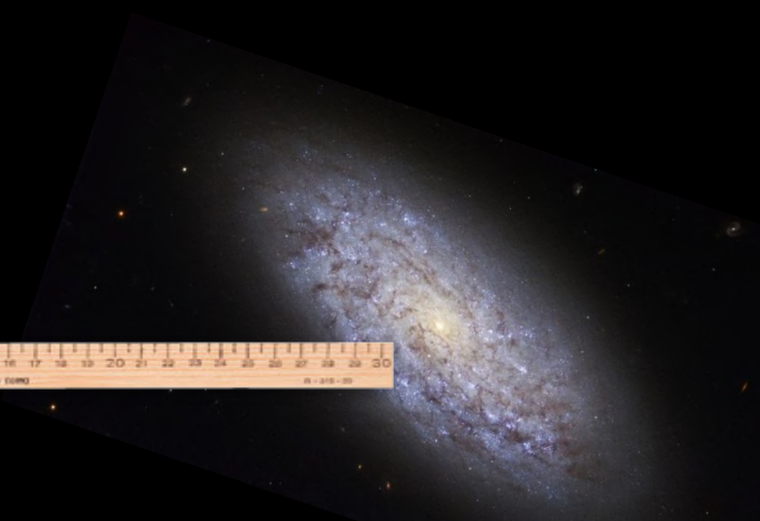
The dark side of matter

François Mernier

mernier@caesar.elte.hu - Wallon Super

Two biggest challenges for astronomers…

- Distance



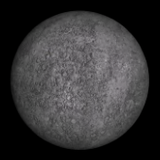
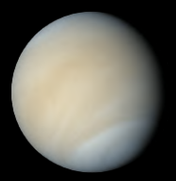
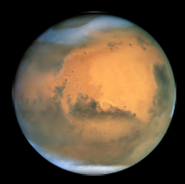
- Mass

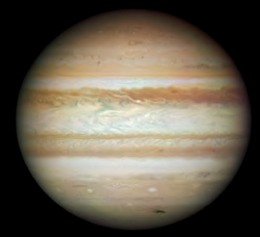
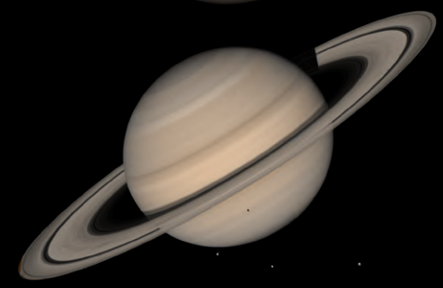
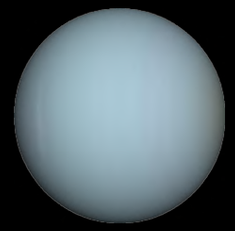
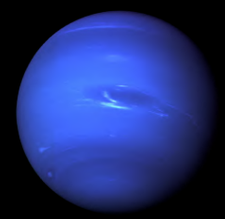
Two biggest challenges for astronomers…

- Distance

- Mass

The Solar System (+ Pluto…)

		v
Mercury		47 km/s
Venus		35 km/s
Earth		30 km/s
Mars		24 km/s

		v
Jupiter		13 km/s
Saturn		10 km/s
Uranus		7 km/s
Neptune		5 km/s
Pluto		4 km/s

Mass can be derived from velocity!

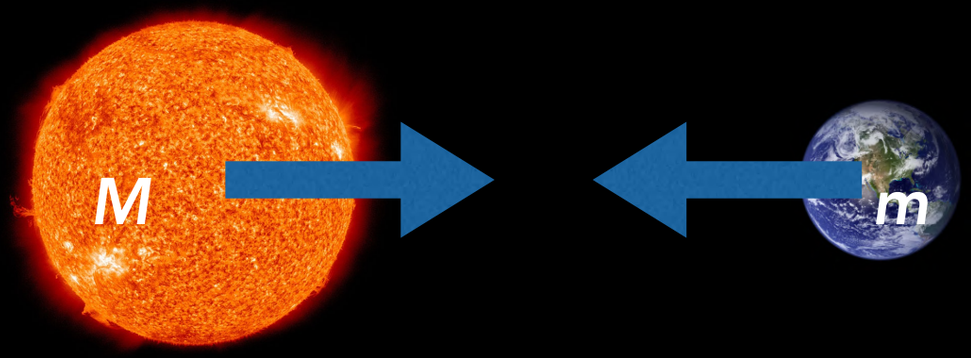
- Newton's gravity law:

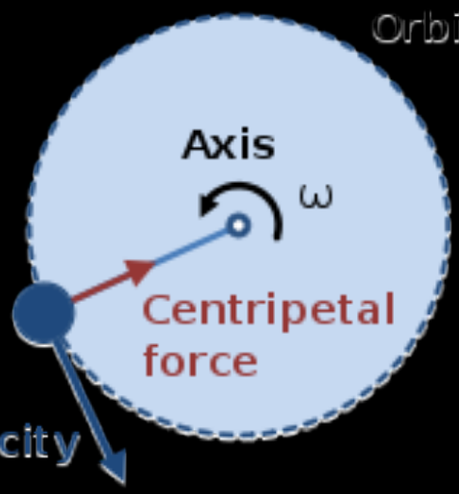
$$F_{\text{grav}} = G\frac{Mm}{R^2}$$

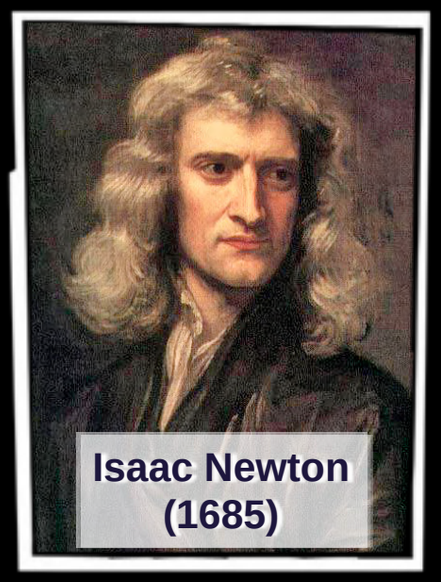
=

- Centripetal force

$$\frac{mv^2}{R} = F_{\text{centr}}$$







$$v = \sqrt{\frac{GM}{R}}$$

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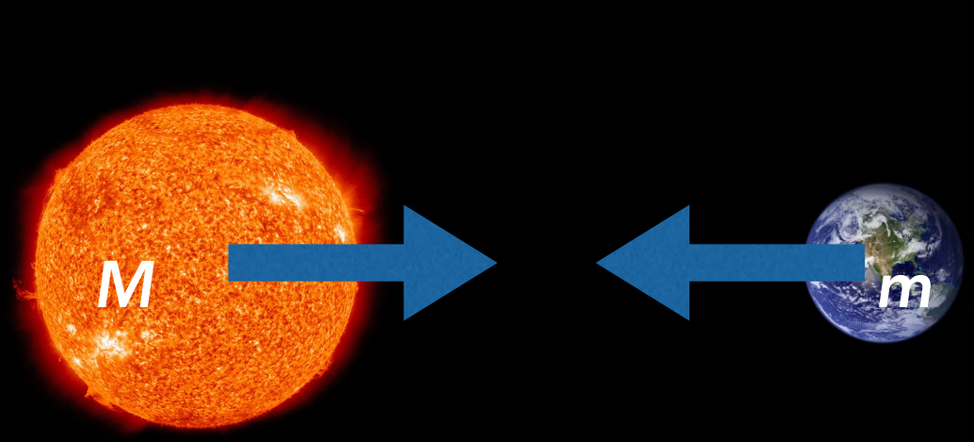

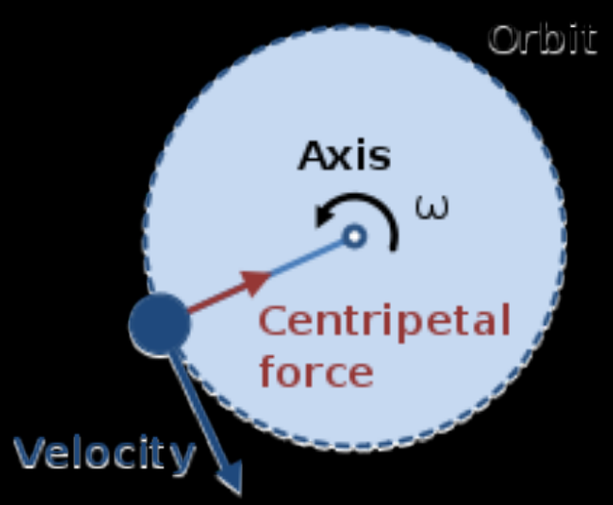

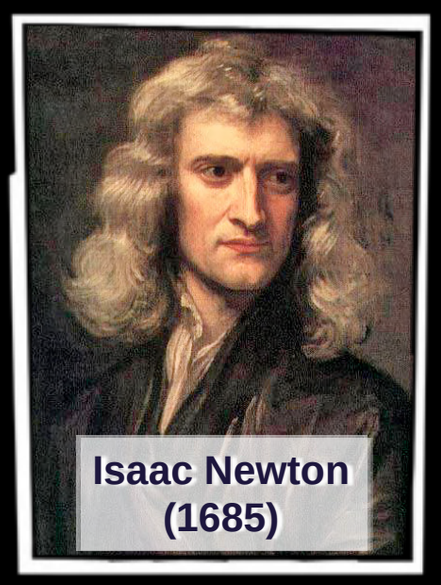

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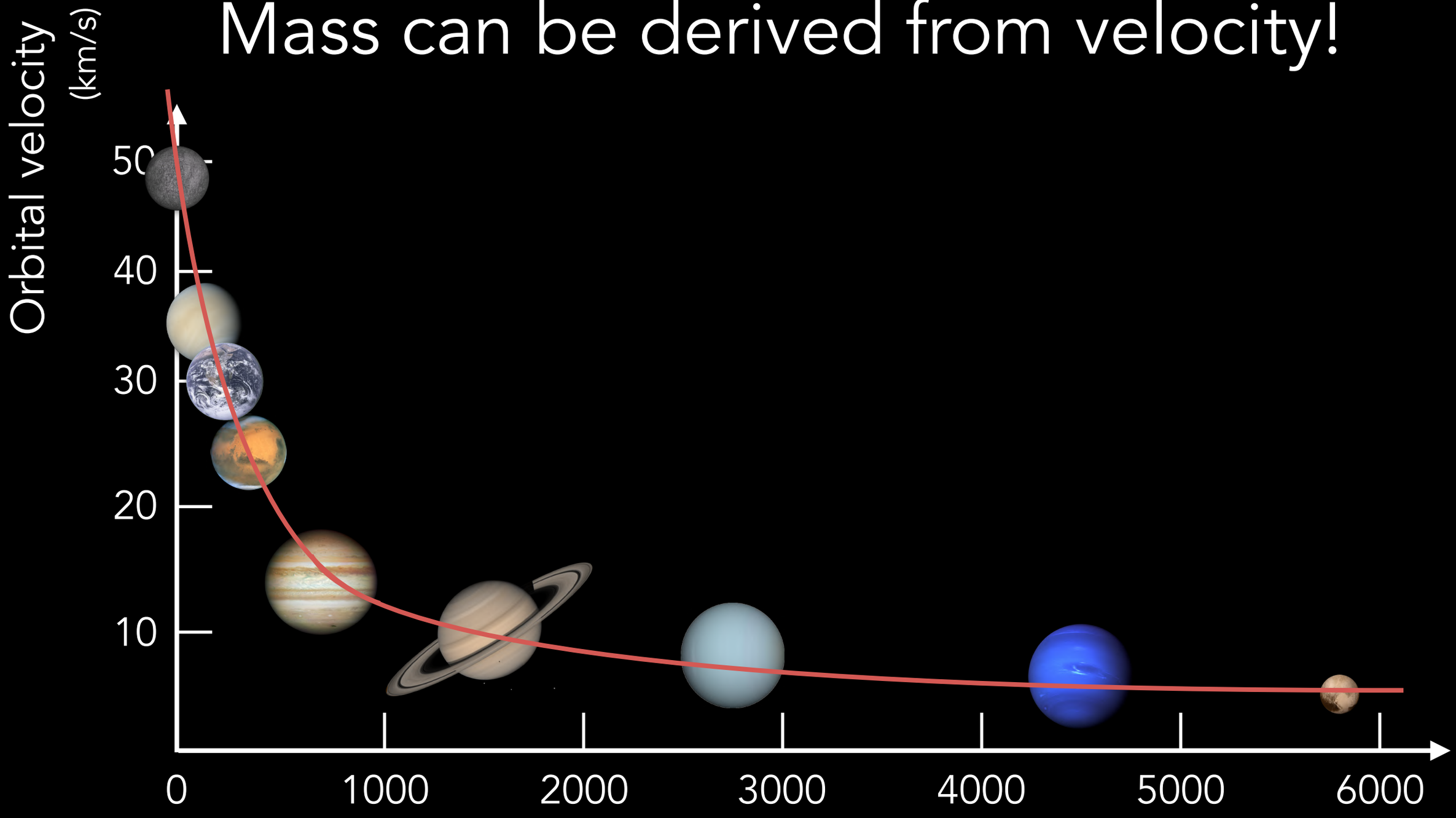

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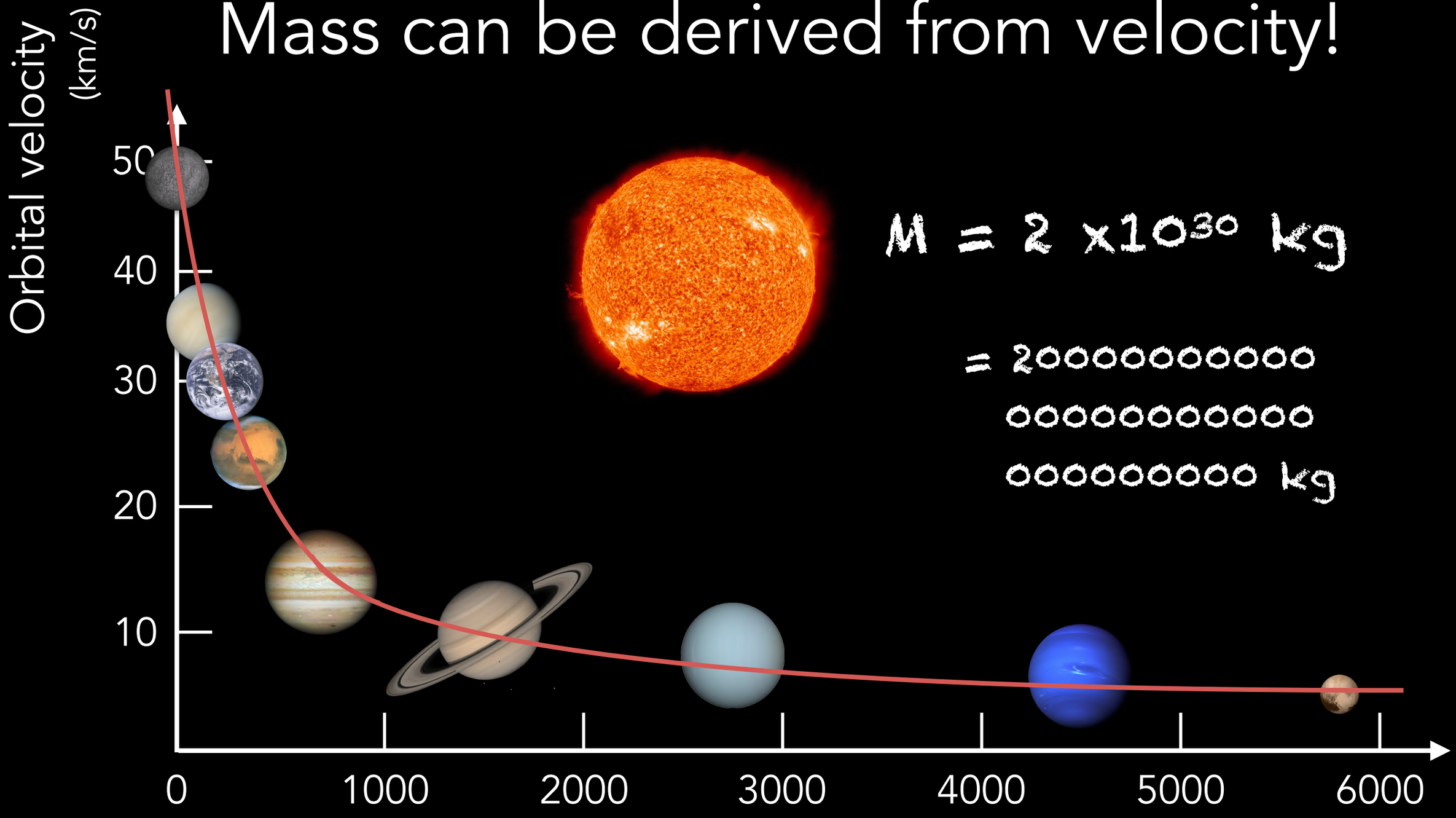

$M = 2 \times 10^{30}$ kg

= 2000000000000000000000000000 kg

$$v = \sqrt{\frac{GM}{R}}$$

How about galaxies?

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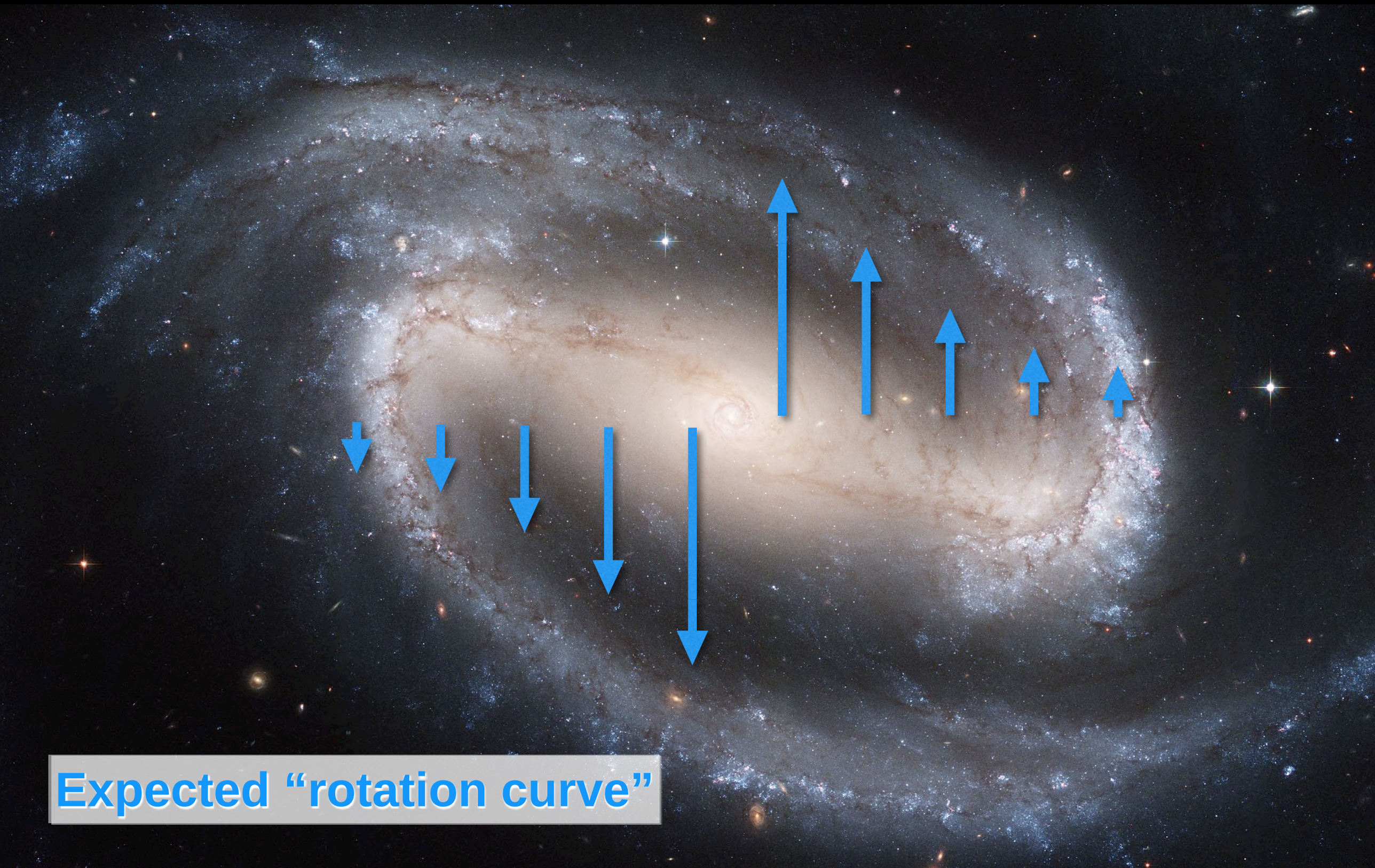
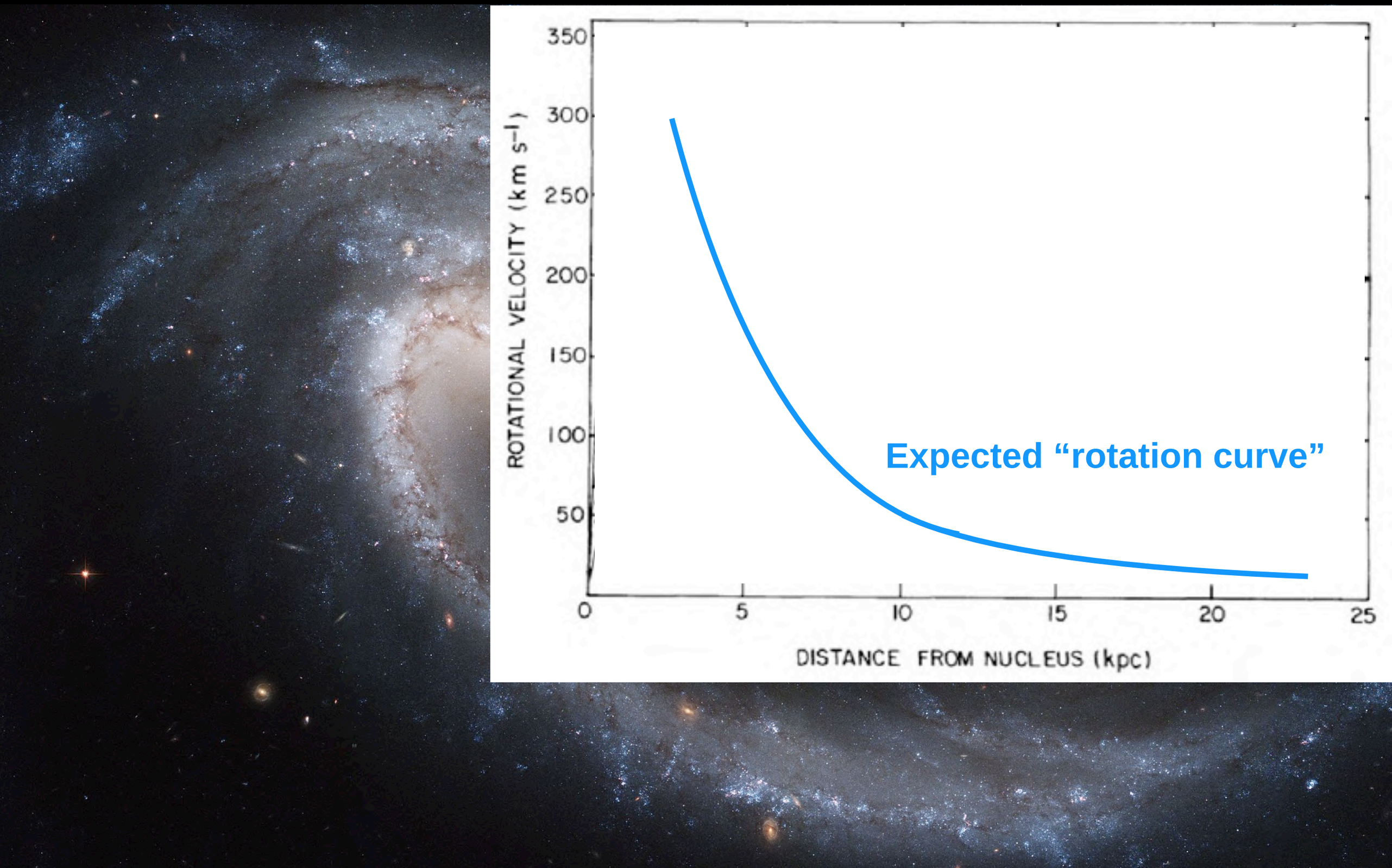


Expected “rotation curve”

How about galaxies?



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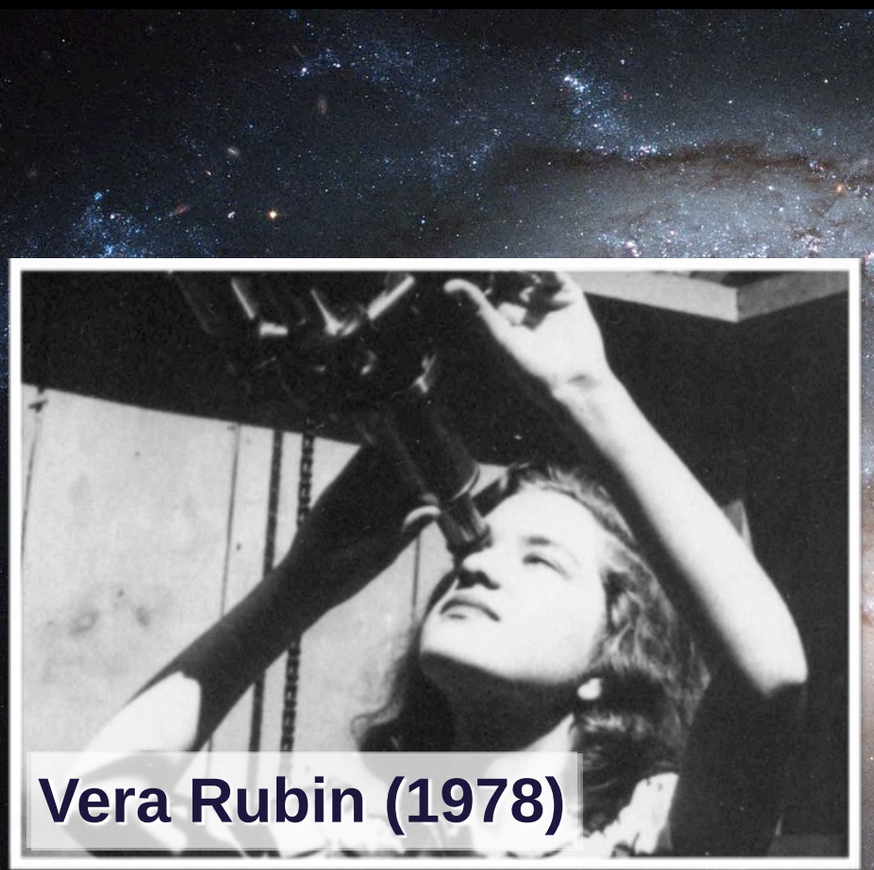
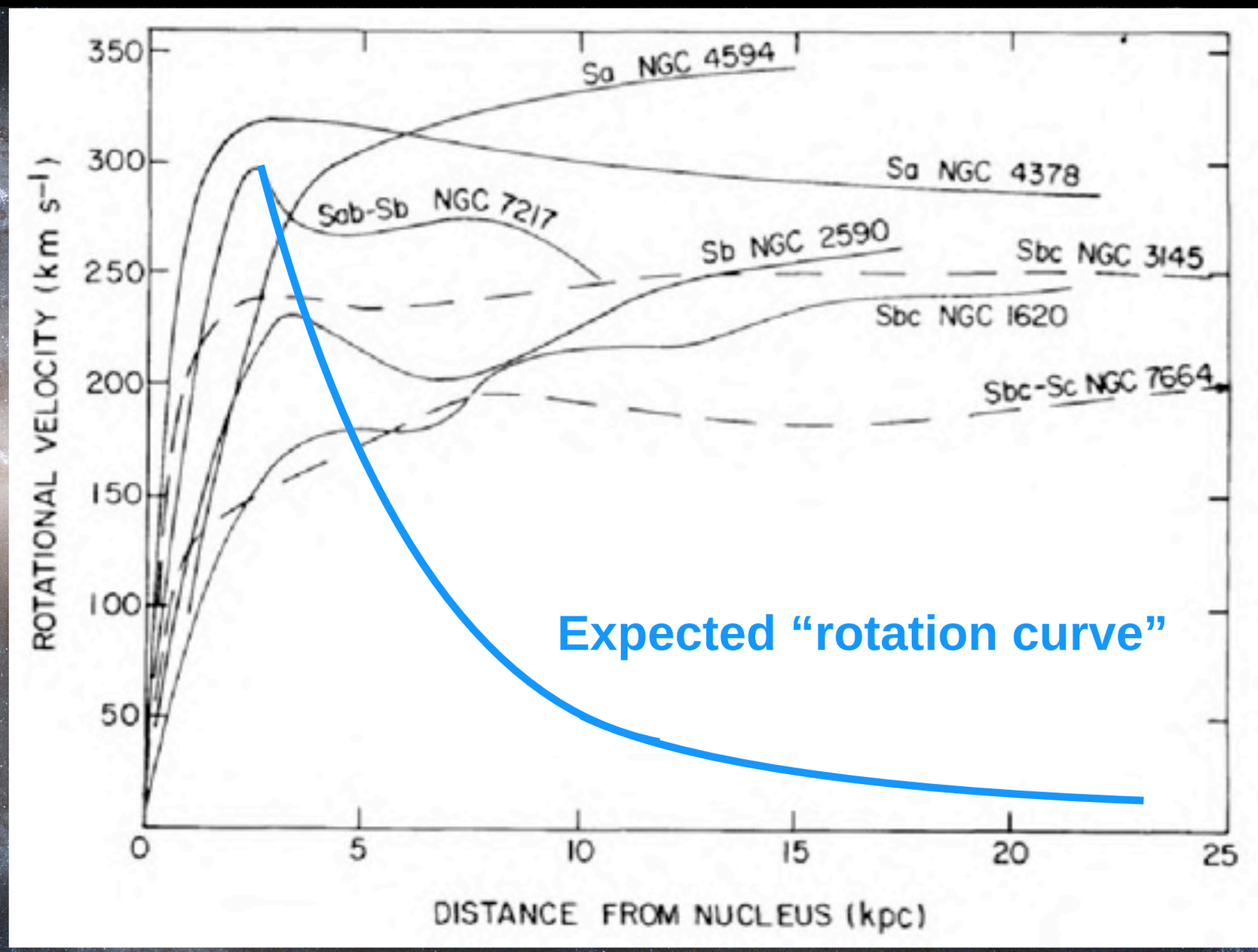
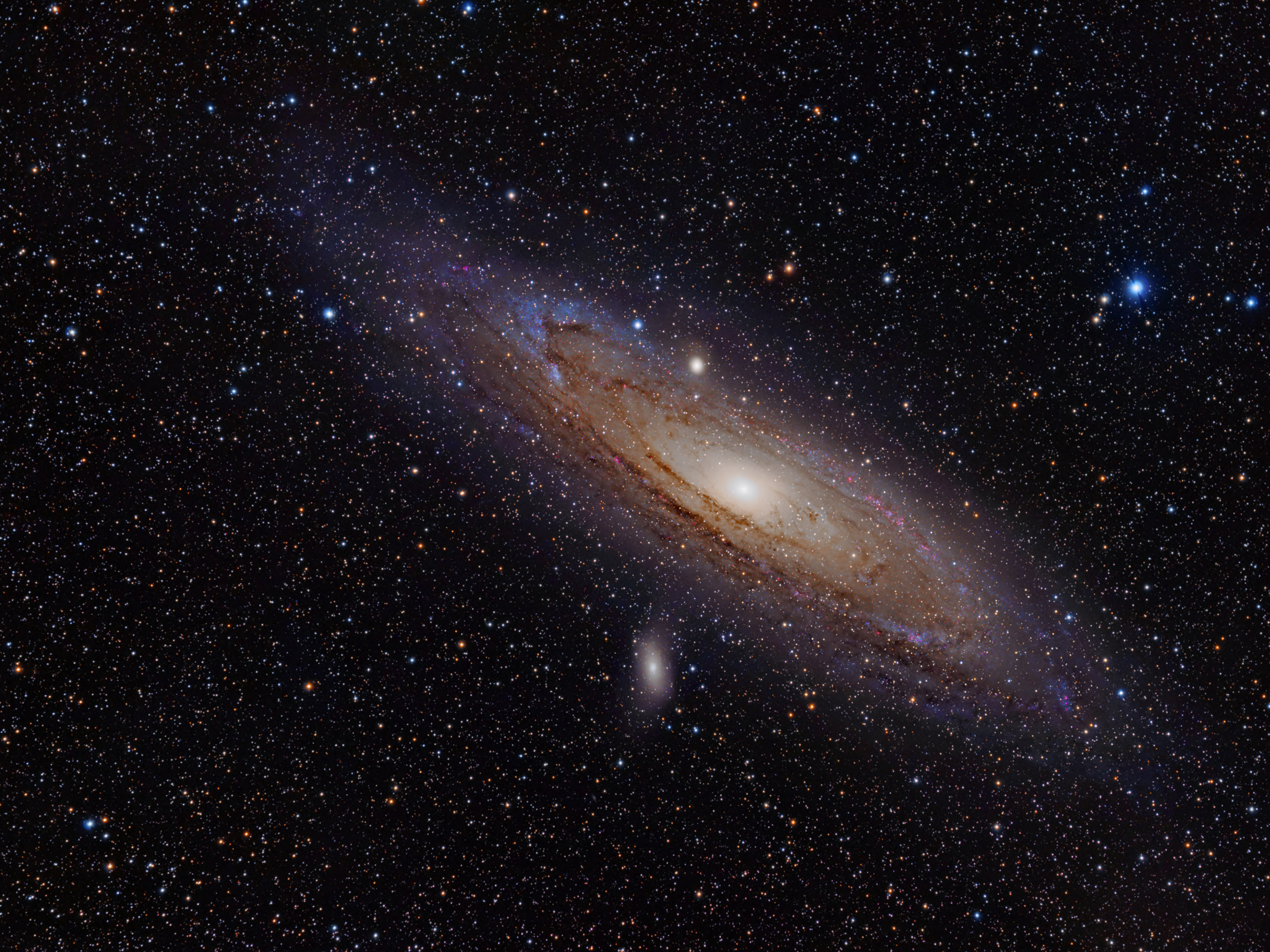
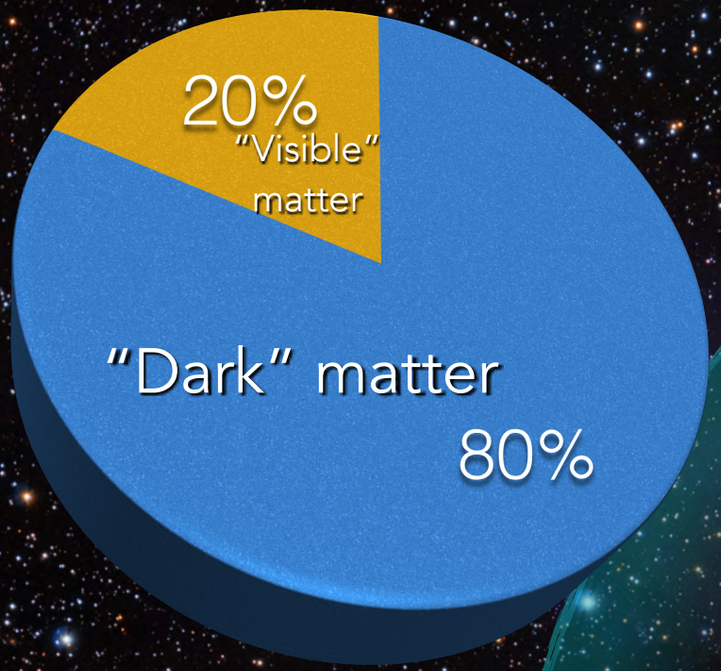


Vera Rubin (1978)



Why do external stars move "too fast"?





Spherical halo around galaxies

Beyond galaxies…

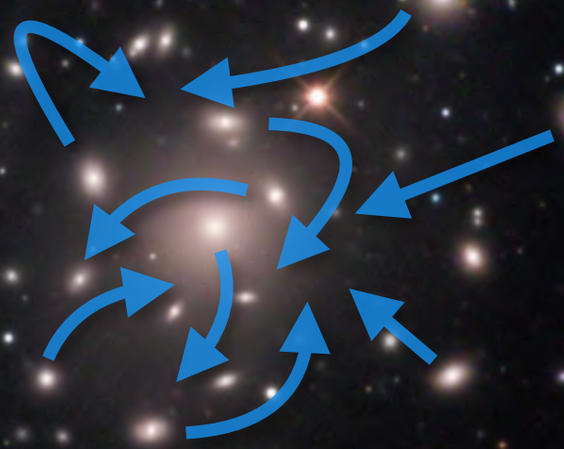
How to derive mass?

Beyond galaxies…

How to derive mass?

- 1) via **velocities**

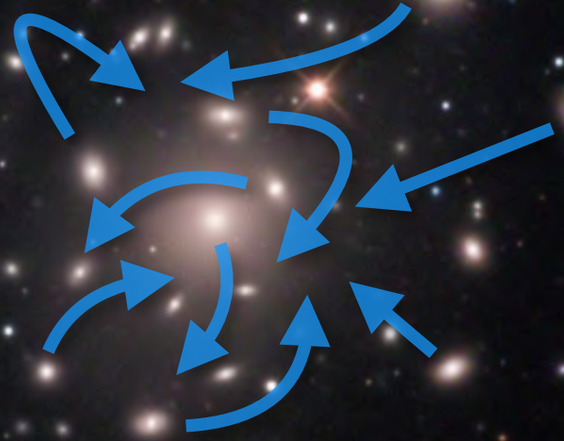
M_{real}



Beyond galaxies…

How to derive mass?

- 1) via **velocities** M_{real}
- 2) via **luminosity** $M_{visible}$
  (→ "count" stars)



Beyond galaxies…

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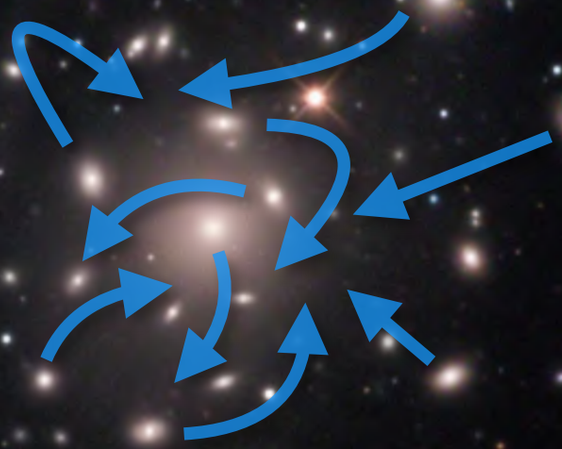
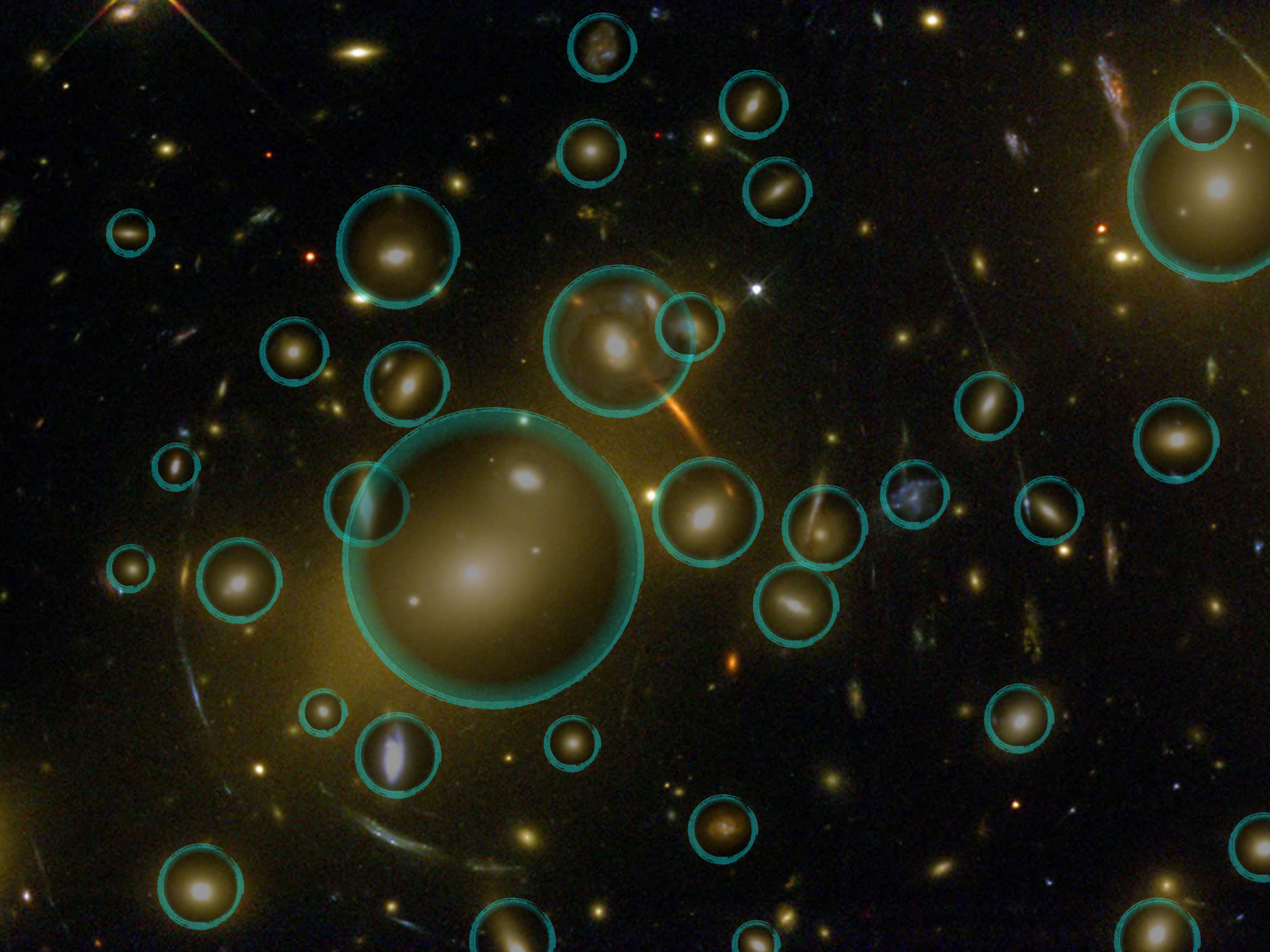
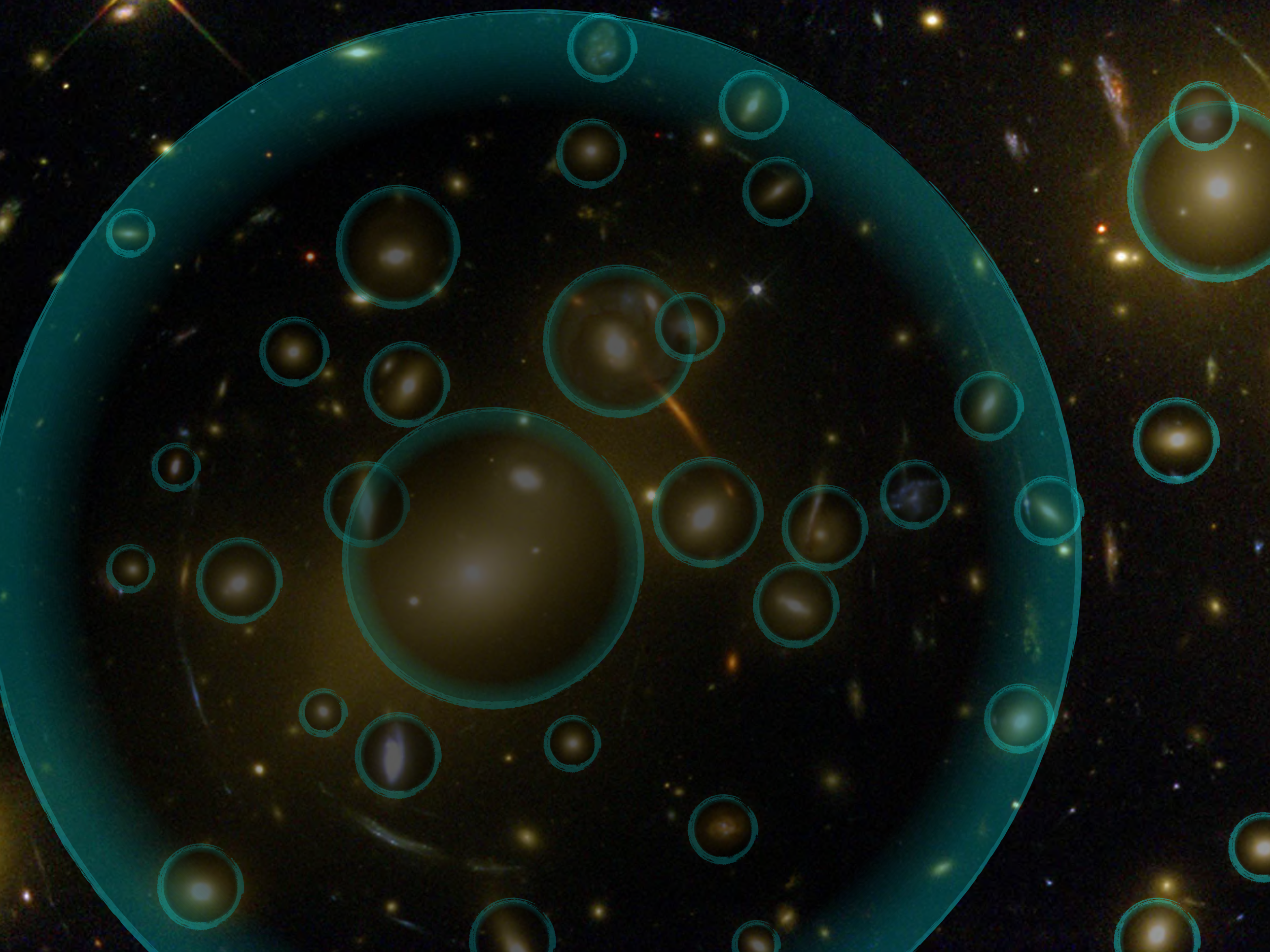


$M_{real} > 400 \times M_{visible}$

Fritz Zwicky (1933)

in Zusammenhang gebracht werden. Einer Expansion von 500 km/sek pro Million Parseks entspricht nach Einstein und de Sitter eine mittlere Dichte $\varrho \leqq 10^{-28}$ gr/cm³. Aus den Beobachtungen an selbstleuchtender Materie schätzt Hubble $\varrho \sim 10^{-31}$ gr/cm³. Es ist natürlich möglich, dass leuchtende plus dunkle (kalte) Materie zusammengenommen eine bedeutend höhere Dichte ergeben, und der Wert $\bar{\varrho} \sim 10^{-28}$ gr/cm³ erscheint daher nicht



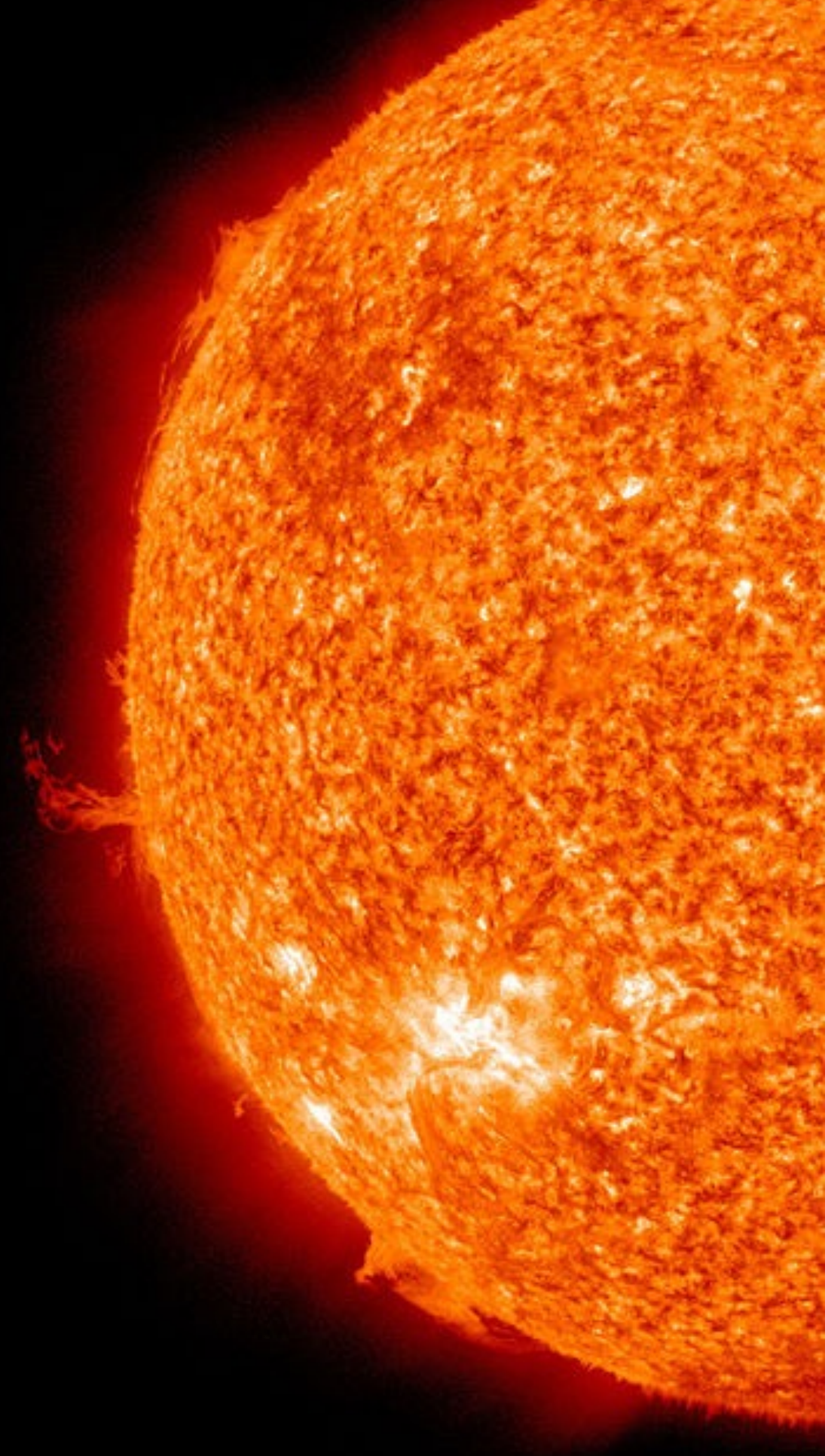


$1 Million

What is "dark" matter made of?

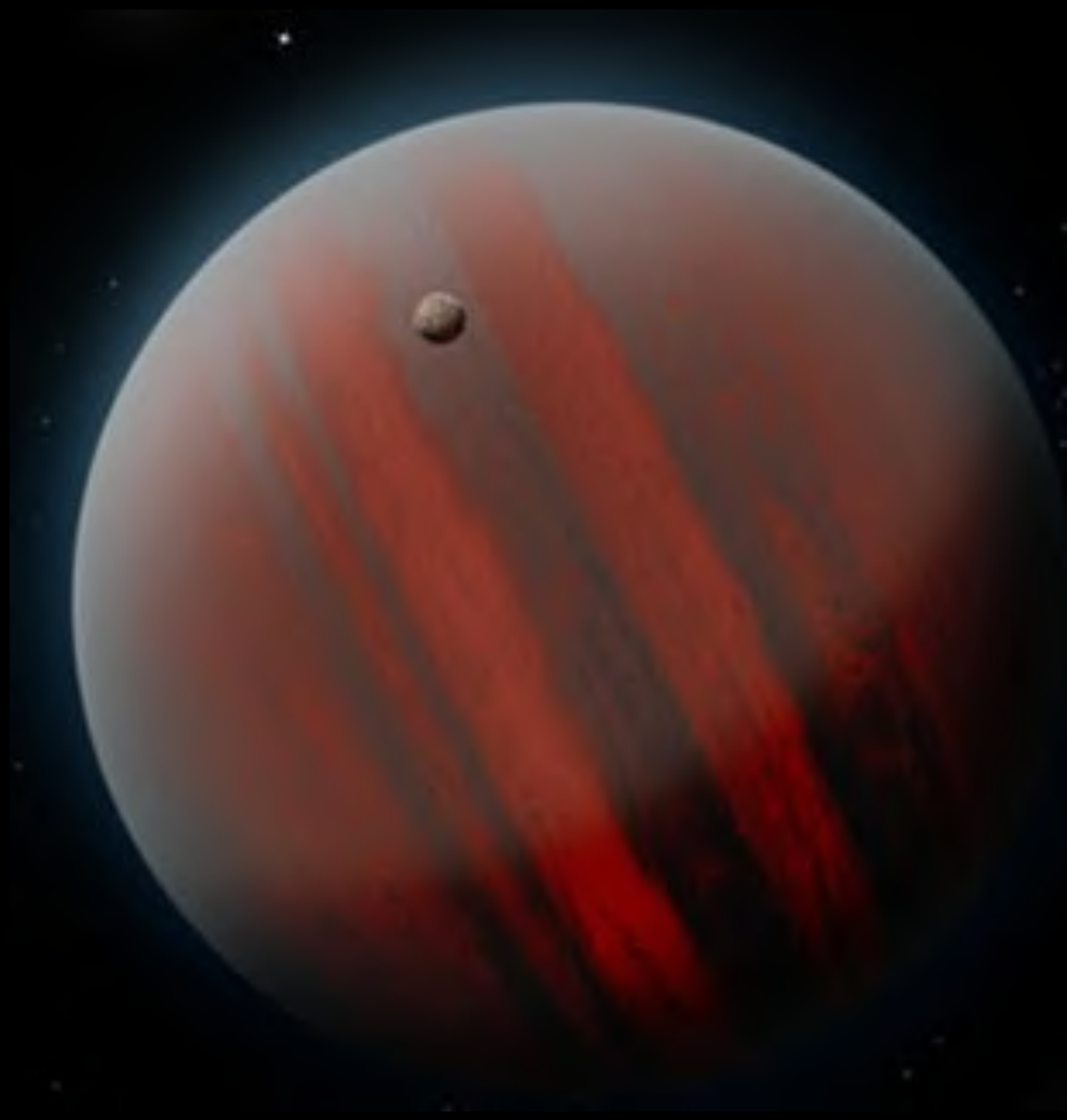
- Planets?

- Would require MANY of them, also far away from stars!
- Inconsistent with our models of planetary formation…

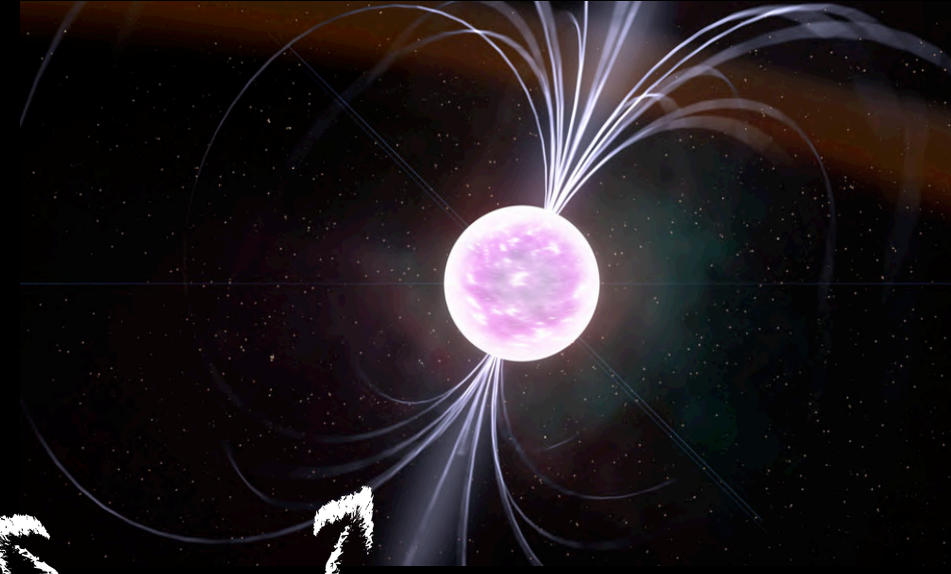


- Brown dwarfs?

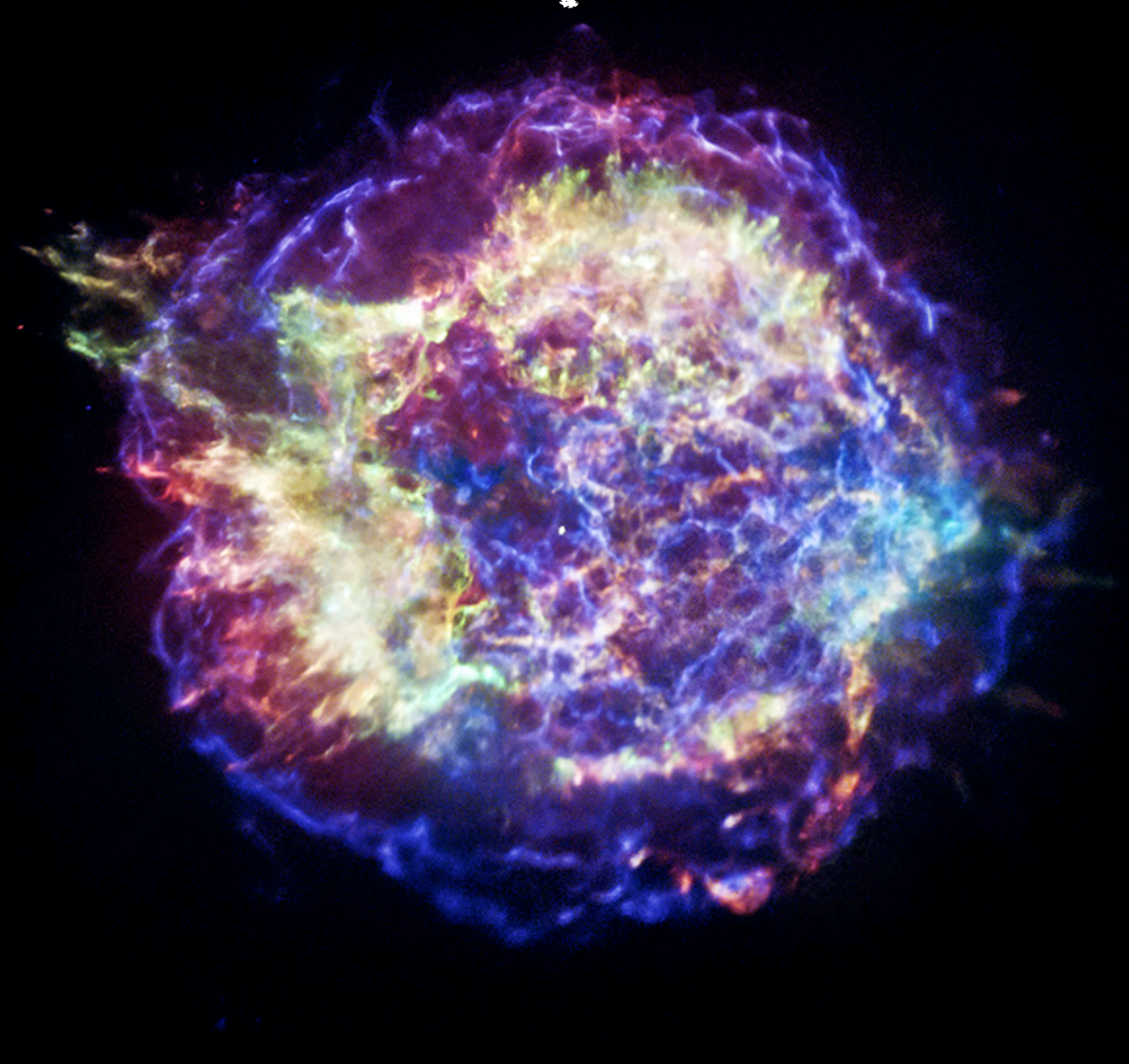
- Astronomers have counted them (they still emit some light in infrared)…
- But not enough to explain dark matter!



- Black holes?
  Neutron stars?

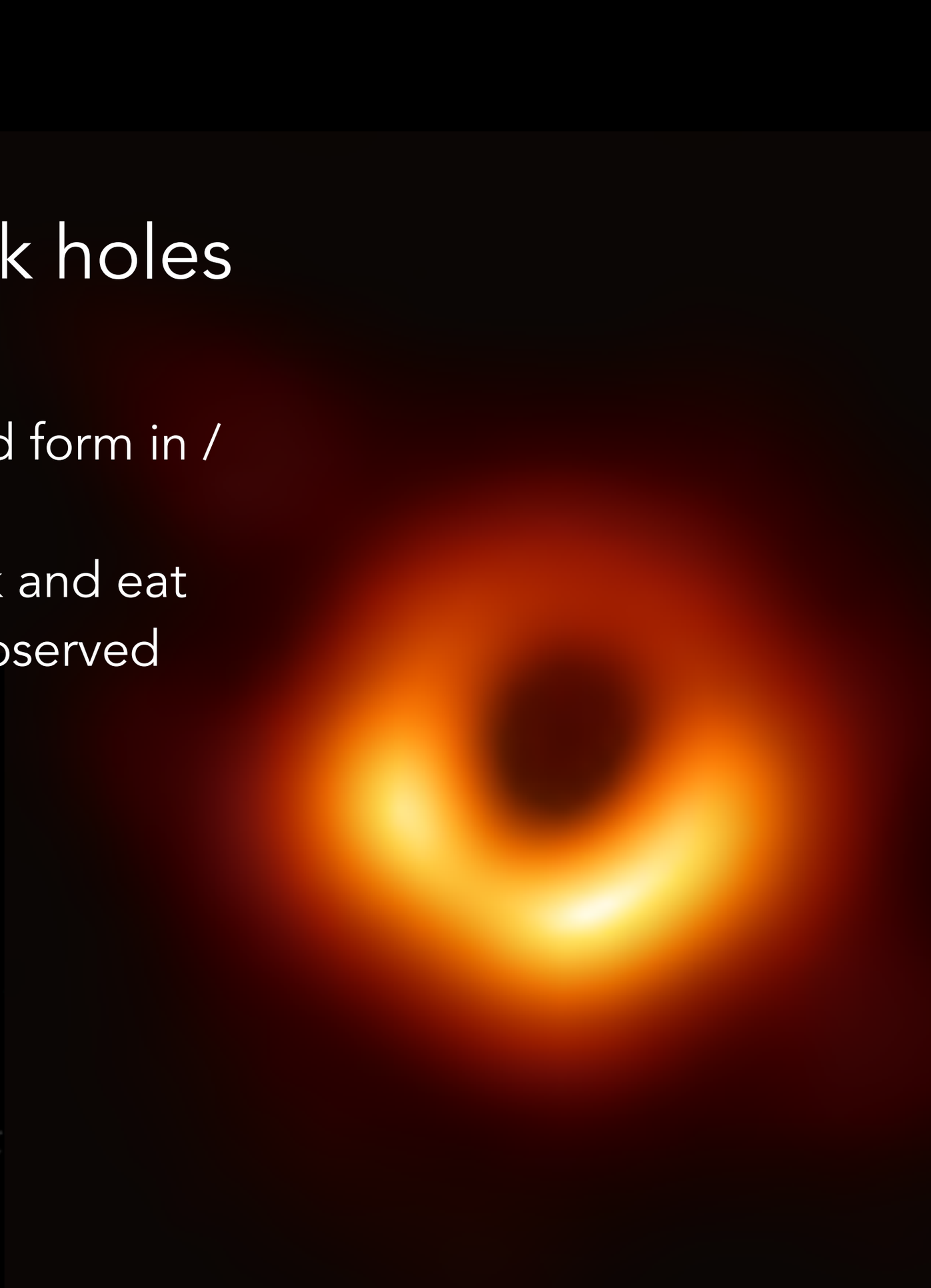


- Both are remnants from massive stars and supernovae…
- Not observed in distant (=past) galaxies!



- Supermassive black holes

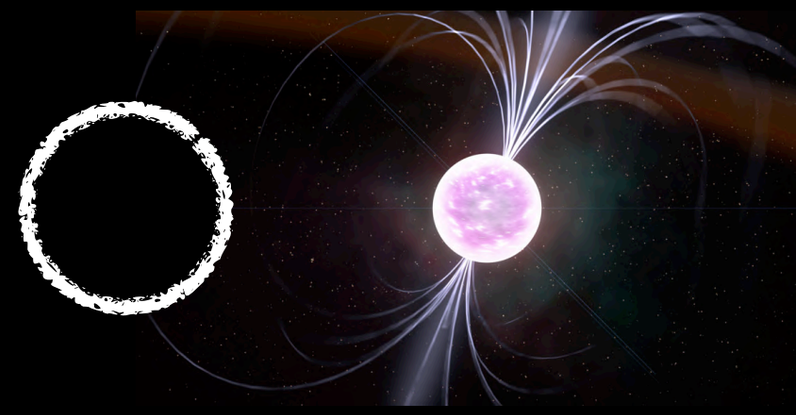
- Co-evolve with galaxies (and form in / sink to their centre)…
- Should cross the galaxy disk and eat some stars/gas… but not observed



- Planets?

- Brown dwarfs?

- Black holes / neutron stars?



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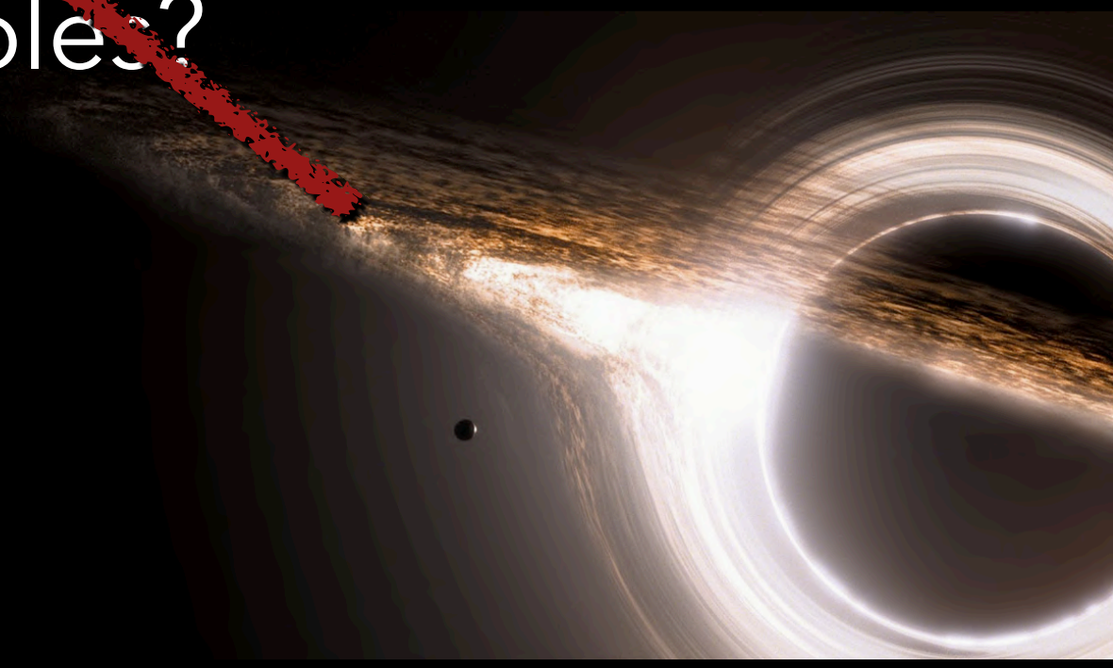

Massive Compact Halo Objects (MACHOs)

- …But does dark matter really exist?

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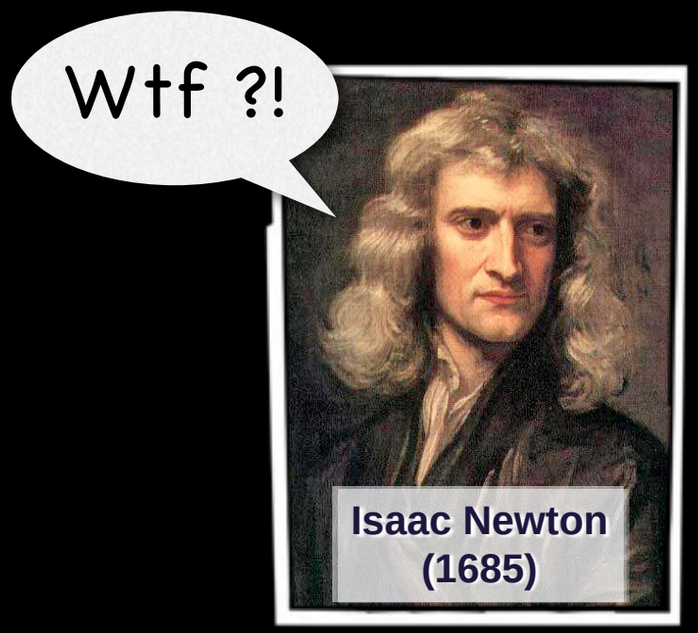
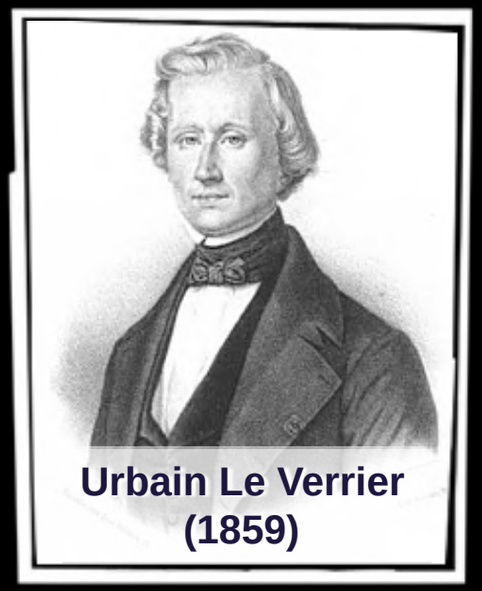
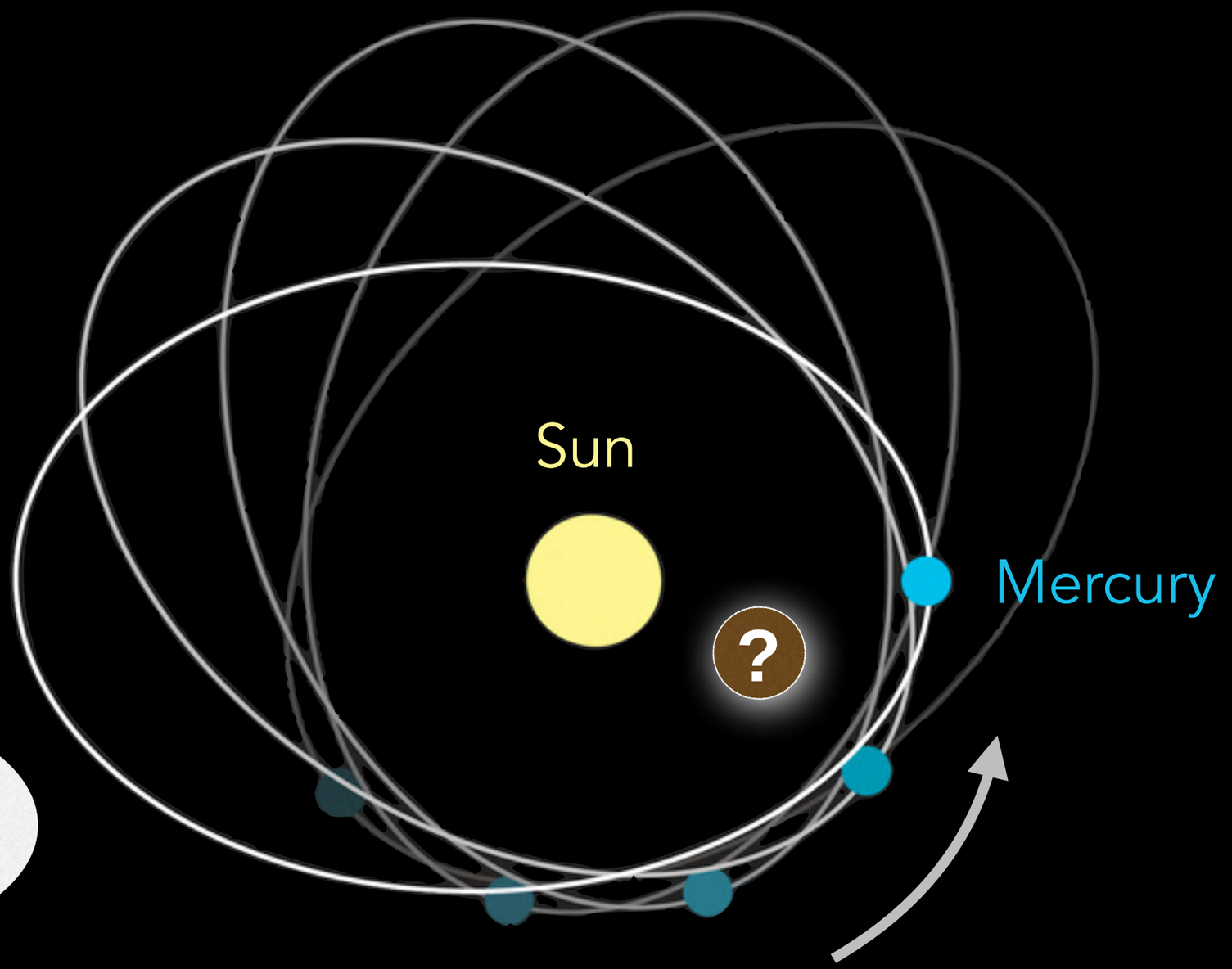
  - A bit of history…





There must be a hidden planet! (Vulcan)



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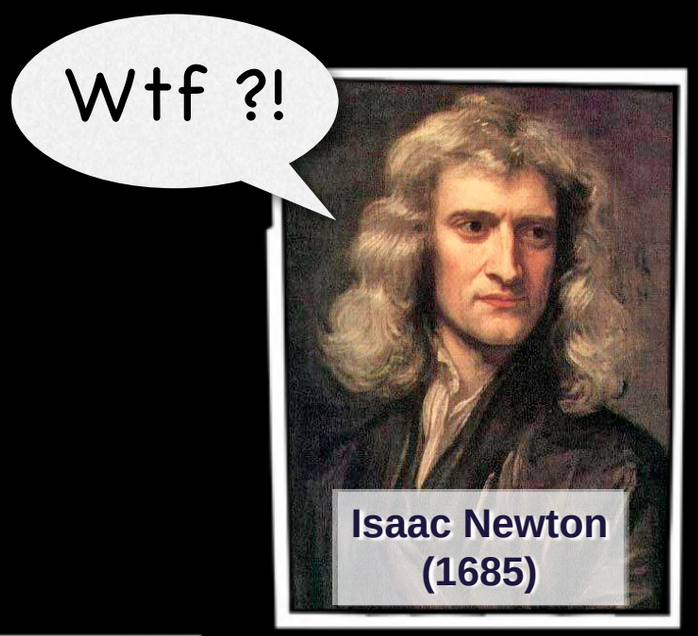
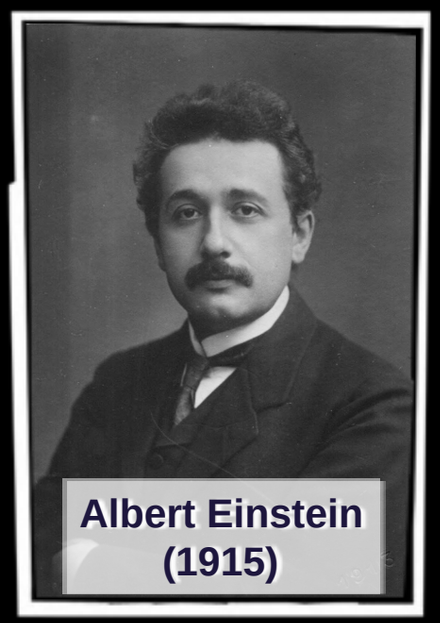
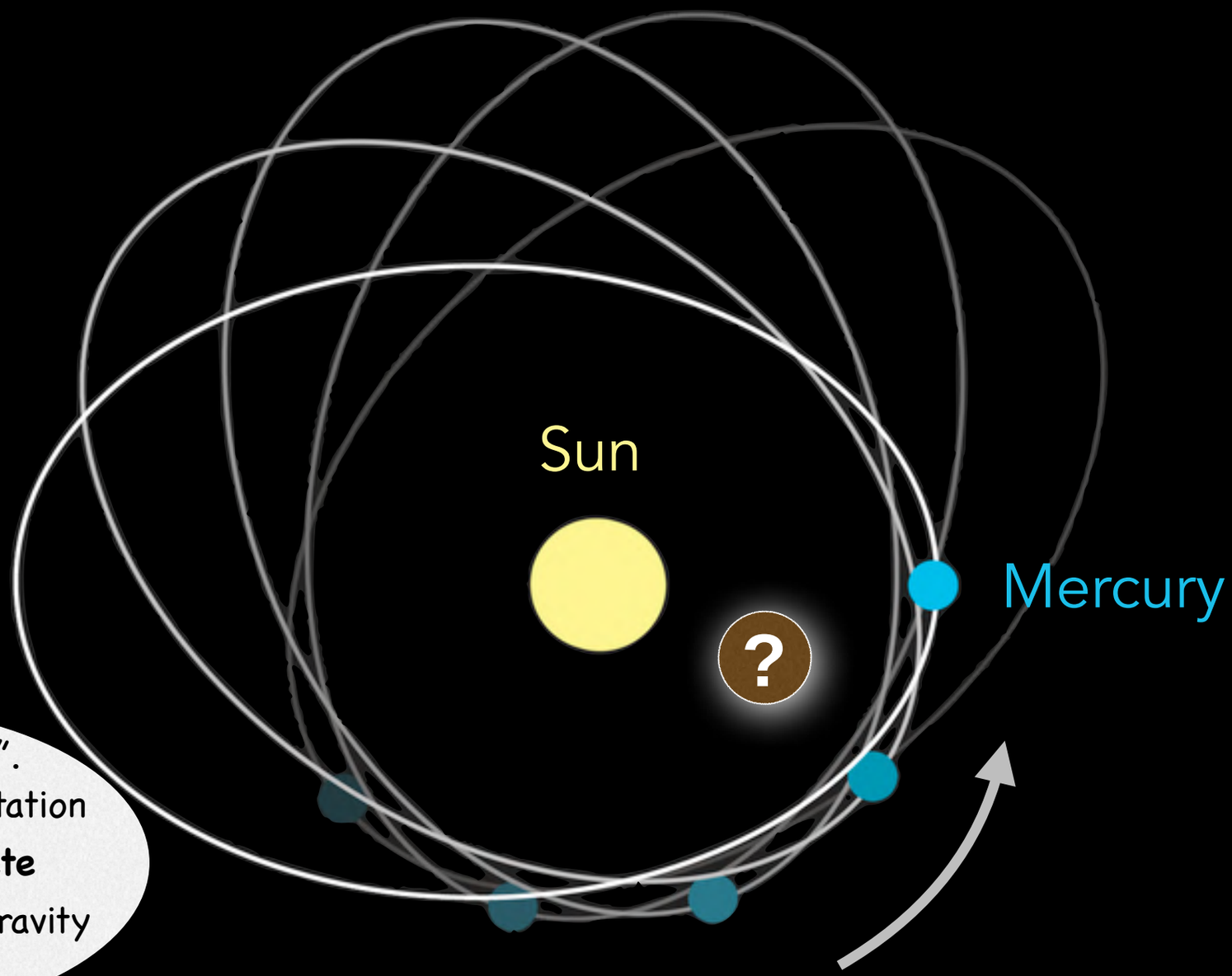




There's no "Vulcan".
Newton's laws of gravitation were just **incomplete** (especially in **strong** gravity fields).



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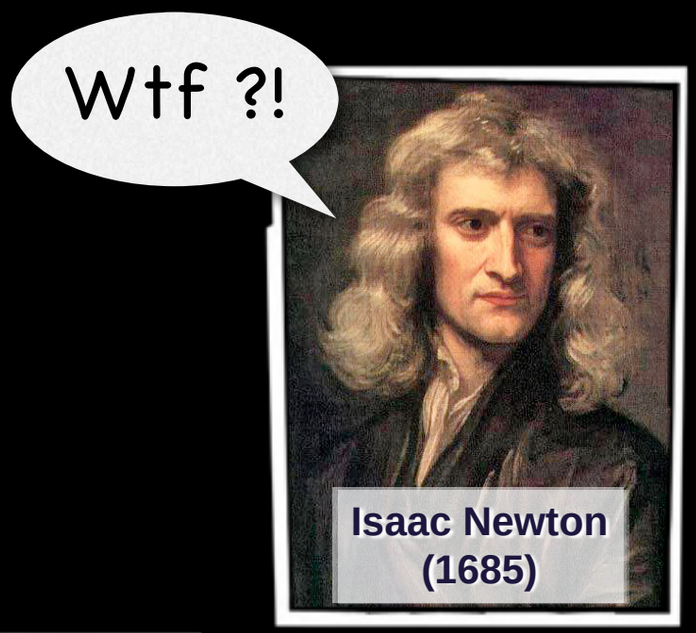

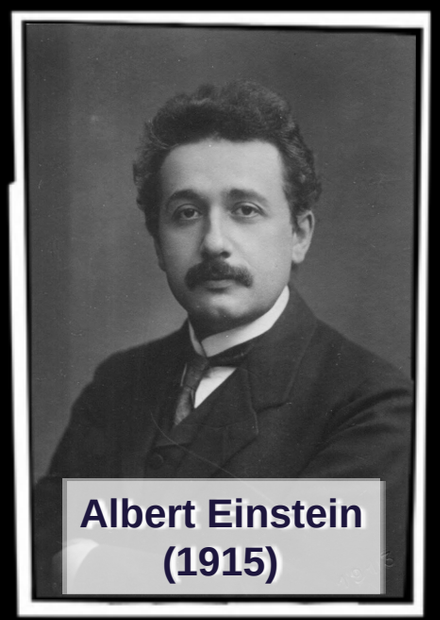

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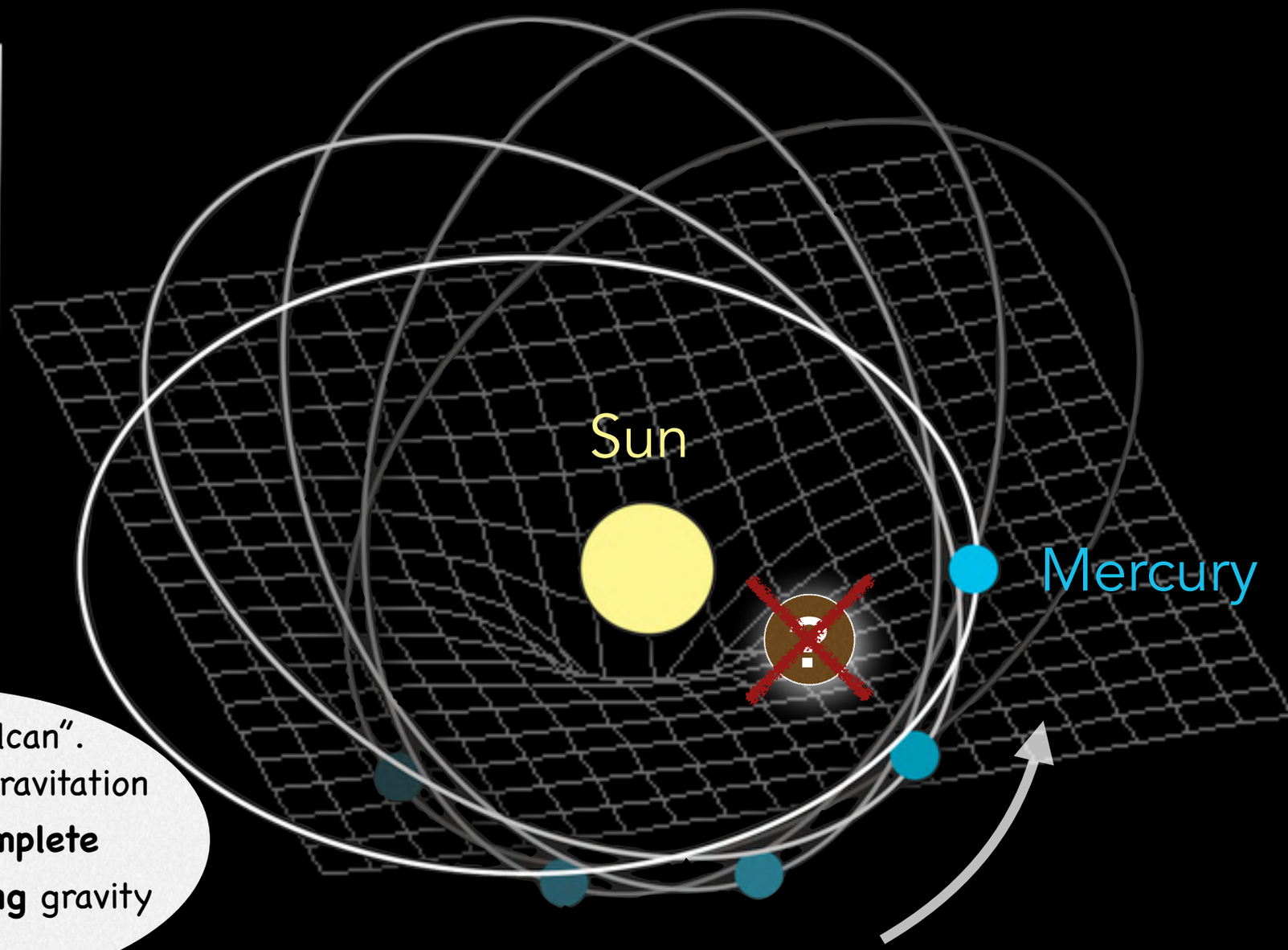
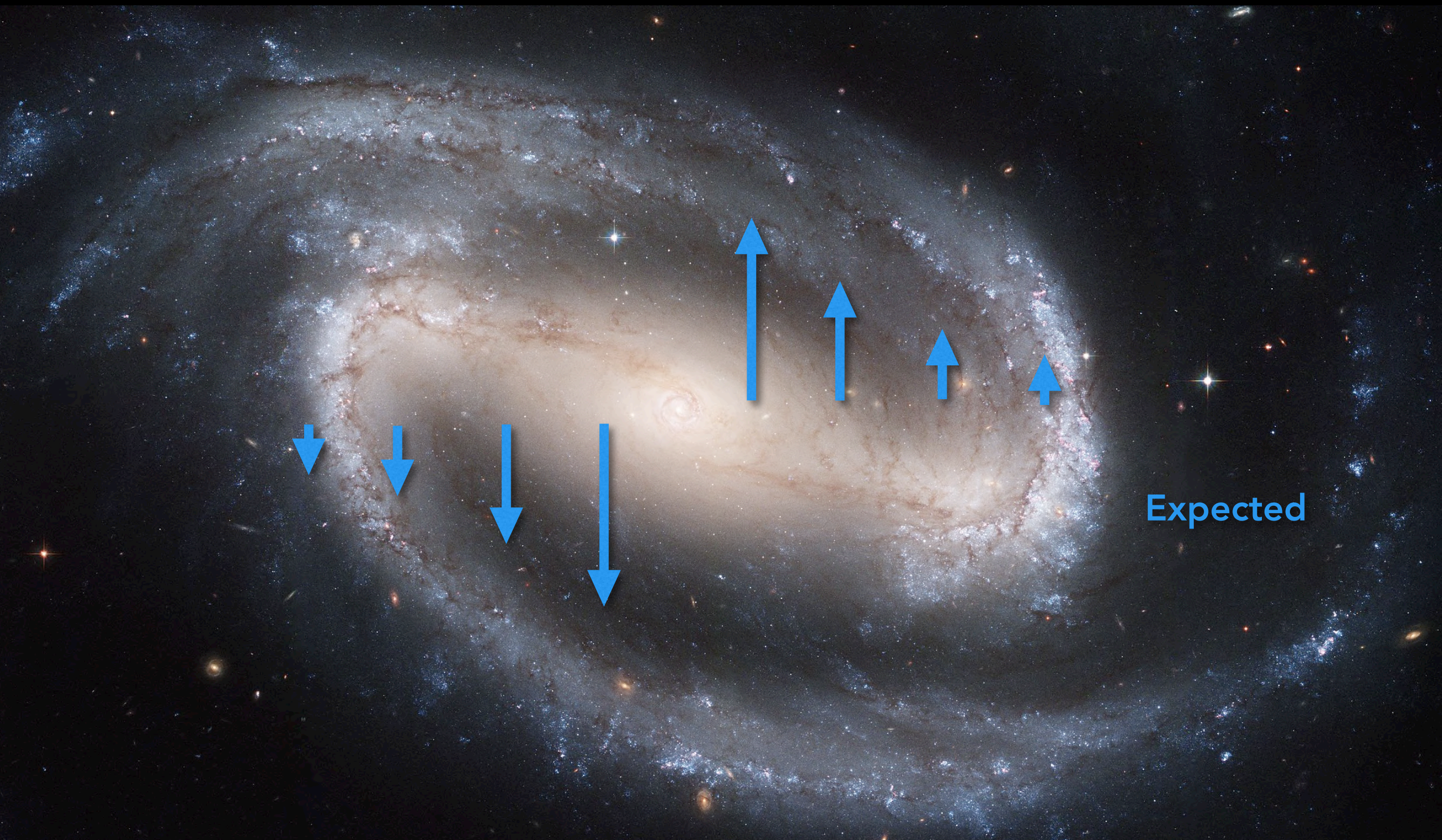
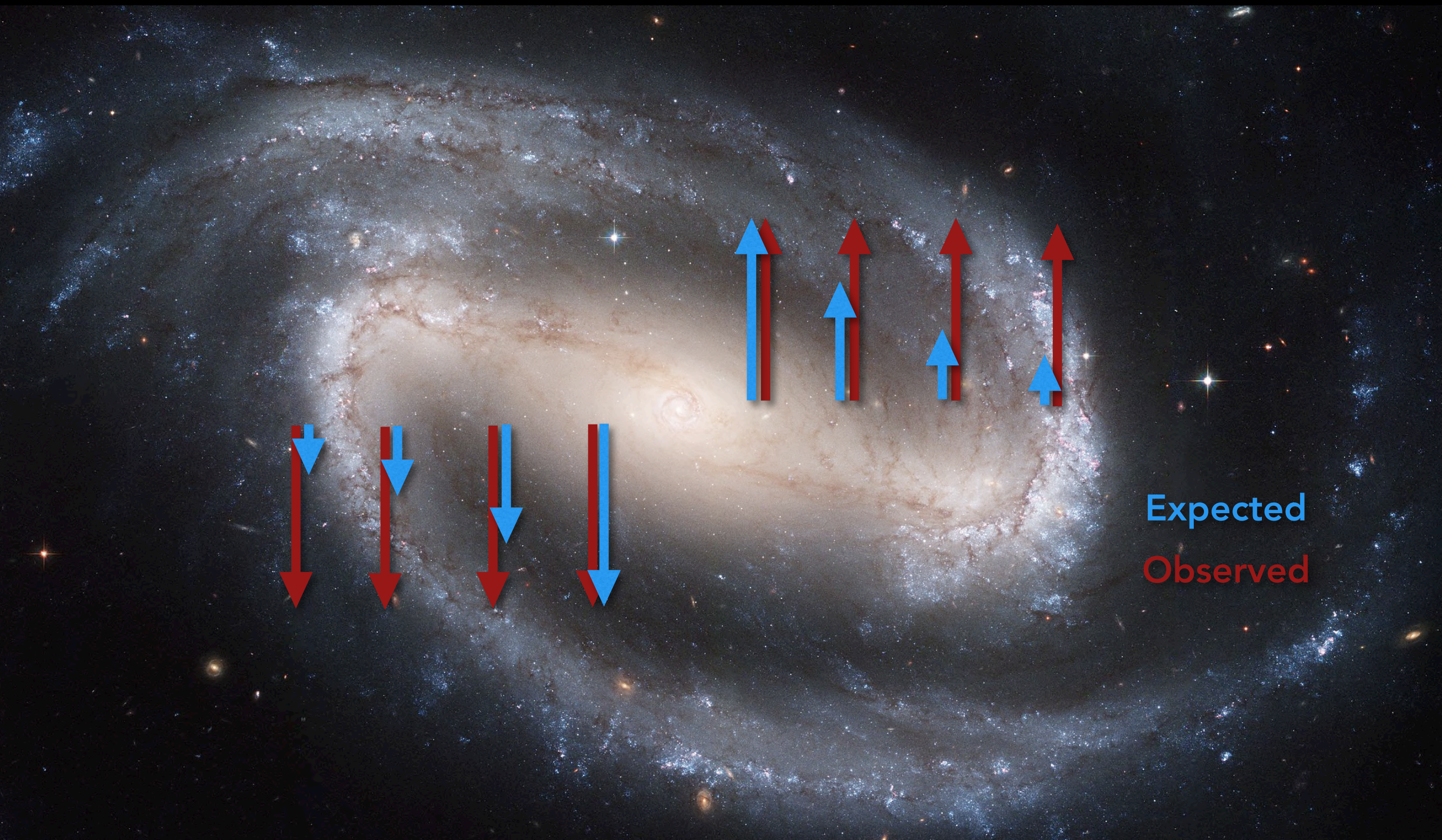



Expected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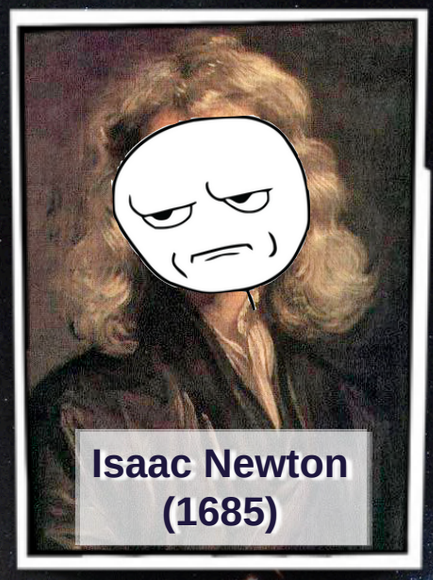
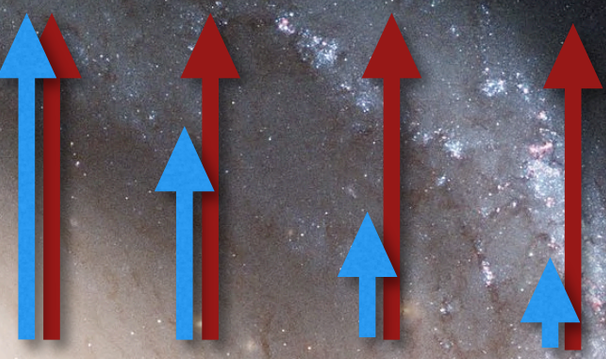
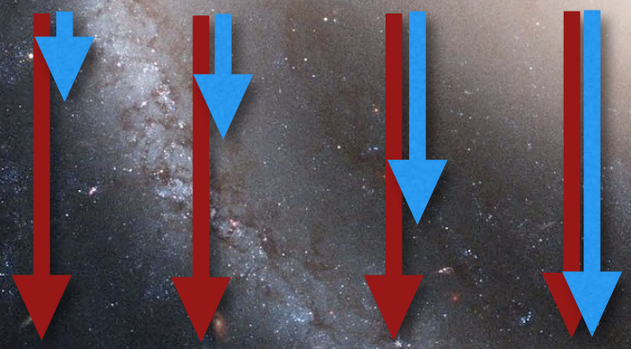
What if Newton's laws of gravitation were incomplete also at very **weak** gravity fields?

Mordehai Milgrom
(1986)



Isaac Newton
(1685)





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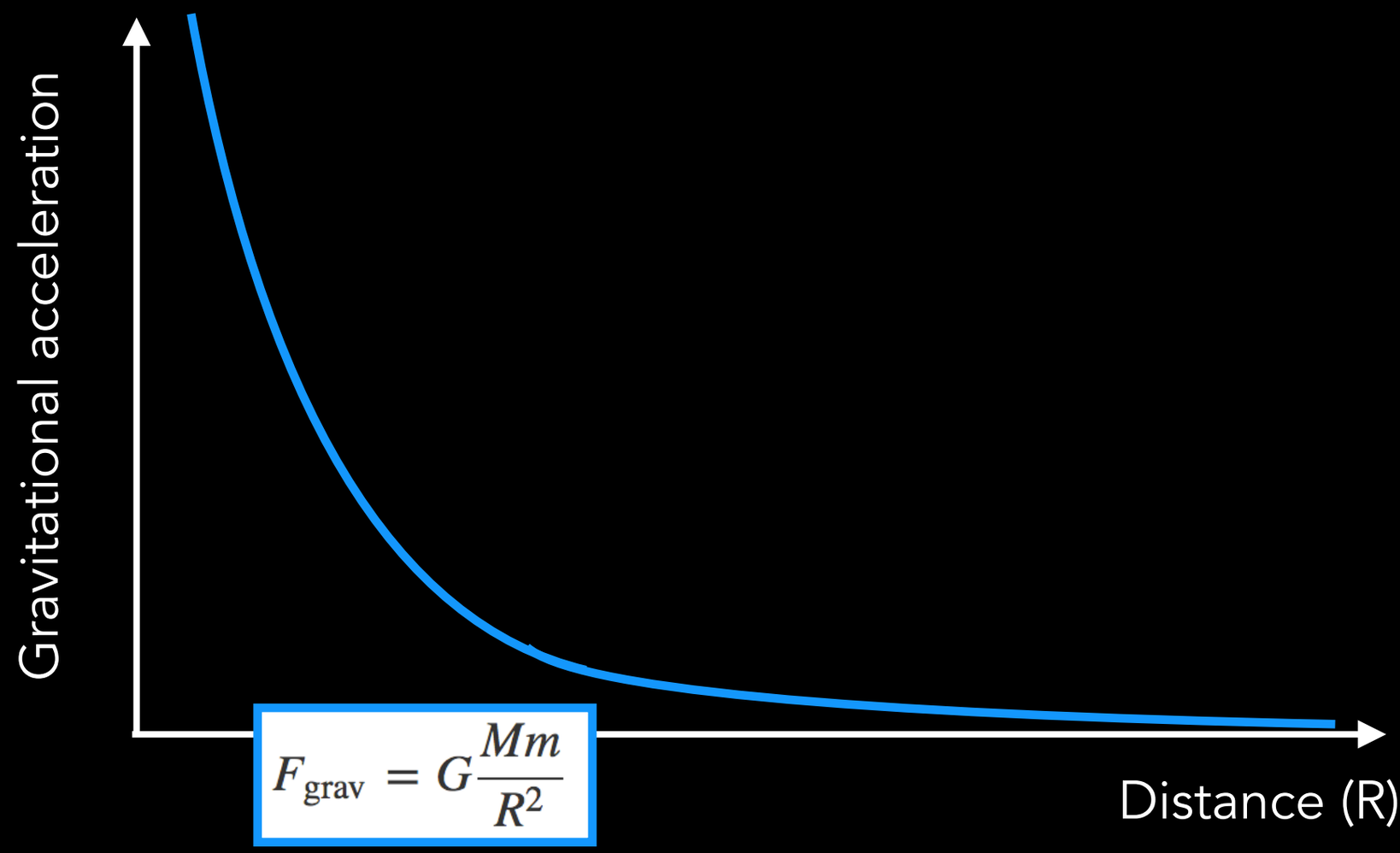

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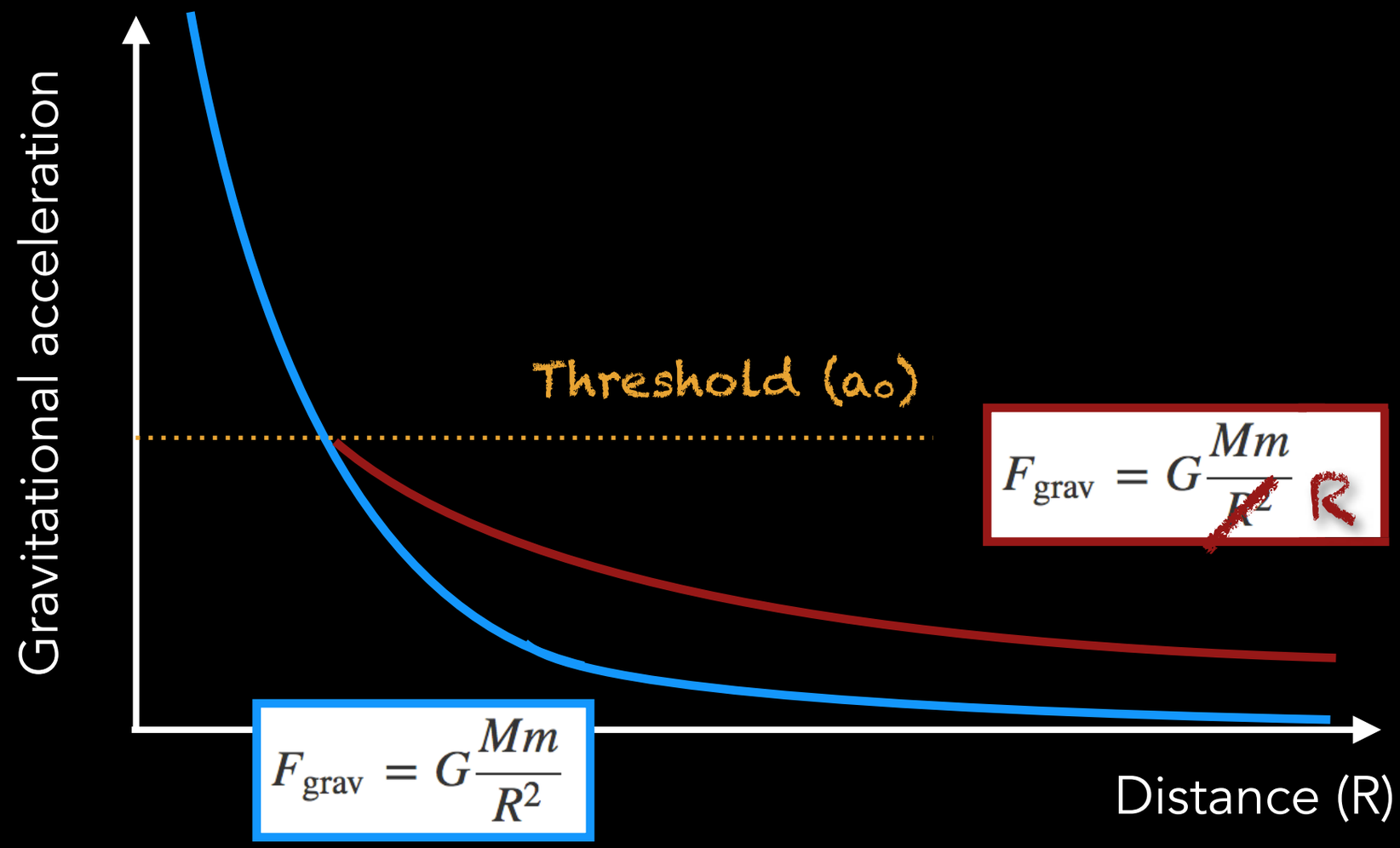

"Modified Newtonian Dynamics" (MOND)

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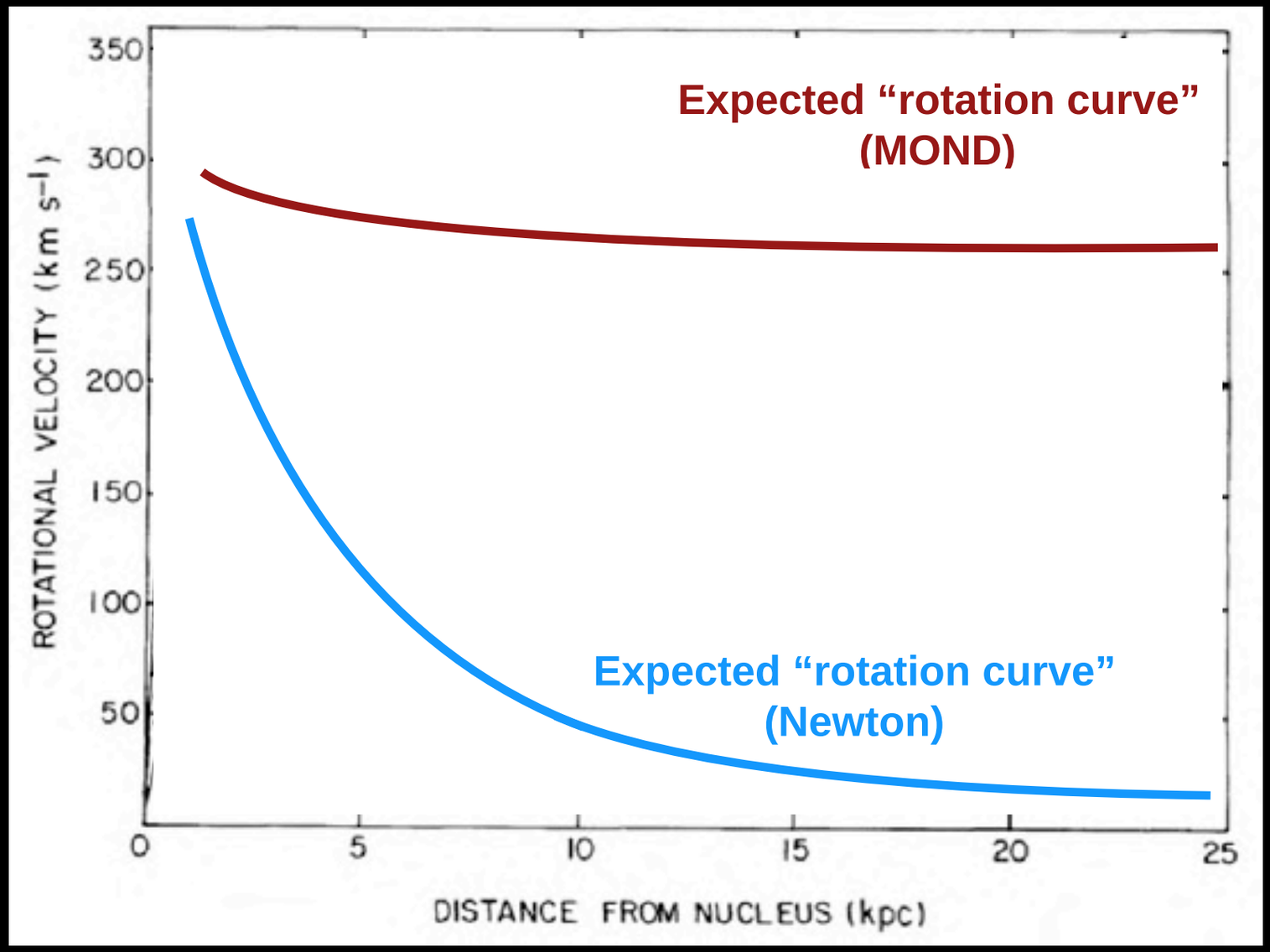

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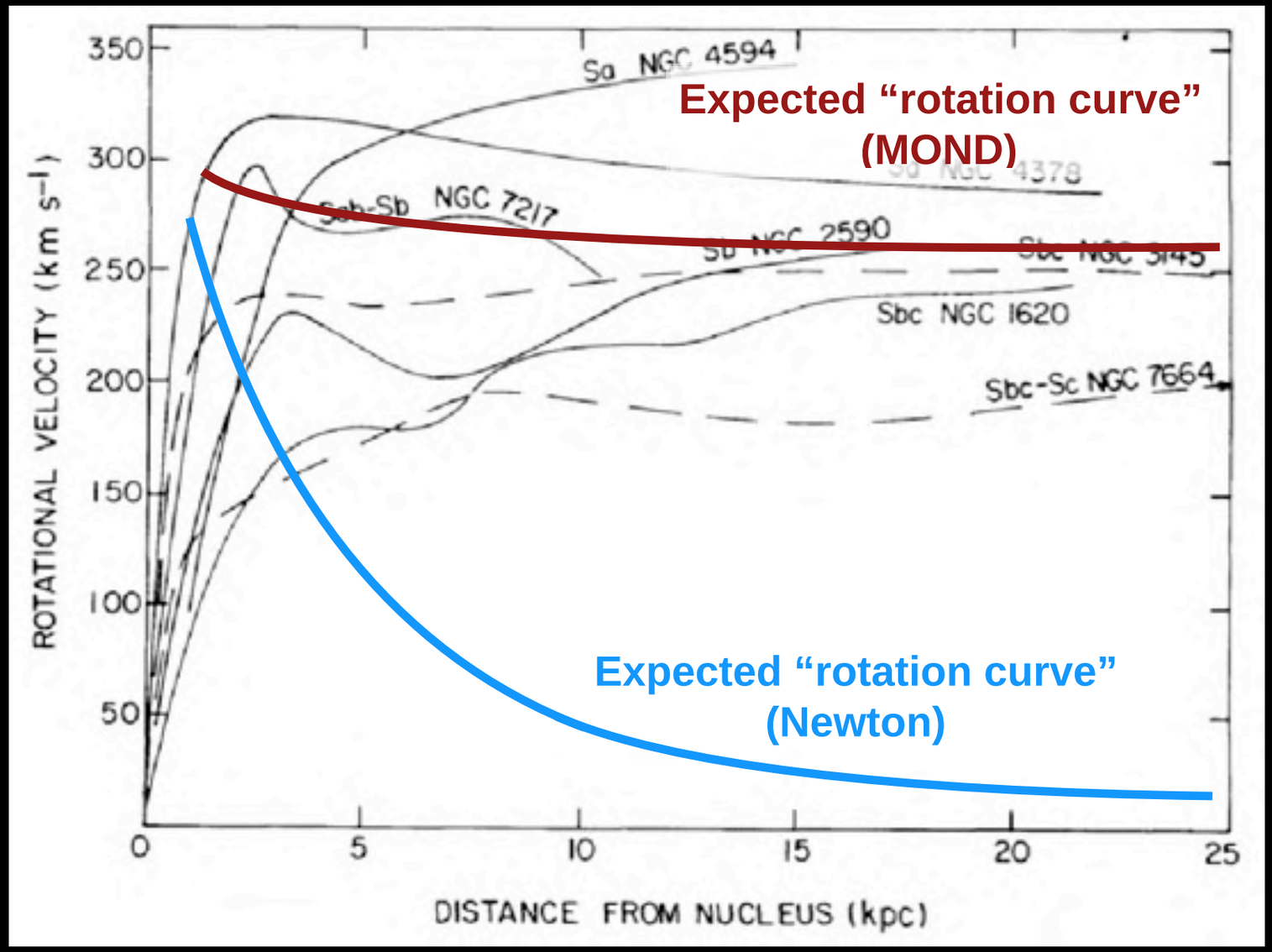
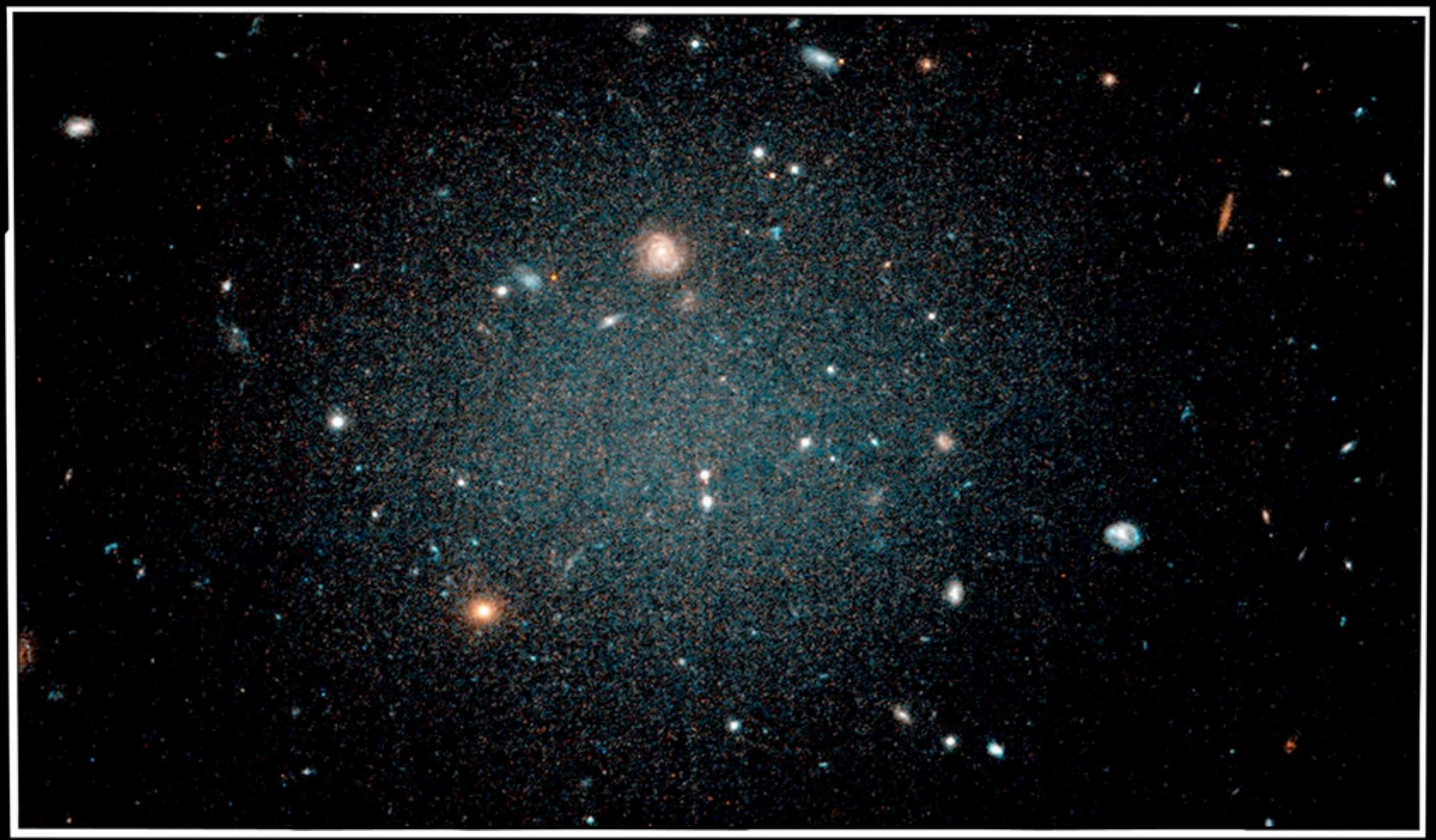


"Modified Newtonian Dynamics"
(MOND)

What if Newton's laws of gravitation were incomplete also at very **weak** gravity fields?

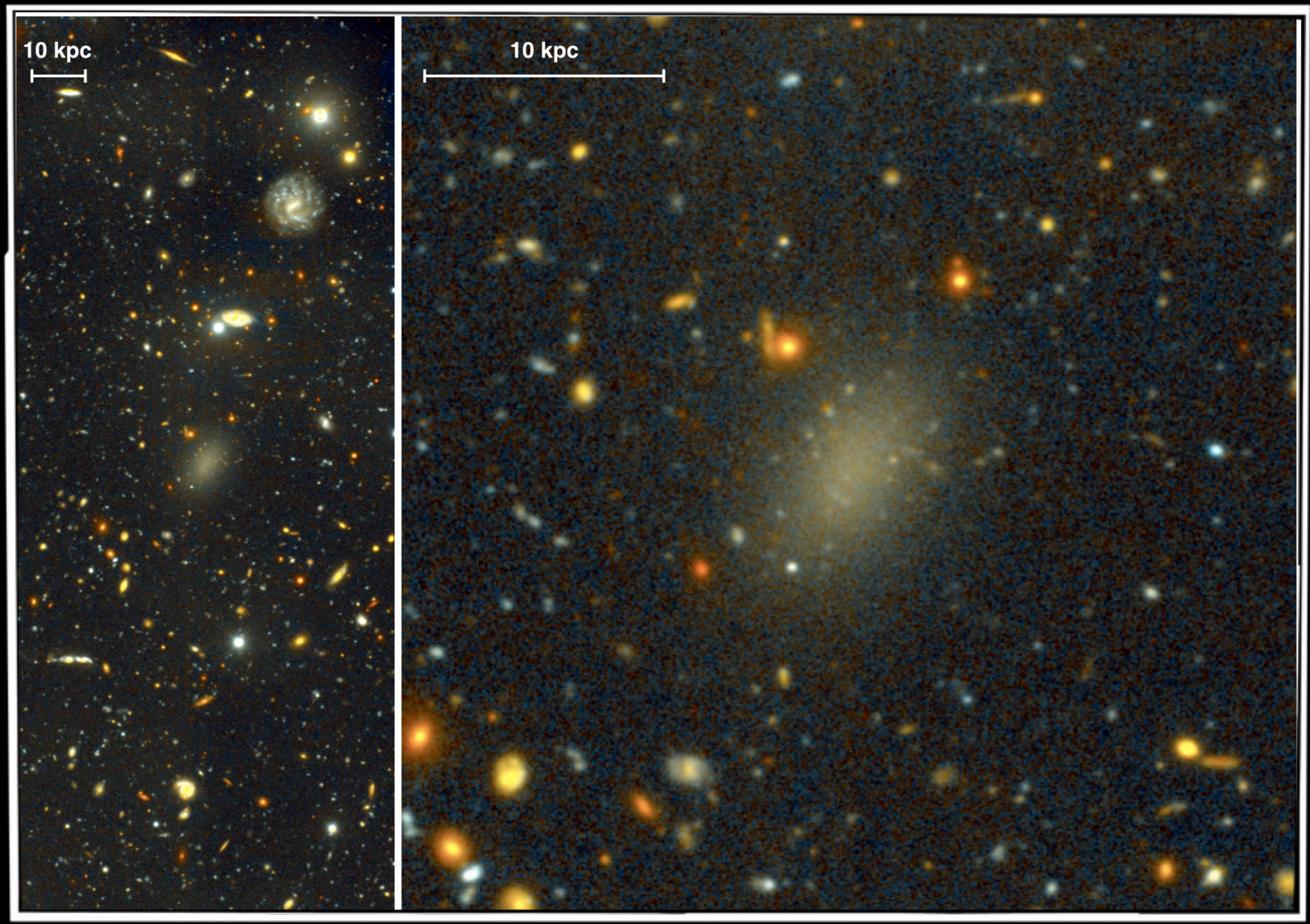
- **"Ad hoc" theory**, why would gravity behave so?
- "Dark" matter should always **follow** "visible" matter…
  - Some galaxies have **almost no dark matter**, some others are **almost entirely made of dark matter**!

NGC 1052-DF2 (almost no dark matter)



van Dokkum et al. (2018)

Dragonfly 44 (98% dark matter!)



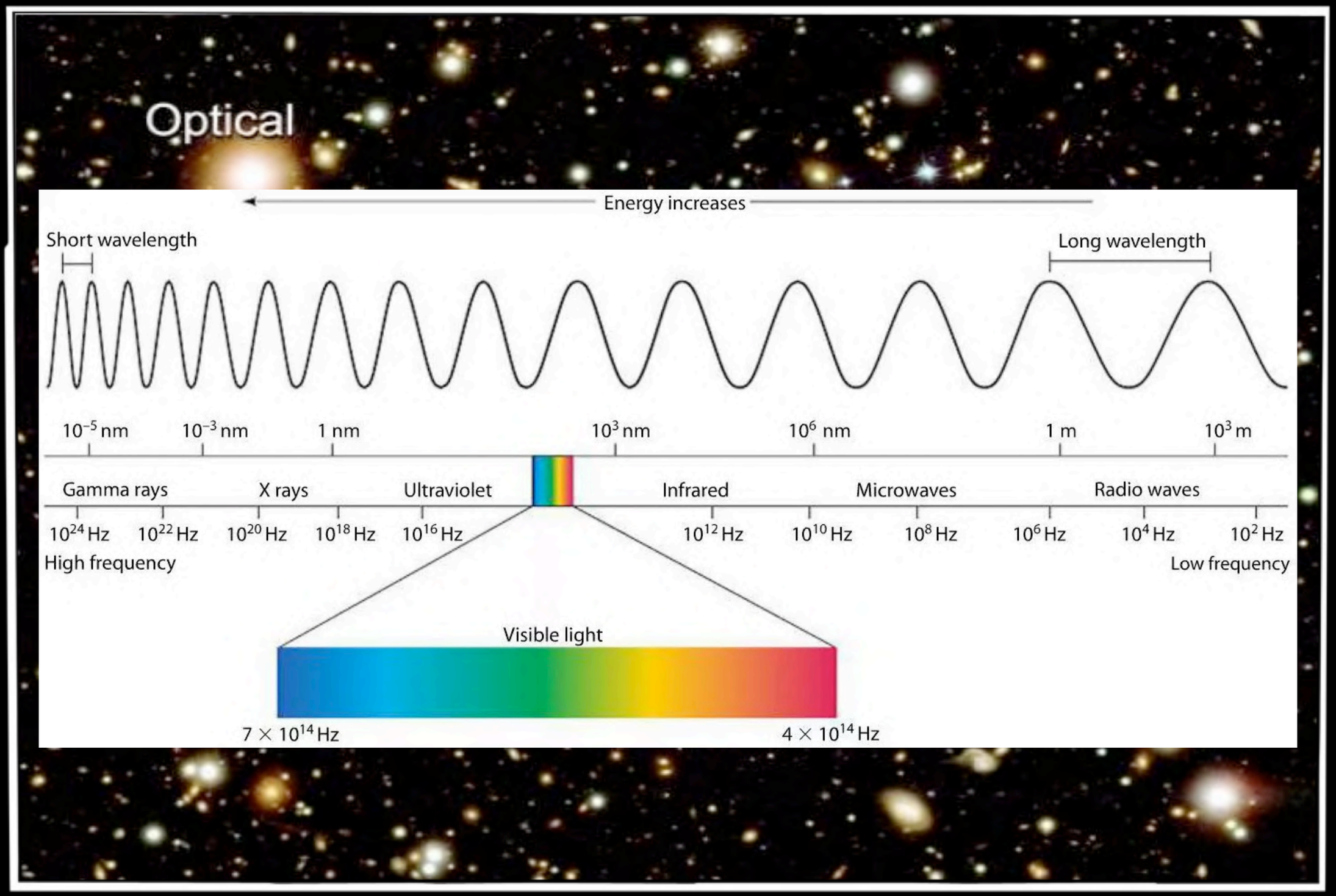
van Dokkum et al. (2016)

What if Newton's laws of gravitation were incomplete also at very **weak** gravity fields?

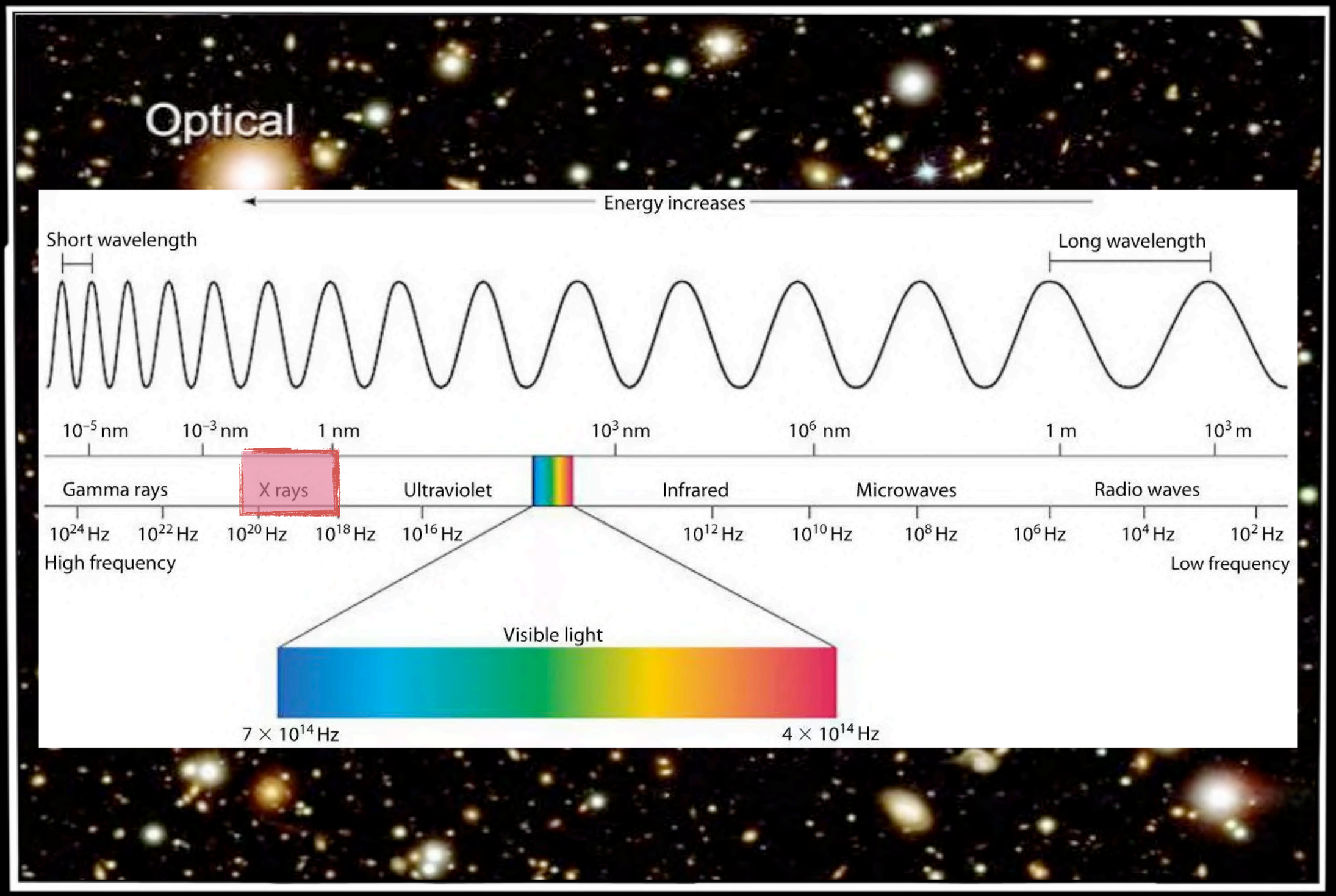
- **"Ad hoc" theory**, why would gravity behave so?
- "Dark" matter should always **follow** "visible" matter…
  - Some galaxies have **almost no dark matter**, some others are **almost entirely made of dark matter**!
  - How to explain the **Bullet Cluster**?

The Bullet Cluster

The Bullet Cluster

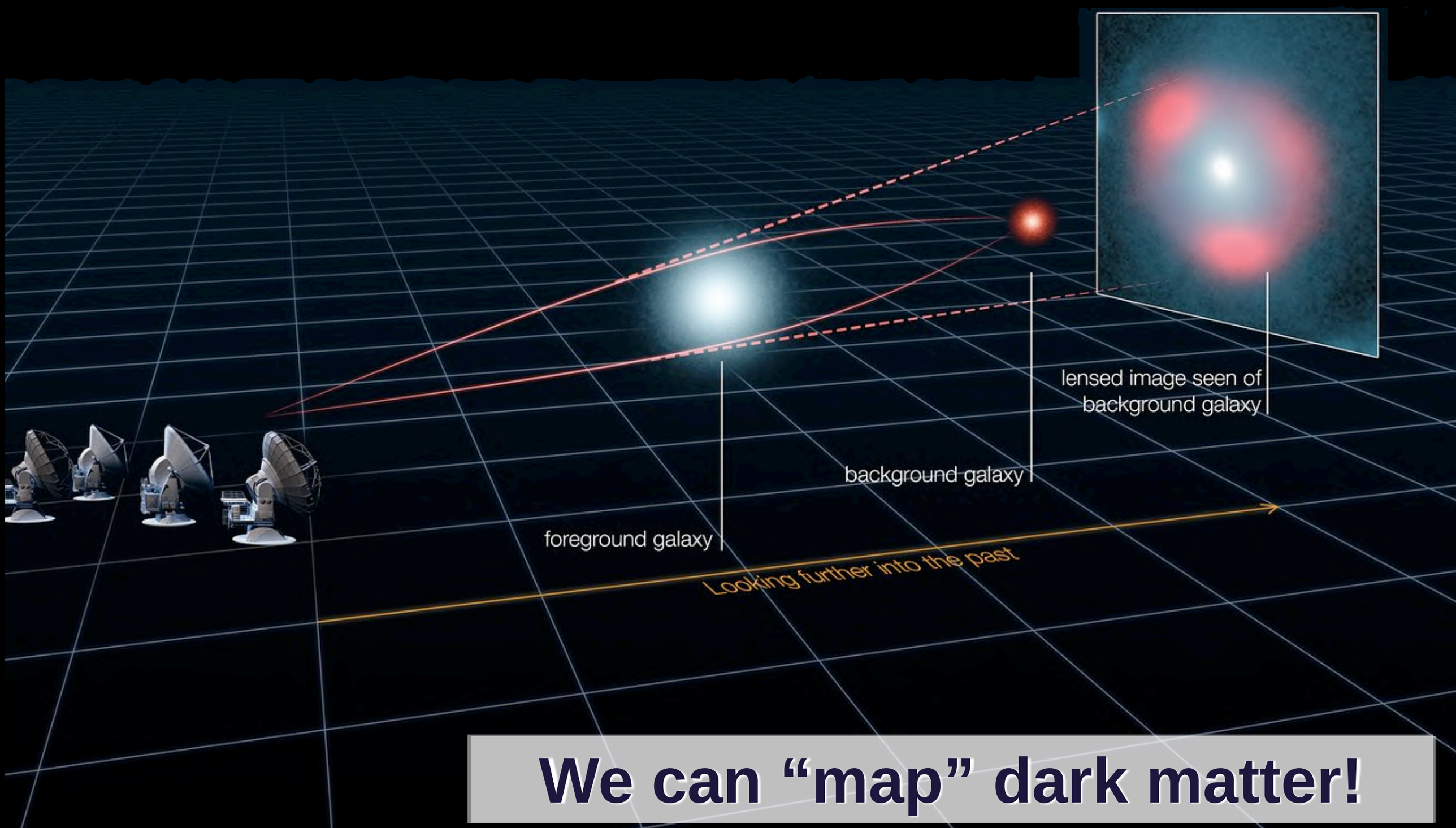


The Bullet Cluster



The Bullet Cluster

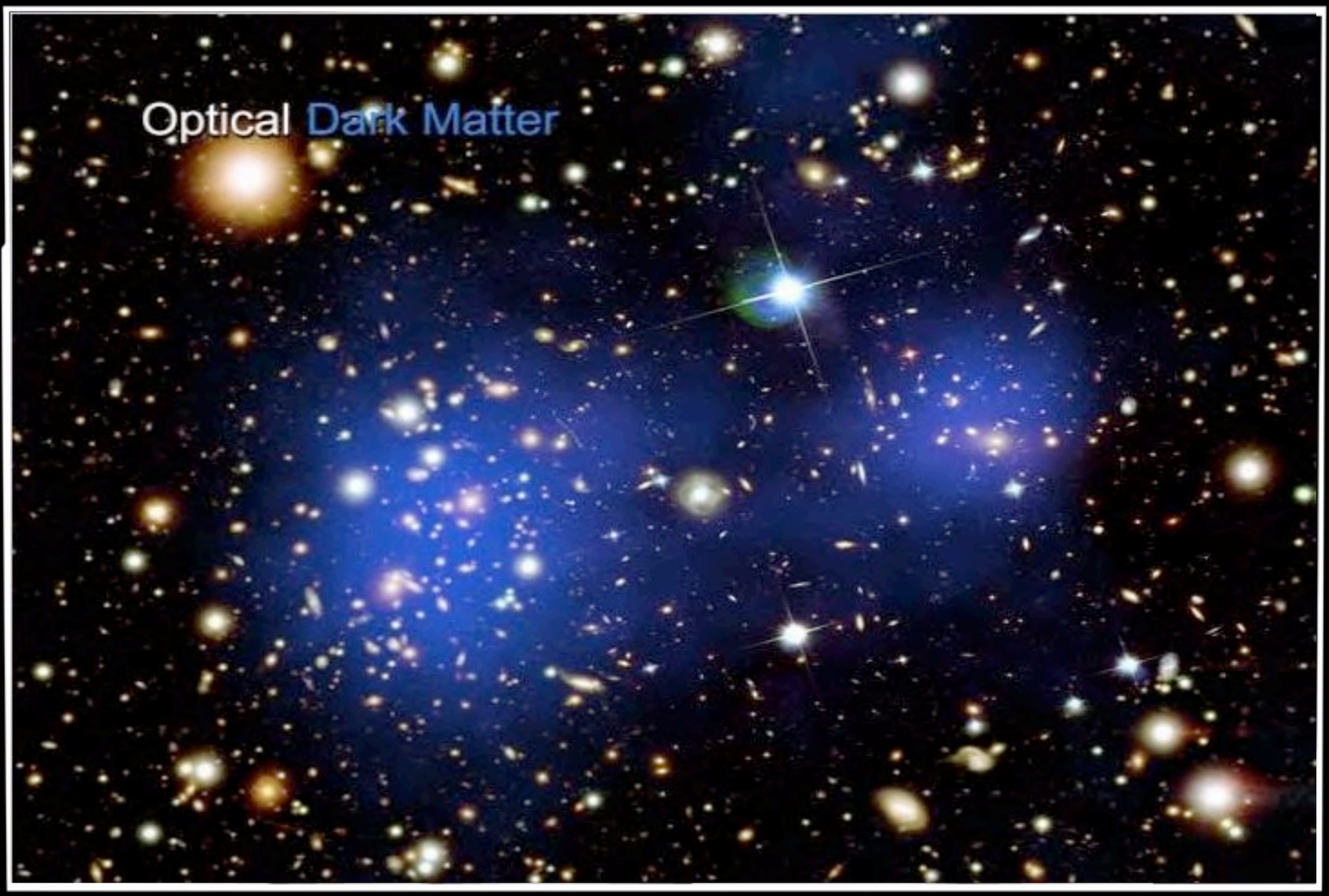
Gravitational lensing



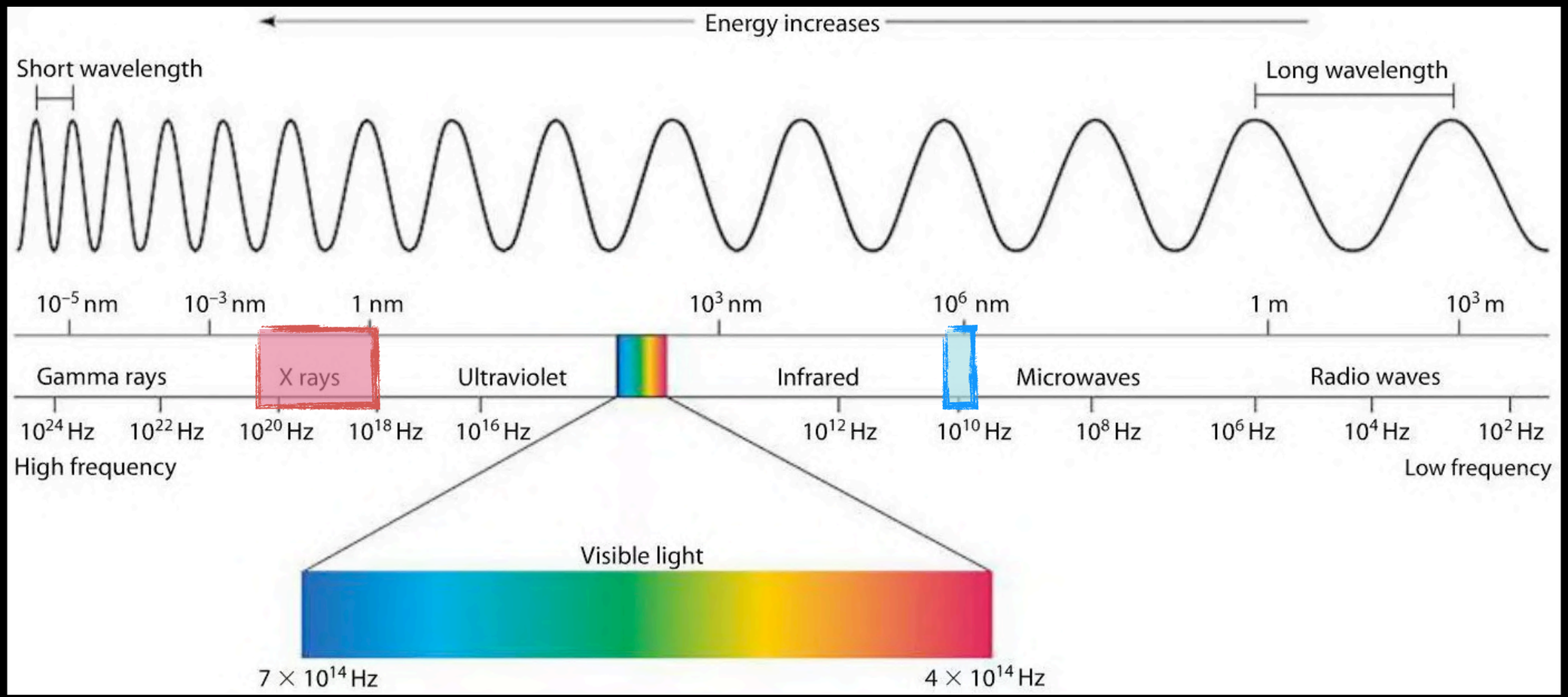
We can “map” dark matter!

The Bullet Cluster

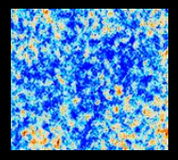
The Bullet Cluster



The Bullet Cluster


Energy increases
Short wavelength
Long wavelength
10^{-5} nm
10^{-3} nm
1 nm
10^{3} nm
10^{6} nm
1 m
10^{3} m
Gamma rays
X rays
Ultraviolet
Infrared
Microwaves
Radio waves
10^{24} Hz
10^{22} Hz
10^{20} Hz
10^{18} Hz
10^{16} Hz
10^{12} Hz
10^{10} Hz
10^{8} Hz
10^{6} Hz
10^{4} Hz
10^{2} Hz
High frequency
Low frequency
Visible light
7×10^{14} Hz
4×10^{14} Hz

The cosmic microwave background

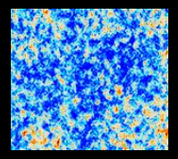


Slightly cooler

Slightly hotter

Microwaves: (almost) uniform emission in the sky…

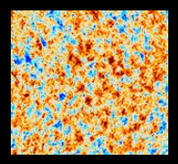
The cosmic microwave background



Slightly cooler

Large scale fluctuations

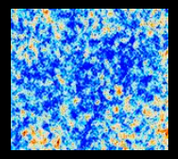
Small scale fluctuations



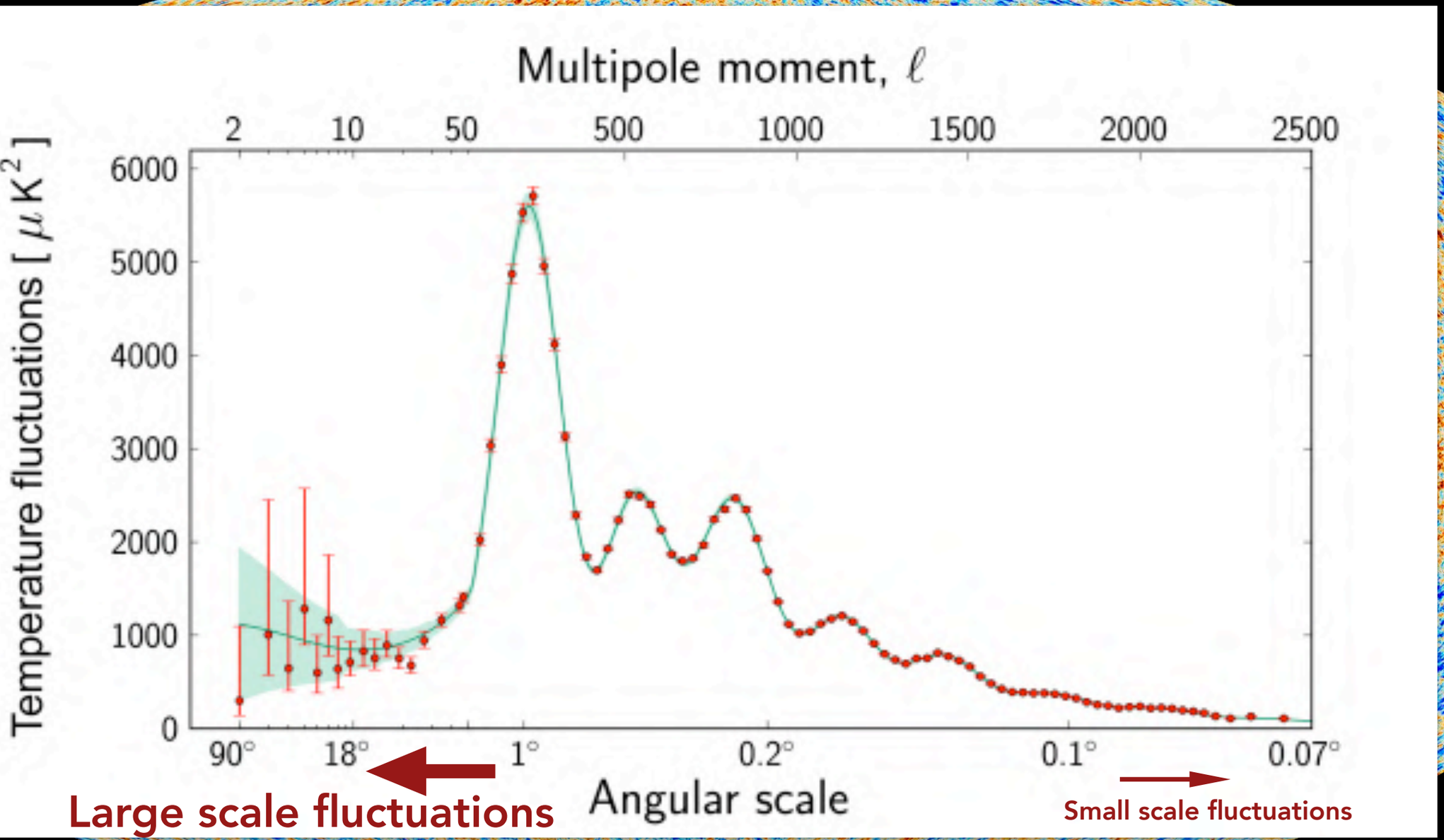
Slightly hotter

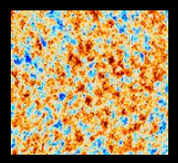
Microwaves: (almost) uniform emission in the sky…

The cosmic microwave background



Slightly cooler





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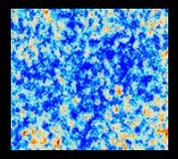
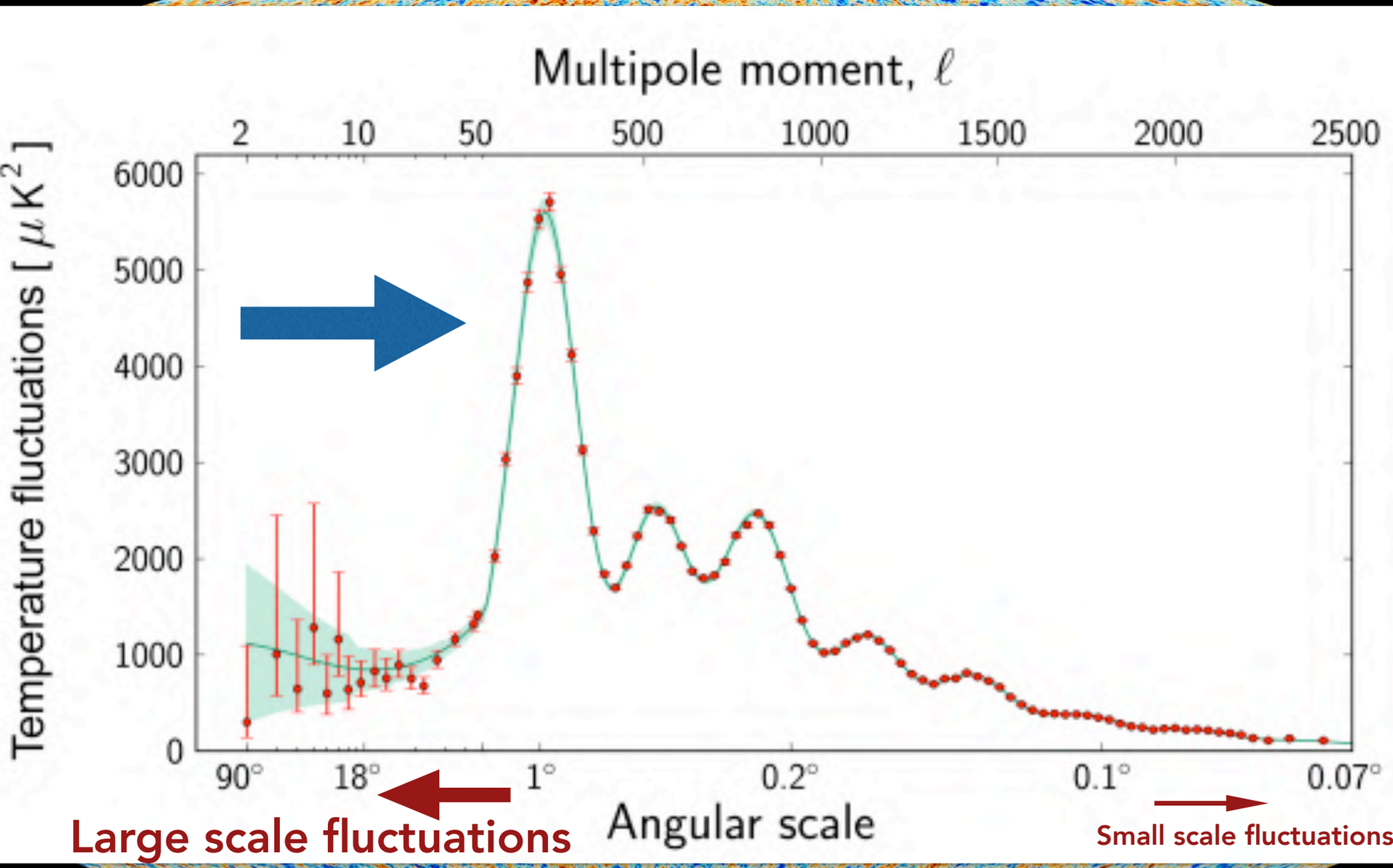
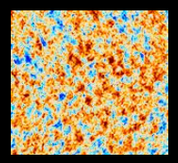
Microwaves: (almost) uniform emission in the sky…

The cosmic microwave background



Slightly cooler





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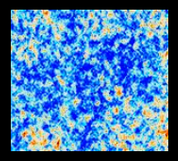
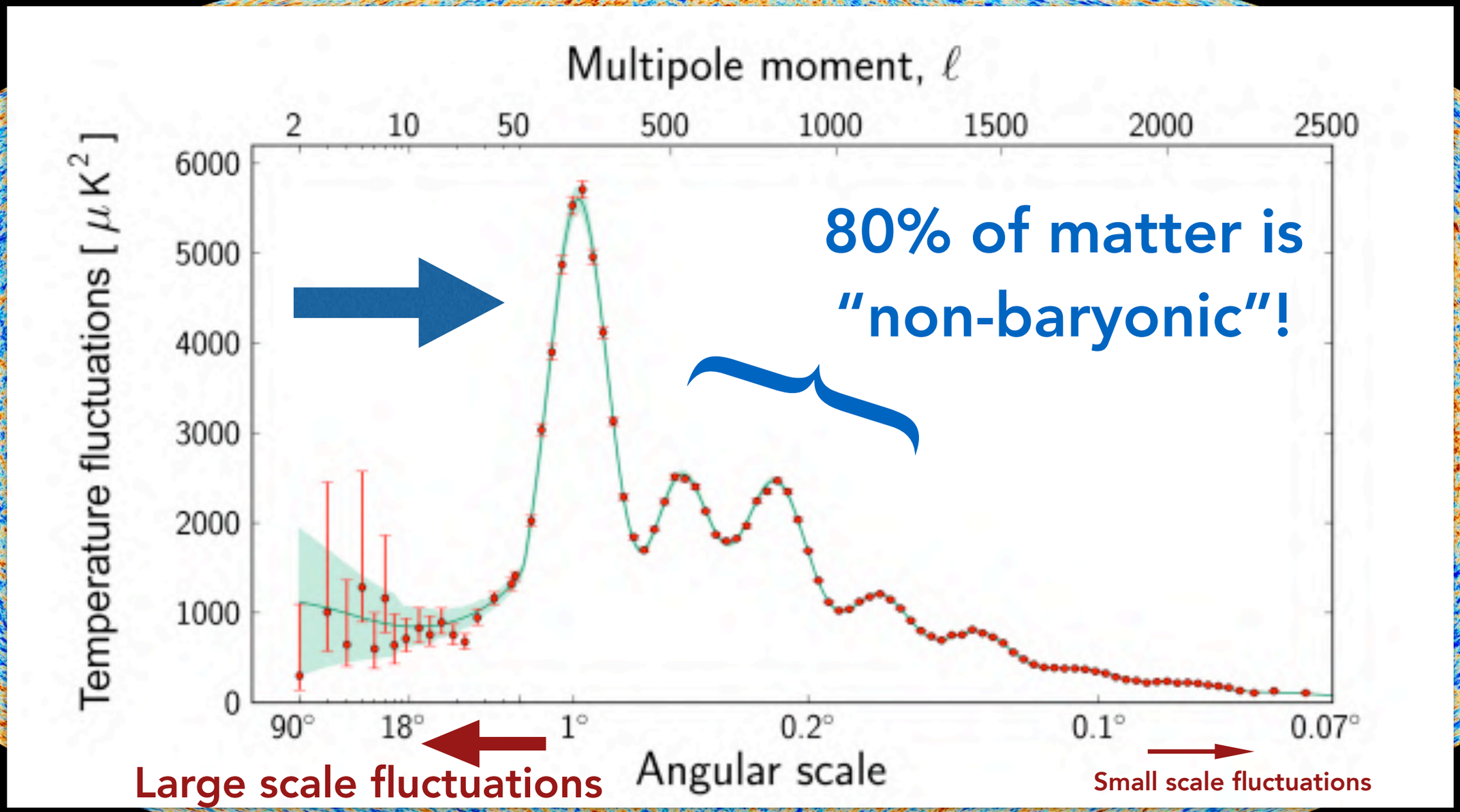
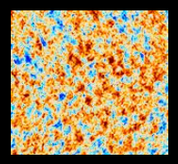
Microwaves: (almost) uniform emission in the sky…

The cosmic microwave background



Slightly cooler

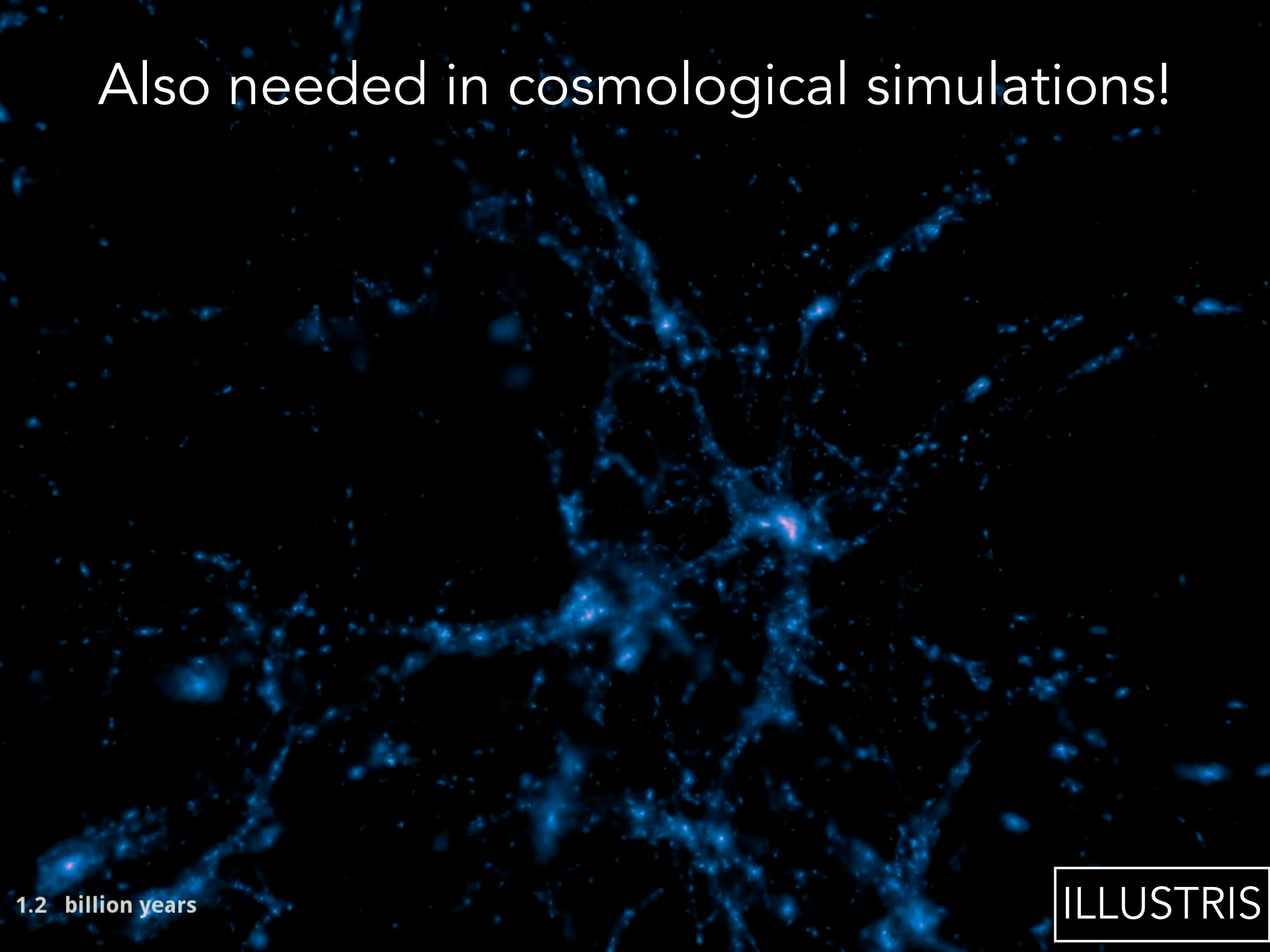




Slightly hotter

Microwaves: (almost) uniform emission in the sky…

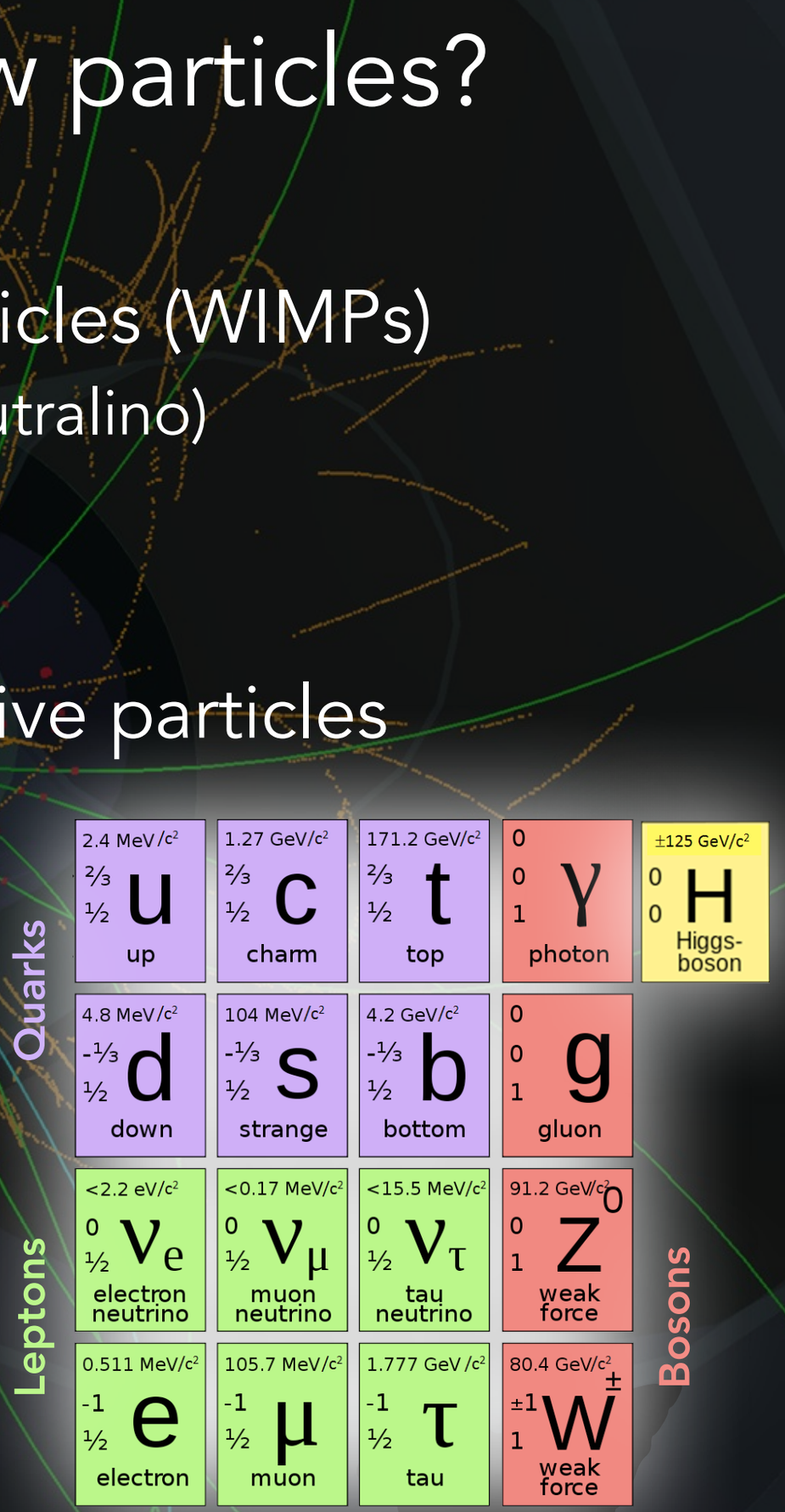
Also needed in cosmological simulations!



Should we search for new particles?

- Weakly Interactive Massive Particles (WIMPs)
  - Supersymmetric particles (e.g. neutralino)
- (Sterile) neutrinos
- Axions
- Gravitationally interacting massive particles (GIMPs)

Standard model



“Non-baryonic” dark matter

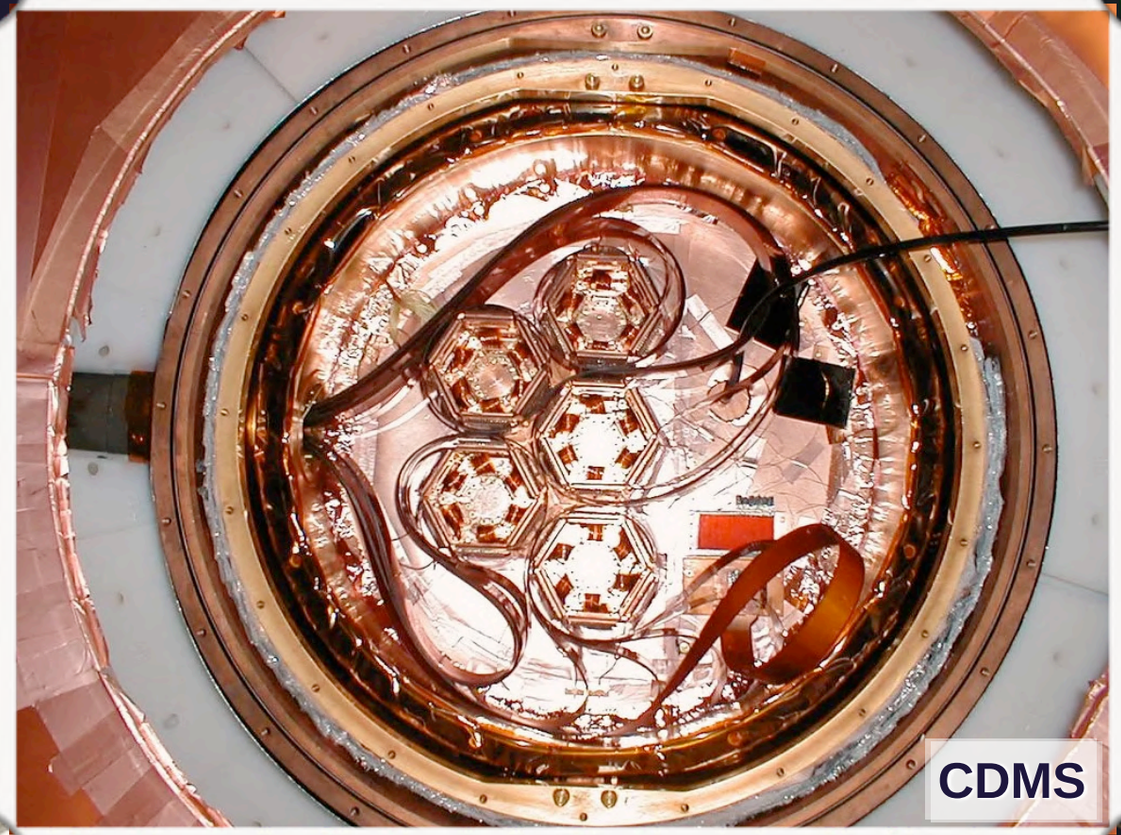
Should we search for new particles?

XENON1T

Large Hadron Collider (CERN)

“Non-baryonic” dark matter

for new particles?

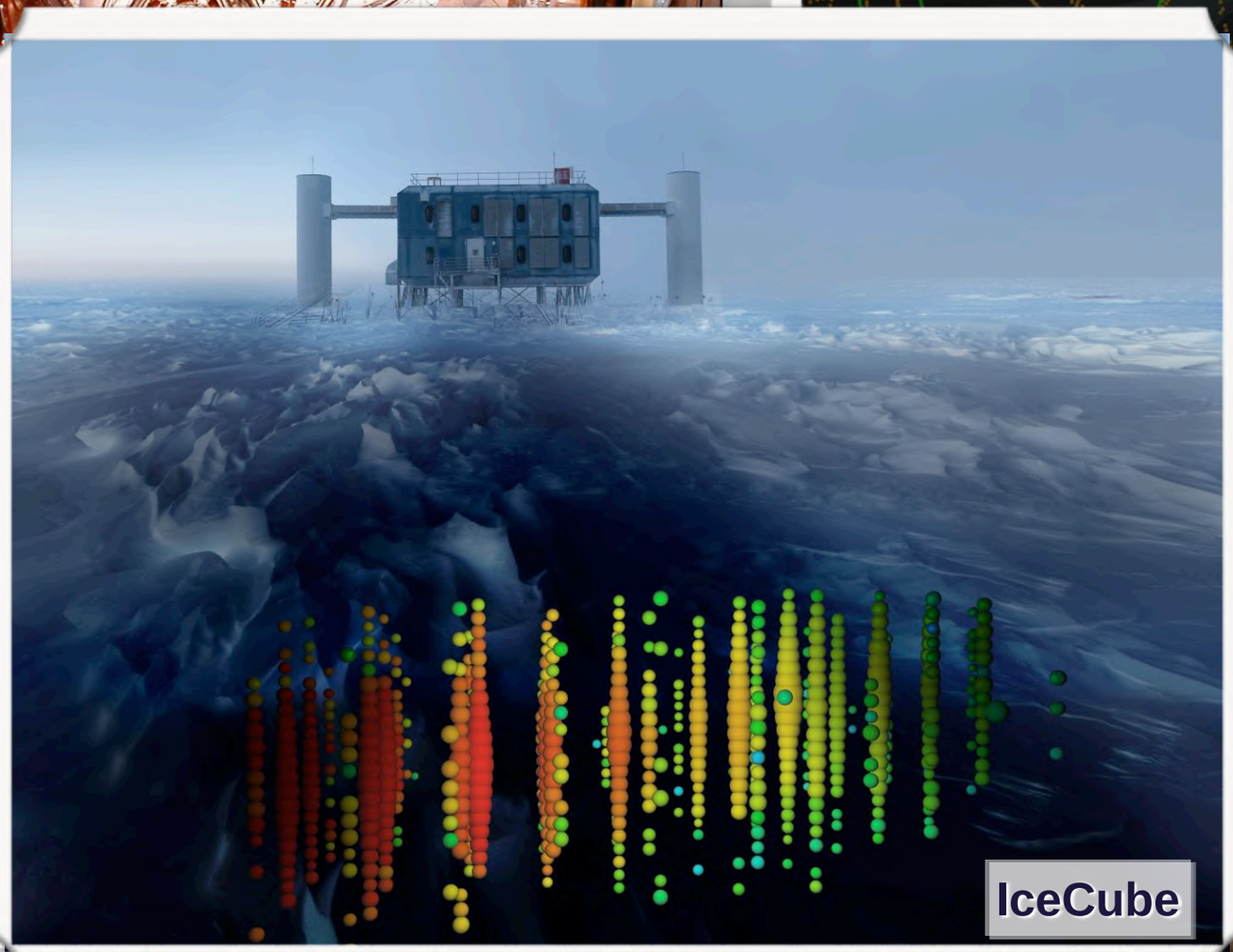

CDMS


XENON1T

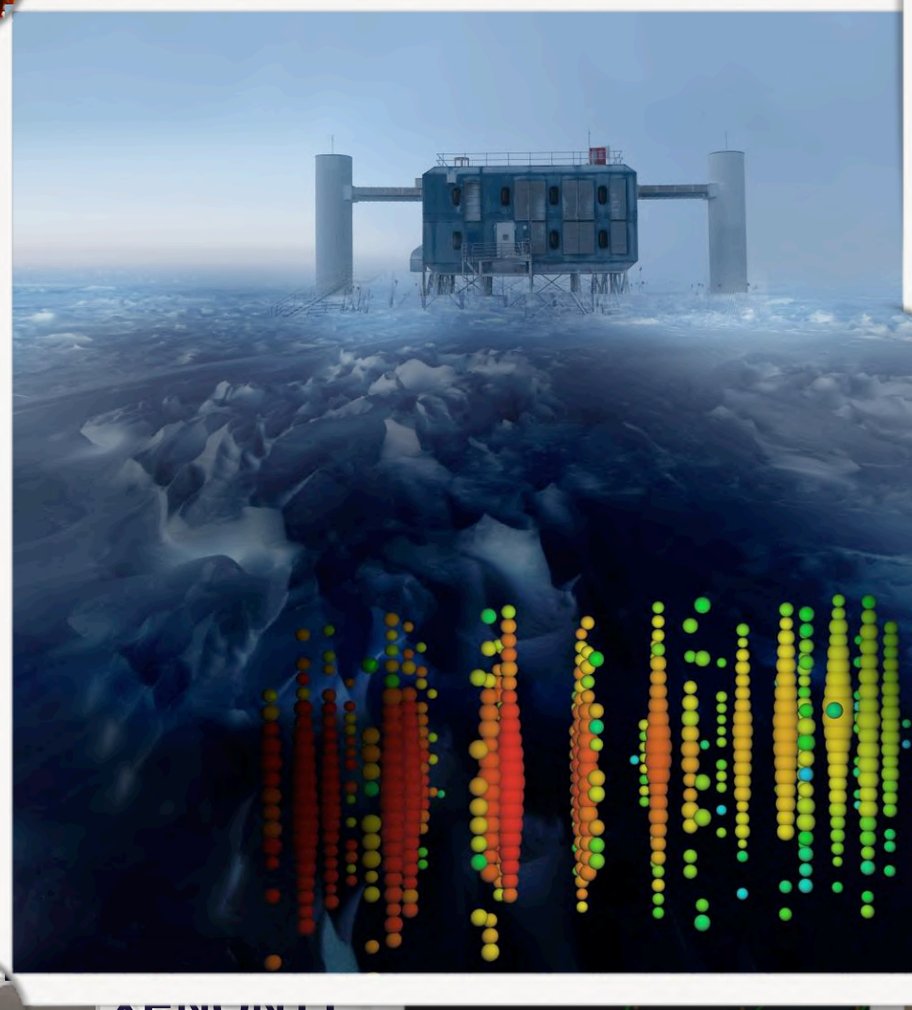

Large Hadron Collider (CERN)

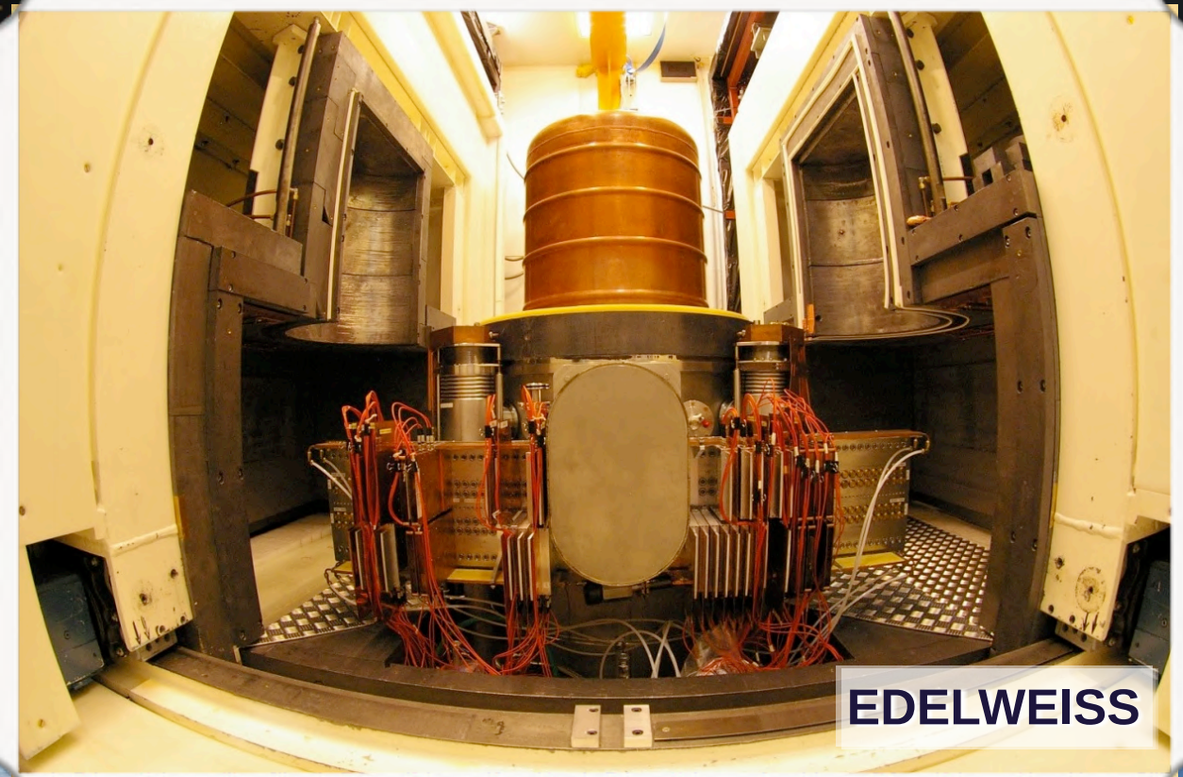
“Non-baryonic” dark matter

for new particles?

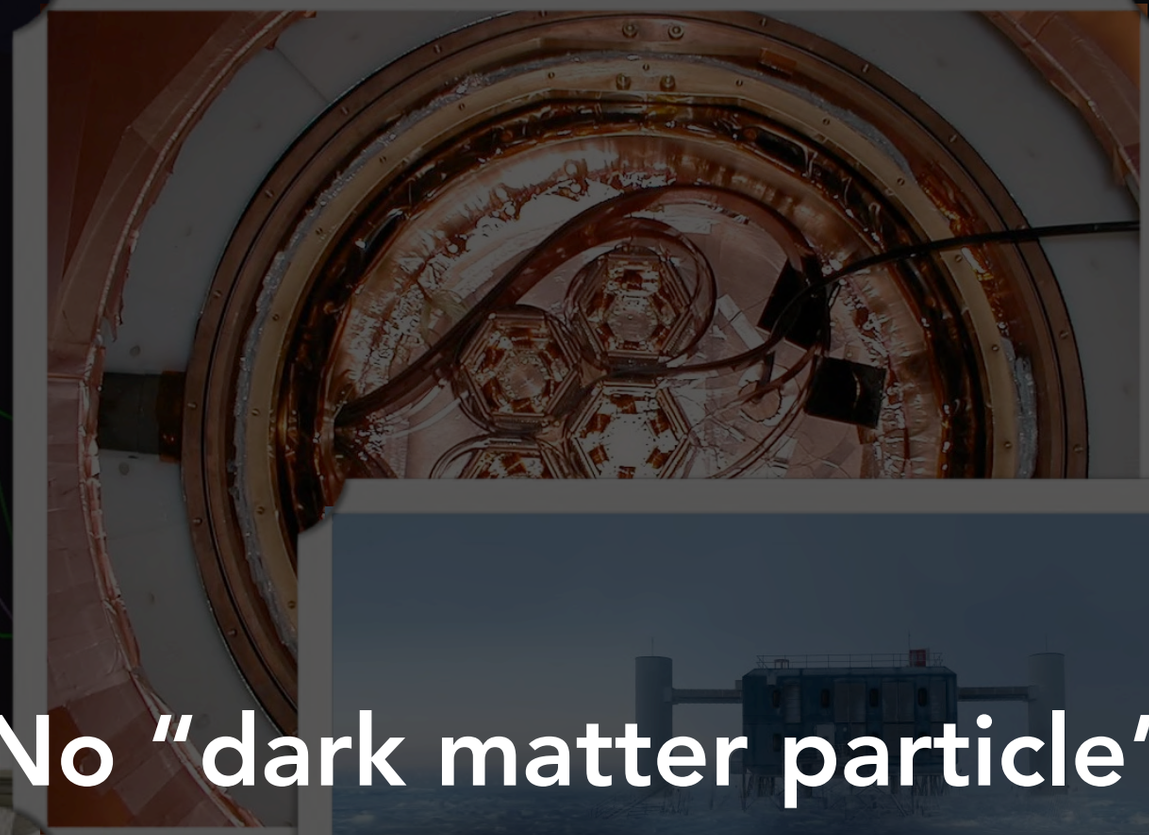


“Non-baryonic” dark matter





“Non-baryonic” dark matter



No “dark matter particle” has been detected so far!

quite worrisome, given the great capabilities of accelerators and detectors…

XENON1T

Large Hadron Collider (CERN)

“Non-baryonic” dark matter

But is MOND really dead…?

In galaxies, radial **acceleration** of **stars** and of **dark matter** are remarkably **correlated**…

Stacy McGaugh (2016)

Work in progress…

What if **gravity** did not really exist as such, but was the result of an **emergent** process?

Erik Verlinde (2017)

McGaugh, Lelli & Schombert (2016)

PRL **117,** 201101 (2016) Selected for a Viewpoint in Physics PHYSICAL REVIEW LETTERS 11 NOVEMBER 2016

Radial Acceleration Relation in Rotationally Supported Galaxies

Stacy S. McGaugh and Federico Lelli
Department of Astronomy, Case Western Reserve University, 10900 Euclid Avenue, Cleveland, Ohio 44106, USA

James M. Schombert
Department of Physics, University of Oregon, Eugene, Oregon 97403, USA
(Received 18 May 2016; revised manuscript received 7 July 2016; published 9 November 2016)

We report a correlation between the radial acceleration traced by rotation curves and that predicted by the observed distribution of baryons. The same relation is followed by 2693 points in 153 galaxies with very different morphologies, masses, sizes, and gas fractions. The correlation persists even when dark matter dominates. Consequently, the dark matter contribution is fully specified by that of the baryons. The observed scatter is small and largely dominated by observational uncertainties. This radial acceleration relation is tantamount to a natural law for rotating galaxies.

DOI: 10.1103/PhysRevLett.117.201101

Introduction.—The missing mass problem in extragalactic systems is well established. The observed gravitational potential cannot be explained by the stars and gas where $\Phi_{\rm tot}$ is the gravitational potential and $V(R)$ is the full, resolved rotation curve. We do not consider pressure-

Verlinde (2017)

SciPost Phys. 2, 016 (2017)

Emergent gravity and the dark universe

Erik Verlinde

Delta-Institute for Theoretical Physics, Institute of Physics, University of Amsterdam, Science Park 904, 1090 GL Amsterdam, The Netherlands

e.p.verlinde@uva.nl

Abstract

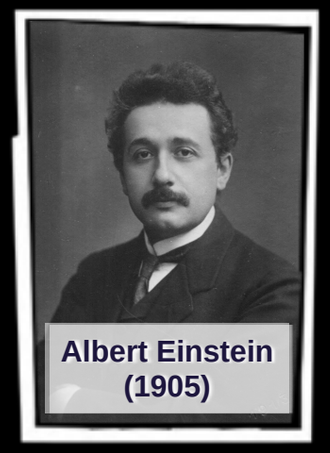
To Maria

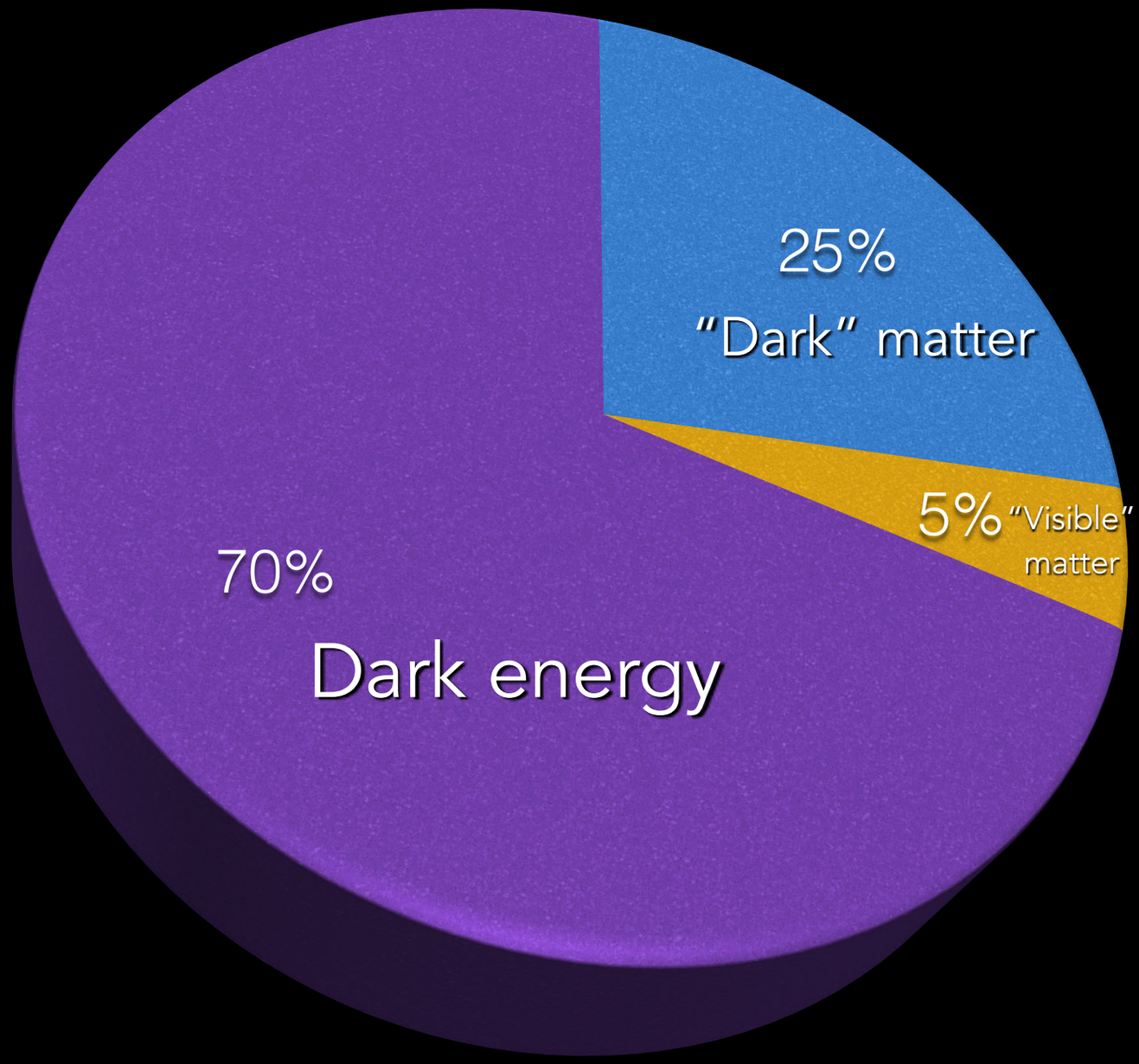
Recent theoretical progress indicates that spacetime and gravity emerge together from the entanglement structure of an underlying microscopic theory. These ideas are best understood in Anti-de Sitter space, where they rely on the area law for entanglement entropy. The extension to de Sitter space requires taking into account the entropy and

Dark matter is NOT dark energy!

$E = mc^2$

(Matter can be converted into energy…)

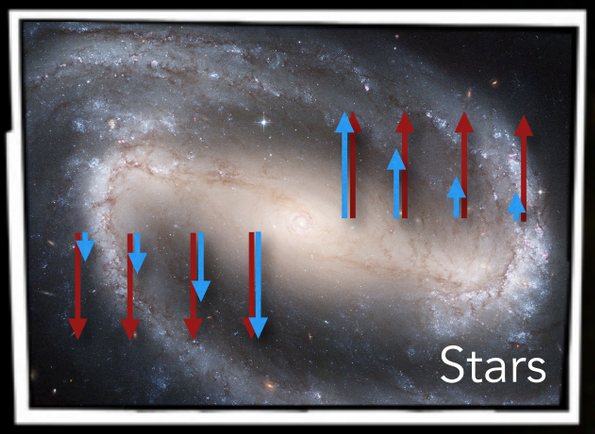


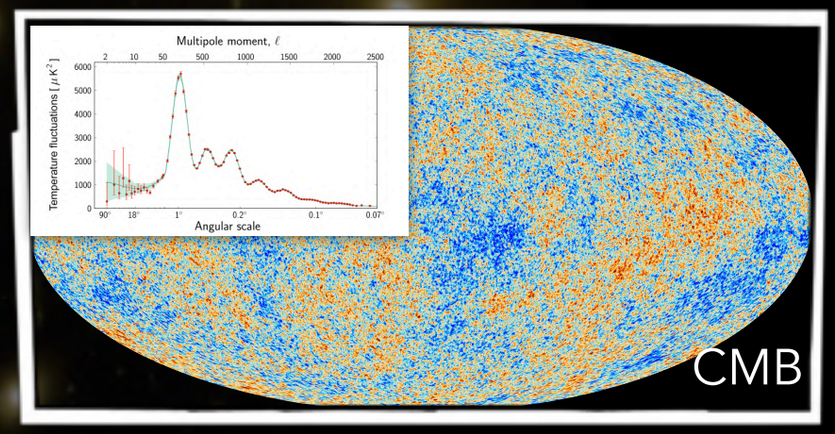


Dark energy is a problem in **cosmology**, required to explain the **acceleration of the expansion of the Universe**…

Summary

1) What is the "dark matter" problem?

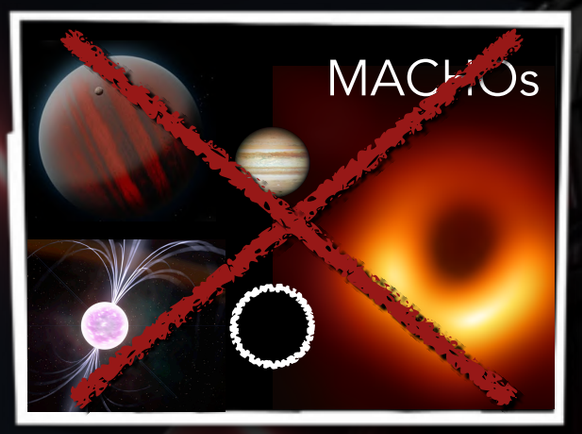


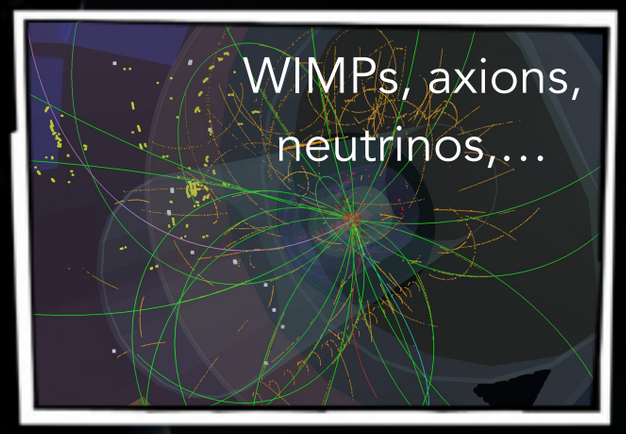


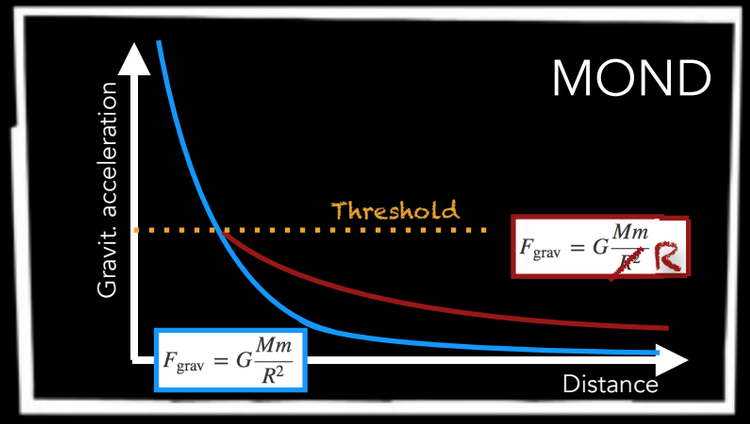
Stars and galaxies move **too fast**… They require some **additional, invisible matter**.

Confirmed by the **first light of the universe** (cosmic microwave background).

2) What is that "dark matter" made of?







We don't know!

Probably unknown **particles**, unless our understanding of **gravitation** is incomplete…