Les Houches Lectures on Cosmic Inflation

Four Parts

1) Introductory material

2) Entropy, Tuning and Equilibrium in Cosmology

3) Classical and quantum probabilities in the multiverse

4) de Sitter equilibrium cosmology

Andreas Albrecht; UC Davis

Les Houches Lectures; July-Aug 2013

Les Houches Lectures Part 3

Classical and quantum probabilities in the multiverse

Andreas Albrecht
UC Davis
Les Houches Lectures
July 2013

Part 3 Outline

1) The multiverse
2) Quantum vs non-quantum probabilities (toy model/multiverse)
3) Everyday probabilities
4) Further Discussion (Implications for the multiverse)

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1) The multiverse

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NB: Very different subject from "make probabilities precise" Stanford sense. (See Silverstein lectures)

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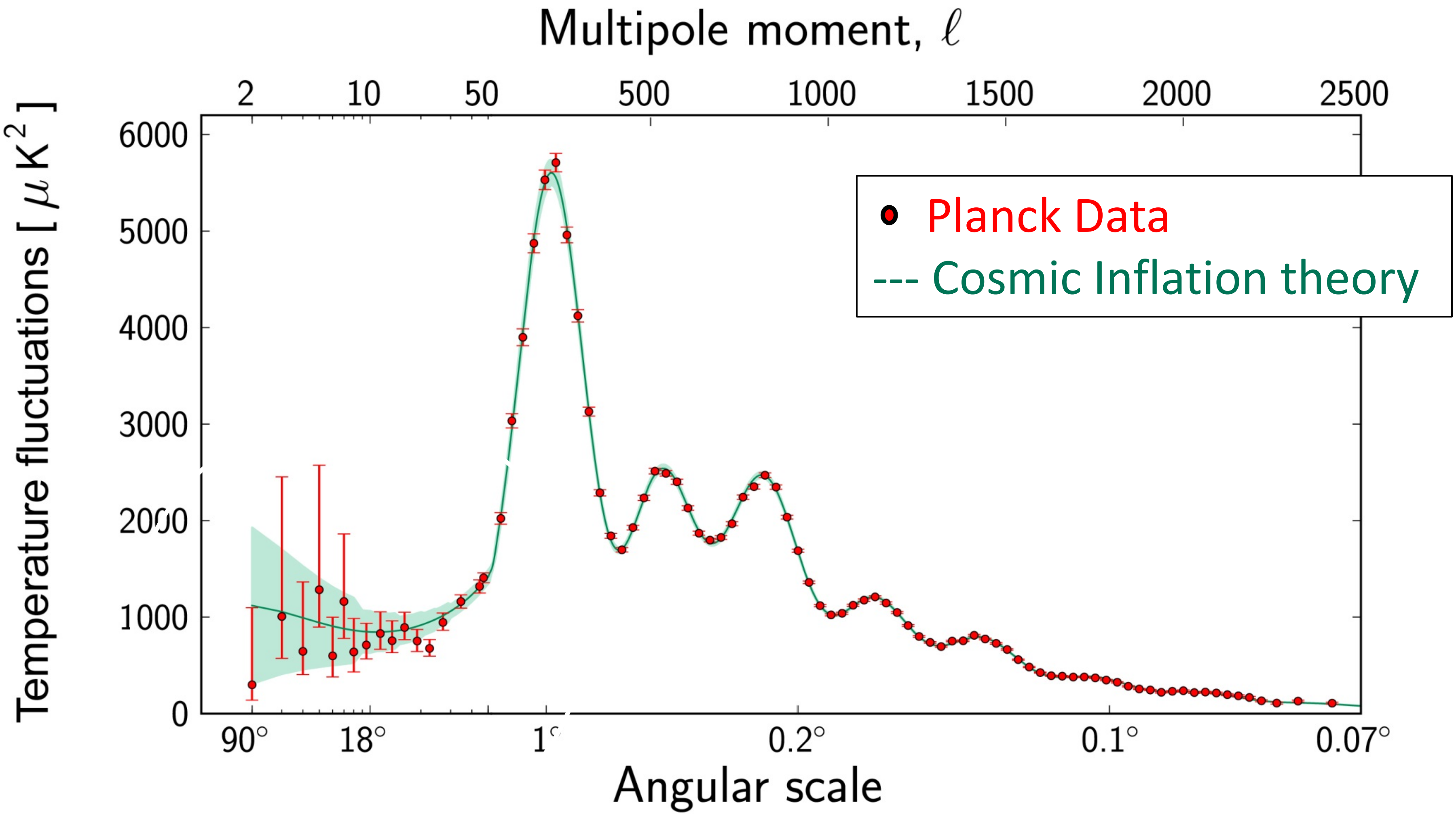
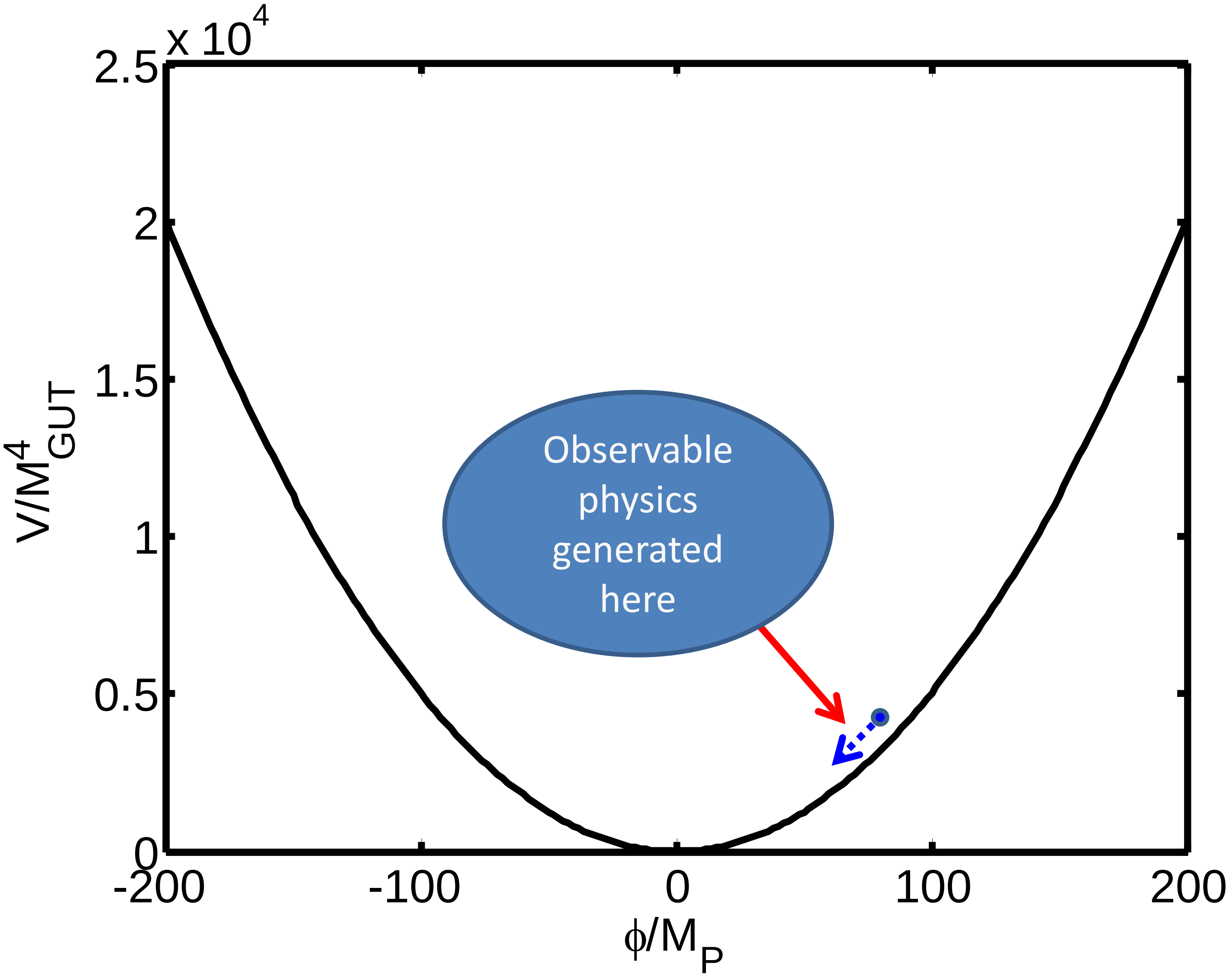

Multipole moment, ℓ
2
10
50
500
1000
1500
2000
2500
Temperature fluctuations [μK^2]
6000
5000
4000
3000
2000
1000
0
Planck Data
--- Cosmic Inflation theory
90°
18°
1°
0.2°
0.1°
0.07°
Angular scale

Slow rolling of inflaton



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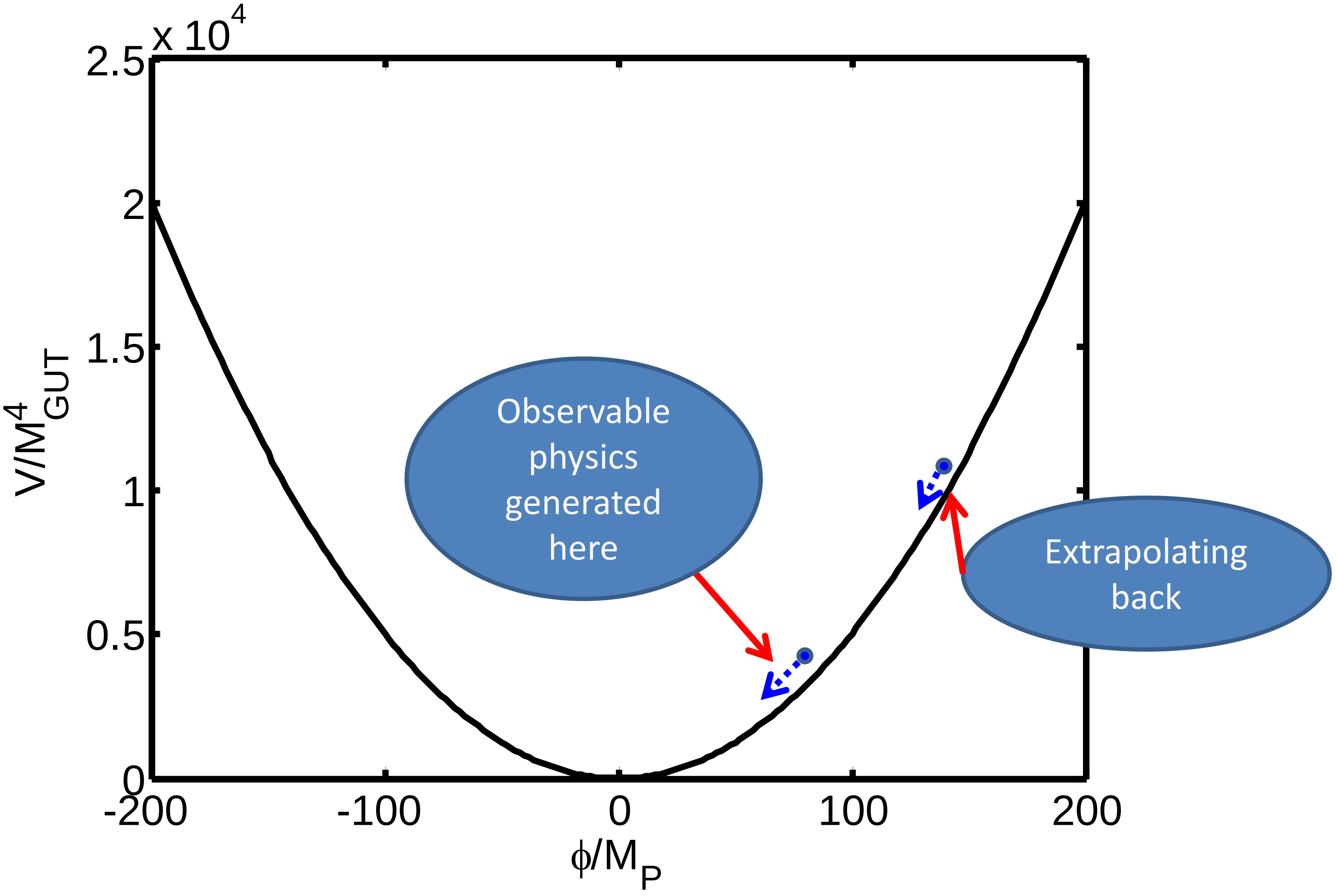
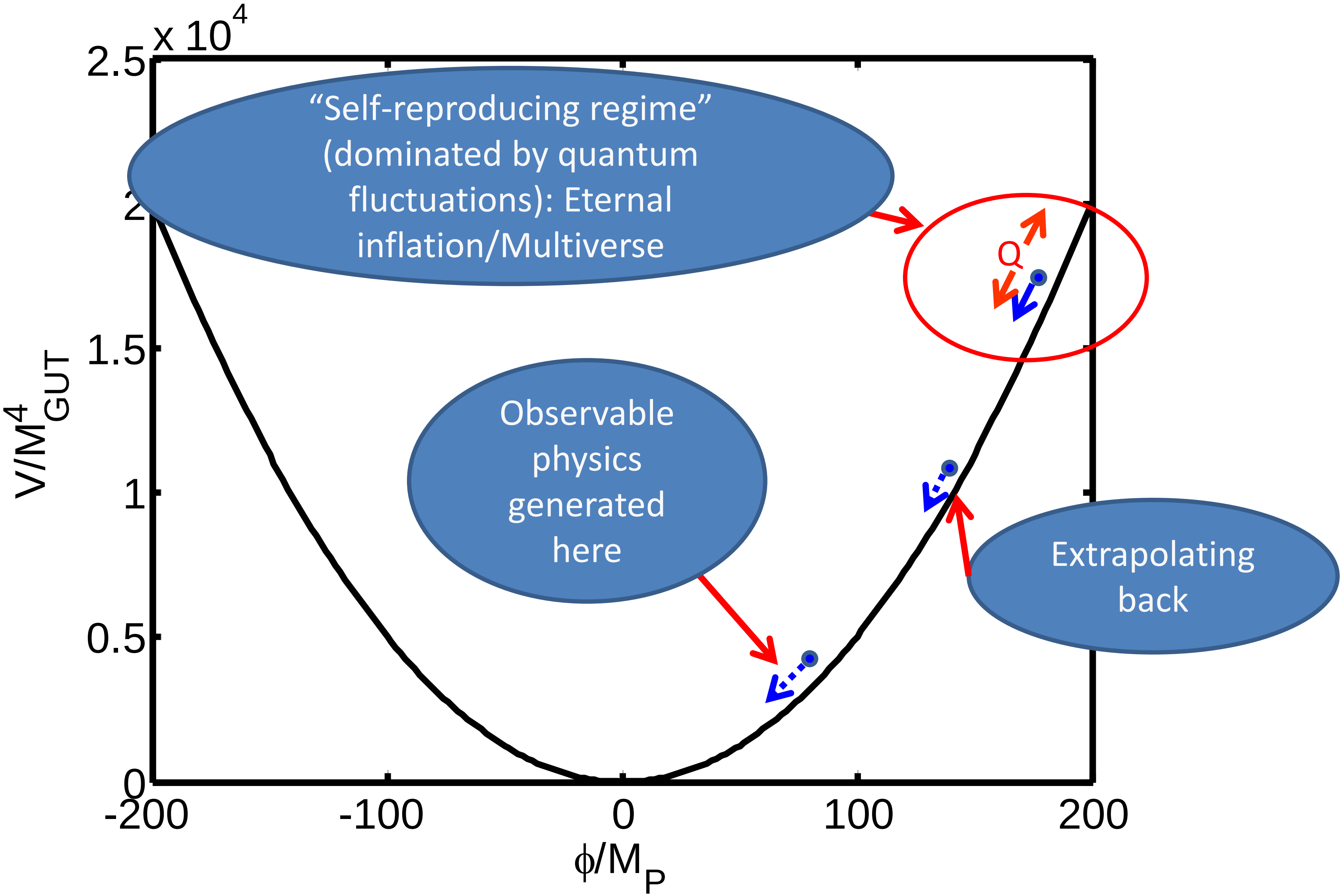


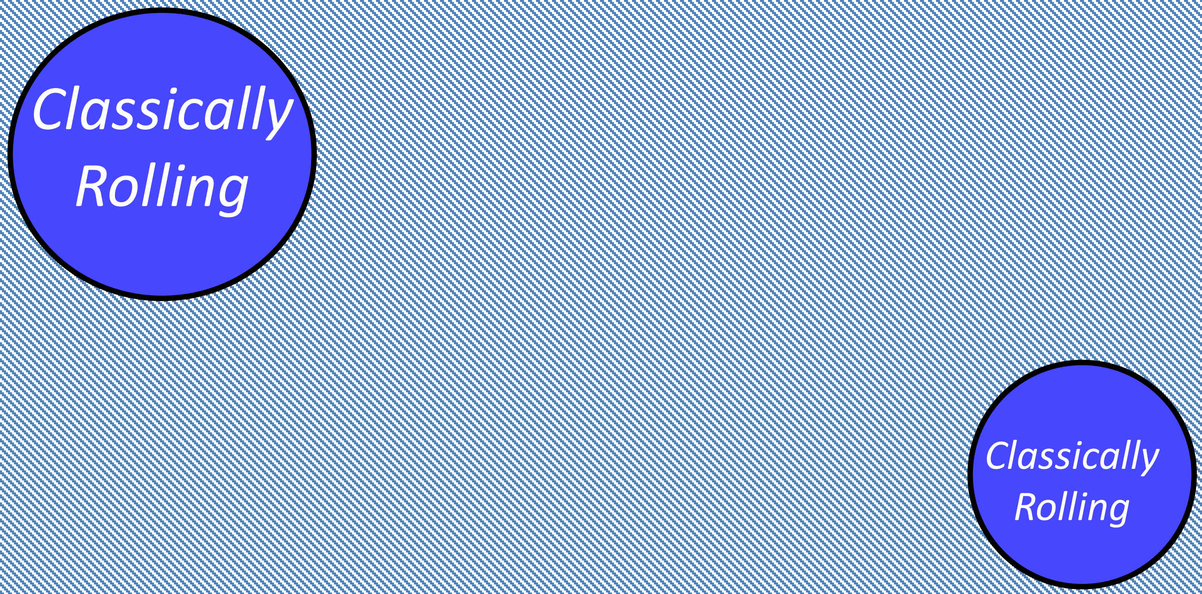
Slow rolling of inflaton



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

The multiverse of eternal inflation

Self-reproduction regime

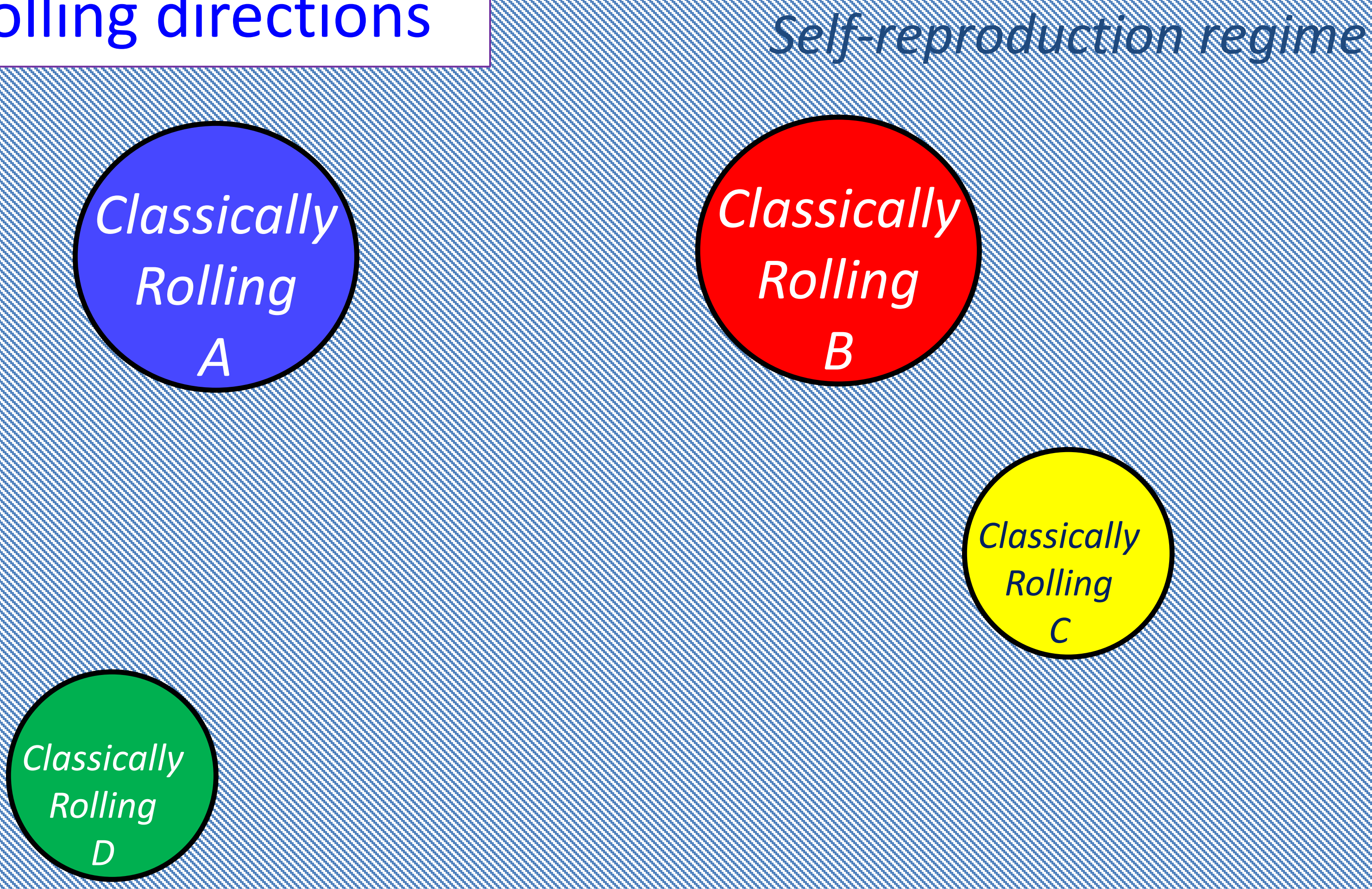


The multiverse of eternal inflation

Self-reproduction regime

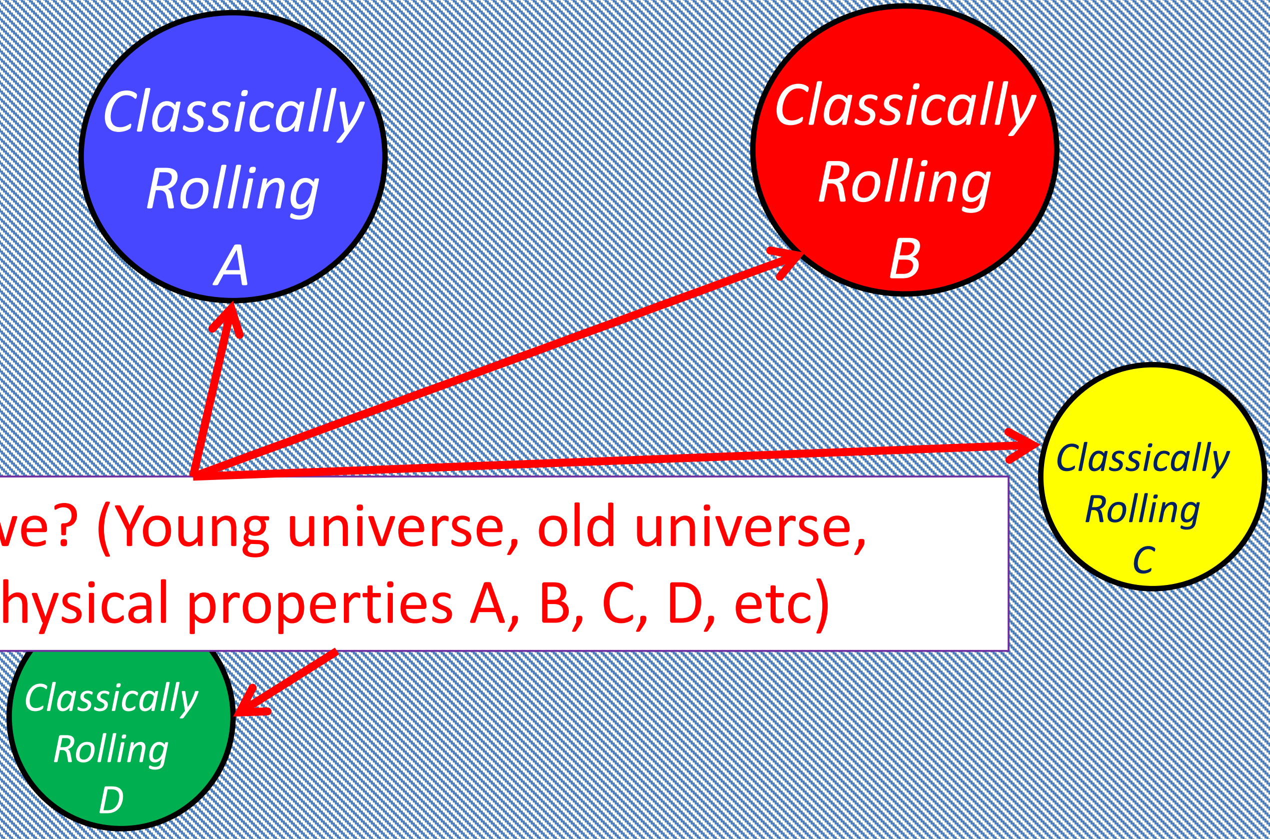
Where are we? (Young universe, old universe, curvature etc)

The multiverse of eternal inflation with multiple classical rolling directions



The multiverse of eternal inflation with multiple classical rolling directions

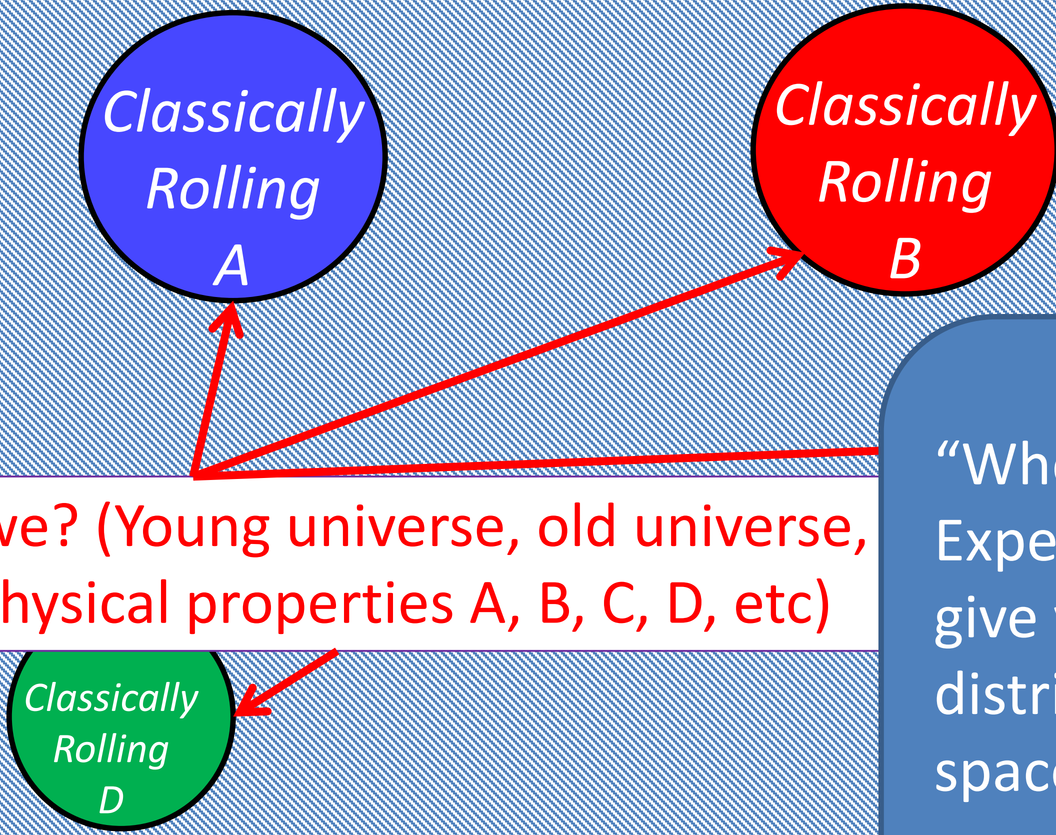
Self-reproduction regime



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 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 Rolling D

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

Challenges for eternal inflation

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

1) Measure Problems

2) Problems defining probabilities

3) Problems/hidden assumptions re initial conditions
   → problem claiming generic predictions about state
      → cannot claim "solution to cosmological problems"
         → Related to 2^{nd} law, low *S* start

Challenges for eternal inflation

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

1) Measure Problems

2) **Problems defining probabilities**

3) Problems/hidden assumptions re in
→ problem claiming generic pr
→ cannot claim "solu
problems
→ Relate

For this talk, focus on probabilities. Assume all other challenges are resolved

Part 3 Outline

1) The multiverse

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

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4) Further Discussion (Implications for the multiverse)

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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 2012

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

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

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

$$U = A$$

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

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Could Write

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Classical Probabilities to measure A, B

$^A|j\rangle^B$

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Does not represent a quantum measurement

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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:

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M y:

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

- All everyday probabilities are quantum probabilities

AA & D. Phillips 2012

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

AA & D. Phillips 2012

- 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 2012

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A problem for many multiverse theories

AA & D. Phillips 2012

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~~Classical Probabilities to measure A, B~~

Where do these come from anyway?

Does not represent a quantum measurement

ments $\Leftrightarrow$ P

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M y:

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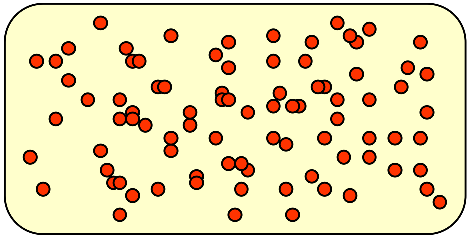
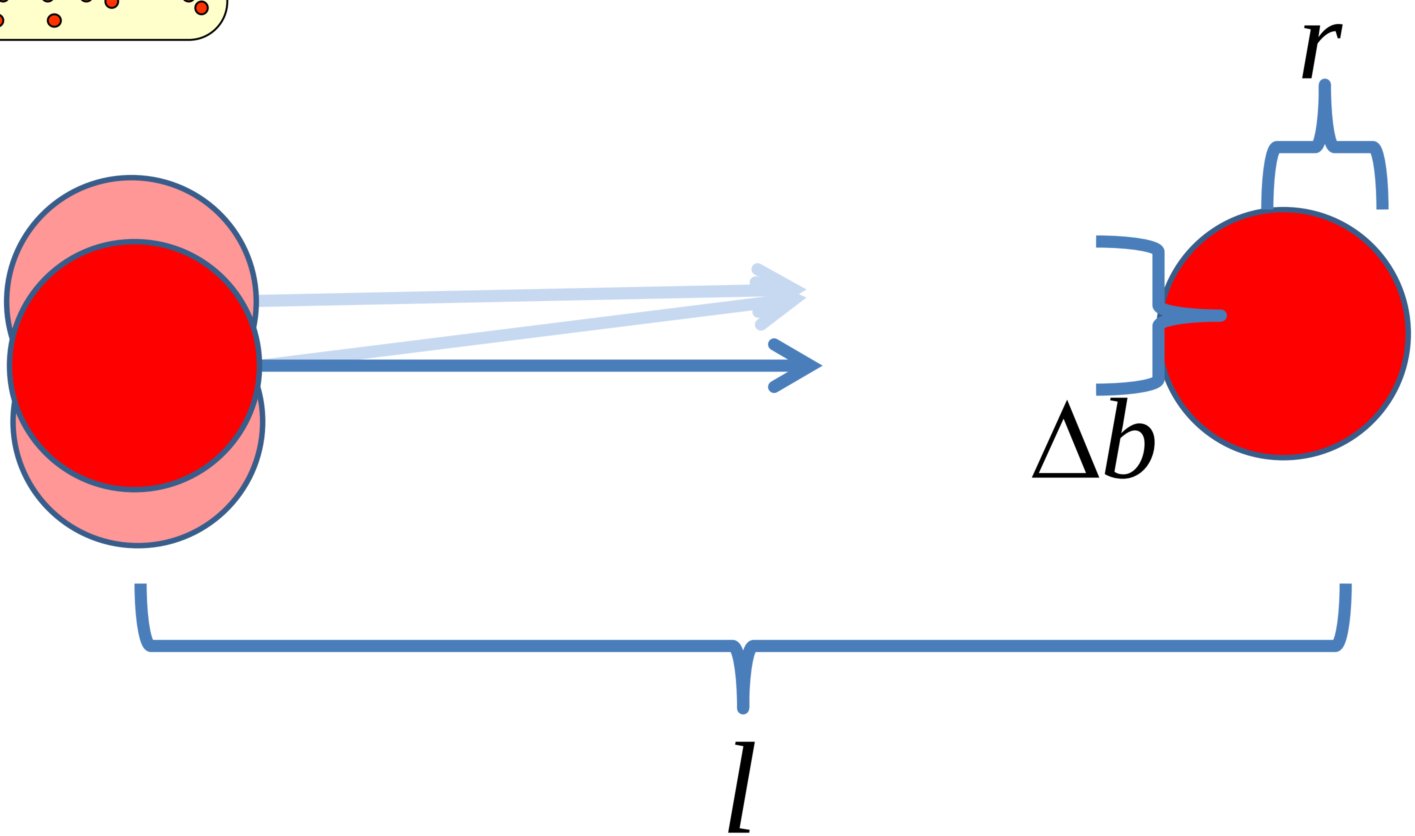
AA & D. Phillips 2012



Quantum effects in a billiard gas



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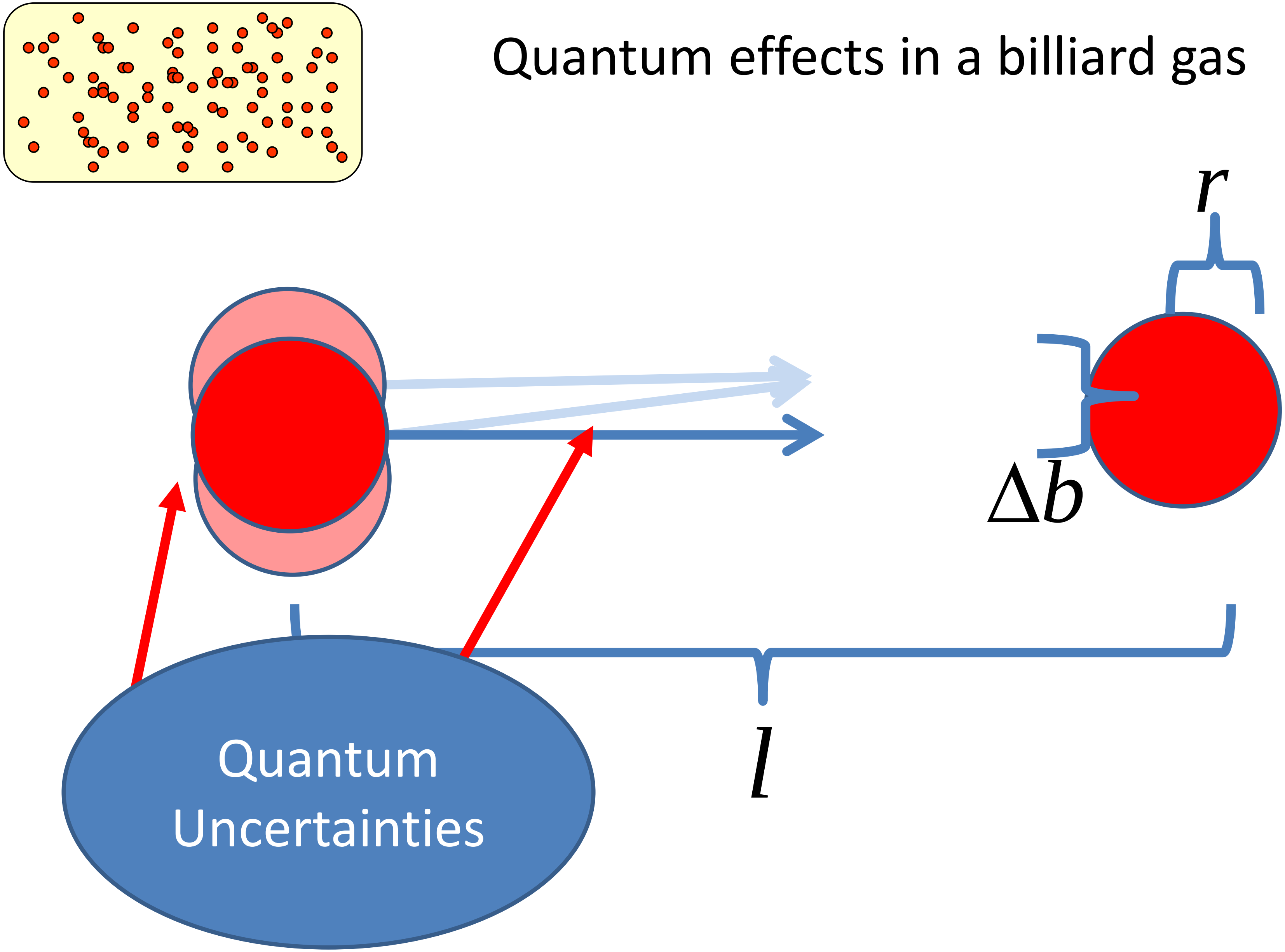

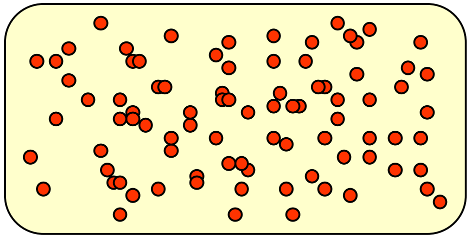

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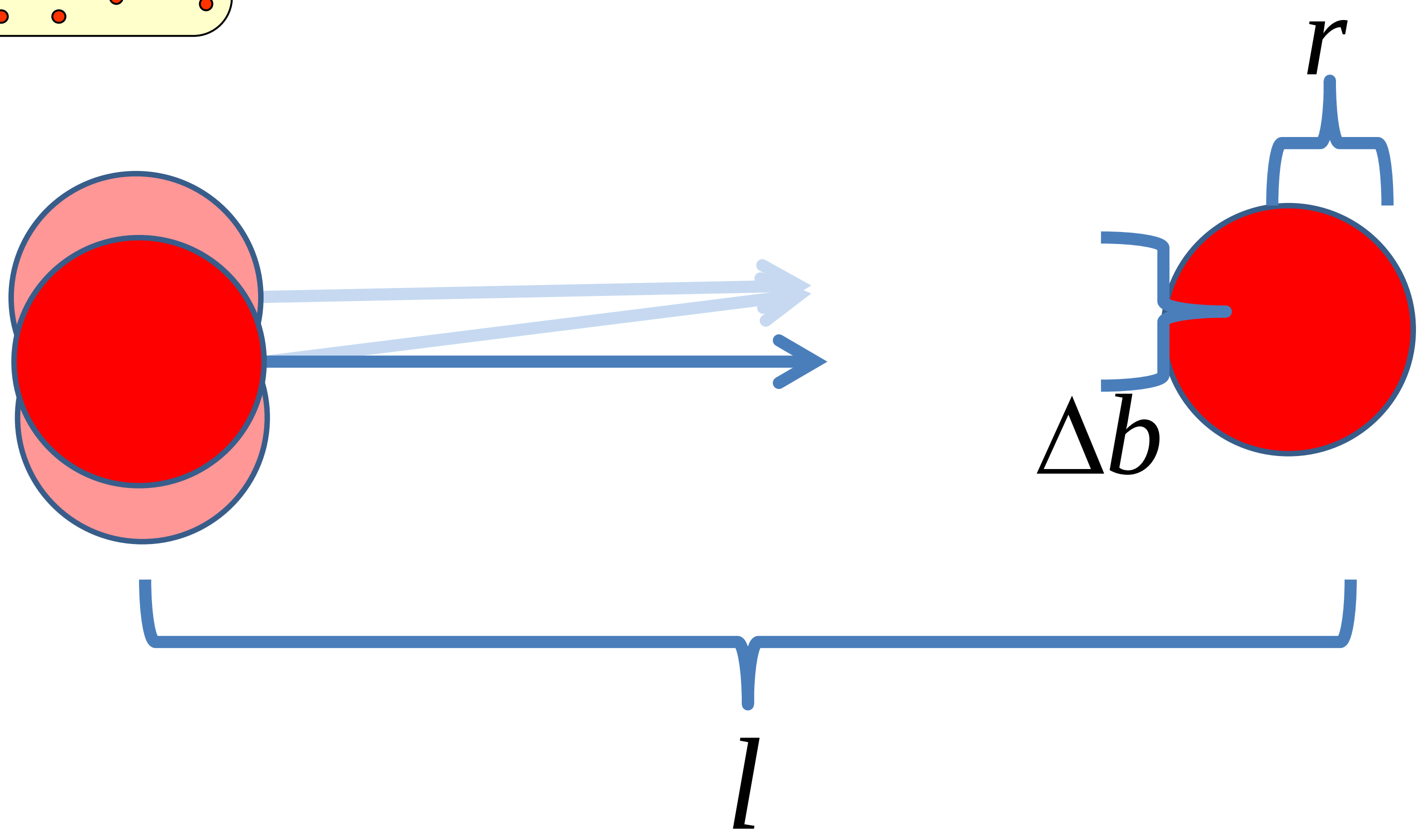
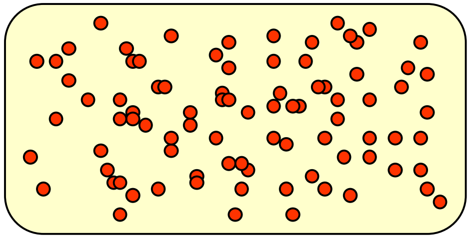


$$\boxed{\Delta b = \delta x_{\perp} + \frac{\delta p_{\perp}}{m}\Delta t}$$



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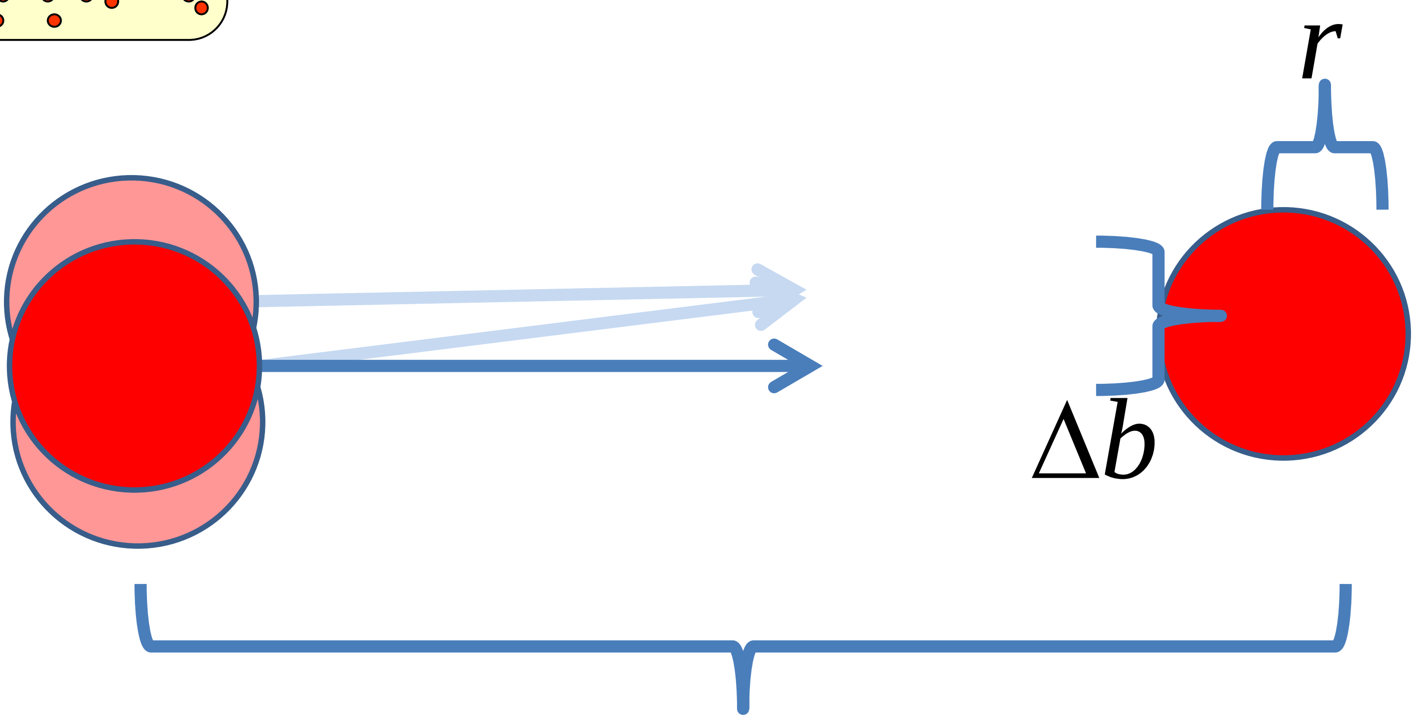
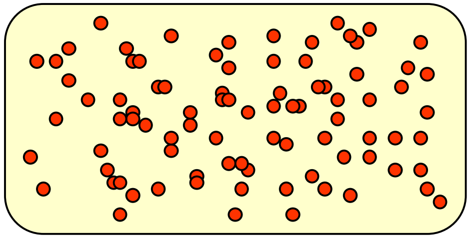


$$\psi \propto \exp\left(\frac{-x^2}{2a^2}\right)$$

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



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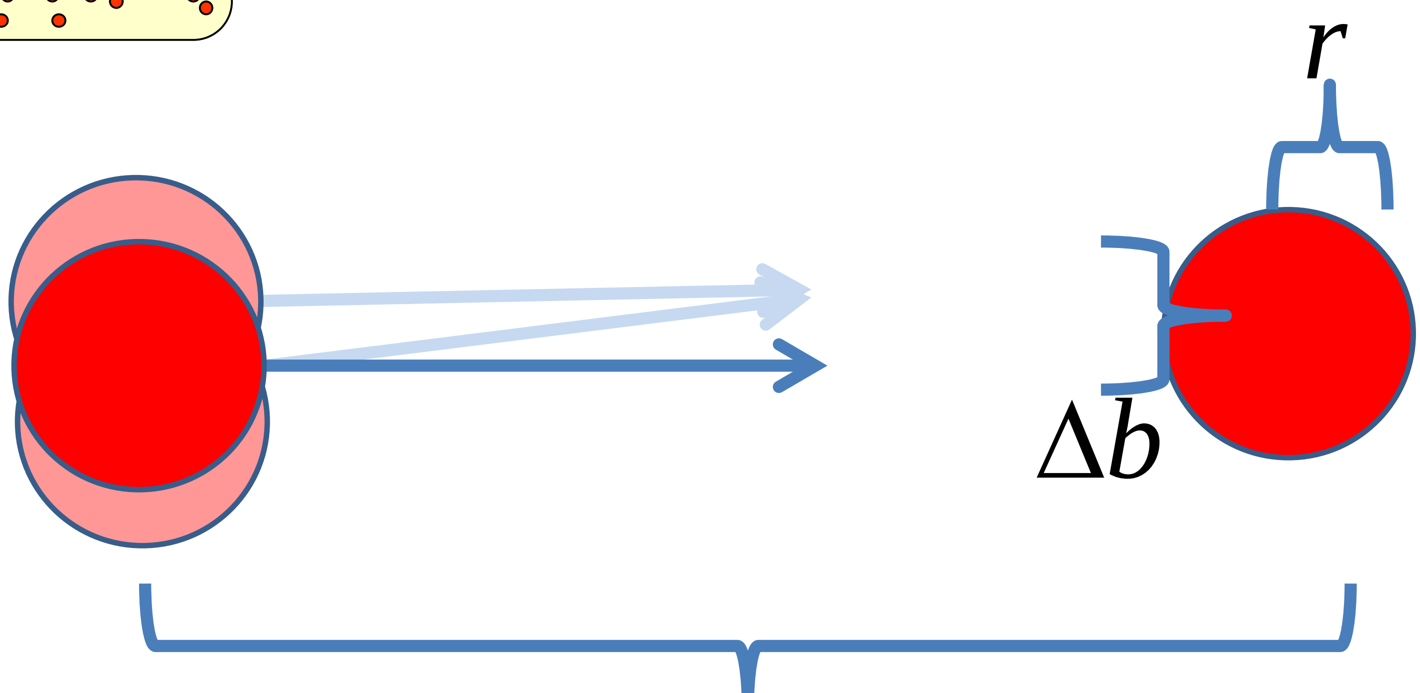
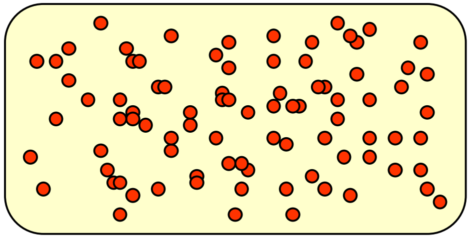


$$\Delta b = \delta x_\perp + \frac{\delta p_\perp}{m}\Delta t = \sqrt{2}\left(a + \frac{\hbar}{2a}\frac{l}{m\bar{v}} \right) \qquad \psi \propto \exp\left(\frac{-x^2}{2a^2}\right)$$

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



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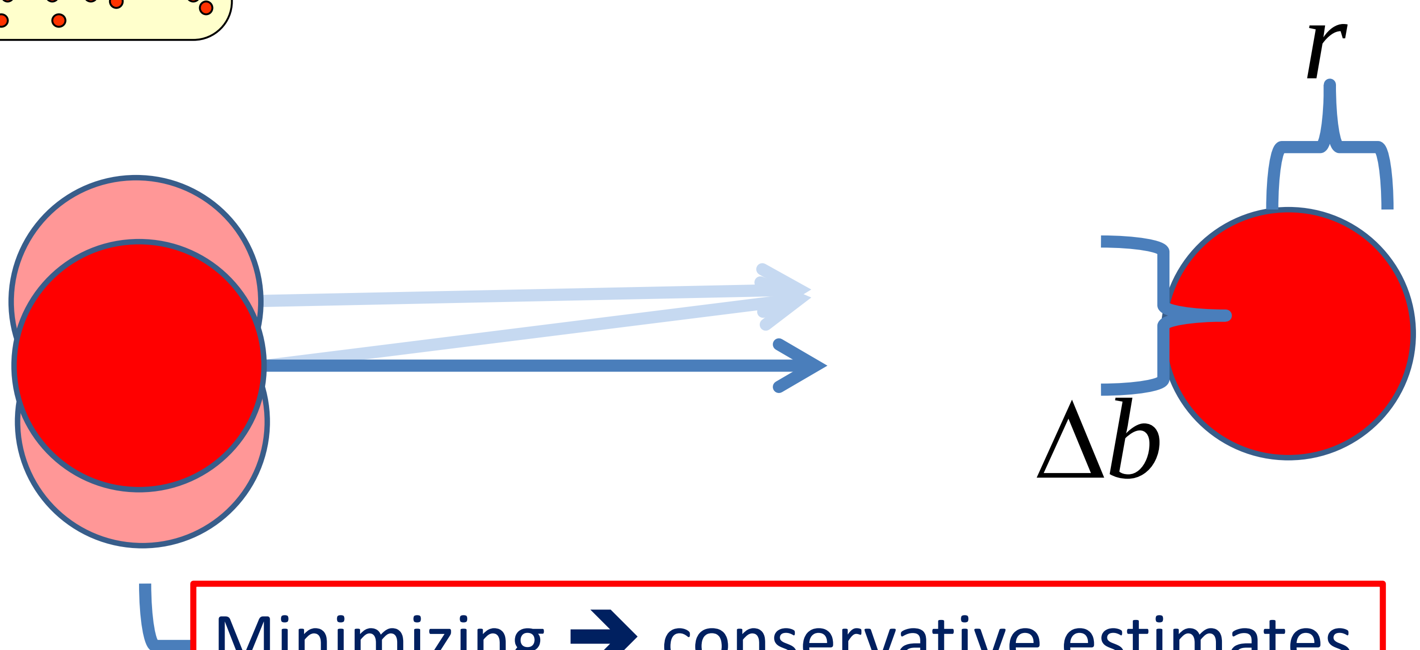
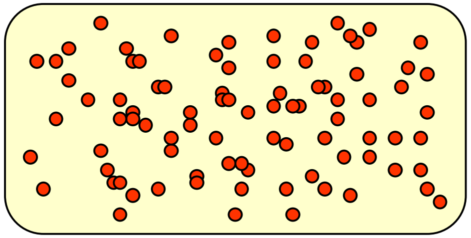


Minimizing ➔ conservative estimates for my purposes (also motivated by decoherence in some cases)

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

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



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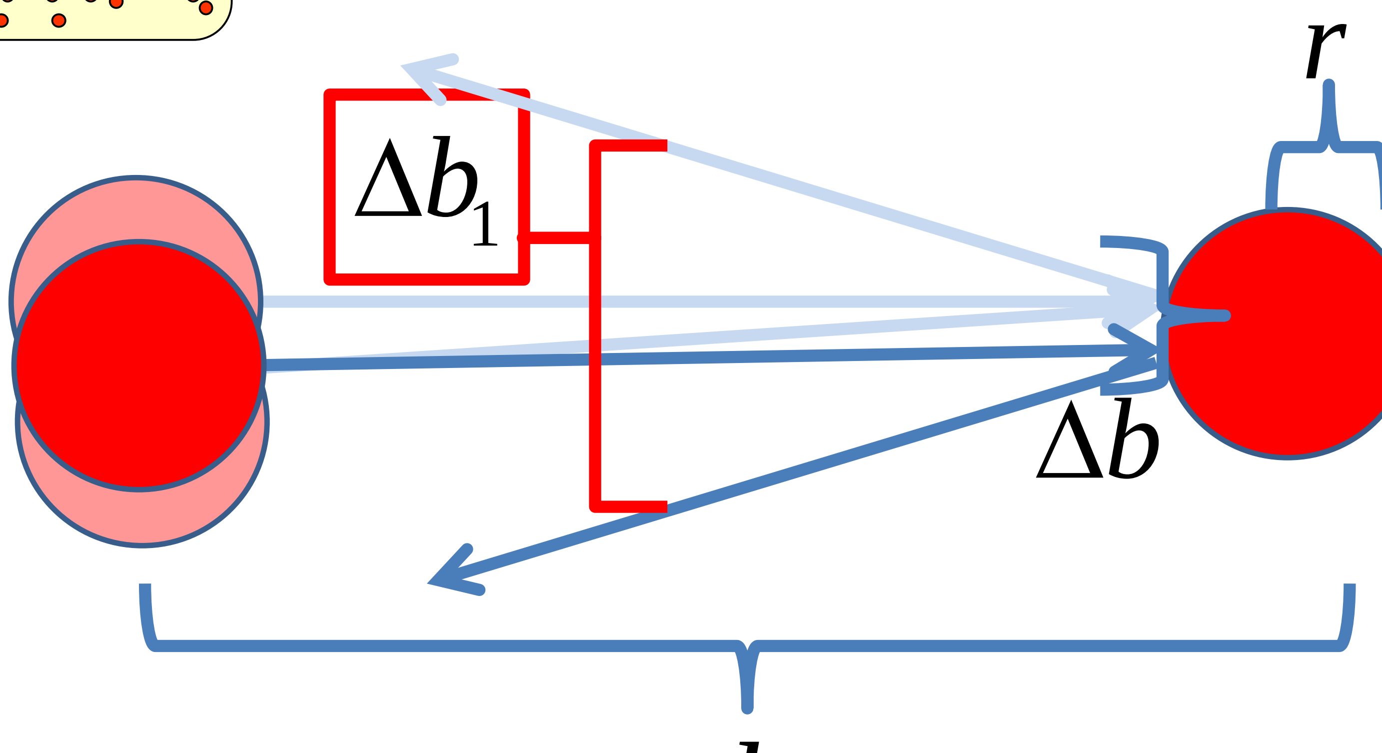
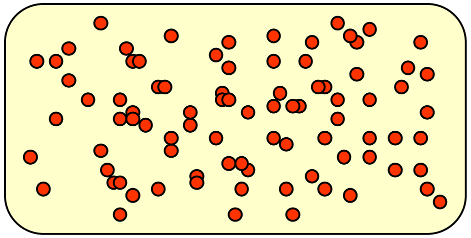
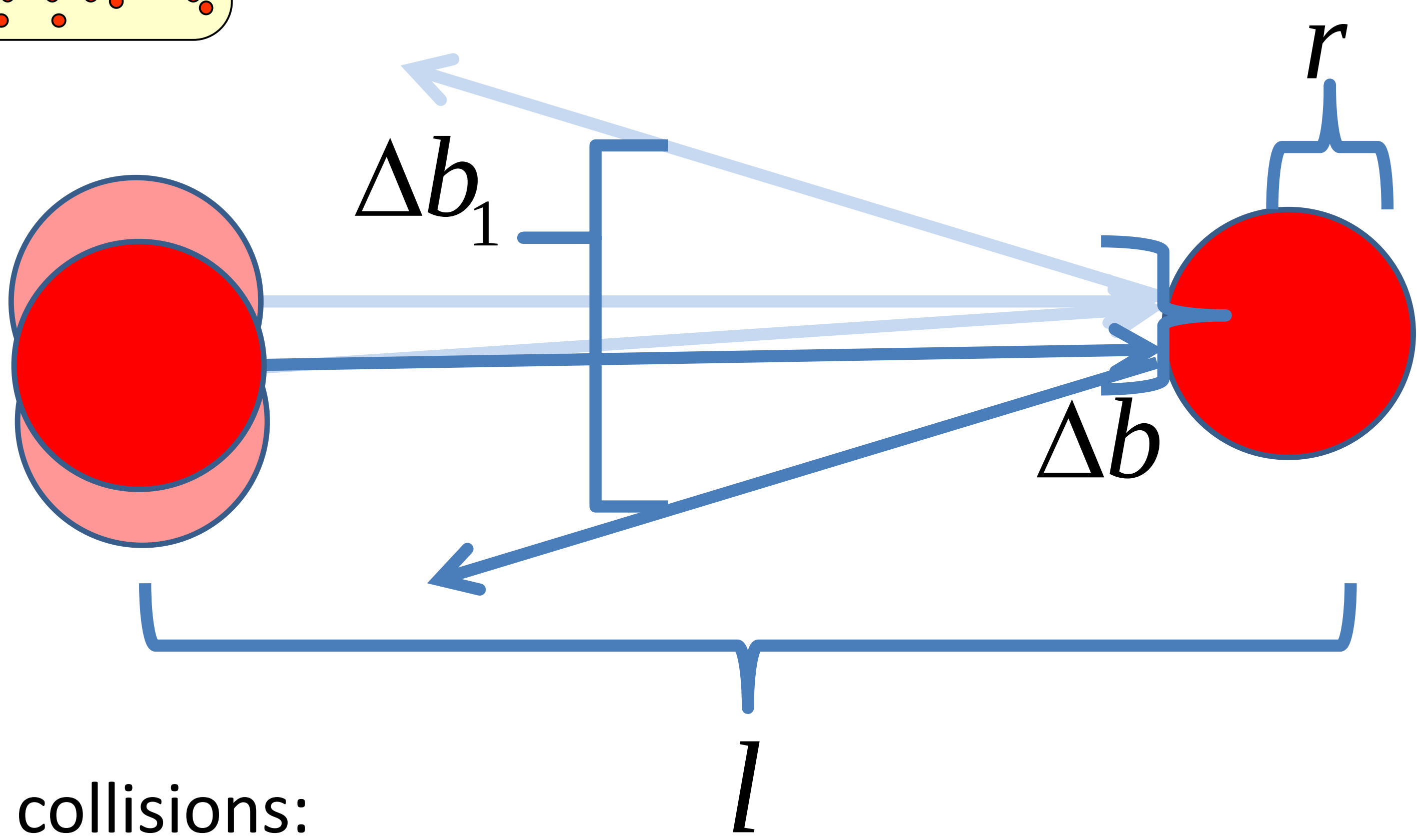


Subsequent collisions amplify the initial uncertainty (treat later collisions classically ➔ additional conservatism)

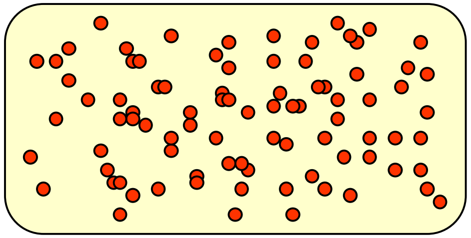
Quantum effects in a billiard gas





After *n* collisions:

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



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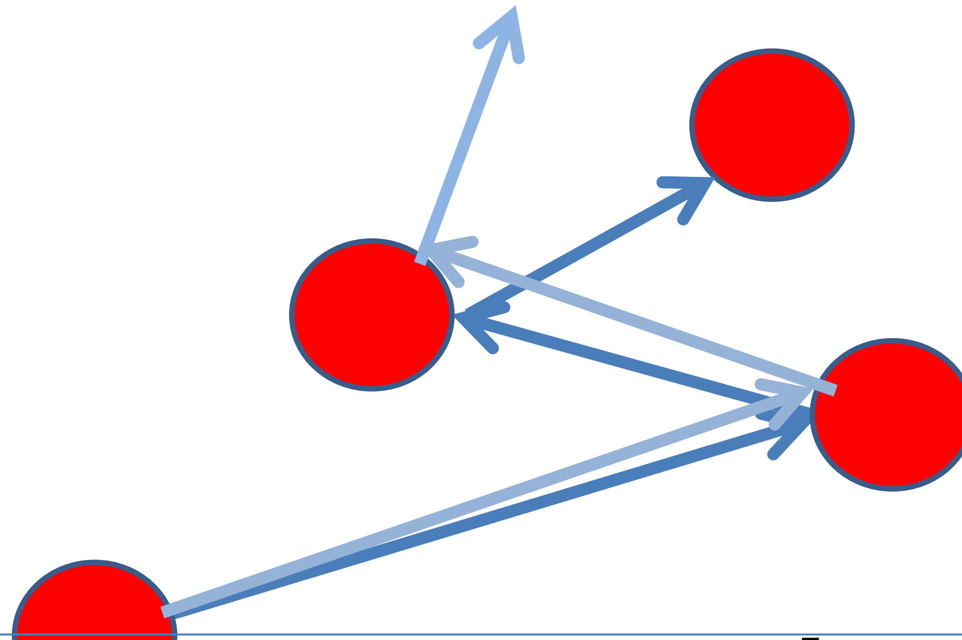

n_Q is the number of collisions so that $\Delta b_{n_Q} = r$

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

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

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

(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}	$\boxed{25}$

n_Q for a number of physical systems

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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}	$\boxed{8}$
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}	$\boxed{0.6}$
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}	$\boxed{-0.3}$
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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n_Q for a number of physical systems

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Billiards	0.029	1	0.16	1	6.6×10^{-34}	5.1 [illegible]	[illegible]
Bumper Car	1	2	150	0.5	1.4×10^{-36}	3. [illegible]	[illegible]

Quantum at every collision

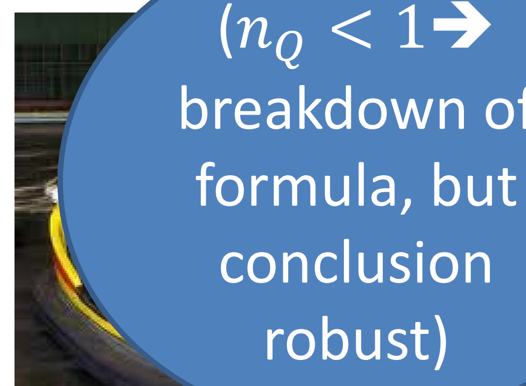
n_Q for a number of physical systems

(all units MKS)

	r	l	m	$\bar{v}$	$\lambdabar_{dB}$	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

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



n_Q for a number of physical systems

(all units MKS)

	r	l	m	$\bar{v}$	$ƛ_{dB}$	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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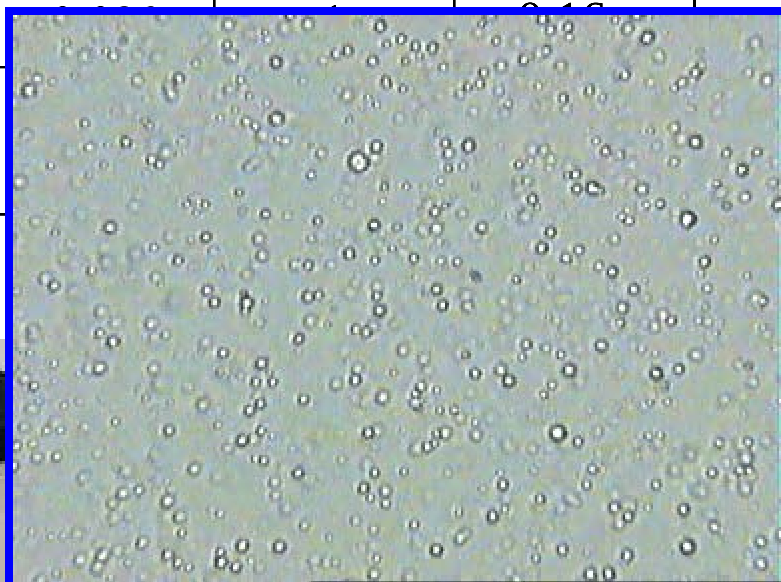
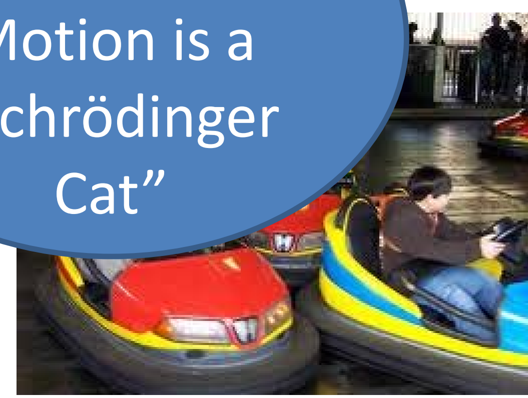
Billiards				1	6.6×10^{-34}	5.1	
Bumper Car				.5	1		





Quantum at every llision

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
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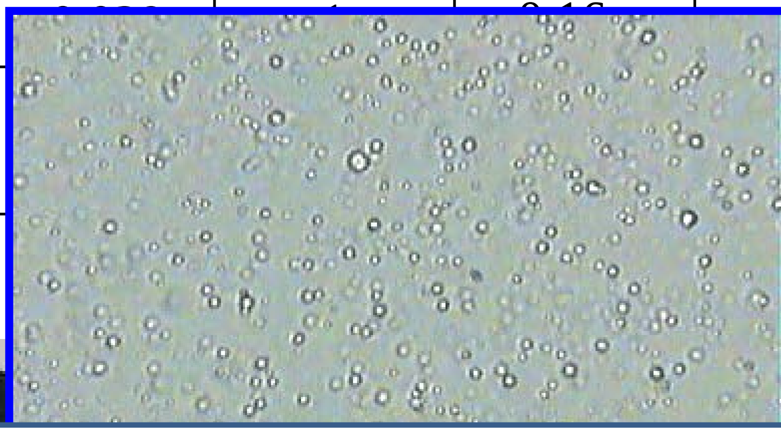
Billiards	[illegible]	[illegible]	[illegible]	1	6.6×10^{-34}	5.1	[illegible]
Bumper Car	[illegible]	[illegible]	[illegible]	.5	1	[illegible]	[illegible]

Quantum at every llision

Every Brownian Motion is a “Schrödinger



(independent of “interpretation”)

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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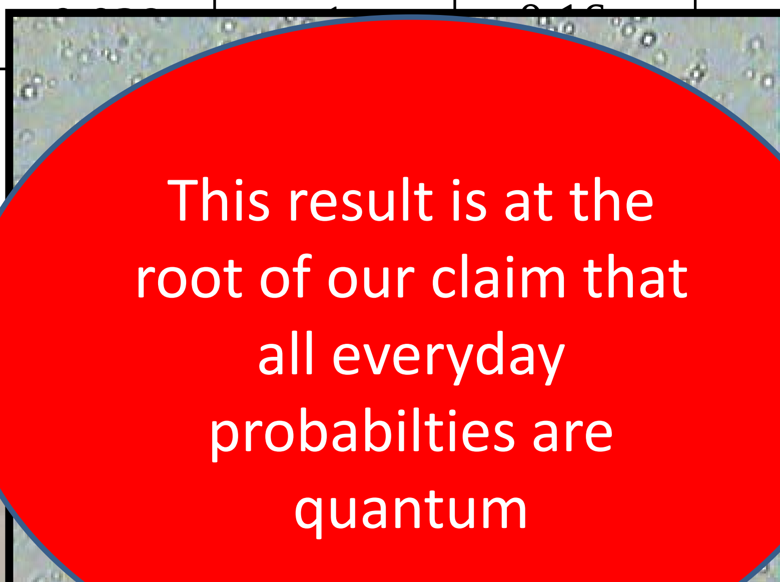
Billiards	[illegible]	[illegible]	[illegible]	[illegible]	6.6×10^{-34}	[illegible]	[illegible]
Bumper Car	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

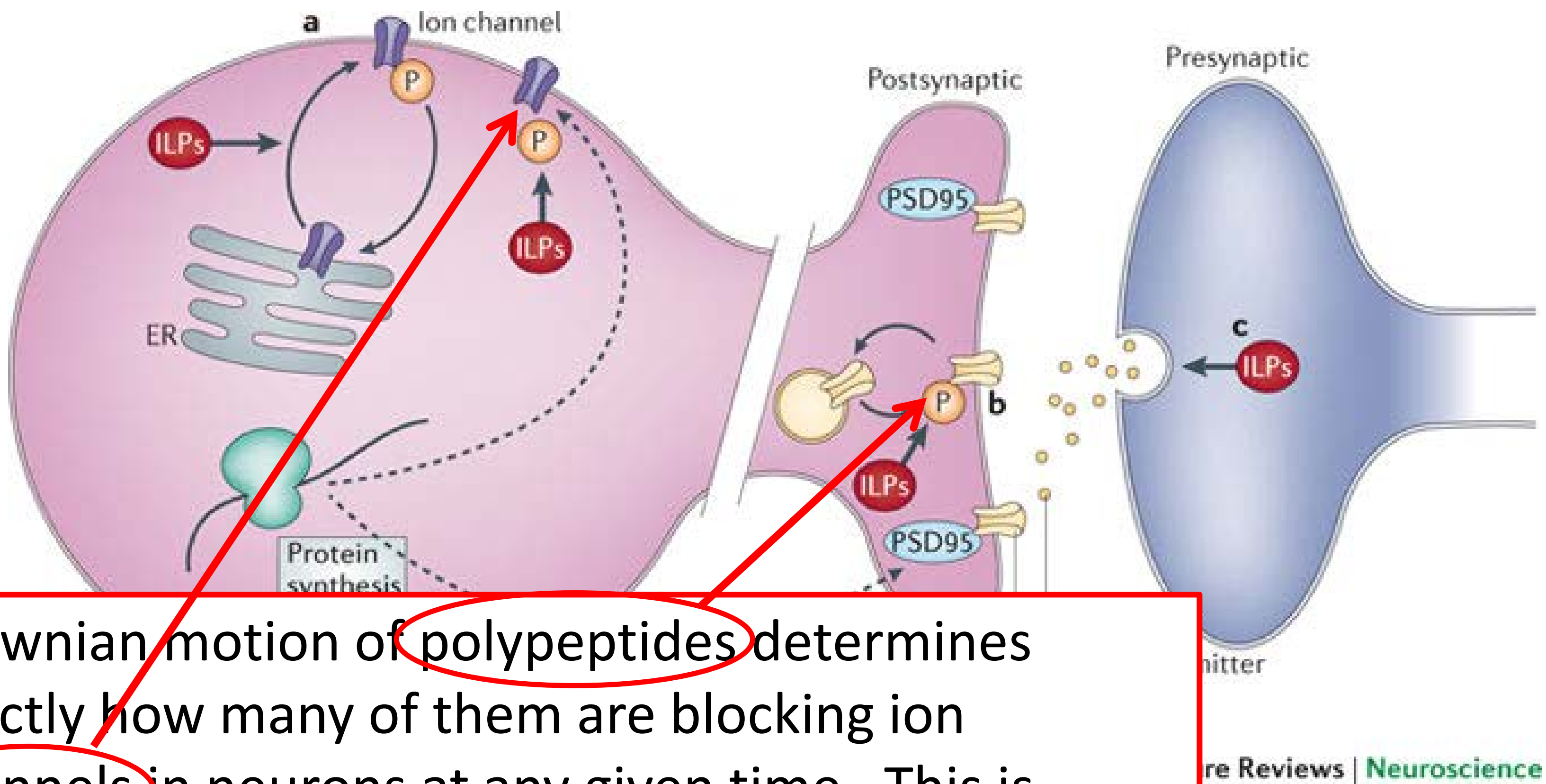


This result is at the root of our claim that all everyday probabilties are quantum

Every Brownian Motion is a "Schrödinger Cat"

Quantum at every [illegible]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

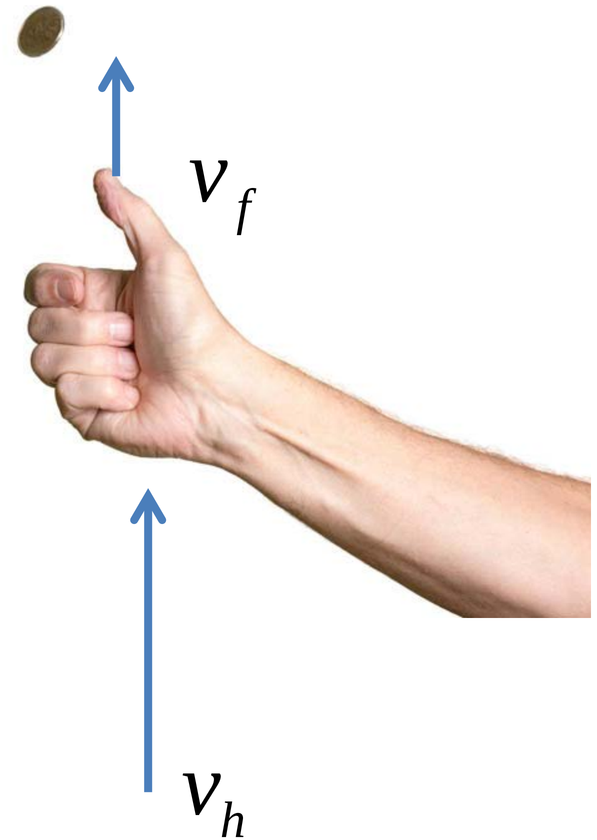
Analysis of coin flip

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

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

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

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



Coin diameter $= d$

Using:

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

$d = 0.01m$

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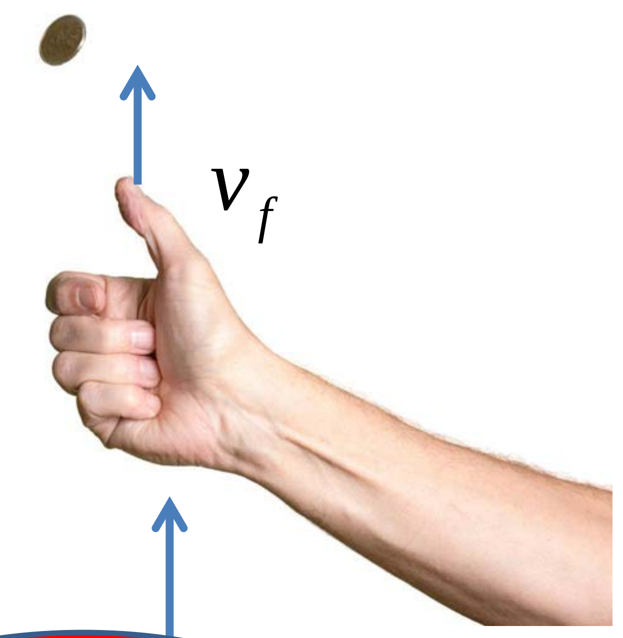

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50-50 coin flip probabilities are a derivable quantum result

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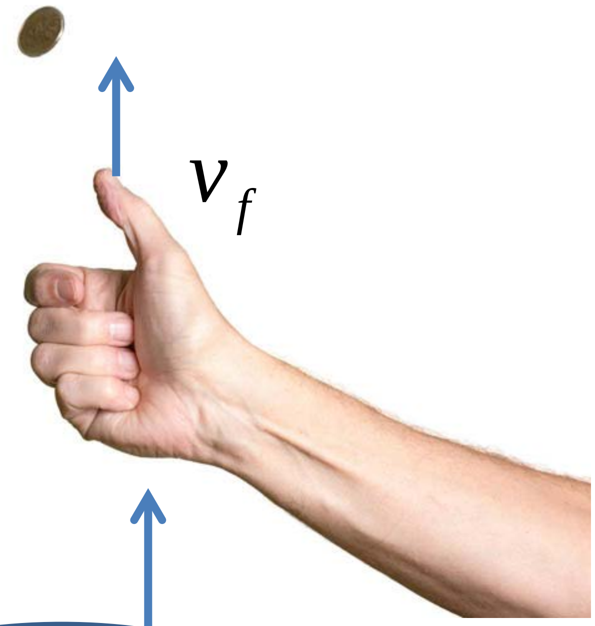

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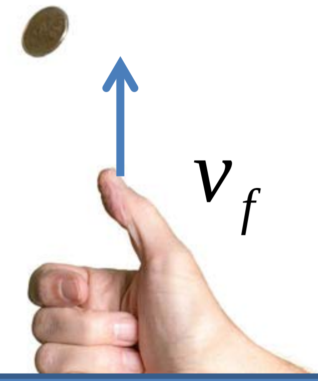
Usin

d

50-50 coin flip probabilities are a derivable quantum result

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

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

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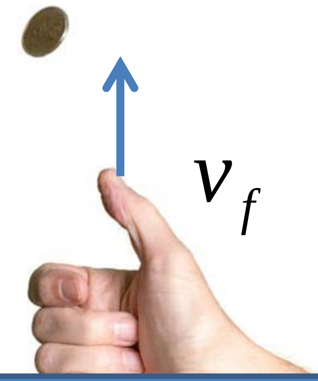

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Still, this is a good illustration of how quantum uncertainties can filter up into the macroscopic world, for systems that *are* random.

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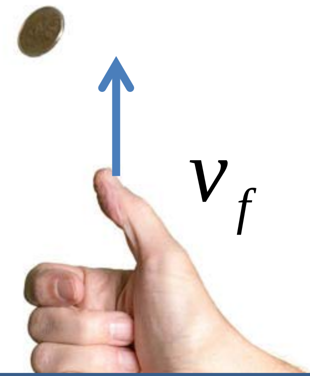

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Physical vs probabilities vs “probabilities of belief”

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 vs probabilities 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 vs probabilities vs "probabilities of belief"

This talk is about physical probability only

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

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Physical vs probabilities vs "probabilities of belief"

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

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

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

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All everyday probabilities are quantum probabilities

- Proof by exhaustion not realistic

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Part 3 Outline

1) The multiverse

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

3) Everyday probabilities

4) Further Discussion (Implications for the multiverse)

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Further discussion

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  - High levels of symmetries
  - (Observer centered: Noumra, Garriga & Vilenkin. Requires one of the above I think)

Further discussion

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Could these "fix" eternal inflation?

Further discussion

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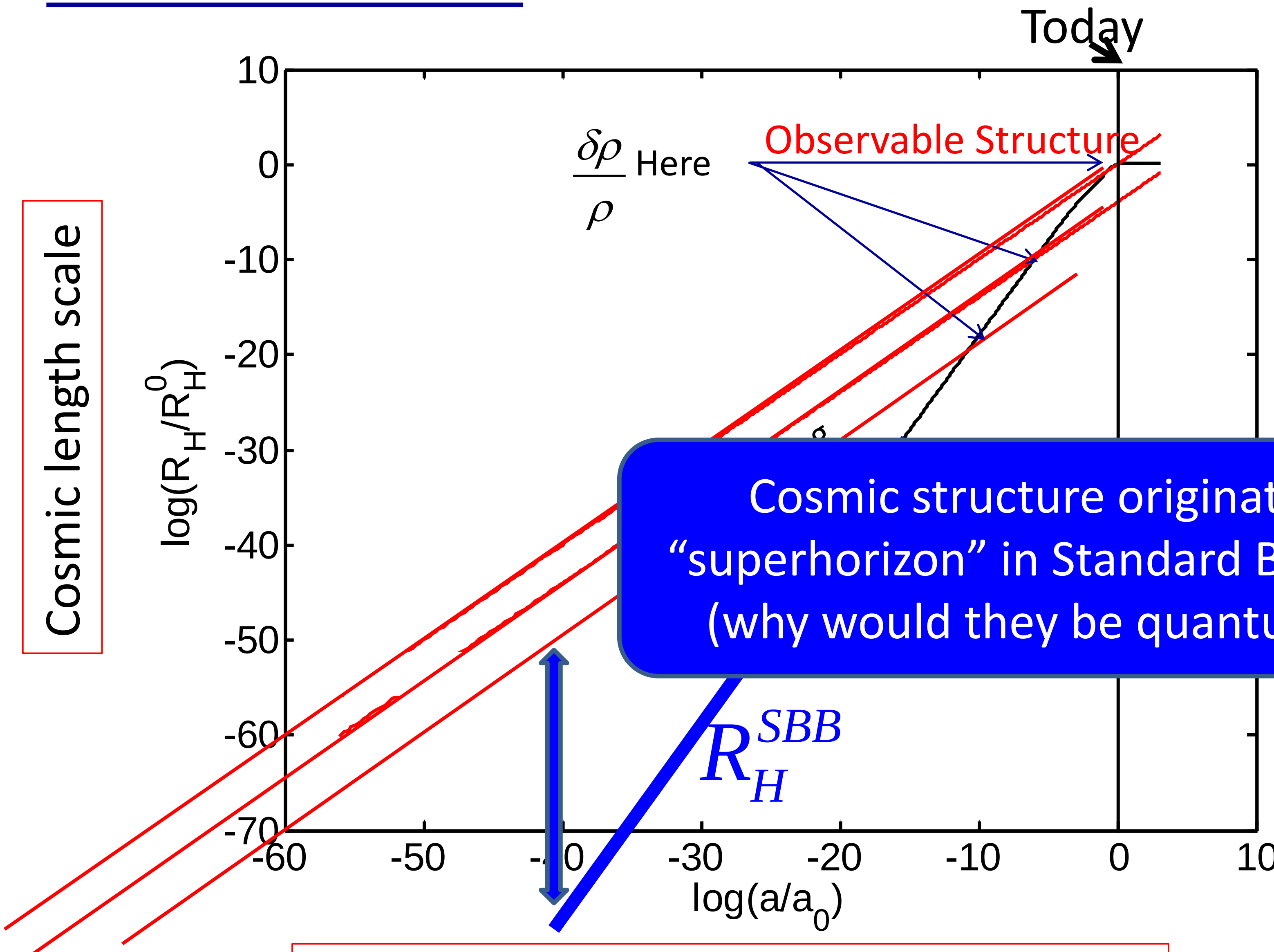
Cosmic structure

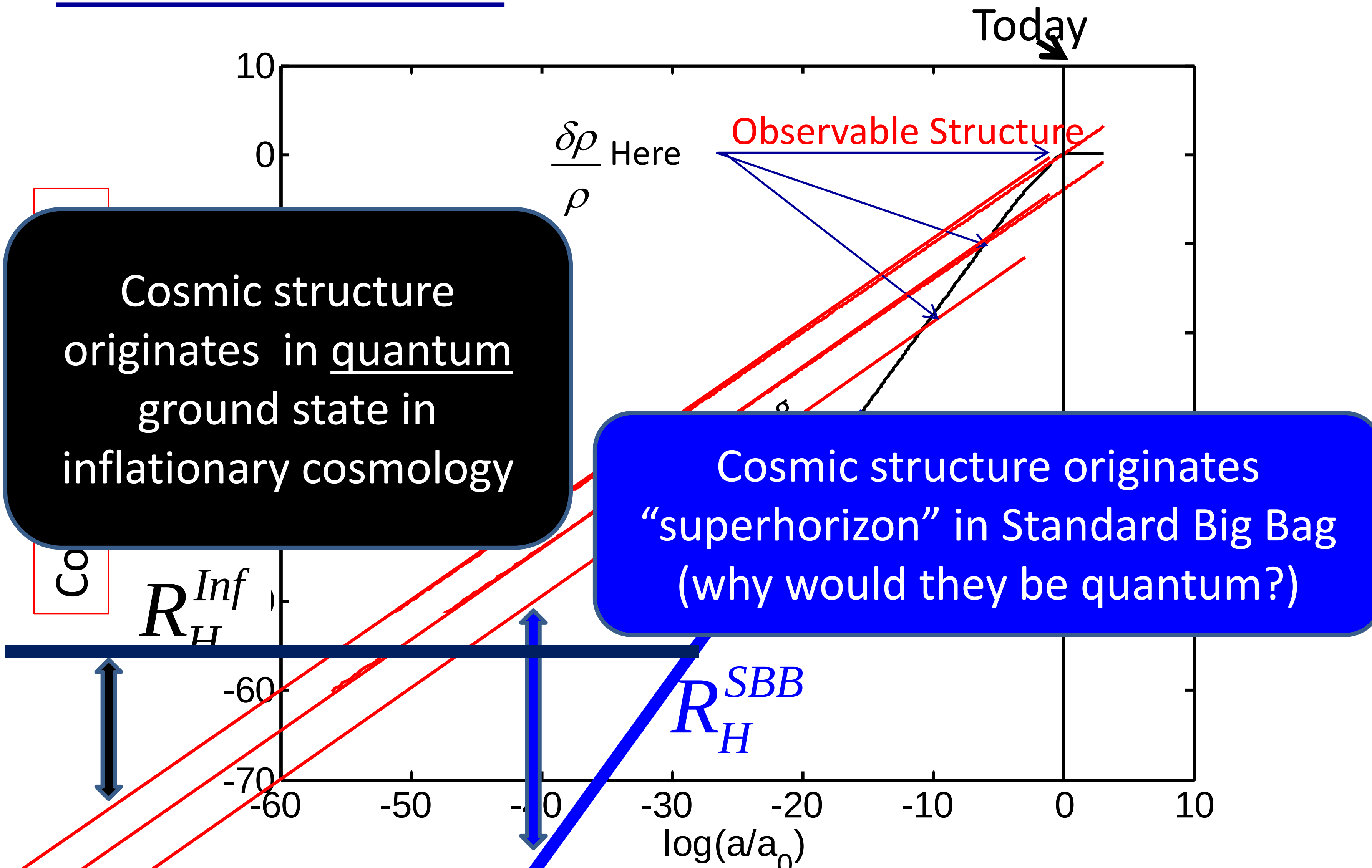
Cosmic length scale



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

Scale factor (measures expansion, time)

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?)

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Compare with identical particle statistics

Further discussion

<u>Many topics that seem "principle-driven" for classical probabilities should actually be derivable from quantum physics</u>

- (Micro)canonical ensemble (vs "equipartiton")
- "principle of indifference"
- etc

Further discussion

Bet on the millionth digit of π (or Chaitin's Ω)

3.14159265358979323846264338327950288419716939937510582097494459230781640628 6
208998628034825342117067982148086513282306647093844609550582231725359408128481
117450284102701938521105559644622948954930381964428810975665933446128475648233
786783165271201909145648566923460348610454326648213393607260249141273724587006
606315588174881520920962829254091715364367892590360011330530548820466521384146
951941511609433057270365759591953092186117381932611793105118548074462379962749
567351885752724891227938183011949129833673362440656643086021394946395224737190
702179860943702770539217176293176752384674818467669405132000568127145263560827
785771342757789609173637178721468440901224953430146549585371050792279689258923
542019956112129021960864034418159813629774771309960518707211349999998372978049
951059731732816096318595024459455346908302642522308253344685035261931188171010
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065485863278865936153381827968230301952035301852968995773622599413891249721775
283479131515574857242454150695950829533116861727855889075098381754637464939319
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782354781636009341721641219924586315030286182974555706749838505494588586926995
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287467764657573962413890865832645995813390478027590099465764078951269468398352
595709825822620522489407726719478268482601476990902640136394437455305068203496

Further discussion

Bet on the millionth digit of π (or Chaitin's Ω)

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

3.1415926535
2089986280
11745028410
786783165271201909145648566923460348610454326648213393607260249141273724587006
606315588174881520920962829254091715364367892590360011330530548820466521384146
951941511609433057270365759591953092186117381932611793105118548074462379962749
567351885752724891227938183011949129833673362440656643086021394946395224737190
702179860943702770539217176293176752384674818467669405132000568127145263560827
785771342757789609173637178721468440901224953430146549585371050792279689258923
542019956112129021960864034418159813629774771309960518707211349999998372978049
951059731732816096318595024459455346908302642522308253344685035261931188171010
003137838752886587533208381420617177669147303598253490428755468731159562863882
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837449448255379774726847104047534646208046684259069491293313677028989152104752
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141441973568548161361157352552133475741849468438523323907394143334547762416862
518983569485562099219222184272550254256887671790494601653466804988627232791786
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626945604241965285022210661186306744278622039194945047123713786960956364371917
287467764657573962413890865832645995813390478027590099465764078951269468398352
595709825822620522489407726719478268482601476990902640136394437455305068203496

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- 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
2089986280З
11745028410
78678316527
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Further discussion

Bet on the millionth digit of π (or Chaitin's Ω)

- 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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5957098258226205224894077267194782684826014769909026401363944374553050682034 96

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- The only randomness in a bet on a digit of π is quantum!

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9519415116
5673518857
7021798609
7857713427
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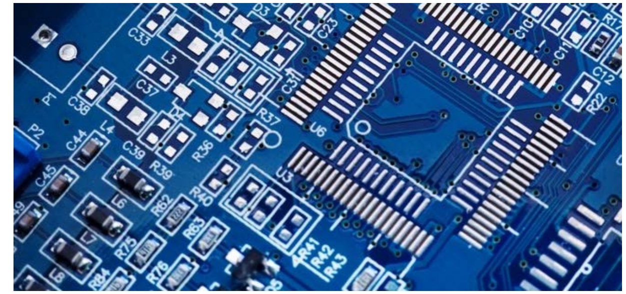
600101655256375678

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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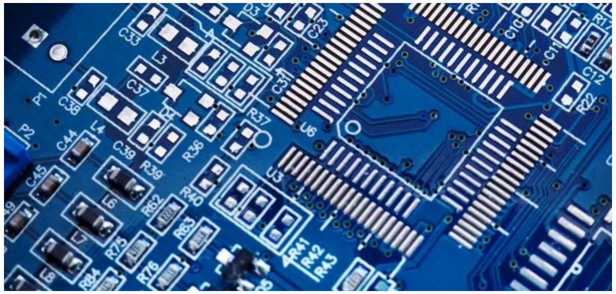
Std. thinking about classical probabilities

Further discussion



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

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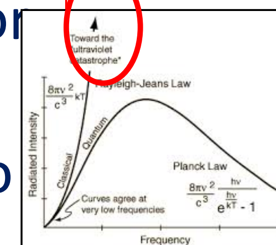

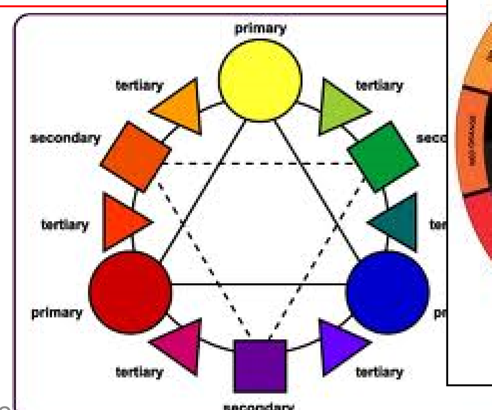

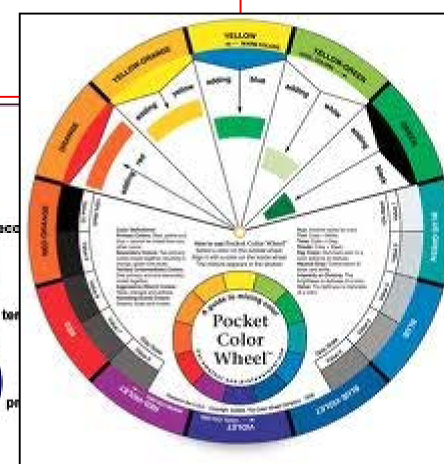

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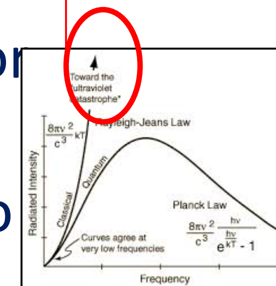

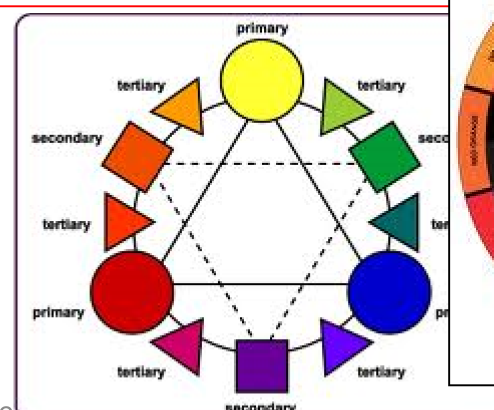

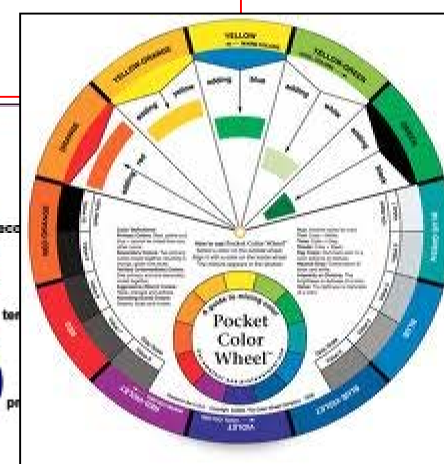

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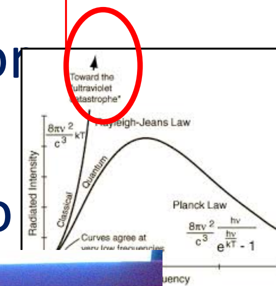

Part 3 Outline

1) The multiverse
2) Quantum vs non-quantum probabilities (toy model/multiverse)
3) Everyday probabilities
4) Further Discussion (Implications for the multiverse)

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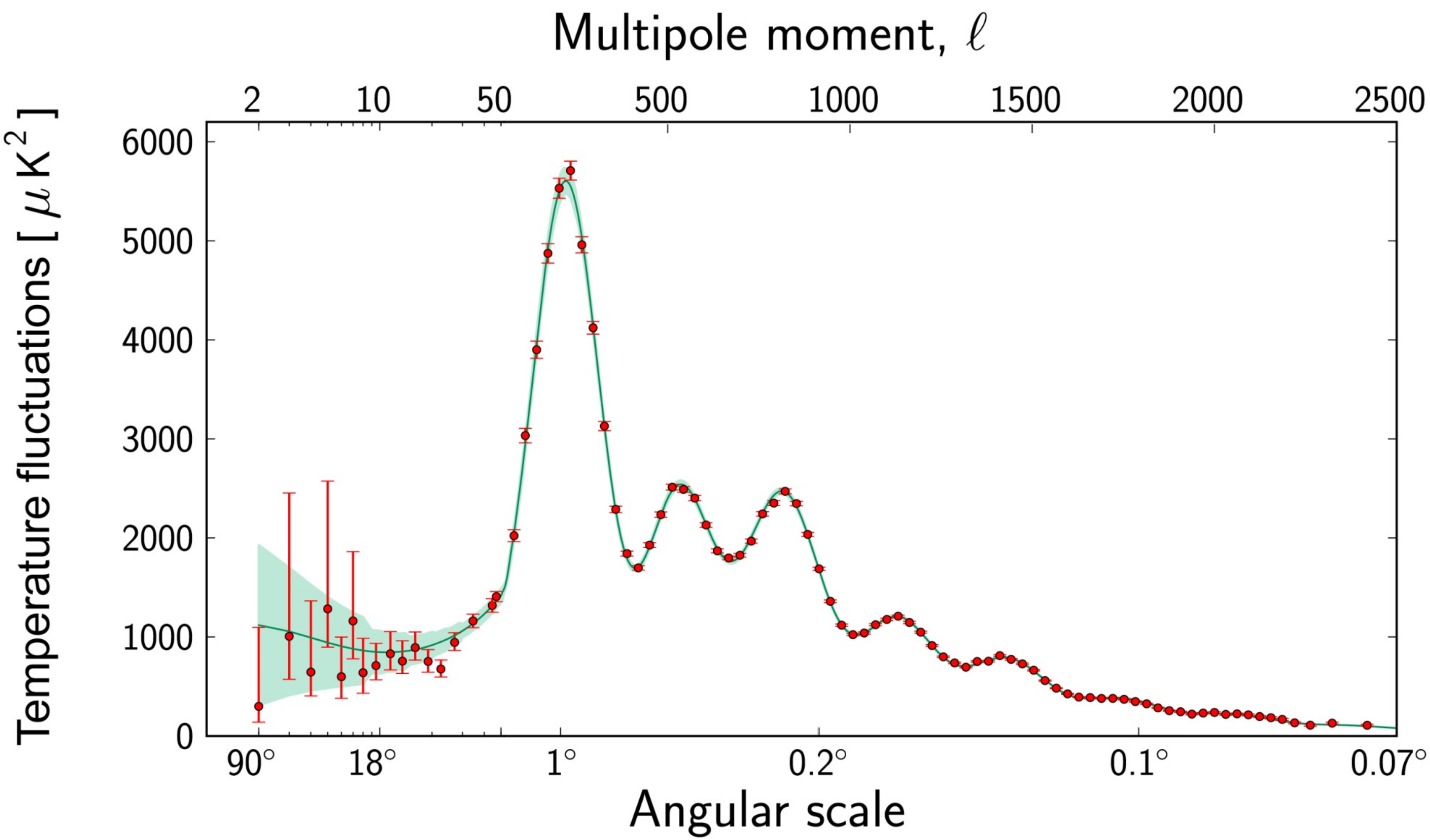

Multipole moment, ℓ
2
10
50
500
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1500
2000
2500
Temperature fluctuations [μK^2]
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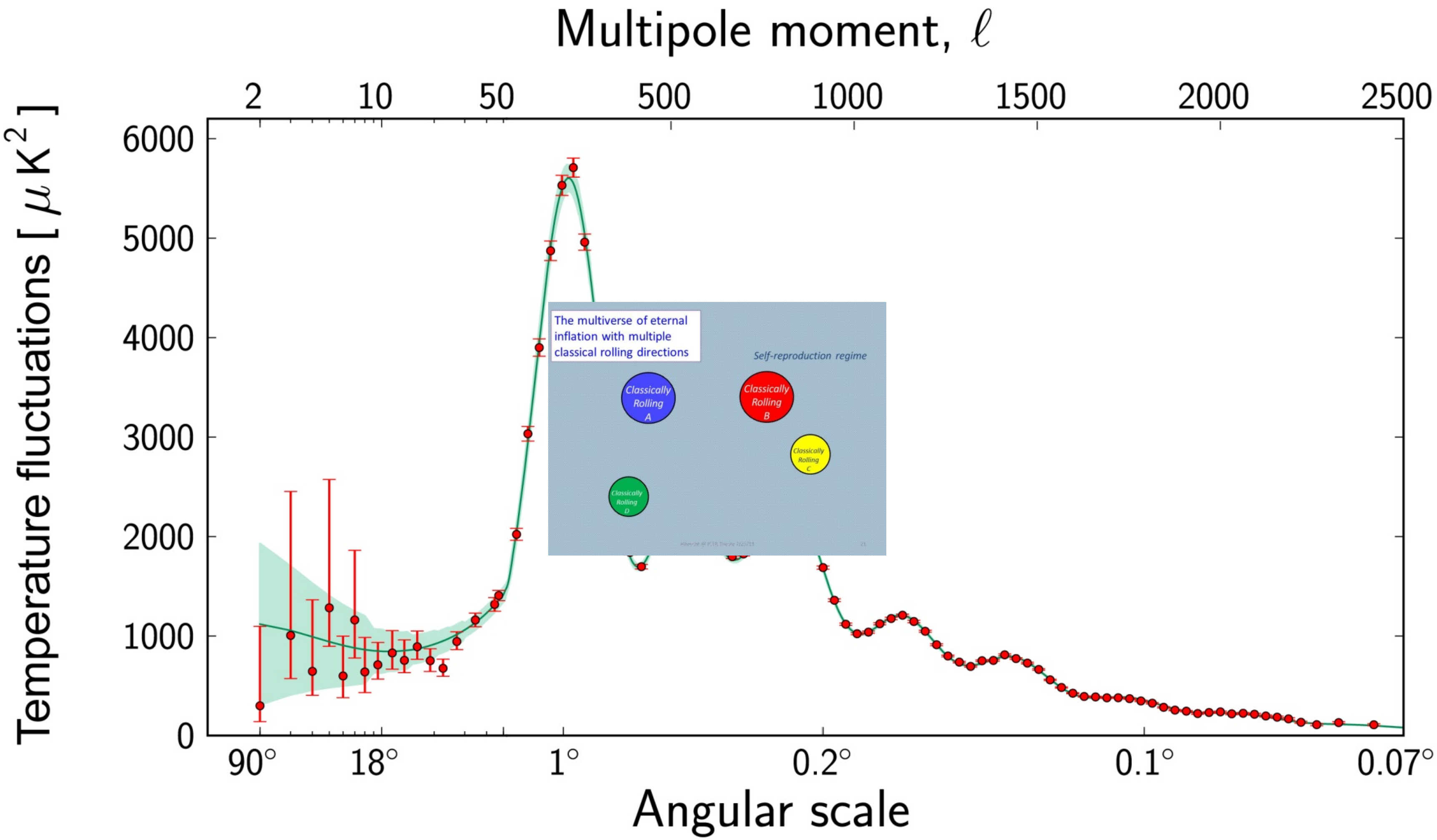
5000
4000
3000
2000
1000
0
90°
18°
1°
0.2°
0.1°
0.07°
Angular scale


Multipole moment, ℓ
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2000
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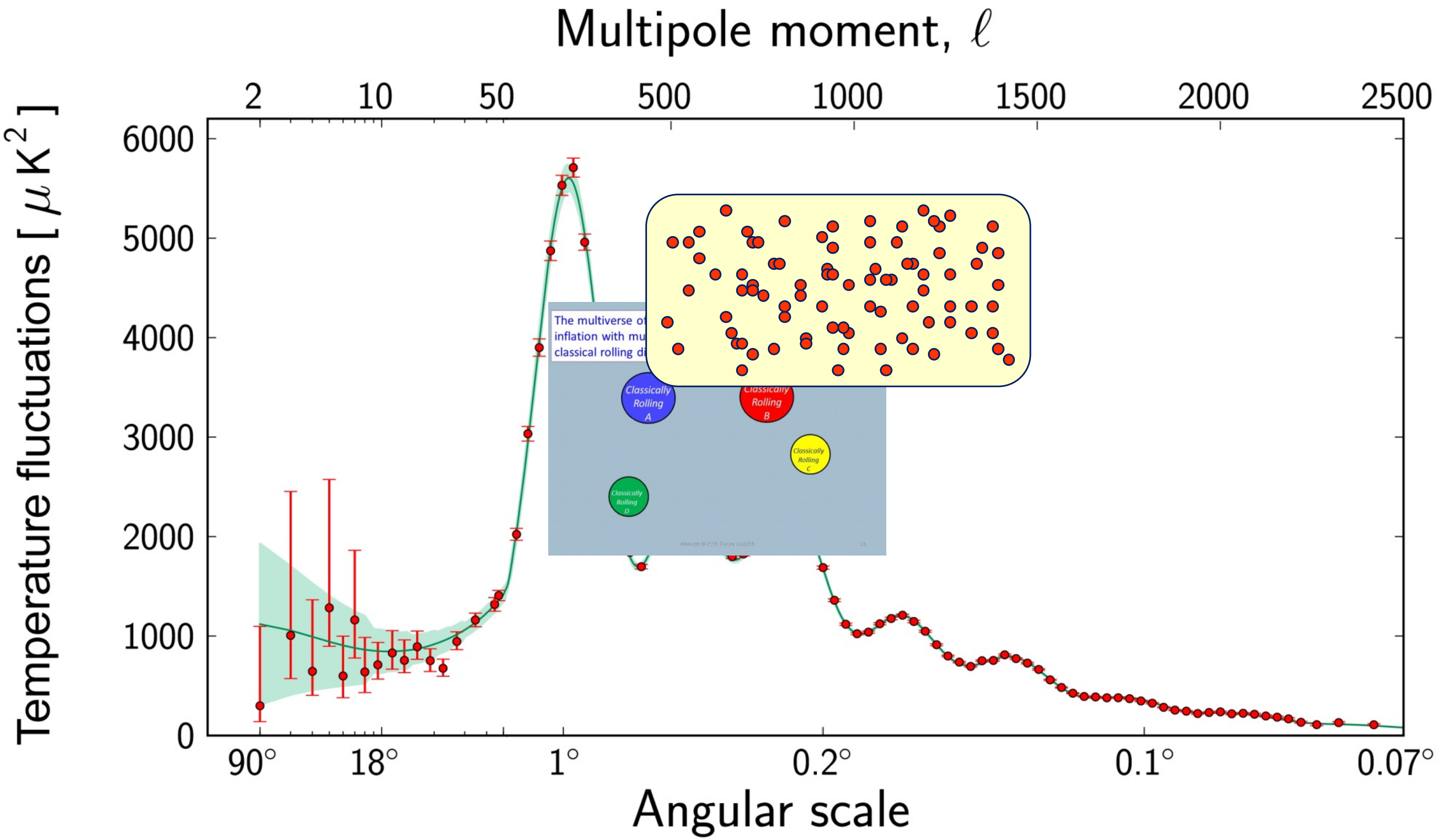
18°
1°
0.2°
0.1°
0.07°
Angular scale
The multiverse of eternal inflation with multiple classical rolling directions
Self-reproduction regime
Classically Rolling A
Classically Rolling B
Classically Rolling C
Classically Rolling D


Multipole moment, ℓ
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Angular scale
The multiverse of
inflation with mu
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Classically Rolling A
Classically Rolling B
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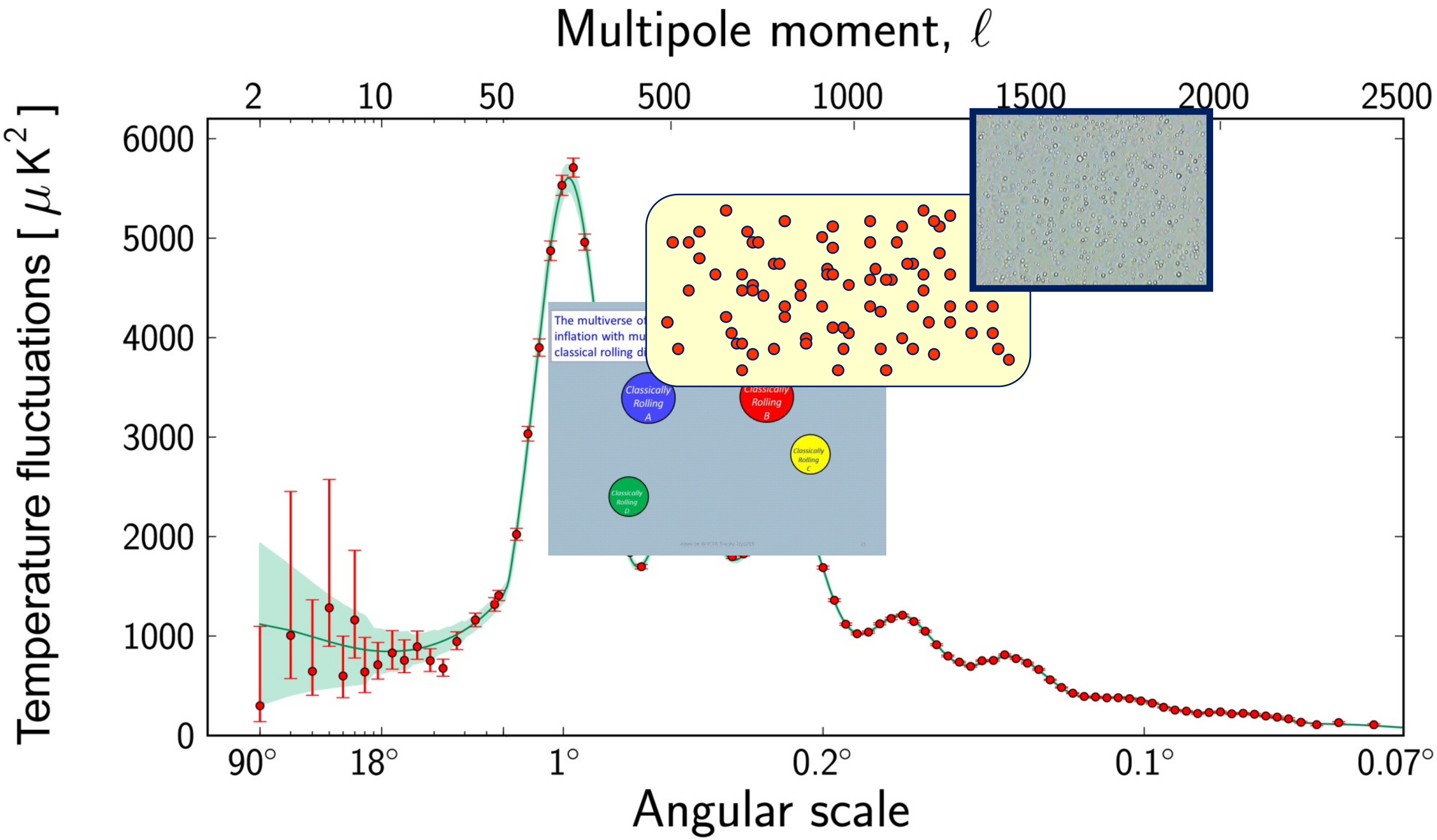
Classically Rolling D


Multipole moment, ℓ
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Temperature fluctuations [μK^2]
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The multiverse of
inflation with mu
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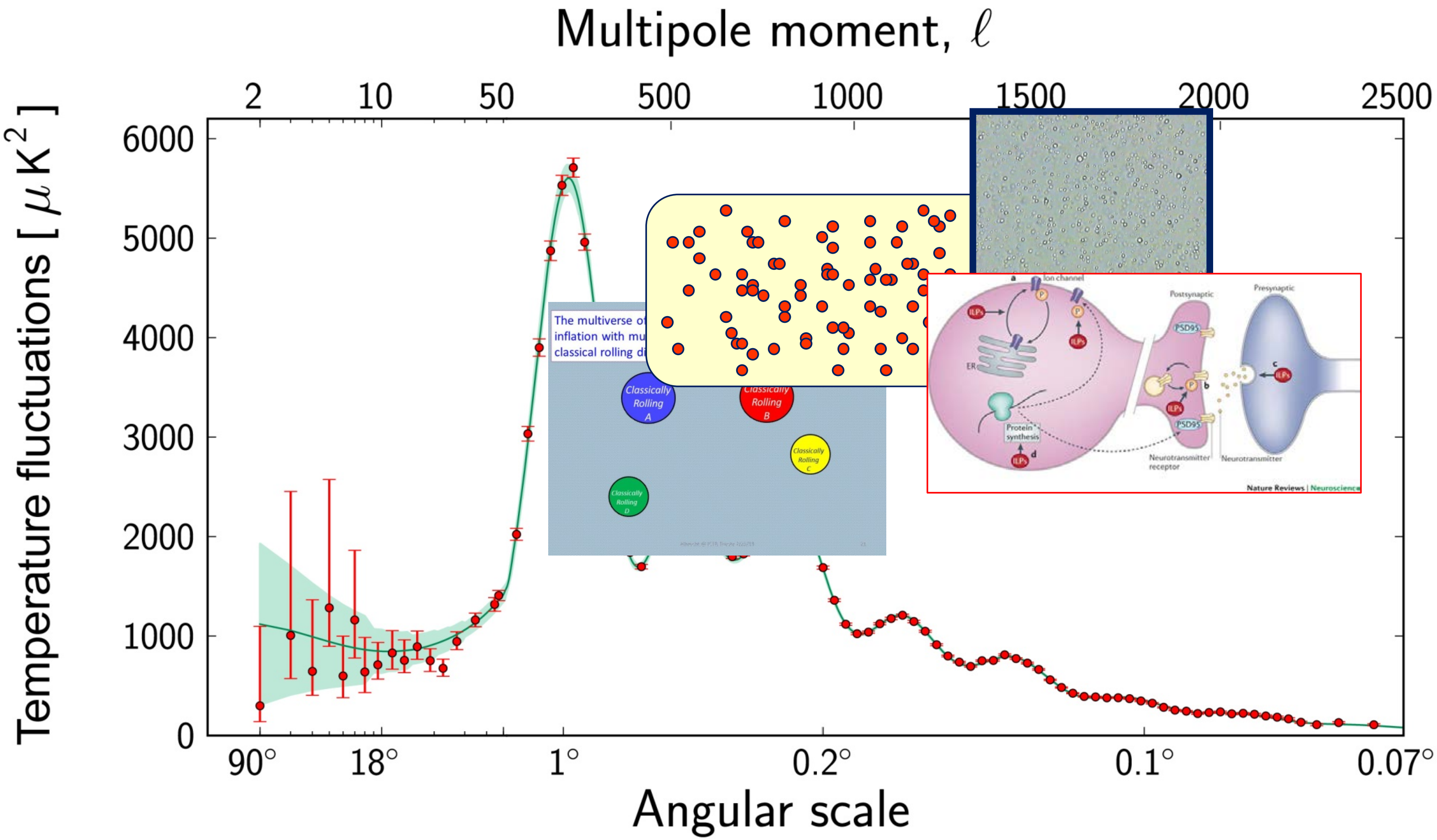
Classically Rolling A
Classically Rolling B
Classically Rolling C
Classically Rolling D



Multipole moment, ℓ
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Temperature fluctuations [μK^2]
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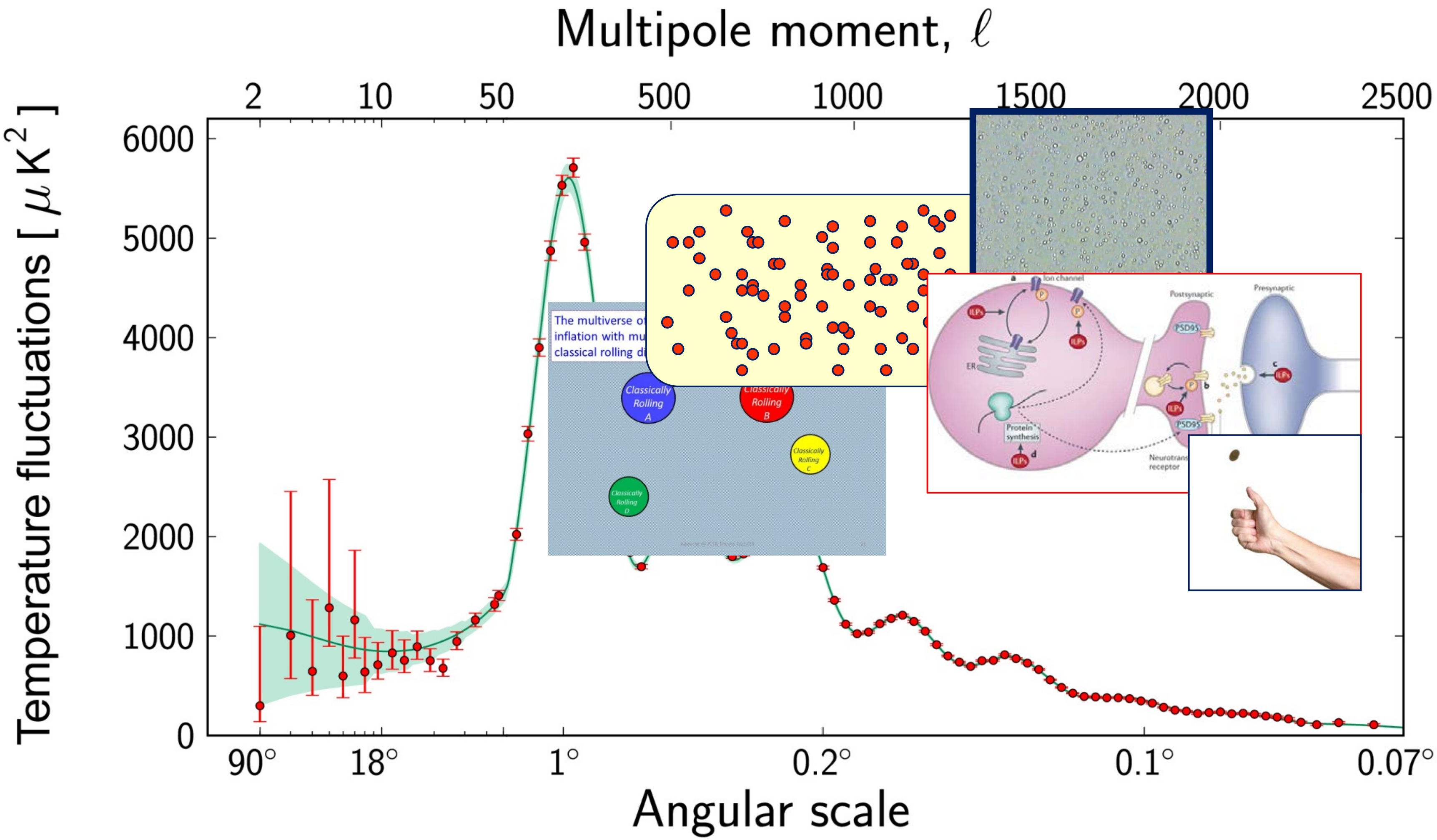
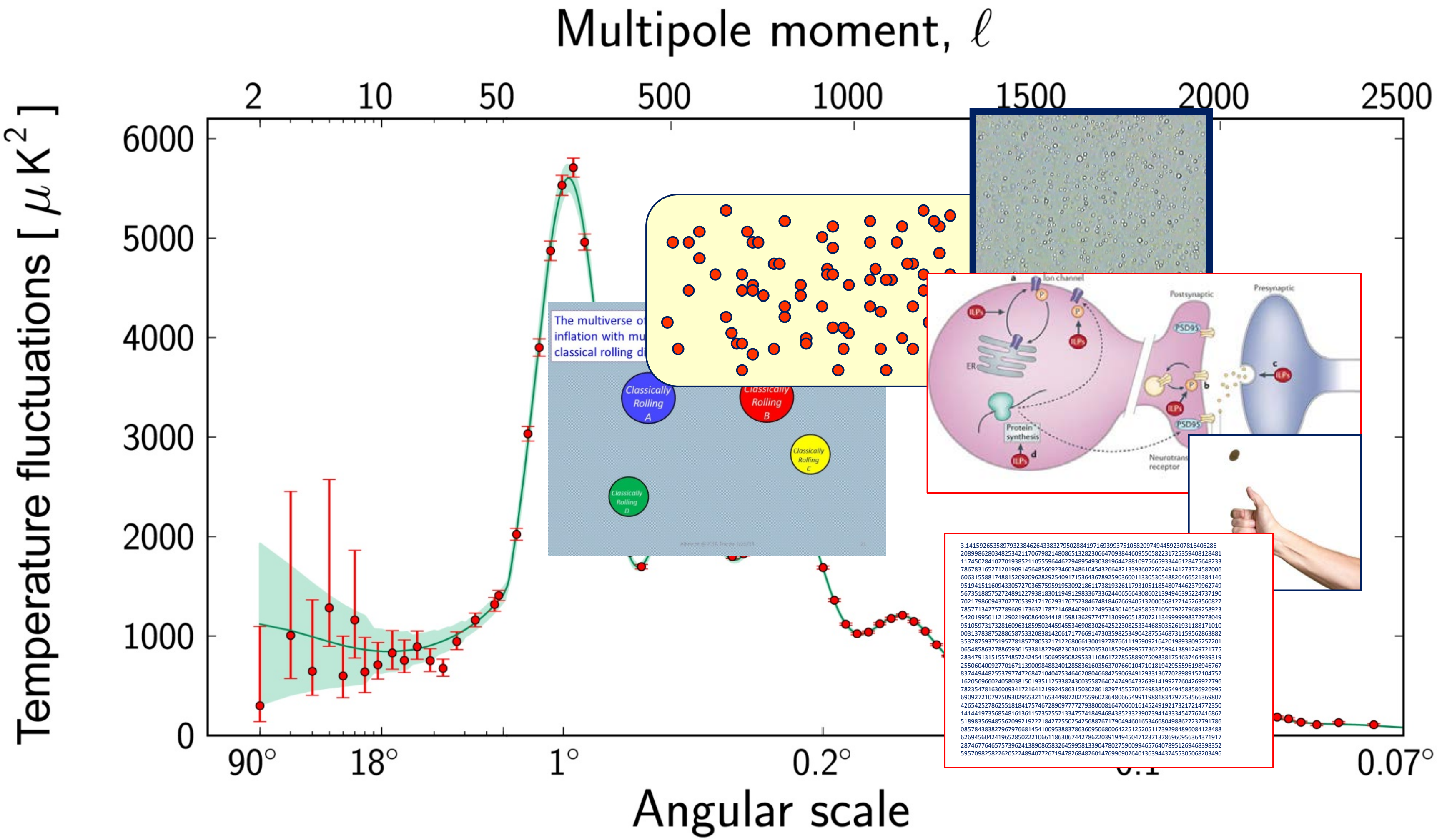
18°
1°
0.2°
0.1°
0.07°
Angular scale
The multiverse of
inflation with mu
classical rolling d
Classically Rolling A
Classically Rolling B
Classically Rolling C
Classically Rolling D
Ion channel
Postsynaptic
Presynaptic
ILPs
ER
PSD95
Protein synthesis
Neurotransmitter receptor
Neurotransmitter
Nature Reviews | Neuroscience



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
Classically Rolling A
Classically Rolling B
Classically Rolling C
Classically Rolling D
Ion channel
Postsynaptic
Presynaptic
ILPs
PSD95
ER
Protein synthesis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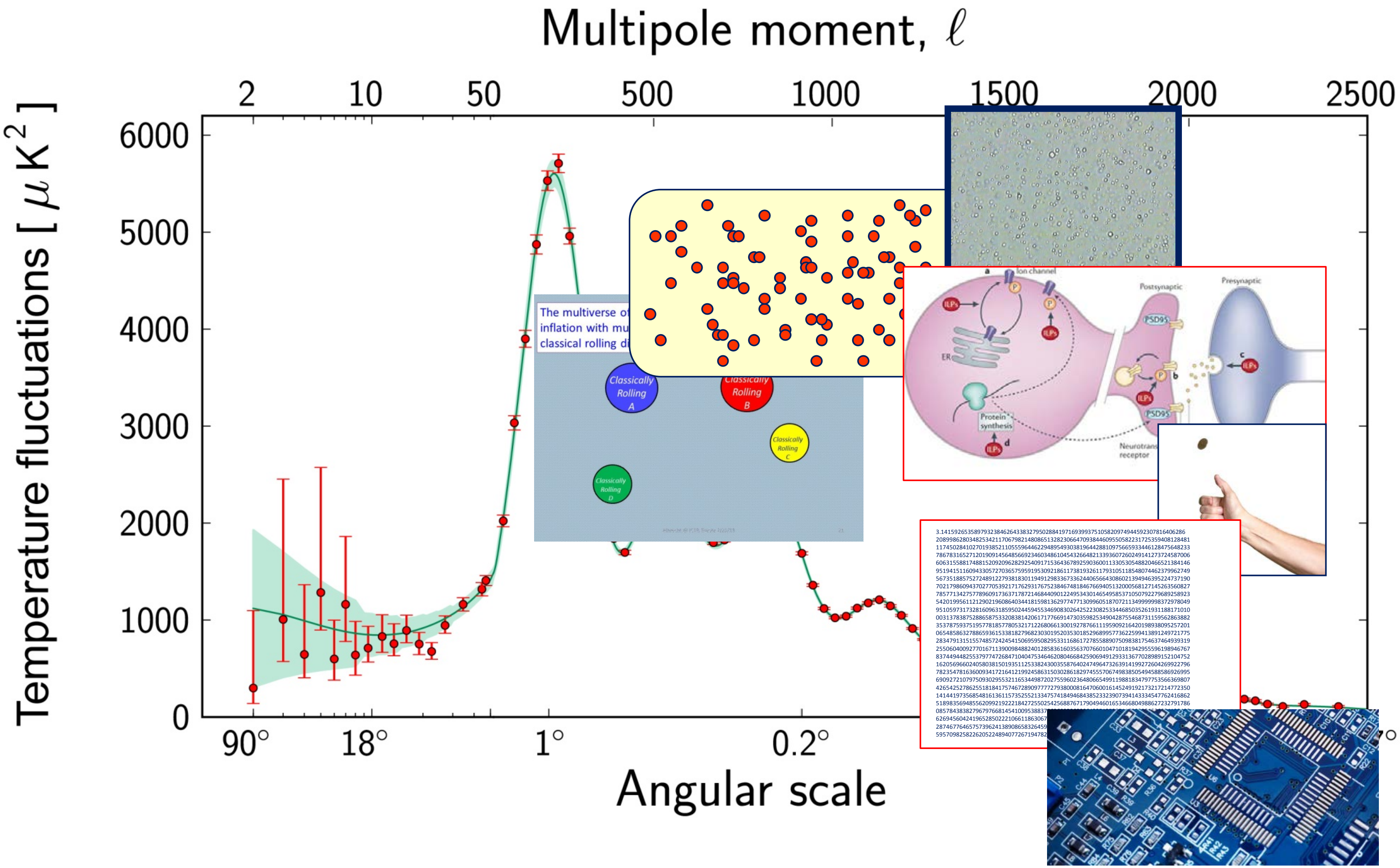
Neurotrans receptor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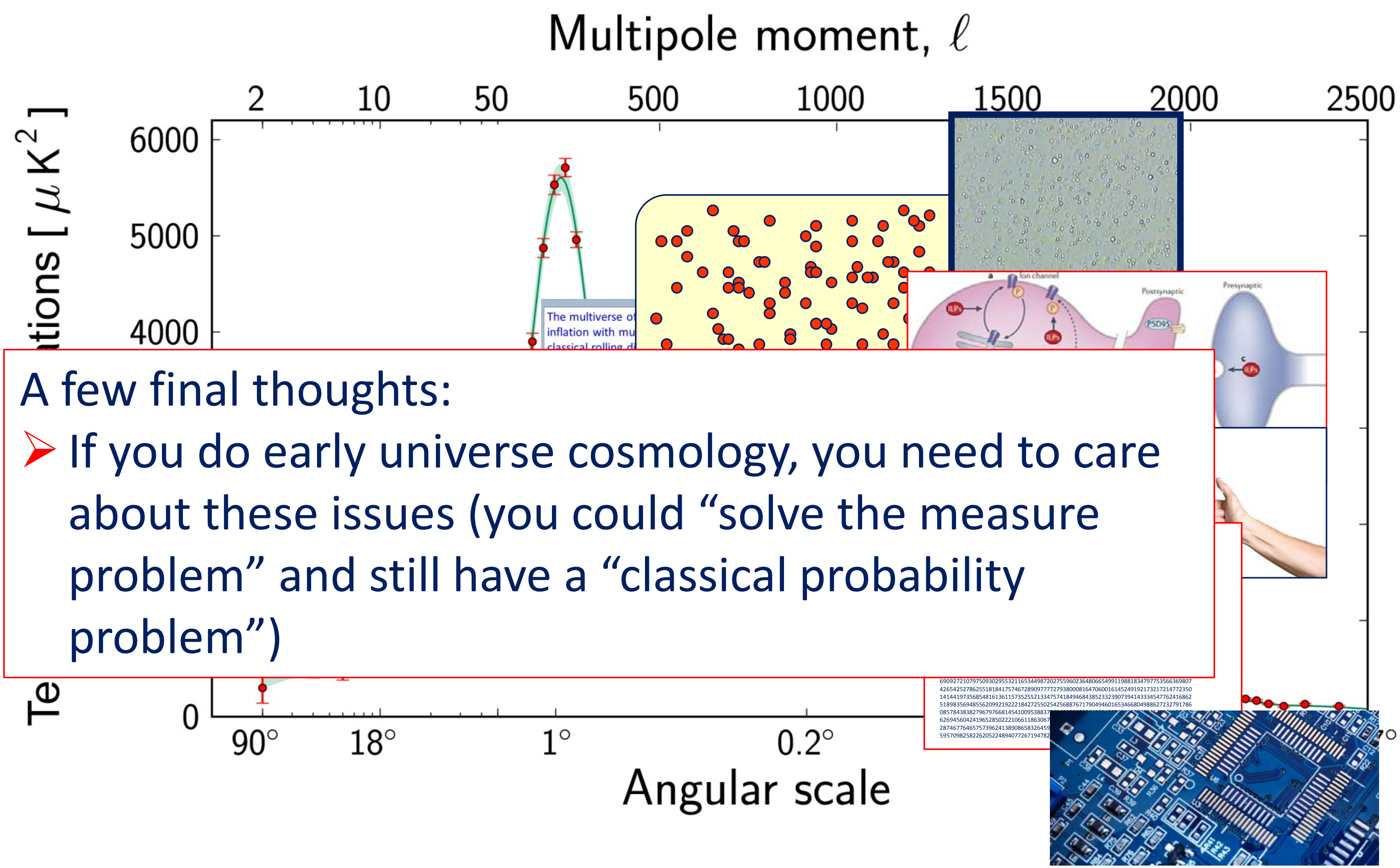
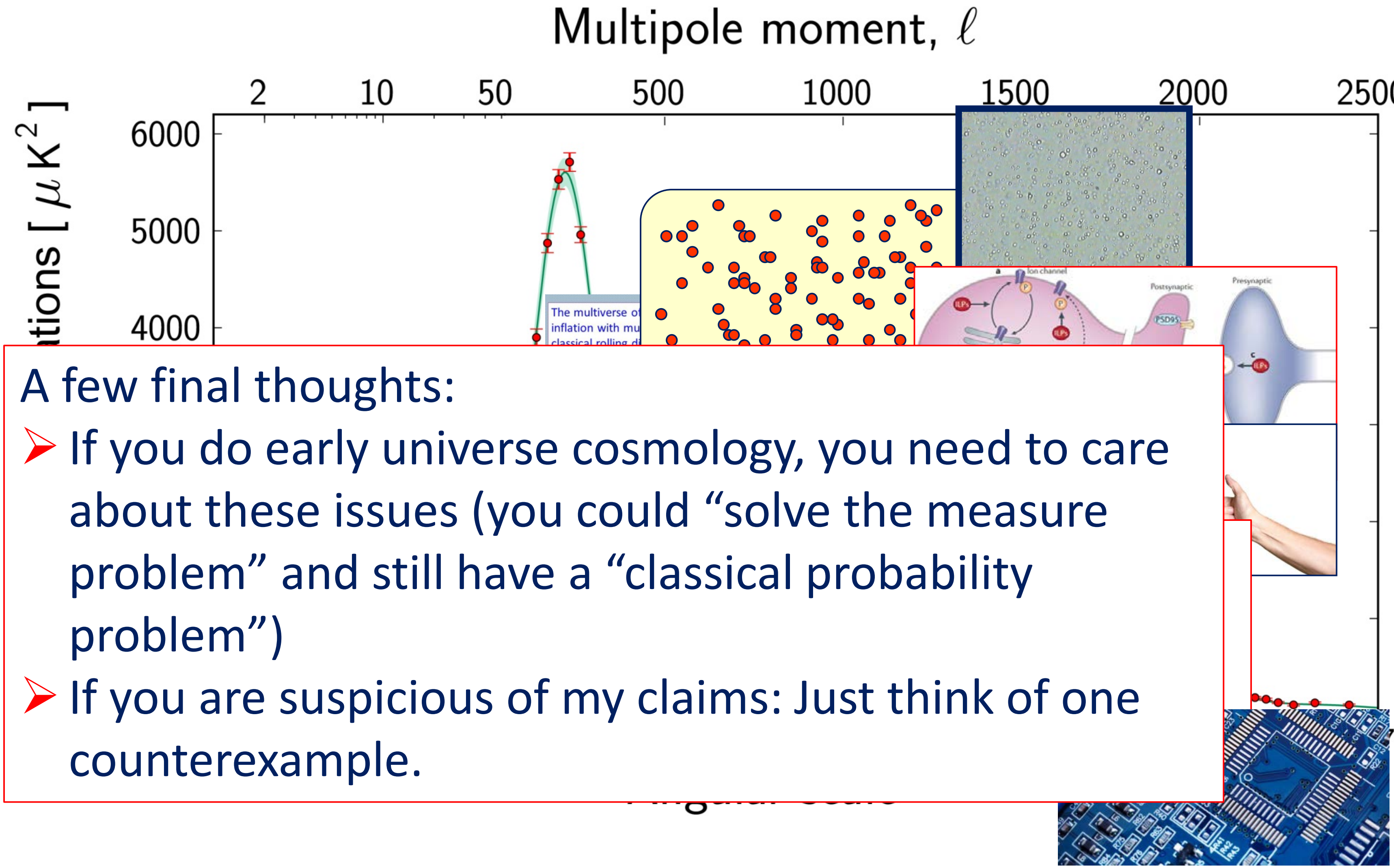


A few final thoughts:

- If you do early universe cosmology, you need to care about these issues (you could "solve the measure problem" and still have a "classical probability problem")



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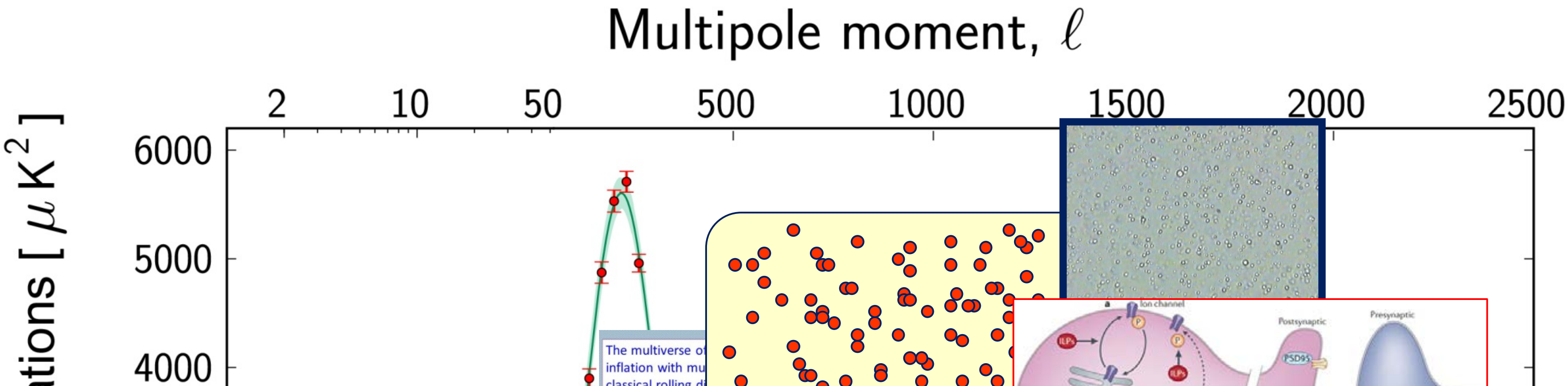

A few final thoughts (Part 3):

- If you do early universe cosmology, you need to care about these issues (you could “solve the measure problem” and still have a “classical probability problem”)
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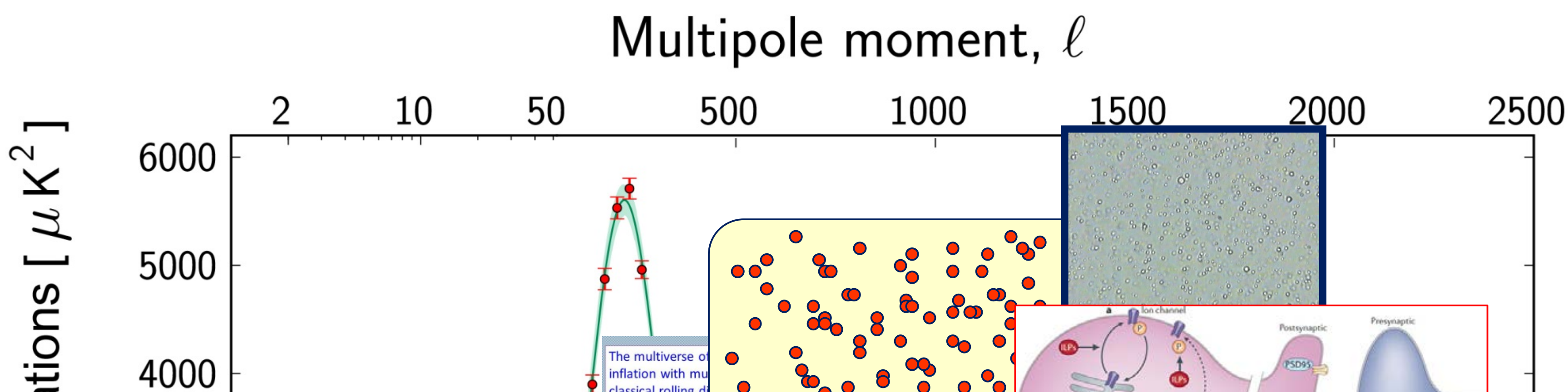
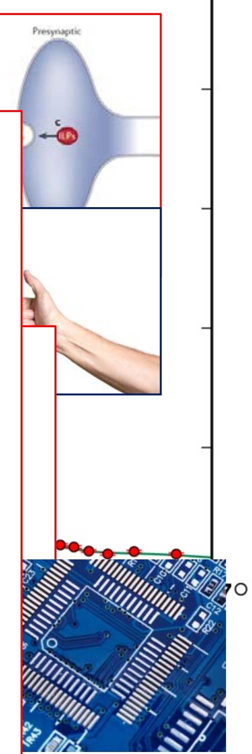
- In any case, I hope you find this mix of ideas as fun as I do!





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Les Houches Lectures on Cosmic Inflation

Four Parts

1) Introductory material

2) Entropy, Tuning and Equilibrium in Cosmology

3) Classical and quantum probabilities in the multiverse

End Part 3

4) de Sitter equilibrium cosmology

Andreas Albrecht; UC Davis
Les Houches Lectures; July-Aug 2013