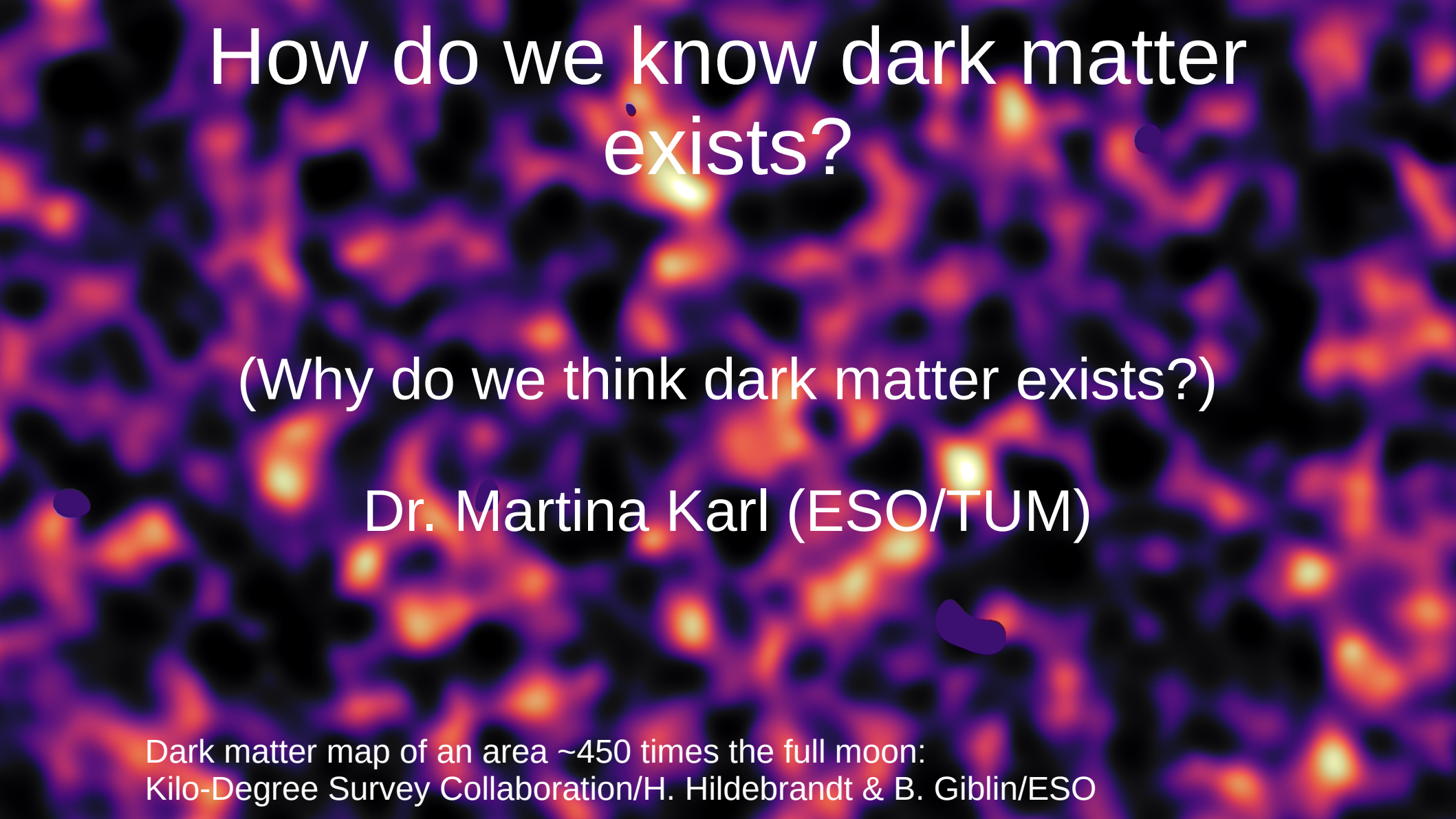
How do we know dark matter exists?

(Why do we think dark matter exists?)

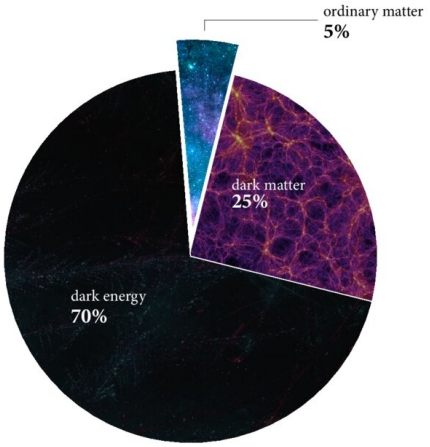
Dr. Martina Karl (ESO/TUM)



Dark matter map of an area ~450 times the full moon:
Kilo-Degree Survey Collaboration/H. Hildebrandt & B. Giblin/ESO

What is dark matter?

- Matter that we don’t see
- It does not interact with light or radiation
- It does interact gravitationally
- Assuming standard model of particle physics and general relativity:



5 x more dark matter
than ordinary matter!

Illustration: Max-Planck-Institute for Astrophysics Garching and Pixabay

Why do we think dark matter exists?

- Existence of dark matter was hypothesized for many years (e.g., Kelvin, Poincaré, Jacobus Kapteyn, Knut Lundmark, Jan Oort, …
- In 1933 **Fritz Zwicky** postulates “dark matter” using virial theorem

Galaxies move “too fast”

- 1933 Fritz Zwicky observes motion of galaxies in the Coma Cluster

Coma Cluster (Credit: SDSS)

Um, wie beobachtet, einen mittleren Dopplereffekt von 1000 km/sek oder mehr zu erhalten, müsste also die mittlere Dichte im Comasystem mindestens 400 mal grösser sein als die auf Grund von Beobachtungen an leuchtender Materie abgeleitete[1]). Falls sich dies bewahrheiten sollte, würde sich also das überraschende Resultat ergeben, dass dunkle Materie in sehr viel grösserer Dichte vorhanden ist als leuchtende Materie.

2. Man kann auch annehmen, dass das Comasystem sich nicht im stationären Gleichgewicht befindet, sondern dass die ganze verfügbare potentielle Energie als kinetische Energie erscheint. Es wäre dann

$$\varepsilon_k = -\varepsilon_p . \qquad (9)$$

Man kann also durch diese Annahme gegenüber 1. nur einen Faktor 2 einsparen, und die Notwendigkeit einer enorm grossen Dichte dunkler Materie bleibt bestehen.

Helvetica Physica Acta, Vol. 6, p. 110-127; 1933

In order to obtain an average Doppler effect of 1000 km/s or more, as observed, the average density in the Coma system would thus have to be at least 400 times greater than that derived on the basis of observations of luminous matter. If this were to be verified, the surprising result would then follow that dark matter is present in very much greater density than luminous matter.

Galaxies move “too fast”

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- Similar observations later for Virgo Cluster

Coma Cluster (Credit: SDSS)

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Further evidence

- 1939 Babcock reports unexpectedly rapid rotation in the outskirts of Andromeda galaxy (10.5479/ADS/bib/1939LicOB.19.41B)
- 1940 Oort reports large non-visible halo of NGC 3115 (Astrophysical Journal, vol. 91, p.273)

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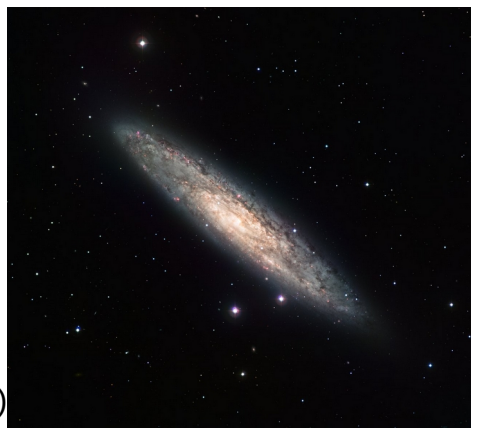
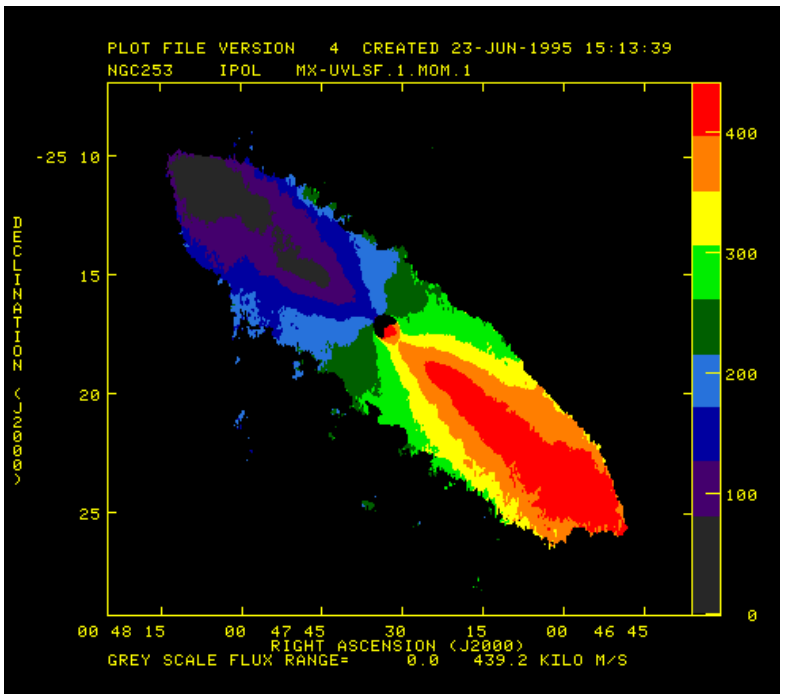
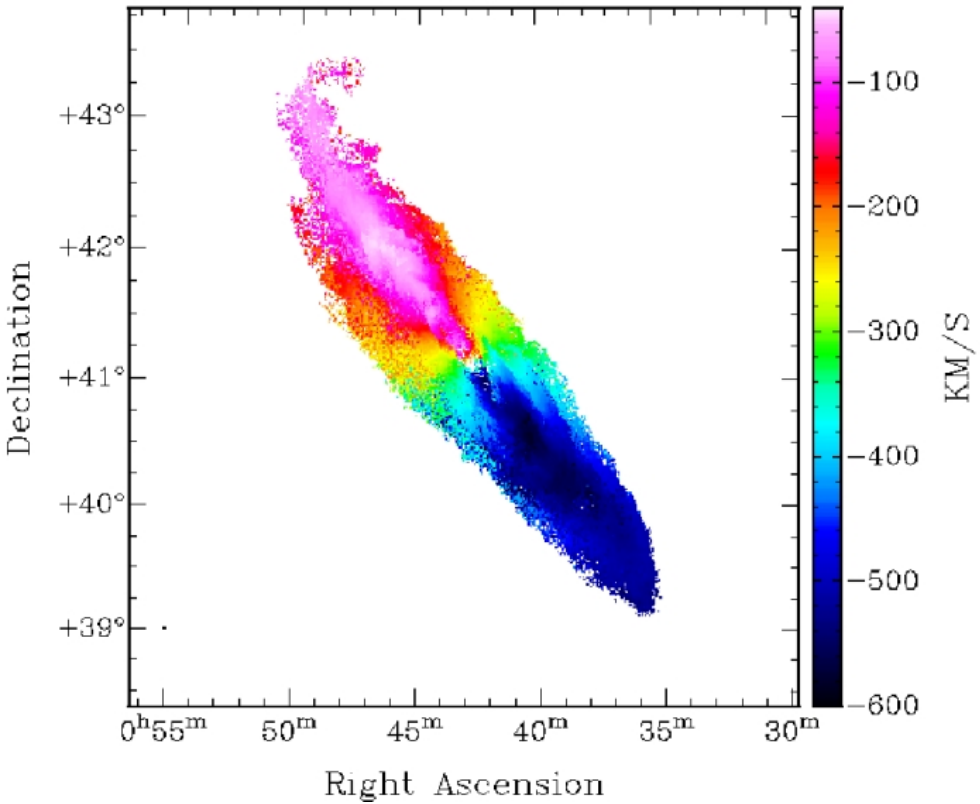


NGC253
(Credit: ESO)

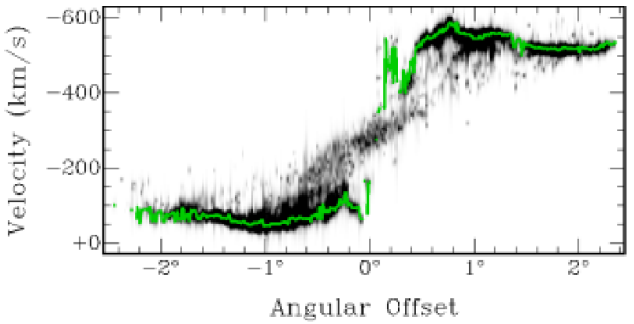


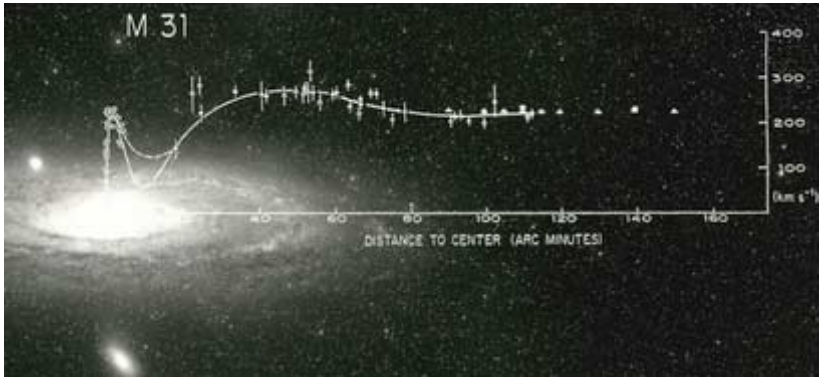
Credit: Australia Telescope Compact Array / Koribalski B.

Rotational Curves of Galaxies



Credit: Chemin et al. 2009

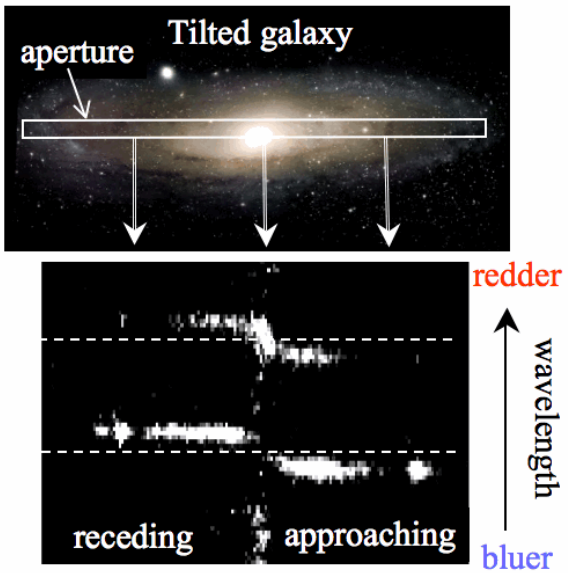




Credit: Vera Rubin

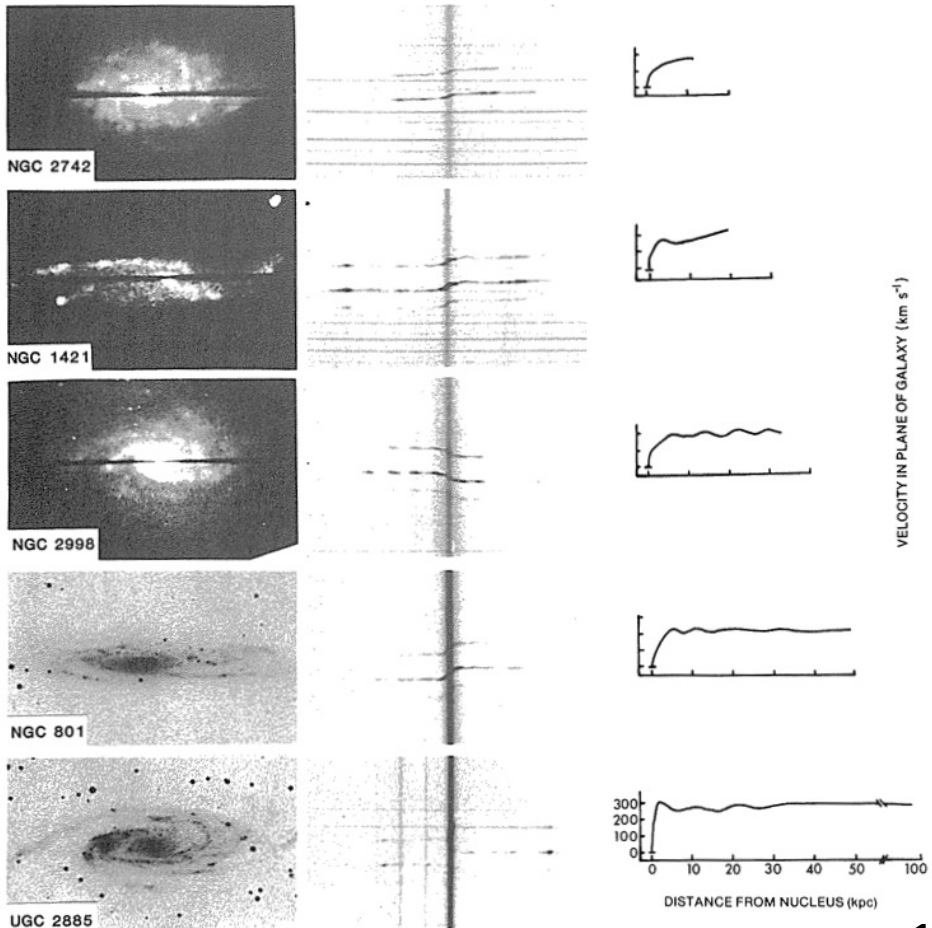
Rotational Curves of Galaxies

Vera Rubin measuring galaxy rotation curves (~1970)



Resulting spectrum of light within aperture

(Courtesy: AIP Emilio Segrè Visual Archives, Rubin Collection)



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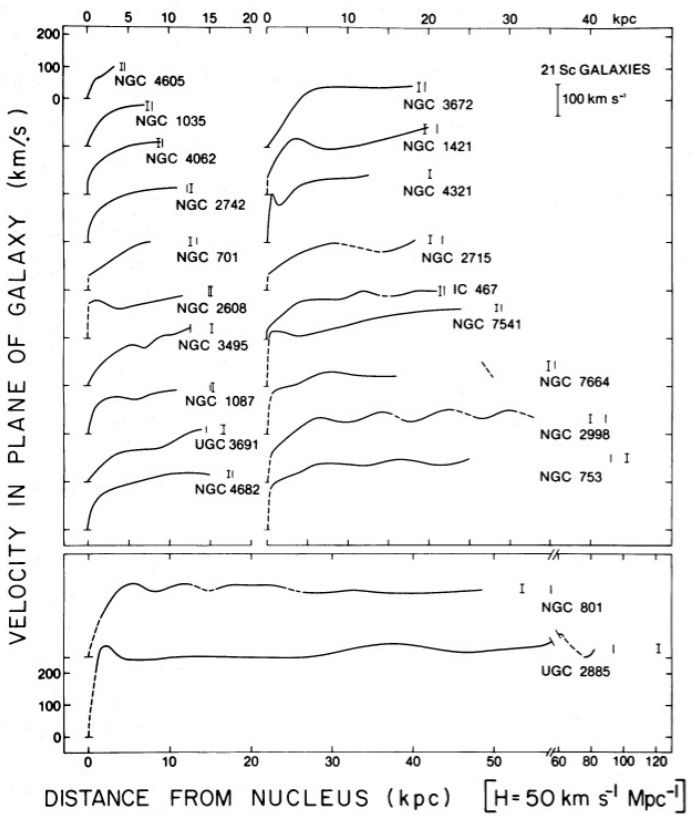
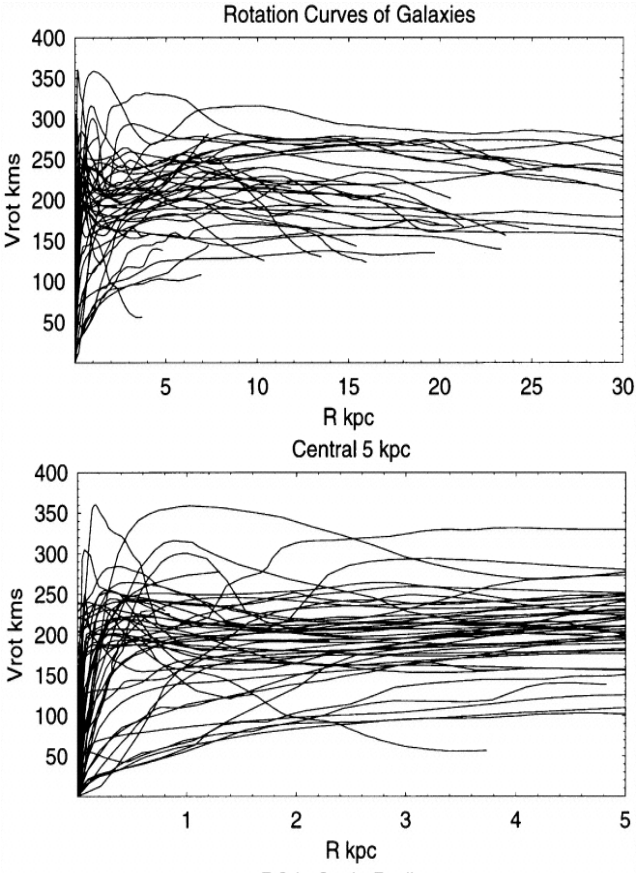


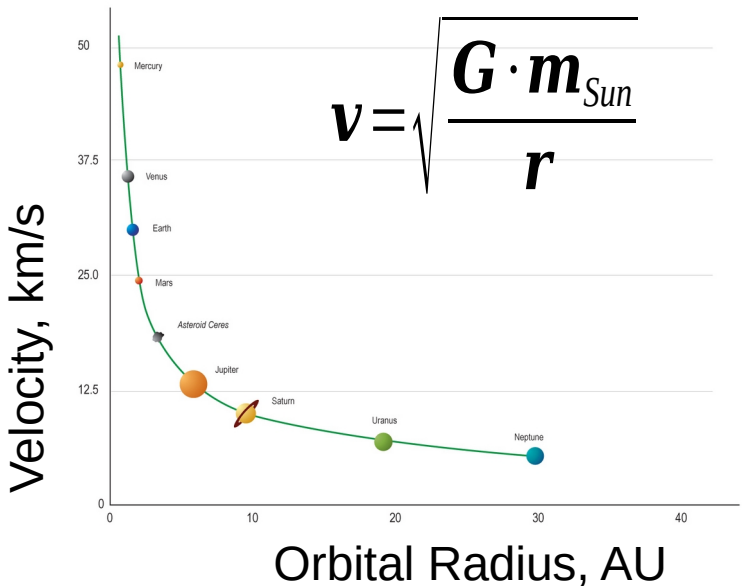
Credit: Rubin, Ford & Thonnard 1980



Credit: Sofue et al. 1999

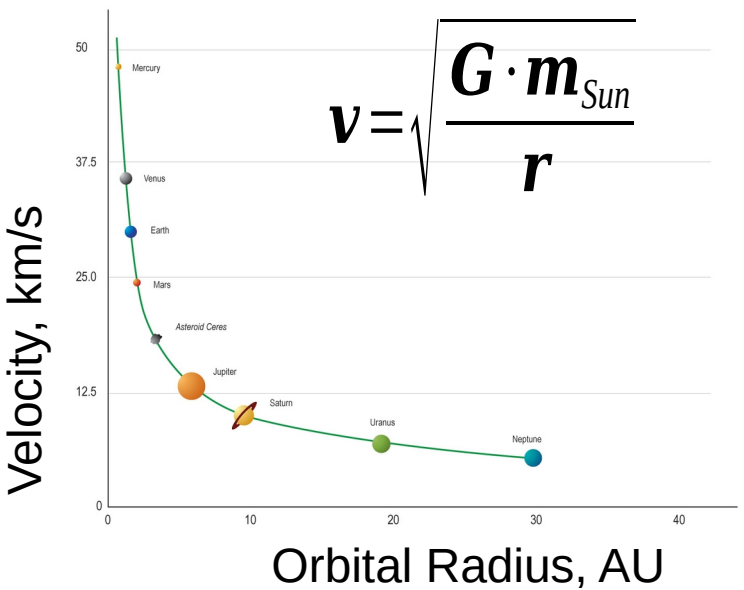
Rotational Curves of Galaxies

$$v = \sqrt{\frac{G \cdot m_{Sun}}{r}}$$



Credit: NASA/SSU/Aurore Simonnet

Rotational Curves of Galaxies



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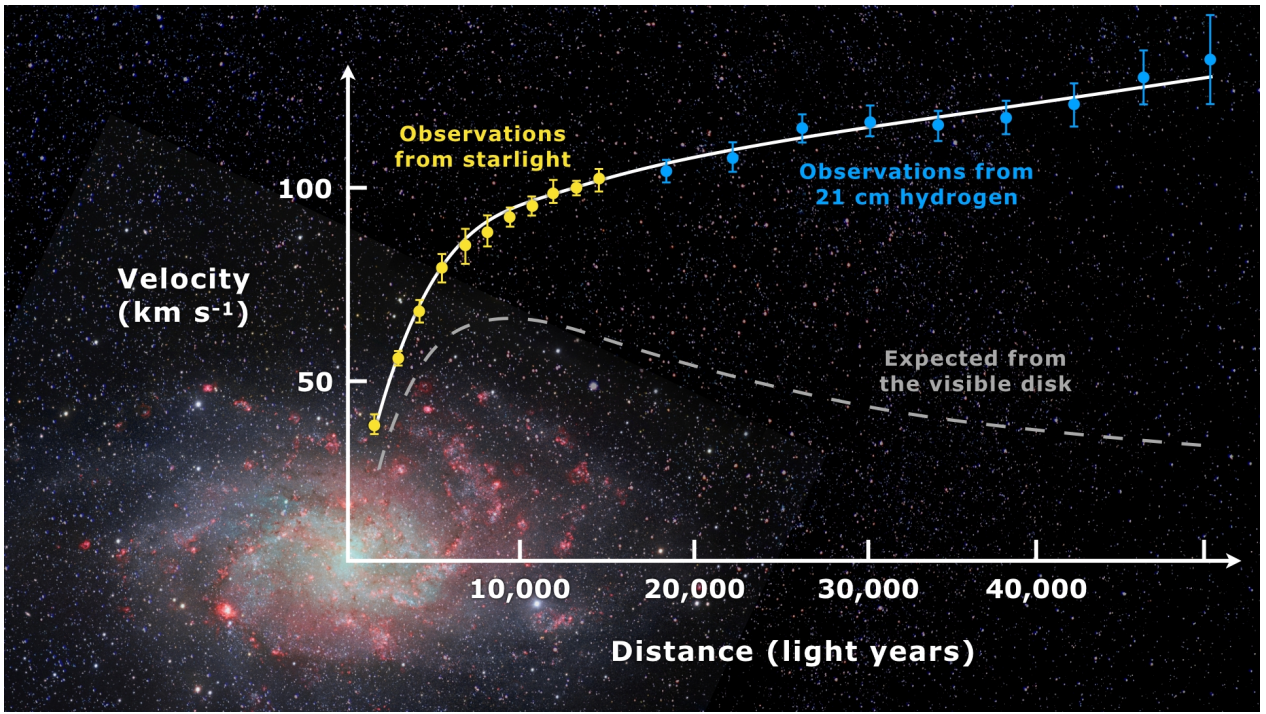
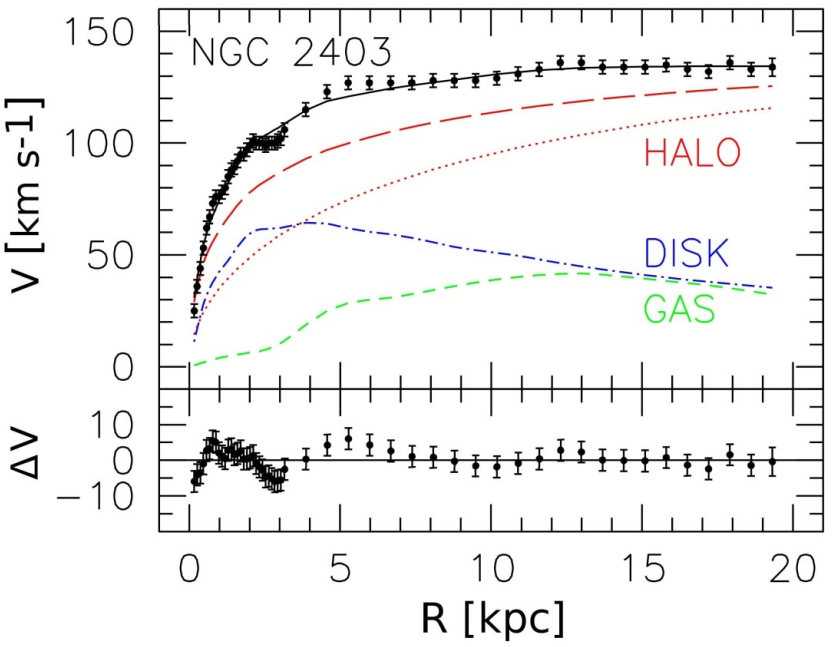
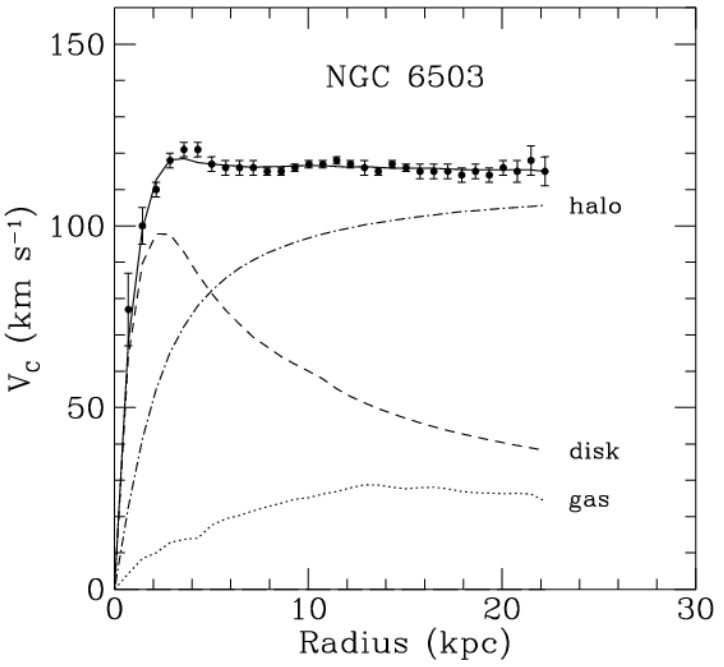


M33, Credit: ESO & Mario De Leo

Rotational Curves of Galaxies

- Add dark matter halo to describe velocity curves





Credit: Begemann, Broeils & Sanders 1991

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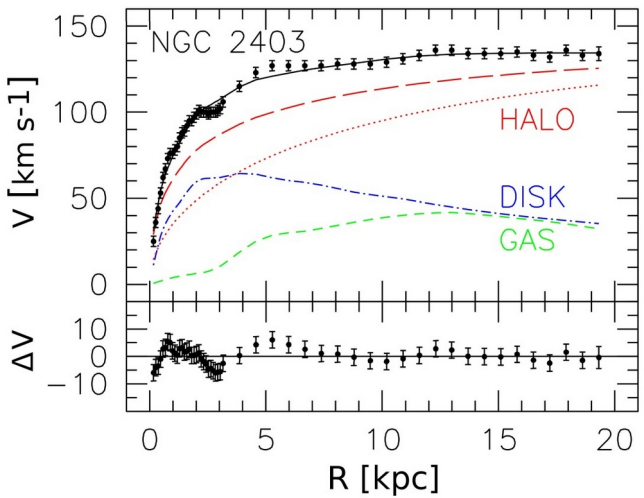
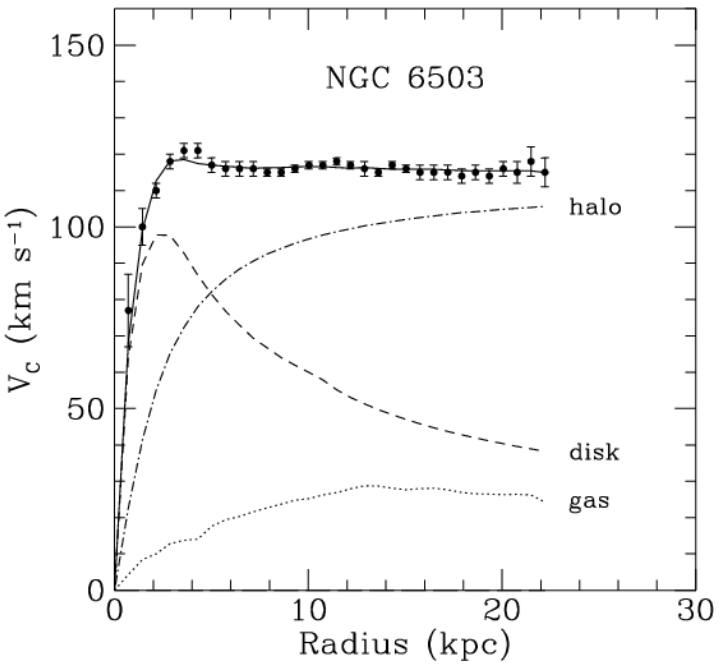
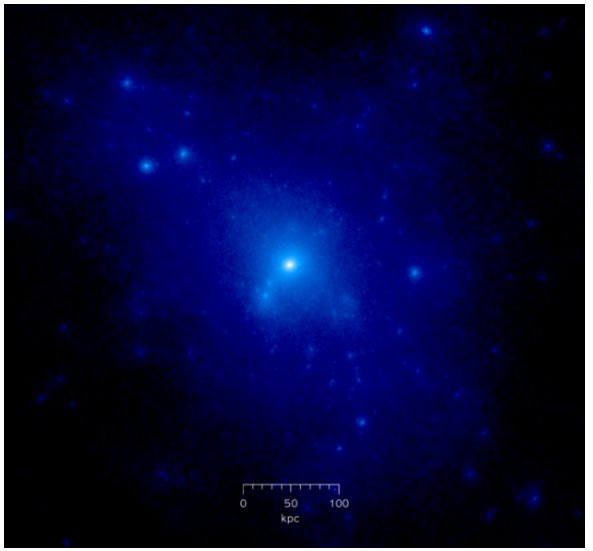






By http://en.wikipedia.org/wiki/User:Cosmo0 - English Wikipedia http://en.wikipedia.org/wiki/Image:Dark_matter_halo.png, Public Domain, https://commons.wikimedia.org/w/index.php?curid=4670264

Visible galaxy extends ~20 kpc at center.

Credit: Begemann, Broeils & Sanders 1991

Back to galaxy clusters:

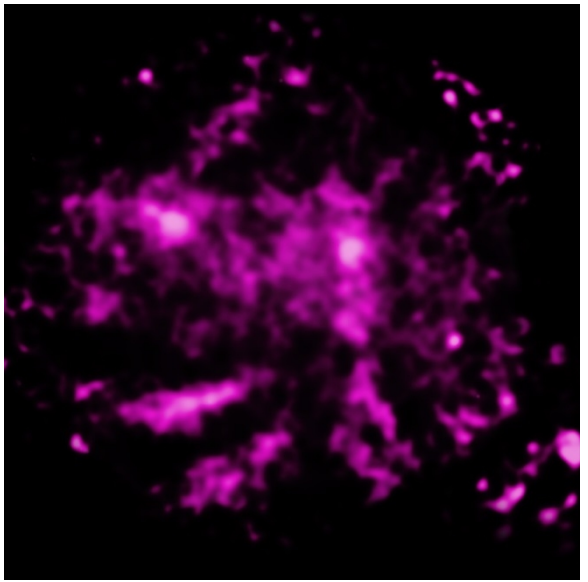
- Motion of galaxies is not the only evidence
- Motion of hot gas galaxy clusters!

Back to galaxy clusters:

- Motion of galaxies is not the only evidence
- Motion of hot gas galaxy clusters! → Moves “too fast”
  Coma cluster:

Optical

X-Ray



Credit: Xray: NASA/CXC/MPE/J. Sanders et al. Optical: SDSS

Bullet Cluster

Bullet Cluster

- Two colliding clusters of galaxies

Credit: X-Ray: NASA/CXC/CfA/M.Markevitch et al.;
Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.
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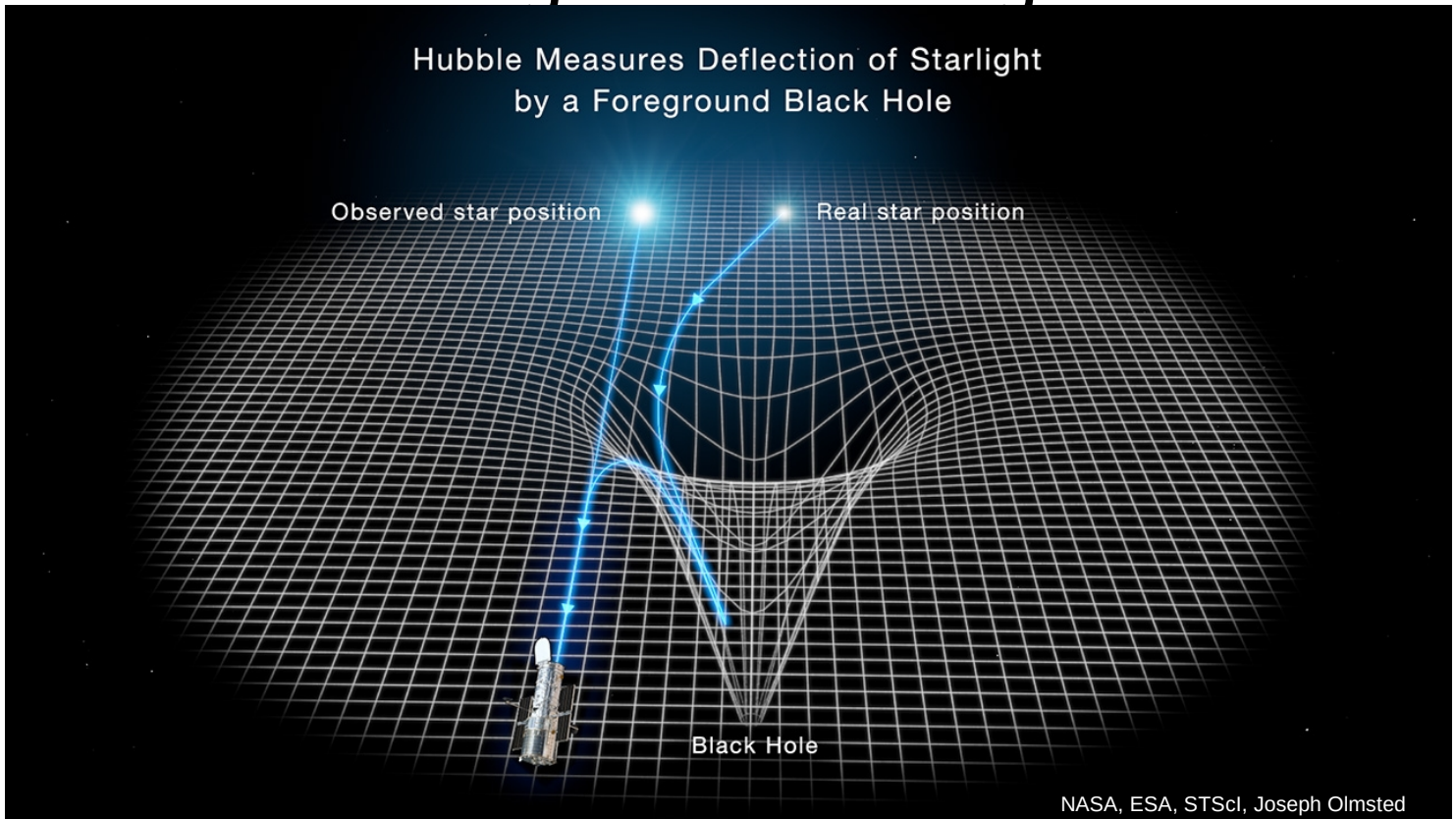
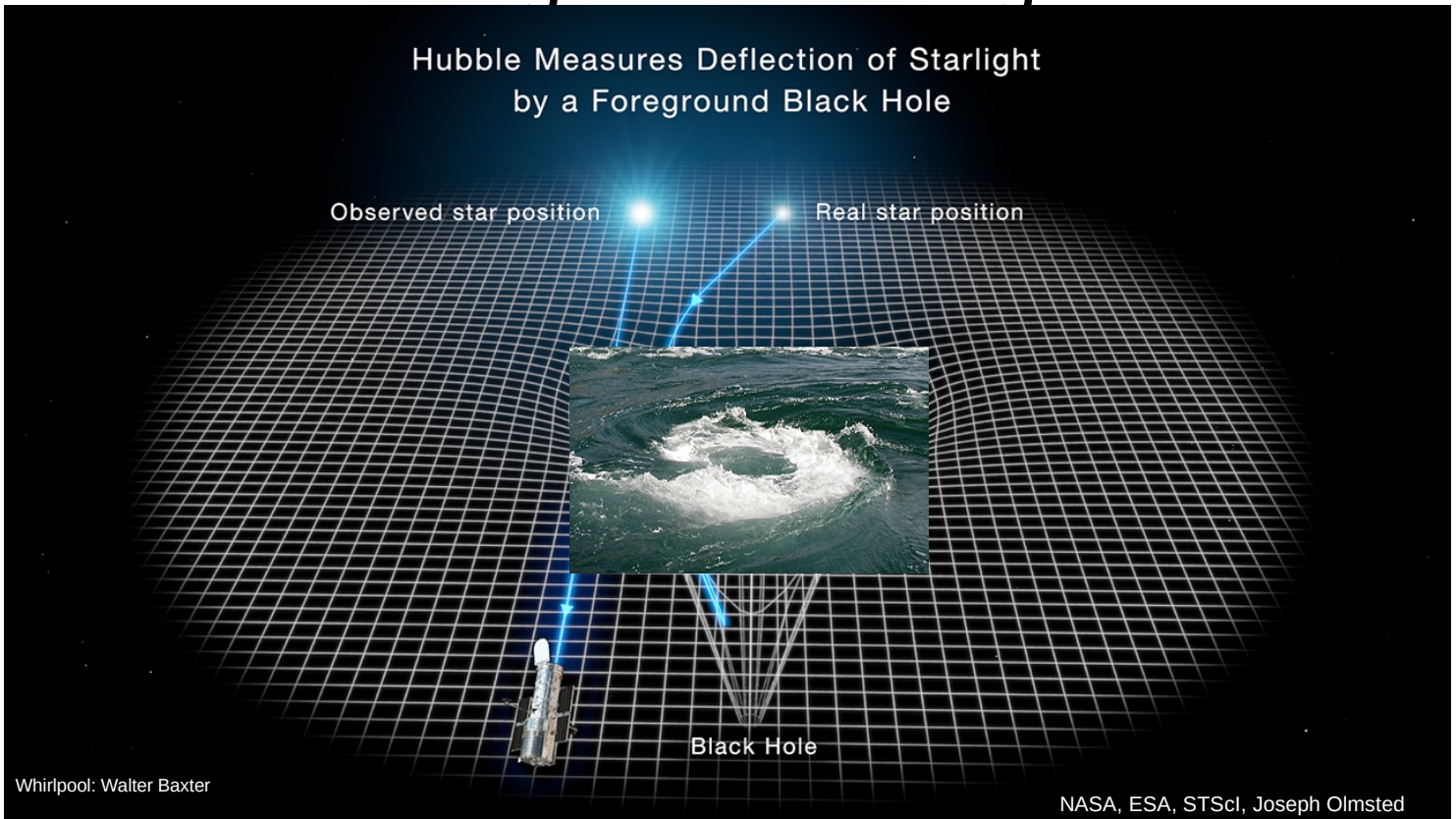


Determine mass distribution with **Gravitational Lensing**

Bullet Cluster

- Two colliding clusters of galaxies



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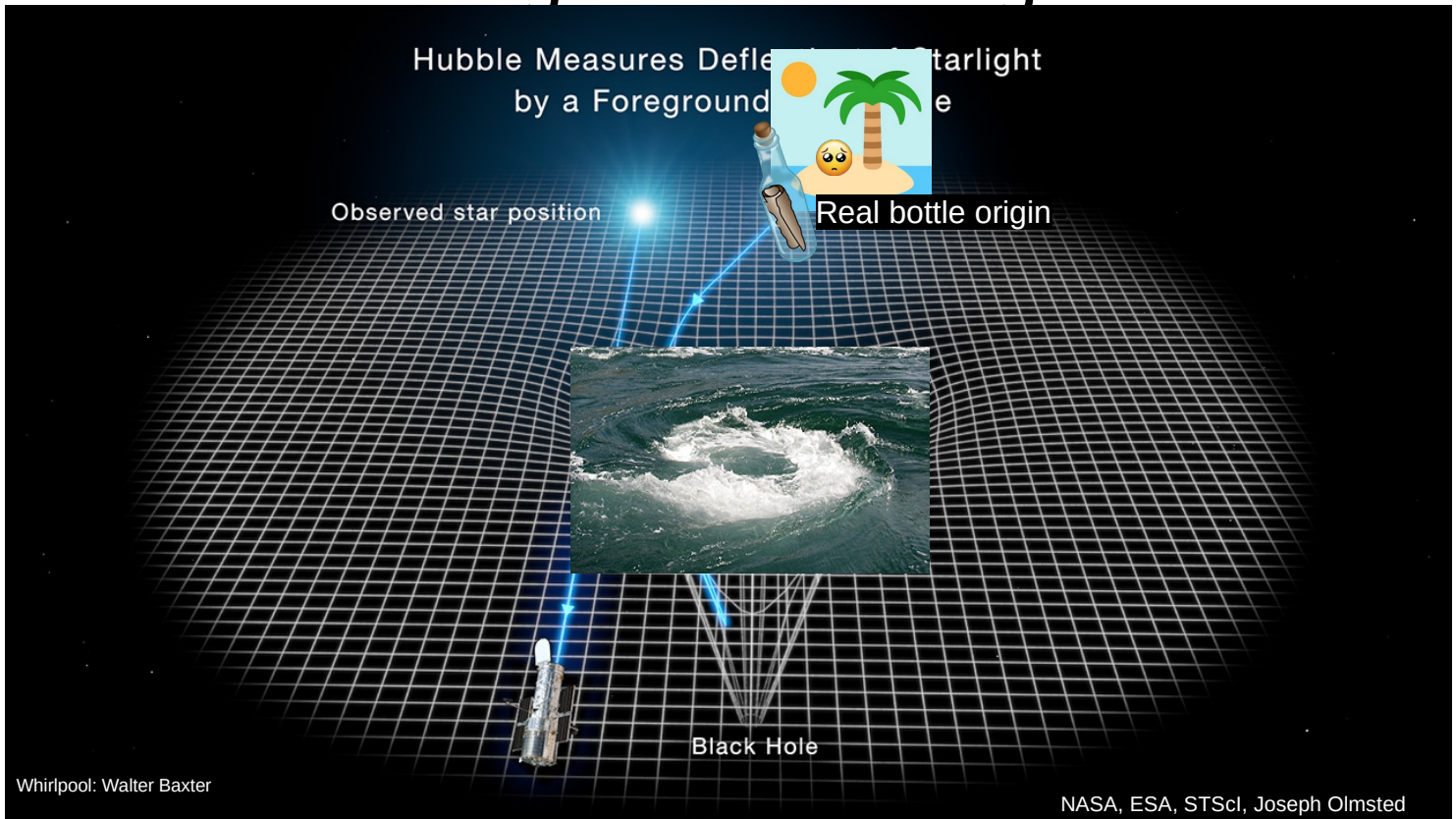

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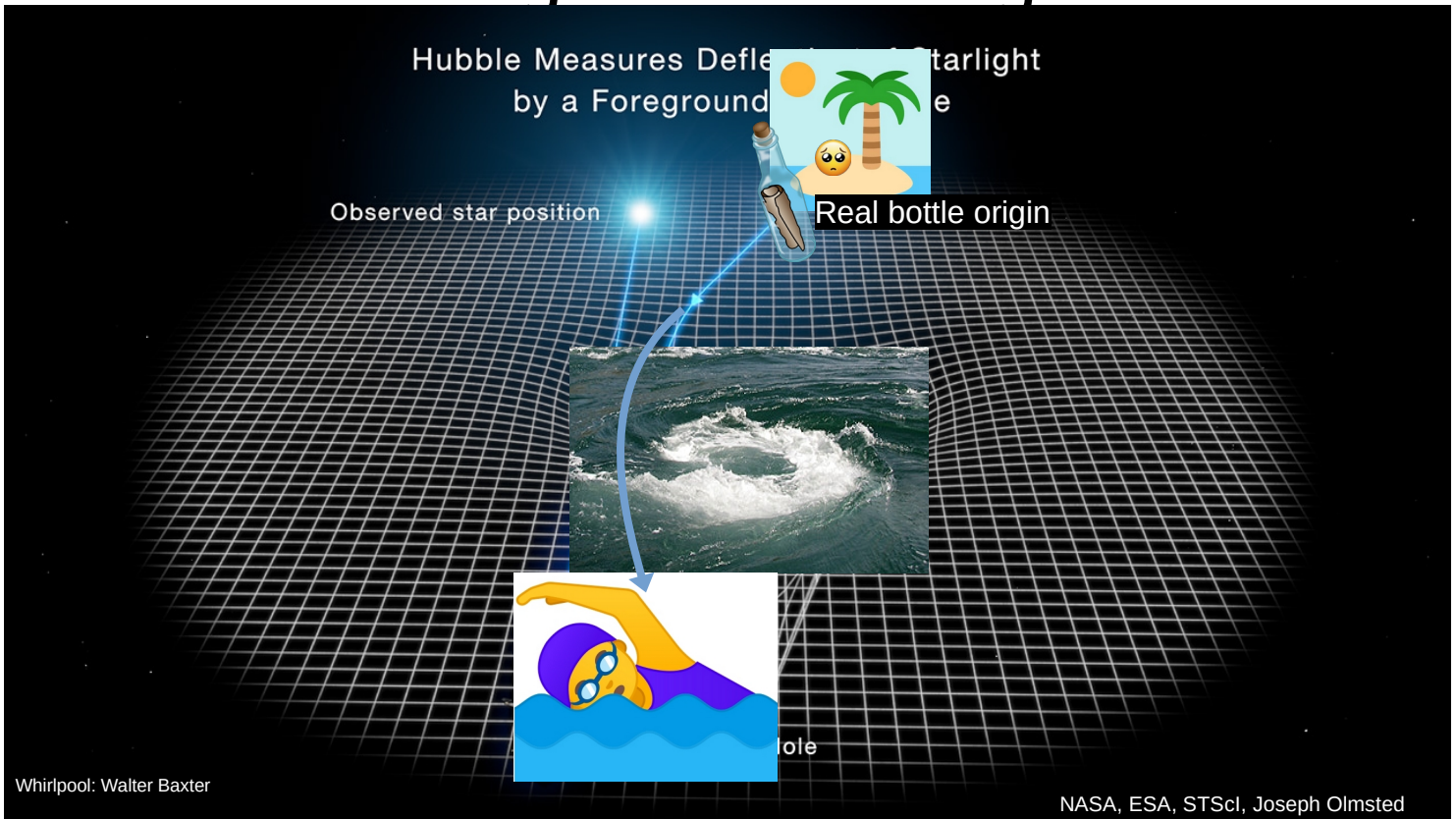

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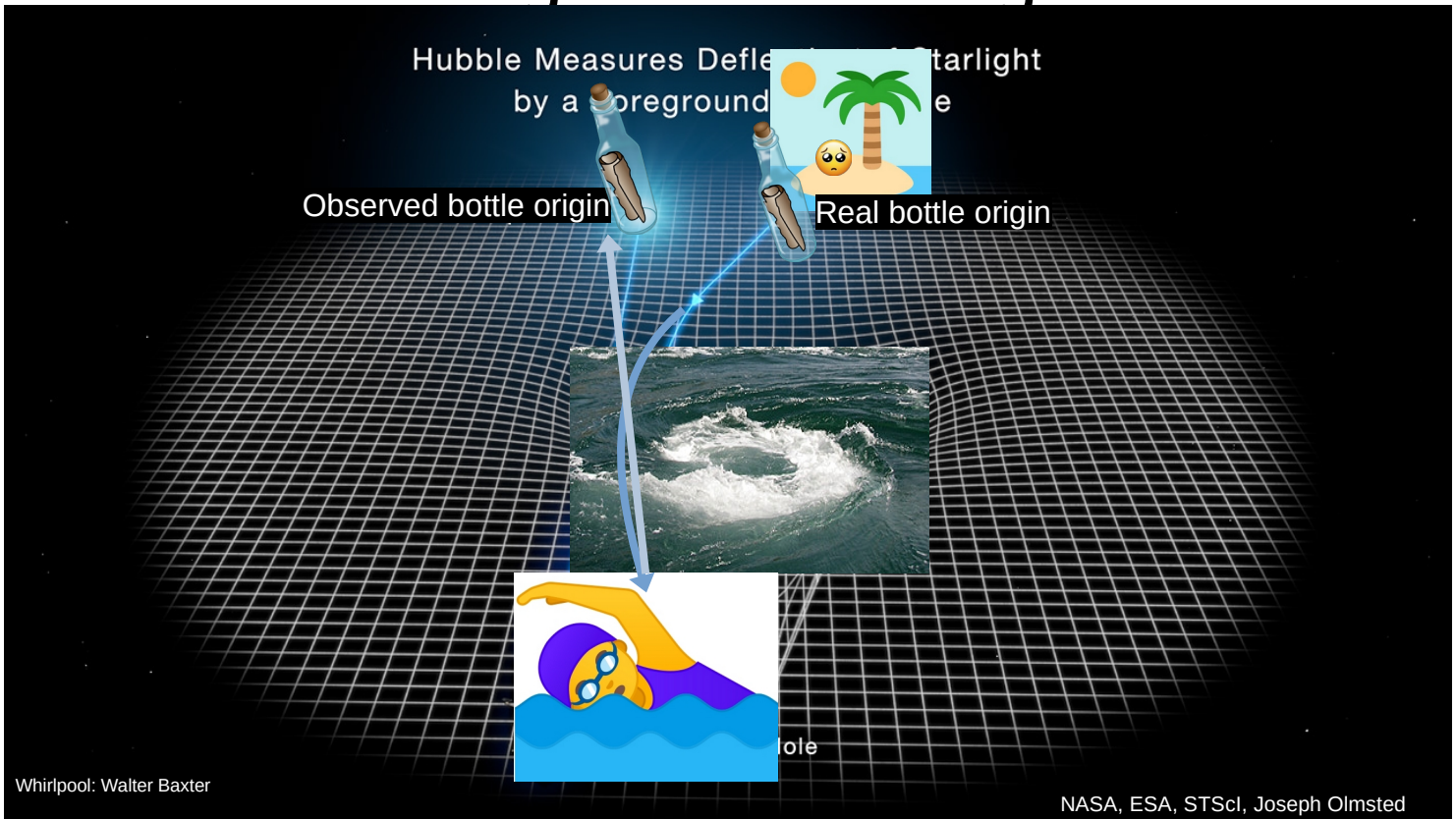

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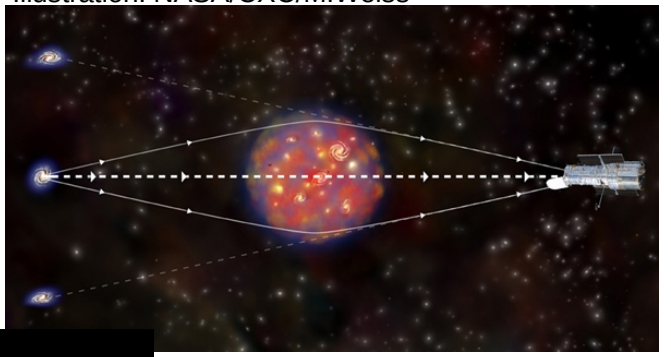
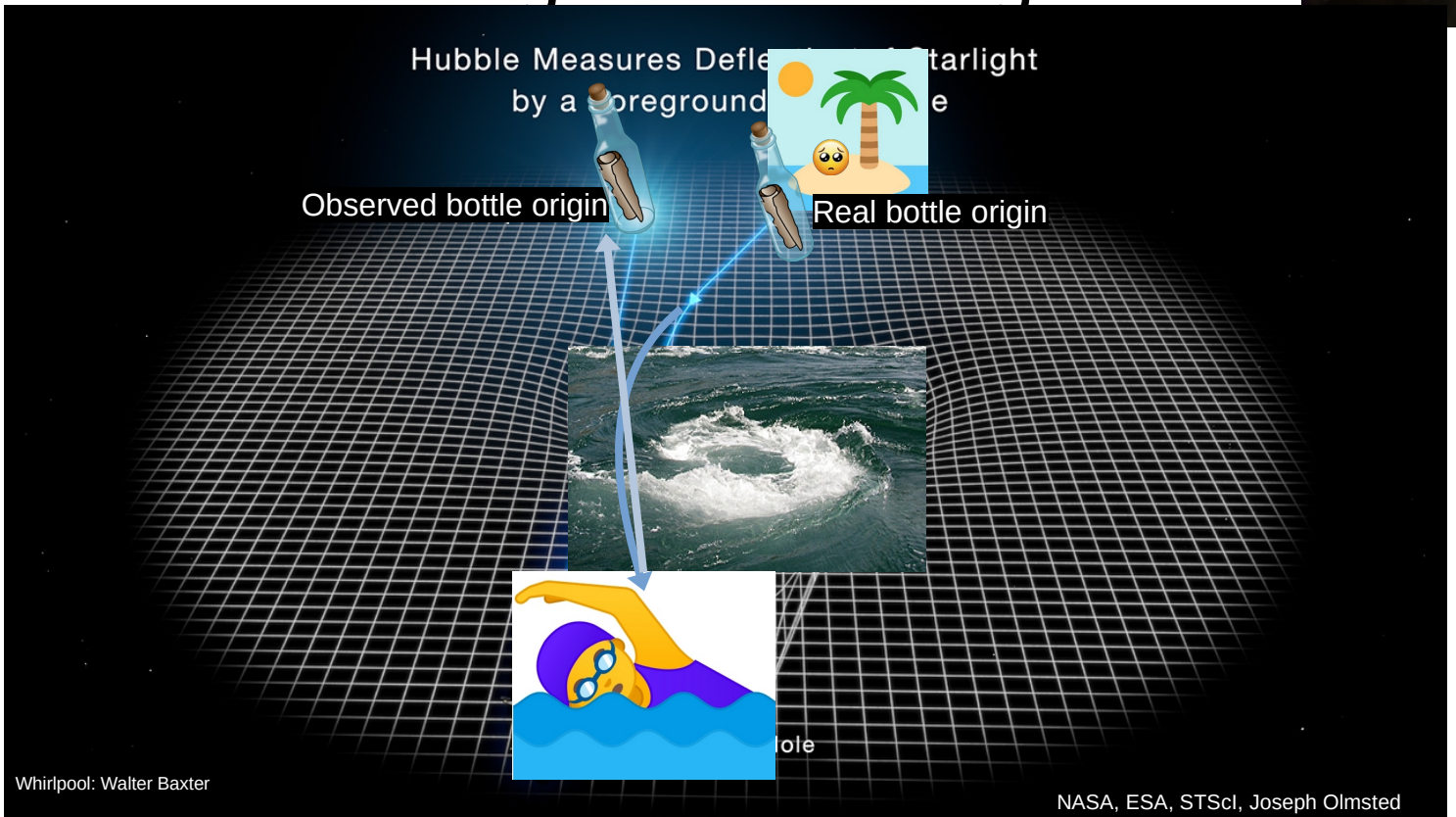
Illustration: NASA/CXC/M.Weiss





Determine mass distribution with **Gravitational Lensing**

Bullet Cluster

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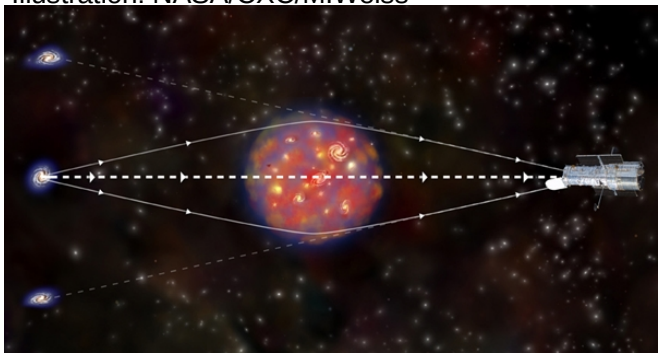
Illustration: NASA/CXC/M.Weiss



Credit: X-Ray: NASA/CXC/CfA/M.Markevitch et al.; Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al. Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Arizona/D.Clowe et al.)

Determine mass distribution with **Gravitational Lensing**

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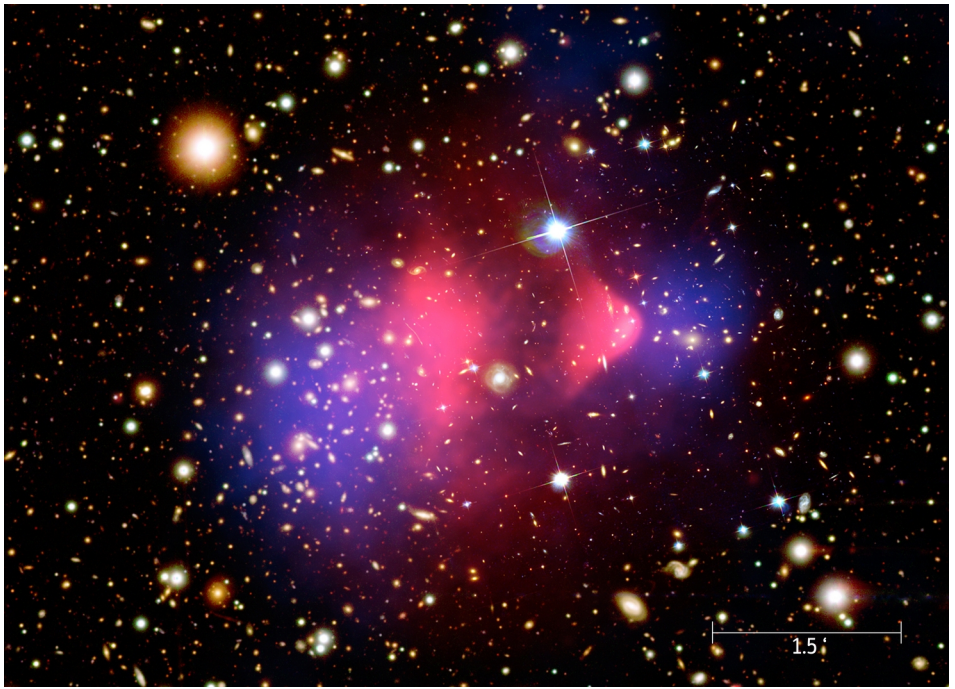

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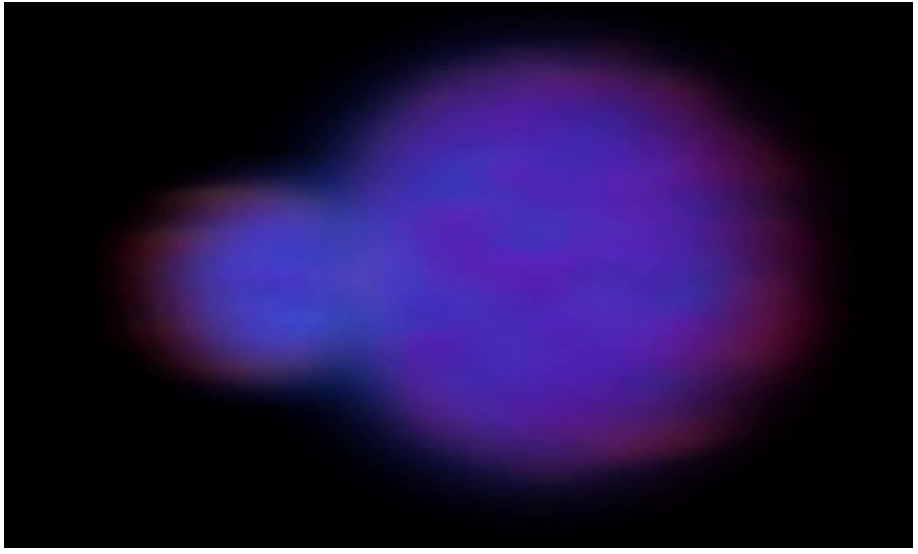
NASA/CXC/M. Weiss - Chandra X-Ray Observatory: 1E 0657-56

Bullet Cluster

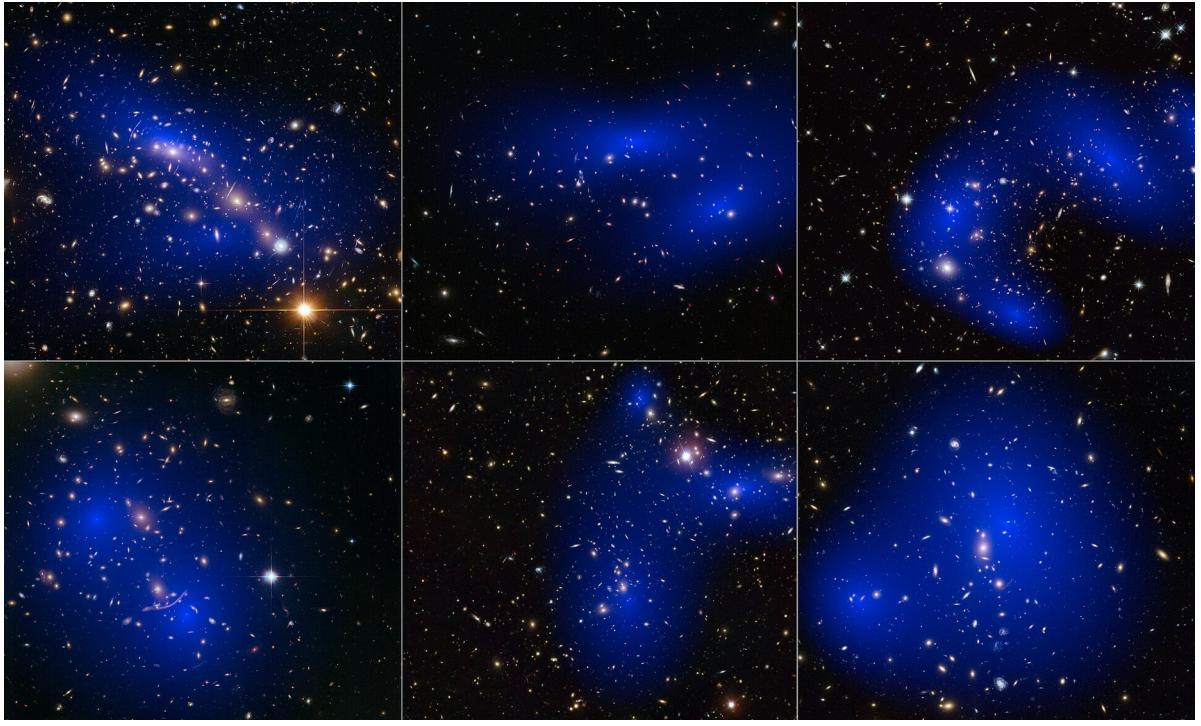
- Dark matter as “collisionless gas”



Credit: NASA/CXC/M. Weiss

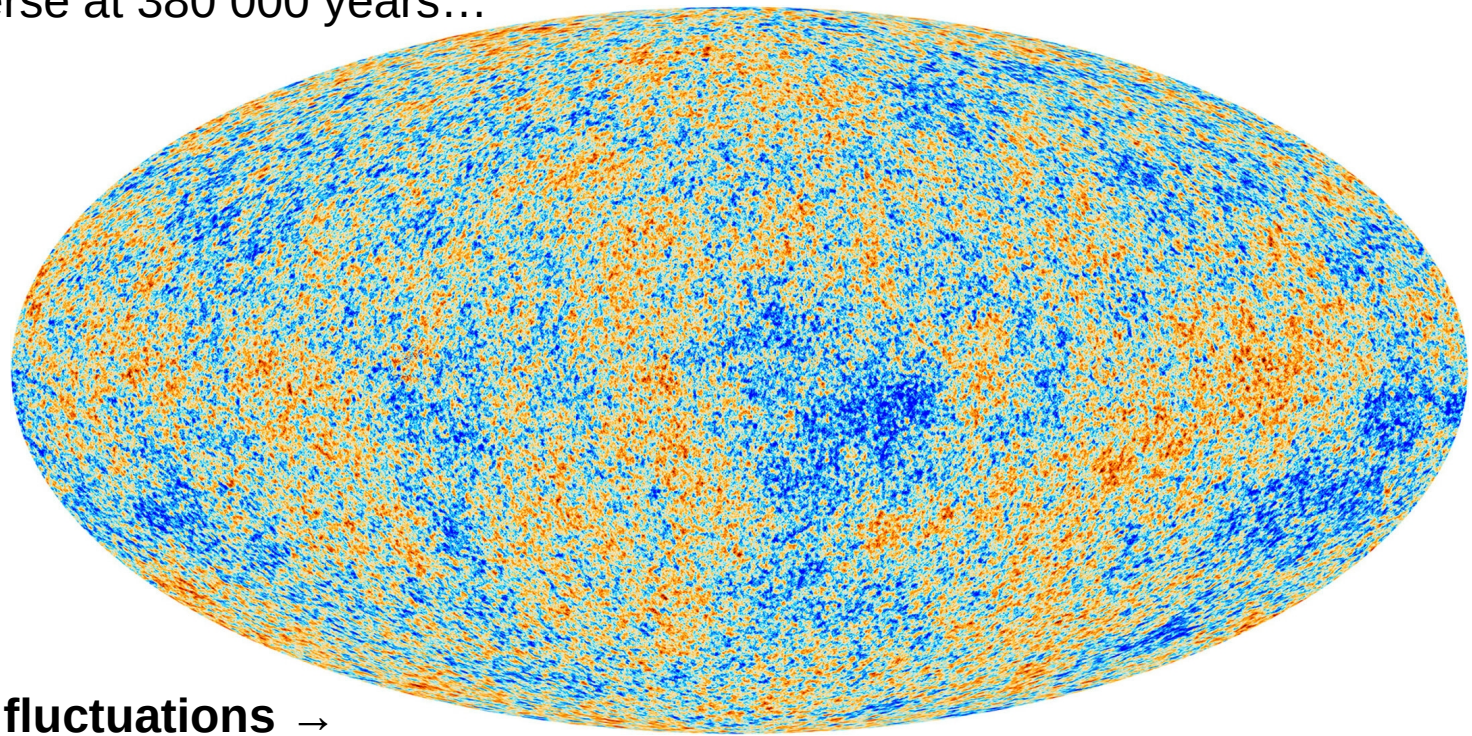
More colliding clusters

- Dark matter as “collisionless gas”



(Large Scale) Structure Formation

Our universe at 380 000 years…



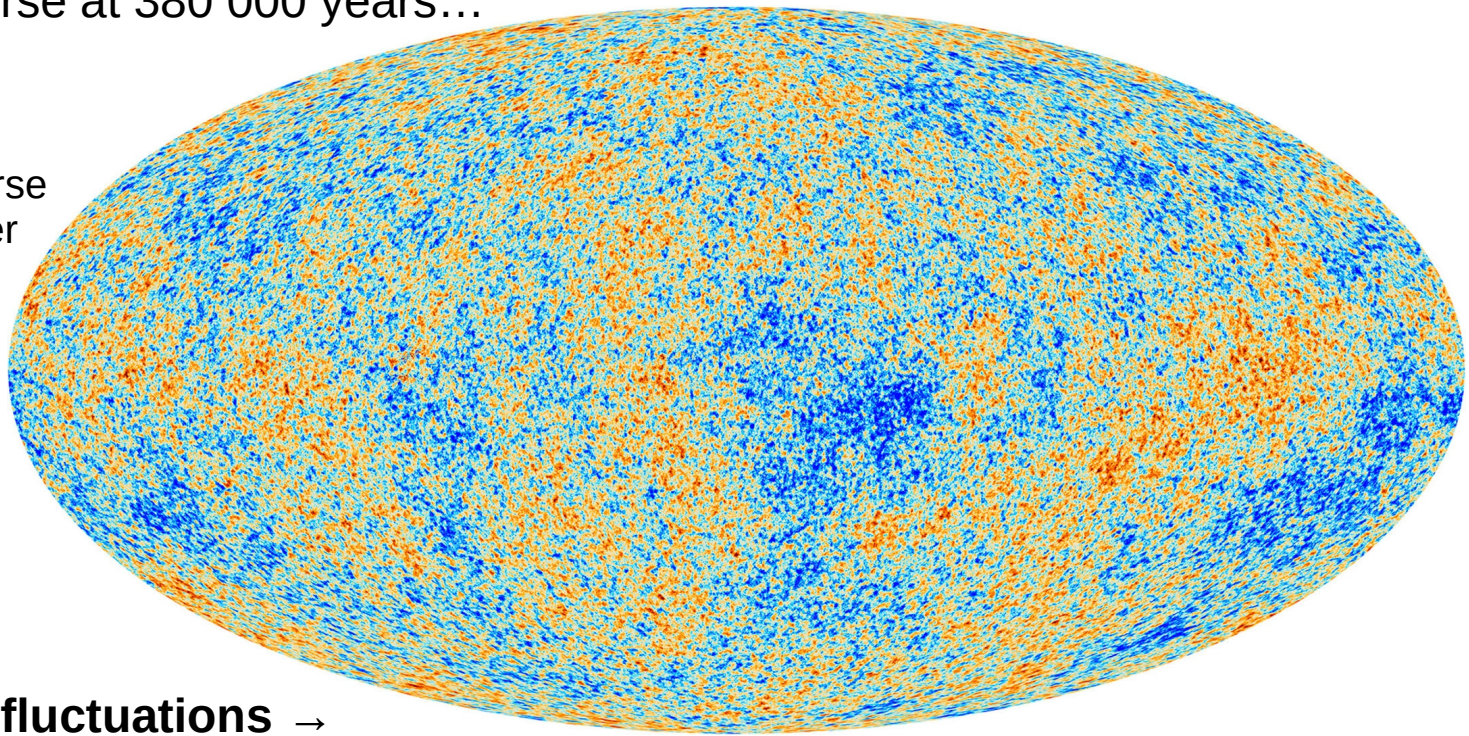
Temperature fluctuations →
slightly different **densities**
seeding future galaxies and stars.

Credit: ESA and the Planck Collaboration

(Large Scale) Structure Formation

Our universe at 380 000 years…

Before: radiation dominated universe → ordinary matter **interacts** with radiation → dark matter does not interact directly



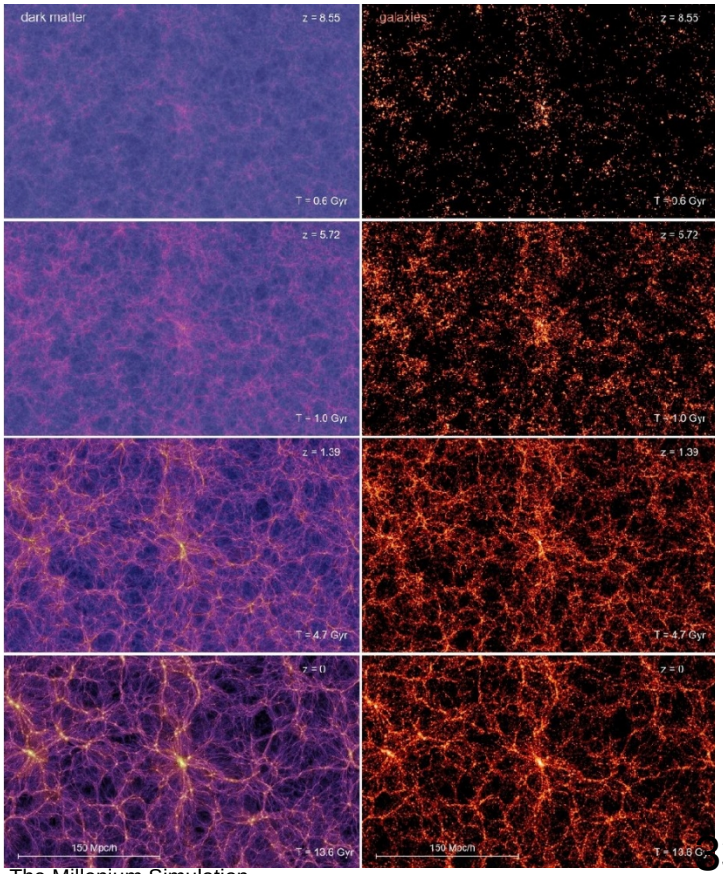
Gravitational potential of dark matter influences density and velocity of ordinary matter, **influencing structures**.

Temperature fluctuations → slightly different **densities** seeding future galaxies and stars.

Credit: ESA and the Planck Collaboration

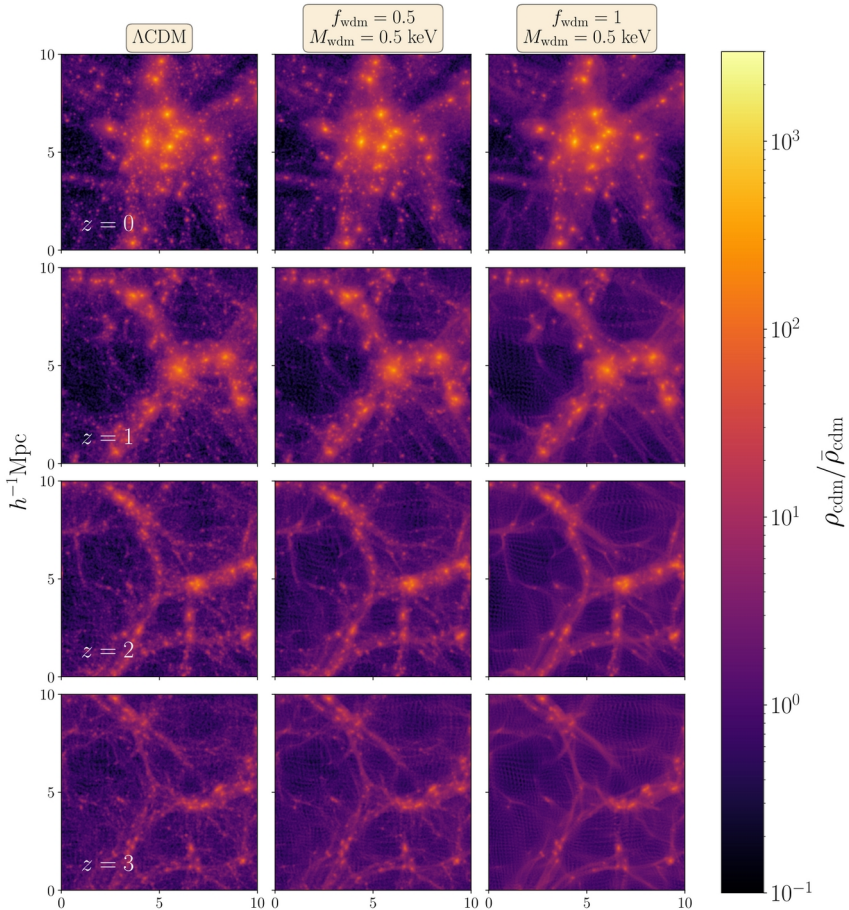
(Large Scale) Structure Formation

Ordinary matter (galaxies) traces dark matter



The Millenium Simulation

(Large Scale) Structure Formation

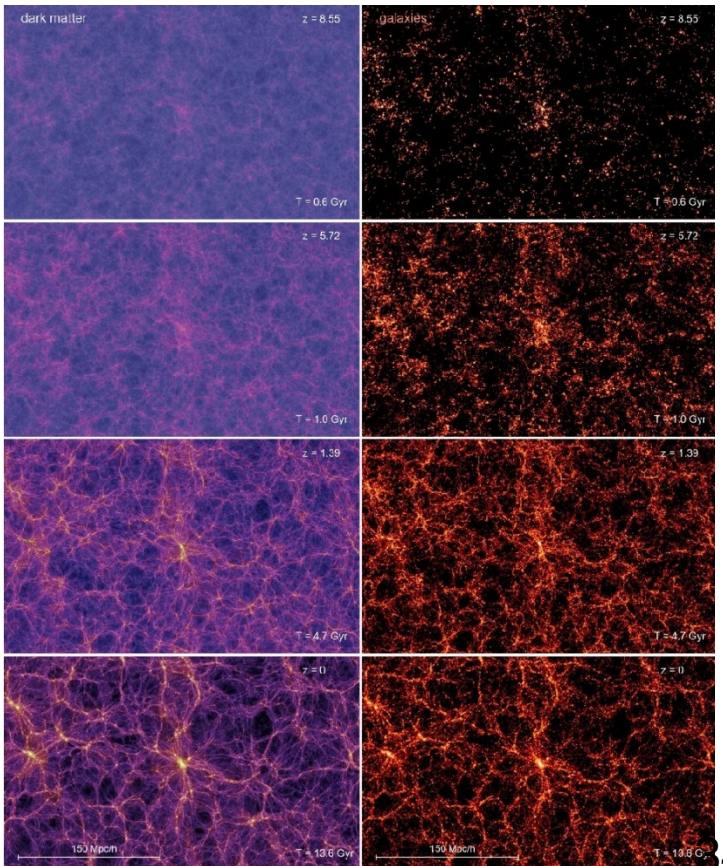


G. Parimbelli et al JCAP12(2021)044

Dark matter **temperature**: **cold** vs. **warm** vs. **hot** dark matter

Washed out structures for hotter (“faster”) dark matter.

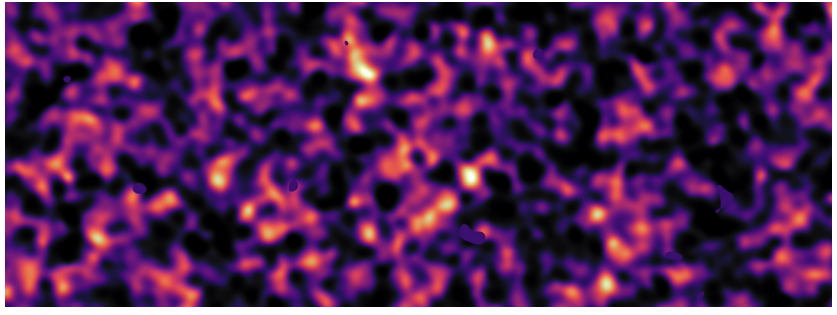
Ordinary matter (galaxies) traces dark matter



The Millenium Simulation

Dark Matter

- Fits many observations
- An easy solution to many discrepancies
- But: not everything matches, e.g. rotation of bars in galaxies, number of dwarf galaxies, ...
- Current research also investigates alternatives, for example modified general relativity



Dark matter map of an area ~450 times the full moon observed with gravitational lensing:
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