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)

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Thank you Katie!!!

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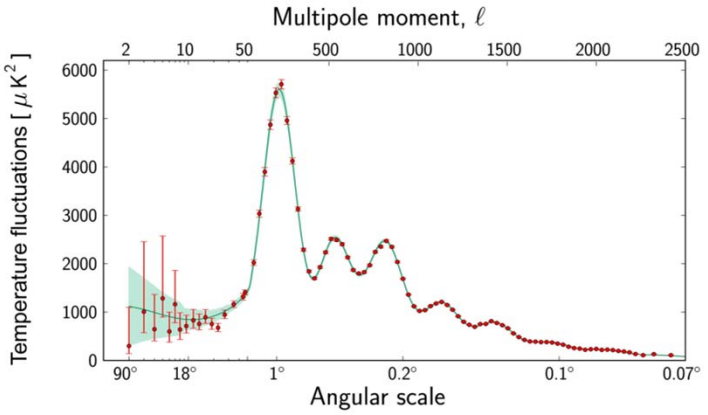
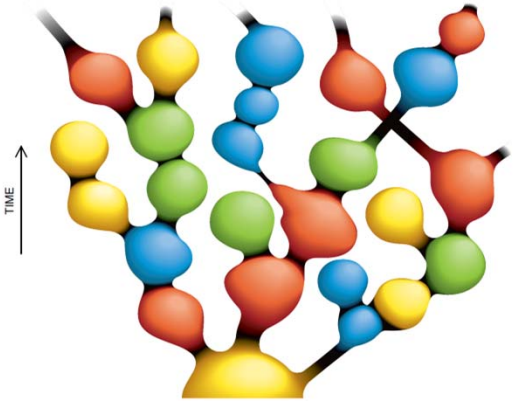
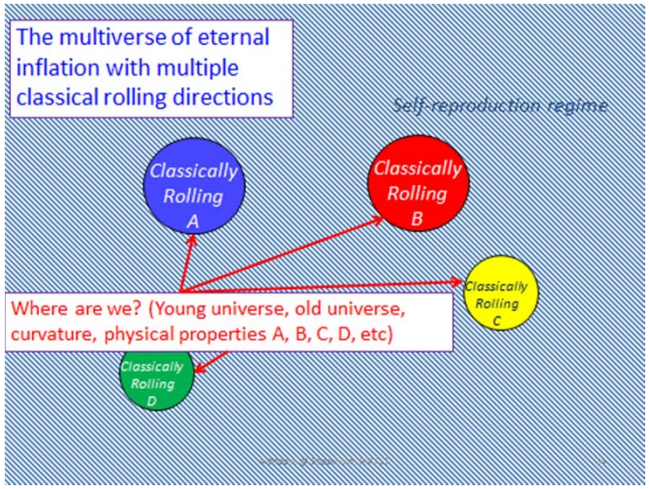
Cosmic Inflation:

Consumers & Producers







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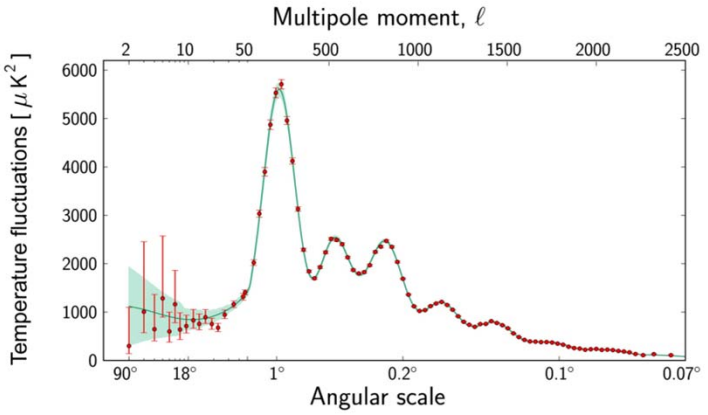

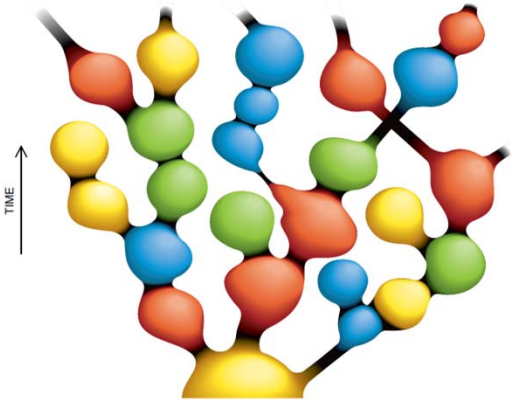

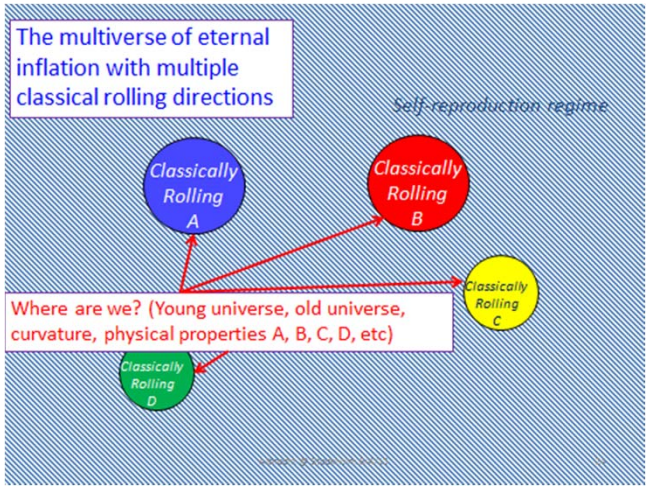

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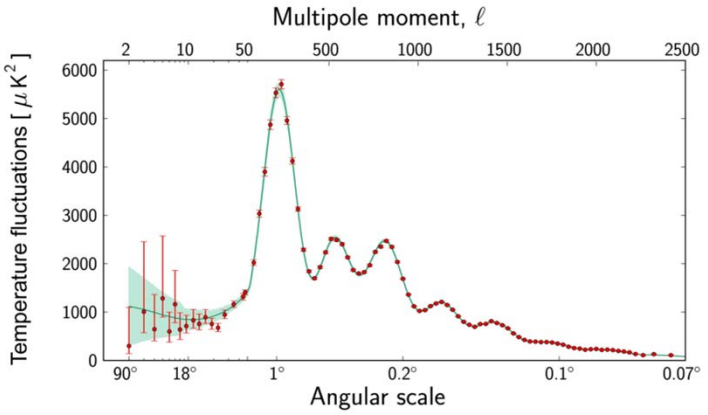

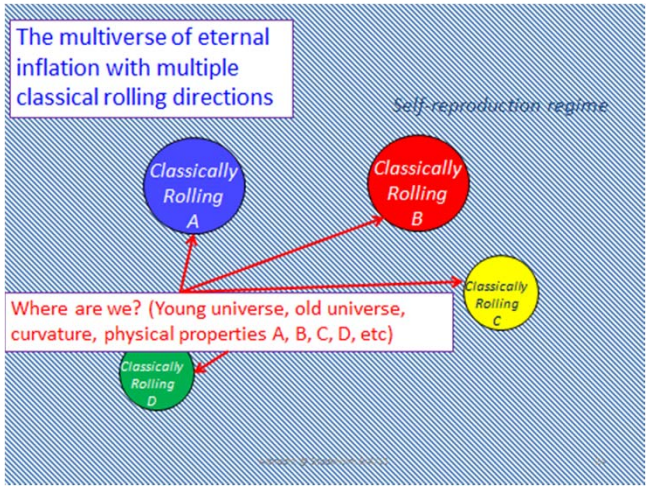

(Blue Monster by Simon Richards)

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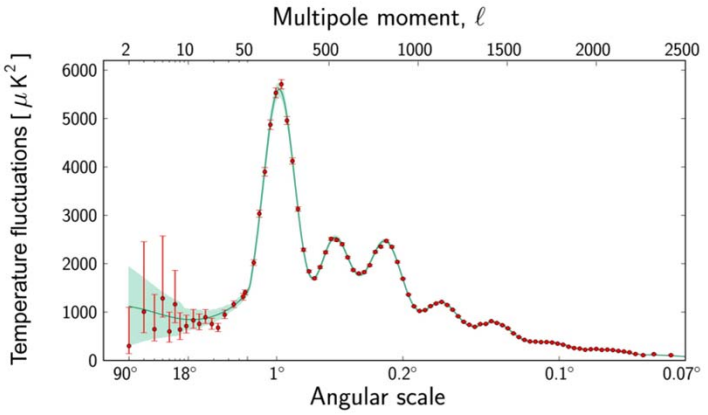

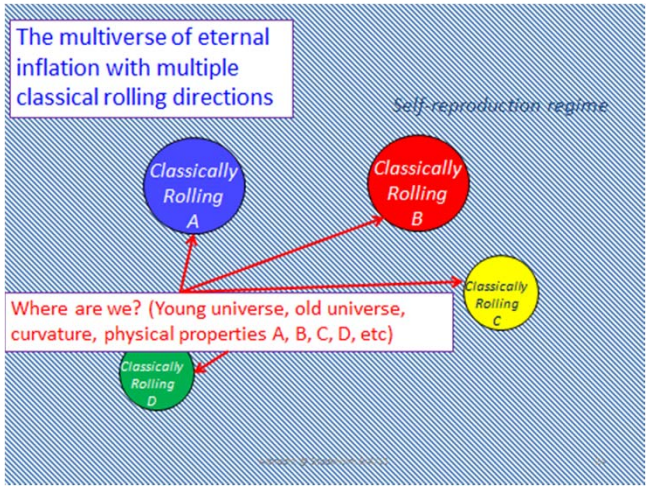

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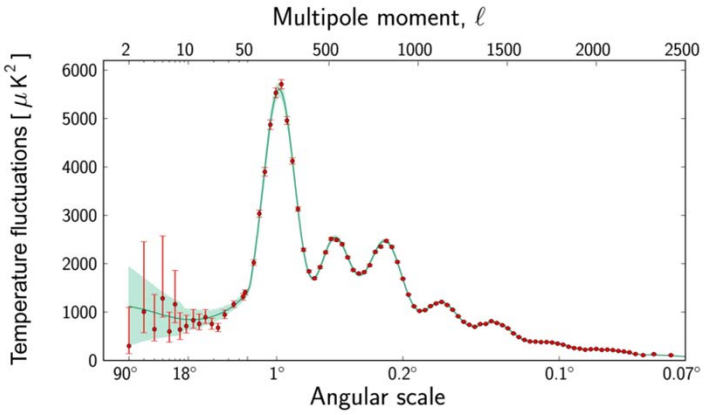

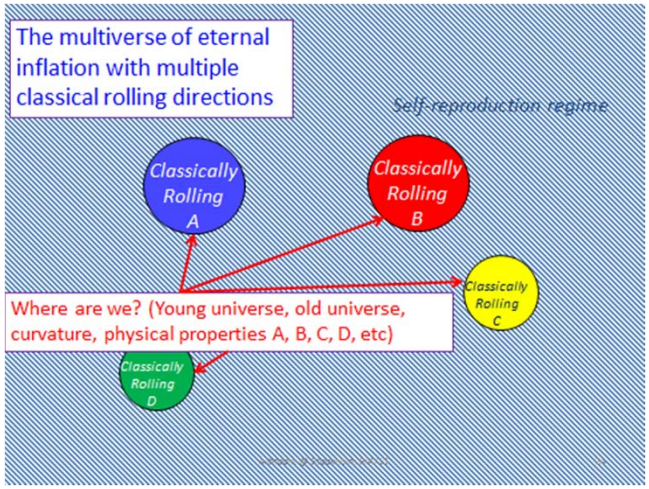

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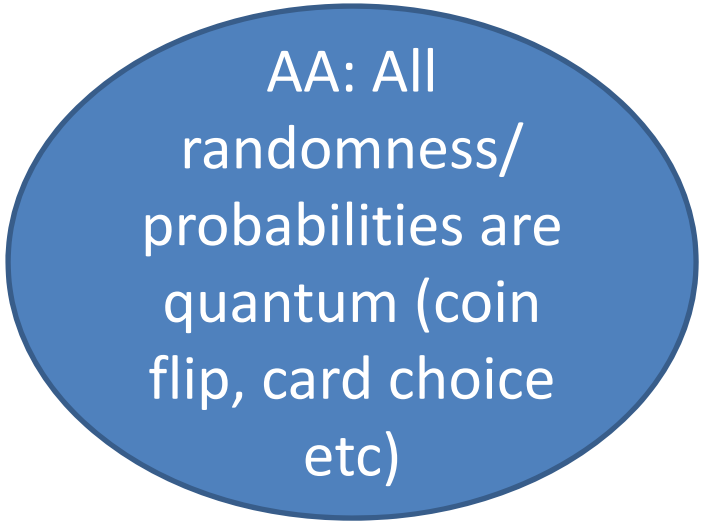

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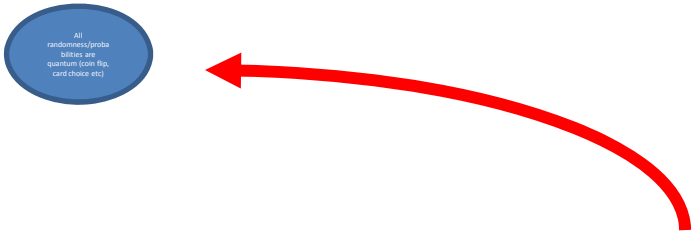

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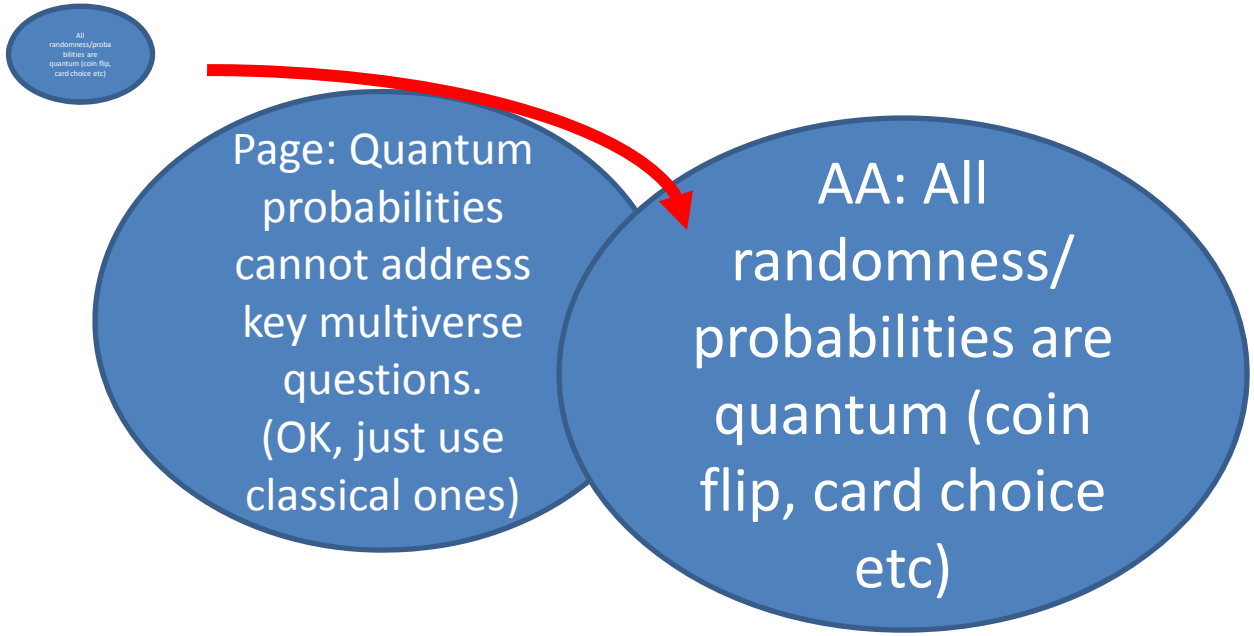

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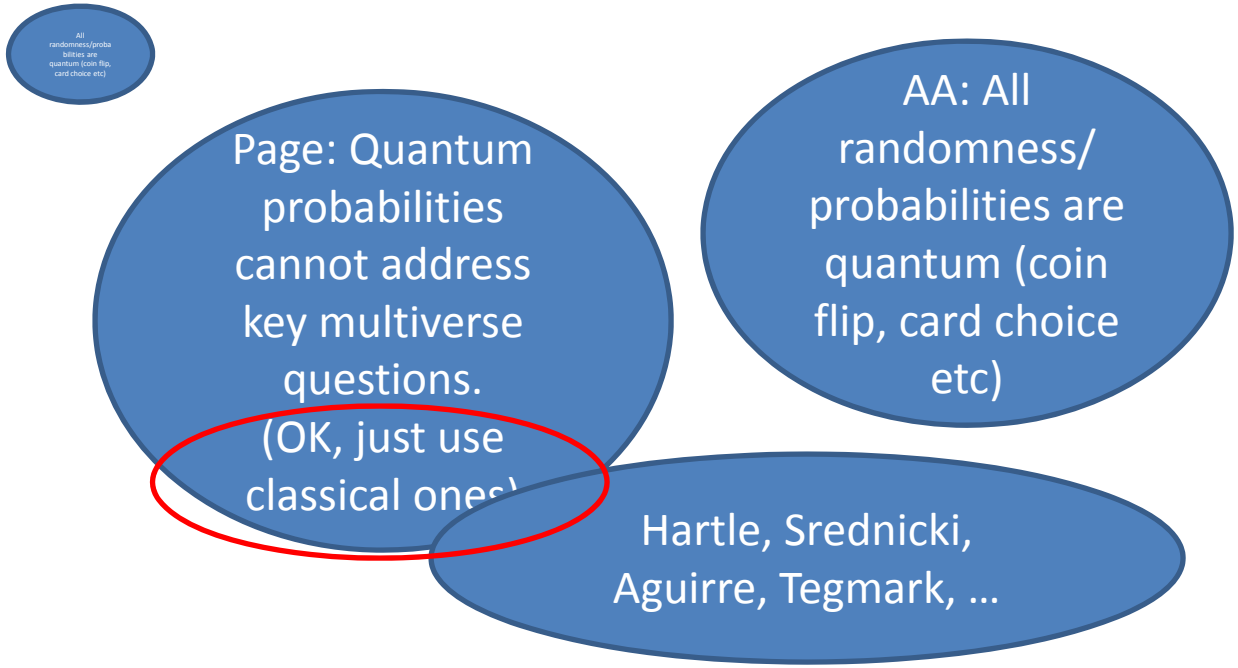

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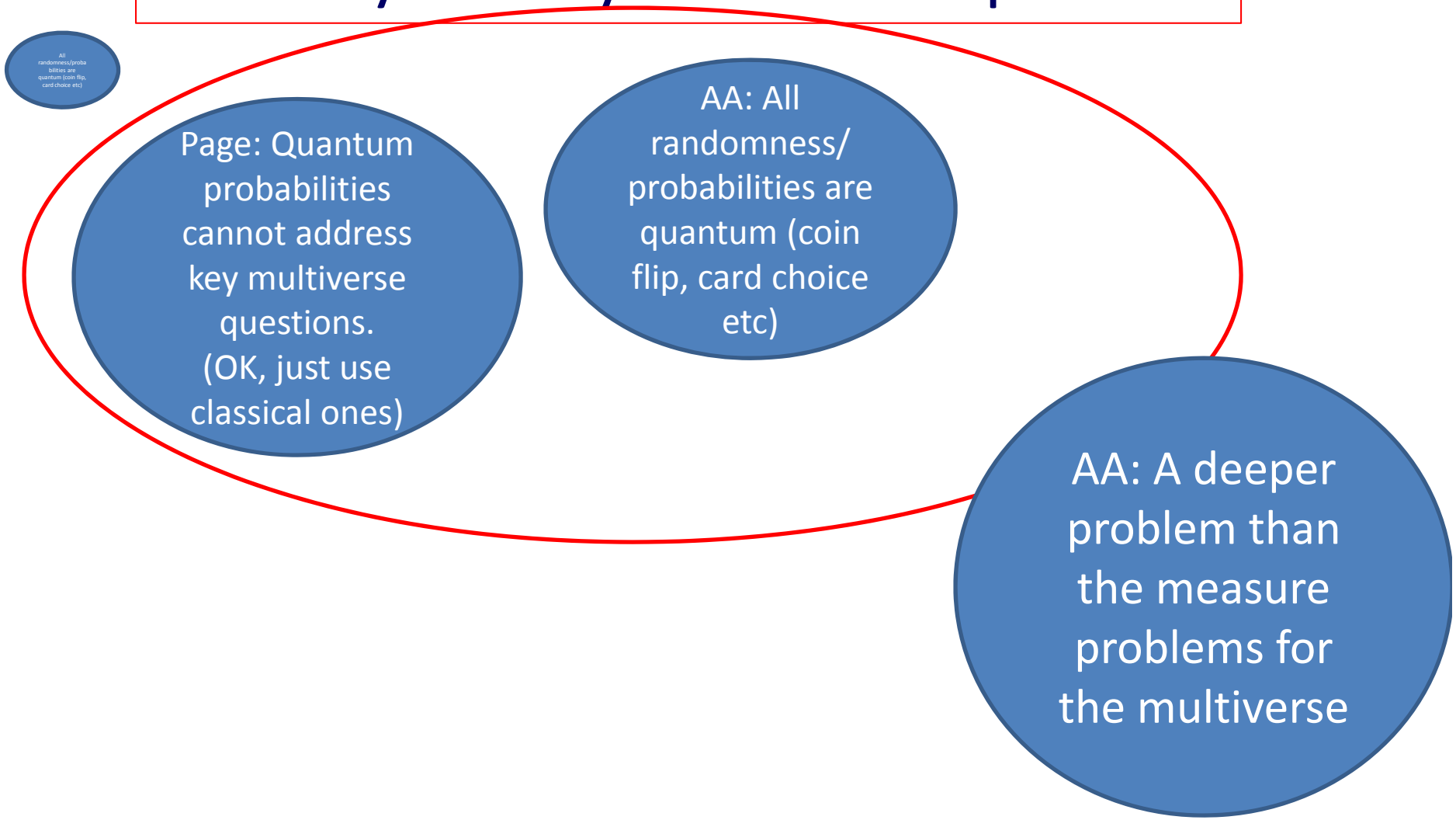

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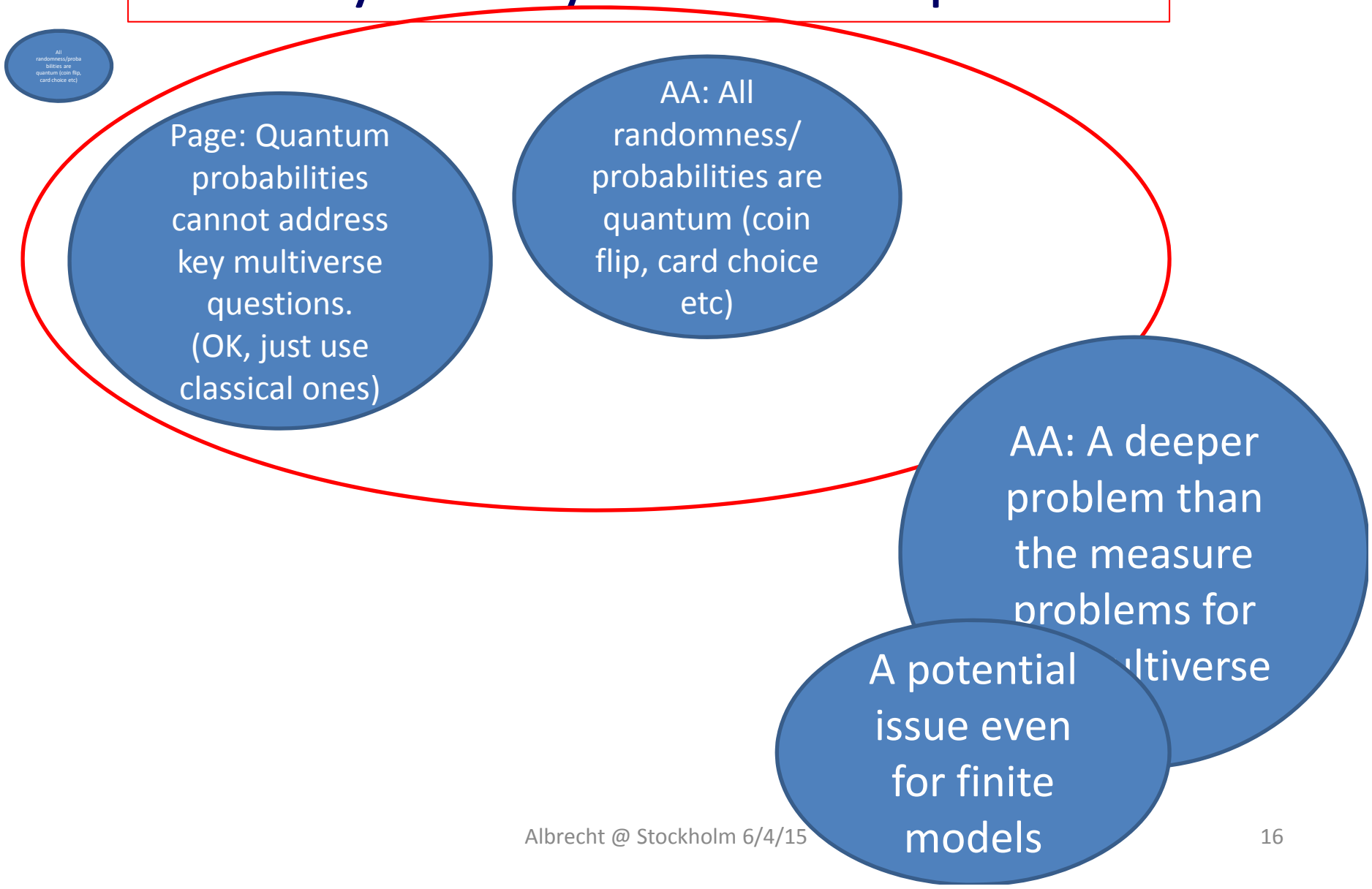

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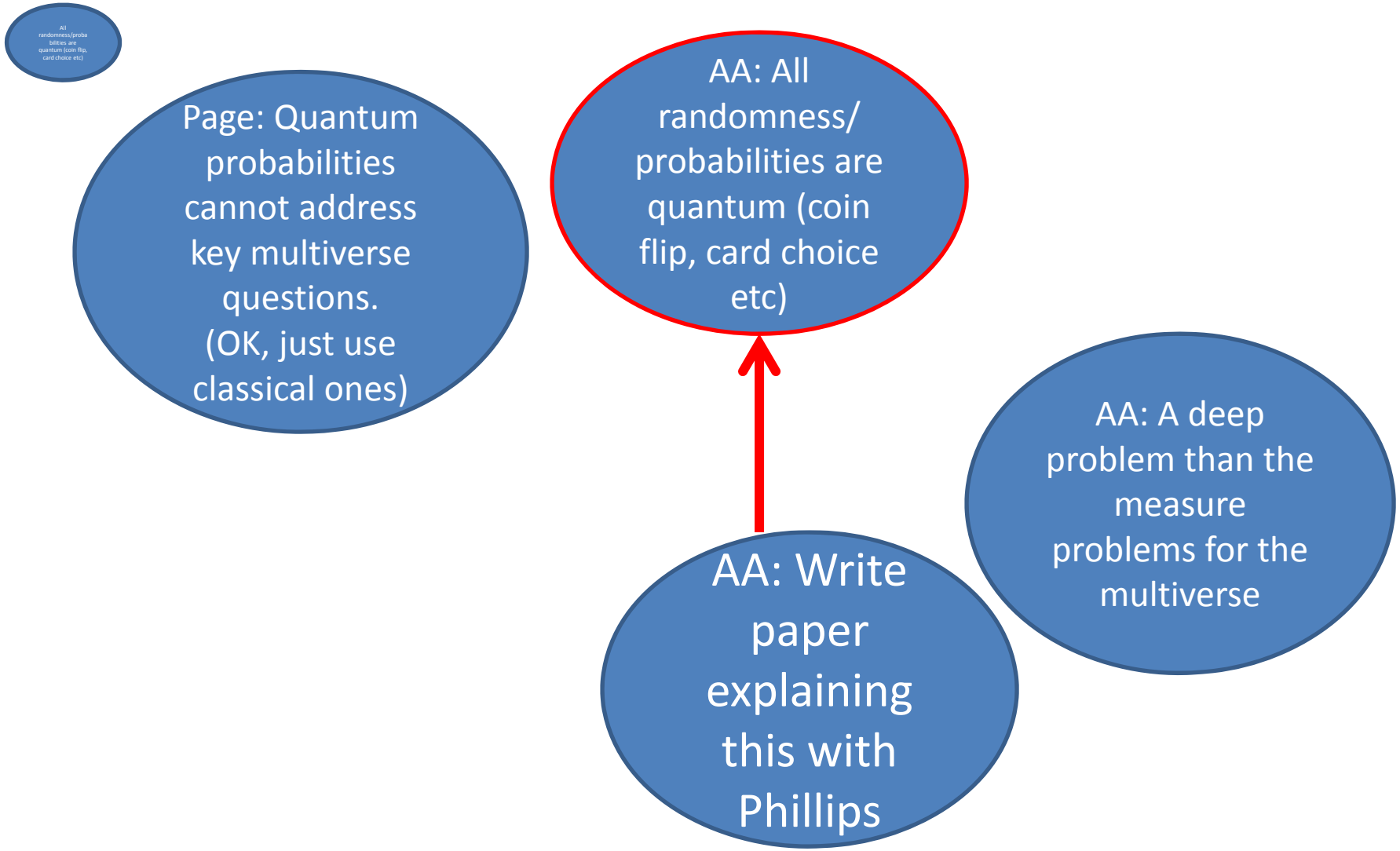

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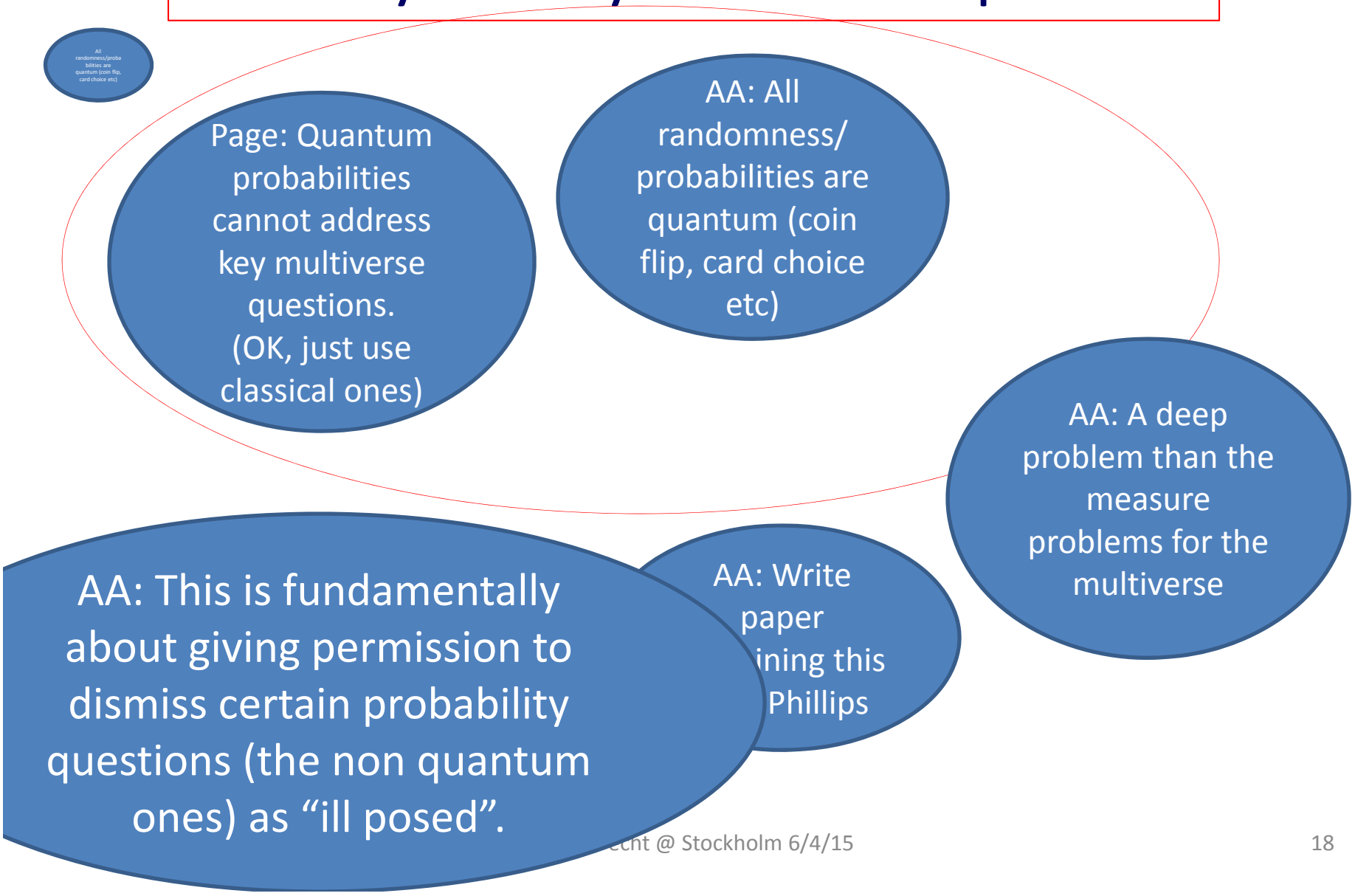

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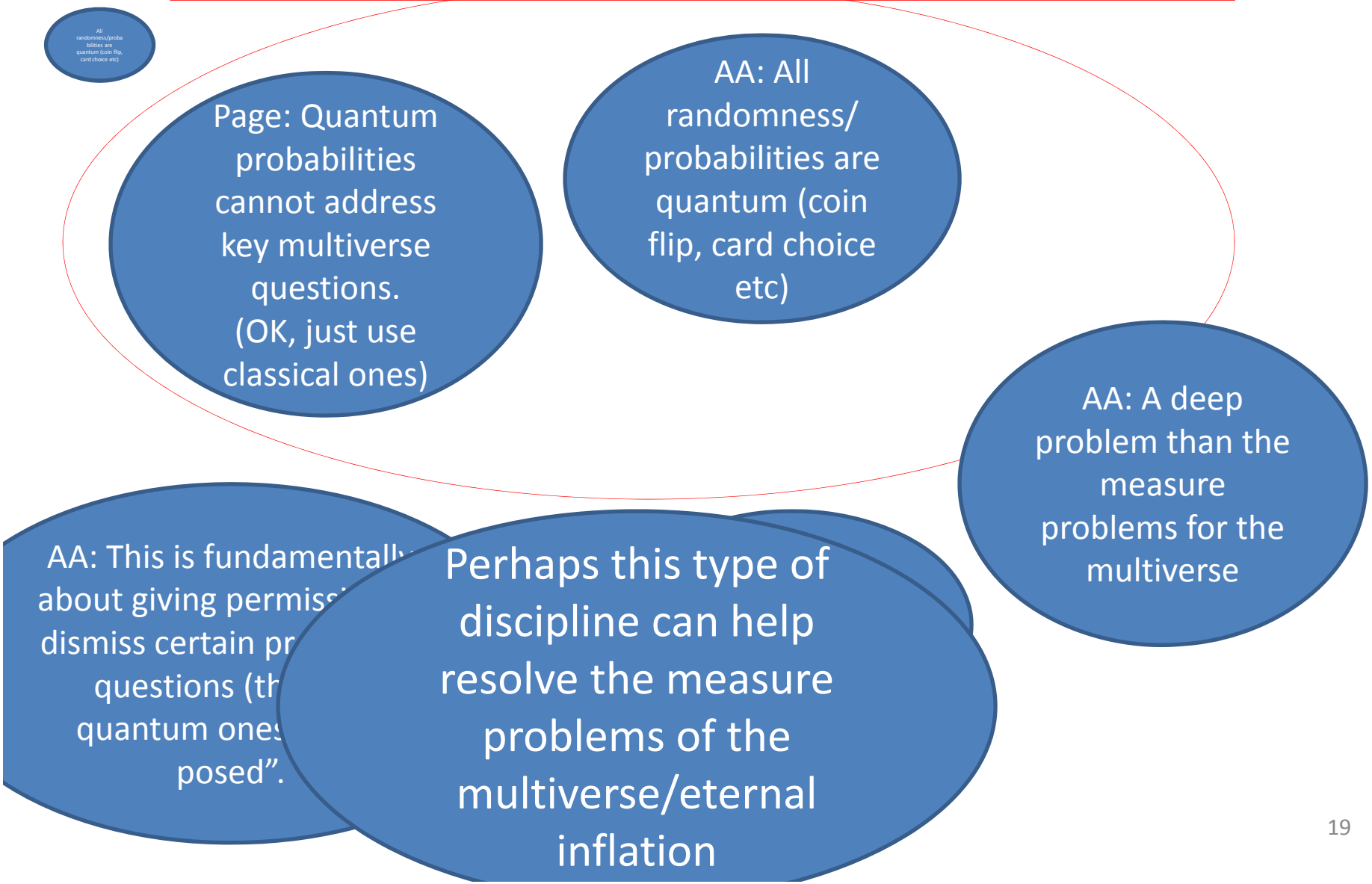

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AA: A deep problem than the measure problems for the multiverse

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

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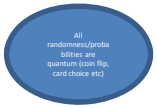

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Outline

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

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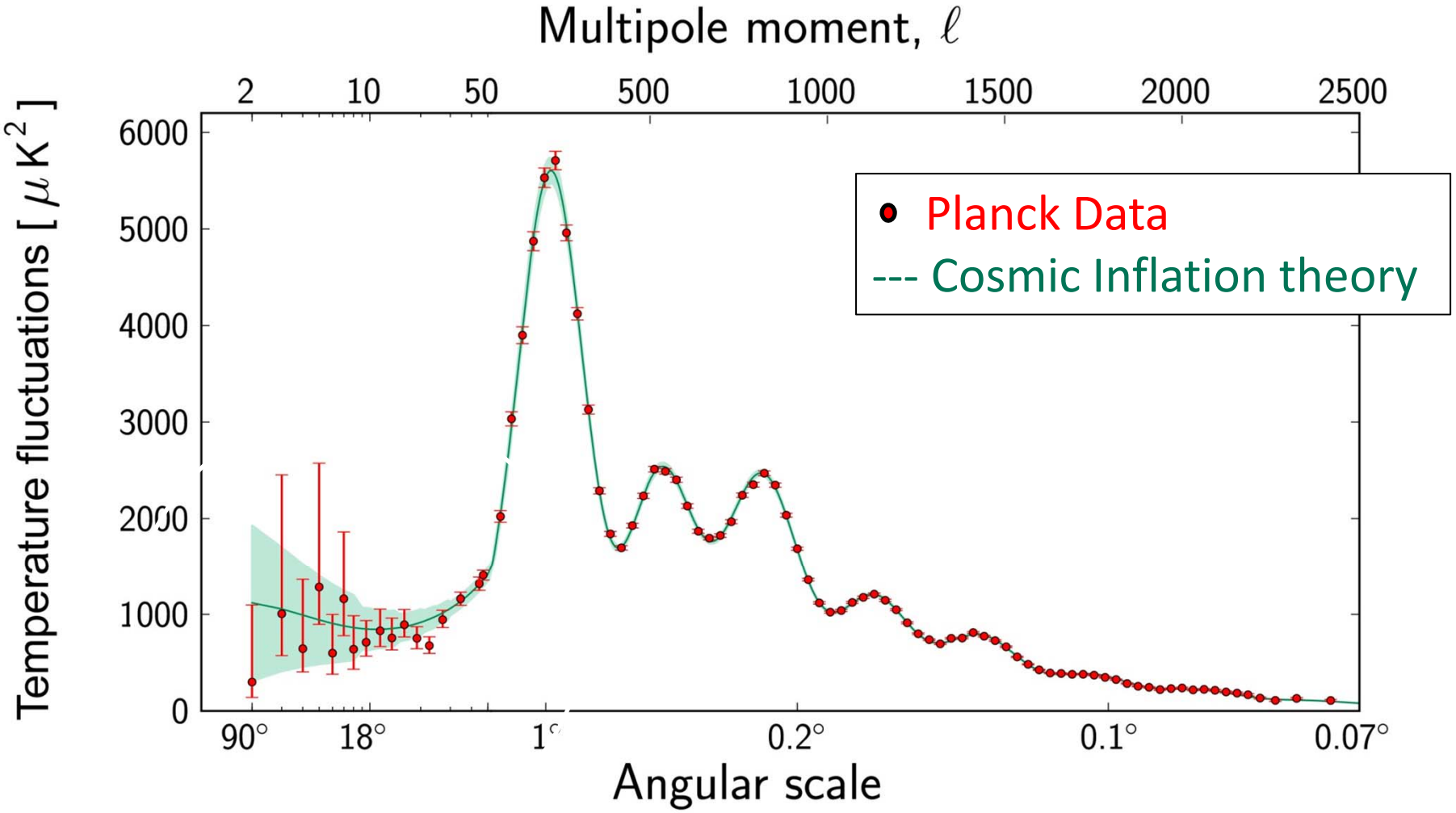
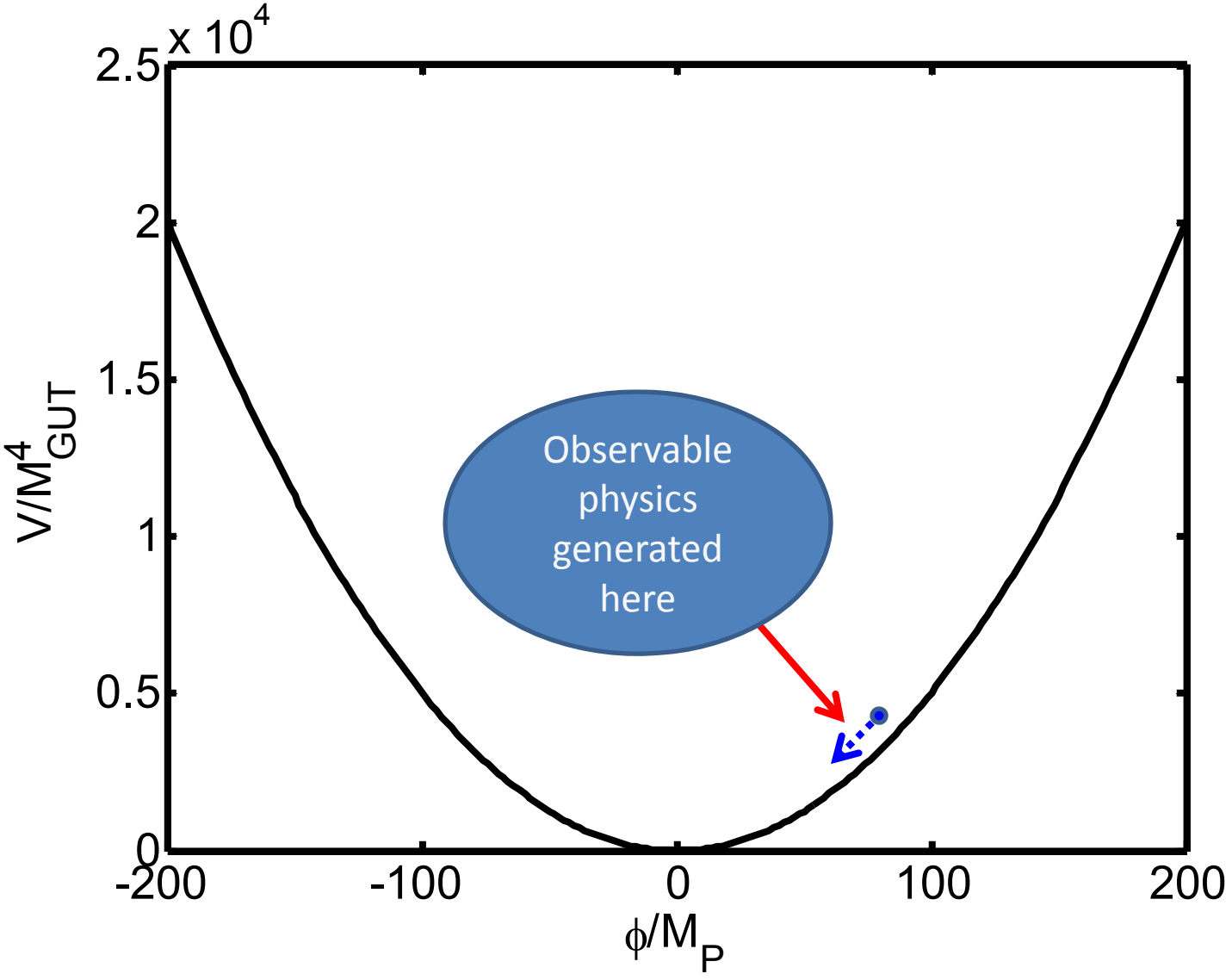

Multipole moment, ℓ
2
10
50
500
1000
1500
2000
2500
Temperature fluctuations [μ K^2]
6000
5000
4000
3000
2000
1000
0
90°
18°
1°
0.2°
0.1°
0.07°
Angular scale
Planck Data
--- Cosmic Inflation theory

Slow rolling of inflaton



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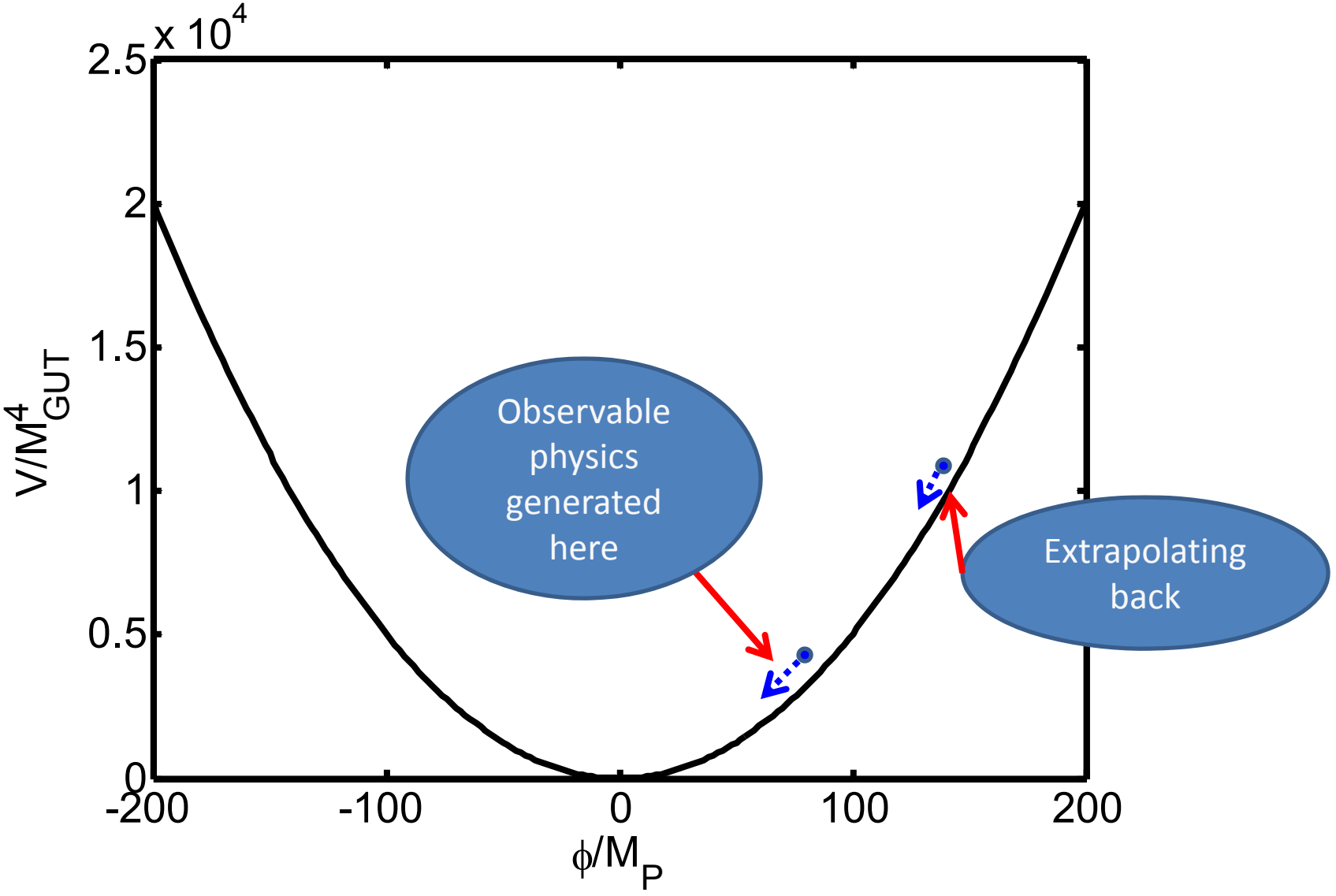

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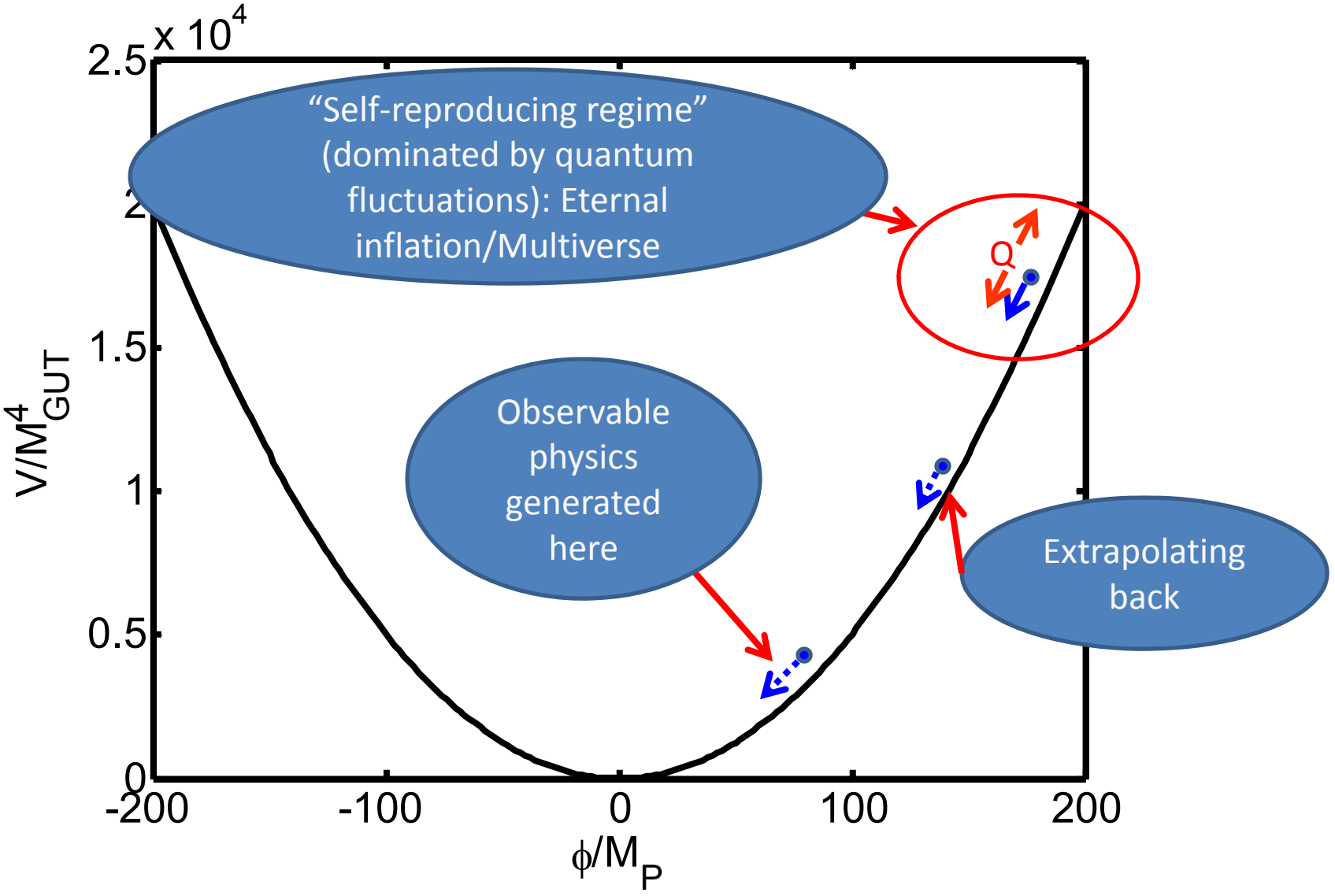

Steinhardt 1982, Linde 1982, Vilenkin 1983, and (then) many others

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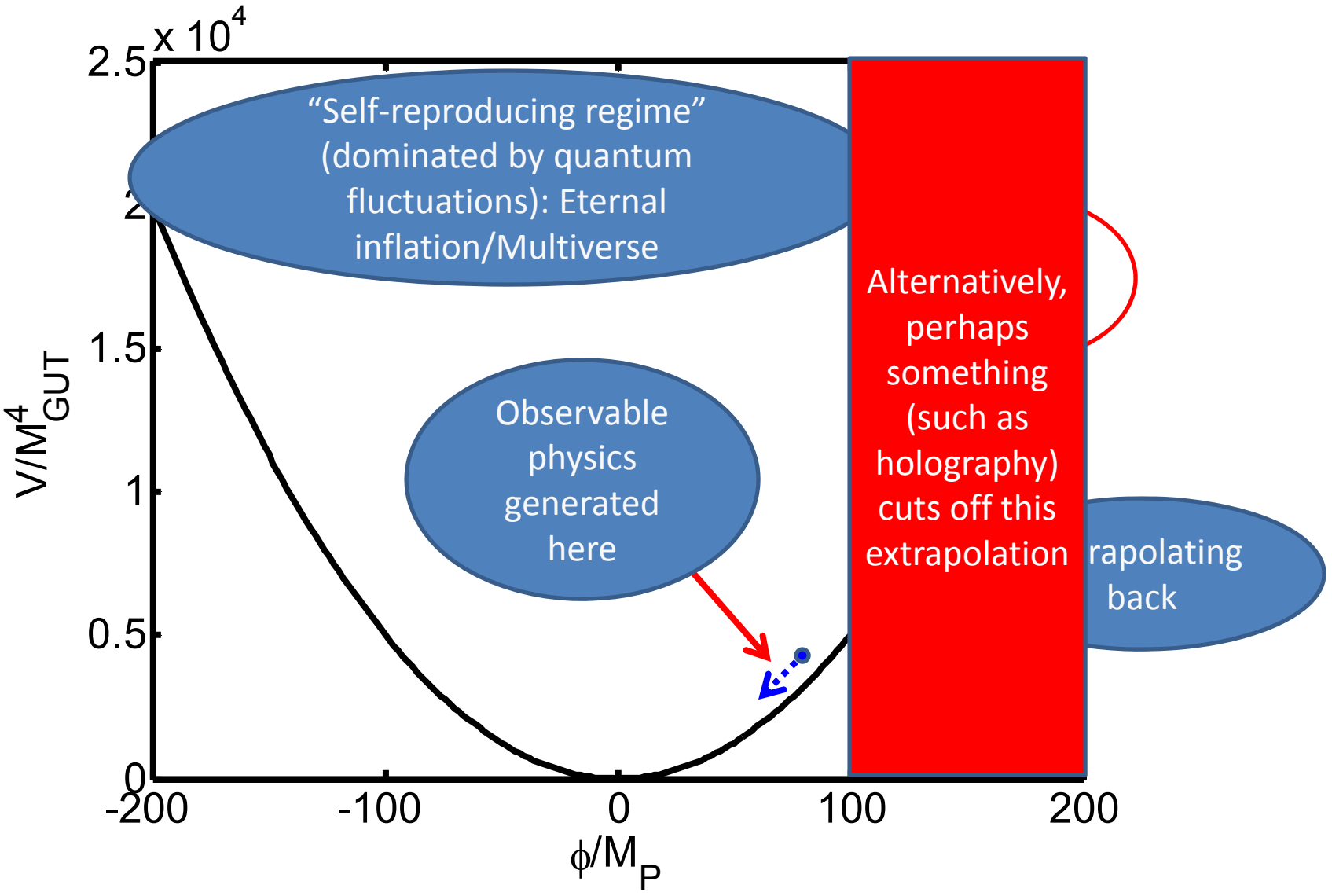

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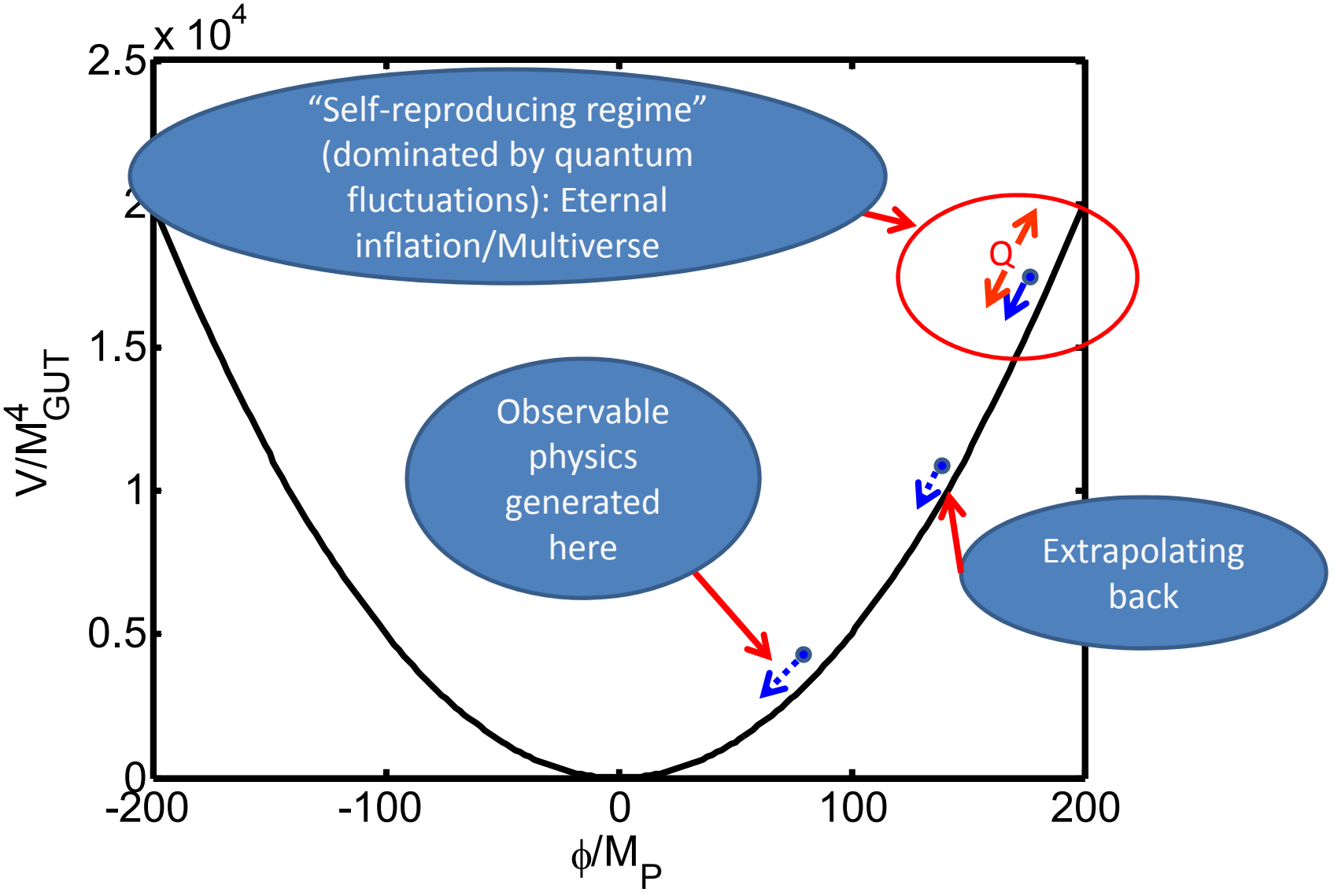

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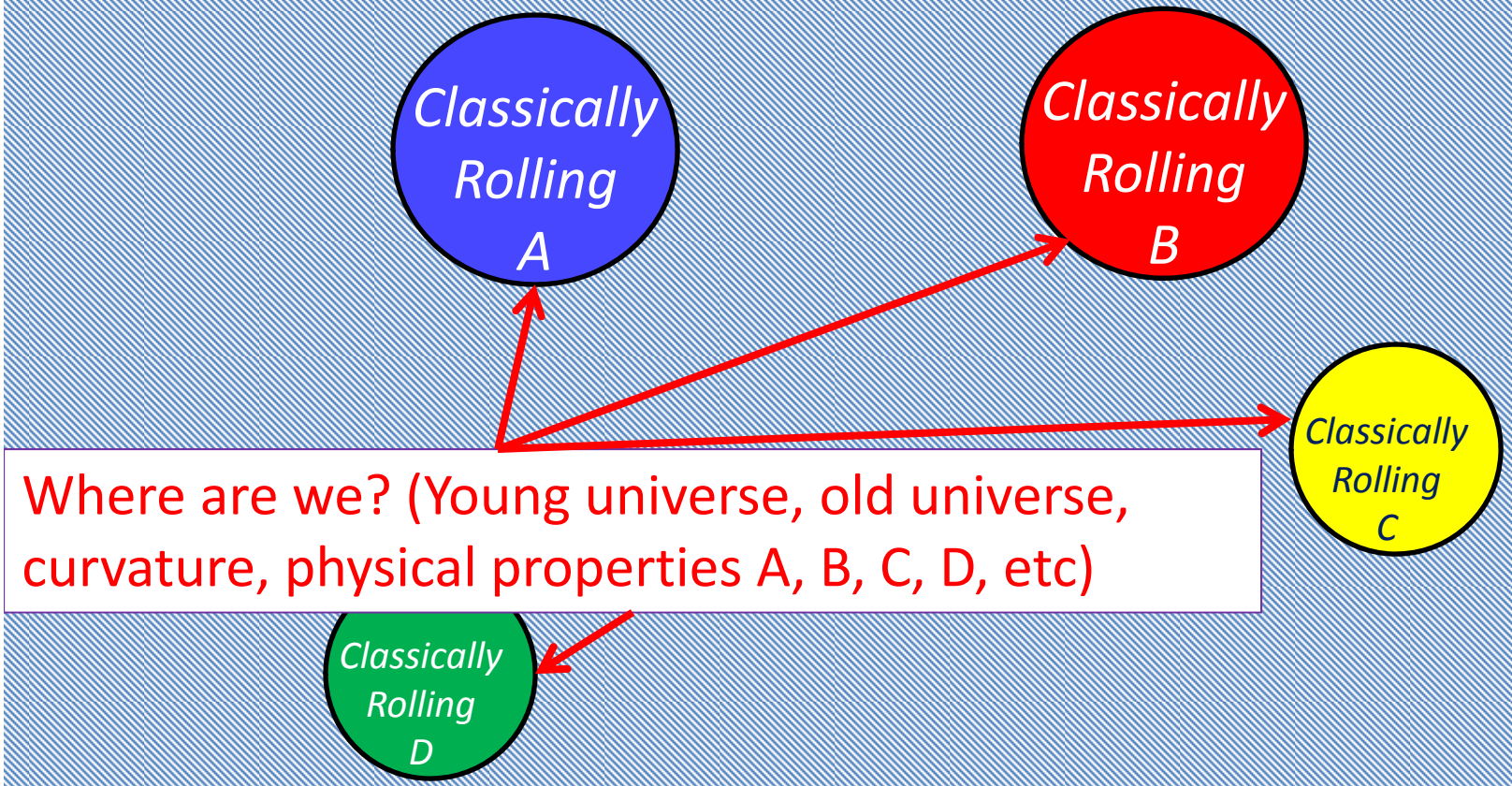
The multiverse of eternal inflation with multiple classical rolling directions

Self-reproduction regime



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

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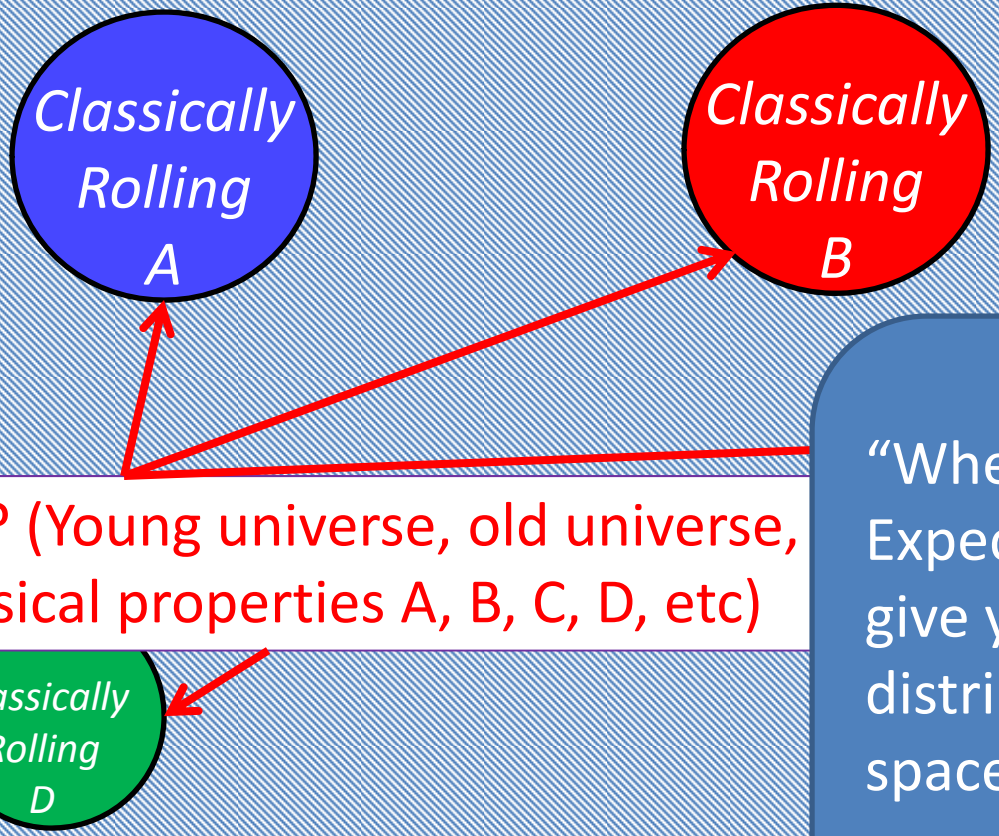

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"Where are we?" ➔ Expect the theory to give you a probability distribution in this space… hopefully with some sharp predictions

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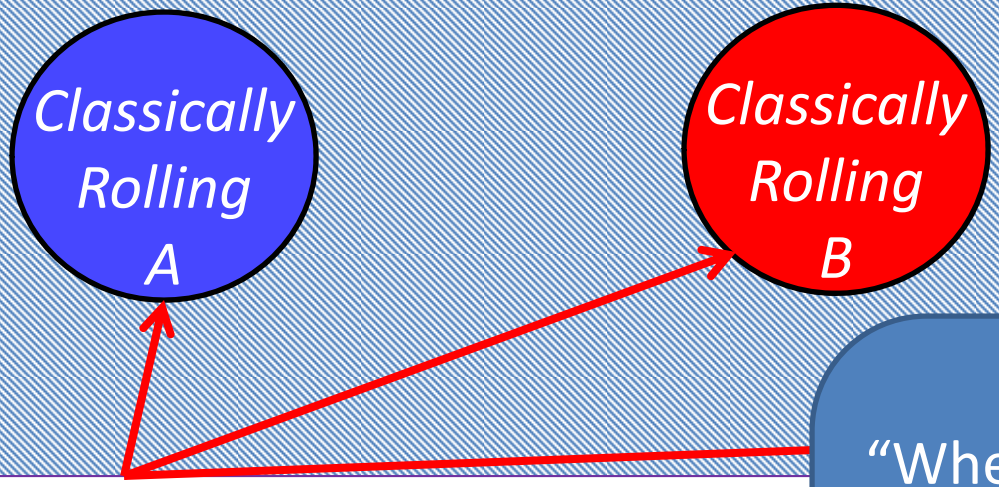

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Classically

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

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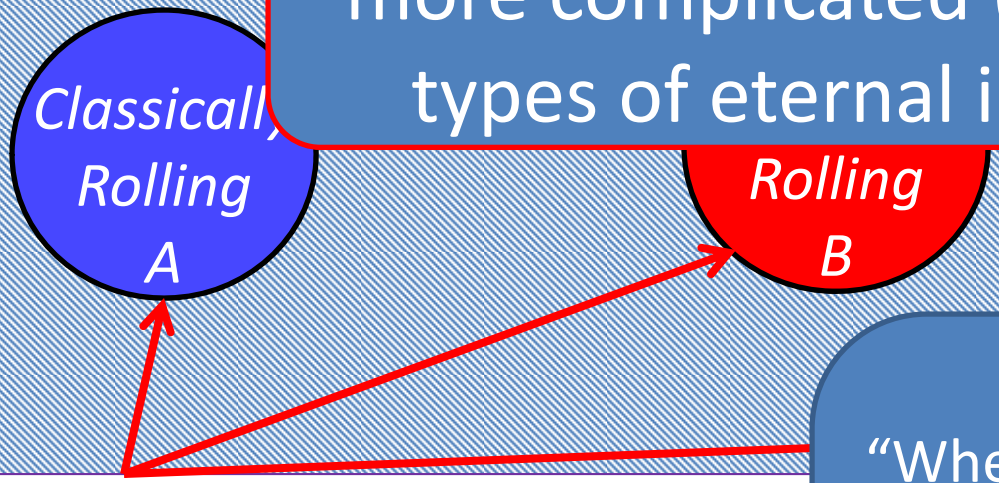
The multiverse of eternal inflation with multiple classical rolling direct

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



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Rolling B

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Quantum vs Non-Quantum probabilities

Non-Quantum probabilities in a toy model:

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

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

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

$U = A$

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.

$^A |j\rangle^B$

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Does not represent a quantum measurement

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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

AA & D. Phillips 2014

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A problem for many multiverse theories (as practiced)

AA & D. Phillips 2014

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

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

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

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

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

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*:

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

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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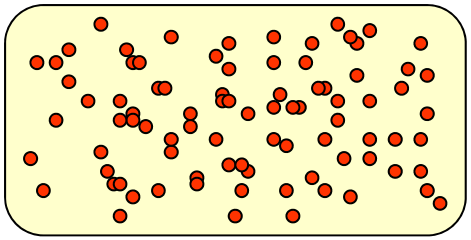
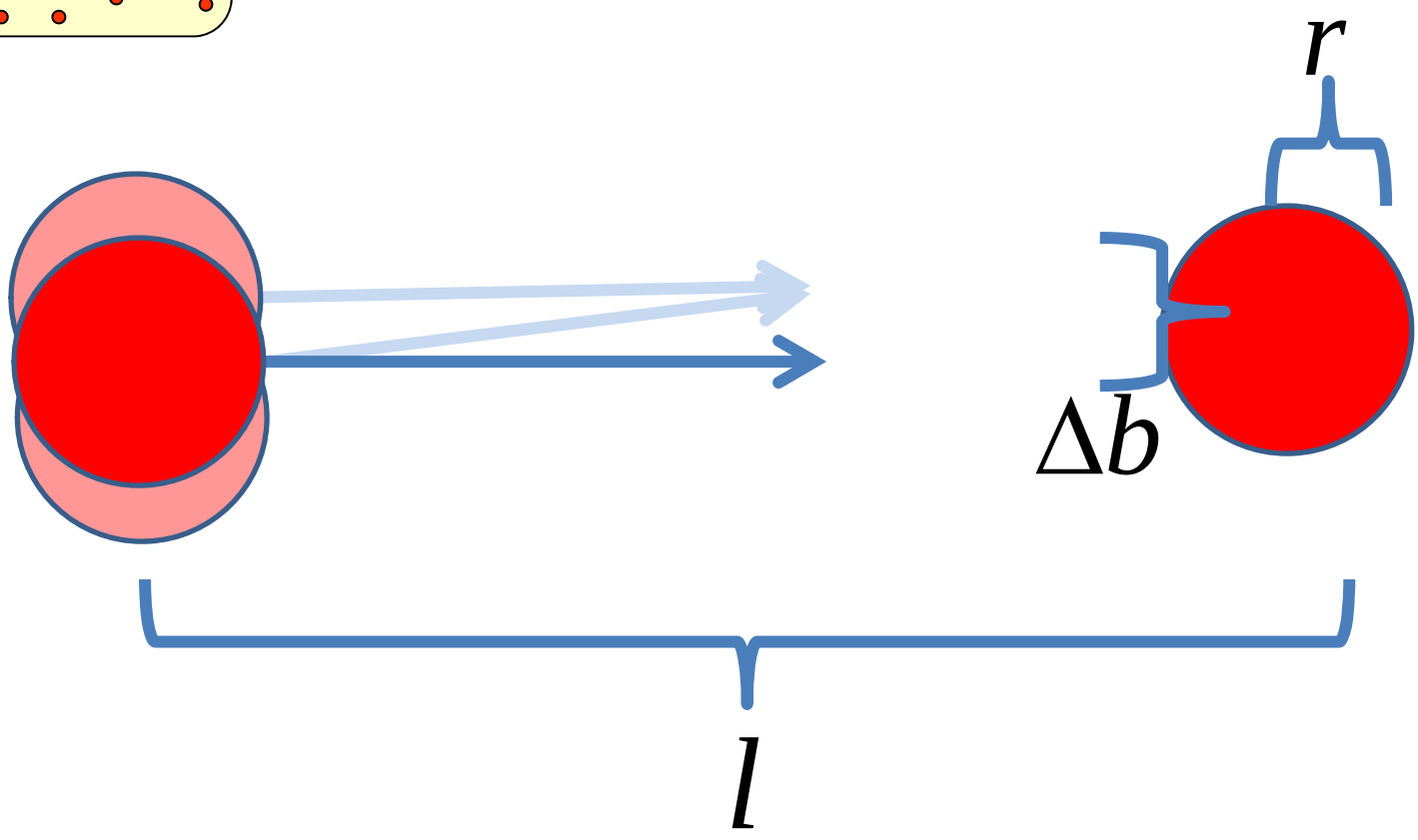
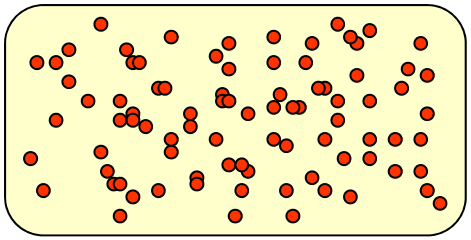


Quantum effects in a billiard gas





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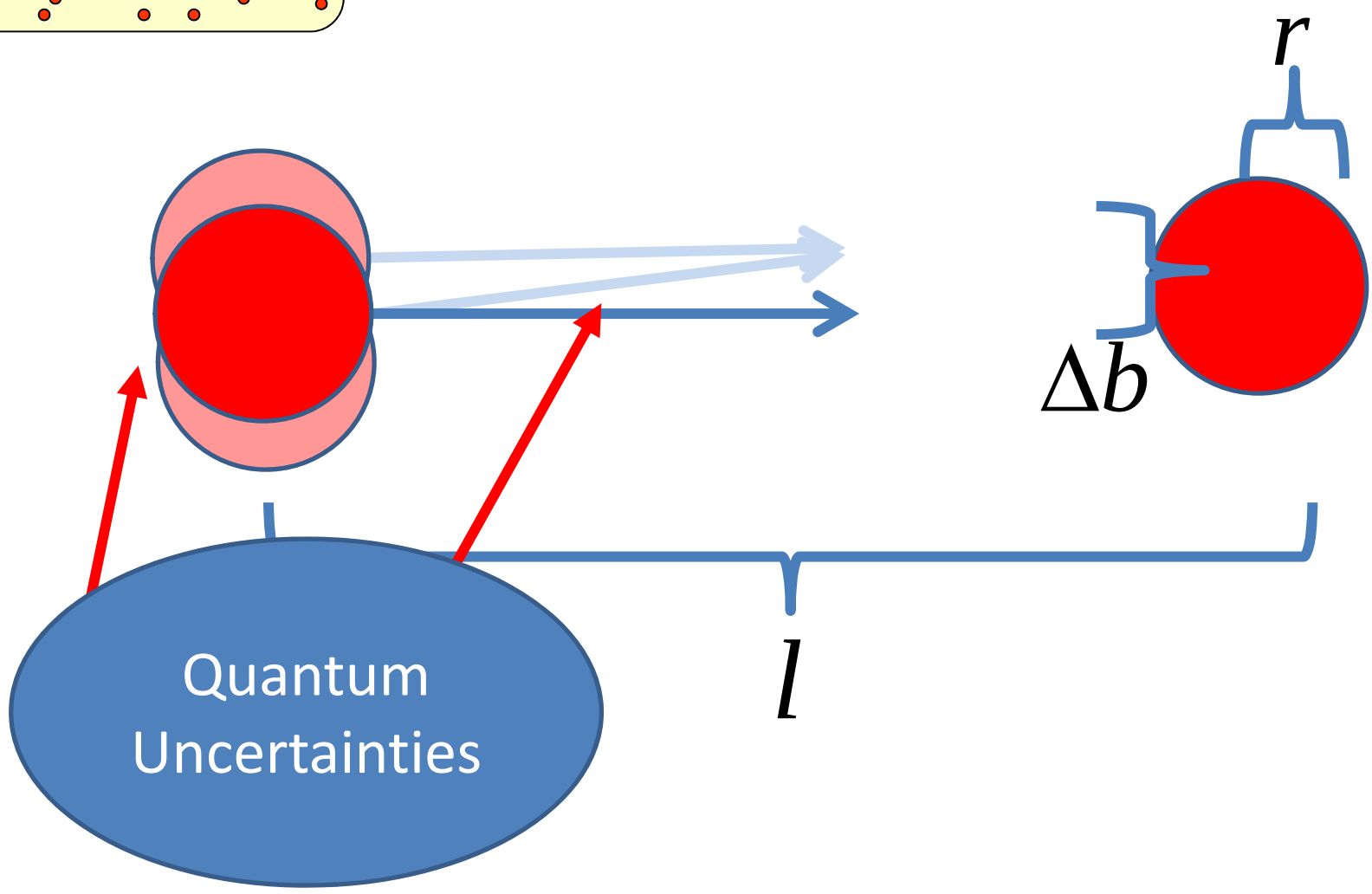

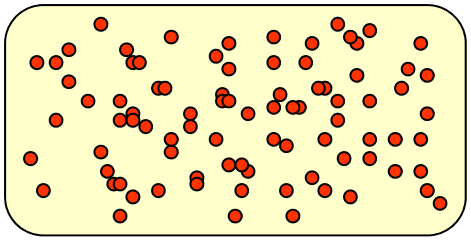

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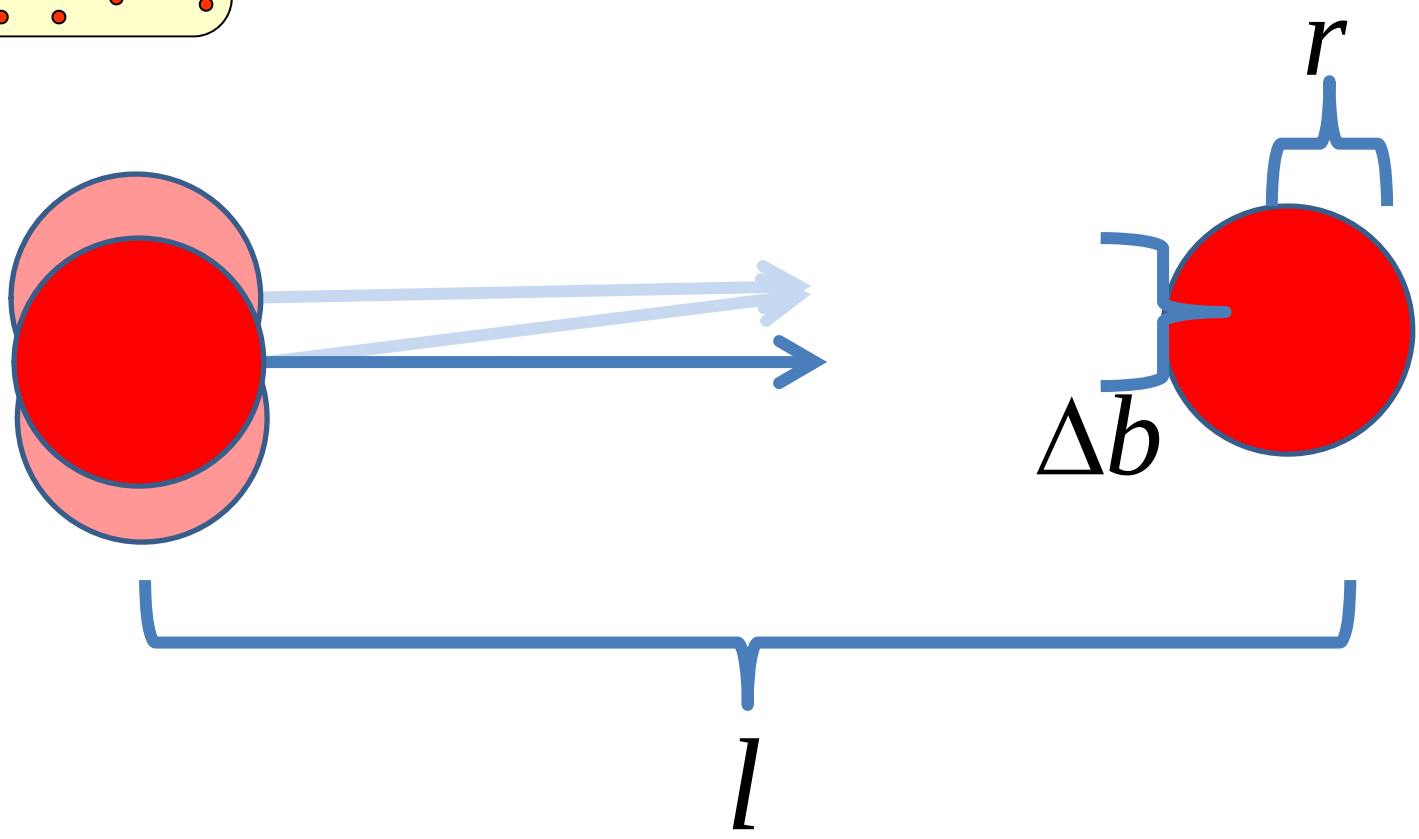
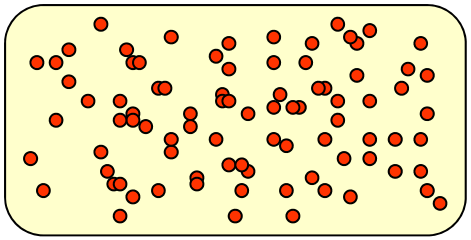


$$\Delta b = \delta x_{\perp} + \frac{\delta p_{\perp}}{m} \Delta t$$



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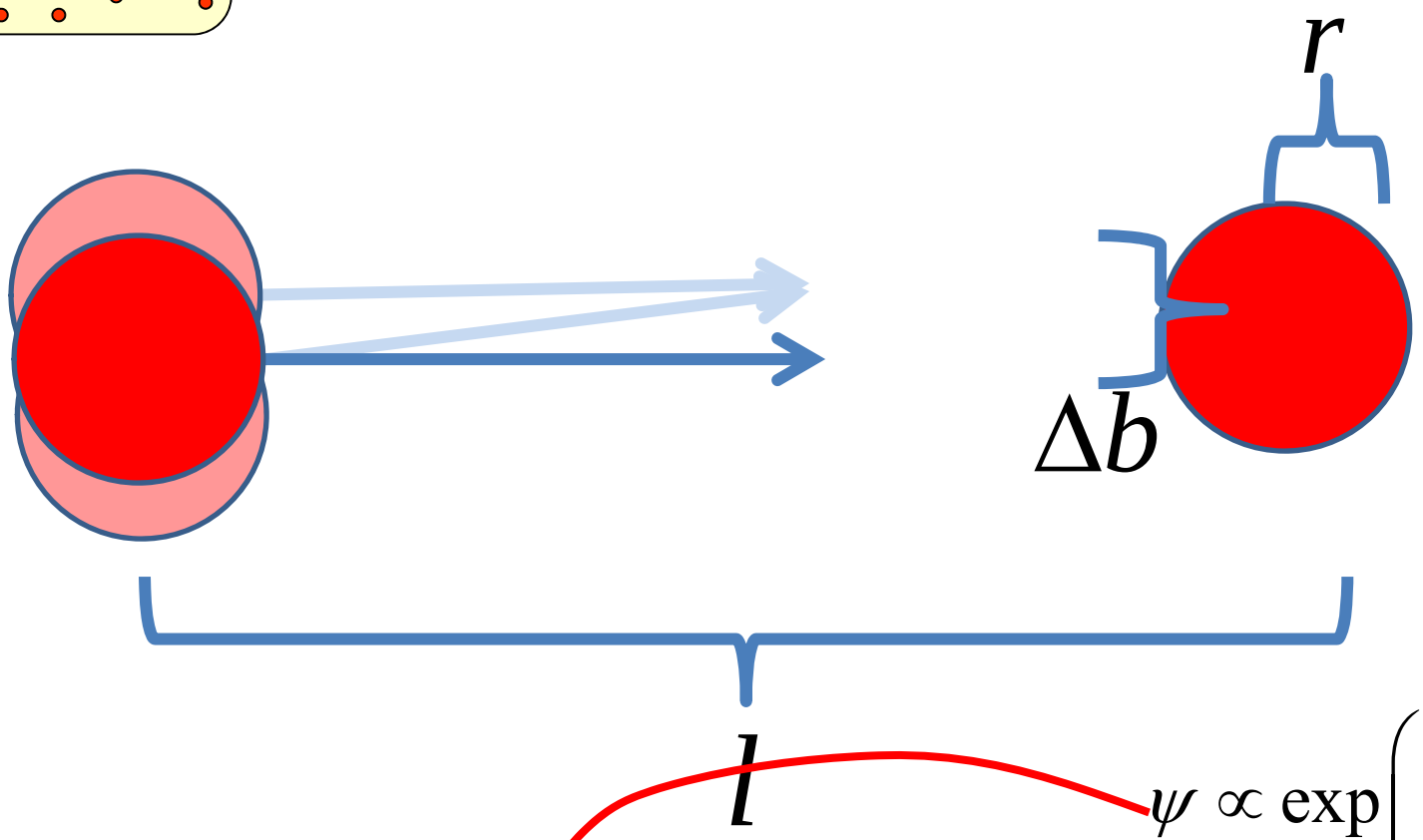
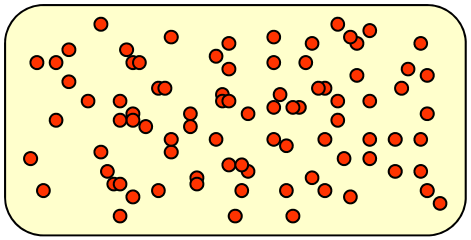


$$\psi \propto \exp\left(\frac{-x^2}{2a^2}\right)$$

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



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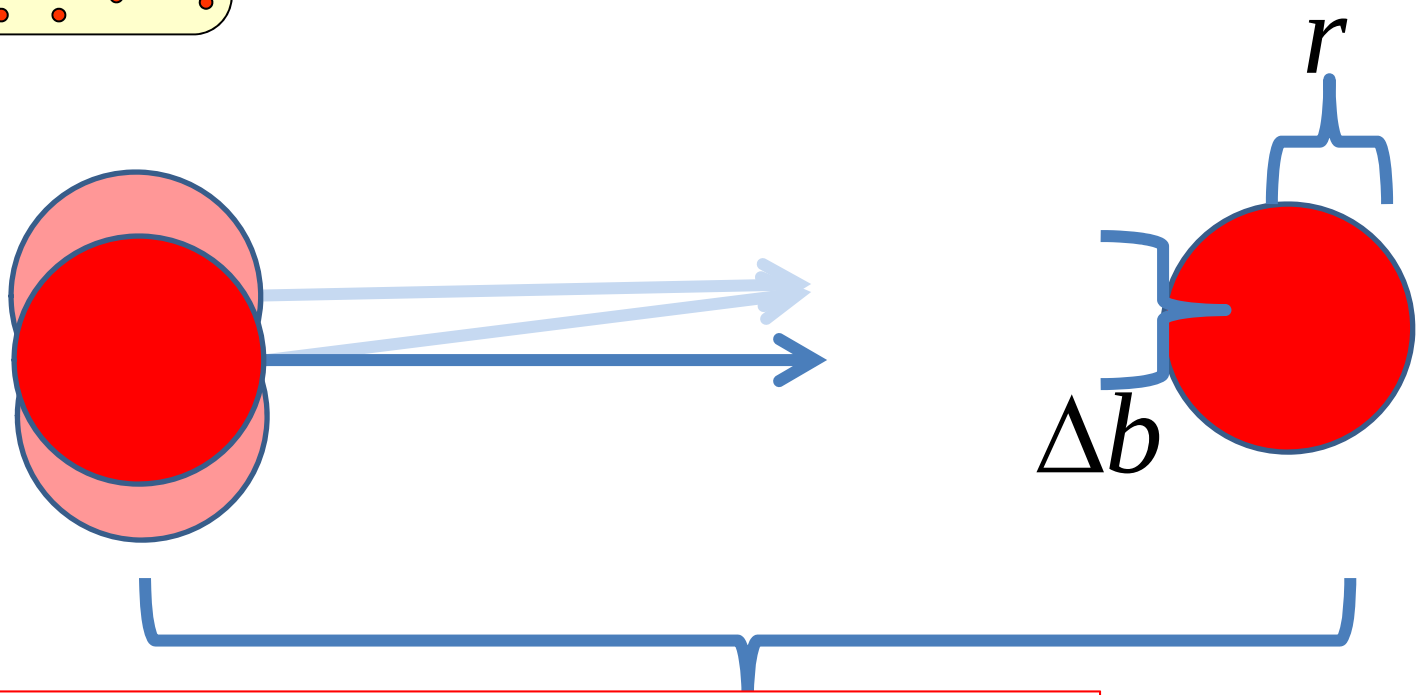
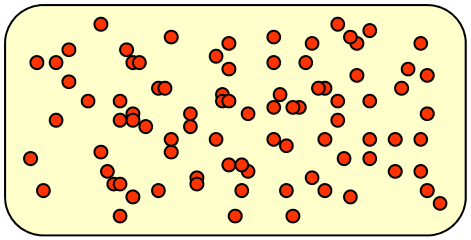


$$\Delta b = \delta x_{\perp} + \frac{\delta p_{\perp}}{m}\Delta t = \sqrt{2}\left(a + \frac{\hbar}{2a}\frac{l}{m\bar{v}}\right) \qquad \psi \propto \exp\left(\frac{-x^2}{2a^2}\right)$$

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



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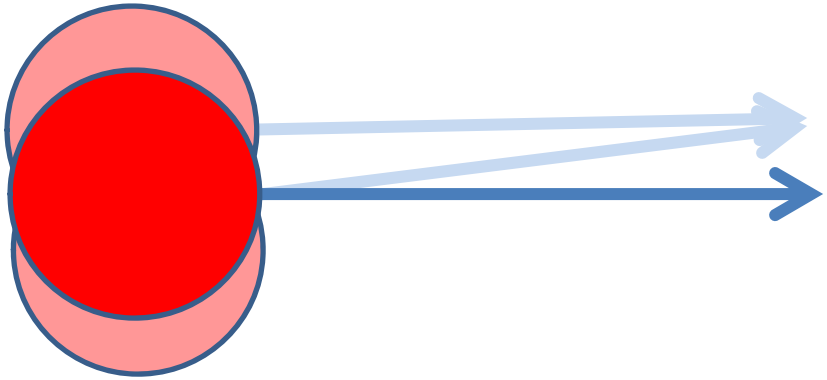
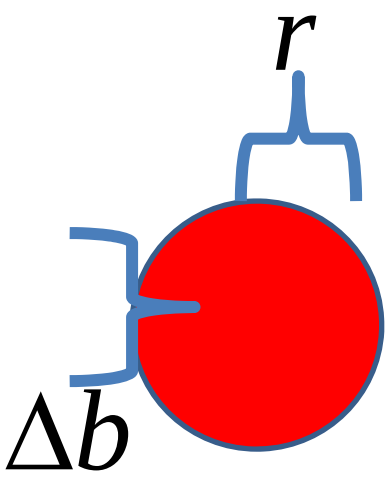


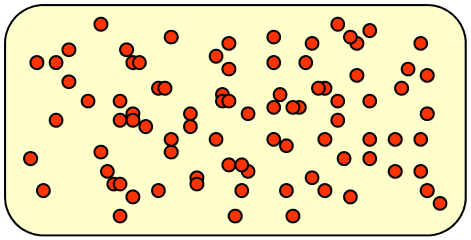


Minimizing ➔ conservative estimates for my purposes (also motivated by decoherence in some cases)

$$\Delta b = \delta x_{\perp}$$

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

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



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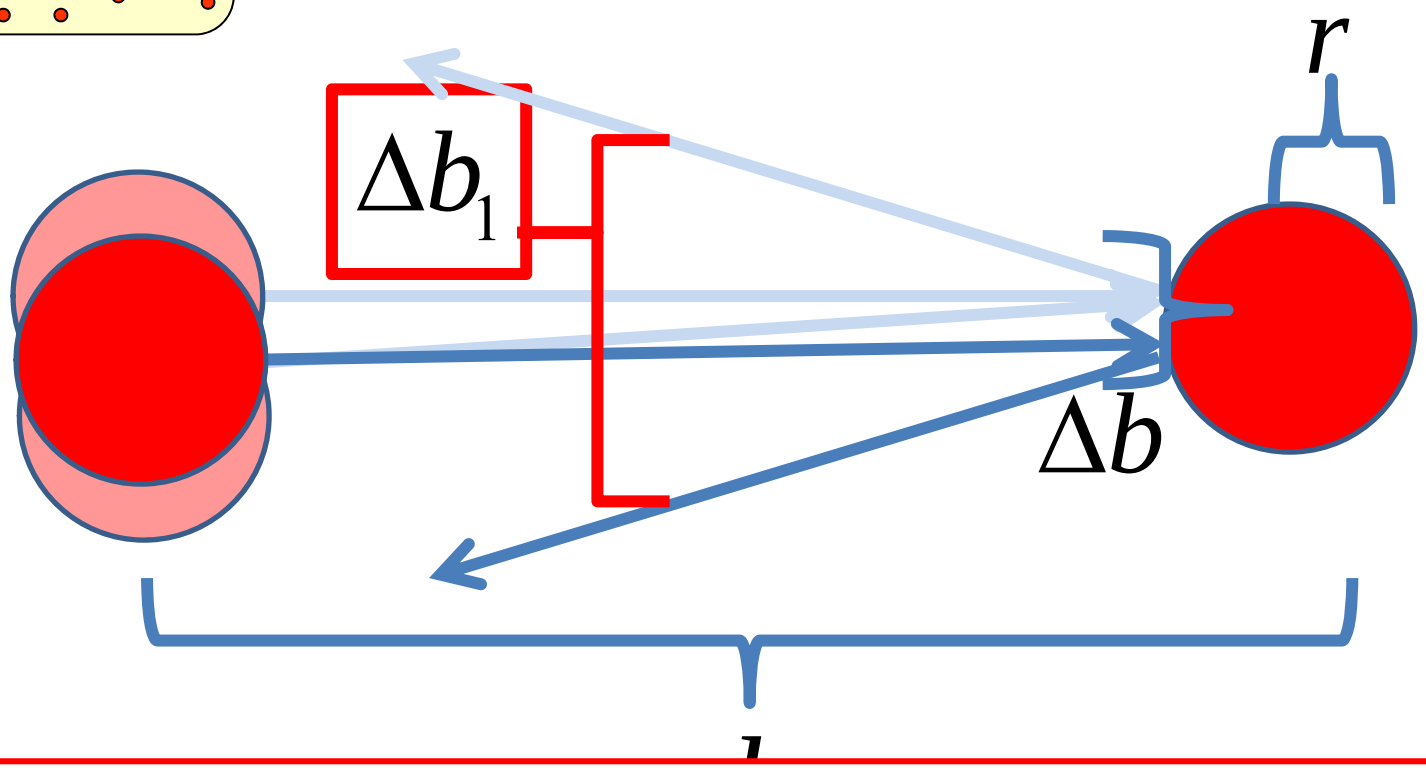
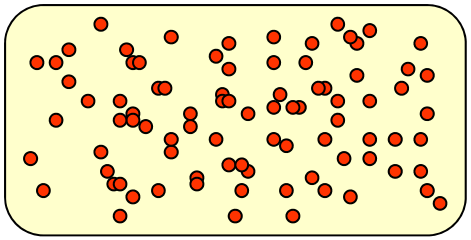


Subsequent collisions amplify the initial uncertainty (treat later collisions classically ➔ additional conservatism)



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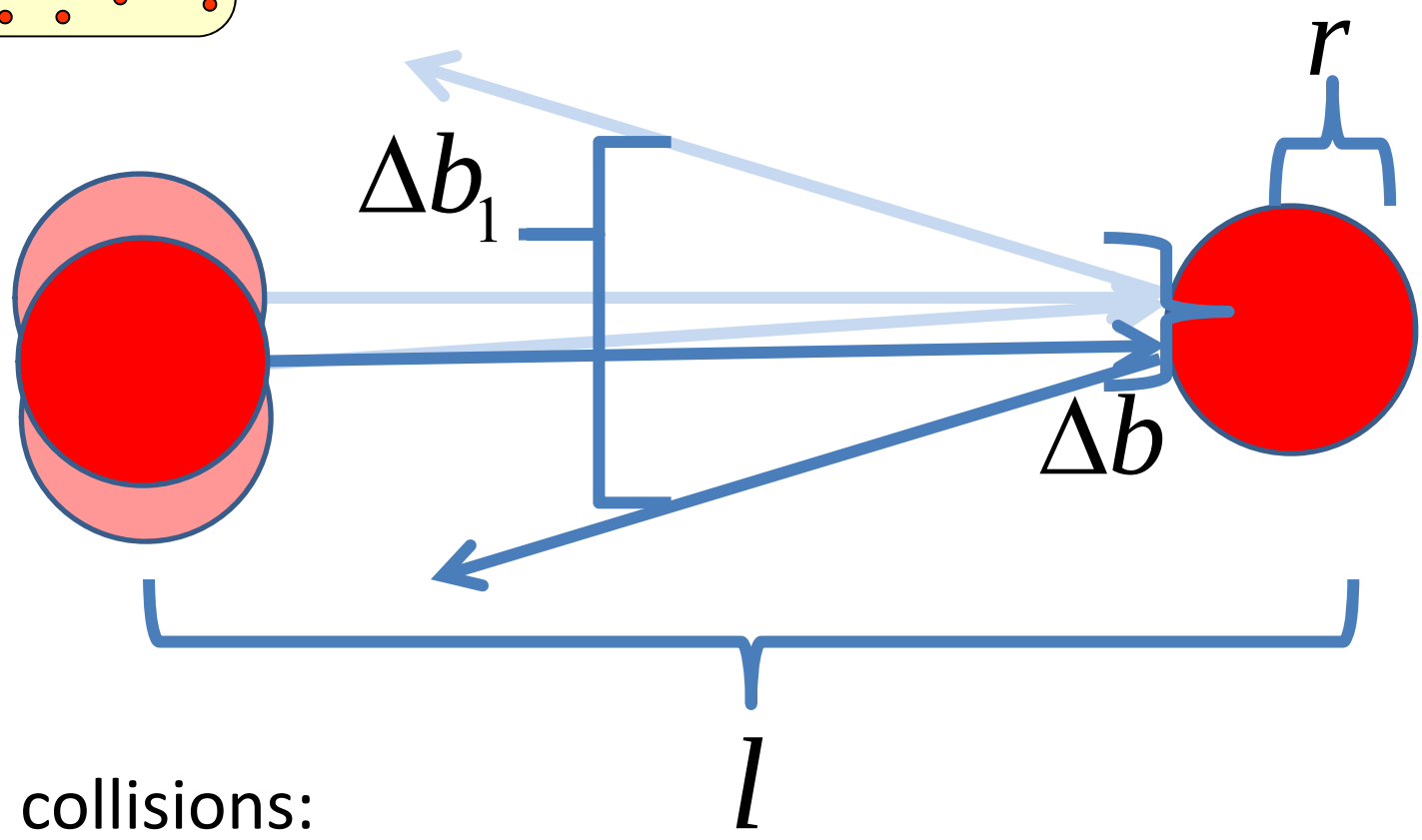
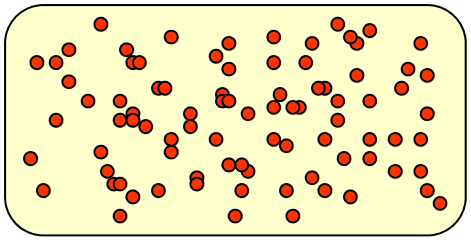


After *n* collisions:

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



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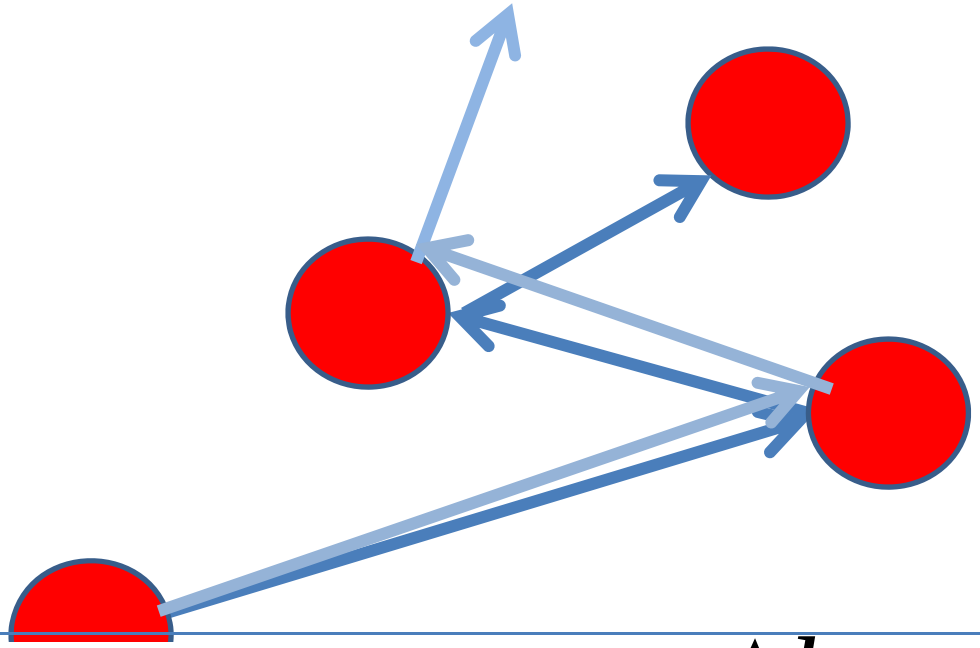

n_Q is the number of collisions so that $\Delta b_{n_Q} = r$

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

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

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							

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

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	r	l	m	$\bar{v}$	$\lambda\!\!\!^{-}_{dB}$	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
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	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
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Quantum at every collision

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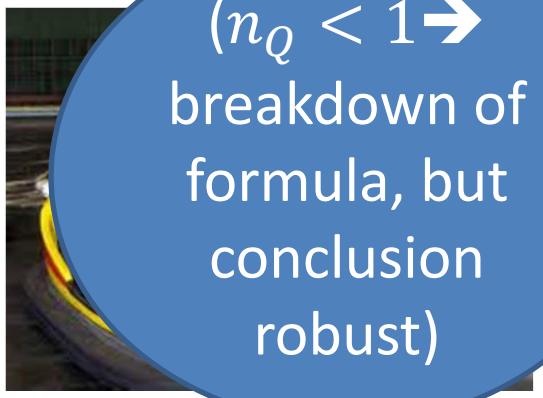
Quantum at every collision

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



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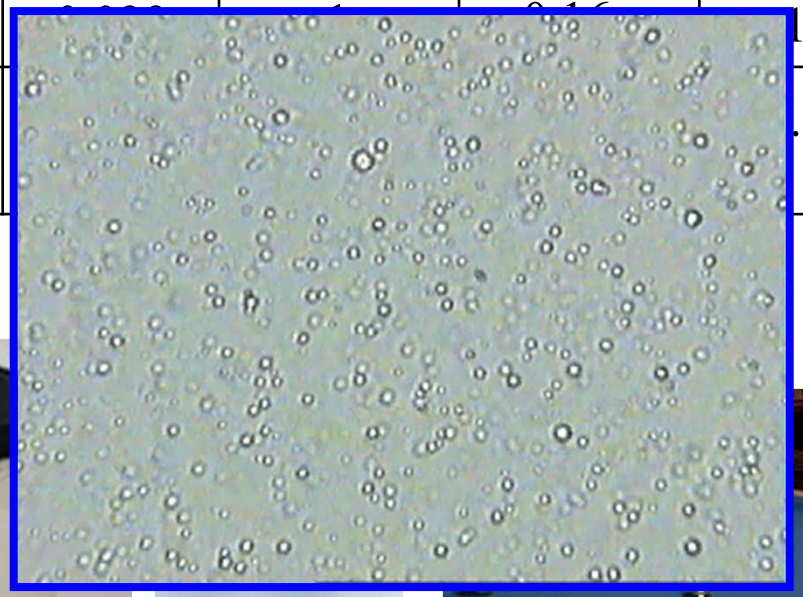
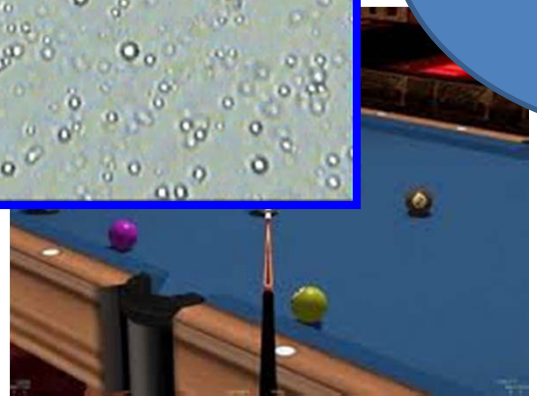
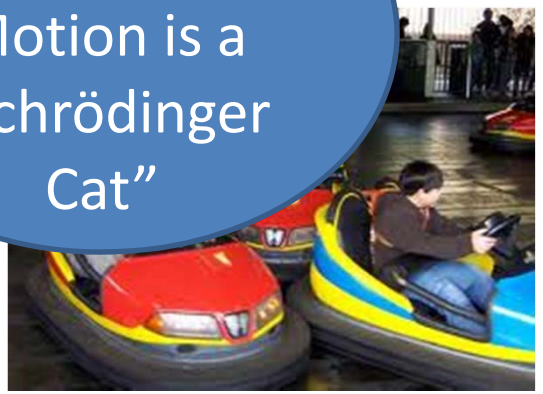
Billiards					6.6×10^{-34}	5.1	
Bumper Car				.5			







Quantum at every collision

Every Brownian Motion is a "Schrödinger Cat"

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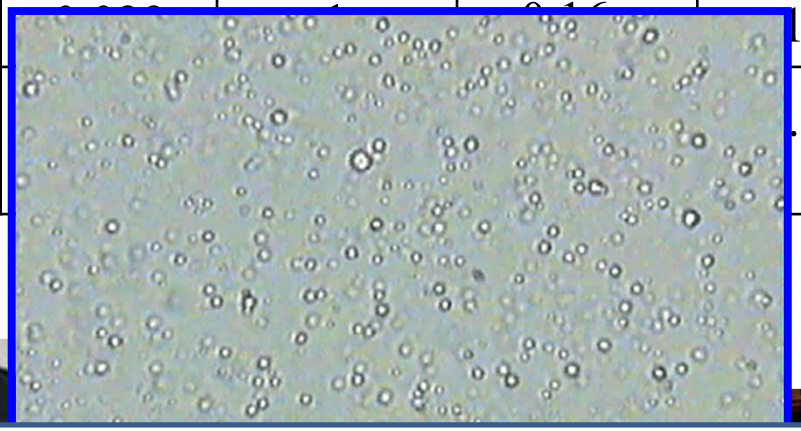
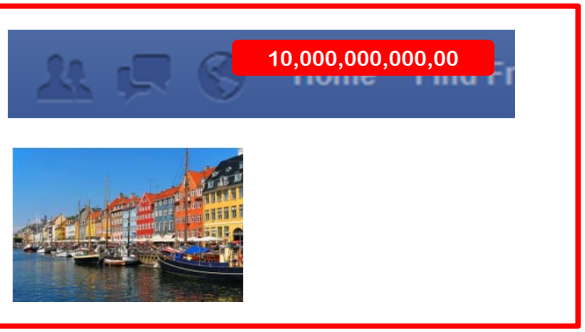


Quantum at every collision

Every Brownian Motion is a "Schrödinger

(independent of "interpretation")



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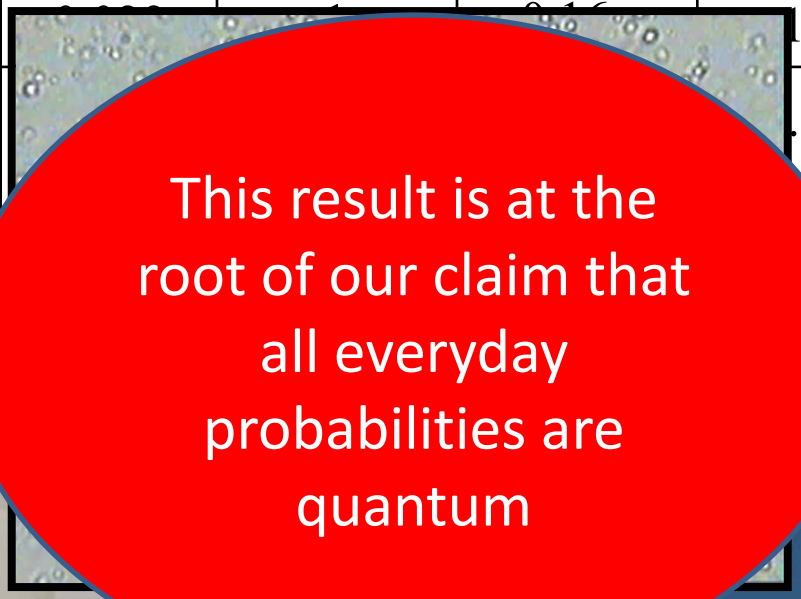
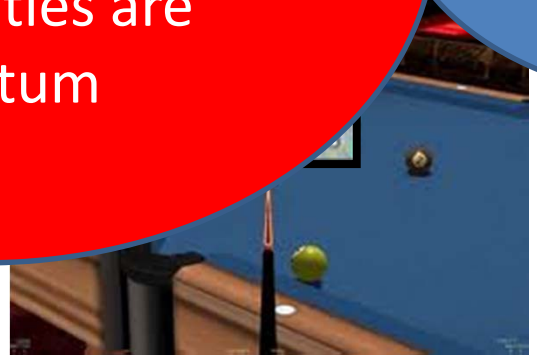
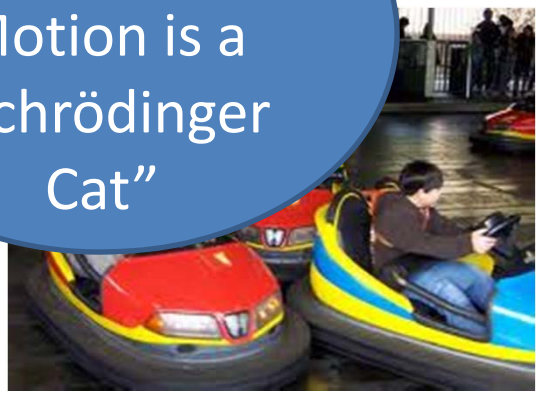
Bumper Car				.5	1		





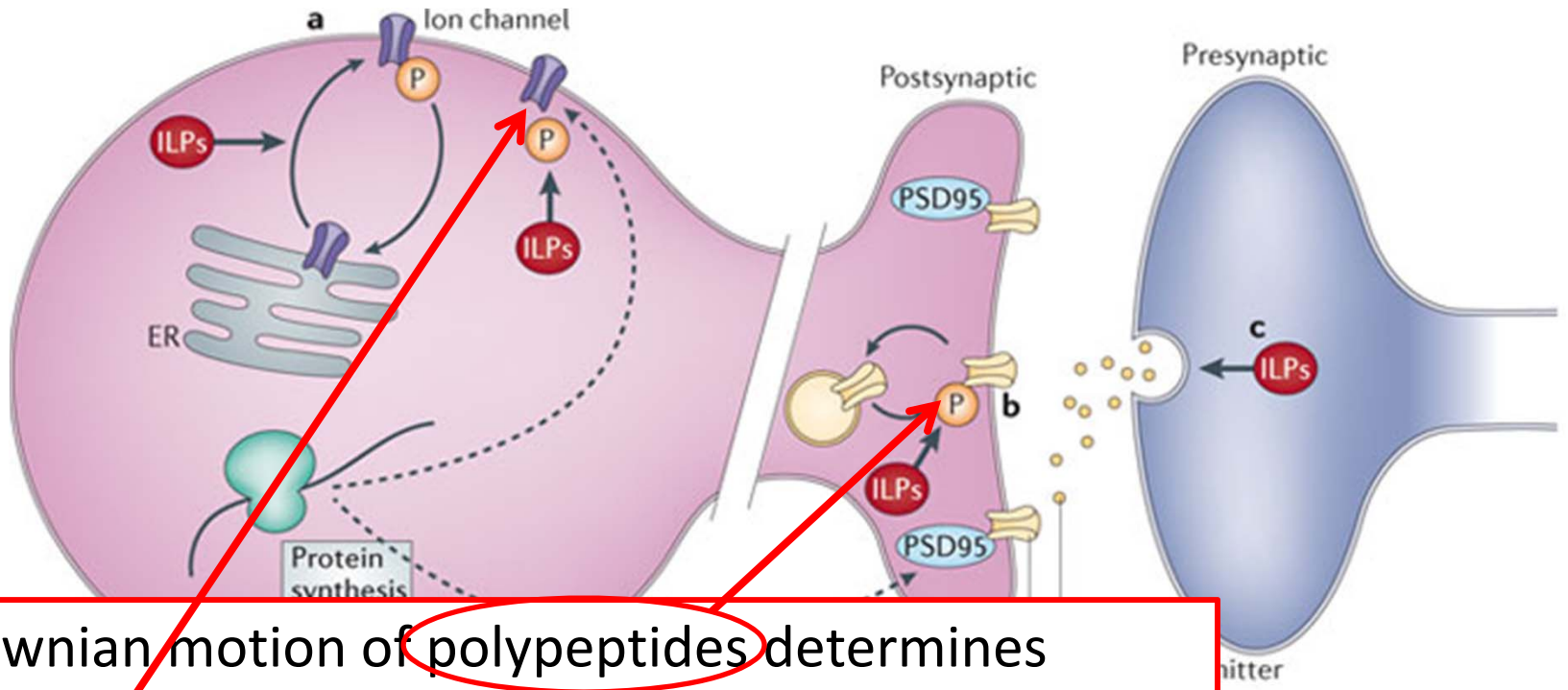


This result is at the root of our claim that all everyday probabilities are quantum

Every Brownian Motion is a "Schrödinger Cat"

Quantum at every collision

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

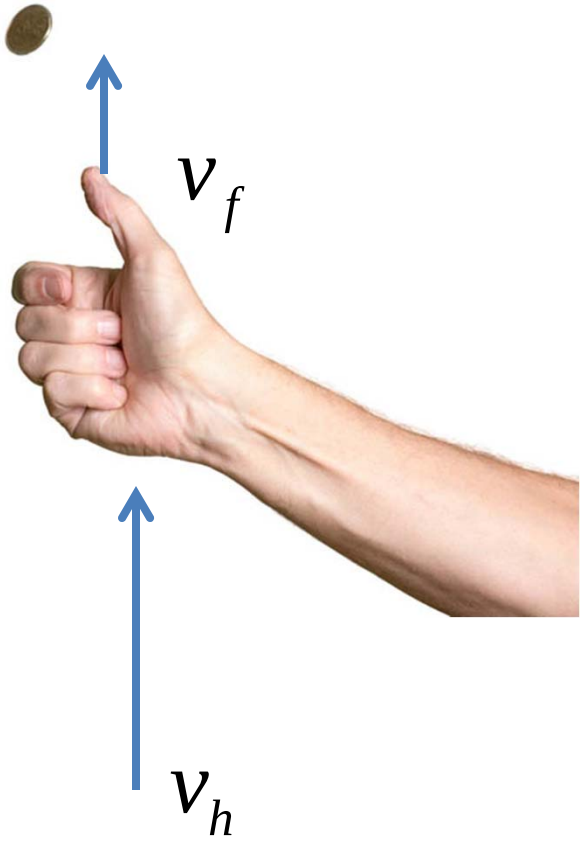
Analysis of coin flip

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

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

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

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



Coin diameter $= d$

Using:

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

$d = 0.01m$

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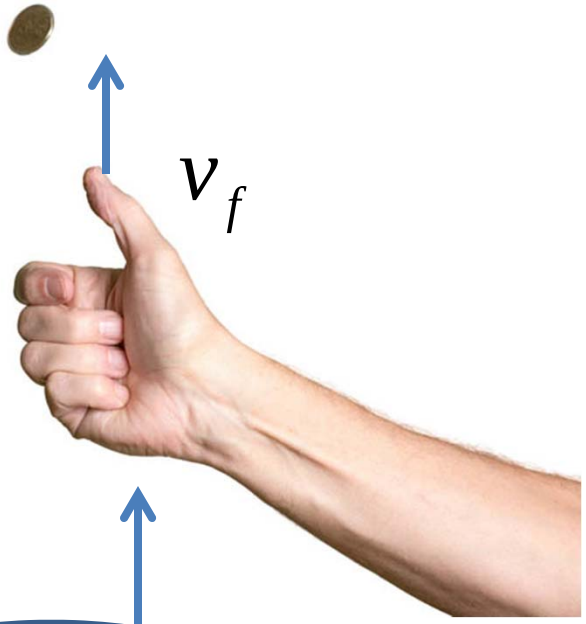

50-50 coin flip probabilities are a derivable quantum result

Using:

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

$d = 0.01m$

Analysis of coin flip

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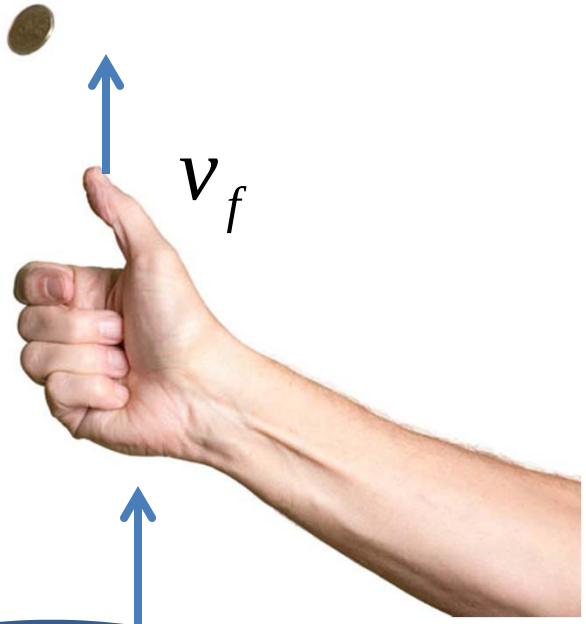

Usin

d =

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

50-50 coin flip probabilities are a derivable quantum result

Analysis of coin flip

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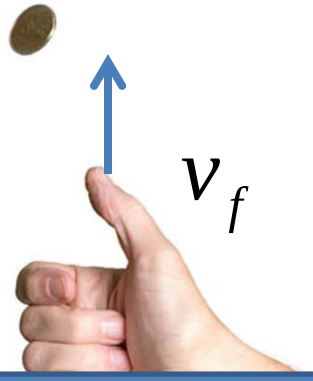

NB: Coin flip is "at the margin" of deterministic vs random: Increasing *d* or deceasing v_h can reduce δN substantially

v_h

Coin diameter $= d$

Using:

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

$d = 0.01m$

Analysis of coin flip

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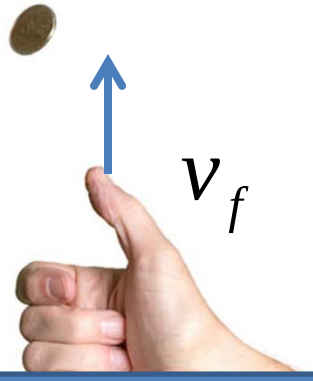

NB: Coin flip is "at the margin" of deterministic vs random: Increasing *d* or deceasing v_h can reduce δN substantially

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

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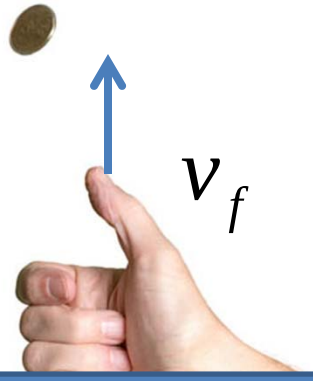
$$f = \frac{4v_f}{\pi d}$$

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



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.

Physical probabilities vs “probabilities of belief”

Physical probability: To do with physical properties of detector etc

Bayes:

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

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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

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Some further thoughts:

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- 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!
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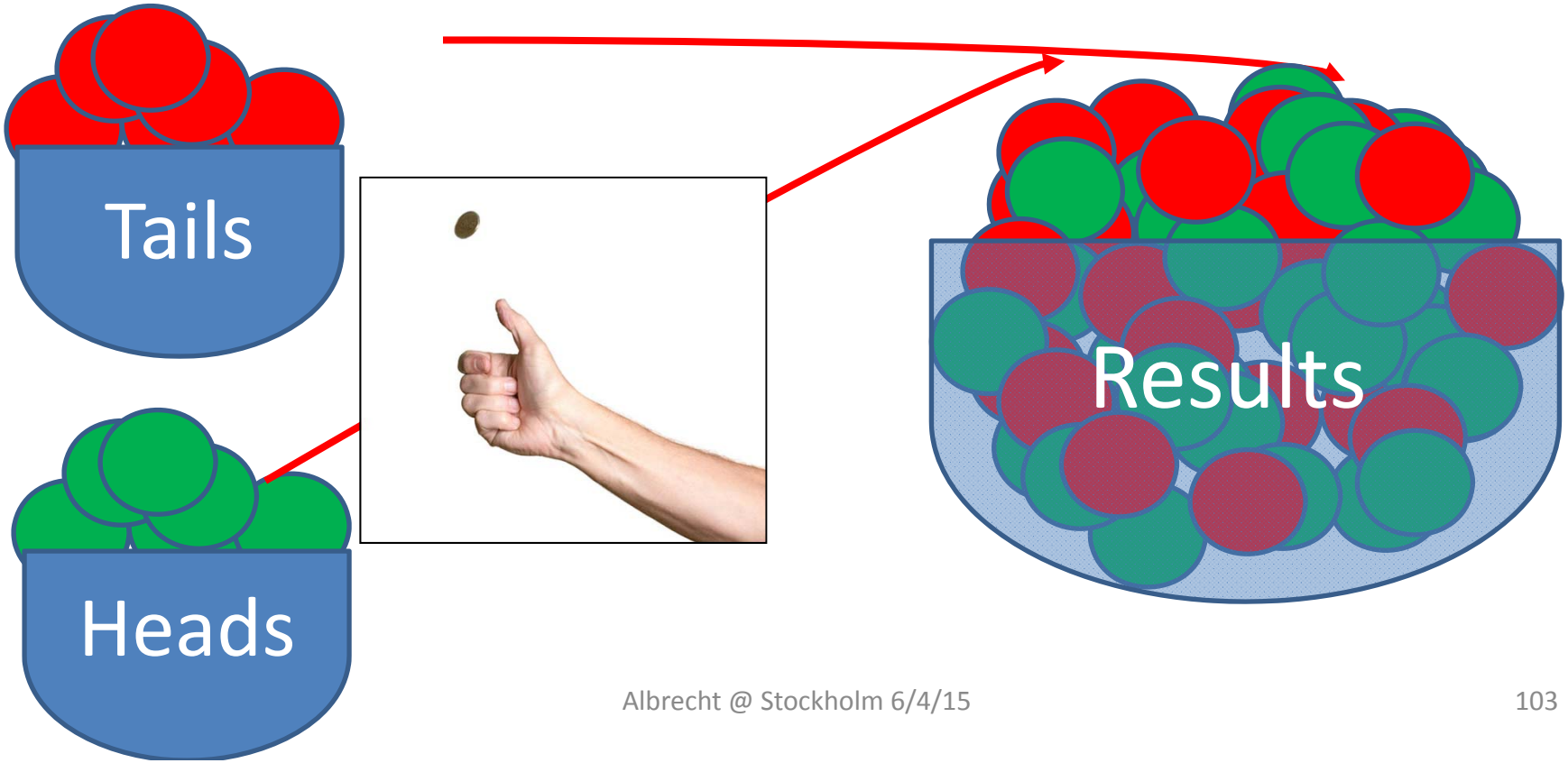

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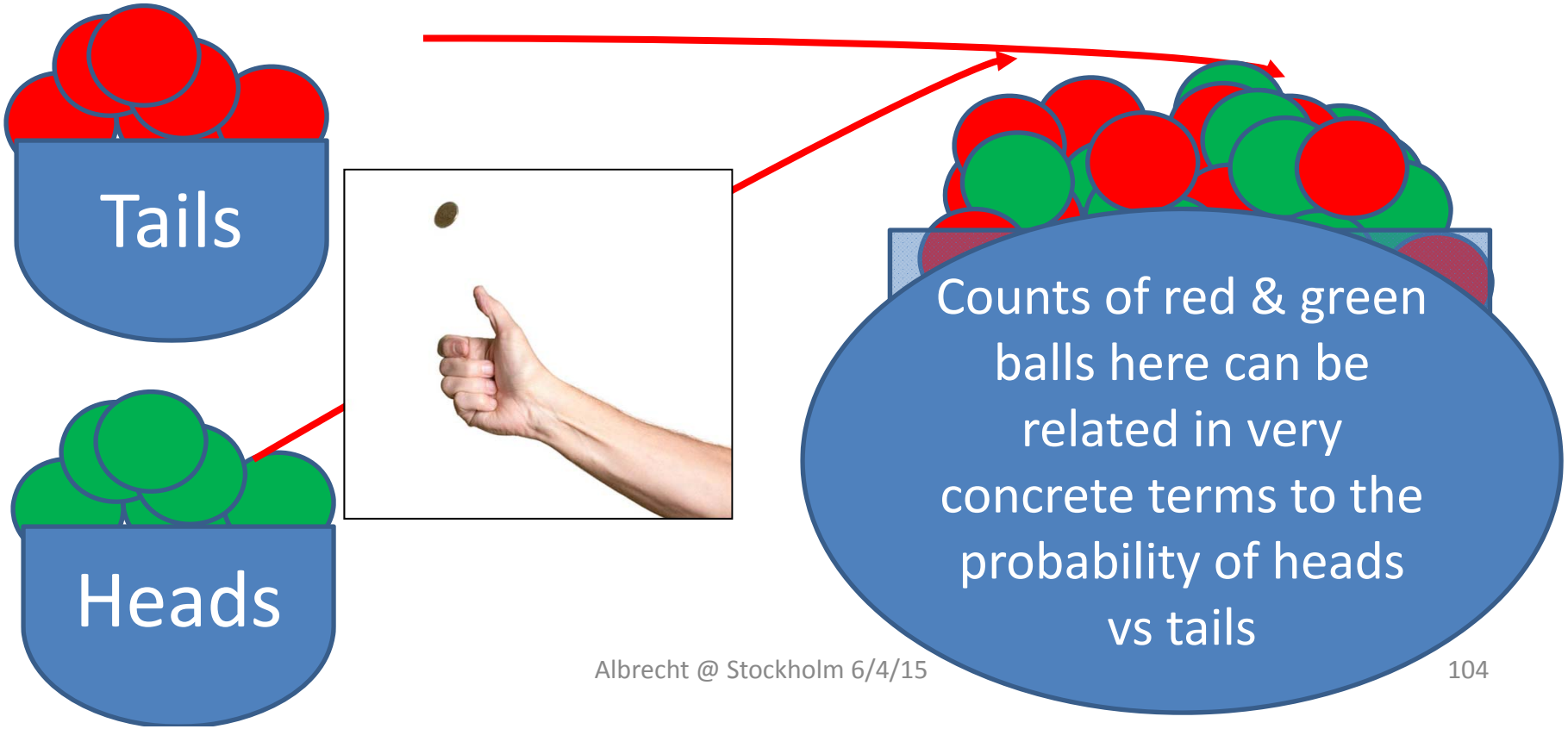

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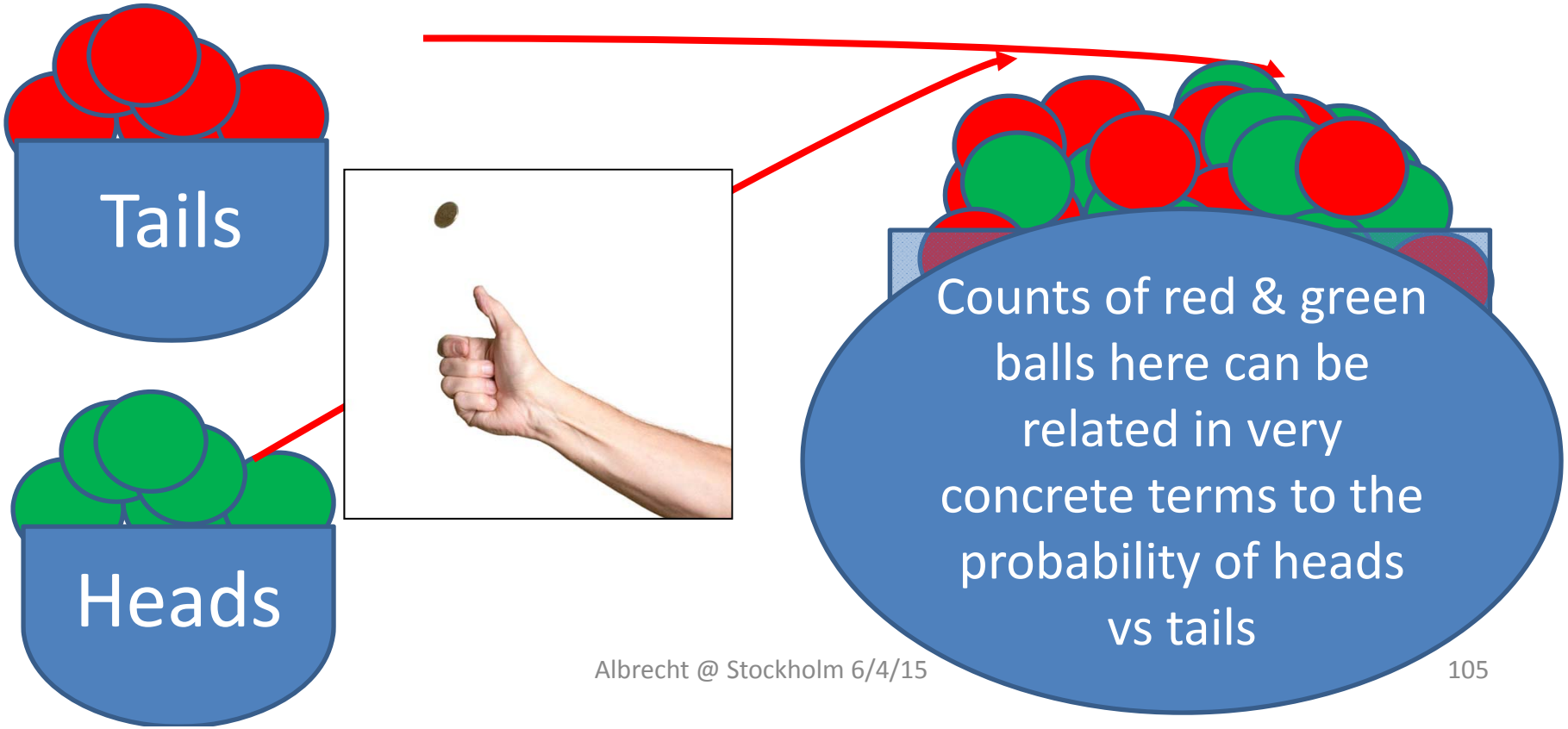

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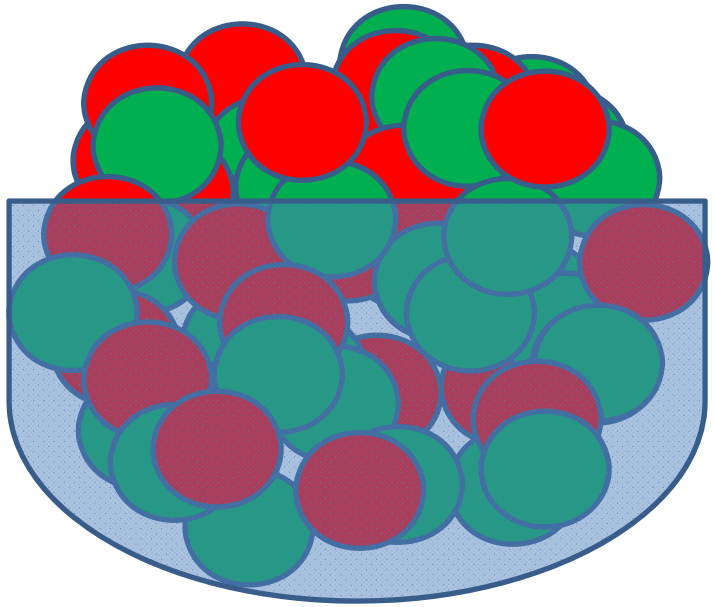

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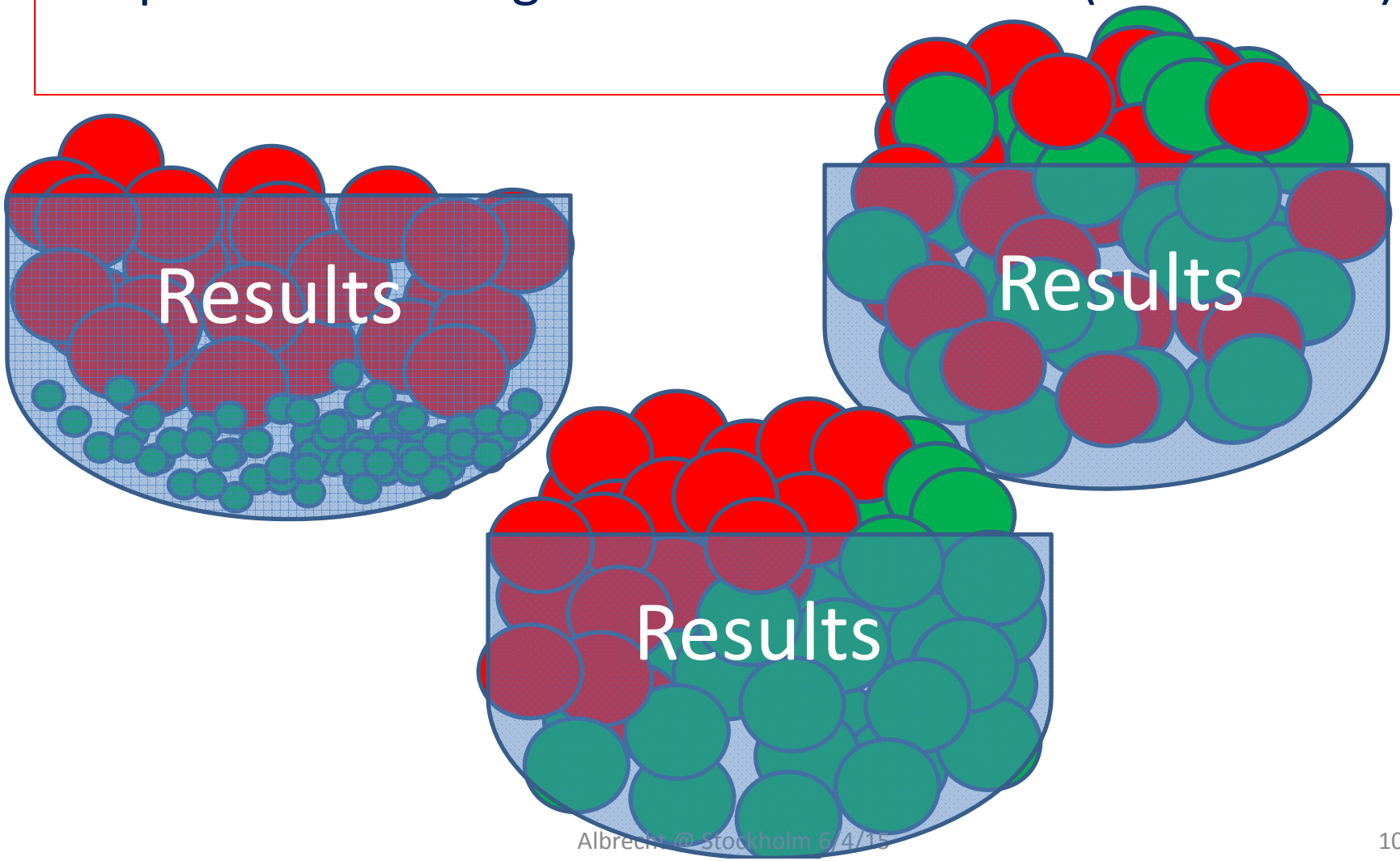

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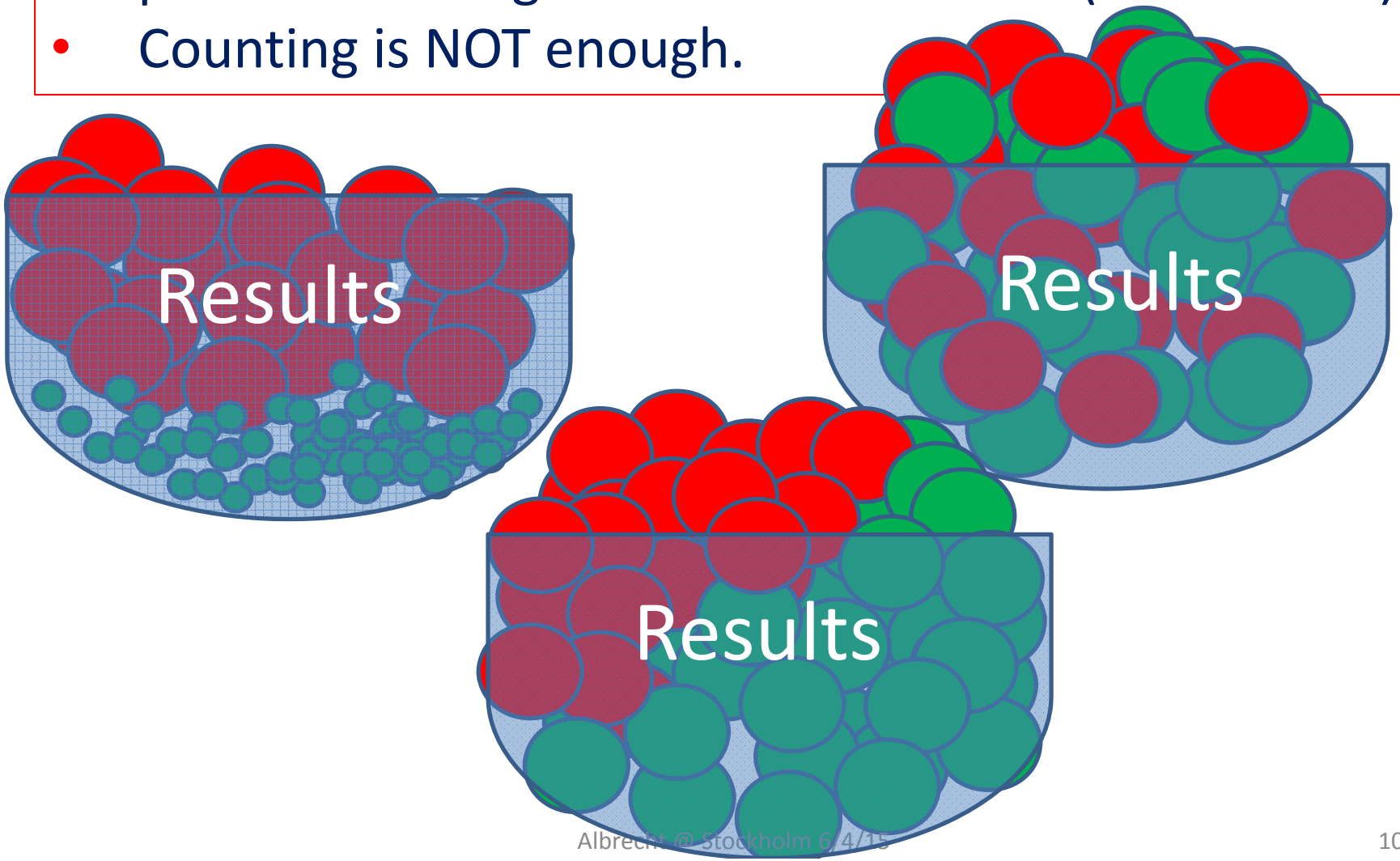

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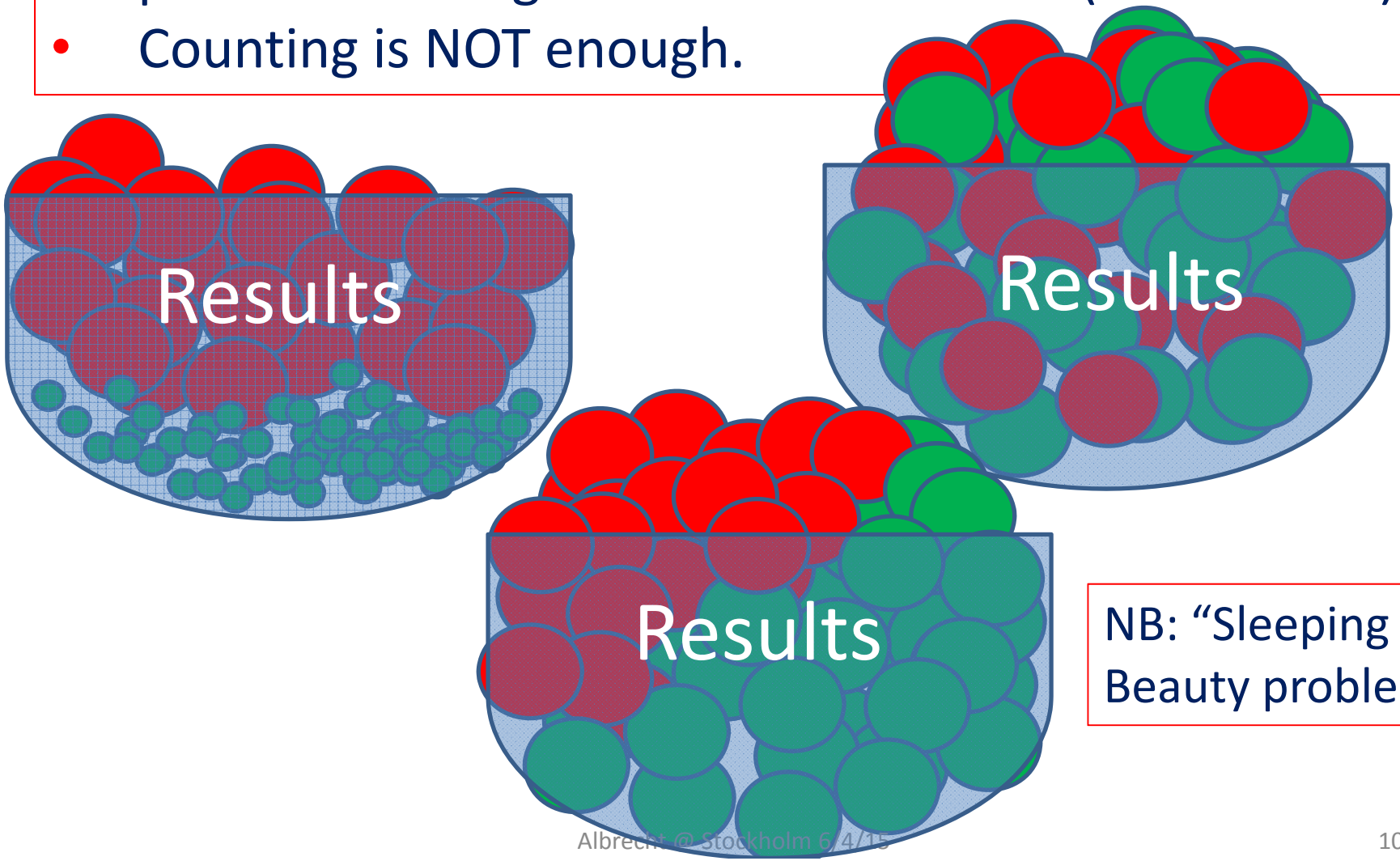

NB: "Sleeping Beauty problem"

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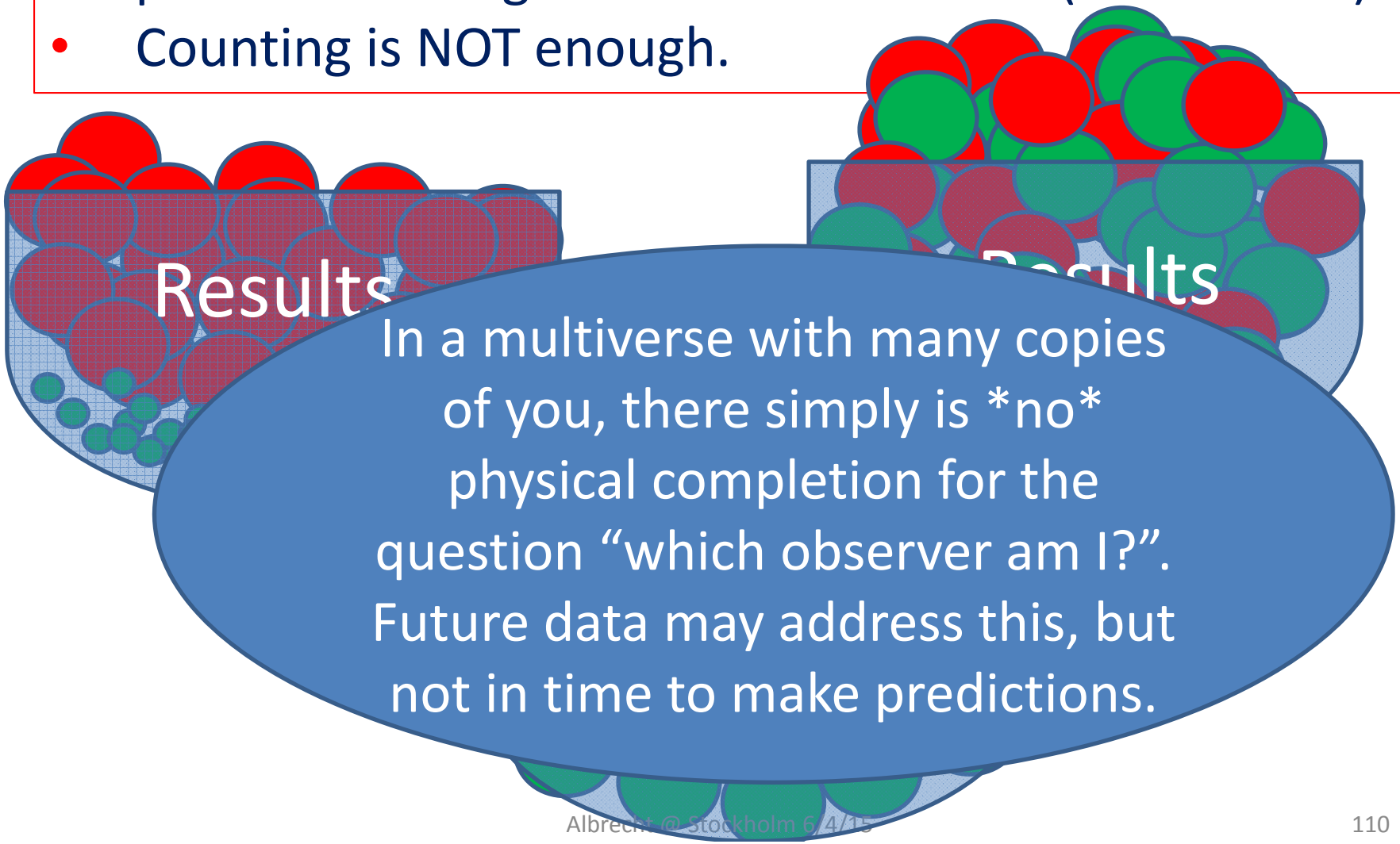

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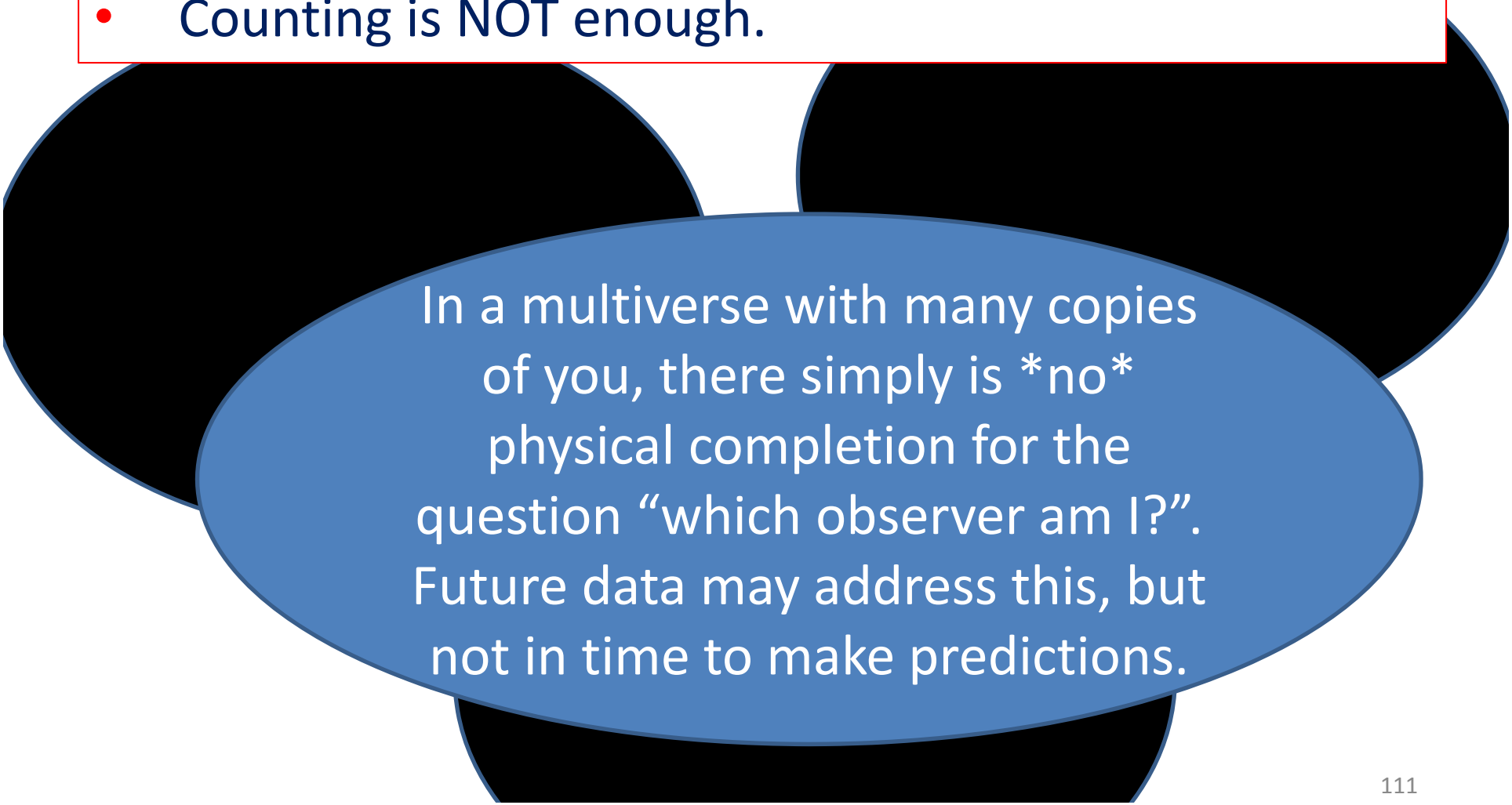

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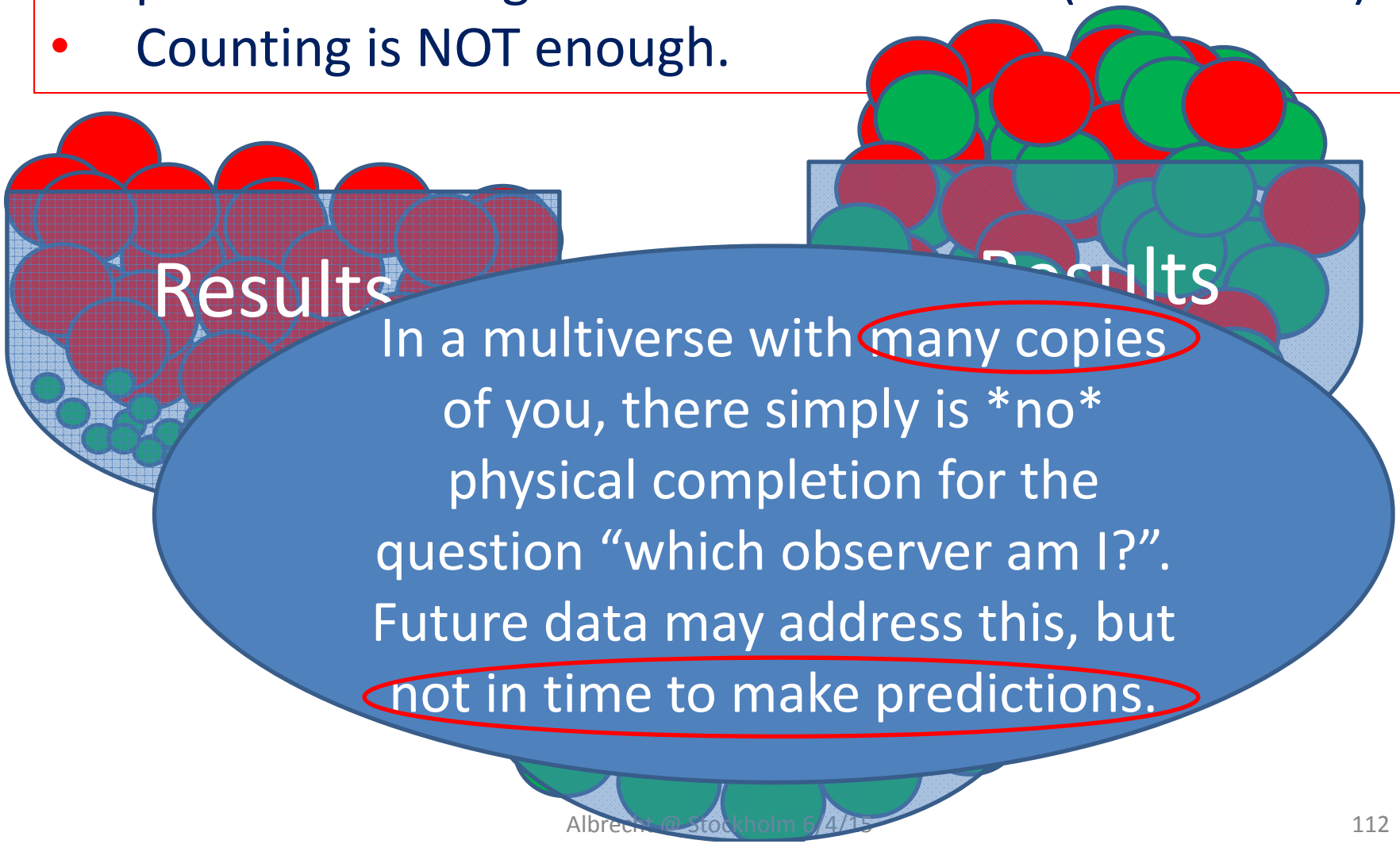

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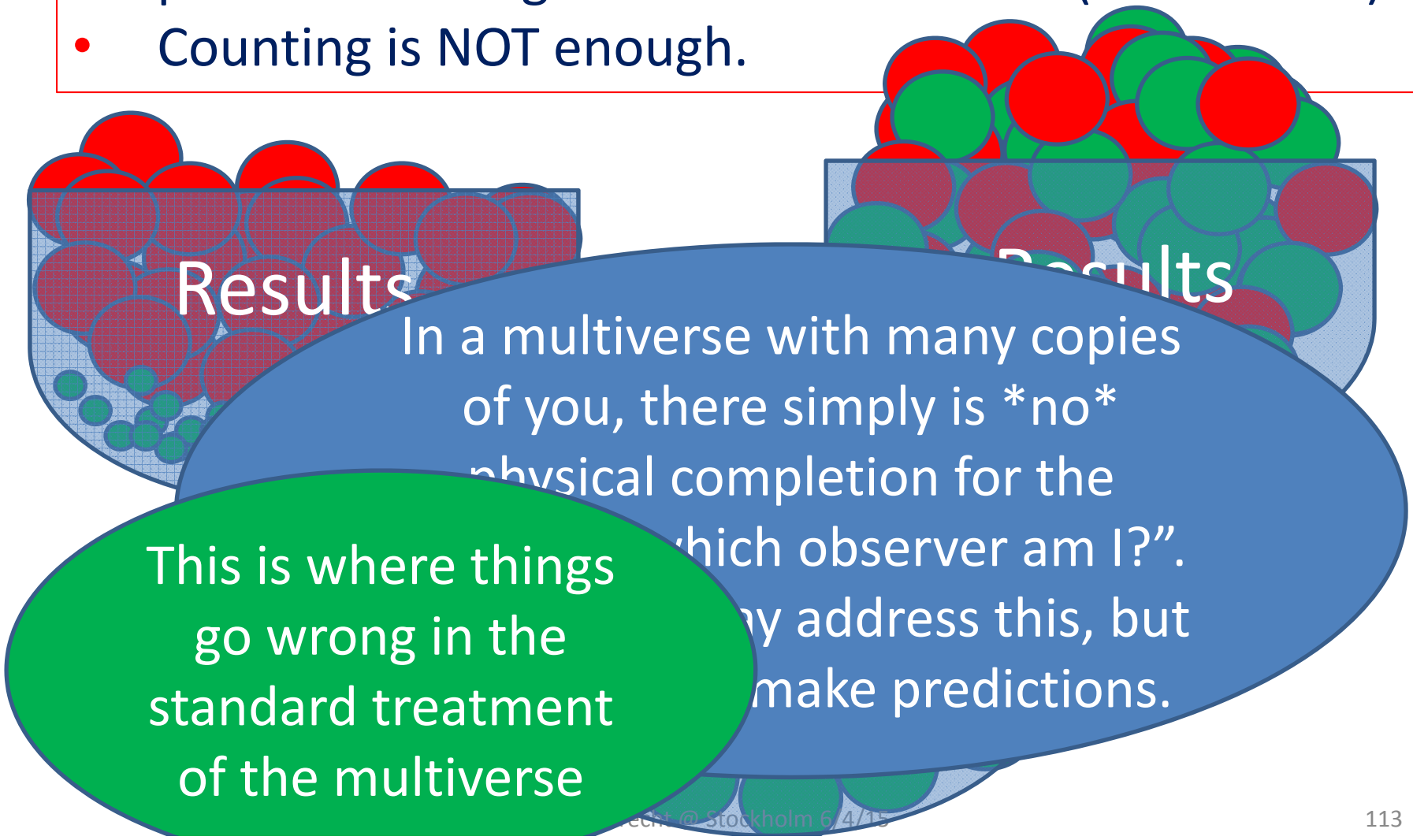

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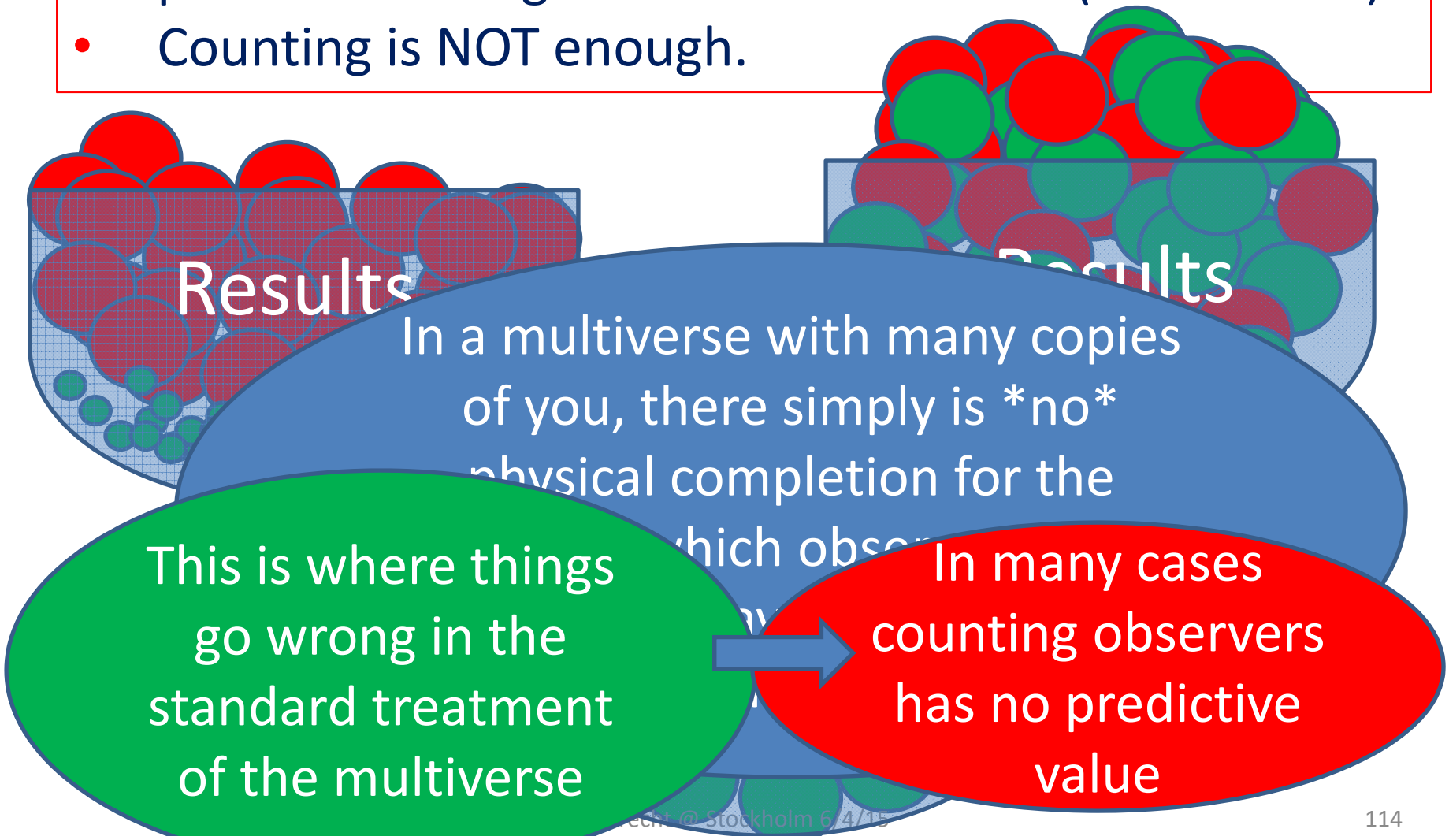

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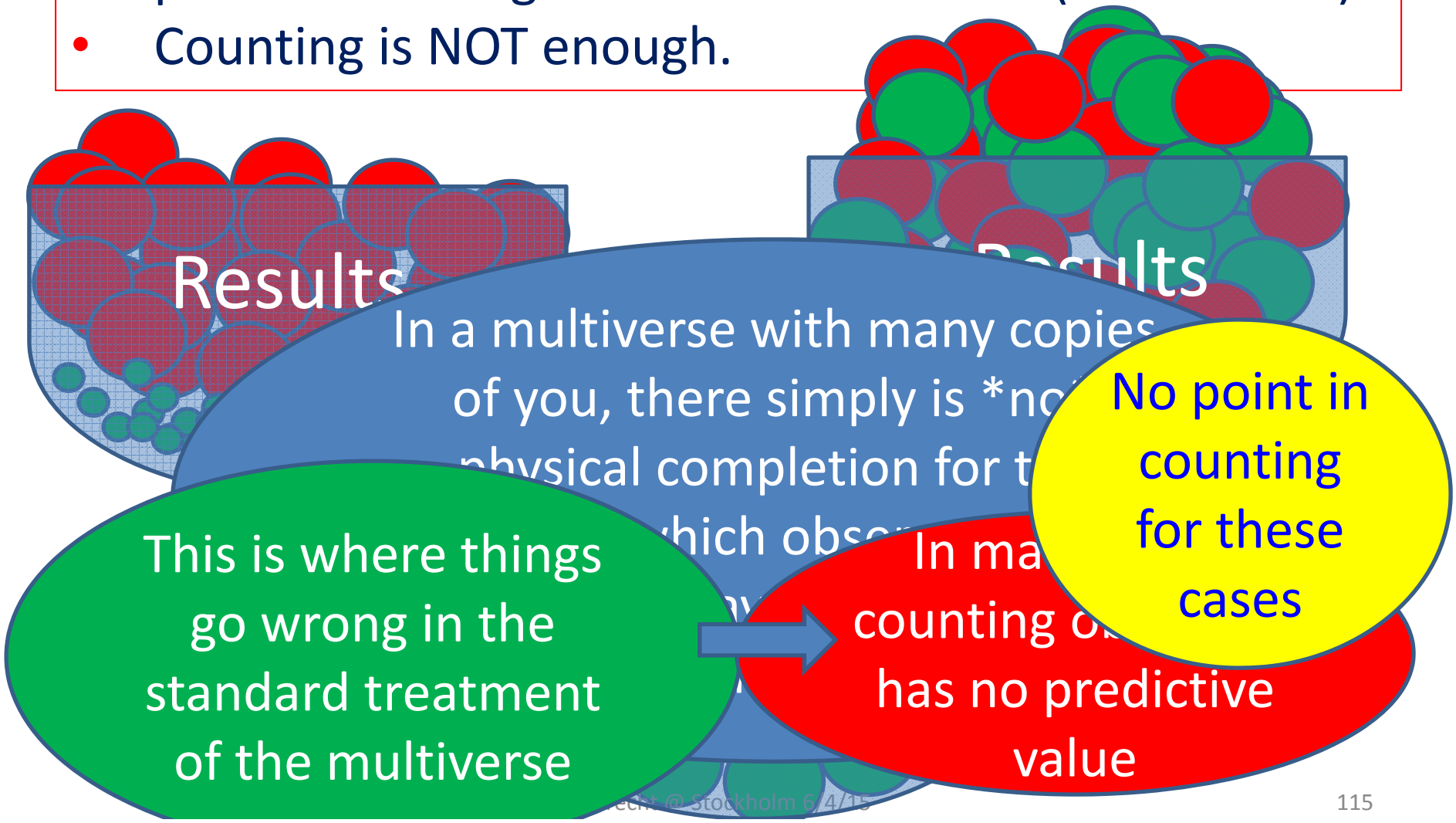

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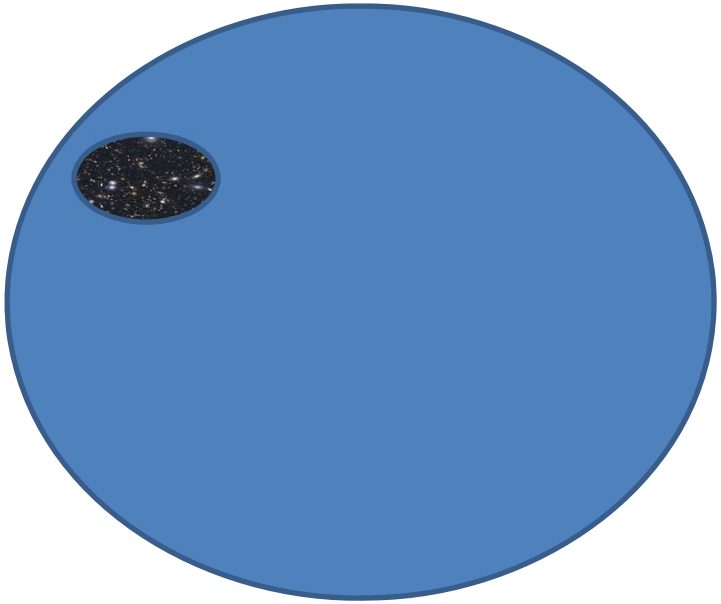
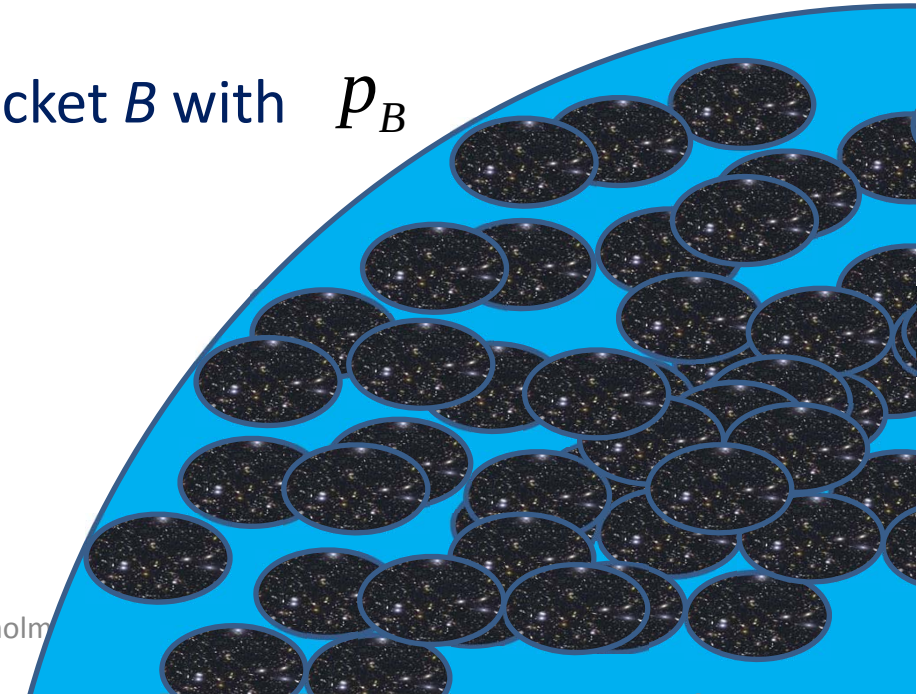
1) No “volume factors”
2) Boltzmann Brain problem reduced
3) No “youngness/end of time” problem

Pocket *A* with p_A



Pocket *B* with p_B



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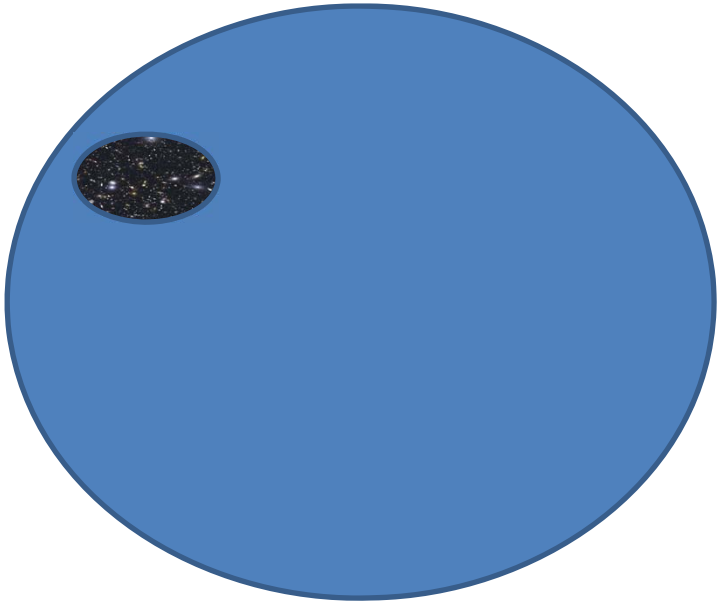
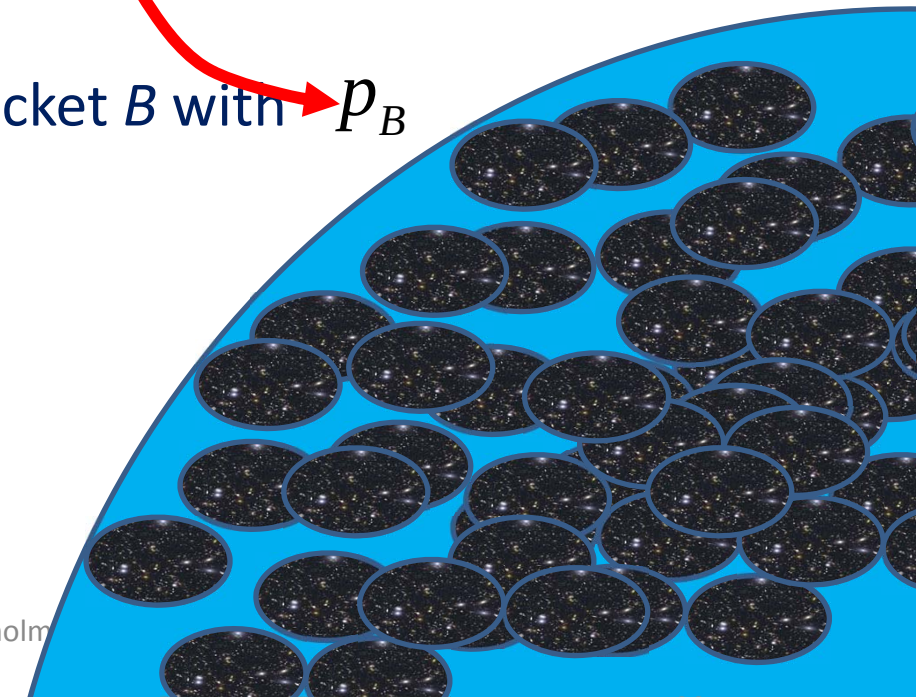
(from quantum branching ratio)

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) does count

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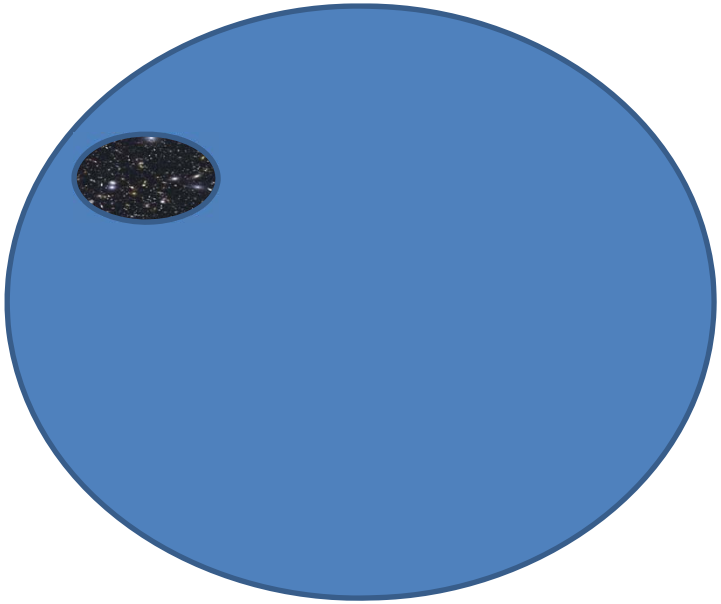

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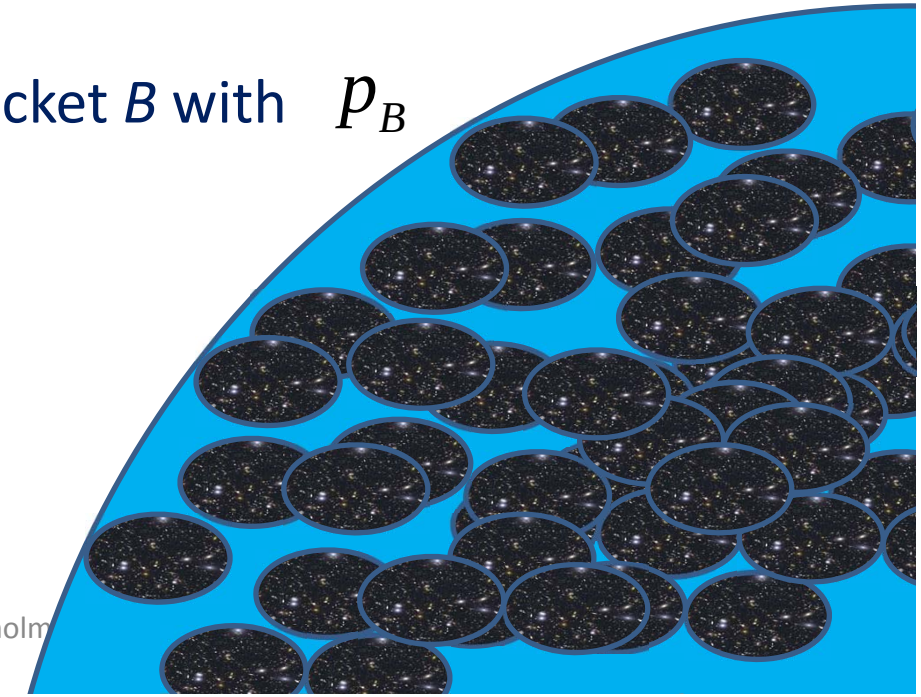

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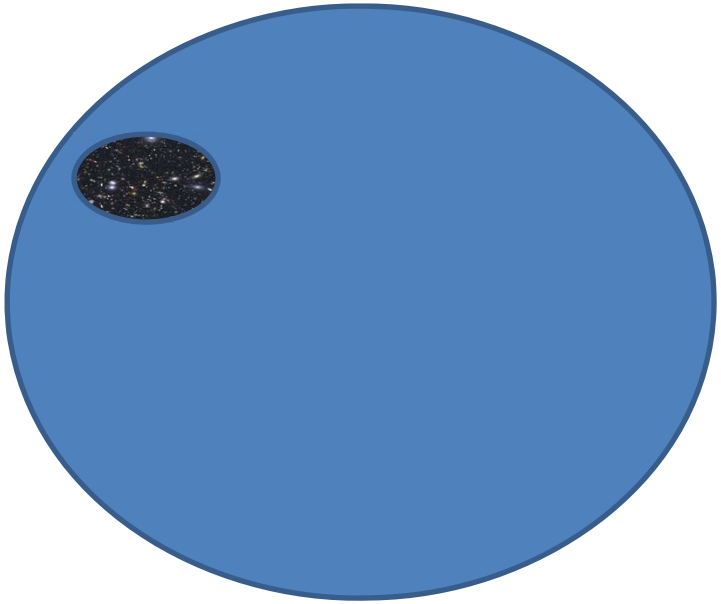

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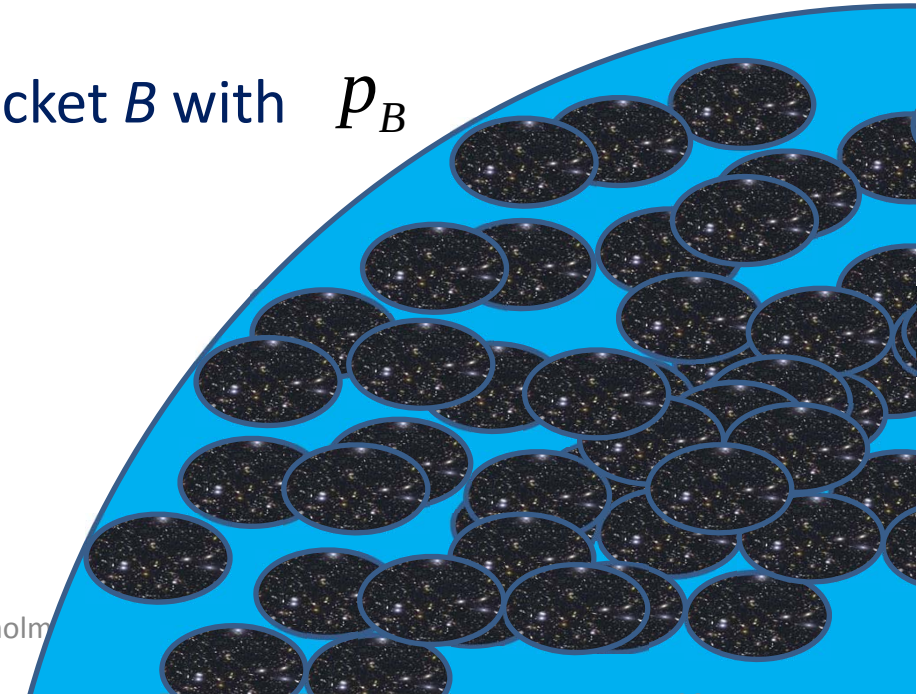

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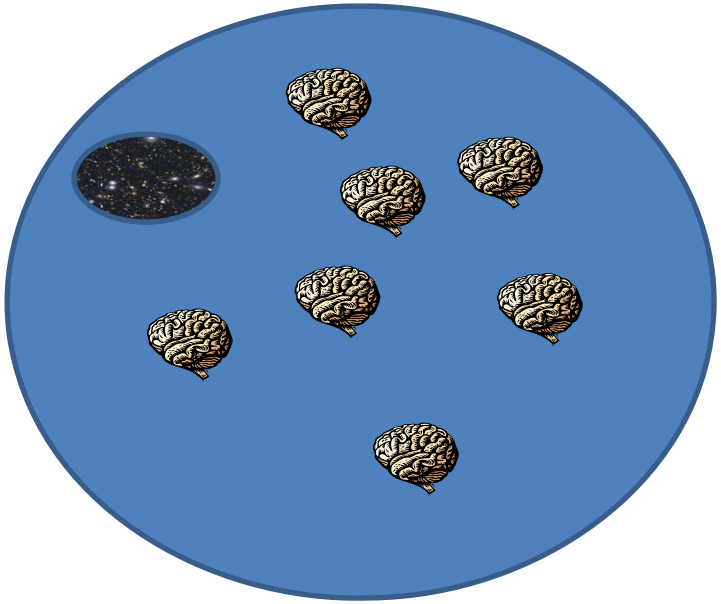

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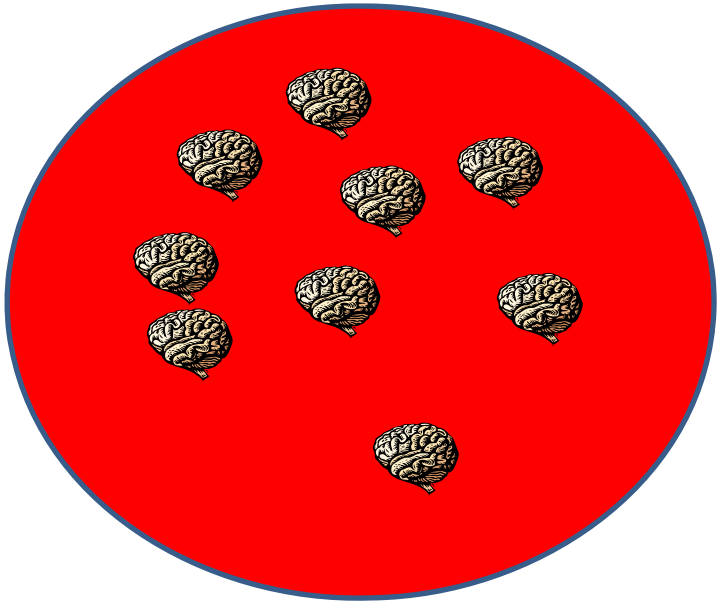

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This model has no “Boltzmann Brain” problem as long as p_A / p_B Is not too small

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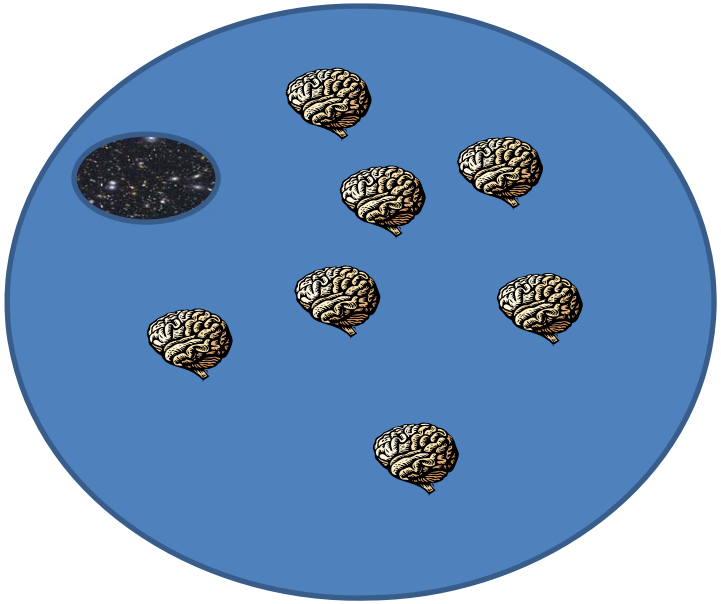

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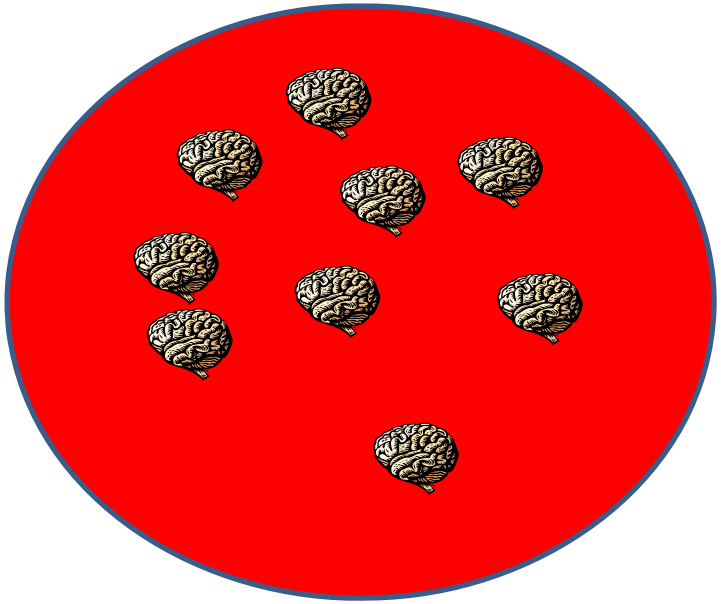

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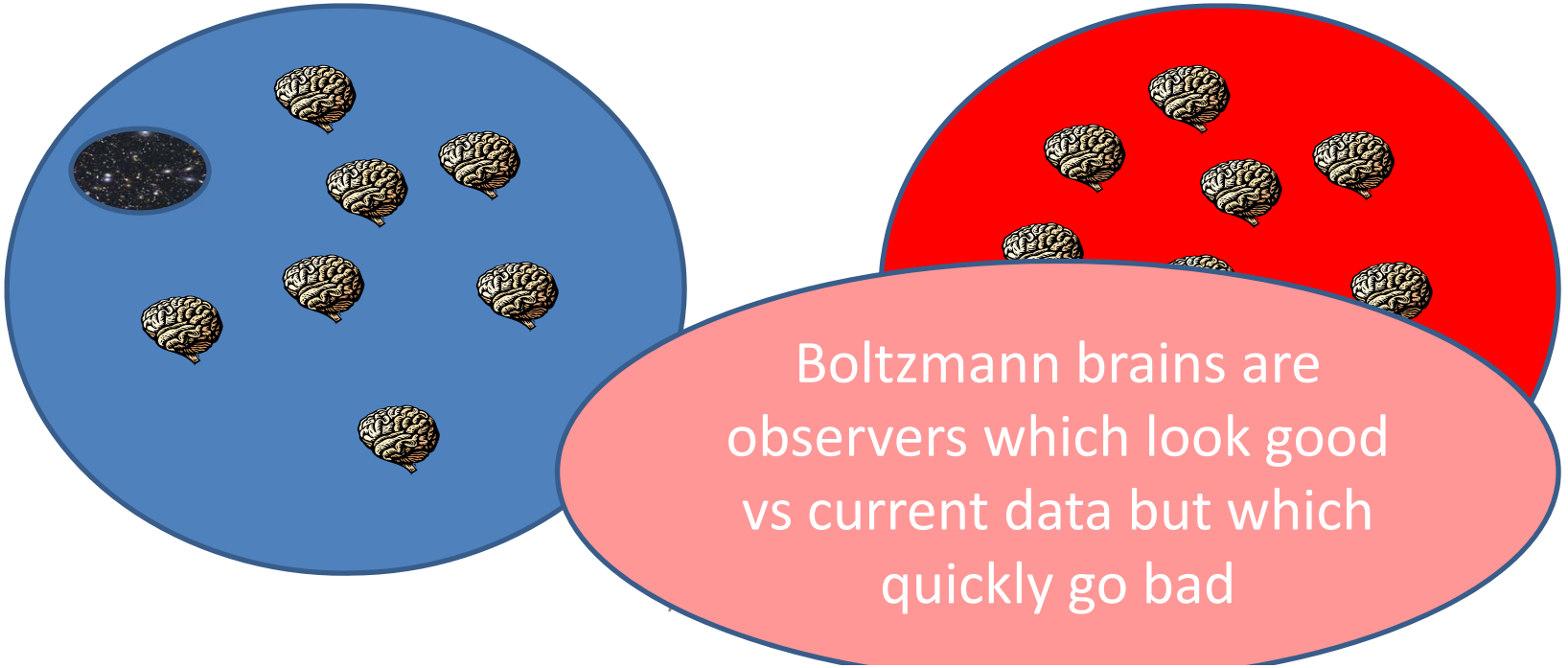

Boltzmann brains are observers which look good vs current data but which quickly go bad

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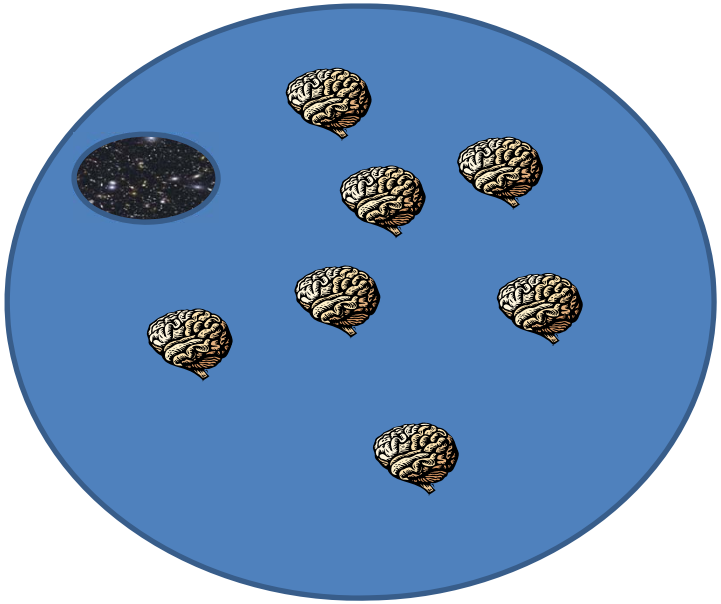

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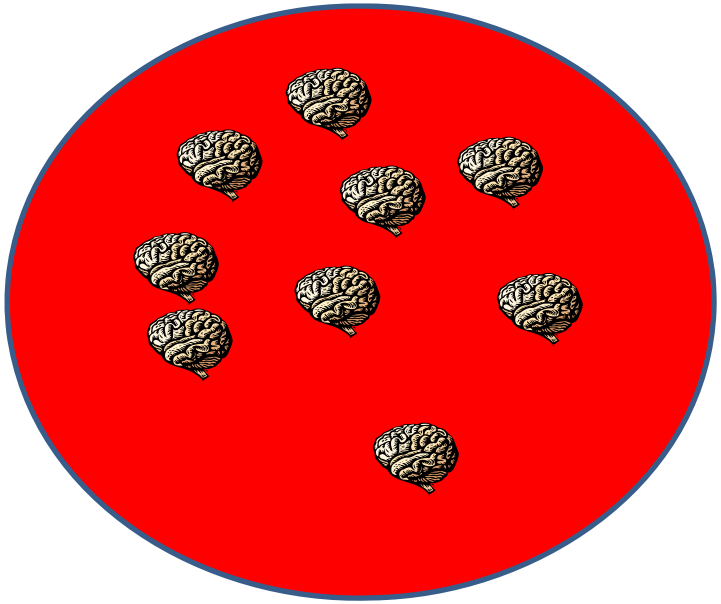

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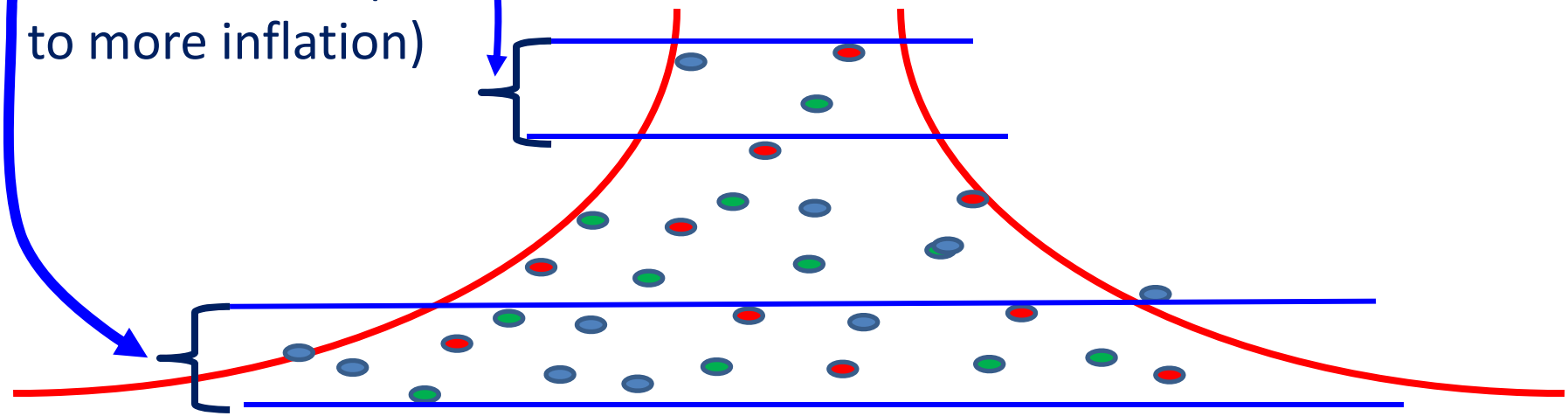
More pocket universes produced later vs earlier (due to more inflation)



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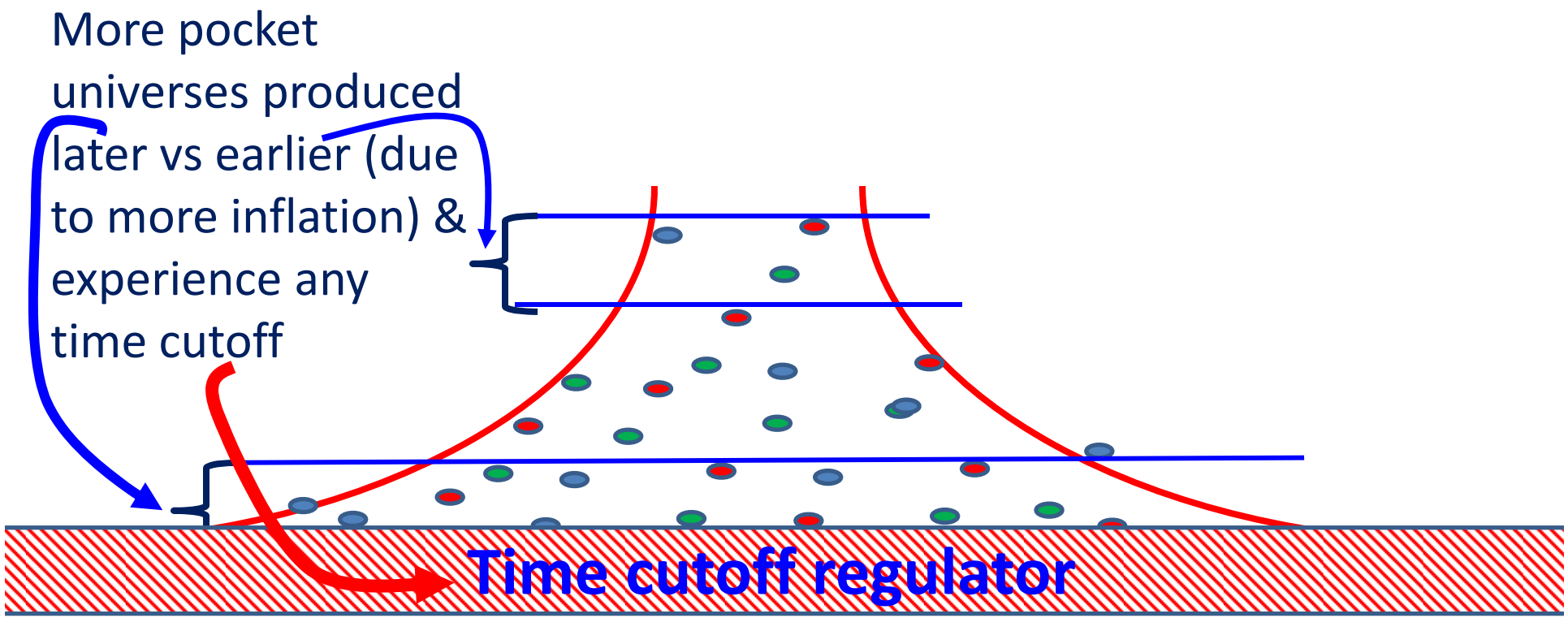

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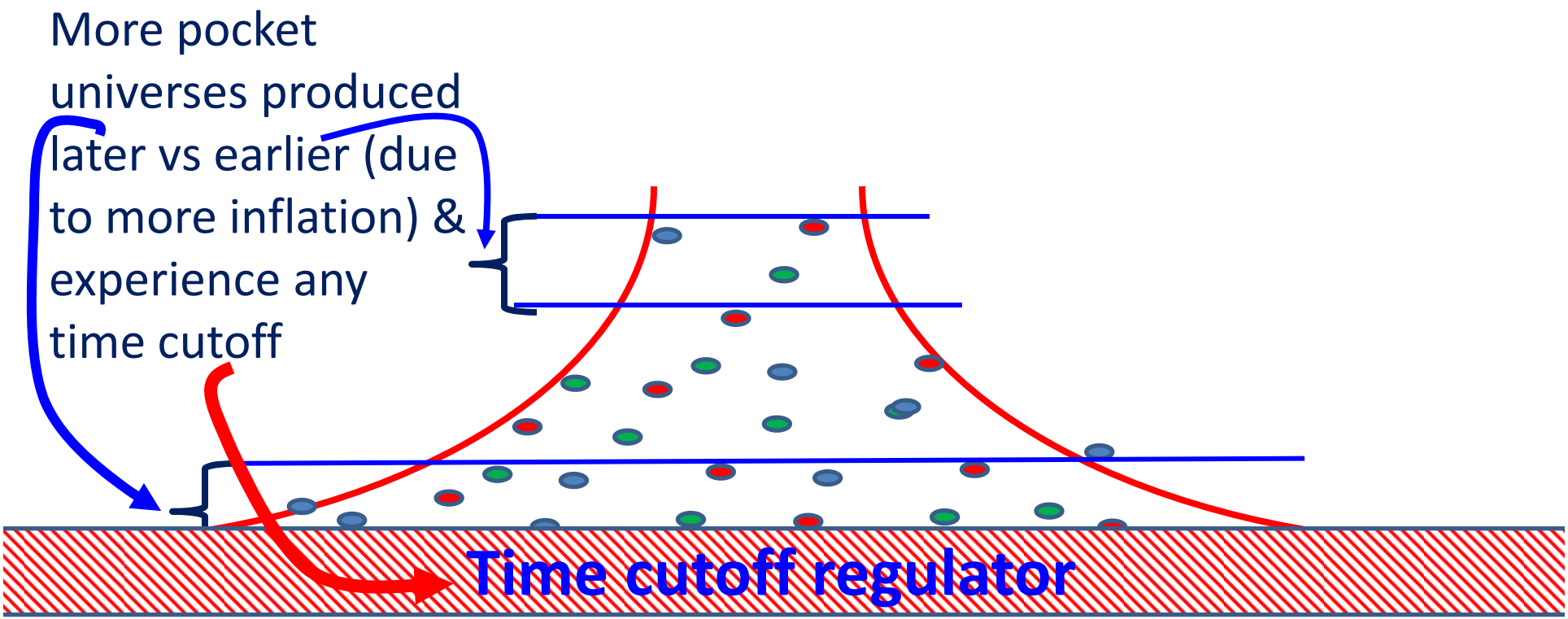

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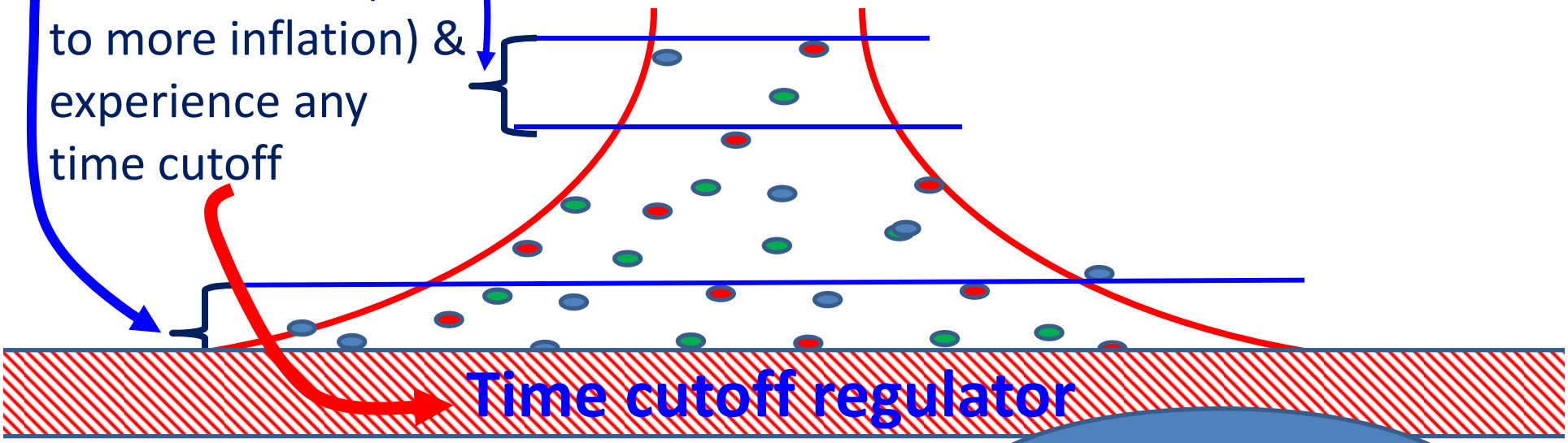
More pocket universes produced later vs earlier (due to more inflation) & experience any time cutoff



See also Guth & Vanchurin

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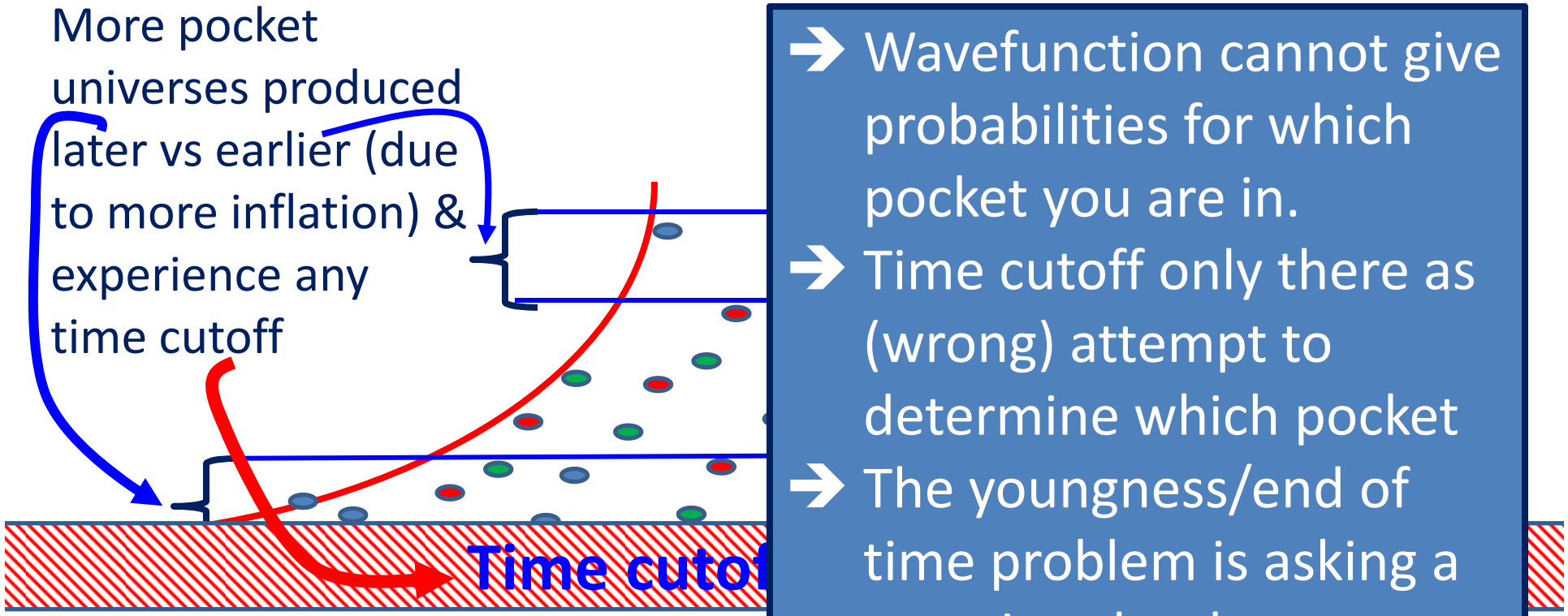

- ➔ Wavefunction cannot give probabilities for which pocket you are in.
- ➔ Time cutoff only there as (wrong) attempt to determine which pocket
- ➔ The youngness/end of time problem is asking a question the theory cannot answer

Conclusions

1) All practically applicable probabilities are of physics (quantum) origin.
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Landscape OK too

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Clashes with my work on the “clock ambiguity”

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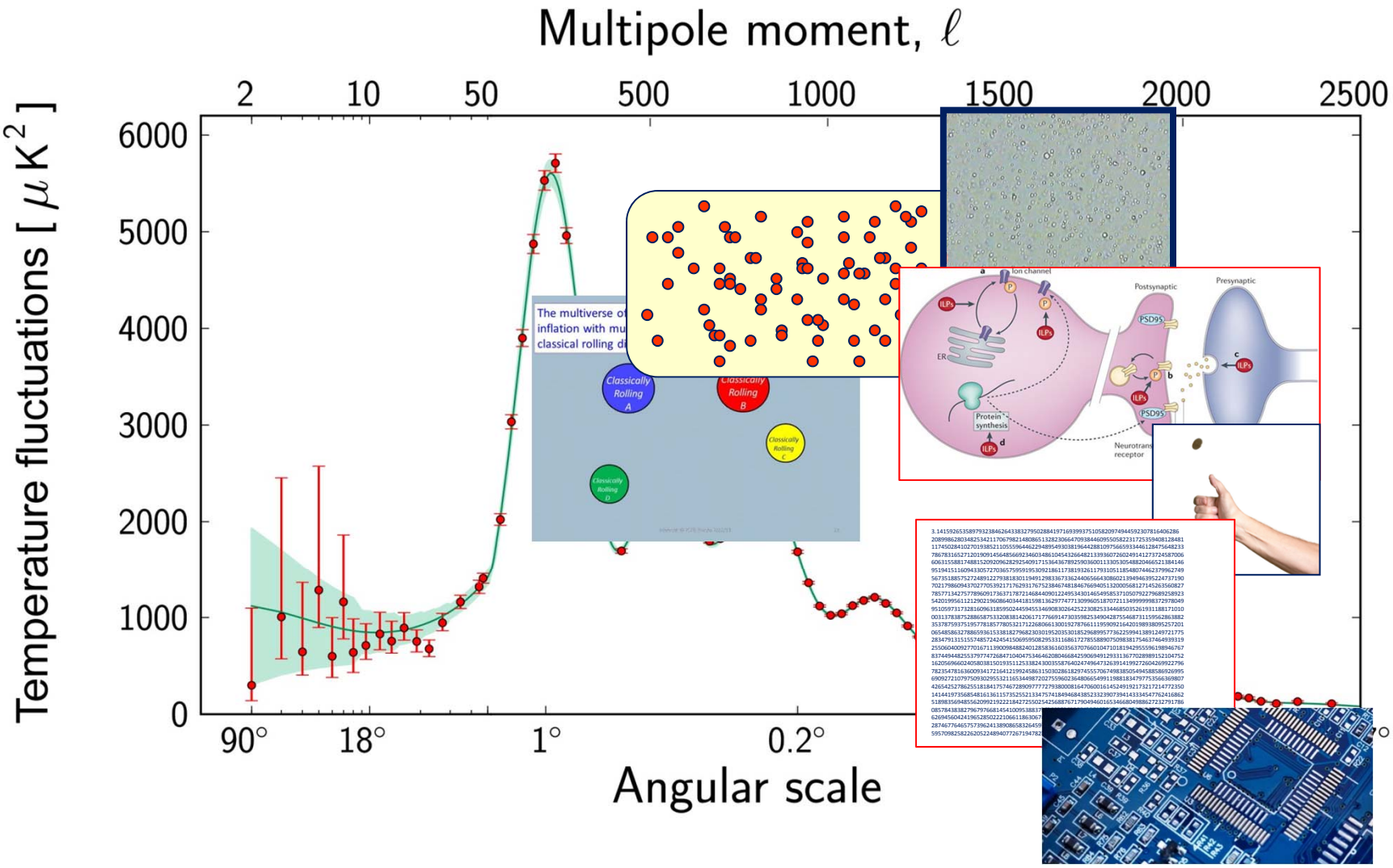
Multipole moment, ℓ
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2500
Temperature fluctuations [μK²]
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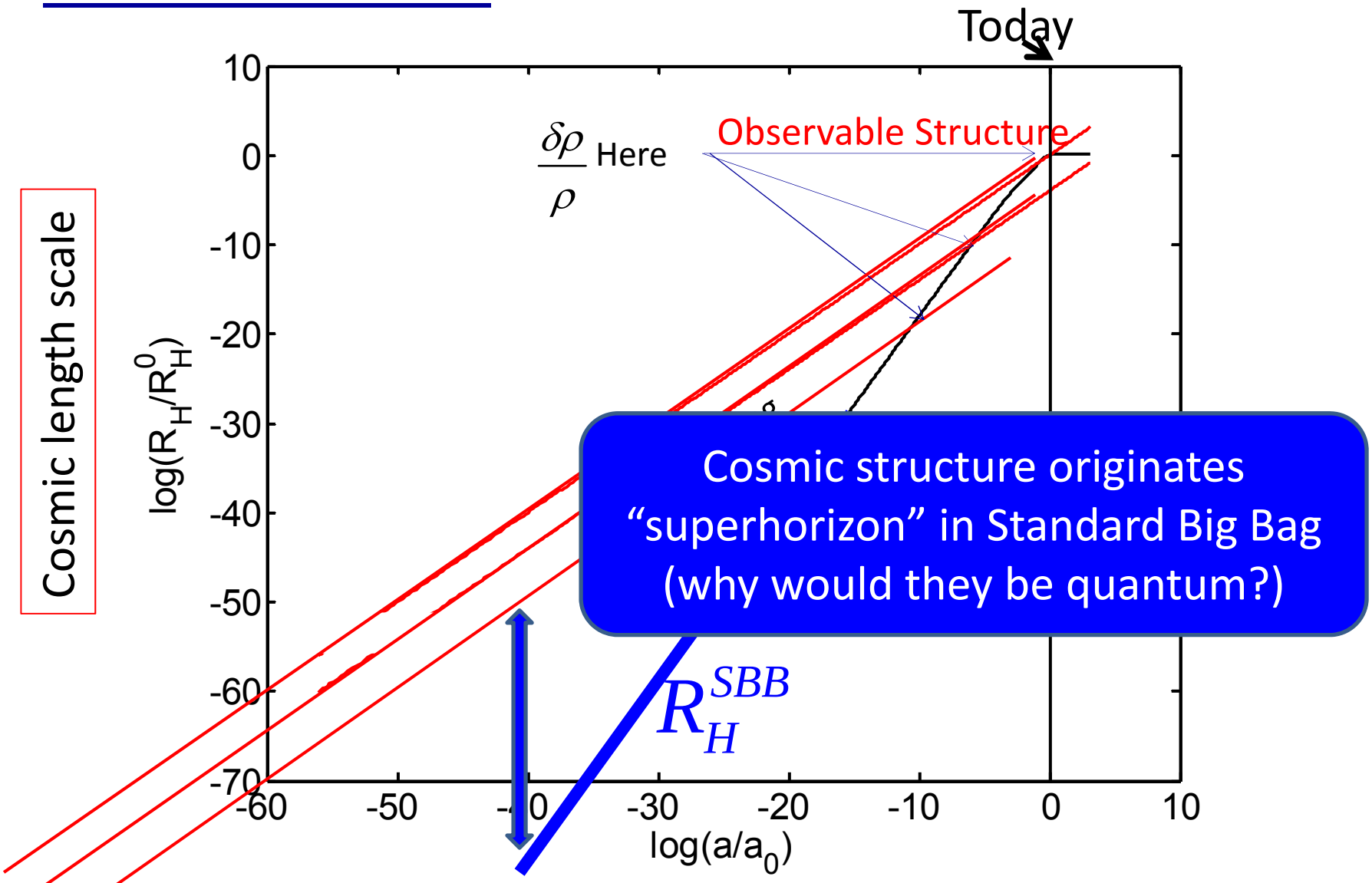
4000
3000
2000
1000
0
90°
18°
1°
0.2°
Angular scale
Classically Rolling A
Classically Rolling B
Classically Rolling C
Classically Rolling D
Ion channel
Postsynaptic
Presynaptic
PSD95
ILPs
ER
Protein synthesis

Additional Slides

A note on “probability censorship”

Cosmic structure



Scale factor (measures expansion, time)

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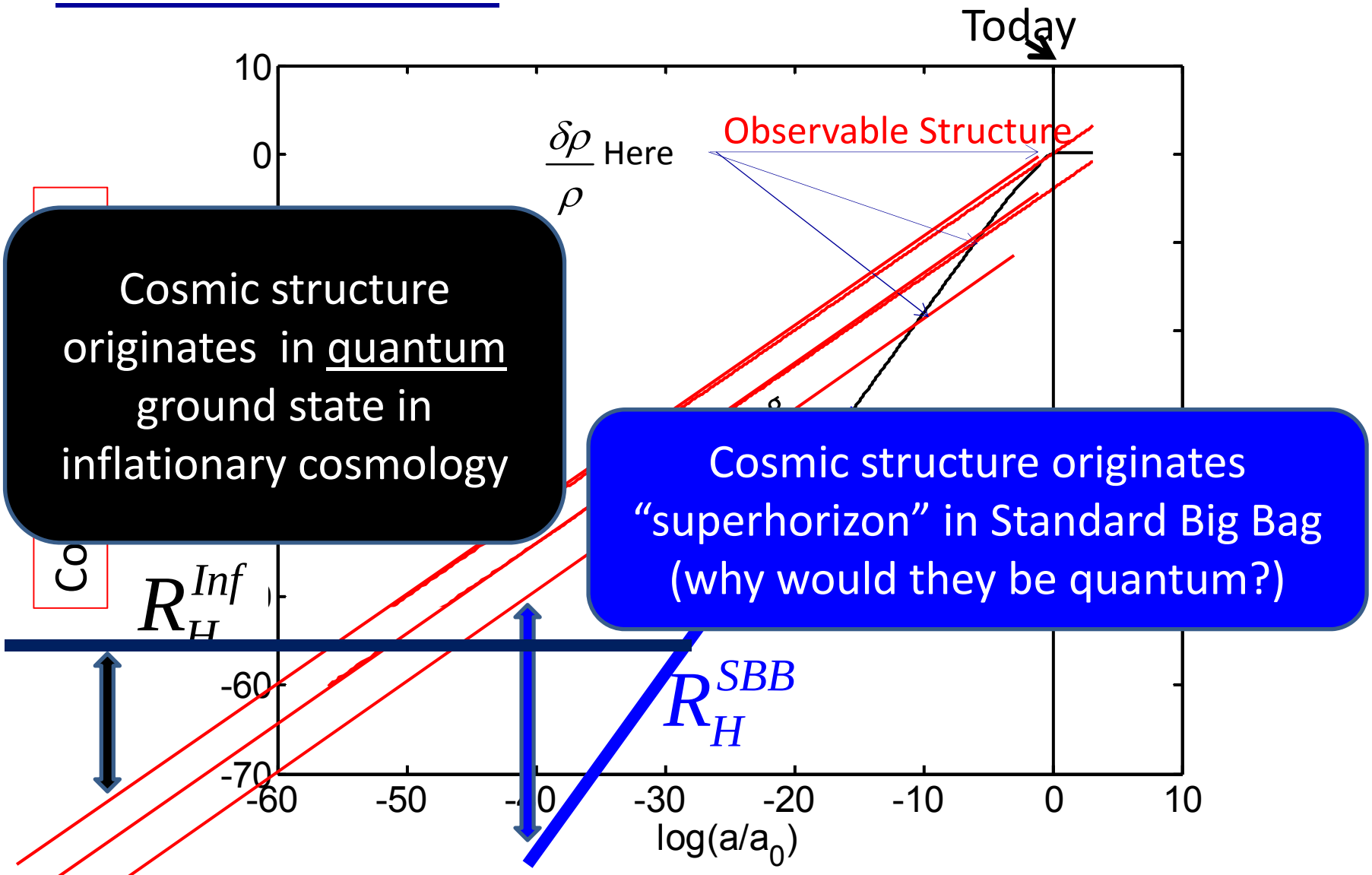

Scale factor (measures expansion, time)

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
- ally do require classical probabilities
  rously (symmetry?... simplicity? See

Compare with identical particle statistics

Cooperman 2011

Further discussion

Bet on the millionth digit of π

3.14159265359...
20899862803482534211706798214808651328230664709384460955058223172535940812848 1
11745028410270193852110555964462294895493038196442881097566593344612847564823 3
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28746776465757396241389086583264599581339047802759009946576407895126946839835 2
59570982582262052248940772671947826848260147699090264013639443745530506820349 6

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Bet on the millionth digit of π

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Albrecht @ Stockholm 6/4/15

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
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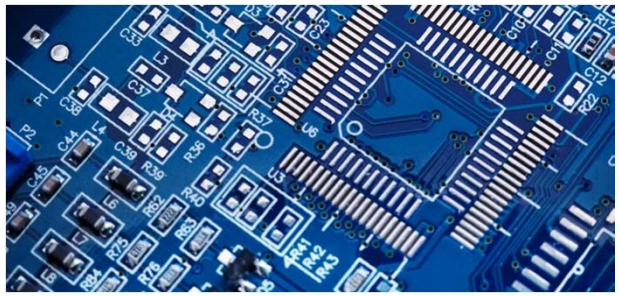
Payout:

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

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.

1000100011110101O

1000100010100101O

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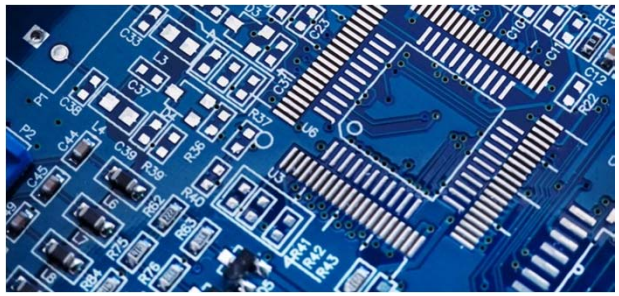
1000100010110101O

Further discussion



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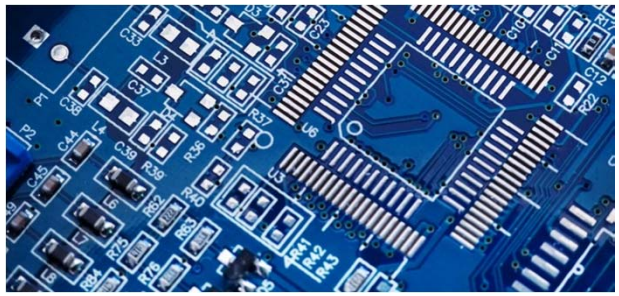
Std. thinking about classical probabilities

Further discussion



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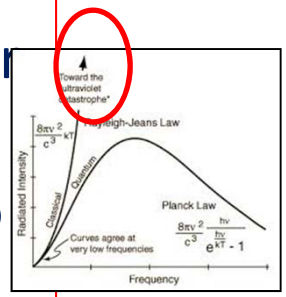
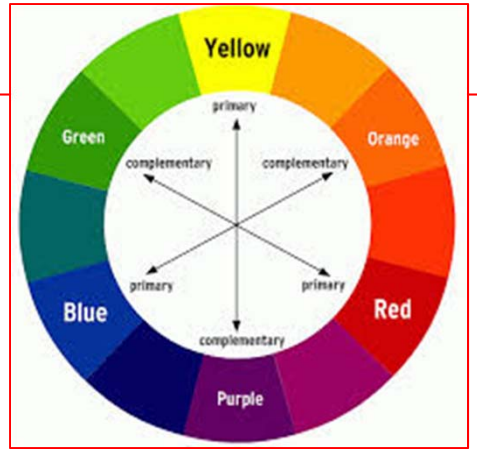
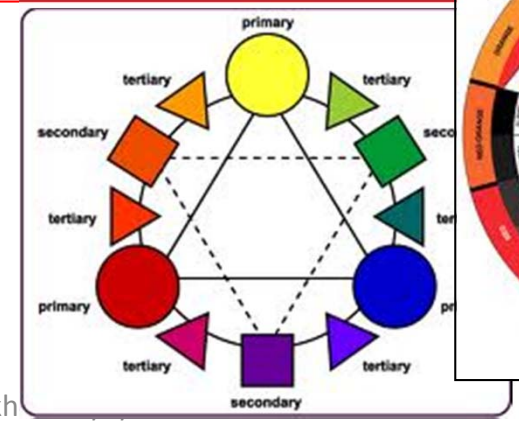
Further discussion

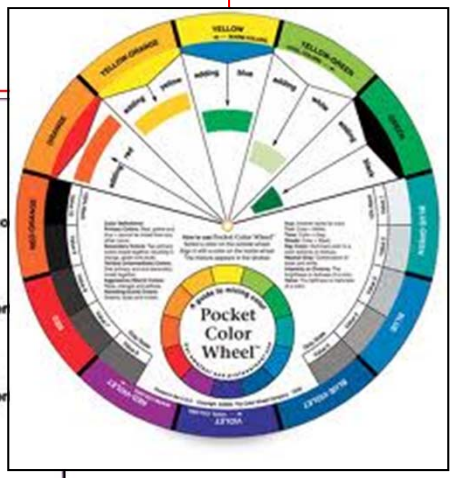
<u>Our ideas about probability are like our ideas about color:</u>

- 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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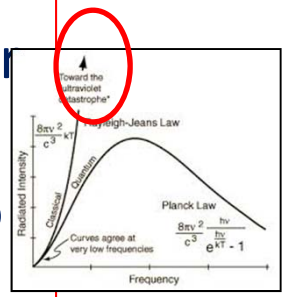

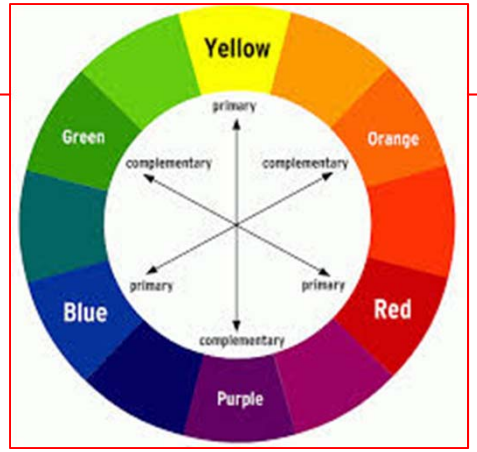

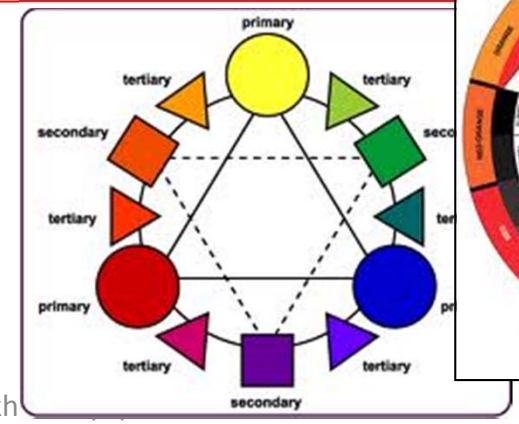

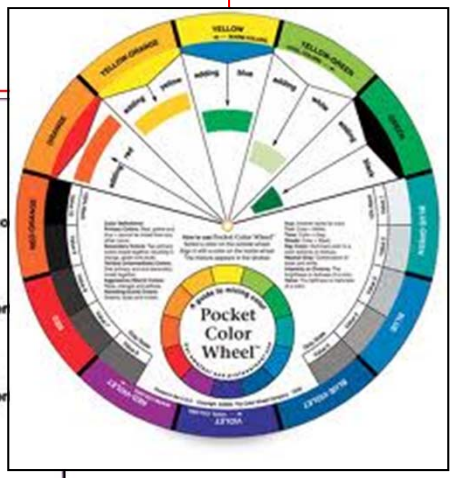

Further discussion

Our ideas about probabilit
color:

- Quantum physics gives
  our understanding
  ' intuition
  ng long time, and works just fine for
  quantum understanding needed to
  sundersta