Update from group C02: Cosmic structure formation

Shin'ichiro Ando
University of Amsterdam / University of Tokyo

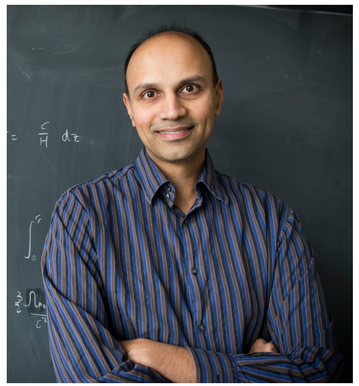
GRAPPA
GRavitation AstroParticle Physics Amsterdam

KAVLI IPMU
INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

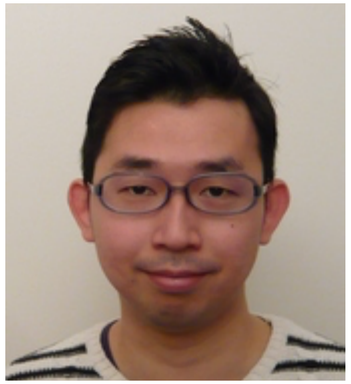
C02: Members

PI + co-I

Shin'ichiro Ando



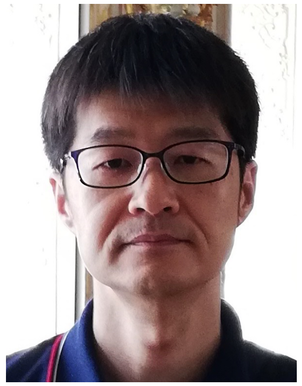
Neal Dalal



Takahiro Nishimichi

Takashi Okamoto

Masato Shirasaki



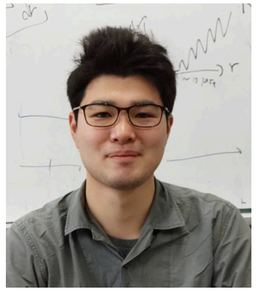
Atsushi Taruya

Project postdocs

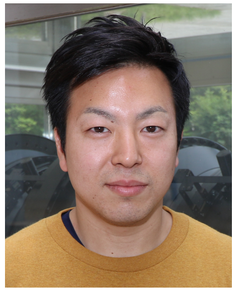
Shunichi Horigome

Shigeki Inoue

Collaborators



Yohsuke Enomoto



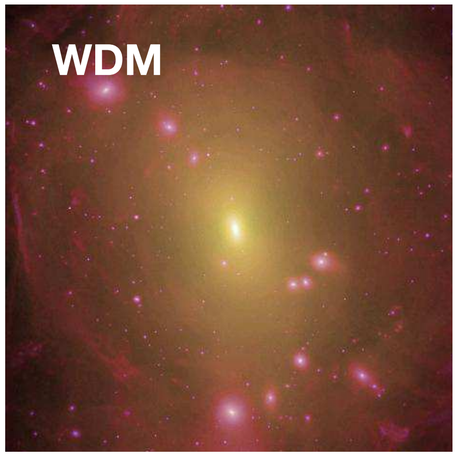
Kohei Hayashi

Tomoaki Ishiyama

Goals: Small scale structure

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

WIMPs, axions, ALPs, PBHs

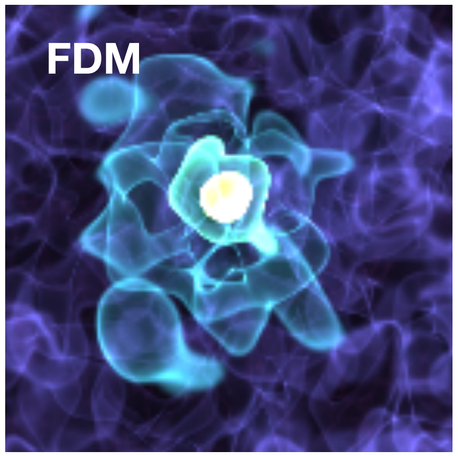


- Cutoff at sub-galaxy scale in the power spectrum

Sterile neutrinos

- Cores in density profiles induced by self scattering

SIMPs, dark atoms

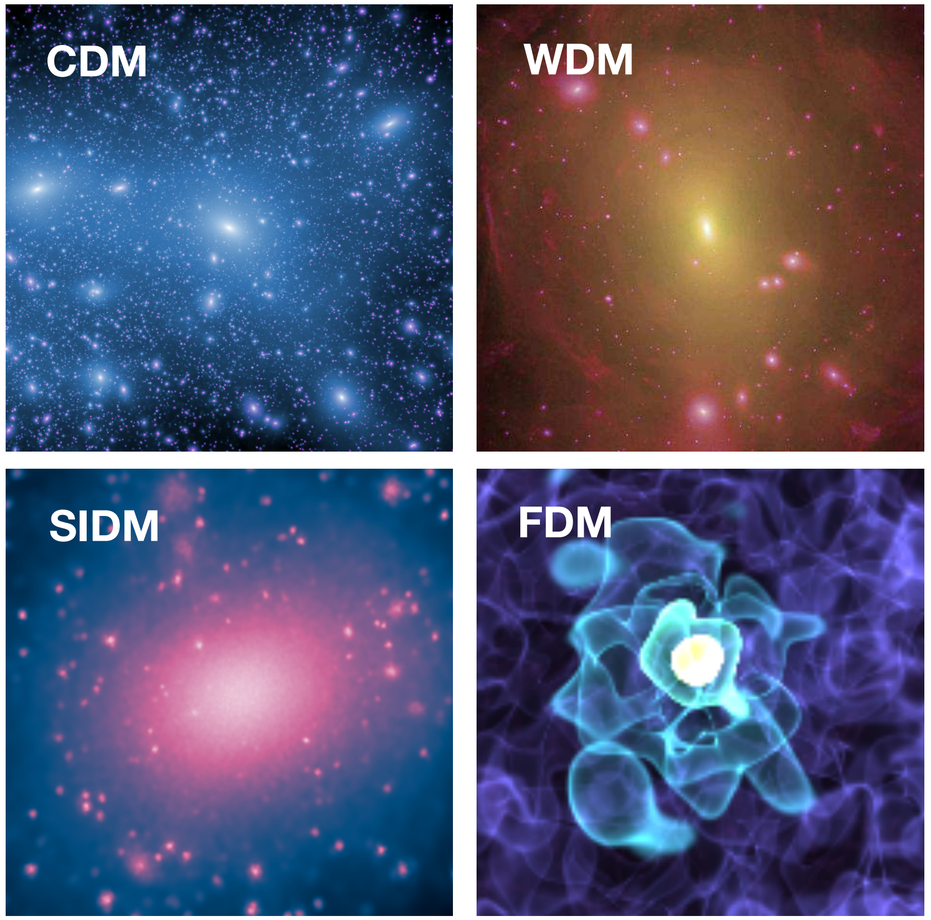


- Pattern induced by de Broglie length at sub-galactic scales

Ultralight bosons

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)**
- **Primordial power (Hiroshima, Nishimichi)**



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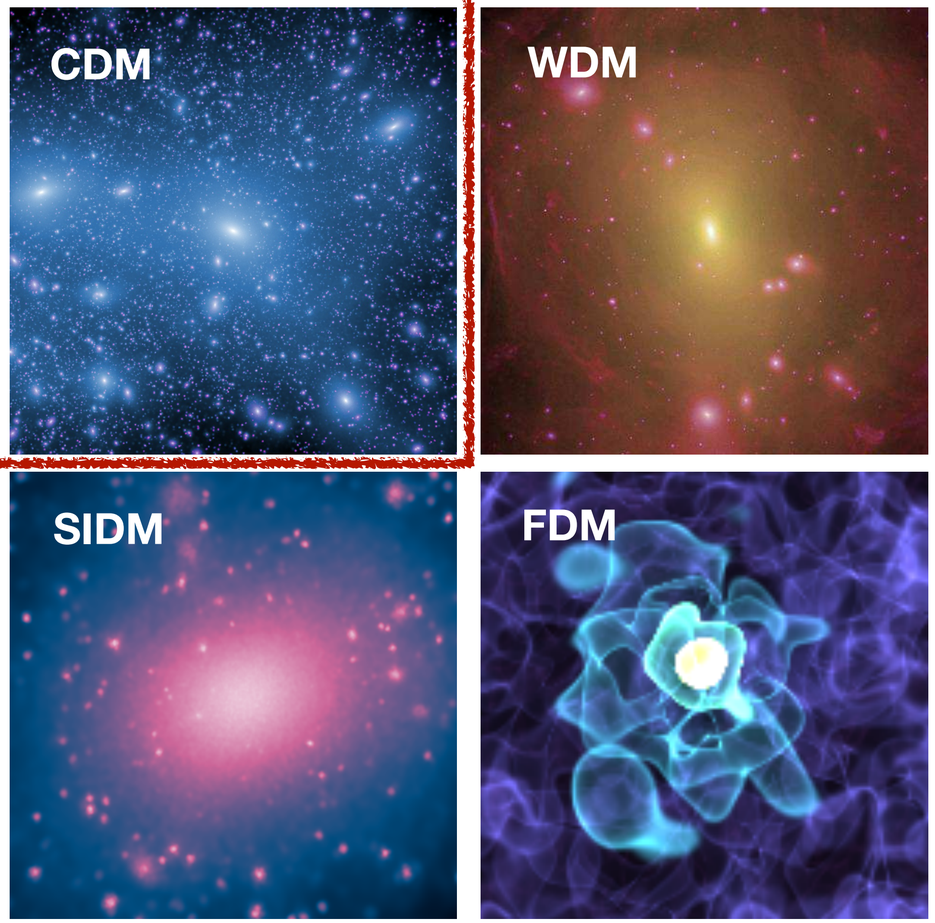

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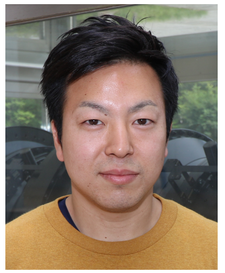
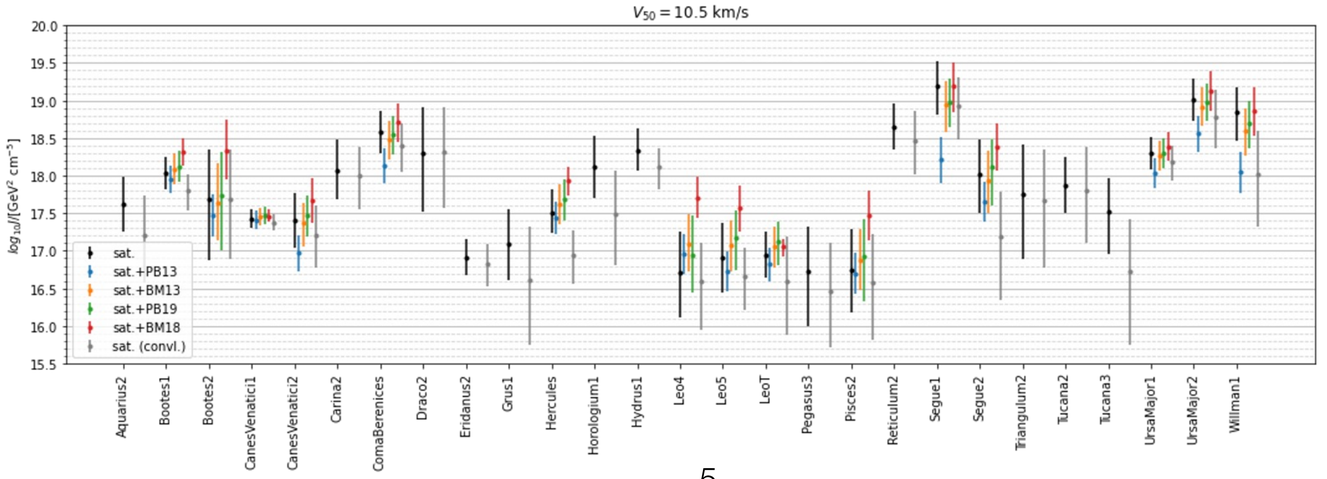
Dark matter density profile estimation with cosmological models

Horigome et al.
arXiv:2207.10378



- Dark matter density profile of astronomical objects (dSph, MW) is important to study the nature of dark matter (mass, cross section, self-interaction)
- Cosmological models are useful to estimate these profiles by using stellar data
  - **Satellire prior**: prior on stuructural parameters of dSph dark matter profiles based on the extended Press-Schechter formalism
  - **SHMR prior**: empirical relation between stellar and dark matter mass
  - **SIDM profile model**: gravothermal fluid model calibrated by N-body simulation



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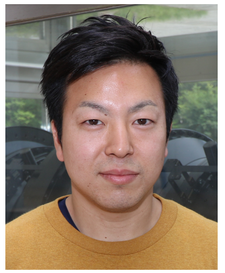

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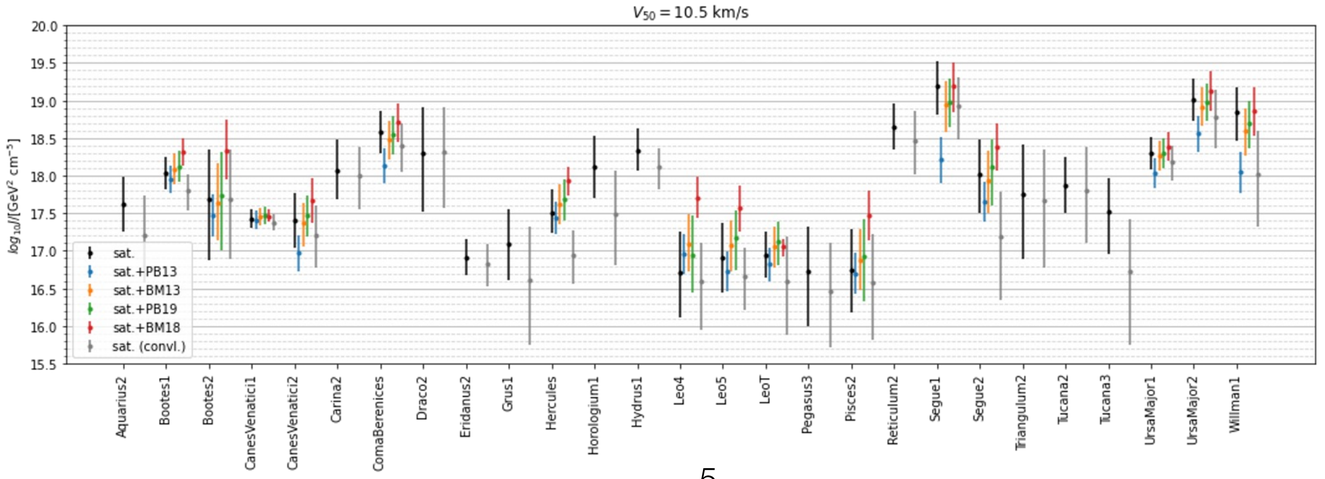
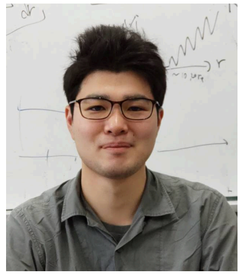
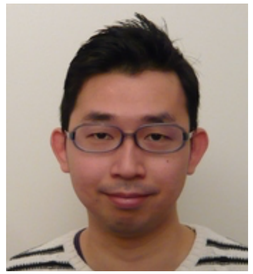
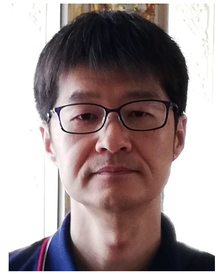


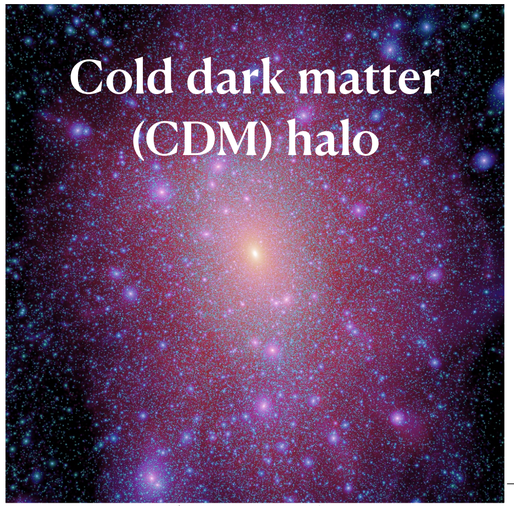
Talk by Horigome

A new universal feature in CDM halos

in cosmological N-body simulations

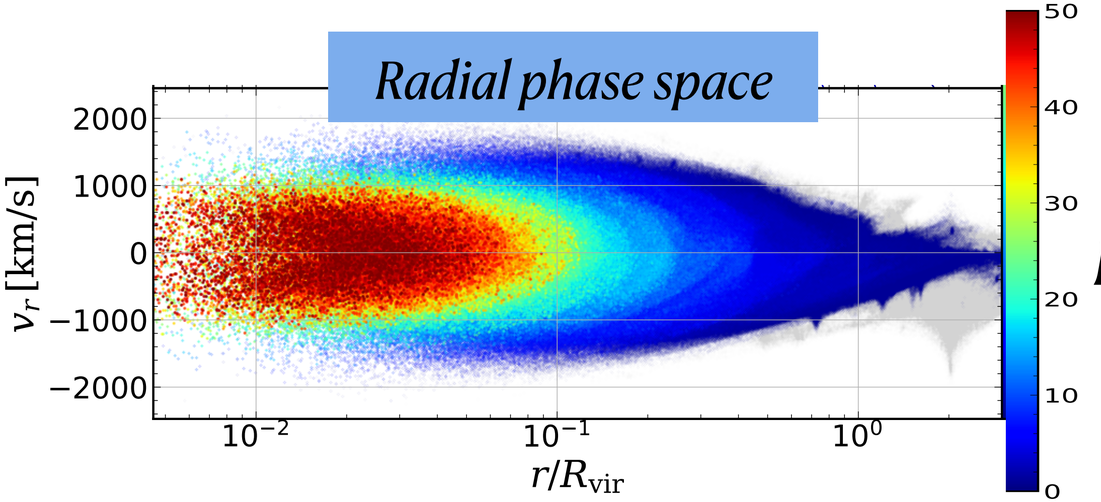
Enomoto, Nishimichi & Taruya
('23) arXiv:2302.01531

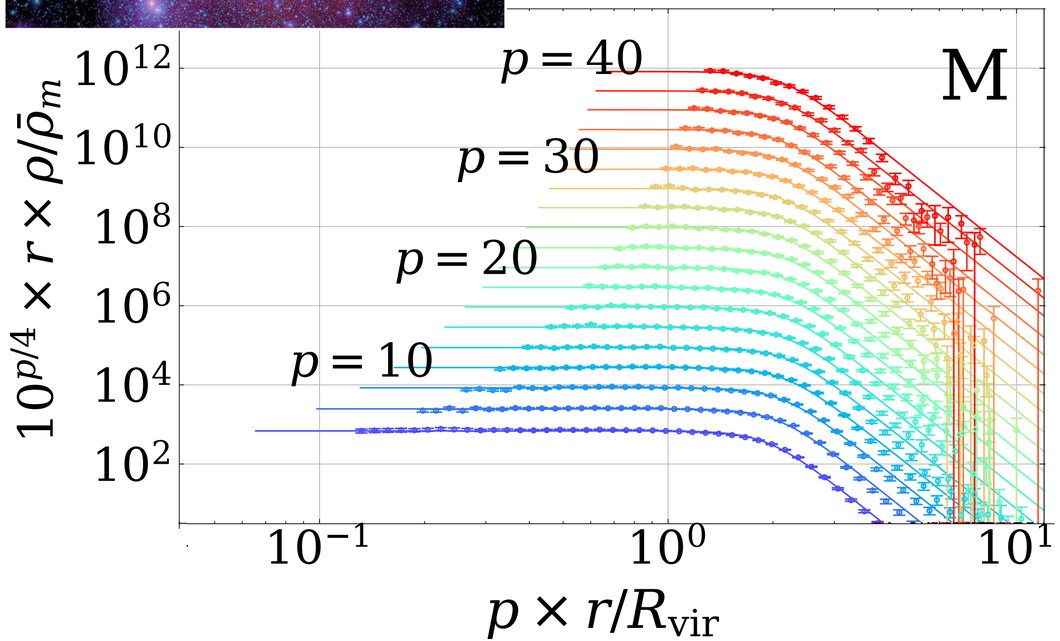






Tracking particle trajectories

With 1,001 snapshots over z=0~5





Radial multi-stream profiles

$$\rho_{\rm stream}(r;p) = \frac{A(p)}{x\,(1+x^7)}\,; \qquad x \equiv \frac{r}{S(p)}$$

With $A(p)$ & $S(p)$ described by a simple fitting form

- holds irrespective of halo mass: $10^{11} \sim 10^{14}\,h^{-1}\,M_\odot$
- (possibly) linked to other universal features

A new universal feature in CDM halos

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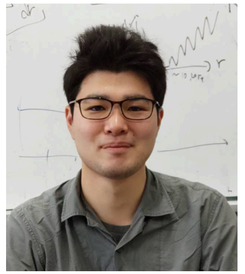
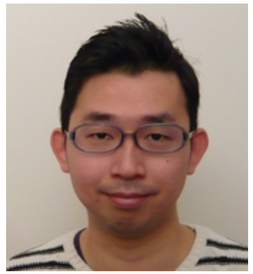
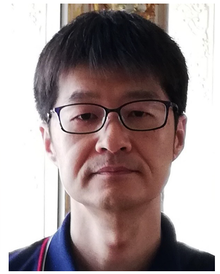

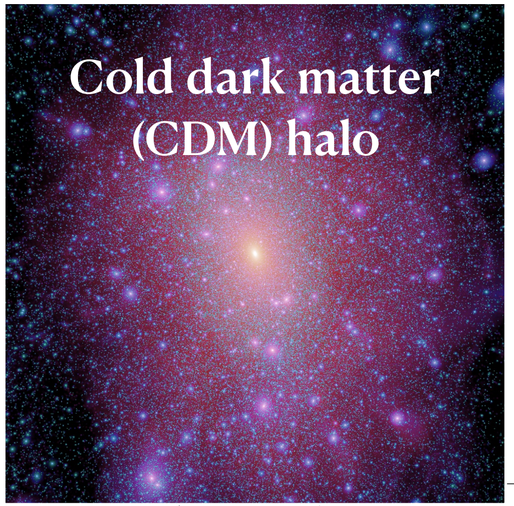

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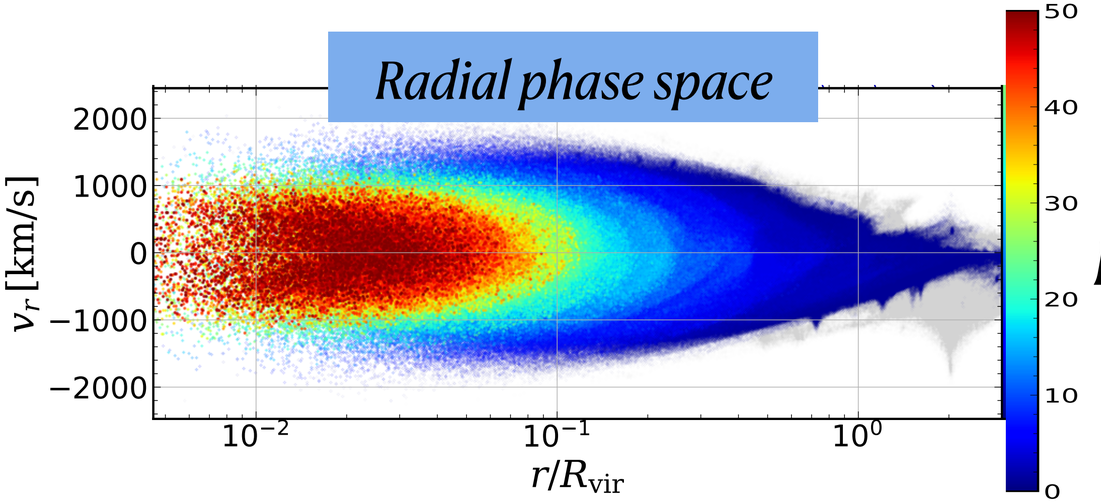
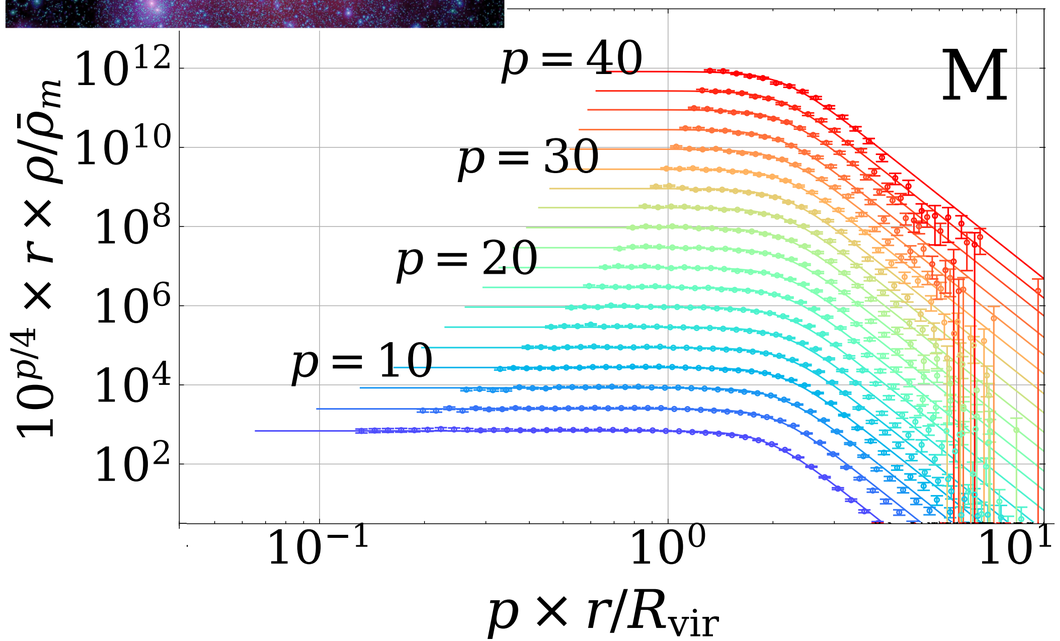


Talk by Taruya



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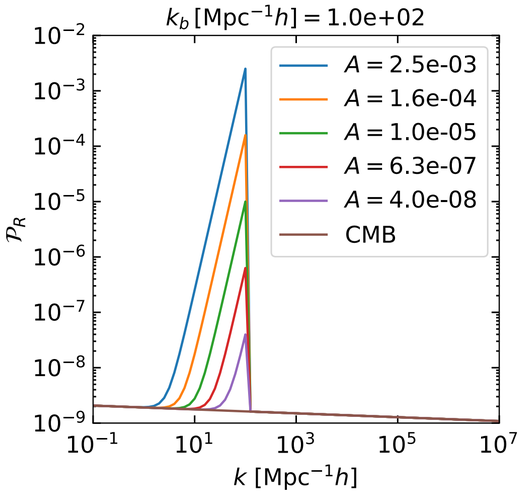
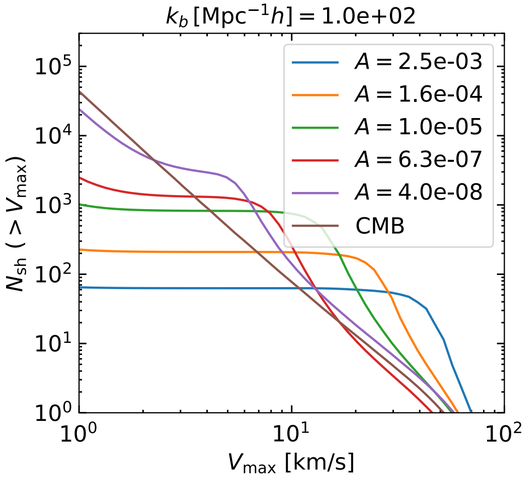
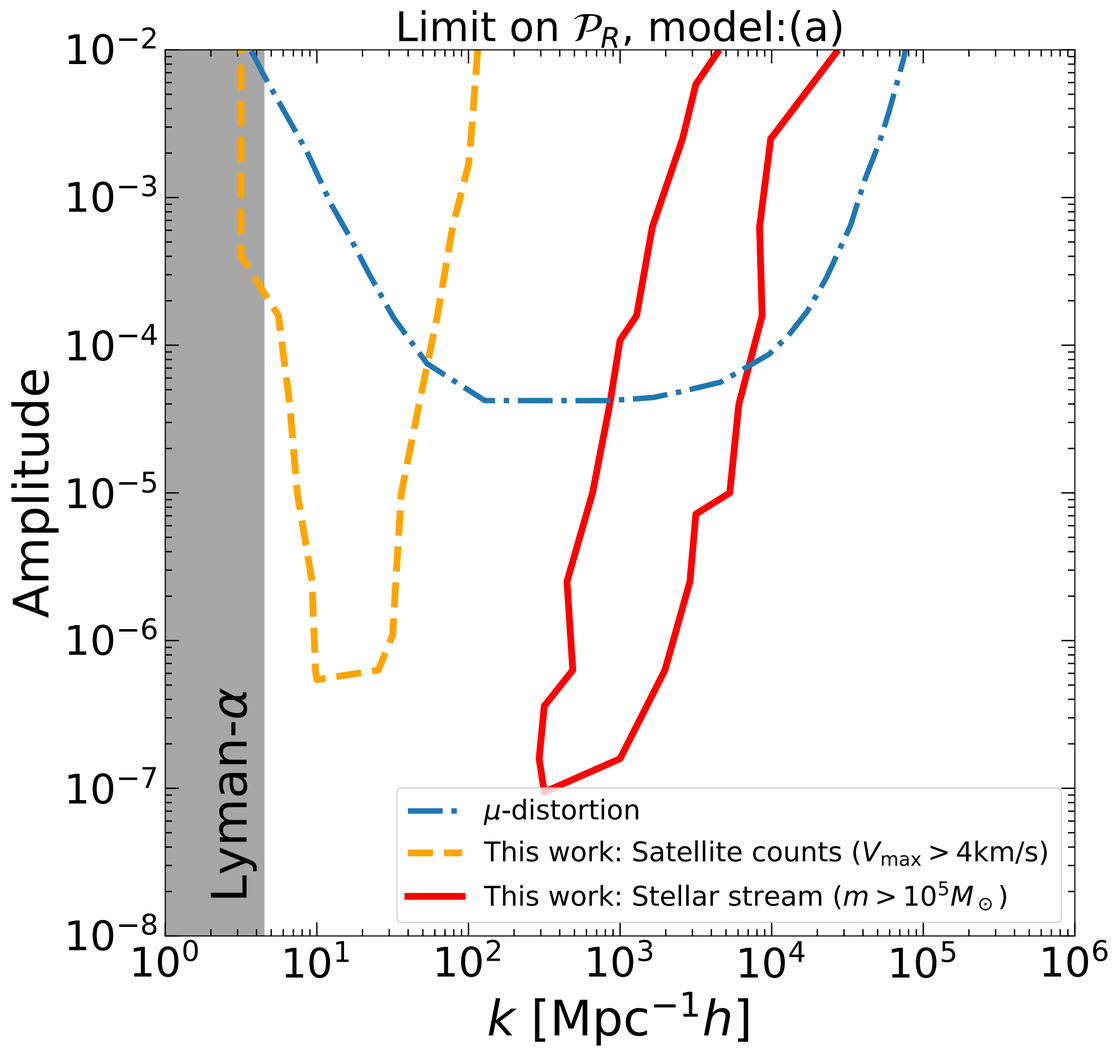
Constraining primordial perturbation





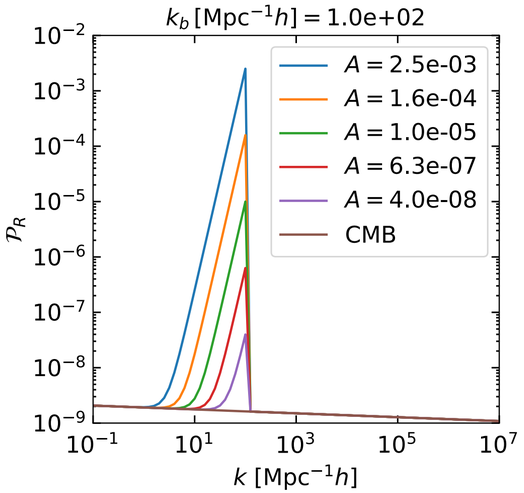


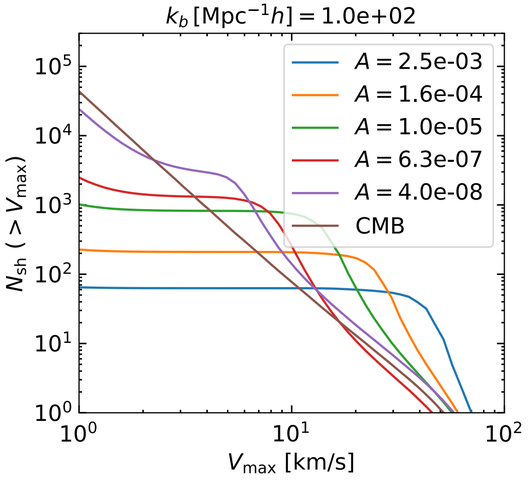
N. Hiroshima K. Ishiwata

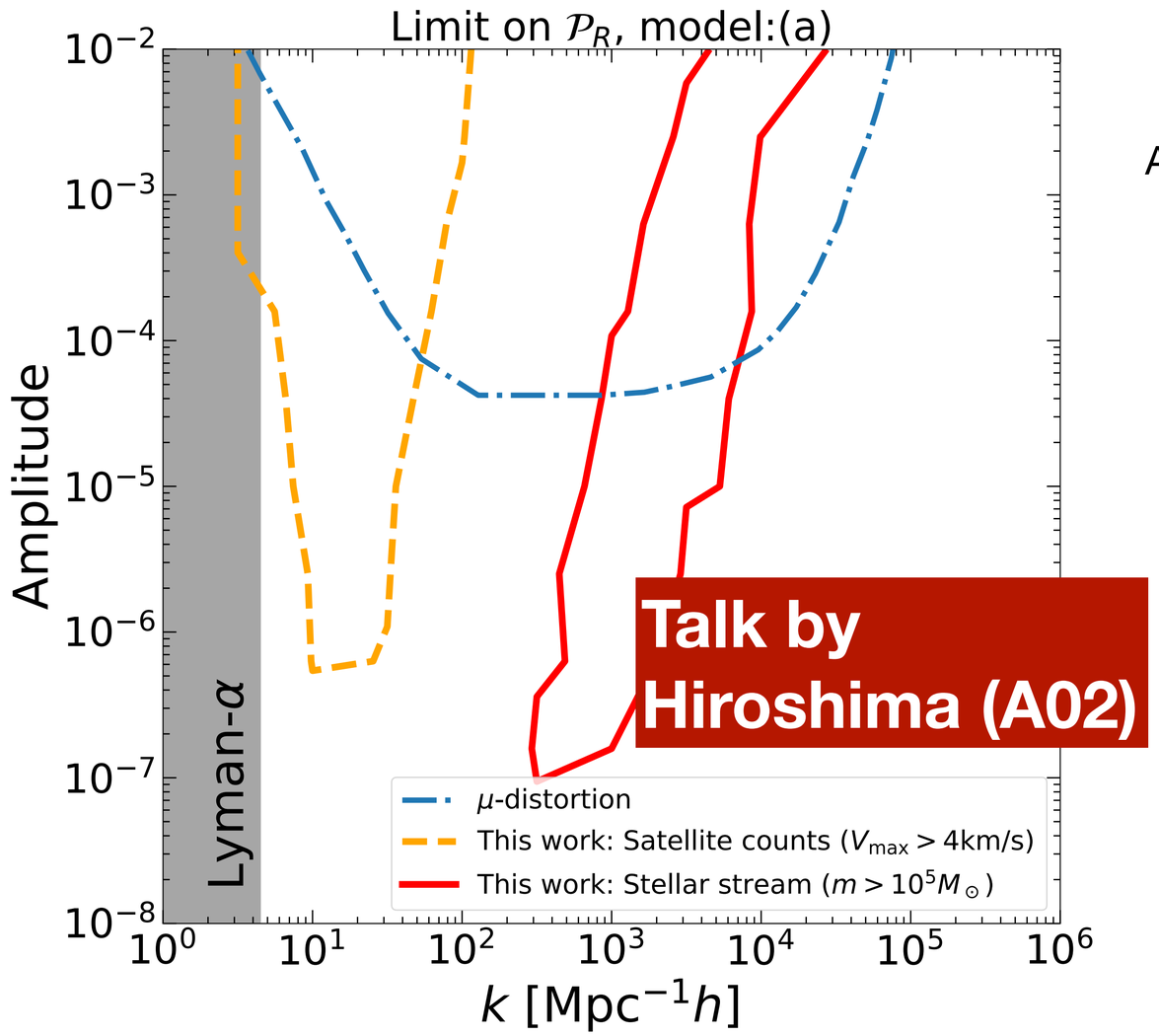
Ando, Hiroshima, Ishiwata, arXiv:2207.05747

- Power spectrum at small scales is hardly constrained
- “Peaked” power spectrum will make a characteristic shape of the subhalo mass function
- Models can be constrained with small-scale measurements of satellite galaxies, stellar streams, etc.

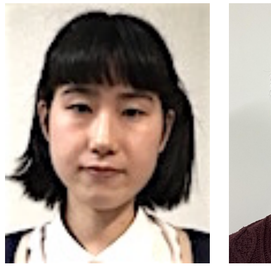
Constraining primordial perturbation







Talk by Hiroshima (A02)



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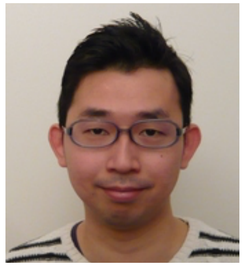
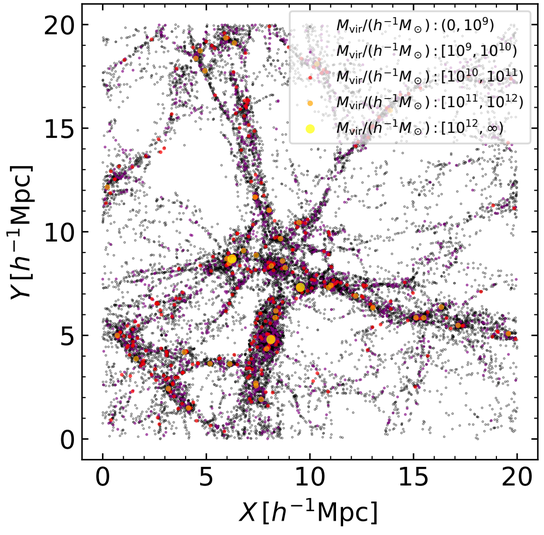
Primordial perturbation: numerical simulations

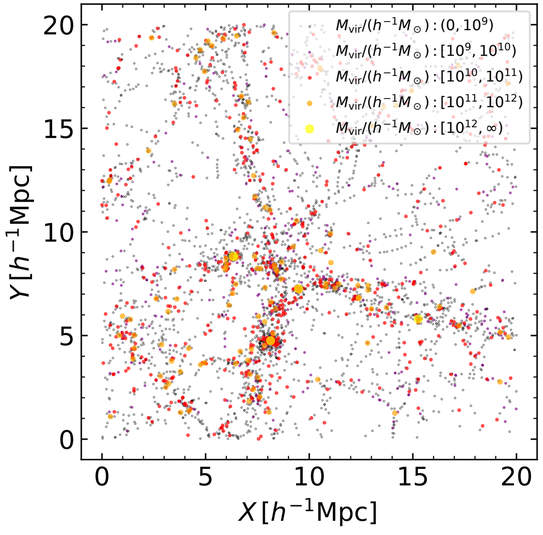
*Nishimichi, Ando (**C02**) Hiroshima (**A02**) & Ishiwata*



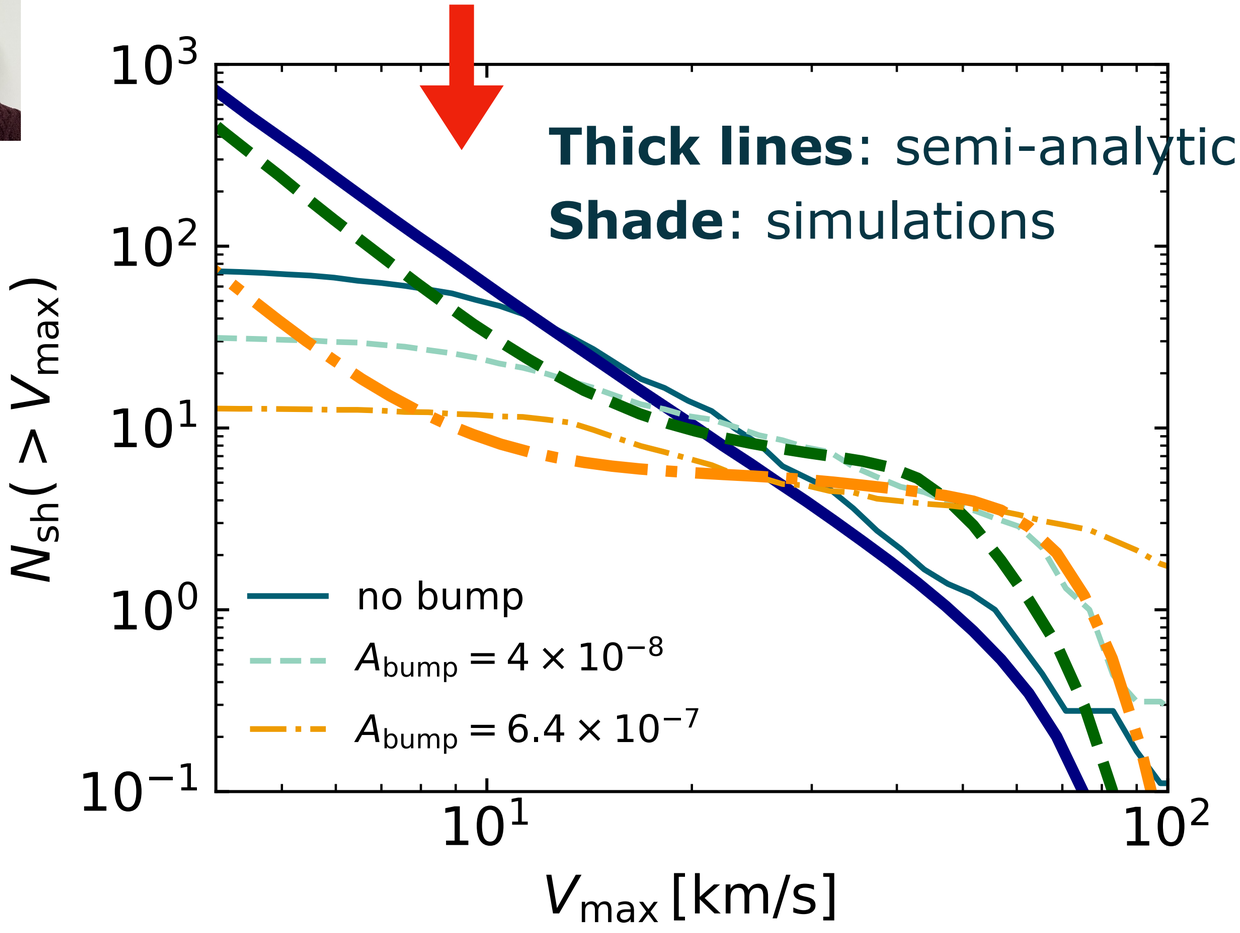
No bump



$A_{\rm bump} = 6.4 \times 10^{-7}$ @ $10\,h{\rm Mpc}^{-1}$



Resolution limit



Numerical simulations clearly show differences in the **abundance of substructures**, confirming the prediction of the semi-analytic model

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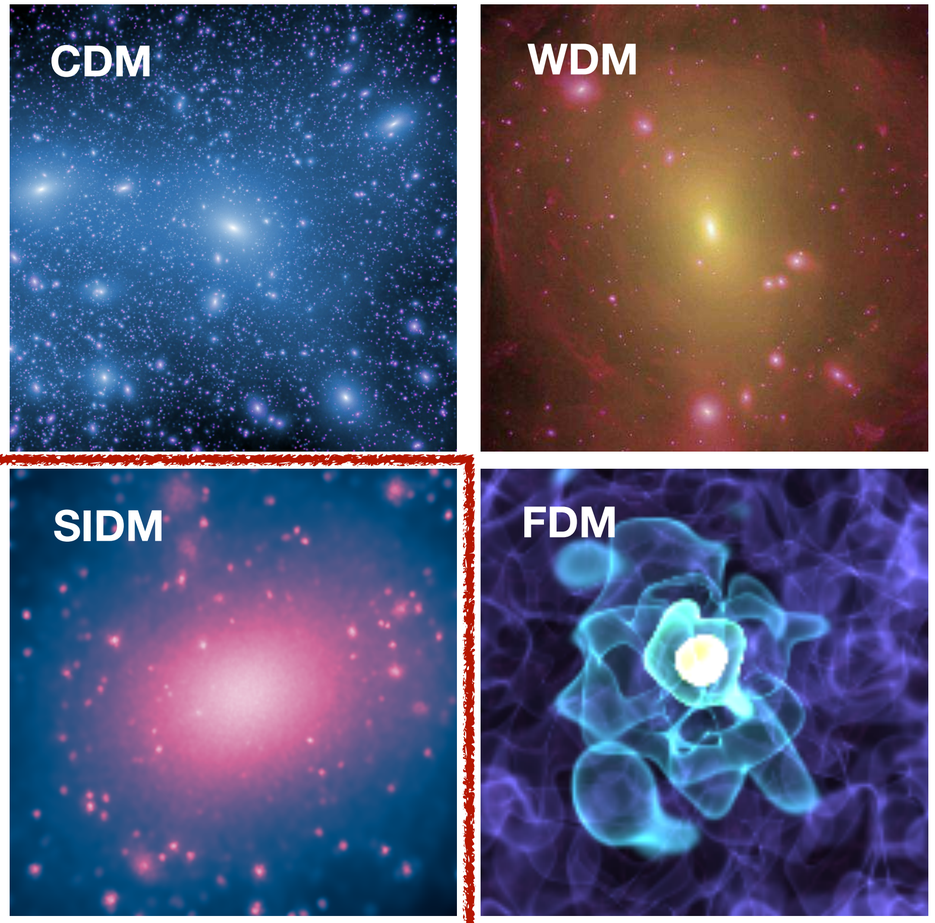

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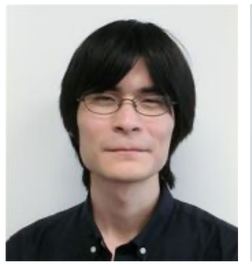
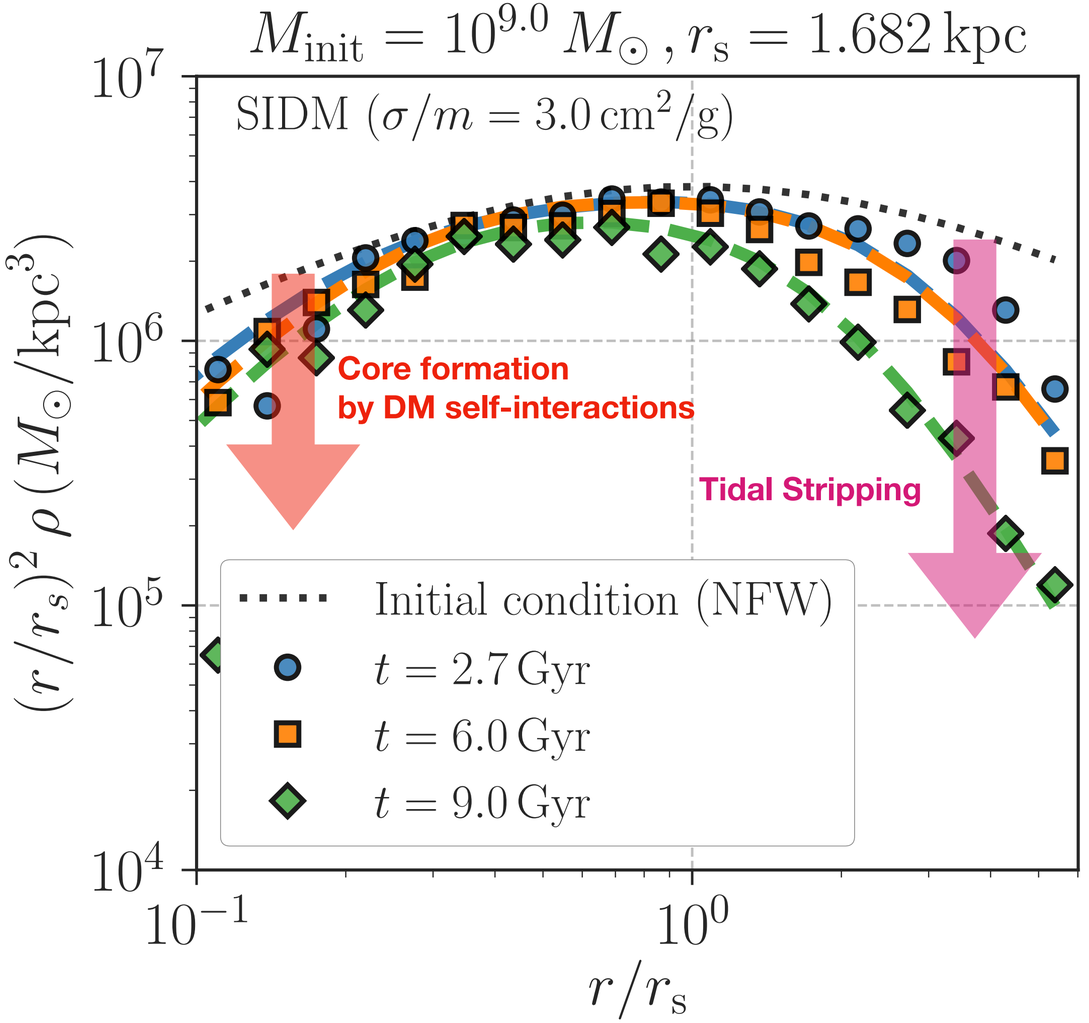
A semi-analytic model of DM subhaloes with self-interactions

Shirasaki, Okamoto, Ando, arXiv:2205.09920






- Develop the model by putting it all together
  - **Gravothermal fluid model** to predict a core formation in a self-interacting halo
  - CDM-like **tidal stripping** to remove the density at a halo boundary
  - **Mass loss rate** motivated by CDM sims
- Compare our model with the ideal N-body sims
- Comparison with cosmological N-body results ongoing (Shirasaki, Horigome, Ishiyama et al.)



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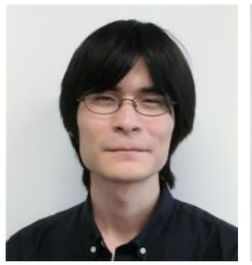


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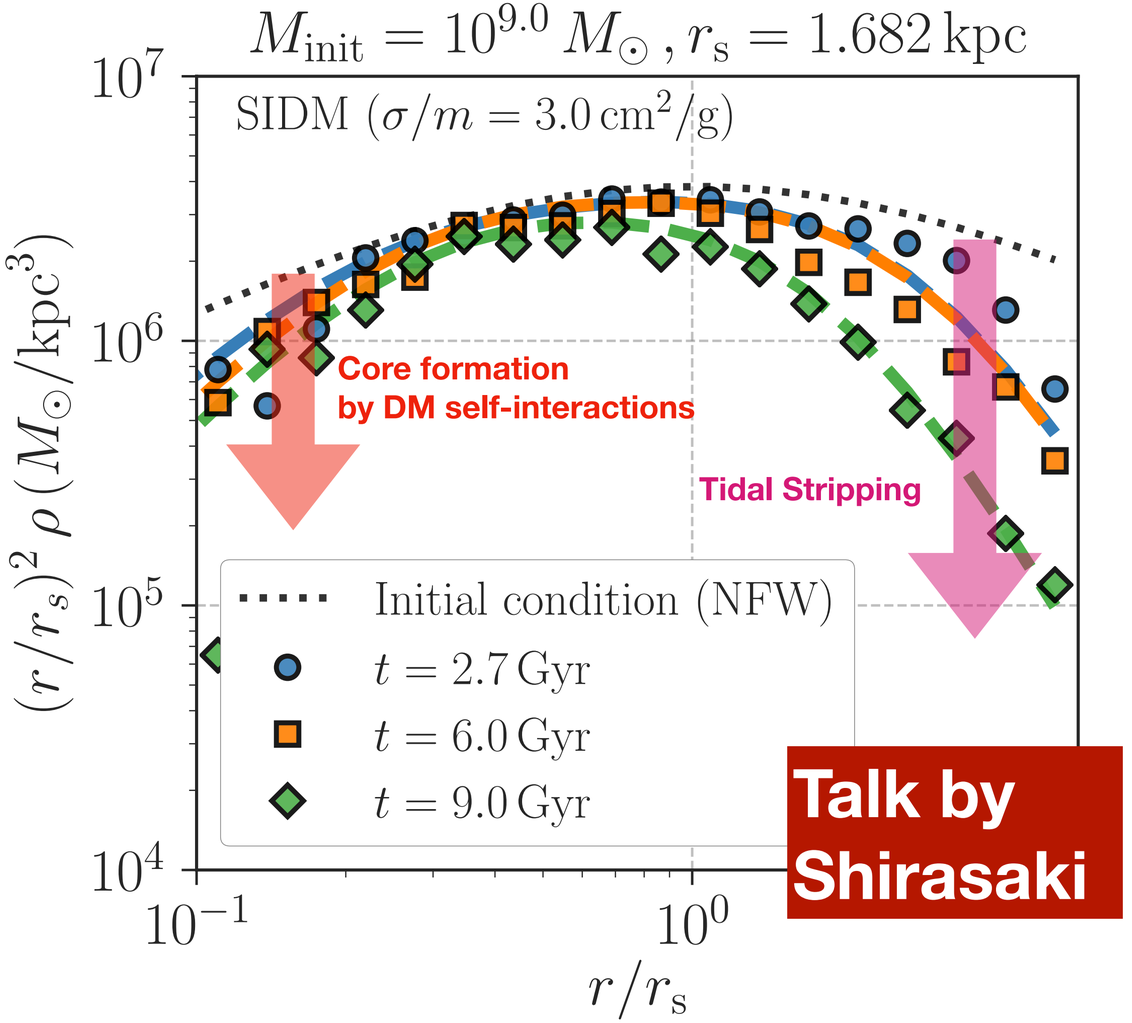

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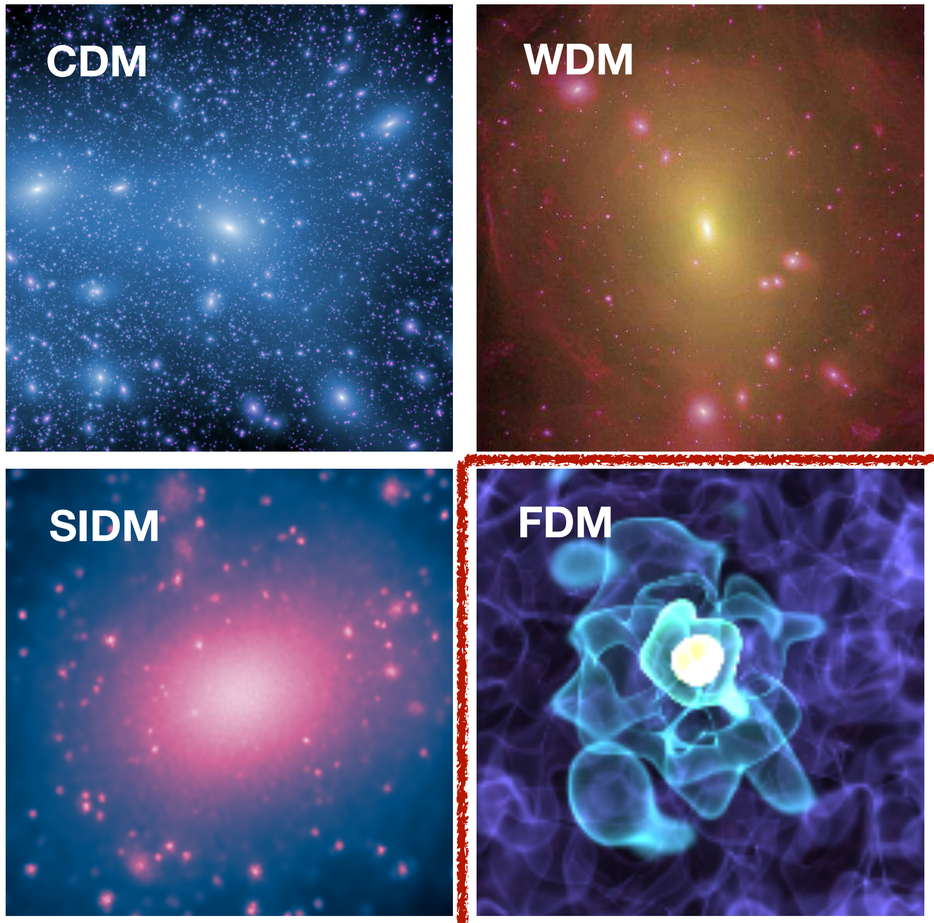

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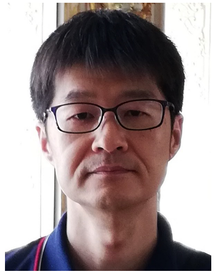
Core-halo structure of fuzzy dark matter



Analytical understanding of

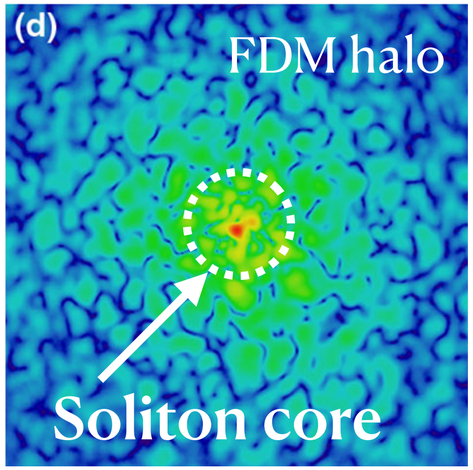
Taruya & Saga, arXiv:2208.006562

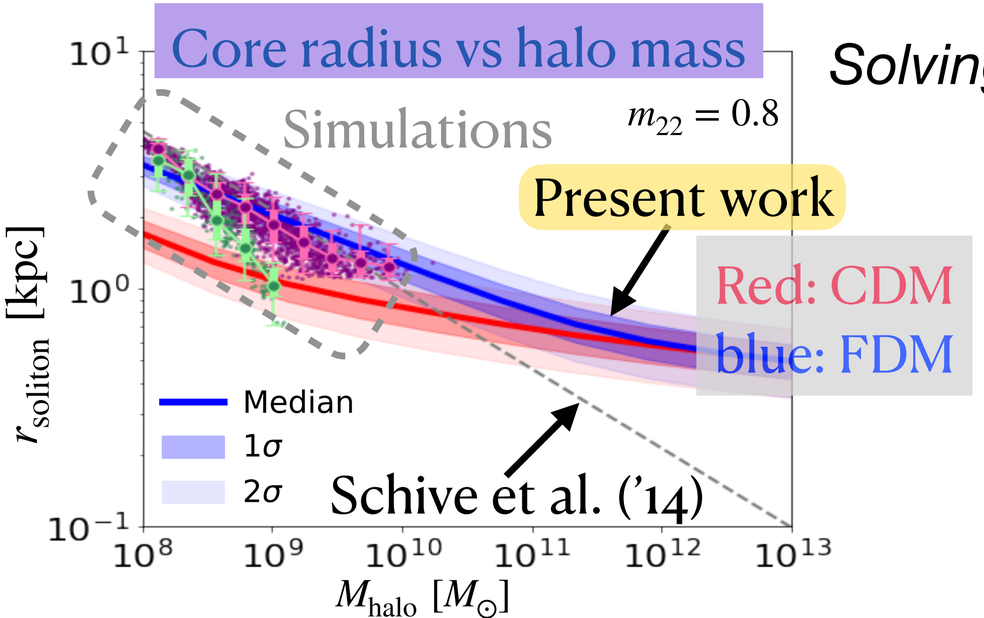
High-density flat core of fuzzy dark matter (FDM) at the center of halos = *soliton*

Early numerical works suggest $r_{\rm soliton} \propto M_{\rm halo}^{-1/3}$ & $M_{\rm soliton} \propto M_{\rm halo}^{1/3}$

$\longrightarrow$ constraining the FDM mass (Schive et al. '14)

Caution !! results are still under debate (e.g., Chan et al. '22)

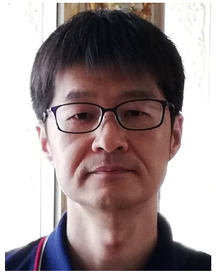




Solving the Schrödinger-Poisson eq. analytically,

Soliton core-halo relations of FDM change with the halo concentration parameter $c_{\rm vir}(M_{\rm halo})$, leading generically to non power-law behaviors having a large scatter

Core-halo structure of fuzzy dark matter



Analytical understanding of

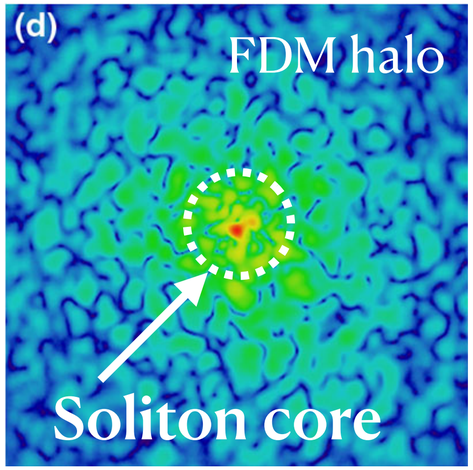
Taruya & Saga, arXiv:2208.006562

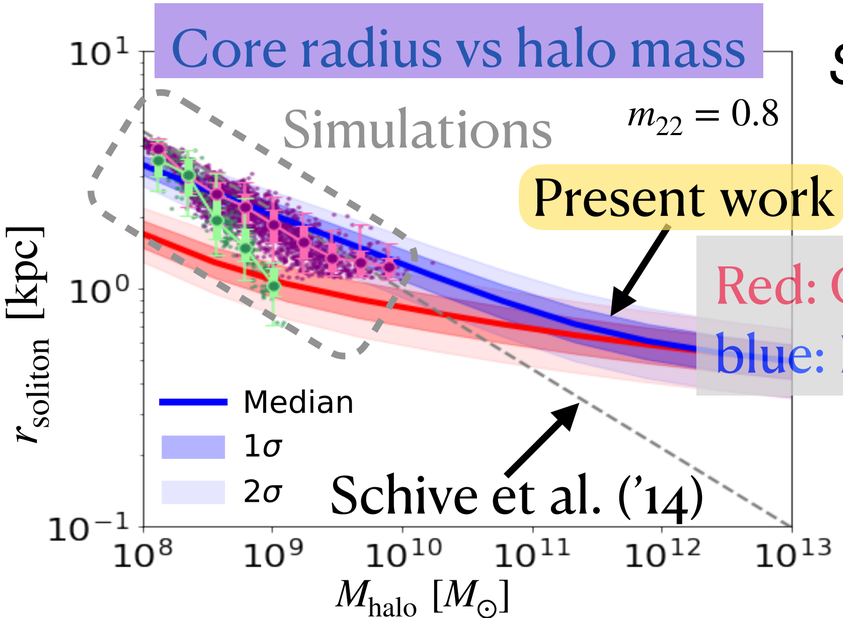
High-density flat core of fuzzy dark matter (FDM) at the center of halos = ***soliton***

Early numerical works suggest $r_{\rm soliton} \propto M_{\rm halo}^{-1/3}$ & $M_{\rm soliton} \propto M_{\rm halo}^{1/3}$

$\longrightarrow$ constraining the FDM mass (Schive et al. '14)

Caution !! results are still under debate (e.g., Chan et al. '22)





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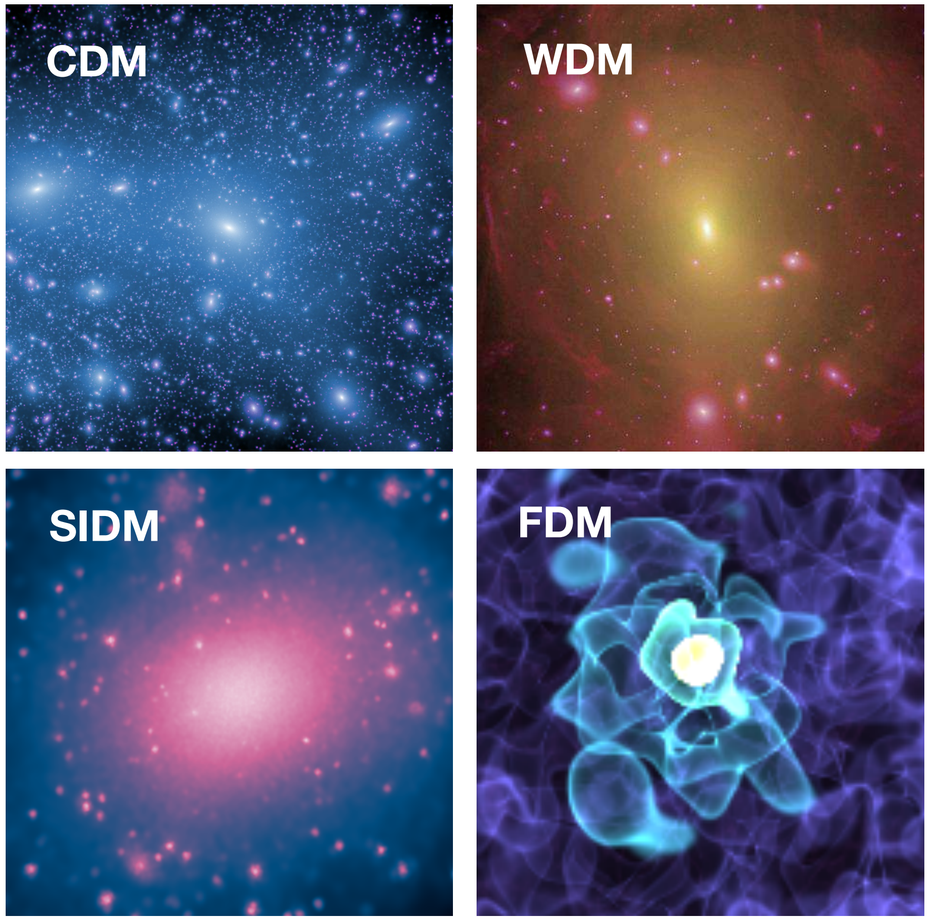
Talk by Taruya

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)**
- **Primordial power (Hiroshima, Nishimichi)**



- Numerical simulations of WDM halos and subhalos (Okamoto, Inoue et al.)
- Developing semi-analytical models and constraints from satellite number counts (Ando et al.)

- **Simulation of SIDM subhalos falling onto the SIDM halo (Shirasaki, Okamoto et al.)**
- **SIDM modeling against cosmological simulations (Shirasaki, Horigome et al.)**

- **Tight constraints using stellar motion in ultrafaint dwarf galaxies (Dalal)**
- **Analytical models of core-halo structure (Taruya)**