2018 Workshop on Gravitational Waves and High-Performance Computing

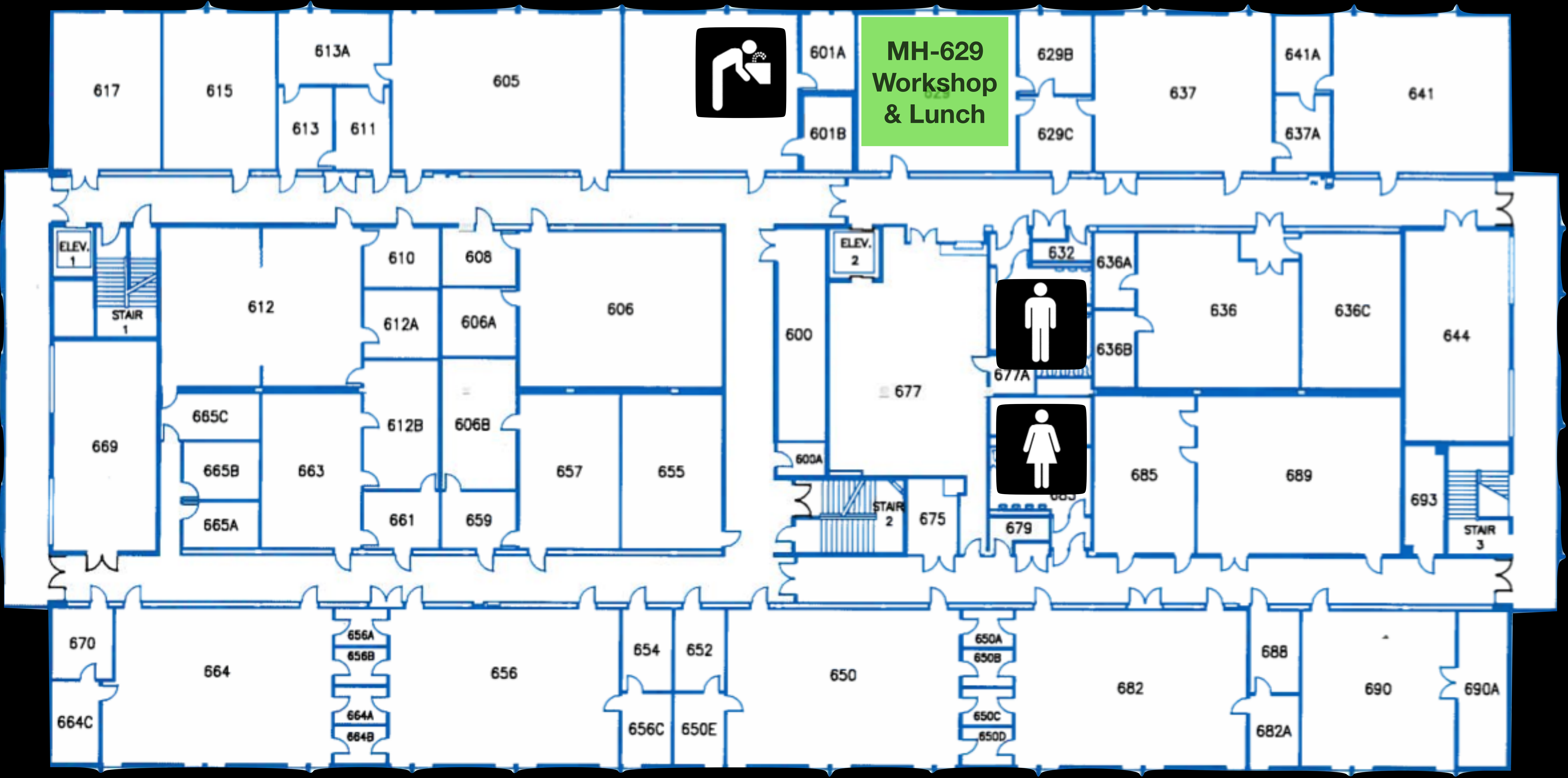
Geoffrey Lovelace

August 13, 2018 – August 17, 2018

Welcome to the workshop!

- Please take an ABCD card and schedule
- Please make a name tag
- Donuts today
- Water next store in MH-601
- Workshop supported by the National Science Foundation

Welcome to the workshop!



Photos

- We would like to take photos during the workshop
- The photos would appear on the Cal State Fullerton website, in news stories about the workshop
- If you agree to have your picture taken, please check the box on the sign-in sheet

Schedule overview

- **Monday**: Powers of 10 & computing, UNIX, thermal noise
- **Tuesday:** Programming with Python
- **Wednesday**: Black holes, gravitational waves
- **Thursday:** Gravitational-wave research, Data Center tour
- **Friday**: visualizing colliding black holes

GW PAC GRAVITATIONAL WAVE
Physics and Astronomy Center

Which brother am I?

C Both

D Neither

E Not sure

Icebreaker

- If you had to gain one superpower, which one would you choose?

A	Ability to fly

A	Ability to fly
B	Power to be invisible

Day 1

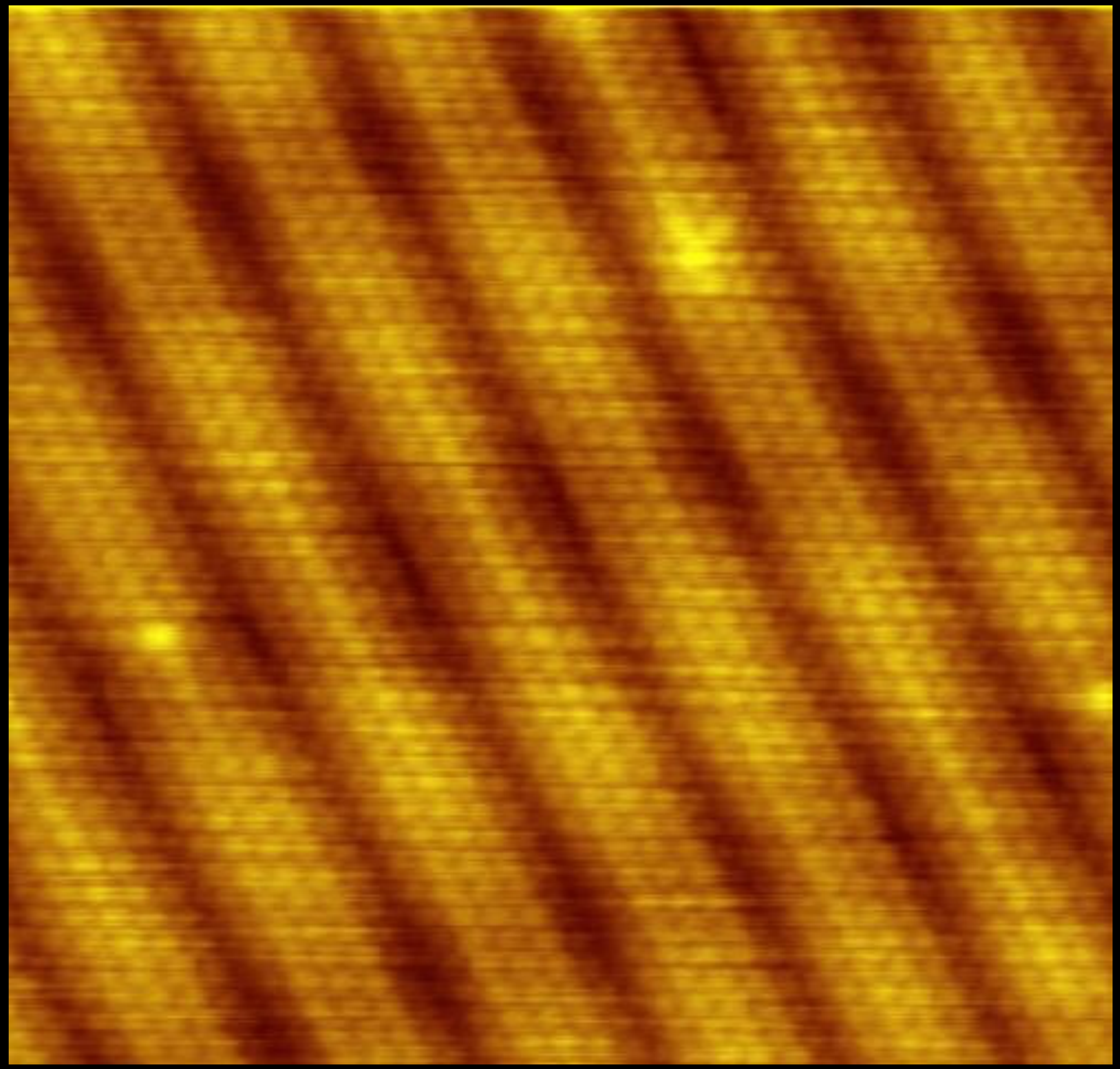
- Powers of 10
- HPC concepts, orders of magnitude, examples
- Unix, nano, batch submission
- Submit thermal noise job

Schedule today

Monday, 8/13	9:30 AM	Welcome
	9:40 AM	Powers of 10, scientific notation
	10:20 AM	Powers of 10 & computing
	11:00 AM	Break
	11:20 AM	Connecting to a supercomputer, UNIX part 1
	12:00 PM	Lunch
	1:30 PM	UNIX part 2, running jobs on a supercomputer
	2:10 PM	Thermal noise for measuring mirror positions
	2:30 PM	Break
	2:50 PM	Computing and visualizing thermal noise on a supercomputer

Powers of 10

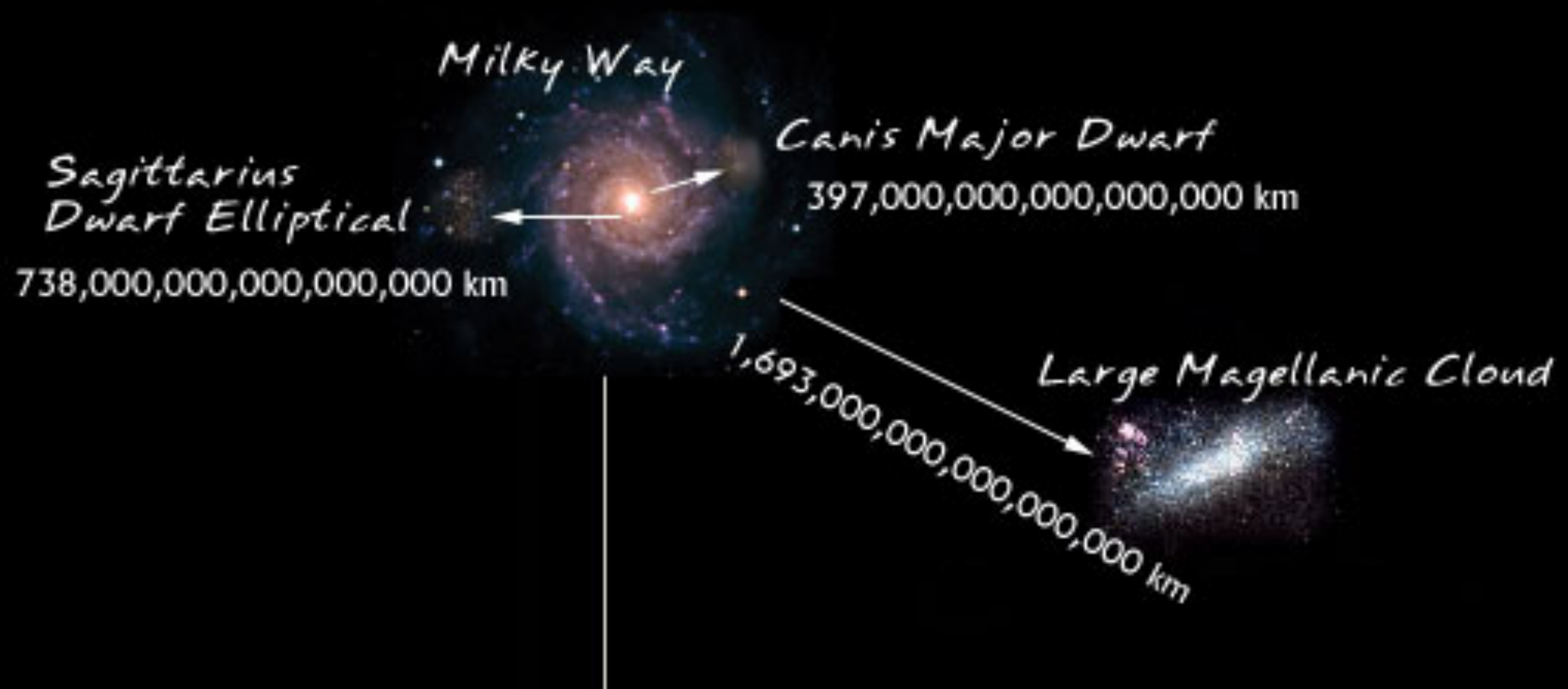
Powers of 10



Gold atoms (false color)

0.0000000003 m diameter

- The universe has many things of many different sizes
- Hard to get a sense of scale
- **Solution: use powers of 10**



Images courtesy wikipedia, NASA

Powers of 10

- $10^0 = 1$
- $10^1 = 10$
- $10^2 = 100$
- $10^3 = 1{,}000$
- $10^6 = 1{,}000{,}000$
- $10^9 = 1{,}000{,}000{,}000$

- $10^0 = 1$
- $10^{-1} = 0.1$
- $10^{-2} = 0.01$
- $10^{-3} = 0.001$
- $10^{-6} = 0.000001$
- $10^{-9} = 0.000000001$

Clicker question #1.0

- To the nearest power of 10, what is the diameter of the earth in meters?
  Hint: $1\ \mathrm{km} = 10^3\ \mathrm{m} = 0.6\ \mathrm{mi}$

A	$10^6\ \mathrm{m}$
B	$10^7\ \mathrm{m}$
C	$10^8\ \mathrm{m}$
D	$10^9\ \mathrm{m}$

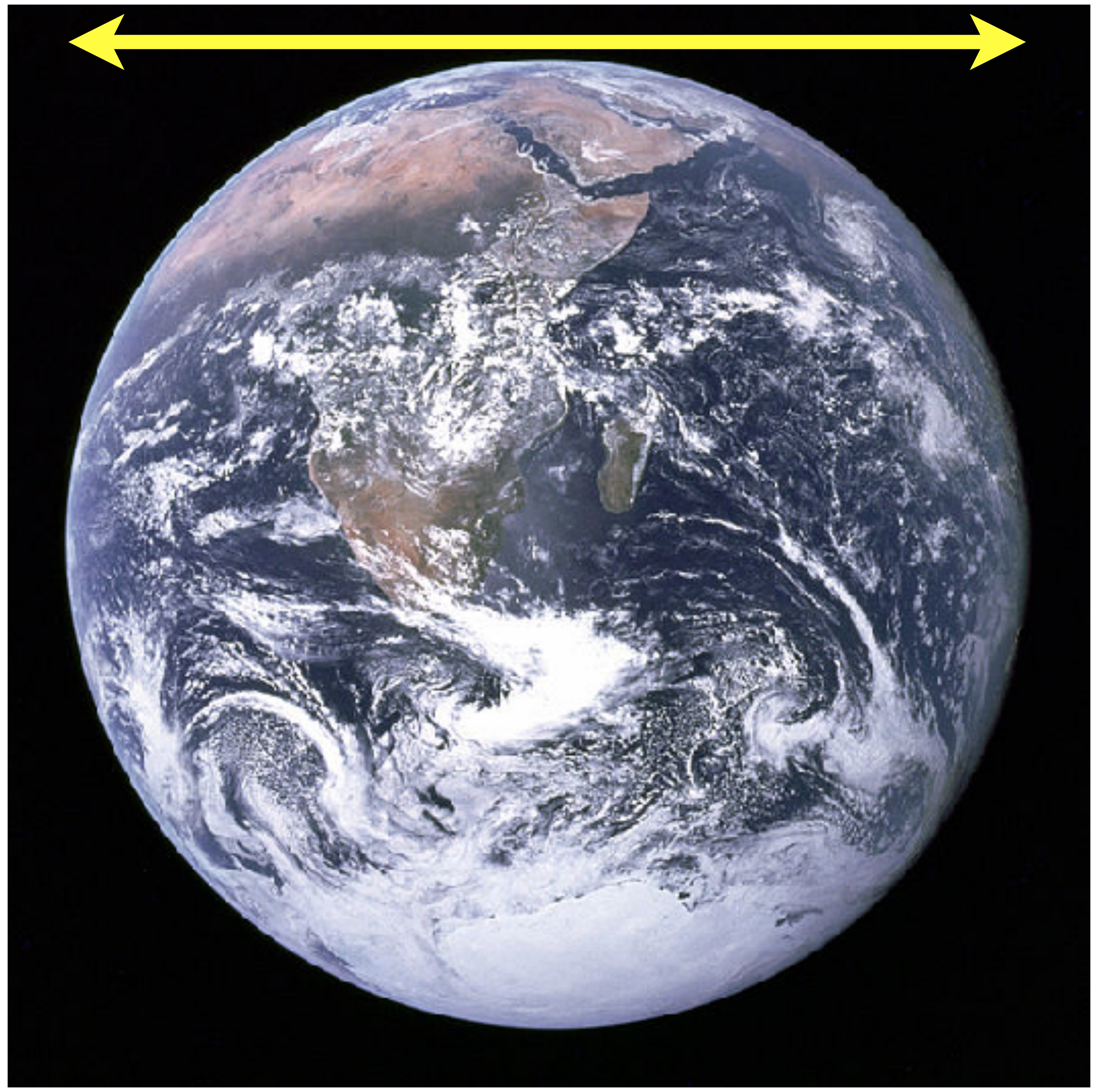


Image courtesy Wikipedia


100 million light years
10^{24}
meters

Clicker question #1.0

- To the nearest power of 10, what is the diameter of the earth in meters?
  Hint: $1 \text{ km} = 10^3 \text{ m} = 0.6 \text{ mi}$

A 10^6 m

B 10^7 m

C 10^8 m

D 10^9 m

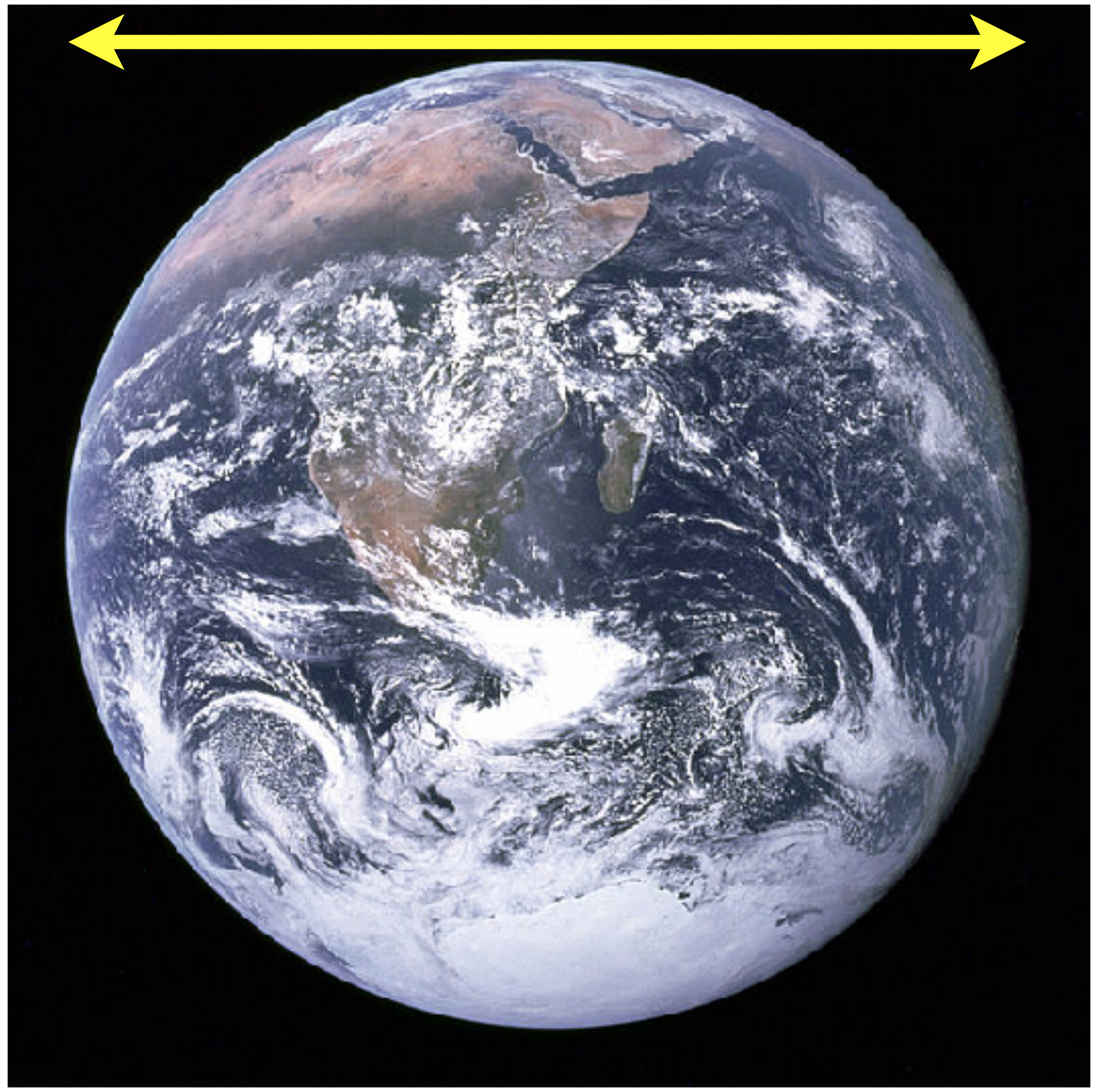


Image courtesy Wikipedia

Clicker question #1.1

- To the nearest power of 10, how far is it from this room to LAX airport in meters?
  Hint: $1\ \mathrm{km} = 10^3\ \mathrm{m} = 0.6\ \mathrm{mi}$

A $10^3\ \mathrm{m}$

B $10^4\ \mathrm{m}$

C $10^5\ \mathrm{m}$

D $10^7\ \mathrm{m}$

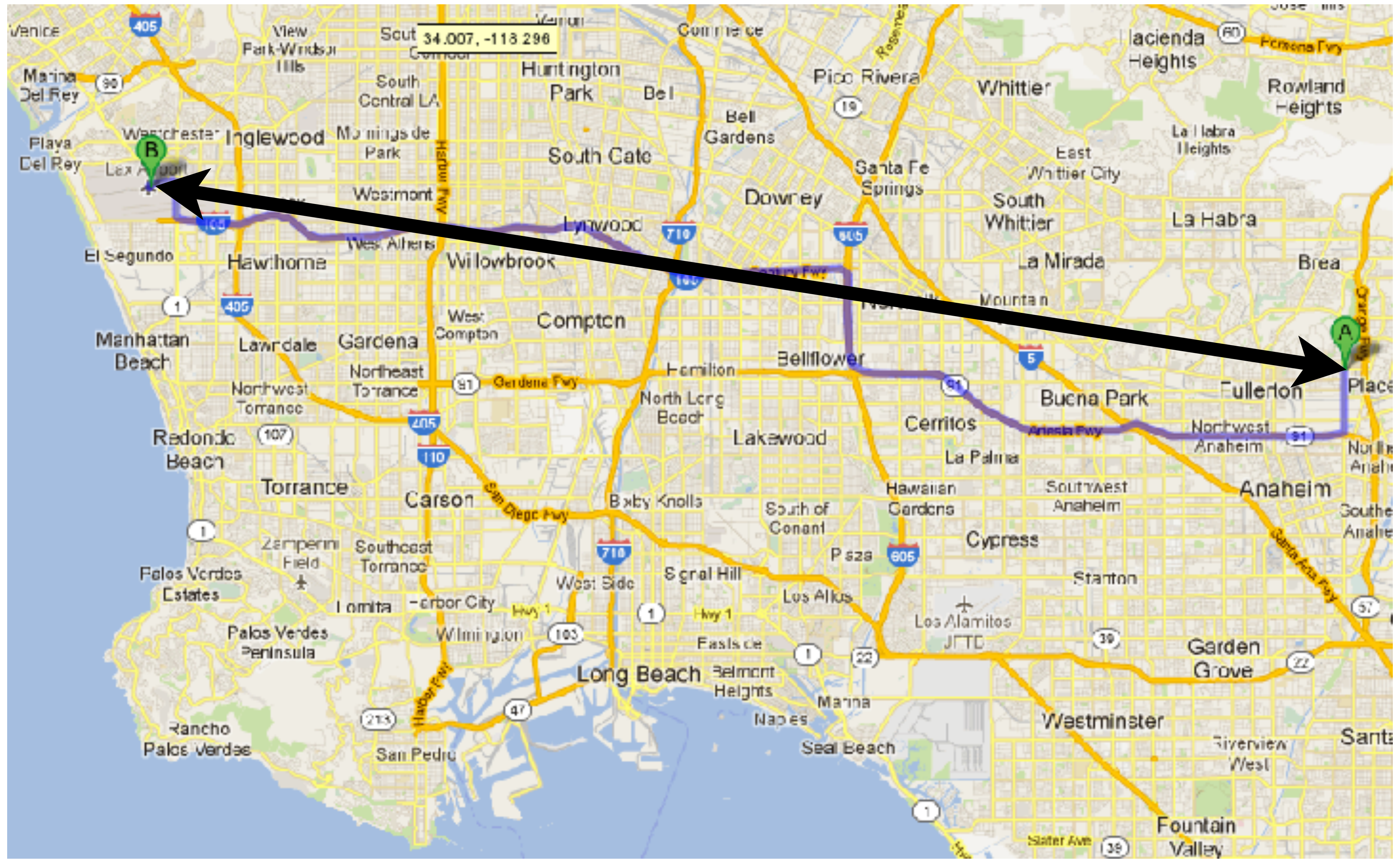


Image courtesy Google maps

Clicker question #1.2

- To the nearest power of 10, how old are you?

A 10^3 seconds

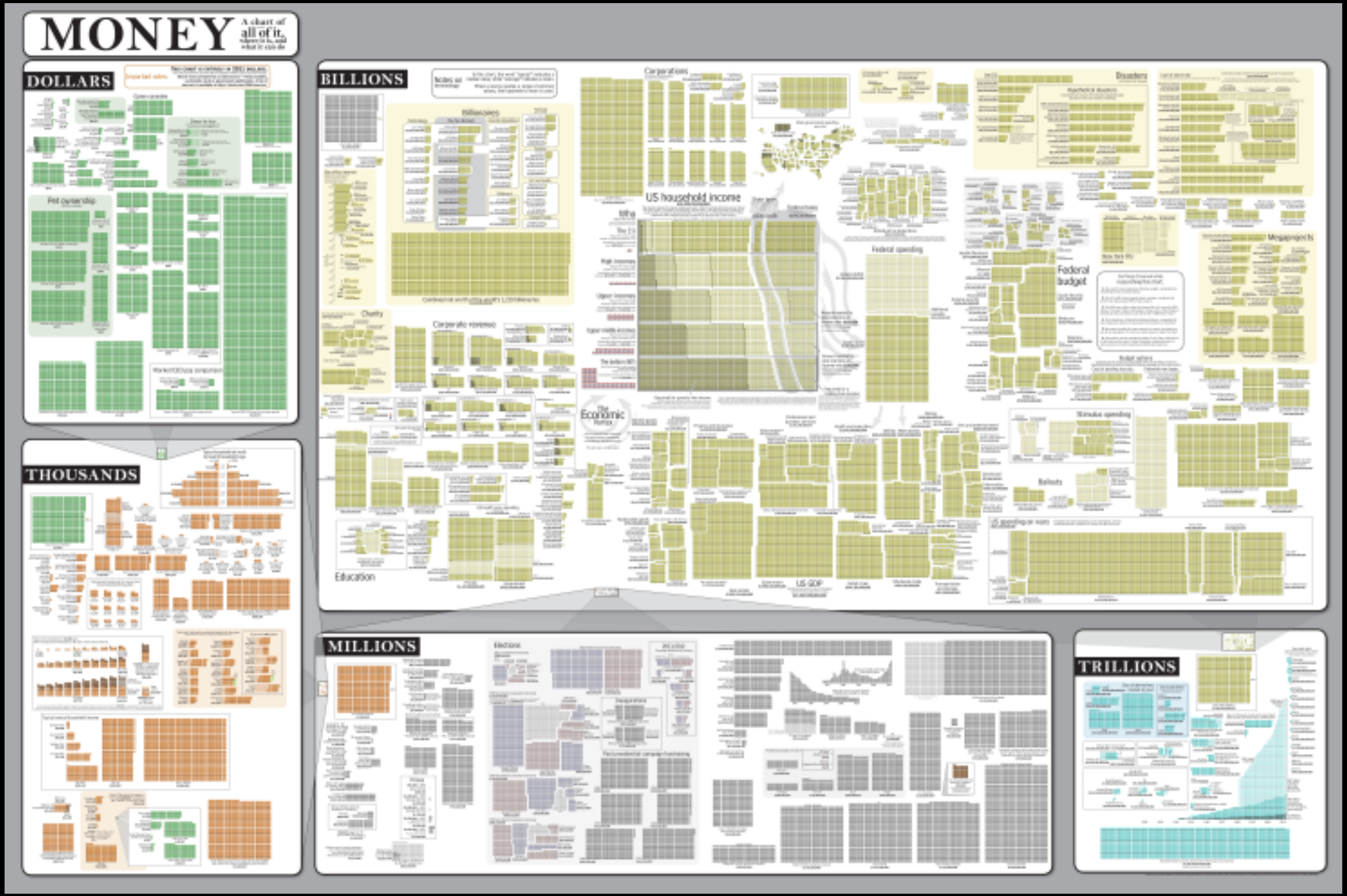
B 10^6 seconds

C 10^9 seconds

D 10^{12} seconds

Powers of 10

- The universe has many things of many different sizes
- So does money https://xkcd.com/980/huge/



Powers of 10

- $10^0 = 1$
- $10^1 = 10$
- $10^2 = 100$
- $10^3 = 1,000$
- $10^6 = 1,000,000$
- $10^9 = 1,000,000,000$

- $10^0 = 1$
- $10^{-1} = 0.1$
- $10^{-2} = 0.01$
- $10^{-3} = 0.001$
- $10^{-6} = 0.000001$
- $10^{-9} = 0.000000001$

Scientific notation

- $5 \times 10^0 = 5$
- $4 \times 10^1 = 40$
- $7 \times 10^2 = 700$
- $4.56 \times 10^3 = 4{,}560$
- $9.8 \times 10^6 = 9{,}800{,}000$
- $3.1 \times 10^9 = 3{,}100{,}000{,}000$

- $10^0 = 1$
- $4 \times 10^{-1} = 0.4$
- $7 \times 10^{-2} = 0.07$
- $4.56 \times 10^{-3} = 0.00456$
- $9.8 \times 10^{-6} = 0.0000098$
- $3.1 \times 10^{-9} = 0.0000000031$

Scientific notation

- $5 \times 10^0 = 5$
- $4 \times 10^1 = 40$
- $7 \times 10^2 = 700$
- $4.56 \times 10^3 = 4,560$
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- $10^0 = 1$
- $4 \times 10^{-1} = 0.4$
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- $3.1 \times 10^{-9} = 0.0000000031$

Activity

- Compute your age in seconds in scientific notation (round to 2 digits)
- Look up any conversions you like online

Powers of 10
& computers

Humans

- First entities called “computers” were teams of people
- Divide up the work into operations done in parallel, by hand (perhaps with mechanical aid)
- Redundant calculations to check accuracy
- Since 1700s
- 10^{-1} to 1 FLOPS / human
  (decimal operations / second / human)

1949 NACA High Speed
Flight Station “Computer Room”)

Image courtesy wikipedia

Colossus (1942)

- First programmable, digital, electronic computer
- Break codes in World War II Britain
- 5×10^5 FLOPS

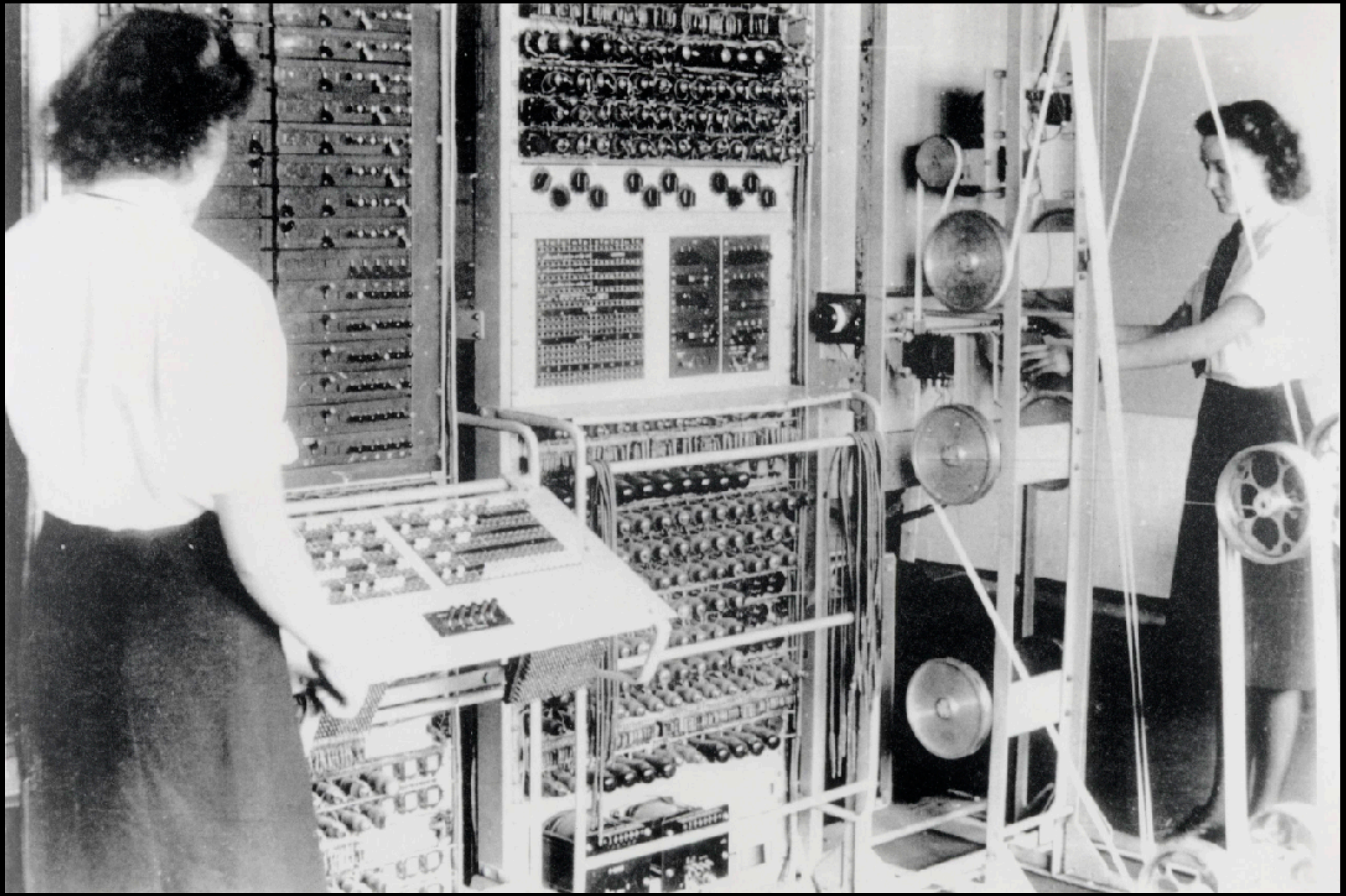


Image courtesy wikipedia

My first Mac (1984)

- First Macintosh
- 1×10^6 FLOPS

Image courtesy wikipedia

My Mac in 2003

- 2 cores
- 2×10^9 FLOPS

Image courtesy Apple

My current Mac

- 4 cores
- 2×10^{11} FLOPS

Image courtesy Apple

My current iPhone

- 6 cores
- 8×10^9 FLOPS

Image courtesy Apple

Clicker question #1.4

- In 1 second, today's high-end smart phones can perform ________ calculations per second (FLOPS).

A 10^4 (10 thousand)

B 10^7 (10 million)

C 10^{10} (10 billion)

D 10^{12} (1 trillion)

Images courtesy wikipedia, NASA

Clicker question #1.5

- In 1 second, today's high-end smart phones can perform as many calculations as _______ humans?

A 10^4 (10 thousand)

B 10^7 (10 million)

C 10^{10} (10 billion)

D 10^{12} (1 trillion)

For comparison:

Humans alive in 2018: 7.6×10^9
Total humans who ever lived: 10^{11}
Sources: google.com, pro.org

Clicker question #1.3

- Today's most powerful computers are __________ times more powerful than *today's high-end personal computers*.

A. 10 (ten)

B. 10^3 (a thousand)

C. 10^6 (a million)

D. 10^9 (a billion)

Images courtesy wikipedia, NASA

Orange-county Relativity Cluster for Astronomy (ORCA)

- Supercomputer for Cal State Fullerton Gravitational-Wave Physics and Astronomy Center
- 600 cores
- 7×10^{12} FLOPS

Blue Waters

- Most powerful computer I have used
- 70,000 cores
- 1×10^{16} FLOPS

Image courtesy Blue Waters

Summit

- Most powerful computer in the world (June 2018)
- 200,000 cores
- 2 x 10^{17} FLOPS
- Record with graphics cards: 2 x 10^{18} FLOPS

Image courtesy Oak Ridge National Laboratory

High performance computing

- Computing beyond what personal devices can do
  - Many cores work together in parallel

FLOPS	Example	Computing Type
10^0	*Addition by human with pen & paper*	*Early*
10^3	*Room-sized computer in 1940s*	
10^6	1980s personal computers (1984)	Personal
10^9	Personal computers around year 2000	
10^{10}	High-end smartphone today	
10^{11}	High-end PC today	
$\mathbf{10^{12}}$	**Small supercomputer today**	**High-Performance**
$\mathbf{10^{16}}$	**Most powerful supercomputer I've used**	
$\mathbf{10^{17}}$	**Most powerful supercomputers today**	

Clicker question #1.3

- Today's most powerful computers are __________ times more powerful than *today's high-end personal computers*.

A 10 (ten)

B 10^3 (a thousand)

C 10^6 (a million)

D 10^9 (a billion)

Images courtesy wikipedia, NASA

Clicker question #1.6

- In 1 second, the most powerful computer in the world can perform as many calculations as _______ humans?

A 10^8 (100 million)

B 10^{11} (100 billion)

C 10^{14} (100 trillion)

D 10^{17} (100 quadrilliion)

For comparison:

Humans alive in 2018: 7.6 x 10^9
Total humans who ever lived: 10^{11}
Sources: google.com, pro.org

Clicker question #1.7

- In 1 second, a small supercomputer like ORCA can perform as many calculations as _______ humans?

A 10^6 (1 million)

B 10^9 (1 billion)

C 10^{12} (1 trillion)

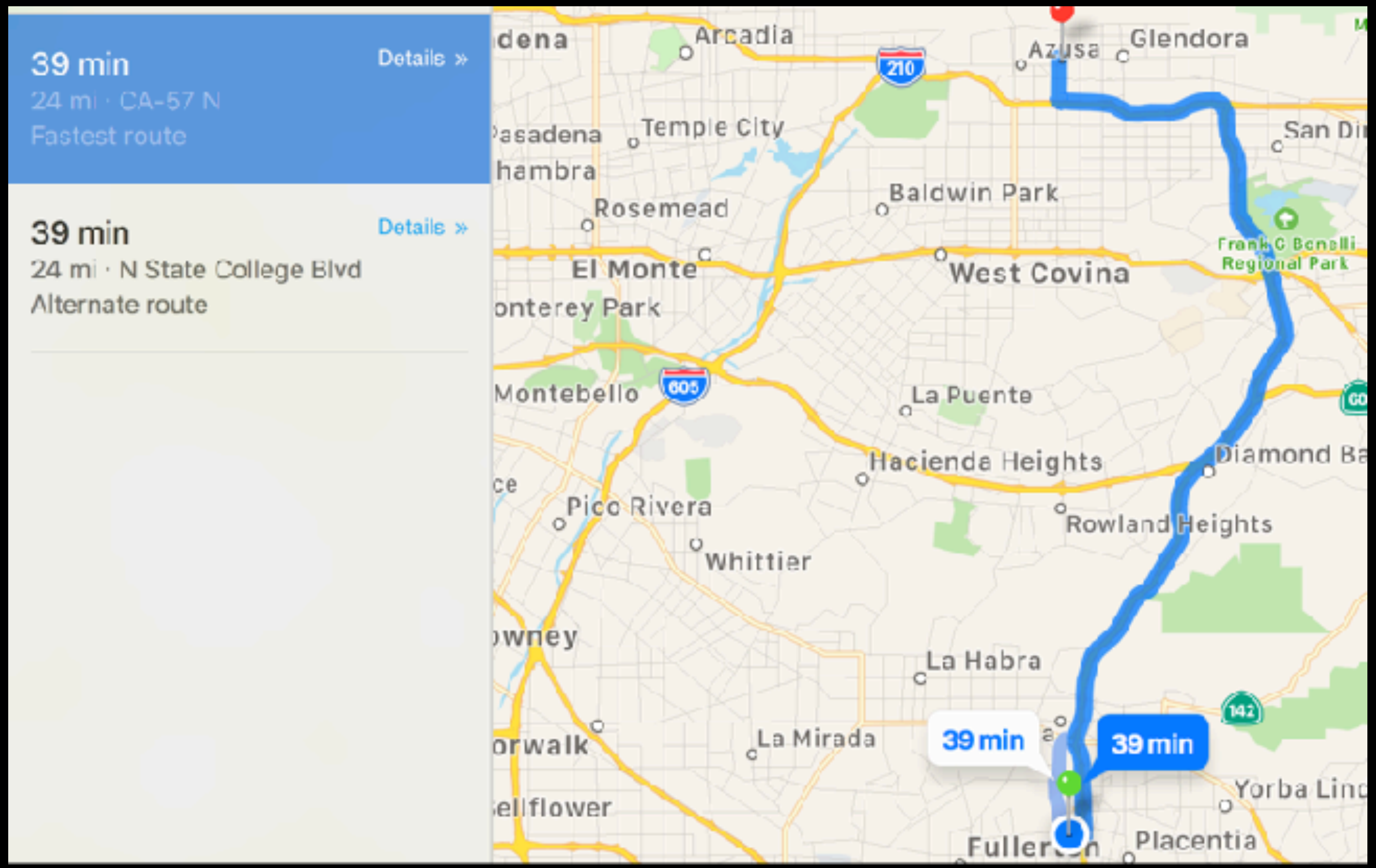
D 10^{15} (1 quadrilliion)

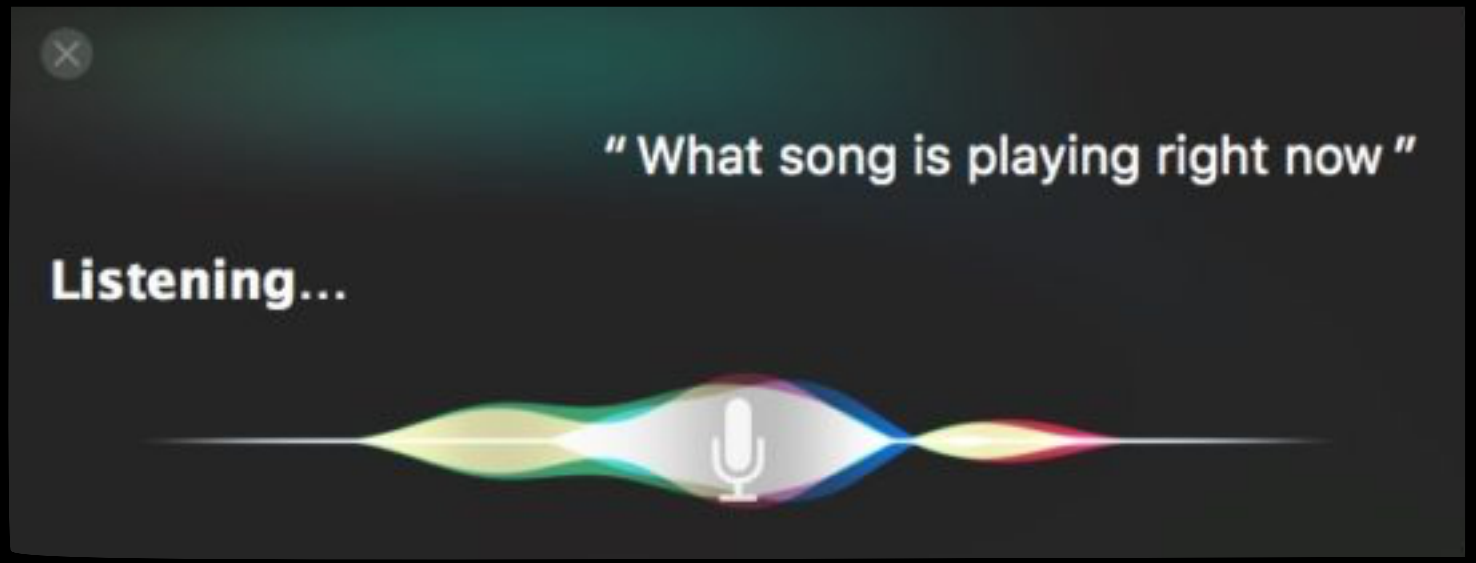
For comparison:

Humans alive in 2018: 7.6 x 10^9
Total humans who ever lived: 10^{11}
Sources: google.com, pro.org

High-performance computing in everyday life

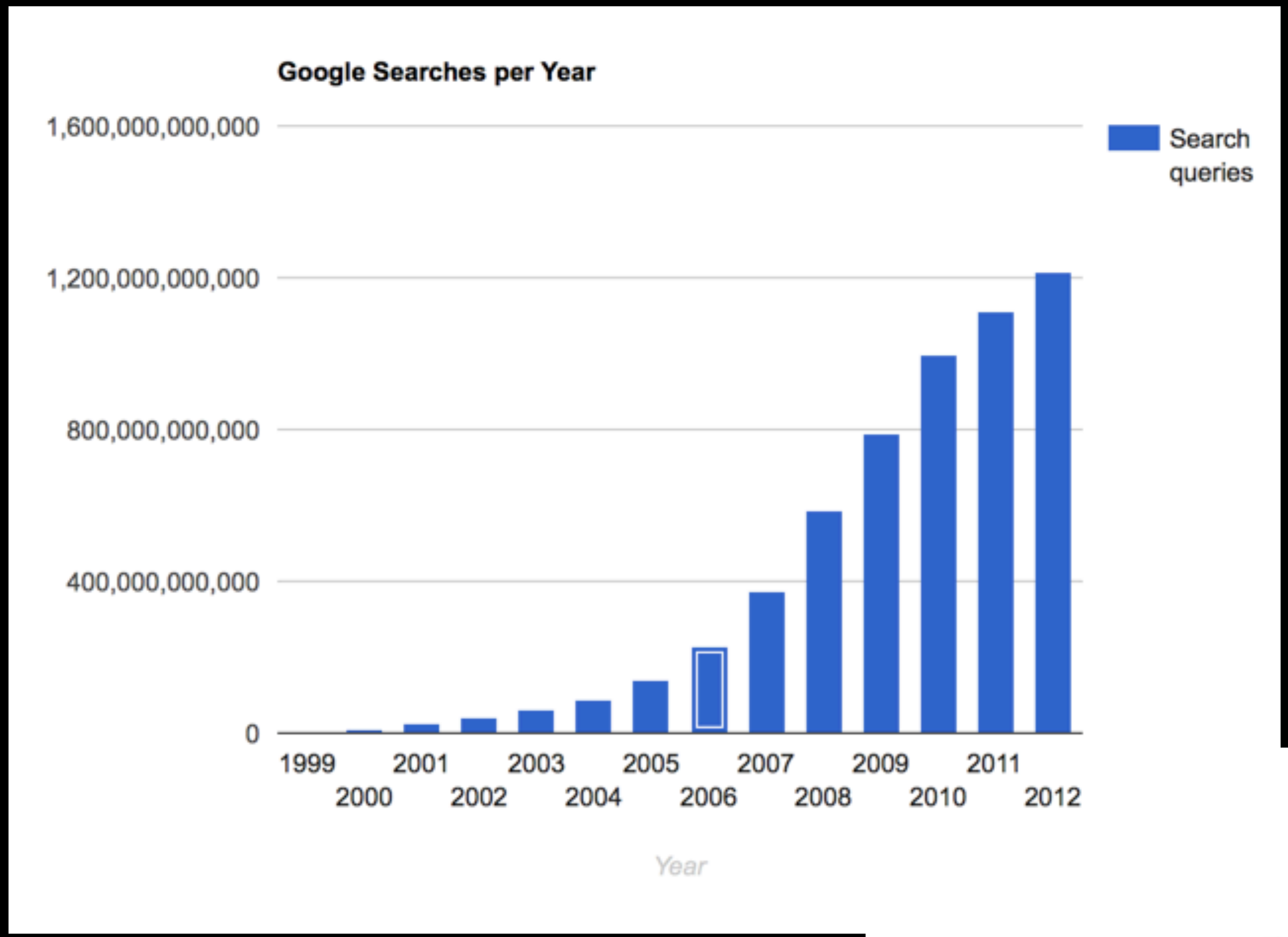
- Cloud computing
  - Search the web
  - Identify a song
  - Get directions
  - Voice assistants
  - Speech recognition





Example: Google search

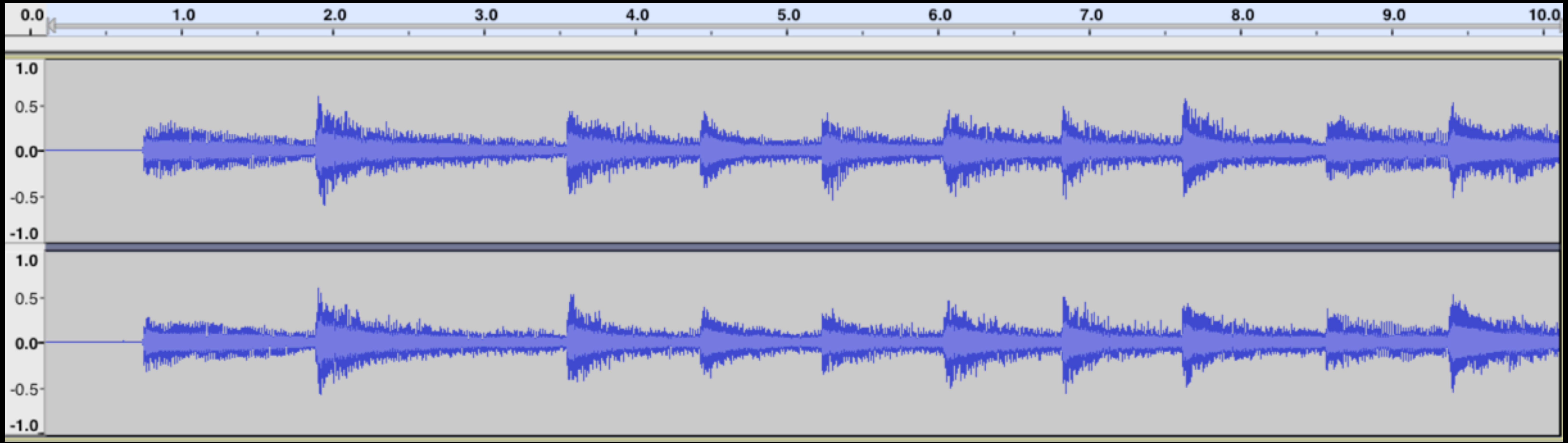
- Search ~ 10^{13} web pages
- 10^3 “servers” per query
- Each query takes about 0.2 seconds
- 4×10^4 queries on average every second of every day
  - If each server is “only” 10^9 FLOPS, Google search requires about 10^{16} FLOPS

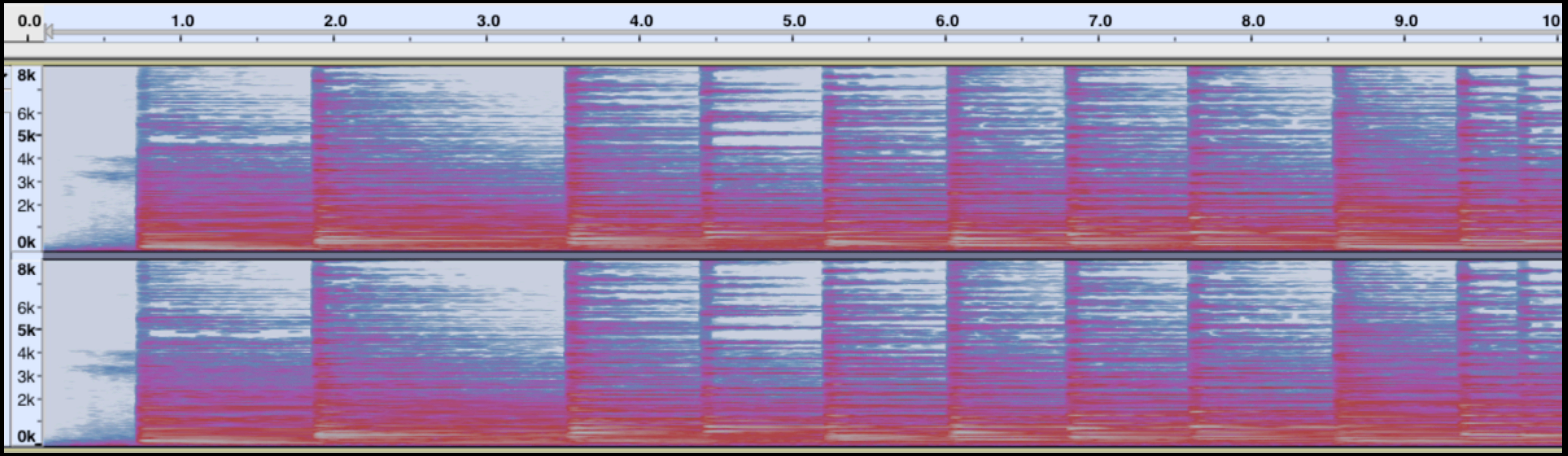


Images courtesy Google, internetlivestats.com

Example: Shazam

- 200 queries on average every second of every day
  - Convert sound into time-frequency plots, filter to keep only the loudest notes
  - Compare to a large library
  - Similar to how LIFO searches data for gravitational waves!
  - One query is a PC-sized calculation, roughly





Amazon web services data center
Courtesy amazon.com

Microsoft Azure data center
(courtesy sensorslab.co)

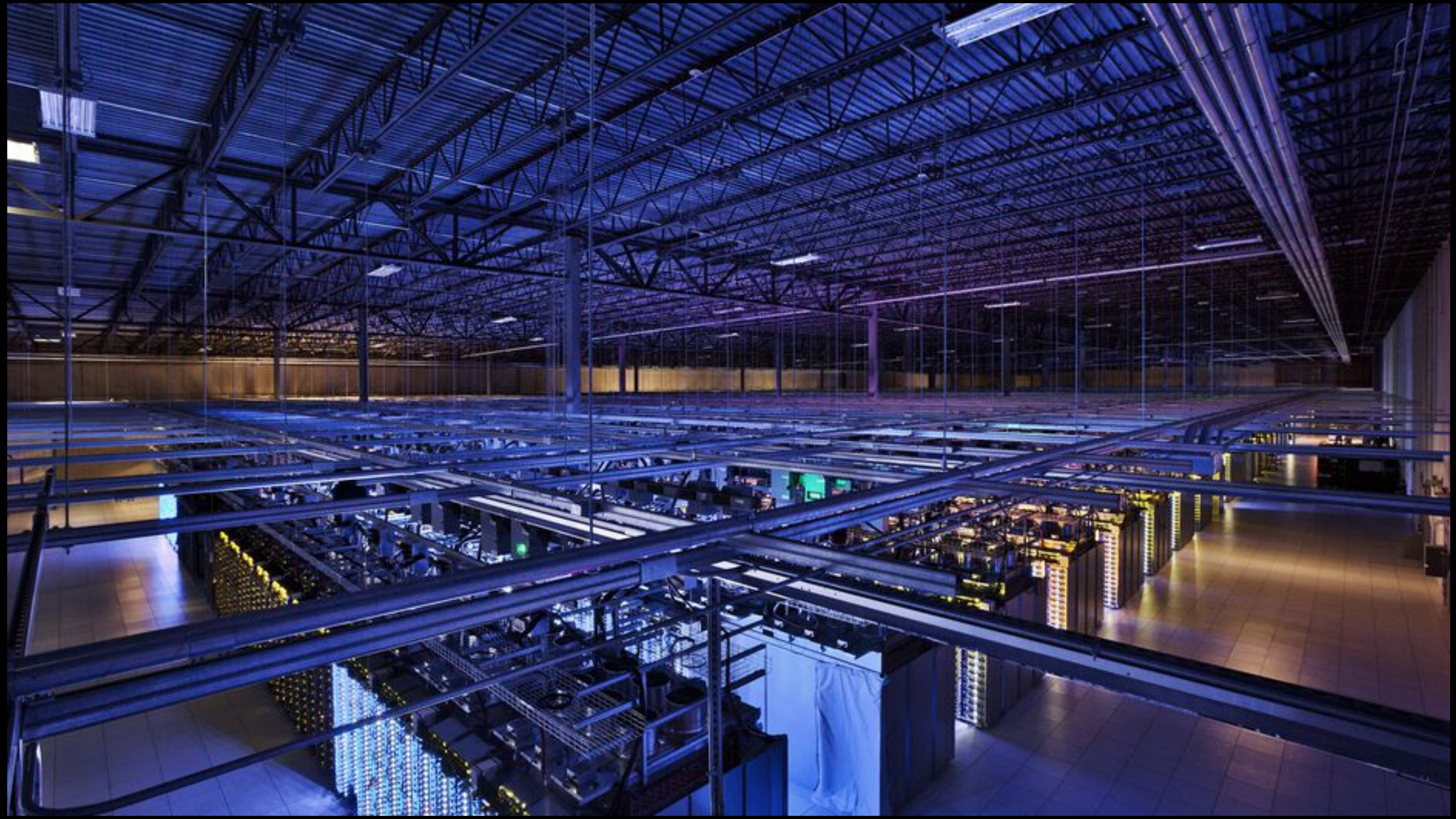


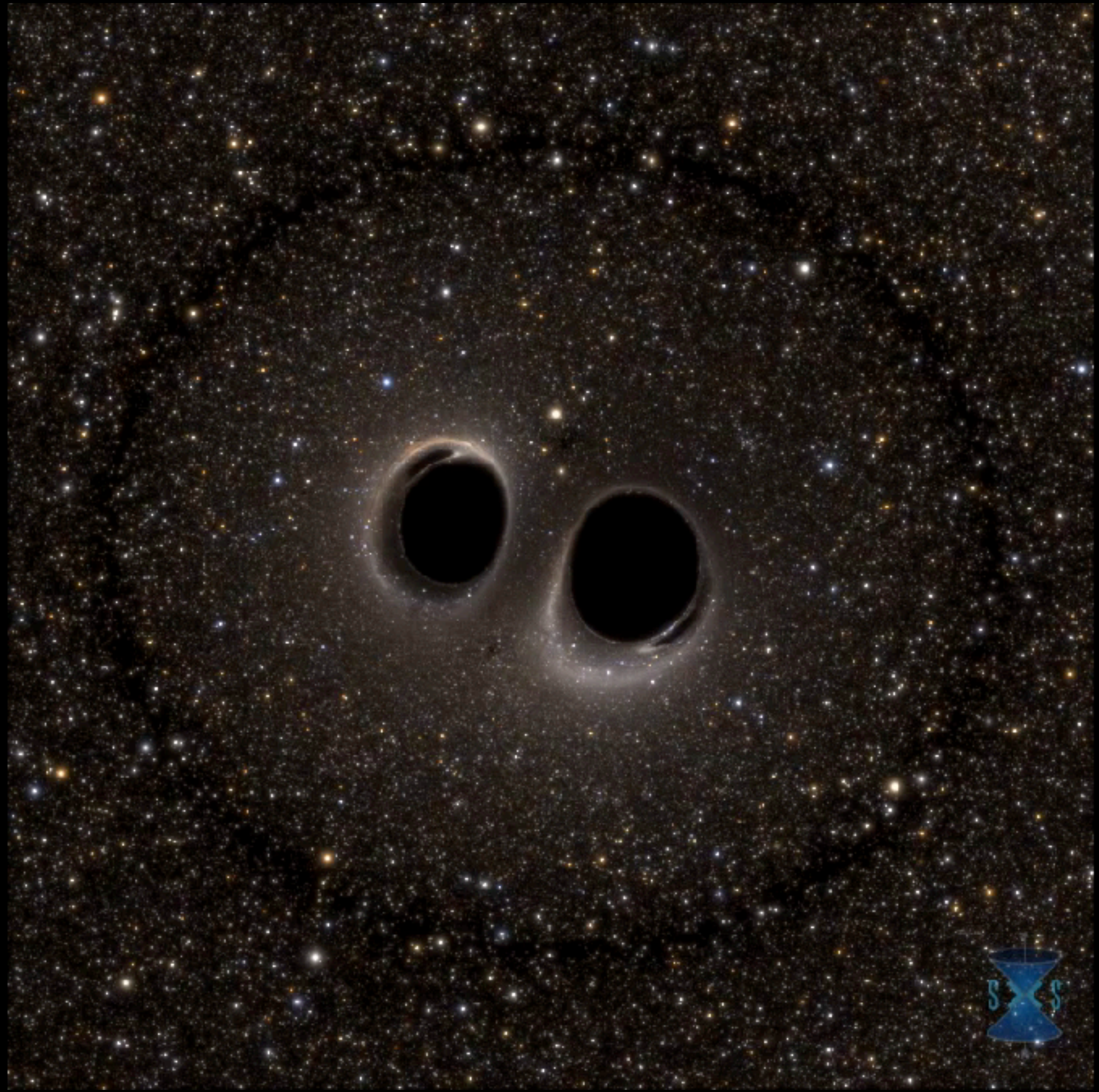
Image courtesy cnet: Google data center, Council Bluffs, Iowa

Google: 60,000 searches/second

Provide many 10^{15} FLOPS
of performance to customers

High-performance computing for science

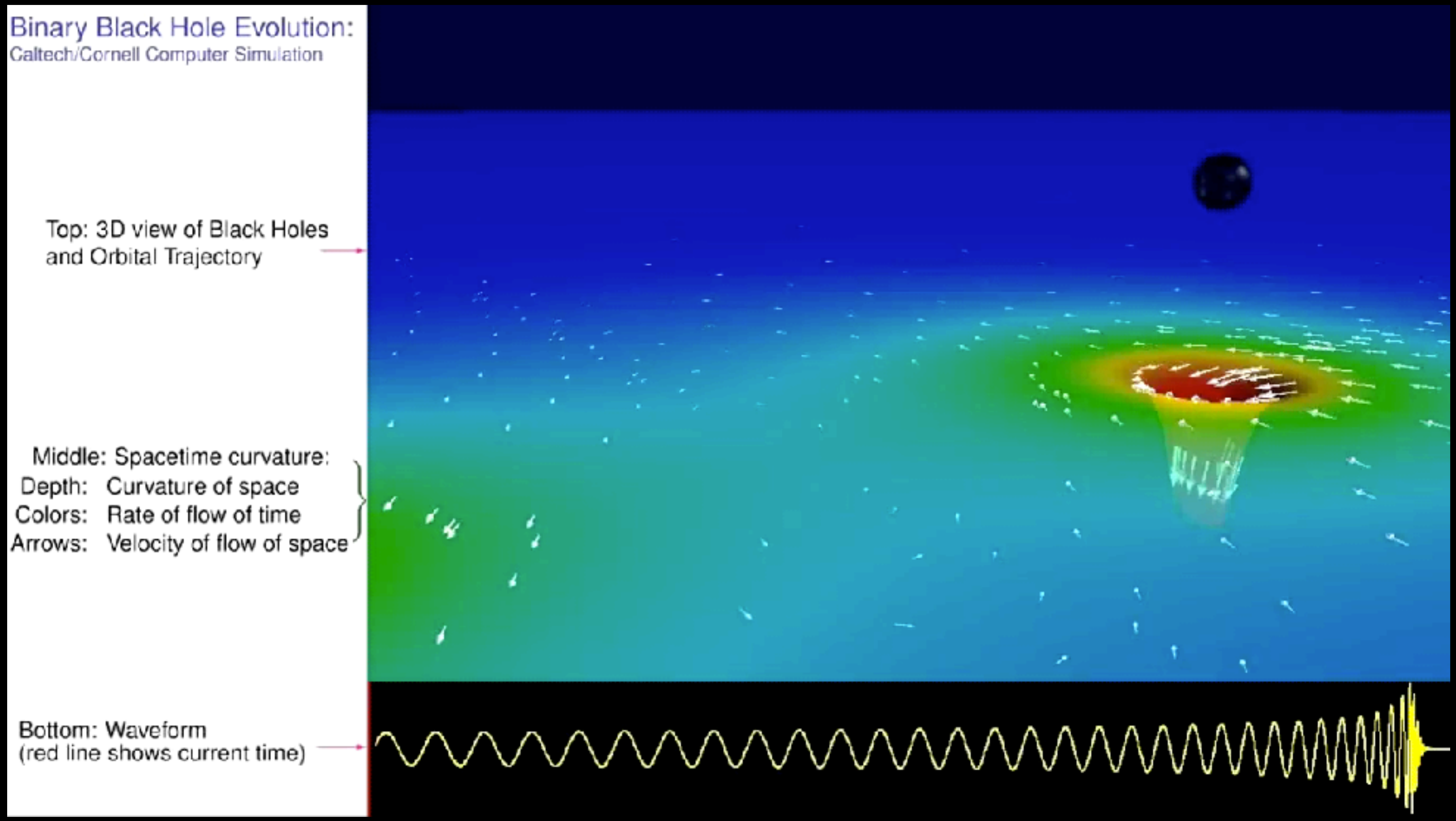
- Solve otherwise unsolvable problems
- Insight into scientific data & results
  - Experimental measurements
  - Results of calculations
  - Complicated pencil & paper results



Movie & calculation by undergraduate
Haroon Khan, Nick Demos,
Simulating eXtreme Spacetimes collaboration

Example: Simulating colliding black holes

- Head-on collision example
  - About 1.4×10^{17} floating-point operations
  - 3 days (48 cores on orca)
  - A month on a typical laptop
- Inspiral, merger, ringdown example
  - About 7.8×10^{17} floating-point operations
  - 17 days (48 cores before merger,
    36 cores after, on orca)
  - Months on a typical laptop



Using ORCA

ssh, UNIX command line, batch submission

Day 2

- Interactive Python tutorial
- Basic Python examples
- Pi dartboard: 1 core
- Accuracy, precision, and speed
- Pi dartboard: multiple cores

Schedule today

Tuesday, 8/14	9:30 AM	Learning to program with Python: basics, Python tutor, Jupyter notebooks
	11:00 AM	Break
	11:20 AM	Programming the Pi dartboard
	12:00 PM	Lunch
	1:30 PM	Learning to program with Python: arrays, plots
	2:10 PM	Resolution, precision & accuracy, timing
	2:40 PM	Break
	3:00 PM	Parallelizing the Pi dartboard, running the dartboard on a supercomputer

Programming is like magic

- Say the right cryptic words and something cool happens
- Mess up a word and the spell fizzles

Images courtesy Warner Bros.

pythontutor.com

- Helps you visualize what the program is doing
- Simplified version that we will use: http://cs1110.cs.cornell.edu/visualizer/

Google colaboratory

- https://colab.research.google.com
- Google lets us program and run on their computers for free

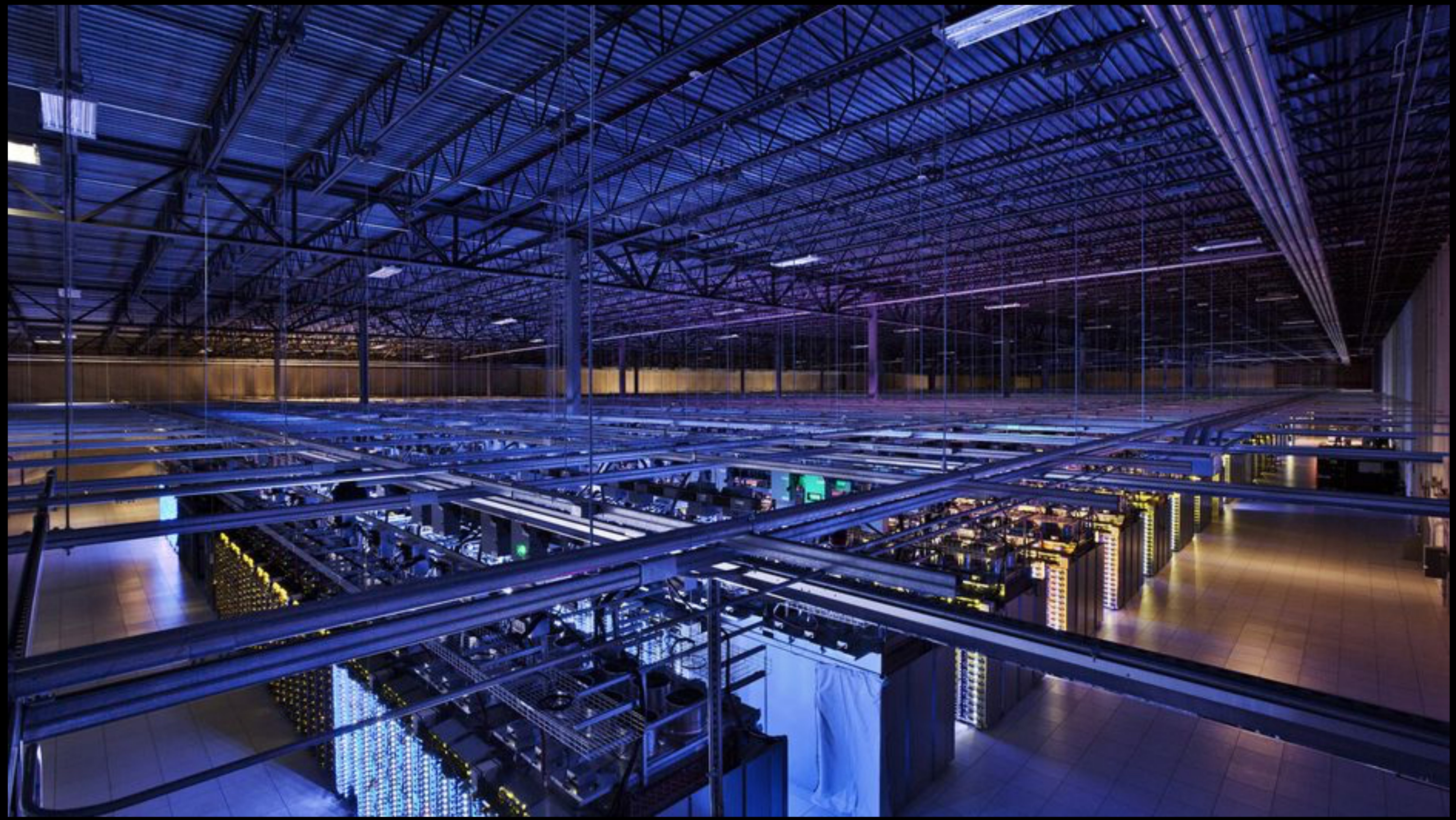


Image courtesy cnet: Google data center, Council Bluffs, Iowa

How to play along

- Open python tutor in a new browser tab in Chrome: http://cs1110.cs.cornell.edu/visualizer/
  - We’ll use the tutor to see “inside” what the code is doing, step by step
- Open colab.research.google.com in another tab, and make a new Python3 notebook
  - Save the notebook on your google drive, rename to “YOURNAME_Workshop2018.ipynb”
  - Share the notebook with me (geoffrey4444@gmail.com)
  - We’ll use notebook to actually run stuff “for real”
- If you get an error, let me know!

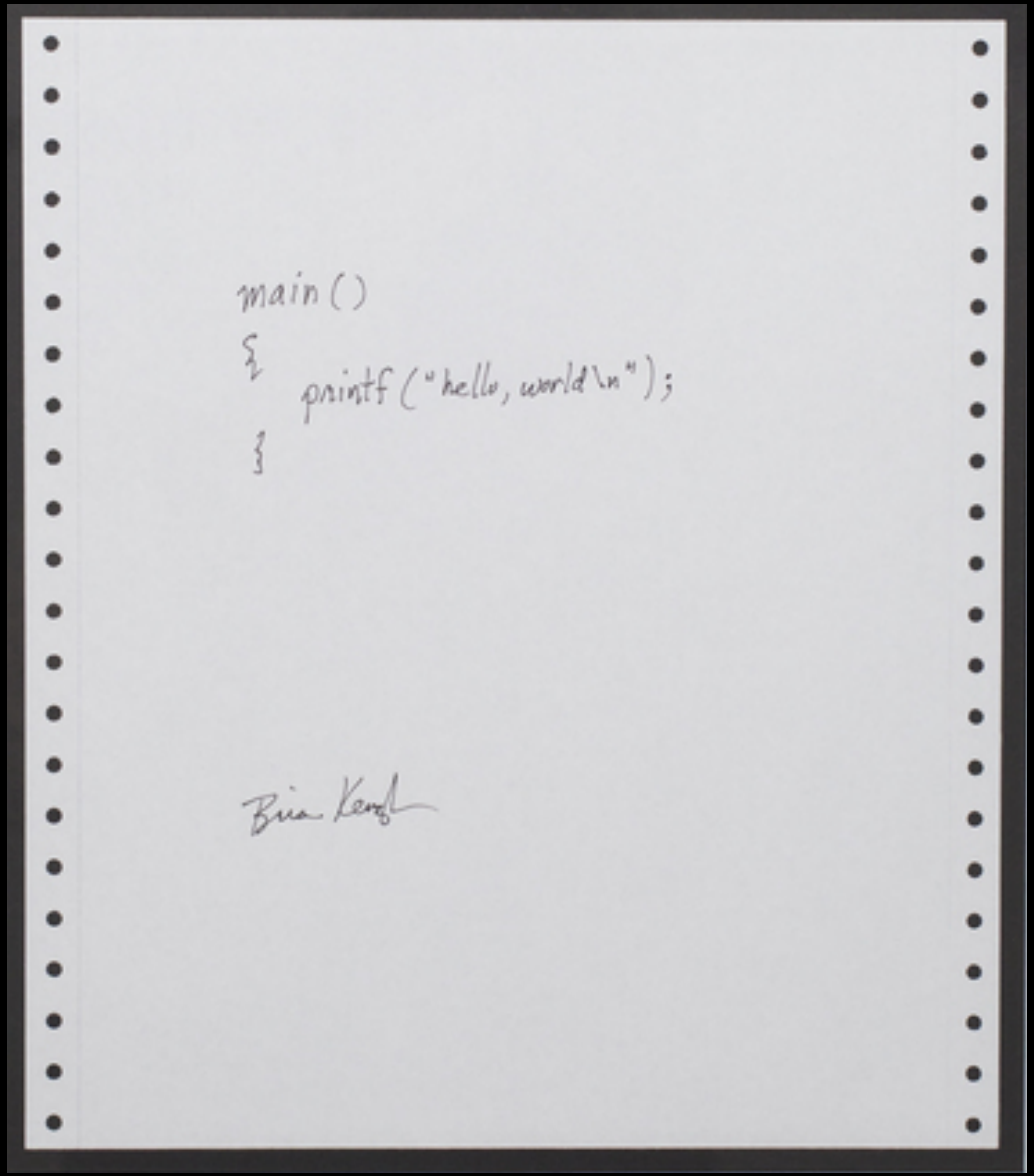
Output

- Your program needs to tell you the result
- Tradition since 1974: first program prints "Hello world"
- Python (language commonly used in scientific computing) makes this easy

Try in tutor: `print("Hello, world!")`

- Print basically anything

Try in tutor: `print(4*4+4-4)`



Brian Kernighan
(early UNIX developer), 1978

Libraries

- Don't reinvent the wheel when you want to hit the road
  - (But OK if you want to learn how to make wheels)
- Python has *many* libraries for numerical computing & everything else
- By "Libraries", I mean any pre-written code that you can use in your programs

Try in tutor:

```
import math
print(math.pi)
```

Math

Try in tutor (only type the left hand side of the ==):

- Arithmetic operations built in

```
(4 + 4) * 4 / 4 - 4
```

- Exponents with **

```
4 ** 4 == 256
```

- Scientific notation

```
4e4 == 40000
```

- The rest in the math library

```
math.sin(4)
math.sqrt(4)
```

Expressions

- Value = piece of data of a particular type
- Type = kind of data
- Operator = combine values to get a new value
  - Behavior depends on type
- Expression = group of values and operators
- Python evaluates expressions, like a calculator

`4.444`	`“Hello world”`
`float`	`string`
`+ - * /`	`+`
`4.0 * 3.0 - 2.0`	`"Hello" + " world"`

Clicker question #2.0

- What does Python get when it evaluates this expression? `4.0 * 3.0 - 2.0`

A 4.0

B 10.0

C Some other number

D An error

Try out some expressions in the tutor

```
4.0 * 3.0 - 2.0
```

```
"Hello" + " world"
```

Try out some expressions in the tutor

```
print(4.0 * 3.0 - 2.0)
```

```
print("Hello" + " world")
```

```
#make up your own
```

Some types we will need

- Float
- Int
- String
- Boolean

Type: float

- **Values**: real numbers ("numbers with decimal points")
  - Examples `4.1234` `4.0` `4.4e2` `-5.2e-3`
  - If you don't include a decimal point, it is an integer!
- **Operators:** `+ - * / **`

Try in tutor:

```
print(22.0 / 7.0)
```

```
print(8.0**2.0)
```

```
print(type(4))
print(type(4.0))
```

```
print(-3.0e-3 * 10.0)
```

```
print(1.0/3.0)
```

Type: int

- **Values**: integers (whole numbers, positive, negative, zero)
  - Examples `-4` `742352046` `7` `-33`
    - Don't use commas when typing an int or float
- **Operators**: `+ - * **` `/` `// %`

Try in tutor:

```
print(2**8)
```

```
print(4 * 3 - 2)
```

```
print(7 / 3) #float in Python3,
             #int in Python2 (avoid!)
```

```
print(7 // 3) # quotient
print(7 % 3)  # remainder
```

Clicker question #2.1

- In Python 3, what is the value of this expression?
  `10 // 3 + 1`

A	4
B	4.3333333333
C	Some other number
D	An error

Type: boolean

- **Values**: true or false
  - Examples `True` `False`

- **Operators**: `and or not`
  - `a and b` is true if both are true, false otherwise
  - `a or b` is true if a is true, b is true, or both are true
    is false if both a and b are false
  - `not a` is true if a is false, false if a is true

= and ==

- = stores results in a named object ("variable")

```
myNumber = 4
print(myNumber * myNumber)
```

```
print(myNumber * myNumber == 16)
True
```

- == tests whether two objects are equal

```
print(2 + 2 == 5)
False
```

Try in the tutor

- = stores results in a named object ("variable")
- == tests whether two objects are equal

```
print(2 + 2 == 4 and 3 + 3 == 6)
print(2 + 2 == 4 and 3 + 3 == 7)
print(2 + 2 == 4 or 3 + 3 == 7)
print(not 3 + 3 == 7)
```

```
a = True
b = True
c = False
d = False
```

```
# Pick a few of these
print(a)
print(not c)
print(not a)
print(a or b)
print(a or c)
print(c or d)
print(a and b)
print(a and c)
print(c and d)
```

Converting types

```
q = 4
print("The number is "+q)
```

```
q = 4
print("The number is "+str(q))
```

Try in tutor:

```
print(type(4))
print(type(str(4)))
print(type(float(4)))
```

Clicker question #2.2

- What does this line print?

```
import math
print("The value of pi is "+math.pi)
```

A The value of pi is 3.141592653589793

B The value of pi is math.pi

C Something else but not an error

D An error

Clicker question #2.2

- What does this line print?

```
import math
print("The value of pi is "+str(math.pi))
```

A The value of pi is 3.141592653589793

B The value of pi is math.pi

C Something else but not an error

D An error

Comments

- Comments explain what you're doing
- Use comments to explain your code
- Use names that help explain, even without comments

```python
# Say hello to someone by name
personName = "Geoffrey"
print("Hello " + personName)
```

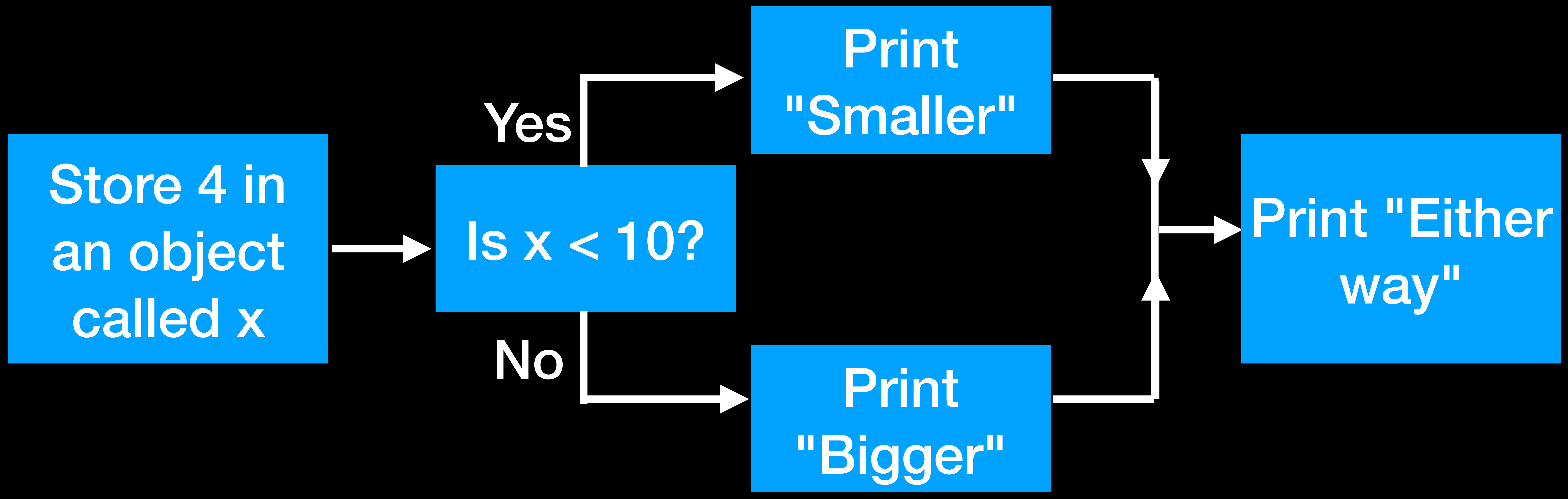
If/else

- If does the first indented thing if the stuff in () is True

- Otherwise it does the indented stuff under "else"

```
x = 4
if(x < 10):
    print("Smaller")
else:
    print("Bigger")
print("Either way.")
```

Try in tutor!



Clicker question #2.2b

- What does this program print?

```python
x = 4
if x==10 or x==11:
    print('yes')
else:
    print('no')
```

A Yes

B No

C The code gives an error

Clicker question #2.2

- What does this program print?

```python
x = 4
if x==10 or 11:
    print('yes')
else:
    print('no')
```

A Yes

B No

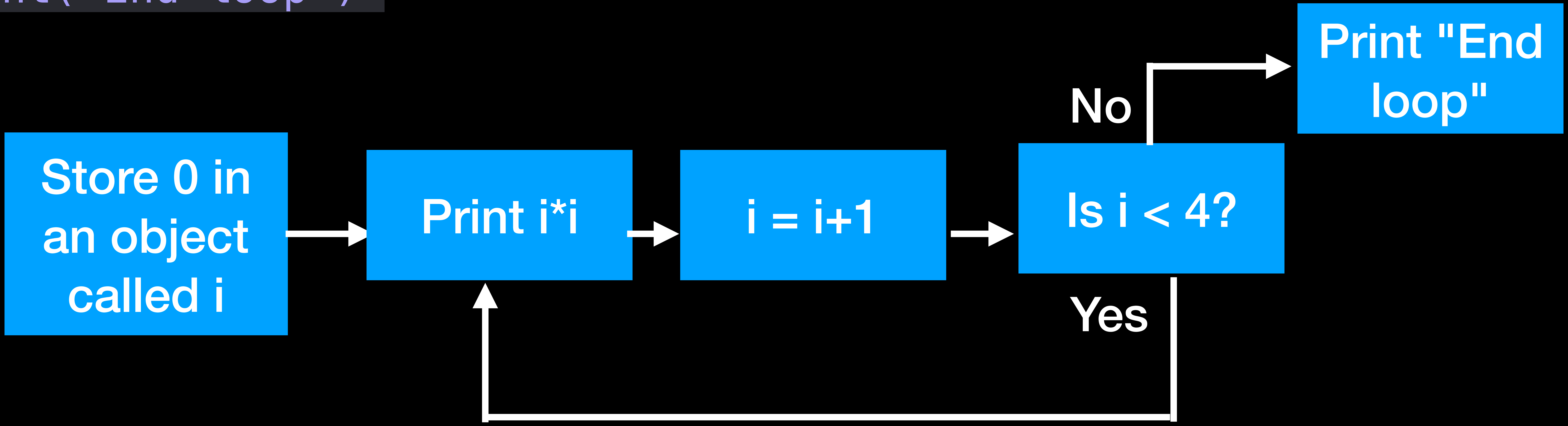
C The code gives an error

Try in tutor!

Loops

```
i = 0
while i < 4:
  print(i*i)
  i = i + 1
print("End loop")
```

```
0
1
4
9
```



Loops

```
for i in [1,2,3,4]:
  print(i*i)
```

```
0
1
4
9
```

```
i = 0
while i < 4:
  print(i*i)
  i = i + 1
```

```
0
1
4
9
```

So far, our programs just run & stop...

How do programs with a user interface work?

Clicker question #2.3

- What does this program print?

```
j = 1
while j < 3:
    j = j + 1
print(j)
```

A 1

B 2

C 3

D 4

Clicker question #2.4

- What does this program print?

```
product = 1
j = 1
while j < 3:
    product = product * j
    j = j + 1
print(product)
```

A	1
B	2
C	6
D	24

Clicker question #2.4b

- What does this program print?

```python
product = 1
j = 1
while j < 4:
    product = product * j
    j = j + 1
print(product)
```

A	1
B	2
C	6
D	24

Clicker question #2.4c

- What value of x makes the program print 24?

```
product = 1
j = 1
while j < x:
    product = product * j
    j = j + 1
print(product)
```

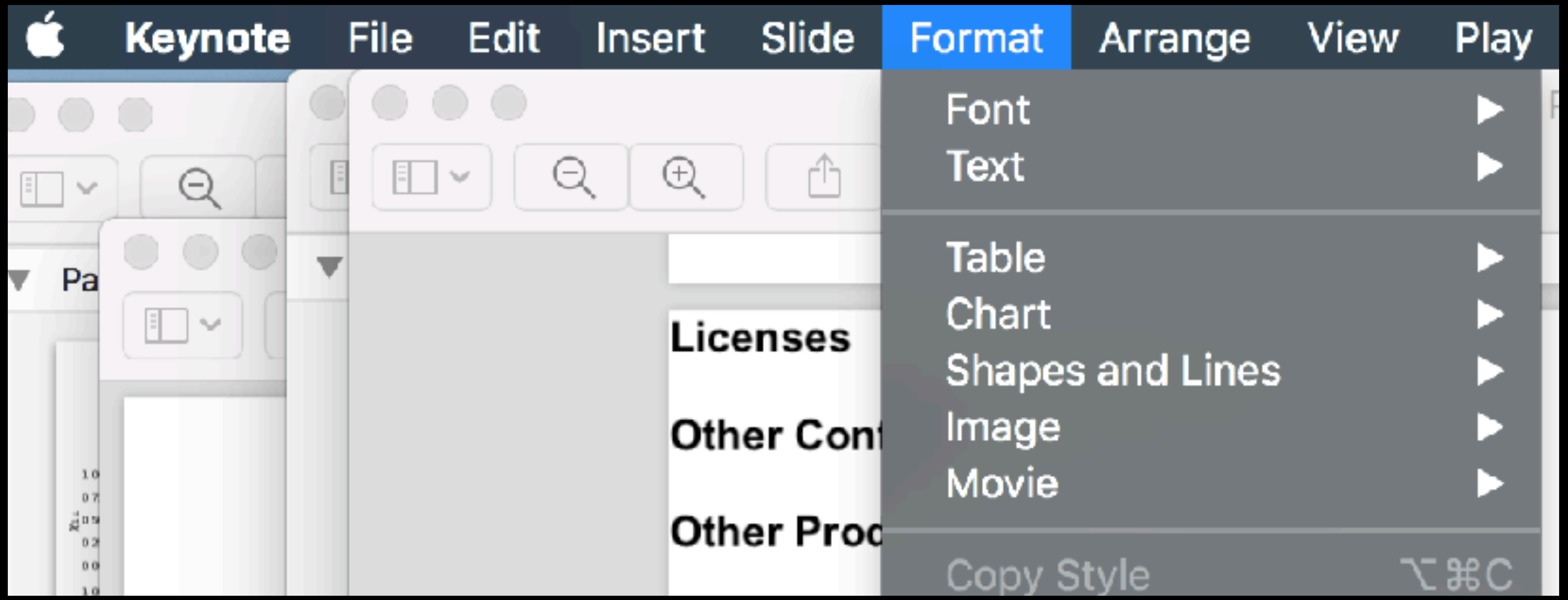
A	3
B	4
C	5
D	6

Loops

- Real life:
  event loop

- Event = key press,
  mouse/trackpad
  click,
  …

```
while message != quit:
  message = get_next_message()
  process_message(message)
```



My first program

- Basic, 1987

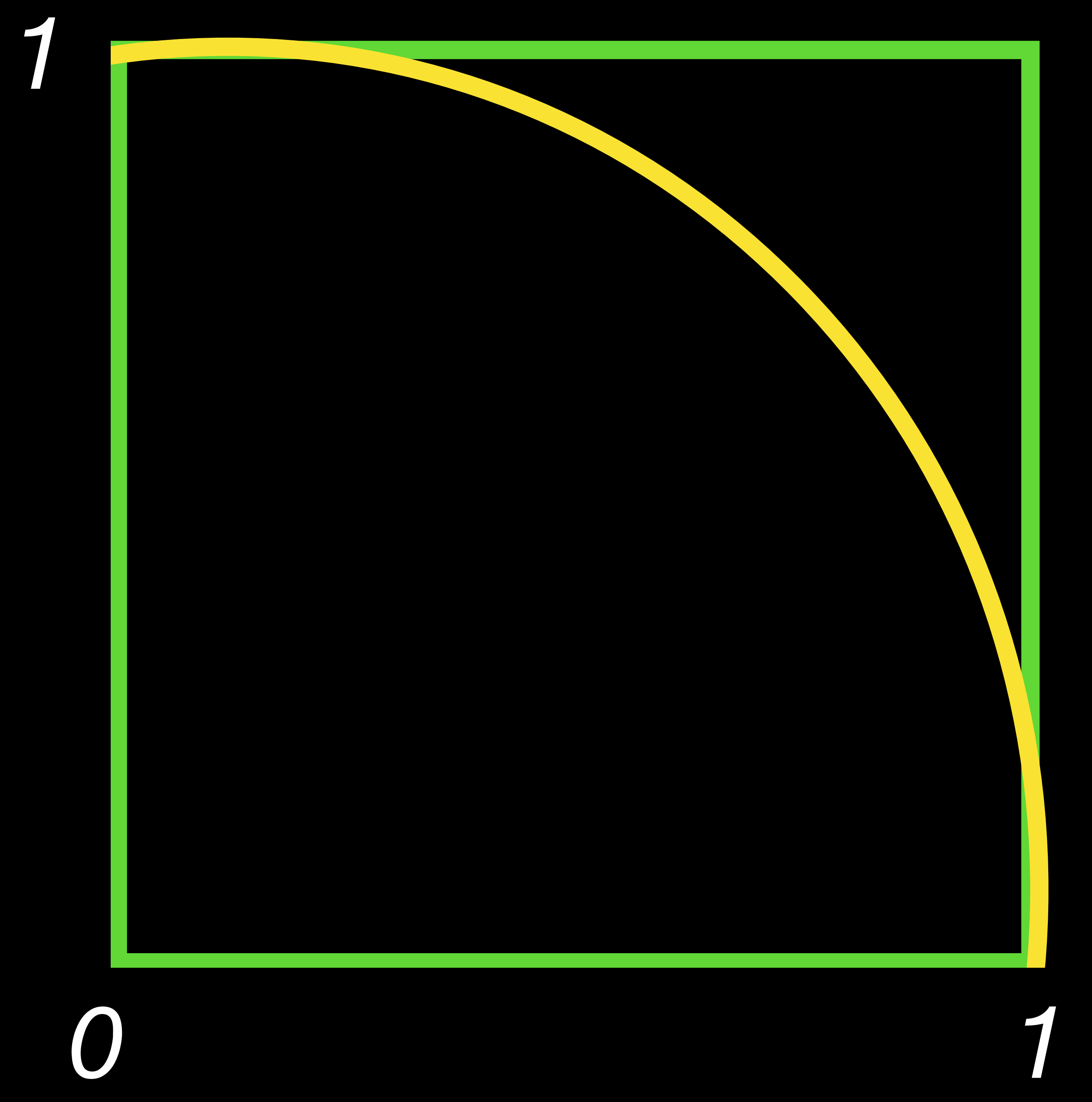
```
10 PRINT "GEOFFREY"
20 GOTO 10
```

- Python equivalent

```python
done = False
while not done:
  print("Geoffrey")
```

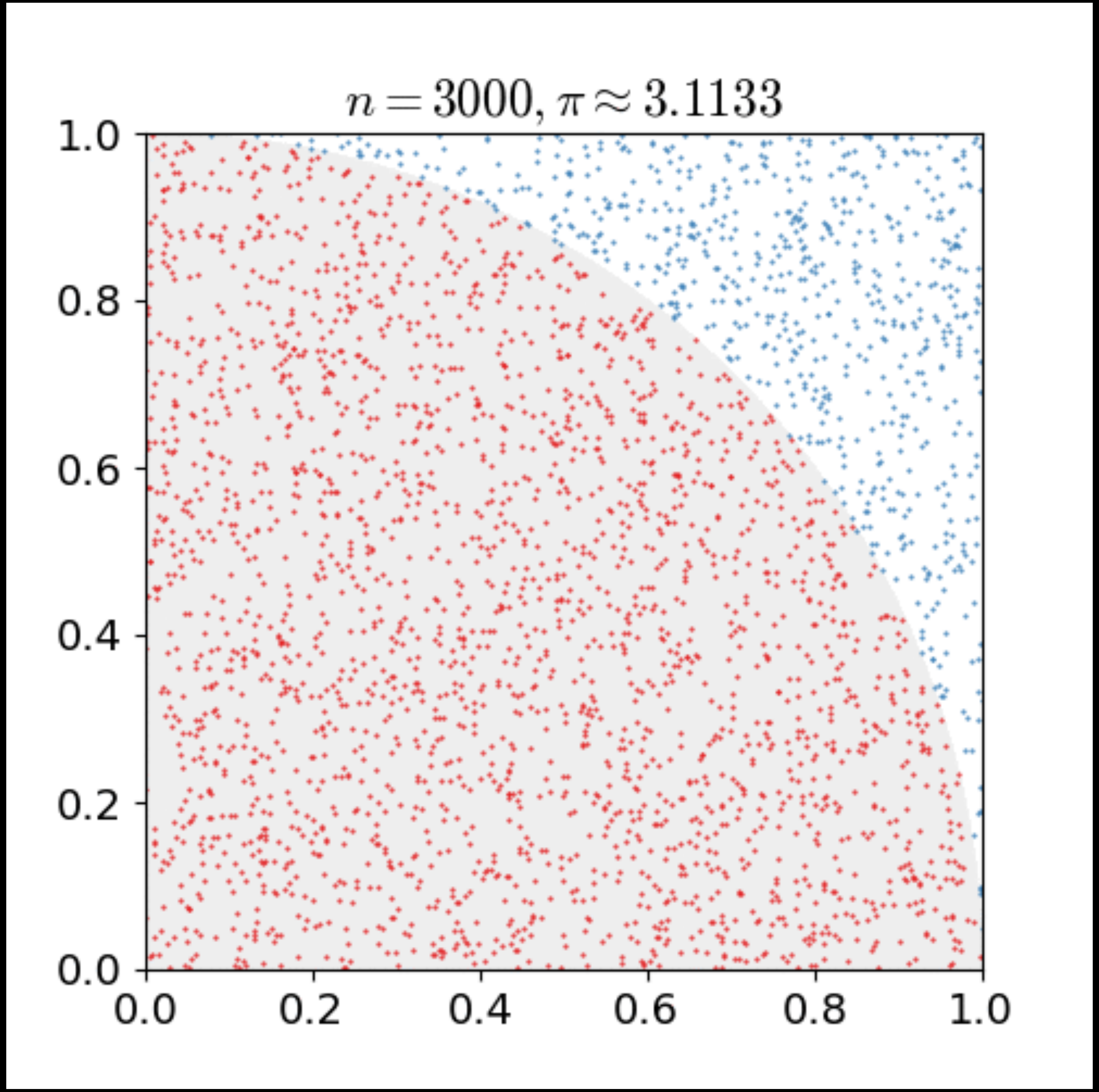
A silly way to compute π

- Area of circle?
- Area of square?
- Idea: throw darts in square
  - (circle area) ÷ (square area) ≈ darts in circle ÷ darts in square = “hits” / (“hits” + “misses”)



A silly way to compute π

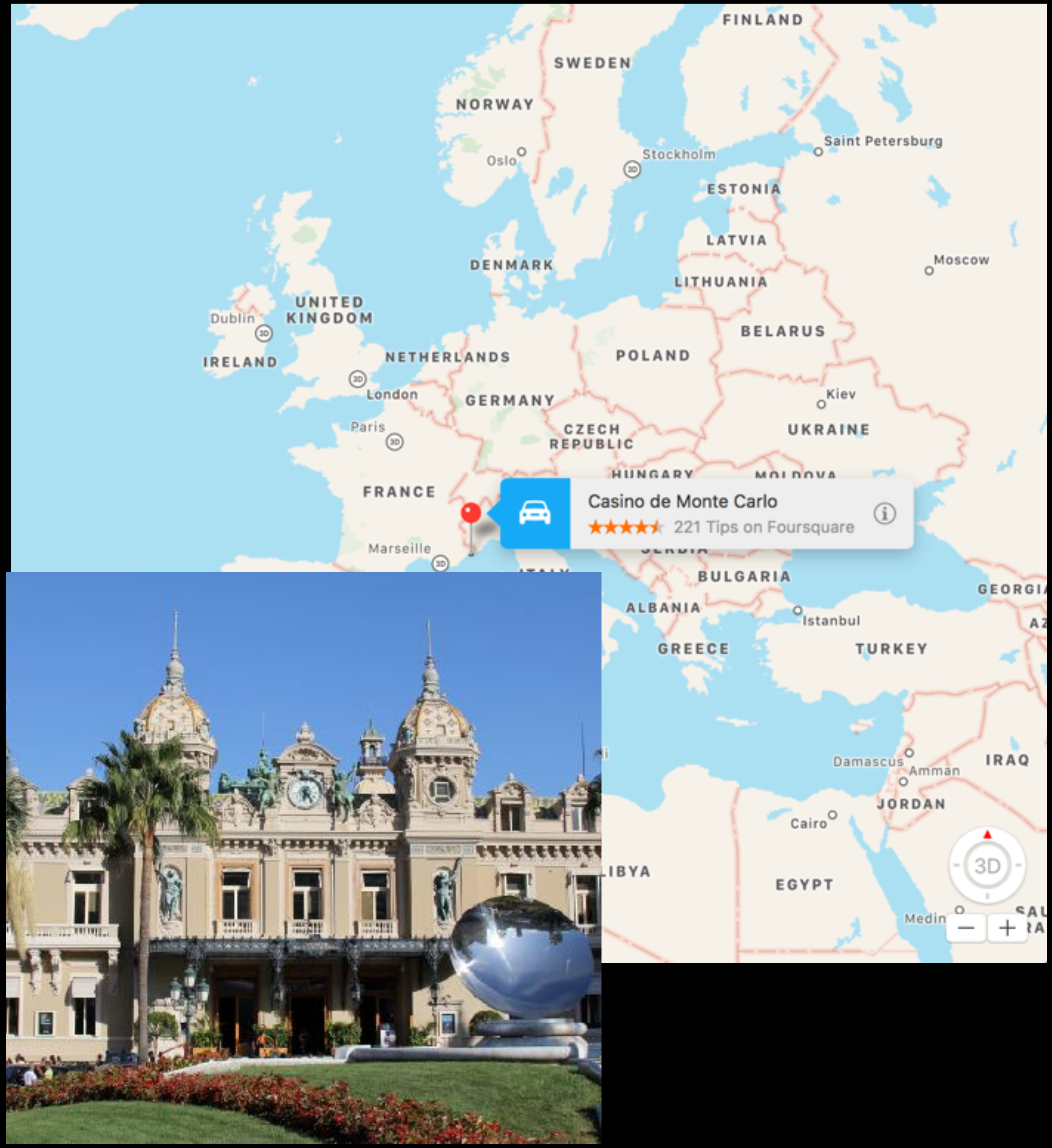
- Throw darts in square
  - (circle area) ÷ (square area) ≈ darts in circle ÷ darts in square = π/4



Courtesy wikipedia

Monte Carlo methods

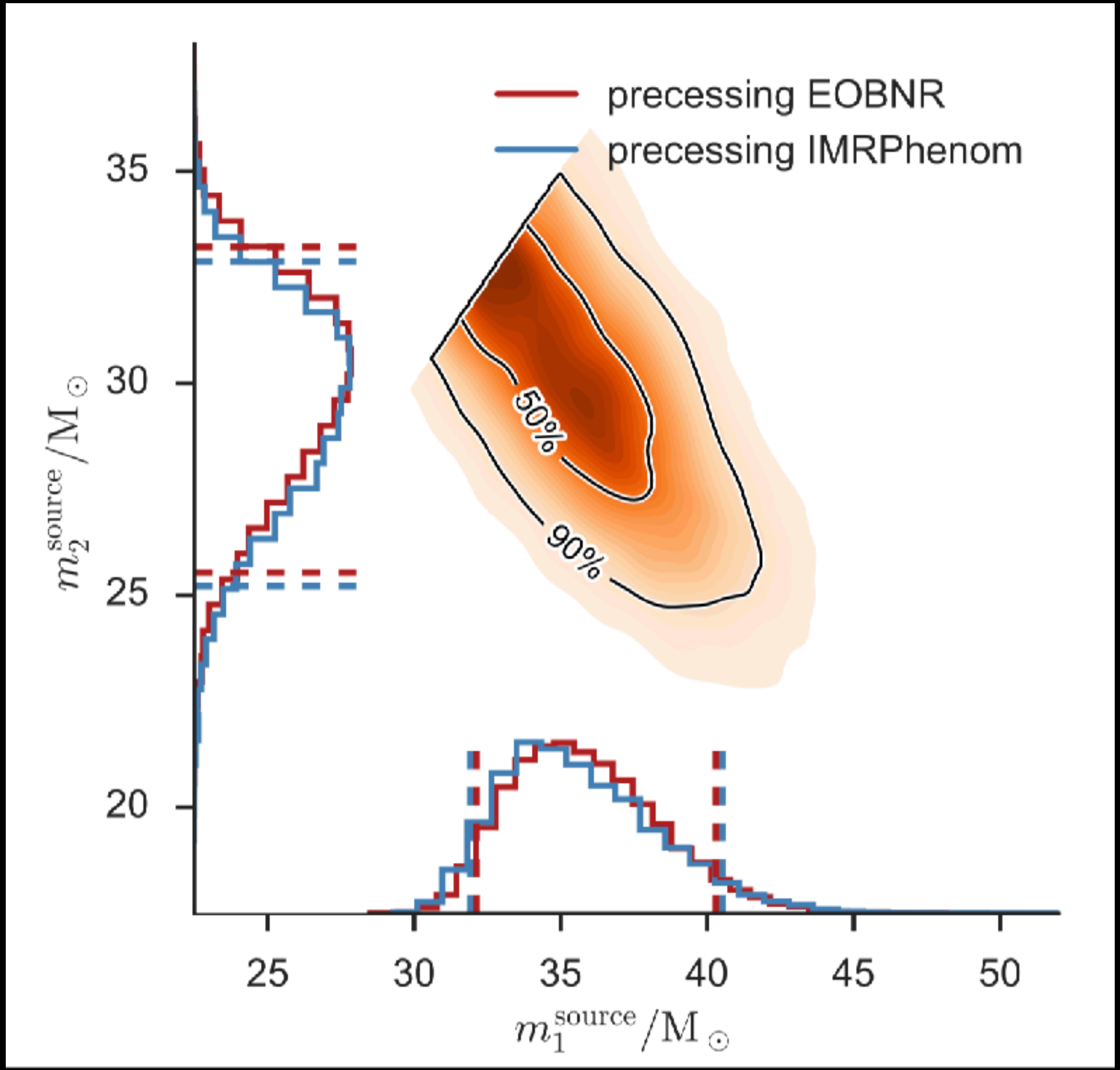
- This idea might seem silly, but it actually has a lot of uses in physics
- **Monte Carlo methods: use repeated random numbers to get results**
  - Min/max of functions
    especially functions of many variables
  - Integrals
    especially high dimensional
  - Explore probability distributions



Images courtesy Wikipedia, Apple Maps

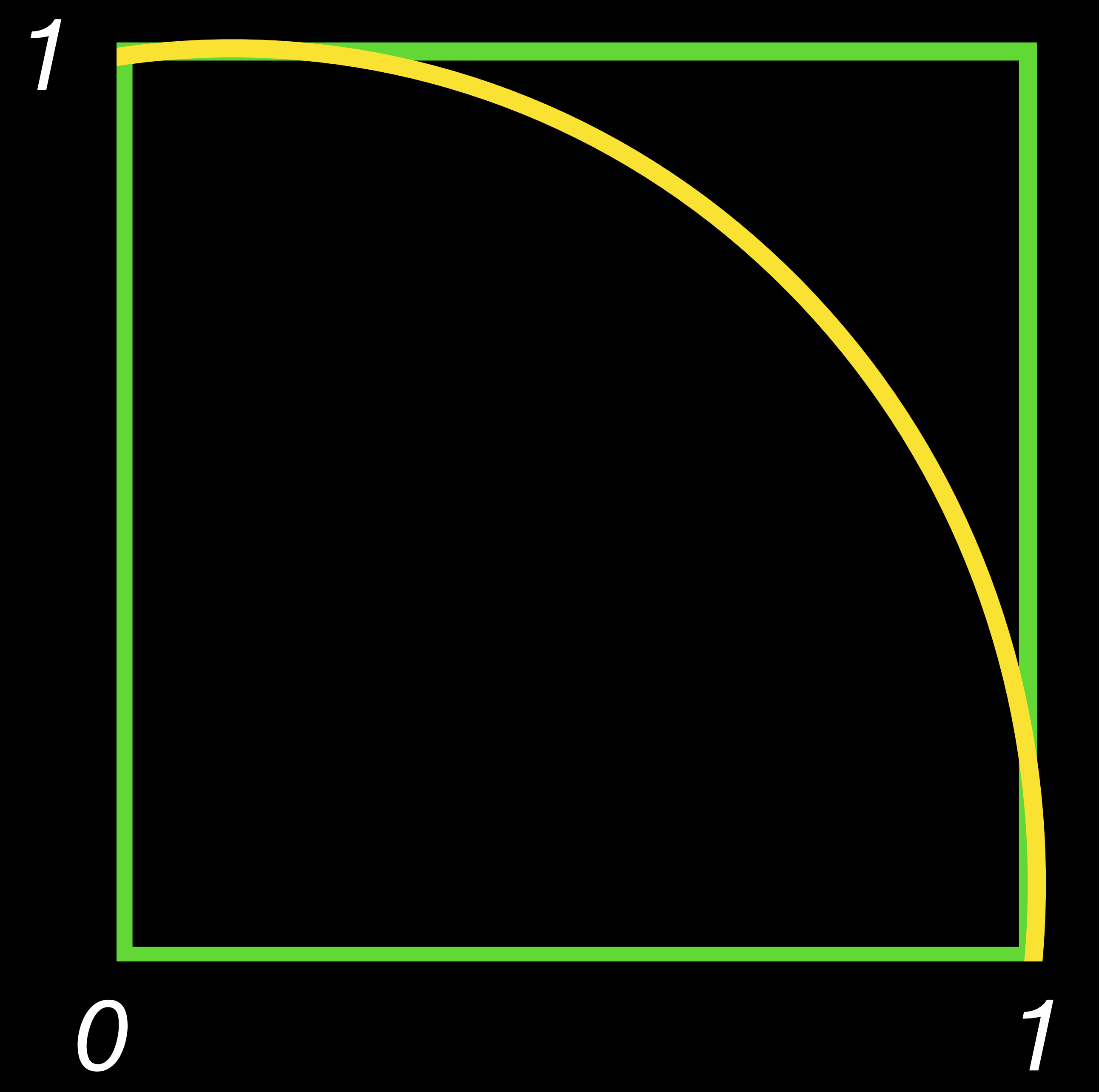
Monte Carlo methods

- This idea might seem silly, but it actually has a lot of uses in physics
- When we observe a gravitational wave from merging black holes…
    - What kinds of black holes made the waves?
        - Choose random parameters (masses, spins, …)
        - Compute the corresponding grav. wave
        - More likely to call the wave a "hit" the better it matches—vs. the last wave "hit"



GW150914: Abbott+ (2016)

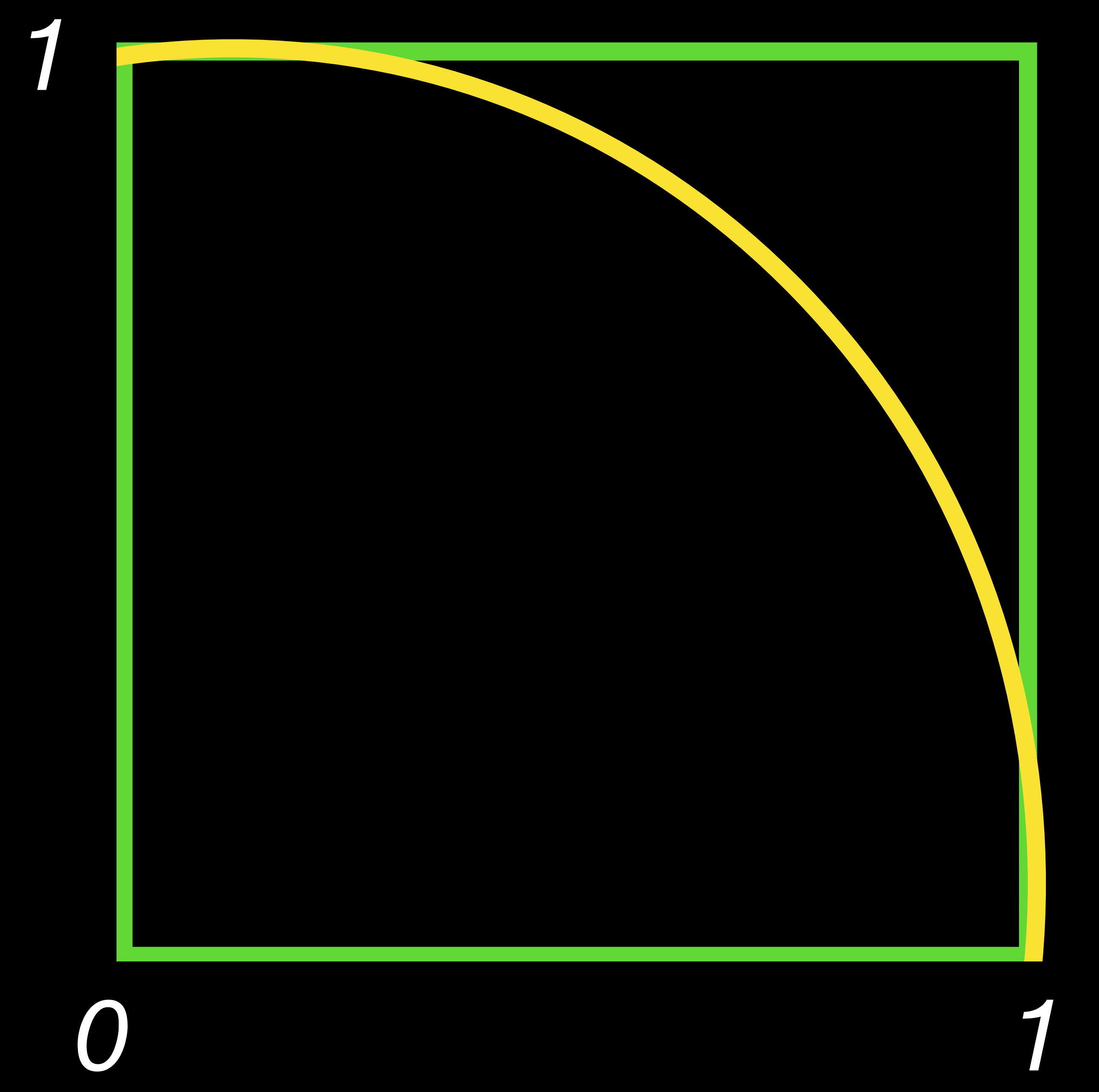
Pi Dartboard 1



- Write a program that prints one random number between 0 and 1

```
import math
import random
print(random.random())
```

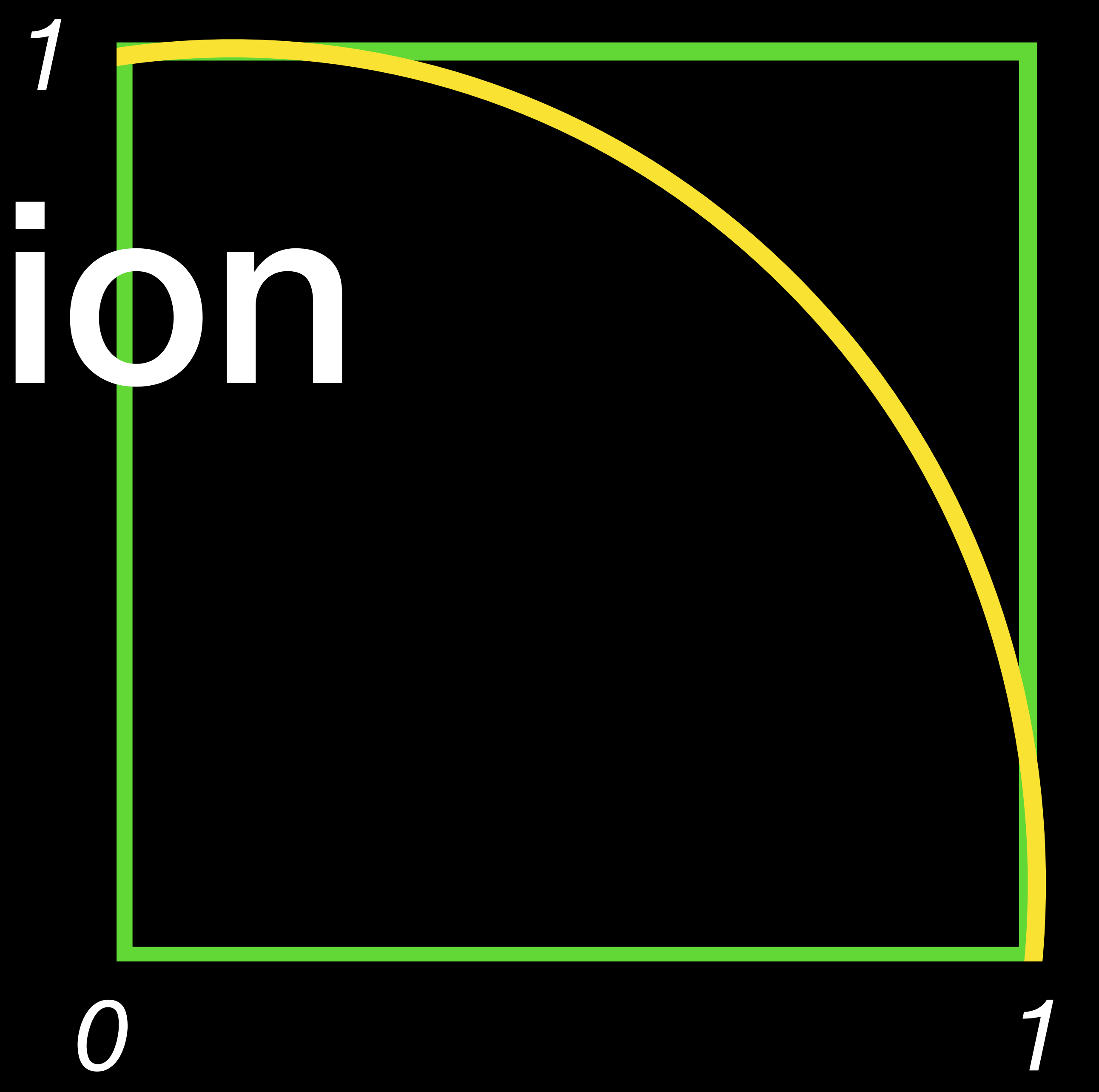
Pi Dartboard 2



- **Challenge:** Modify your program
  - Store the random number in a variable x
  - Store a second random number in a variable y
  - Print x and y

```
import math
import random
print(random.random())
```

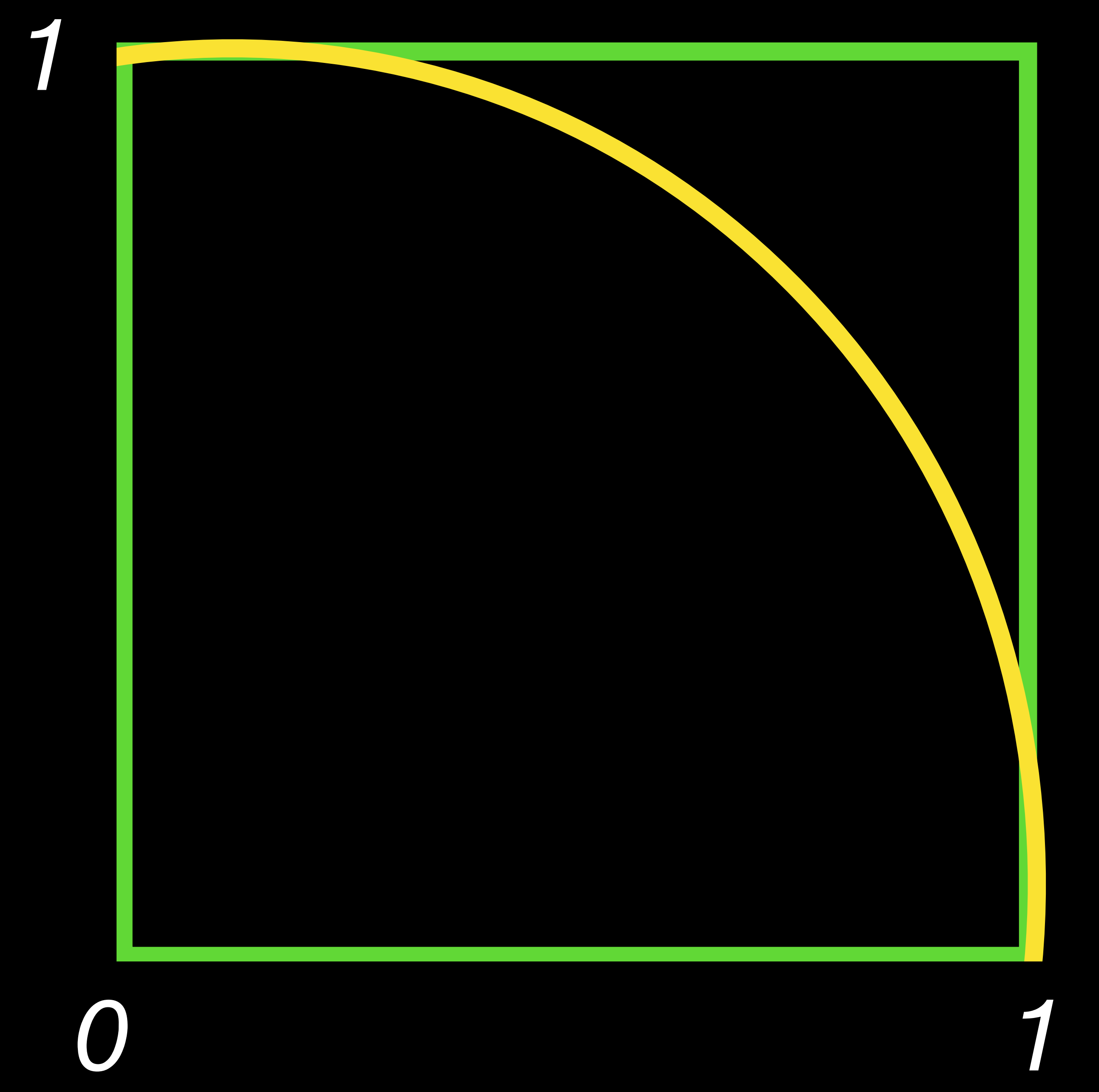
Pi Dartboard 2 Solution



- **Challenge:** Modify your program
  - Store the random number in a variable x
  - Store a second random number in a variable y
  - Print x and y

```
import math
import random

x = random.random()
y = random.random()

print(x)
print(y)
```

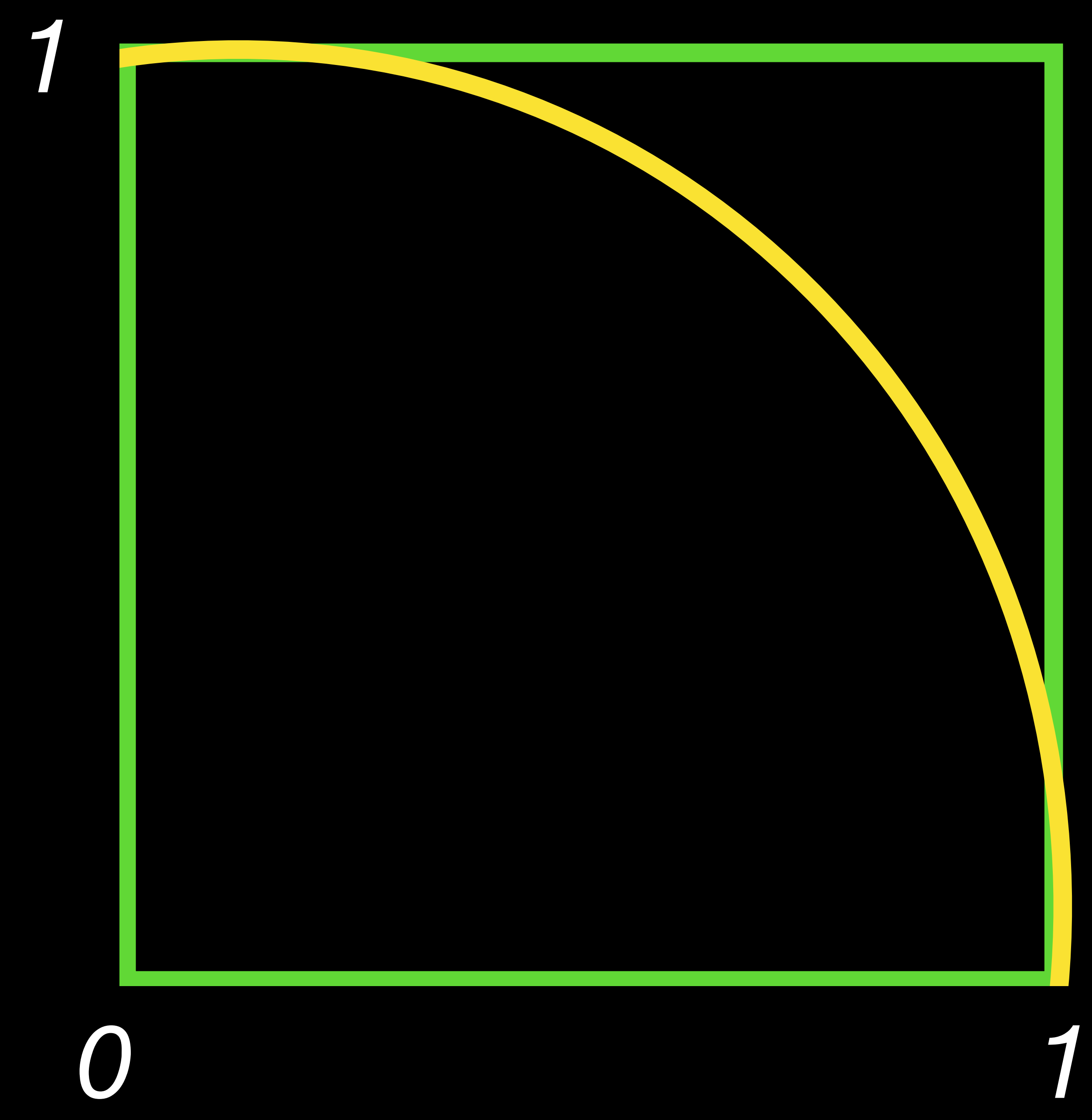
Pi Dartboard 3



- **Challenge:** Modify your program
  - Print $x^2 + y^2$ instead of just x and y

```
import math
import random
x = random.random()
y = random.random()
print(x)
print(y)
```

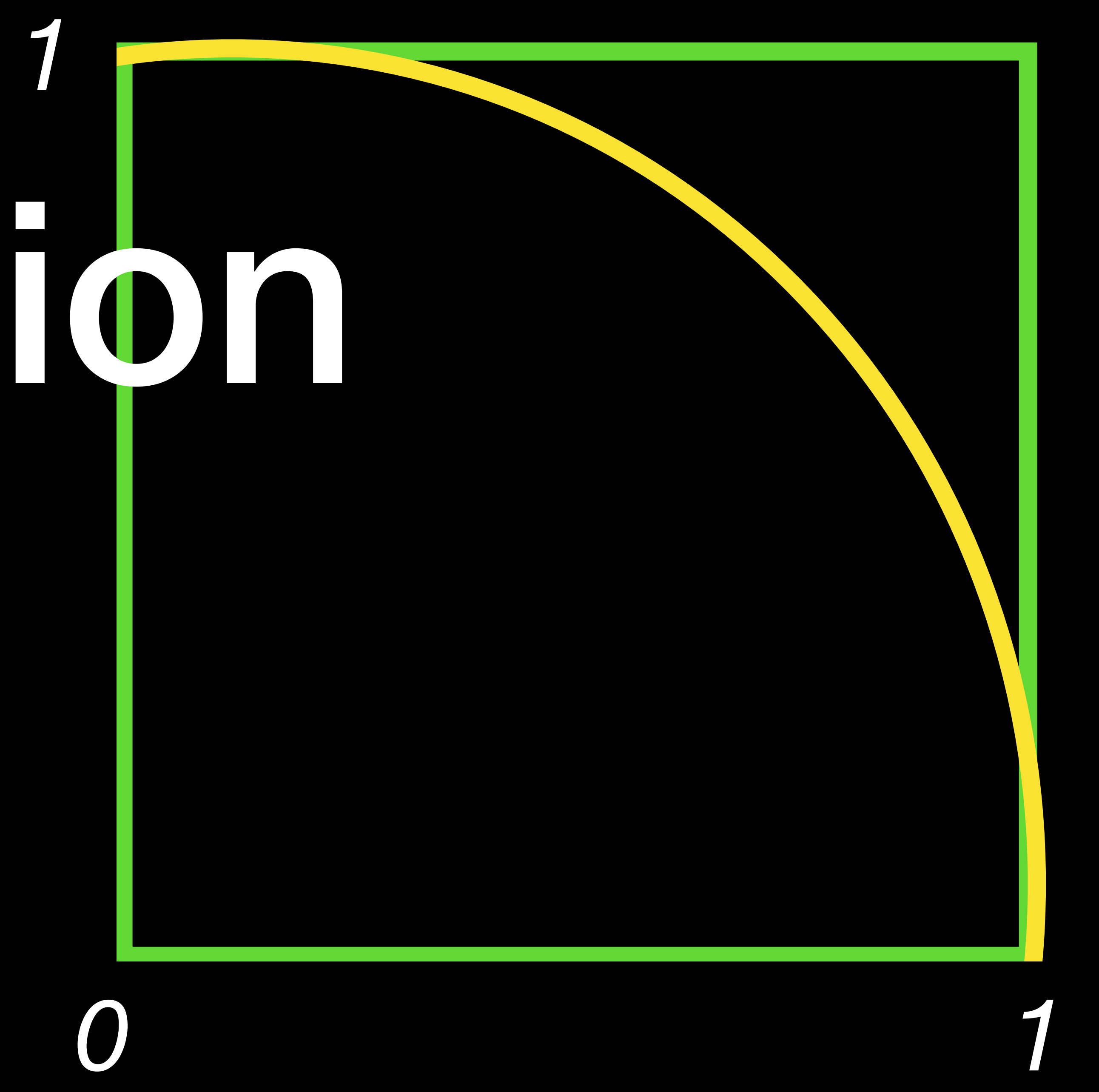
Pi Dartboard 3



- **Challenge:** Modify your program
  - Compute $x^2 + y^2$ and store it in a variable rSquared
  - Print rSquared instead of just x and y

```
import math
import random

x = random.random()
y = random.random()

print(x)
print(y)
```

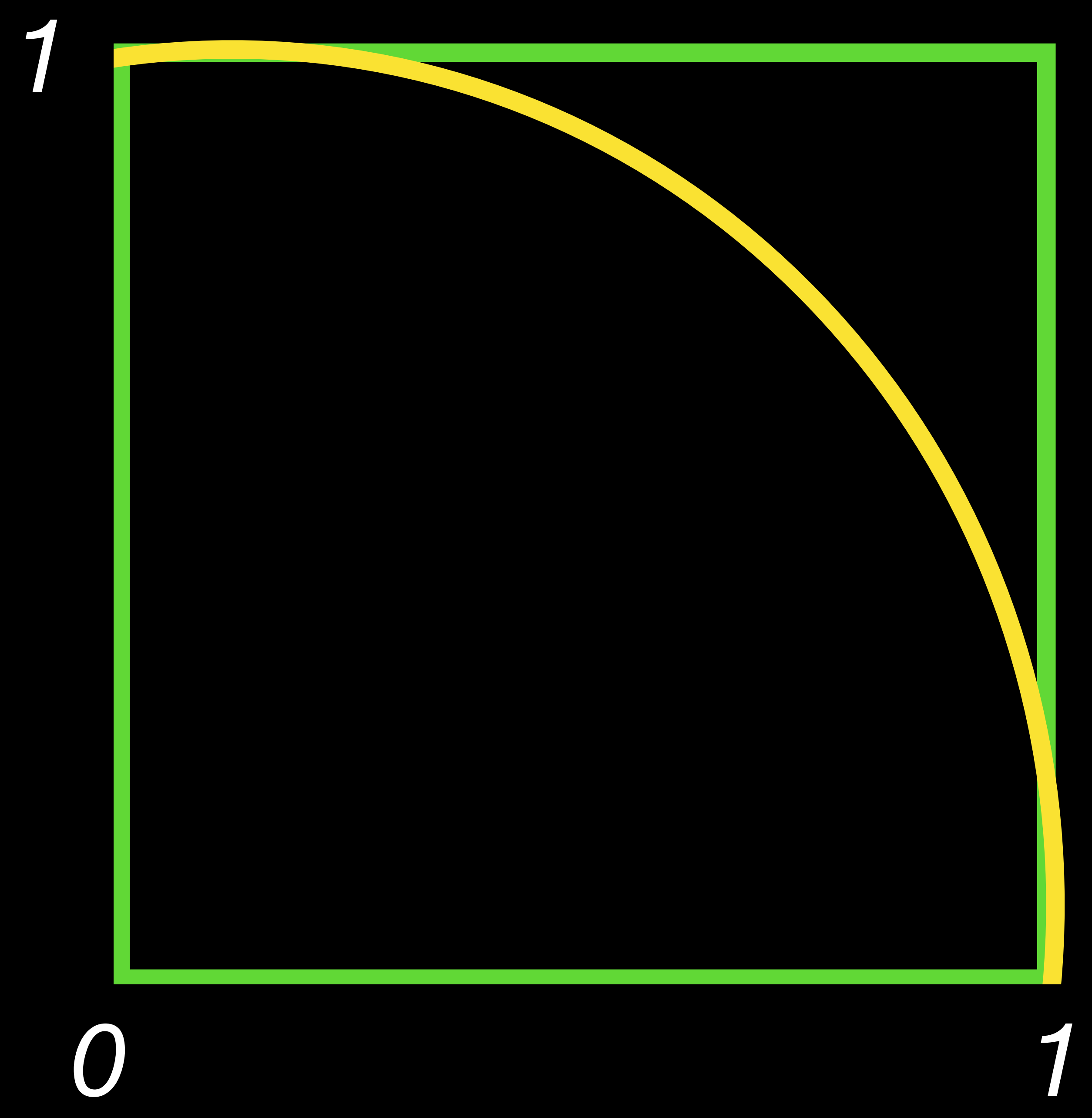
Pi Dartboard 3 Solution



- **Challenge:** Modify your program
  - Compute $x^2 + y^2$ and store it in a variable rSquared
  - Print rSquared instead of just x and y

```
import math
import random

x = random.random()
y = random.random()

rSquared = x**2 + y**2
print(rSquared)
```

Clicker question #2.5



- Which could be a number the program prints?

```python
import math
import random

x = random.random()
y = random.random()

rSquared = x**2 + y**2
print(rSquared)
```

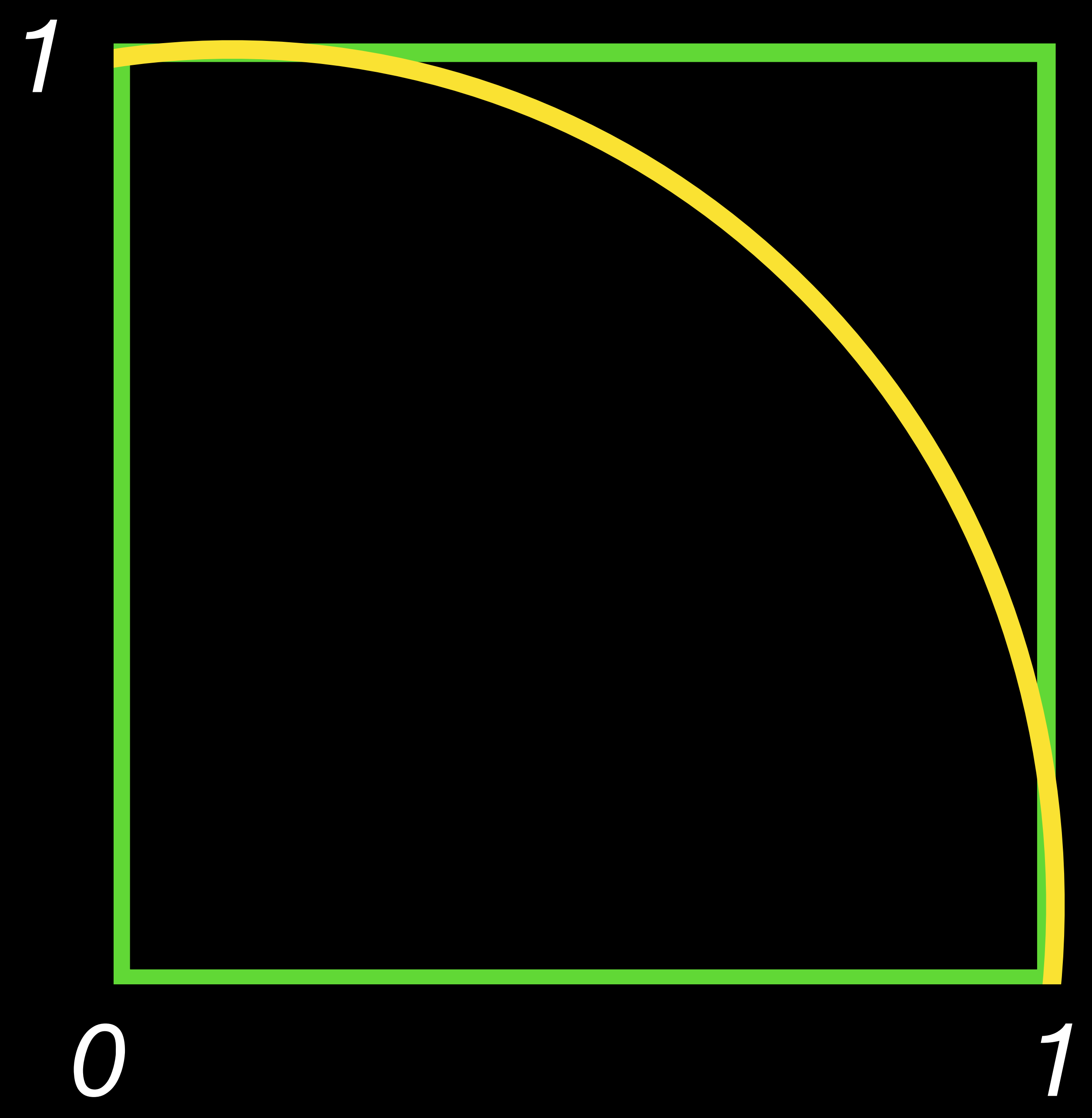
A -1.51

B 2.43

C -0.32

D 1.01

Clicker question #2.5



- If the dart is inside the **circle**, which could be the number printed by the program?

```
import math
import random

x = random.random()
y = random.random()

rSquared = x**2 + y**2
print(rSquared)
```

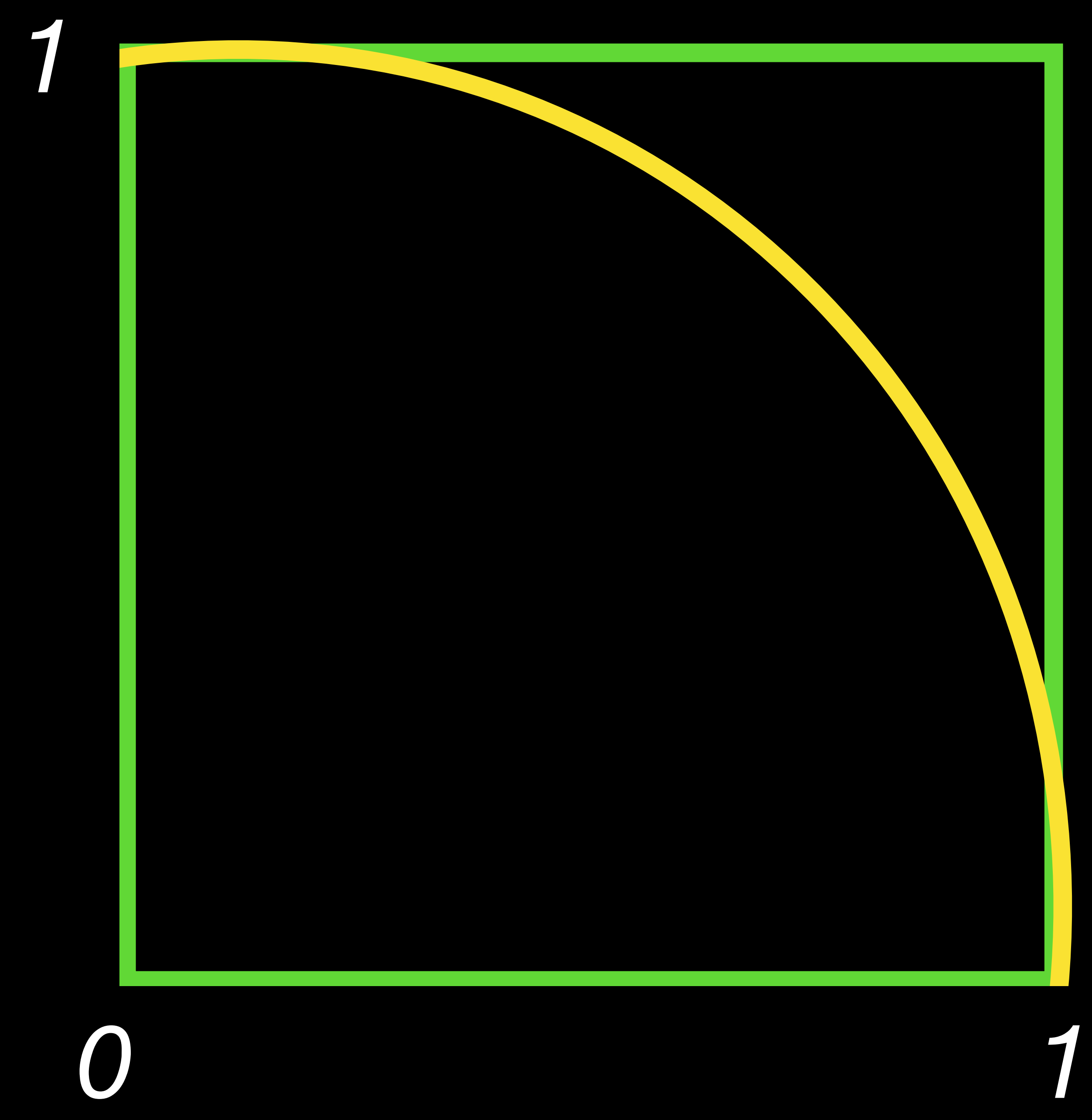
A 1.43

B 0.99

C 1.01

D More than one of ABC

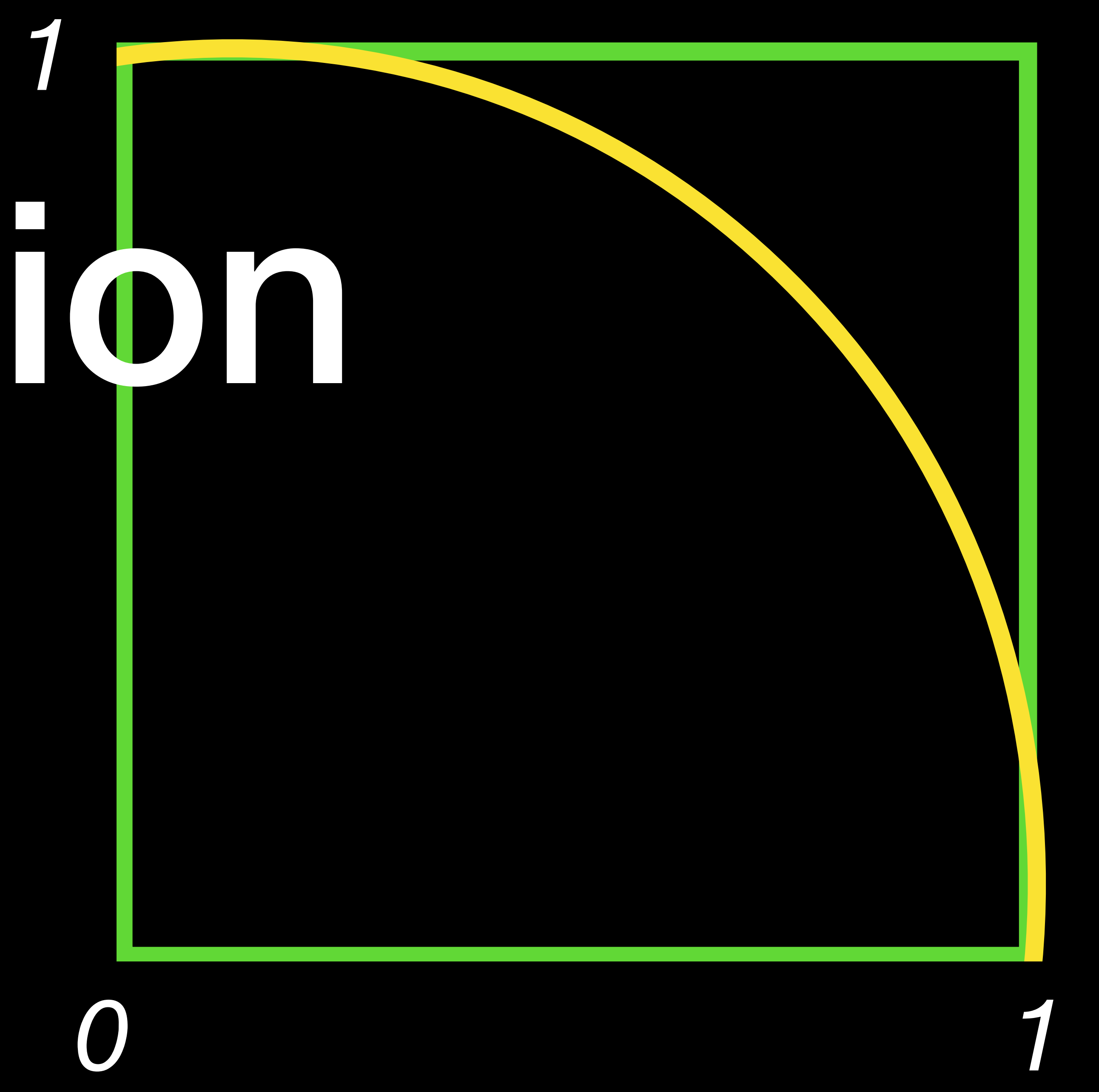
Pi Dartboard 4



- **Challenge:** Modify your program
  - Just below import random, make a new variable called “hits”, set to 0
  - If rSquared < 1, add 1 to hits
  - Print hits instead of rSquared

```
import math
import random

x = random.random()
y = random.random()

rSquared = x**2 + y**2
print(rSquared)
```

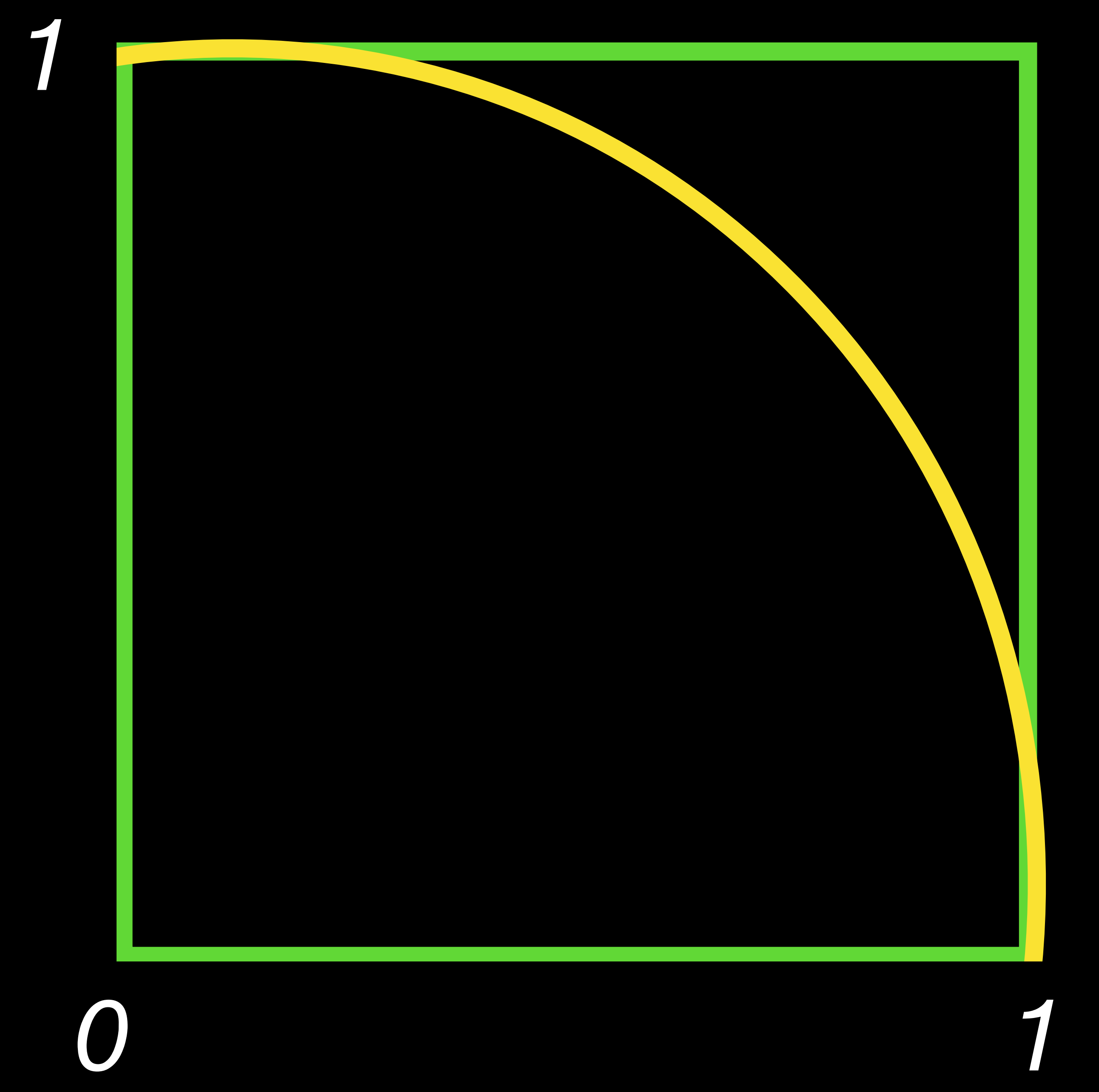
Pi Dartboard 4 Solution



- **Challenge:** Modify your program
  - Just below import random, make a new variable called “hits”, set to 0
  - If rSquared < 1, add 1 to hits
  - Print hits instead of rSquared

```python
import math
import random
hits = 0
x = random.random()
y = random.random()
rSquared = x**2 + y**2
if rSquared < 1:
    hits = hits + 1
print(hits)
```

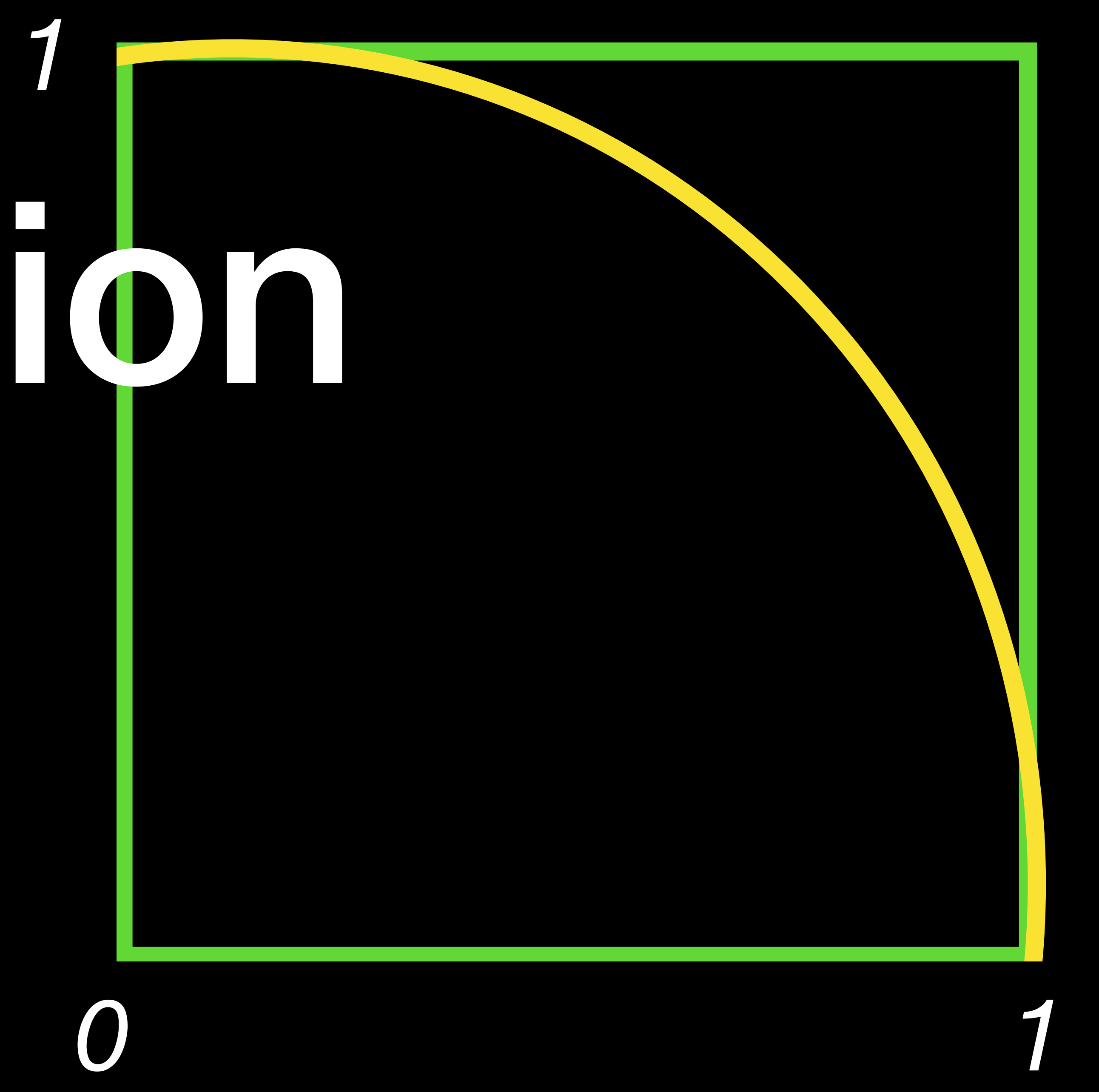
Pi Dartboard 5



- **Challenge:** Modify your program
  - Add a new variable, just below hits, called throws. Set it equal to 10.
  - Put the code that throws the dart and sees if it hit inside a while loop, so that you throw 10 darts instead of 1 dart
  - Don't forget to increment your while loop counter variable (i or j or whatever)

```
import math
import random
hits = 0
x = random.random()
y = random.random()
rSquared = x**2 + y**2
if rSquared < 1:
    hits = hits + 1
print(hits)
```

Pi Dartboard 5 Solution

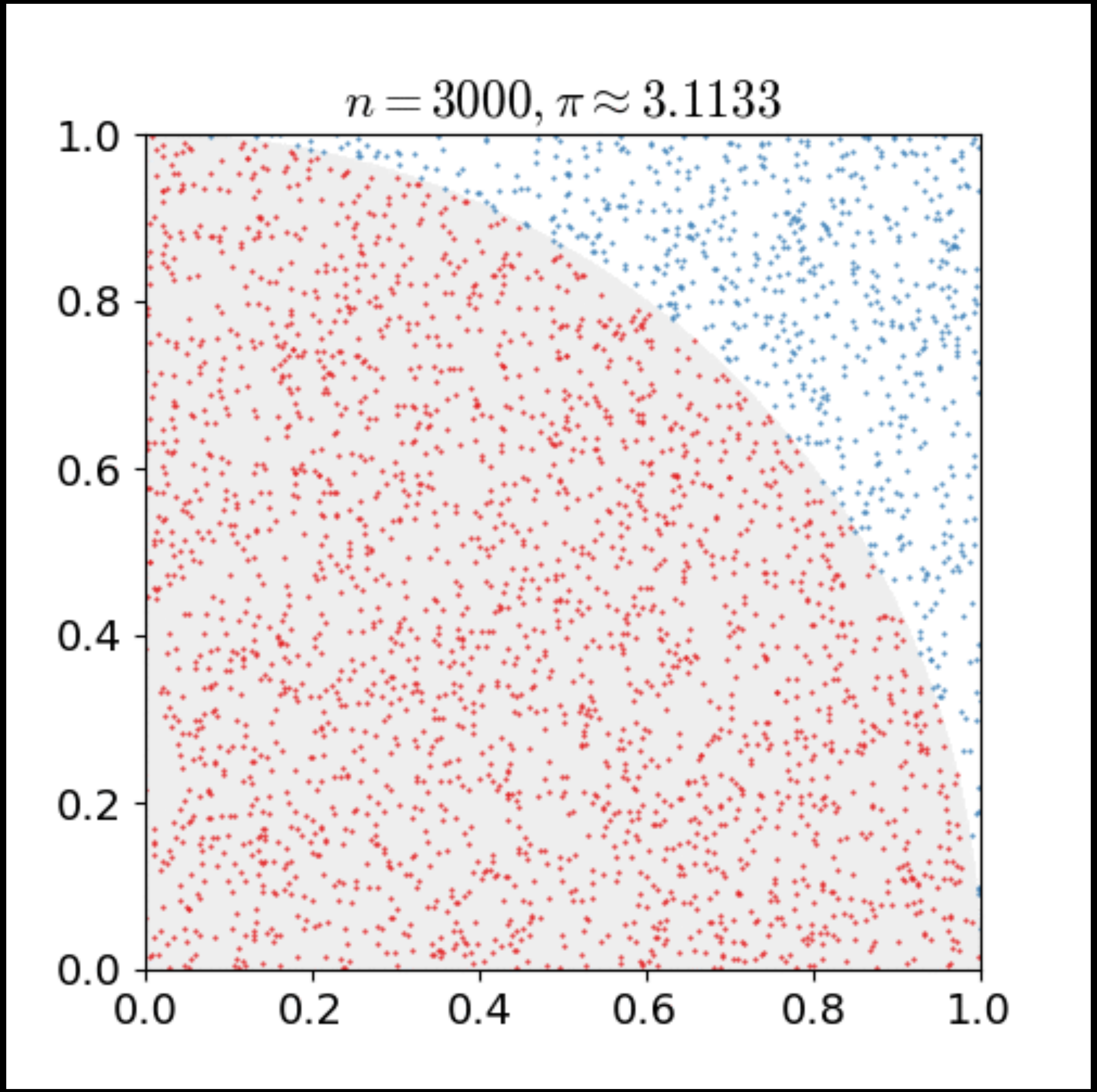


- **Challenge:** Modify your program
  - Add a new variable, just below hits, called throws. Set it equal to 10.
  - Put the code that throws the dart and sees if it hit inside a while loop, so that you throw 10 darts instead of 1 dart

```python
import math
import random

hits = 0
throws = 10

i = 0
while i < throws:
    x = random.random()
    y = random.random()

    rSquared = x**2 + y**2
    if rSquared < 1:
        hits = hits + 1
    i = i + 1

print(hits)
```

A silly way to compute π

- Throw darts in square
  - (circle area) ÷ (square area) ≈ hits ÷ throws = π/4
  - So π ≈ 4 * (hits ÷ throws)

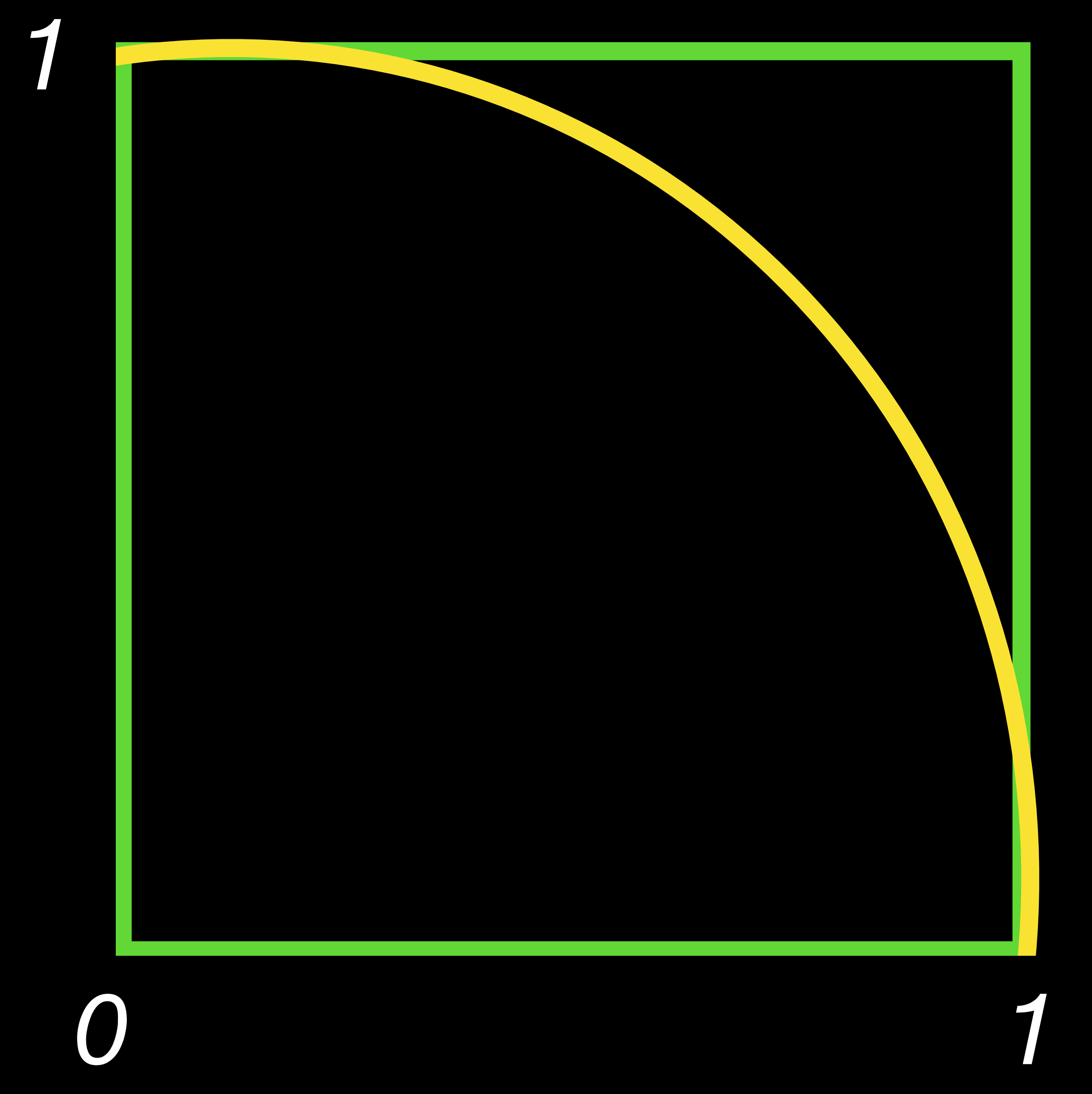


Courtesy wikipedia

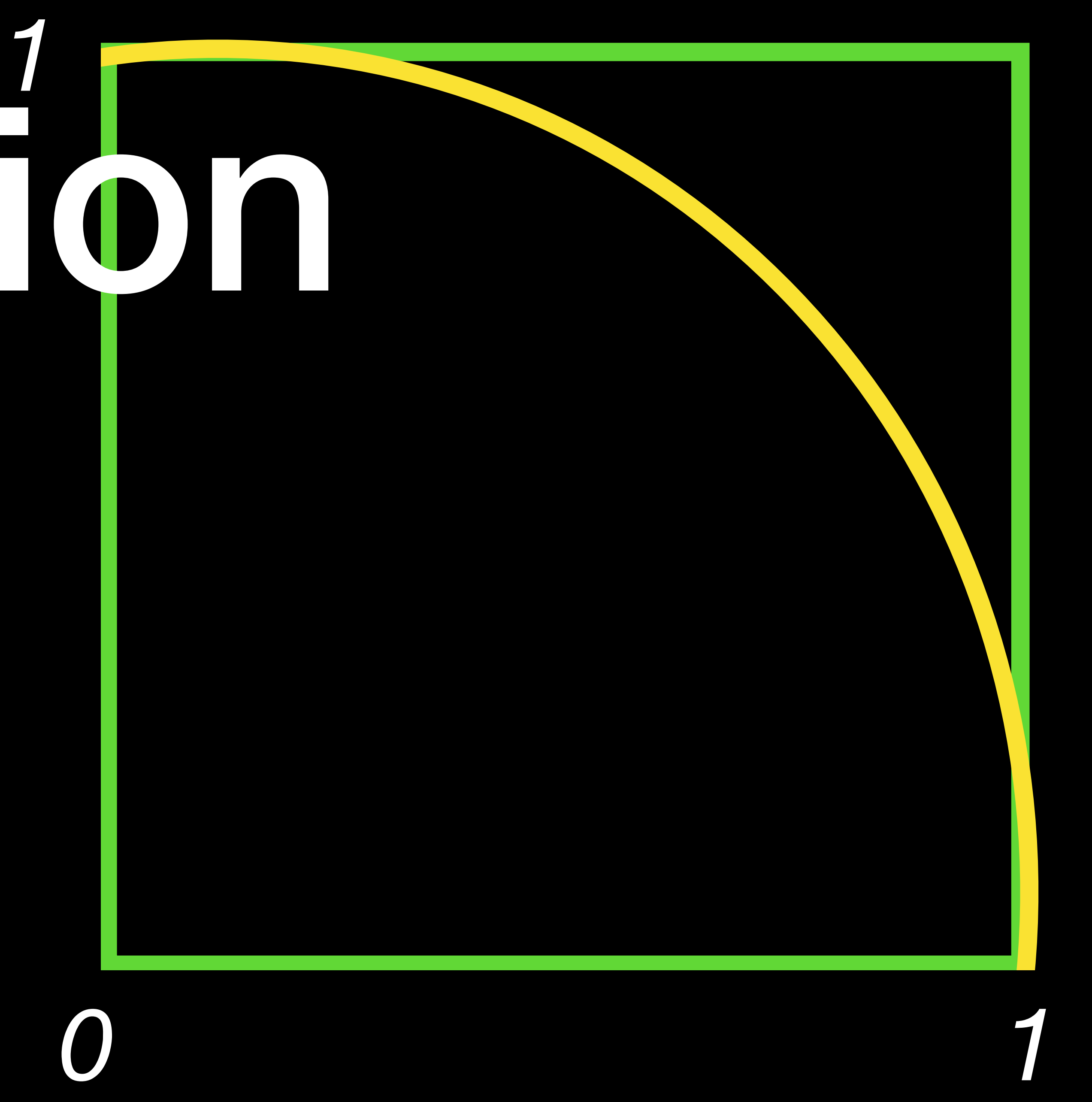
Pi Dartboard 6

- Finish the dartboard
  - Compute pi as 4.0 * float(hits) / float(throws)
  - Print your pi estimate

```
import math
import random

hits = 0
throws = 10

i = 0
while i < throws:
    x = random.random()
    y = random.random()

    rSquared = x**2 + y**2
    if rSquared < 1:
        hits = hits + 1
    i = i + 1

print(hits)
```



Pi Dartboard 6 Solution



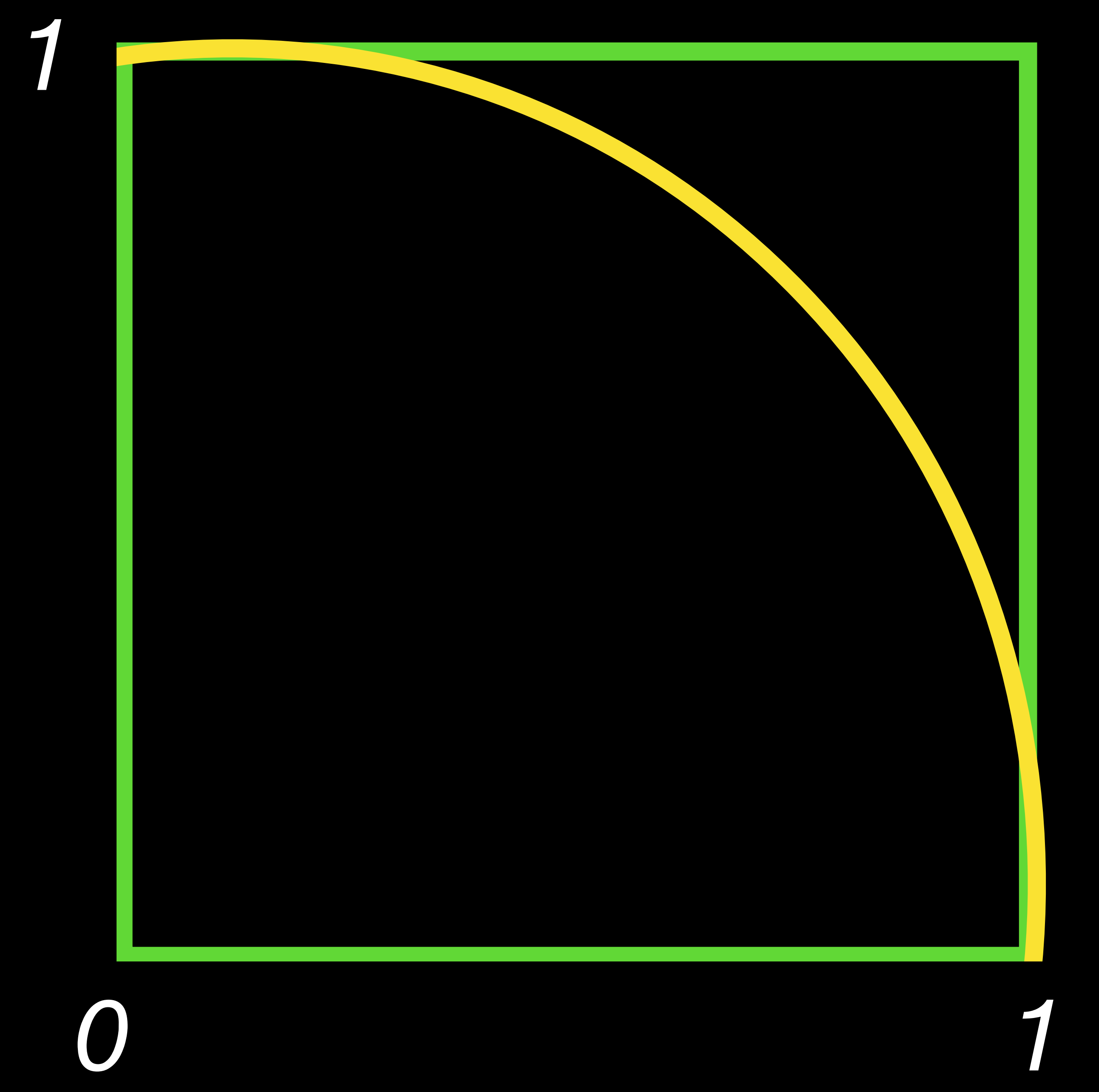
- Finish the dartboard
  - Compute pi as 4.0 * float(hits) / float(throws)
  - Print your pi estimate

```python
import math
import random

hits = 0
throws = 10

i = 0
while i < throws:
    x = random.random()
    y = random.random()

    rSquared = x**2 + y**2
    if rSquared < 1:
        hits = hits + 1
    i = i + 1

pi = 4.0 * float(hits) / float(throws)
print(pi)
```

Pi Dartboard 7

- The tutor won't let us run lots of darts
- So paste this into a cell in Jupyter on colab.google.com and run it
  - See what happens as you make throws 10**n, n=1,2,3,4,5,6,7

```
import math
import random

hits = 0
throws = 10

i = 0
while i < throws:
    x = random.random()
    y = random.random()

    rSquared = x**2 + y**2
    if rSquared < 1:
        hits = hits + 1
    i = i + 1

pi = 4.0 * float(hits) / float(throws)
print(pi)
```

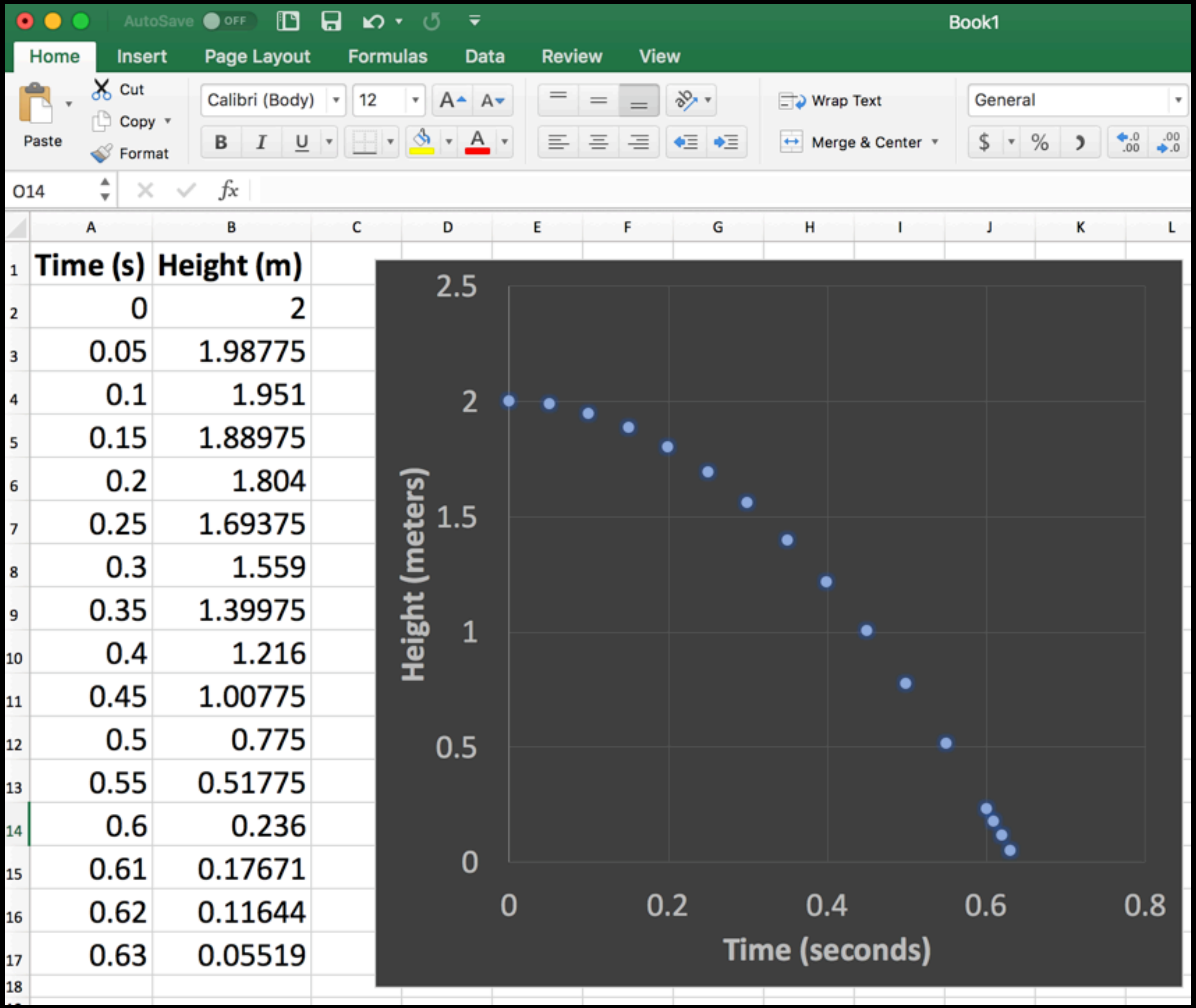


Plotting your results

- Scatter plots
- Lists and numpy arrays
- Pyplot plotting

Scatter plots

- Data: result or output given some input
- Example: dropped marker height vs. time
- Tools to make scatter plots
  - Excel
  - Python
    - Lists of numbers
    - Computations on lists of numbers: numpy arrays
    - pyplot: makes scatter plots



Lists

- **Values -** ordered sets of objects, all the same type (like floats or ints)

```
x = [-2.0, -1.0, 0.0, 1.0, 2.0]
y = ["Hello", "world"]
z = [1, 4, 9, 16]
```

```
z.append(25) == [1, 4, 9, 16, 25]
```

- **Operators - [ ], .append()**

```
x[0] == -2.0
x[1] == -1.0
x[4] == 2.0
y[0] == "Hello"
y[-1] == "world"
z[-1] == 16
z[0] == 1
```

- **Easily add on elements in loops** with .append()

Loop over lists

```
for i in [1,2,3,4]:
  print(i*i)
```

```
0
1
4
9
```

```
import numpy as np
print(np.arange(1,5,1))
[1,2,3,4]
```

```
import numpy as np
myCountArray = np.arange(1,5)
myList = []
for i in myCountArray:
    myList.append(i*i)
print(myCountArray)
print(myList)
```

```
[1,2,3,4]
[1,4,9,16]
```

Clicker question #2.6

- What value does the program print?

```
x = [1.0, 4.0, 9.0]
print(x[1])
```

A	1.0
B	4.0
C	9.0
D	The entire list

Numpy arrays

- **Values -** ordered sets of objects, all the same type (like floats or ints)
- **Operators - [ ], +, -, *, /, np.sqrt(), np.sin(), np.cos(), …**
- **Easily do math on whole lists at once** (like formulas in Excel)

```
x = np.array([-2.0, -1.0, 0.0, 1.0, 2.0])
y = np.array(["Hello", "world"])
q = np.array([1, 2, 3, 4])
r = q * 2
s = q + r
z = q * q
```

```
r == np.array([2, 4, 6, 8])
```

```
s == np.array([3, 6, 9, 12])
z == np.array([1, 4, 9, 16])
```

```
x[0] == -2.0
x[1] == -1.0
x[4] == 2.0
y[0] == "Hello"
y[-1] == "world"
z[-1] == 16
z[0] == 1
```

Making sample data

- Annoying to type [1,2,3,4,…] all the time
- Instead: np.arange(start, stop, step)
- What do all these numbers mean??
  - Make a plot to visualize them

Try in colab!

```python
import numpy as np
x = np.arange(-4.0, 4.0, 0.01)
y = np.sin(x)**3
print(x)
print(y)
```

```
-9.99825171e-01 -9.99351433e-01 -9.98578166e-01 -9.97505912e-01
-9.96135421e-01 -9.94467651e-01 -9.92503769e-01 -9.90245148e-01
-9.87693366e-01 -9.84850205e-01 -9.81717651e-01 -9.78297888e-01
-9.74593301e-01 -9.70606471e-01 -9.66340175e-01 -9.61797379e-01
-9.56981241e-01 -9.51895105e-01 -9.46542499e-01 -9.40927131e-01
-9.35052889e-01 -9.28923832e-01 -9.22544191e-01 -9.15918365e-01
-9.09050915e-01 -9.01946561e-01 -8.94610179e-01 -8.87046794e-01
-8.79261581e-01 -8.71259853e-01 -8.63047062e-01 -8.54628794e-01
-8.46010761e-01 -8.37198799e-01 -8.28198860e-01 -8.19017011e-01
-8.09659425e-01 -8.00132377e-01 -7.90442239e-01 -7.80595473e-01
-7.70598629e-01 -7.60458333e-01 -7.50181290e-01 -7.39774268e-01
-7.29244102e-01 -7.18597680e-01 -7.07841944e-01 -6.96983877e-01
-6.86030504e-01 -6.74988880e-01 -6.63866088e-01 -6.52669231e-01
-6.41405427e-01 -6.30081800e-01 -6.18705479e-01 -6.07283586e-01
-5.95823237e-01 -5.84331527e-01 -5.72815532e-01 -5.61282298e-01
-5.49738839e-01 -5.38192126e-01 -5.26649084e-01 -5.15116589e-01
-5.03601455e-01 -4.92110435e-01 -4.80650212e-01 -4.69227393e-01
-4.57848505e-01 -4.46519990e-01 -4.35248195e-01 -4.24039375e-01
-4.12899678e-01 -4.01835147e-01 -3.90851715e-01 -3.79955193e-01
-3.69151273e-01 -3.58445520e-01 -3.47843366e-01 -3.37350109e-01
-3.26970907e-01 -3.16710771e-01 -3.06574566e-01 -2.96567003e-01
-2.86692639e-01 -2.76955868e-01 -2.67360924e-01 -2.57911871e-01
```

Plotting sample data

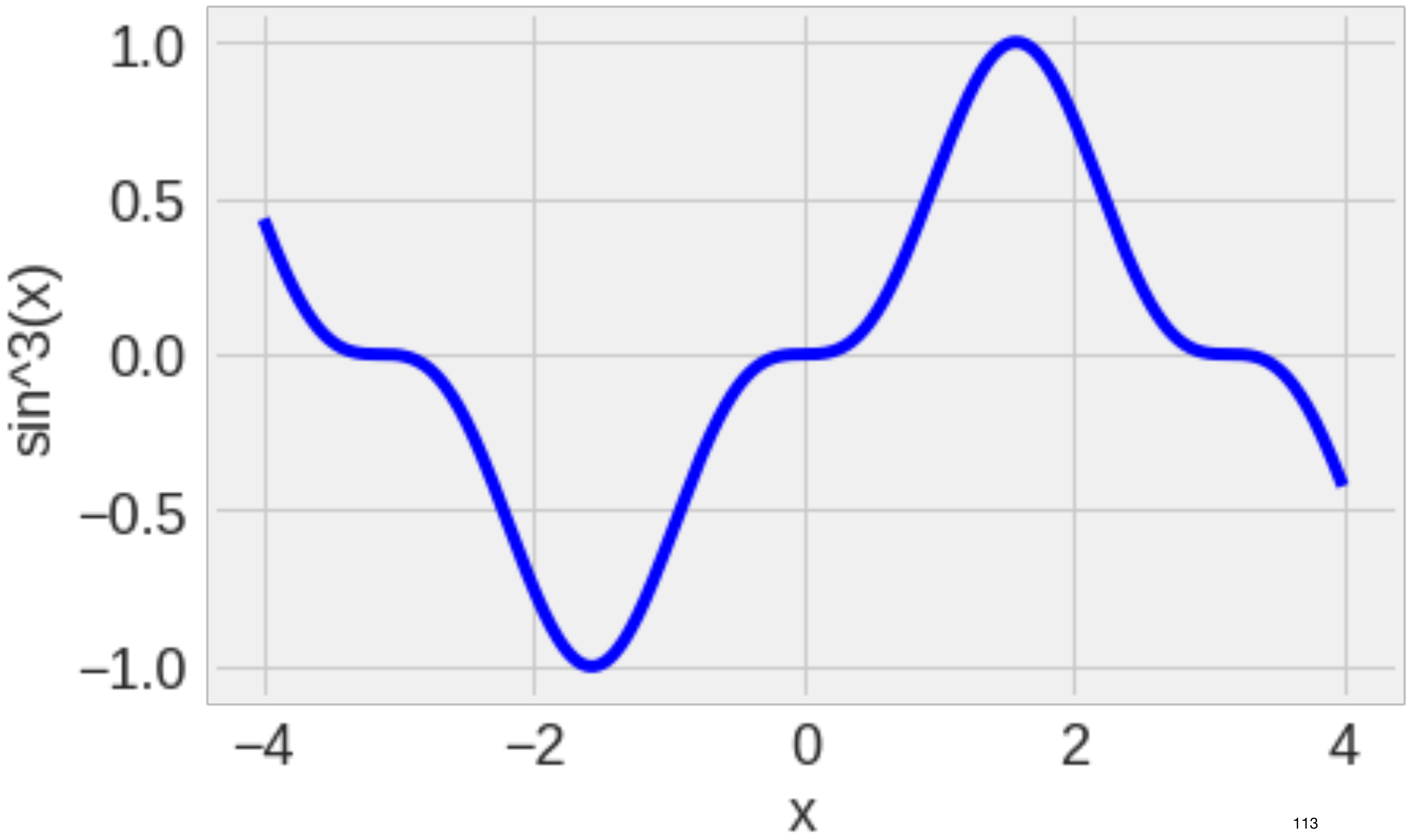
Try in colab!

```
import numpy as np
import matplotlib
from matplotlib import pyplot as plt
matplotlib.rc('axes', labelsize=18)
matplotlib.rc('xtick', labelsize = 18)
matplotlib.rc('ytick', labelsize = 18)
```

- Make plots with pyplot

```
x = np.arange(-4.0, 4.0, 0.01)
y = np.sin(x)**3
```

```
plt.clf() #clear figure
plt.plot(x,y, color='b')
plt.xlabel('x')
plt.ylabel('sin^3(x)')
plt.show()
```


1.0
0.5
0.0
−0.5
−1.0
sin^3(x)
−4
−2
0
2
4
x

Functions

Try in tutor!

```
def square(x):
  return x*x
```

```
square(4)
16
```

- Input(s) ("arguments")
- Returns output
- Functions can call other functions

Activity in the tutor

- Define a function that takes a decimal x and returns cos(cos(x))
    - Hint: use math.cos()
- Print the result for some test number

Activity in the tutor

- Define a function "cos2Times" that takes a decimal x and returns cos(cos(x))
  - Hint: use math.cos()
- Print the result

```
import math
def cos2Times(x):
    return math.cos(math.cos(x))
print(cos2Times(44.44))
print(cos2Times(0.0))
```

```python
i = 0
while i < 4:
  print(i*i)
  i = i + 1
0
1
4
9
```

- As you increase n, what does cosNTimes give you?

Challenge solution

```python
import math

def cos2Times(x):
    return math.cos(math.cos(x))

def cosNTimes(x, n):
    result = x
    i = 0
    while i < n:
        result = math.cos(result)
        i = i + 1
    return result

print(cos2Times(4.444))
print(cosNTimes(4.444, 2))
print(cosNTimes(4.444, 500))
```

Plotting π 1

- **Activity: edit your code**
  - Make everything but the last two lines inside a function that takes one input, n
  - Instead of setting throws = 10, set throws=n
  - Return the pi estimate

```
import math
import random

hits = 0
throws = 10

i = 0
while i < throws:
    x = random.random()
    y = random.random()

    rSquared = x**2 + y**2
    if rSquared < 1:
        hits = hits + 1
    i = i + 1
pi = 4.0 * float(hits) / float(throws)
print(pi)
```

Solution 1

- **Activity: edit your code**
  - Make everything but the last two lines inside a function that takes one input, n
  - Instead of setting throws = 10, set throws=n
  - Return the pi estimate

```
import math
import random

def estimatePi(throws):
  hits = 0
  i = 0
  while i < throws:
        x = random.random()
        y = random.random()

        rSquared = x**2 + y**2
        if rSquared < 1:
              hits = hits + 1
        i = i + 1

  pi = 4.0 * float(hits) / float(throws)
  return pi

print(estimatePi(1e4))
```

Plotting π 2

- **Activity: edit your code**
  - Make a list of different numbers of throws: 10, 100, 1000, … up to 1e7
  - Make an empty list called piEstimates
  - Loop over the list you made, estimating π for different numbers of throws

```python
import math
import random

def estimatePi(throws):
  # (same definition of estimatePi function here)
  return pi

print(estimatePi(1e4))
```

Plotting π solution 2

- **Activity: edit your code**
  - Make a list of different numbers of throws: 10, 100, 1000, … up to 1e7
  - Make an empty list called piEstimates
  - Loop over the list you made, estimating π for different numbers of throws

```python
import math
import random

def estimatePi(throws):
  # (same definition of estimatePi function here)
  return pi

throwsList = [1e1, 1e2, 1e3, 1e4, 1e5, 1e6, 1e7]
piEstimatesList = []
for throws in throwsList:
    piEstimatesList.append(estimatePi(throws))
print(piEstimatesList)
```

Plotting π 3

- **Activity: edit your code**
  - Don’t print piEstimatesList
  - Instead, make a scatter plot of throwsList vs. piEstimatesList
  - Use a log scale on the x axis: plt.xscale(‘log’)

```
import math
import random

def estimatePi(throws):
  # (same definition of estimatePi function here)
  return pi

throwsList = [1e1, 1e2, 1e3, 1e4, 1e5, 1e6, 1e7]
piEstimatesList = []
for throws in throwsList:
    piEstimatesList.append(estimatePi(throws))
print(piEstimatesList)
```

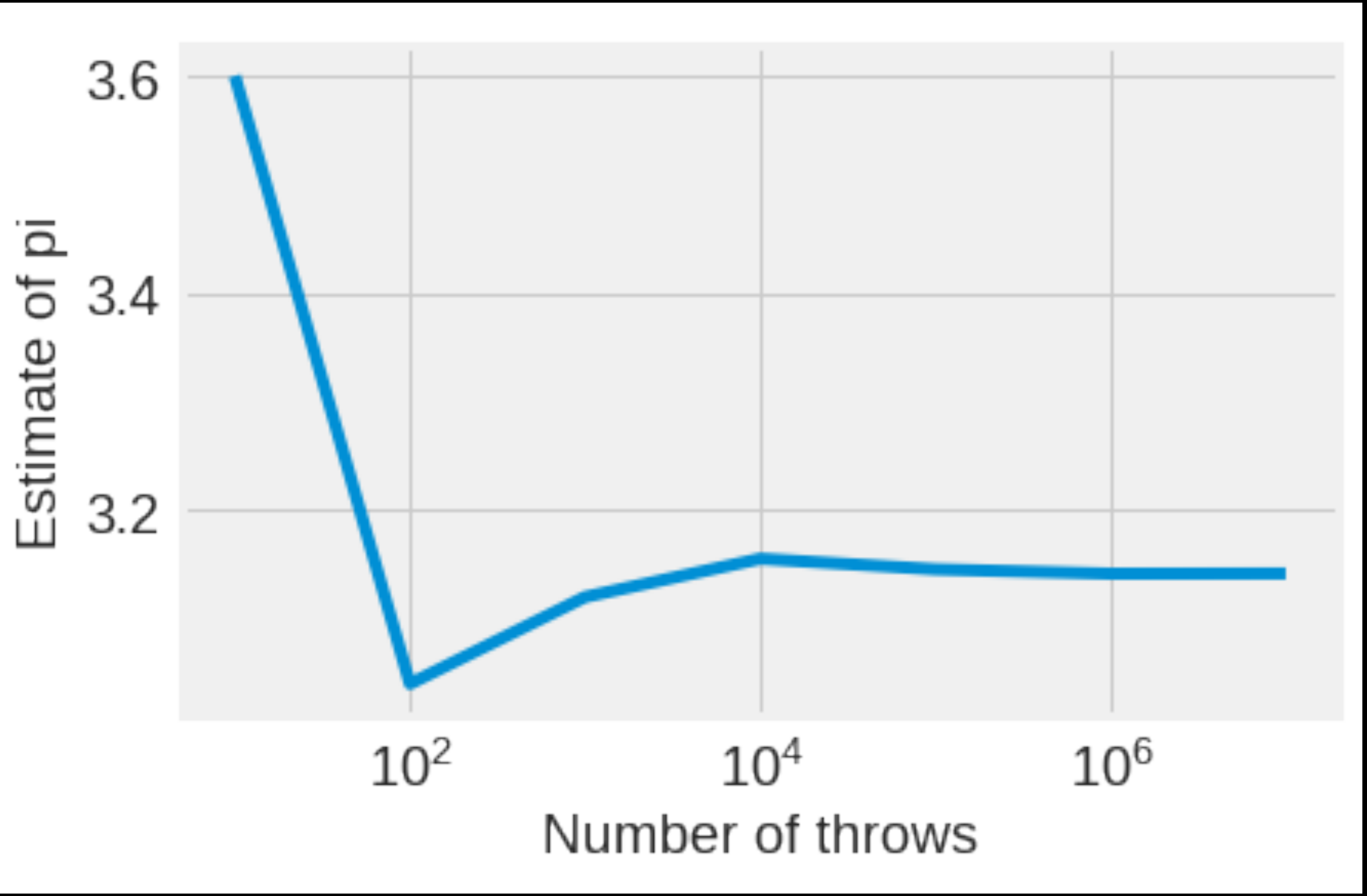
Solution 3

- **Activity: edit your code**
  - Don't print piEstimatesList
  - Instead, make a scatter plot of throwsList vs. piEstimatesList
  - Use a log scale on the x axis: plt.xscale('log')

```
import math
import random
import numpy as np
import matplotlib
from matplotlib import pyplot as plt
matplotlib.rc('axes', labelsize=18)
matplotlib.rc('xtick', labelsize = 18)
matplotlib.rc('ytick', labelsize = 18)

def estimatePi(throws):
  # (same definition of estimatePi function here)
  return pi

throwsList = [1e1, 1e2, 1e3, 1e4, 1e5, 1e6, 1e7]
piEstimatesList = []
for throws in throwsList:
    piEstimatesList.append(estimatePi(throws))

plt.clf()
plt.plot(throwsList, piEstimatesList)
plt.xlabel('Number of throws')
plt.xscale('log')
plt.ylabel('Estimate of pi')
plt.show()
```

Accuracy of the π dart board

- As throws goes up, answer gets closer to pi
- But it's hard to see how close it is later on
- So instead, plot the difference between the estimate and the real answer



Plotting π 4

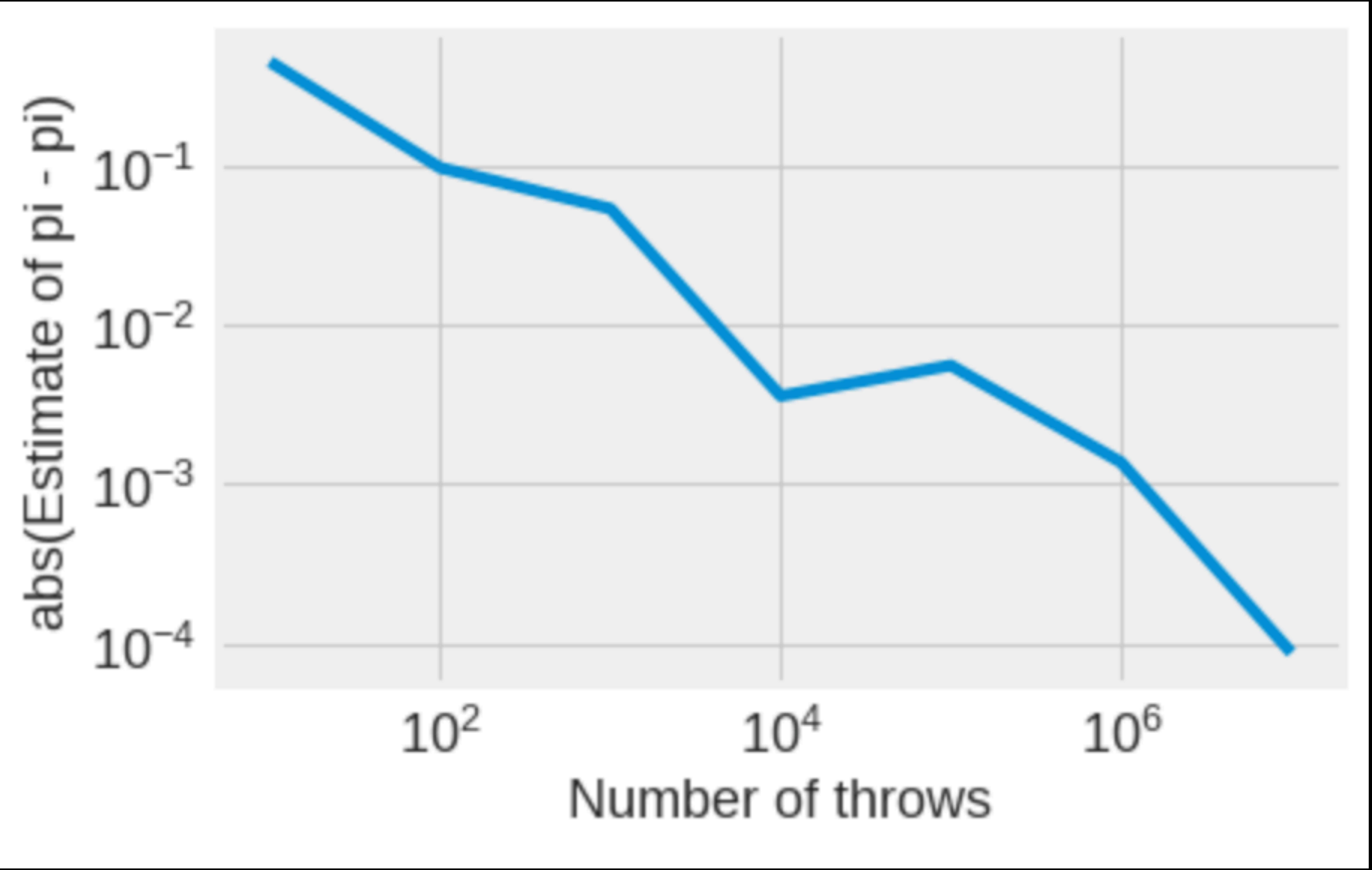
- **Challenge: edit your code**
  - import numpy as np
  - piEstimates = np.array(piEstimatesList)
  - Plot throwsList vs. abs(piEstimates - math.pi)
  - Put y axis on a log scale
  - Update y axis label to be abs(estimate of pi - pi)

```
# … code that computes pi

throwsList = [1e1, 1e2, 1e3, 1e4, 1e5, 1e6, 1e7]
piEstimatesList = []
for throws in throwsList:
    piEstimatesList.append(estimatePi(throws))

plt.clf()
plt.plot(throwsList, piEstimatesList)
plt.xlabel('Number of throws’)
plt.xscale('log')
plt.ylabel('Estimate of pi')
plt.show()
```

Solution 4

- **Challenge: edit your code**
  - import numpy as np
  - piEstimates = np.array(piEstimatesList)
  - Plot throwsList vs. abs(piEstimates - math.pi)
  - Put y axis on a log scale
  - Update y axis label to be abs(estimate of pi - pi)

```
# … code that computes pi

throwsList = [1e1, 1e2, 1e3, 1e4, 1e5, 1e6, 1e7]
piEstimatesList = []
for throws in throwsList:
    piEstimatesList.append(estimatePi(throws))

plt.clf()
piEstimates = np.array(piEstimatesList)
plt.plot(throwsList, abs(piEstimates - math.pi))
plt.xlabel('Number of throws')
plt.xscale('log')
plt.yscale('log')
plt.ylabel('abs(Estimate of pi – pi)')
plt.show()
```



abs(Estimate of pi - pi)
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{2}
10^{4}
10^{6}
Number of throws

Concepts in numerical programming

- Resolution
- Accuracy
- Precision

Resolution

Low resolution

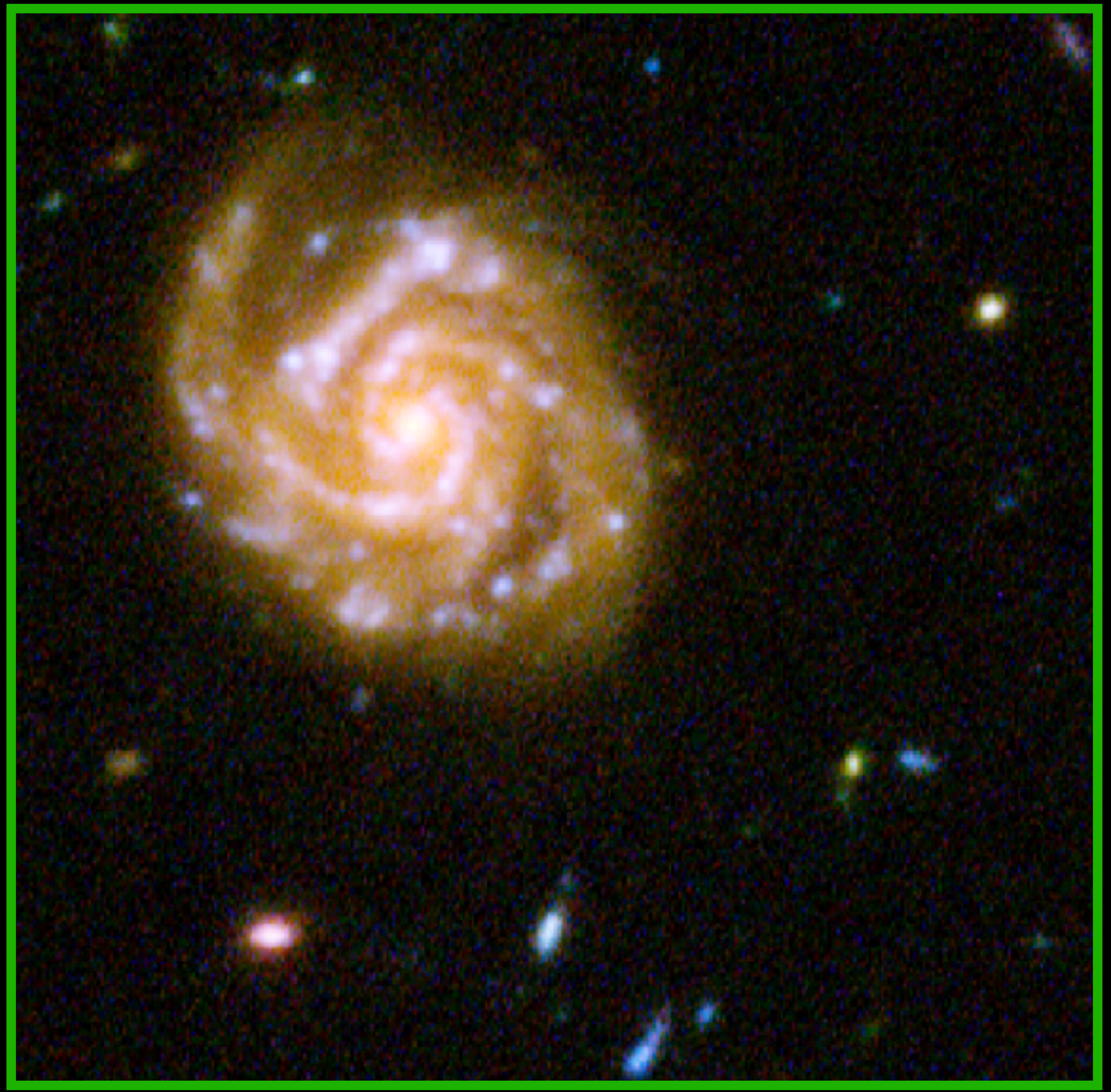
Entire image: 227KB

Large galaxies
1 billion light years away

Small galaxies up to
13 billion light years away

Image courtesy NASA

Resolution



High resolution

Entire image: 110MB

Large galaxies
1 billion light years away

Small galaxies up to
13 billion light years away

Image courtesy NASA

Resolution

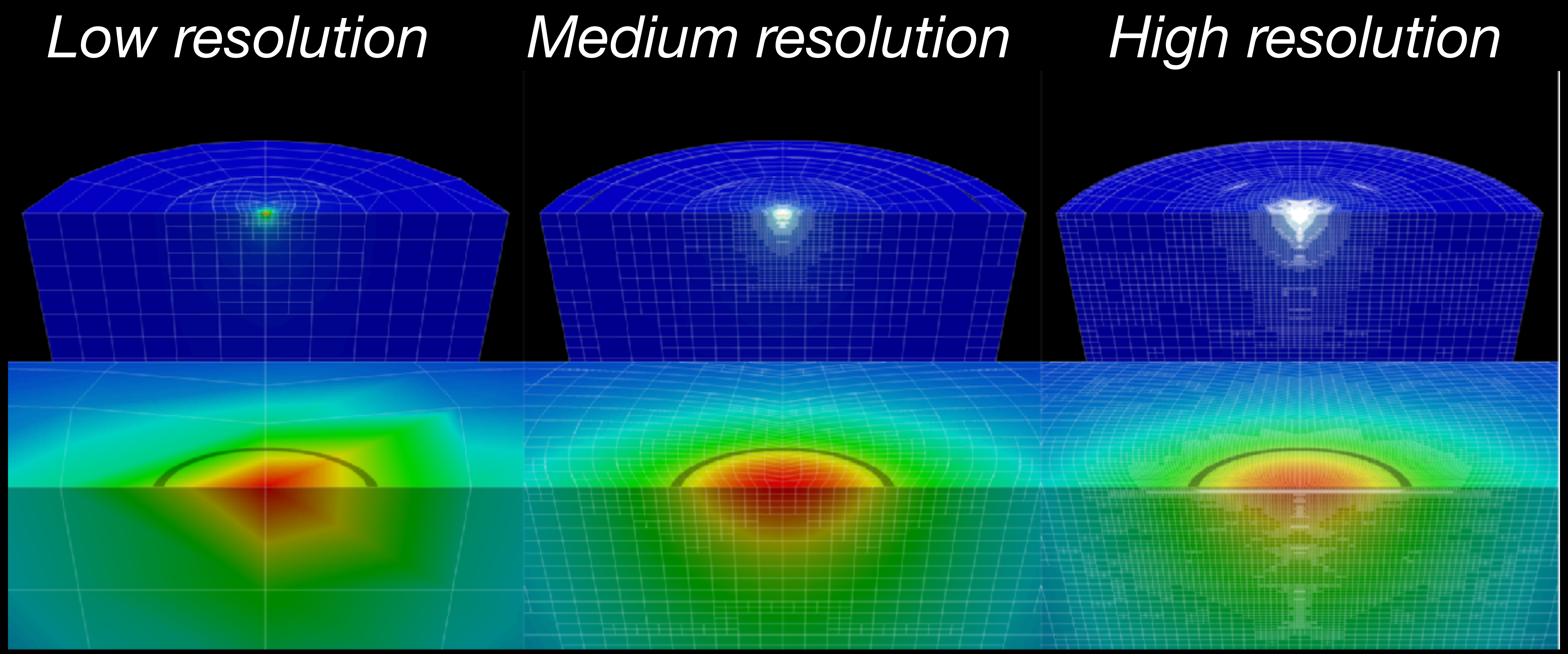
- **Low resolution**
  - Smaller data
  - Faster computation
  - Less precise
- **High resolution**
  - Bigger data
  - Slower computation
  - More precise

Precision & accuracy

- **Precision**
  - How much result changes when you add more resolution
  - "How many digits"
- **Accuracy**
  - How close result is to the correct result

Example: thermal noise

- Thermal noise of a mirror in LIGO depends on how much potential energy it gets when you push on the face

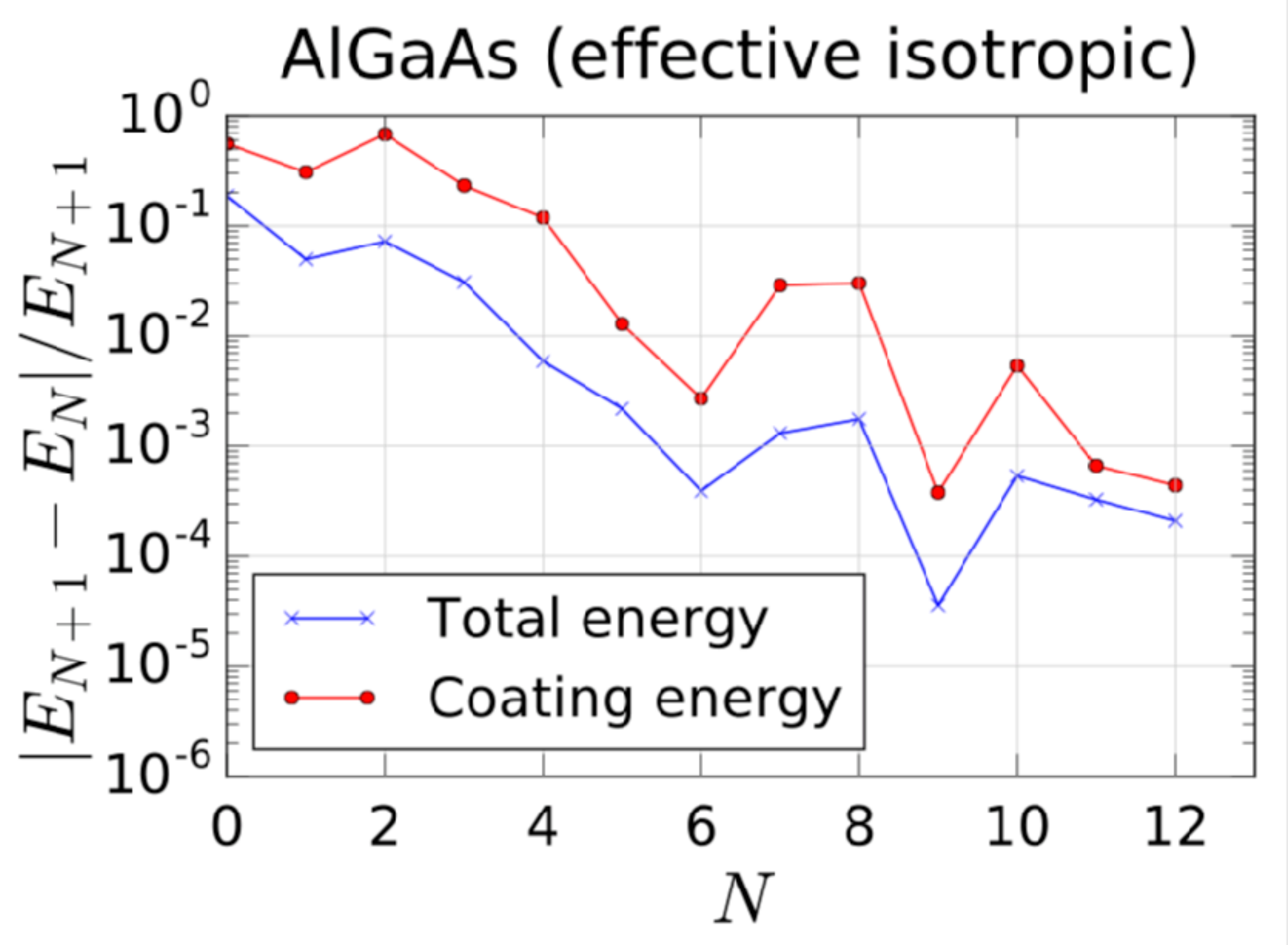


Color = how much mirror deforms

Lovelace, Demos, Khan (2018)

Example: thermal noise

- Potential energy *E* in deformed mirror
  - Precision of energy as resolution increases
    - Label resolution by integer *N*

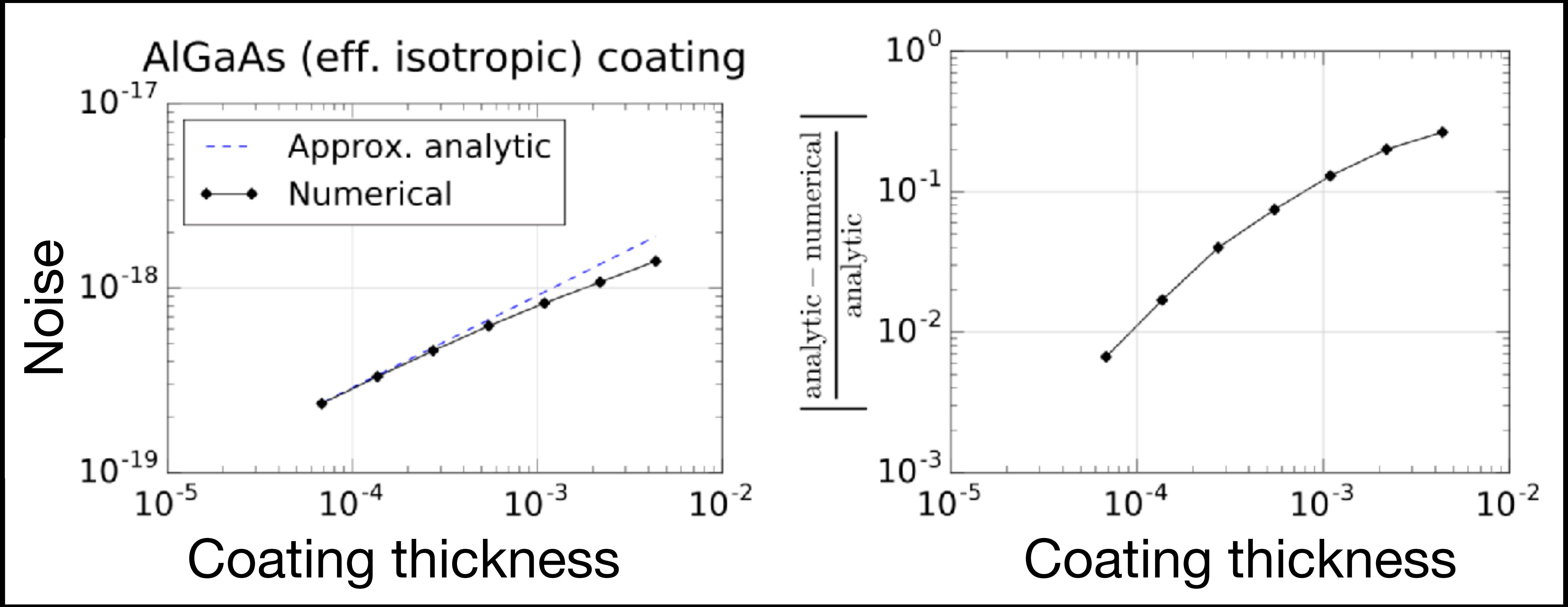


Higher resolution

Lovelace, Demos, Khan (2018)

Example: thermal noise

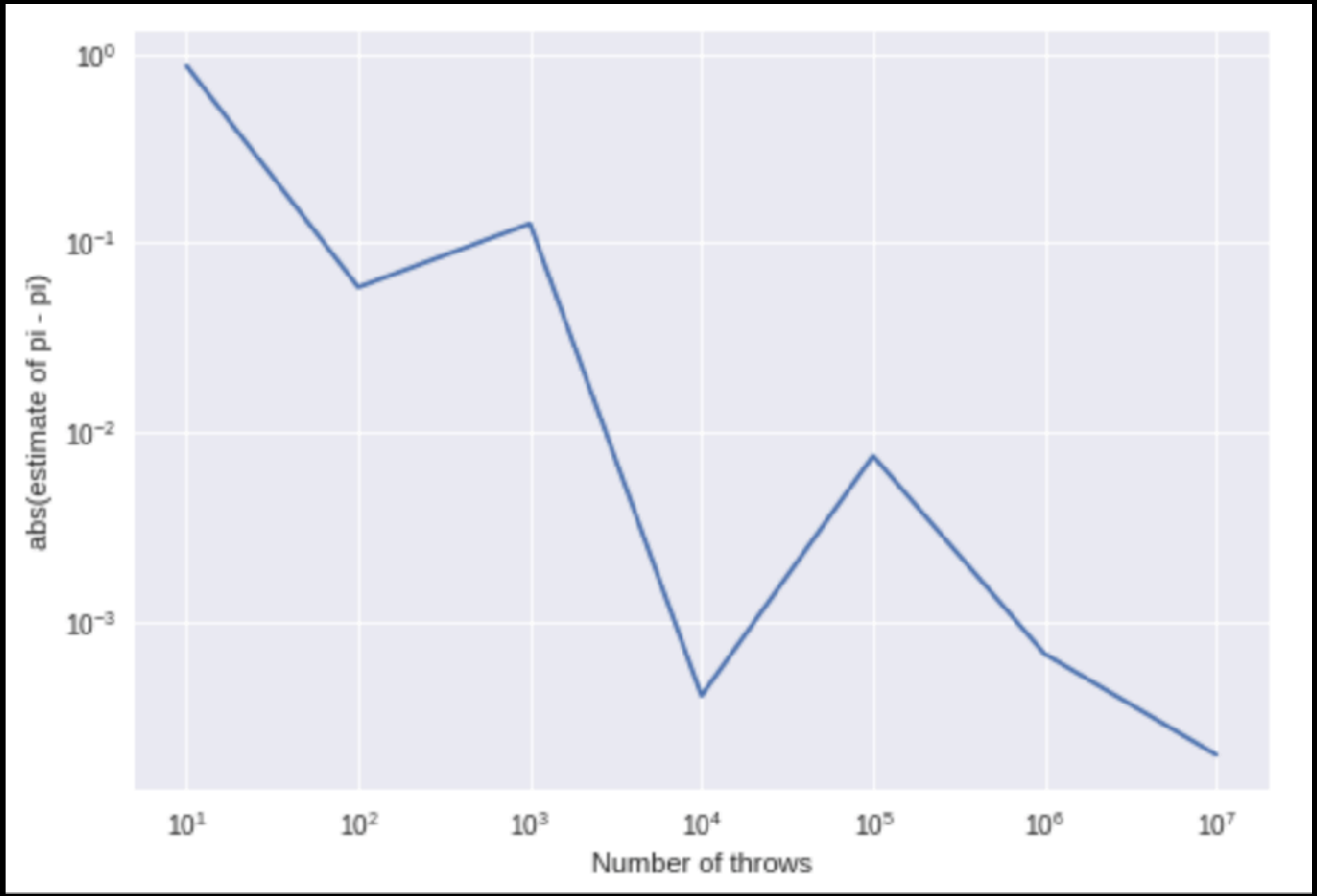
- Thermal noise of thin coating
  - Accuracy: compare code to known "analytic" solution



Lovelace, Demos, Khan (2018)

Clicker question #2.7a

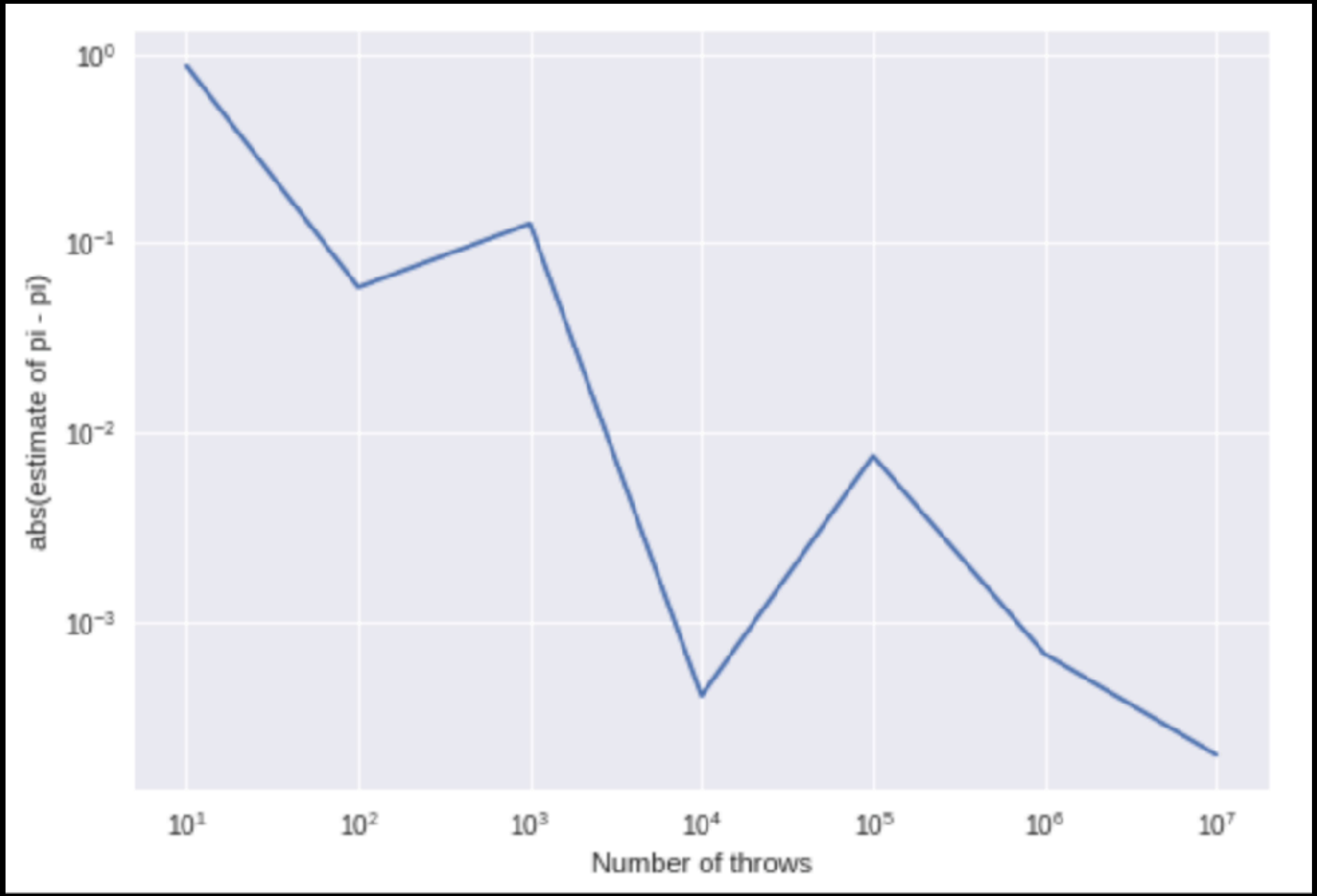
- Your graph plots abs(estimate of pi - pi) vs number of throws. The **horizontal axis** shows



A	Precision
B	Accuracy
C	Resolution
D	None of ABC

Clicker question #2.7b

- Your graph plots abs(estimate of pi - pi) vs number of throws. The **vertical axis** shows



A Precision

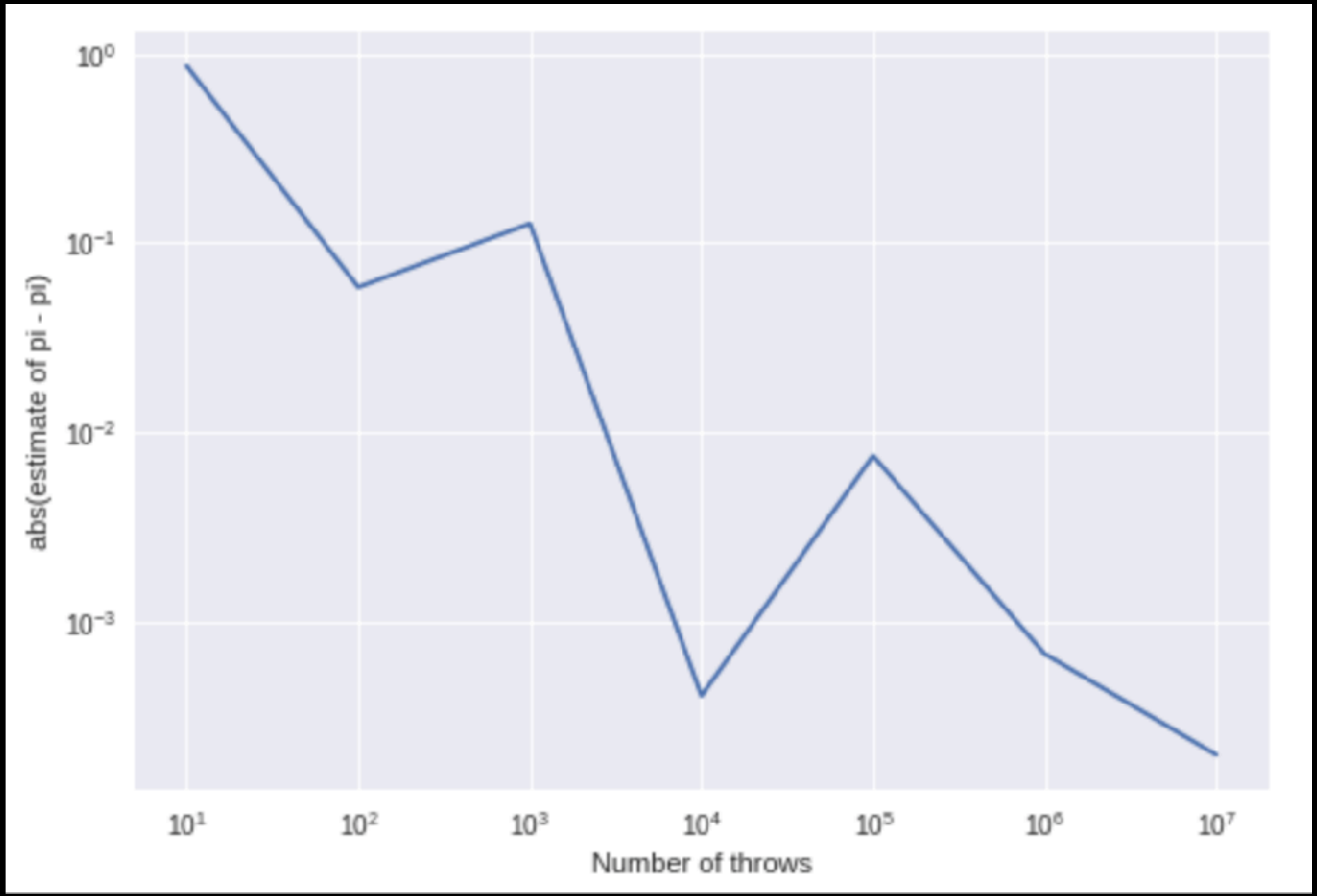
B Accuracy

C Resolution

D None of ABC

Clicker question #2.7c

- As the number of throws increases, the **resolution**



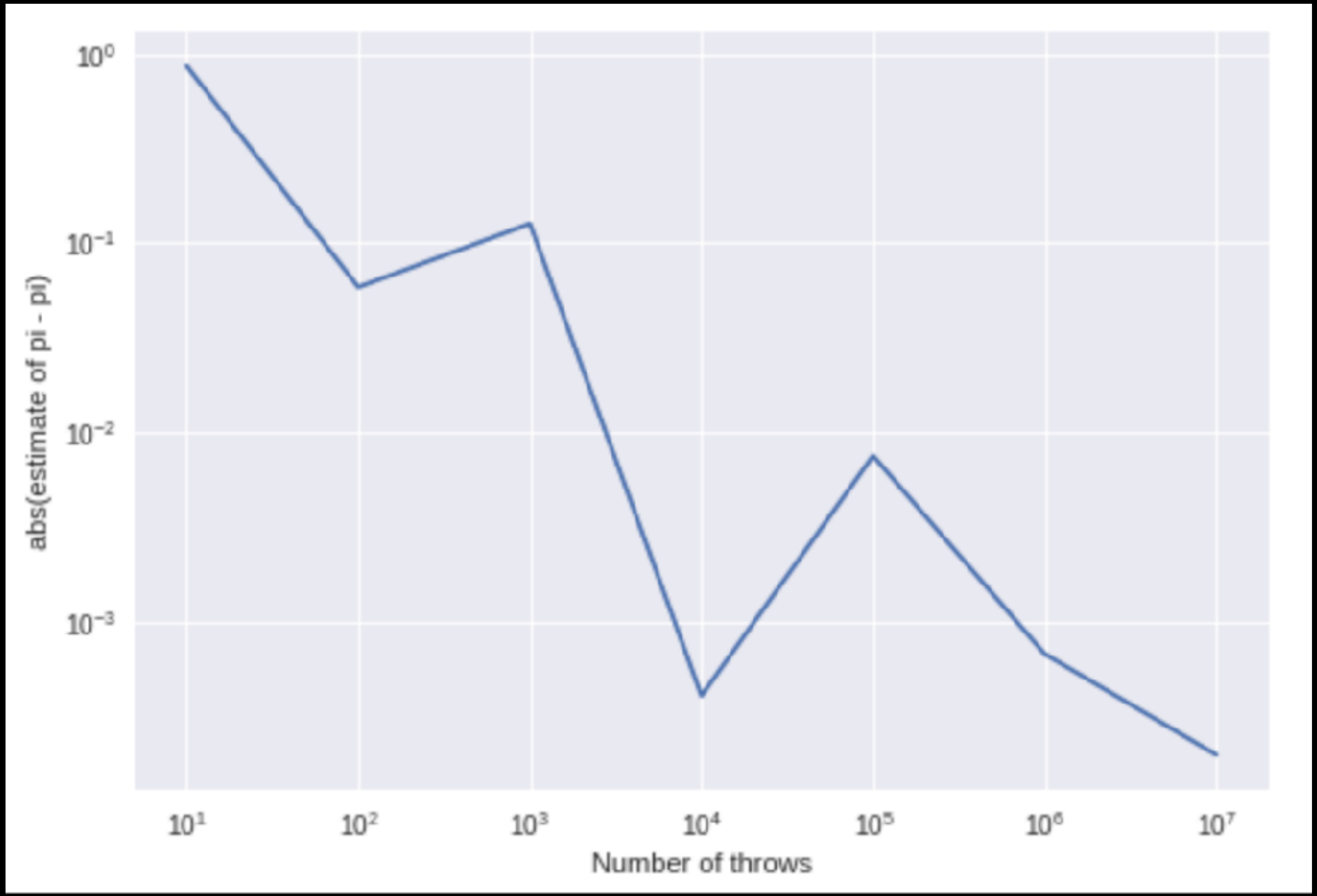
A Increases

B Decreases

C Stays the same

Clicker question #2.7d

- As the number of throws increases, the **accuracy**



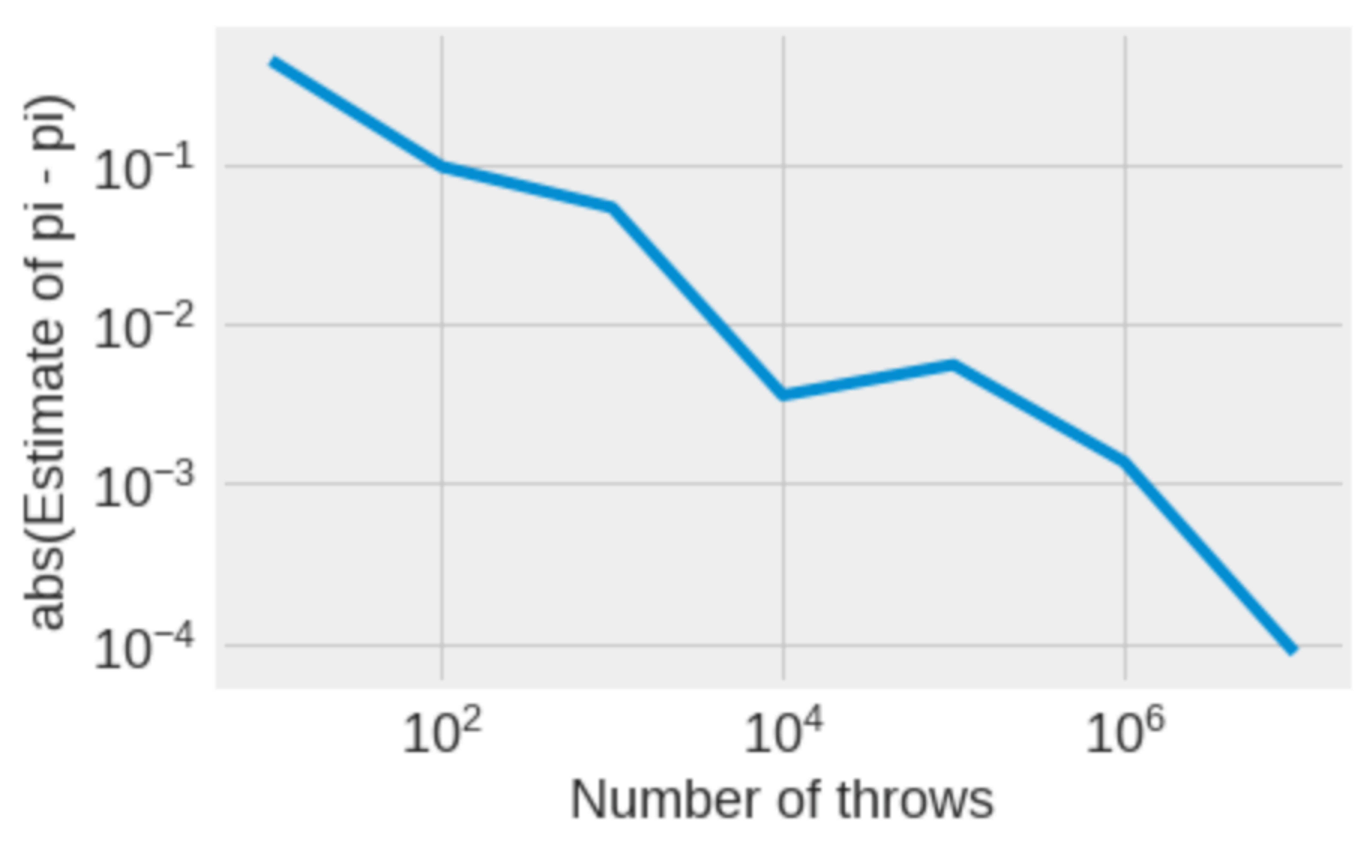
A Increases

B Decreases

C Stays the same

Example: π dart board

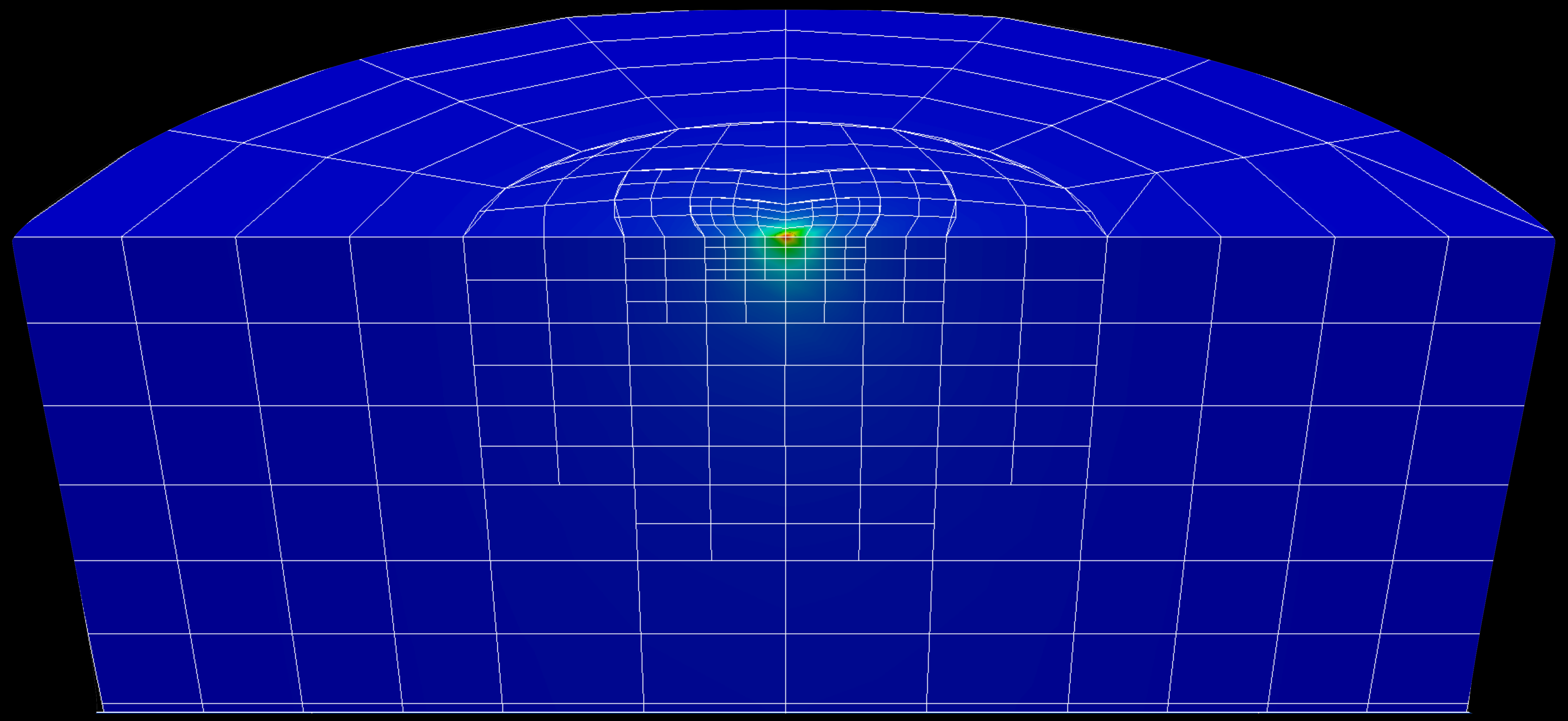
- Need roughly 100x more darts to get 10x more accuracy
  - That is, 100x darts gives you 10x more accuracy
  - This gets slow fast!
  - Can we do better?



Goal of next activity

- Run a calculation that simulates pushing on the mirror, computes thermal noise

- To do this, need to learn some UNIX



Unix terminal on the web

- Go to https://mybinder.org/v2/gh/geoffrey4444/NRDataExample/master

- Choose "New Terminal"

UNIX command line crash course activity

- **Commands to know**
  - ls, pwd, cd, mkdir
  - ./, ../, paths
  - cp, mv, rm, rmdir
  - cat, less
  - nano
  - whoami, date, …

- **Play along with me…**
  - mkdir YOURNAME and cd into it
  - Navigate file system: ls, pwd, cd, ./ and ../
  - Use nano to write a text file
  - Copy, rename, remove a file
  - Cat, less, more, head, tail
  - > to redirect output
  - Grab bag: whoami, date, grep, sed, zip…

Unix commands to know

- **Commands to know**
  - ls, pwd, cd, mkdir
  - ./, ../, paths
  - cp, mv, rm, rmdir
  - cat, less
  - nano
  - whoami, date, …

- **Play along with me…**
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  - Use nano to write a text file
  - Copy, rename, remove a file
  - Cat, less, more, head, tail
  - > to redirect output
  - Grab bag: whoami, date, grep, sed, man, …

Clicker question #1.8

- I want to list the files in the directory I'm in. Which command would I use?

A ls

B cd

C pwd

D nano

Clicker question #1.9

- Which command edits the file “Hello.txt” in the directory I am currently in?

A nano ./Hello.txt

B cat ./Hello.txt

C nano ../Hello.txt

D cat ../Hello.txt

Clicker question #1.9

- Which command makes a new directory called "TestFolder"?

A ls TestFolder

B cd TestFolder

C mkdir TestFolder

D cp TestFolder

Clicker question #1.9

- Which command removes everything in the current directory, which is not empty?

A rmdir ./

B rm -r ./*

C rm -r . /*

D More than one of these will work

Unix activity

- **Commands to know**
  - ls, pwd, cd, mkdir
  - ./, ../, paths
  - cp, mv, rm, rmdir
  - cat, less
  - nano
  - whoami, date, …

- Use nano to write a bash script (each line is a command like you would enter on the command line)
- The script should…
  - Print the current date and time
  - Print the current directory
  - Copy /proc/cpuinfo into the current directory
  - Get the first line of the copied file, and save it to a file called FirstLineOfProc.txt
  - Bonus: Use grep to only show the line with "cpu cores"
  - Bonus: use sed to remove all but the core number
  - Bonus: instead of copying the /proc/cpuinfo file, copy whatever file users specify as an argument (google bash arguments)

Parallel computing

- Supercomputers have lots of cores
- But each core is not much faster than a PC
- To take full advantage, you have to write code that can run on more than one core at the same time
  - That is, code that runs in parallel

Image courtesy Blue Waters

Parallel computing 1

- Log into orca
- Do this

```
#Replace GeoffreyLovelace with YourName
cd GeoffreyLovelace

mkdir PiDart
cd PiDart
source /share/apps/python/2.7.15/bin/activate #set up python
```

Parallel computing 2

- Log into binder: mybinder.org, load geoffrey4444/NRDataExample
- nano Hello.py

```
print("Hello")
```

- mpirun -np 8 python Hello.py
  - **What happens? What happens if you change 8 to another number less than 8?**

What happened?

- mpirun ran many copies of “Hello.py”
- Each copy printed “Hello”
  - But the processors are not working together yet, or even doing anything different
- Next: make different processors do different things

Parallel computing 3

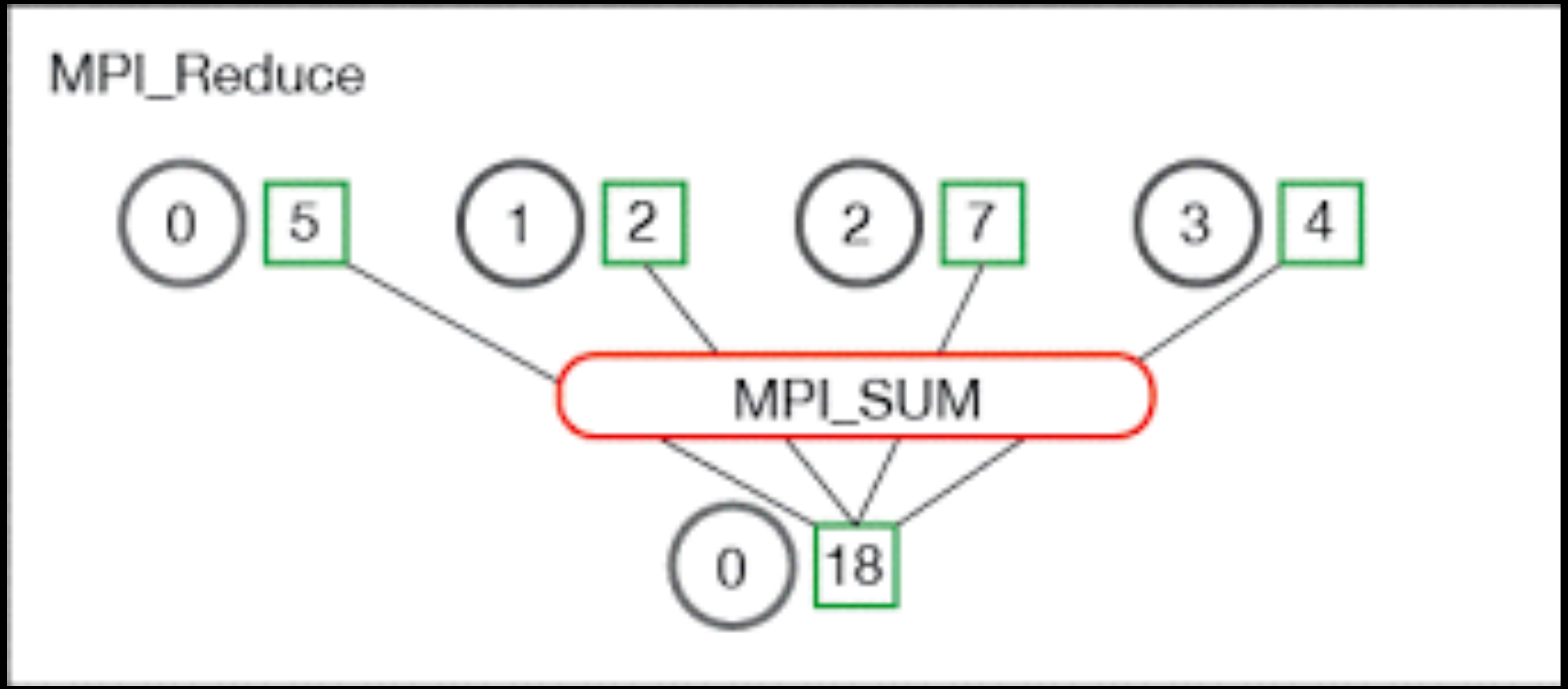
- `cp Hello.py MpiHello.py`
- `nano MpiHello.py`

```
from mpi4py import MPI
comm = MPI.COMM_WORLD
rank = comm.Get_rank()
size = comm.Get_size()
print("Hello from processor "+str(rank)+" out of "+str(size))
```

- `mpirun -np 4 python MpiHello.py`
- `mpirun -np 8 python MpiHello.py`

Paralleizing the dartboard

- **What if we combined results from the whole class's π dartboard?**
- **Even batter**
    - Run lots of copies of the dartboard on lots of cores
    - At the end, each copy tells the others how many hits it had
    - Each copy adds up the number of hits on all processors and computes pi



Parallelizing the dartboard 2

- `cp /home/workshopStudent2018/SharedStuff/Tuesday/piEstimate.py .`
- `nano piEstimate.py`
- `#Add the same mpi4py lines at the top`

```python
from mpi4py import MPI
comm = MPI.COMM_WORLD
rank = comm.Get_rank()
size = comm.Get_size()
```

Parallelizing the dartboard 3

- nano piEstimate.py

- #At the bottom, instead of getting pi, print the number of hits on each processor

```
print(str(hits)+" hits on processor "+str(rank)+" out of "+str(throws)+" throws.")
```

- mpirun -np 12 python piEstimate.py
  - What happens?

Parallelizing the dartboard 4

- `nano piEstimate.py`
- `#Divide the darts to throw among the processors, instead of each processor throwing the total`

```
hits = 0
throws = 1e7 // size
i = 0
while i < throws:
# … rest of program
```

- `mpirun -np 12 python piEstimate.py`
  - What happens?

Parallelizing the dartboard 5

- nano piEstimate.py

- #Have on processor add up the totals across all processors

```
print(str(hits)+" hits on processor "+str(rank)+" out of "+str(throws)+" throws.”)
```

```
throwsAllProcessors = throws * size
hitsAllProcessors = comm.allreduce(hits, op=MPI.SUM)
```

```
if rank == 0:
    print(str(hitsAllProcessors)+" hits on all processors, with "+str(throwsAllProcessors)+" throws.")
```

-

Parallelizing the dartboard 6

- nano piEstimate.py

- #Compute pi

```
if rank == 0:
    print(str(hitsAllProcessors)+" hits on all processors, with "+str(throwsAllProcessors)+" throws.”)

    pi = 4.0 * float(hitsAllProcessors) / float(throwsAllProcessors)
    print(pi)
```

-

Parallelizing the dartboard 7

- nano piEstimate.py
- How long does it take?
- At top:

```python
import time
start = time.time()
```

- At bottom

```python
print(pi)
end = time.time()
print("Run in "+str(end-start)+" seconds.")
```

-

How many darts can we run on the entire cluster?

- 1e7 on on core
- About 500 cores
- So in the same time, we should be able to run 500e7 = 5e9

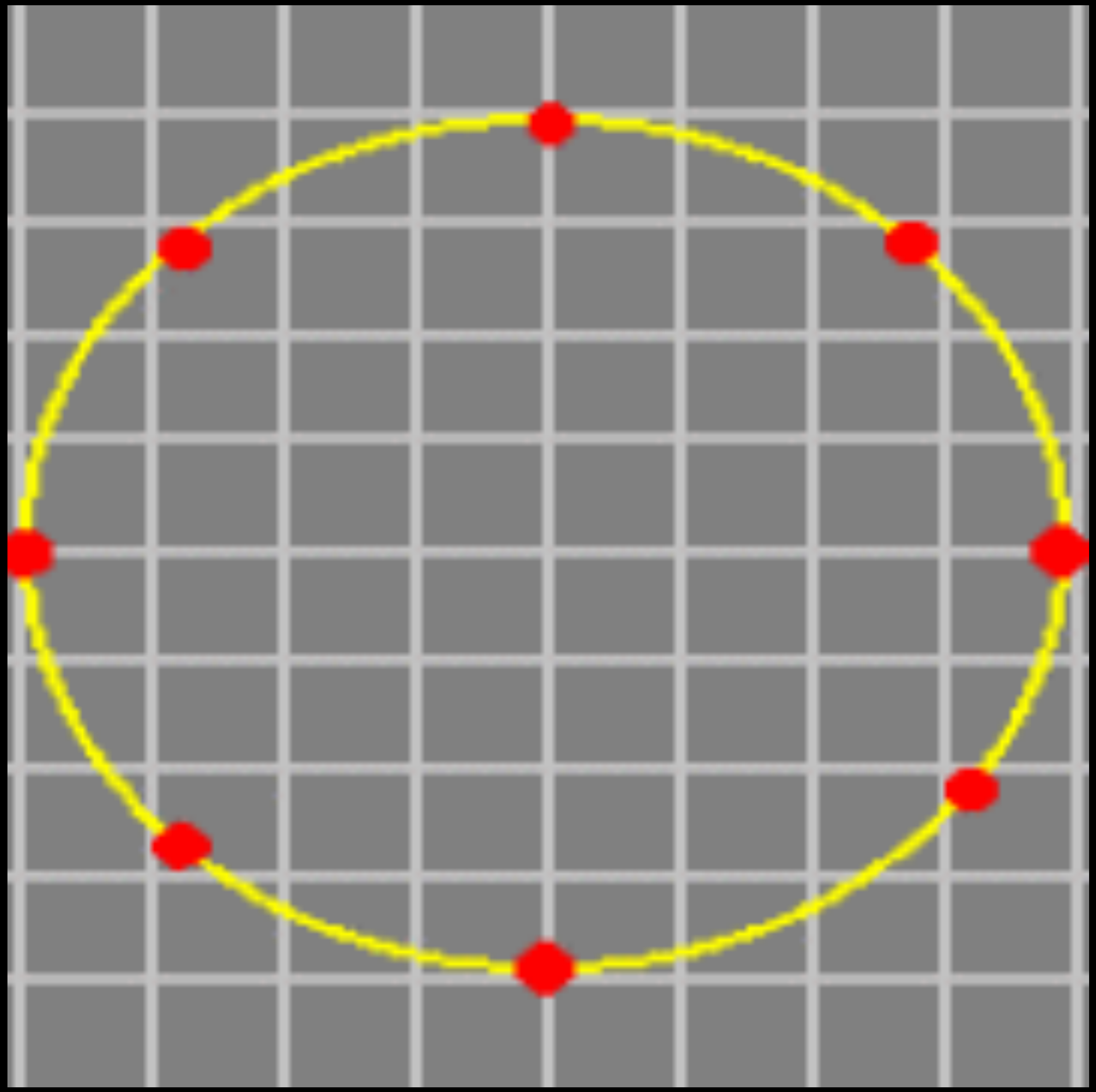
Modeling Thermal Noise in Gravitational-Wave Detectors

How small is 10^{-21}?

Fractional length change: 10^{-21}

- Suppose circle radius = 4 km (2.5 miles)
- Then positions of red balls change by 10^{-18} m
- How small is that?

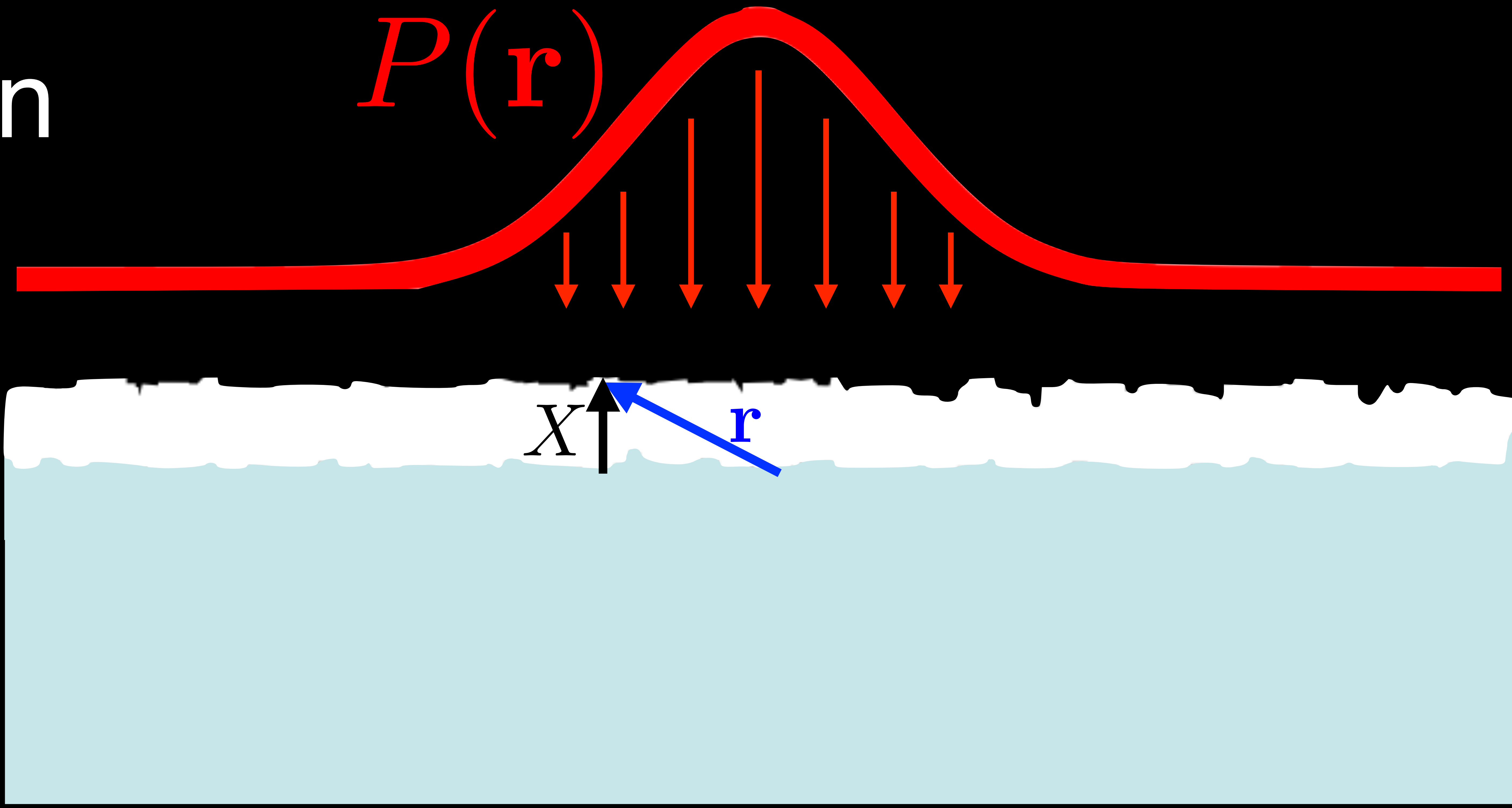
1 m	Human height
÷ 10000	Human hair width
÷ 100	Wavelength of light
÷ 10000	Size of atom
÷ 100000	Size of proton
÷ 1000	10^{-18} m (LIGO)



How could we possibly hope to measure this?

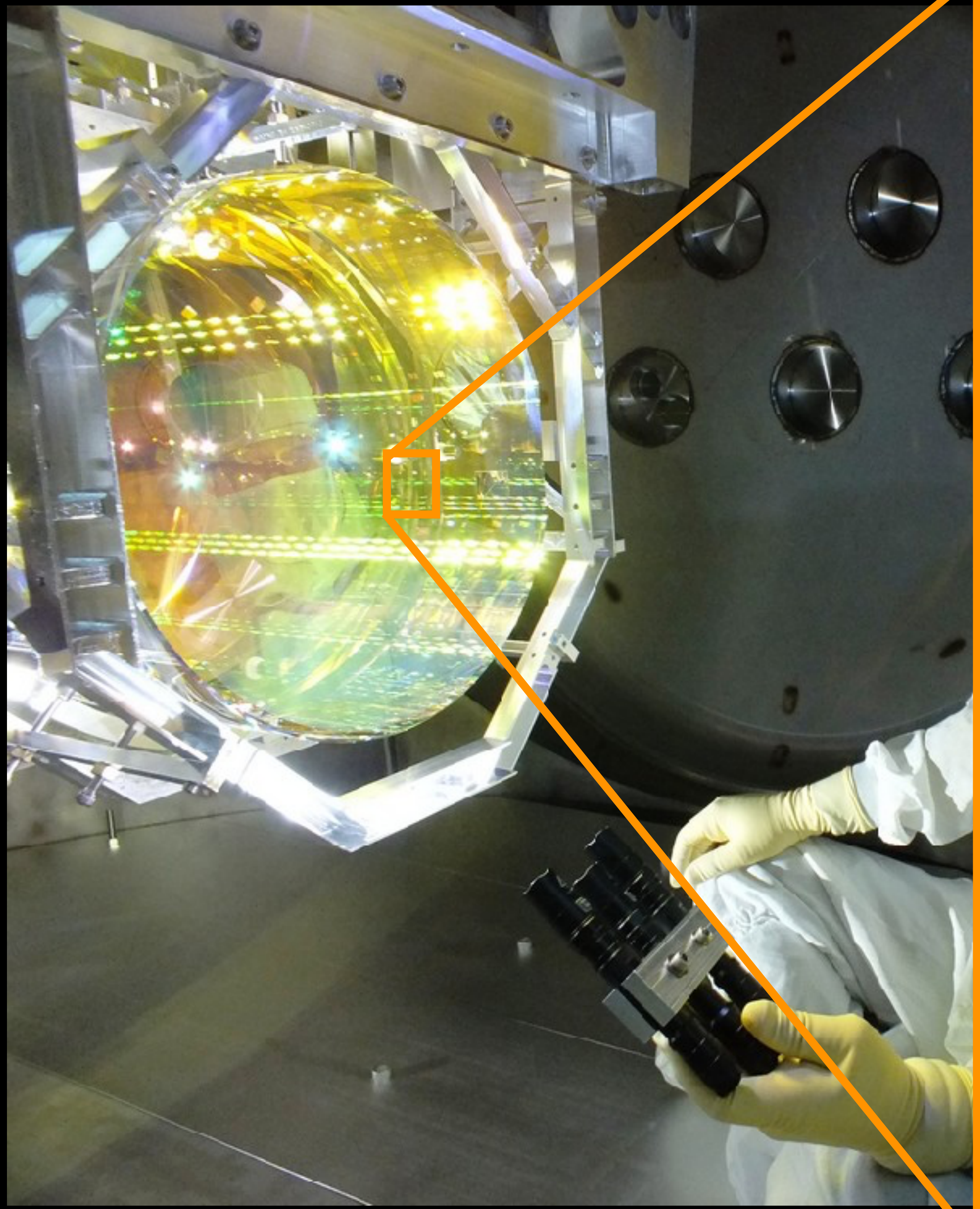

Movie courtesy LIGO

Measuring mirror position



- LIGO measures positions of mirrors
  - Gravitational waves change the distance between mirrors
  - **To measure:**
    Shine laser
    (lots of light particles ("photons"))
    on mirror
    - Measured position is average of the many positions measured by the many photons
- But surface is fluctuating…

Thermal motion



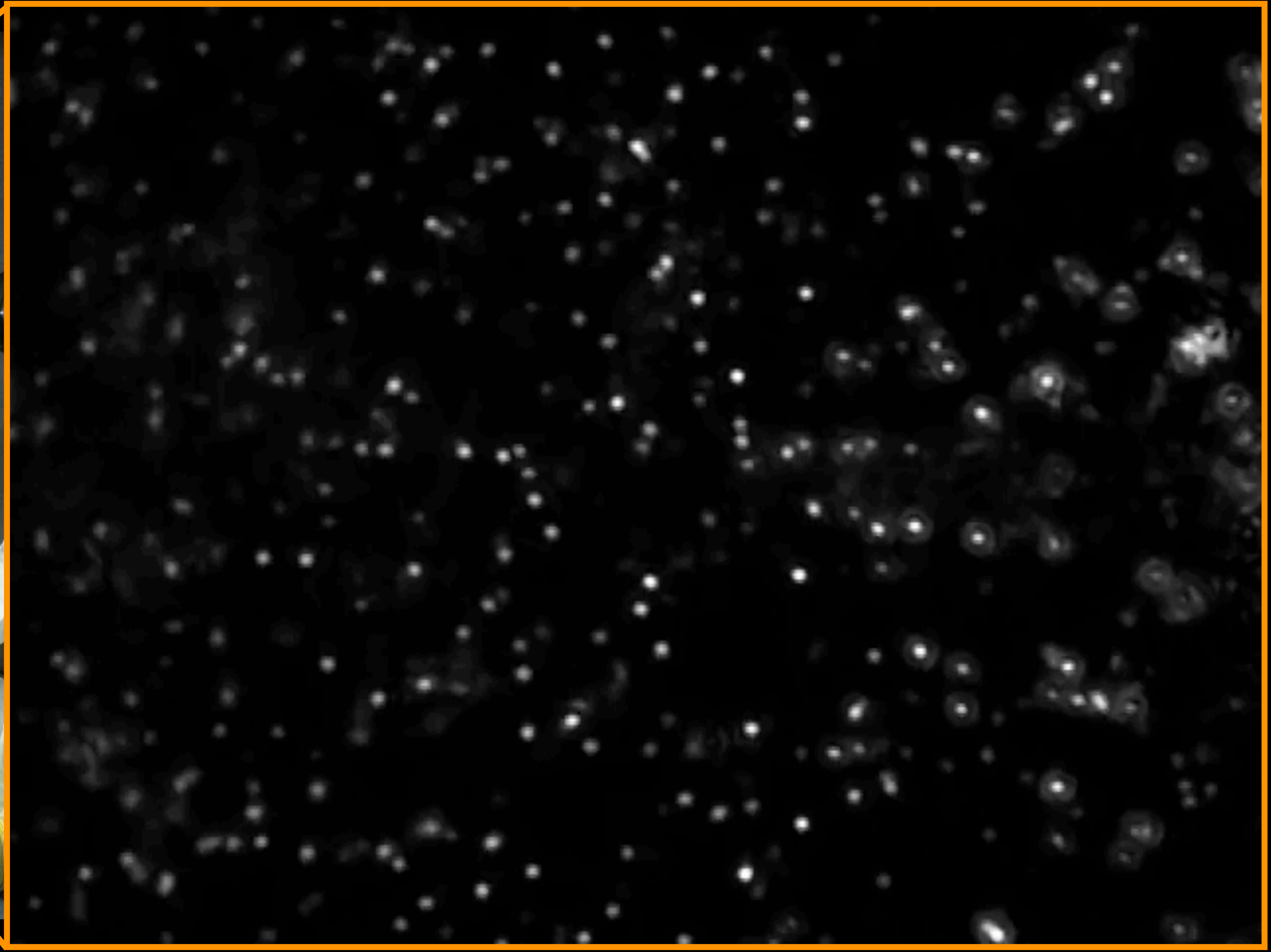


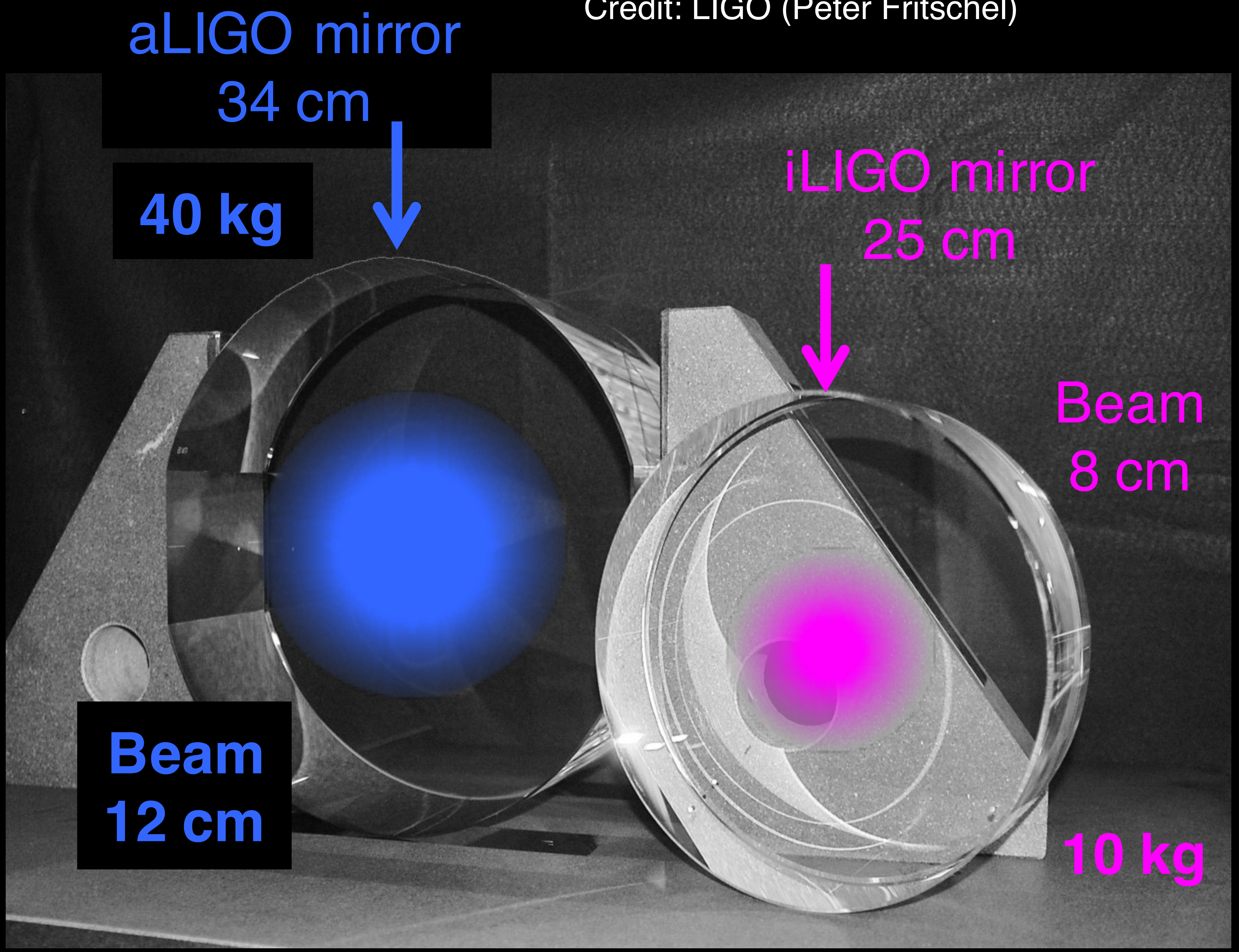
Image credit LIGO

Rutger Saly, YouTube, "We filmed Brownian motion, random movement of particles in water…"

Reducing coating thermal motions

- Larger beam spots on mirrors
- Longer arms
- Improved mechanical loss in optical coatings
  - Goal of Center for Coating Research (Stanford, Syracuse, Fullerton, et al.)
- Cryogenically cool mirrors
  - Being pioneered in Japan's KAGRA

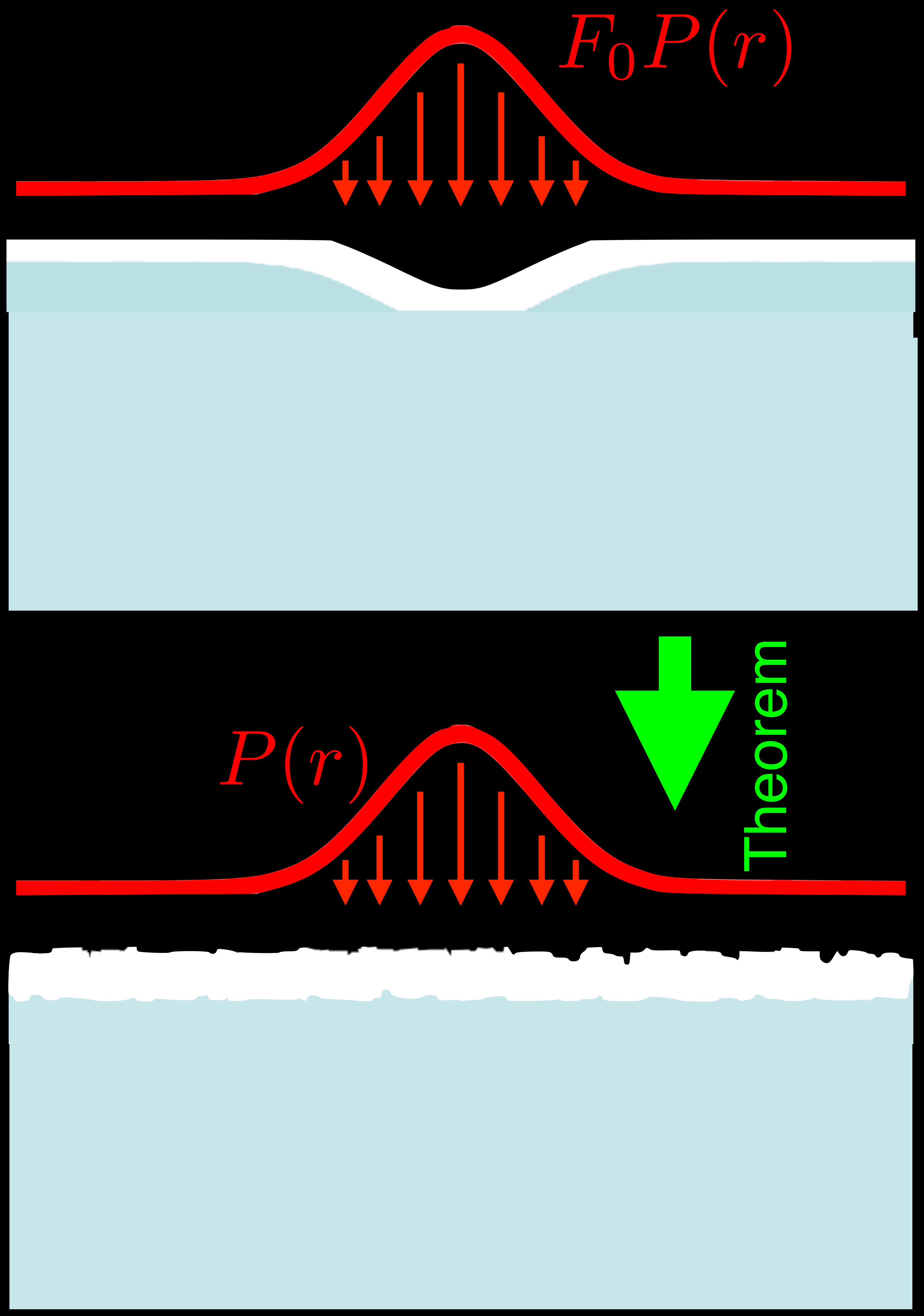
Credit: LIGO (Peter Fritschel)



Modeling thermal noise

- Fluctuation dissipation theorem
  Levin 1997
  – Push on mirror at temperature *T* with pressure at freq. *f*, beam shape
  – Then fluctuations S_x depend on power dissipated W_{diss}
  – T = Temperature in Kelvin = (°C + 273)

$$S_x = \frac{8 W_{\text{diss}} k_B T}{4\pi^2 f^2 F_0^2}$$



Clicker question #1.8

- If you cut the temperature in half, the coating Brownian thermal noise would be

A 2 times larger

B 2 times smaller

C 4 times larger

D 4 times smaller

Clicker question #1.8b

- If you cut the temperature (in Kelvins) in half in this room, the room would be

A Colder, but not uncomfortable

B Uncomfortably cold but livable

C Too cold for us to live

Room temperature
= 68°F = 20°C

Kelvins
= (°C + 273)

Model thermal noise II

- **Commands to know**
  - ls, pwd, cd, mkdir
  - ./, ../, paths
  - cp, mv, rm, rmdir
  - cat, less
  - nano
  - whoami, date, …

- **Play along with me…**
  - Tail Energy.dat
  - Download the *vtk files
  - Open these files in ParaView and explore them

The π dartboard on a supercomputer

- Idea of parallel computing
- Activity

Day 3

- Gravitational-wave concepts (with Jocelyn)
- Explore data from simulations of merging black holes
- Compare accuracy and speed for head-on collision vs res
- (Choose one head-on collision and submit it)

Connect to orca

- Open "PuTTY 64-bit" on the desktop
- Under "saved sessions" select "orca"
- Click "Open"
- Username: workshopStudent2018
- Passphrase
  - Front 2 rows: fullertonGW!
  - Back 2 rows: FullertonGW!

UNIX command line crash course activity

- **Commands to know**
  - ls, pwd, cd, mkdir
  - ./, ../, paths
  - cp, mv, rm, rmdir
  - cat, less
  - nano
  - whoami, date, …

- **Play along with me…**
  - mkdir YOURNAME and cd into it
  - Navigate file system: ls, pwd, cd, ./ and ../
  - Use nano to write a text file
  - Copy, rename, remove a file
  - Cat, less, more, head, tail
  - > to redirect output
  - Grab bag: whoami, date, grep, sed, zip…

Unix commands to know

- **Commands to know**
  - ls, pwd, cd, mkdir
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  - cp, mv, rm, rmdir
  - cat, less
  - nano
  - whoami, date, …

- **Play along with me…**
  - mkdir YOURNAME and cd into it
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  - Use nano to write a text file
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  - > to redirect output
  - Grab bag: whoami, date, grep, sed, man, …

Clicker question #1.8

- I want to list the files in the directory I'm in. Which command would I use?

A	ls	C	pwd
B	cd	D	nano

Clicker question #1.9

- Which command edits the file “Hello.txt” in the directory I am currently in?

A nano ./Hello.txt

B cat ./Hello.txt

C nano ../Hello.txt

D cat ../Hello.txt

Clicker question #1.9

- Which command makes a new directory called "TestFolder"?

A ls TestFolder

B cd TestFolder

C mkdir TestFolder

D cp TestFolder

Clicker question #1.9

- Which command removes everything in the current directory, which is not empty?

A rmdir ./

B rm -r ./*

C rm -r . /*

D More than one of these will work

Start your own simulation of merging black holes

- Start from rest, collide head-on
- Choose mass ratio between 1 and 1.2
- Choose spin = 0,0,0 on the smaller black hole (B)
- Choose spin = 0,0,X on the larger black hole (A), where X is between 0 and 0.2
- Set Omega0 = 0, adot0=0, D0=35

```
cd $HOME
cd YOURNAME
mkdir BlackHoleMerger
cd BlackHoleMerger
source /home/workshopStudent2018/SharedStuff/Wednesday/spec/MakefileRules/this_machine.env
PrepareID -t bbh2 -no-reduce-ecc
nano Params.input
# Omega0 = 0.0
# adot0 = 0.0
# D0 = 35.0
# MassRatio = 1.2 #or 1.0, or something in between
# @SpinA = (0.0, 0.0, 0.0) #can make 1 component up to 0.2 instead of 0.1
# @SpinB = (0.0, 0.0, 0.0)
nano Ev/DoMultipleRuns.input
# MaxLev = 1
./StartJob.sh
```

```
qstat
qstat -f YOURJOBNUMBER
ShowQueue
```

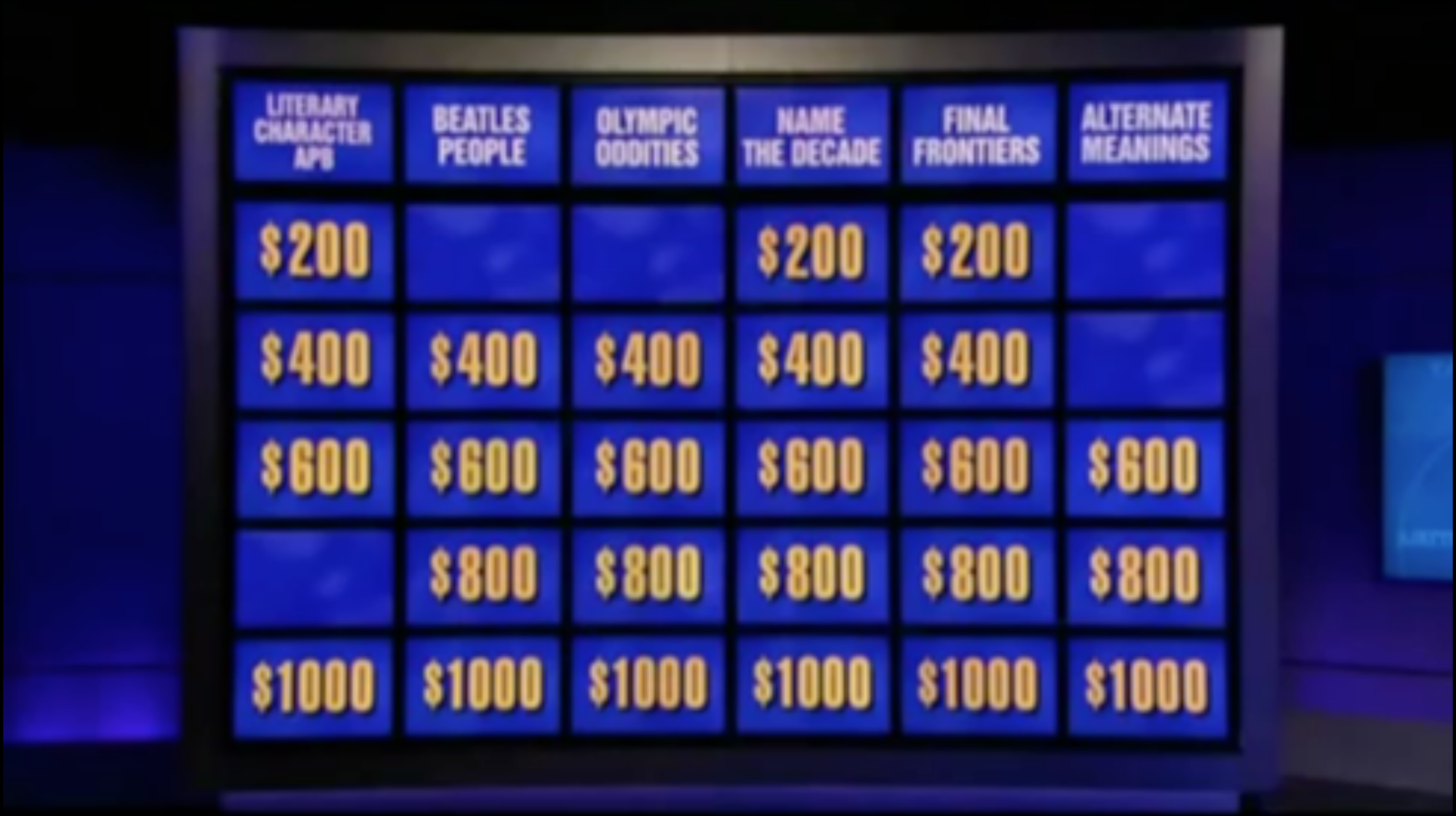
orca.fullerton.edu/ganglia

Unix activity

- **Commands to know**
  - ls, pwd, cd, mkdir
  - ./, ../, paths
  - cp, mv, rm, rmdir
  - cat, less
  - nano
  - whoami, date, …

- Use nano to write a bash script (each line is a command like you would enter on the command line)
- The script should…
  - Print the current date and time
  - Print the current directory
  - Copy /proc/cpuinfo into the current directory
  - Get the first line of the copied file, and save it to a file called FirstLineOfProc.txt
  - Bonus: Use grep to only show the line with "cpu cores"
  - Bonus: use sed to remove all but the core number
  - Bonus: instead of copying the /proc/cpuinfo file, copy whatever file users specify as an argument (google bash arguments)


IBM


LITERARY CHARACTER APB
BEATLES PEOPLE
OLYMPIC ODDITIES
NAME THE DECADE
FINAL FRONTIERS
ALTERNATE MEANINGS
$200
$200
$200
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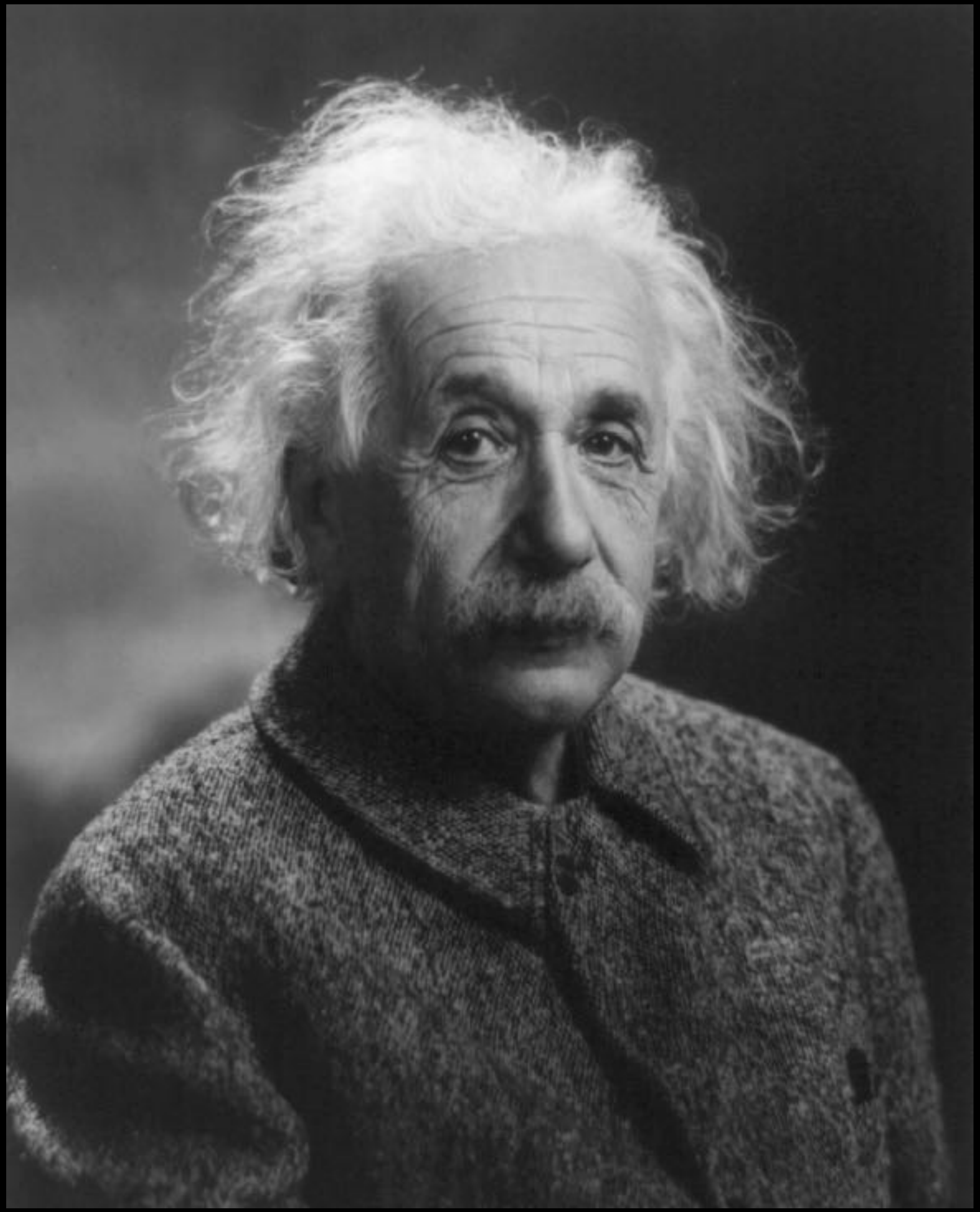
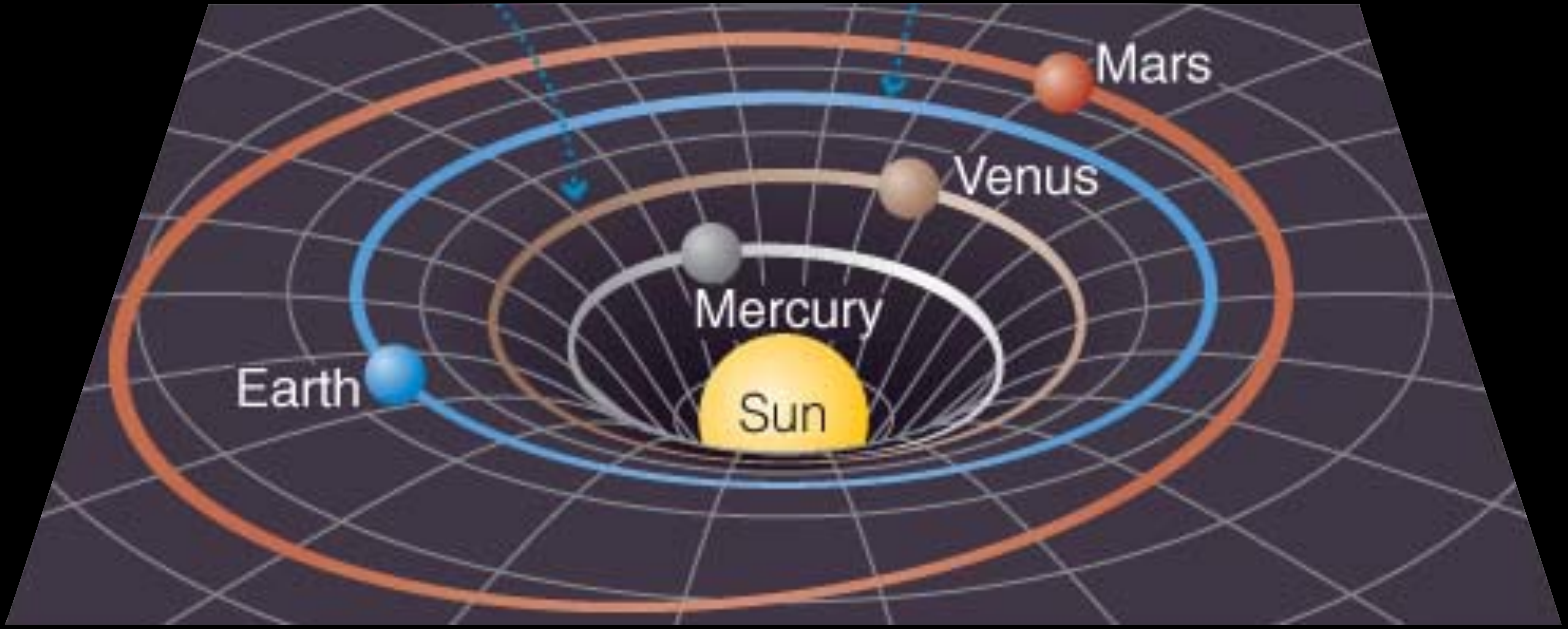
$1000

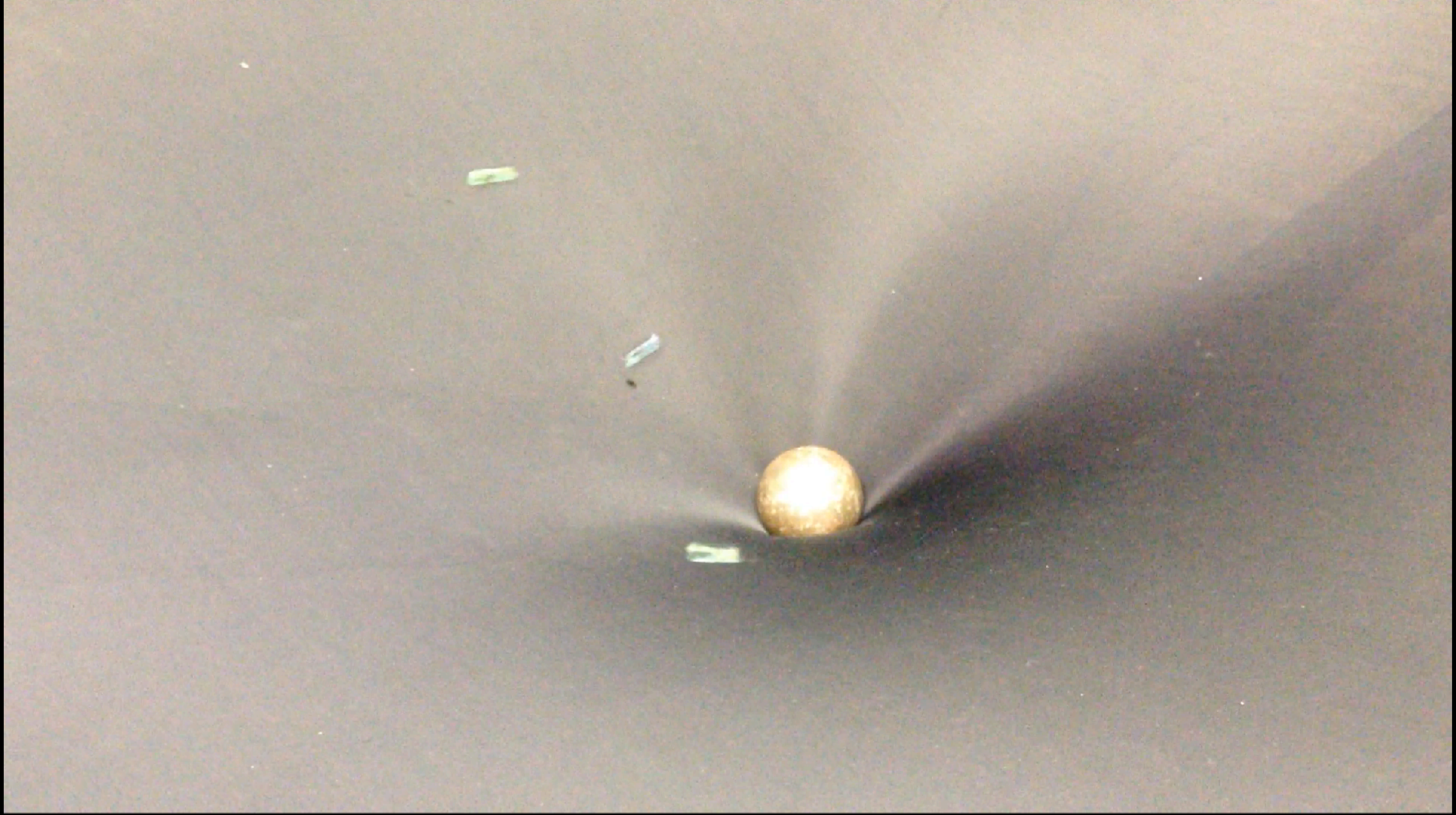
Curved spacetime



Credit: The Library of Congress

"Matter tells space-time how to curve and space-time tells matter how to move."
— John A. Wheeler

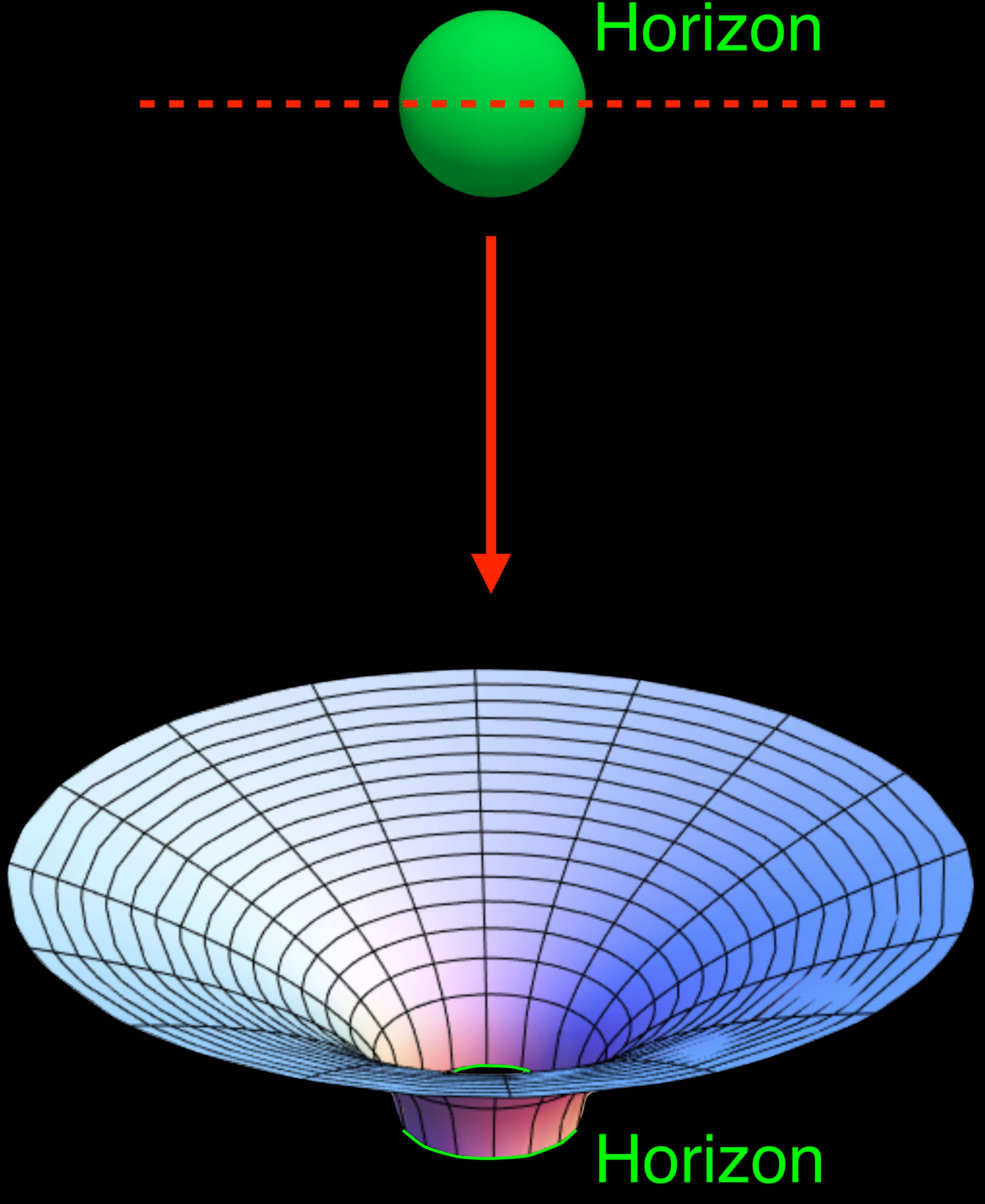




Larry Kiwano, Astrocamp, November 7, 2013

What are black holes?

- Gravity so strong...
  - Nothing (even light) can escape from inside hole's horizon (surface)
- Formed when the most massive stars die



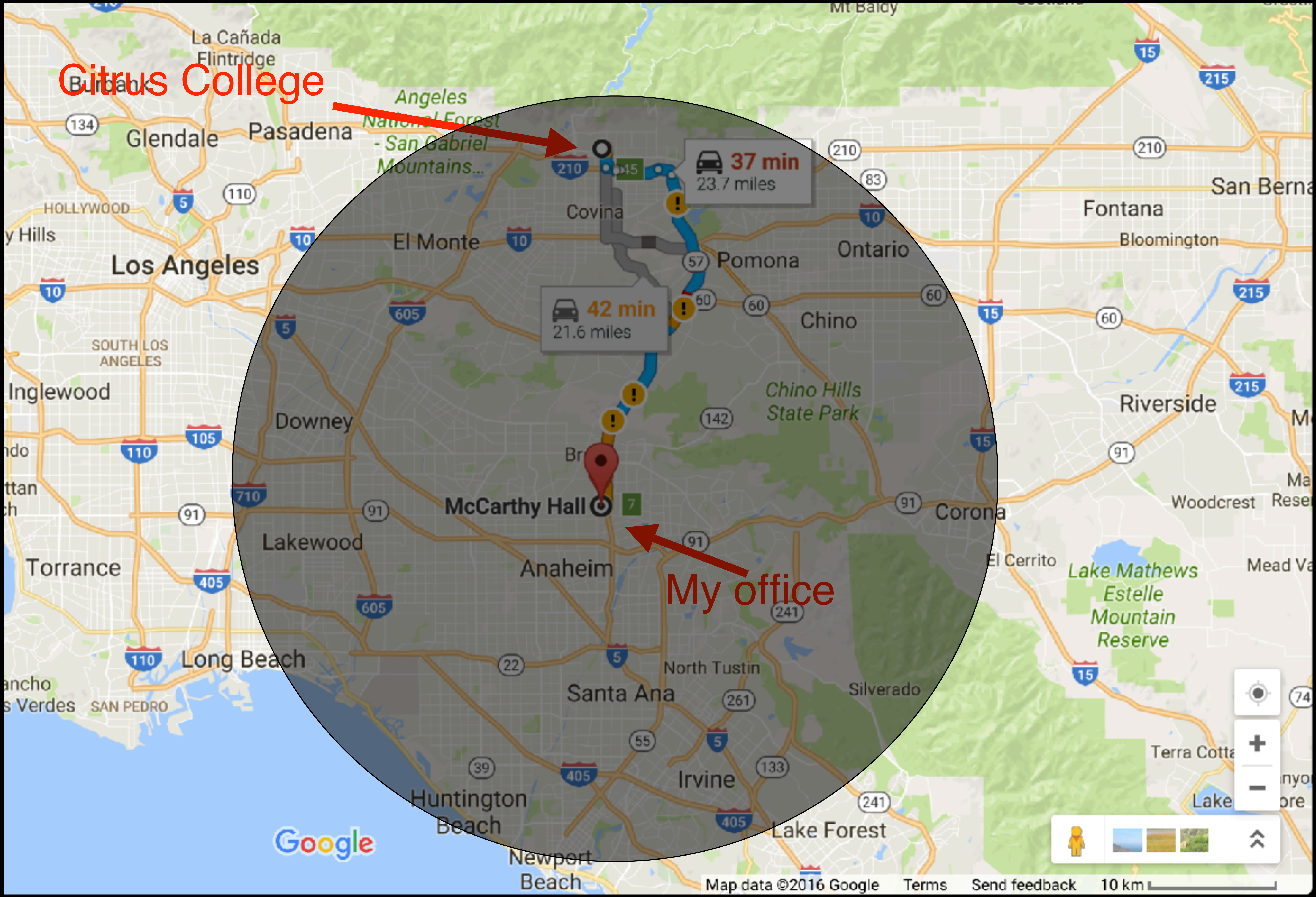
Movie courtesy J Burk

How big are black holes?

- Mass: huge!
  - Two kinds
  - 3 to 70 $M_\odot$
  - Millions+ $M_\odot$
- Radius: small!

$$r = \frac{2G}{c^2} M = 3\ \mathrm{km} \left(\frac{\mathrm{mass}}{M_\odot} \right)$$

Size of earth-mass black hole



Size of 10-$M_\odot$ black hole

Image courtesy Google maps

Clicker question #3.1

- A black hole's circumference has doubled. The hole's mass has ____________________.

A halved

B not changed

C doubled

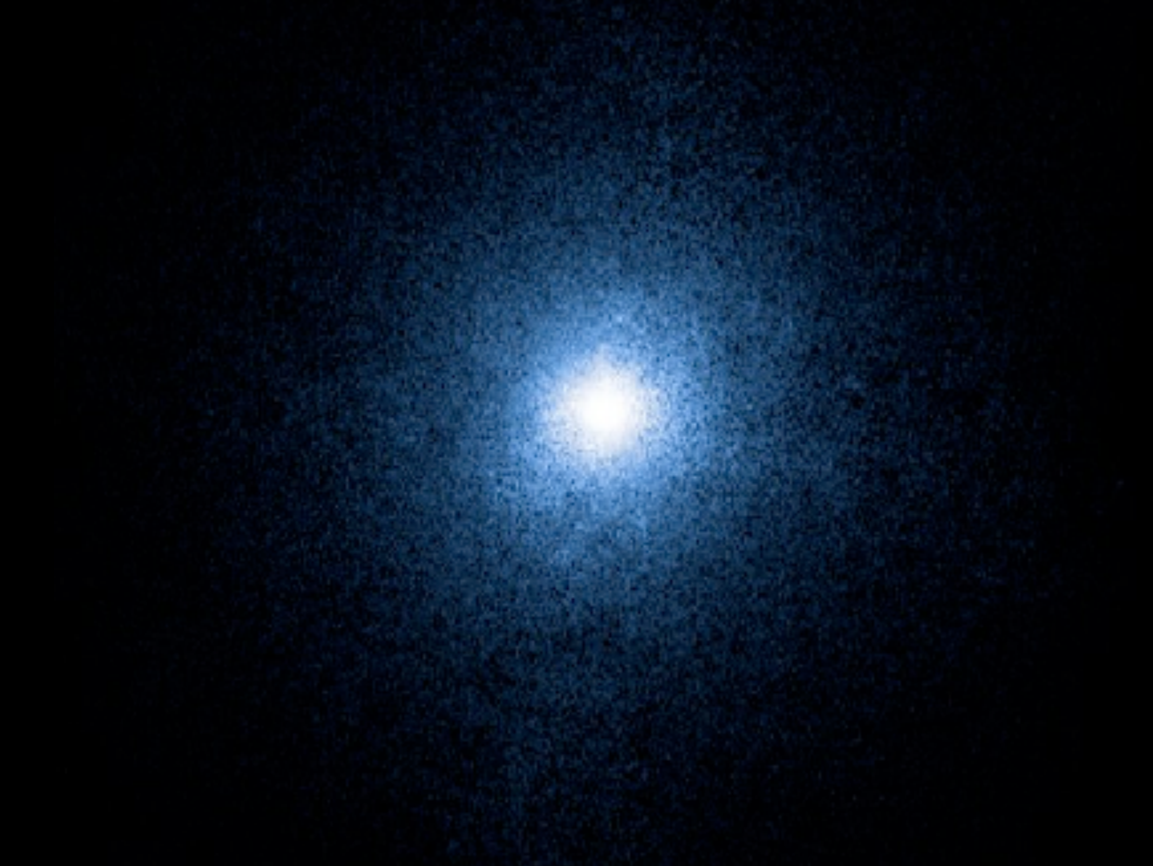
D quadrupled

Images courtesy NASA, ESO/VLT

How to observe black holes?

- Indirectly
  - –Gravity affects motion of objects nearby: infer mass
  - –Gas heats up & glows as it falls in: infer spin (uncertain!)

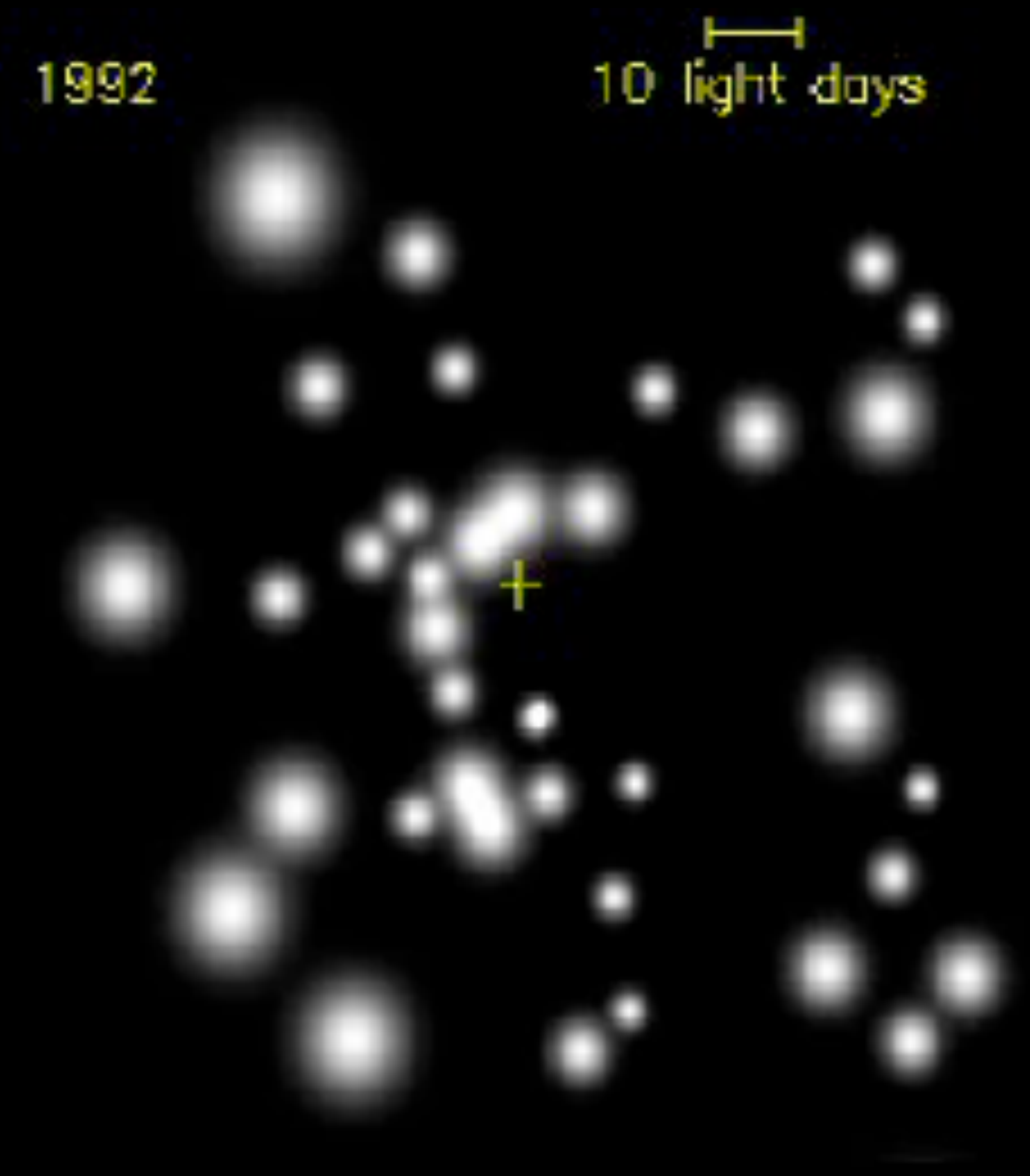
Cygnus X-1



First black hole discovered

$M/M_{\rm sun} \approx 15$

$\chi \gtrsim 0.983$ — Gou *et al.* (2014)



Sagittarius A*

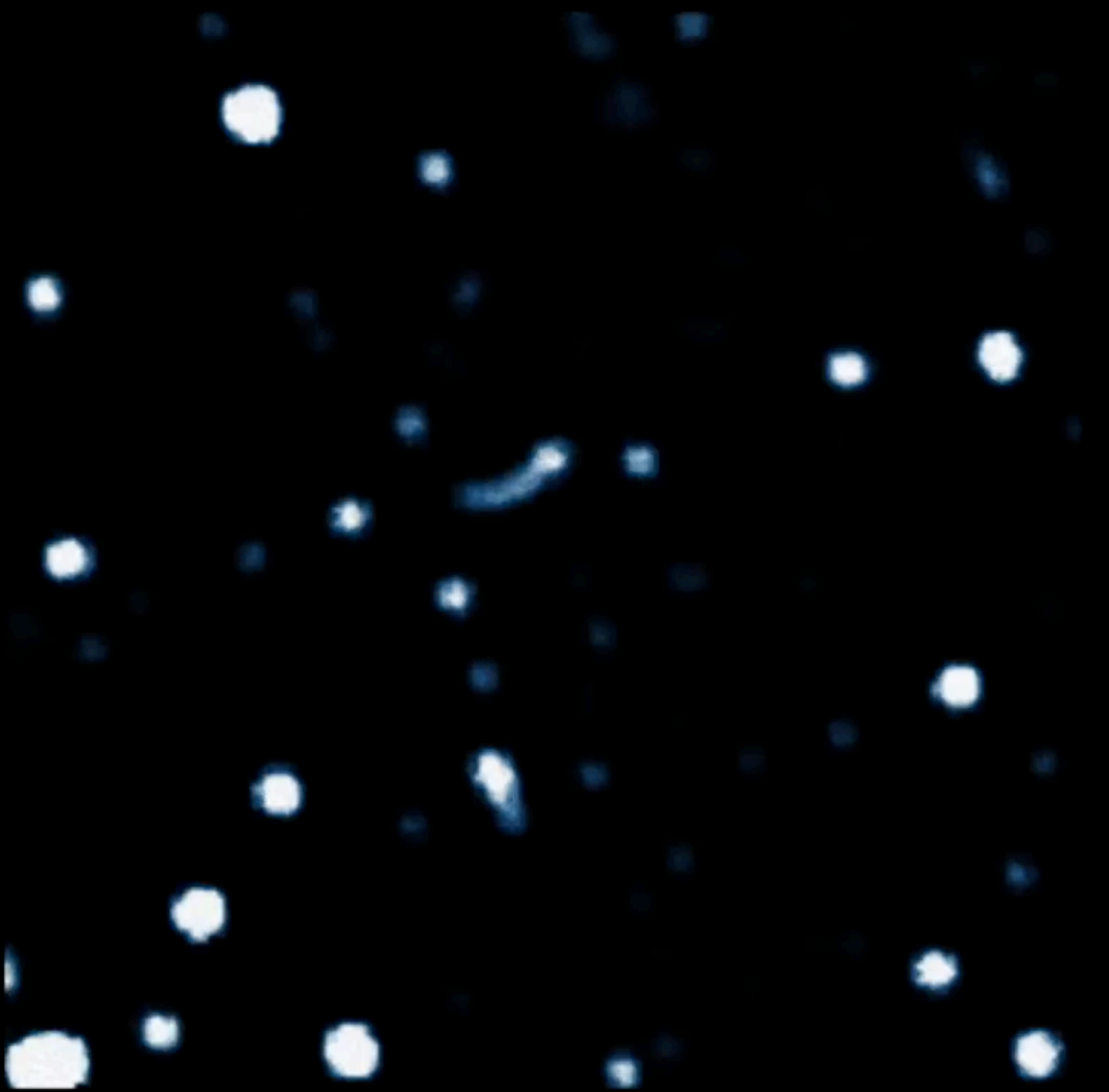
Black hole at center of our galaxy

$M/M_{\rm sun} \approx 4 \times 10^6$

$\chi \approx 0$ —Broderick *et al.* (2010)

20-year time lapse

ESO very large telescope



Movie courtesy ESO…2 weeks ago

If a planet is in a circular orbit of a 1 Solar Mass black hole, with the same radius as Earth's orbit around the sun, it will...

A Orbit once each Earth year, the same as Earth.

B Orbit much faster than Earth, circling many times in each Earth year.

C Orbit much slower than Earth, taking many Earth years to complete one cycle

D Quickly fall into the black hole

Clicker question 3.2

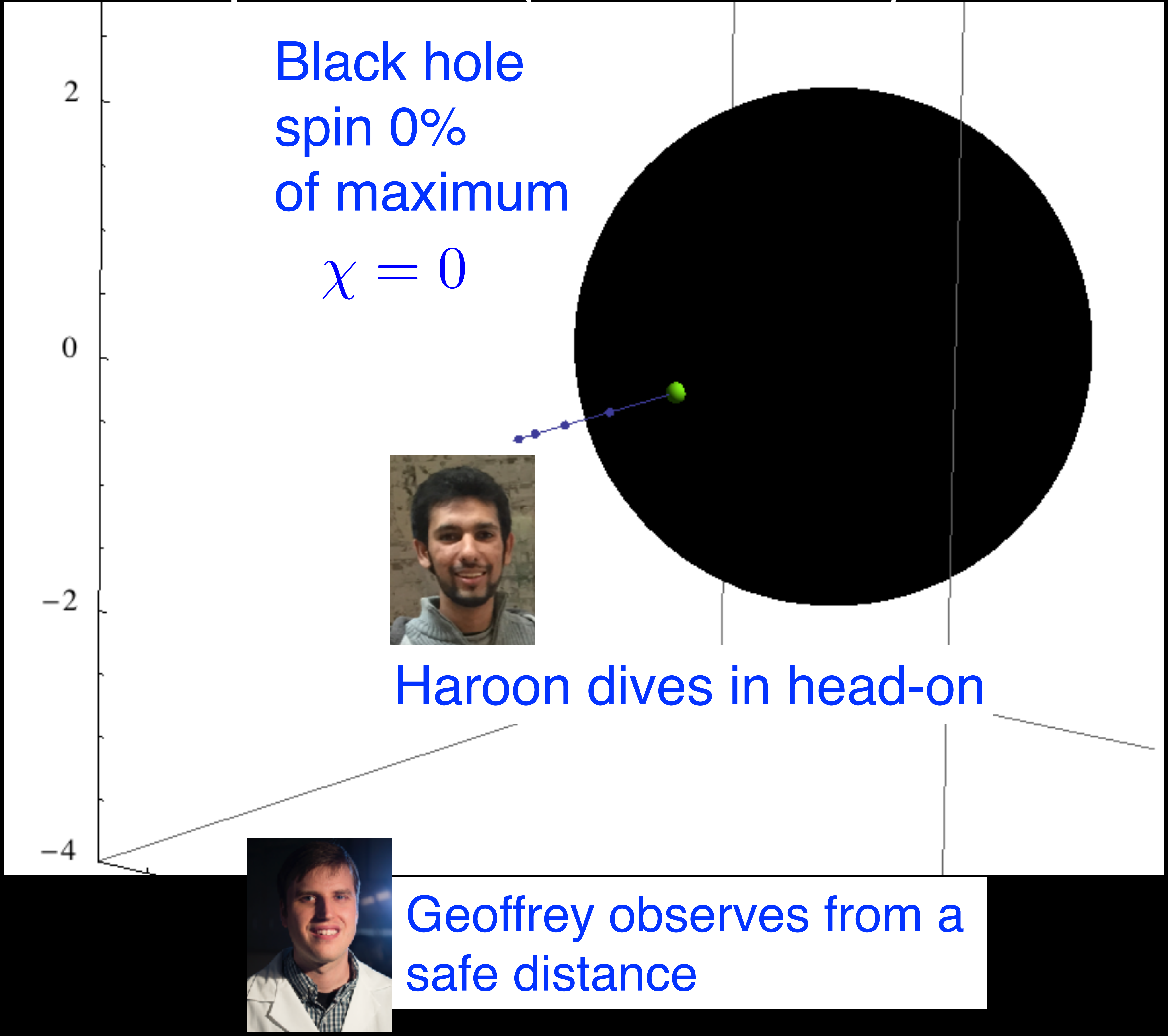
If the Sun was suddenly replaced with a black hole of the same mass, what would happen to Earth?

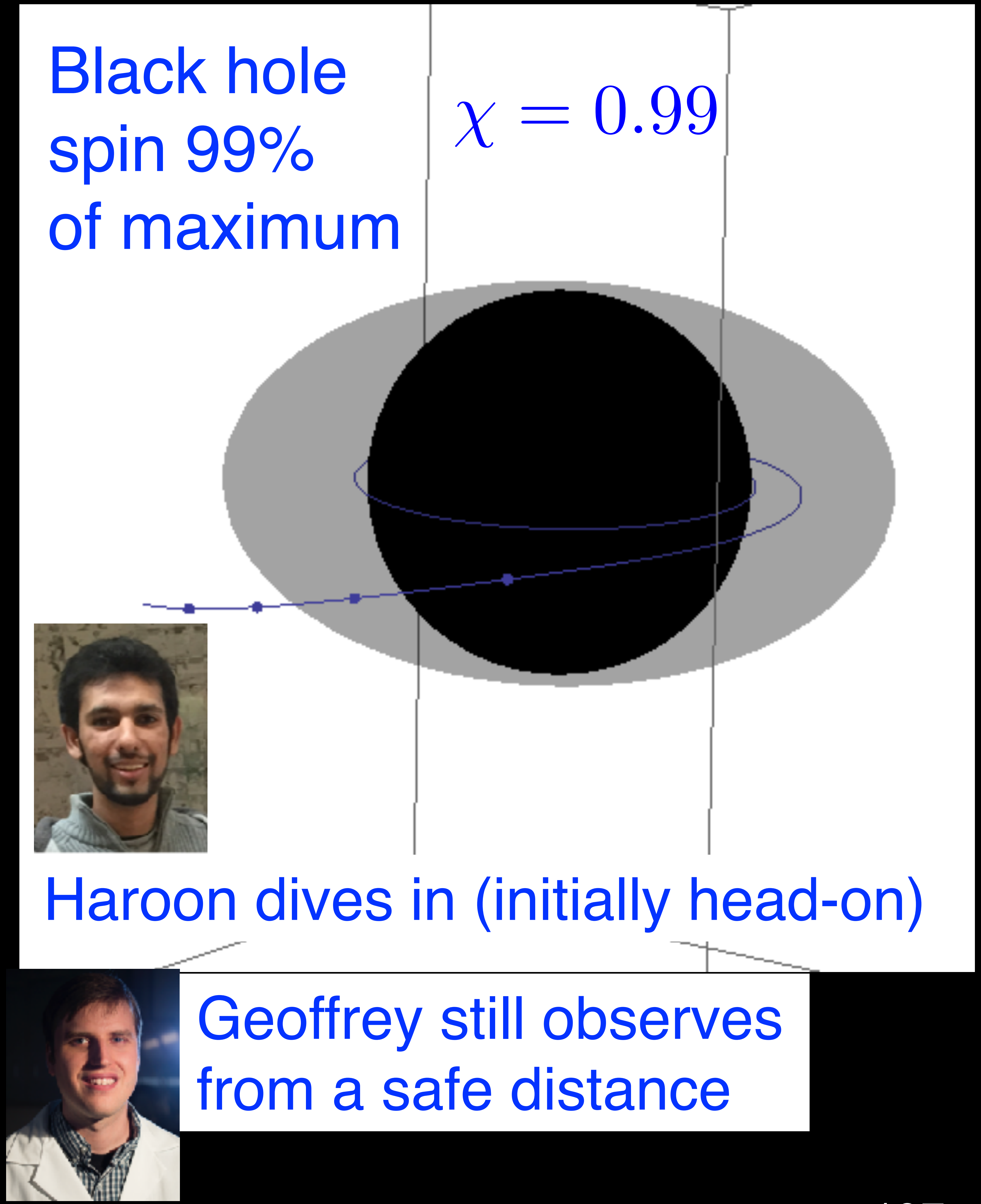
- A It would be ejected from the solar system
- B It would continue in its orbit exactly as before
- C It would spiral into the black hole
- D It would continue to orbit, but the orbit would be much smaller

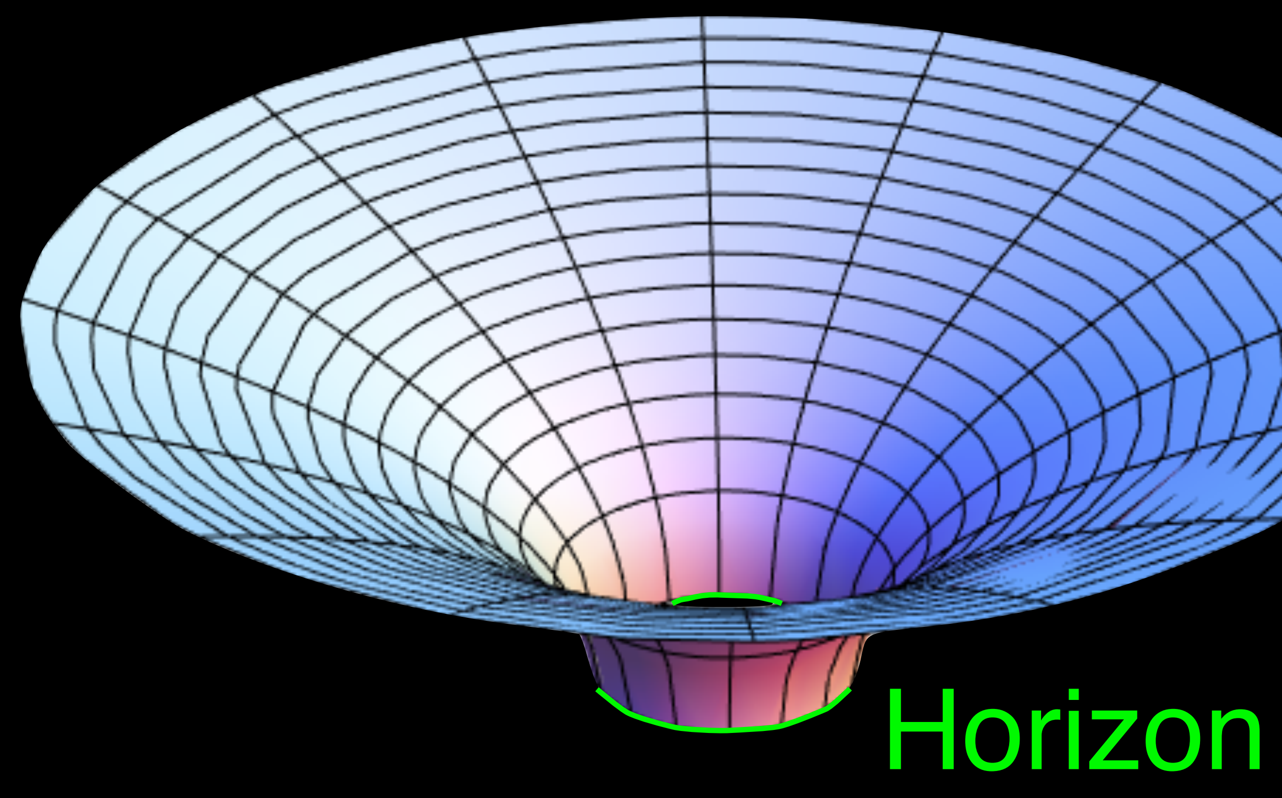
Clicker question 3.3

Black holes rotate and warp time

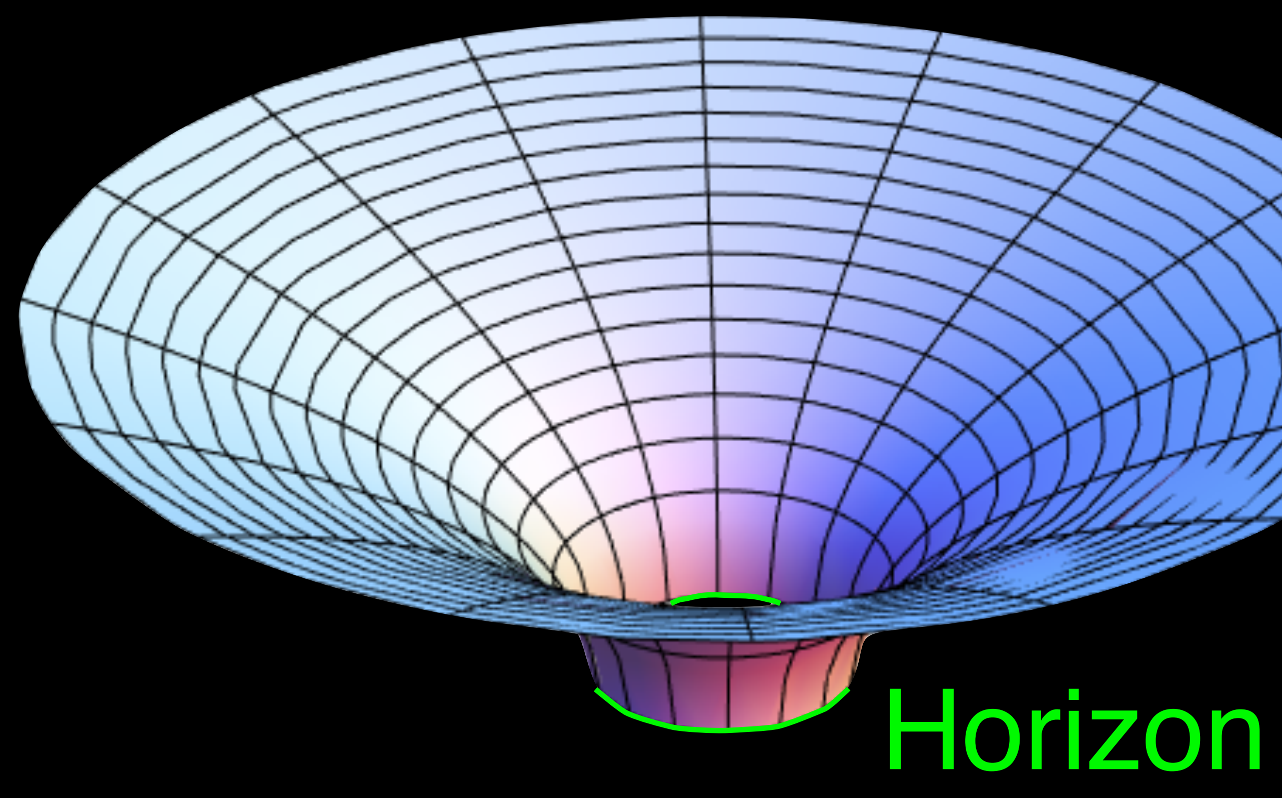
- An experiment (not to scale)






Horizon

+


Horizon

= ?

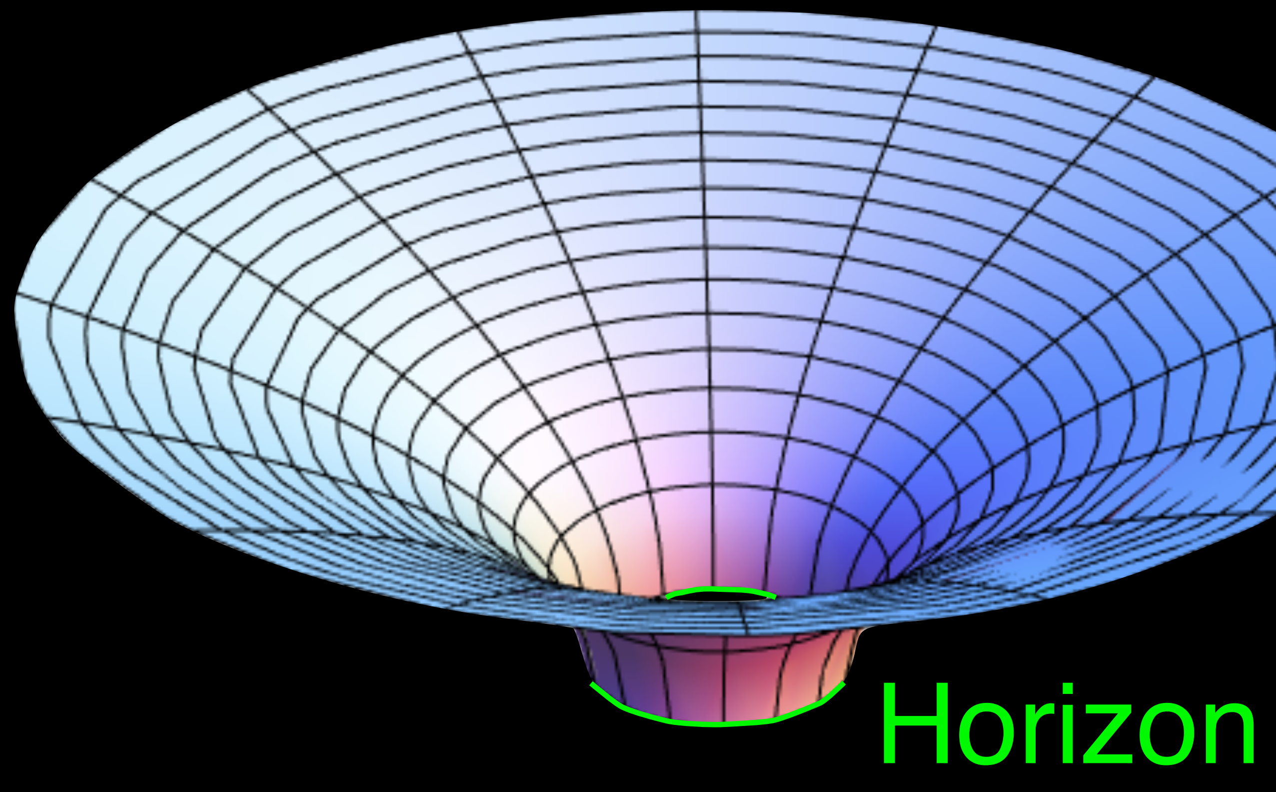
Linear and nonlinear physics

- Linear
  - Whole is sum of parts
  - Example: sound in this room
  - Total sound = sum of individual sounds
- Nonlinear
  - Whole is more than sum of parts
  - Example: water + wind
  - Example: two black holes
  - Need supercomputers

Single black hole

Colliding black holes

Images courtesy Kip Thorne



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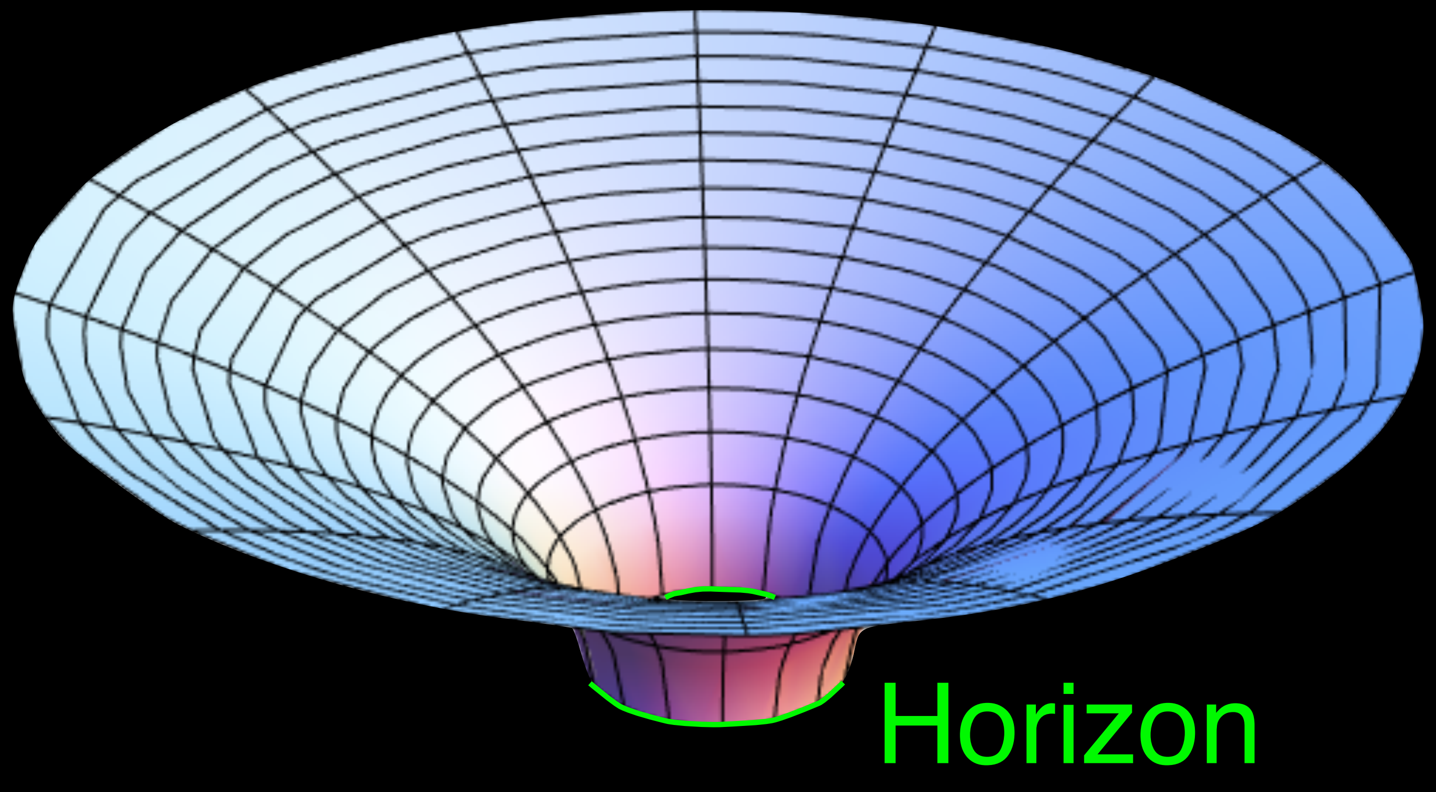

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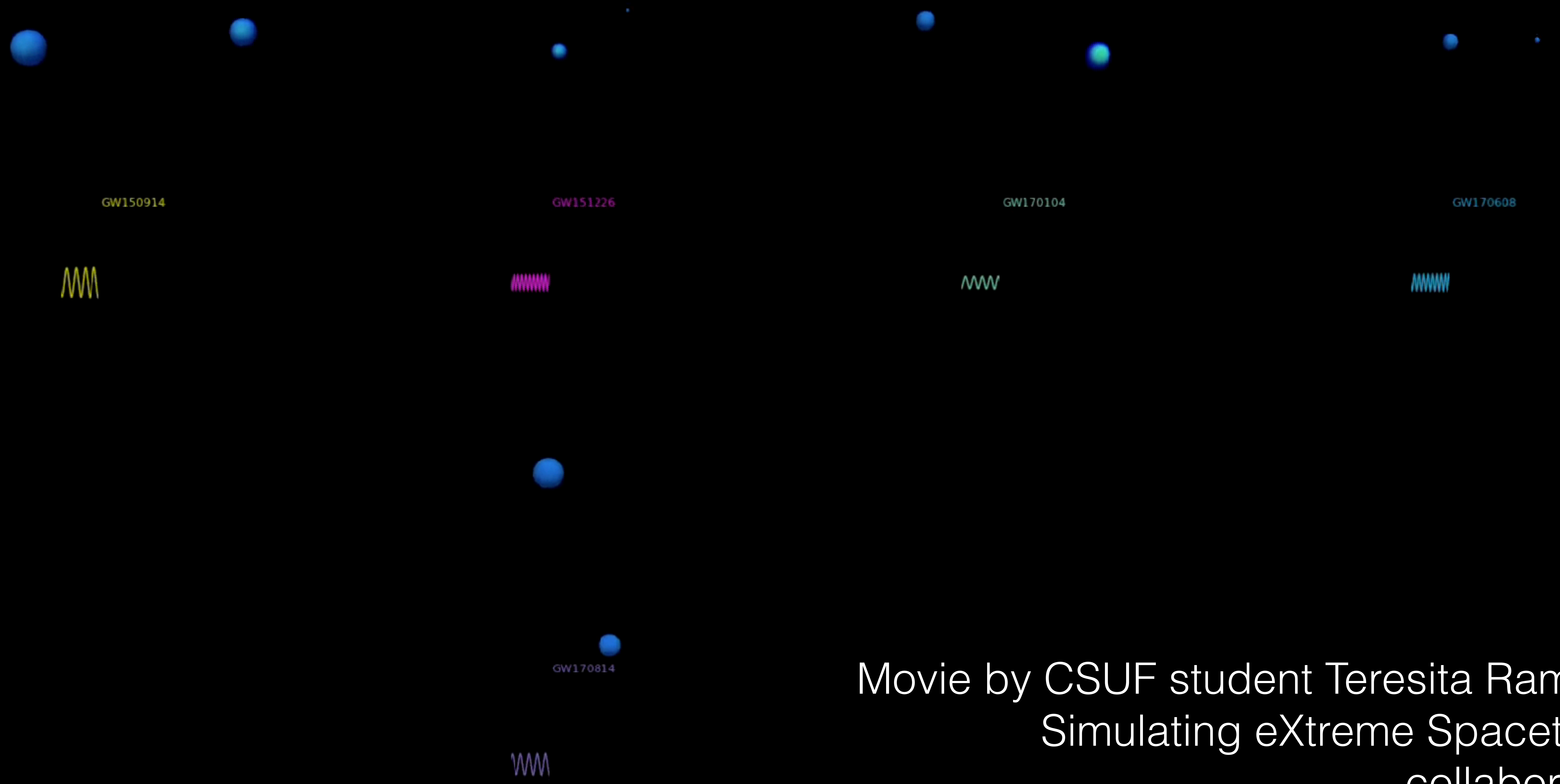
Merging black holes & gravitational waves

Colliding binary black holes that led to gravitational-wave signals detected during the 1st and 2nd Advanced LIGO and Advanced Virgo observing runs

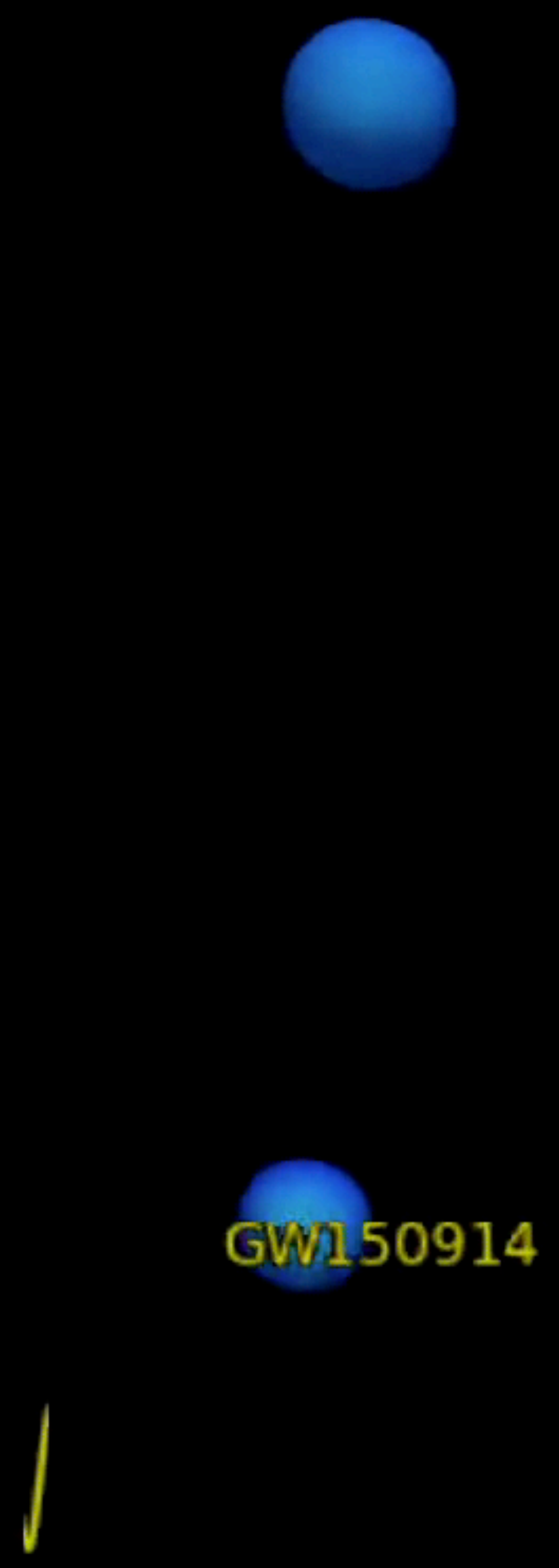
Time: -0.51 seconds



Movie by CSUF student Teresita Ramirez, Simulating eXtreme Spacetimes collaboration

Colliding binary black holes that led to gravitational-wave signals detected during the 1st and 2nd Advanced LIGO and Advanced Virgo observing runs

Time: -0.67 seconds



Supercomputer simulations of colliding black holes

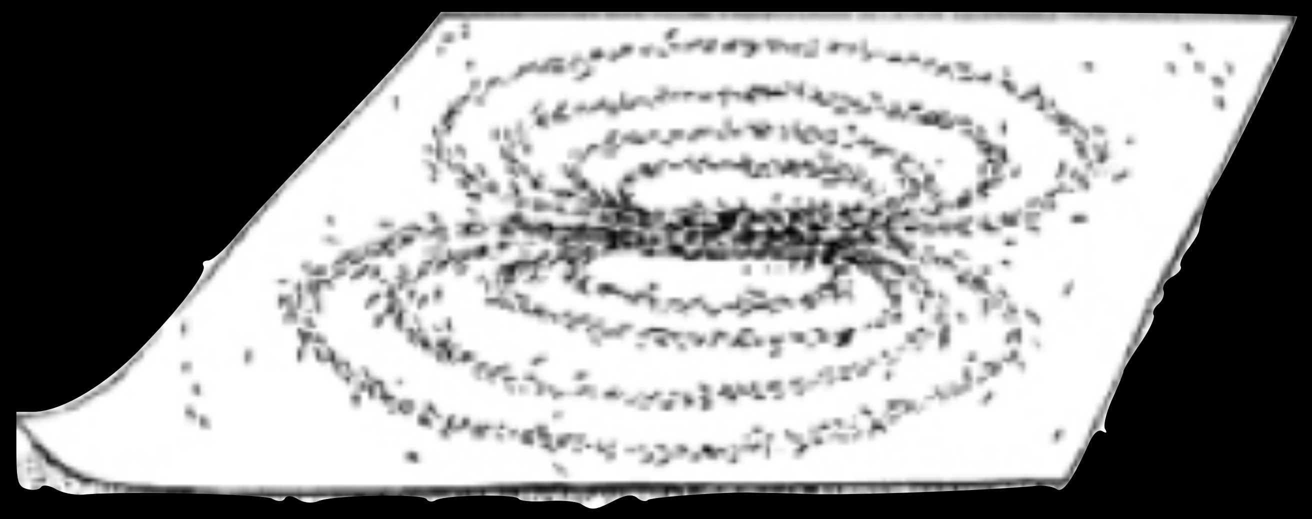
– Goal: solve Einstein's equations for warped spacetime

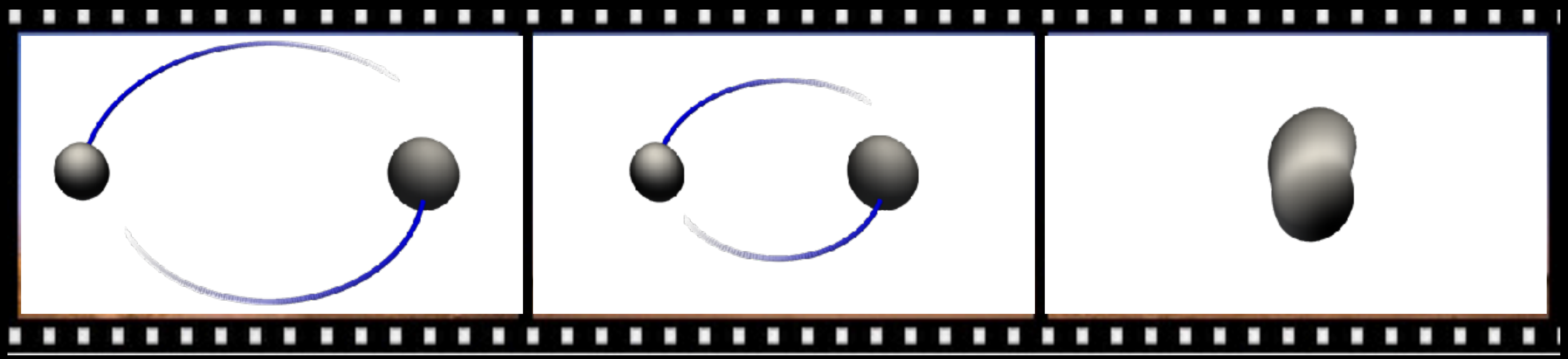
– Strategy

- 1. Solve Einstein's constraint equations for first frame
- 2. Solve Einstein's evolution equations for next frame
- 3. Go back to step 2

Example constraint:

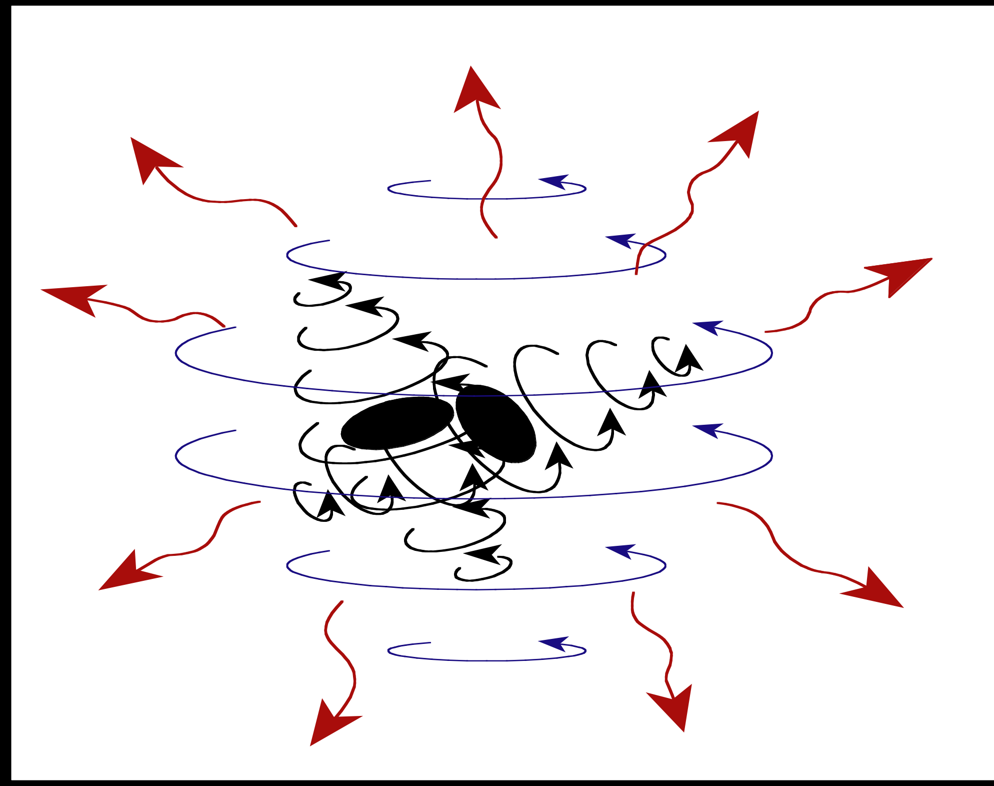
magnetic field lines are loops with no ends





Images courtesy Kip Thorne

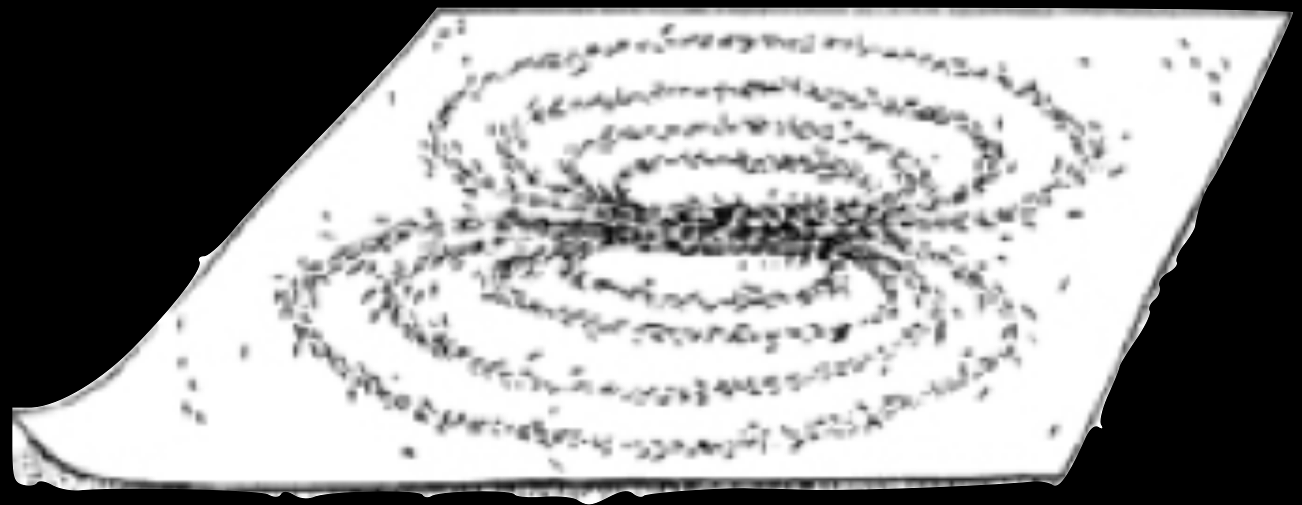
Challenges



- –Einstein equations hard to solve
  - Nonlinear: sum of solutions *not* a solution
  - Singularities
  - Keep constraint equations satisfied
    - –Must write the equations in just the right way
    - –Must treat the boundaries in just the right way
  - Computationally expensive
- –Many different binaries (different masses & spins): need many different simulations!

Example constraint:

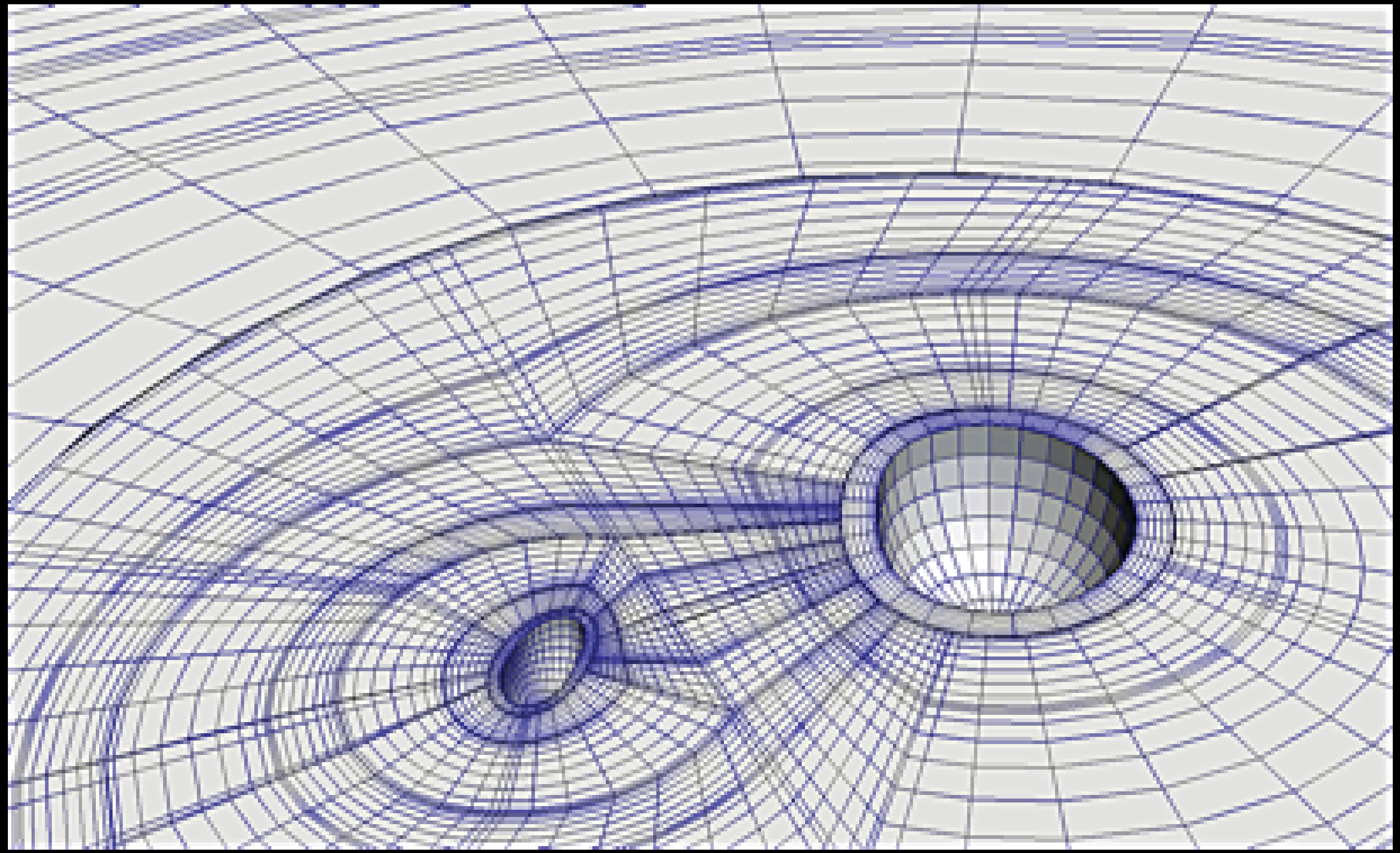
magnetic field lines are loops with no ends



Images courtesy Kip Thorne

Supercomputer simulations of colliding black holes

- Spectral Einstein Code (SpEC)
  black-holes.org/SpEC.html
  - Developed by the Simulating eXtreme Spacetimes collaboration
- And many other groups, codes, following Pretorius (2005)



CALIFORNIA INSTITUTE OF TECHNOLOGY 1891

CALIFORNIA STATE UNIVERSITY FULLERTON

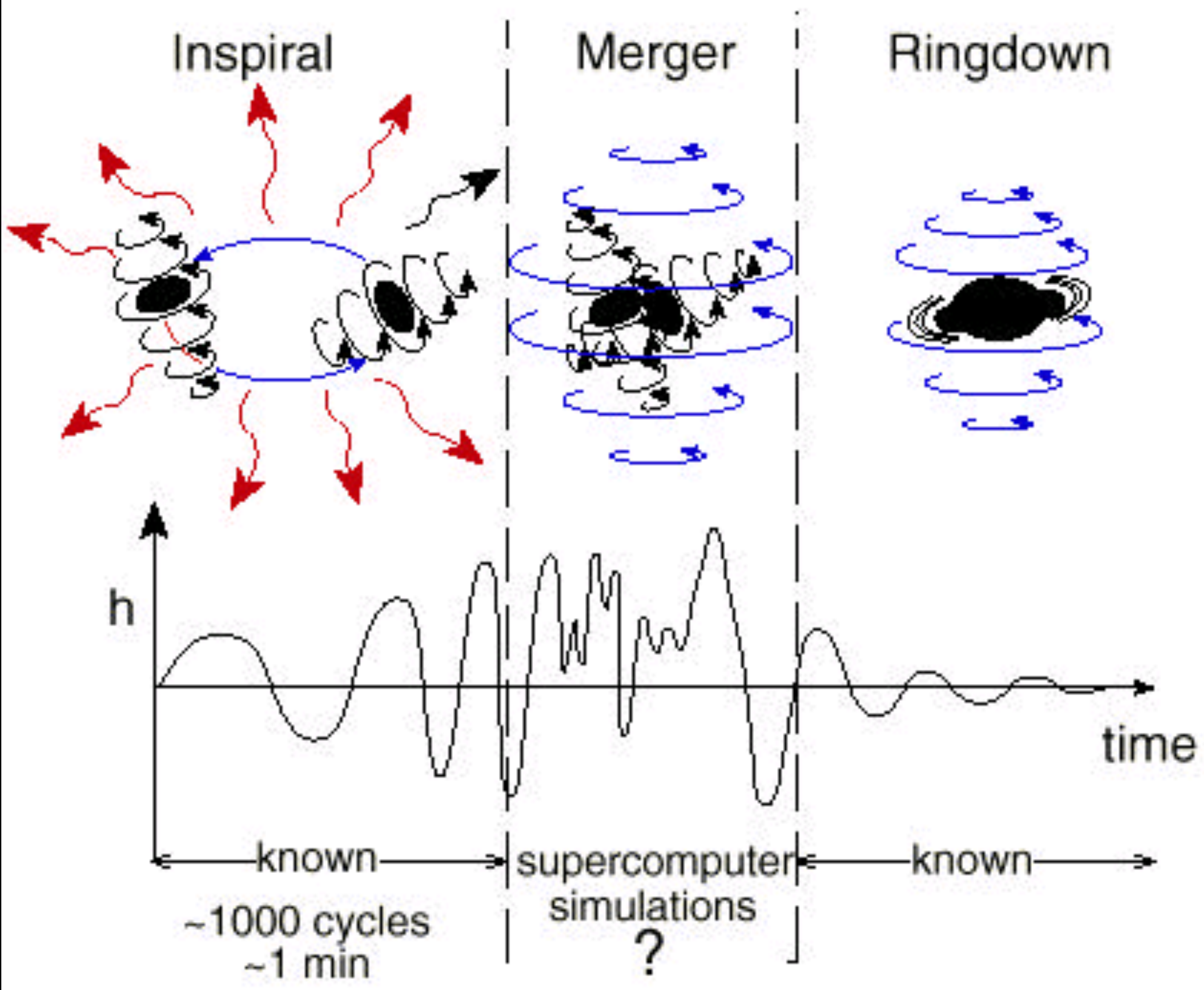
CITA–ICAT

CORNELL UNIVERSITY FOUNDED A.D. 1865

Max-Planck-Institut für Gravitationsphysik (Albert-Einstein-Institut)

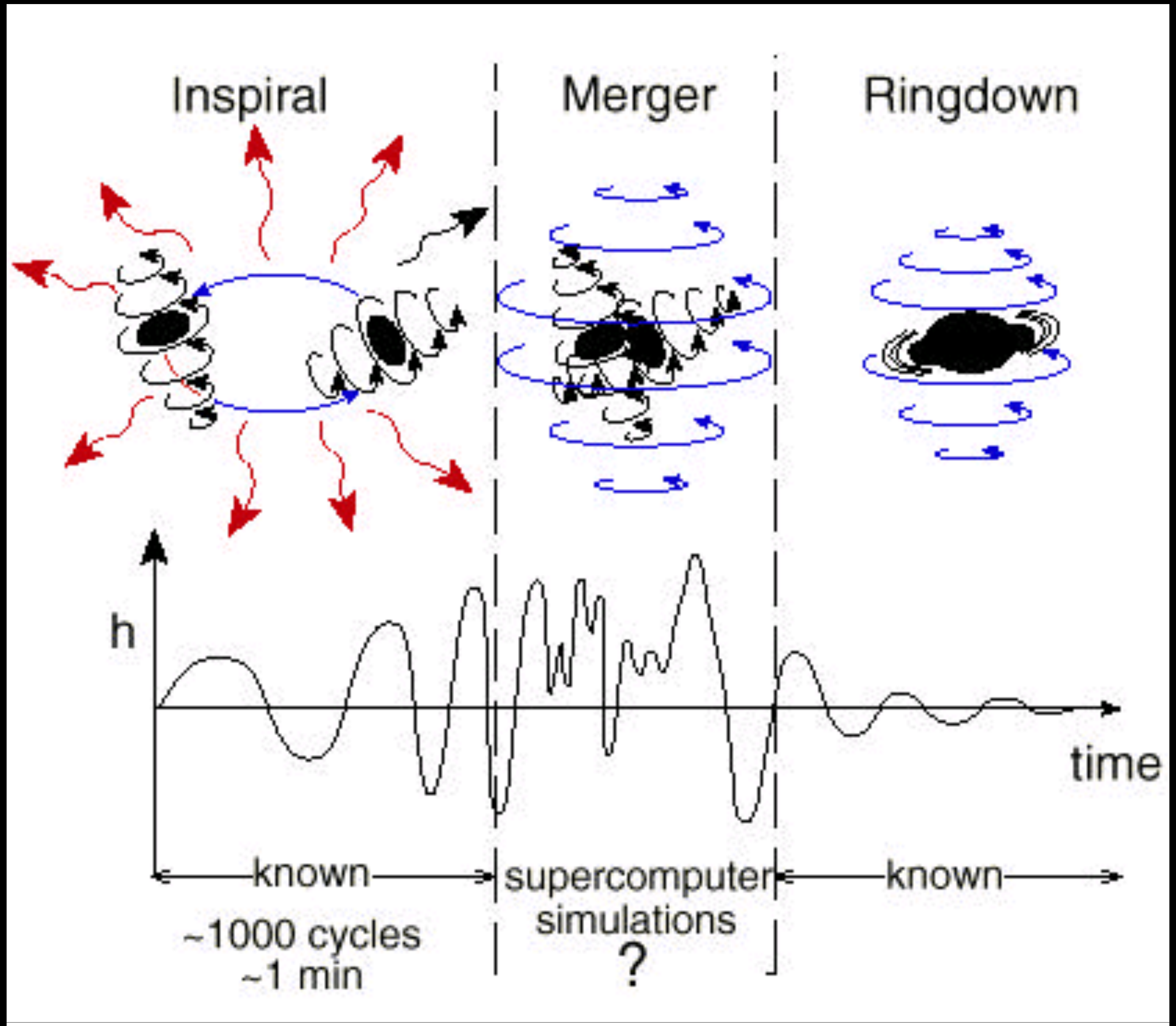
SXS

Images courtesy Evan Foley, SXS Collaboration



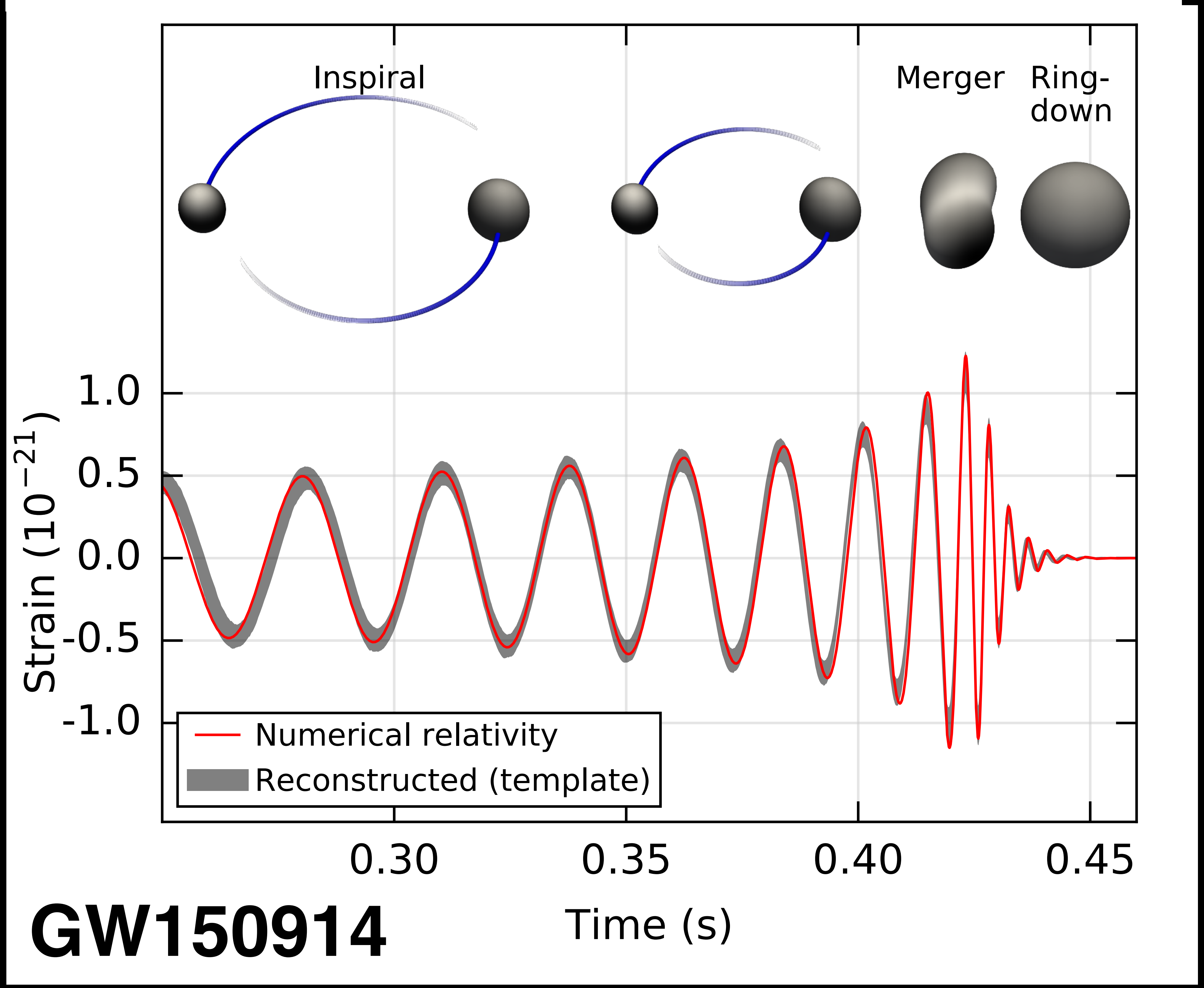
KS Thorne, "Spacetime warps and the quantum world: speculations about the future", in RH Price, ed, *The Future of Spacetime* (WW Norton, NY, 2002)

"I have bet these numerical relativists that gravitational waves will be detected from black-hole collisions before their computations are sophisticated enough to simulate them. I expect to win, but hope to lose, because the simulation results are crucial to interpreting the observed waves." —Kip Thorne



KS Thorne, "Spacetime warps and the quantum world: speculations about the future", in RH Price, ed, *The Future of Spacetime* (WW Norton, NY, 2002)

Abbott+, PRL **116**, 061102 (2016)



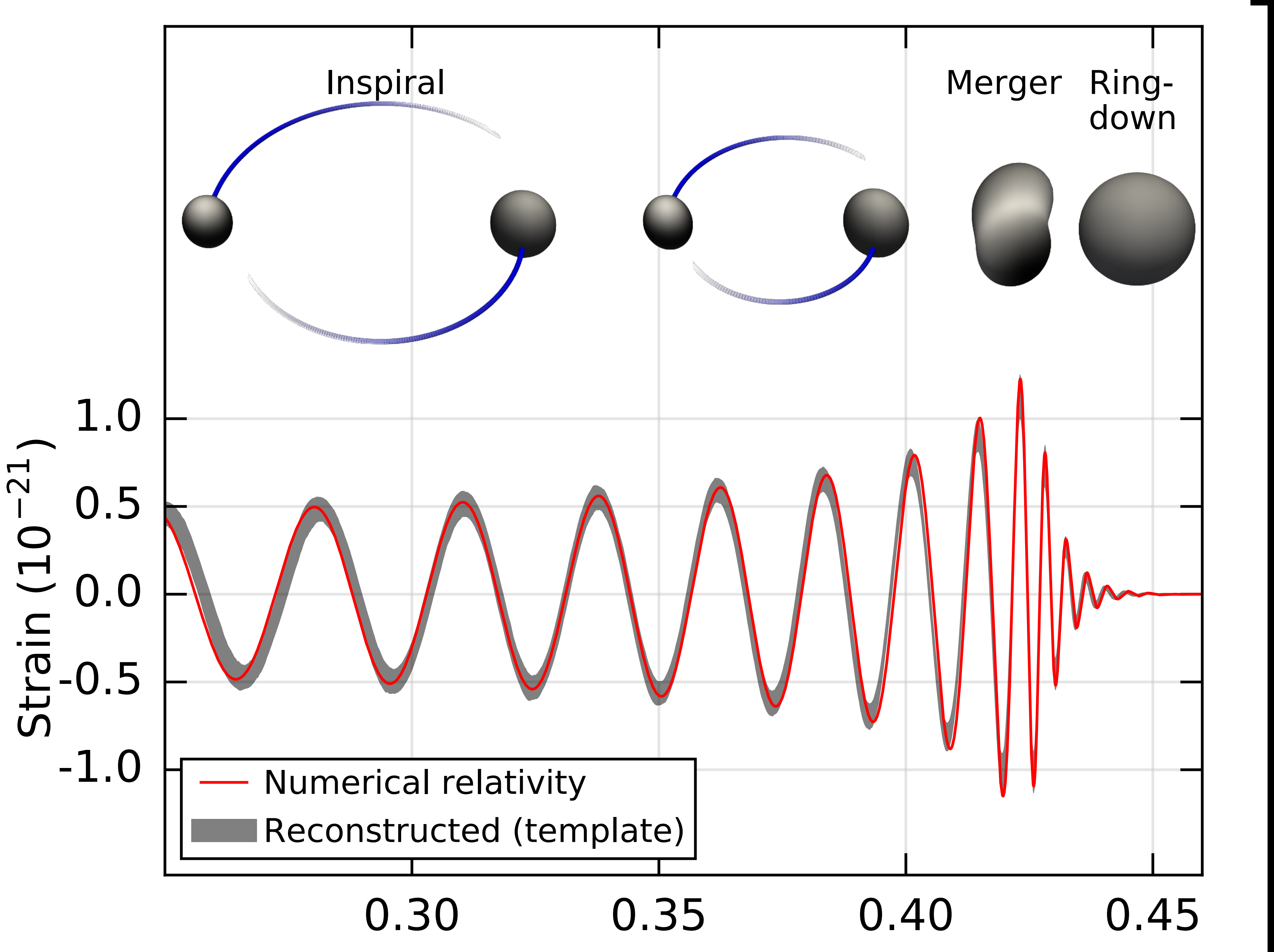
Warped spacetime dynamics

Abbott+, PRL **116**, 061102 (2016)

Horizons shaded by their curvature
Orbits as black holes spiral together

Waveform prediction

Calibrate, validate analytic templates used in template reconstruction



GW150914

Fullerton's role

Students, GL: perform the supercomputer calculations

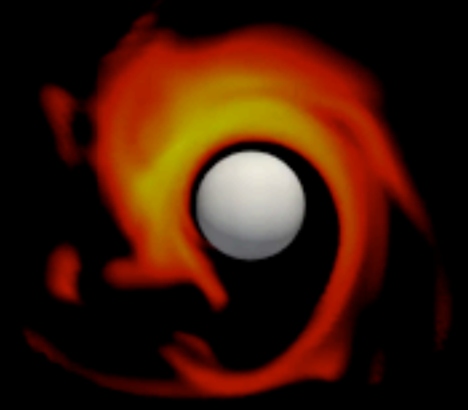
Solve Einstein's equations for merging black holes + gravitational waves
Create movies visualizing this computation

Josh Smith, Jocelyn Read, GL: design, create the figure

Clicker question #3.4

- Jennifer Sanchez (CSUF undergraduate) used numerical relativity to model a neutron star being torn apart by a black hole.

To make the data for this movie, the SpEC code solved…



Time: 8365.000000

A the Einstein evolution equations once

B the Einstein evolution equations many times

C the Einstein constraint equations many times

D None of ABC

Explore data for numerical relativity simulation of merging black holes

- Orbit
- Mass vs. time
- Strength of gravitational waves
- Resolution vs. "accuracy" and speed
- Load this github page in colab.research.google.com
  - https://github.com/geoffrey4444/NRDataExample.git

Gravitational-Wave Concepts

Jocelyn Read

Play with gravitational waves in Python

Jocelyn Read

Play with gravitational waves in Python

- Go to colab.research.google.com
- Load the GitHub repo https://github.com/gwastro/PyCBC-Tutorials
- Load tutorial/3_WaveformMatchedFilter.ipynb
- We'll run through this notebook together

Play with gravitational waves in Python

- Save an audio file of your model waveform, open in audacity

- Try changing the masses to 5, or the spins to 0.99

```
from scipy.io import wavfile
import numpy as np

hp, hc = get_td_waveform(approximant="SEOBNRv4_opt",
                         mass1=10,
                         spin1z=0,
                         mass2=10,
                         spin2z=0,
                         delta_t=1.0/4096,
                         f_lower=30.0)

fileName = 'BBH_5_5_0_0.wav'
wavfile.write(fileName, 4096.0, np.array(hp)/max(hp))
from google.colab import files
files.download(fileName)
```

Clicker question #3.5

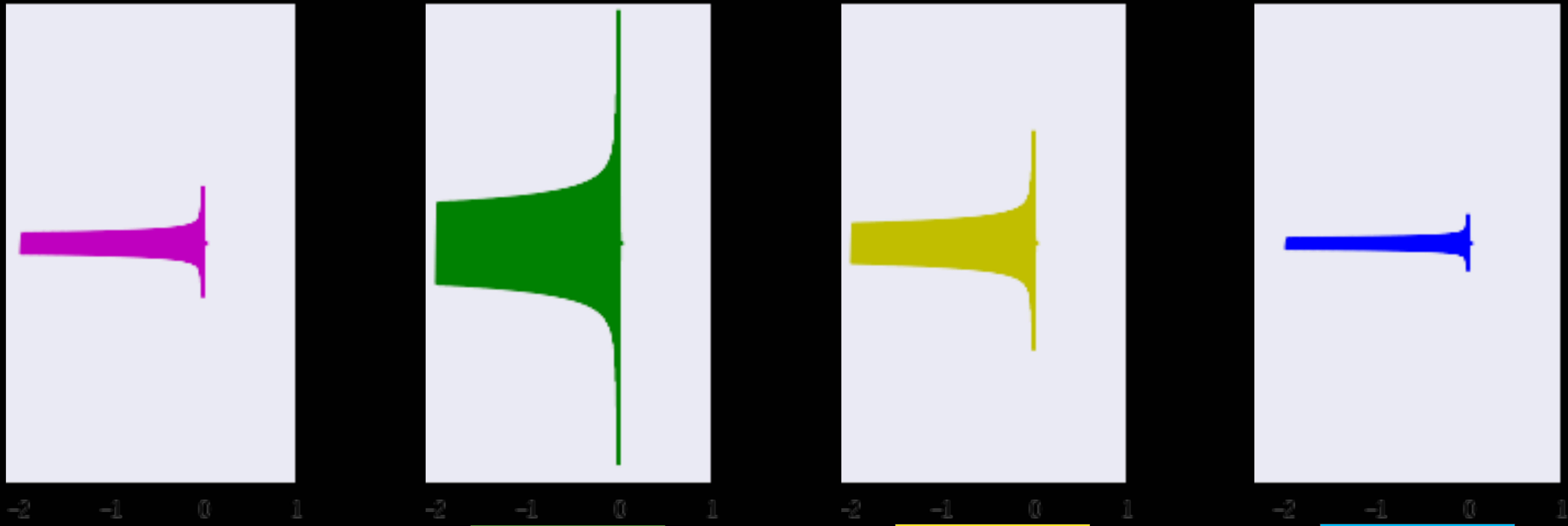
- A gravitational-wave detector detects 4 waves. Each wave starts at the same frequency. Which one came from black holes with the largest total mass?

Clicker question #3.6

- A gravitational-wave detector detects 4 waves. Each wave starts at the same frequency. Which one came from black holes with the **smallest total mass?**

Clicker question #3.7

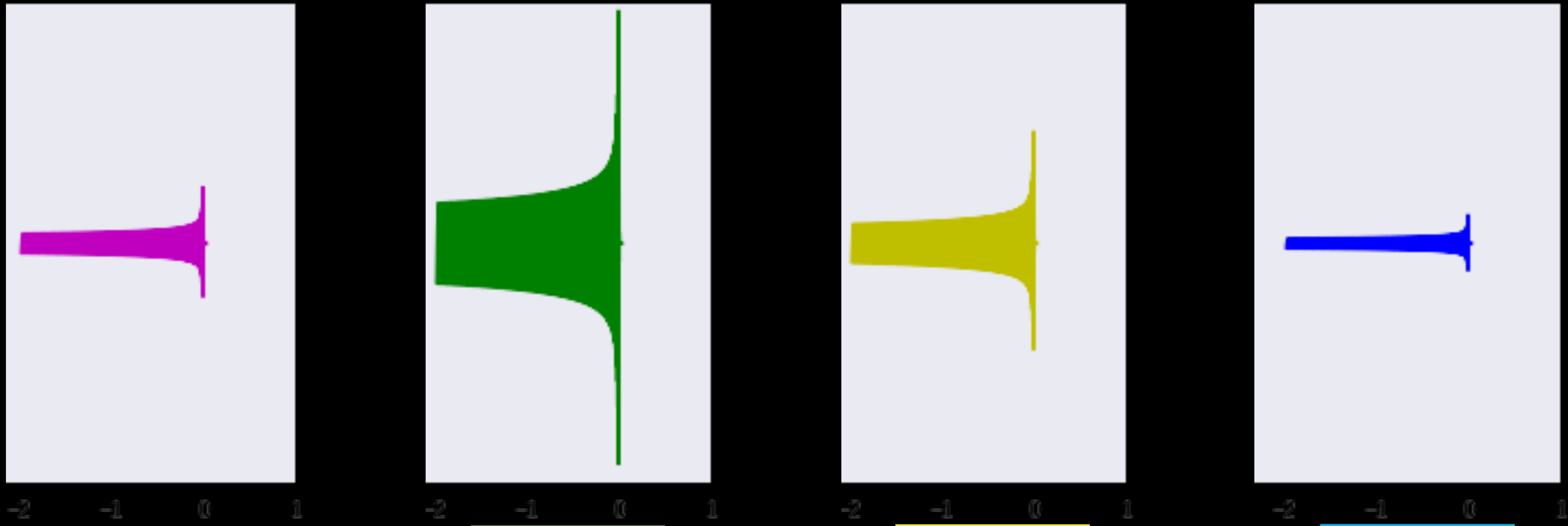
- A gravitational-wave detector detects 4 waves. Each wave came from binary black holes that are identical except for how far away they are. Which wave's source was **closest** to the detector?



A B C D

Clicker question #3.8

- A gravitational-wave detector detects 4 waves. Each wave came from binary black holes that are identical except for how far away they are. Which wave's source was **farthest** from the detector?



A B C D

Simulations help LIGO observe more waves

- Compare LIGO observations to predictions of relativity
- Help LIGO observe more waves
  - We help LIGO know what the waves will “sound like”
  - Like hearing your name in a crowded room

Simulations help LIGO observe more waves

- Compare LIGO observations to predictions of relativity
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  - We help LIGO know what the waves will “sound like”
  - Like hearing your name in a crowded room

Day 4

- Invited speakers: cutting-edge gravitational-wave science research
- Student researchers present
- Data center tour

Unix terminal on the web

- Go to https://mybinder.org/v2/gh/geoffrey4444/NRDataExample/master
- Choose "New Terminal"

Parallel computing

- Supercomputers have lots of cores
- But each core is not much faster than a PC
- To take full advantage, you have to write code that can run on more than one core at the same time
    - That is, code that runs in parallel

Image courtesy Blue Waters

Parallel computing 1

- Log into orca
- Do this

```
#Replace GeoffreyLovelace with YourName
cd GeoffreyLovelace

mkdir PiDart
cd PiDart
source /share/apps/python/2.7.15/bin/activate #set up python
```

Parallel computing 2

- Log into binder: mybinder.org, load geoffrey4444/NRDataExample
- nano Hello.py

```
print(“Hello")
```

- mpirun -np 8 python Hello.py
  - **What happens? What happens if you change 8 to another number less than 8?**

What happened?

- mpirun ran many copies of “Hello.py”
- Each copy printed “Hello”
    - But the processors are not working together yet, or even doing anything different
- Next: make different processors do different things

Parallel computing 3

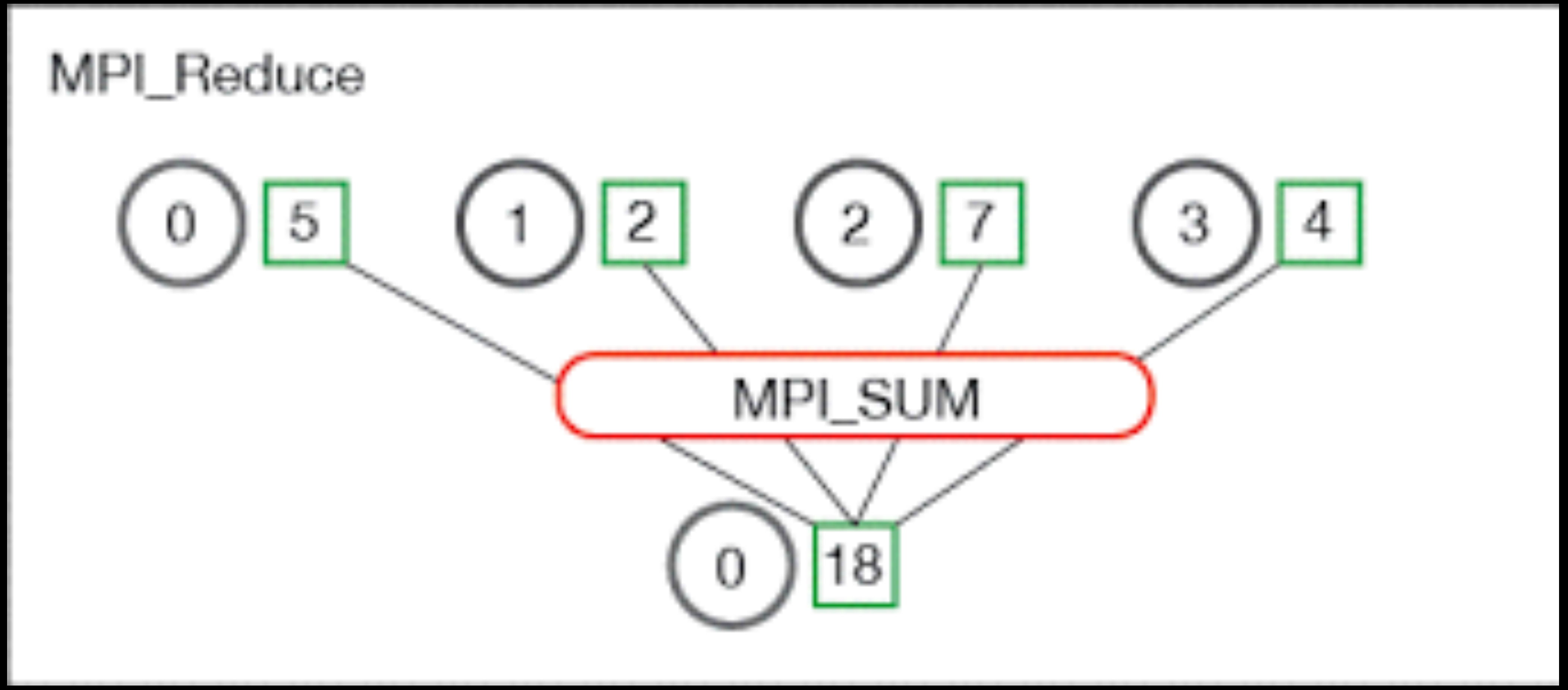
- `cp Hello.py MpiHello.py`
- `nano MpiHello.py`

```python
from mpi4py import MPI
comm = MPI.COMM_WORLD
rank = comm.Get_rank()
size = comm.Get_size()
print("Hello from processor "+str(rank)+" out of "+str(size))
```

- `mpirun -np 4 python MpiHello.py`
- `mpirun -np 8 python MpiHello.py`

Paralleizing the dartboard

- **What if we combined results from the whole class's π dartboard?**
- **Even batter**
  - Run lots of copies of the dartboard on lots of cores
  - At the end, each copy tells the others how many hits it had
  - Each copy adds up the number of hits on all processors and computes pi



Parallelizing the dartboard 2

- cp /home/workshopStudent2018/SharedStuff/Tuesday/piEstimate.py .
- nano piEstimate.py
- #Add the same mpi4py lines at the top

```python
from mpi4py import MPI
comm = MPI.COMM_WORLD
rank = comm.Get_rank()
size = comm.Get_size()
```

Parallelizing the dartboard 3

- nano piEstimate.py
- #At the bottom, instead of getting pi, print the number of hits on each processor

```
print(str(hits)+" hits on processor "+str(rank)+" out of "+str(throws)+" throws.")
```

- mpirun -np 12 python piEstimate.py
  - What happens?

Parallelizing the dartboard 4

- nano piEstimate.py
- #Divide the darts to throw among the processors, instead of each processor throwing the total

```python
hits = 0
throws = 1e7 // size
i = 0
while i < throws:
# … rest of program
```

- mpirun -np 12 python piEstimate.py
  - What happens?

Parallelizing the dartboard 5

- nano piEstimate.py
- #Have on processor add up the totals across all processors

```
print(str(hits)+" hits on processor "+str(rank)+" out of "+str(throws)+" throws.”)
```

```
throwsAllProcessors = throws * size
hitsAllProcessors = comm.allreduce(hits, op=MPI.SUM)
```

```
if rank == 0:
    print(str(hitsAllProcessors)+" hits on all processors, with "+str(throwsAllProcessors)+" throws.")
```

-

Parallelizing the dartboard 6

- nano piEstimate.py
- #Compute pi

```
if rank == 0:
    print(str(hitsAllProcessors)+" hits on all processors, with "+str(throwsAllProcessors)+" throws.”)

    pi = 4.0 * float(hitsAllProcessors) / float(throwsAllProcessors)
    print(pi)
```

-

Parallelizing the dartboard 7

- nano piEstimate.py
- How long does it take?
- At top:

```python
import time
start = time.time()
```

- At bottom

```python
print(pi)
end = time.time()
print("Run in "+str(end-start)+" seconds.")
```

-

How many darts can we run on the entire cluster?

- 1e7 on on core
- About 500 cores
- So in the same time, we should be able to run 500e7 = 5e9

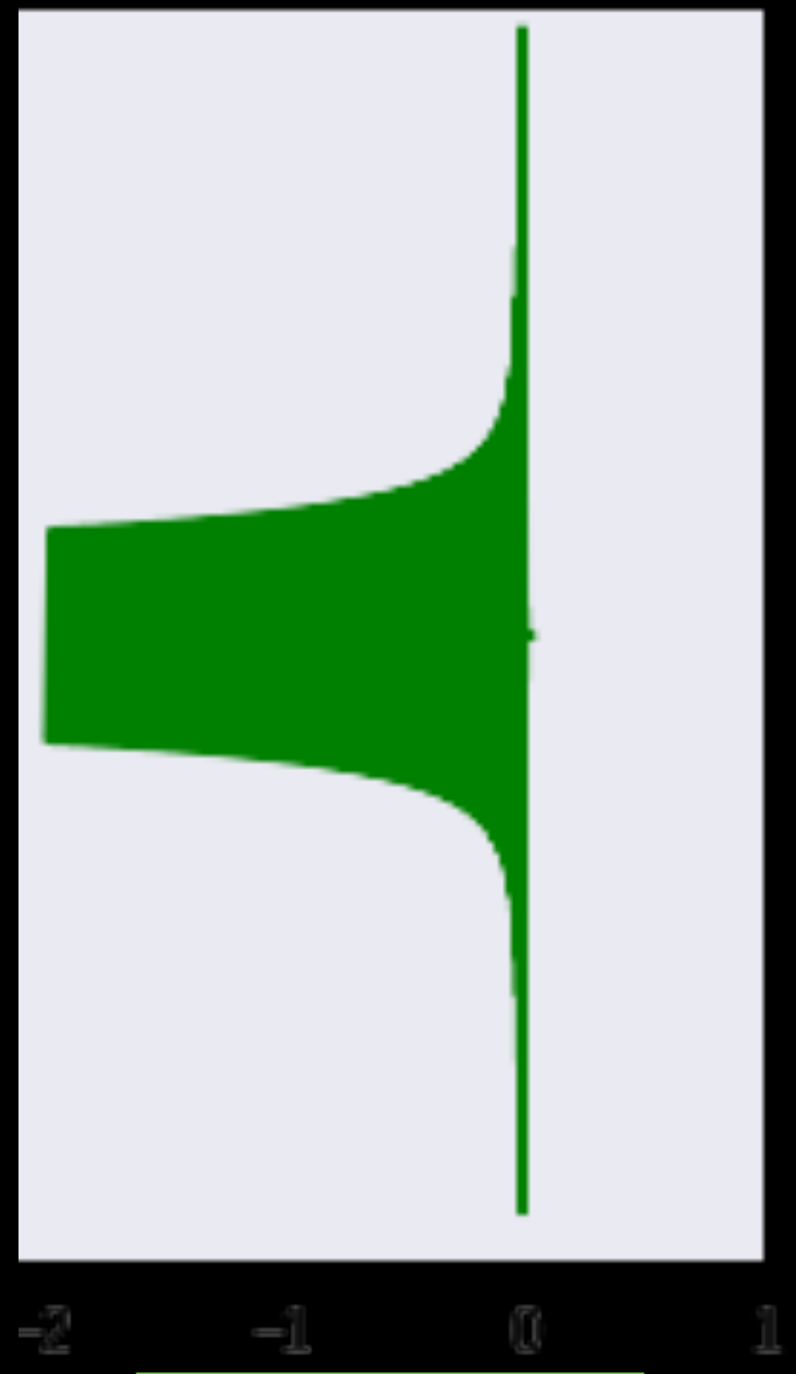
Clicker question #3.6

- A gravitational-wave detector detects 4 waves. Each wave starts at the same frequency. Which one came from black holes with the **smallest total mass?**

Clicker question #3.7

- A gravitational-wave detector detects 4 waves. Each wave came from binary black holes that are identical except for how far away they are. Which wave's source was **closest** to the detector?

A



B

C

D

Day 5

- ParaView visualizations: movies and stills from their simulations
- Research experience panel
- Transfer to 4-year, CSUF, panel

```
#connect to orca
cd YOURNAME/BlackHoleMerger
ArchiveBbhRuns.py -v --no-cce --contact-
email=geoffrey4444@gmail.com .
cd BBH*/Lev1/
ConvertH5SurfaceToVtk -v -s 2 -dir AhA.dir HorizonsDump.h5
ConvertH5SurfaceToVtk -v -s 2 -dir AhB.dir HorizonsDump.h5
ConvertH5SurfaceToVtk -v -s 10 -l 1500 -dir AhC.dir
HorizonsDump.h5
mkdir Vis
mv Ah* Vis
zip Vis
zip -r Vis.zip Vis
#download to laptop, make movie in ParaView
```

```
#save frames, upload to orca
module load ffmpeg
ffmpeg -framerate 30 -i BeforeMerger.%04d.png  -r 60 -
pix_fmt yuv420p -codec:v libx264 BeforeMerger.mp4
ffmpeg -framerate 30 -i AfterMerger.%04d.png  -r 60 -pix_fmt
yuv420p -codec:v libx264 AfterMerger.mp4
Nano FilesToJoin.txt
# each line should be as follows:
# file 'BeforeMerger.mp4'
# file 'AfterMerger.mp4'
ffmpeg -f concat -i FilesToConvert.txt -c copy 
BeforeAndAfterMerger.mp4
# download 'BeforeAndAfterMerger.mp4'
```

Exit survey

- http://fullerton.qualtrics.com/jfe/form/SV_ehAa6CwHaxMMeJT