How to weigh the Milky Way

Denis Erkal

Astro evening - January 16th 2019




How do we weigh things?

How do we weigh things?

- Count up how much stuff there is

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How do we weigh things?

- Count up how much stuff there is

- Use a weighing scale

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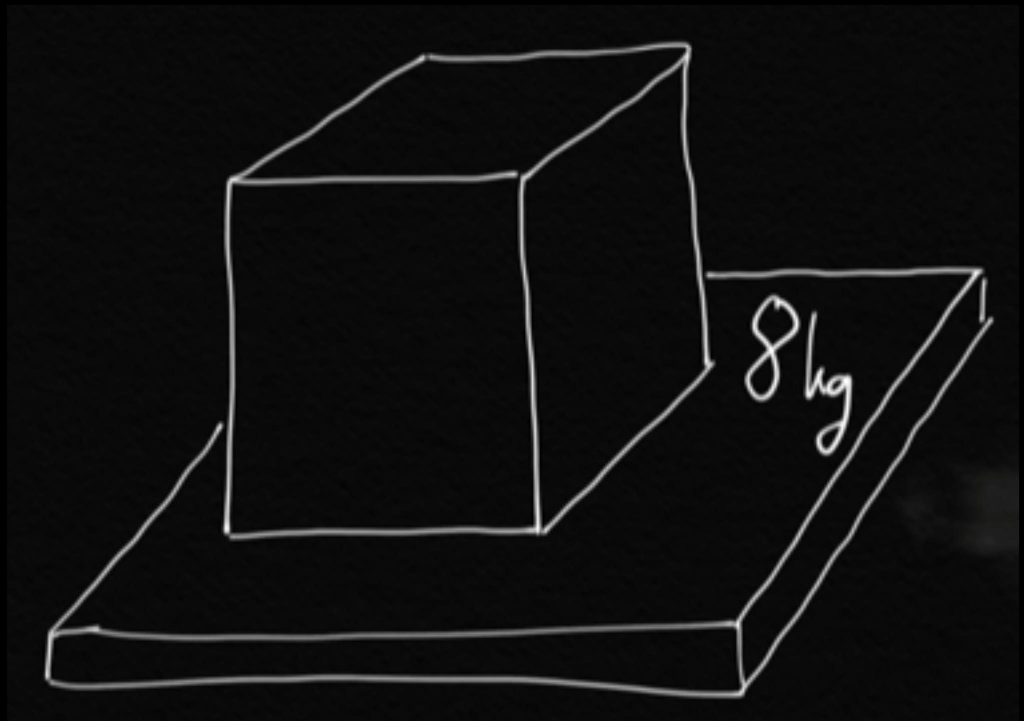

How do we weigh the Earth?

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- Count up how much stuff there is

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- Count up how much stuff there is
  - Dig a very deep hole?

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Stepanovas Alexander

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Kola Superdeep Borehole

Rakot13

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Kola Superdeep Borehole

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Only 12 km deep…

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  - Use neutrinos to take an “x-ray” of the Earth

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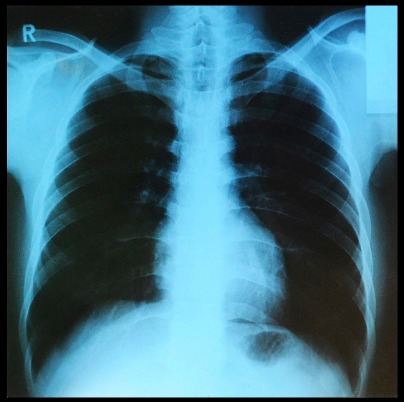

Sudraben

How do we weigh the Earth?

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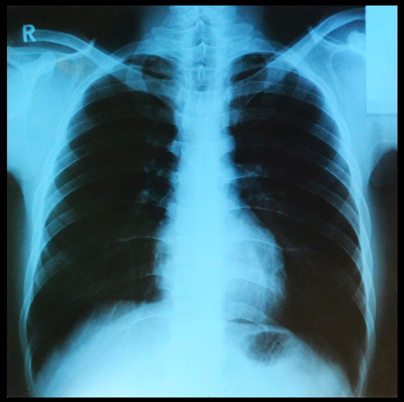

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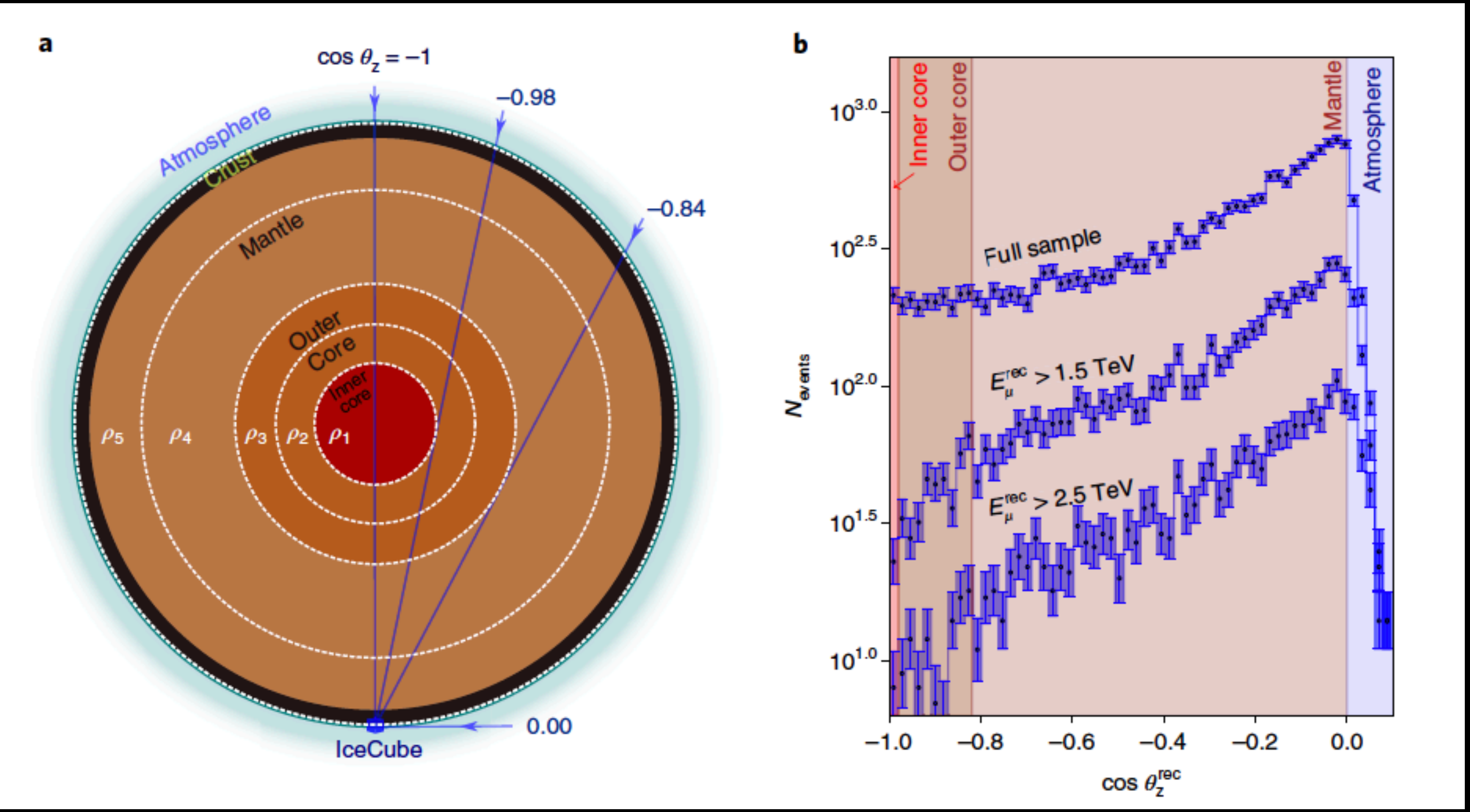

Donini et al. 2019

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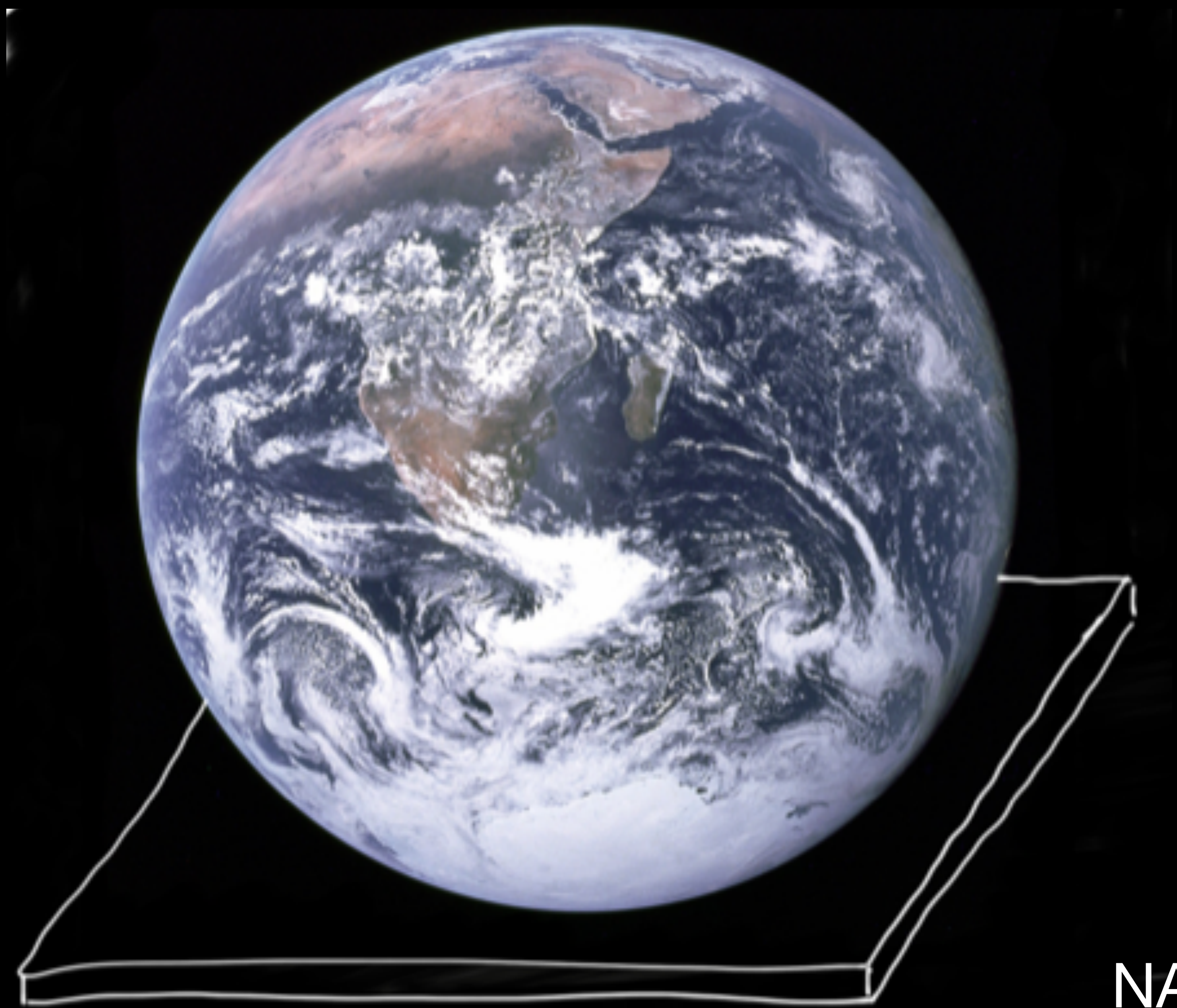

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NASA

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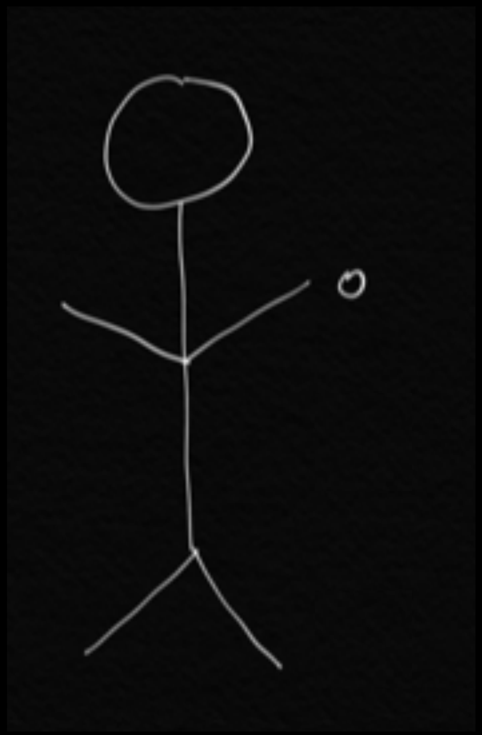

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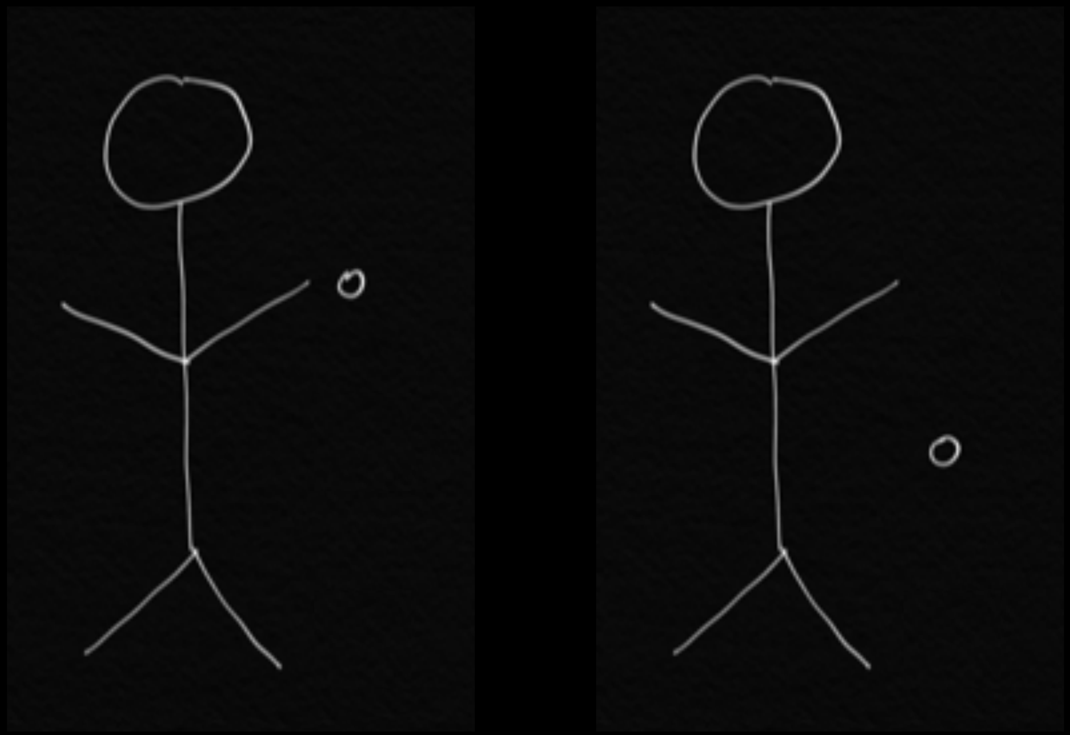

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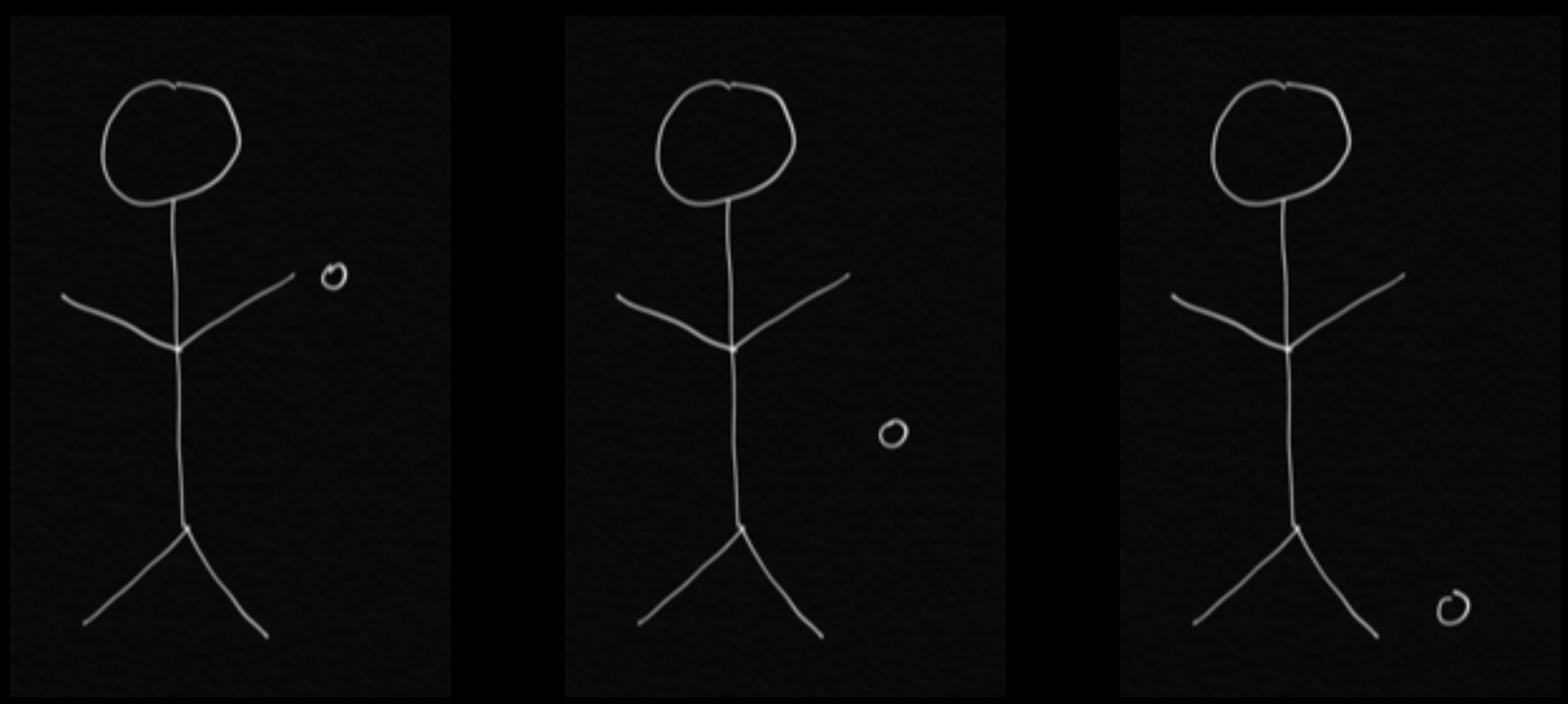

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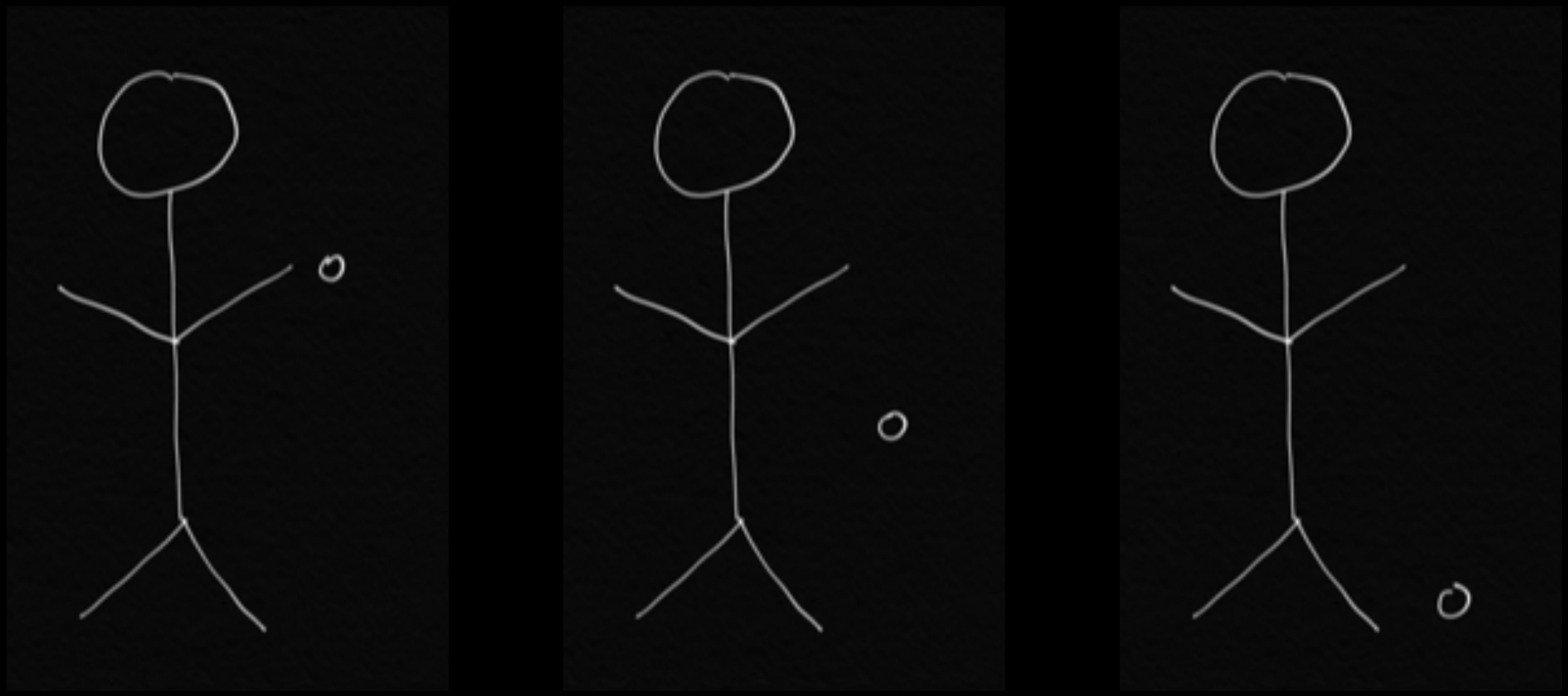

This tells us the acceleration

How do we weigh the Earth?

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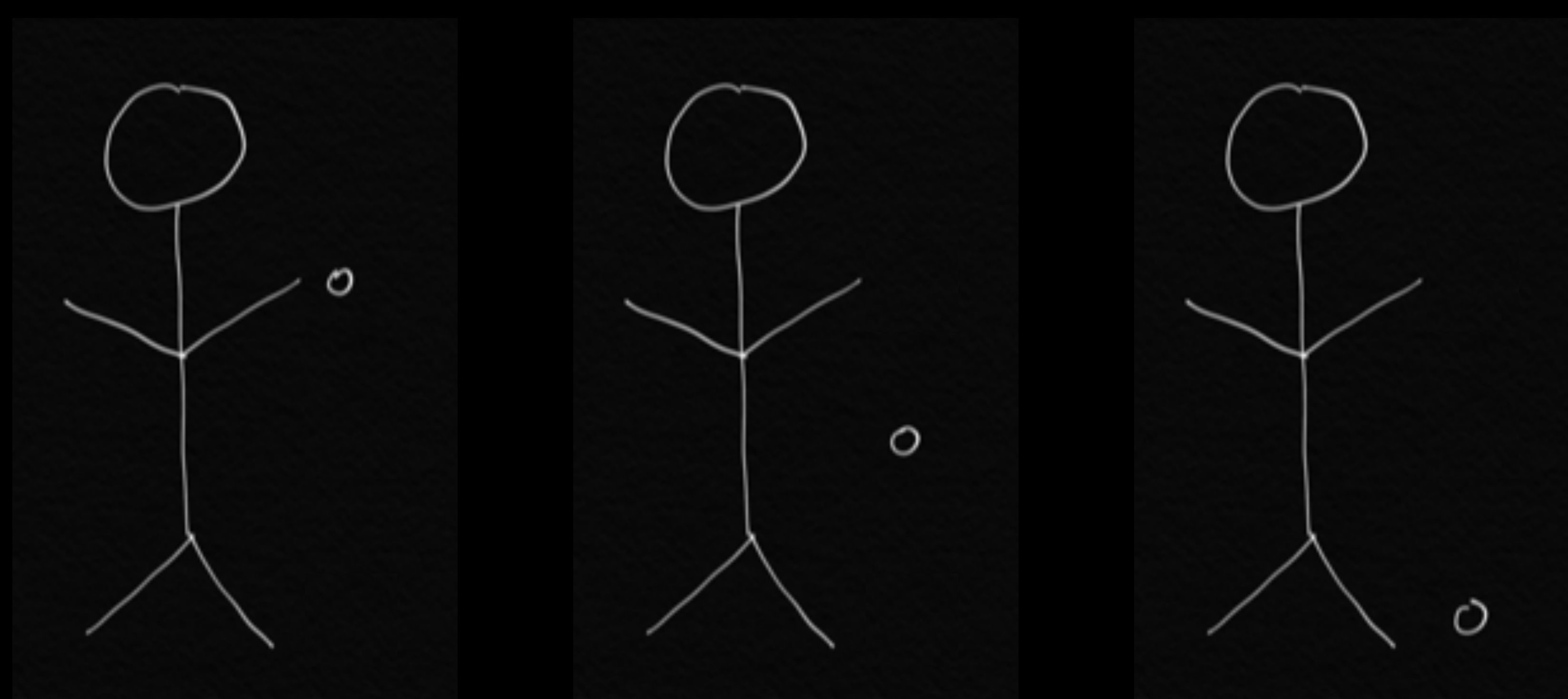

$$g = \frac{GM}{R^2}$$

This tells us the acceleration

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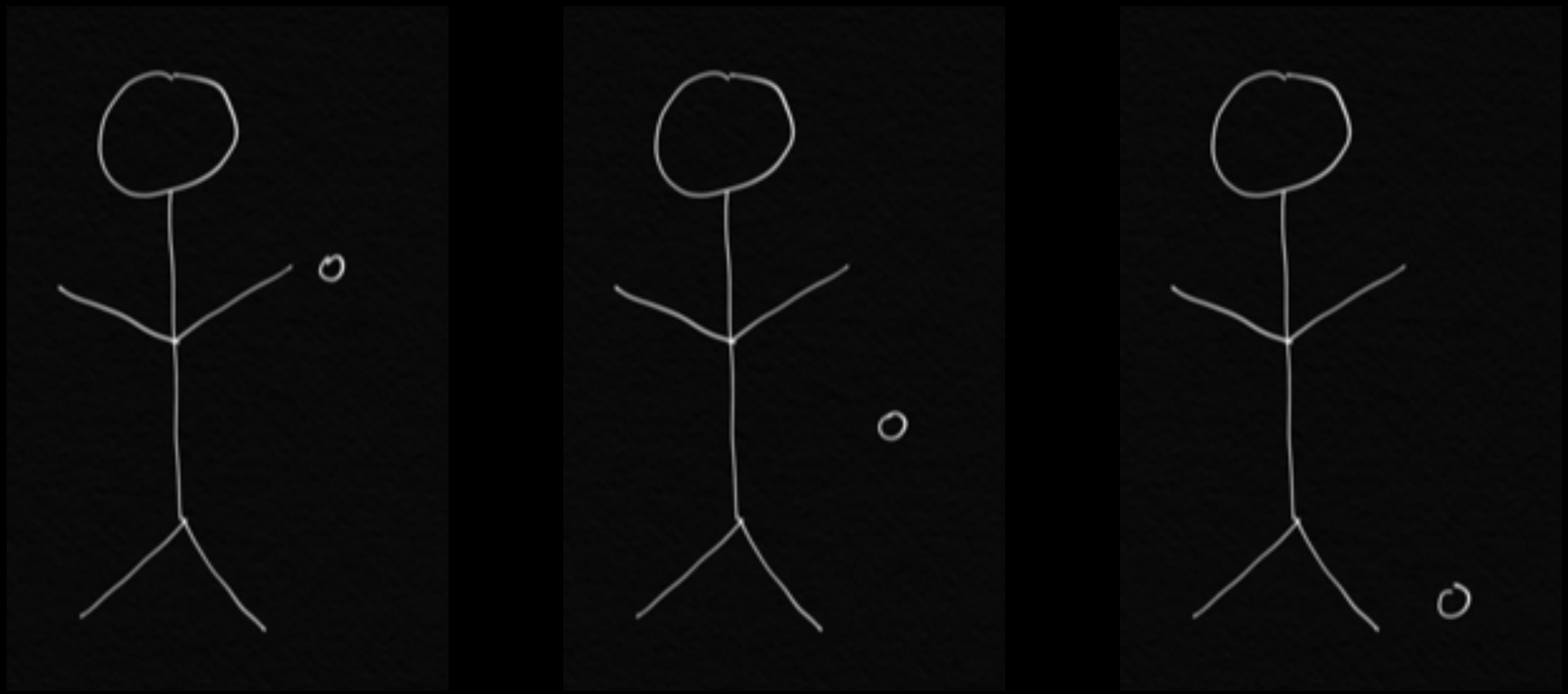

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Acceleration tells us the mass!

How do we weigh the Earth?

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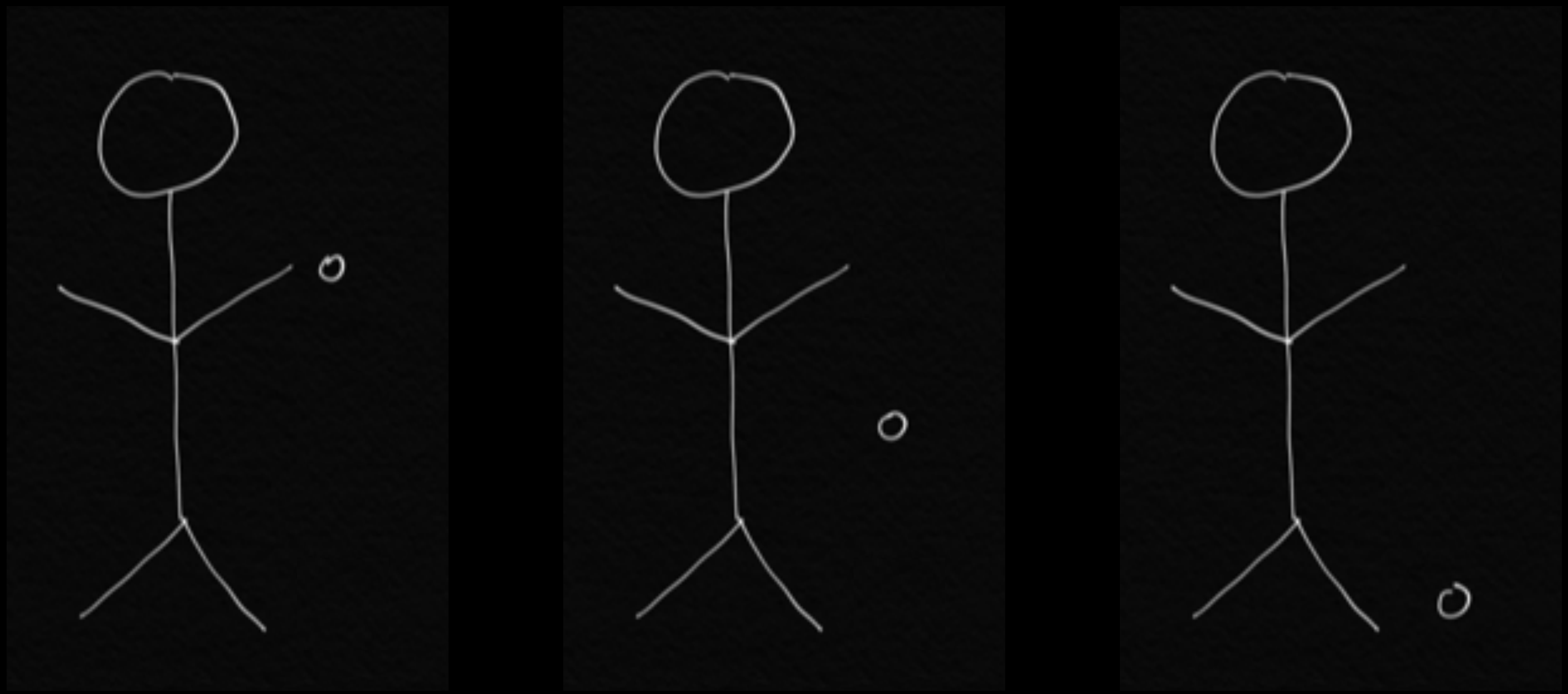

$$g = \frac{GM}{R^2}$$

This tells us the acceleration

Acceleration tells us the mass!

$$M = \frac{gR^2}{G}$$

How do we weigh the Earth?

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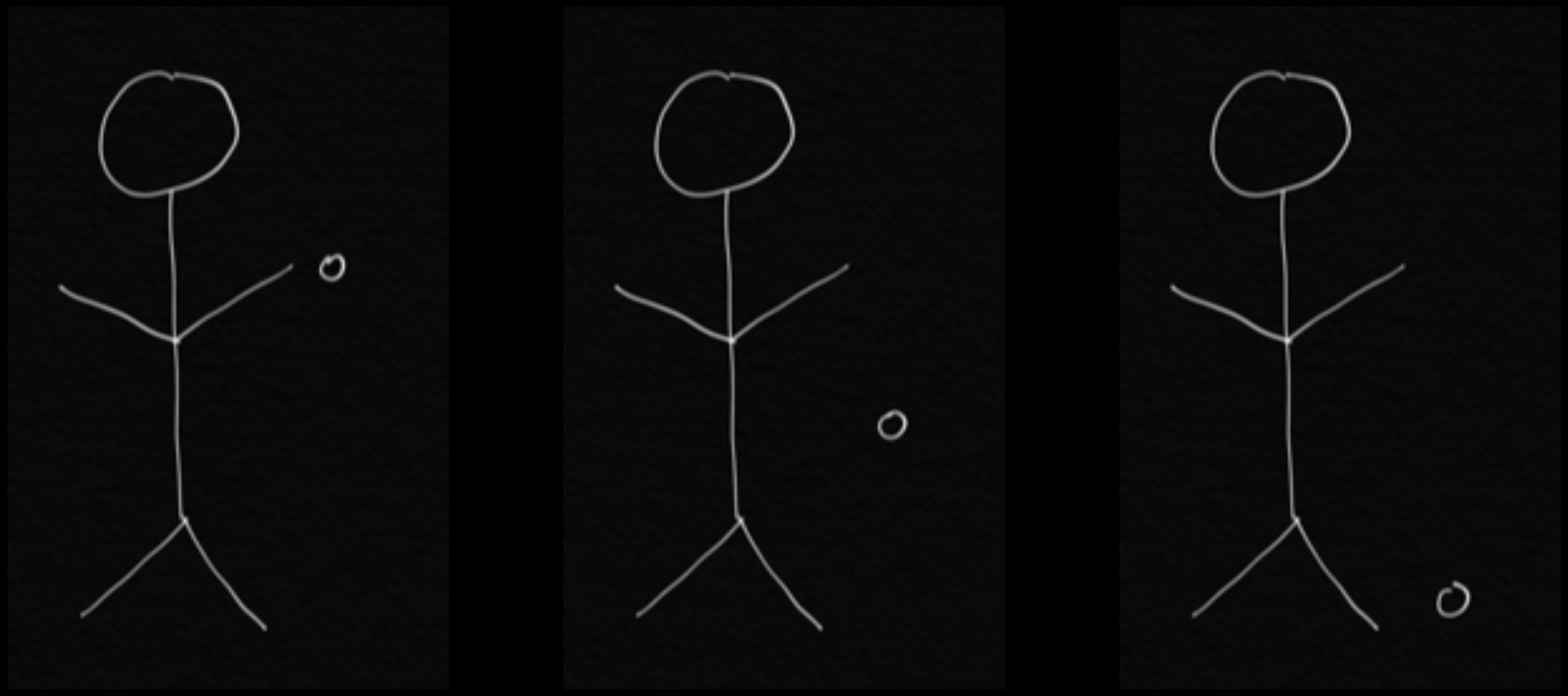

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Acceleration tells us the mass!

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> From the results of the fit, we compute the mass of the Earth as weighted by neutrinos and obtain $M_{\oplus}^{\nu} = (6.0^{+1.6}_{-1.3}) \times 10^{24}$ kg (Fig. 4a), to be compared to the most precise gravitational measurement to date[22,23] of $M_{\oplus}^{\mathrm{grav}} = (5.9722 \pm 0.0006) \times 10^{24}$ kg. Clearly, albeit within large uncertainties, both results are in very good agreement.

Donini et al. 2019

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Direct measurement agrees with gravitational measurement

Donini et al. 2019

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    - Stars + gas

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- Count up how much stuff there is
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  - e.g. on the stars and gas in the object

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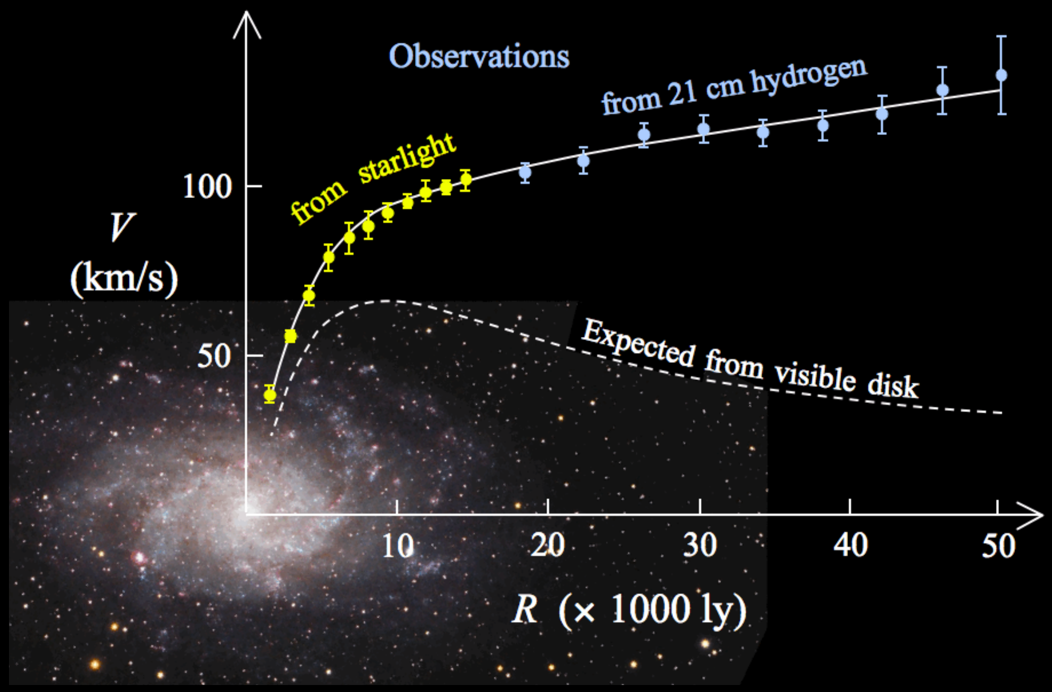

Image credit: Stefania Deluca

Vera Rubin

How do we weigh larger objects?

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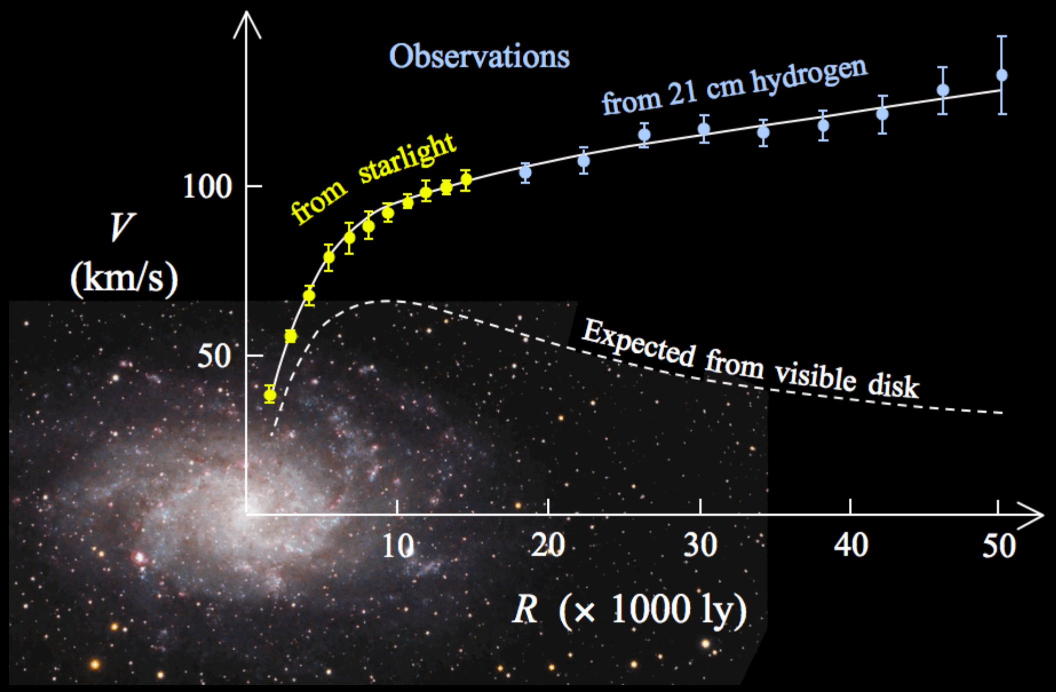
$$a = \frac{V^2}{R}$$



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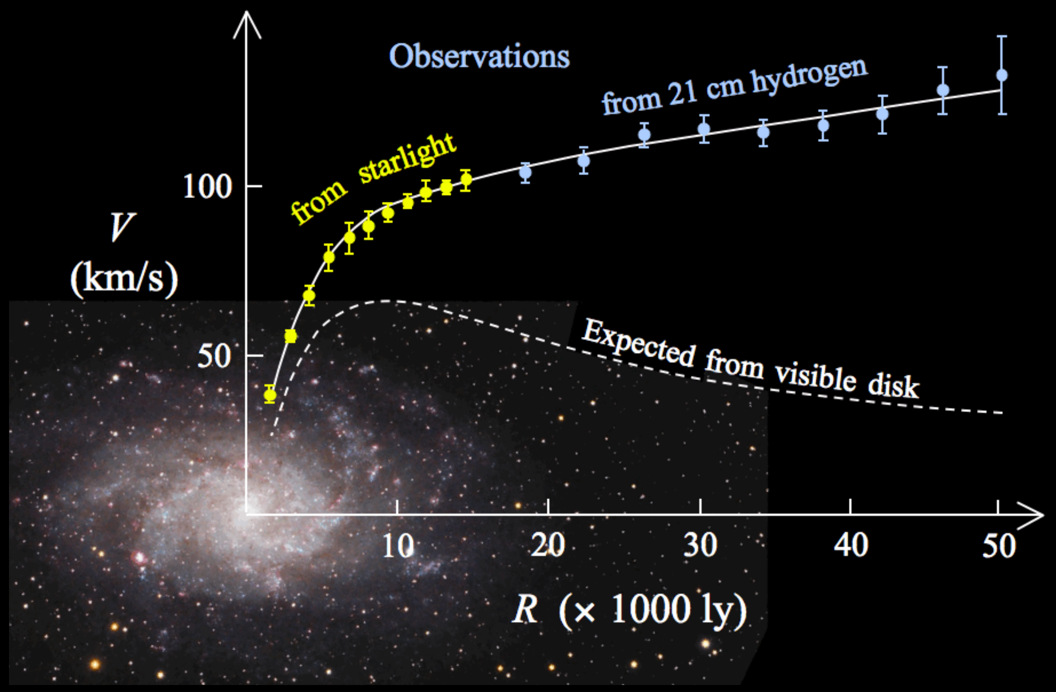

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The difference is due to dark matter!

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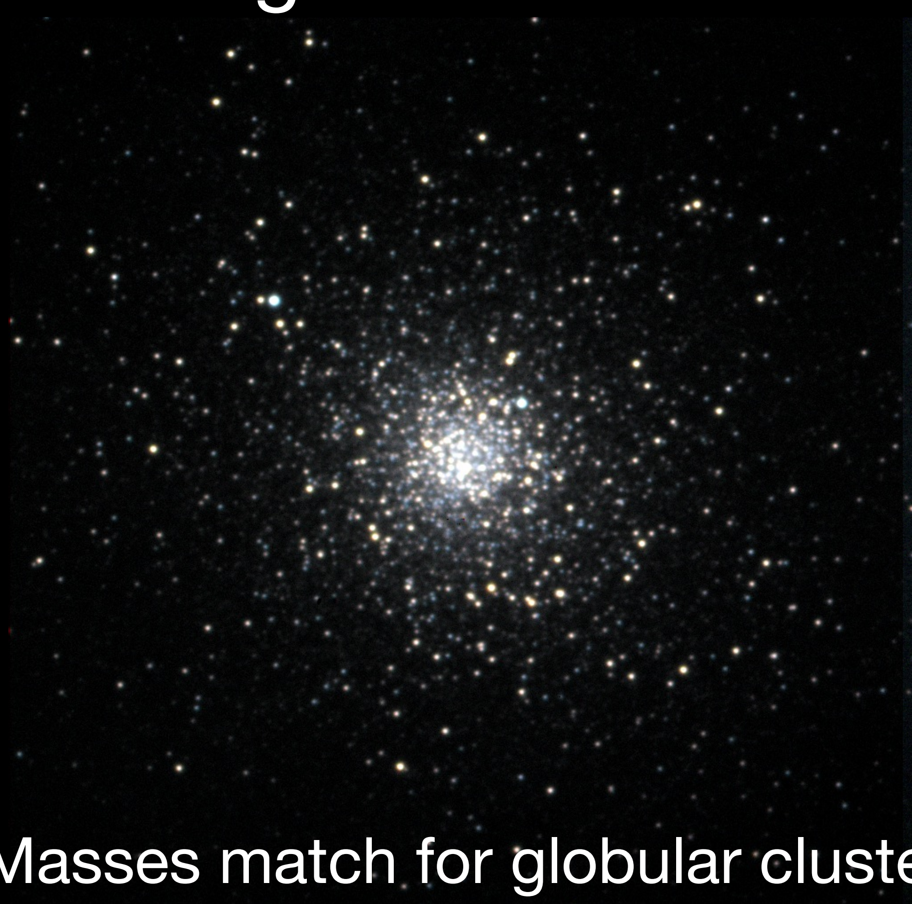

Masses match for globular clusters

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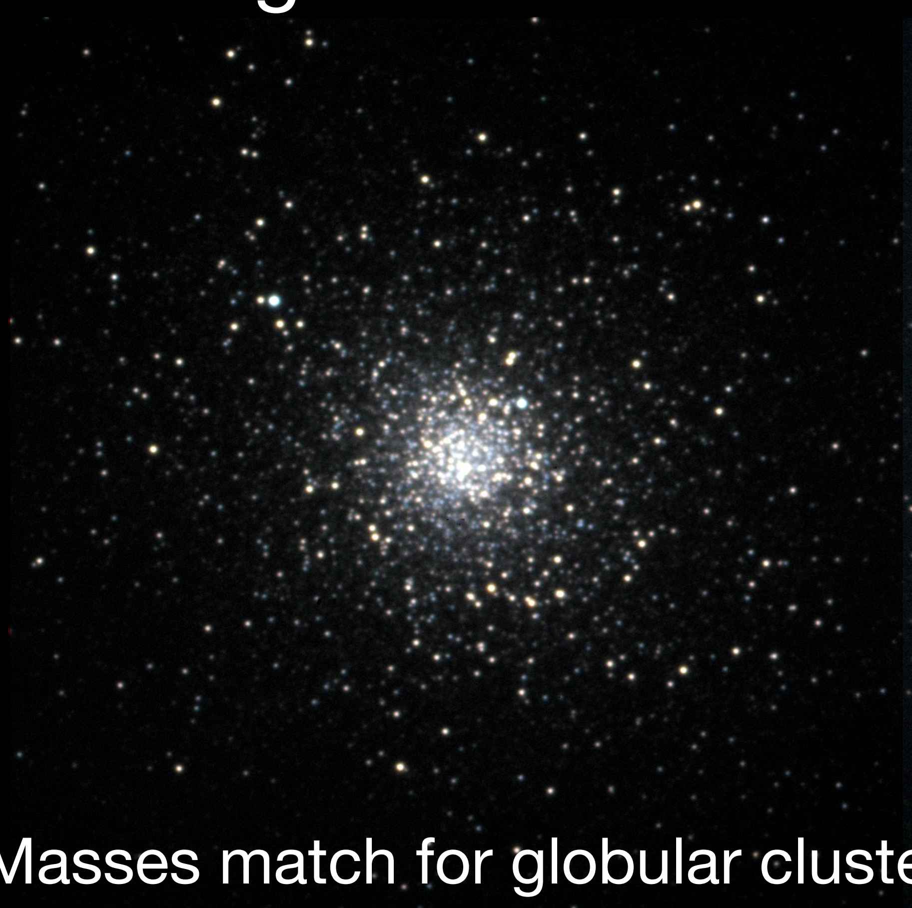

Masses match for globular clusters

Masses do not match for galaxies

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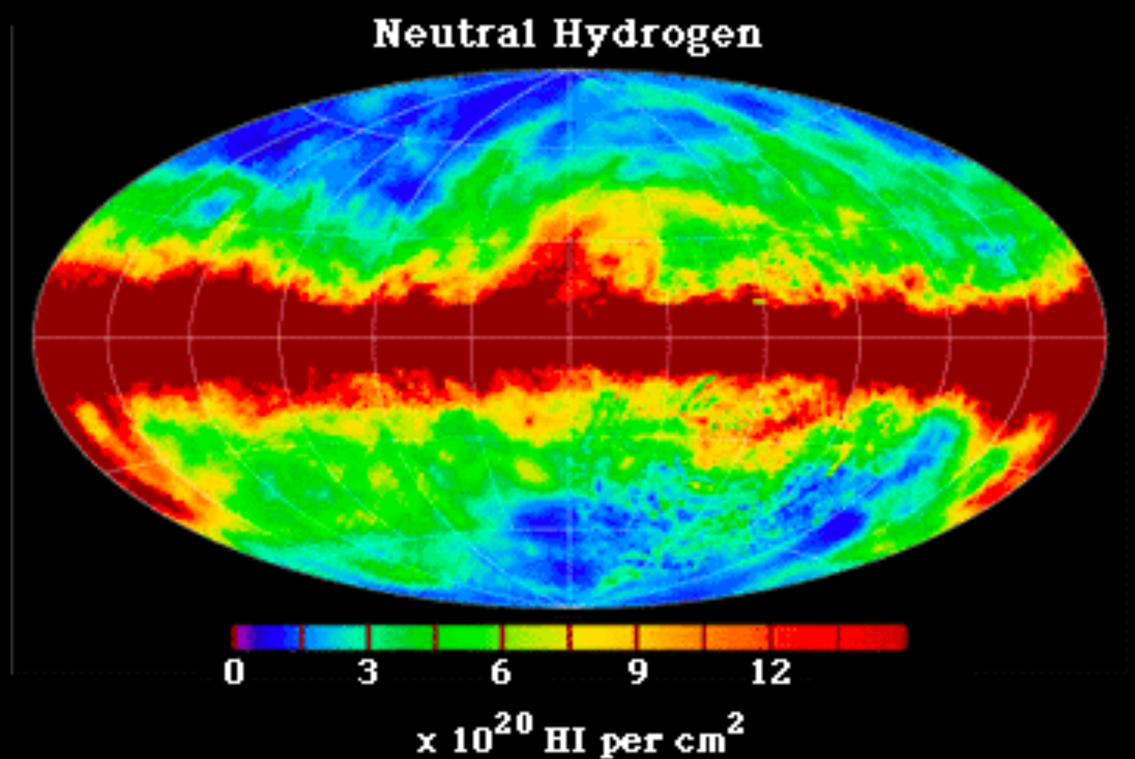
Gas



Dickey & Lockman 1990

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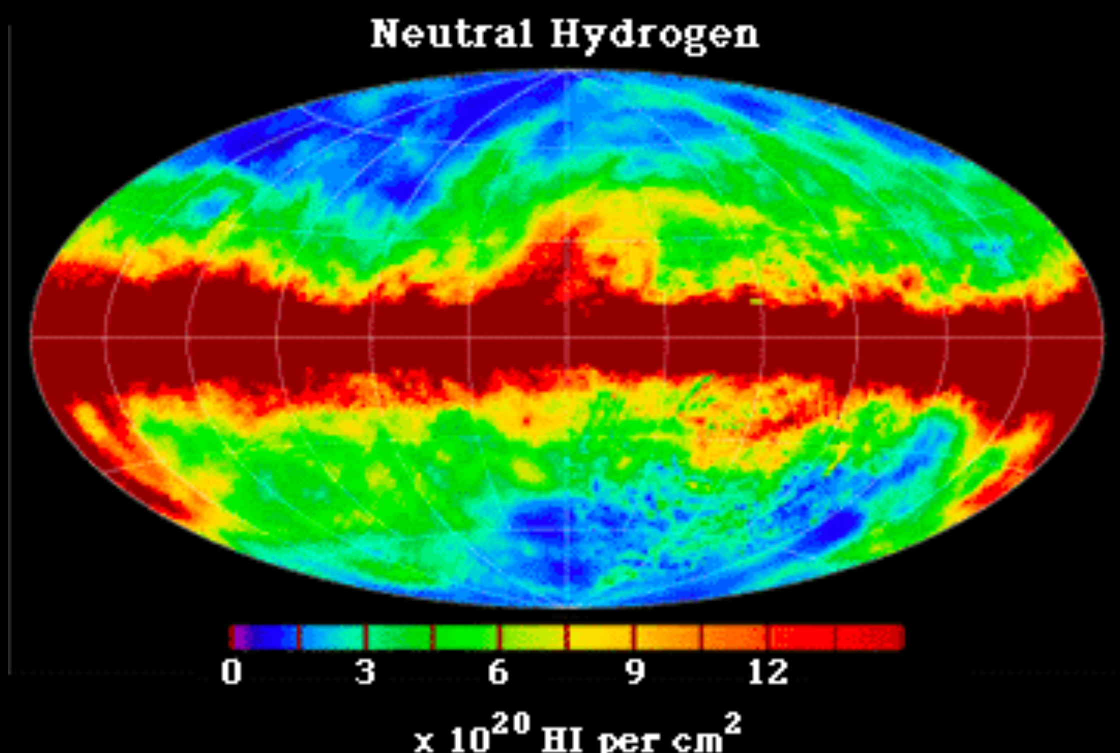

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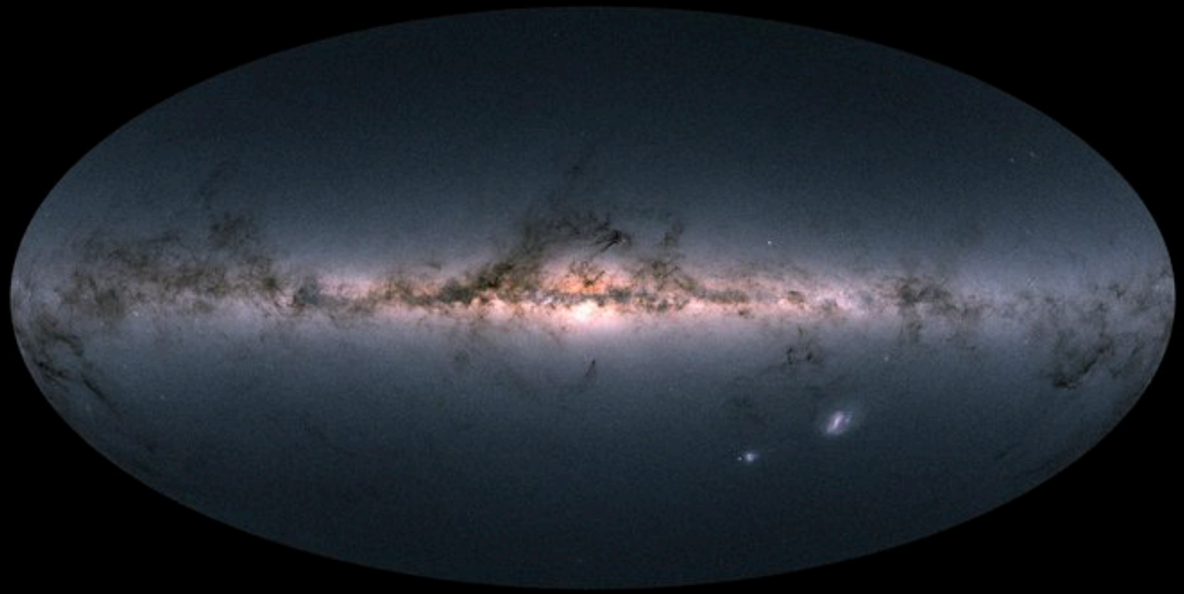
Stars



ESA/Gaia/DPAC

How do we weigh the Milky Way?

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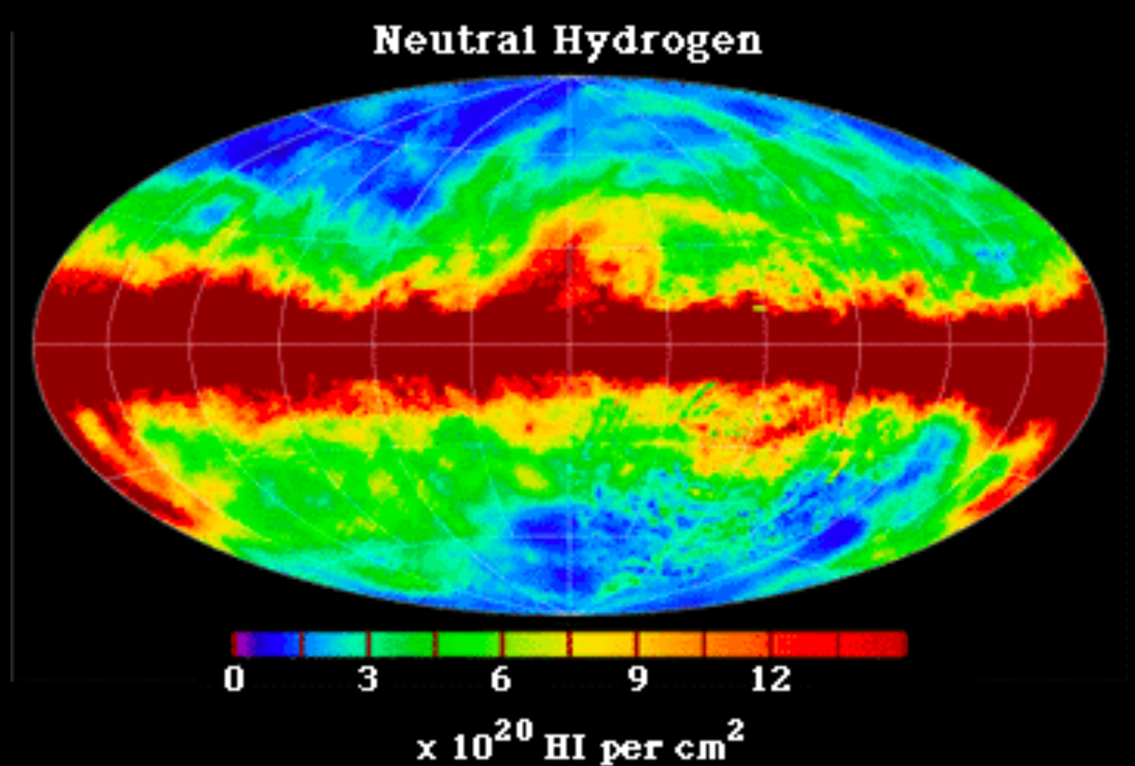
Gas



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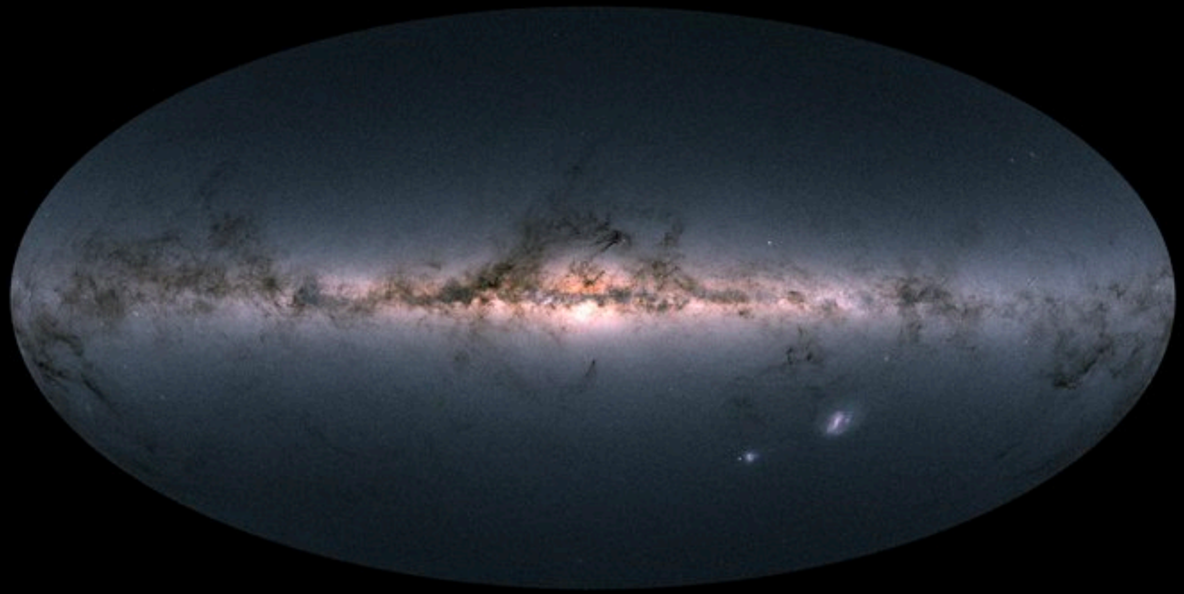

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ESA/Gaia/DPAC

12 billion solar masses

How do we weigh the Milky Way?

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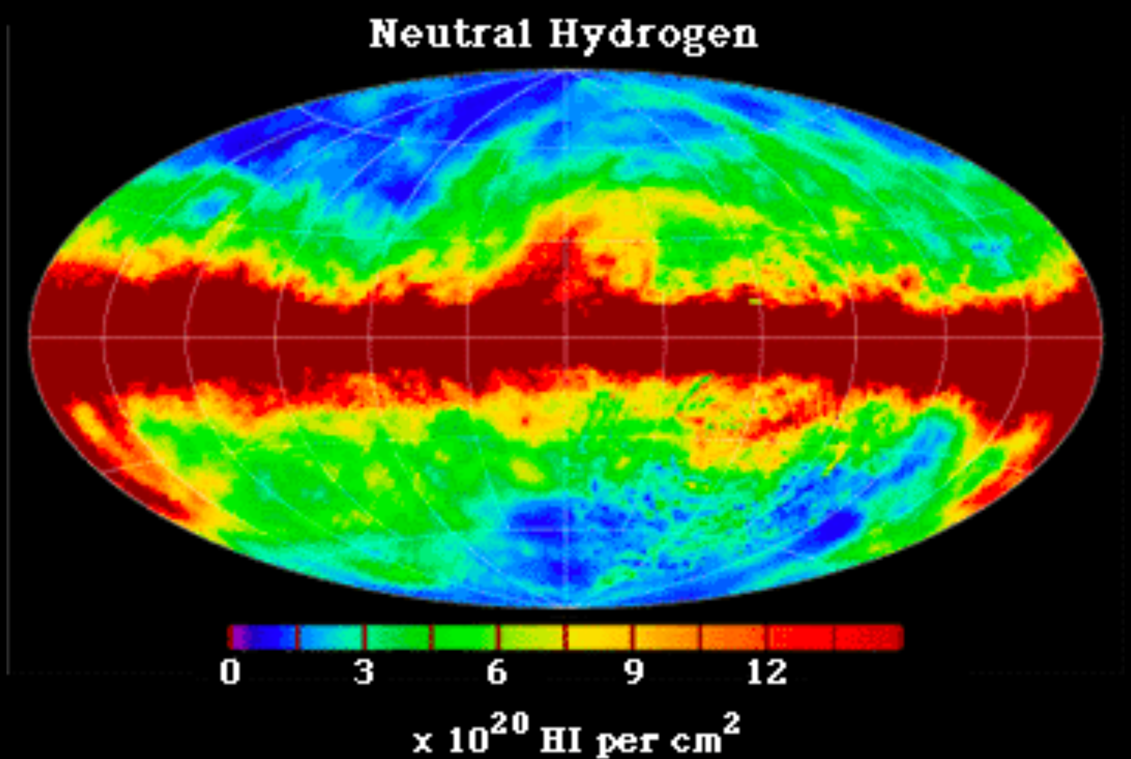
Gas



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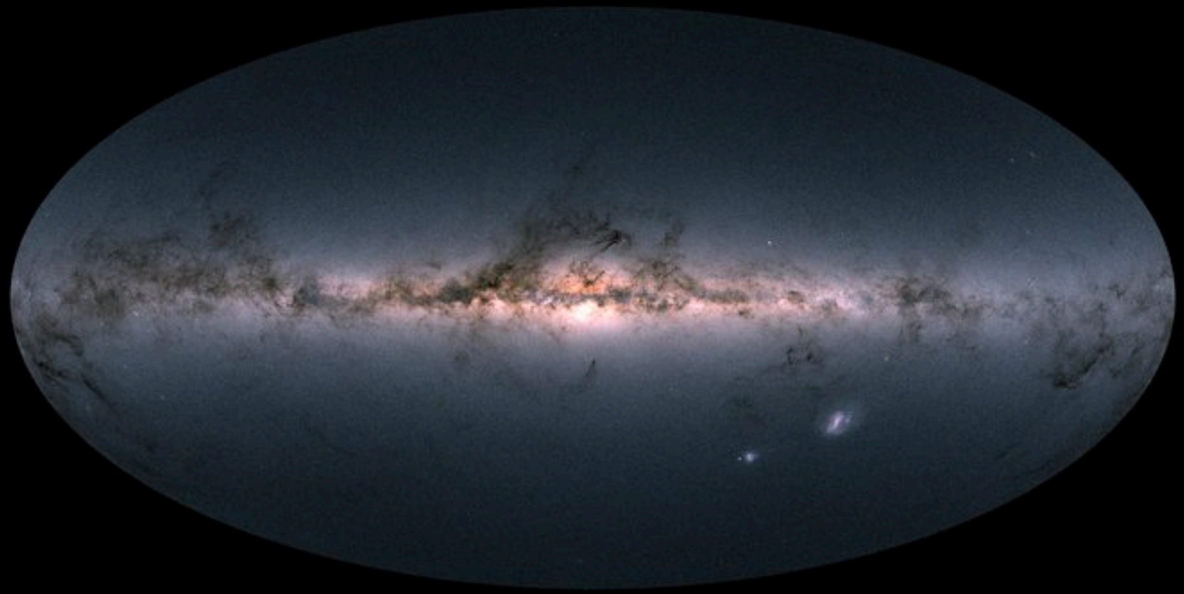

ESA/Gaia/DPAC

54 billion solar masses

How do we weigh the Milky Way?

- Count up all the gas and stars
- Through its gravitational acceleration on another object

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Image alone is not enough, need acceleration

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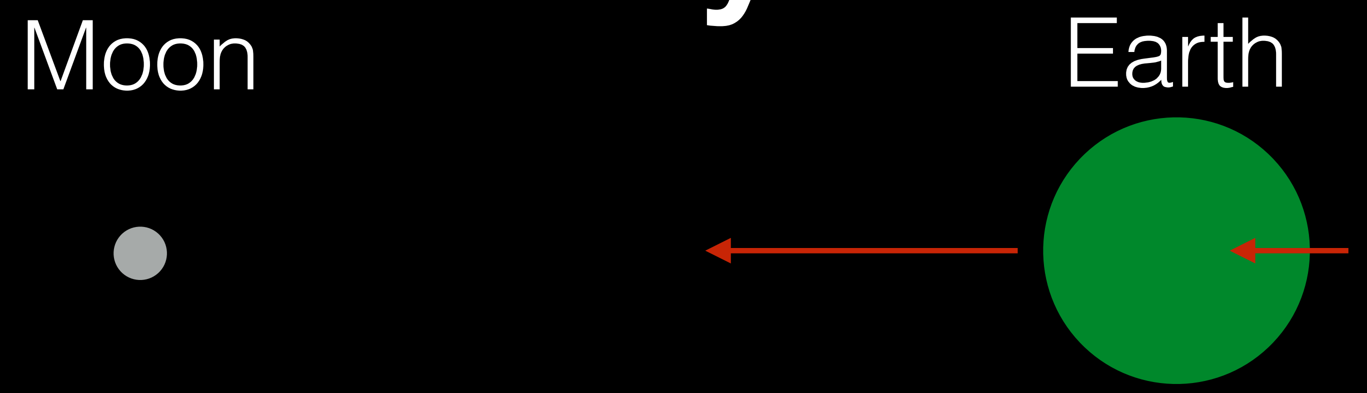

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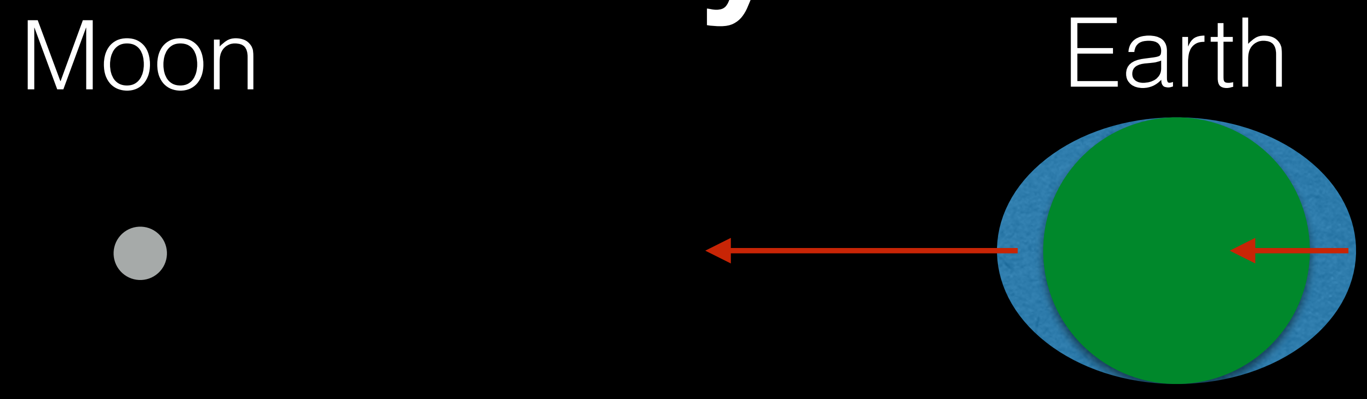

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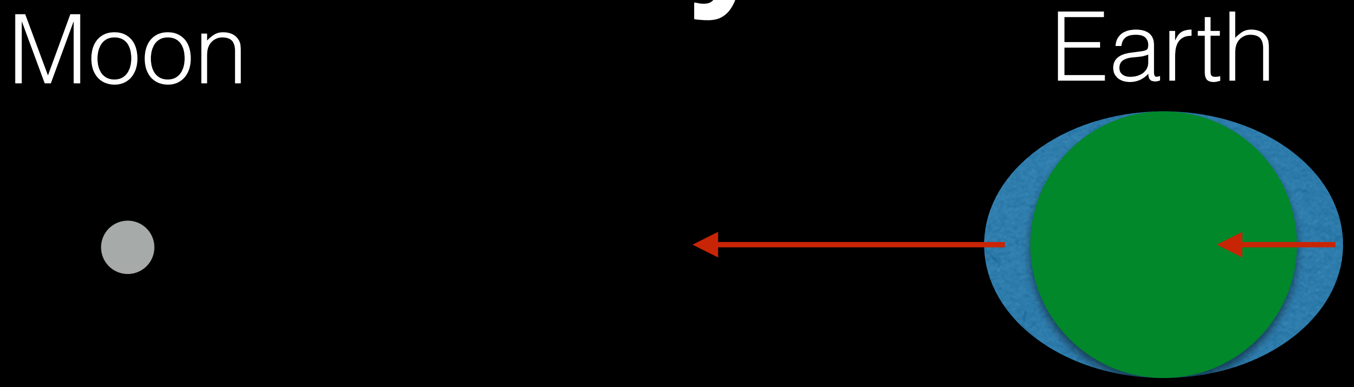

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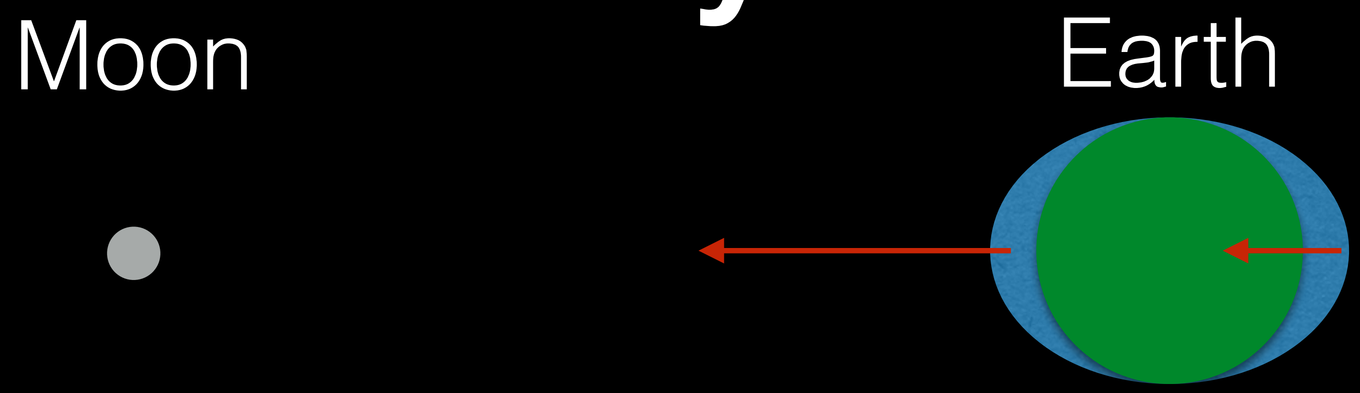

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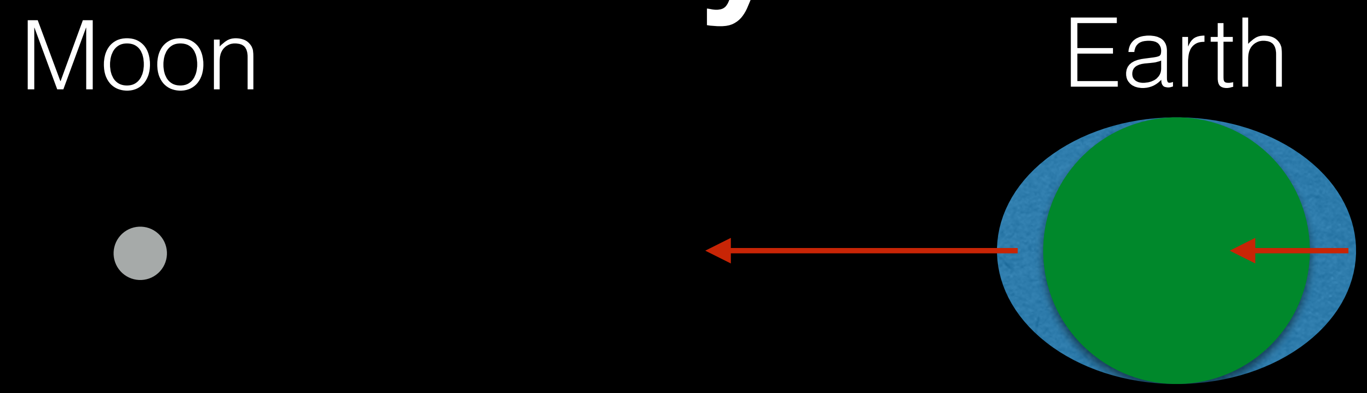

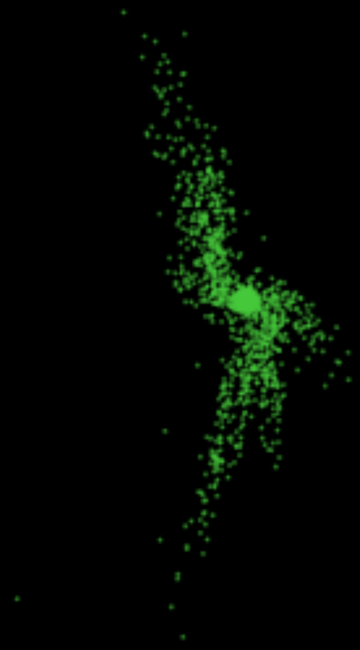

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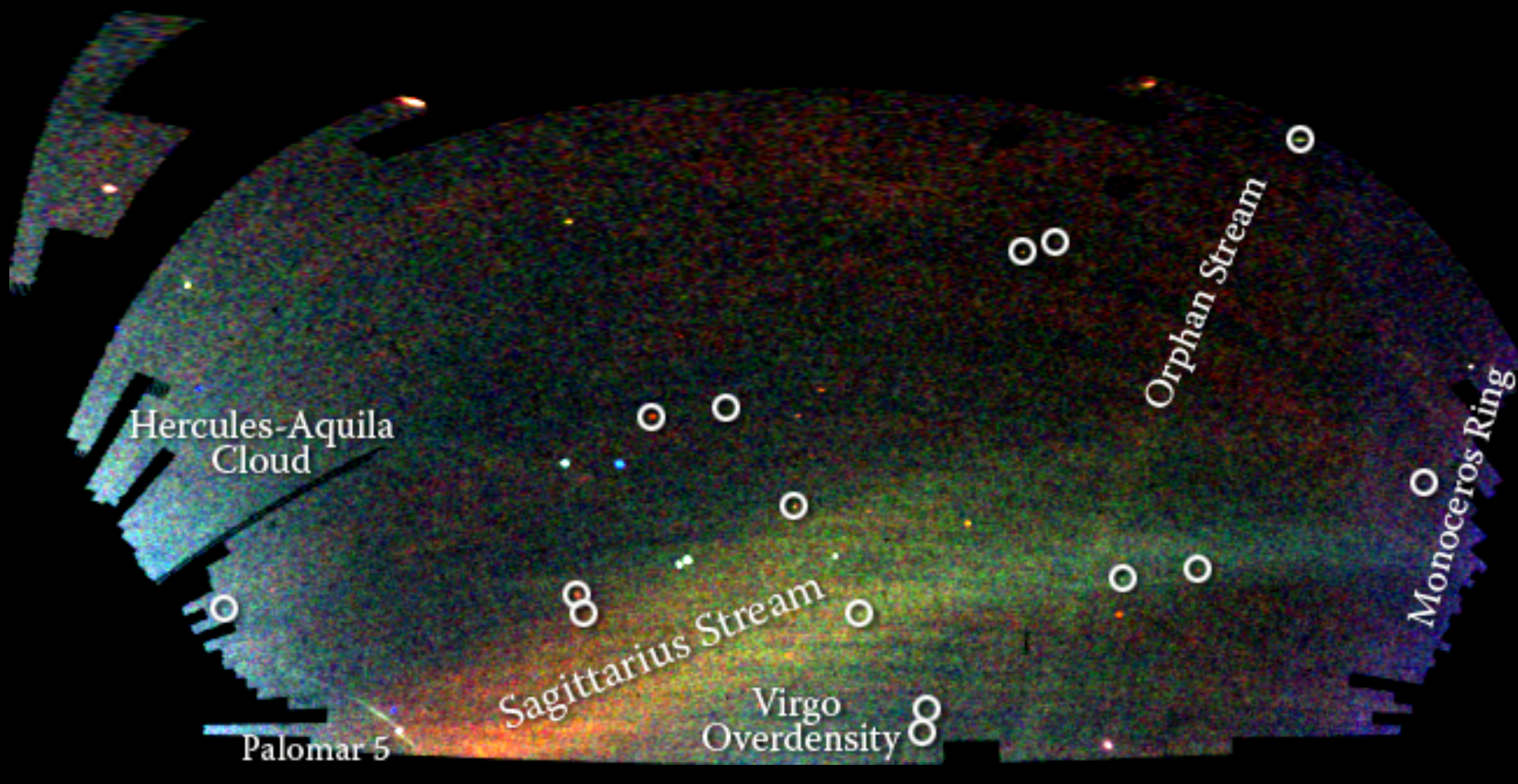

Credit: V. Belokurov and the Sloan Digital Sky Survey.

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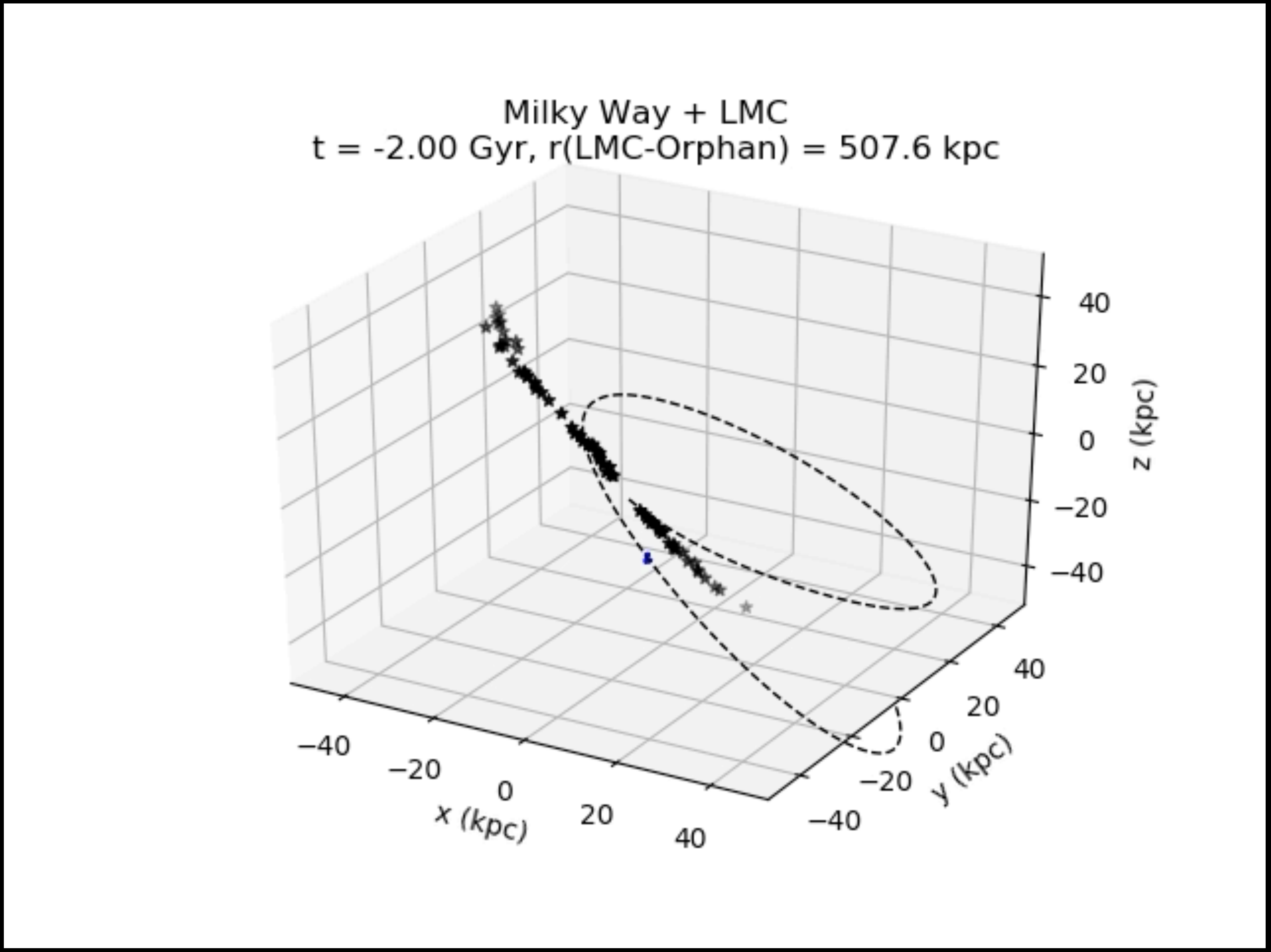

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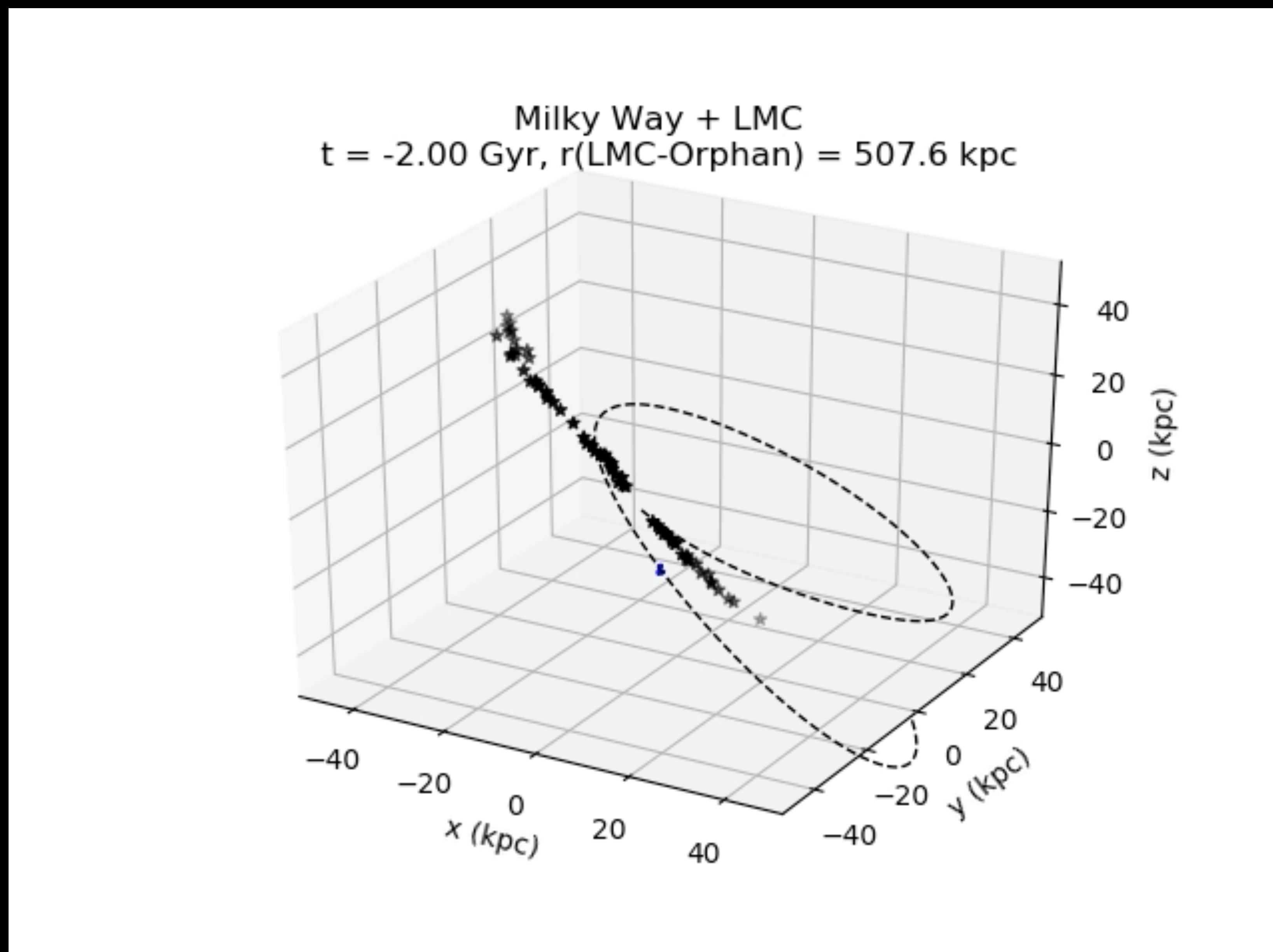

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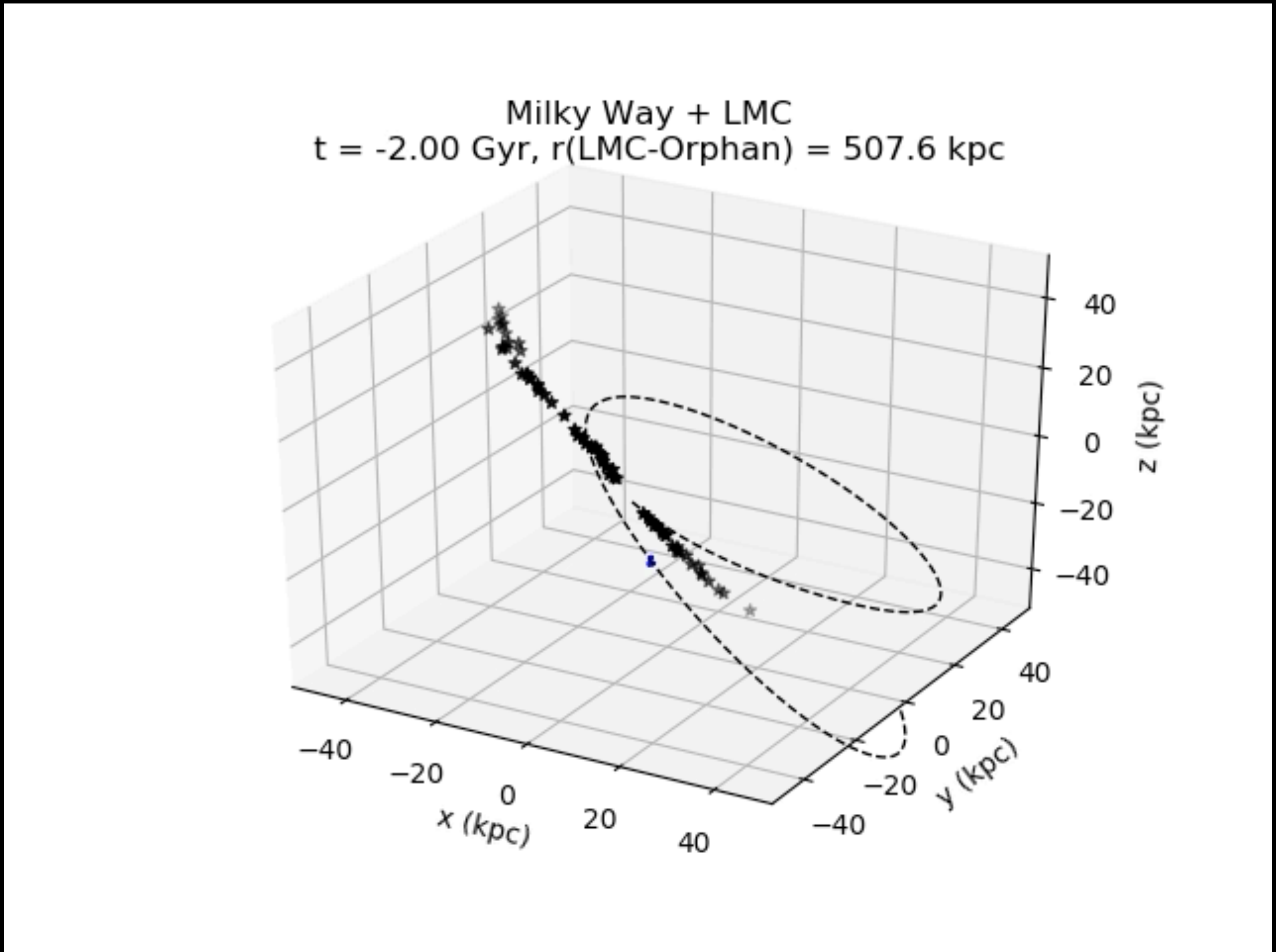


Gives a Milky Way mass of 940 billion solar masses

How do we weigh the Milky Way?

How do we weigh the Milky Way?

- Count up all the gas and stars

How do we weigh the Milky Way?

- Count up all the gas and stars
  - 66 billion solar masses

How do we weigh the Milky Way?

- Count up all the gas and stars
  - 66 billion solar masses
- Through its gravitational acceleration on another object

How do we weigh the Milky Way?

- Count up all the gas and stars
  - 66 billion solar masses
- Through its gravitational acceleration on another object
  - 940 billion solar masses

How do we weigh the Milky Way?

- Count up all the gas and stars
  - 66 billion solar masses
- Through its gravitational acceleration on another object
  - 940 billion solar masses
- So 7% of the mass in the Milky Way is in stars and cool gas

How do we weigh the Milky Way?

How do we weigh the Milky Way?

- This also gives the mass of the Large Magellanic Cloud

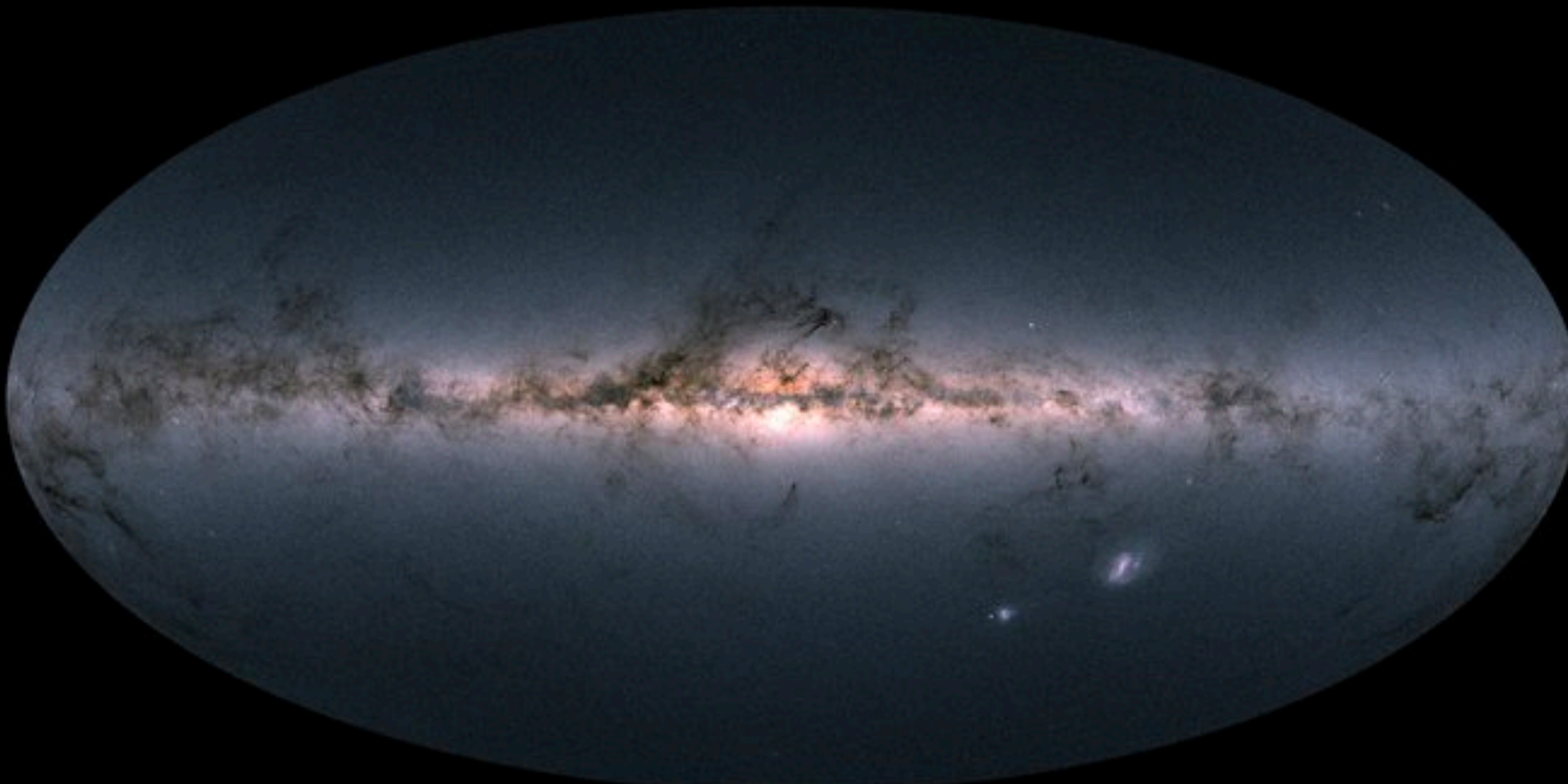
How do we weigh the Milky Way?

- This also gives the mass of the Large Magellanic Cloud
  - 138 billion solar masses

How do we weigh the Milky Way?

- This also gives the mass of the Large Magellanic Cloud
  - 138 billion solar masses

How do we weigh the Milky Way?



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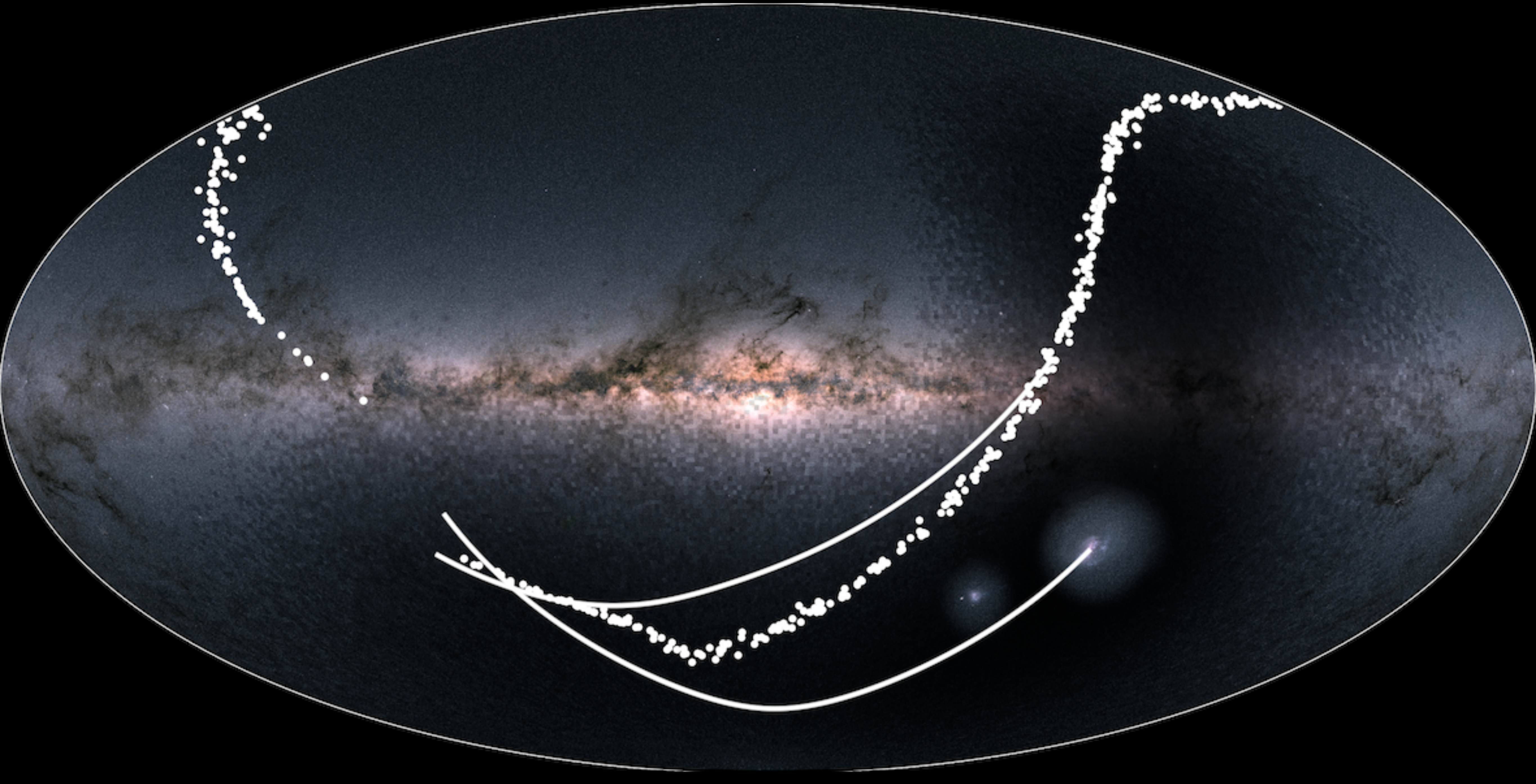
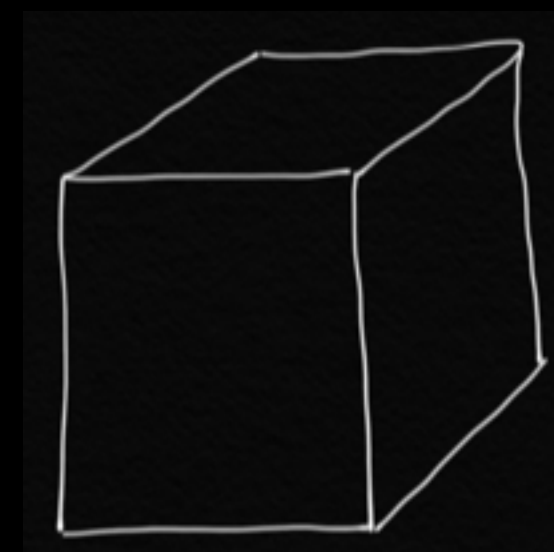
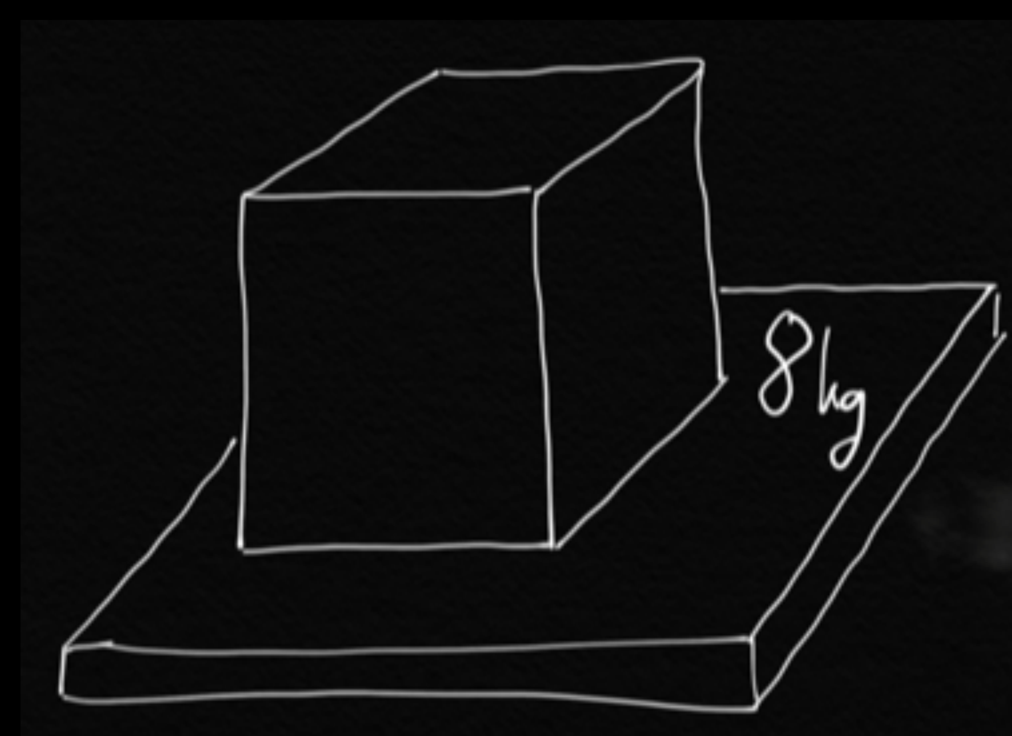


How do we weigh things?

- Count up how much stuff there is



- Use a weighing scale



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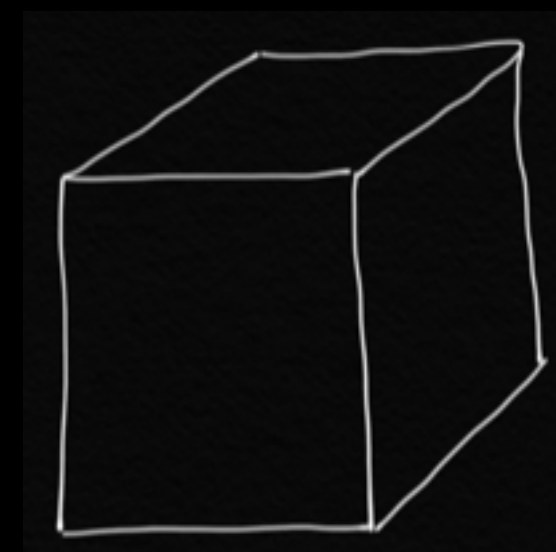
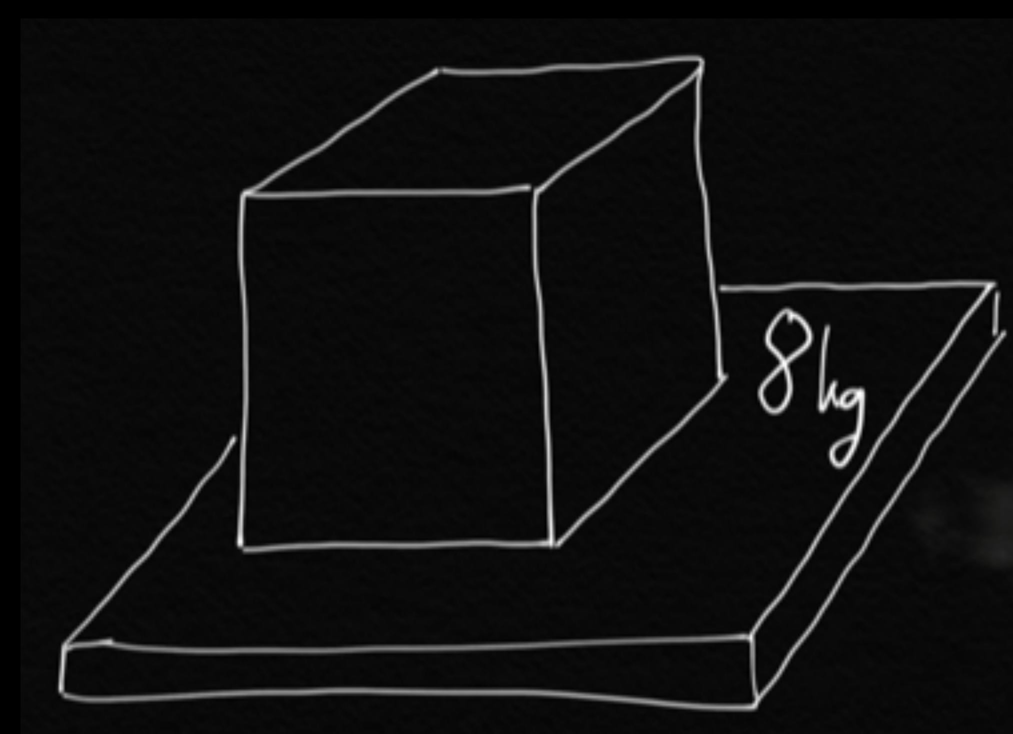


- ~~Use a weighing scale~~

  Use gravity!



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- Count how much stuff there is

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- Through its gravitational acceleration on another object

How to weigh the Milky Way

- Count how much stuff there is
- Through its gravitational acceleration on another object
  - Earth acceleration - 9.8 m/s^2

How to weigh the Milky Way

- Count how much stuff there is
- Through its gravitational acceleration on another object
  - Earth acceleration - 9.8 m/s^2
  - Sun's acceleration on the Earth - 0.006 m/s^2

How to weigh the Milky Way

- Count how much stuff there is
- Through its gravitational acceleration on another object
  - Earth acceleration - 9.8 m/s^2
  - Sun's acceleration on the Earth - 0.006 m/s^2
  - Milky Way's acceleration on the Earth - $2x10^{-10}$ m/s^2

How to weigh the Milky Way

- Count how much stuff there is
- Through its gravitational acceleration on another object
  - Earth acceleration - 9.8 m/s^2
  - Sun's acceleration on the Earth - 0.006 m/s^2
  - Milky Way's acceleration on the Earth - $2x10^{-10}$ m/s^2
- Acceleration tells you the mass

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  - Earth acceleration - 9.8 m/s^2
  - Sun's acceleration on the Earth - 0.006 m/s^2
  - Milky Way's acceleration on the Earth - 2×10^{-10} m/s^2
- Acceleration tells you the mass

Thank you!