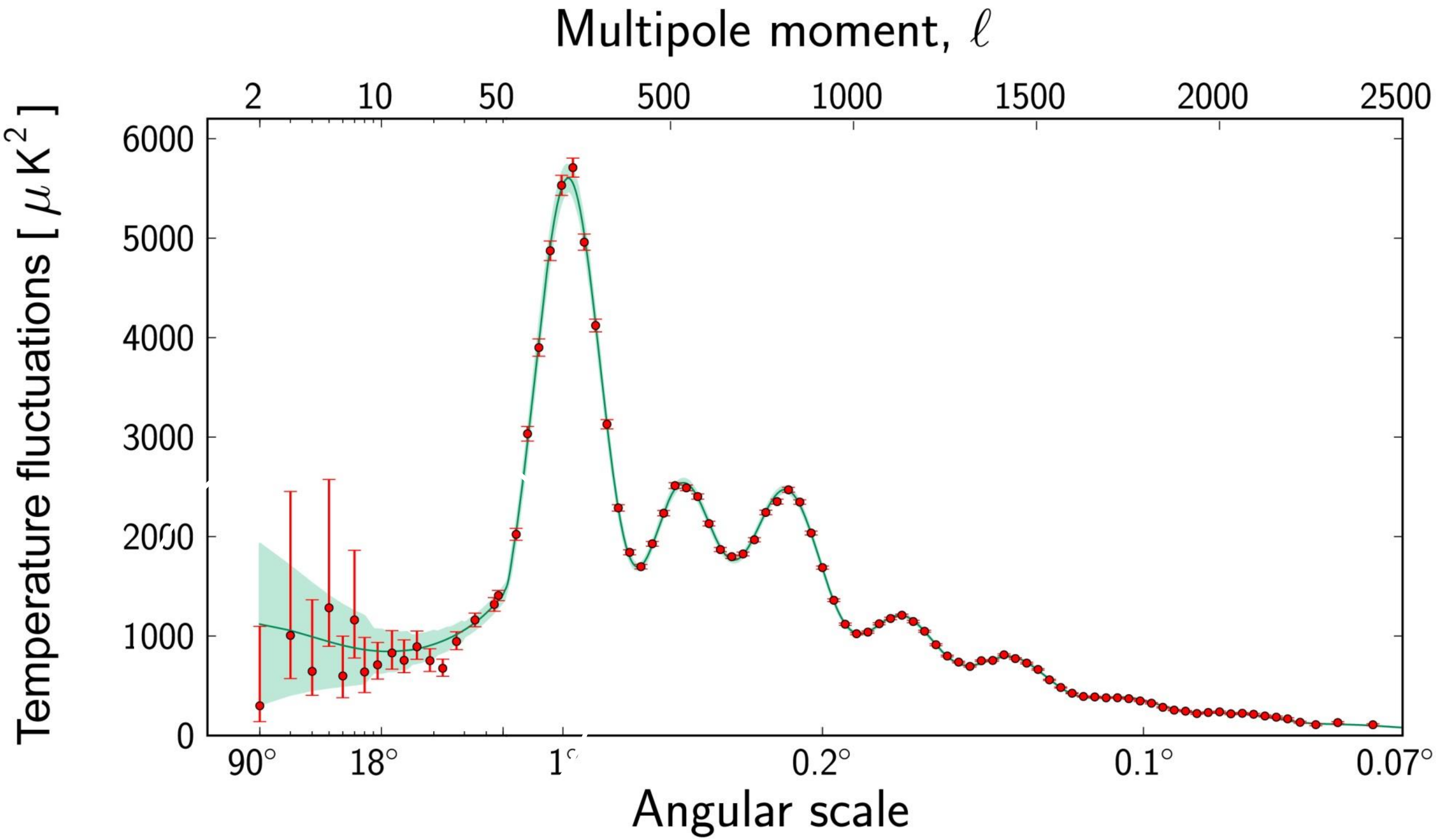
Challenges for theoretical cosmology

Andreas Albrecht

Fundamental Questions in Cosmology
UC Davis May 2013


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

Challenges for Cosmic Inflation (eternal inflation)

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

From Monday Panel Discussion

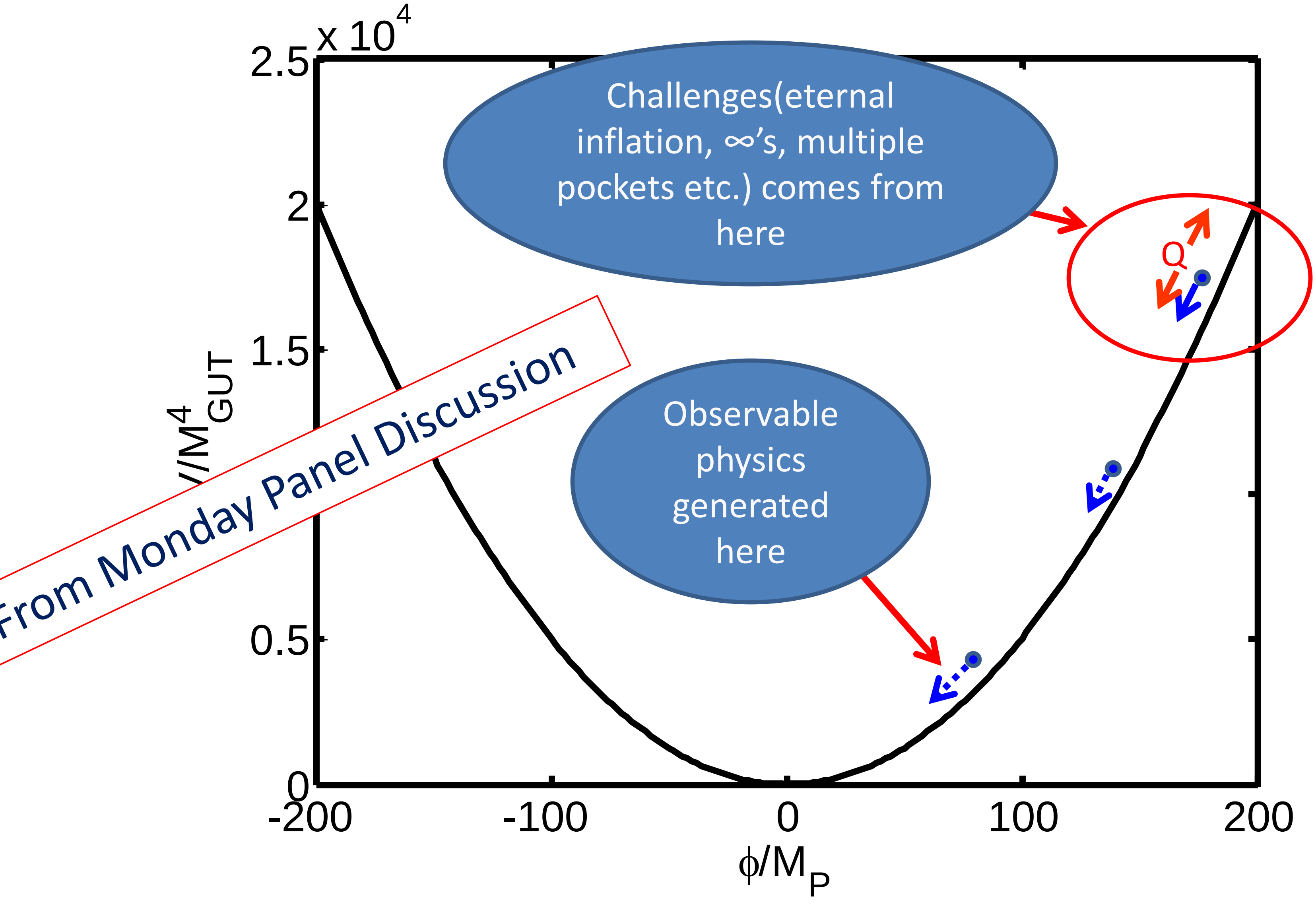
1) Measure Problems

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 2nd law, low *S* start

4) **Yet**, Successful fits to data

Slow rolling of inflaton



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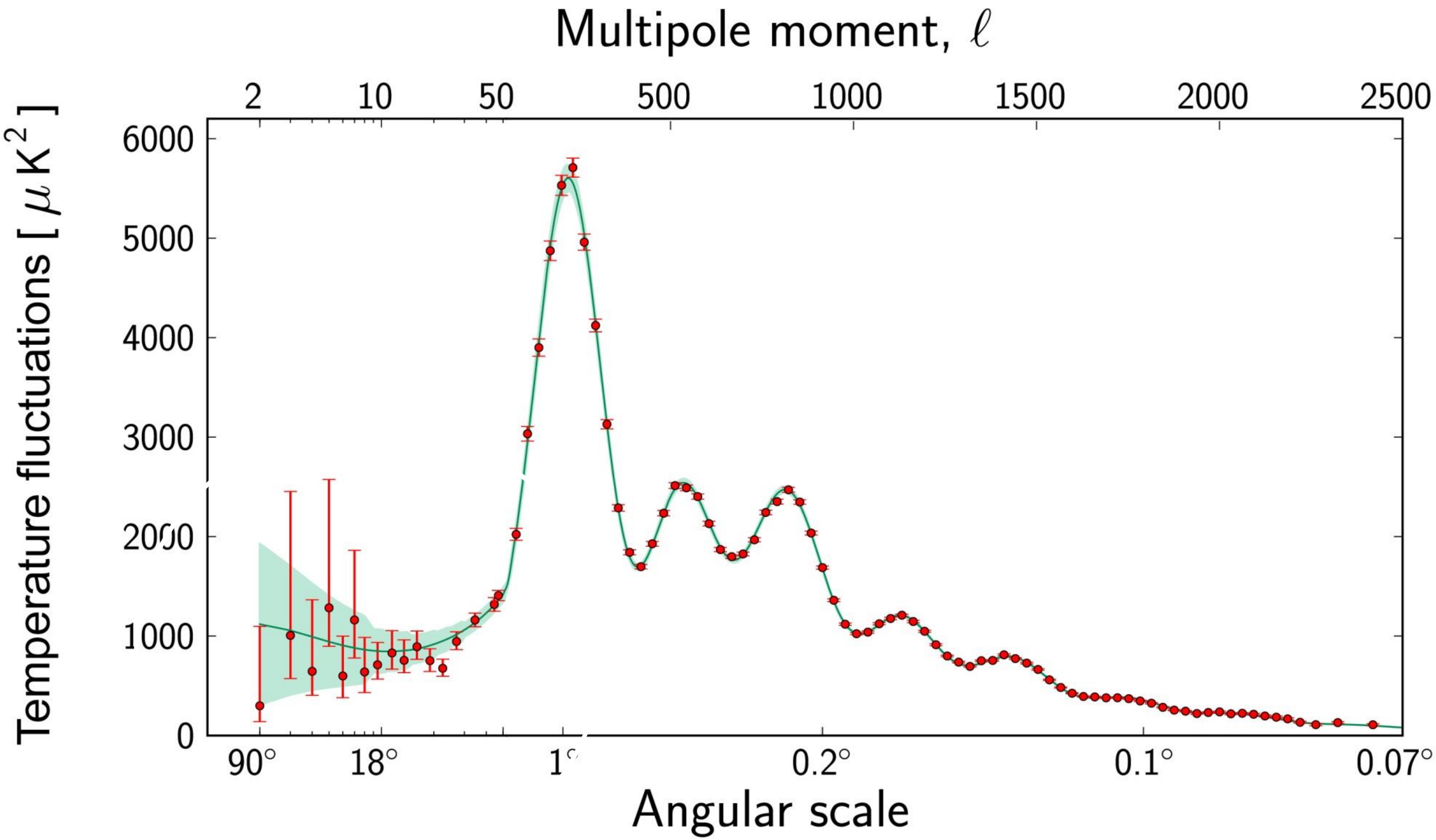

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Challenges: Answer these questions re your theories & beliefs:

1) Do you predict the observed state of the universe to be likely or natural? (And do you care?)

2) Do you treat infinities rigorously?

3) Do you require a probability tooth fairy?

1) Do you predict the observed state of the universe to be likely or natural? (And do you care?)

- Beware hidden assumptions about initial conditions (often related to 2nd law: $\dot{S} > 0$ ➔ S initially small ➔ starting in limited part of phase space)

Gibbons & Turok
Carroll & Tam
Shiffren & Wald
Penrose

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(just as true of cyclic models)

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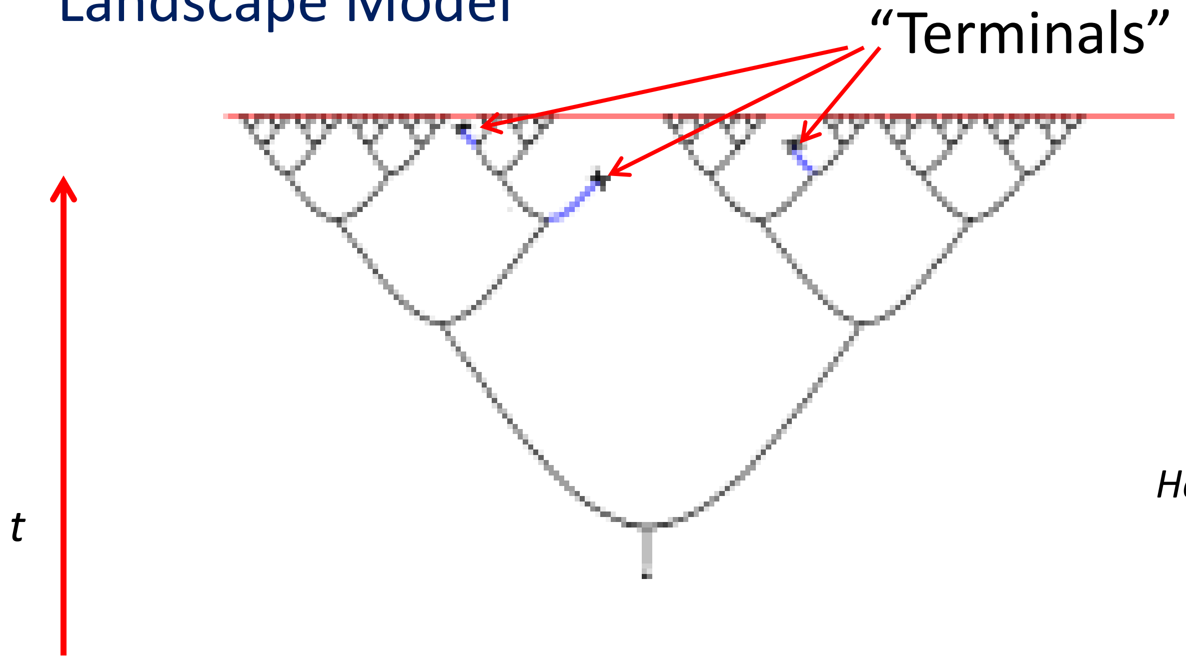
Landscape Model



Harlow et al 2012

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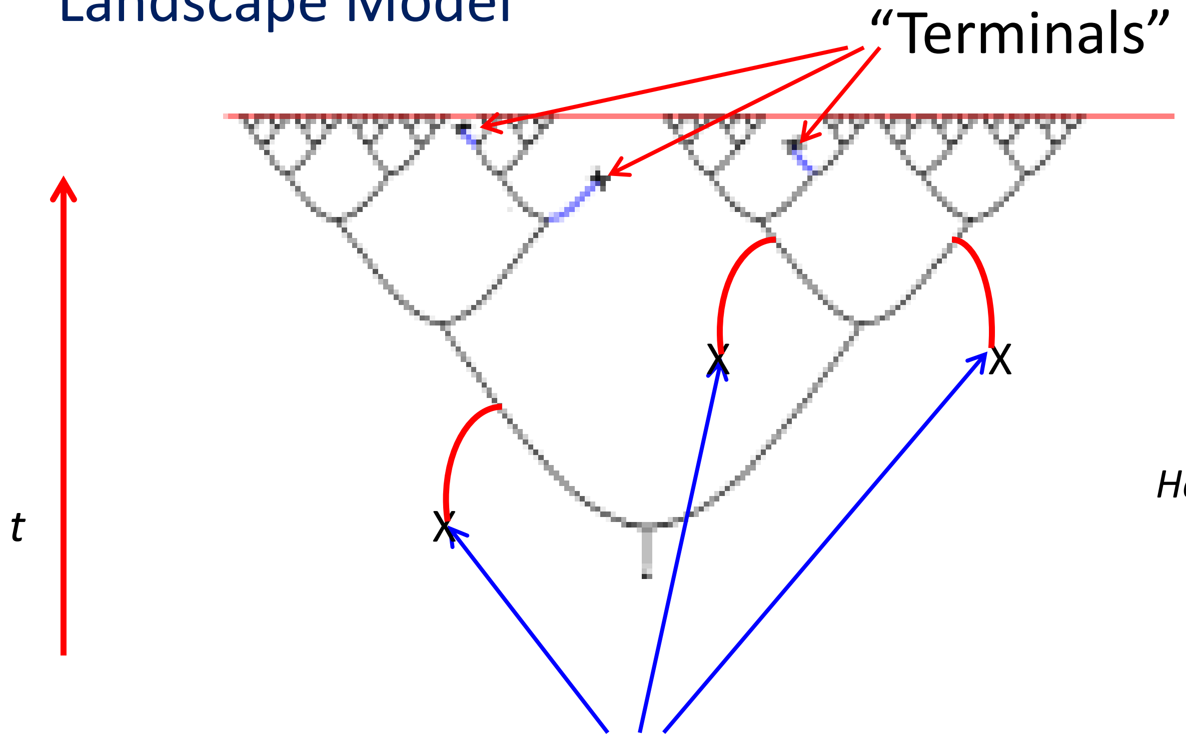

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Neglecting “arrival terminals” ➔ extreme fine tuning of initial conditions

1) Do you predict the observed state of the universe to be likely or natural? (And do you care?)

In general: Need a quantitative theory for your starting point (inflation, cyclic, whatever) to make this claim.

Attempts I know to create this rigor have led to surprises.

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X	**Y**
Volume of inflated regions	Probability for starting inflation
Entropy	Probability of starting a cyclic universe
Number of observers (in my theory) who see a universe like ours	The infinitely many other observers who see something totally different

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Need more rigor:

- Hernley, AA & Dray (2013) ←→ Guth toy model
- AA & Sorbo (2004)

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Non-Quantum probabilities in a toy model:

$$U = A \otimes B$$

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

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

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

3) Do you

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

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

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

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

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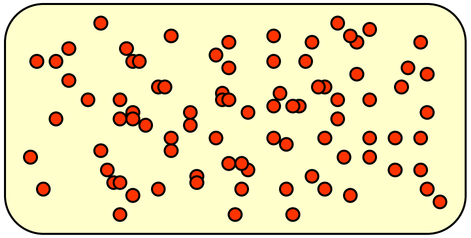
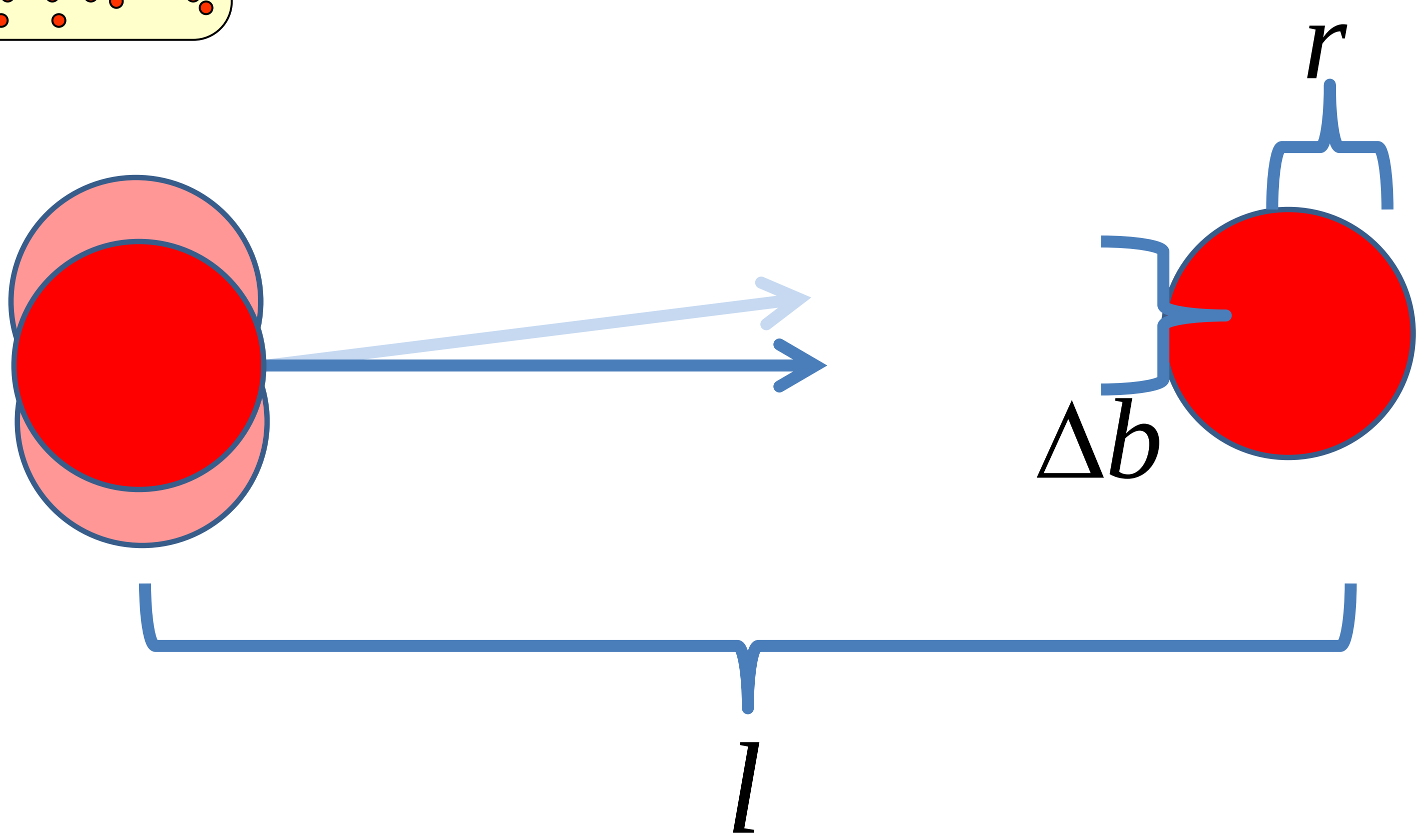
AA & D. Phillips 2012

Quantum effects in a billiard gas





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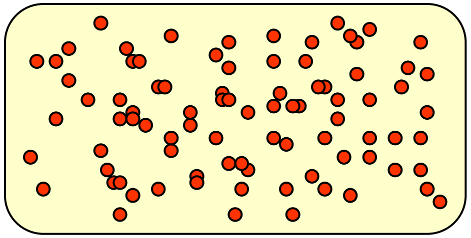

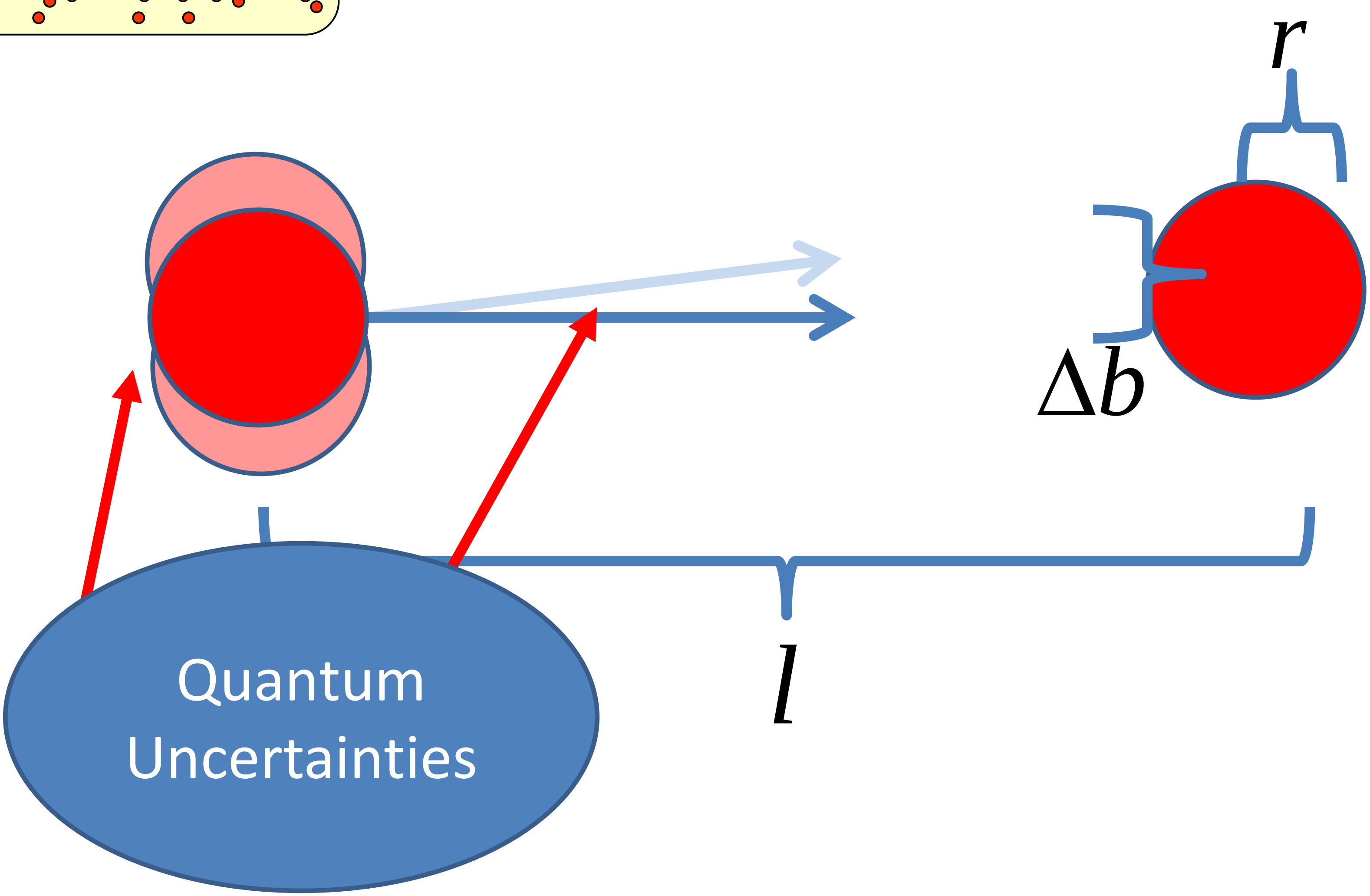

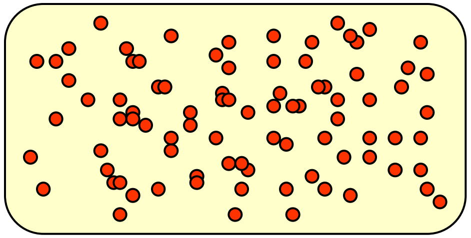

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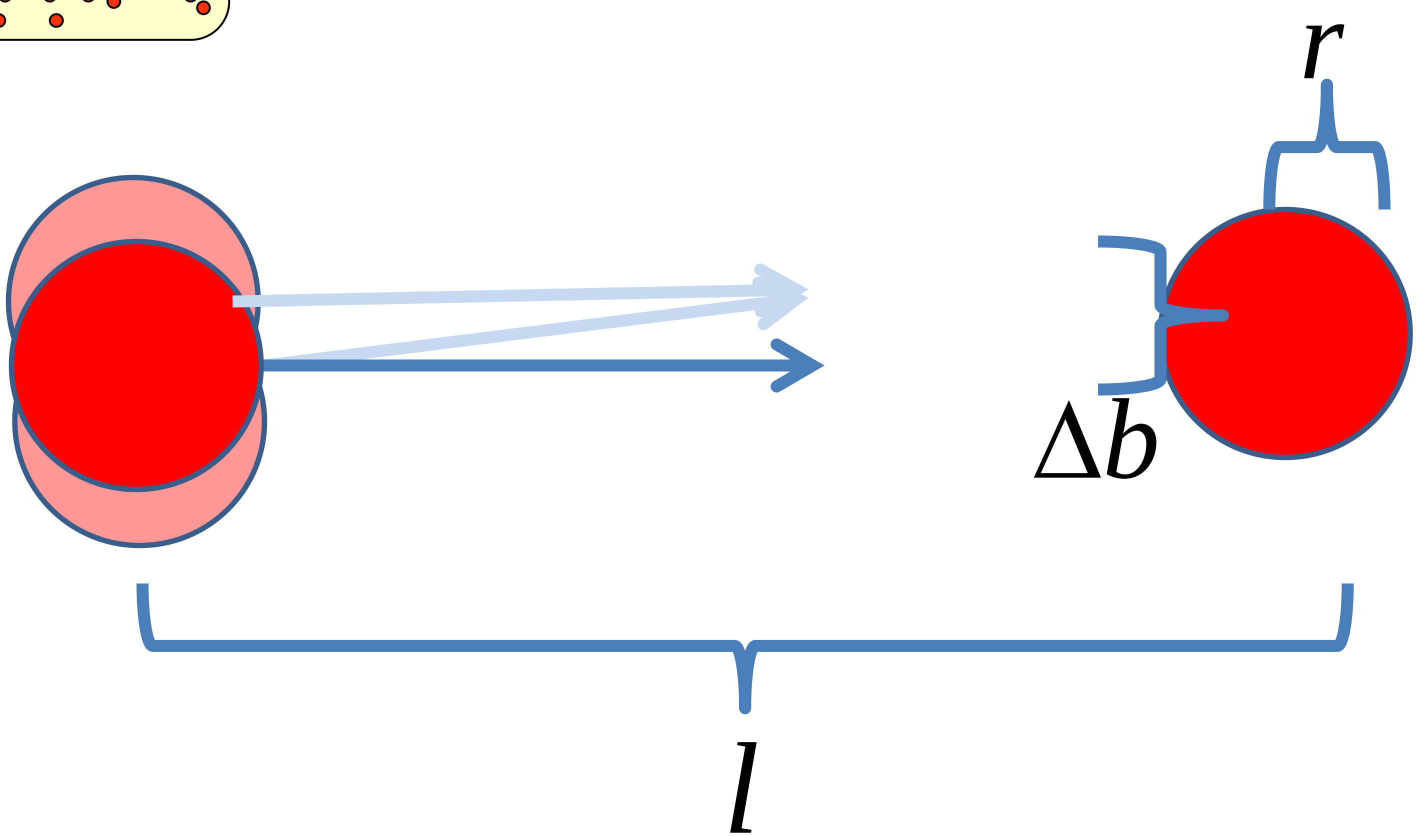
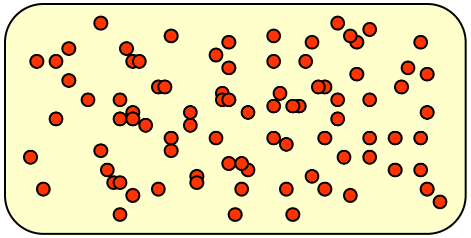


$$\Delta b = \delta x_{\perp} + \frac{\delta p_{\perp}}{m} \Delta t$$



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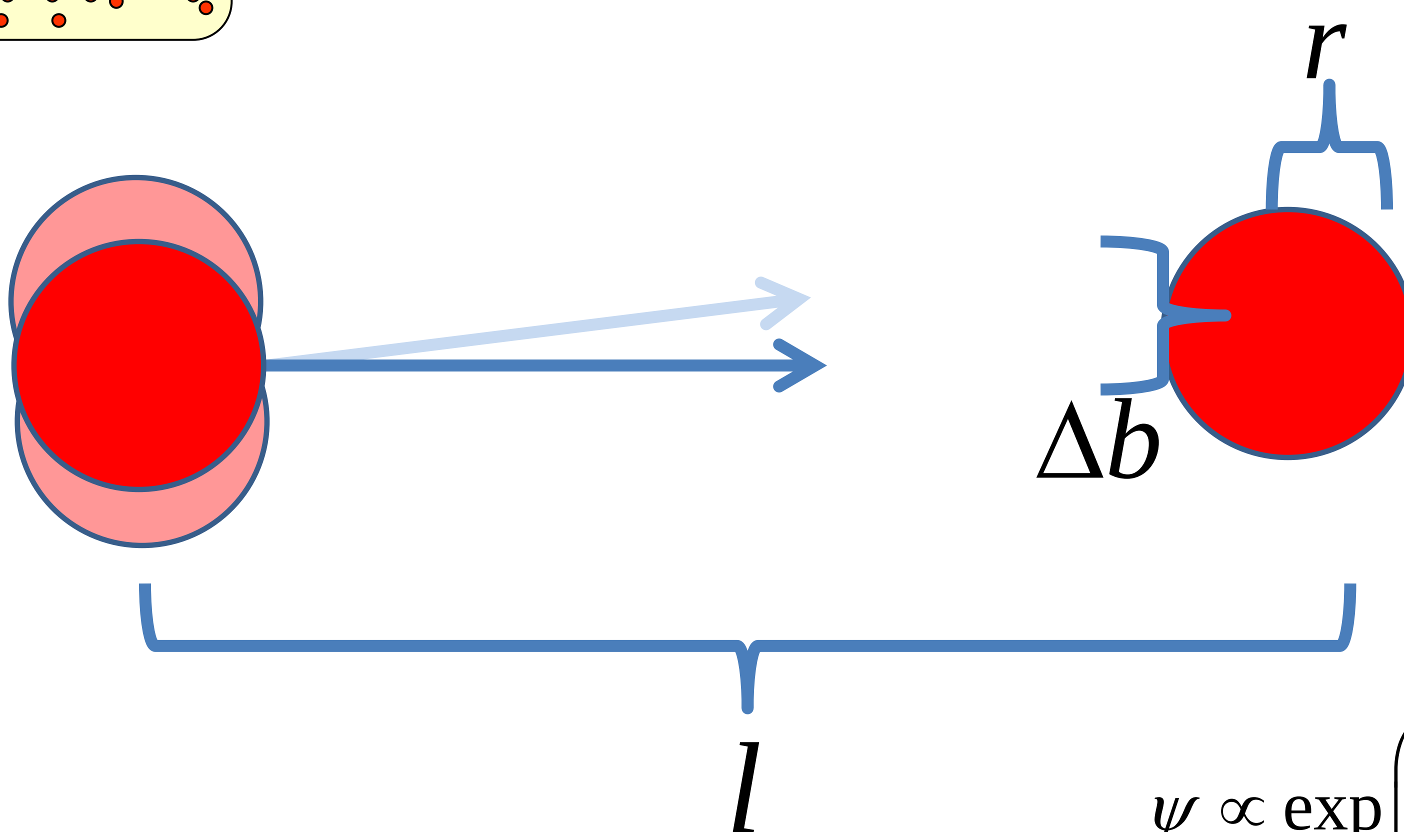
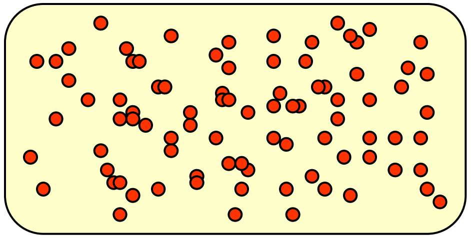


$$\psi \propto \exp\left(\frac{-x^2}{2a^2}\right)$$

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



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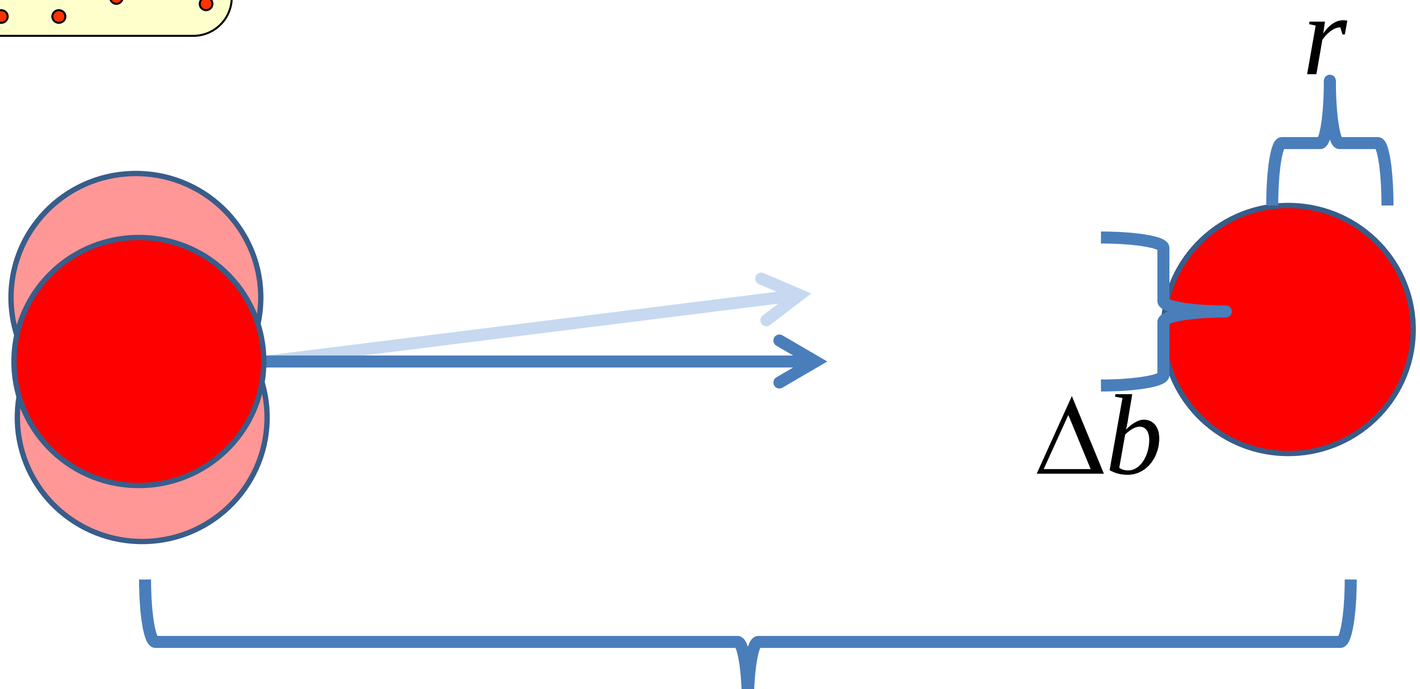
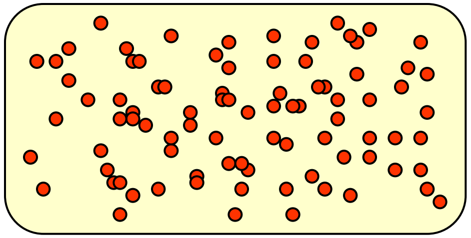


$$\Delta b = \delta x_{\perp} + \frac{\delta p_{\perp}}{m}\Delta t = \sqrt{2}\left(a + \frac{\hbar}{2a}\frac{l}{m\bar{v}} \right) \qquad \psi \propto \exp\left(\frac{-x^2}{2a^2} \right)$$

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



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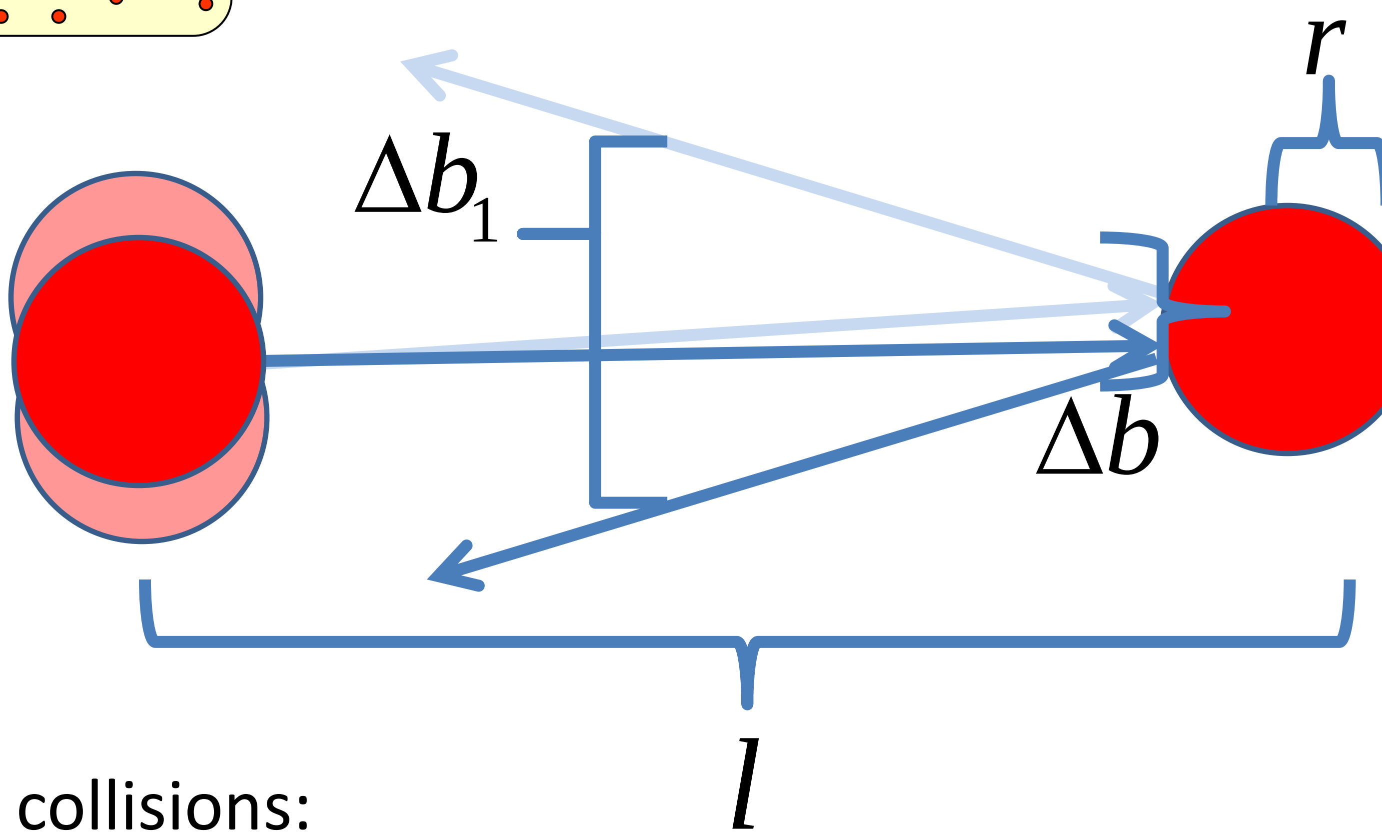
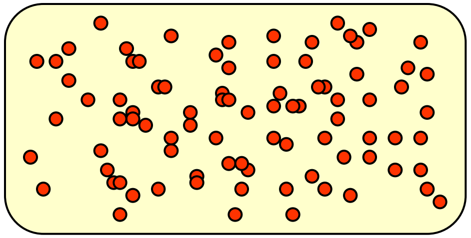


After *n* collisions:

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



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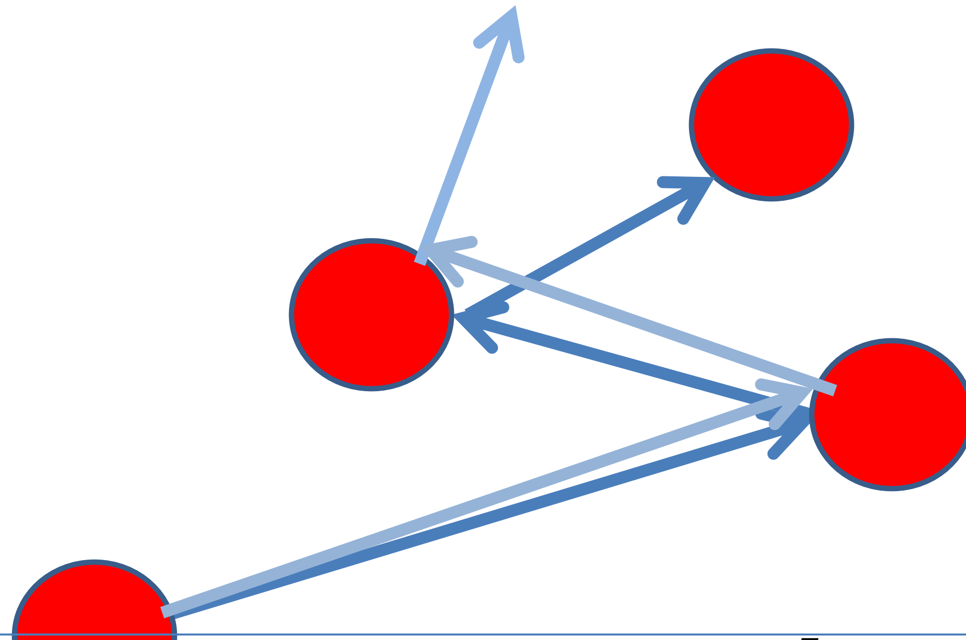

n_Q is the number of collisions so that $\Delta b_{n_Q} = r$

(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	$\bar{v}$	λ_{dB}	Δb	n_Q
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Bumper Car	1	2	150	0.5	1.4×10^{-36}	3.4×10^{-18}	25

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	r	l	m	$\bar{v}$	$\bar{\lambda}_{dB}$	Δb	n_Q
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n_Q for a number of physical systems

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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}	0.6
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Quantum at every collision

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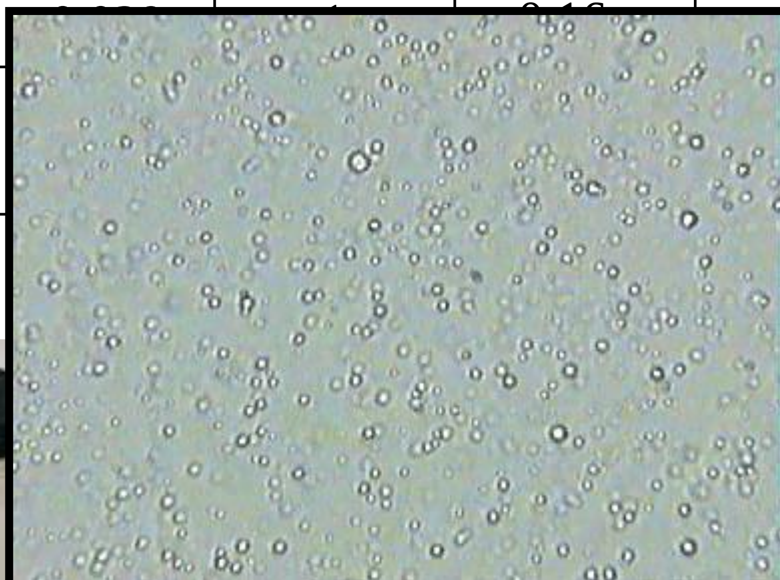

Quantum at every llision

Every Brownian Motion is a "Schrödinger Cat"

n_Q for a number of physical systems

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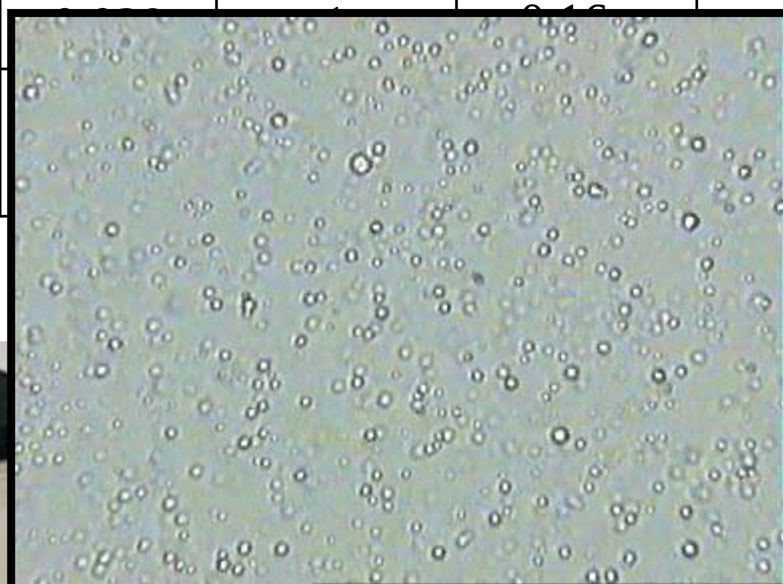

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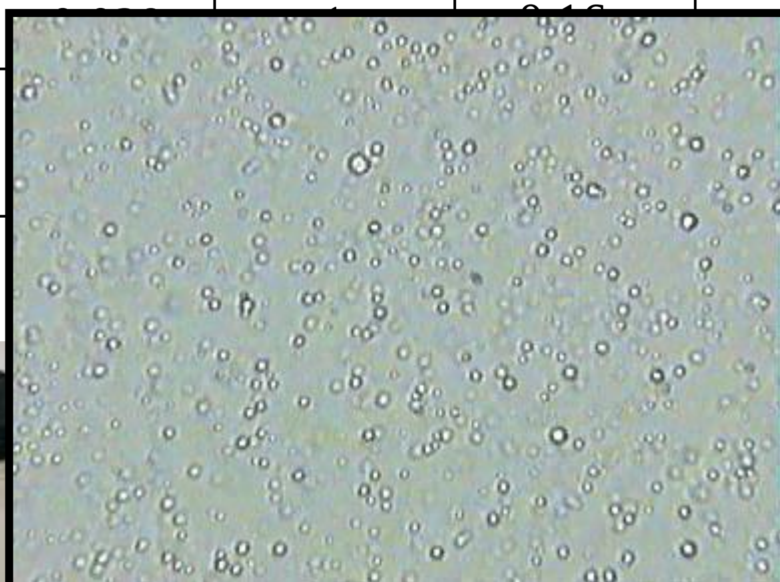
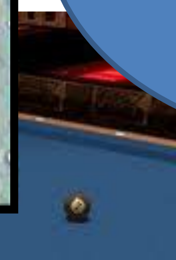
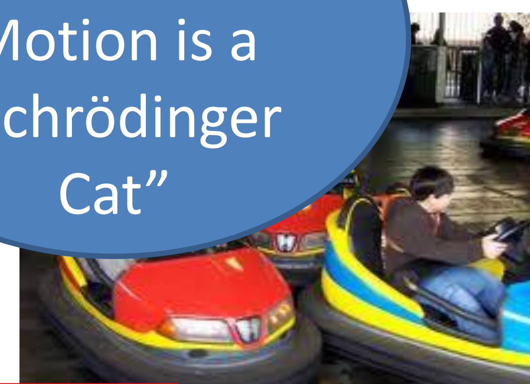






Quantum at every collision

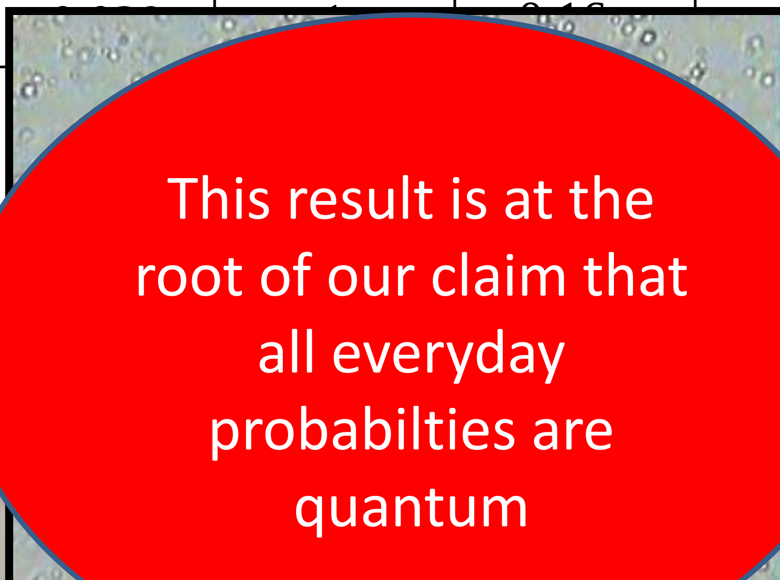
Every Brownian Motion is a “Schrödinger Cat”

(independent of “interpretation”)

n_Q for a number of physical systems

(all units MKS)

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

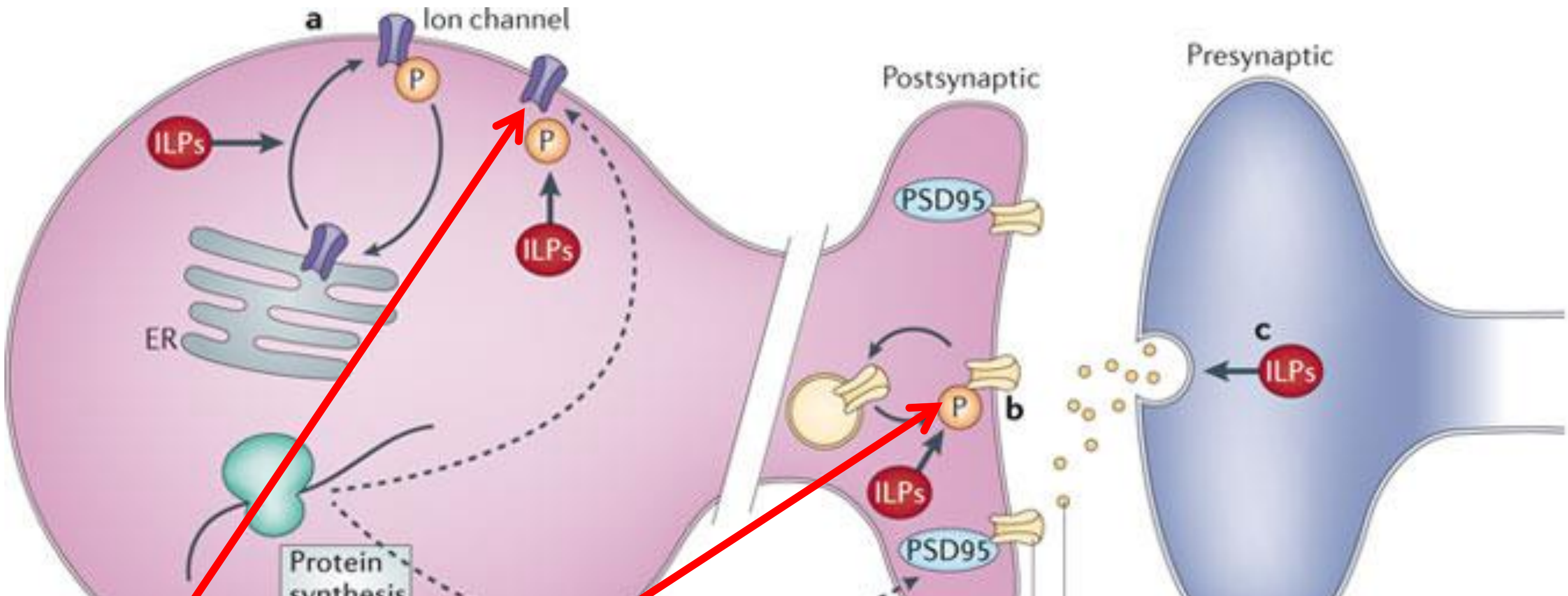


This result is at the root of our claim that all everyday probabilties are quantum

Every Brownian Motion is a “Schrödinger Cat”

Quantum at every collision

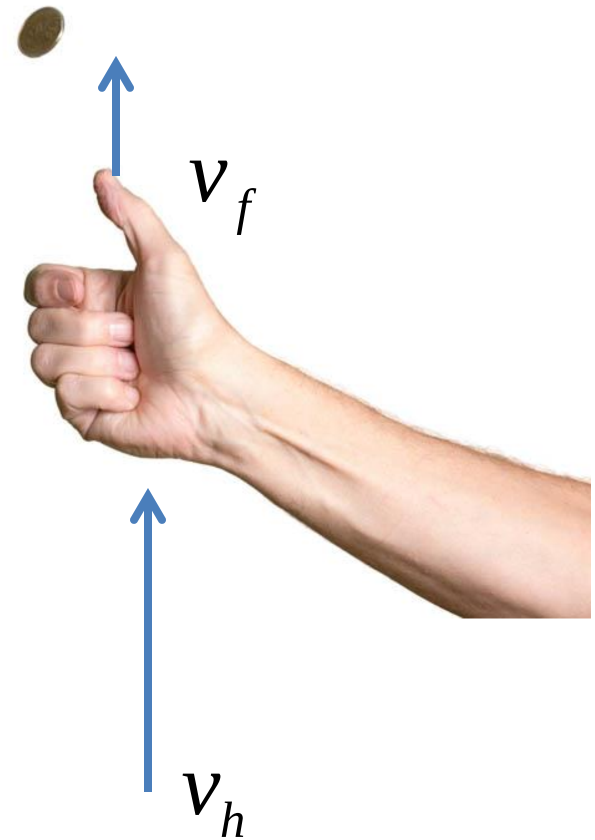
An important role for Brownian motion: Uncertainty in neuron transmission times



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



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

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

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

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

Coin diameter $= d$

Using:

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

$d = 0.01 m$

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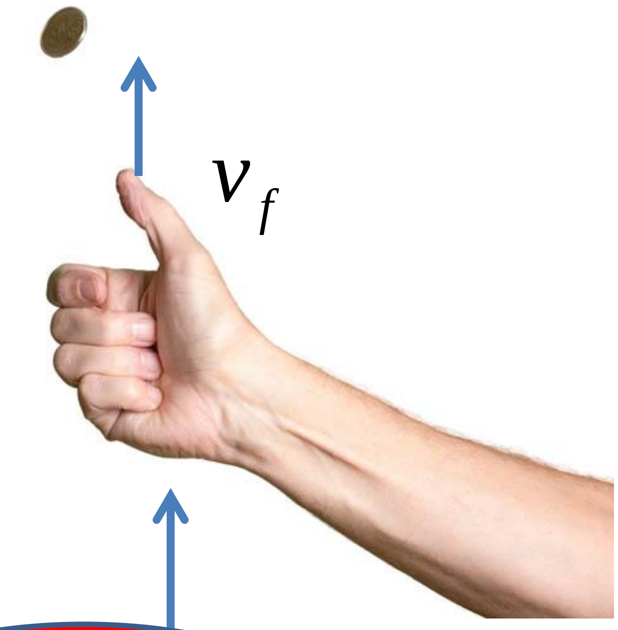

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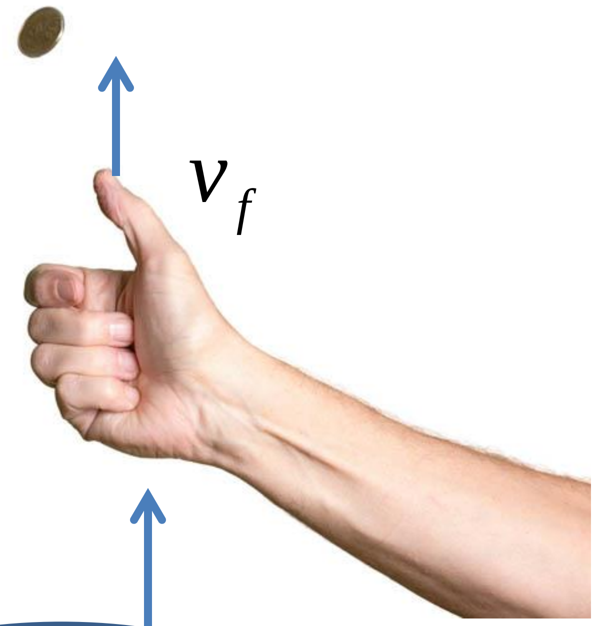

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Usin

d -

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

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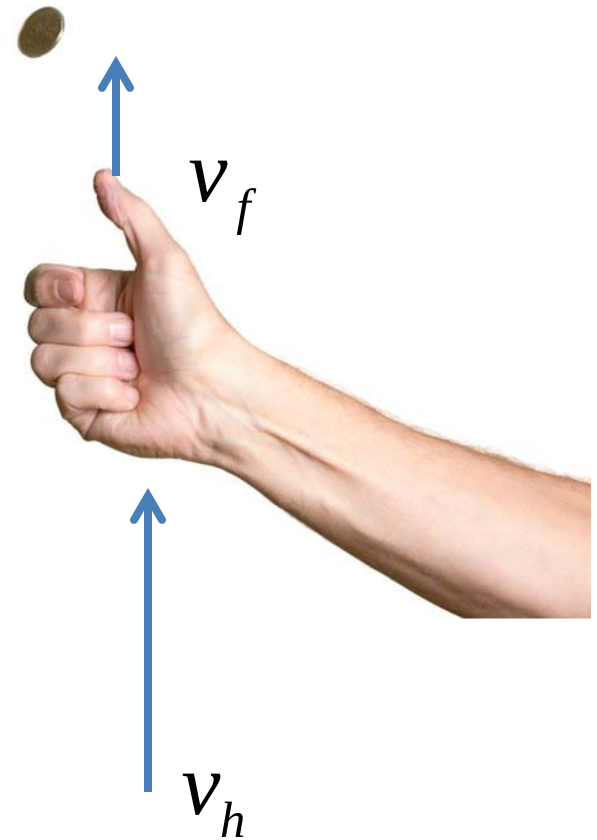

NB: Coin flip is "at the margin" of classical vs quantum control: Increasing *d* or deceasing v_h can reduce δN substantially

All everyday probabilities are quantum probabilities

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1) Find a foundation for inflation (or an alternative theory) that can be *well* tested with modern data. Meet the "Challenges for theorists"

2) Only then can we claim to resolve the famous cosmological puzzles *(Monopoles already OK)*.

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4) Run risk of being "stuck" like standard model of particle physics has been (so far).

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We can do better!

From Monday Panel Discussion

Challenges: Answer these questions re your theories & beliefs:

1) Do you predict the observed state of the universe to be likely or natural? (And do you care?)

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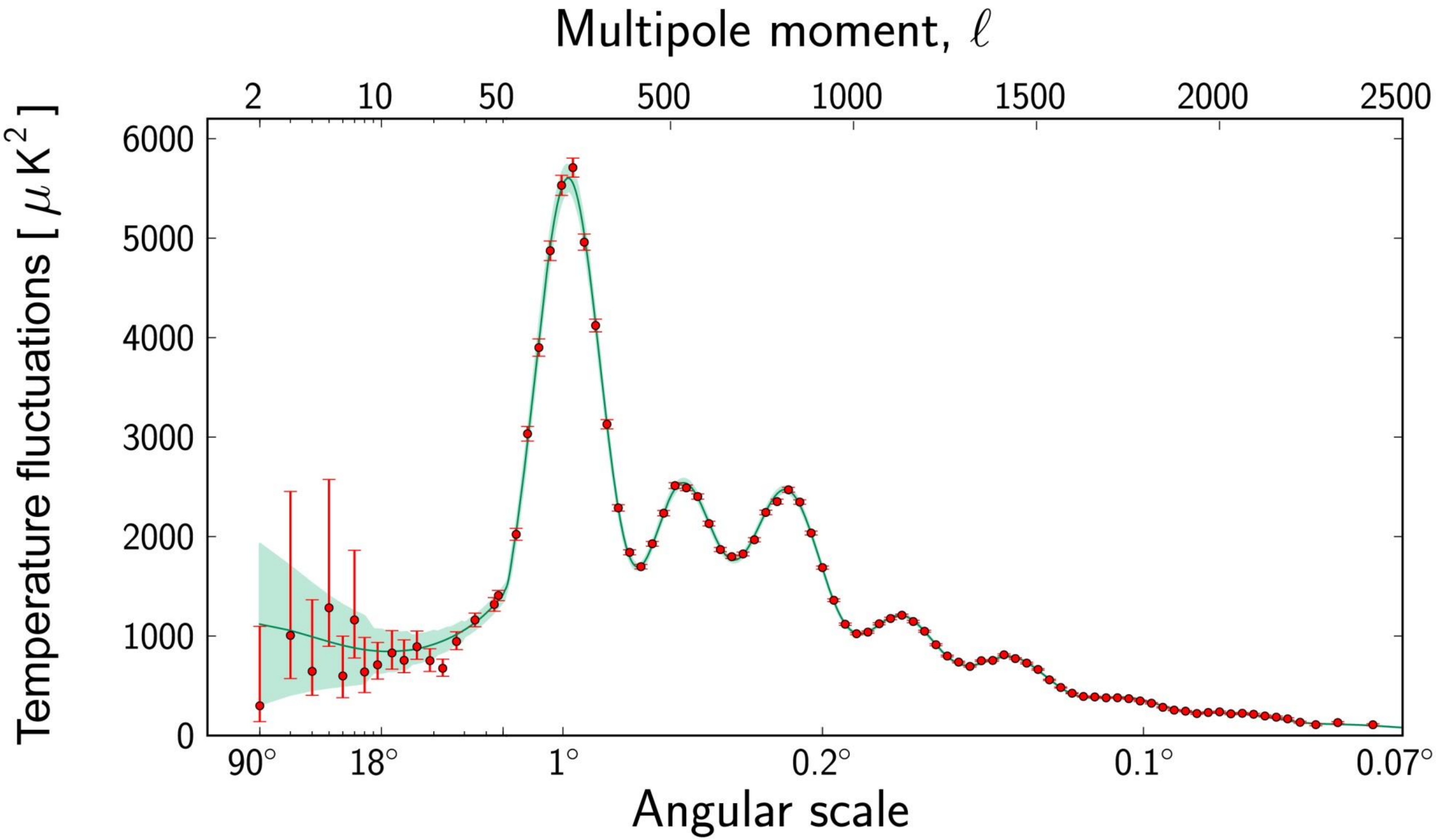
Multipole moment, ℓ
2
10
50
500
1000
1500
2000
2500
Temperature fluctuations [μK^2]
6000
5000
4000
3000
2000
1000
0
90°
18°
1°
0.2°
0.1°
0.07°
Angular scale

Challenges: Answer these questions re your theories & beliefs:

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YES

YES

2) Do you treat infinities rigorously?

Finite

3) Do you require a probability tooth fairy?

No