Dark (Matter) Galaxies: Simulations and Observations

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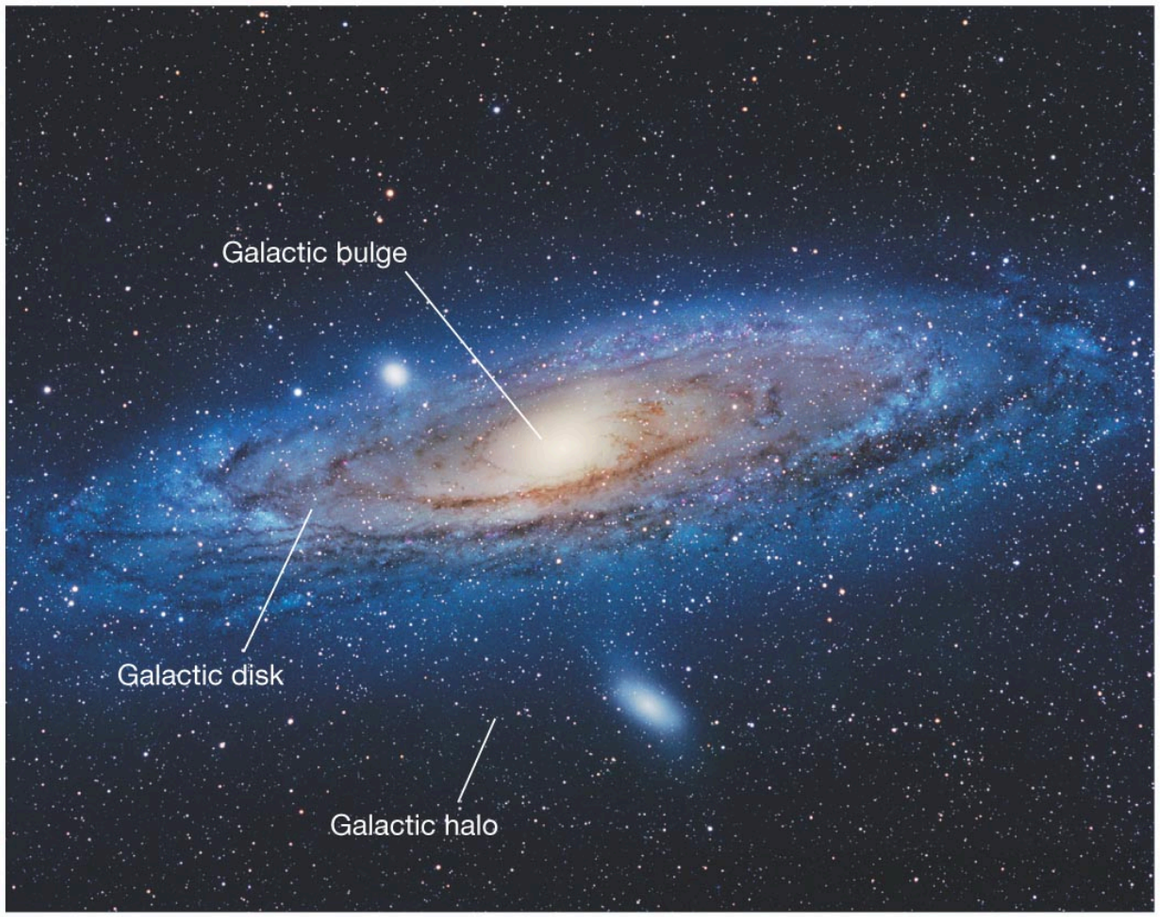
Thanks to Prof. Donghui Jeong



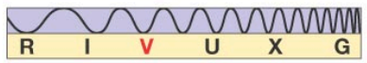


June 29, 2023

When we say a galaxy



(a)



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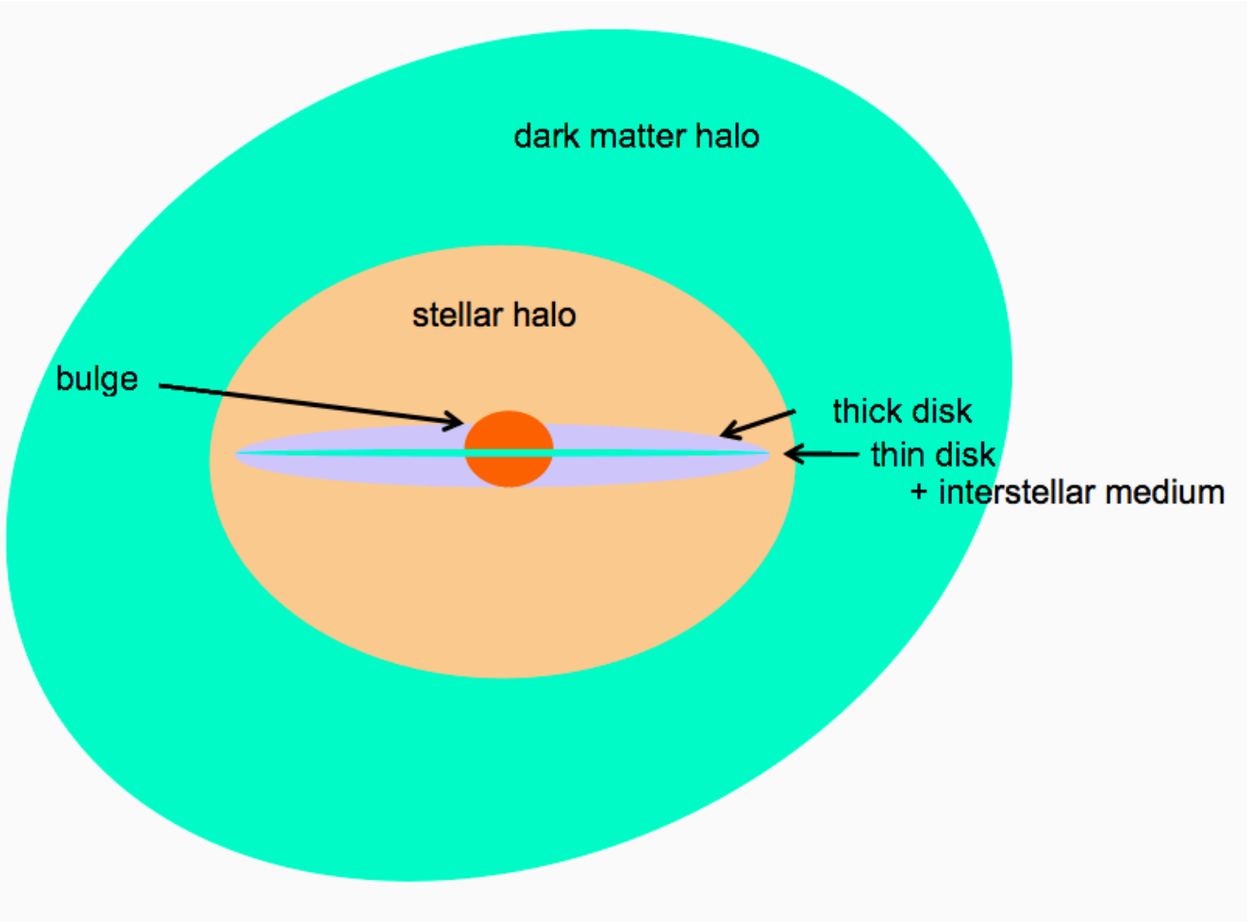
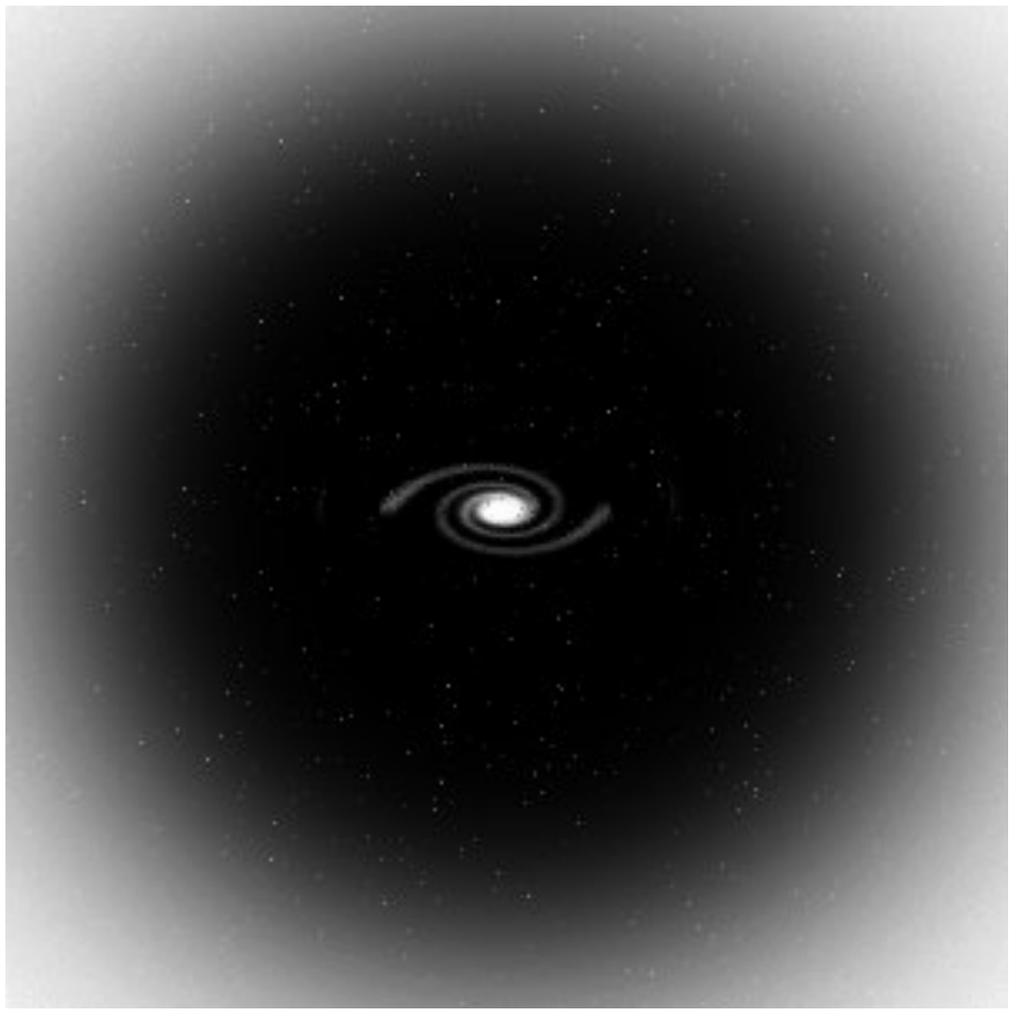


- **In a galaxy**
  (e.g. M_{total}(Milky Way)~1×10^{12} M_{sun})
  - **Dark matter: ~94% (mass)**
  - **Stars: ~5%**
  - **Gas/dust: ~1%**
  - **Black hole: ~<0.1%**



When we say a galaxy



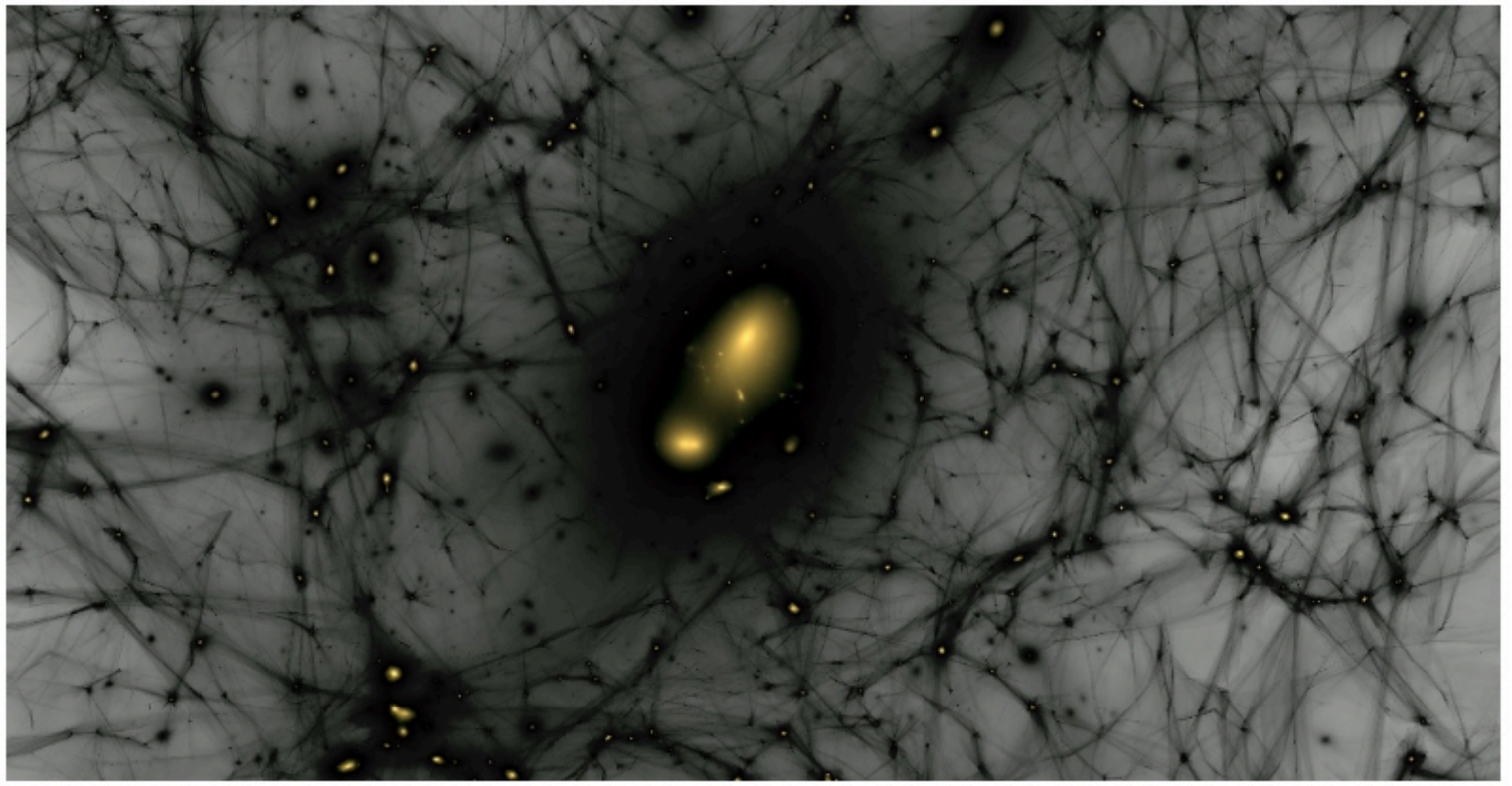
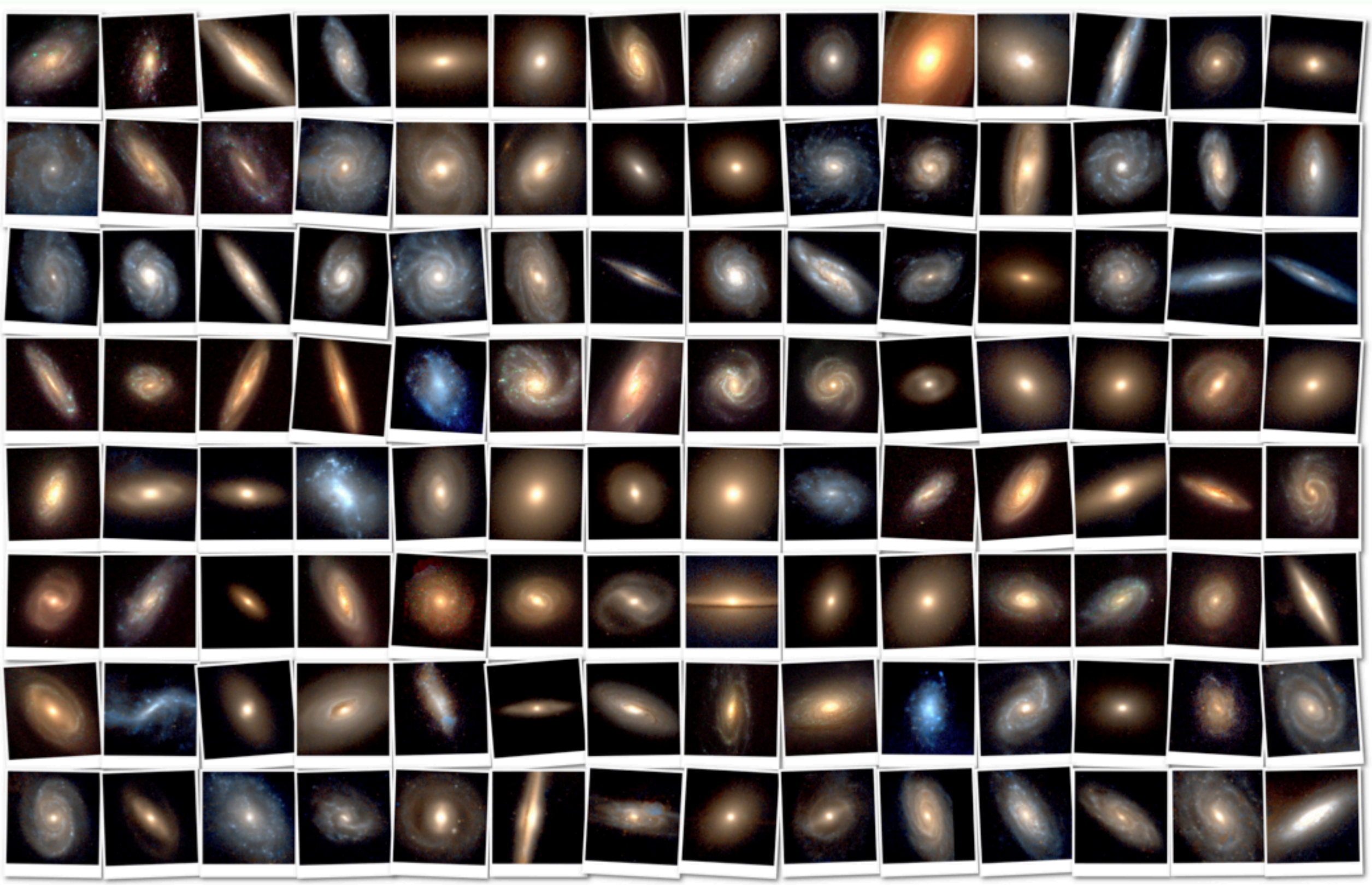


Image: Ralf Kaehler/SLAC National Accelerator Laboratory

In our Universe, there are many types of galaxies



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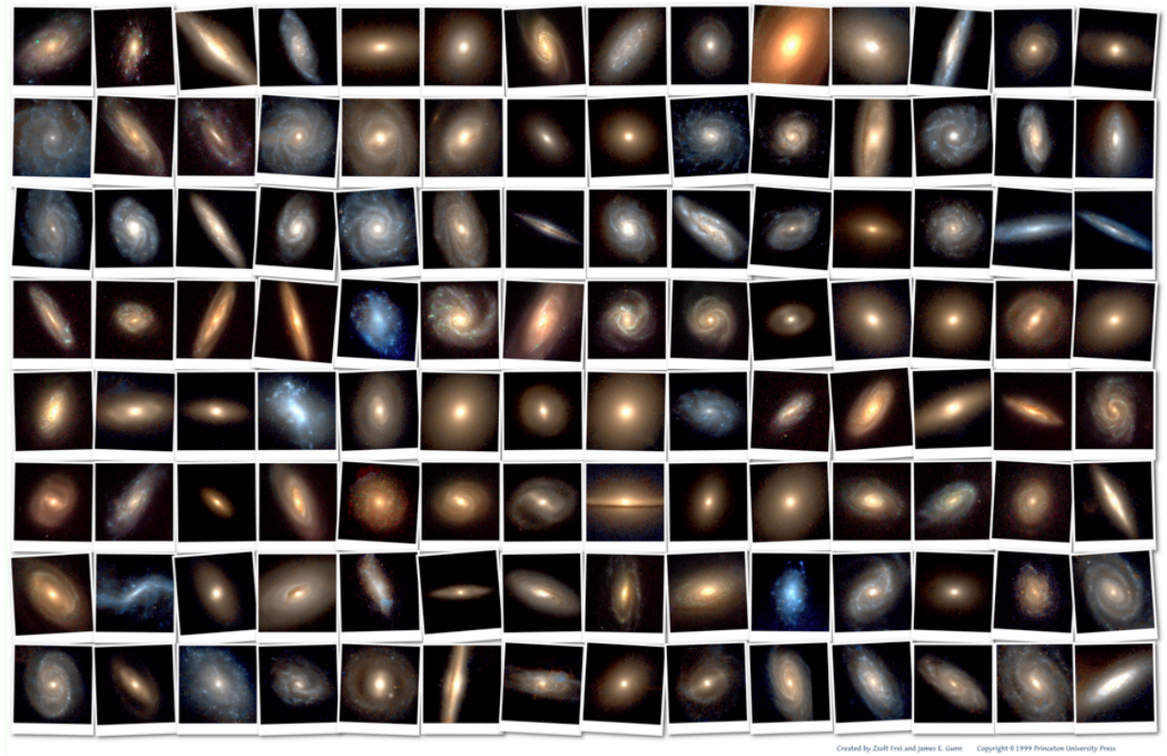
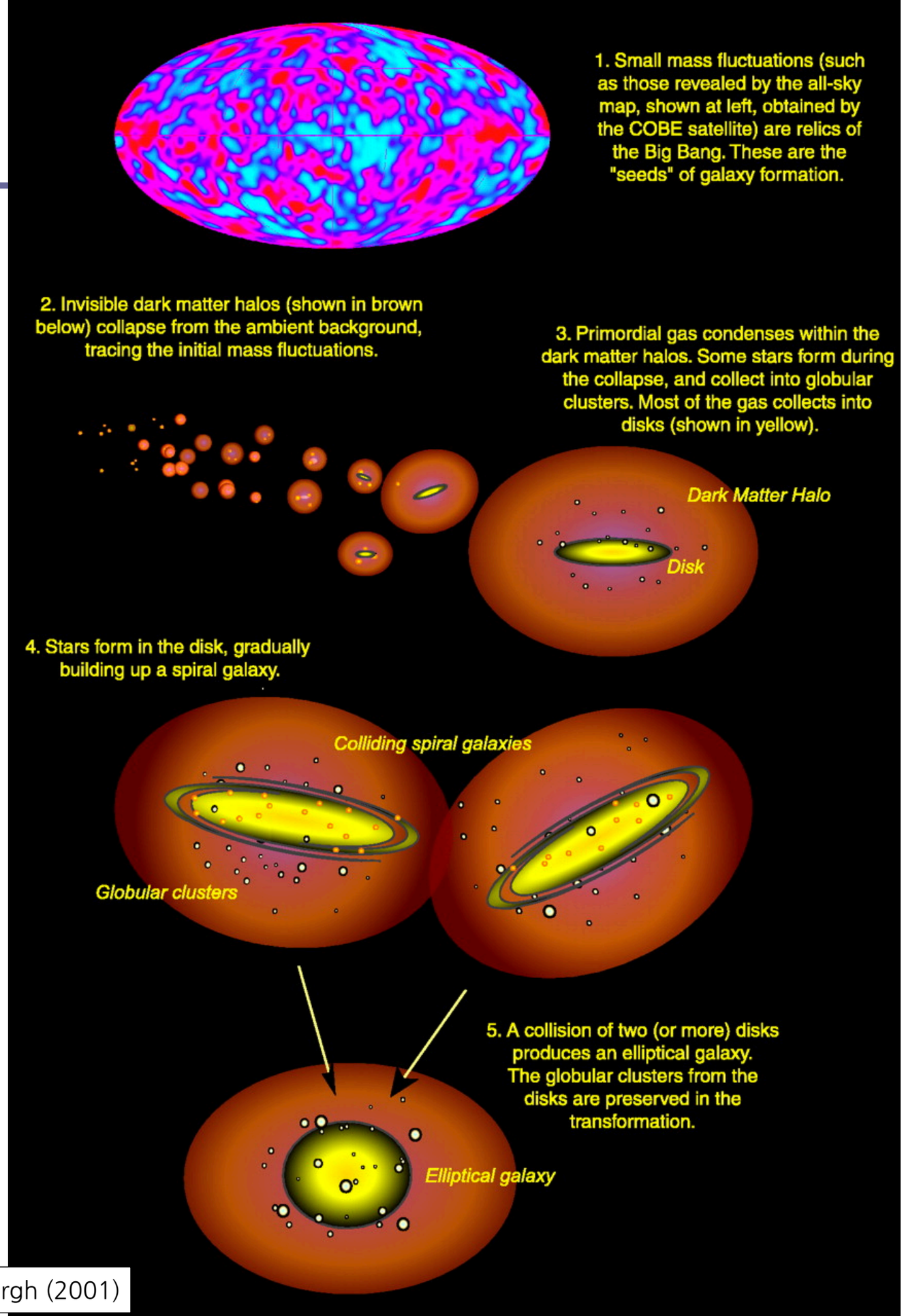
In our Universe, there are many types of galaxies



- **Q1: What makes this diversity of galaxy shape?**
- **Despite this diversity, all galaxies are believed to have dark matter halos.**
- **Q2: How to understand the formation of galaxies along with dark matter halos?**

A Summary of Galaxy Formation



Abraham & van den Bergh (2001)

Galaxy Formation Simulations: Large Scales



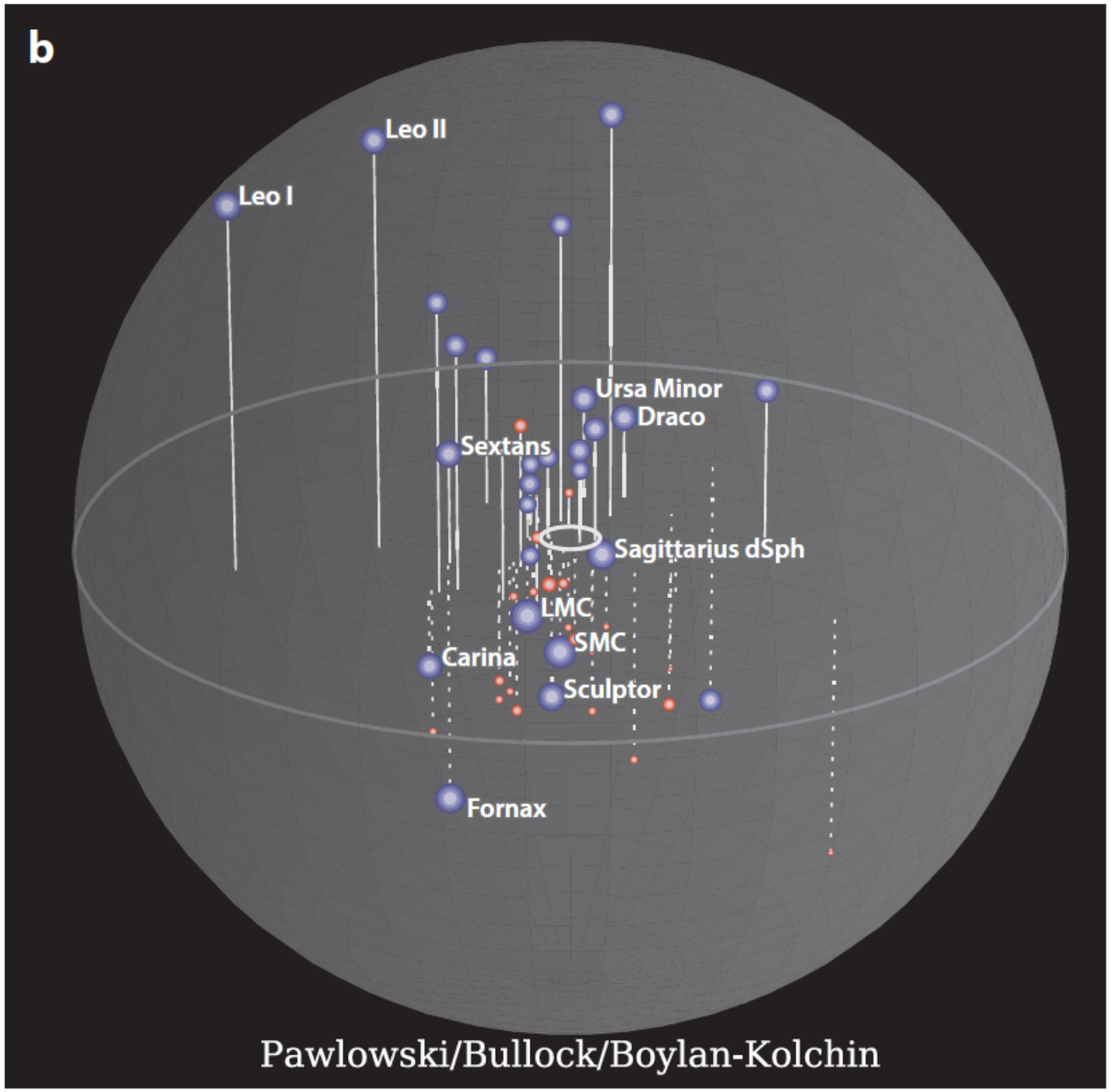
Galaxy Formation Simulations: Smale Scales

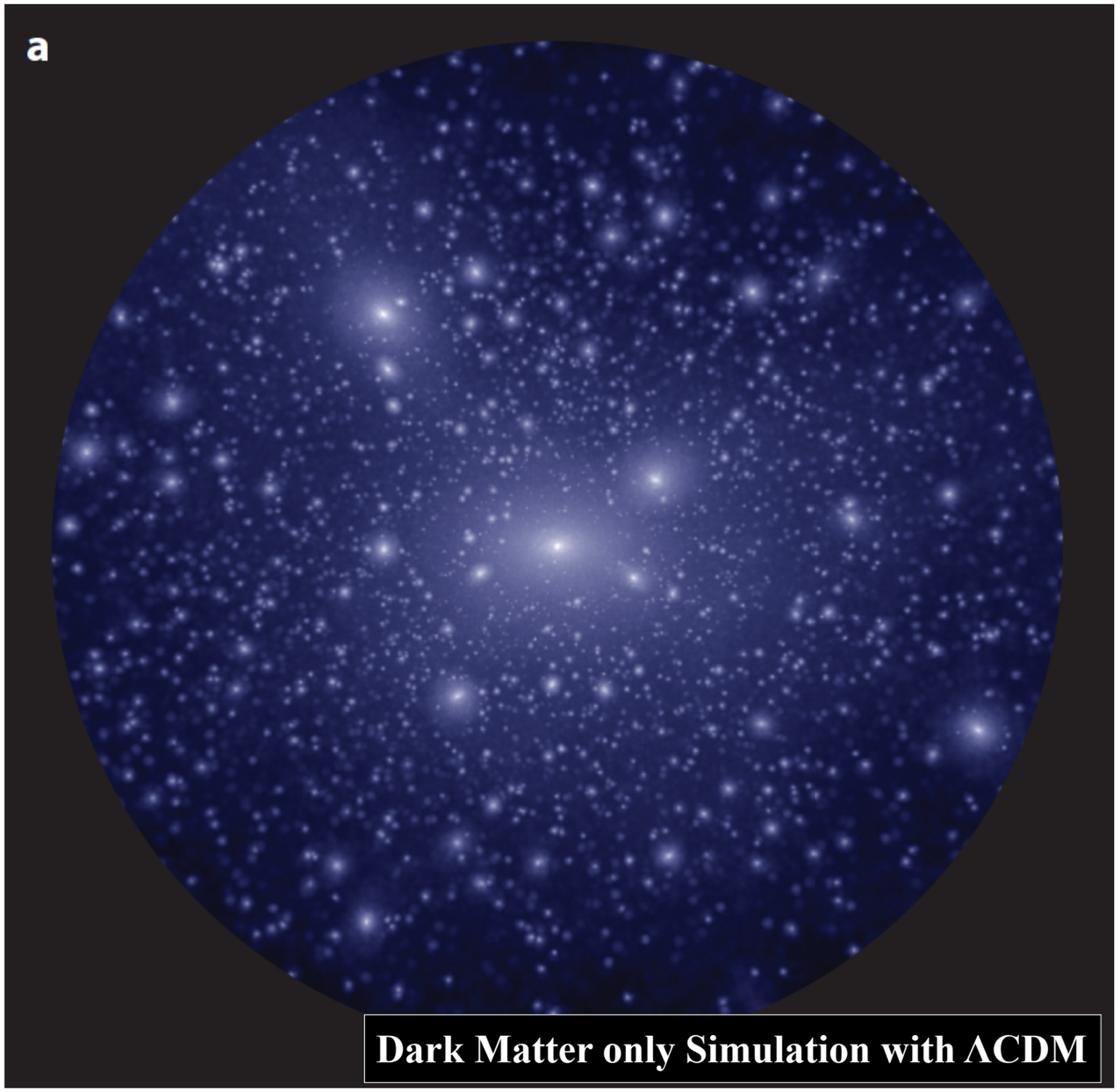
Gas (Hydrogen)

Dark Matter

Stars

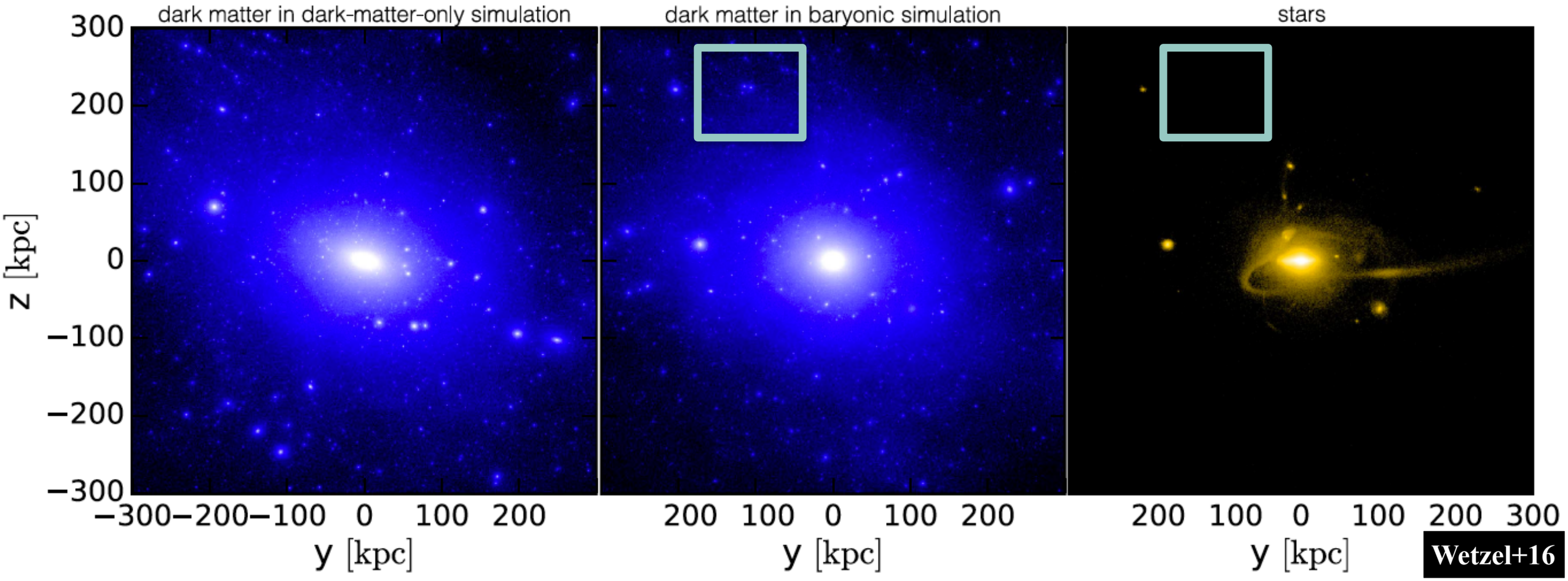
ΛCDM: Missing Satellite Problem





Bullock & Boylan-Kolchin 17

ΛCDM: Missing Satellite Problem - One Solution



- **Implementation of Baryonic physics?**
  - **Latte Project (Wetzel+16; see also ParkC+18; Jung,Kim+23): the Milky Way on Feedback in Realistic Environments (FIRE)**
    - **FIRE's stellar feedback generate dark-matter cores with reduced dynamical masses and the stellar velocity dispersions**
    - **Host galaxy's stellar disk destroys some sub halos.**

=> This naturally predicts the existence of dark matter only subhalos! (i.e. dark galaxies)

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Letter

Understanding galaxy rotation curves with Verlinde's emergent gravity

Of course, some people say we do not need dark matter..

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Abstract

We present the results from the analysis of galaxy rotation curves with Verlinde's emergent gravity. We use the data in the *Spitzer* Photometry and Accurate Rotation Curves database, which contains a sample of 175 nearby disk galaxies with 3.6 μm surface photometry and rotation curves. We compute the gravitational acceleration at different galactocentric radii expected from the baryon distribution of the galaxies with the emergent gravity, and compare it with the observed gravitational acceleration derived from galactic rotation curves. The predicted and observed accelerations agree well with a mean offset $\mu[\log(g_{obs}) - \log(g_{Ver})] = -0.060 \pm 0.004$ and a scatter $\sigma[\log(g_{obs}) - \log(g_{Ver})] = 0.137 \pm 0.004$ by assuming a de Sitter Universe. These offset and scatter become smaller when we assume a more realistic Universe, quasi de Sitter Universe, as $\mu = -0.027 \pm 0.003$ and $\sigma = 0.129 \pm 0.003$. Our results suggest that Verlinde's emergent gravity could be a good solution to the missing mass problem without introducing dark matter.

Dark Galaxies

MNRAS **465,** 3913–3926 (2017)
Advance Access publication 2016 November 17
doi:10.1093/mnras/stw2982

The properties of 'dark' ΛCDM haloes in the Local Group

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ABSTRACT

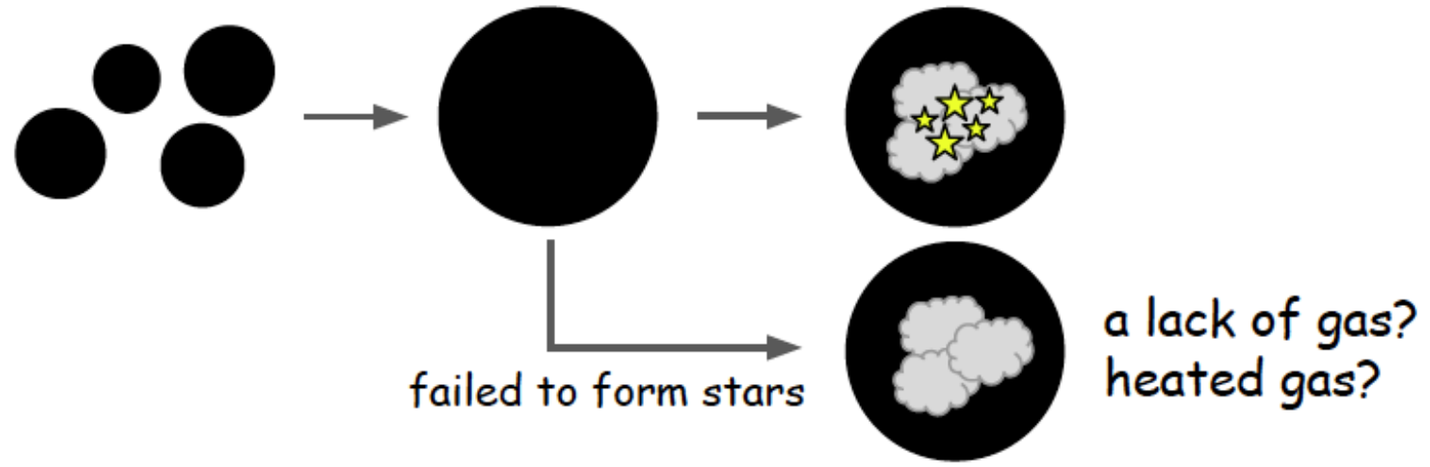
We examine the baryon content of low-mass Λ cold dark matter (ΛCDM) haloes ($10^8 < M_{200}/\mathrm{M}_\odot < 5 \times 10^9$) using the APOSTLE cosmological hydrodynamical simulations. Most of these systems are free of stars and have a gaseous content set by the combined effects of cosmic reionization, which imposes a mass-dependent upper limit, and of ram-pressure stripping, which reduces it further in high-density regions. Haloes mainly affected by reionization (RELHICs; REionization-Limited H I Clouds) inhabit preferentially low-density regions and make up a population where the gas is in hydrostatic equilibrium with the dark matter potential and in thermal equilibrium with the ionizing UV background. Their thermodynamic properties are well specified, and their gas density and temperature profiles may be predicted in detail. Gas in RELHICs is nearly fully ionized but with neutral cores that span a large range of H I masses and column densities and have negligible non-thermal broadening. We present predictions for their characteristic sizes and central column densities; the massive tail of the distribution should be within reach of future blind H I surveys. Local Group RELHICs (LGRs) have some properties consistent with observed Ultra Compact High Velocity Clouds (UCHVCs) but the sheer number of the latter suggests that most UCHVCs are not RELHICs. Our results suggest that LGRs (i) should typically be beyond 500 kpc from the Milky Way or M31; (ii) have positive Galactocentric radial velocities; (iii) H I sizes not exceeding 1 kpc, and (iv) should be nearly round. The detection and characterization of RELHICs would offer a unique probe of the small-scale clustering of CDM.

What is a dark galaxy?



➢ **Dark galaxy is an object with little or no stars, and believed to be made up almost entirely of dark matter.**

➢ **The ΛCDM model predicts the existence of dark galaxies.**



➢ **Detecting dark galaxies in normal, optical images is challenging because of their faintness.**

➢ **If they have a gas component, they could be detectable!**

A slide from Gain Lee

➢ **Our goal is to Find dark galaxies in our real world**

➢ **To examine whether the current galaxy formation scenario along with ΛCDM is correct or not.**

➢ **To know where to search,**

➢ **We will use cosmological hydrodynamic simulations first to identify them and to characterize their physical properties.**

모래사장에서 바늘 찾기

등록 2011.07.30 11:06:13 | 수정 2016.12.29 10:33:14

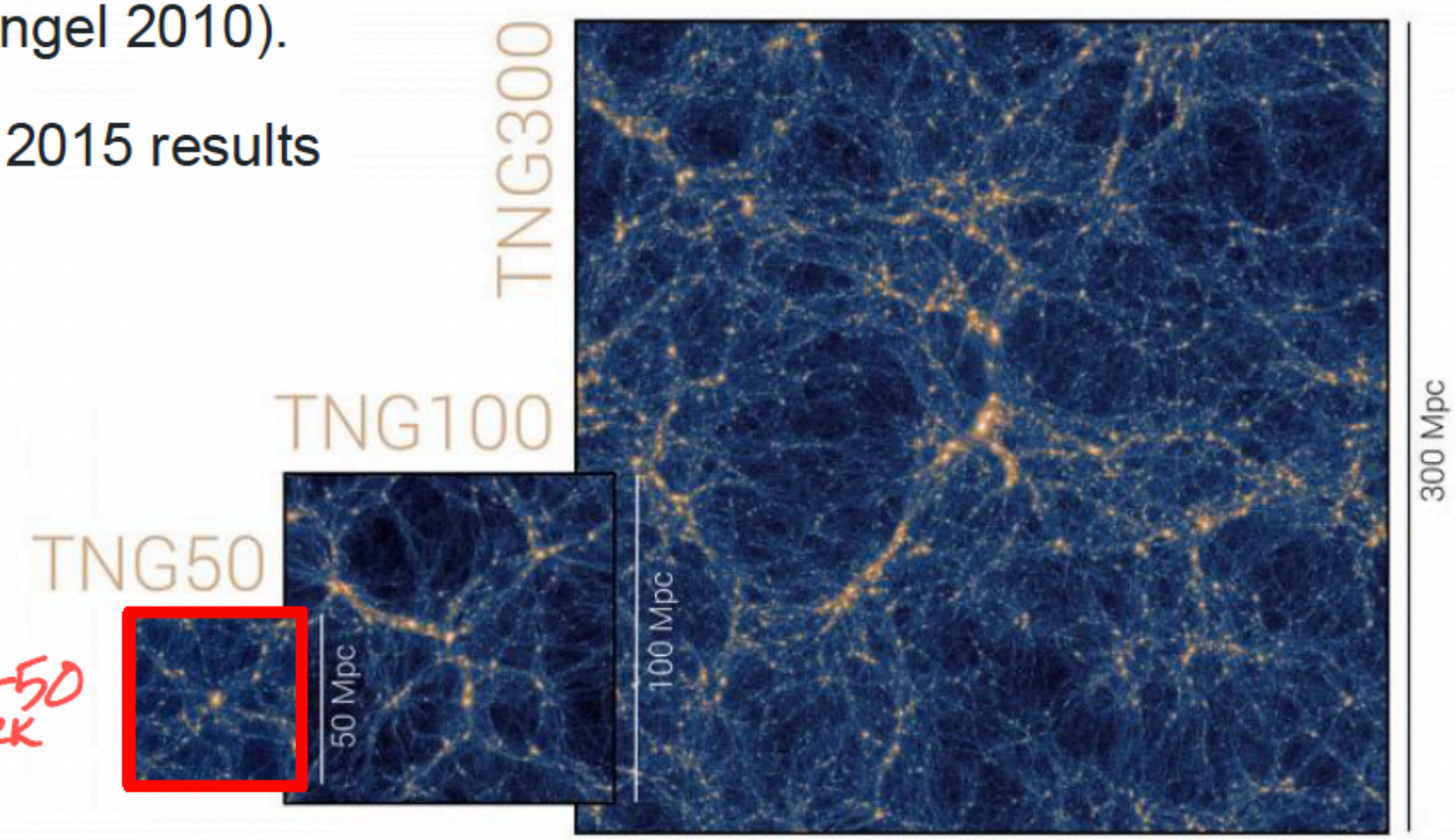


Let's talk about how to find them in Simulations First

The IllustrisTNG Simulation

- **Illustris*TNG*** project is the successor of the **Illustris** simulation.
  (✳ TNG = The Next Generation)
- A suite of large volume, cosmological, gravo-magnetohydrodynamical simulations run with the particle-based code **Arepo** (Springel 2010).
- **Cosmological parameters**: Planck 2015 results

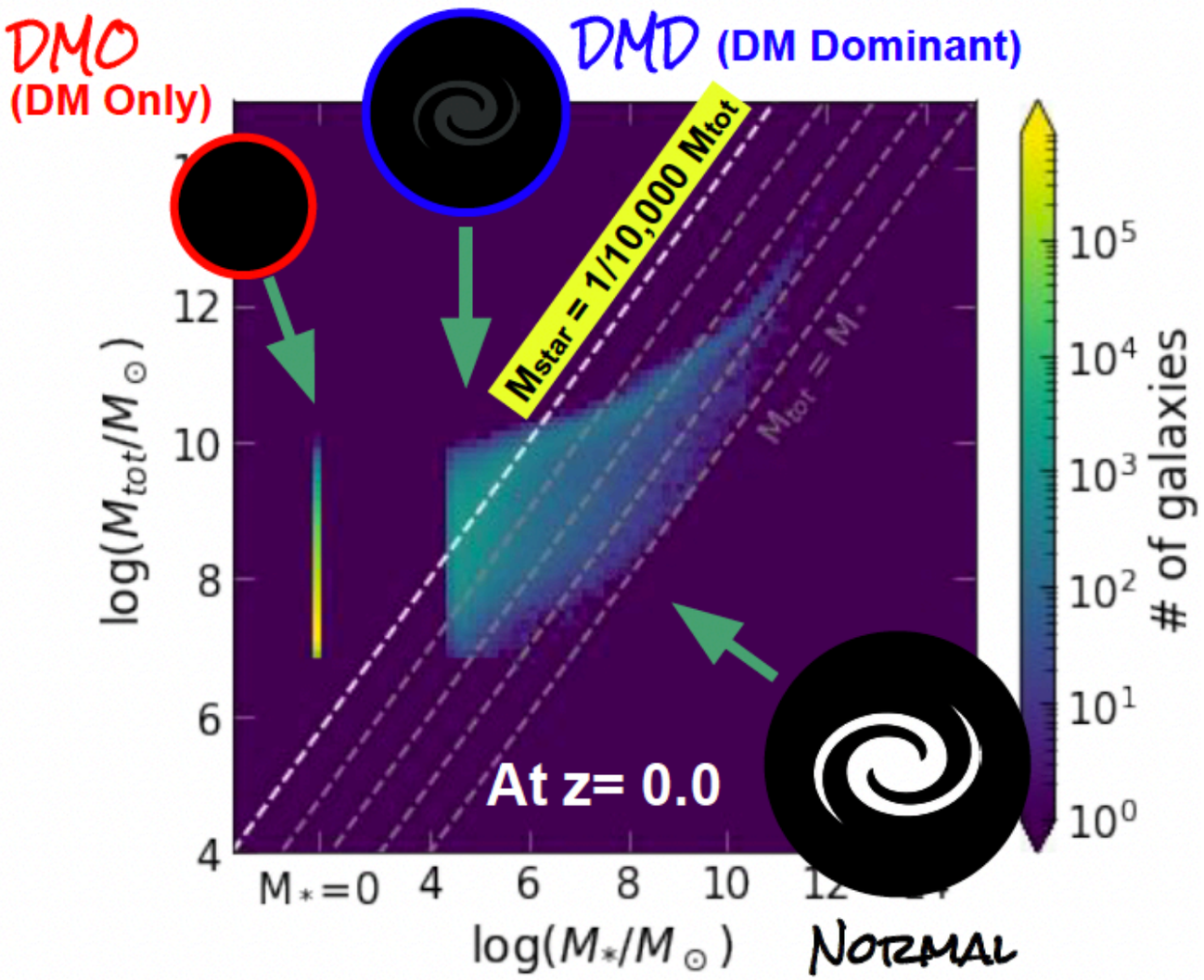
$\Omega_{\Lambda,0} = 0.6911, \Omega_{m,0} = 0.3089, \Omega_{b,0} = 0.0486,$
$\sigma_8 = 0.8159, n_s = 0.9667$ and $h = 0.6774$



A slide from Gain Lee

Sample Selection

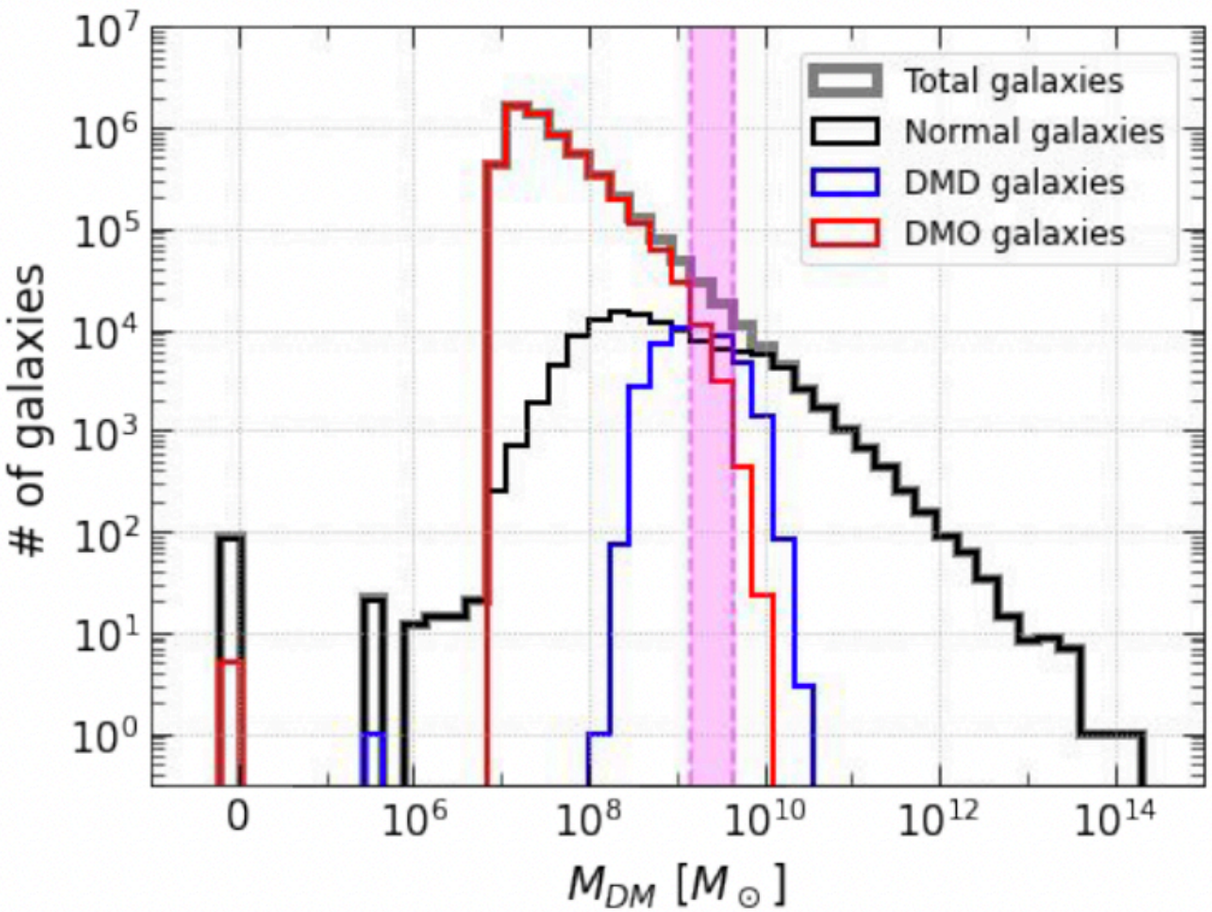
Definitions for Normal / Dark Galaxies



For mass completeness,

1.5×10^9 Msun $\leqq$ $M_{DM} < 4.3 \times 10^9$ Msun

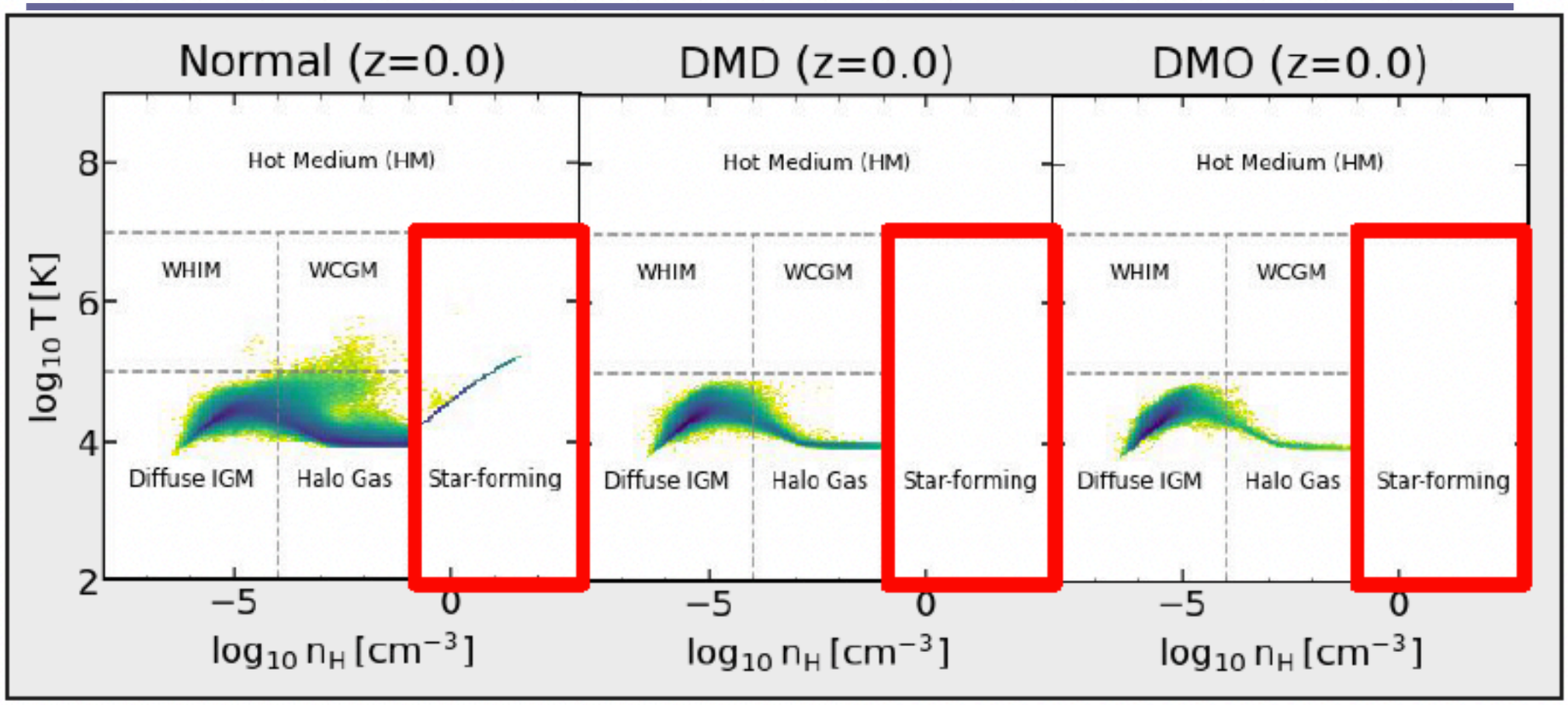
All selected galaxies have similar DM halo masses.



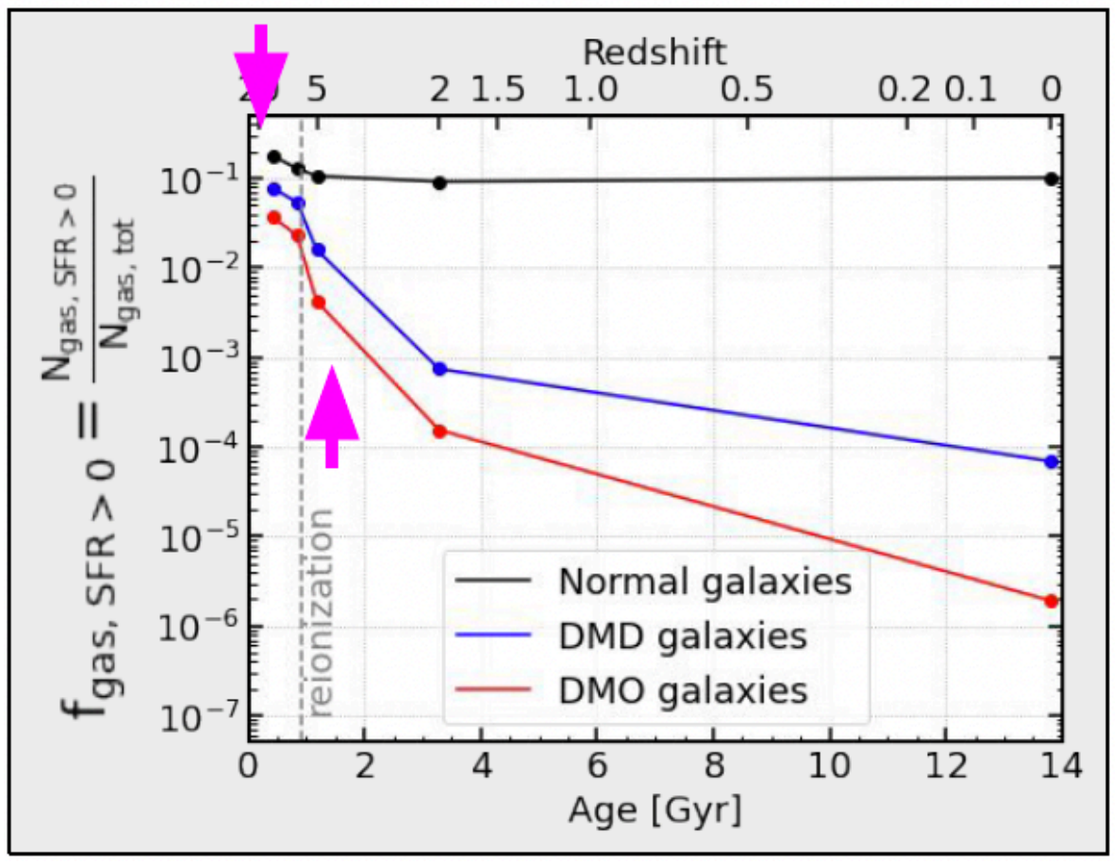
Q: How are they (DMO, DMD, Normal galaxies) different?

A slide from Gain Lee

Star Forming Gas: Fuel!



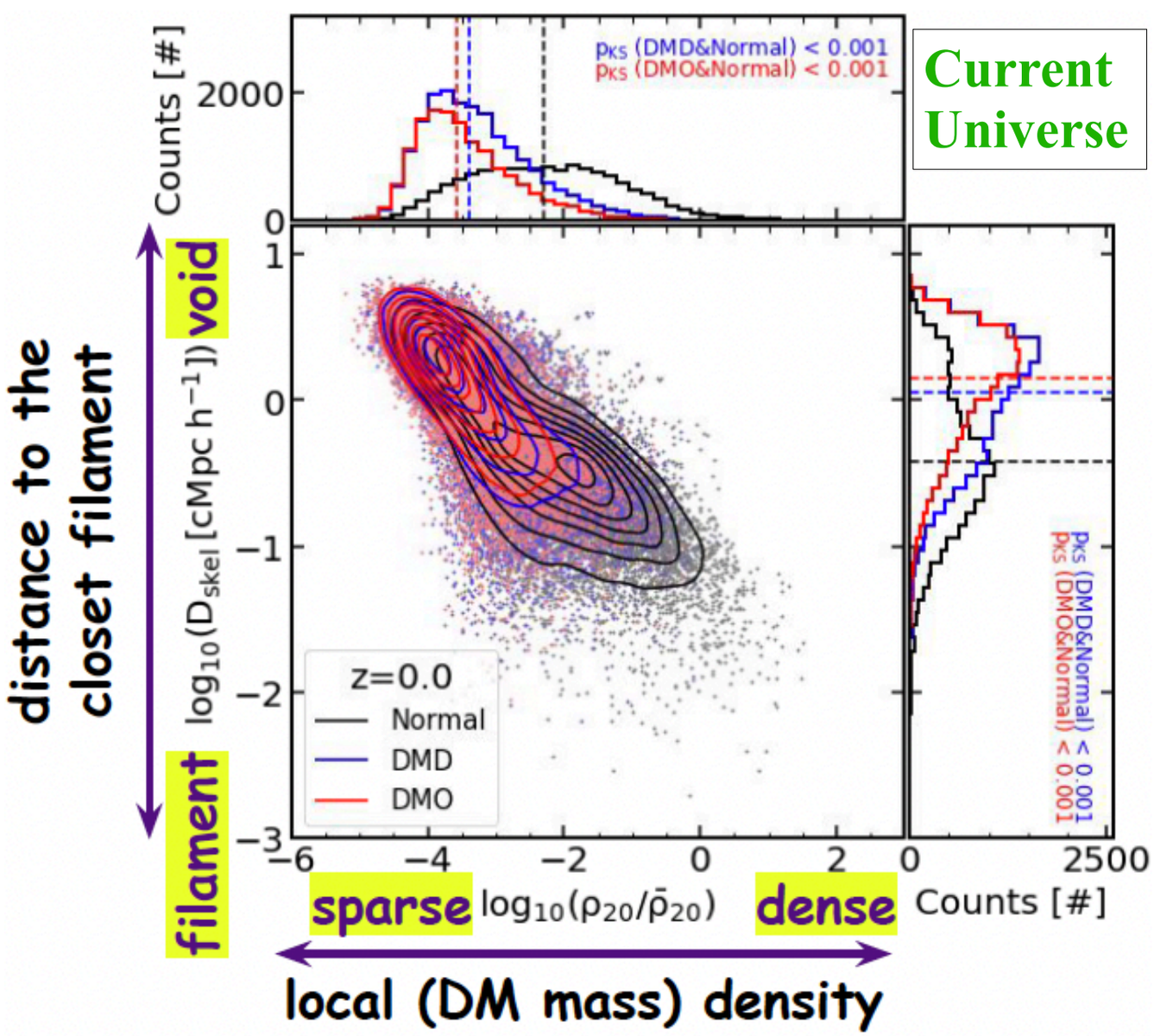
A slide from Gain Lee

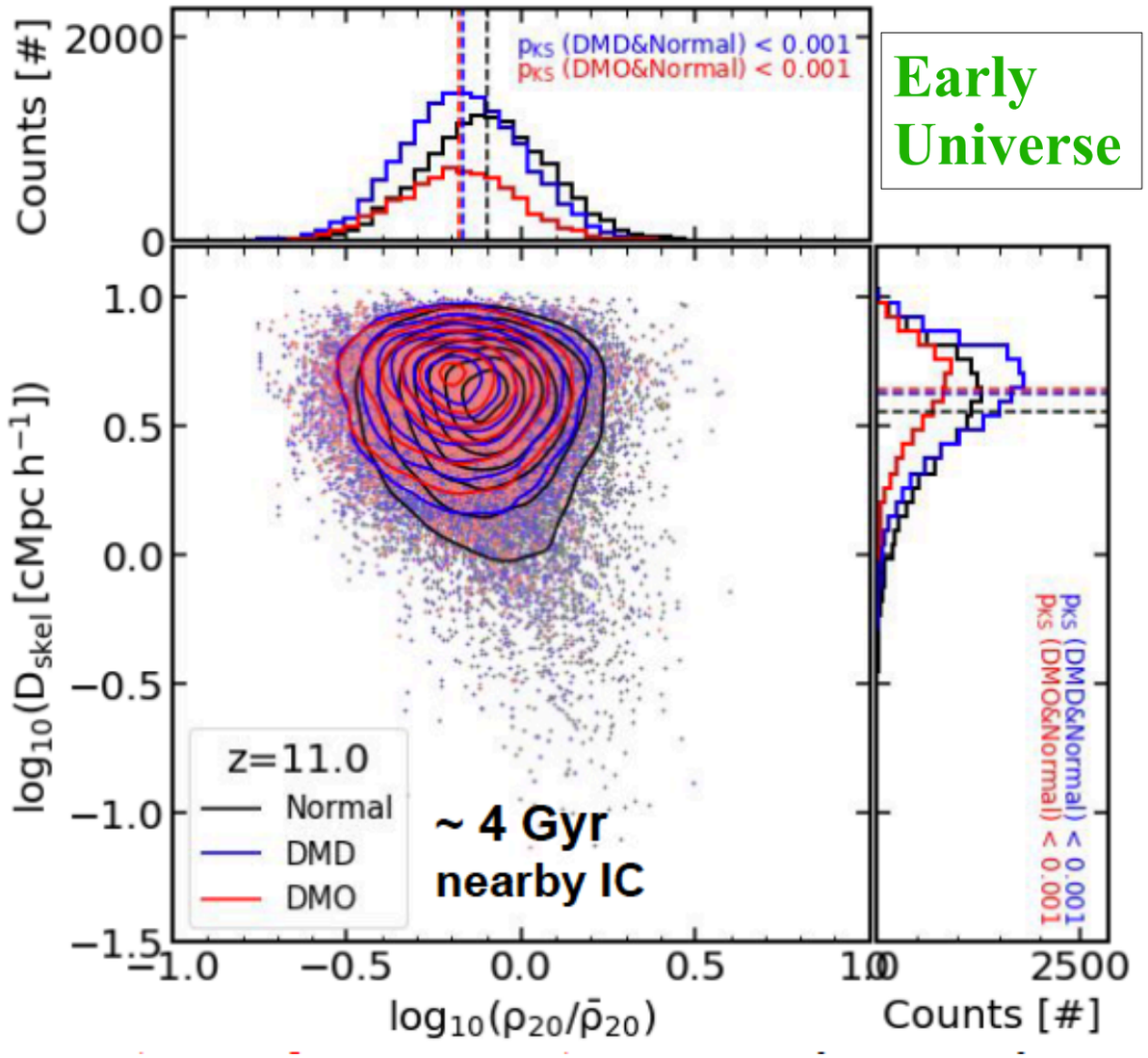


- **No star-forming gas in dark galaxies at z=0 (Not surprising!)**
- **Dark galaxies contain less star-forming gas even in the early universe.**
- **The star-forming gas fraction in dark galaxies decreases significantly after the cosmic reionization!**

Galaxy Environment

➢ **Dark and Normal galaxies live different environments in both early/late universe. => Significant impact on the gas accretion and mass growth.**



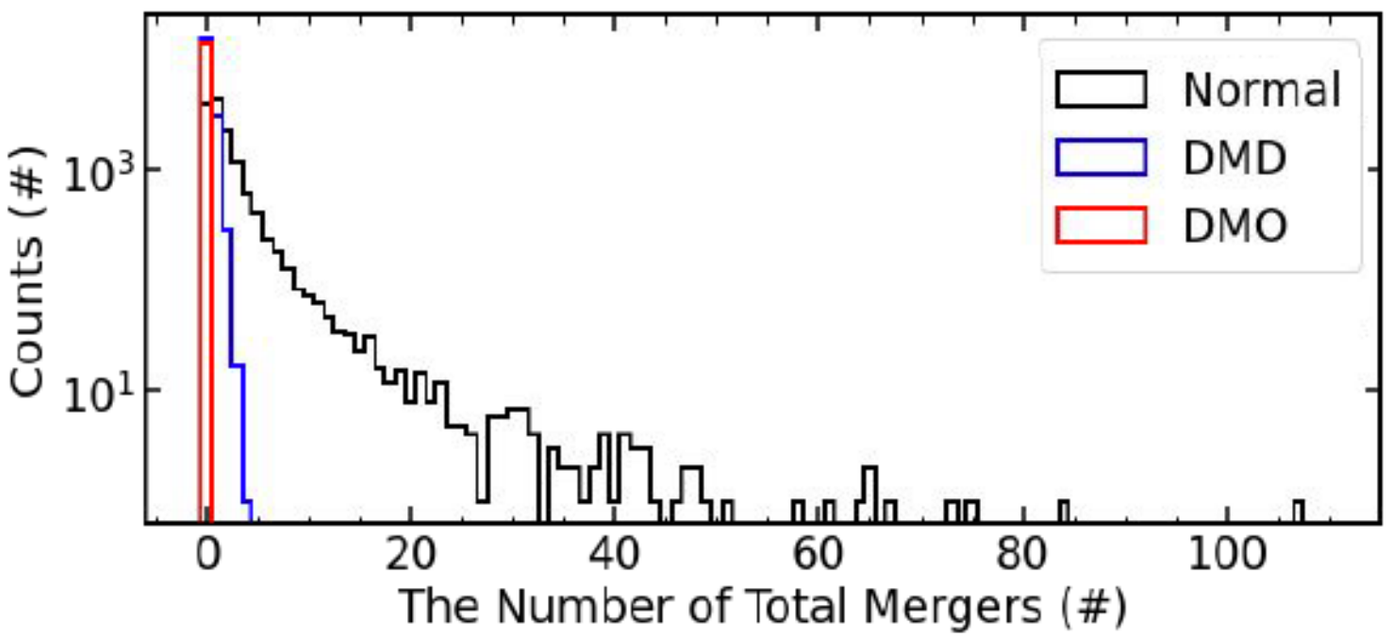


A slide from Gain Lee

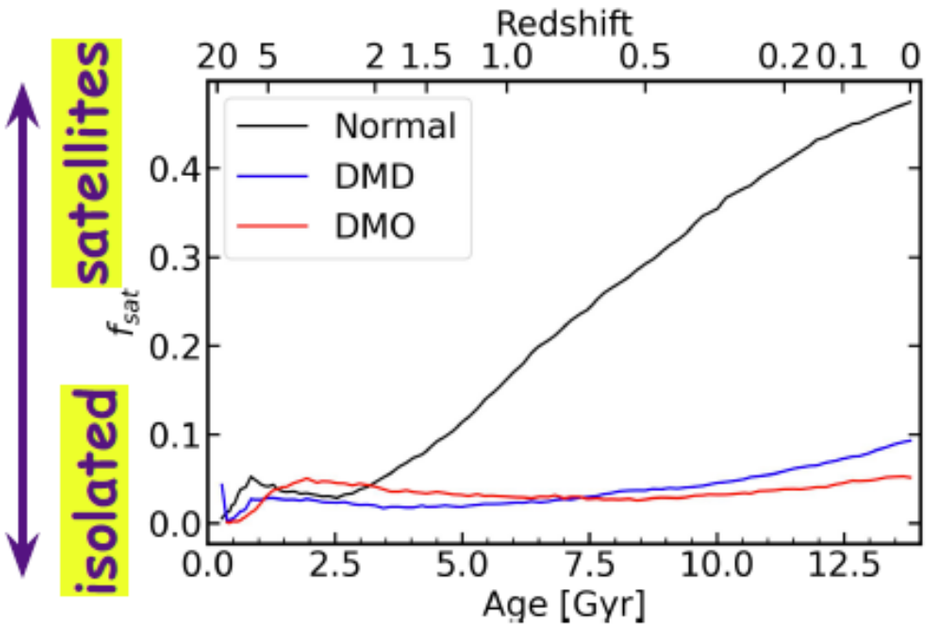
Discussion: Origin of Dark Galaxies

1. **The initial condition plays an importnat role!**
   Less dense birthplace → Dark galaxy
   A lack of SF gas

2. **The difference becomes more pronounced as they evolve in the different environments.**
   1. **Normal galaxies experience more merging compared to dark galaxies.**
   2. **As a result, normal galaxies tend to become satellites, vut dark galaxies remain as centrals => dark galaxies are isolated and hardly interact with other galaxies.**



fraction of satellites



A slide from Gain Lee

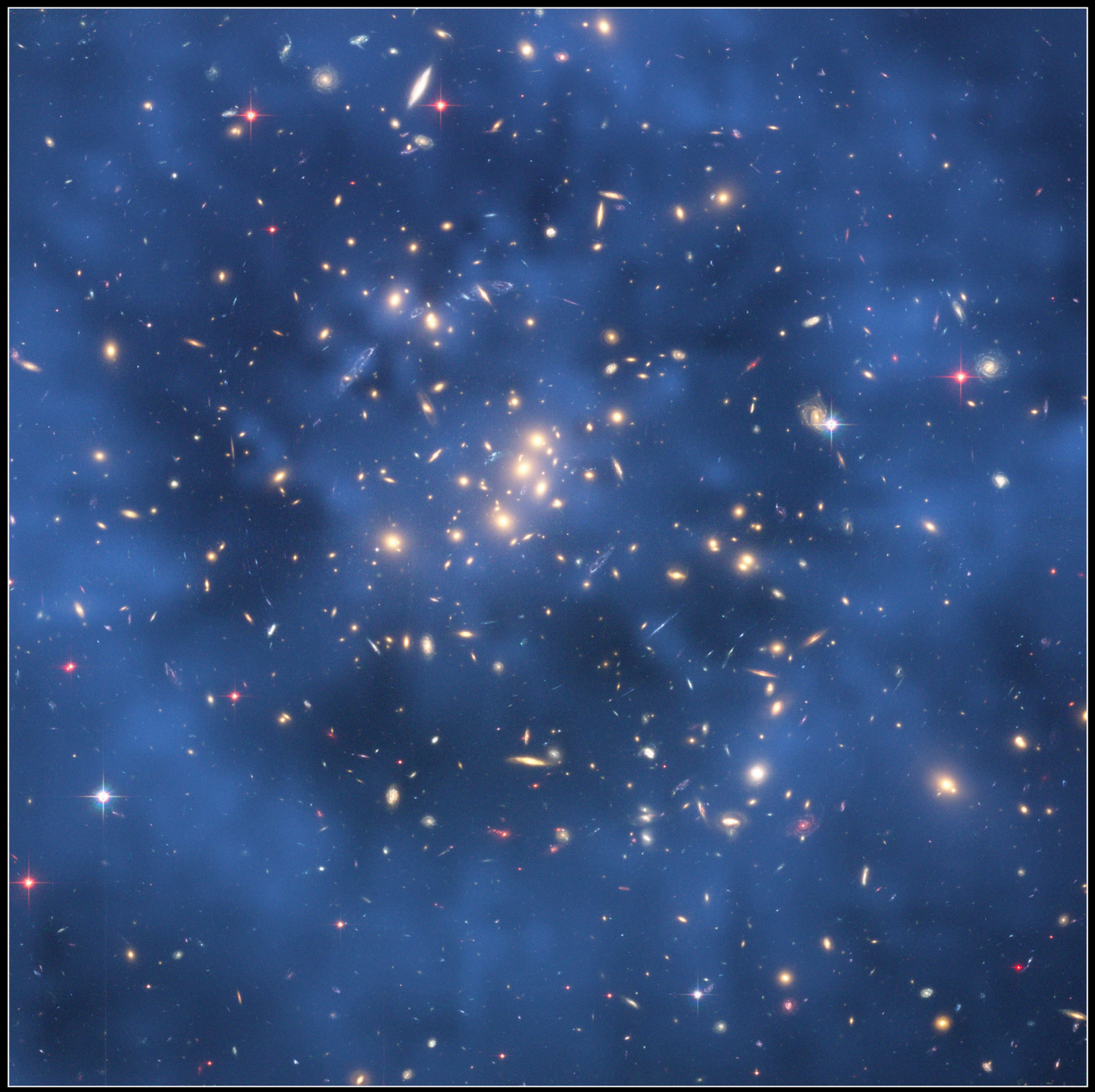
Origin of Dark Galaxies

3. **Cosmic reionization also play a role in the formation of dark galaxies: Heating & expelling gas particles**
   1. **Survivors (i.e. shielding) => Normal galaxy**
   2. **Non-Survivors => Dark galaxy**

Q: How about in our real world?!

Dark Galaxy Search

- **The Key is to find an extragalactic object with gas, but without stars!**
- **In astronomical term: HI sources without optical counterparts!**



Dark Matter Ring in Galaxy Cluster Cl 0024+17 (ZwCl 0024+1652)

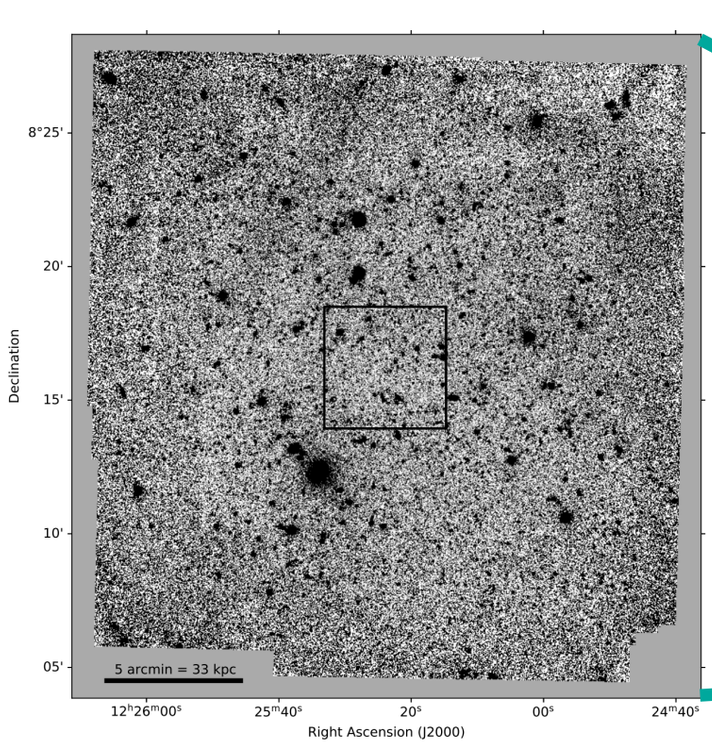
Hubble Space Telescope • ACS/WFC

NASA, ESA, and M.J. Jee (Johns Hopkins University)

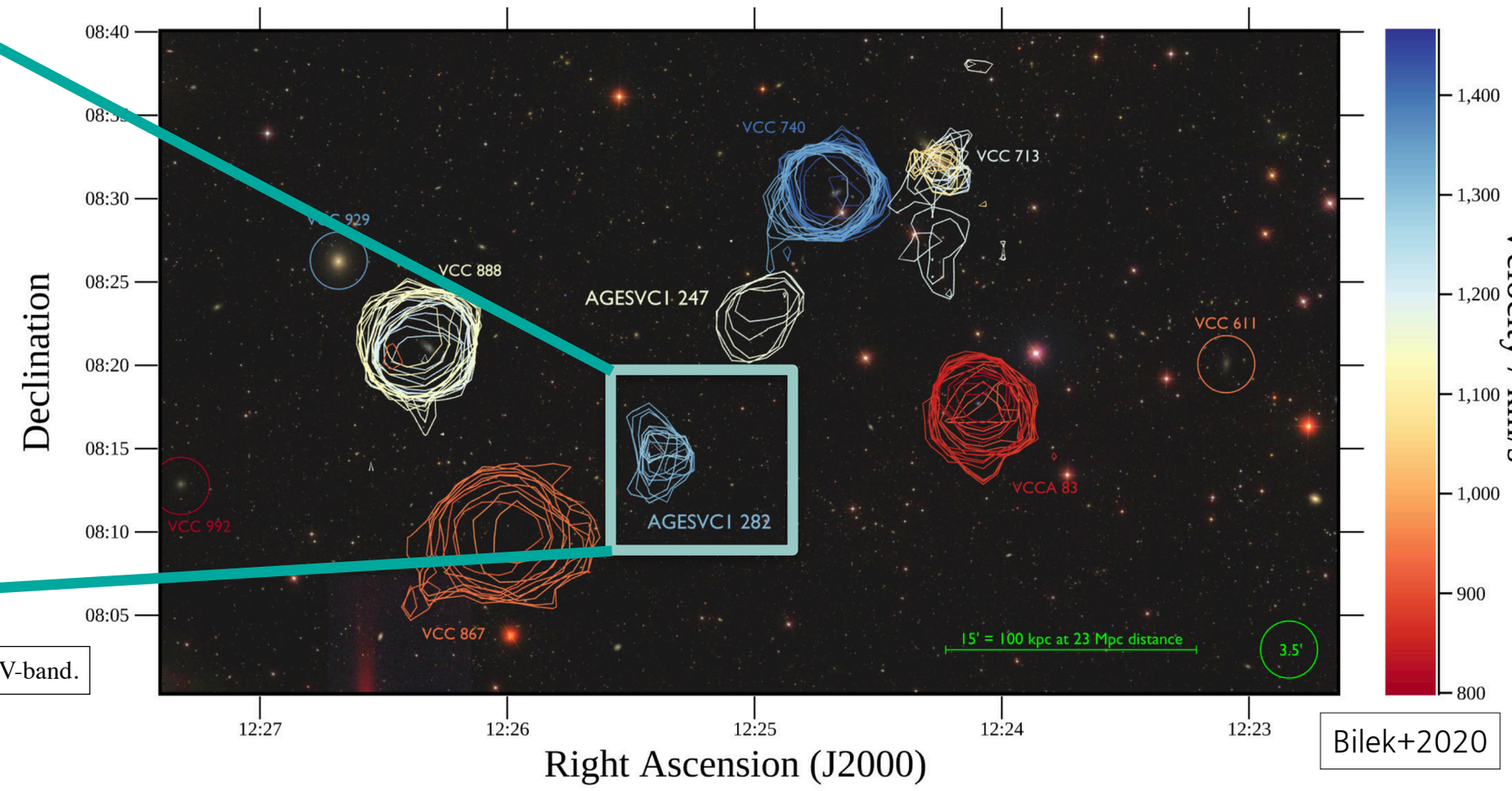
STScI-PRC07-17a

In Observations

- **Several candidates for dark galaxies were proposed:**
  - **e.g. VIRGOHI21 (Minchin+2005), Dragonfly 44 (Van Dokkum+ 2015), AGESVC1 282 (Bilek+2020), AGC 229101 (Leisman+2021) and FAST J0139+4328 (Xu+2023)**
  - **They are not totally dark!**
  - **There is no systematic search!**



Surface Brightness limt of 29.05±0.04 mag arcsec^{-2} in the V-band.



Bilek+2020

A slide from Gain Lee

Dark Galaxy Search with Radio Telescope





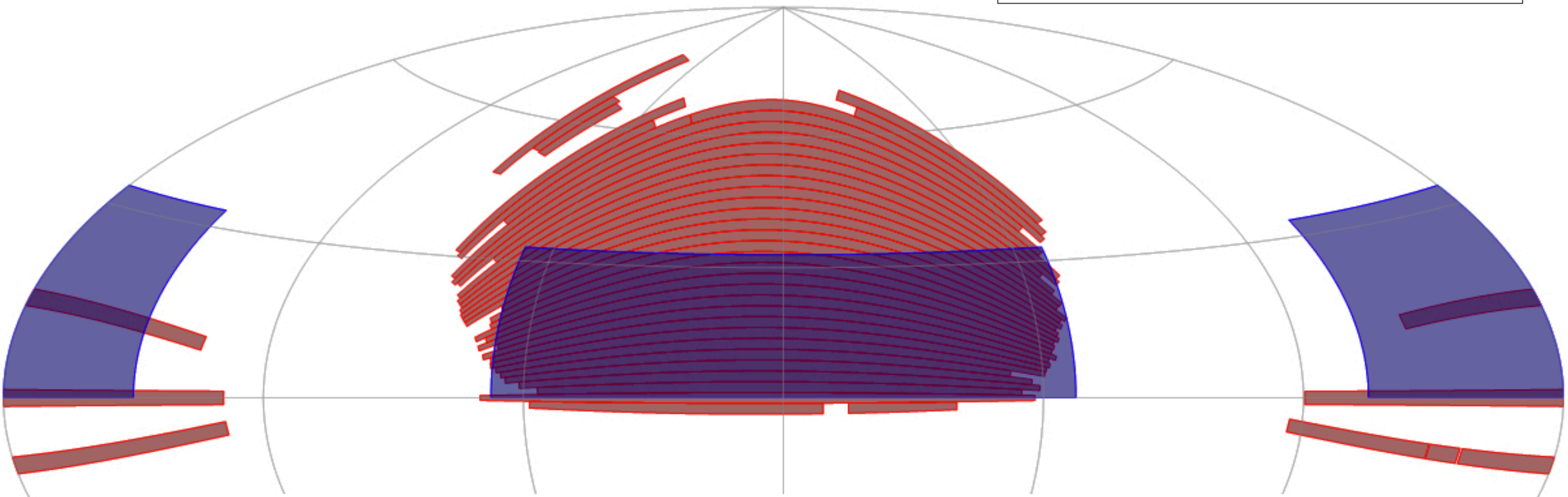
Arecibo 305m radio telescope in Puerto Rico.

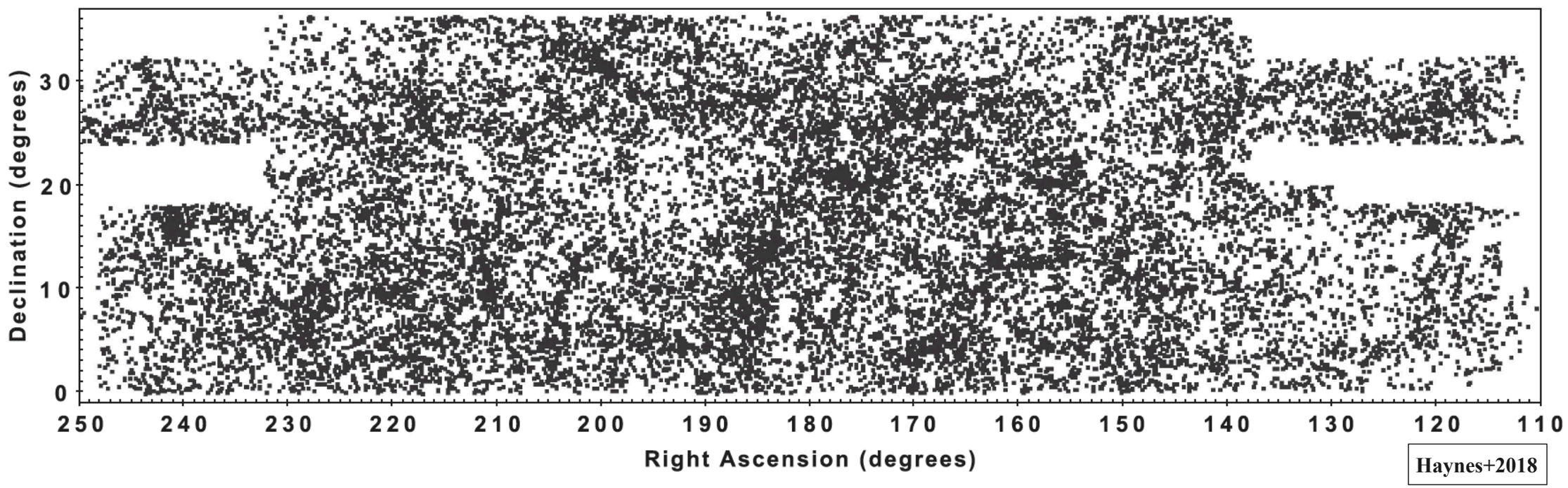


Dark Galaxy Search with Radio Telescope

➢ **HI (ALFALFA) + Optical (SDSS)**

Footprint of ALFALFA (blue) on the Sloan Digital Sky Survey (red).





Haynes+2018

Dark Galaxy Search with Radio Telescope

The Astrophysical Journal, 861:49 (19pp), 2018 July 1 https://doi.org/10.3847/1538-4357/aac95
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The Arecibo Legacy Fast ALFA Survey: The ALFALFA Extragalactic H I Source Catalog

Martha P. Haynes[1], Riccardo Giovanelli[1], Brian R. Kent[2], Elizabeth A. K. Adams[3,4], Thomas J. Balonek[5], David W. Craig[6], Derek Fertig[7], Rose Finn[8], Carlo Giovanardi[9], Gregory Hallenbeck[10], Kelley M. Hess[3,4], G. Lyle Hoffman[11], Shan Huang[1], Michael G. Jones[12], Rebecca A. Koopmann[13], David A. Kornreich[1], Lukas Leisman[14], Jeffrey Miller[15], Crystal Moorman[16], Jessica O'Connor[17], Aileen O'Donoghue[15], Emmanouil Papastergis[4,18], Parker Troischt[19], David Stark[20], and Li Xiao[21]
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Abstract

We present the catalog of ∼31,500 extragalactic H I line sources detected by the completed Arecibo Legacy Fast ALFA (ALFALFA) survey out to $z < 0.06$, including both high signal-to-noise ratio (>6.5) detections and ones of lower quality that coincide in both position and recessional velocity with galaxies of known redshift. We review the observing technique, data reduction pipeline, and catalog construction process, focusing on details of particular relevance to understanding the catalog's compiled parameters. We further describe and make available the digital H I line spectra associated with the cataloged sources. In addition to the extragalactic H I line detections, we report nine confirmed OH megamasers (OHMs) and 10 OHM candidates at $0.16 < z < 0.22$ whose OH line signals are redshifted into the ALFALFA frequency band. Because of complexities in data collection and processing associated with the use of a feed-horn array on a complex single-dish antenna in the terrestrial radio frequency interference environment, we also present a list of suggestions and caveats for consideration by users of the ALFALFA extragalactic catalog for future scientific investigations.

Dark Galaxy Search with Radio Telescope

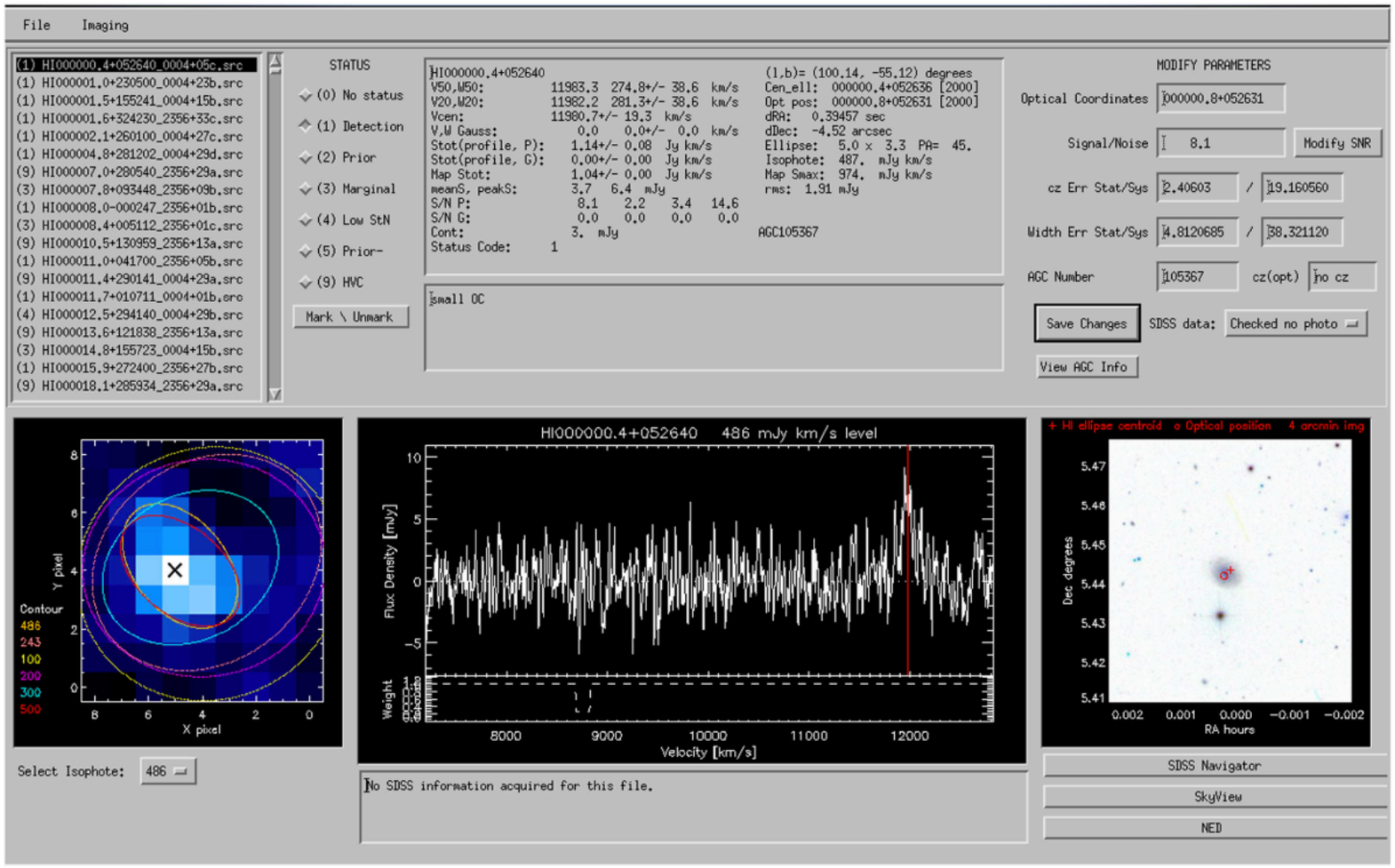


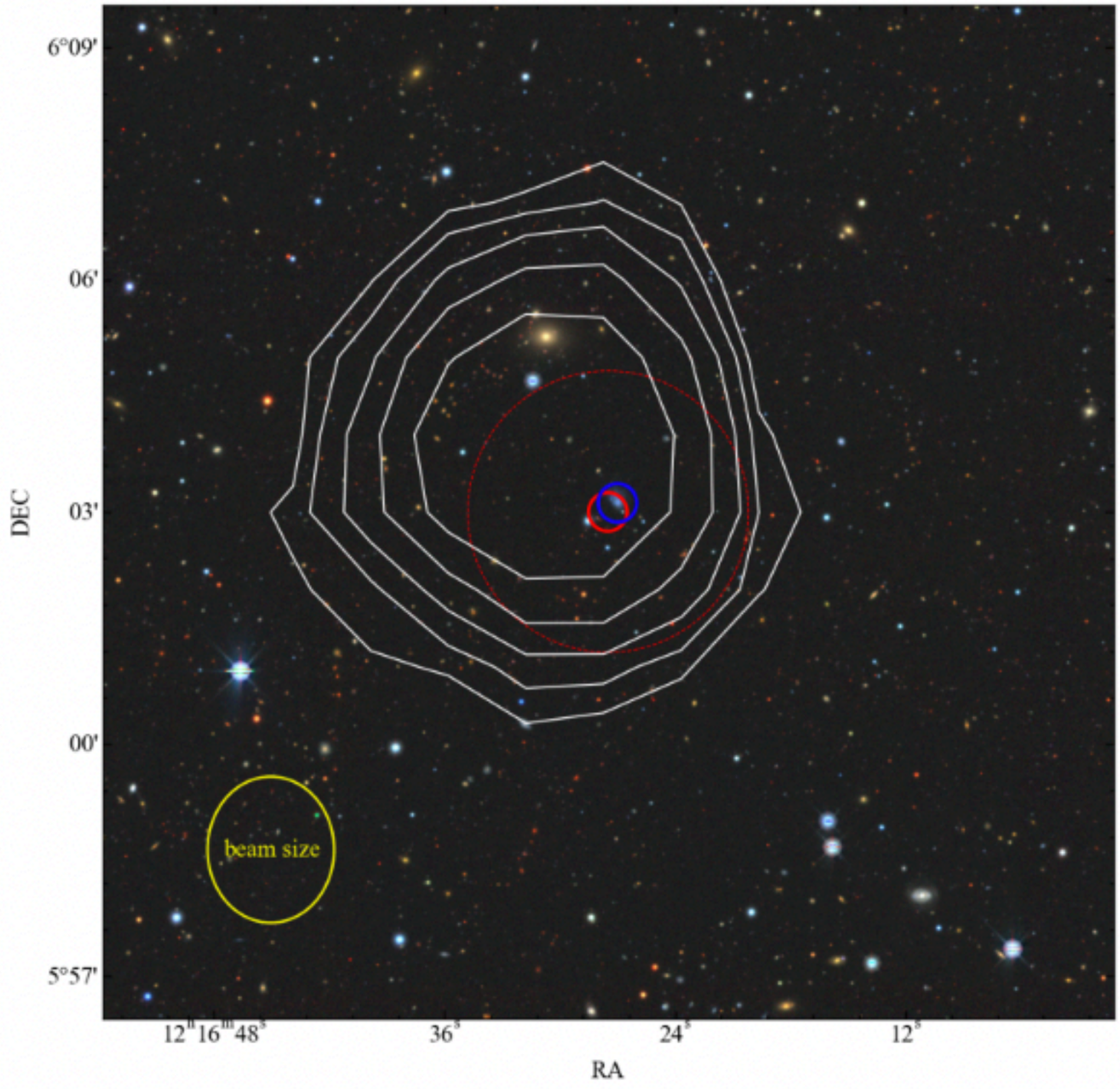
Figure 8. GalCat application GUI created in IDL. The catalog of ALFALFA sources is displayed as a list at top left. For each source selected from that list, a summary is presented in the interface, including the measured parameters (top center), the isophotal fits (bottom left), the extracted "postage stamp" spectrum and its normalized weight at each spectral point (bottom center), and the optical image (bottom right). The top right panel offers the possibility to modify parameters as necessary.

- **~31,500 HI sources with optical counterparts**
- **~567 HI sources without optical counterparts!**

Table 2
ALFALFA Extragalactic H I Source Catalog

AGC ID	Name	H I Position J2000	OC Position J2000	$cz_\odot$ (km s^{-1})	W_{50} (km s^{-1})	W_{20} (km s^{-1})	$\int SdV$ (Jy km s^{-1})	S/N	rms (mJy)	D_H (Mpc)	log $M_{\rm H\,I}$ log $M_\odot$	Code
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
105367		000000.4+052636	000000.8+052633	11983	274(39)	281	1.14(0.08)	8.1	1.91	166.0(2.3)	9.87(0.05)	1
333313		000000.9+245432	235959.4+245427	11181	313(20)	333	1.80(0.09)	11.3	2.02	154.8(2.3)	10.01(0.05)	1
331060	478-009b	000002.5+230505	000003.4+230515	4463	160(4)	184	1.96(0.07)	14.7	2.35	50.6(10.4)	9.07(0.18)	1
331061	456-013	000002.5+155220	000002.1+155254	6007	260(45)	268	1.13(0.09)	6.5	2.40	85.2(2.4)	9.29(0.06)	1

ALFALFA contour



➢ **Because of poor resolution of ALFALFA images, we plan to conduct detailed HI observations with GMRT.**

Plots from Minseong Kwon

Summary

- **Our goal is to Find dark galaxies in our real world**
  - **To examine whether the current galaxy formation scenario along with ΛCDM is correct or not.**

- **If we can find such objects in real world; this can**
  - **Be an important test of current galaxy formation scenario along with ΛCDM**
  - **Tell us where to look for direct study of dark matter**