2024.12.5 東京女子大学　理論物理研究室

From invisible to visible: our Universe of dark matter

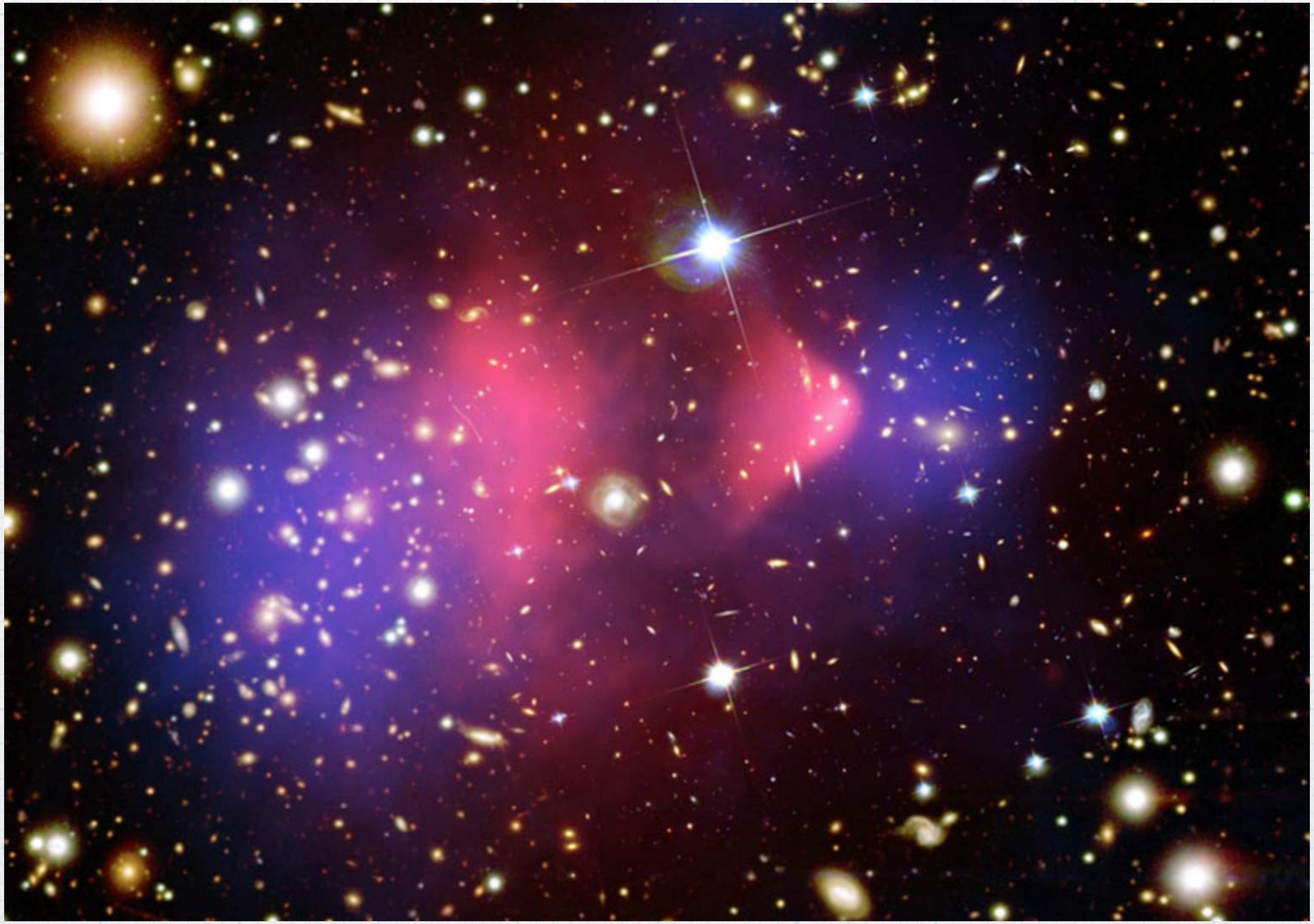
Nagisa Hiroshima (YNU, iTHEMS RIKEN)

contents:

1. our Universe

image?

- **bullet cluster 1E0657-558** Clowe et al., 2006



image?

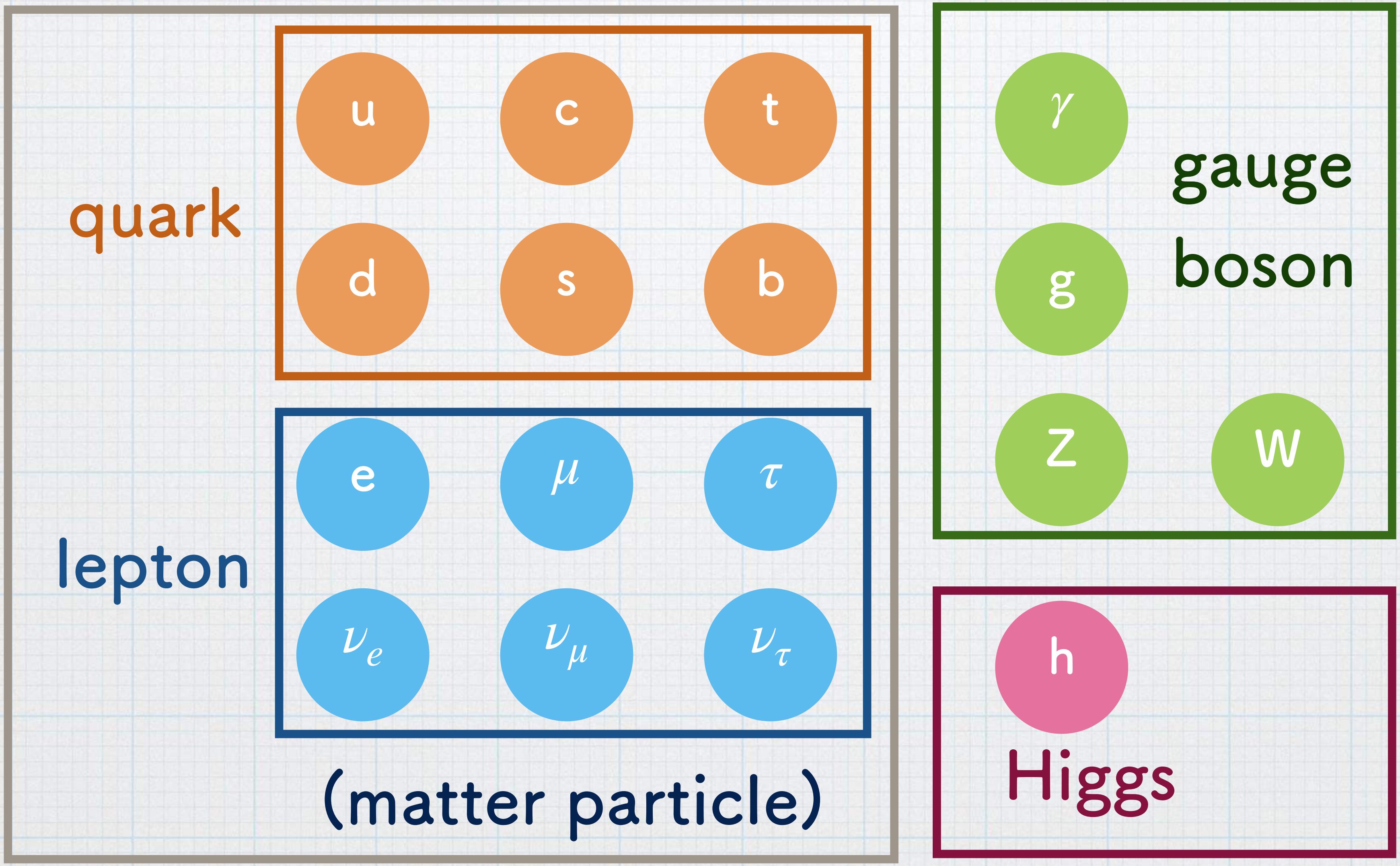
- galaxies & galaxy clusters
- ordinary stars (e.g. Sun, ⋯)
- exotic stars (neutron star, white dwarf, ..)
- planet
- ⋯

our "visible" Universe

(our eye: γ, ν, $e^{\pm}$, p, $\bar{p}$, gravitational wave,⋯)

ingredients of visible world

the Standard Model (SM) of the particle physics



quark

u c t

d s b

lepton

e μ τ

ν_e ν_μ ν_τ

(matter particle)

γ g Z W

gauge boson

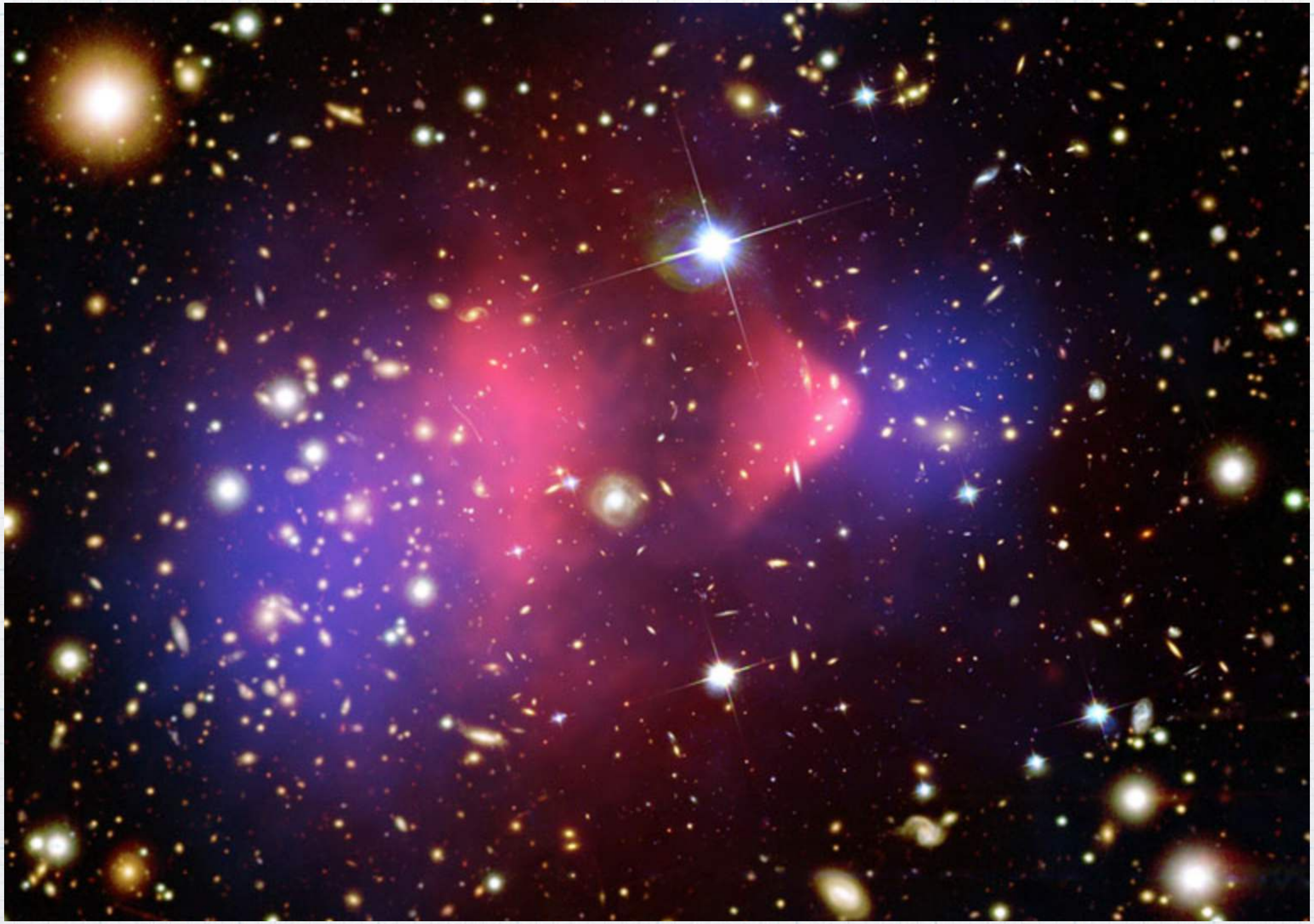
h

Higgs

visible Universe: galaxy cluster

- bullet cluster 1E0657-558

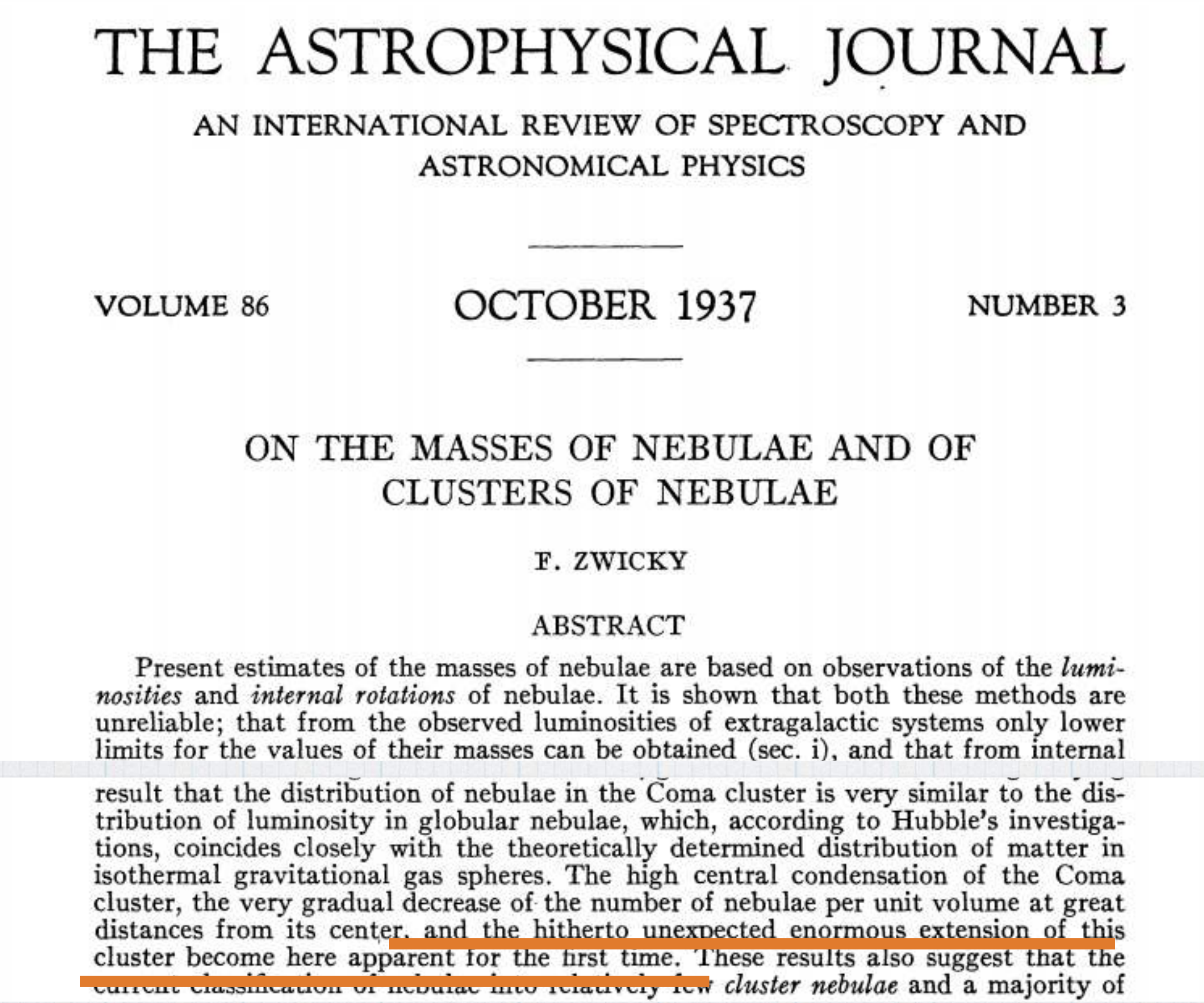
Clowe et al., 2006



passing mass?

visible Universe: galaxy cluster

Zwicky, 1937



THE ASTROPHYSICAL JOURNAL

AN INTERNATIONAL REVIEW OF SPECTROSCOPY AND ASTRONOMICAL PHYSICS

VOLUME 86 OCTOBER 1937 NUMBER 3

ON THE MASSES OF NEBULAE AND OF CLUSTERS OF NEBULAE

F. ZWICKY

ABSTRACT

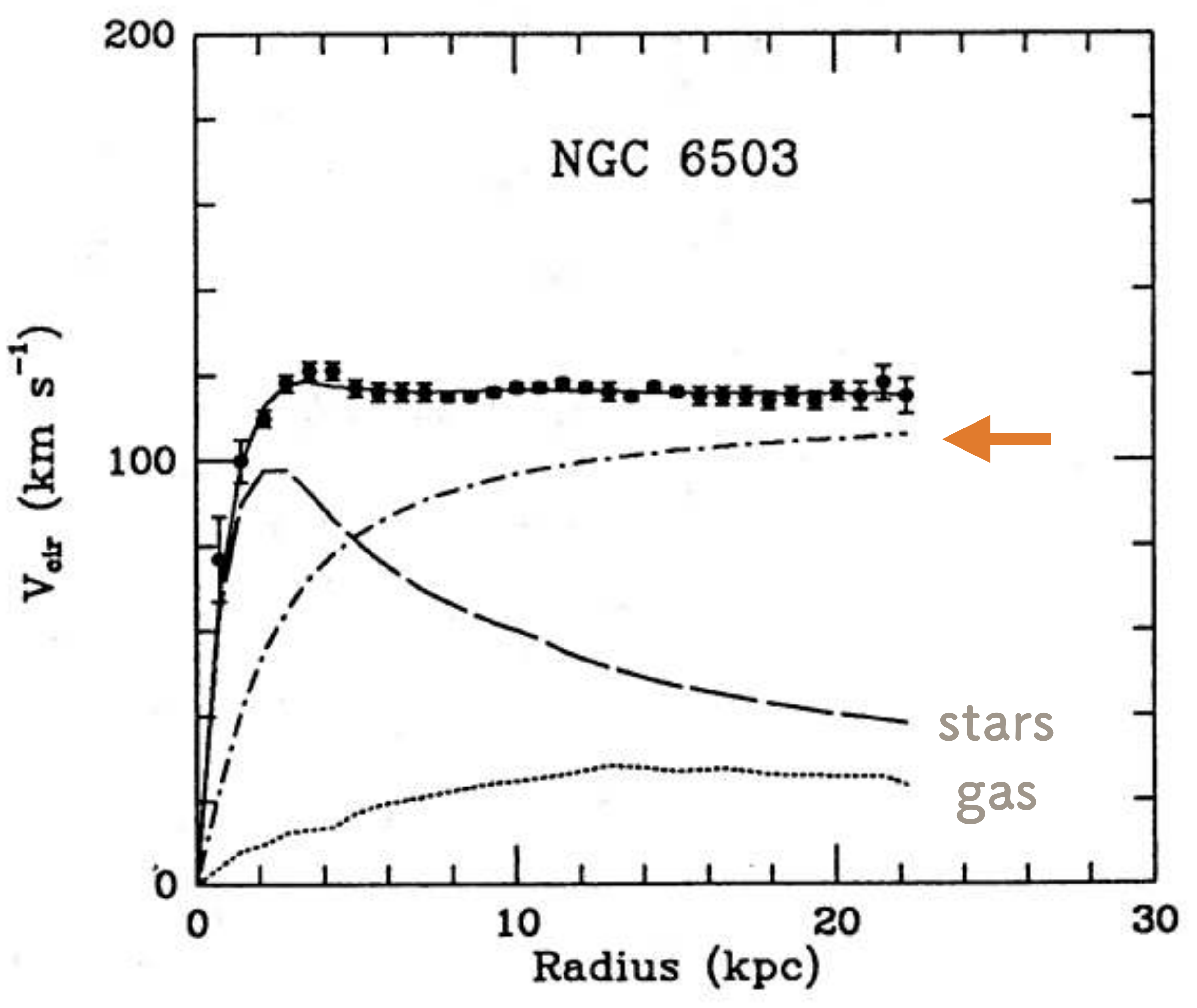
Present estimates of the masses of nebulae are based on observations of the *luminosities* and *internal rotations* of nebulae. It is shown that both these methods are unreliable; that from the observed luminosities of extragalactic systems only lower limits for the values of their masses can be obtained (sec. i), and that from internal

result that the distribution of nebulae in the Coma cluster is very similar to the distribution of luminosity in globular nebulae, which, according to Hubble's investigations, coincides closely with the theoretically determined distribution of matter in isothermal gravitational gas spheres. The high central condensation of the Coma cluster, the very gradual decrease of the number of nebulae per unit volume at great distances from its center, and the hitherto unexpected enormous extension of this cluster become here apparent for the first time. These results also suggest that the current classification of nebulae into relatively few *cluster nebulae* and a majority of

invisible mass?

visible Universe: galaxy

Begeman et al., 1991



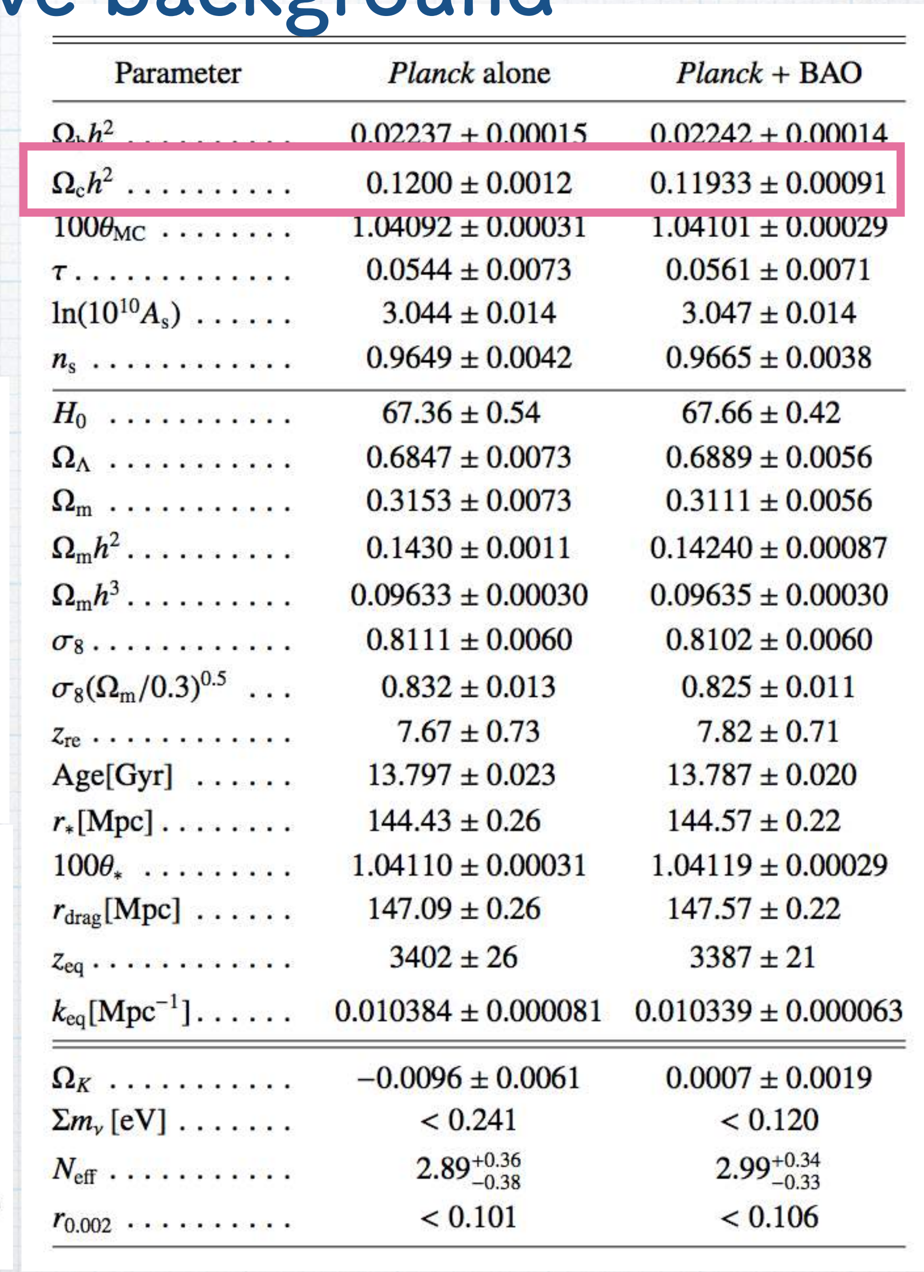
invisible mass?

visible Universe: CMB observation

cosmic microwave background

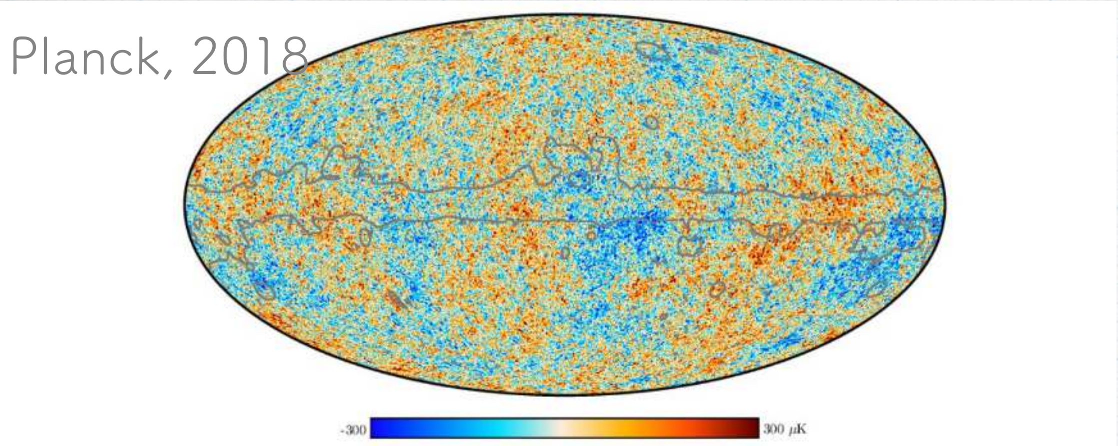
temperature fluctuation
∼ density fluctuation

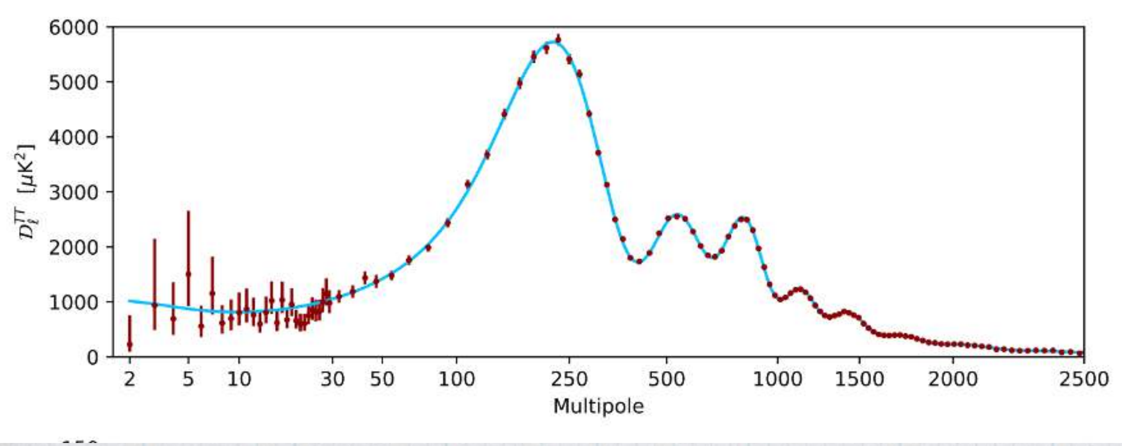
cosmological requirement



Parameter	*Planck* alone	*Planck* + BAO
$\Omega_b h^2$	0.02237 ± 0.00015	0.02242 ± 0.00014
$\Omega_c h^2$	0.1200 ± 0.0012	0.11933 ± 0.00091
$100\theta_{MC}$	1.04092 ± 0.00031	1.04101 ± 0.00029
τ	0.0544 ± 0.0073	0.0561 ± 0.0071
$\ln(10^{10} A_s)$	3.044 ± 0.014	3.047 ± 0.014
n_s	0.9649 ± 0.0042	0.9665 ± 0.0038
H_0	67.36 ± 0.54	67.66 ± 0.42
Ω_Λ	0.6847 ± 0.0073	0.6889 ± 0.0056
Ω_m	0.3153 ± 0.0073	0.3111 ± 0.0056
$\Omega_m h^2$	0.1430 ± 0.0011	0.14240 ± 0.00087
$\Omega_m h^3$	0.09633 ± 0.00030	0.09635 ± 0.00030
σ_8	0.8111 ± 0.0060	0.8102 ± 0.0060
$\sigma_8(\Omega_m/0.3)^{0.5}$ . . .	0.832 ± 0.013	0.825 ± 0.011
z_{re}	7.67 ± 0.73	7.82 ± 0.71
Age[Gyr]	13.797 ± 0.023	13.787 ± 0.020
r_*[Mpc]	144.43 ± 0.26	144.57 ± 0.22
$100\theta_*$	1.04110 ± 0.00031	1.04119 ± 0.00029
r_{drag}[Mpc]	147.09 ± 0.26	147.57 ± 0.22
z_{eq}	3402 ± 26	3387 ± 21
k_{eq}[Mpc^{-1}]	0.010384 ± 0.000081	0.010339 ± 0.000063
Ω_K	-0.0096 ± 0.0061	0.0007 ± 0.0019
Σm_ν [eV]	< 0.241	< 0.120
N_{eff}	$2.89^{+0.36}_{-0.38}$	$2.99^{+0.34}_{-0.33}$
$r_{0.002}$	< 0.101	< 0.106

Planck, 2018

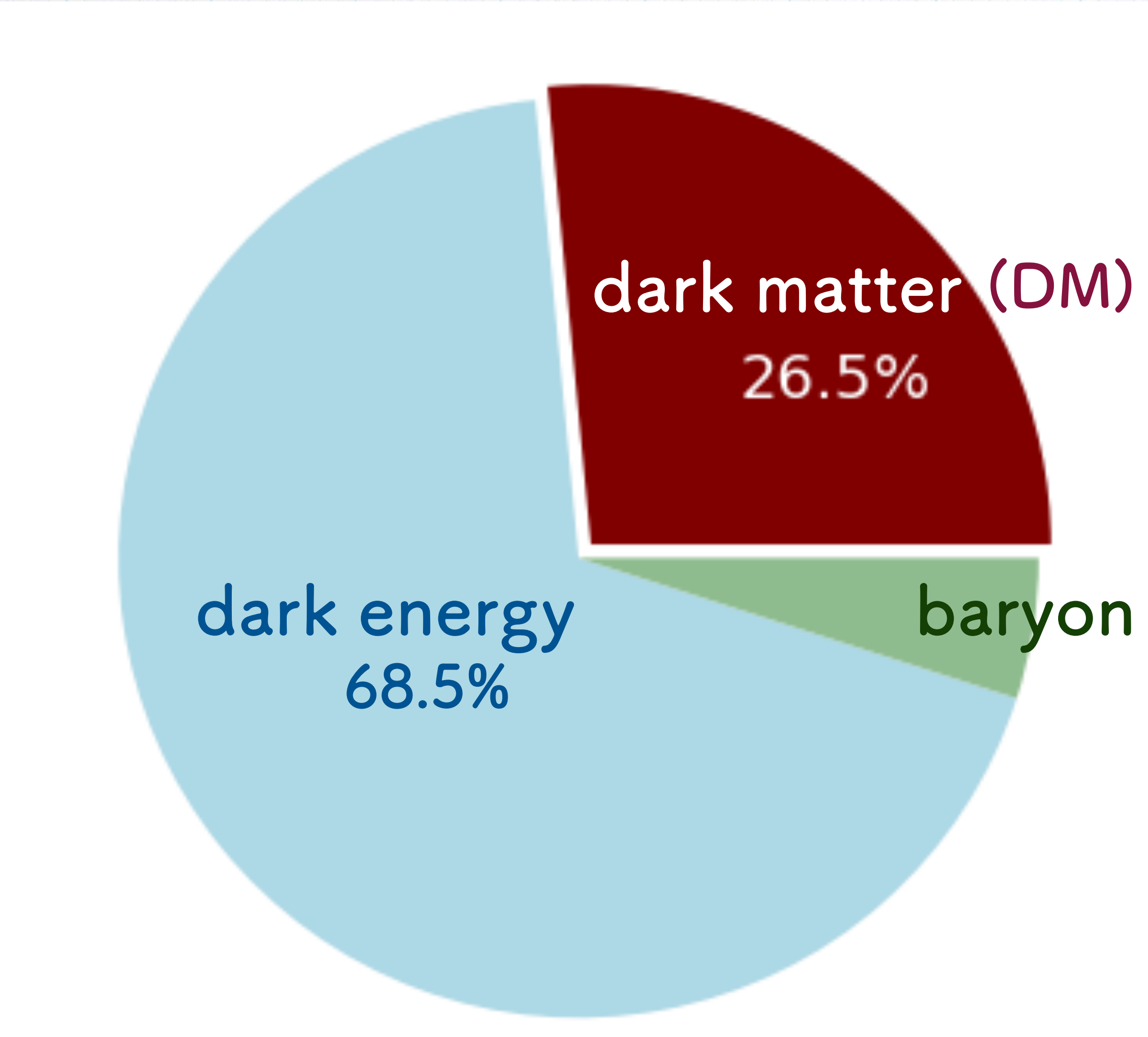




2.the things we know about dark matter

in order to achieve the CMB pattern…

energy density chart of our Universe



radiation: 0.0..%

cf. property of each component

- matter(baryon)

  matter in the Standard Model, $\rho \propto V^{-1} \propto a^{-3}$

- dark matter (DM)

  matter-like something, $\rho \propto a^{-3}$

- dark energy

  not matter-like something, $\rho \propto a^{0}$

- radiation($\ll$ 1%)

  (mainly) photons(γ) and neutrinos(ν), $\rho \propto a^{-4}$

brief cosmological history

Inflation(0s)

↓

radiation dominated era

↓

matter dominated era $T \sim 10^4$ K (z=3500)

DM (halo) structure formation starts

CMB(photon decoupling) $T \sim 10^3$ K (z=1100)

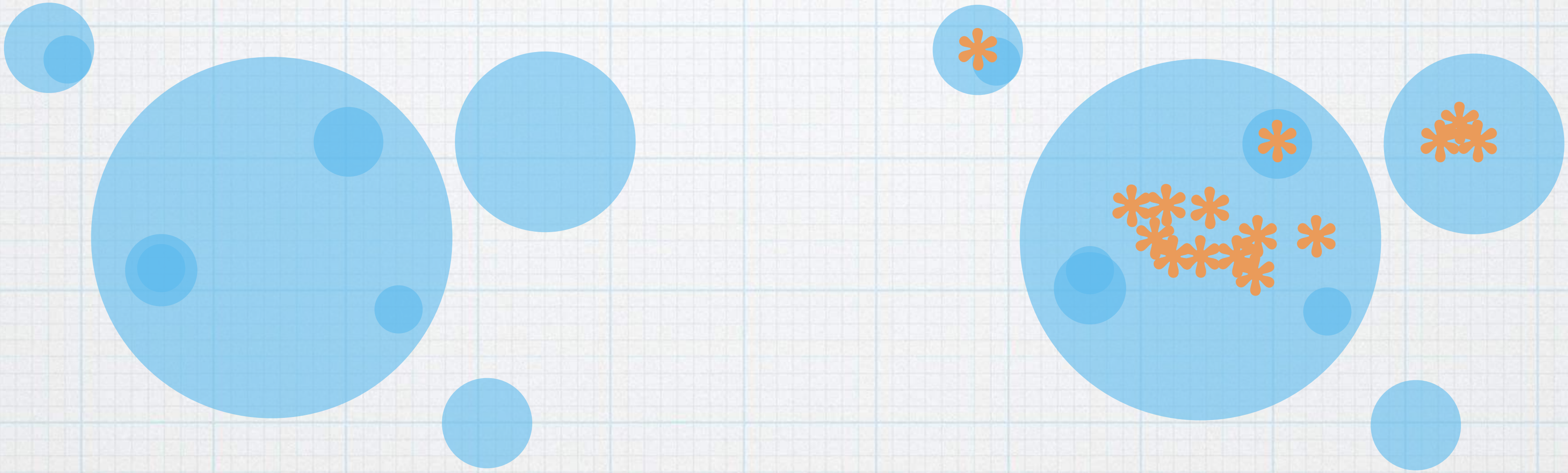
baryon structure formation starts

↓

current Universe $T \sim 2.7\mathrm{K}$ (z=0)

dark matter should

provide gravitational potential
for baryon fluctuations to evolve



DM structure: halo
(form earlier)

↔

baryon structure: galaxy

we need “matter” different from baryon

what we have learned so far···

- feel gravity
- cold (warm, hot)
- stable (or lifetime longer than cosmic age)
- (almost) neutral
- (almost) invisible

what we have learned so far…

- feel gravity
  because it should form halos and provide potential
- cold (warm, hot)
  in order not to erase small-scale fluctuations
- stable (or lifetime longer than cosmic age)
  because otherwise it should decay
- (almost) neutral
  in order to start structure formation before decoupling
- (almost) invisible
  since we have not seen electromagnetic signatures

candidate = anything which satisfies these properties

examples

- Weakly Interacting Massive Particle (WIMP)
- Strongly/self- interacting massive particle (SIMP)
- sterile neutrinos
- axion and/or axion-like particle (ALP)
- primordial black hole (PBH)
- …

indicators of DM

- stellar motions in stars:

  gravitational potential controls the motion

- anomalous emissions from Universe

  DM interaction leads to SM particle emissions?

- modulation of astrophysical emissions

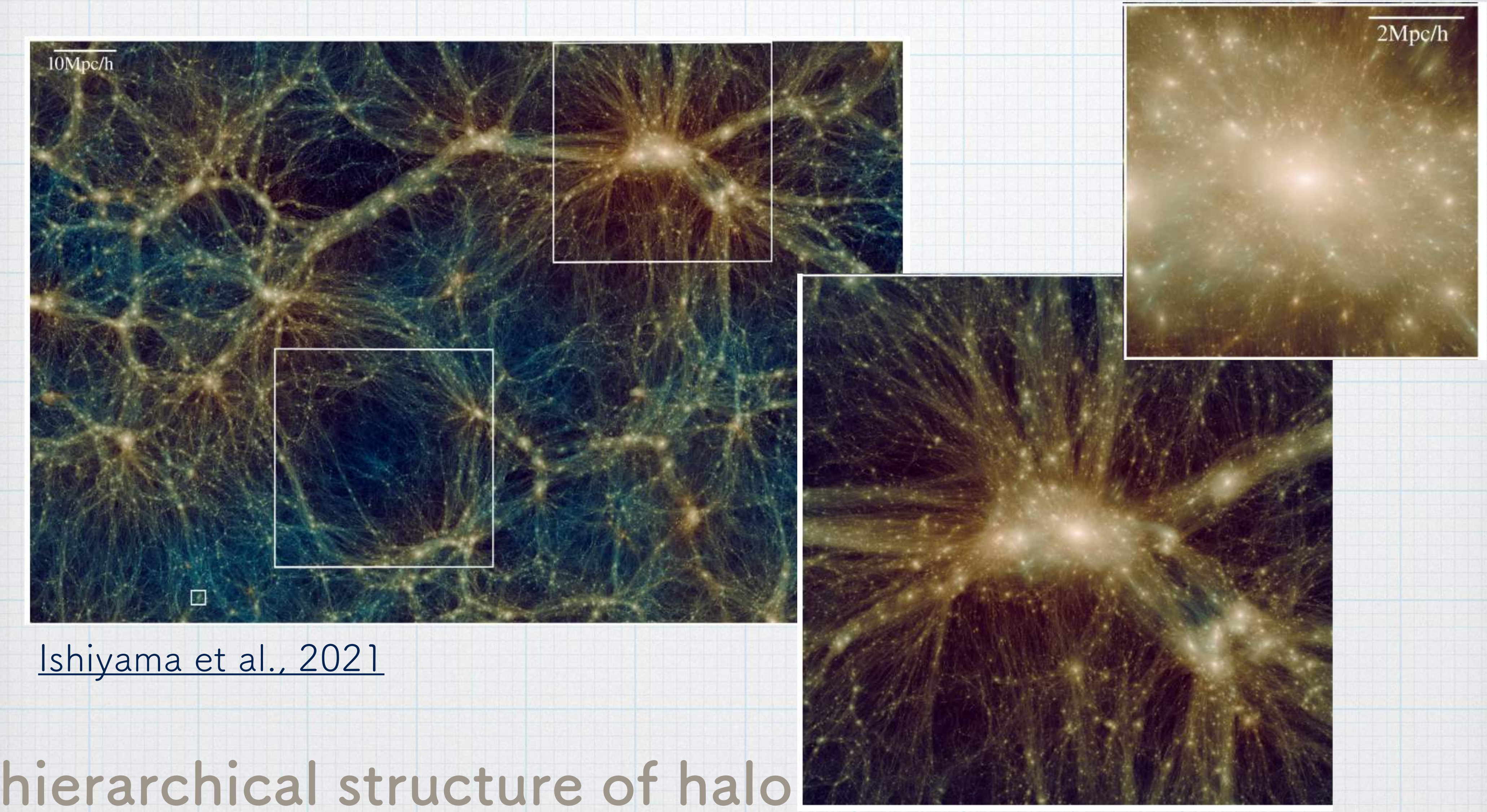
  Can DM interaction can change the prediction for

  astrophysical emissions in the SM context?

What kinds of interactions can we assume?

gravitational interaction

Requirement for DM



Ishiyama et al., 2021

hierarchical structure of halo

3. physics of dark matter halo

characterization of halo

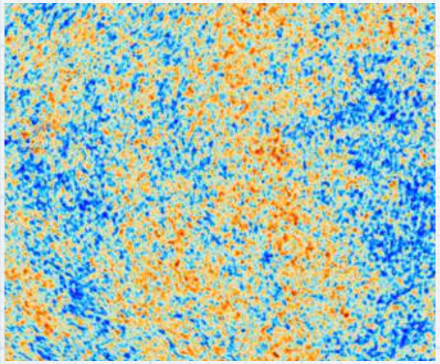
- redshift range $z_{\rm eq}\ -\ 0$
- mass range: $\mathcal{O}(10^{-6})M_\odot?\ -\ \mathcal{O}(10^{16})M_\odot$

  mass function $\dfrac{dN}{dm} = m^{-\alpha}\quad(\alpha \sim 2)$
- hierarchical structure formed through accretion, merger, and tidal interaction
- density profile (e.g. NFW $\rho(r) = \rho_s\left(\dfrac{r}{r_s}\right)^{-1}\left(1+\dfrac{r}{r_s}\right)^{-2}$)

physics of halo ranges widely

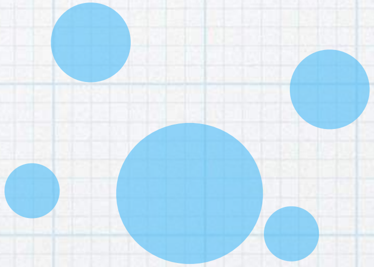
story of DM halo

1, initial fluctuation

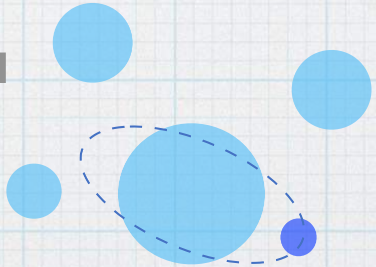


2, **gravitational collapse**

(halo formation)

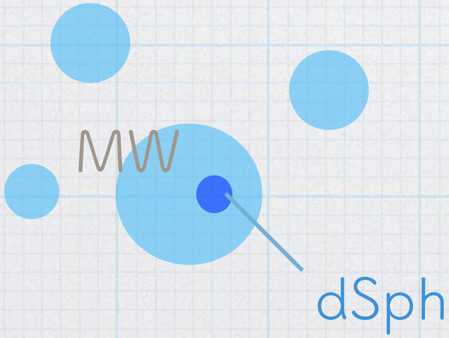


3, halo evolution



- merger
- accretion
- tidal stripping

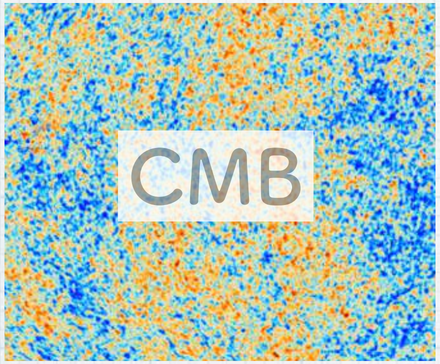
4, hierarchical structure



story of DM halo

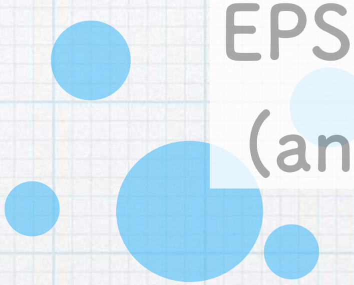
(semi-) analytic description

1, initial fluctuation



2, **gravitational collapse**

(halo formation)



EPS theory

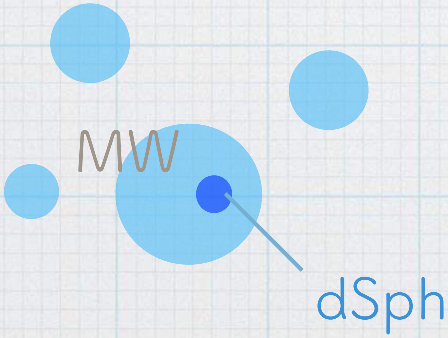
(analytic)

3, halo evolution

analytic descritpion

- merger
- accretion
- tidal stripping

4, hierarchical structure



why (semi-) analytic?

numerical (e.g. N-body simulation) :

- precise (most physical processes can be included)
- high computational costs
- resolution limit

(semi-)analytic:

- approximation & simplification
- no resolution limit & wide scale coverage
- cost effective

high applicability in halo study

halo formation and evolution

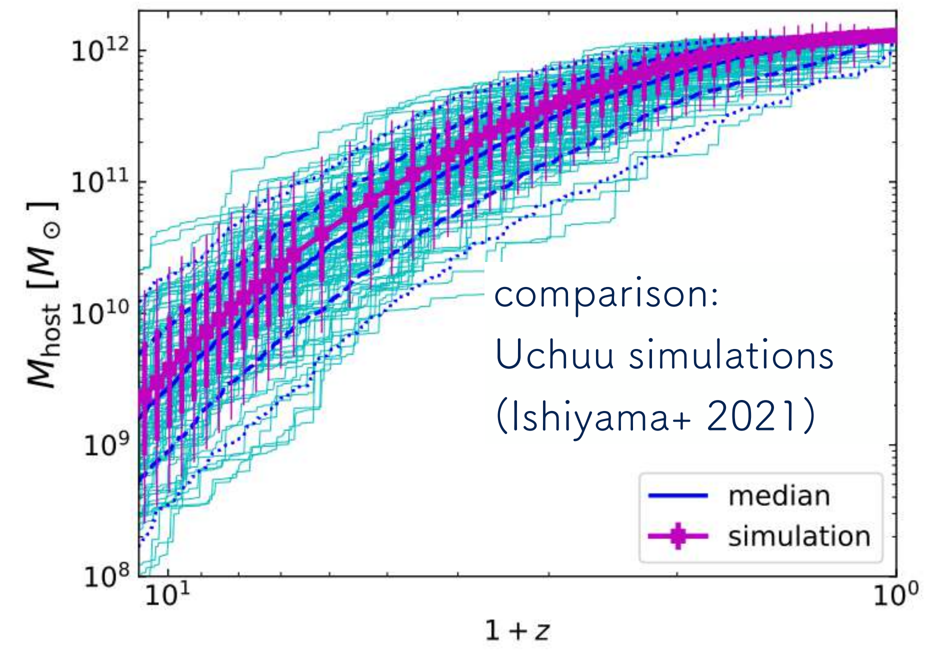
Extended Press-Schechter formalism:

$$f(\sigma^2(m), \delta(z+\Delta z)\,|\,\sigma^2(M), \delta(z)) = \frac{1}{\sqrt{2\pi}}\frac{\delta(z+\Delta z)-\delta(z)}{[\sigma^2(m)-\sigma^2(M)]^{3/2}}\exp\left[-\frac{(\delta(z+\Delta z)-\delta(z))^2}{2(\sigma^2(m)-\sigma^2(M))}\right]$$

fraction of halo of which mass was m at $z+\Delta z$ in M at z

- halo formation
  = collapse of overdensity
- two parameters:
  - collapse redshift $\delta(z)$
  - mass scale $\sigma(M)$

NH, Ando, Ishiyama, 2022

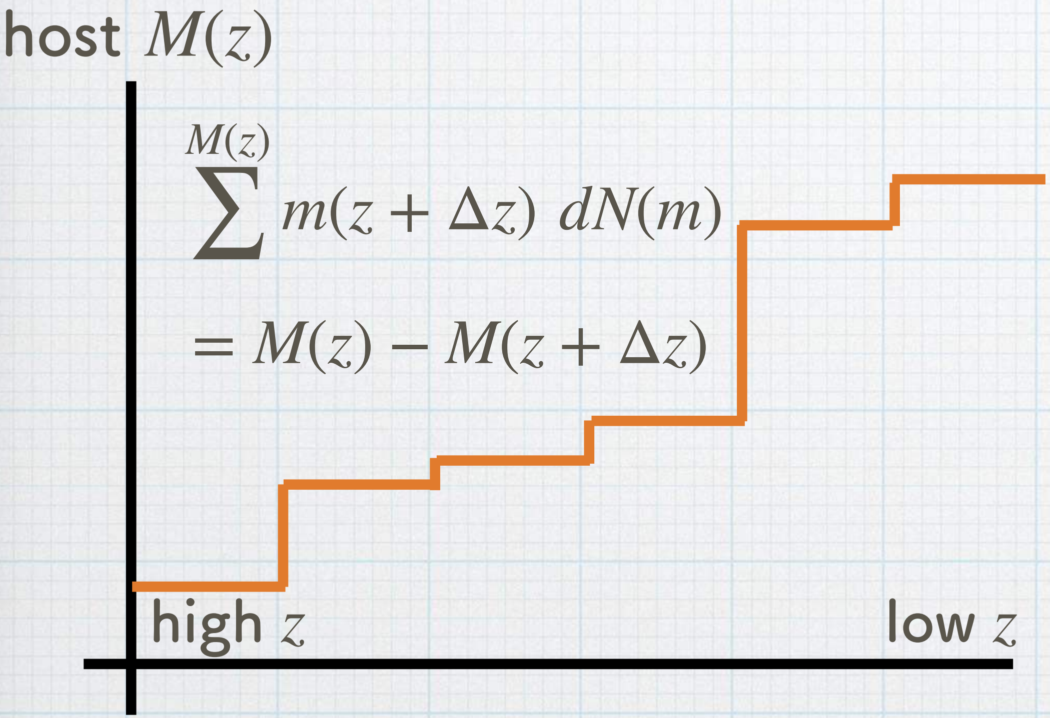


comparison:
Uchuu simulations
(Ishiyama+ 2021)

$^\exists m(z+\Delta z) > M(z)/2 \Rightarrow$ **unique progenitor**

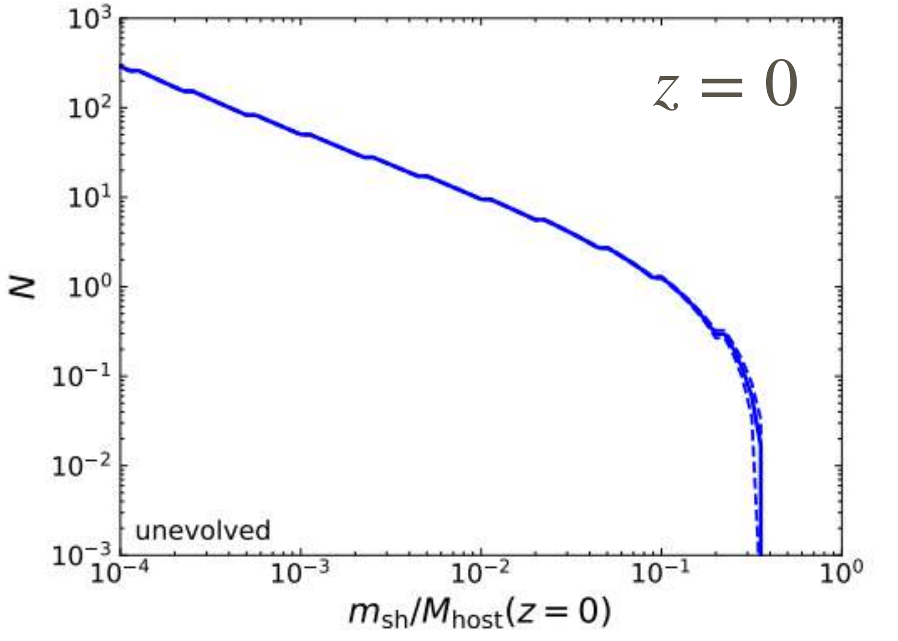
subhalo accretion:

mass increment of the host = sum of accreted halo mass



$$\sum^{M(z)} m(z+\Delta z)\ dN(m) = M(z) - M(z+\Delta z)$$

NH, Ando, Ishiyama, 2022



normalization condition

from host evolution

unevolved mass function

as the sum of ones at each z

“unevolved” subhalo mass function

evolution after accretion

1. mass-loss rate: $\dot{m} = \left[m - m(<r_t)\right] T^{-1}$
2. host potential

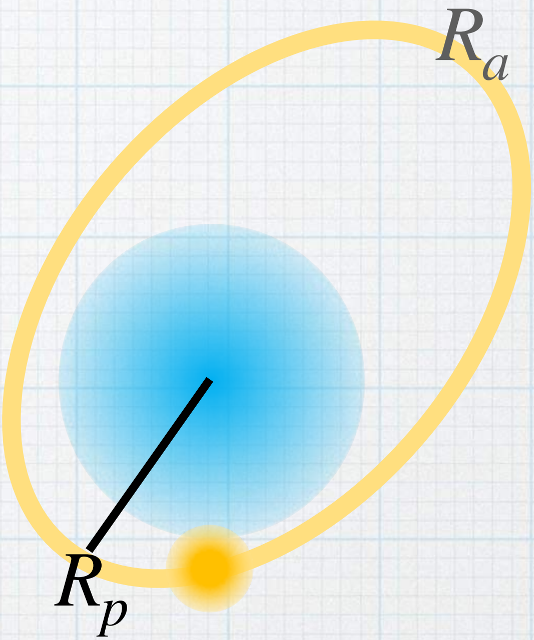
$$\Phi(R) = -V_{\rm vir}^2 \frac{\ln\left[1 + c_{\rm vir}^{\rm host} R/R_{\rm vir}\right]}{f(c_{\rm vir}^{\rm host}) R/R_{\rm vir}}, \quad c_{\rm vir} = r_{\rm vir}/r_s$$

3. pericenter(R_p) & apocenter(R_a)

$$R^{-2} + 2\left[\Phi(R) - E\right] L^{-2} = 0$$

4. orbital period: $T = 2\int_{R_p}^{R_a} \frac{dR}{\sqrt{2(E - \Phi(R)) - L^2/R^2}}$
5. truncation radius

$$r_t = R_p \left[\frac{m(<r_t)\,.\,M(<R_p)}{2 + L^2(R_p G M(<R_p))^{-1} - d\ln M/d\ln R\big|_{R_p}}\right]^{1/3}$$

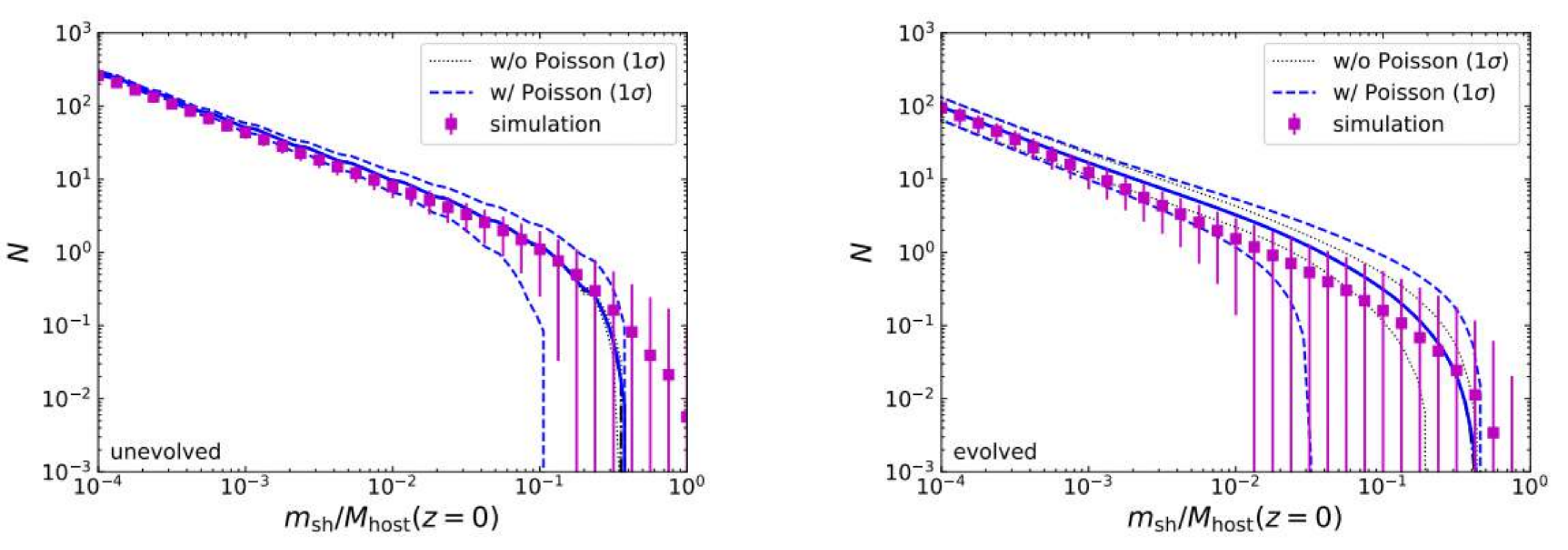


subhalo mass function at $z = 0$

assumption:

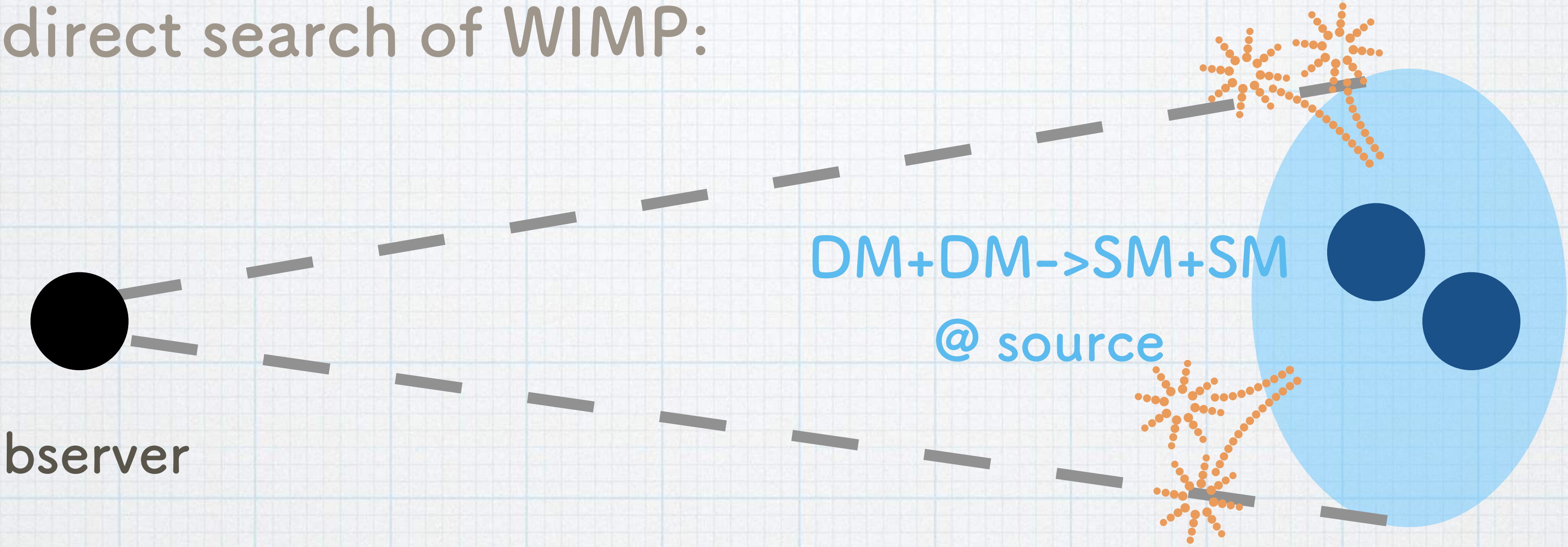
- Milky Way-like host ($M \sim 1.3 \times 10^{12} M_\odot$)
- tidal mass-loss rate at pericenter

NH, Ando, Ishiyama, 2022



application: density profile

indirect search of WIMP:



$$\phi_\gamma = \frac{1}{8\pi}\frac{\langle\sigma v\rangle}{m_{\mathrm{DM}}^2}\int_{E_{\mathrm{th}}}^{m_{\mathrm{DM}}}\frac{dN}{dE}dE \cdot \boxed{\int_{\Delta\Omega} d\Omega \int_{l.o.s} ds\rho_{\mathrm{DM}}^2}$$

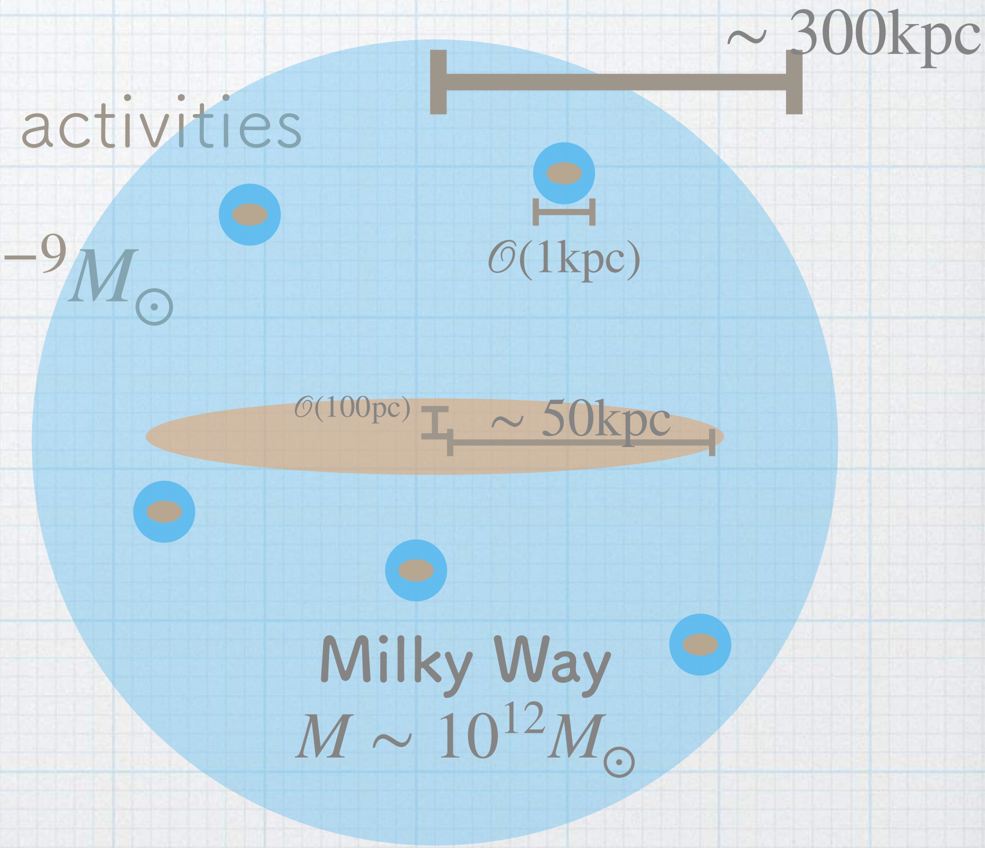
(astrophysical) J-factor

high J ↔ high flux from DM annihilation

application: density profile

target: dwarf spheroidal galaxies (dSphs)

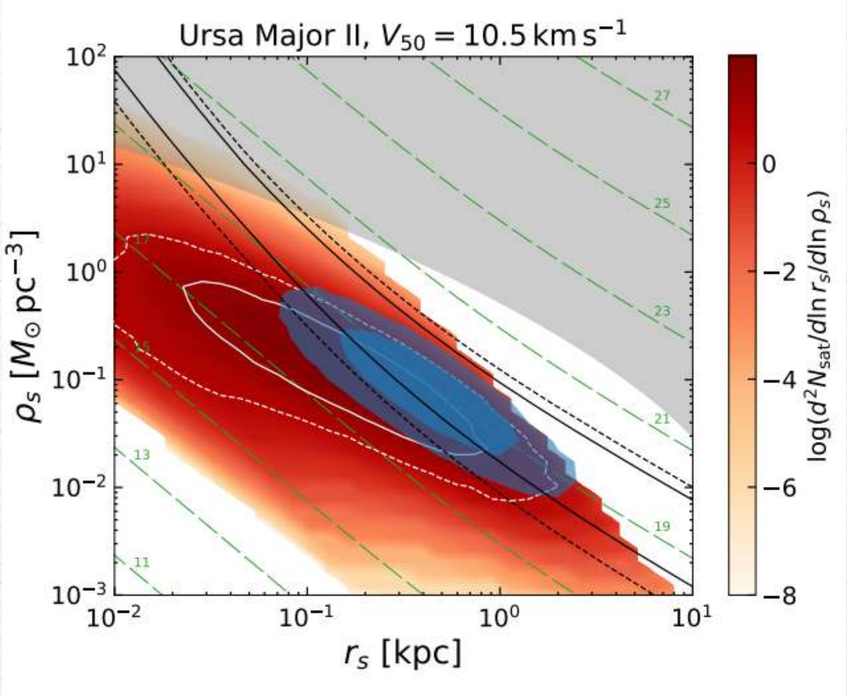
- ~40 are confirmed
- do not show star formation activities
- $M/L \lesssim 10^3 M_\odot / L_\odot$, $M \sim 10^{8-9} M_\odot$
- $\Delta\theta \lesssim \mathcal{O}(1^\circ)$
- # of stars: $\mathcal{O}(10 - 1000)$



dark & dense galaxies in subhalos of Milky Way

application: density profile

- # of subhalos at accretion : EPS prediction
- tidal evolution after accretion: analytical model
- density profile: NFW (w/ truncation) assumption
- profile parameter evolution: fitting formula from N-body simulation
- stellar kinematics: constraints on (ρ_s, r_s) plain



red: # of the satellite with EPS theory =physical prior(white)

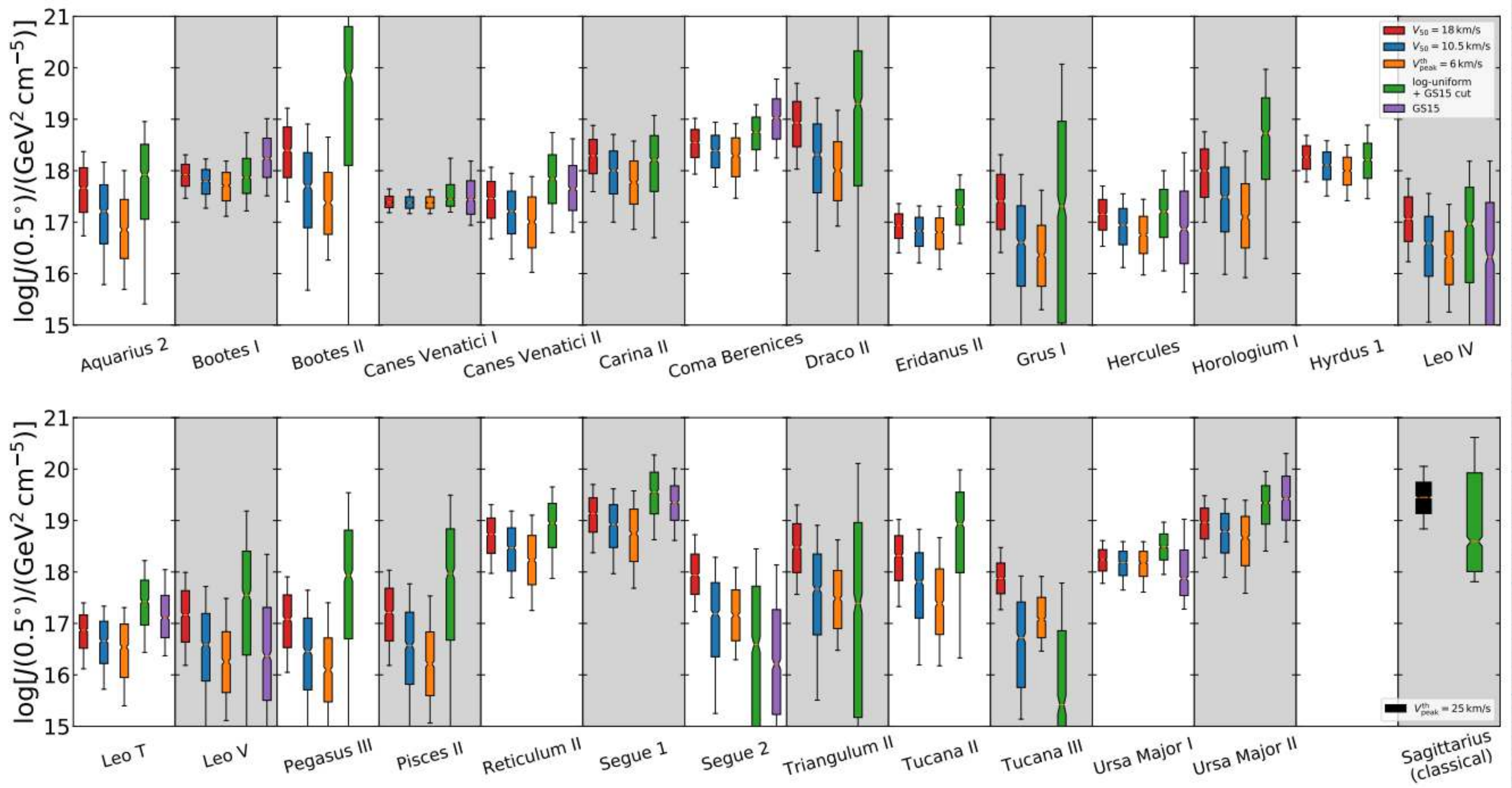
black: likelihood

blue: posterior

Ando, Geringer-Samteh, NH, Hoof, Trotta, Walker, 2020

application: density profile

Ando, Geringer-Samteh, NH, Hoof, Trotta, Walker, 2020

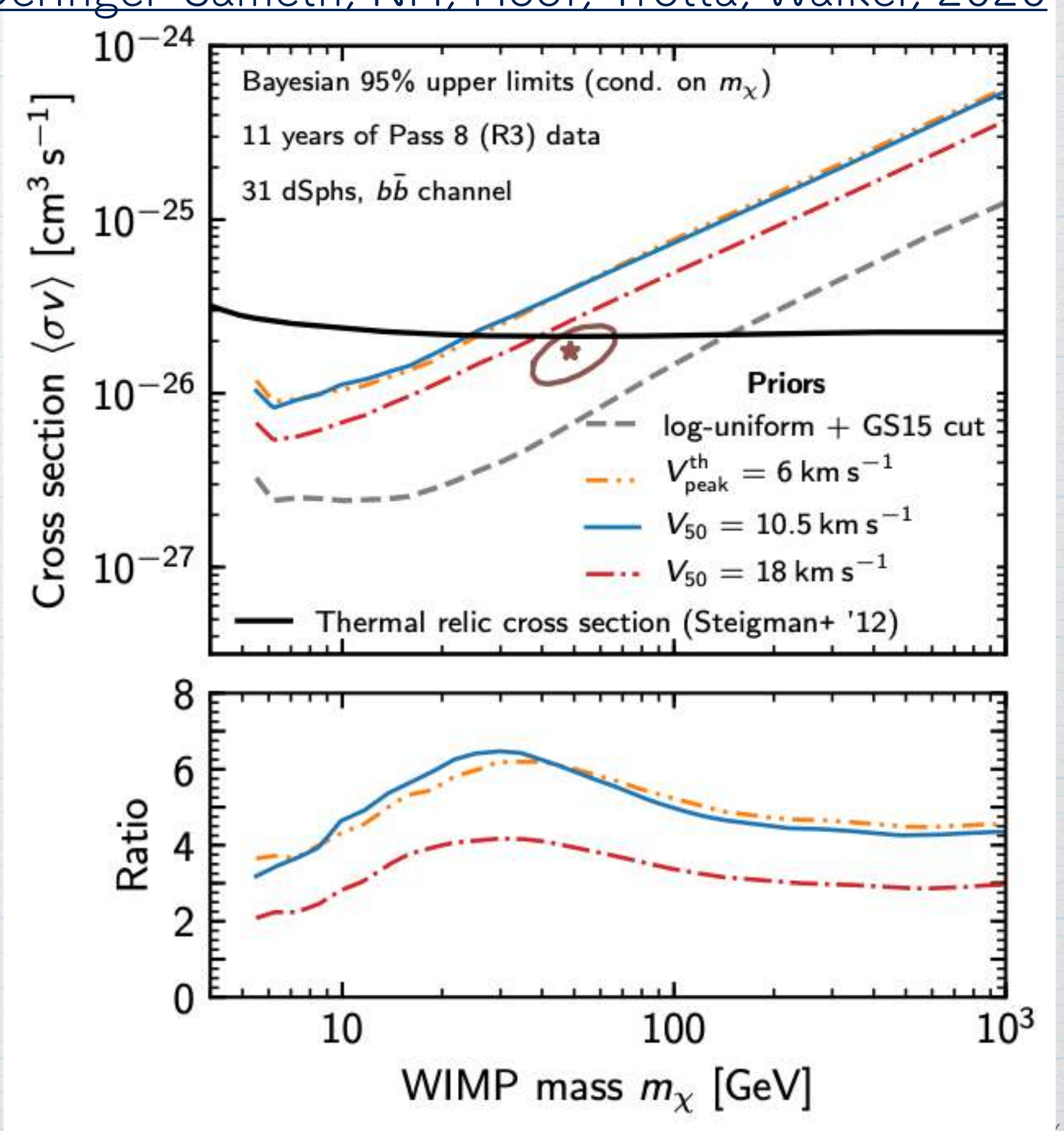


application: density profile

Ando, Geringer-Sameth, NH, Hoof, Trotta, Walker, 2020

$$\boxed{\phi_\gamma = \frac{1}{8\pi}\frac{\langle\sigma v\rangle}{m_{\mathrm{DM}}^2}\left(\int\frac{dN}{dE}dE\right)\cdot J}$$

- Bayesian analysis combining 31 dSph's data
- Weaker constraints (by a factor of 2-6)

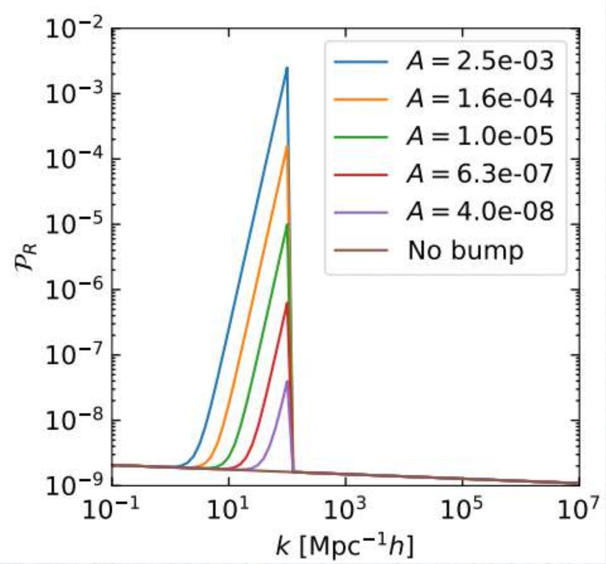


halo physics impacts constraints on WIMP models

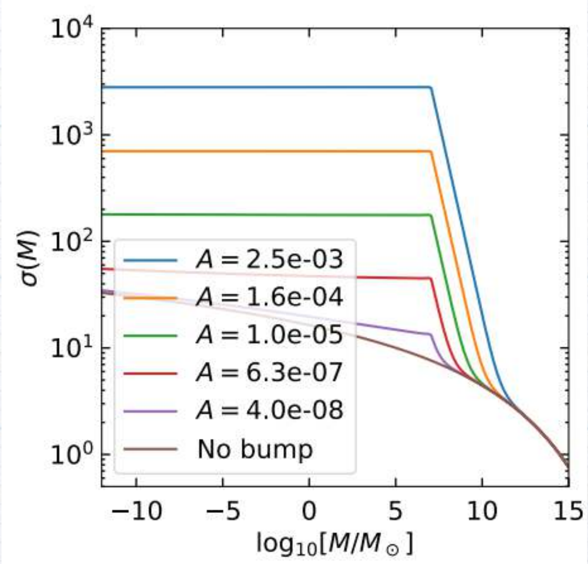
Ando, NH, Ishiwata, 2022

application: cosmology

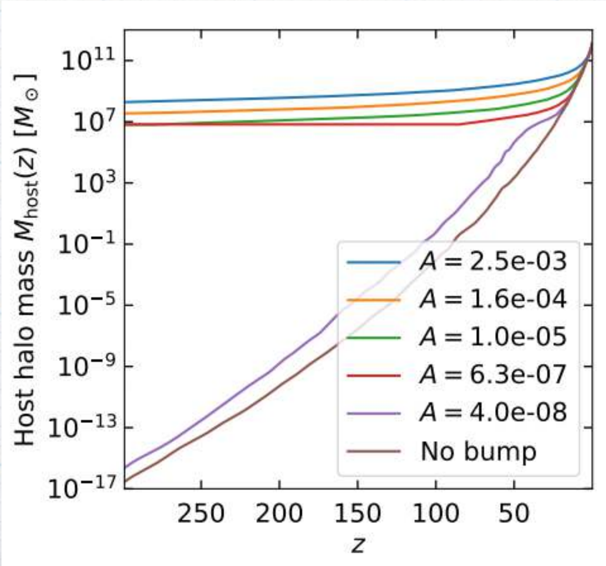
curvature perturbation $\mathscr{P}_R(k) = \mathscr{P}_R^{(0)} + \mathscr{P}_R^{\text{bump}}$



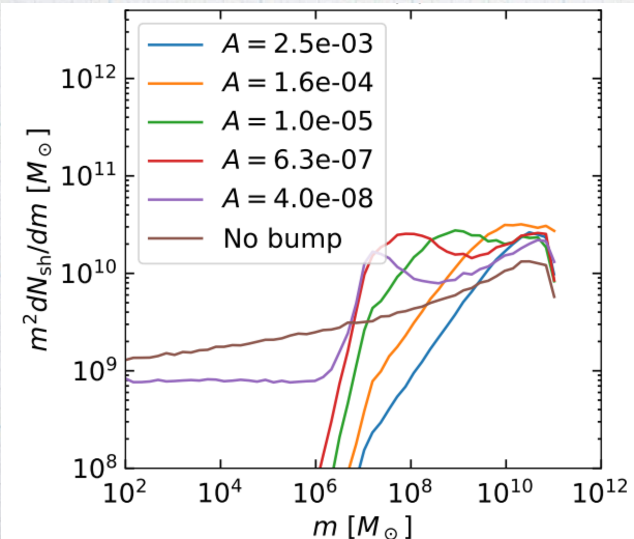
different $P(k)$



different $\sigma(M)$



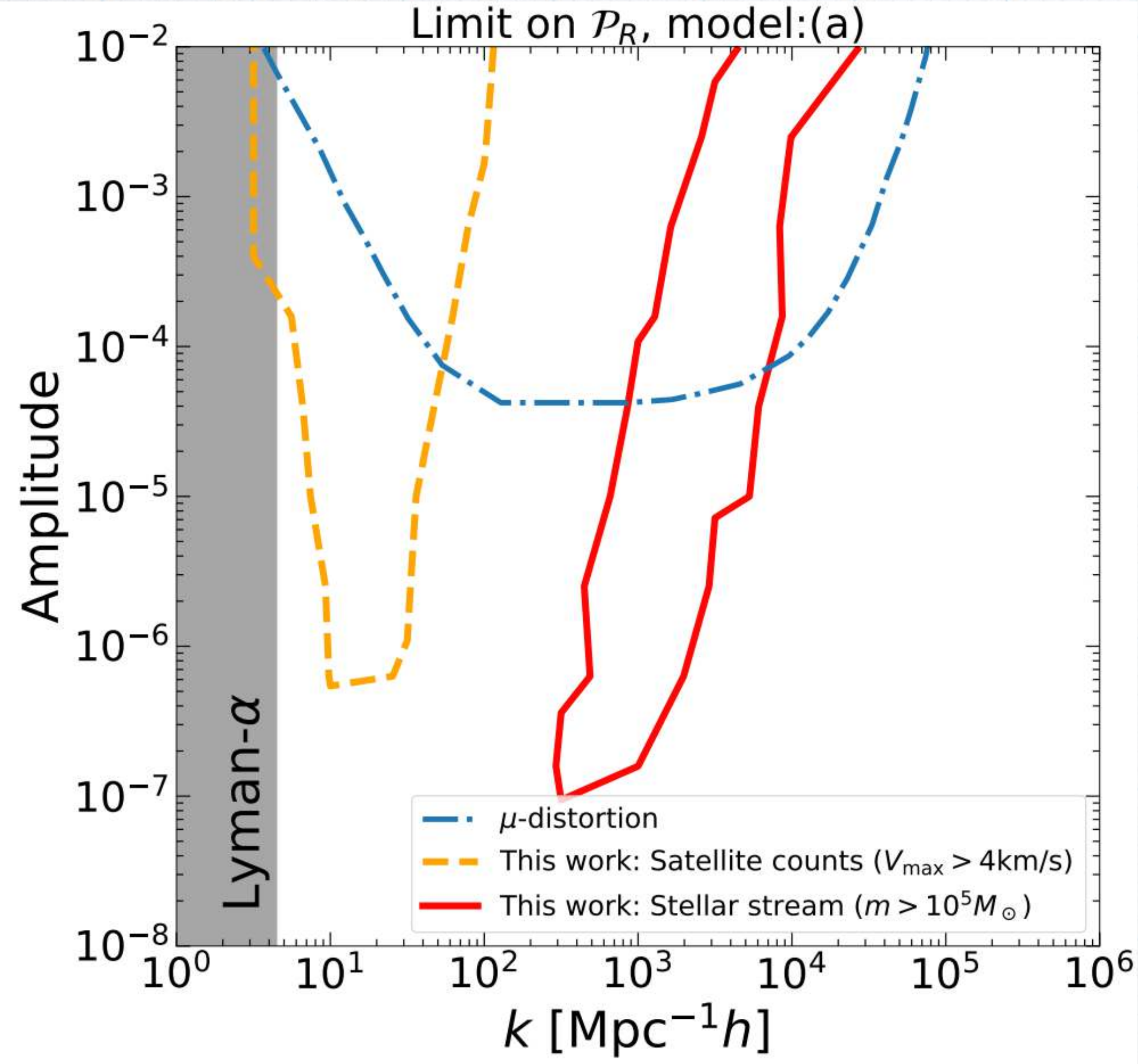
different
host
evolution



different
subhalo
mass function

& satellite
galaxy count

application: cosmology



Ando, NH, Ishiwata, 2022

$$\mathscr{P}_R(k) = \mathscr{P}_R^{(0)} + \mathscr{P}_R^{\mathrm{bump}}$$

bump ($n_b = 4$)

$$\begin{cases} (A - \mathscr{P}_R^{(0)}(k_b))\left(\frac{k}{k_b}\right)^{n_b} & (k \leq k_b) \\ 0 & (k > k_b) \end{cases}$$

requirement:

counts of satellites

$$N(V_{\max} > 4\mathrm{km/s}) > 94$$

&

GD-1 stream observation

4. summary

message

- We need dark matter to realize our Universe.
- Dark matter form halos through its gravitational interaction.
- Understanding of halo is important for unravelling the nature of dark matter.
- (Semi-)analytic framework is powerful in investigating halo physics which ranges in wide mass and redshift spaces.