

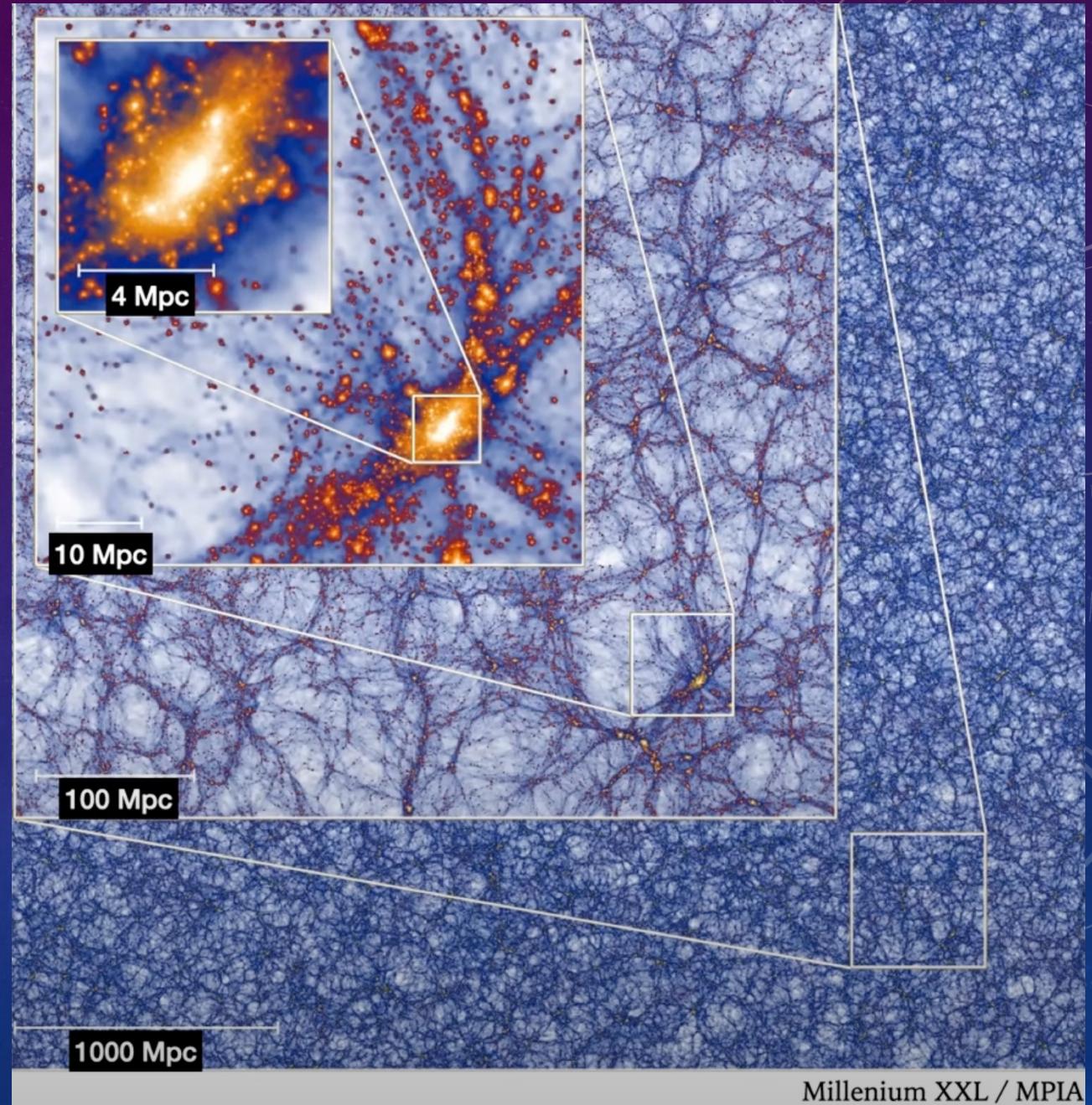


GALAXY CLUSTER MERGERS

UNIQUE LABORATORIES FOR PROBING AND
CONSTRAINING DARK MATTER

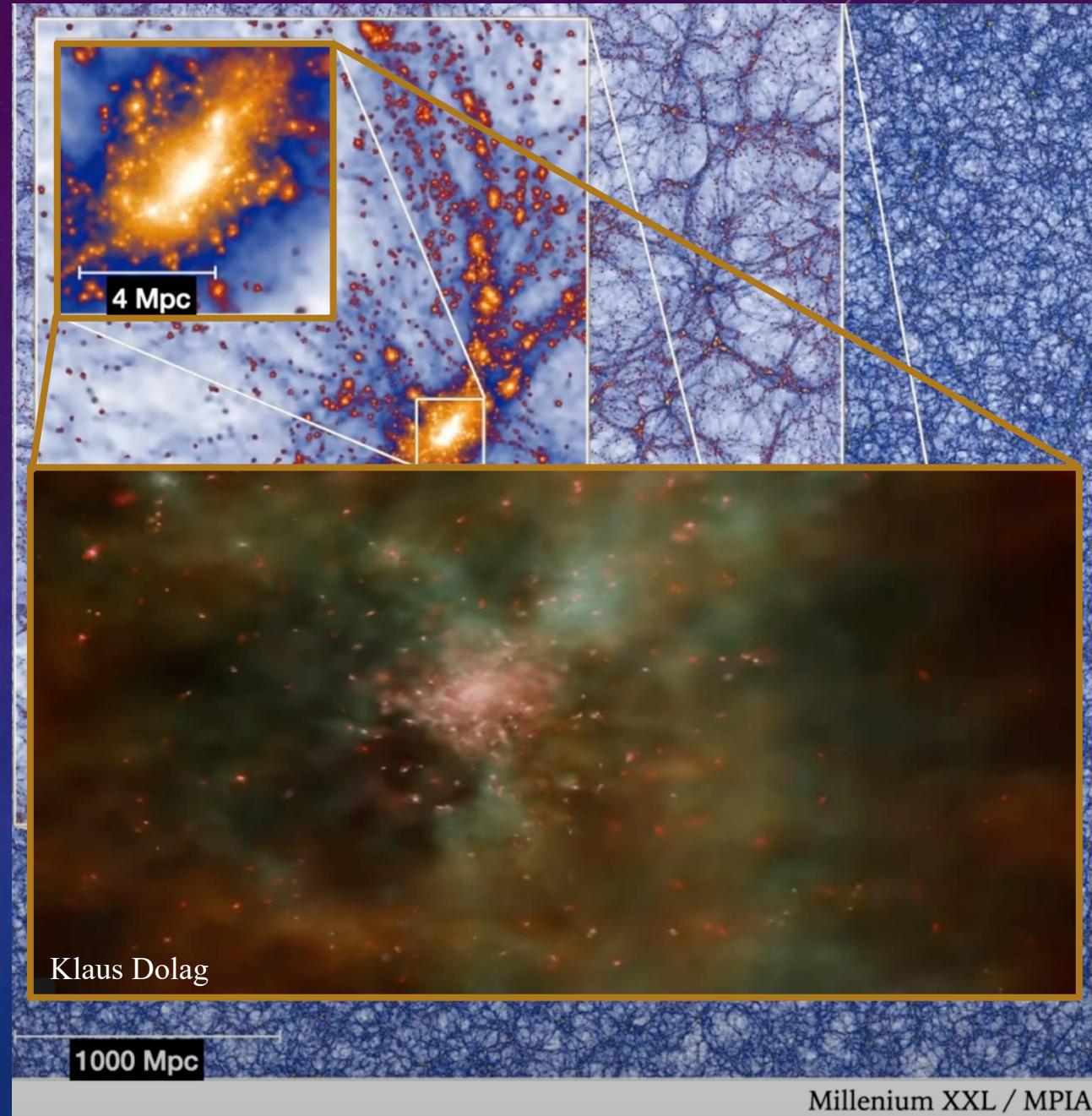
What are galaxy clusters?

- Largest gravitationally bound systems in the Universe
- Grow via hierarchical structure formation (e.g. galaxies)
- Mergers have tremendous energy ($\sim 10^{64}$ ergs)
- Astrophysical laboratories



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Merger Components

Diffuse ICM

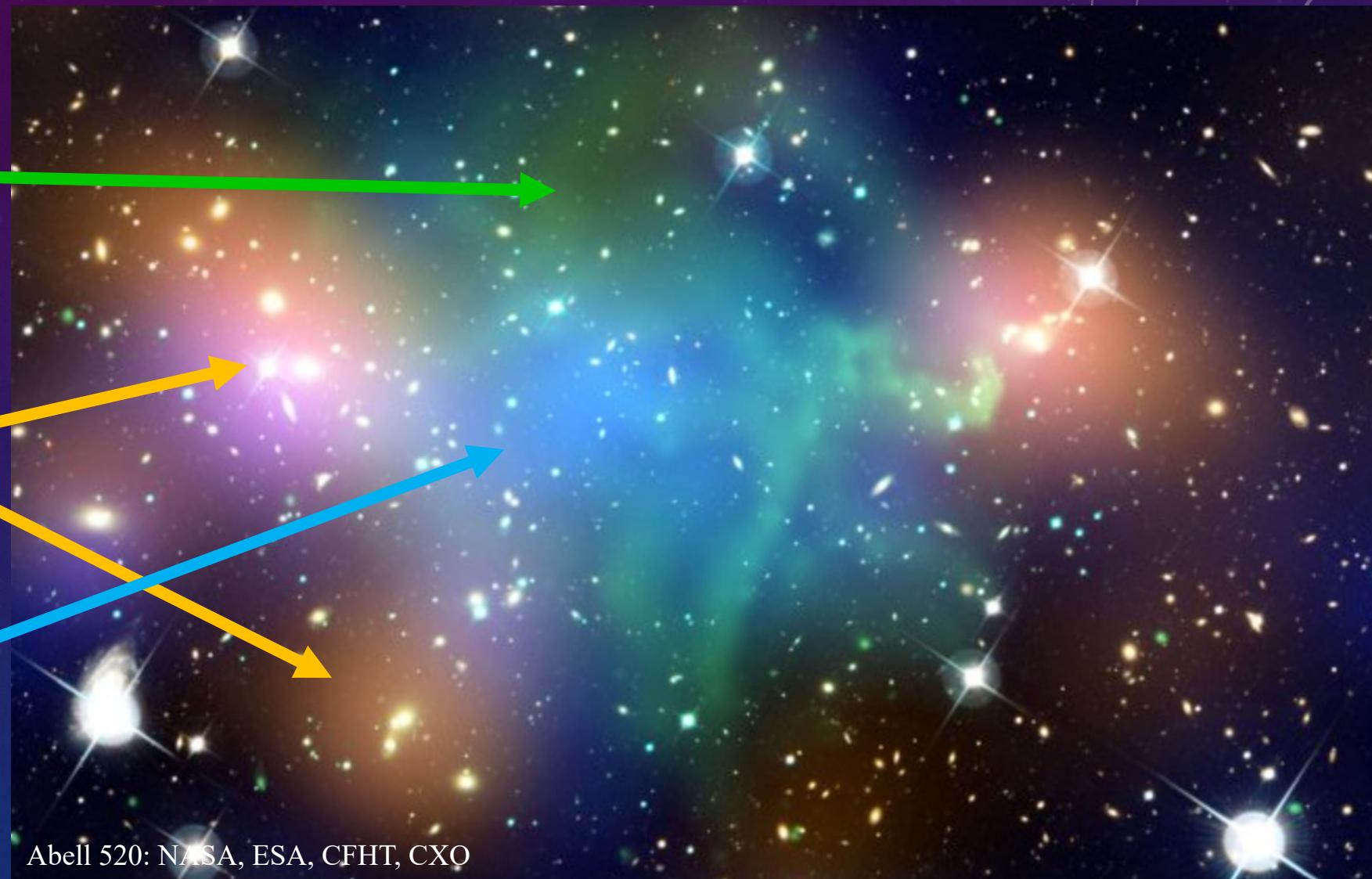
Thermal components
Hot: $10^7 - 10^8$ K
Sparse: 10^{-3} parts/cm 3

Component Galaxies

$\sim 1000s$

Dark Matter

Majority of mass



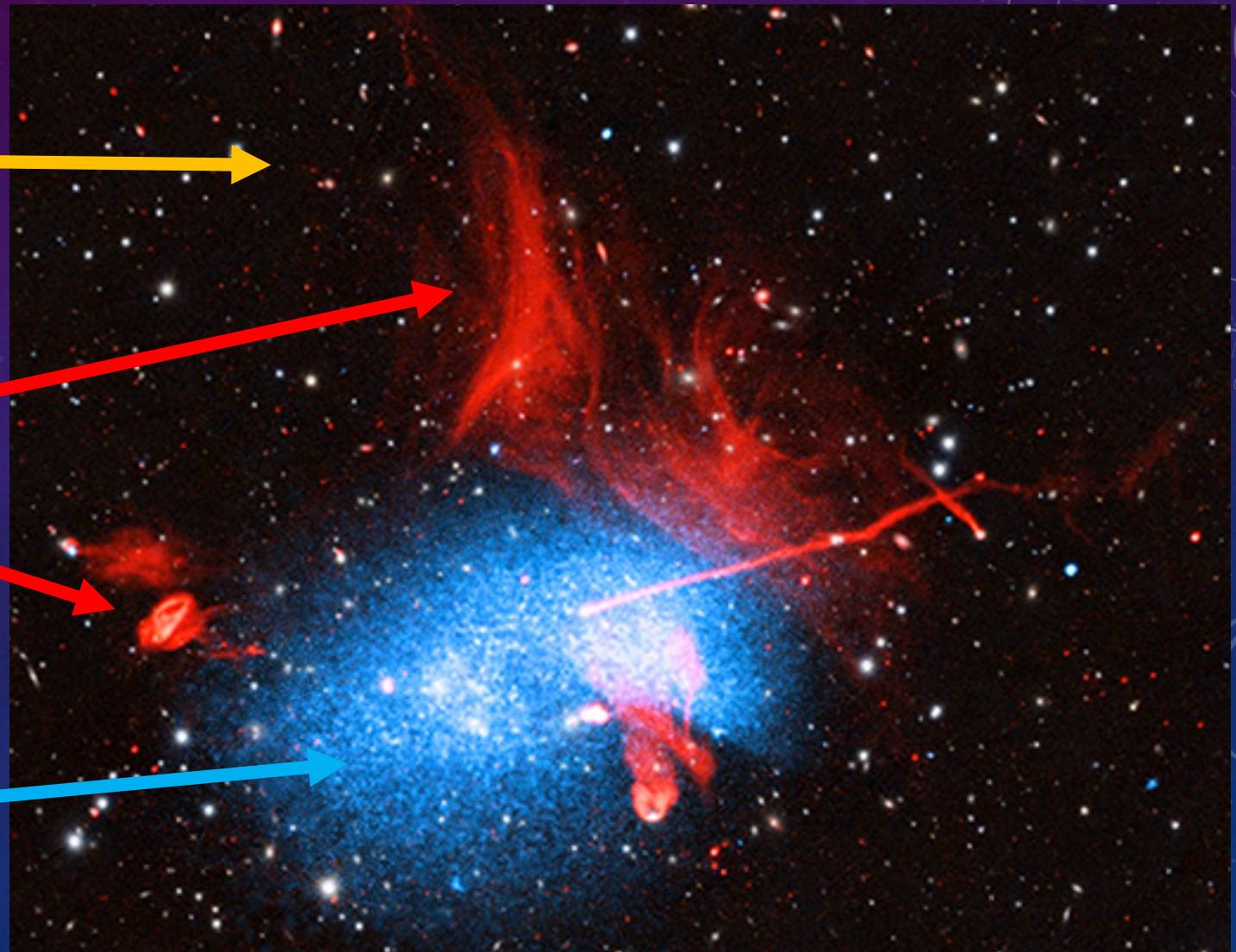
Abell 520: NASA, ESA, CFHT, CXO

What are galaxy clusters?

Component Galaxies
~1000s

Radio Structure
Re-accelerated e⁻
Non-thermal components

Diffuse ICM
Thermal components
Hot: $10^7 - 10^8$ K
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Abell 2256: NASA, ESA, LOFAR, PanSTARRS

The Bullet Cluster



Markevitch et al. 2002

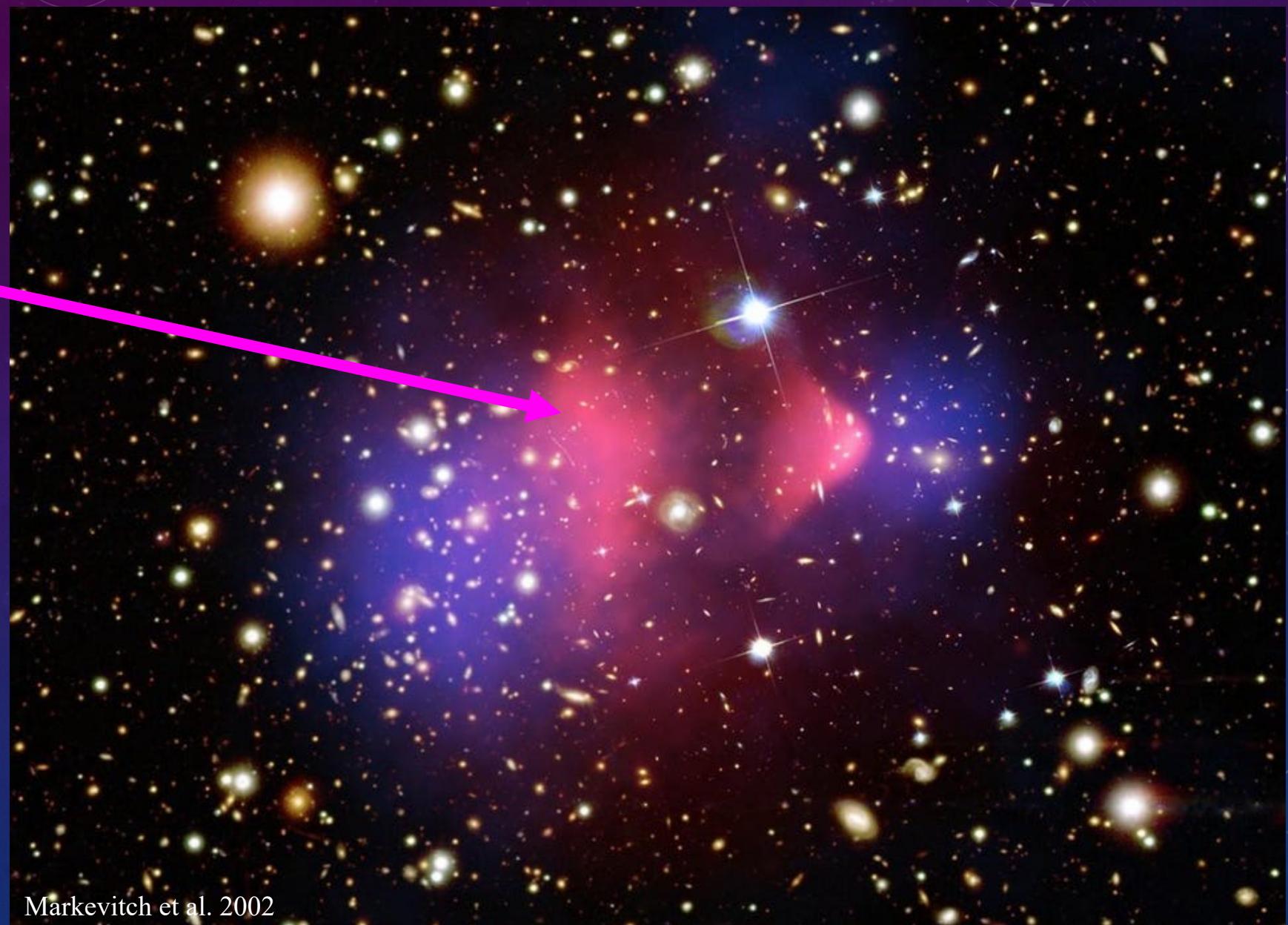
The Bullet Cluster

Diffuse ICM – X-ray

Thermal components

$10^7 - 10^8 \text{ K}$

$10^{-3} \text{ parts/cm}^3$



Markevitch et al. 2002

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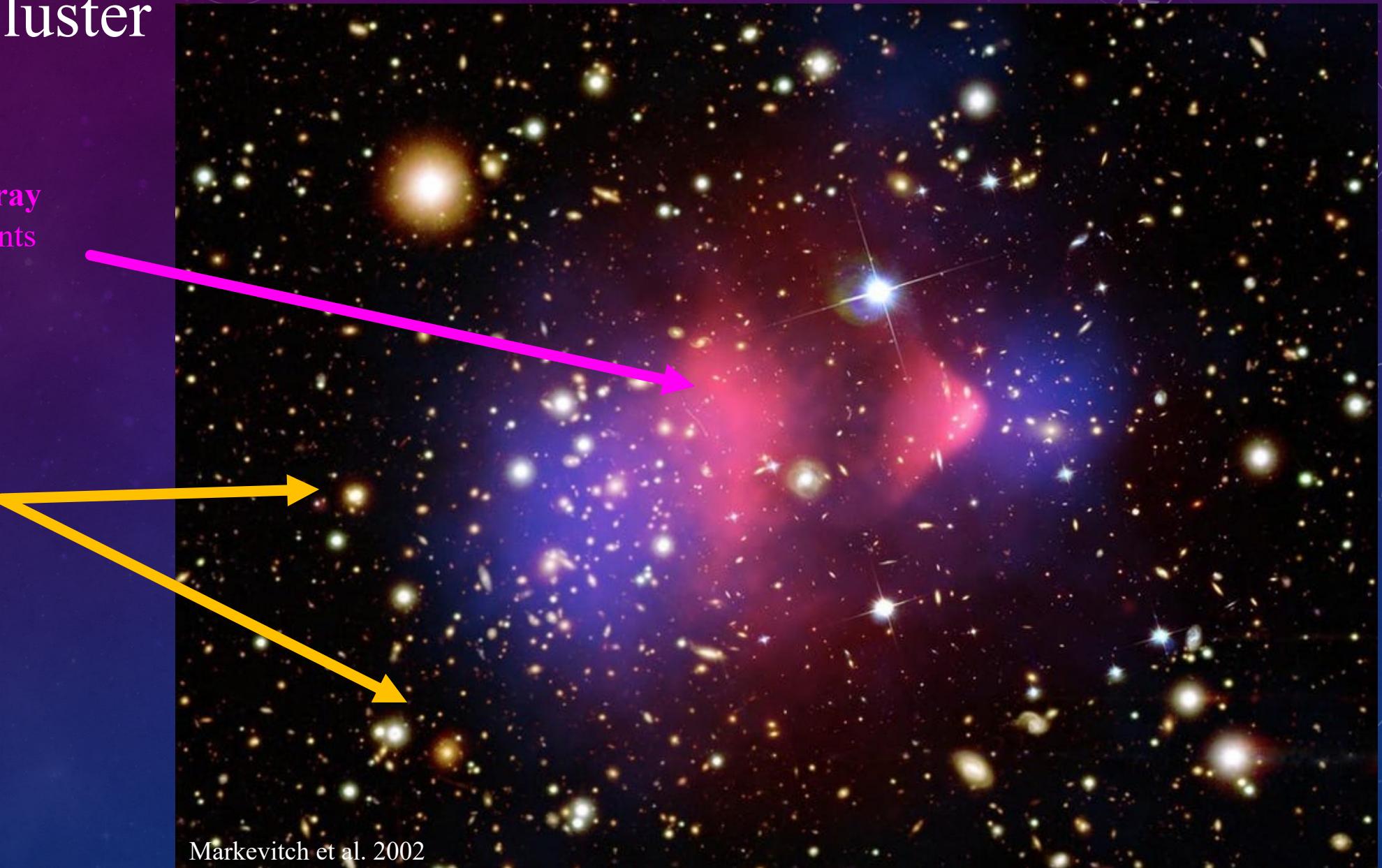
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Component Galaxies

Optical, for lensing

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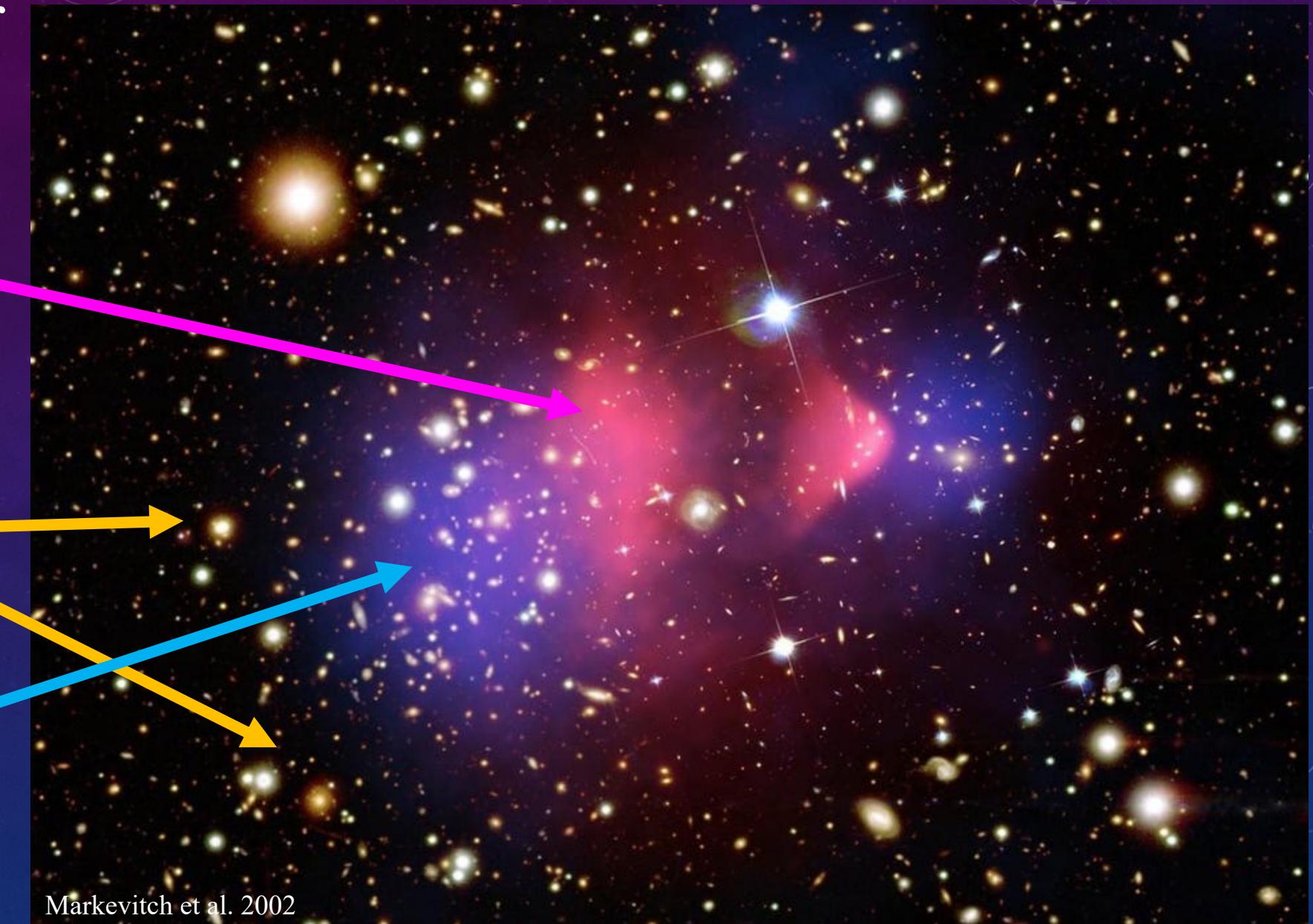
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Lensing

Majority of mass



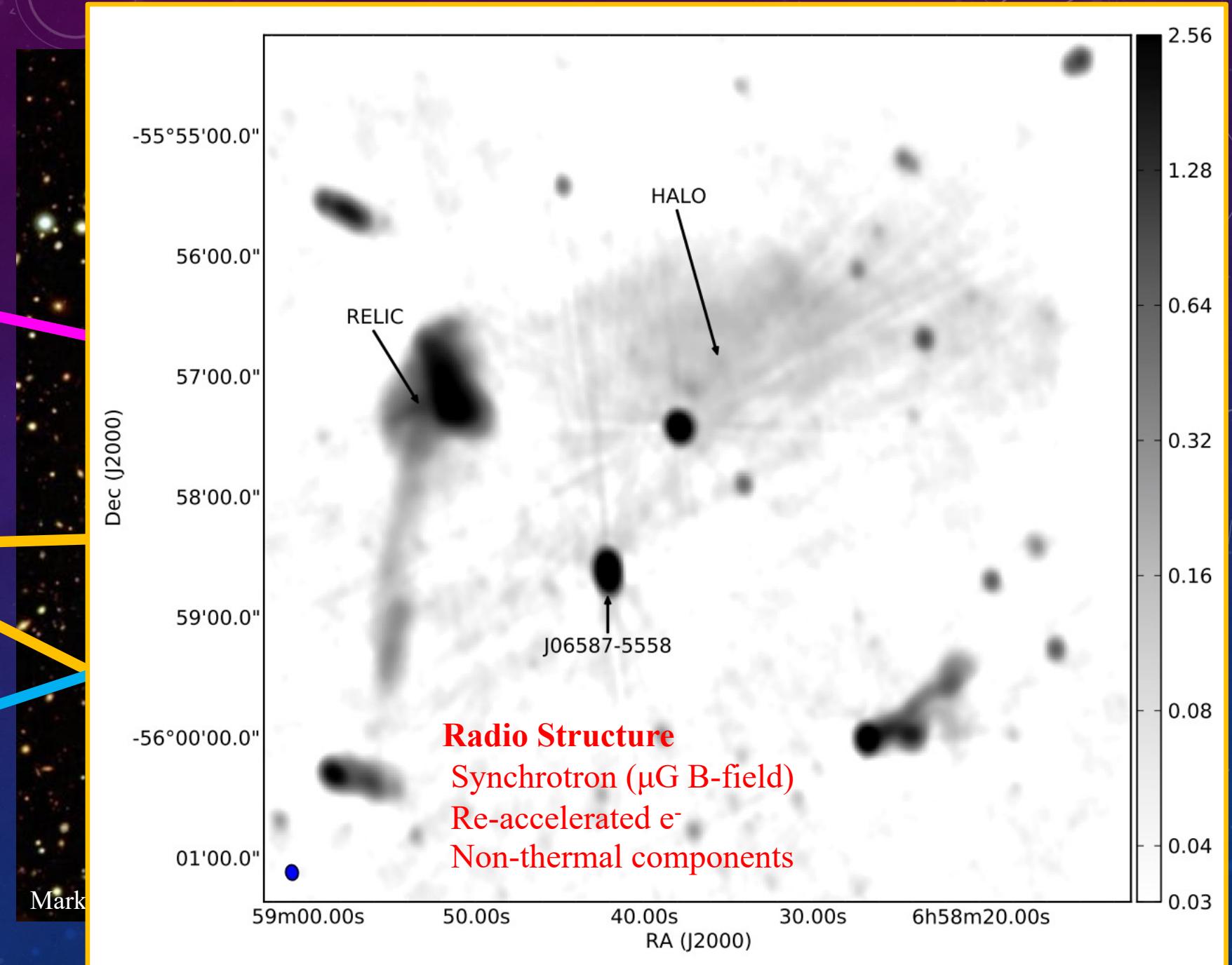
Markevitch et al. 2002

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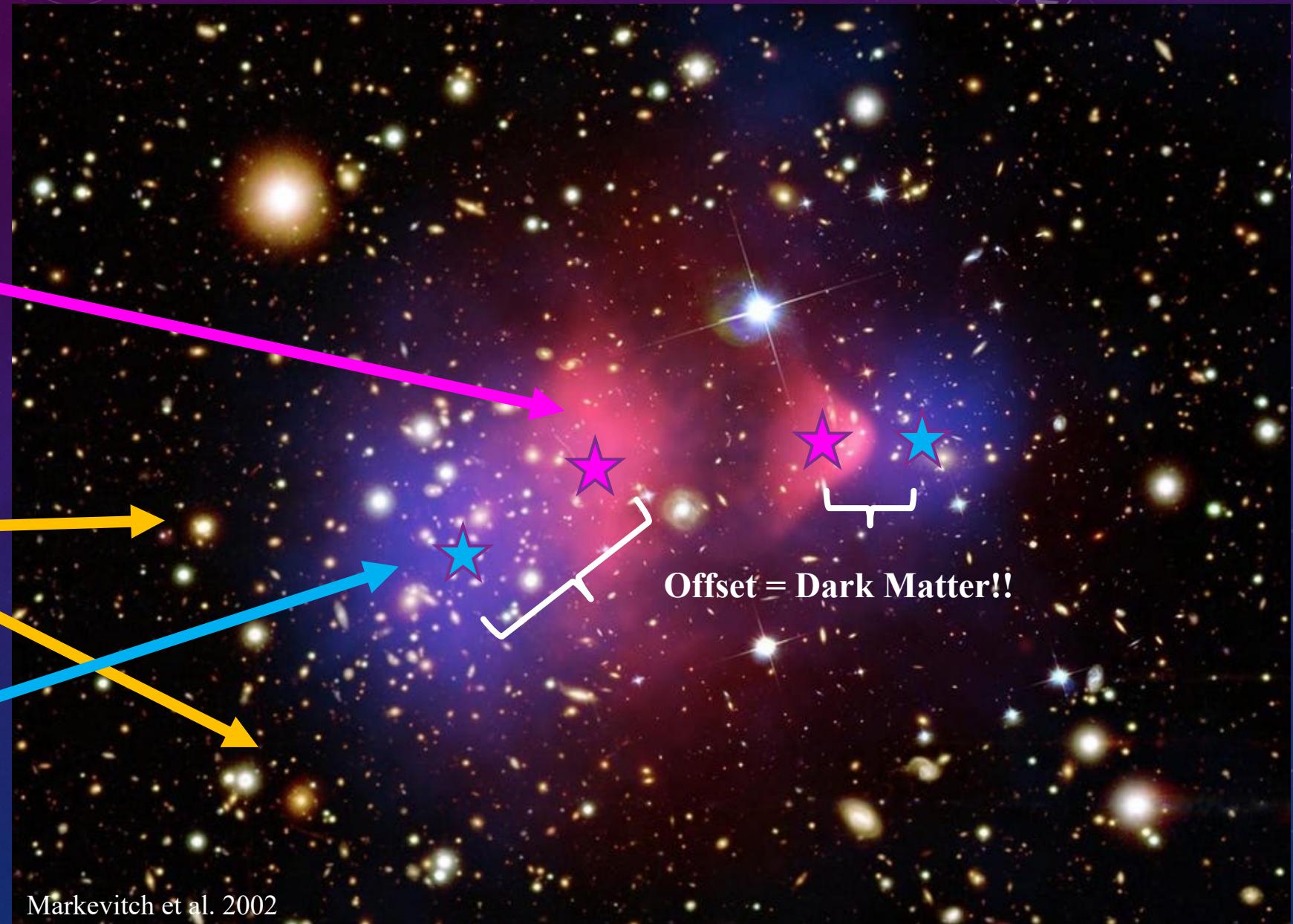


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Λ CDM

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Fundamental dark energy
constant w/ constant
energy density

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Fundamental dark energy
constant w/ constant
energy density

Non-baryonic
Cold
Dissipationless
Collisionless

Λ CDM

CDM

Large-scale ✓

Small-scale ✗

- Core/cusp problem
- Dwarf galaxies problem
- Missing satellites problem (solved)
- High redshift galaxy problem (JWST!)

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So (ignoring
baryons),
CDM might need a
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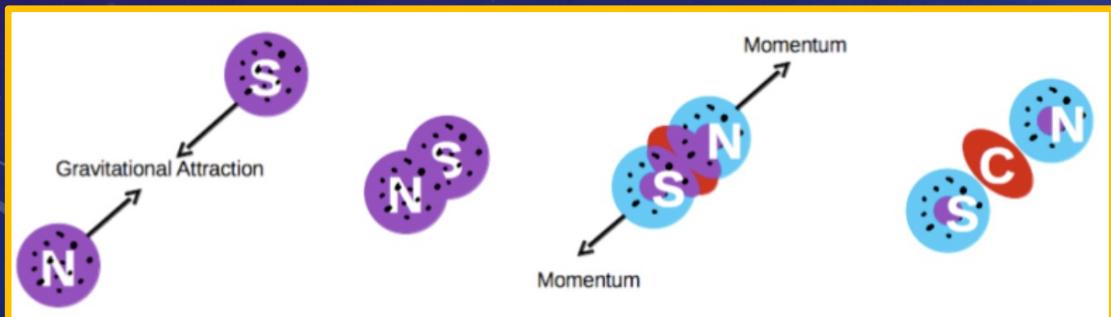
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Cold Dark Matter (CDM)



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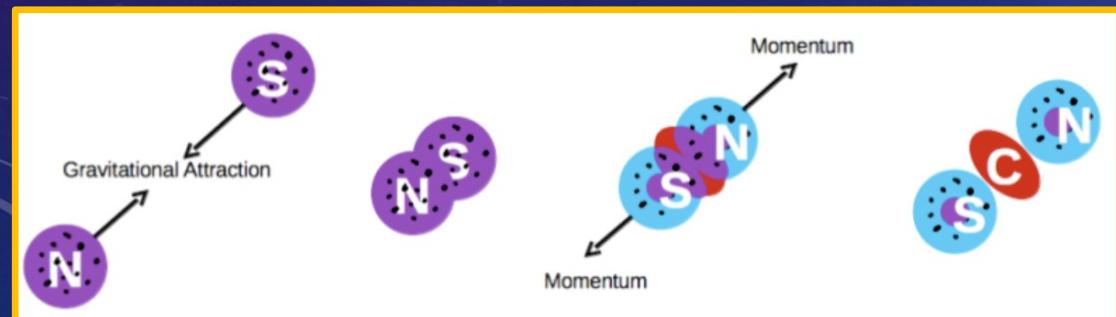
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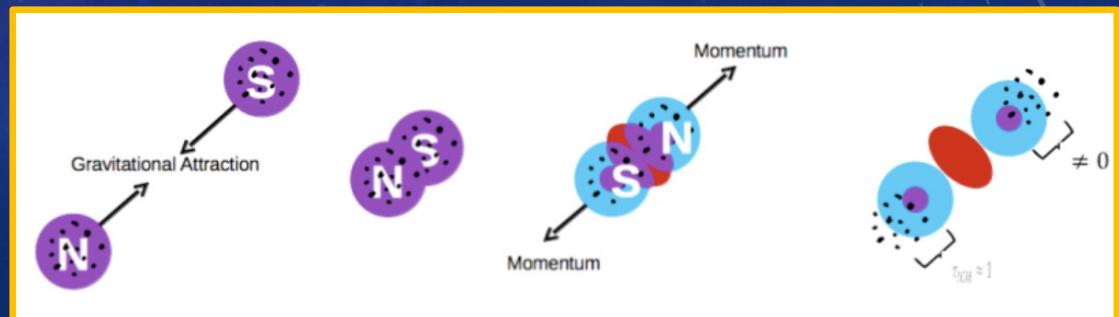
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What if CDM was
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Cold Dark Matter (CDM)



Self-interacting Dark Matter (SIDM)



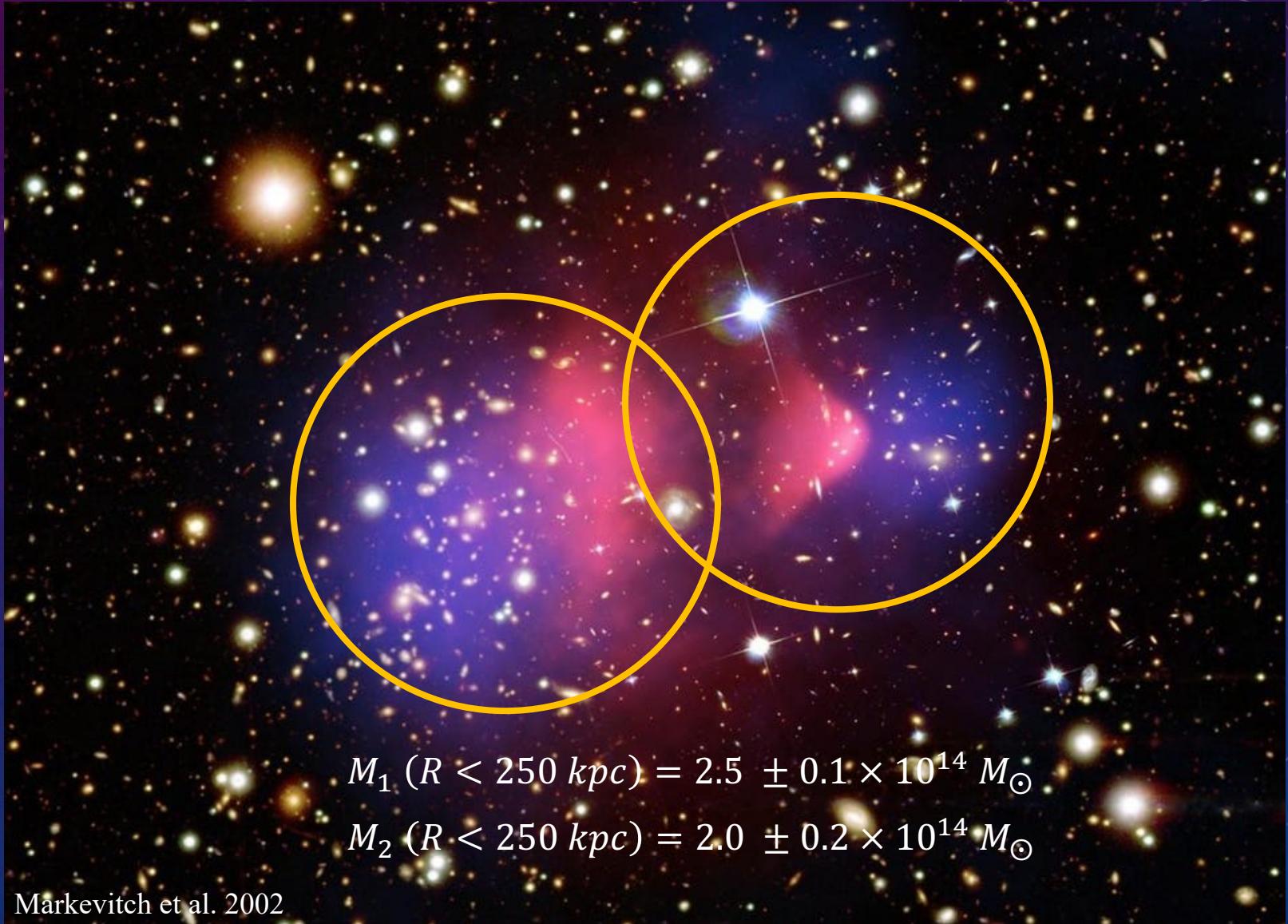
What type of mergers?



Markevitch et al. 2002

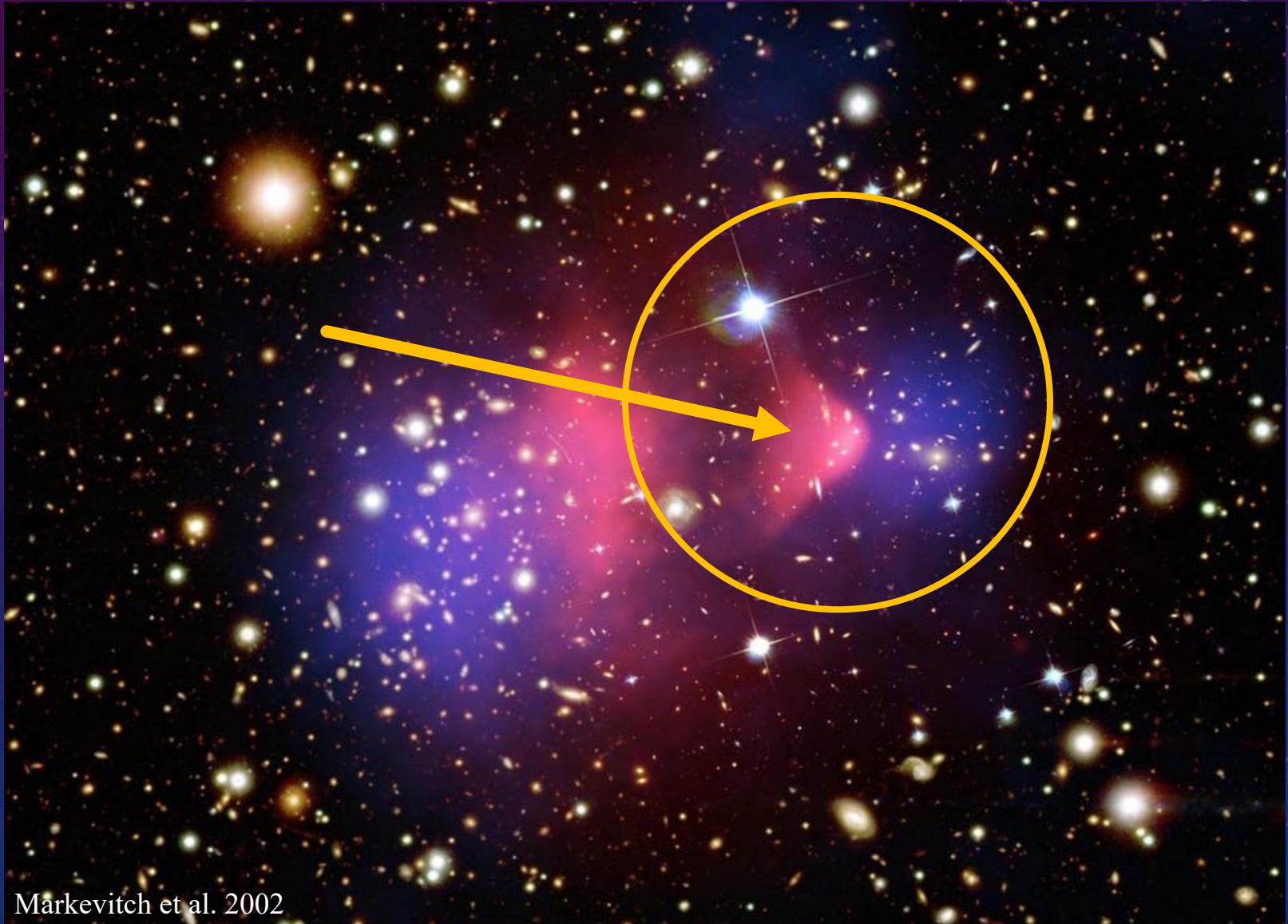
What type of mergers?

- Two subclusters of comparable mass



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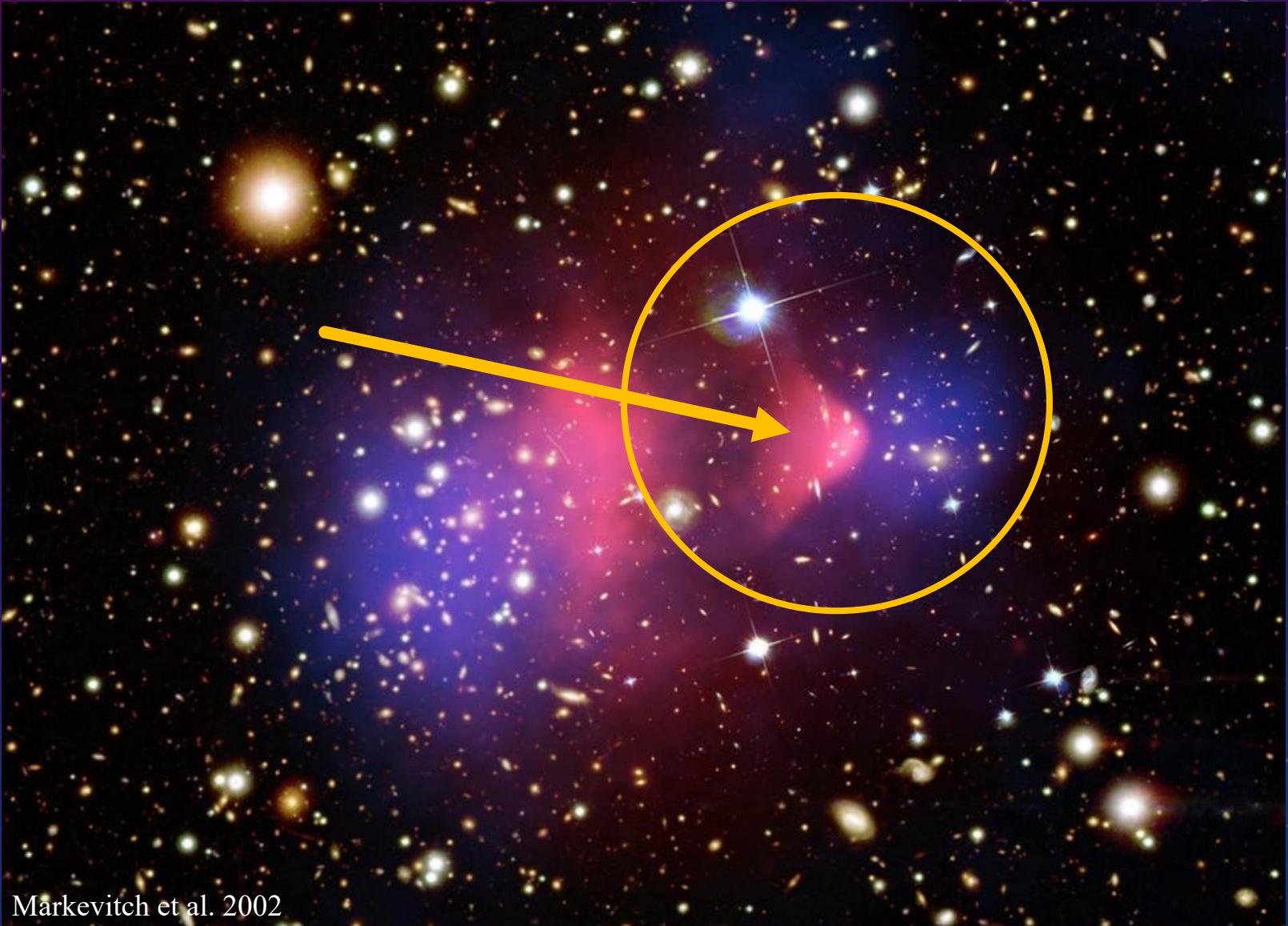
- Two subclusters of comparable mass
- Small impact parameter (nearly head on)



Markevitch et al. 2002

What type of mergers?

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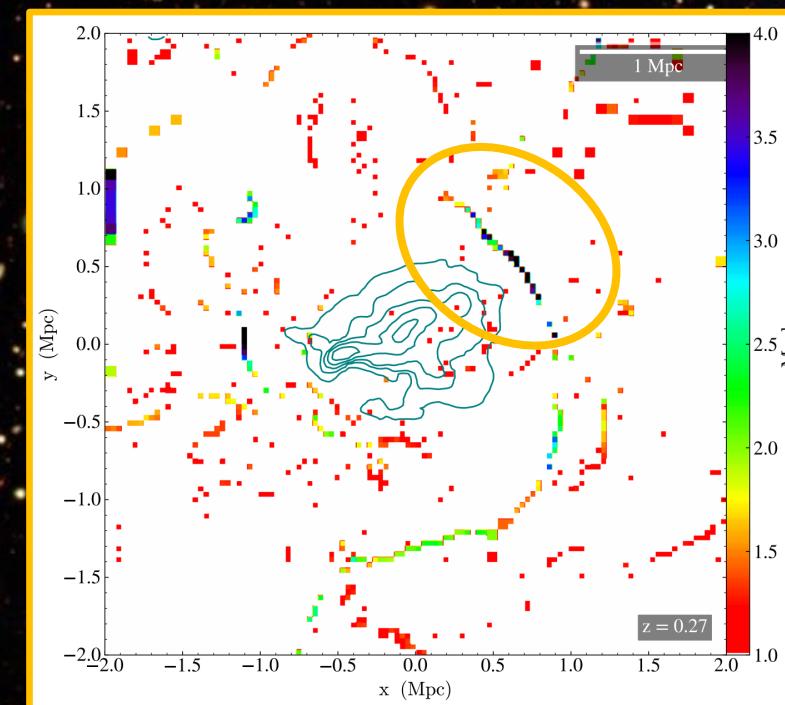


Markevitch et al. 2002

What type of mergers?

- Two subclusters of comparable mass
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- Occurs transverse to LOS (maximizing observed angular separation)
- Before DM halos relax!

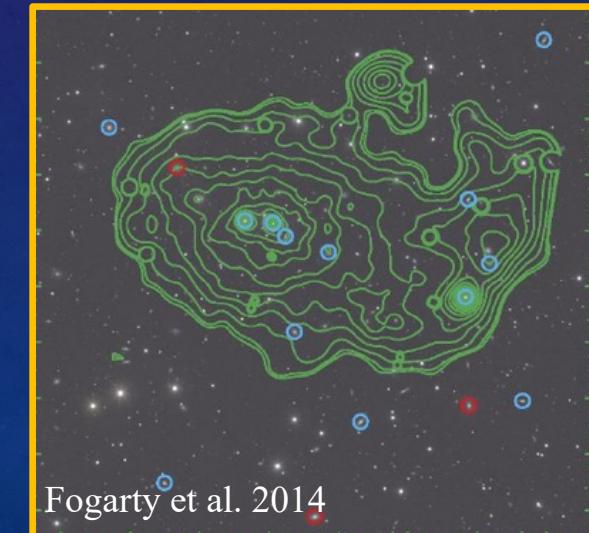
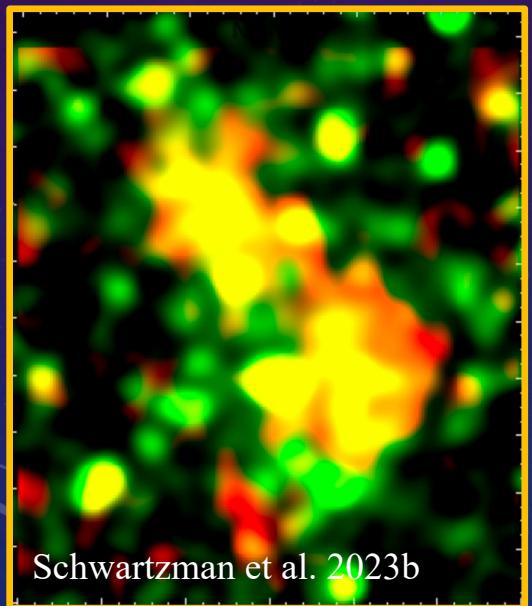
Paul et al. 2018



$M = 3.5 \rightarrow$ strong shock

Markevitch et al. 2002

Post-core passage, dissociative mergers



Merger Analysis:

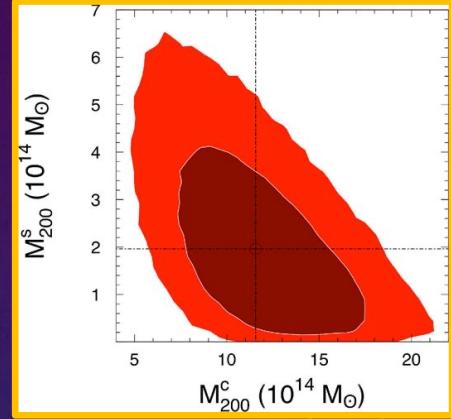
Weak-Lensing:

lensed background galaxies

Shape of merger, component galaxies

BCG location, subcluster mass

Line-of-sight of merger



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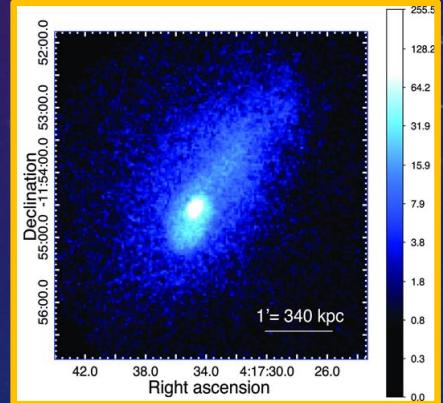
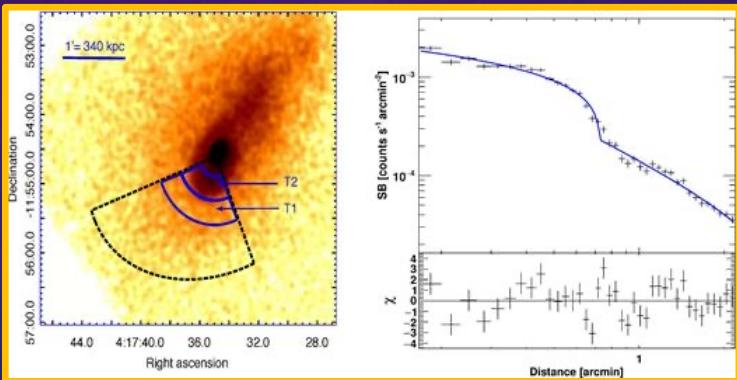
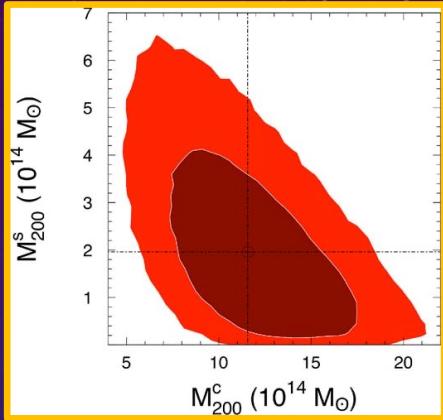
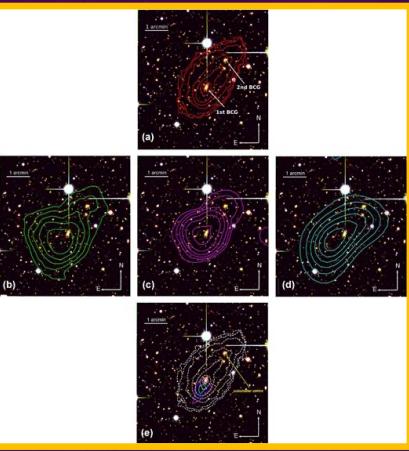
Line-of-sight of merger

X-ray:

Emission of ICM

Distribution + peak location

Substructure!



Merger Analysis:

Weak-Lensing:

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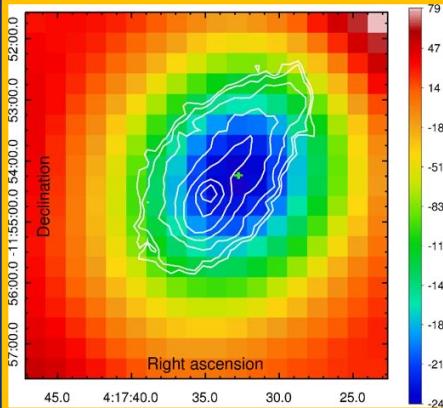
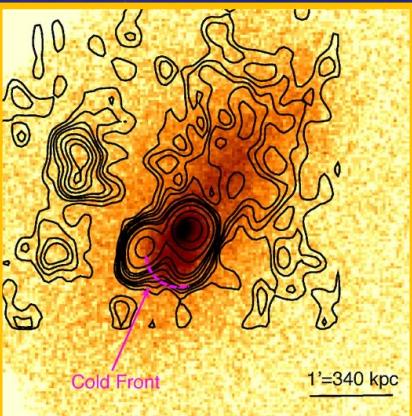
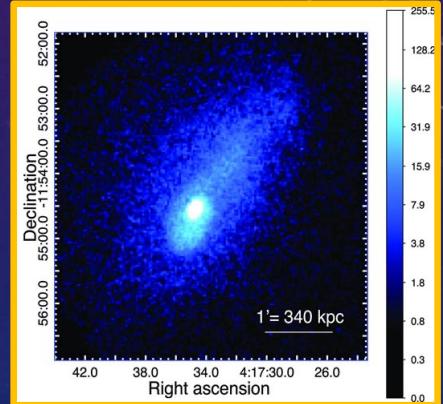
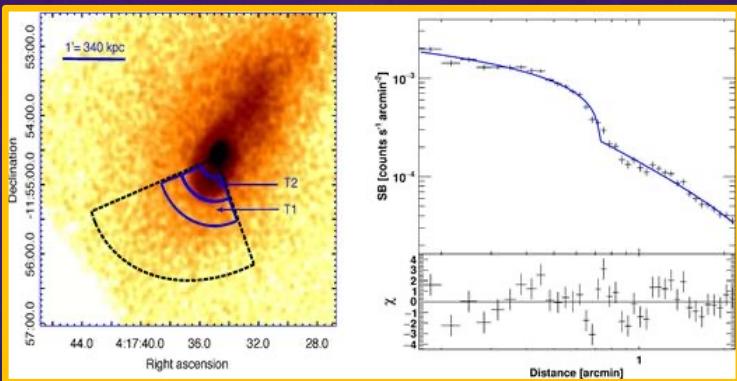
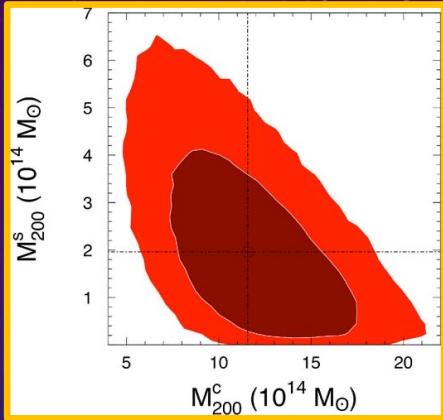
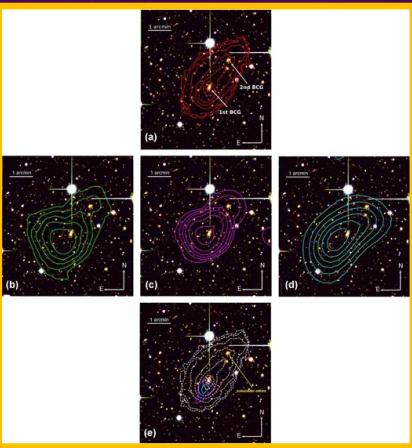
Radio:

Synchrotron emission

Substructure – shocks, fossil plasma

Re-acceleration mechanisms

Polarization



SIDM Constraints – What are we actually measuring?

$$\frac{\sigma_m}{m_{DM}}$$

DM cross section
per unit DM
particle mass

Observable processes at various energy scales:

Gas-DM offset → mass surface density

Subcluster Mass Loss → velocity loss

Survival of DM Cluster → particle loss

Dark Matter Core Profiles → density profiles

Wobbly BCGs → displacement

Bullet Cluster:

Mass-to-light ratio → constrains possible integrated mass loss

Projected DM halo density → DM halo becomes optically thick

Peak location → projected offsets between DM and galaxies

SIDM Constraints

Results from Bullet Cluster:

Projected DM density of
main subcluster halo

$$< 3 \text{ cm}^2/\text{g}$$

Mass-to-light ratio

$$< 0.7 \text{ cm}^2/\text{g}$$

Mass peak locations

$$< 1.25 \text{ cm}^2/\text{g}$$

CDM would be = 0 cm²/g...



SIDM Constraints

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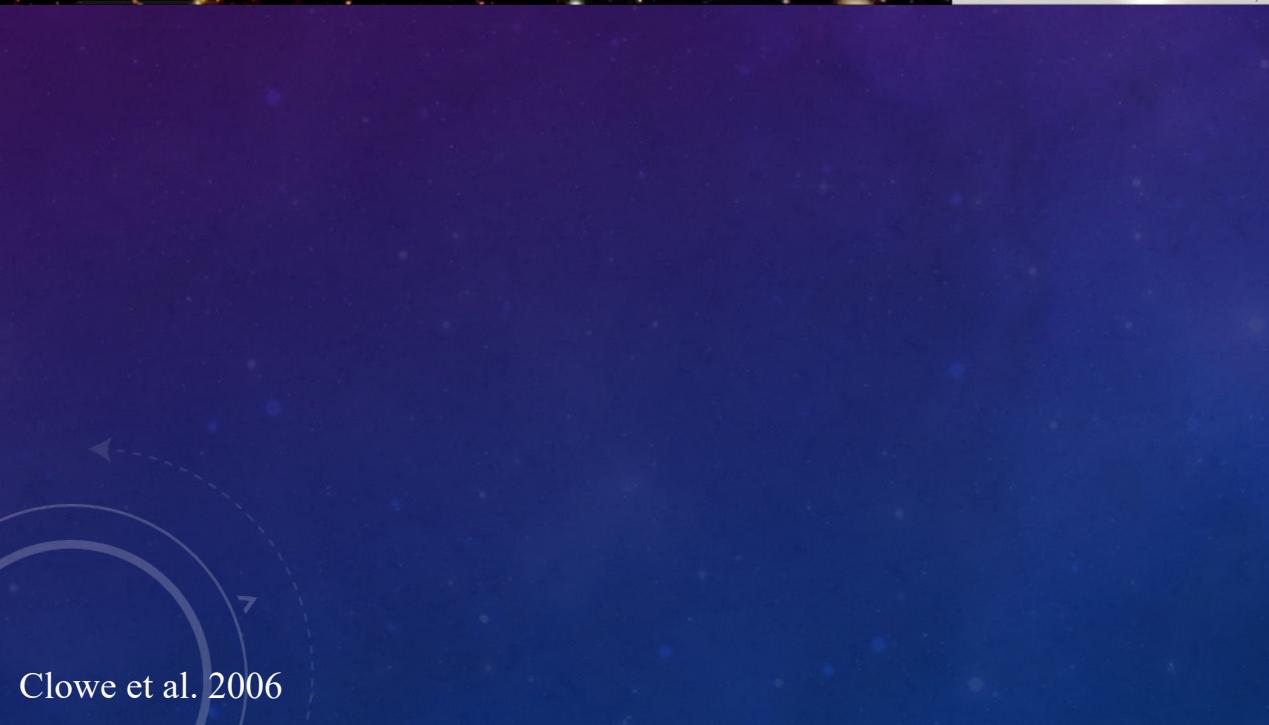
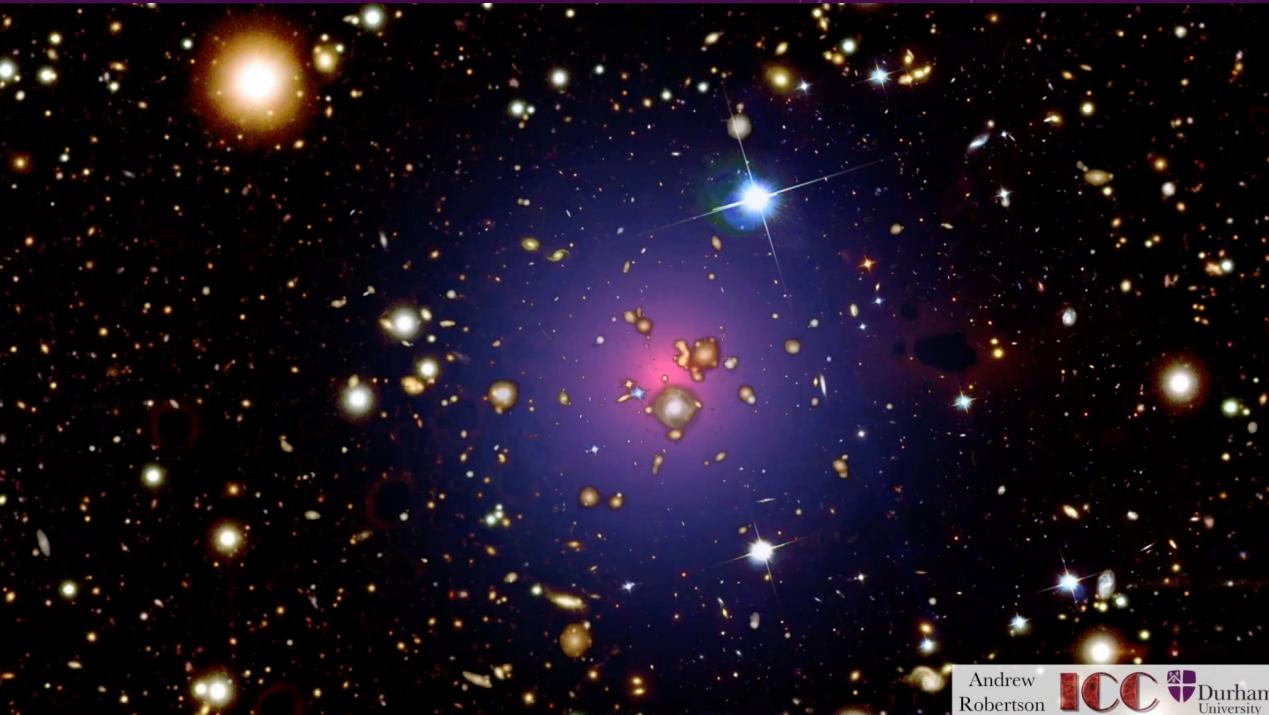
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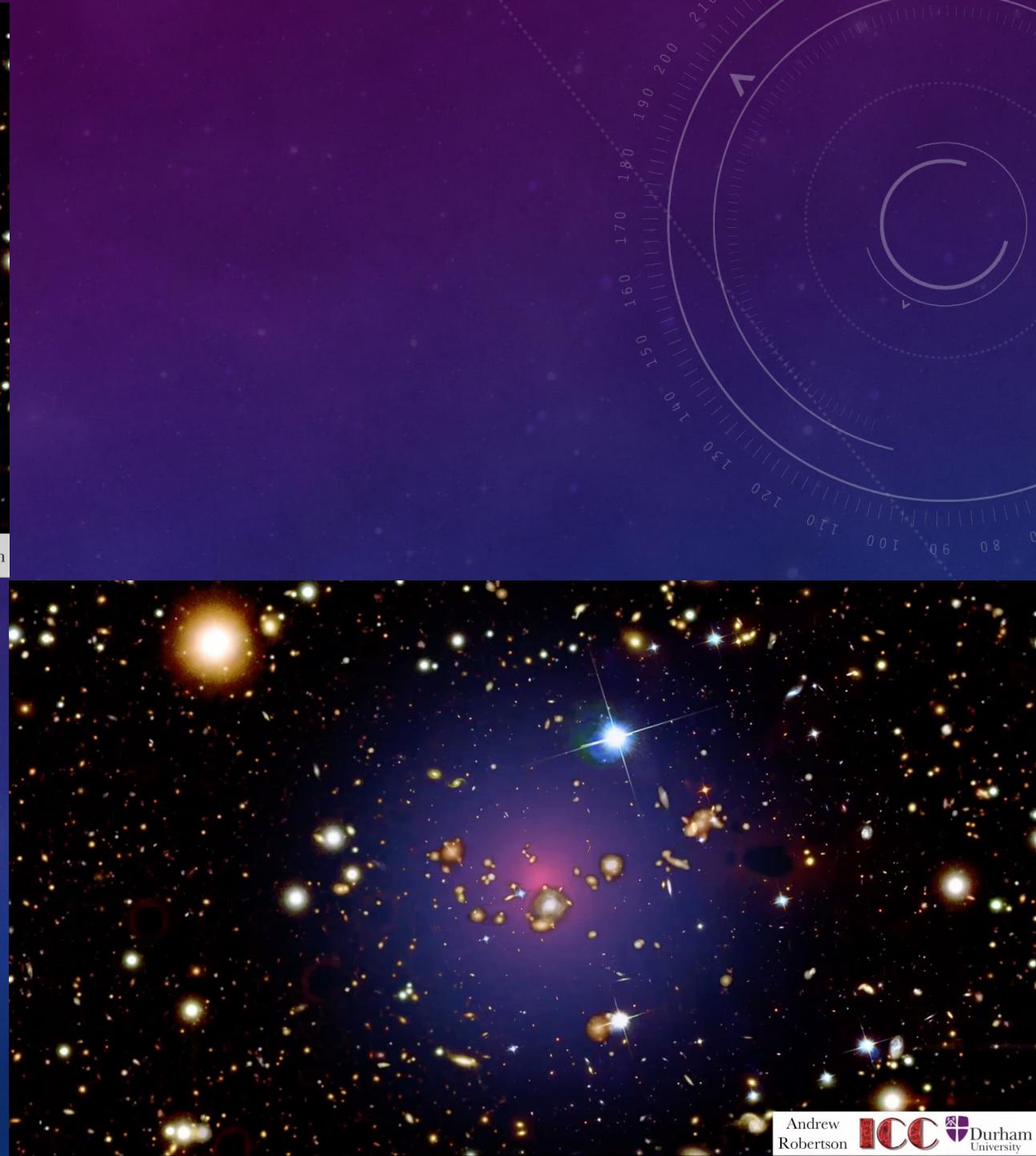
CDM would be = 0 cm^2/g ...

Bullet Cluster is NOT
entirely collisionless, and
cannot be described by CDM!

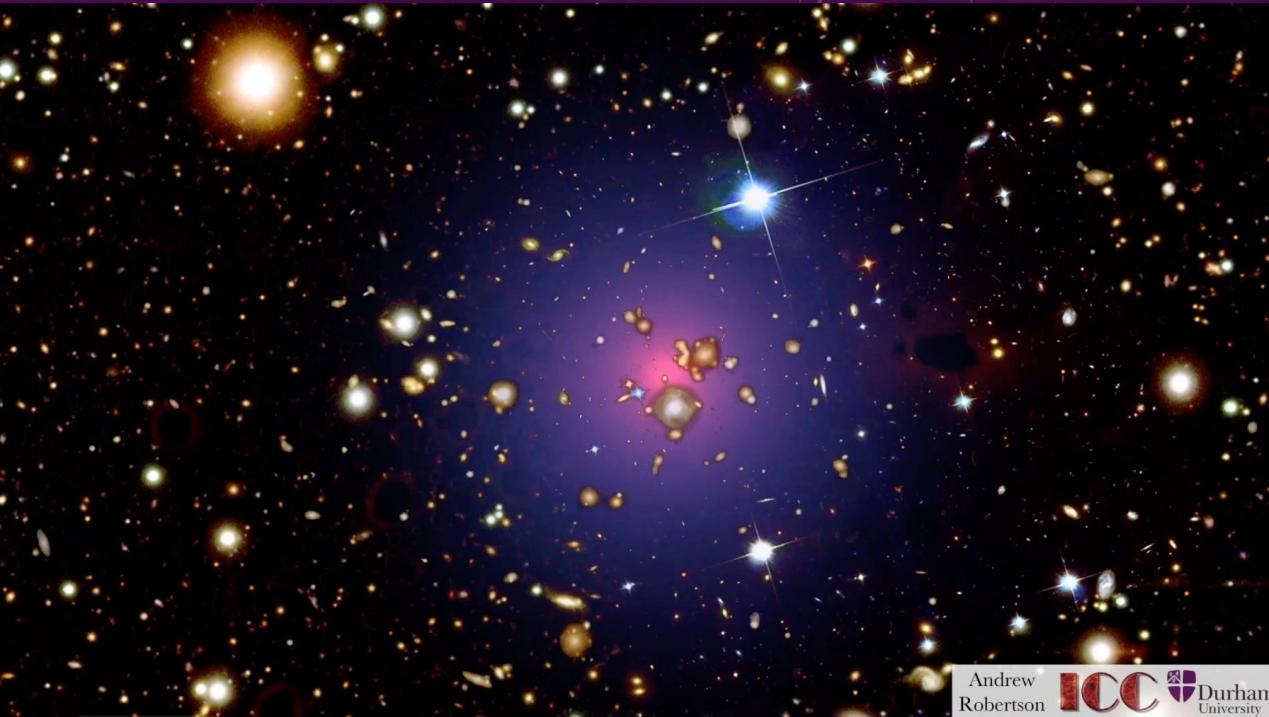




Clowe et al. 2006

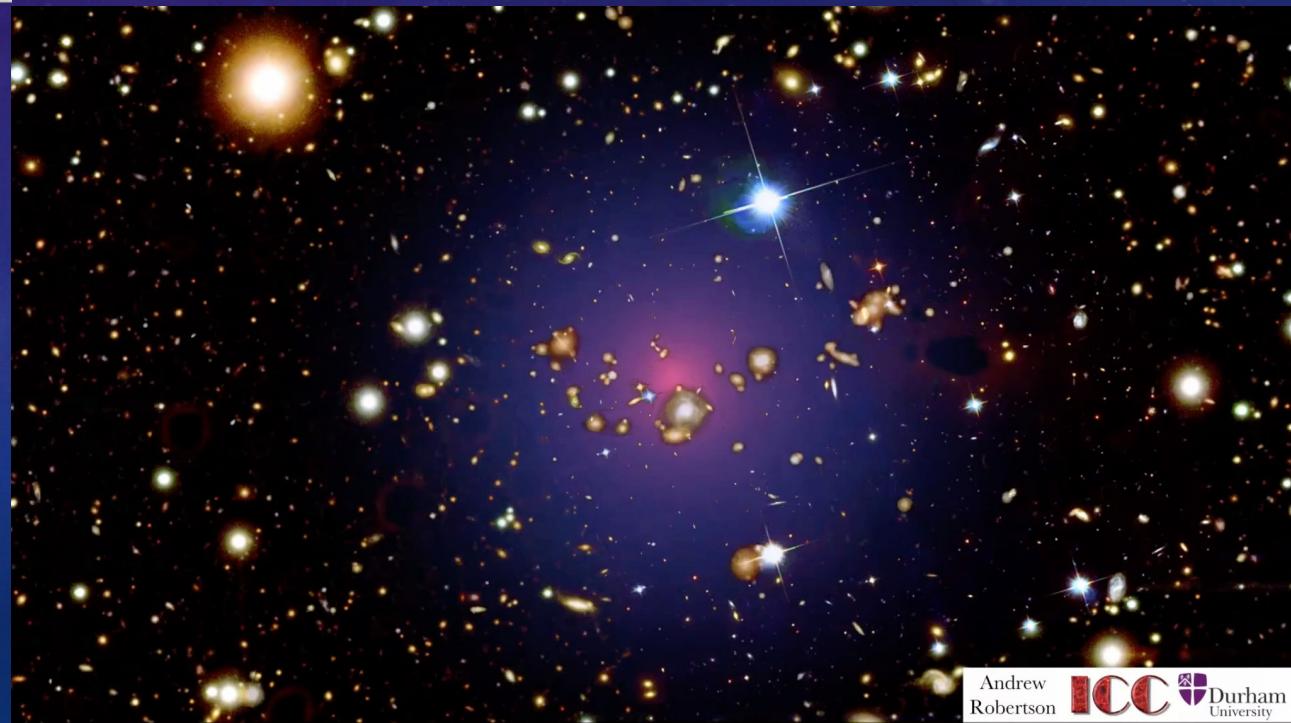


Andrew Robertson ICCC Durham University

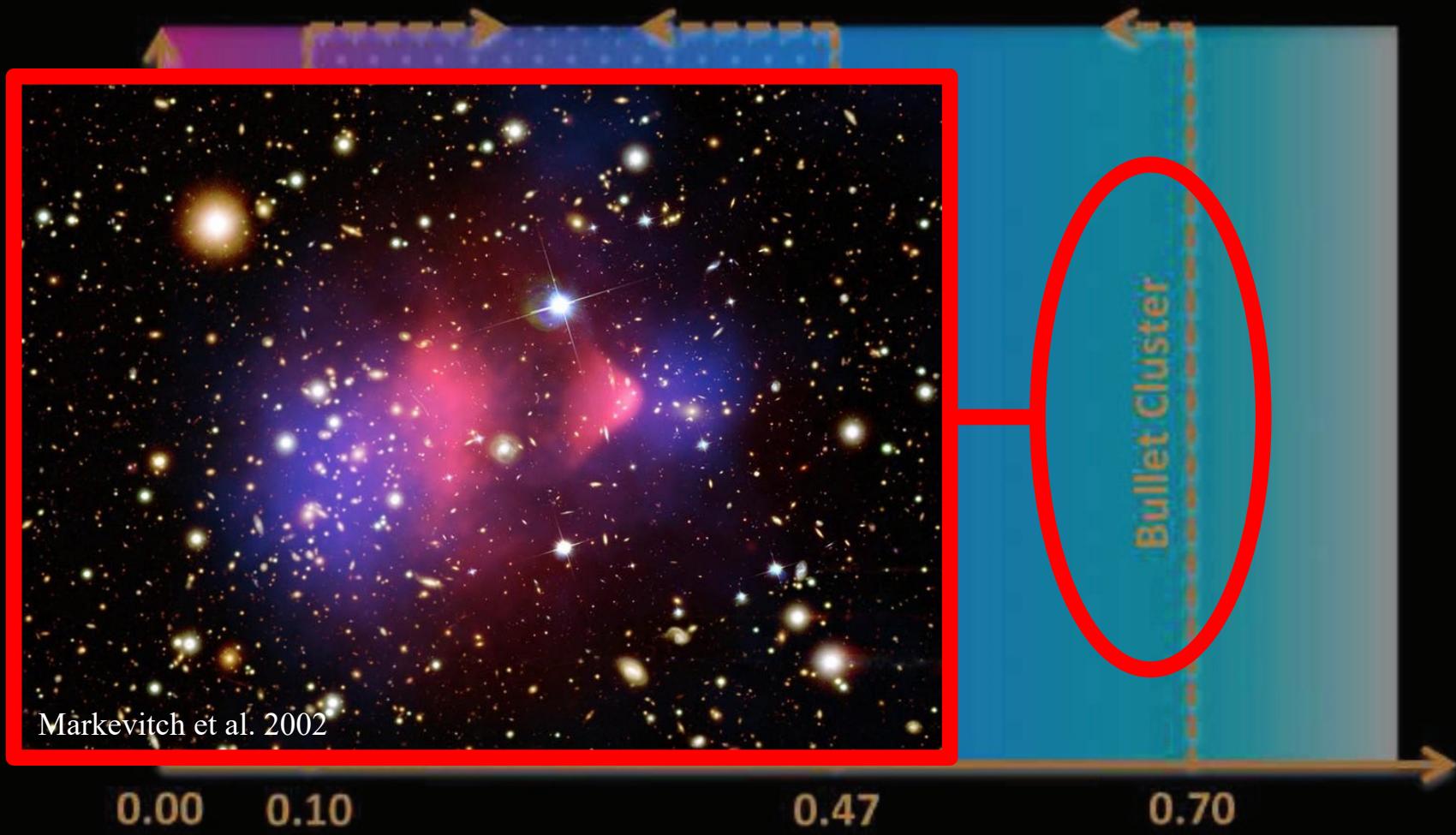


SIDM →

← CDM



THE NEW PICTURE OF DARK MATTER

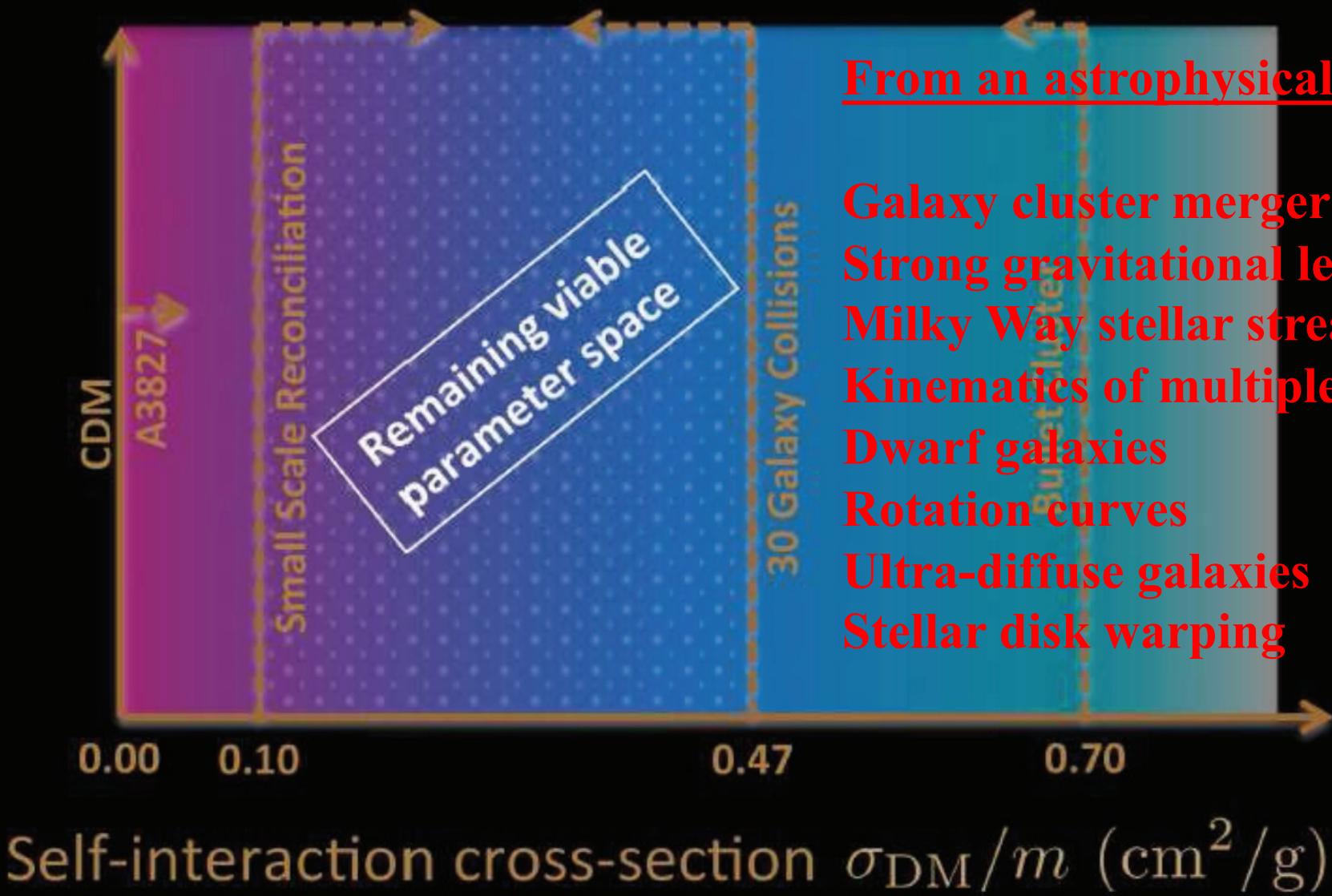


THE NEW PICTURE OF DARK MATTER



Self-interaction cross-section σ_{DM}/m (cm^2/g)

THE NEW PICTURE OF DARK MATTER



From an astrophysical perspective:

- Galaxy cluster mergers
- Strong gravitational lensing
- Milky Way stellar streams
- Kinematics of multiple BCGs
- Dwarf galaxies
- Rotation curves
- Ultra-diffuse galaxies
- Stellar disk warping

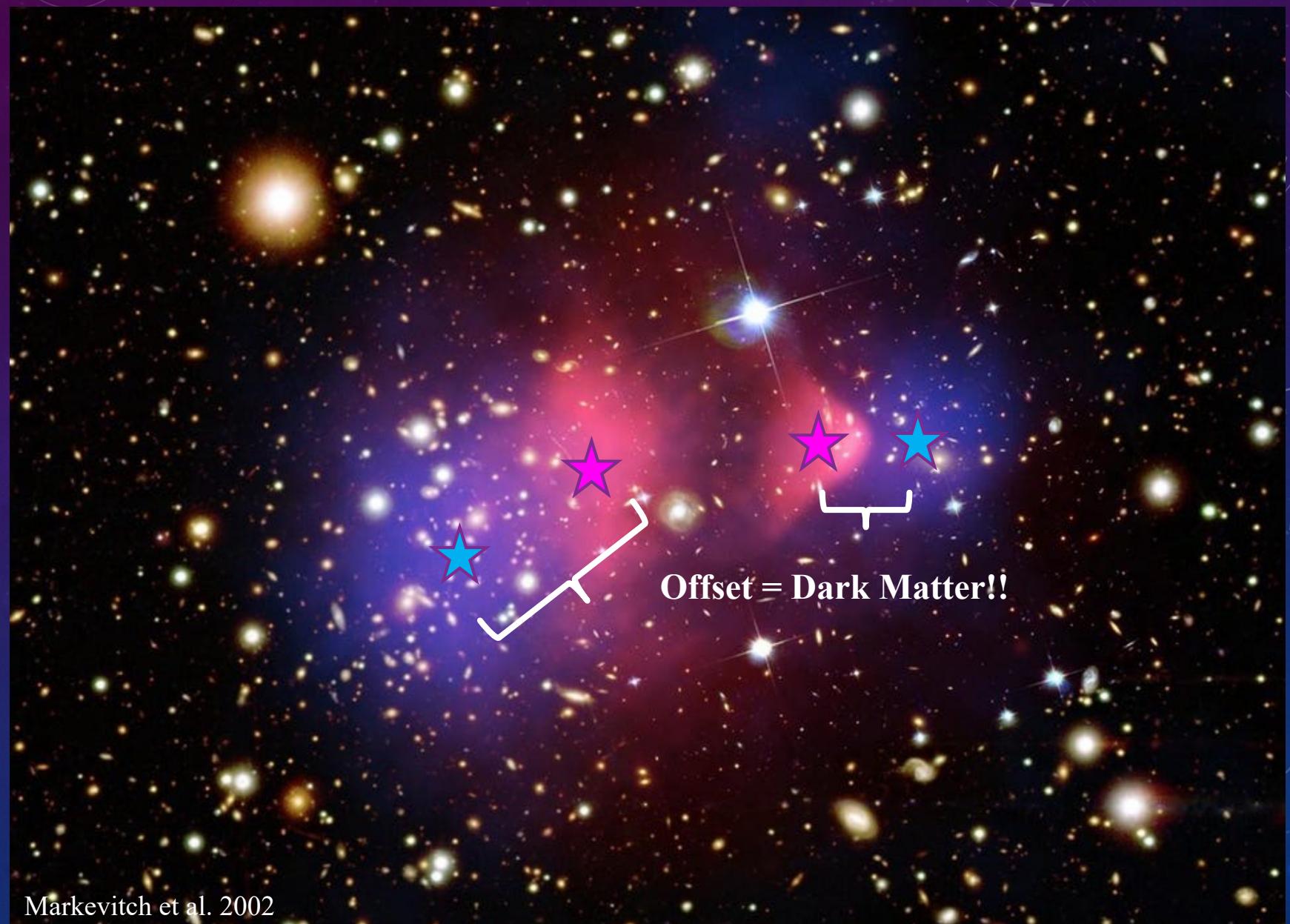
Conclusions

Galaxy cluster mergers are direct proof of dark matter.

Mergers can be used to study and improve the currently accepted Λ CDM model.

Cosmology is fundamental and thus it is crucial that we continually improve our models.

Galaxy clusters and dark matter are inseparable. We should build our understanding of them together.



Markevitch et al. 2002



QUESTIONS?

