Dark Matter Symposium
March 29, 2022

Update from group C02: Cosmic structure formation

Shin'ichiro Ando

University of Amsterdam / University of Tokyo

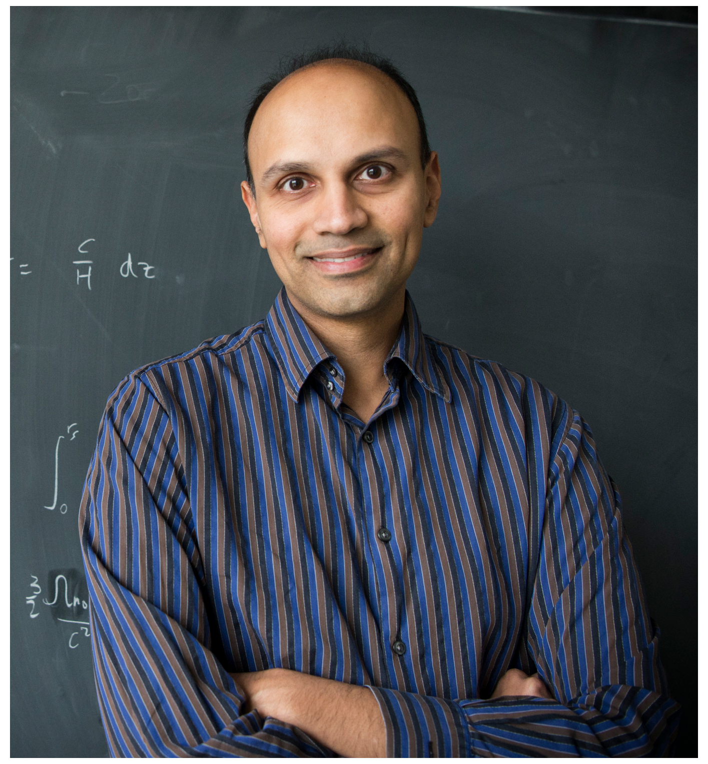
GRAPPA
GRavitation AstroParticle Physics Amsterdam

KAVLI IPMU
INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

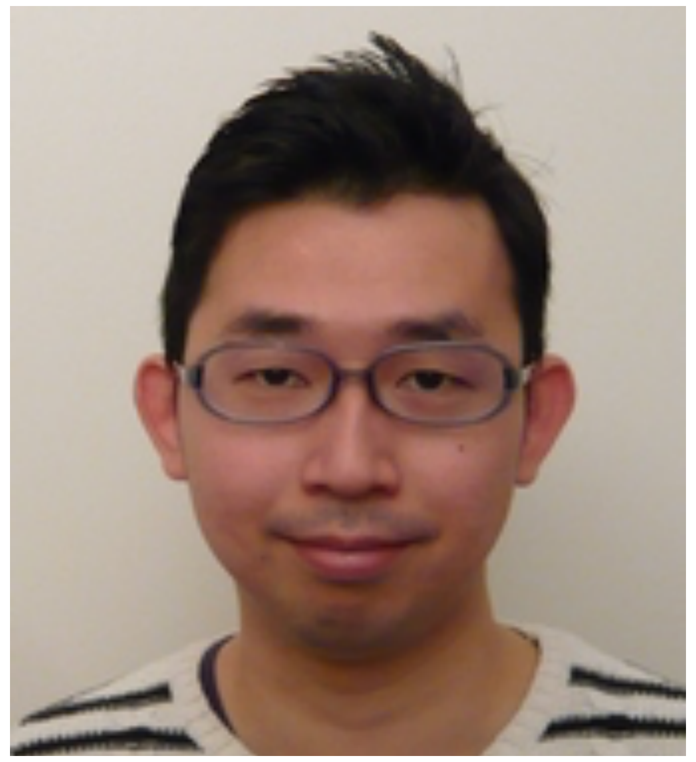
C02: Members

PI + co-I

Shin'ichiro Ando



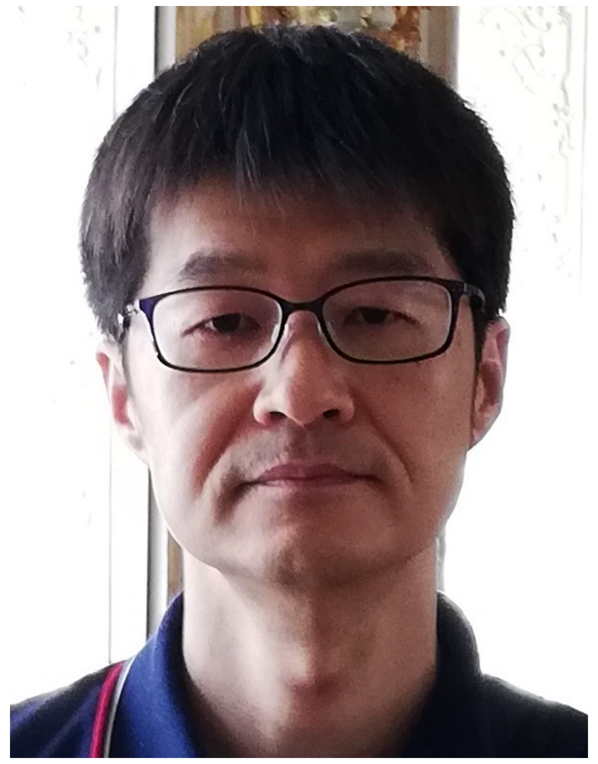
Neal Dalal



Takahiro Nishimichi

Takashi Okamoto

Masato Shirasaki



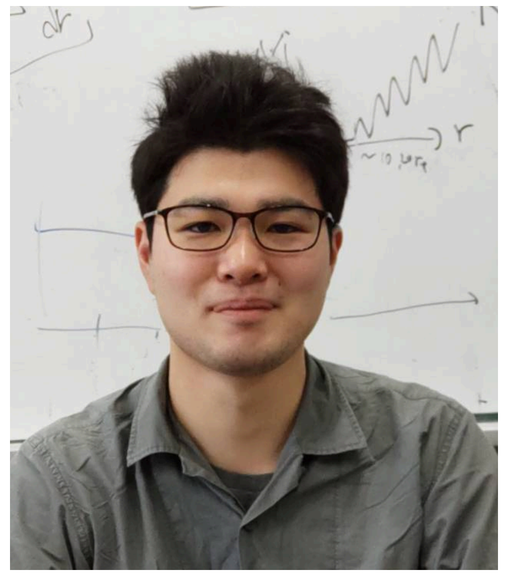
Atsushi Taruya

Project postdocs

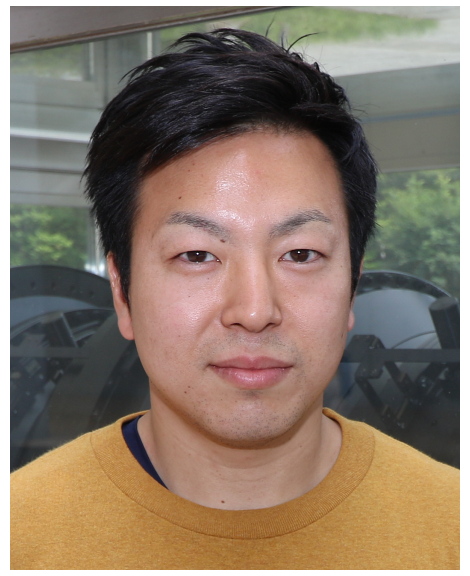
Shunichi Horigome

Shigeki Inoue

Collaborators



Yohsuke Enomoto



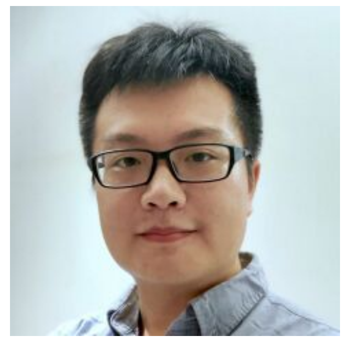
Kohei Hayashi

Tomoaki Ishiyama

N. Hiroshima

A. Dekker

C. A. Correa

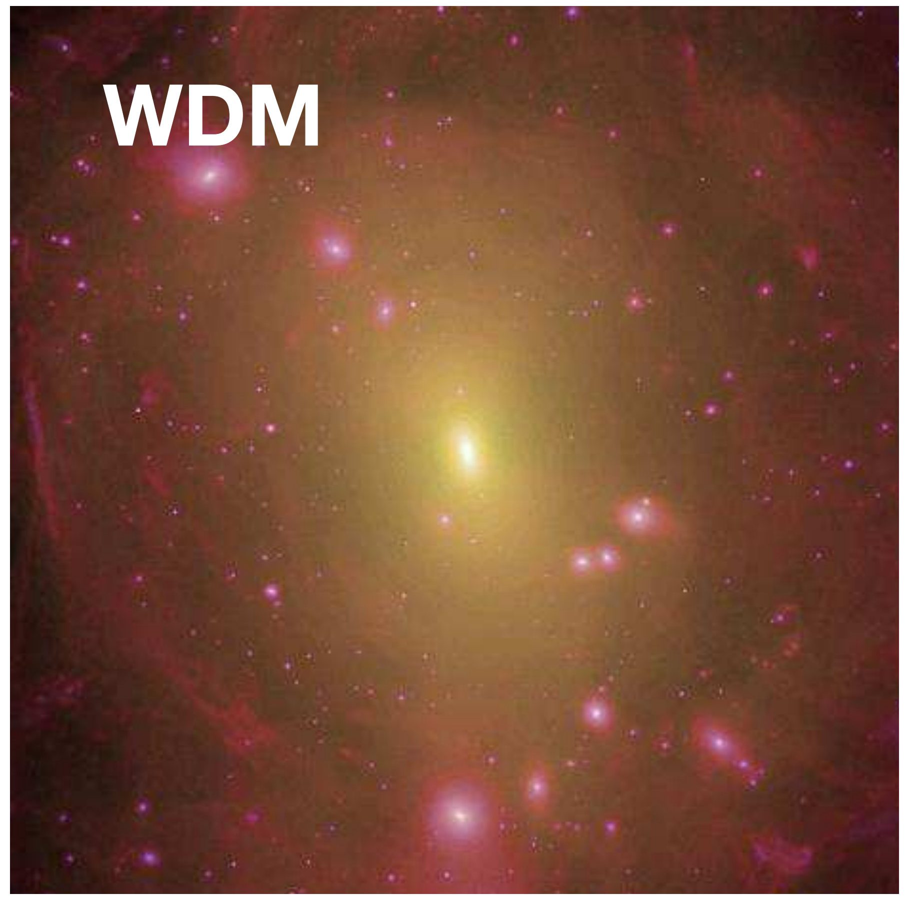


K.C.Y. Ng

Goals: Small scale structure

WIMPs, axions, ALPs, PBHs

- Cusps in density profiles
- Very many small (sub)structures

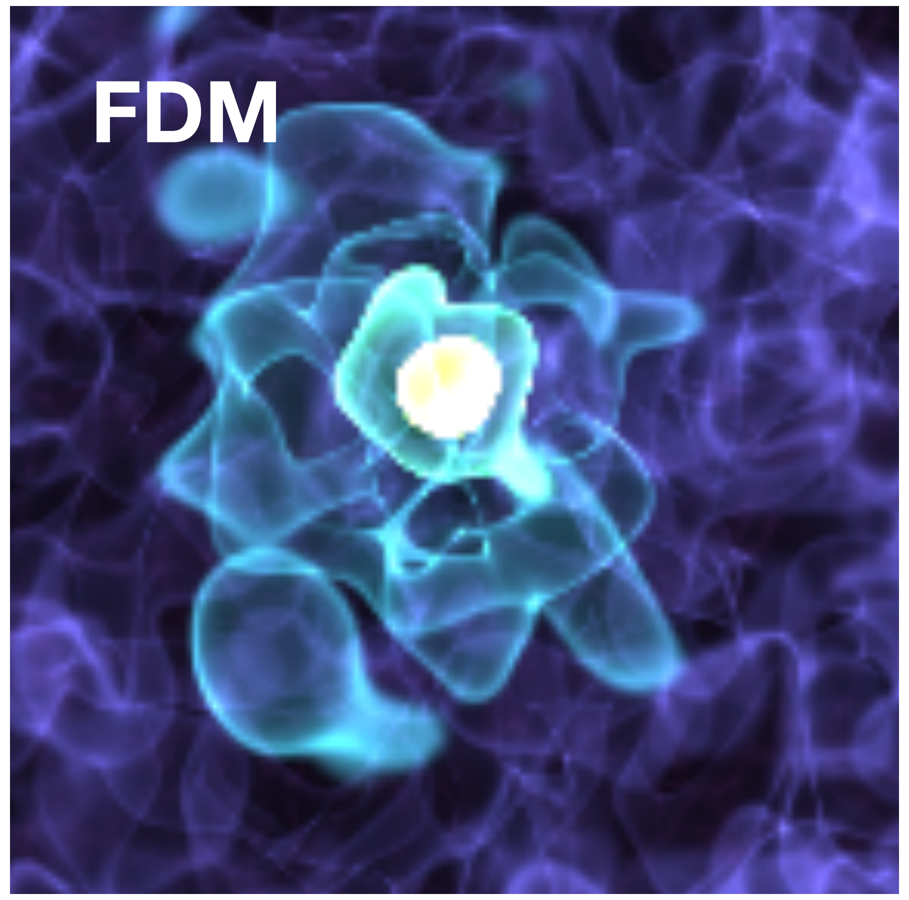


Sterile neutrinos

- Cutoff at sub-galaxy scale in the power spectrum

SIMPs, dark atoms

- Cores in density profiles induced by self scattering

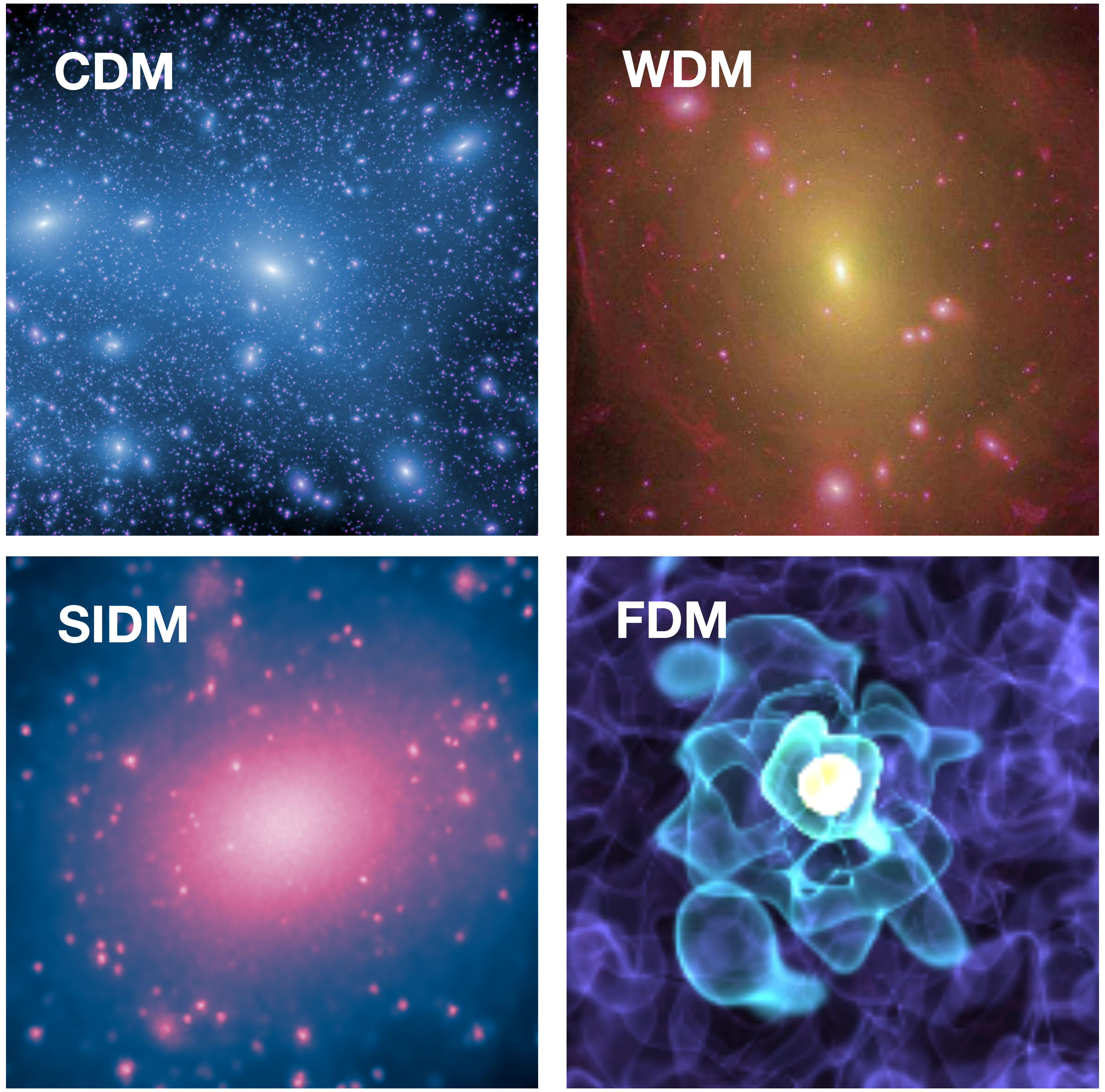


Ultralight bosons

- Pattern induced by de Broglie length at sub-galactic scales

Output: Small scale structure

- Release of public codes (Ando et al.)
- Dwarf galaxies (Horigome et al.)
- Galaxies and dark matter structure classification (Inoue, Okamoto et al.)
- Phase-space structure (Enomoto, Nishimichi, Taruya)
- Simulation of SIDM subhalos falling onto the SIDM halo (Shirasaki et al.)



- Numerical simulations of WDM halos and subhalos (Okamoto, Inoue et al.)
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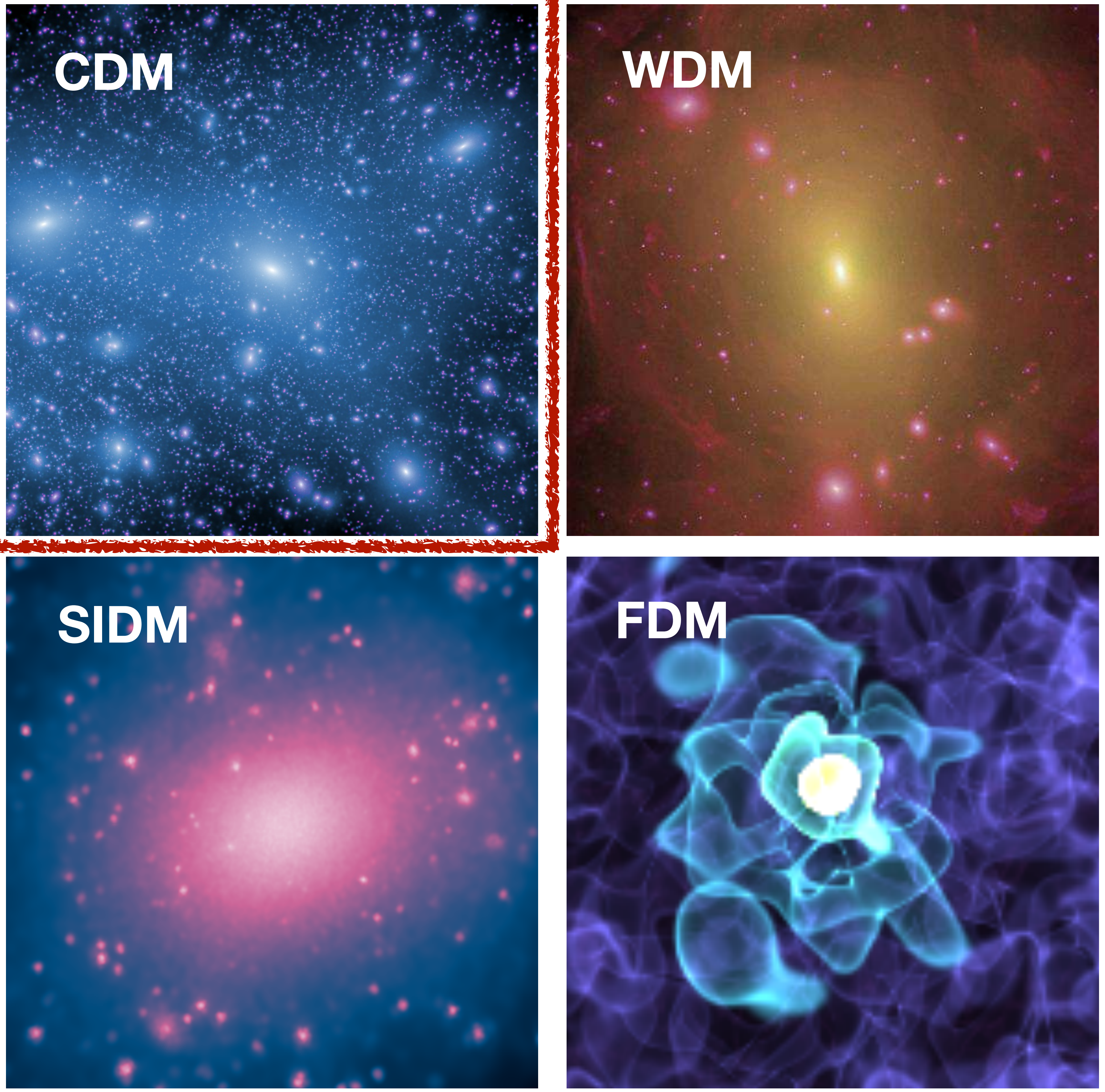

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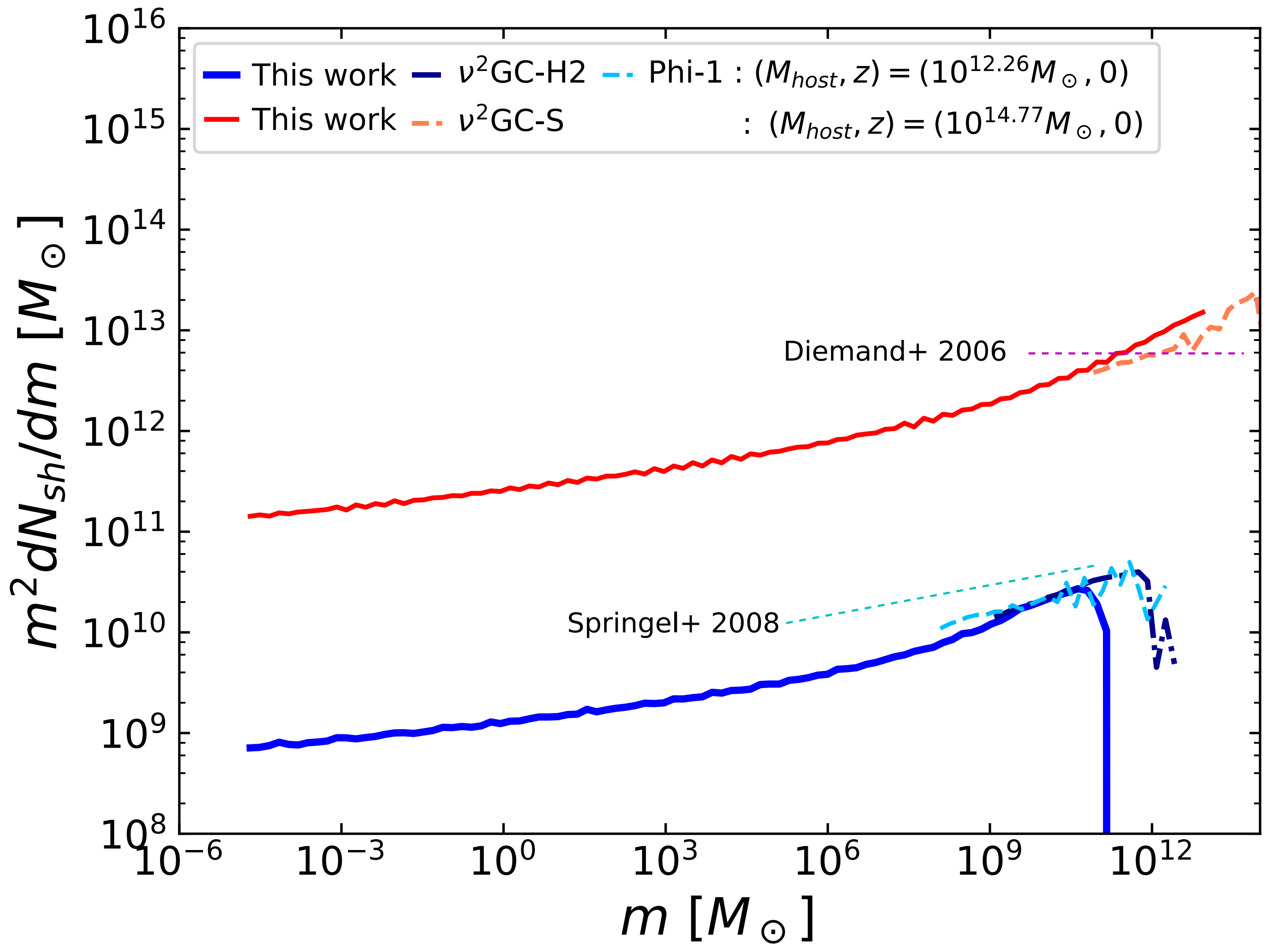
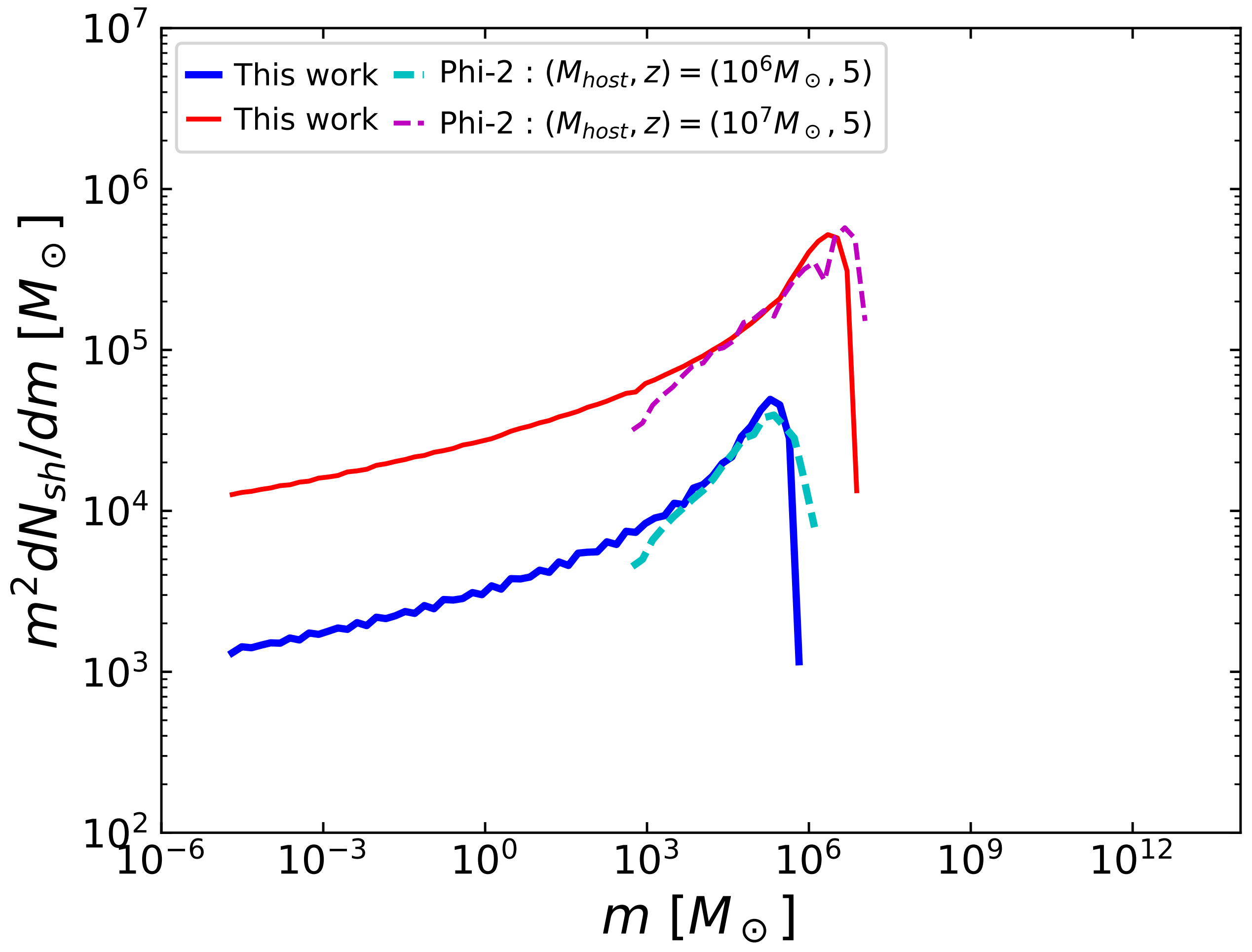
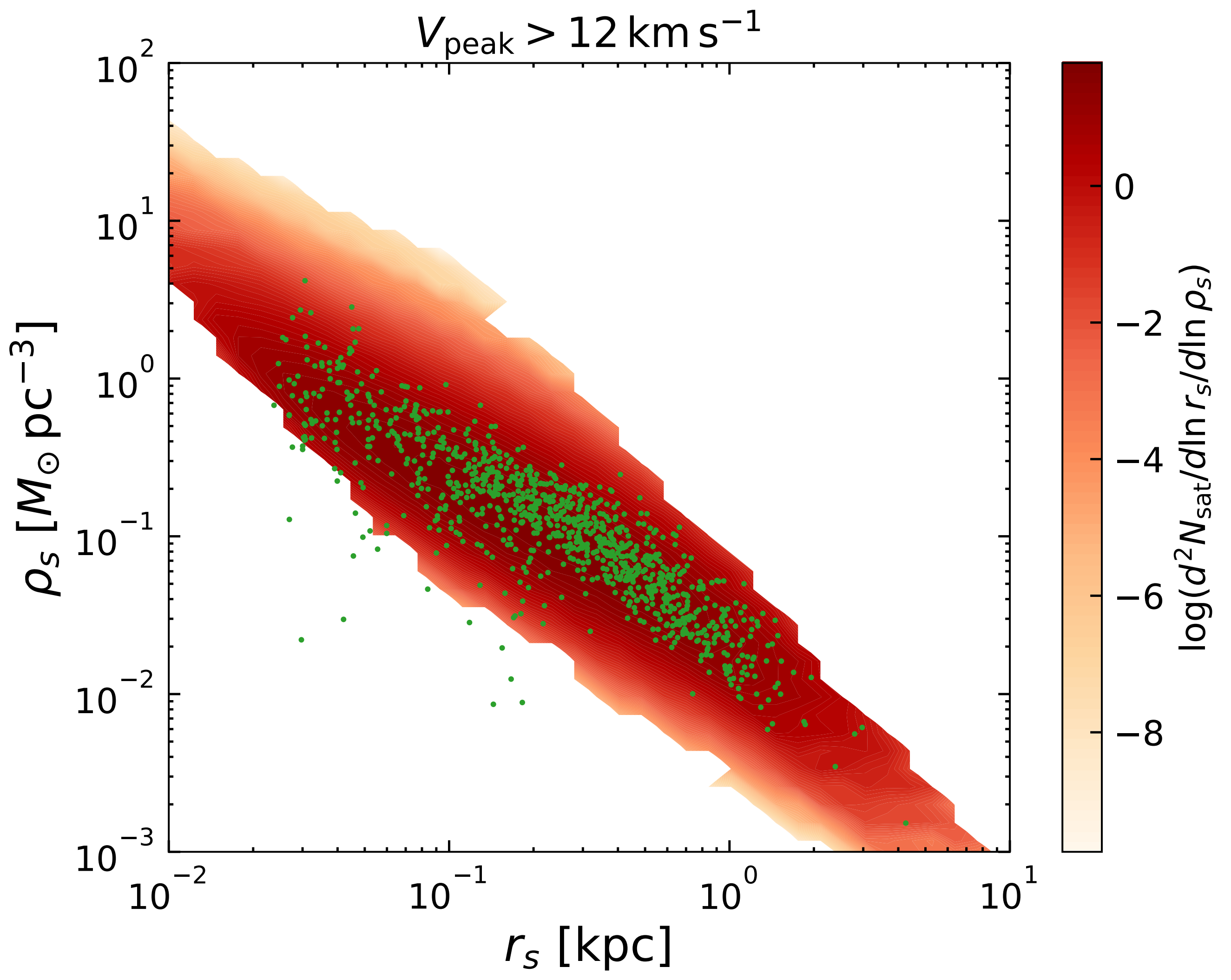
Release of public codes for semi-analytical subhalo models (CDM)

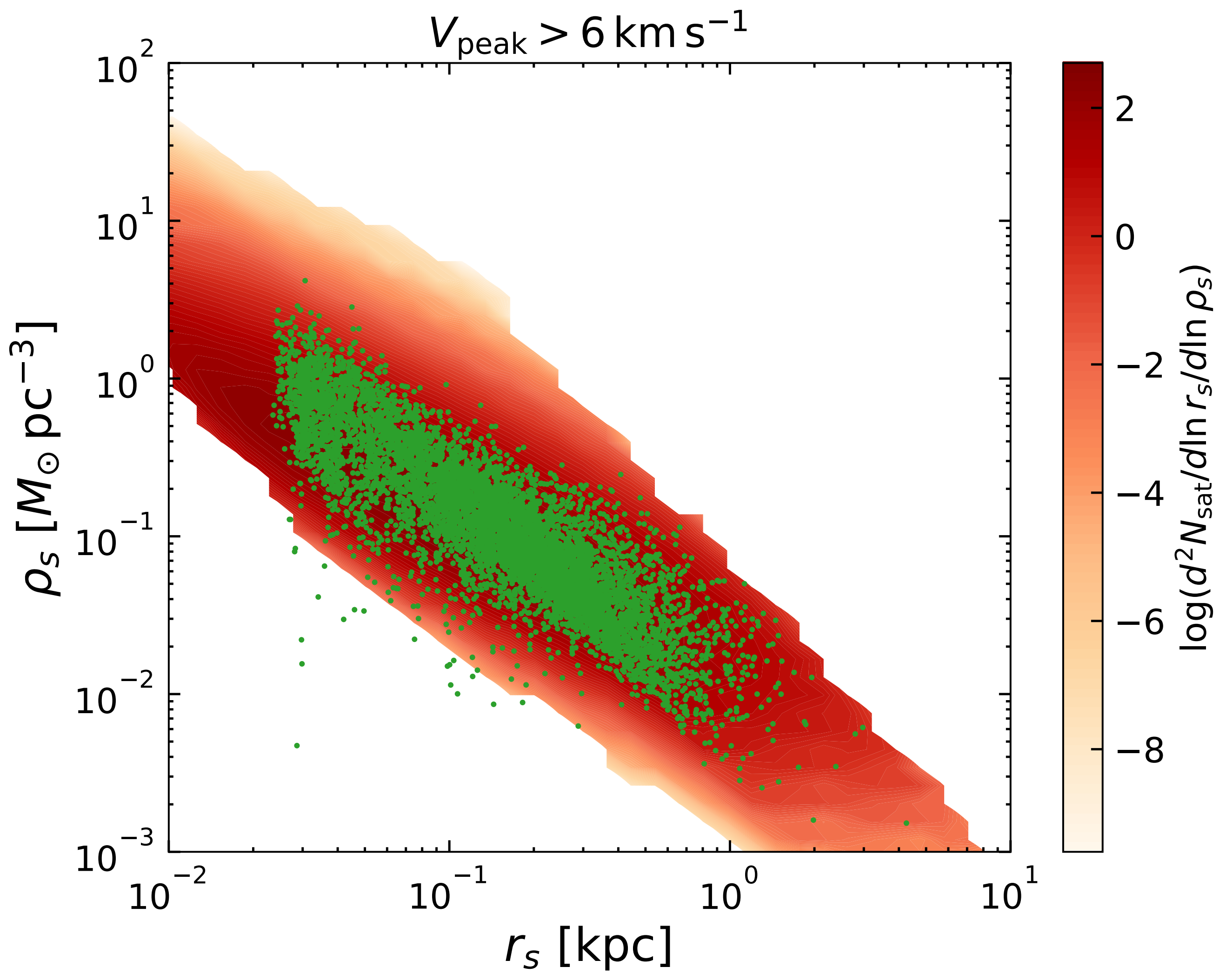
N. Hiroshima T. Ishiyama

Hiroshima, Ando, Ishiyama, *Phys. Rev. D* **97**, 123002 (2018)









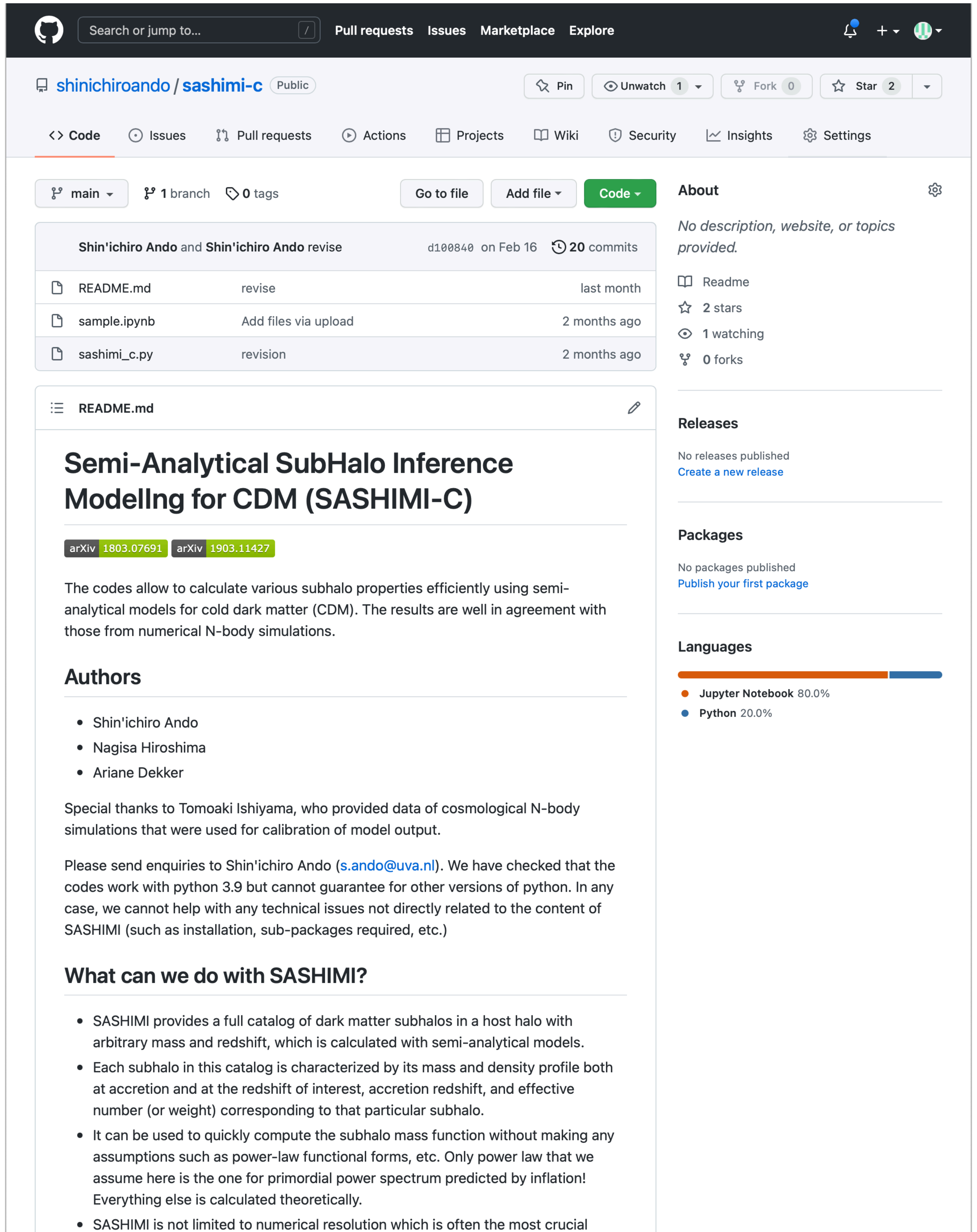
Ando, Geringer-Sameth, Hiroshima, Hoof, Trotta, Walker, *Phys. Rev. D* **102**, 061302 (2020)

- Recap: Semi-analytical models combining the extended Press-Schechter formalism with tidal-evolution prescription
- Well recovers subhalo mass function and distribution of density profile parameters
- Cost-effective, free from numerical resolution and Poisson noise

Release of public codes for semi-analytical subhalo models (CDM)

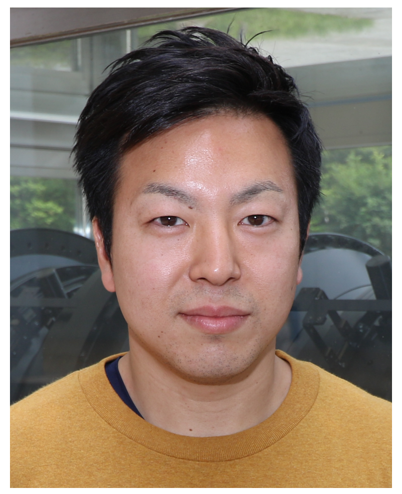
N. Hiroshima

A. Dekker



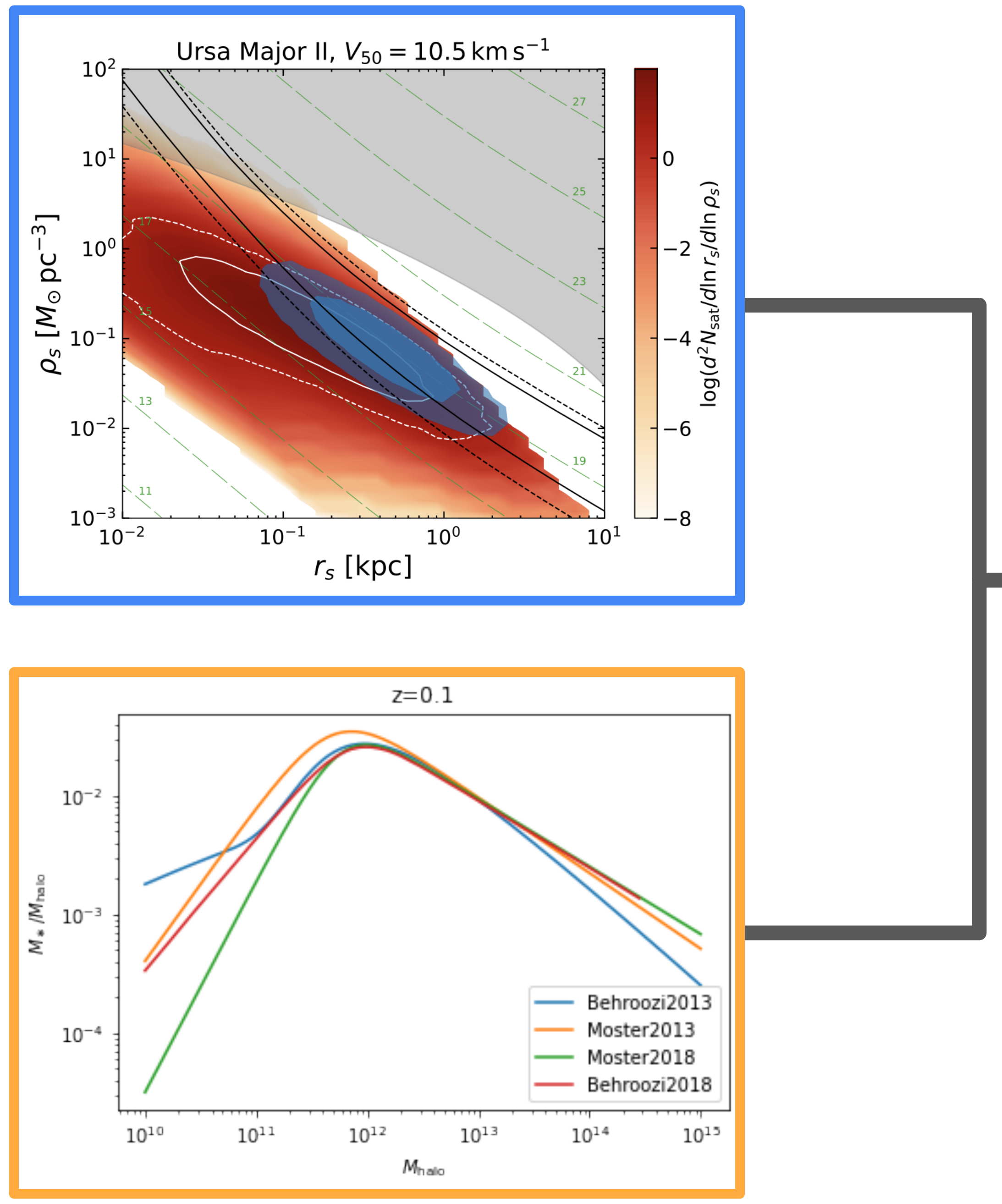
- **S**emi-**A**nalytical **S**ub**H**alo **I**nference **M**odel**I**ng
- "Cold" SASHIMI: *github.com/shinichiroando/sashimi-c*
- Only 760 lines of simple python codes, which enable to calculate (nearly) everything we did in Hiroshima et al. (2018)
  - Subhalo mass function, substructure boost of dark matter annihilation, etc.
- Well documented and useful sample codes provided

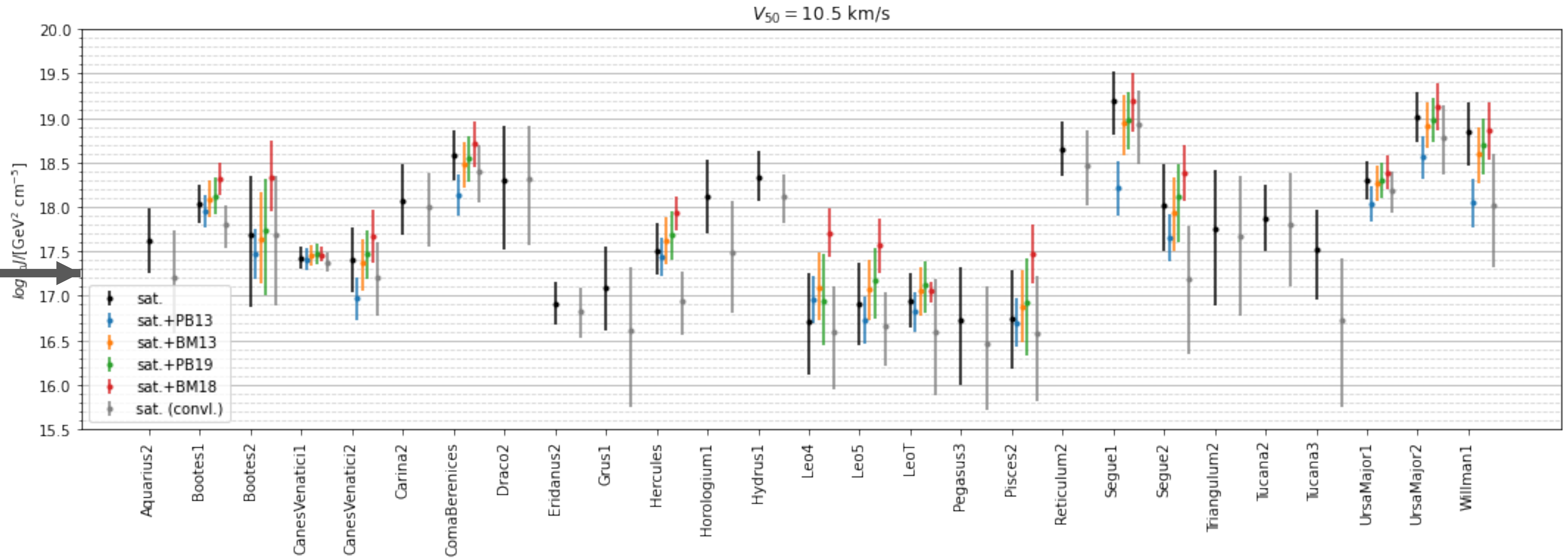
Cosmological prior for the J-factor estimation of dwarf spheroidal galaxies

S. Horigome
K. Hayashi

- Dwarf spheroidal galaxies (dSph) play important roles for dark matter detection but their dark matter halo profiles have large uncertainties
- For the halo profile estimation of dSphs, we apply two **cosmological priors**:
  - **Satellite prior**: constraint distribution of halo parameter based on a structure formation model
  - **Stellar-to-halo mass relation prior**: empirical relation between stellar mass and halo mass
- The cosmological priors are useful to decrease the uncertainty in the estimation and give a better understanding of dSphs

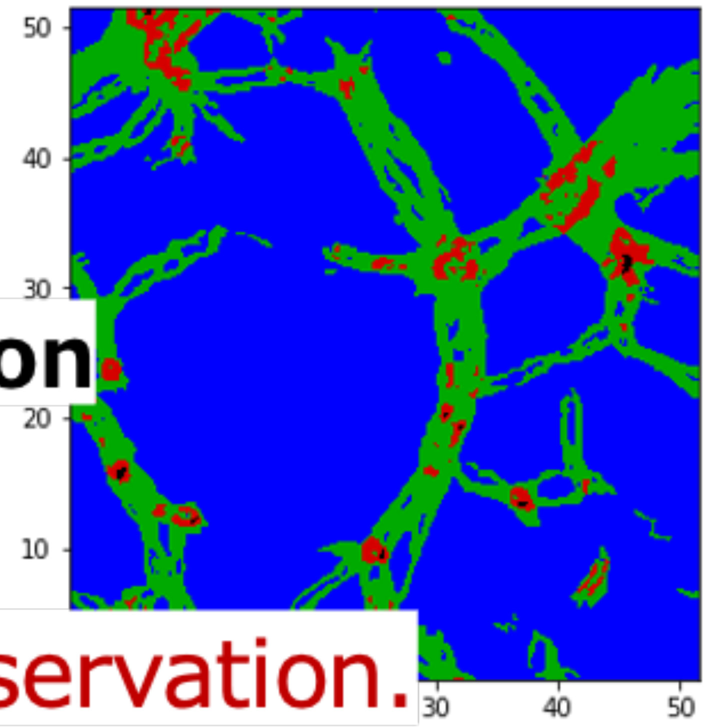


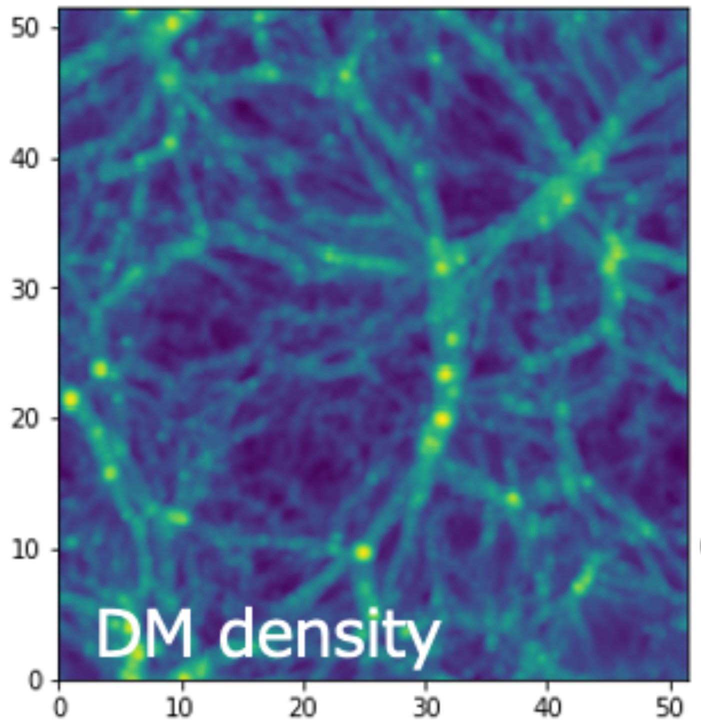


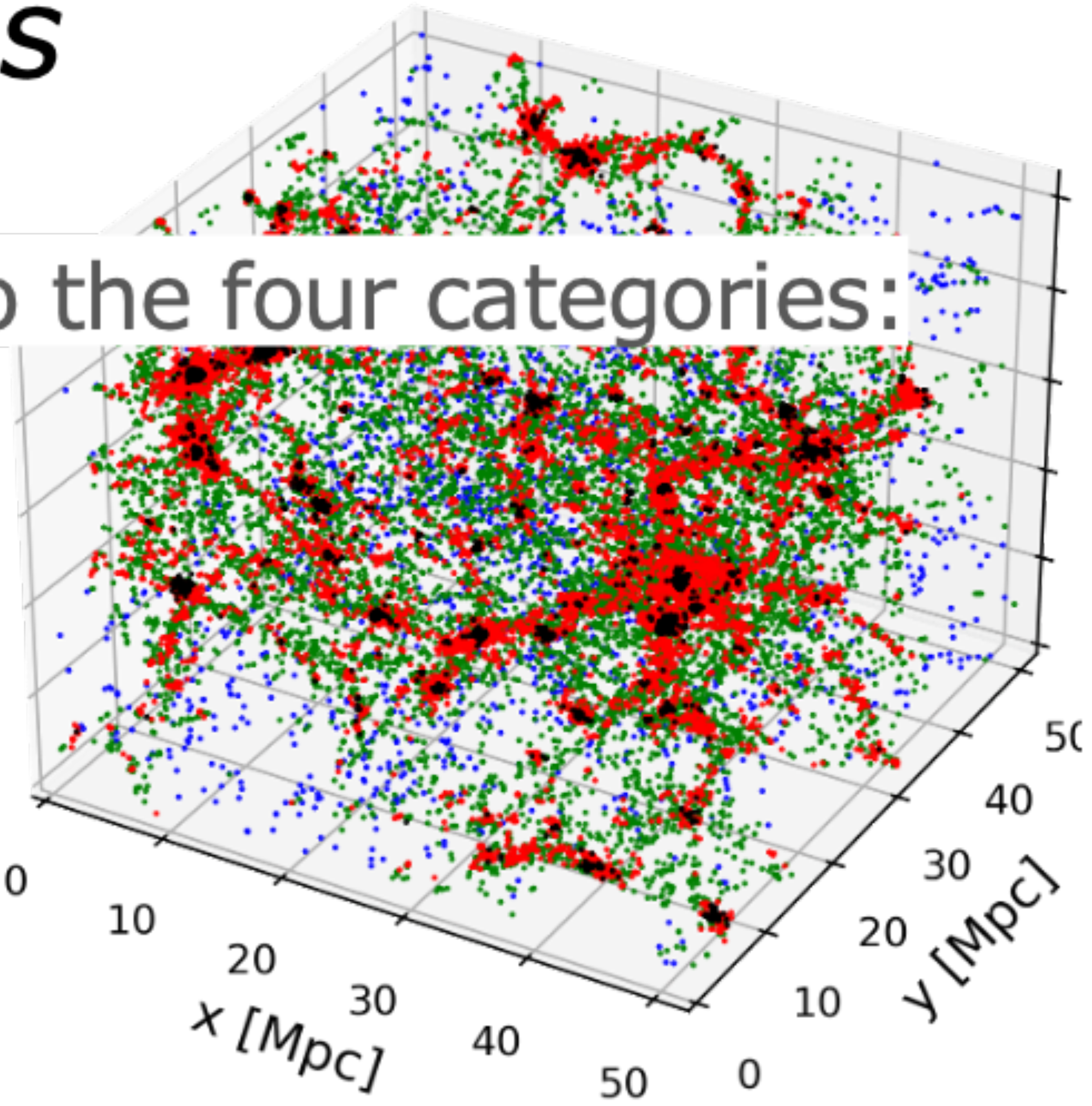
Classification of cosmic structures for galaxies with machine learning: connecting cosmological simulations with observations

Shigeki Inoue, Xiaotian Si, Takashi Okamoto & Moka Nishigaki

- In theory, using **DM density**, large-scale structures are classified into the four categories:
  - **Knot**, **Filament**, **Sheet** and **Void**



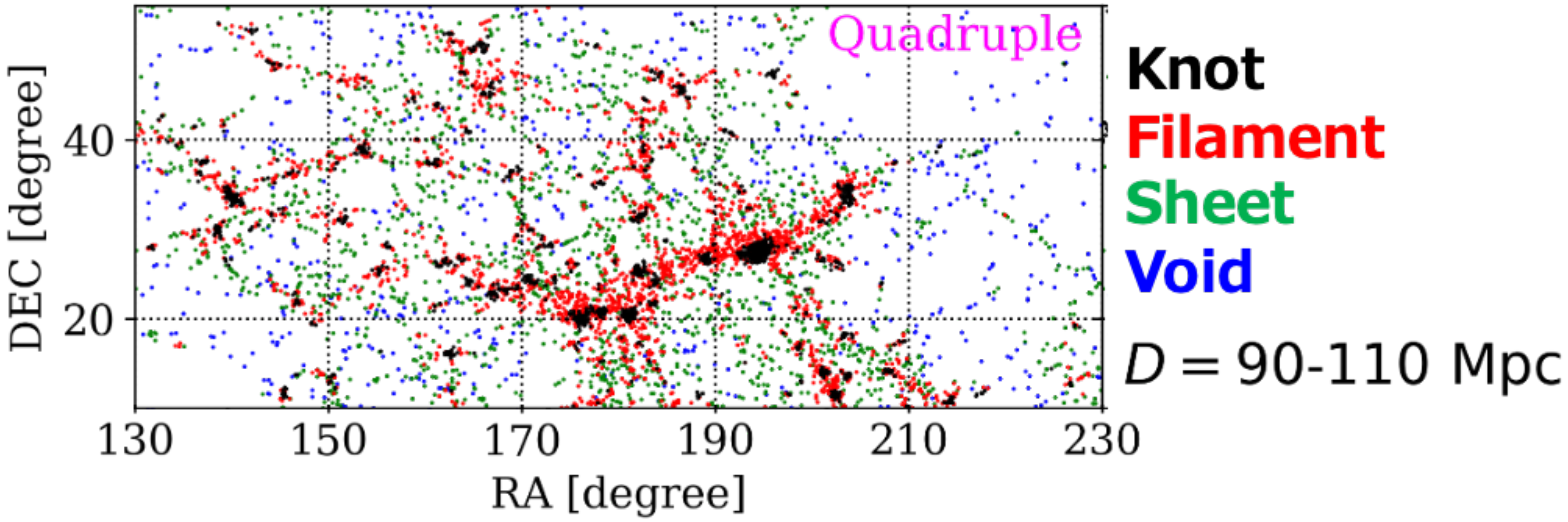




- However, since DM is unobservable
  - Observations use **galaxy distribution**
- Thus, the structure classification is inconsistent between theory and observation.

- This study construct a machine-learning model to solve the problem.
  - Learning data of a cosmological simulation including baryons to learn the relationship between
    - **the DM-based classification**
    - **galaxy distribution**
  - **3D-CNN**
    - **applied to SDSS**

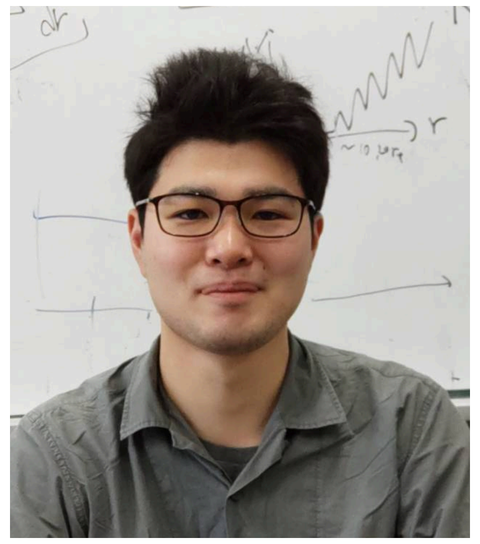
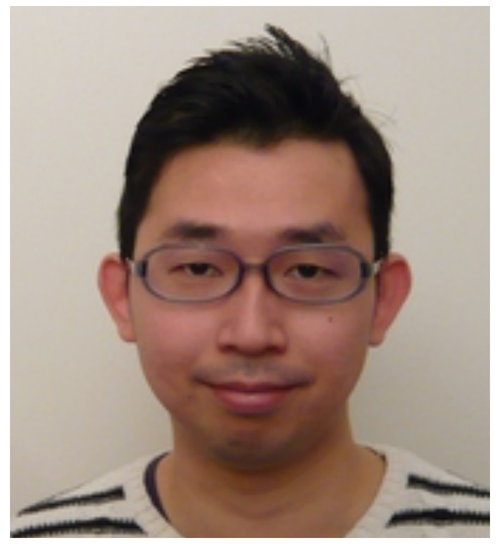
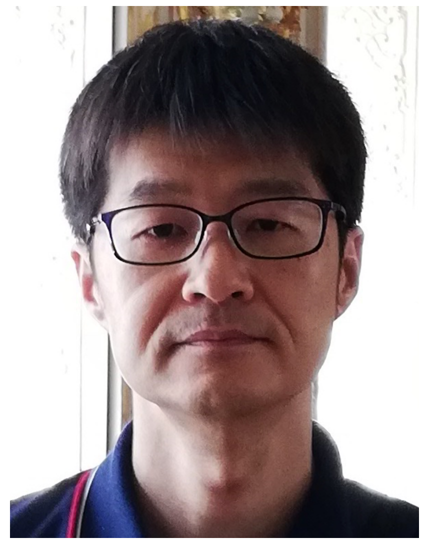
Observed galaxies are classified using DM!!



S. Inoue

T. Okamoto

Inner structure of cold dark matter (CDM) halo

Enomoto, Nishimichi & Taruya ('22, in prep)

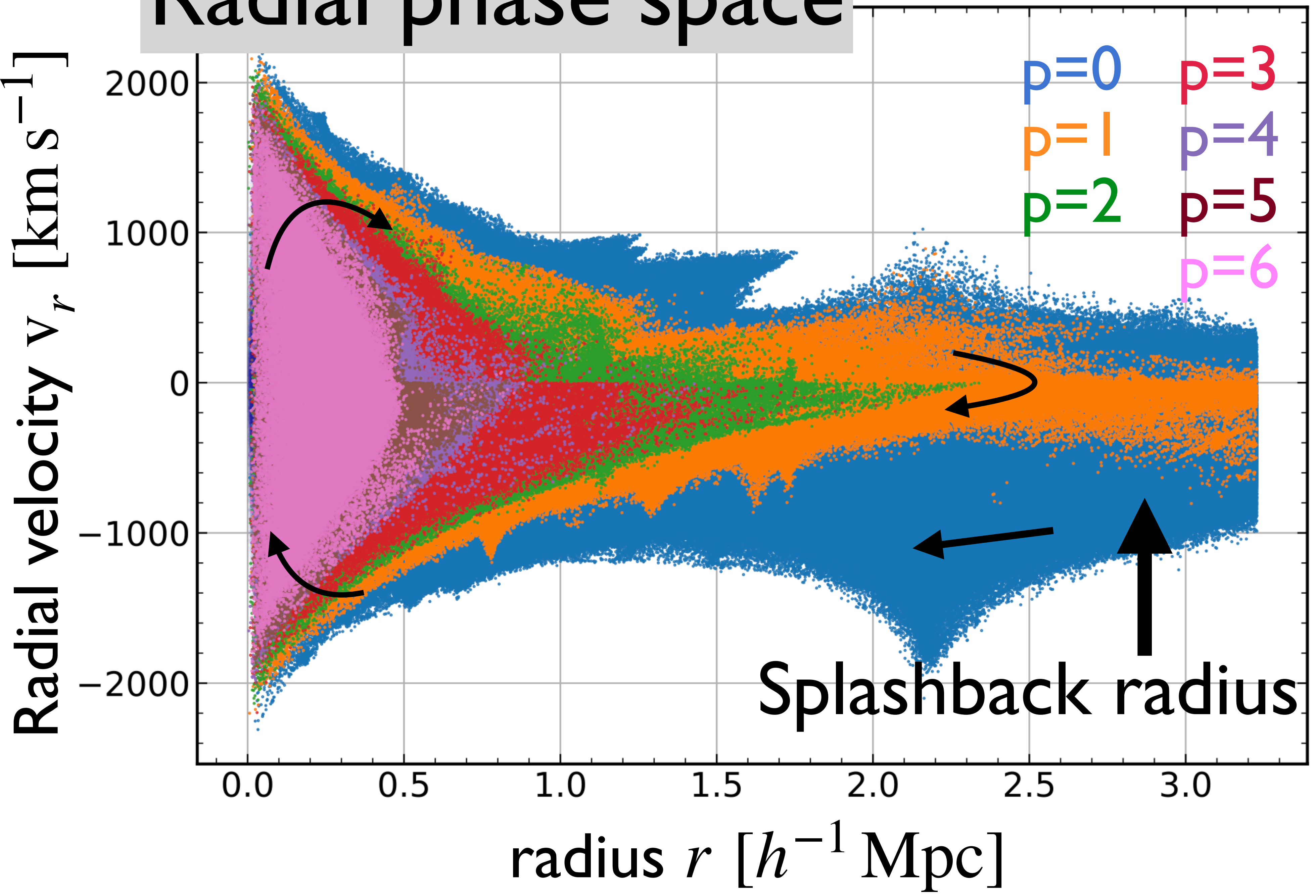
Phase-space structure of dark matter halos by tracking particle trajectories in cosmological *N*-body simulations → a clue to clarify nature of dark matter

Applying the improved version of the method developed by Sugiura et al. ('20),

Up to *p*~60

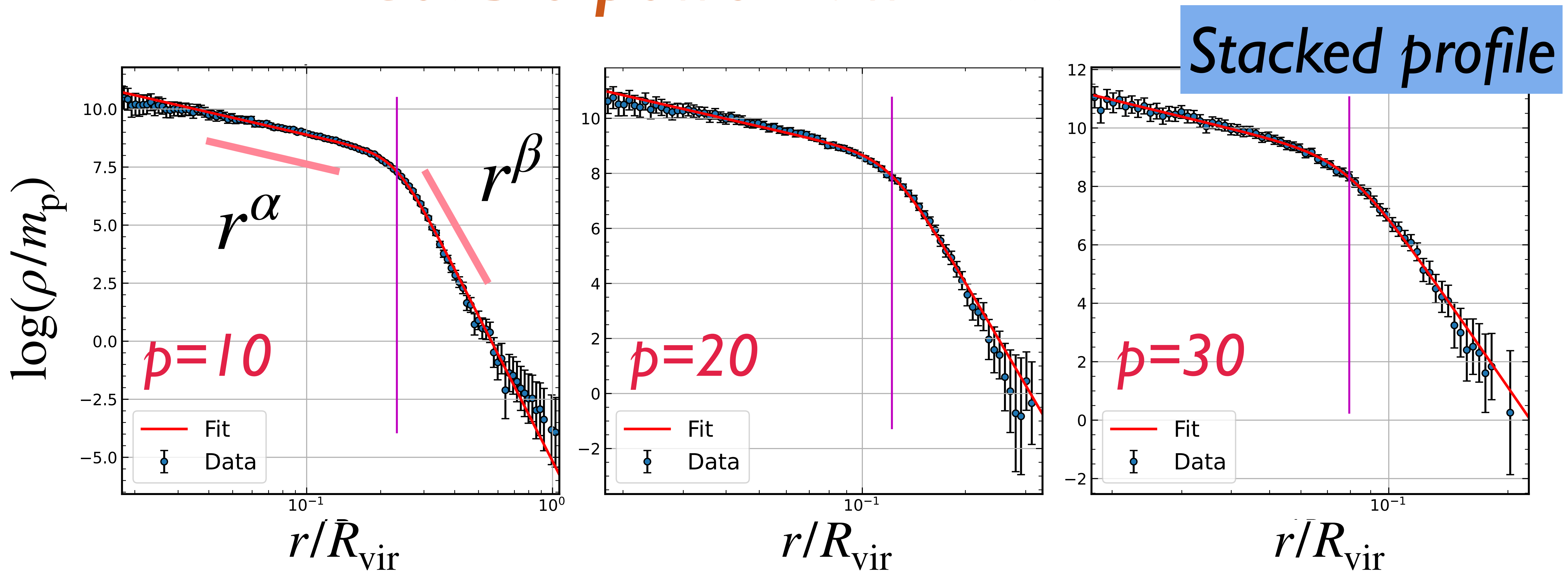
N-body particles in CDM halos are classified by # of apocenter passages, *p*

Radial phase space



Surprisingly !!

Density profile for each *p* shows a ***double power-law*** feature



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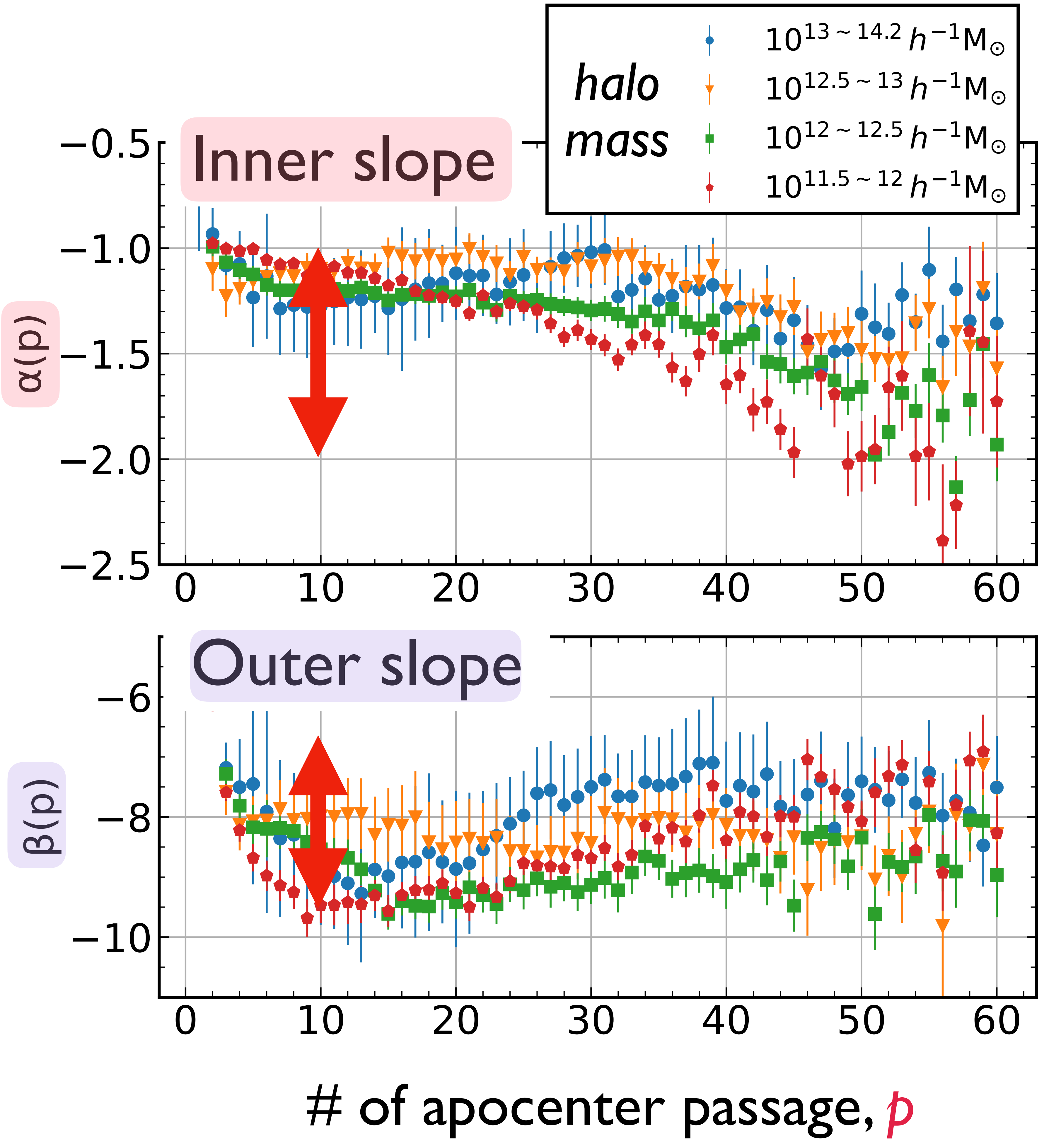
Enomoto, Nishimichi & Taruya ('22, in prep)

Fitting function $$\rho(r;p) = \frac{A(p)}{x^{-\alpha(p)}[1 + x^{\alpha(p)-\beta(p)}]}; \quad x \equiv \frac{r}{S(p)}$$



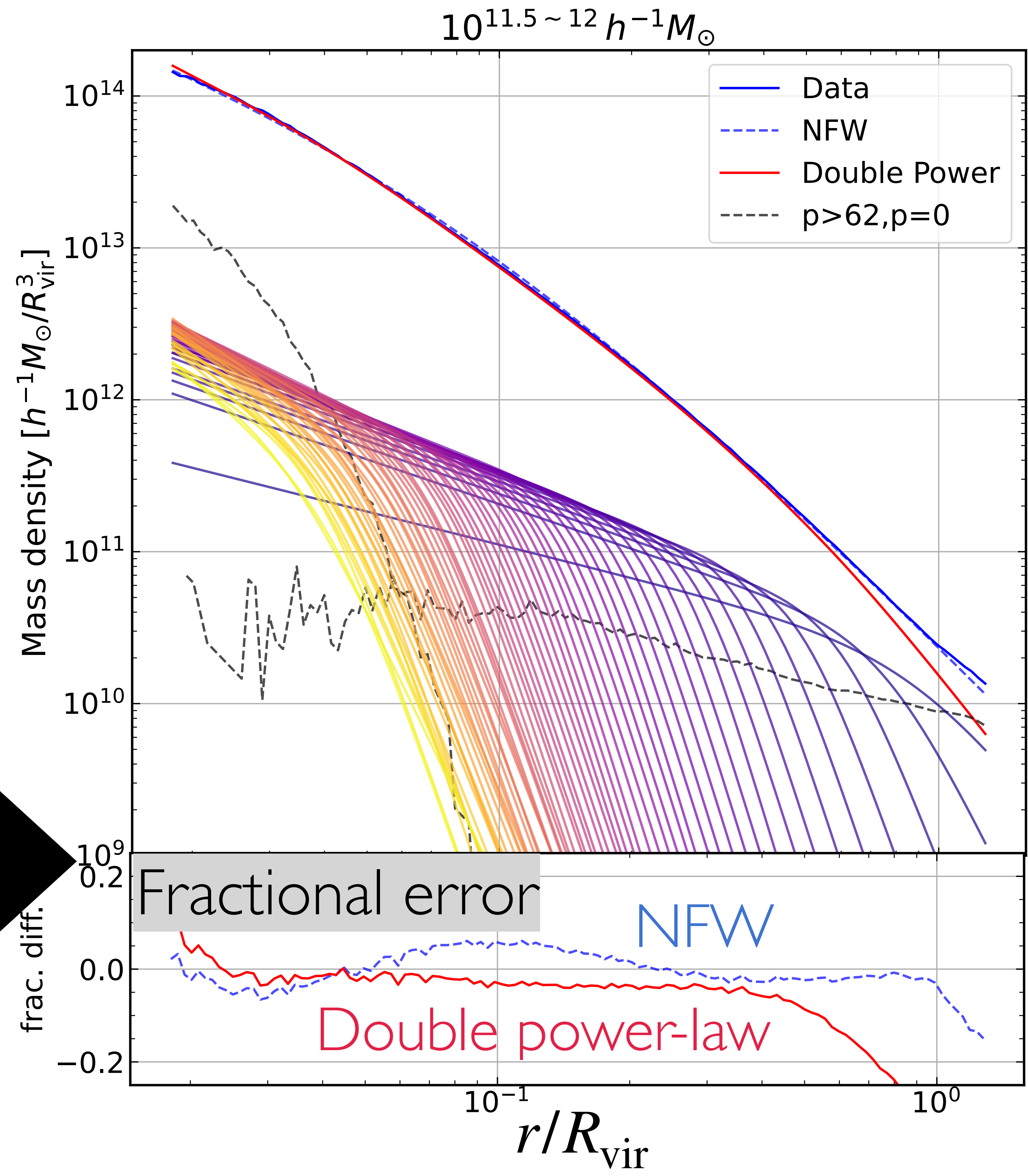
Irrespective of p or halo mass,

$$\alpha(p) = -1 \sim -2$$

$$\beta(p) = -8 \sim -9$$

Summing up all contributions leads to total profile (≈ NFW profile)

consistently



Inner cusp in NFW profile has been already built up in each multi-stream flow → Hint of its origin

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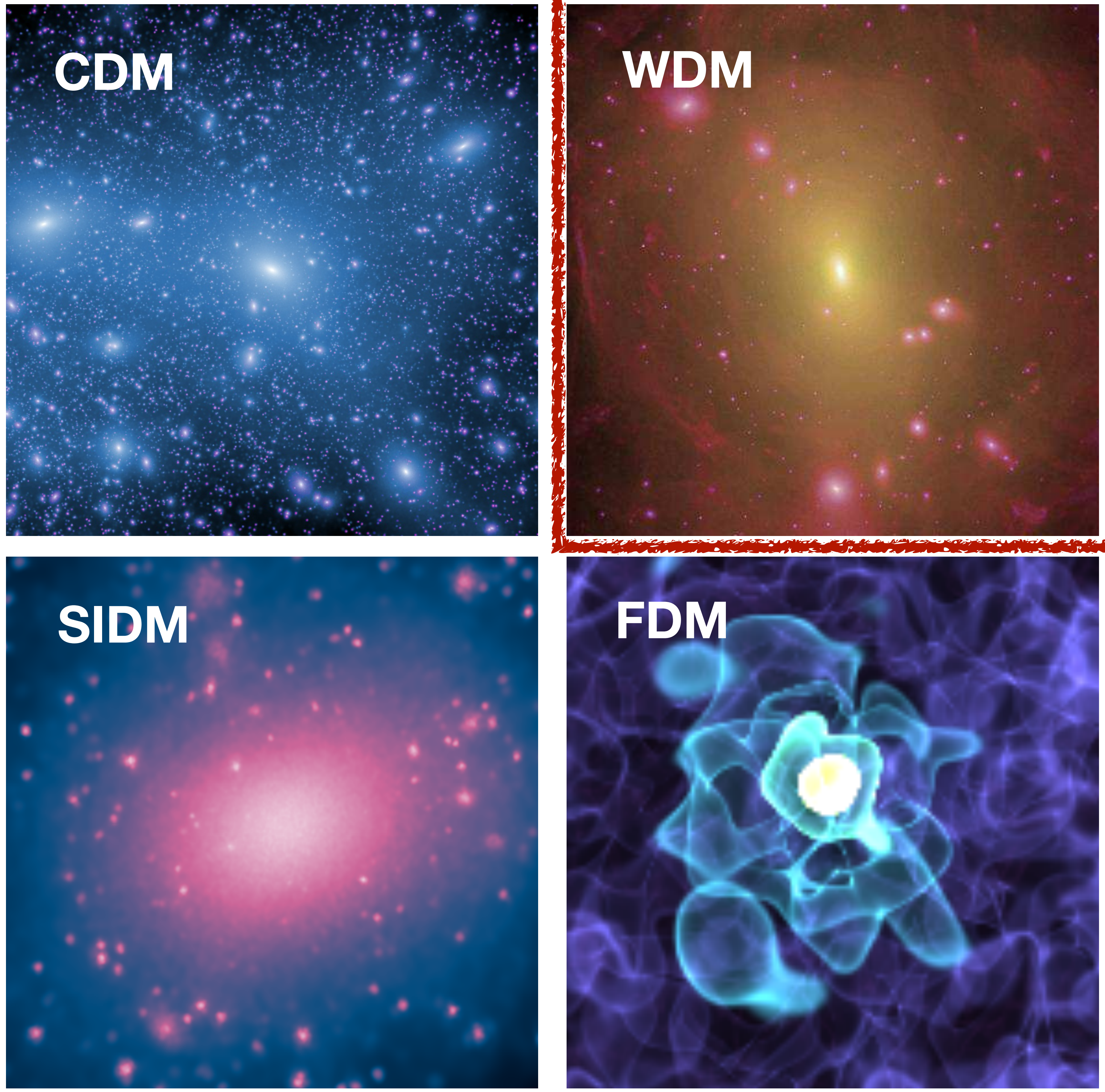

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Warm Dark Matter simulations

T. Okamoto

S. Inoue

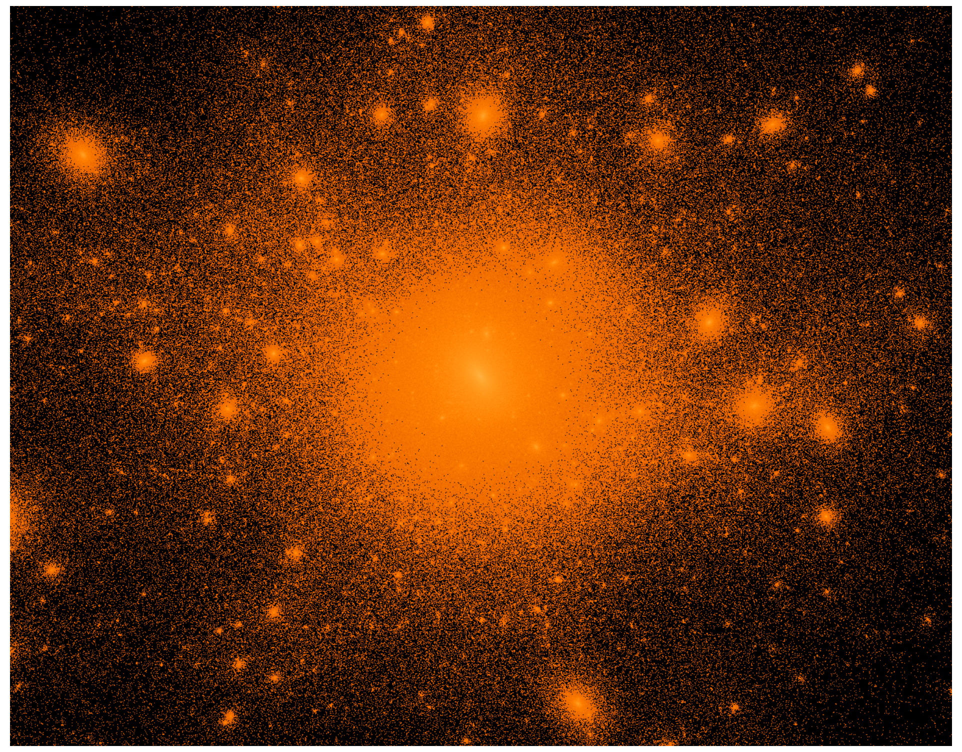
- A parameterization of the WDM mass function relative to that of the CDM is needed
- Lovell (2020) gives such a fitting function with WDM simulations of the half-mode mass of $M_{\rm hm} = 5 \times 10^8 - 3.5 \times 10^9\ M_\odot$.
- We first extend their work to a wider range of the WDM mass $m_{WDM} = 1 - 10$ keV ($M_{\rm hm} = 6.4 \times 10^6 - 1.3 \times 10^{10}\ M_\odot$) and benchmark their fitting function
- Then construct a theoretical model that explains the simulation results.

Simulations

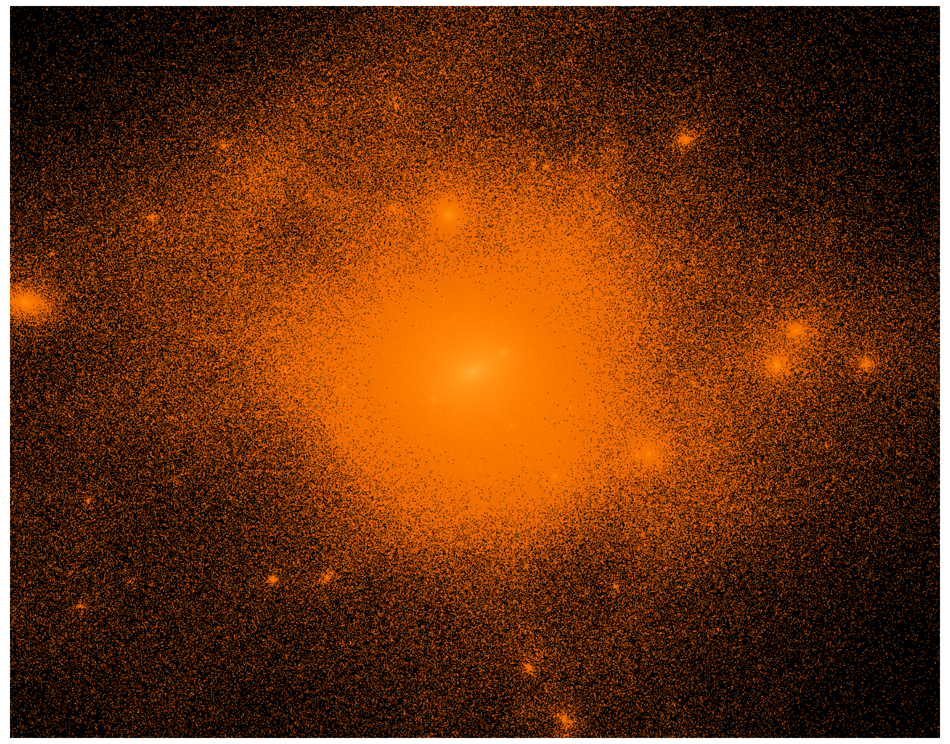
- Zoom simulations of a Milky Way mass halo
  - $M_{200} = 1.18 \times 10^{12}\ M_{\odot}$
  - Mass resolution: $m_{\rm DM} = 2.491 \times 10^{3}\ M_{\odot}$
  - The mean particle separation: $3.05 \times 10^{-3} h^{-1}$ cMpc

	1 keV	3 keV	10 keV	CDM
$M_{\rm hm}\ (h^{-1}\ M_{\odot})$	1.37x10^{10}	3.52x10^{8}	6.40x10^{6}	N/A
$\lambda_{\rm fs}\ (h^{-1}\ Mpc)$	0.048	0.014	0.0037	N/A
Status	Running	if necessary	Done	Done

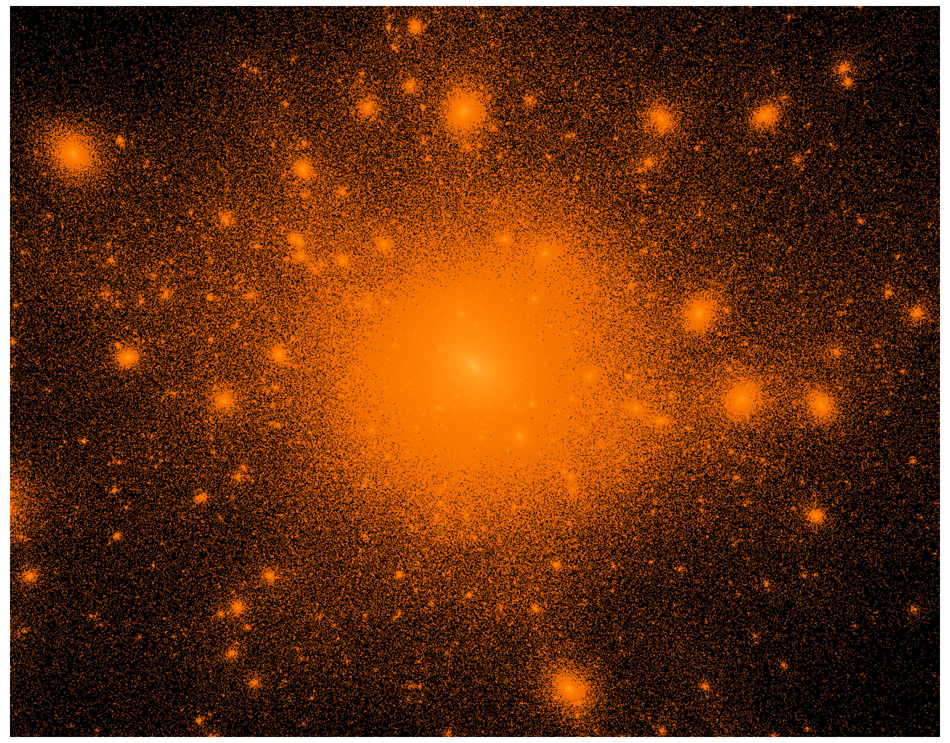
CDM (low-resolution)



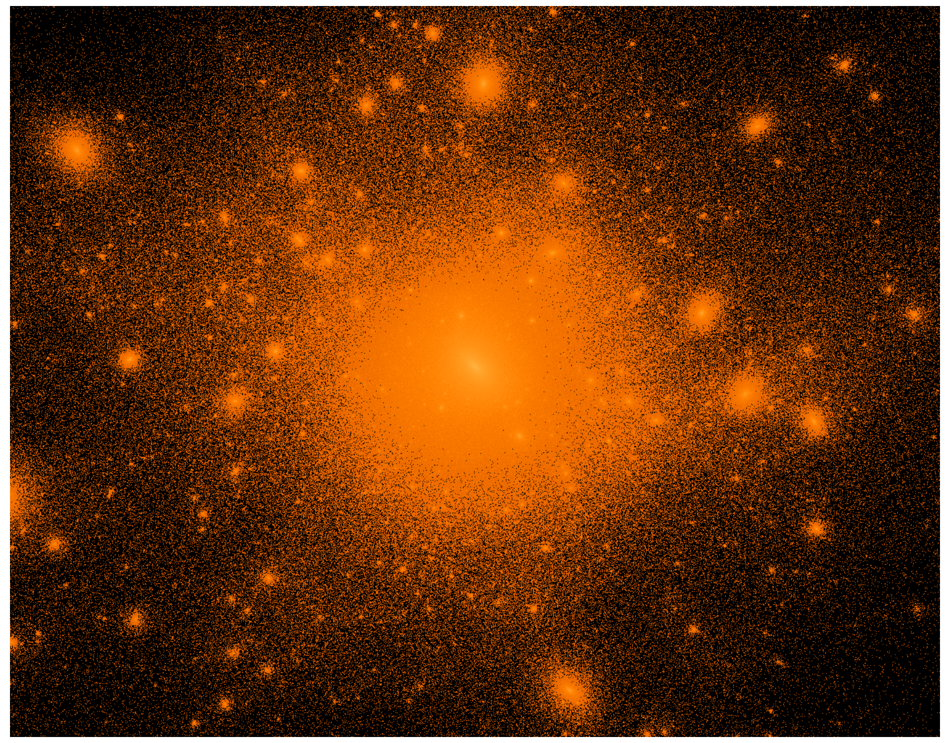
WDM 1 keV (low-resolution)



CDM (high-resolution)

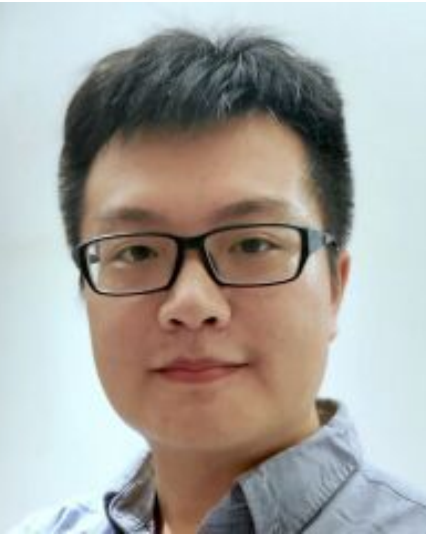


WDM 10 keV (high-resolution)



Semi-analytical models

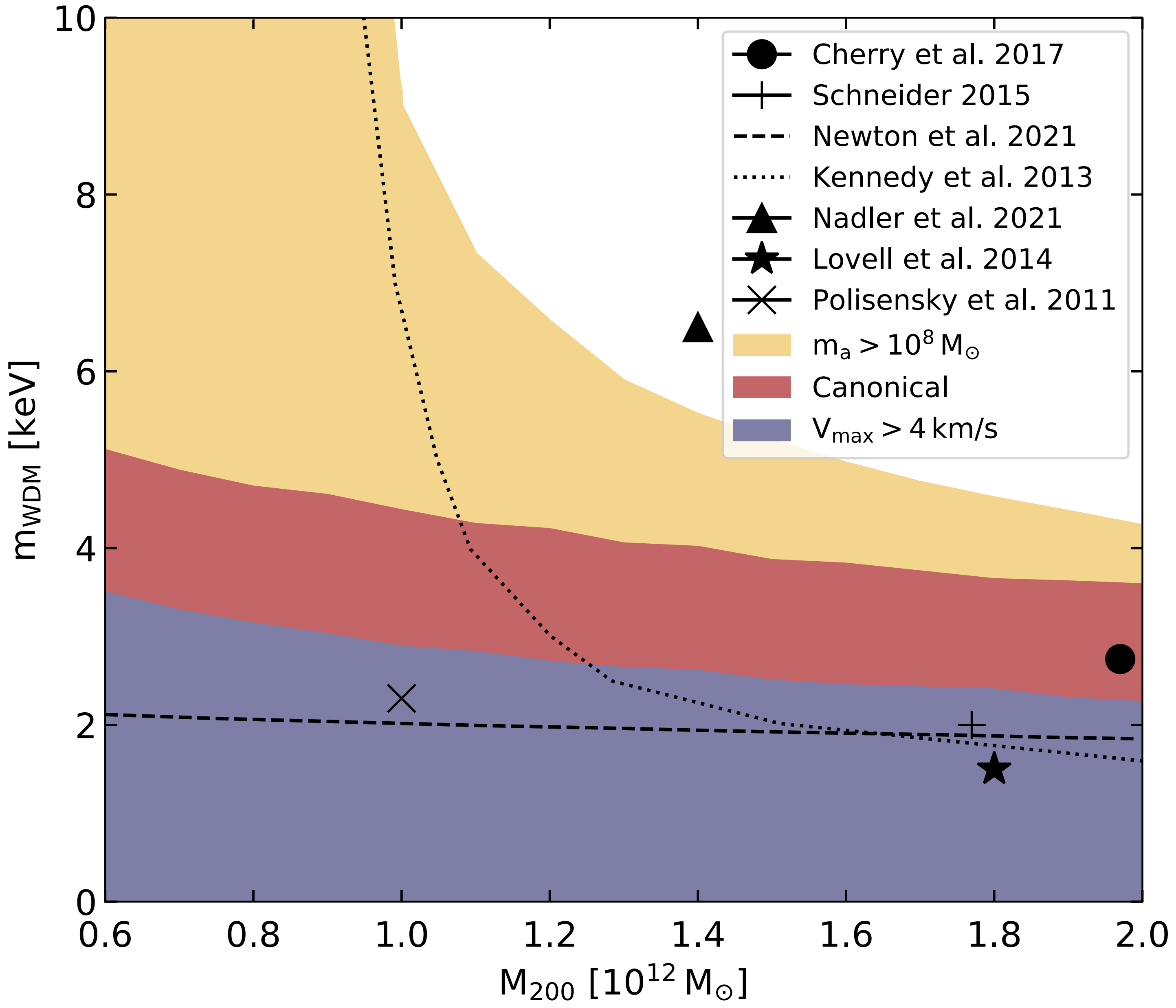


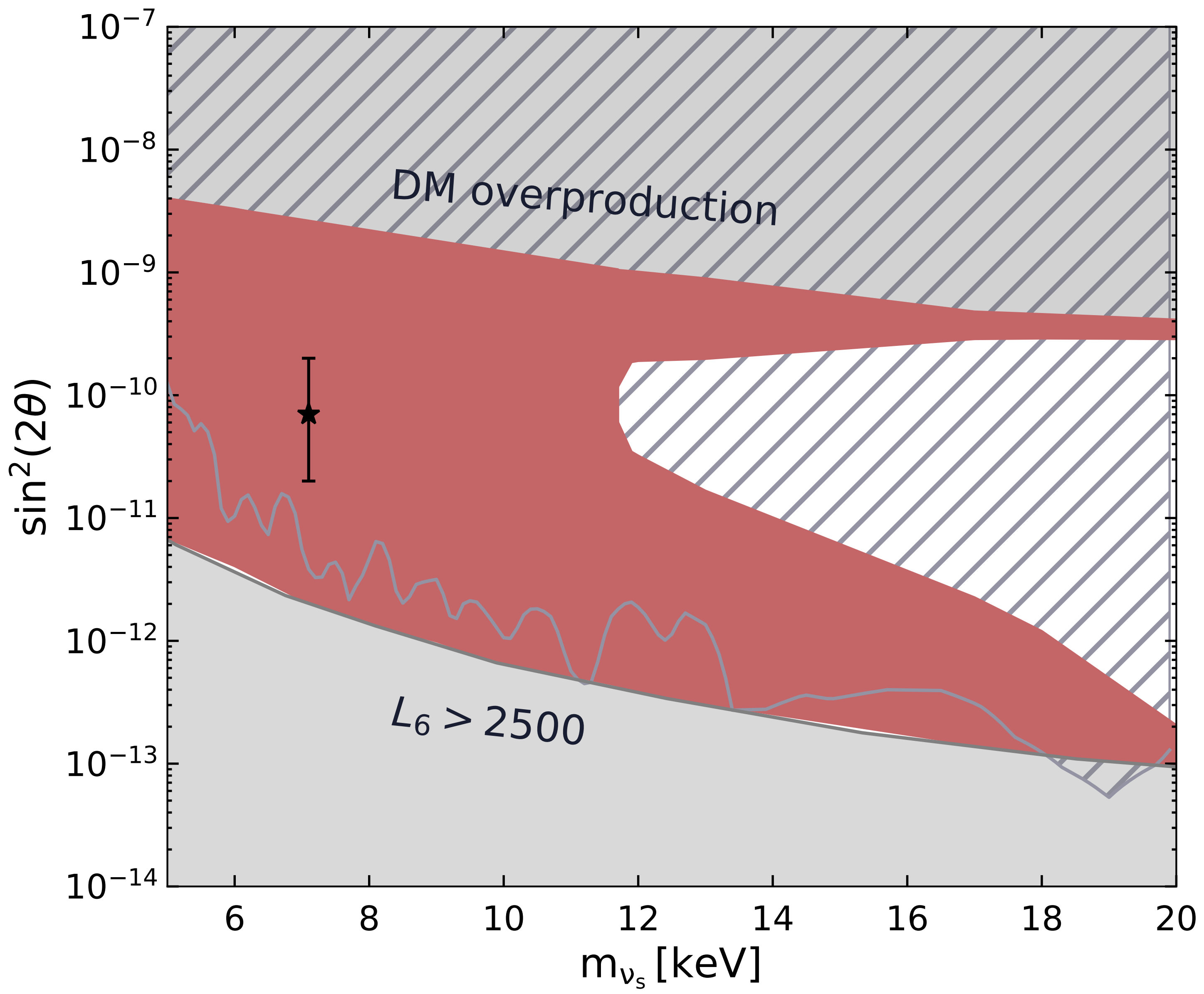


A. Dekker C. A. Correa K. C. Y. Ng

- “Warm” SASHIMI (*github.com/shinichiroando/sashimi-w*)
    - Applied SASHIMI codes to the case of WDM by modifying power spectrum, etc.
- Compare with satellite number counts (DES+PanSTARRS1)
    - Excluding WDM mass of < 3.6-5.1 keV (without baryon physics uncertainties)
    - Excluding sterile neutrino dark matter (combined with X rays)

Dekker, Ando, Correa, Ng, arXiv:2111.13137 [astro-ph.CO]





This needs to be calibrated against more numerical simulations!

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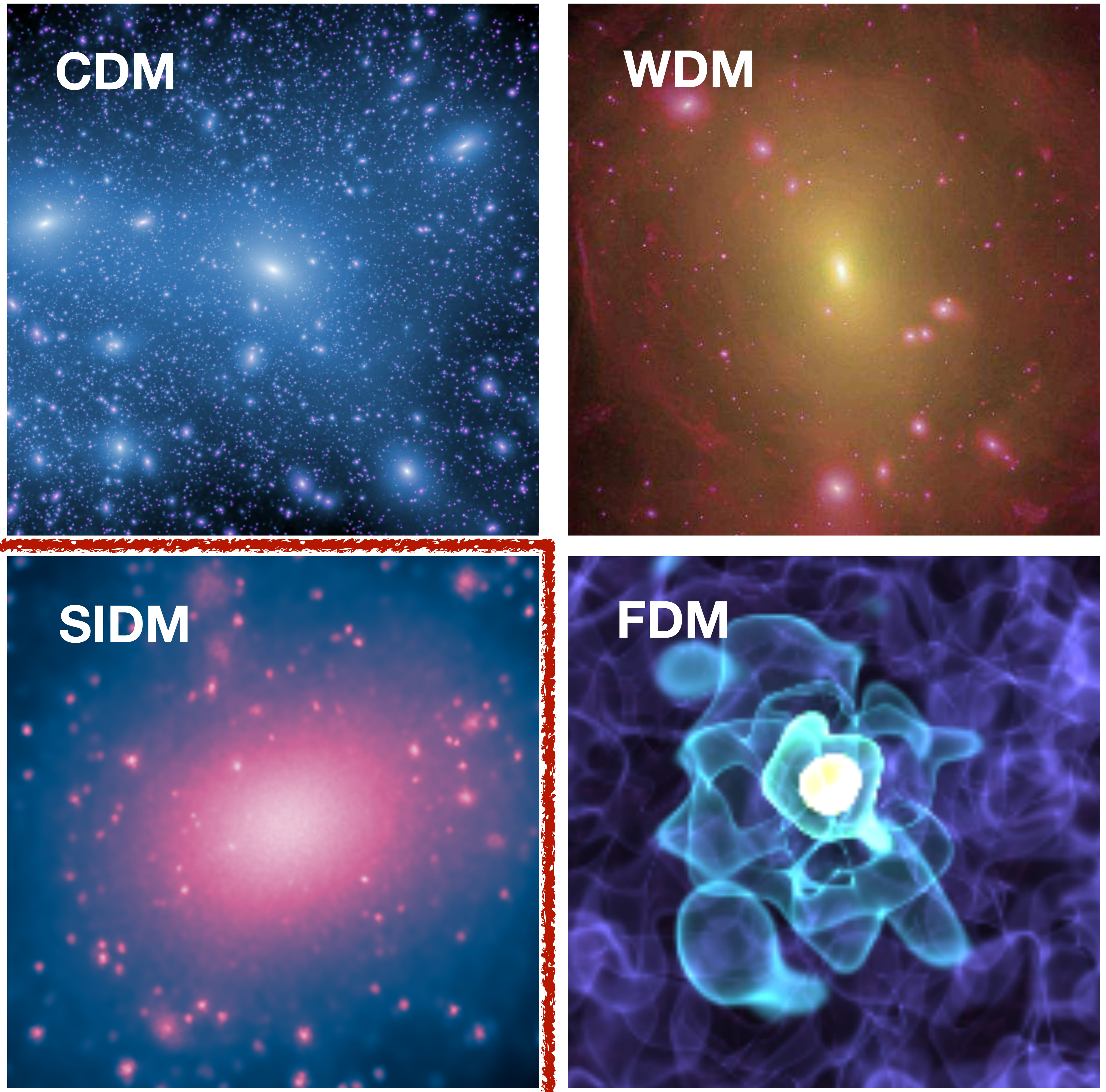

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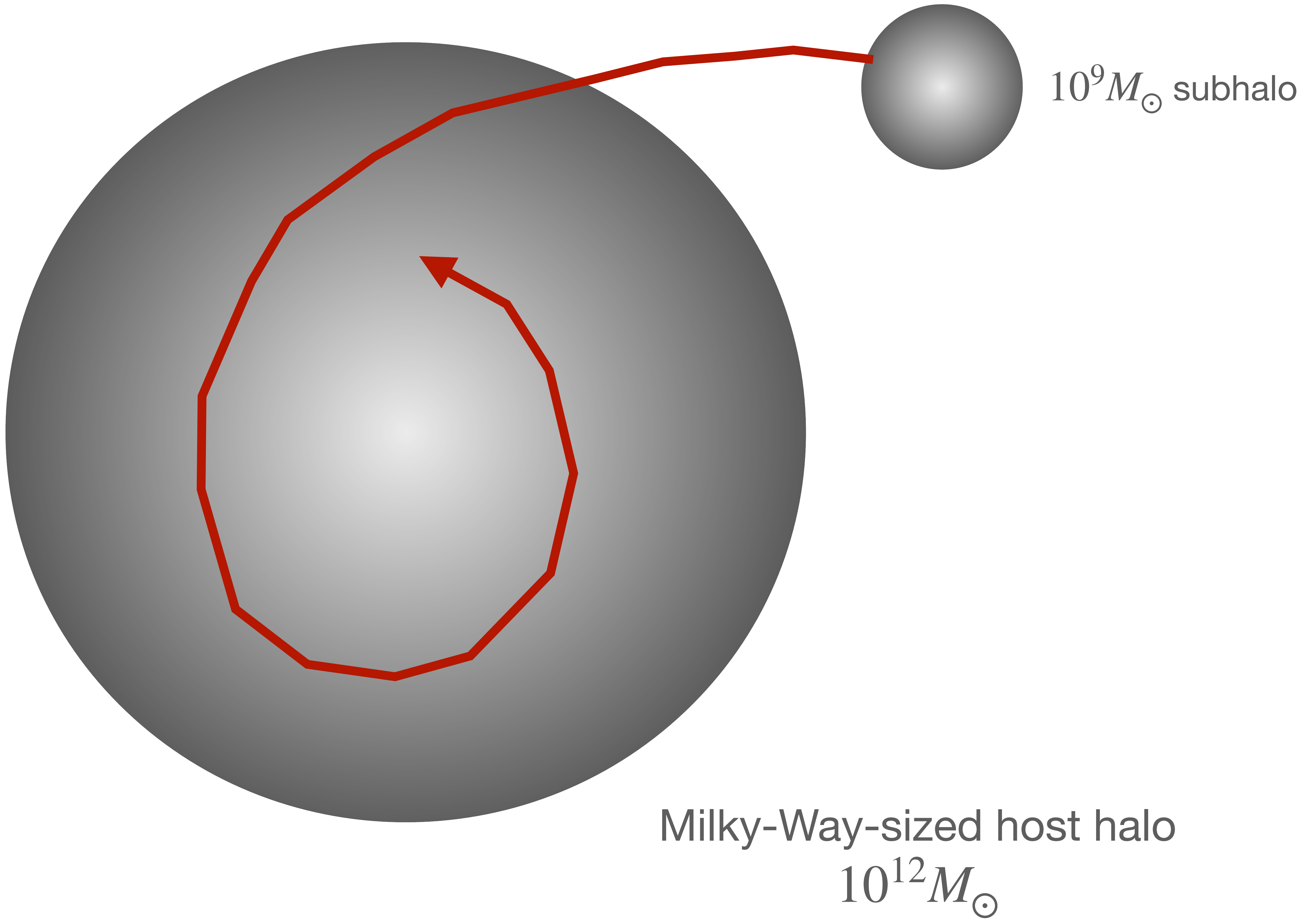
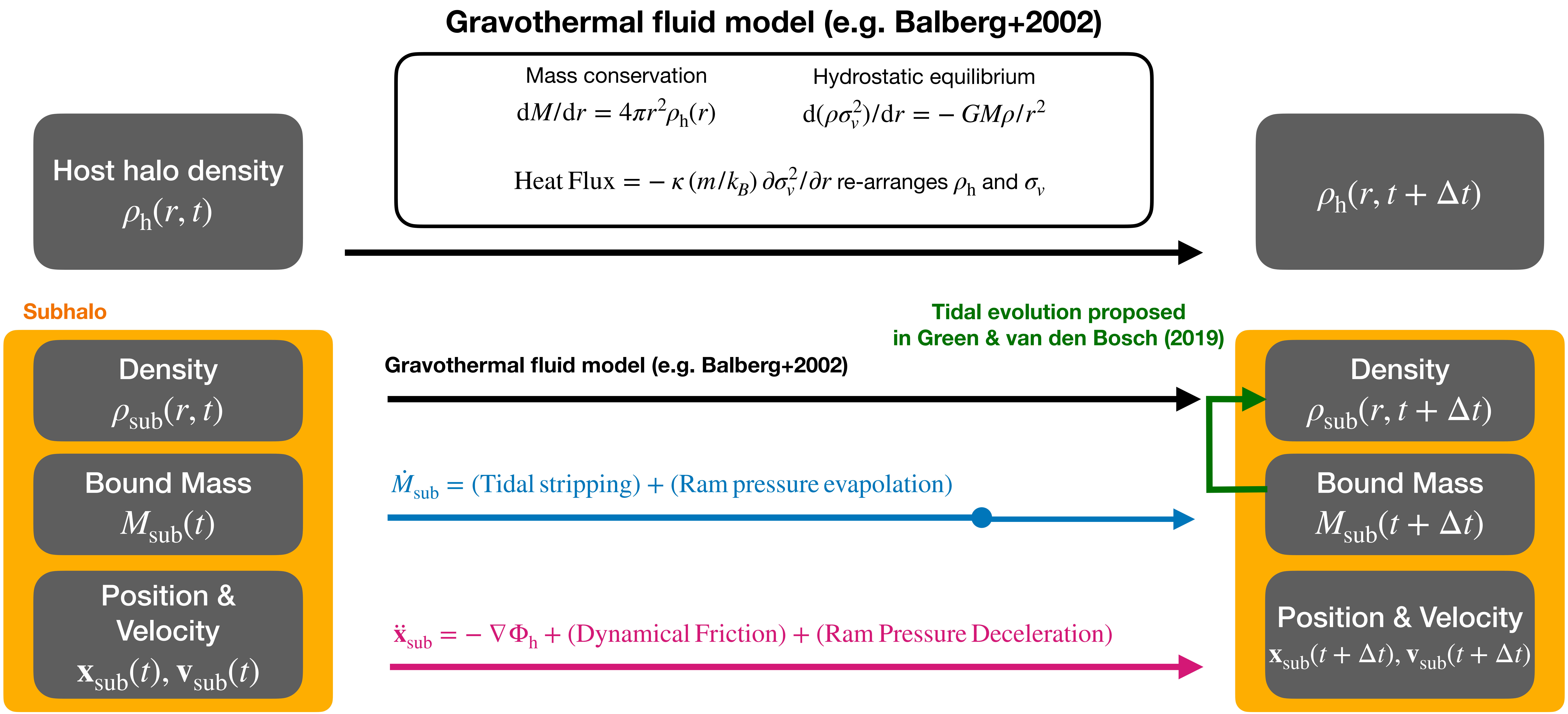
Semi-analytic model of SIDM subhaloes

Calibration with ideal N-body simulations of minor mergers

- Testing self-interactions of DM particles would require a precise modeling of
  - thermalization of SIDM halo/ subhalo
  - Tidal stripping / Ram pressure
- Develop a semi-analytic model of infalling subhalos to a MW-sized halo and calibrate it with (isolated) N-body simulations

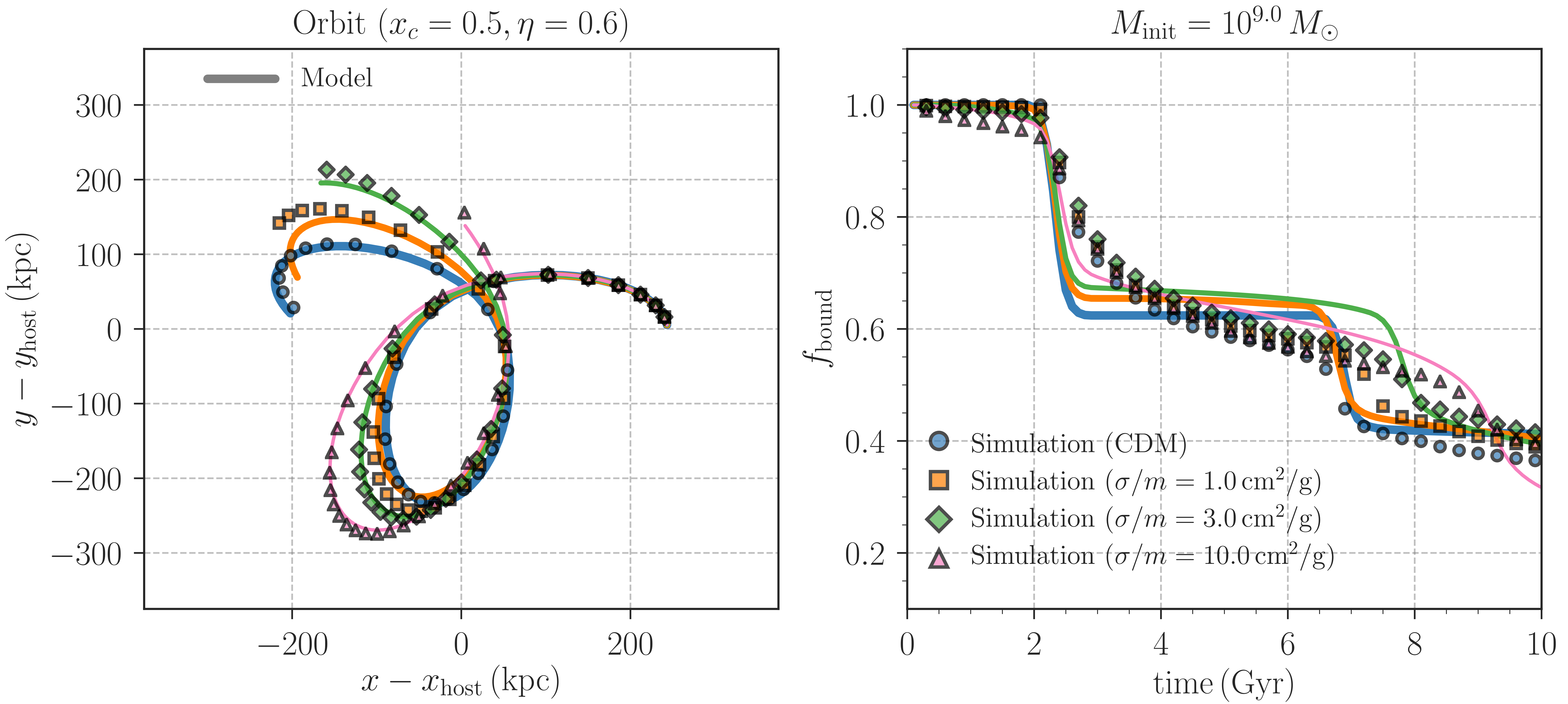


A brief summary of our model



Note: We ignore possible changes of subhalo density profiles due to ram pressure effects

Comparison with our model and simulations



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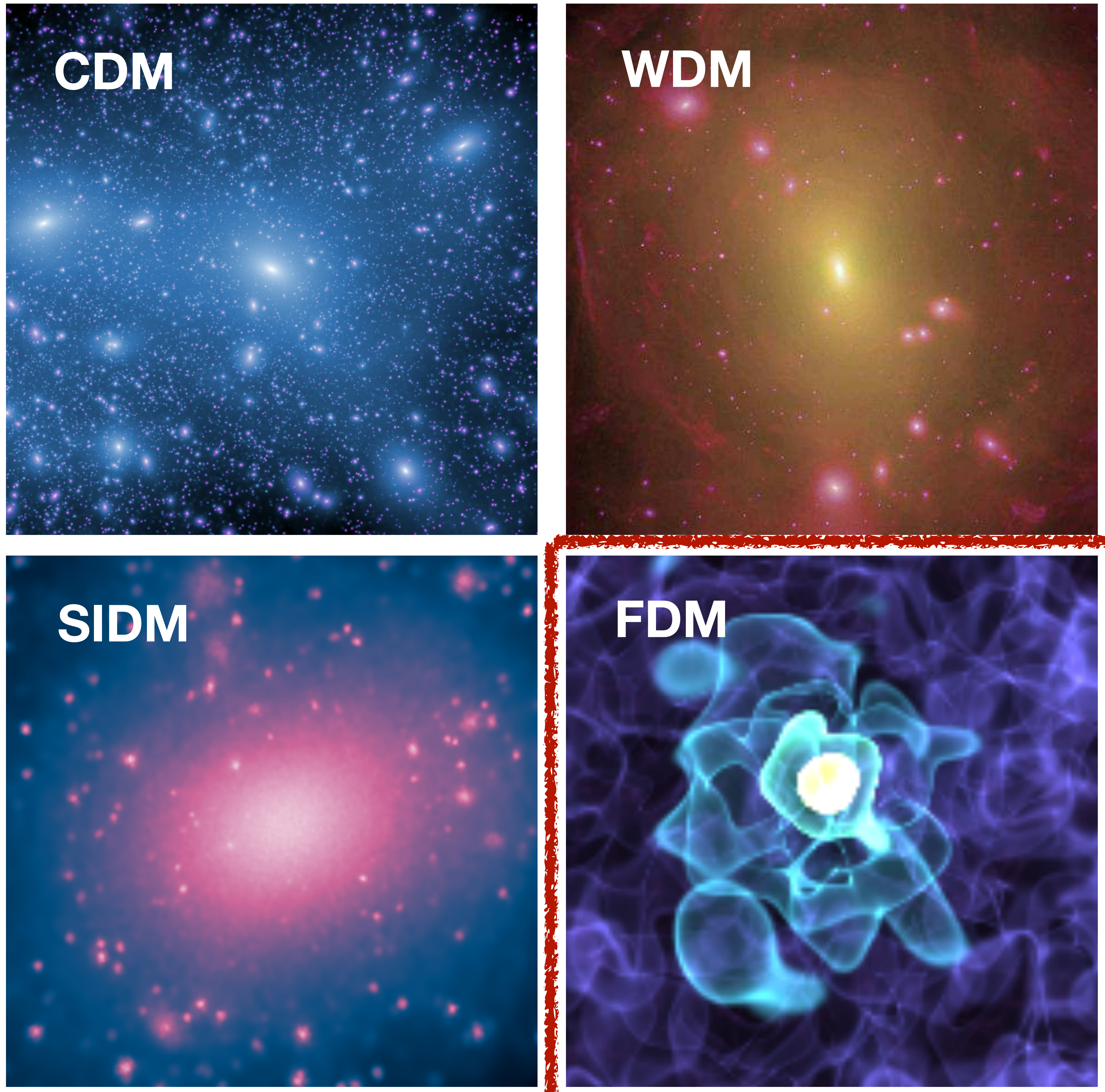

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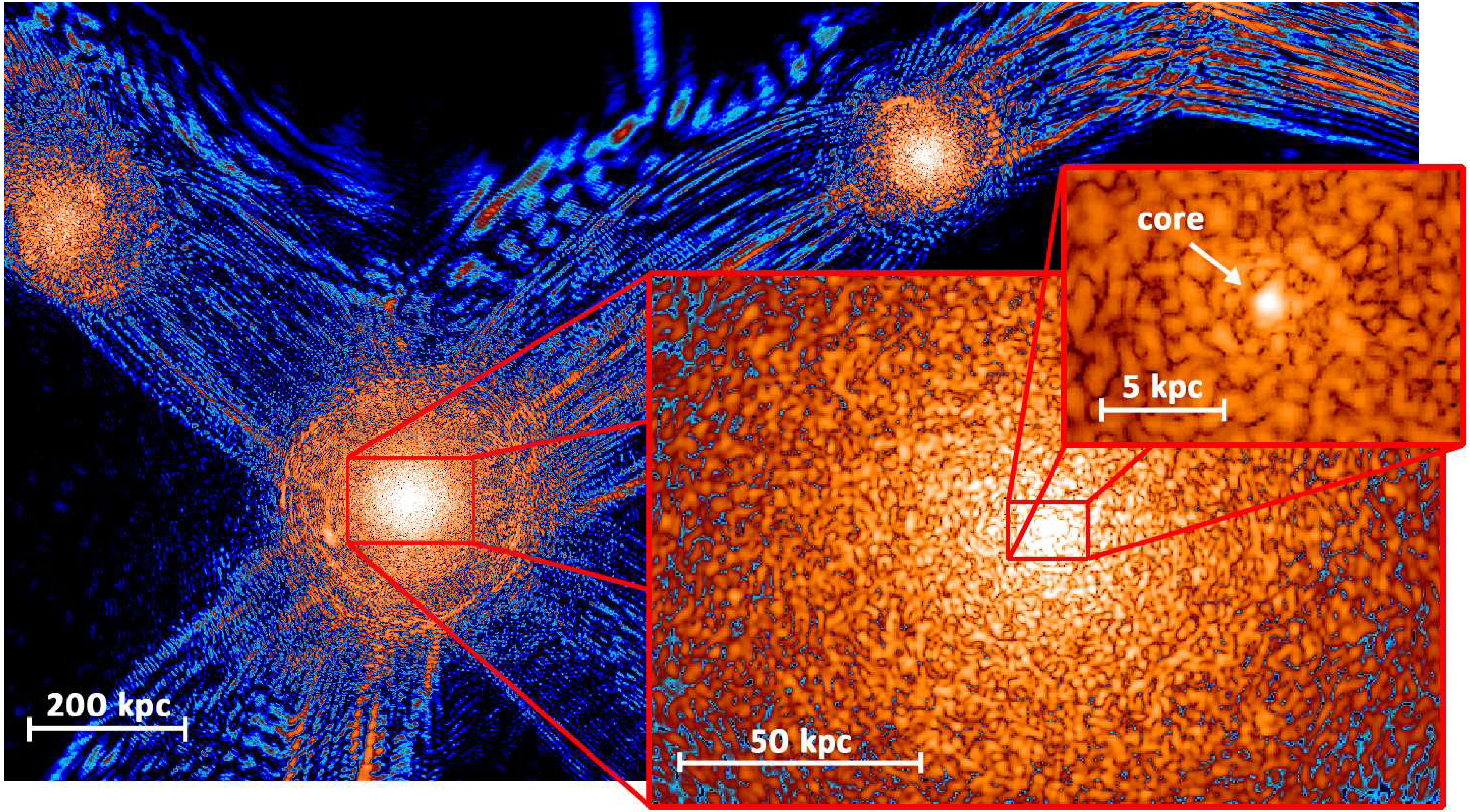
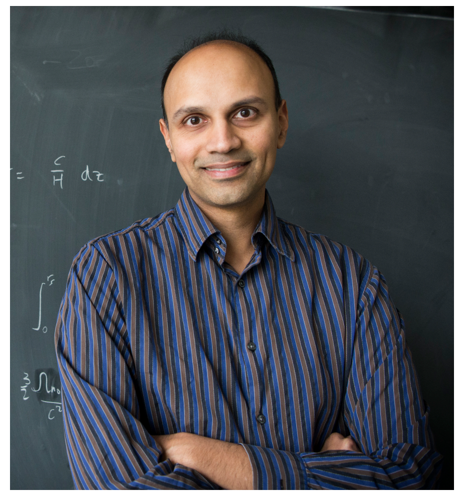
FDM wave interference



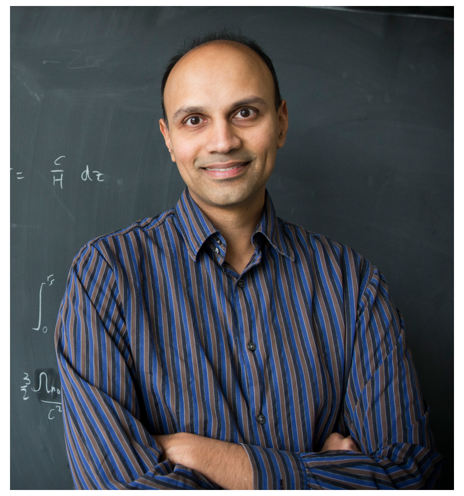
Schive et al., Nature Physics, 10, 496 (2014)

Gravitational heating from FDM



N. Dalal

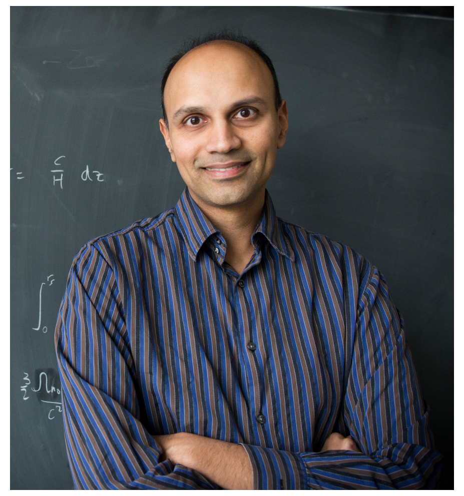
Gravitational heating from FDM



N. Dalal

- Interference fringes have density contrast $\delta\rho \sim \rho$ everywhere all of the time
- These lead to fluctuating gravitational forces that can perturb stars

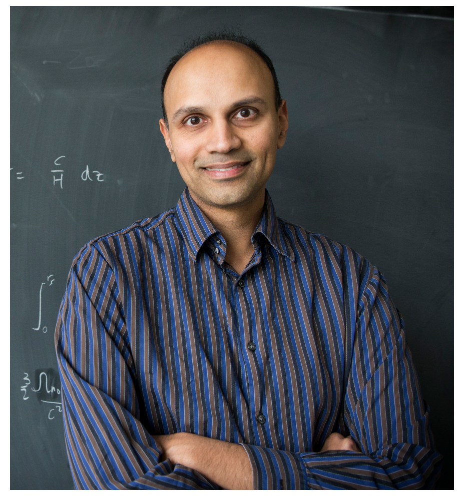
Gravitational heating from FDM



N. Dalal

- Interference fringes have density contrast $\delta\rho \sim \rho$ everywhere all of the time
- These lead to fluctuating gravitational forces that can perturb stars
- Where to look for this signature of FDM? Crude estimate:
  - $\delta M \sim \delta\rho\, \lambda^3 \propto \rho/\sigma_v^3 \Rightarrow$ acceleration perturbation $\delta a \sim G\, \delta M/\lambda^2 \propto G\rho/\sigma_v$

Gravitational heating from FDM



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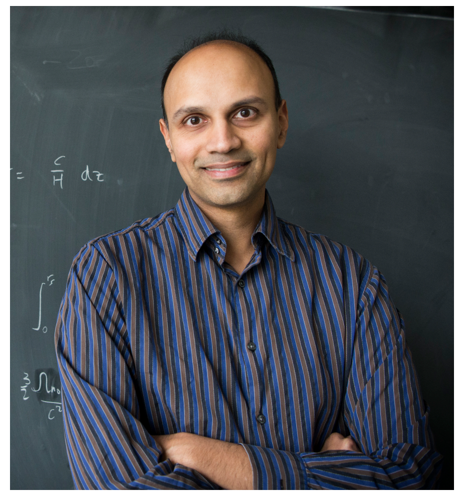
Gravitational heating from FDM



N. Dalal

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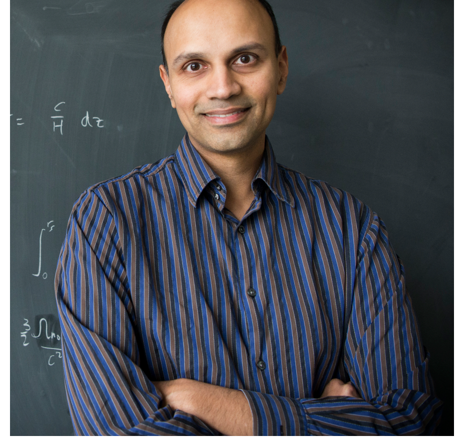

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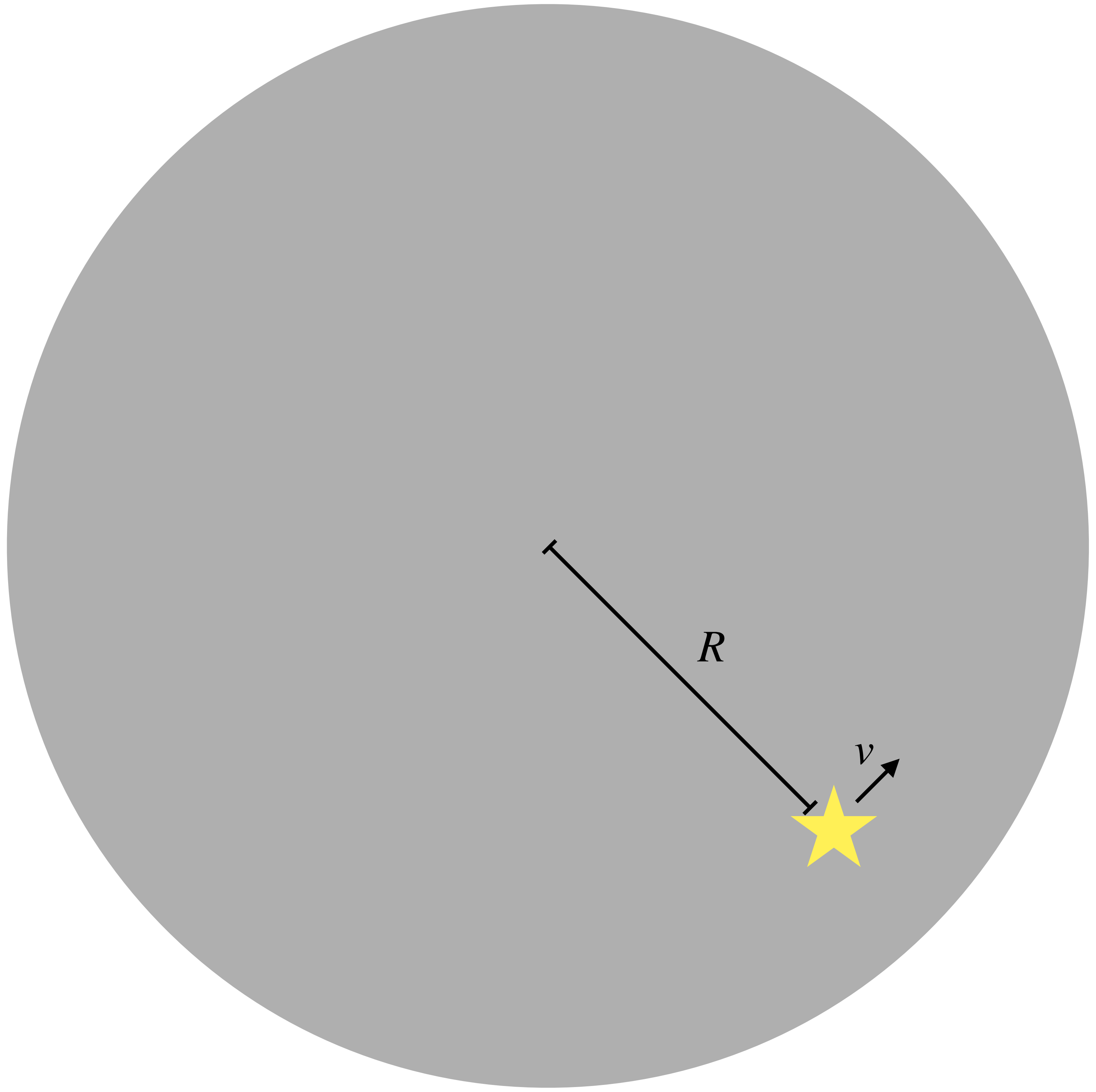
- Biggest effect where R is small and σ_v is small, i.e. **centres of smallest halos -> *ultrafaint dwarf galaxies***

Ballpark estimate

- Consider typical star in galaxy of size R, moving at velocity $v \sim \sigma_v$



Dalal, Kravtsov, arXiv:2203.05750 [astro-ph.CO]

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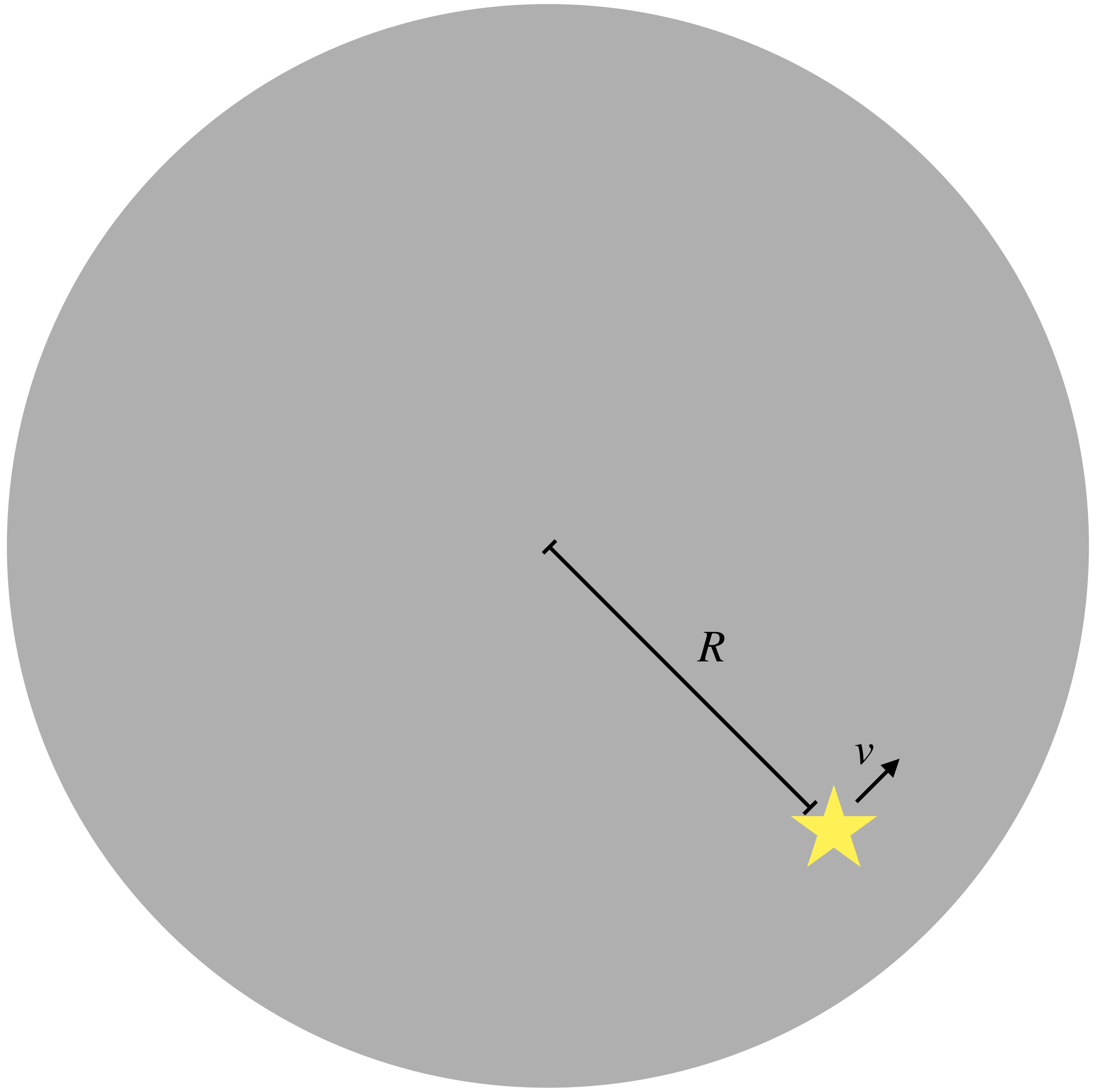

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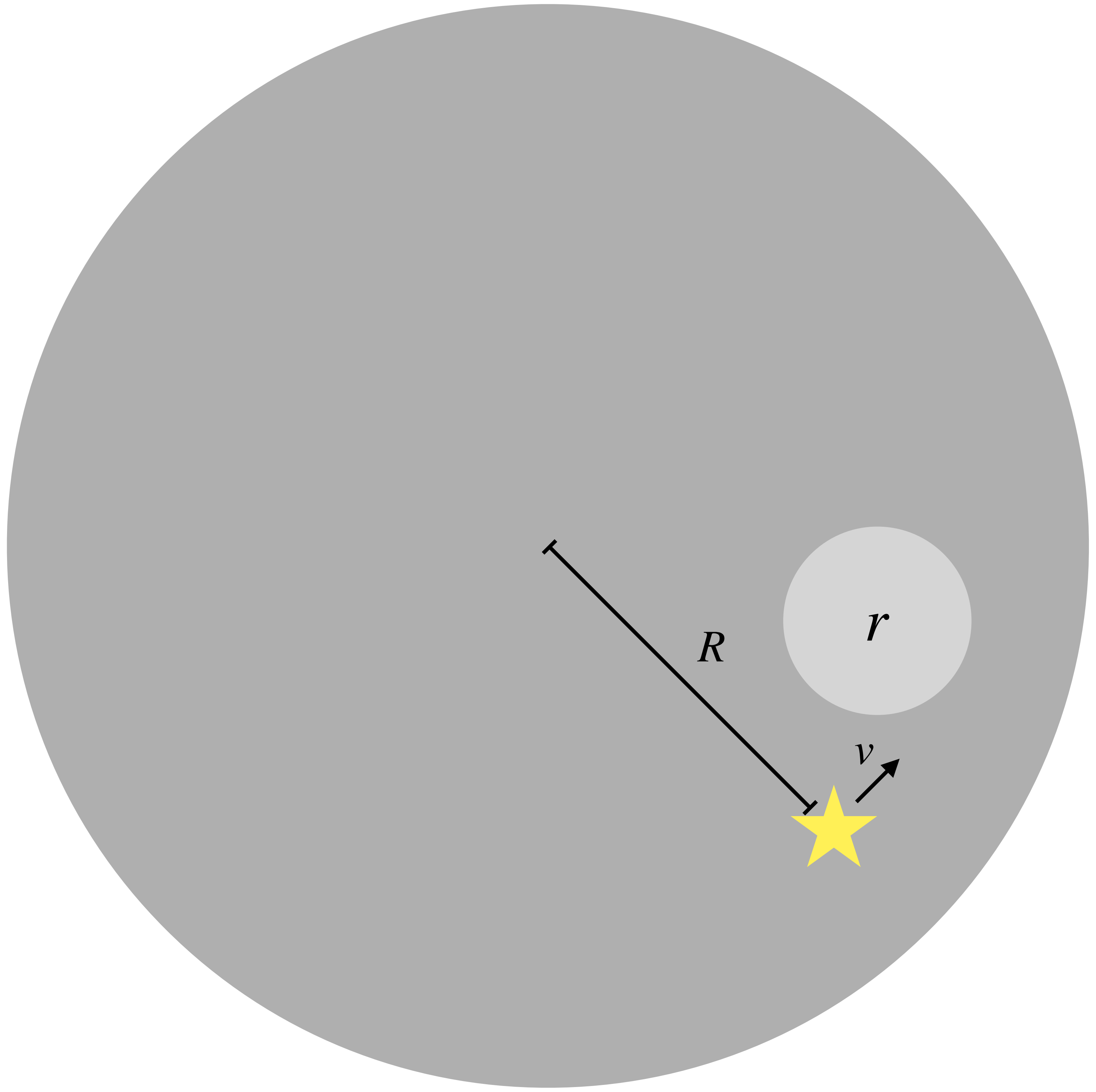

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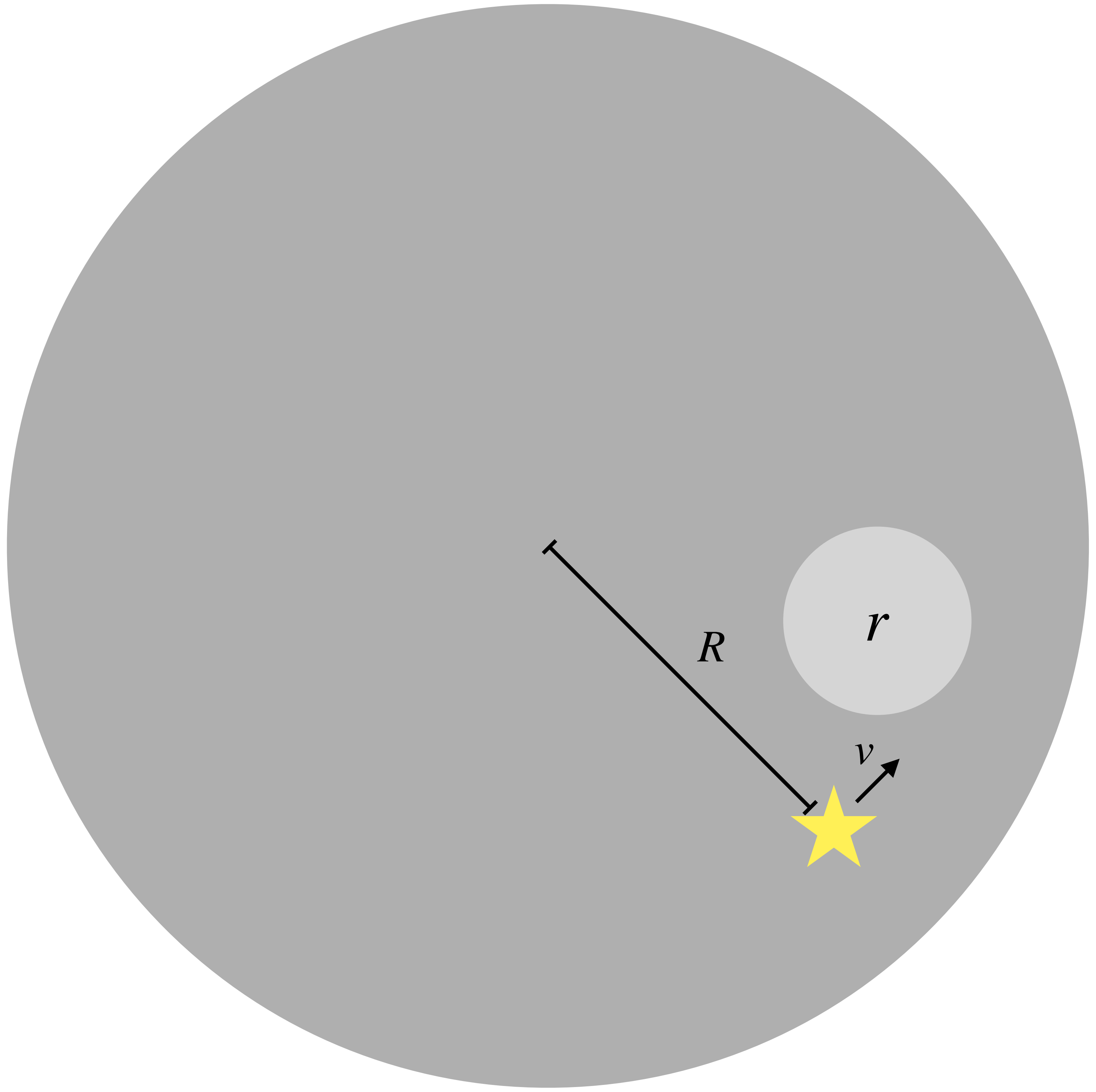

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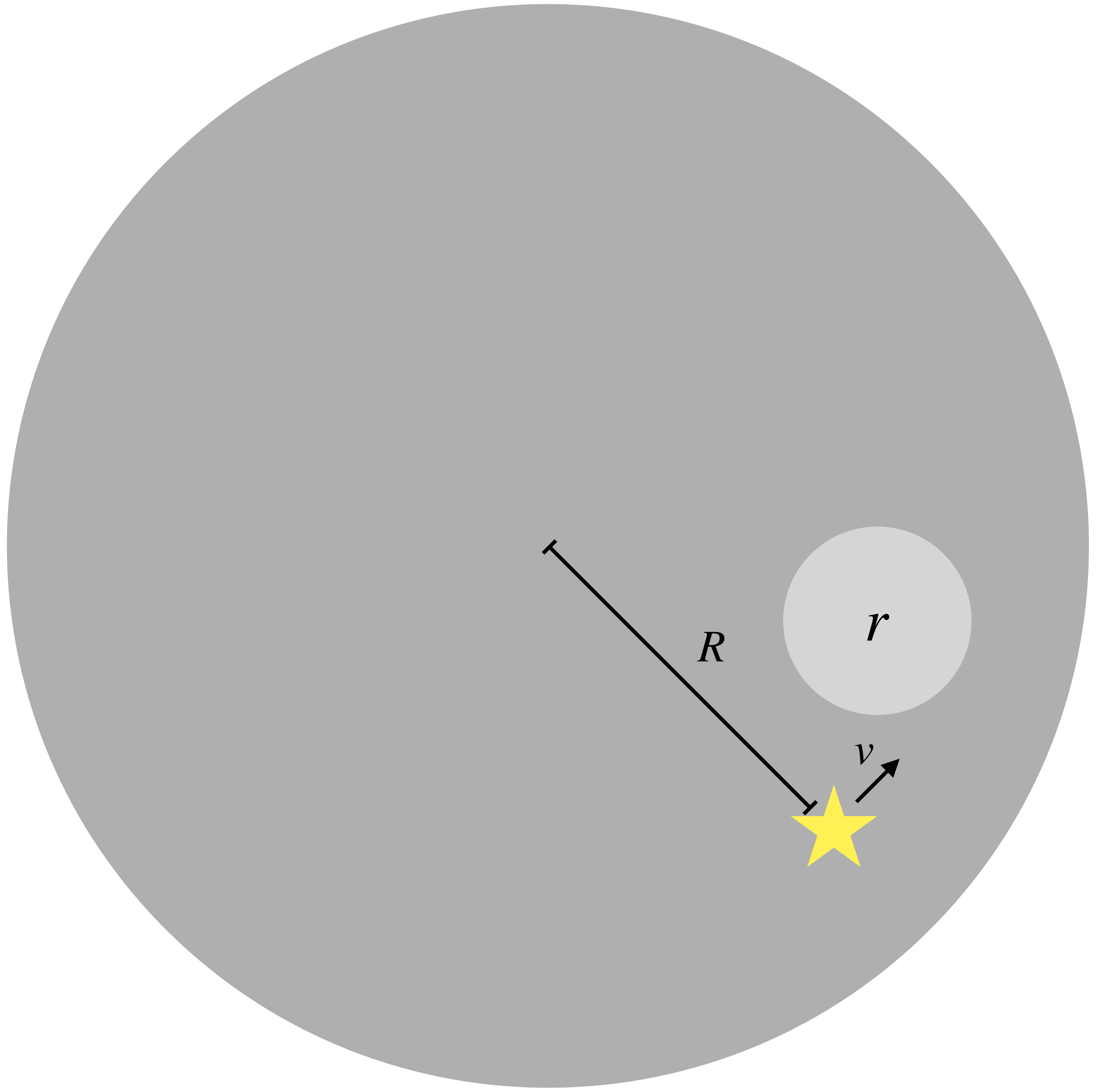

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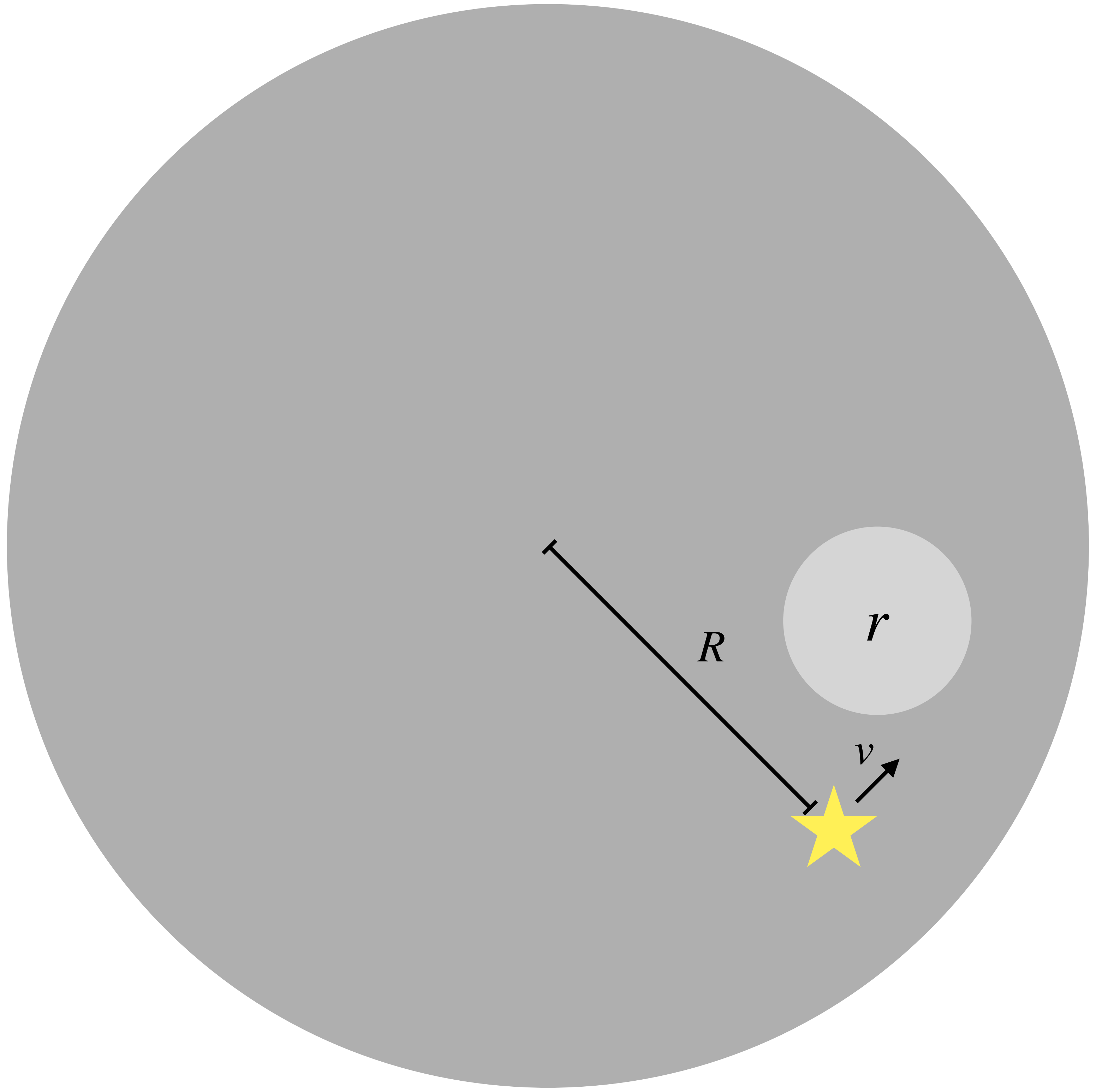

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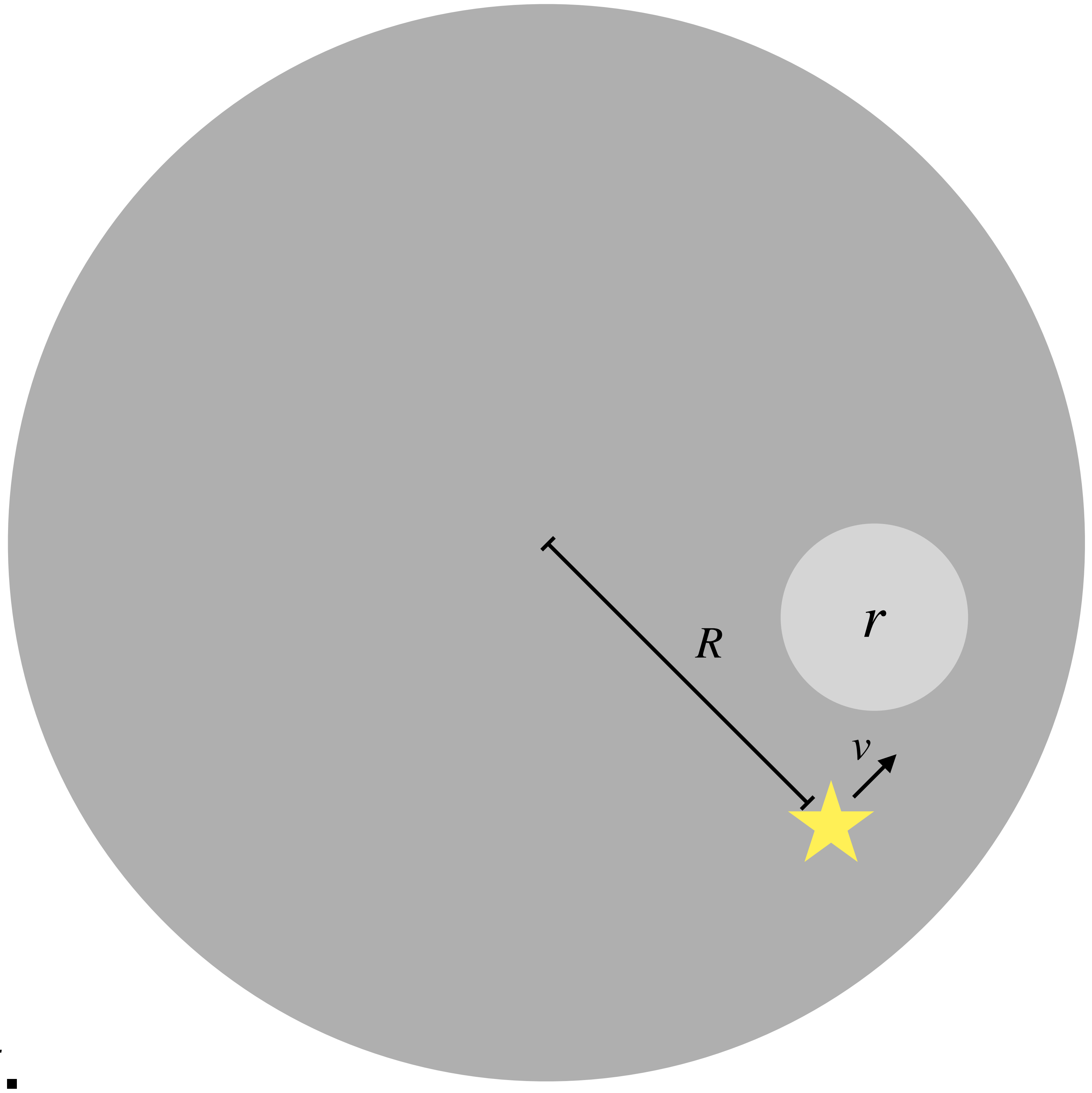
- So we can solve for mass m that makes $\delta\sigma_v^2 \approx \sigma_v^2$ in time t. Plugging in $t = 10\,\mathrm{Gyr}, R = 50\,\mathrm{pc}, \sigma_v = 3\,\mathrm{km/s}$ gives $m \sim 10^{-19}\ \mathrm{eV}$



Dalal, Kravtsov, arXiv:2203.05750 [astro-ph.CO]

Results

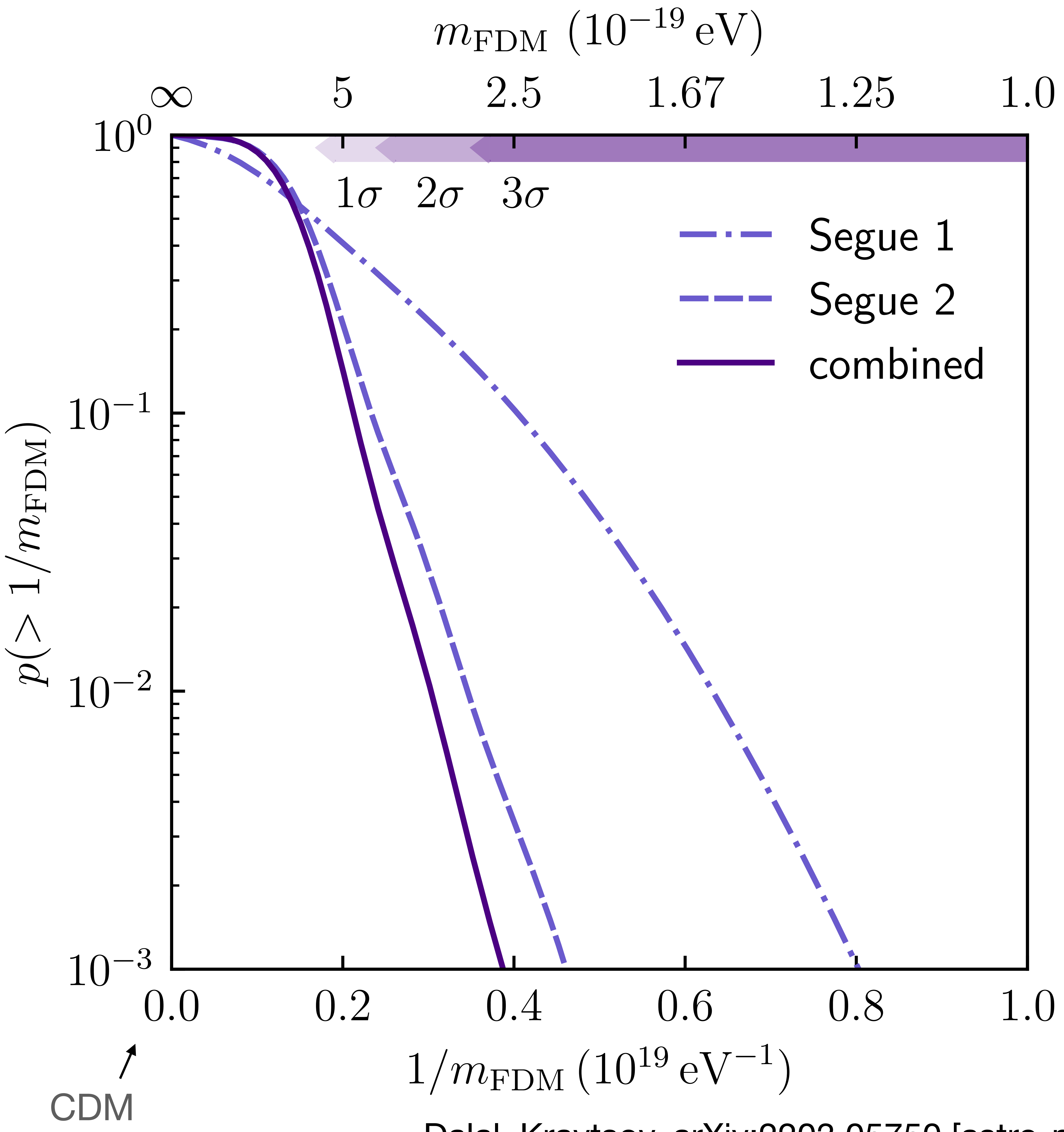
- Find $m_{\rm FDM} > 3 \times 10^{-19}\,{\rm eV}$ at >99% confidence, using Segue 1 & Segue 2. Previous bounds from Ly-α forests are $m \gtrsim 10^{-21}\,{\rm eV}$

- Essentially, rules out "fuzzy" regime:

  - linear power spectrum identical to LCDM out to $k \sim 200\,{\rm Mpc}^{-1}$

  - halo mass function identical to LCDM down to $M \sim 2 \cdot 10^5 M_\odot$

- Constraints of similar strength are obtained by a dynamical analysis of ultrafaint dwarf galaxies (Hayashi et al. 2021)



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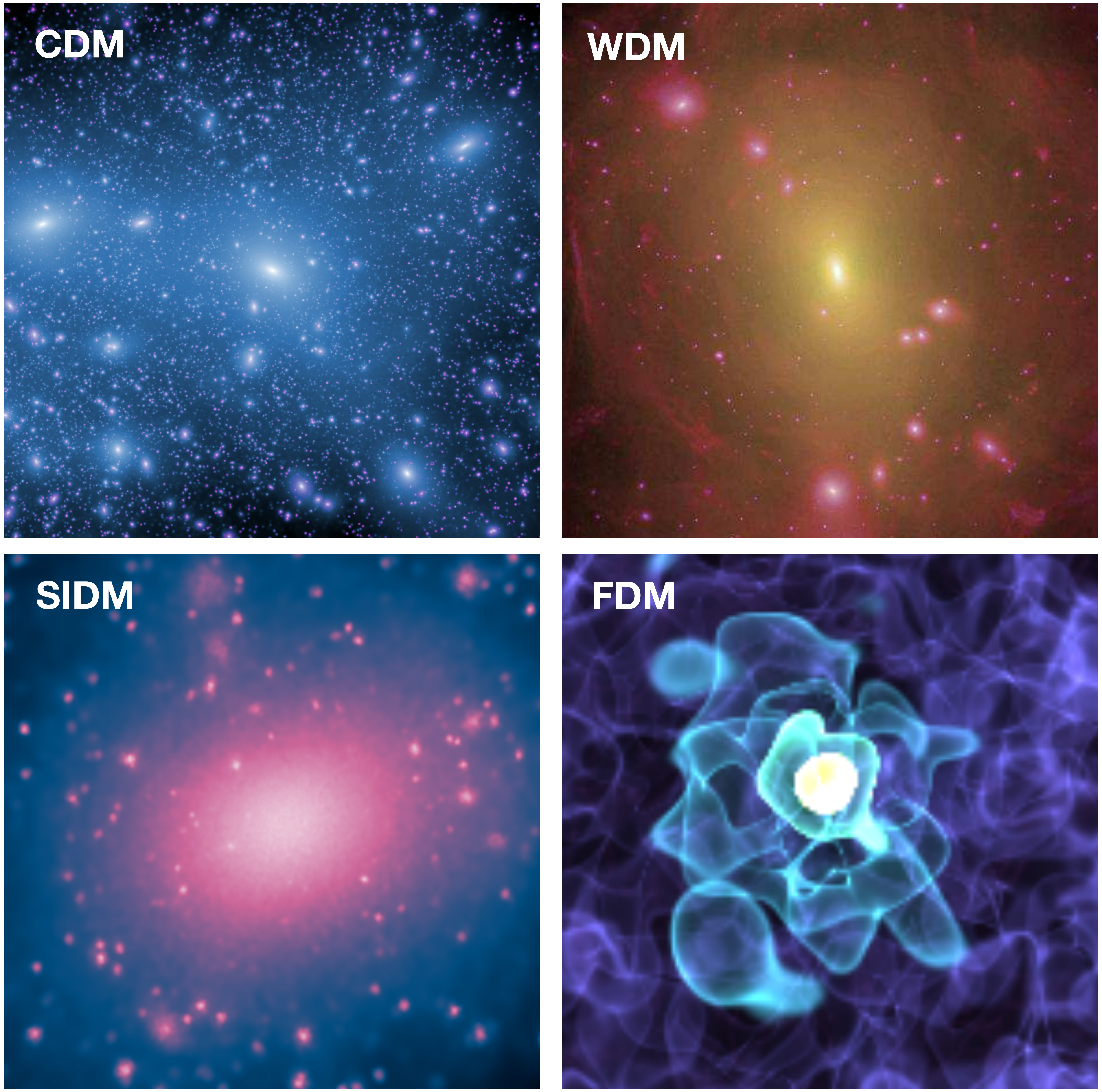
Conclusions



- Good progress is being made in all the four directions (CDM, WDM, SIDM, FDM)
- Results worth highlighting:
    - **Strong constraints on WDM** and sterile neutrinos using satellite counts (and public codes SASHIMI)
    - **Strong constraints on FDM** using stellar velocity data in ultrafaint galaxies
- Exploration of **CDM phase space**, **SIDM modeling**, and **numerical simulations** is ongoing with exciting results
- More detailed talks by Horigome and Inoue
- ***Looking forward to collaborations with other groups for FY 2022!***