Title: Testing CDM with Galaxies

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Abstract:


testing CDM with galaxies
David W. Hogg
CCPP, New York University

summary

- the cosmological "standard model" (CDM) and *requires* many things at small scales
  - especially dark-matter halos and merging
- galaxy merger rates can be constrained observationally and they are *low*
- is CDM okay?
  - I'm not going to say

talk outline

- grandiose, self-important, lengthy philosophical introduction
- distraction with immense amounts of beautiful but fundamentally irrelevant data
- trivial, technical result with no easily understood punchline
  - this project will take decades

CDM at large scales

- possibly *the most well-tested theory in all of the physical sciences*
  - diversity is key
- CMB
- large-scale structure
- cluster abundance
- geometry
  - baryon acoustic feature
  - supernovae

dark energy task force

- measure w and w-prime as best as you possibly can
- (and some other stuff)

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CDM at small scales

- there are many theories that look like CDM on large scales but are very different at small scales
  - read: nonlinear regime
- small-scale implications are non-trivial and robust
- observations abound

the *most robust* implications

- dark-matter halos
  - sizes
  - radial profiles
  - shapes
  - substructure
- merging
  - hierarchical growth
  - violent interactions
  - time dependence

the fundamental problem

- LambdaCDM is a very well-specified theory with a small number of parameters
- observational tests require observations of photons (at present) and therefore additional postulates and theories
  - stars, plasma, thermodynamics, magnetic fields, *etc*
- fundamental *vs* auxiliary theory
  - you never test your fundamental theory *directly*

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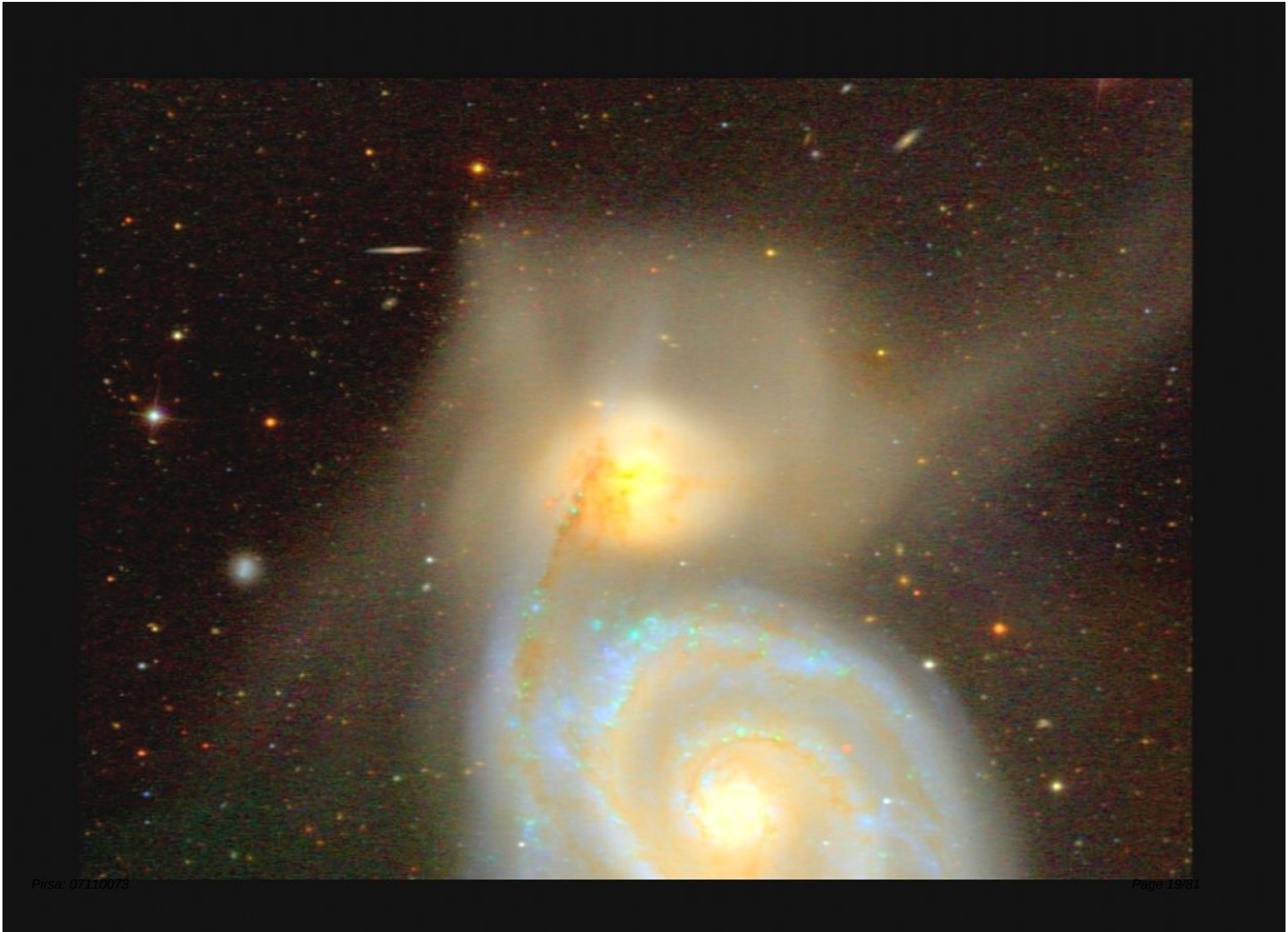
two attitudes

- Lambda-CDM is *incontrovertibly demonstrated*; there can be nothing wrong with this beautiful, fundamental theory!
- Galaxies are such messy objects and there are so many uncertainties, the observed Universe will be consistent with *any theory*!

our position

- CDM makes *strong predictions* in nonlinear regime
- these predictions must be tested
  - *we are physicists, dammit!*
- tests are only tests if they have the power to *falsify* the fundamental theory
  - isn't this obvious?
- we ain't the dark energy task force!
  - Peebles & Hogg, "in preparation"



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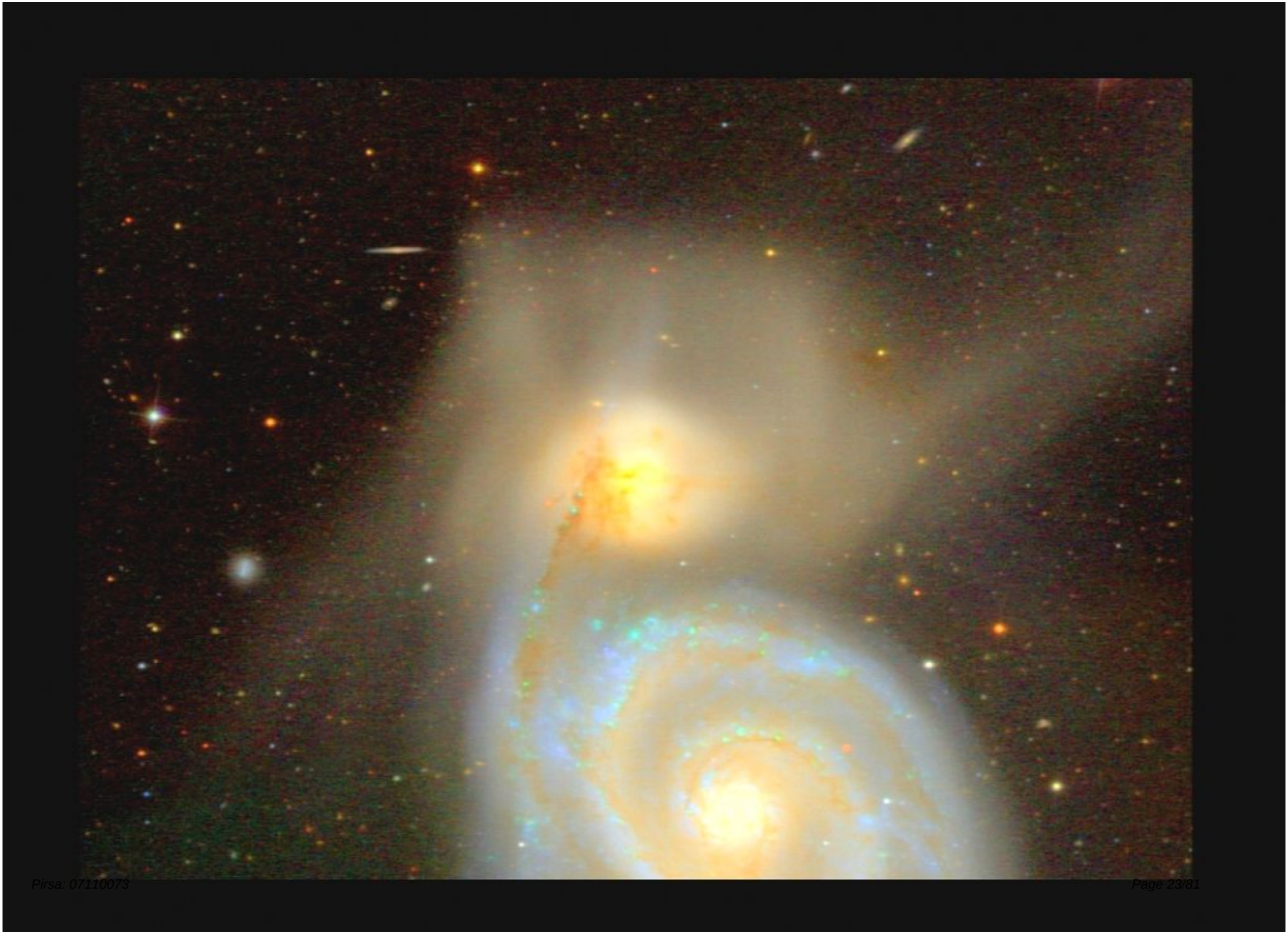
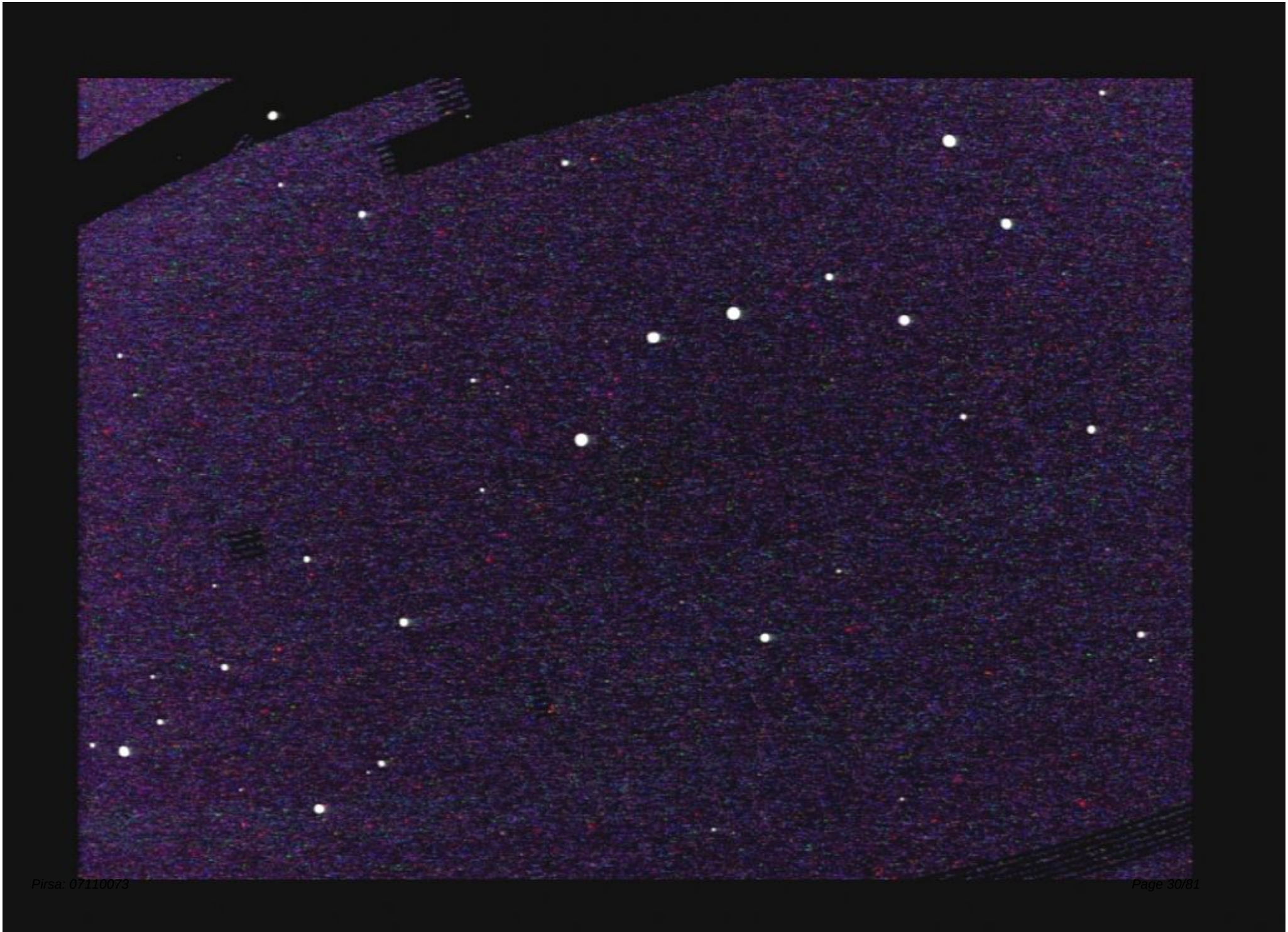
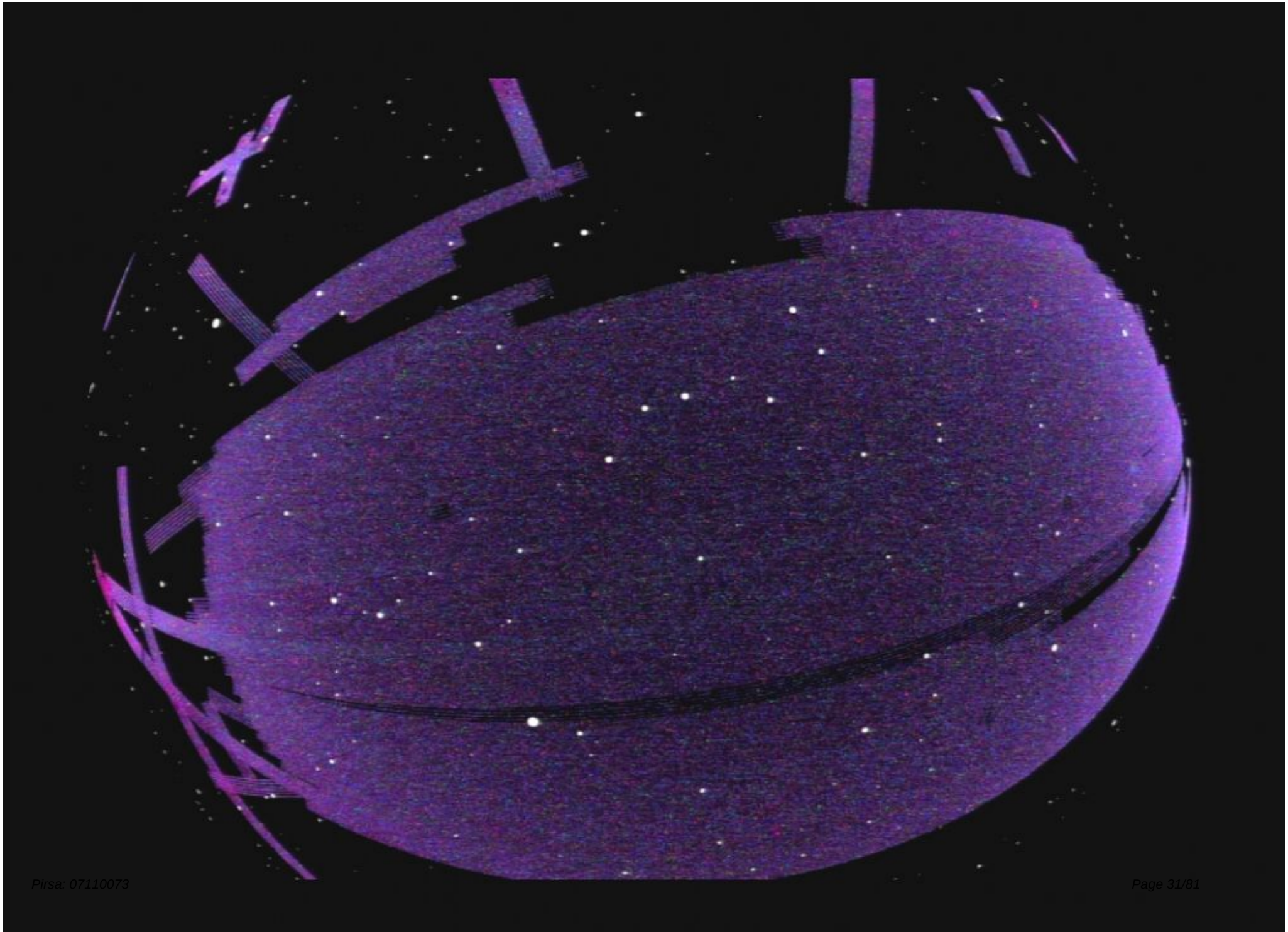
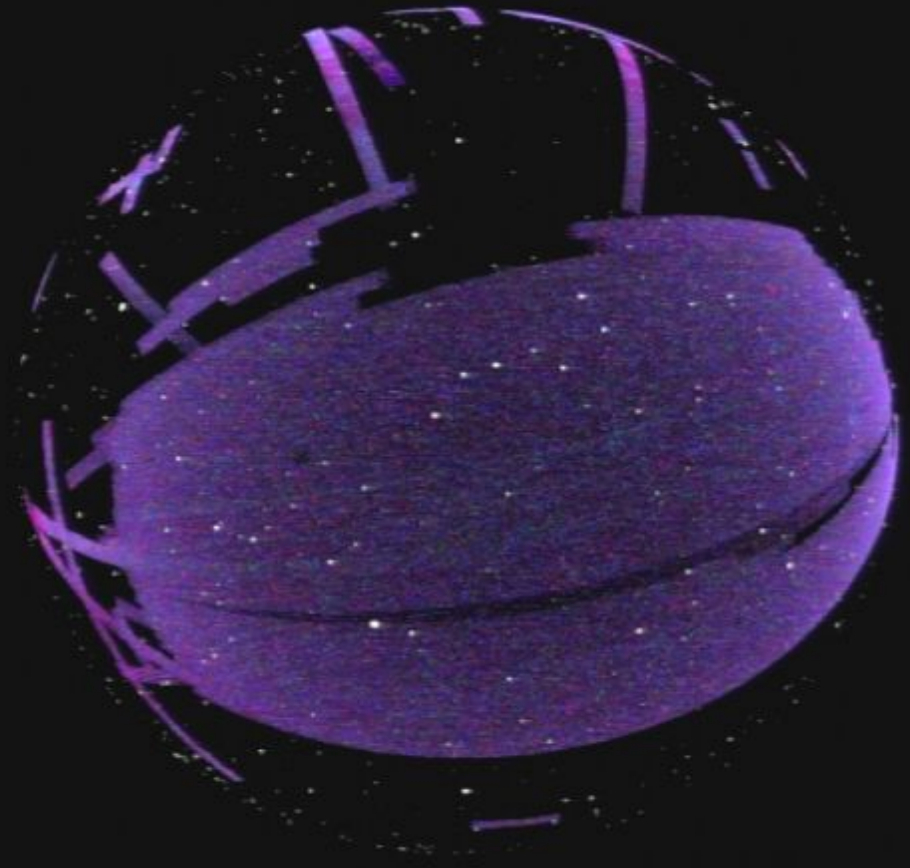


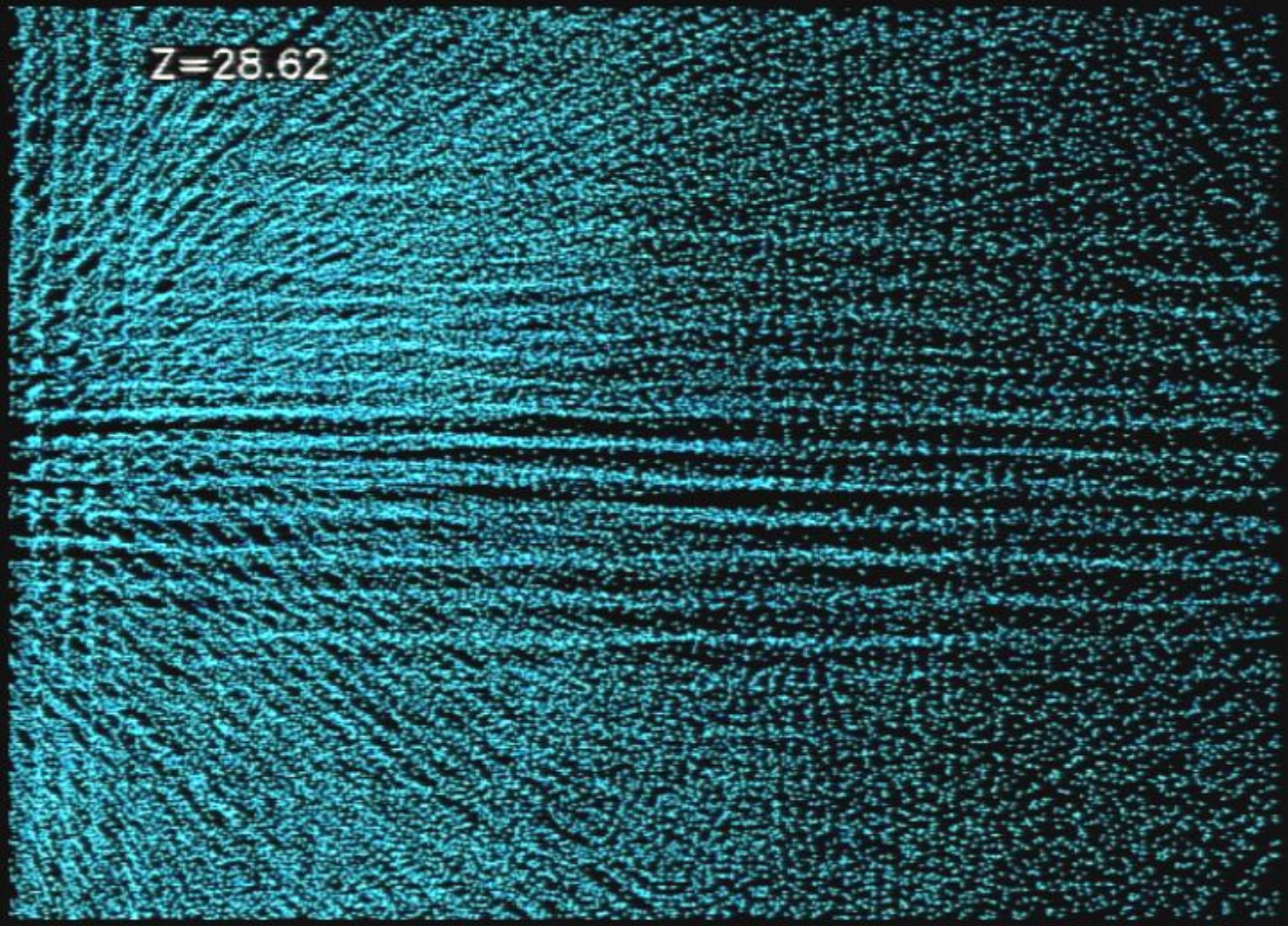




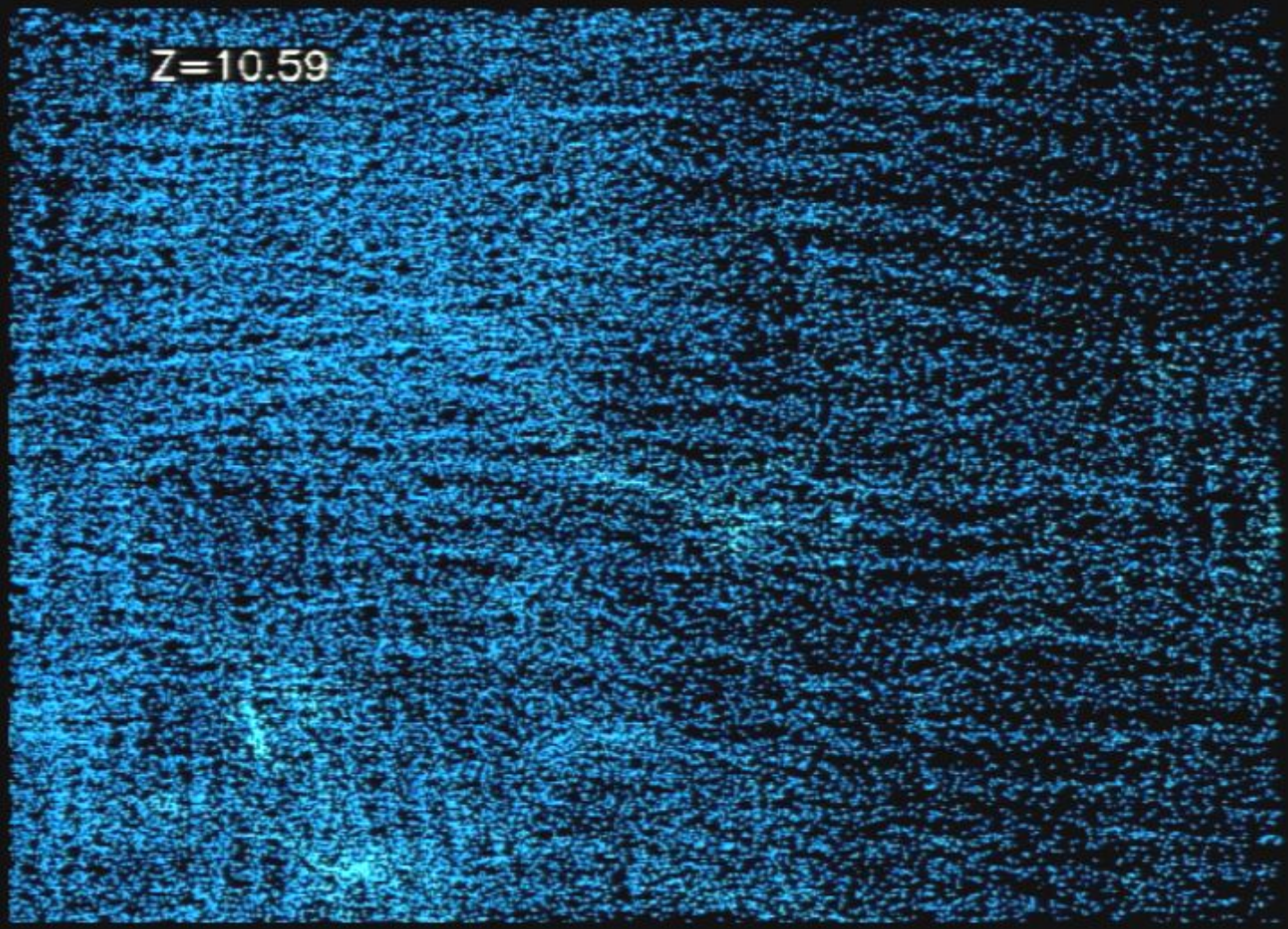


information and physics

- look at quantities that can be predicted
  - our goal is to *falsify* models
  - predictions are evolving rapidly
- do the experiments that are most informative
  - *ie*, produce the largest amount of *Fisher information*
- use *observations* to predict observations
  - rule out or inform auxiliary models



Kravtsov *et al*



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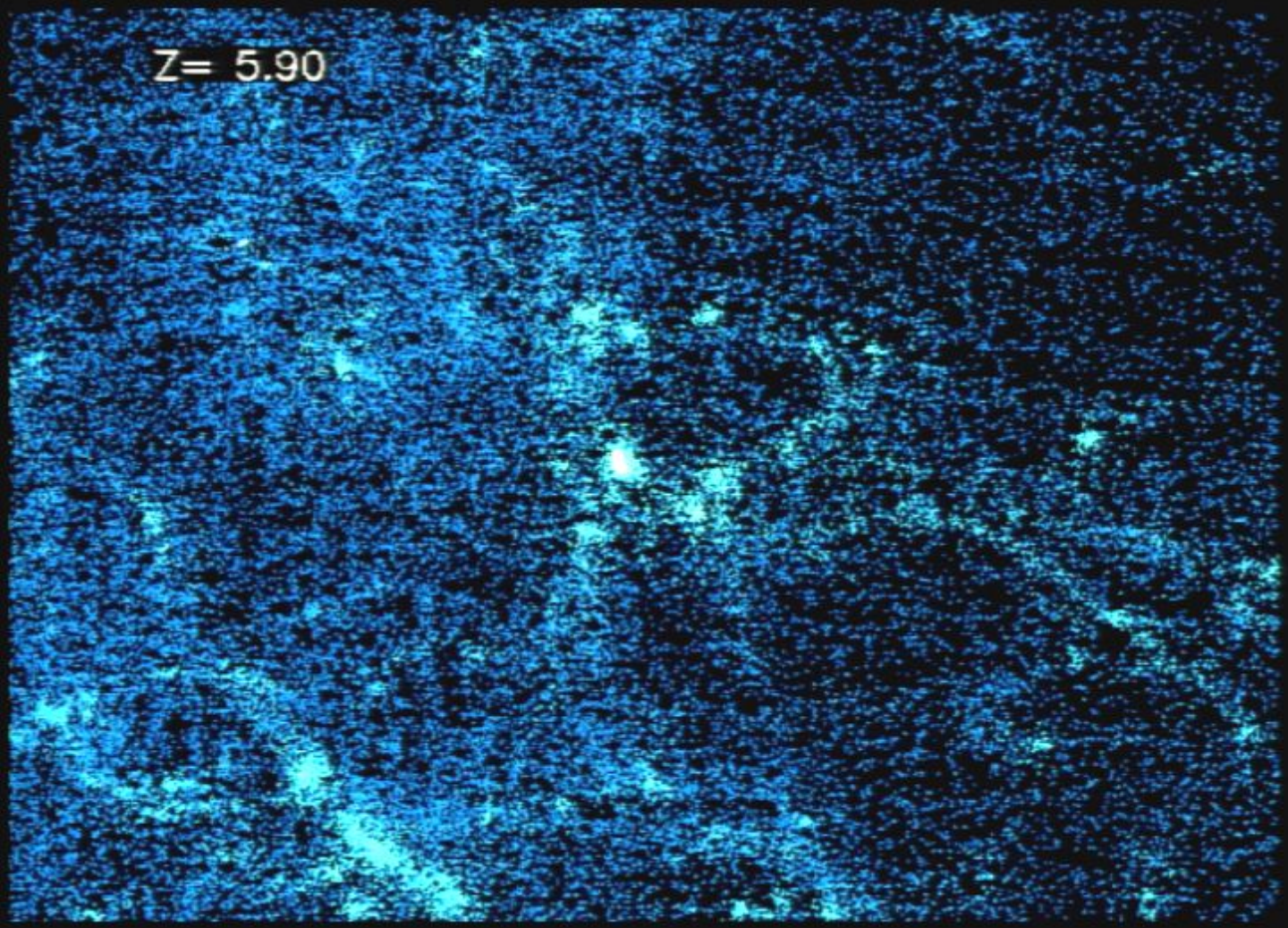

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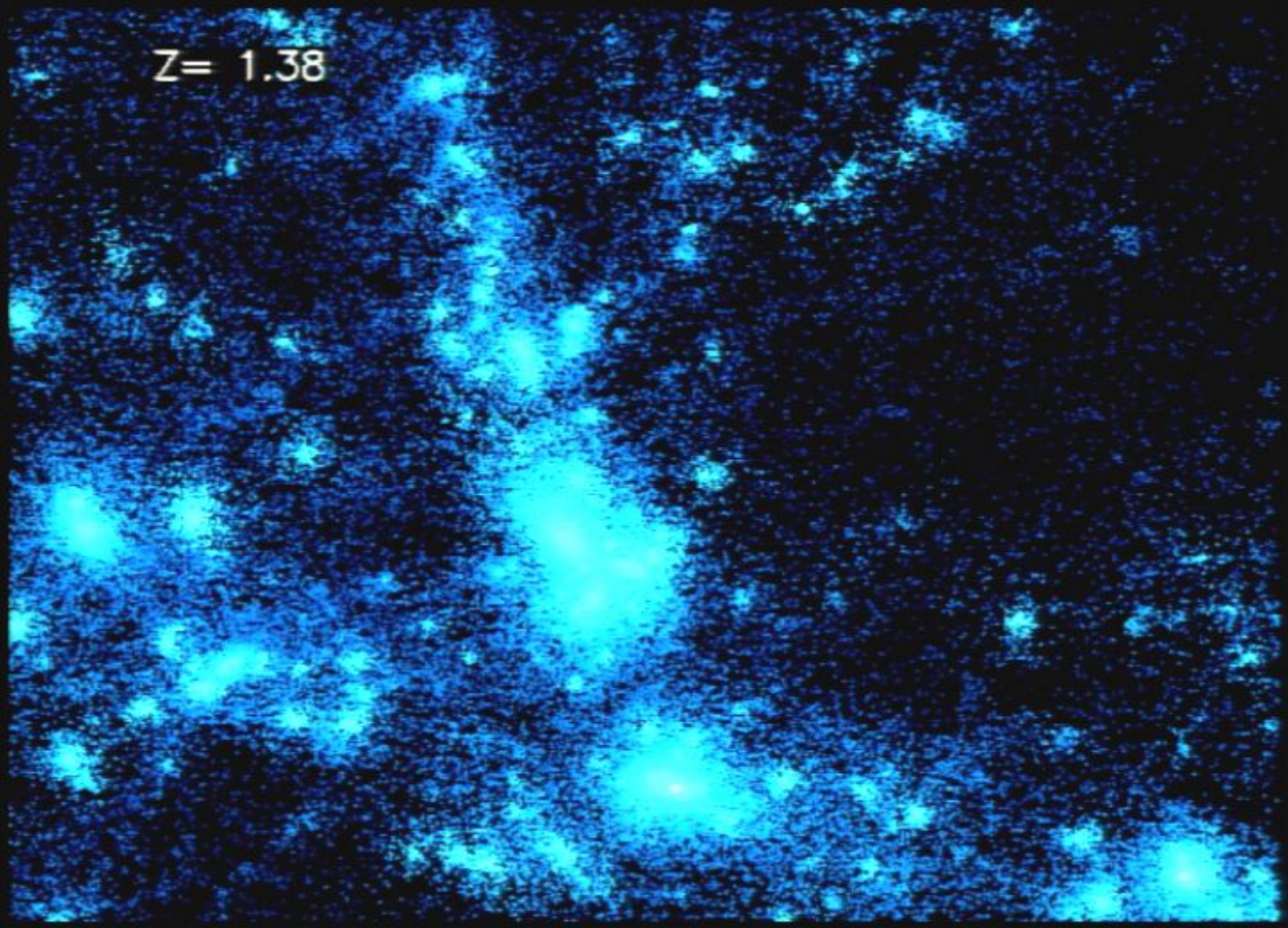

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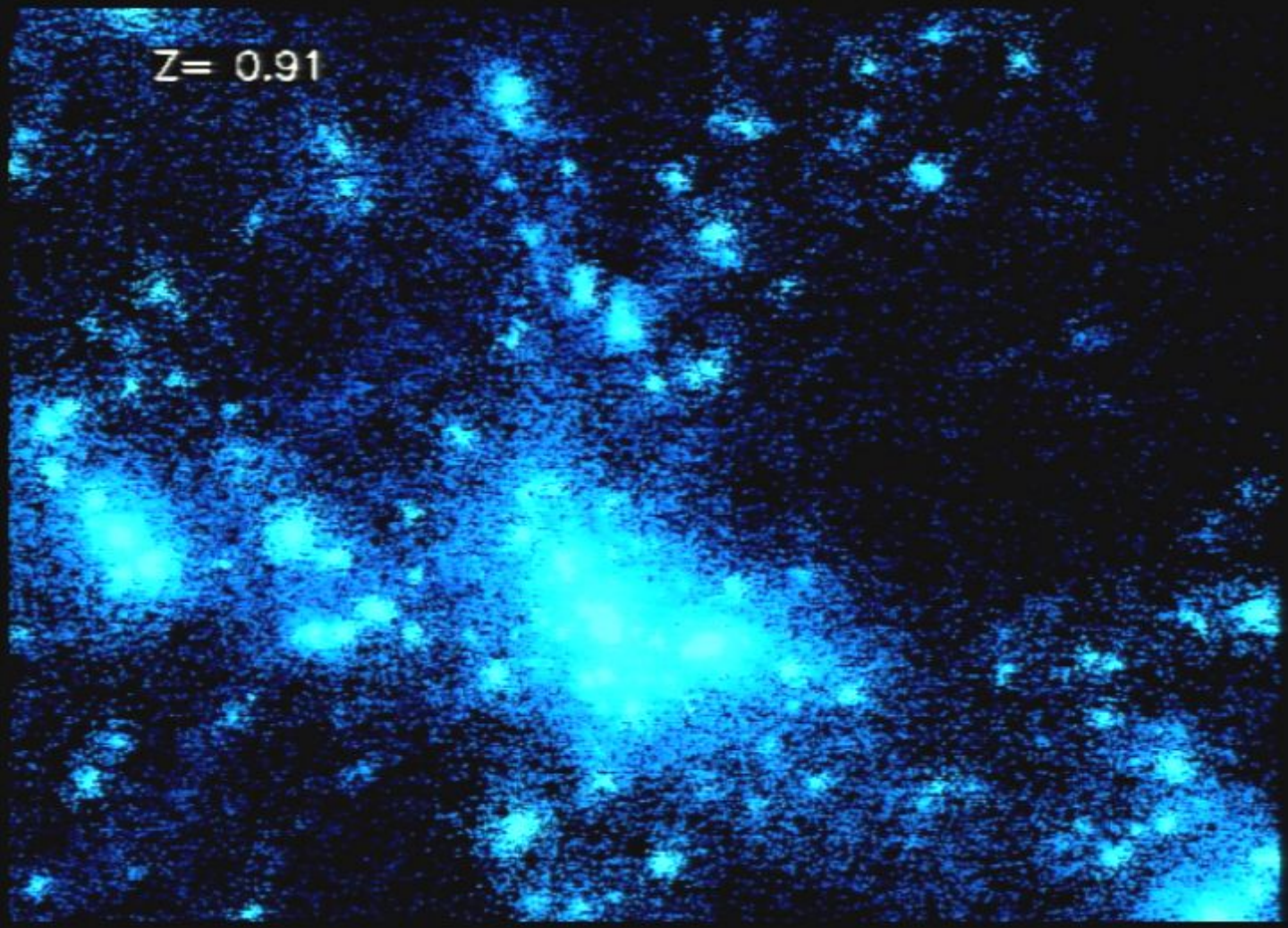

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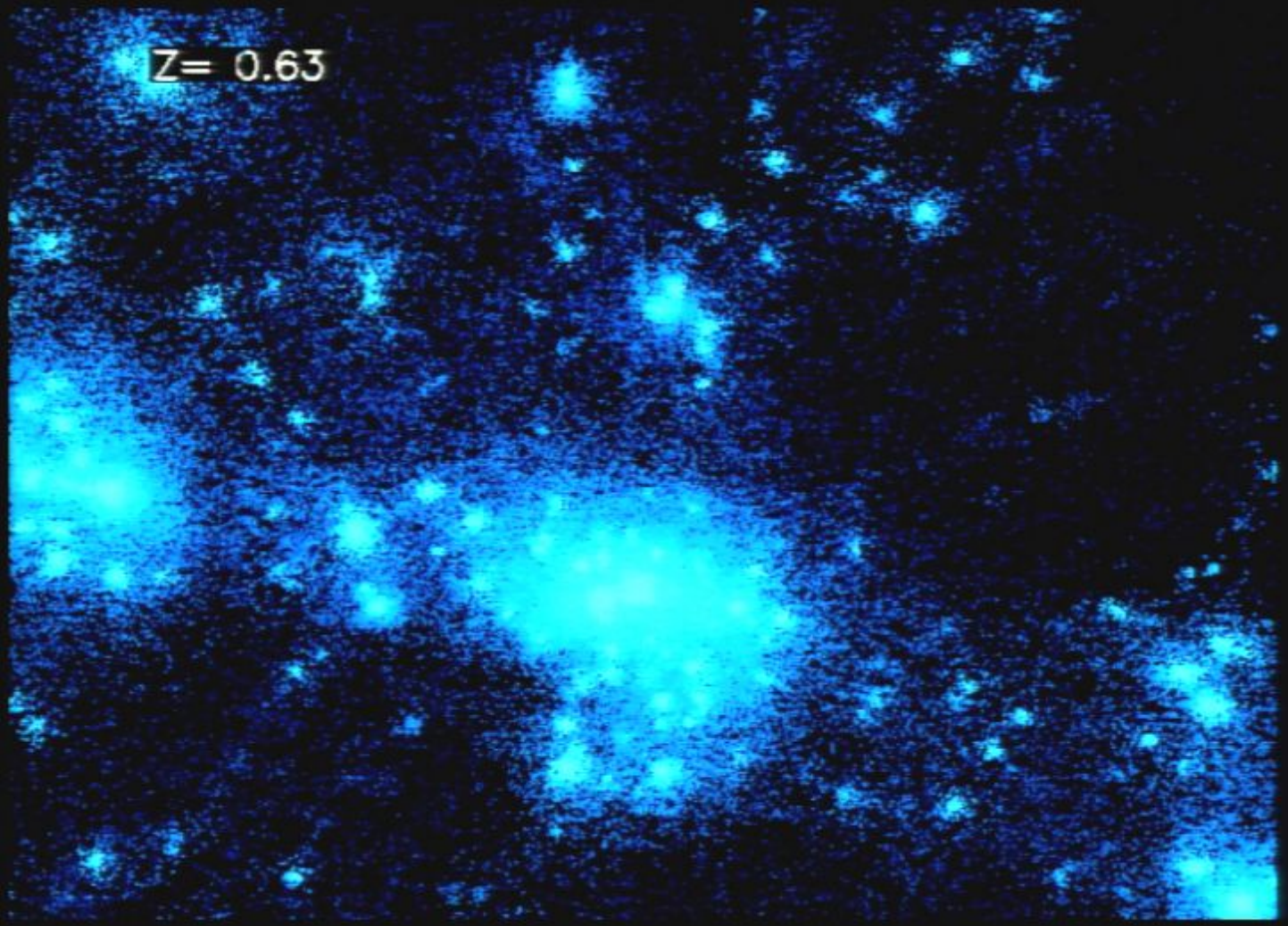

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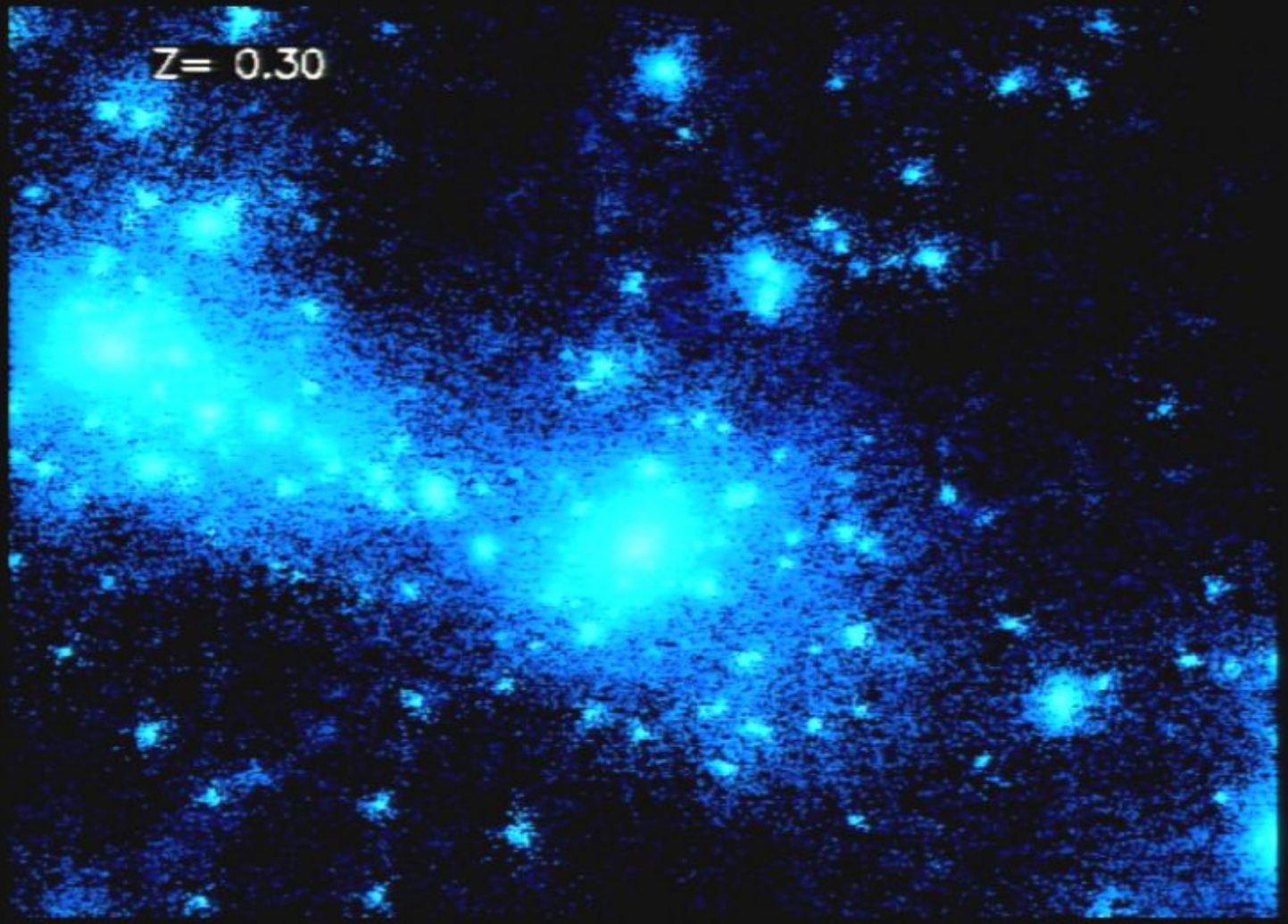

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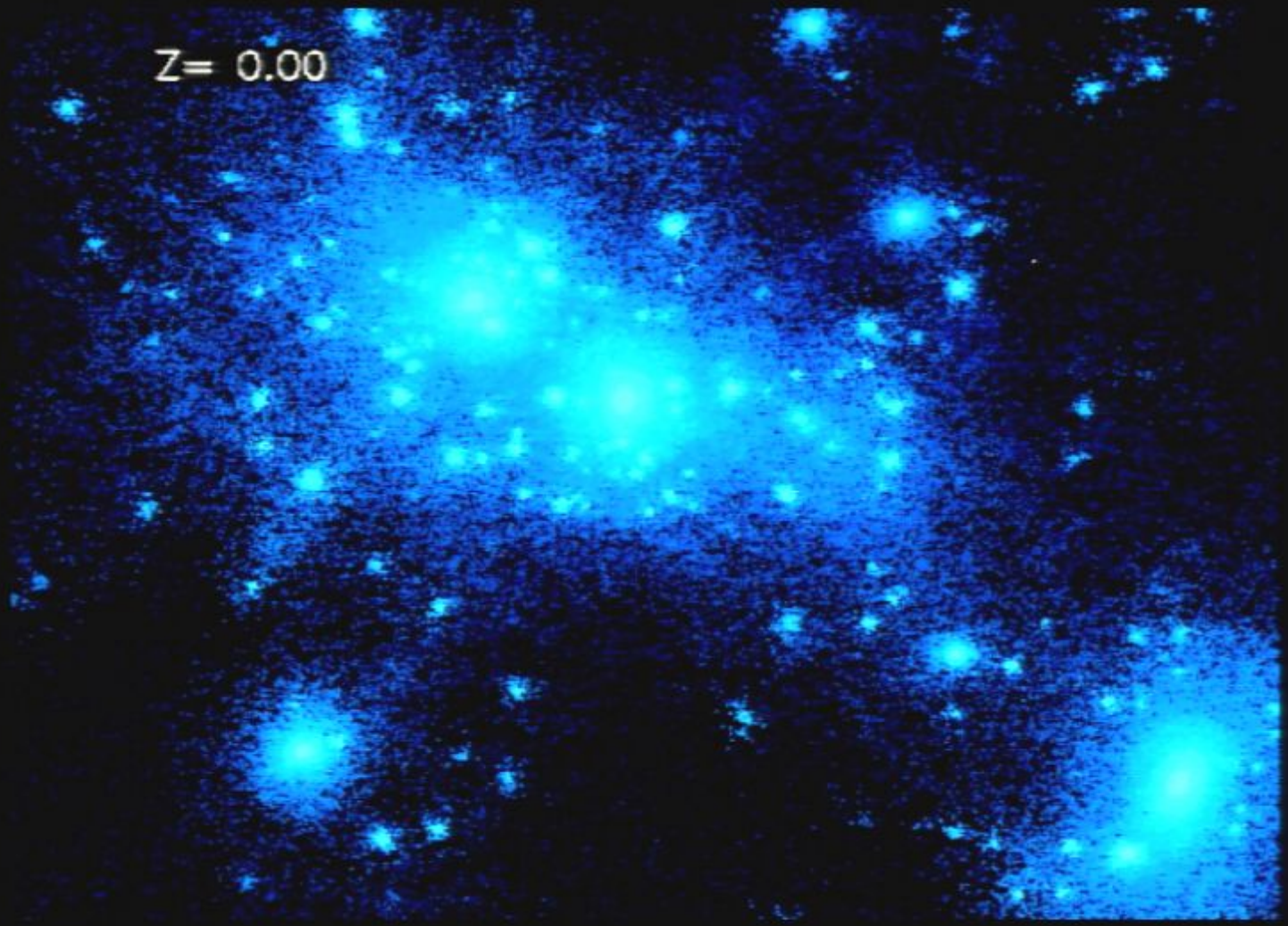

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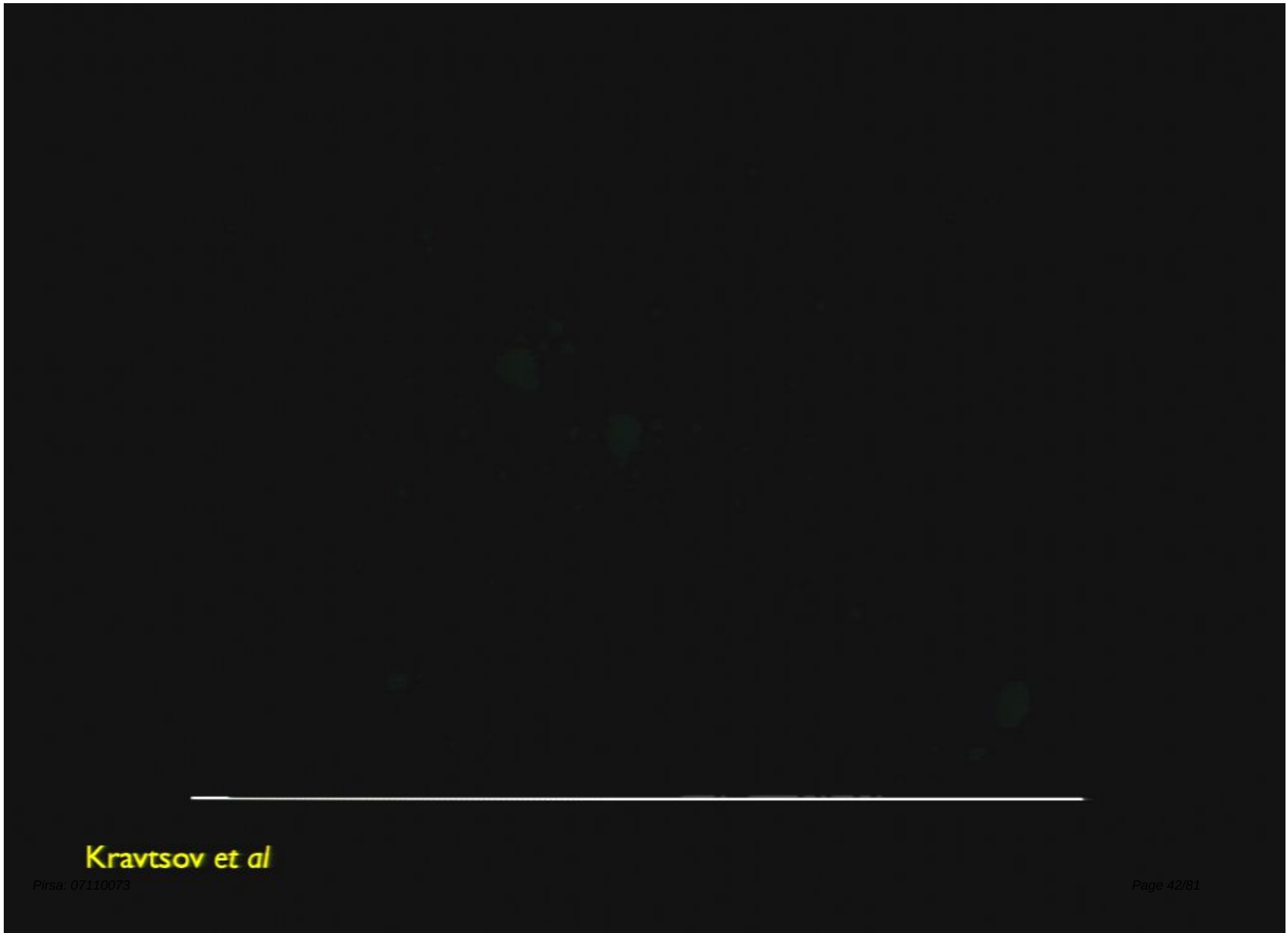
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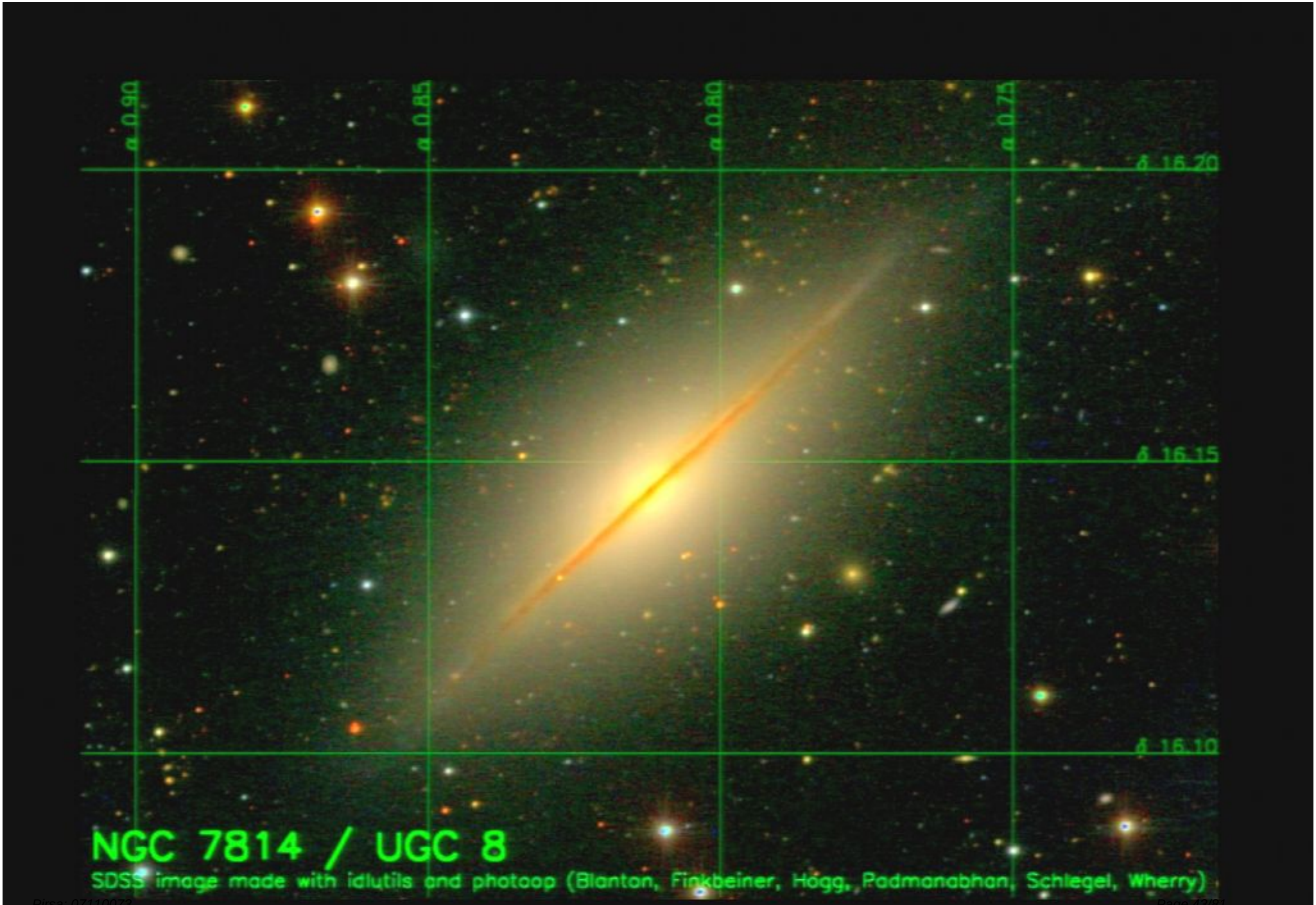
α 0.90
α 0.85
α 0.80
α 0.75
δ 16.20
δ 16.15
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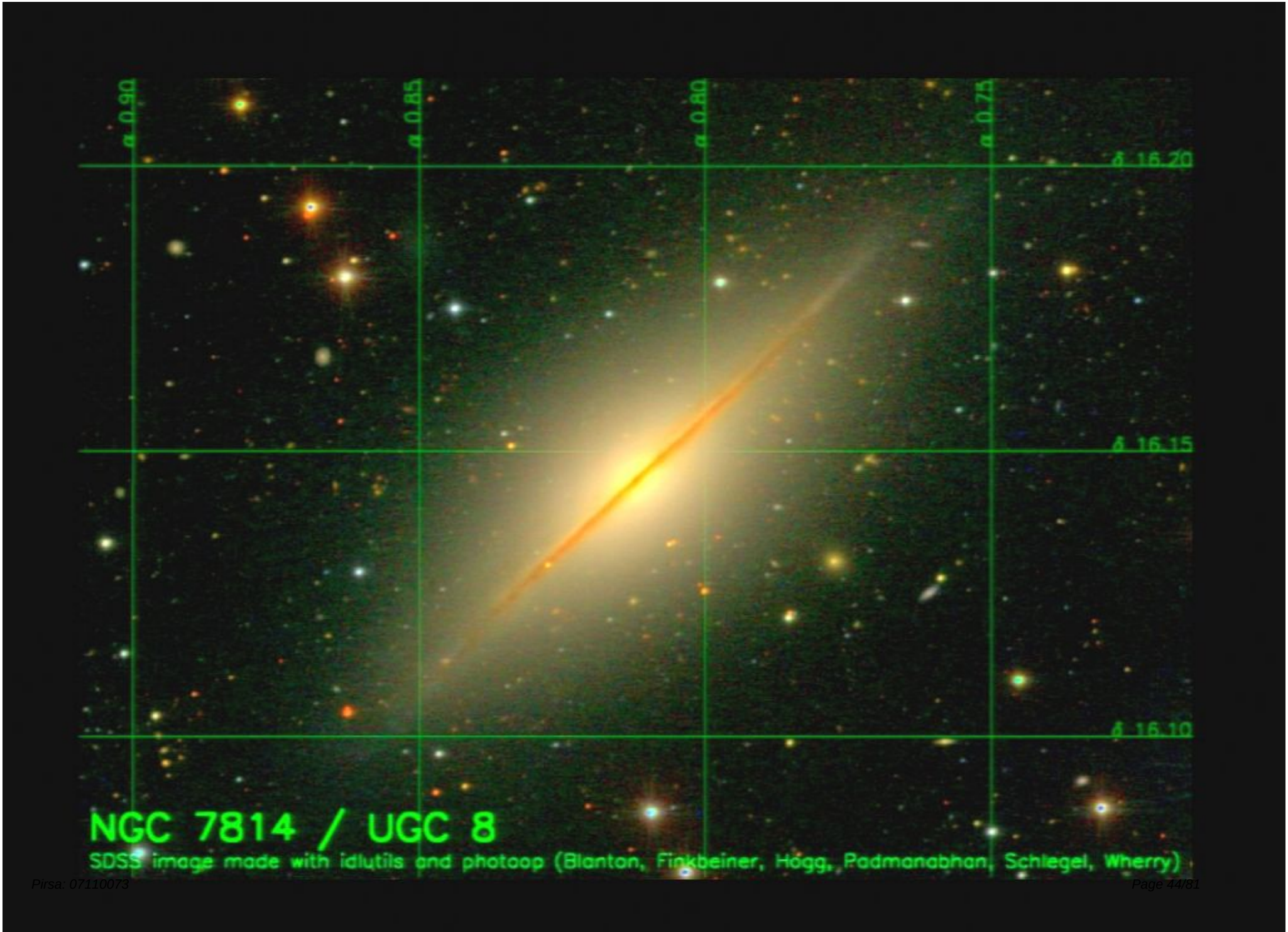
NGC 7814 / UGC 8
SDSS image made with idlutils and photoop (Blanton, Finkbeiner, Hogg, Padmanabhan, Schlegel, Wherry)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Colliding Galaxies NGC 4038 and NGC 4039 HST • WFPC2

PRC97-34a • ST ScI OPO • October 21, 1997 • B, Whitmore (ST ScI) and NASA

the light sector is quiet

- massive galaxies show little evidence of recent merging or accretion
  - thin, old stellar disks
  - great regularities among galaxies
  - tidal features are rare
  - the halo is locally spherical
  - the star-formation history is uneventful
- *obvious* mergers are very rare

the tension

- the dark sector is active
- the light-emitting Universe is quiet
- (this isn't necessarily a problem)
  - galaxies are much smaller than their DM halos
  - baryons are subject to different dynamics than the dark matter
  - star-formation is non-trivial
  - though DM dominates the dynamics, the baryons are not negligible (feedback and adiabatic contraction)

galaxies *ought to be* merging

- *if* CDM is correct in the *non-linear regime* (Mpc scales), then virialized halos are merging prodigiously at the present day
  - still true in accelerating models
- when halos merge, at least *some* galaxies must merge
- galaxy mergers are observationally tractable

galaxies *are* merging (a bit)

- galaxies come in two basic types
  - red, old, fading, spheroidal galaxies
  - blue, young, star-forming, disky galaxies
- the red population is growing in total mass with time (Bell, Faber, Blanton, Brown, *etc*)
- this growth is almost certainly involves merging
  - red galaxies "look like" merger remnants and vice versa
  - blue galaxies need a "reason" to stop forming stars

galaxy continuity

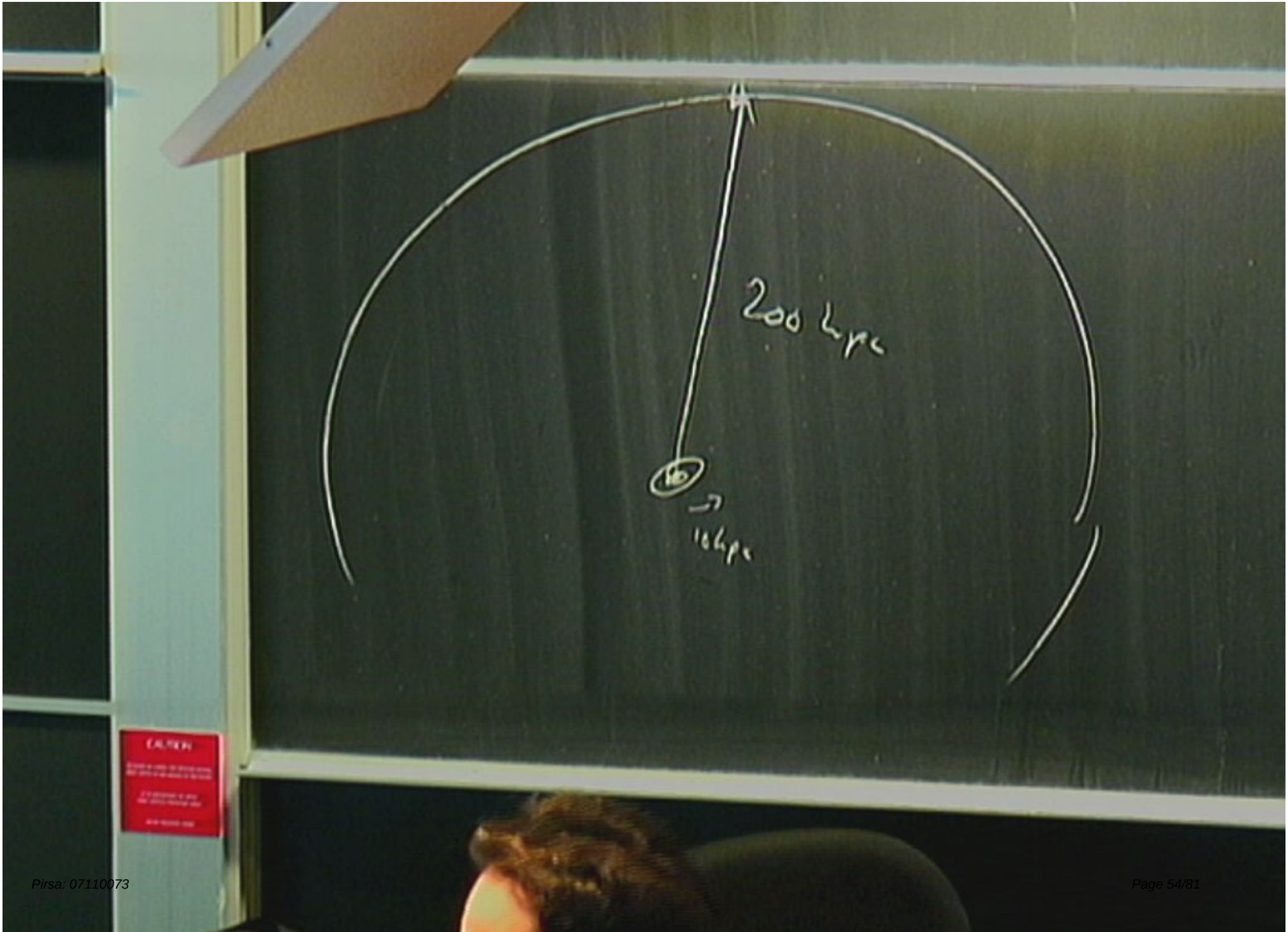
- use your observations to make predictions and test them
- the Universe is a continuous process
  - galaxies have sources, sinks, and evolutionary tracks
  - each redshift slice contains objects and activity that can be used to predict the next slice
- if the red sequence is growing by mergers, there must be close pairs
  - the prediction is *quantitative*

redshift of one-third

- huge, complete, uniform survey volumes, especially the SDSS
  - I have *many* collaborators!
  - tens of millions of useful sources
  - millions of spectra
- high signal-to-noise ratio measurements (spectra and imaging)
- *but*, not at the peak of galaxy evolution activity

luminous red galaxies

- old, spheroidal, very massive galaxies
  - selected on the basis of color and magnitude in SDSS imaging data
  - redshifts 0.1 to 0.45; pivot 0.35
  - ~100,000 spectra (plus 600,000 more in a few years)
  - >3x the mass of the MW
  - known to reside in very massive halos (Eisenstein *et al* 2003; Zehavi *et al* 2004, 2005)
  - stellar populations and morphologies are *relatively* simple
  - we understand the most massive stuff best

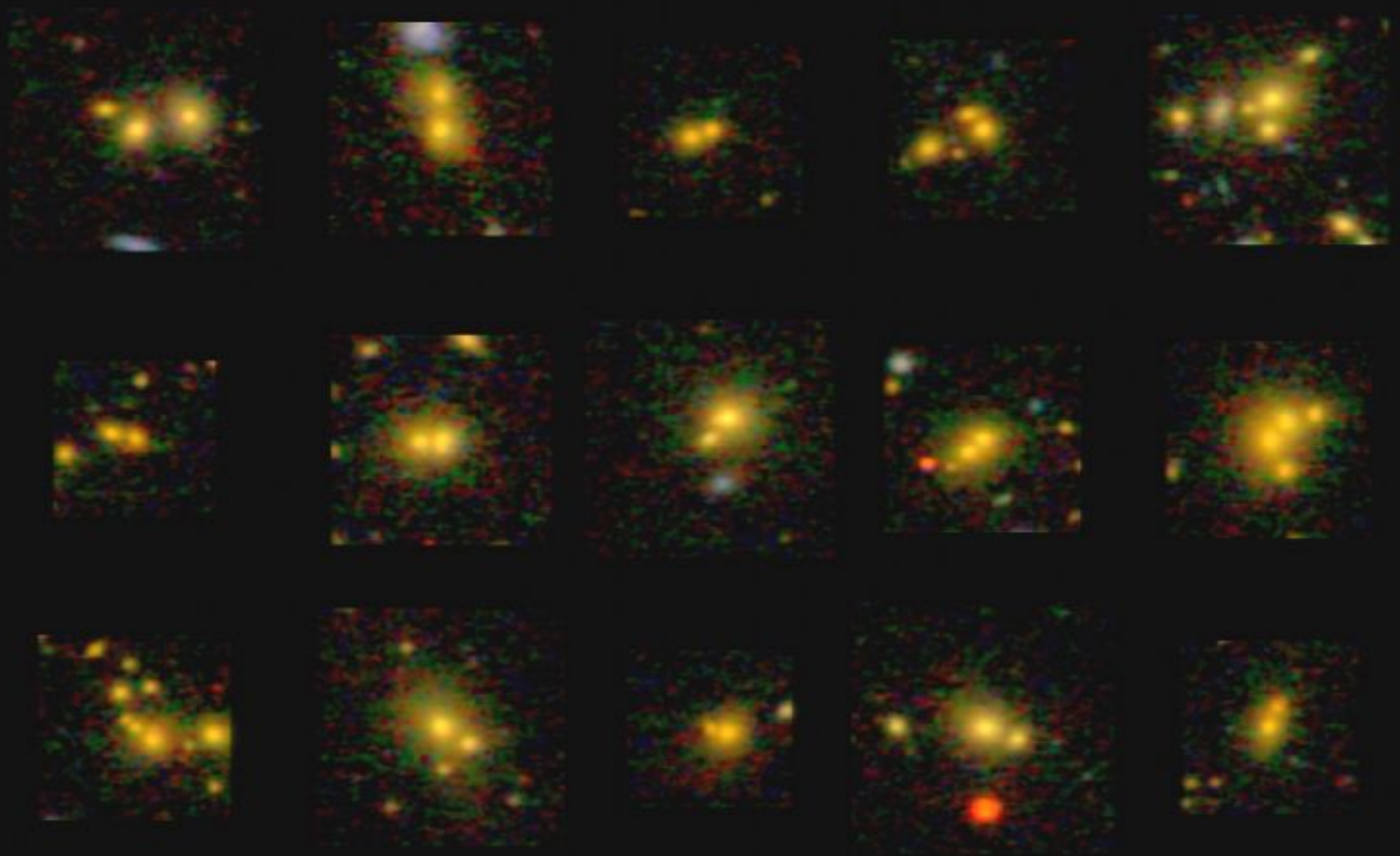

200 kpc
10 kpc


Messier 87

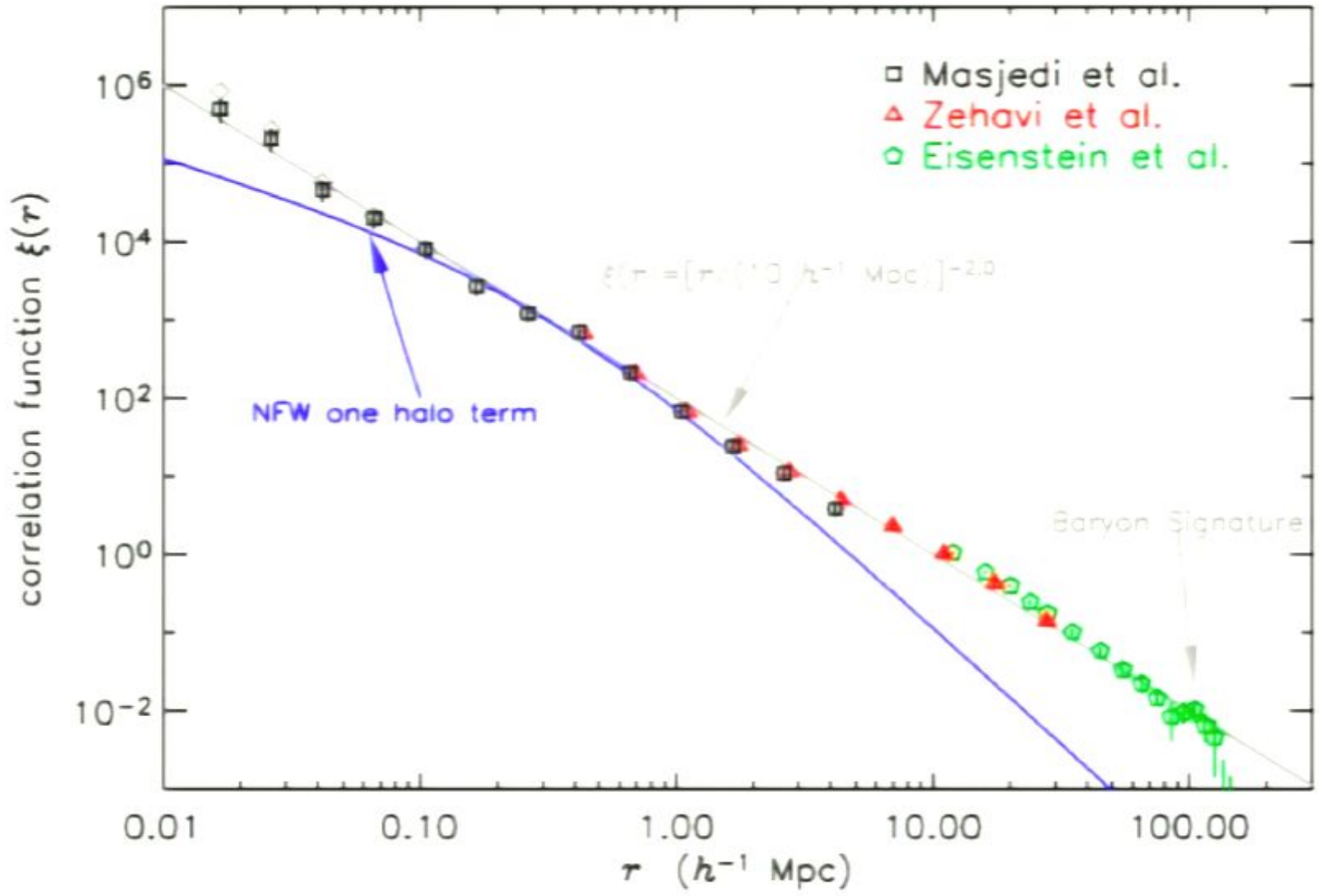

Messier 87

merger rate of red galaxies

- if two galaxies merge, then at some time earlier, they were *spatially close*
- so we count pairs *about* to merge
  - *ie*, measure the 3d "deprojected" *correlation function* so there are no projection issues
  - need to use cross-correlation techniques to escape spectrograph constraints
- galaxies can't merge faster than a dynamical time



Masjedi, Hogg, *et al* 2006



Masjedi, Hogg, *et al* 2006, *ApJ* **644** 54

merger rate of LRGs

- at <100 kpc, dynamical friction acts
- merger rate is (at most) the mean number of close pairs divided by the dynamical time
- each LRG has <1 percent probability of an LRG merger every Gyr at redshift 1/3
  - strict upper limit (because of auxiliary uncertainties)
  - Masjedi, Hogg, *et al* 2006 ApJ **644** 54
  - see also papers by Carlberg, Patton, and collaborators
- this *maximal* rate is *low?*

theoretical merging

- no papers yet predict *exactly* what we observe
  - many choices about mass scales etc
  - working on it
- closest papers predict rates in the five to ten percent per Gyr range
  - Conroy *et al*
  - Maller *et al*
  - Murali *et al*

auxiliary models

- the issue is: where do galaxies reside in the dark matter field?
  - halo occupation approach
  - ab initio approach
- the answer to this question makes predictions
  - correlation function
  - high-order statistics
  - gravitational lensing (galaxy-mass correlations)
  - redshift evolution

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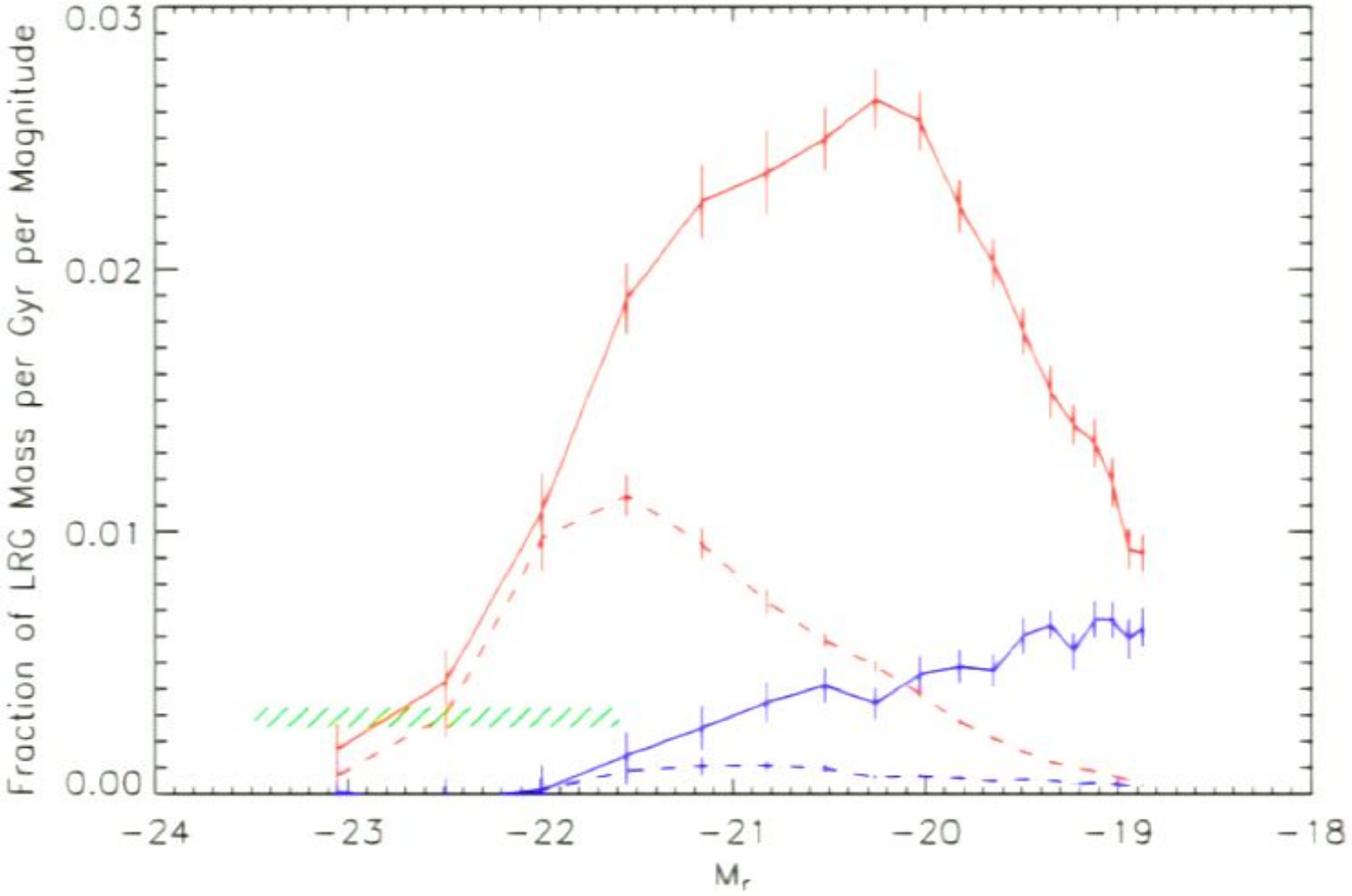

Masjedi & Hogg in press

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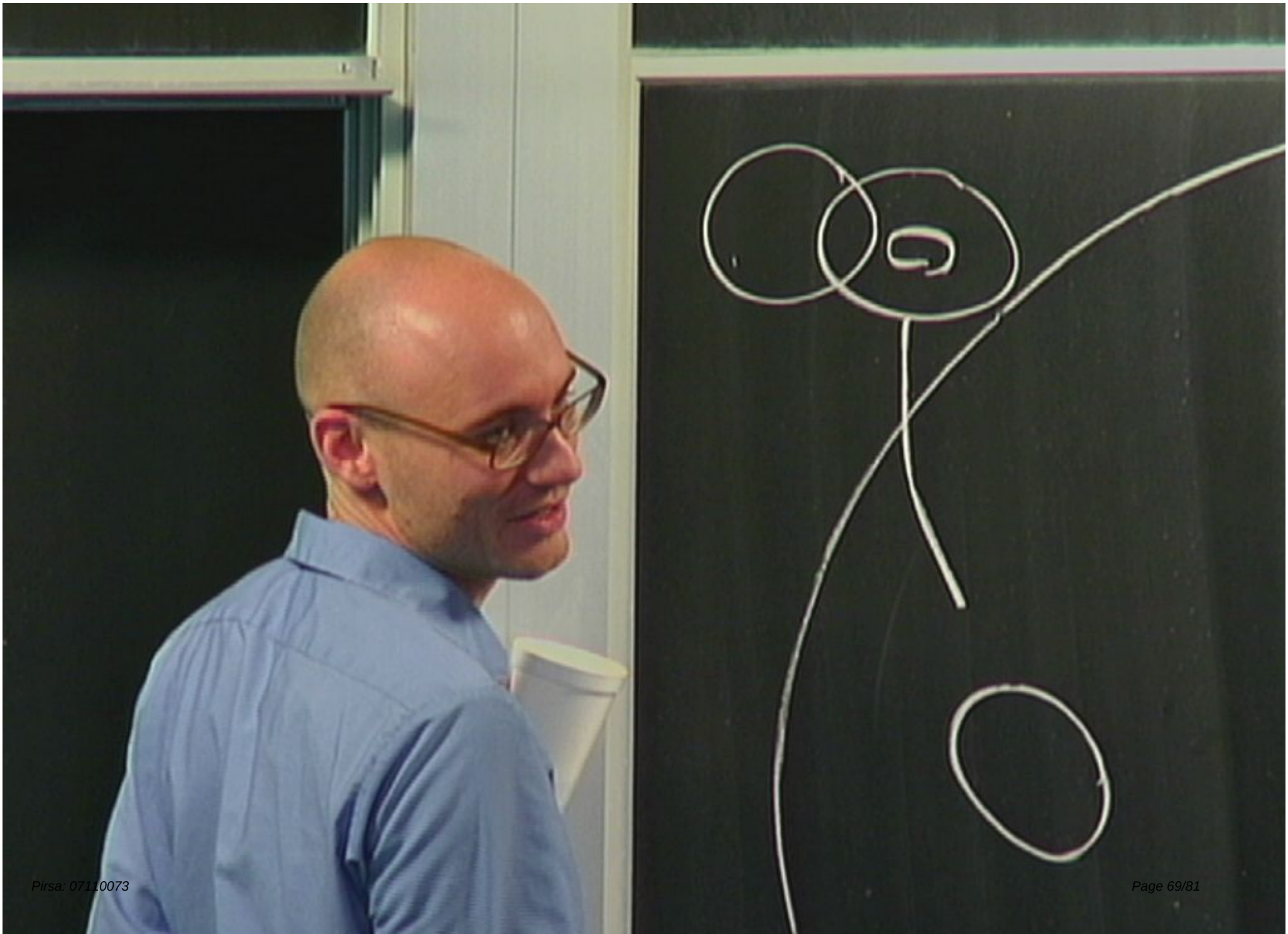

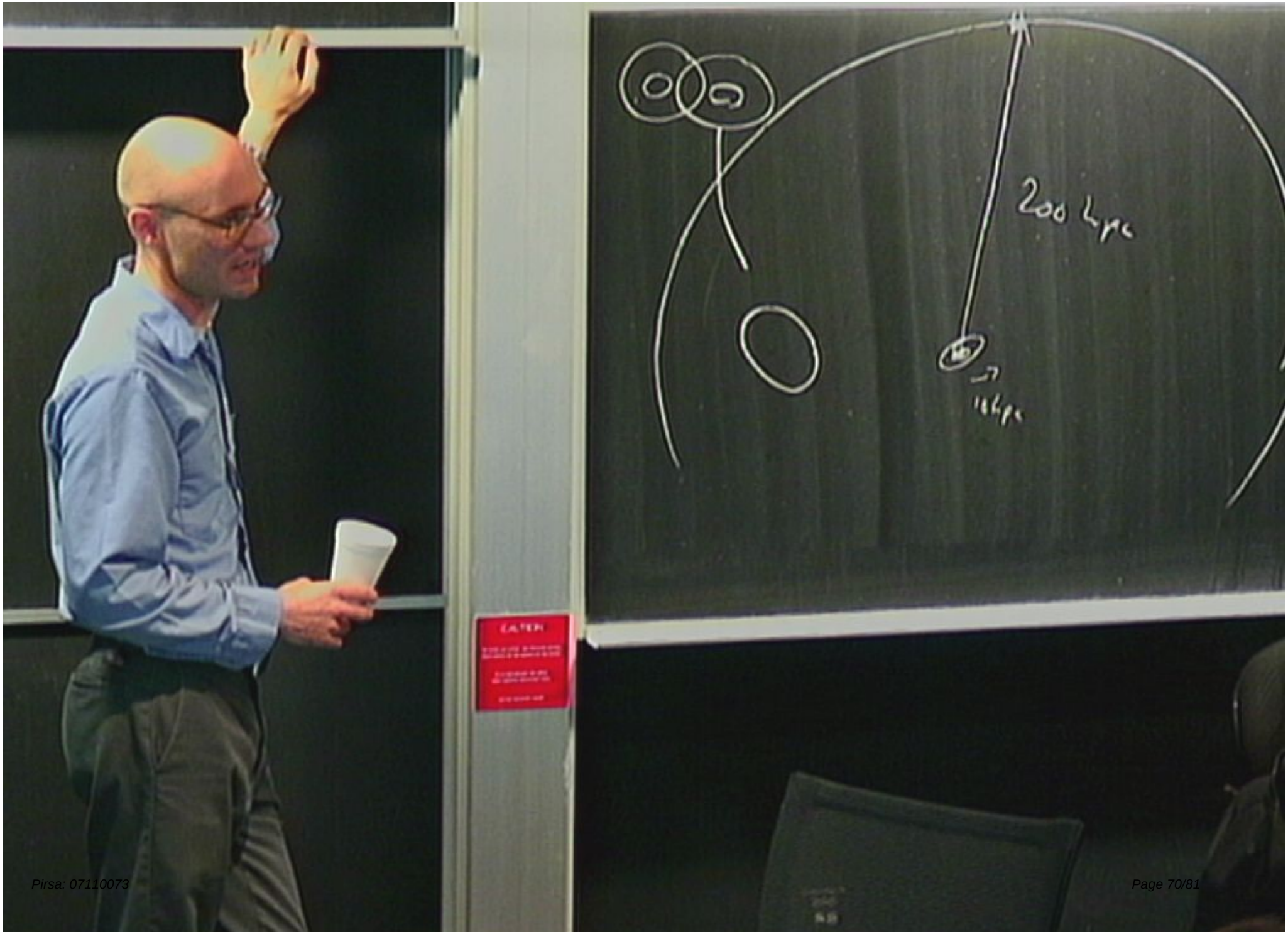
200 kpc
16kpc

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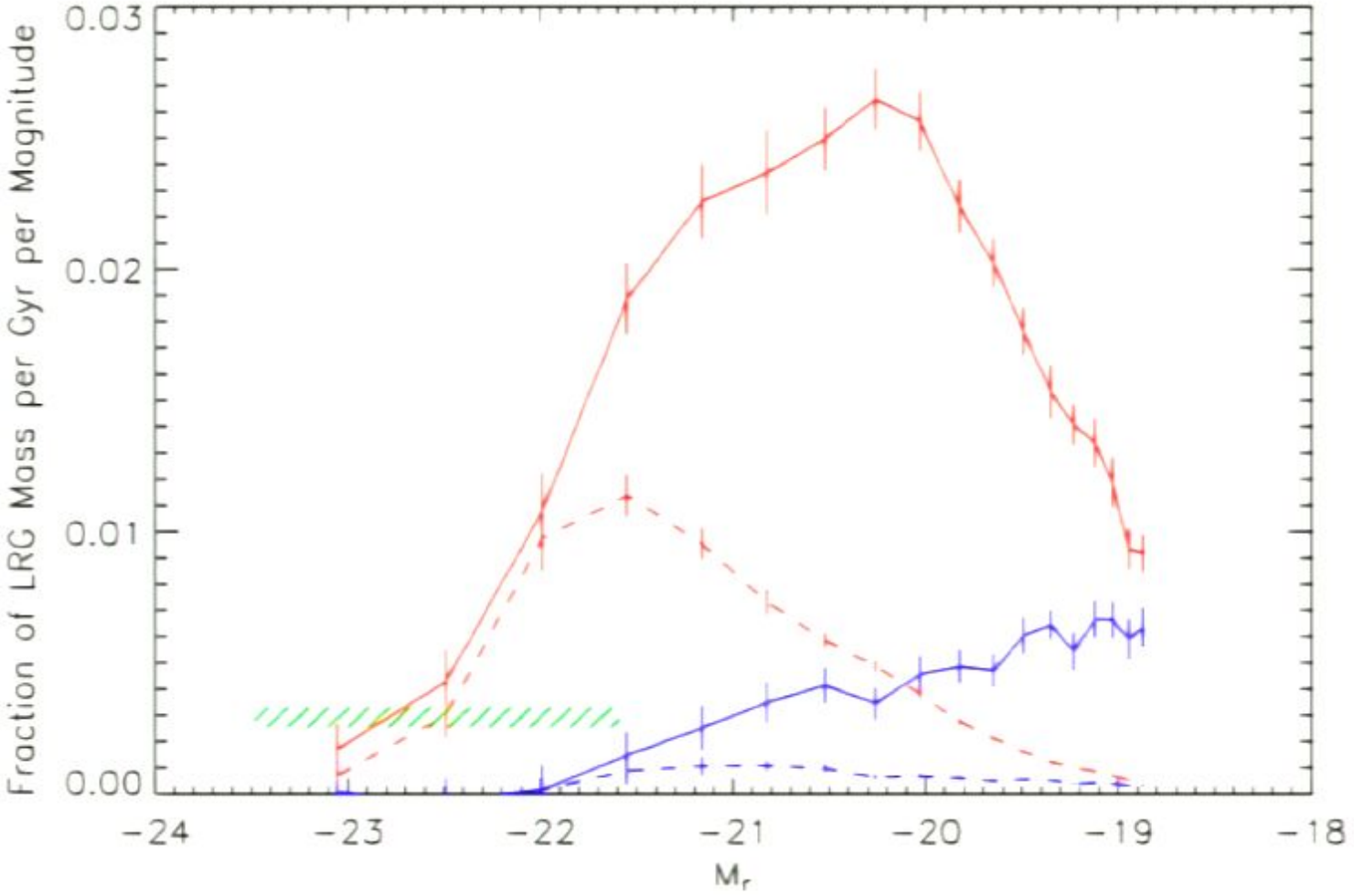


Masjedi & Hogg in press

accretion onto LRGs

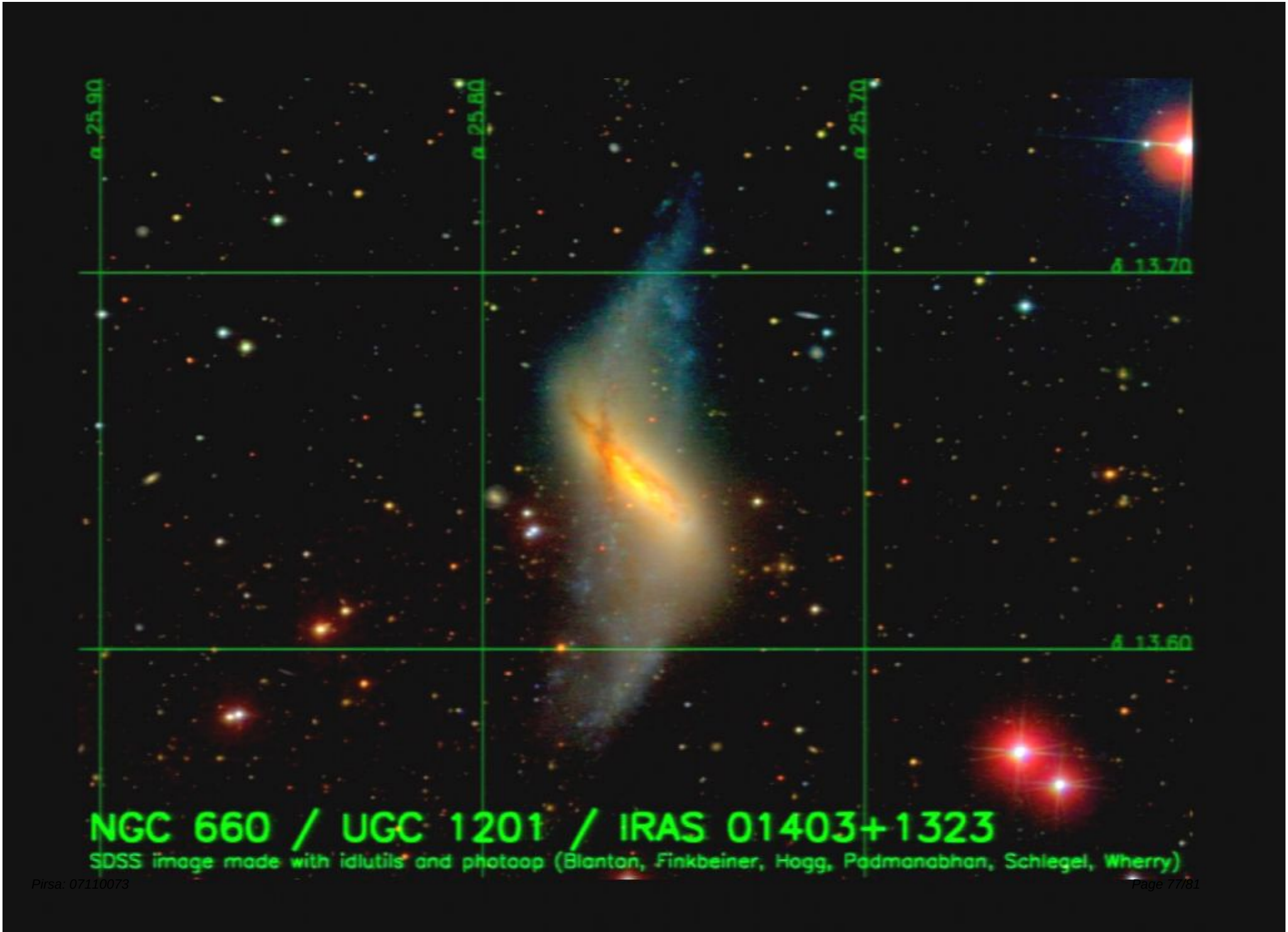
- we have generalized to include all kinds of "minor mergers"
  - cross-correlations, not auto-correlations
  - many technical challenges
- maximal accretion rate is *dominated* by dry merging around L*
- accretion rate onto LRGs is *at most* 3 percent per Gyr at redshift 1/3
  - Masjedi & Hogg in press

evidence of late merging

- close pairs
- tidal features and morphological mergers
- star-formation events

Colliding Galaxies NGC 4038 and NGC 4039 HST • WFPC2

PRC97-34a • ST ScI OPO • October 21, 1997 • B, Whitmore (ST ScI) and NASA


α 25.90
α 25.80
α 25.70
δ 13.70
δ 13.60
NGC 660 / UGC 1201 / IRAS 01403+1323
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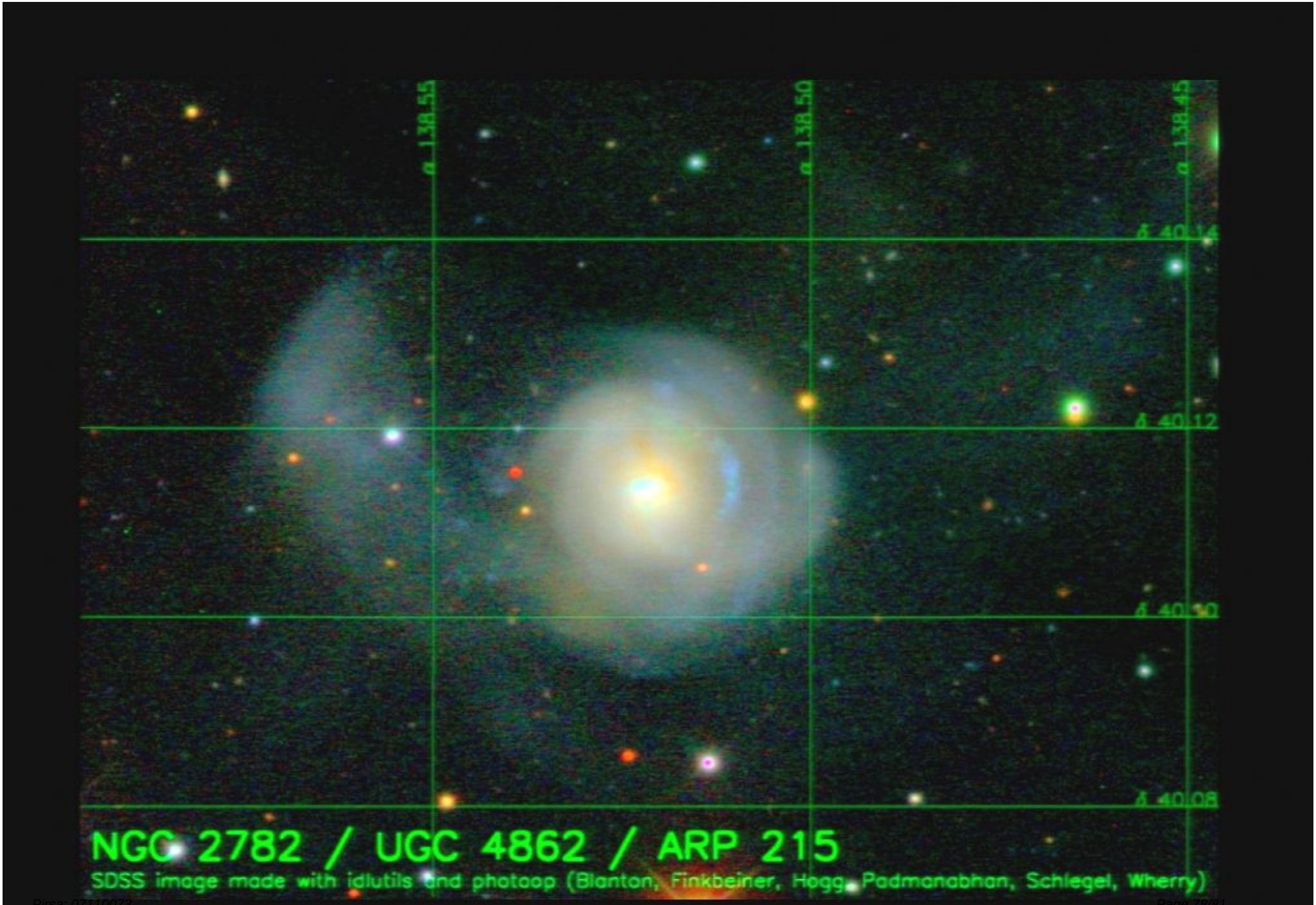
α 138.55
α 138.50
α 138.45
δ 40 14
δ 40 12
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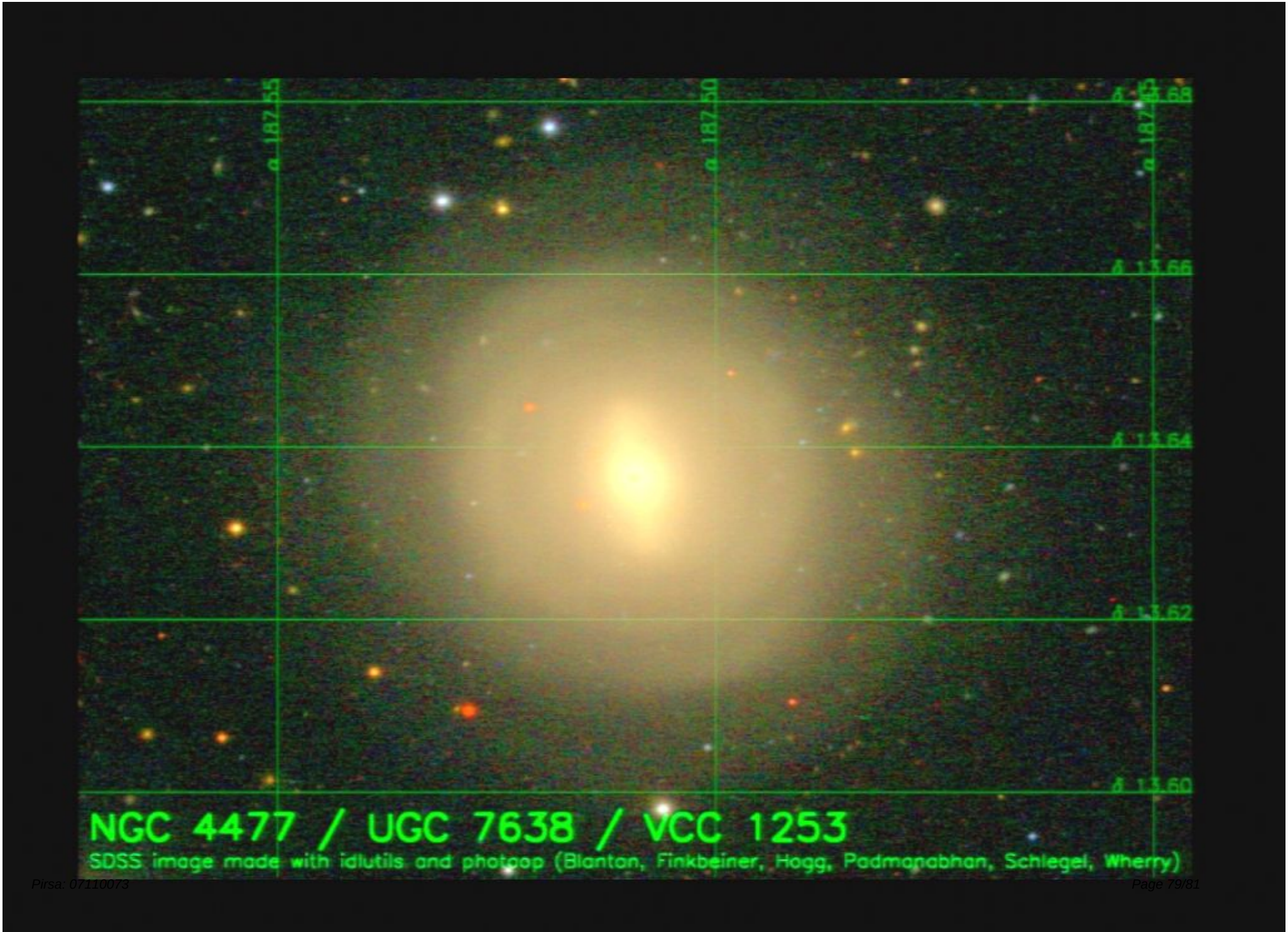
α 187.55
α 187.50
α 187.45
δ 13.66
δ 13.64
δ 13.62
δ 13.60
NGC 4477 / UGC 7638 / VCC 1253
SDSS image made with idlutils and photoop (Blanton, Finkbeiner, Hogg, Padmanabhan, Schlegel, Wherry)

morphological merger rate

- clearly merging galaxies are *rare*
- to get a rate density, you need an abundance and a time scale
- some features can last for many dynamical times
- even *individual systems* might have things to say about dark matter dynamics
  - a great goal that has been abandoned by the youth

summary

- the cosmological "standard model" (CDM) and *requires* many things at small scales
  - especially dark-matter halos and merging
- galaxy merger rates can be constrained observationally and they are *low*
- is CDM okay?
  - I didn't say
  - the project will take many people many years
  - main issue is auxiliary models