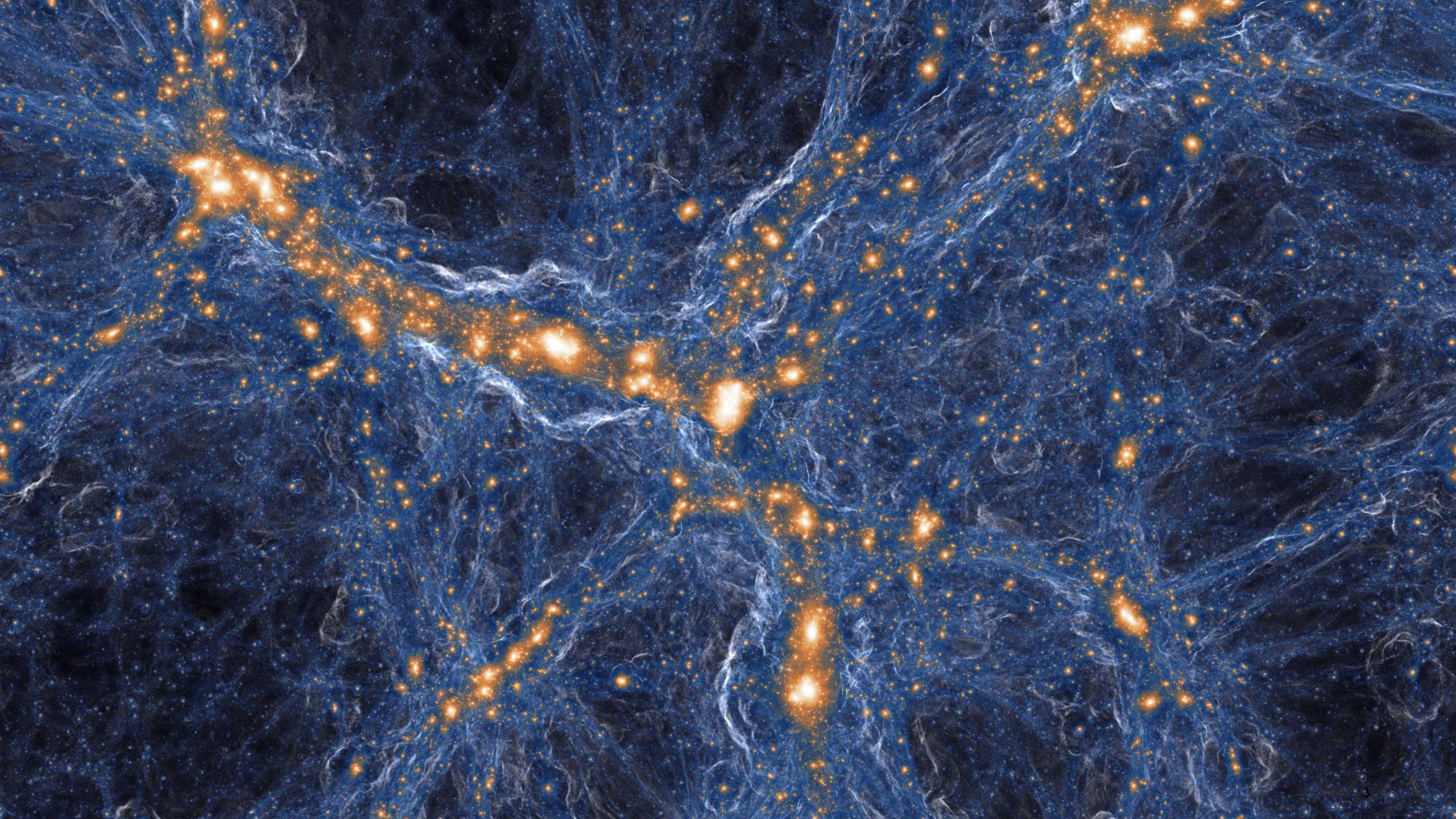


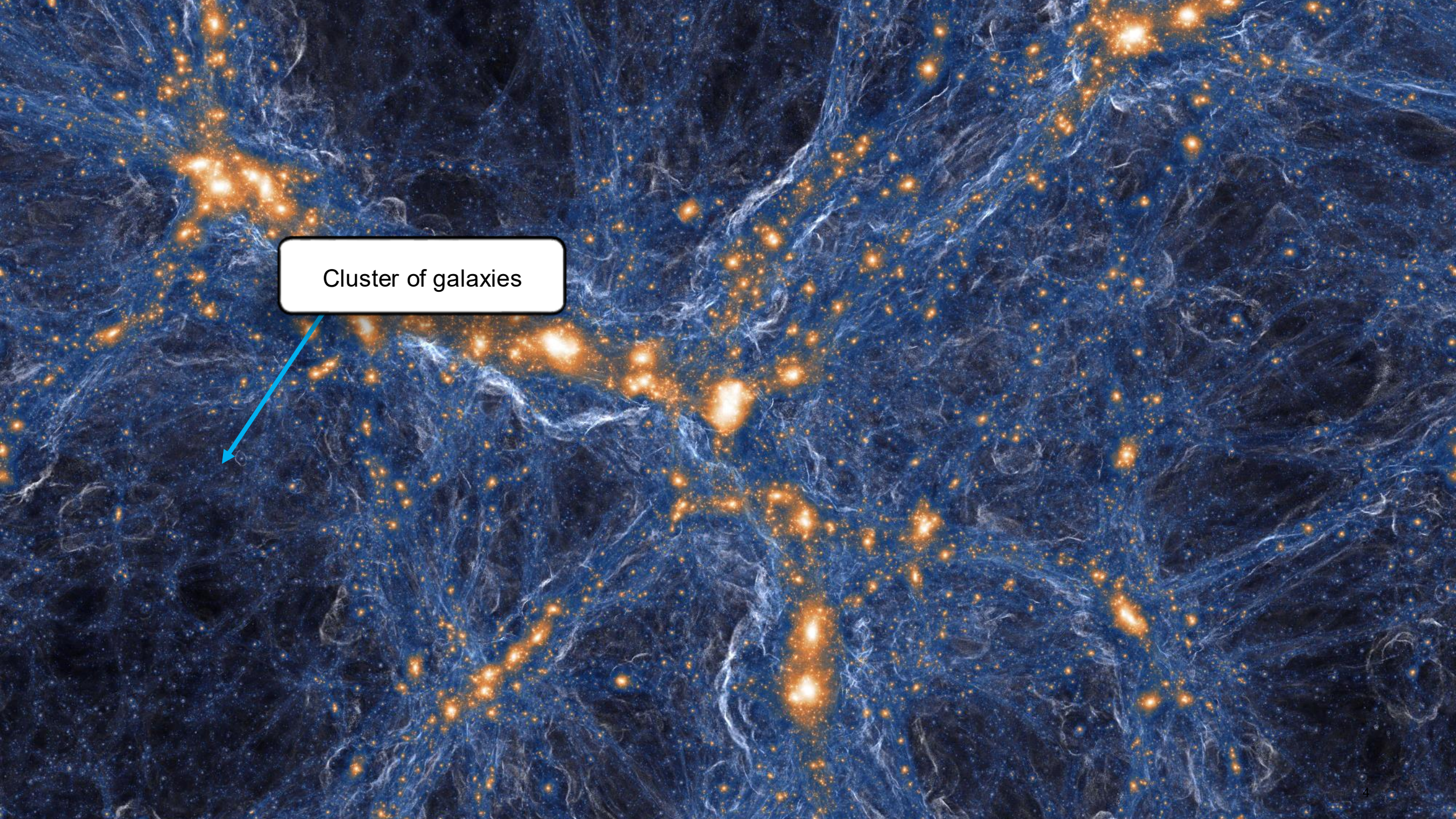
Dark Matter

An introduction to the phenomenon

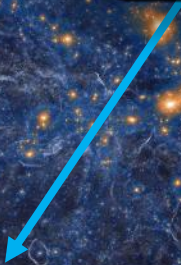
Marek Matas
FJFI – JČF
ČVUT
marek.matas@fjfi.cvut.cz

WHAT IS DARK MATTER | ?





Cluster of galaxies



Unknown new particles



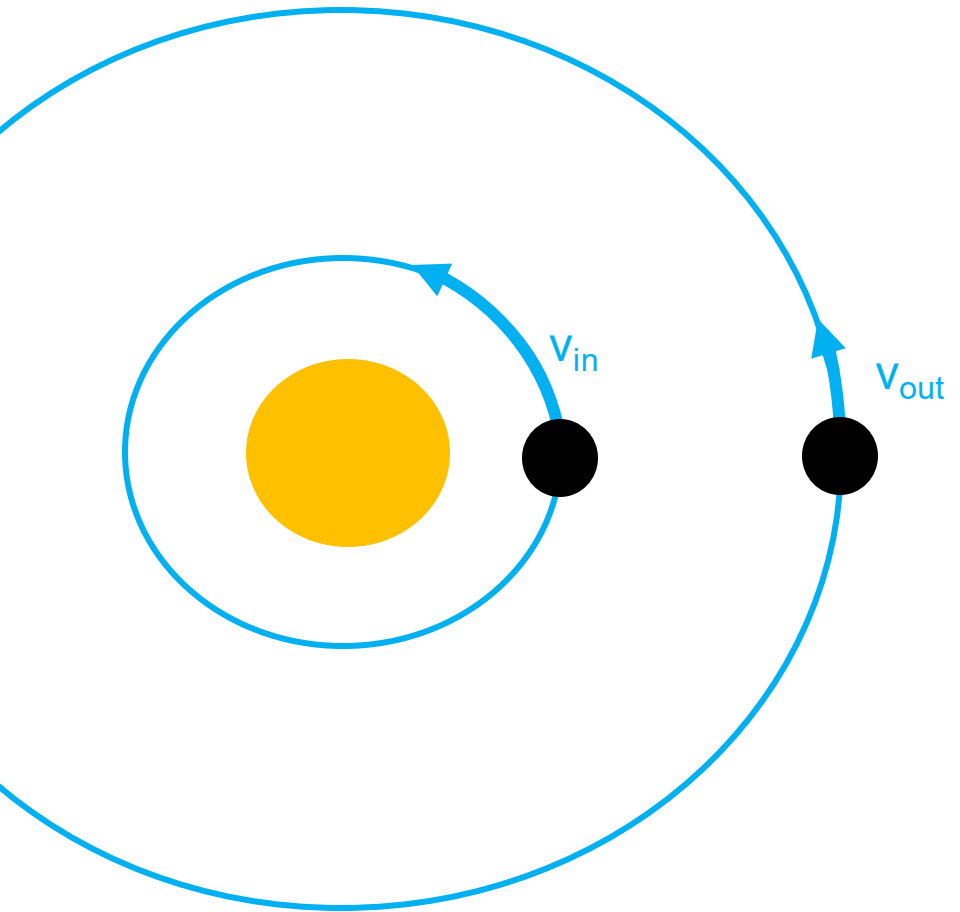
**HOW DO WE
KNOW THAT**

?

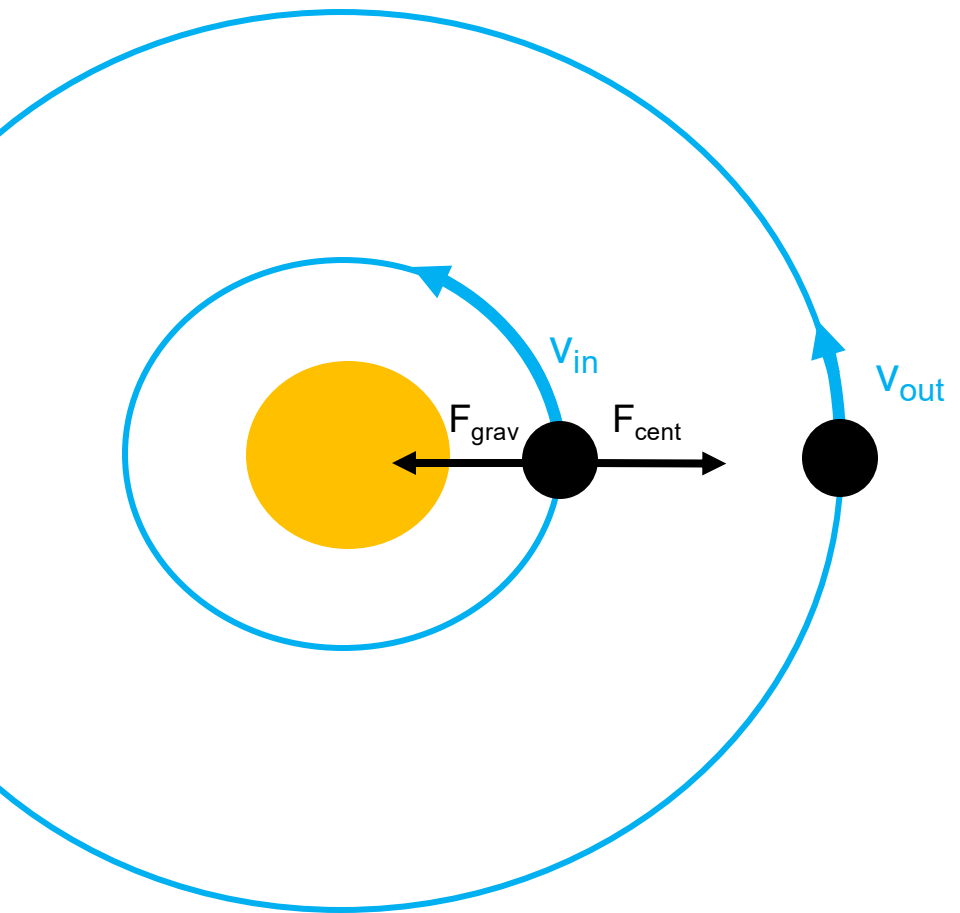
GALACTIC ROTATION CURVES



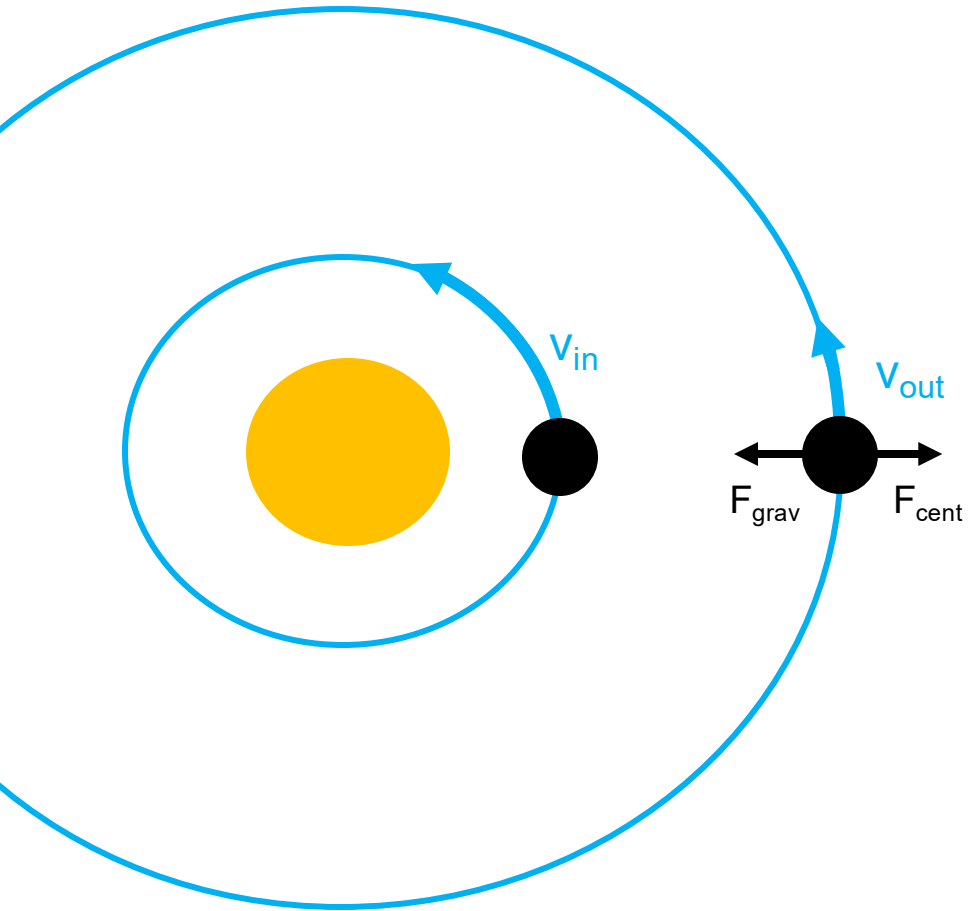
GALACTIC ROTATION CURVES



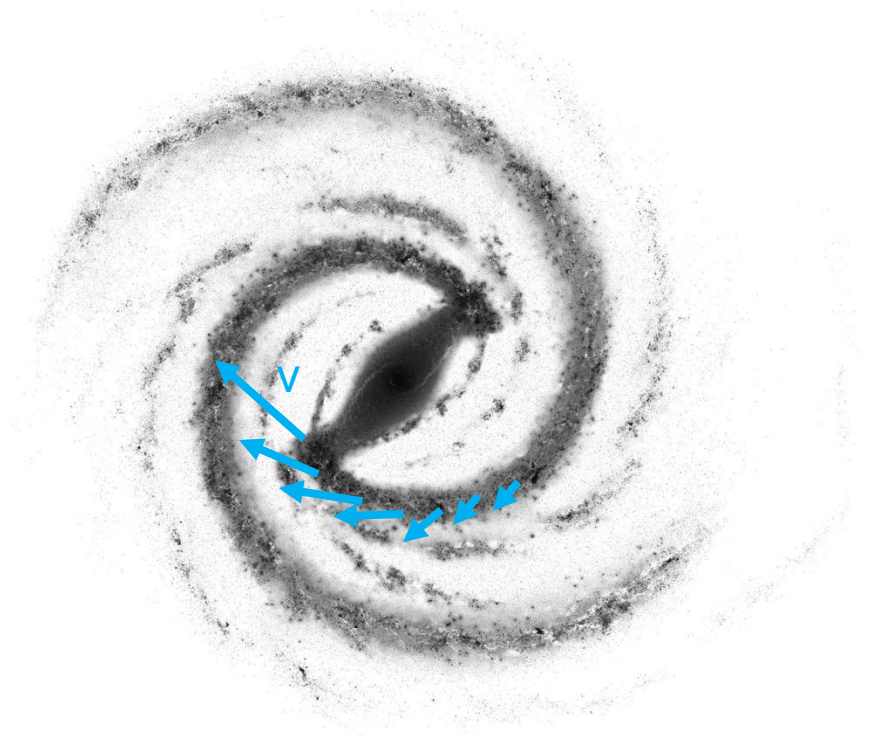
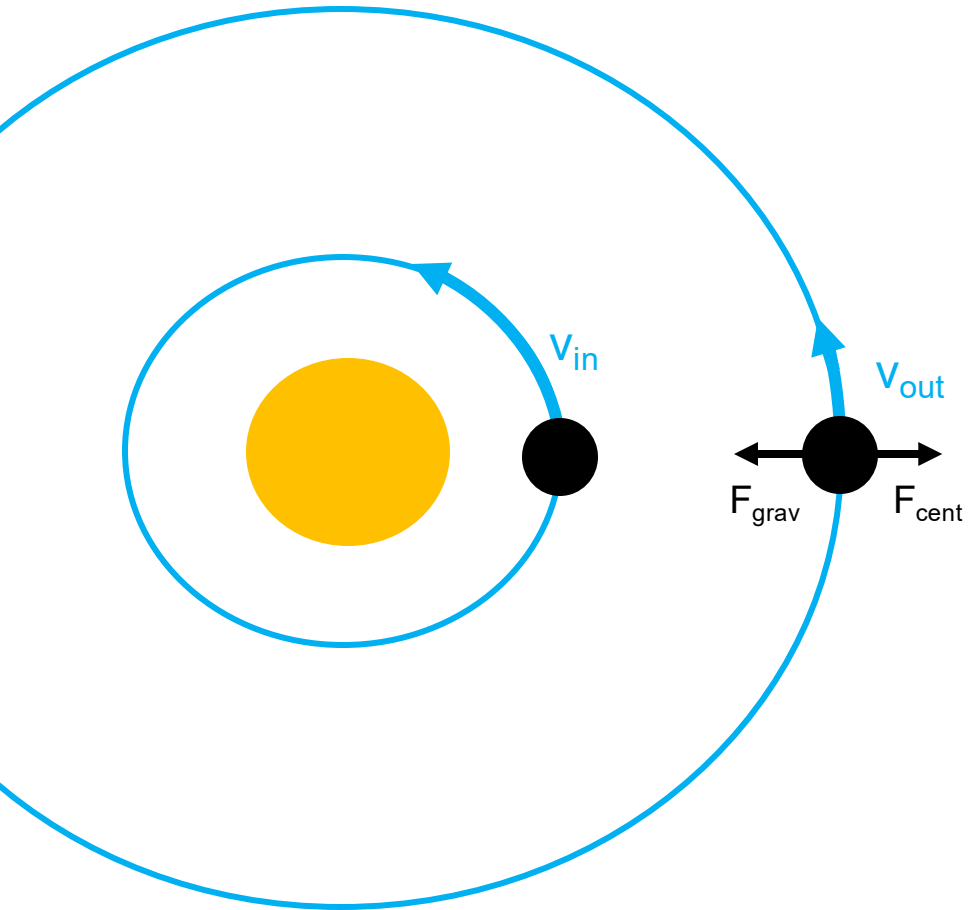
GALACTIC ROTATION CURVES



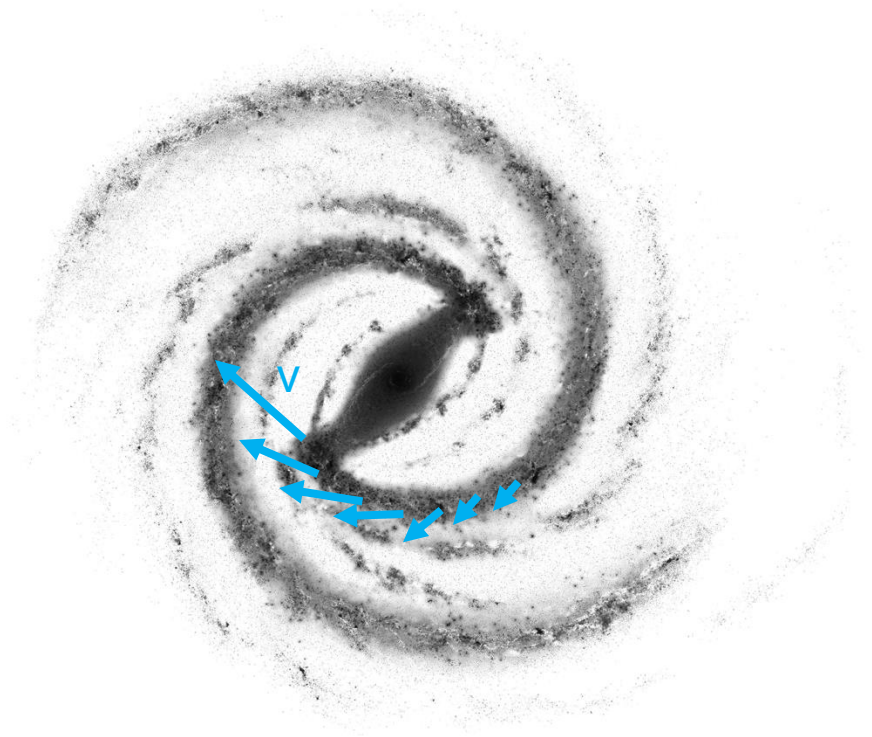
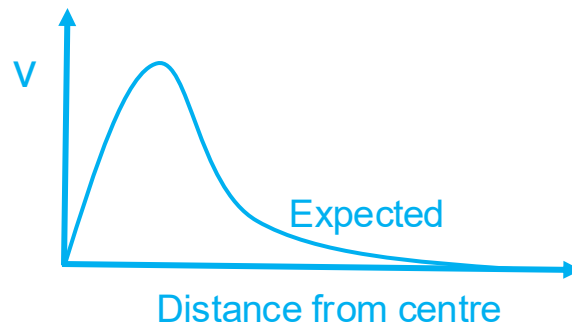
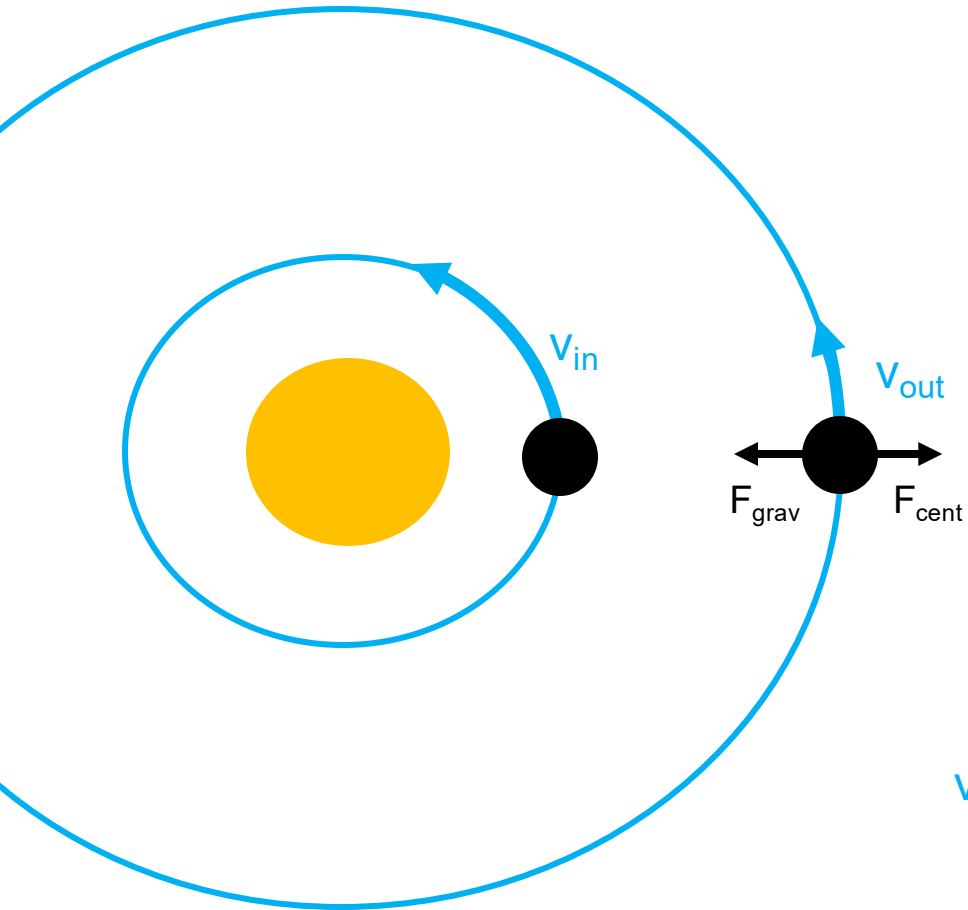
GALACTIC ROTATION CURVES



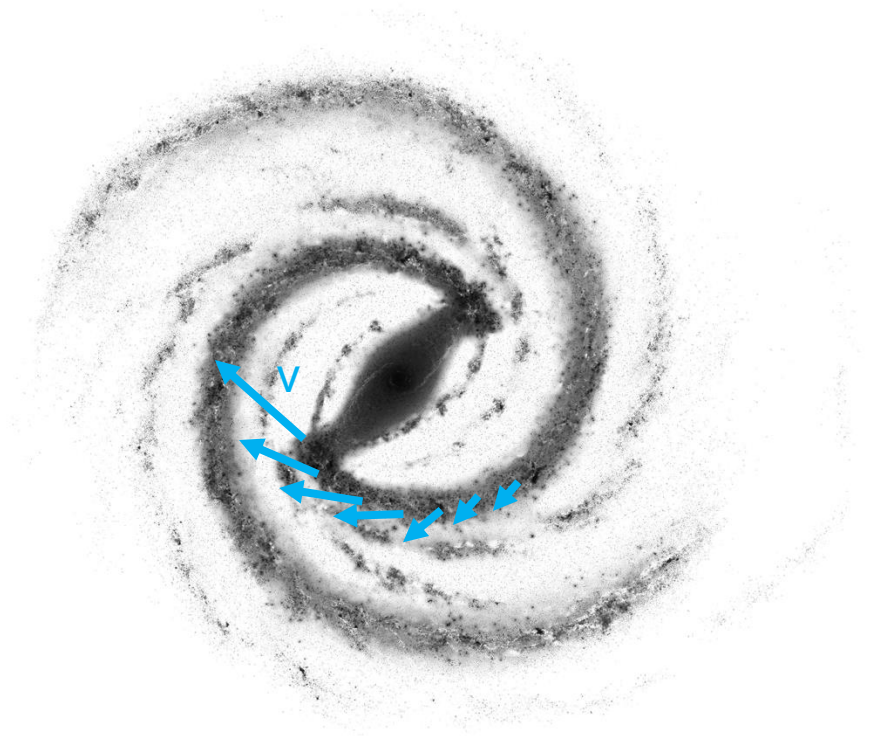
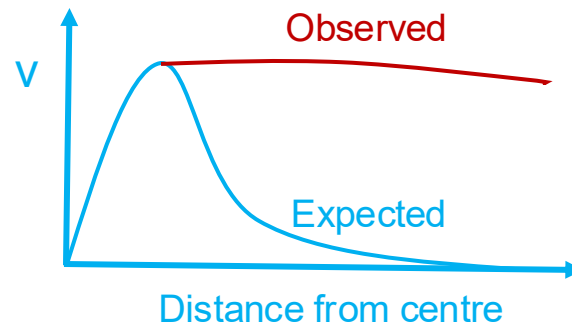
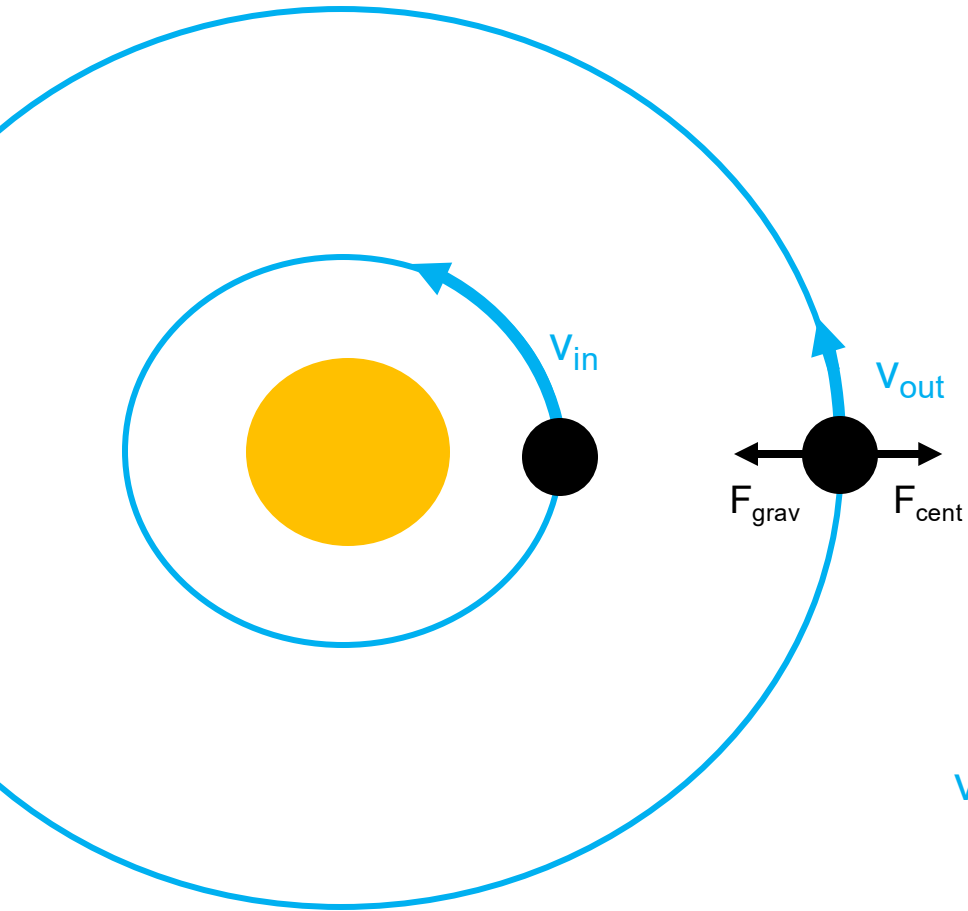
GALACTIC ROTATION CURVES



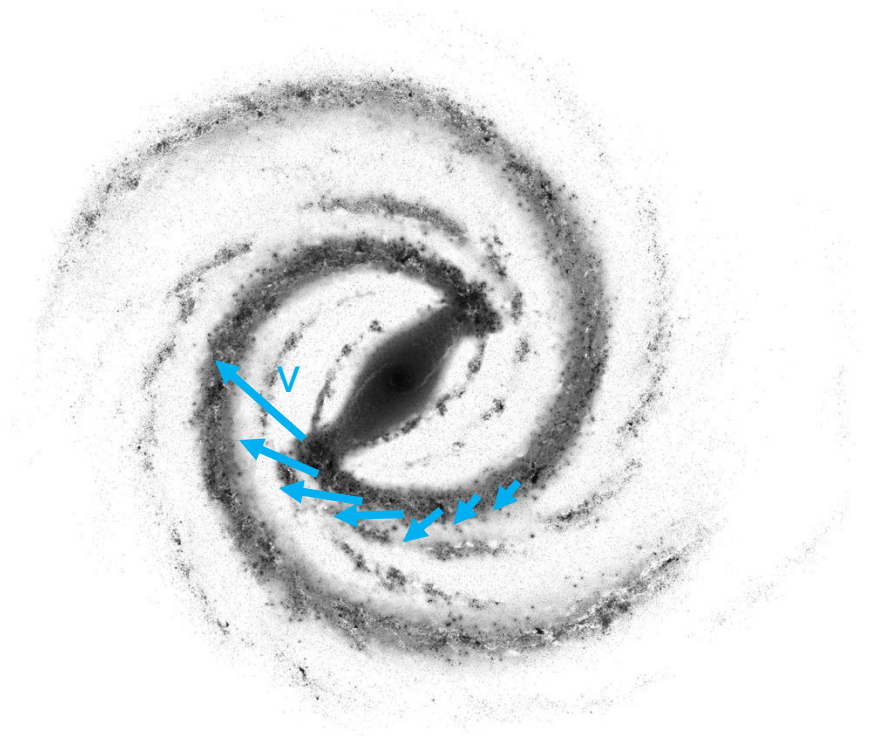
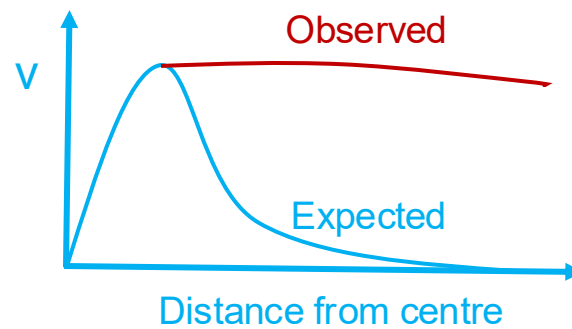
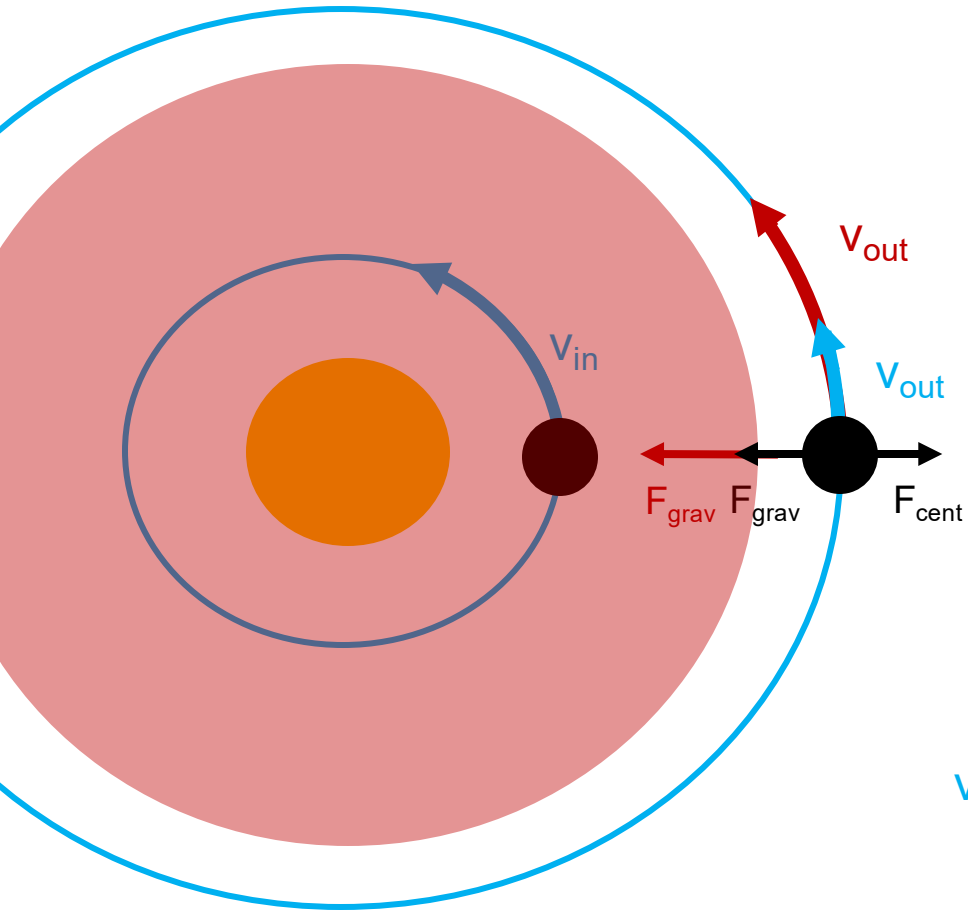
GALACTIC ROTATION CURVES



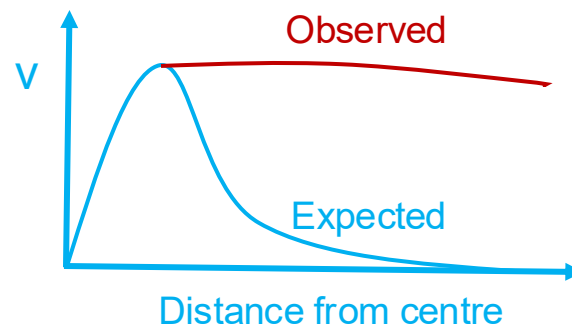
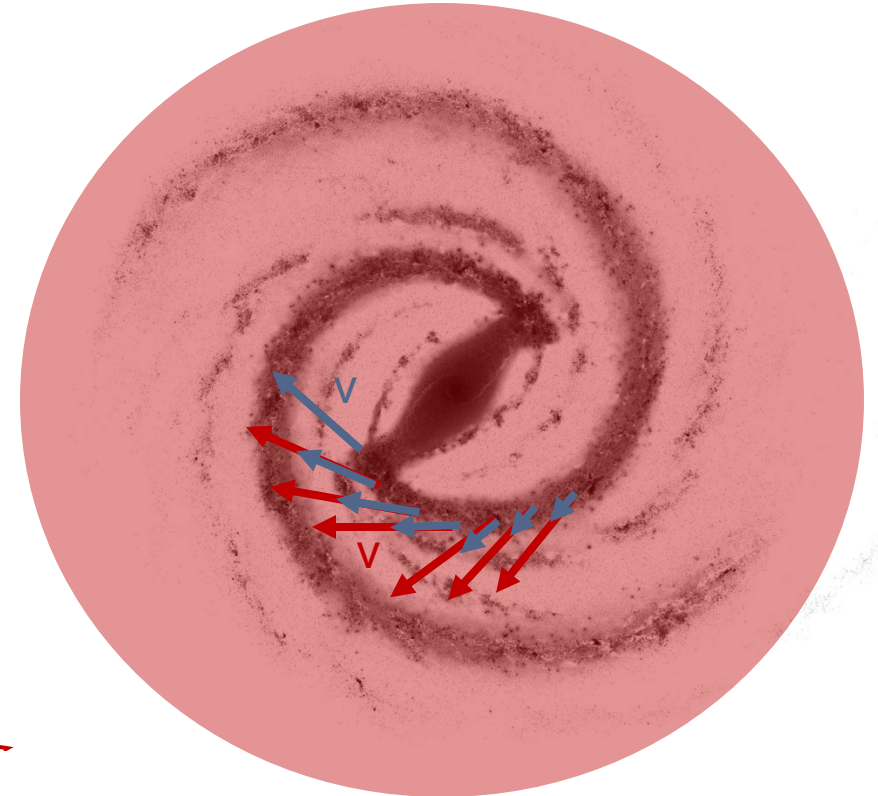
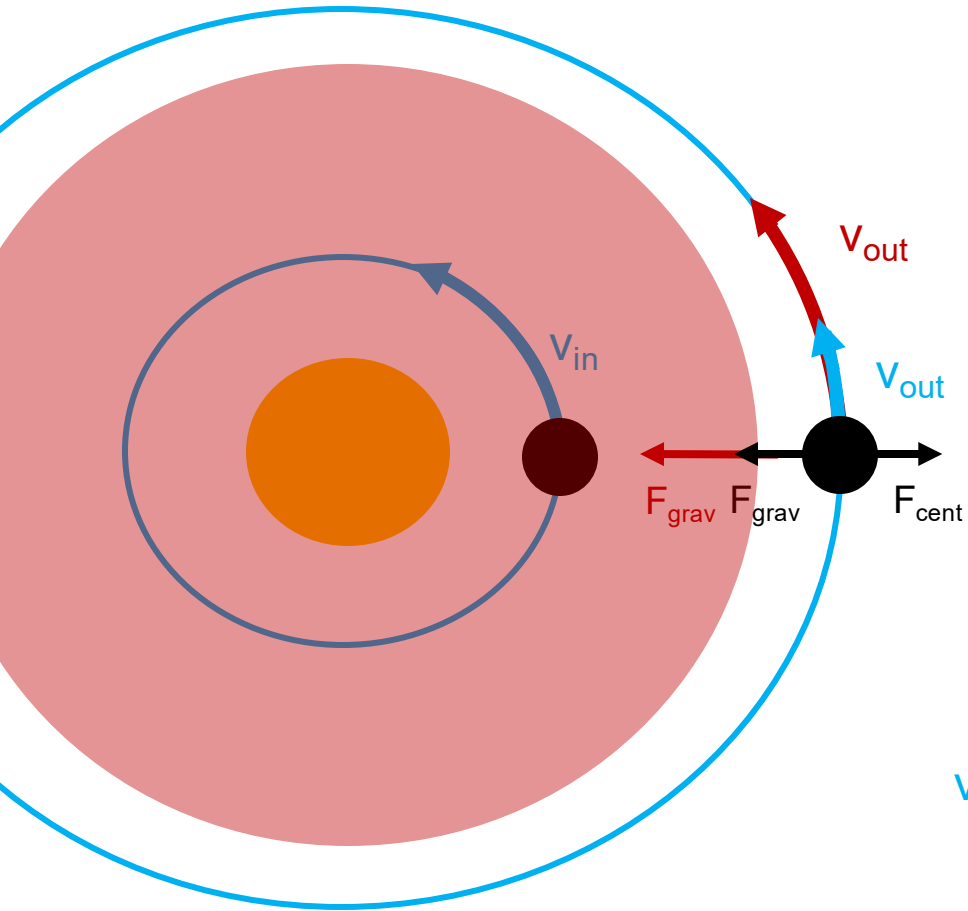
GALACTIC ROTATION CURVES



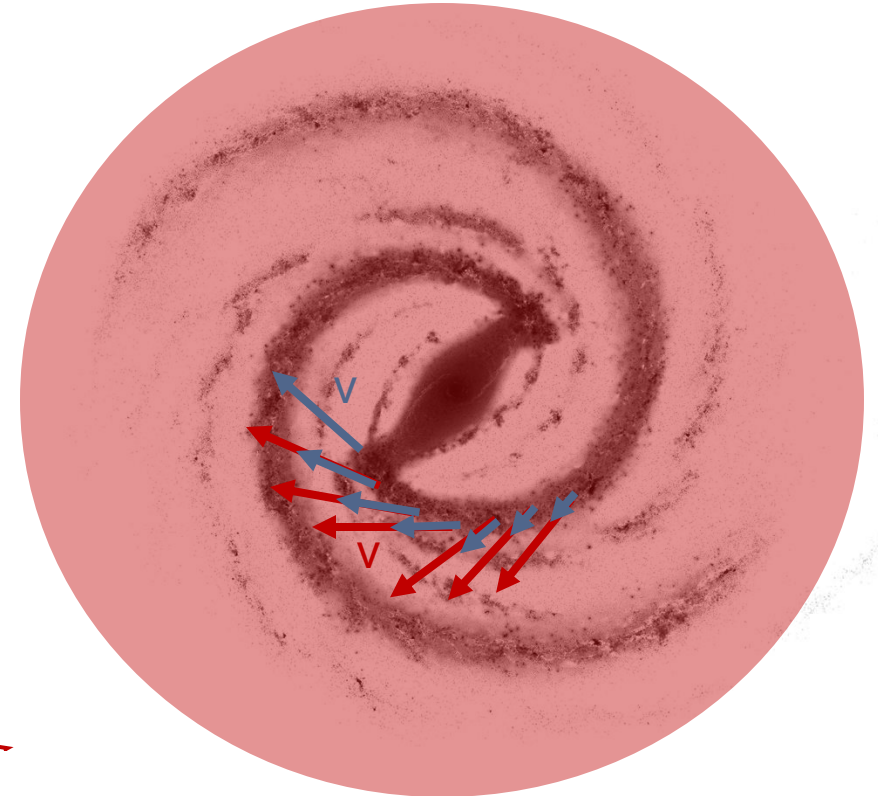
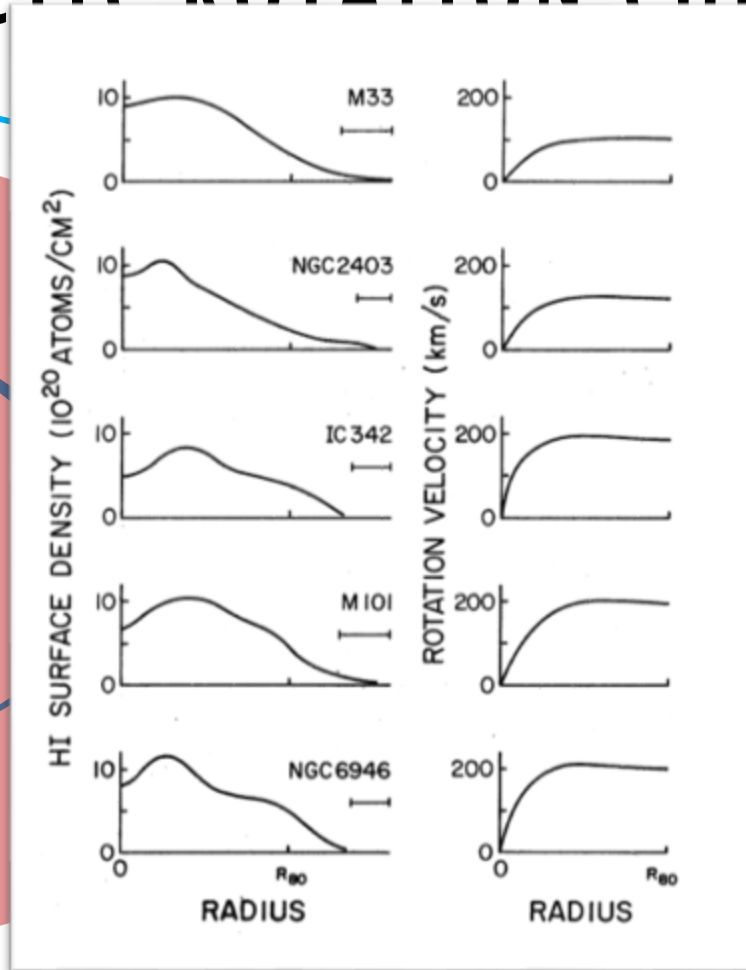
GALACTIC ROTATION CURVES



GALACTIC ROTATION CURVES



GALACTIC ROTATION CURVES



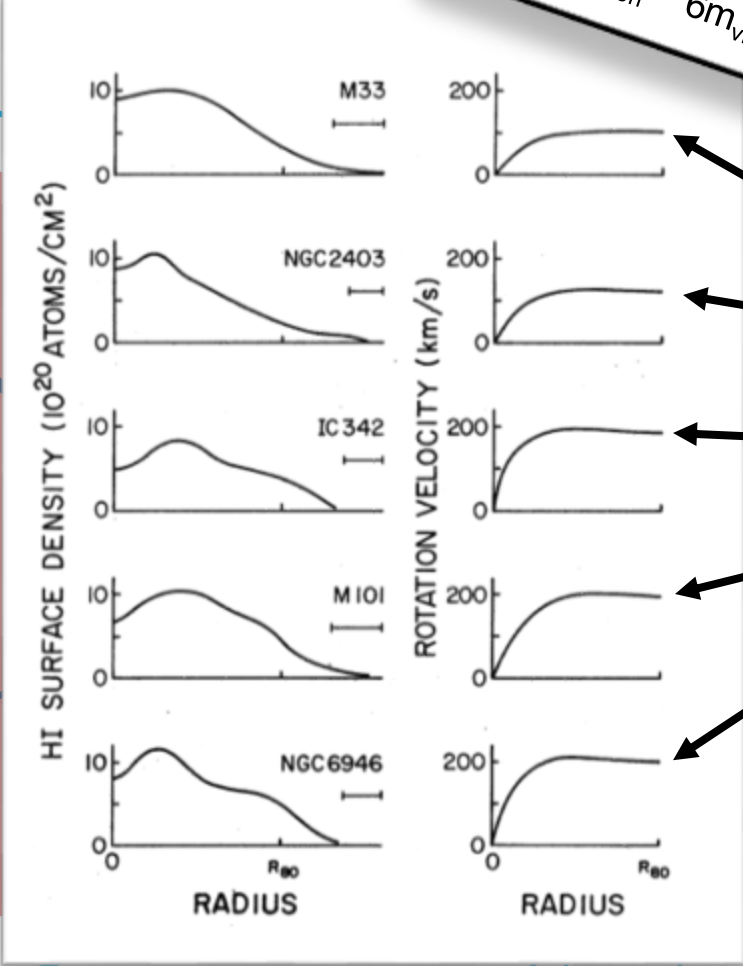
Observed

Expected

Distance from centre

GALACTIC ROTATION CURVES

$m_{\text{hidden}} \sim 6m_{\text{visible}}$

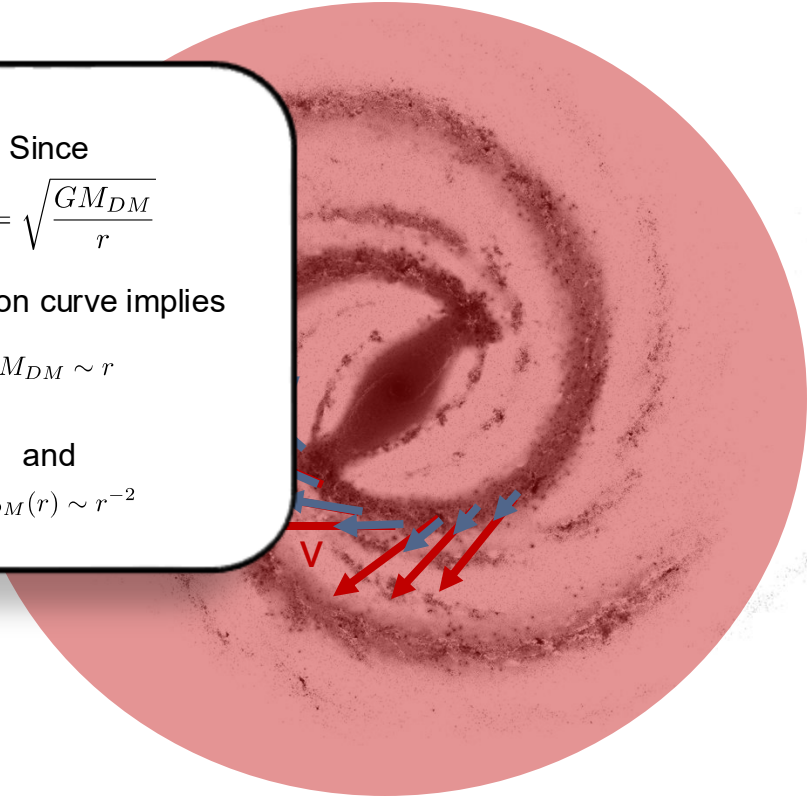
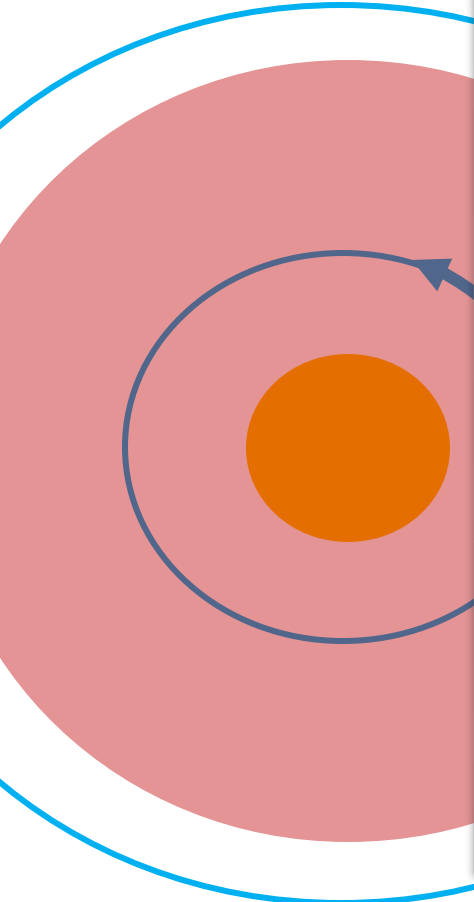


Since

$$v_{\text{orb}} = \sqrt{\frac{GM_{DM}}{r}}$$
 flat rotation curve implies

$$M_{DM} \sim r$$
 and

$$\rho_{DM}(r) \sim r^{-2}$$



Observed

Expected

Distance from centre

GALACTIC CLUSTERS

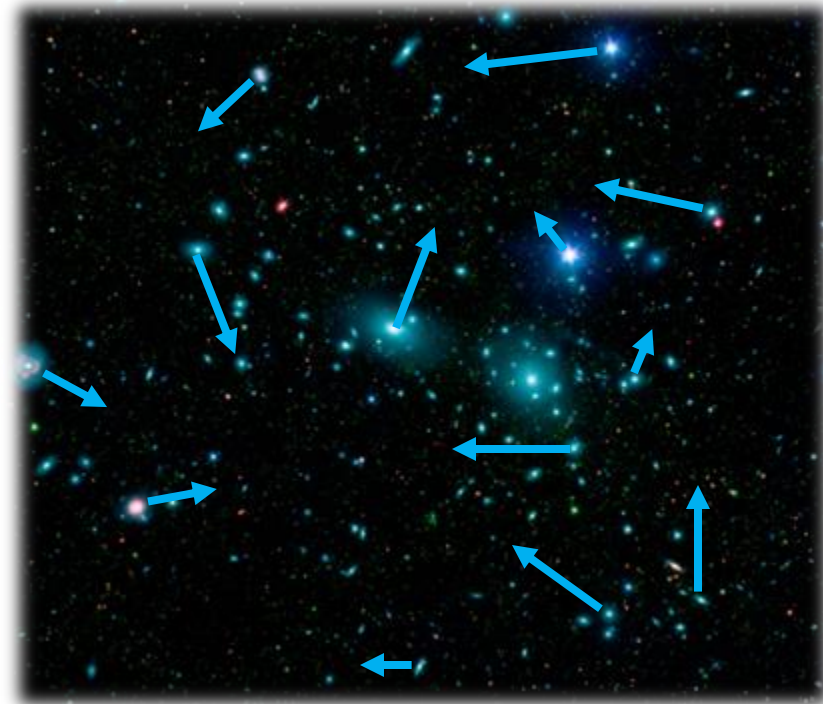


VELOCITY DISPERSION IN GALACTIC CLUSTERS

- Fritz Zwicky – 1933 Coma Cluster
- Velocity dispersion $\sigma \sim m_{\text{cluster}}$

$$\sigma = \sqrt{\frac{\sum^N (v_i - \bar{v})^2}{N}}$$

- Expected dispersion ~ 80 km/s
- Observed dispersion ~ 1000 km/s



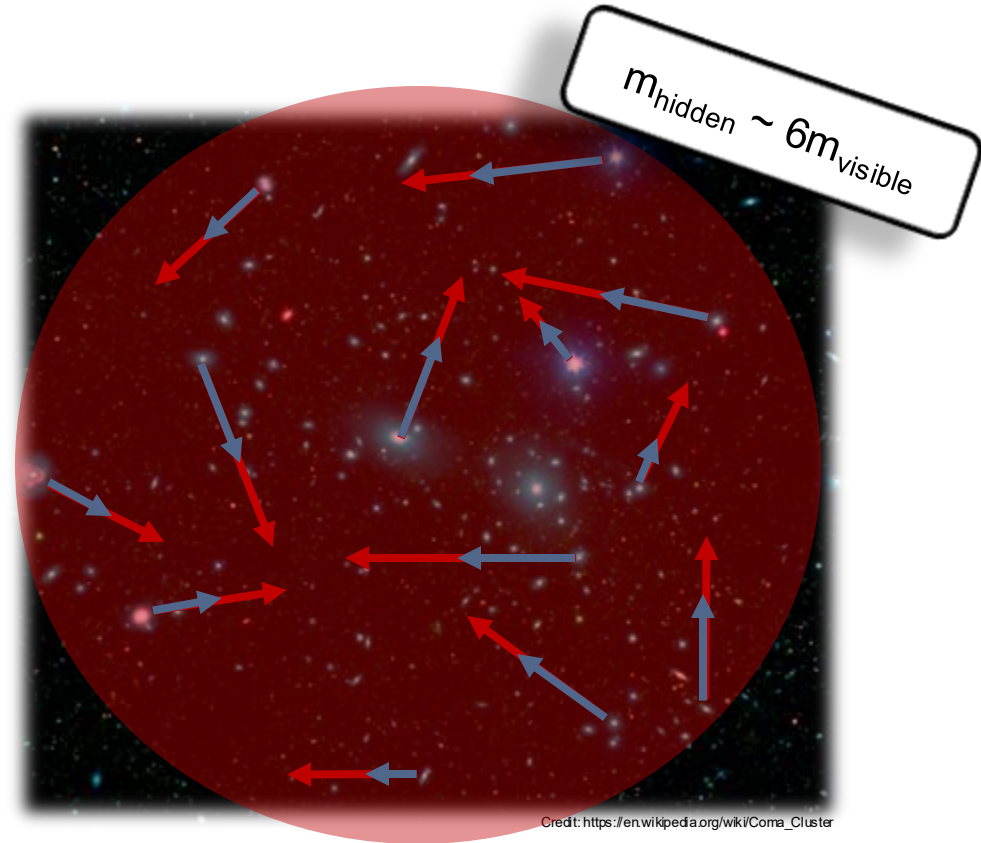
Credit: https://en.wikipedia.org/wiki/Coma_Cluster

VELOCITY DISPERSION IN GALACTIC CLUSTERS

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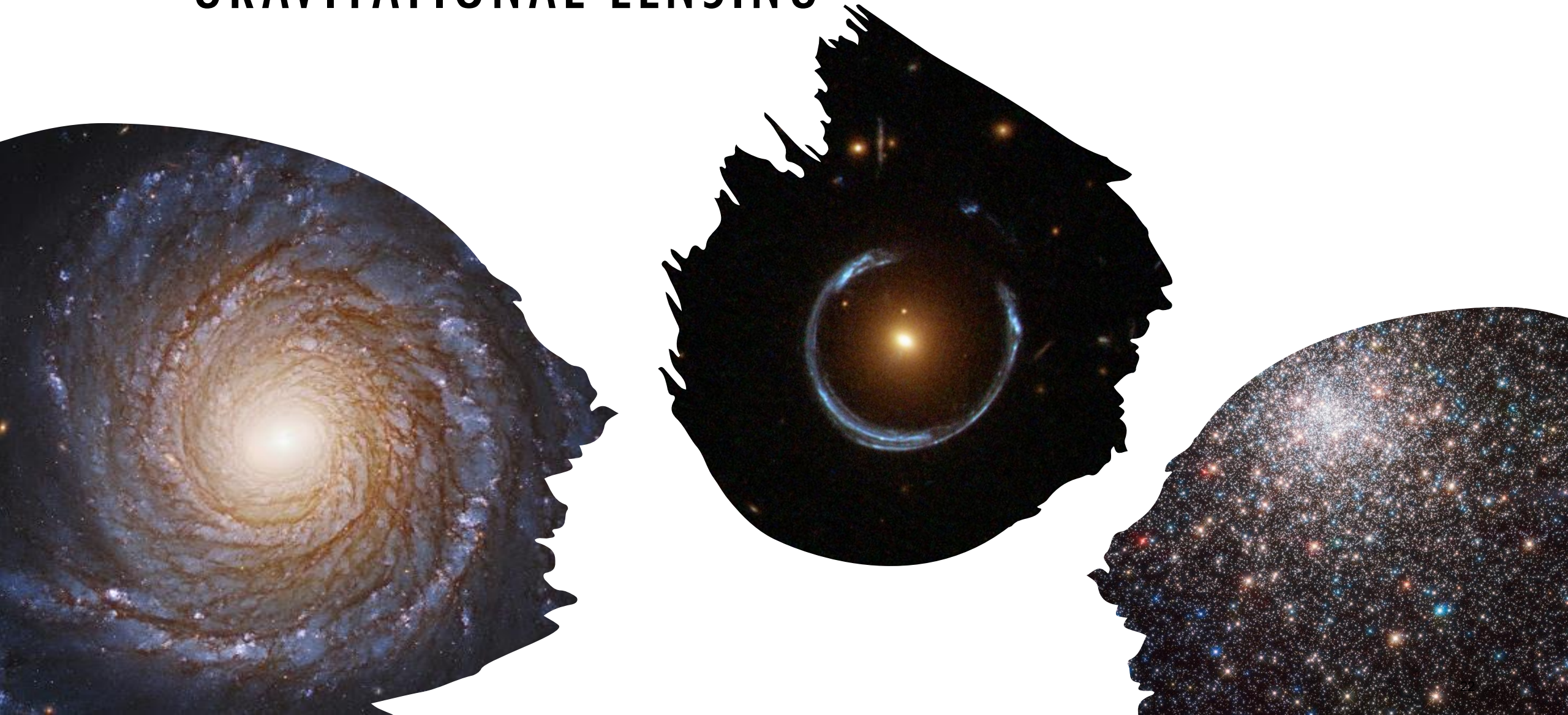
$$\sigma = \sqrt{\frac{\sum^N (v_i - \bar{v})^2}{N}}$$

- Expected dispersion ~ 80 km/s
- Observed dispersion ~ 1000 km/s



If this would be confirmed, we would get the surprising result that dark matter is present in much greater amount than luminous matter.

GRAVITATIONAL LENSING

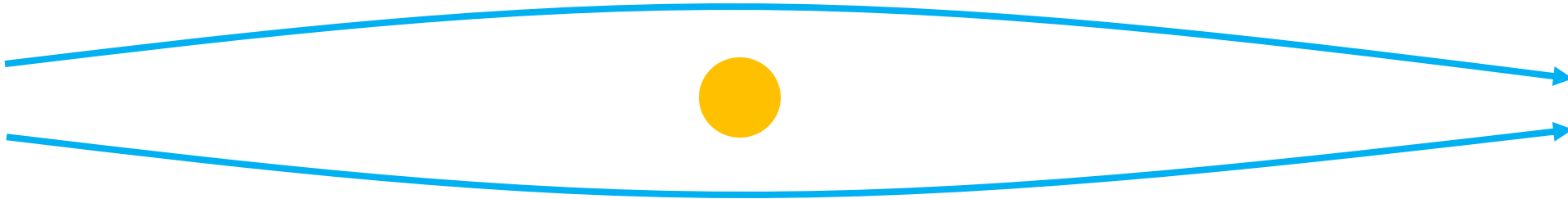
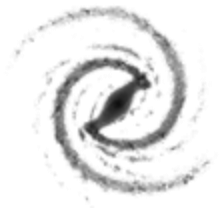


GRAVITATIONAL LENSING

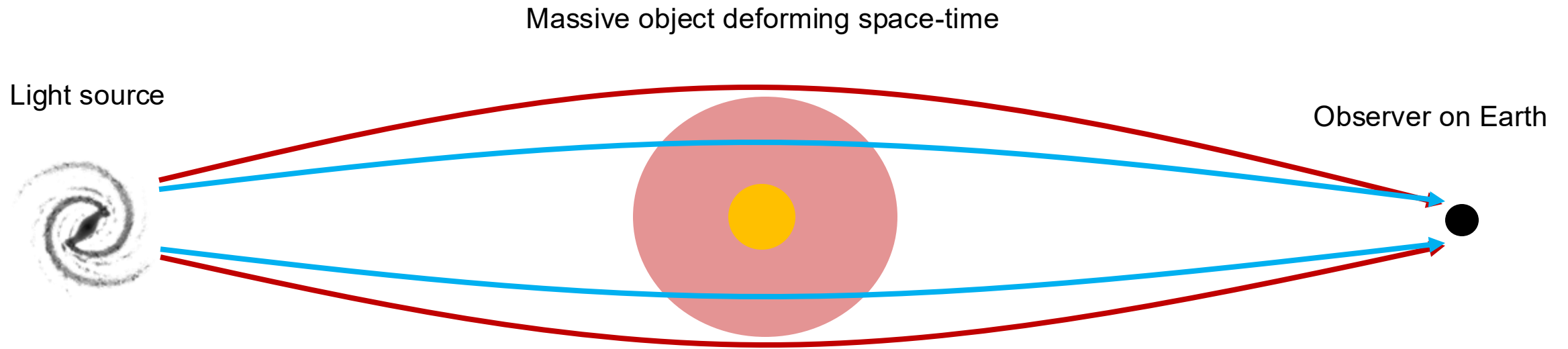
Massive object deforming space-time

Light source

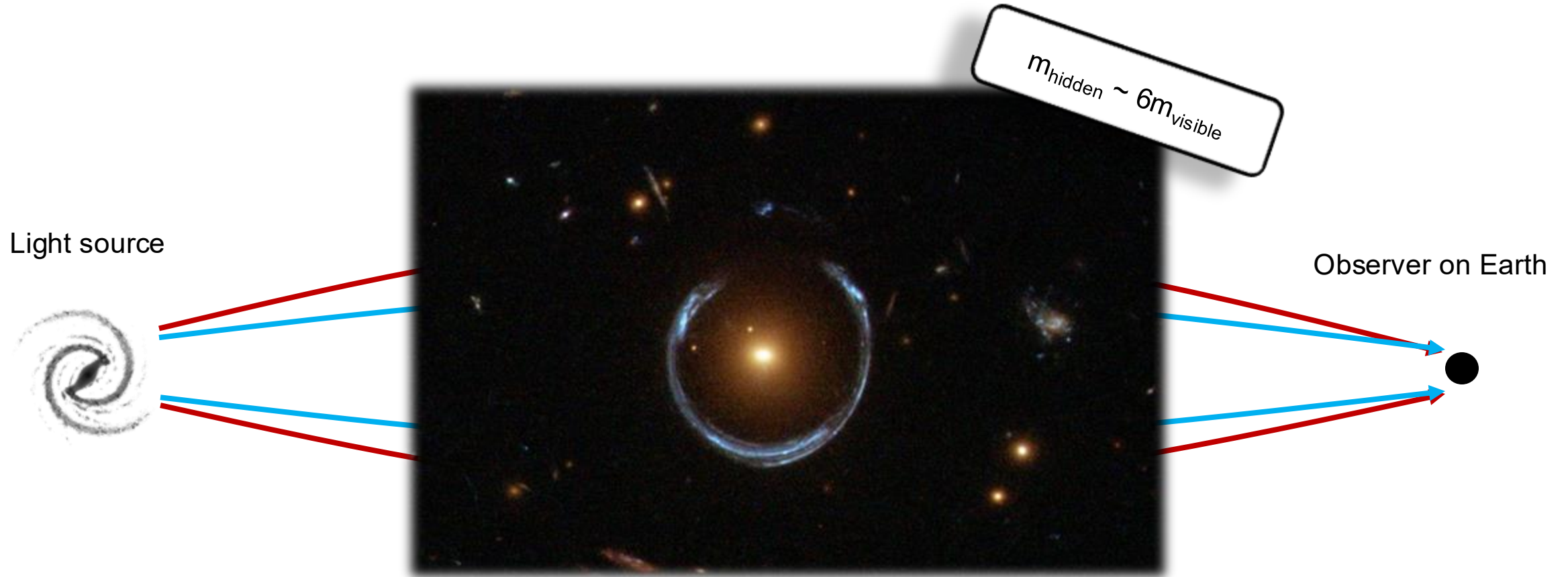
Observer on Earth



GRAVITATIONAL LENSING



GRAVITATIONAL LENSING



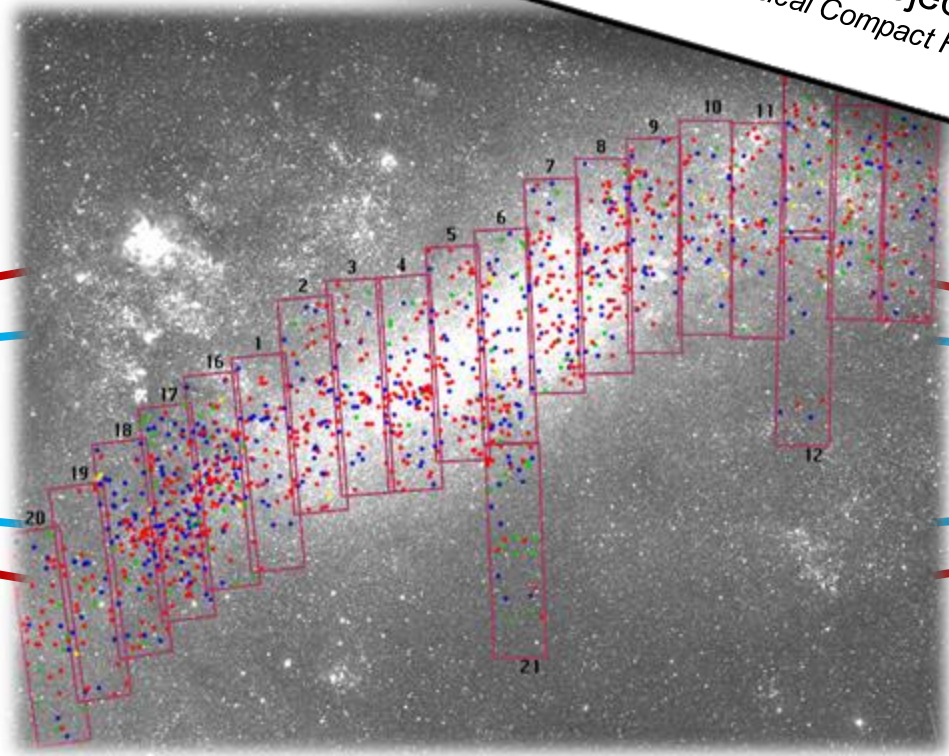
GRAVITATIONAL LENSING

MACHO Project
(*Massive Astrophysical Compact Halo Objects*)

Light source



Observer on Earth

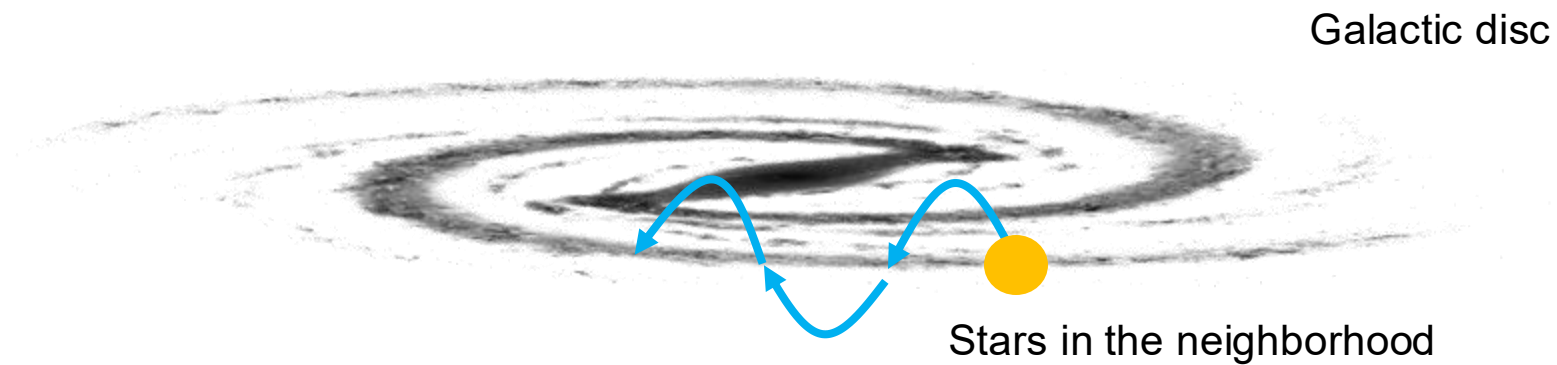


Credit: Michael Richmond

LOCAL OSCILLATIONS



LOCAL OSCILLATIONS



LOCAL OSCILLATIONS

$$\rho_{\text{DM}} \sim 1/3 \text{ GeV/cm}^3$$

Dark disc

Galactic disc

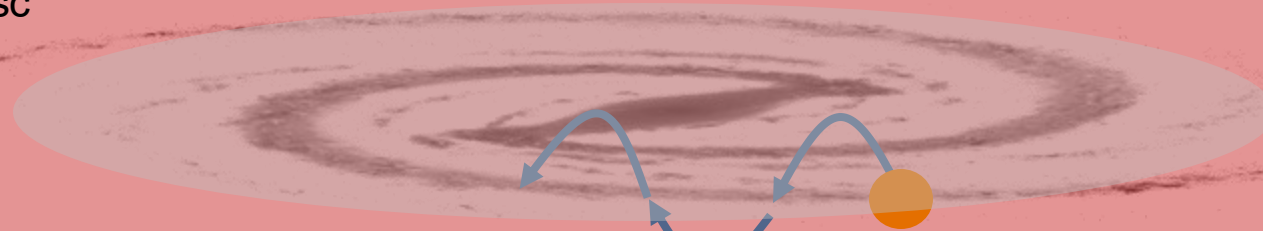
Stars in the neighborhood

LOCAL OSCILLATIONS

$$\rho_{\text{DM}} \sim 1/3 \text{ GeV/cm}^3$$

Dark disc

Galactic disc

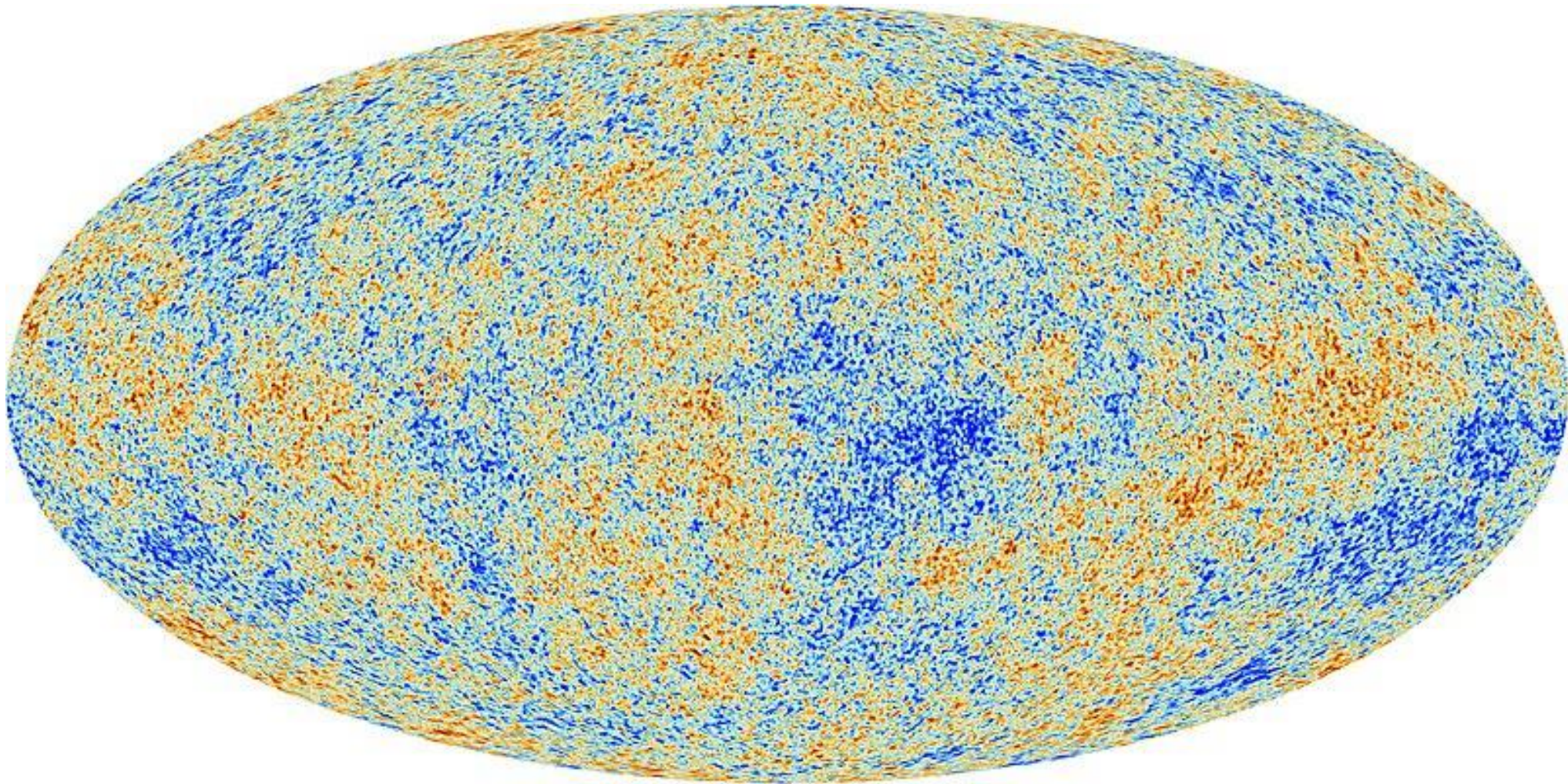


Stars in the neighborhood

THE BIG BANG



BARYOGENESIS AND CMB FLUCTUATIONS



BARYOGENESIS AND CMB FLUCTUATIONS

When the temperature is right,
baryogenesis onsets

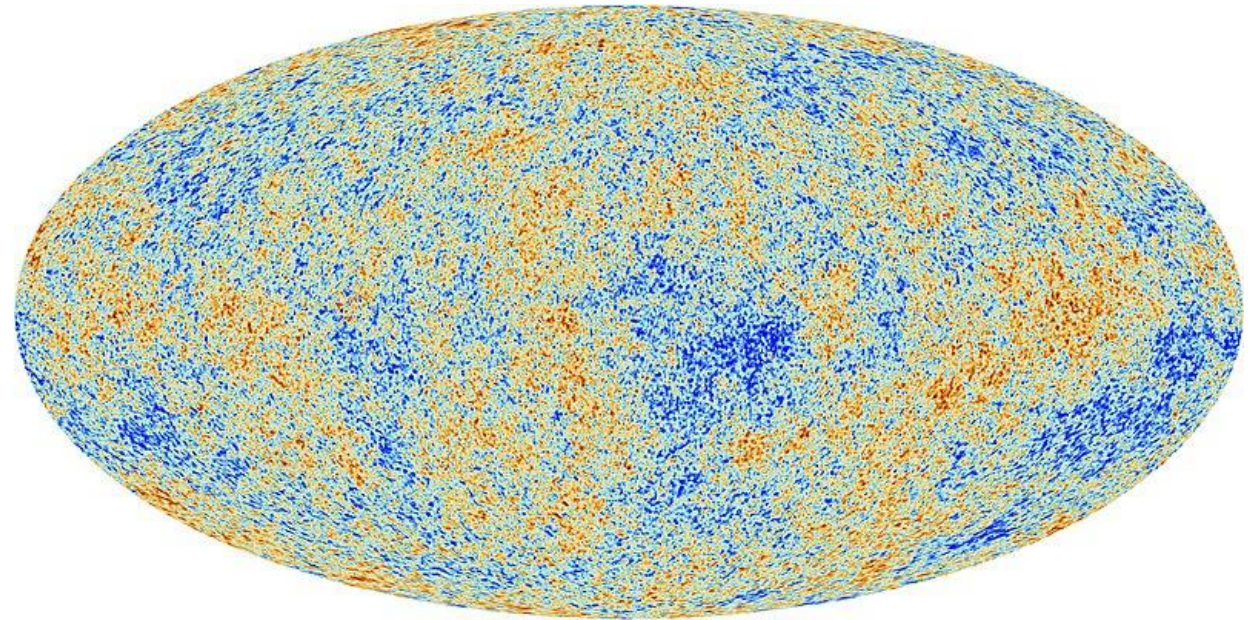


This process is sensitive to the baryon density ρ_B

- Too large and they all burn to ${}^3\text{He}$
- Too low and they do not fuse at all

The observed abundances imply $m_{\text{DM}} \sim 6m_{\text{visible}}$

DM is not baryonic



STRUCTURE FORMATION

Structure formation (galaxies) is driven by DM



DM traps itself due to the expansion of the Universe
(collapsed DM)



These pockets of DM then trap baryons and form structures

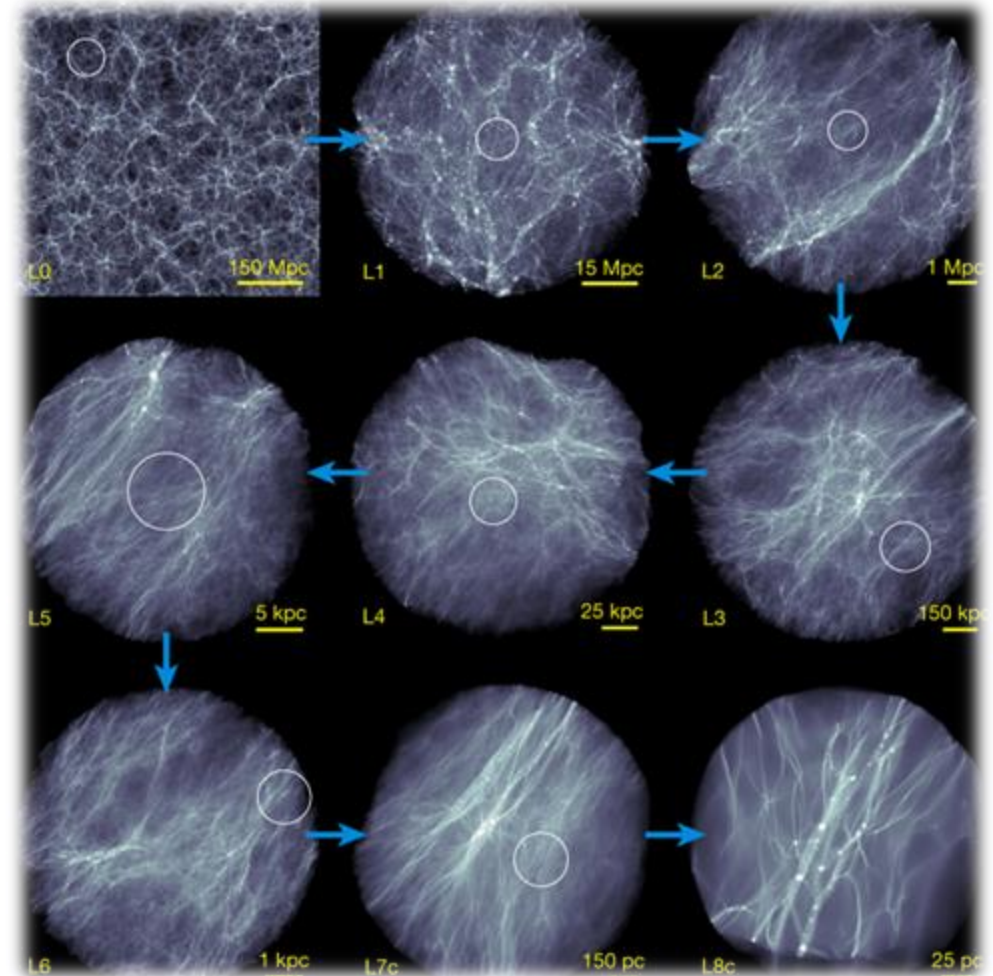


Observation and morphology of structures confirm

$$m_{\text{DM}} \sim 6m_{\text{visible}}$$



DM is non-relativistic
(not neutrinos)



Wang et al. *Nature* **585**, 39–42 (2020)



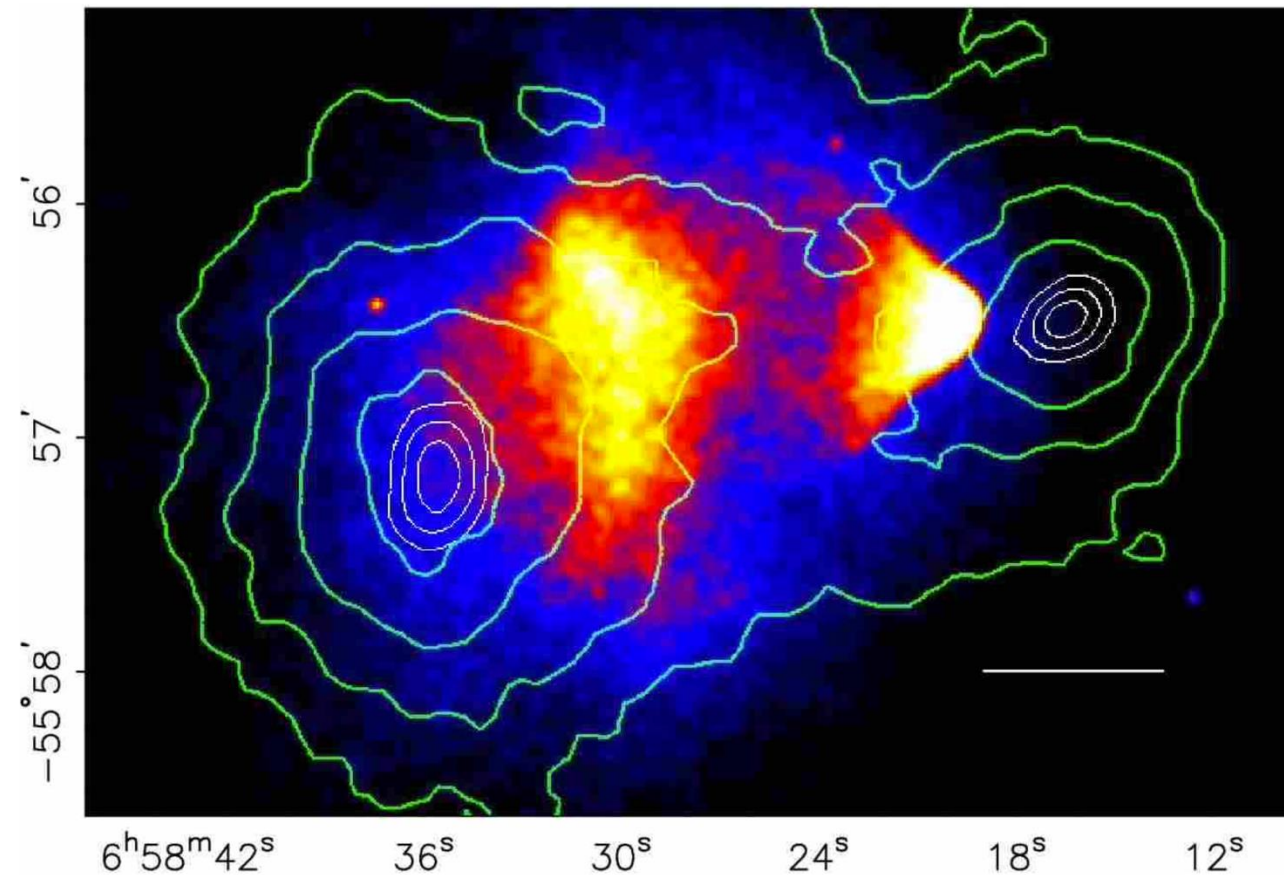
WHY PARTICLES | ?

THE BULLET CLUSTER COLLISION

A DIRECT EMPIRICAL PROOF OF THE EXISTENCE OF DARK MATTER *

DOUGLAS CLOWE¹, MARUŠA BRADAČ², ANTHONY H. GONZALEZ³, MAXIM MARKEVITCH^{4,5}, SCOTT W. RANDALL⁴,
CHRISTINE JONES⁴, AND DENNIS ZARITSKY¹

ApJ Letters in press



**ALSO, GALAXIES
WITHOUT DM**



That's all Folks!

REFERENCES AND FURTHER READING

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