

Galaxy Mergers on FIRE

Jorge Moreno

 [@astroboy_moreno](https://twitter.com/astroboy_moreno)
[#galpath16](https://twitter.com/astroboy_moreno)

CAL POLY POMONA



HARVARD-SMITHSONIAN
CENTER FOR ASTROPHYSICS

Paul Torrey | Phil Hopkins
Sara Ellison | David Patton
Lars Hernquist + FIRE Collaboration



AZTLÁN INSTITUTE
BANNEKER INSTITUTE

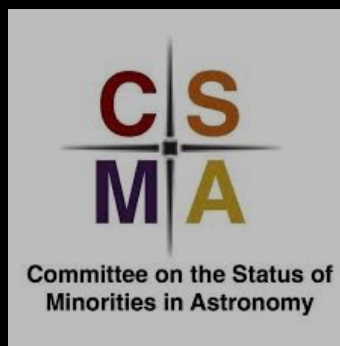


Remi Rimple | Adrianna Pérez | Luis Nuñez | José Flores | Areli Rojas
(Not Shown: Francisco Mercado)

Award #1516374



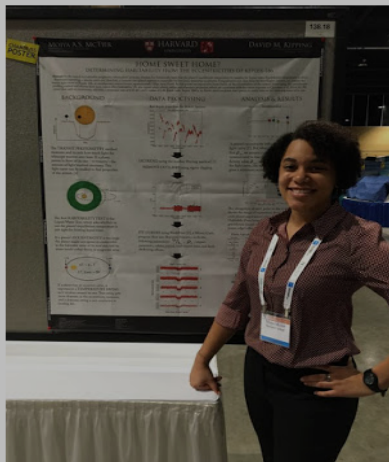
National Science Foundation
WHERE DISCOVERIES BEGIN



Astronomy in Color

In pursuit of social justice, diversity and excellence in astronomy

<http://astronomyincolor.blogspot.com>



Moiya McTier (Harvard '16)
Recipient of the 2016 Chambliss Award



Dr. Elisa Quintana, NASA Senior Research Fellow
at NASA AMES, lead discoverer of the Earth analog
Kepler-186f, and 2015 Hispanic Scientist of the Year



Carl Fields, ASU Astrophysics and Physics major and recipient
of the Beth Brown Memorial Award and Carl Rouse Fellowship



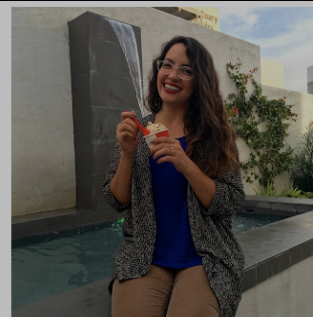
Ivanna Escala, graduate student at Caltech
Award recipient at the 2015 CAMP Symposium



Amy Steele (PhD Candidate, UMPC)
Hon. Mention, 2016 Chambliss Award



Dr. Lia Corrales, Postdoc at MIT
Recipient of the Einstein Prize Fellowship



Katy Rodriguez Wimberly . Master's student at CSU Long Beach
Recipient of an NSF Graduate Research Fellowship
Next Fall: Ph.D Candidate at **UC Irvine**



Christopher Moore, University of Colorado graduate student and
Beth Brown Memorial Prize recipient, speaking at the 227th AAS
meeting.



Greg Mosby is a PhD student at the University of Wisconsin - Madison
He is the recipient of a NASA Postdoctoral Fellowship



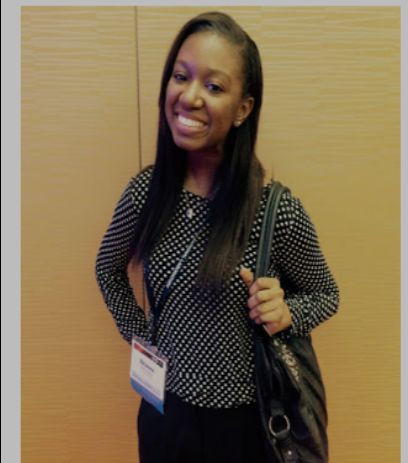
Xzavier Flowers, undergraduate Astronomy and Astrophysics major at
Florida Institute of Technology and Founder and CEO of Future
Astronomers.



Dr. Maritza Lara López
Assistant Professor at the IA-UNAM
Recipient of the 2016 L'Oreal's Award



Dr. Louise Edwards
Now: Astronomy Lecture at Yale
Next: Assistant Professor at Cal Poly San Luis Obispo

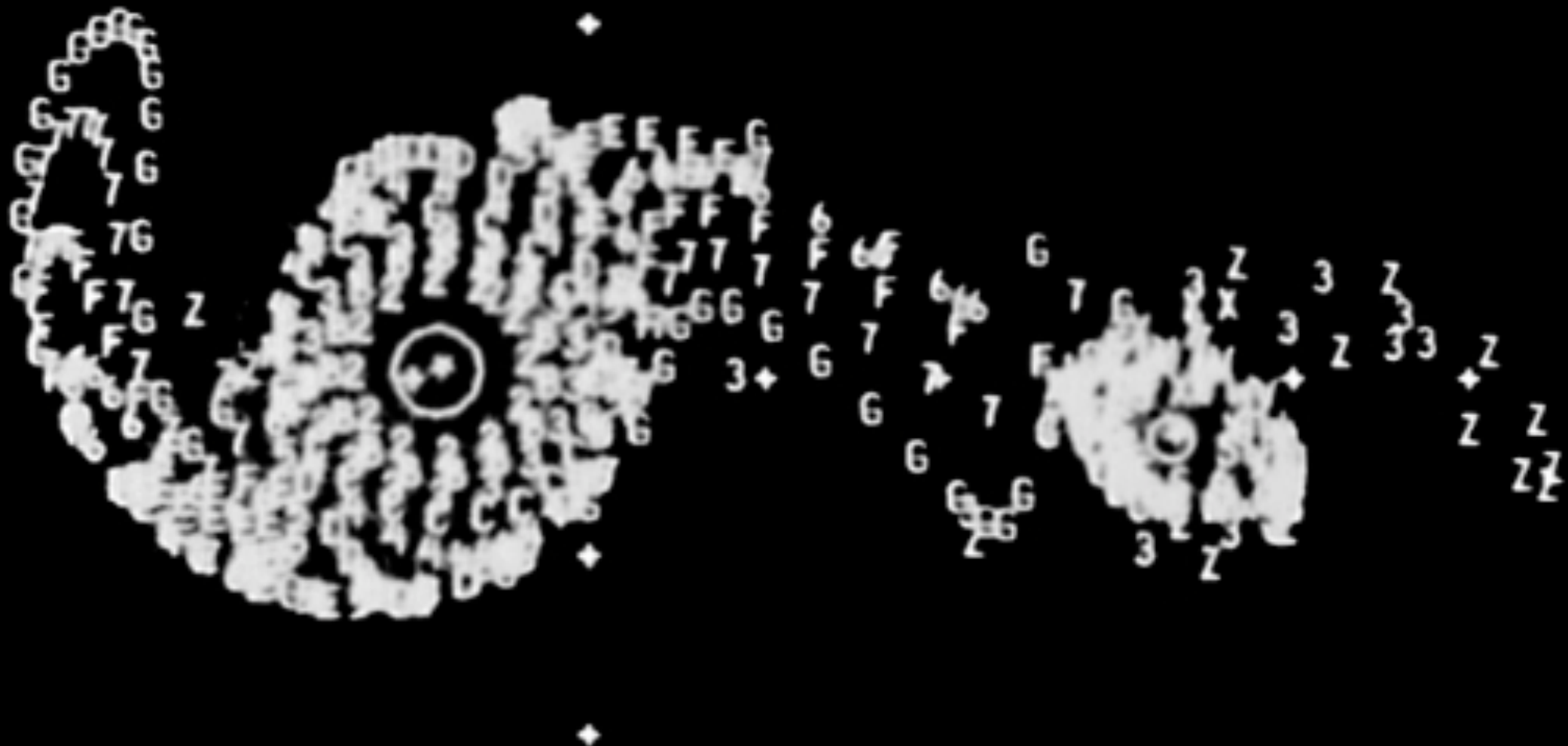


Brianna Thomas (Howard '17)
Recipient of the 2016 Chambliss Award

The background of the slide is a deep space image. It features a dark, almost black, field filled with numerous small, bright white stars. Some stars are sharp points of light, while others have a soft, out-of-focus glow. In the center of the image, there is a large, diffuse, and irregularly shaped cloud of light. This cloud has a mottled appearance with various shades of grey and white, suggesting a complex structure like a nebula or a galaxy in the process of merging. The overall effect is one of vastness and cosmic activity.

Galaxy Merger Simulations

Toomre & Toomre (1972)
Restoration: Michael Lauter



Holmberg (1941)

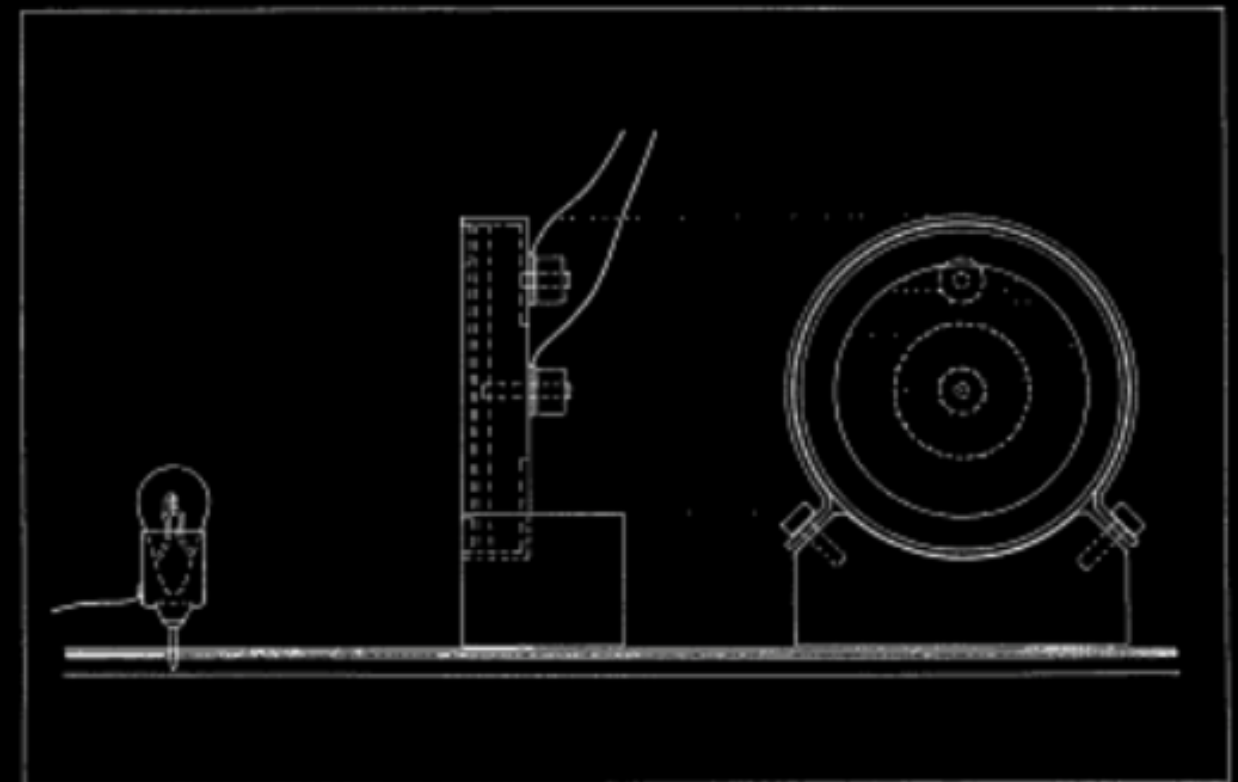
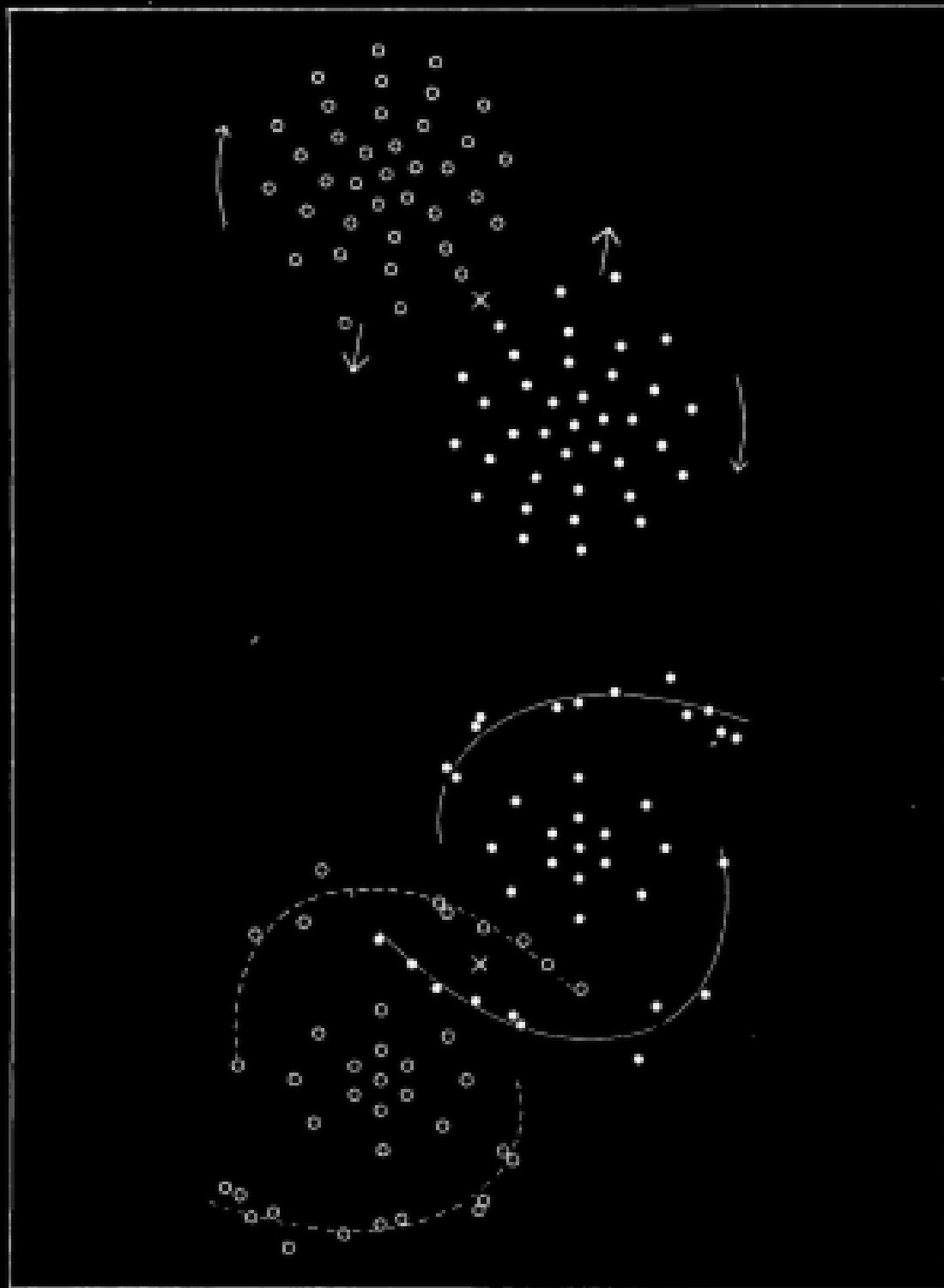
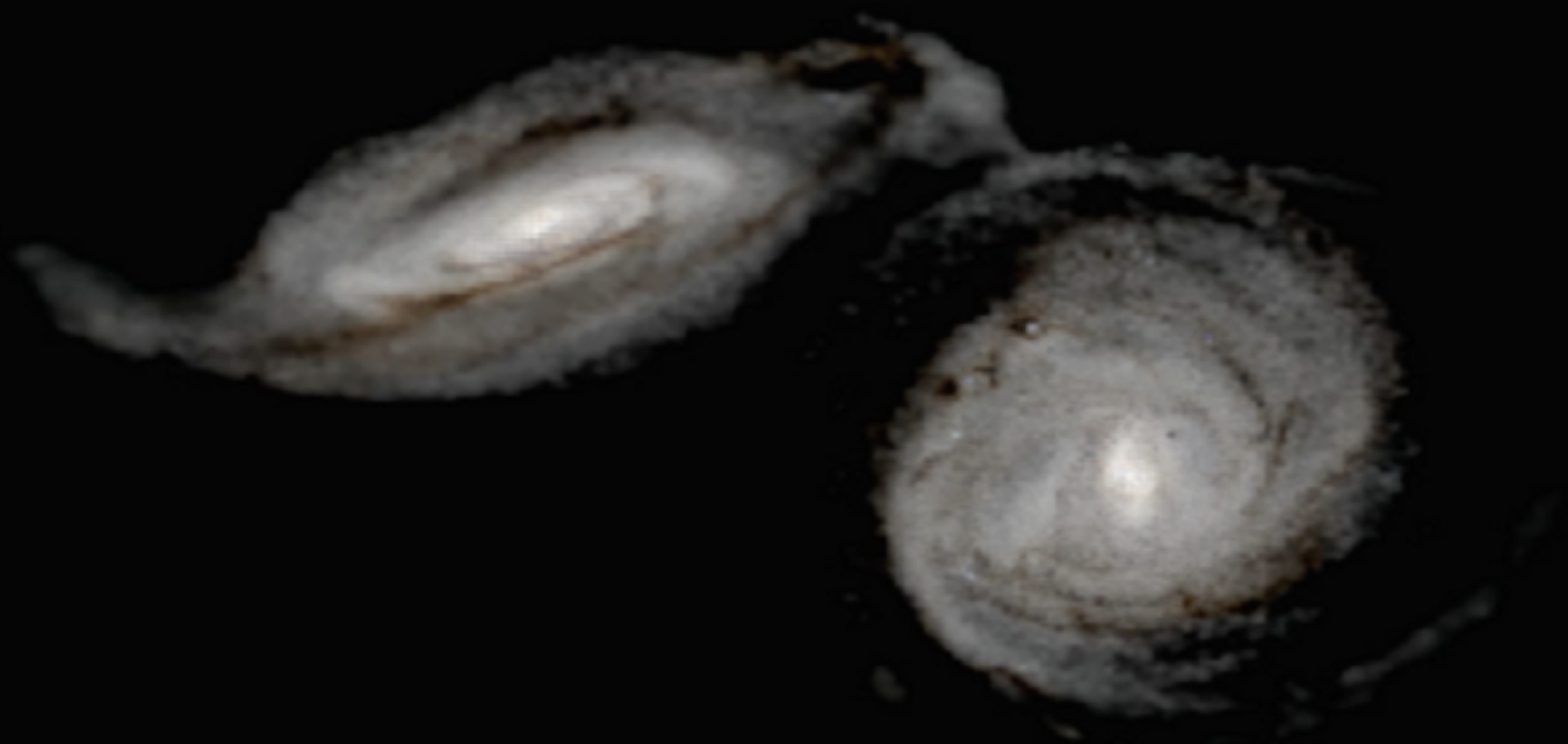


FIG. 1.—Cross-section of light-bulb and photocell (half-size)



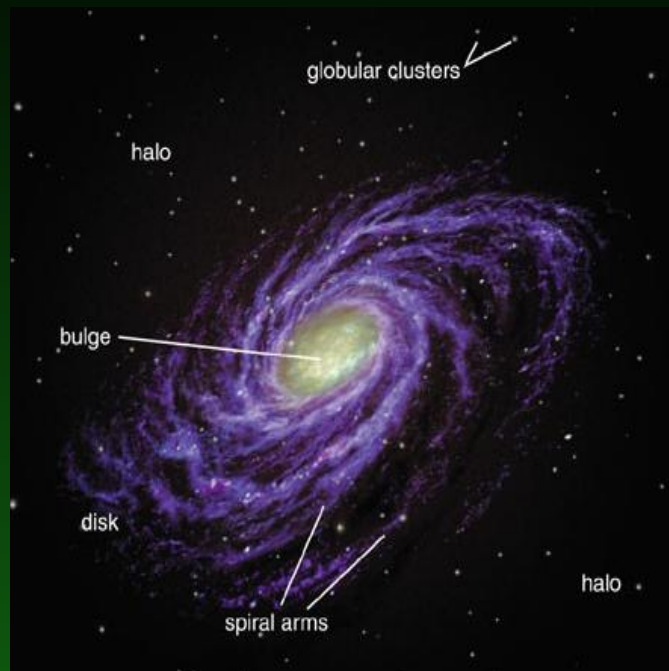


The background of the slide is a dark, deep space scene. It features a prominent, glowing nebula or galaxy core in the center, with intricate patterns of light and dark clouds. Scattered throughout the dark background are numerous stars of varying brightness, some appearing as sharp points of light and others as soft, out-of-focus glows. The overall color palette is dominated by blacks, greys, and the warm, reddish-pink hues of the nebula.

Motivation for New Galaxy Merger Simulations

Pillars of Galaxy Evolution

Internal Structure



Environment



Interaction History

Messier 81

Messier 82



The background of the slide is a dark, deep-space image. It features a prominent, bright, and diffuse nebula or galaxy core in the center, with a complex, filamentary structure. Scattered throughout the dark field are numerous small, bright stars, some of which exhibit prominent diffraction spikes. The overall color palette is dominated by blacks and greys, with the central nebula providing a source of light and texture.

Our Suites of Merger Simulations

Two Merger Suites



Orbits

Mass Ratios





Orbits Suite

FIXED: Mass, Mass Ratio, Morphology & Gas Fraction

VARYING:

Eccentricities:

$$\epsilon = \{0.85, 0.95, 1.05\}$$

Impact Parameters:

$$b = \{2, 8, 16\} \text{ kpc}$$

Spin-orbit orientations:

$$\{e, f, k\}$$

(prograde, perpendicular, retrograde)



Mass Ratios Suite

FIXED: Eccentricity, Impact Parameter & Orientation

VARYING: Mass

Morphology:

Gas fraction:

M_{disk} [$M_{\odot}$]	M_{bulge} [$M_{\odot}$]	$f_{\text{g,init}}$
6.6×10^8	1.3×10^7	38%
3.3×10^9	2.8×10^8	29%
9.4×10^9	1.1×10^9	24%
2.9×10^{10}	6.5×10^9	20%

The FIRE Project



The FIRE Project

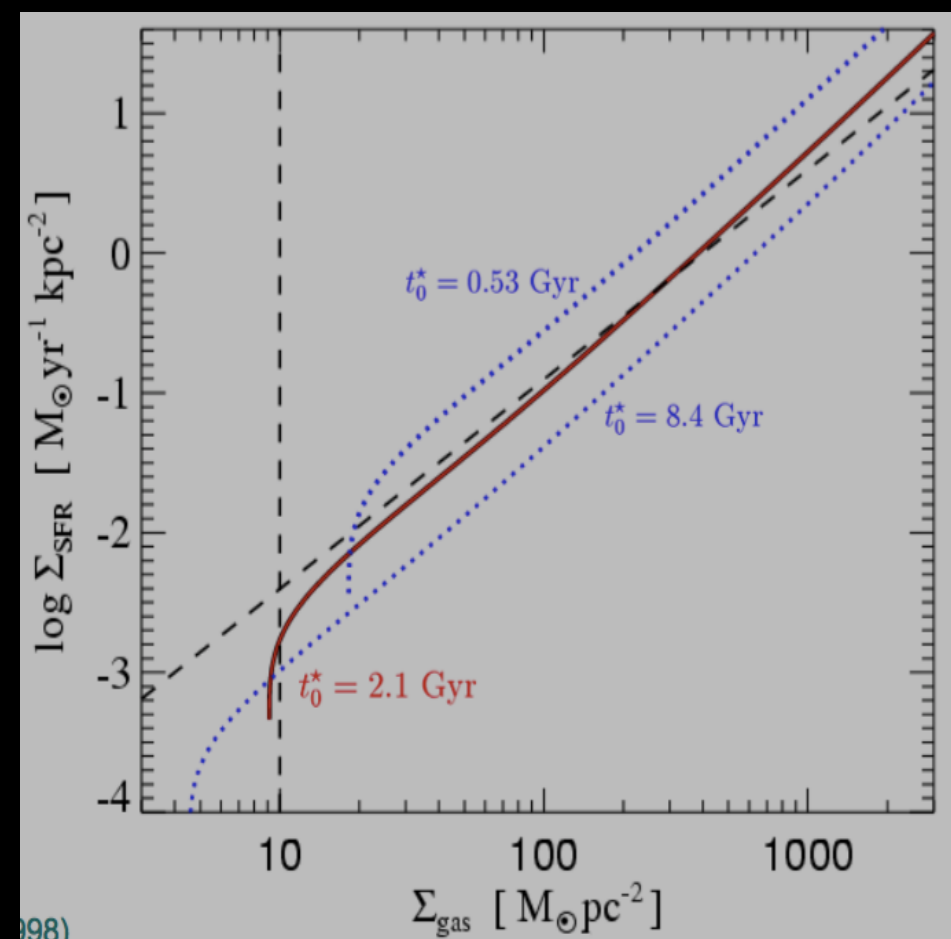
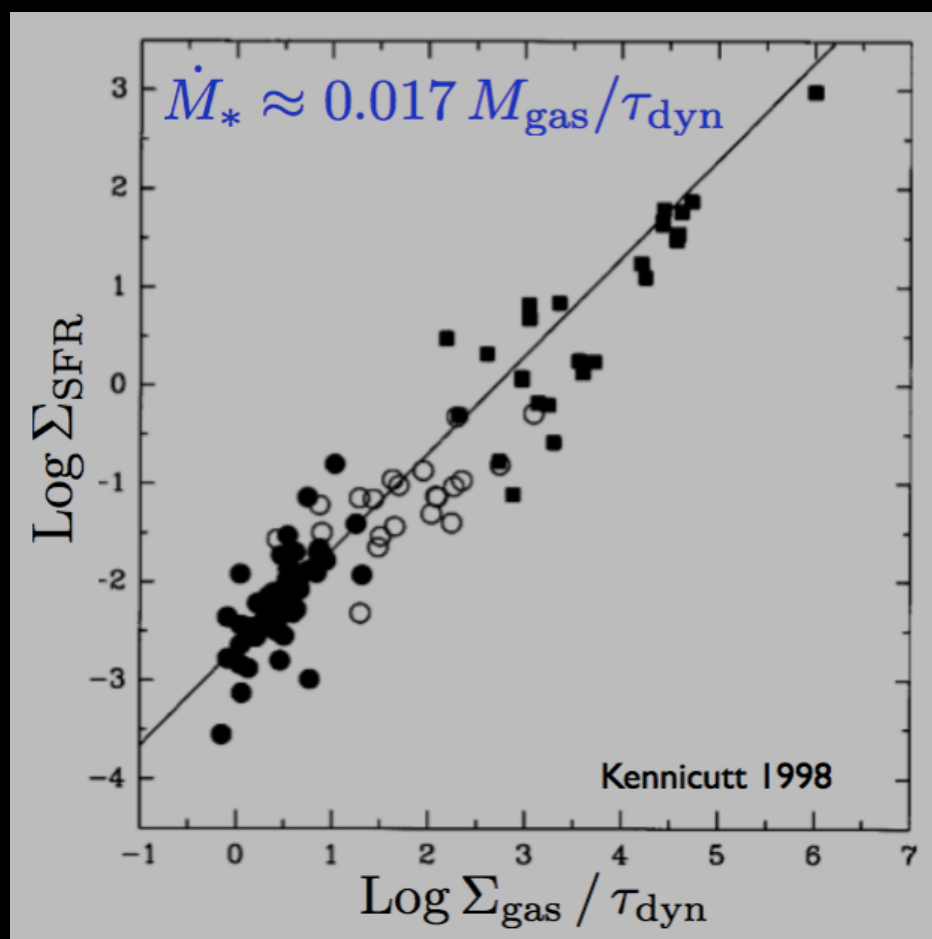
(Feedback In Realistic Environments)

PIs: Hopkins, Faucher-Giguere, Keres & Quataert
<http://fire.northwestern.edu>

Gadget (precursor)

(Springel et al. 2001, Springel & Hernquist 2003)

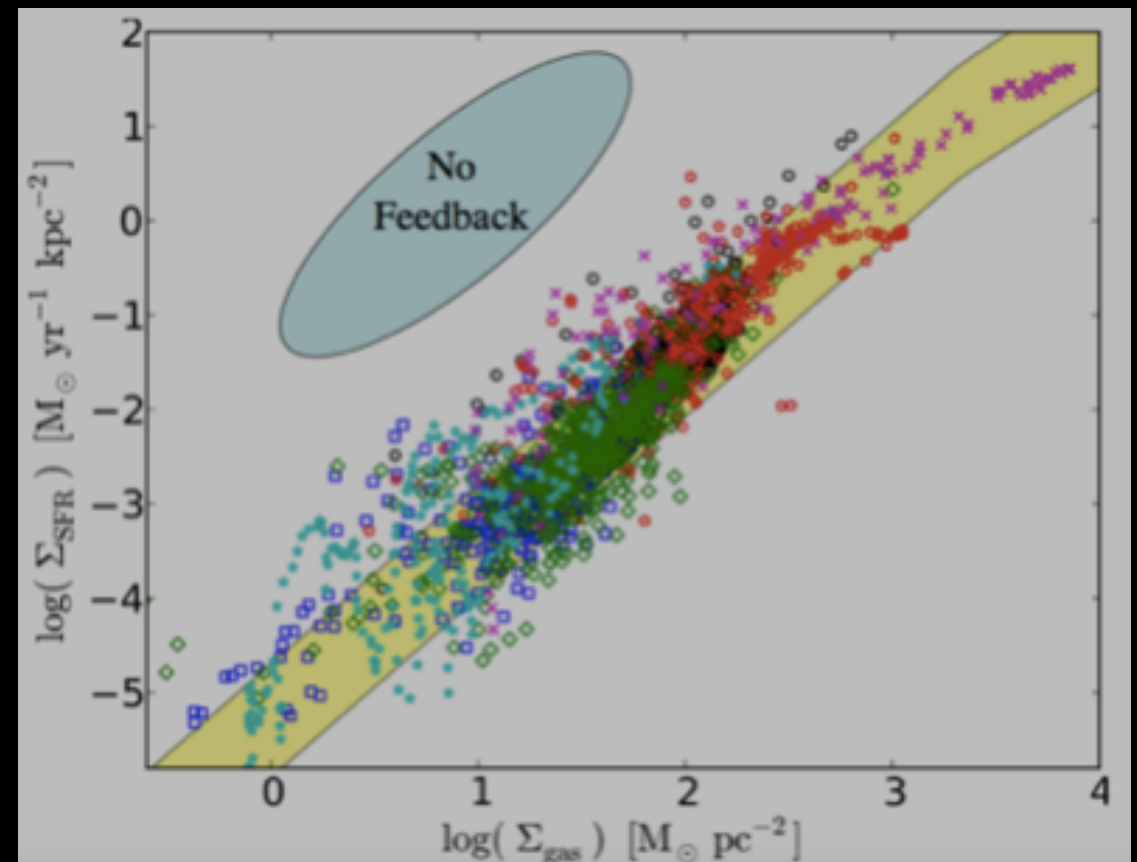
- Smoothed Particle Hydrodynamics (SPH)
- Kennicutt Law
=> Subgrid Star Formation Rule

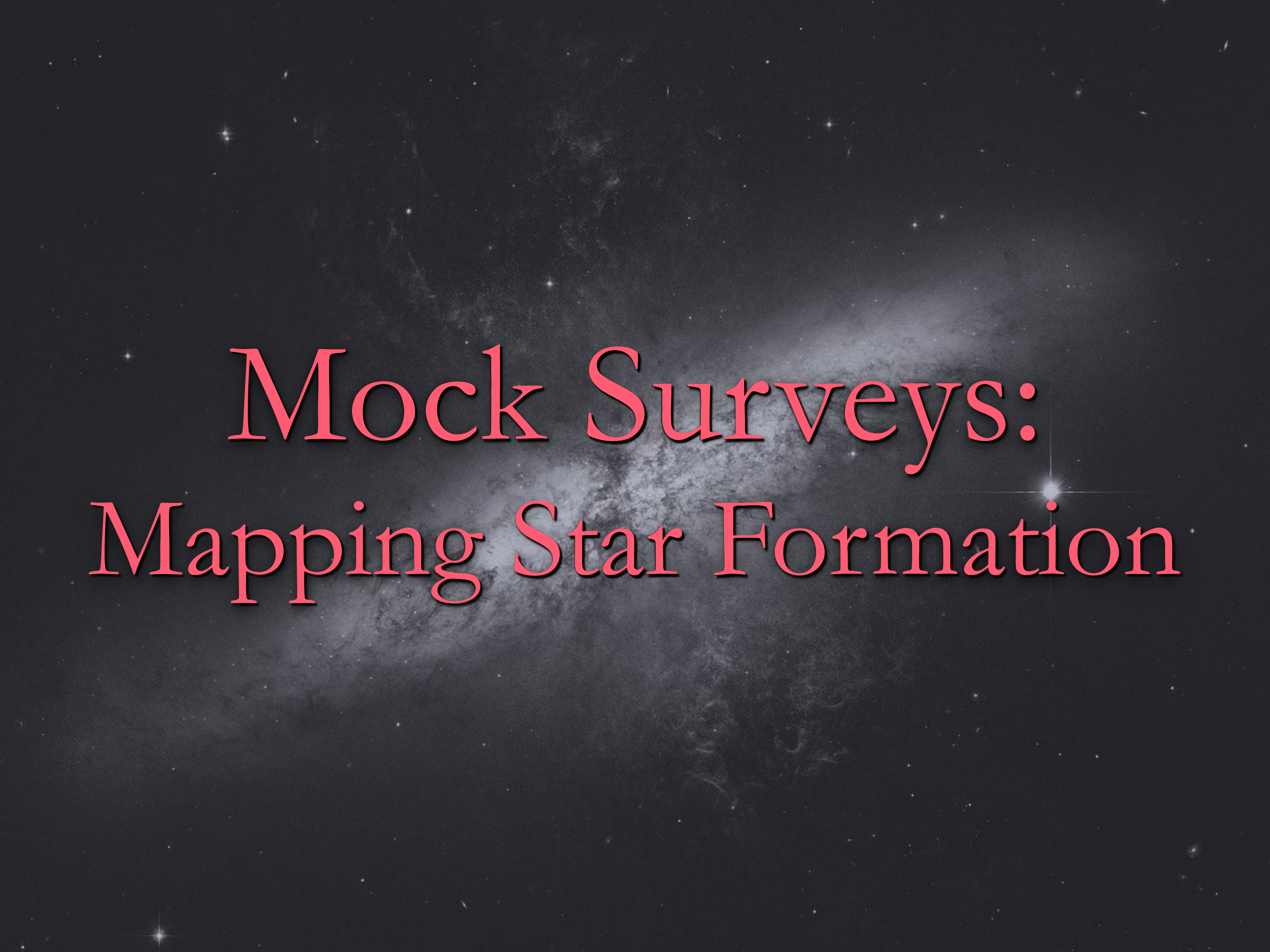


FIRE: Highlights

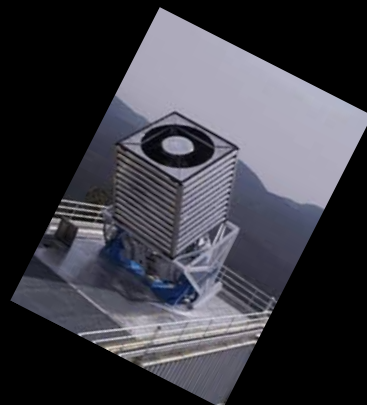
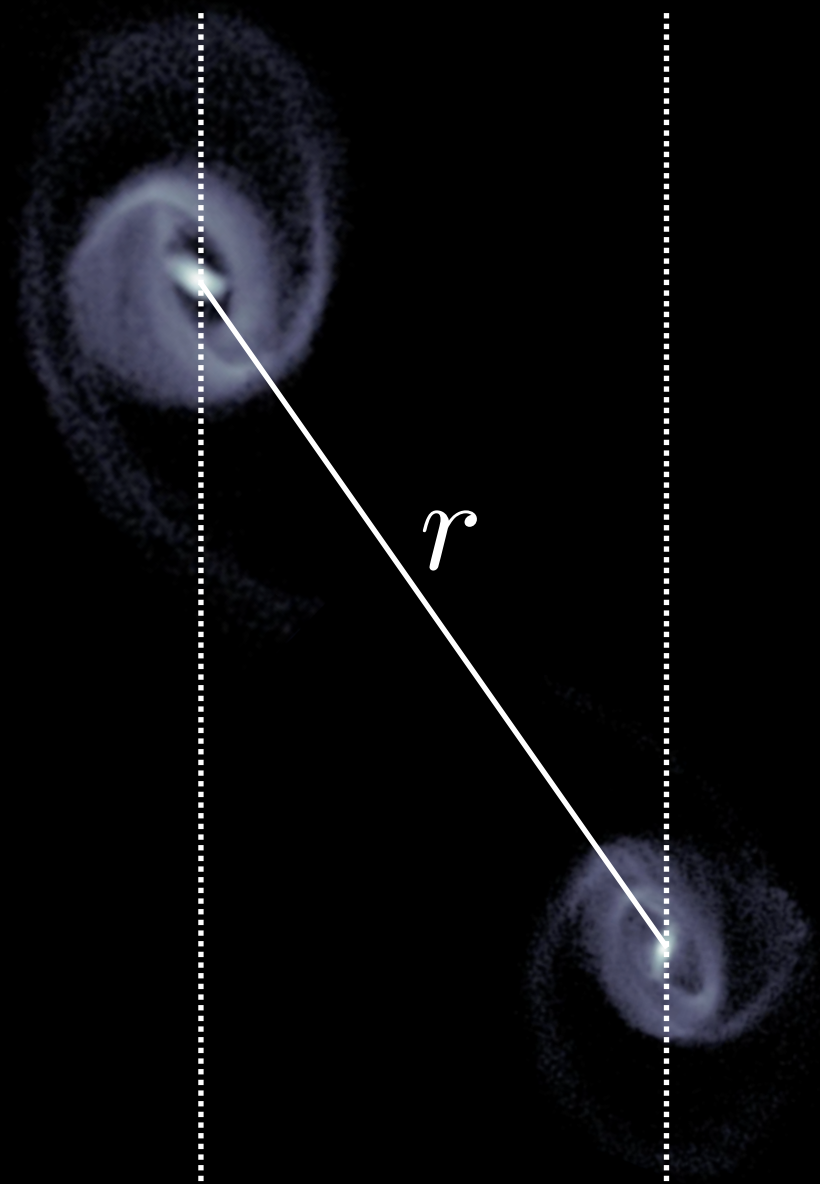
(Hopkins et al. 2014)

- GIZMO: meshless hydro solver
- Kennicutt Law: prediction, not an input
- Self-gravitating dense molecular gas regions
=> star formation in one dynamical time!
- Realistic Feedback:
 - Stellar Winds (O & AGB stars)
 - SN II & Ia
 - Photoionization & photoelectric
 - Radiative Pressure





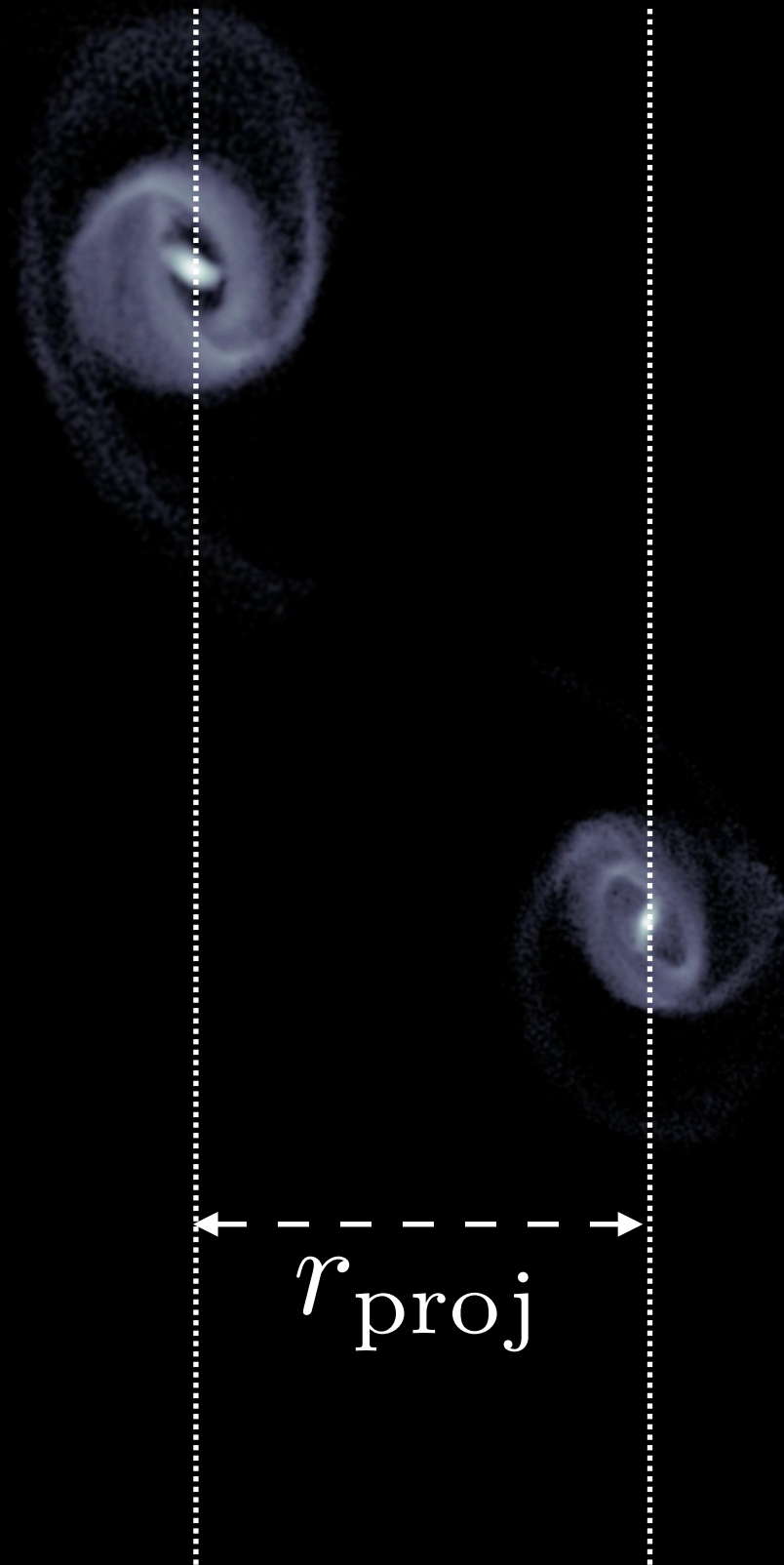
Mock Surveys: Mapping Star Formation

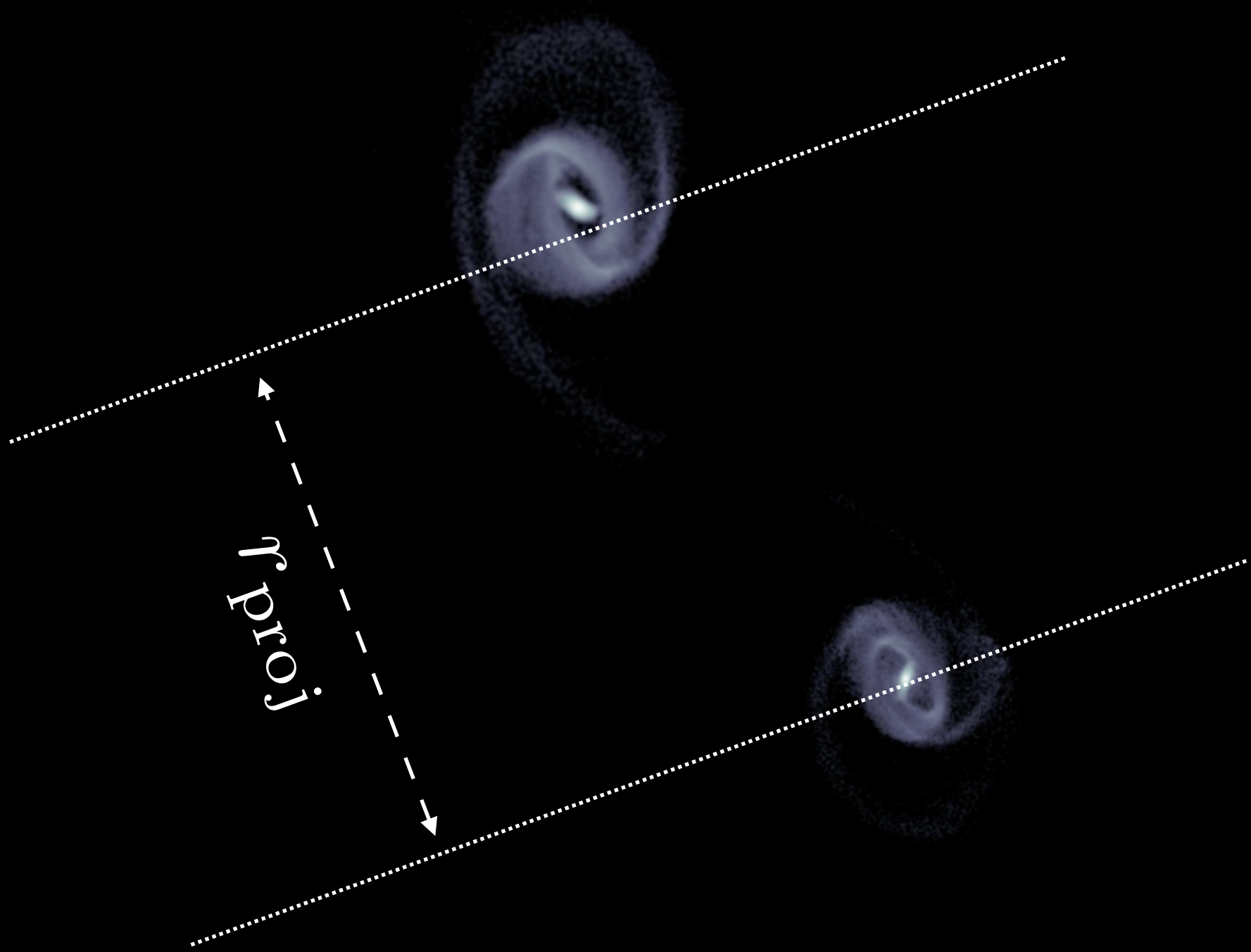


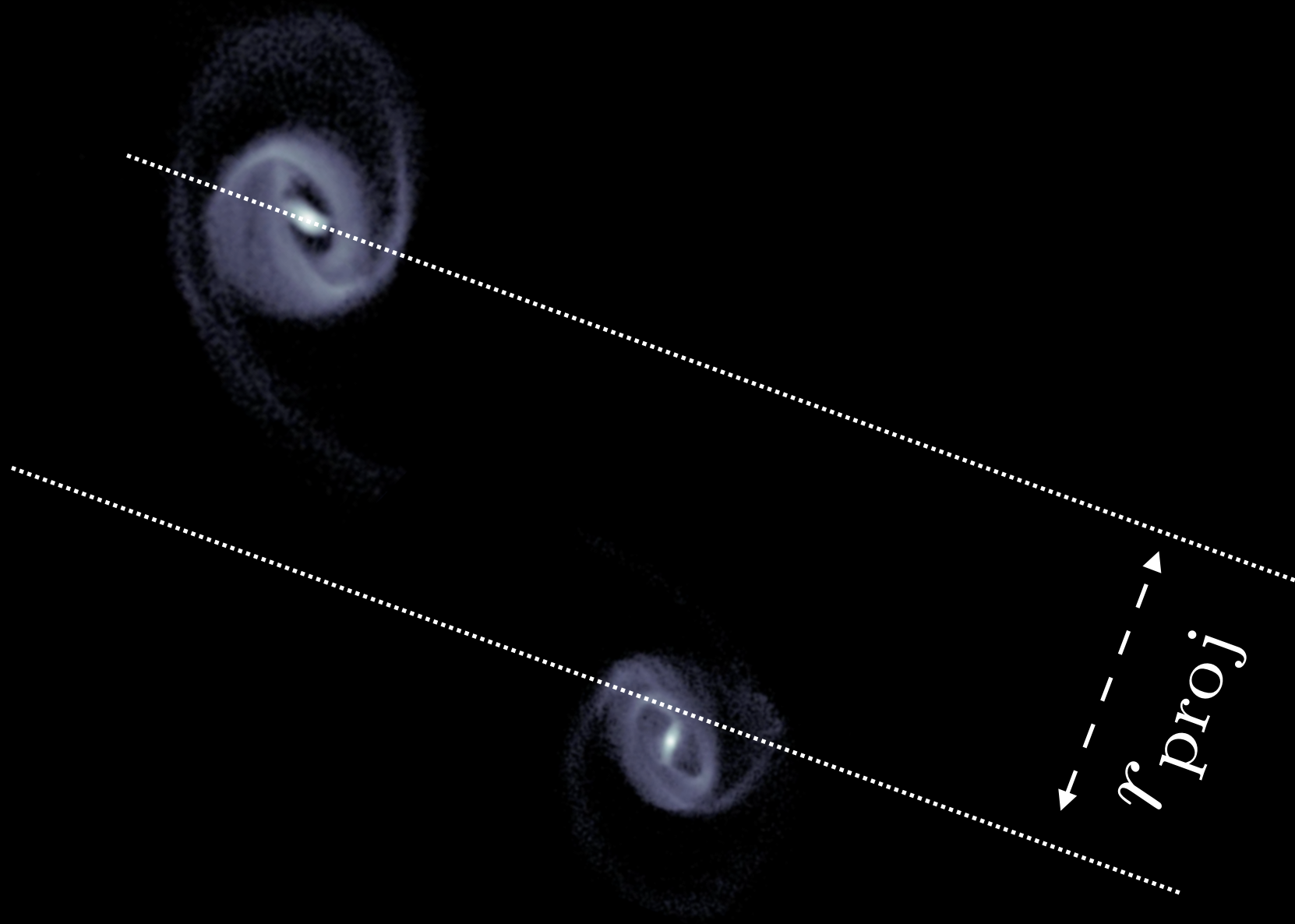
MOCK SURVEY:

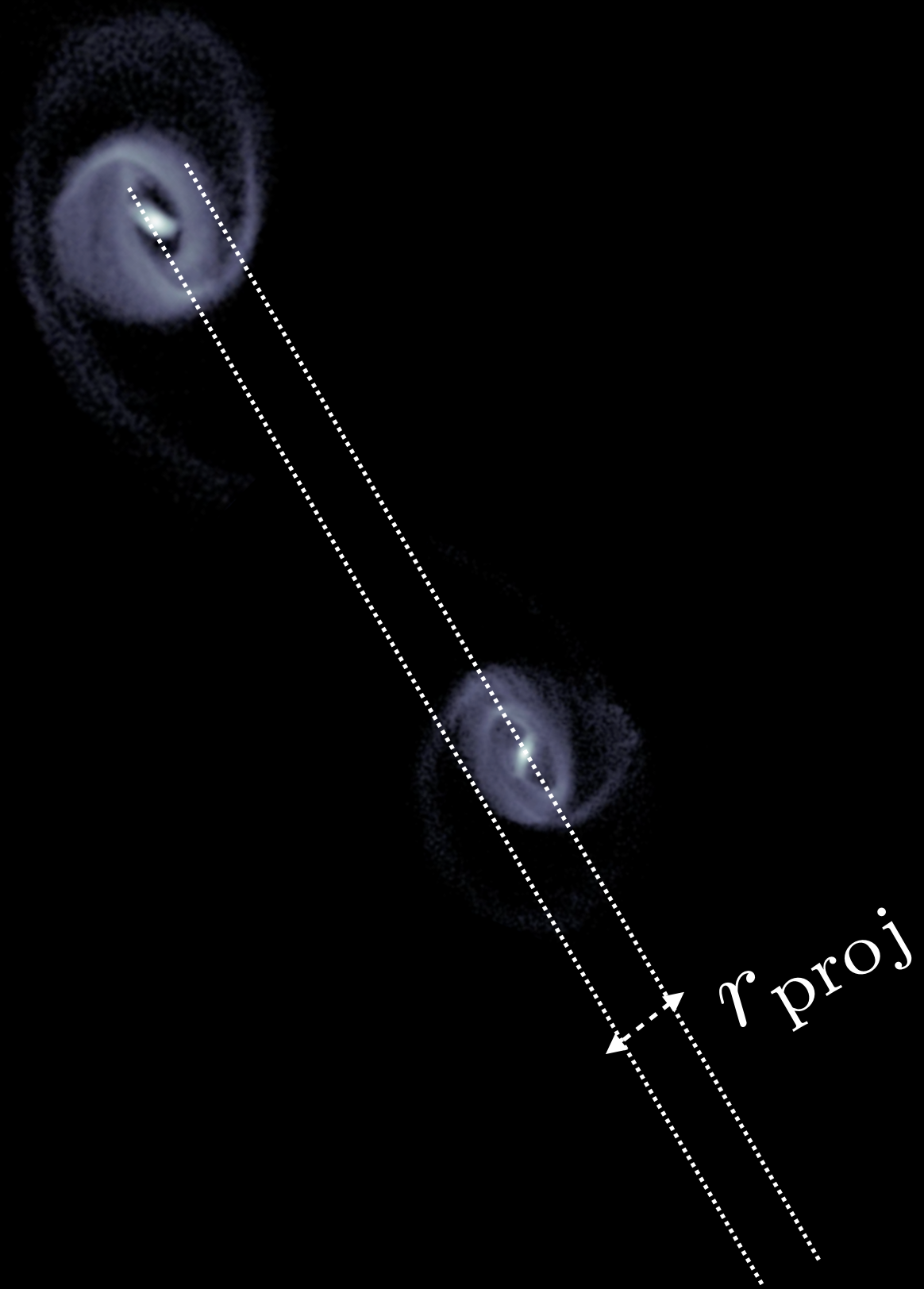
For Every Merger
For Every Time Snapshot

Many Random Views!

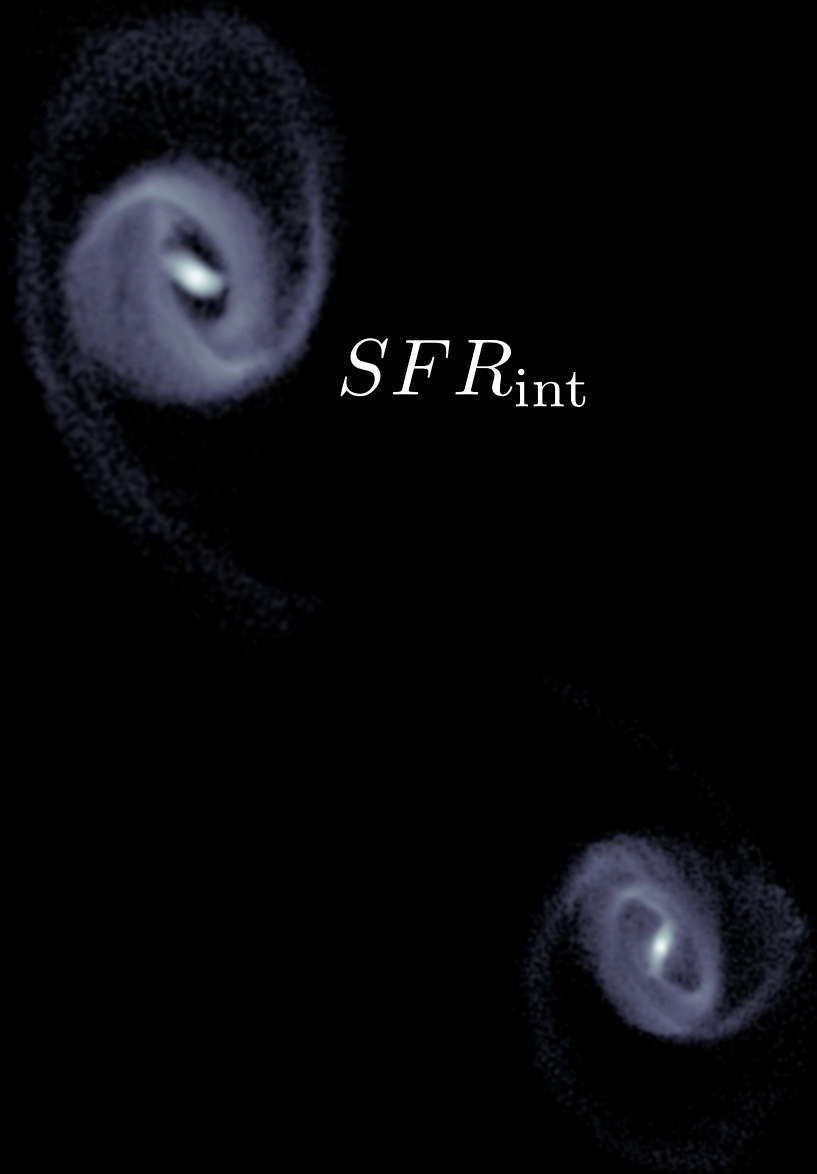






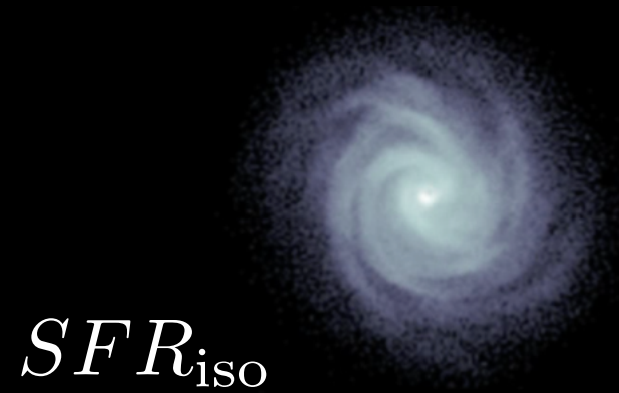


Interacting



SFR_{int}

Isolated Control

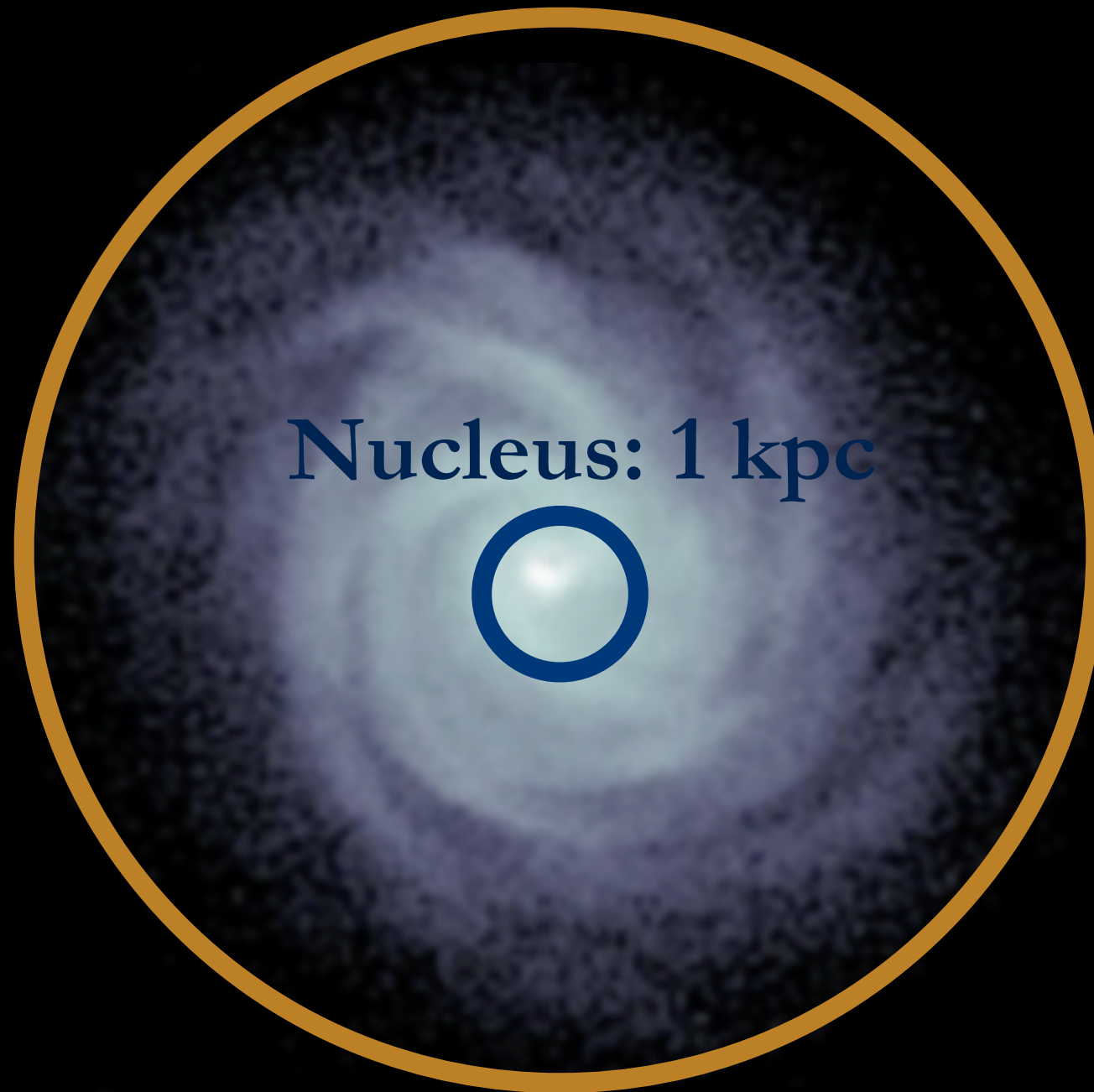


SFR_{iso}

Star Formation Rate
Enhancement:

$$\Delta SFR \equiv \frac{SFR_{\text{int}}}{SFR_{\text{iso}}}$$

Mapping Star Formation

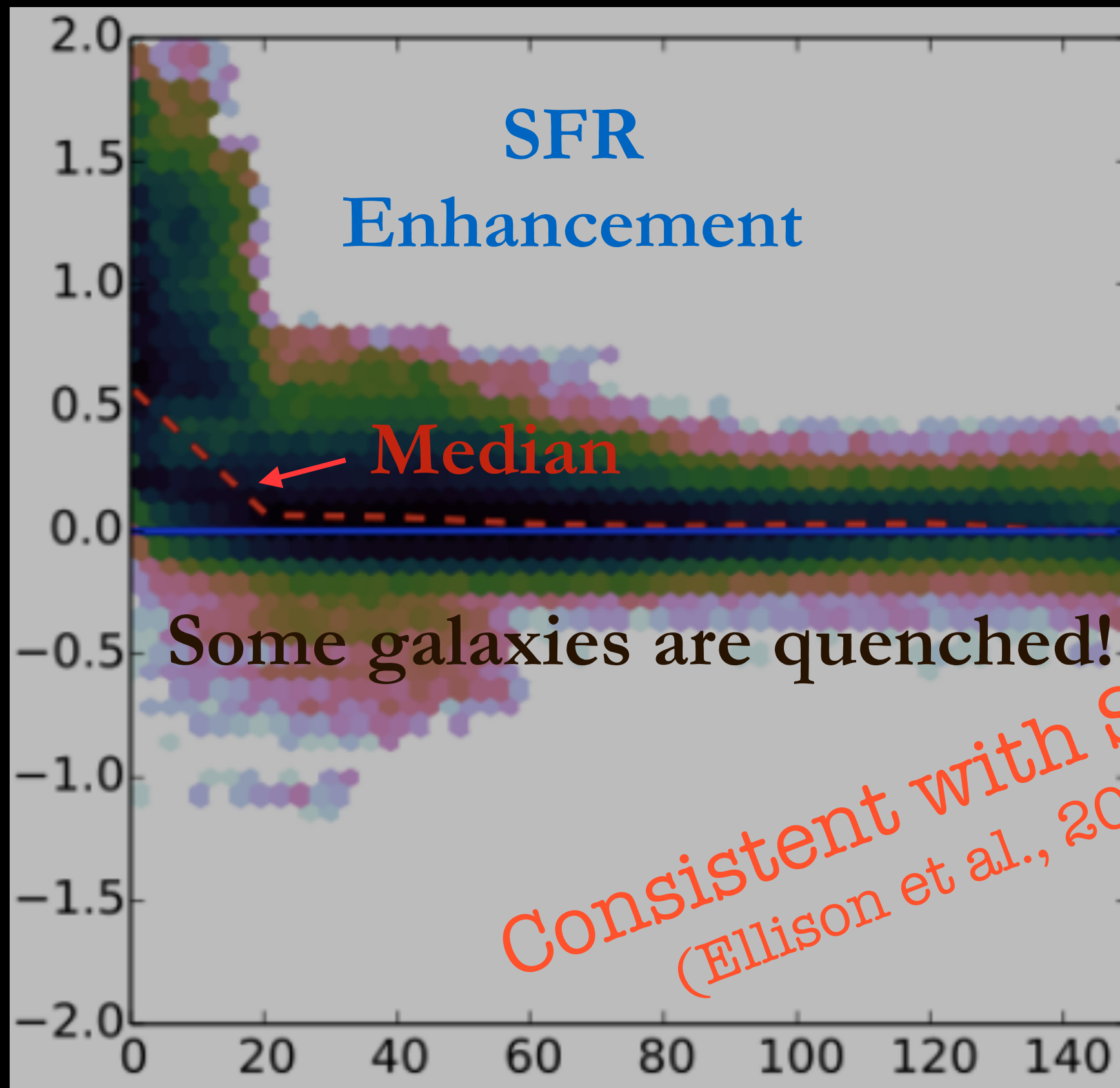


Outer Disk : 1 — 20 kpc

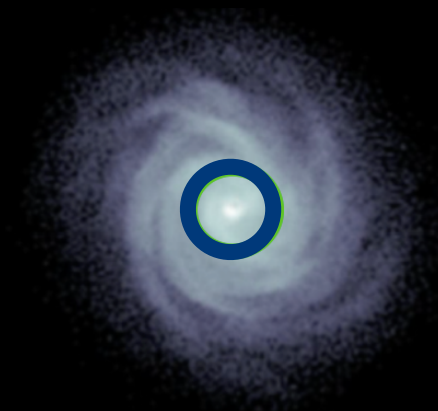


Results: Mapping Star Formation

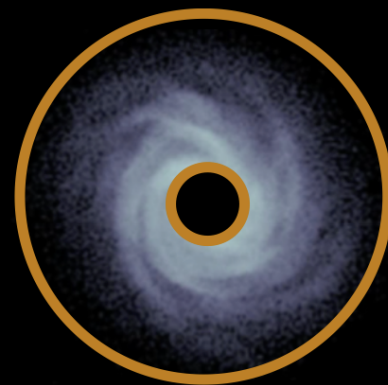
$\log \text{SFR (interacting)} / \text{SFR (isolated)}$



Projected Separation

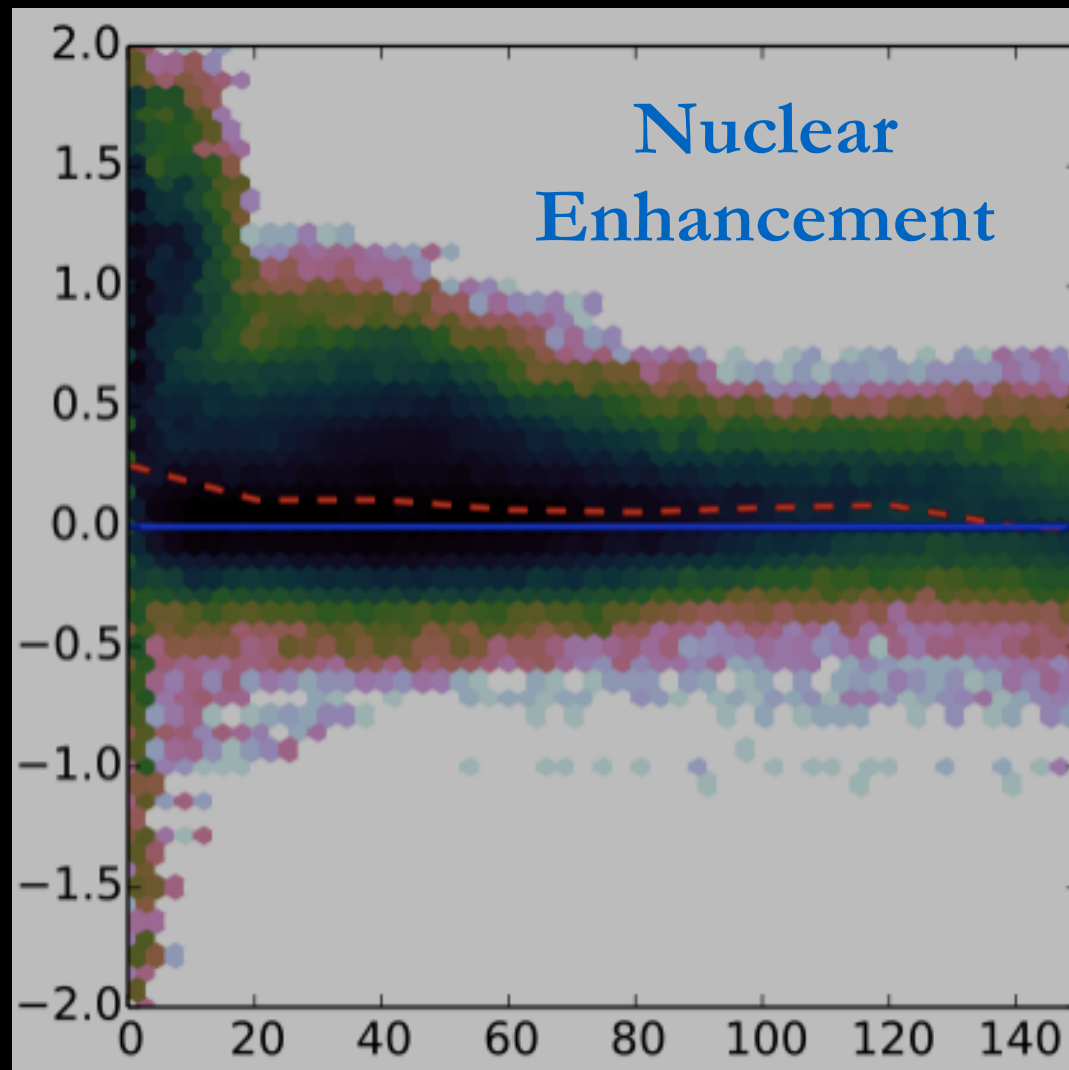


Nucleus
(0 -1 kpc)



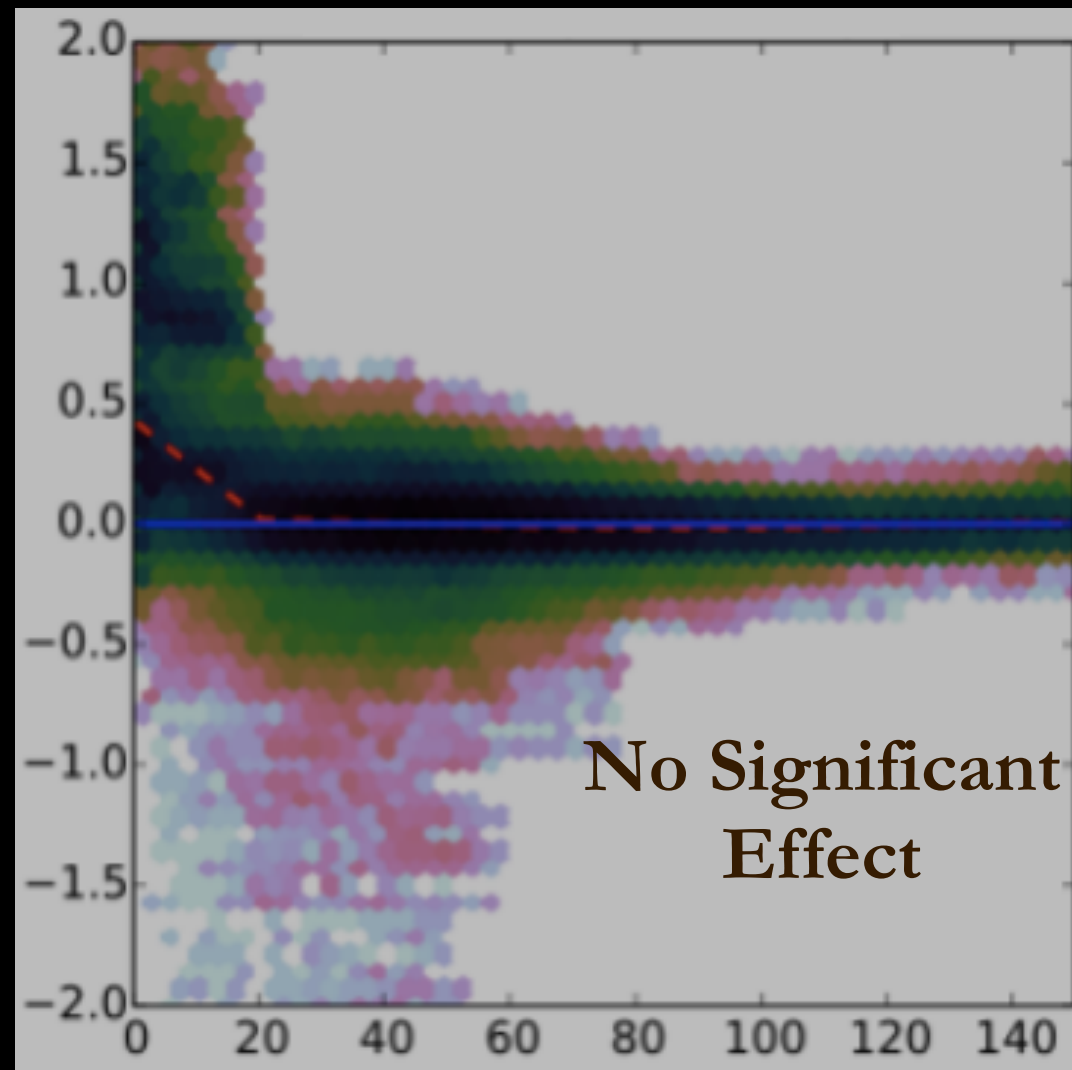
Outer Disk
(1 -20 kpc)

$\log \text{SFR (interacting)} / \text{SFR (isolated)}$



Projected Separation

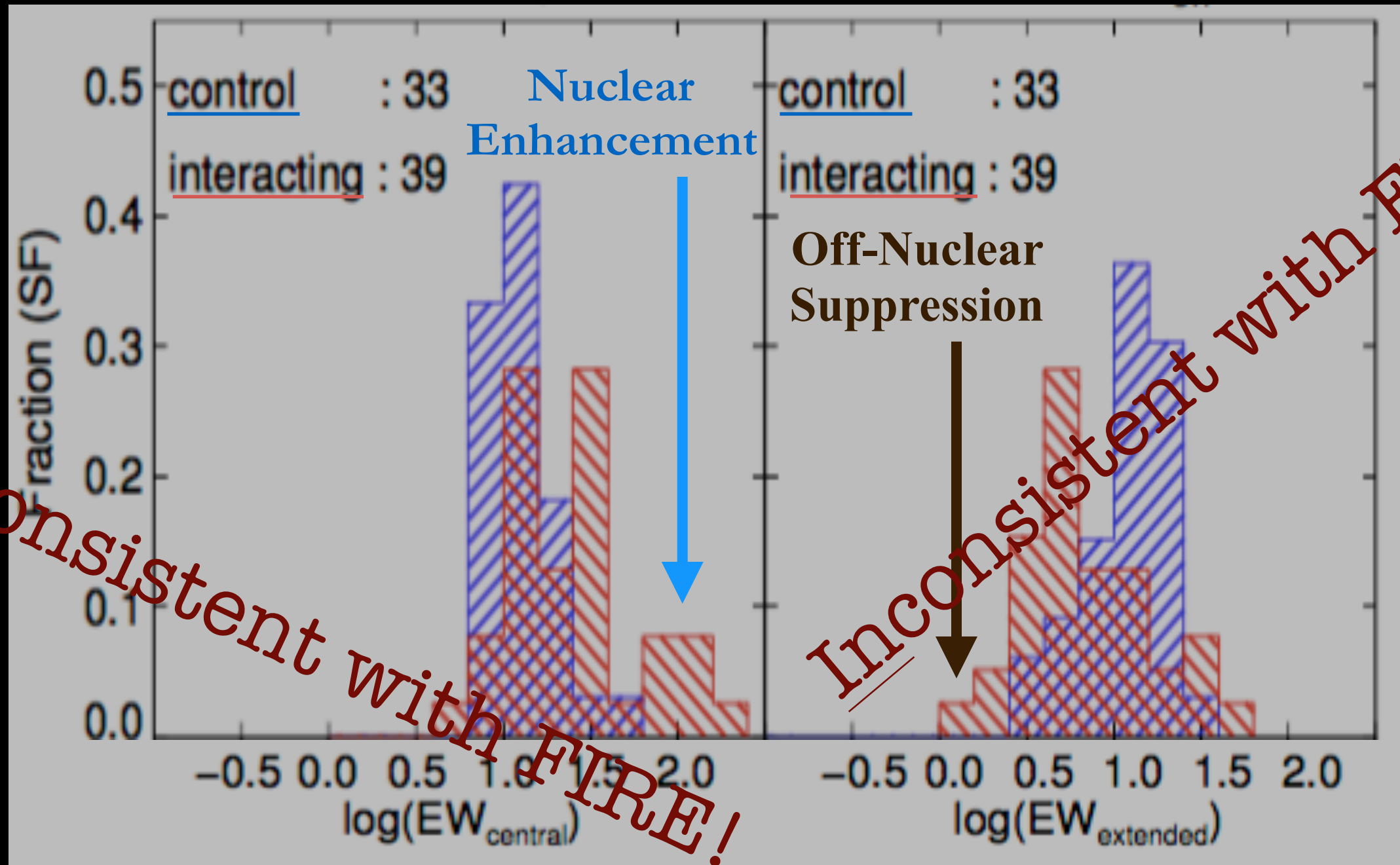
$\log \text{SFR (interacting)} / \text{SFR (isolated)}$



Projected Separation

Comparison with IFS Observations

(Barrera-Ballesteros + CALIFA Collaboration)

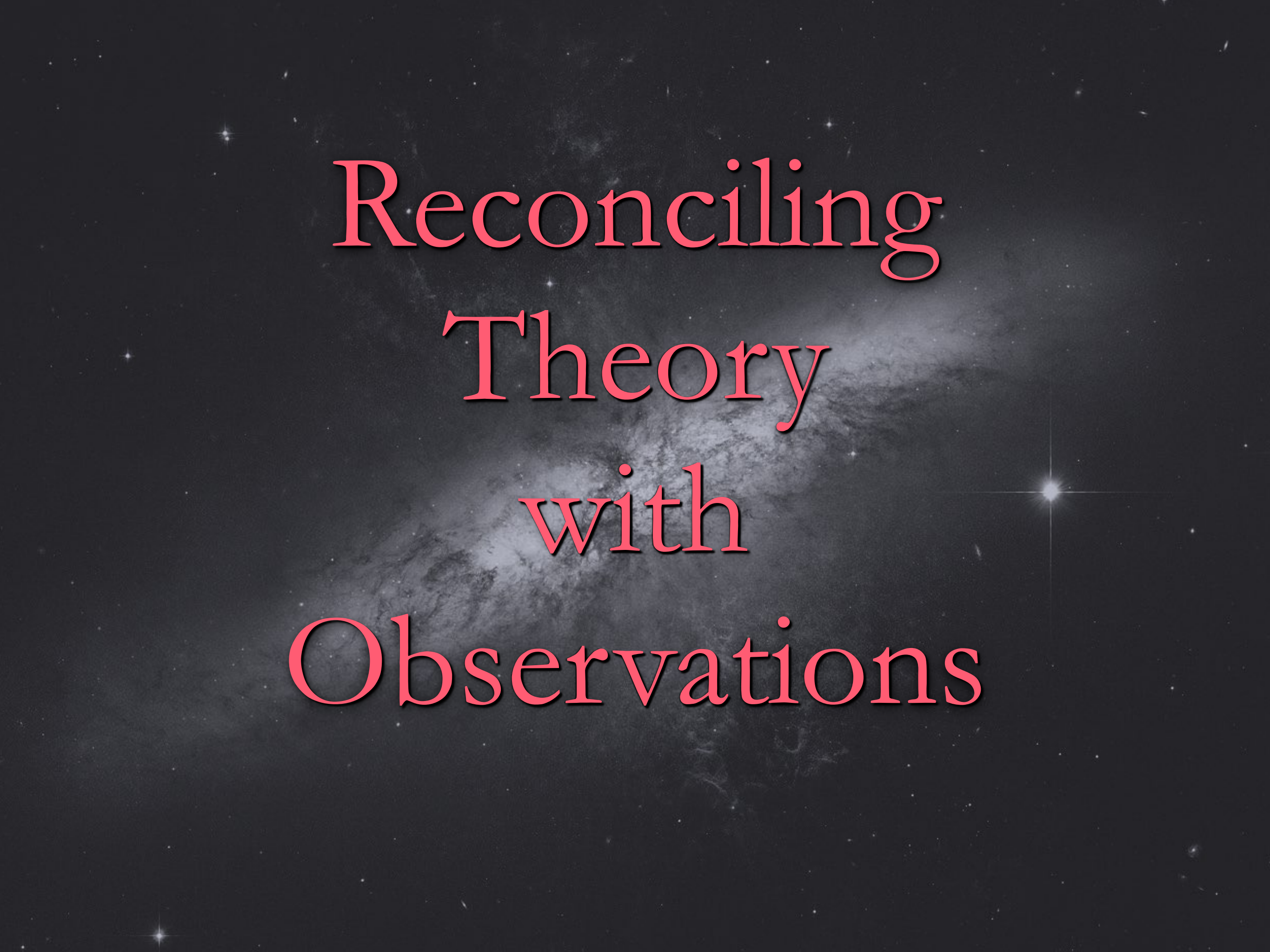


The background of the slide is a deep space image. It features a dark, almost black, field filled with numerous small, bright stars of varying sizes and colors. A prominent, glowing nebula or galaxy core is visible in the center, showing intricate patterns of light and dark matter. The overall effect is a sense of vastness and mystery.

Are
Observations
Wrong?

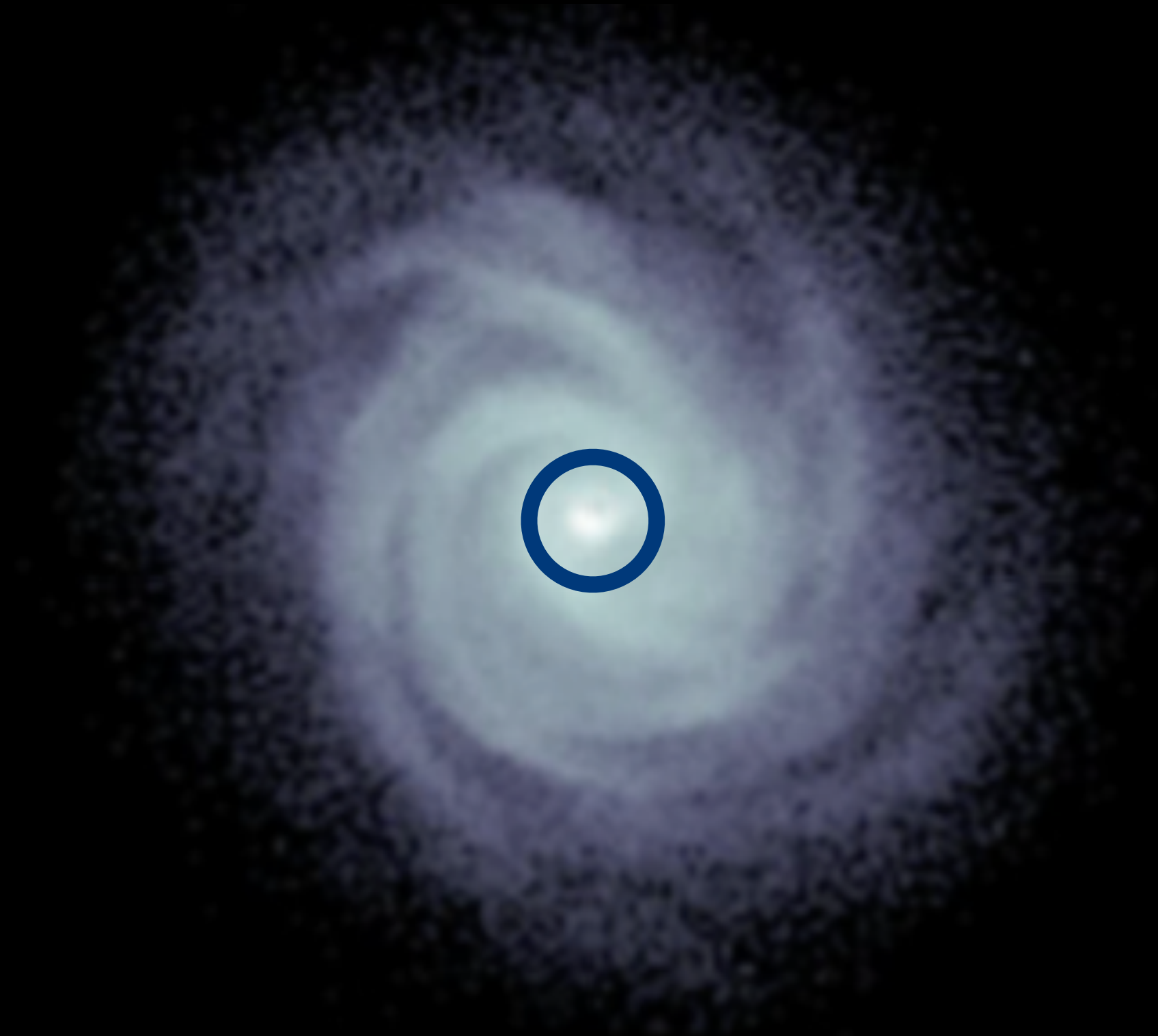
Are
Observations
A Bunch of
Malarkey?

malarkey

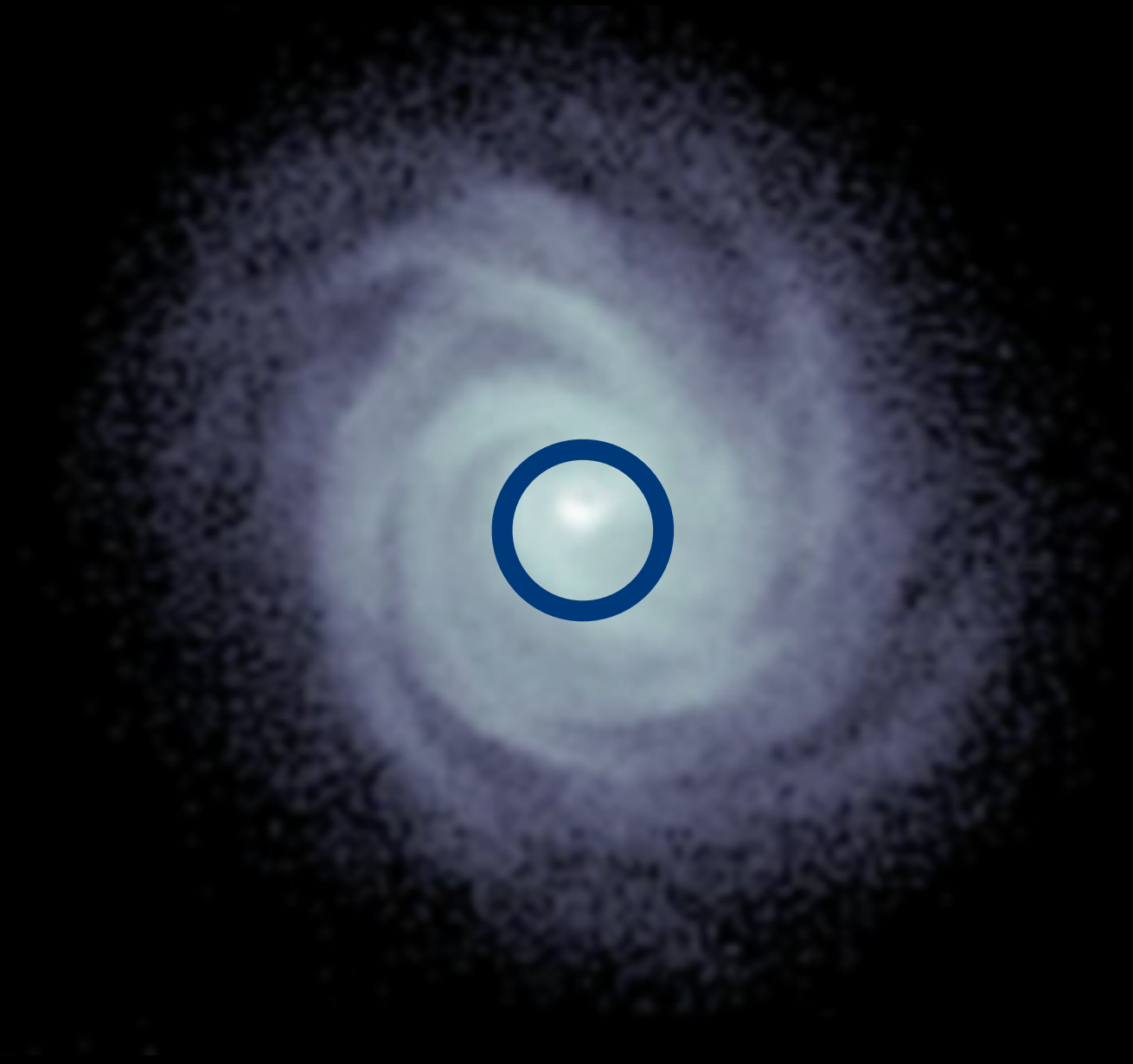
The background of the slide is a deep space image. It features a dark, star-filled sky with a prominent, bright, and diffuse nebula or galaxy core in the center. Several sharp, bright stars are visible, some with prominent diffraction spikes. The overall color palette is dark, with shades of black, grey, and blue, accented by the red text and the white/yellow light of the celestial objects.

Reconciling Theory with Observations

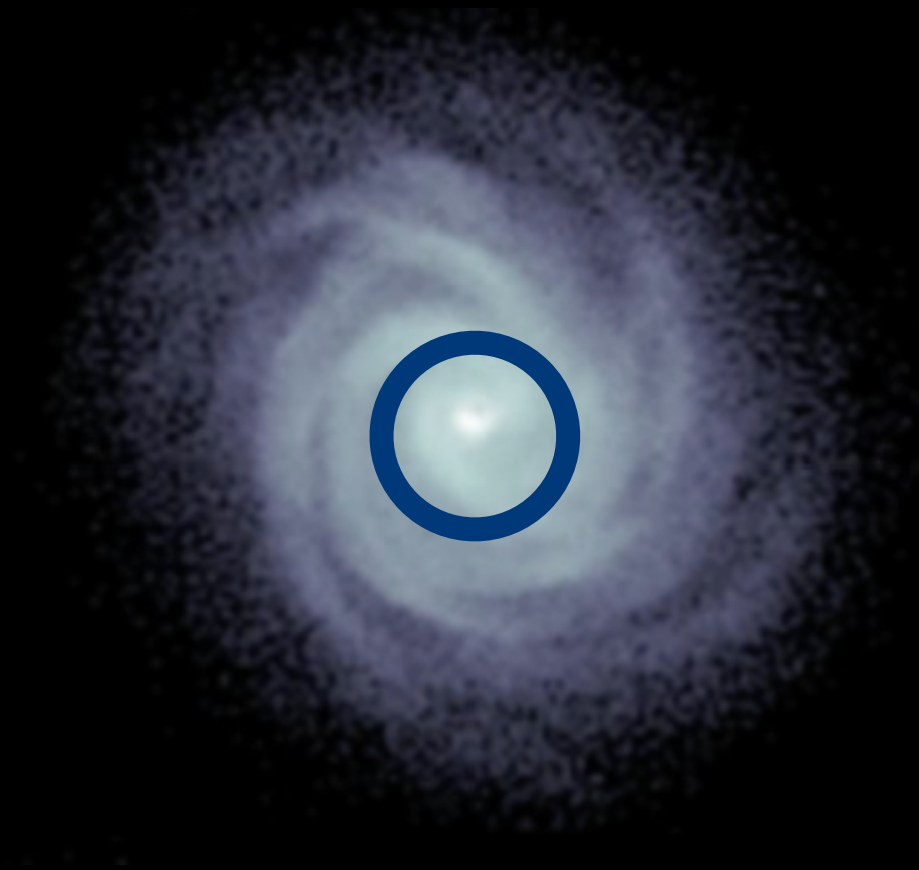
Nearby galaxy



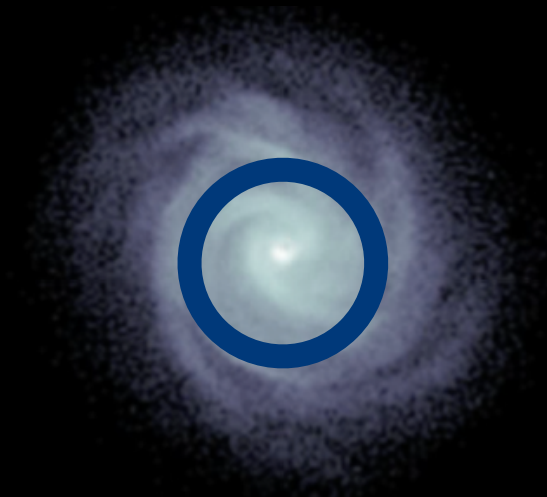
Distant galaxy



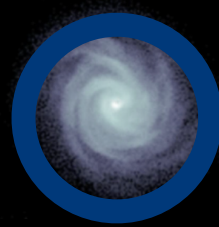
Very distant galaxy



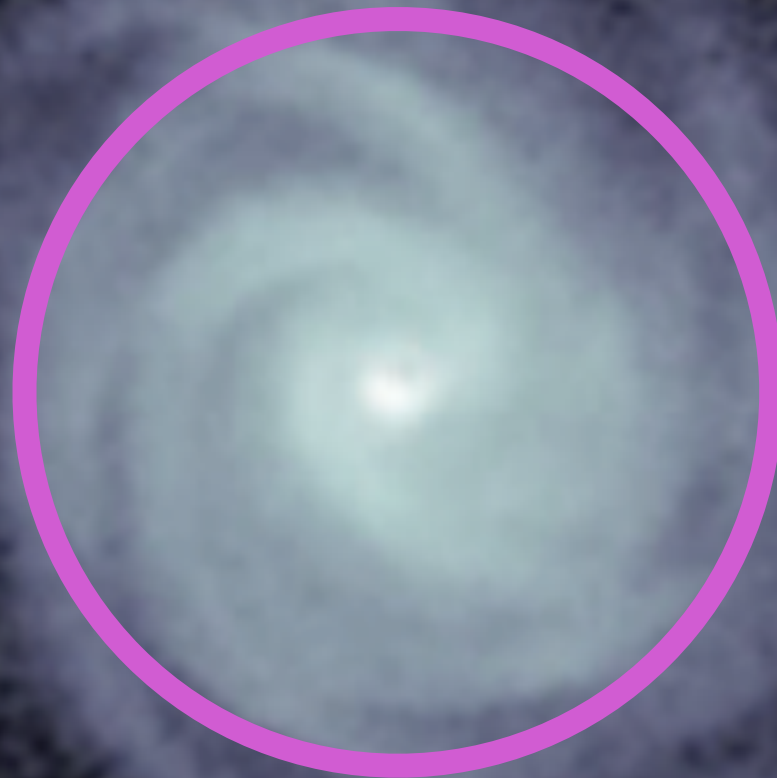
Extremely distant galaxy



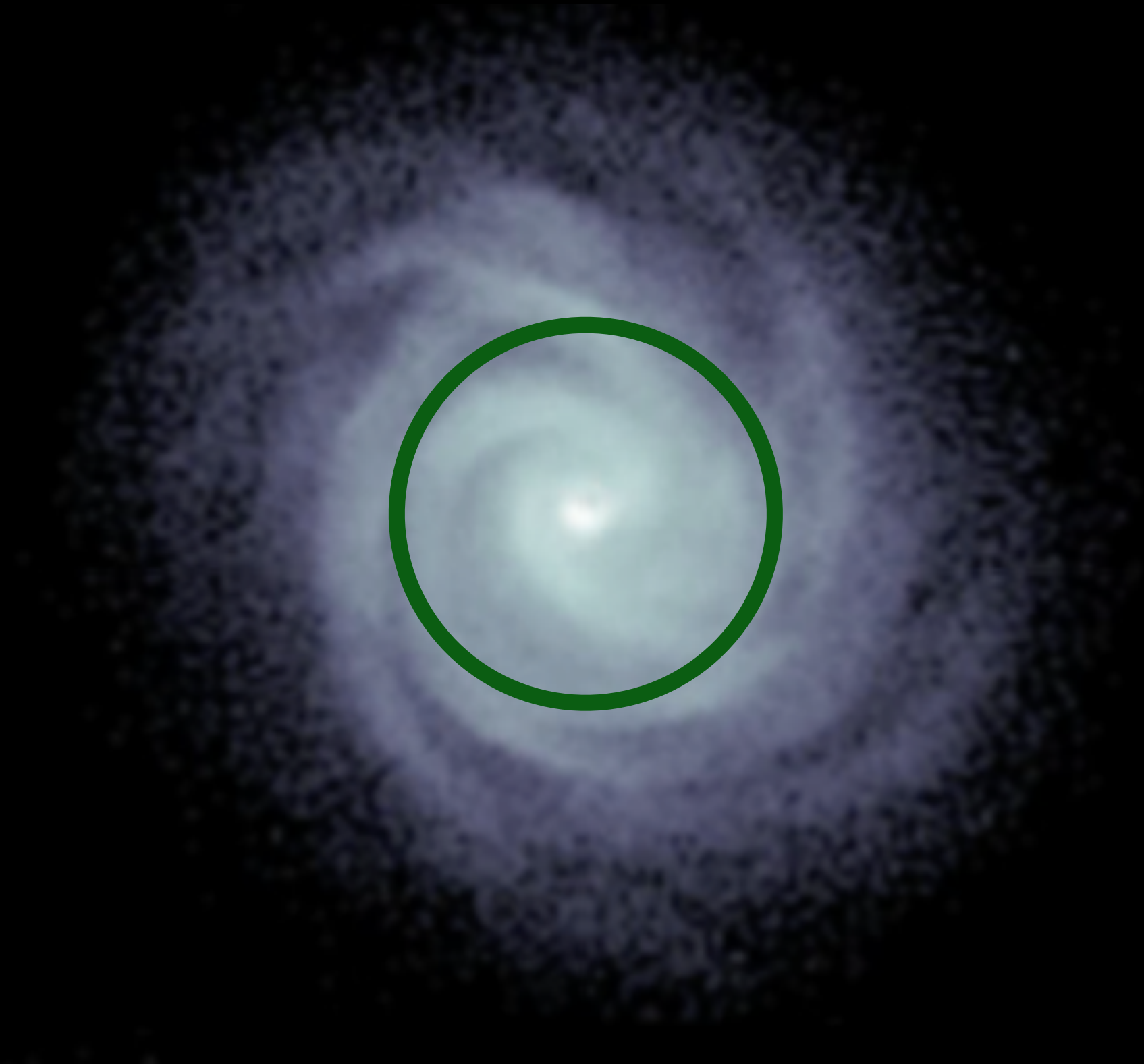
In a galaxy far far away!



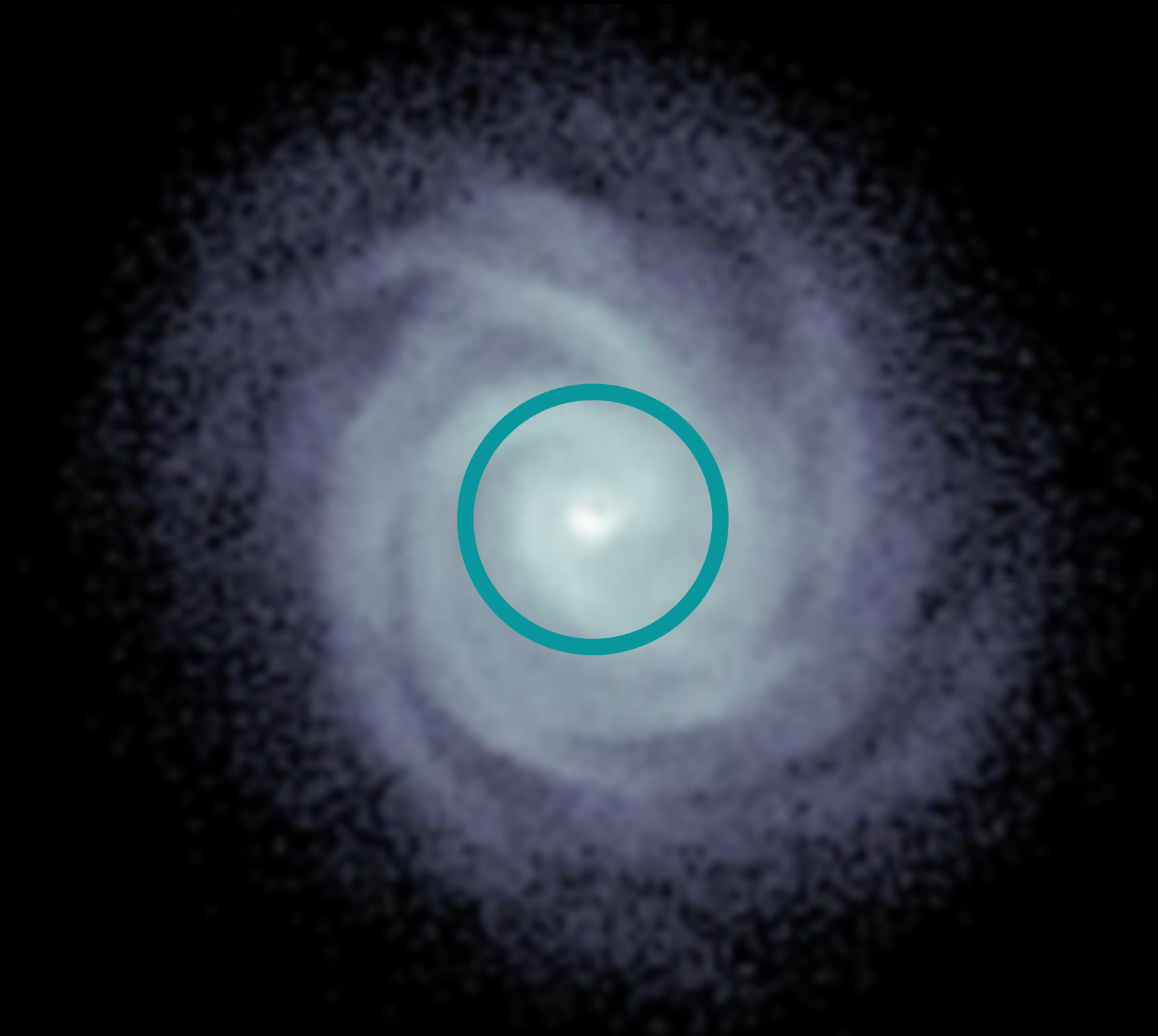
Extremely distant galaxy



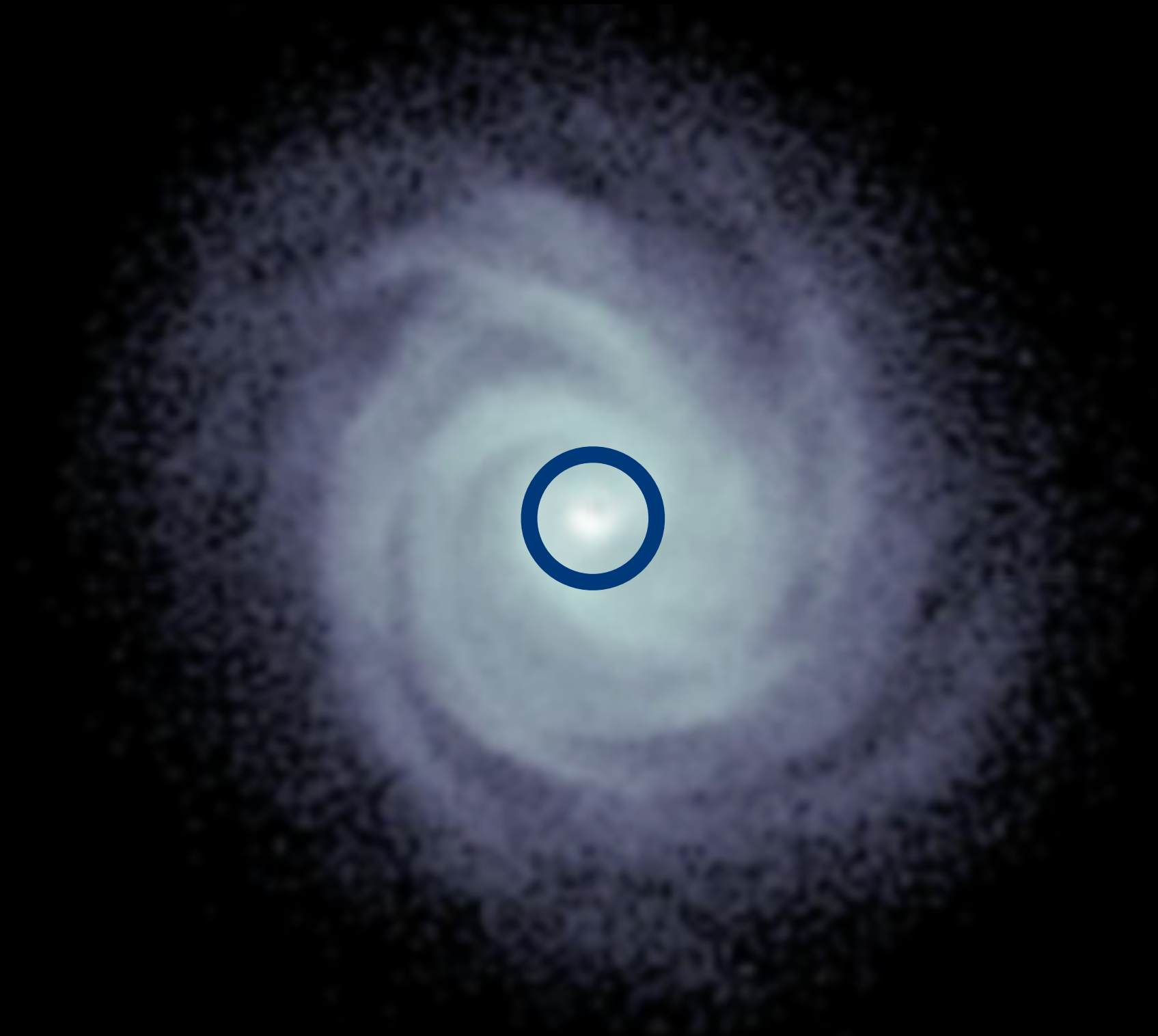
Very distant galaxy



Distant galaxy

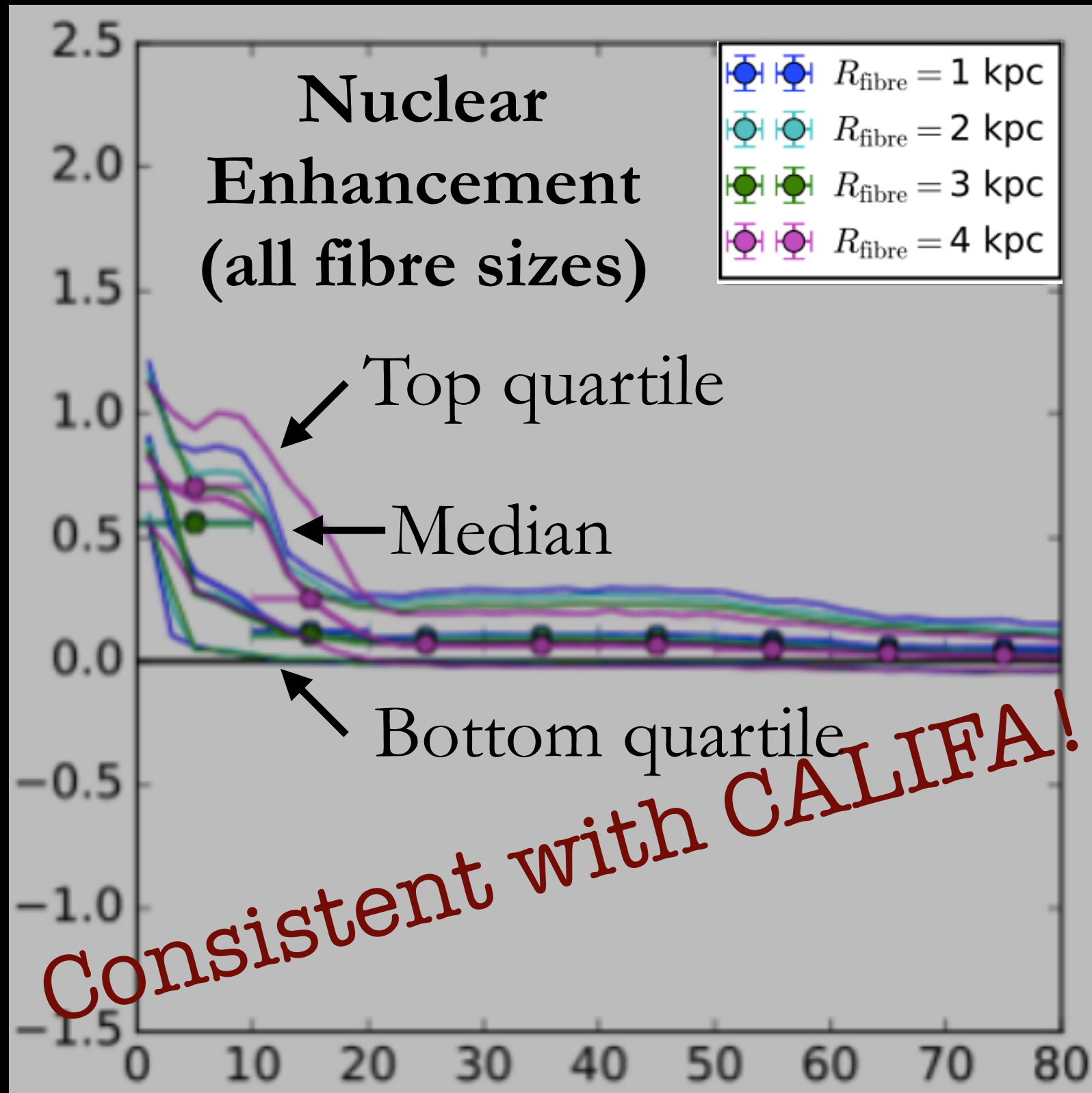


Nearby galaxy



Nuclear Region

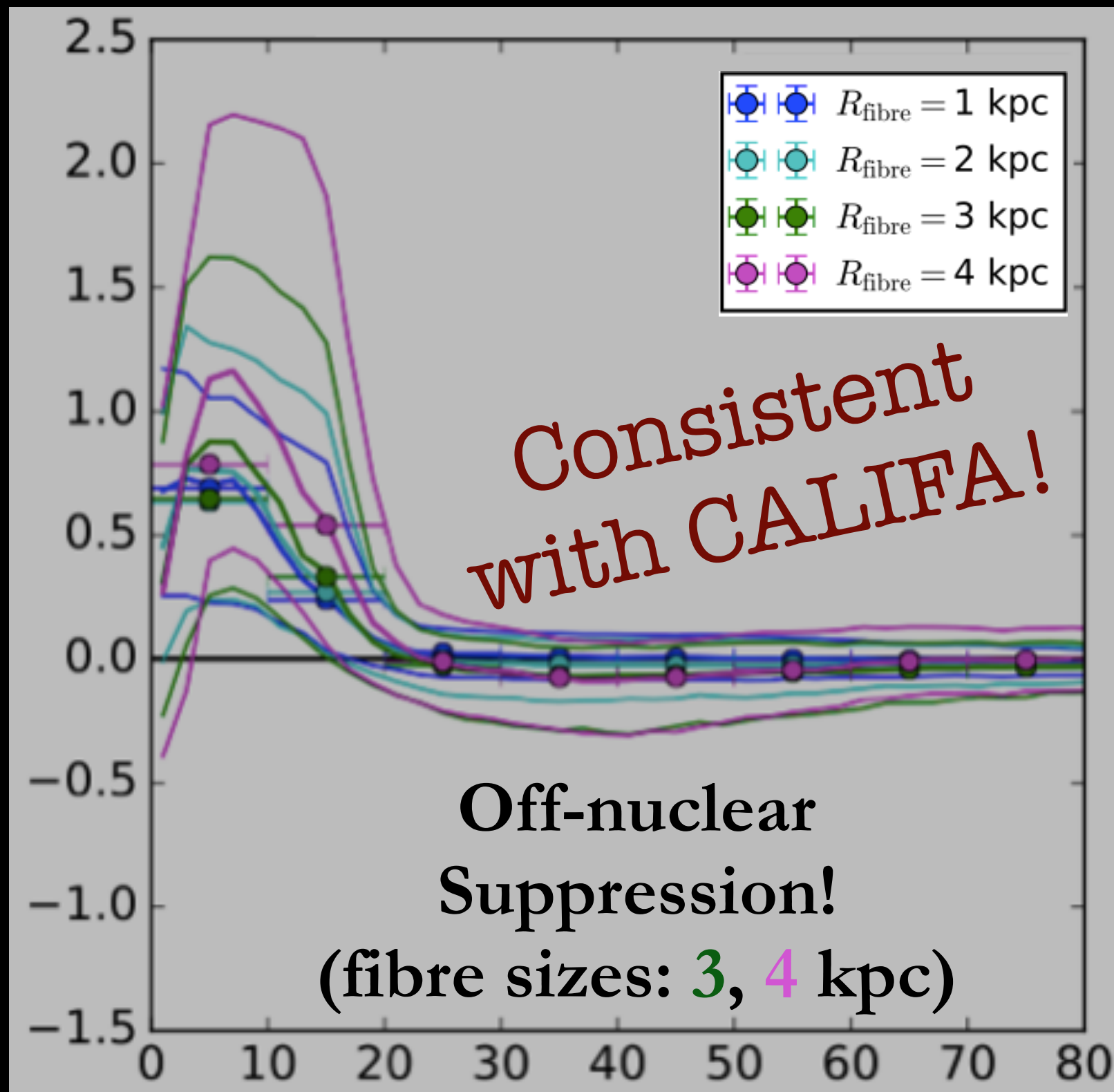
$\log \text{SFR (interacting)} / \text{SFR (isolated)}$



Projected Separation

Off-nuclear Region

$\log \text{SFR (interacting)} / \text{SFR (isolated)}$



Projected Separation

Thank You!

- **Gadget**: Subgrid feedback, Kennicutt Law is an **input**
- **FIRE**: Resolved feedback, Kennicutt Law is a **prediction**
- **Enhanced** Nuclear Star Formation
- **Suppressed** Off-nuclear Star Formation (beyond 2-3 kpc)
- Agreement with observations (CALIFA)

Any Questions?