# Dark Matter in Galaxy Clusters: Past, Present, and Future


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AAPT 2016 Summer Meeting

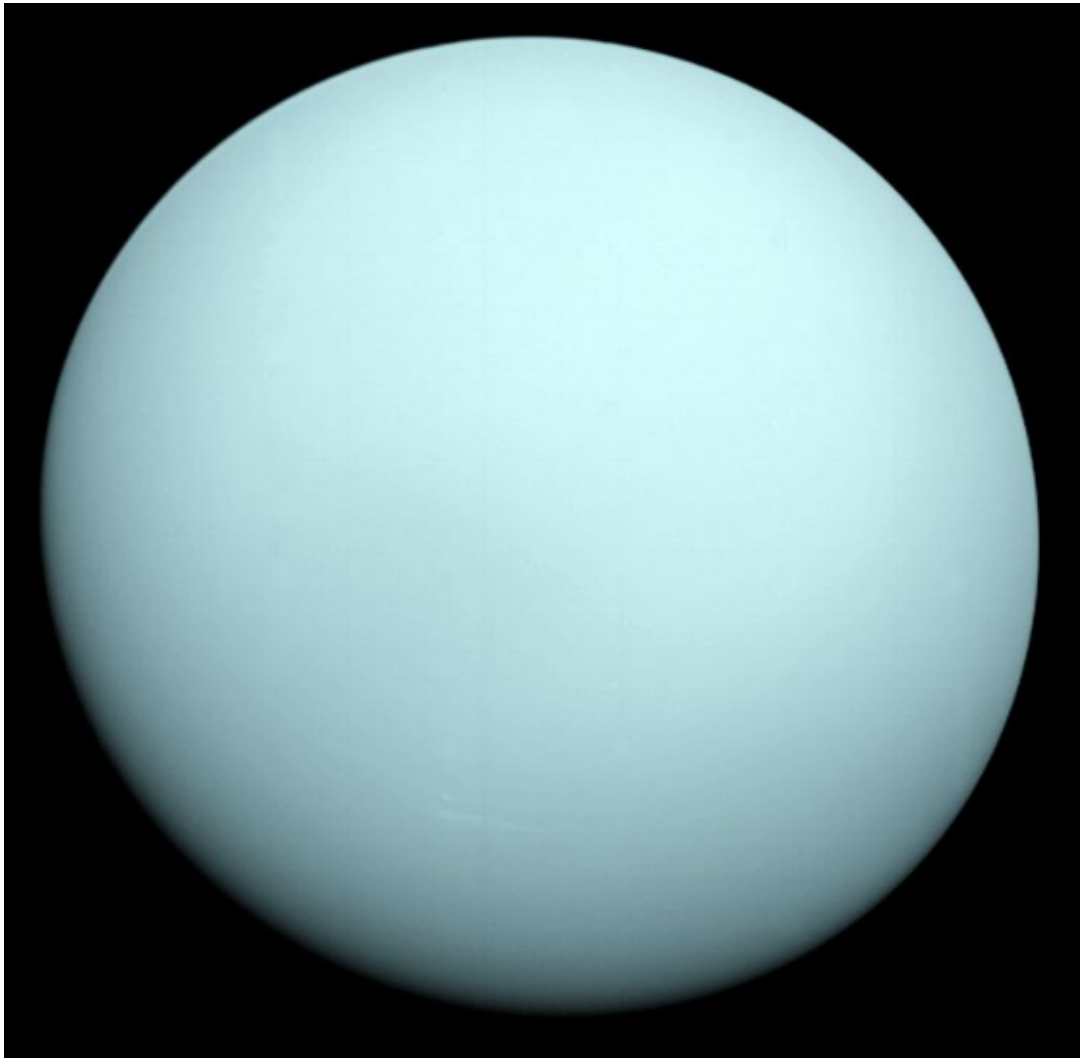
MERGING CLUSTER COLLABORATION

NSF

# Dark matter or modified gravity: case study #1

Wm. Herschel

Discovered Uranus 1781



# Uranus' orbit: poor fit to Newtonian model of solar system

Suggested causes of poor fit:

- **Unseen matter:** unseen planet perturbing Uranus
- **Modified gravity:** inverse-square law may fail at large distances

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**Another option:** reject discrepant data

# Are these options equally likely?

Consider:

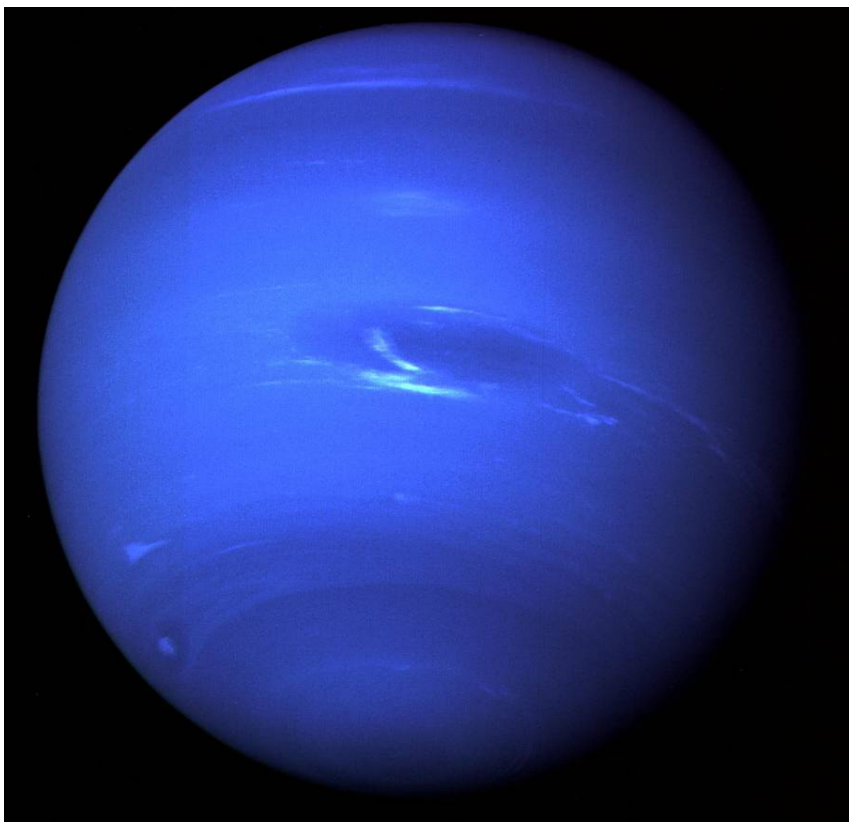
- inverse-square law explains an enormous array of other data



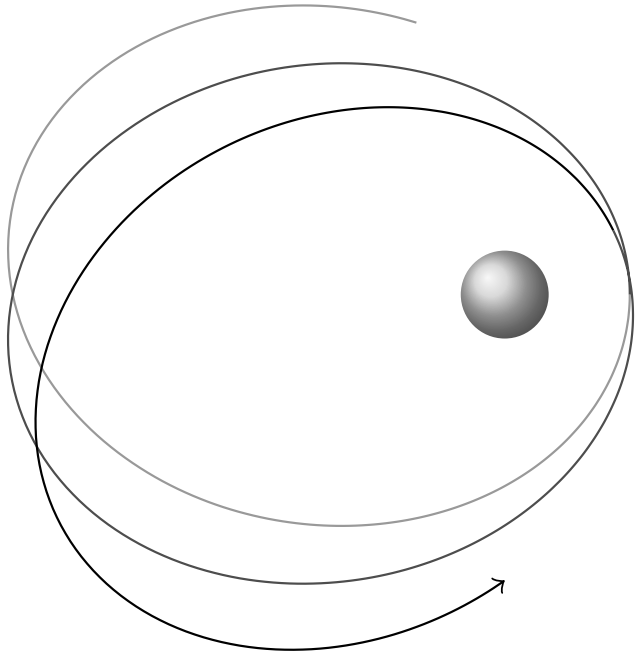

- clues from residual pattern
- simplicity of hypotheses (Occam's razor): physics may be the *only* class your students are exposed to this!

# Resolution: unseen mass

Urbain Le Verrier predicted position and mass of unseen planet in 1846—it was discovered after *one hour* of searching near predicted position.



# Case study #2: Mercury precesses too much



- "Normal" precession: $0.15^\circ$/century
- "Anomalous" precession: $0.012^\circ$/century

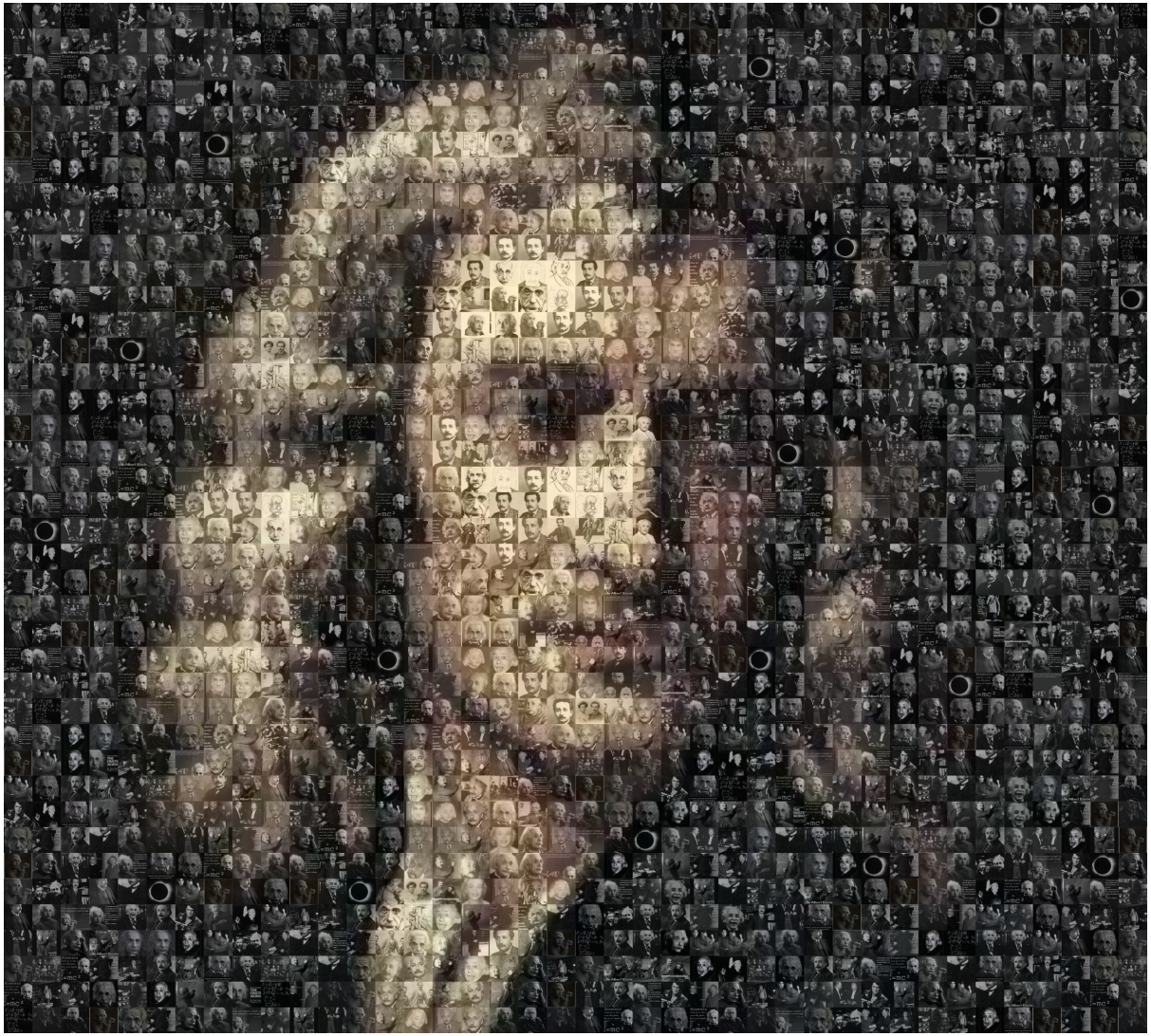
# Hypotheses

- **Unseen matter:** unseen planet ("Vulcan") orbiting near Sun
- **Modified gravity:** steeper than inverse-square? Tinker with speed?

**Which seems more likely?**

# Surprise resolution

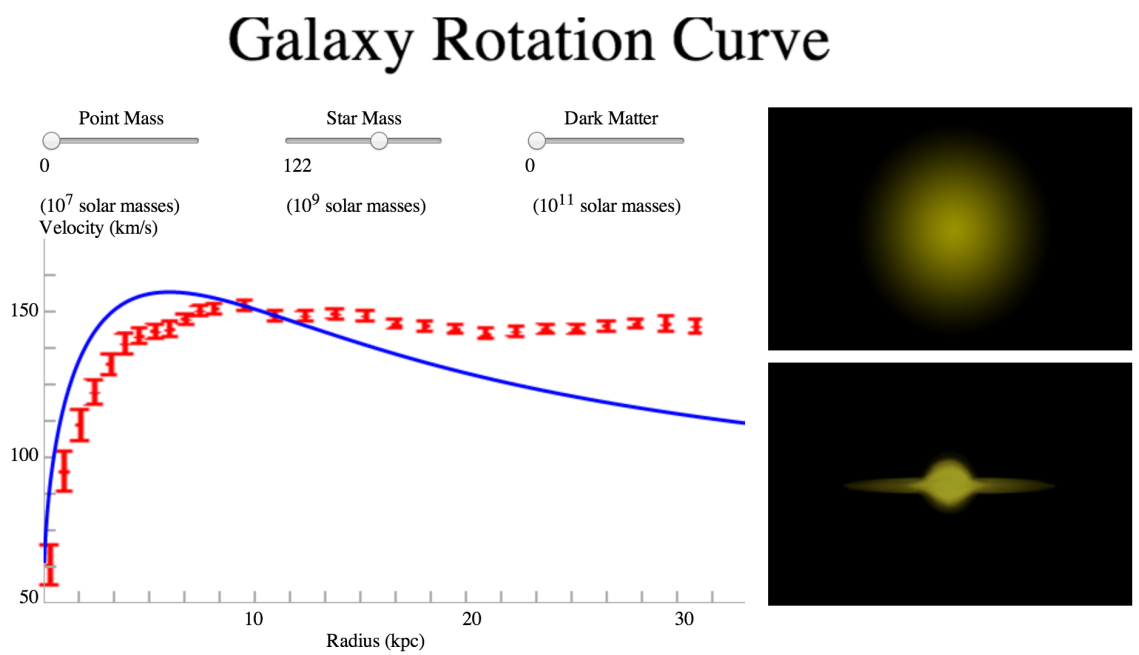
By 1915 general relativity explained the anomalous precession.



What if we found orbital mismatches *everywhere in the universe*?

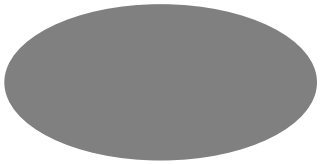
# Zwicky (1935): Galaxy Cluster Dynamics

# "Dark Matter" Dynamics: Everywhere You Look



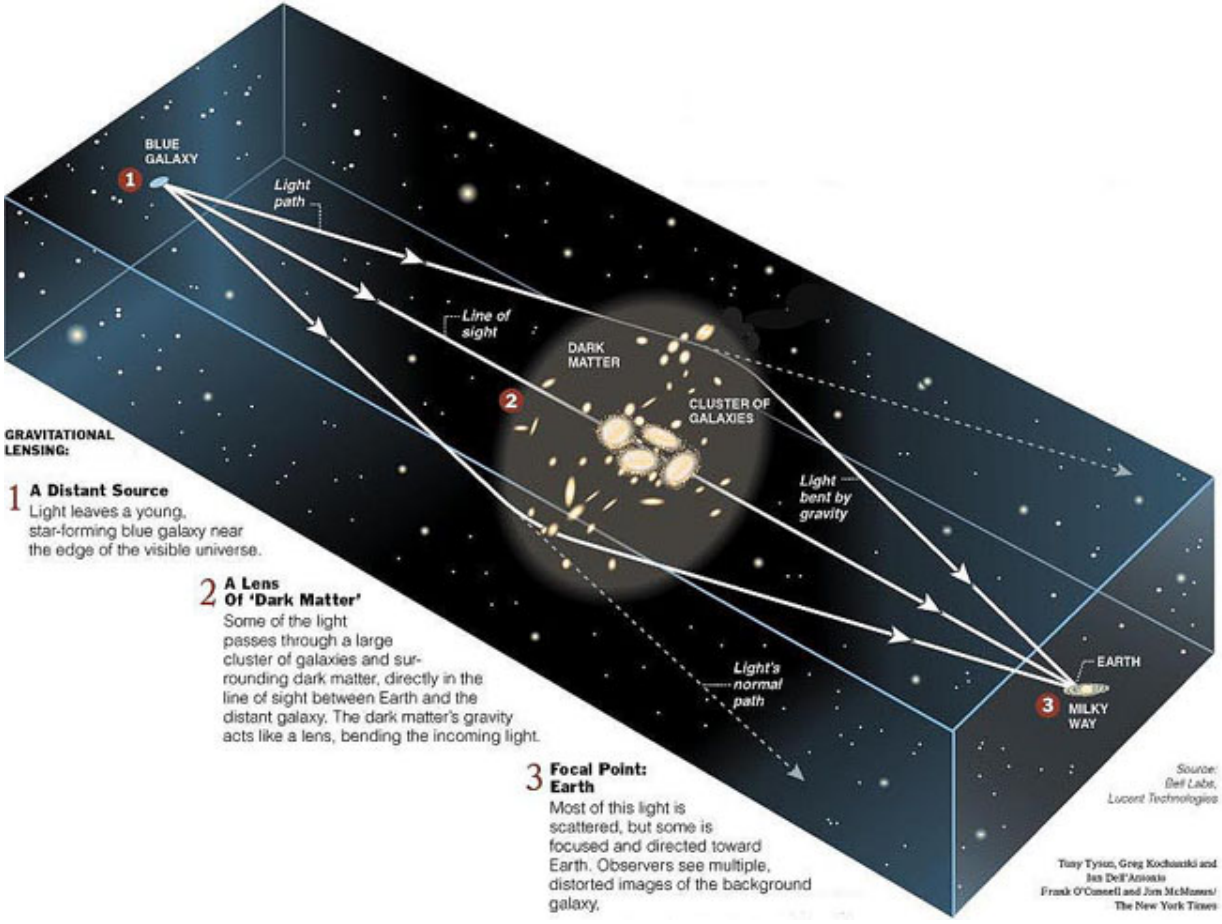

http://wittman.physics.ucdavis.edu/Animations/RotationCurve/

- rotation curves of spiral galaxies
- $\sigma_v$ of elliptical galaxies
- X-rays from galaxy clusters
- galaxy mergers
- structure formation
- cosmic microwave background



# Gravitational lensing

Probes the mass distribution *independent of dynamical state* and *without normal-matter tracers*.

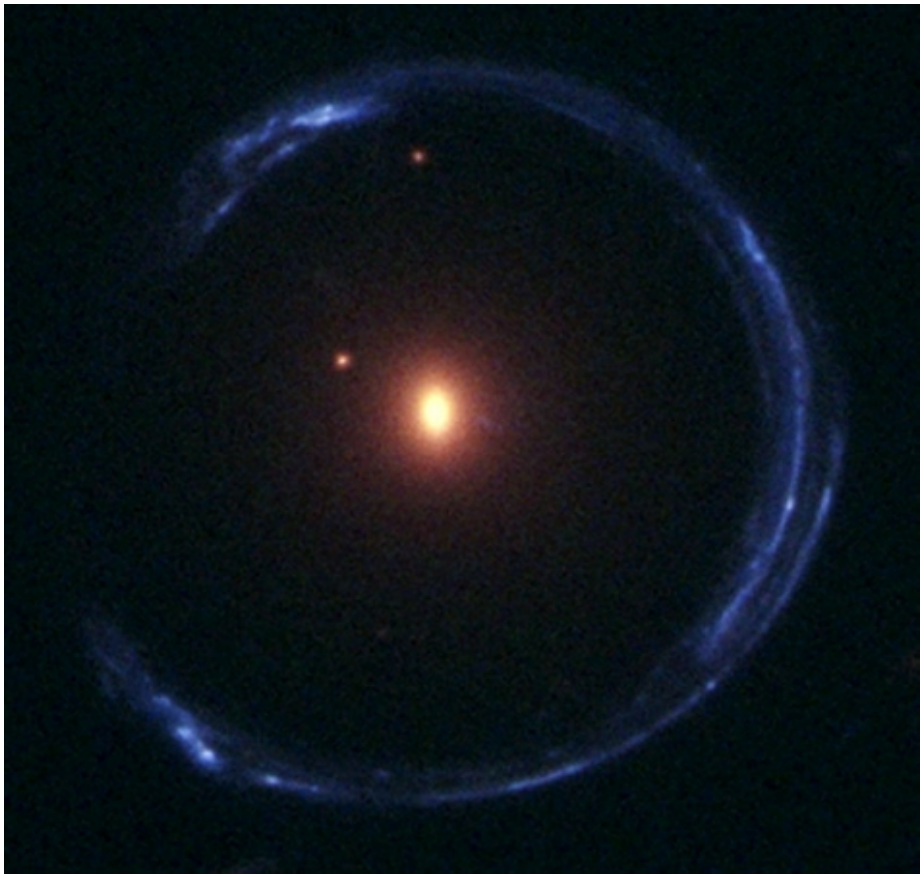



Credit: New York Times

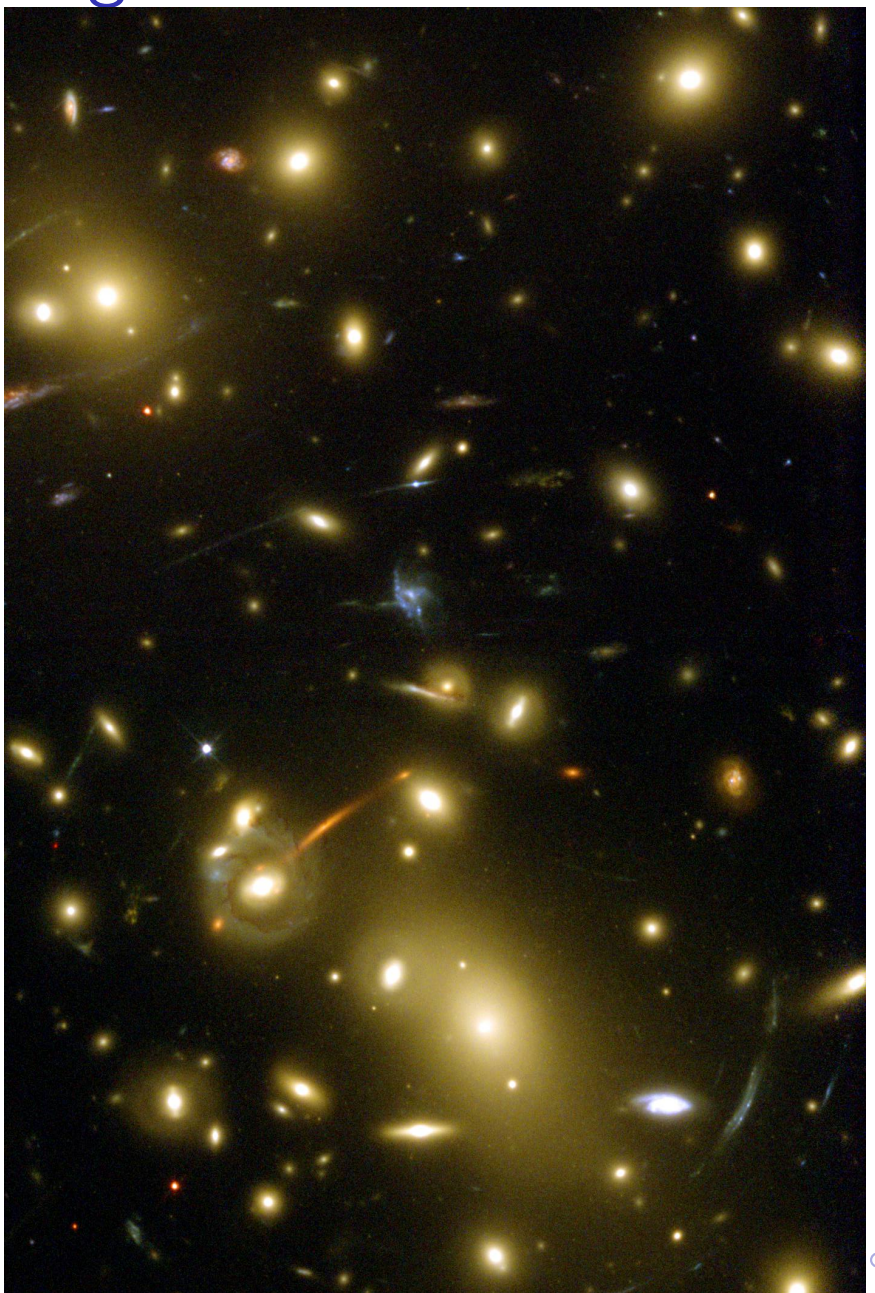
# Gravitational lensing analogies

Credit: Melinda Keller, Oberlin College

# Gravitational lensing in action



NASA/HST



# More lensing in action

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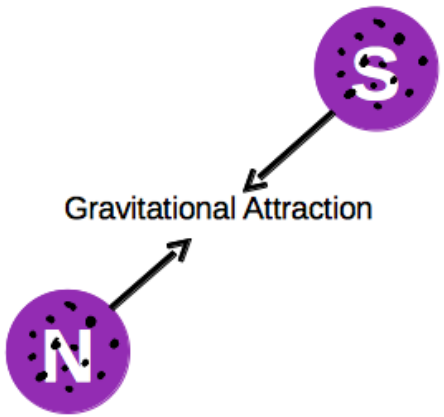
# Dark matter or modified gravity?

- dark matter is (can be?) an extravagant hypothesis
- but modified gravity struggles to fit so many different environments, e.g. cluster centers vs galaxy outskirts

$\Longrightarrow$ dark matter overwhelmingly favored

**Can we prove DM more directly by isolating it from normal matter?**

# Anatomy of a Merger




Predict where the mass will be found!

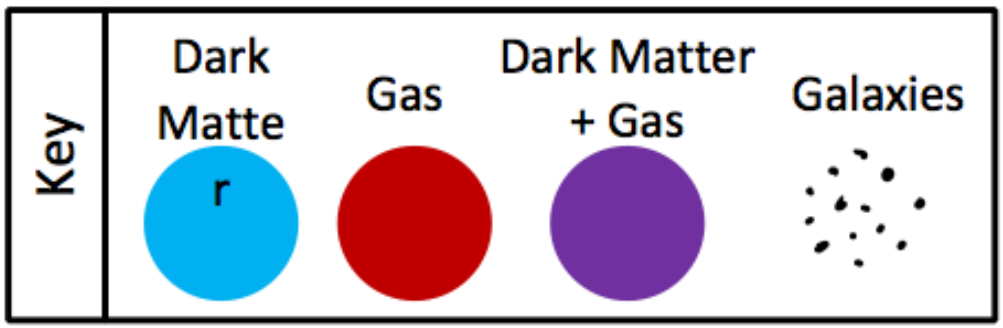



Figure credit: Will Dawson

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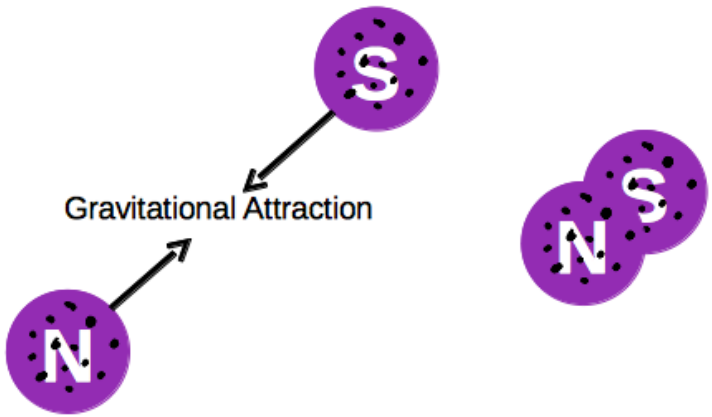


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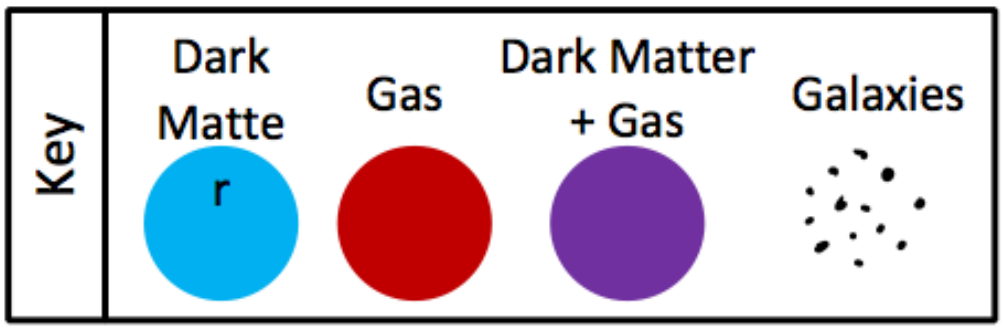


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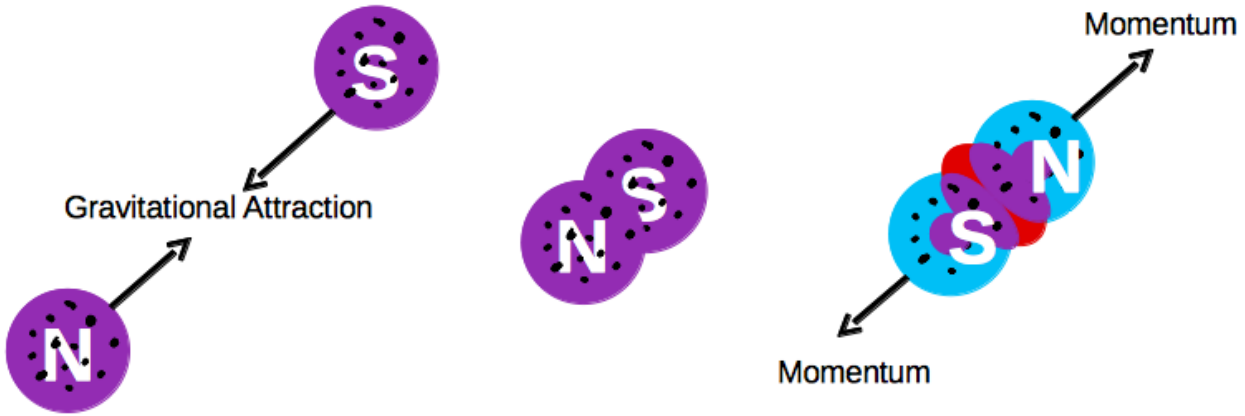


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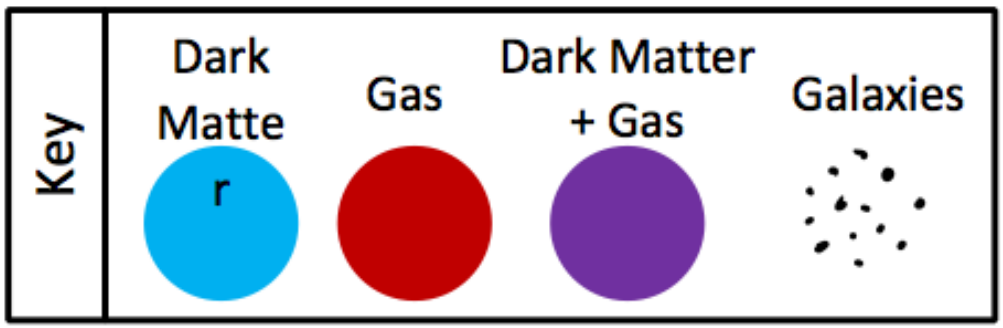


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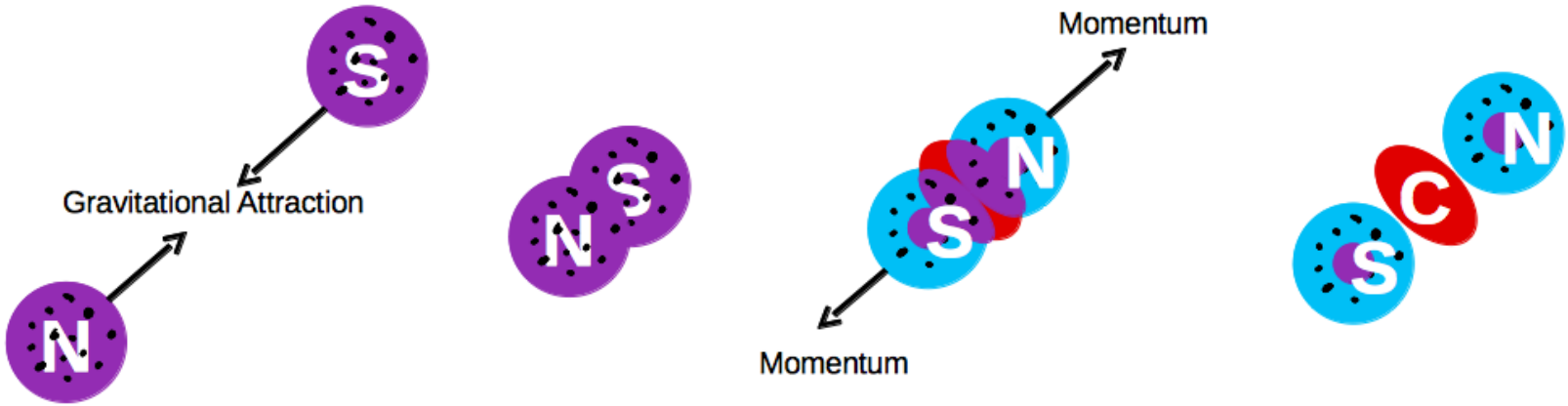


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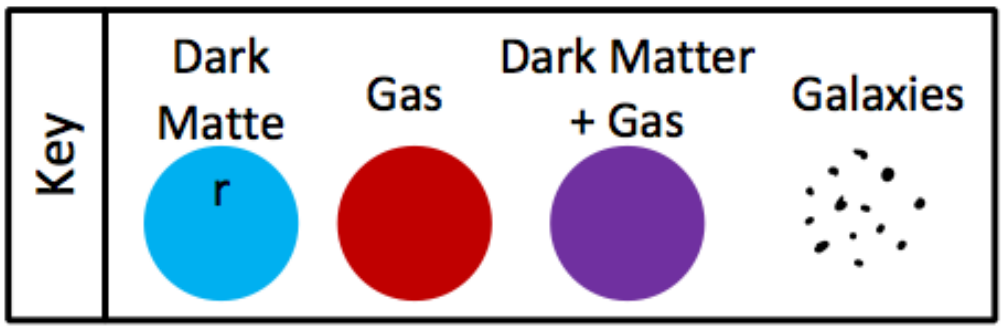



Figure credit: Will Dawson

# Bullet Cluster

Clowe et al (2006): "A direct empirical proof of the existence of dark matter"

gas (from X-rays); mass (from grav. lensing)

# So what *is* dark matter?

We know what it's *not*:

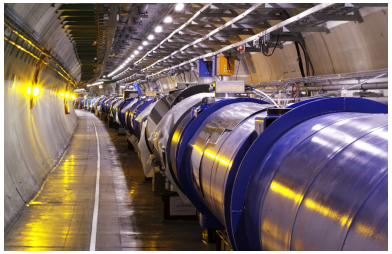
- not made of protons or neutrons
- does not interact with light

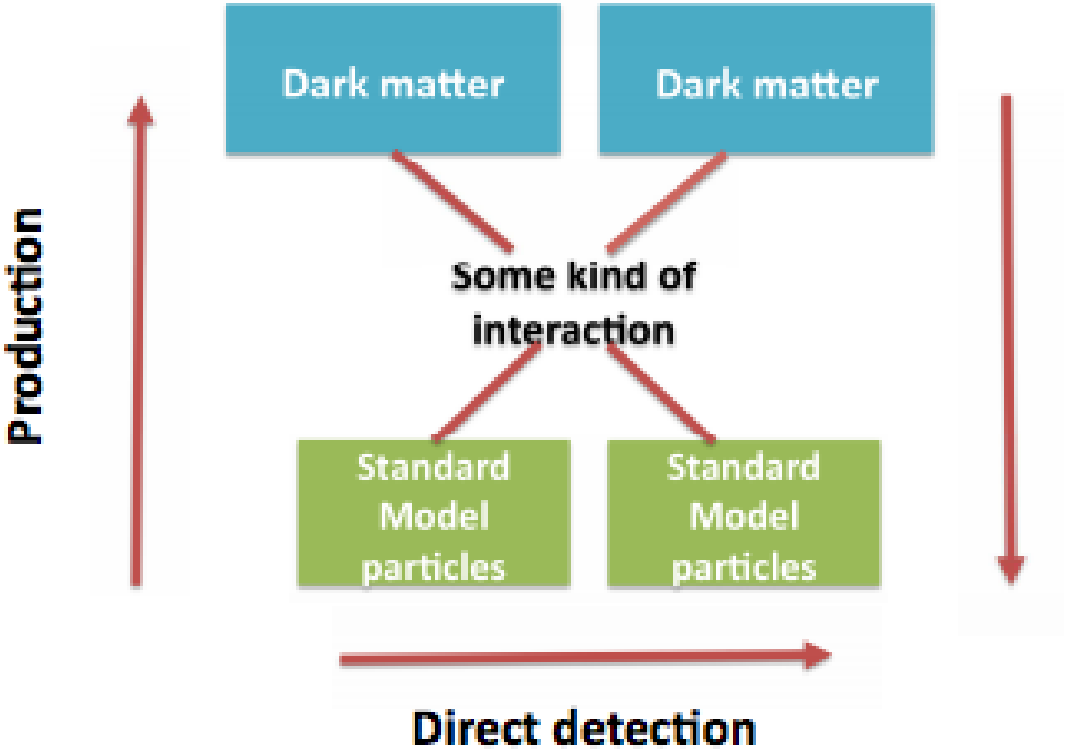
$\Longrightarrow$ new particle or particles w/these properties:

- stable (ish)
- "cold" (nonrelativistic)
- collective density $\sim 2 \times 10^{-27}$ kg/m$^3$
- does not interact with SM particles (except perhaps weakly)

Lots of models to test: WIMPs, axions, hidden-sector models....

# Unified picture of (most) dark matter searches





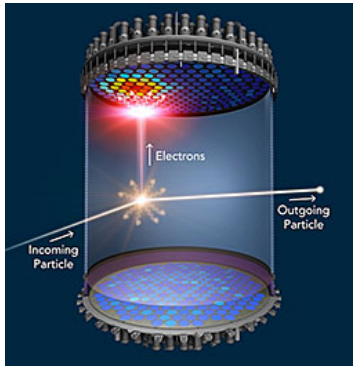
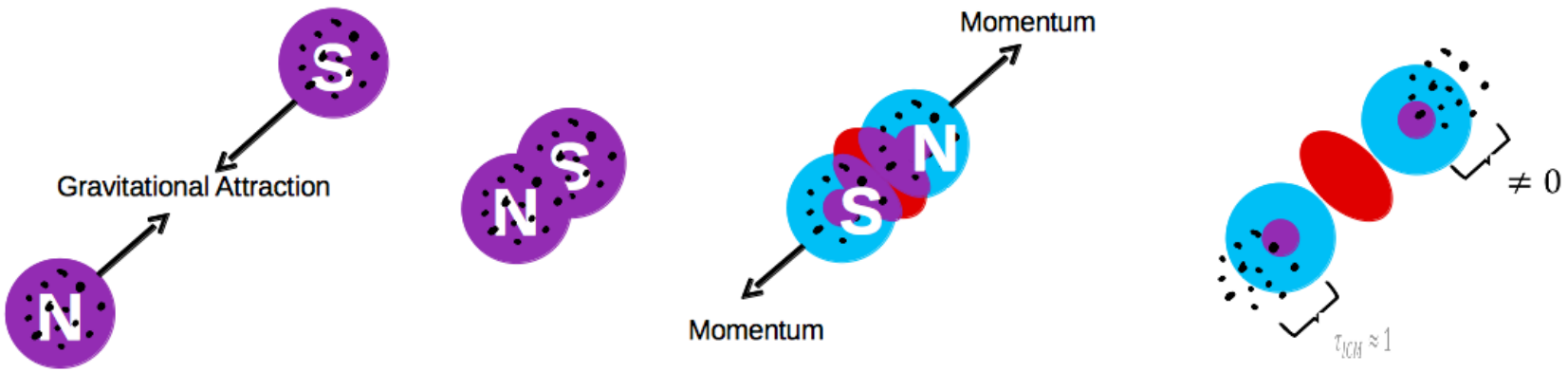




Figure credit: Annika Peter, arXiv:1201.3942

But this figure is incomplete...

# The drag force awakens

*Self*-interacting dark matter (SIDM) would transfer momentum in a collision:




Offset in Bullet is consistent with zero $\implies \sigma_{SIDM} \lesssim 2$ barn/GeV (Randall+08)

# Wait, 2 *barns* per GeV??

- $\sim 10^{20}$ times larger than upper limits on DM interacting with normal matter
- Incredibly, we don't yet know whether DM particles interact with each other at this level
- Some "hidden sector" particle models predict this, and some galaxy data suggest it
- *Only astrophysics can constrain these models!*

Can we use clusters as natural colliders to learn more about the DM particle?

# Merging cluster collaboration: find/analyze more Bullets!

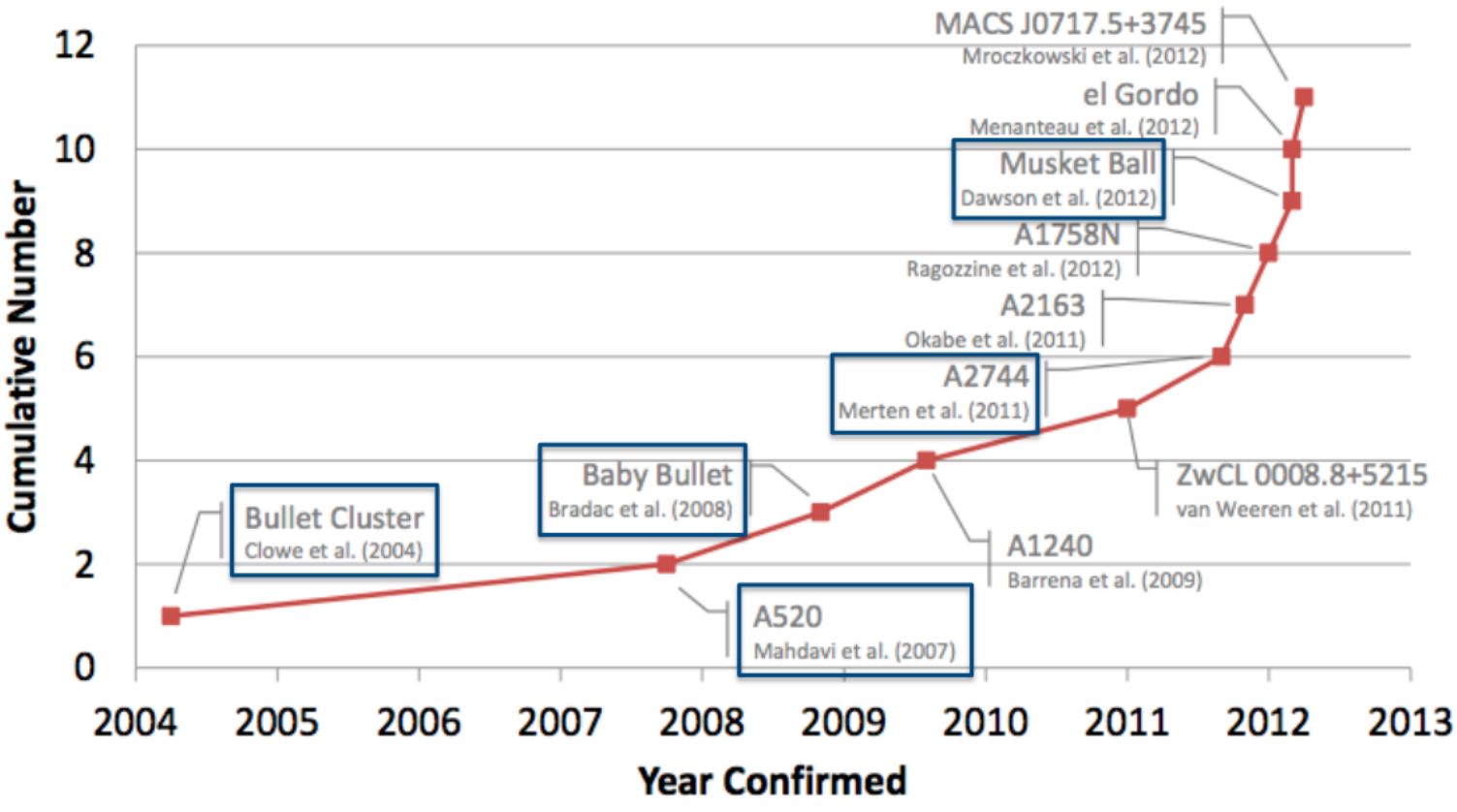
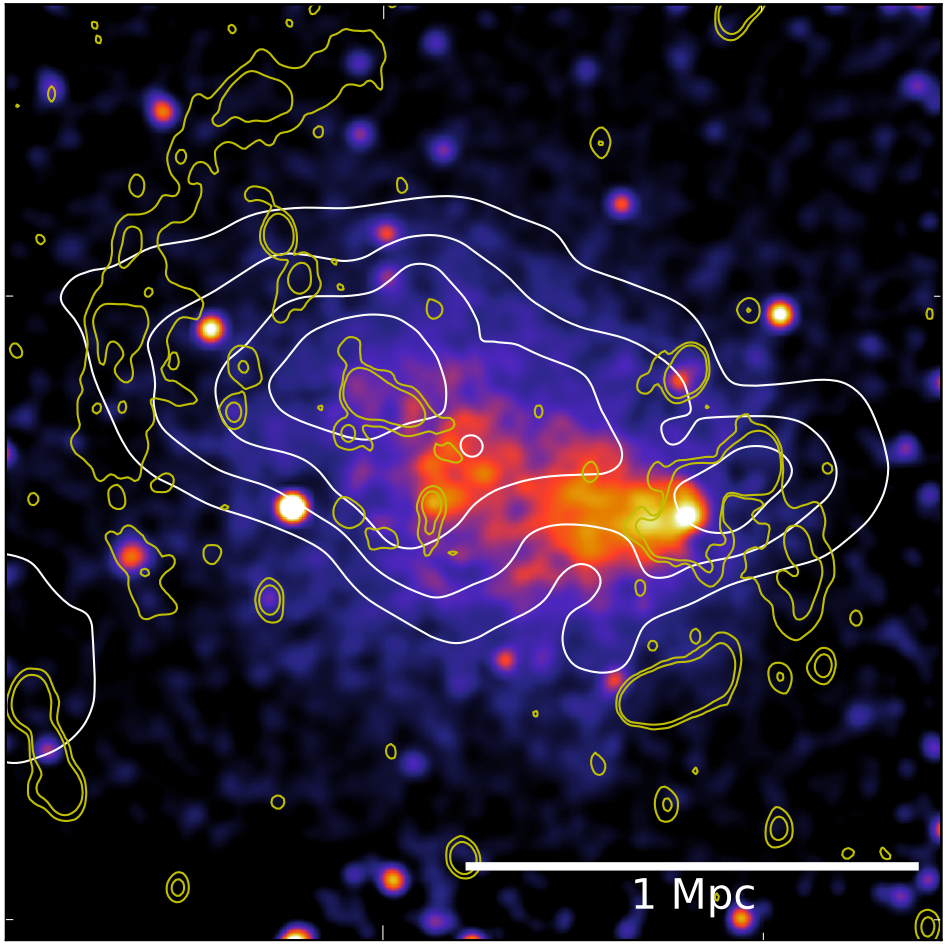
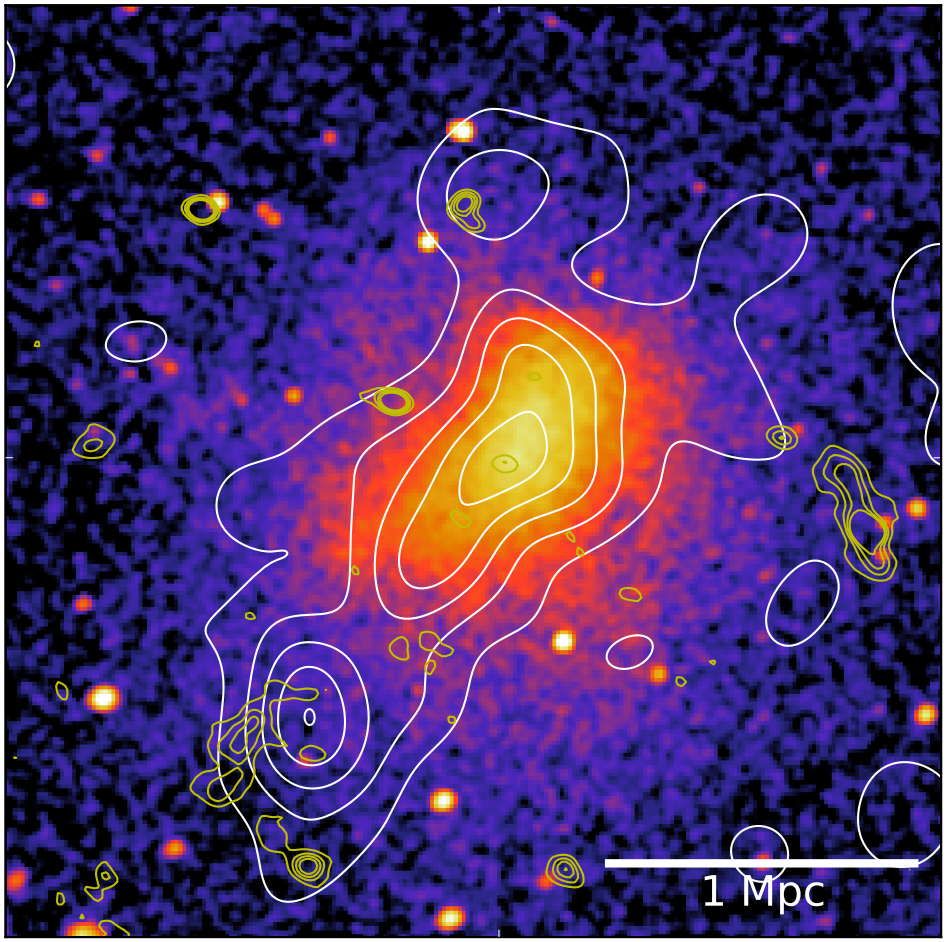




Figure credits: Will Dawson

# Two recent MCC discoveries



# Merging clusters can probe the *type* of interaction

(1) Frequent interactions w/small momentum transfer—long range force like E&M

(2) infrequent interactions with large momentum transfer—like hard sphere scattering

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(2) infrequent interactions with large momentum transfer—like hard sphere scattering

(3) no interaction

# Summary

- the Bullet cluster was the first picture of dark matter without its usual camouflage
- nature provides many more!
- these "Large Dark Matter Colliders" will test particle models robustly

*Astronomy and physics work together beautifully to reveal unseen aspects of nature.*