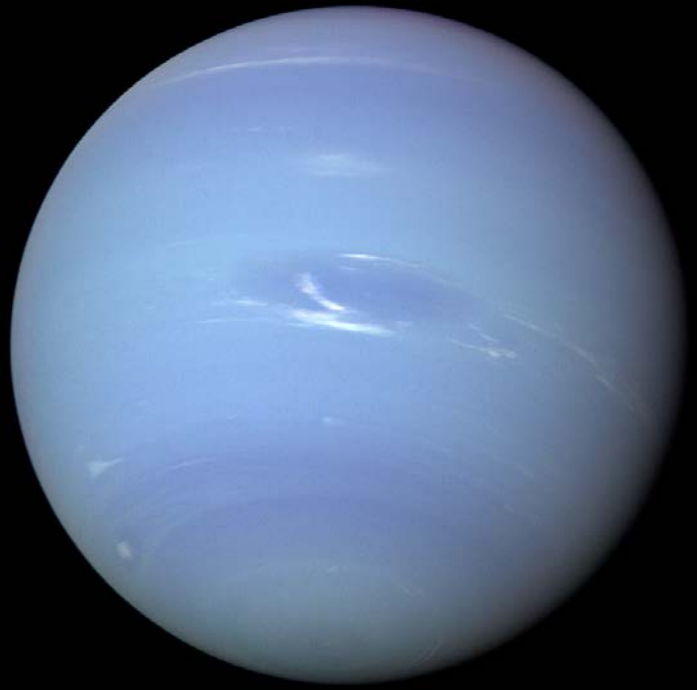
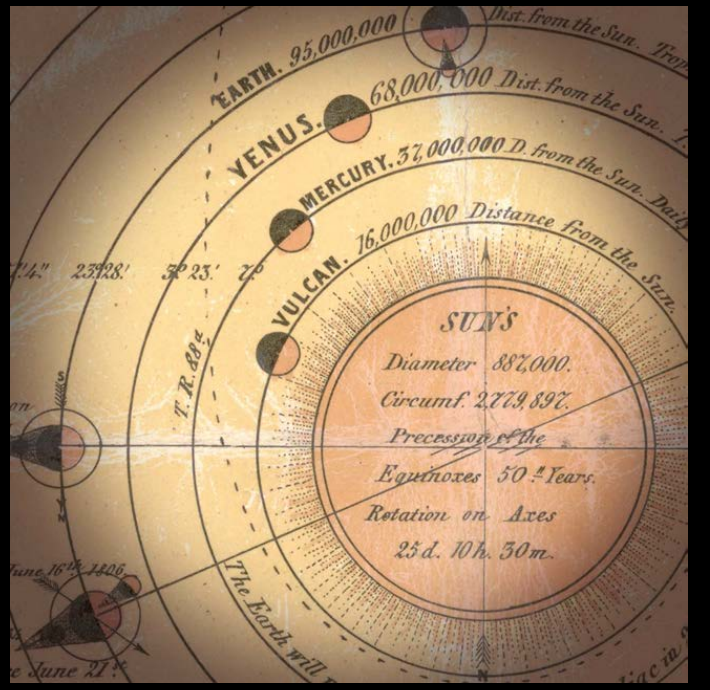
Precision cosmology before Einstein: Neptune and Vulcan as dark matter in the 19th century





Yasushi Suto Department of Physics, the University of Tokyo

Physics Department Colloquium @ Kyoto University: 15:00-16:30 October 18, 2023

http://www-utap.phys.s.u-tokyo.ac.jp/~suto/mypresentation_2023e.html

Today's talk

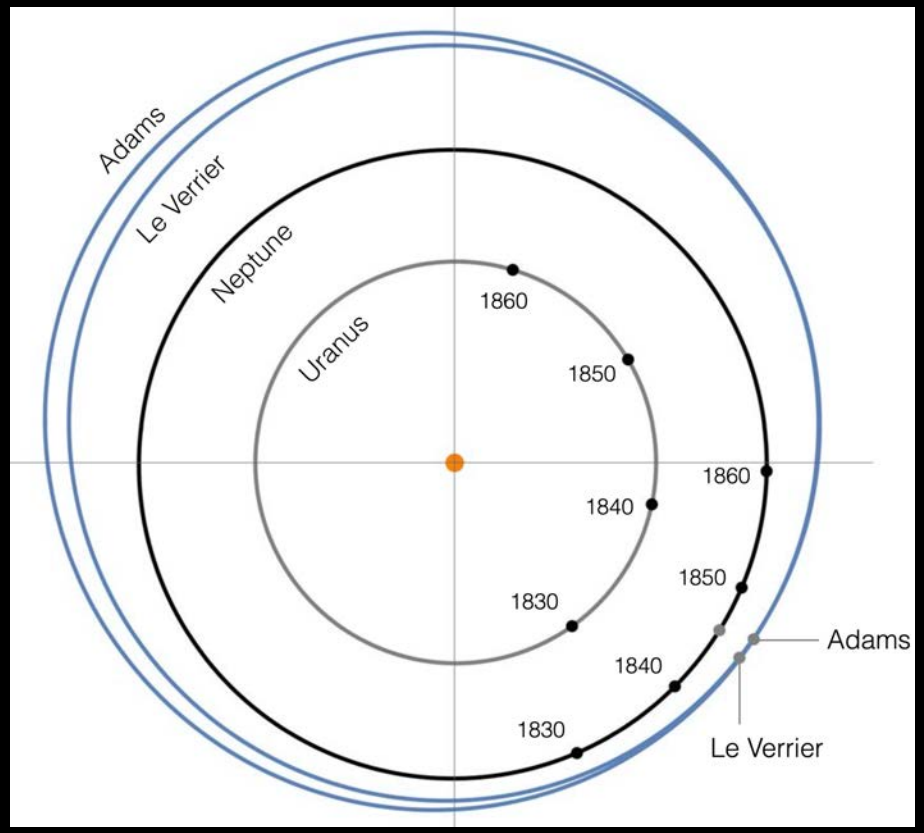
1 Neptune, Vulcan, and Pluto
as "dark matter in the universe"

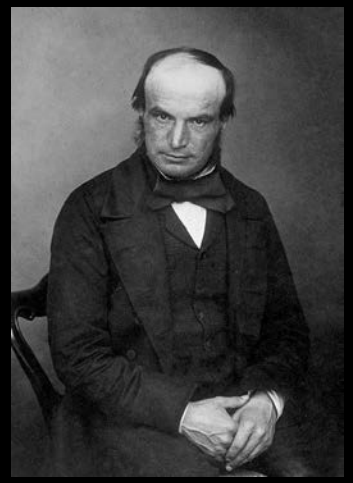
2 Can AI take over the role of Newton, Le Verrier and/or Adams? (very preliminary on-going project)

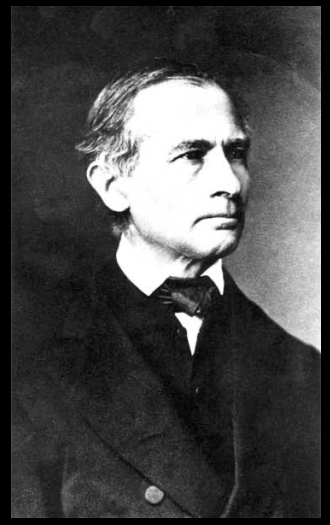
3 Summary

1 Neptune, Vulcan, and Pluto as “dark matter in the universe”

Discovery of Neptune



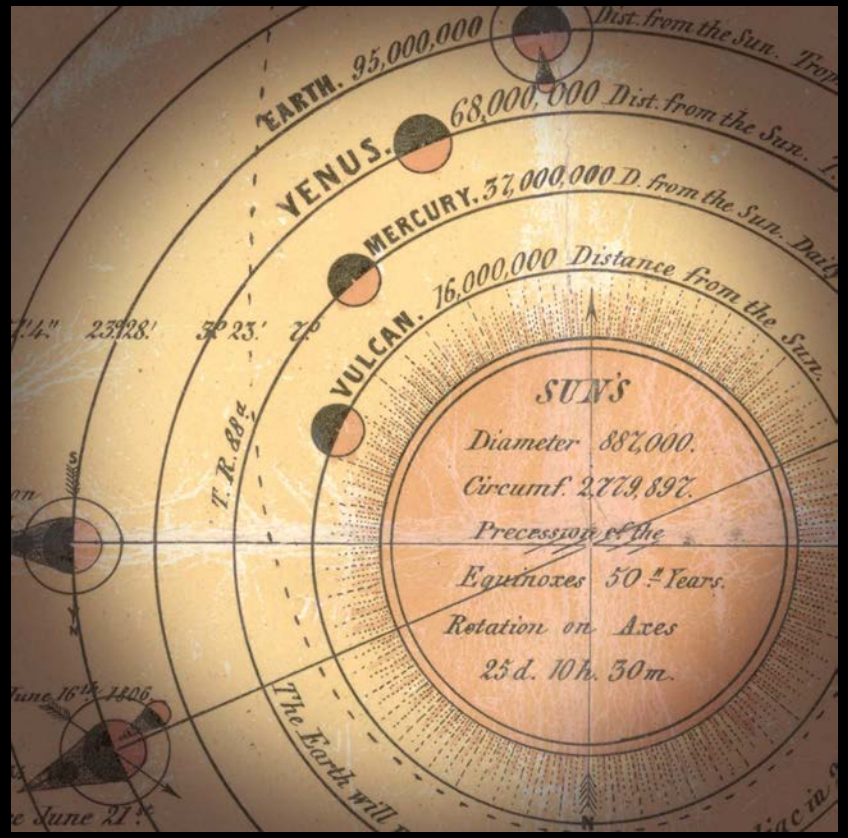




- **Uranus (1781)**
  - discovered in March 1781 by William Herschel
  - its orbit is not fully consistent with Newtonian prediction
  - 8th planet? by Alexis Bouvard

- **Neptune (1846)**
  - independently predicted by Adams and Le Verrier
  - discovered in September 1846 by J.G. Galle

Mercury's "anomalous" perihelion shift and Vulcan



- **Vulcan (1859)**
  - Le Verrier recognized the precession of Mercury is inconsistent with Newtonian theory by 38" per century
  - Le Verrier predicted an unknown planet inside Mercury's orbit in 1859 and named it Vulcan
  - Lescarbault "discovered" its transit over the Sun on March 26, 1859, and was awarded the Légion d'honneur

- **Mercury's perihelion shift (532" per century)**

  = 276.38(Venus) + 91.41(Earth) + 2.48(Mars) + 153.98(Jupiter)
  + 7.31(Saturn) + 0.14(Uranus) + 0.04(Neptune) + 43(GR)

Was Newton indeed right?

1894AJ....

ASTRONOMICAL JOURNAL.

No. 319.

VOL. XIV. BOSTON, 1894 JUNE 2. NO. 7.

A SUGGESTION IN THE THEORY OF *MERCURY*,

By A. HALL.

About forty years ago LeVerrier found that the line of apsides of the orbit of *Mercury* is in motion at the rate of 38″ a century more than the known forces will explain. Since then Professor Newcomb has made a new investigation of this question, and from a more extended series of observations has confirmed the result found by LeVerrier. Newcomb's result is a little greater, being 43″ a century. This anomalous motion in the line of apsides is the starting point of LeVerrier's theory of an intra-Mercurial planet, situated nearly in the plane of the orbit of *Mercury*. Several such planets have been supposed to be found; one by Dr. Lescarbault in 1859, with a period of 20 days, and others by Professors Watson and Swift in 1878. These discoveries, however, have not been confirmed to the satisfaction of astronomers. There are also theoretical objections to the introduction of such bodies, since they would disturb the motions of other planets. Some years ago Tisserand

If the Newtonian law of attraction is not a rigorous law of nature, or if it is modified slightly under certain conditions, probably this lack of rigor would become apparent first among the swiftly moving bodies of our solar system, such as our *Moon* and the planet *Mercury*. In his *Principia*, Book I, Newton has given some computations in which he assumes the law of attraction to be not exactly as the inverse second power of the distance. He shows that the perihelia would move under the action of such a central force; and on the other hand the observed fixity of the perihelia is a strong proof of his law of attraction. Laplace in his *Mécanique Céleste*, Book XVI, Chap. IV, has investigated some assumed changes of the law of attraction, and has shown in what terms of the *Moon's* motion these changes would become apparent. In 1873 Bertrand brought for-

Perihelion shift under non-Newtonian gravity $\propto 1/r^{1+\delta}$

$$L = \frac{1}{2}(\dot{r}^2 + r^2\dot{\varphi}^2) - V(r)$$

$$V(r) = -\frac{\alpha}{r^{1+\delta}}$$

$$\ddot{r} = r\dot{\varphi}^2 - (1+\delta)\frac{\alpha}{r^{2+\delta}}$$

$$\dot{\varphi} = \frac{h}{r^2}$$

$$\ddot{x} = \frac{h^2}{(a+x)^3} - (1+\delta)\frac{\alpha}{(a+x)^{2+\delta}} \approx \frac{h^2}{a^3} - (1+\delta)\frac{\alpha}{a^{2+\delta}} - (1-\delta)\frac{h^2}{a^4}x$$

$$\frac{w_\varphi}{w_r} = \frac{1}{\sqrt{1-\delta}} \quad \Rightarrow \quad \Delta\varphi = \left(\frac{2\pi}{\sqrt{1-\delta}} - 2\pi\right)\frac{T}{P_{\text{orb}}} \approx \pi\delta\frac{T}{P_{\text{orb}}}$$

$$\delta = \frac{\Delta\varphi P_{\text{orb}}}{\pi T} = \frac{43'' \times 88\text{days}}{\pi \times 100\text{yrs}} \approx 1.6 \times 10^{-7}$$

$$V(r) \propto \frac{1}{r^{1.00000016}}$$

Serious consideration of hypotheses that may explain Mercury's anomalous perihelion shift

THE ELEMENTS

OF THE

FOUR INNER PLANETS

AND THE

FUNDAMENTAL CONSTANTS OF ASTRONOMY

The elements of the four inner planets and the fundamental constants of astronomy (1897)

SIMON NEWCOMB

Supplement to the American Ephemeris and Nautical Almanac for 1897

Page.

CHAPTER VI.—EXAMINATION OF HYPOTHESES AND DETERMINATION OF THE MASSES BY WHICH THE DEVIATIONS OF THE SECULAR VARIATIONS FROM THEIR THEORETICAL VALUES MAY BE EXPLAINED.

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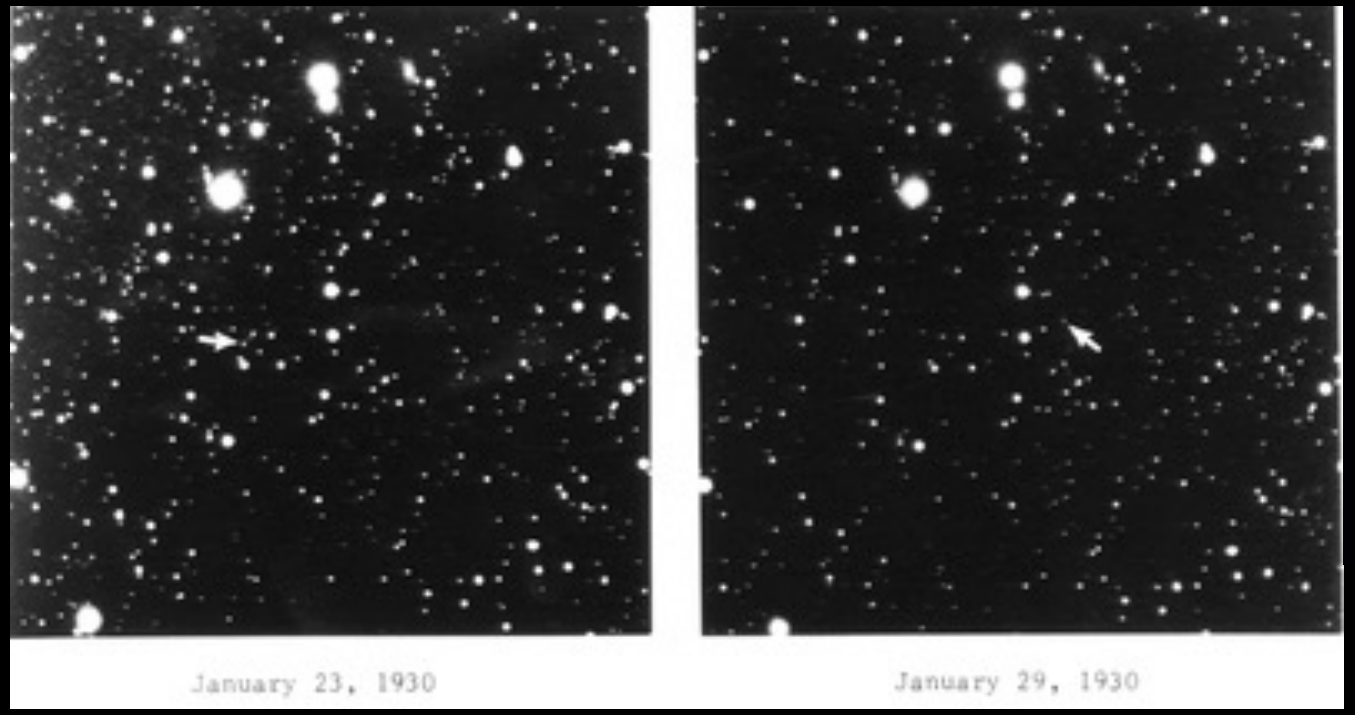
§ 61. Hypothesis that gravitation toward the Sun is not exactly as the inverse square of the distance 118

Planet X and discovery of Pluto

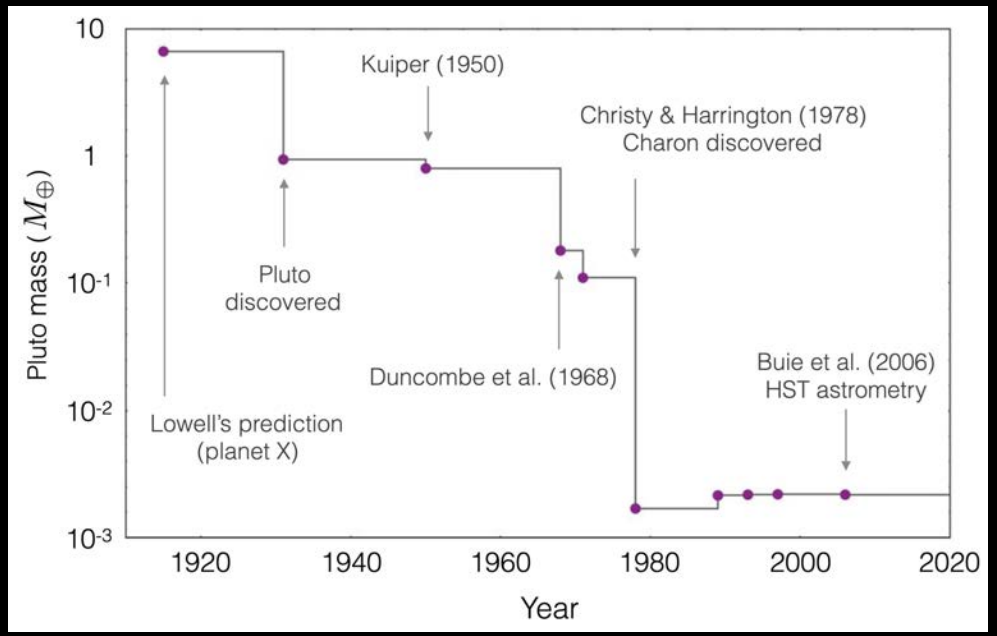
- **Percival L. Lowell (1855-1916)**
  - Born in a very rich family, and founded the Lowell observatory by himself
  - Believed intelligent life forms exist on Mars
    - *Mars (1895), Mars and Its Canals (1906), and Mars As the Abode of Life (1908)*
  - Predicted Planet X that disturbs the orbits of Uranus and Neptune

- **Elizabeth Langdon Williams (1879-1981)**
  - a human computer and astronomer hired by Lowell
  - Her calculations led to Lowell's prediction for the location of Planet X that **Clyde Tombaugh** used to locate an image in a region of the sky photographed in 1915. He discovered a new "planet" named ***PL***uto in 1930

Rise and fall of Pluto

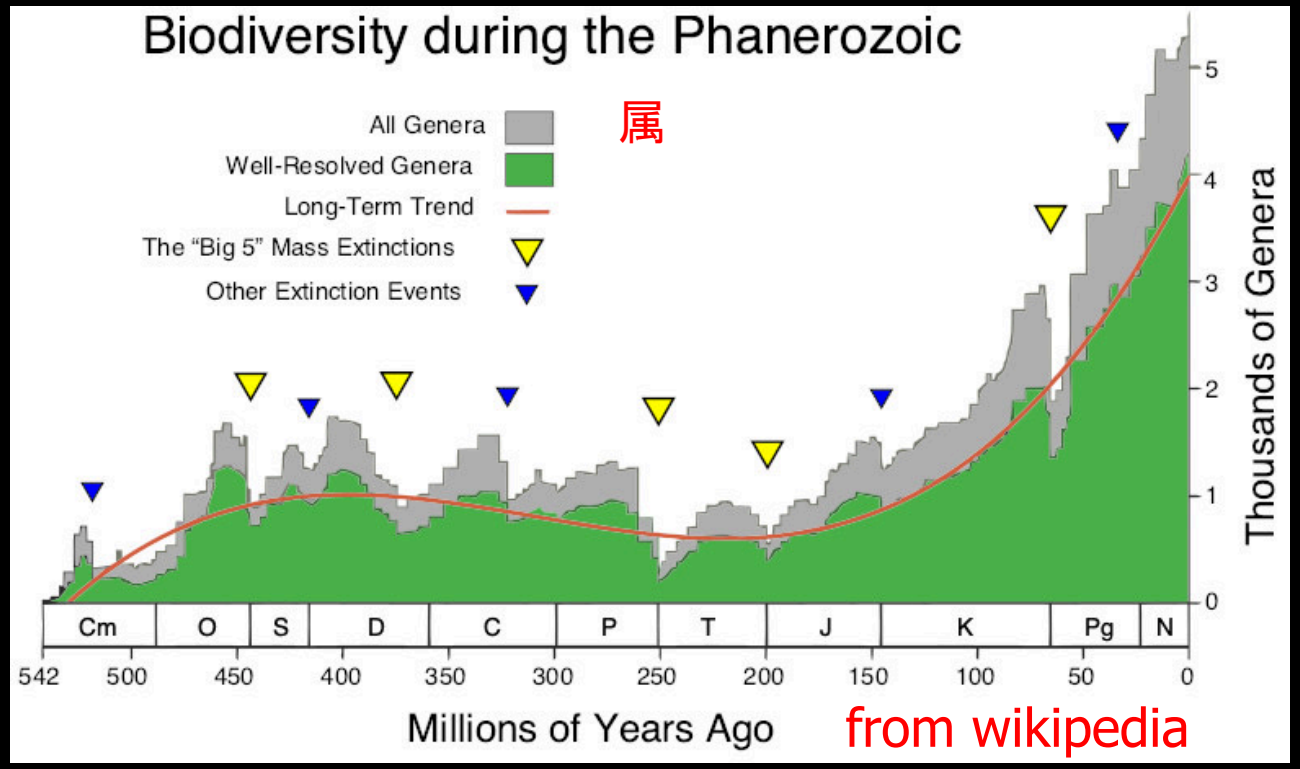


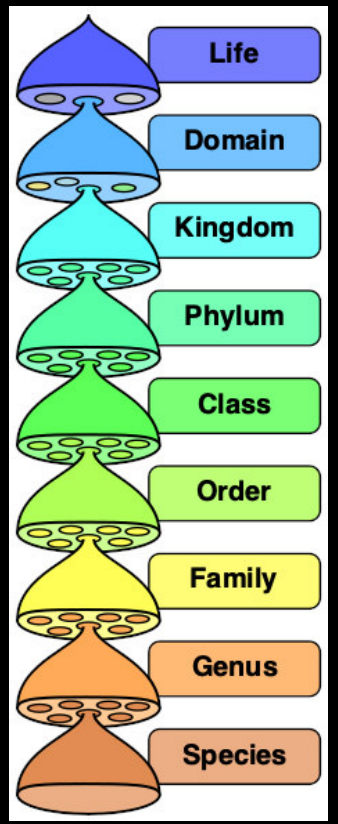
- A great success story !?
  - Lowell's prediction was totally wrong
  - the discovery in 1930 was just accidental !
  - Walt Disney's Pluto in 1931
  - Plutonium in 1941
  - stepdown as a dwarf planet in 2006



Nemesis explains extinction events ?

- Dinosaur's extinction 65Myr ago
  - KT boundary: collision of a (10-15)km asteroid (Alvarez et al. 1980)
- 12 extinction events over the past 250Myr (?)
  - **Nemesis**: an eccentric brown dwarf companion of the Sun: 26Myr period and semi-major axis of 88,000 au (Davis, Hut and Muller 1984)





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Modified gravity law or dark matter?

- Uranus's strange motion
  - Newton's law + dark matter (=Neptune) ? ⇒Yes
- Mercury's anomalous perihelion shift
  - Newton's law + dark matter (=Vulcan) ? ⇒ No
  - modified gravity law ($\propto 1/r^{2.00000016}$) ? ⇒ No
  - perfectly explained by modified gravity law (=general relativity)
- Neptune's strange motion
  - Newton's law + dark matter (=Pluto) ? ⇒ No! but…
  - incorrect prediction led to the accidental detection of Pluto

Lessons learned

	New physics or dark matter?	implication
Neptune	First detection of unknown object ("dark matter") from accurate theoretical prediction	Law of known physics (Newton's law of gravity) is great
Vulcan	First false-positive of unknown object from an incorrect hypothesis in known physics	Amazing accuracy and reliability of astronomical data Eventually solved by new physics (GR) without Vulcan
Pluto	Serendipitous detection of unknown object from incorrect computation	Even not-so-smart theorists may be useful sometimes

New physics beyond standard cosmology?

- Accelerated expansion of the universe
  - GR + dark energy ?
  - modified gravity (without dark energy) ?
- Nature of dark matter and dark energy
  - interaction with ordinary matter other than gravity ?
  - how to incorporate them in particle physics model ?
- Hubble tension
  - mismatch of the Hubble constant measured from the SN Ia ($z<2$) and from CMB ($z=1000$) ?
- S_8 tension
  - mismatch of the fluctuation amplitude measured from gravitational lensing and from CMB ?
- **Remember lessons from Neptune, Vulcan, and Pluto!**

2 Can AI take over the role of Newton, Le Verrier and/or Adams?

(very preliminary on-going project)

Florian Lalande, YS, Alessandro Trani, Toshinori Hayashi,
Pablo Lemos, & Shirley Ho (in preparation)

arXiv:2202.02306

Rediscovering orbital mechanics with machine learning

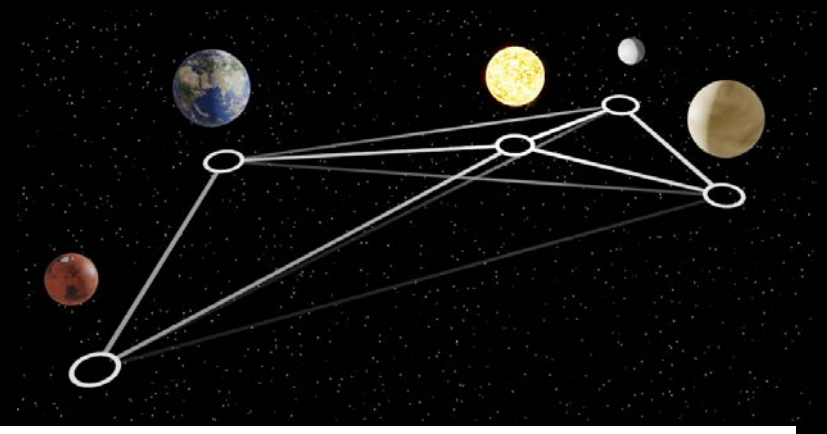
Pablo Lemos [*1,2], Niall Jeffrey [†3,2], Miles Cranmer[4], Shirley Ho[4,5,6,7], and Peter Battaglia[8]

[1]Department of Physics and Astronomy, University of Sussex,Brighton, BN1 9QH, UK
[2]University College London, Gower St, London, UK
[3]Laboratoire de Physique de l'Ecole Normale Supérieure, ENS, Université PSL, CNRS, Sorbonne Université Université de Paris, Paris, France
[4]Department of Astrophysical Sciences, Princeton University, Princeton, New Jersey 08544, USA
[5]Center for Computational Astrophysics, Flatiron Institute, New York, NY 10010, USA
[7]Department of Physics, New York University, New York, NY 10011, USA
[6]Department of Physics, Carnegie Mellon University, Pittsburgh, PA 15217, USA
[8]DeepMind, London, N1C 4AG, UK

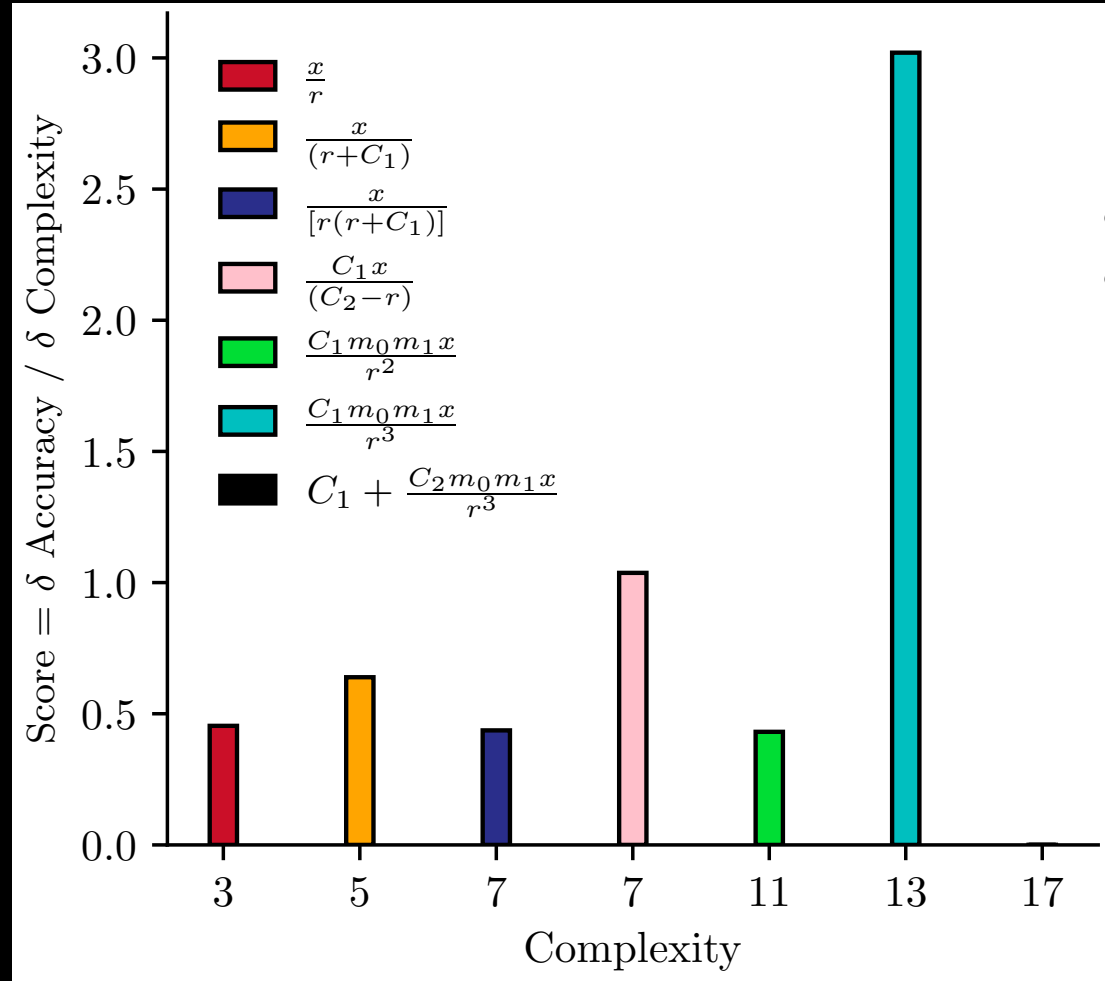
an interesting attempt to discover an analytic gravity law combining Graph Neural Network and symbolic regression

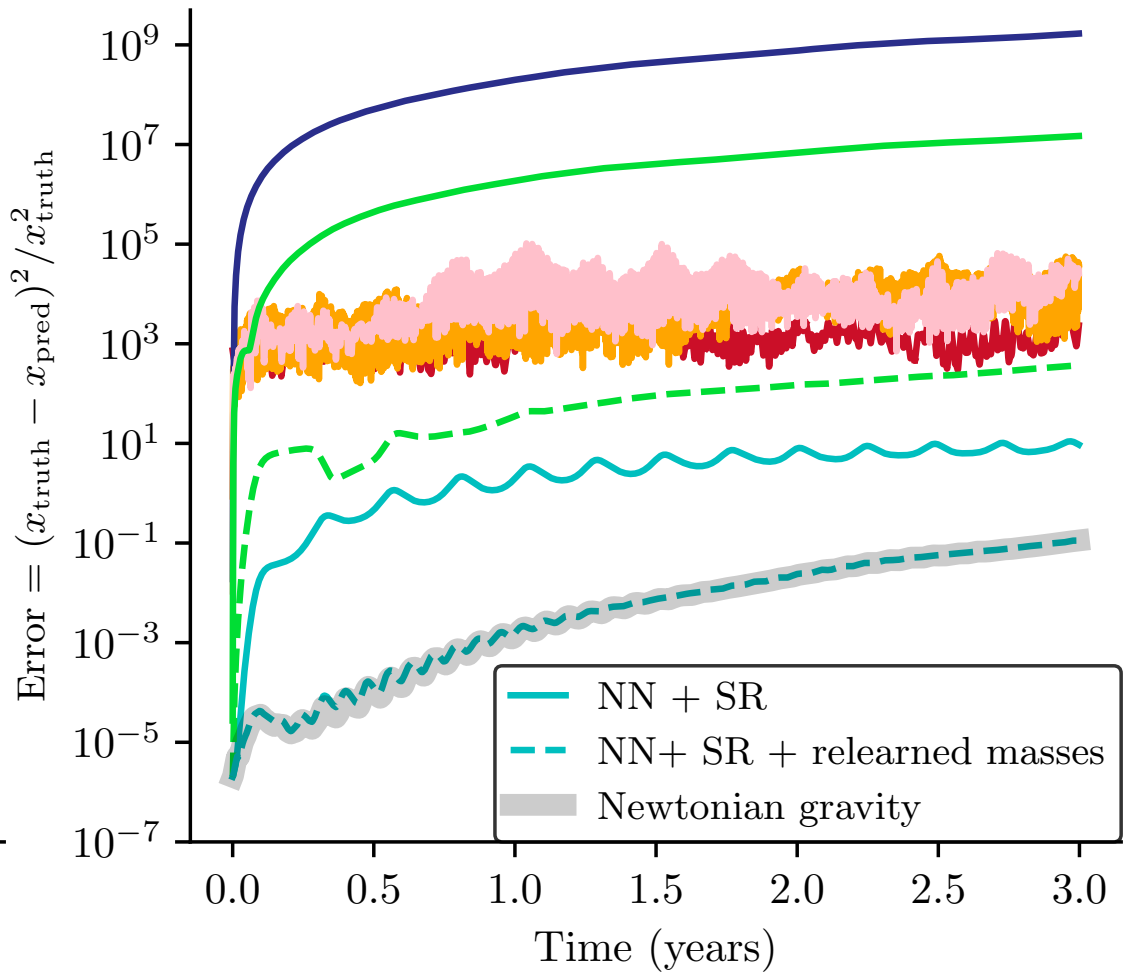
We present an approach for using machine learning to automatically discover the governing equations and hidden properties of real physical systems from observations. We train a "graph neural network" to simulate the dynamics of our solar system's Sun, planets, and large moons from 30 years of trajectory data. We then use symbolic regression to discover an analytical expression for the force law implicitly learned by the neural network, which our results showed is equivalent to Newton's law of gravitation. The key assumptions that were required were translational and rotational equivariance, and Newton's second and third laws of motion. Our approach correctly discovered the form of the symbolic force law. Furthermore, our approach did not require any assumptions about the masses of planets and moons or physical constants. They, too, were accurately inferred through our methods. Though, of course, the classical law of gravitation has been known since Isaac Newton, our result serves as a validation that our method can discover unknown laws and hidden properties from observed data. More broadly this work represents a key step toward realizing the potential of machine learning for accelerating scientific discovery.

Discovered equations from Graph Neural Network + Symbolic Regression



Lemos et al. arXiv:2202.02306

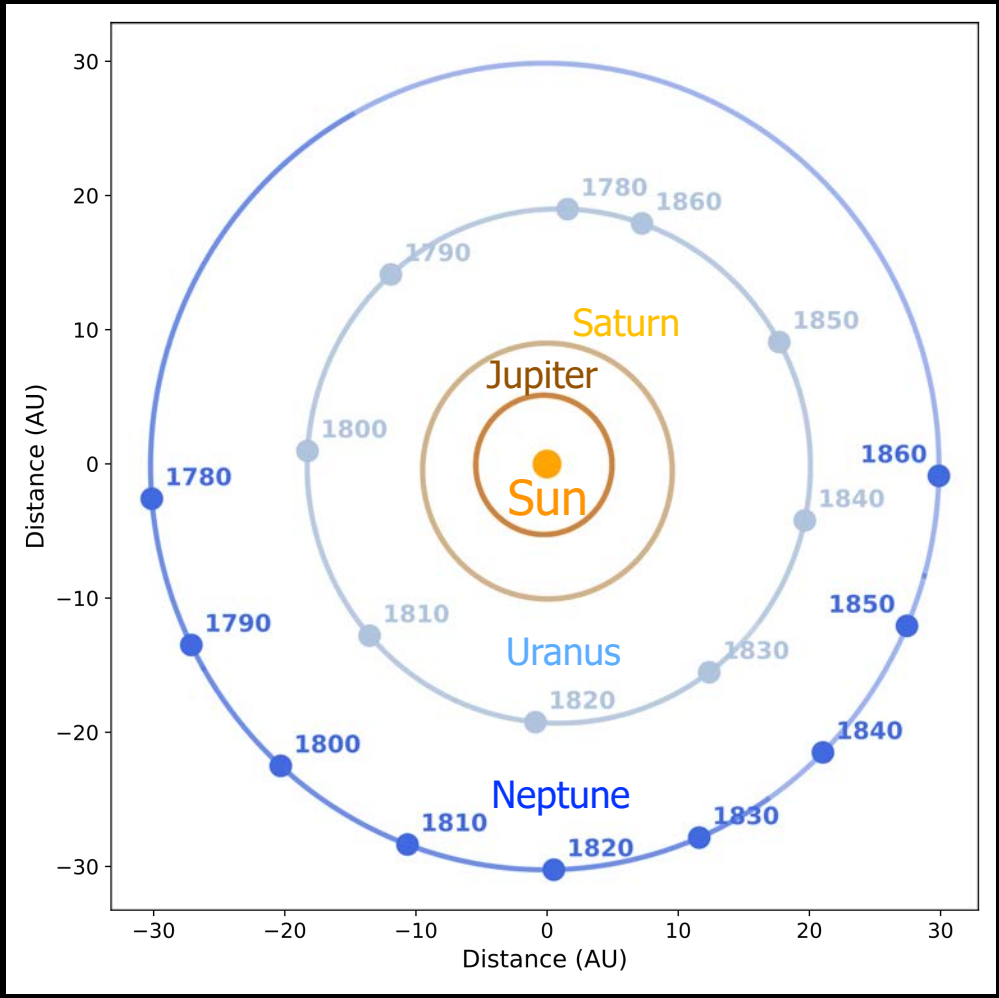




Our current project is complementary and *probably more modest* "Can AI find new physics beyond the standard model?" or " Can AI predict an unknown component under the standard physics?"

- Can AI practically reproduce the law of gravity from the Solar system dynamics?
  - empirical discovery of the inverse square law of gravity
  - AI vs. Newton
- Can AI predict the presence of an unknown planet beyond Uranus without assuming the inverse square law?
  - AI vs. Le Verrier and Adams

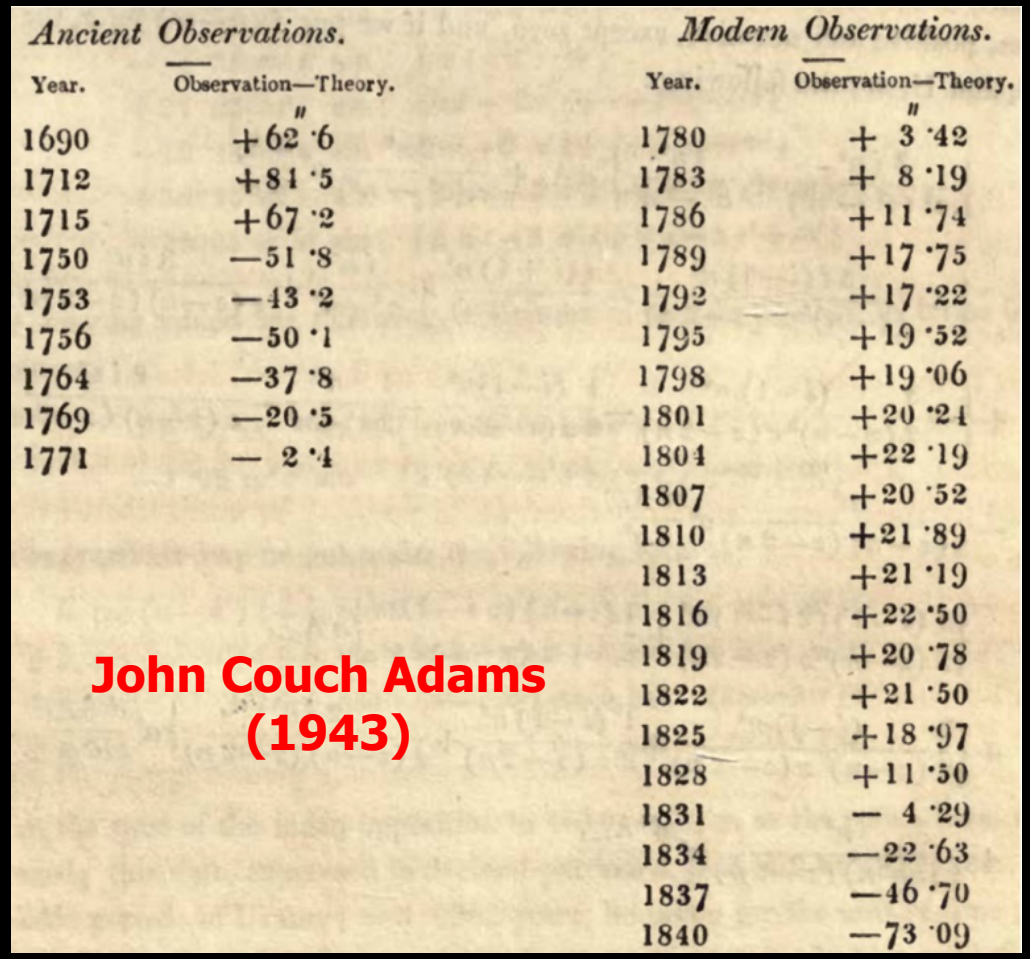
Distinguishing between the gravity-law and the effect of Neptune



- Uranus and Neptune are in an inferior conjunction around **1820**
  - Before 1820, Neptune accelerates the orbital motion of Uranus
  - After 1820, Neptune decelerates the orbital motion of Uranus
- This phase-dependent effect of Neptune is unlikely to be mimicked by any modified law of gravity
  - Uranus discovered in 1781=1820-39
  - Neptune discovered in 1846=1820+26

Qualitative estimate of the required accuracy for detecting Neptune

	Uranus	Neptune
Mass	$4.3\times10^{-5}M_{sun}$	$5.1\times10^{-5}M_{sun}$
Semi-major axis	19.2au	30.2au
Eccentricity	0.046	0.0097
Orbital period	84.3 years	164.8 years



Ancient Observations.

Year.	Observation—Theory.
	"
1690	+62·6
1712	+81·5
1715	+67·2
1750	—51·8
1753	—43·2
1756	—50·1
1764	—37·8
1769	—20·5
1771	— 2·4

Modern Observations.

Year.	Observation—Theory.
	"
1780	+ 3·42
1783	+ 8·19
1786	+11·74
1789	+17·75
1792	+17·22
1795	+19·52
1798	+19·06
1801	+20·24
1804	+22·19
1807	+20·52
1810	+21·89
1813	+21·19
1816	+22·50
1819	+20·78
1822	+21·50
1825	+18·97
1828	+11·50
1831	— 4·29
1834	—22·63
1837	—46·70
1840	—73·09

John Couch Adams (1943)

- Fractional force by Neptune relative to the Sun that Uranus receives in 1820

$$\frac{GM_N/(a_N-a_U)^2}{GM_{sun}/a_U^2}\approx 5.1\times10^{-5}/0.5^2\approx 2\times10^{-4}$$

Unfortunately, too demanding…

- Modulation of orbital phase of Uranus for the first 40 years since 1820

$$\frac{360\ deg}{84\ years}\times2\times10^{-4}\times40\ years \approx 0.034\ \text{deg} = 122''$$

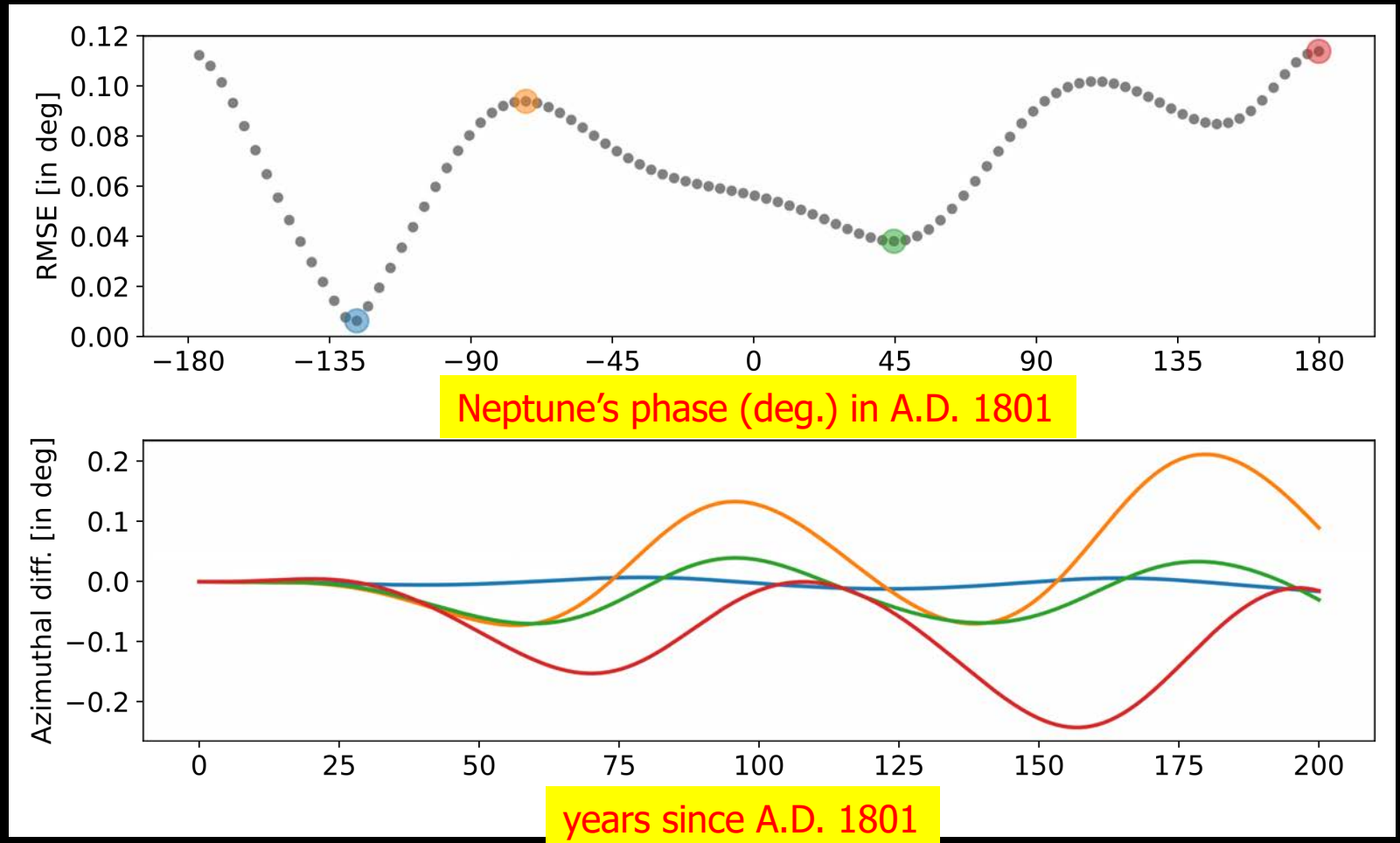
1st trial: recovery of Neptune's location for the inverse-square law of gravity $\propto 1/r^2$

- if true mass and semi-major axis are adopted, the orbital phase of Neptune is reproduced

RMSE (root-mean squared error) of Uranus's azimuthal angles (obs-pred) over 200 years between 1800 and 2000

The true value of Neptune's orbital phase in 1801 is 129.9 deg.

different color curves correspond to the four different phases in the upper panel



2nd trial: recovery of Neptune's parameters for the inverse-square law of gravity $\propto 1/r^2$

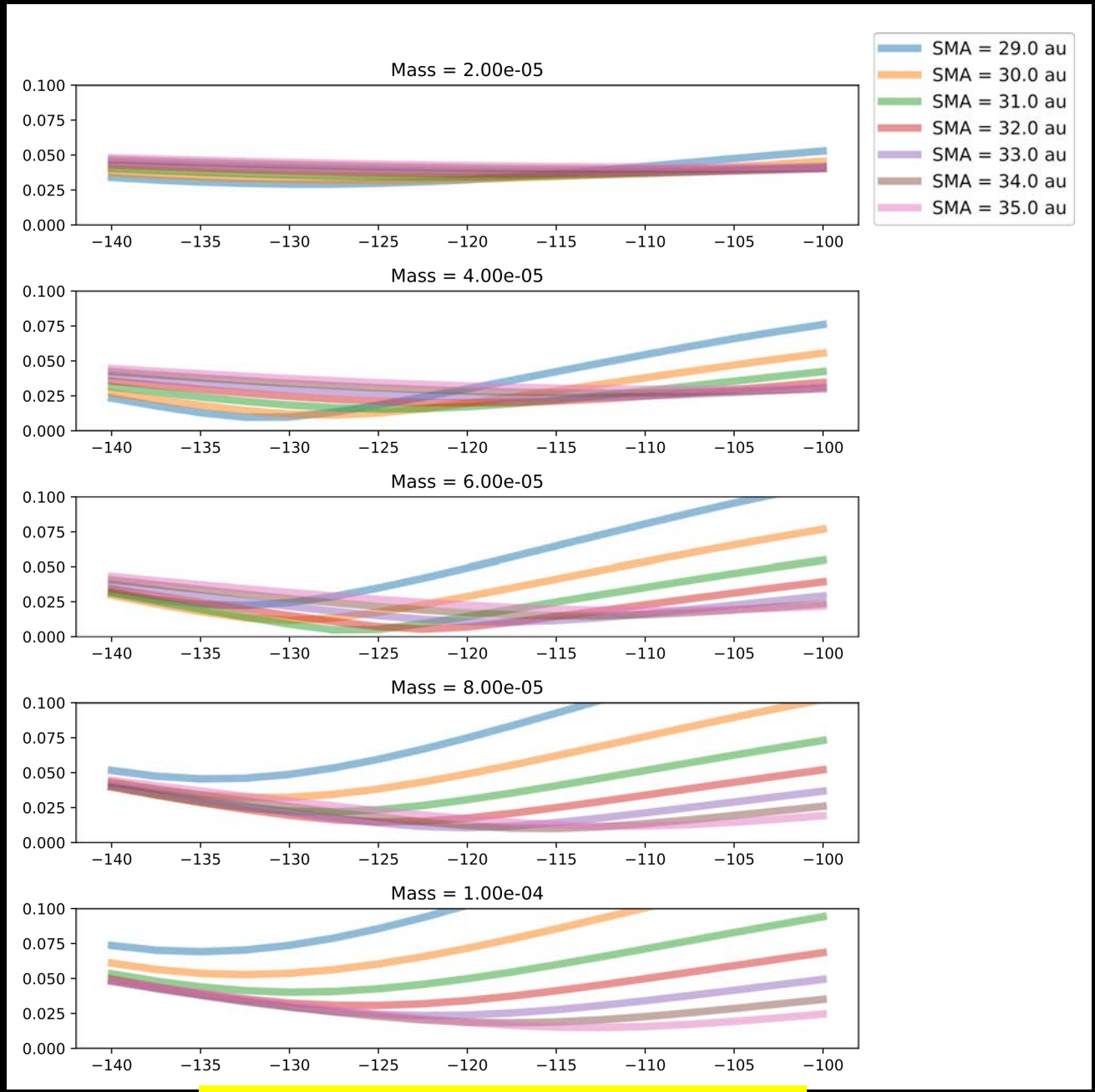
- simultaneous fit of the mass, semi-major axis, and phase of Neptune

True values:

$\varphi = 129.9$ **deg.**

$a = 30.2$ **au**

$m = 5.12\times10^{-5}\mathrm{M}_{\odot}$



Neptune's phase (deg.) in A.D. 1801

2nd trial: recovery of Neptune's parameters for the inverse-square law of gravity $\propto 1/r^2$

- simultaneous fit of the mass, semi-major axis, and phase of Neptune

True values:

$\varphi = 129.9$ **deg.**

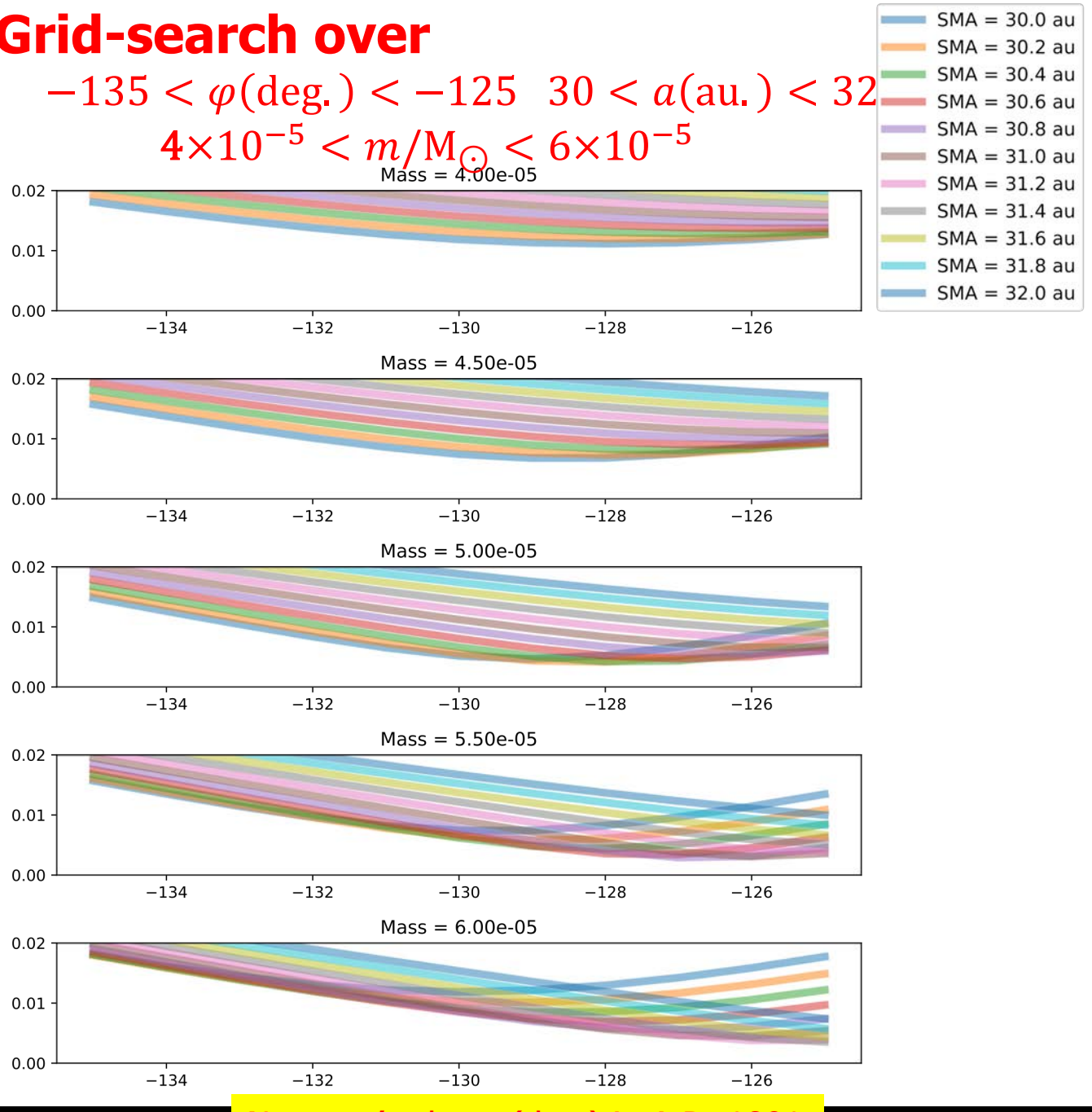
$a = 30.2$ **au**

$m = 5.12\times10^{-5}\mathrm{M}_\odot$

Grid-search over

$-135 < \varphi(\mathrm{deg.}) < -125 \quad 30 < a(\mathrm{au.}) < 32$

$4\times10^{-5} < m/\mathrm{M}_\odot < 6\times10^{-5}$



Recovering the gravity law from acceleration

- Adopted assumptions
  - locations of planets are accurately known
  - observed acceleration of the i-th object

$$\boldsymbol{V}_i(t+\frac{1}{2}\Delta t) \equiv \frac{\boldsymbol{r}_i(t+\Delta t)-\boldsymbol{r}_i(t)}{\Delta t}$$

$$\boldsymbol{A}_i(t) \equiv \frac{\boldsymbol{V}_i(t+\Delta t/2)-\boldsymbol{V}_j(t-\Delta t/2)}{\Delta t} = \frac{\boldsymbol{r}_i(t+\Delta t)-2\boldsymbol{r}_i(t)+\boldsymbol{r}_i(t-\Delta t)}{(\Delta t)^2}$$

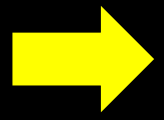
  - acceleration is superposition of the force from the j-th object

$$\boldsymbol{A}_i(t) = \sum_{j\neq i} \boldsymbol{g}(m_j, \boldsymbol{r}_j; \boldsymbol{r}_i)$$

  - translational and rotational invariance

$$\boldsymbol{g}(m_j, \boldsymbol{r}_j; \boldsymbol{r}_i) = \boldsymbol{g}(m_j, \boldsymbol{r}_j - \boldsymbol{r}_i)$$

$$\boldsymbol{g}(m_j, \boldsymbol{r}_j - \boldsymbol{r}_i) = g(m_j, r_{ji})\frac{\boldsymbol{r}_{ji}}{r_{ji}}$$



$$\boldsymbol{g}(m_j, \boldsymbol{r}_j - \boldsymbol{r}_i) = Gm_j\tilde{g}(r_{ji})\frac{\boldsymbol{r}_{ji}}{r_{ji}}$$

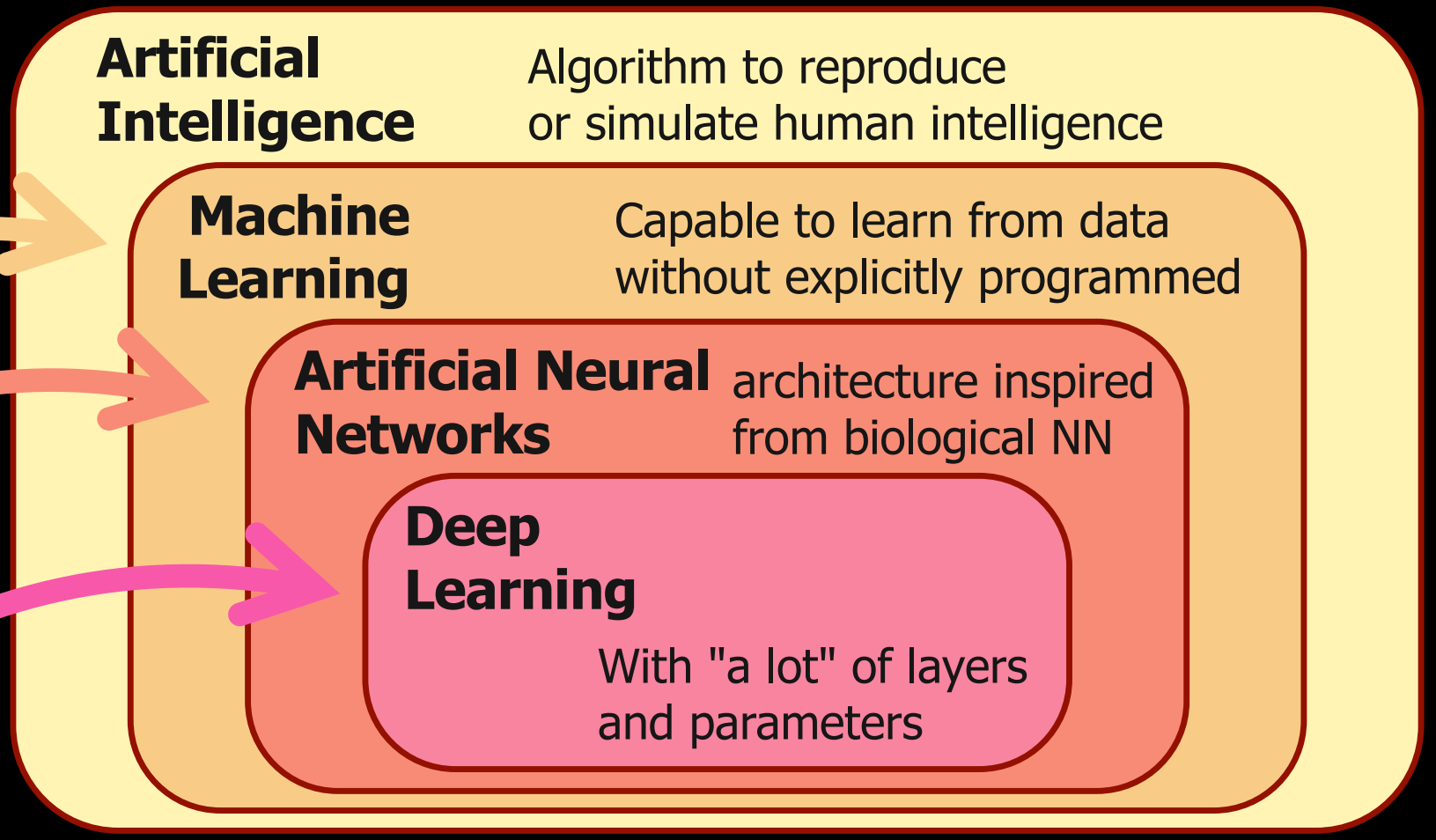
Artificial Intelligence in a nutshell

Deep Blue
hard-coded program
to beat World Chess
champion in 1997

Linear regression

Perceptron
A fully-coded artificial
neural network with
a single layer of neurons

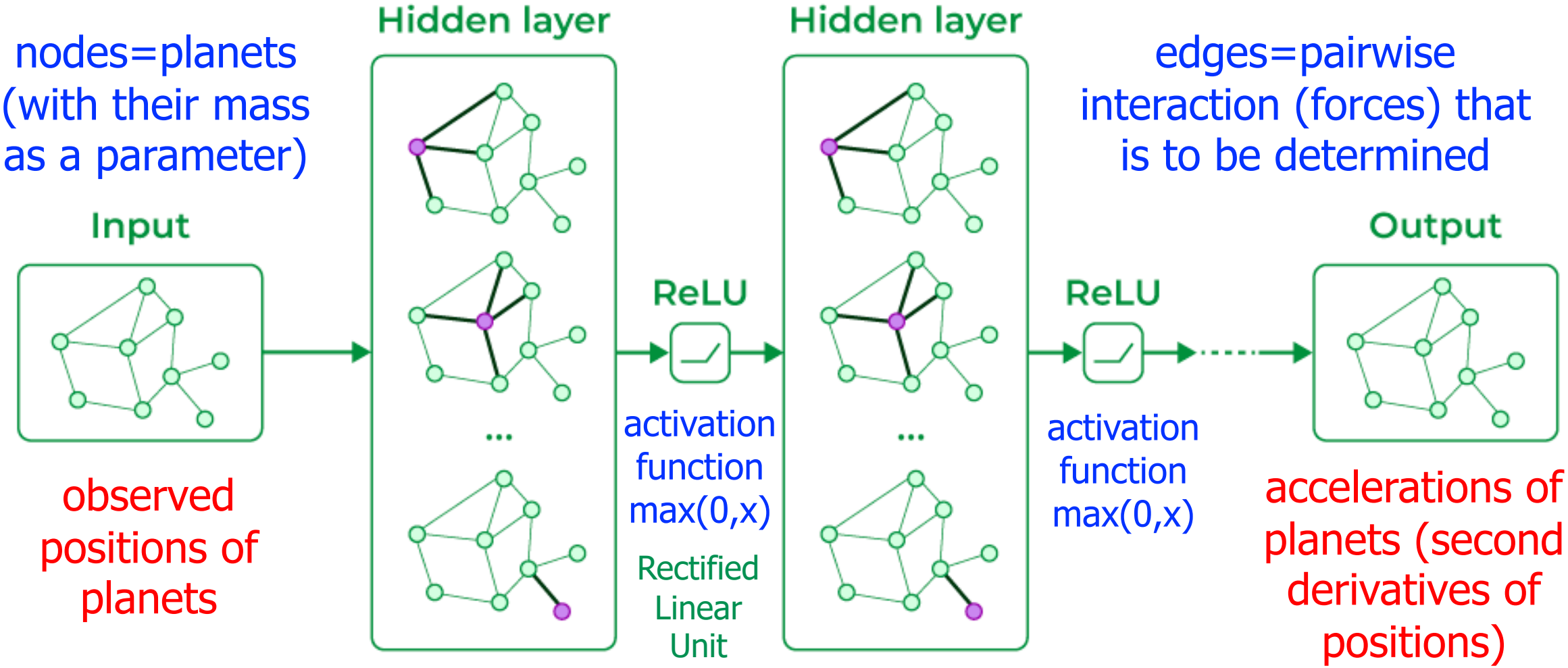
Multi-Layer Perceptron
Convolutional Neural Network
Transformer models (ChatGPT)



(slide by Florian Lalande)

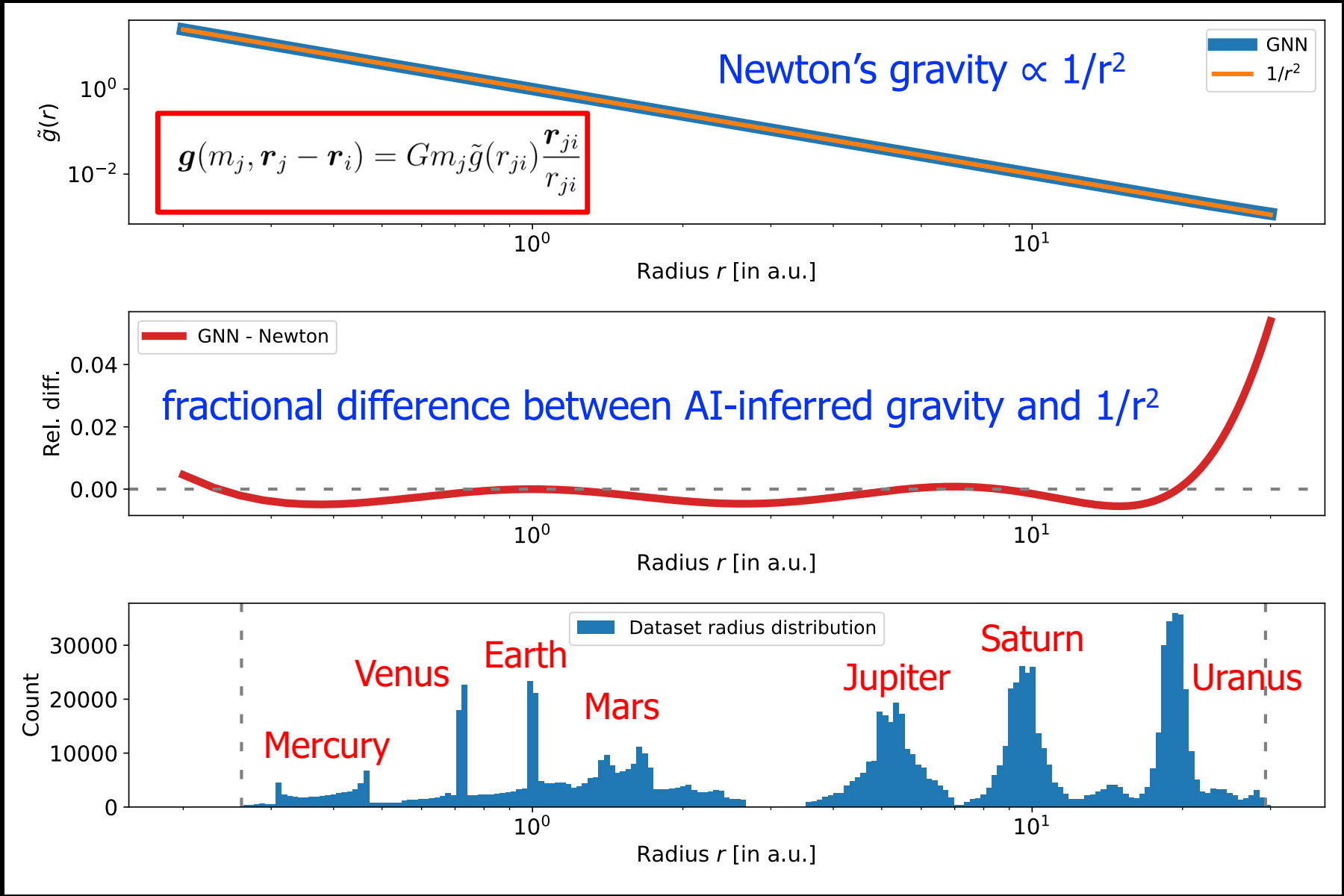
GNN (Graph Neural Network)

Our GNN may fit into the "Deep Learning" category , even though not so many trainable parameters

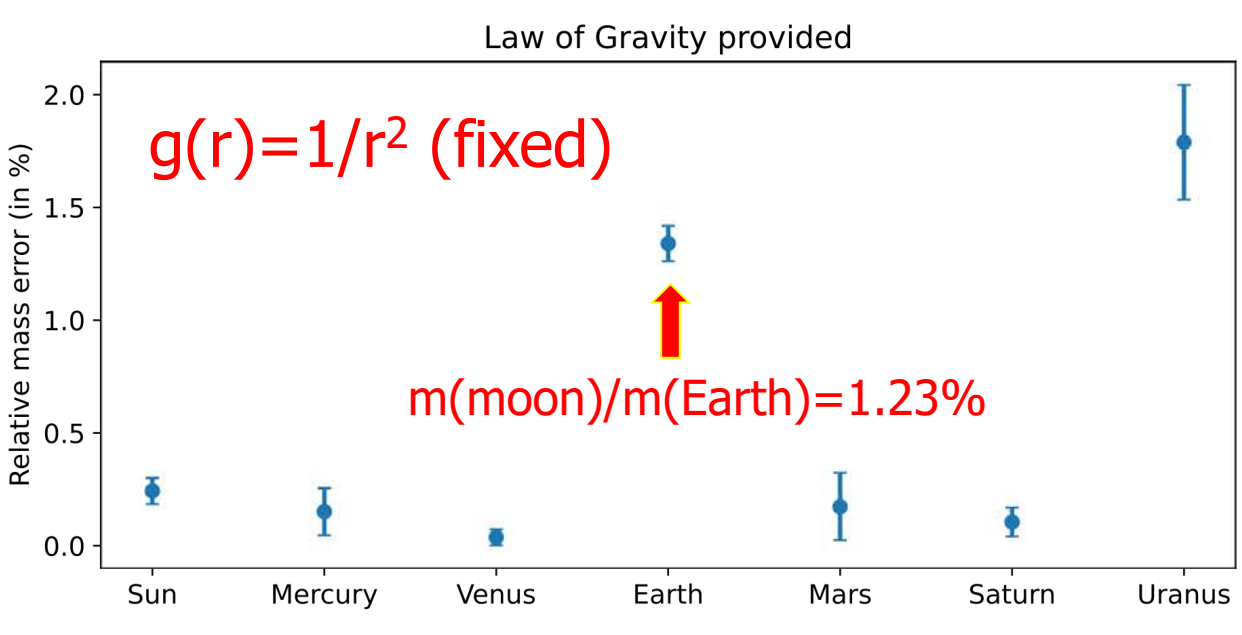


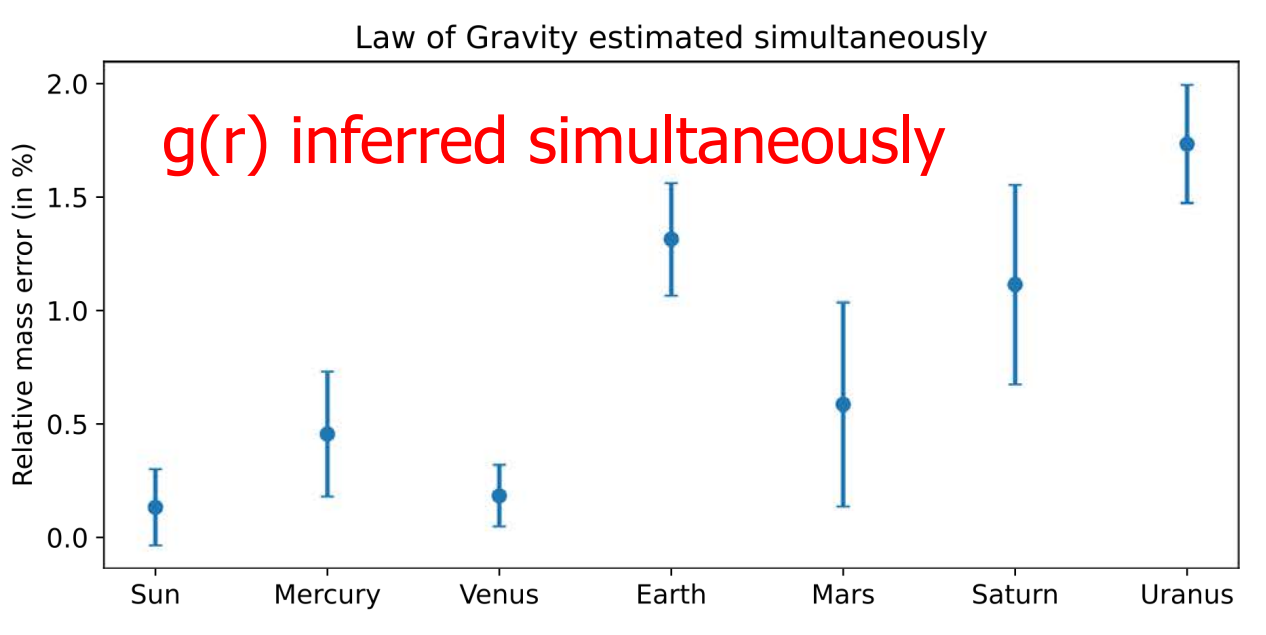
(slide by Florian Lalande)

Recovered gravity law from GNN



Recovered mass of planets from 50 runs of GNN

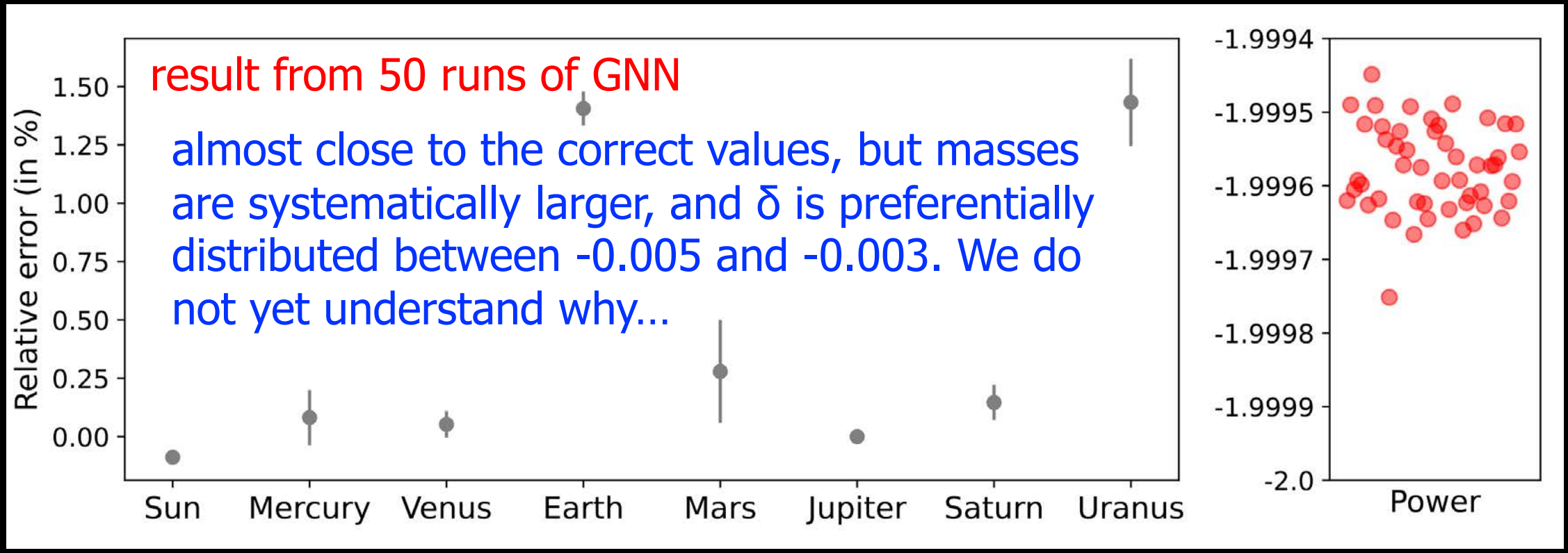




We need to fix the mass of one of the objects.
In the above plots, we chose the mass of Jupiter as the normalization.

a strong additional assumption
a single power-law gravity; $g(r)=1/r^{2+\delta}$

- simultaneous fit to mass of 7 objects + a power-law index δ



3 Summary

Robust summary

- In cosmology, Zwicky's 1933 paper is often quoted as the first indication of dark matter
  - Zwicky correctly pointed out that member galaxies in Coma cluster have high velocity dispersions exceeding the escape velocity of the visible mass of the cluster
- Discovery of Neptune in 1846 is the first directly detected "dark matter" based on Newton's law of gravity
- Vulcan in 1859 is the first false-positive of "dark matter" due to the incorrect extrapolation of Newton's law of gravity
- Which is the next breakthrough in cosmology, unknown dark component or modified law of physics?

Preliminary summary

- Can AI discover new physics?
  - Identification of inconsistencies between precise theoretical predictions and big experimental/observational data will not be feasible anymore without AI
  - Can AI can discover a new law of physics in an analytic/mathematical manner thanks to the universal approximation theorem?
    - AI may discover Newton's law from planetary motion, but not general relativity from Mercury's perihelion shift, because it was not a training dataset but a validation dataset for Einstein.
    - Is it inevitable to have a sort of sense of beauty (i.e., aesthetic bias) in formulating the law of physics? (e.g., Lemos et al. arXiv:2202.02306)
  - A proof-of-concept study with AI is on-going concerning modified gravity vs. unknown object for Uranus' motion