

# PHY 517 / AST 443: Observational Techniques in Astronomy

Lecture 4:  
Statistics, part I

# Lab 2

- Request your transit dates ASAP!

# Lab 1

- remember to do your weekly check-ins for Lab 1 with me or the TAs

## General Information

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Class time and place: MonWed 2:30 - 5:30pm, ESS 450

Credits: 3 (PHY 517) or 4 (AST 443)

Instructor: Simon Birrer (simon.birrer 'at' stony brook.edu, ESS 457-A)

Office hours (TBD):

- Tue 11:30am-12:30pm (ESS 450, Ben Levine)
- Thu 3:00-4:00pm (ESS 457-A, Simon Birrer)
- Fri 1:00-2:00pm (ESS 450, Zhi Chen)

TAs:

- Ben Levine (benjamin.c.levine 'at' stonybrook.edu), office hours Tue TBD, ESS 450 or by appointment
- Zhi Chen (zhi.chen.3 'at' stonybrook.edu), office hours Fri TBD, ESS 450 or by appointment

# Significant digits

Code output with way  
too many digits:

$$99.123456789 \\ \pm 0.004556789$$

Round the uncertainty  
to one (or two) digits:

$$0.00455679 \rightarrow 0.005$$

The location of this  
digit tells you the  
location of the last  
significant digit:

$$99.123 \\ \pm 0.005$$

Voila:

$$99.123 \pm 0.005$$

# Plagiarism

(a) Which of these are examples of plagiarism? (More than one answer may be correct.)

- i. Copying your lab-mate's introduction section of a lab report.
- ii. Taking somebody else's lab report, slightly modifying each sentence / paragraph, and submitting it as your own.
- iii. Copying your buddy's telescope proposal for the JWST telescope, and submitting it as your own.
- iv. Stating a "fact" from wikipedia without citing the original source.
- v. Using ChatGPT and quoting ChatGPT as the source.

(b) What happens when you get a "Q" grade? (Answer yes/no/maybe.)

**maybe**      i. Immediate expulsion from school.

**yes**          ii. You lose your scholarship.

**maybe**      iii. You receive an "F" for the course grade.

**yes**          iv. You have to take the "Q" course.

STONY BROOK

ASTRO  
CLUB

8PM THURSDAYS  
ESS 450

ALL MAJORS!  
NO PRIOR KNOWLEDGE REQUIRED!  
ROOFTOP OBSERVING!

MAILING LIST

DISCORD



(A brief intro to)  
**Statistics**

# Statistics in Astronomy

- we are almost always working in the low signal-to-noise regime
- have to be very careful to make correct inferences from our data!
- robust (and advanced) statistical techniques play a very important role in astronomy

# Measurements

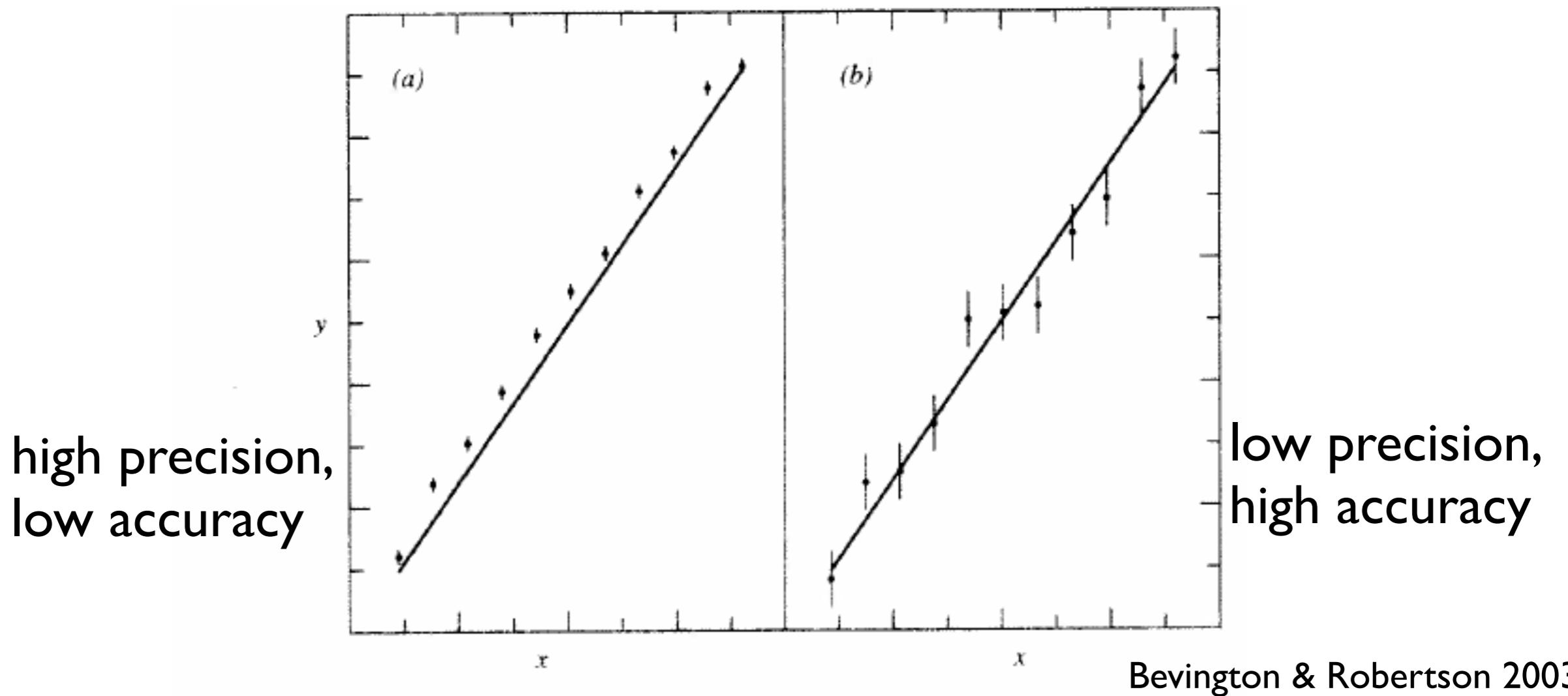
- example:  $99.123 \pm 0.005$
- what is 0.005 called?
  - (measurement) **uncertainty**
  - NOT “error” (inaccurate, though often used)
- what does this mean?
  - if we repeat the measurement many times, in 68% of the cases the true value would fall within the quoted uncertainty interval
  - not-quite-right interpretation: the quoted interval has a 68% chance of containing the true value

# “Error”

- **error**: difference between *measured* and *true value*
- can be due to:
  - random fluctuations (statistical error)
  - instrumental / algorithmic limitations (systematic error)
  - mistakes (illegitimate error)
- measurements are meaningless if not accompanied by an estimate of the error
- but truth is unknown, have to estimate error indirectly

# Accuracy vs. Precision

- **accuracy:** how close a measurement is to the truth
- **precision:** size of (statistical) measurement uncertainty

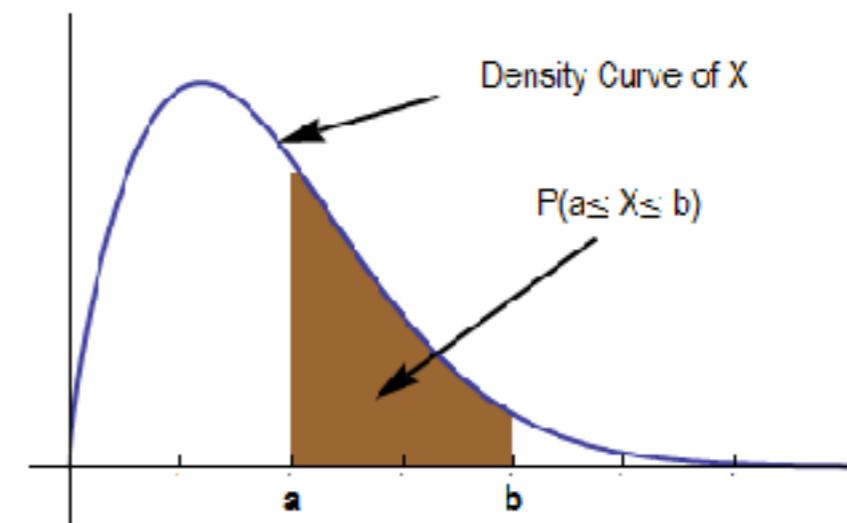
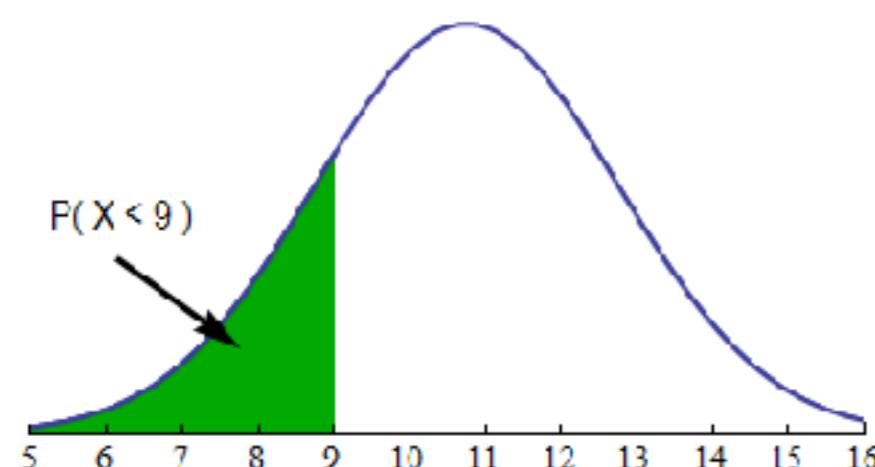
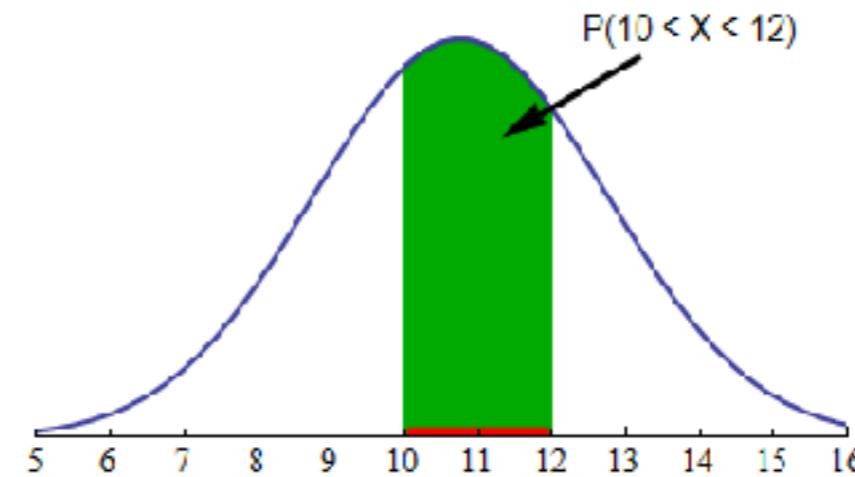
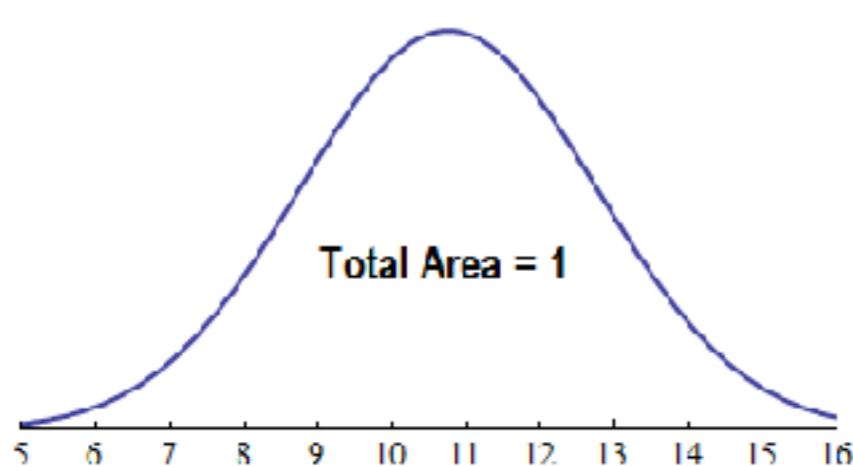


**FIGURE 1.1**

Illustration of the difference between precision and accuracy. (a) Precise but inaccurate data.  
(b) Accurate but imprecise data. True values are represented by the straight lines.

# Probability Distributions

- probability distributions: describe expected / measured distributions of measurements
- integrate over range of values to find probability to be in that range



# Sample vs. Parent Distribution

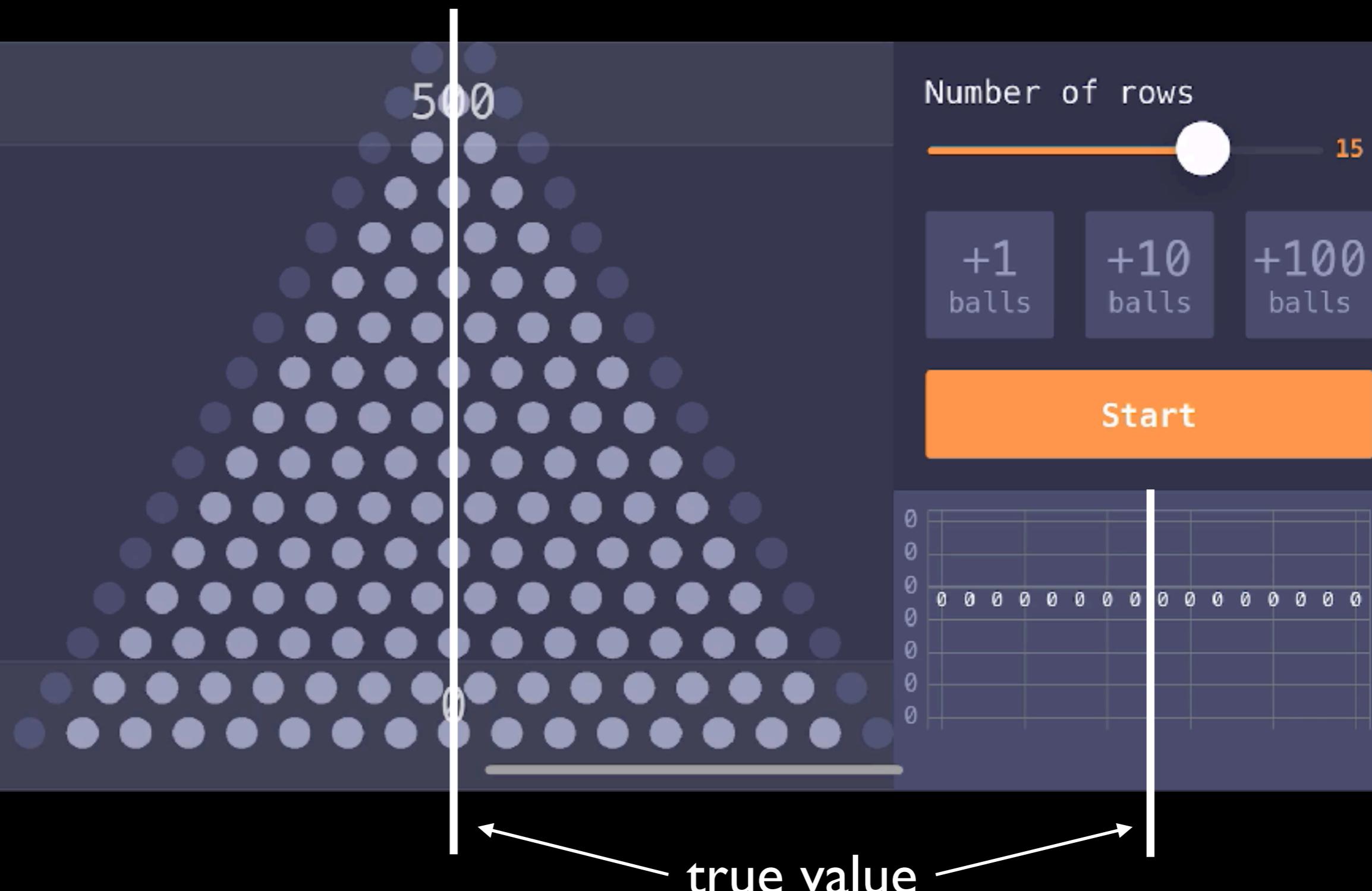
- measurement  $x_i$  of a quantity  $x$ :
  - approximates  $x$
  - not necessarily equal to  $x$  because of statistical uncertainty
- many measurements  $x_i$ :
  - expected to be distributed about true value
  - **sample distribution**
- **parent distribution**:
  - probability of particular result from single measurement
  - idealized outcome of infinite number of measurements

the sample distribution *samples* the parent distribution

# Galton Board:

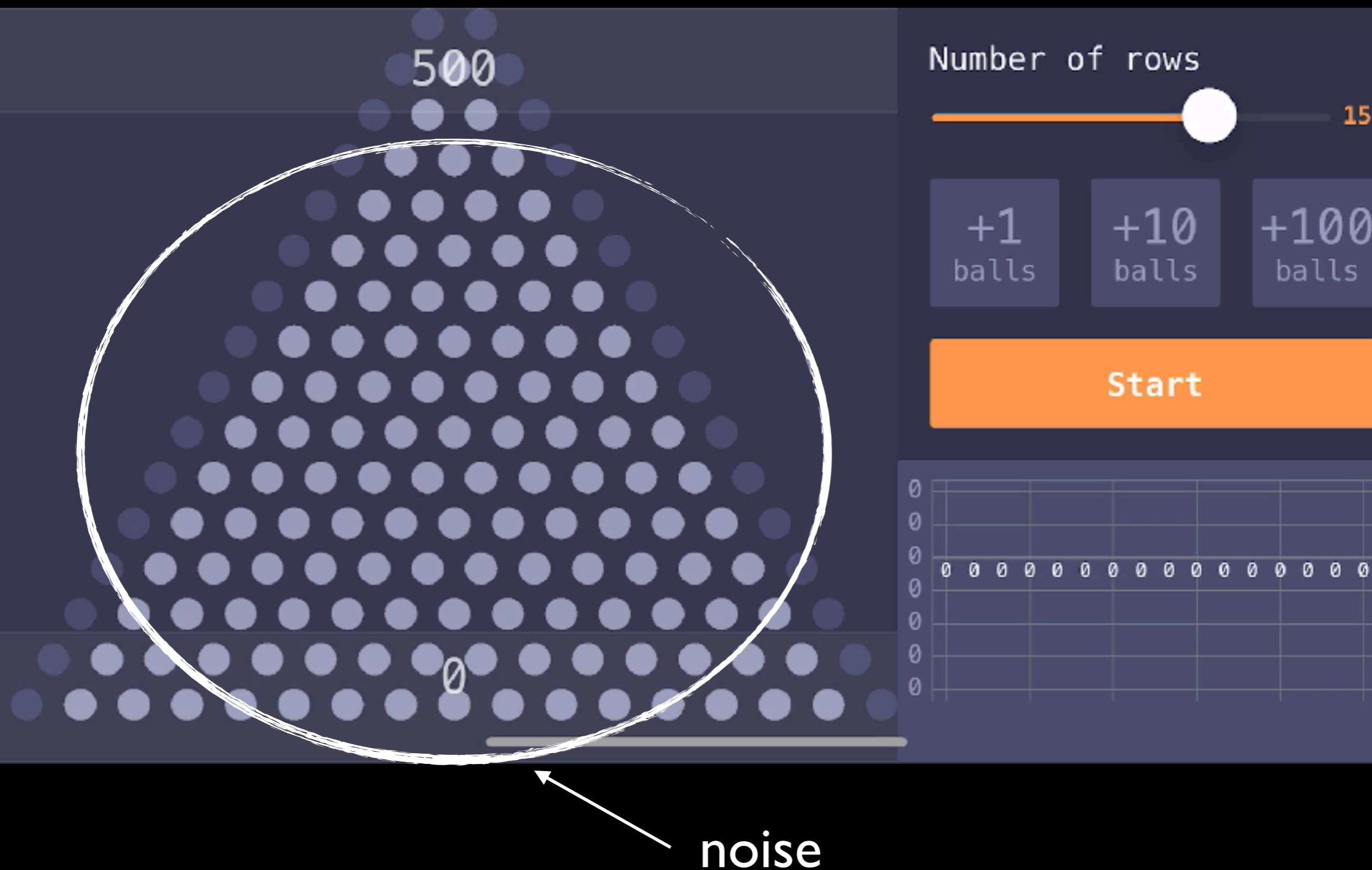


# Galton Board:



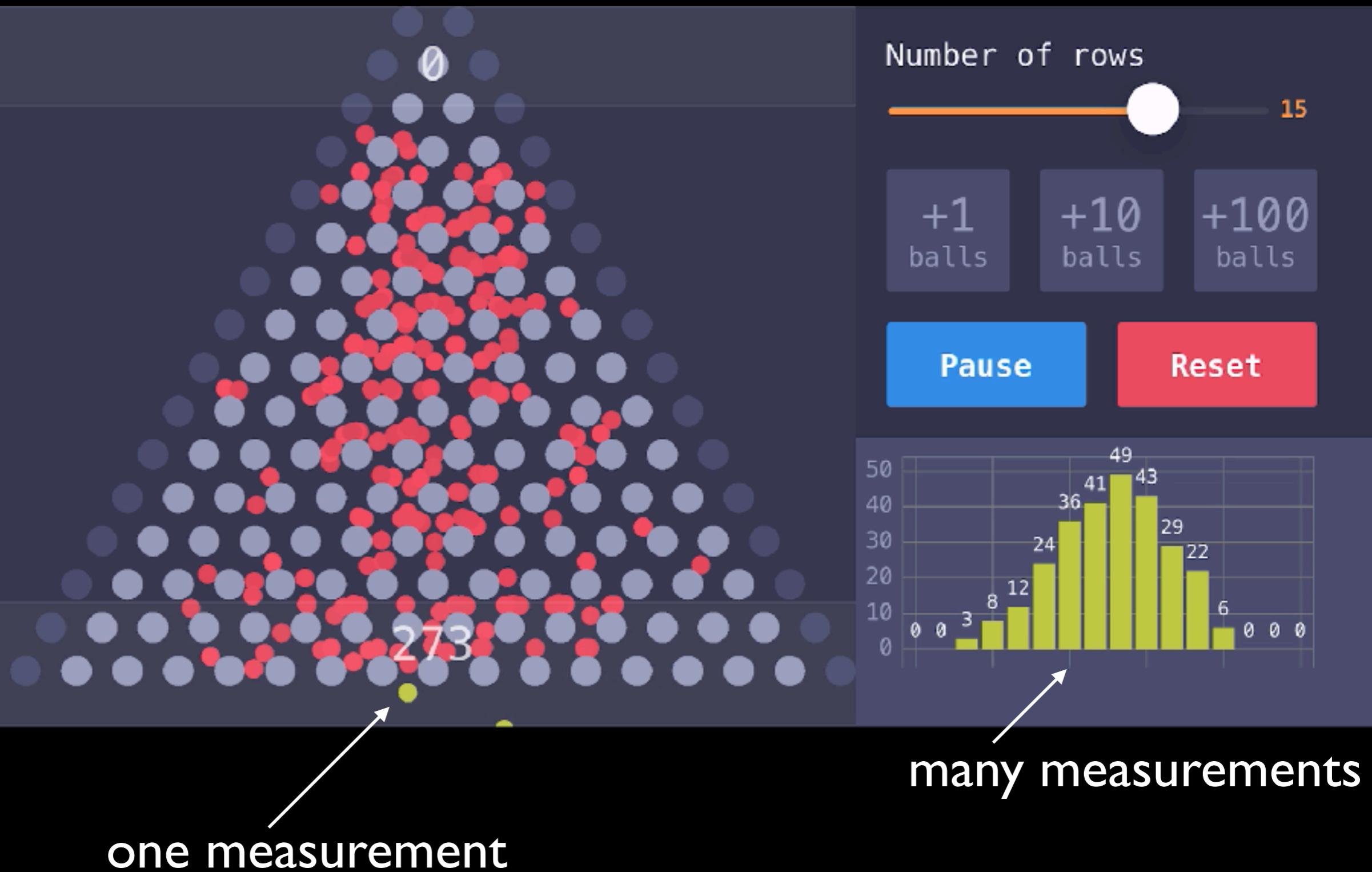
Galton Board App for iOS, Edwin Veger

# Galton Board:

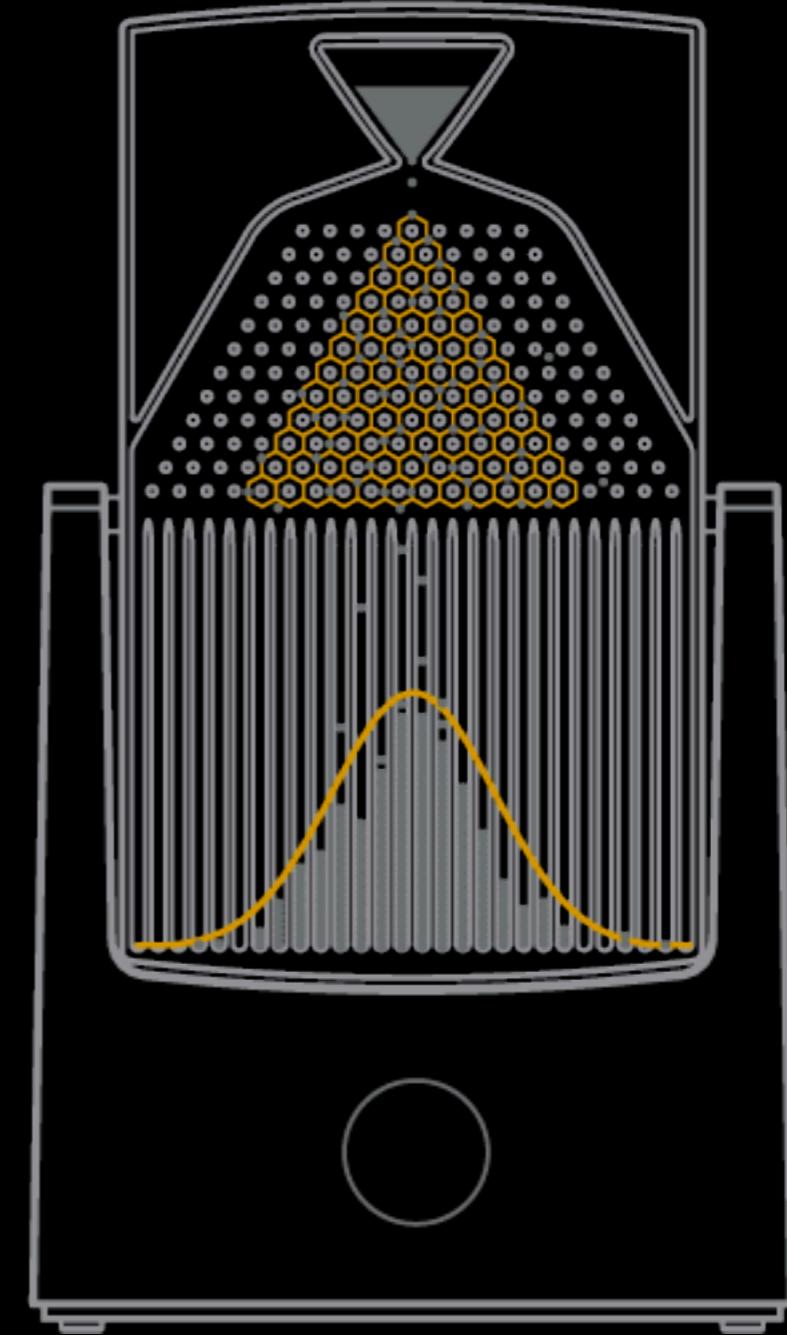
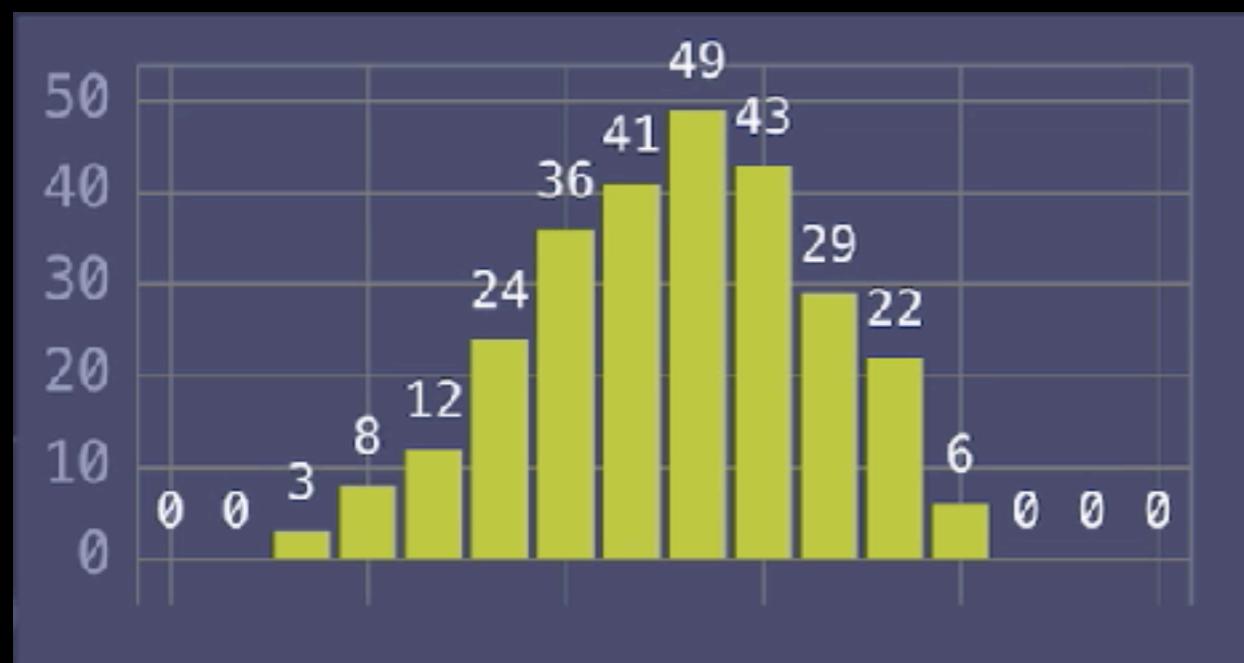


Galton Board App for iOS, Edwin Veger

# Galton Board:



# Galton Board:



sample population: distribution of many measurements

parent population: Gaussian / normal distribution

# Summary statistics

- only the full sample distribution is the full description of your data
- but usually, it is helpful to describe the sample distribution with a few numbers → summary statistics

*Q: can you think of examples?*

# Mean, median, and mode

- (unweighted) **mean** of the sample distribution:

$$\bar{x} = \frac{1}{N} \sum_i x_i$$

- IF there are no systematic errors, the mean of the parent population is:

$$\mu = \lim_{N \rightarrow \infty} \frac{1}{N} \sum_i x_i$$

# Mean, median, and mode

- **median:** 50th percentile of distribution (half the measurements are smaller, half are greater)

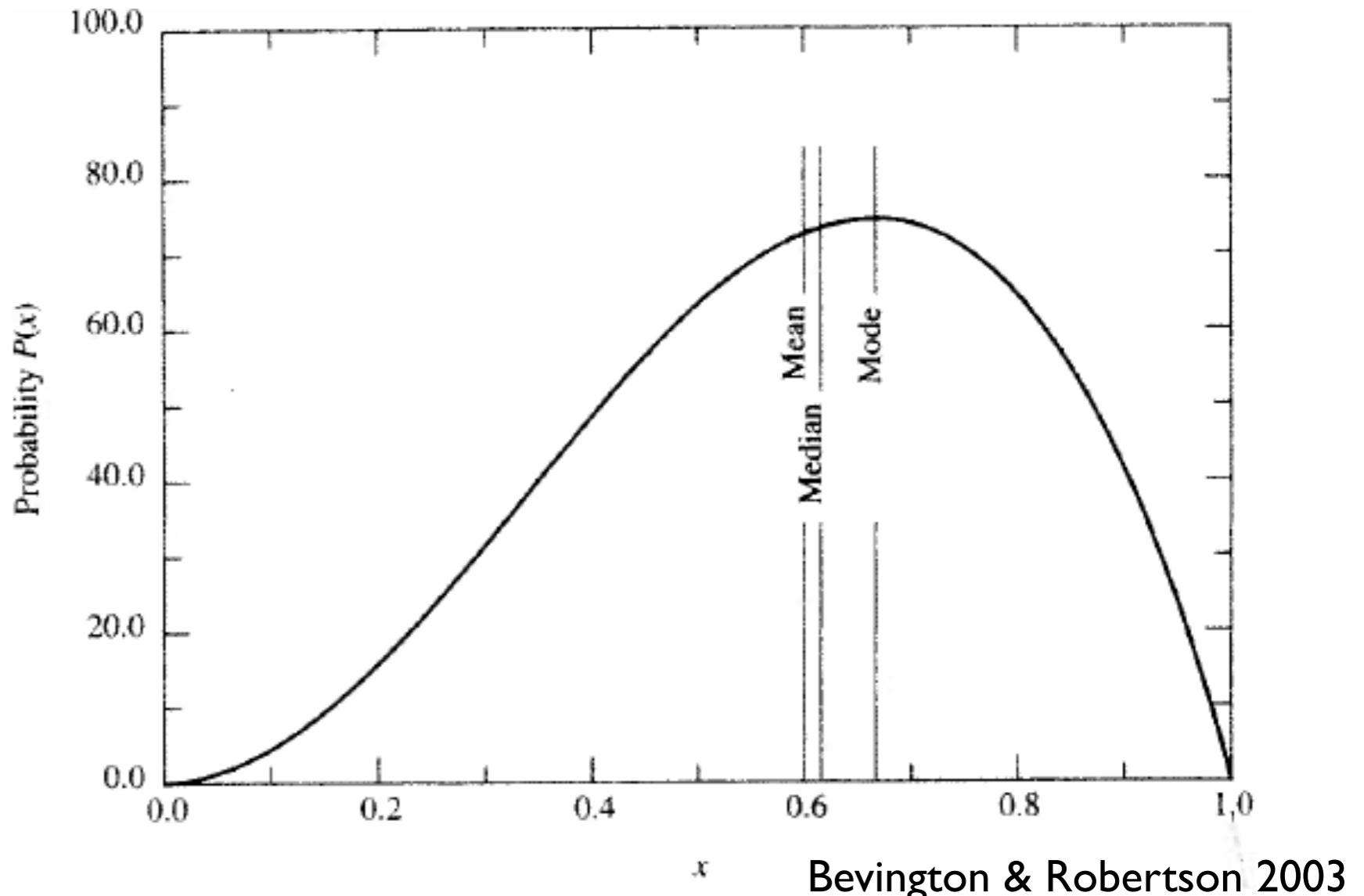
motivation: less susceptible to “outliers” than the mean

- **mode:** the most common measurement value

motivation: the most likely value

# Mean, median, and mode

mean, median and mode for an example distribution:



- generally not equal to each other
- all 3 are useful; which to quote depends on the problem (and personal preference)

# Deviation / variance / std. deviation

- **deviation** of one measurement:  $d_i = x_i - \mu$
- sample **variance**: average of the squares of the deviations

$$\sigma^2 = \frac{1}{N} \sum_i (x_i - \mu)^2$$

- when computing from sample population:

$$s^2 = \frac{1}{N-1} \sum_i (x_i - \bar{x})^2$$

- **standard deviation**:  $\sigma = \sqrt{\text{variance}}$

*indicates how much the measurements typically deviate from the mean*

# How well can we measure the mean?



- width of sample distribution (std. dev.) remains the same
- the more measurements, the closer the mean to the true value

# Uncertainty on the mean

- variance and std. deviation are measures of the *width* of the sample distribution
- with increasing number  $N$  of measurements, the typical deviation of **measured mean and true mean** decreases
- measurement uncertainty on the mean:  
$$\sigma_{\bar{x}} = \frac{\sigma}{\sqrt{N}}$$
- width of distribution of repeated measurements of the mean
- $\sigma$ : distribution of single measurements around the true value
- $\sigma_{\bar{x}}$ : distribution of means of  $N$  measurements around the true value

# Weighted mean

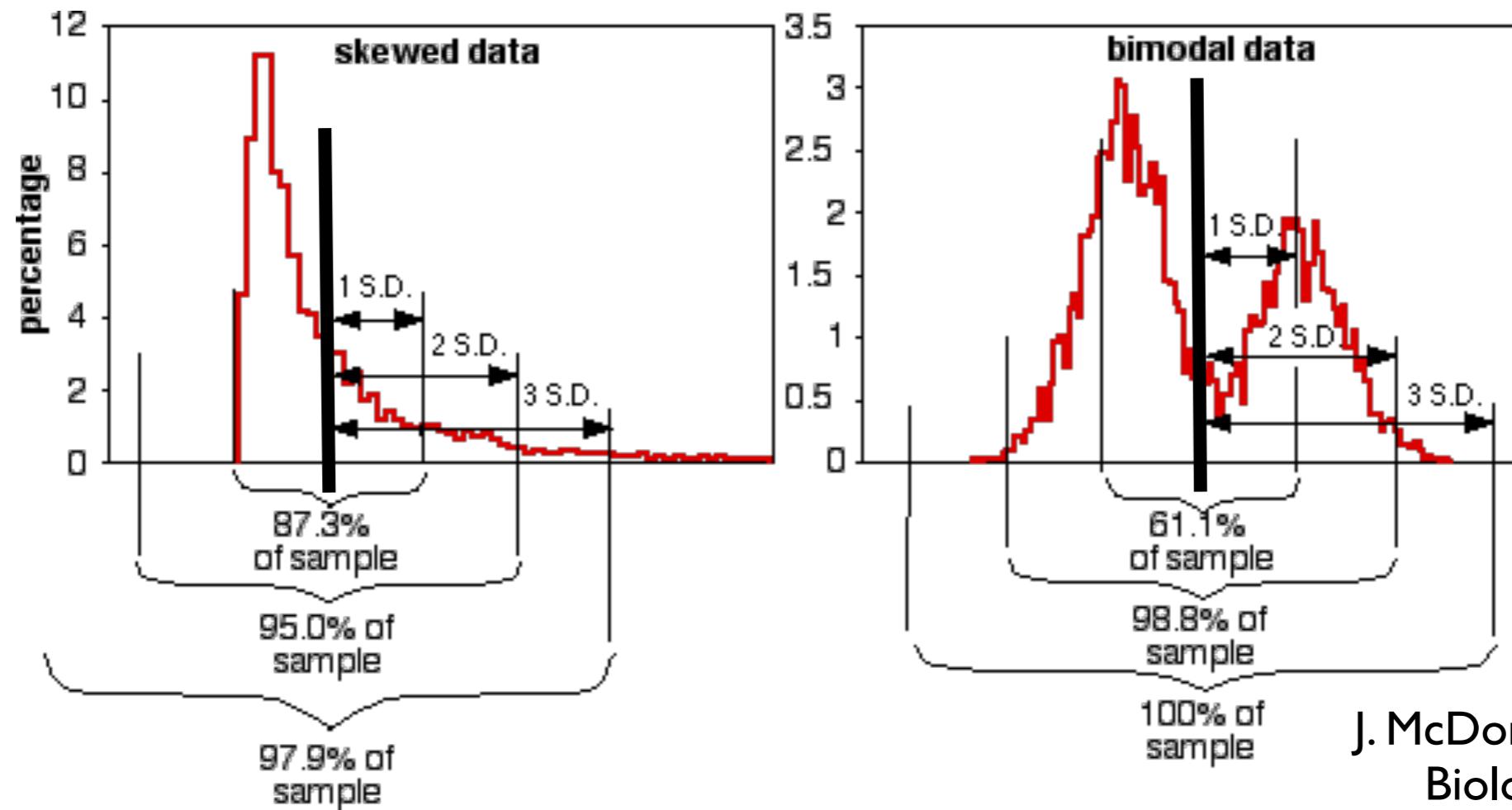
- previously, all measurements had equal weight
- some measurements are more precise than others; can assign weight  $w_i$  to each measurement  $x_i$
- weighted mean:

$$\bar{x} = \frac{\sum_i w_i x_i}{\sum_i w_i} \quad \sigma_{\bar{x}}^2 = \frac{1}{\sum_i w_i}$$

- for reasonable (Gaussian) distributions, optimal weight is the inverse of the variance of each measurement:

$$\bar{x} = \frac{\sum_i x_i / \sigma_i^2}{\sum_i 1 / \sigma_i^2} \quad \sigma_{\bar{x}}^2 = \frac{1}{\sum_i 1 / \sigma_i^2}$$

- can calculate mean, variance, etc. for any set of data points
- *that does not guarantee that they are useful descriptions of the distribution !*



- if we know the shape of the parent distribution, we know which summary statistics to use

# Common Probability Distributions

- many, many possible distributions have been quantified; here, consider 3 particularly important ones:
  - **Binomial distribution:** for experiments with only a small number of possible final states (e.g. coin toss)
  - **Poisson distribution:** counting experiments for discrete events (e.g. photon counts)
  - **Gaussian (or Normal) distribution:** distribution of events about the mean for a wide variety of processes; limiting case of binomial and poisson distributions

# Binomial Distribution

- experiment with only two possible outcomes:
  - state 0: probability  $p$
  - state 1: probability  $q = (1-p)$
- $n$  realizations
- probability that  $x$  of the  $n$  realizations are in state 0:

$$P_B(x|n,p) = \frac{n!}{x!(n-x)!} p^x (1-p)^{n-x}$$

- $x$ : positive integers;  $0 \leq x \leq n$
- $0 < p < 1$
- $\sum_{x=0}^n P_B(x|n,p) = 1$

# Binomial Distribution

- mean of the binomial distribution:

$$\mu = \sum_{x=0}^n (x \cdot P_B(x|n,p)) = np$$

(agrees with intuition!)

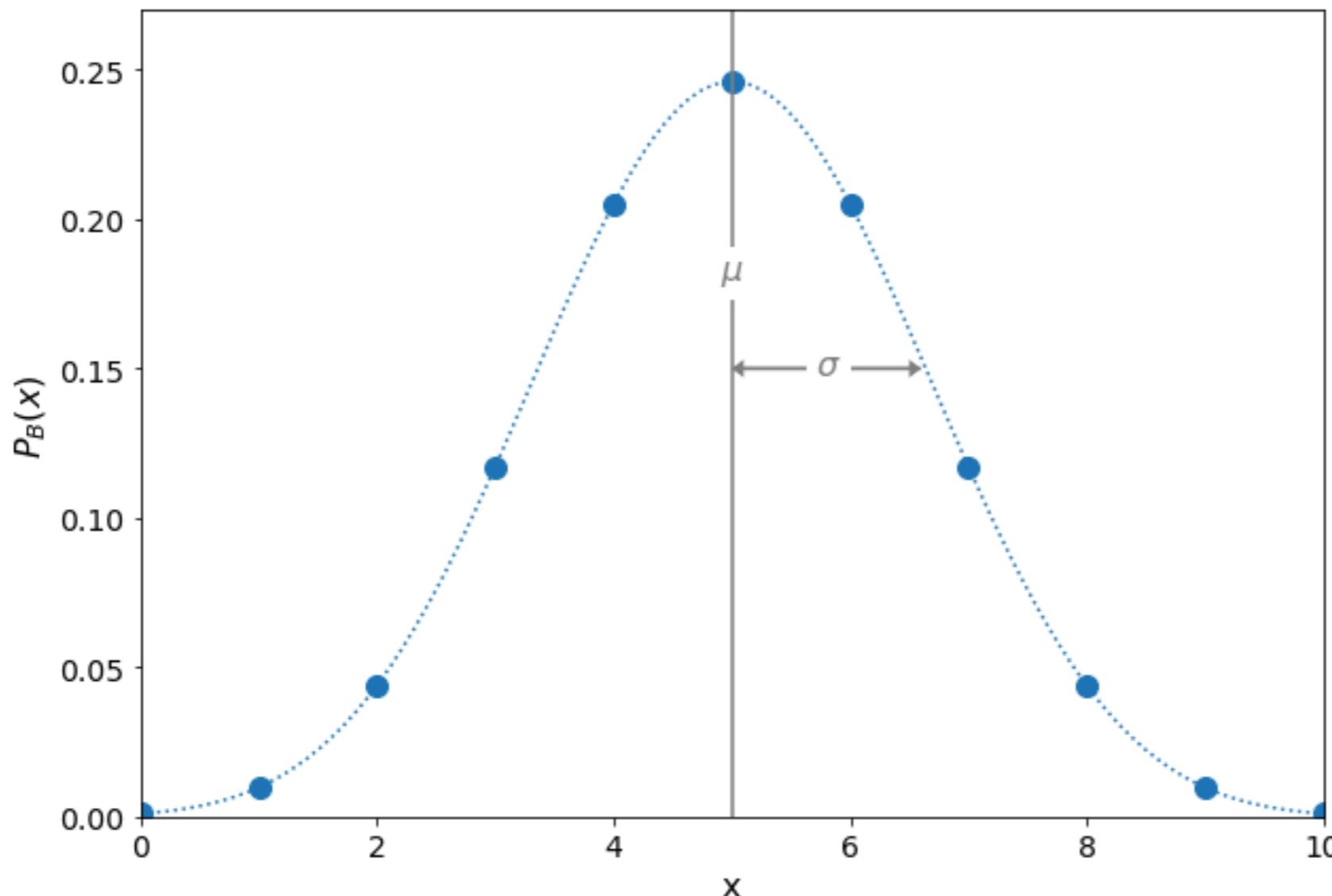
- variance of the binomial distribution:

$$\sigma^2 = \sum_{x=0}^n ((x - \mu)^2 \cdot P_B(x|n,p)) = np(1 - p)$$

# Binomial Distribution - Example (I)

tossing 10 coins,  $x$  = number of tails

$$n = 10, p = 0.5 \rightarrow P(x) = P_B(x|10, 0.5)$$



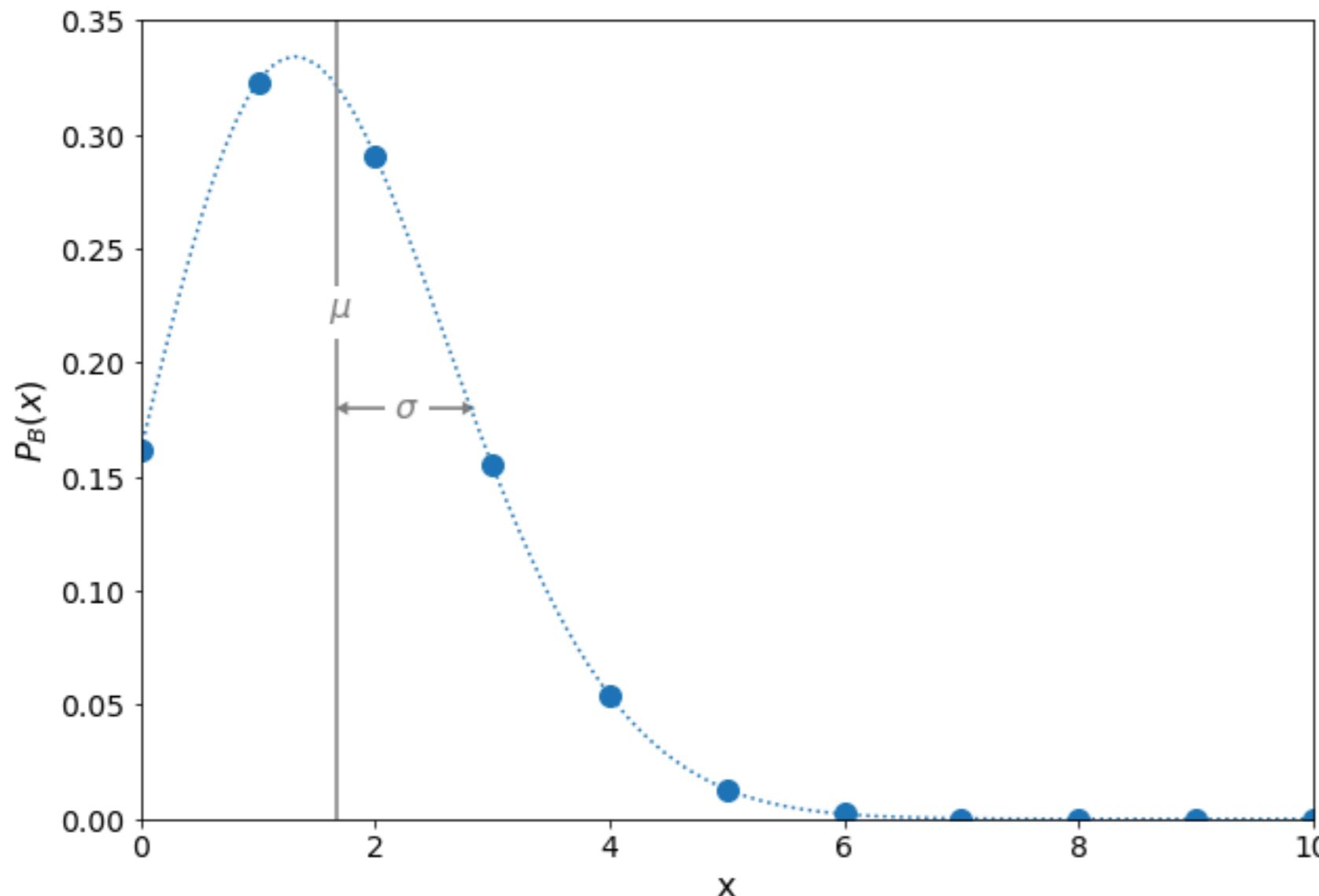
$$\begin{aligned}\mu &= np = 5 \\ \sigma^2 &= np(1-p) \\ &= 2.5\end{aligned}$$

since  $q=p$ : distribution is symmetric

# Binomial Distribution - Example (2)

roll 10 dice,  $x$  = number of rolls with 6 eyes

$$n = 10, p = 1/6 \rightarrow P(x) = P_B(x|10, 1/6)$$



$$\begin{aligned}\mu &= np = 5/3 \\ \sigma^2 &= np(1-p) \\ &= 1.39\end{aligned}$$

note: mean is  
not the mode

since  $q \neq p$ : distribution is not symmetric

# Poisson Distribution

- limit of binomial distribution if number of trials is large, and probability of “success” in a given trial is small, while the mean  $\mu = np$  remains finite

$$P_{\text{P}}(x|\mu) = \lim_{\substack{n \rightarrow \infty \\ p \rightarrow 0}} P_{\text{B}}(x|n, p) = \frac{\mu^x}{x!} e^{-\mu}$$

- for experiments where a mean number of events,  $\mu$ , can be measured
- neither the number of realizations  $n$ , nor the probability of “success”  $p$  need to be known
- example: “counting” experiments, e.g. flux measurements

# Poisson Distribution

- mean of the Poisson distribution:  $\mu$
- variance of the Poisson distribution:  $\sigma^2 = \mu$
- standard deviation:  $\sigma = \sqrt{\mu}$
- a flux measurement typically consists of measuring a number of events,  $N$ , per time interval  $\Delta t$ , with  $\mu = N/\Delta t$
- assuming that the time interval is precisely known, we can assign an uncertainty to a single measurement from  $\sqrt{N}$

# Poisson Distribution - Example

On your CCD, you count a flux of 100 photons from a star.

*Q: Report an estimate of the flux (in number of photons) and the uncertainty.*

Only 1 measurement → flux estimate ( $\mu$ ) is 100 photons.

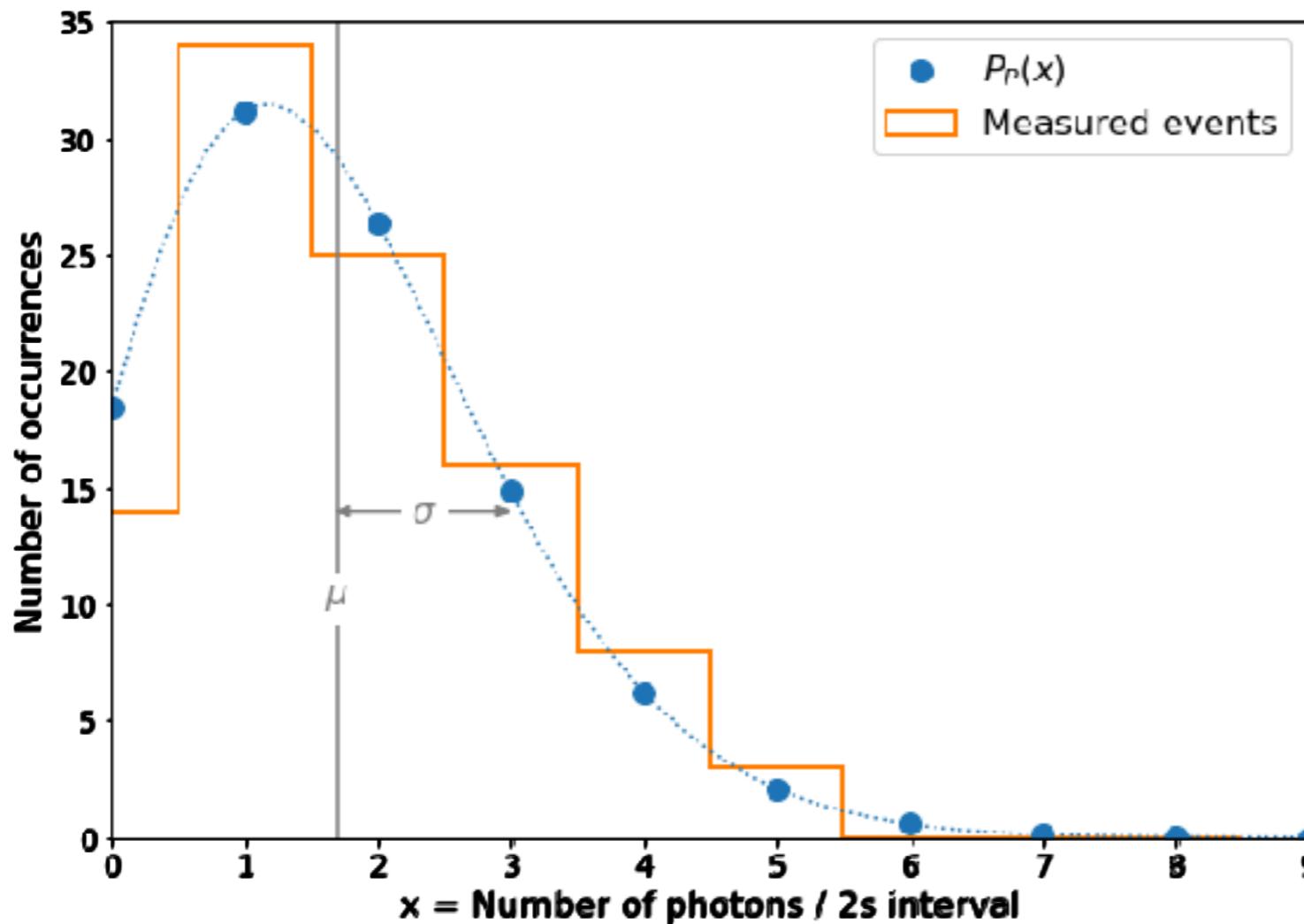
Counting experiment: standard deviation is  $\sqrt{\mu}$ .

Measurement:  $F = 100 \pm 10$

*Q: How can multiple measurements improve on this?*

# Poisson Distribution - Example

a detector measures the number of gamma-ray photons per 2 second interval, making 100 measurements:



measured mean:

$$\bar{x} = 1.69$$

blue points:

$$P_P(x | 1.69)$$

note: Poisson distribution is defined for positive, integer values of x

# Gaussian / Normal Distribution

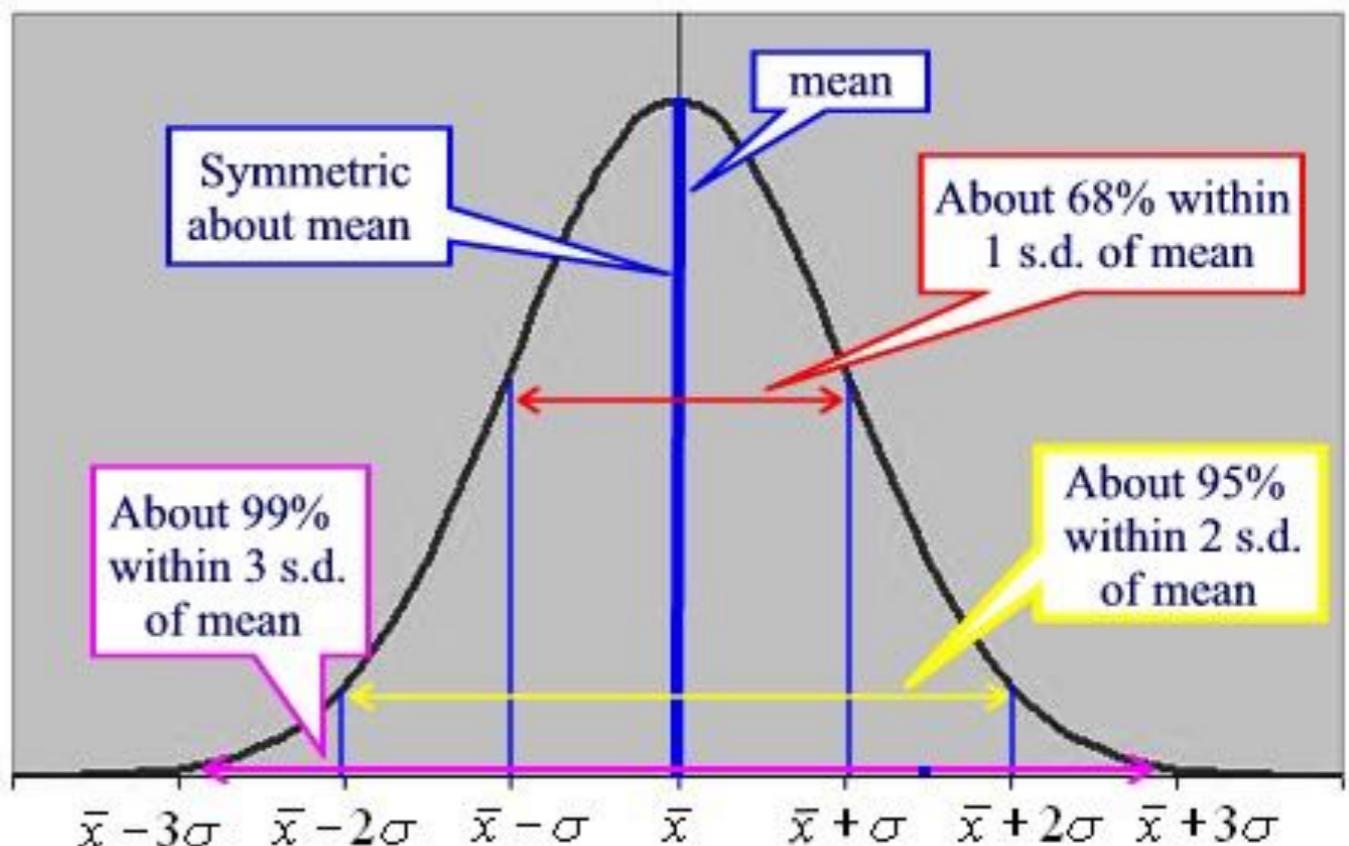
- the most commonly encountered probability distribution

$$P_G(x|\mu, \sigma) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left(-\frac{(x - \mu)^2}{2\sigma^2}\right)$$

- mean:  $\mu$ , standard deviation:  $\sigma$

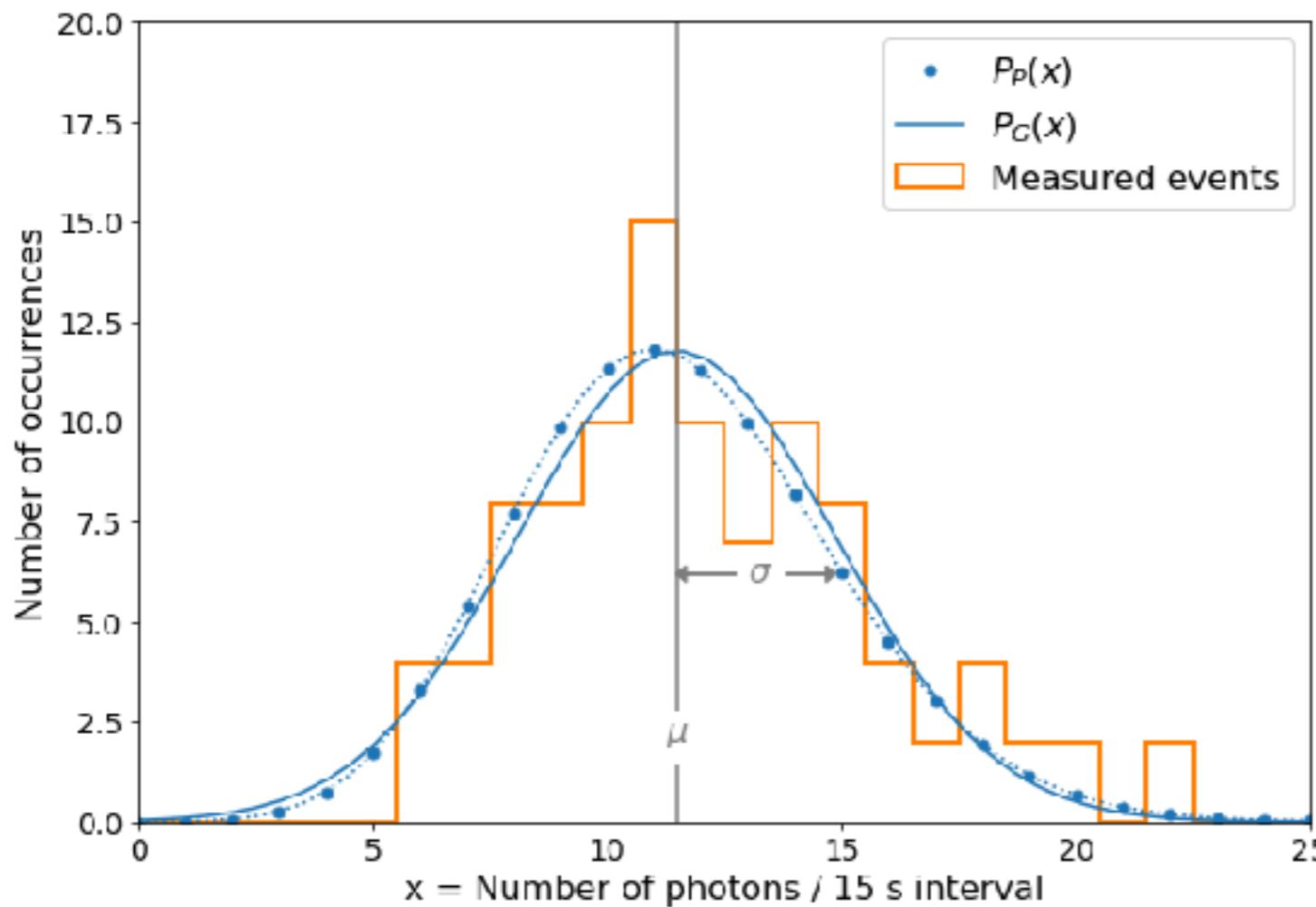
- can be derived as limit of the Poisson distribution for large values of the mean,  $\mu \geq 30$

- can also be derived as limit of many other distributions



# Gauss Distribution - Example

a detector measures the number of gamma-ray photons per 15 second interval, making 60 measurements:



measured mean:

$$\bar{x} = 11.48$$

blue points:

$$P_P(x|11.48)$$

blue curve:

$$P_G(x|\bar{x}, \sqrt{\bar{x}})$$

note: unlike Poisson distribution, Gaussian is continuous and defined for all  $x$