Uncovering the nature of dark matter with stellar streams in the Milky Way
Our Milky Way Galaxy Weighs As Much As 1.5 Trillion Suns
By Mike Wall 10 days ago  Science & Astronomy

The Milky Way Contains the Mass of 1.5 Trillion Suns
By Monica Young | March 18, 2019

Scientists discover what the Milky Way weighs
We are here

$7 \times 10^{10} \, M_{\odot}$

$\sim 90\%$ of the Milky Way galaxy is invisible

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The Guardian
Scientists discover what the Milky Way weighs
Significant resources are dedicated to the search for dark matter

Interacts with ordinary matter?

[LUX experiment: $10M]
Significant resources are dedicated to the search for dark matter.

Interacts with ordinary matter?

[LUX experiment: $10M]

[Produces gamma rays?]

[Fermi satellite: $600M]
Significant resources are dedicated to the search for dark matter

Interacts with ordinary matter?

[Image of a mine]

LUX experiment: $10M

Produces gamma rays?

Fermi satellite: $600M

Can be produced in a lab?

LHC in CERN: $8B
The nature of dark matter is encoded in its spatial distribution

Particle mass \( \sim \) GeV
The nature of dark matter is encoded in its spatial distribution.

Particle mass ~ GeV

Particle mass ~ keV
The nature of dark matter is encoded in its spatial distribution

Particle mass ~ GeV

Particle mass ~ keV

Particle mass ~ $10^{-22}$

Goal: Create a high-resolution map of dark matter in the Milky Way
Gravitational pull of the Moon creates tides
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Gravitational pull of the Moon creates tides

Moon

Earth (from Earth's perspective)
Gravitational pull of the Moon creates tides

\[
\frac{\Delta a}{a} = \left( \frac{R}{d} \right)^2 \frac{m}{M} \frac{1 - 2d/R}{(1 - d/R)^2}
\]
Gravitational pull of the Moon creates tides

Moon

Earth (from Earth's perspective)

\[ \Delta a \quad \frac{d}{a} \quad \left( \frac{R}{d} \right)^2 \quad \frac{m}{M} \quad \frac{1-2d/R}{(1-d/R)^2} \quad 10^{-5}\% \]

\[ = 0.00001\% \]

Tidal acceleration

Earth's acceleration (gravity)

\[ M = 81 \times m \]

\[ d = 60 \times R \]
Gravitational pull of the Milky Way creates tides, too!
Gravitational pull of the Milky Way creates tides, too!

For a star cluster close to the Sun

\[
\frac{R}{d} = 5 \times 10^{-4}
\]

\[
\frac{m}{M} = 2 \times 10^8
\]
Pleiades: \[ \frac{\Delta a}{a} = 5\% \]

Hyades: \[ \frac{\Delta a}{a} = 1\% \]
Globular clusters lose stars to form tidal streams

800 million years
Globular cluster Palomar 5 has a tidal stream of stars

Legacy Surveys + PI Bonaca
Stellar streams preserve a record of all gravitational interactions

Stellar stream in a smooth galaxy
Stellar streams preserve a record of all gravitational interactions

Stellar stream in a smooth galaxy

Stellar stream in a clumpy galaxy
Stellar halo of the Milky Way is rich with structure
Gaia's view of the GD-1 stellar stream
Gaia's view of the GD-1 stellar stream
Gaia's view of the GD-1 stellar stream

Proper motion selection

$\phi_2$ [deg]

$\mu_{\phi_1}$ [mas yr$^{-1}$]

Price-Whelan & Bonaca (2018)
Gaia's view of the GD-1 stellar stream
Gaia's view of the GD-1 stellar stream

Proper motion selection

Proper motion and photometry selection

Price-Whelan & Bonaca (2018)
Gaia's view of the GD-1 stellar stream

Proper motion selection

Proper motion and photometry selection

Price-Whelan & Bonaca (2018)
Gaia's view of the GD-1 stellar stream

Proper motion selection

Proper motion and photometry selection

Previously undetected

Gaps
Gaia's view of the GD-1 stellar stream

Proper motion selection

Proper motion and photometry selection
Gaia's view of the GD-1 stellar stream

Price-Whelan & Bonaca (2018)
Observed GD-1 stellar stream

Model stellar stream
Who perturbed the GD-1 stream?

Whodunit:
(or candidates for the perturber)
Who perturbed the GD-1 stream?

Whodunit:
(or candidates for the perturber)

Globular cluster?
Dark matter clump?
Black hole?
Who perturbed the GD-1 stream?

**Whodunit:**
(or candidates for the perturber)

**Howdunit:**
(or properties of the perturber)

- Globular cluster?
- Dark matter clump?
- Black hole?
Who perturbed the GD-1 stream?

**Whodunit:**
(or candidates for the perturber)

- Globular cluster?
- Dark matter clump?
- Black hole?

**Howdunit:**
(or properties of the perturber)

- Mass
- Size
- Closest distance
Stream structure constrains the encounter parameters.
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- Mass: 1.10^6 M_☉
- Size: 0 pc
- Distance: 1 pc
- Mass: 5.10^6 M_☉
- Size: 10 pc
- Distance: 15 pc
- Mass: 1.10^7 M_☉
- Size: 100 pc
- Distance: 50 pc

Phases: Φ_1 [deg] and Φ_2 [deg]
The GD-1 perturber is not a known satellite of the Milky Way.
Dark matter subhalo is a plausible perturber of GD-1
Additional signatures of the hypothetical perturber:

- Annihilation (e.g., Albert et al. 2017)
- Disk disturbances (e.g., Antoja et al. 2018)
- Perturbations of halo stars (e.g., van Tilburg et al. 2018)
Relative velocity will determine the perturber's orbit
Perturbed stars are moving at the speed of unperturbed stars.
In the next decade, we will find streams throughout the Milky Way.