Title: Examining challenges to LCDM model near and far: from nearby dwarf galaxies to UV bright galaxies at z>5

Speakers: Andrey Kravtsov

Series: Cosmology & Gravitation

Date: September 19, 2023 - 11:00 AM

URL: https://pirsa.org/23090109

Abstract: I will present a galaxy formation model within the Lambda Cold Dark Matter (LCDM) framework that is calibrated on the results of galaxy formation simulations and some of the empirical properties of nearby dwarf galaxies. I will then use the model to interpret a number of ostensible challenges to the LCDM framework, such as the "too-big-too-fail problem", "central density problem" and the "planes of satellites" problem and will argue that none of these pose a serious challenge to LCDM, as the corresponding observations can be largely understood within the current galaxy formation modeling. I will also show that the same galaxy formation model can explain the abundance of UV-bright galaxies at z>5 measured by the Hubble Space Telescope and James Webb Space Telescope recently, if the expected increase of burstiness of star formation in galaxies towards early epochs is taken into account.

Zoom link https://pitp.zoom.us/j/91798519705?pwd=Nk9rM0tFSXcrWDhLdXFhVmJWbGgvUT09

Examining challenges to the Lambda Cold Dark Matter (LCDM) model near and far:

from nearby faint dwarf galaxies to bright galaxies at z>5

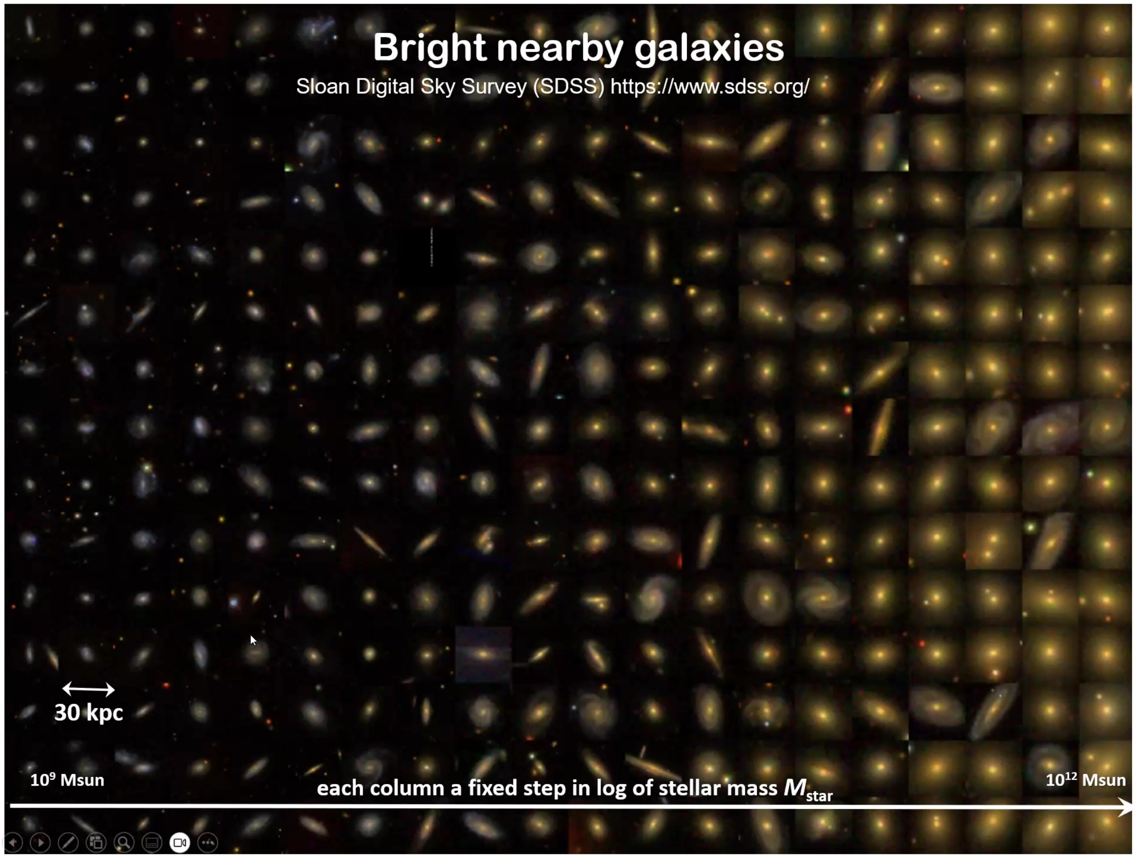
Leo IV dwarf galaxy
Legacy Survey (DES camera)
https://www.legacy.org/

Andrey Kravtsov

The University of Chicago

kravtsov@uchicago.edu

Credits: NASA, ESA, CSA, M. Zamani, Brant Robertson, S. Tacchella, E. Curtis-Lake, S. Carniani, JADES Collaboration.


Bright nearby galaxies
Sloan Digital Sky Survey (SDSS) https://www.sdss.org/
30 kpc
10^9 Msun
each column a fixed step in log of stellar mass M_{star}
10^{12} Msun

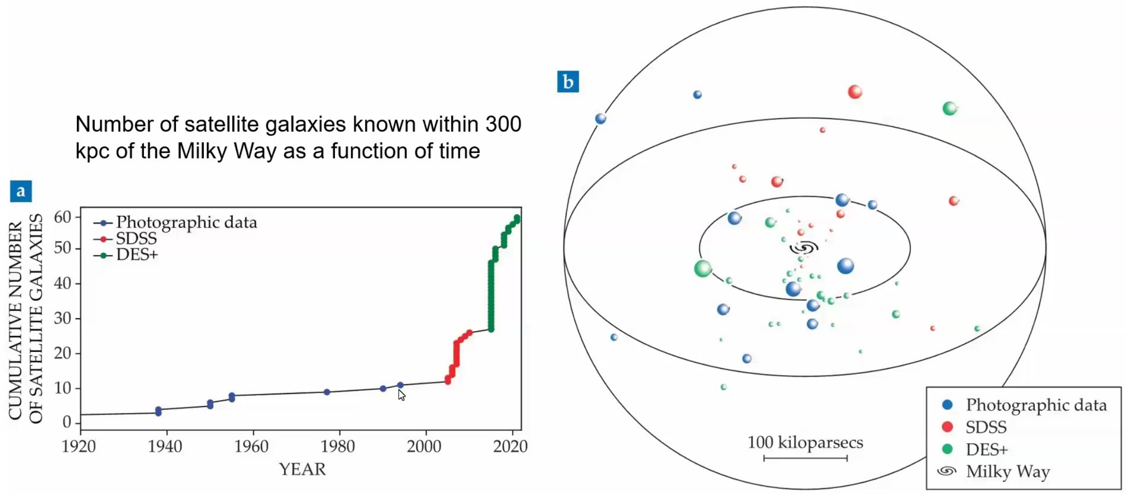

$M_\star \sim 10^7 M_\odot$ dwarf galaxy
D = 10 Mpc
Legacy Survey (DES camera)
https://www.legacy.org/


$M_\star \sim 10^4 M_\odot$ Leo IV dwarf galaxy
D = 145 kpc
Legacy Survey (DES camera)
https://www.legacy.org/

The number of known dwarf satellite galaxies around the Milky Way has rapidly increased over the past two decades

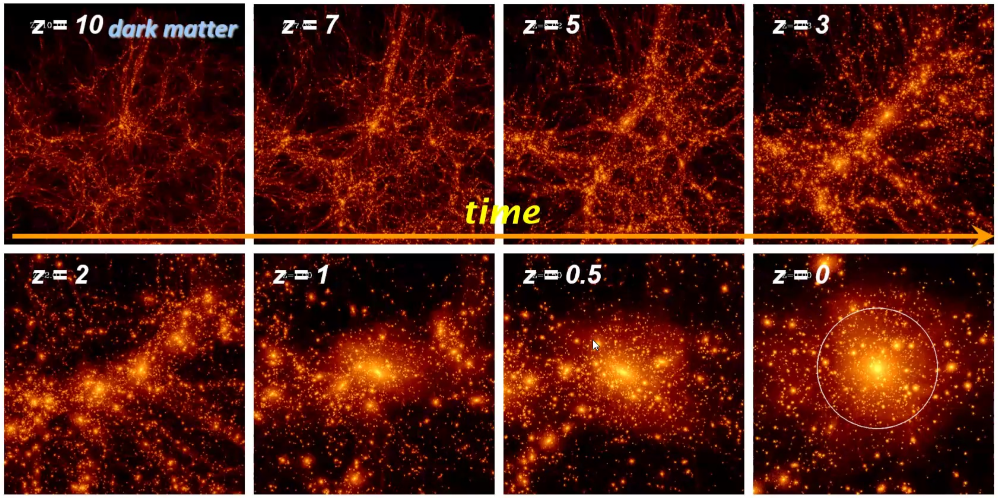
and now constrains properties of dark matter particles

Number of satellite galaxies known within 300 kpc of the Milky Way as a function of time



Simon, J. & Geha, M. 2021, Physics Today 74, 11, 30
https://physicstoday.scitation.org/doi/10.1063/PT.3.4879

Evolution of a Milky Way-sized halo in Lambda Cold Dark Matter (LCDM)



Kravtsov, A. 2010, Advances in Astronomy (arXiv/0906.3295)

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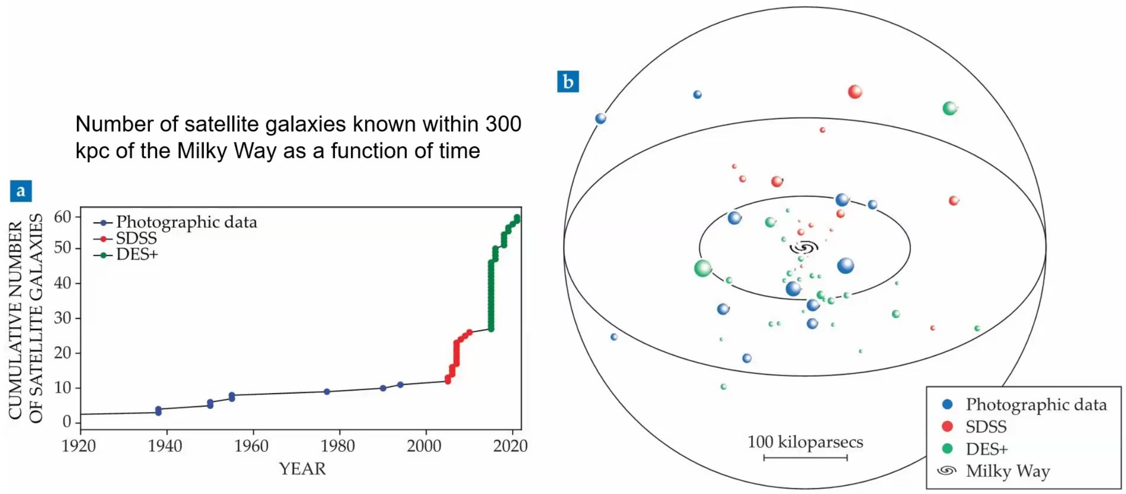

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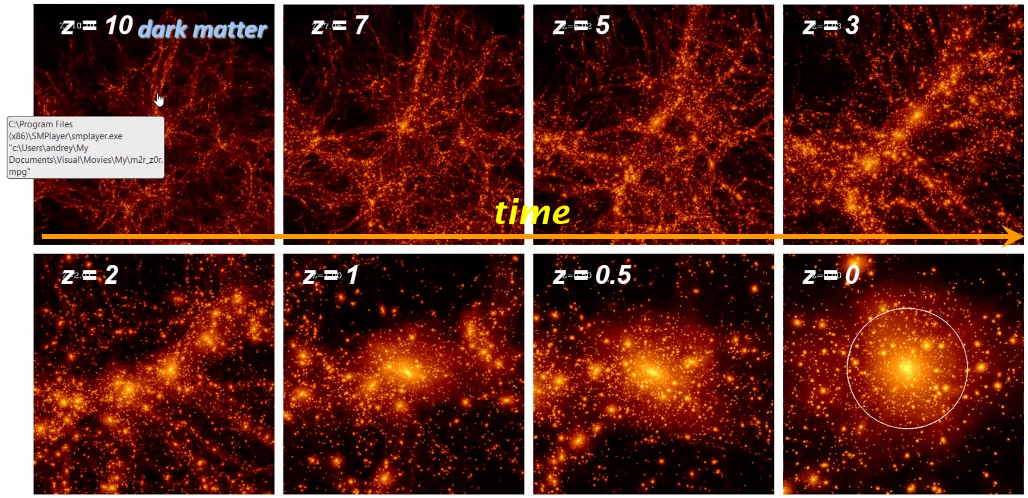
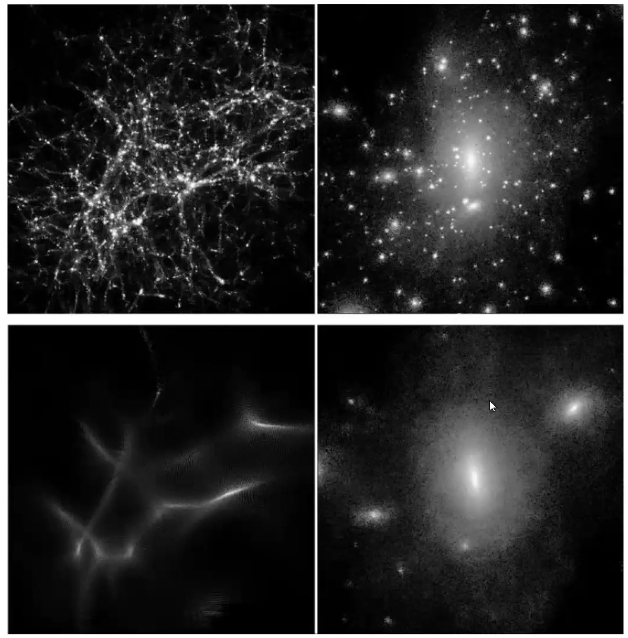


Kravtsov, A. 2010, Advances in Astronomy (arXiv/0906.3295)

In the Warm Dark Matter (WDM) model particle velocities erase density fluctuations below a certain scale which reduces amount of small-scale structure in halos



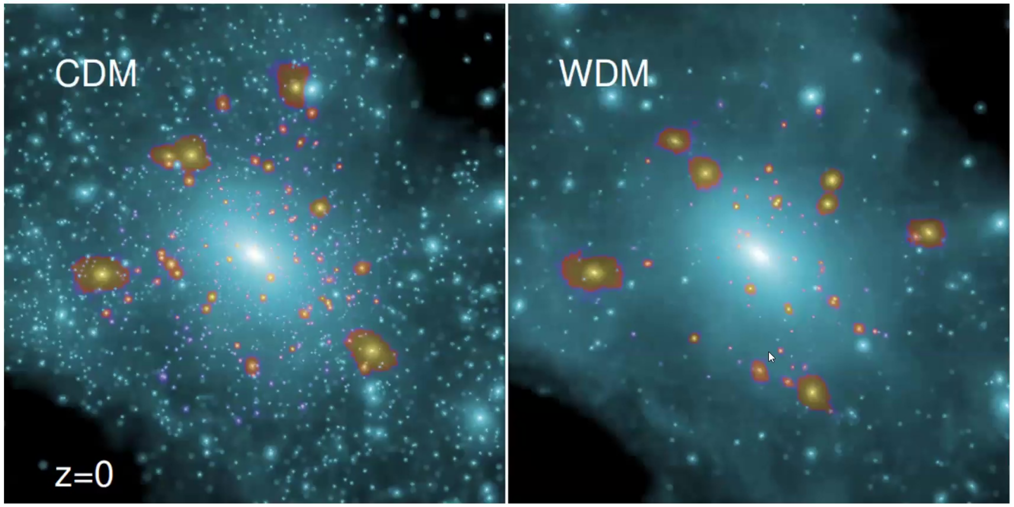
Top and bottom rows: the same patch of space (left column) and the same halo (right column) simulated in the CDM and WDM scenarios

WDM particle has a light mass which leads to erasure of small-scale structure

Credit: Moore, B. et al. 1999, MNRAS 310, 1147

The WDM particle mass can be increased until the abundance of halos that can host observable dwarf galaxies matches the observed number of dwarf galaxies

blue = dark matter distribution
orange/red = subhalos that are expected to host observable dwarf galaxies



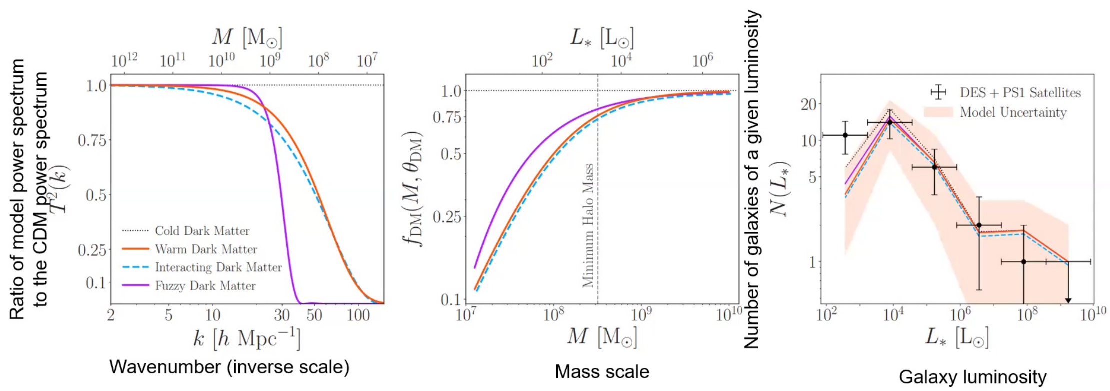
Credit: Lovell, M. et al. 2021, MNRAS 507, 4826

Constraints on dark matter models using luminosity function of dwarf satellite galaxies of the Milky Way

To match the observed number of dwarf galaxies around Milky Way at different luminosities parameters of WDM, self-interacting dark matter, and fuzzy dark matter model are constrained to be

Nadler et al. 2021, Phys Rev Letters 126(9), 091101

Dark matter paradigm	Parameter	Constraint	Derived property	Constraint
Warm dark matter	Thermal relic mass	$m_{\rm WDM} > 6.5\,{\rm keV}$	Free-streaming length	$\lambda_{\rm fs} \lesssim 10\,h^{-1}\,{\rm kpc}$
Interacting dark matter	Velocity-independent DM-Proton cross section	$\sigma_0 < 8.8 \times 10^{-29}\,{\rm cm}^2$	DM-Proton coupling	$c_p \lesssim (0.3\,{\rm GeV})^{-2}$
Fuzzy dark matter	Particle mass	$m_\phi > 2.9 \times 10^{-21}\,{\rm eV}$	de Broglie wavelength	$\lambda_{\rm dB} \lesssim 0.5\,{\rm kpc}$



Structure and halo formation Fuzzy Dark Matter (FDM)

TERMINOLOGY

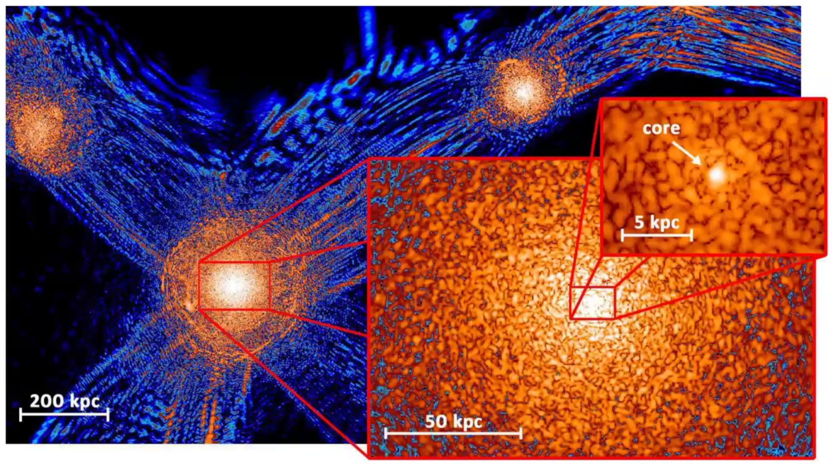
We use the term axion to loosely refer to both the QCD axion and an axion-like particle, ALP (Section 2). The term fuzzy dark matter, FDM, is reserved for the ultralight part of the mass spectrum, $m \sim 10^{-22}$–10^{-20} eV. Wave dark

Hu, Barkana & Gruzinov 2000, PRL

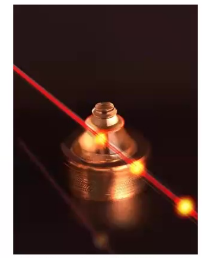
Recent reviews:
Hui, L. 2021, ARAA
Ferreira, E.G.M. 2021, A&A Reviews
Niemeyer, J.C. 2020 Prog. Part. Nucl Phys

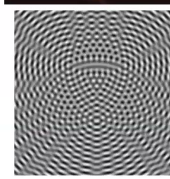
In such model de Broglie wavelength of DM particles is macroscopic (100s of pc to ~kpc) and wave properties of particles are manifested on the scale of dwarf galaxies

Simulations show widespread interference pattern in forming halos with a typical density fluctuation amplitude of $\delta\rho \sim \rho$



Schive, Chiueh & Broadhurst. 2014, Nature Physics





The Fuzzy Dark Matter regime is excluded by observed properties of dwarf galaxies

If stars in dwarf galaxies were embedded in fuzzy dark matter they would get heated by the perturbations arising from wave interference. This is rigorously shown using numerical simulations of stars in FDM halos

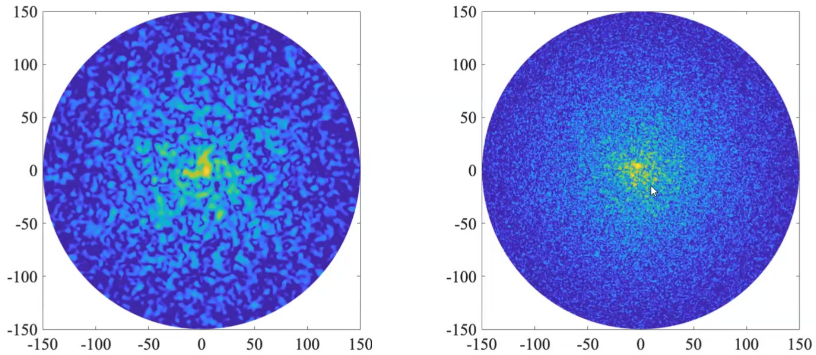
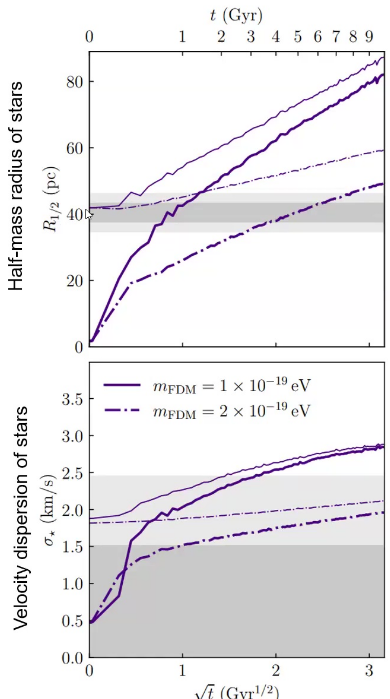


FIG. 1. Example FDM density snapshots for NFW halos. The left panel shows a simulation with $m_{\rm FDM} = 2 \times 10^{-19}$ eV, while the right panel has $m_{\rm FDM} = 8 \times 10^{-19}$ eV. Length units are parsecs, and the color scale is logarithmic in density ρ. For comparison, the galaxies that we analyze have half-light radii $R_{1/2} \simeq 25 - 40$ pc.

Dalal & Kravtsov 2022,
Phys Rev D 106(6), 063517 (arXiv/2203.05750)

Dynamical heating of stars in the faintest dwarfs by FDM fluctuations excludes FDM as the dominant dark matter



Observed sizes and velocity dispersion of smallest dwarf galaxies around Milky Way exclude FDM with particle masses < 3 x 10^{-19} eV

Dalal & Kravtsov 2022,
Phys Rev D 106(6), 063517 (arXiv/2203.05750)

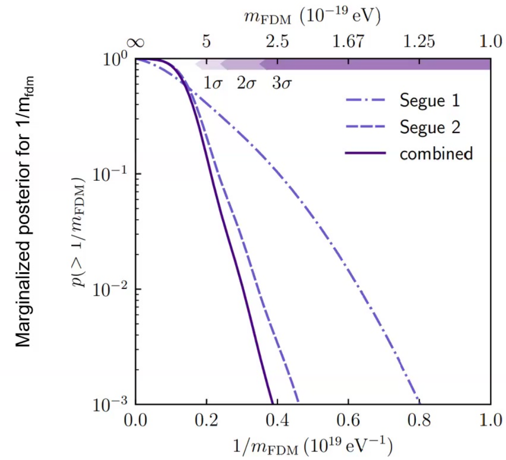


FIG. 4. Marginalized posterior likelihood of $m_{\rm FDM}$. Each curve shows the cumulative posterior pdf of $m_{\rm FDM}^{-1}$, while the arrowheads at top indicate the derived 1, 2, and 3−σ exclusion regions for joint constraints combining Segue 1 and Segue 2.

over the last decade observations with HST and now JWST telescopes
have found many galaxies with dwarf stellar masses at z>5
(<1 Gyr after Big Bang)

https://esahubble.org/images/heic0611b/
Hubble Space Telescope Ultra Deep Field
Credit: NASA, ESA, and S. Beckwith (STScI) and the HUDF Team

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Hubble Space Telescope Ultra Deep Field

Credit: NASA, ESA, and S. Beckwith (STScI) and the HUDF Team

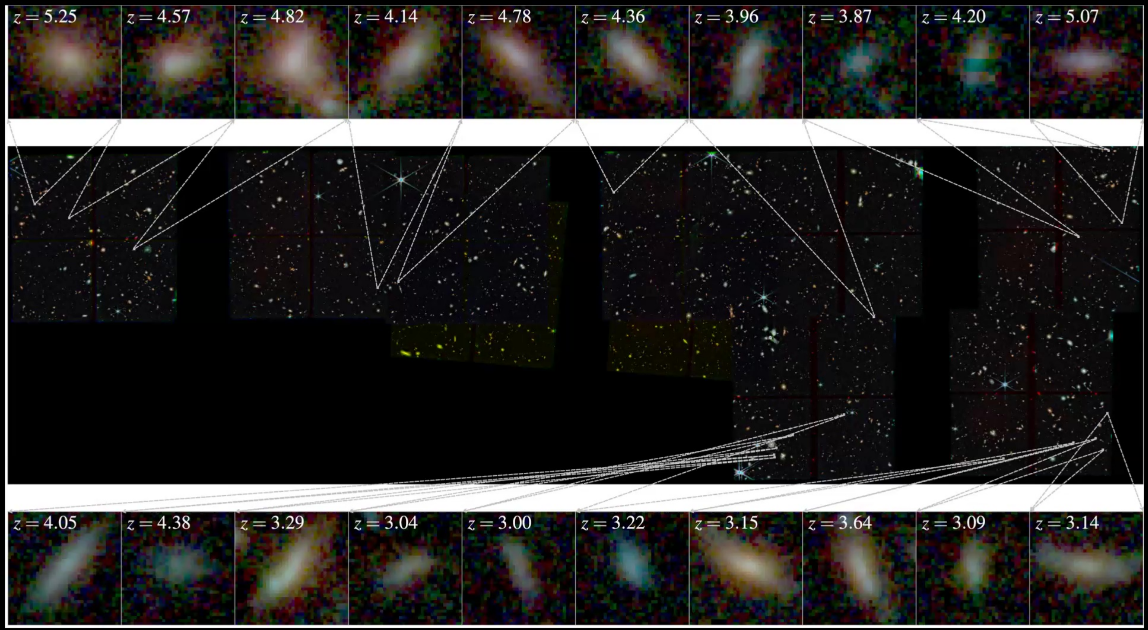
James Webb Space Telescope (JWST) images of galaxies at z~3-9

many galaxies have irregular morphology

Credit: NASA/STScI/CEERS/TACC/S. Finkelstein/M. Bagley/Z. Levay/J. Carltartepe

James Webb Space Telescope (JWST) images of galaxies at z~3-9

A sizeable fraction of galaxies have regular elliptical and disky morphologies



Credit: NASA/STScI/JADES survey: B. Robertson et al. 2023

Two commonalities between local dwarf galaxies and most distant galaxies observed with HST and JWST

- The first is that they both involve “dwarf” galaxies with stellar masses <~ billion solar masses

- And the second is…

C:\Program Files (x86)\SMPlayer\smplayer.exe "c:\Users\andrey\My Documents\Visual\Movies\My\m2r_z0r.mpg"

RESEARCH ARTICLE | ASTRONOMY

Cold dark matter: Controversies on small scales

David H. Weinberg, James S. Bullock, Fabio Governato, Rachel Kuzio de Naray, and Annika H. G. Peter -1 Authors Info & Affiliations

Edited by Neta A. Bahcall, Princeton University, Princeton, NJ, and approved December 2, 2014 (received for review June 4, 2013)

February 2, 2015 | 112 (40) 12249-12255 | https://doi.org/10.1073/pnas.1308716112

SCIENTIFIC AMERICAN.

SPACE & PHYSICS

Dancing Dwarf Galaxies Deepen Dark Matter Mystery

A surprising alignment between small satellites of the galaxy Centaurus A challenges the standard model of cosmology

By Shannon Stirone on February 1, 2018

Science

BBC

Dwarf galaxies suggest dark matter theory may be wrong

16 September 2011

https://darkmattercrisis.wordpress.com/

The unexpected new data coming back from the telescope are inspiring panic among astronomers

BY NEWS ON AUGUST 13, 2022 7 MINUTE READ

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Cosmic controversy: James Webb Telescope findings challenge best-established theories

The James Webb Space Telescope seems to be finding multiple galaxies that grew too massive too soon after the Big Bang, possibly leading to changes in prevailing cosmology theories.

NEWS CREATION SCIENCE UPDATE THE UNIVERSE WAS CREATED RECENTLY

James Webb Telescope Data: Challenges for the Big Bang?

SCIENCE & TECHNOLOGY

Apr 13, 2023

James Webb Space Telescope Images Challenge Theories of How Universe Evolved

- The James Webb Space Telescope spotted six galaxies that grew too quickly after the Big Bang.
- The galaxies grew quicker than the leading cosmology theory predict.
- Explaining the quick growth could involve new particles or reexamining the age of the universe.

New Galaxies Discovered That Shouldn't Exist! [Web...

7.2K views • 5 months ago

National Science Foundation News

How did the **James Webb Space Telescope** (

0:11 ... that are showing very large massive

Webb Telescope sees Galaxies Too Big To Exist....

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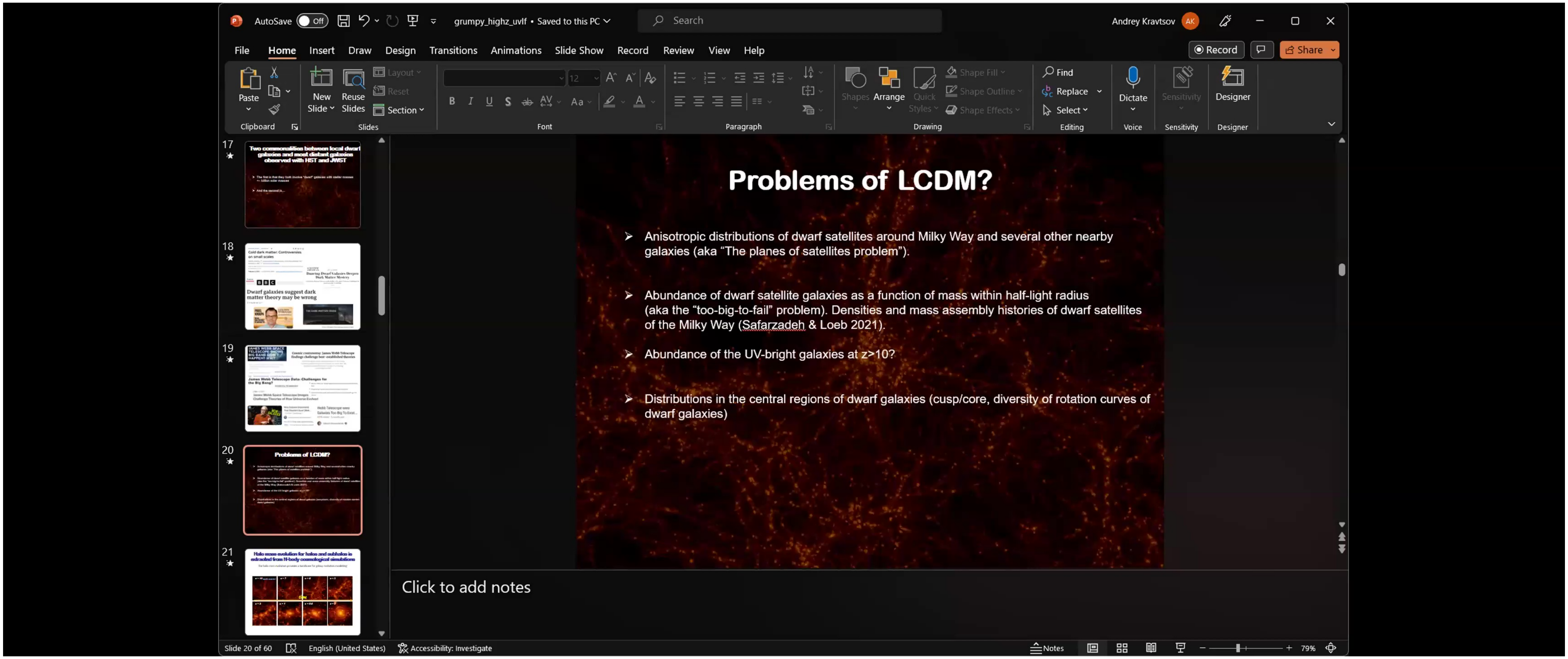
Sabine Hossenfelder

Problems of LCDM?

- Anisotropic distributions of dwarf satellites around Milky Way and several other nearby galaxies (aka “The planes of satellites problem”).
- Abundance of dwarf satellite galaxies as a function of mass within half-light radius (aka the “too-big-to-fail” problem). Densities and mass assembly histories of dwarf satellites of the Milky Way (Safarzadeh & Loeb 2021).
- Abundance of the UV-bright galaxies at $z>10$?
- Distributions in the central regions of dwarf galaxies (cusp/core, diversity of rotation curves dwarf galaxies)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Click to add notes
Slide 20 of 60

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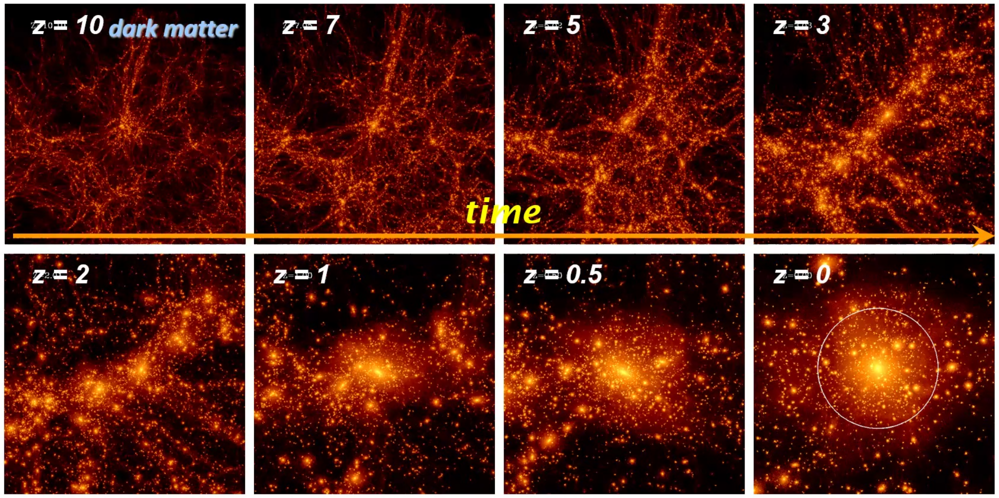
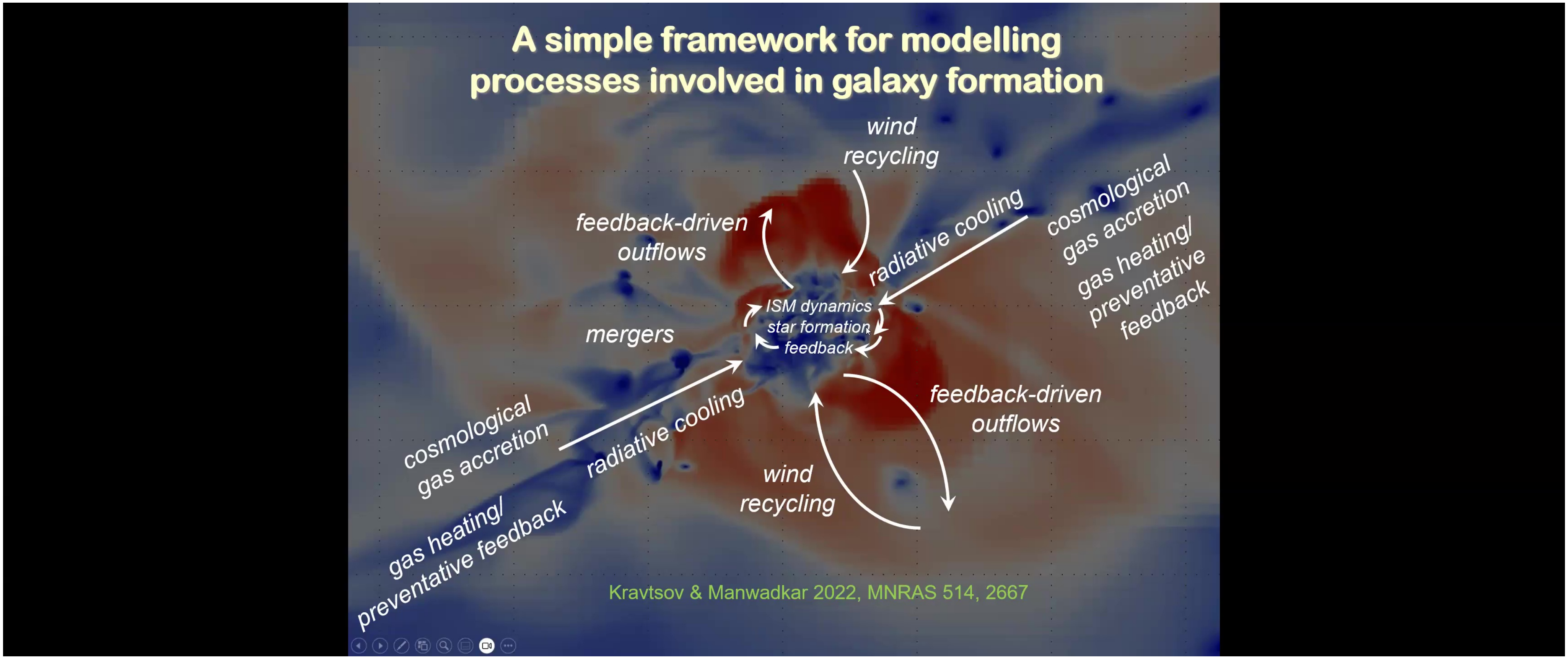
Halo mass evolution for halos and subhalos is extracted from N-body cosmological simulations

The halo mass evolution provides a backbone for galaxy evolution modelling





A simple framework for modelling processes involved in galaxy formation
wind recycling
feedback-driven outflows
radiative cooling
cosmological gas accretion
gas heating/ preventative feedback
ISM dynamics
star formation
feedback
mergers
feedback-driven outflows
cosmological gas accretion
radiative cooling
wind recycling
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Kravtsov & Manwadkar 2022, MNRAS 514, 2667

GRUMPY model summary

Kravtsov & Manwadkar 2022, MNRAS 514, 2667
github.com/kibokov/GRUMPY

Viraj Manwadkar
(UChicago->Stanford)

outflows $\dot{M}_{\rm out} = \eta \dot{M}_\star$

$\eta = \eta(M_\star) \propto M_\star^{-0.4}$

$\dot{M}_{\rm g,in} = \epsilon_{\rm in} \frac{\Omega_{\rm b}}{\Omega_{\rm m}} \dot{M}_{\rm halo}$

$\epsilon_{\rm in}$ is modulated by UV heating after reionization (Okamoto+09)

ISM gas mass evolution

$$\dot{M}_{\rm g} = \dot{M}_{\rm g,in} - \dot{M}_\star - \dot{M}_{\rm out}$$

cosmological gas accretion

Gas is distributed in an exponential disk

$$\Sigma_{\rm g}(R) = \frac{M_{\rm g}}{2\pi R_d^2} \exp\left(-R/R_d\right) \qquad R_d = \xi R_{200c}(t)$$

star formation $$\dot{M}_\star = \frac{M_{\rm H_2}}{\tau_{\rm dep,H_2}} \qquad \tau_{\rm dep,H_2} = 2\,{\rm Gyr}$$

molecular gas mass using Gnedin & Draine '14 model

$$M_{\rm H_2} = 2\pi \int_0^\infty f_{\rm H_2}(\Sigma_{\rm g}, Z_{\rm g}, f_{\rm UV})\, \Sigma_{\rm g}(R)\, R\, dR$$

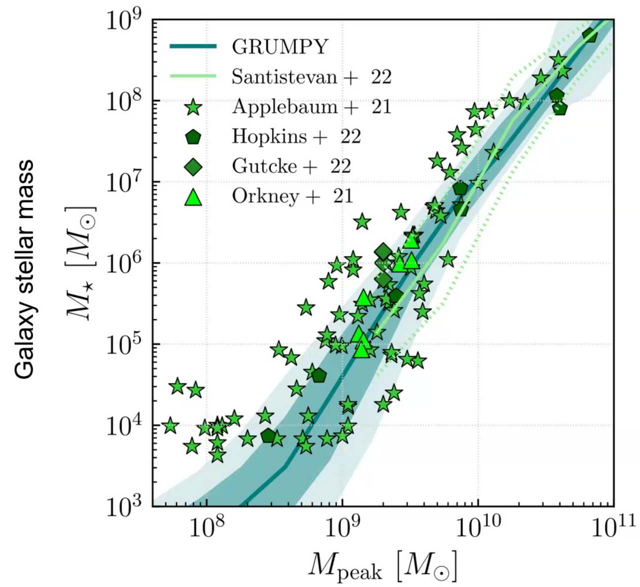
Heavy element mass evolution

$$Z_{\rm g} = M_{Z,\rm g}/M_{\rm g}$$

$$\dot{M}_{\rm Z,g} = Z_{\rm IGM}\dot{M}_{\rm g,in} + y_{\rm Z}\dot{M}_\star - \eta Z_{\rm g}\dot{M}_\star$$
$$\dot{M}_{\rm Z,\star} = Z_{\rm g}\dot{M}_\star$$

The stellar mass – halo mass relation

This simple model reproduces stellar-mass halo mass relation of galaxies formed in high-resolution simulations of dwarf galaxies (Manwadkar & Kravtsov 2022) and Milky Way-sized galaxies (Belokurov & Kravtsov 2022)

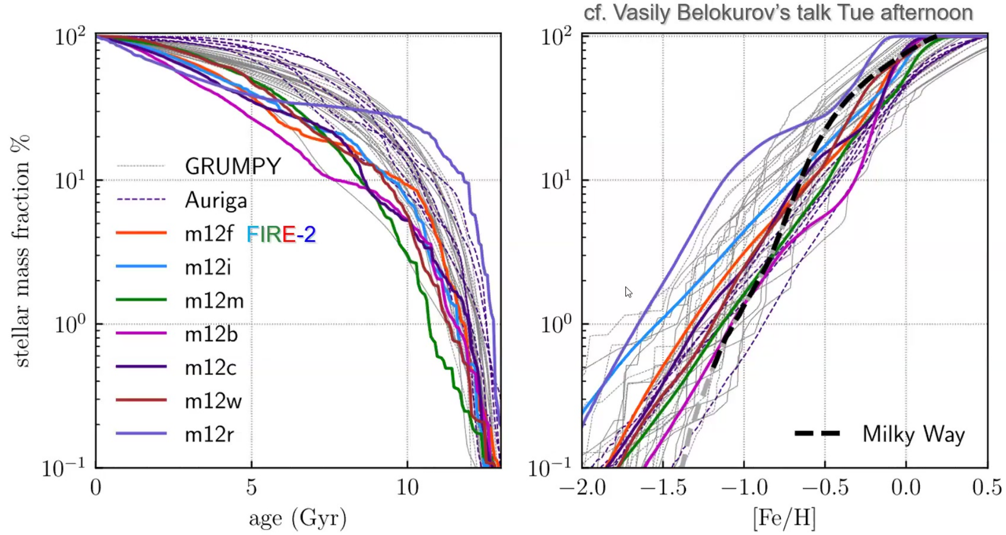


largest (peak) M_{200c} during halo evolution

GRUMPY model results for L<~L* galaxies are quite similar to results of recent galaxy formation simulations

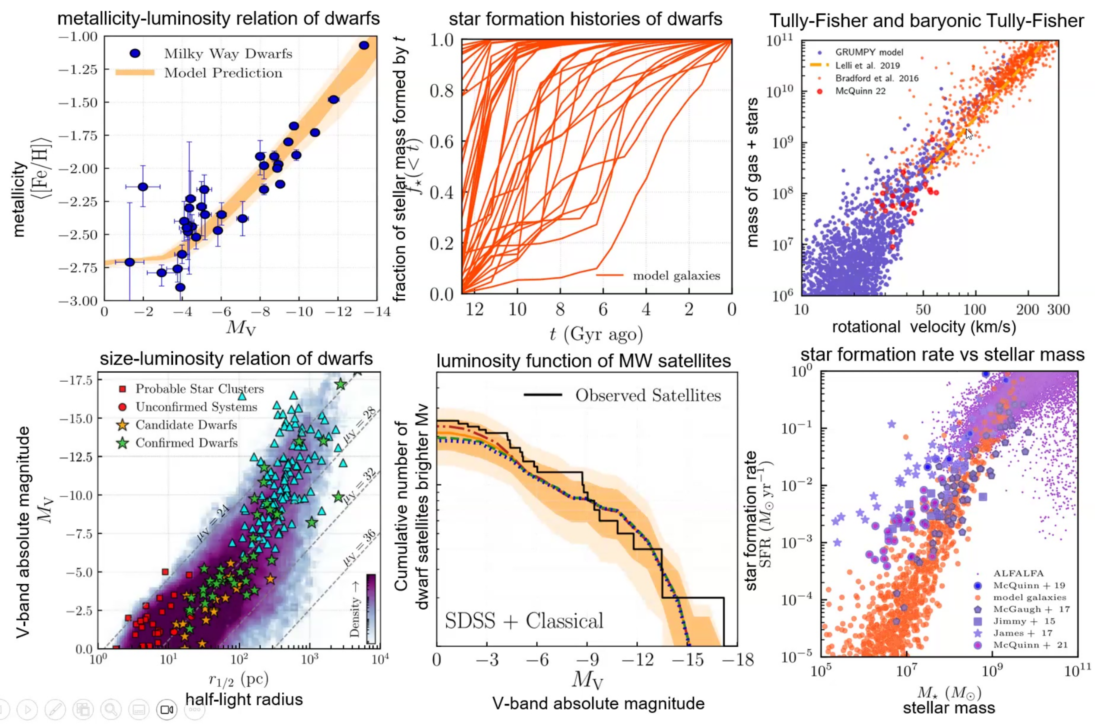
mass fraction of the in-situ stellar mass formed in the M_{200c}~10^{12} Msun halos
as a function of stellar age (left) and metallicity (right)
modelled in GRUMPY (gray) and in the Auriga (magenta dotted) and FIRE-2 (colored)
simulations of MW-sized objects; black dashed line (right) is measurement in the MW.

Belokurov & Kravtsov 2022, MNRAS 514, 689
cf. Vasily Belokurov's talk Tue afternoon



A wide range of observed dwarf galaxy properties and correlations are reproduced well by the GRUMPY model

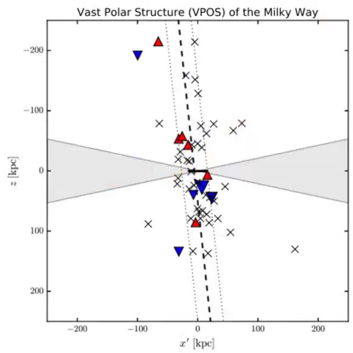
Kravtsov & Manwadkar 2022, MN 514, 2667; Manwadkar & Kravtsov 2022, MN 516, 3944; Kravtsov & Wu 2023, MN 525, 325



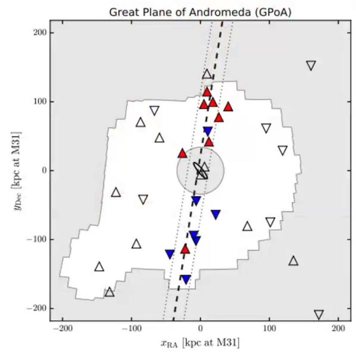
Spatial distribution of dwarf galaxies around Milky Way, Andromeda and Centaurus A galaxies

Pawlowski, M., 2018
arxiv.org/abs/1802.02579

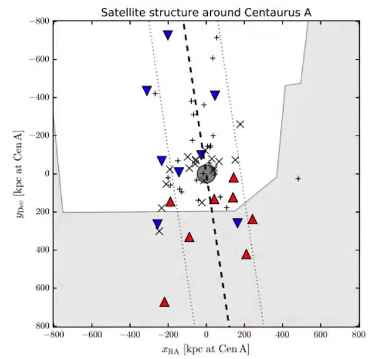
Milky Way

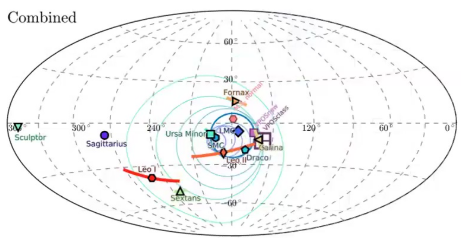


Andromeda



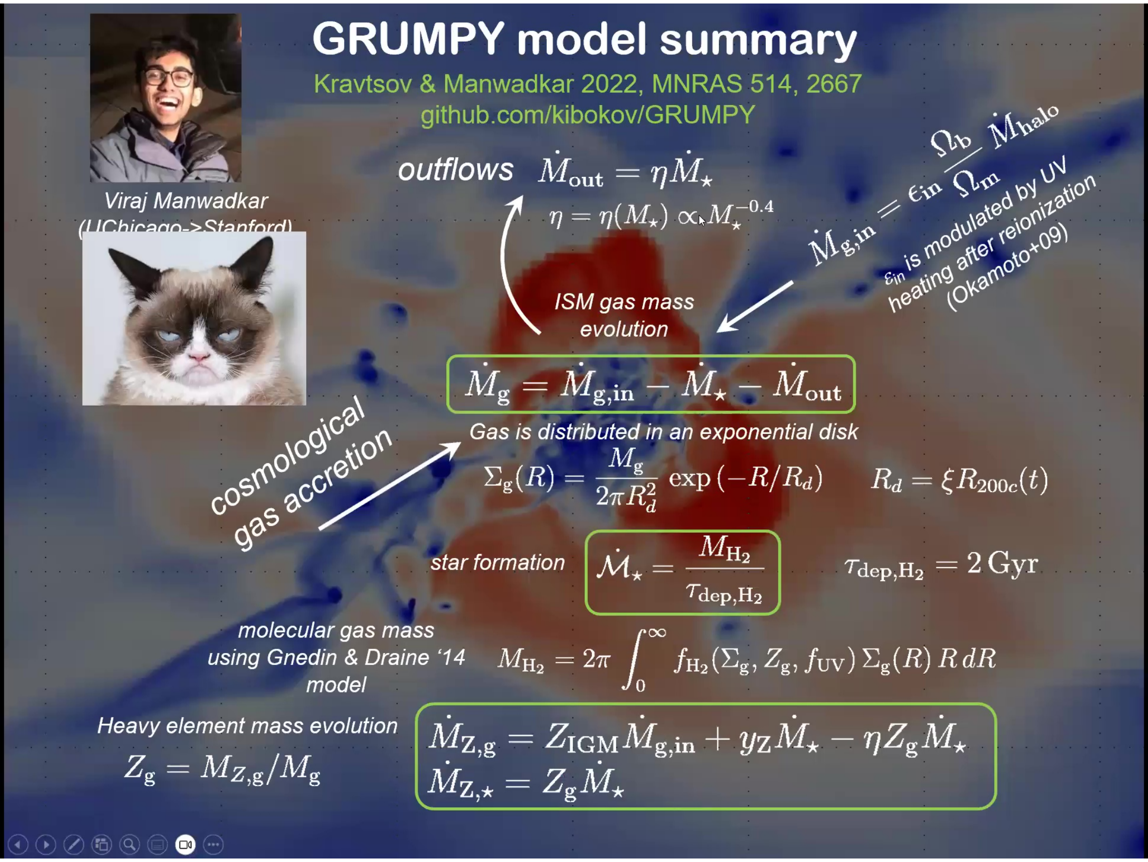
Centaurus A





In the Milky Way the orbital poles of satellite orbits are correlated

Pawlowski & Kroupa 2020
MN 491, 3042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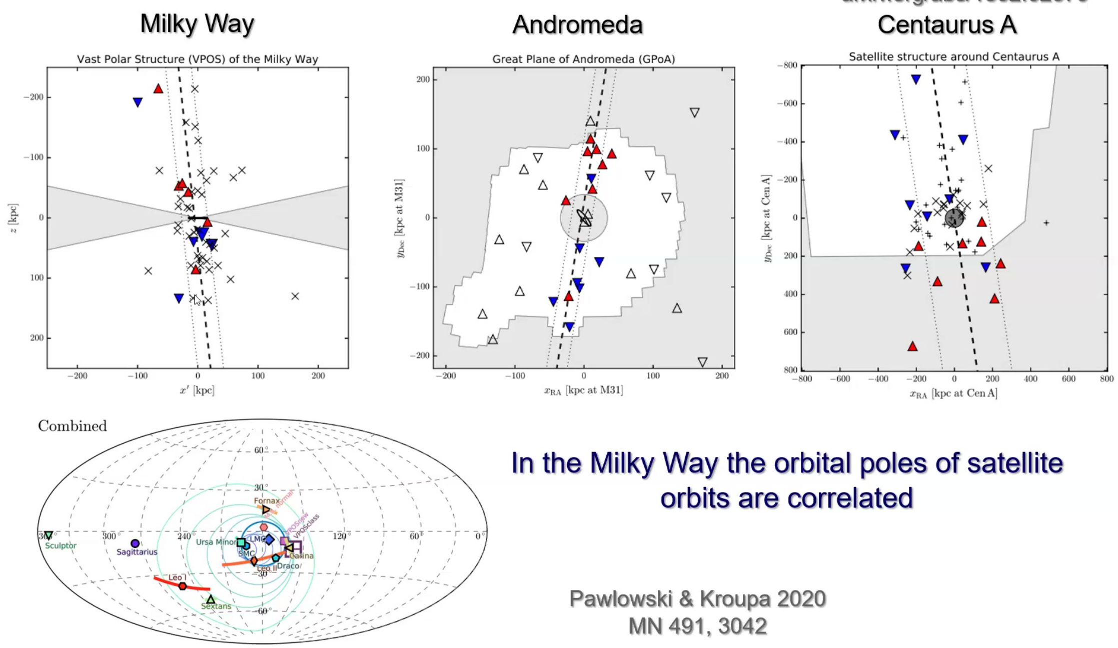
Spatial distribution of dwarf galaxies around Milky Way, Andromeda and Centaurus A galaxies

Pawlowski, M., 2018
arxiv.org/abs/1802.02579



In the Milky Way the orbital poles of satellite orbits are correlated

Pawlowski & Kroupa 2020
MN 491, 3042

The claim was that such flattened configurations are exceedingly rare in LCDM

Comment | Published: 13 December 2021

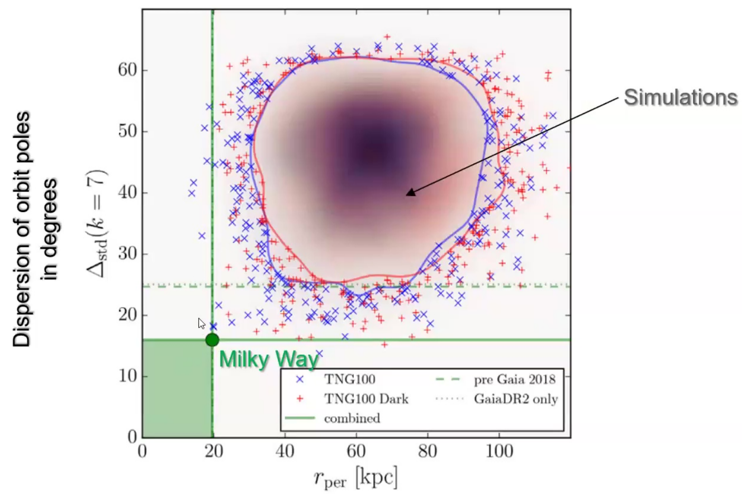
It's time for some plane speaking

Marcel S. Pawlowski

Nature Astronomy **5**, 1185–1187 (2021) | Cite this article

The Milky Way, Andromeda and Centaurus A host flattened arrangements of satellite dwarf galaxies with correlated kinematics. The rarity of similar structures in cosmological simulations constitutes a major problem for the ΛCDM model, with no obvious solution in sight.

Pawlowski & Kroupa 2020
MN 491, 3042



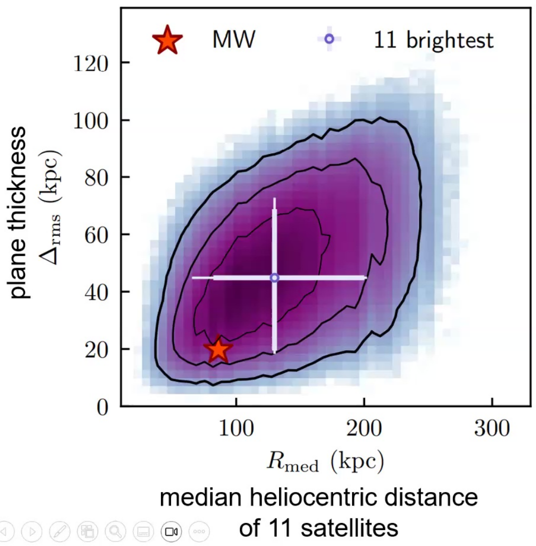
Thickness of the satellite distribution

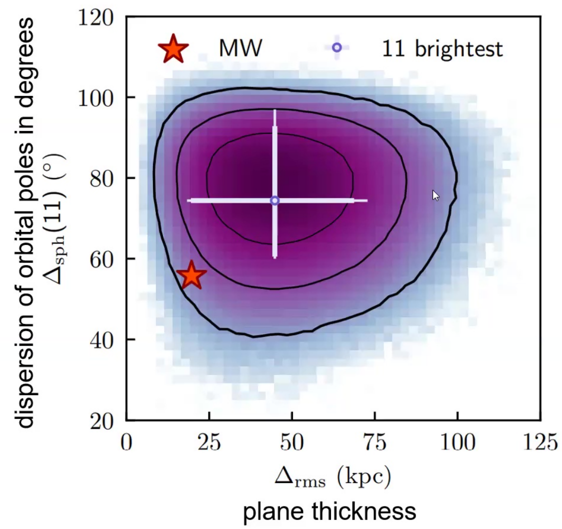
Getting distance distribution right is important in evaluating incidence of the satellite "planes": more concentrated distribution -> thinner plane

Pham, Kravtsov & Manwadkar 2023, MN 520, 3937 (arXiv/2209.02714); Sawala+22;

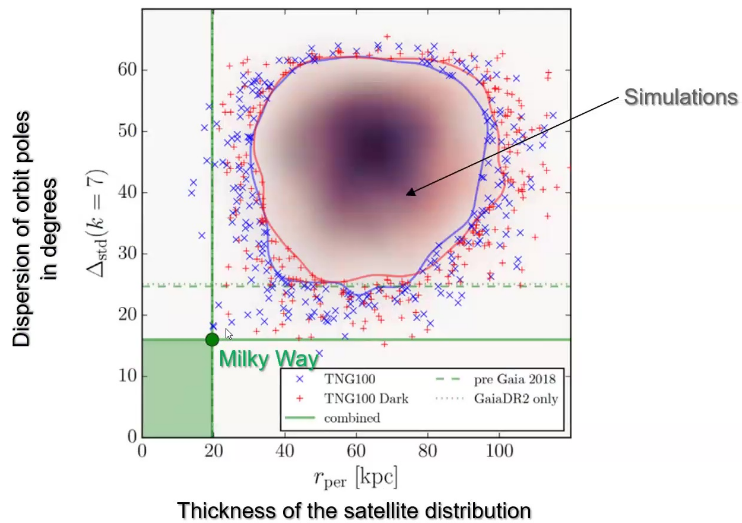
Satellite ''planes'', as thin and as coherent in their orbital poles as those of the MW, are rare for MW-sized halos in LCDM, but not too rare (MW is a 2-3 sigma outlier).

Similar configurations in nearby galaxies may be due to our location in the Local Sheet (Libeskind+15)





Pawlowski & Kroupa 2020
MN 491, 3042

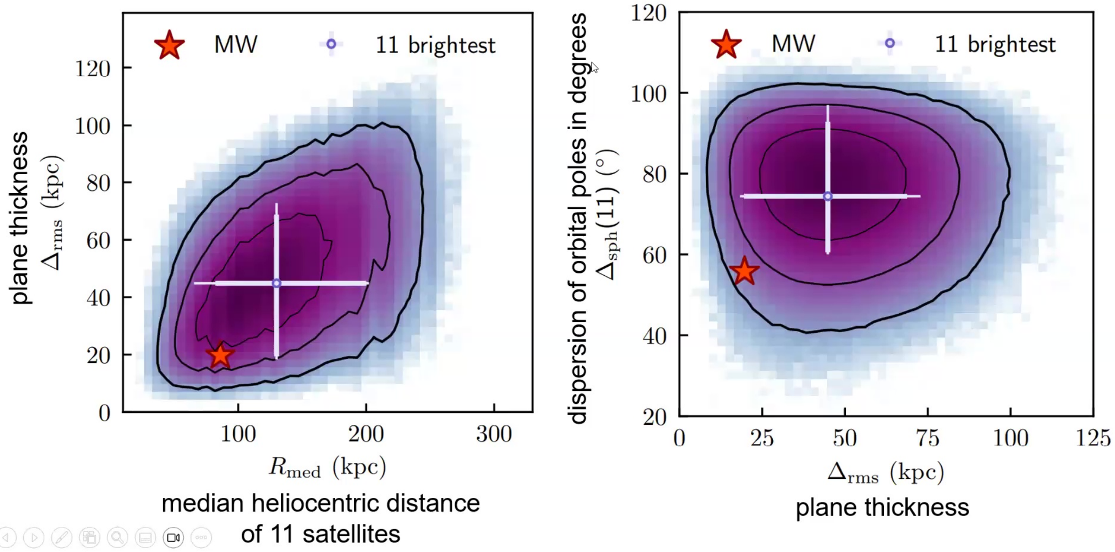


Getting distance distribution right is important in evaluating incidence of the satellite "planes": more concentrated distribution -> thinner plane

Pham, Kravtsov & Manwadkar 2023, MN 520, 3937 (arXiv/2209.02714); Sawala+22;

Satellite ''planes'', as thin and as coherent in their orbital poles as those of the MW, are rare for MW-sized halos in LCDM, but not too rare (MW is a 2-3 sigma outlier).

Similar configurations in nearby galaxies may be due to our location in the Local Sheet (Libeskind+15)



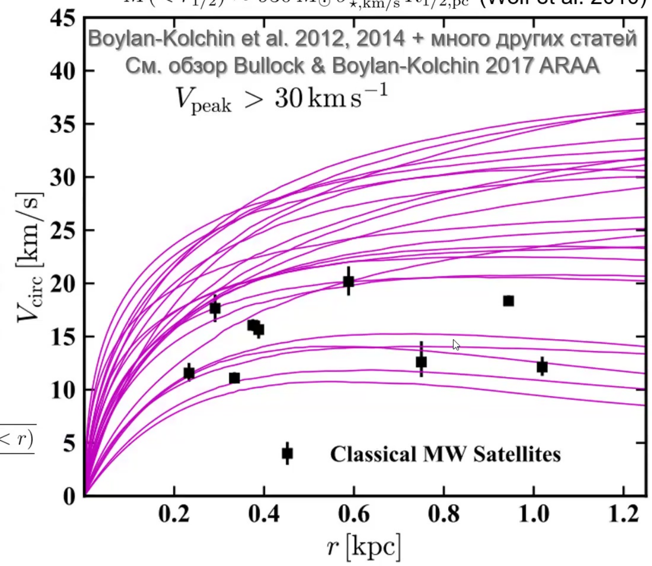
The “too-big-to-fail problem”

The “problem” is that LCDM presumably predicts more massive satellites (using total mass within half-light radius of galaxies) than is observed around Milky Way and Andromeda. Such massive satellites should not have “failed” to form observable galaxies according to galaxy formation models, so why are such galaxies not observed?

$M(< r_{1/2}) \approx 930\, M_\odot\, \sigma^2_{\star,\mathrm{km/s}}\, R_{1/2,\mathrm{pc}}$ (Wolf et al. 2010)

Circular velocity

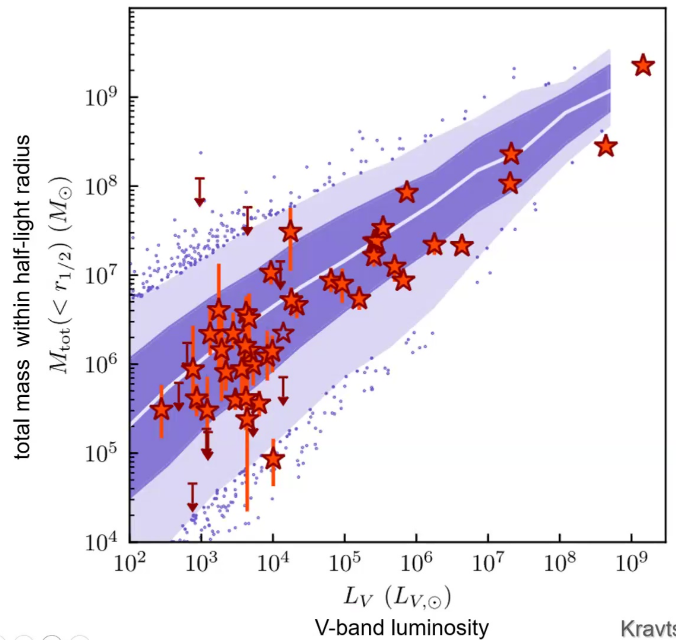
$$V_{\rm circ}(r) = \sqrt{\frac{GM(<r)}{r}}$$



Distance to galaxy center in kiloparsecs

Total mass within half-light radius as a function of galaxy luminosity

Relation exhibited by observed galaxies (stars and upper limits) is reproduced by model galaxies (median line and 1- and 2-sigma scatter shown by shaded bands)



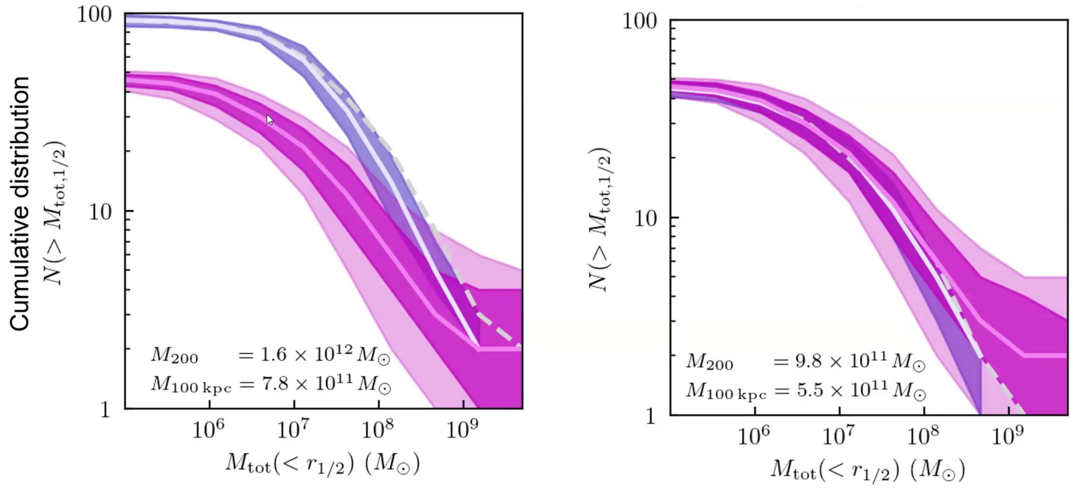
Kravtsov & Wu 2023, MN 525. 325

Examining the "too-big-to-fail" problem: cumulative distributions of $M_{tot}(<r_{1/2})$ in MW-sized halos

Magenta shows distribution for the Milky Way satellites: line is median, shaded regions are 1σ and 2σ bands estimated using bootstrap and taking into account $M_{tot}(<r_{1/2})$ uncertainties

Blue band shows median and scatter of the model distribution using parent subhalo mass and concentration and assuming Lazar+20 profile accounting for feedback.
Gray dashed lines shows median for masses estimated using NFW profile

Halos with $M_{tot}(<100 \text{ kpc}) = (5.7\text{+-}0.8) \times 10^{11}$ Msun (close to the MW Vasiliev+21) tend to have t $N(>M_{tot,1/2})$ distributions consistent with that of the MW satellites

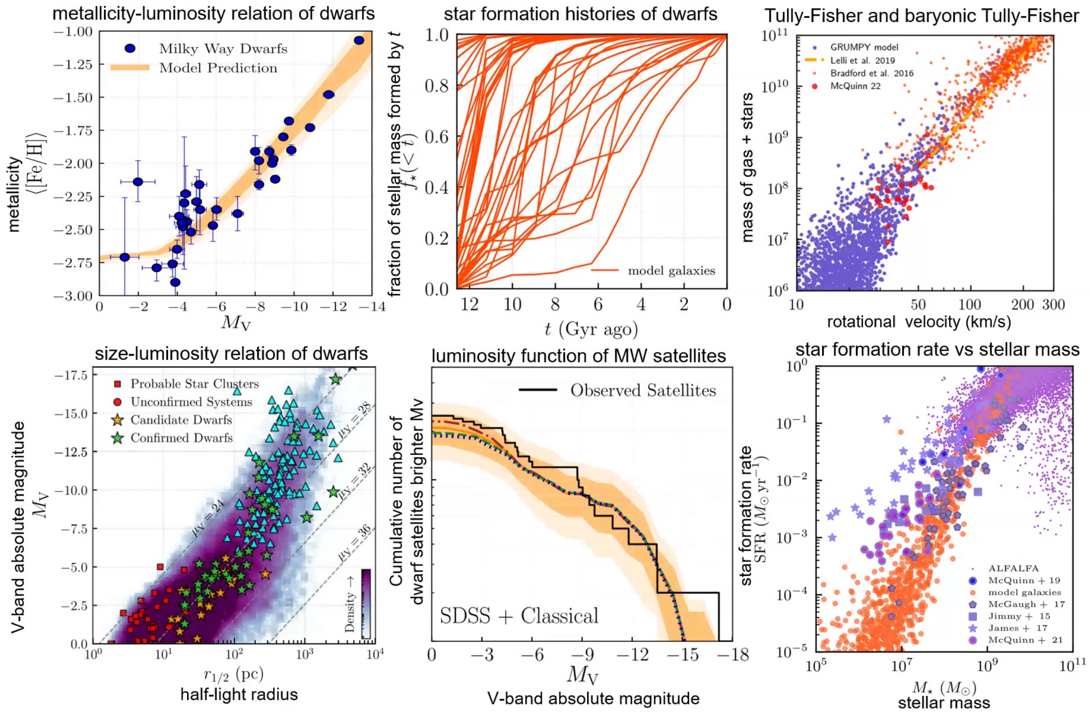


total mass within half-light radius

Kravtsov et al., in prep

A wide range of observed dwarf galaxy properties and correlations are reproduced well by the GRUMPY model

Kravtsov & Manwadkar 2022, MN 514, 2667; Manwadkar & Kravtsov 2022, MN 516, 3944; Kravtsov & Wu 2023, MN 525, 325



A model for additional star formation rate (SFR) stochasticity driven by formation and disruption of individual star forming regions

Based on the stochastic SFR framework of Caplar & Tacchella 2019; Tacchella et al. 2020; Iyer et al. 2020, 2022
Pan & Kravtsov 2023, to be submitted

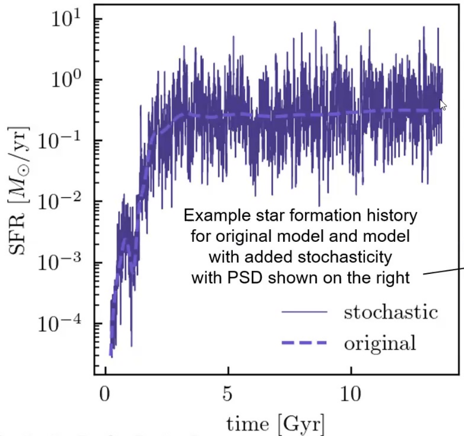
- Draw Gaussian random numbers Δ with a specified power spectral density (PSD).
- Perturb SFR(t): $SFR_{stochastic}$ = SFR x 10^{Δ}

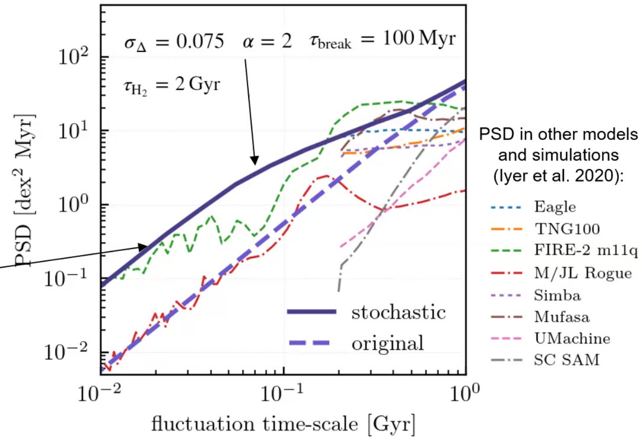
$$\mathrm{SFR}(t_n) = \frac{1}{N}\sum_{k=0}^{N-1} S_k \cdot \exp\left(\frac{i2\pi n}{N}k\right)$$

$$\mathrm{PSD}(k) = \frac{(\Delta t)^2}{T}|S_k|^2$$ ← time span of SFH

$$\mathrm{PSD}(f) = \frac{\sigma_\Delta^2}{1+(\tau_{\rm break} f)^\alpha}$$

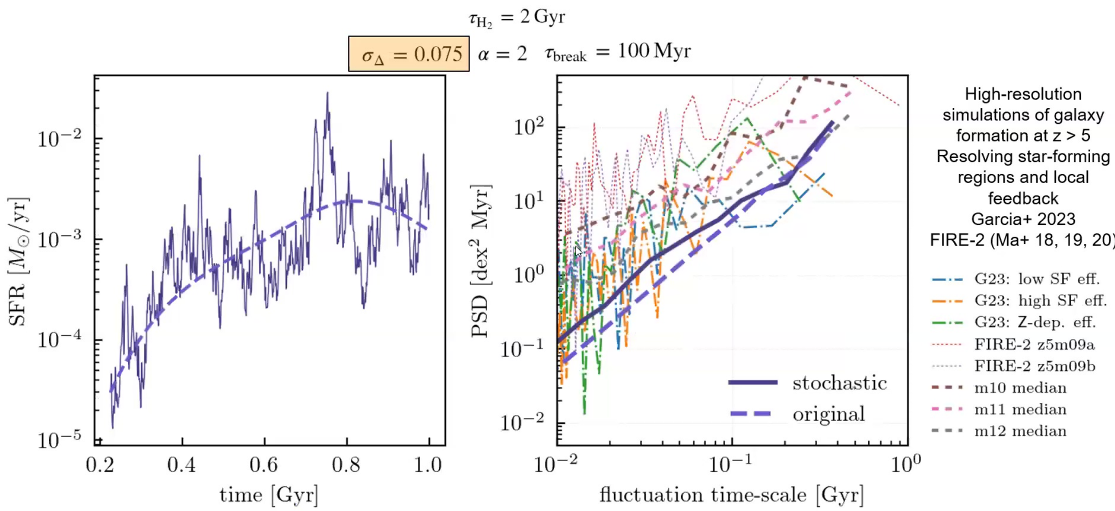
frequency: $f_k = k/T$





A model for additional star formation rate (SFR) stochasticity: high redshifts (z > 5)

High-resolution zoom-in galaxy formation simulations of galaxies at z > 5 exhibit much higher levels of SFR stochasticity than at lower z (but see Pallotini & Ferrara, arXiv/2307.03219)



High-resolution simulations of galaxy formation at z > 5 Resolving star-forming regions and local feedback Garcia+ 2023 FIRE-2 (Ma+ 18, 19, 20)

A model for additional star formation rate (SFR) stochasticity: high redshifts (z > 5)

High-resolution zoom-in galaxy formation simulations of galaxies at z > 5
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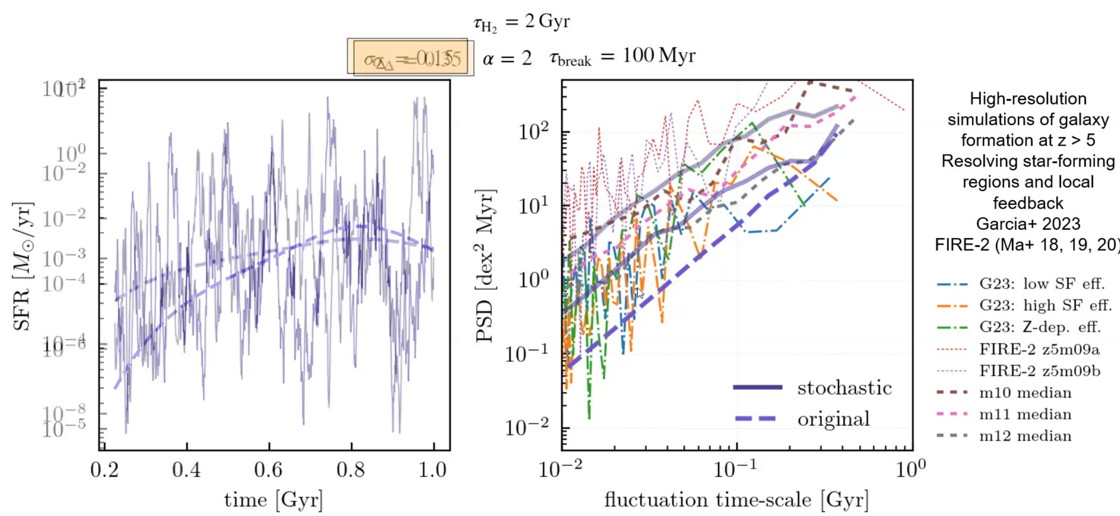
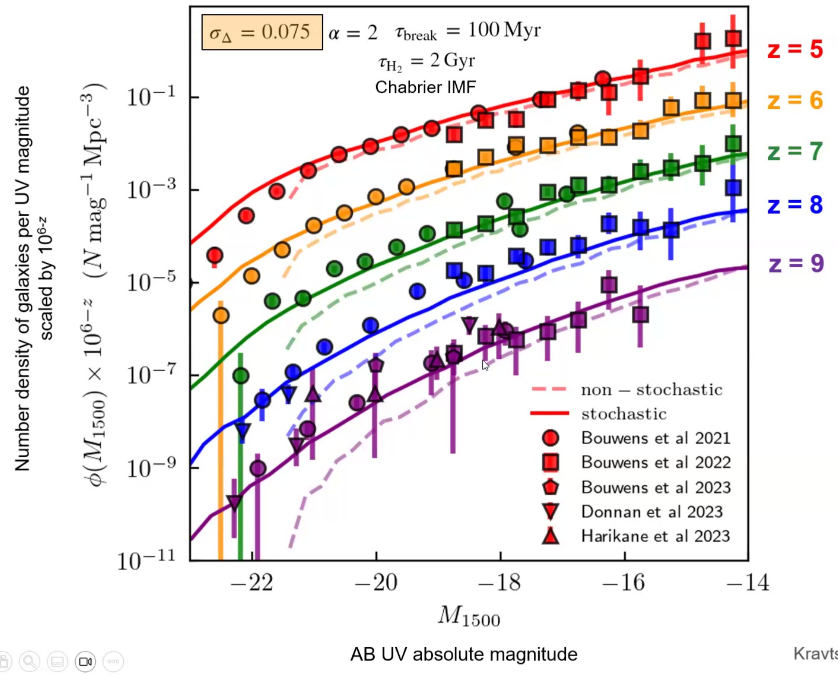


UV luminosity functions at z~5-9 are well reproduced by the GRUMPY model that reproduces z=0 properties of dwarf galaxies

with a moderate level of additional stochasticity typical for zoom-in simulations of galaxy formation

Galaxies in halos following expected halo mass function at each z,
Mass assembly history evolved using an accurate approximation for halo mass accretion rate

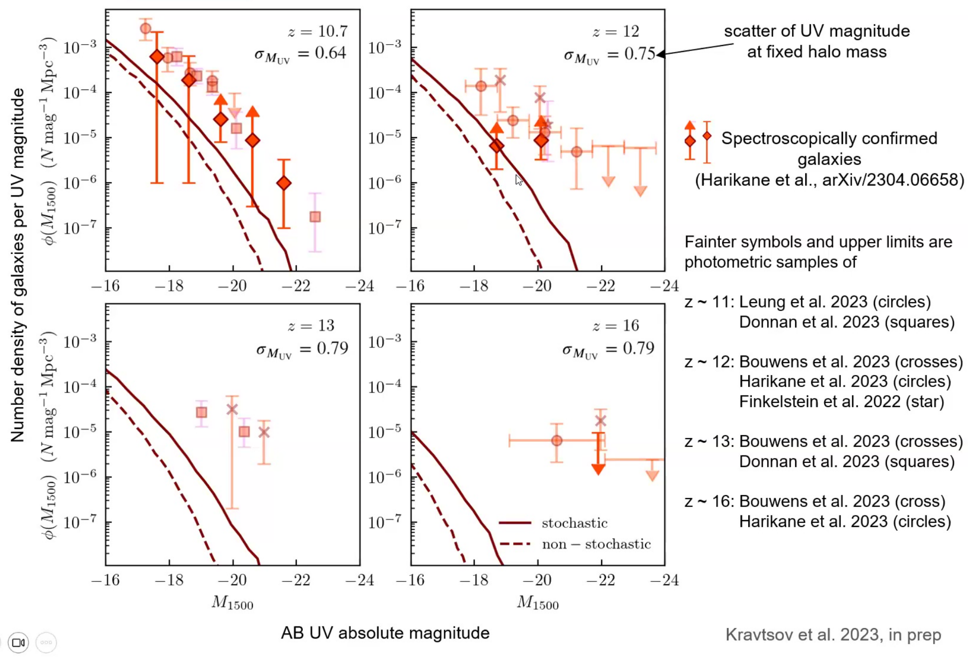


Kravtsov et al. 2023, in prep

The model with the same parameters and level of SFR stochasticity as for z<10 underpredicts z>10 UV luminosity functions

Consistent with many previous studies using models with regular low-z SFR stochasticity
(e.g., Yung et al. 2023; Shen et al. 2023; Qin et al. 2023, …)

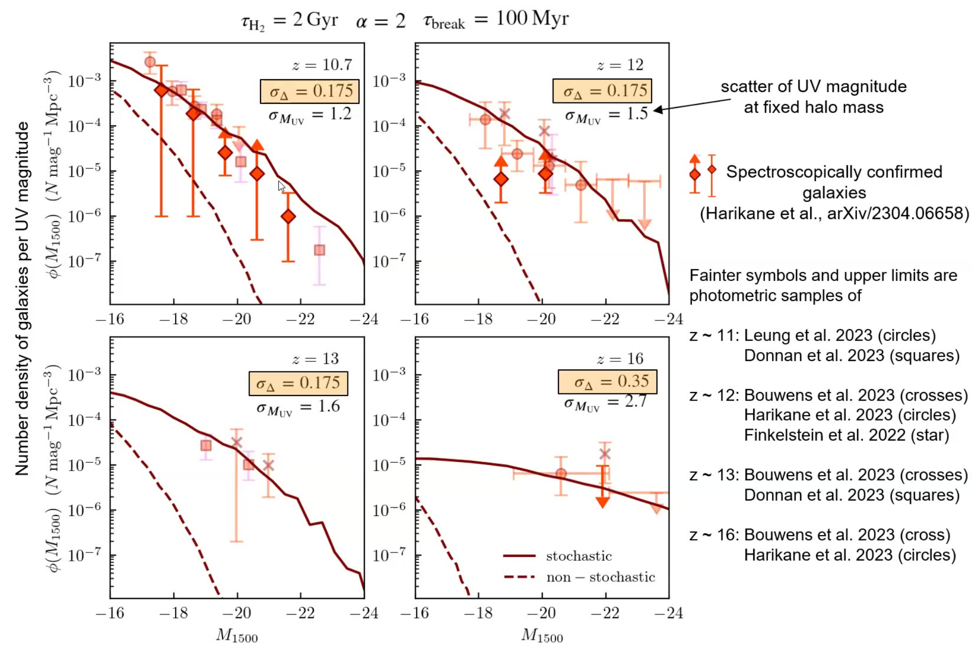
$\sigma_\Delta = 0.075$ $\alpha = 2$ $\tau_{\rm break} = 100\,{\rm Myr}$ $\tau_{\rm H_2} = 2\,{\rm Gyr}$ Chabrier IMF



Kravtsov et al. 2023, in prep

z>10 UV luminosity functions can be reproduced with z=0 molecular depletion time and high but reasonable SFR stochasticity

See also Shen et al., arXiv/2305.05769 and Sun et al., arXiv/2307.15305



Kravtsov et al. 2023, in prep

summary and implications

- Basic processes that govern the formation of dwarf galaxies can be captured by a relatively simple model that reproduces many observed galaxy properties and correlations.

- Such model within LCDM framework can be used to assess challenges to the model:

  - The incidence of the satellite planes as thin and orbitally coherent as observed are found in 2-5% of the MW-sized hosts.

  - The “too-big-to-fail” problem exists only in halos more massive than Milky Way, for which recent mass estimates indicate Mtot(<100 kpc) = $5.7 \pm 0.4 \times 10^{11}$ Msun, and $M_{200} = 9 \pm 1 \times 10^{11}$ Msun, when subhalo disruption due to disk tides, observational detection probability of model galaxies are taken into account.

  - UV luminosity functions (LFs) of galaxies at redshifts z~5-16 can be reproduced with regular galaxy formation physics when stochasticity of star formation rate (SFR) is explicitly modeled. The same model reproduces z=0 dwarf galaxy properties well.

GRUMPY model and modeling of z=0 dwarf galaxies and its applications:
Kravtsov & Manwadkar 2022, MN 514, 2667 (model description)
Manwadkar & Kravtsov 2022, MN 516, 3944 (modelling MW satellites)
Pham, Kravtsov & Manwadkar 2023, MN 520, 3937 (planes of satellites)
Kravtsov & Wu 2023, MN 525, 325 (model comparison for Mtot(<rhalf)-L relation)
Pan & Kravtsov, 2023, MN to be submitted (SFR stochasticity of dwarf galaxies)
Kravtsov et al. 2023, in prep (modelling z>5 UV luminosity functions)