

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

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**Lecture Notes
KIAS-SNU Physics2025**

2. DARK MATTER MODELS

DARK MATTER

• • • Needs confirmation • • •

PROPERTIES				
$I(J^{PC})$	MASS	WIDTH	DECAY MODES	PRODUCTION
$?(???)$	$? \pm ?$	$? \pm ?$	STABLE ?	$\sigma(?? \rightarrow ??) = ?$

Table 1: *Summary of currently known Dark Matter properties.*

Among these models, one thing we could say that cold dark matter model has worked best!



Cold Dark Matter Model!

Cold dark matter (CDM):

$$m \sim 100 \text{ GeV}, \\ v_{\text{th}}^{z=0} \approx 0 \text{ km s}^{-1}$$

Warm dark matter (WDM):

$$m \sim 1 \text{ keV}, \\ v_{\text{th}}^{z=0} \sim 0.03 \text{ km s}^{-1}$$

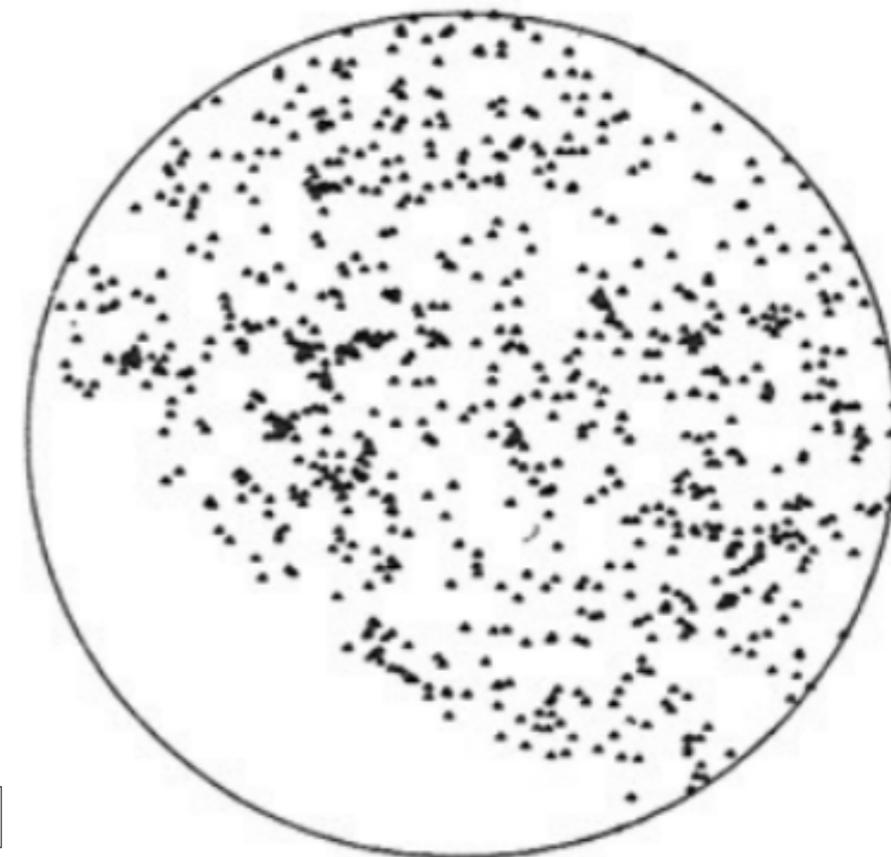
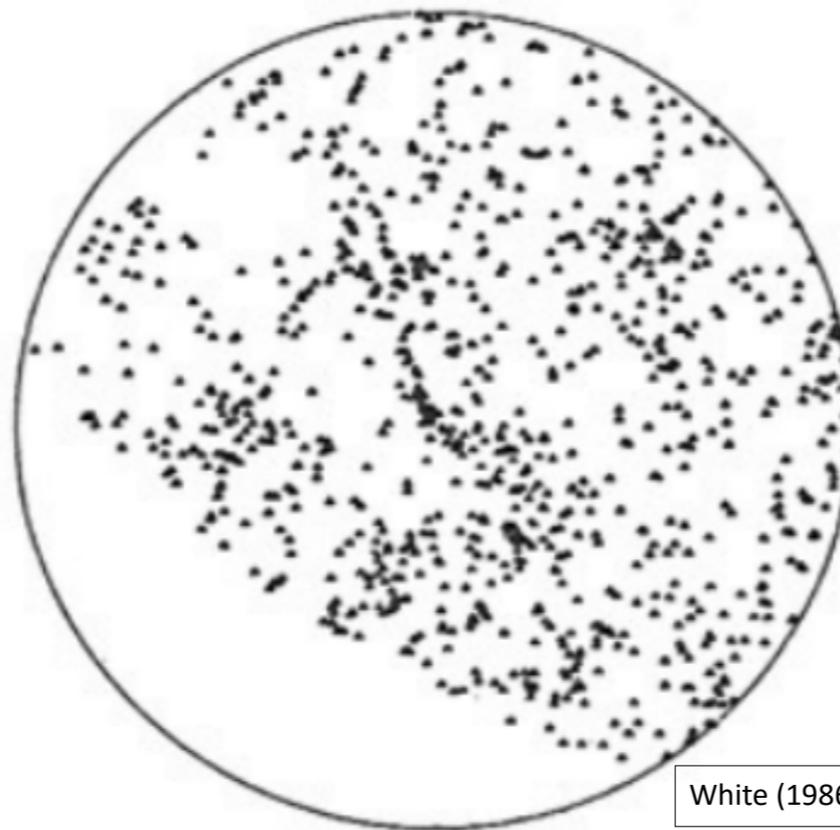
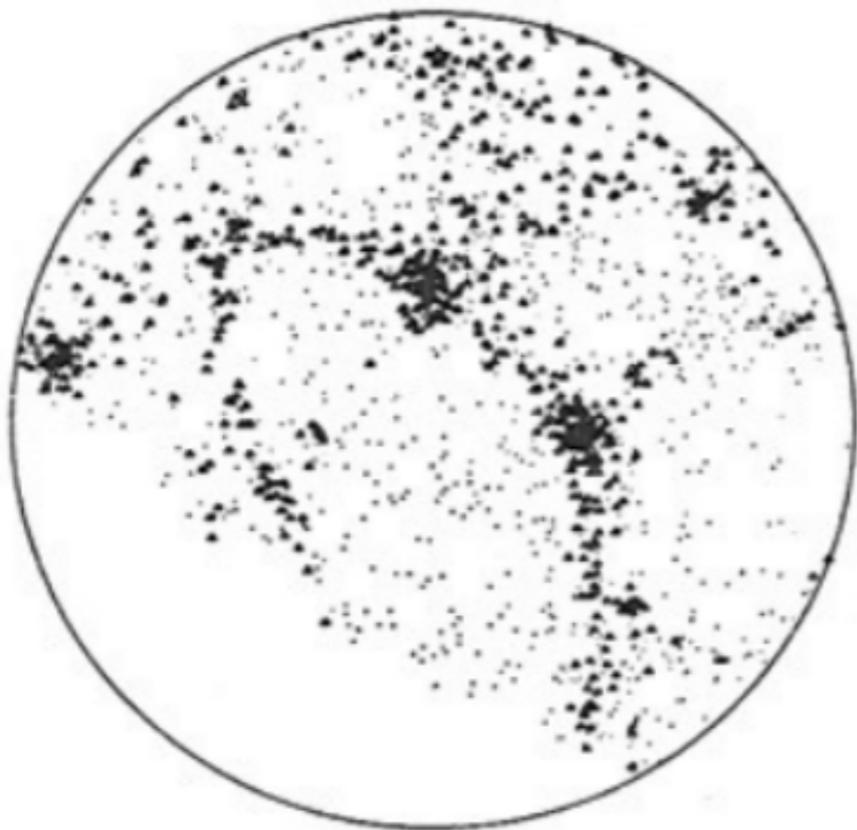
Hot dark matter (HDM):

$$m \sim 1 \text{ eV}, \\ v_{\text{th}}^{z=0} \sim 30 \text{ km s}^{-1}$$

Hot Dark Matter

Observed Galaxy Distribution

Cold Dark Matter



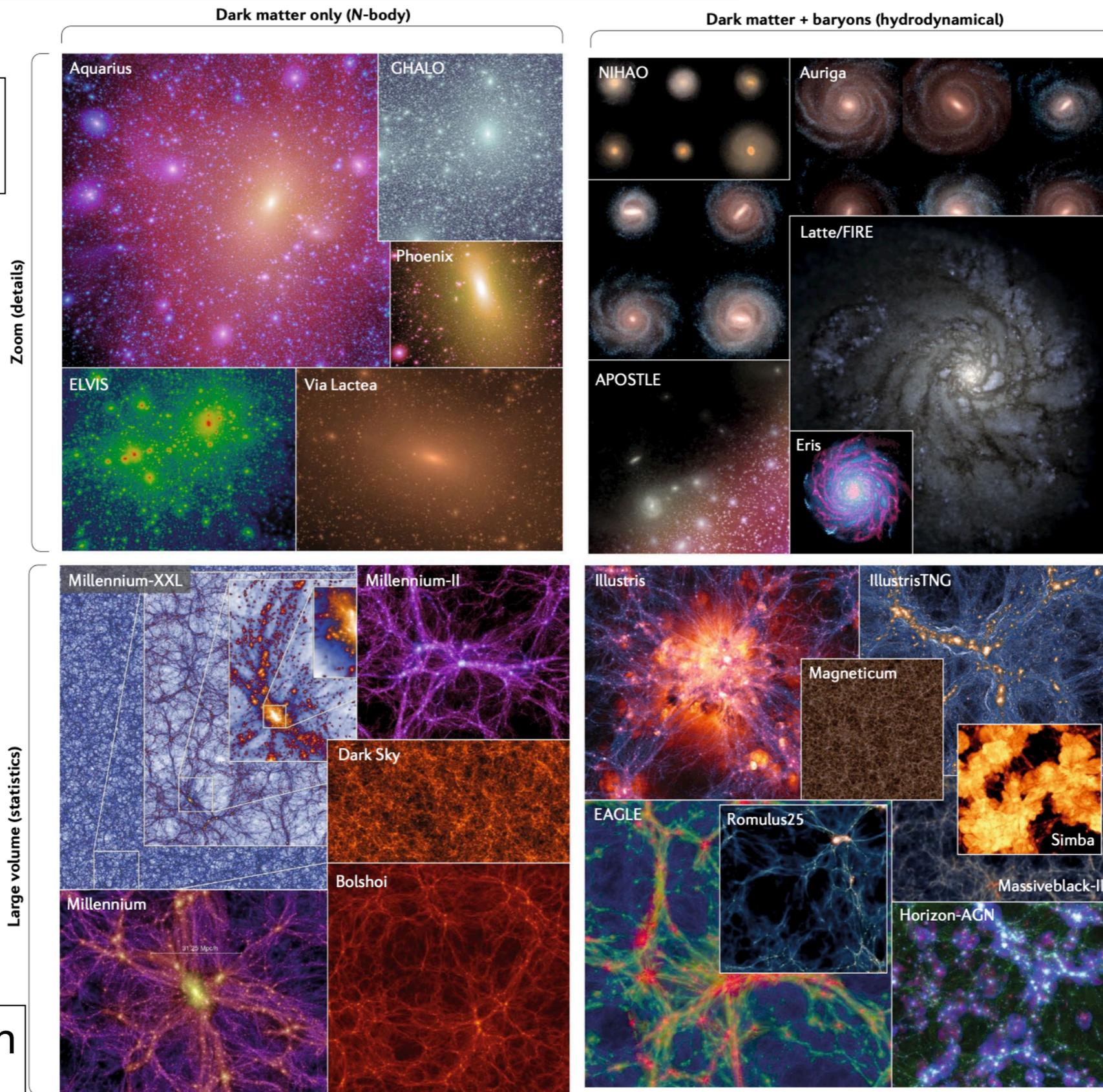
White (1986)

Galaxy distribution can tell something important!

Non-linear Structure Formation

Numerical Simulations of Structure Formation

Vogelsberger
(2020)



(Horizon Run
1-4) +

+ (Horizon
Run 5)

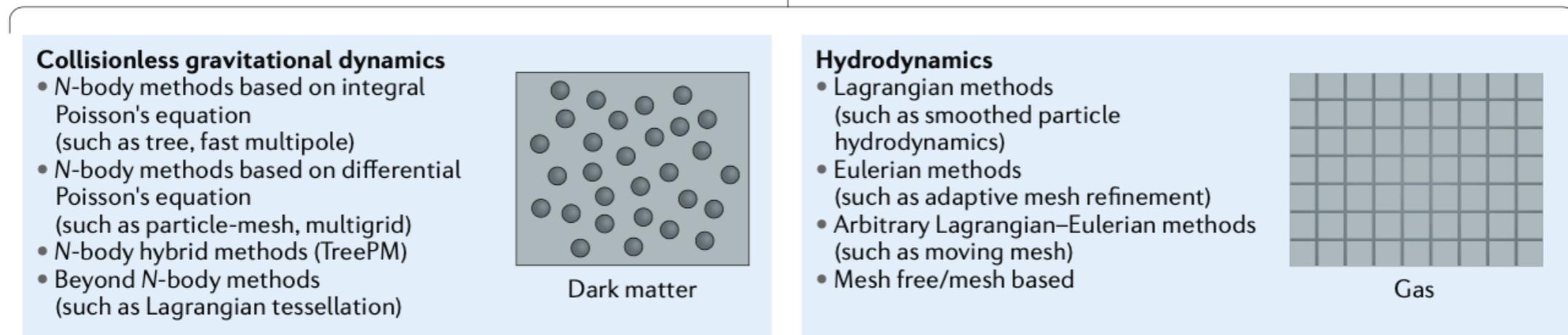
Non-linear Structure Formation

Numerical Simulations of Structure Formation

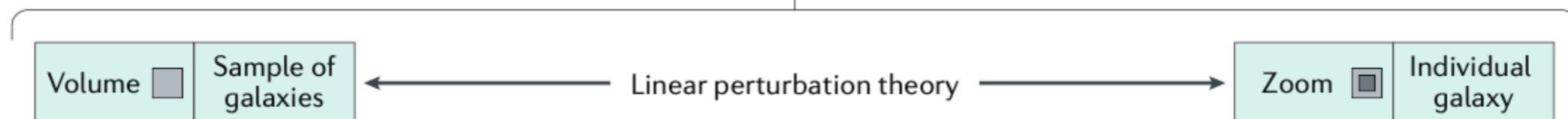
Most important astrophysical processes

Gas cooling	Interstellar medium	Star formation	Stellar feedback	Supermassive black holes	Active galactic nuclei	Magnetic fields	Radiation fields	Cosmic rays
Atomic/molecular/metals/tabulated network	Effective equation of state/multiphase	Initial stellar mass function/probabilistic sampling/enrichment	Kinetic/thermal/variety of sources from stars, supernovae	Numerical seeding/growth by accretion/prescription/merging	Kinetic/thermal/radiative/quasar model radio mode	Ideal MHD/cleaning schemes/constrained transport	Ray tracing/Monte Carlo/moment based	Production/heating/anisotropic diffusion/streaming

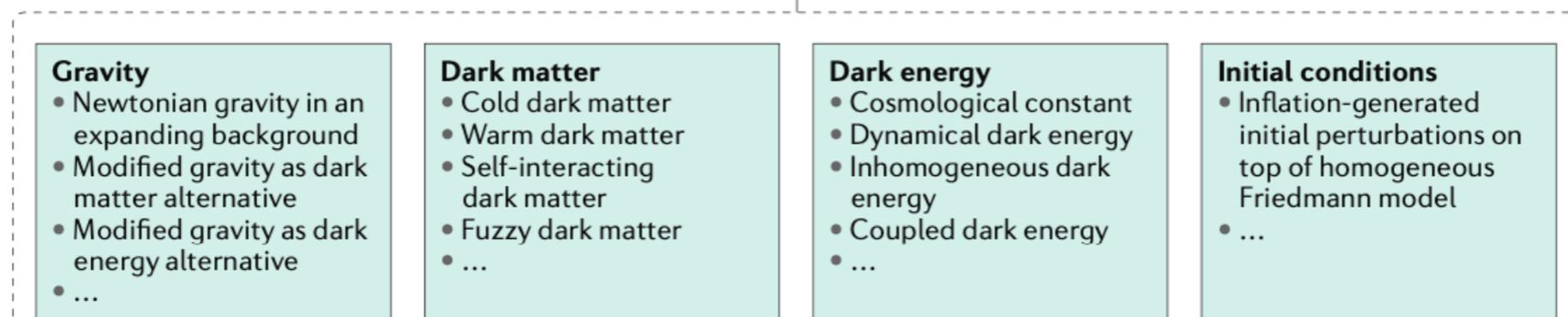
Numerical discretization of matter components



Generating initial conditions



Cosmological framework



The background of the slide is a deep space image filled with numerous stars and galaxies. The stars are scattered across the dark field, with some appearing as bright, multi-colored points of light. Several galaxies are visible, showing spiral and irregular structures. The overall scene is a rich, multi-colored representation of the universe's evolution.

Horizon Run 5 Simulation of the Evolution of the Universe – A Journey to the Past

HR5 team - Full version: https://www.youtube.com/watch?v=oDEQ6Y_5Qdo

Cold Dark Matter Model!

Numerical Simulations of Structure Formation

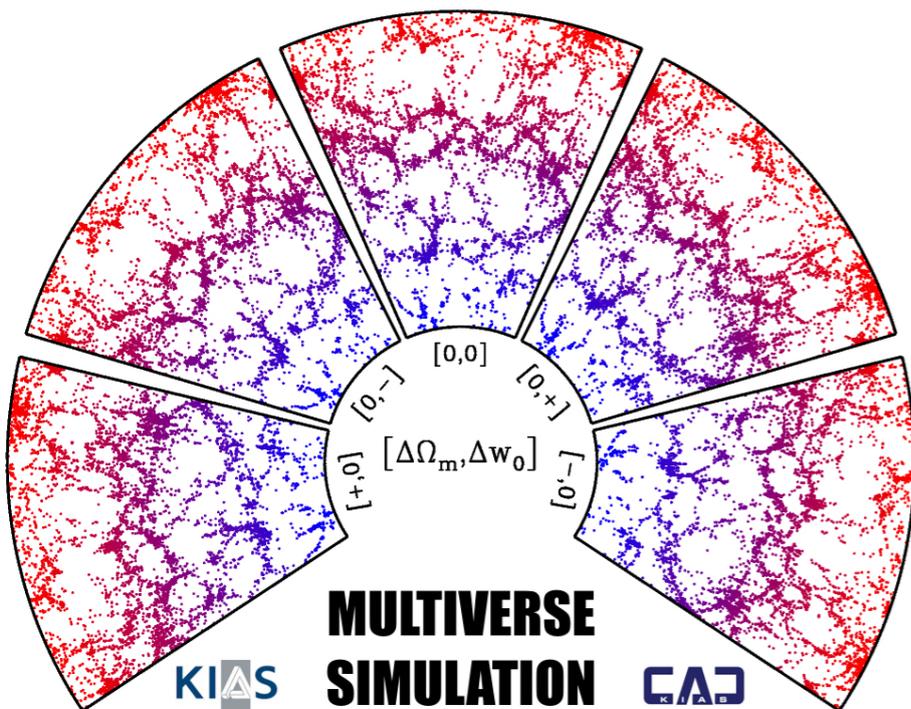
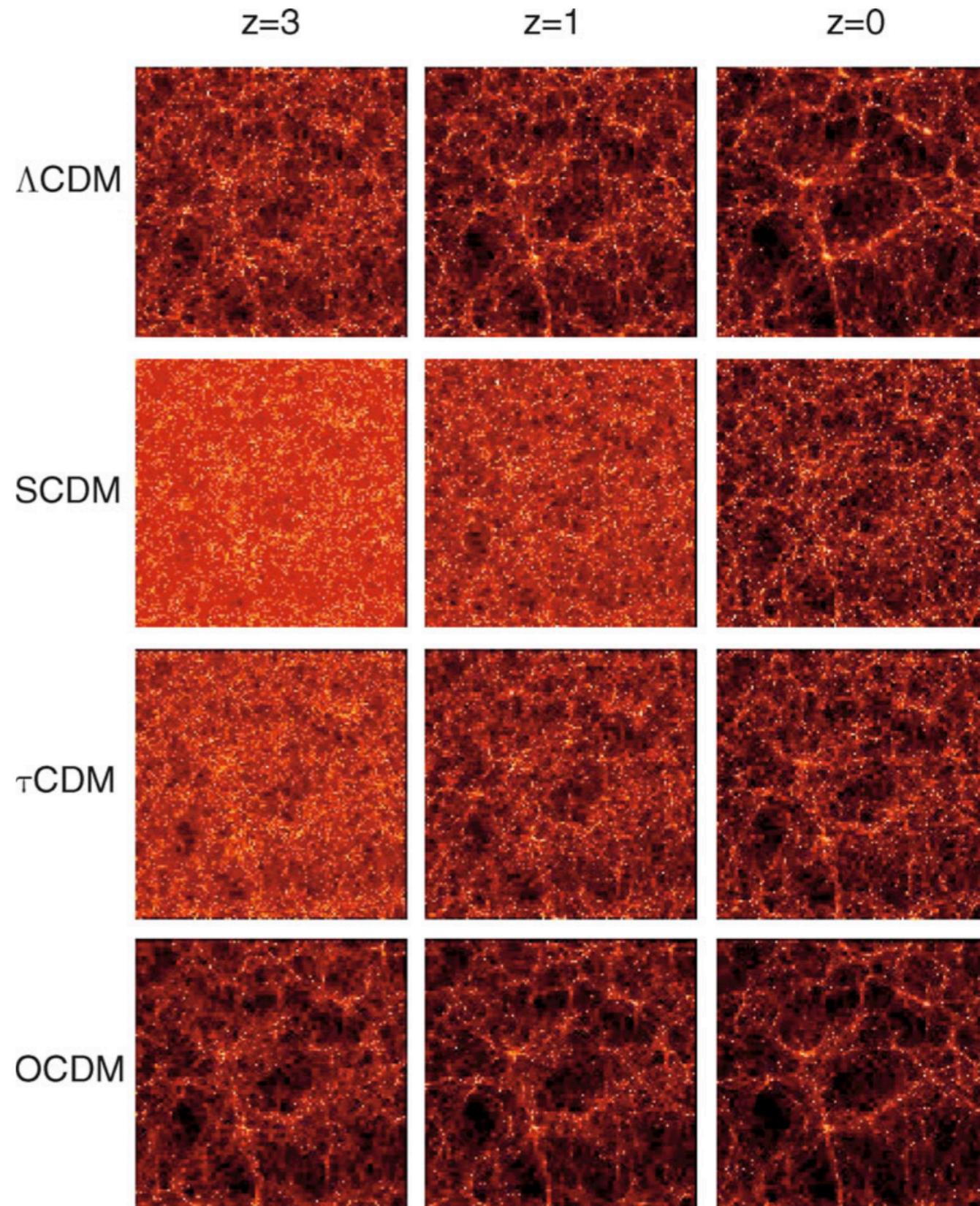
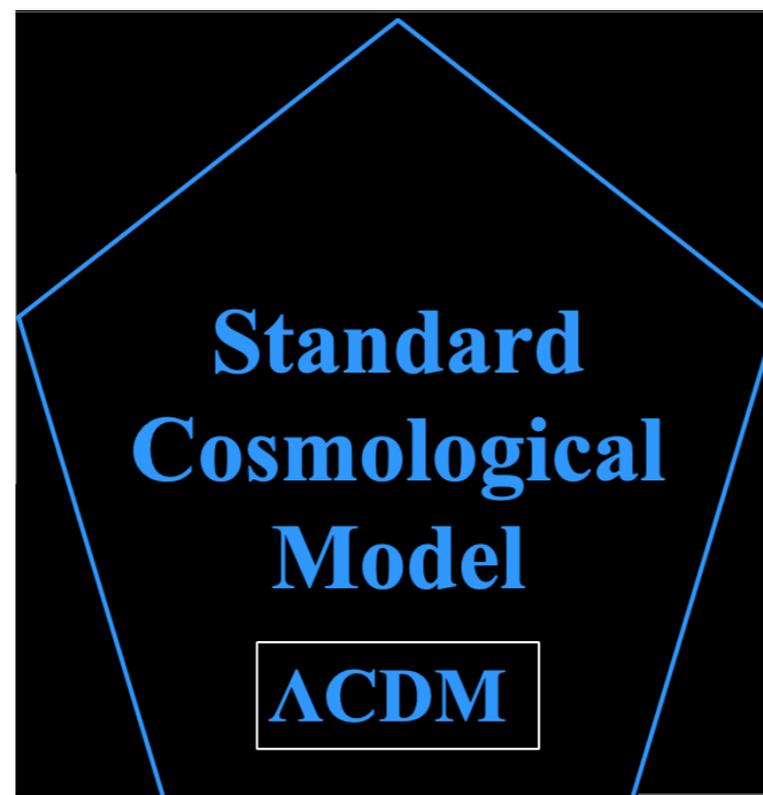


Fig. 7.11 Simulations of the dark matter distribution in the Universe for four different cosmological models: $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$ (Λ CDM), $\Omega_m = 1.0$, $\Omega_\Lambda = 0.0$ (SCDM and τ CDM), and $\Omega_m = 0.3$, $\Omega_\Lambda = 0$ (OCDM). The two Einstein–de Sitter models differ in their shape parameter Γ which specifies the shape of the power spectrum $P(k)$ through the location of its peak. For each of the models, the mass distribution is presented for three different redshifts, $z = 3$, $z = 1$, and today, $z = 0$. Whereas the current mass distribution is quite similar in all four models (the model parameters were chosen as such), they clearly differ at high redshift. We can see, for instance, that significantly less structure has formed at high redshift in the SCDM model compared to the other models. From the analysis of the matter distribution at high redshift, one can therefore distinguish between the different models. In these simulations by the VIRGO Consortium, 256^3 particles were traced; the side length of the simulated volume is $\sim 240h^{-1}$ Mpc. Credit: VIRGO Collaboration, J. Colberg/MPA Garching. The simulations were carried out by the Virgo Supercomputing Consortium using computers based at the Computing Centre of the Max-Planck Society in Garching and at the Edinburgh parallel Computing Centre. Research article: A. Jenkins et al. 1998, *Evolution of Structure in Cold Dark Matter Universes*, ApJ 499, 20

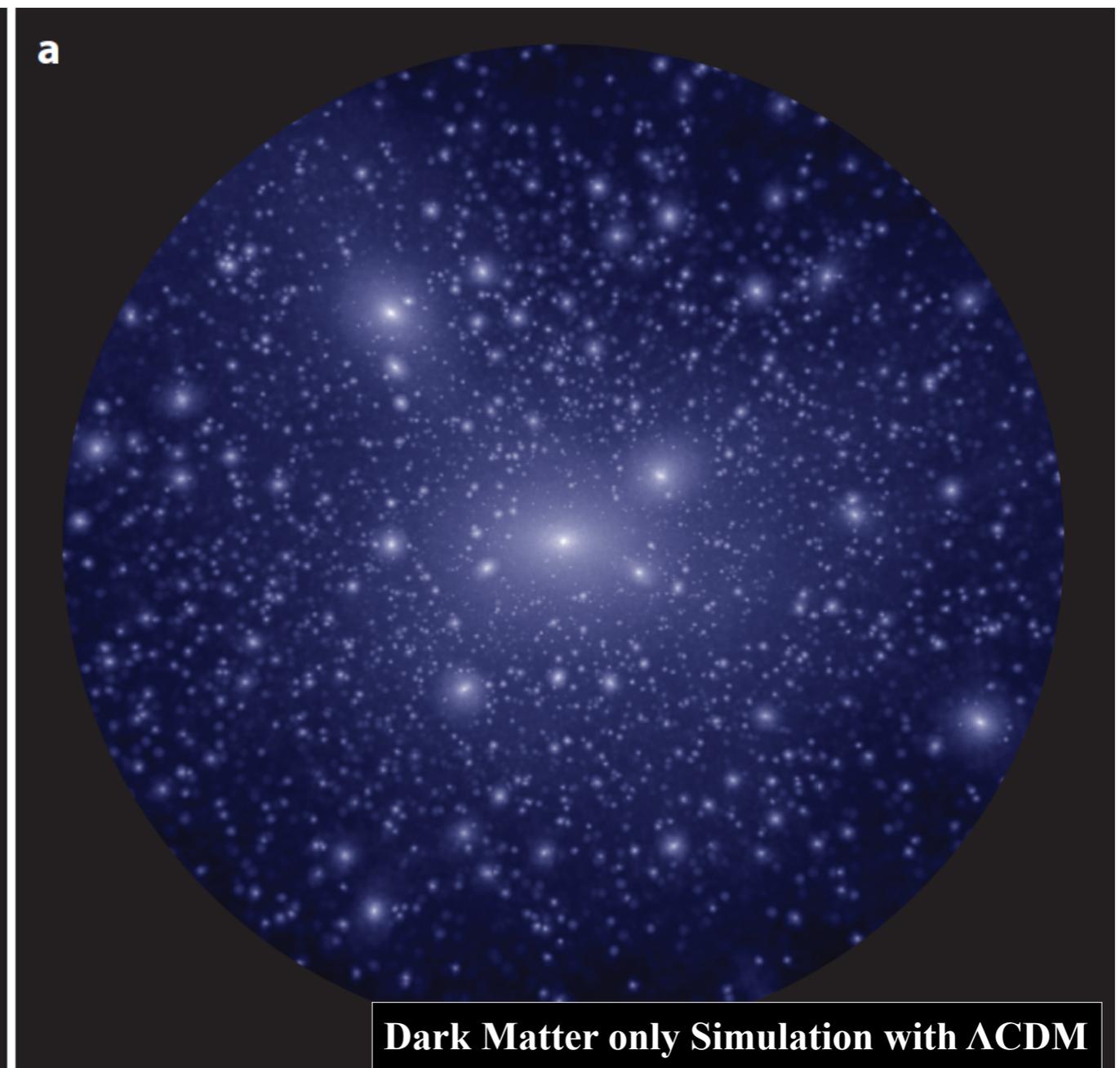
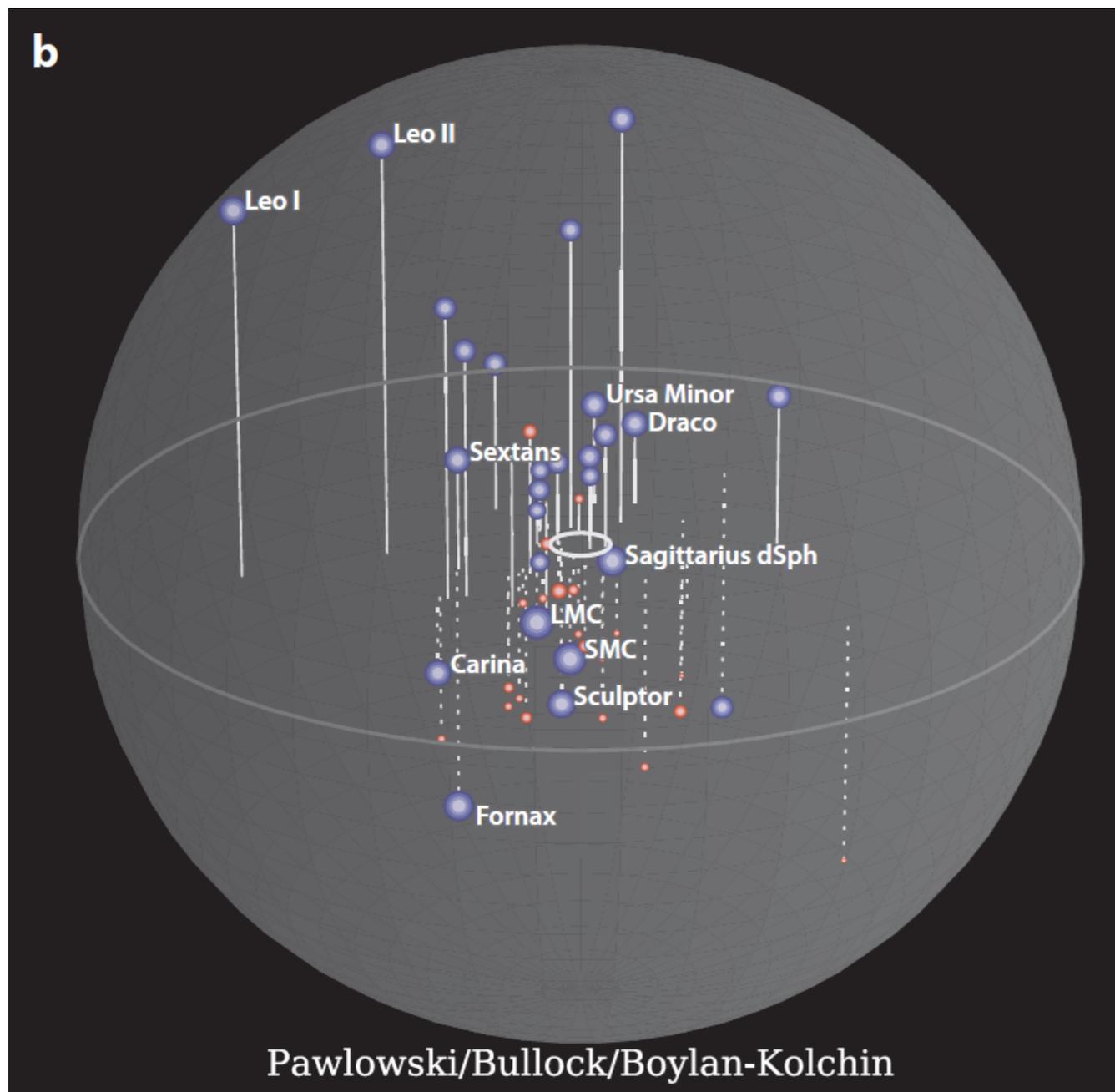


Observational Challenges to Λ CDM

- Missing Satellite Problem
- Low-Density Cores Versus High-Density Cusps
- Too-Big-to-Fail
- Planes of Satellite Galaxies



1. Missing Satellite Problem



Bullock & Boylan-Kolchin 17

Dark Matter only Simulation with Λ CDM

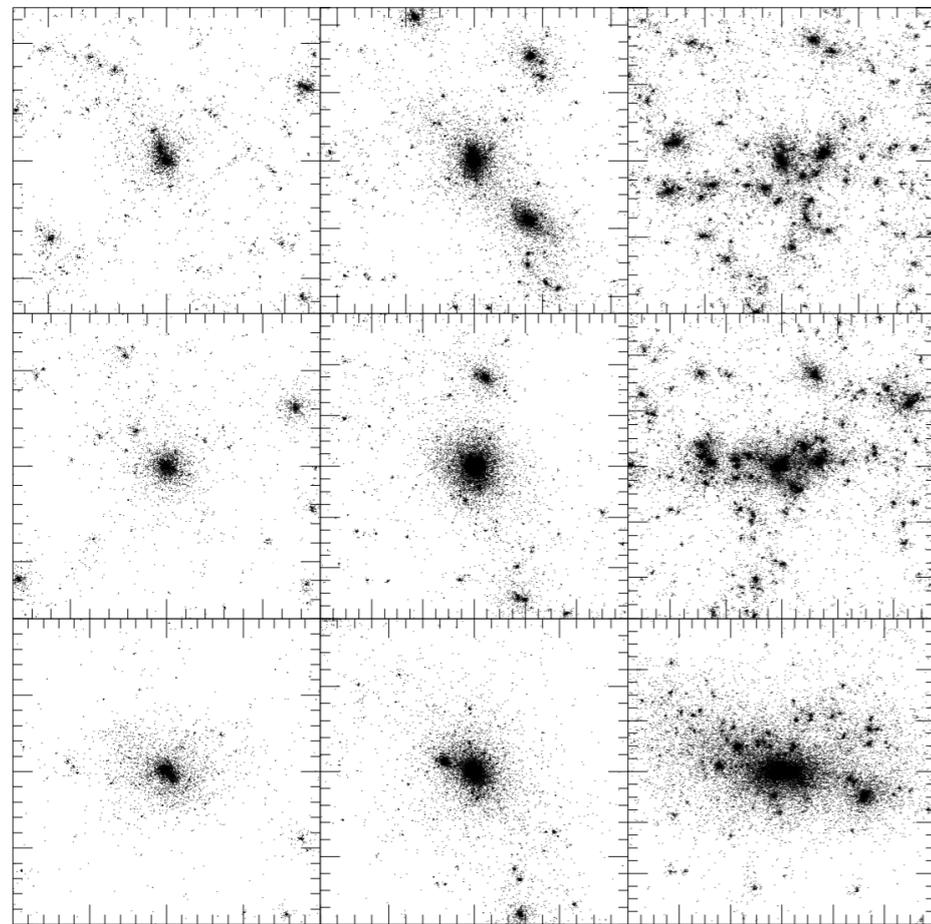
Q: Where are those satellite halos (i.e. galaxies)?

2. Low-Density Cores Versus High-Density Cusps

Profile of Dark Matter Halos

$$\rho(r) = \frac{\rho_s}{(r/r_s)(1+r/r_s)^2}, \quad (7.59)$$

➤ The density profile of halos over spherical shells seems to have a universal function form (by Julio Navarro, Carlos Frenk & Simon White); NFW profile

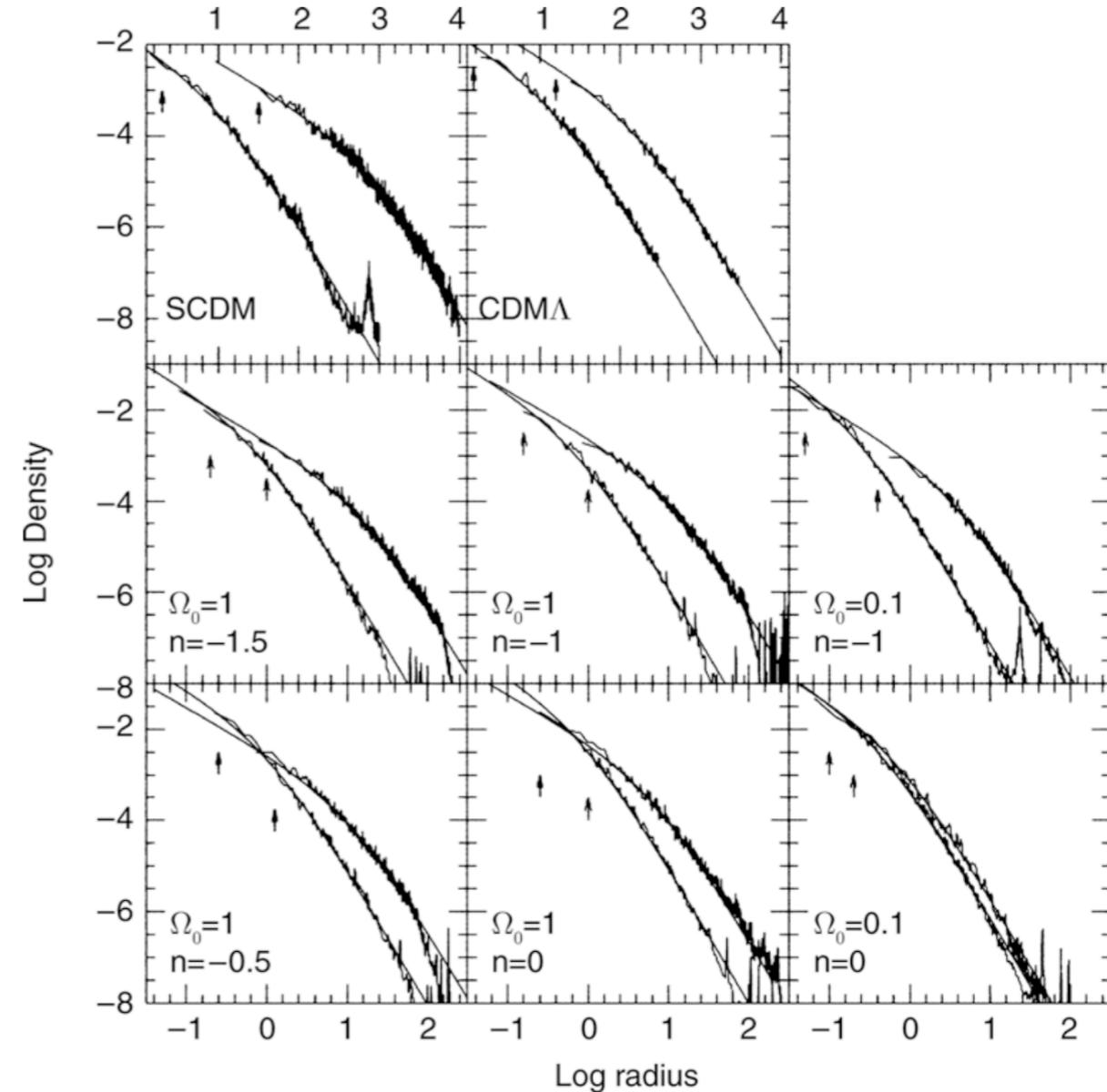


$M < M_*$

$M \sim M_*$

$M > M_*$

Fig. 7.17 For eight different cosmological simulations, the density profile is shown for the most massive and the least massive halo, each as a function of the radius, together with the best fitting density profile (7.59). The cosmological models represent an EdS model (here denoted by SCDM, *top left*), a Λ CDM model (*top right*), and different models with power spectra that are assumed to be power laws locally, $P(k) \propto k^n$. The *arrows* indicate the softening length in the gravitational force for the respective halos; thus, the major part of the profiles is numerically well resolved. Source: J.F. Navarro et al. 1997, *A Universal Density Profile from Hierarchical Clustering*, ApJ 490, 493, p. 496, Fig. 2. ©AAS. Reproduced with permission



➤ Using a suite of simulations, of different cosmologies, they showed that the density profiles of the dark matter haloes can always be fit by a universal fitting function.

7.6 Properties of Dark Matter Halos

7.6.1 Profile of Dark Matter Halos

➤ The density profile of halos over spherical shells seems to have a universal function form (by Julio Navarro, Carlos Frenk & Simon White); NFW profile

$$\rho(r) = \frac{\rho_s}{(r/r_s)(1+r/r_s)^2}, \quad (7.59)$$

where r_s is a characteristic radius where the slope of the density profile changes

- At $r \ll r_s$; $\rho \propto r^{-1}$
- At $r \gg r_s$; $\rho \propto r^{-3}$

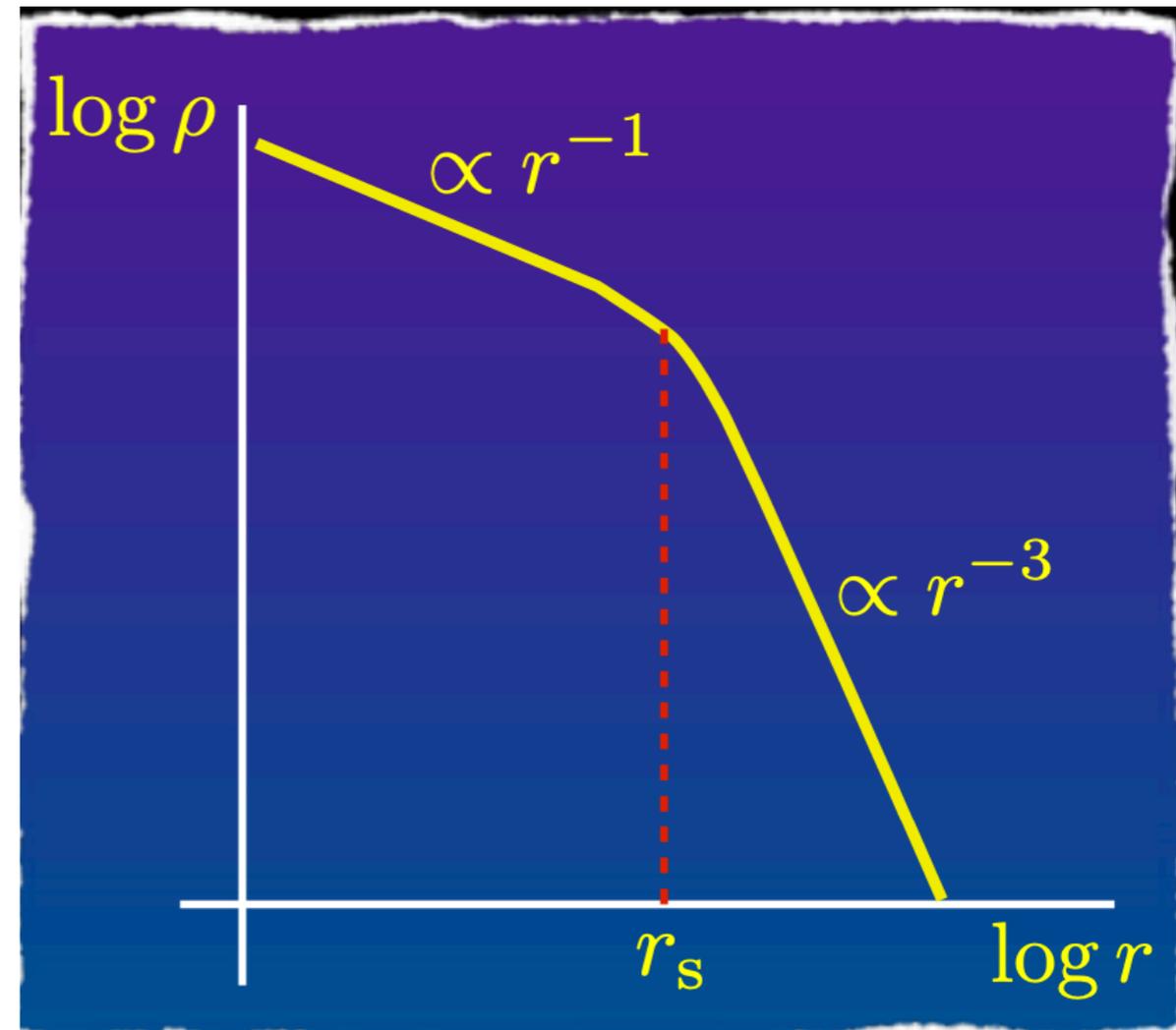
$$\begin{aligned} \bar{\rho} &= 200\rho_{\text{cr}}(z) = \frac{3}{4\pi r_{200}^3} \int_0^{r_{200}} 4\pi r^2 dr \rho(r) \\ &= 3\rho_s \int_0^1 \frac{dx x^2}{c x (1+cx)^2}, \end{aligned} \quad (7.60)$$

where

➤ $x = r/r_{200}$

➤ Concentration index:

$$c := \frac{r_{200}}{r_s}$$



(7.61)

$$\rho_s = \frac{200}{3} \rho_{\text{cr}}(z) \frac{c^3}{\ln(1+c) - c/(1+c)}$$

2. Low-Density Cores Versus High-Density Cusps

➤ The central regions of DM-dominated galaxies as inferred from rotation curves tend to be both less dense (in normalization) and less cuspy (in inferred density profile slope) than predicted for standard CDM halos.

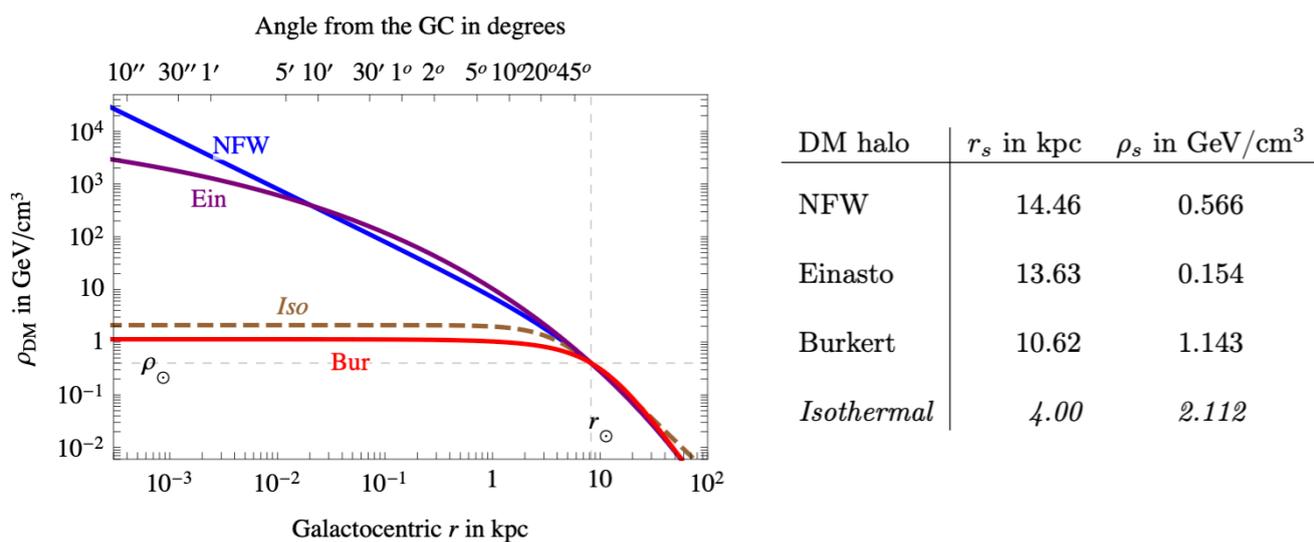
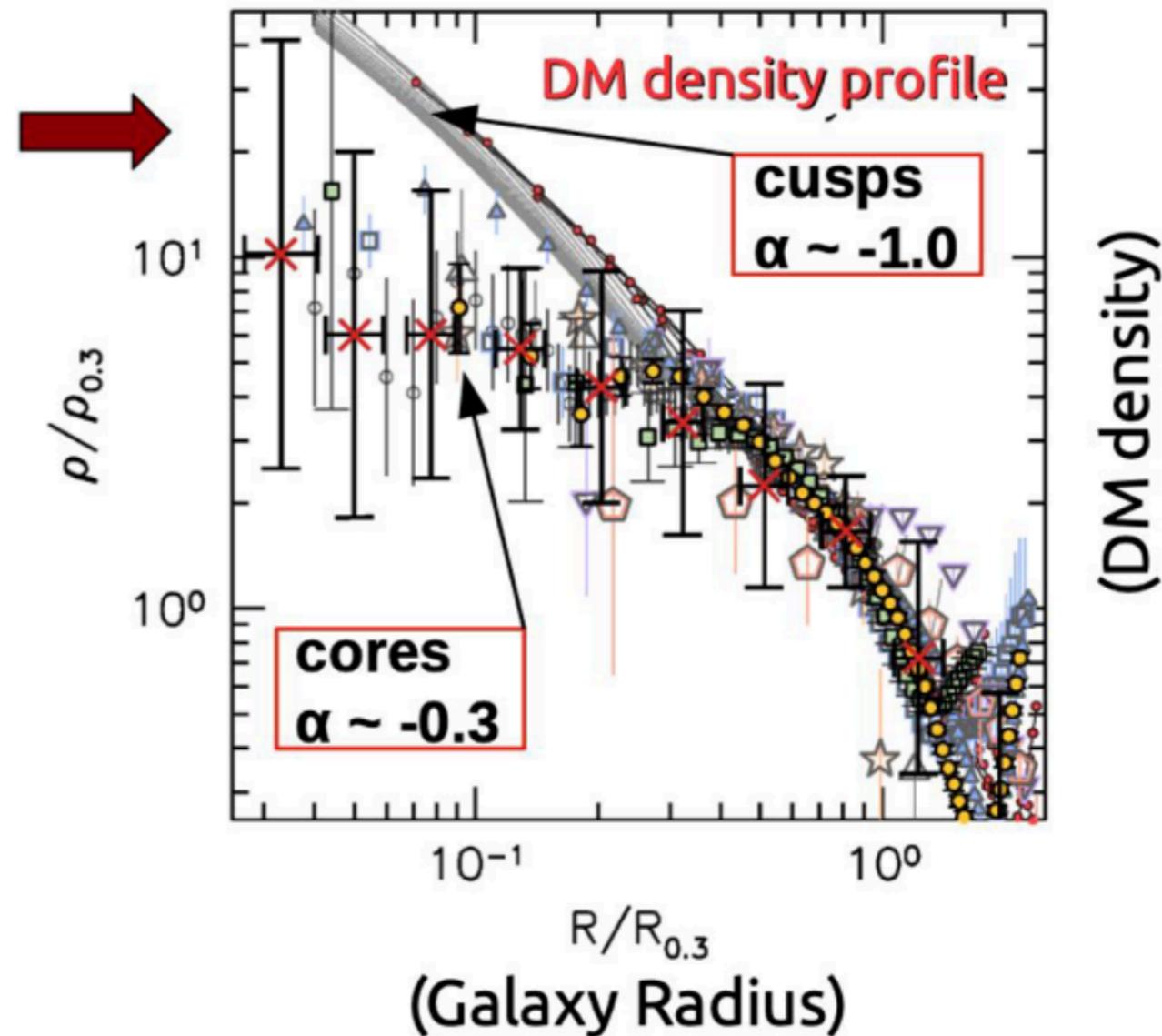


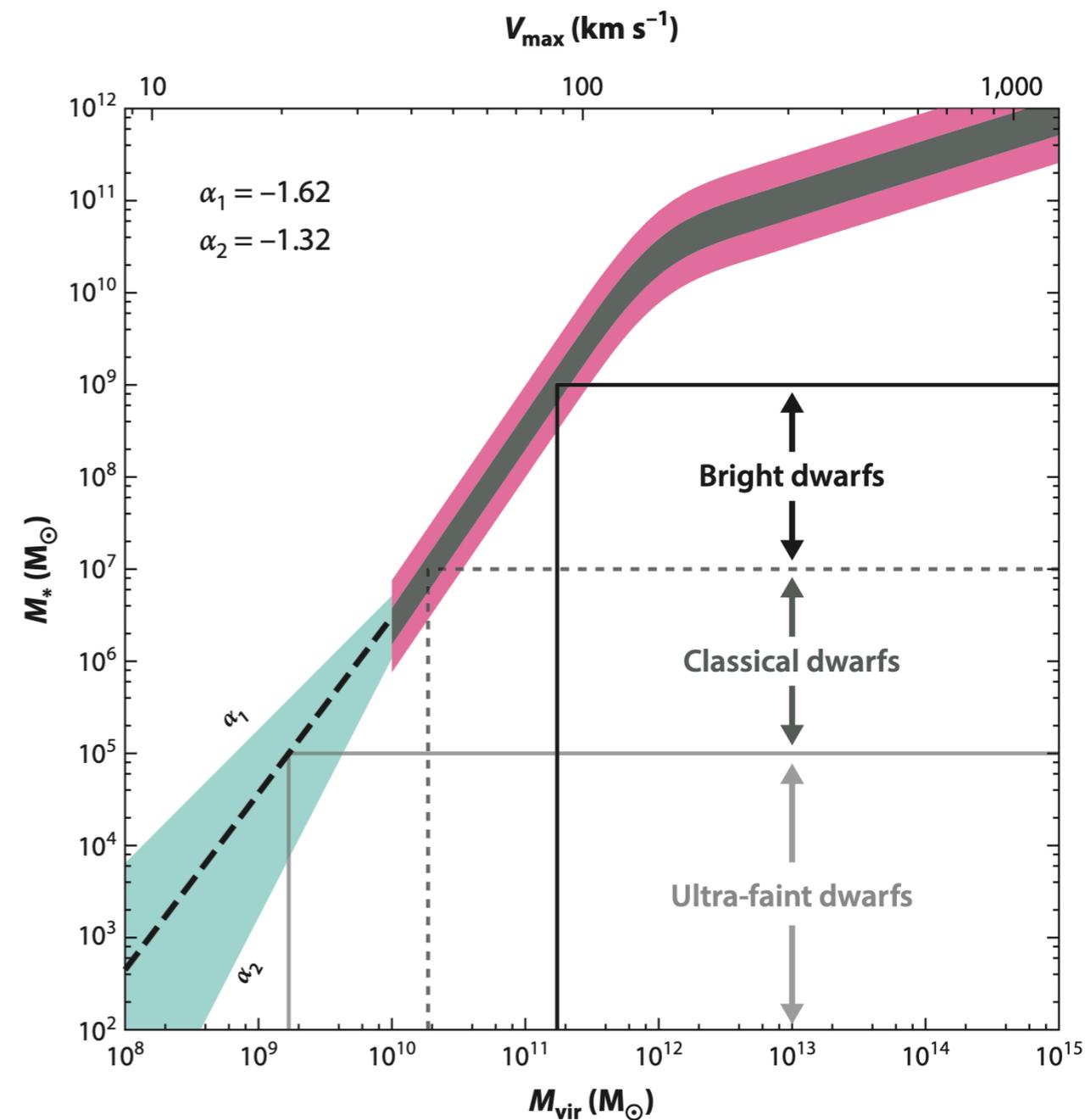
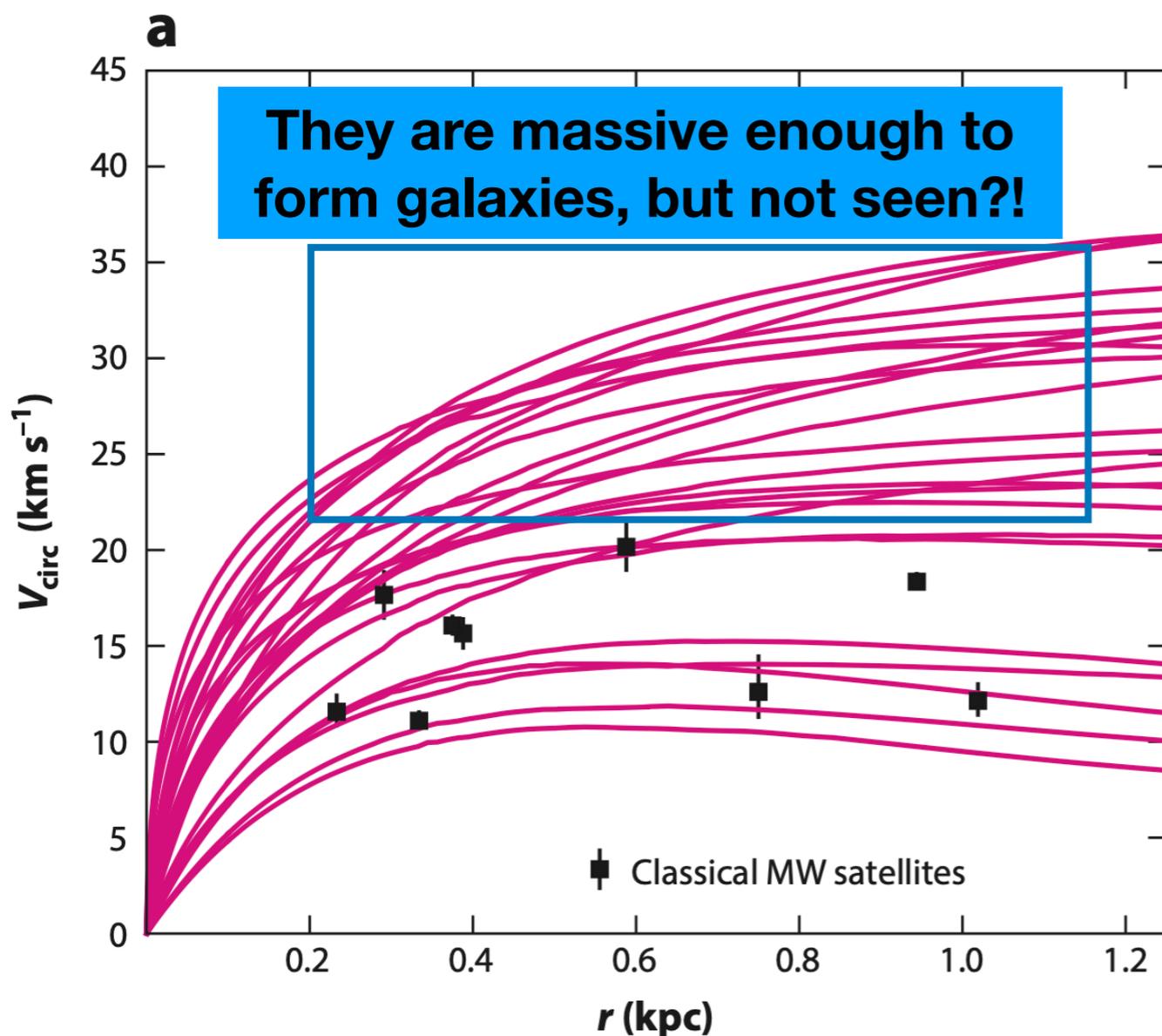
Figure 2.3: *DM profiles* (figure left) and (table right) the corresponding parameters in the parametrizations of the profiles in Table 2.1. The procedure to determine the parameters of the Isothermal profile is different from the other ones, see the text for details. In the table we provide r_s (ρ_s) to 2 (3) significant digits, a precision sufficient for most computations. Still more precise inputs are needed in specific cases, such as to precisely reproduce the J factors (discussed in section 6.2) for small angular regions around the Galactic Center.



Oh et al. (2015)

3. Too-Big-to-Fail (대마불사 大馬不死)

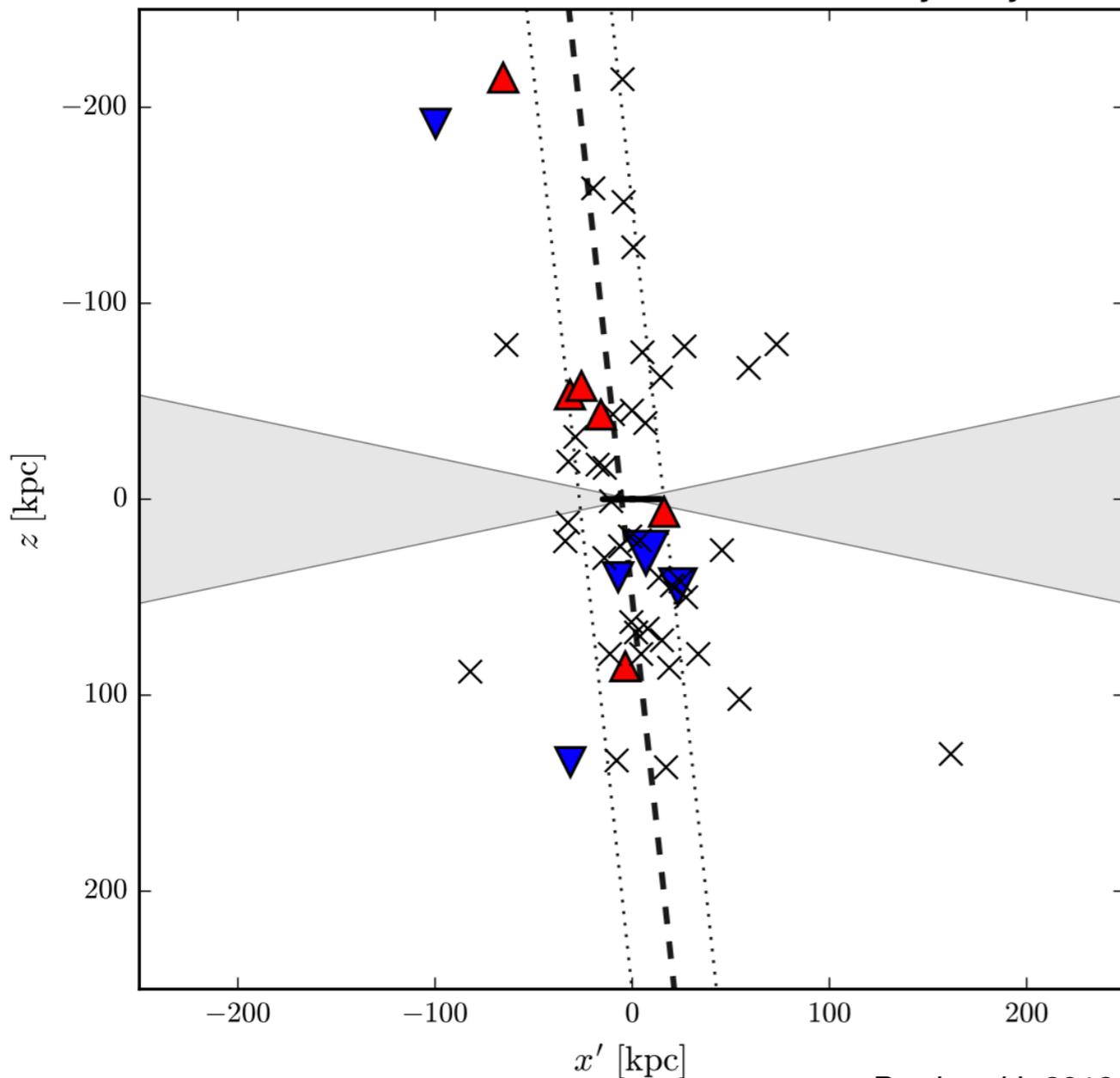
- The local Universe contains too few galaxies with central densities indicative of $M_{\text{vir}} \simeq 10^{10} M_{\odot}$ halos.
- Halos of this mass are generally believed to be too massive to have failed to form stars, so the fact that they are missing is hard to understand.



4. Planes of Satellite Galaxies

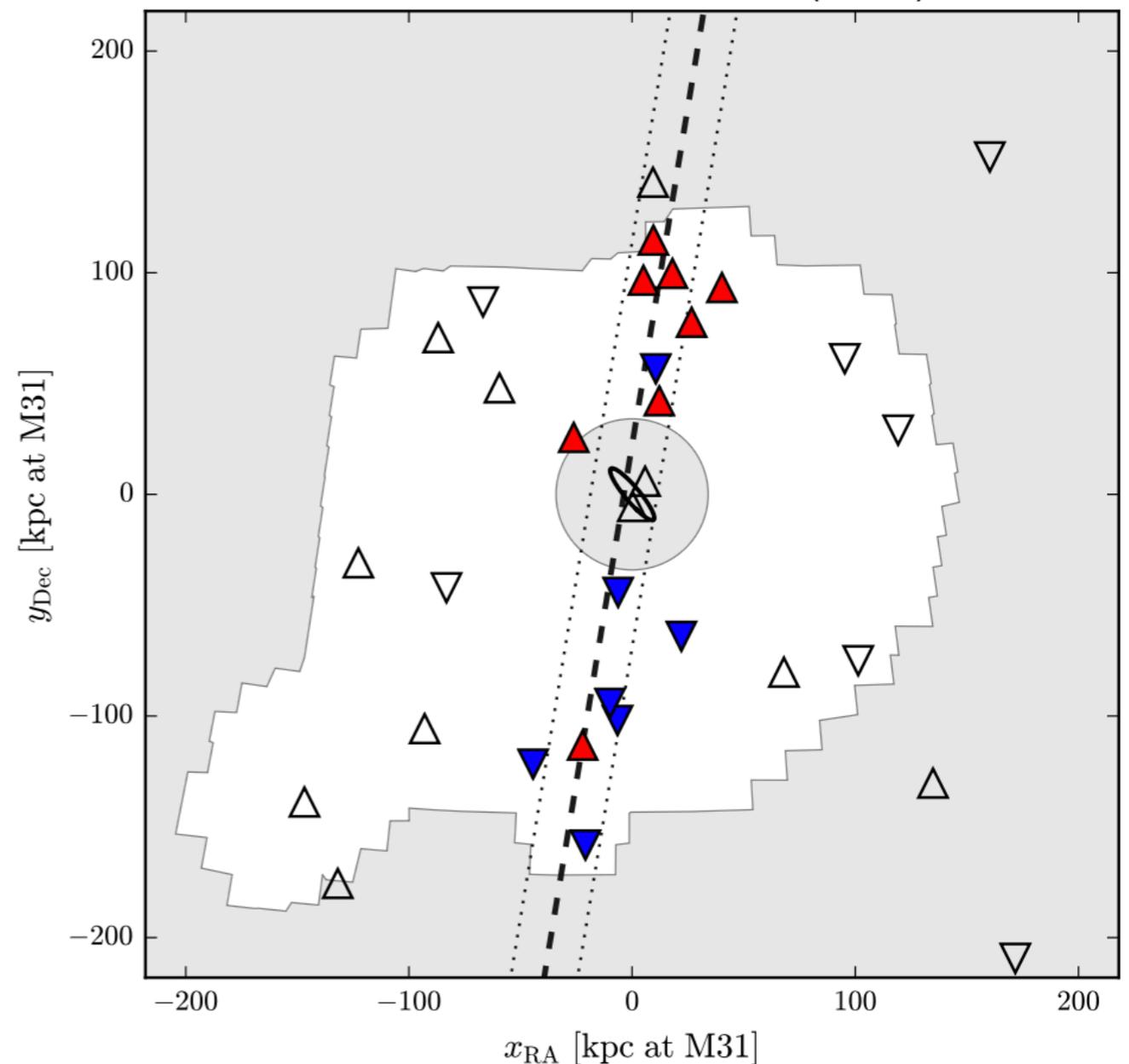
- The orbits of the satellite galaxies of the Milky Way, of M31, and of Centaurus A (CenA), whose properties are well-measured, tend to be aligned in significantly flattened configurations. Moreover, the satellites have significant kinematic correlations. These spatial alignments and kinematic coherence are extremely rare in CDM simulations.
- The combination of the spatial and kinematic coherence has probability $\sim 10^{-3}$ of appearing in CDM simulations.

Vast Polar Structure (VPOS) of the Milky Way



Pawlowski+2018

Great Plane of Andromeda (GPoA)



Observational Challenges to Λ CDM

- Missing Satellite Problem
- Low-Density Cores Versus High-Density Cusps
- Too-Big-to-Fail
- Planes of Satellite Galaxies

- How to solve these problems?
 - Do more realistic simulations: i.e. baryon physics - hydrodynamics for star formation
 - Adopt different dark matter models

- First, why do we need non-baryonic matter for dark matter?

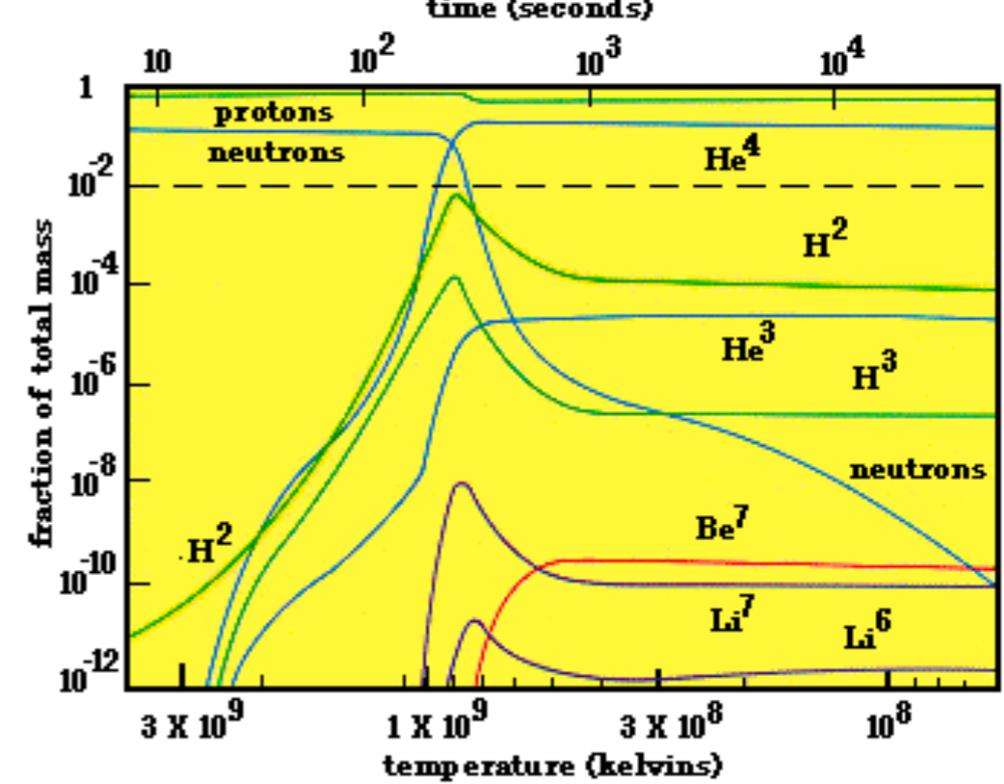
WHY NOT NORMAL MATTER?

Big Bang Nucleosynthesis (BBN) limits the amount of baryons (atoms) in the universe.

- Constraints from Helium and Deuterium abundance fix

$$\Omega_b \lesssim 0.1 \Omega_{\text{crit}}$$

- However, dynamical mass estimates require $\Omega_m \approx 0.30$
- Therefore, Dark Matter **Must** be Non-Baryonic.



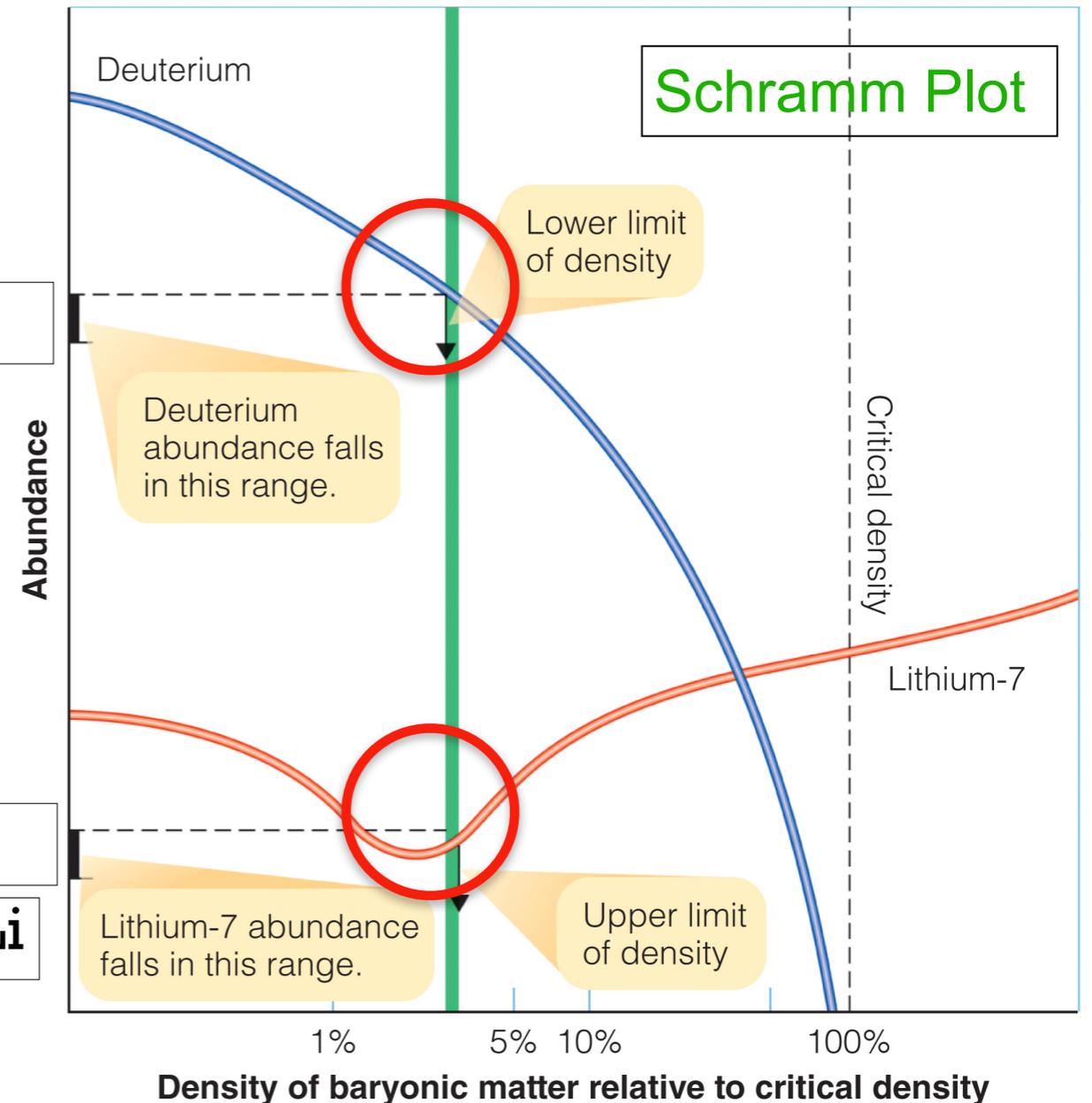
Observation 1: deuterium =>

Candidates Ruled Out:

Gas, Dust, Brown Dwarfs, and Planets (MACHOs) cannot account for the full deficit.

Observation 2: Lithium =>

${}^7\text{Li}$



Thermal History of the Universe

Schramm Plot

Primordial Nucleosynthesis

Baryon content of the Universe

➤ Measurements of the relative strength of the Ly α lines of H and D, which have slightly different transition frequencies due to the different masses of their nuclei, in QSO absorption lines : $D/H \approx 3.4 \times 10^{-5}$

➤ It looks ok, but there was a difference in Lithium abundance between observations (y-axis) and predictions (cross of cyan and purple)! - Cosmological Lithium Problem!

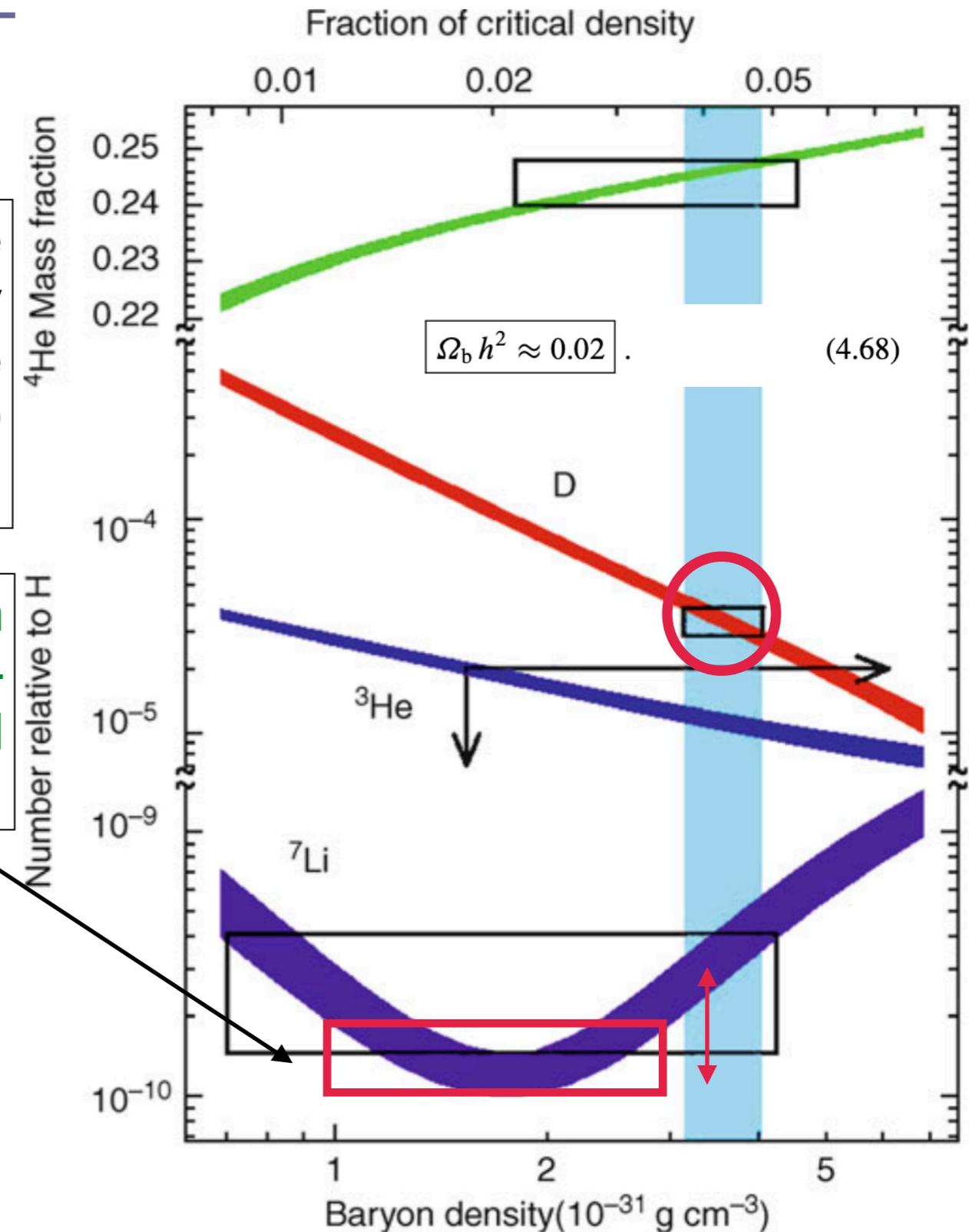


Fig. 4.17 BBN predictions of the primordial abundances of light elements as a function of today's baryon density ($\rho_{b,0}$, lower axis) and the corresponding density parameter Ω_b where $h = 0.65$ was assumed.

4.4 Thermal History of the Universe

[최신뉴스](#)

일 대학졸업반 학생들이 "우주탄생 유력 가설 뒤집었다"

송고 2017-02-14 15:41

"빅뱅 직후 '리튬 부족' 기존 가설로는 설명 불가능"...세계적 권위 미 물리학회지 게재

(서울=연합뉴스) 이해영 기자 = 일본 교토(京都)대학 이(理)학부 졸업반 학생 20여 명이 졸업연구과제로 추진한 물리실험 결과가 학계의 주목을 받고 있다. 이들의 연구결과는 우주의 시작으로 일컬어지는 '대폭발(빅뱅)' 이론의 남은 수수께끼로 꼽혀온 '우주 리튬 문제'에 파문을 일으키는 성과로 평가되고 있다.

14일 아사히(朝日)신문에 따르면 그동안 학계에서 유력시돼온 가설을 뒤집은 이들의 연구논문은 세계적 권위의 미국 물리학회지 이달 3일 자에 실렸다.

빅뱅이론에 따르면 대폭발 직후 수소, 헬륨 등의 원소와 함께 똑같이 가벼운 리튬도 생겨나는 것으로 돼 있다. 그러나 별 관측 등을 통해 파악한 리튬의 양은 이론상 계산된 양의 3분의 1에 불과한 것으로 판명돼 우주탄생 수수께끼의 하나로 남아있다.

4.4 Thermal History of the Universe

학계는 원소주기율표 3번인 리튬의 옆에 있는 4번 베릴륨의 성질에 주목해 왔다. 베릴륨7에 전자가 하나 합쳐지면 리튬으로 바뀐다. 이론상 추정보다 리튬 이외의 원소로 바뀔 확률이 높아 실제 리튬의 양이 이론의 3분의 1밖에 안된다는 게 그동안 유력한 가설이었다. 그렇지만 이 가설은 확인을 위한 실험이 어려워 증명되지 못했다.

가와바타 다카히로 교수를 비롯한 실험팀은 이 점에 착안, 취급이 어렵고 불안정한 헬륨으로도 정밀한 데이터를 얻을 실험방법을 고안해 냈다. "학생들에게 본격적인 연구경험을 쌓도록 해주고 싶어" 2014년 당시 4학년 학생들을 이 실험에 도전하게 했지만, 성과는 바로 나오지 않았다. 실험기구를 개량하는 등 4학년 학생들이 3대에 걸쳐 도전을 계속한 끝에 올해 마침내 훌륭한 데이터를 얻었다.

실험결과 베릴륨이 헬륨으로 바뀔 확률은 높지 않은 것으로 밝혀졌다. 졸업반 학생들은 "기존 가설로는 리튬 부족을 설명할 수 없다"는 결론을 내렸다.

In conclusion, it does not solve the problem, but proved that the promising theory is not correct.

가와바타 교수는 "수수께끼가 더욱 깊어졌다. 우주 리튬 문제에 대해서는 다른 가설을 검토해야 한다"고 말했다. 학계는 유력한 가설을 부정하는 실험결과를 얻은 것을 큰 성과로 평가하고 있다.

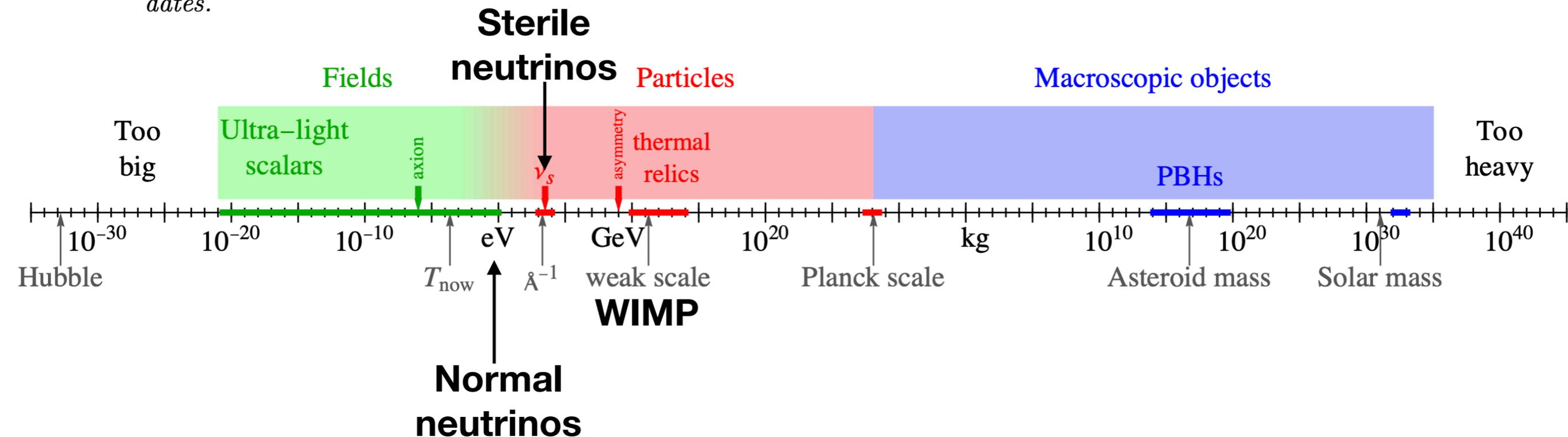
이에 따라 이달 들어 세계적으로 가장 권위 있는 잡지의 하나로 꼽히는 "피지컬 리뷰 래터스"에 논문이 실리게 됐다.

가와바타 교수는 "졸업연구에서 이런 결과가 나오는 일은 좀처럼 없다"고 칭찬했다. 실험에 참가했던 고시카와 아미(23)는 "실험 중 설계한 기구가 망가지지 않을까 조마조마했다"면서 "귀중한 경험을 했지만 엄청난 일을 해냈다는 걸 실감한 건 아주 최근"이라고 말했다.

Dark Matter Candidates

Candidate	Date	Reference(s)	Section
Primordial BH	1966, 1971	Zeldovich & Novikov, Hawking [86]	3.1.1
MACHOs	1981, 1986	Petrou; Paczynski [83]	3.1
<hr style="border-top: 1px dashed black;"/>			
Gravitinos	1981, 1982	Fayet; Witten; Pagel & Primack [100]	10.1.2
Axions	1983	Preskill, Wise & Wilczek [101]	10.4
Neutralinos	1984	Ellis et al. [102]	10.1.2
Strangelets	1984	Witten; Fahri & Jaffe [103]	9.1.2
Q-balls	1984	Witten [104]	10.5.3
Extra-dimensional DM	1984	Kolb & Slansky; Servant & Tait [105]	10.1.3
WIMPs	1985	Steigman & Turner [106]	9.3.3
Sterile neutrinos	1993	Dodelson & Widrow [107]	9.2.2
Fuzzy DM	2000	Hu, Barkana & Gruzinov [108]	3.4
Sub-GeV DM	2003	Boehm, Fayet et al. [109]	4.1.4

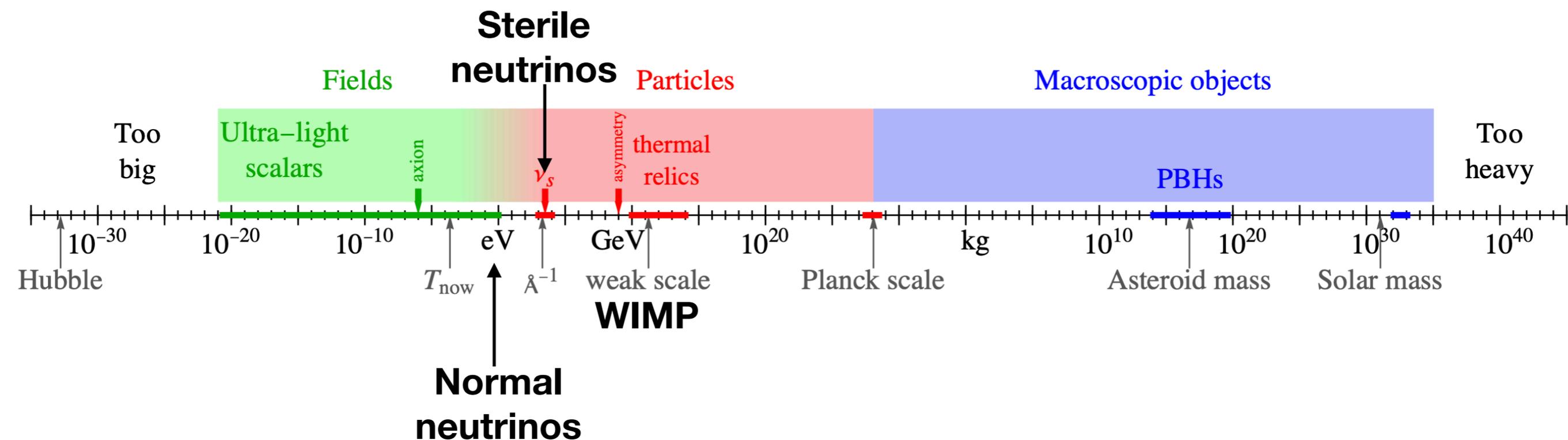
Table 3.1: *Some historic DM candidates (mostly in the particle DM category) or classes of candidates.*



Dark Matter Particles

1. Motivation for Particle Dark Matter

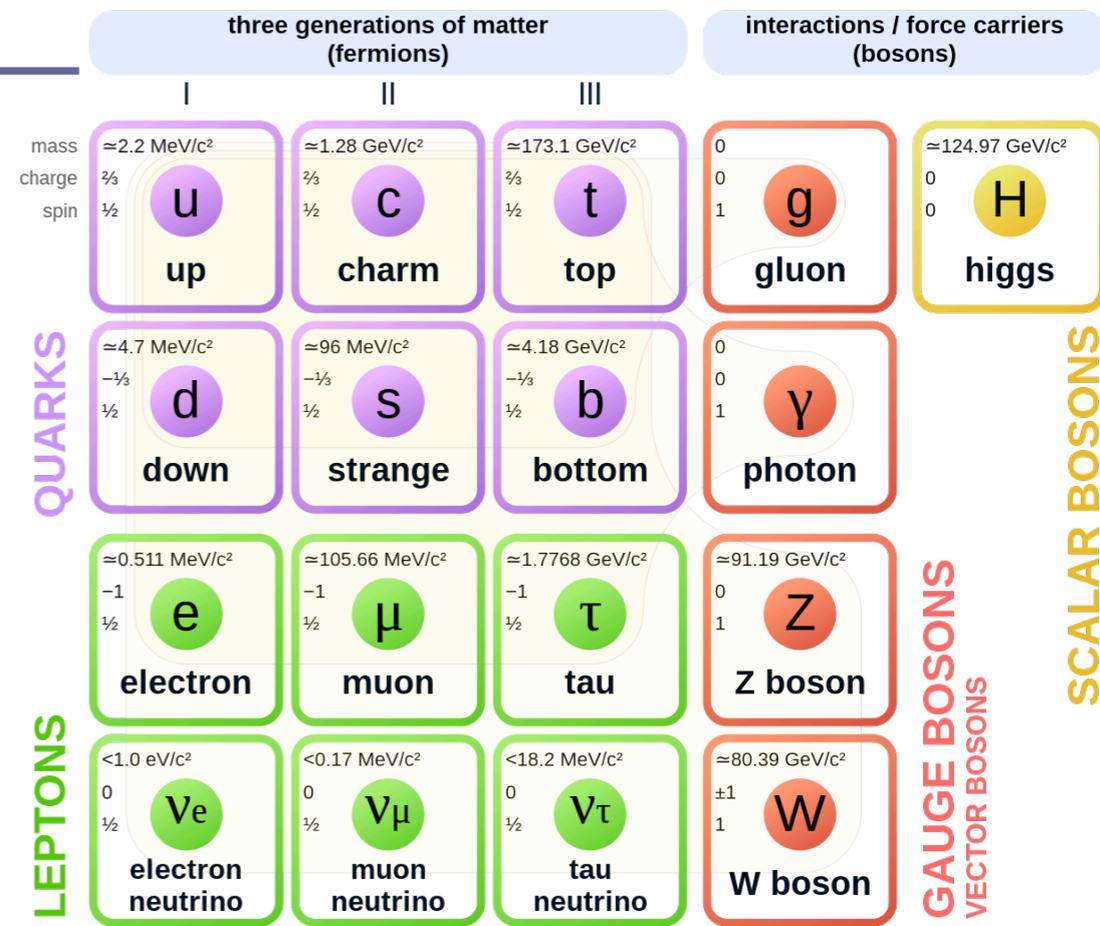
- Astrophysical evidence alone (rotation curves, clusters, CMB anisotropies, structure formation) strongly implies a dominant non-luminous matter component.
- To explain the microphysical nature of this matter - what it is - requires models of new fundamental particles.
- Such particles must be stable (or long-lived), non-baryonic, and non-relativistic (cold) at the era of structure formation to match observations.



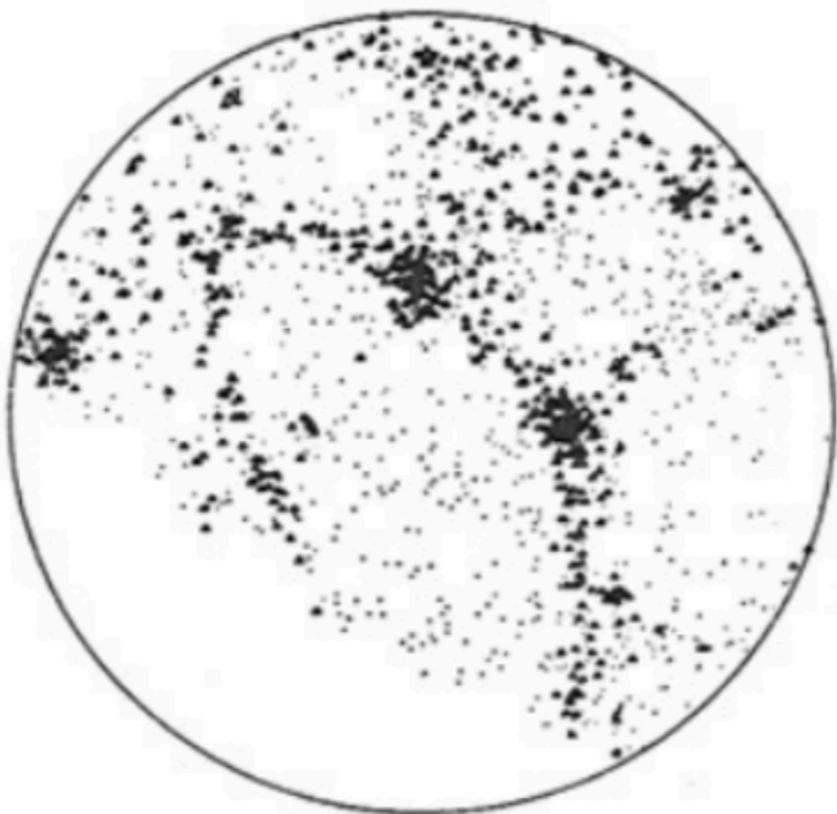
1) Normal (Active) Neutrinos

- Active neutrinos are real and massive, but they are too light to be dark matter.
- Their relativistic free-streaming suppresses small-scale structure, limiting their contribution to a minor hot dark matter component.

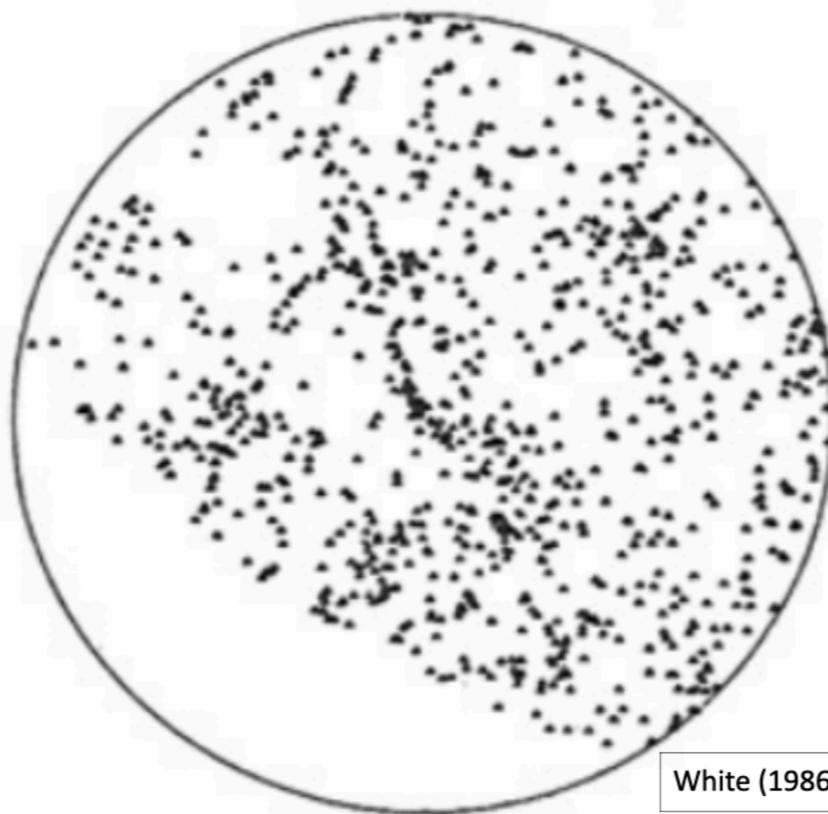
Standard Model of Elementary Particles



Hot Dark Matter



Observed Galaxy Distribution



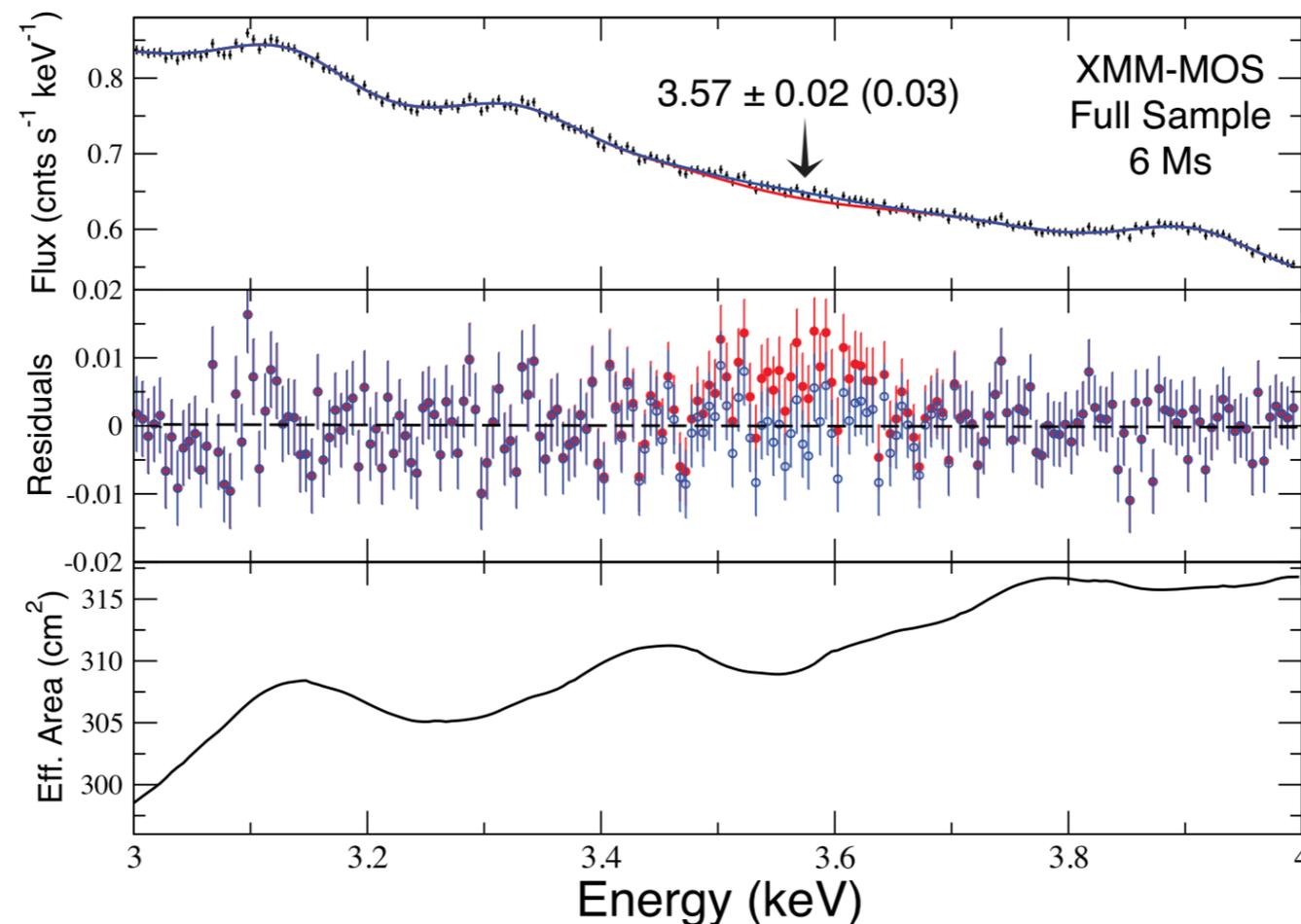
White (1986)

Cold Dark Matter



2) Sterile (Non-Active) Neutrinos

- Neutrino-like particles that do not interact via Standard Model forces (no weak interaction) except gravity and possibly mixing.
- Warm dark matter: if their mass is \sim keV, they behave between hot and cold dark matter, affecting small-scale structures and leaving distinct signatures in galaxy formation.
- Remain viable in some parameter space and motivate X-ray and cosmological searches.
 - **Production:** Mixing with active neutrinos in the early universe.
 - **Decay:** Can decay radiatively into a photon + neutrino.
 - **Anomaly:** X-ray telescopes (Chandra, XMM-Newton) saw a hint of a line at 3.5 keV in galaxy clusters, though it remains controversial (could be Potassium line).



2) Sterile (Non-Active) Neutrinos

K.N. Abazajian / *Physics Reports* 711–712 (2017) 1–28

$$\Gamma_\gamma(m_s, \sin^2 2\theta) \approx 1.36 \times 10^{-30} \text{ s}^{-1} \left(\frac{\sin^2 2\theta}{10^{-7}} \right) \left(\frac{m_s}{1 \text{ keV}} \right)^5$$

$\sin^2 2\theta$: Production rate of sterile neutrinos via oscillations from active neutrinos
 → more sterile neutrinos
 → higher dark-matter abundance.

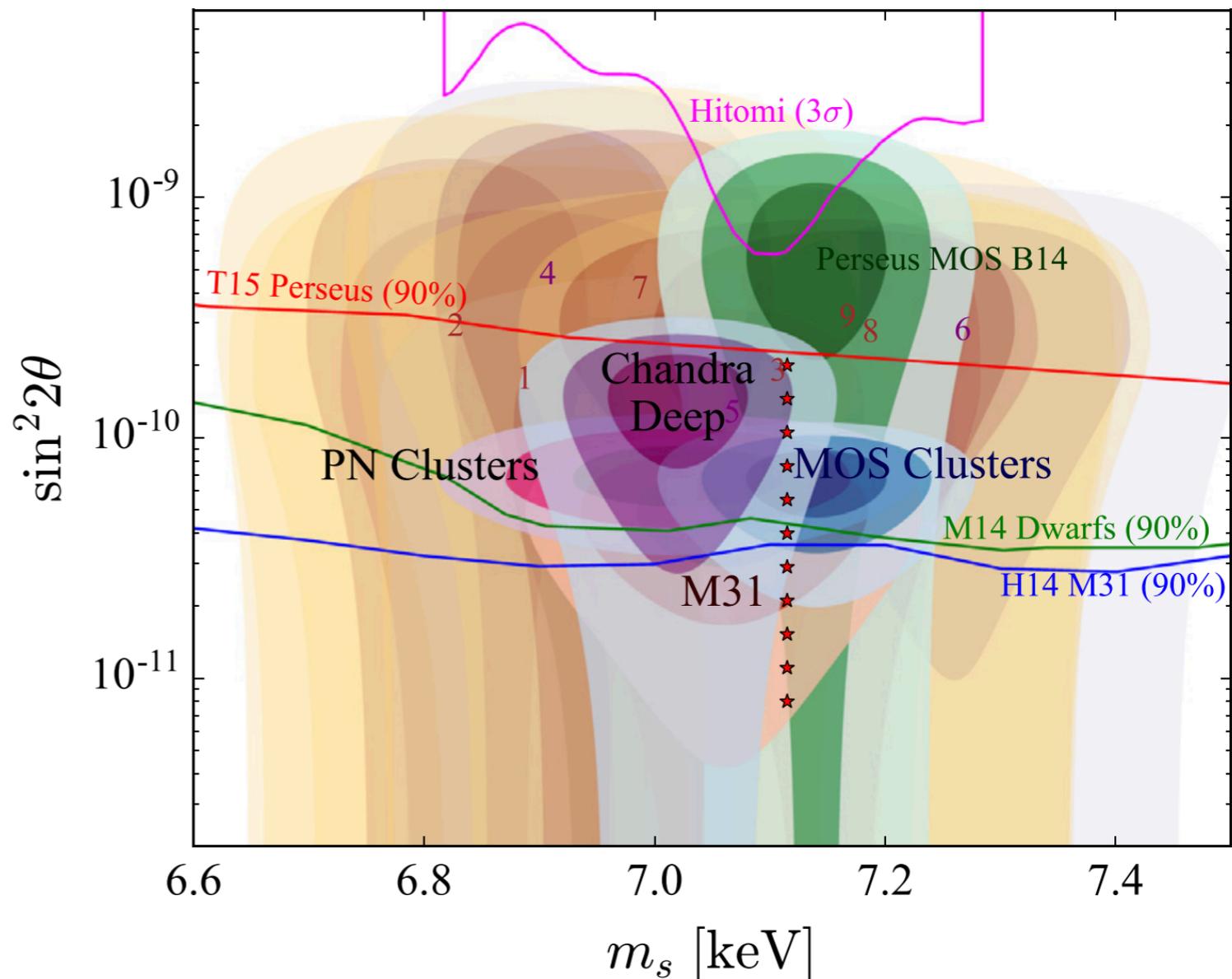


Fig. 7. X-ray line detections consistent with sterile neutrino dark matter are shown here. The dark colored regions are 1, 2 and 3 σ from the MOS (blue) and PN (red) stacked clusters by Bulbul et al. [29], the Bulbul et al. core-removed Perseus cluster (green), and M31 (orange) from Boyarsky et al. [30]. Also shown are the 1 and 2 σ regions of the detection in the Galactic Center (GC) [210] as well as the $> 2\sigma$ line detections in 1. Abell 85; 2. Abell 2199; 3. Abell 496 (MOS); 4. Abell 496 (PN); 5. Abell 3266; 6. Abell S805; 7. Coma; 8. Abell 2319; 9. Perseus by Iakubovskiy et al. [215]. Numbers in the plot mark the centroid of the regions, with MOS detections in orange and PN in purple. We also show, in purple, the region consistent with the signal in *Chandra* Deep Field observations, with errors given by the flux uncertainty, *i.e.*, not including dark matter profile uncertainties [216]. The lines show constraints at the 90% level from *Chandra* observations of M31 (14) [131], stacked dwarf galaxies (M14) [204], and Suzaku observations of Perseus (T15) [205]. Stars mark the models shown in Fig. 4.

3) Weakly Interacting Massive Particles (WIMPs)

- Despite the successes of the (particle physics) standard model, it is known to be incomplete!
 - According to the standard model, neutrinos should be massless - but it is not!
- The standard model needs an extension which allows the existence of a finite neutrino mass.
- There are other issues:
 - it is “technically unnatural” since the energy scale of the Higgs boson, ~ 125 GeV is so much smaller than the Planck mass (10^{19} GeV); gauge hierarchy problem => one needs some new physics at an energy scale of 100 GeV (e.g. quantum gravity?).
 - it can also not explain why there are more baryons than anti-baryons in the current Universe.
- Solution: there exists a electrically neutral particle X which is stable, has a mass of order the energy scale of the model, i.e., somewhere between 100 GeV and 10 TeV, and interacts only weakly - Weakly Interacting Massive Particles (WIMPs)!

➤ At $T_{\text{universe}} \sim m_X c^2 = \mathcal{O}(1 \text{ TeV})$ (i.e. particles are non-relativistic) during thermodynamic equilibrium, the density is described by the Boltzmann factor (+ normalization factor $T^{3/2}$),

Q: Who first introduced WIMPs?

$$n_{X,\text{eq}} \propto (m_X T)^{3/2} e^{-m_X/T}$$

➤ At $T \approx 0.05 m_X$, no more equilibrium (no more production) - freeze out! (i.e. constant comoving density)

➤ If $m_X \approx 300 \text{ GeV}$, the resulting density of these WIMPs would yield $\Omega_X \sim 0.2 \approx \Omega_{\text{dm}}$! - WIMP miracle!

Standard Model of Elementary Particles

	three generations of matter (fermions)			interactions / force carriers (bosons)	
	I	II	III		
mass	$\approx 2.2 \text{ MeV}/c^2$	$\approx 1.28 \text{ GeV}/c^2$	$\approx 173.1 \text{ GeV}/c^2$	0	$\approx 124.97 \text{ GeV}/c^2$
charge	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0	0
spin	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	0
QUARKS	u up	c charm	t top	g gluon	H higgs
	$\approx 4.7 \text{ MeV}/c^2$	$\approx 96 \text{ MeV}/c^2$	$\approx 4.18 \text{ GeV}/c^2$	0	
	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	0	
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	
	d down	s strange	b bottom	γ photon	
	$\approx 0.511 \text{ MeV}/c^2$	$\approx 105.66 \text{ MeV}/c^2$	$\approx 1.7768 \text{ GeV}/c^2$	$\approx 91.19 \text{ GeV}/c^2$	
	-1	-1	-1	0	
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	
LEPTONS	e electron	μ muon	τ tau	Z Z boson	
	$< 1.0 \text{ eV}/c^2$	$< 0.17 \text{ MeV}/c^2$	$< 18.2 \text{ MeV}/c^2$	$\approx 80.39 \text{ GeV}/c^2$	
	0	0	0	± 1	
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson	

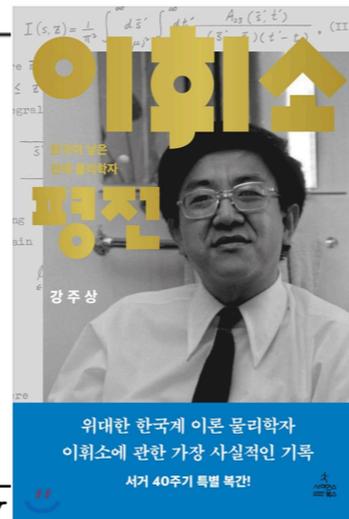
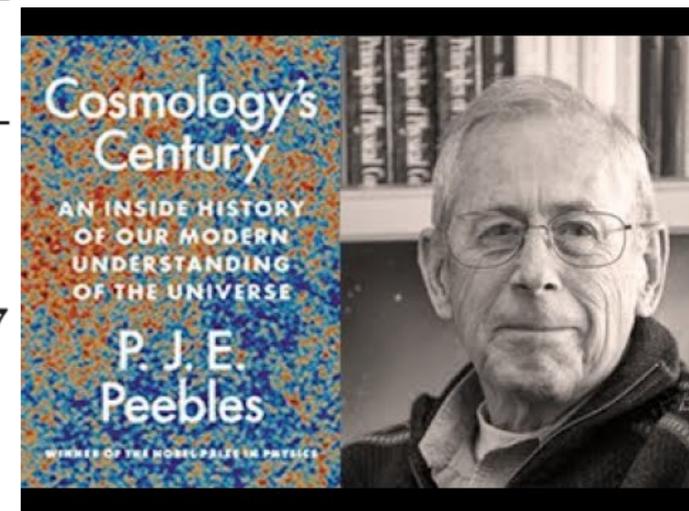
GAUGE BOSONS VECTOR BOSONS

SCALAR BOSONS

3) WIMP

Table 7.1. The 1977 Introduction of the CDM Prototype

Paper	Date received	Date published
Hut (1977)	April 25	July 18, 1977
Lee and Weinberg (1977a)	May 13	July 25, 1977
Sato and Kobayashi (1977)	May 23	December 1, 1977
Dicus, Kolb, and Teplitz (1977)	May 31	July 25, 1977
Vysotskii, Dolgov, and Zel'dovich (1977)	June 30	August 5, 1977



THE ASTROPHYSICAL JOURNAL, 223:1015–1031, 1978 August 1
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SOME ASTROPHYSICAL CONSEQUENCES OF THE EXISTENCE OF A HEAVY STABLE NEUTRAL LEPTON

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Received 1977 December 1; accepted 1978 February 14

ABSTRACT

Recently, high-energy particle theorists have constructed new extended gauge theories which may fit experiment somewhat better than previous already very successful theories. One of the predictions which is often discussed is the possible existence of a stable neutral lepton, probably with a mass of a few GeV/c^2 . Following this motivation we here investigate some cosmological consequences of the existence of any stable, massive, neutral lepton, and show that it could well dominate the present mass density in the universe. The contribution to the mass density depends on the mass of the lepton, which should eventually be determined with high-energy accelerators. It is interesting that the more massive the lepton, the smaller its contribution to the present mass density. It is unlikely that these leptons affect big bang nucleosynthesis or condense into stellar size objects. However, such a lepton is an excellent candidate for the material in galactic halos and for the mass required to bind the great clusters of galaxies. Annihilation radiation from these structures should be detectable. At the end of the paper a brief mention is made of the astrophysical constraints on the mass-lifetime relationship if the neutral lepton is unstable.

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Cosmological Lower Bound on Heavy-Neutrino Masses

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(Received 13 May 1977)

The present cosmic mass density of possible stable neutral heavy leptons is calculated in a standard cosmological model. In order for this density not to exceed the upper limit of $2 \times 10^{-29} \text{ g/cm}^3$, the lepton mass would have to be greater than a lower bound of the order of 2 GeV.

4) Self Interacting Dark Matter

- Self-Interacting Massive Particles (SIMPs) and other strongly interacting dark matter classes are considered to address galactic dynamics or small-scale structure without contradicting large-scale constraints.
- These particles interact strongly among themselves but weakly with ordinary matter, thereby affecting halo structure differently from collisionless dark matter.

VOLUME 84, NUMBER 17

PHYSICAL REVIEW LETTERS

24 APRIL 2000

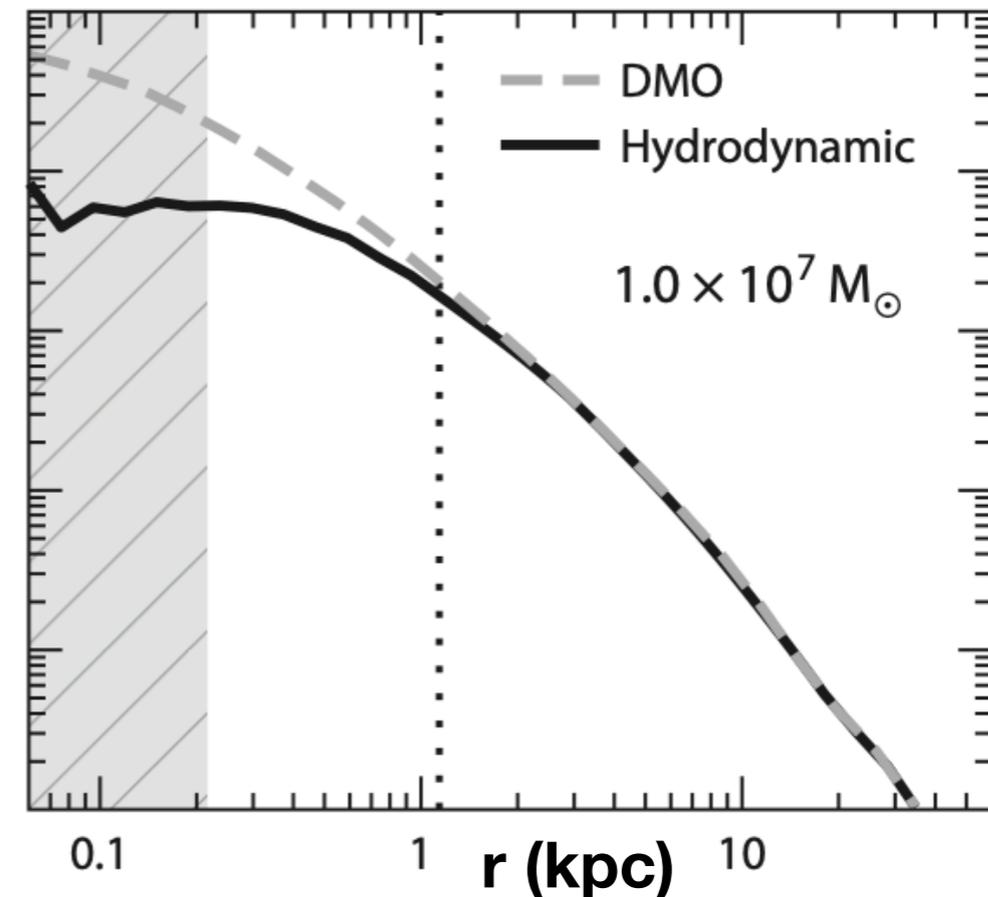
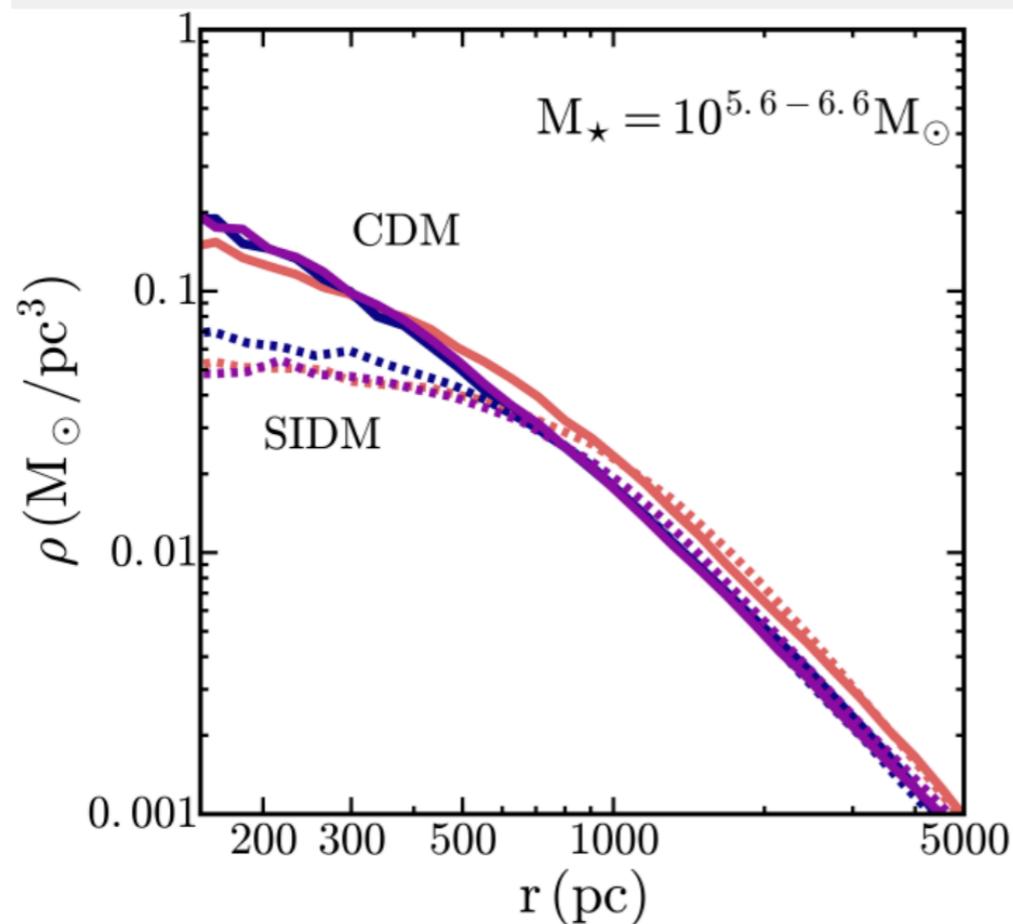
Observational Evidence for Self-Interacting Cold Dark Matter

David N. Spergel and Paul J. Steinhardt

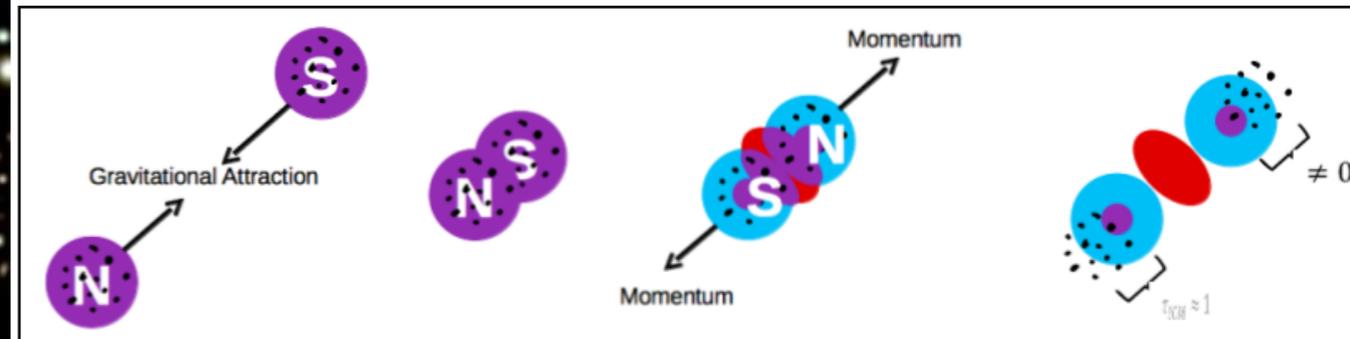
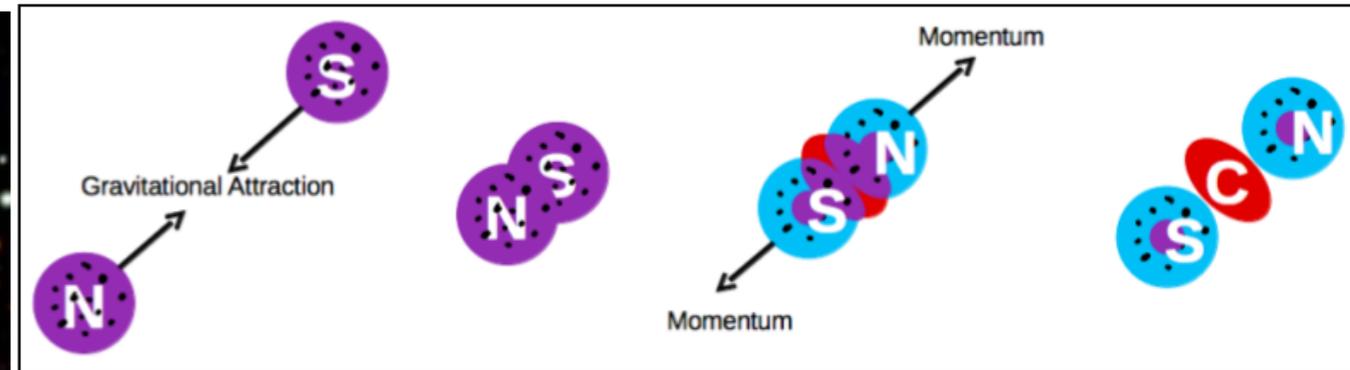
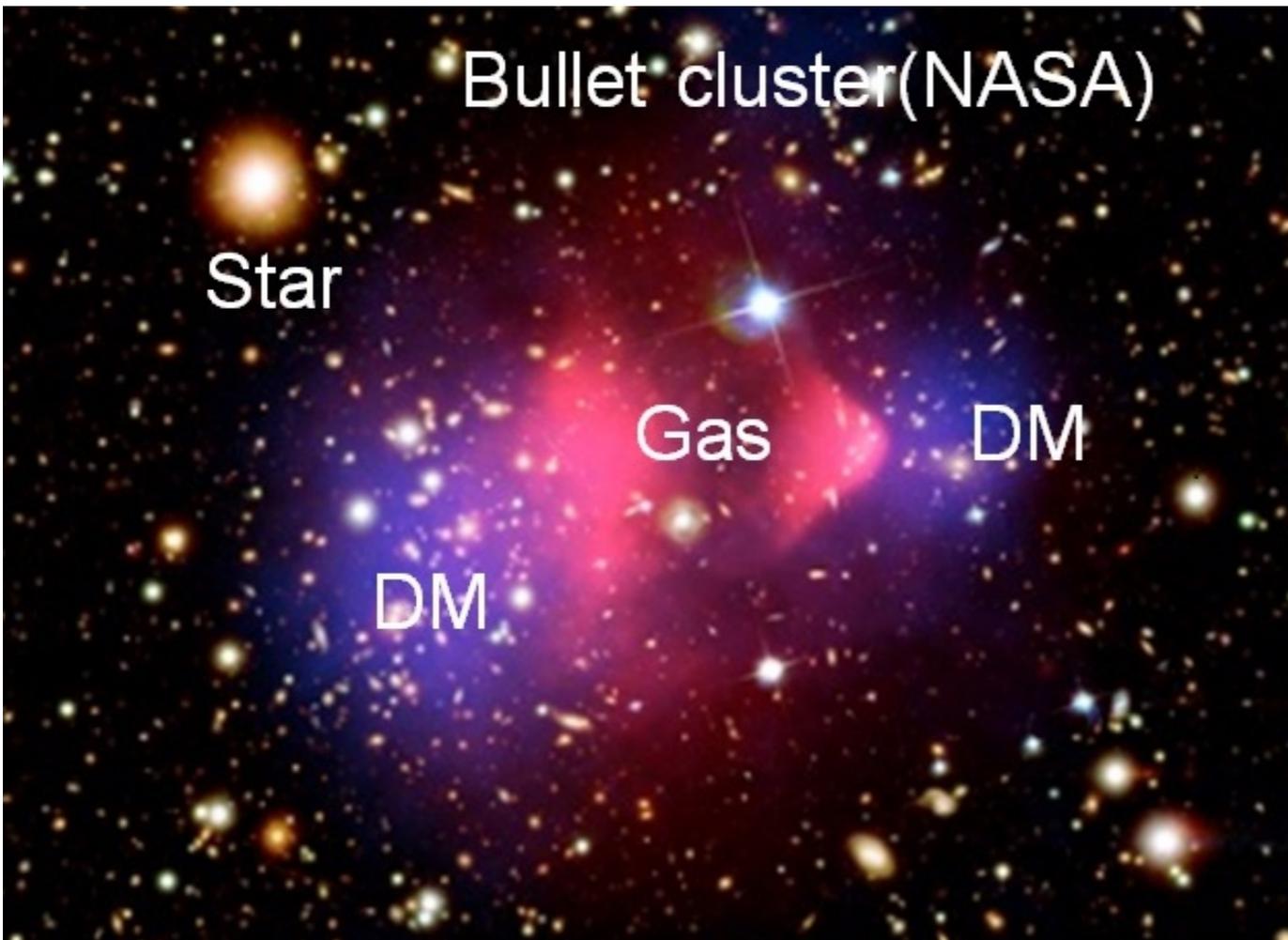
Princeton University, Princeton, New Jersey 08544

(Received 20 September 1999)

Cosmological models with cold dark matter composed of weakly interacting particles predict overly dense cores in the centers of galaxies and clusters and an overly large number of halos within the Local Group compared to actual observations. We propose that the conflict can be resolved if the cold dark matter particles are self-interacting with a large scattering cross section but negligible annihilation or dissipation. In this scenario, astronomical observations may enable us to study dark matter properties that are inaccessible in the laboratory.



4) Self Interacting Dark Matter



From Bullet Cluster: $\sigma/m \lesssim 0.2 \text{ cm}^2\text{g}^{-1}$ (Cha+2025)

1. Missing Satellite Problem: Solutions?

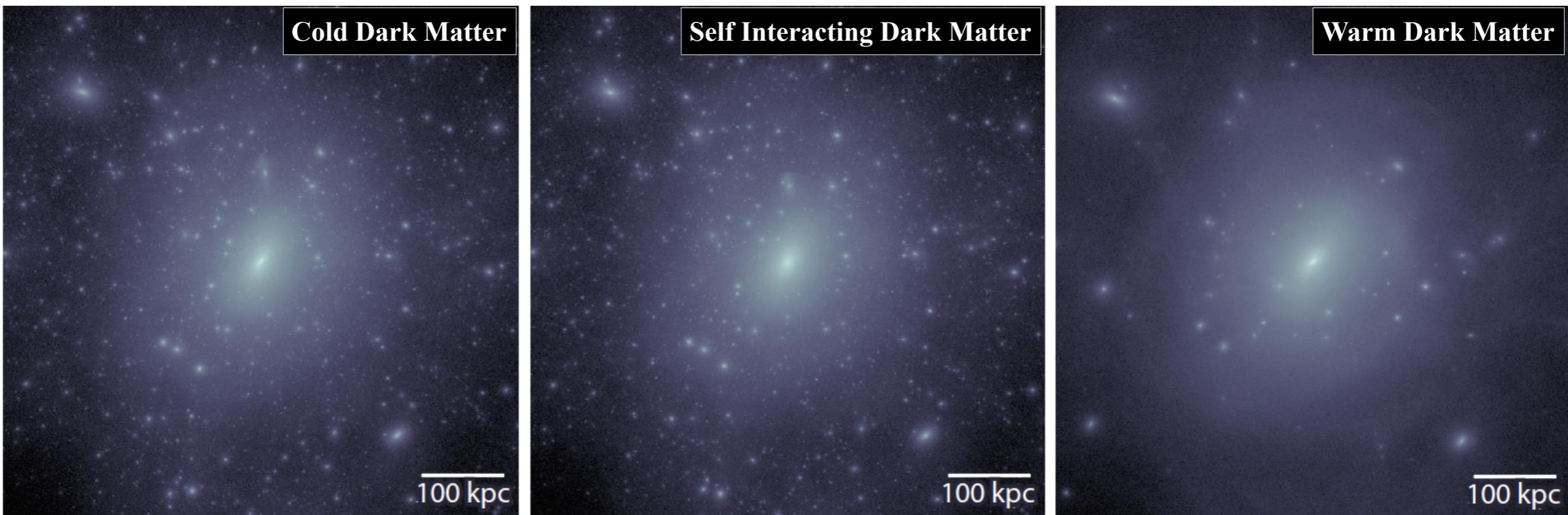
1. Different Dark Matter Model?

1. Cold Dark Matter
2. Warm Dark Matter
3. Self-Interacting Dark Matter?
4. ...

2. Implementation of Baryonic physics (i.e. galaxy formation mechanism)?

1. Dark matter only simulations
2. Not all dark matter halos form galaxies
3. Role of Baryonic physics
⇒ Cosmological Hydrodynamic Simulation!

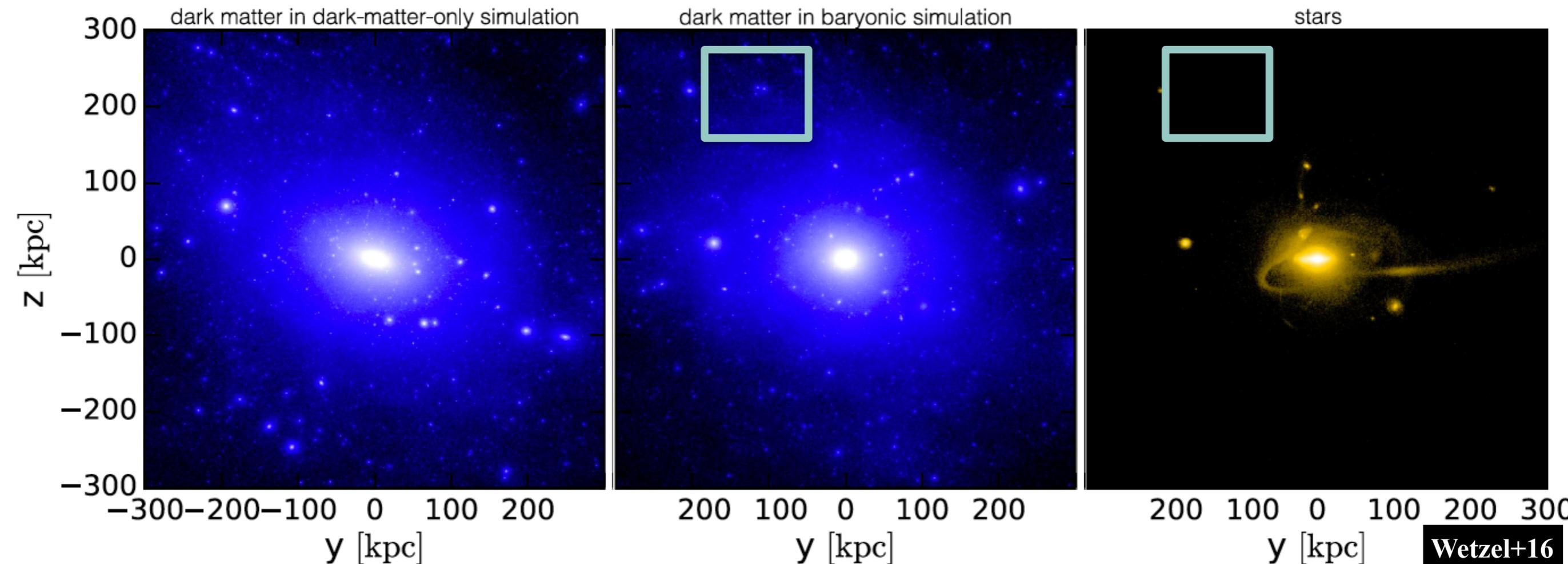
Effects of Dark Matter: Different Structure Formation Depending on Dark Matter Properties



Bullock & Boylan-Kolchin 17

Clearly Different Dark Matter models make differences!

Λ CDM: 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)**

5) Axions and Axion-like Particles

➤ Axions were originally proposed to solve the strong CP (charge + parity) problem in QCD (quantum chromodynamics), and later recognized as excellent dark matter candidates (you need to ask particle physicist for details).

➤ They are very light, weakly interacting bosons produced non-thermally (e.g., via the misalignment mechanism), and can behave like cold dark matter despite low mass.

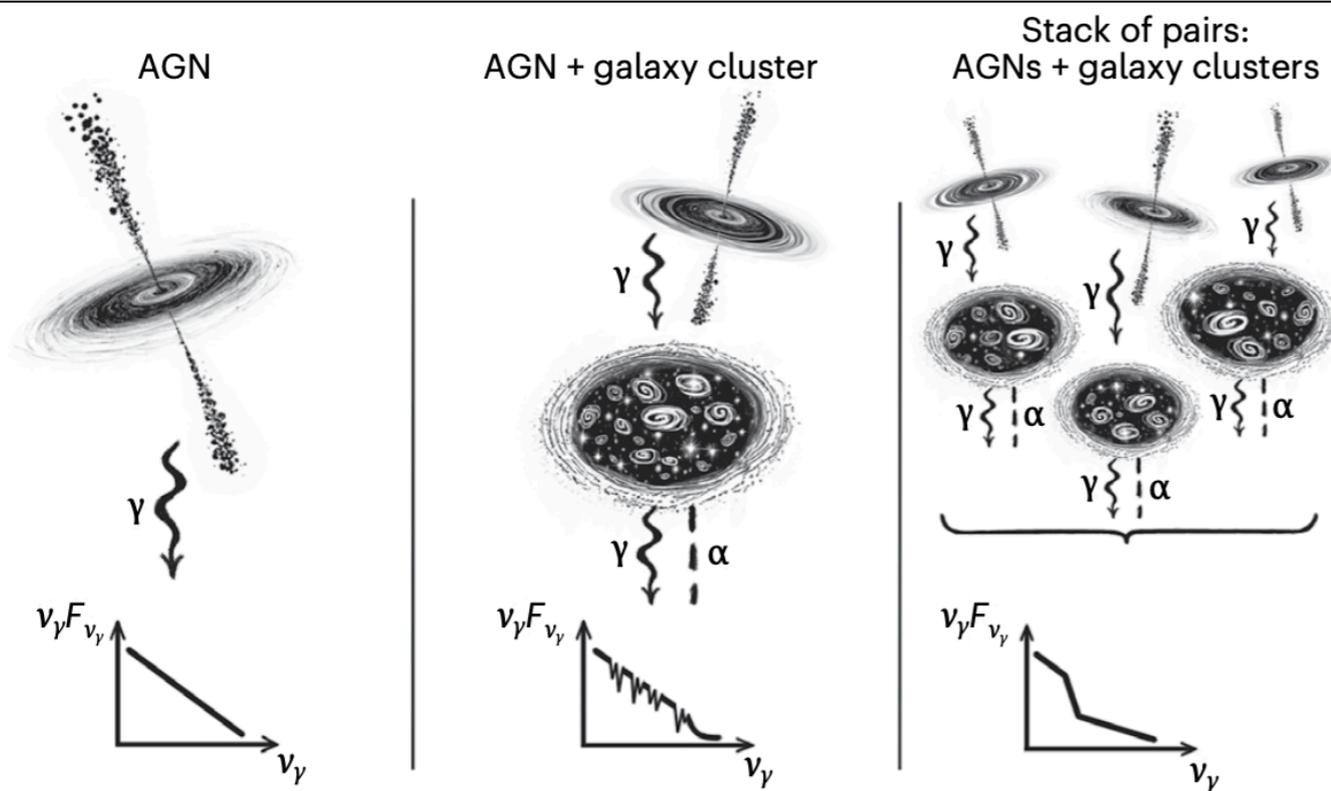


Fig. 1 | Illustration of how stacking spectra reveals information about photon-to-ALP conversion. Left: AGNs have featureless spectra of γ -ray emission. If ALPs exist in nature, some of the AGN photons will be converted to ALPs while passing through galaxy clusters that are large reservoirs of magnetic fields. Such a photon-to-ALP conversion creates a set of absorption features in the AGN spectra. Centre: for each particular AGN, these features cannot be predicted due to the lack of detailed knowledge about the magnetic field in individual clusters. Right: by stacking many observational pairs (AGNs plus clusters), the overall absorption feature becomes regularly shaped. ν_γ , photon frequency; F_{ν_γ} , spectral flux density.

Detection of Axion-Like Particles from astronomical observations
(Malyshev+2025)

6) Ultralight Bosons (“Fuzzy Dark Matter”)

- Models with ultralight scalar particles (mass $\lesssim 10^{-21}$ eV) have re-emerged to address small-scale structure tensions (e.g., cores vs cusps in dwarf galaxies).
- This "Fuzzy" nature prevents structure formation below the wavelength scale.
- At such tiny masses, quantum pressure produces wave-like dark matter halos with cores.
- These models can alleviate some discrepancies between cold dark matter predictions and observations at galactic scales.

Because of the **de Broglie wavelength**:

$$\lambda_{\text{dB}} = \frac{h}{mv}$$

For a particle with:

- $m \sim 10^{-22}$ eV
- $v \sim 10^{-3}c$ (typical galactic velocities)

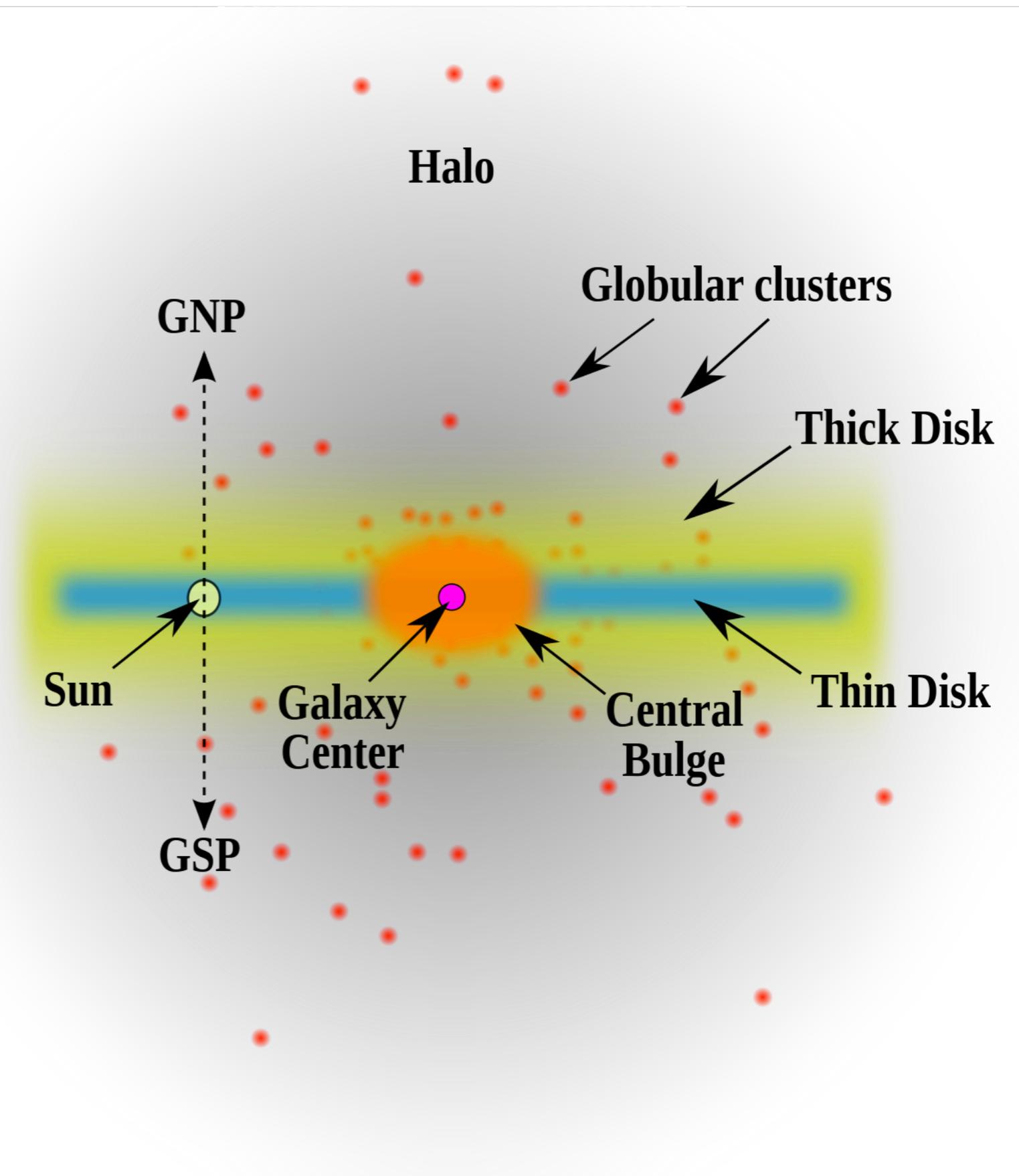
you get:

$$\lambda_{\text{dB}} \sim \text{kpc}$$

➔ **The wavelength is comparable to galaxy cores**

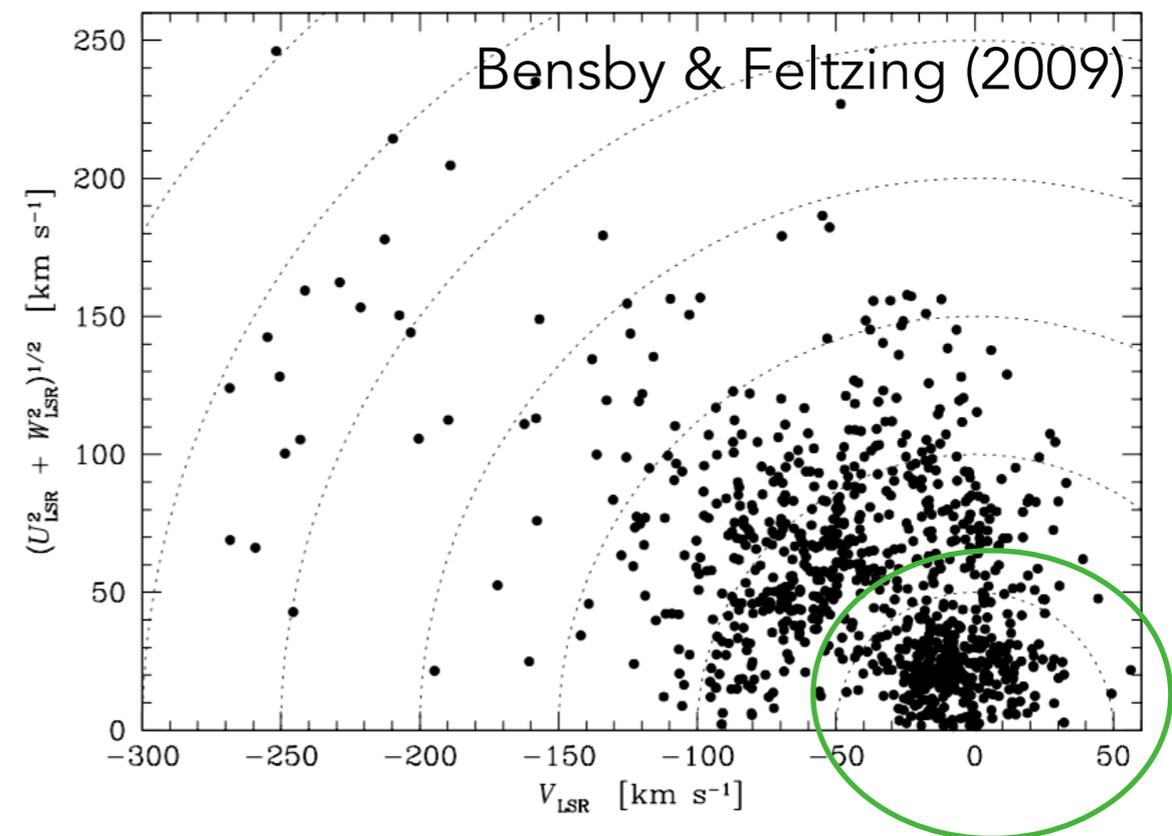
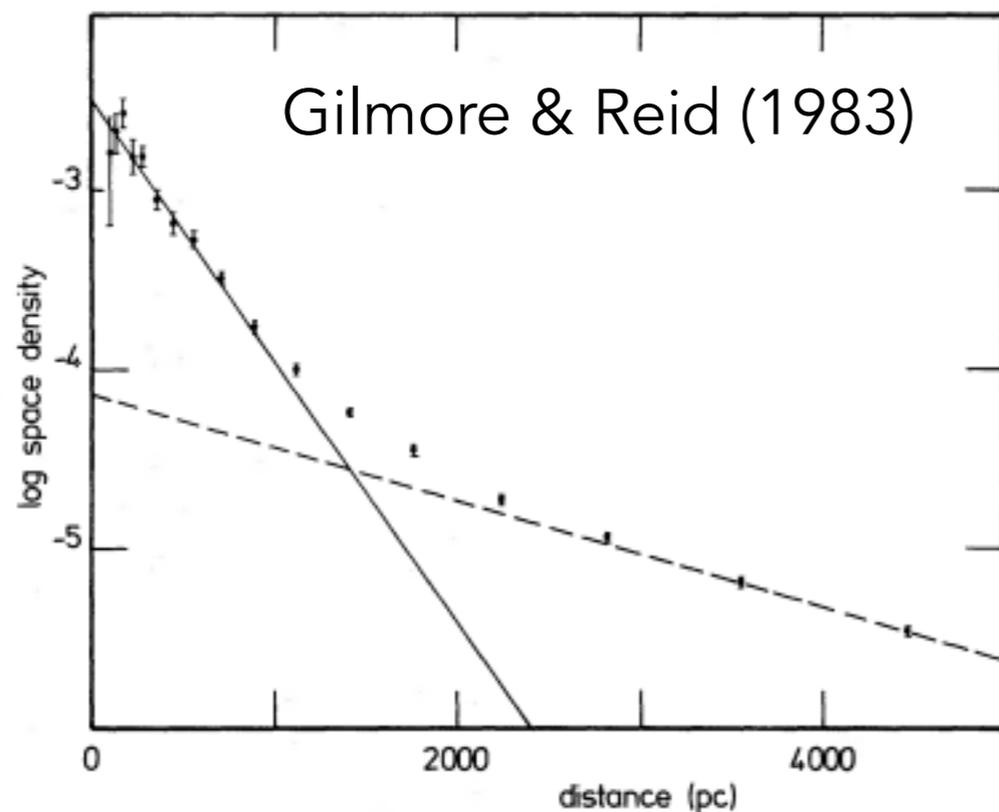
DM - More than one type?

Milky Way - Disk Galaxy

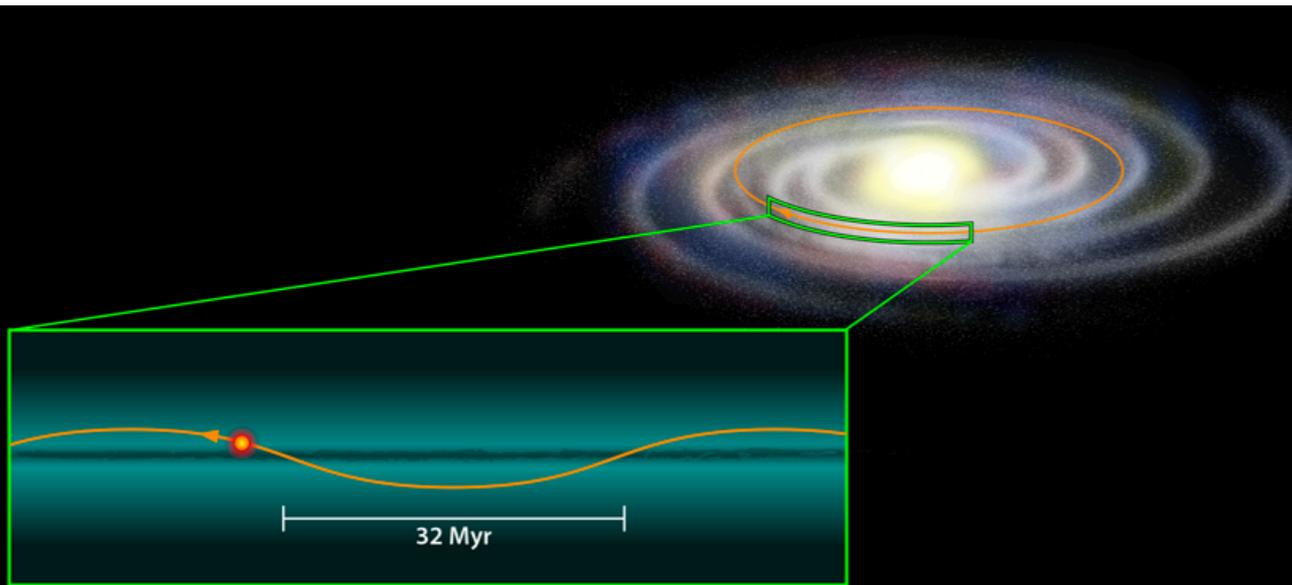


Disk of the Milky Way: General structure

- Thin disk (young stars, H I, CO, star clusters, OB associations)
 - Young thin disk : $h_z \sim 100$ pc
 - Old thick disk: $h_z \sim 325$ pc
- Thick disk (old stars) : $h_z = 1.5$ kpc, only 2% of the total mass
- Gaseous disk : $h_z = 65$ pc

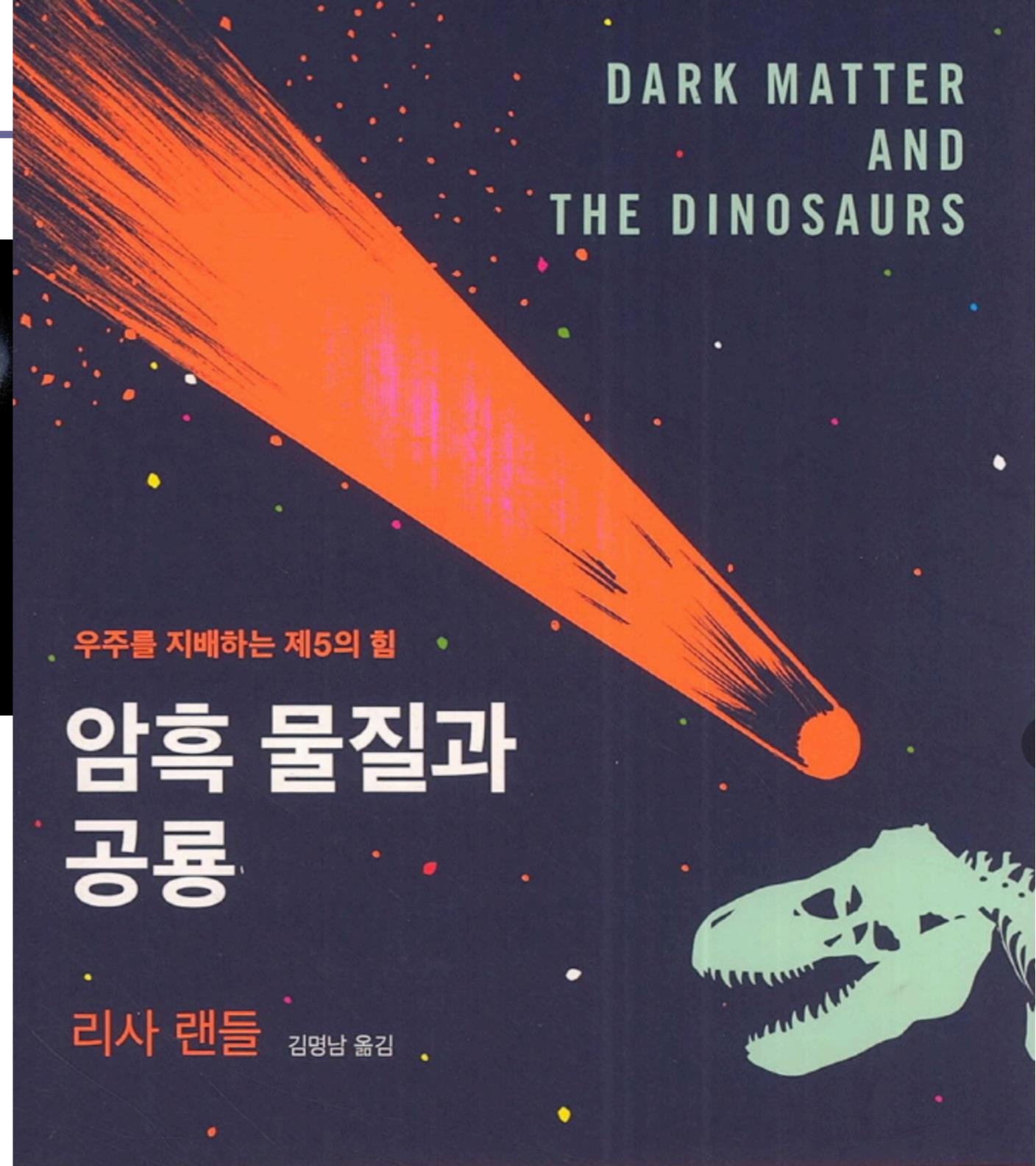


Disk Galaxies



Dark matter disk:
height - 50 pc or less

- Thin disk (young stars, H I, CO, star clusters, OB associations)
 - Young thin disk : $h_z \sim 100$ pc
 - Old thick disk: $h_z \sim 325$ pc
- Thick disk (old stars) : $h_z = 1.5$ kpc, only 2% of the total mass
- Gaseous disk : $h_z = 65$ pc



물리학 여신이 밝혀낸 공룡 멸종의 수수께끼!

물리학, 천문학, 지질학, 고생물학을 관통하는 유쾌한 모험!

—킵 손(캘리포니아 공과 대학 교수, 「인터스텔라의 과학」 저자)

암흑 물질과 여분 차원의 물리학이 밝히는 우주 생명의 비밀



Dark-Disk Universe

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(Received 5 March 2013; revised manuscript received 22 April 2013; published 23 May 2013)

We point out that current constraints on dark matter imply only that the majority of dark matter is cold and collisionless. A subdominant fraction of dark matter could have much stronger interactions. In particular, it could interact in a manner that dissipates energy, thereby cooling into a rotationally supported disk, much as baryons do. We call this proposed new dark matter component double-disk dark matter (DDDM). We argue that DDDM could constitute a fraction of all matter roughly as large as the fraction in baryons, and that it could be detected through its gravitational effects on the motion of stars in galaxies, for example. Furthermore, if DDDM can annihilate to gamma rays, it would give rise to an indirect detection signal distributed across the sky that differs dramatically from that predicted for ordinary dark matter. DDDM and more general partially interacting dark matter scenarios provide a large unexplored space of testable new physics ideas.

Dark Matter Detection

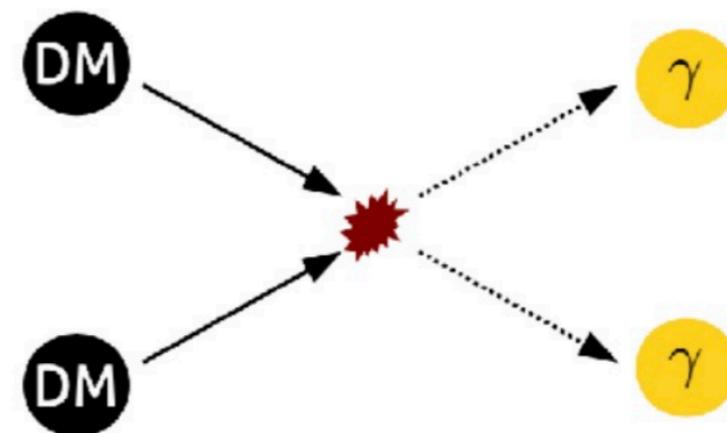
1. 직접검출

1. 우리 주변 암흑물질이 지하의 검출기에 있는 원자핵에 부딪혀서 얻게 되는 원자핵의 변화를 측정하는 것

2. 간접검출

1. 우리 은하나 그 밖에 존재하는 암흑물질이 소멸하거나 붕괴할 때 나오는 대전된 입자나 중성미자 또는 감마선, 엑스선과 같은 신호를 검출하는 것.

Two-body annihilation into photons



3. 가속기에서 검출

1. 거대강입자가속기(Large Hadron Collider, LHC)와 같은 고에너지 가속기에서 양성자를 가속하여 서로 충돌시킬 때, 암흑물질이 만들어지고 검출기에는 반응을 하지 않으므로 사라진 에너지의 양으로부터 간접적으로 암흑물질을 검출하는 것.

1. Direct Detection

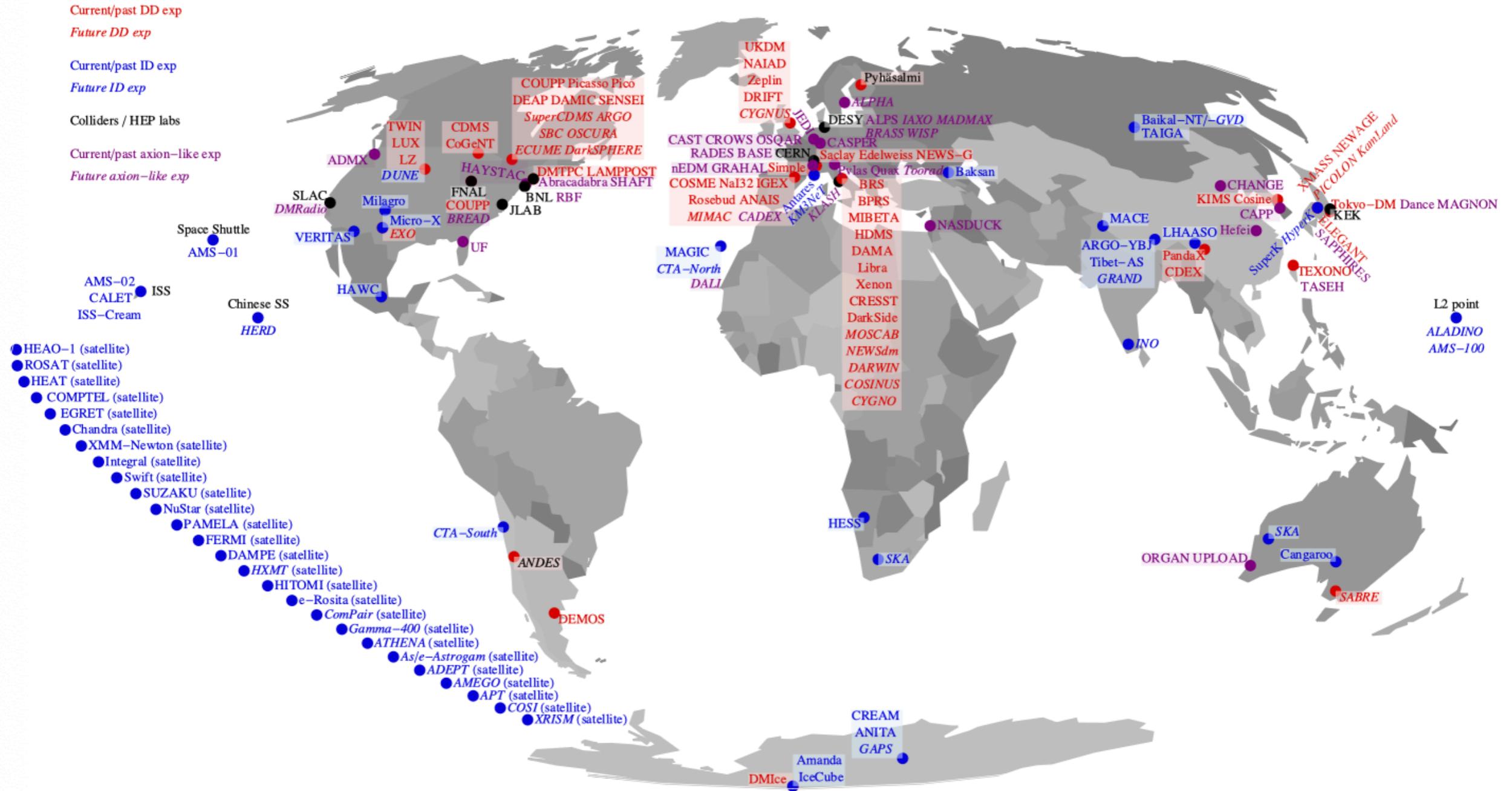
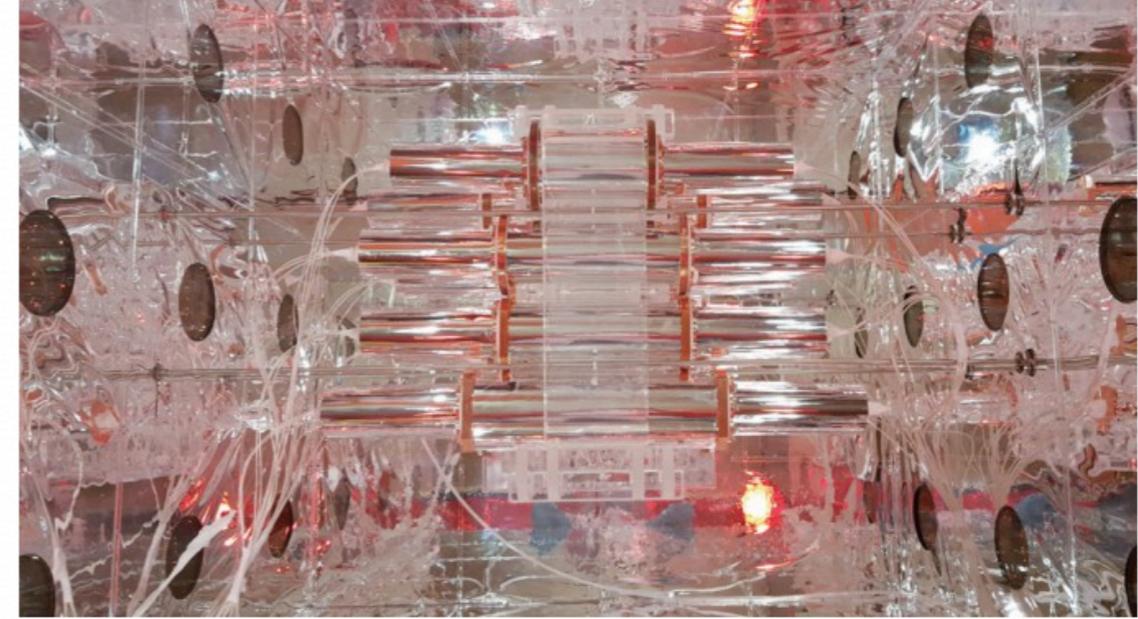
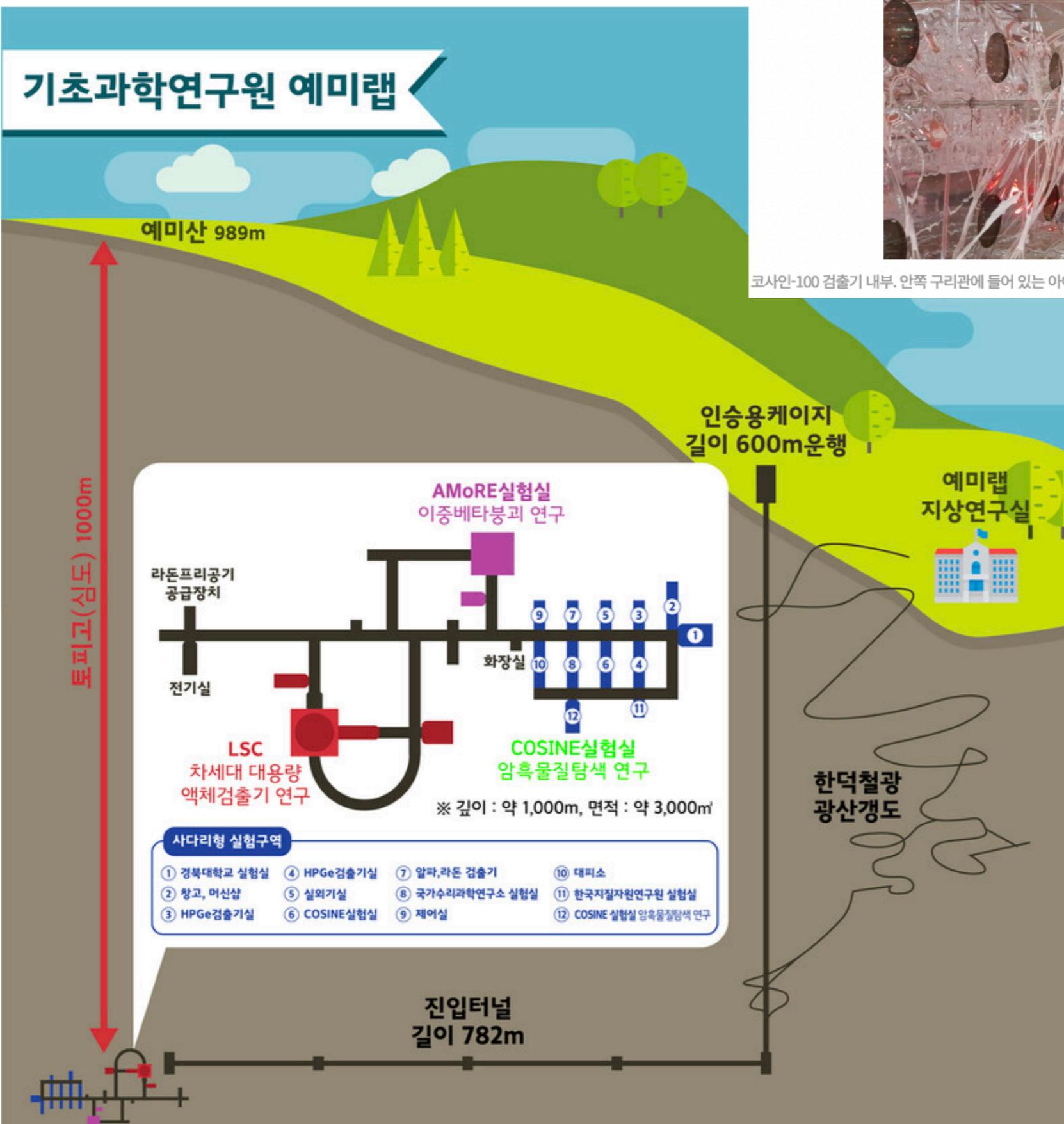


Figure 4.7: The *experiments* trying to detect particle DM are performed all over the Earth (on surface as well as below ground and in orbit).

1. Direct Detection



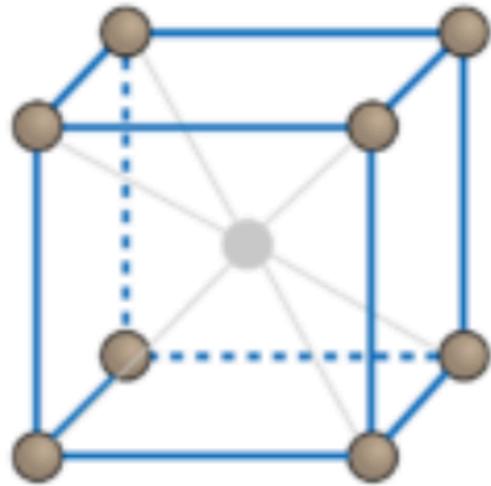
코사인-100 검출기 내부. 안쪽 구리관에 들어 있는 아이오딘화나트륨 원자핵이 암흑물질과 충돌해 빛을 방출하면 검출기가 이 빛을 감지한다. IBS 지하실험연구단 제공



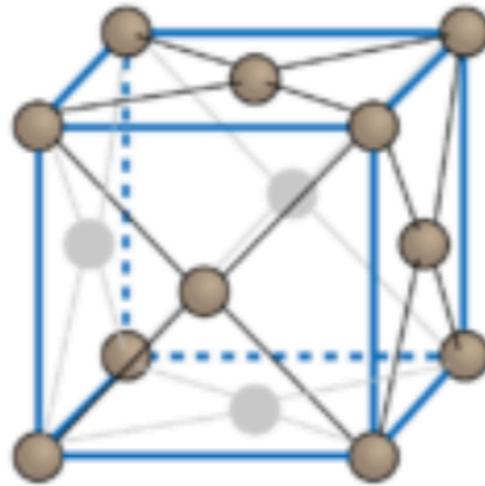
Solid-state crystals

Bonds and bands in silicon

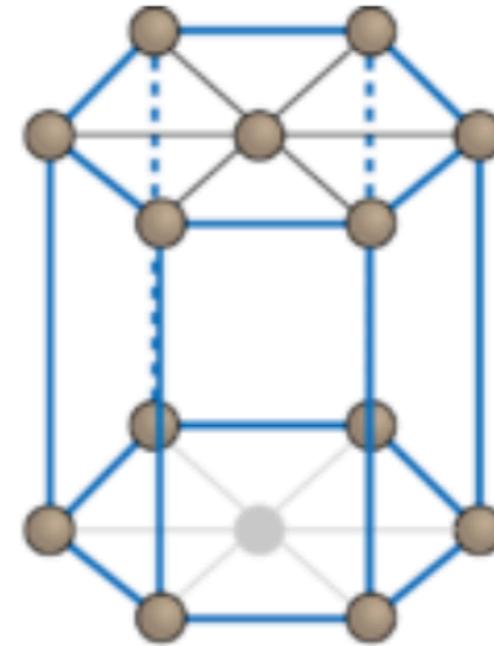
- A crystal: a mega-molecule in which the pattern of atoms and bonds repeats periodically with location



Cubic body centered (bcc)
Fe, V, Nb, Cr



Cubic face centered (fcc)
Al, Ni, Ag, Cu, Au

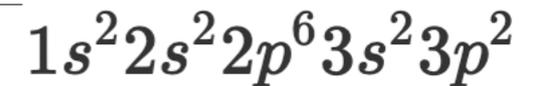


Hexagonal
Ti, Zn, Mg, Cd

Solid-state crystals

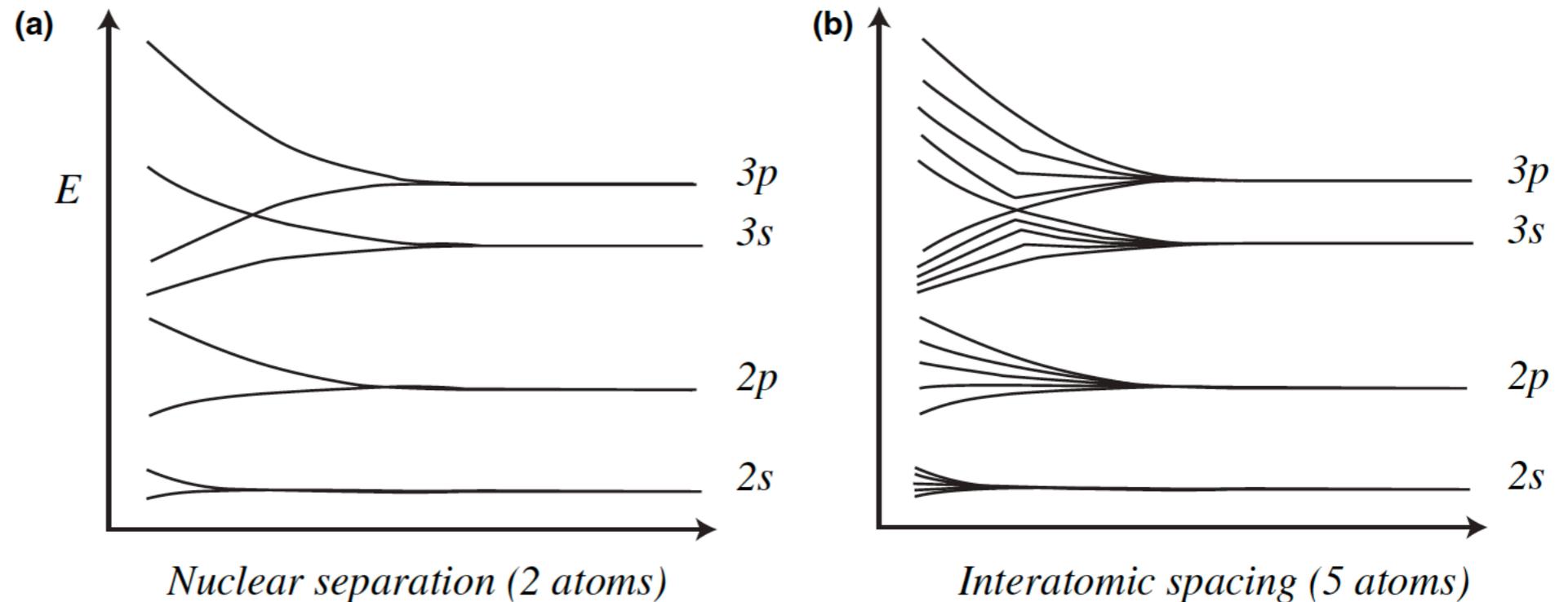
Bonds and bands in silicon

➤ Consider the formation of a silicon crystal (atomic number: 14)



- What happens to the energy levels of an isolated silicon atom when a second silicon atom is brought closer and closer to it
- The nearer the neighbor, the greater is its influence, and the greater the splitting of levels
- If we construct a crystal atom by atom, new energy states appear with each addition

Fig. 7.4 (a) Changes in the electron energy levels in a silicon atom as a second atom is brought into close proximity. (b) The same diagram for the case of five atoms in a linear matrix.



Solid-state crystals

Bonds and bands in silicon

- Consider the formation of a silicon crystal (atomic number: 14)
 - Even a tiny crystal containing on the order of 10^{17} atoms, each causing a split in the energy levels, the spacing between levels must be on the order of 10^{-17} eV
 - Treated as a continuous band of available energies
 - If bands do not overlap, they are separated by energy band gaps.

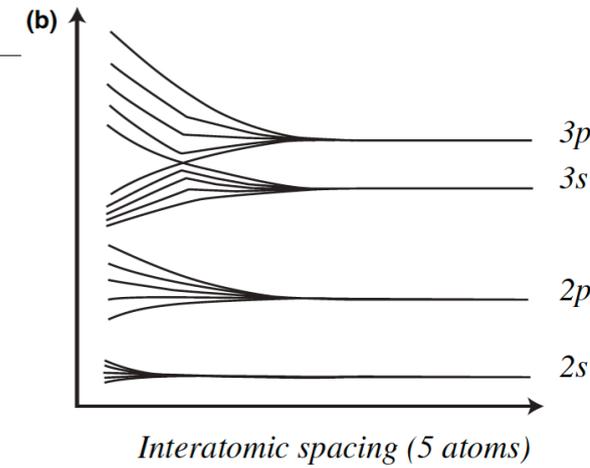
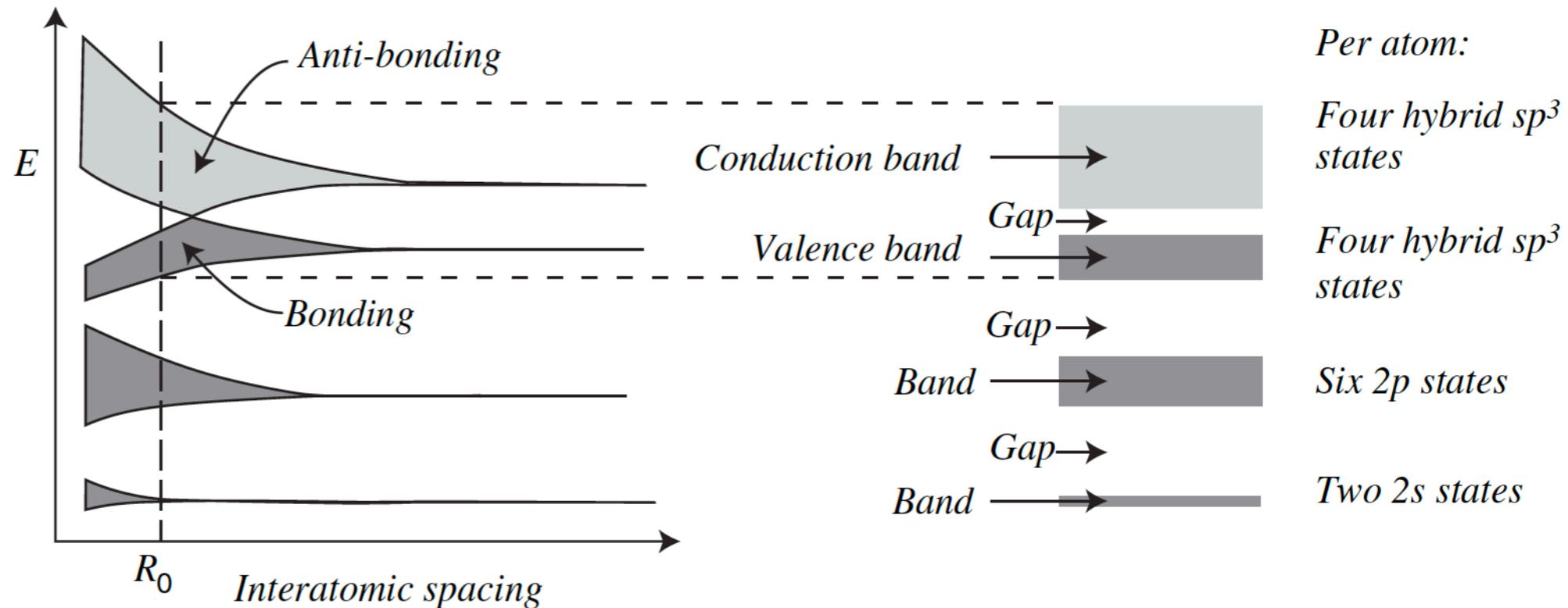
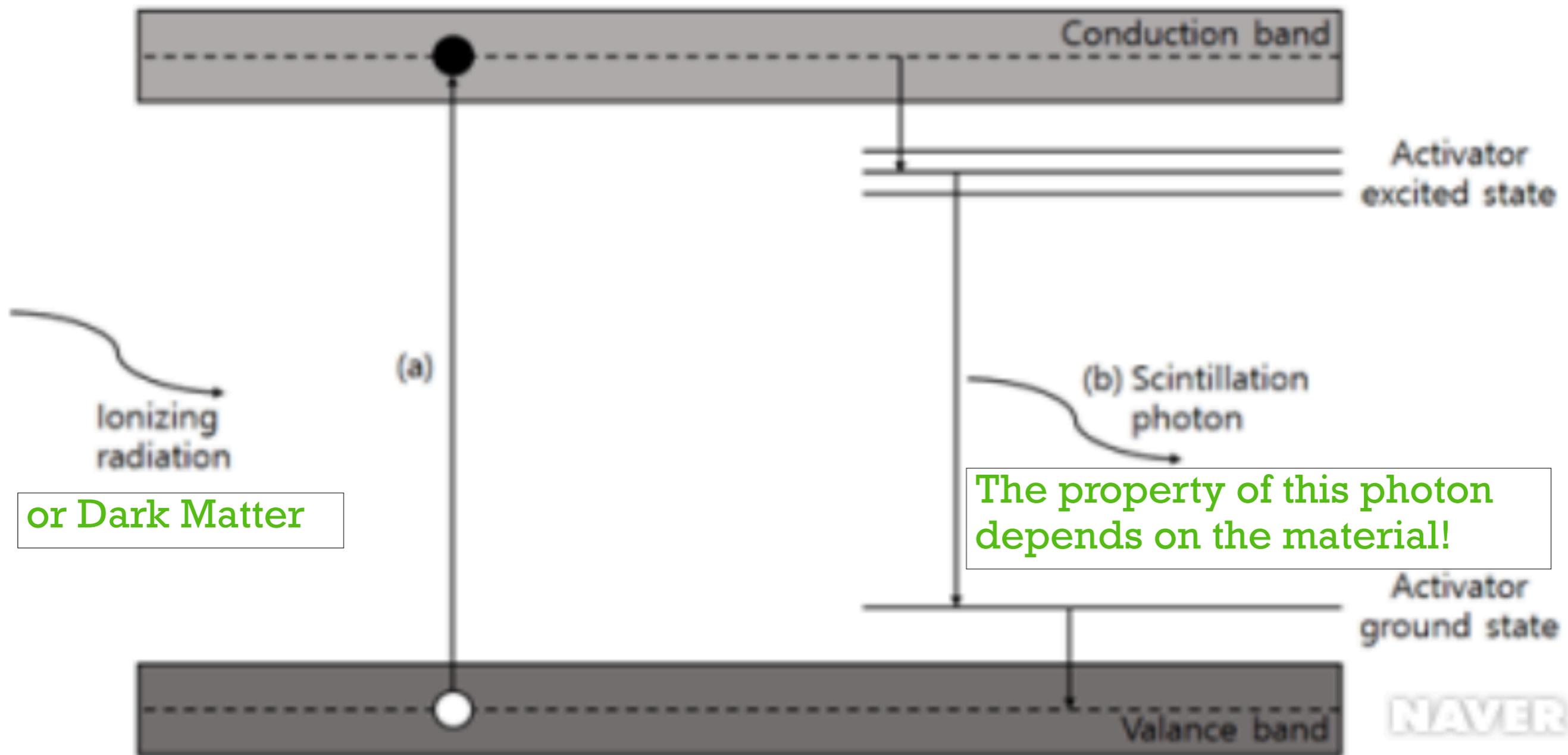


Fig. 7.5 Schematic diagram of the bands in silicon crystals. The diagram at right shows the bands formed at the preferred inter-atomic spacing. Dark-gray bands are occupied, light-gray are empty but permitted. Energies in the band gaps (white) are forbidden to electrons.



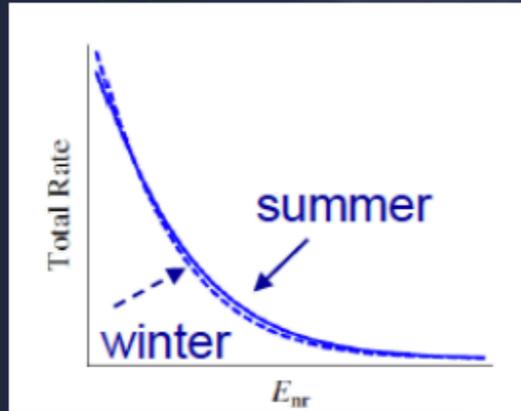
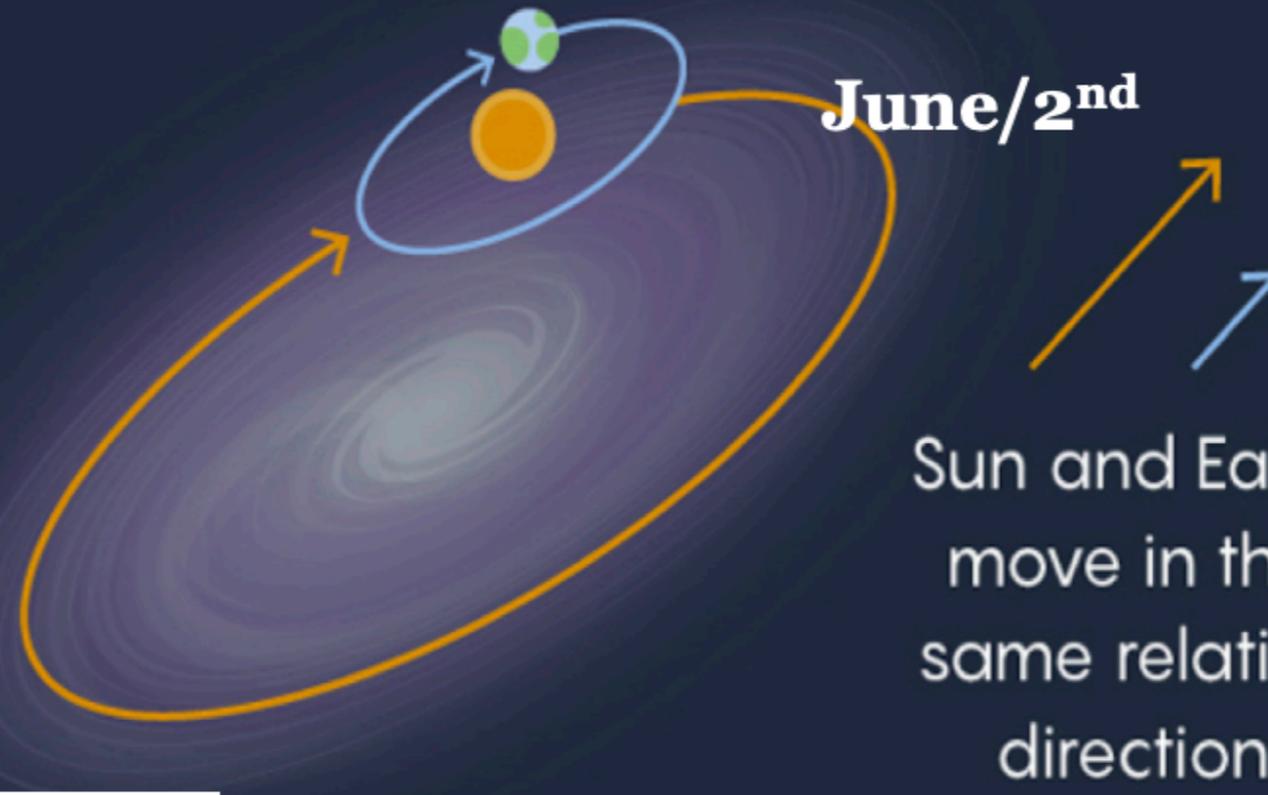


| 그림 1. 2-레벨에서 섬광의 과정 (출처: 한국물리학회)

Annual modulation of dark matter

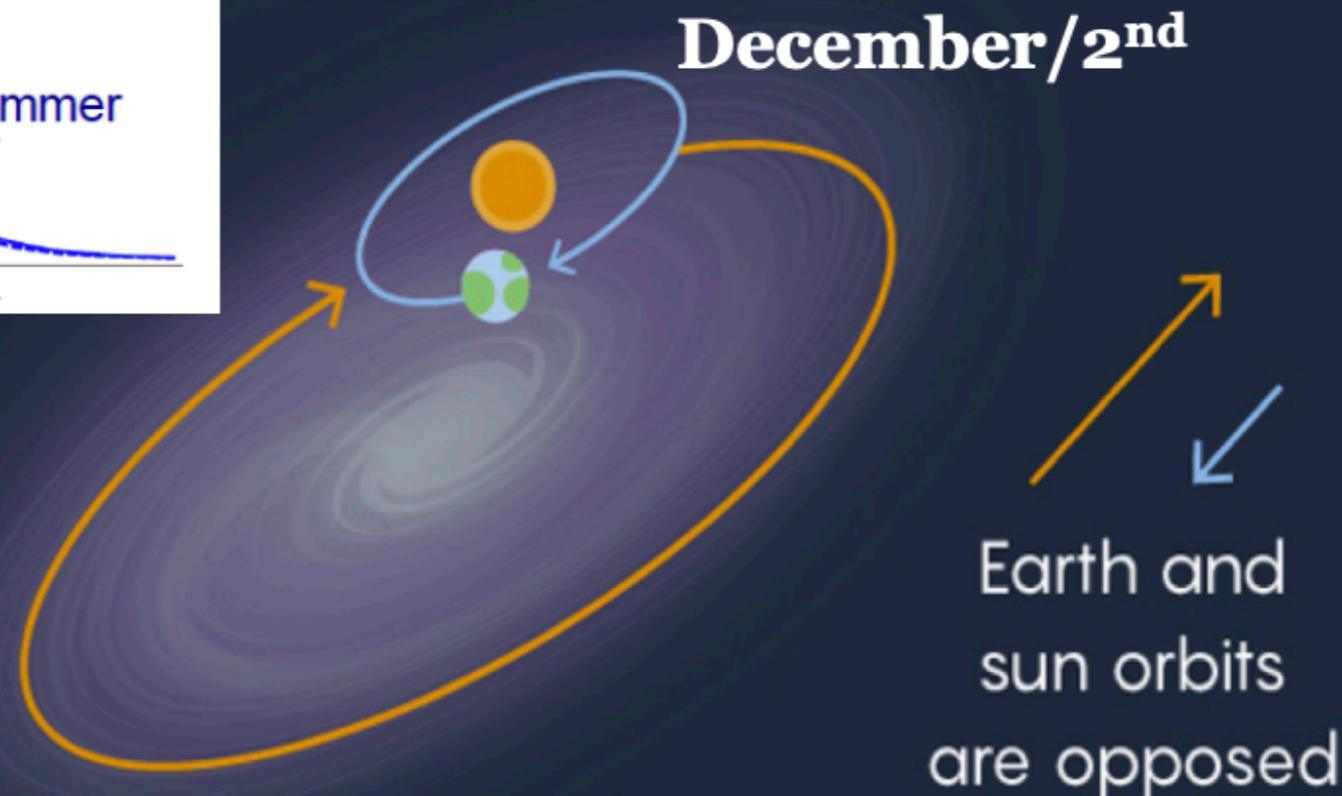
The Highs

In June, Earth moves at its fastest speed through the dark matter halo.



The Lows

In December, Earth moves at its slowest speed.



Nal crystal for particle detection

Pro

- High light output
 - ❖ 40,000 photons/MeV
 - ❖ >60,000 photons/MeV?
- Easy to grow
 - ❖ Cheap
 - ❖ Large size
- **The most widely used scintillator**

* The light is in the visible range.

Con

- Huge hygroscopic materials
- Contamination of **natural Potassium**
 - ❖ ~ 3keV X-ray from ^{40}K
- **No good identification of nuclear recoil**



The first 32 inch diameter NaI(Tl) crystal. Pictured from left to right are Dr. Swinehart, Ed Jablon, Joe Knaus and Marko Sfilgou.



Properties	From Saint-Gobain
Density [g/cm ³]	3.67
Melting point [K]	924
Thermal expansion coefficient [C ⁻¹]	47.4 x 10 ⁻⁶
Cleavage plane	<100>
Hardness (Mho)	2
Hygroscopic	yes
Wavelength of emission max [nm]	415
Refractive index @ emission max.	1.85
Primary decay time [ns]	250
Light yield [photons/keV γ]	38
Temperature coefficient of light yield	-0.3%C ⁻¹

* DAMA experiment claimed the detection of dark matter, which was not reproduced in any other experiments!

NaI(Tl) for rare event searches : Dark Matter



Physics Letters B
Volume 295, Issues 3–4, 3 December 1992, Pages 330-336



1992

Search for neutralino dark matter with NaI detectors

LNGS

A. Bottino, V. de Alfaro, N. Fornengo, G. Mignola, S. Scopel, Beijing - Roma - Saclay (BRS) Collaboration, C. Bacci ^a, P. Belli ^b, R. Bernabei ^b, Dai Changjiang ^c, Ding Linkai ^c, E. Gaillard ^d, G. Gerbier ^d, Kuang Haohuai ^c, A. Incicchitti ^a, J. Mallet ^d, R. Marcovaldi ^a, L. Mosca ^d ... Xie Yigang ^c

[Show more](#)

DAMA/LIBRA

PHYSICAL REVIEW C

VOLUME 47, NUMBER 2

1993

RAPID COMMUNICATIONS
FEBRUARY 1993

Application of a large-volume NaI scintillator to search for dark matter

K. Fushimi, H. Ejiri, H. Kinoshita, * N. Kudomi, K. Kume, K. Nagata, H. Ohsumi, K. Okada, † H. Sano, and J. Tanaka

Department of Physics, Osaka University, Toyonaka, Osaka 560, Japan

(Received 30 September 1992)

Kamioka

PICO-LON



Physics Letters B
Volume 433, Issues 1–2, 6 August 1998, Pages 150-155



1998

Measurement of scintillation efficiencies and pulse-shapes for nuclear recoils in NaI(Tl) and CaF₂(Eu) at low energies for dark matter experiments

Boulby Mine

D.R. Tovey ^a, V. Kudryavtsev ^a, M. Lehner ^a, J.E. McMillan ^a, C.D. Peak ^a, J.W. Roberts ^a, N.J.C. Spooner ^a, J.D. Lewin ^b

COSINE



Nuclear Physics B - Proceedings Supplements
Volume 48, Issues 1–3, May 1996, Pages 73-76



1996

A Search for annual and daily modulations of dark matter with NaI scintillators at Canfranc

Canfranc

M.L. Sarsa, A. Morales, J. Morales, E. García, A. Ortiz de Solórzano, J. Puimedón, C. Sáenz, A. Salinas, J.A. Villar

ANAIS

*** DAMA experiment claimed the detection of dark matter, which was not reproduced in any other experiments!**

SCIENCE ADVANCES | RESEARCH ARTICLE

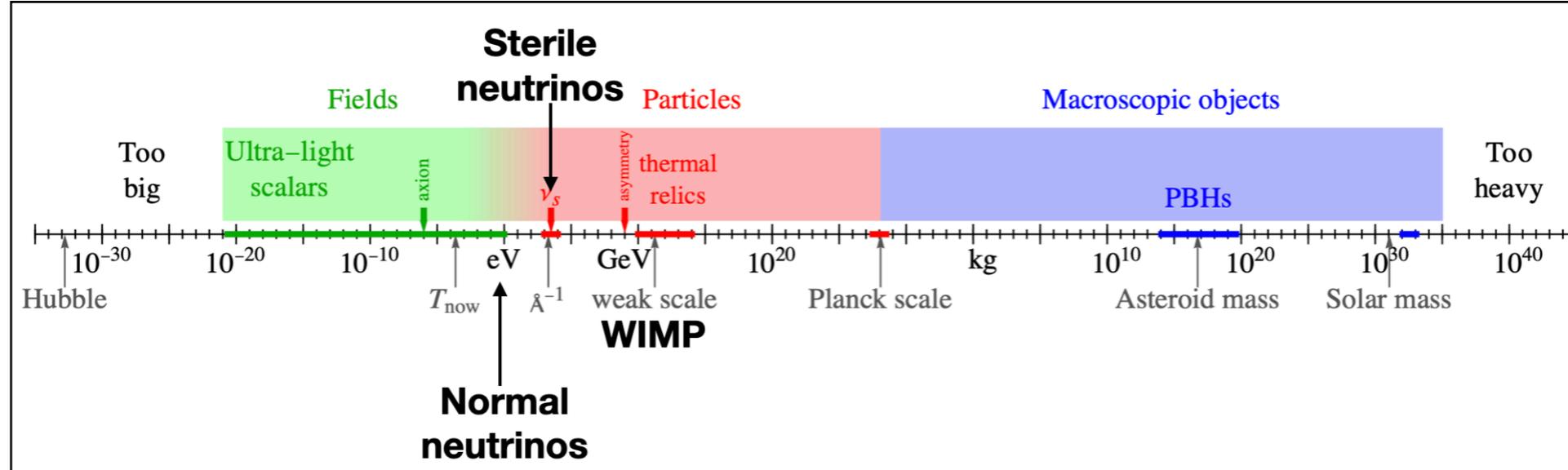
PHYSICS

COSINE-100 full dataset challenges the annual modulation signal of DAMA/LIBRA

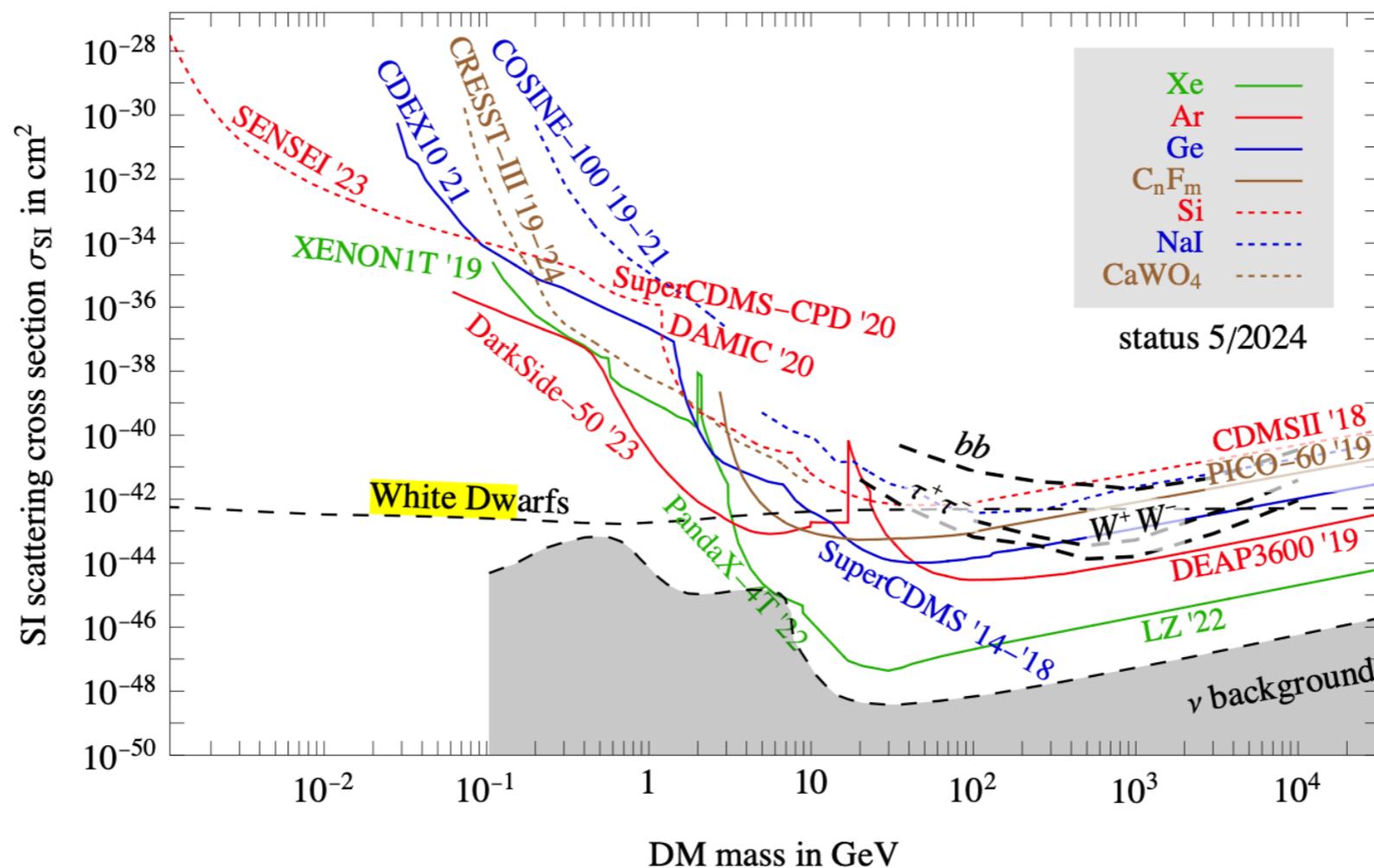
Nelson Carlin¹, Jae Young Cho^{2,3}, Jae Jin Choi^{4,2}, Seonho Choi⁴, Anthony C. Ezeribe⁵, Luis Eduardo França¹, Chang Hyon Ha⁶, In Sik Hahn^{7,8,9}, Sophia J. Hollick¹⁰, Eunju Jeon^{2,9}, Han Wool Joo⁴, Woon Gu Kang², Matthew Kauer¹¹, Bongho Kim², Hongjoo Kim³, Jinyoung Kim⁶, Kyungwon Kim², SungHyun Kim², Sun Kee Kim⁴, Won Kyung Kim^{9,2}, Yeongduk Kim^{2,9}, Yong-Hamb Kim^{2,9}, Young Ju Ko^{12*}, Doohyeok Lee³, Eun Kyung Lee², Hyunseok Lee^{9,2}, Hyun Su Lee^{2,9*}, Hye Young Lee⁷, In Soo Lee², Jaison Lee², Jooyoung Lee³, Moo Hyun Lee^{2,9}, Seo Hyun Lee^{9,2}, Seung Mok Lee^{4†*}, Yujin Lee⁶, Douglas S. Leonard², Nguyen Thanh Luan³, Vitor Hugo de Almeida Machado¹, Bruno B. Manzato¹, Reina H. Maruyama¹⁰, Robert J. Neal⁵, Stephen L. Olsen², Byung Ju Park^{9,2}, Hyang Kyu Park¹³, Hyeonseoo Park¹⁴, Jong-Chul Park¹⁵, Kangsoon Park², Se Dong Park³, Ricardo L. C. Pitta¹, Hafizh Prihtiadi¹⁶, Sejin Ra², Carsten Rott^{17,18}, Keon Ah Shin², David F. F. S. Cavalcante¹, Min Ki Son¹⁵, Neil J. C. Spooner⁵, Lam Tan Truc³, Liang Yang¹⁹, Gyun Ho Yu^{17,2}

For over 25 years, the DAMA/LIBRA collaboration has claimed to observe an annual modulation signal, suggesting the existence of dark matter interactions. However, no experiment using different target materials has observed a dark matter signal consistent with their result. To address this puzzle, the COSINE-100 collaboration conducted a model-independent test using sodium iodide crystal detectors, the same target material as DAMA/LIBRA. Analyzing data collected over 6.4 years by the effective mass of 61.3 kilograms, with improved energy calibration and time-dependent background modeling, we found no evidence of an annual modulation signal, challenging the DAMA/LIBRA result with a confidence level greater than 3σ . This finding represents a substantial step toward resolving the long-standing debate surrounding DAMA/LIBRA's dark matter claim, indicating that the observed modulation is unlikely to be caused by dark matter interactions.

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Direct Detection constraints on SI scattering



- Neutrino (ν) background
 - Neutrinos scatter off nuclei just like WIMPs do.
 - Once we hit this floor, a WIMP signal becomes statistically indistinguishable from the neutrino background without advanced techniques (like directional detection).

Dark Matter Detection

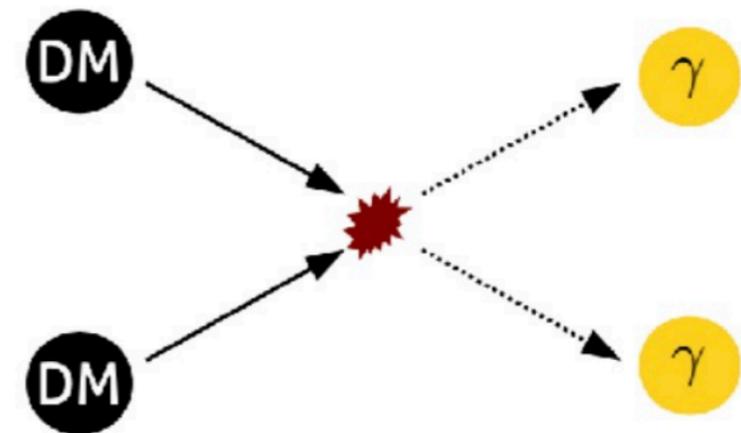
1. 직접검출

1. 우리 주변 암흑물질이 지하의 검출기에 있는 원자핵에 부딪혀서 얻게 되는 원자핵의 변화를 측정하는 것

2. 간접검출

1. 우리 은하나 그 밖에 존재하는 암흑물질이 소멸하거나 붕괴할 때 나오는 대전된 입자나 중성미자 또는 감마선, 엑스선과 같은 신호를 검출하는 것.

Two-body annihilation into photons



3. 가속기에서 검출

1. 거대강입자가속기(Large Hadron Collider, LHC)와 같은 고에너지 가속기에서 양성자를 가속하여 서로 충돌시킬 때, 암흑물질이 만들어지고 검출기에는 반응을 하지 않으므로 사라진 에너지의 양으로부터 간접적으로 암흑물질을 검출하는 것.

2. Indirect Detection

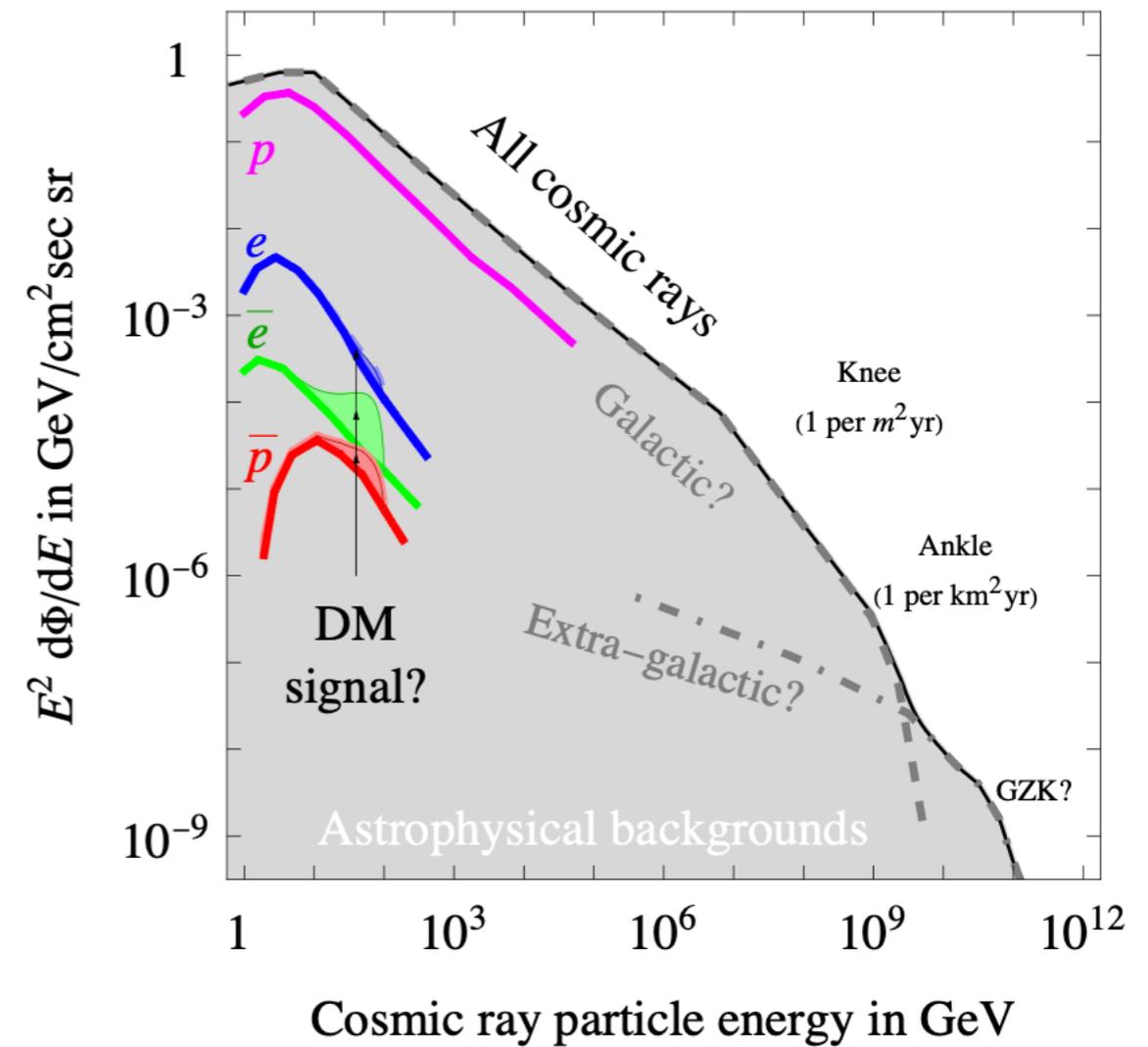
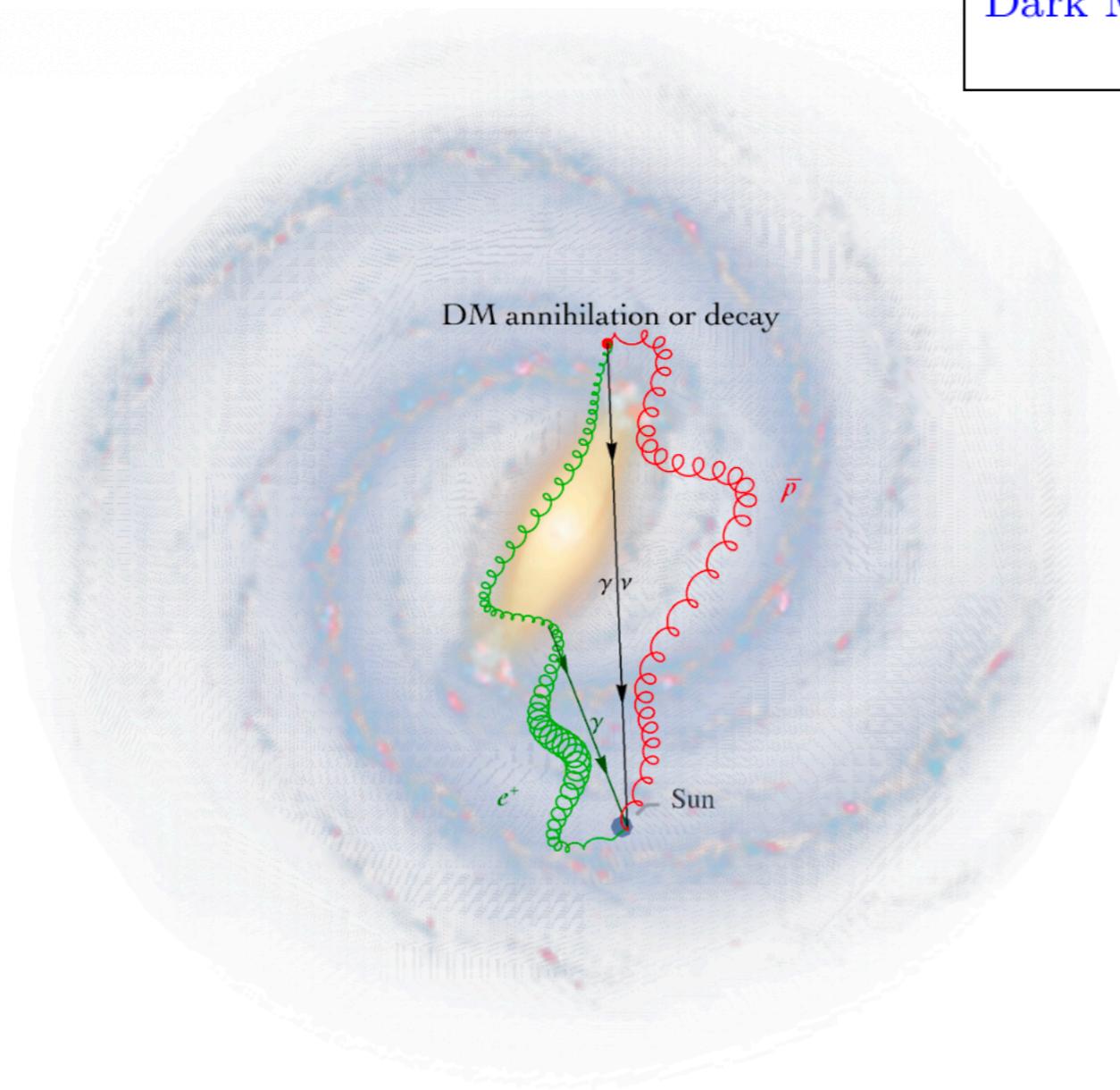
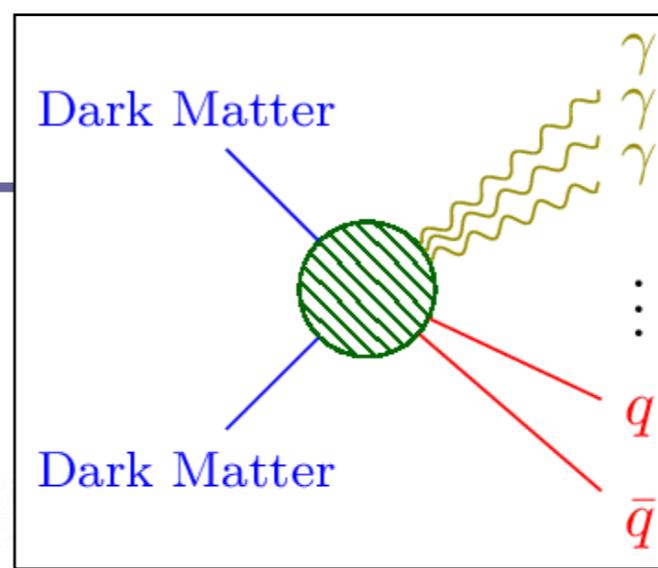


Figure 6.1: *Cartoon of indirect detection: DM annihilations or decays in the Milky Way produce SM particles that reach the observer in a solar system, possibly producing an excess in the energy spectrum of cosmic rays over the observed astrophysical background.*

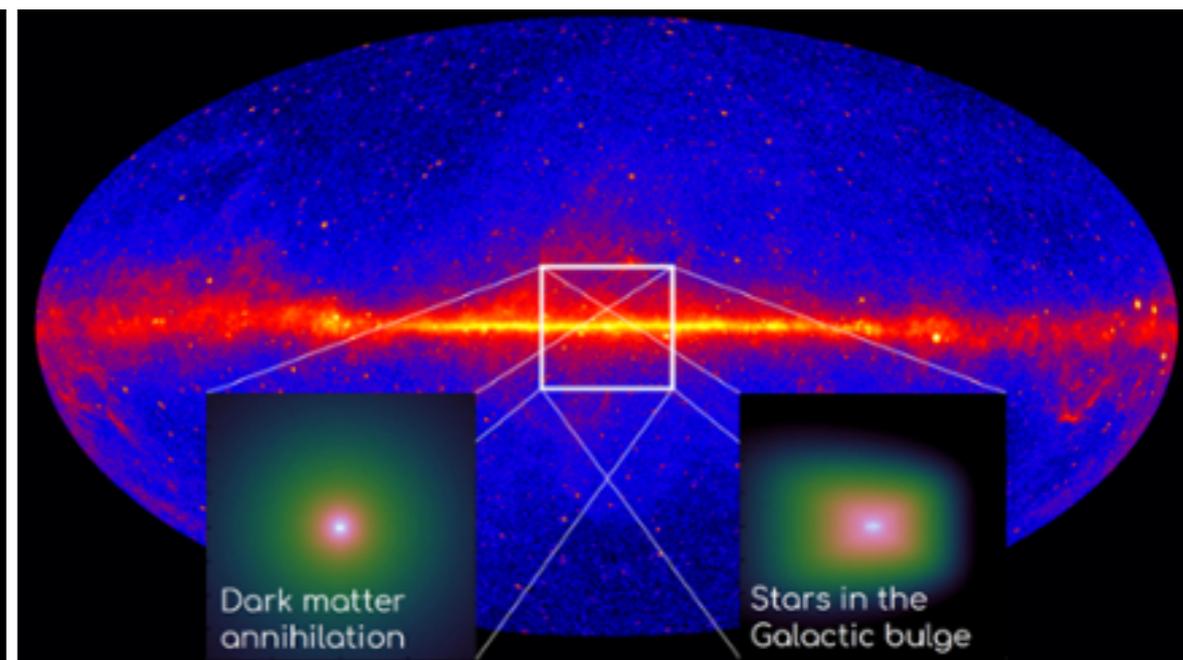
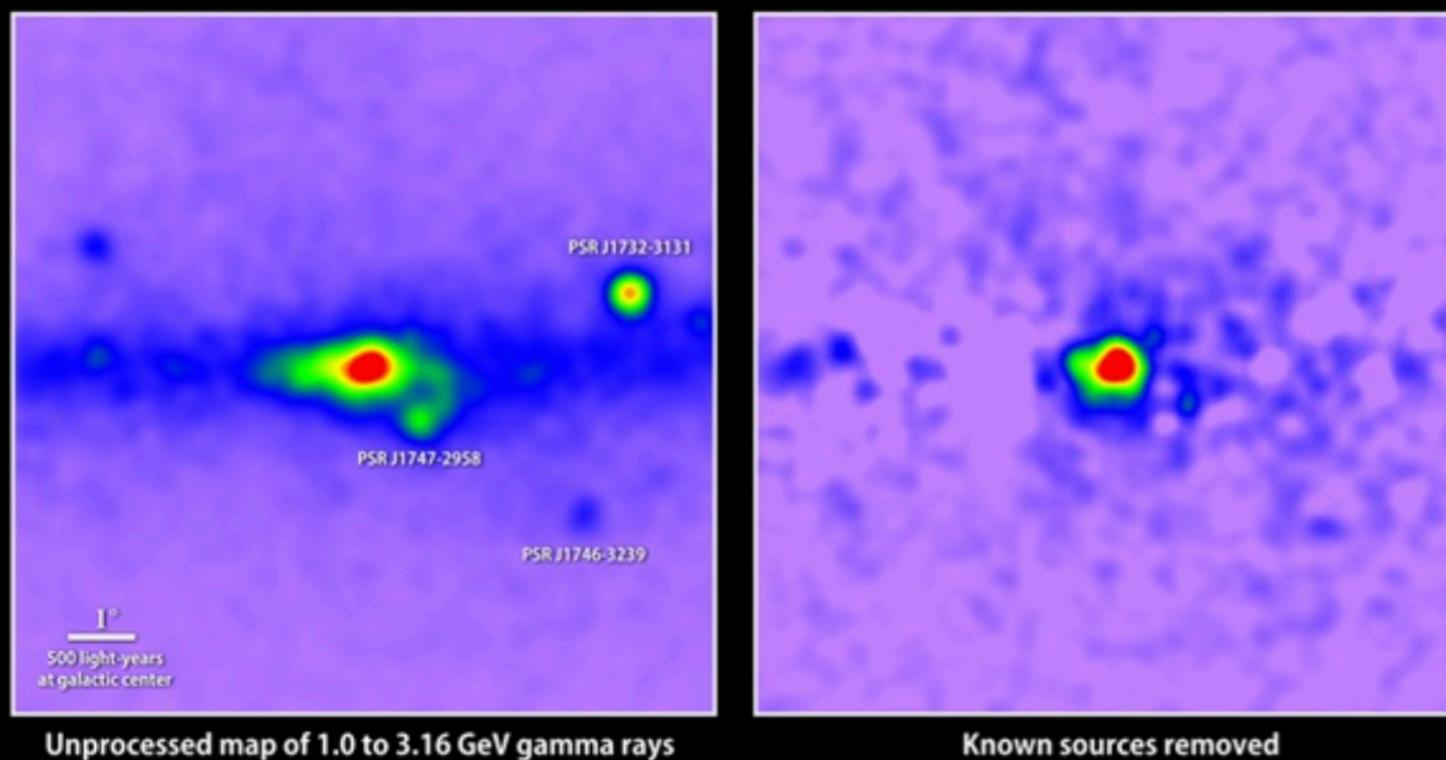
Indirect Detection

LETTERS

Discovery of very-high-energy γ -rays from the Galactic Centre ridge

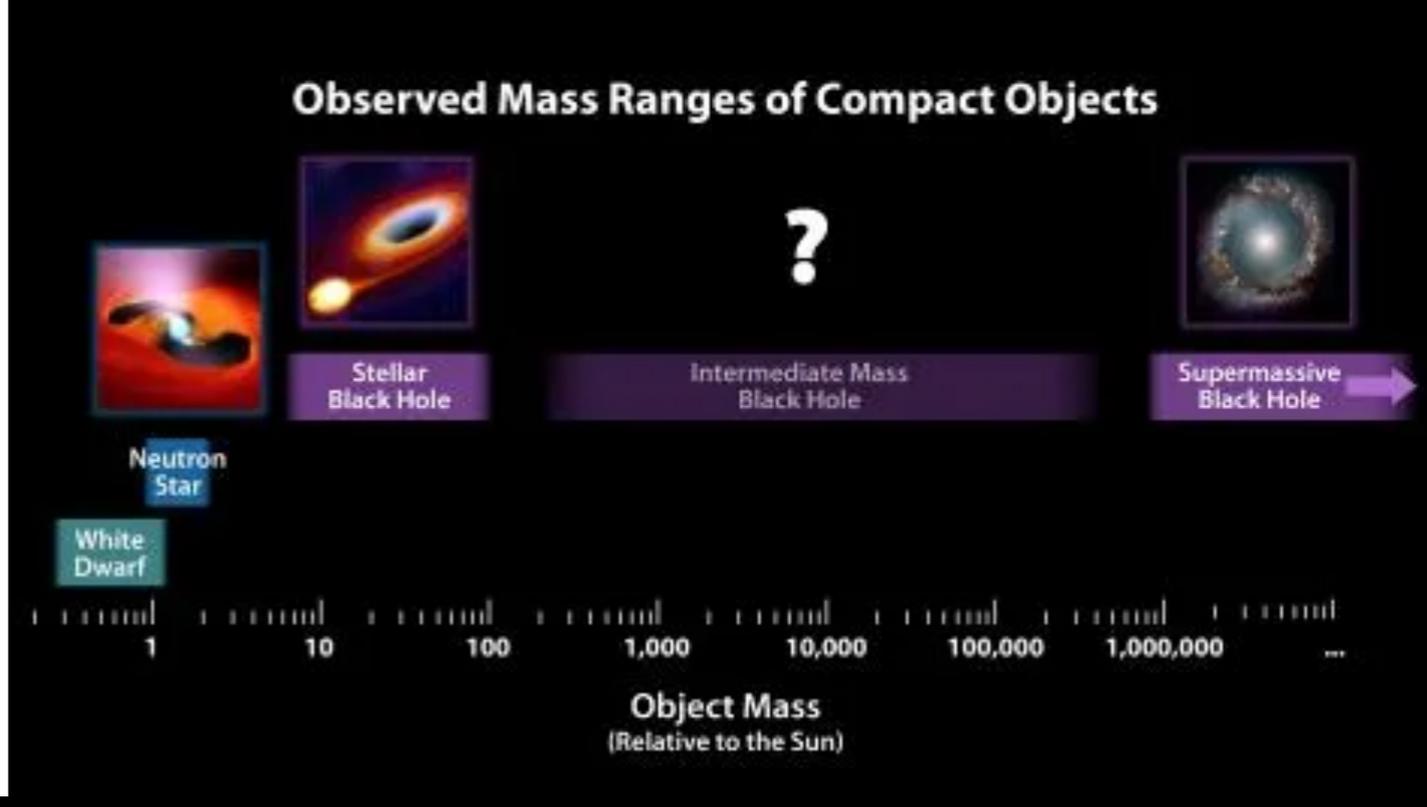
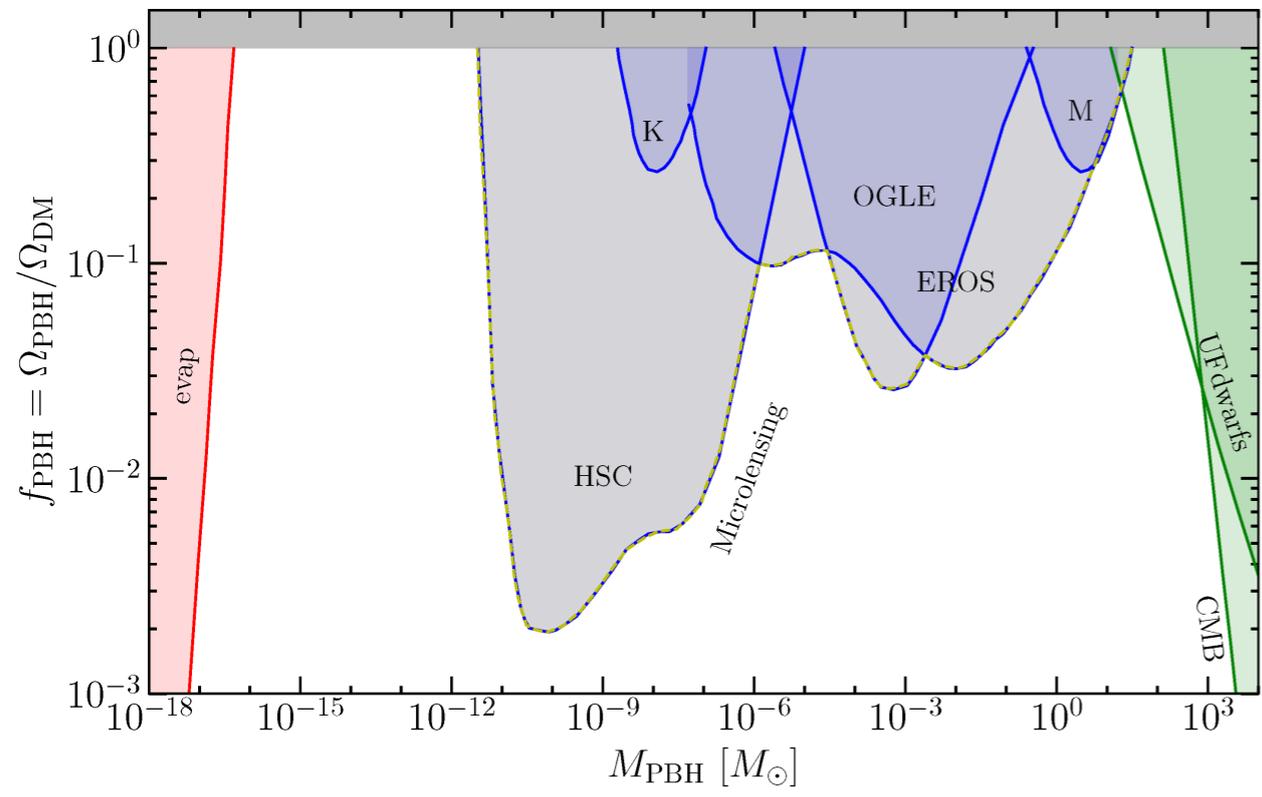
F. Aharonian¹, A. G. Akhperjanian², A. R. Bazer-Bachi³, M. Beilicke⁴, W. Benbow¹, D. Berge¹, K. Bernlöhner^{1,5},

Uncovering a gamma-ray excess at the galactic center



Observed gamma-ray emission from the Galactic disk, with the bulge region indicated. The insets show the expected profiles of excess radiation coming from dark matter and stars respectively. The researchers were able to show that the stars profile matches the measurements much better than the dark matter profile (Bartels+2018)

At left is a map of gamma rays with energies between 1 and 3.16 GeV detected in the galactic center by Fermi's LAT; red indicates the greatest number. Prominent pulsars are labeled. Removing all known gamma-ray sources (right) reveals excess emission that may arise from dark matter annihilations.



PRIMORDIAL BLACK HOLES (PBH)



ORIGIN

Formed from the collapse of large overdensities in the universe fractions of a second after the Big Bang.



LENSING

Microlensing surveys (MACHO, EROS, Subaru) constrain their abundance. They cannot make up 100% of DM in most mass ranges.



GW SIGNATURES

LIGO mergers might be PBH binaries. If true, this links DM to Gravitational Wave astronomy.

Summary of Major Dark-Matter Models

Dark matter model	Typical mass	Dominant interaction	How to detect	Key observational signatures
WIMPs (Weakly Interacting Massive Particles)	~1 GeV – 10 TeV	Weak-scale	Direct, indirect, collider	Nuclear recoils (SI/SD), γ -rays, neutrinos
Axions / ALPs	~ 10^{-12} – 10^{-3} eV (QCD axion narrower)	Axion–photon, axion–fermion	Direct (haloscopes), astrophysical	Resonant microwave photons, stellar cooling
Sterile neutrinos	~1–100 keV	Weak mixing with ν	Indirect (X-ray)	Mono-energetic X-ray line
Fuzzy DM (ultralight bosons)	~ 10^{-22} eV	Gravitational	Structure formation	Suppressed small-scale structure, solitonic cores
Self-interacting DM (SIDM)	~MeV – TeV	DM–DM scattering	Astrophysical	Cored halos, cluster offsets
Asymmetric DM	~1–10 GeV	Model-dependent	Direct, collider	No annihilation signal
Primordial Black Holes (PBHs)	~ 10^{15} g – 100 M_{\odot}	Gravity only	Lensing, GW, dynamics	Microlensing, merger rates

Summary of Major Dark-Matter Models

Detection channels vs models (at a glance)

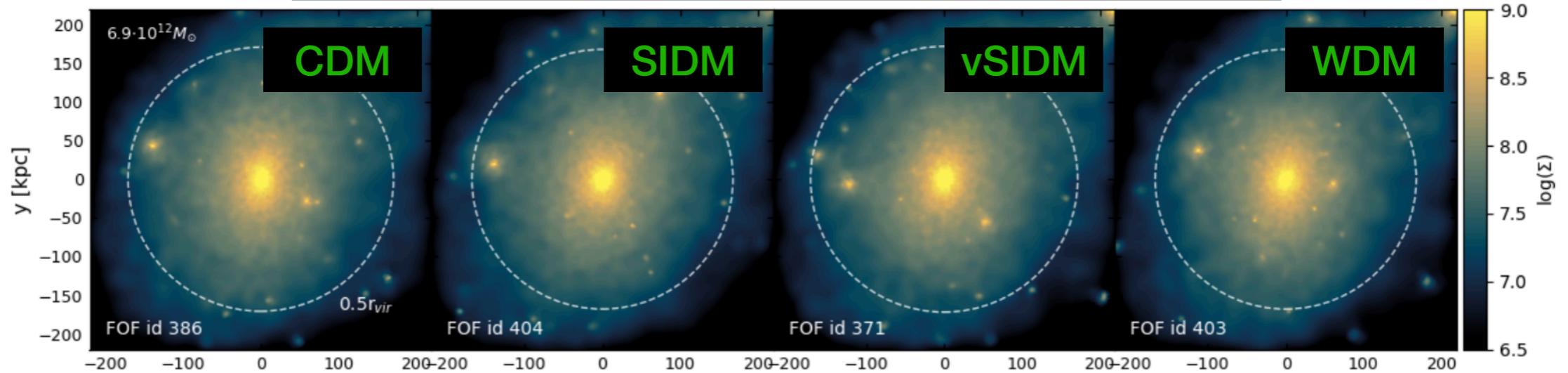
Detection method	Best-suited models
Direct detection (nuclear recoil)	WIMPs, asymmetric DM
Direct detection (electron / photon)	Axions, dark photons
Indirect detection	WIMPs, sterile neutrinos, decaying DM
Collider searches	WIMPs, dark-sector mediators
Astrophysical structure	Fuzzy DM, SIDM
Gravitational probes	PBHs

Numerical Simulations with Various dark matter models

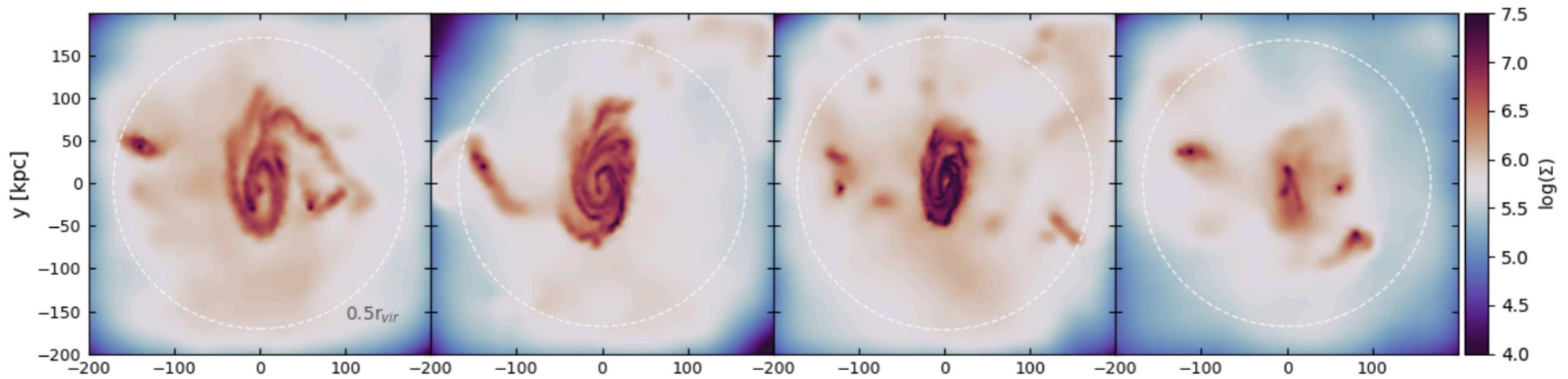
The AIDA-TNG project

galaxy formation in alternative dark matter models

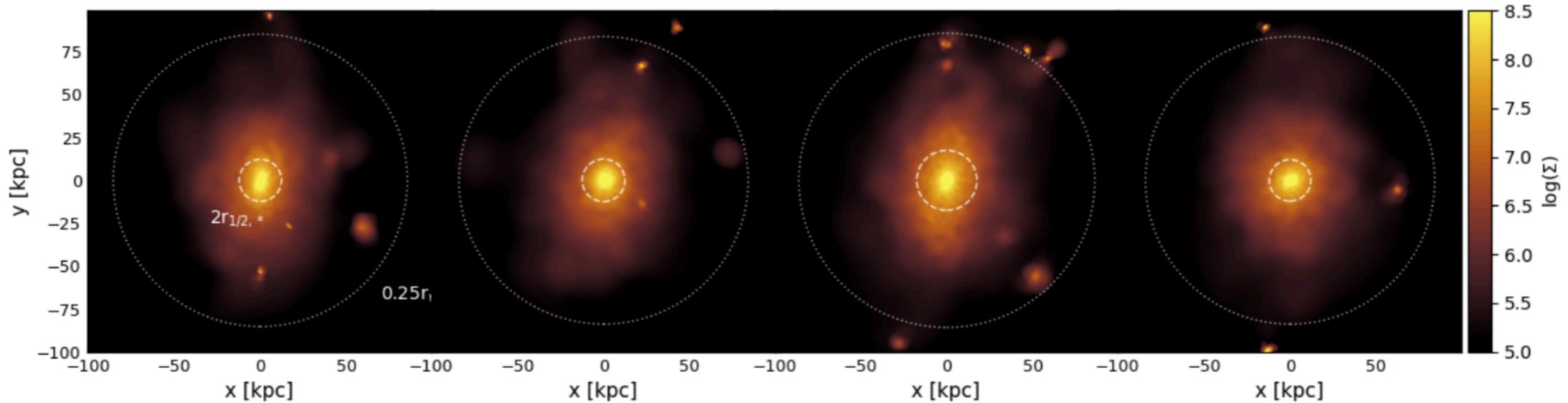
Dark Matter



Gas



Stars



Numerical Simulations with Various dark matter models

The AIDA-TNG project galaxy formation in alternative dark matter models

Name	Box [Mpc]	Physics	m_{DM} [M_{\odot}]	m_{bar} [M_{\odot}]	$\epsilon_{\text{DM},*}^{z=0}$ [kpc]	CDM	WDM 1 keV	WDM 3 keV	WDM 5 keV	SIDM 1 $\text{cm}^2 \text{g}^{-1}$	vSIDM Correa+21
100/A	110.7	DMO	7.1×10^7	–	1.48	✓	–	✓	–	✓	✓
		FP	6.0×10^7	1.1×10^7	1.48	✓	–	✓	–	✓	✓
100/B	110.7	DMO	5.7×10^8	–	2.95	✓	✓	✓	–	✓	✓
		FP	4.8×10^8	8.9×10^7	2.95	✓	✓	–	–	✓	✓
50/A	51.7	DMO	4.3×10^6	–	0.57	✓	–	✓	✓	✓	✓
		FP	3.6×10^6	6.8×10^5	0.57	✓	–	✓	–	✓	✓
50/B	51.7	DMO	3.4×10^7	–	1.15	✓	✓	✓	–	✓	✓
		FP	2.9×10^7	5.4×10^6	1.15	✓	✓	✓	–	✓	✓

Notes. We run each box at two resolution levels, where ‘A’ is the highest. The 100/A(B) and 50/A(B) boxes start from the same initial conditions of the TNG100-2(3) and TNG50-2(3) boxes of the original IllustrisTNG project (Nelson et al. 2019). We list the resolution of each run and mark the dark matter models that are included in this work.

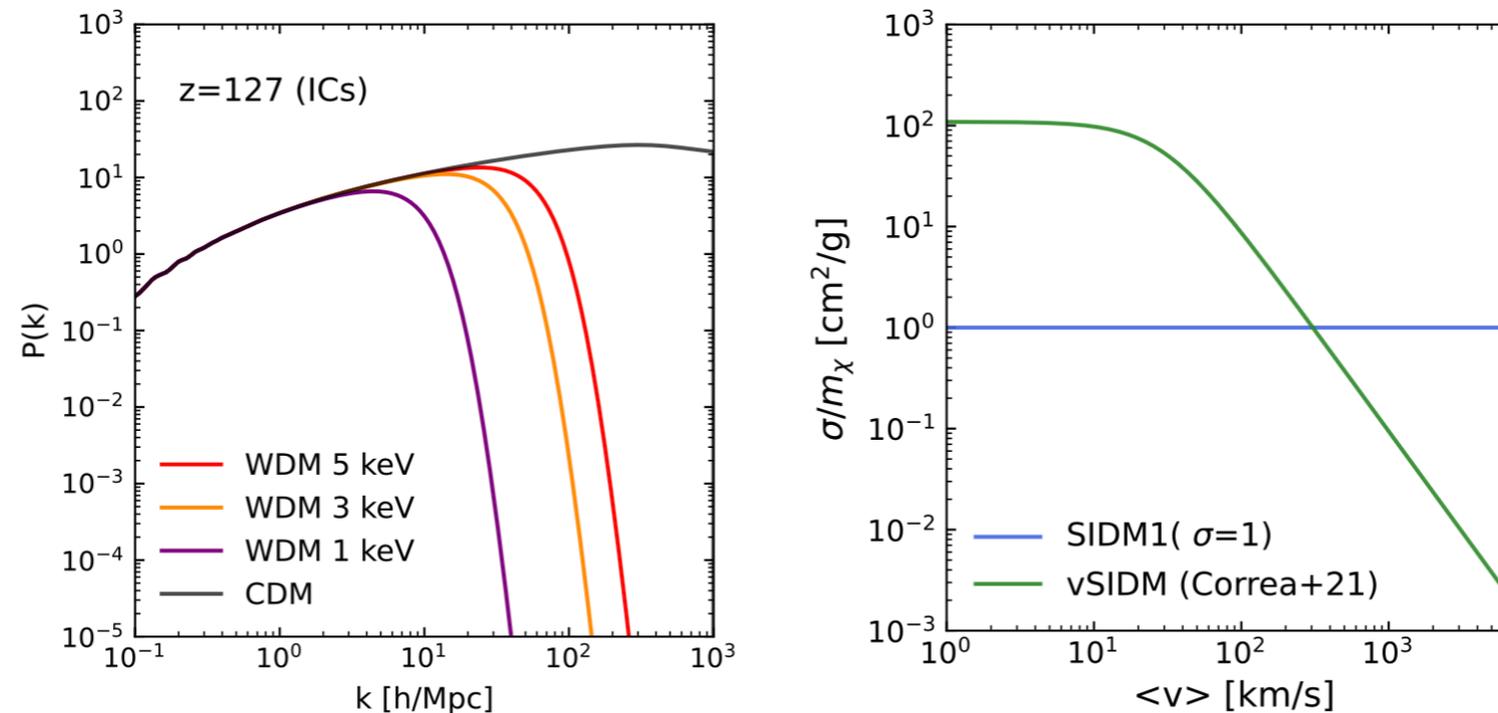


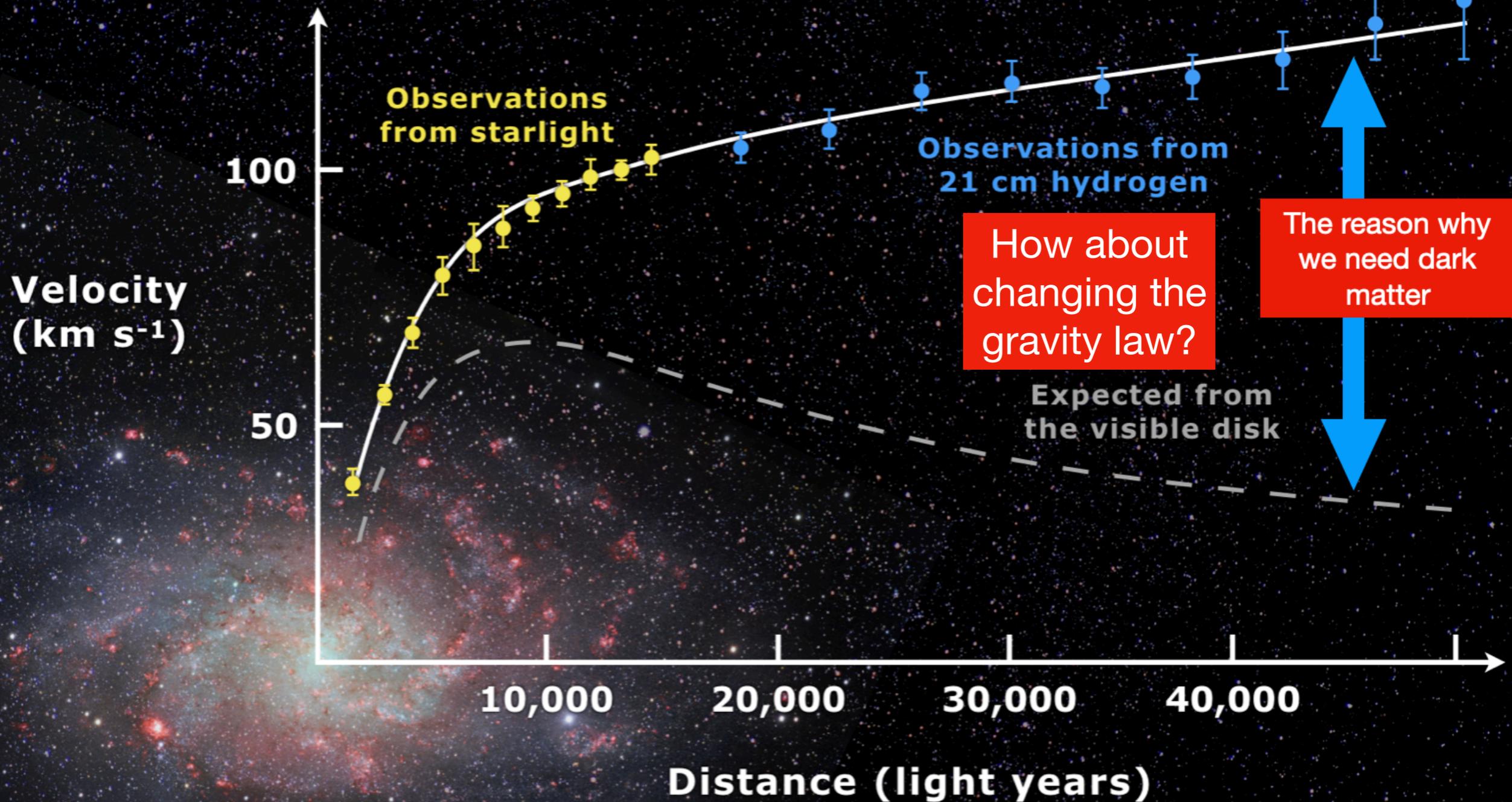
Fig. 2. Properties that distinguish alternative models from CDM. Left: Input matter power spectrum $P(k)$ in CDM and WDM models at the initial time of the simulations ($z = 127$). Warmer models show a cut-off at increasingly larger scales, corresponding to smaller k values. Right: Self-interaction cross-section σ/m_{χ} as a function of velocity. We consider a model with a constant cross-section (blue line) and one with a steep velocity dependence (green line) from Correa (2021).

V. Alternatives



MOND, Emergent Gravity

WITHOUT dark matter?



WITHOUT dark matter?

P. Bull et al. / Physics of the Dark Universe 12 (2016) 56–99

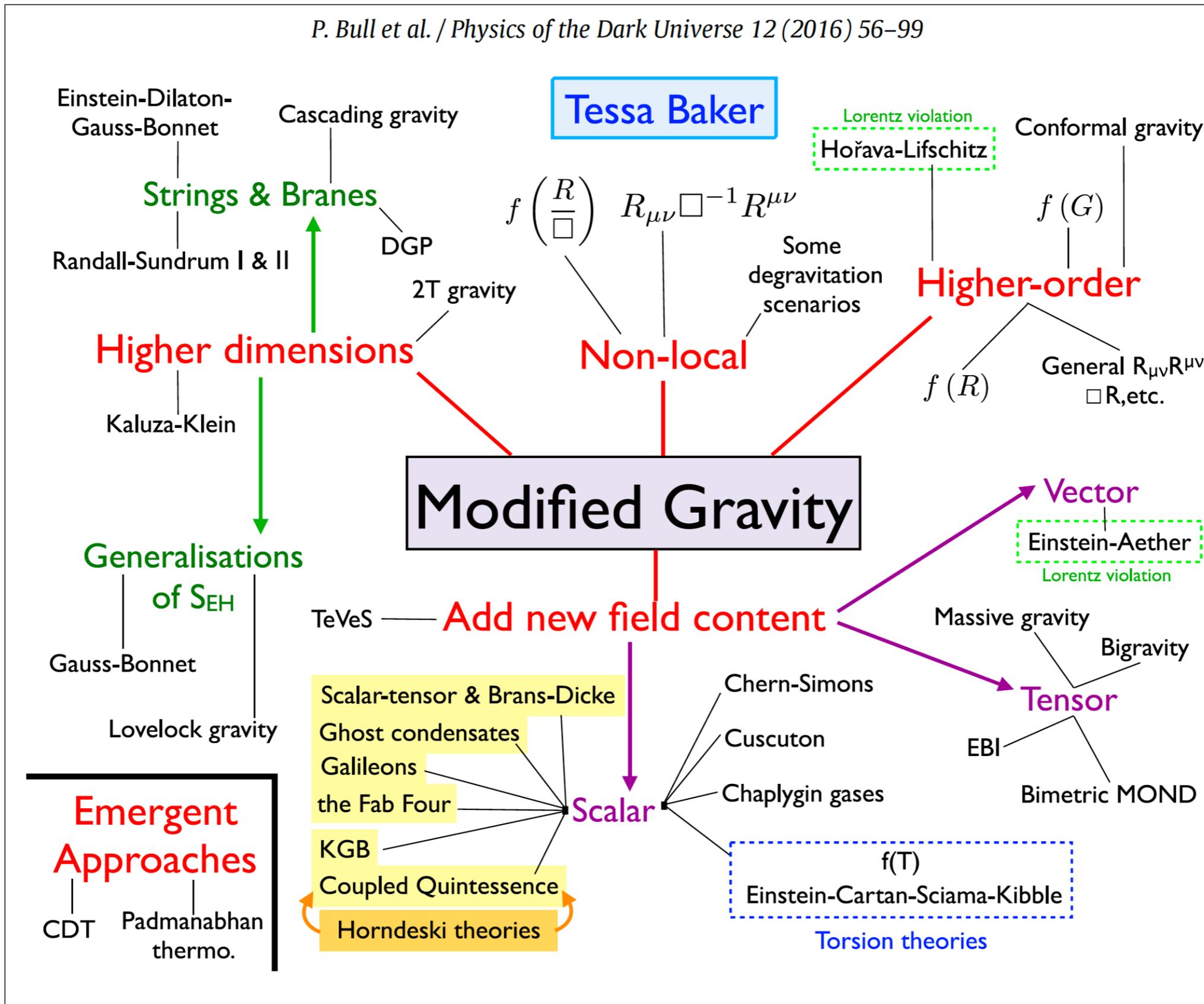


Fig. 3. Tree diagram of modified theories of gravity. Source: (Tessa Baker, reproduced with permission.)

채규현 세종대 물리천문학과 교수, 뉴턴 이론 뒤집어

박숙자 기자 | 입력 2023.07.26 12:00 | 댓글 0

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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.

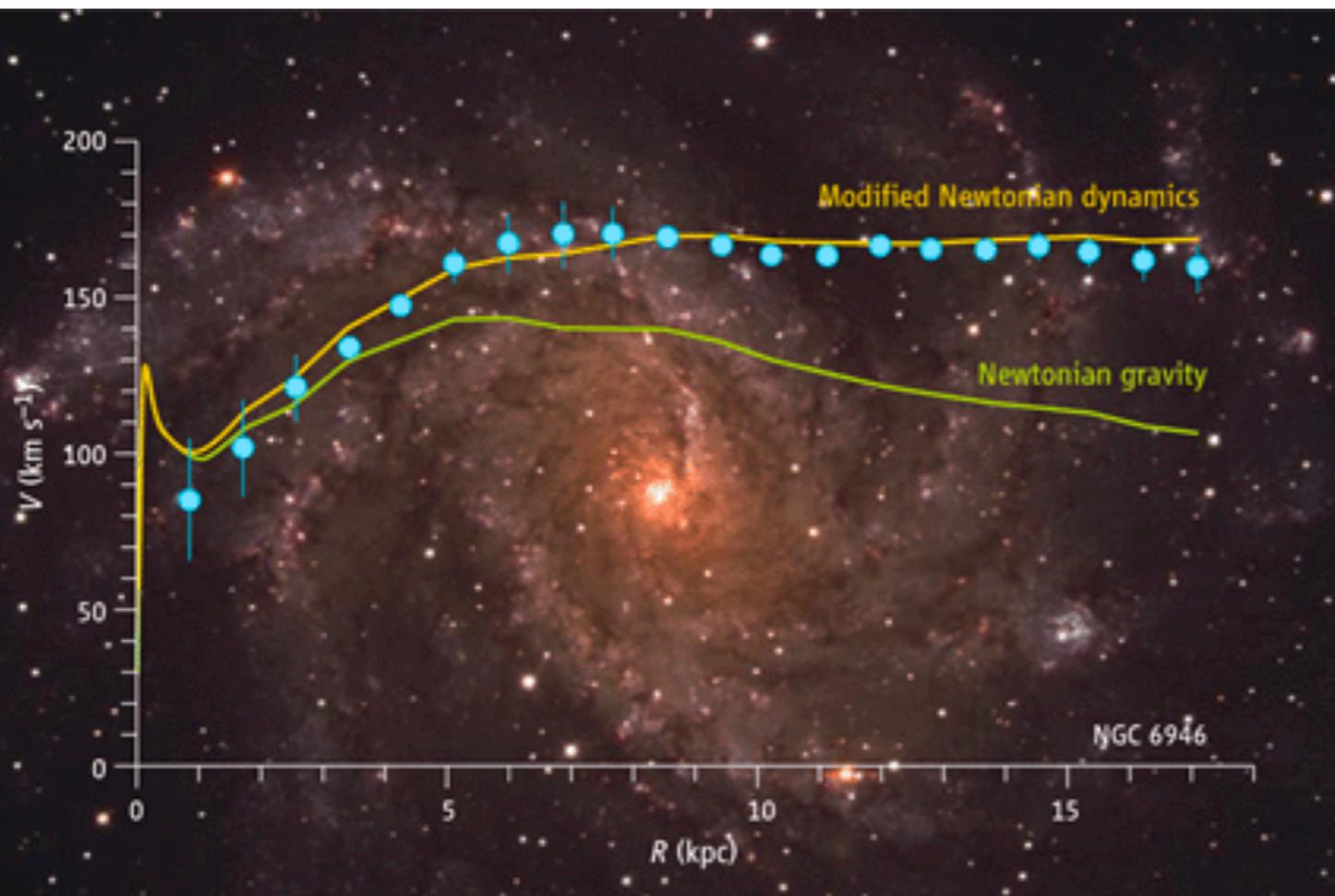
채규현 교수는 이를 위해 미국의 하버드대학교의 카림 엘바드리 박사의 도움을 받아 650광년 이내의 2만6500여 개의 장주기 쌍성에 대한 유럽항공우주국의 가이아(Gaia) 우주망원경의 최신 데이터를 사용했다.

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**



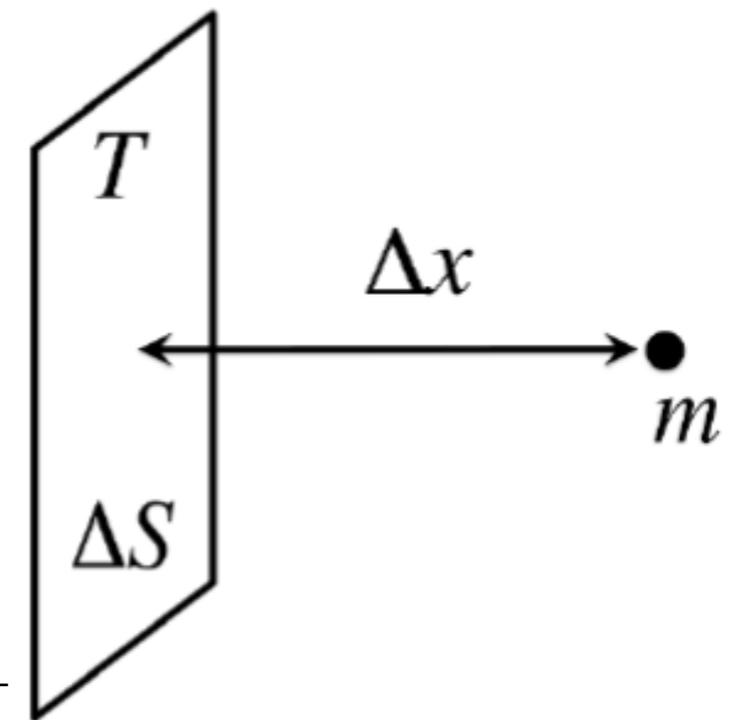
What is important here is not the emergent gravity model itself, but is a trial without considering dark matter!

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 acceleration in the Verlinde's emergent gravity:

$$g_{\text{Ver}} = \sqrt{g_{\text{B}}^2 + g_{\text{D}}^2}$$

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

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

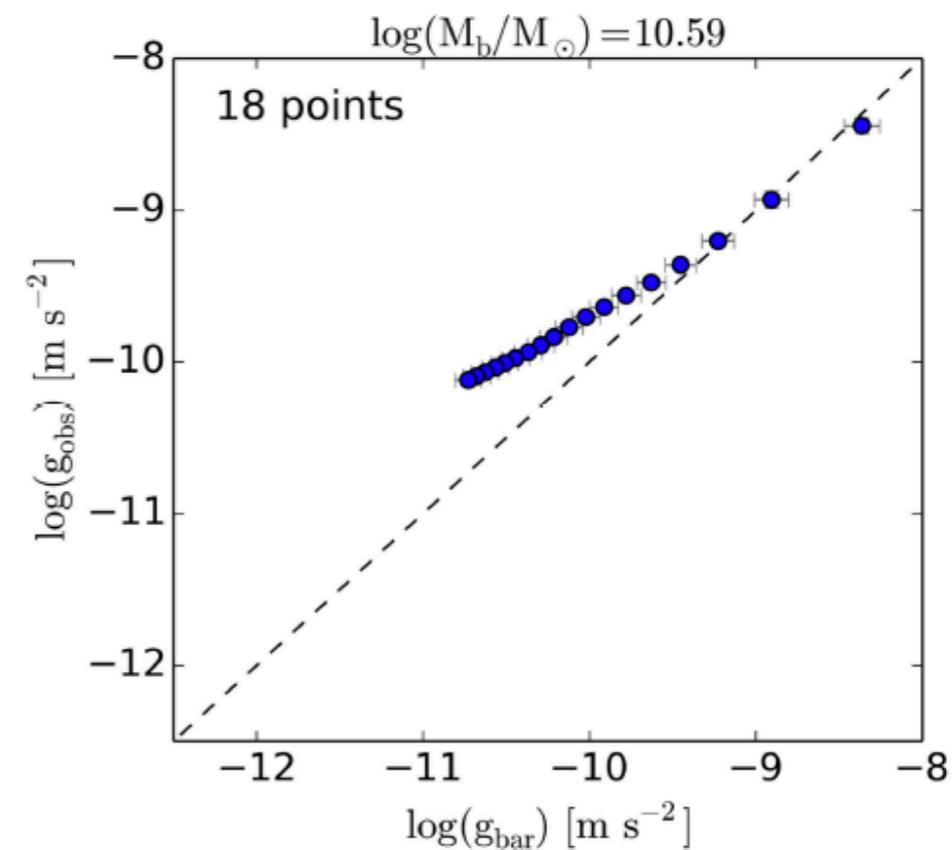
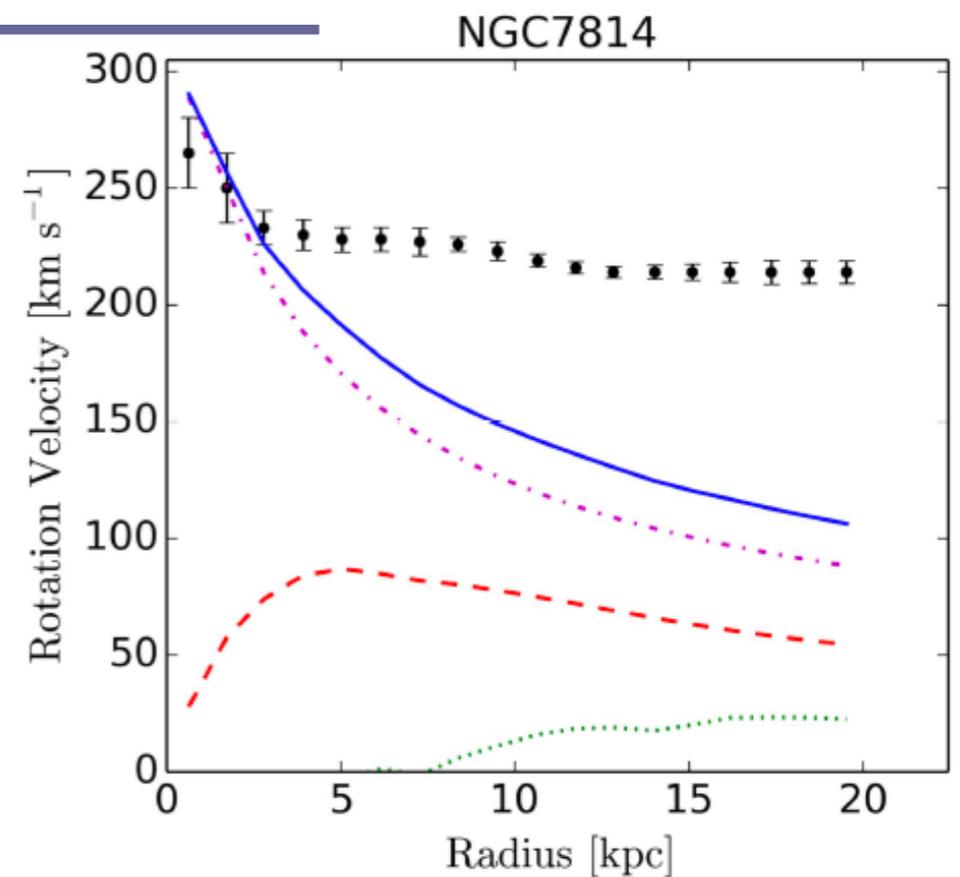
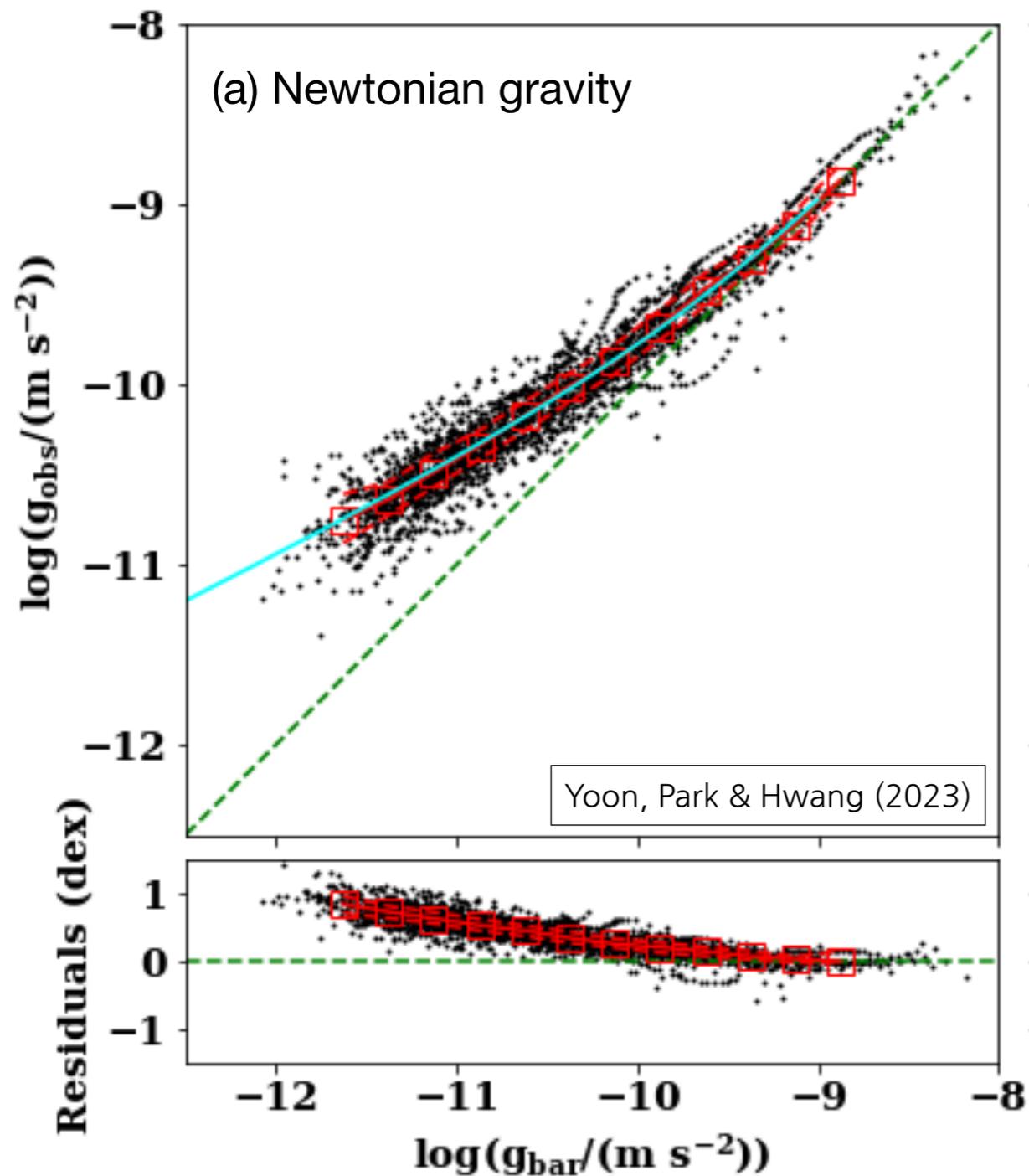
$$\Phi_{\text{B}} = -\frac{2g_{\text{B}}^2}{4\pi G\rho_{\text{B}} + \vec{n} \cdot \nabla g_{\text{B}}}$$

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

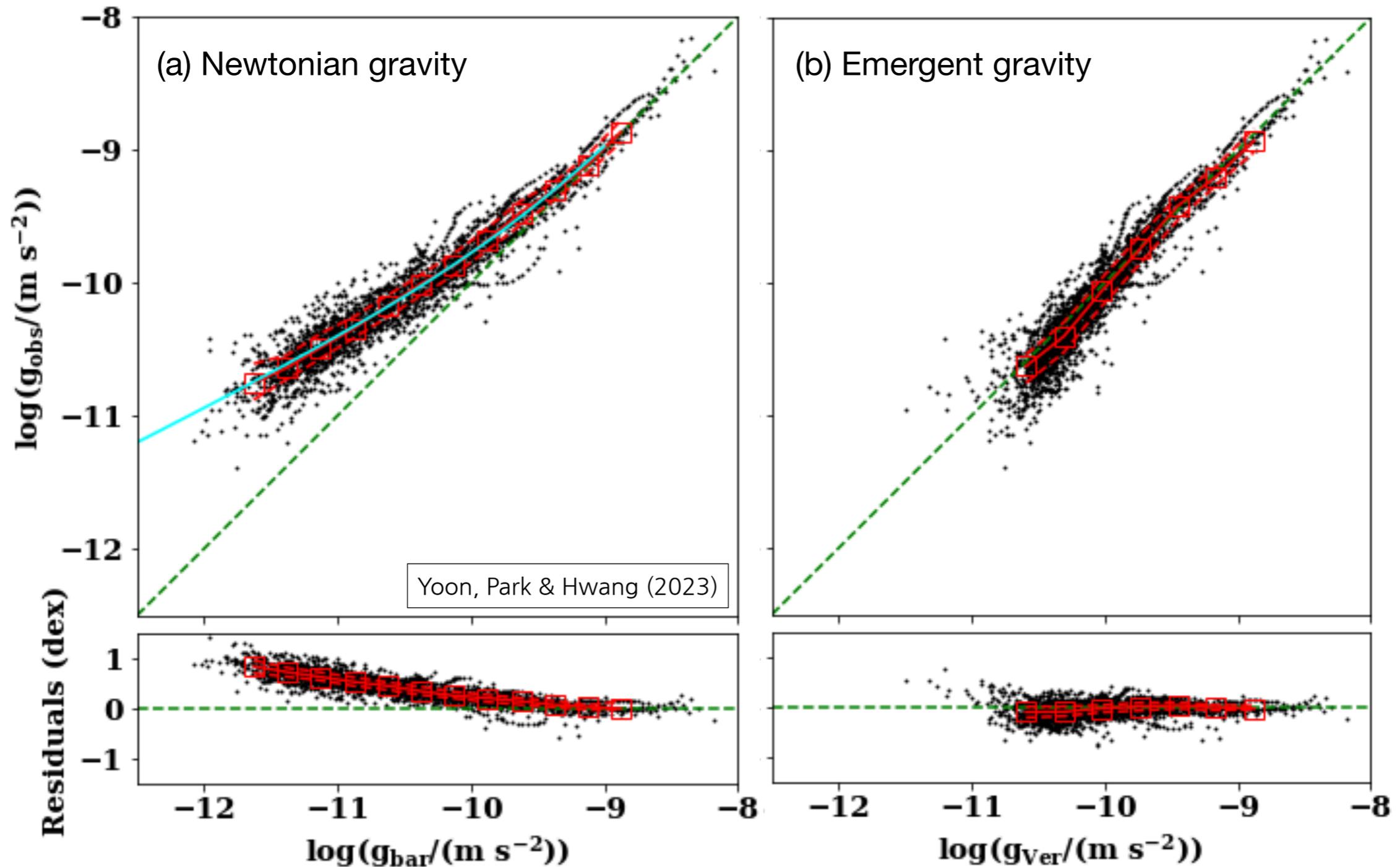
1. Radial acceleration relation: **observed acceleration from rotation curves vs. acceleration from baryon mass**



Emergent Gravity

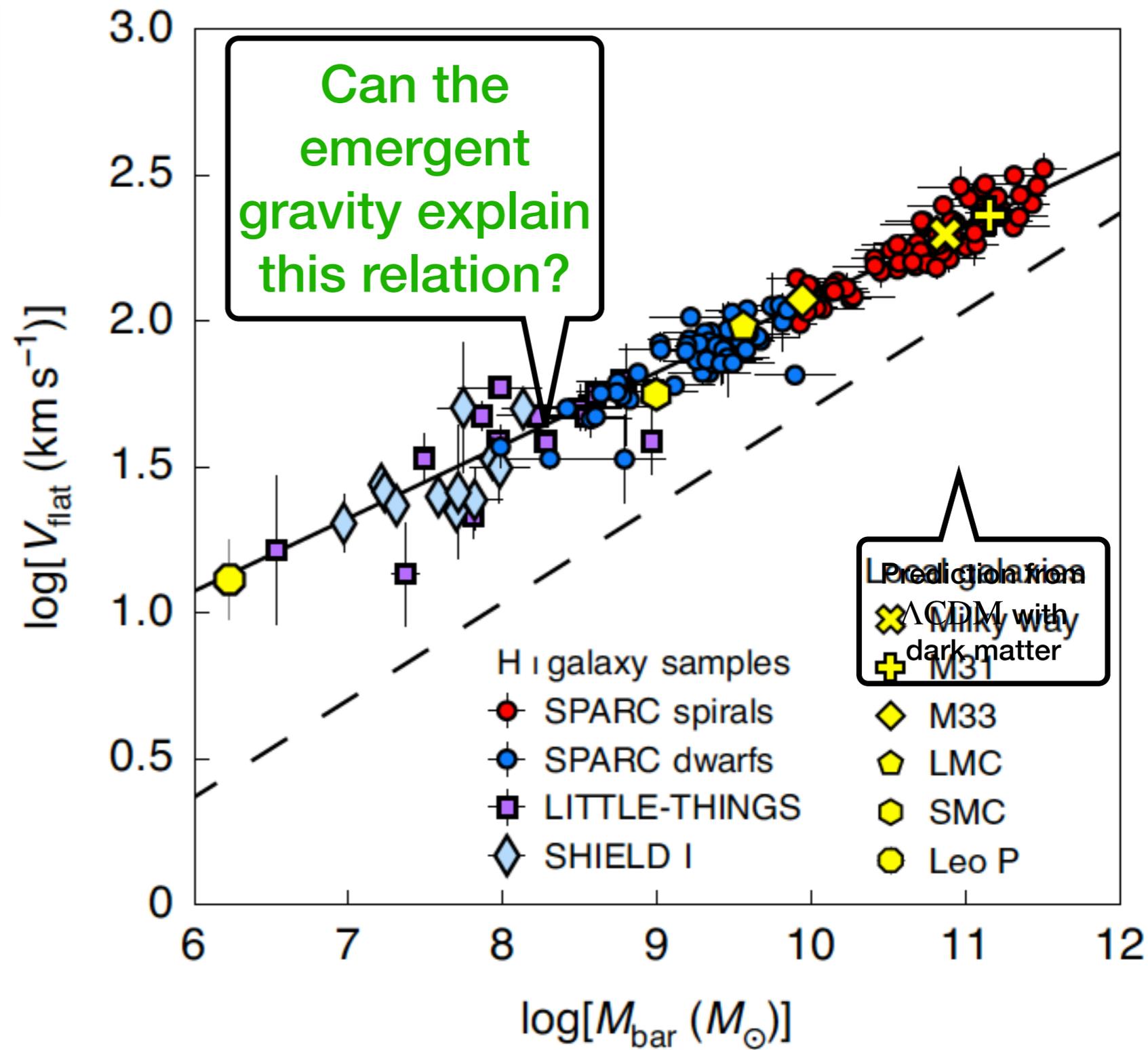
1. Radial acceleration relation

➤ 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

