Beholding Black Holes & Quickening Grains of Space

How well the skillful gardener drew
Of flow’rs and herbs this dial new;
Where from above the milder sun
Does through a fragrant zodiac run;
And, as it works, th’industrious bee
Computes its time as well as we.
How could such sweet and wholesome hours
Be reckoned but with herbs and flow’rs!

— *Andrew Marvell*

Hibiscus moscheutus
9-11am

Phemeranthus
teretifolius
noon-2pm

Ippomoea spp. 3-5am

Carl Linnaeus

R: Escobaria
vivipara
3-5pm

L: Oenothera
fruticosa
6-8pm

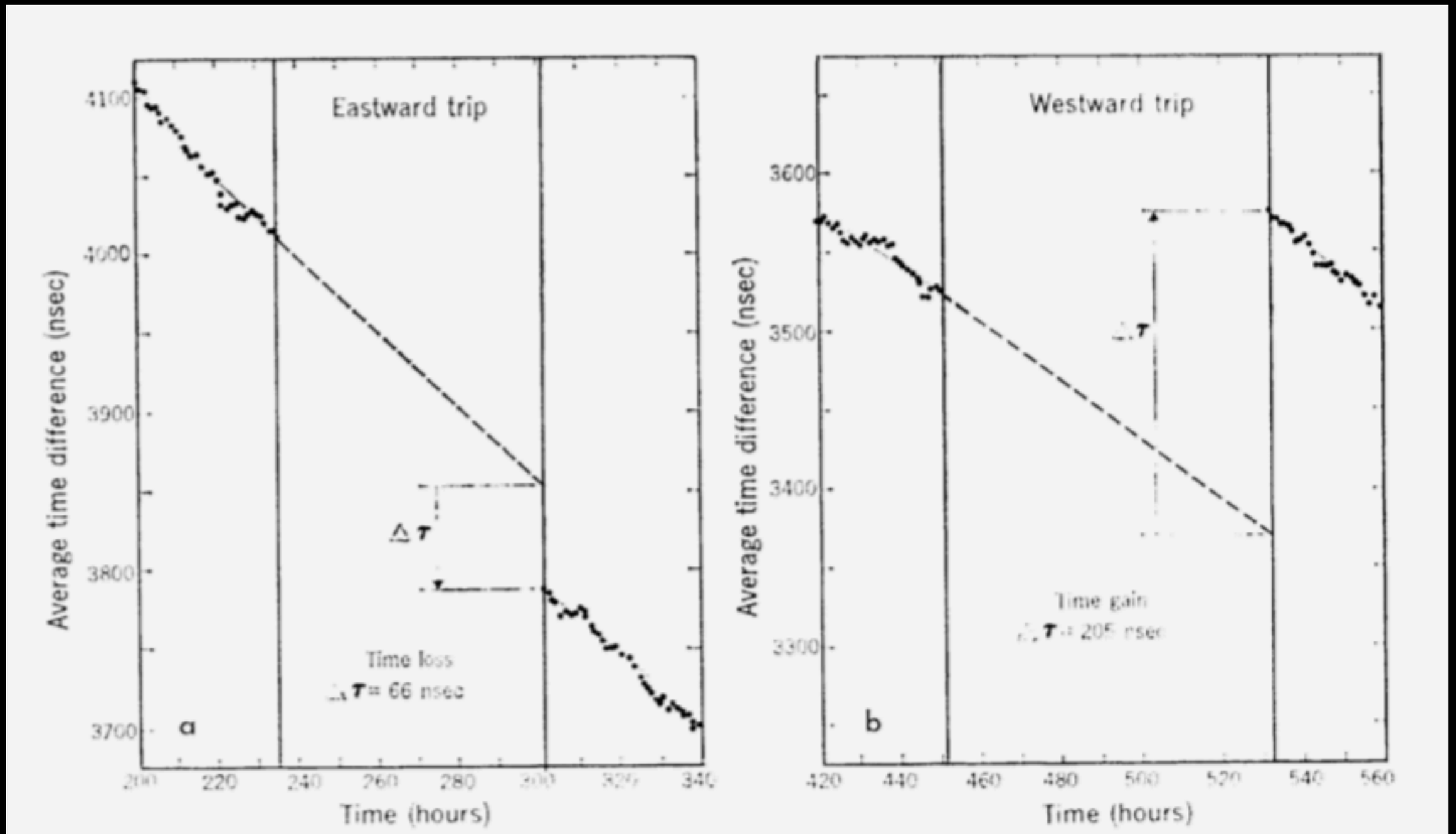
European bindweed (Convolvulus arvensis), for example, may open like the chiming of a clock at 5 a.m. But, Ms. Sifton said: “No gardener wants that weed. It has roots that go down to hell.”

Three Ideas

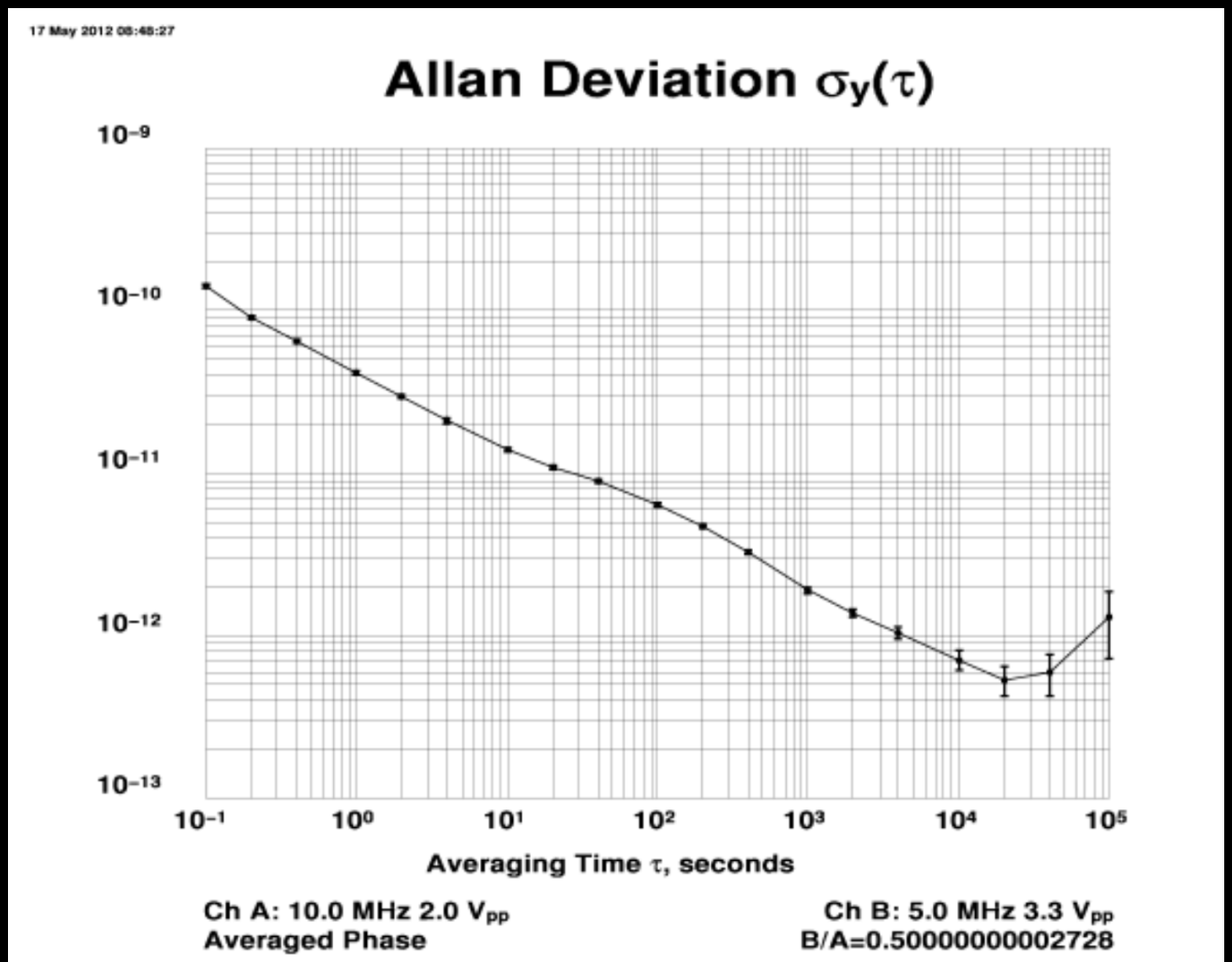
Time Melts: Time is a malleable medium, flowing at different rates depending on your motion & locale.

In 1971 Hafele and Keating flew four atomic clocks around the world.

They found that the traveling clocks disagreed with clocks left on the ground.



I hope in the near future to be able to do these experiments on mountaintops with students.



A Rubidium clock about the size of a quarter.

Three Ideas

Time Melts: Time is a malleable medium, flowing at different rates depending on your motion & locale.

Black Holes Abound: A variety of black holes never seen before have been observed in the last four years.

What is a black hole?

photo courtesy of Thrasher Magazine

Forces are contact forces

$\vec{F}_{BM}$

$\vec{F}_g$

$\vec{F}_g$

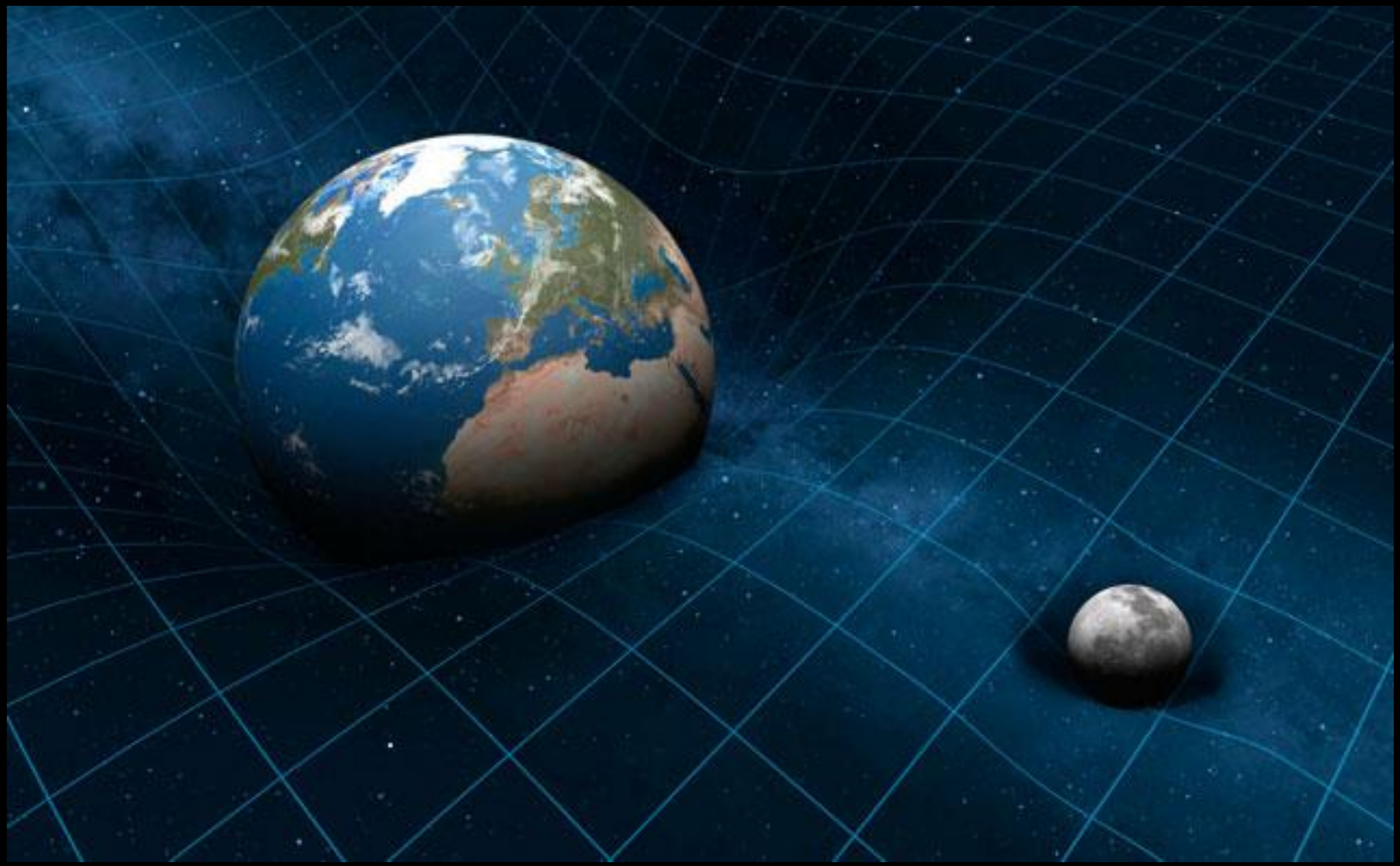
except for the force of gravity (and E & M).

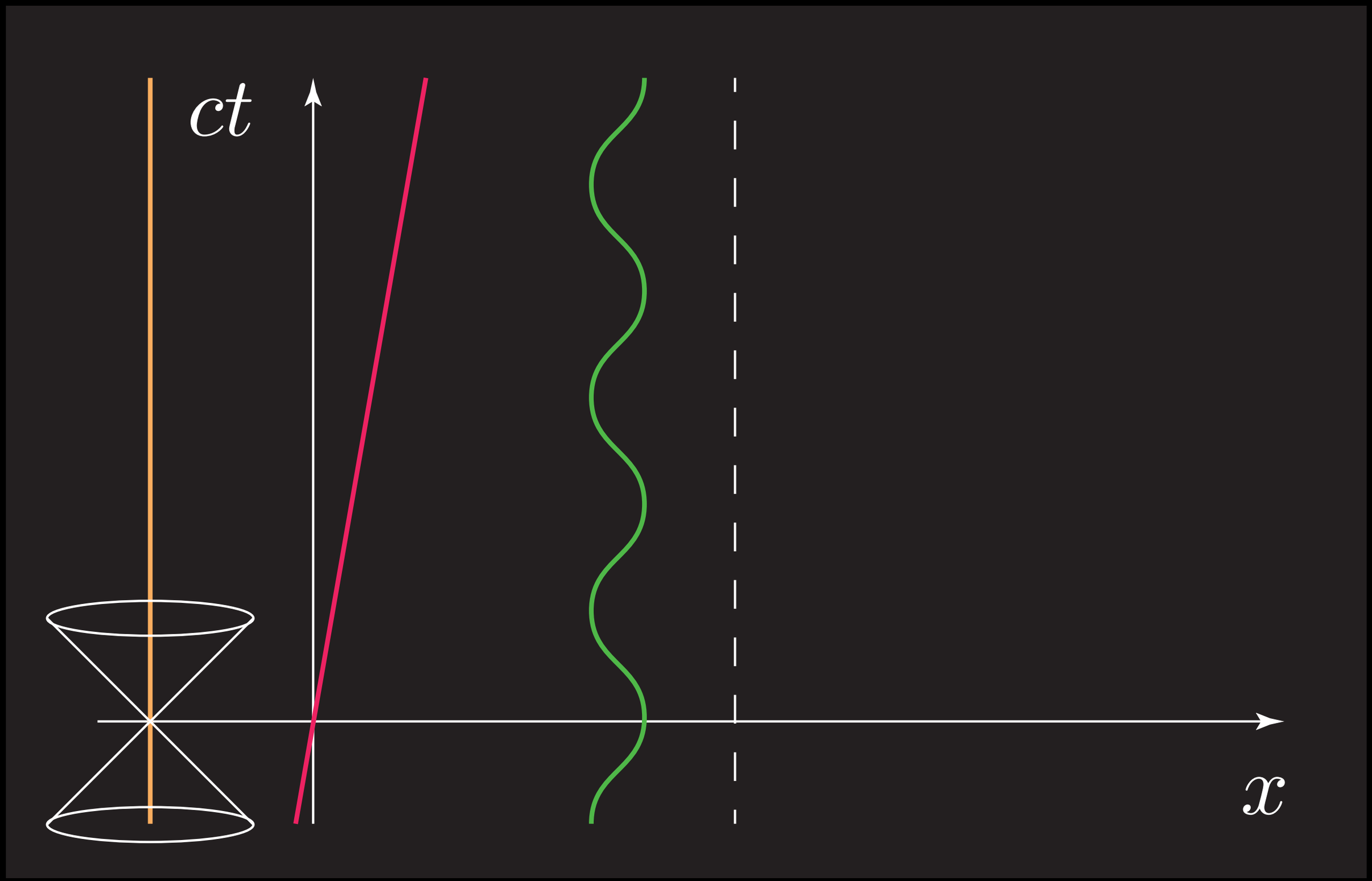
Action at a distance

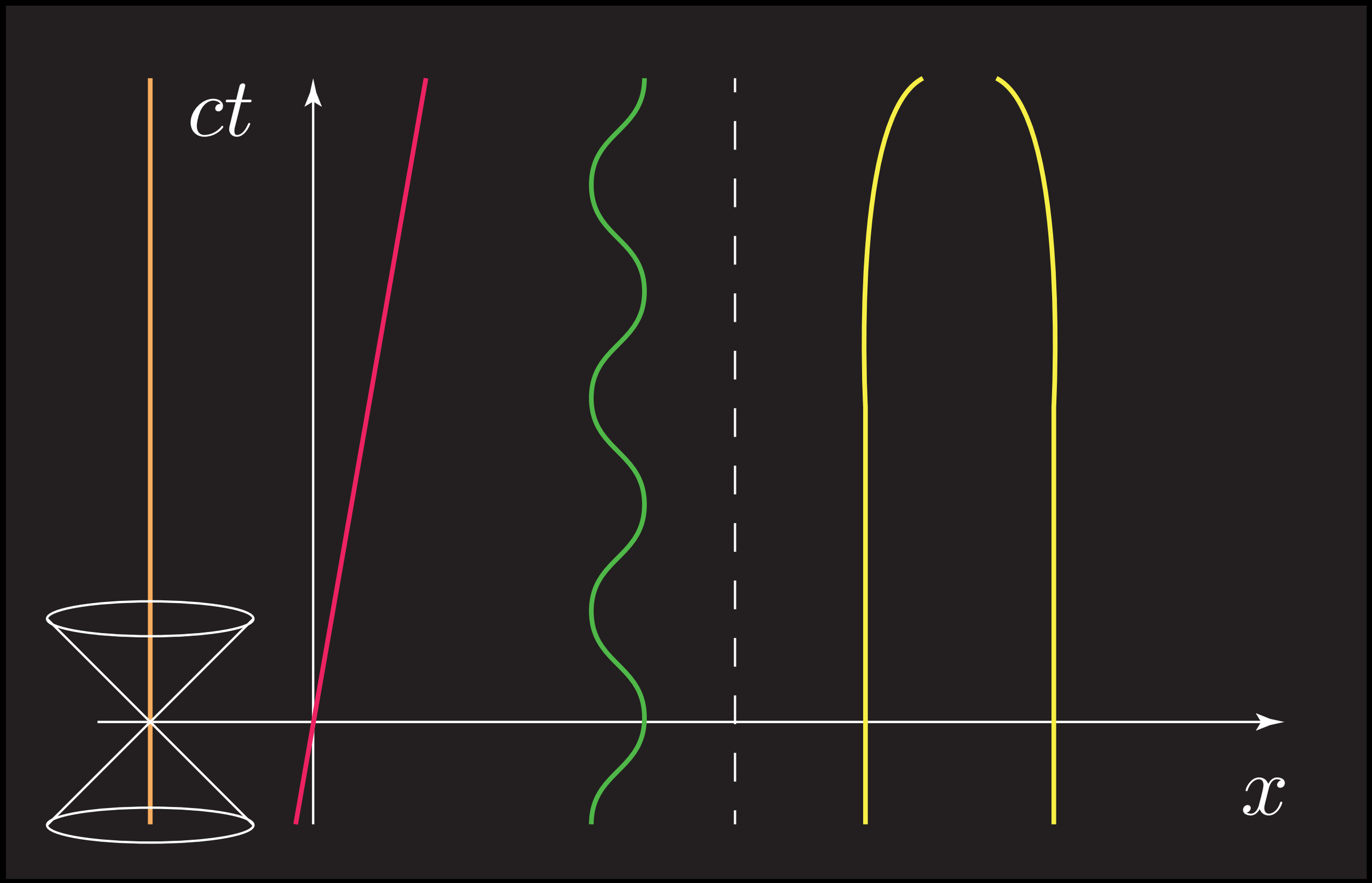
$$F = G\frac{mM}{r^2}$$

"That one body may act upon another at a distance through a vacuum without the mediation of anything else, by and through which their action and force may be conveyed from one another, is to me so great an absurdity that, I believe, no man who has in philosophic matters a competent faculty of thinking could ever fall into it."

–Isaac Newton




ct
x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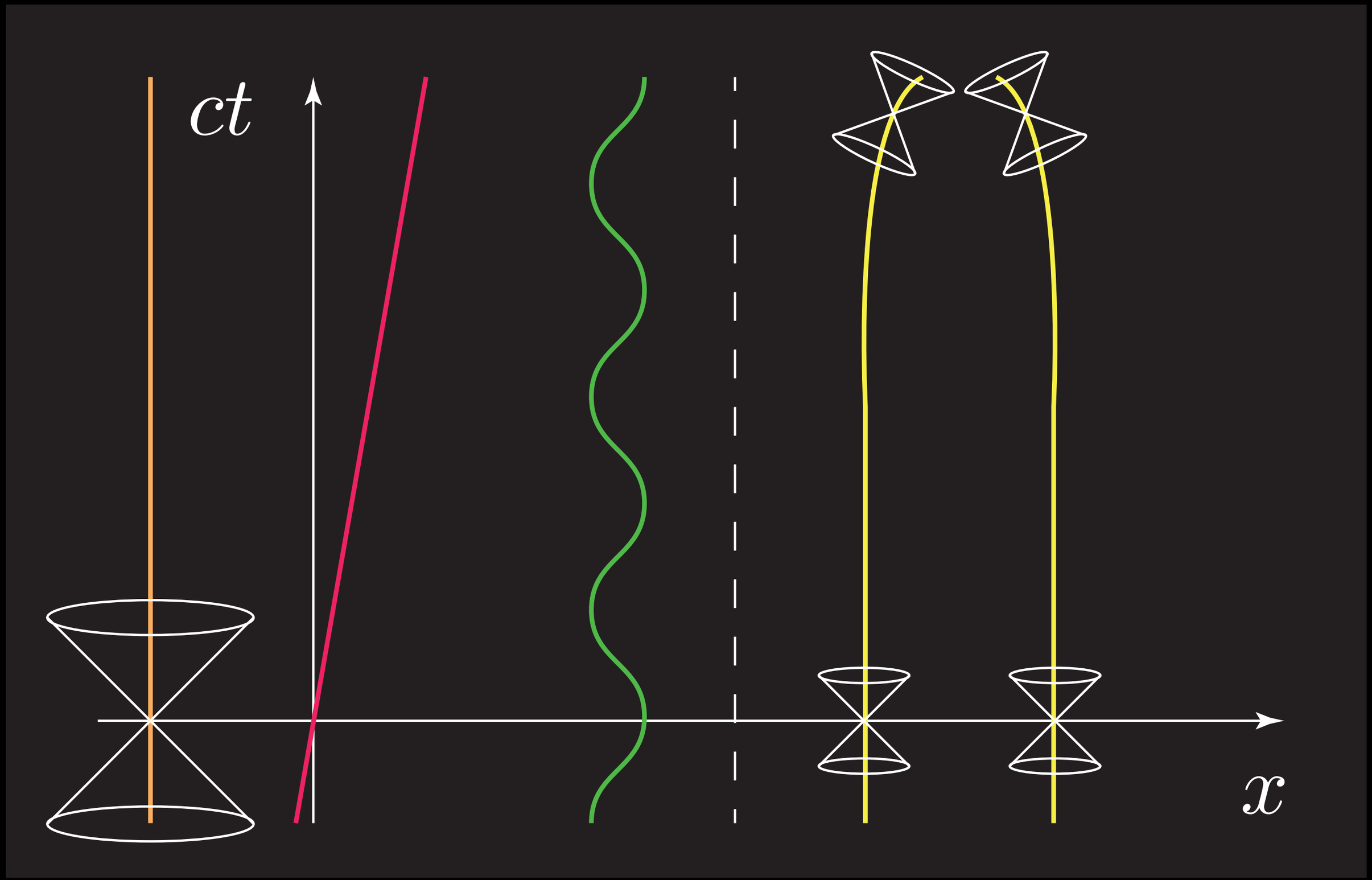
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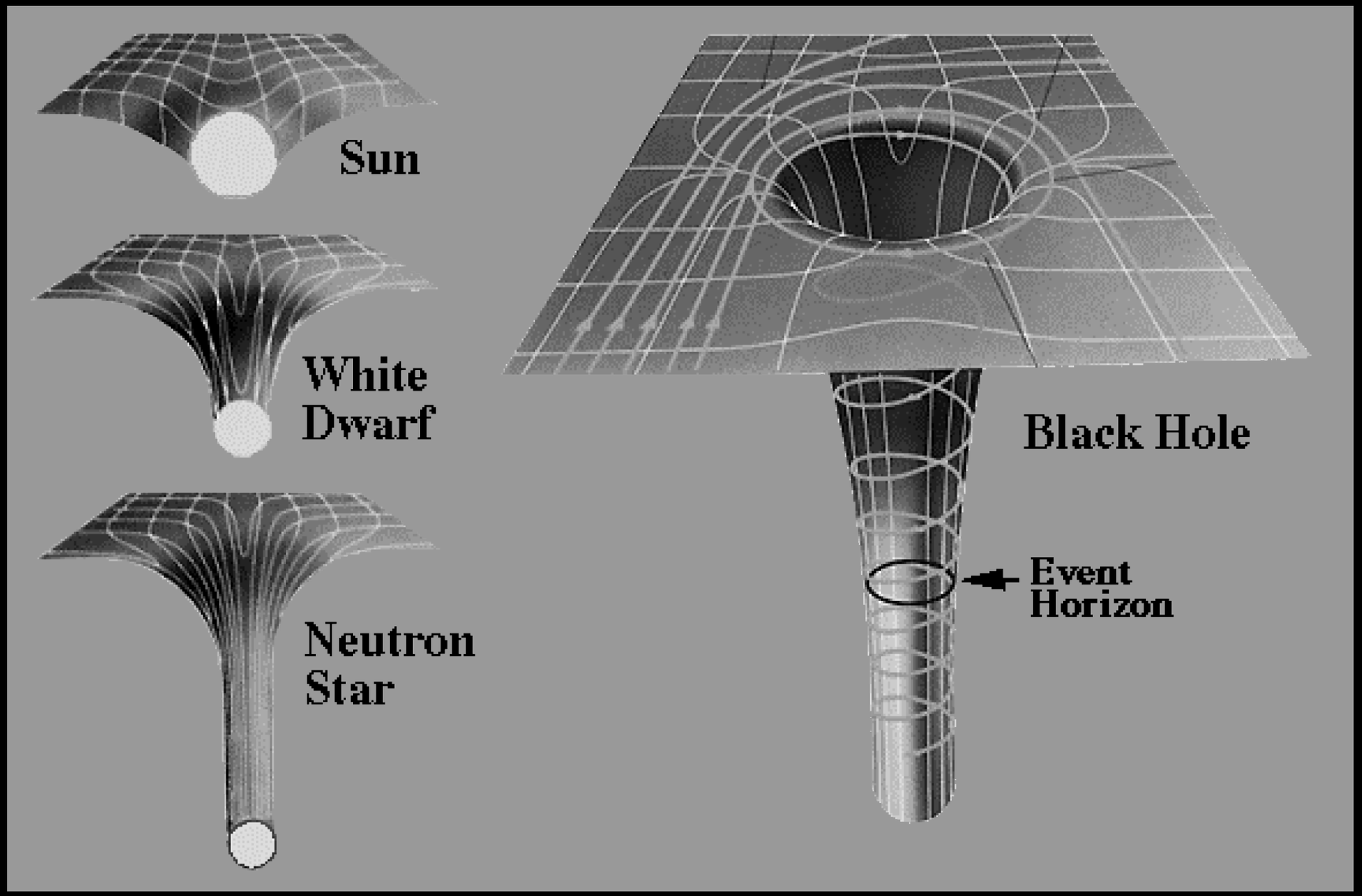
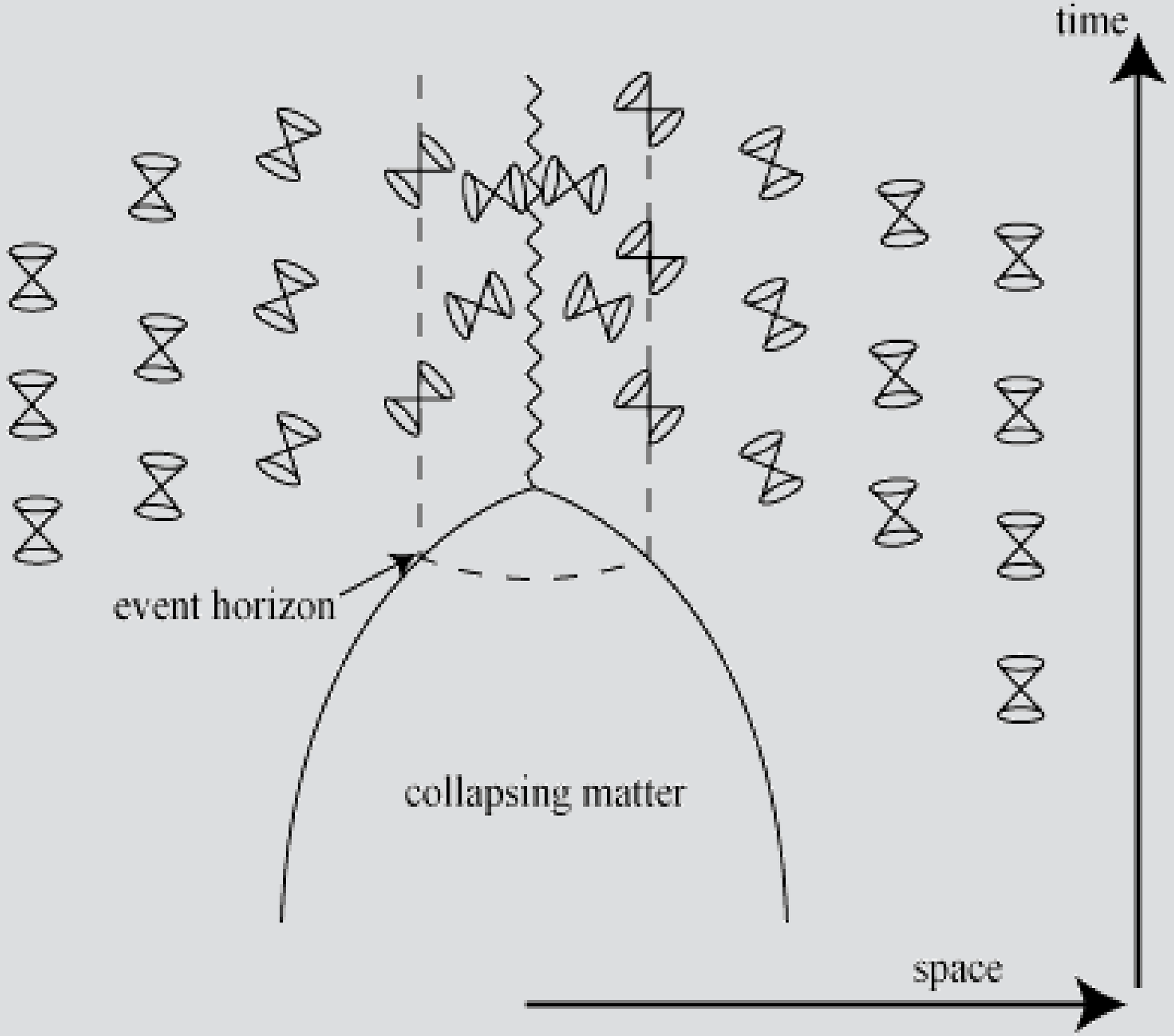
Black Holes

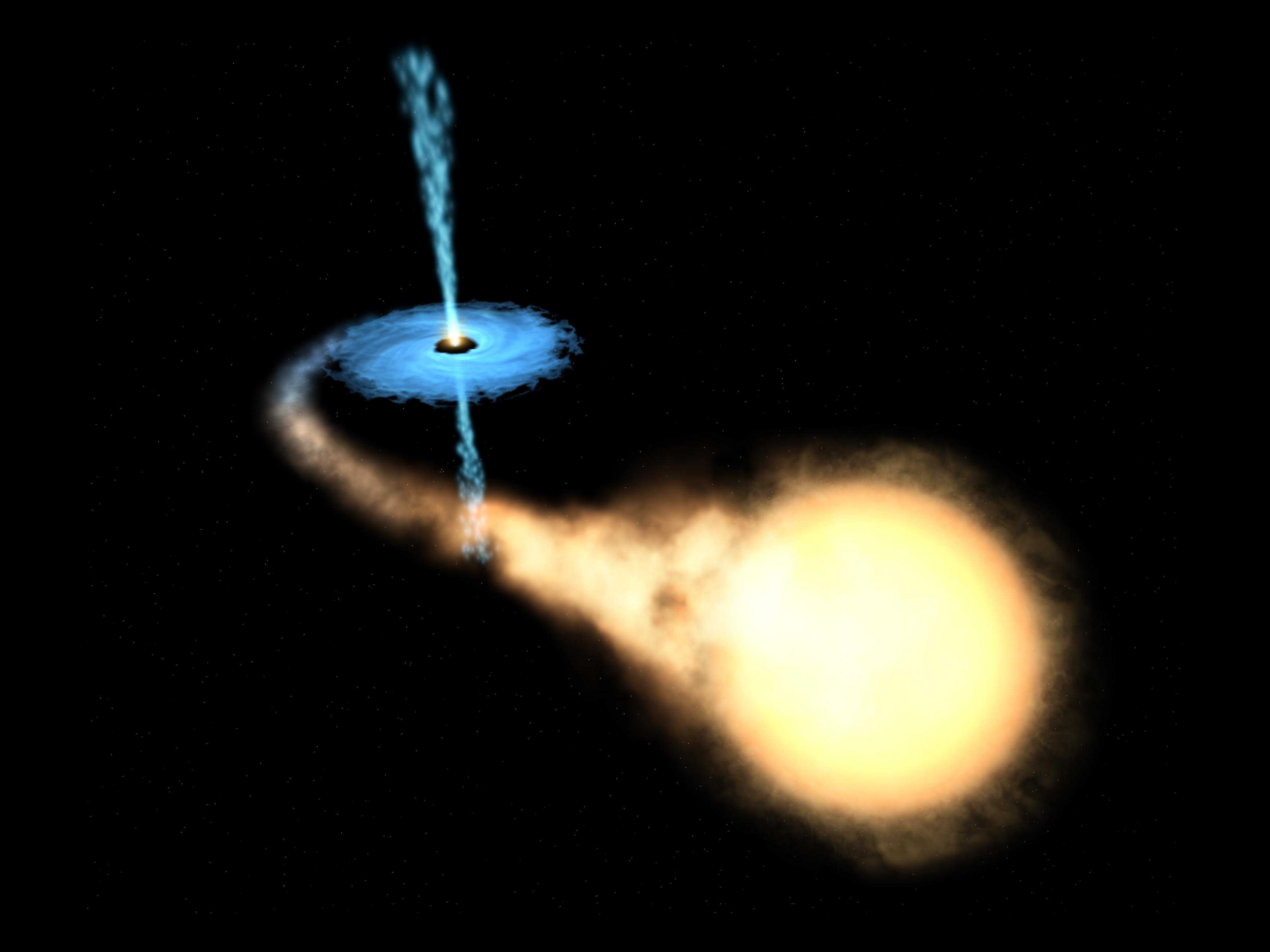




The event horizon is "a perfect unidirectional membrane: causal influences can cross it in only one direction". —D. Finkelstein 1958

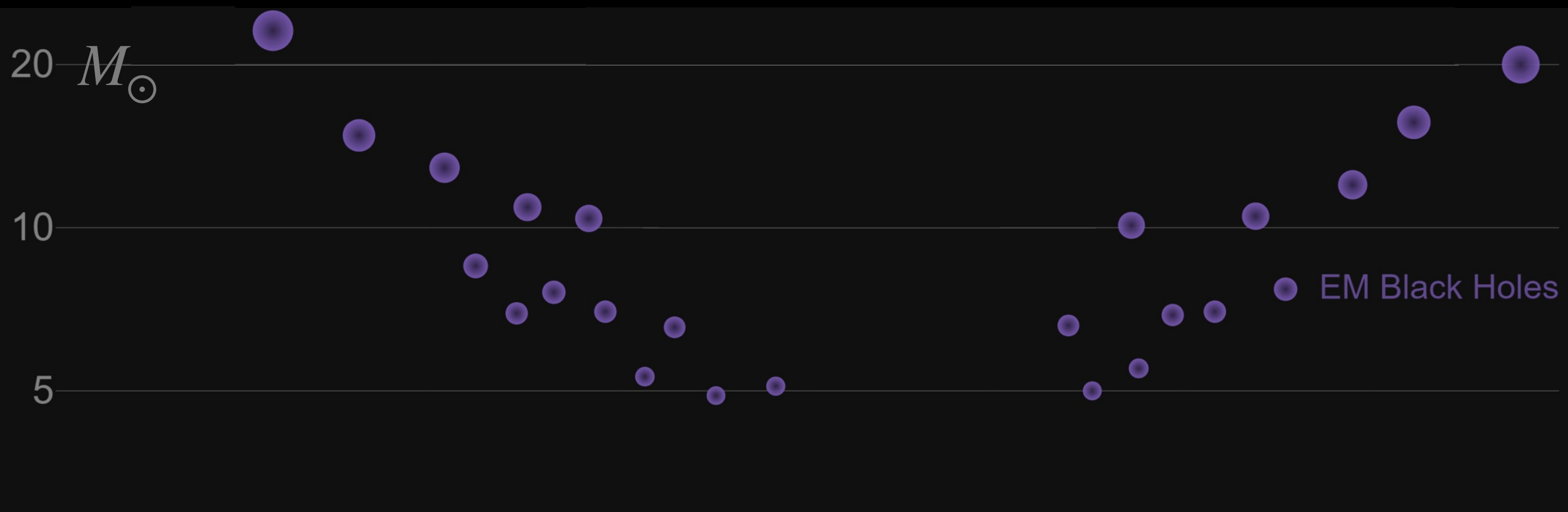
Observations before 2015

X-ray Binaries



X-ray Binary Population

In solar masses: 2×10^{30} kg



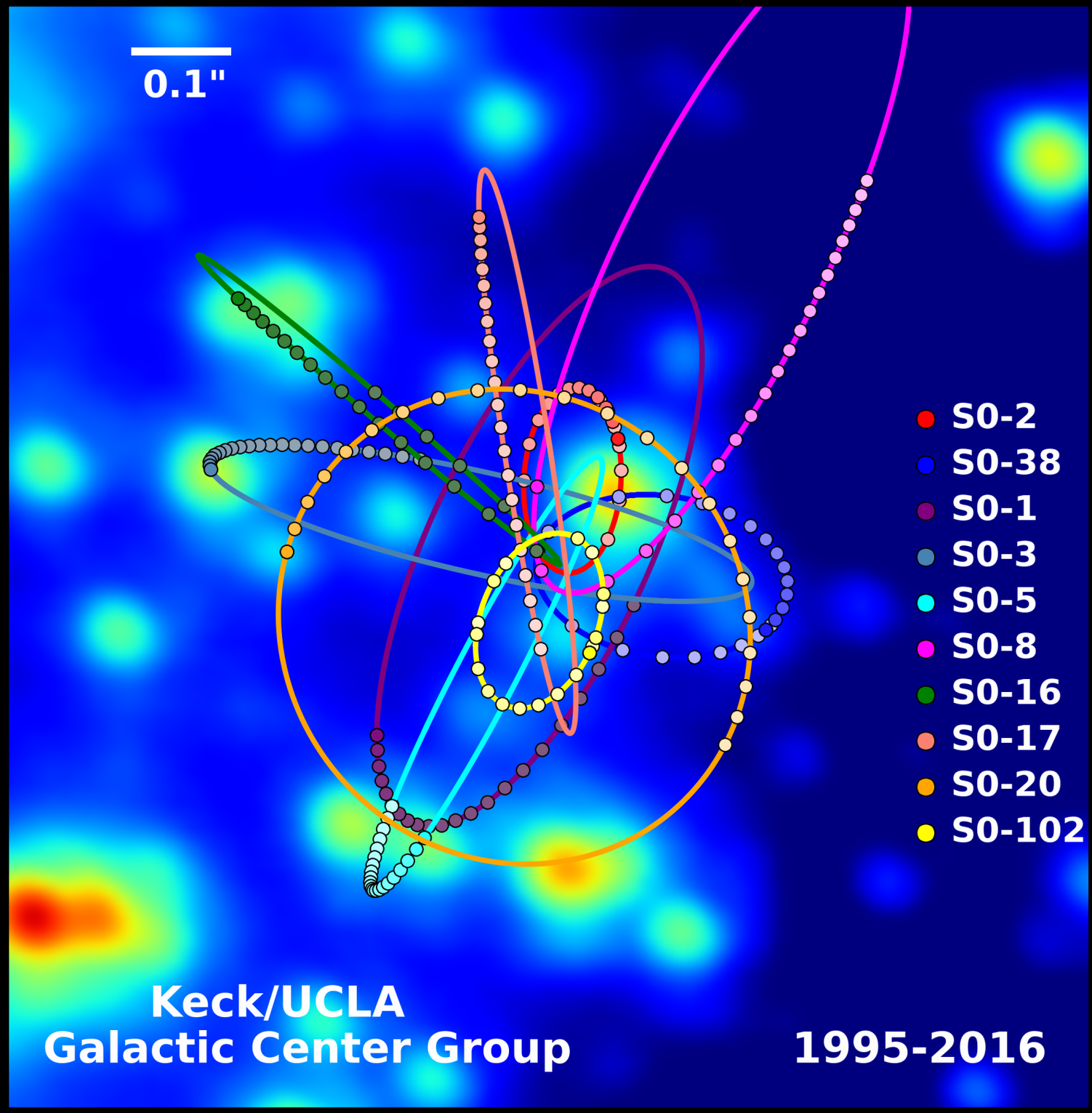
Tracking stars, the mass of Sag A* was initially put at $4 \times 10^6 M_\odot$.

Continued tracking has accurately established the mass at

$$4.3 \times 10^6 M_\odot$$

in a region of diameter

$$< 3.3 \text{ light minutes}$$

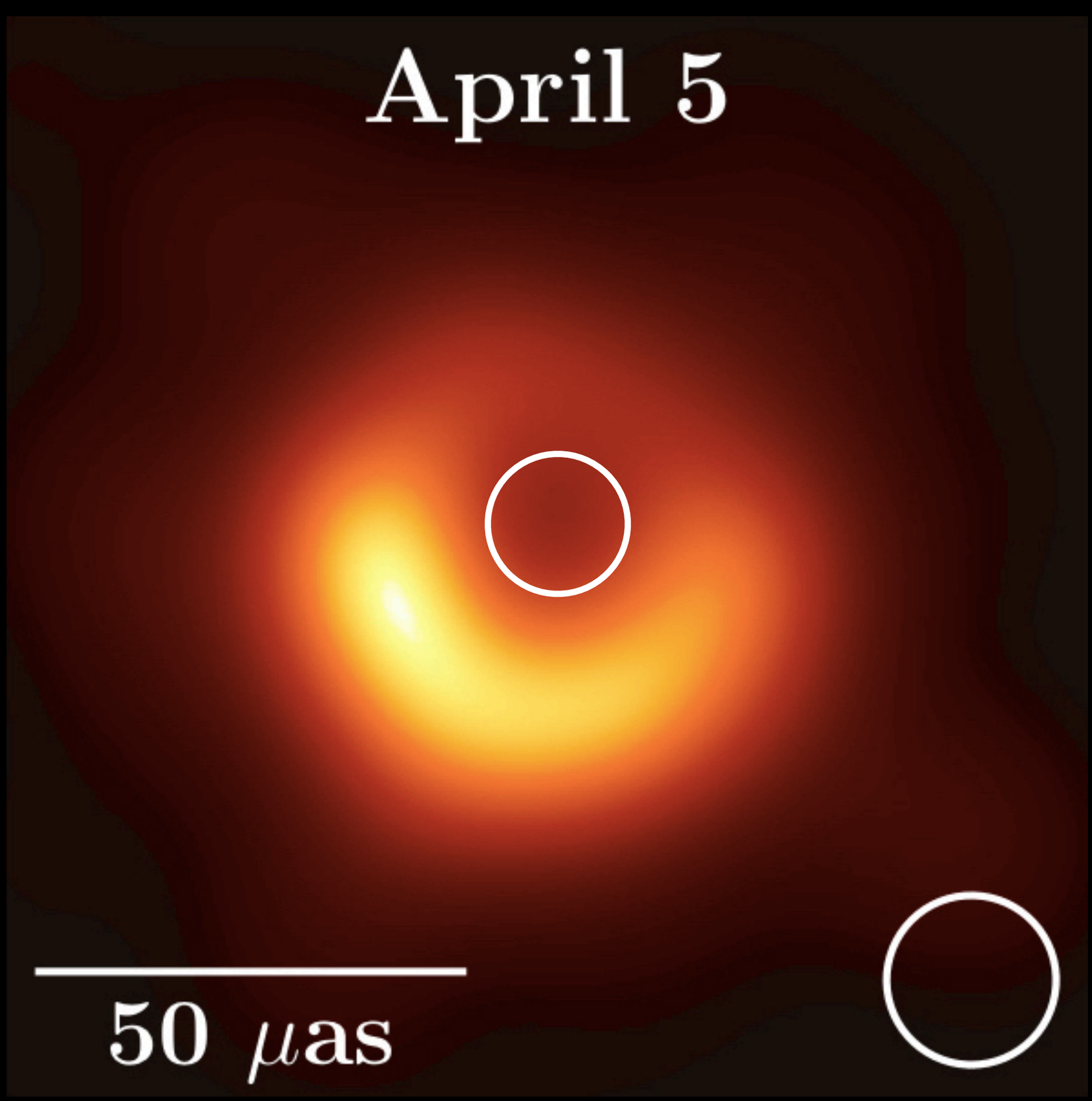


Observations since 2015

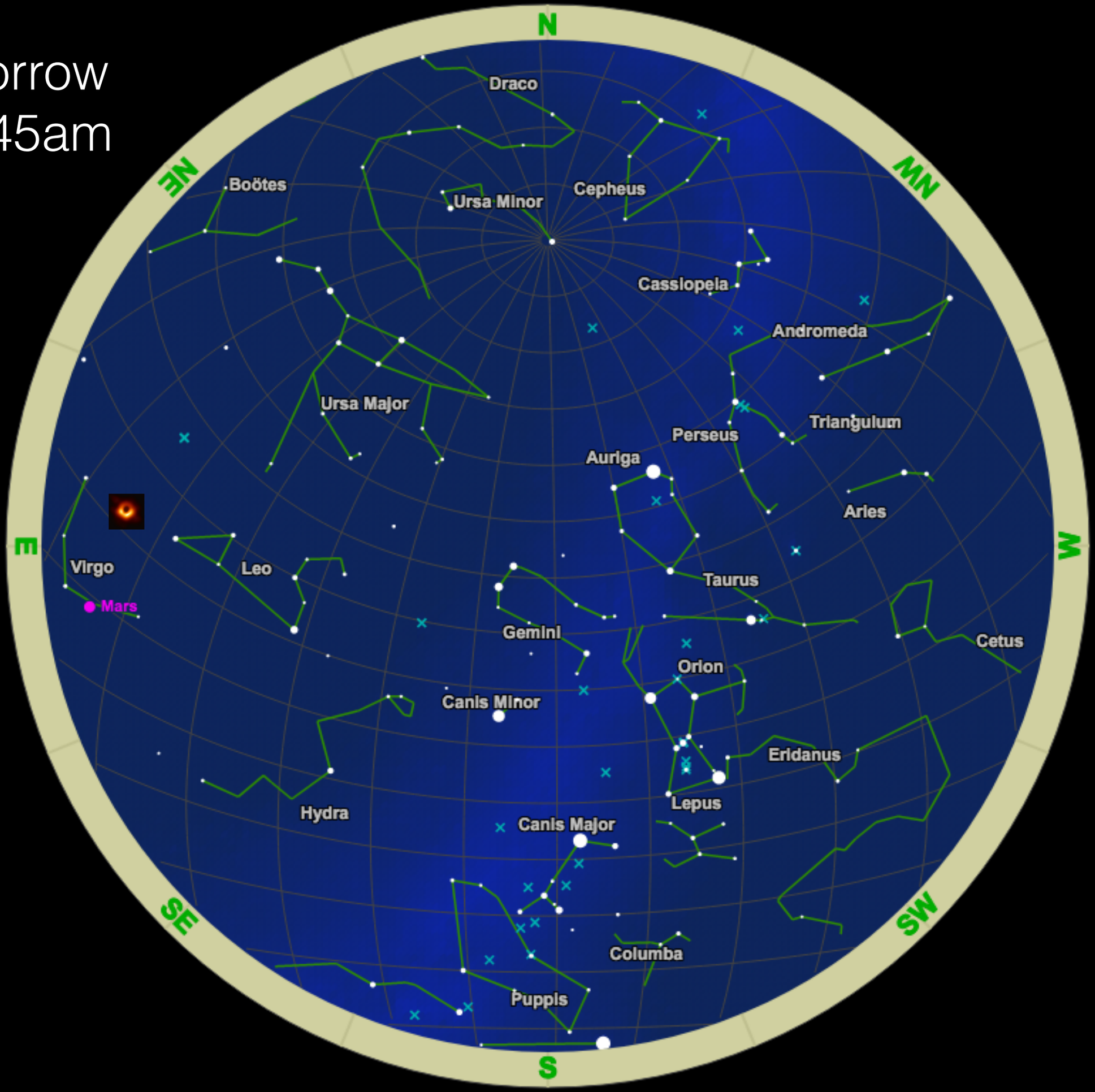
M87*: Pōwehi

(embellished dark source of unending creation)

April 5



Tomorrow
at 6:45am



https://in-the-sky.org

Binary Black Holes

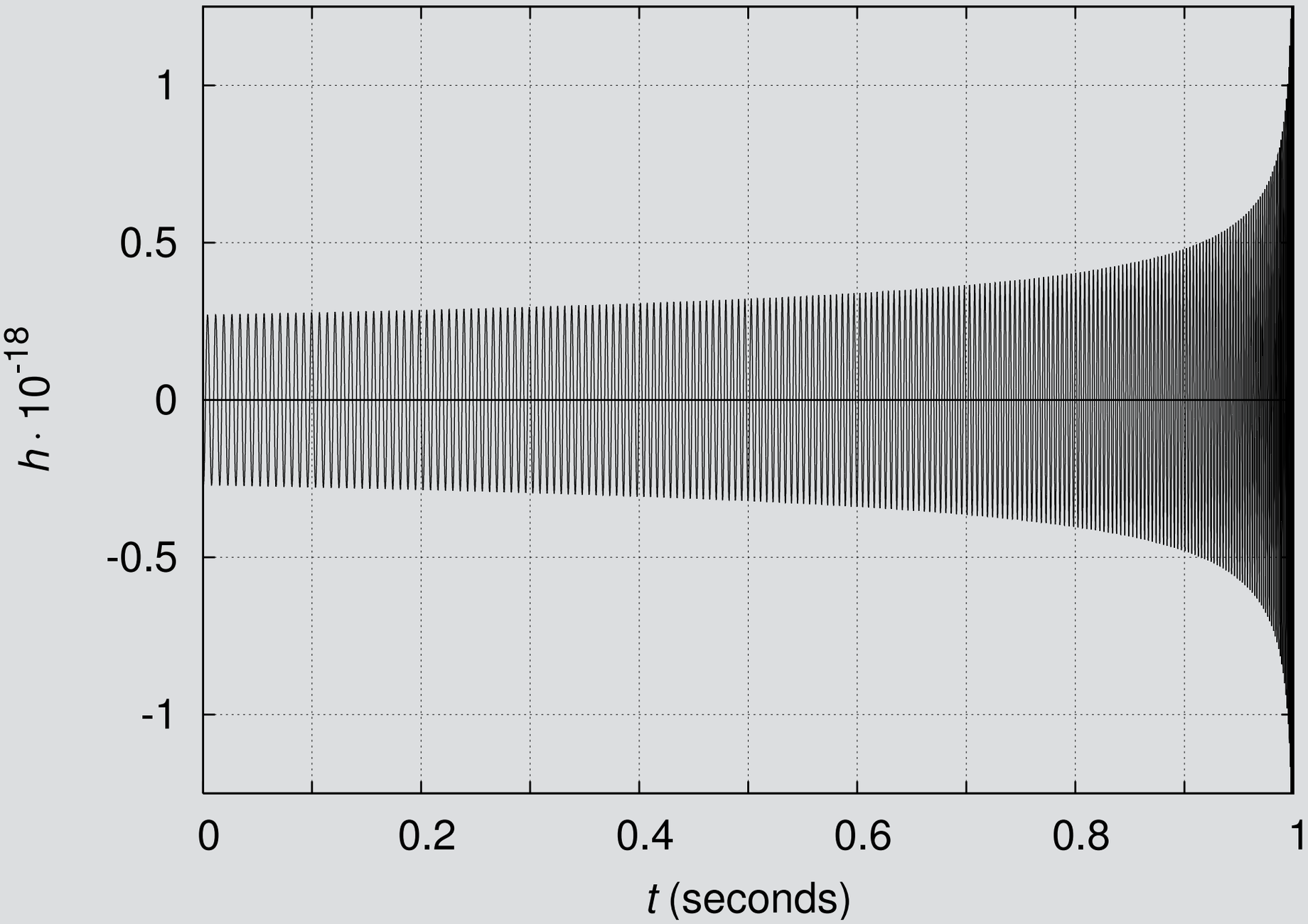
Kepler's 3rd Law

The cube of the period
is proportional to the
square of the orbit radius

When the wave carries energy off,
the black holes get closer.

Smaller $R \rightsquigarrow$ smaller P

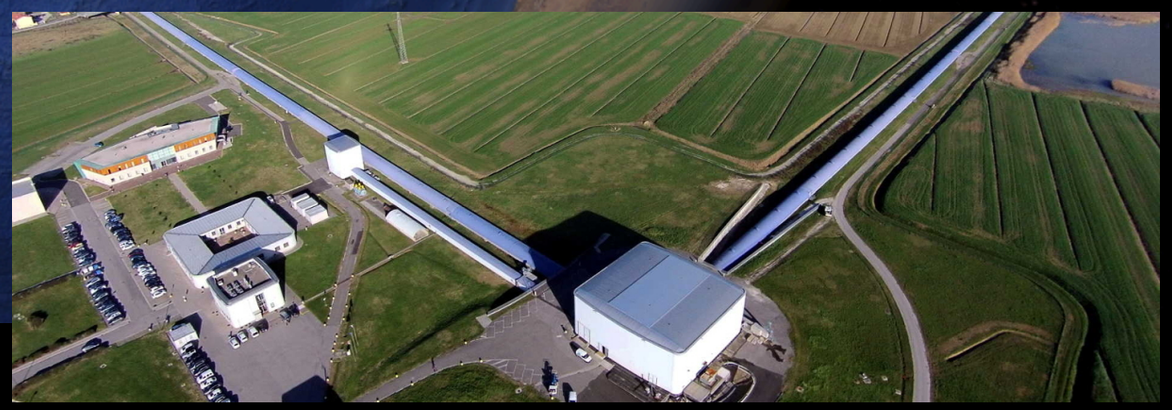
The wave begins to chirp



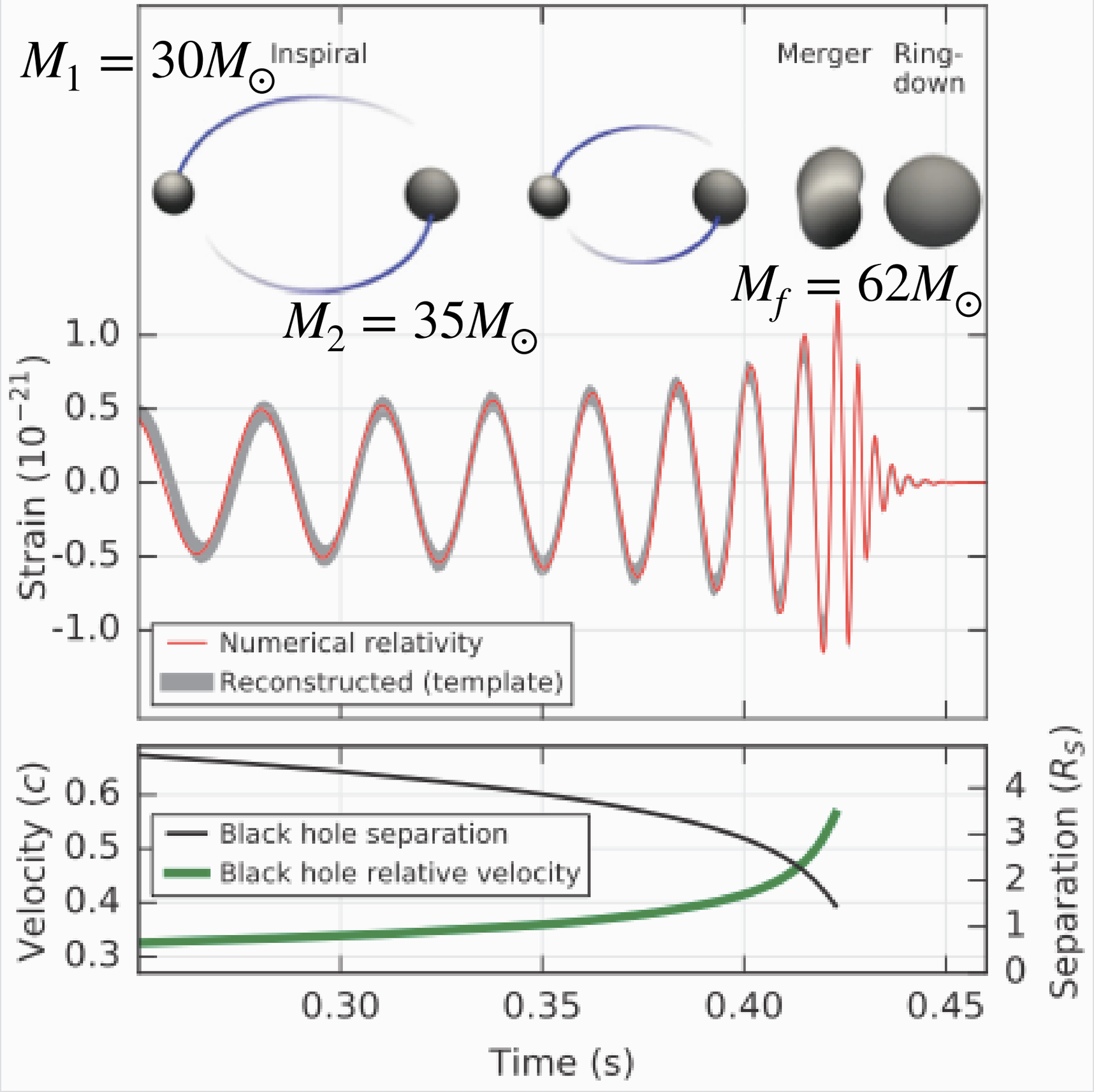
$$h(t) = \mathscr{A}\cos(\Phi(t))$$

LIGO-Hanford

LIGO-Livingston

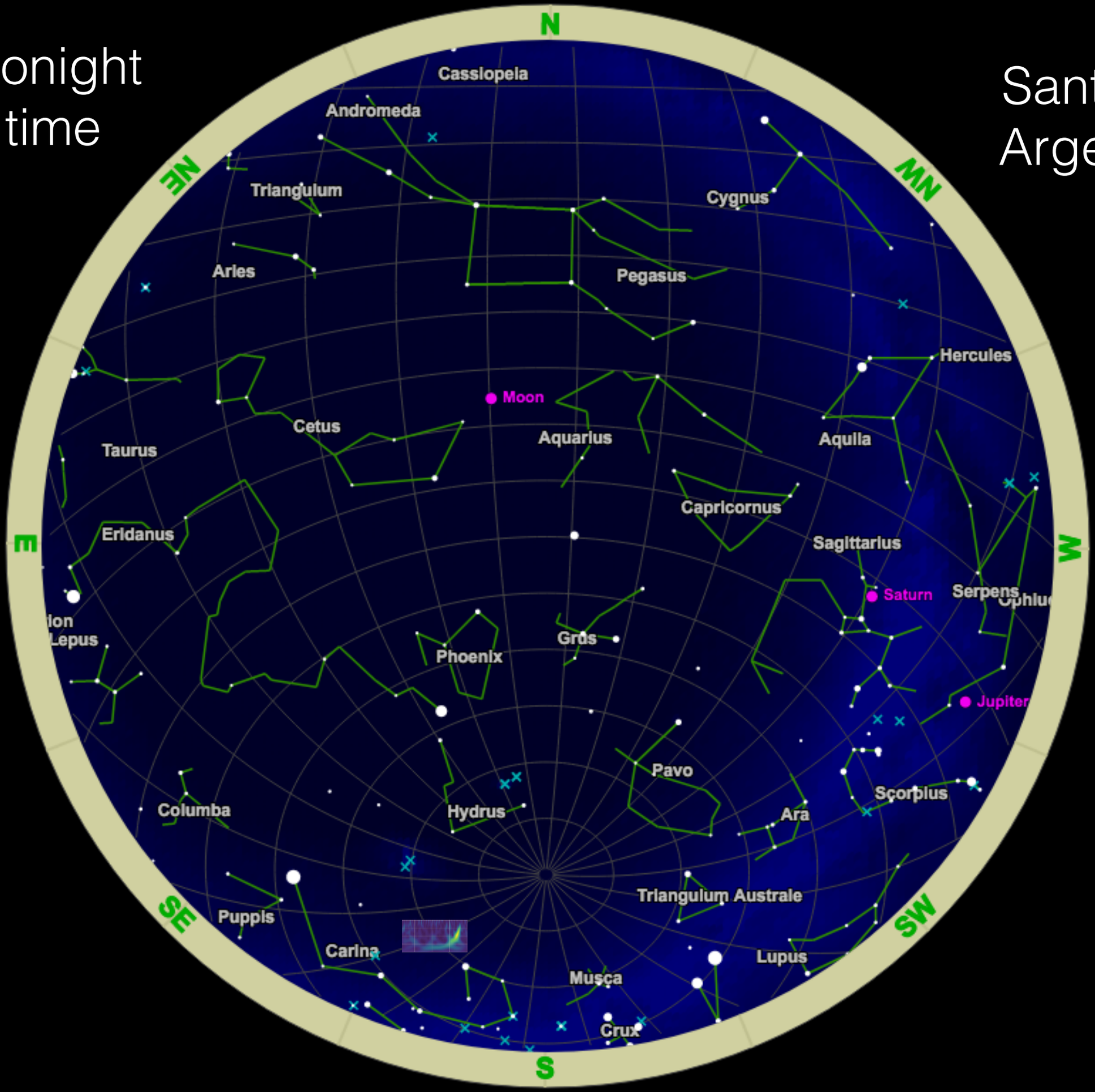


VIRGO-Cascina


$M_1 = 30M_\odot$
Inspiral
Merger
Ring-down
$M_2 = 35M_\odot$
$M_f = 62M_\odot$
Strain (10^{-21})
1.0
0.5
0.0
-0.5
-1.0
Numerical relativity
Reconstructed (template)
Velocity (c)
0.6
0.5
0.4
0.3
Black hole separation
Black hole relative velocity
Separation (R_S)
0
1
2
3
4
0.30
0.35
0.40
0.45
Time (s)

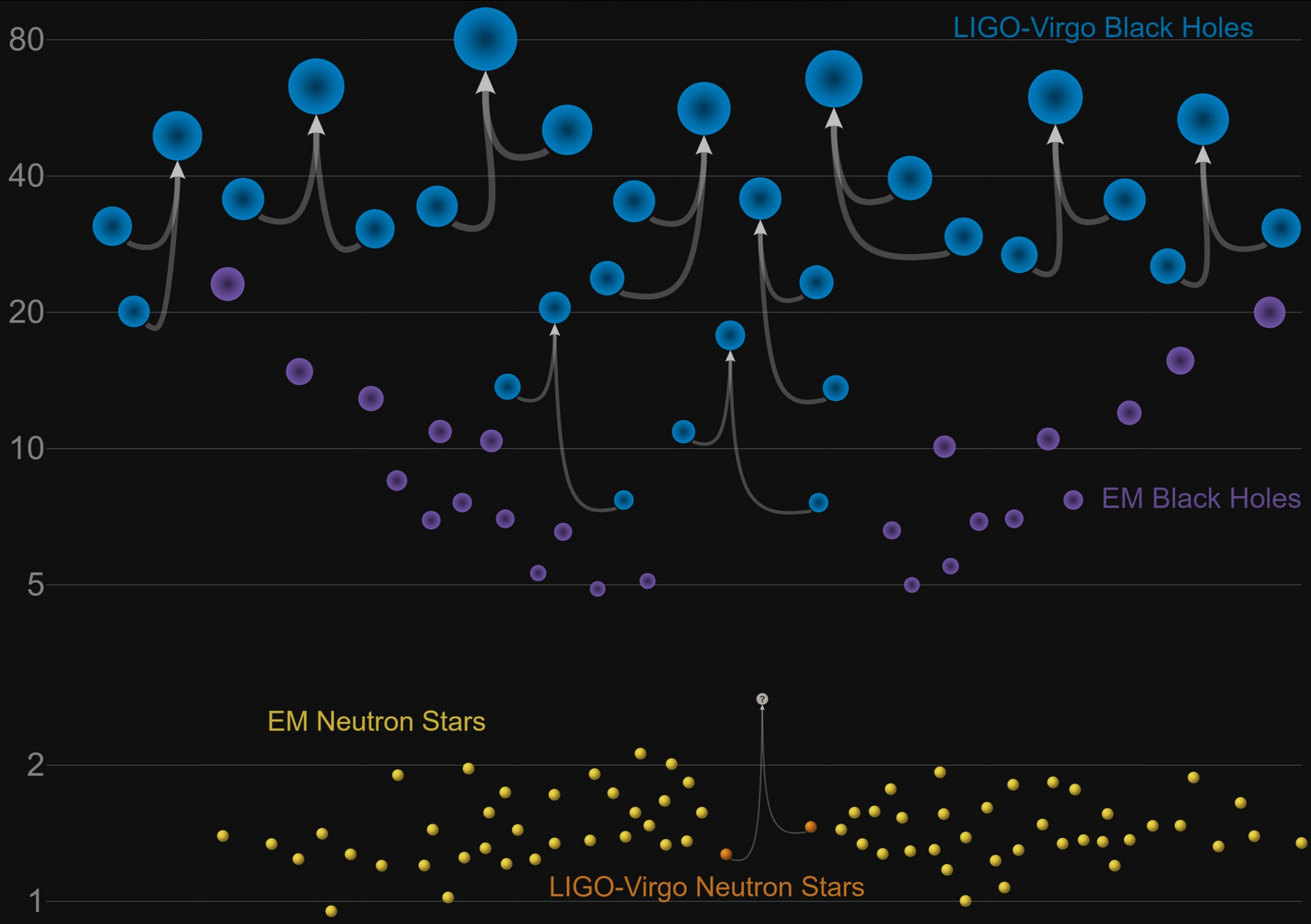
11pm tonight
local time

Santa Fe,
Argentina



https://in-the-sky.org

In solar masses



LIGO-Virgo | Frank Elavsky | Northwestern

Three Ideas

Time Melts: Time is a malleable medium, flowing at different rates depending on your motion & locale.

Black Holes Abound: A great variety of black holes never seen before have been observed in the last four years.

Space is discrete: Black holes are hot! Their temperature hints that space and time should have a, perhaps subtle, discreteness.

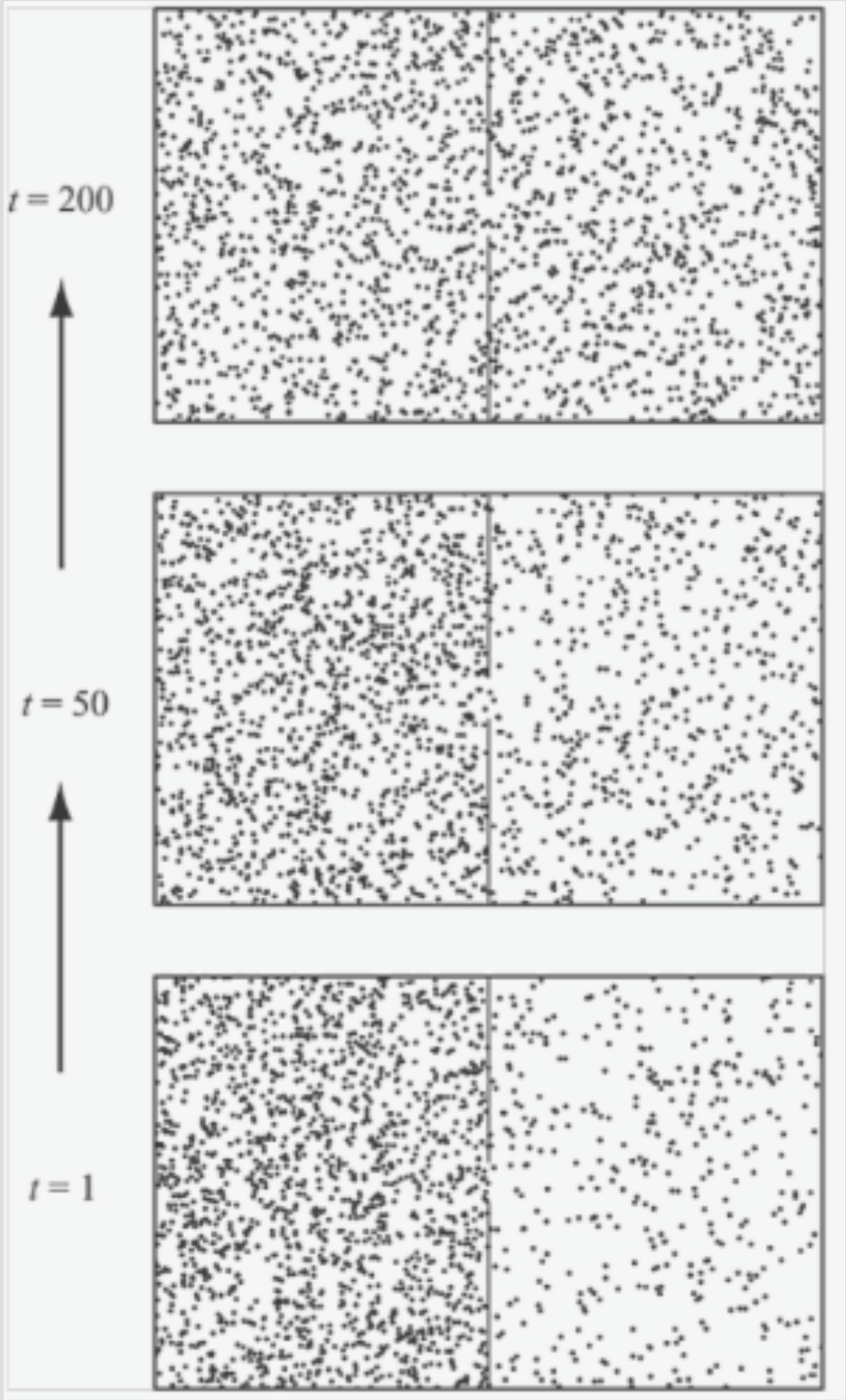
“If it is hot, it must have microstructure”

— Boltzmann Principle

Equal left and right

1400 molecules on the left,
600 on the right

1600 molecules on the left,
400 on the right



In the early 1970's Hawking argued that black holes have a temperature

Ever since we have searched for the microstructure of black holes and of space and time more generally

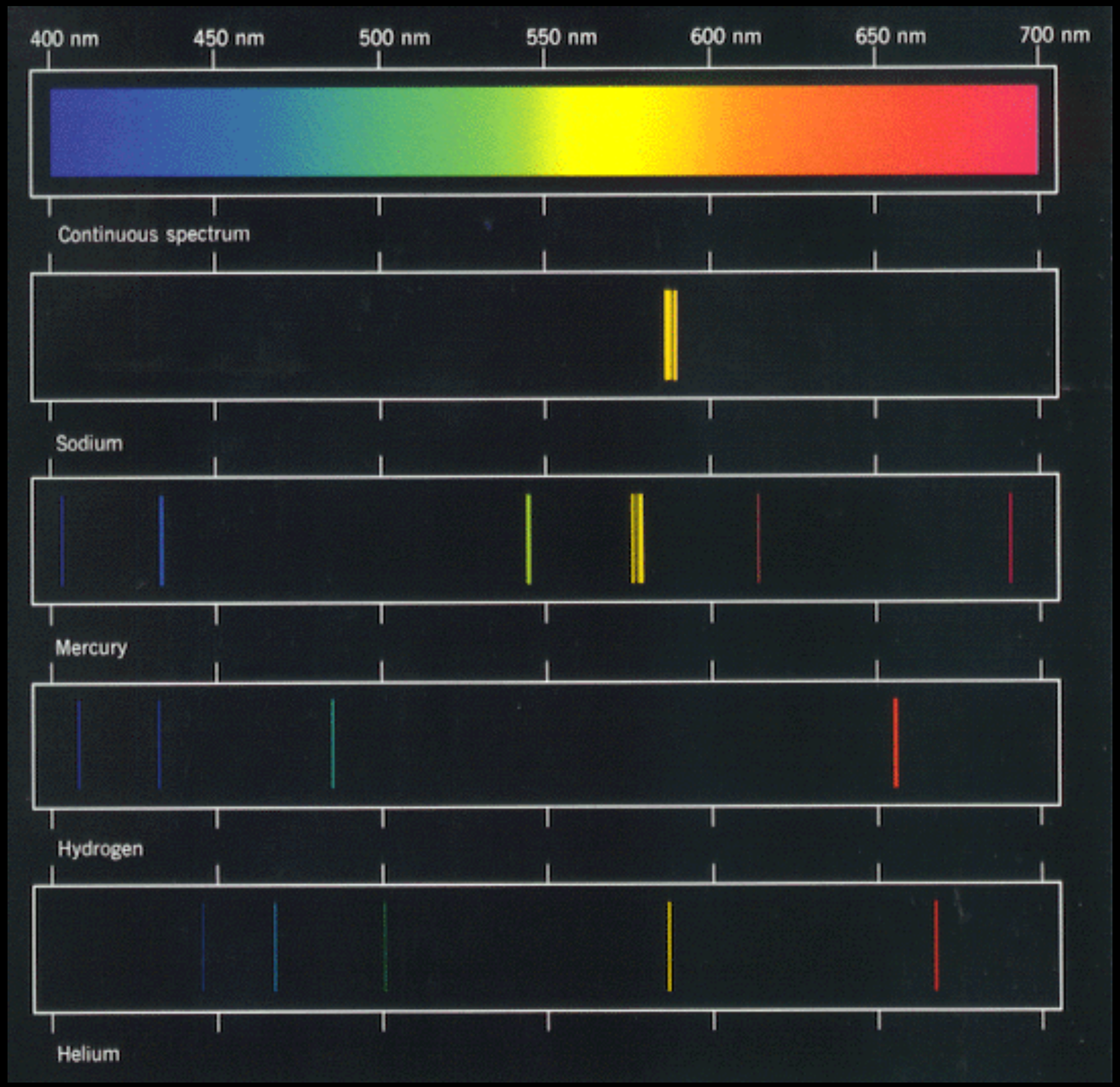
But, what sort of discreteness are we talking about?

Is it like that of atoms in a material?

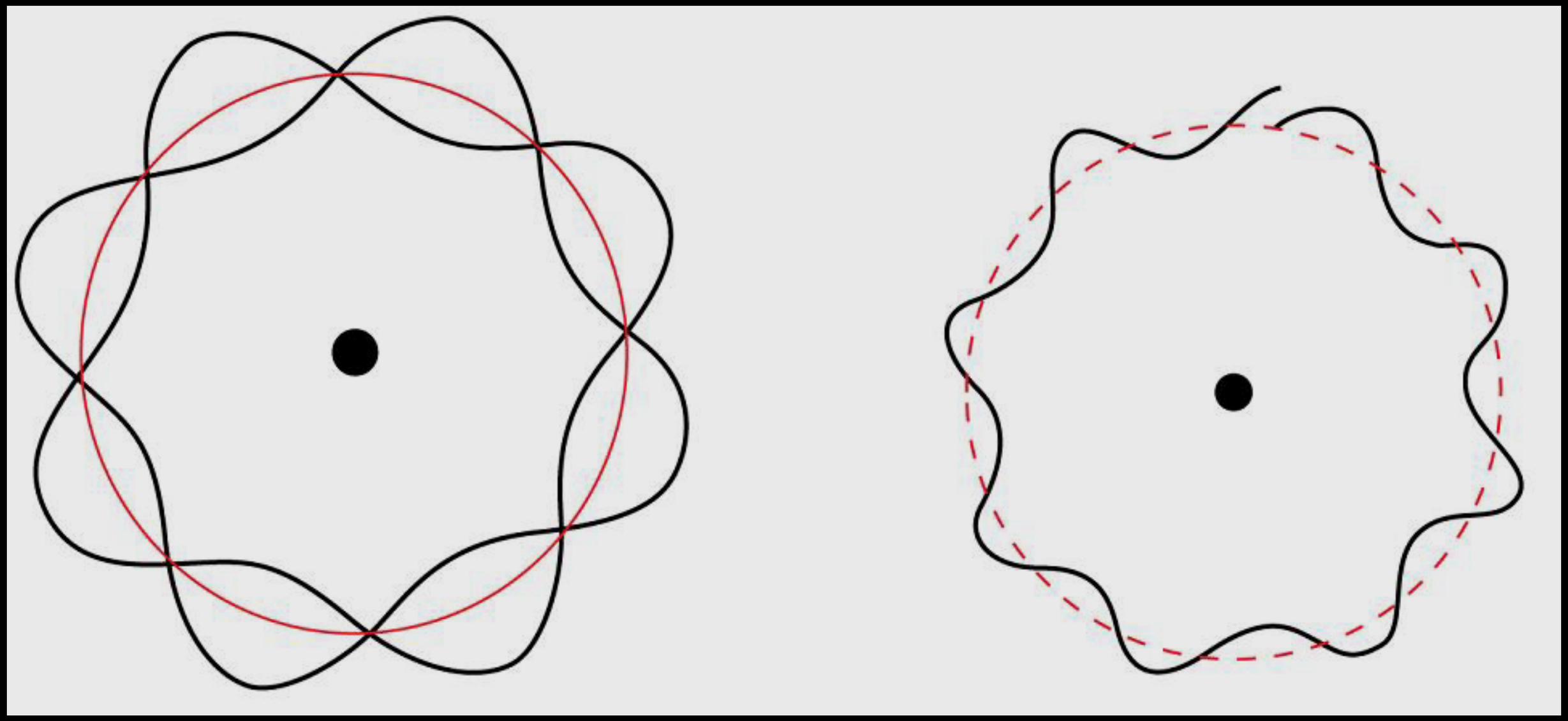
Or is it like the spectral lines that atoms radiate when they are energetically excited?

Or, perhaps, it is a combination of both?

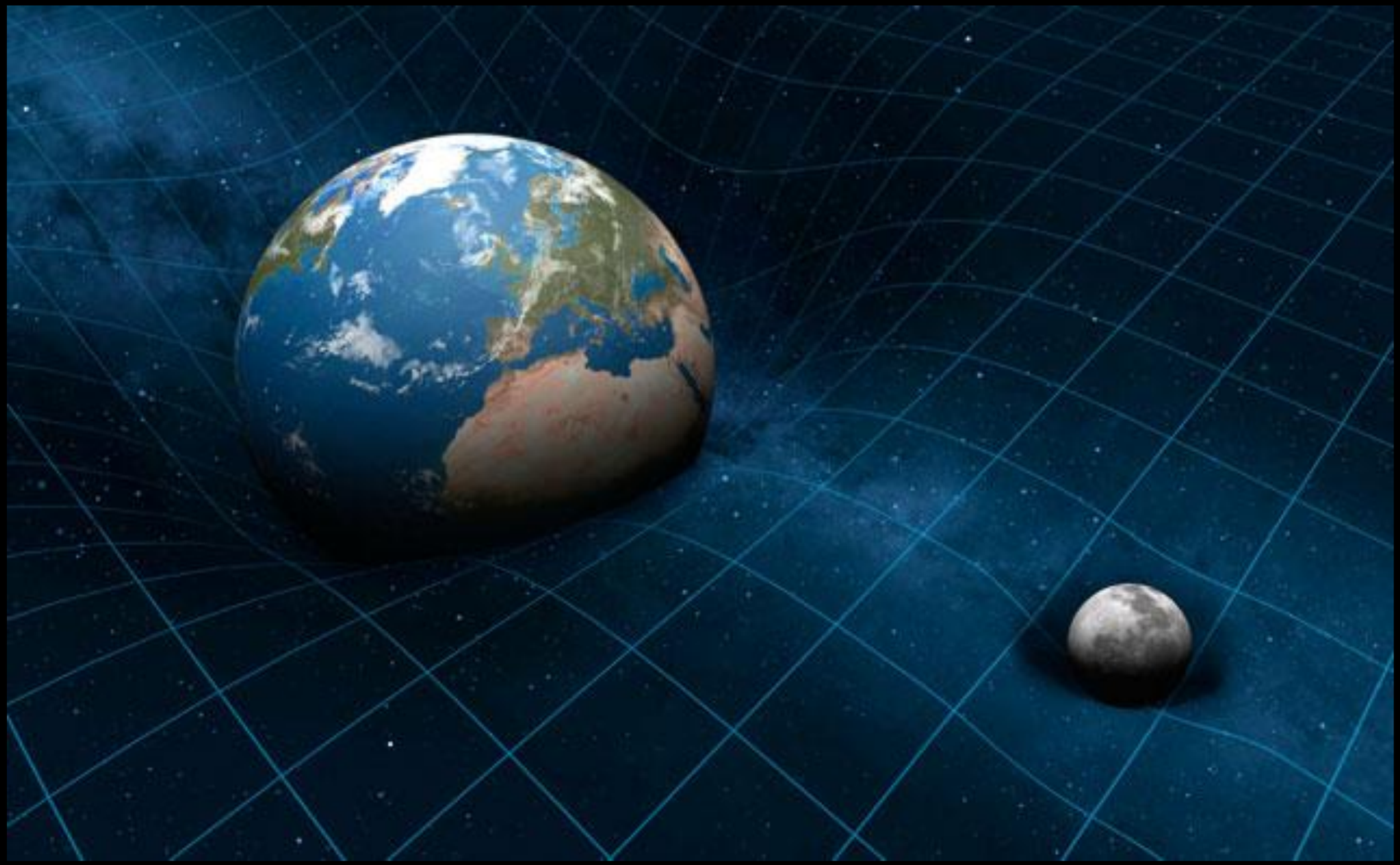
Pure samples of an atom or molecule are found to emit only certain, specific wavelengths of light.



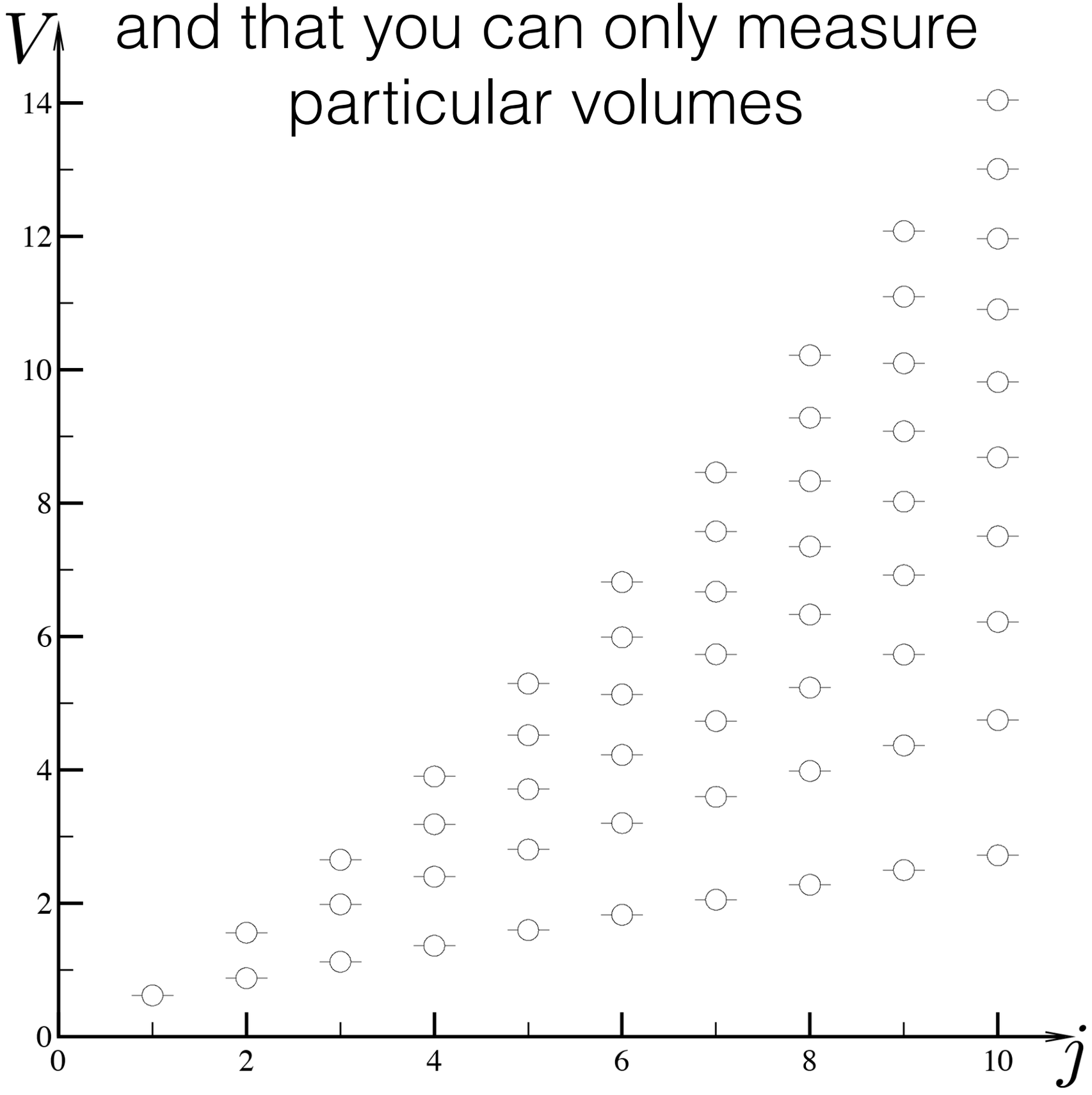
We call this spectral discreteness and it was at the heart of the birth of Quantum Mechanics



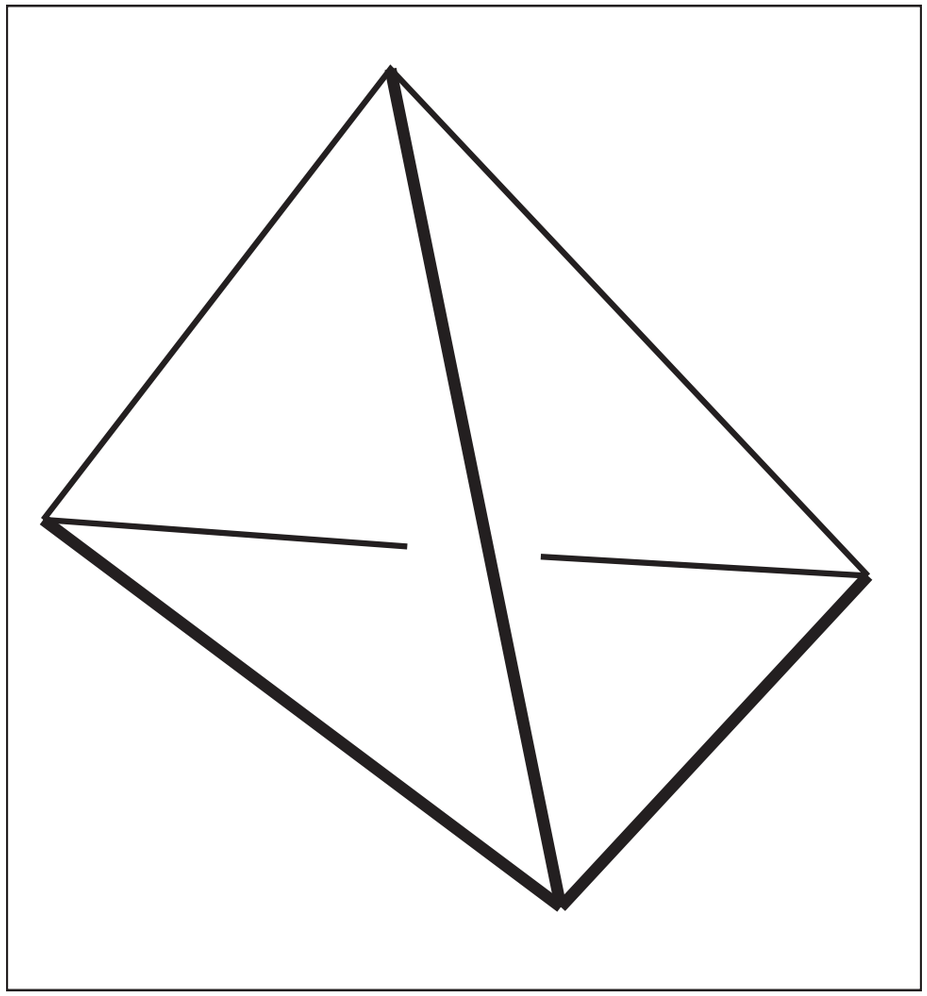
Analogous efforts to quantize space were rigorous and complicated. They resulted in discrete volumes.



Thus Quantum Gravity predicts that space is granular, and that you can only measure particular volumes

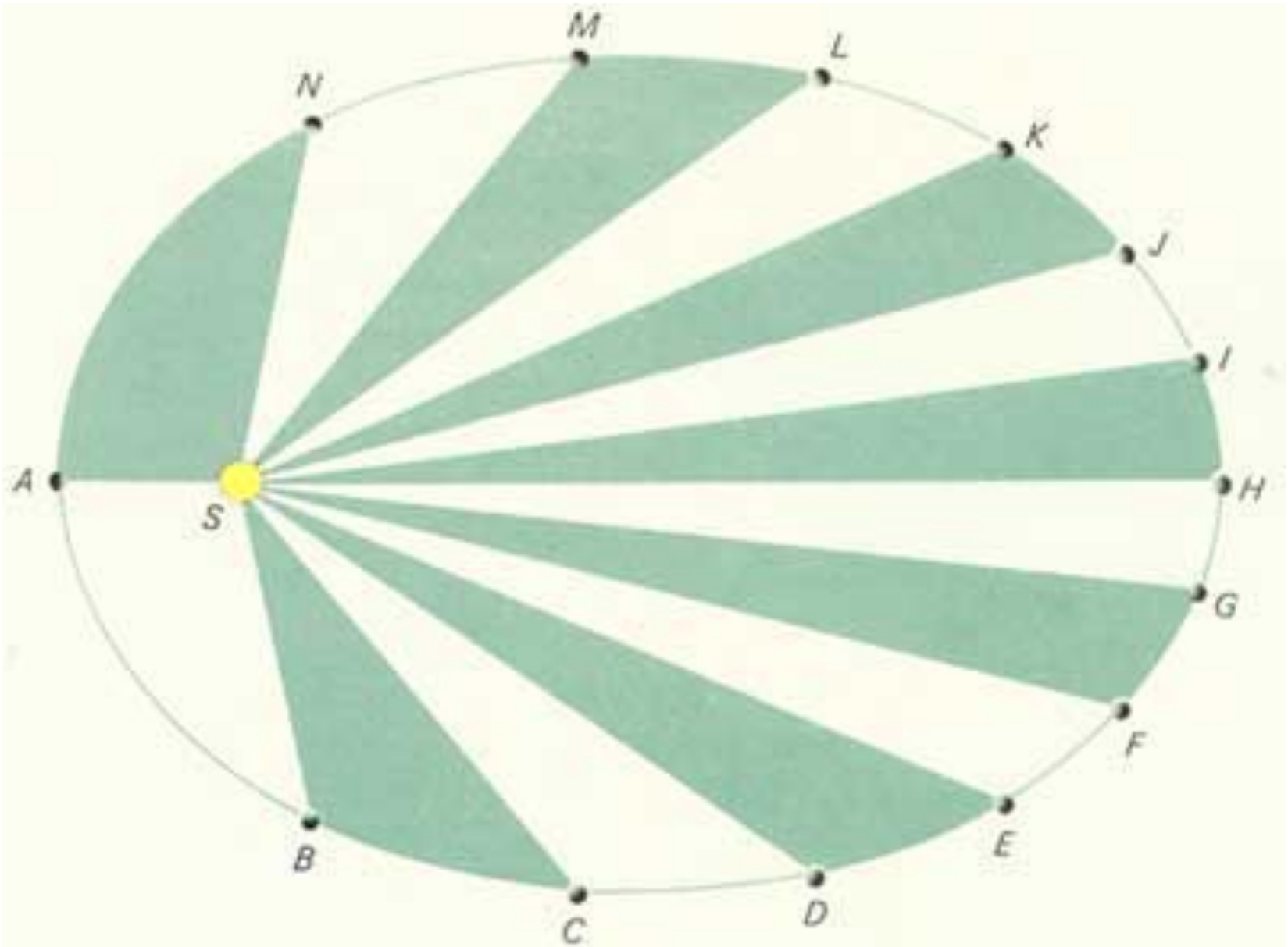


Can we perhaps model a grain of space directly by a pyramid or tetrahedron?

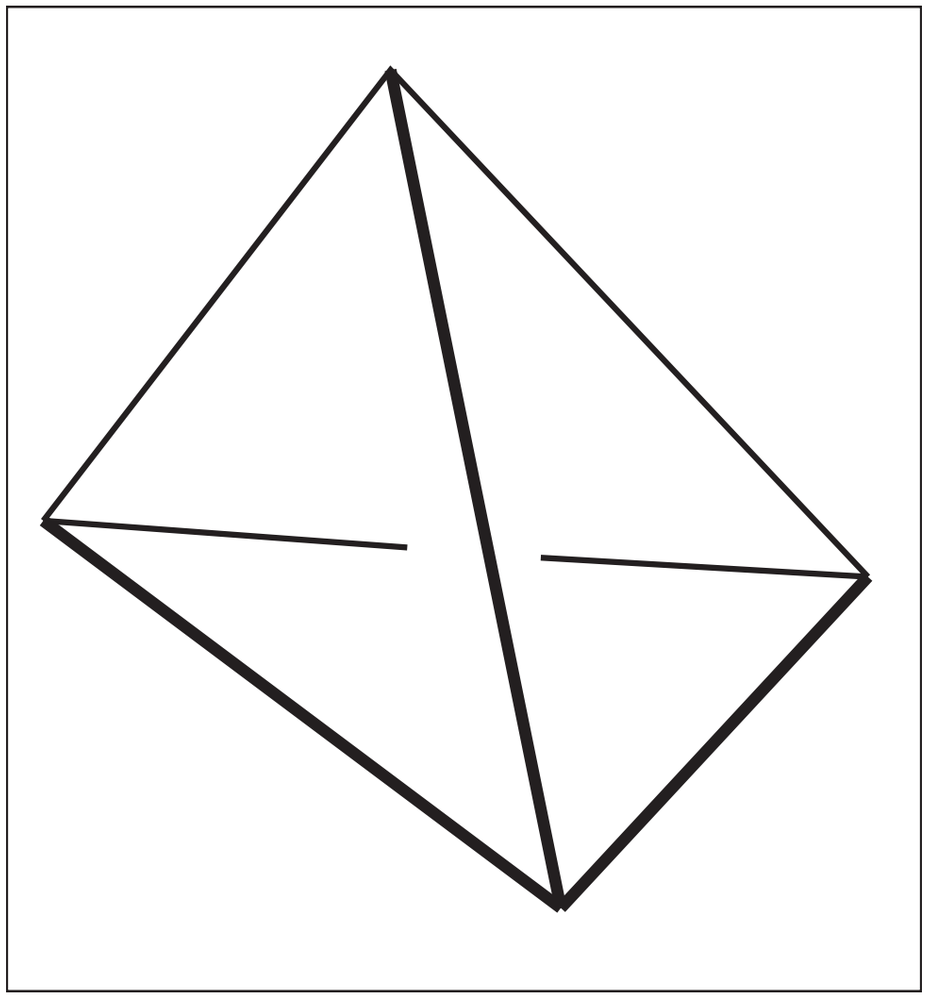


To do so, and still capture Einstein's idea of dynamical spacetime, it would have to evolve.

Physics provides a hint: Kepler's 2nd law states that the orbit of a planet sweeps out equal areas in equal times.

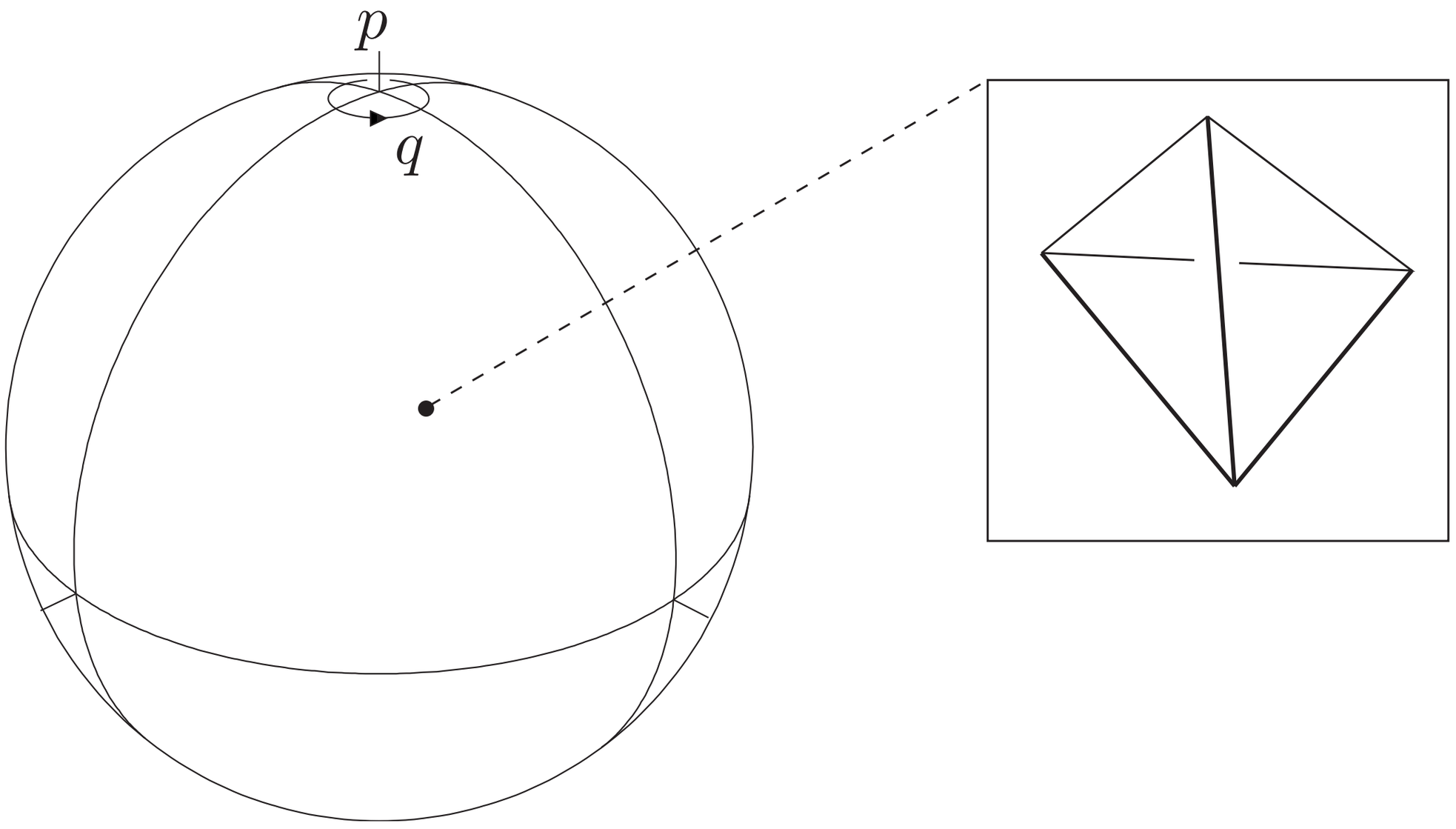


Euclid appreciated that specifying a tetrahedron by its six edge lengths is rigid—they fit together or they don't.



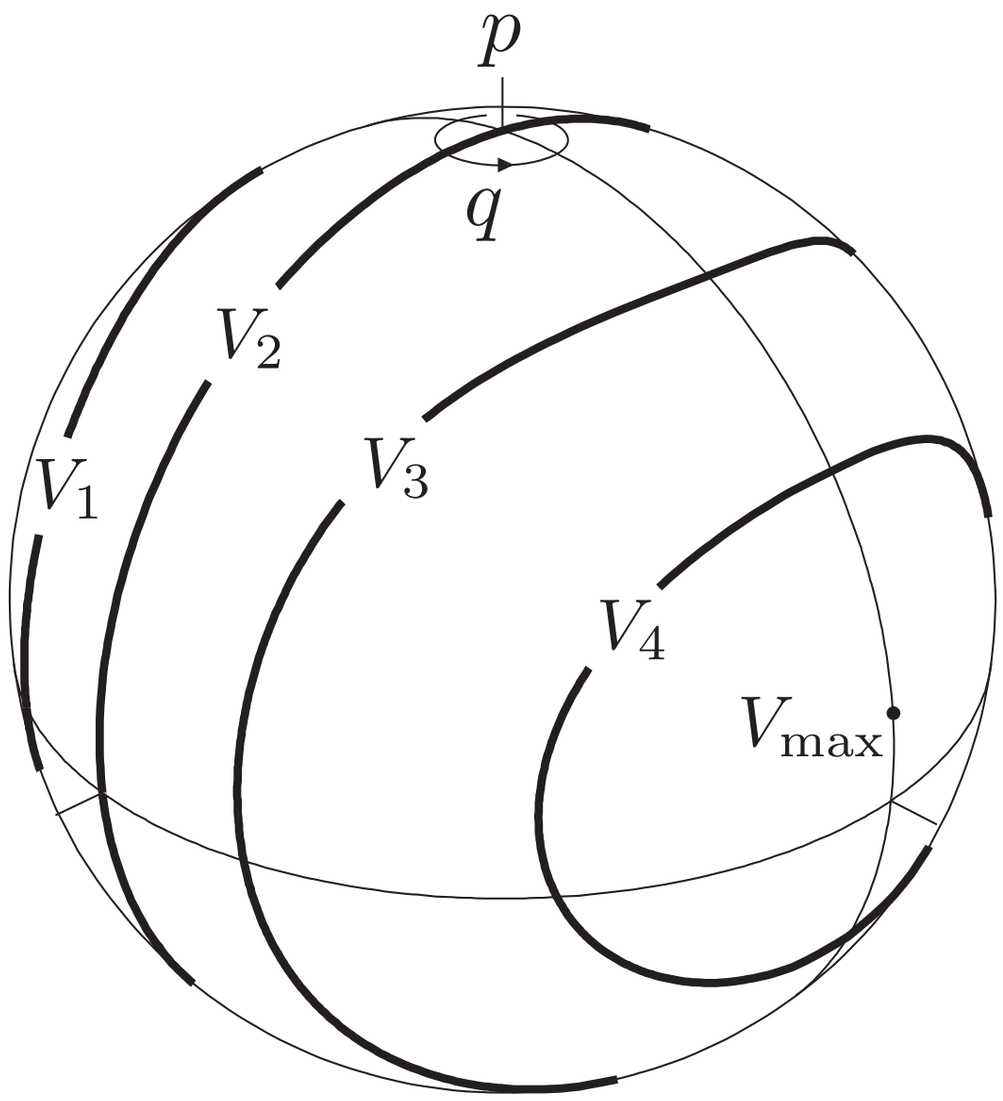
It is also possible to partially describe a tetrahedron by specifying its four face areas: A_1, A_2, A_3, and A_4.

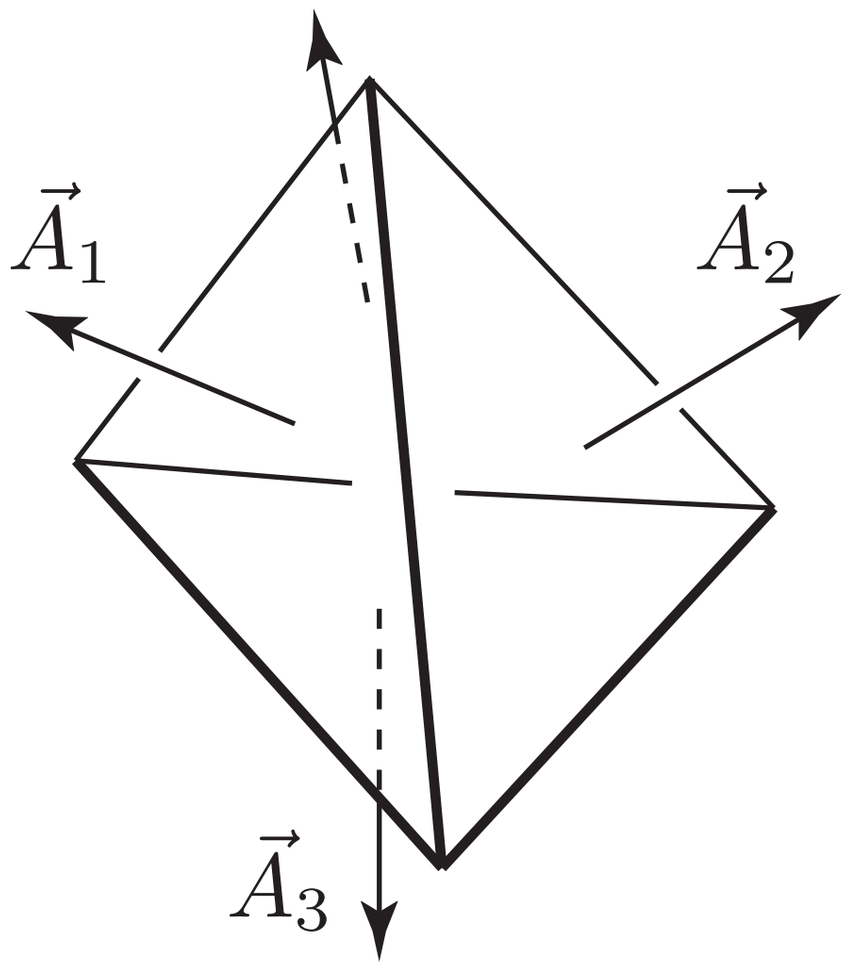
Wonderfully, the space of all tetrahedra with fixed face areas A_1, A_2, A_3, and A_4 is a sphere!



Can we pick out all tets in this space with a given V? Yes!

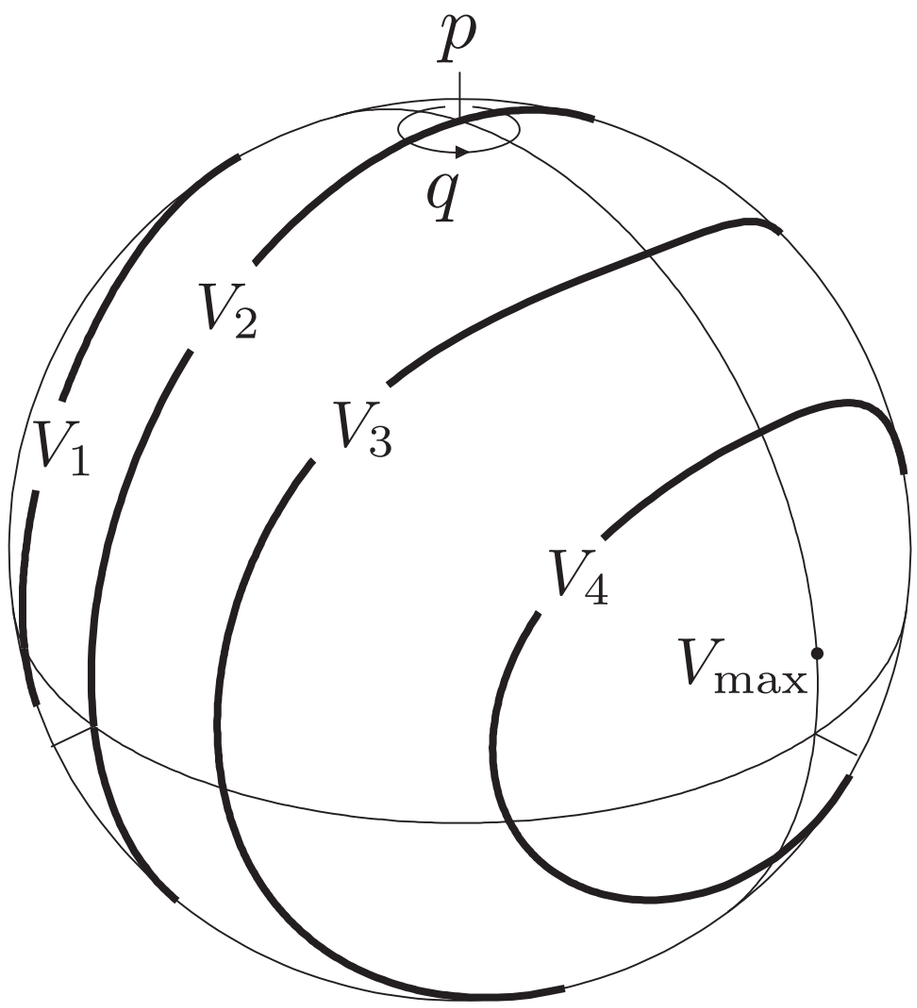
Families of tetrahedra with volumes V_1, V_2, V_3, and V_4.



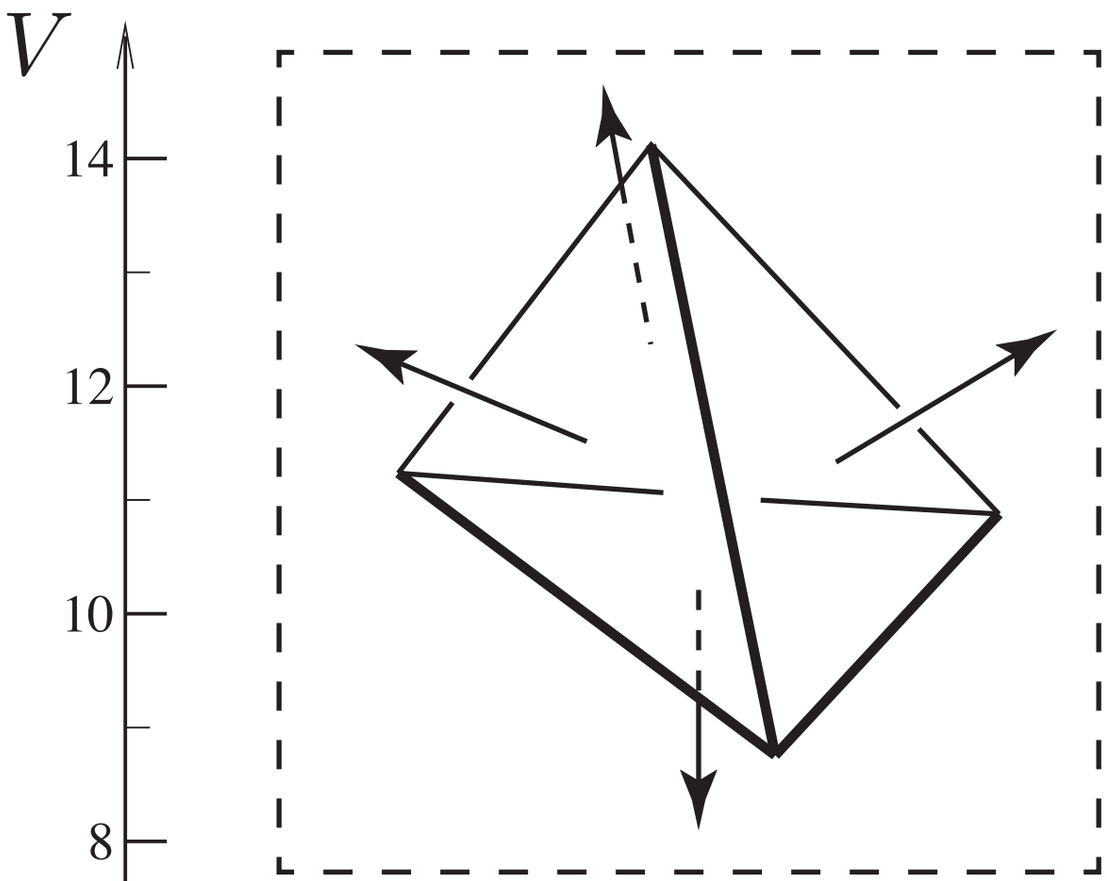


It turns out: $V = \frac{\sqrt{2}}{3}\sqrt{|\vec{A}_1 \cdot (\vec{A}_2 \times \vec{A}_3)|}$

Following Bohr and Sommerfeld, we can now ask: what if a grain of space is a wave spread out over all tets of a given volume?



Are there special volumes where this wave matches up?



$$V_{\mathrm{Tet}} = \frac{\sqrt{2}}{3} \times \sqrt{|\vec{A}_1 \cdot (\vec{A}_2 \times \vec{A}_3)|}$$

$$A_1 = j + 1/2$$
$$A_2 = j + 1/2$$
$$A_3 = j + 1/2$$
$$A_4 = j + 3/2$$

$\circ$ = Numerical

$\bullet$ = Bohr-Som

Is this proof that space (and even time?) are fundamentally discrete? Certainly not!

The best proof for that would be empirical. This is difficult. The scale of the predicted discreteness is the Planck length $\sim 10^{-35}$ m.

But, it is a remarkable confluence of the ideas that led to general relativity and to quantum mechanics.

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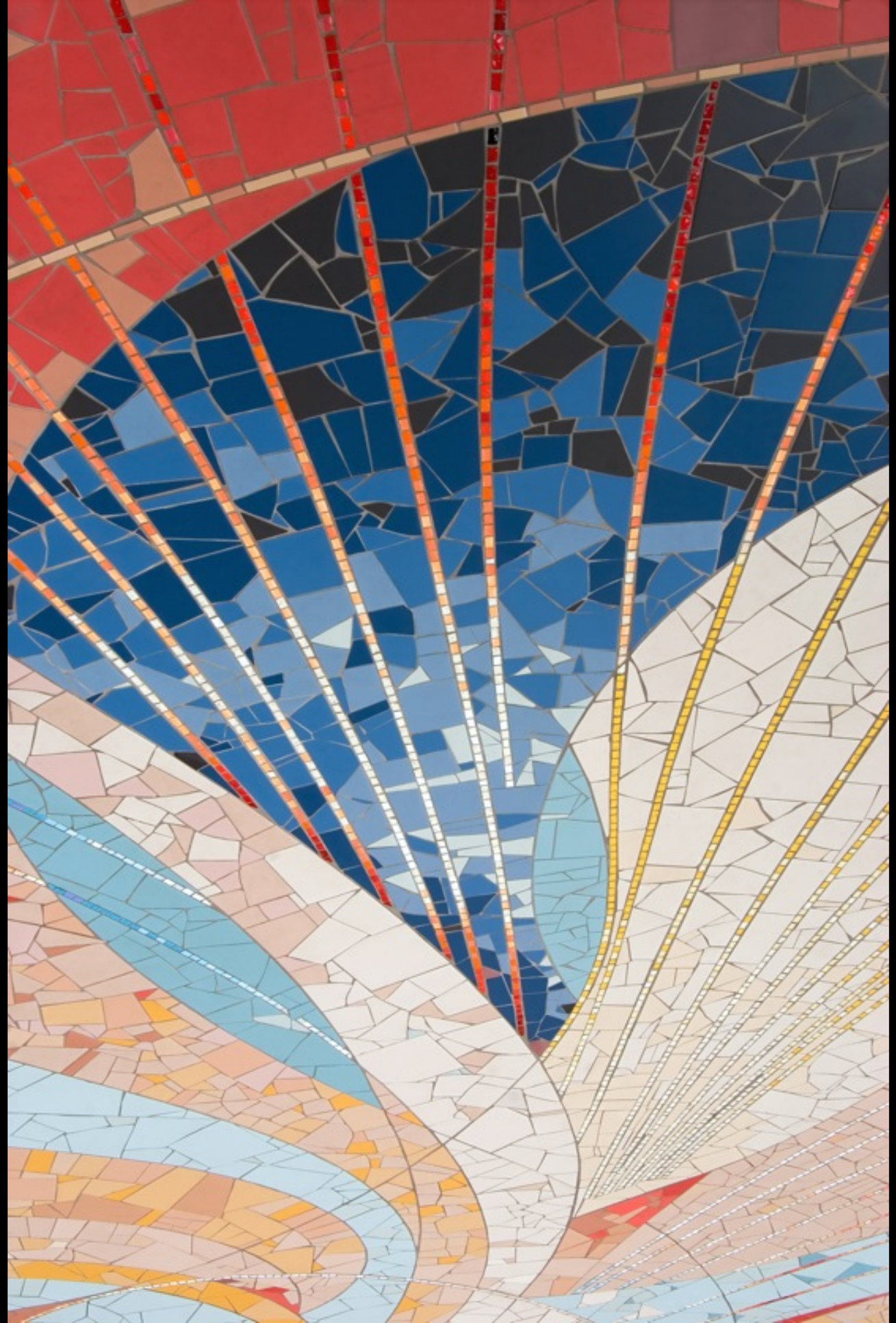
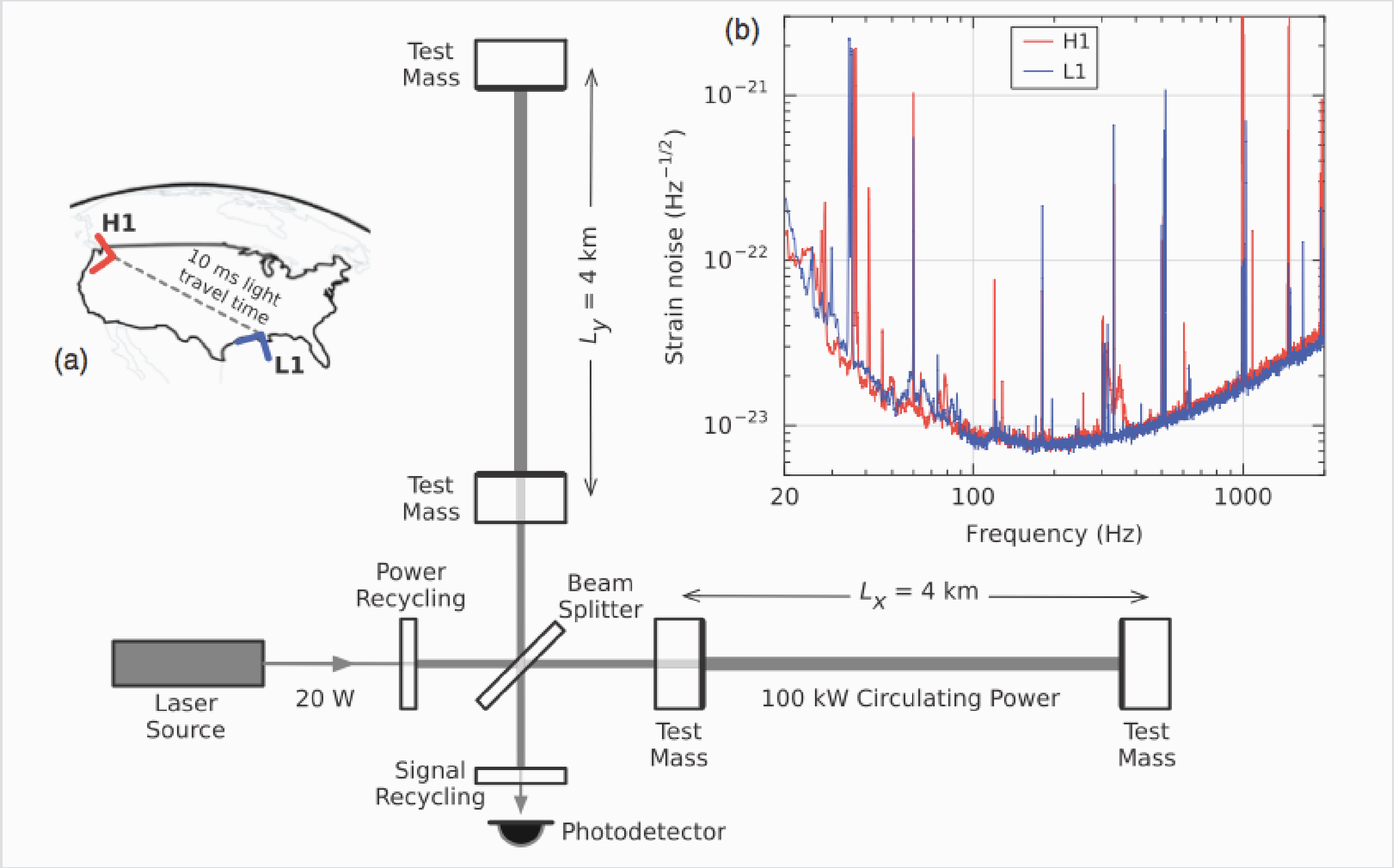
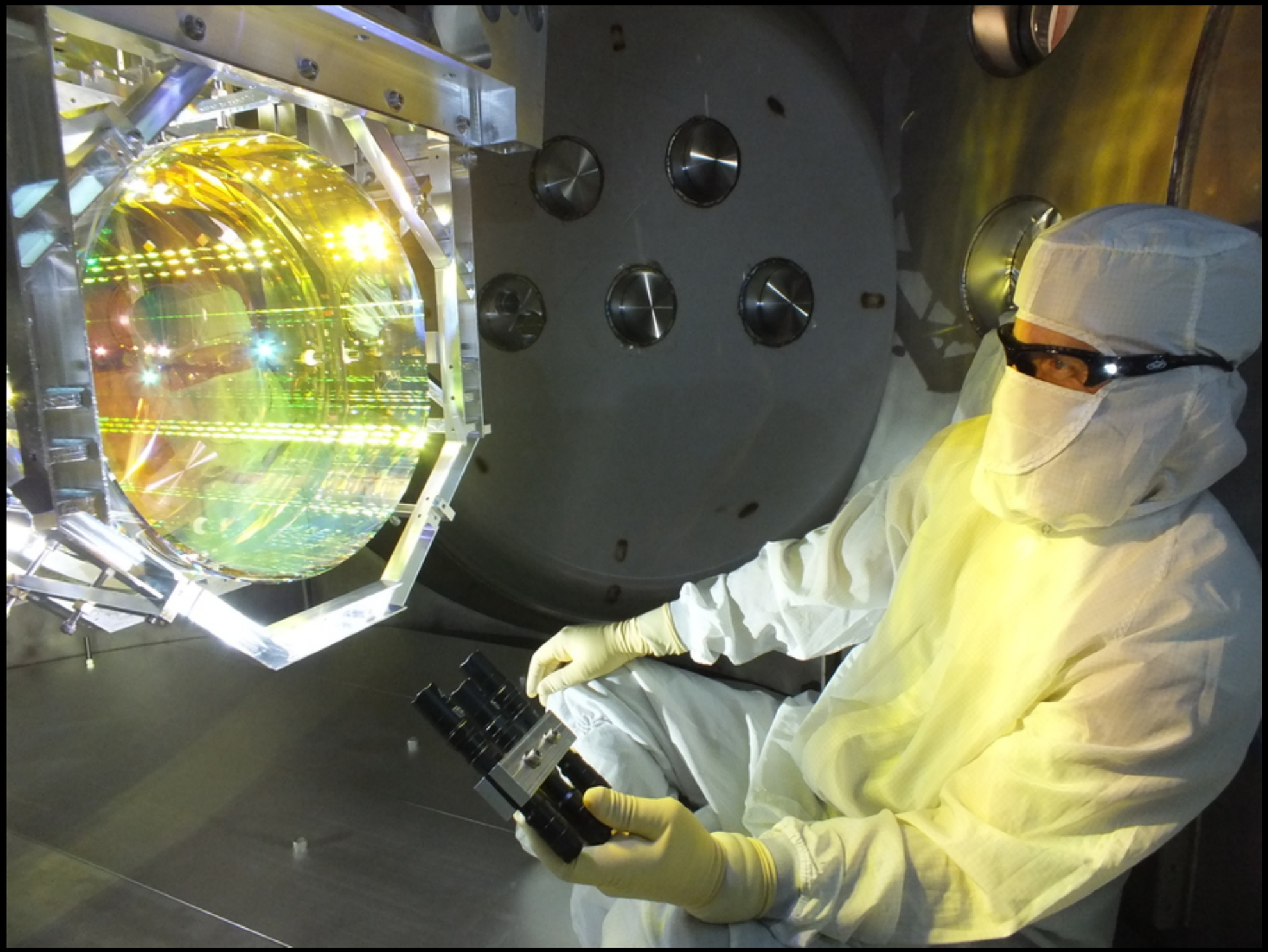


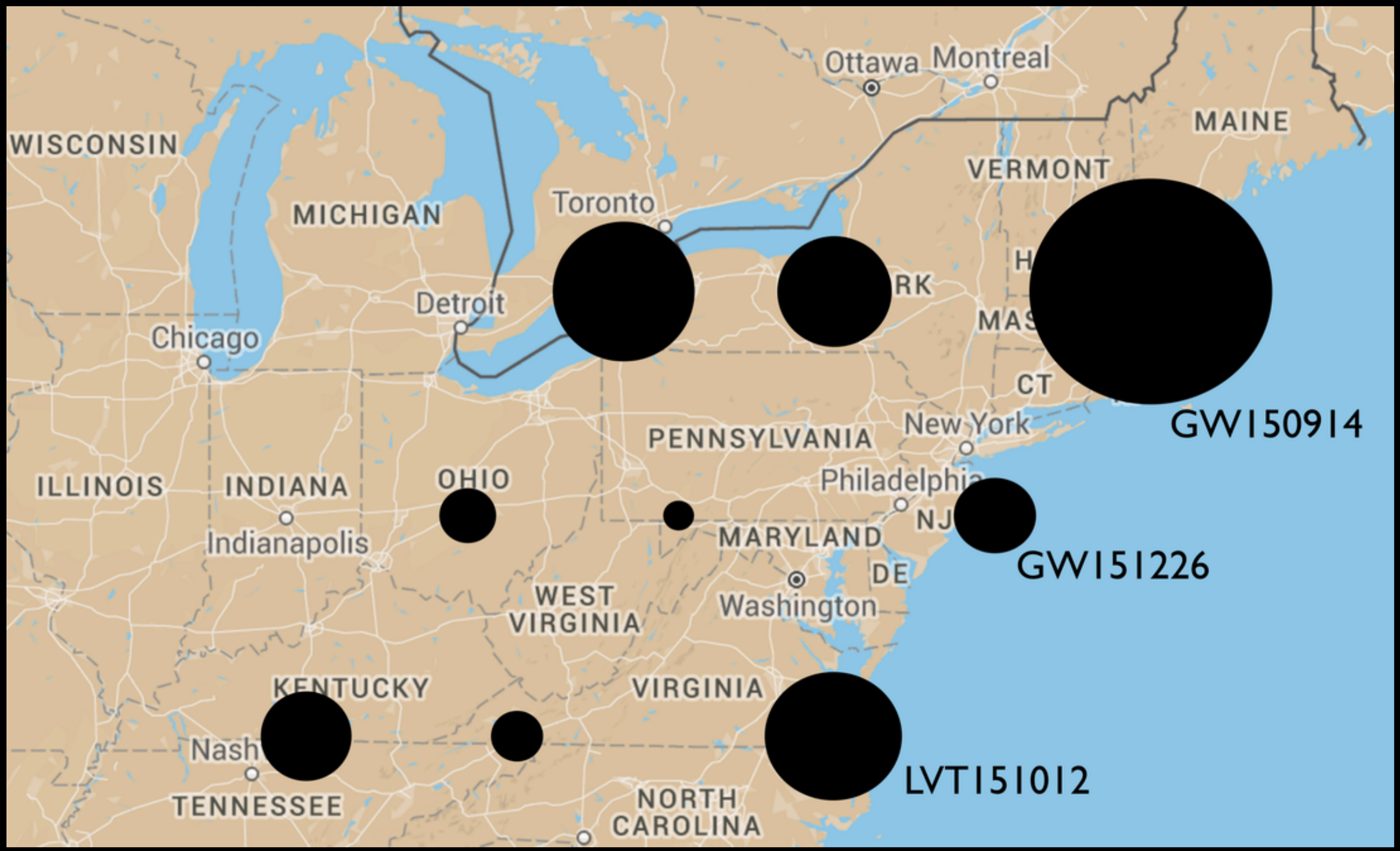
The End

How did they do something so spectacular?



The mirrors

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APRIL 2019

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MAY 2019

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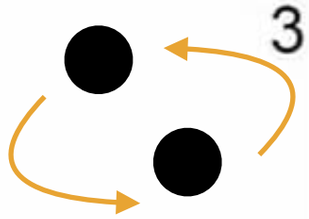
28	29	30	1	2	3 	4
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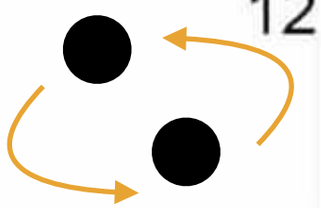
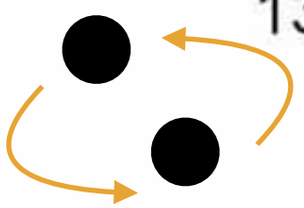
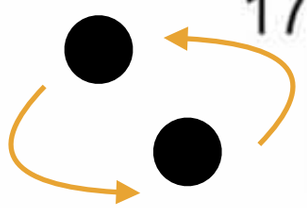
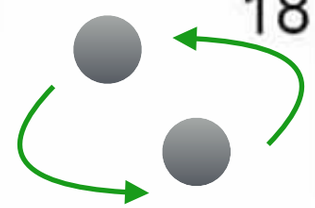
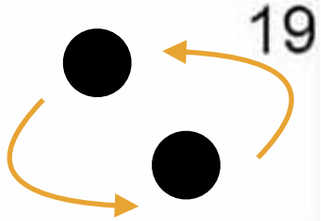
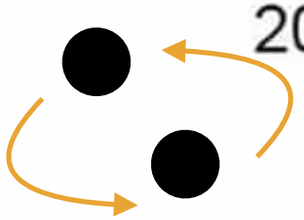
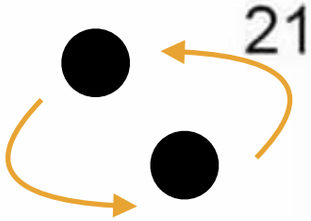
12 	13 	14	15	16	17 	18 
19 	20 	21 	22	23	24	25
26	27	28	29	30	31	

LIGO is currently on hiatus, but in November check out GraceDB

gracedb.ligo.org/latest/

gracedb.ligo.org/latest/

GraceDB — Gravitational-Wave Candidate Event Database

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Latest — as of 11 October 2019 18:40:56 UTC

Test and MDC events and superevents are not included in the search results by default; see the query help for information on how to search for events and superevents in those categories.

Query:

Search for: Superevent

Search

UID	Labels	t_start	t_0	t_end	FAR (Hz)	Created (UTC)
S190930t	ADVOK EM_Selected SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1253889264.685342	1253889265.685342	1253889266.685342	1.543e-08	2019-09-30 14:34:30 UTC
S190930s	PE_READY ADVOK EM_Selected SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1253885758.235347	1253885759.246810	1253885760.253734	3.008e-09	2019-09-30 13:36:04 UTC