Origin of probabilities and their application to the multiverse

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Center for Quantum Mathematics and Physics (QMAP)
UC Davis

NBI
Nov 1, 2019

AA & D. Phillips (PRD Dec 2014) (more info here:
http://albrecht.ucdavis.edu/special-topics/origin-probabil)

Ways to experience this talk:

Have you thought about the
“multiverse”, “eternal inflation”
cosmological “measure
problems” etc?

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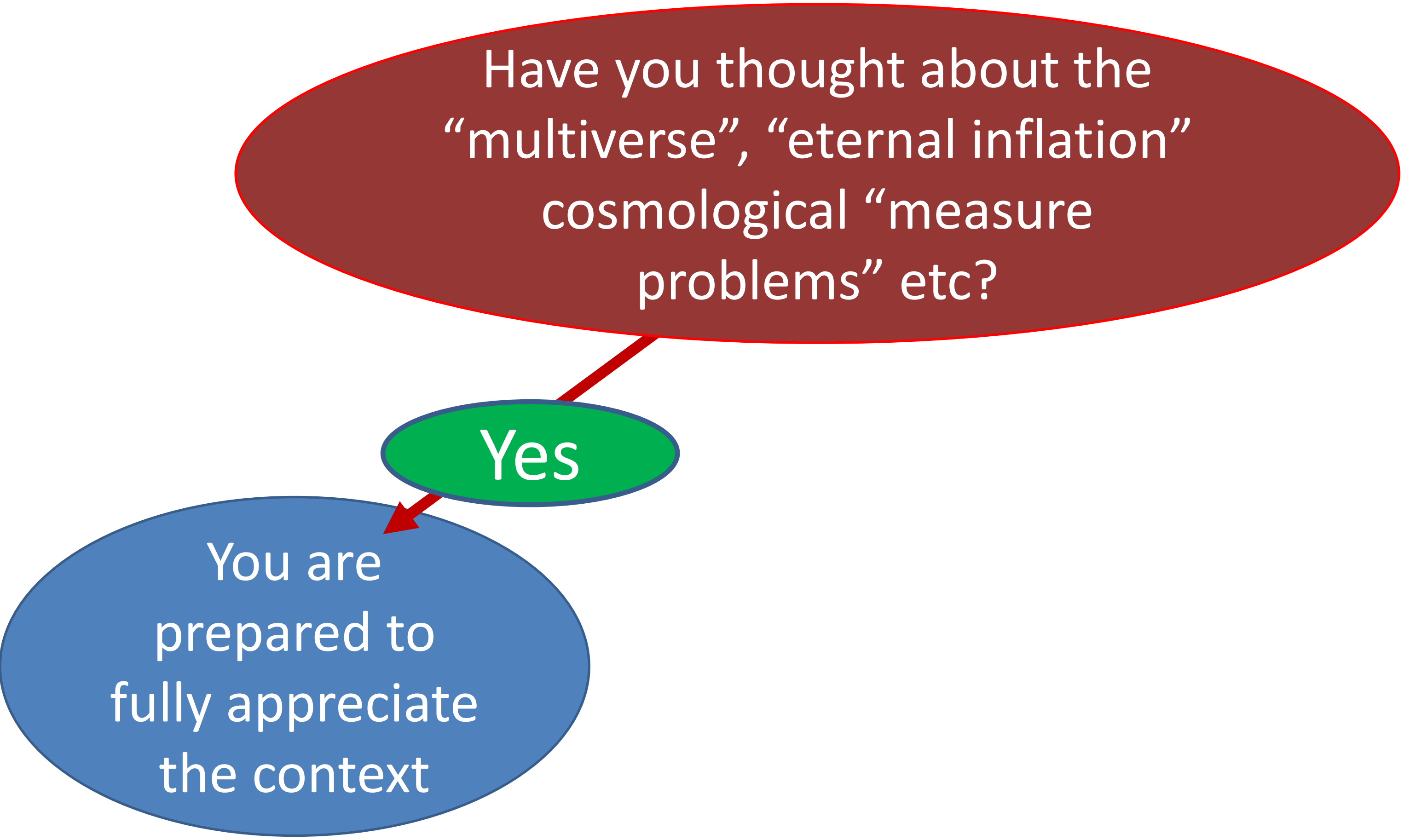

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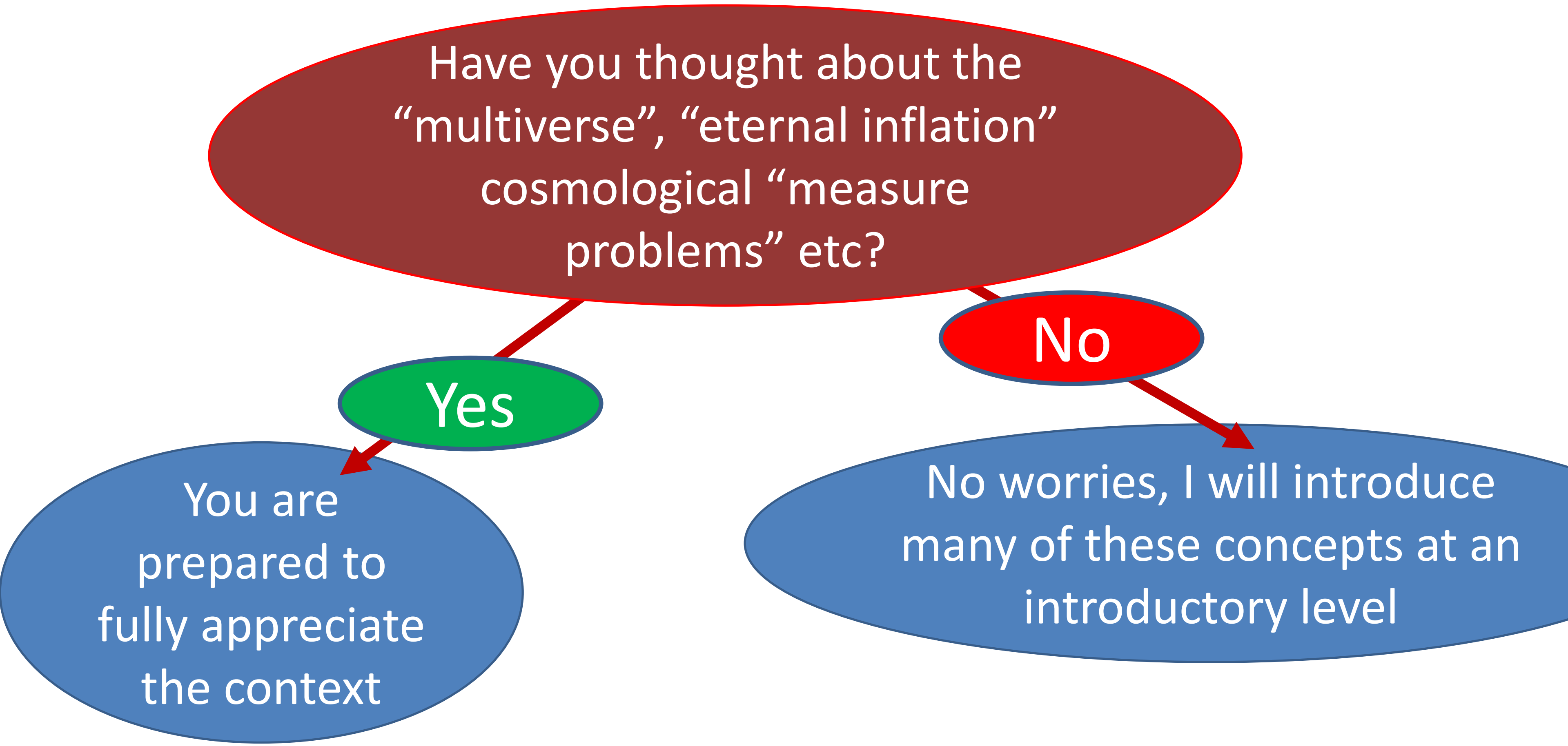

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Have you thought about the "multiverse", "eternal inflation" cosmological "measure problems" etc?

Yes

You are prepared to fully appreciate the context

No

No worries, I will introduce many of these concepts at an introductory level

Still confused?

Ignore cosmology motivations and consider my (provocative) claims purely in the context of everyday/laboratory physics

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Based on undergrad physics only

My history with this topic

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

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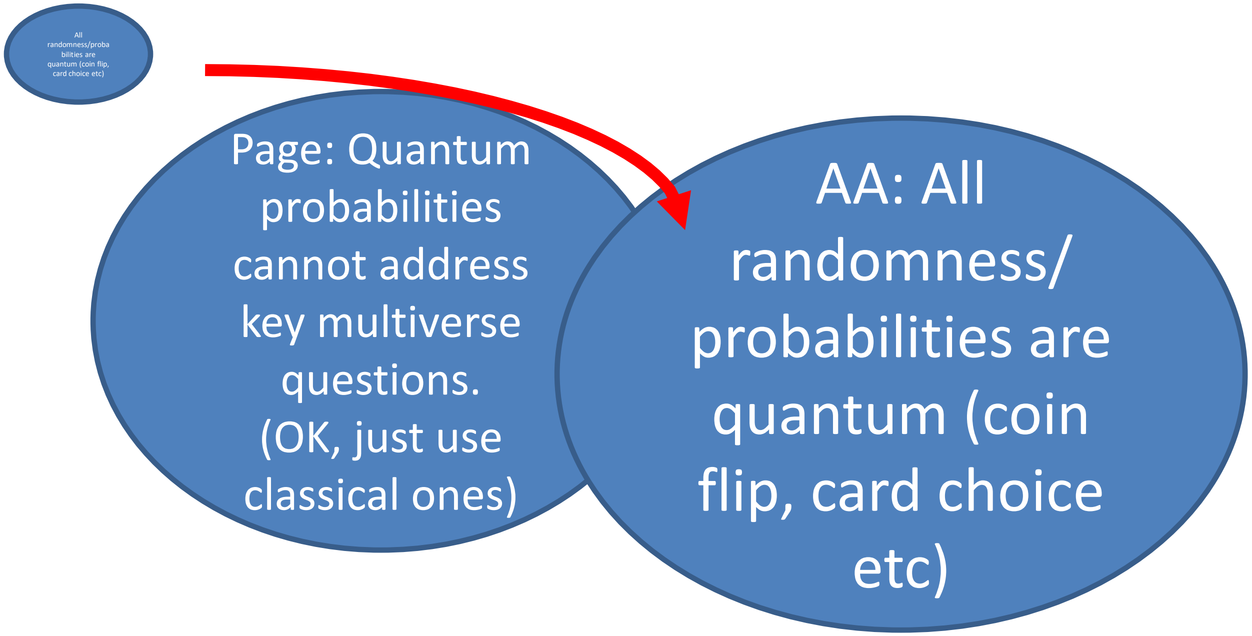

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Hartle, Srednicki, Aguirre, Tegmark, …

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A potential issue even for finite models

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

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

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X ?

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

(Or not)

Outline

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

2) Everyday probabilities

3) Be careful about counting!

4) Implications for multiverse/eternal inflation

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

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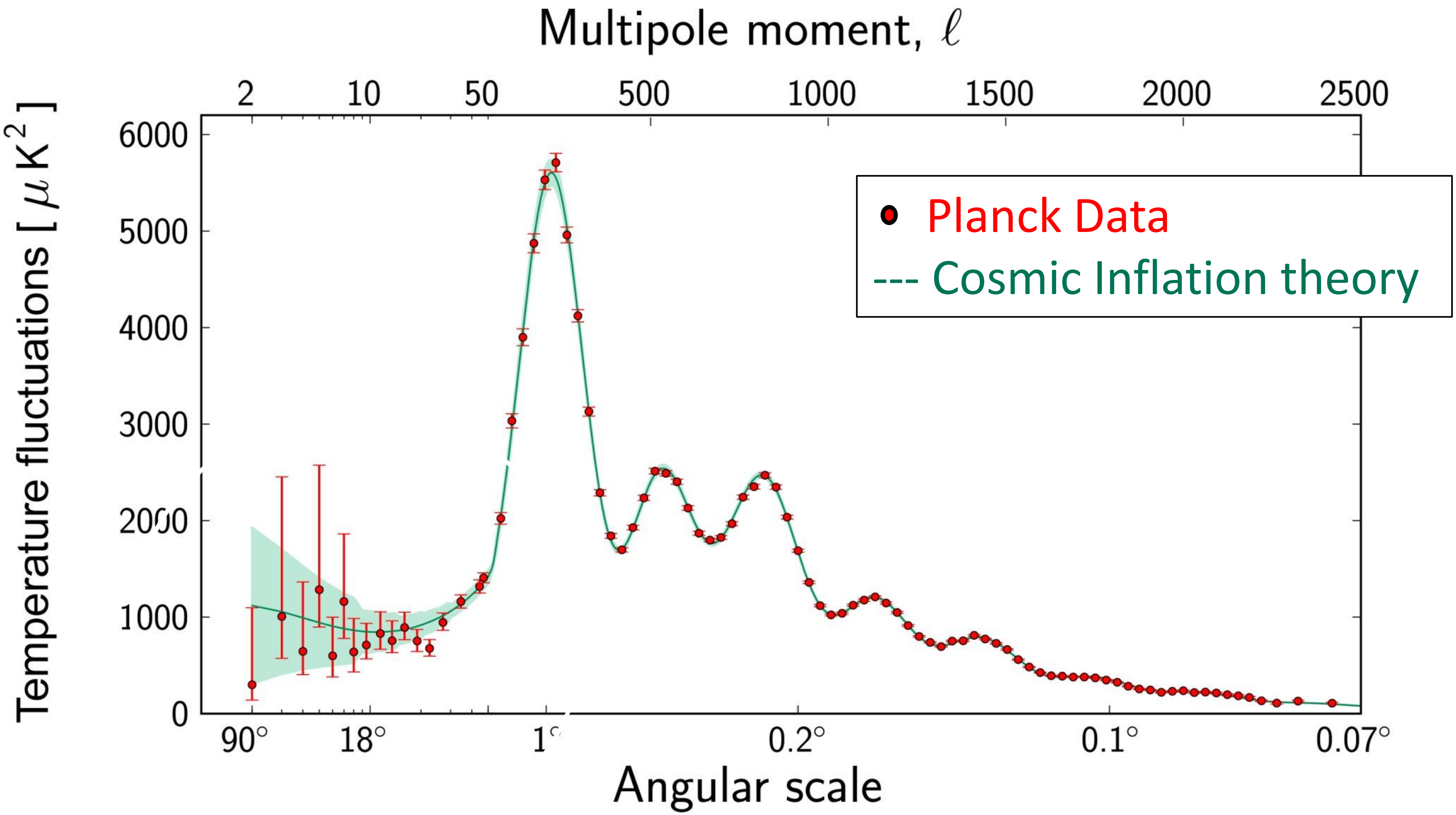
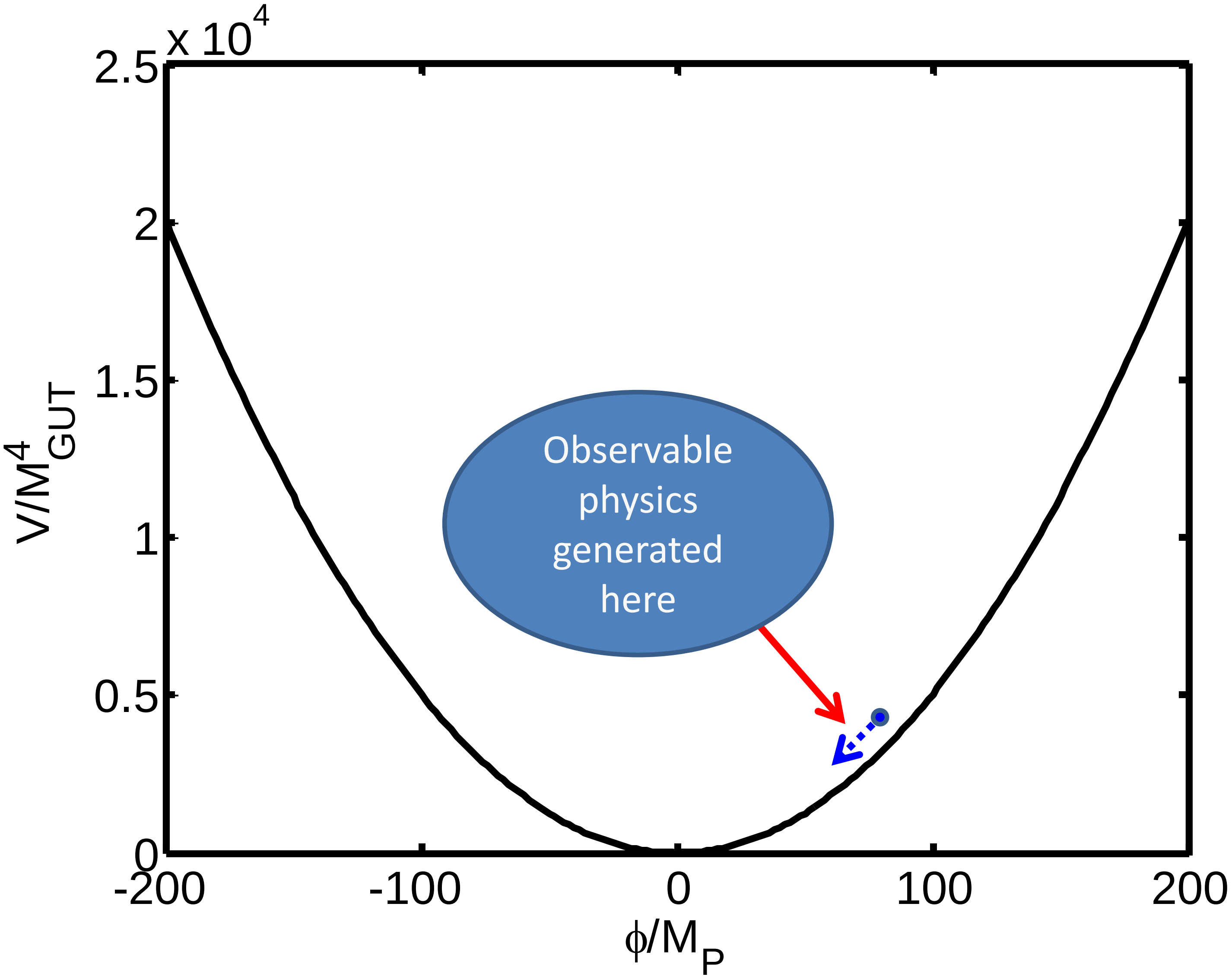

Multipole moment, ℓ
2
10
50
500
1000
1500
2000
2500
Temperature fluctuations [μK^2]
6000
5000
4000
3000
2000
1000
0
90°
18°
1°
0.2°
0.1°
0.07°
Angular scale
Planck Data
--- Cosmic Inflation theory

Slow rolling of inflaton



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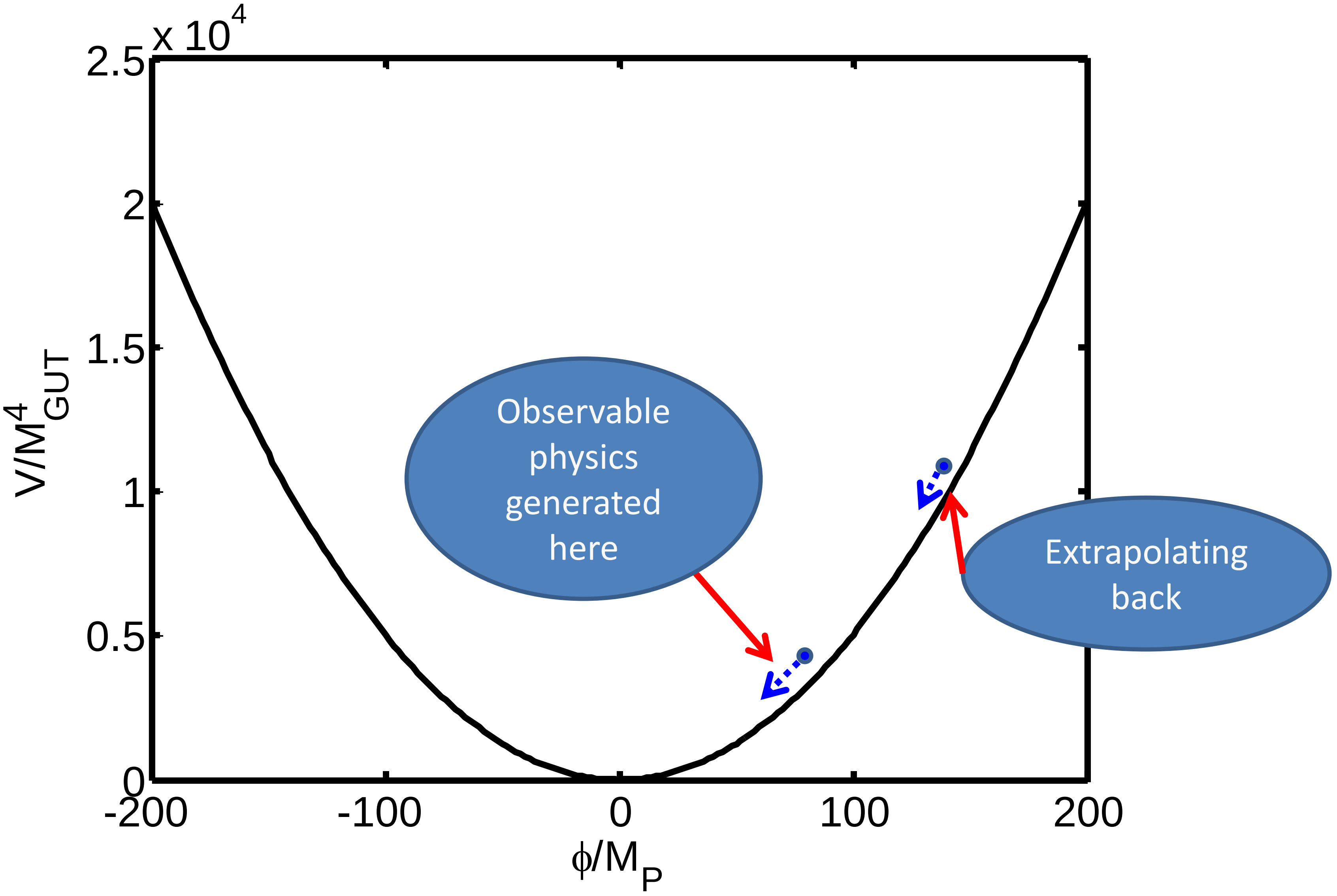

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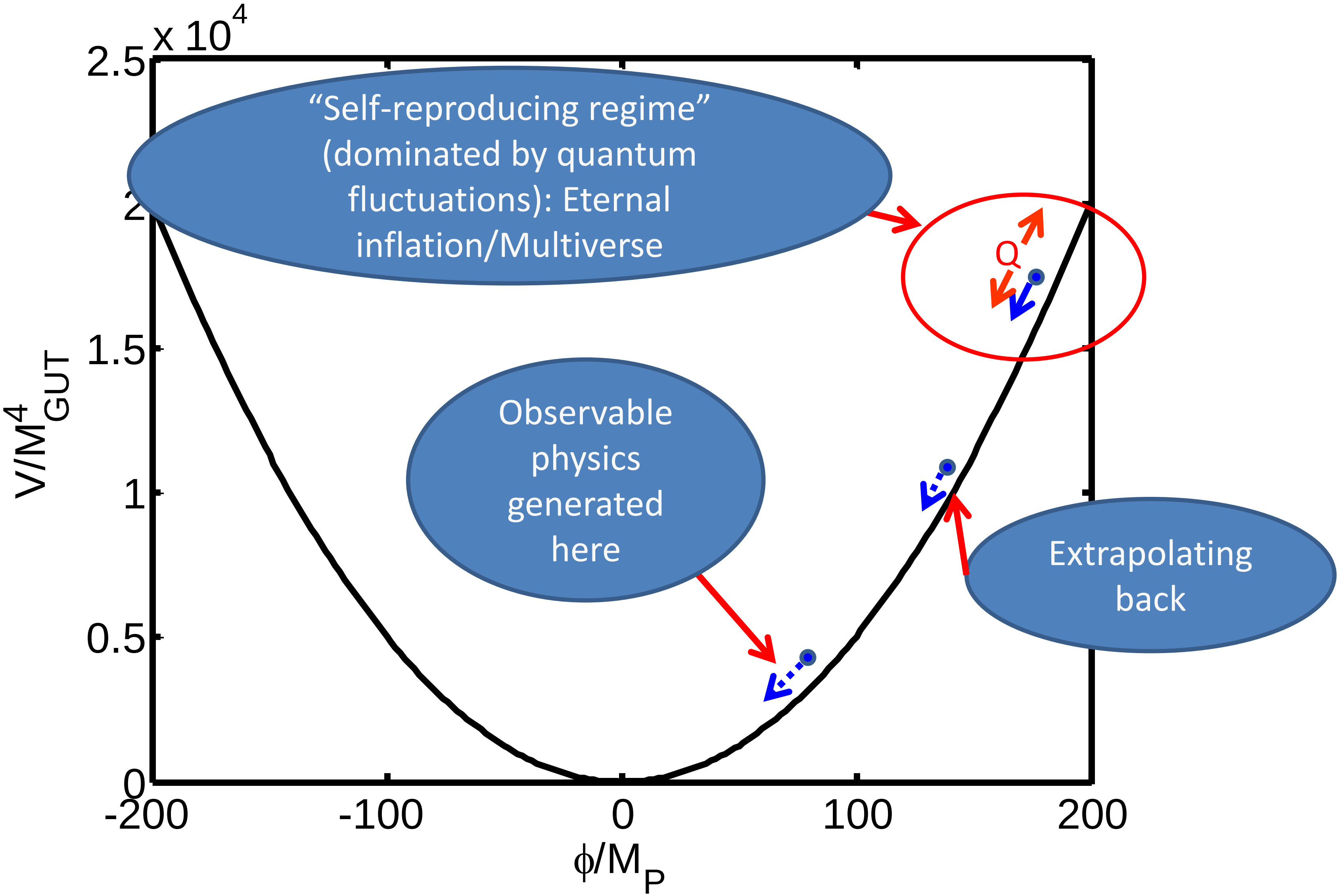

Steinhardt 1982, Linde 1982, Vilenkin 1983, and (then) many others

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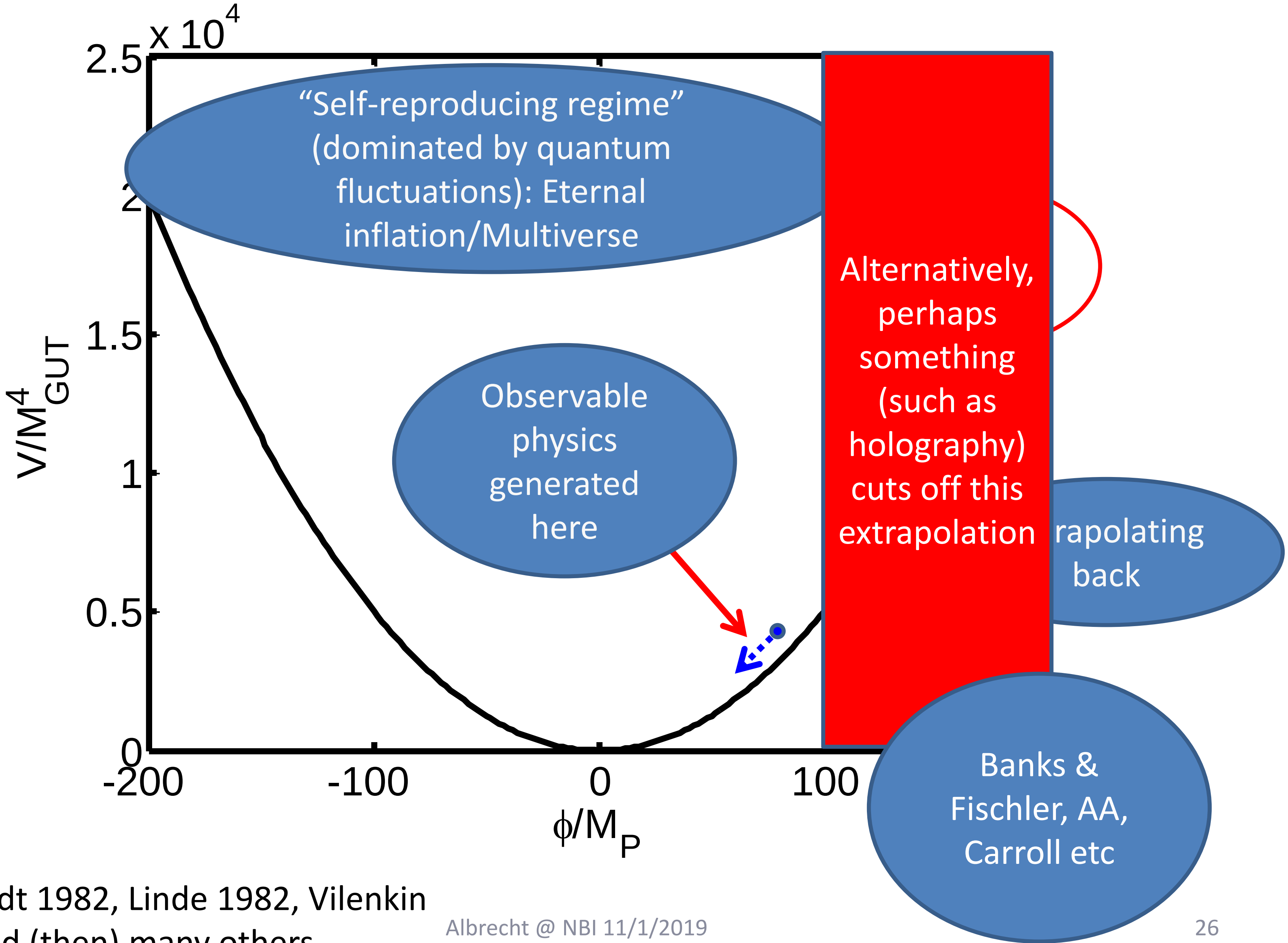

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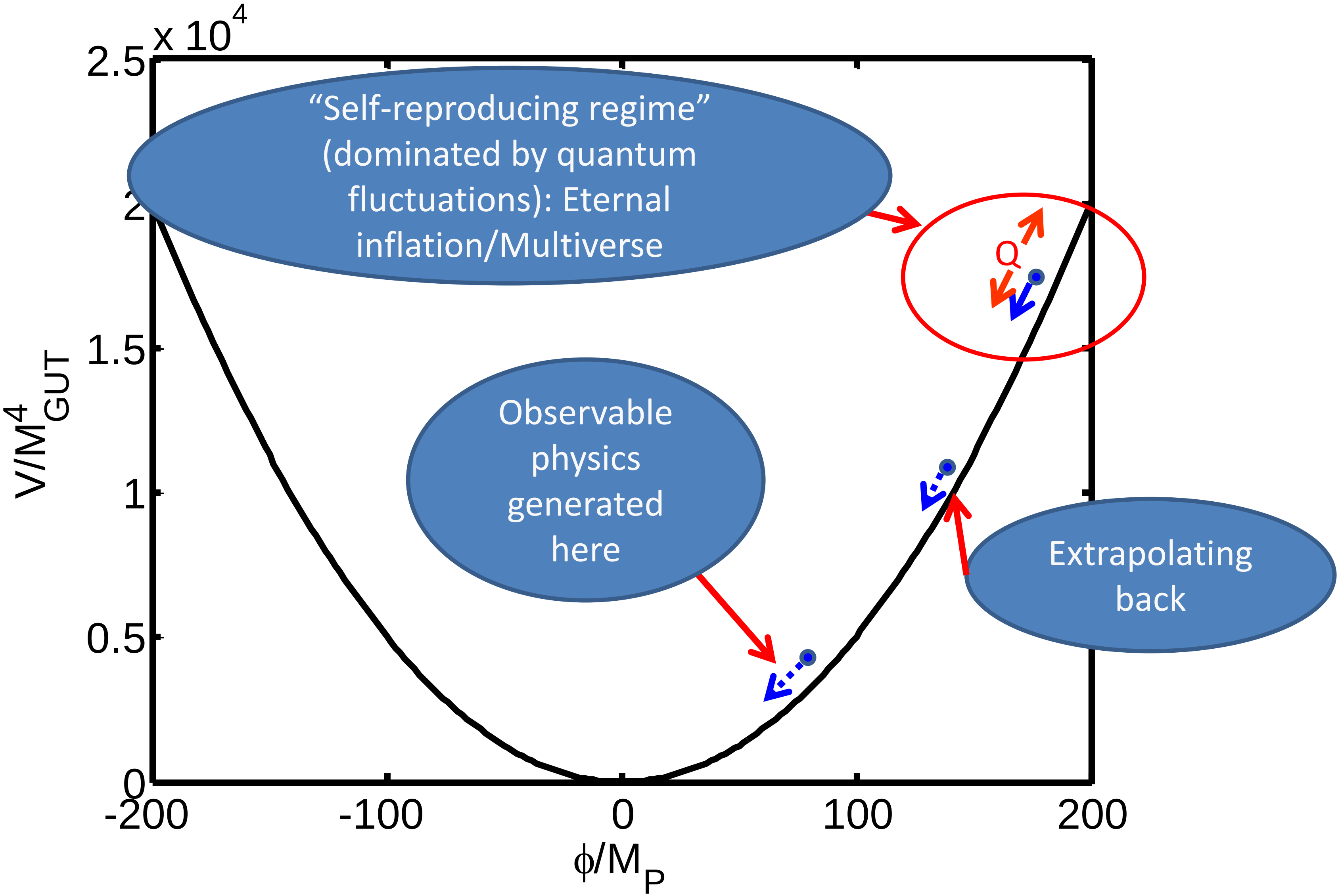

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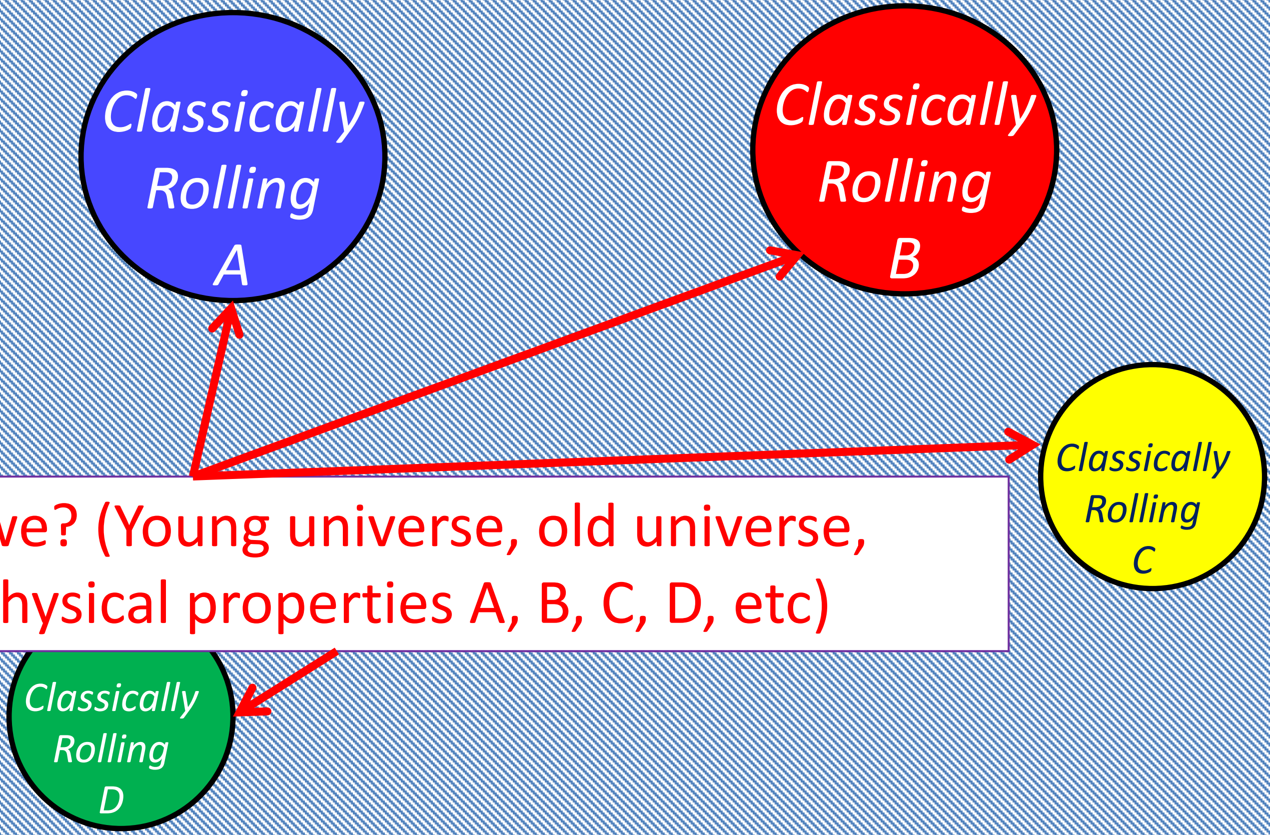
The multiverse of eternal inflation with multiple classical rolling directions

Self-reproduction regime



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

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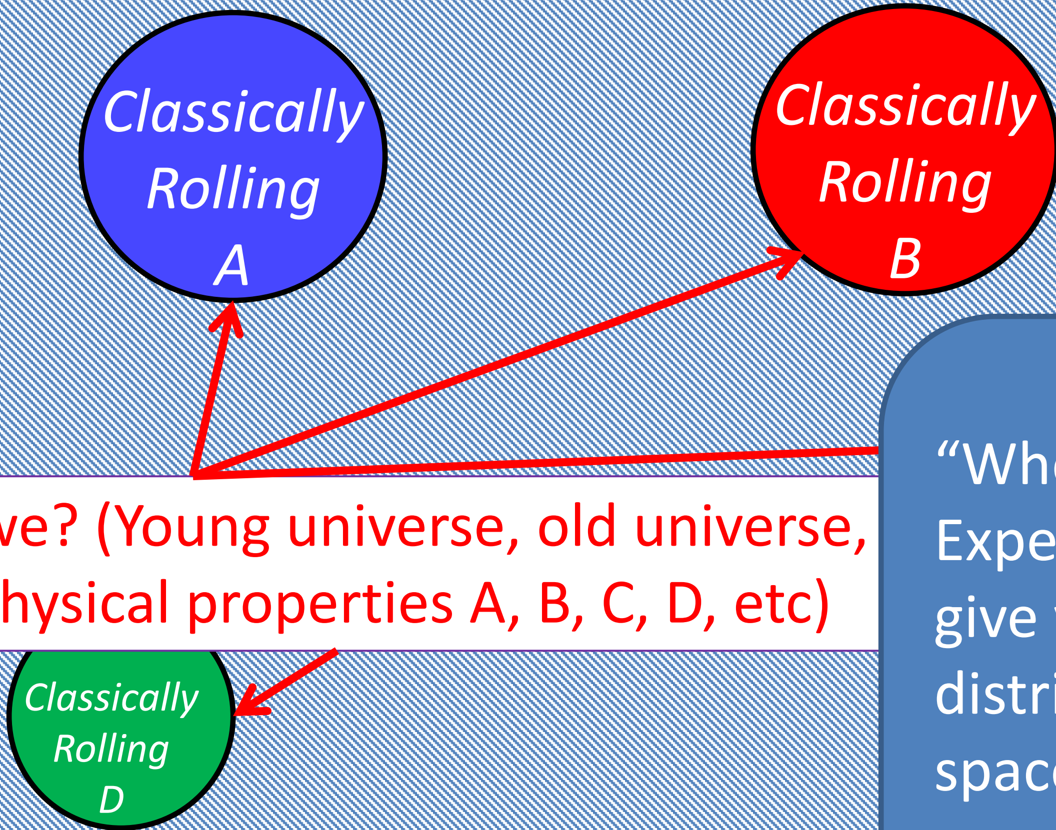

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"Where are we?" ➔ Expect the theory to give you a probability distribution in this space… hopefully with some sharp predictions

The multiverse of eternal inflation with multiple classical rolling directions

Self-reproduction regime

Classically Rolling A

Classically Rolling B

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"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)

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Self-reproduction regime

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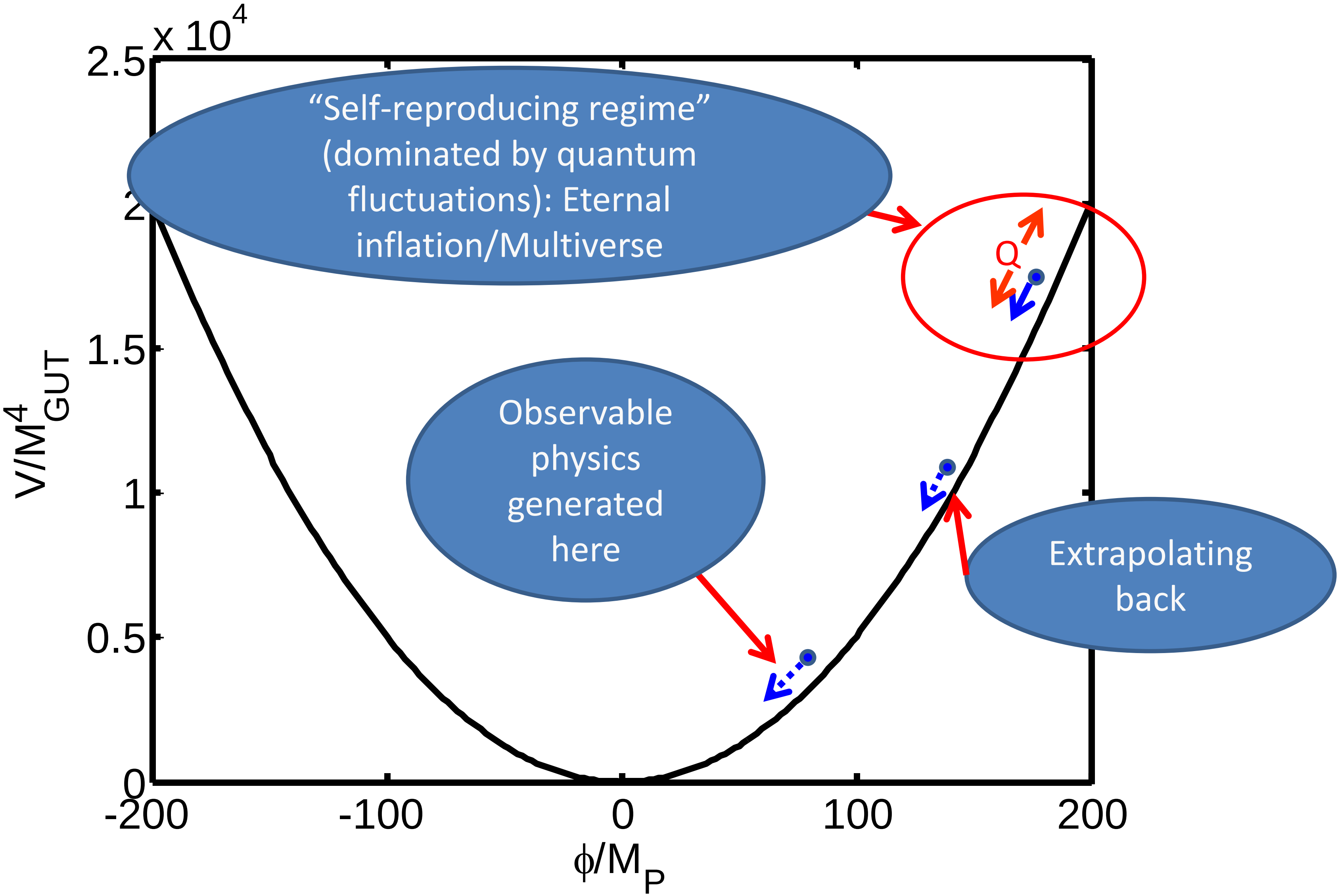

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Quantum vs Non-Quantum probabilities

Non-Quantum probabilities in a toy model:

$$U = A \otimes B$$

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

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

Page, 2009; These slides follow AA & Phillips 2014

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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

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.

$$U = A \ldots$$

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

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- All everyday probabilities are quantum probabilities

AA & D. Phillips 2014

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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

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A problem for many multiverse theories (as practiced)

AA & D. Phillips 2014

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Where do these come from anyway?

$U = A$

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Does not represent a quantum measurement

ments ←→ P

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

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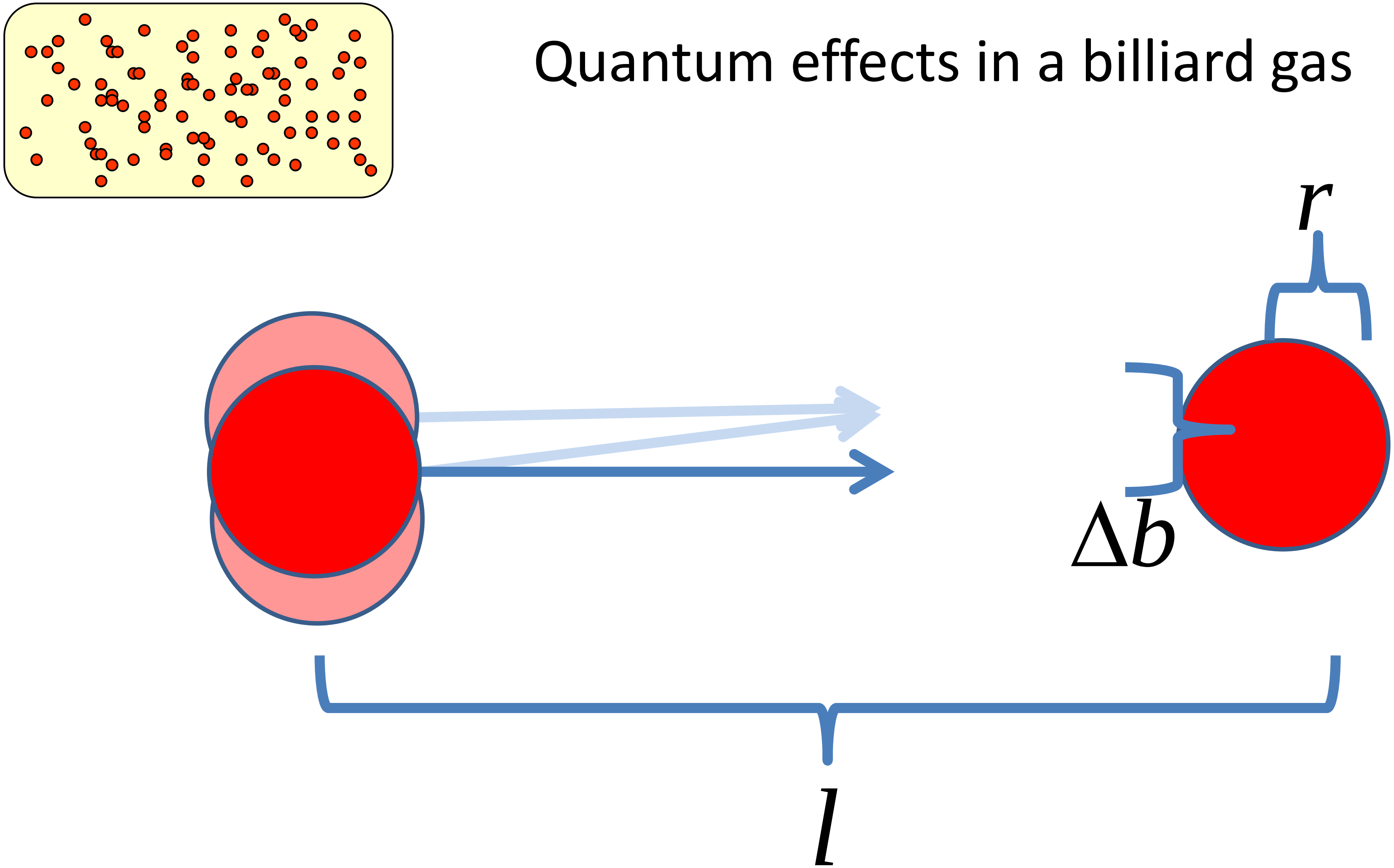
Quantum effects in a billiard gas



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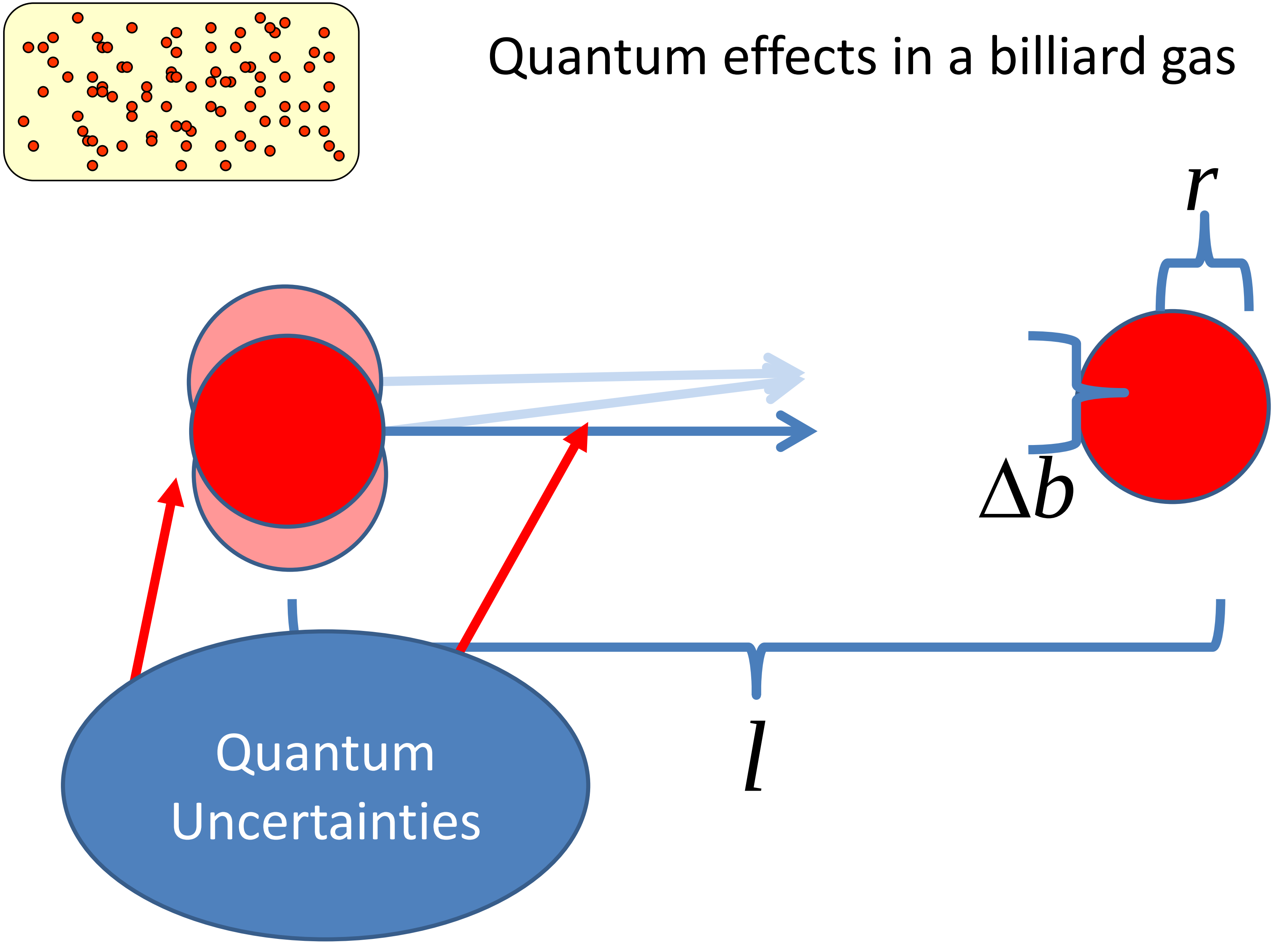

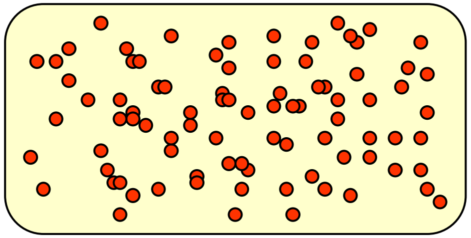

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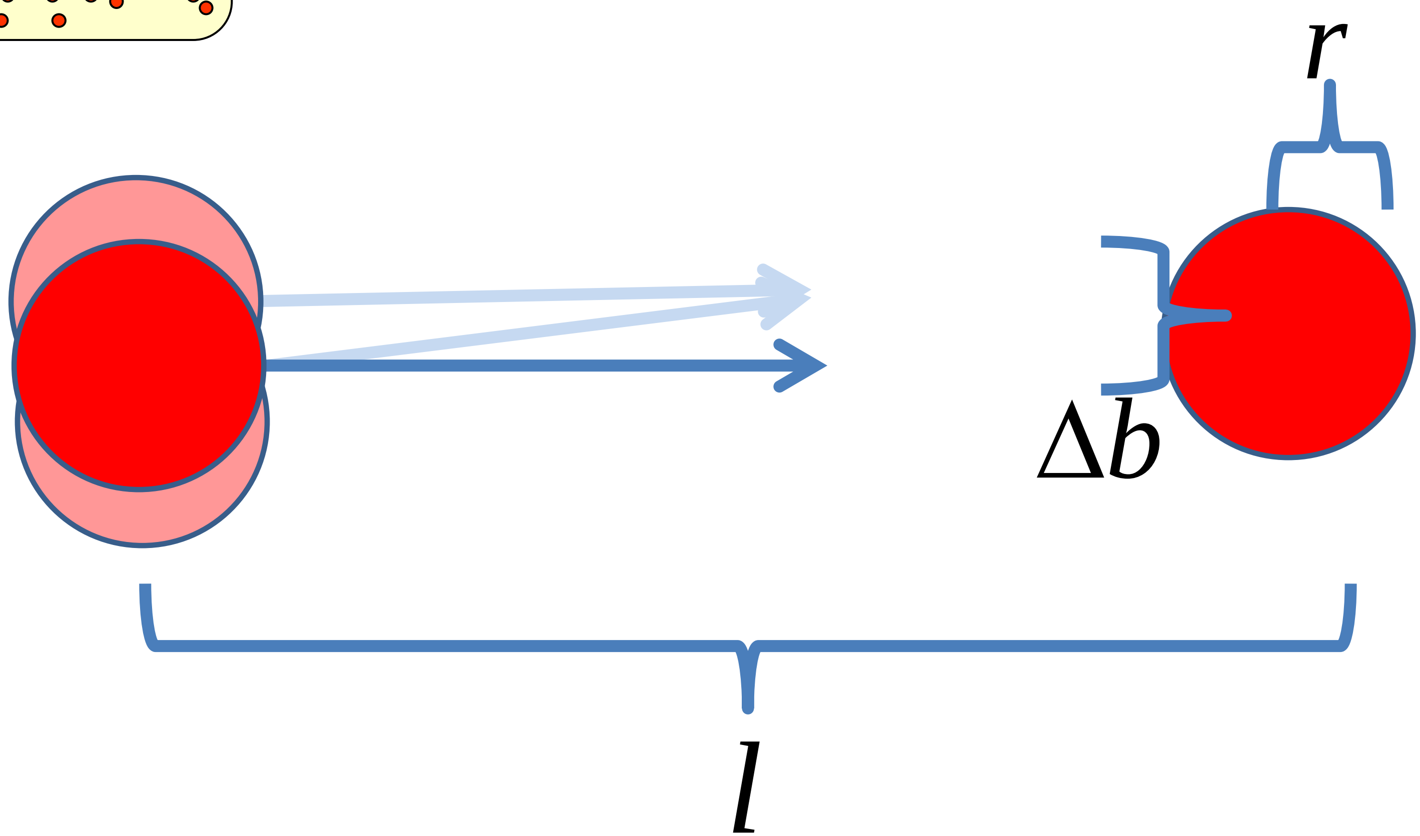
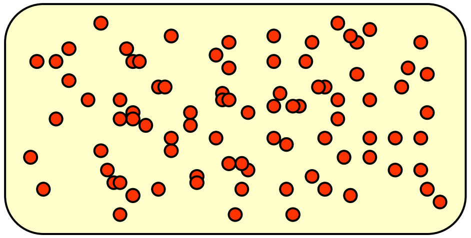


$$\boxed{\Delta b = \delta x_{\perp} + \frac{\delta p_{\perp}}{m} \Delta t}$$



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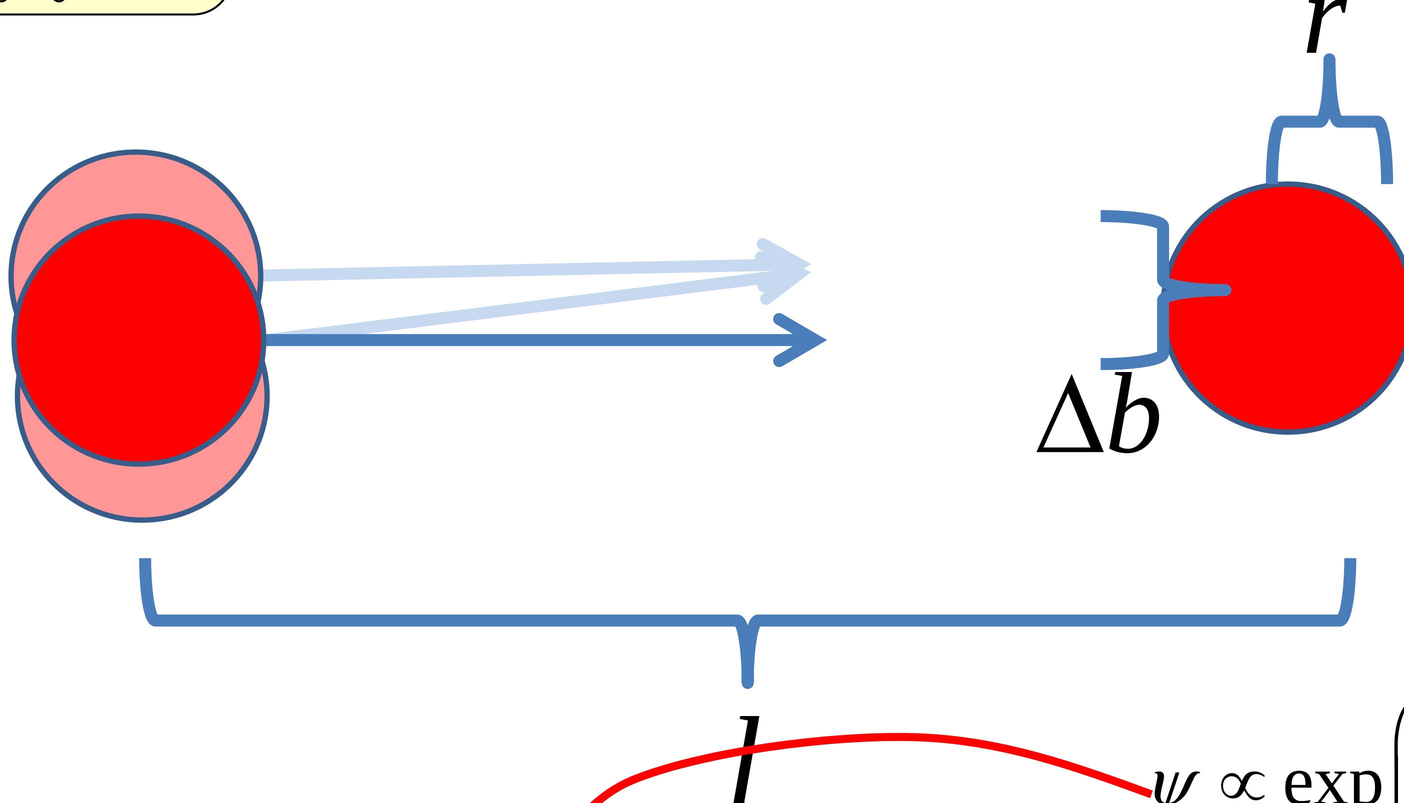
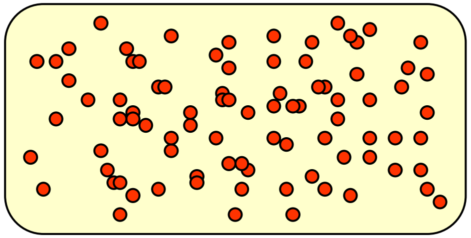


$$\psi \propto \exp\left(\frac{-x^2}{2a^2}\right)$$

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



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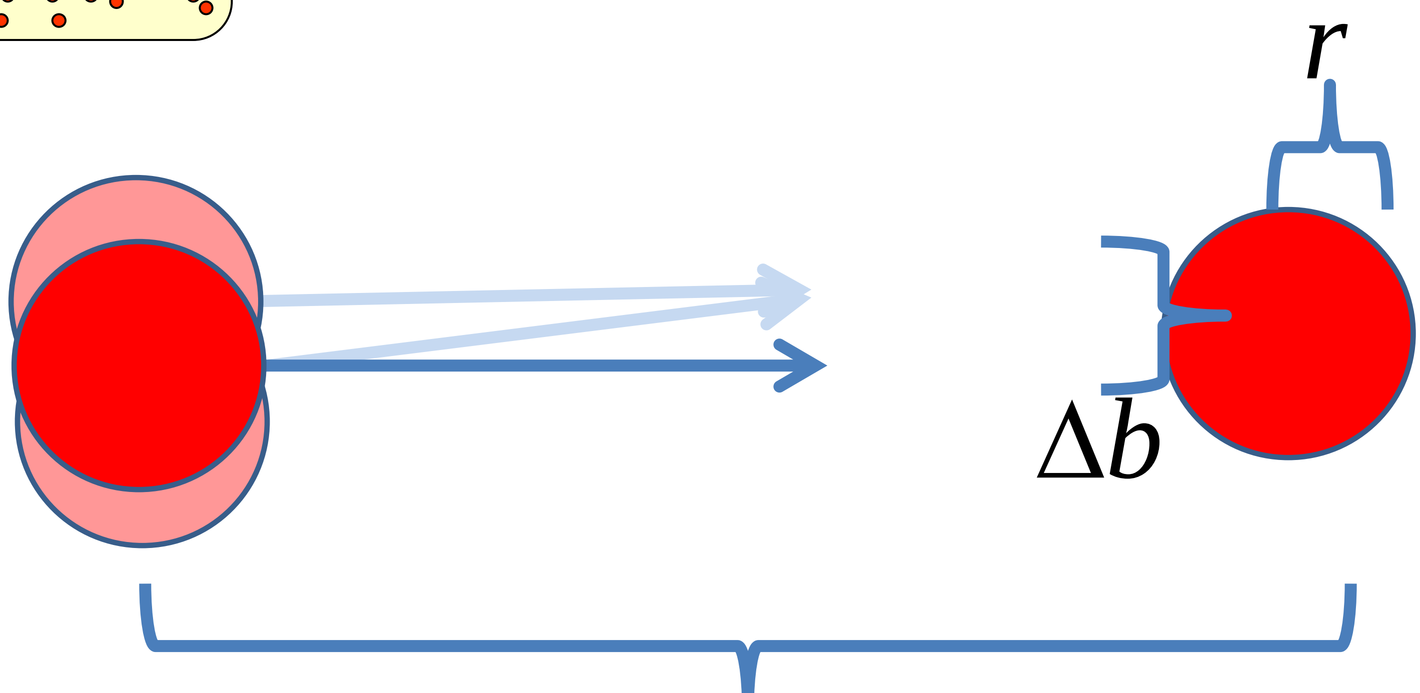

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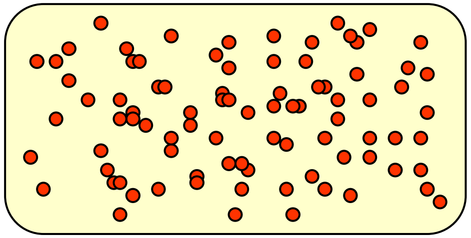
$$\xrightarrow{\min} 2^{3/2}\left(\frac{\hbar l}{2m\bar{v}}\right) \equiv \sqrt{l\lambda\!\!\!^{-}_{dB}/2}$$



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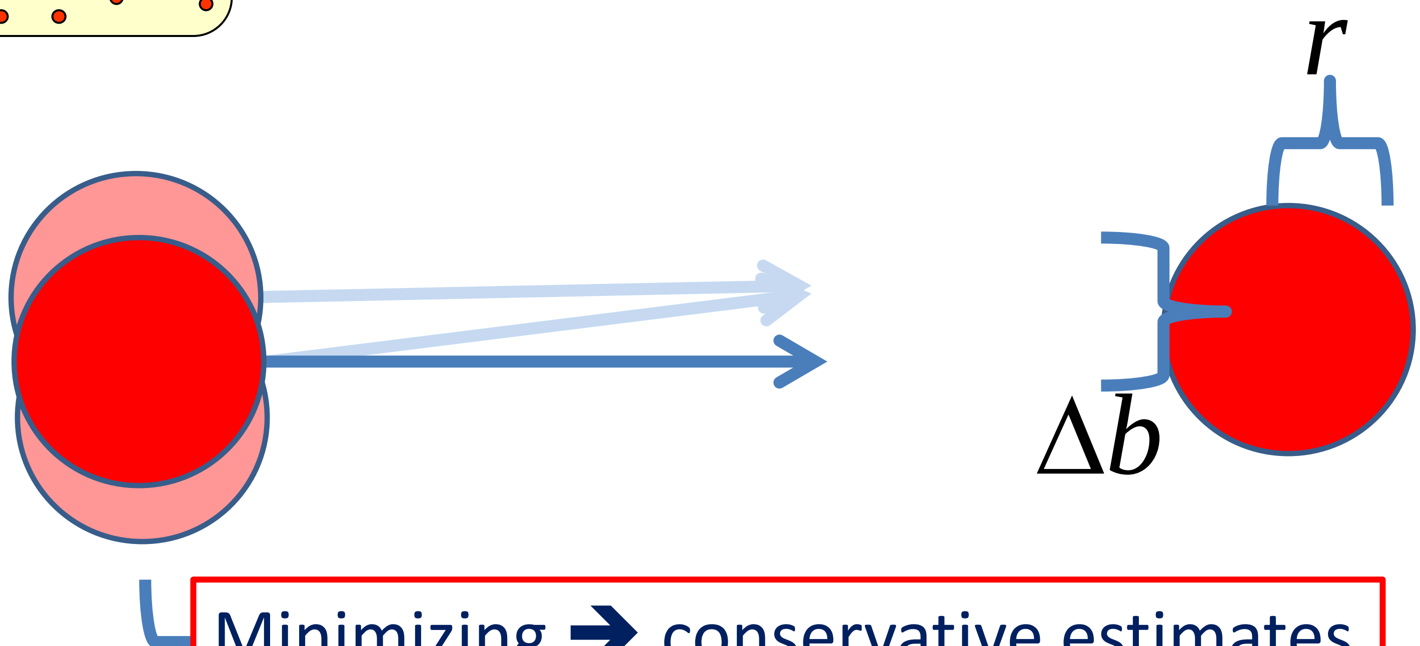

Minimizing ➔ conservative estimates for my purposes (also motivated by decoherence in some cases)

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

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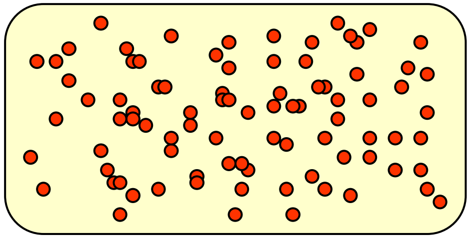

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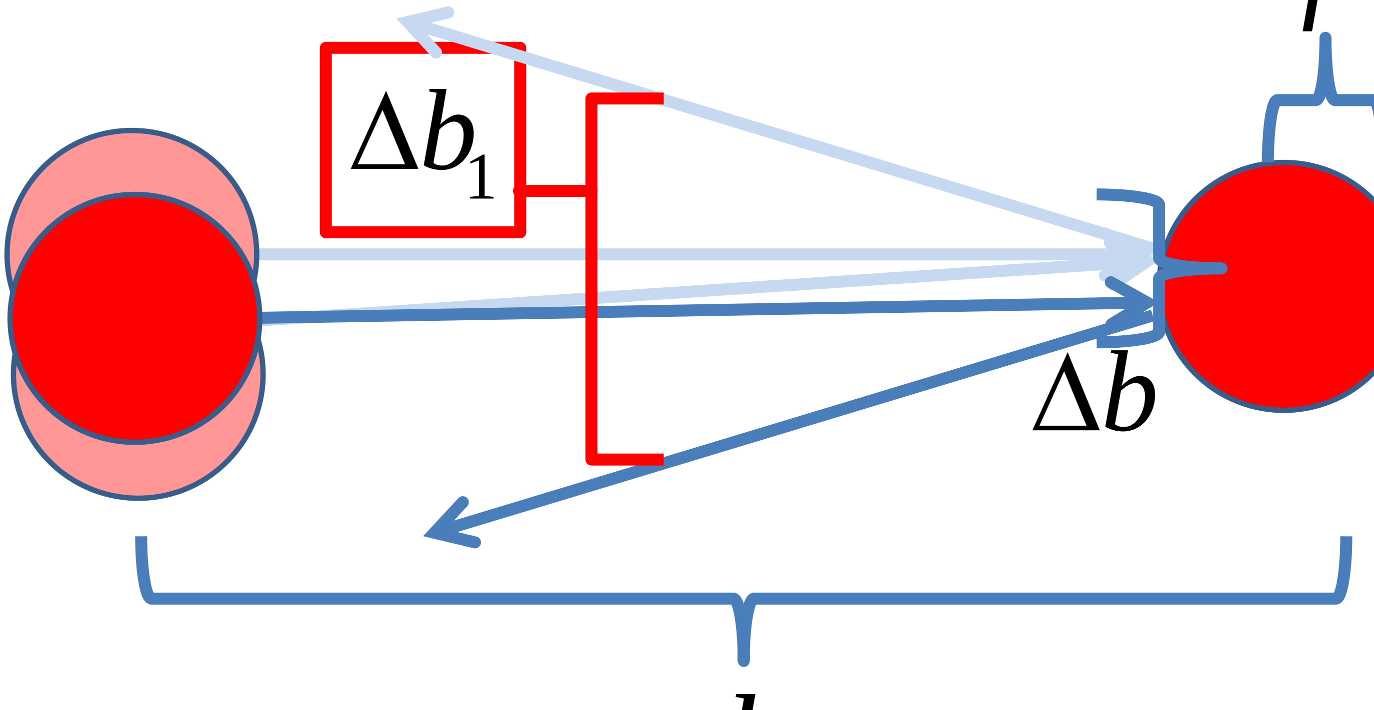
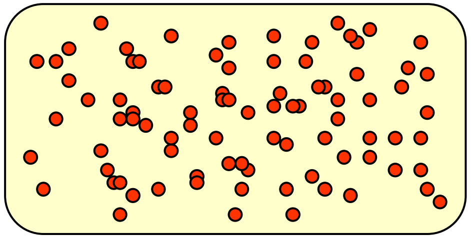
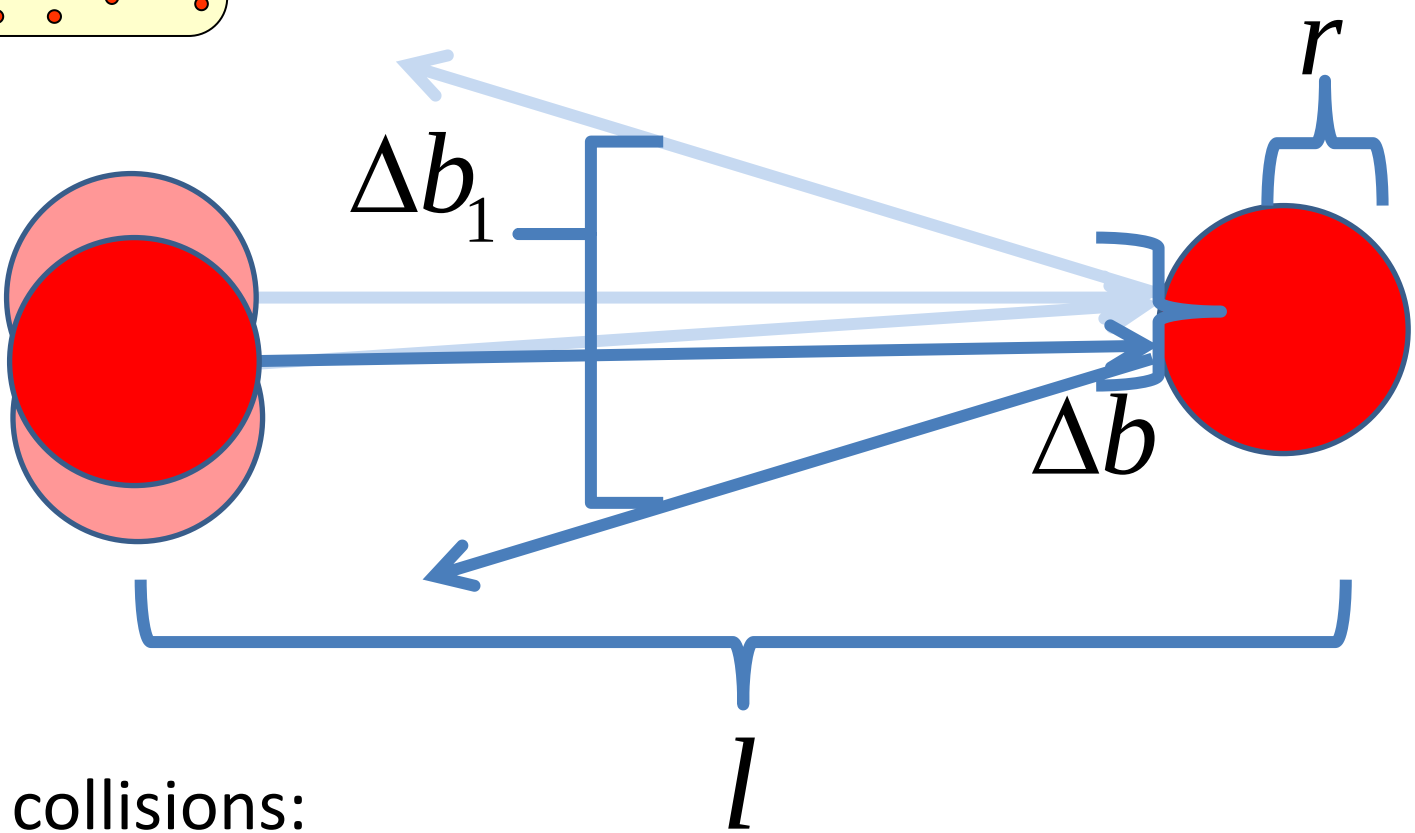


Subsequent collisions amplify the initial uncertainty (treat later collisions classically ➔ additional conservatism)

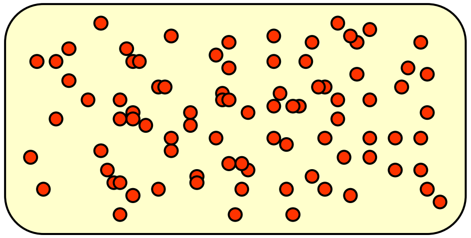
Quantum effects in a billiard gas





After *n* collisions:

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



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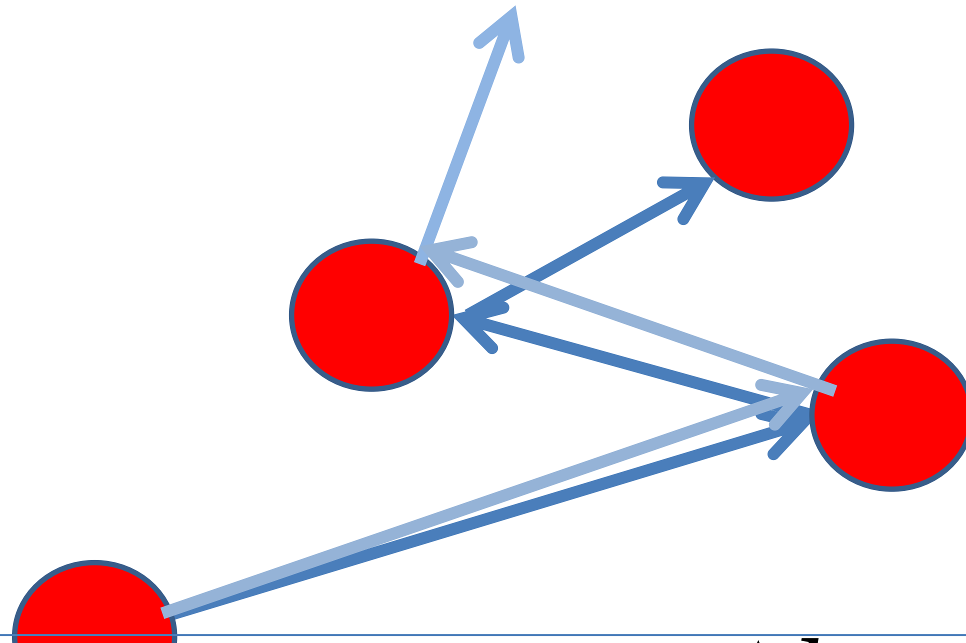

n_Q is the number of collisions so that $\Delta b_{n_Q} = r$

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

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

n_Q for a number of physical systems

(all units MKS)

	r	l	m	$\bar{v}$	$\lambda\!\!\!^{-}_{dB}$	Δb	n_Q
Air							
Water							
Billiards							
Bumper Car							

n_Q for a number of physical systems

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

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	r	l	m	$\bar{v}$	$\lambda\!\!\!^{-}_{dB}$	Δb	n_Q
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	r	l	m	$\bar{v}$	λ_{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}	$\boxed{0.6}$
Billiards	0.029	1	0.16	1	6.6×10^{-34}	5.1×10^{-17}	8
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	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}	$\boxed{-0.3}$
Water	3.0×10^{-10}	5.4×10^{-10}	3×10^{-26}	460	7.6×10^{-12}	1.3×10^{-10}	0.6
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Bumper Car	1	2	150	0.5	1.4×10^{-36}	3.	

Quantum at every collision

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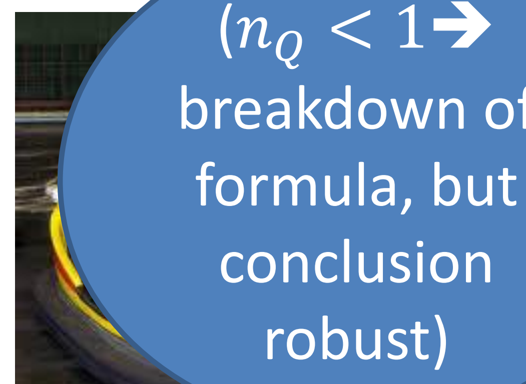
Quantum at every collision

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



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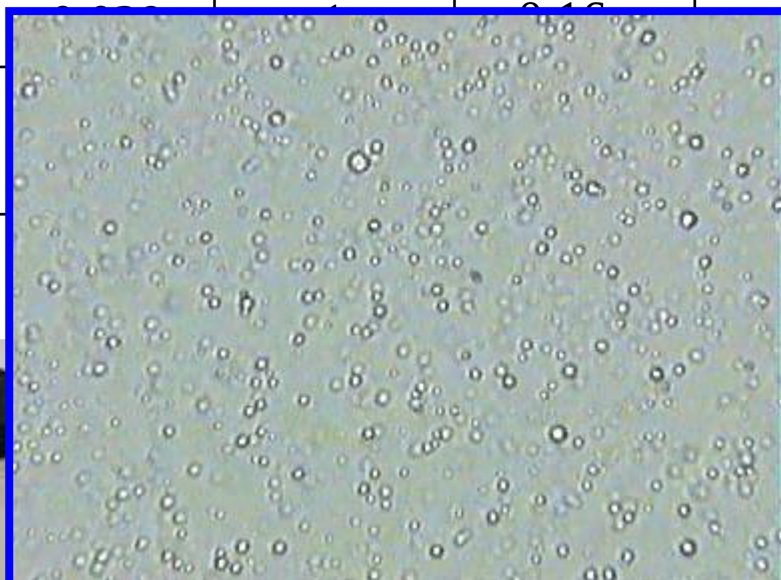

Quantum at every collision

Every Brownian Motion is a "Schrödinger Cat"

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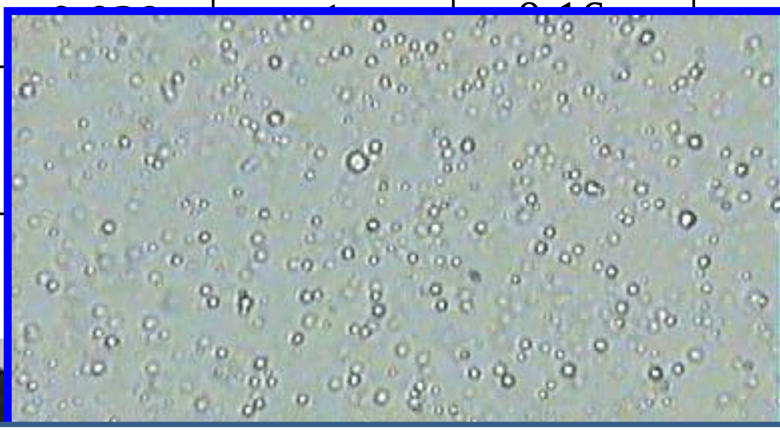
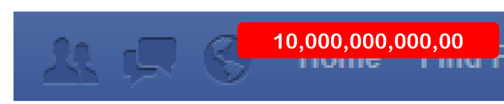


Quantum at every ollision

Every Brownian Motion is a “Schrödinger

(independent of “interpretation”)



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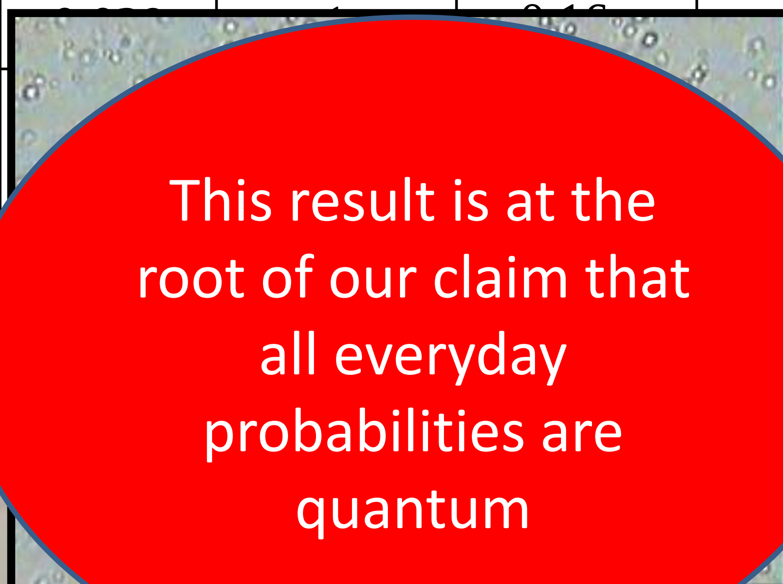
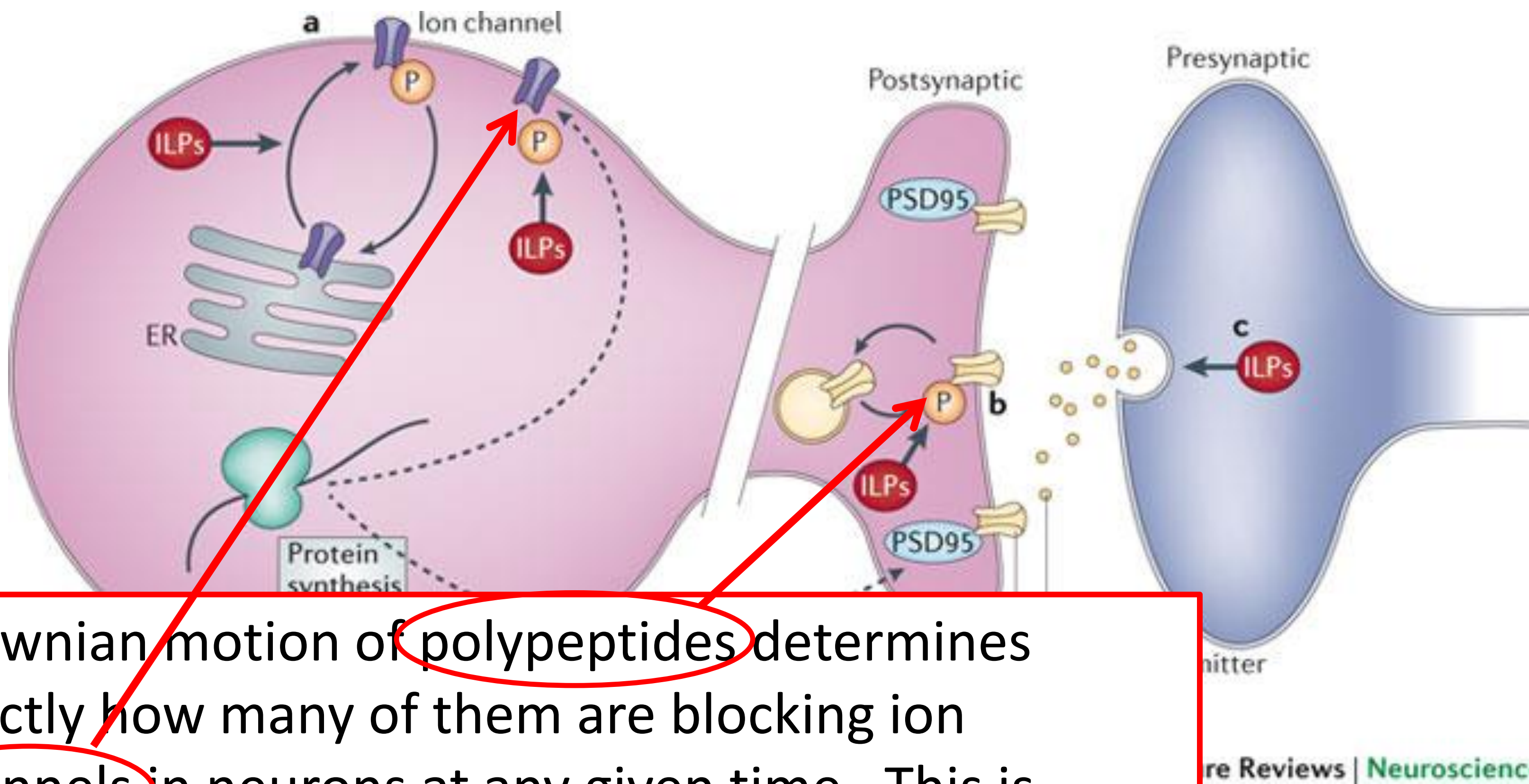


This result is at the root of our claim that all everyday probabilities are quantum

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

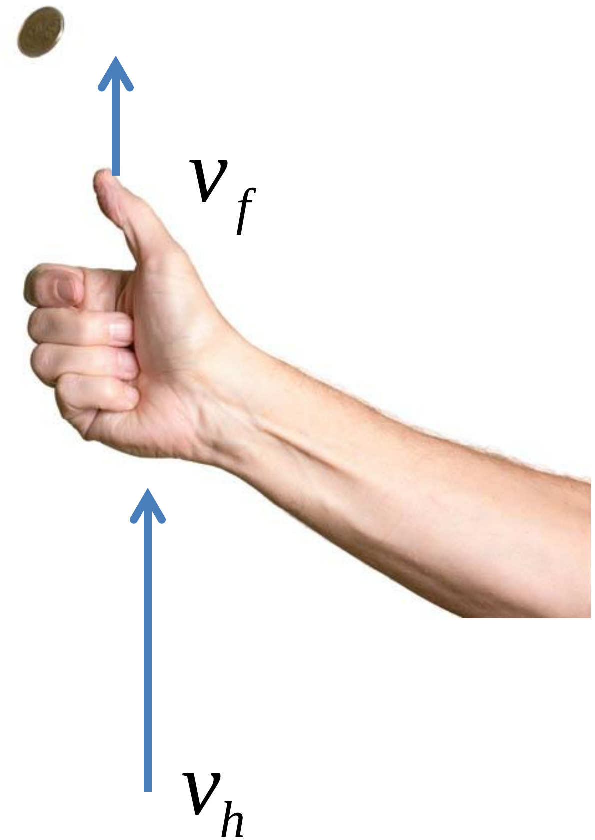
Analysis of coin flip

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

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

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

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



Coin diameter $= d$

Using:

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

$d = 0.01m$

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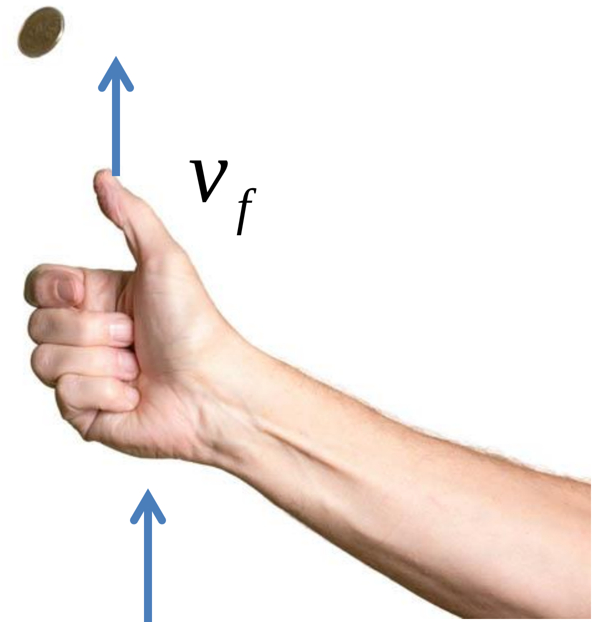

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50-50 coin flip probabilities are a derivable quantum result

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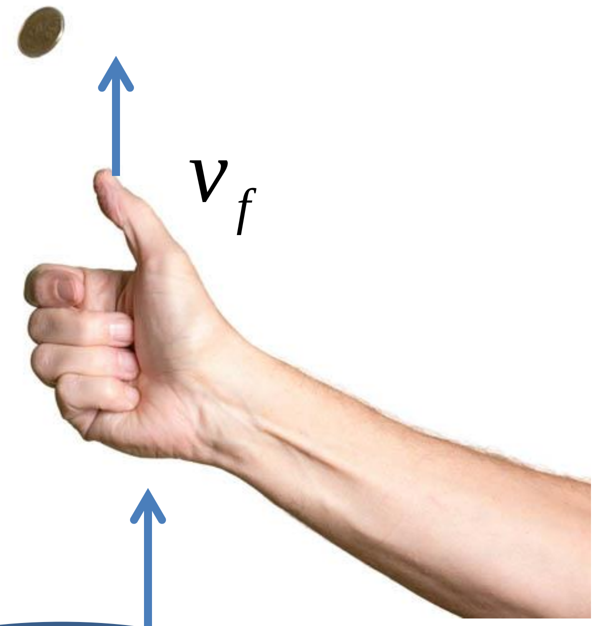
Analysis of coin flip



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Usin

Without reference to "principle of indifference" etc. etc.

d

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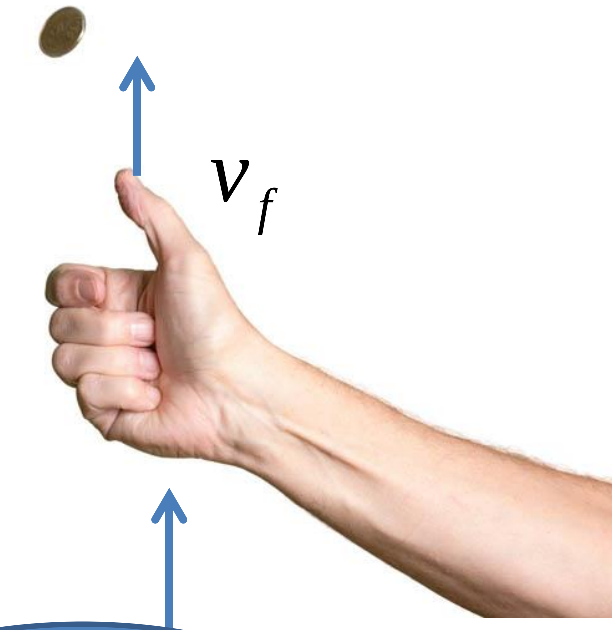

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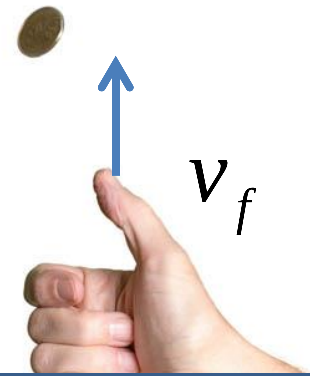

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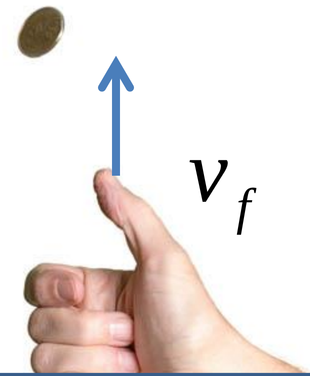

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Still, this is a good illustration of how quantum uncertainties can filter up into the macroscopic world, for systems that *are* random.

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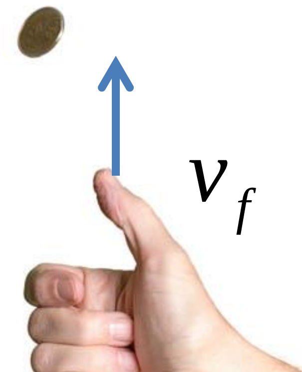

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Physical randomness vs "probabilities of belief"

Physical randomness: To do with physical properties of detector etc

Bayes:

$$P(Theory\,|\,Data) = \frac{P(Data\,|\,Theory)}{P(Data)} P(Theory)$$

Physical randomness vs “probabilities of belief”

Bayes:

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

Probabilities of belief:

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

Physical randomness vs "probabilities of belief"

This talk is about physical randomness only

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Physical randomness vs "probabilities of belief"

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

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Physical randomness vs "probabilities of belief"

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

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Some further thoughts:

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- Special relationship to cosmic structure from inflation: “(cosmic) 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

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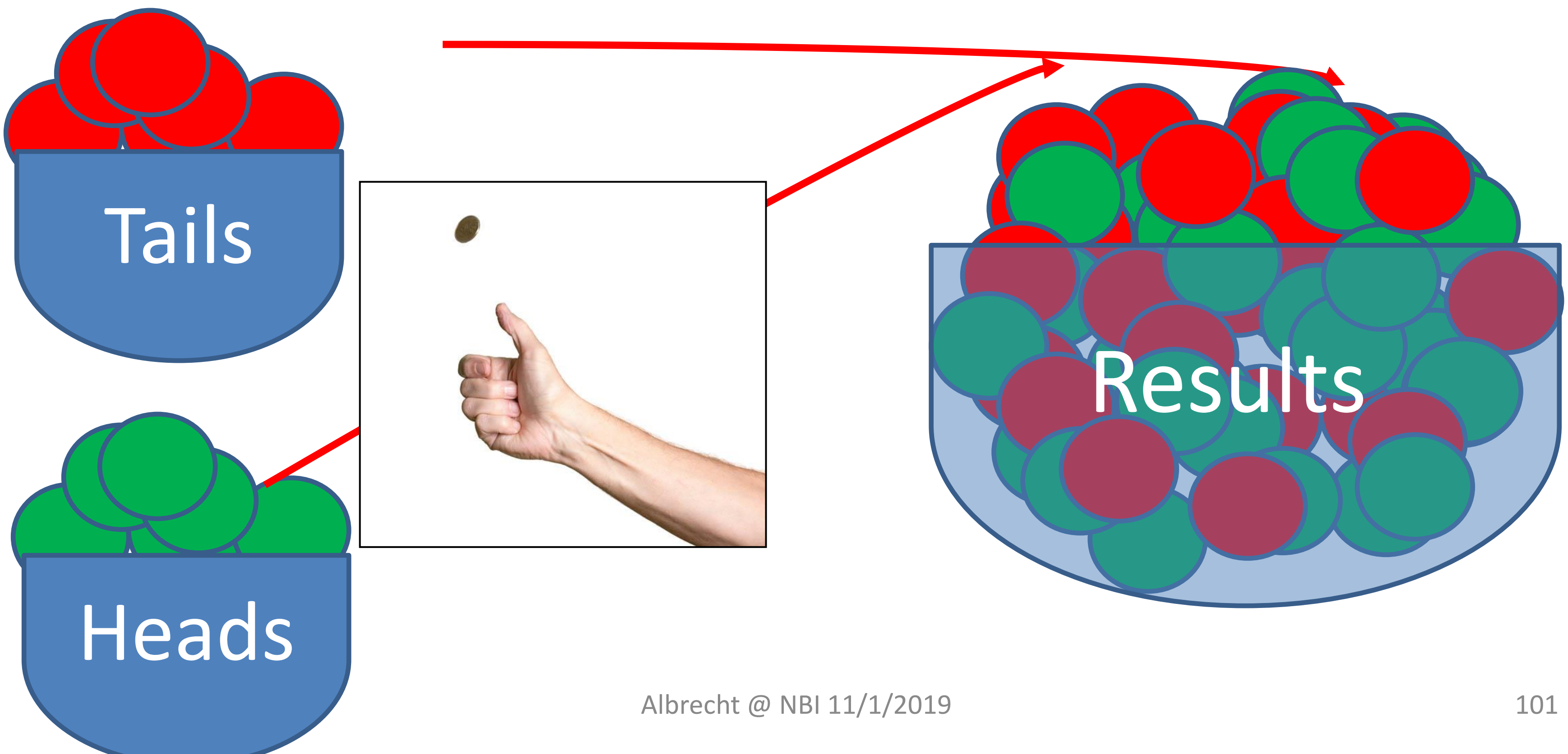

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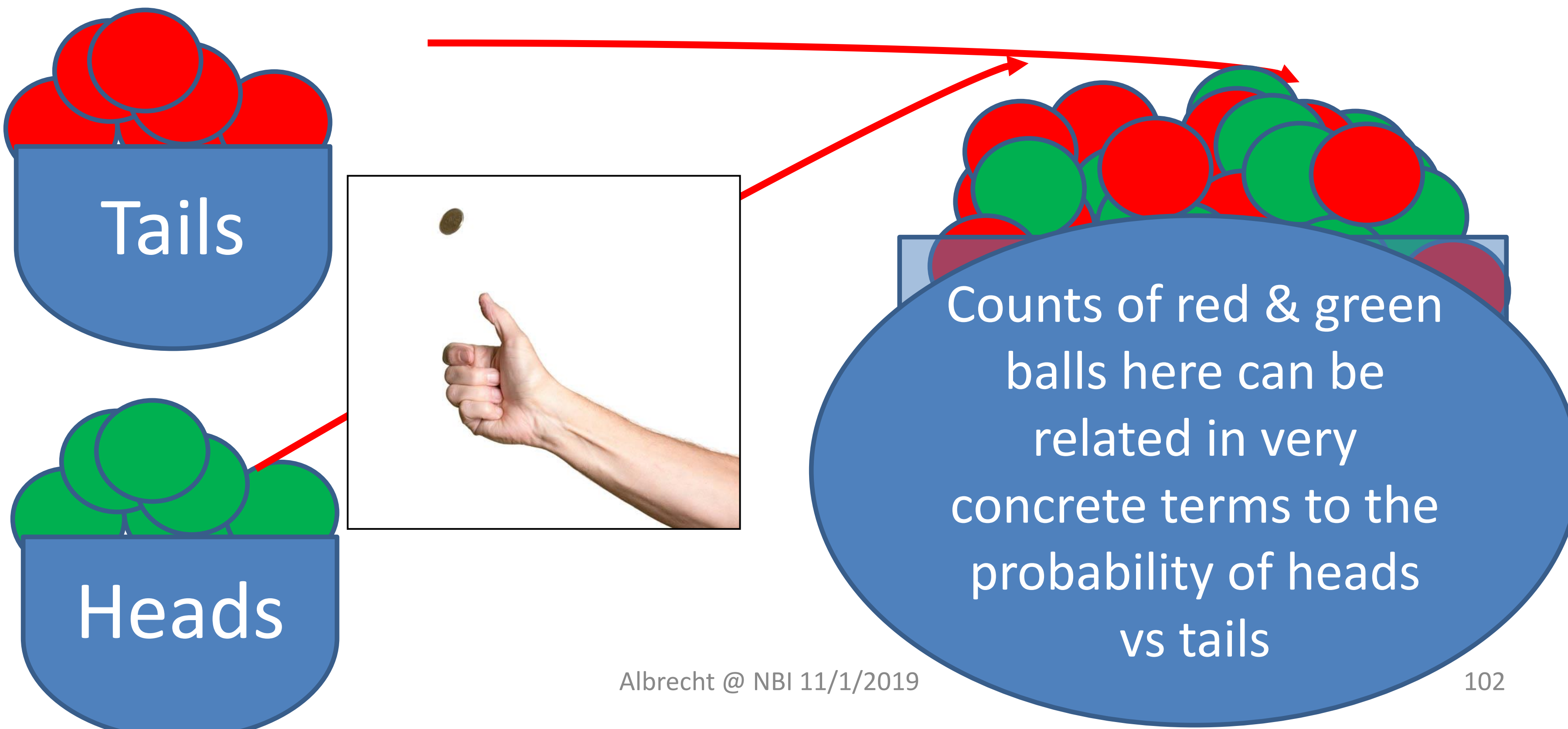

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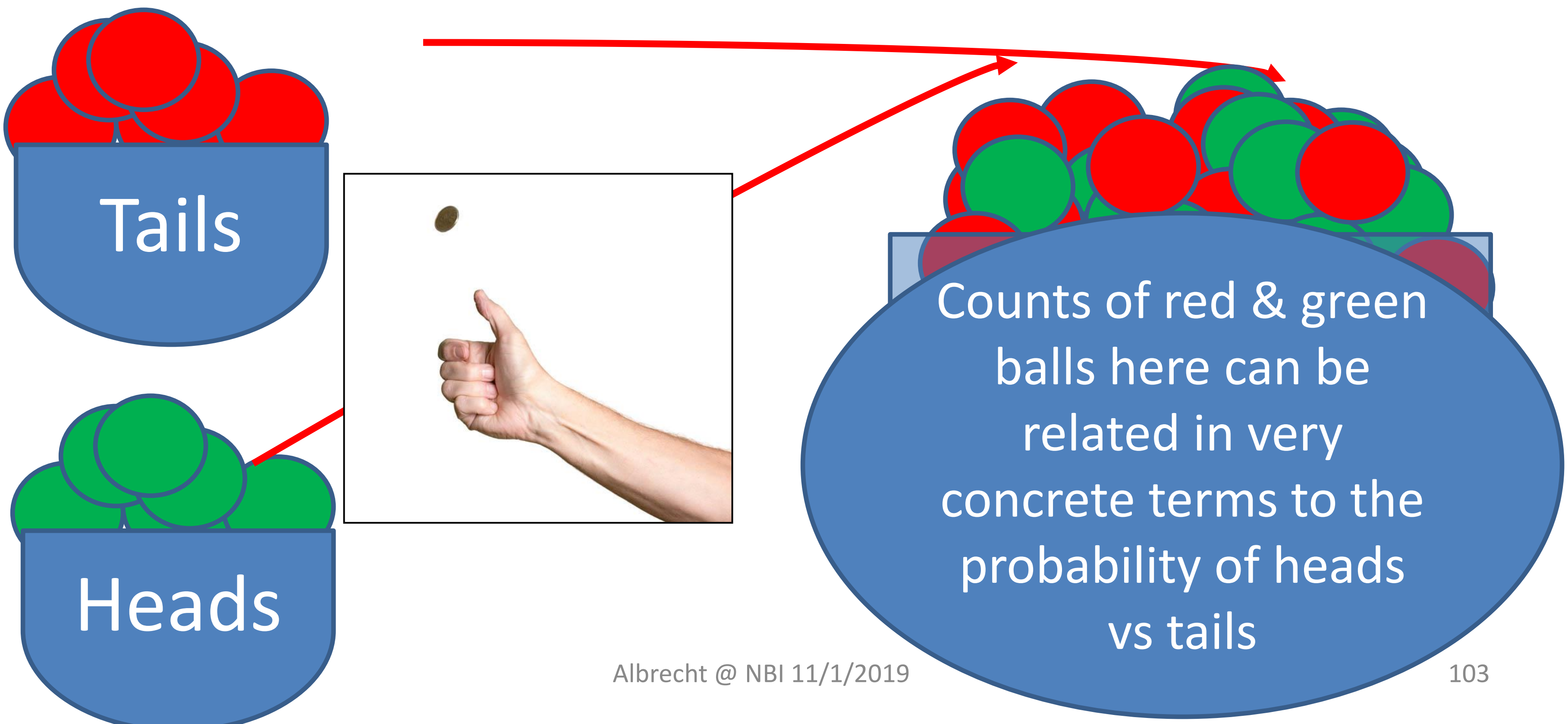
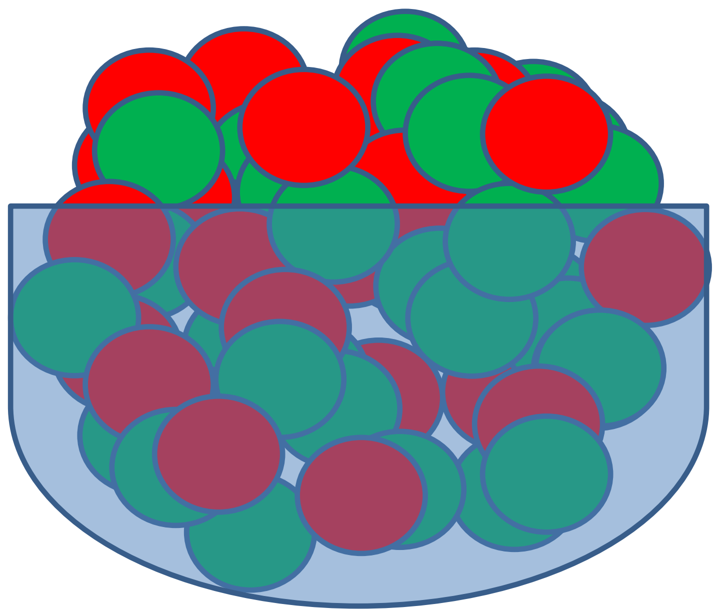


Now ask: What is the probability that a ball drawn from the "Results" bowl is red?



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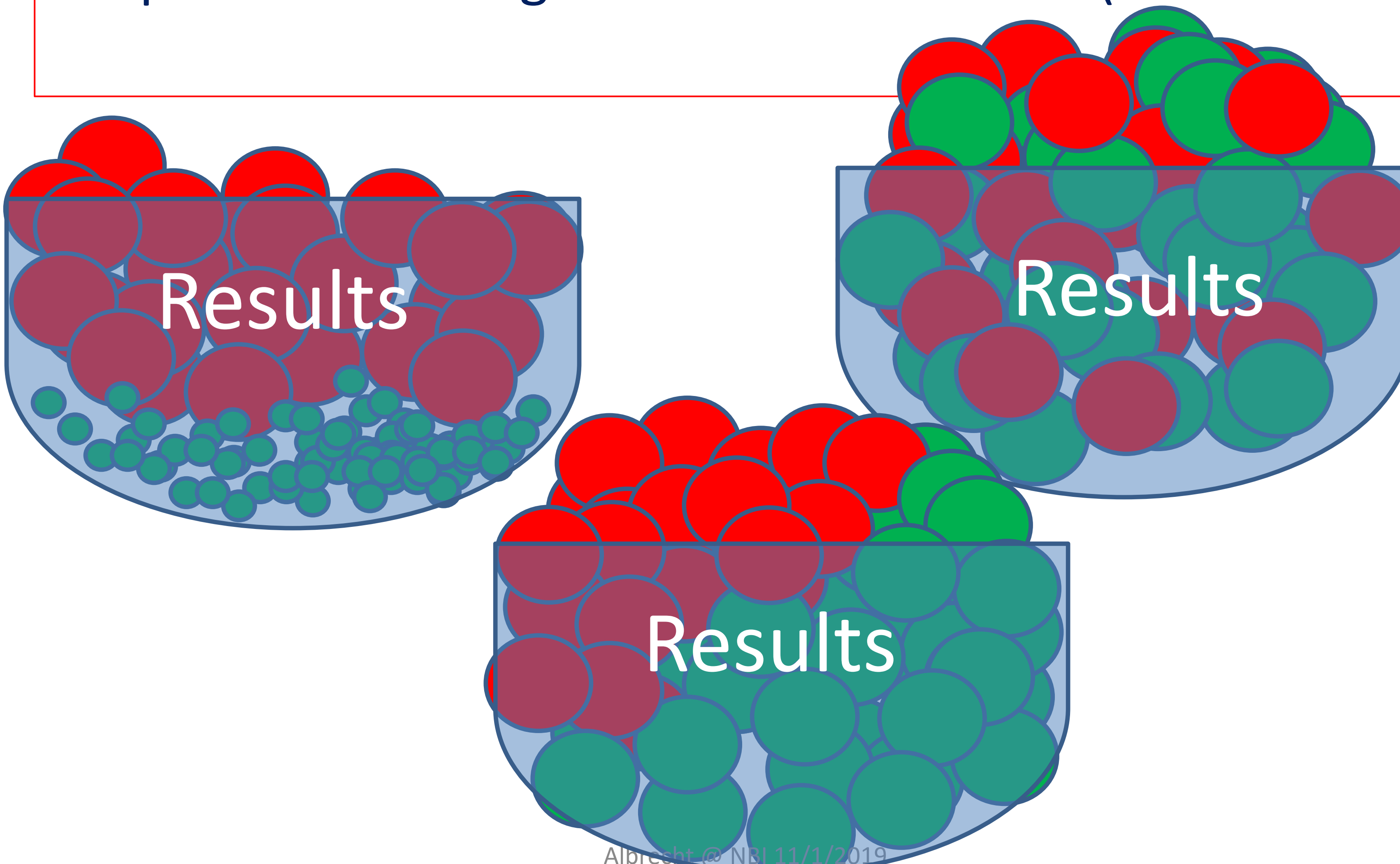
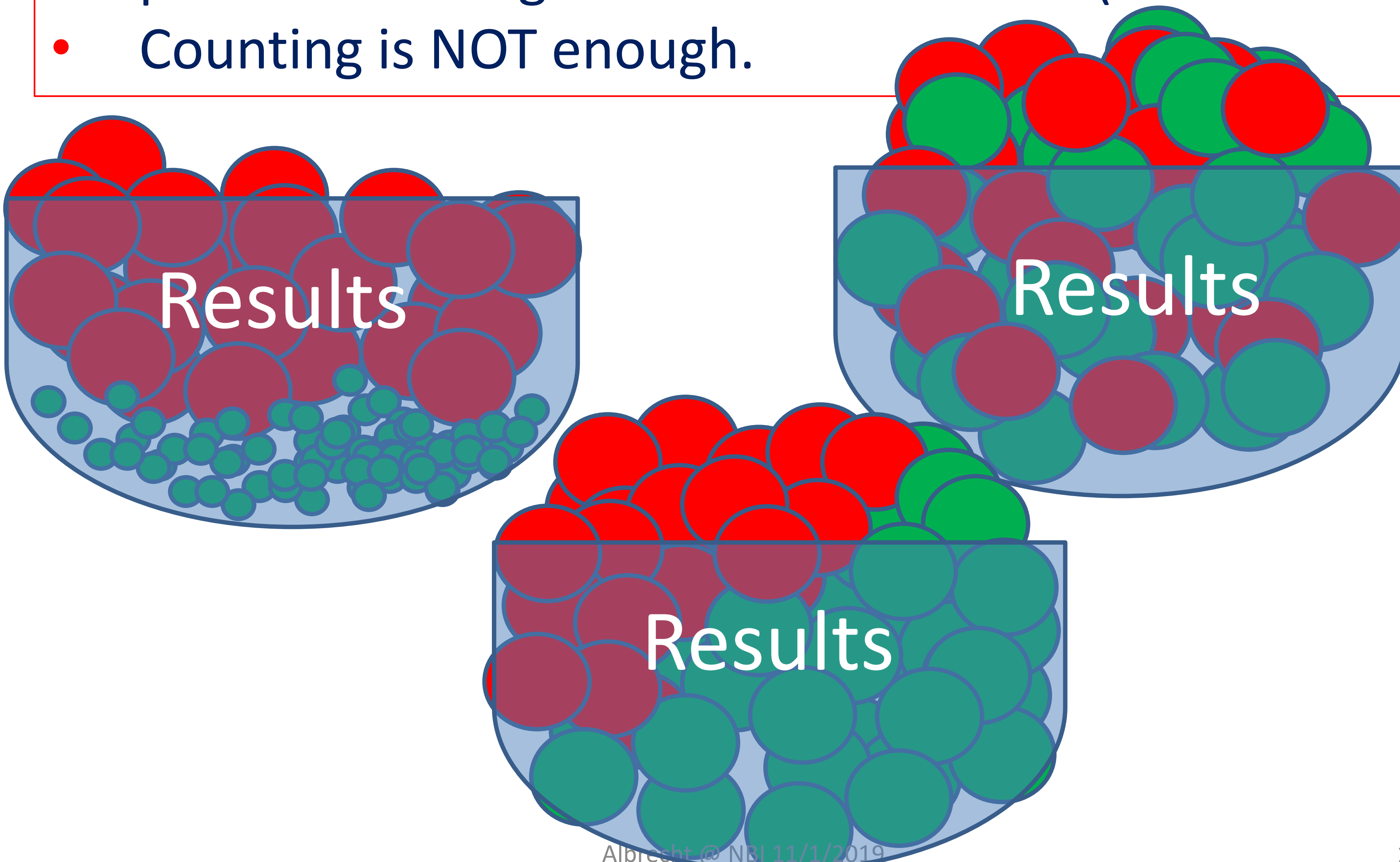


Now ask: What is the probability that a ball drawn from the "Results" bowl is red?

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



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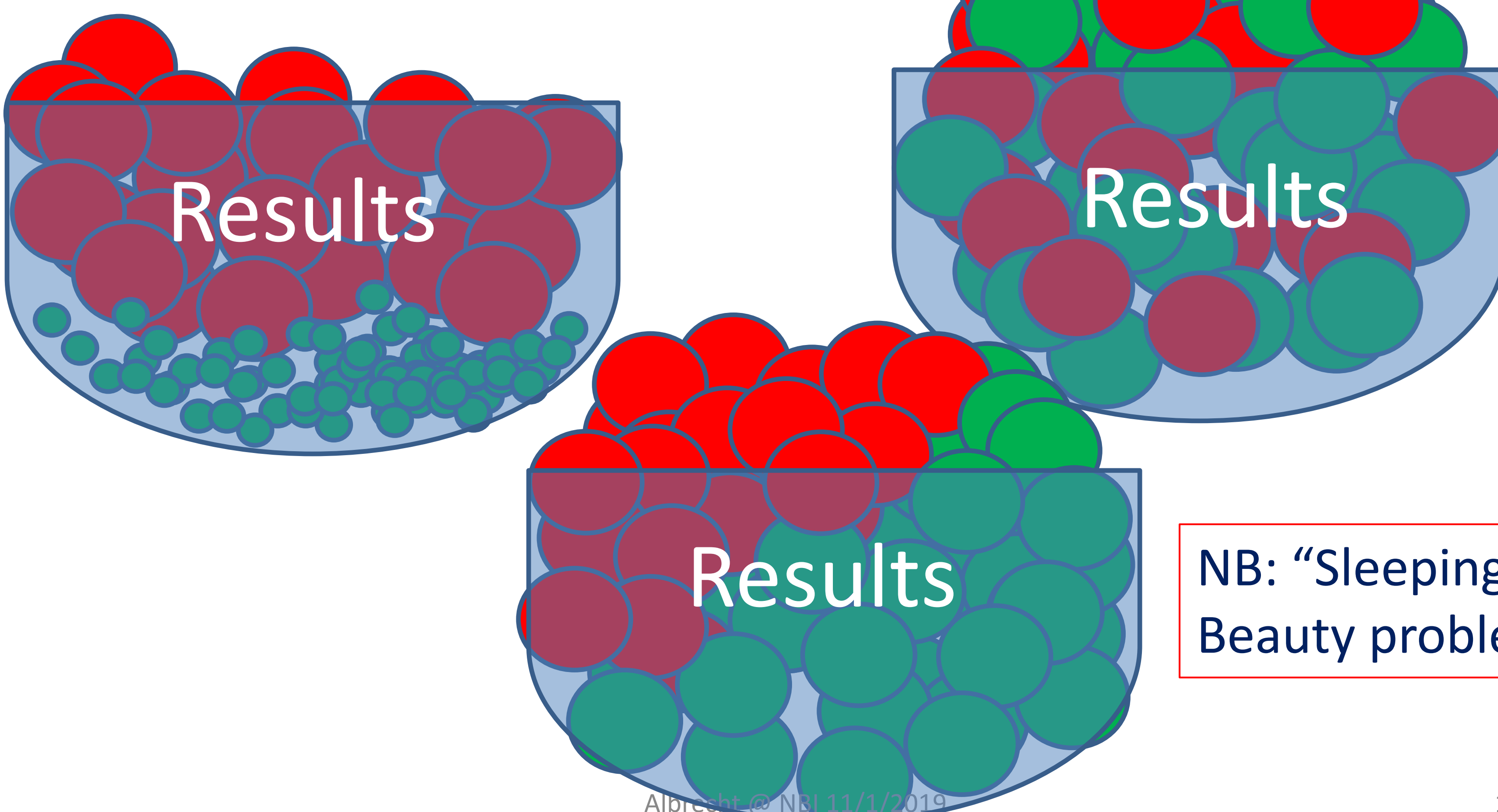

NB: “Sleeping Beauty problem”

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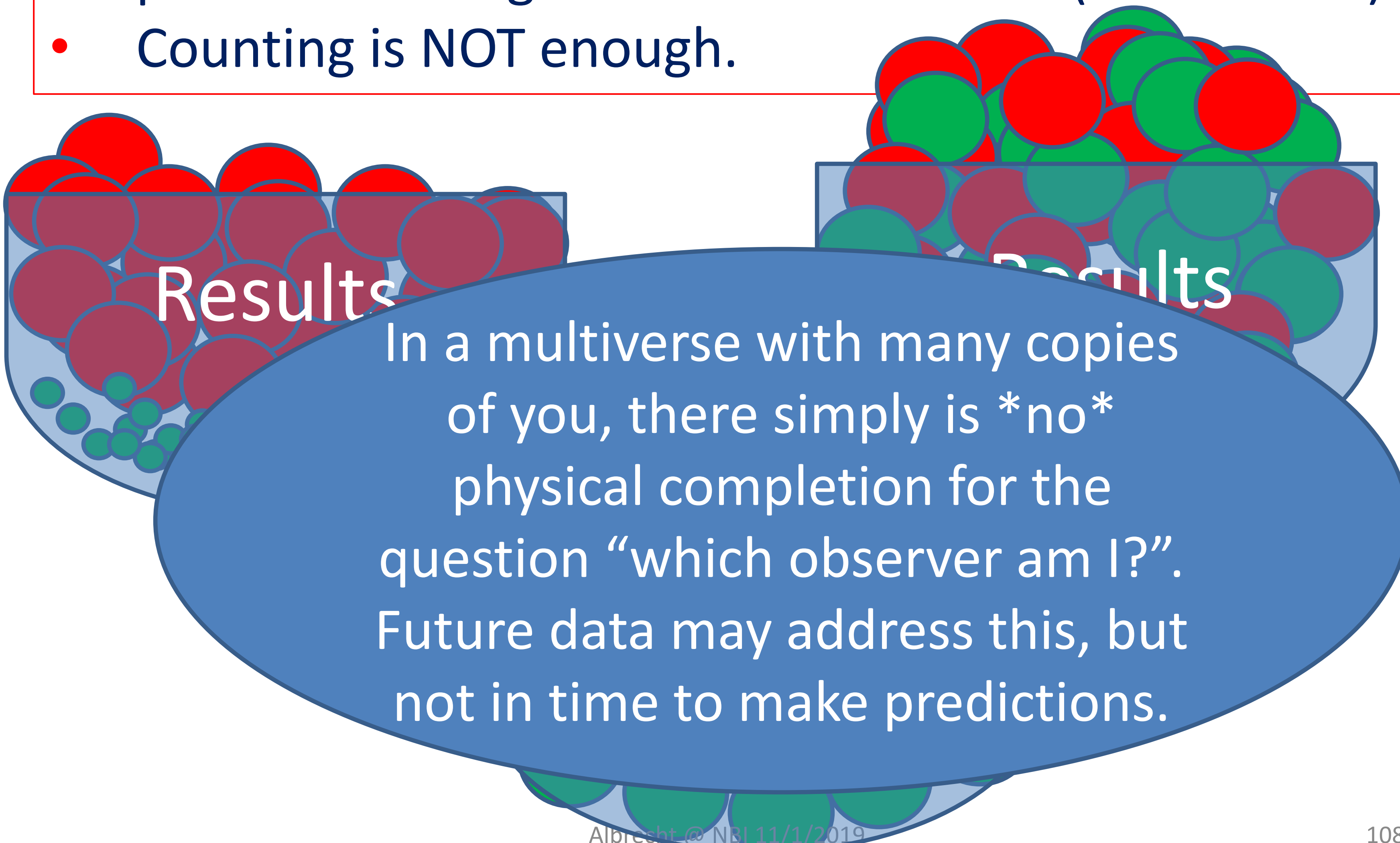

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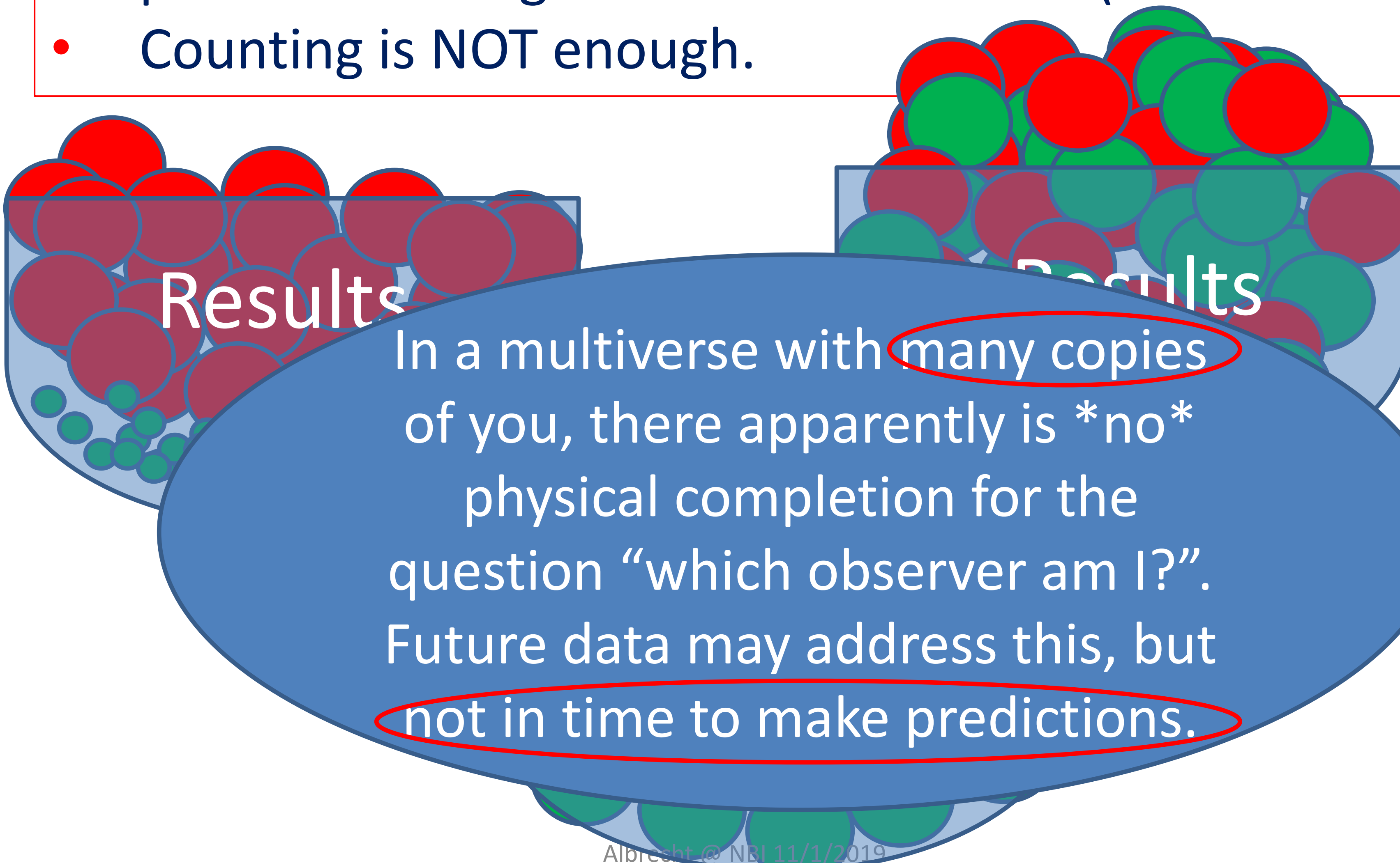

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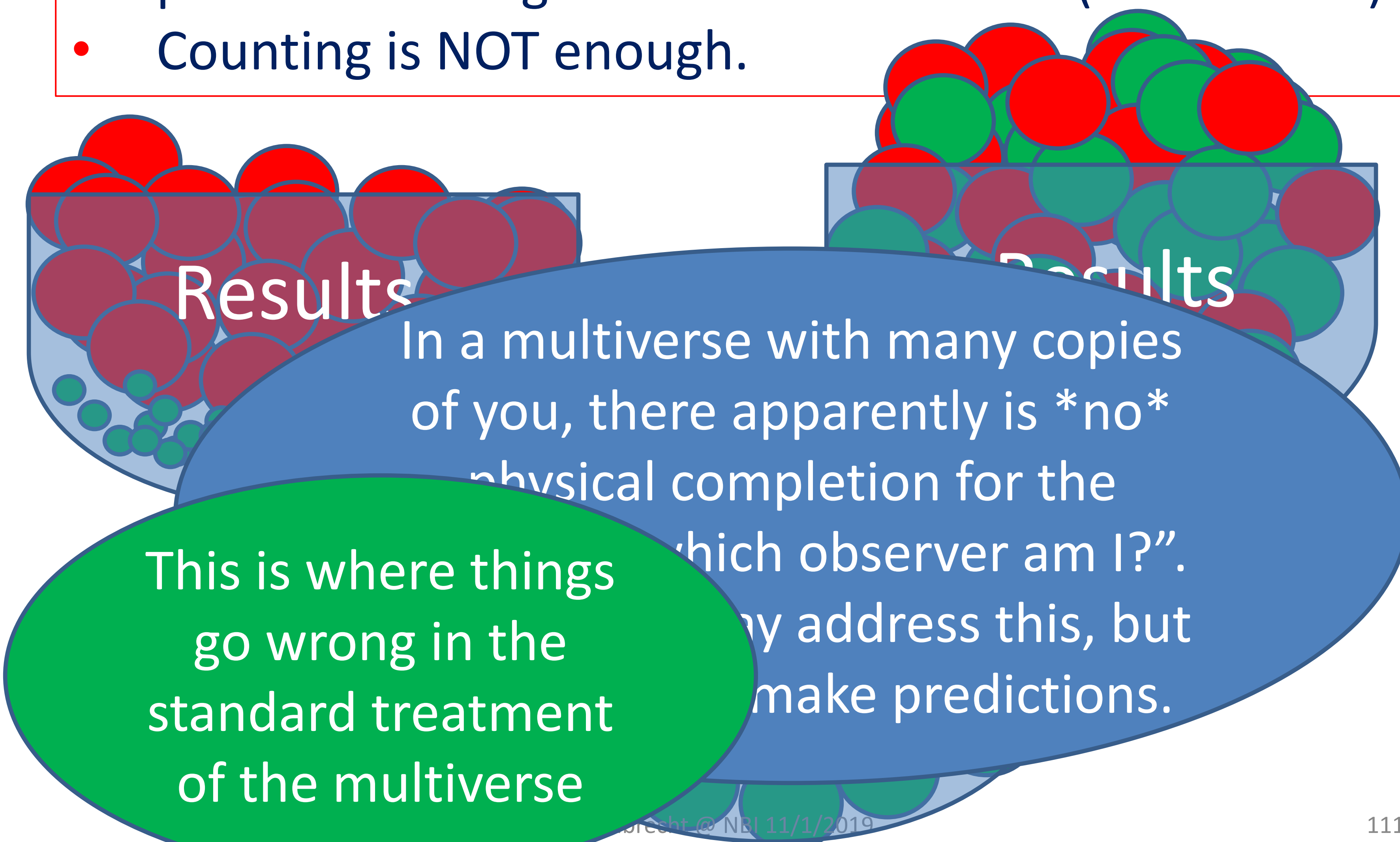

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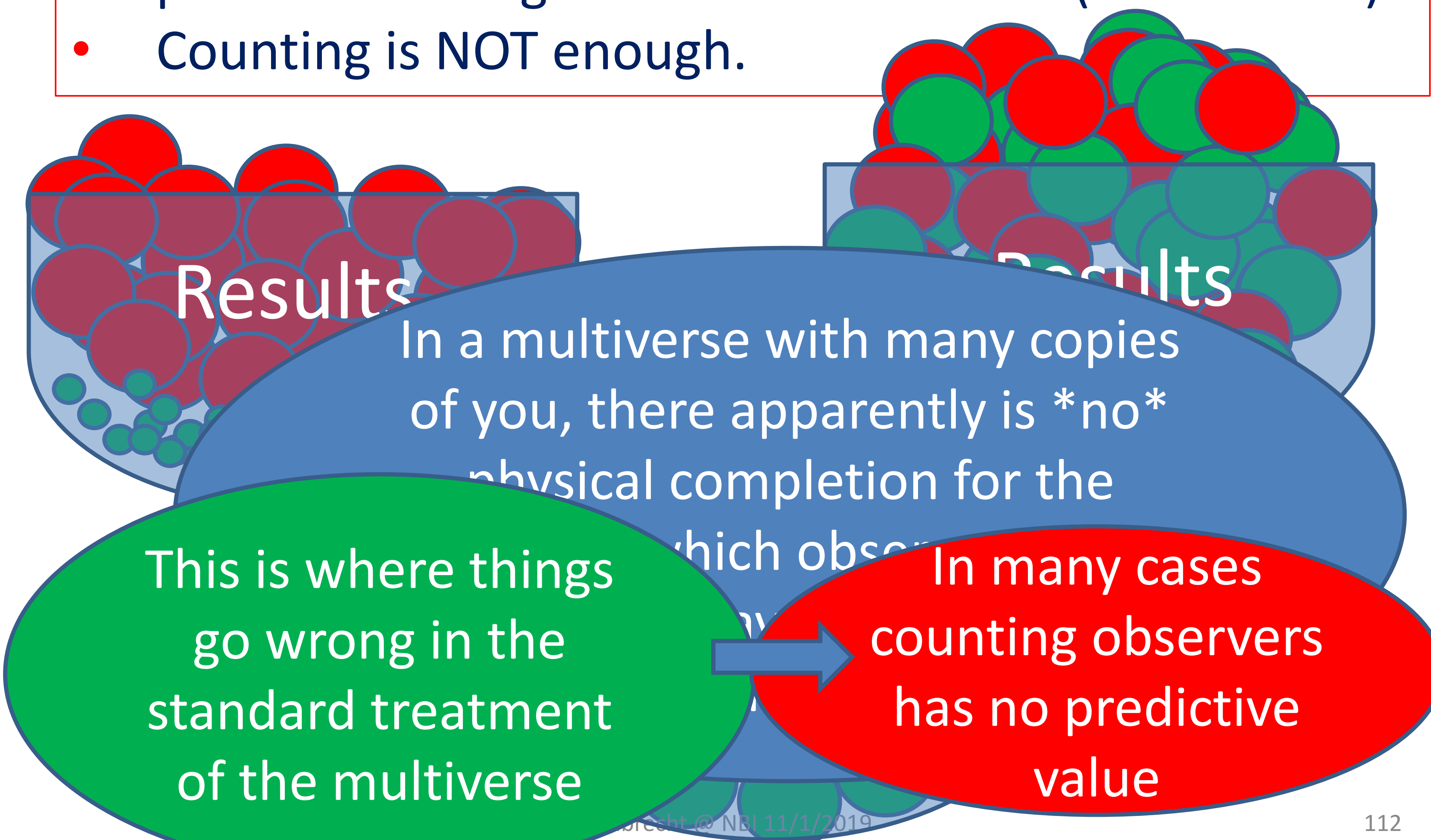

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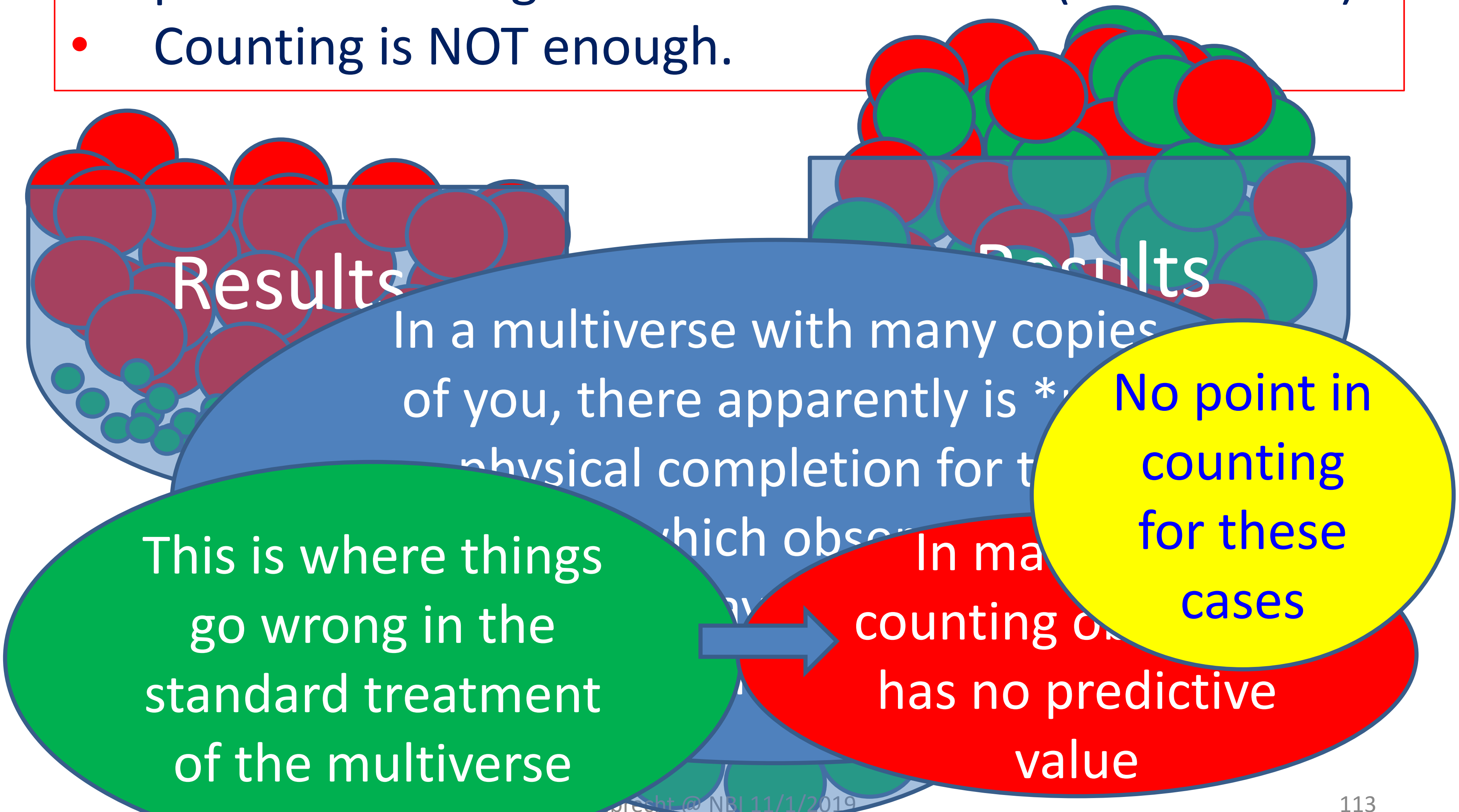

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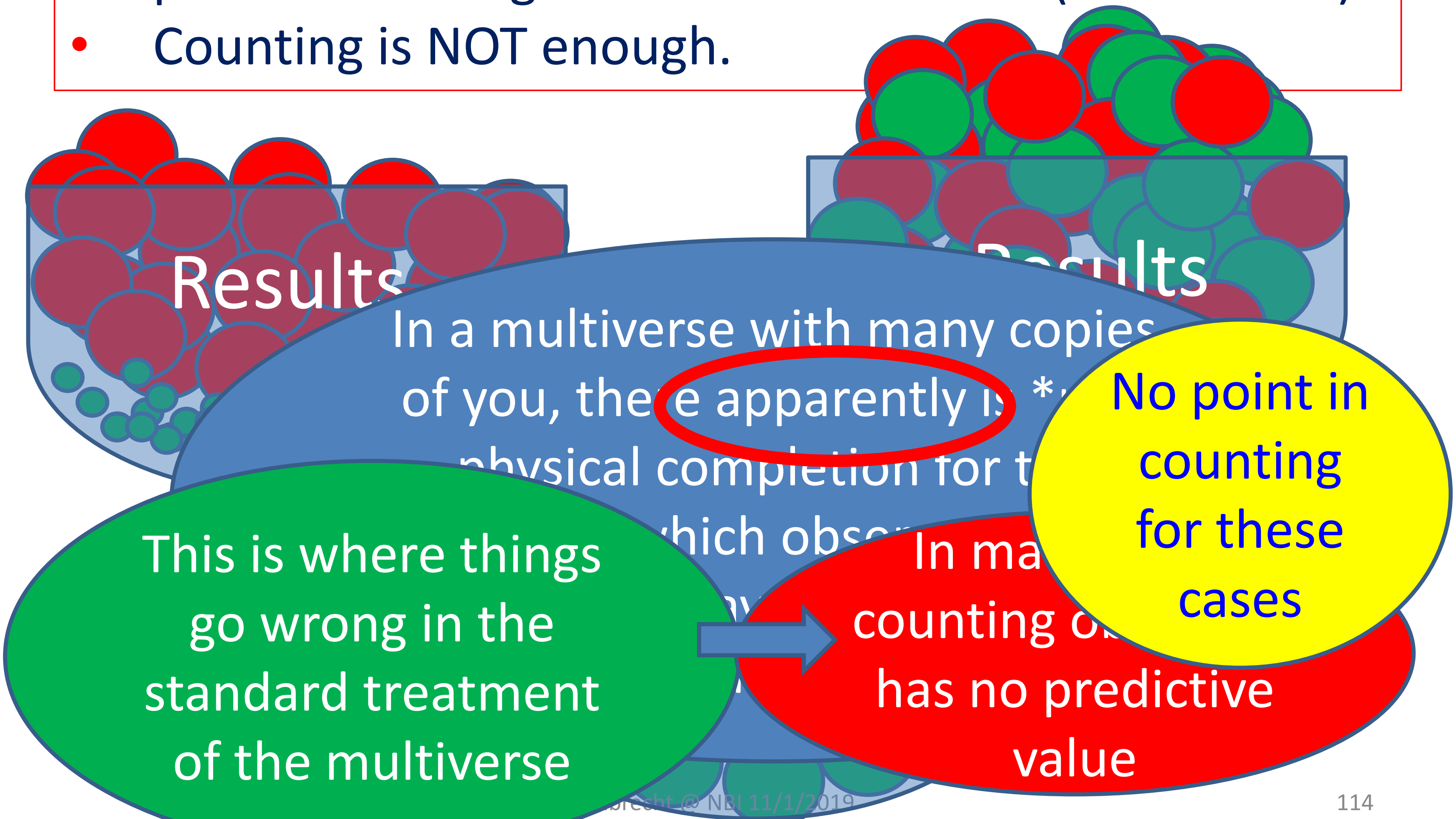

Outline

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

2) Everyday probabilities

3) Be careful about counting!

4) Implications for multiverse/eternal inflation

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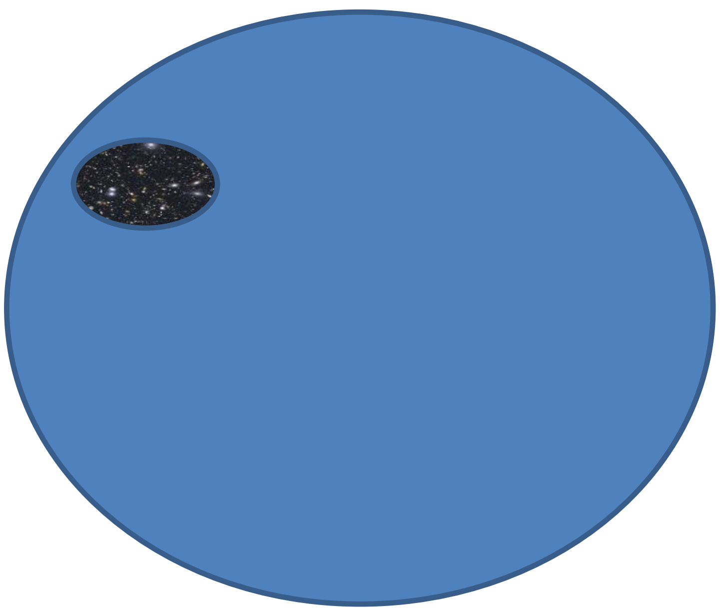
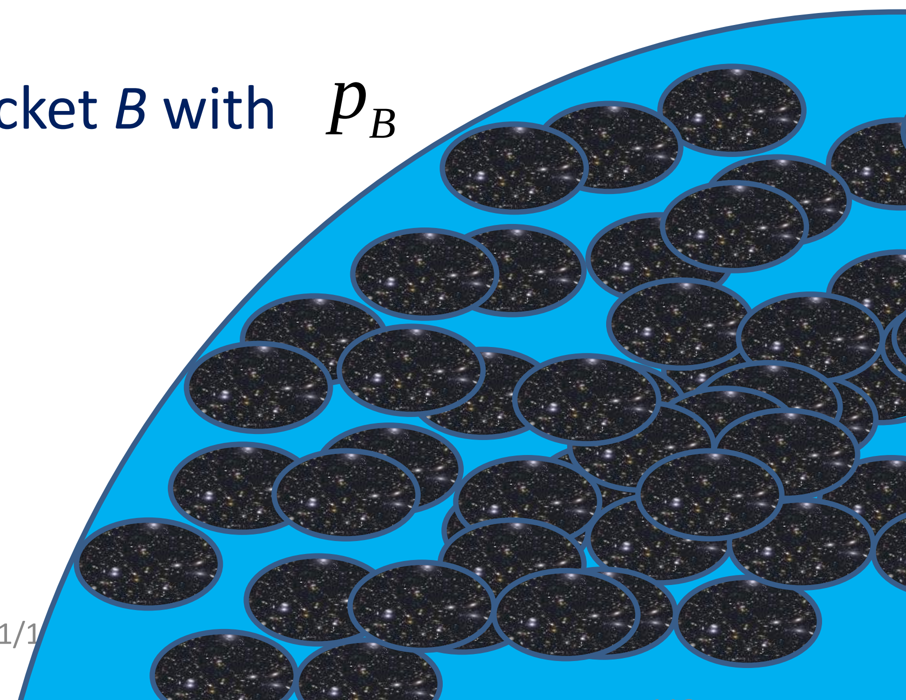
Implications for eternal inflation

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



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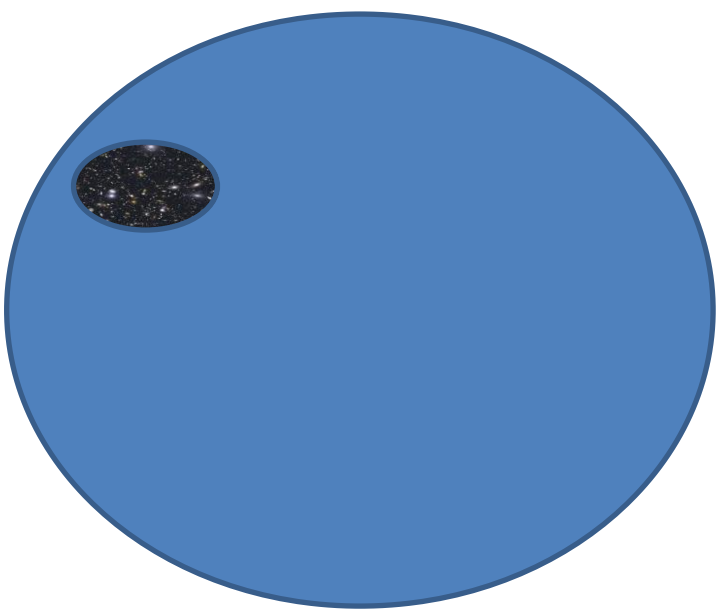
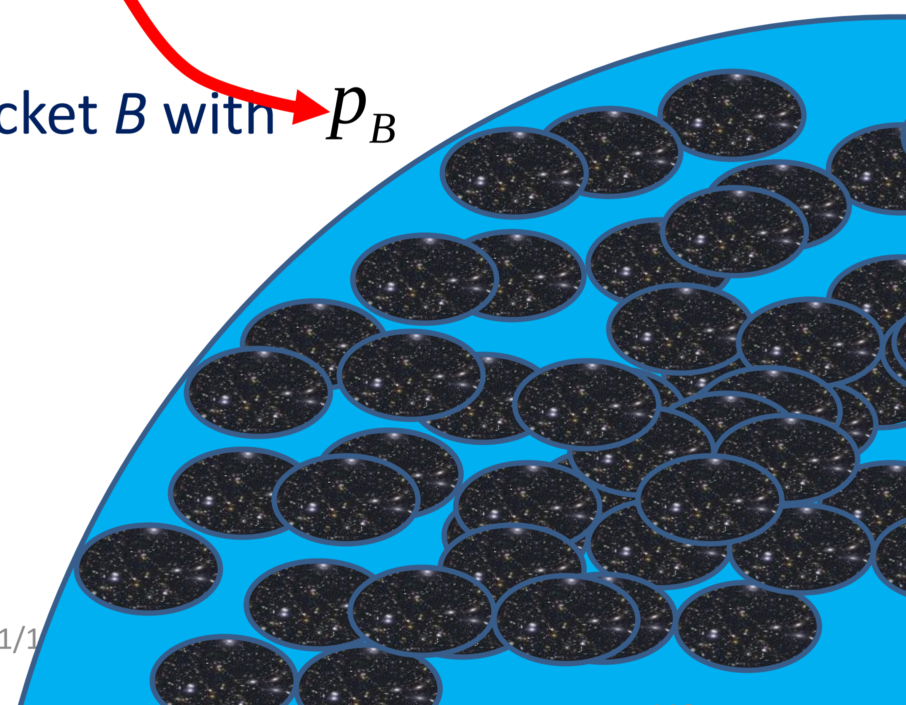
Pocket *A* with p_A

(from quantum branching ratio)

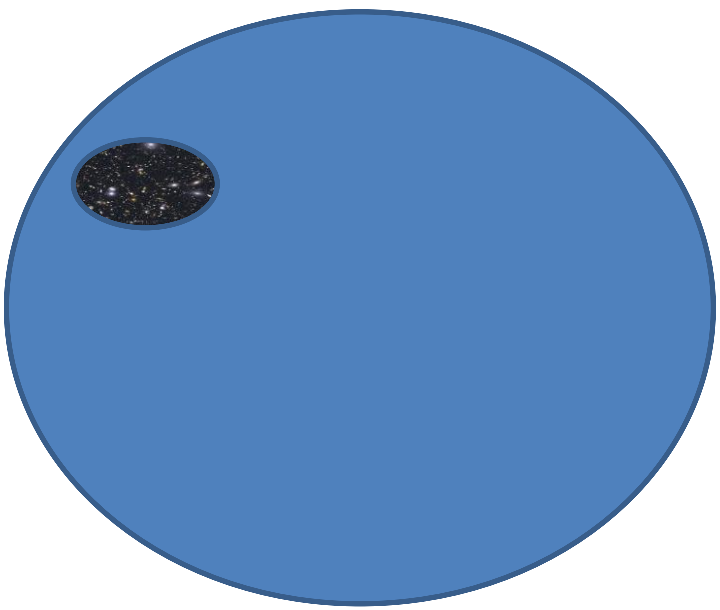
Pocket *B* with p_B





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



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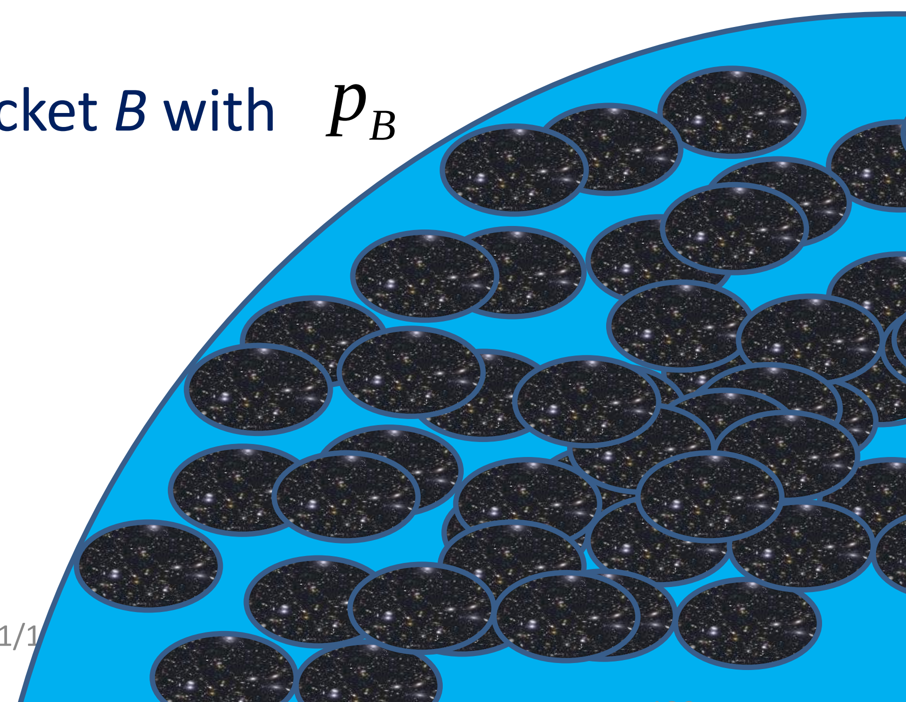

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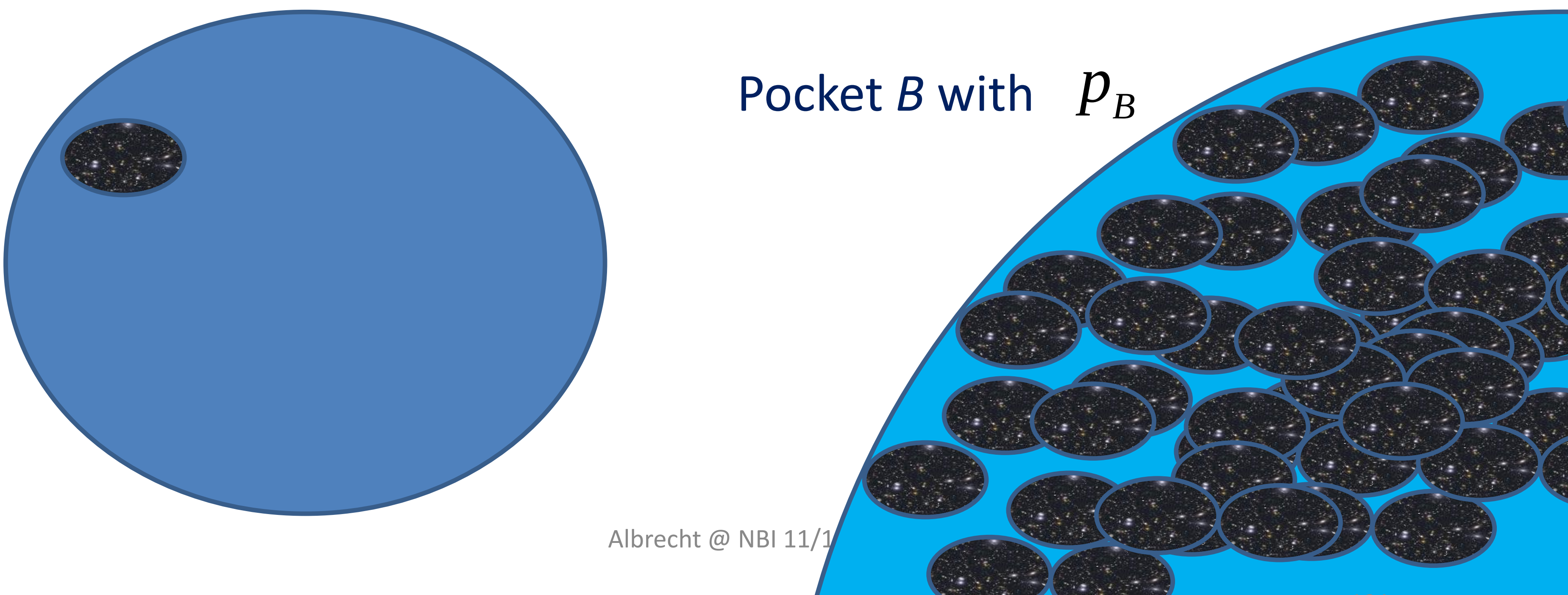
Pocket *A* with p_A

Pocket *B* with p_B



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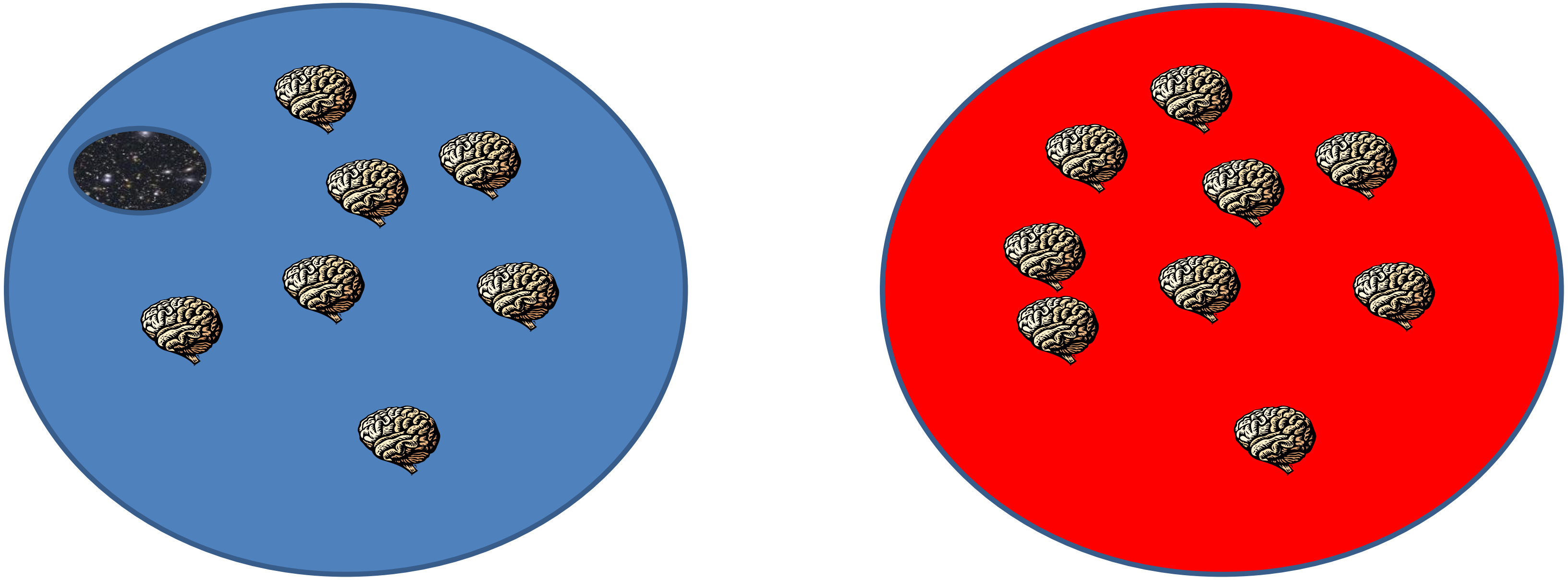
Pocket *A* with p_A Pocket *B* with p_B



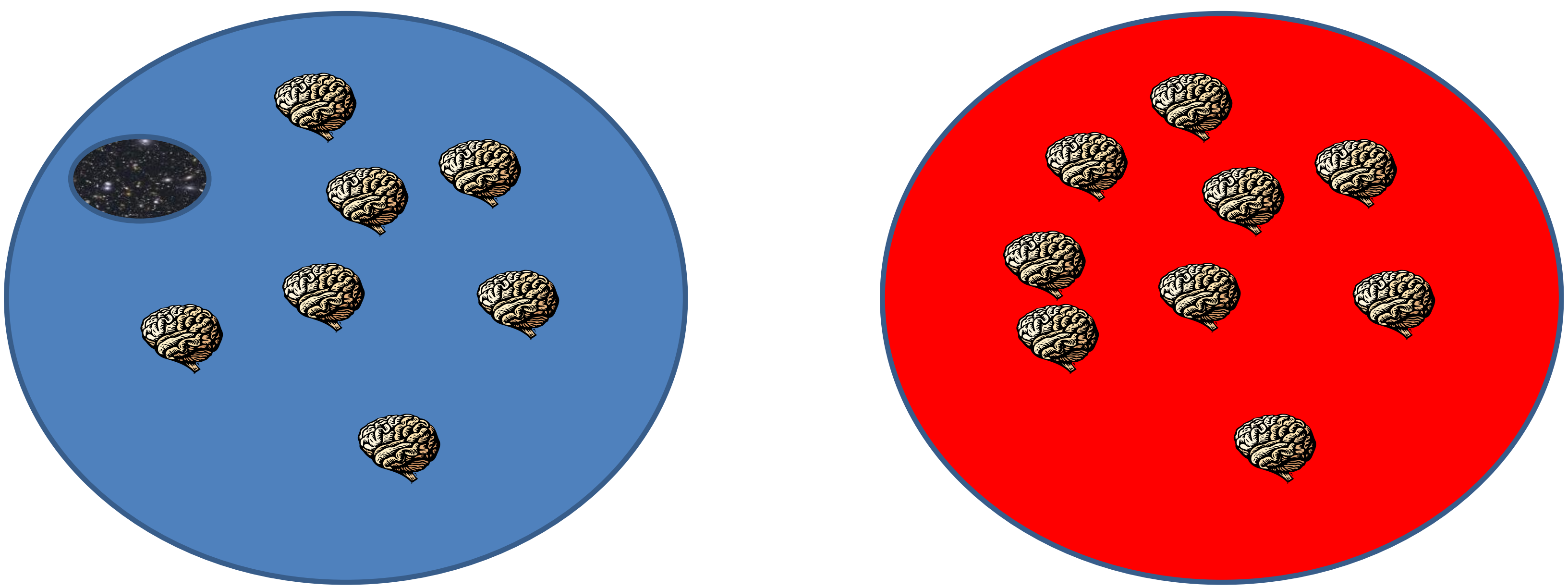
Implications for eternal inflation

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



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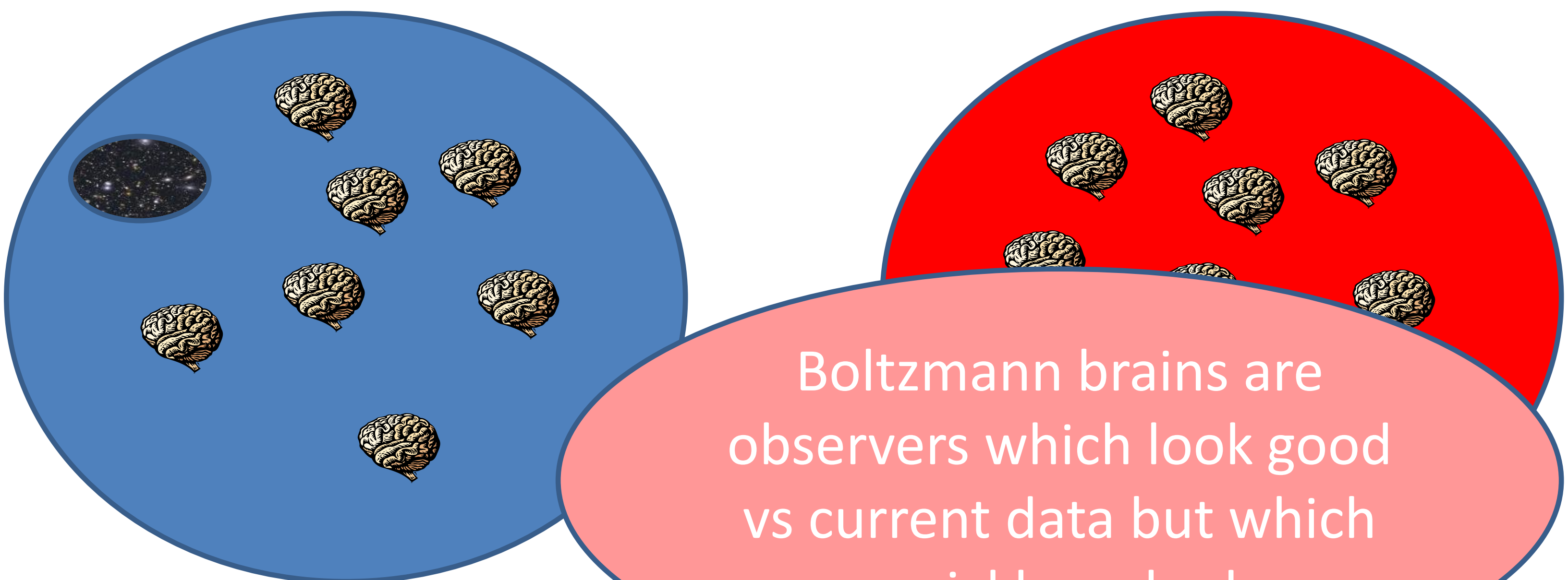

Boltzmann brains are observers which look good vs current data but which quickly go bad

Implications for eternal inflation

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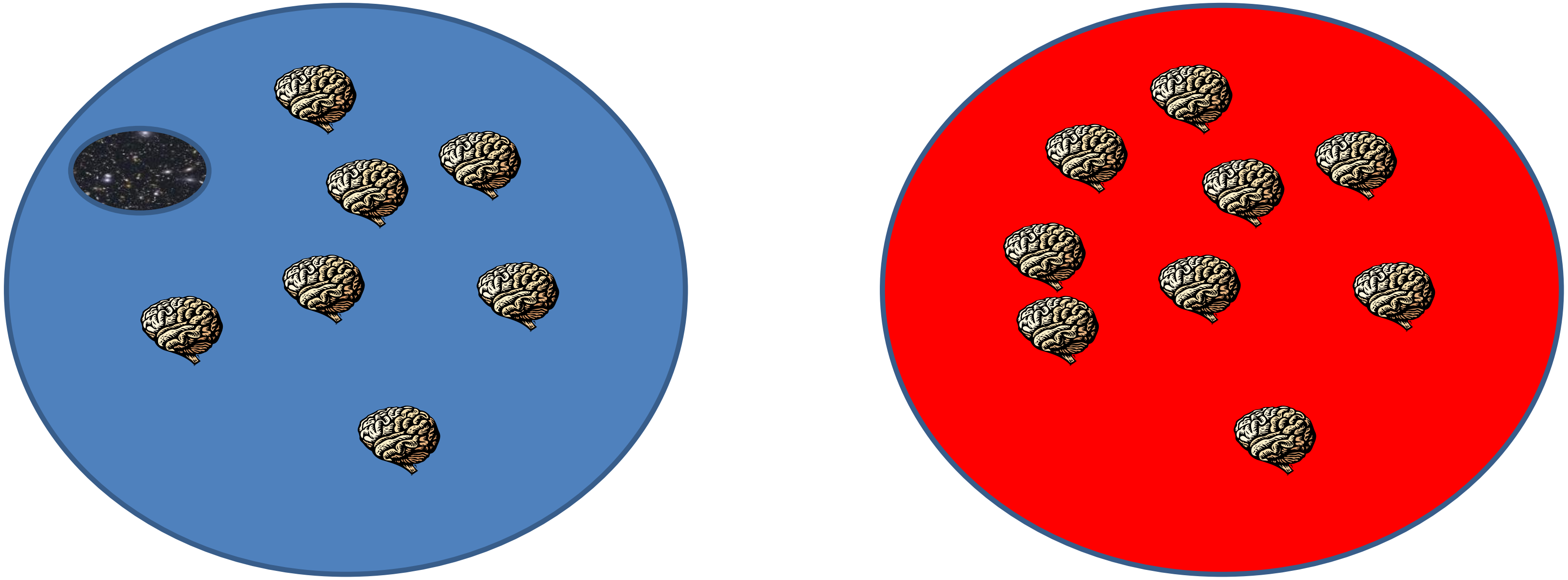
Pocket *A* with p_A

Pocket *B* with p_B



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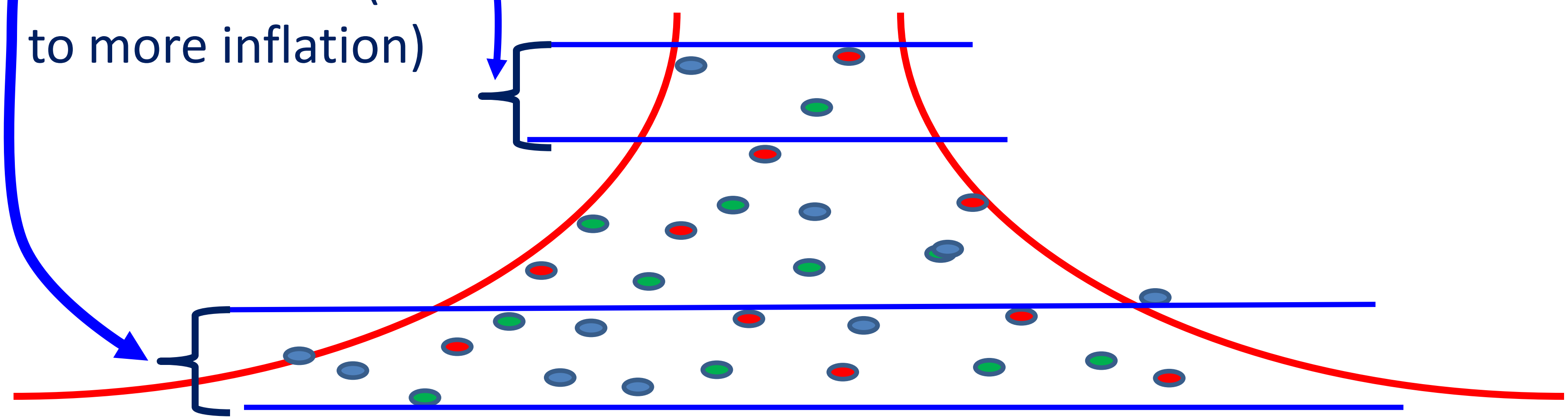
More pocket universes produced later vs earlier (due to more inflation)



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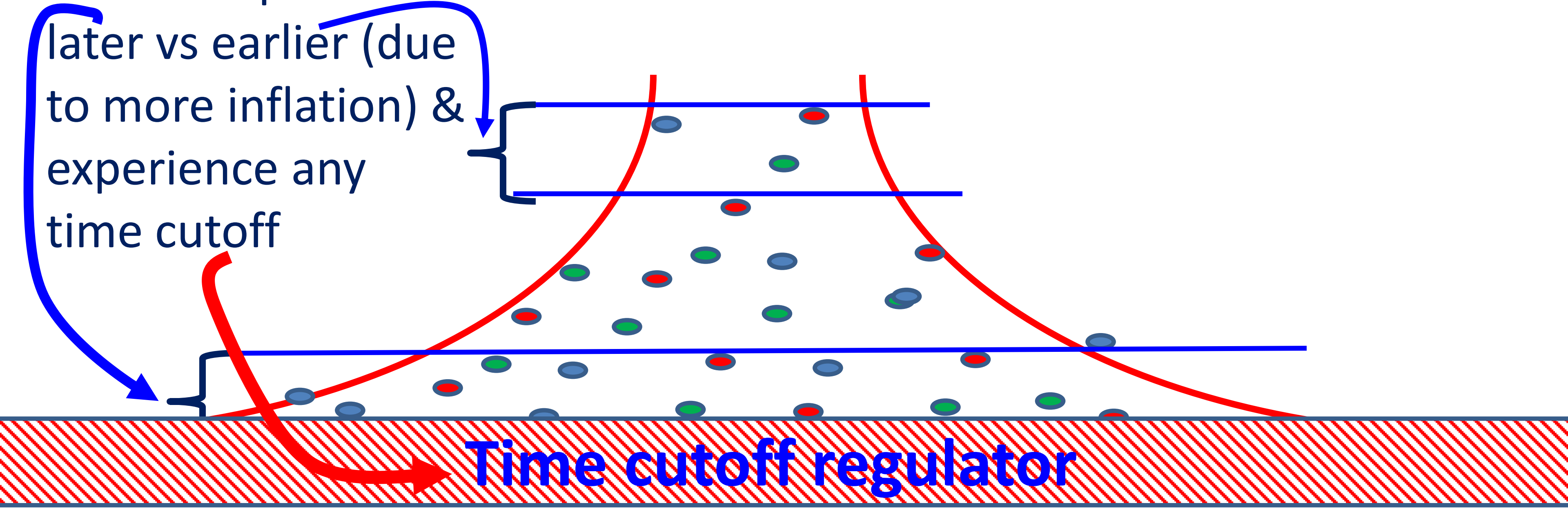
More pocket universes produced later vs earlier (due to more inflation) & experience any time cutoff



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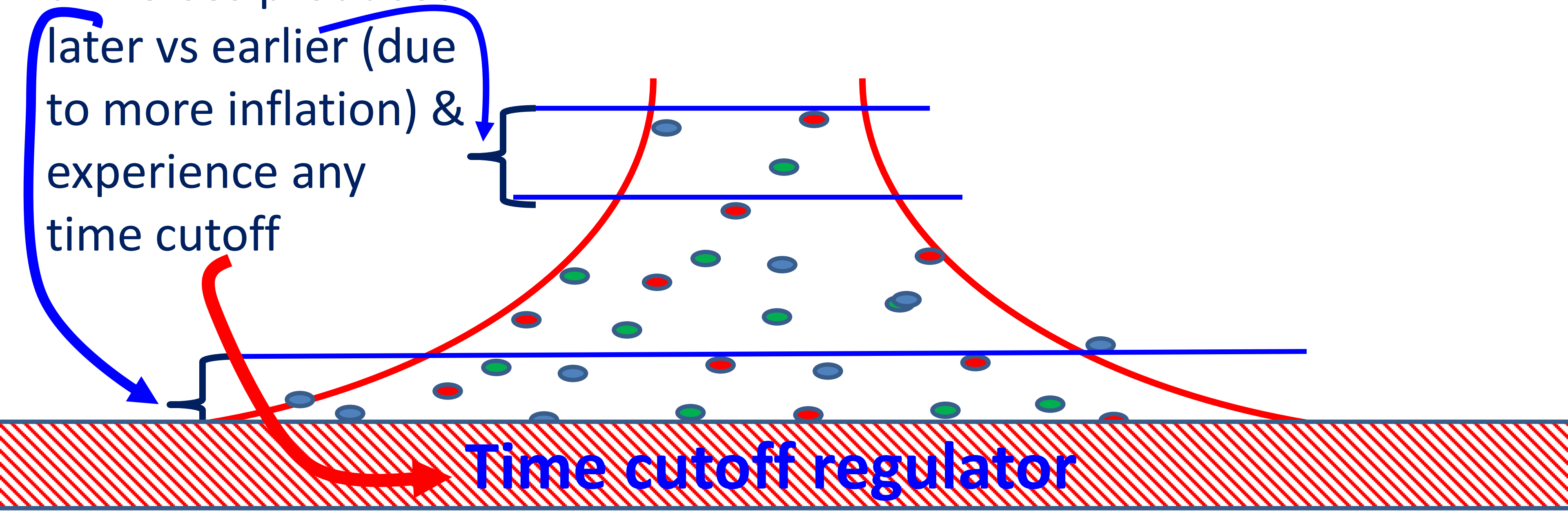

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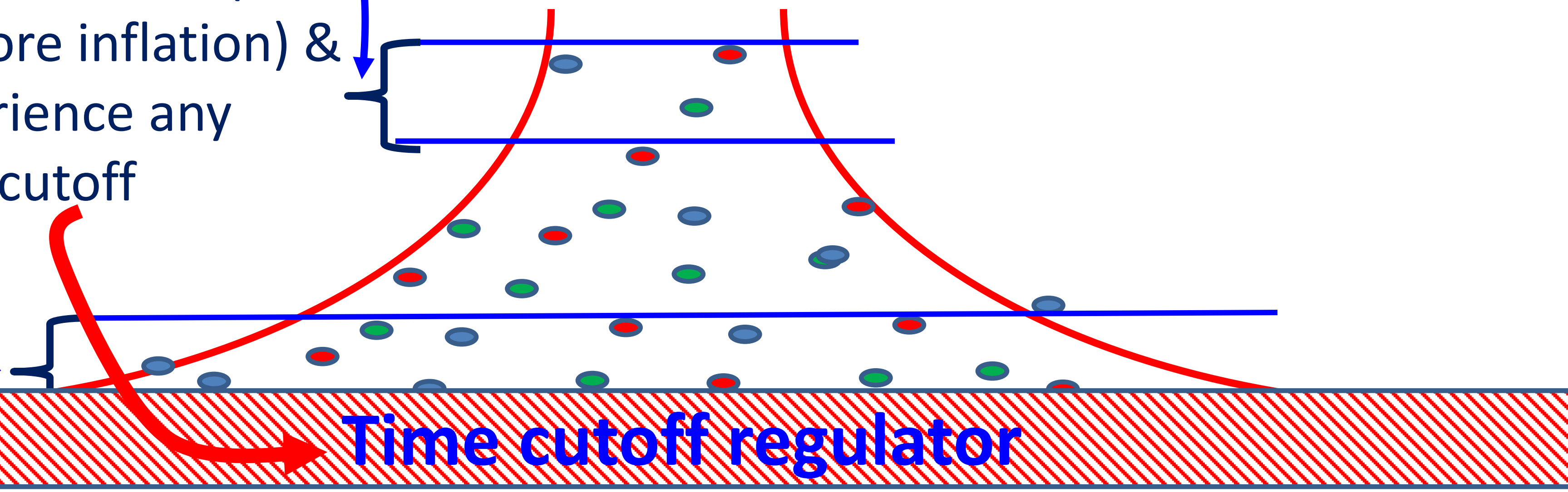

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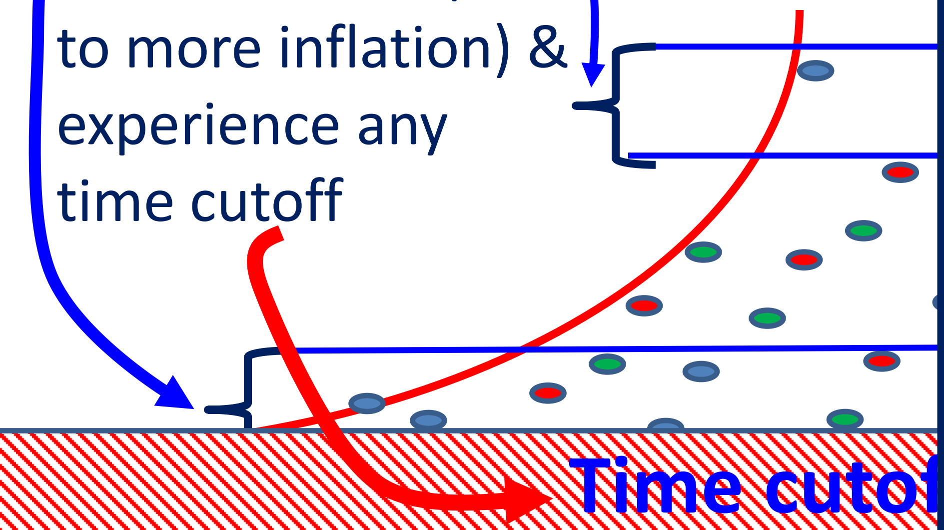

- Wavefunction cannot give probabilities for which pocket you are in.
- Time cutoff only there as (wrong) attempt to determine which pocket
- The youngness/end of time problem is asking a question the theory cannot answer

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) The "principle of indifference" has only ever been a phenomenology of point 1), nothing deeper. (Thus it should not form the basis of a "derivation of the Born rule".)
5) 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
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Also related to "Boltzmann Brains"

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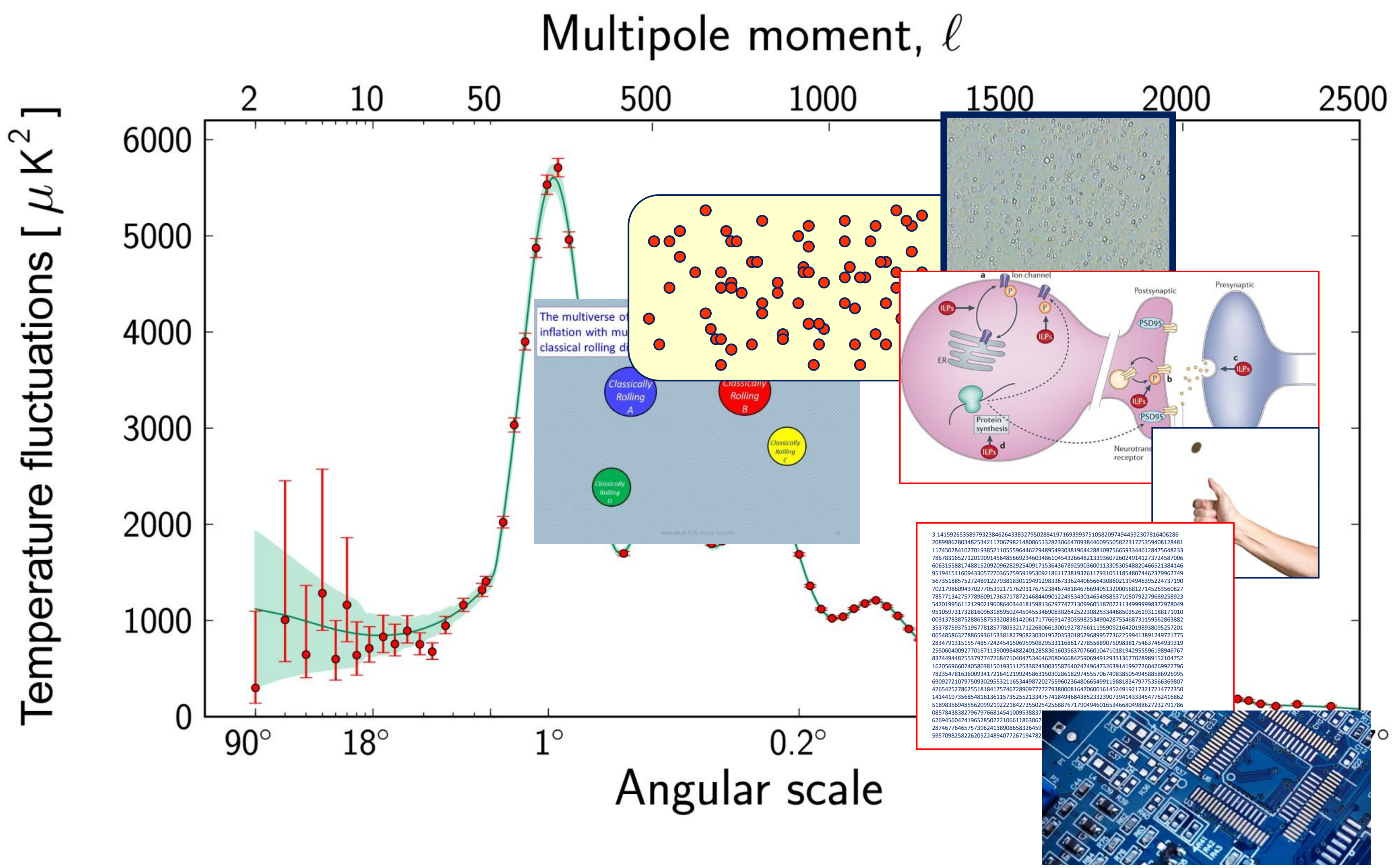
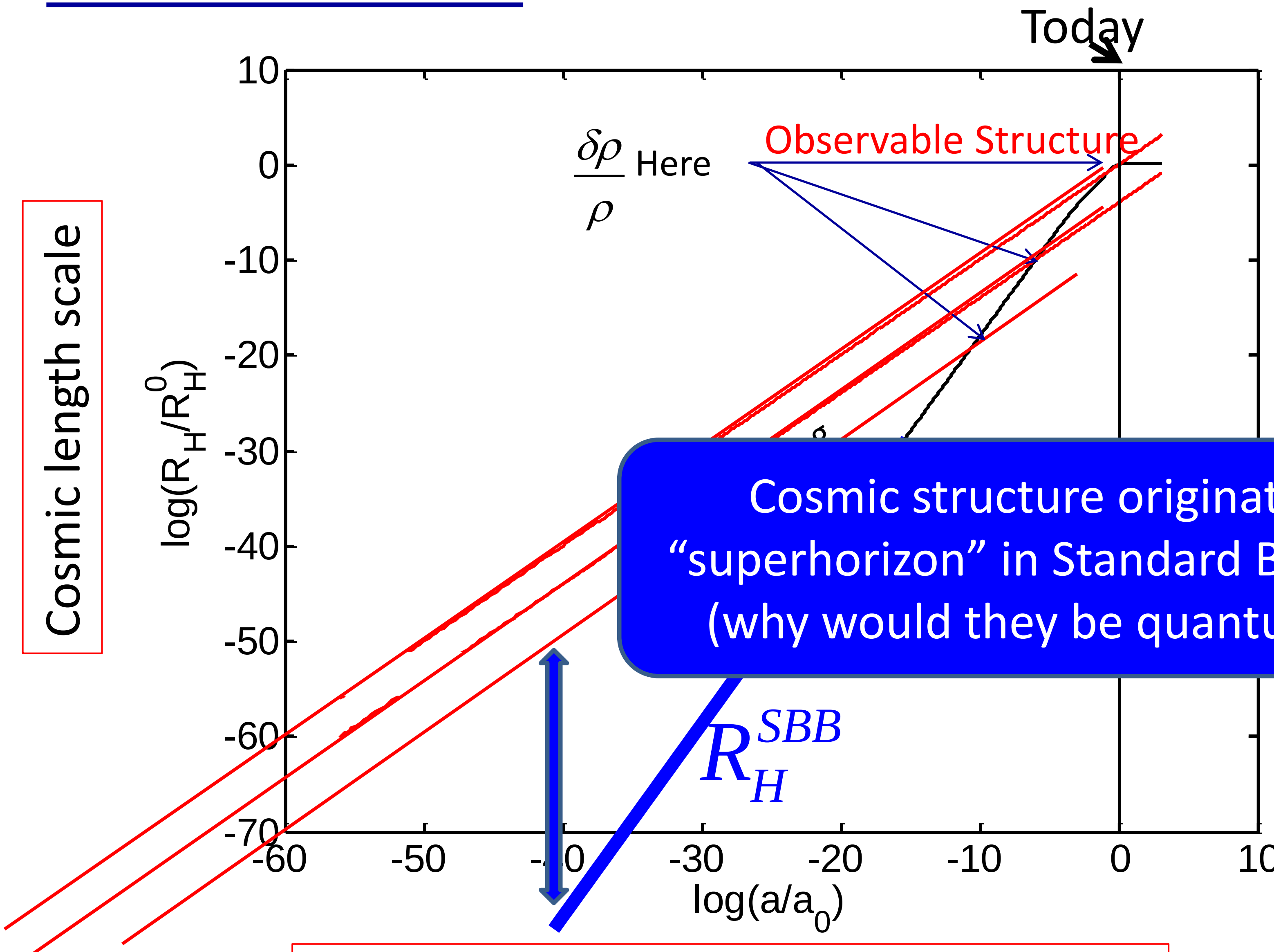


Multipole moment, ℓ
2
10
50
500
1000
1500
2000
2500
Temperature fluctuations [μK^2]
6000
5000
4000
3000
2000
1000
0
90°
18°
1°
0.2°
Angular scale
Classically Rolling A
Classically Rolling B
Classically Rolling C
Classically Rolling D
Ion channel
Postsynaptic
Presynaptic
ILPs
PSD95
ER
Protein synthesis

Additional Slides

Cosmic structure

A note on "probability censorship"



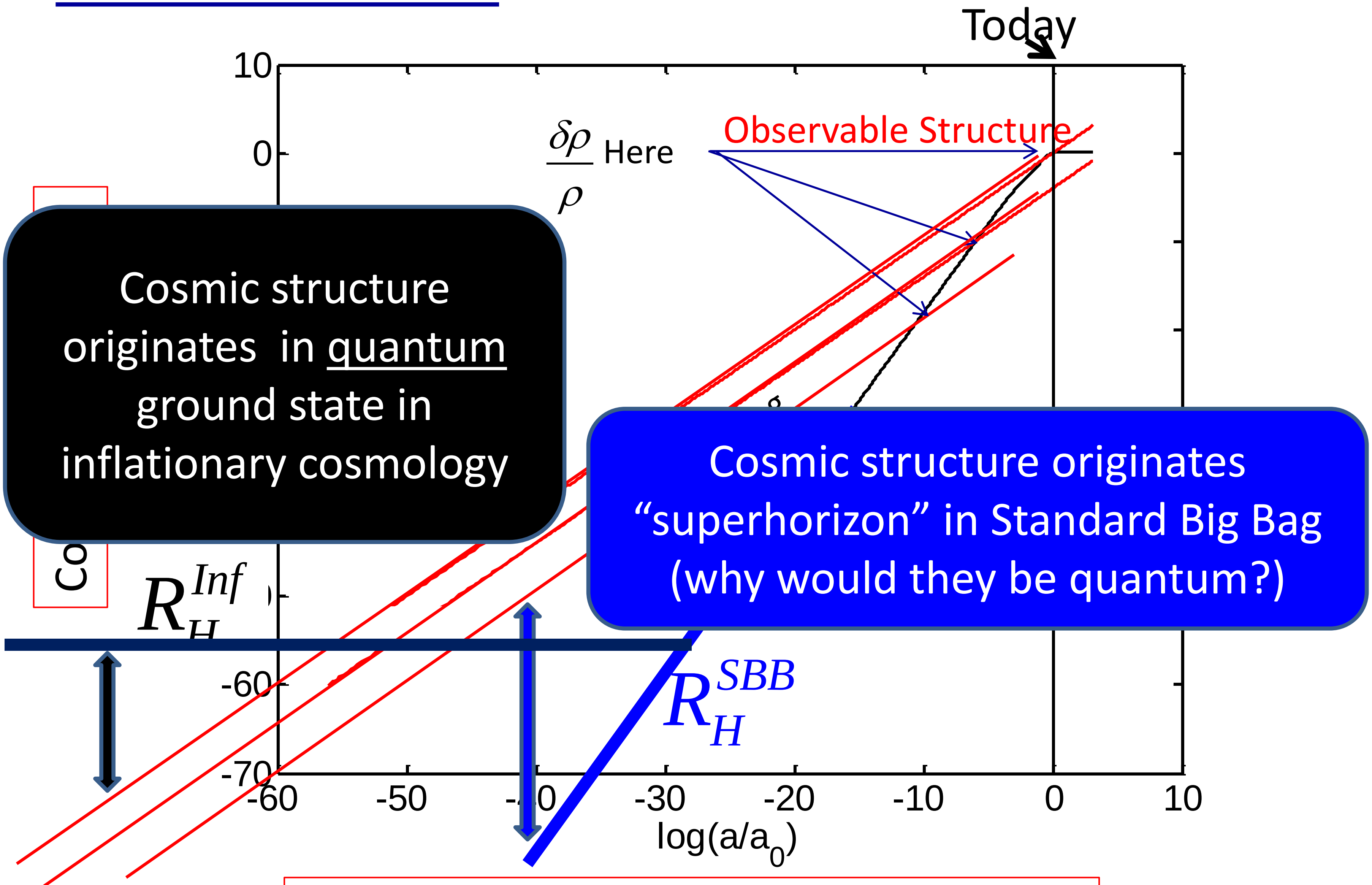
Cosmic length scale

Scale factor (measures expansion, time)

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

Cosmic structure

A note on "probability censorship"



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

3.1415926535897932384626433832795028841971693993751058209749445923078164062862
2089986280348253421170679821480865132823066470938446095505822317253594081284811
1745028410270193852110555964462294895493038196442881097566593344612847564823378
6783165271201909145648566923460348610454326648213393607260249141273724587006
6063155881748815209209628292540917153643678925903600113305305488204665213841469
5194151160943305727036575959195309218611738193261179310511854807446237996274956
7351885752724891227938183011949129833673362440656643086021394946395224737190
7021798609437027705392171762931767523846748184676694051320005681271452635608277
8577134275778960917363717872146844090122495343014654958537105079227968925892354
2019956112129021960864034418159813629774771309960518707211349999998372978049
9510597317328160963185950244594553469083026425223082533446850352619311881710100
0313783875288658753320838142061717766914730359825349042875546873115956286388235
3787593751957781857780532171226806613001927876611195909216420198938095257201
0654858632788659361533818279682303019520353018529689957736225994138912497217752
8347913151557485724245415069595082953311686172785588907509838175463746493931925
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2354781636009341721641219924586315030286182974555706749838505494588586926995
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1441973568548161361157352552133475741849468438523323907394143334547762416862
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8578438382796797668145410095388378636095068006422512520511739298489608412848862
6945604241965285022210661186306744278622039194945047123713786960956364371917
2874677646575739624138908658326459958133904780275900994657640789512694683983525
9570982582262052248940772671947826848260147699090264013639443745530506820349625

Further discussion

Bet on the millionth digit of π

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

3.1415926535
20899862803
11745028410
7867831652712019091456485669234603486104543266482133936072602491412737245870066
0631558817488152092096282925409171536436789259036001133053054882046652138414695
1941511609433057270365759591953092186117381932611793105118548074462379962749
567351885752724891227938183011949129833673362440656643086021394946395224737190
702179860943702770539217176293176752384674818467669405132000568127145263560827
785771342757789609173637178721468440901224953430146549585371050792279689258923
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003137838752886587533208381420617177669147303598253490428755468731159562863882
353787593751957781857780532171226806613001927876611195909216420198938095257201
065485863278865936153381827968230301952035301852968995773622599413891249721775
283479131515574857242454150695950829533116861727855889075098381754637464939319
255060400927701671139009848824012858361603563707660104710181942955596198946767
837449448255379774726847104047534646208046684259069491293313677028989152104752
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782354781636009341721641219924586315030286182974555706749838505494588586926995
690927210797509302955321165344987202755960236480665499119881834797753566369807
426542527862551818417574672890977772793800081647060016145249192173217214772350
141441973568548161361157352552133475741849468438523323907394143334547762416862
518983569485562099219222184272550254256887671790494601653466804988627232791786
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626945604241965285022210661186306744278622039194945047123713786960956364371917
287467764657573962413890865832645995813390478027590099465764078951269468398352
595709825822620522489407726719478268482601476990902640136394437455305068203496

Further discussion

Bet on the millionth digit of π

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- Fairness is about lack of correlation between digit choice and digit value

3.1415926535
2089986280 3
11745028410
78678316527
60631558817
95194151160
56735188575
70217986094370277053921717629317675238467481846766940513200056812714526356082 7
78577134275778960917363717872146844090122495343014654958537105079227968925892 3
5420199561121290219608640344181598136297747713099605187072113499999983729780 49
95105973173281609631859502445945534690830264252230825334468503526193118817101 0
00313783875288658753320838142061717766914730359825349042875546873115956286388 2
35378759375195778185778053217122680661300192787661119590921642019893809525720 1
06548586327886593615338182796823030195203530185296899577362259941389124972177 5
28347913151557485724245415069595082953311686172785588907509838175463746493931 9
25506040092770167113900984882401285836160356370766010471018194295559619894676 7
83744944825537977472684710404753464620804668425906949129331367702898915210475 2
16205696602405803815019351125338243003558764024749647326391419927260426992279 6
78235478163600934172164121992458631503028618297455570674983850549458858692699 5
69092721079750930295532116534498720275596023648066549911988183479775356636980 7
42654252786255181841757467289097777279380008164706001614524919217321721477235 0
14144197356854816136115735255213347574184946843852332390739414333454776241686 2
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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

3.1415926535
2089986280
1174502841
7867831652
6063155881
9519415116
5673518857
7021798609
7857713427
5420199561
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0654858632
2834791315
2550604009
8374494482
1620569660
782354781636009341721641219924586315030286182974555706749838505494588586926995
690927210797509302955321165344987202755960236480665499119881834797753566369807
426542527862551818417574672890977772793800081647060016145249192173217214772350
141441973568548161361157352552133475741849468438523323907394143334547762416862
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595709825822620522489407726719478268482601476990902640136394437455305068203496

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2089986280
1174502841
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1414419735685481613611573525521334757418494684385233239073941433345477624168 62
5189835694855620992192221842725502542568876717904946016534668049886272327917 86
0857843838279679766814541009538837863609506800642251252051173929848960841284 88
6269456042419652850222106611863067442786220391949450471237137869609563643719 17
2874677646575739624138908658326459958133904780275900994657640789512694683983 52
5957098258226205224894077267194782684826014769909026401363944374553050682034 96

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Further discussion

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20899862803
11745028410
78678316527
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56735188575
70217986094
78577134275
54201995611
95105973173
00313783875
35378759375
06548586327
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25506040092
83744944825
16205696602
78235478163
69092721079
42654252786
14144197356854816136115
3323907394143334547762416862
518983569485562099219222
94601653466804988627232791786
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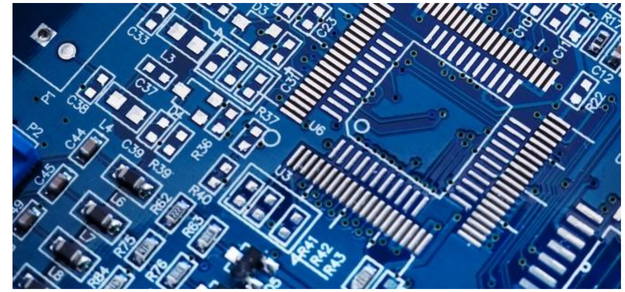
Payout:

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

Further discussion



Classical Computer: 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.

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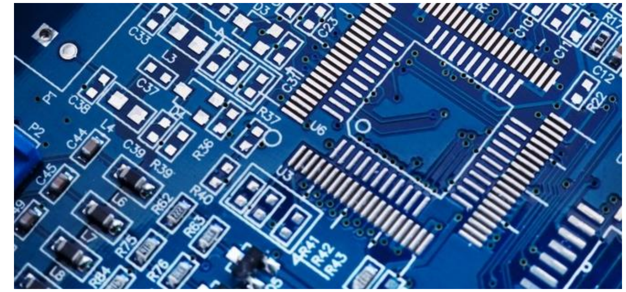
Further discussion



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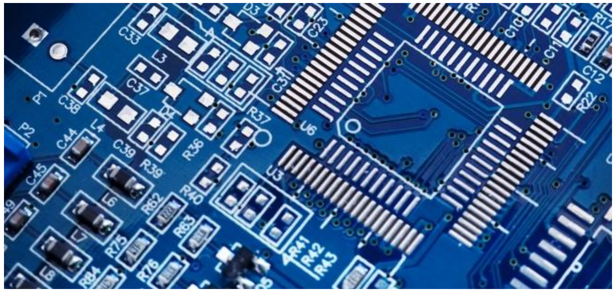
Std. thinking about classical probabilities

Further discussion



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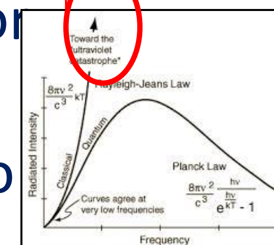
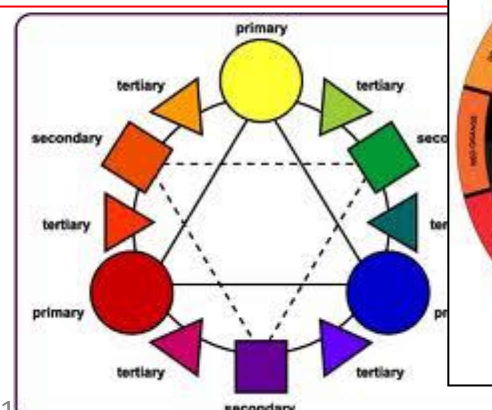
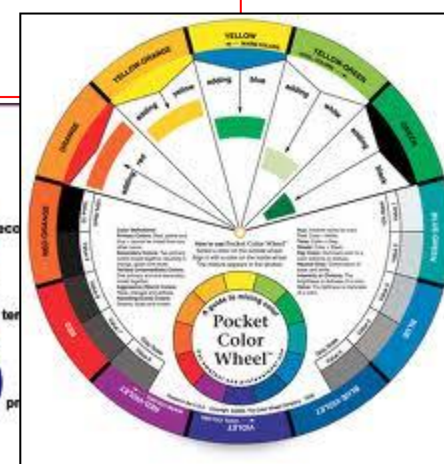
Further discussion

<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.







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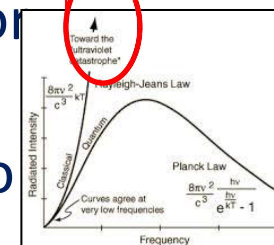

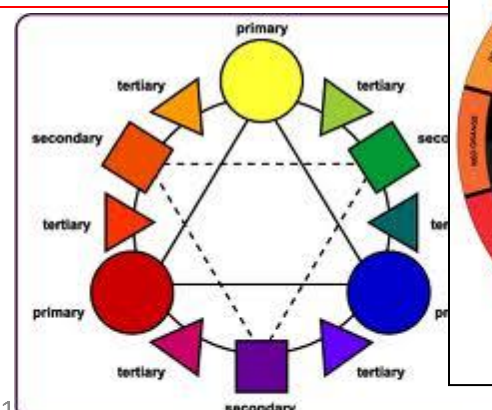

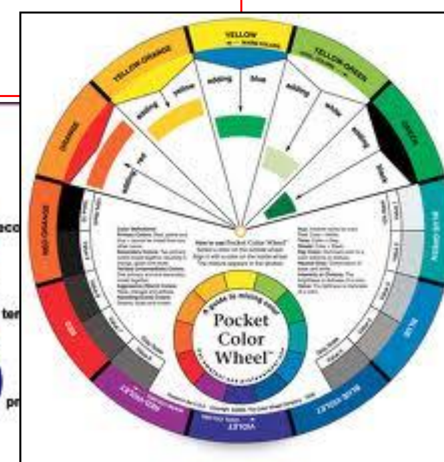

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