

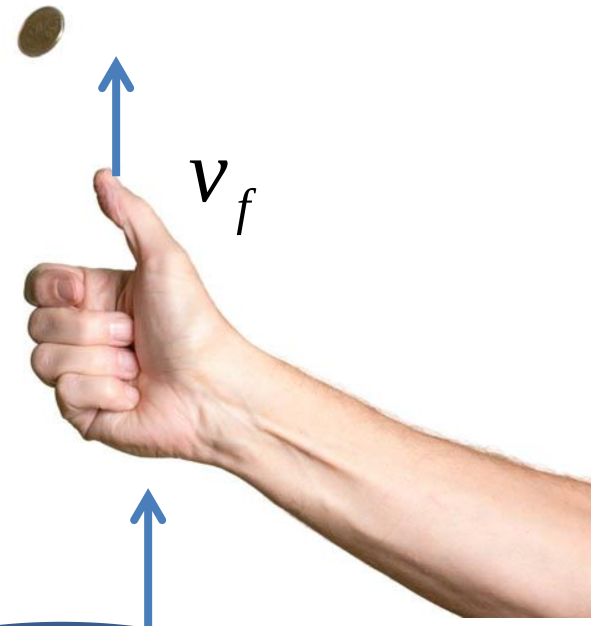
Using:

$$\delta t_n \approx 1ms \qquad v_h = v_f = 5$$

$$d = 0.01m$$

50-50 coin flip probabilities are a derivable quantum result

Analysis of coin flip



$$\delta t_f = \delta t_n \times \left(\frac{v_h}{v_h + v_f} \right)$$

$$\delta t_t = \sqrt{2}\,\delta t_f$$

$$f = \frac{4 v_f}{\pi d}$$

$$\delta N = f\,\delta t_t = 0.5$$

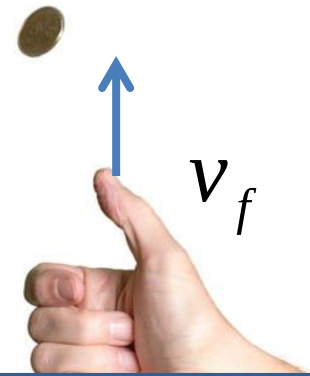
Usin

d

Without reference to “principle of indifference” etc. etc.

50-50 coin flip probabilities are a derivable quantum result

Analysis of coin flip



v_f

$$\delta t_f = \delta t_n \times \left(\frac{v_h}{v_h + v_f} \right)$$

$$\delta t_t = \sqrt{2}\,\delta t_f$$

$$f = \frac{4 v_f}{\pi d}$$

$$\delta N = f\,\delta t_t = 0.5$$

NB: Coin flip is "at the margin" of deterministic vs random: Increasing *d* or deceasing v_h can reduce δN substantially

v_h

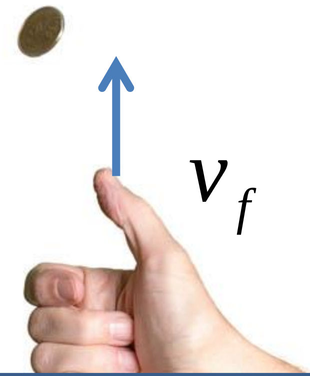
Coin diameter $= d$

Using:

$\delta t_n \approx 1ms$ $\quad v_h = v_f = 5m/s$

$d = 0.01m$

Analysis of coin flip



v_f

$$\delta t_f = \delta t_n \times \left(\frac{v_h}{v_h + v_f} \right)$$

$$\delta t_t = \sqrt{2}\,\delta t_f$$

$$f = \frac{4 v_f}{\pi d}$$

$$\delta N = f\,\delta t_t = 0.5$$

NB: Coin flip is "at the margin" of deterministic vs random: Increasing *d* or deceasing v_h can reduce δN substantially

v_h

Coin diameter $= d$

Using:

Still, this is a good illustration of how quantum uncertainties can filter up into the macroscopic world, for systems that *are* random.

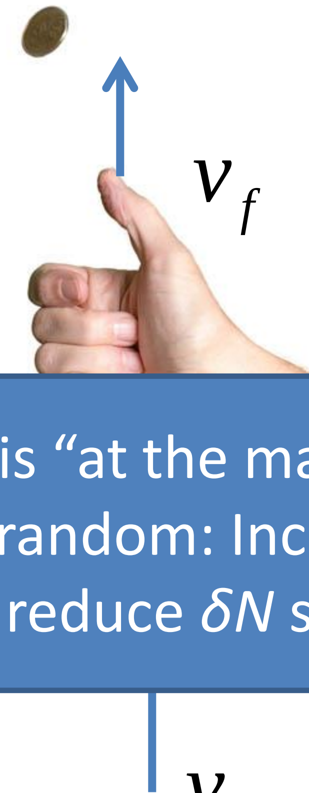
Analysis of coin flip

$$\delta t_f = \delta t_n \times \left(\frac{v_h}{v_h + v_f} \right)$$

$$\delta t_t = \sqrt{2}\,\delta t_f$$

$$f = \frac{4 v_f}{\pi d}$$

$$\delta N = f\,\delta t_t = 0.5$$



Coin diameter $= d$

NB: Coin flip is “at the margin” of deterministic vs random: Increasing *d* or deceasing v_h can reduce δN substantially

Using:

Still, this is a good illustration of how quantum uncertainties can filter up into the macroscopic world, for systems that *are* random.

Physical probabilities vs “probabilities of belief”

Physical probability: To do with physical properties of detector etc

Bayes:

$$P(Theory \mid Data) = \frac{P(Data \mid Theory)}{P(Data)} P(Theory)$$

Physical probabilities vs "probabilities of belief"

Bayes:

$$P(Theory \mid Data) = \frac{P(Data \mid Theory)}{P(Data)} P(Theory)$$

Probabilities of belief:

- Which data you trust most
- Which theory you like best

Physical probabilities vs "probabilities of belief"

This talk is about physical probability only

Bayes:

$$P(Theory \mid Data) = \frac{P(Data \mid Theory)}{P(Data)} P(Theory)$$

Physical probabilities vs "probabilities of belief"

Bayes:

$$P(Theory \mid Data) = \frac{P(Data \mid Theory)}{P(Data)} P(Theory)$$

NB: The goal of science is to get sufficiently good data that probabilities of belief are inconsequential

Physical probabilities vs "probabilities of belief"

Bayes:

$$P(Theory \mid Data) = \frac{P(Data \mid Theory)}{P(Data)} P(Theory)$$

NB: The goal of science is to get sufficiently good data that probabilities of belief are inconsequential

Physical probabilities vs “probabilities of belief”

Adding new data (theory priors can include earlier data sets):

$$P_4(T \mid D_4) = \frac{P(D_4 \mid T)}{P(D_4)} P_3(T)$$

$$P_5(T \mid D_5) = \frac{P(D_5 \mid T)}{P(D_5)} P_4(T)$$

Physical probabilities vs “probabilities of belief”

Adding new data (theory priors can include earlier data sets):

$$P_1(T \mid D_1) = \frac{P(D_1 \mid T)}{P(D_1)} P_0(T)$$

$$P_4(T \mid D_4) = \frac{P(D_4 \mid T)}{P(D_4)} P_3(T)$$

$$P_5(T \mid D_5) = \frac{P(D_5 \mid T)}{P(D_5)} P_4(T)$$

Physical probabilities vs "probabilities of belief"

Adding new data (theory priors can include earlier data sets):

$$P_1(T \mid D_1) = \frac{P(D_1 \mid T)}{P(D_1)} P_0(T)$$

This initial "model uncertainty" prior is the only *P(T)* that is a *pure* probability of belief.

$$P_4(T \mid D_4) = \frac{P(D_4 \mid T)}{P(D_4)} P_3(T)$$

$$P_5(T \mid D_5) = \frac{P(D_5 \mid T)}{P(D_5)} P_4(T)$$

Physical probabilities vs “probabilities of belief”

Adding new data (theory priors can include earlier data sets):

$$P_1(T|D_1) = \frac{P(D_1|T)}{P(D_1)} P_0(T)$$

This initial “model uncertainty” prior is the only *P(T)* that is a *pure* probability of belief.

$$P_4(T|D_4) = \frac{P(D_4|T)}{P(D_4)} P_3(T)$$

$$\frac{P(D_5|T)}{\ldots D_5)} P_4(T)$$

This talk is only about $P(D|T)$ wherever it appears

Physical probabilities vs "probabilities of belief"

Adding new data (theory priors can include earlier data sets):

$$P_1(T|D_1) = \frac{P(D_1|T)}{P(D_1)} P_0(T)$$

This initial "model uncertainty" prior is the only *P(T)* that is a *pure* probability of belief.

This talk is only about $P(D|T)$ wherever it appears

NB: The goal of science is to get sufficiently good data that probabilities of belief are inconsequential

Physical probabilities vs "probabilities of belief"

Adding new data (theory priors can include earlier data sets):

$$P_1(T \mid D_1) = \frac{P(D_1 \mid T)}{P(D_1)} P_0(T)$$

This initial "model uncertainty" prior is the only *P(T)* that is a *pure* probability of belief

This is the only part of the formula where physical randomness appears

This talk is only about $P(D \mid T)$ … appears

NB: The goal of science is to get sufficiently good data that probabilities of belief are inconsequential

Physical probabilities vs "probabilities of belief"

Adding new data (theory priors can include earlier data sets):

$$P_1(T|D_1) = \frac{P(D_1|T)}{P(D_1)} P_0(T)$$

This initial "model uncertainty" prior is the only *P(T)* that is a *pure* probability of belief

This is the only part of the formula where physical randomness appears

This talk is only about $P(D|T)$ appears

NB: The goal of science is to get sufficiently good data that probabilities of belief are inconsequential

All everyday probabilities are quantum probabilities

- Proof by exhaustion not realistic

All everyday probabilities are quantum probabilities

- Proof by exhaustion not realistic
- One counterexample (practical utility of non-quantum probabilities) will undermine our entire argument.

All everyday probabilities are quantum probabilities

- Proof by exhaustion not realistic
- One counterexample (practical utility of non-quantum probabilities) will undermine our entire argument
- Can still invent classical probabilities just to do multiverse cosmology

All everyday probabilities are quantum probabilities

- Proof by exhaustion not realistic
- One counterexample (practical utility of non-quantum probabilities) will undermine our entire argument
- Can still invent classical probabilities just to do multiverse cosmology
- Not a problem for many finite theories (AA, Banks & Fischler)

All everyday probabilities are quantum probabilities

- Proof by exhaustion not realistic
- One counterexample (practical utility of non-quantum probabilities) will undermine our entire argument
- Can still invent classical probabilities just to do multiverse cosmology
- Not a problem for many finite theories (AA, Banks & Fischler)
- Which theories really do require classical probabilities not yet resolved rigorously.

All everyday probabilities are quantum probabilities

- Proof by exhaustion not realistic
- One counterexample (practical utility of non-quantum probabilities) will undermine our entire argument
- Can still invent classical probabilities just to do multiverse cosmology
- Not a problem for many finite theories (AA, Banks & Fischler)
- Which theories really do require classical probabilities not yet resolved rigorously (symmetry?... simplicity? See below)

All everyday probabilities are quantum probabilities

- Proof by exhaustion not realistic
- One counterexample (practical utility of non-quantum probabilities) will undermine our entire argument
- Can still invent classical probabilities just to do multiverse cosmology
- Not a problem for many finite theories (AA, Banks & Fischler)
- Which theories really do require classical probabilities not yet resolved rigorously (symmetry?... simplicity? See below)

Some further thoughts:

Some further thoughts:

- Special relationship to cosmic structure from inflation: "probability censorship"
- A counterexample: Betting on the digits of Pi (Not!)
- Compare with classical computer
- Compare with color:

Outline

1) Quantum vs non-quantum probabilities (toy model/multiverse)

2) Everyday probabilities

3) Be careful about counting!

4) Implications for multiverse/eternal inflation

Outline

1) Quantum vs non-quantum probabilities (toy model/multiverse)

2) Everyday probabilities

3) Be careful about counting!

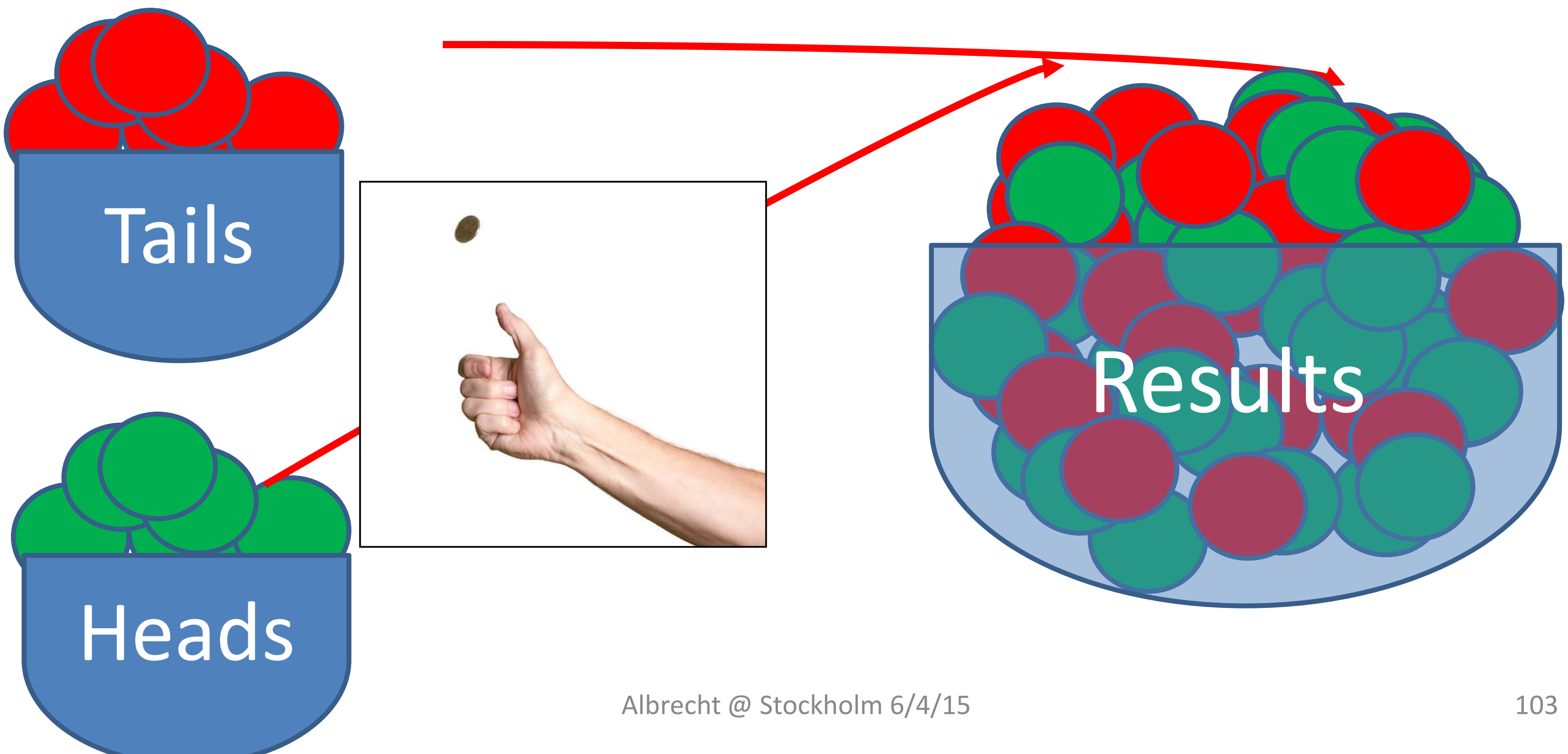
4) Implications for multiverse/eternal inflation

Central message:

- "Randomness is (quantum) physics"
- Counting may or MAY NOT have a role in inferring or representing physical randomness

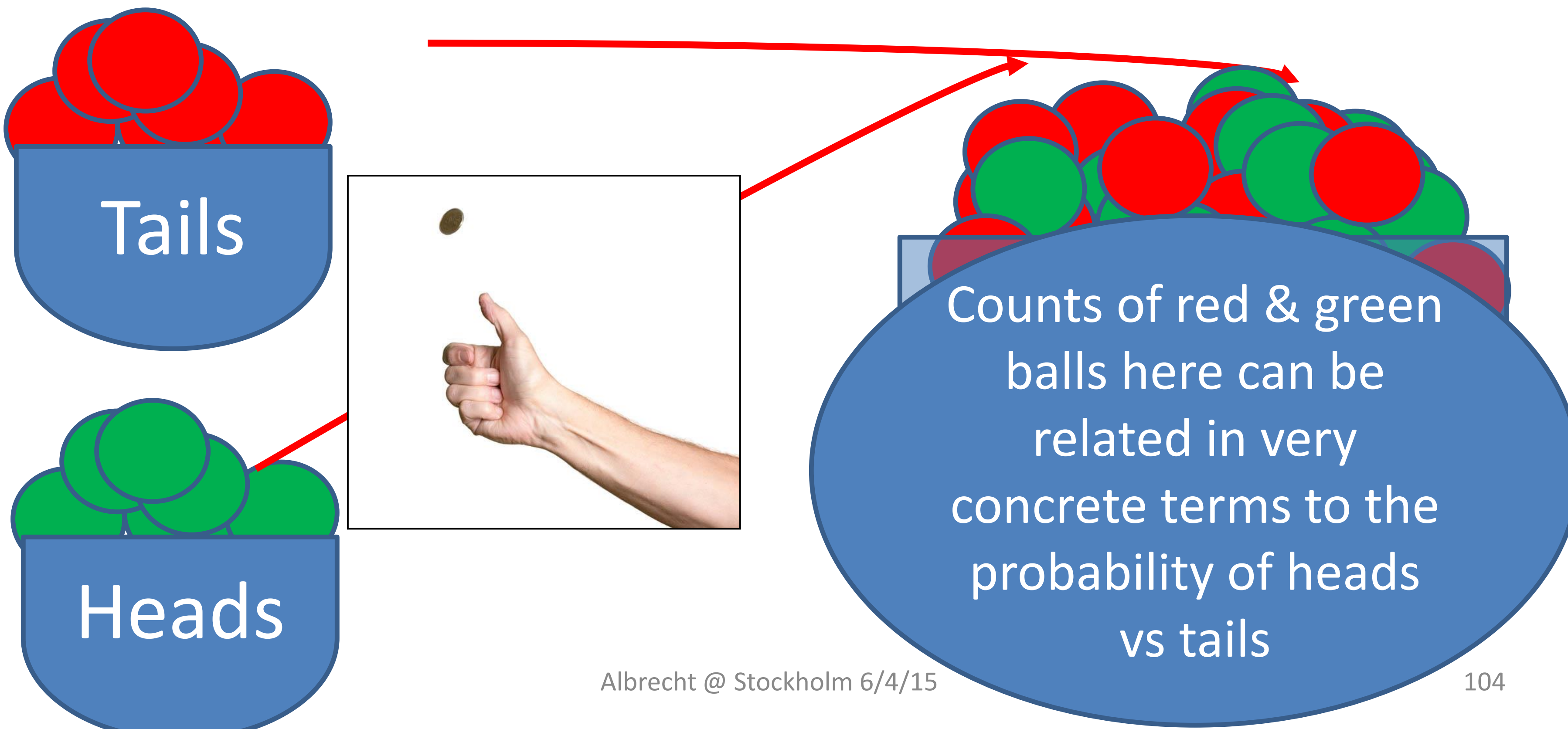
Central message:

- "Randomness is (quantum) physics"
- Counting may or MAY NOT have a role in inferring or representing physical randomness
- Example: Flip a coin and choose a ball:



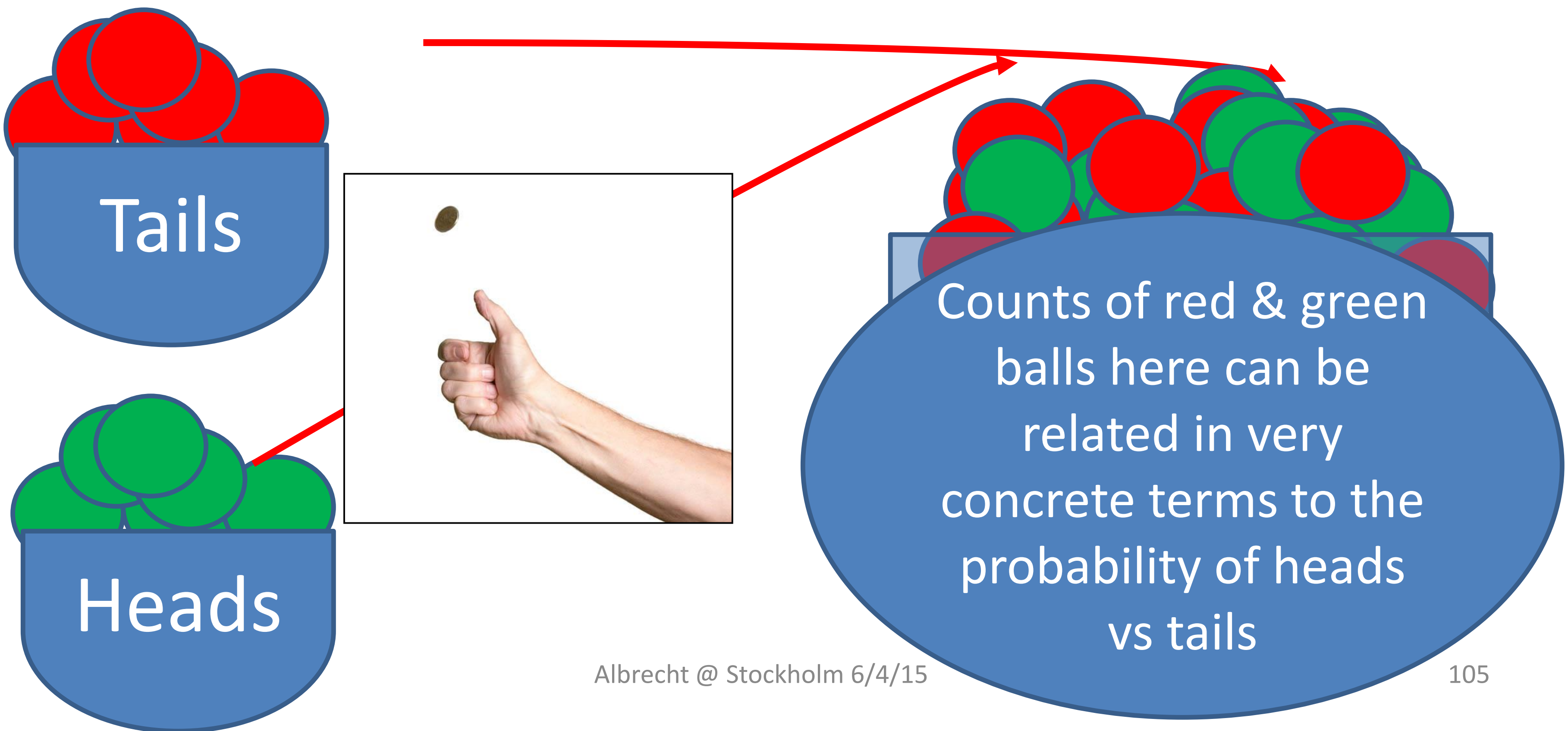
Central message:

- "Randomness is (quantum) physics"
- Counting may or <u>MAY NOT</u> have a role in inferring or representing physical randomness
- Example: Flip a coin and choose a ball:

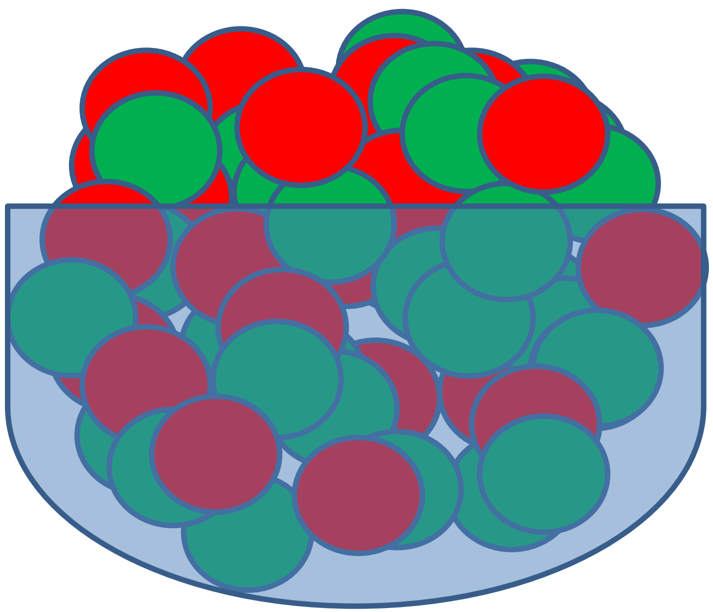


Central message:

- "Randomness is (quantum) physics"
- Counting may or <u>MAY NOT</u> have a role in inferring or representing physical randomness
- Example: Flip a coin and choose a ball:

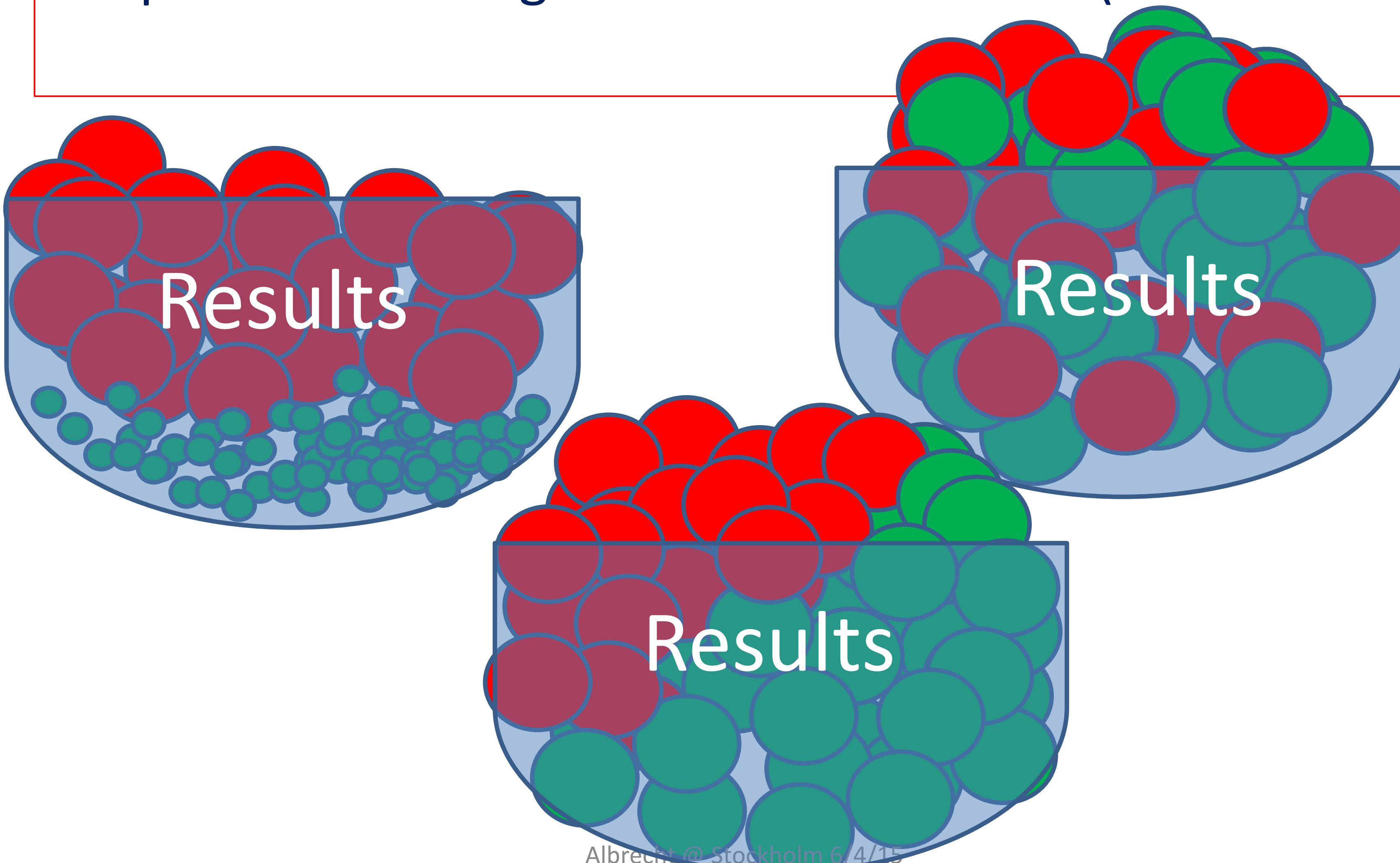


Now ask: What is the probability that a ball drawn from the “Results” bowl is red?



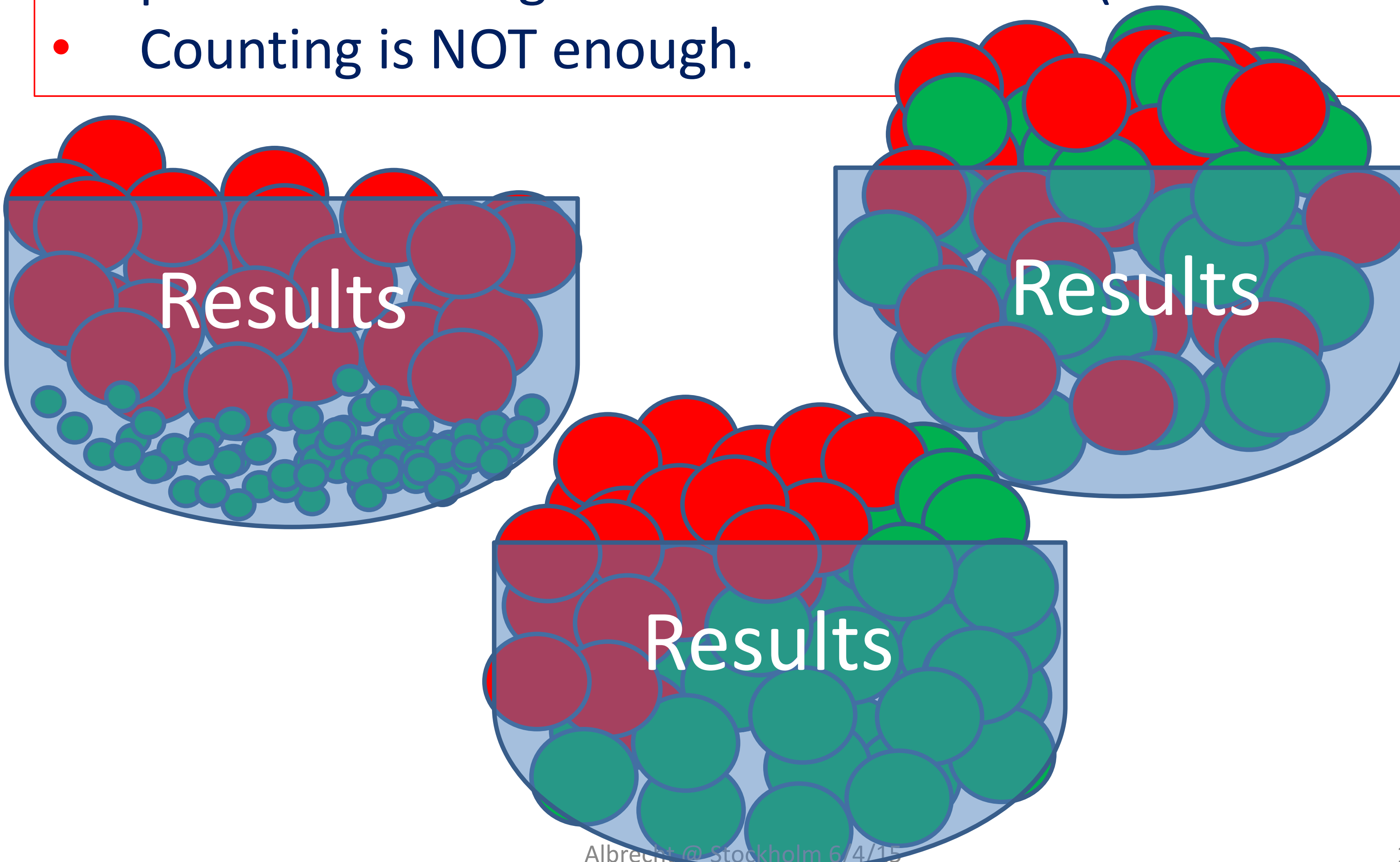
Now ask: What is the probability that a ball drawn from the "Results" bowl is red?

- Different physical "completions" of this question are possible which give different answers. (≈ measures)



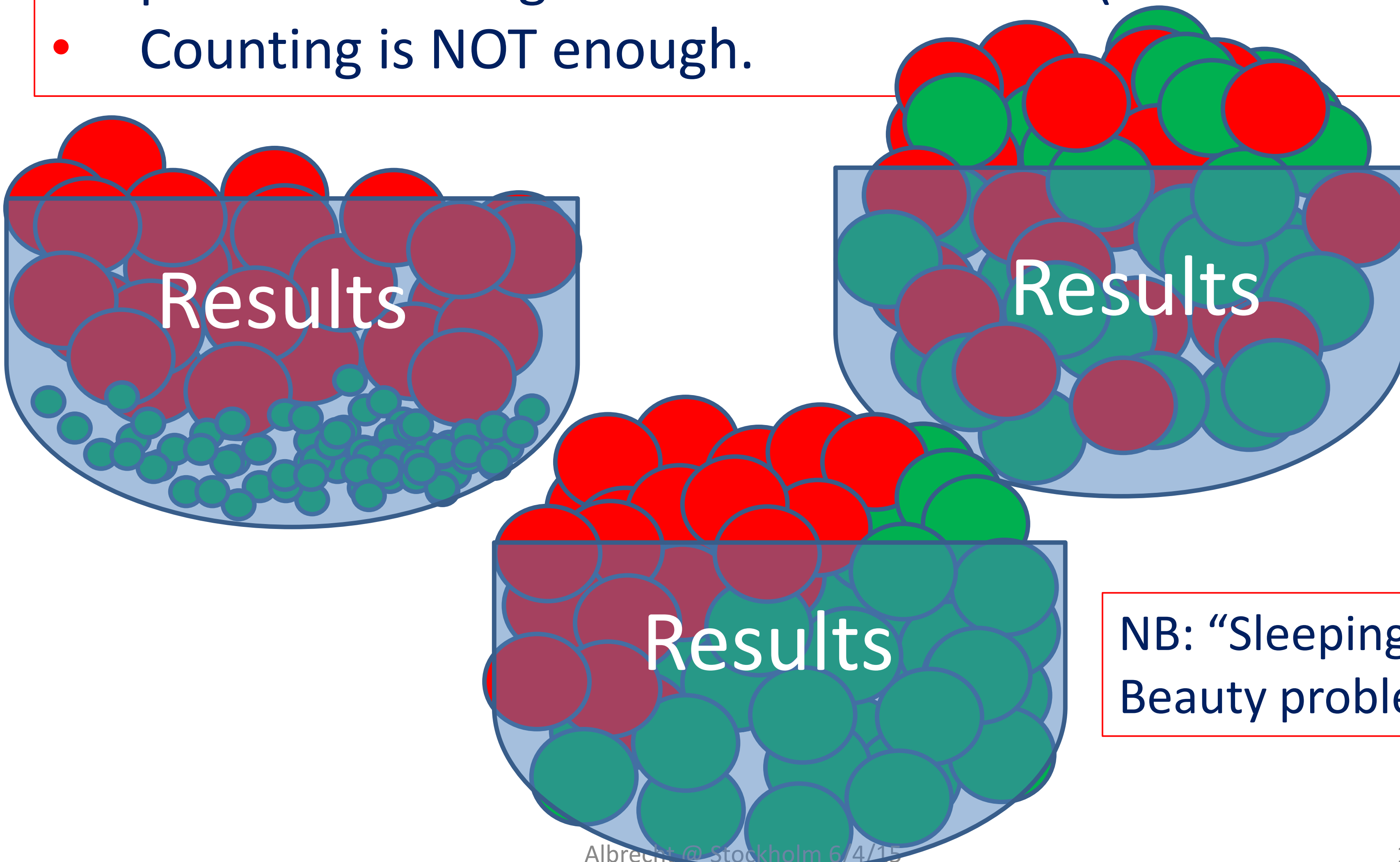
Now ask: What is the probability that a ball drawn from the “Results” bowl is red?

- Different physical “completions” of this question are possible which give different answers. (≈ measures)
- Counting is NOT enough.



Now ask: What is the probability that a ball drawn from the "Results" bowl is red?

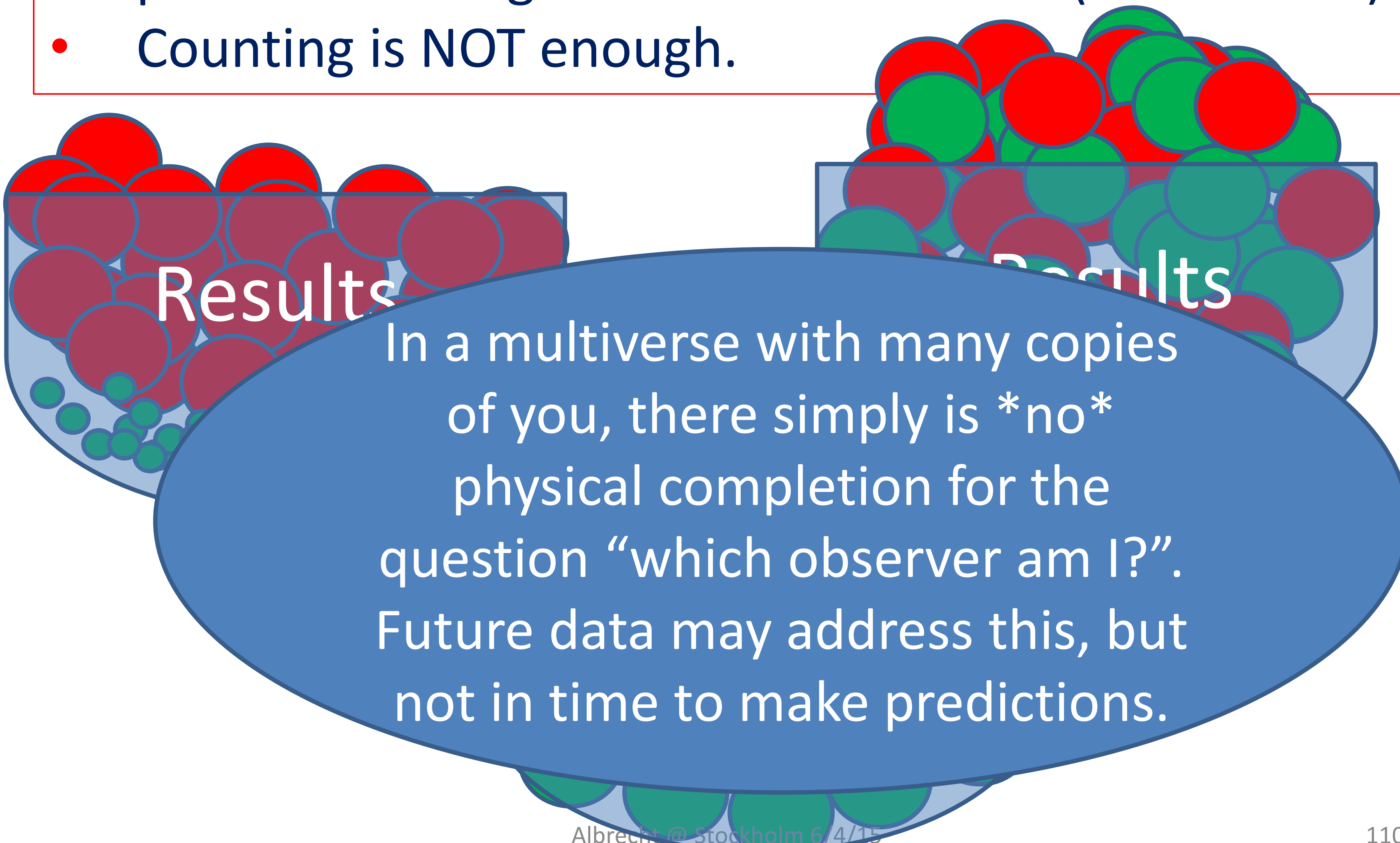
- Different physical "completions" of this question are possible which give different answers. (≈ measures)
- Counting is NOT enough.



NB: "Sleeping Beauty problem"

Now ask: What is the probability that a ball drawn from the “Results” bowl is red?

- Different physical “completions” of this question are possible which give different answers. (≈ measures)
- Counting is NOT enough.



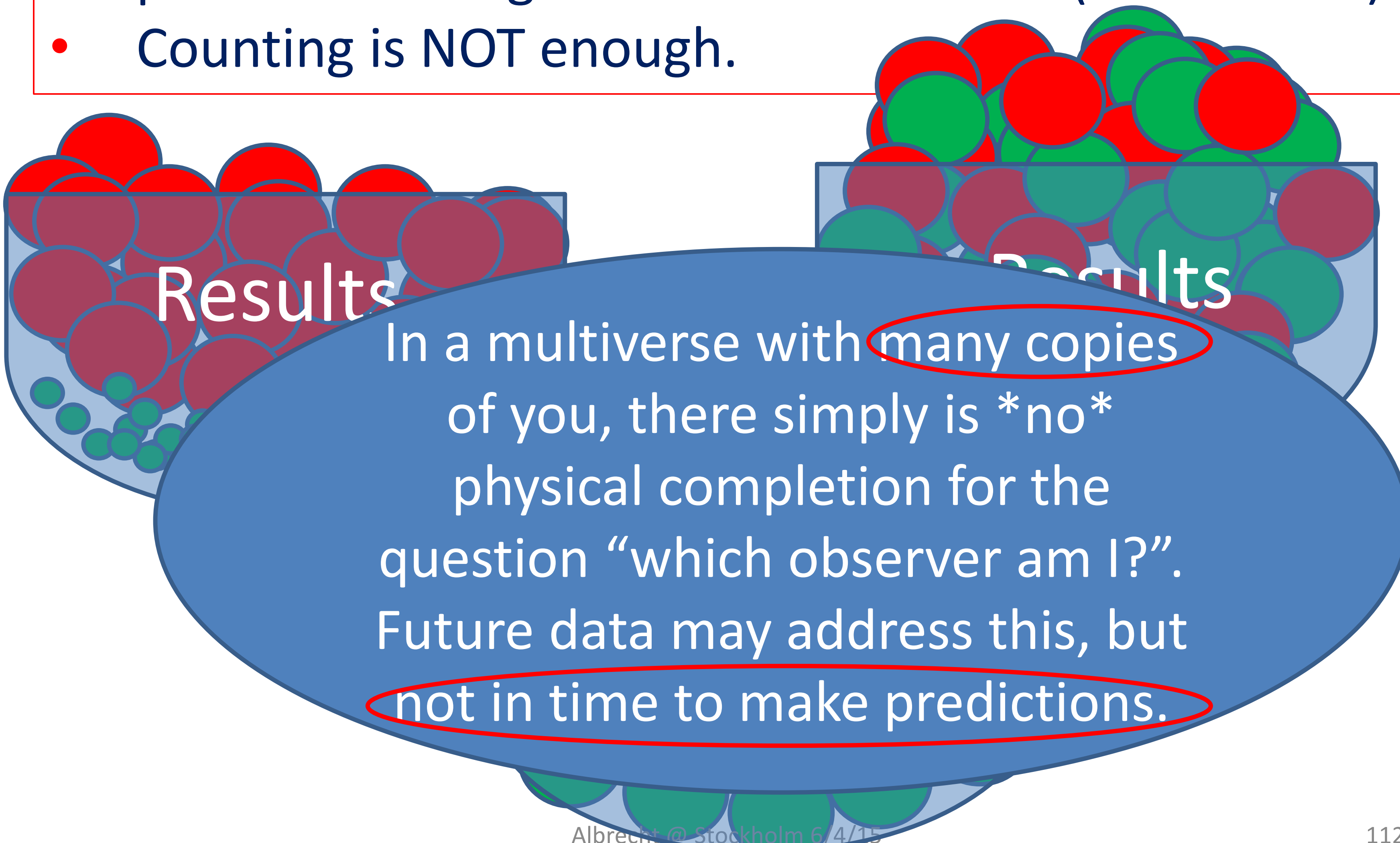
Now ask: What is the probability that a ball drawn from the “Results” bowl is red?

- Different physical “completions” of this question are possible which give different answers. (≈ measures)
- Counting is NOT enough.

In a multiverse with many copies of you, there simply is *no* physical completion for the question “which observer am I?”. Future data may address this, but not in time to make predictions.

Now ask: What is the probability that a ball drawn from the "Results" bowl is red?

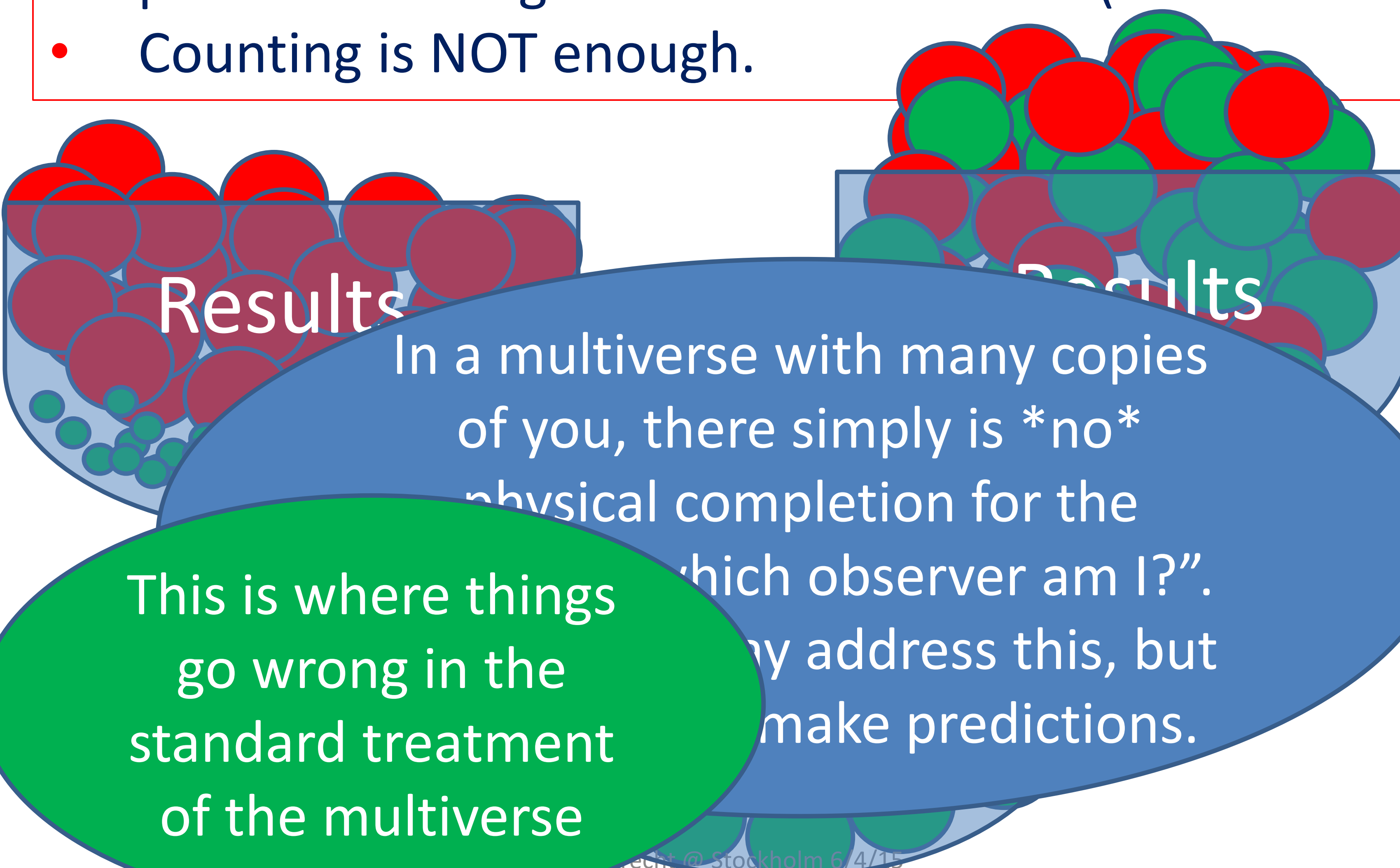
- Different physical "completions" of this question are possible which give different answers. (≈ measures)
- Counting is NOT enough.



In a multiverse with many copies of you, there simply is *no* physical completion for the question "which observer am I?". Future data may address this, but not in time to make predictions.

Now ask: What is the probability that a ball drawn from the “Results” bowl is red?

- Different physical “completions” of this question are possible which give different answers. (≈ measures)
- Counting is NOT enough.

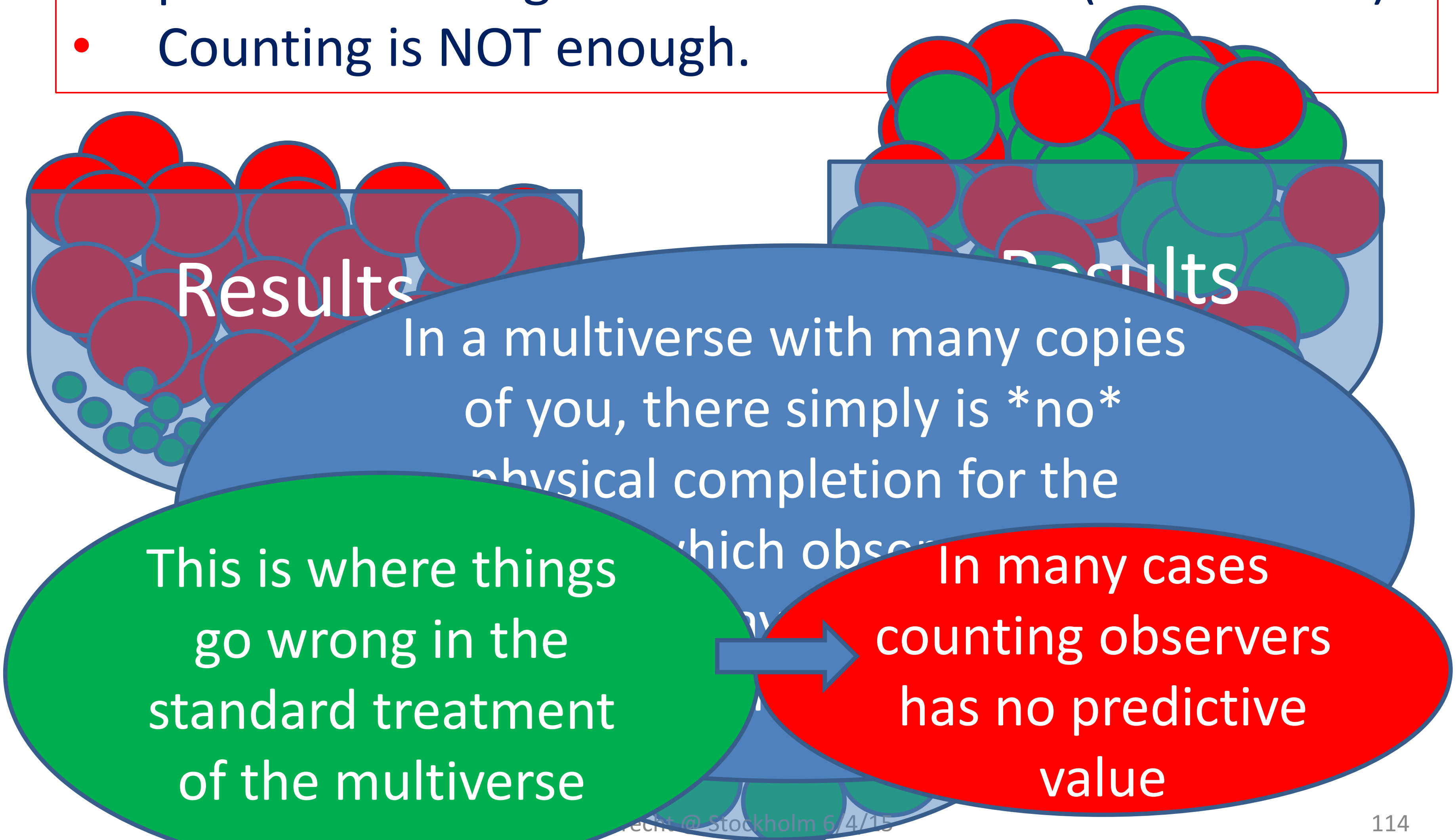


In a multiverse with many copies of you, there simply is *no* physical completion for the … hich observer am I?”. … y address this, but … make predictions.

This is where things go wrong in the standard treatment of the multiverse

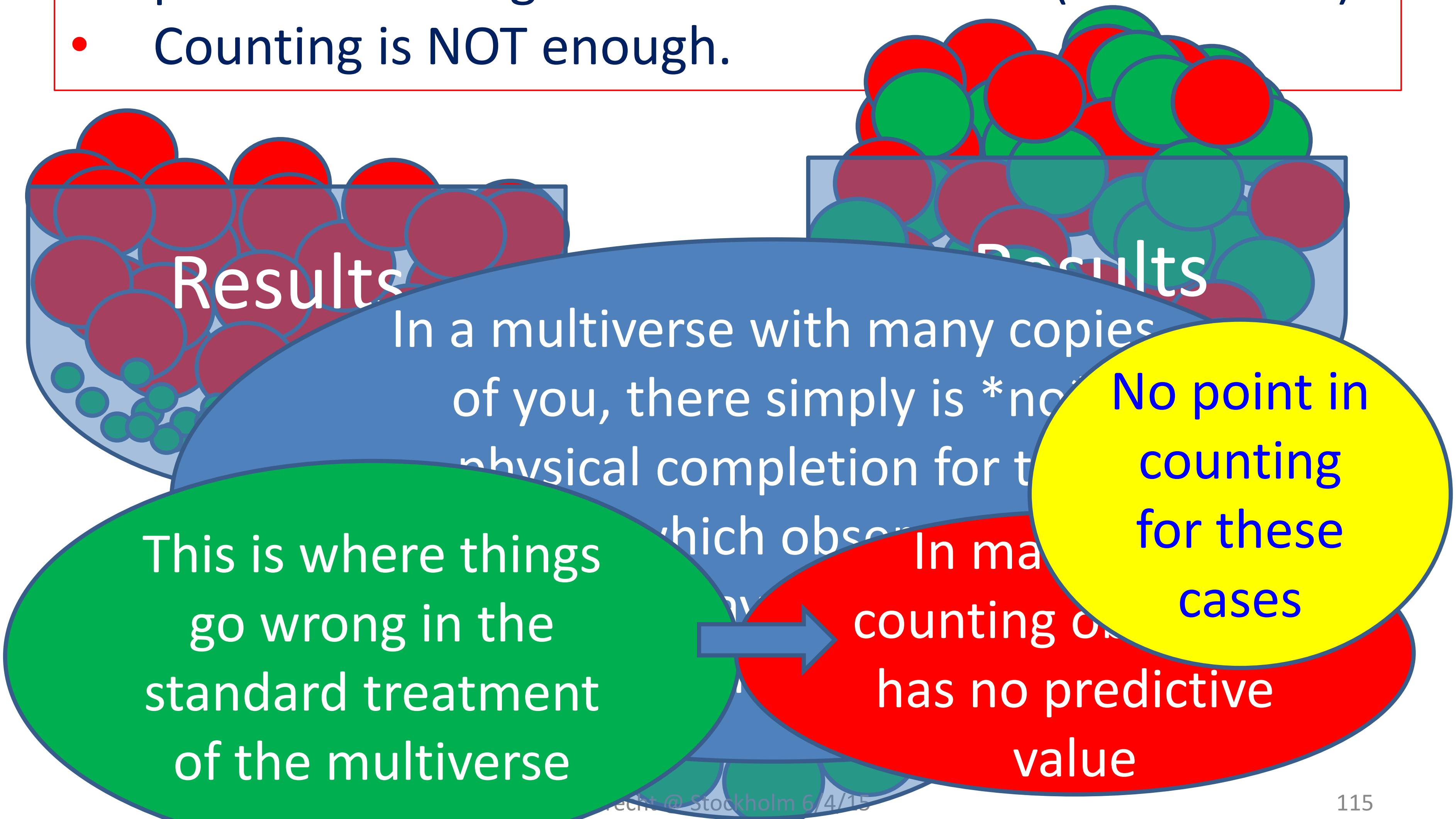
Now ask: What is the probability that a ball drawn from the “Results” bowl is red?

- Different physical “completions” of this question are possible which give different answers. (≈ measures)
- Counting is NOT enough.



Now ask: What is the probability that a ball drawn from the “Results” bowl is red?

- Different physical “completions” of this question are possible which give different answers. (≈ measures)
- Counting is NOT enough.



Outline

1) Quantum vs non-quantum probabilities (toy model/multiverse)

2) Everyday probabilities

3) Be careful about counting!

4) Implications for multiverse/eternal inflation

Outline

1) Quantum vs non-quantum probabilities (toy model/multiverse)

2) Everyday probabilities

3) Be careful about counting!

4) Implications for multiverse/eternal inflation

Outline

1) Quantum vs non-quantum probabilities (toy model/multiverse)

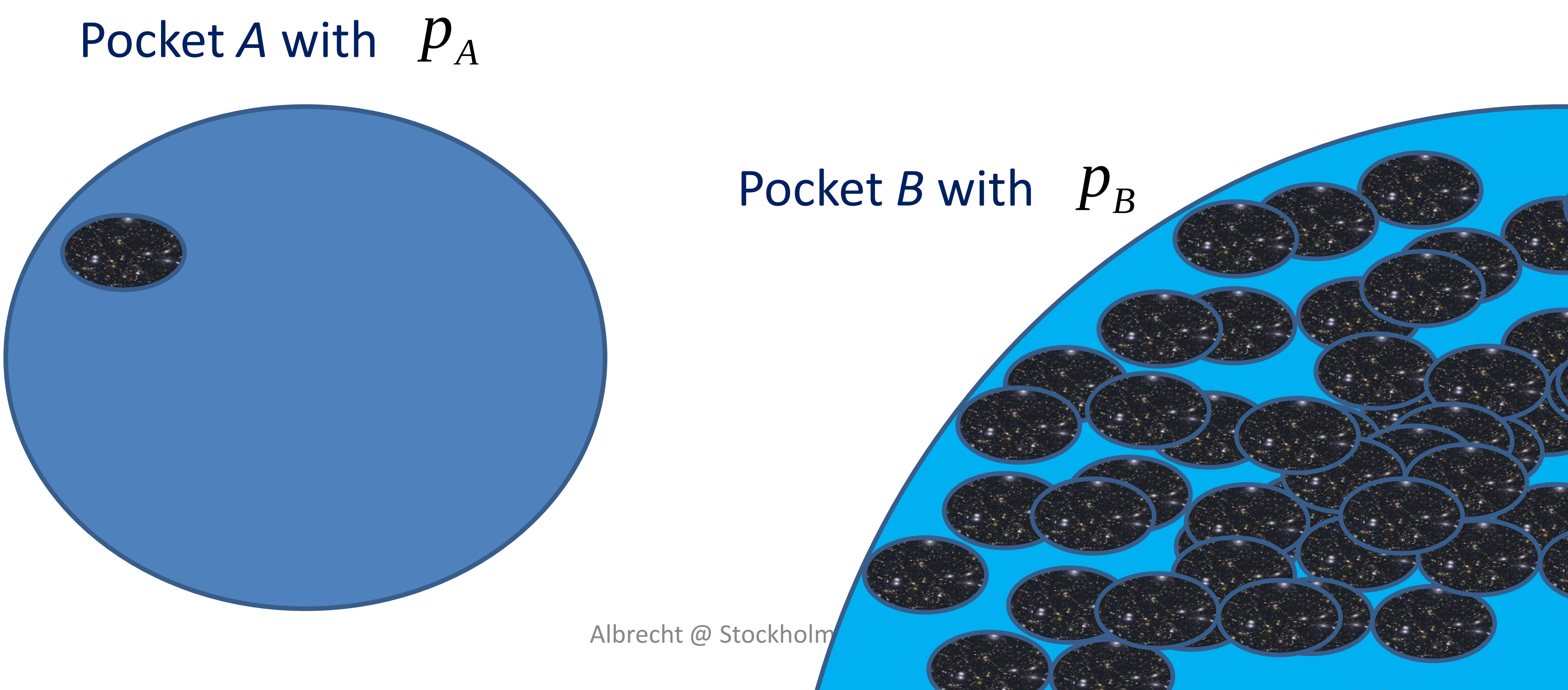
2) Everyday probabilities

3) Be careful about counting!

4) Implications for multiverse/eternal inflation

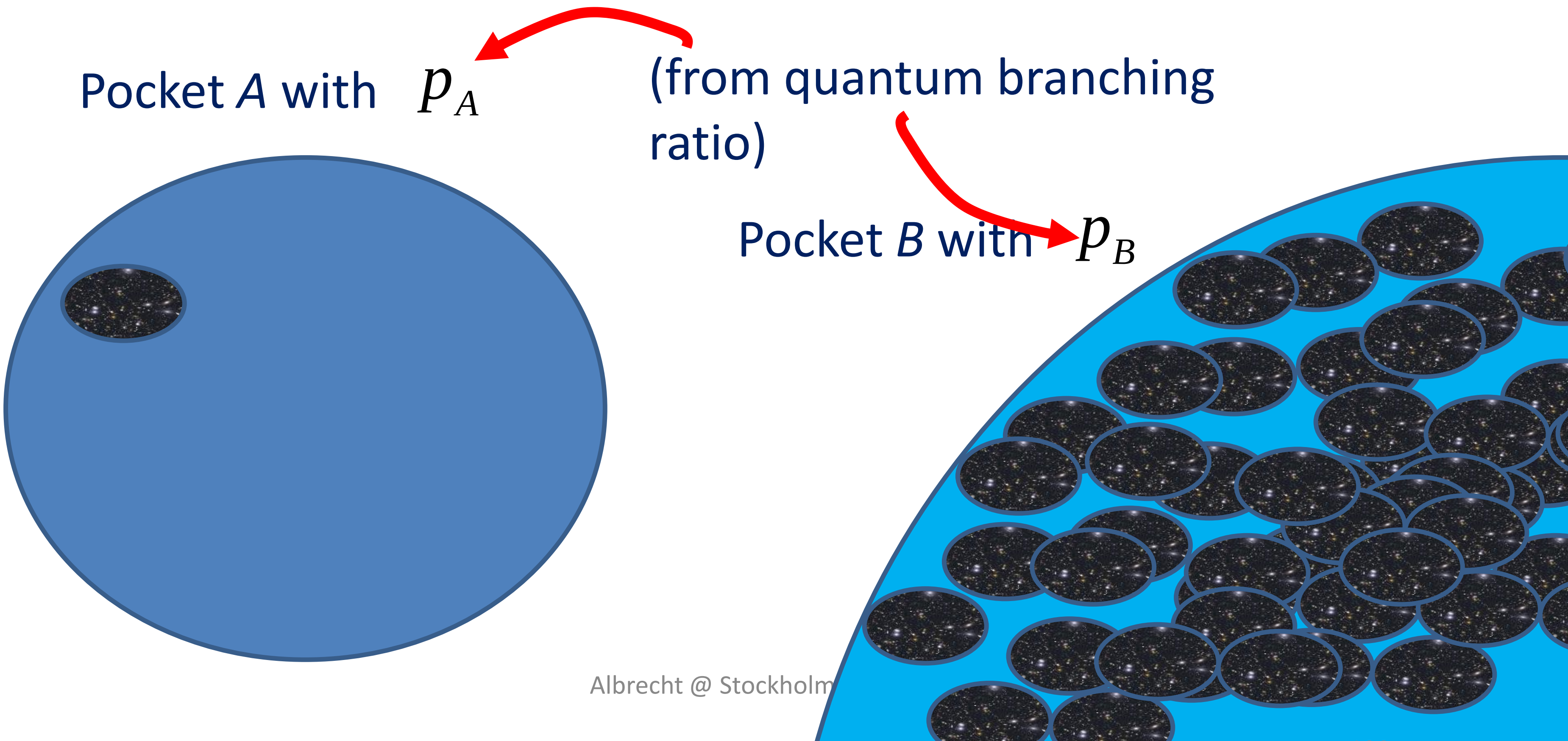
Implications for eternal inflation

1) No "volume factors"
2) Boltzmann Brain problem reduced
3) No "youngness/end of time" problem



Implications for eternal inflation

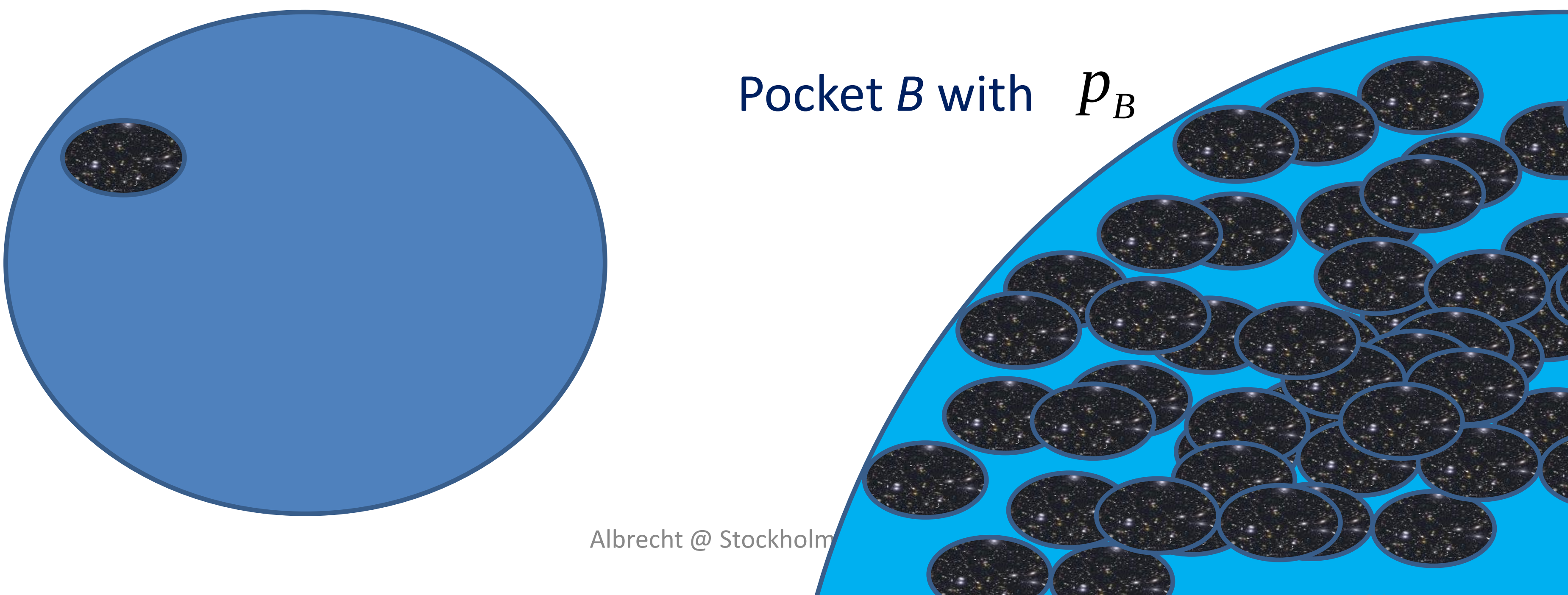
1) No “volume factors”
2) Boltzmann Brain problem reduced
3) No “youngness/end of time” problem



One semiclassical universe having many more possible observers in it than another (often counted by volume), does *not* give that universe greater statistical weight. Quantum branching ratio into one vs the other (p_A / p_B) <u>does</u> count

Pocket *A* with p_A

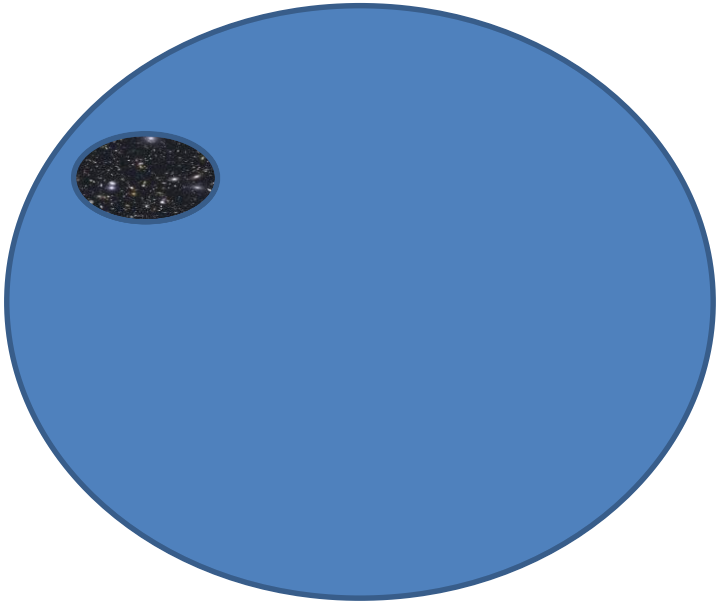
Pocket *B* with p_B



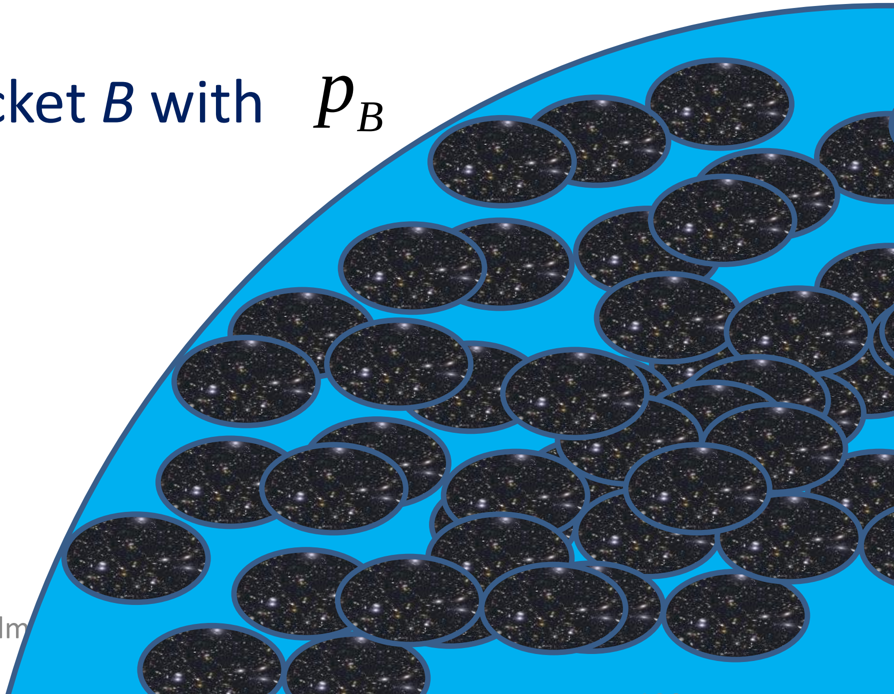
Implications for eternal inflation

1) No "volume factors"
2) Boltzmann Brain problem reduced
3) No "youngness/end of time" problem

Pocket *A* with p_A



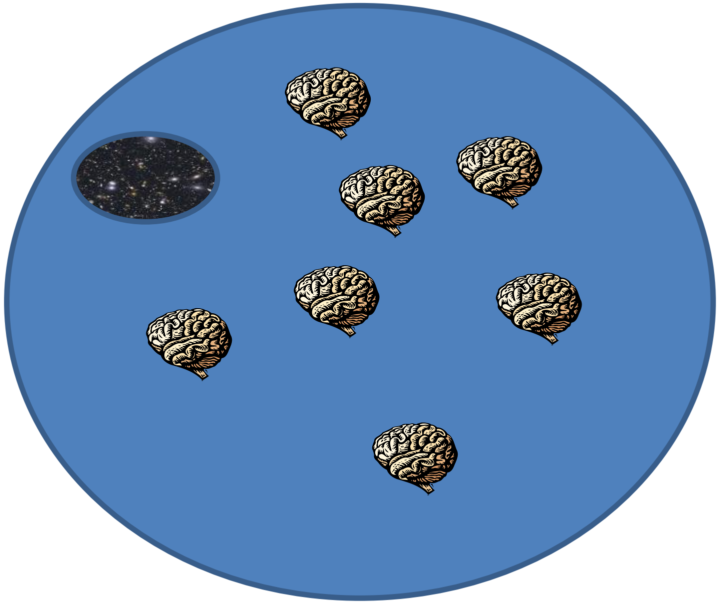
Pocket *B* with p_B



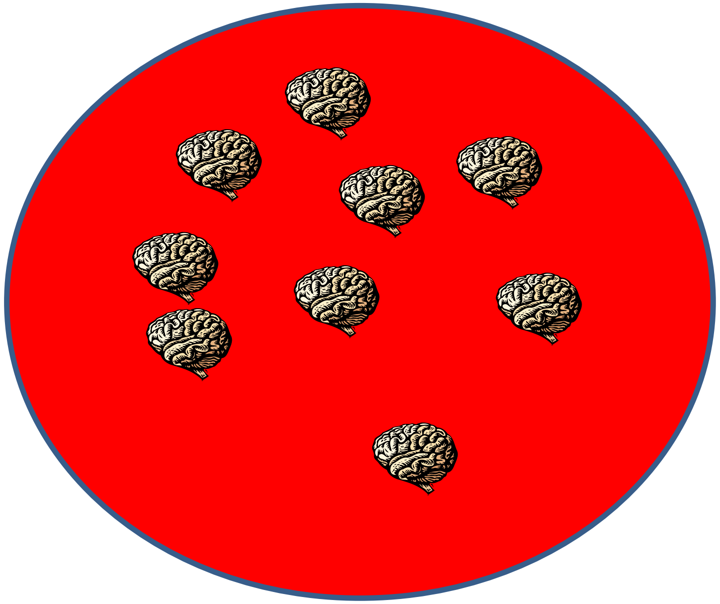
Implications for eternal inflation

1) No “volume factors”
2) Boltzmann Brain problem reduced
3) No “youngness/end of time” problem

Pocket *A* with p_A



Pocket *B* with p_B

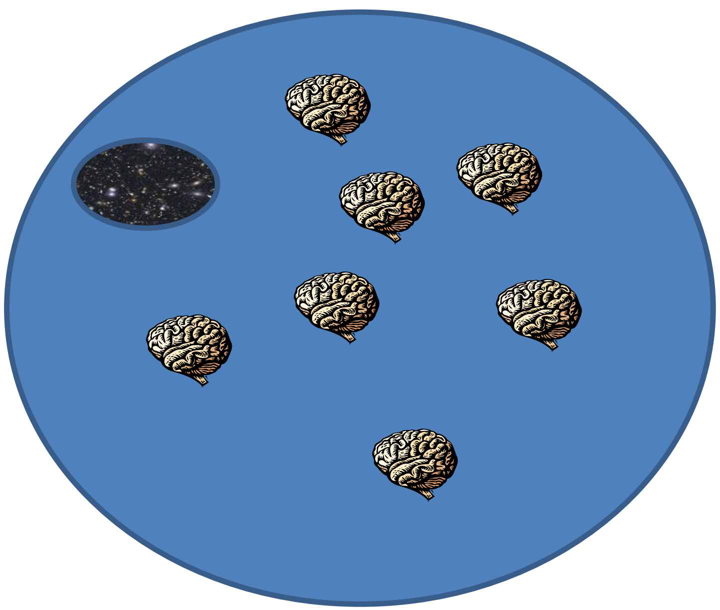


Implications for eternal inflation

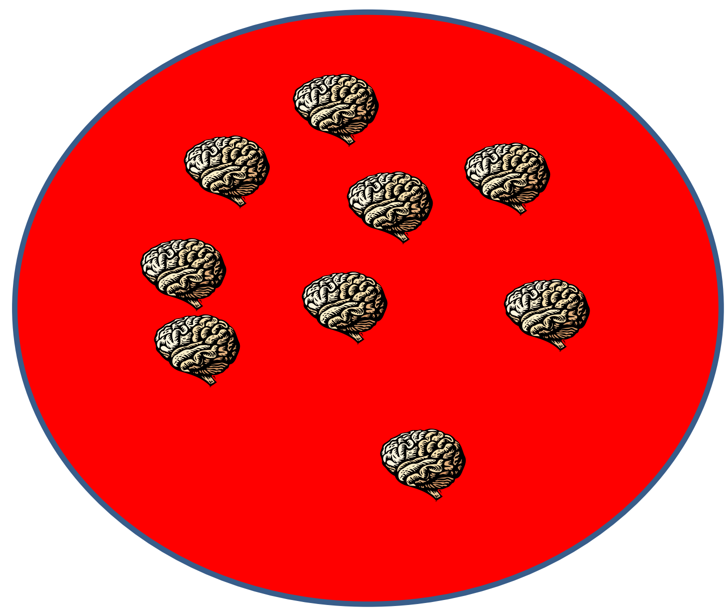
1) No "volume factors"

This model has no "Boltzmann Brain" problem as long as p_A / p_B Is not too small

Pocket *A* with p_A



Pocket *B* with p_B



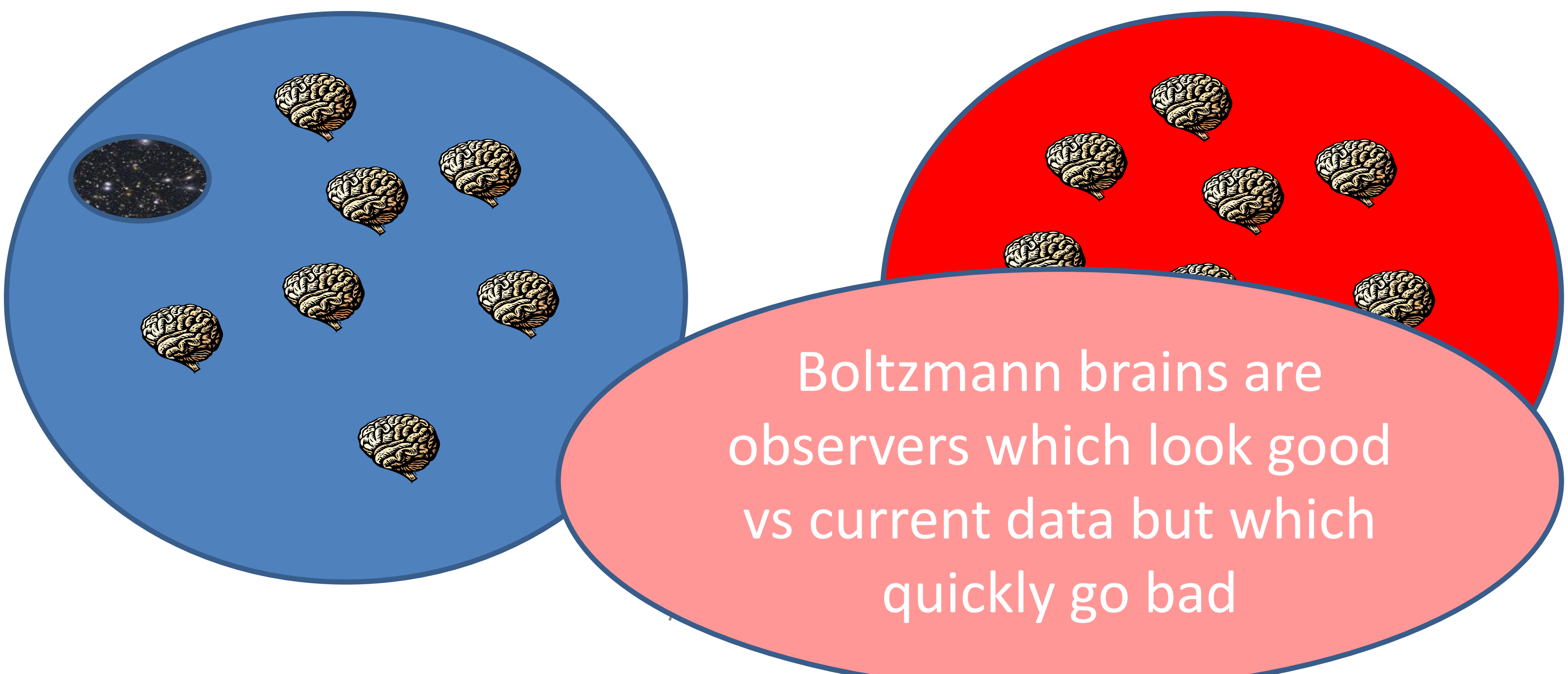
Implications for eternal inflation

1) No “volume factors”

This model has no “Boltzmann Brain” problem as long as p_A / p_B Is not too small

Pocket *A* with p_A

Pocket *B* with p_B



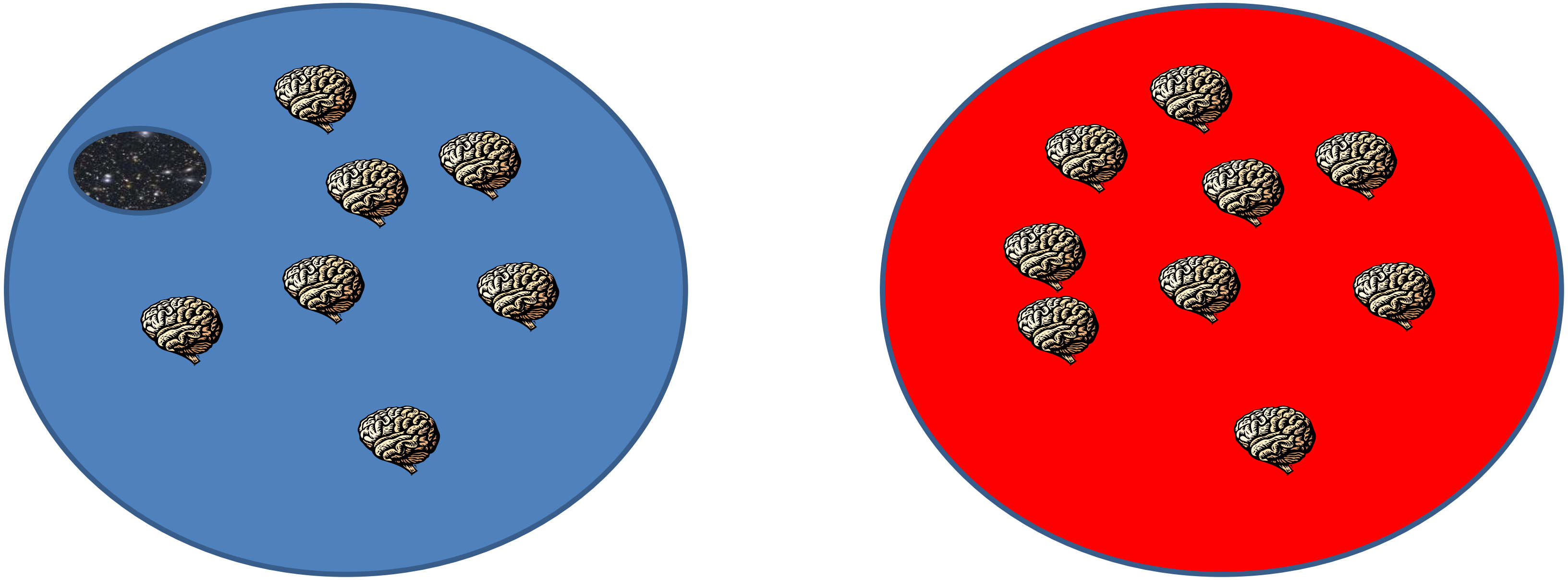
Boltzmann brains are observers which look good vs current data but which quickly go bad

Implications for eternal inflation

1) No “volume factors”
2) Boltzmann Brain problem reduced
3) No “youngness/end of time” problem

Pocket *A* with p_A

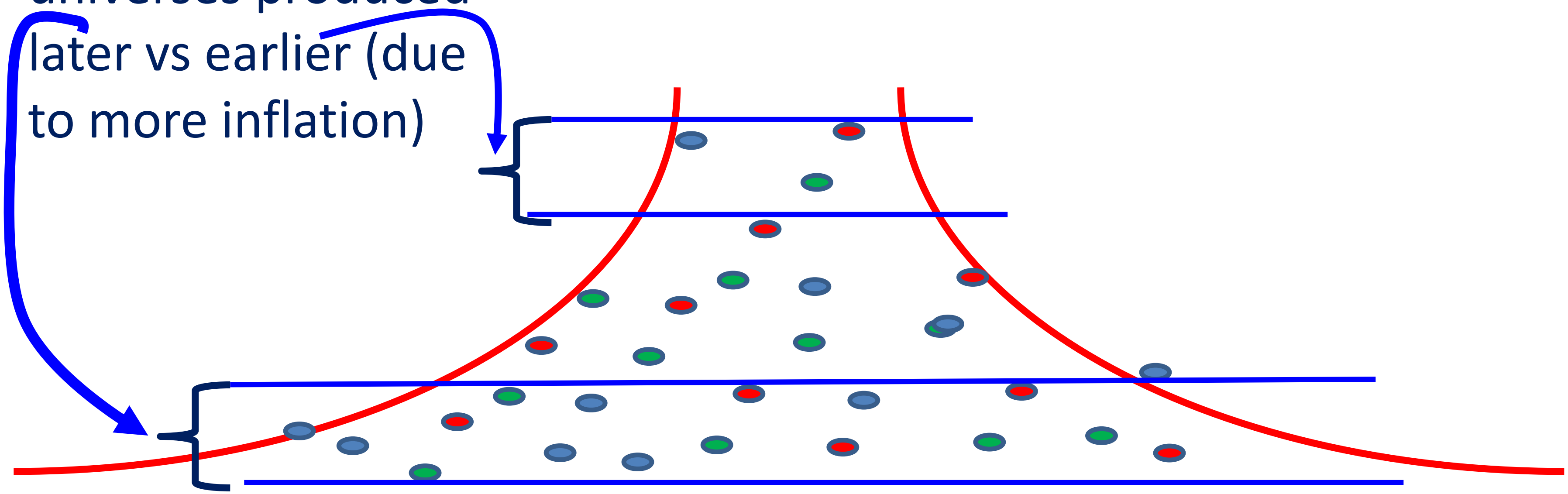
Pocket *B* with p_B



Implications for eternal inflation

1) No “volume factors”
2) Boltzmann Brain problem reduced
3) No “youngness/end of time” problem

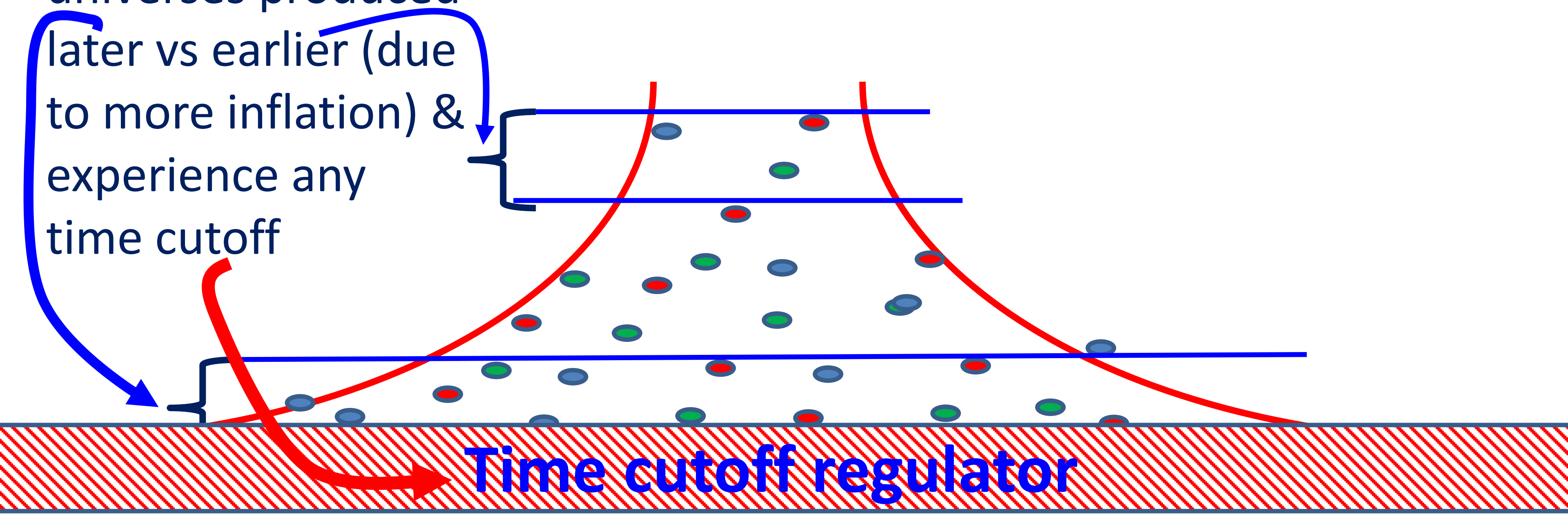
More pocket universes produced later vs earlier (due to more inflation)



Implications for eternal inflation

1) No “volume factors”
2) Boltzmann Brain problem reduced
3) No “youngness/end of time” problem

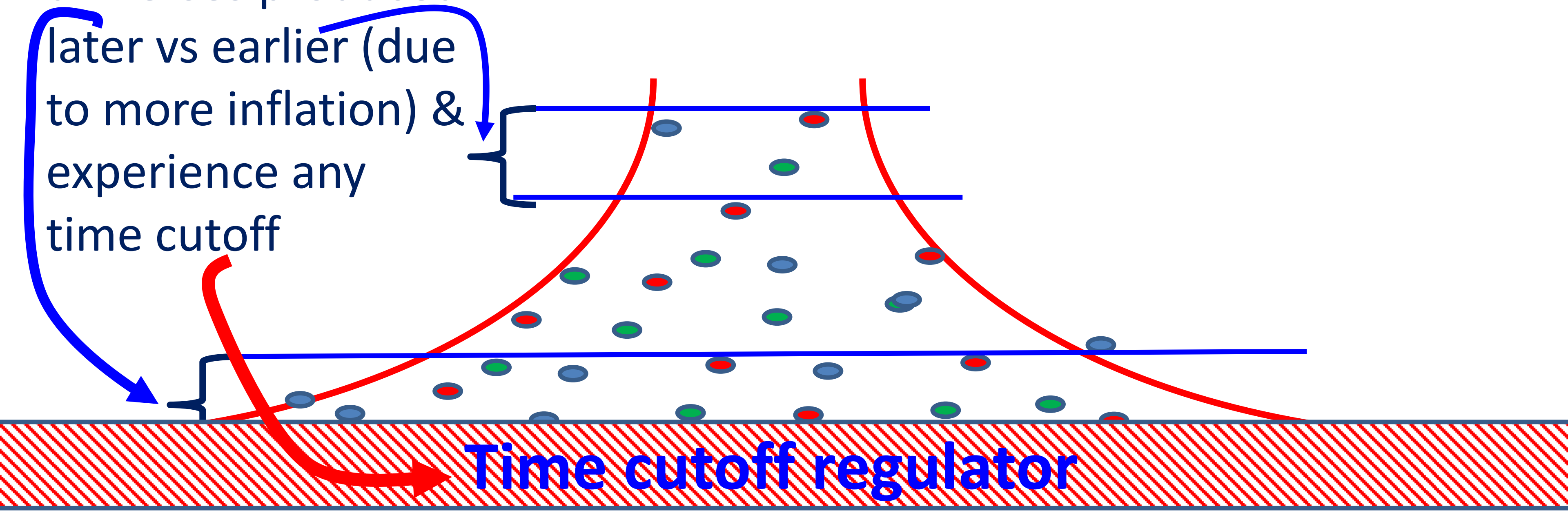
More pocket universes produced later vs earlier (due to more inflation) & experience any time cutoff



Implications for eternal inflation

1) No "volume factors"
2) Boltzmann Brain problem reduced
3) No "youngness/end of time" problem

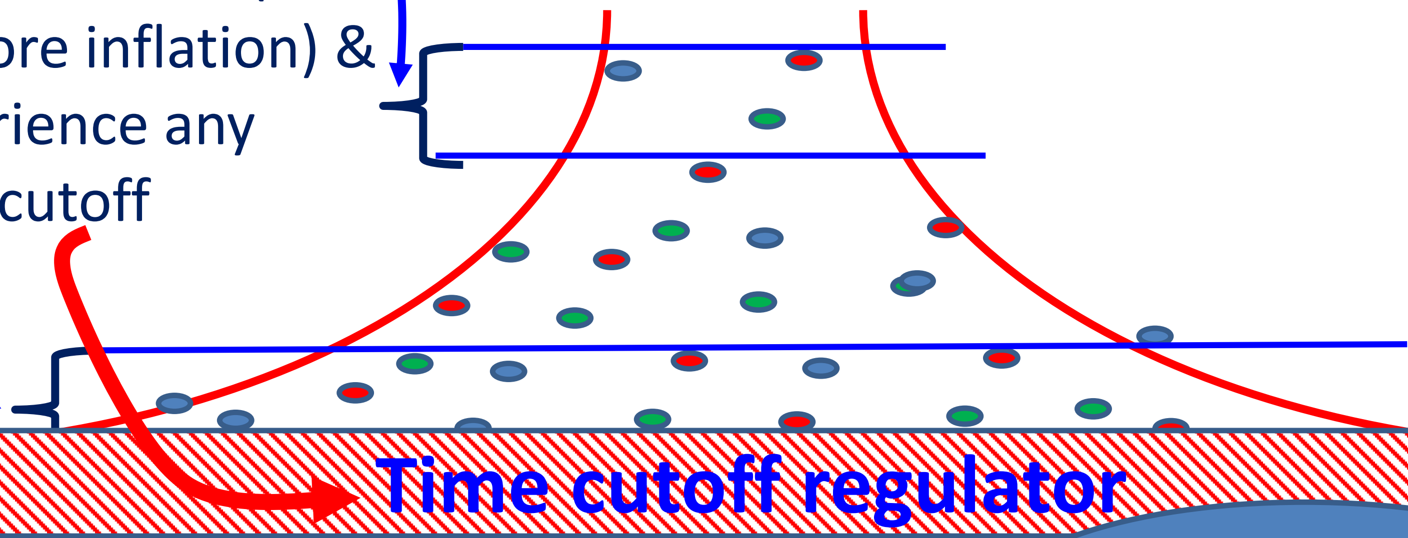
More pocket universes produced later vs earlier (due to more inflation) & experience any time cutoff



Implications for eternal inflation

1) No “volume factors”
2) Boltzmann Brain problem reduced
3) No “youngness/end of time” problem

More pocket universes produced later vs earlier (due to more inflation) & experience any time cutoff

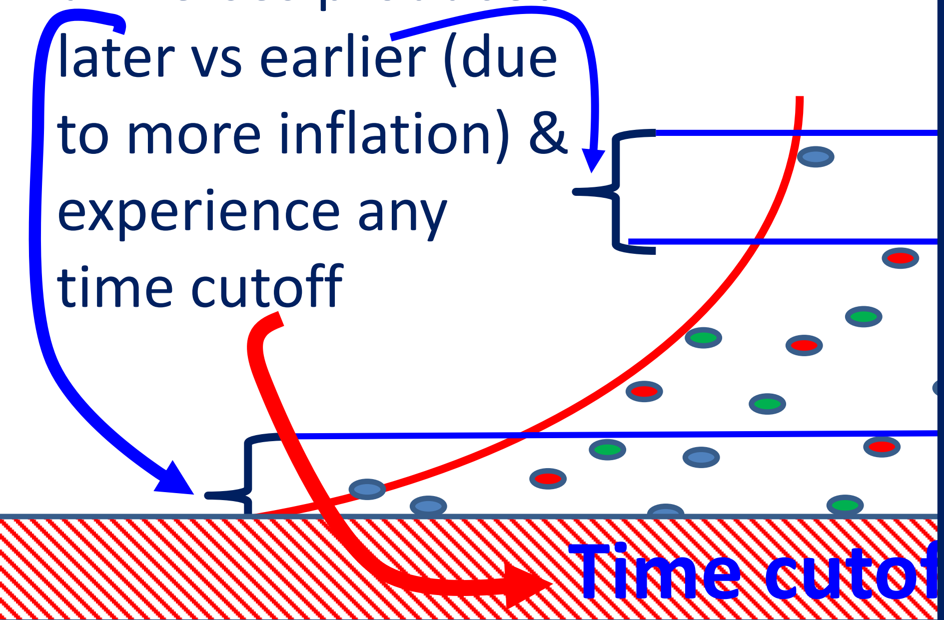


See also Guth & Vanchurin

Implications for eternal inflation

1) No "volume factors"
2) Boltzmann Brain problem reduced
3) No "youngness/end of time" problem

More pocket universes produced later vs earlier (due to more inflation) & experience any time cutoff



- → Wavefunction cannot give probabilities for which pocket you are in.
- → Time cutoff only there as (wrong) attempt to determine which pocket
- → The youngness/end of time problem is asking a question the theory cannot answer

Conclusions

1) All practically applicable probabilities are of physics (quantum) origin.
2) Counting of objects may or MAY NOT be a way of accessing legitimate quantum probabilities
3) Standard discussions of probabilities in cosmology often make errors re 2)
4) 1) and care about 2) allow us to introduce better discipline into cosmological discussions (just say "no"). Implications so far:
    a) No (counting based) volume factors
    b) Reduced Boltzmann Brain problem
    c) No youngness/end of time problem
    d) Measure problems apparently resolved?
5) More rigorous treatment of eternal inflation (etc) needed to determine full implications.

Co

→ I still have other concerns about eternal inflation that makes me prefer finite theories,

→ but this “probability discipline” may resolve what I used to think was the most troubling issue

ties are of physics

T be a way of

abilities

ities in cosmology often

4) 1) and ... about 2) allow us to introduce better discipline into cosmological discussions (just say “no”). Implications so far:
   a) No (counting based) volume factors
   b) Reduced Boltzmann Brain problem
   c) No youngness/end of time problem
   d) Measure problems apparently resolved?
5) More rigorous treatment of eternal inflation (etc) needed to determine full implications.

Co

➔ I still have other concerns about eternal inflation that makes me prefer finite theories,

➔ but this "probability discipline" may resolve what I used to think was the most troubling issue

…ties are of physics

…T be a way of

…abilities

…ities in cosmology often

Landscape OK too

4) 1) and … about 2) a… …uce better discipline into cosmol… …s (just say "no"). Implications so far:

   a) No (counting based) volume factors
   b) Reduced Boltzmann Brain problem
   c) No youngness/end of time problem
   d) Measure problems apparently resolved?

5) More rigorous treatment of eternal inflation (etc) needed to determine full implications.

→ I still have other concerns about eternal inflation that makes me prefer finite theories,

→ but this "probability discipline" may resolve what I used to think was the most troubling issue

In a systematic treatment the classical probabilities will reappear as "priors". Same math but very different role.

Landscape OK too

4) 1) and ... about 2) a... ...uce be... discipline into cosmol... ...s (just say "no"). Implications so far:

   a) No (counting based) volume factors
   b) Reduced Boltzmann Brain problem
   c) No youngness/end of time problem
   d) Measure problems apparently resolved?

5) More rigorous treatment of eternal inflation (etc) needed to determine full implications.

Co…

→ I still have other concerns about eternal inflation that makes me prefer finite theories,
→ but this "probability discipline" may resolve what I used to think was the most troubling issue

In a systematic treatment the classical probabilities will reappear as "priors". Same math but very different role.

Landscape OK too

4) 1) and … about 2) a… …uce be… discipline into cosmol… …s (just say "no"). Implications so far:
   a) No (counting based) volume factors
   b) Reduced Boltzmann Brain problem
   c) No youngness/end of time pr…
   d) Measure problems appar…
5) More rigorous treatment of eter… needed to determine full implica…

→ Perhaps related to work by Nomura and Garriga & Vilenkin and collaborators

➔ I still have other concerns about eternal inflation that makes me prefer finite theories,

➔ but this "probability discipline" may resolve what I used to think was the most troubling issue

In a systematic treatment the classical probabilities will reappear as "priors". Same math but very different role.

4) 1) and ... about 2) a... ...duce ... discipline into cosmol... ...s (just say "no"). Implications so far:

Landscape OK too

a) No (counting based) volume factors
b) Reduced Boltzmann Brain problem
c) No youngness/end of time pr...
...blems appar...
...of eter...
...implica...

Clashes with my work on the "clock ambiguity"

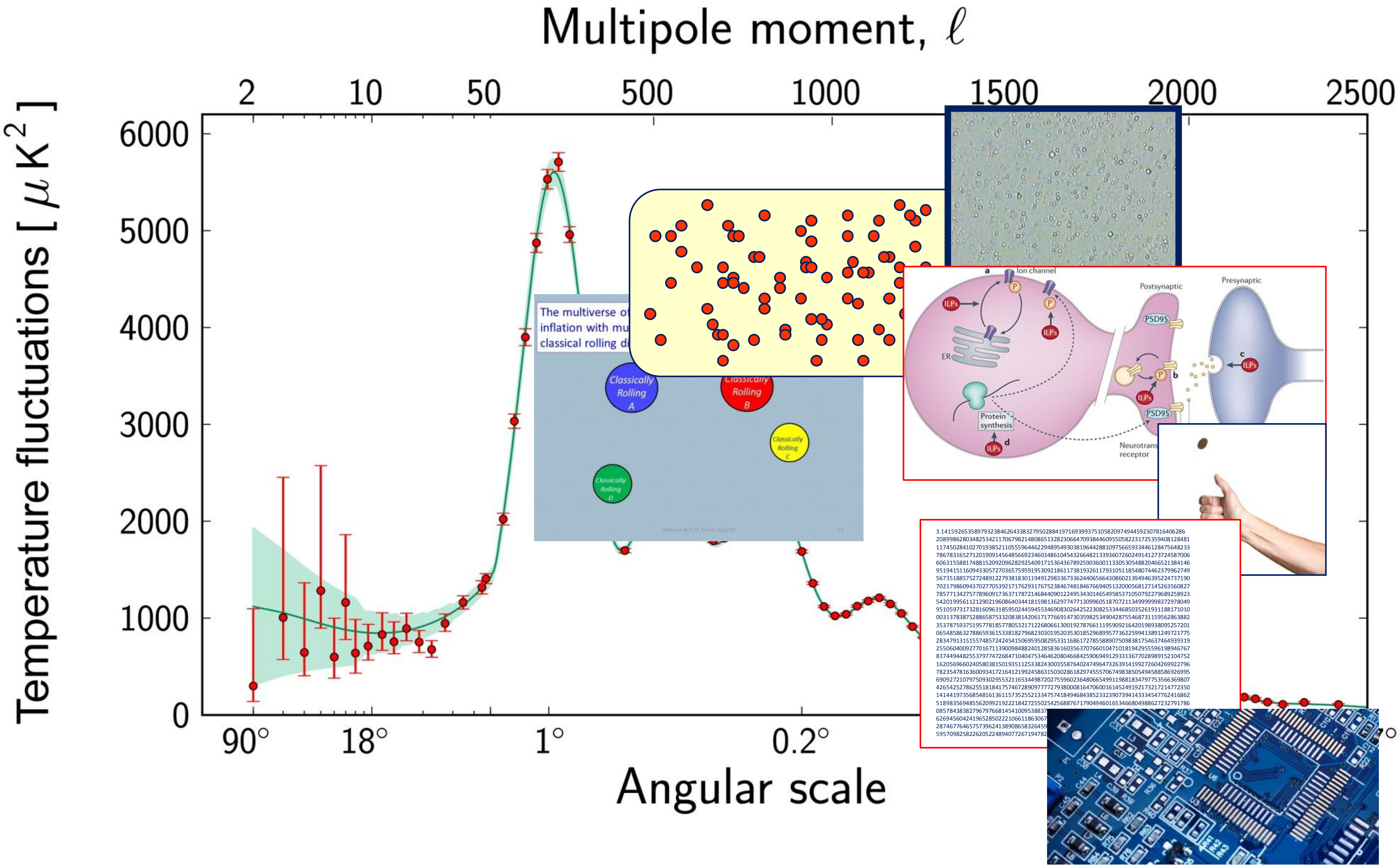
➔ Perhaps related to work by Nomura and Garriga & Vilenkin and collaborators

Conclusions

1) All practically applicable probabilities are of physics (quantum) origin.
2) Counting of objects may or MAY NOT be a way of accessing legitimate quantum probabilities
3) Standard discussions of probabilities in cosmology often make errors re 2)
4) 1) and care about 2) allow us to introduce better discipline into cosmological discussions (just say “no”). Implications so far:
    a) No (counting based) volume factors
    b) Reduced Boltzmann Brain problem
    c) No youngness/end of time problem
    d) Measure problems apparently resolved?
5) More rigorous treatment of eternal inflation (etc) needed to determine full implications.

Conclusions

1) All practically applicable probabilities are of physics (quantum) origin.
2) Counting of objects may or MAY NOT be a way of accessing legitimate quantum probabilities
3) Standard discussions of probabilities in cosmology often make errors re 2)
4) 1) and care about 2) allow us to introduce better discipline into cosmological discussions (just say “no”). Implications so far:
    a) No (counting based) volume factors
    b) Reduced Boltzmann Brain problem
    c) No youngness/end of time problem
    d) Measure problems apparently resolved?
5) More rigorous treatment of eternal inflation (etc) needed to determine full implications.



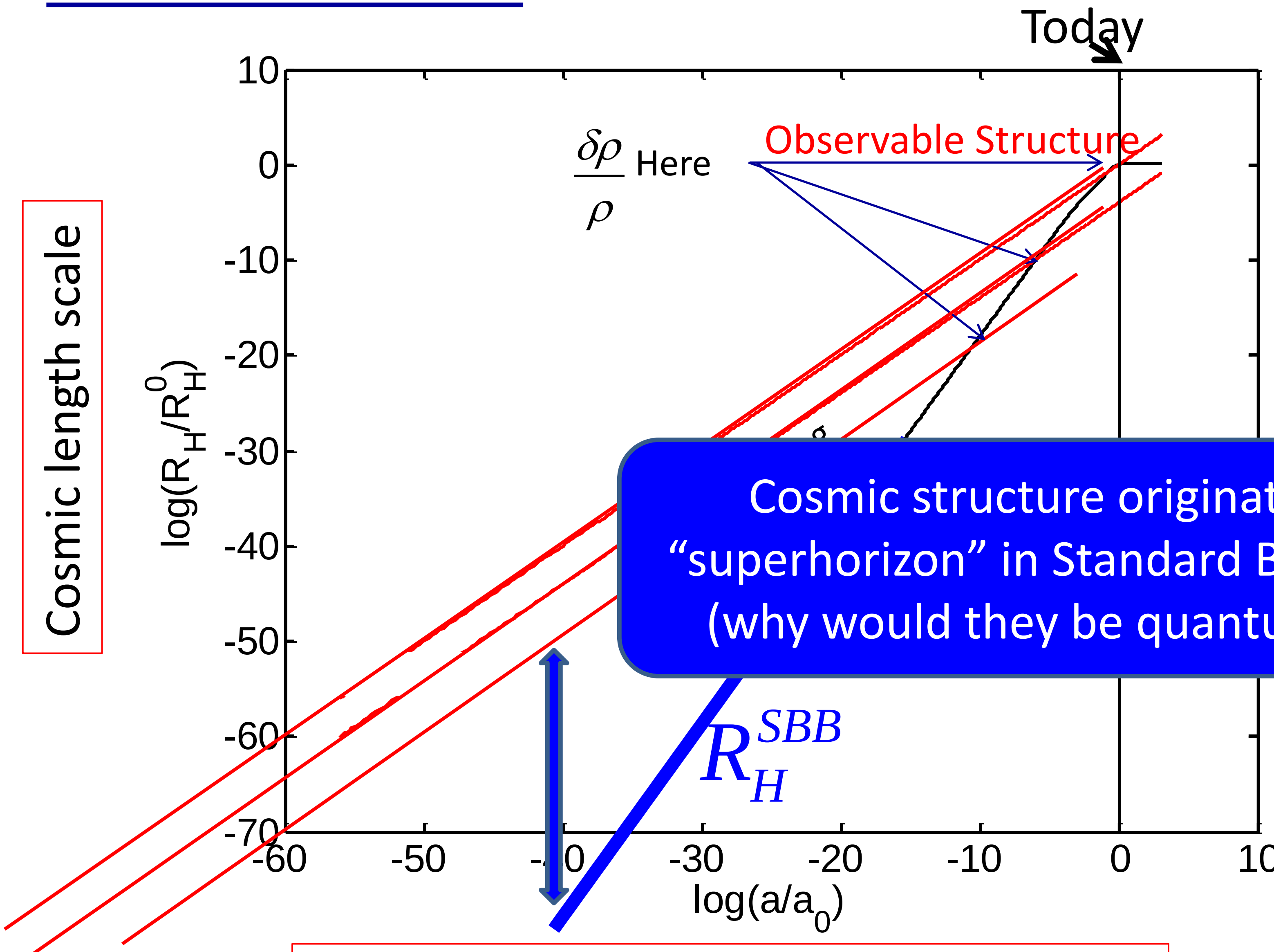
Multipole moment, ℓ
2
10
50
500
1000
1500
2000
2500
Temperature fluctuations [μK²]
6000
5000
4000
3000
2000
1000
0
90°
18°
1°
0.2°
Angular scale
Classically Rolling A
Classically Rolling B
Classically Rolling C
Classically Rolling D
Ion channel
Postsynaptic
Presynaptic
ILPs
ER
PSD95
Protein synthesis

Additional Slides

Cosmic structure

A note on "probability censorship"

Cosmic length scale

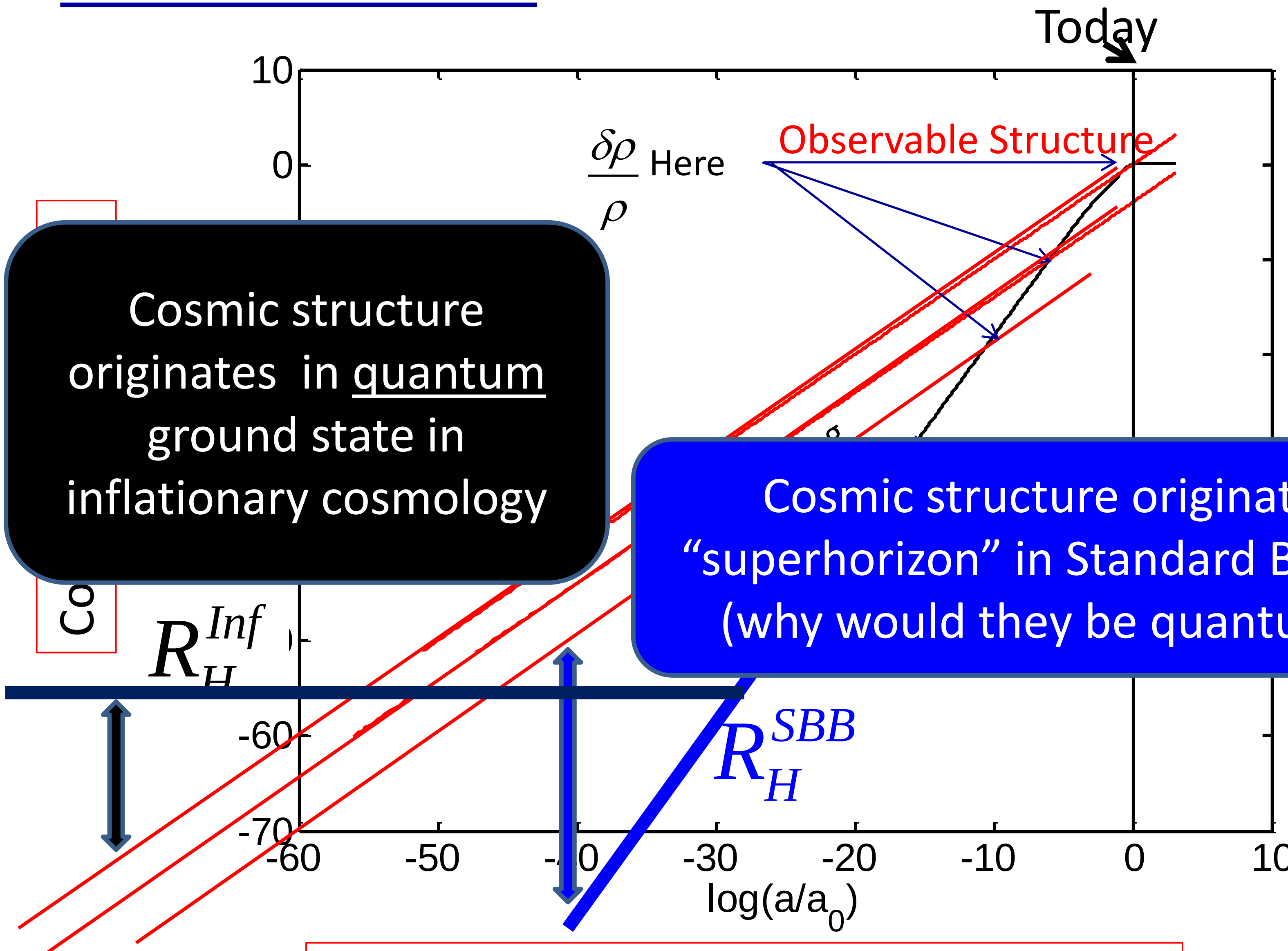


Cosmic structure originates "superhorizon" in Standard Big Bag (why would they be quantum?)

Scale factor (measures expansion, time)

A note on "probability censorship"

Cosmic structure



Cosmic structure originates in quantum ground state in inflationary cosmology

Cosmic structure originates "superhorizon" in Standard Big Bag (why would they be quantum?)

Scale factor (measures expansion, time)

All everyday probabilities are quantum probabilities

- Proof by exhaustion not realistic
- One counterexample (practical utility of non-quantum probabilities) will undermine our entire argument
- Can still invent classical probabilities just to do multiverse cosmology
- Not a problem for many finite theories (AA, Banks & Fis…
- …lly do require classical probabilities …rously (symmetry?... simplicity? See

Compare with identical particle statistics

Cooperman 2011

Further discussion

Bet on the millionth digit of π

3.141592653589793238462643383279502884197169399375105820974944592307816406286
208998628034825342117067982148086513282306647093844609550582231725359408128481
117450284102701938521105559644622948954930381964428810975665933446128475648233
786783165271201909145648566923460348610454326648213393607260249141273724587006
606315588174881520920962829254091715364367892590360011330530548820466521384146
951941511609433057270365759591953092186117381932611793105118548074462379962749
567351885752724891227938183011949129833673362440656643086021394946395224737190
702179860943702770539217176293176752384674818467669405132000568127145263560827
785771342757789609173637178721468440901224953430146549585371050792279689258923
542019956112129021960864034418159813629774771309960518707211349999998372978049
951059731732816096318595024459455346908302642522308253344685035261931188171010
003137838752886587533208381420617177669147303598253490428755468731159562863882
353787593751957781857780532171226806613001927876611195909216420198938095257201
065485863278865936153381827968230301952035301852968995773622599413891249721775
283479131515574857242454150695950829533116861727855889075098381754637464939319
255060400927701671139009848824012858361603563707660104710181942955596198946767
837449448255379774726847104047534646208046684259069491293313677028989152104752
162056966024058038150193511253382430035587640247496473263914199272604269922796
782354781636009341721641219924586315030286182974555706749838505494588586926995
690927210797509302955321165344987202755960236480665499119881834797753566369807
426542527862551818417574672890977772793800081647060016145249192173217214772350
141441973568548161361157352552133475741849468438523323907394143334547762416862
518983569485562099219222184272550254256887671790494601653466804988627232791786
085784383827967976681454100953883786360950680064225125205117392984896084128488
626945604241965285022210661186306744278622039194945047123713786960956364371917
287467764657573962413890865832645995813390478027590099465764078951269468398352
595709825822620522489407726719478268482601476990902640136394437455305068203496

Further discussion

Bet on the millionth digit of π

- The *only* thing random is the choice of digit to bet on

3.1415926535
2089986280З
11745028410
7867831652712019091456485669234603486104543266482133936072602491412737245870066
0631558817488152092096282925409171536436789259036001133053054882046652138414695
1941511609433057270365759591953092186117381932611793105118548074462379962749
5673518857527248912279381830119491298336733624406566430860213949463952247371907
0217986094370277053921717629317675238467481846766940513200056812714526356082778
5771342757789609173637178721468440901224953430146549585371050792279689258923
5420199561121290219608640344181598136297747713099605187072113499999983729780499
5105973173281609631859502445945534690830264252230825334468503526193118817101000
3137838752886587533208381420617177669147303598253490428755468731159562863882
3537875937519577818577805321712268066130019278766111959092164201989380952572010
6548586327886593615338182796823030195203530185296899577362259941389124972177528
3479131515574857242454150695950829533116861727855889075098381754637464939319
2550604009277016711390098488240128583616035637076601047101819429555961989467678
3744944825537977472684710404753464620804668425906949129331367702898915210475216
2056966024058038150193511253382430035587640247496473263914199272604269922796
7823547816360093417216412199245863150302861829745557067498385054945885869269956
9092721079750930295532116534498720275596023648066549911988183479775356636980742
6542527862551818417574672890977772793800081647060016145249192173217214772350
1414419735685481613611573525521334757418494684385233239073941433345477624168625
1898356948556209921922218427255025425688767179049460165346680498862723279178608
5784383827967976681454100953883786360950680064225125205117392984896084128488
6269456042419652850222106611863067442786220391949450471237137869609563643719172
8746776465757396241389086583264599581339047802759009946576407895126946839835259
5709825822620522489407726719478268482601476990902640136394437455305068203496

Further discussion

Bet on the millionth digit of π

- The *only* thing random is the choice of digit to bet on
- Fairness is about lack of correlation between digit choice and digit value

3.1415926535
2089986280
11745028410
78678316527
60631558817
95194151160
56735188575
7021798609437027705392171762931767523846748184676694051320005681271452635608277
7857713427577896091736371787214684409012249534301465495853710507922796892589235
542019956112129021960864034418159813629774771309960518707211349999998372978049
9510597317328160963185950244594553469083026425223082533446850352619311881710100
0313783875288658753320838142061717766914730359825349042875546873115956286388
35378759375195778185778053217122680661300192787661119590921642019893809525720
06548586327886593615338182796823030195203530185296899577362259941389124972177
28347913151557485724245415069595082953311686172785588907509838175463746493931
25506040092770167113900984882401285836160356370766010471018194295559619894676
83744944825537977472684710404753464620804668425906949129331367702898915210475
16205696602405803815019351125338243003558764024749647326391419927260426992279
78235478163600934172164121992458631503028618297455570674983850549458858692699
69092721079750930295532116534498720275596023648066549911988183479775356636980
42654252786255181841757467289097777279380008164706001614524919217321721477235
14144197356854816136115735255213347574184946843852332390739414333454776241686
51898356948556209921922218427255025425688767179049460165346680498862723279178
08578438382796797668145410095388378636095068006422512520511739298489608412848
62694560424196528502221066118630674427862203919494504712371378696095636437191
28746776465757396241389086583264599581339047802759009946576407895126946839835
59570982582262052248940772671947826848260147699090264013639443745530506820349

Further discussion

Bet on the millionth digit of π

- The *only* thing random is the choice of digit to bet on
- Fairness is about lack of correlation between digit choice and digit value
- Choice of digit comes from
  - Brain (neurons with quantum uncertainties)
  - Random number generator → seed → time stamp (when you press ENTER) →brain
  - Etc

3.1415926535
2089986280
1174502841
7867831652
6063155881
9519415116
5673518857
7021798609
7857713427
5420199561
9510597317
0031378387
3537875937
0654858632
2834791315
2550604009
8374494482
1620569660
78235478163600934172164121992458631503028618297455570674983850549458858692699 5
69092721079750930295532116534498720275596023648066549911988183479775356636980 7
42654252786255181841757467289097777279380008164706001614524919217321721477235 0
14144197356854816136115735255213347574184946843852332390739414333454776241686 2
51898356948556209921922218427255025425688767179049460165346680498862723279178 6
08578438382796797668145410095388378636095068006422512520511739298489608412848 8
62694560424196528502221066118630674427862203919494504712371378696095636437191 7
28746776465757396241389086583264599581339047802759009946576407895126946839835 2
59570982582262052248940772671947826848260147699090264013639443745530506820349 6

Further discussion

Bet on the millionth digit of π

- The *only* thing random is the choice of digit to bet on
- Fairness is about lack of correlation between digit choice and digit value
- Choice of digit comes from
  - Brain (neurons with quantum uncertainties)
  - Random number generator → seed → time stamp (when you press ENTER) →brain
  - Etc
- The only randomness in a bet on a digit of π is quantum!

3.141592653
2089986280
1174502841
7867831652
6063155881
9519415116
5673518857
7021798609
7857713427
5420199561
9510597317
0031378387
3537875937
0654858632
2834791315
2550604009
8374494482
1620569660
7823547816
6909272107
426542527862551818417574672890977772793800081647060016145249192173217214772350
141441973568548161361157352552133475741849468438523323907394143334547762416862
518983569485562099219222184272550254256887671790494601653466804988627232791786
085784383827967976681454100953883786360950680064225125205117392984896084128488
626945604241965285022210661186306744278622039194945047123713786960956364371917
287467764657573962413890865832645995813390478027590099465764078951269468398352
595709825822620522489407726719478268482601476990902640136394437455305068203496

Further discussion

3.1415926535
2089986280
1174502841
7867831652
6063155881
9519415116
5673518857
7021798609
7857713427
5420199561
9510597317
0031378387
3537875937
0654858632
2834791315
2550604009
8374494482
1620569660
7823547816
6909272107
42654252786
141441973568548161361157 … 23323907394143334547762416862
51898356948556209921922 … 946016534668049886272327917 86
08578438382796797668145 4
626945604241965285022210
2874677646575739624138908658326459958 13
59570982582262052248940772671947826848 2

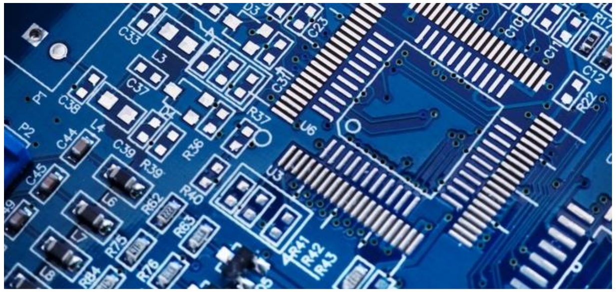
Bet on the millionth digit of π

- The *only* thing random is the choice of digit to bet on
- Fairness is about lack of correlation between digit choice and digit value
- Choice of digit comes from
  - Brain (neurons with quantum uncertainties)
  - Random number generator → seed → time stamp (when you press ENTER) →brain
  - Etc
- The only randomness in a bet on a digit of π is quantum!

Payout:

$$P_\pi = \lim_{N_{tot}\to\infty} \frac{1}{N_{tot}} \sum_{\{i\}} \left(N_\pi^i - 4.5 \right) = 0$$

Further discussion



<u>Classical Computer</u>: The "computational degrees of freedom" of a classical computer are very classical: Engineered to be well isolated from the quantum fluctuations that are everywhere

→

- Computations are deterministic
- "Random" is artificial
- Model a classical billiard gas on a computer:
  - ➢ All "random" fluctuations are determined by (or "readings of") the initial state.

10001000111101010

↓

10001000101001010

↓

11011000101001010

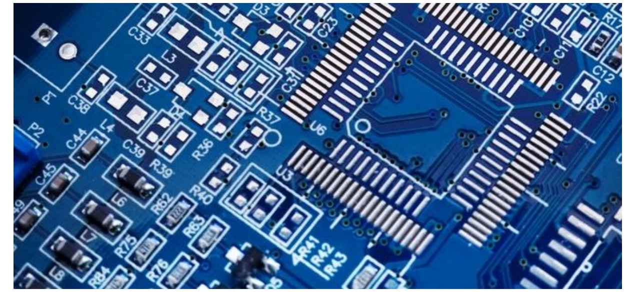
↓

10001010111101010

↓

10001000101101010

Further discussion



<u>Classical Computer</u>: The "computational degrees of freedom" of a classical computer are very classical: Engineered to be well isolated from the quantum fluctuations that are everywhere

→

- Computations are deterministic
- "Random" is artificial
- Model a classical billiard gas on a computer:
  - ➢ All "random" fluctuations are determined by (or "readings of") the initial state.

1000100011101010

10001000101001010

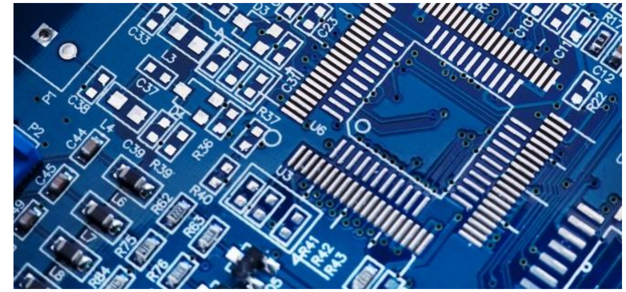
11011000101001010

010

010

Std. thinking about classical probabilities

Further discussion



<u>Classical Computer</u>: The "computational degrees of freedom" of a classical computer are very classical: Engineered to be well isolated from the quantum fluctuations that are everywhere

→

- Computations are deterministic
- "Random" is artificial
- Model a classical billiard gas on a computer:
  - ➢ All "random" fluctuations are determined by (or "readings of") the initial state.

10001000111101010

10001000101001010

11011000101001010

010

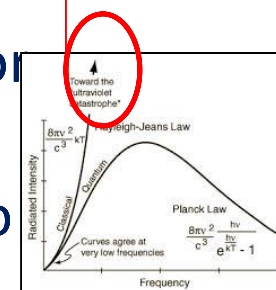
010

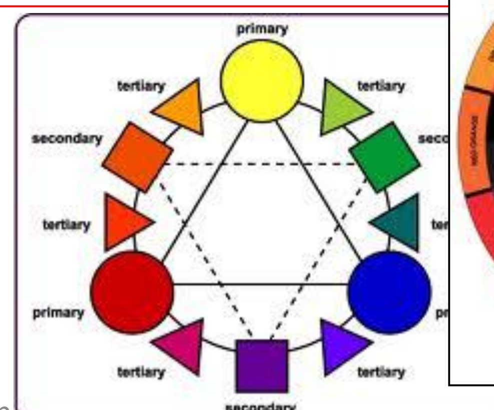
Std. thinking about classical probabilities

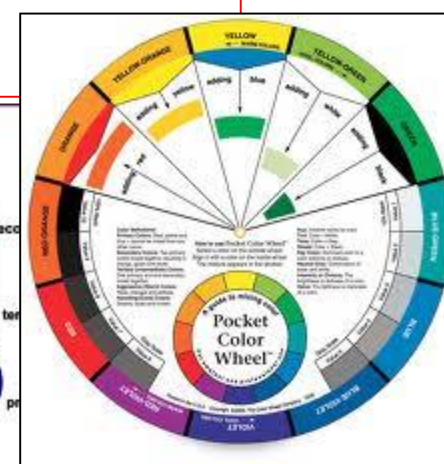
Further discussion

<u>Our ideas about probability are like our ideas about color:</u>

- Quantum physics gives the correct foundation to our understanding
- Our "classical" intuition predates our knowledge of QM by a long long time, and works just fine for most things
- Fundamental quantum understanding needed to fix classical misunderstandings in certain cases.



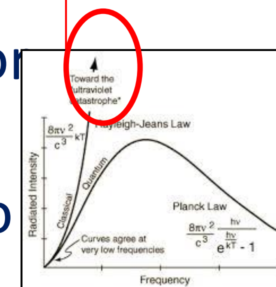


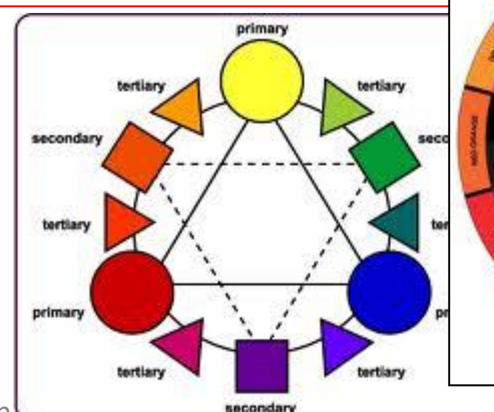


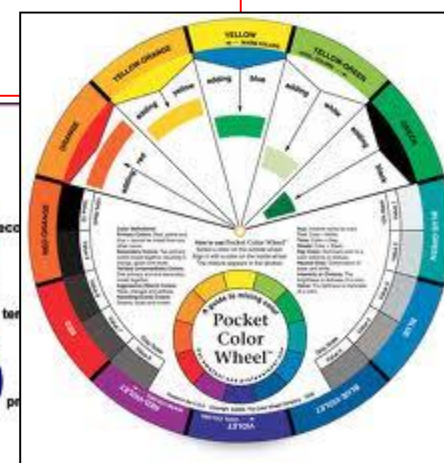
Further discussion

<u>Our ideas about probability are like our ideas about color:</u>

- Quantum physics gives the correct foundation to our understanding
- Our “classical” intuition predates our knowledge of QM by a long long time, and works just fine for most things
- Fundamental quantum understanding needed to fix classical misunderstandings in certain cases.







Further discussion

Our ideas about probabilit
color:

- Quantum physics gives t
  our understanding
  ' intuition
  ng long time, and works just fine for

  quantum understanding needed to
  sunderst