Dark Worlds in Astronomy: Exploring the Cosmic Mystery of Dark Matter

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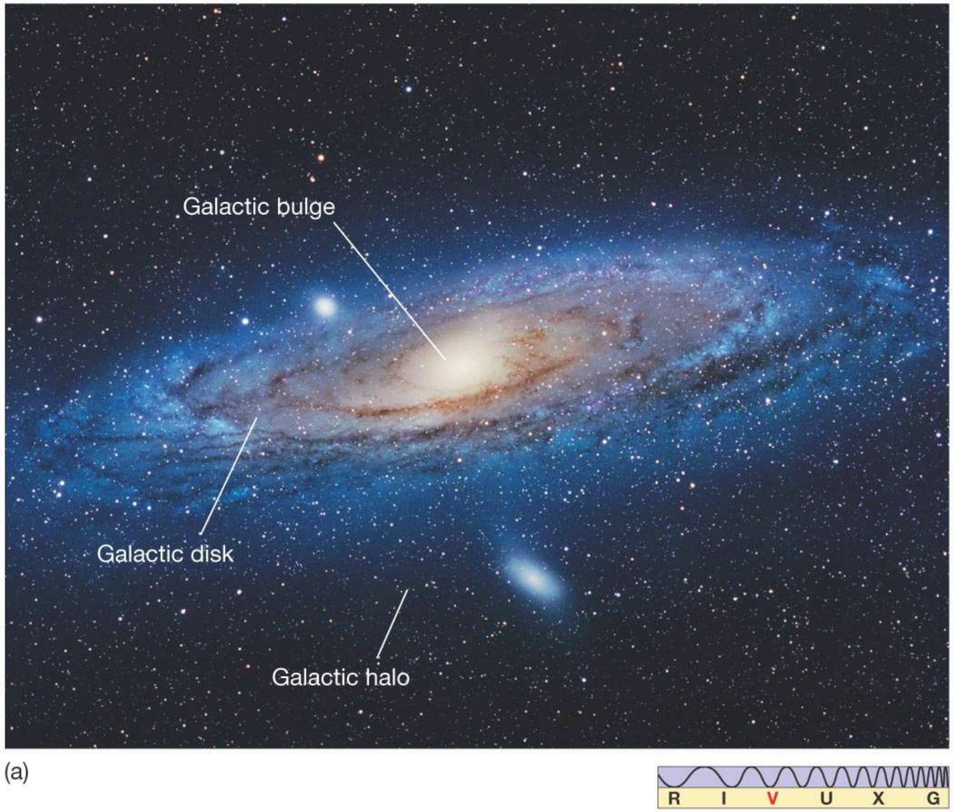
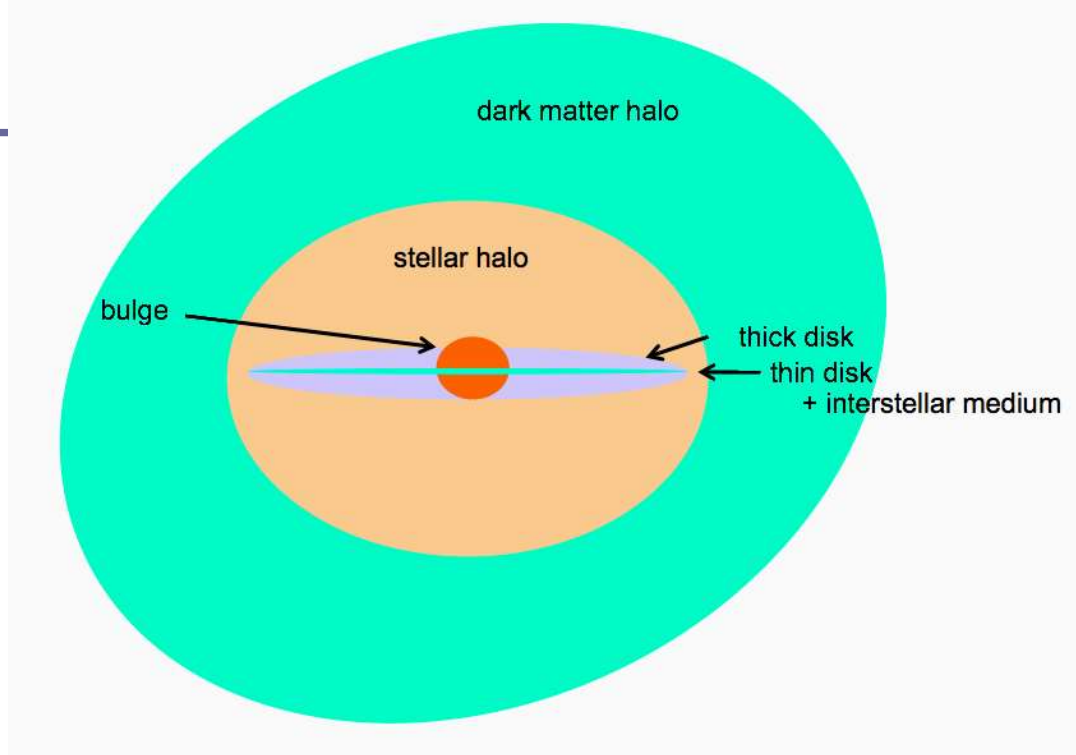
Lecture Notes

KIAS-SNU Physics2025

3. Dark Matter Study in Practice

When we say a galaxy



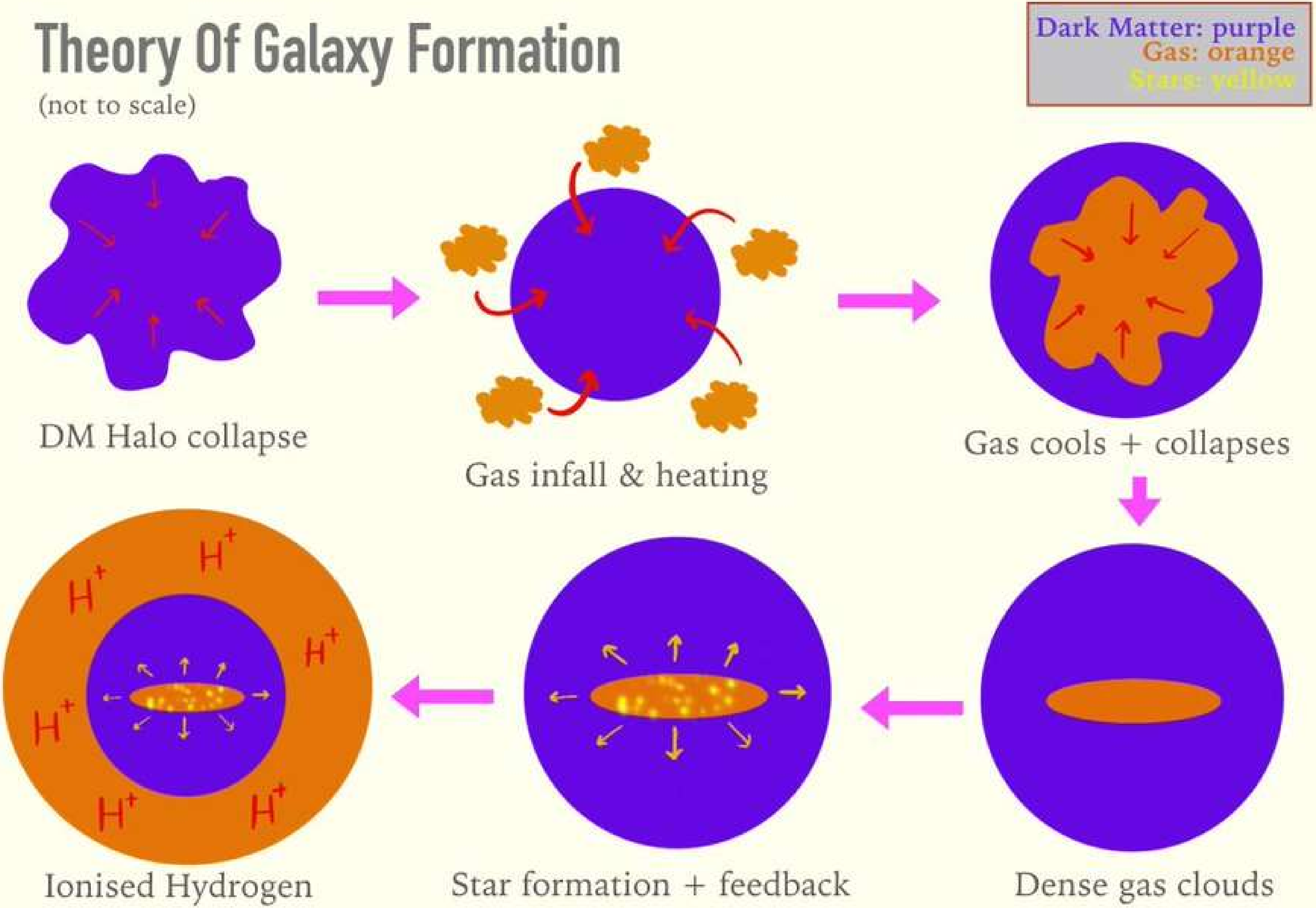


* In a galaxy (e.g. M_{total}(Milky Way)~1x10^{12} Msun)
  * Dark matter: ~94% (mass)
  * Stars: ~5%
  * Gas/dust: ~1%
  * Black hole: ~<0.1%

Q: How to understand the formation of galaxies along with dark matter halos?

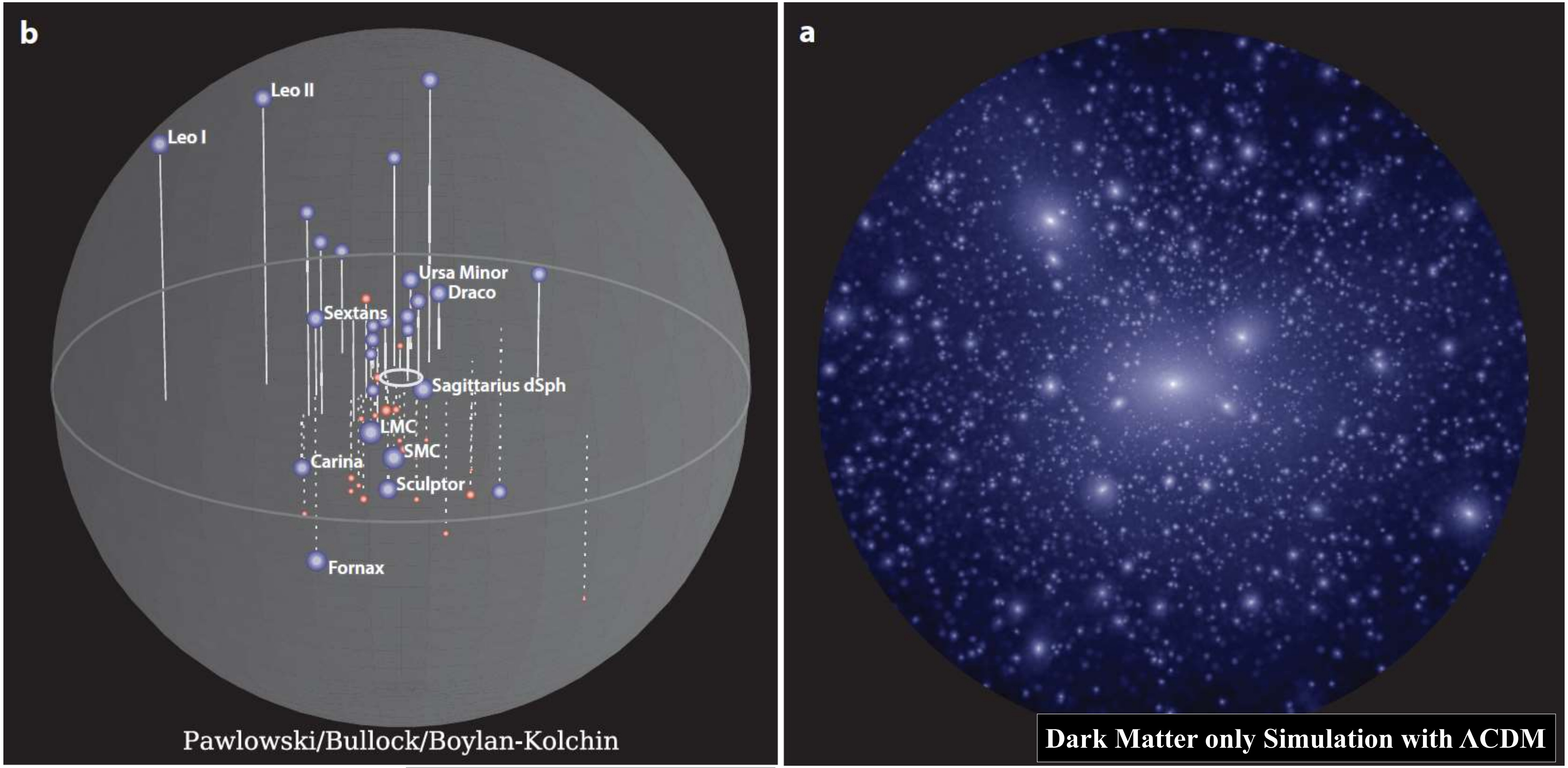
Theory Of Galaxy Formation

(not to scale)



Pratik Gandhi (@astrogandhi)

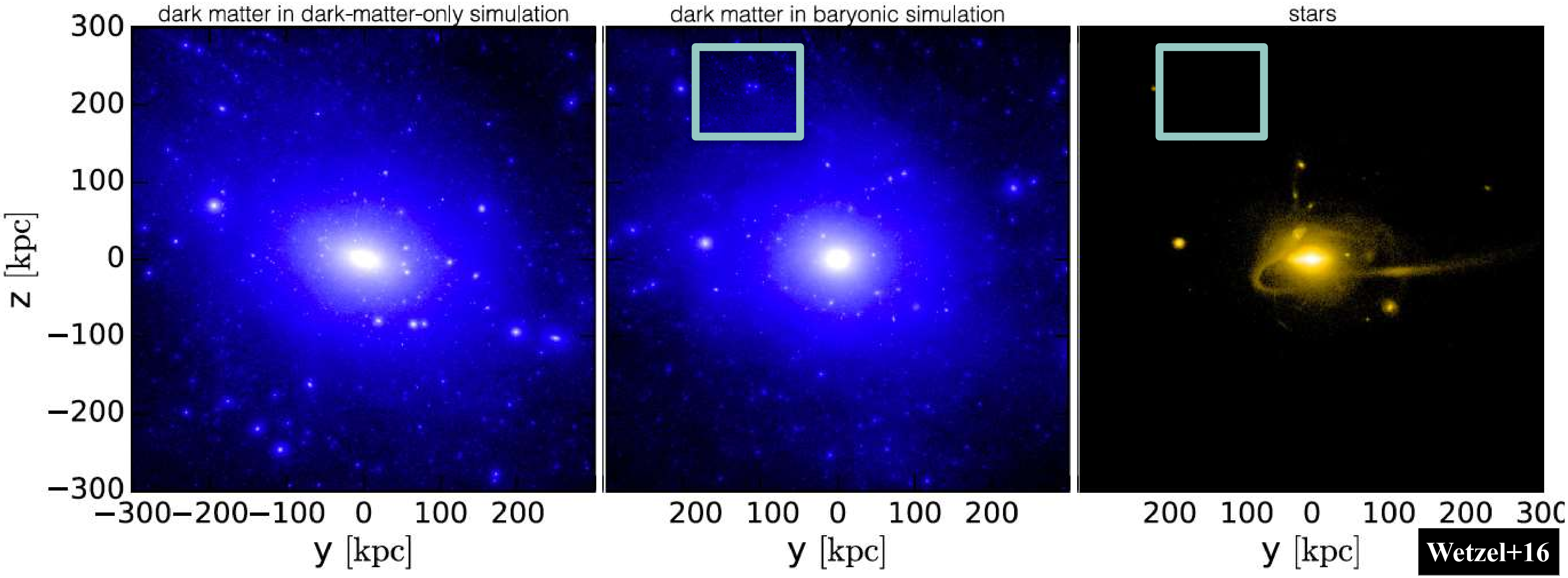
ΛCDM: Missing Satellite Problem



Bullock & Boylan-Kolchin 17

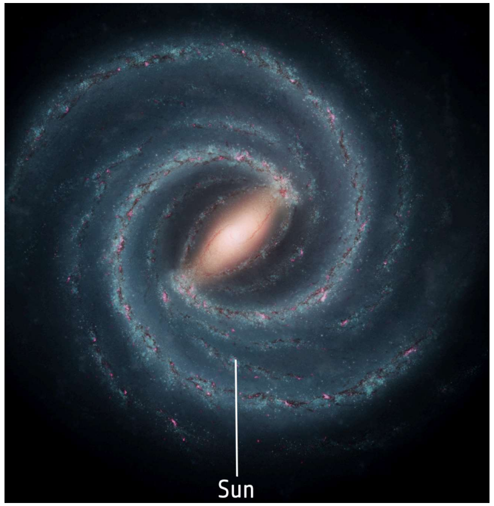
Q: Where are those satellite halos (i.e. galaxies)?

ΛCDM: Missing Satellite Problem - One Solution

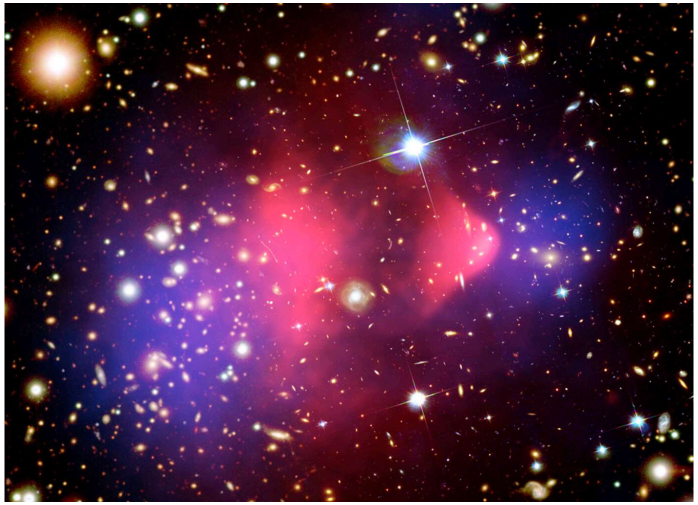


- **Implementation of Baryonic physics?**
  - **Latte Project (Wetzel+16; see also ParkC+18; Jung,KimJ+23): the Milky Way on Feedback in Realistic Environments (FIRE)**
    - **FIRE's stellar feedback generate dark-matter cores with reduced dynamical masses and the stellar velocity dispersions**
   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

=> This naturally predicts the existence of dark matter only objects! (i.e. 1) dark clumps in a galaxy, 2) dark galaxies)



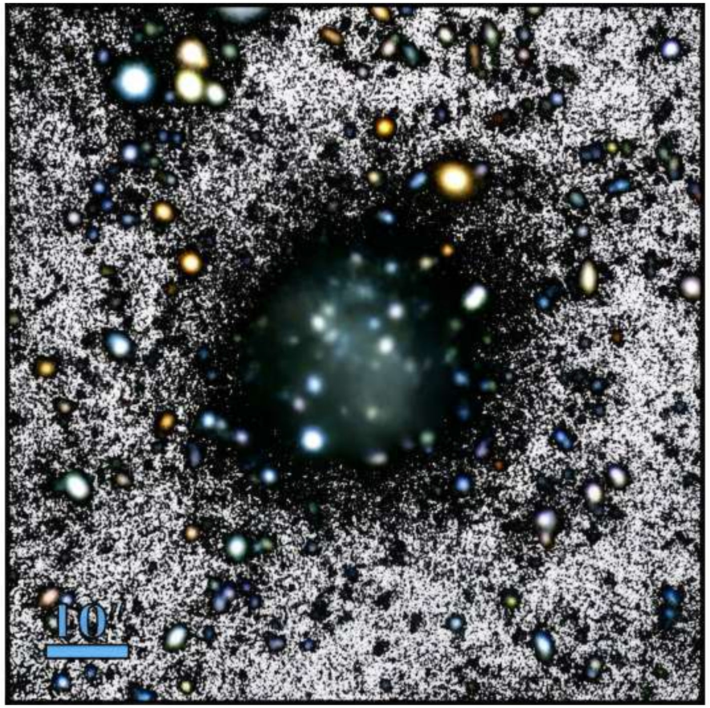
10^3 light years:
Dark Matter Density and its Map around the Sun



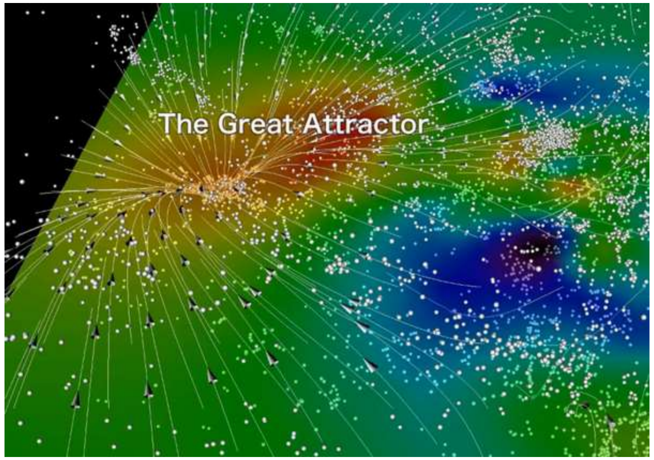
10^5 light years:
Dark Cores in Galaxy Clusters

Scales in Light Years
(1 light year ~ 9.46×10^{12} km)

10^4 light years:
Dark Galaxies

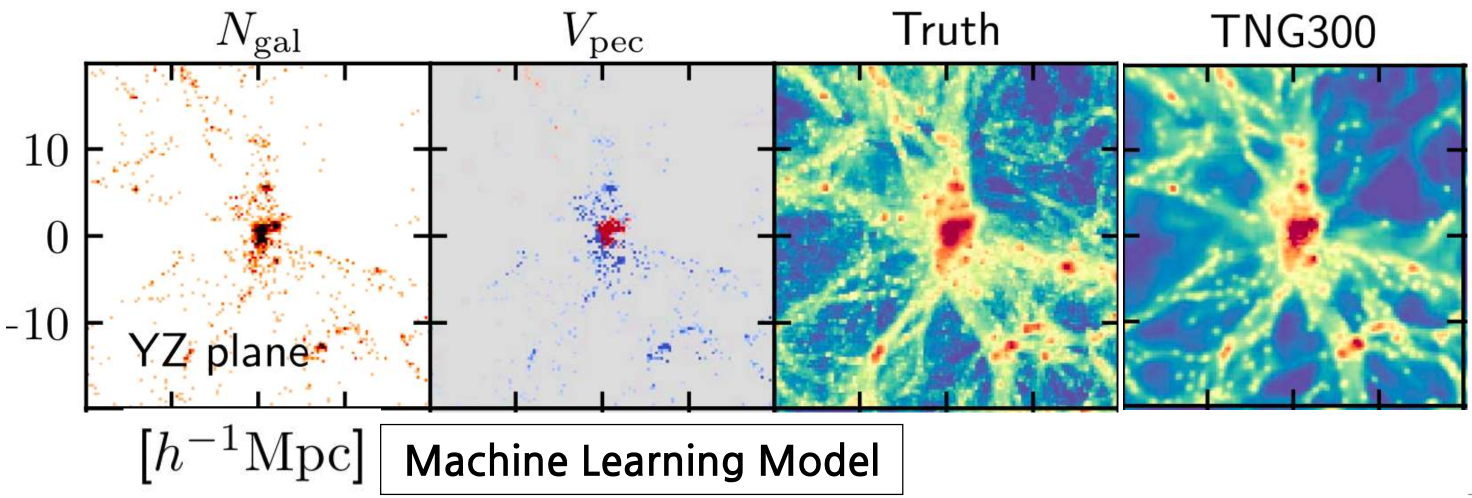


10^6 light years:
Dark Structures on cosmological scales

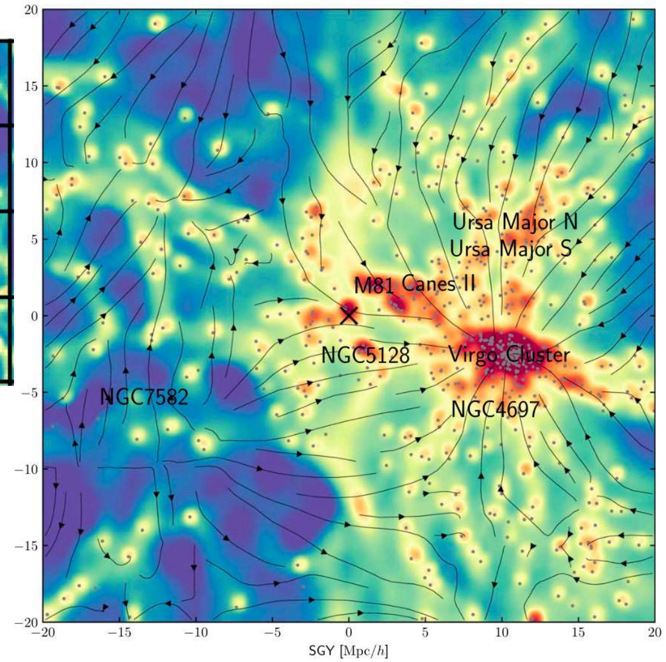


1) Dark Matter Density and its Map around the Sun (physical scale: ~10^3 light years or 10^{16} km)

- **We cannot directly observe dark matter, but infer from the kinematics of visible components (e.g. stars/galaxies): e.g. Hong+2021**



Machine Learning Model

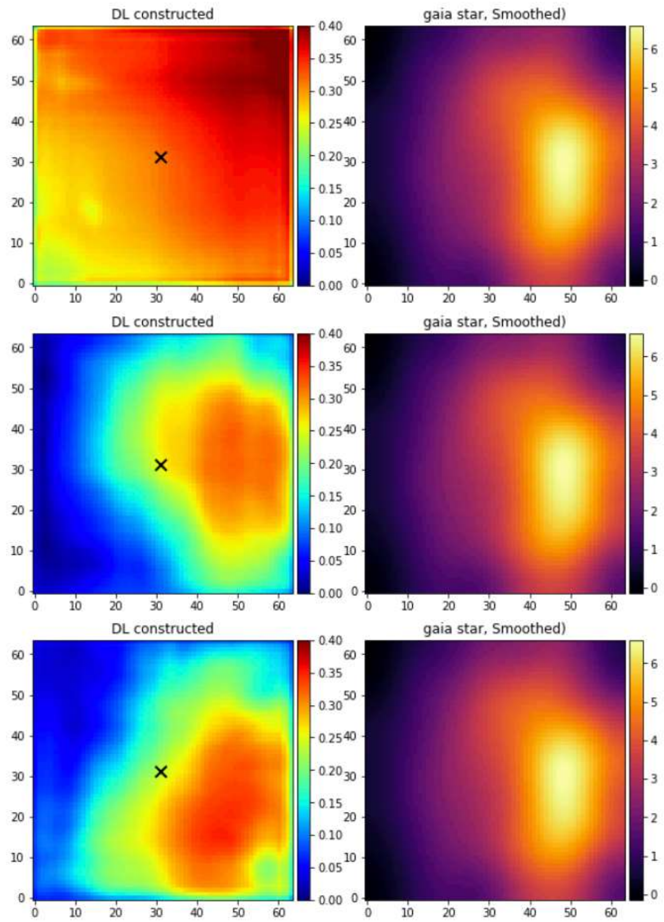


Application to Observational Data

- **We (with Prof. Donghui Jeong) plan to map the dark matter distribution from the position and velocity data of Galactic stars (i.e. GAIA)**
  1. **machine learning technique**
  2. **direct computation of acceleration from the time-series data**

1-1. Tracing stars in MW for dark matter

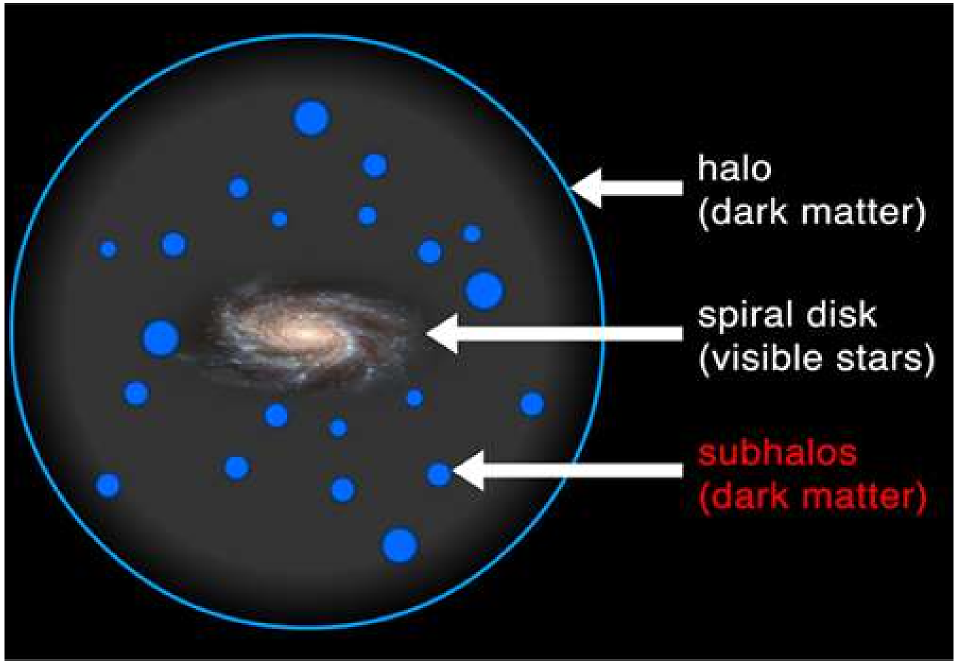
Machine predicted DM density in the Milky Way



PM + RV

Density + PM

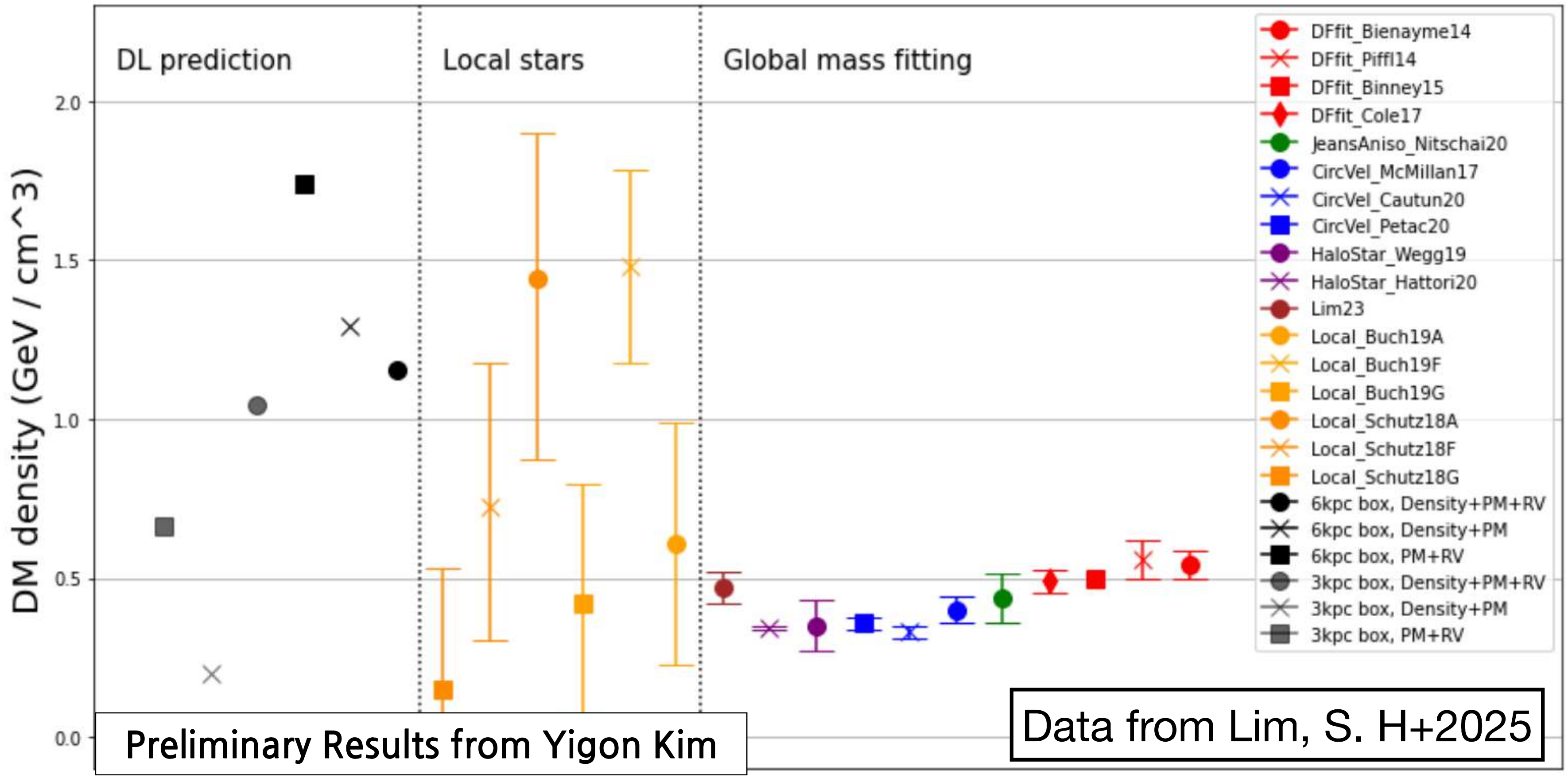
Density + PM + RV



Preliminary Results from Yigon Kim

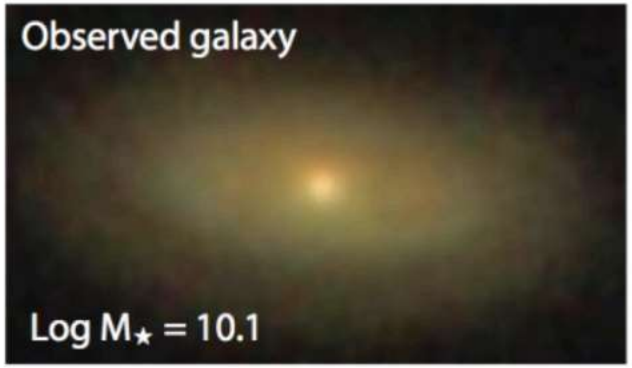
- Although there are many things to improve,
  - This demonstrates the possibility that we can map the dark matter distribution within the Milky Way.
  - By comparing this map with that of visible components (i.e. stars/gas), we can identify dark matter only clumps! – test of ΛCDM.

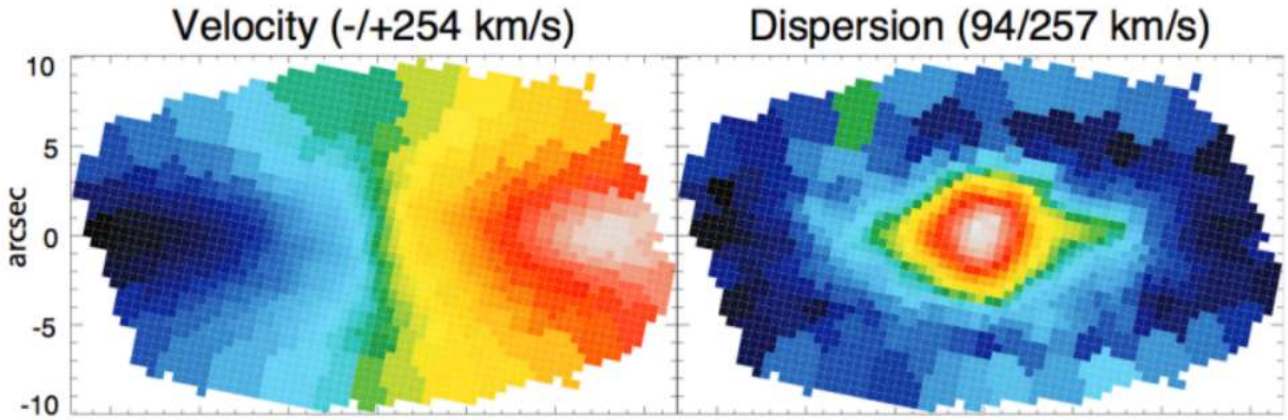
1-1. Tracing stars in MW for dark matter



➢ **We can provide independent constraints on the dark matter density around the Sun!**

2) Mapping the dark matter distribution in External Galaxies

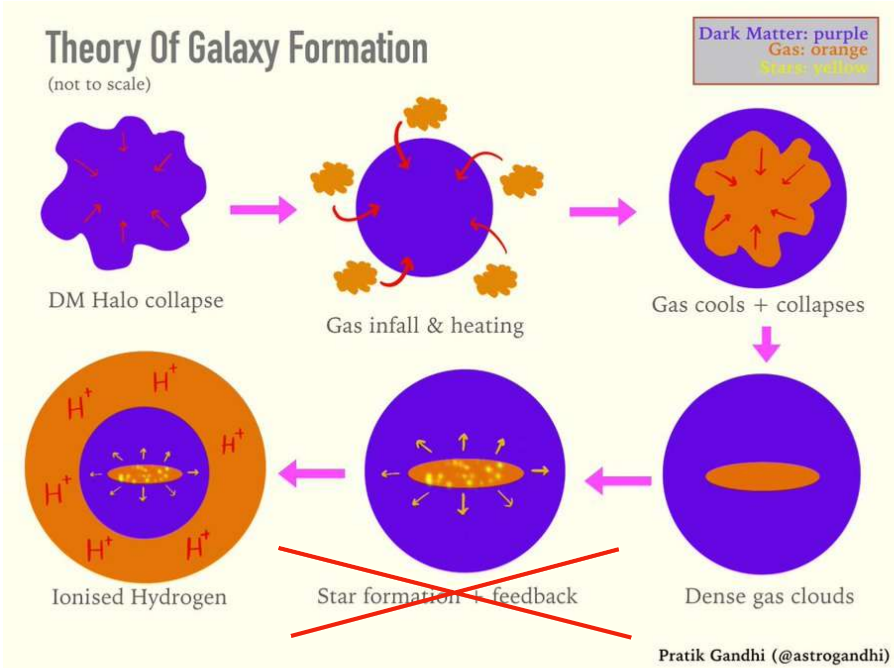




Dark Matter Distribution?

2) Dark Galaxies (physical scale: ~10^4 light years or 10^{17} km)

- **Dark galaxy:** objects with little or no stars, and believed to be made up almost entirely of dark matter.
- **The ΛCDM model naturally predicts the existence of dark galaxies.**



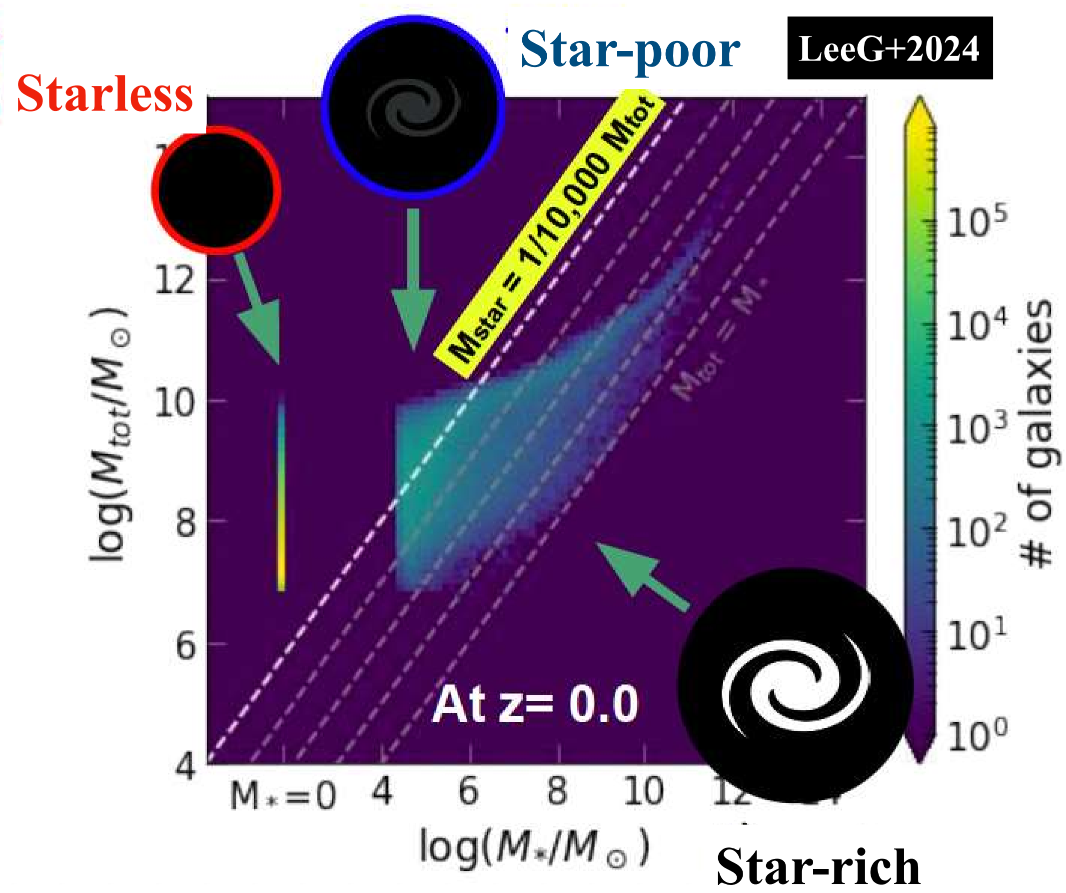
- **Detecting dark galaxies in normal, optical images is challenging because of their faintness.**
- **If they have a gas component, they could be detectable!**

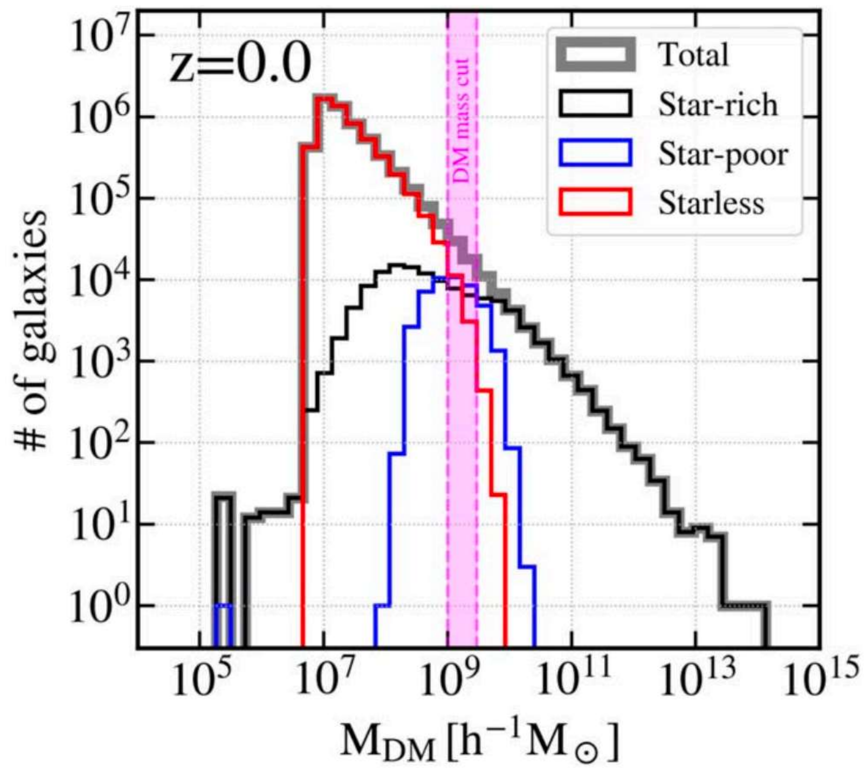
- **We would like to find dark galaxies in our real world**
  - **To examine whether the current galaxy formation scenario along with ΛCDM is correct or not.**

- **To have an idea where to search,**
  - **We will use cosmological hydrodynamic simulations first to identify them and to characterize their physical properties.**

Sample Selection from IllustrisTNG

Definitions for Normal / Dark Galaxies





- ➢ We found many dark (or starless) galaxies in simulations! (Details in LeeG+2024)
- ➢ We learned why they did not form stars: e.g. no cold gas for star formation.

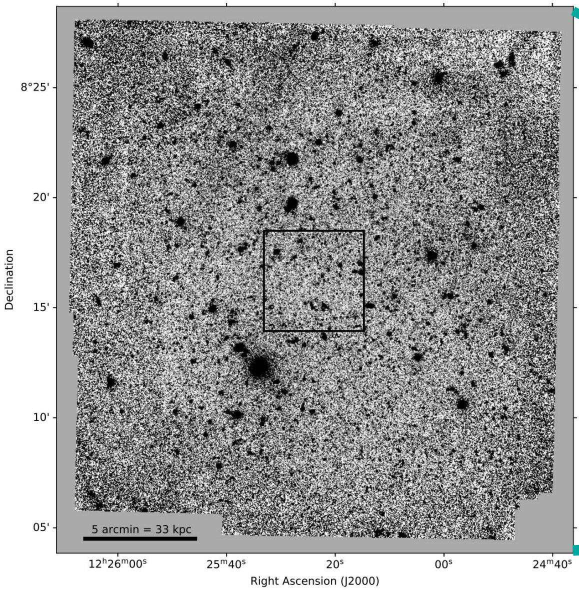
Q: How about in our real world?!

Dark Galaxy Search

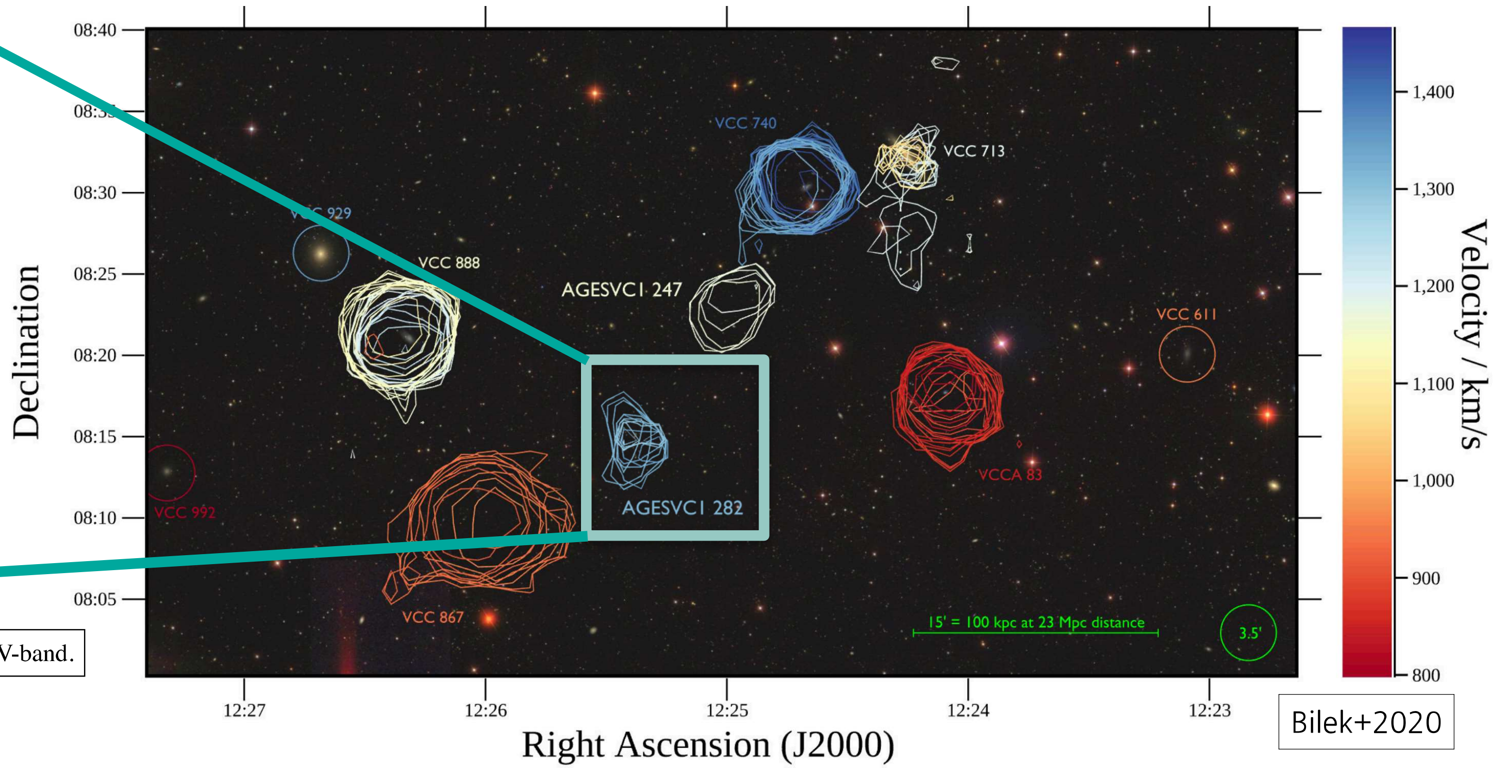
- ➢ The key is to find an extragalactic object with gas, but without stars!
- ➢ In astronomical term: HI sources without optical counterparts!

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)**
  - **There is no systematic search!**



Surface Brightness limit 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 - Parkes Telescope

My Fair Lady

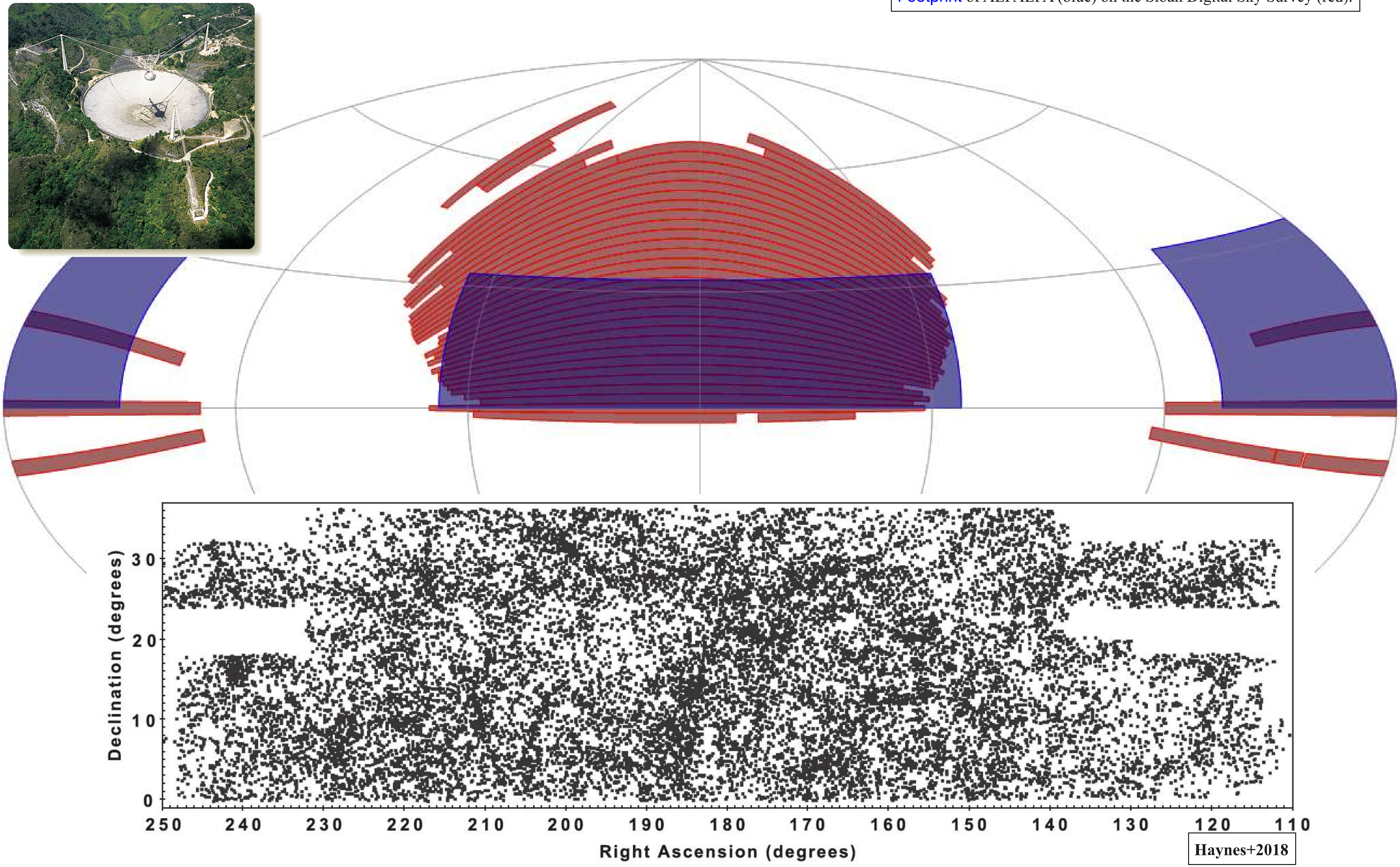
Official poster

Also known as	*Yojo Lady* *The Perfect Girl*
Genre	Romance, Drama
Starring	Kim Hee-sun Go Soo Park Han-byul Son Chang-min
Country of origin	South Korea

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

Arecibo 305m Radio Telescope at Pueto Rico

Dark Galaxy Search with Radio Telescope

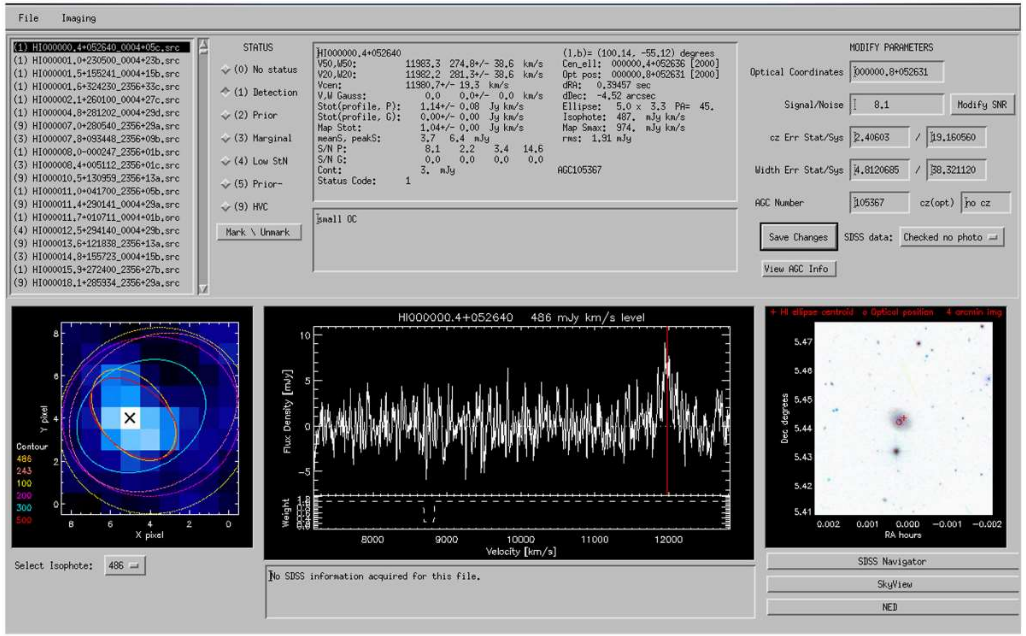


Figure 8. GalCat application GUI created in IDL. The catalog of ALFALFA sources is displayed as a list at top left. For each source selected from that list, a summar is presented in the interface, including the measured parameters (top center), the isophotal fits (bottom left), the extracted "postage stamp" spectrum and its normalize 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.

- ➢ **Haynes+2018**
  - ➢ **~31,500 HI sources with optical counterparts**
  - ➢ **~344 HI sources without optical counterparts!**
- ➢ **KwonM+2025**
  - ➢ **142 dark galaxy candidates!**

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Searching for Dark Galaxies with H I Detection from the Arecibo Legacy Fast ALFA (ALFALFA) Survey

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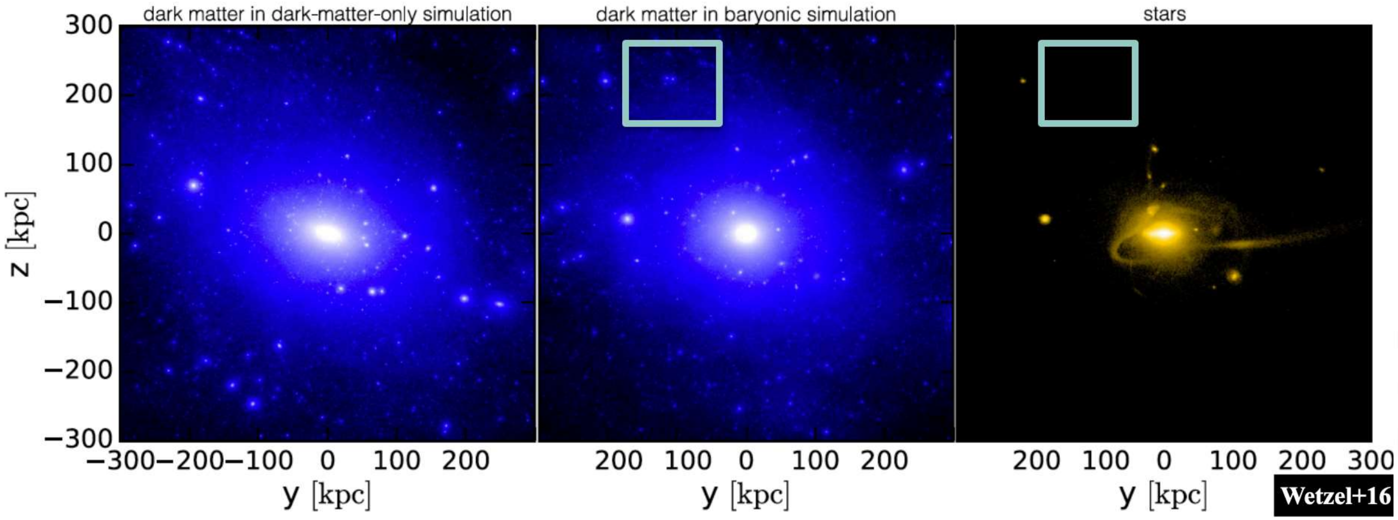
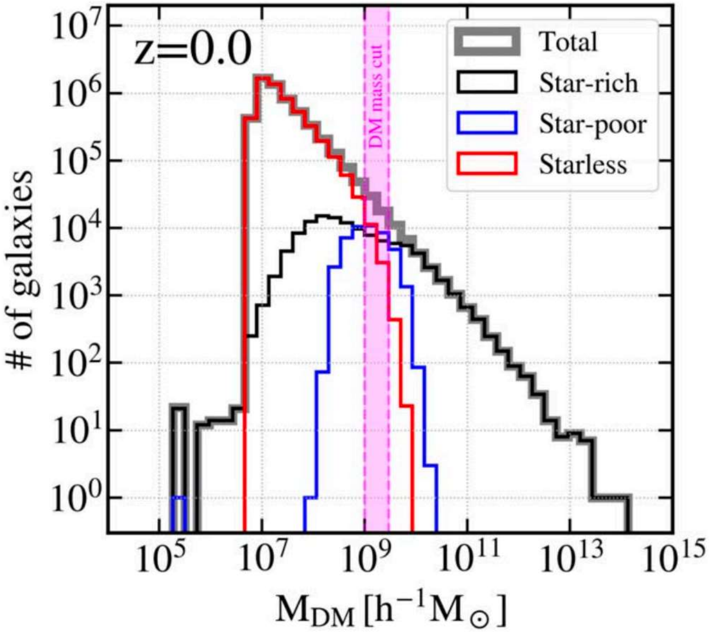
Abstract

We present a catalog of 142 dark galaxy candidates in a region covered by the Arecibo Legacy Fast ALFA (ALFALFA) survey. We start with 344 ALFALFA H I sources without optical counterparts and remove those that

ΛCDM: Missing Satellite Problem - One Solution





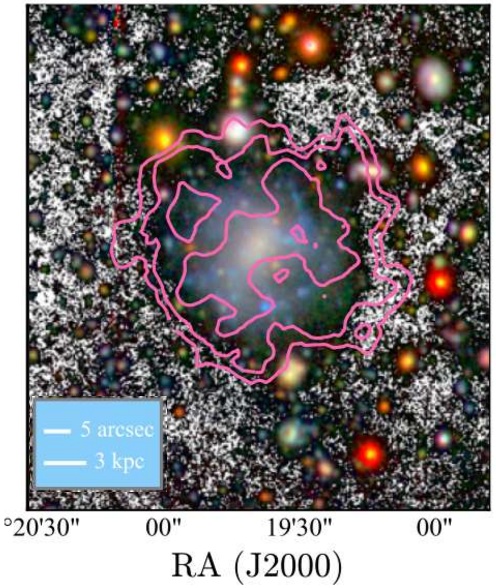
- **Implementation of Baryonic physics?**
  - **Latte Project (Wetzel+16; see also ParkC+18; Jung,KimJ+23): the Milky Way on Feedback in Realistic Environments (FIRE)**
    - **FIRE's stellar feedback generate dark-matter cores with reduced dynamical masses and the stellar velocity dispersions**
   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

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

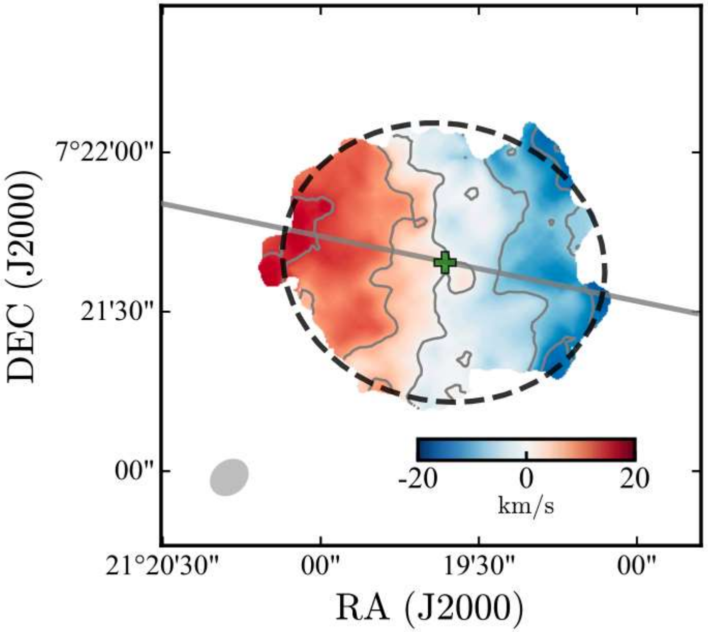
- ➢ **Our large sample of dark galaxy candidates confirms that the missing satellite problem of ΛCDM can be really understood!**
- ➢ **If we think about the number ratio of dark and luminous galaxies (i.e. >10:1), somethings are still strange.**

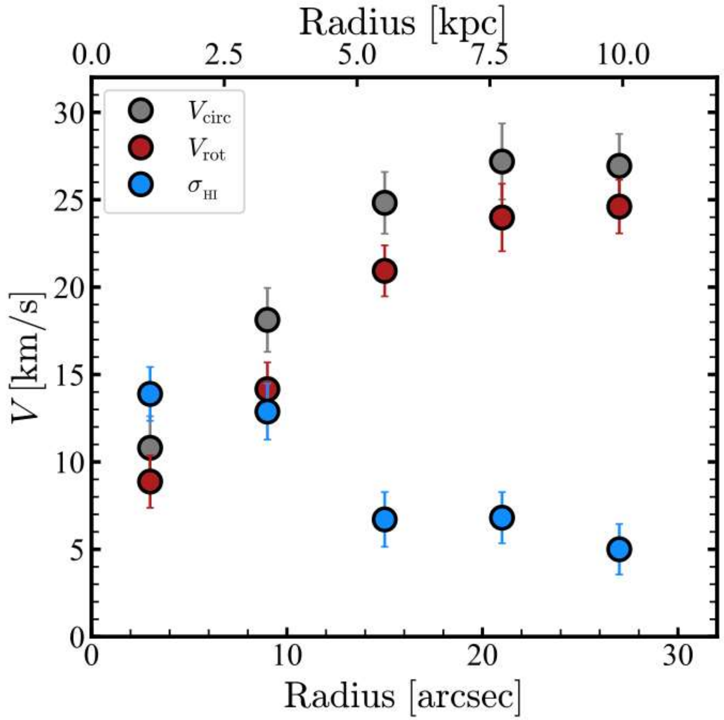
What can Dark Galaxies tell us about DM properties?

➢ **We can do dynamical modeling of rotation curves to test which dark matter model works best!**



AGC 114905 (even though it is not totally dark, Mancera Piña+2024)





$$V_{\rm circ}^2 \equiv R\frac{\partial \Phi}{\partial R}\Big|_{z=0} = V_{\rm rot}^2 + \frac{R}{\rho}\frac{\partial(\rho\,\sigma_{\rm HI}^2)}{\partial R}$$

$$V_{\rm circ}^2 = V_*^2 + V_{\rm gas}^2 + V_{\rm DM}^2$$

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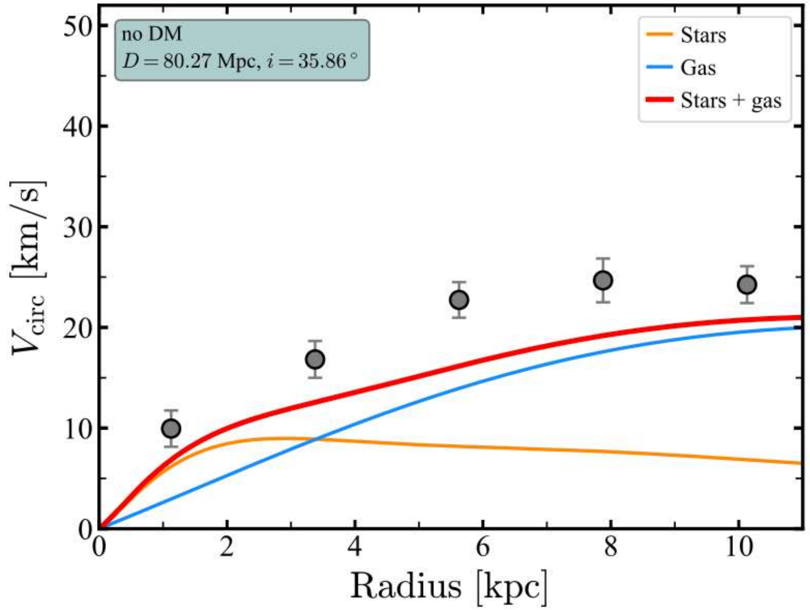
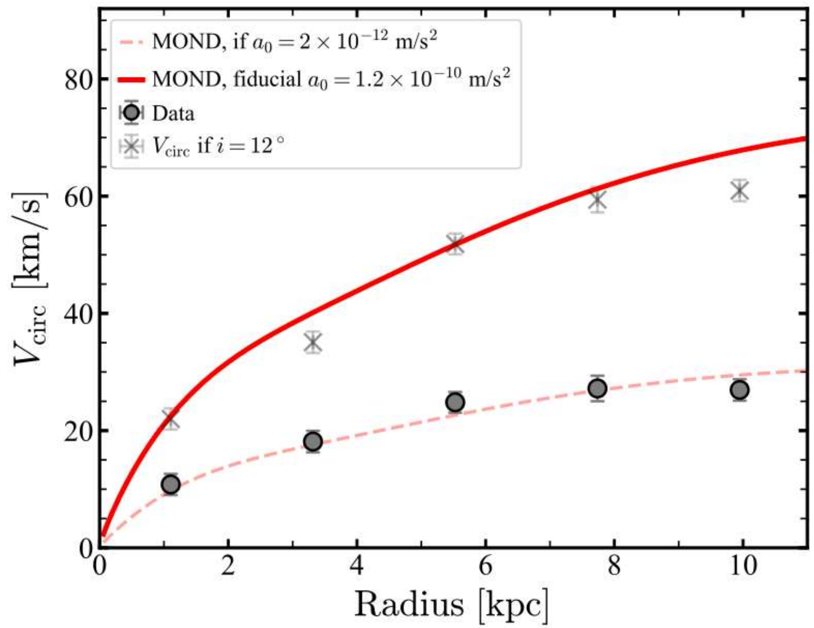


1.1 No Dark Matter: baryon only



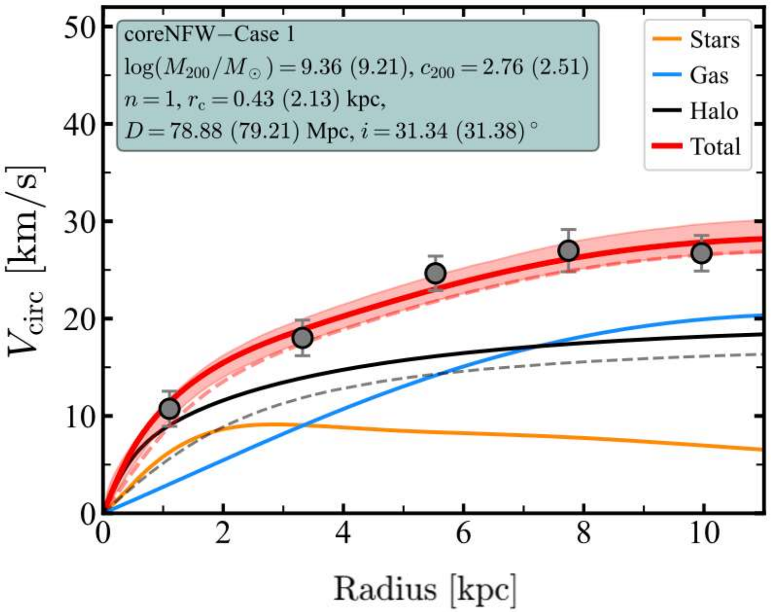
1.2 No Dark Matter: Modified Newtonian Dynamics (MOND)

$$V^2_{\rm MOND}(r) = V^2_{\rm bar} + \frac{V^2_{\rm bar}}{2}\left(\sqrt{1 + \frac{4\,a_0\,r}{V^2_{\rm bar}}} - 1\right)$$

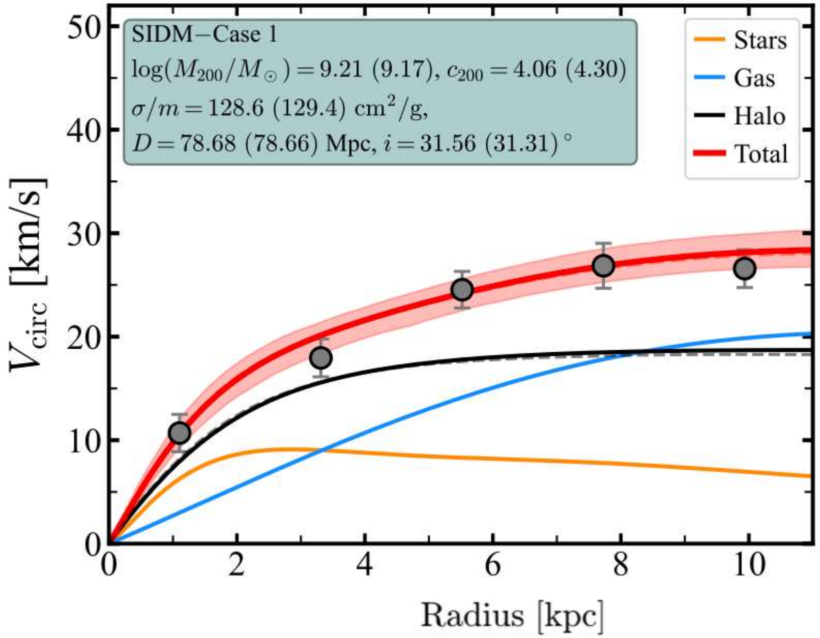
where $V^2_{\rm bar} = V^2_{\rm gas} + V^2_*$.

What can Dark Galaxies tell us about DM properties?

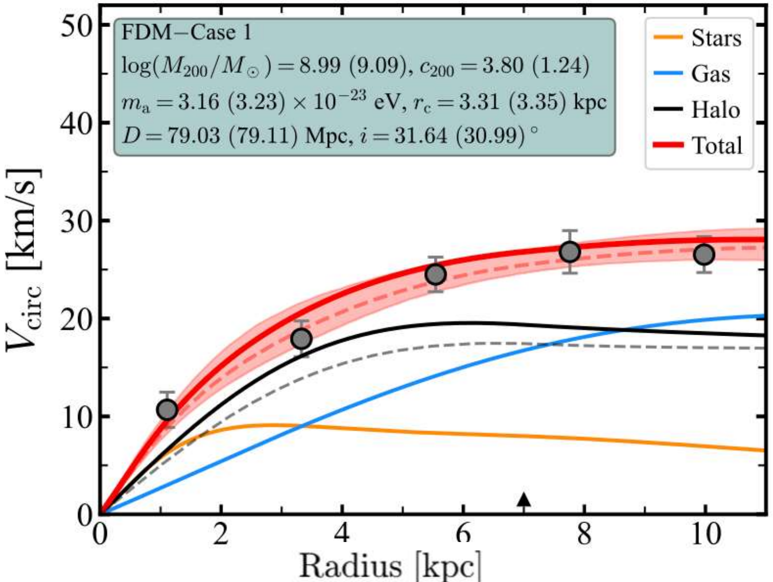
2. Cold Dark Matter



3. Self-Interacting Dark Matter



4. Fuzzy Dark Matter



What can Dark Galaxies tell us about DM properties?

Table 1. Structural properties of the fitted dark matter haloes.

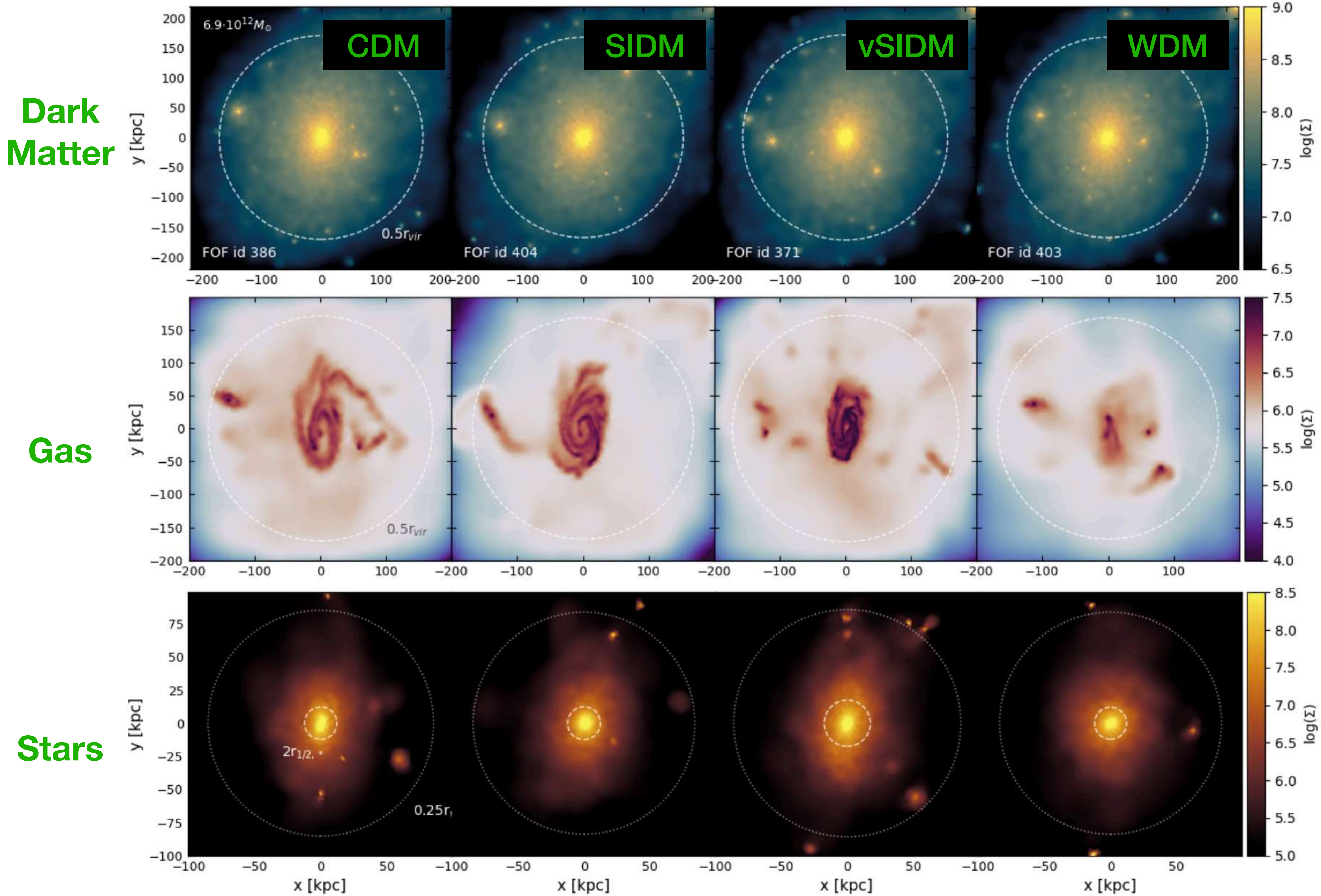
Halo	$\log(M_{200})$ [$\log(M_{\odot})$]	$\log(c_{200})$	$\log(M_{200})_{\rm MLE}$ [$\log(M_{\odot})$]	$\log(c_{200})_{\rm MLE}$	$V_{2\,\rm kpc}$ [km/s]	$V_{\rm max}$ [km/s]	$R_{\rm max}$ [kpc]	BIC
CDM, coreNFW, Case 1	$9.36^{+0.37}_{-0.31}$	$0.44^{+0.39}_{-0.27}$	9.21	0.40	$11.1^{+1.6}_{-1.6}$	$19.6^{+6.0}_{-3.5}$	$21.4^{+29.4}_{-11.8}$	$11.13^{+2.51}_{-1.05}$
CDM, coreNFW, Case 2	$10.06^{+0.13}_{0.07}$	$0.08^{+0.10}_{-0.06}$	9.99	0.02	$11.3^{+1.0}_{-0.8}$	$33.6^{+3.7}_{-2.0}$	$84.4^{+14.9}_{-18.2}$	$11.32^{+1.67}_{-0.53}$
CDM, DPL, Case 1 (*)	$9.24^{+0.35}_{-0.29}$	$0.57^{+0.15}_{-0.24}$	9.20	0.63	$6.8^{+3.4}_{-2.9}$	$13.0^{+4.4}_{-5.7}$	$13.7^{+20.5}_{-5.8}$	$12.99^{+3.17}_{-1.39}$
CDM, DPL, Case 2 (*)	$10.16^{+0.39}_{-0.15}$	$0.18^{+0.13}_{-0.12}$	10.03	0.19	$4.3^{+1.5}_{-1.1}$	$19.9^{+8.8}_{-5.2}$	$71.5^{+40.0}_{-24.5}$	$17.20^{+4.38}_{-3.48}$
SIDM, Case 1	$9.21^{+0.25}_{-0.22}$	$0.61^{+0.16}_{-0.19}$	9.17	0.63	$12.0^{+2.2}_{-2.4}$	$19.0^{+3.5}_{-2.7}$	$11.1^{+10.2}_{-4.5}$	$9.81^{+2.97}_{-1.41}$
SIDM, Case 2	$10.08^{+0.21}_{-0.09}$	$0.17^{+0.14}_{-0.11}$	10.01	0.10	$7.5^{+1.4}_{-0.9}$	$35.1^{+6.7}_{-2.5}$	$65.6^{+26.4}_{-21.9}$	$17.50^{+2.44}_{-1.49}$
FDM, Case 1	$8.99^{+0.41}_{-0.57}$	$0.58^{0.60}_{-0.42}$	9.09	0.09	$9.7^{+2.8}_{-2.1}$	$18.8^{+2.6}_{-2.2}$	$7.0^{+10.9}_{-1.8}$	$16.26^{+2.03}_{-1.37}$
FDM, Case 2	$10.04^{+0.11}_{-0.06}$	$0.08^{+0.10}_{-0.06}$	9.99	0.02	$9.1^{+2.1}_{1.5}$	$33.3^{+3.0}_{-1.7}$	$84.1^{+12.8}_{-18.6}$	$18.95^{+1.70}_{-1.08}$

- **"No DM models" do not fit well.**
- **CMD model can fit with parameters rarely seen in cosmological simulations: e.g. 4x higher baryon fraction.**
- **SIDM/FDM can fit well.**
- **A larger sample of galaxies with less baryon contamination is necessary! (Our sample)**
- **We also need to develop more methods/parameter spaces to test dark matter models.**

What can Dark Galaxies tell us about DM properties?

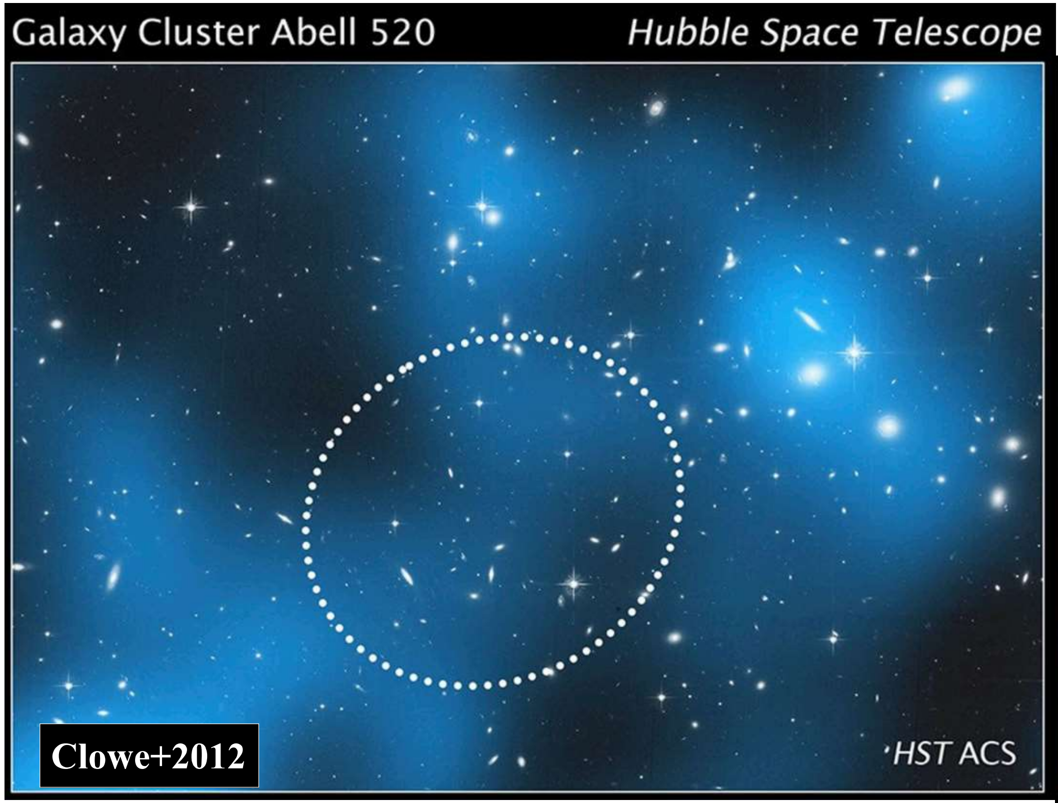
The AIDA-TNG project

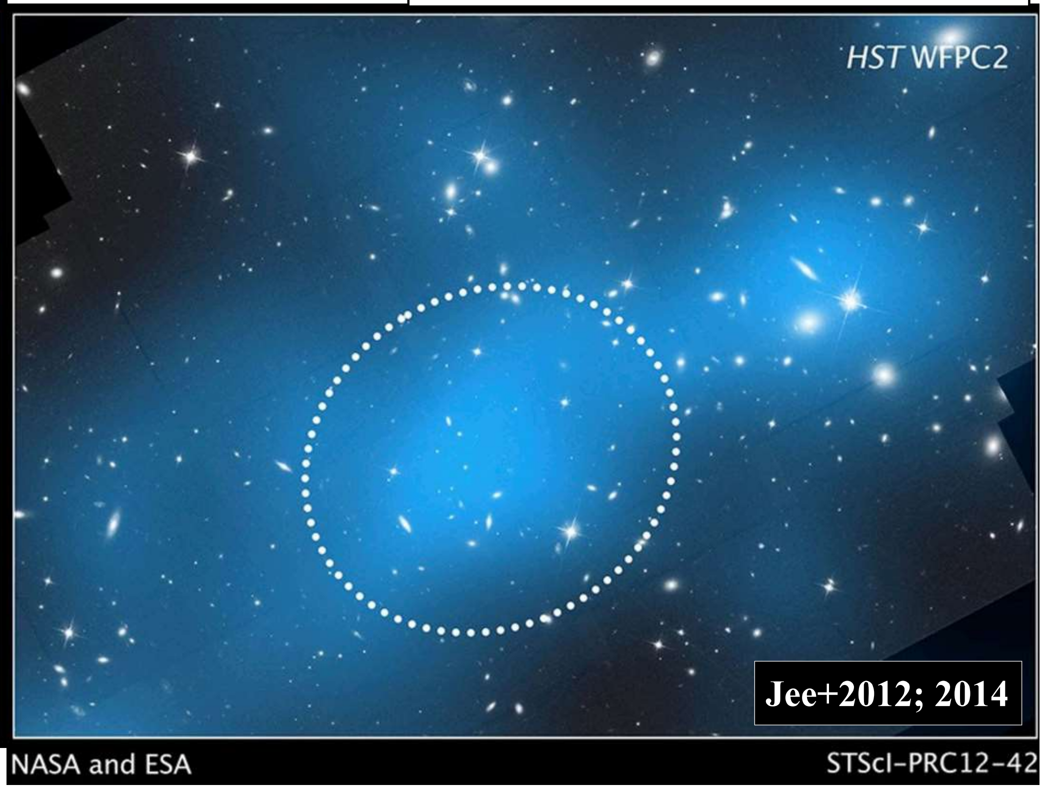
galaxy formation in alternative dark matter models



3) Dark Cores in Galaxy Clusters (physical scale: ~10^5 light years or 10^{18} km)

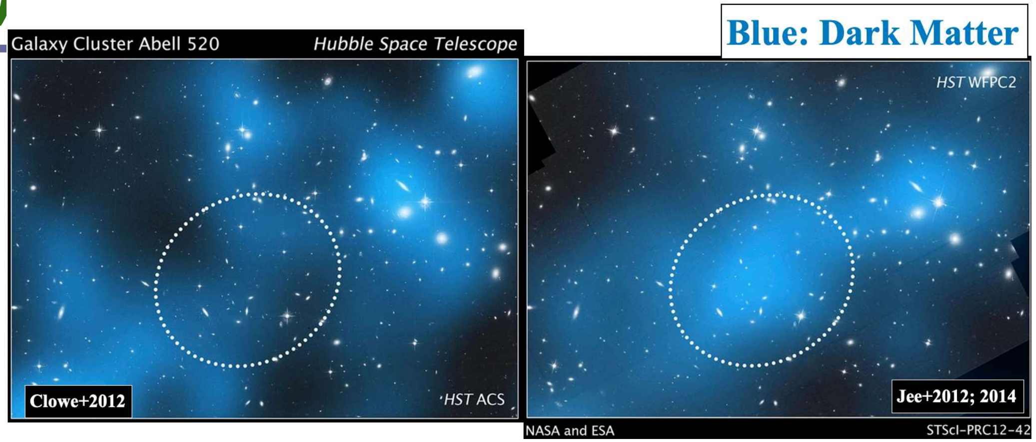
Blue: Dark Matter





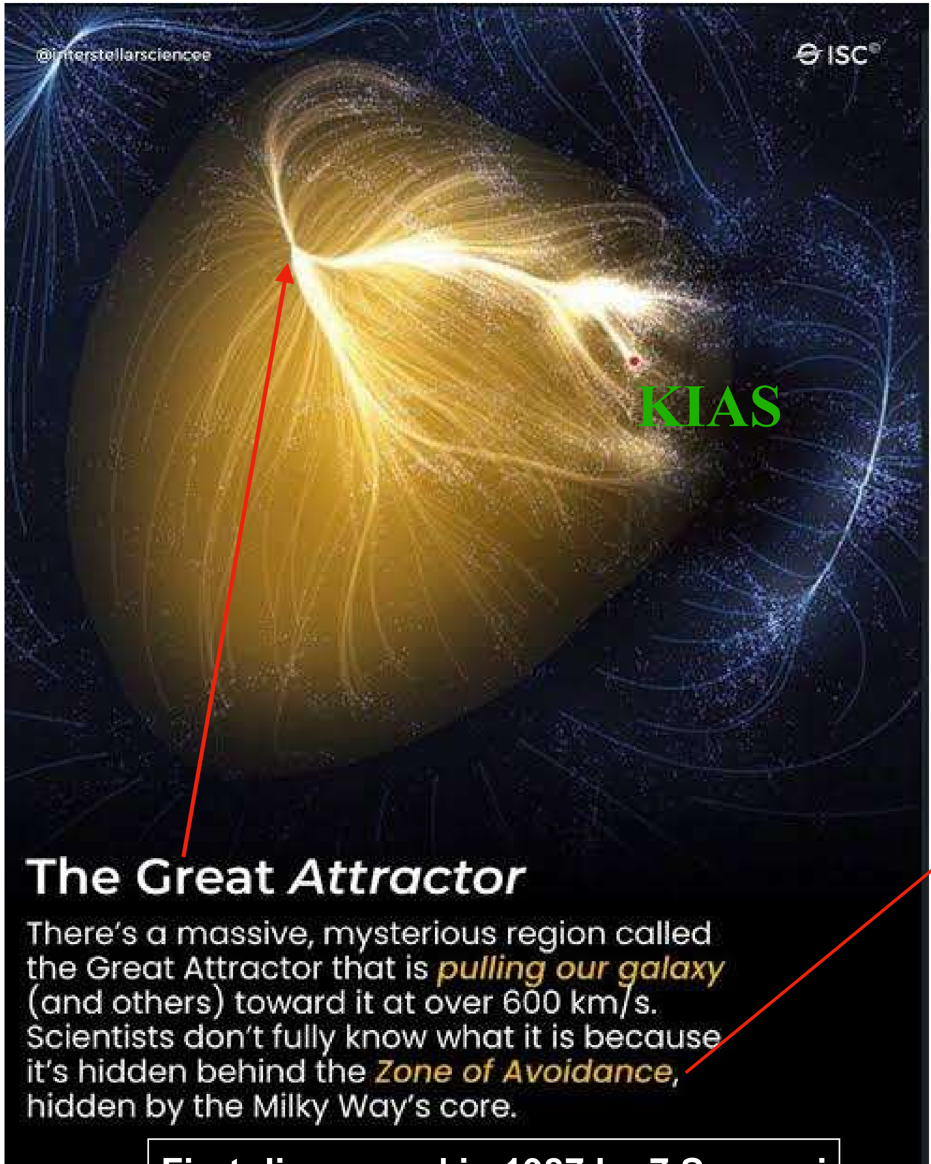
- ➢ Jee+2012 claimed to find a "Dark Core" with few galaxies using HST/WFPC2 (Right panel)
- ➢ Clowe+2012 could not find such a core with HST/ACS data (Left panel)
- ➢ Jee+2014 analyzed the same HST/ACS data, and found again the dark core!
- ➢ **No independent examination of this dark mass has been conducted!**

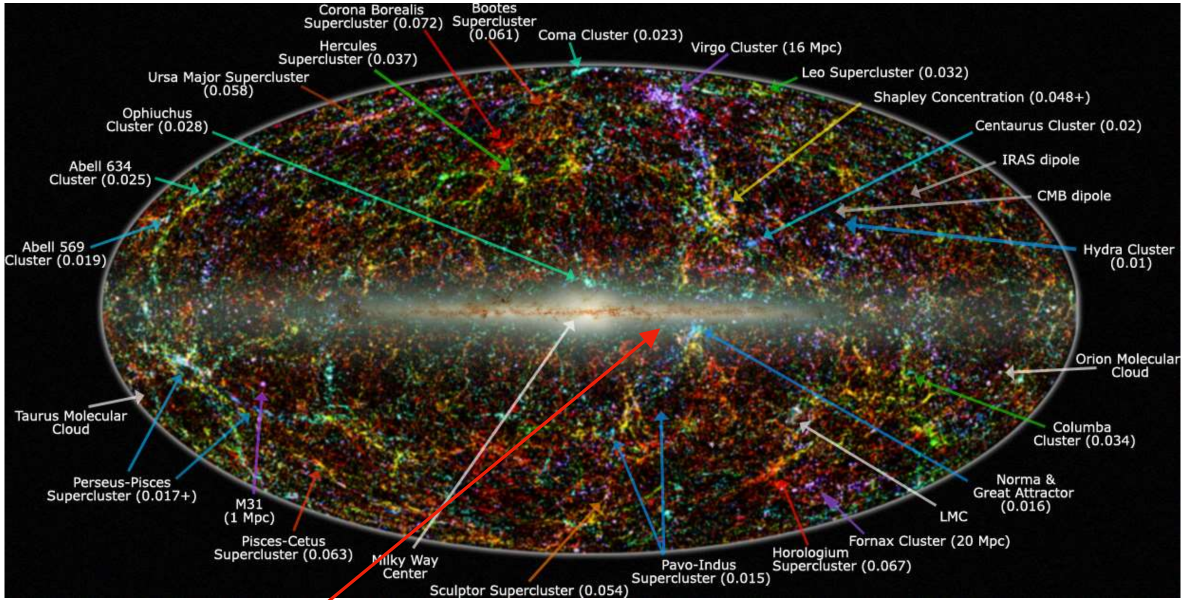
3) Dark Cores in Galaxy Clusters (physical scale: ~10^5 light years or 10^{18} km)



- **Our plan to reveal the nature of this core:**
  - **Spectroscopic observations of galaxies in this region**
    - **Selection of cluster galaxies with similar radial velocities**
    - **Estimation of velocity dispersion for independent measure of core mass ; compare with the lensing measurement**
- **Search for such cores through the comparison of lensing and galaxy surveys for further application.**

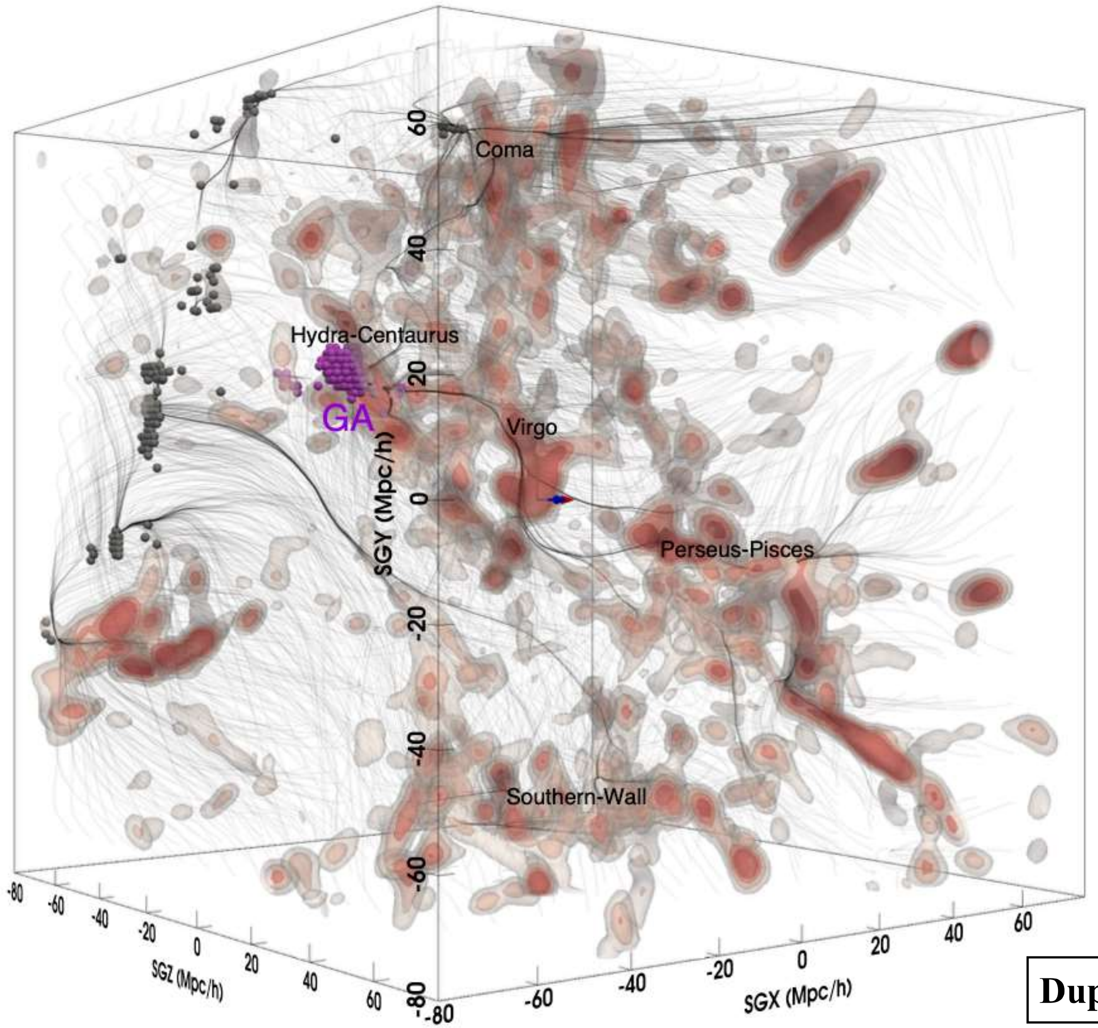
4) Dark Structures on cosmological scales (physical scale: ~10^6 light years or 10^{19} km)





First discovered in 1987 by 7 Samurai (Dressler+1987; Lynden-Bell+1988)

4) Dark Structures on cosmological scales (physical scale: ~10^6 light years or 10^{19} km)

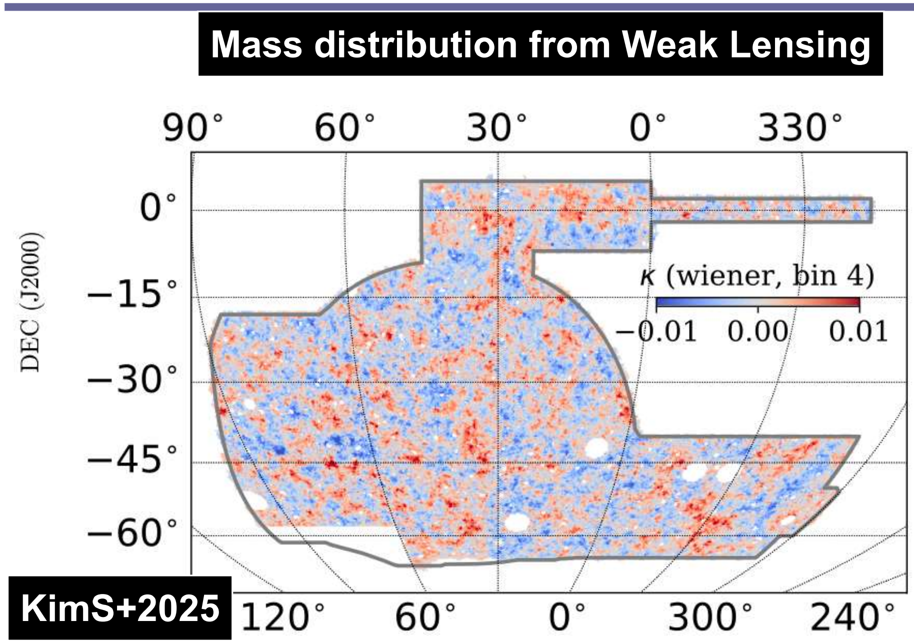


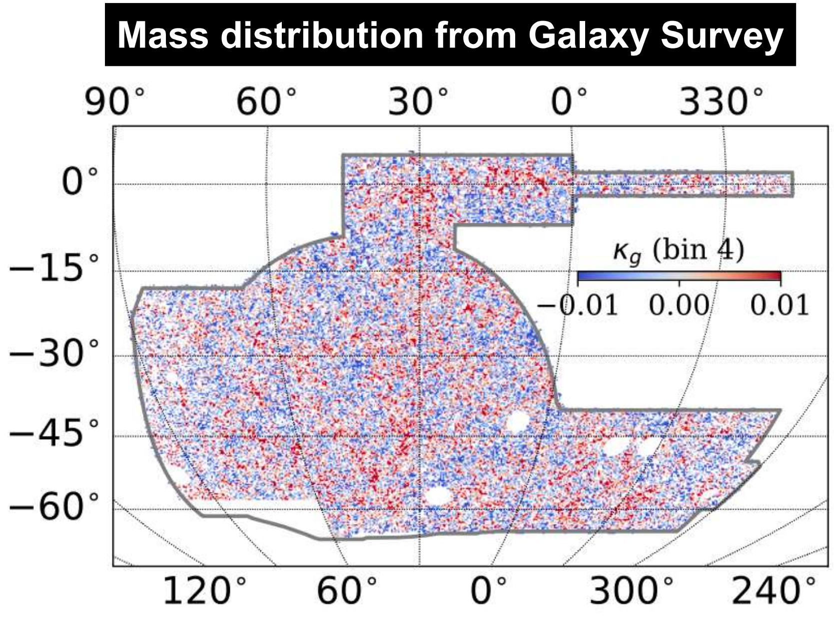
Dupoy+2025

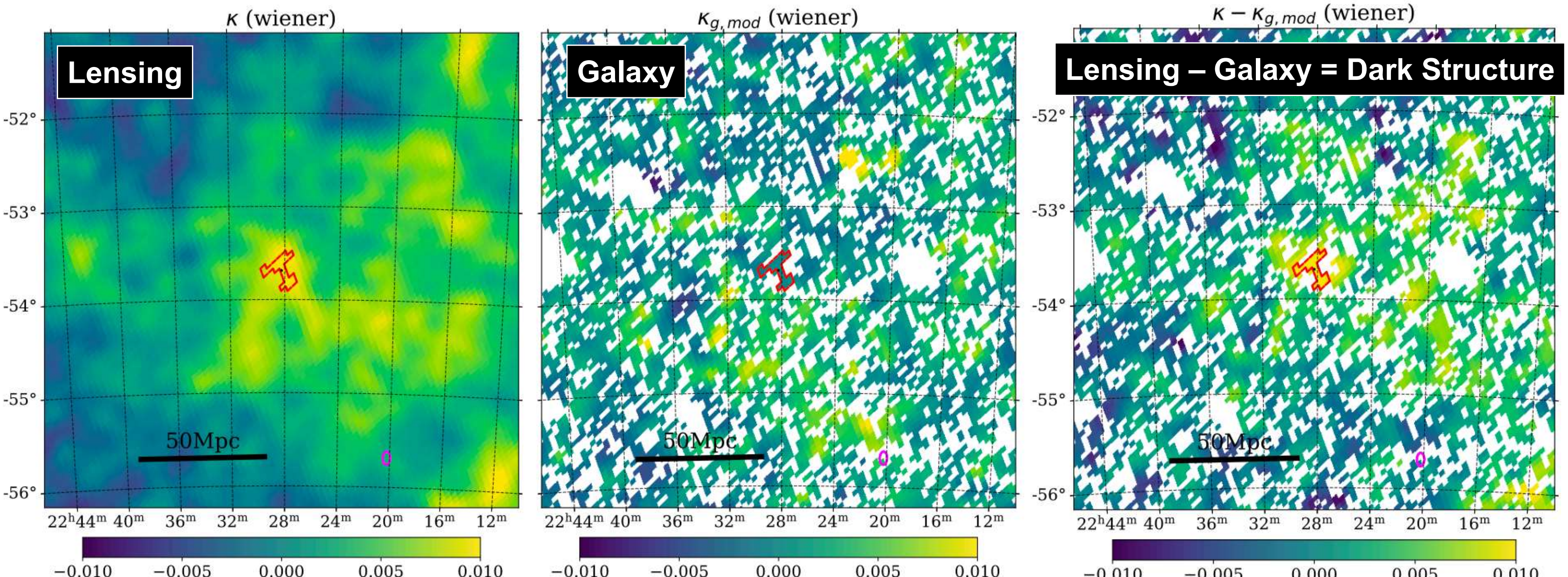
Q1: Why is not the number of galaxies in the Great Attractor high?

Q2: Are there any other such dark structures?

4) Dark Structures on cosmological scales (physical scale: ~10^6 light years or 10^{19} km)







4) Dark Structures on cosmological scales (physical scale: ~10^6 light years or 10^{19} km)

Draft version June 5, 2025
Typeset using LaTeX **twocolumn** style in AASTeX631

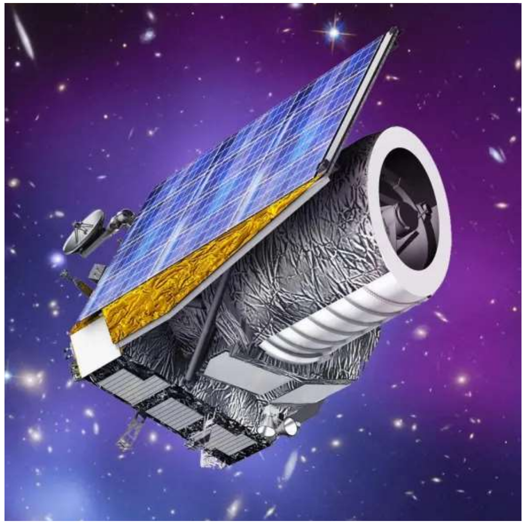
Searching for Dark Structures: A Comparison of Weak Lensing Convergence Maps and Lensing-Weighted Galaxy Density Maps

Soojin Kim[1], Ho Seong Hwang[1,2,3] and Niall Jeffrey[4]

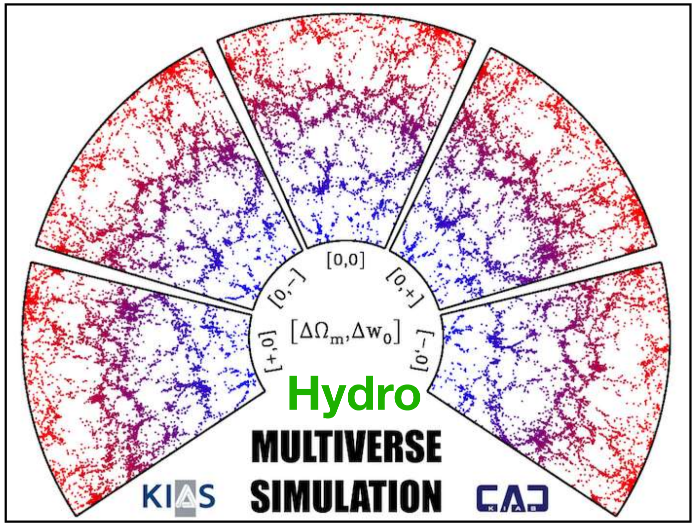
[1] *Astronomy Program, Department of Physics and Astronomy, Seoul National University, 1 Gwanak-ro, Gwanak-gu, Seoul 08826, Republic of Korea*
[2] *SNU Astronomy Research Center, Seoul National University, 1 Gwanak-ro, Gwanak-gu, Seoul 08826, Republic of Korea*
[3] *Australian Astronomical Optics - Macquarie University, 105 Delhi Road, North Ryde, NSW 2113, Australia*
[4] *Department of Physics and Astronomy, University College London, Gower Street, London WC1E 6BT, UK*

➢ **We have developed a novel method to find such structures using weak-lensing and galaxy survey data (KimS+2025).**

- ➢ **We plan to extend this analysis to recent, improved data**

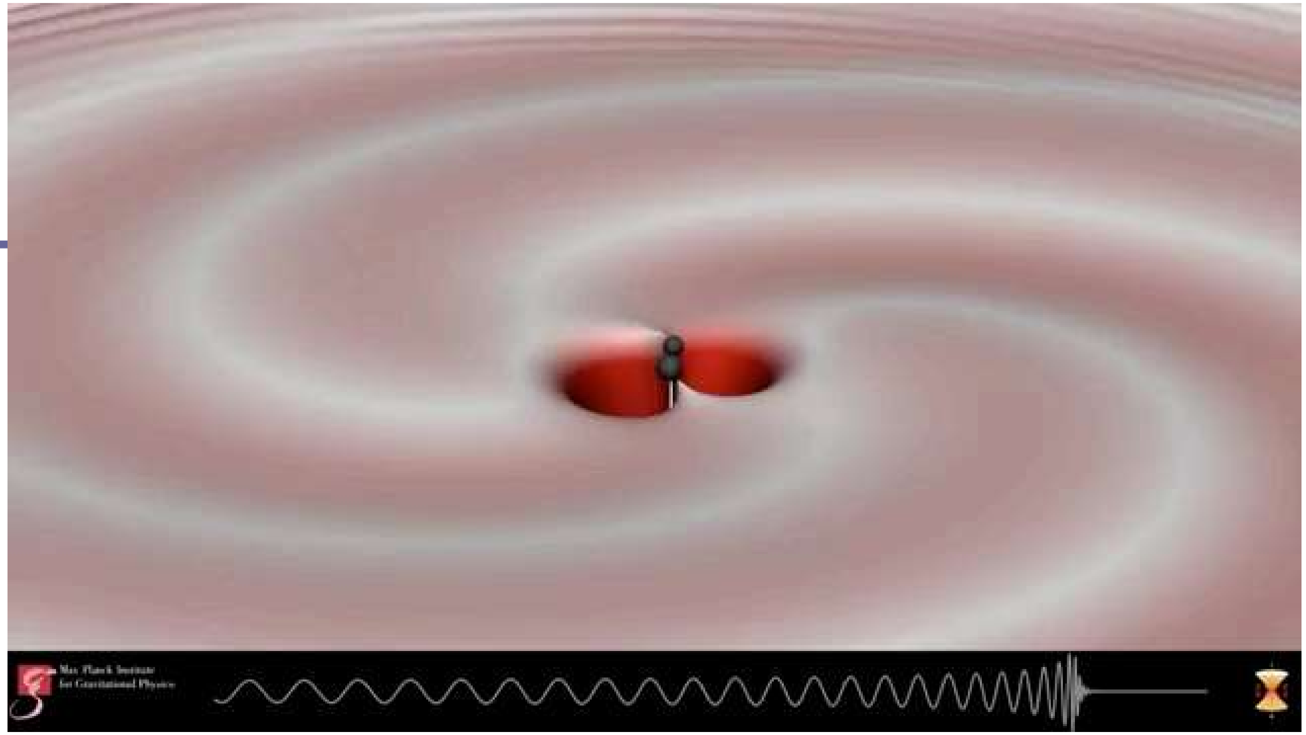


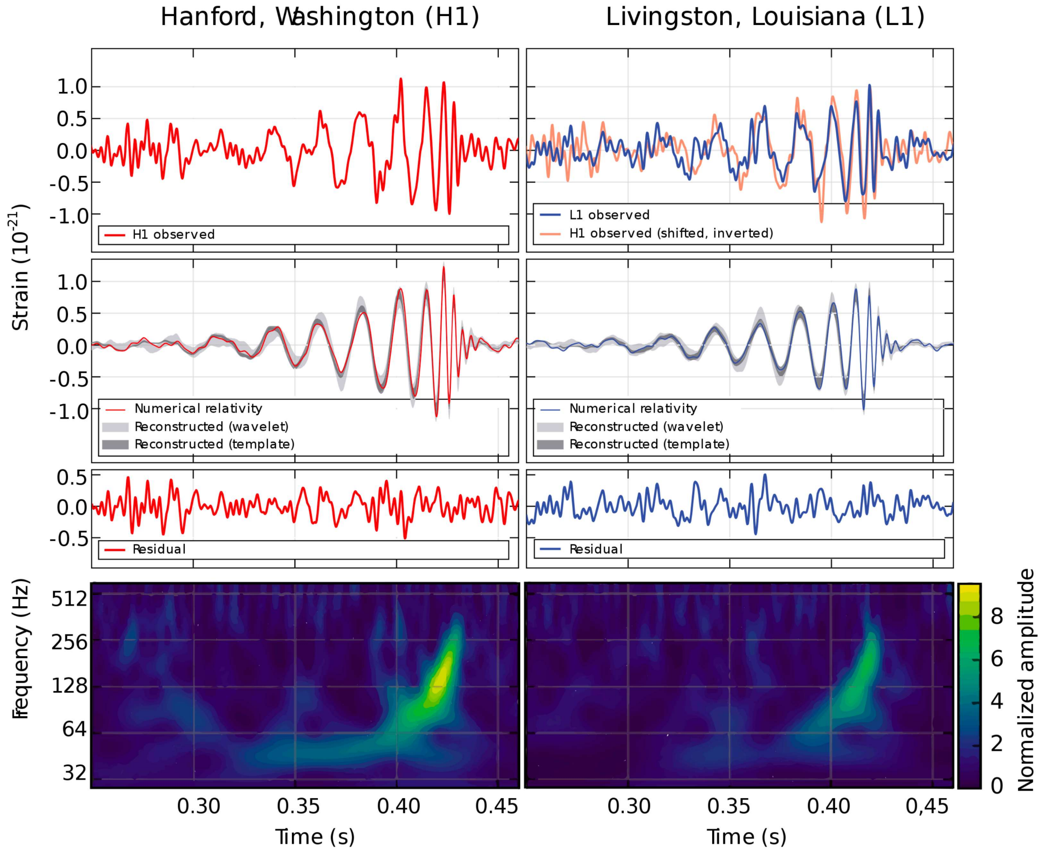
VERA C. RUBIN OBSERVATORY



February 11 in 2016

Beyond the EM Wave Observations





LIGO Scientific Collaboration and Virgo Collaboration (2016)

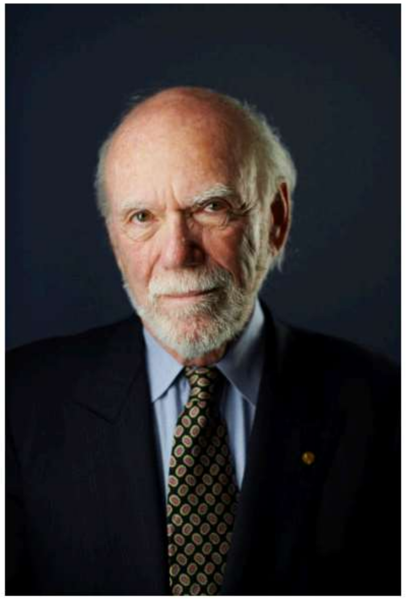
노벨물리학상: 천문학 분야 #9

The Nobel Prize in Physics 2017

© Nobel Media AB. Photo: A. Mahmoud

Rainer Weiss

Prize share: 1/2



© Nobel Media AB. Photo: A.Mahmoud

Barry C. Barish

Prize share: 1/4

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Kip S. Thorne

Prize share: 1/4

The Nobel Prize in Physics 2017 was divided, one half awarded to Rainer Weiss, the other half jointly to Barry C. Barish and Kip S. Thorne "for decisive contributions to the LIGO detector and the observation of gravitational waves."

➢ **바이스, 배리시, & 손:**
라이고 검출기를 이용한 중력파 검출에 기여

Beyond the EM Wave Observations

KOREAN GRAVITATIONAL WAVE GROUP

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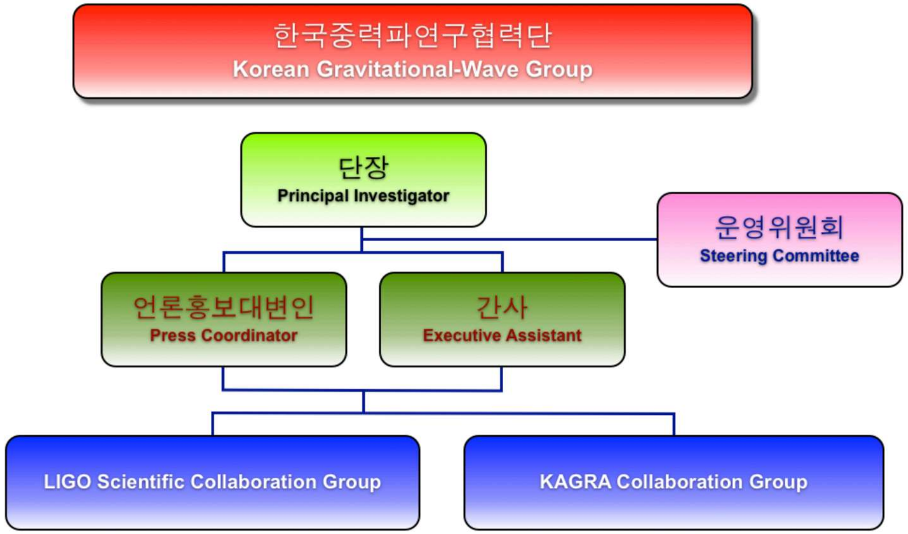


한국중력파연구협력단

- 단장: 이형목 (서울대학교)
- 언론홍보대변인: 강궁원(한국과학기술정보연구원)
- 총무간사: 오정근(국가수리과학연구소)
- 운영위원회: 이형목(서울대학교), 강궁원(한국과학기술정보연구원), 오정근(국가수리과학연구소), 이현규(한양대학교), 이창환(부산대학교), 윤태현(고려대학교), 이형원(인제대학교), 오상훈(국가수리과학연구소), 조규만(서강대학교)
- LIGO Scientific Collaboration

Data Analysis Group 연구책임자: 이형목(서울대학교)

- KAGRA Collaboration

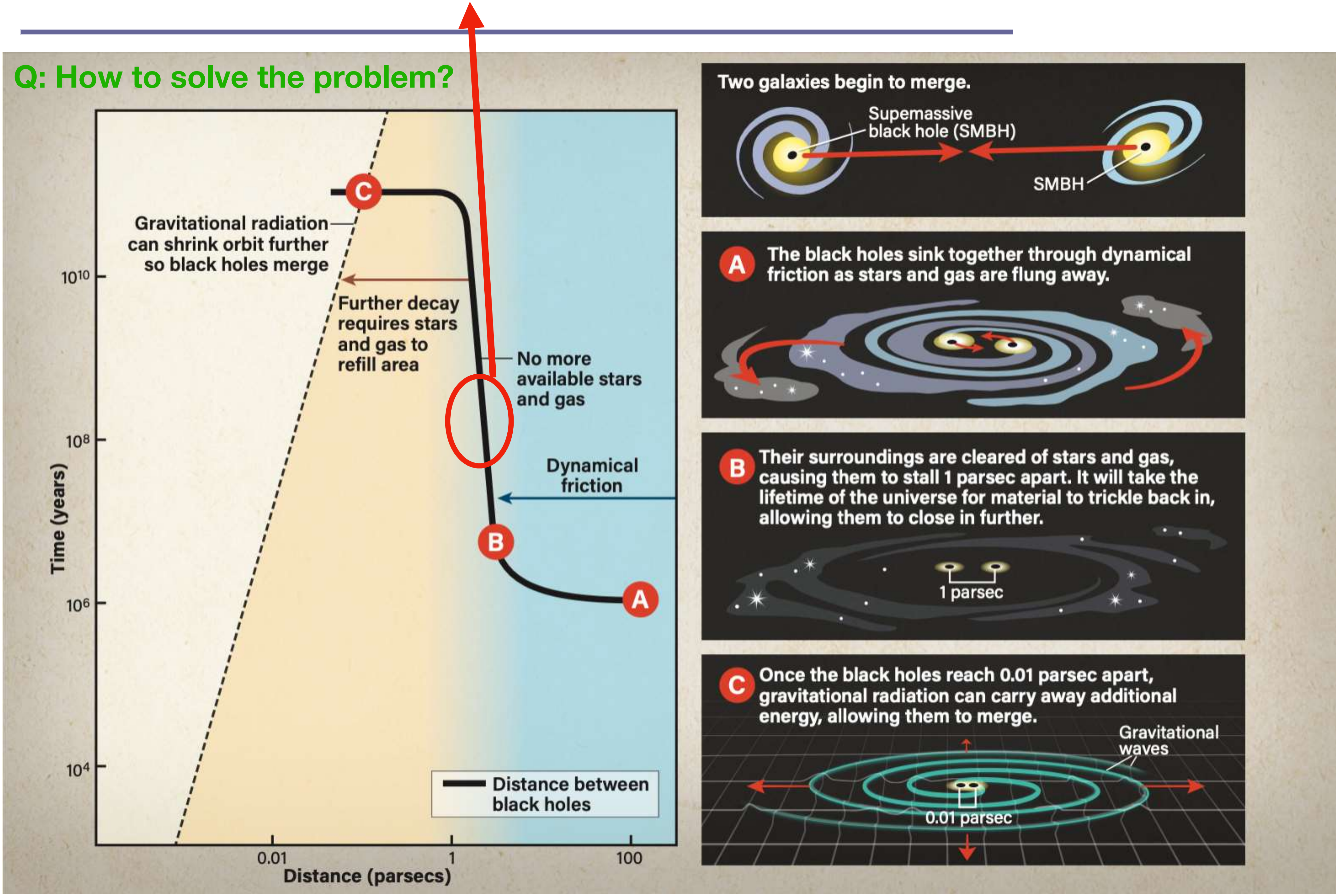
Detector Instrumental Group Leader: 윤태현(고려대학교)

Data Analysis Group Leader: 이형원(인제대학교)

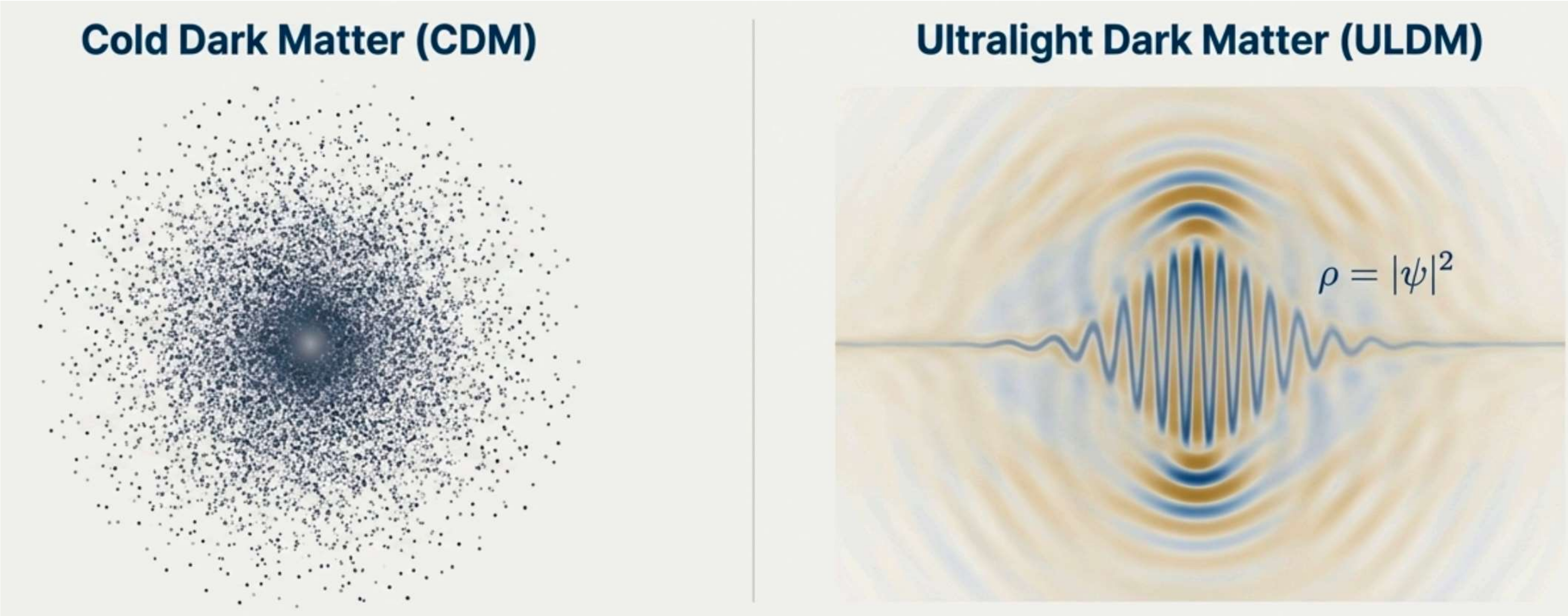
Detector Characterization Group Leader: 오정근(국가수리과학연구소)

- Web Support: 오정근(국가수리과학연구소), 오상훈(국가수리과학연구소), 손재주(국가수리과학연구소)

Final Parsec Problem

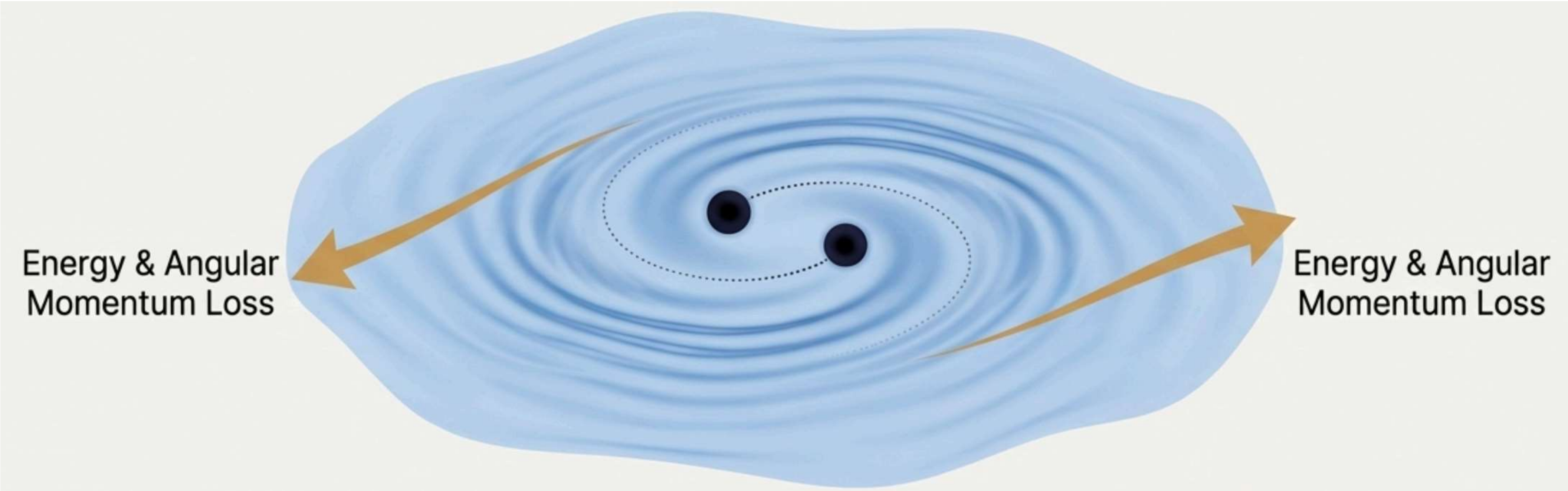


A New Candidate: Ultralight Dark Matter as a Quantum Wave



- ➢ Ultralight Dark Matter (ULDM), or "fuzzy dark matter," is a leading alternative to CDM that could resolve its small-scale issues (e.g., core-cusp problem, missing satellites).
- ➢ It proposes that dark matter consists of extremely light scalar particles ($m \gtrsim 10^{-22}$ eV) in a Bose-Einstein condensate state.
- ➢ On galactic scales, ULDM does not behave like individual particles but as a single, coherent macroscopic wave function.
- ➢ It is this collective, wavelike nature that offers a new physical mechanism.

The Hypothesis: Dark Matter Waves Drain Orbital Energy



- ➢ **Our hypothesis is that an SMBHB orbiting within a ULDM halo will generate "dark matter waves" that efficiently carry away its orbital energy and angular momentum.**
  - ➢ **Dynamical Friction (DF): The moving black holes create a gravitational wake in the ULDM field, generating waves that exert a drag force.**
  - ➢ **Gravitational Cooling (GC): The binary's perturbation of the halo excites its quasi-normal modes, causing the halo to relax by ejecting ULDM waves and carrying away excess kinetic energy.**

- ➢ **Crucially, these mechanisms circumvent the loss-cone problem (i.e. nothing to carry out the angular momentum), allowing the binary to rapidly spiral inwards.**

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Letter

Final parsec problem of black hole mergers and ultralight dark matter

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[a] Physics Department, University of Seoul, Seoul 02504, Korea
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ARTICLE INFO

Editor: P. Brax

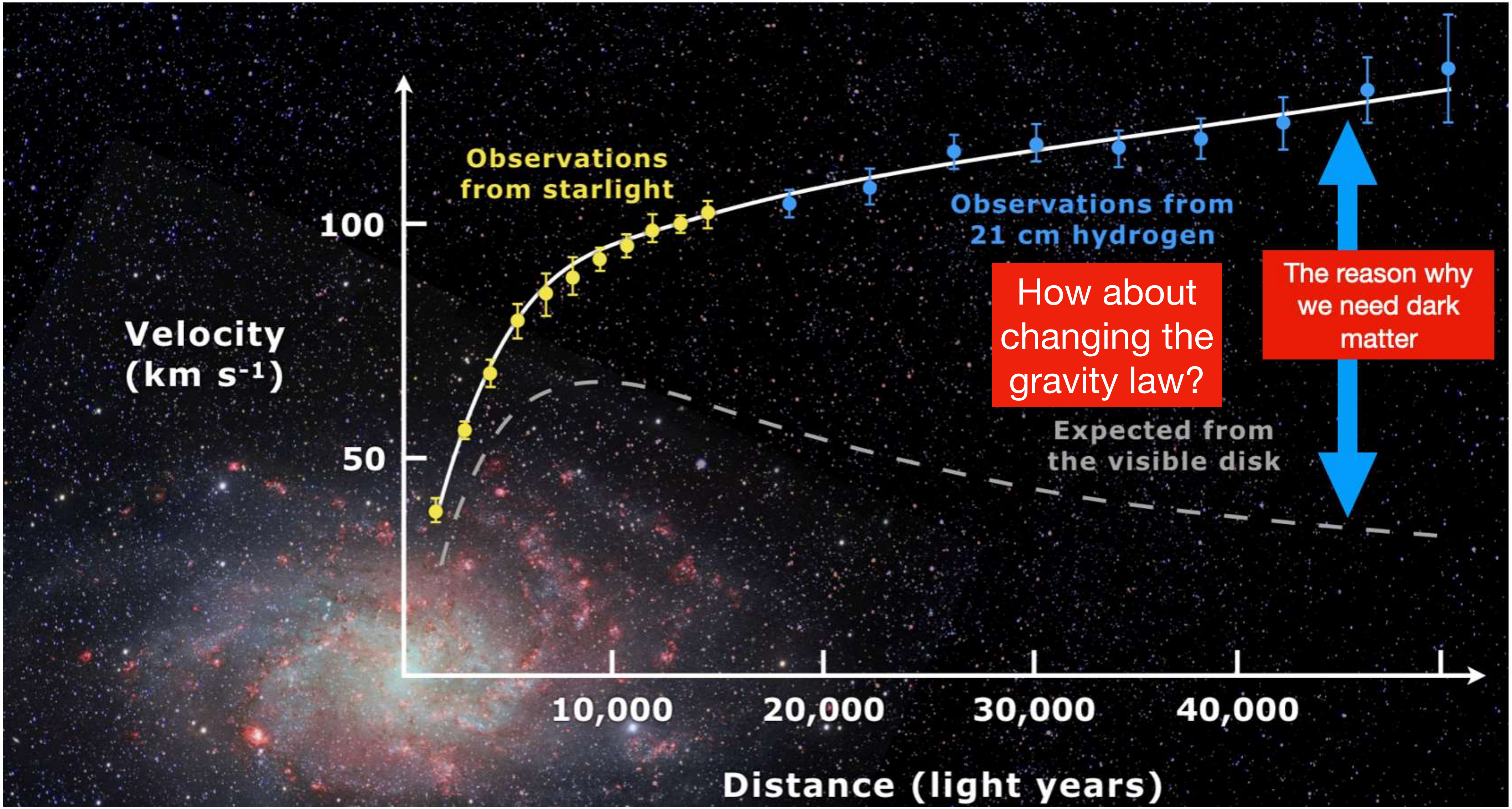
ABSTRACT

When two galaxies merge, they often produce a supermassive black hole binary (SMBHB) at their center. Numerical simulations with stars and cold dark matter show that SMBHBs typically stall out at a distance of a few parsecs apart and take billions of years to coalesce. This is known as the final parsec problem. We suggest that ultralight dark matter (ULDM) halos around SMBHBs can generate dark matter waves due to dynamical friction. These waves can effectively carry away orbital energy from the black holes, rapidly driving them together. To test this hypothesis, we performed numerical simulations of black hole binaries inside ULDM halos. Due to gravitational cooling and quasi-normal modes, the loss-cone problem can be avoided. The decay time scale gives lower bounds on masses of the ULDM particles and SMBHBs comparable to observational data. Our results imply that ULDM waves can lead to the rapid orbital decay of black hole binaries.

V. Alternatives

MOND, Emergent Gravity

WITHOUT dark matter?



WITHOUT dark matter?

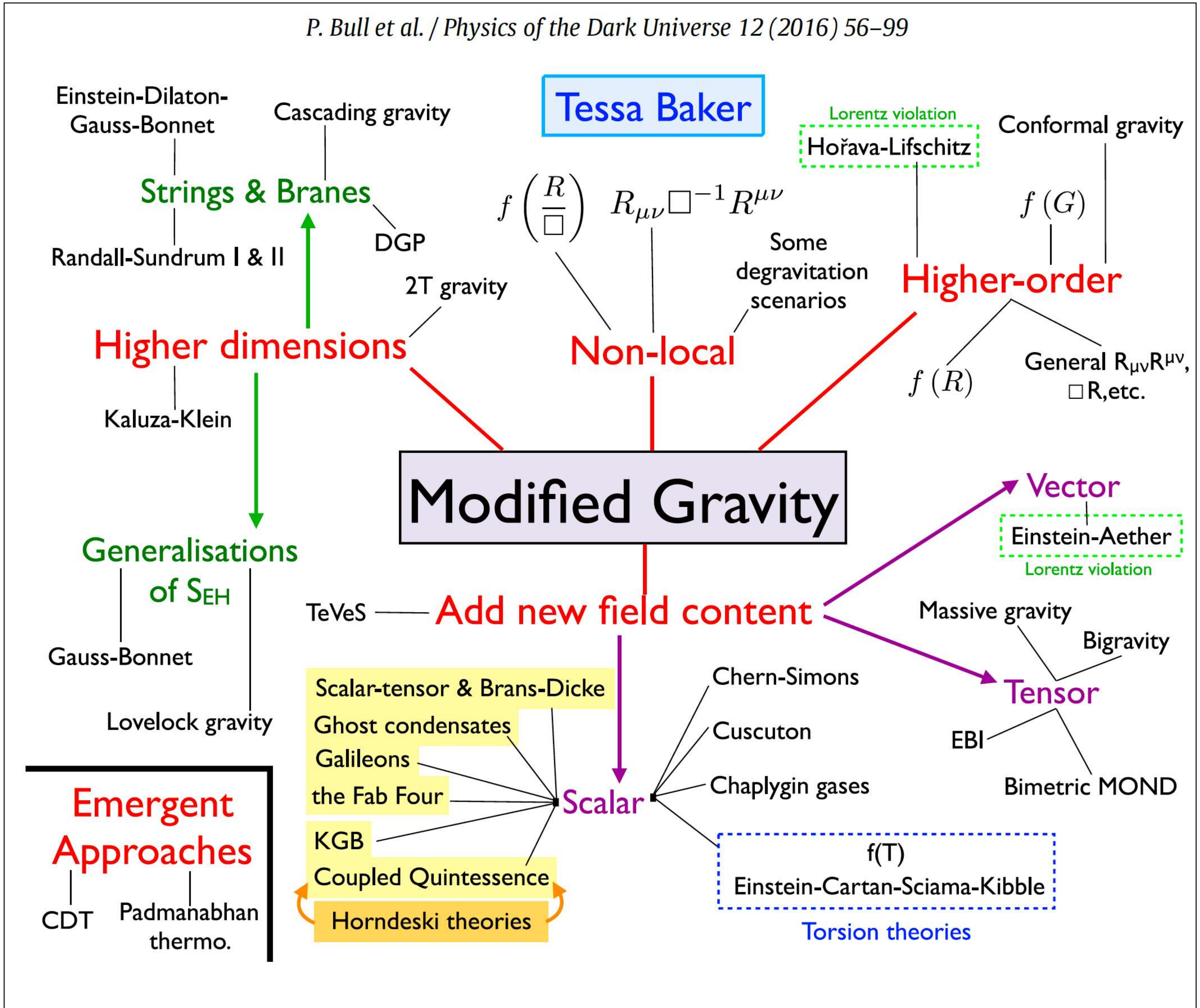


Fig. 3. Tree diagram of modified theories of gravity.
Source: (Tessa Baker, reproduced with permission.).

대안 중력 이론

speconomy.com/news/articleView.html?idxno=318653

채규현 세종대 물리천문학과 교수, 뉴턴 이론 뒤집어

박숙자 기자 | 입력 2023.07.26 12:00 | 댓글 0

가 가

> 장주기 쌍성의 궤도운동서 뉴턴역학 붕괴의 결정적 증거발견
> “새 중력이론의 과학 혁명 도래…우주론 전반에 막대한 영향”

채규현 세종대 물리천문학과 교수. [사진=세종대]

[스페셜경제=박숙자 기자] 채규현 세종대학교(총장 배덕효) 물리천문학과 교수가 장주기 쌍성의 궤도운동에서 뉴턴역학이 붕괴한다는 결정적인 증거를 얻었다.

26일 세종대에 따르면 이 연구 결과는 중력이 약해질 때 뉴턴역학이 붕괴한다는 직접적인 증거로, 300년과 100년간 각각 지속한 뉴턴역학과 일반상대성이론이 수정돼야 한다는 결정적 증거다.

일반상대성이론에 기초한 빅뱅우주론도 수정돼야 하고, 뉴턴역학과 일반상대성이론에 의해서 요구되는 많은 양의 암흑물질이 우주에 더 이상 필요치 않다는 것을 의미한다는 게 세종대 측 설명이다.

이 연구 결과는 미국 천문학회에서 발간하는 천체물리학저널 온라인에 최근 실렸다.

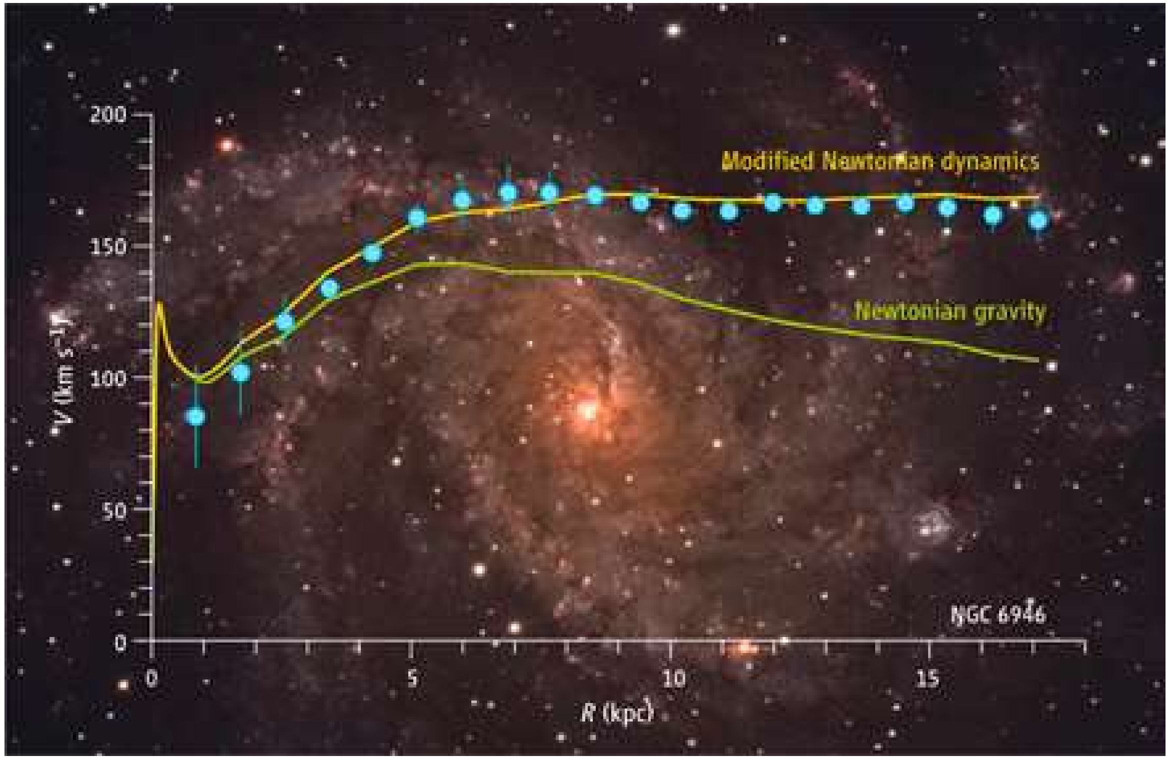
채규현 교수는 이를 위해 미국의 하버드대학교의 카림 엘바드리 박사의 도움을 받아 650광년 이내의 2만6500여 개의 장주기 쌍성에 대한 유럽항공우주국의 가이아(Gaia) 우주망원경의 최신 데이터를 사용했다.

이는 쌍성에 대한 현존하는 가장 규모가 크고 정밀한 데이터이다.

채규현 교수는 ”장주기 쌍성으로 중력을 테스트하려는 시도는 그동안 여러 차례 있었으나 결정적인 결과는 얻지 못했다. 다만, 이번 연구에서 중력이 가속도임에 주목하고 쌍성이 경험하는 가속도를 정확하게 계산하는 새로운 파이썬 코드를 개발했다. 이 코드에 의해서 이번 결과를 얻었다“고 말했다.

WITHOUT dark matter?

- ➢ **MOND (Modified Newtonian dynamics by Milgrom (1983)):**
  Successful in explaining galaxy rotation curves, but
  1. **Difficult to reproduce the large-scale distribution of galaxies yet**
  2. **No physical background why the gravitational constant should change with physical scale**
- ➢ **Another alternative model: emergent gravity**

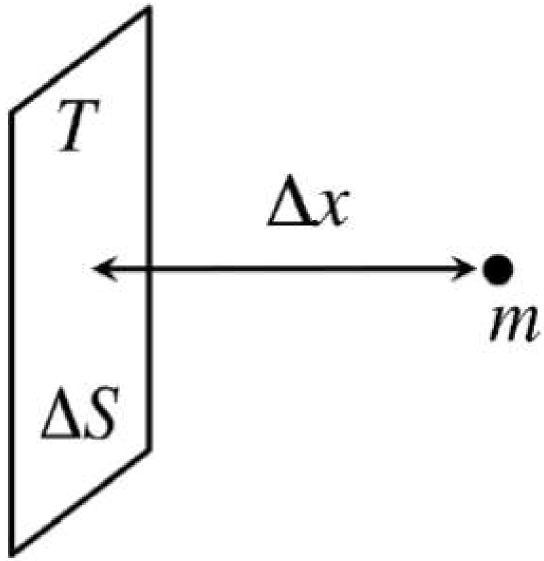


What is important here is not the emergent gravity model itself, but is a trial without considering dark matter!

Emergent Gravity

Erik Verlinde thinks

"The observed phenomena that are currently attributed to dark matter are
- the consequence of the emergent nature of gravity and
- caused by an elastic response due to the volume law contribution to the entanglement entropy in our universe"



Verlinde (2011; 2017)

- ➢ **By adding mass into the space,**
  dark energy (in our universe with positive Λ) acts like elastic medium &
  the elastic response of dark energy is interpreted as an apparent dark matter.

Emergent Gravity

➢ **Gravitational accelartion in the Verlinde's emergent gravity:** $g_{\mathrm{Ver}} = \sqrt{g_{\mathrm{B}}^2 + g_{\mathrm{D}}^2}$

where g_B is the Newtonian gravity from baryonic matter and g_D is the gravity from apparent dark matter.

Thanks to my collaborator working on the theory

$$g_{\mathrm{D}}^2 = \frac{a_0}{6}(\vec{n} \cdot \nabla \Phi_{\mathrm{B}} + 2g_{\mathrm{B}})$$

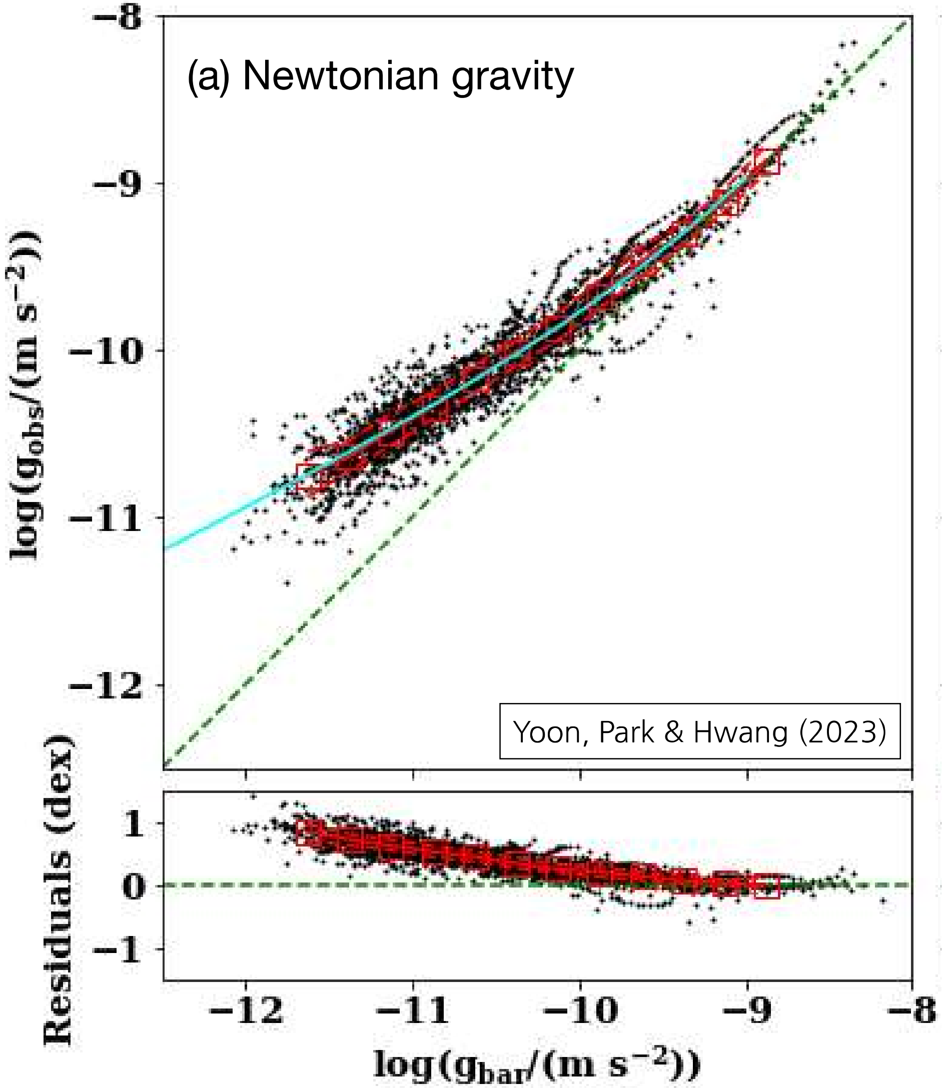
$$\Phi_{\mathrm{B}} = -\frac{2g_{\mathrm{B}}^2}{4\pi G\rho_{\mathrm{B}} + \vec{n} \cdot \nabla g_{\mathrm{B}}}$$

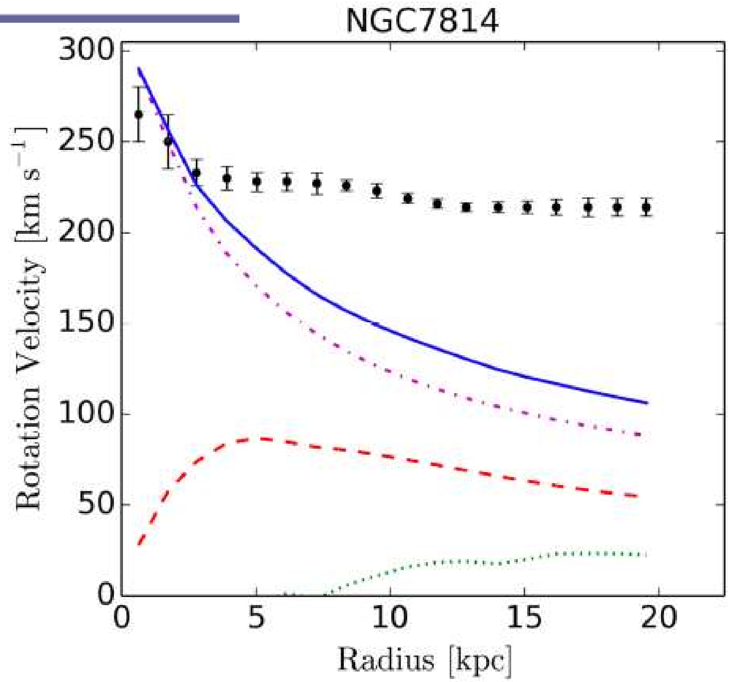
where ρ_B is the the baryonic matter density,
$\vec{n}$ is the direction of the Newtonian gravity,
a_0 is the constant, and
Φ_B is the potential.

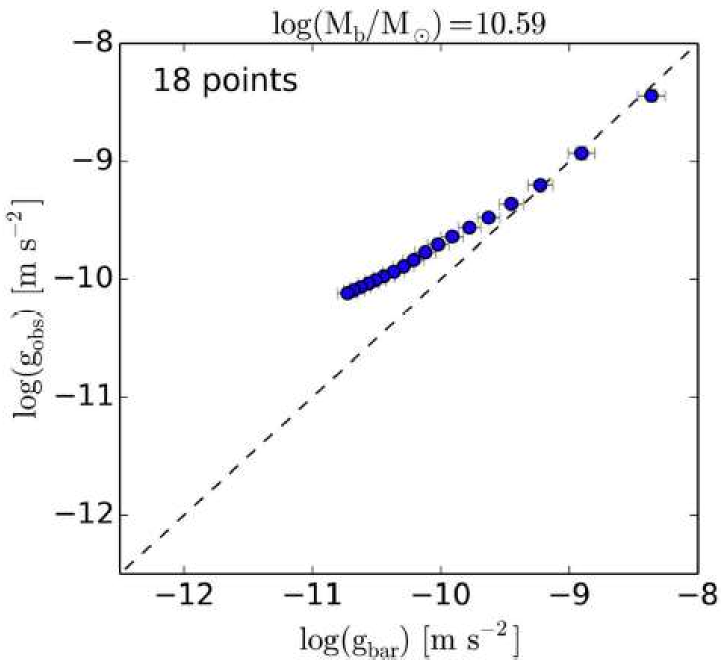
Q: Can this model explain well the observational results?
(e.g. scaling relation for galaxies;
kinematic data vs. baryon data)

Emergent Gravity

1. **Radial acceleration relation:** **observed acceleration from rotation curves vs. acceleration from baryon mass**



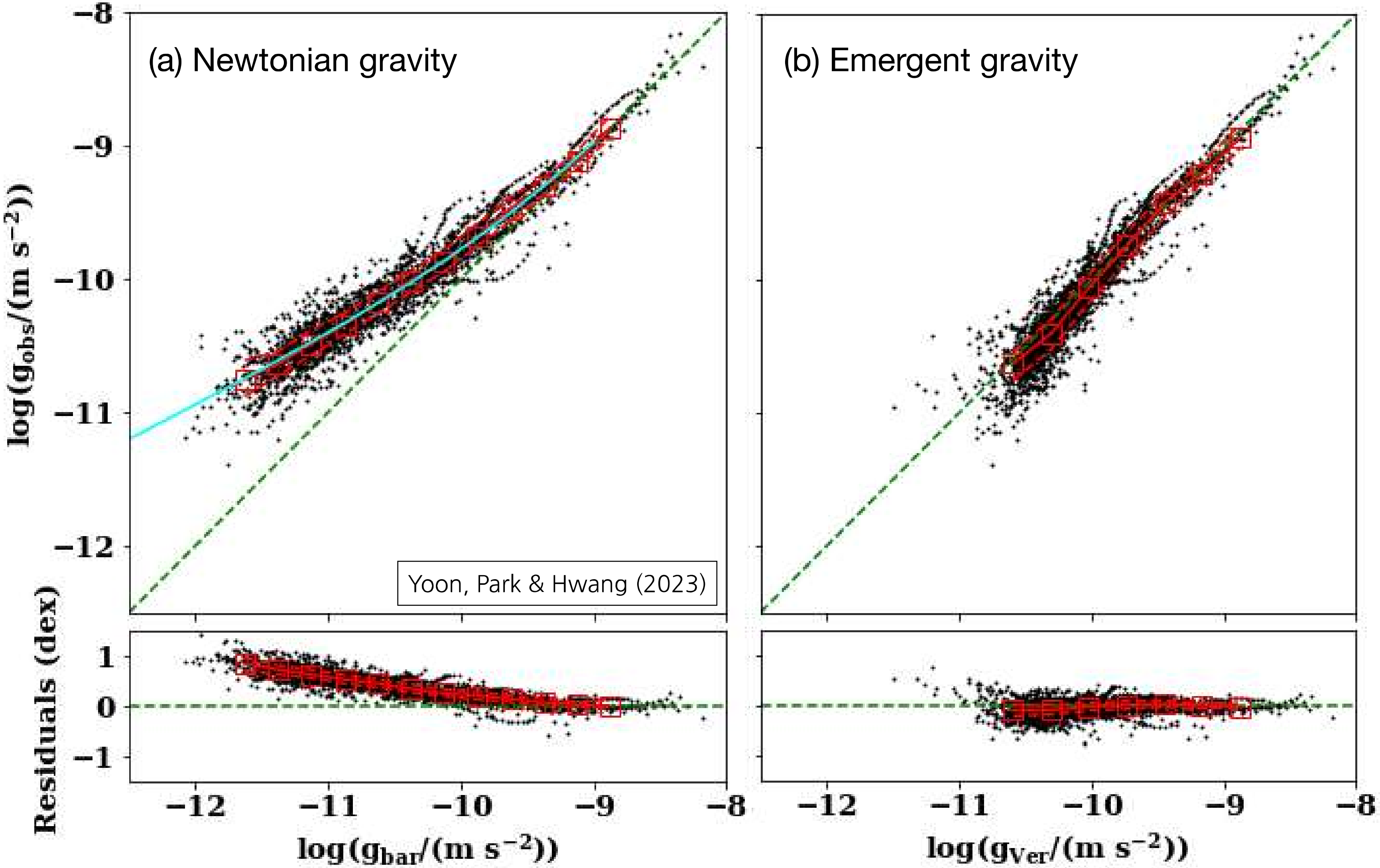




Emergent Gravity

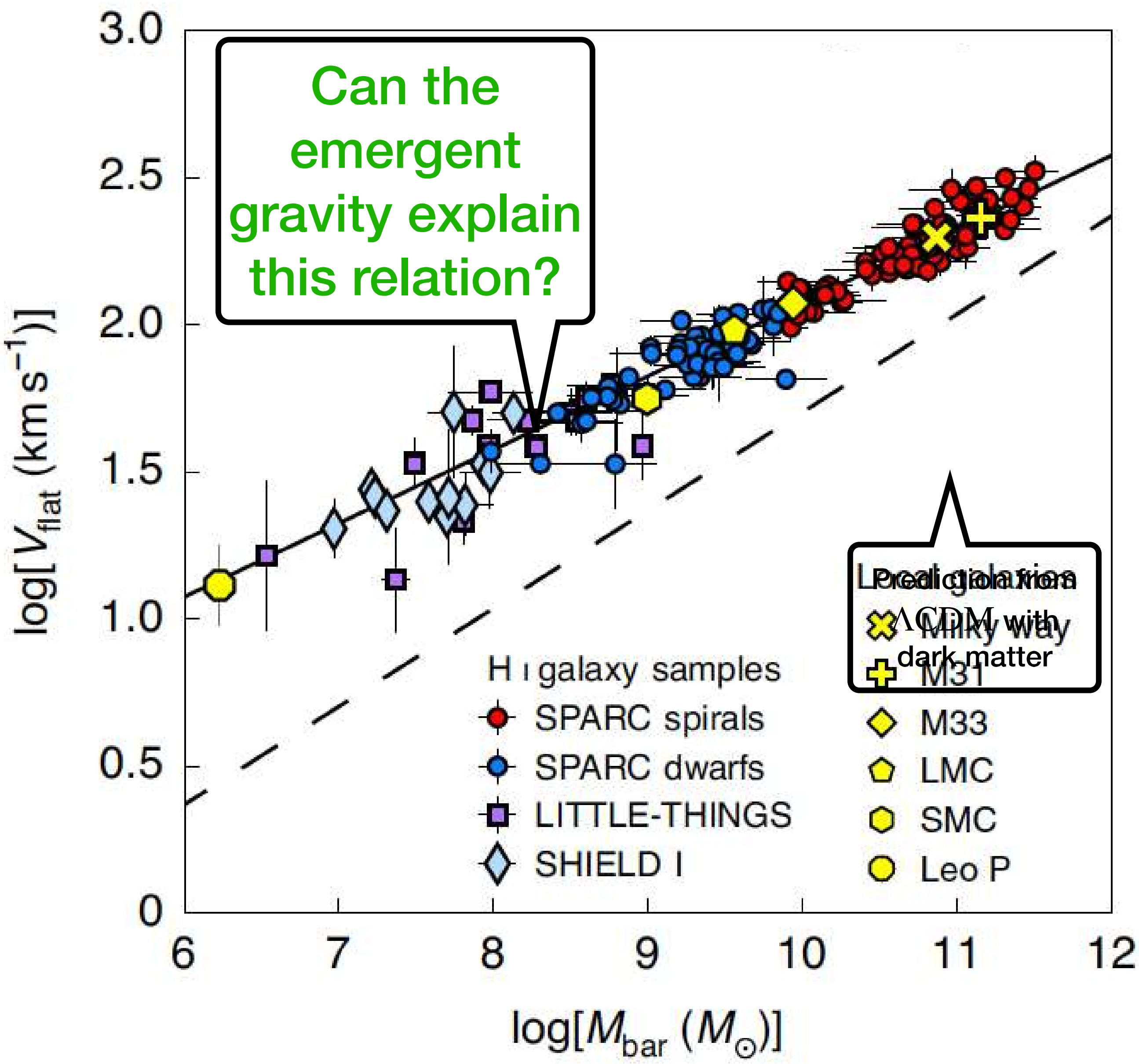
1. **Radial acceleration relation**

➢ **We could successfully explain this relation with the emergent gravity without considering dark matter!**



Emergent Gravity

2. Baryonic Tully-Fisher Relation: an empirical relationship between the mass of a spiral galaxy and its rotation velocity



Of course, "the probability of success is difficult to estimate, but if we never search, the chance of success is zero" G. Cocconi & P. Morrison, Nature, September 1959

Goal of this lecture:

To understand 1) why we need dark matter, 2) what we know about it, & 3) what to do with it!

- **Part 1: History of Dark Matter**
  - Ref: Bertone & Hooper 2018, Rev. Mod. Phys. 90, 045002

- **Part 2: Dark Matter Models**
  - Refs:
    - "Dark Matter" by Cirelli+2024 (arXiv:2406.01705)
    - "Small-Scale Challenges to the ΛCDM Paradigm" by James S. Bullock and Michael Boylan-Kolchin (2017, Annu. Rev. Astron. Astrophys., 55, 343)

- **Part 3: Dark Mater Studies in practice**

- **General Refs:**
  - "Gravitational probes of dark matter physics" by Buckely & Peter (2018, Physics Reports, 761, 1)
  - "Dark Matter" by Cirelli+2024 (arXiv:2406.01705)