

How clumpy is the Dark Matter in the Milky Way?

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Questions for today

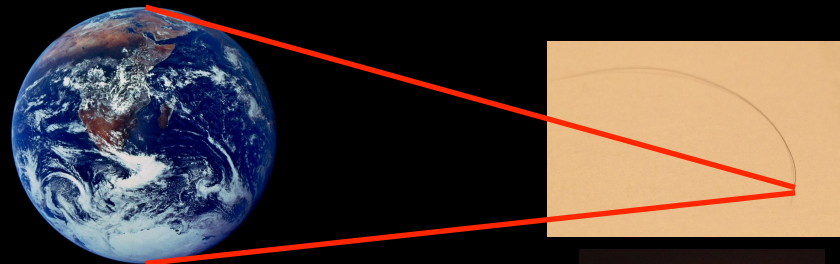
- What is dark matter?
- How do we know dark matter exists?
- How clumpy should the dark matter be?
- How can we tell if dark matter is clumpy?
- How clumpy is dark matter?



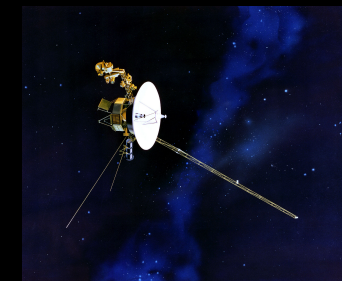


Crash course on distances

- If we made the Earth as wide as a human hair...



- The Sun would be 40 centimeters away
- Voyager 1 would be 27 meters away
- 1 light year would be 12.6 kilometres away
- 1 parsec would be 41 kilometers away
- The nearest star would be 55 kilometers away, in London
- The center of the Milky Way would be at the moon



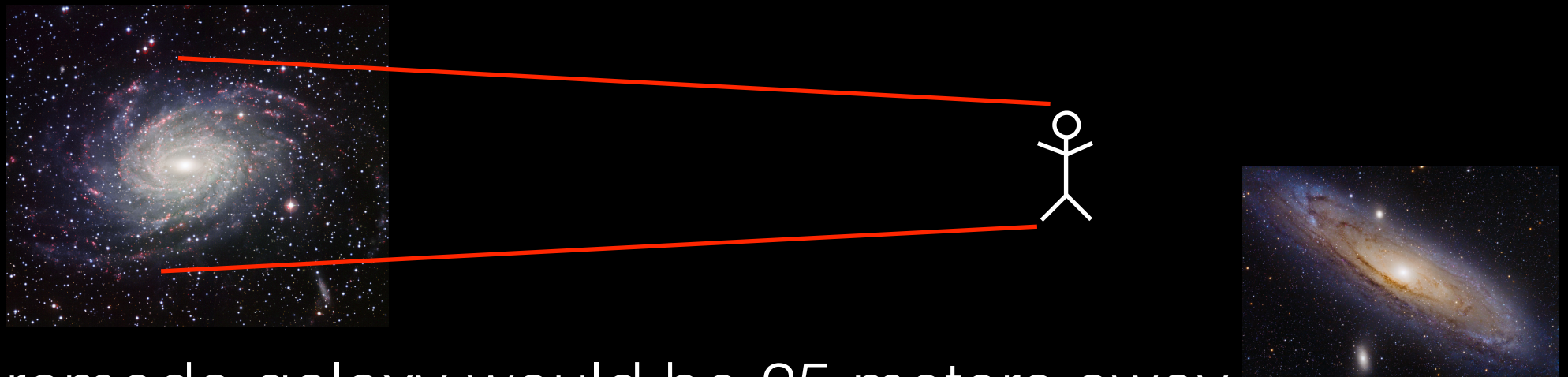
NASA/JPL



So the Milky Way is pretty big compared to Earth

Crash course on distances

- If we made the Milky Way as big as you...



- The Andromeda galaxy would be 25 meters away
- The size of the observable universe would go out to Edinburgh, 480 kilometers away
- I will give all distances in terms of the disk of the Milky Way



The universe is not that big compared to the Milky Way

What is dark matter?

- No one knows yet
- It has mass and interacts with gravity
- It doesn't interact with light
- It doesn't interact much with itself

?

How do we know dark matter exists?

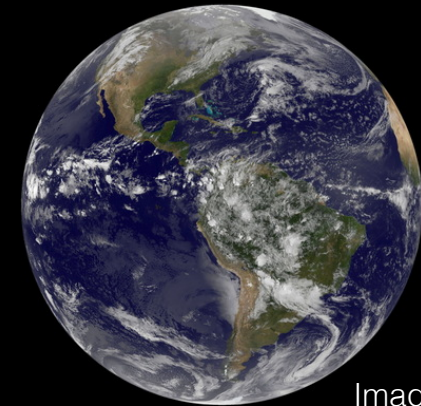
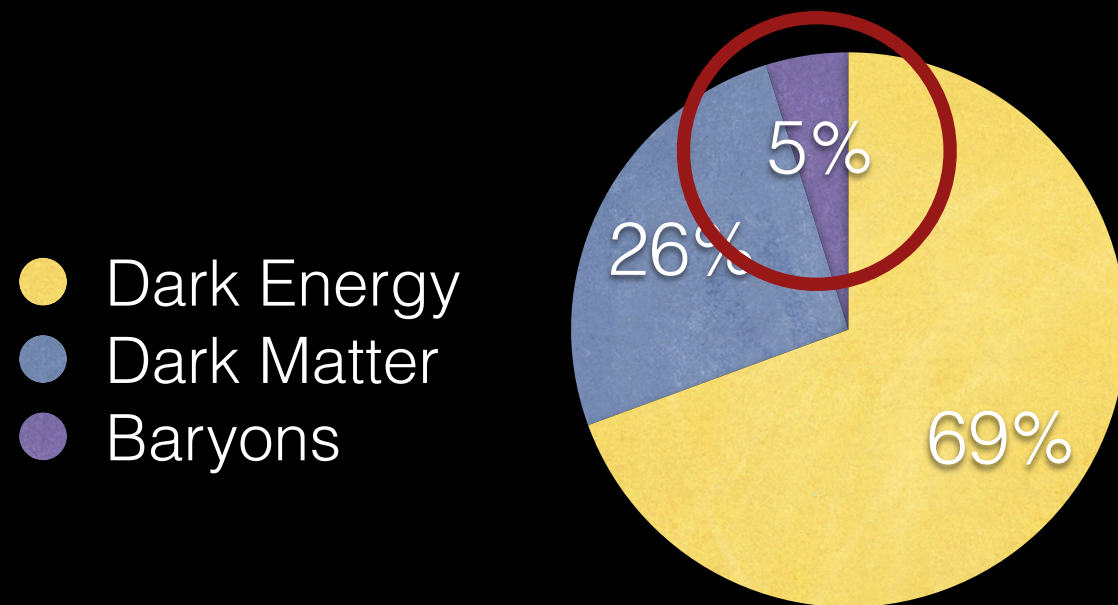
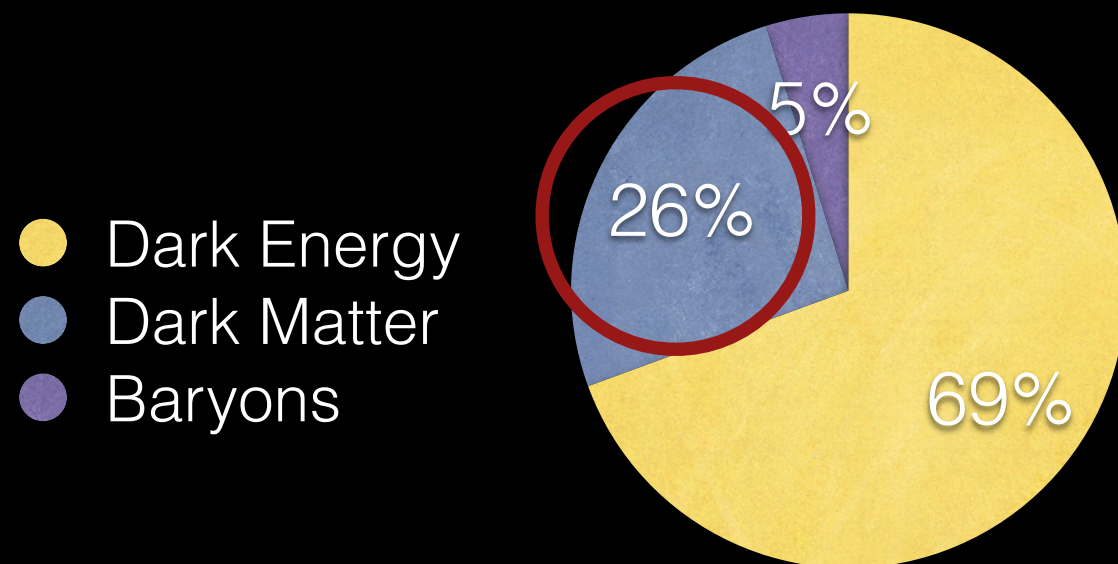


Image credit: NASA



The matter you know and love

How do we know dark matter exists?



Just like regular matter but
doesn't interact with light
(it's invisible!)

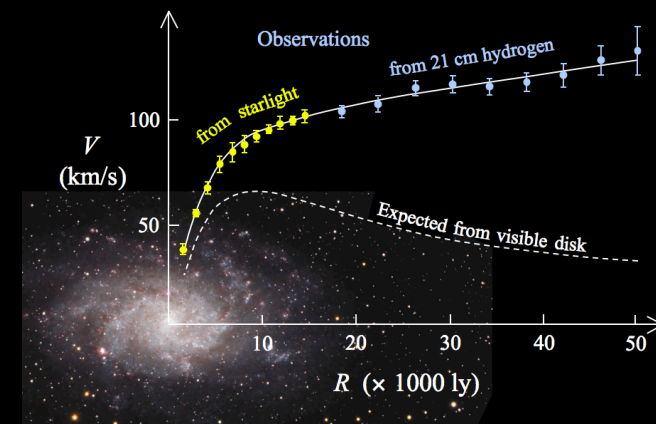


Image credit: Stefania Deluca



Image credit: NASA

How do we know dark matter exists?

Galaxies rotate faster than expected

M33 rotation curve

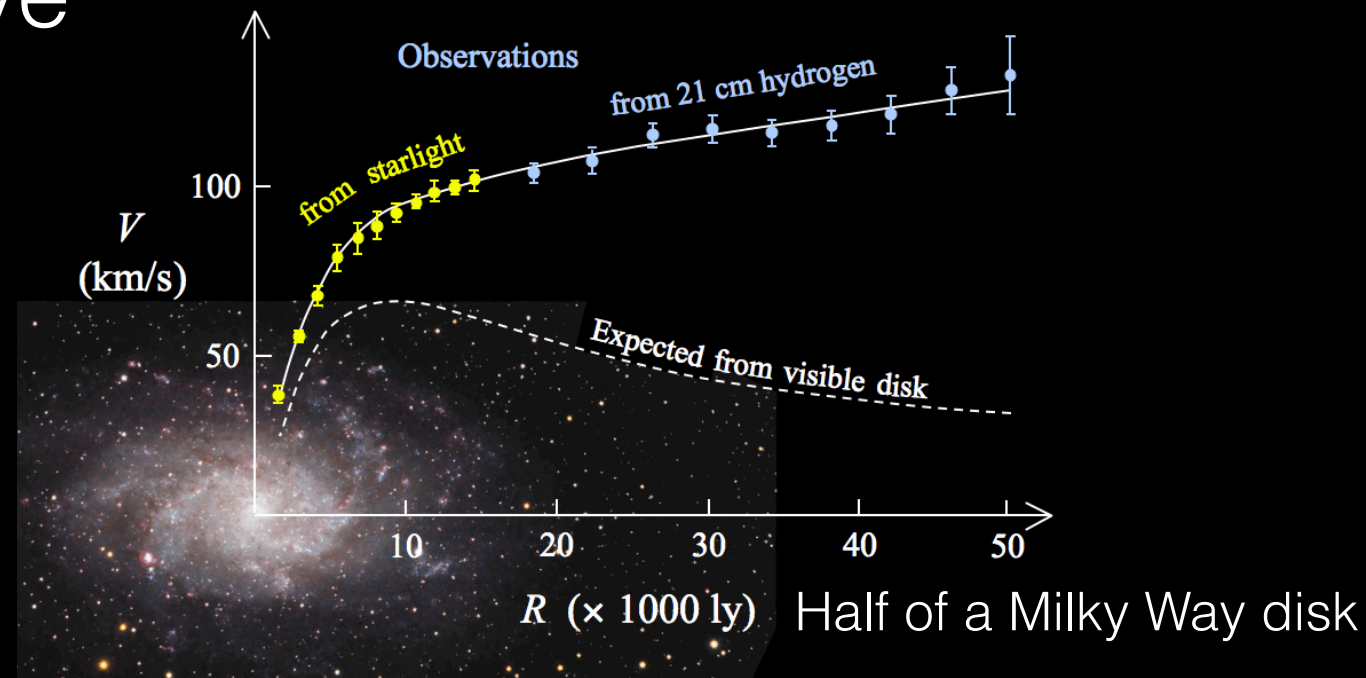


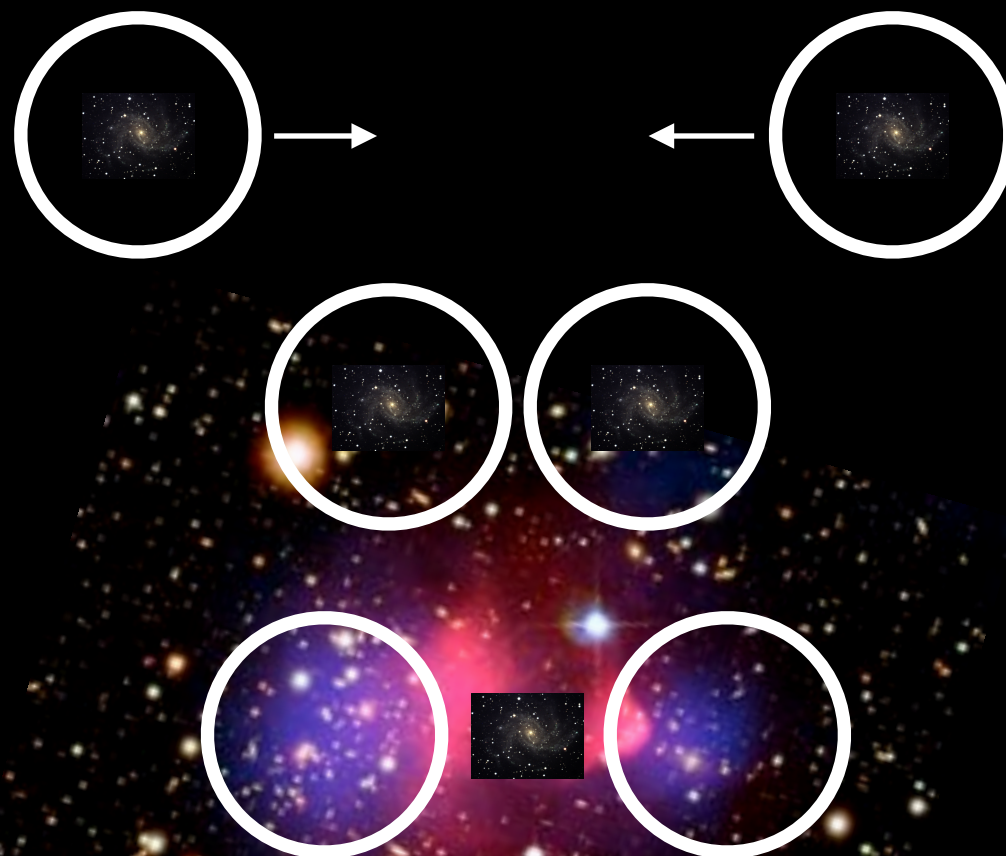
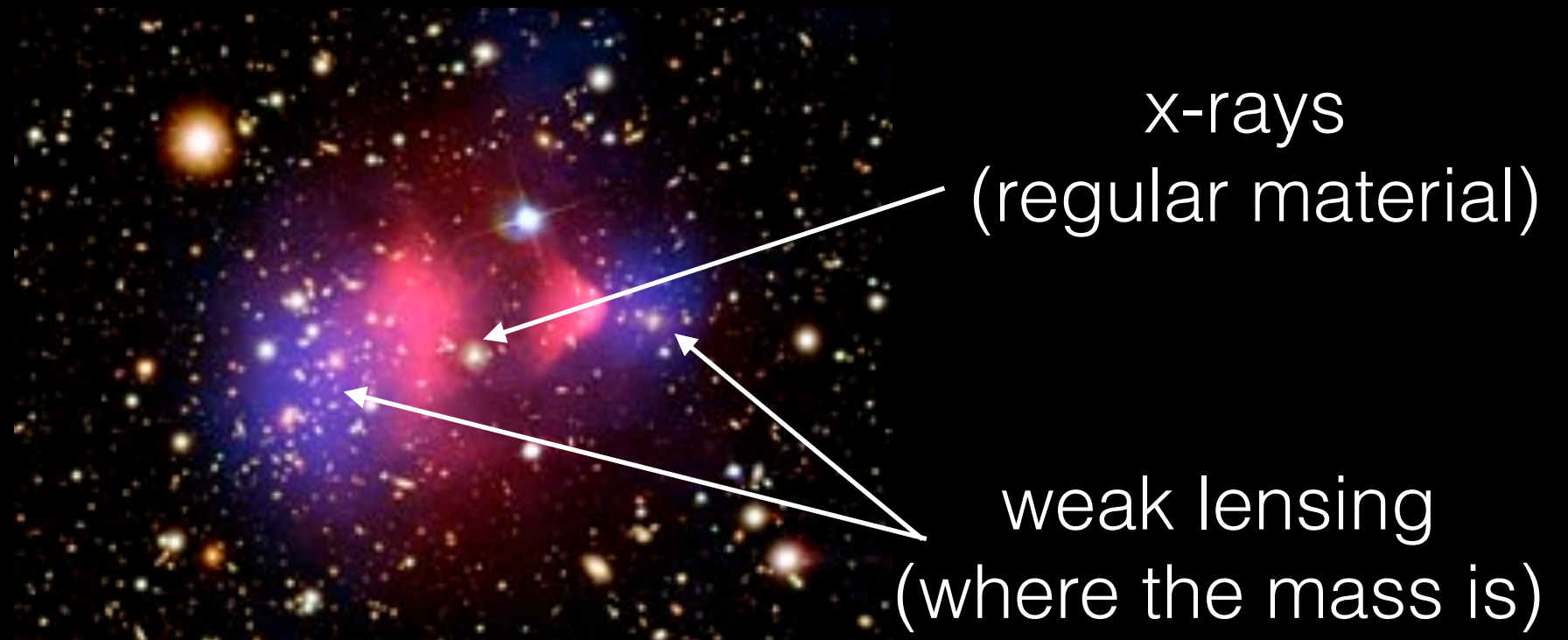
Image credit: Stefania Deluca

Centripetal acceleration = Gravitational acceleration

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

How do we know dark matter exists?

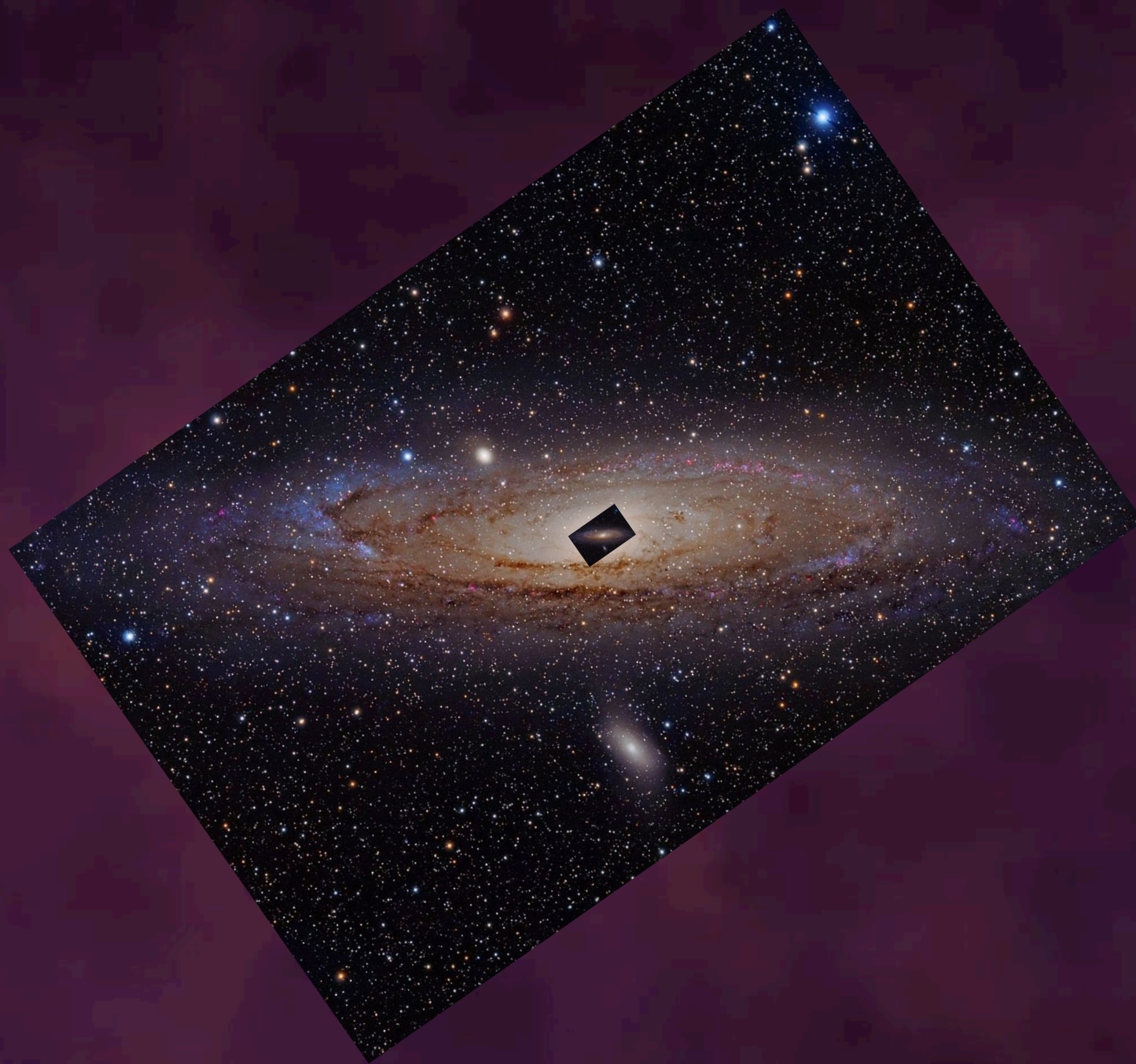
Bullet cluster



How clumpy should the dark matter
be?

$z = 48.4$

$T = 0.05 \text{ Gyr}$

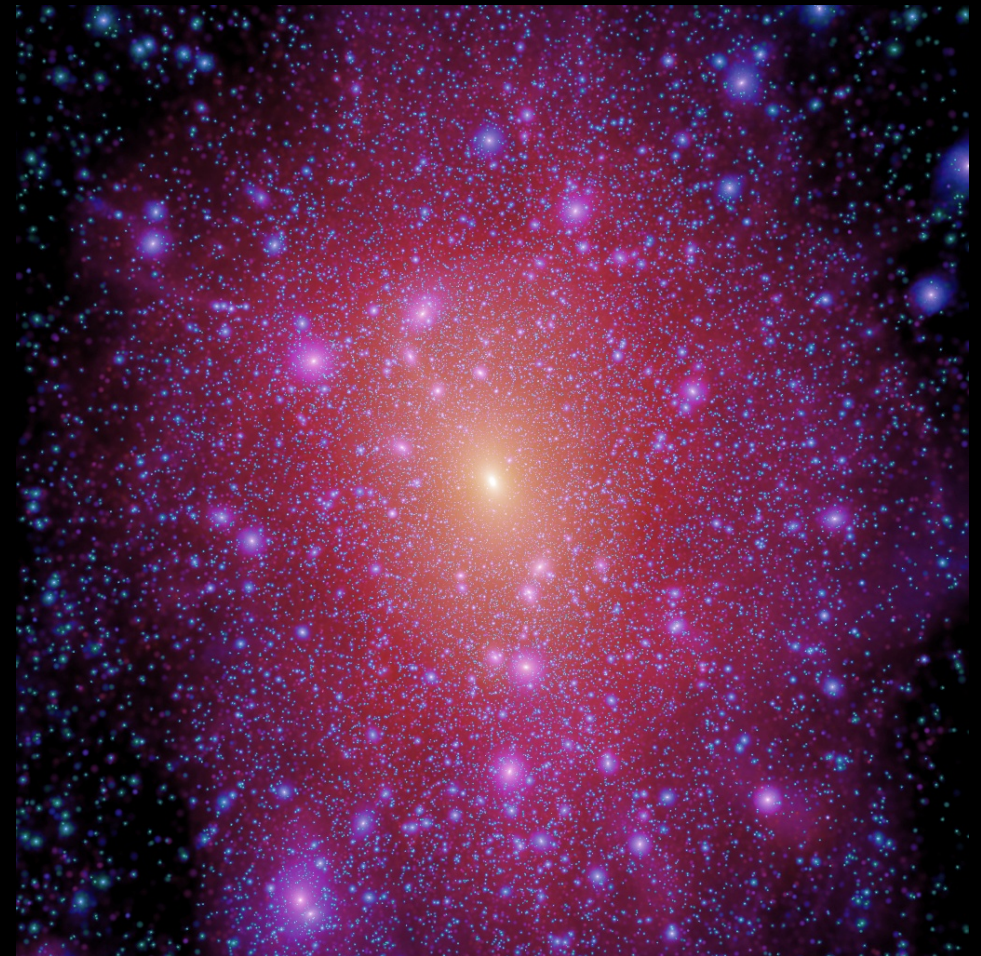


17 Milky Way disks

500 kpc

How clumpy should the dark matter be?

- Small clumps collapse first then merge first to form larger clumps
- Each clump weighs more than 100000 Suns
- Add up the mass of all the clumps
- Compare to the smooth dark matter halo
- ~10% of dark matter is in clumps!



400 kpc
13 Milky Way disks

How can we tell if dark matter is clumpy?

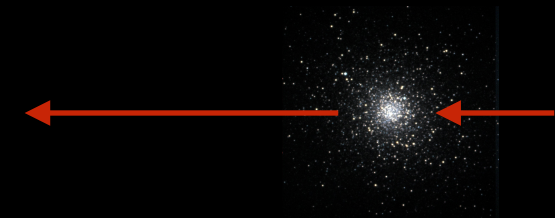
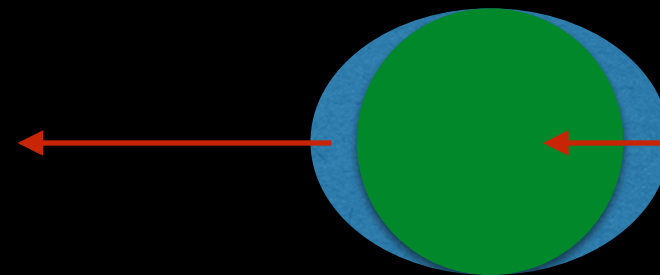
- We can't see dark matter
- The clumps are massive, more than 100000 Suns
- We need dark matter to pull on something we can see

How can we tell if dark matter is clumpy? Tidal Streams!

Moon



Earth

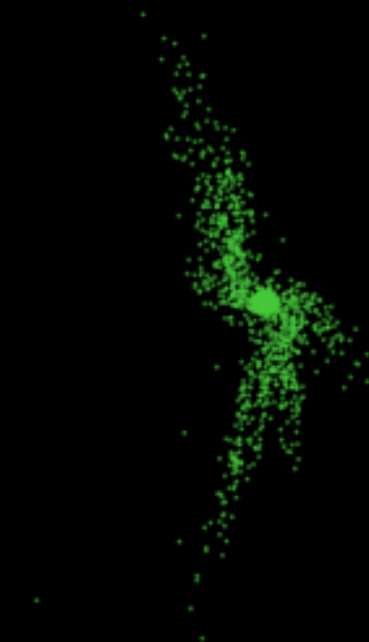
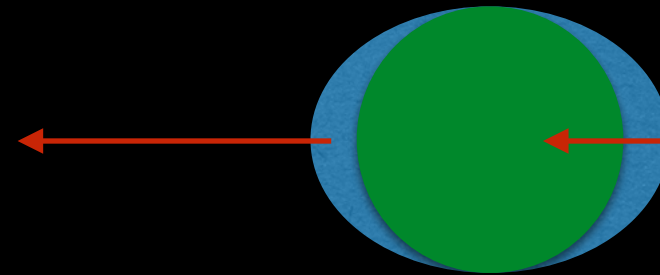


How can we tell if dark matter is clumpy? Tidal Streams!

Moon



Earth



How can we tell if dark matter is clumpy? Tidal Streams!



How can we tell if dark matter is clumpy? Tidal Streams!

Tidal streams from globular clusters

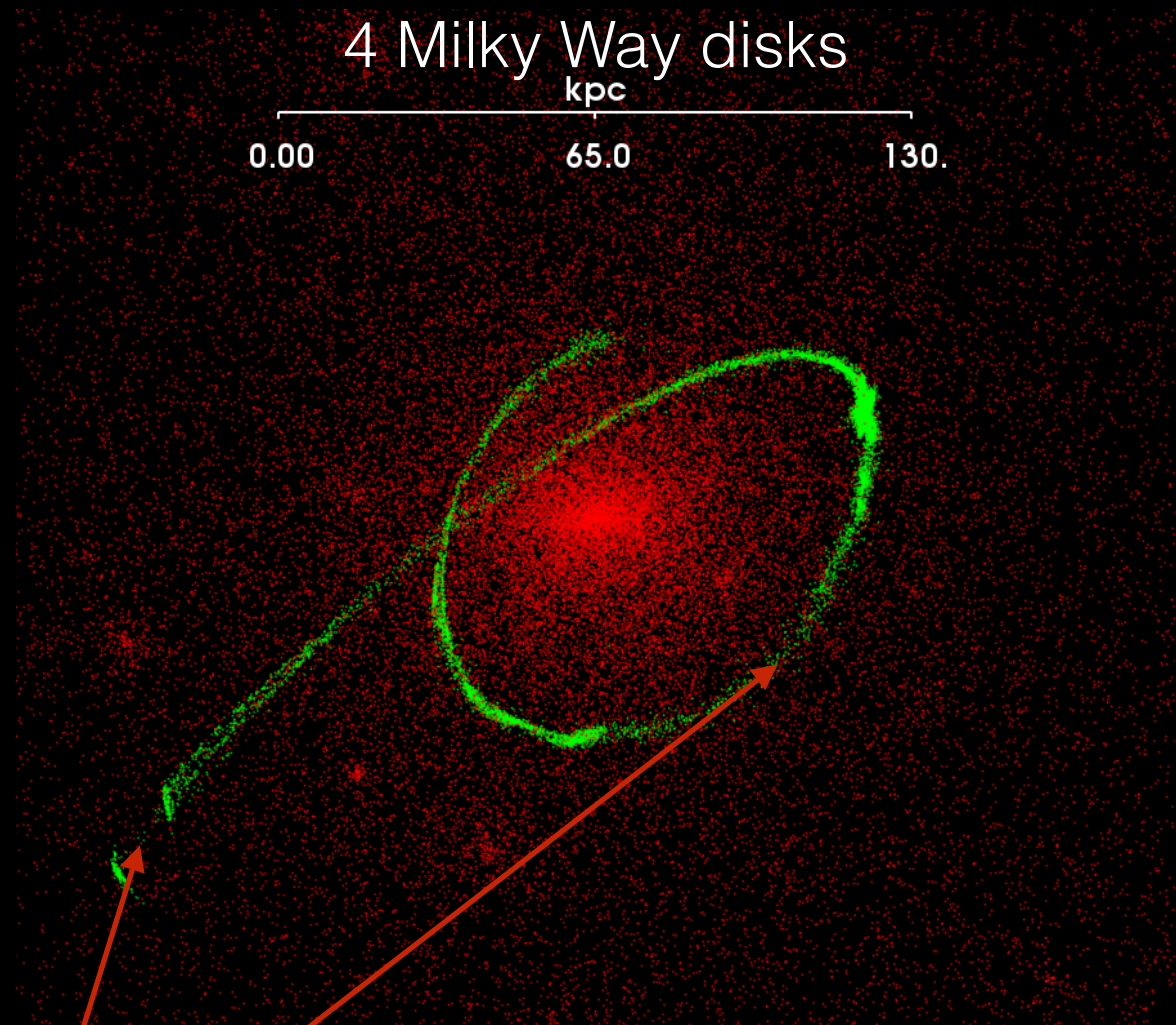
4 Milky Way disks



Smooth Dark Matter

4 Milky Way disks

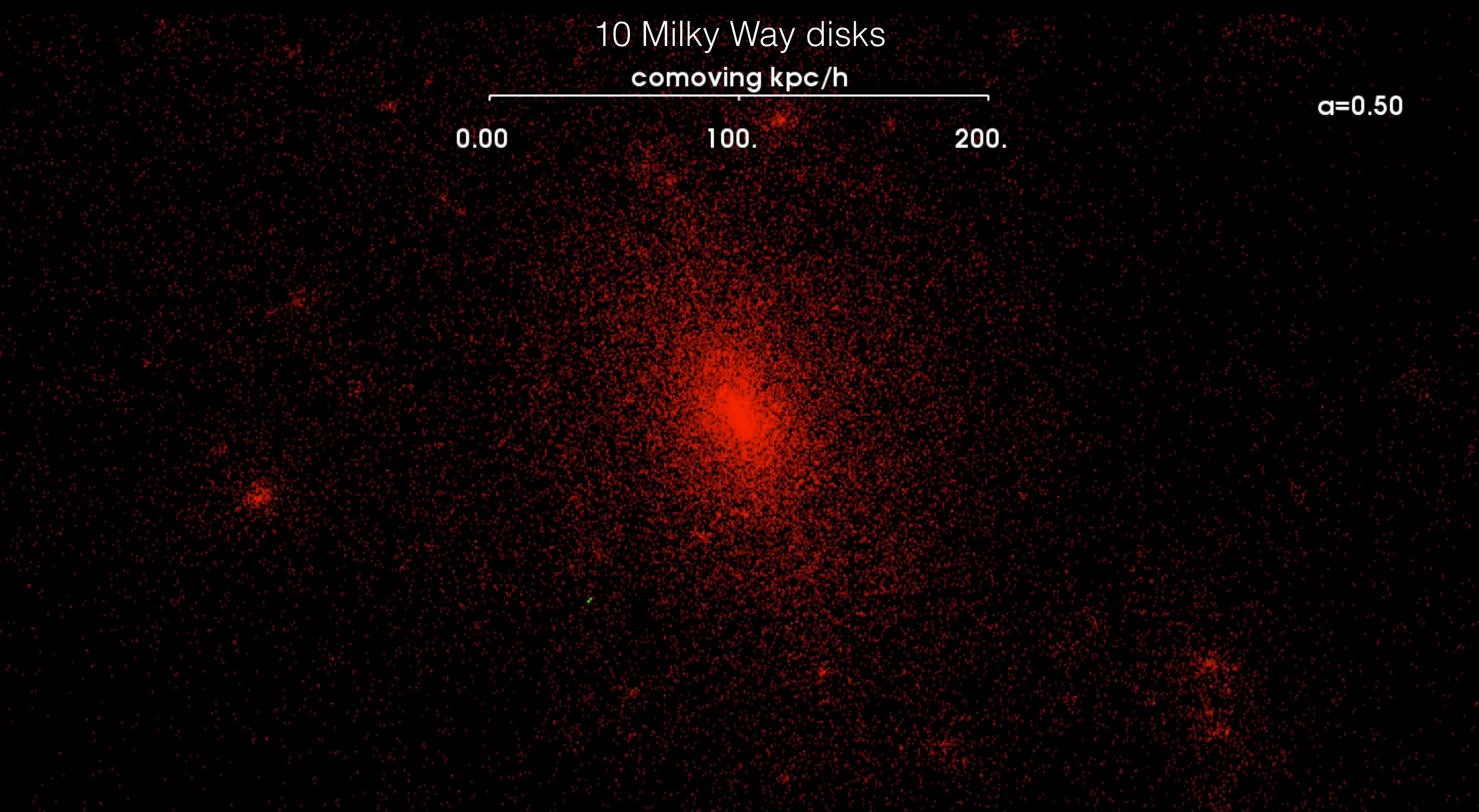
kpc
0.00 65.0 130.



Lumpy Dark Matter

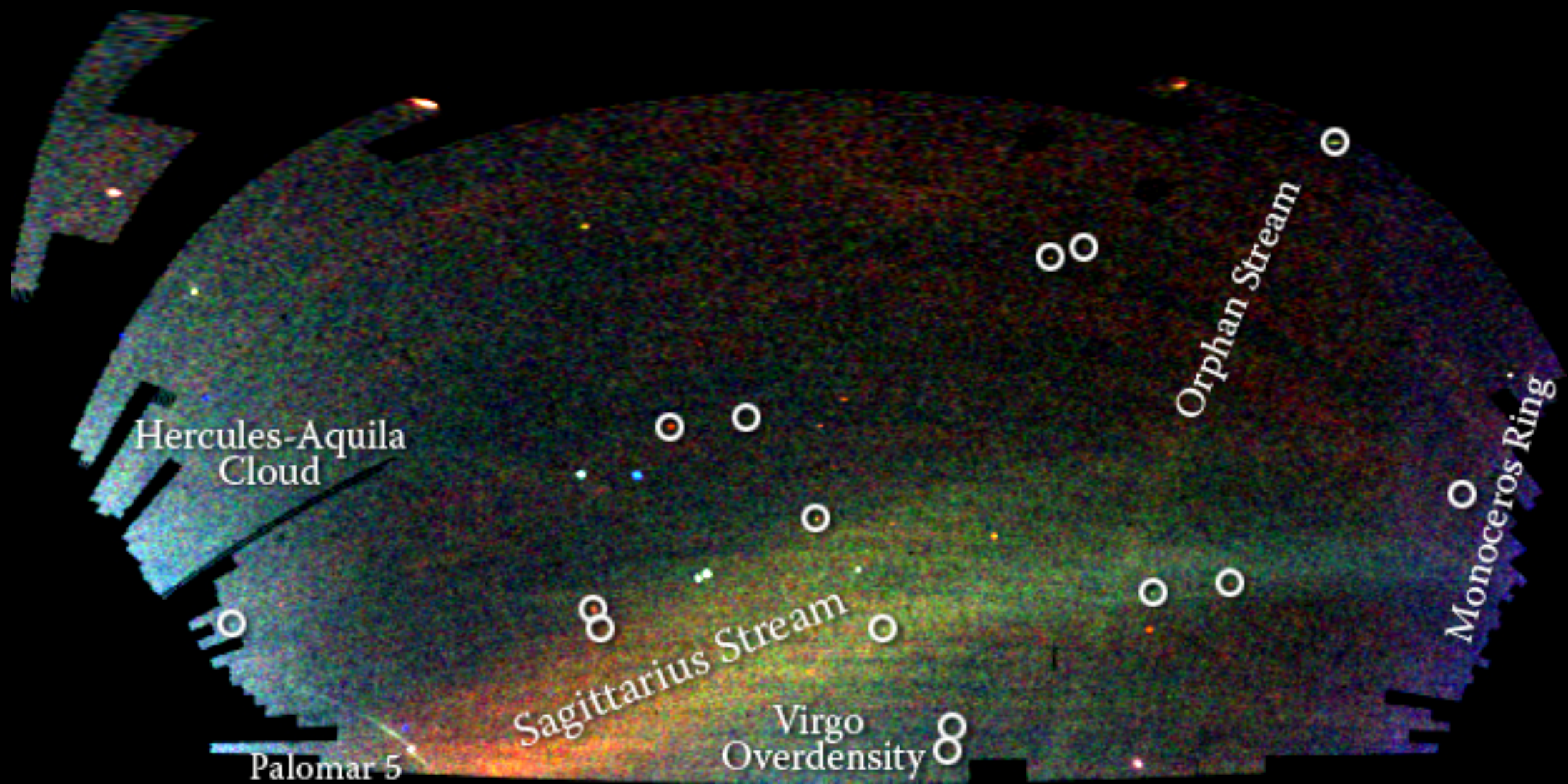
Interaction with dark matter clump

Simulation of a Tidal Stream in the Milky Way



Wiggles in tidal stream tell us about invisible dark matter!

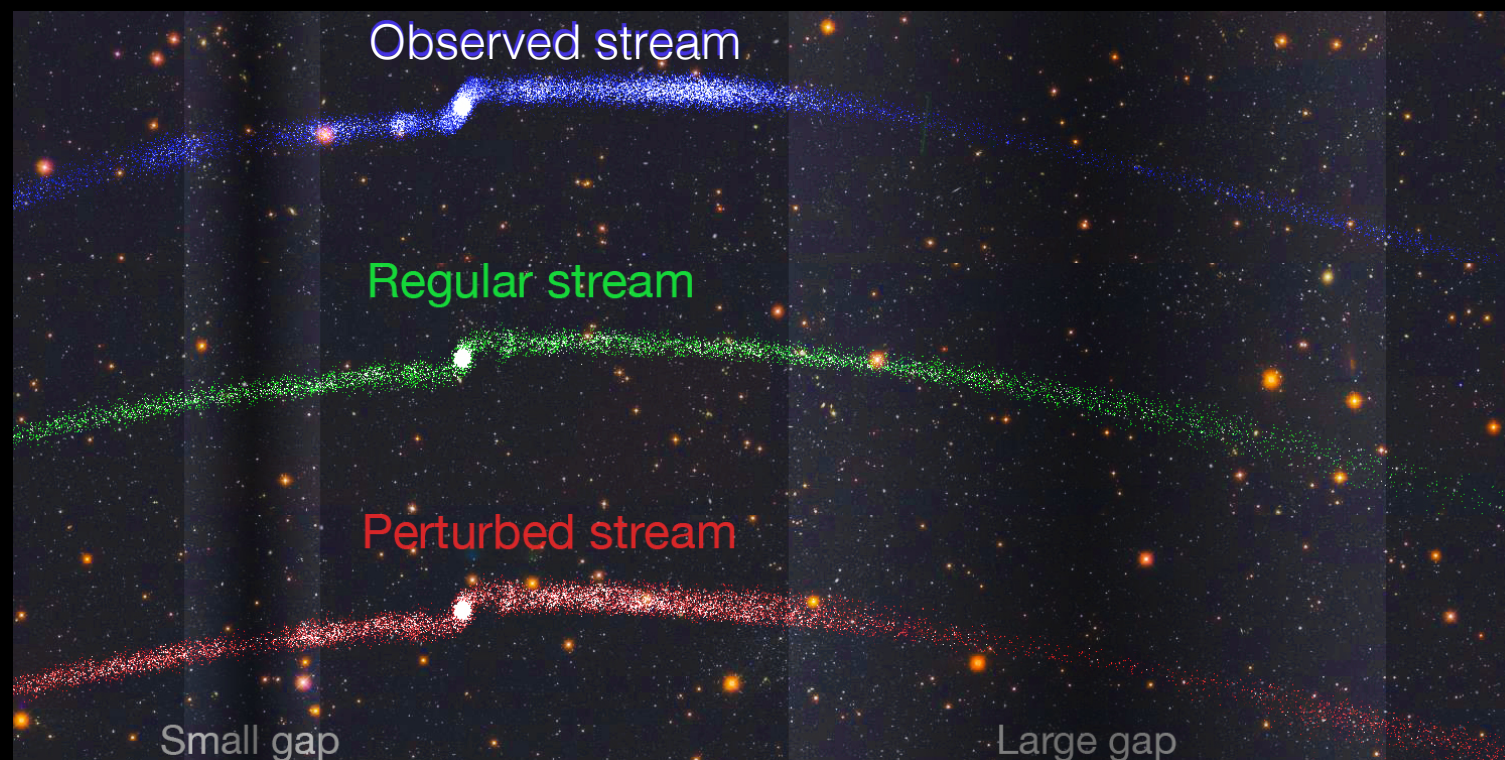
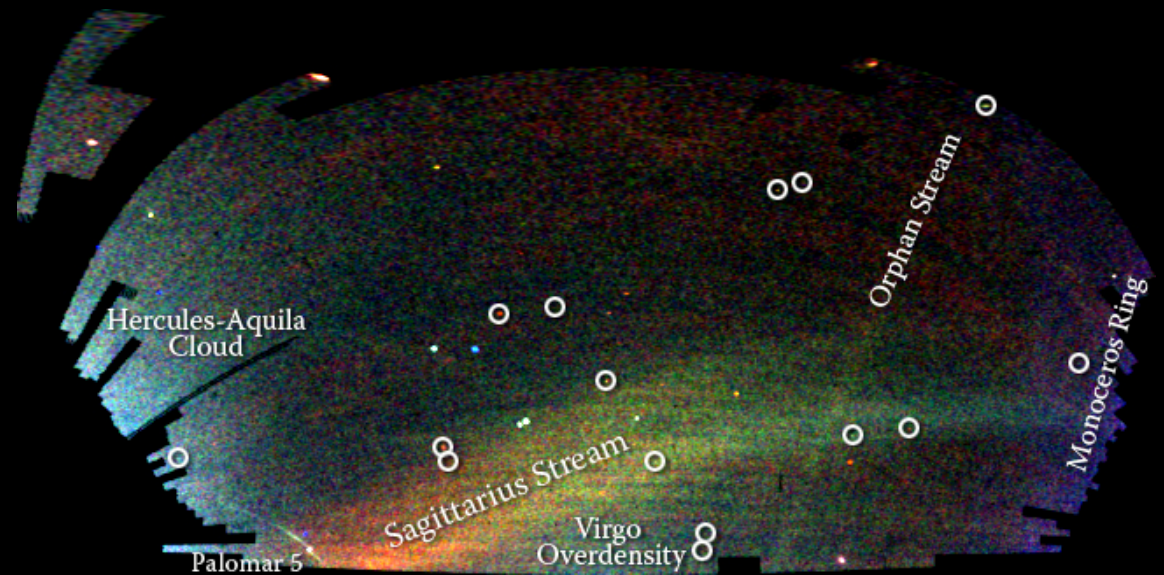
Now for real tidal streams



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

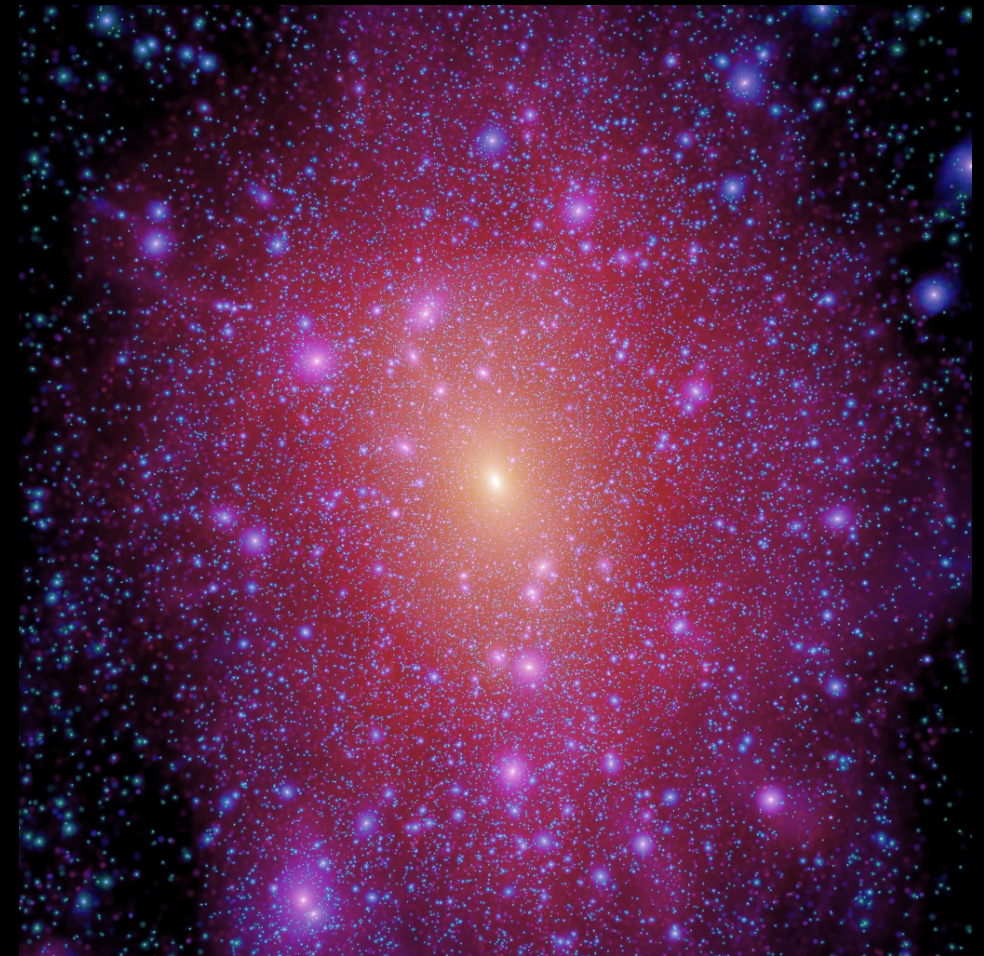
Now for real tidal streams

- Palomar 5 - long and thin stream
- 2/3 of a Milky Way disk away
- We expected 0-2 gaps in the stream
- We see 2 gaps
- Created by clumps with masses between 1 million and 100 million solar masses



Questions for today

- What is dark matter?
 - No one knows: it has mass but it's invisible
- How do we know dark matter exists?
 - From how fast galaxies rotate
 - The bullet cluster
- How clumpy should the dark matter be?
 - ~10% of dark matter should be in clumps
- How can we tell if dark matter is clumpy?
 - Look at tidal streams which we can see
- How clumpy is dark matter?
 - As clumpy as expected by our models!



V. Springel



Thank you!