Galaxy Mergers on FIRE

Jorge Moreno @astroboy_moreno

#galpath16

CAL POLY POMONA

CfA 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

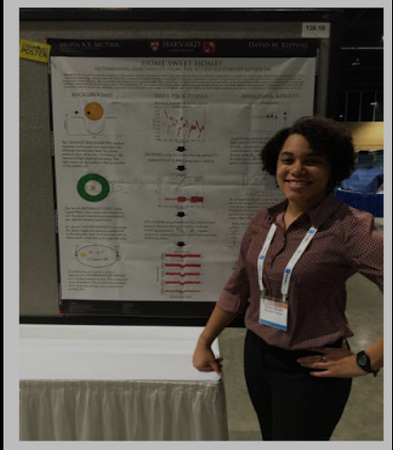
CSMA
Committee on the Status of Minorities in Astronomy

Astronomy in Color

In pursuit of social justice, diversity and excellence in astronomy

http://astronomyincolor.blogspot.com

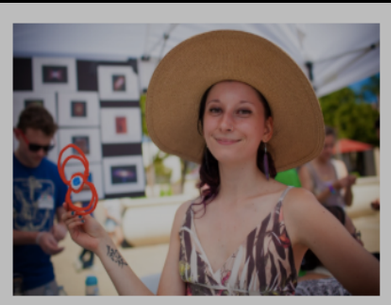
AAS



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



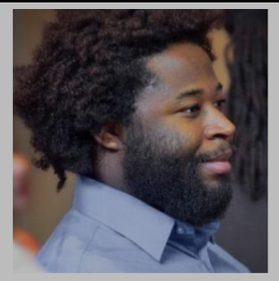
Ivanna Escala, graduate student at Caltech
Award recipient at the 2015 CAMP Symposium

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

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

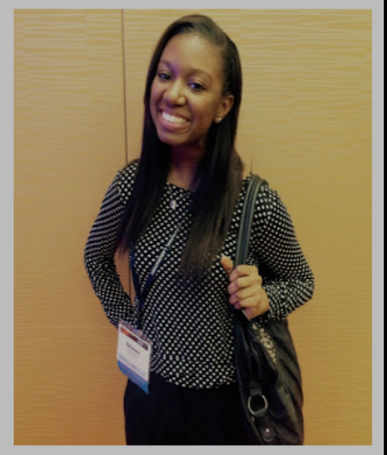
Katy Rodriguez Wimberly . Master's student at CSU Long Beach
Recipient of an NSF Graduate Research Fellowship
Next Fall: Ph.D Candidate at UC Irvine

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



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

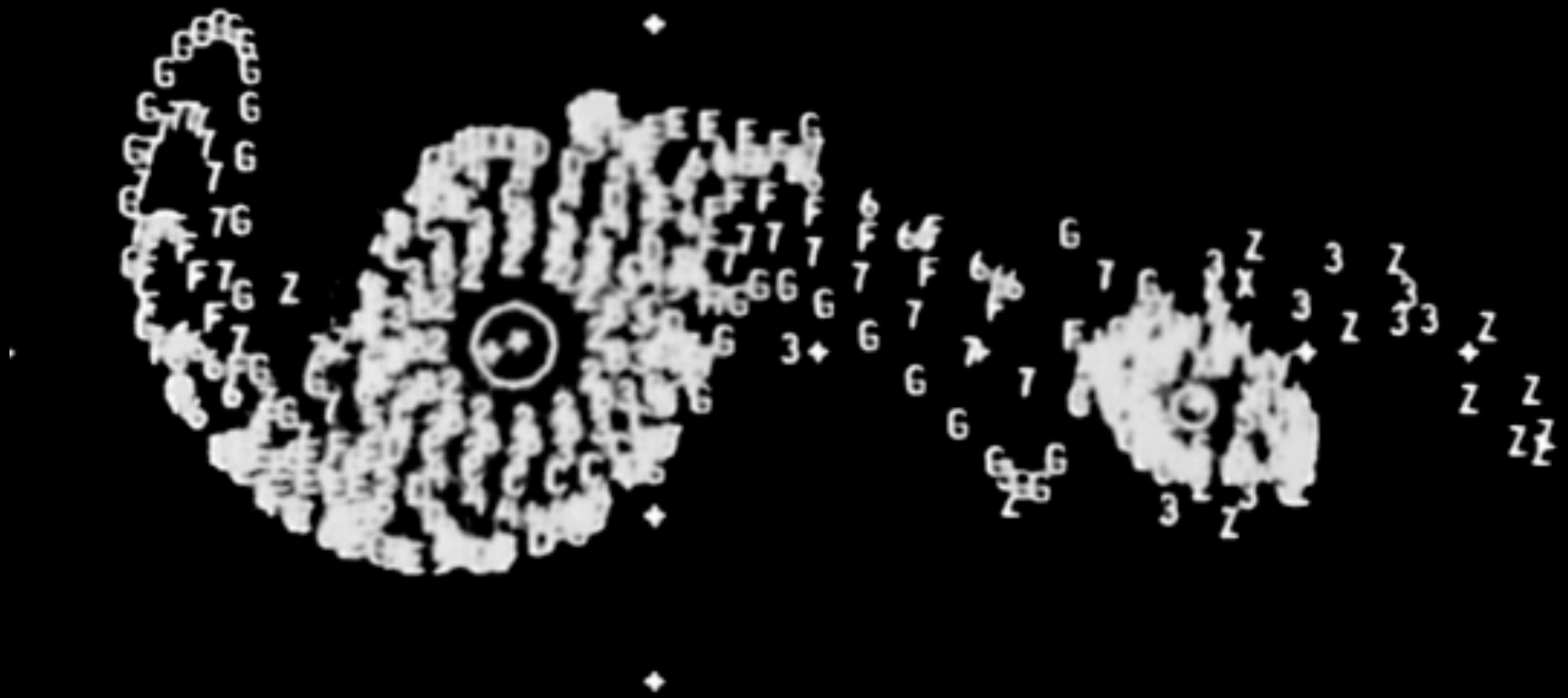
Xzavier Flowers, undergraduate Astronomy and Astrophysics major at Florida Institute of Technology and Founder and CEO of Future Astronomers.

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

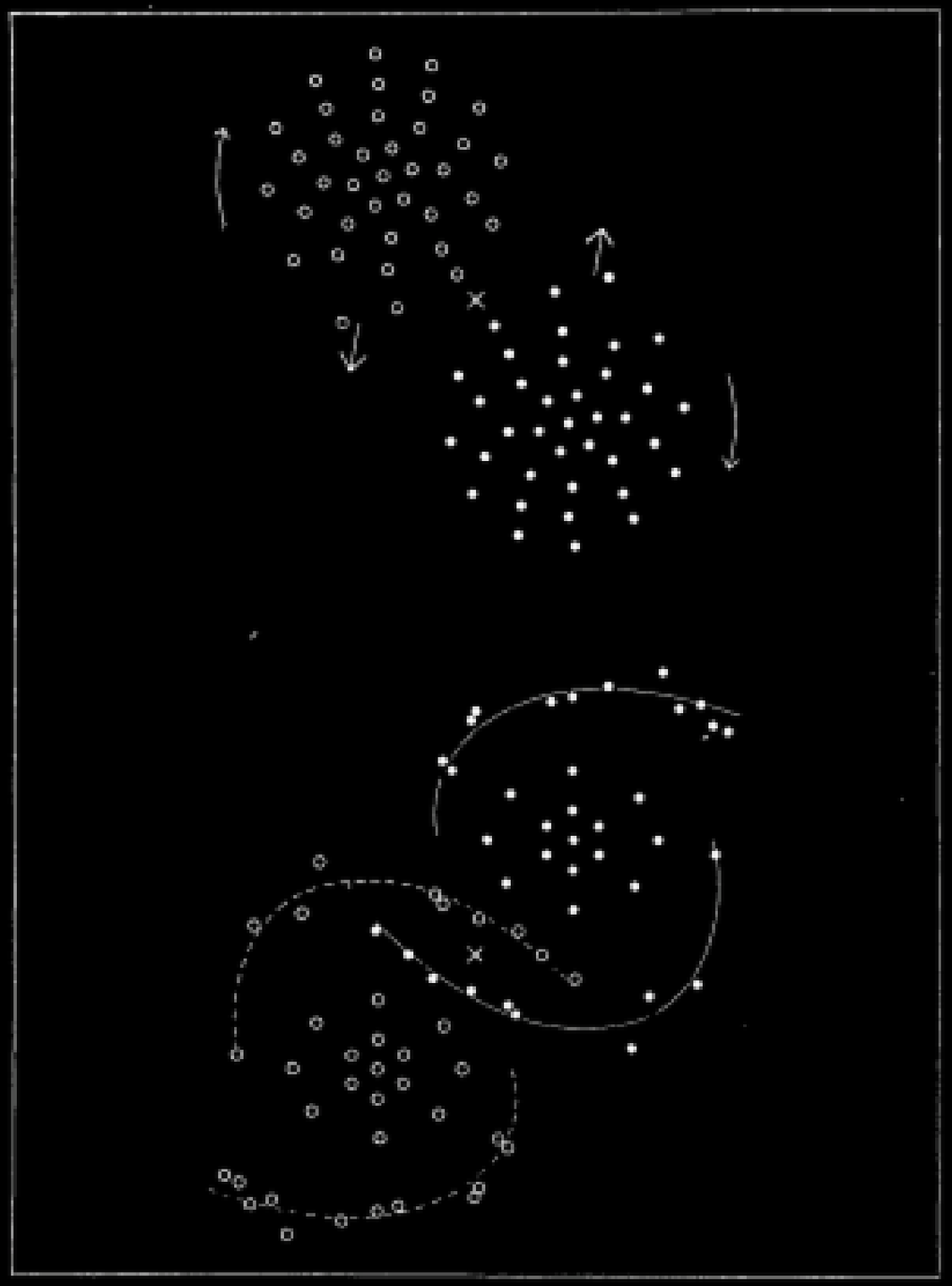
Dr. Louise Edwards
Now: Astronomy Lecture at Yale
Next: Assistant Professor at Cal Poly San Luis Obispo

Galaxy Merger Simulations

Toomre & Toomre (1972)
Restoration: Michael Lauter



Holmberg (1941)



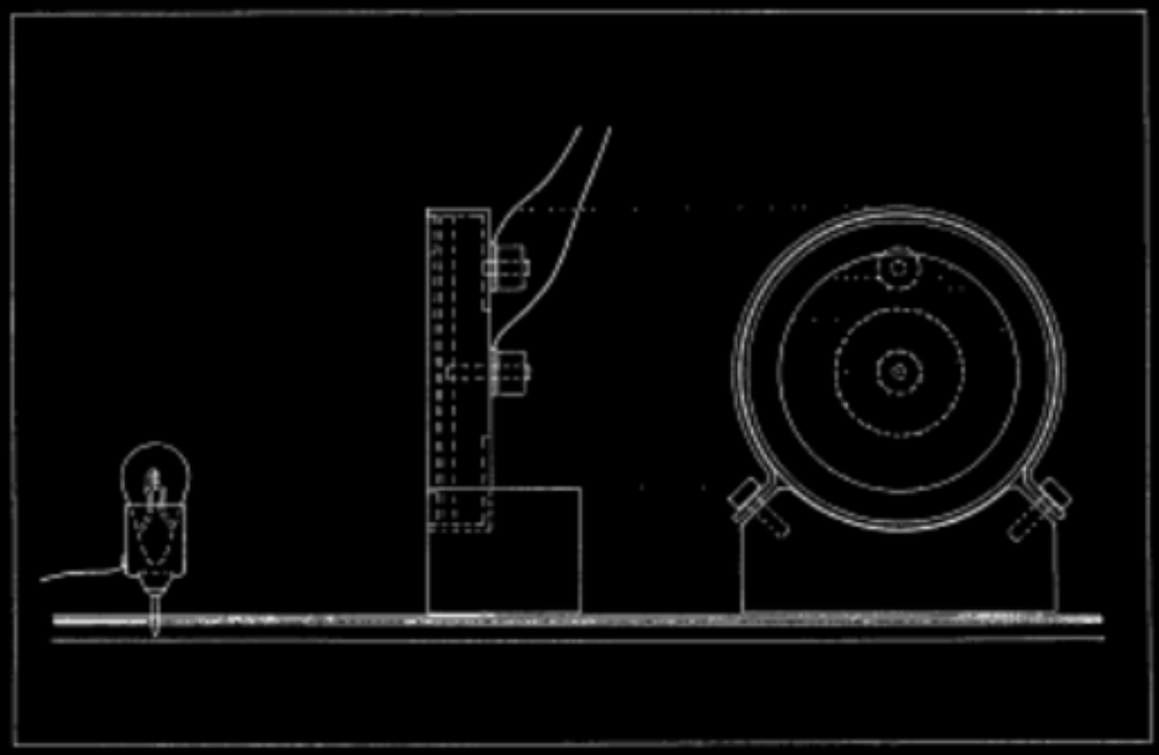
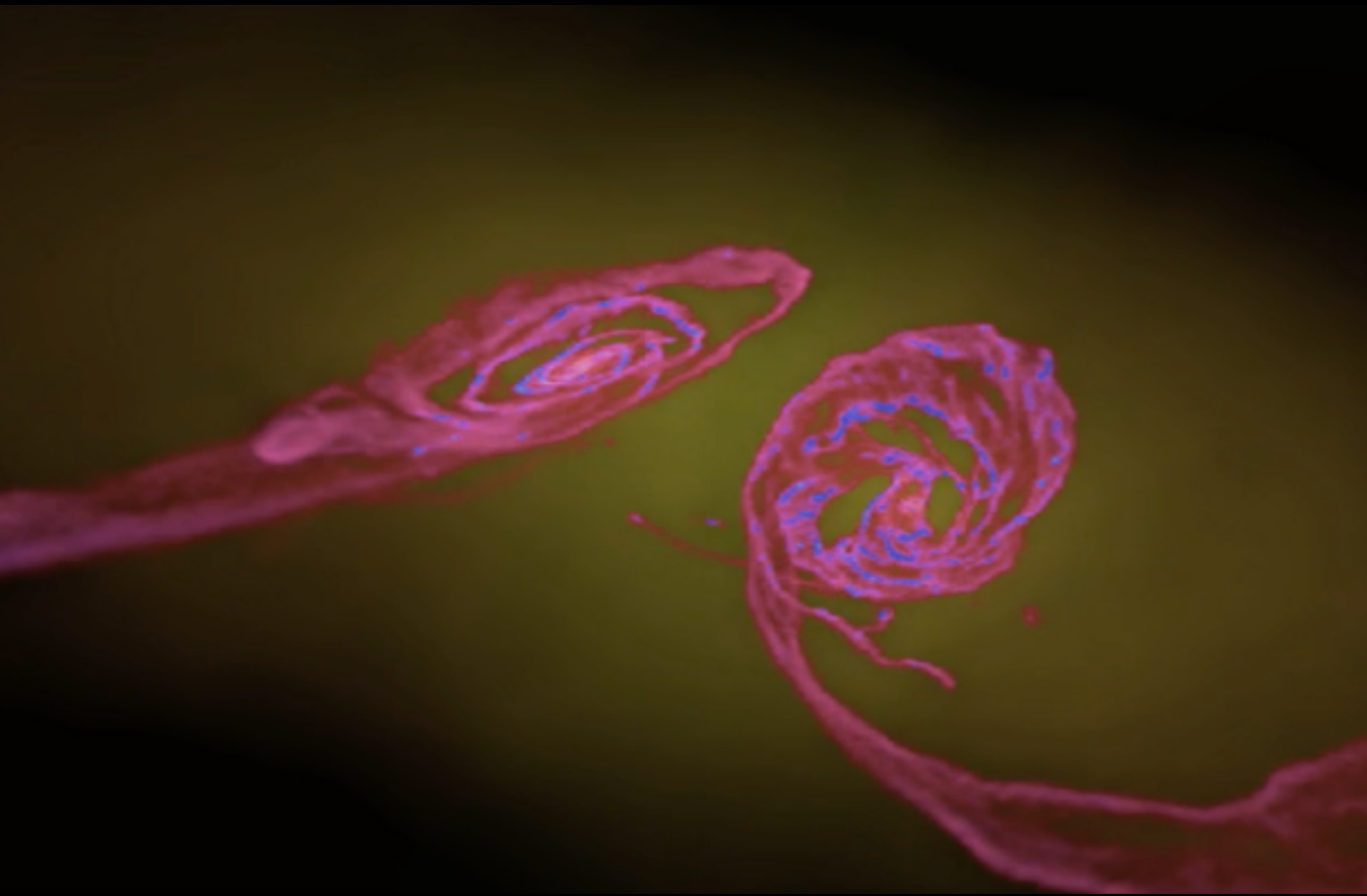
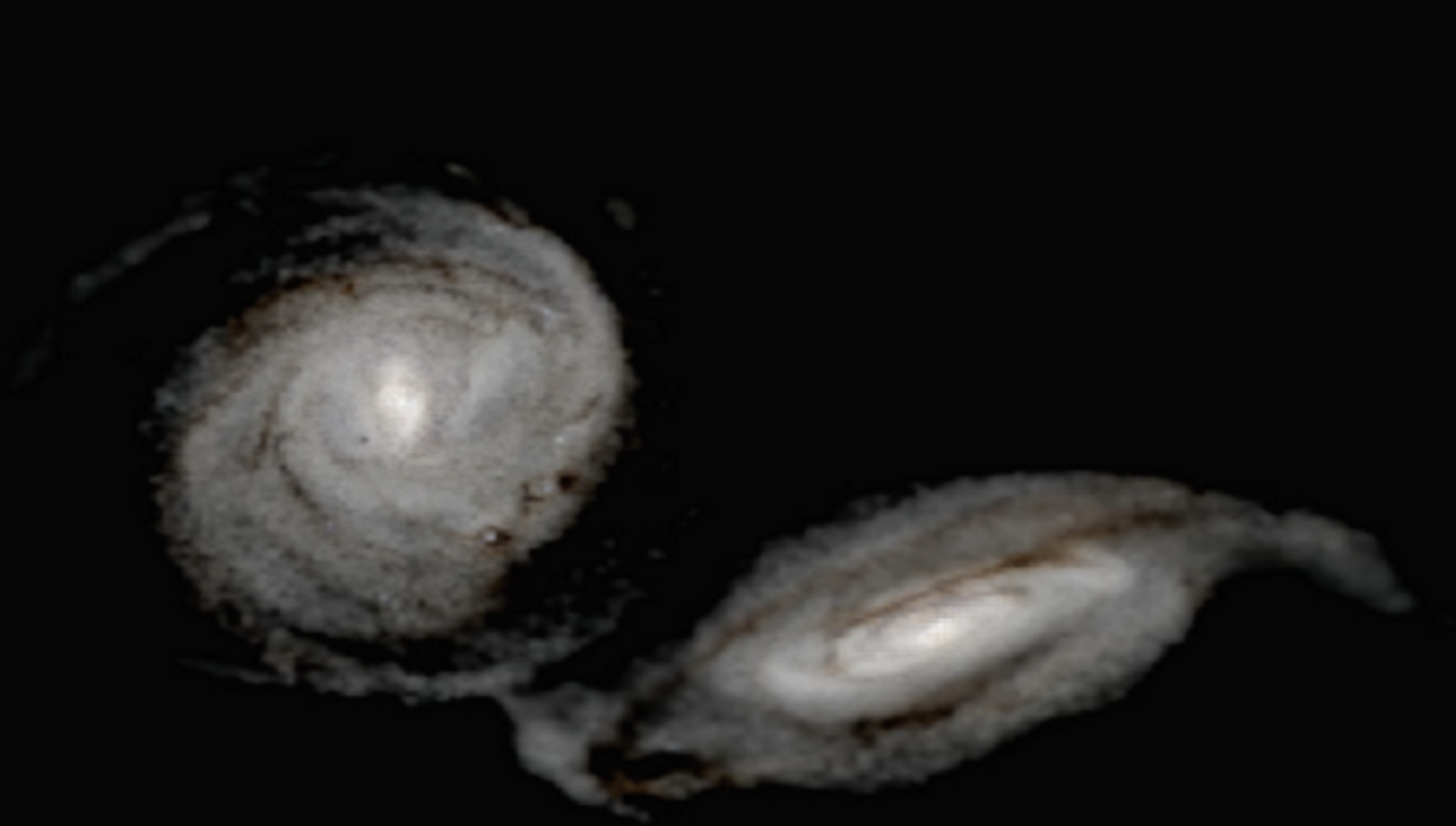


FIG. 1.—Cross-section of light-bulb and photocell (half-size)

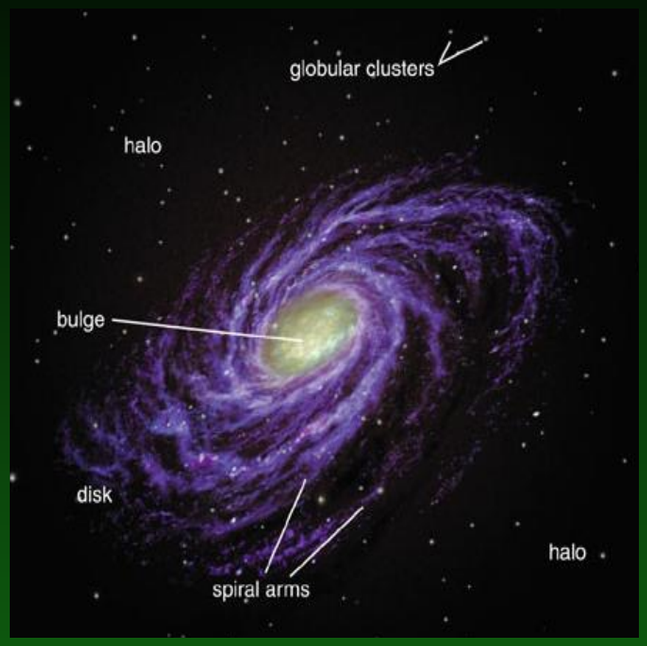




Motivation for New Galaxy Merger Simulations

Pillars of Galaxy Evolution

Internal Structure



Environment

Interaction History

Messier 81

Messier 82

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: $b = \{2, 8, 16\}\,\mathrm{kpc}$

Spin-orbit orientations: $\{\mathrm{e},\ \mathrm{f},\ \mathrm{k}\}$

(prograde, perpendicular, retrograde)

Mass Ratios Suite

FIXED: Eccentricity, Impact Parameter & Orientation

VARYING: Mass

Morphology: Gas fraction:

$M_{\rm disk}$ $[M_\odot]$	$M_{\rm bulge}$ $[M_\odot]$	$f_{\rm g,init}$
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)

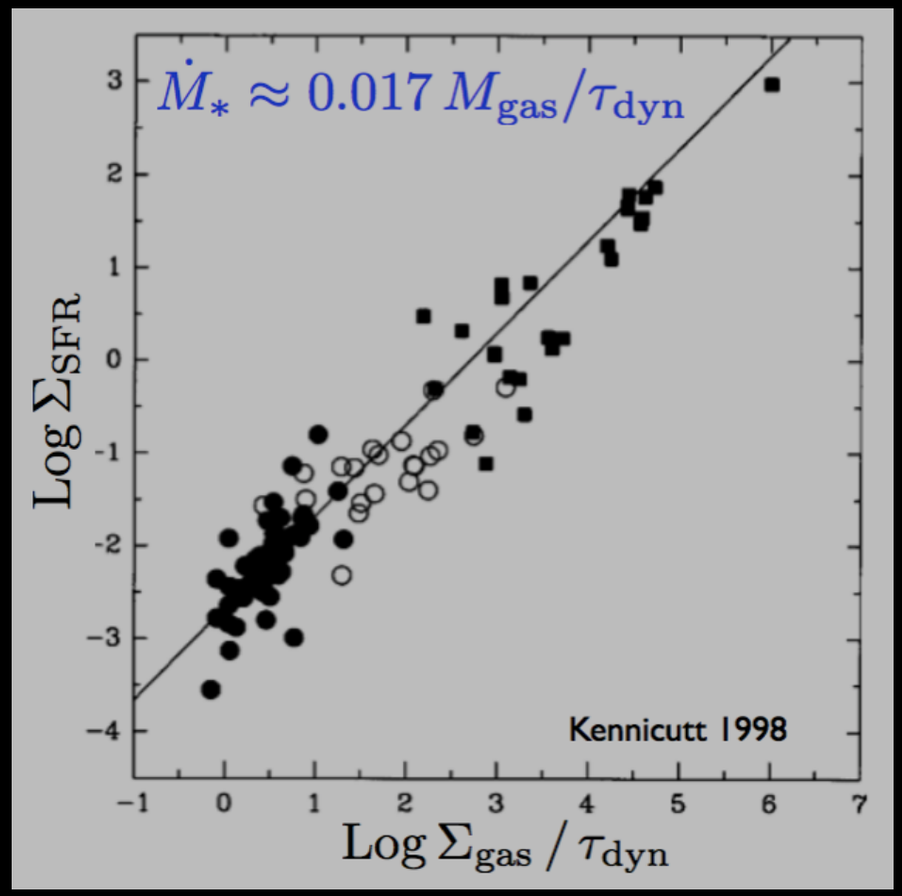
PIs: Hopkins, Faucher-Giguere, Keres & Quataert

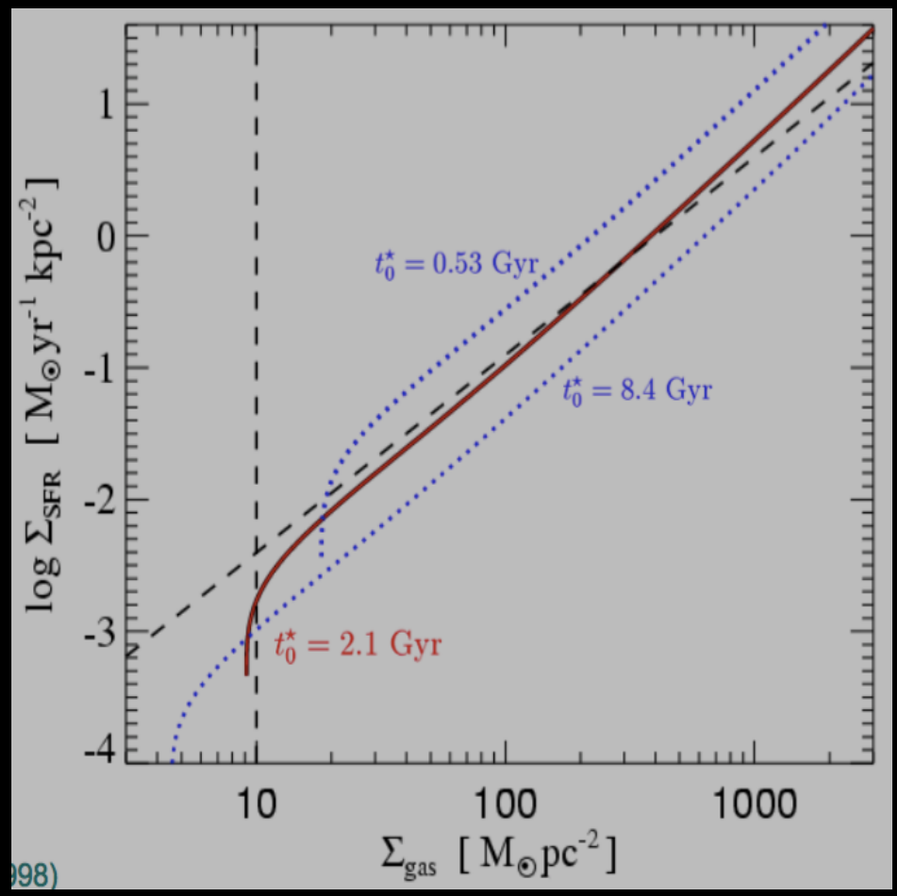
http://fire.northwestern.edu

Gadget (precursor)

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

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



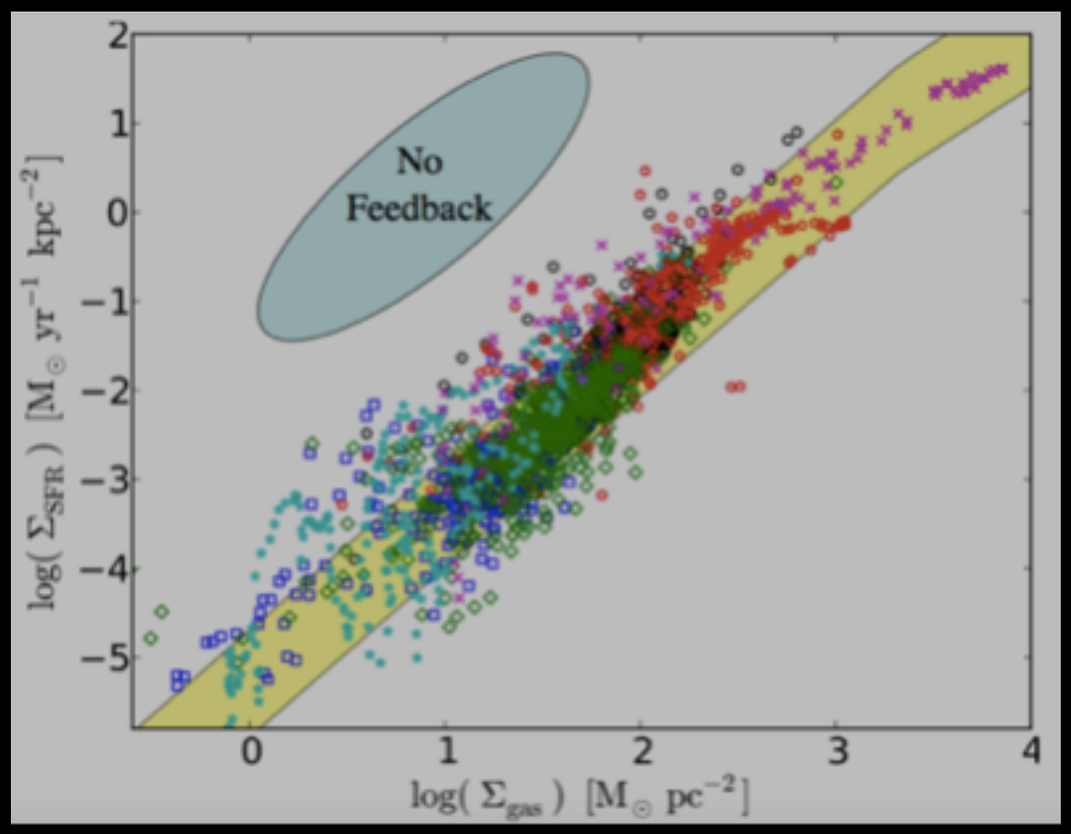


FIRE: Highlights

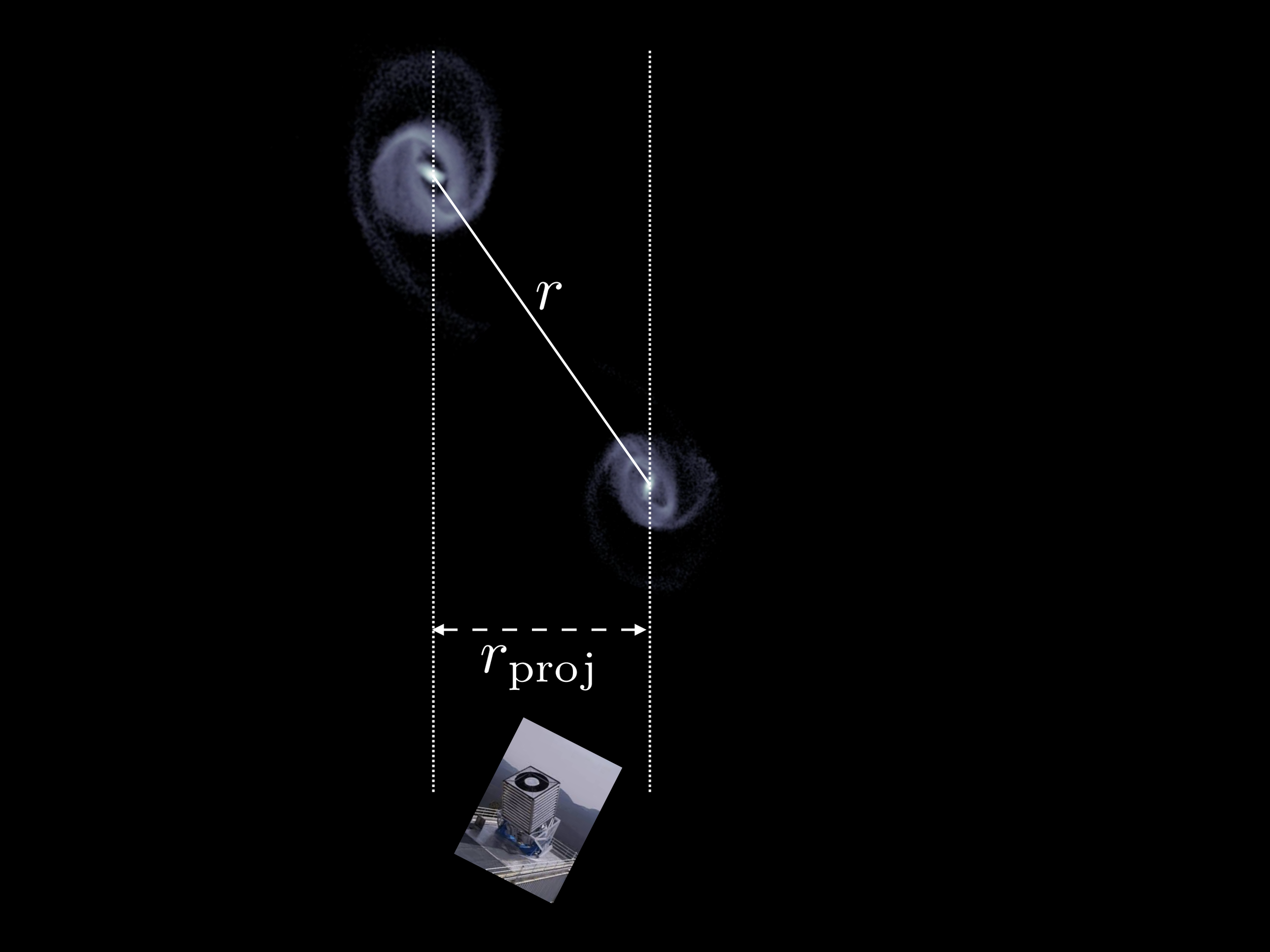
(Hopkins et al. 2014)

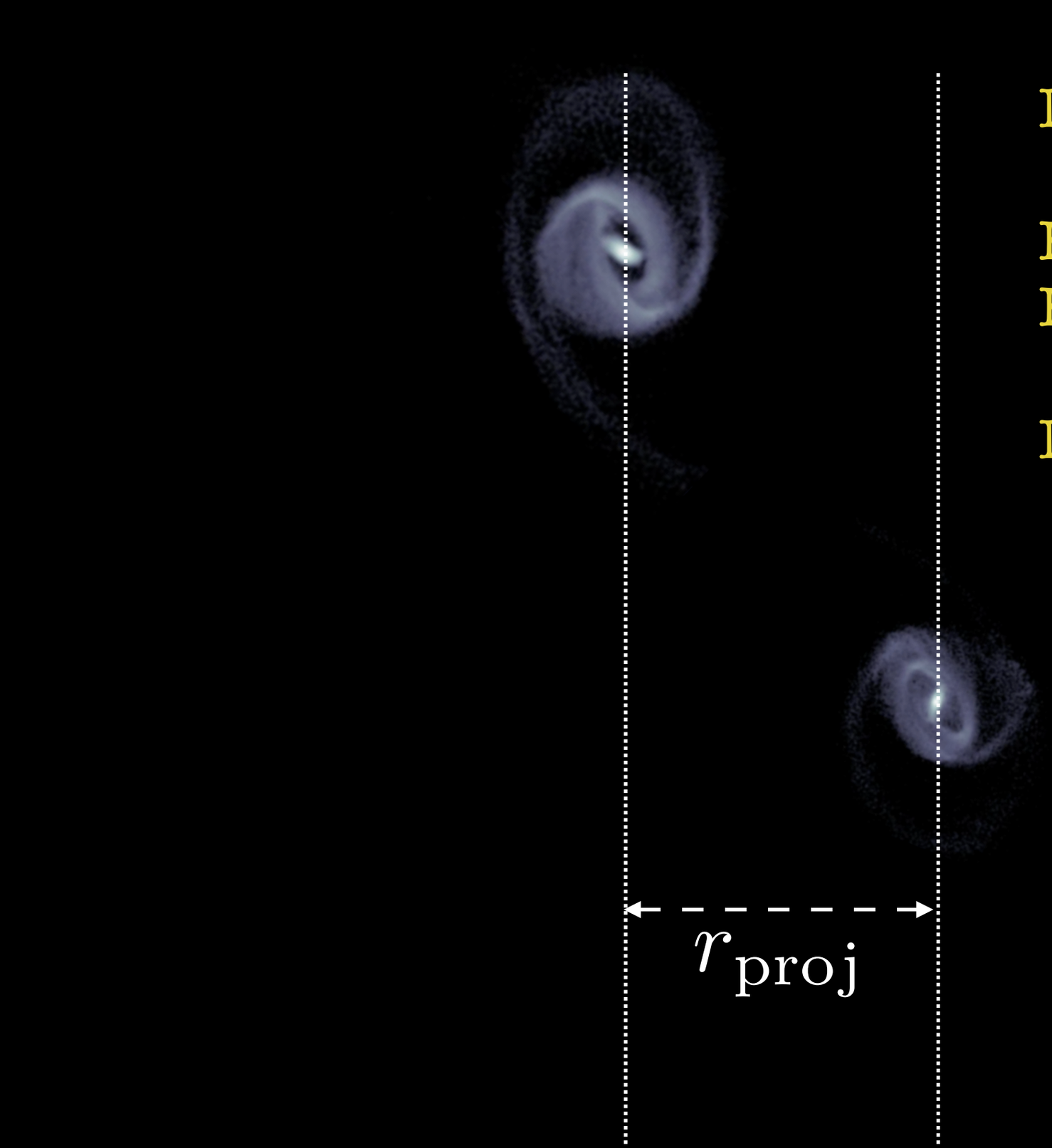
- GIZMO: meshless hydro solver
- Kennicutt Law: prediction, not an input
- Self-gravitating dense molecular gas regions
  => star formation in one dynamical time!

- Realistic Feedback:
  - Stellar Winds (O & AGB stars)
  - SN II & Ia
  - Photoionization & photoelectric
  - Radiative Pressure



Mock Surveys: Mapping Star Formation

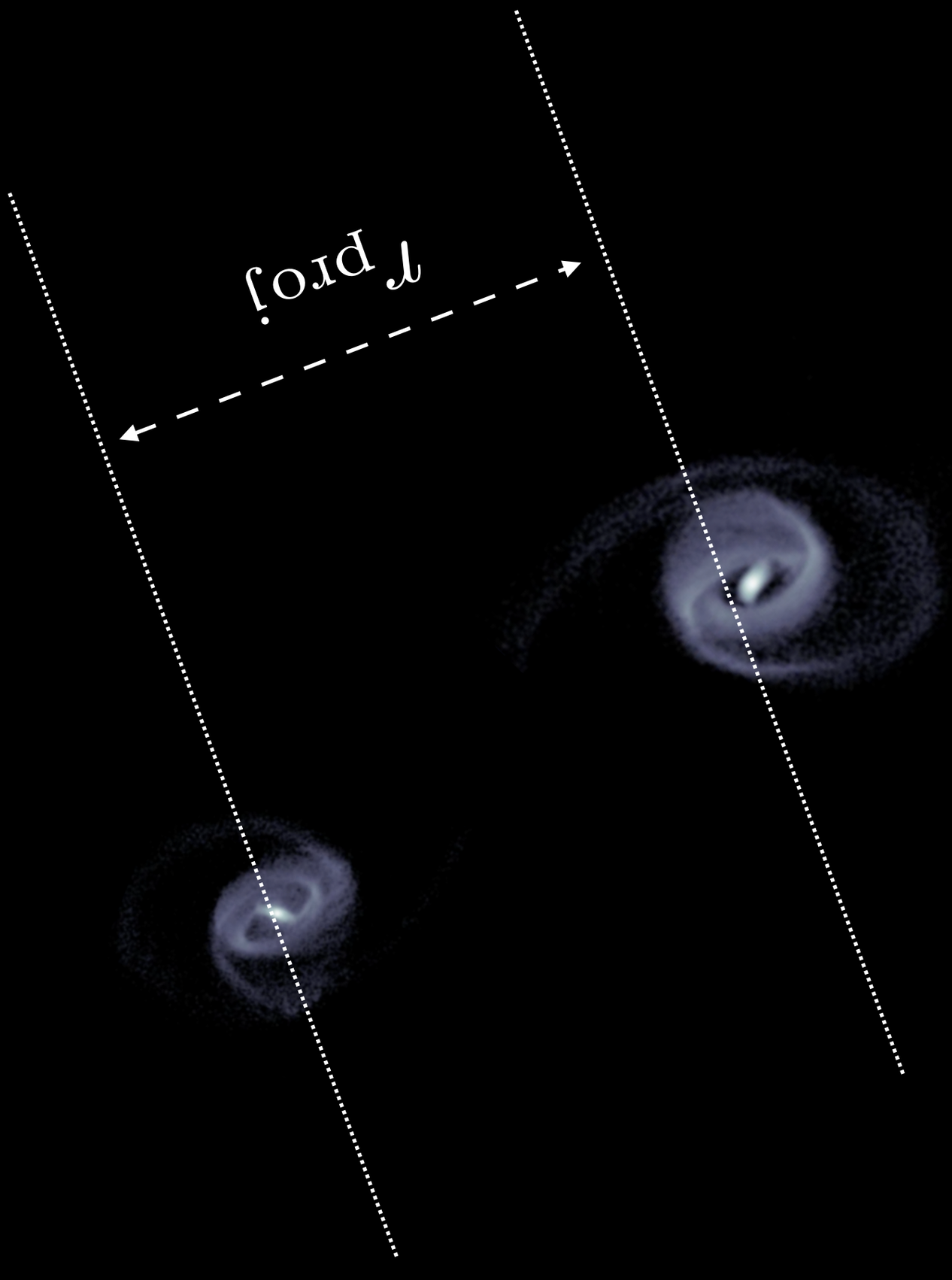

r
r_{proj}

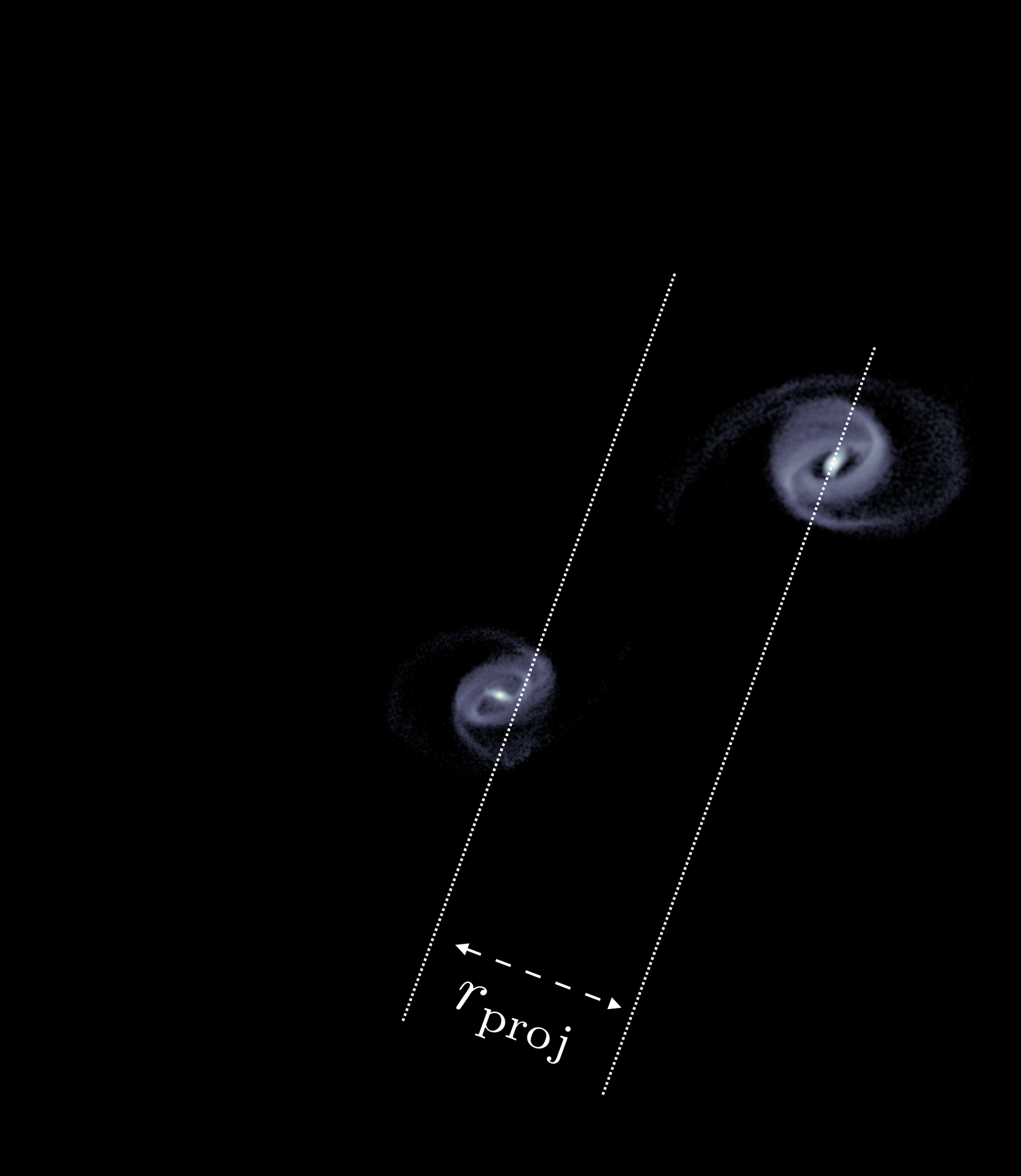


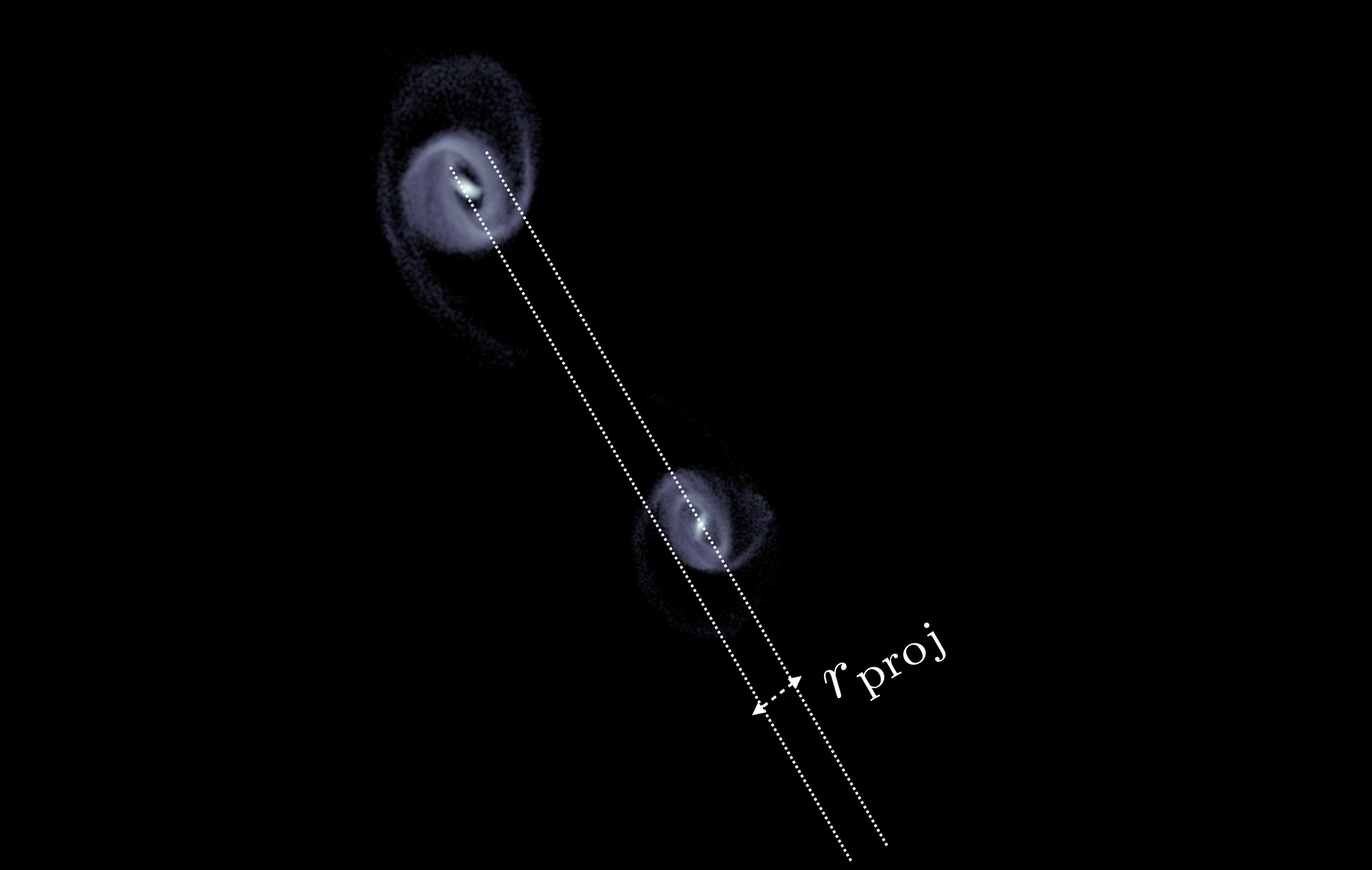
MOCK SURVEY:

For Every Merger
For Every Time Snapshot

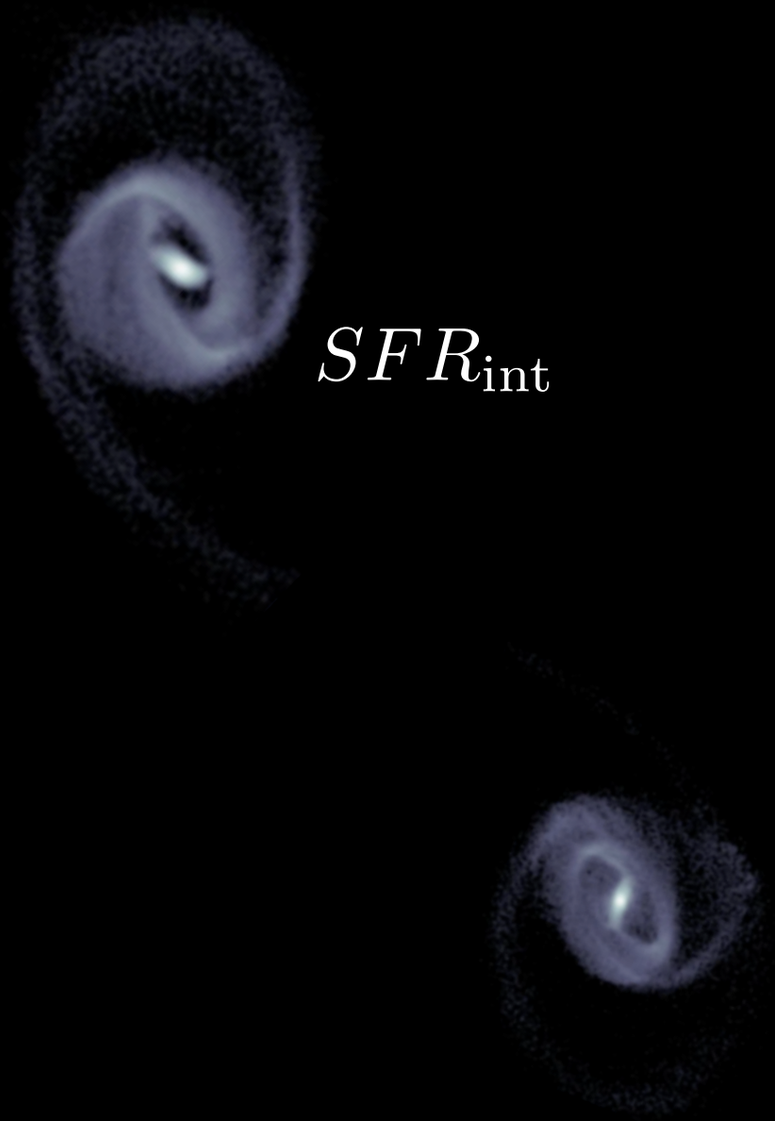
Many Random Views!


r_{proj}


r_{proj}

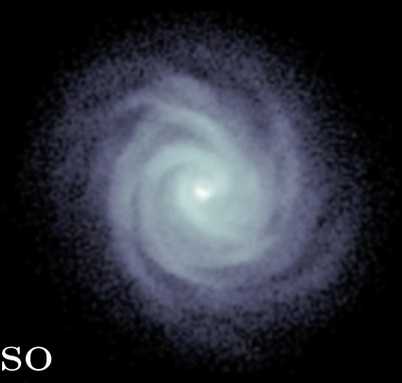

r_{proj}

Interacting



$SFR_{\rm int}$

Isolated Control

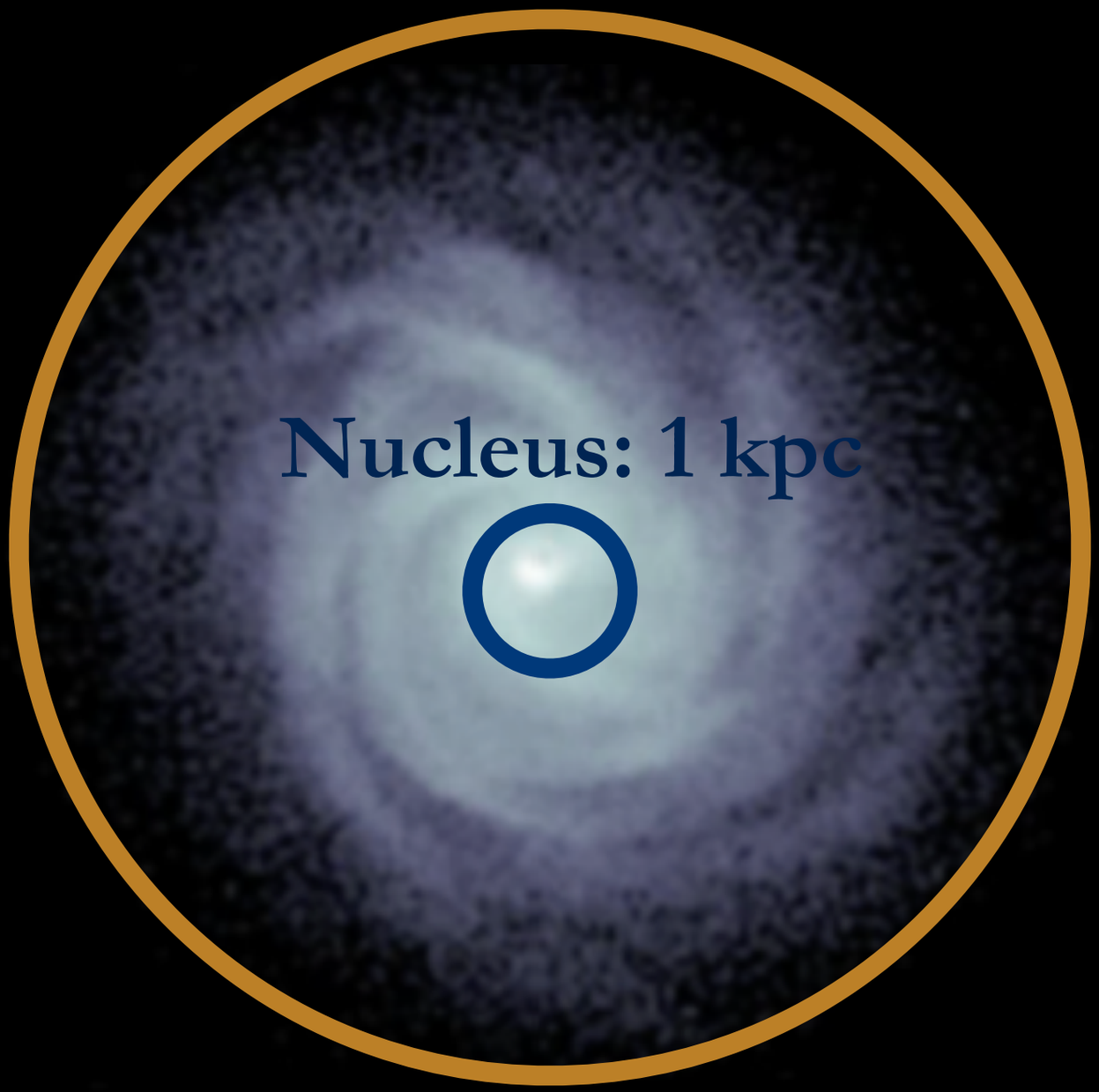


$SFR_{\rm iso}$

Star Formation Rate Enhancement:

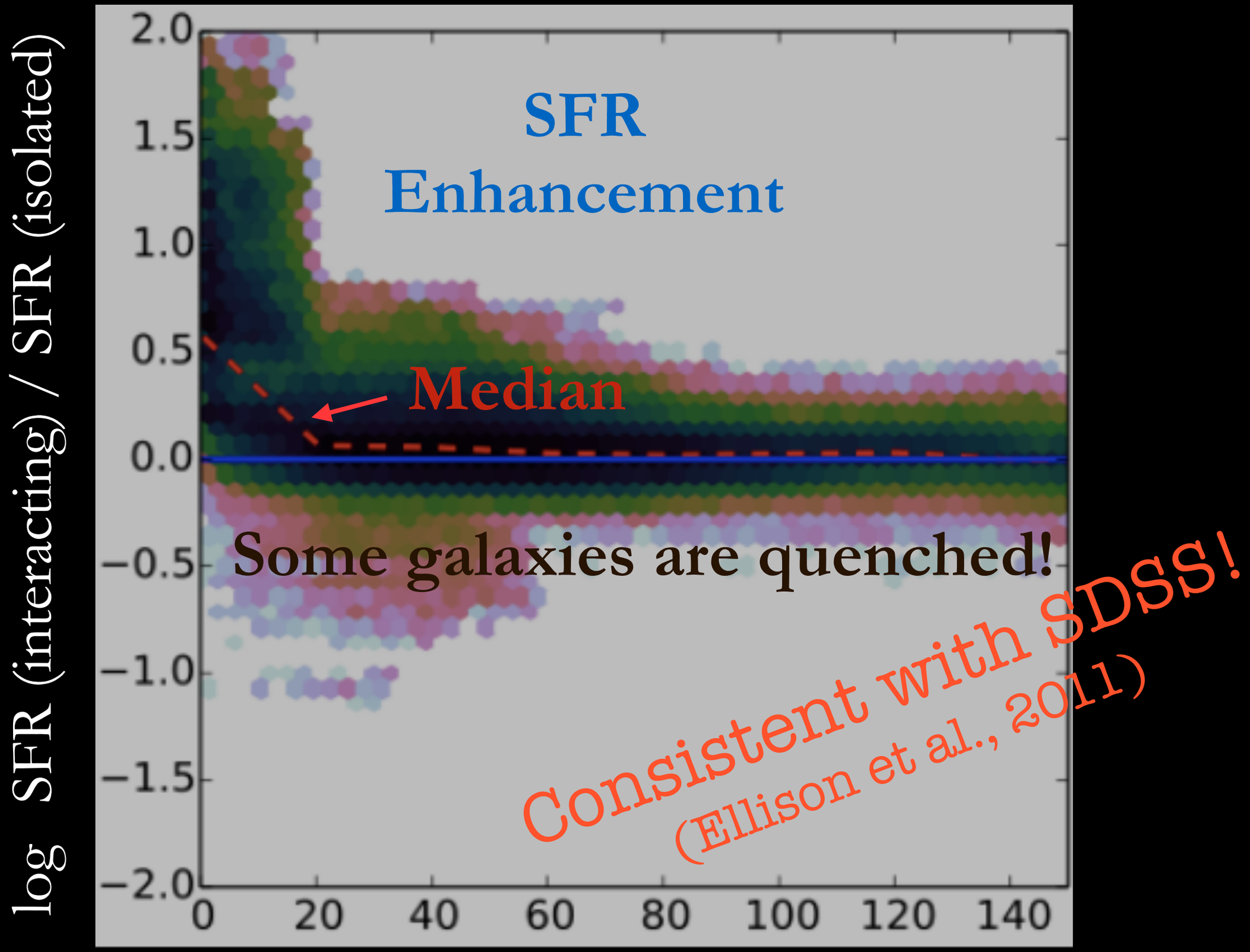
$$\Delta SFR \equiv \frac{SFR_{\rm int}}{SFR_{\rm iso}}$$

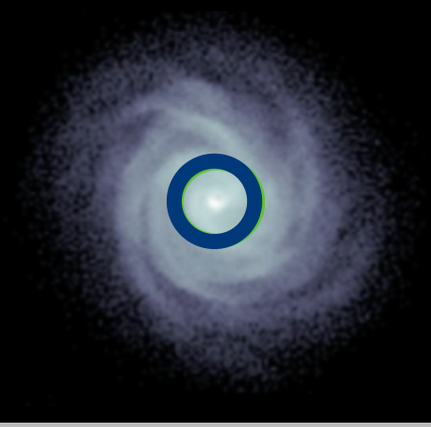
Mapping Star Formation



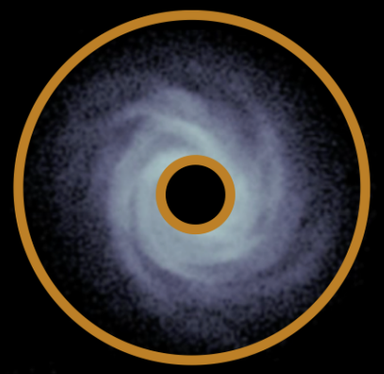
Outer Disk : $1 - 20\,\mathrm{kpc}$

Results:
Mapping Star Formation

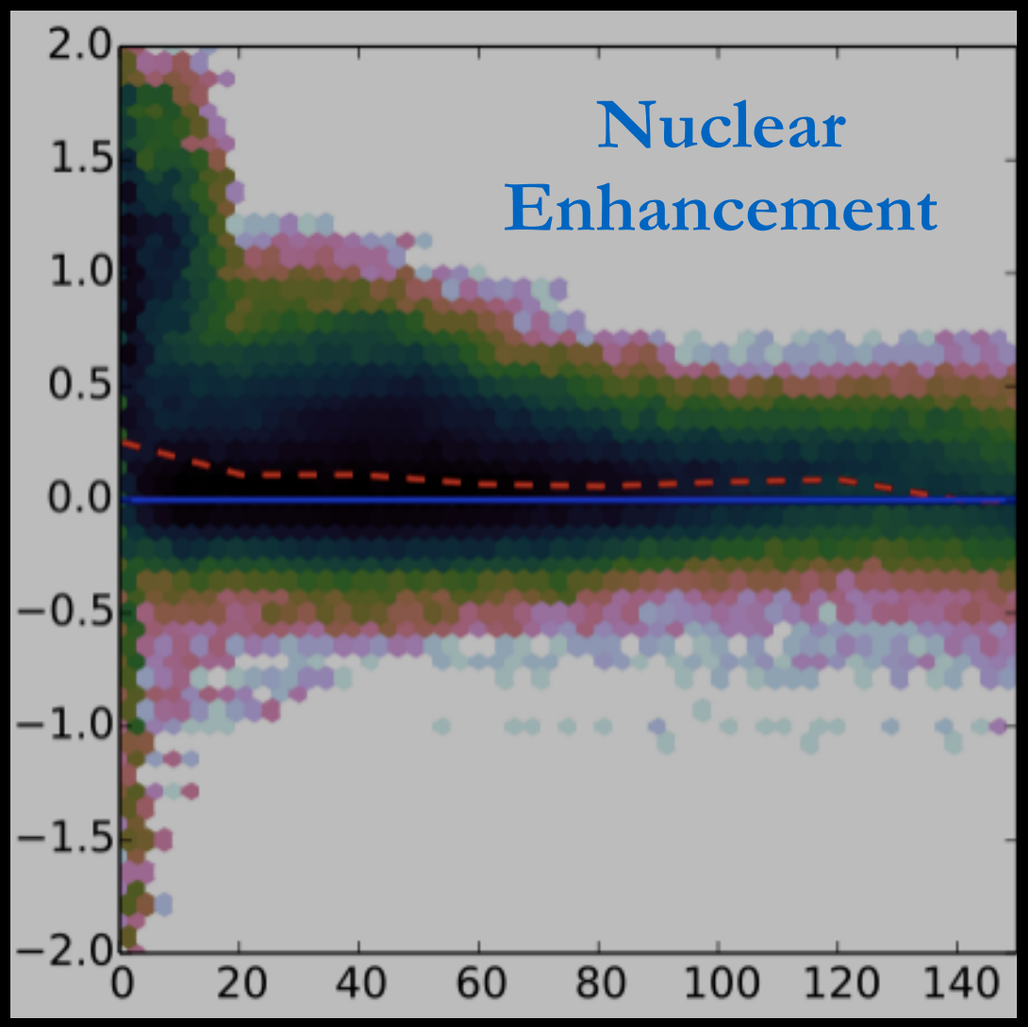

log SFR (interacting) / SFR (isolated)
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
−2.0
0
20
40
60
80
100
120
140
Projected Separation
SFR
Enhancement
Median
Some galaxies are quenched!
Consistent with SDSS!
(Ellison et al., 2011)

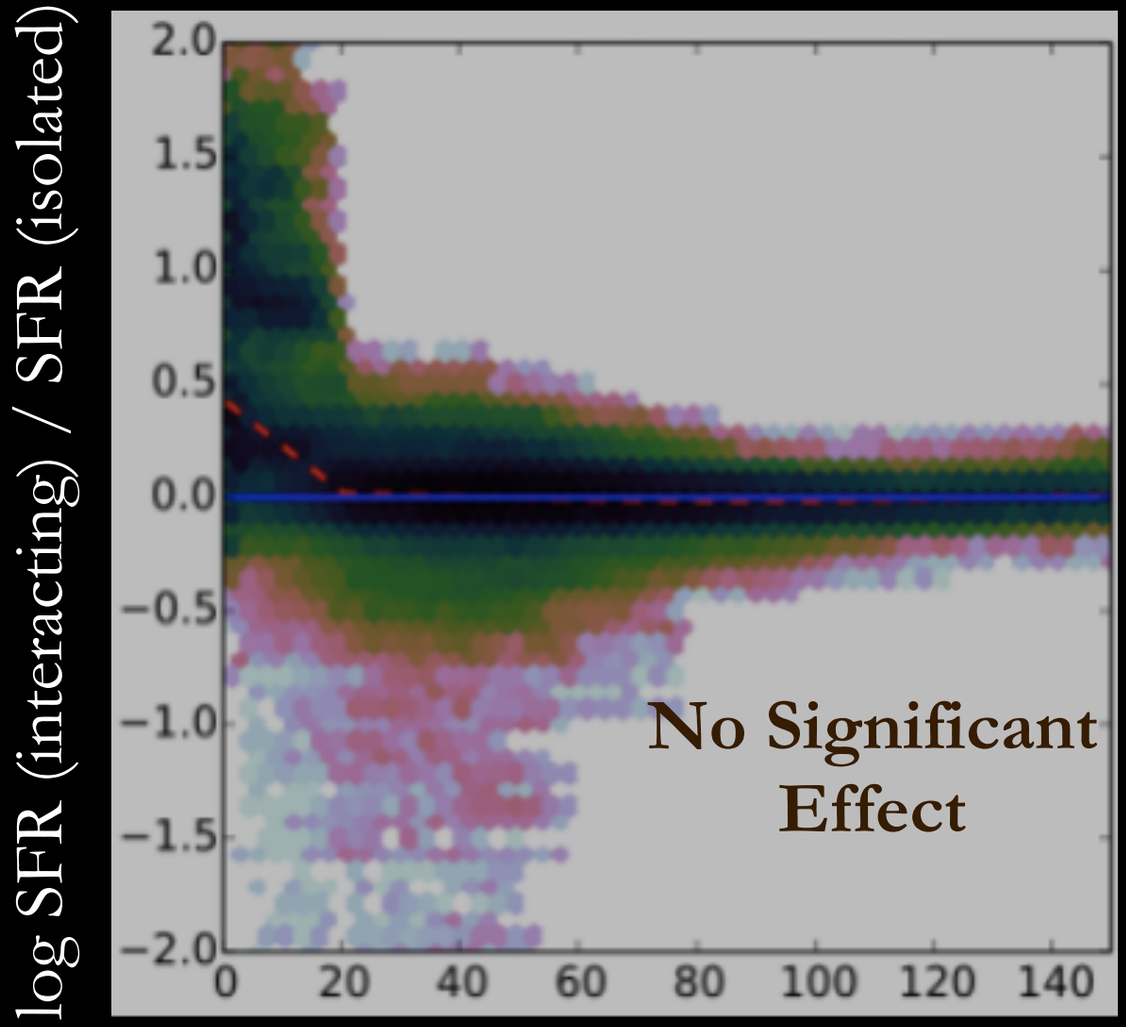


Nucleus
(0 -1 kpc)



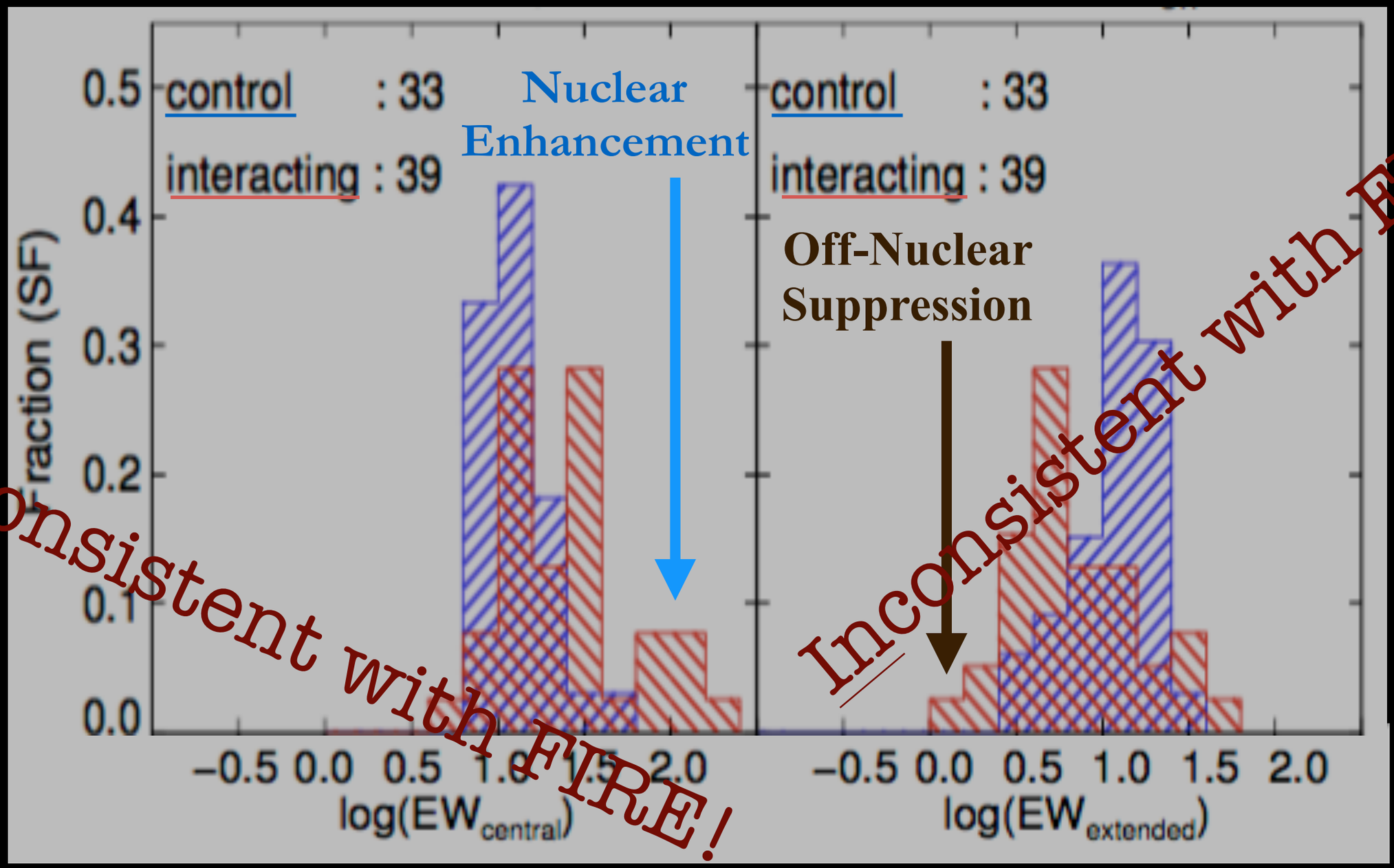
Outer Disk
(1 -20 kpc)





Comparison with IFS Observations

(Barrera-Ballesteros + CALIFA Collaboration)



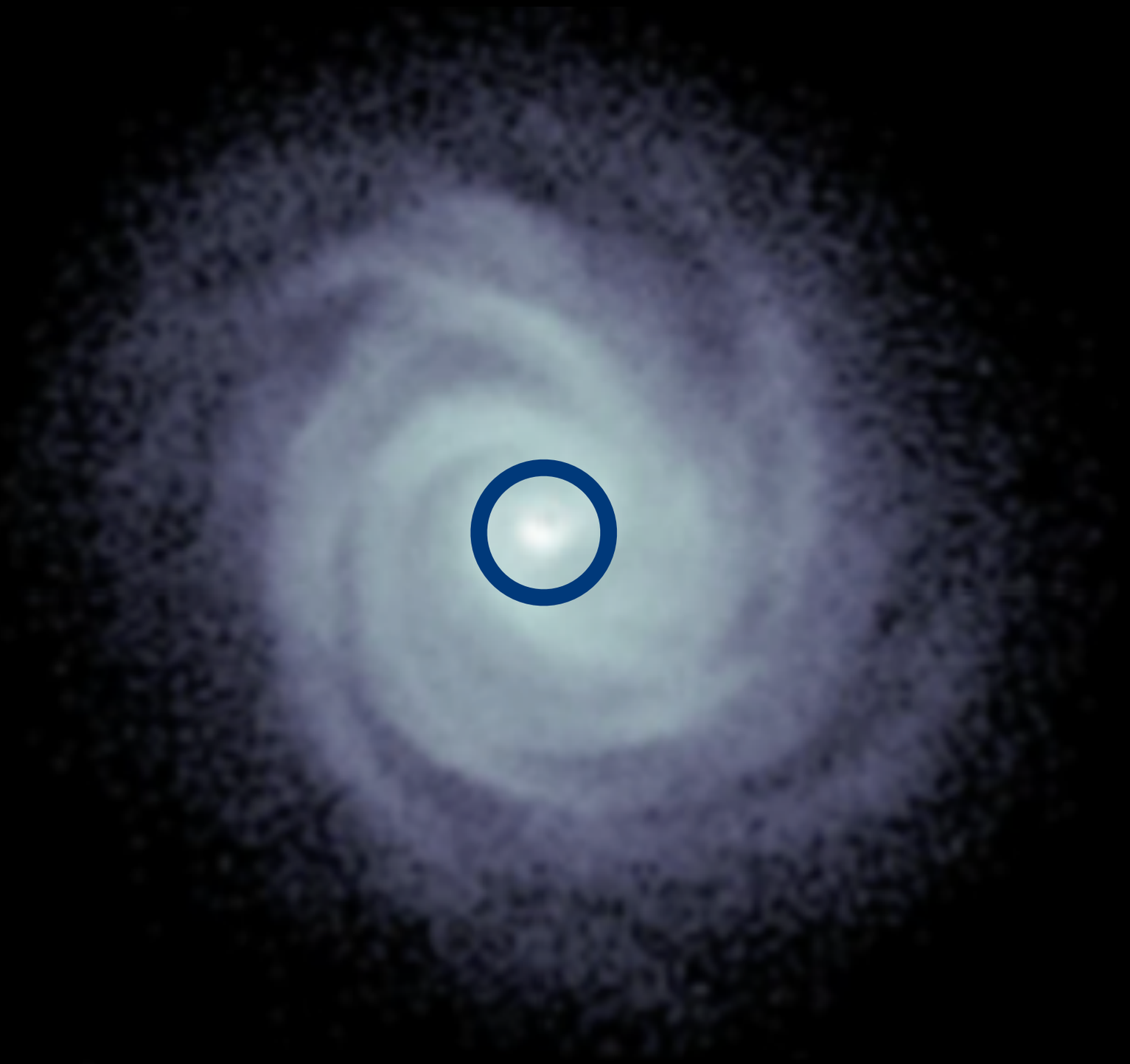
Are Observations Wrong?

Are Observations A Bunch of Malarkey?

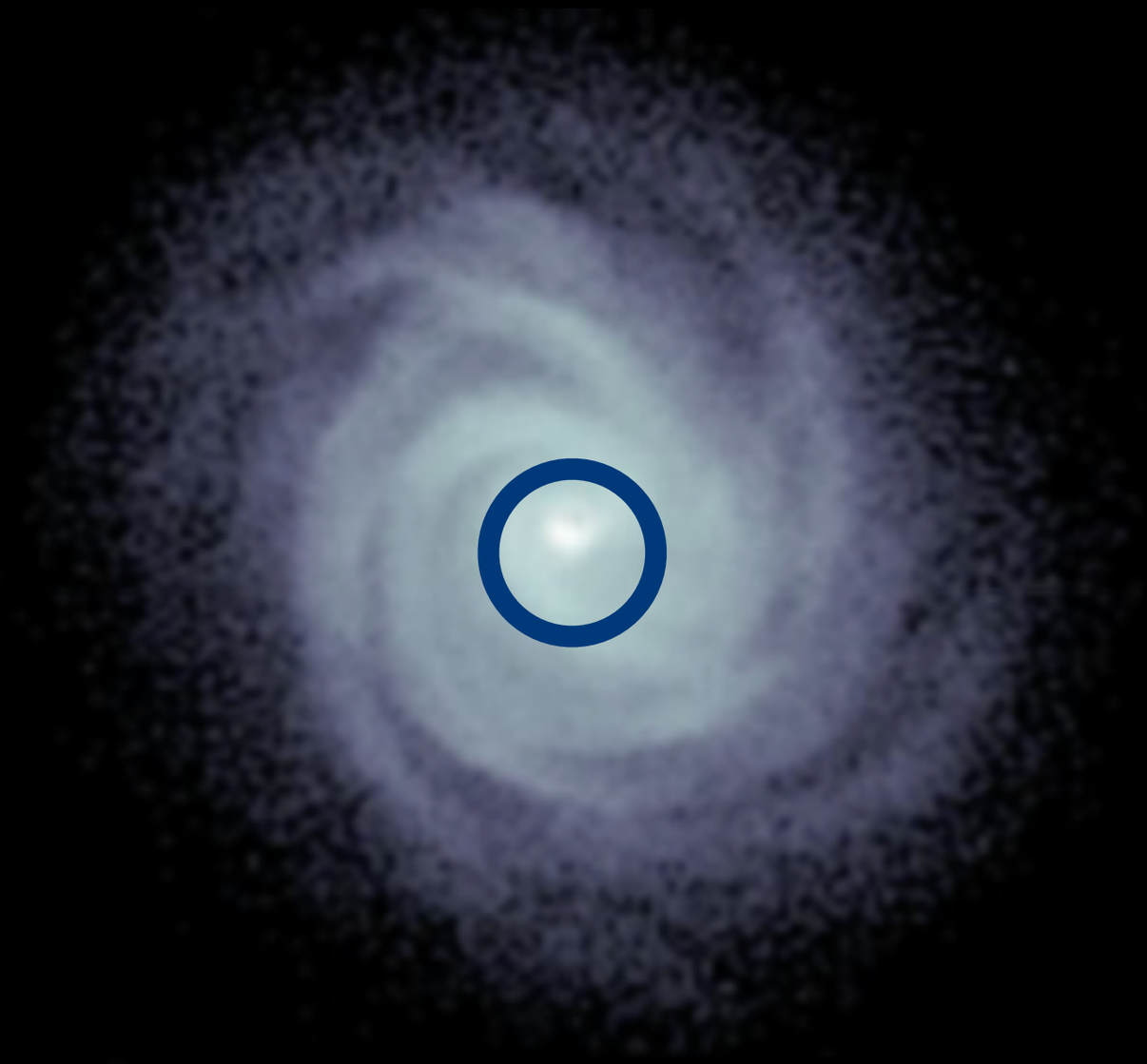
malarkey

Reconciling Theory with Observations

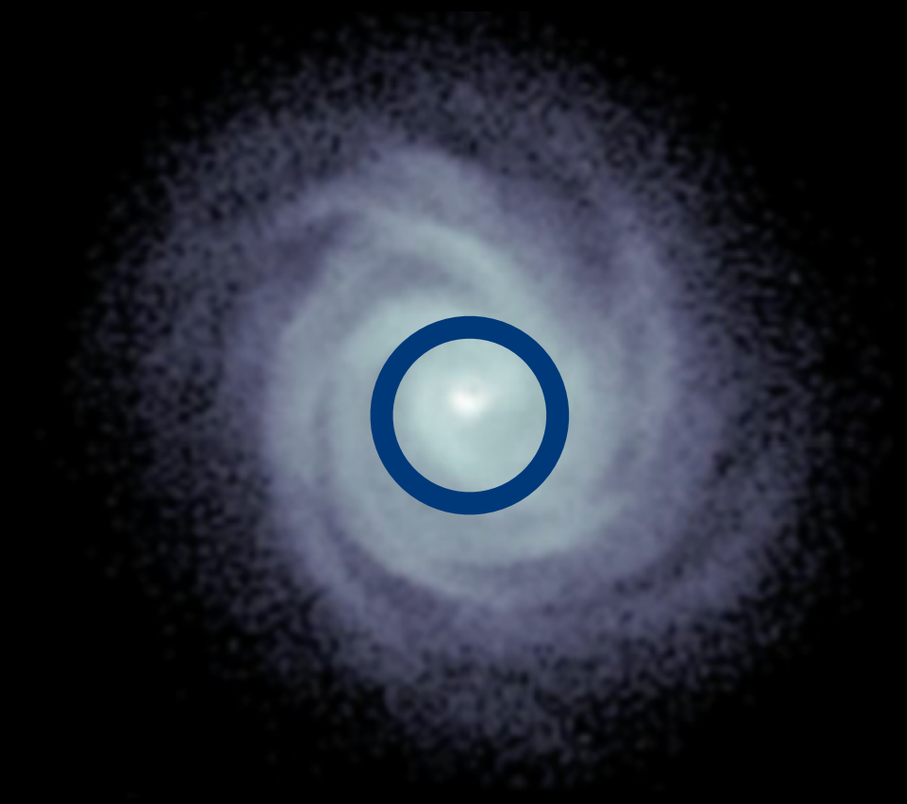
Nearby galaxy



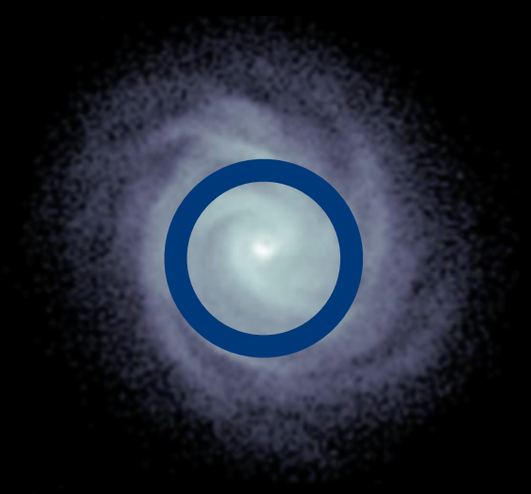
Distant galaxy



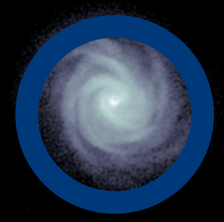
Very distant galaxy



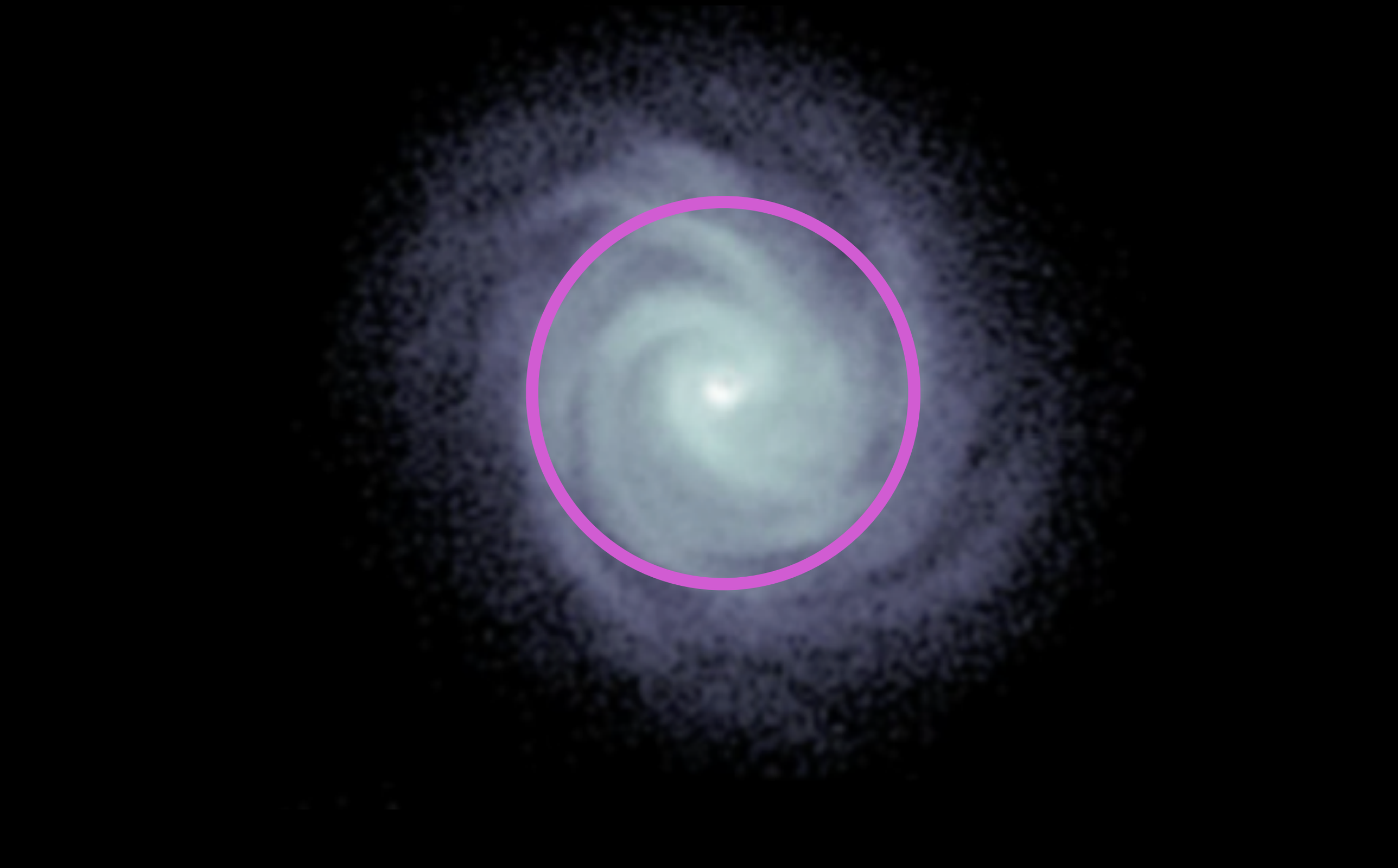
Extremely distant galaxy



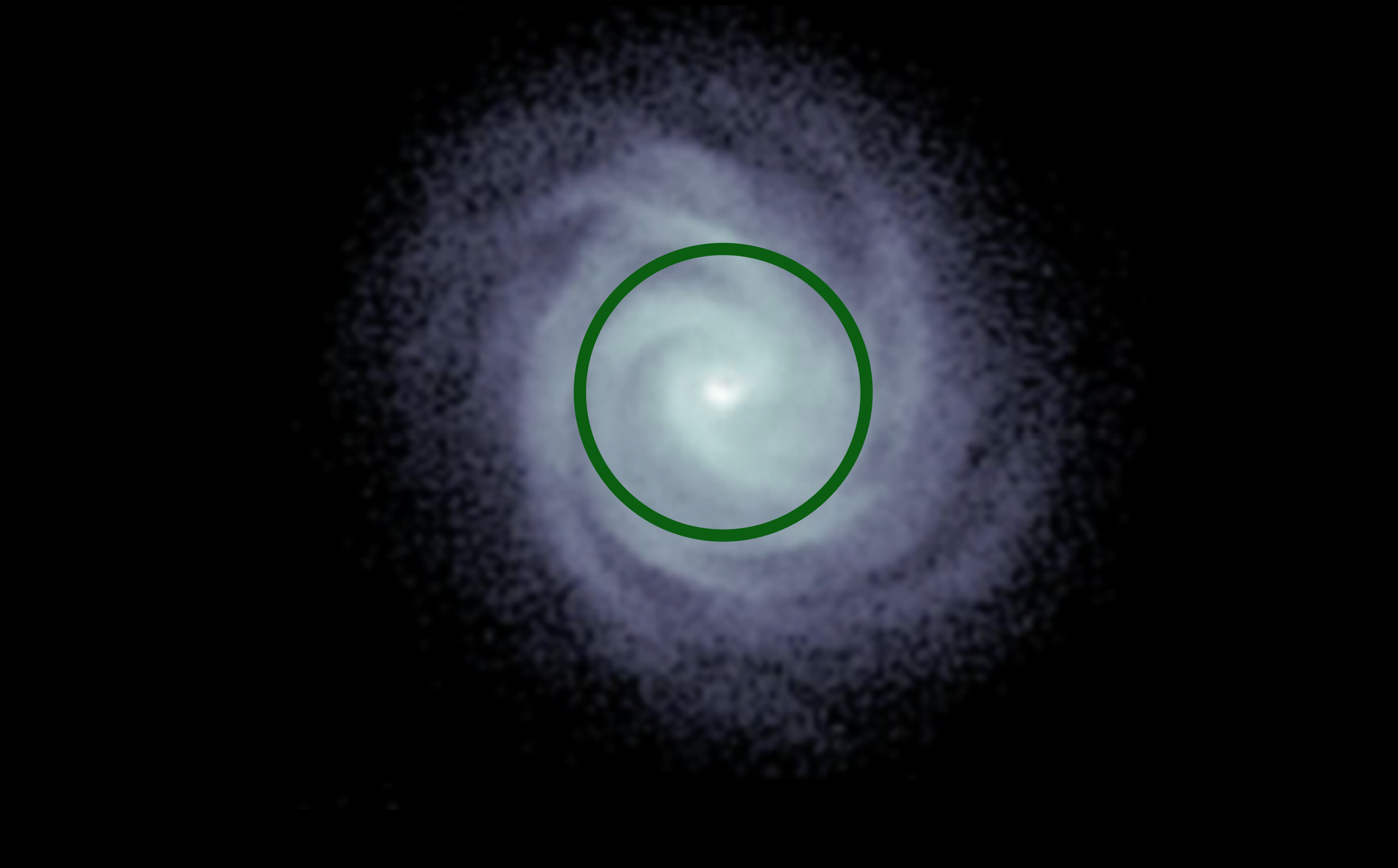
In a galaxy far far away!



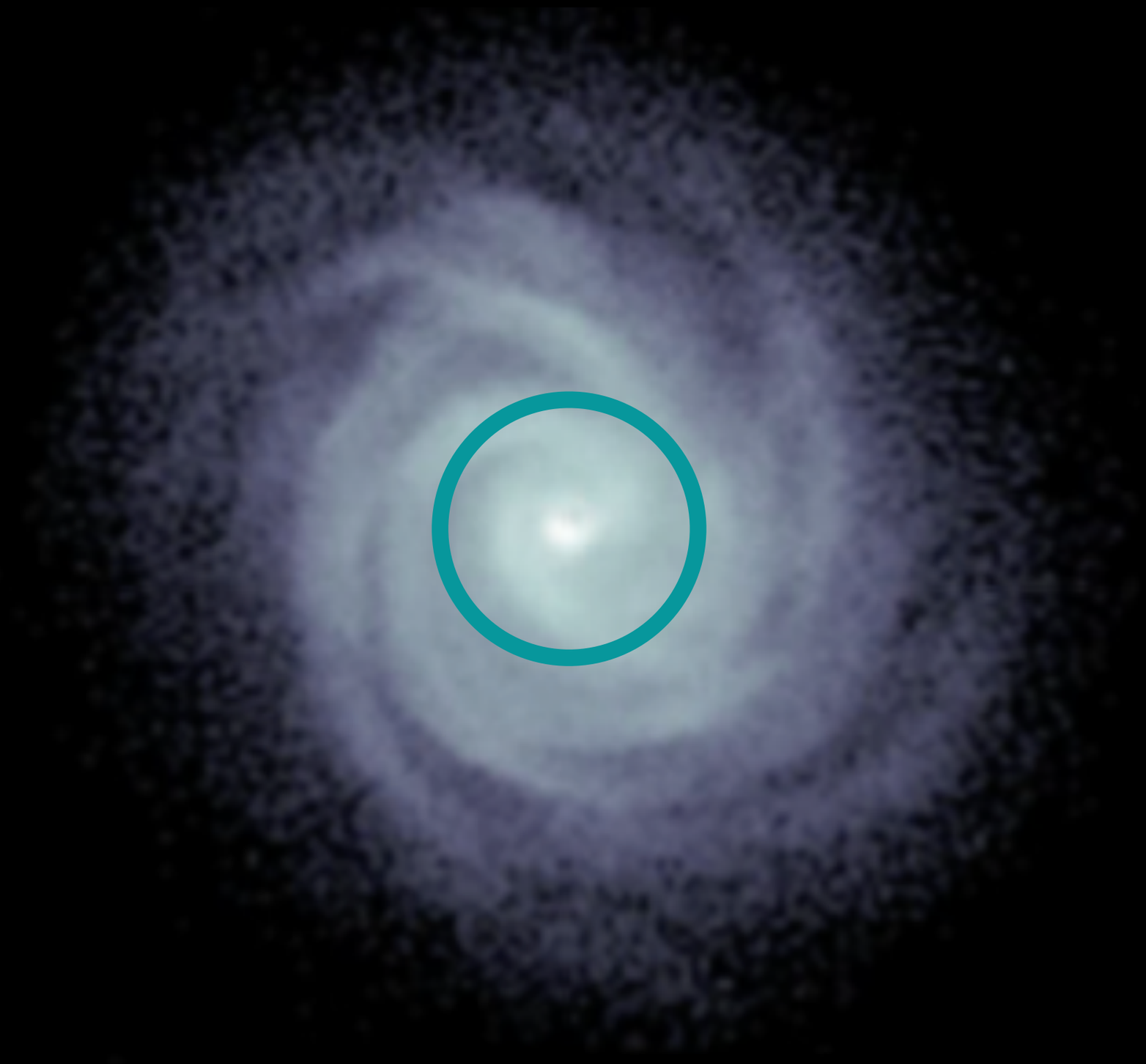
Extremely distant galaxy



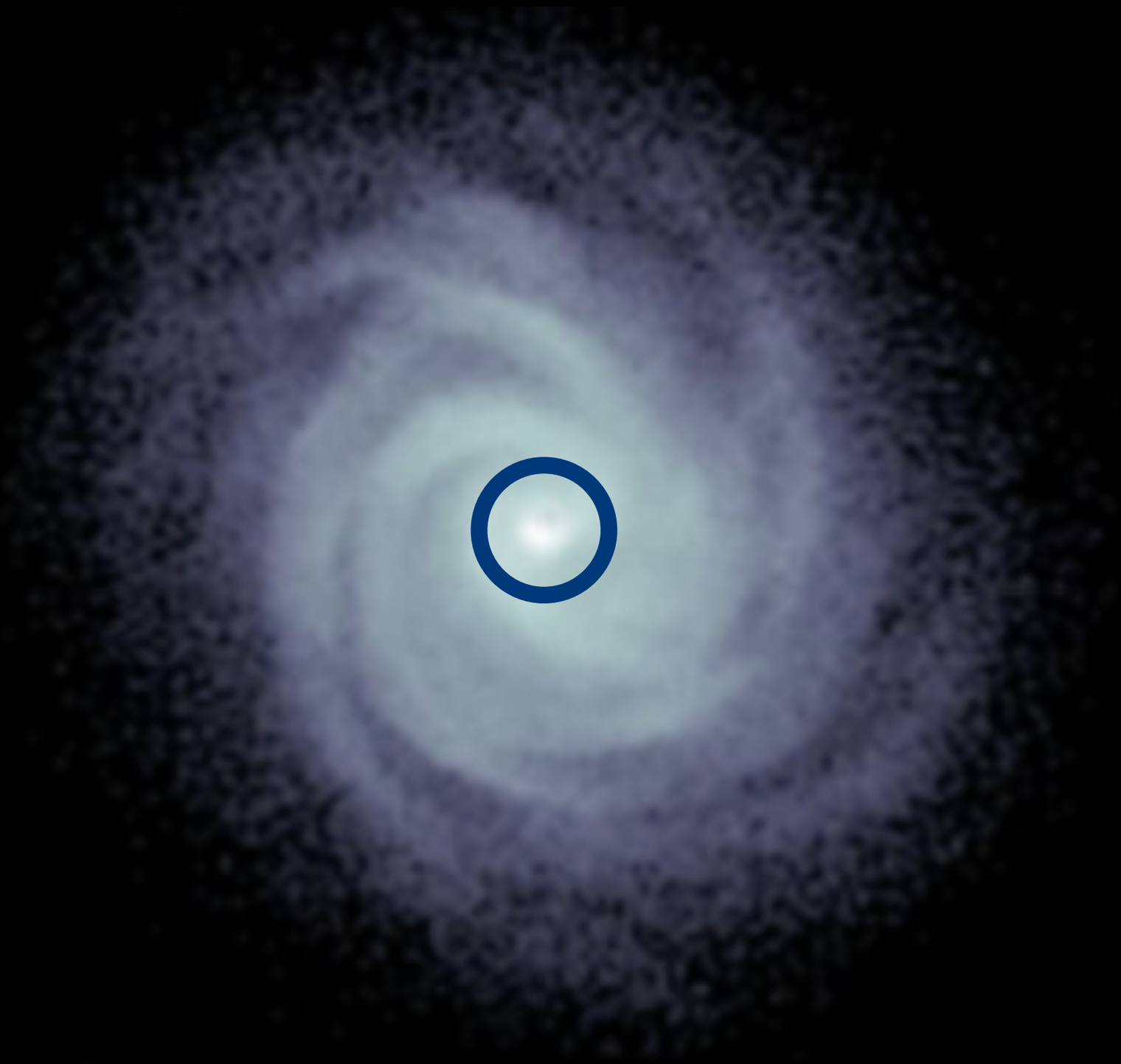
Very distant galaxy



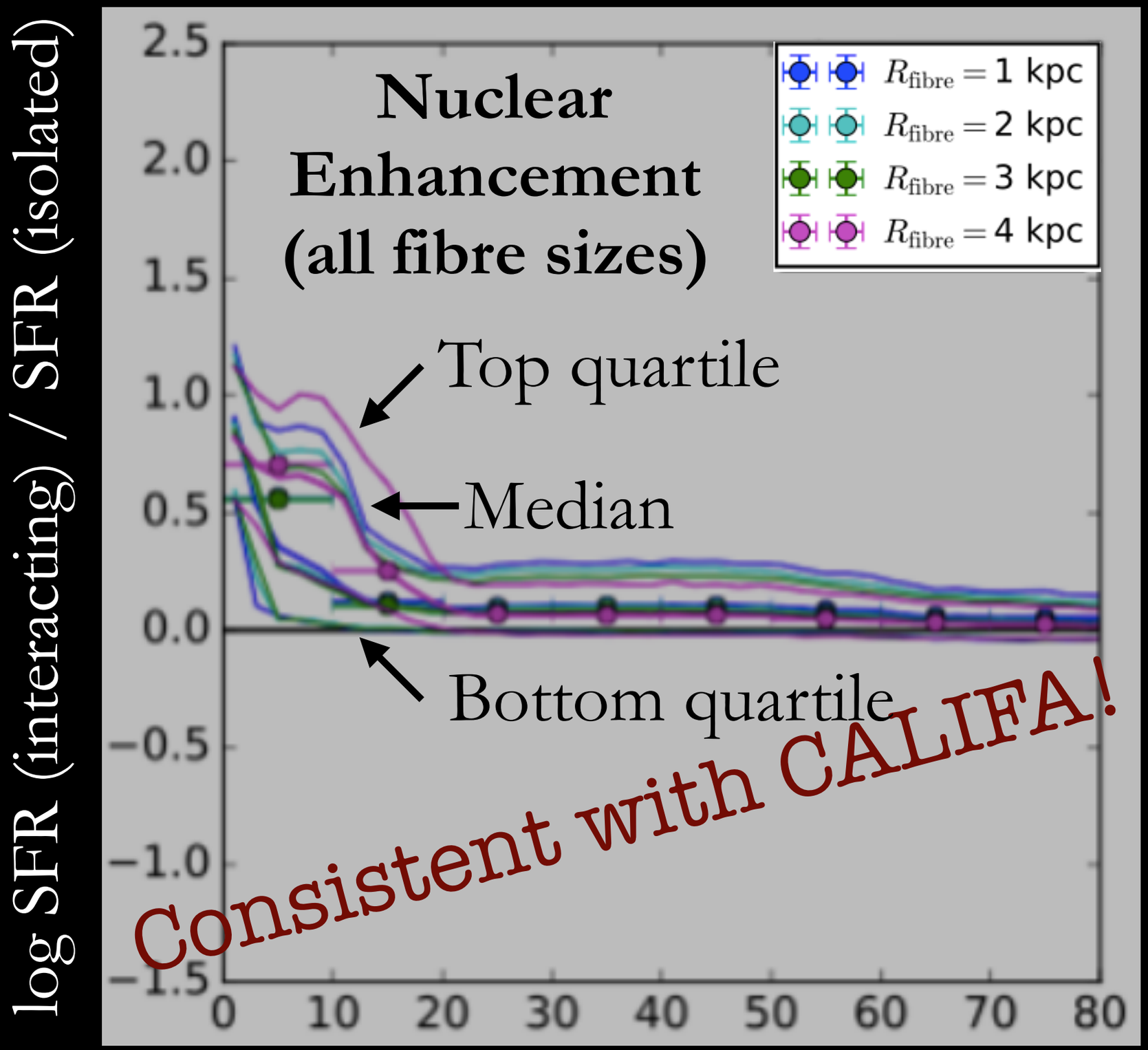
Distant galaxy



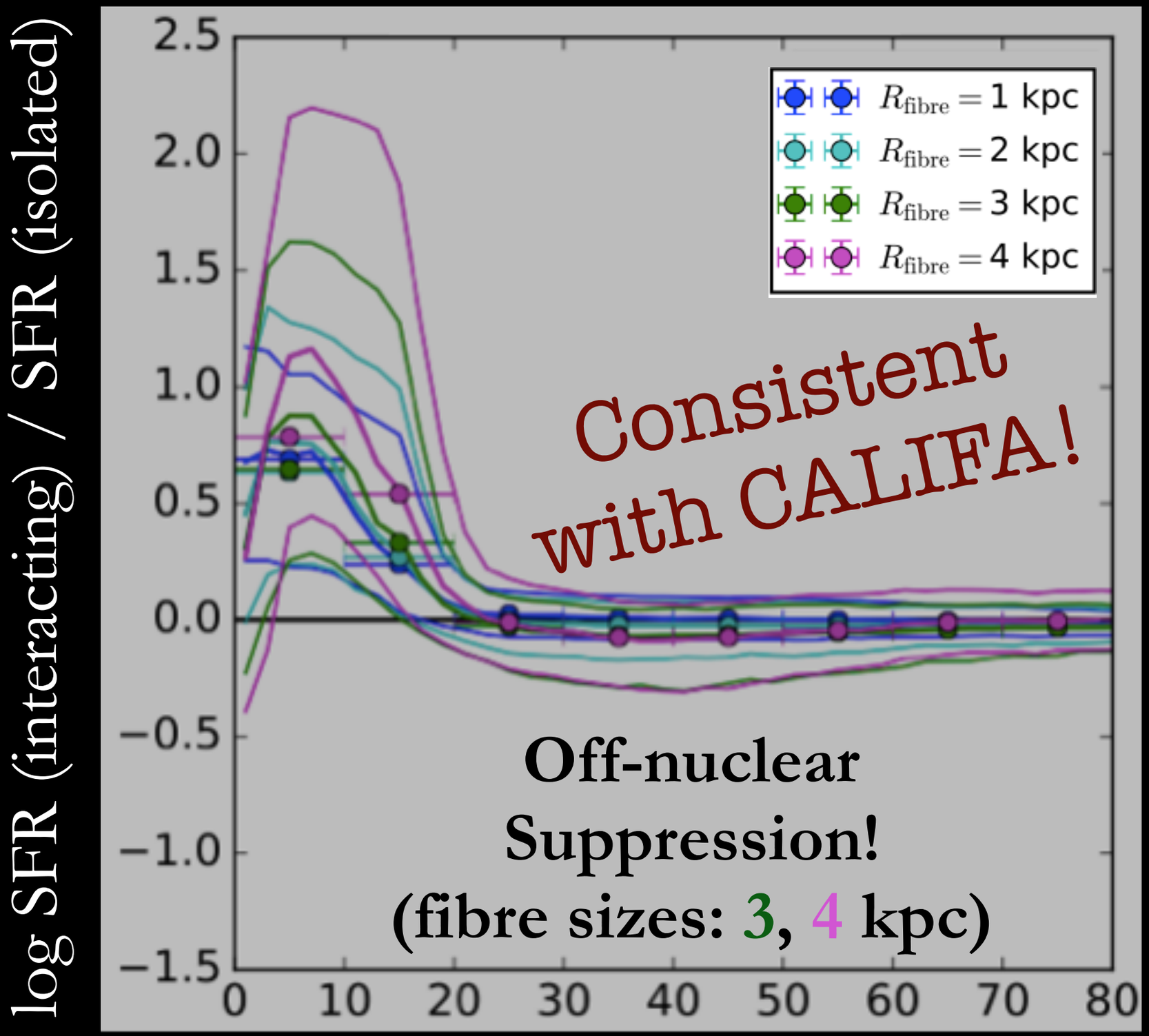
Nearby galaxy



Nuclear Region



Off-nuclear Region



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?