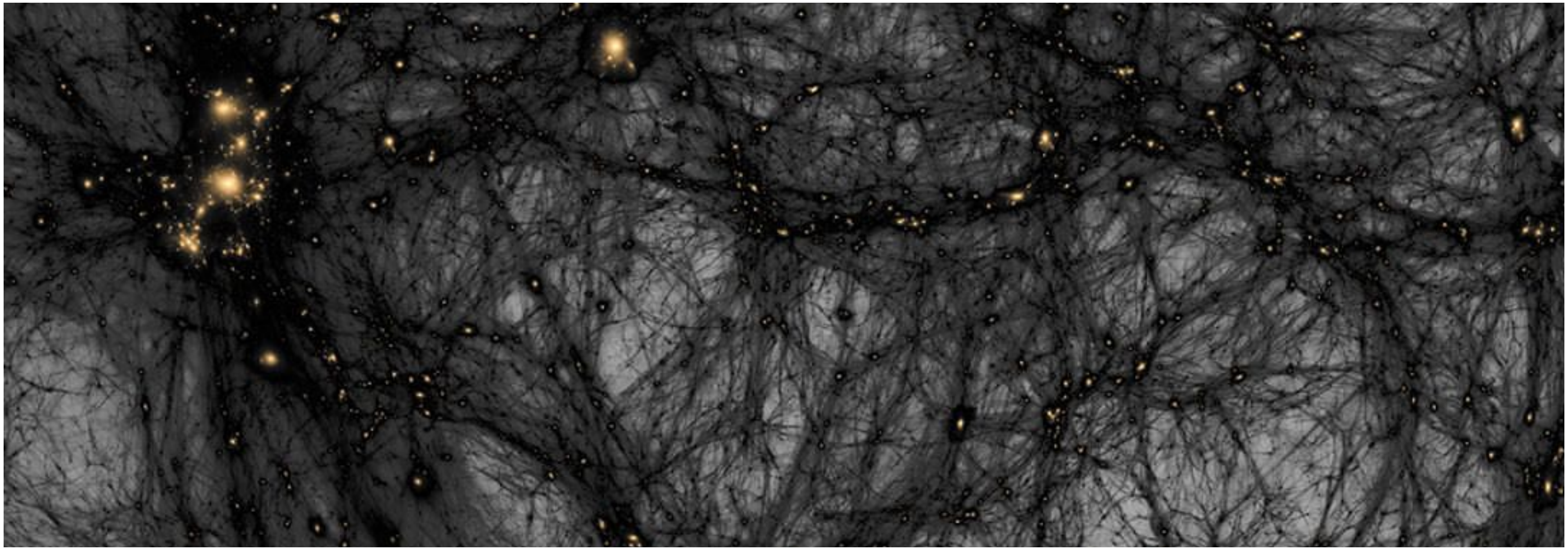
Connecting the dots:

From astronomical surveys and experiments to fundamental physics of dark universe



Yao-Yuan Mao

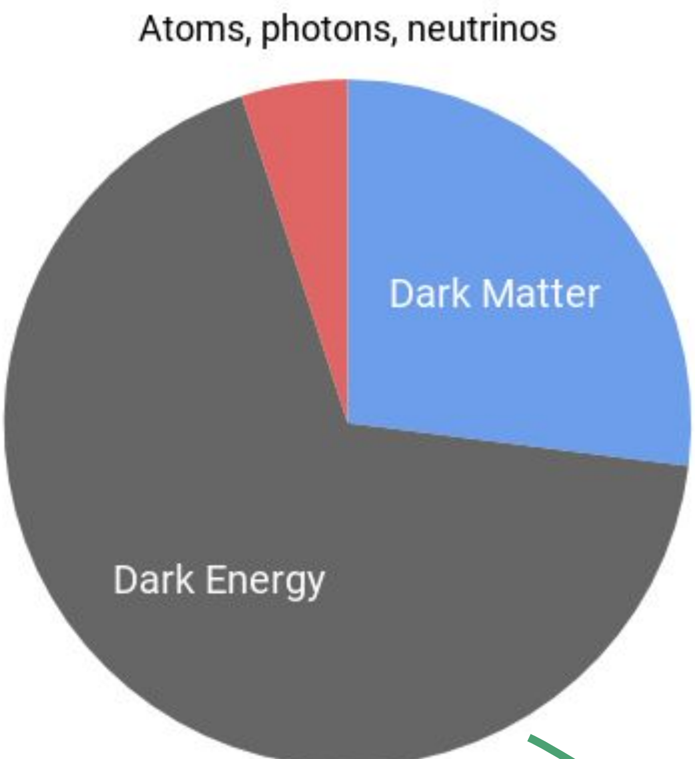
NASA Einstein Fellow, Rutgers

yymao.github.io | 茅耀元

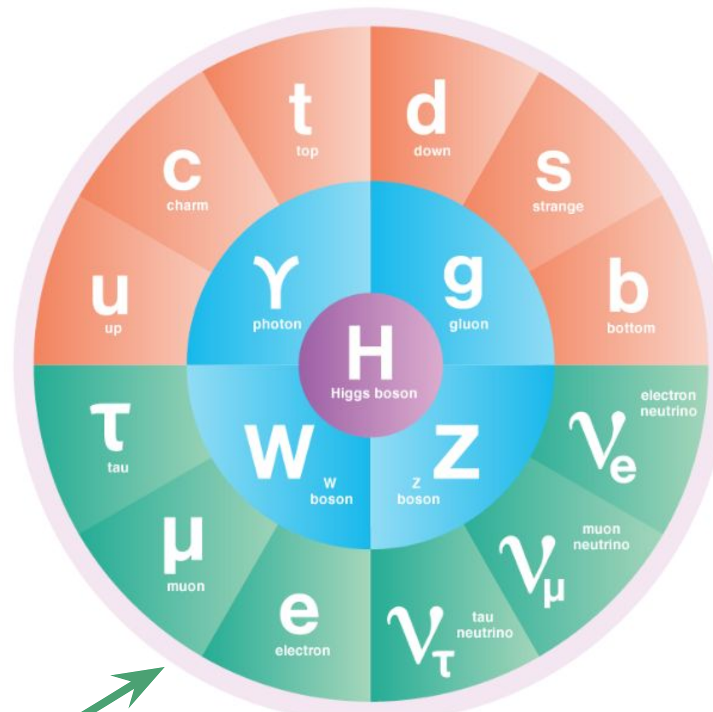
02/18/2020 @ U of Wisconsin, Madison

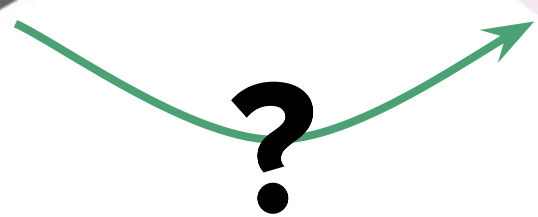
The Dark Universe: (Lost) Keys to New Physics

Standard Model of Cosmology

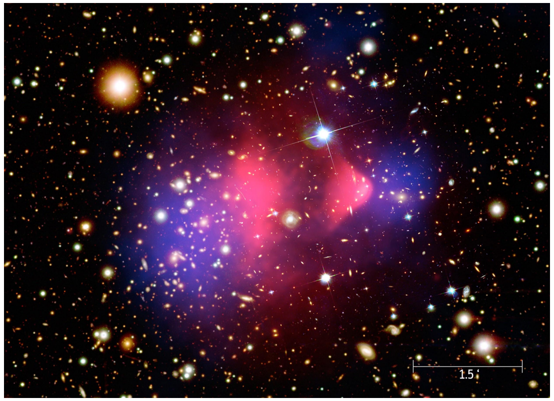


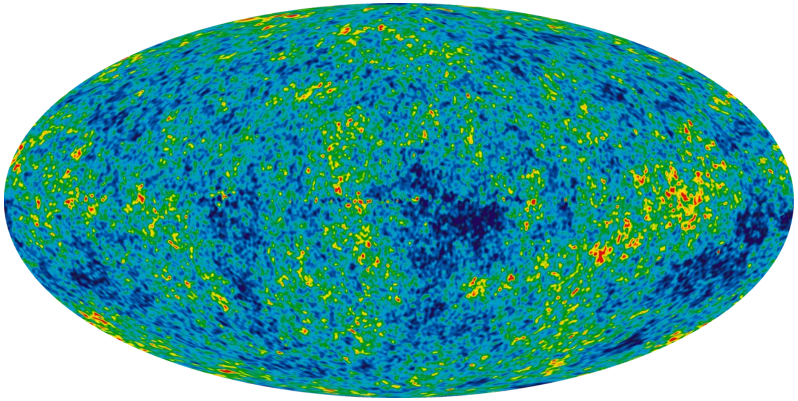
Standard Model of Particle Physics





www.symmetrymagazine.org/standard-model

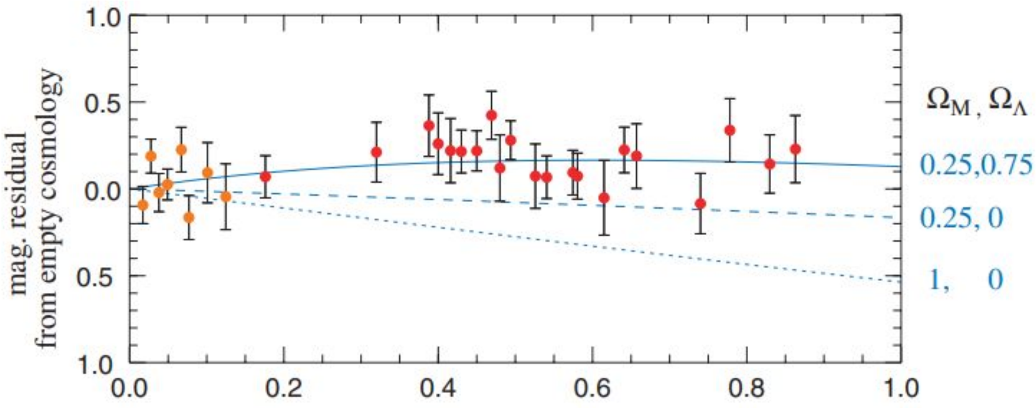


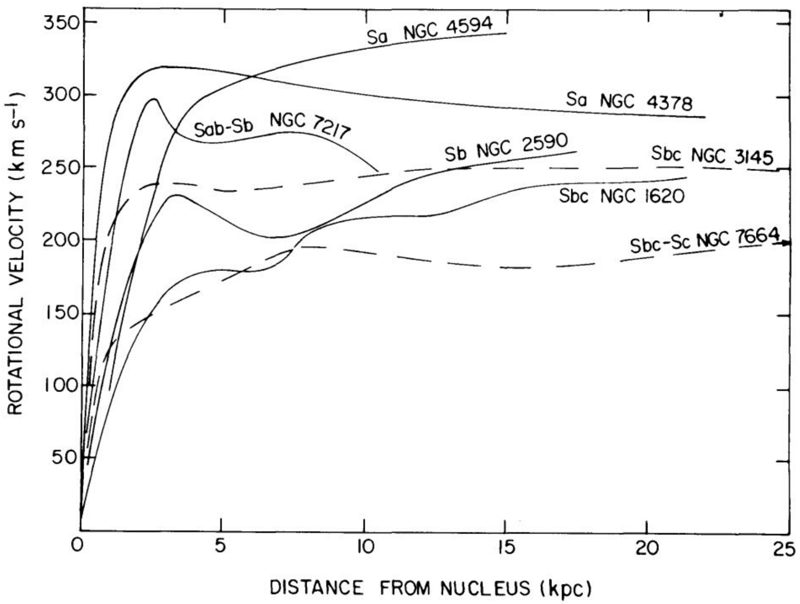


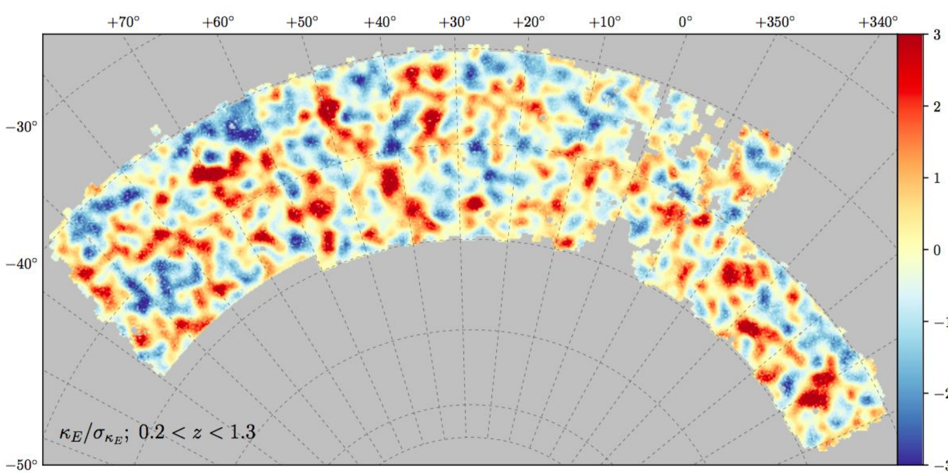
↖ Bullet cluster [NASA/Chandra/Hubble & Magellan]
⬆ Einstein Ring [NASA/Hubble]
↗ CMB map [NASA/WMAP]

➡ Supernova Cosmology Project [Knop+ ApJ 2003]

↙ Galaxy rotation curves [V. Rubin+ ApJL 1978]
↘ DES Y1 WL Mass Map [C. Chang+ MNRAS 2018]





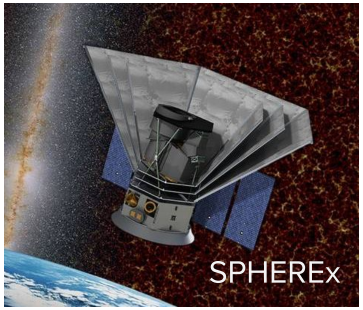


Upcoming surveys await

- Ground-based telescopes + space missions
- Multi-wavelength sky mapper + gravitational waves
- Particle and astrophysical experiments

Rubin Observatory

LSST

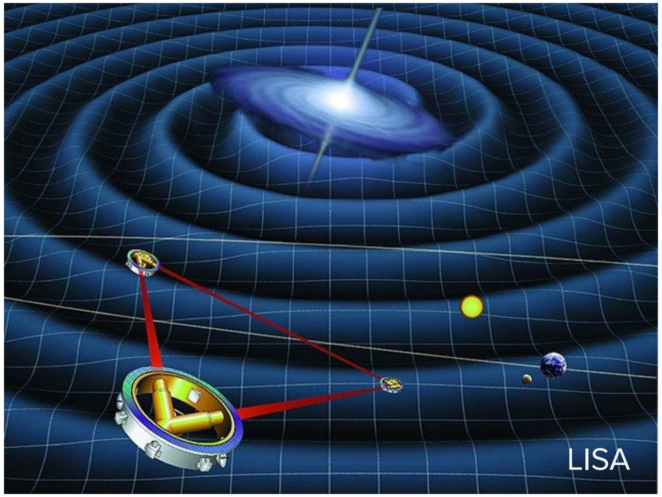


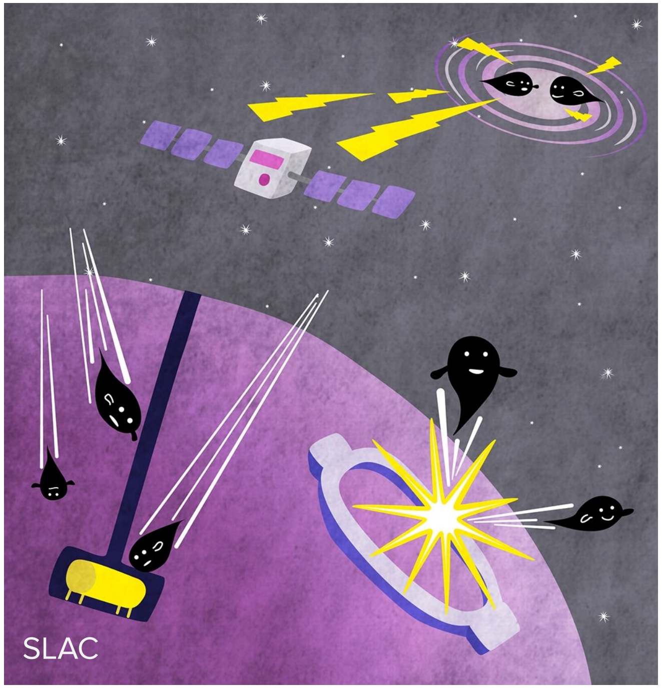
euclid

SIMONS OBSERVATORY

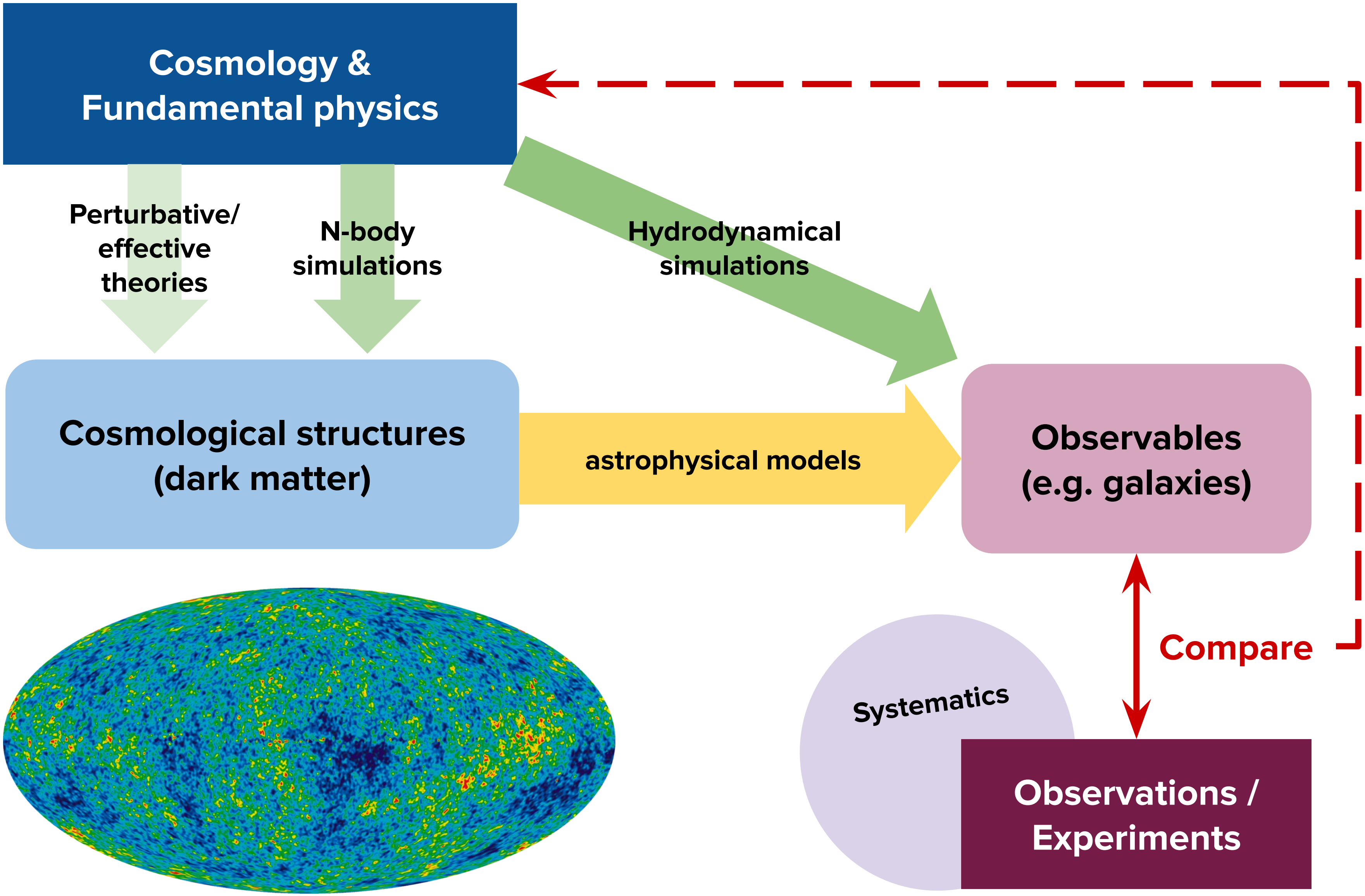
WIDE-FIELD INFRARED SURVEY TELESCOPE
WFIRST
ASTROPHYSICS • DARK ENERGY • EXOPLANETS

CMB-S4
Next Generation CMB Experiment

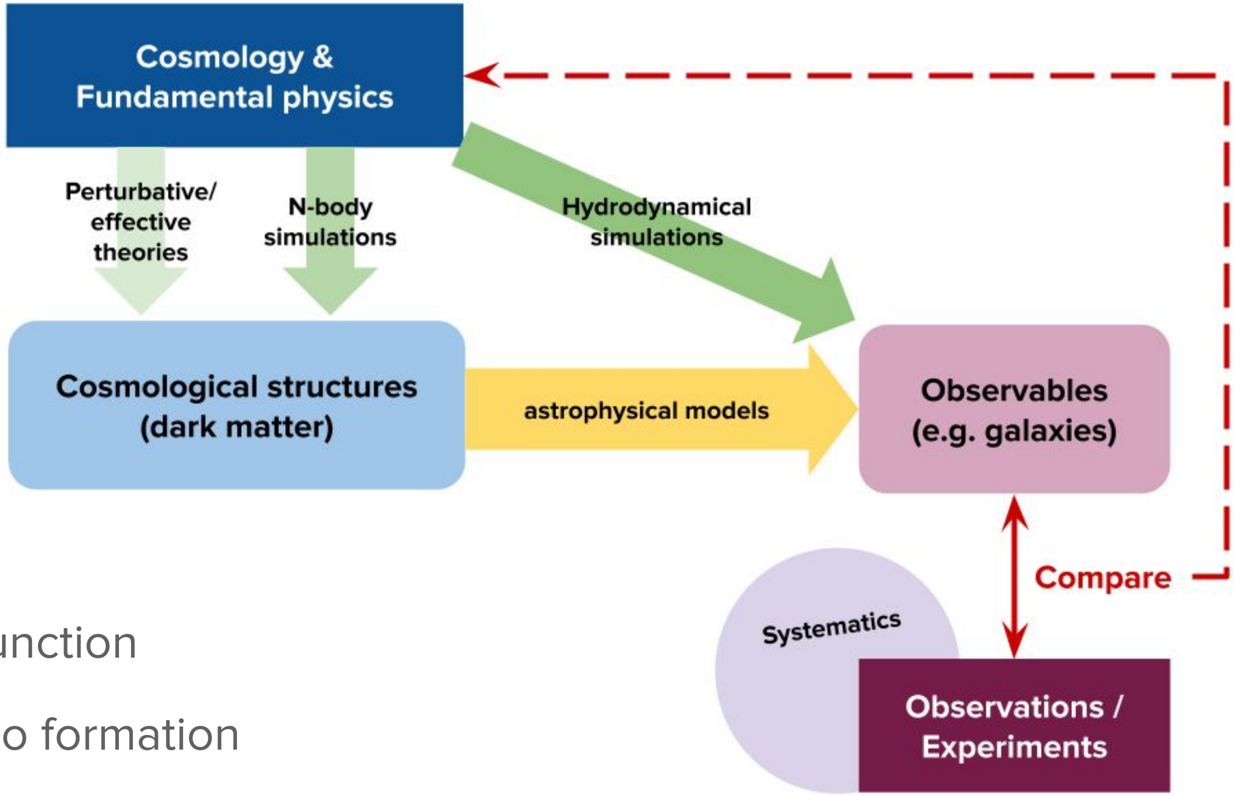




How to find those keys? Connecting the dots!



Outline



Dark matter distribution

- Velocity distribution function
- Substructures and halo formation

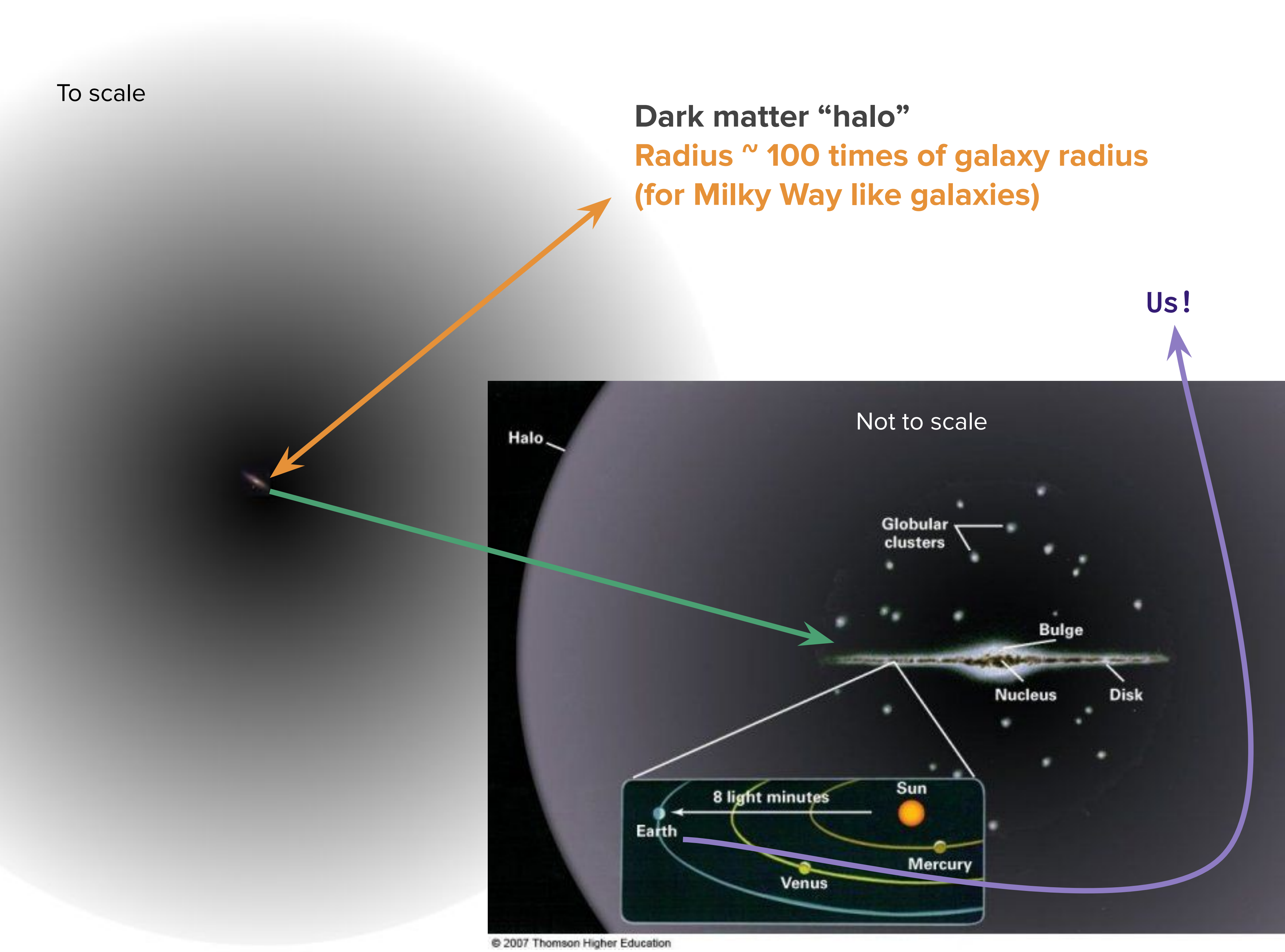
Galaxy-halo connection

- Mitigation of assembly bias for quantitative cosmology
- Comprehensive empirical models for satellite galaxies

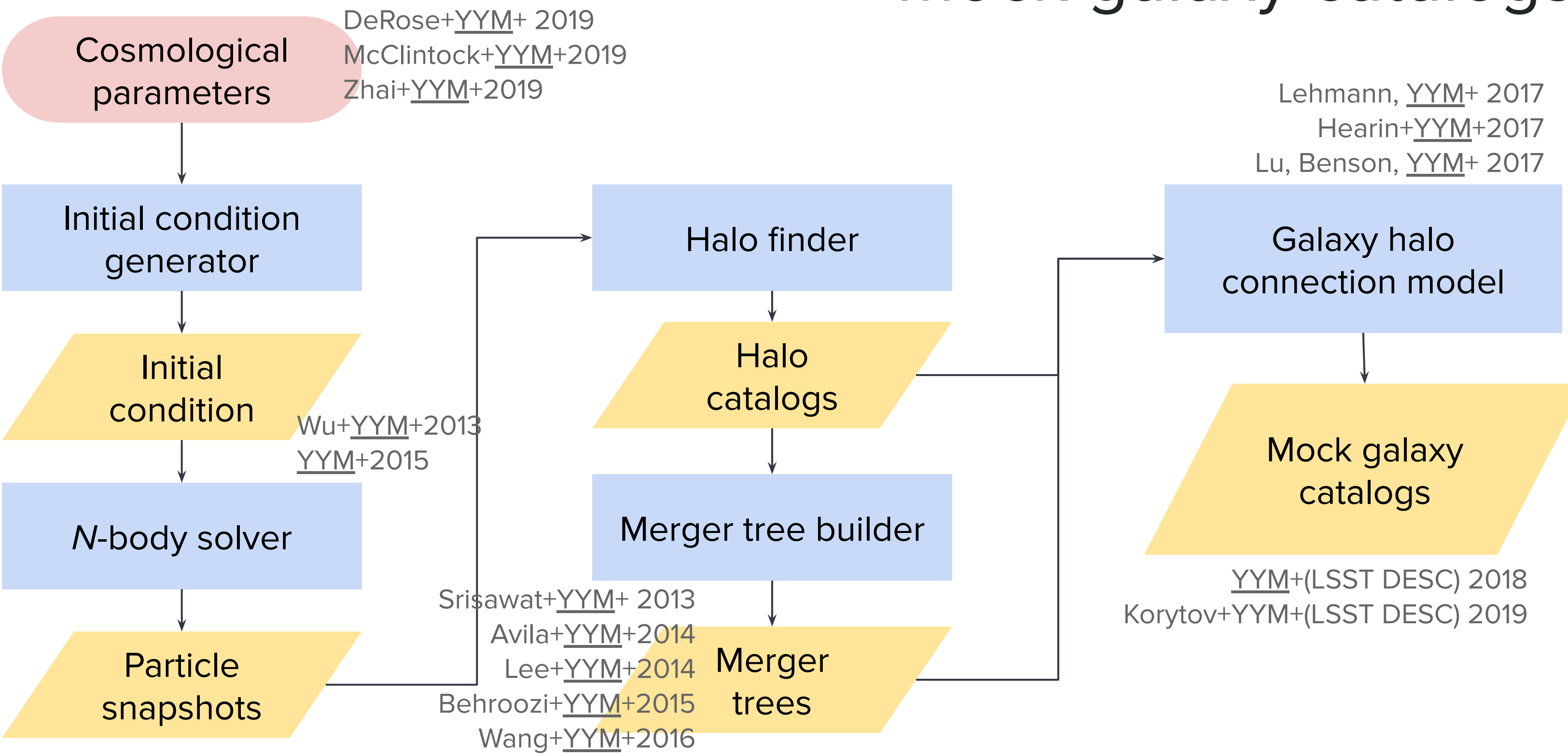
Large-scale surveys

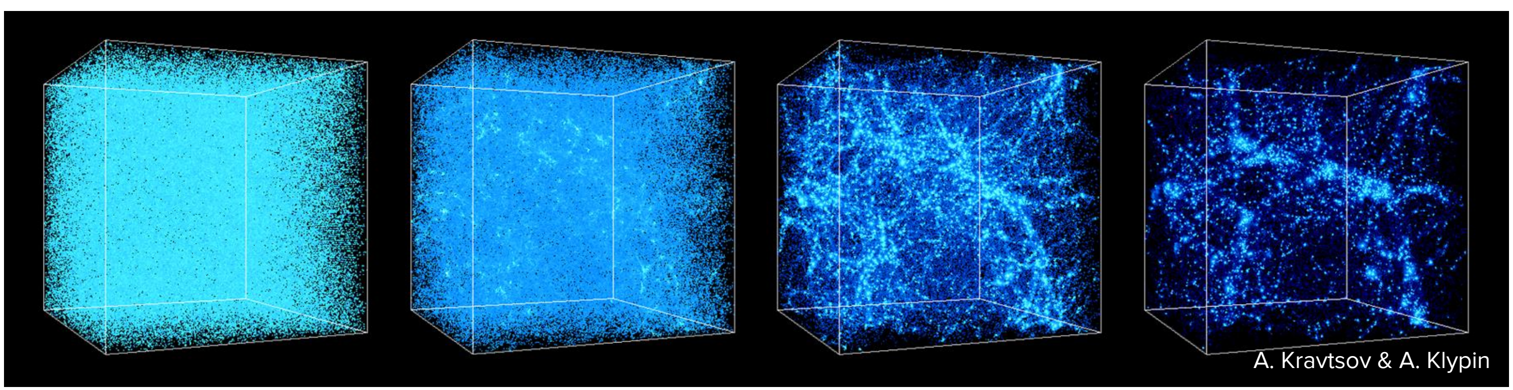
- Dwarf galaxies as dark matter laboratories: precursor survey to VRO/LSST
- End-to-end simulations in the LSST Dark Energy Science Collaboration (DESC)

Dark Matter
Visualized by Ralf Kaehler (SLAC)


To scale
Dark matter "halo"
Radius ~ 100 times of galaxy radius
(for Milky Way like galaxies)
Us!
Not to scale
Halo
Globular
clusters
Bulge
Nucleus
Disk
8 light minutes
Sun
Earth
Mercury
Venus
© 2007 Thomson Higher Education

From cosmological parameters to mock galaxy catalogs





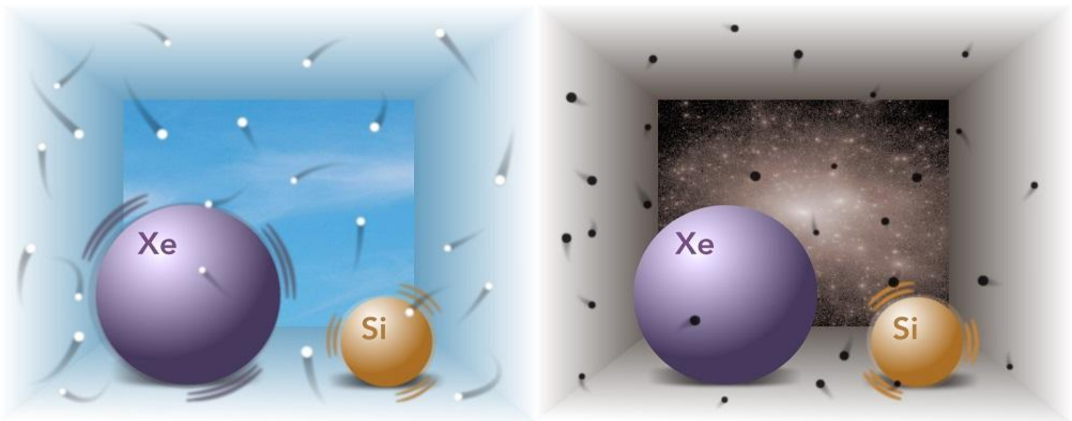
Direct detection of dark matter

The differential event rate of the DM-nucleon collision depends on:

1. Galactic Density
2. Galactic Velocity Distribution Function (VDF)

$$\left.\frac{dR}{dQ}\right|_Q = \frac{\rho_0}{m_{\rm dm} m_N} \int_{v_{\rm min}(Q)} d^3v\, v f(\mathbf{v}+\mathbf{v_e}) \frac{d\sigma}{dQ}$$
$$= \frac{\rho_0 \sigma_0}{2\mu^2 m_{\rm dm}} A^2 |F(Q)|^2 \int_{v_{\rm min}(Q)} d^3v\, \frac{f(\mathbf{v}+\mathbf{v_e})}{v}$$

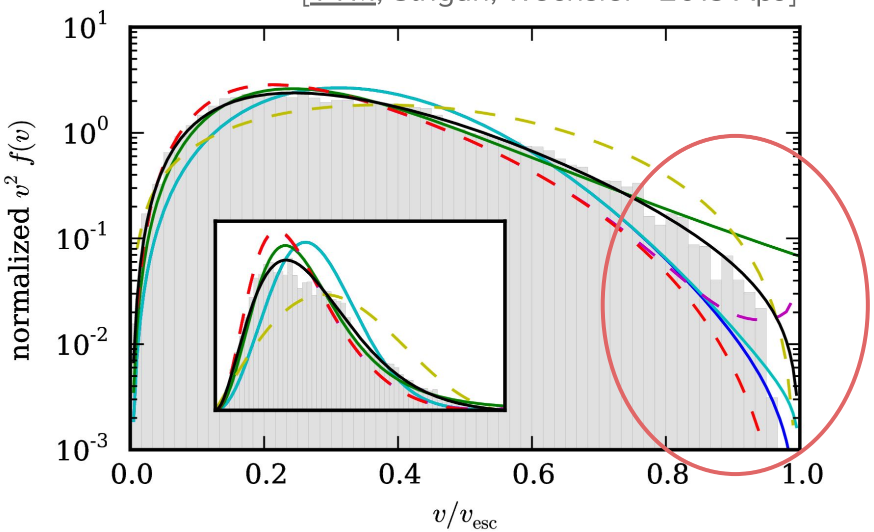
[Lewin & Smith, 1996]



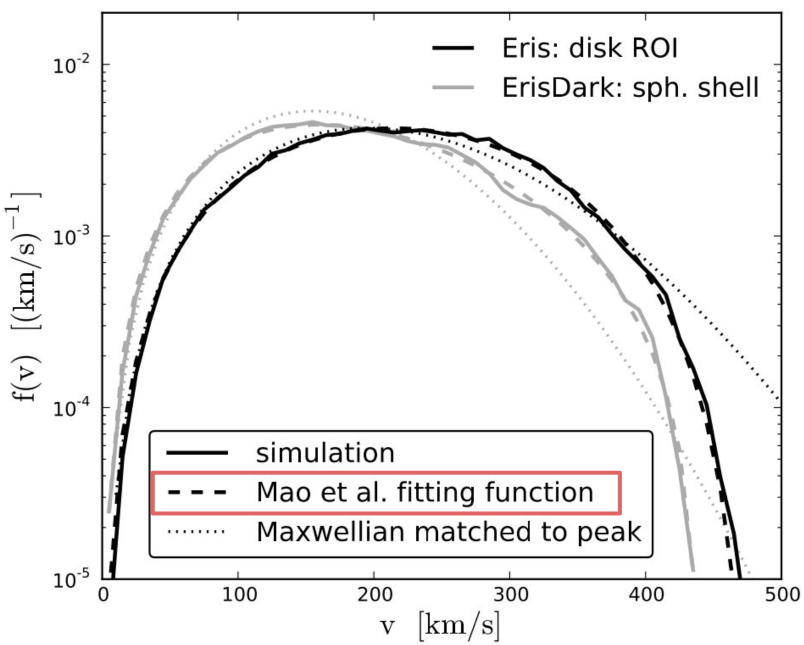
[YYM, Strigari, Wechsler 2013 PRL. Illustration:Greg Stewart/SLAC]

What do simulations tell us?

[YYM, Strigari, Wechsler+ 2013 ApJ]



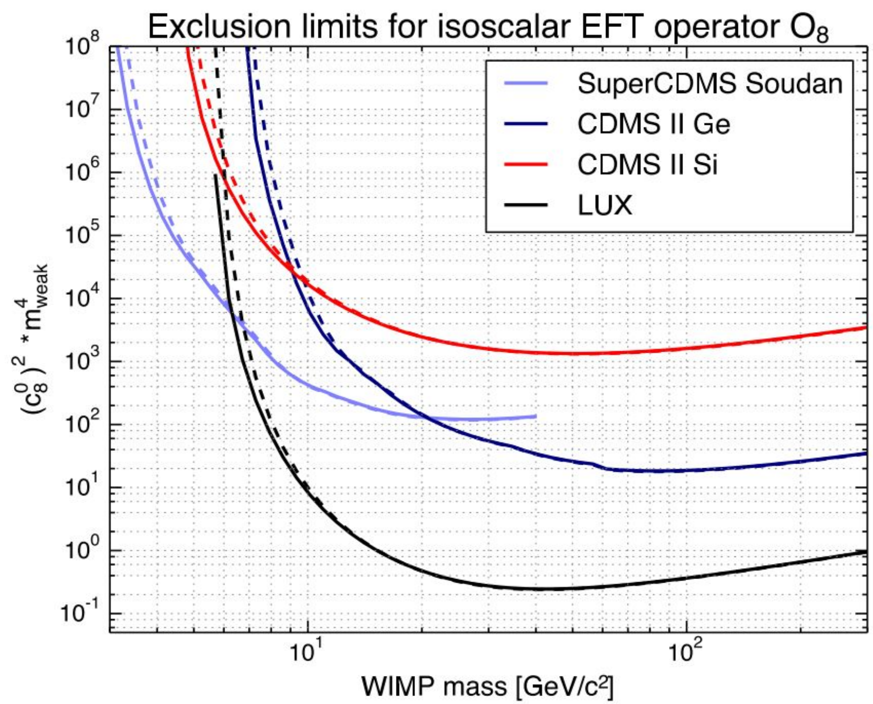
[Kuhlen+ 2013]



Does it matter?

In 2013, yes.

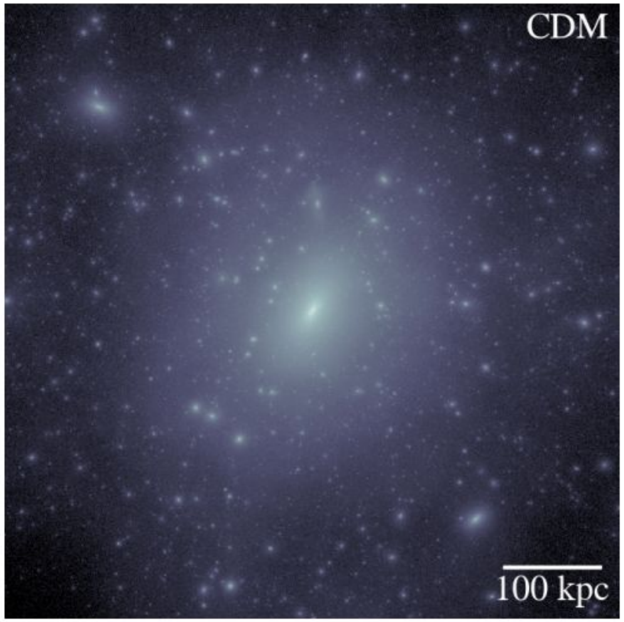
[Schneck+ (SuperCDMS) 2015]

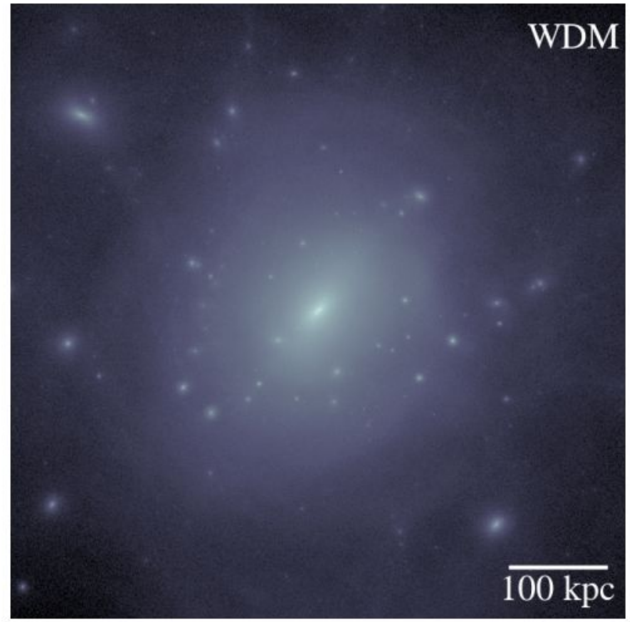


Accurate VDF modeling will become crucial when we see direct detection signals and start to infer properties of dark matter and of the MIlky Way.

Dark substructures ("subhalos") as dark matter probes

Cold Dark Matter

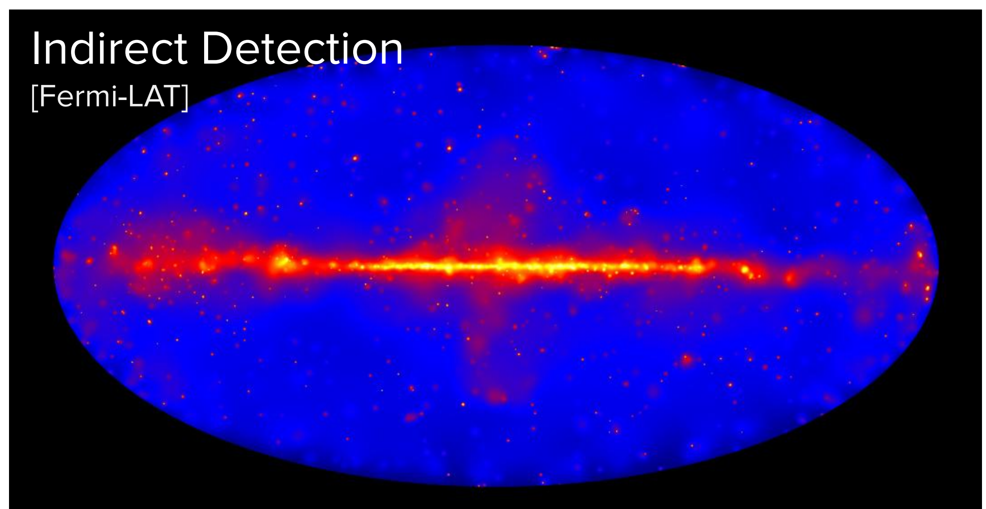




Warm Dark Matter

Fewer subhalos

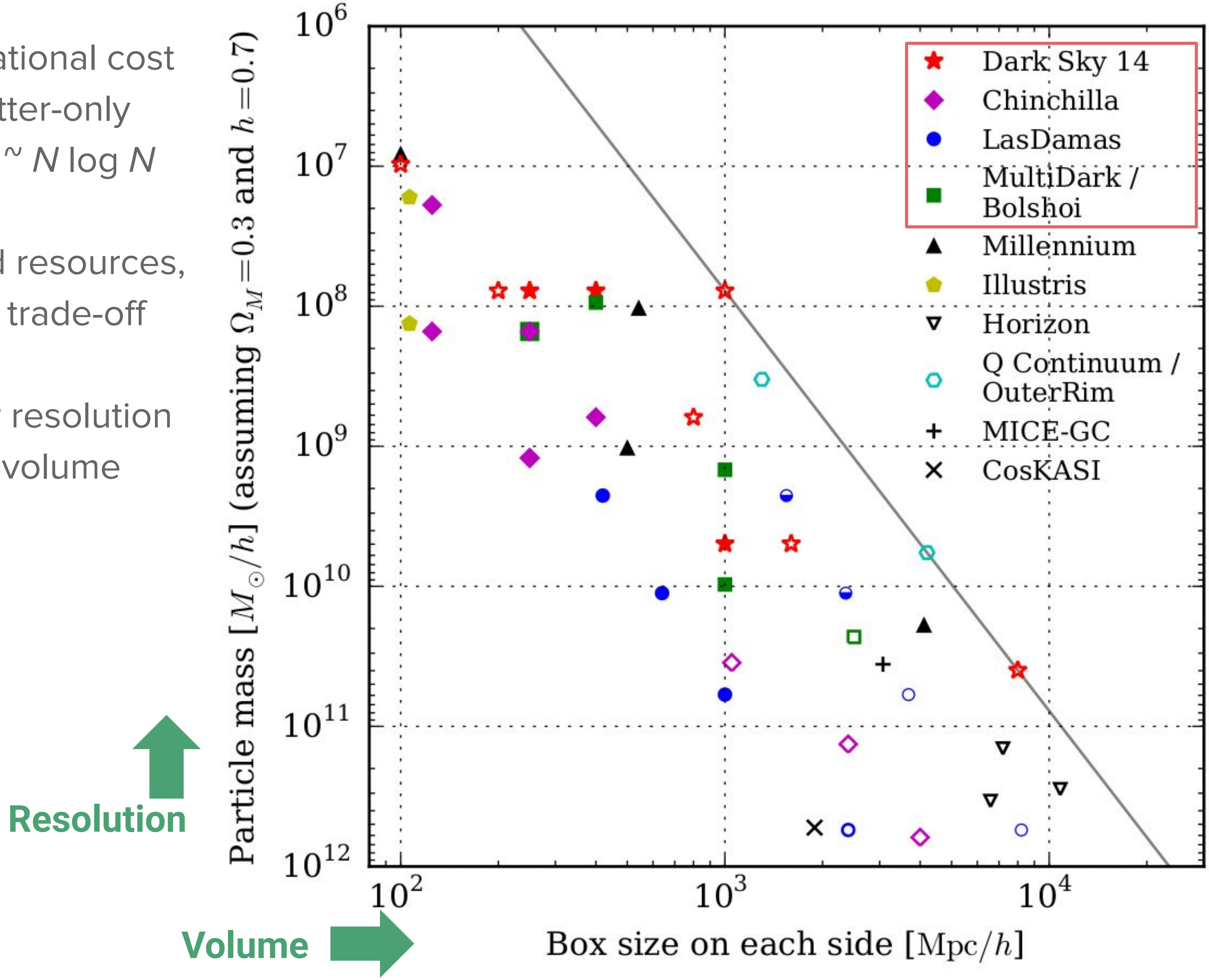
[Images: Bullock & Boylan-Kolchin 2017. Simulations: V. Robles, T. Kelley, and B. Bozek+]



The computational cost of a dark matter-only simulation is ~ $N \log N$

Given limited resources, it is always a trade-off between:

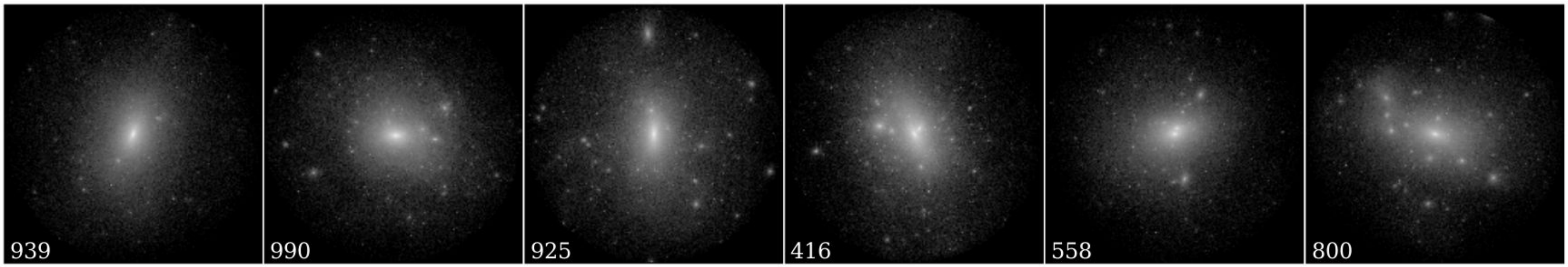
- a higher resolution
- a larger volume



Zoom-in simulations and subhalo models

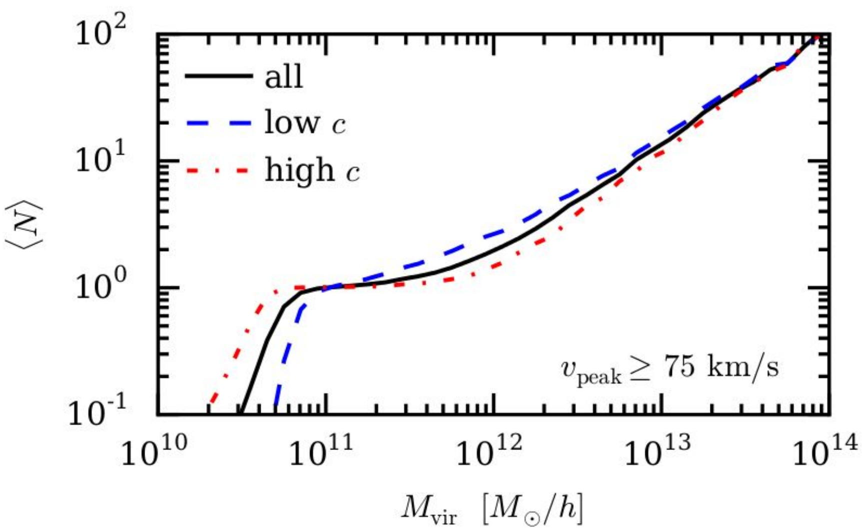
Form earlier
Fewer substructures

Form later
More substructures



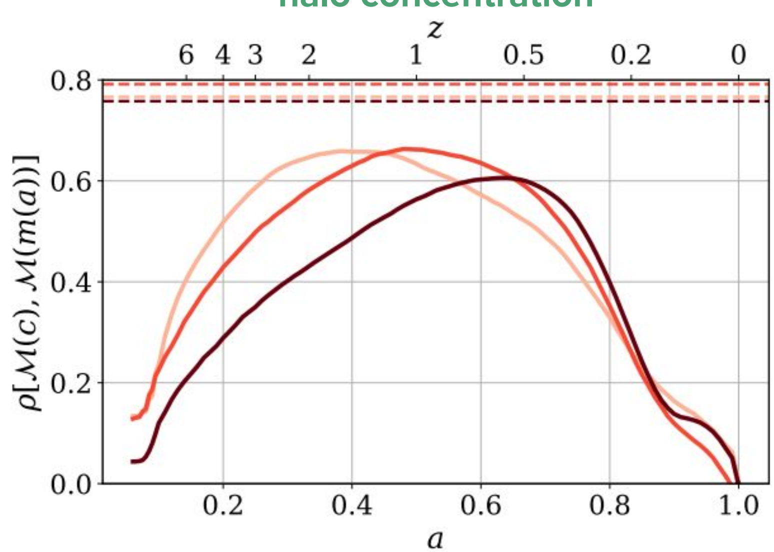
[YYM, Williamson, Wechsler 2015 ApJ]

Substructure abundance correlates with halo concentration

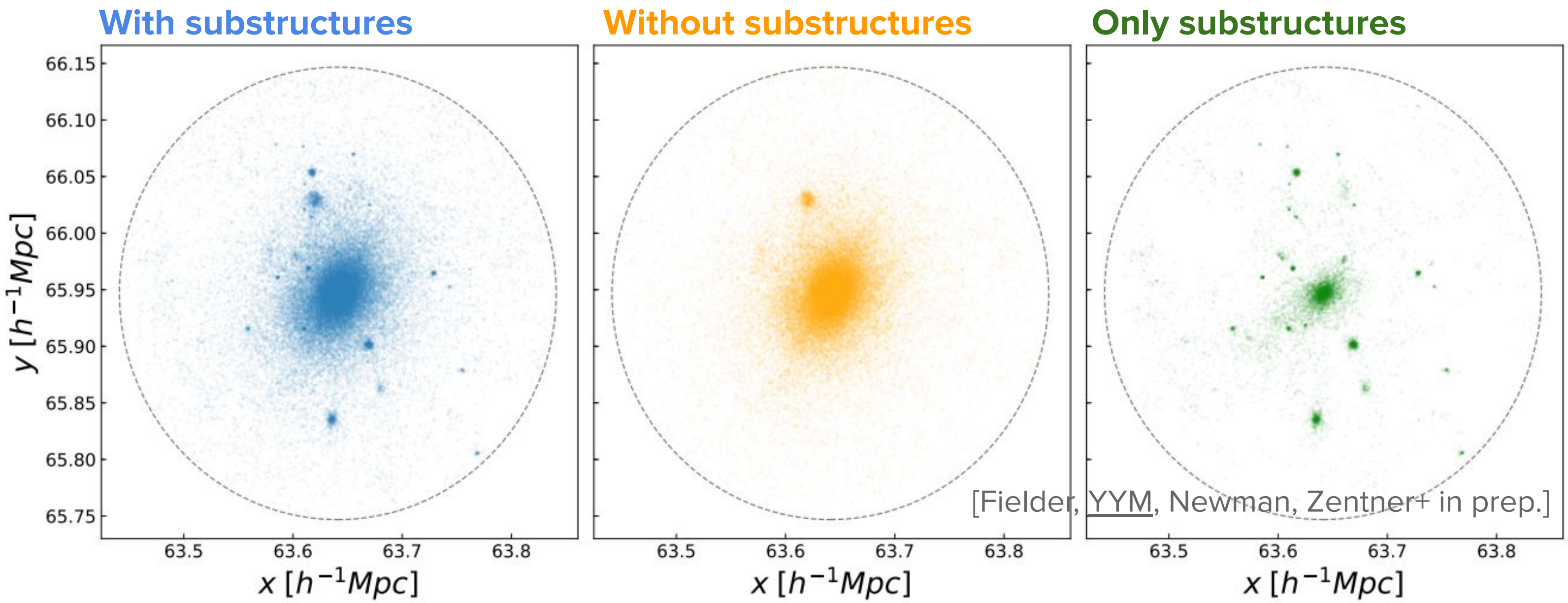


[YYM, Williamson, Wechsler 2015 ApJ]

Halo formation time correlates with halo concentration

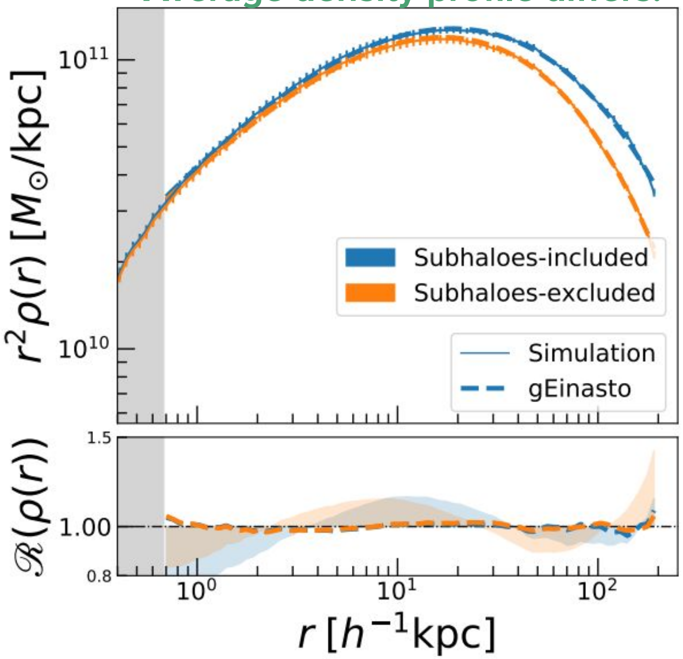


[Wang, YYM, Zentner+ in prep.]



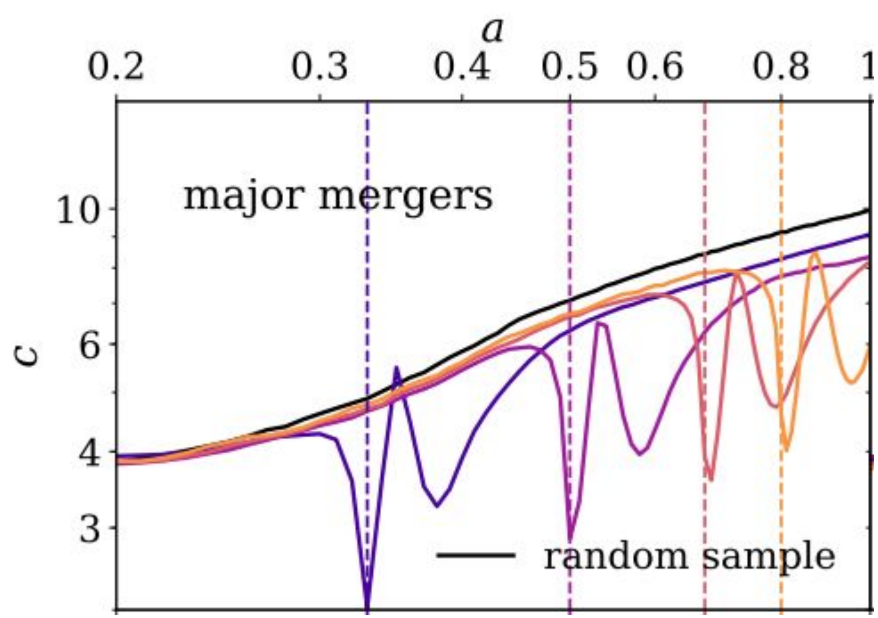
[Fielder, YYM, Newman, Zentner+ in prep.]

Average density profile differs!



[Fielder, YYM, Newman, Zentner+ in prep.]

Merger events changes density profile!

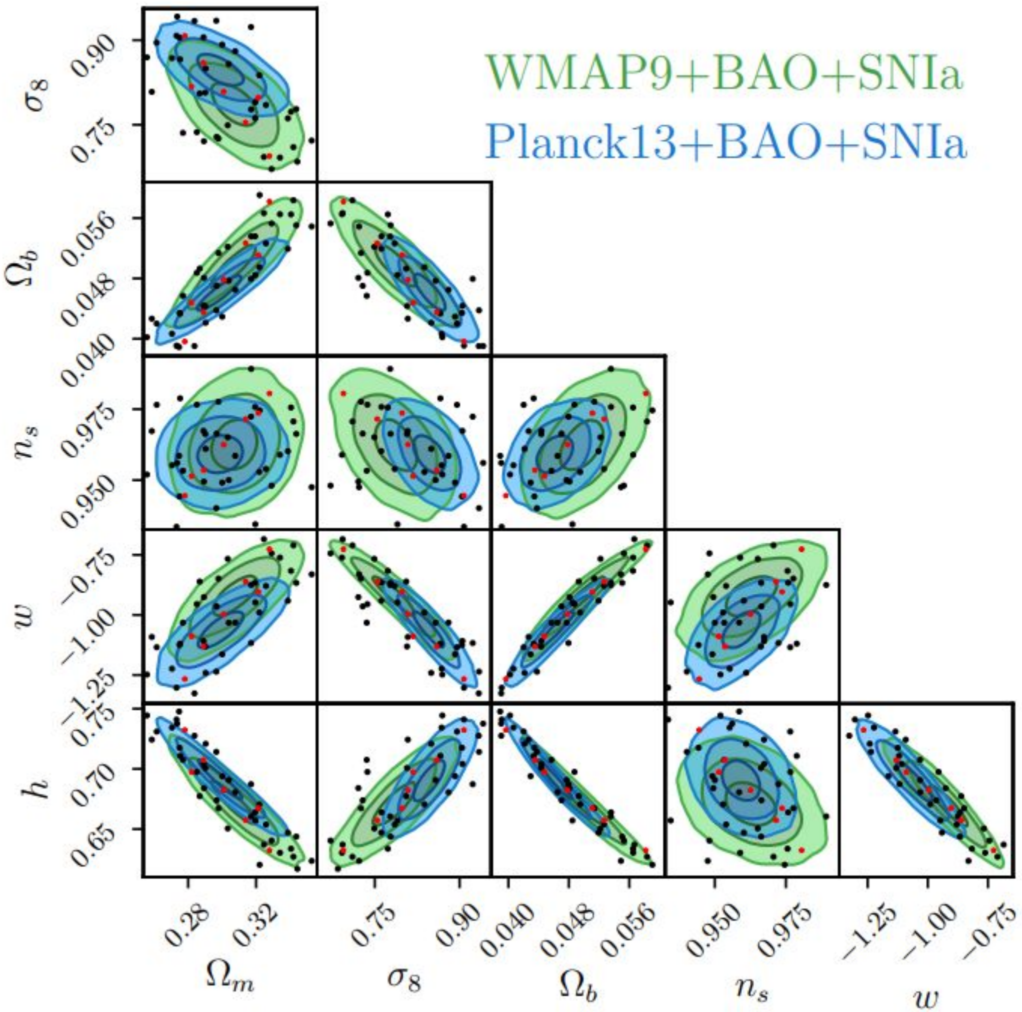


[Wang, YYM, Zentner+ in prep.]

Cosmology / dark matter dependence?

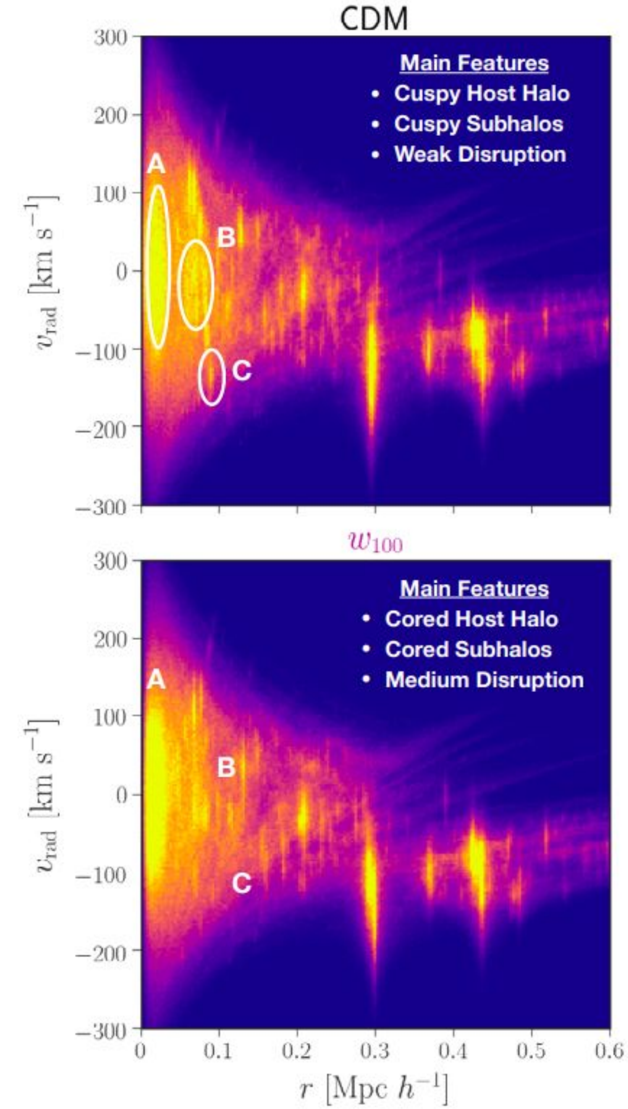
Aemulus Project

Emulating N-body sims



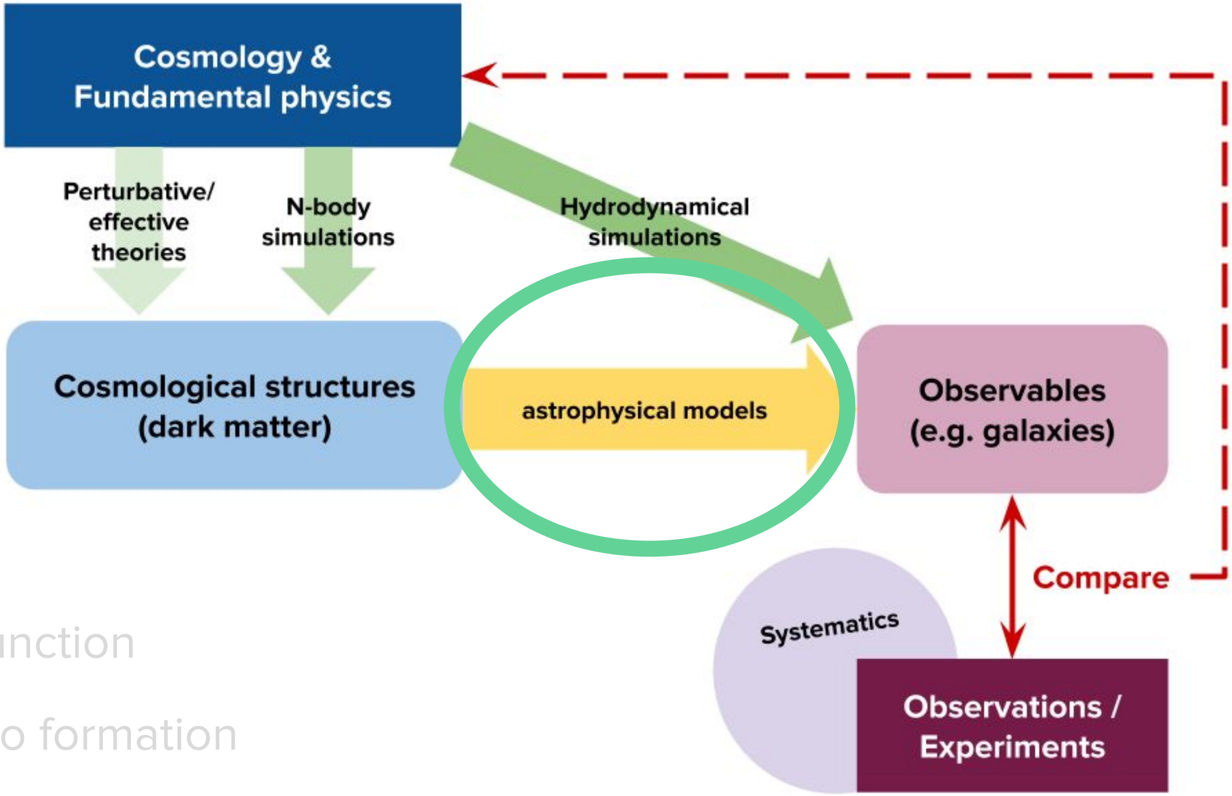
[DeRose, Wechsler, Tinker, Becker, YYM+ 2019 ApJ]

SIDM simulations



[Nadler, Banerjee, Adhikari, YYM+ 2020]

Outline



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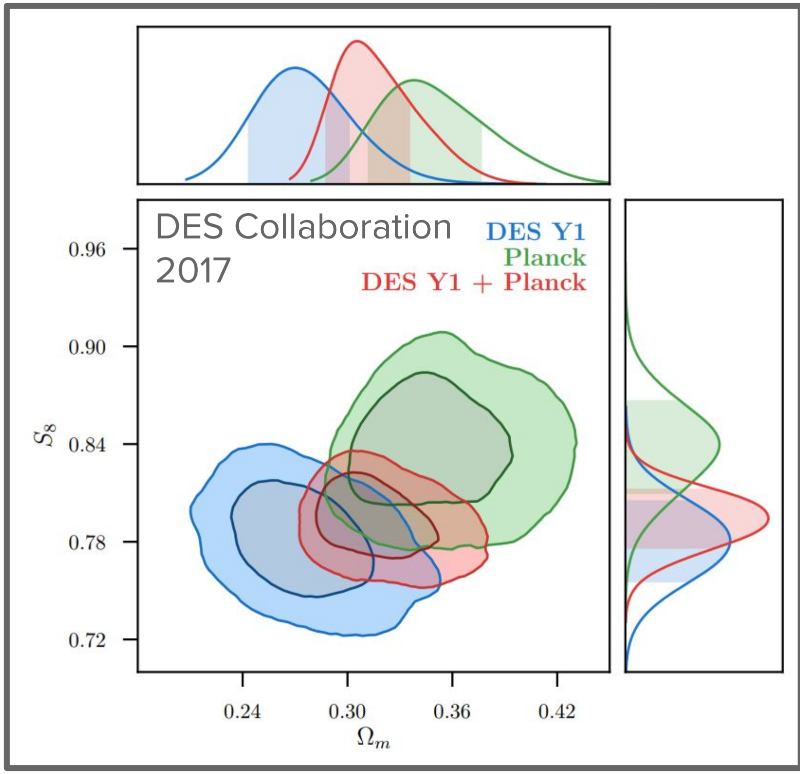
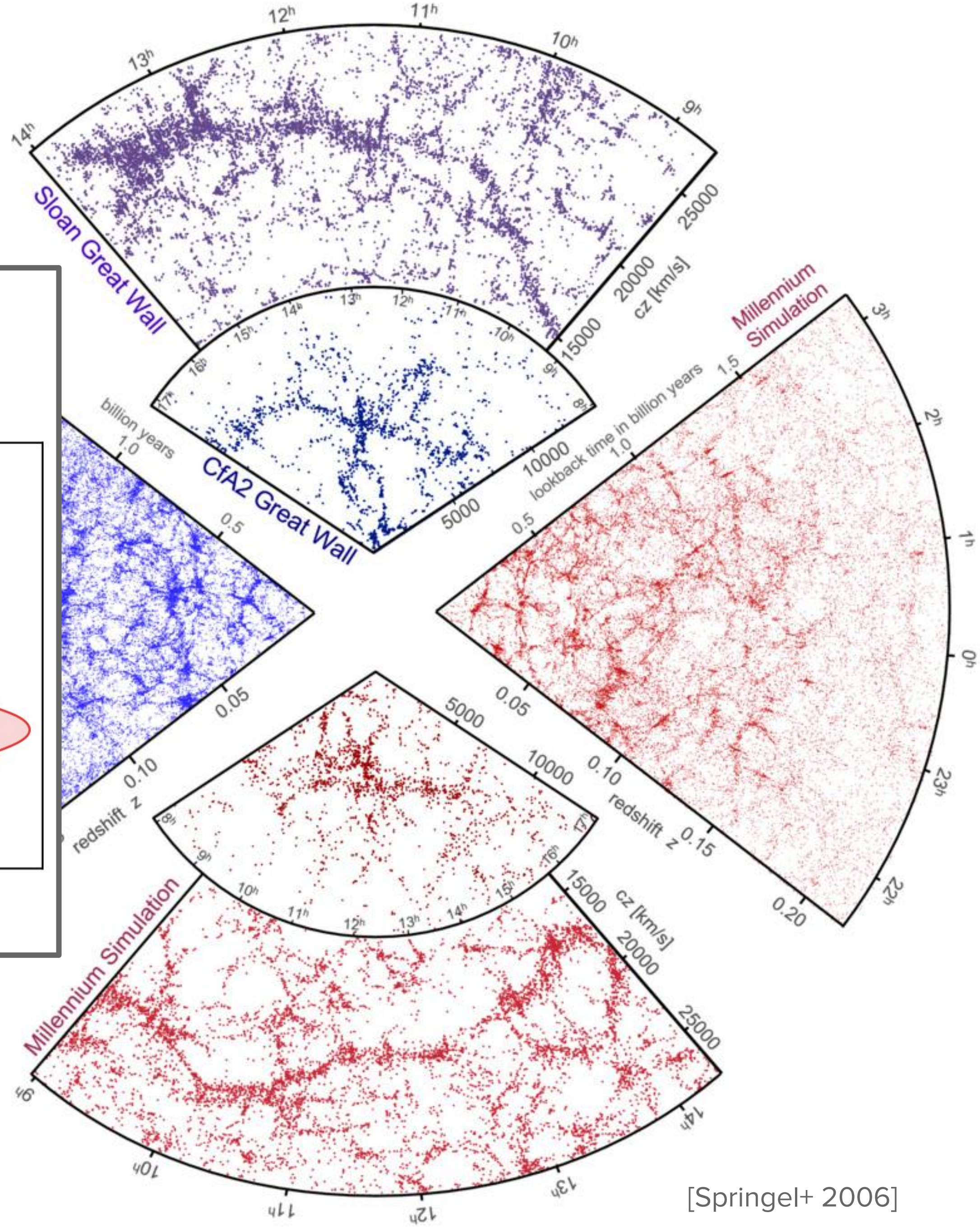
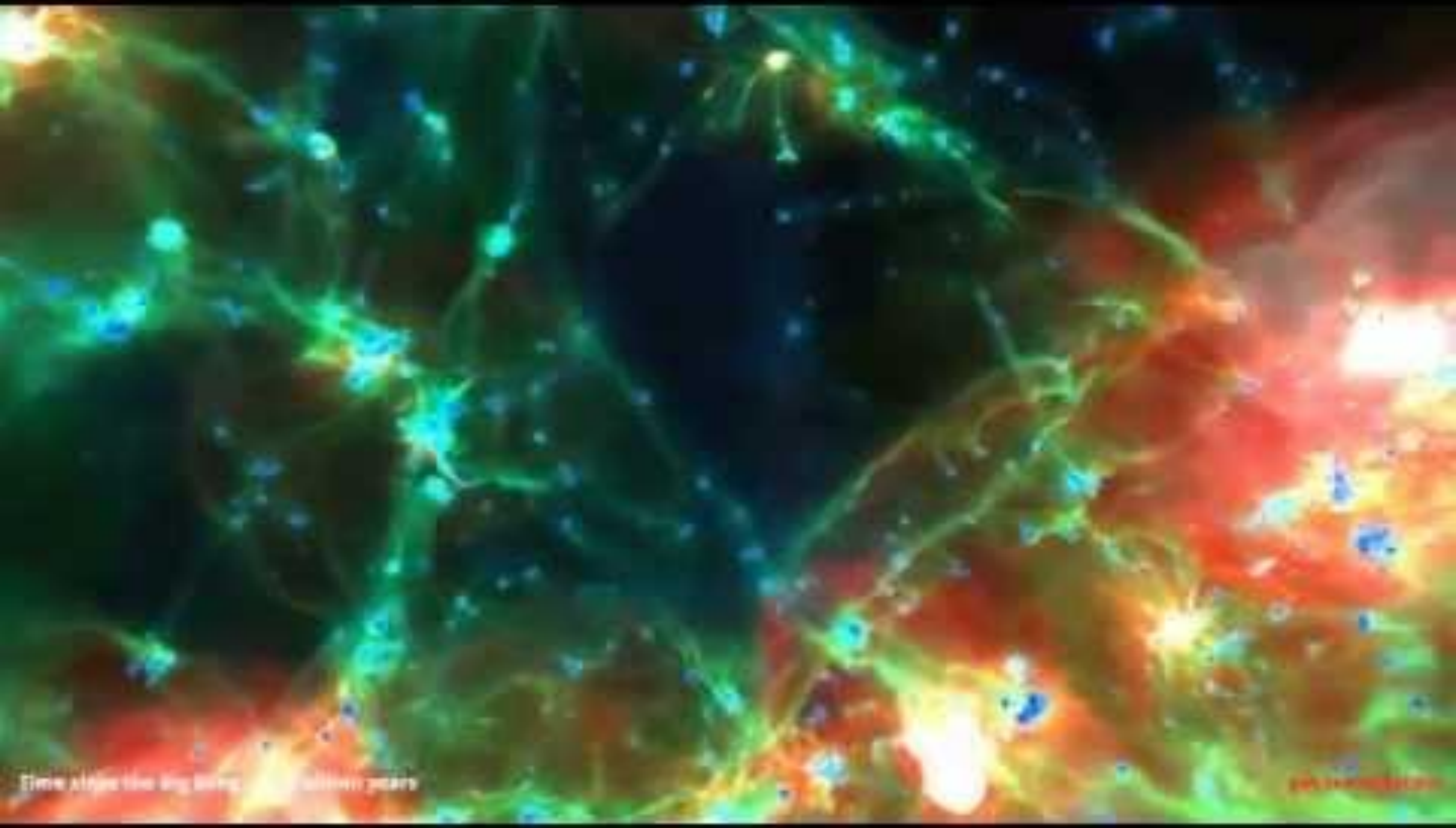
ΛCDM works reasonably well in the late universe...



if we *know* how to map galaxies onto dark structures.



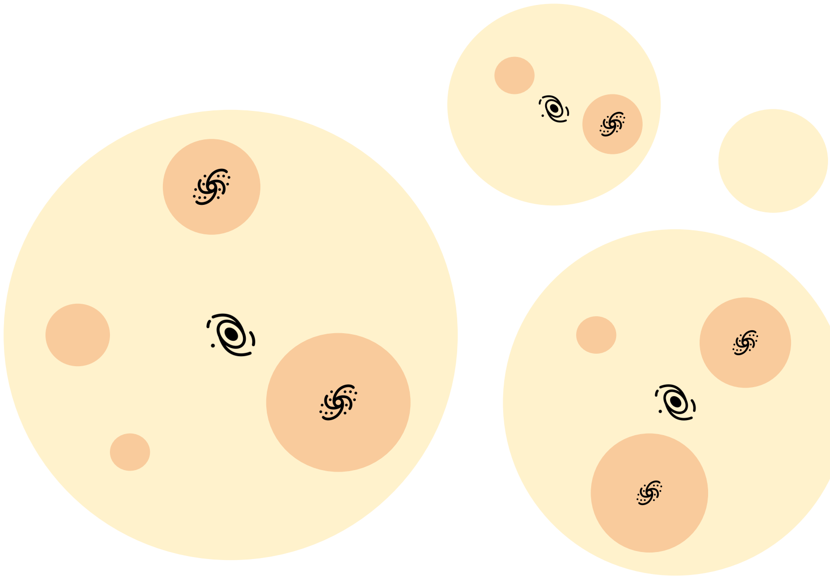
[Springel+ 2006]



[Illustris Simulation of the Universe]
NASA, Harvard CfA, Illustris Collaboration

Empirical modeling of the galaxy-halo connection

A coarse-grained / zoom-out view of galaxy formation. Parametrized models reduce computational costs, and can be marginalized over for cosmological studies.



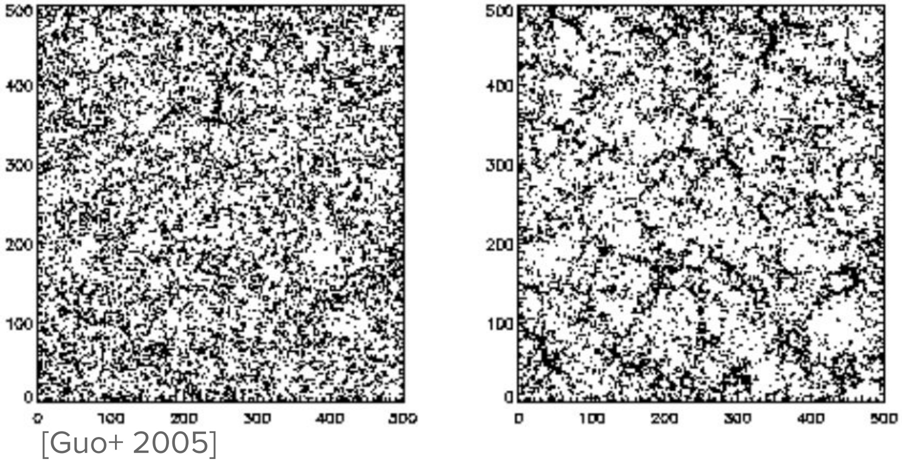
Galaxy properties:
luminosity, stellar mass, colors, sizes, etc.

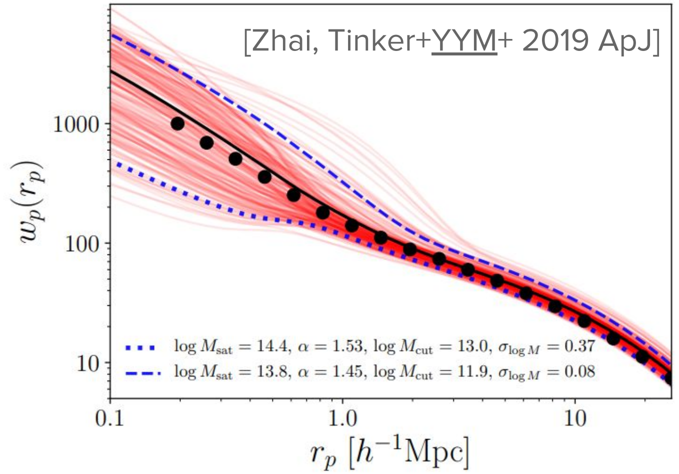
$$P\left(X_1^{\mathrm{gal}}, X_2^{\mathrm{gal}}, \cdots \,\middle|\, X_1^{\mathrm{halo}}, X_2^{\mathrm{halo}}, \cdots\right)$$

Galaxy-halo connection model

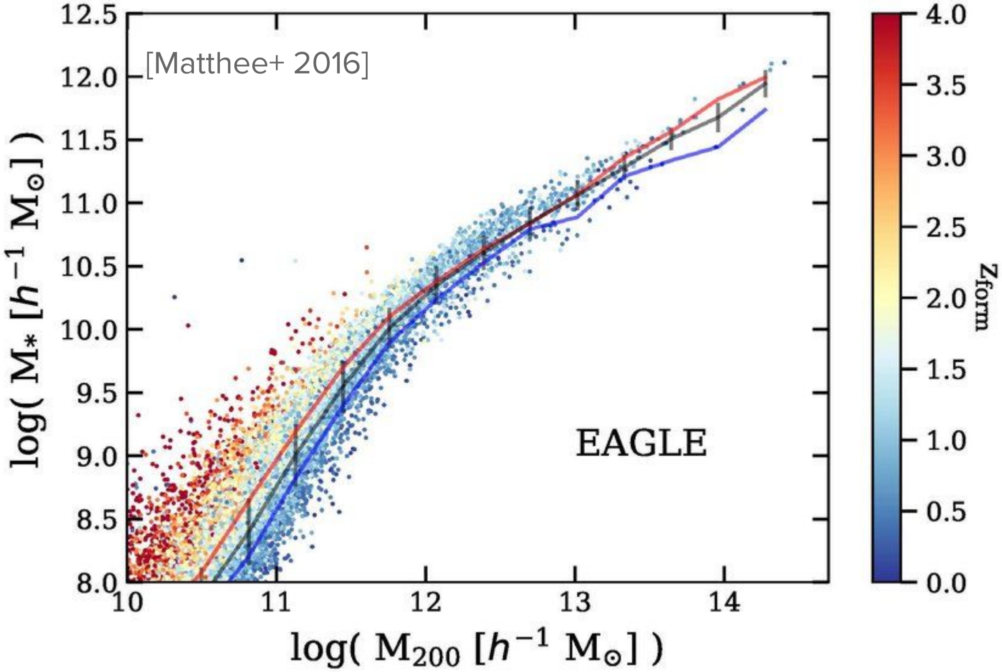
(Sub)Halo properties:
mass, concentration, assembly history, etc

Galaxy assembly bias





Galaxy stellar mass



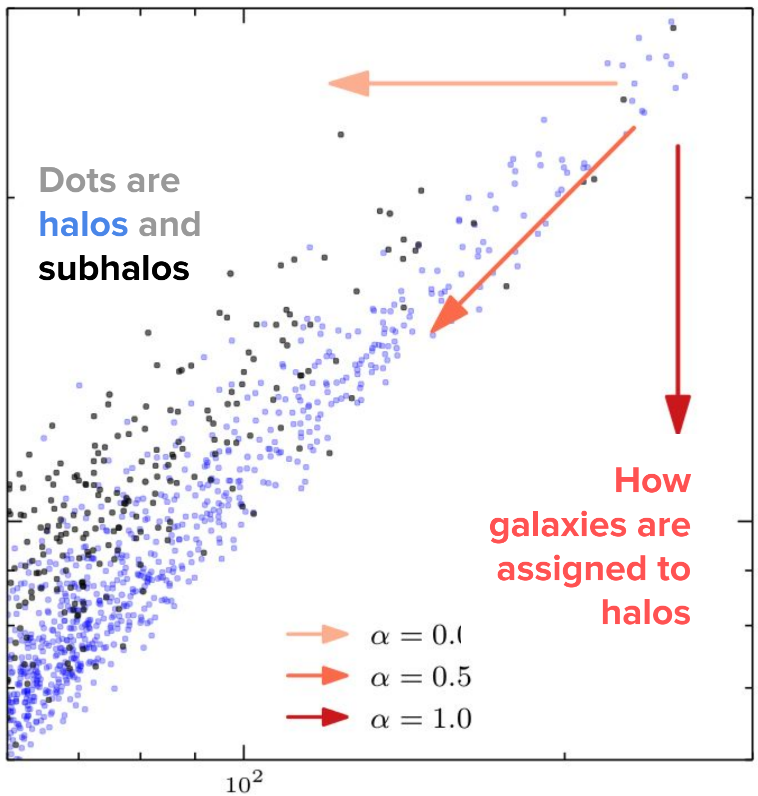
(Host) halo mass

Constraining galaxy assembly bias

A new flexible “subhalo abundance matching” model

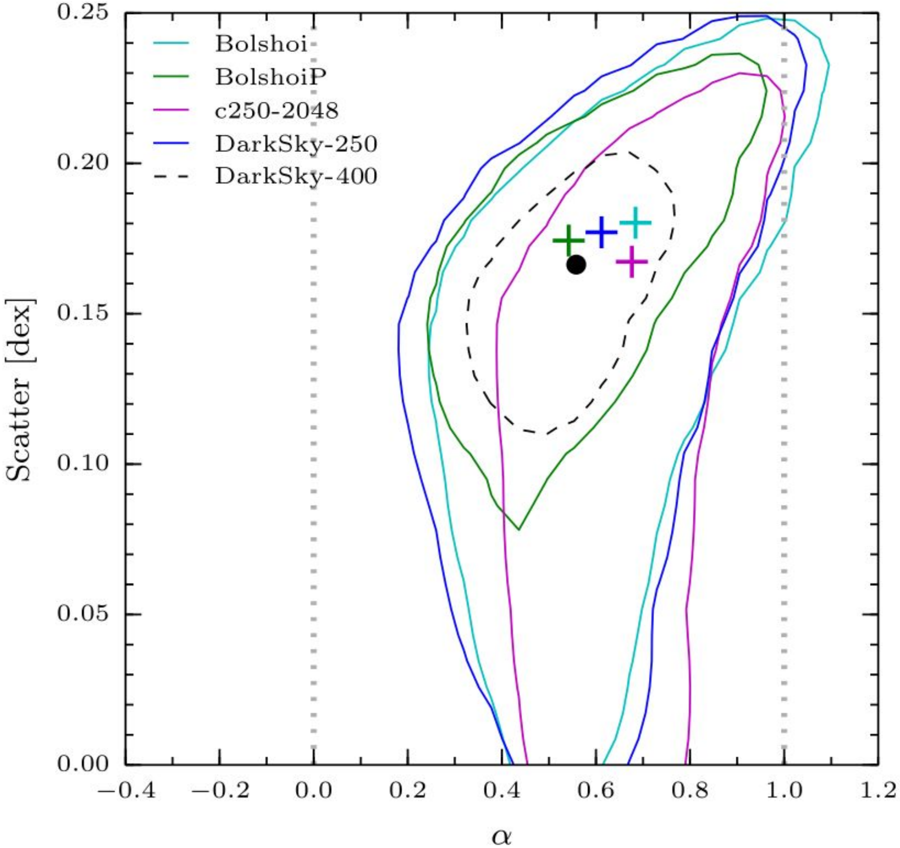
Lehmann, YYM+ 2017 ApJ

Core mass



Conventional mass definition

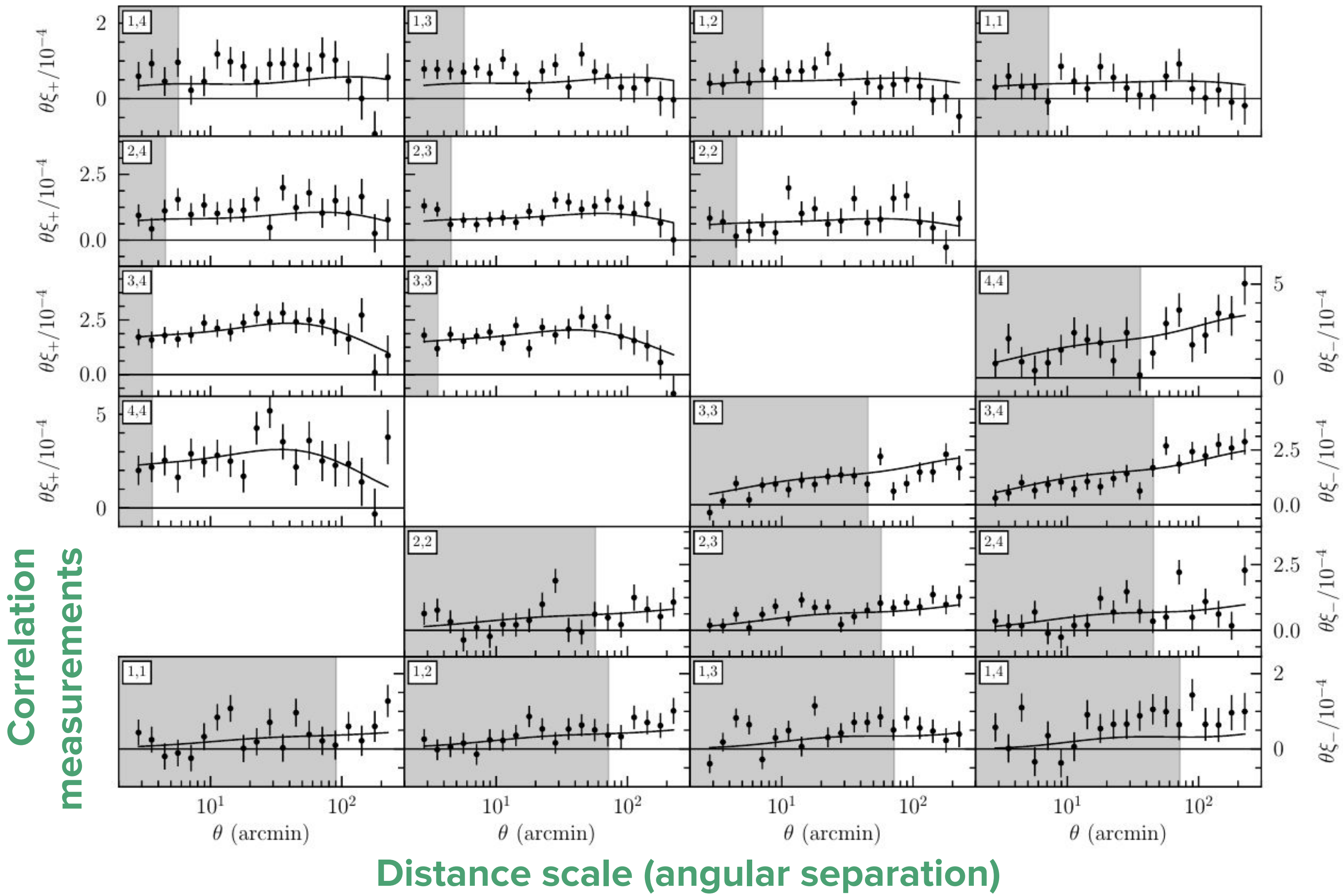
Fit to SDSS data



Conventional mass definition

Core mass

These challenges *already* impact our ability to study cosmology

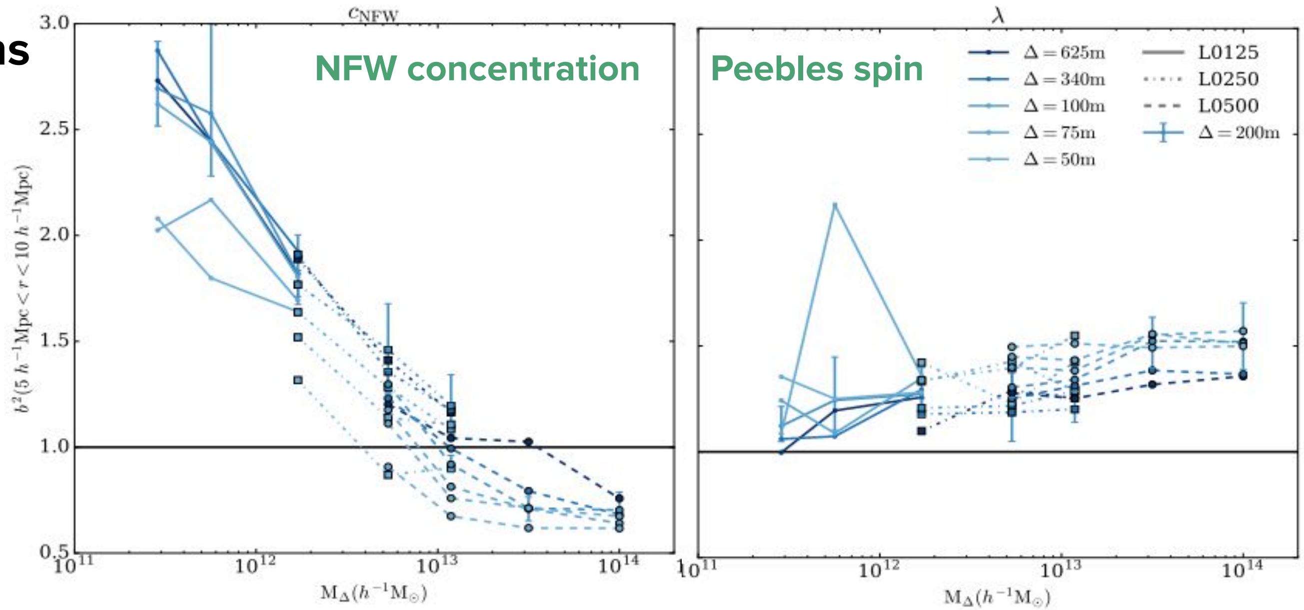


Troxel+ (DES) 2018
Y1 Cosmology from Cosmic Shear

Mitigation of assembly bias

Find better halo definitions

Clustering (bias)



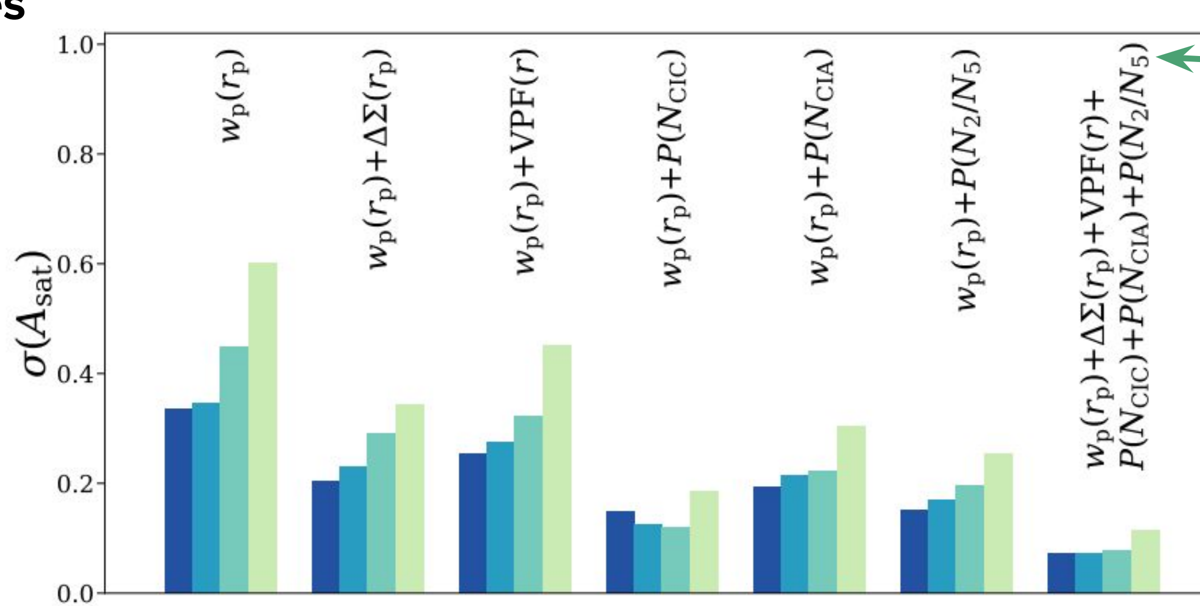
Villarreal, Zentner, YYM+ 2017 MNRAS

See also: YYM+ 2018 MNRAS

Find observables that provide strong priors

Uncertainty

(Inverse of constraining power)



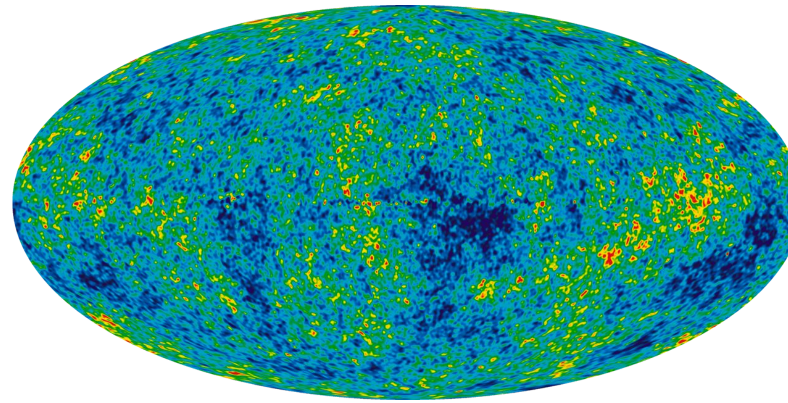
Combinations of observables

Wang, YYM, Znetner, 2019 MNRAS

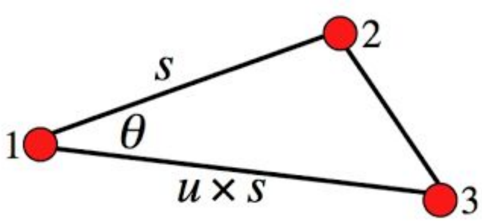
Mitigation: cross-correlation and joint analysis

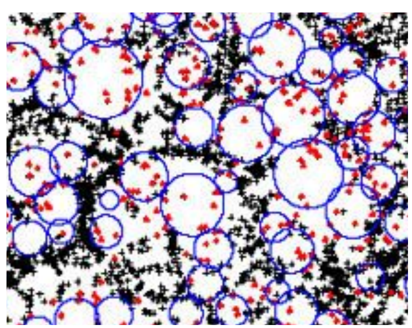
3x2pt analysis
galaxy-galaxy, galaxy-shear, shear-shear

6x2pt analysis
3x2pt + (galaxy, shear, CMB) x CMB

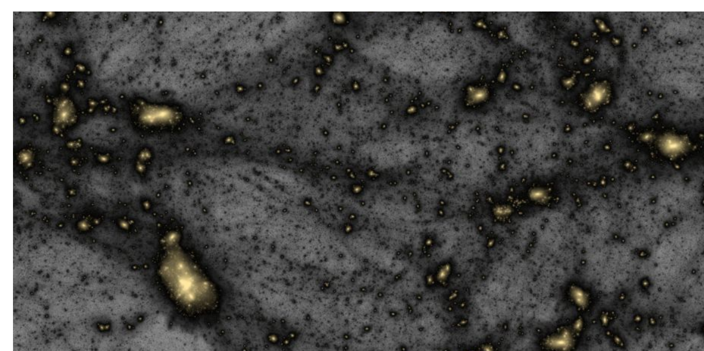


New observables
3pt, n-pt, cylinder stats, void stats



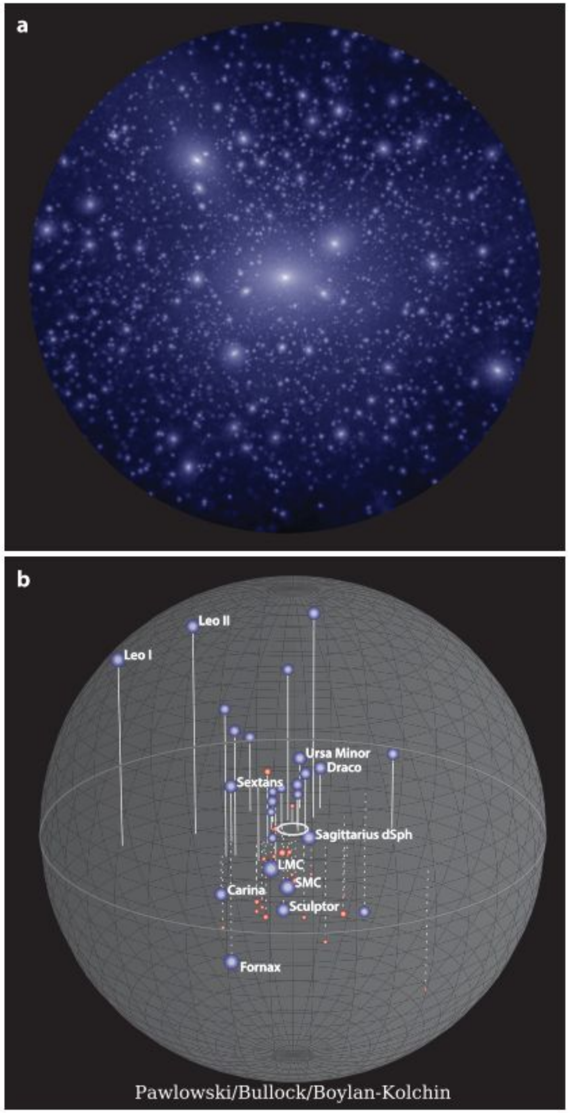


Simulations are still key for developing mitigation plan



Images: DECaLS, NASA, Marin+2011 Pan+ 2011

Applications to small-scale challenges



Images taken from Bullock & Boylan-Kolchin 2017
Simulations done by V. Robles, T. Kelley, and B. Bozek+

Missing Satellites Problem
Observed satellite count does not match simulated substructure counts: too may substructures

Core-cusp Problem
Simulated halo density profile is too cuspy (steep) near the center

Too big to fail Problem
Observed satellites have lower circular velocity than their simulated counterparts

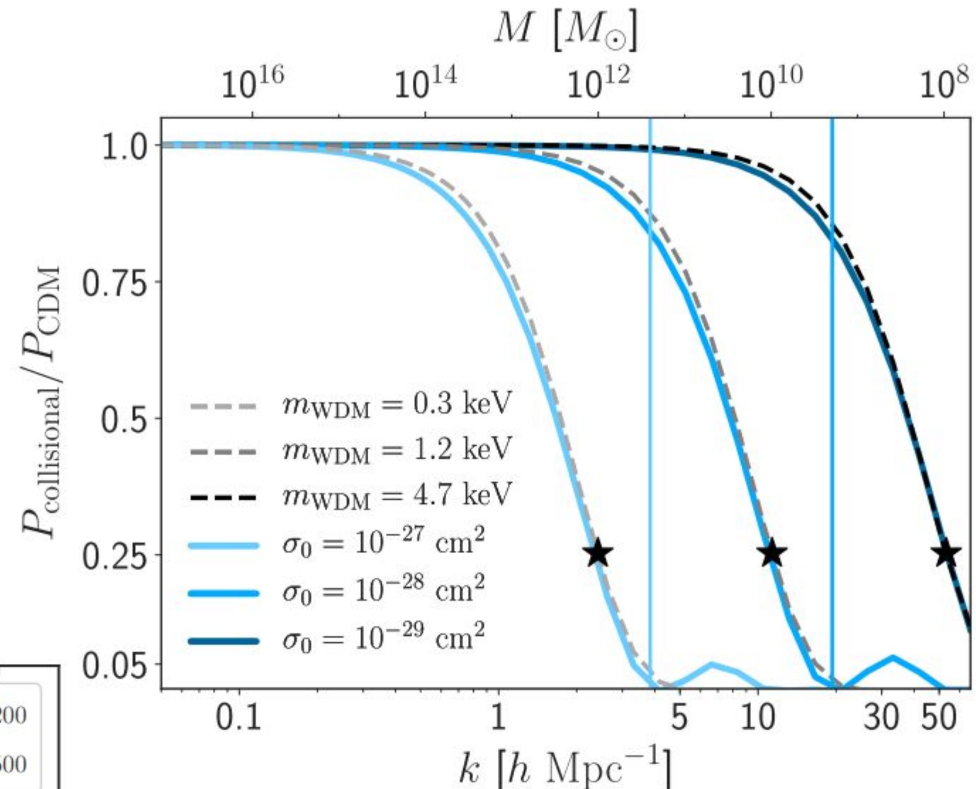
Tight Radial Acceleration Relation
Observed and baryonic radial accelerations have a very tight relationship

Developing a theoretical framework for modeling satellite-dark subhalo connection

Nadler, YYM+ 2018 ApJ

Physical Ingredient	Assumptions	Parameterization	Free Parameter?
3.1 Host Halo Properties	Fixed by zoom-in simulations	None	*No* ($M_{\rm host} = 10^{12.1\pm0.03}$ $M_\odot$)
3.2 Satellite Luminosities	Abundance match to GAMA survey	Non-parametric	*No*
	Extrapolate luminosity function	Faint-end slope α	**Yes** (α is free)
	Lognormal $(M_V \vert V_{\rm peak})$ distribution	Constant scatter σ_M	**Yes** (σ_M is free)
	No satellites below $M_{\rm peak}$ threshold	Cut on $M_{\rm peak} < \mathcal{M}_{\rm min}$	**Yes** ($\mathcal{M}_{\rm min}$ is free)
3.3 Satellite Locations	On-sky positions set by subhalos	None	*No*
	Distances set by scaled subhalo radii	$r_{\rm sat} \equiv \chi r_{\rm sub}$	*No* ($\chi = 1$)
3.4 Satellite Sizes	Jiang et al. (2018) sizes at accretion	$r_{1/2} \equiv \mathcal{A}\,(c/10)^\gamma R_{\rm vir}$	*No* ($\mathcal{A} = 0.02$, $\gamma = -0.7$)
	Size reduction set by stripping	$r'_{1/2} \equiv r_{1/2}\,(V_{\rm max}/V_{\rm acc})^\beta$	*No* ($\beta = 1$)
	Lognormal $(r'_{1/2} \vert R_{\rm vir})$ distribution	Constant scatter σ_R	*No* ($\sigma_R = 0.01$ dex)
3.5 Baryonic Effects	Nadler et al. (2018) disruption model	$p_{\rm disrupt} \rightarrow p_{\rm disrupt}^{1/\mathcal{B}}$	**Yes** ($\mathcal{B}$ is free)
3.6 Orphan Satellites	Correspond to disrupted subhalos	None	*No*
	NFW host + dynamical friction	$\ln\Lambda = -\ln(m_{\rm sub}/M_{\rm host})$	*No*
	Stripping after pericentric passages	$\dot{m}_{\rm sub} \sim -\frac{m_{\rm sub}}{\tau_{\rm dyn}}\left(\frac{m_{\rm sub}}{M_{\rm host}}\right)^{0.07}$	*No*
	$p_{\rm disrupt}$ set by time since accretion	$p_{\rm disrupt} \equiv (1-a_{\rm acc})^{\mathcal{O}}$	*No* ($\mathcal{O} = 1$)

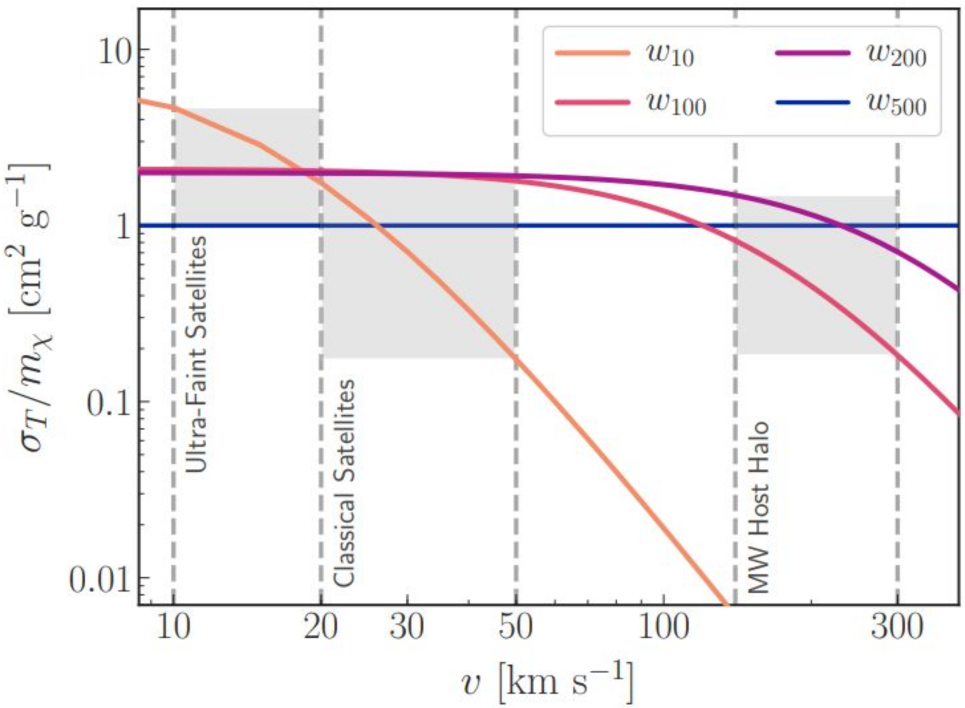
Nature of dark matter impacts macroscopic observations



Warm or Fuzzy Dark Matter →

suppressing power spectrum at high-k end and reduce subhalos

[Nadler+ 2019]



← Velocity-dependent self-interacting DM

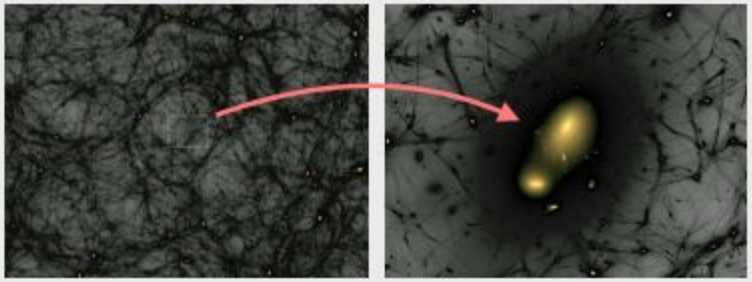
High-v end is well constrained by clusters but much room exist at low-v end

[Nadler, Banerjee, Adhikari, YYM+ 2020]

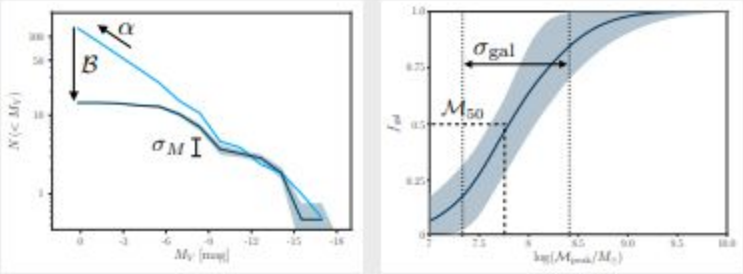
Developing a theoretical framework for satellites

Markov Chain Monte Carlo

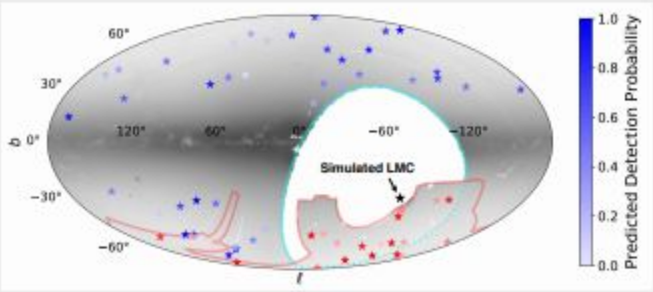
1. Resimulate Milky Way-like halos from large cosmological volume.



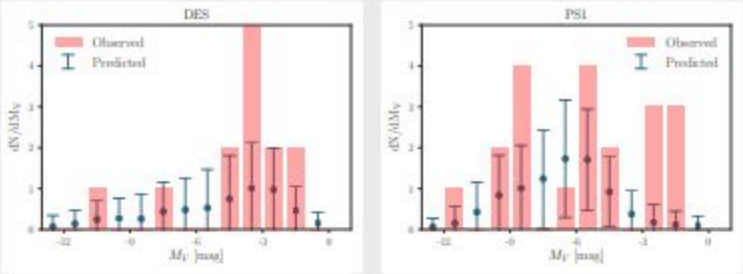
2. Paint satellite galaxies onto subhalos using galaxy—halo model.



3. Apply observational selection functions based on imaging data.

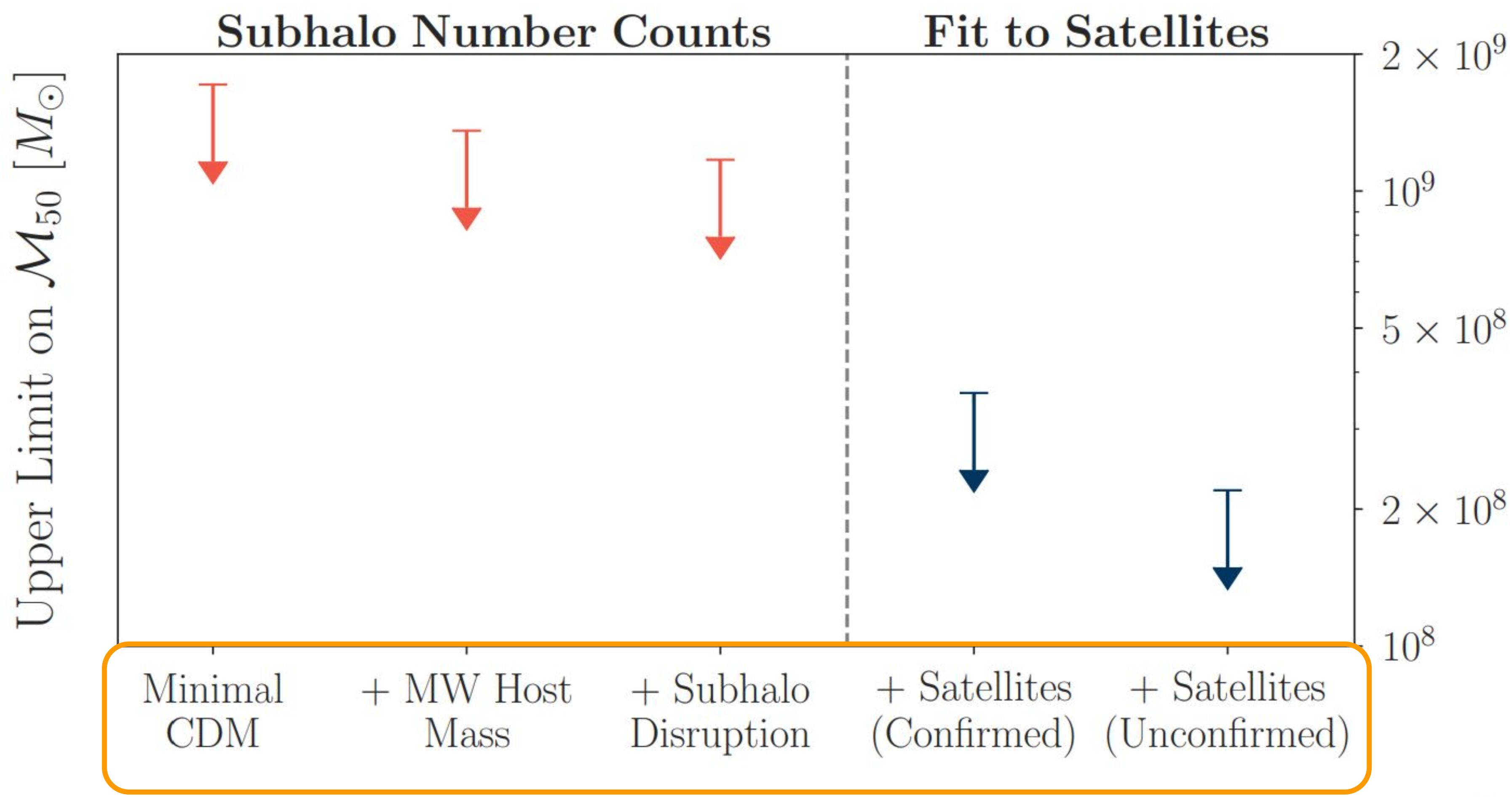


4. Calculate likelihood of observed satellites given galaxy—halo connection parameters.



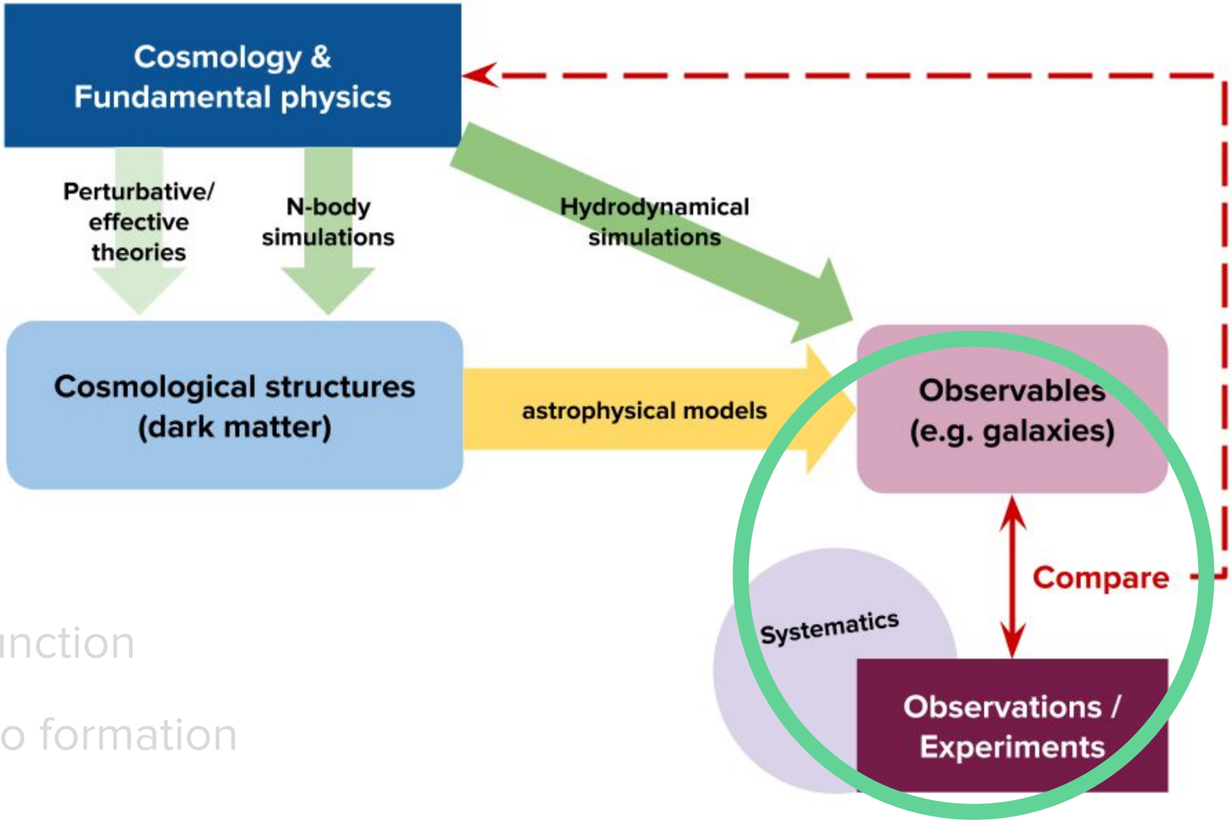
Nadler+YYM+ (DES) 2019

MW satellites ➜ subhalo mass function constraints



Nadler+YYM+ (DES) 2019

Outline



Dark matter distribution

- Velocity distribution function
- Substructures and halo formation

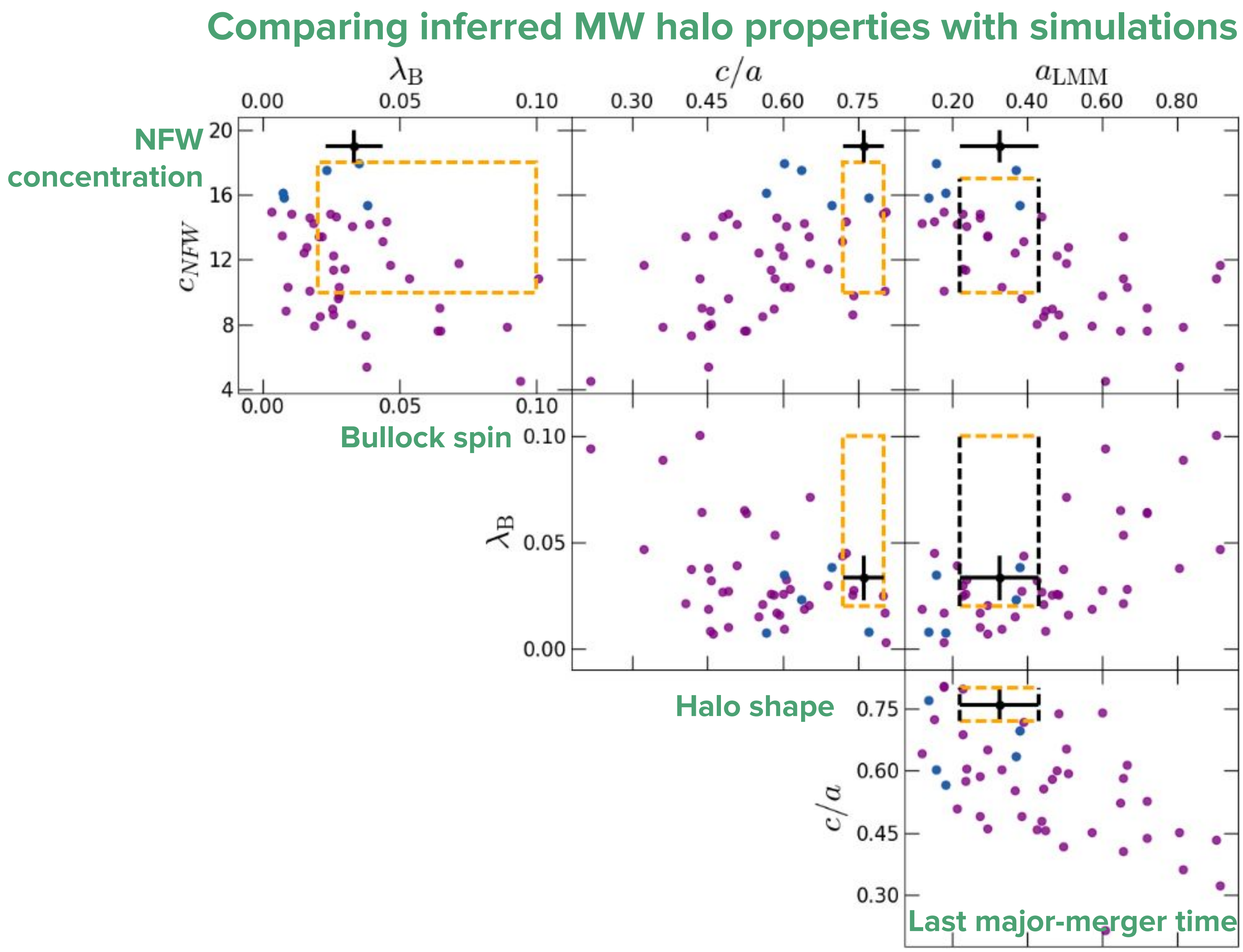
Galaxy-halo connection

- Mitigation of assembly bias for quantitative cosmology
- Comprehensive empirical models for satellite galaxies

Large-scale surveys

- Dwarf galaxies as dark matter laboratories: precursor survey to VRO/LSST
- End-to-end simulations in the LSST Dark Energy Science Collaboration (DESC)

What if Milky Way (or Local Group) is an outlier?

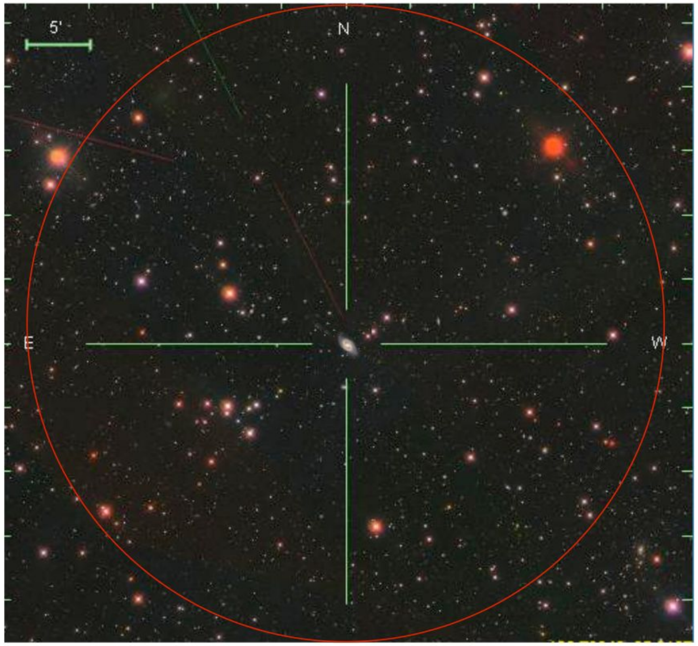


Fielder, YYM, Newman, Zentner+ 2018 MNRAS

With the SAGA Team, including:
Marla Geha (Yale)
Risa Wechsler (Stanford)
Erik Tollerud (STScI)
Ben Weiner (U of Arizona)
Nitya Kallivayalil (UVa)
Ethan Nadler (Stanford)

sagasurvey.org

SAGA Survey Design

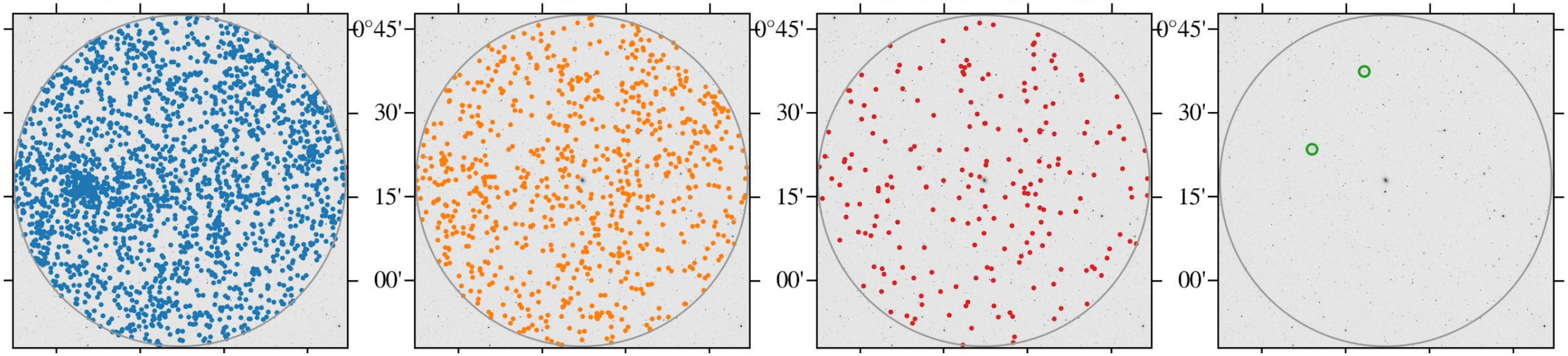


Spectroscopic survey to obtain confirmed distance for satellites

Goal: observe ~**100 MW-like systems between 25 to 40 Mpc.**

Field of view: at 30 Mpc, a virial radius (300 kpc) is equivalent to ~ 1 degree.

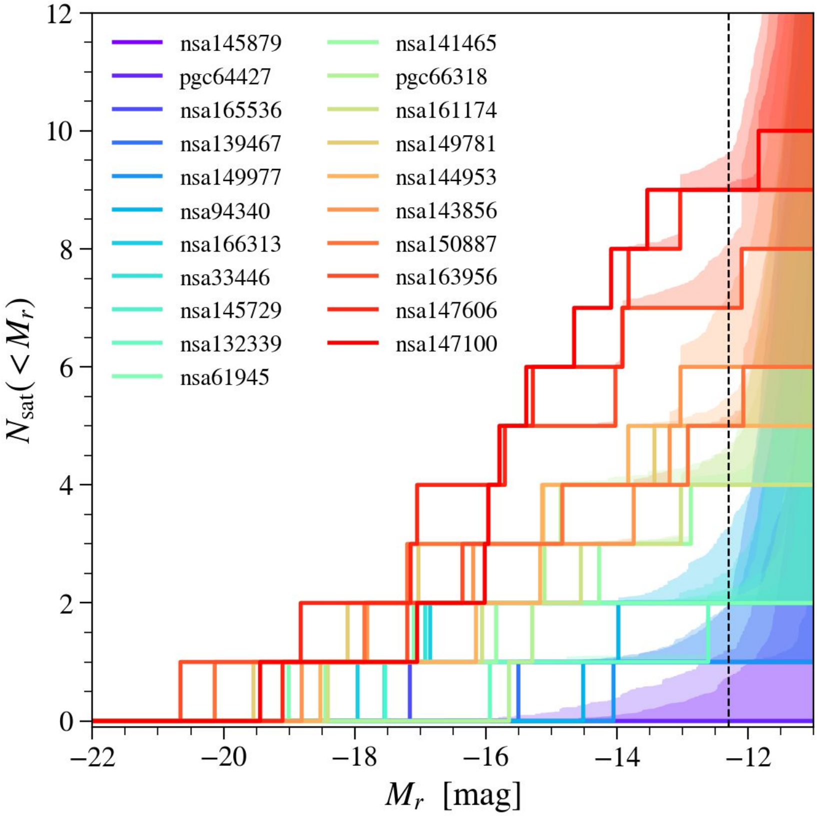
Depth: Mr = -12 is equivalent to r = 21 at 30 Mpc.



[Geha, Weschler, YYM+ 2017. YYM, Geha, Weschler+, in prep.]

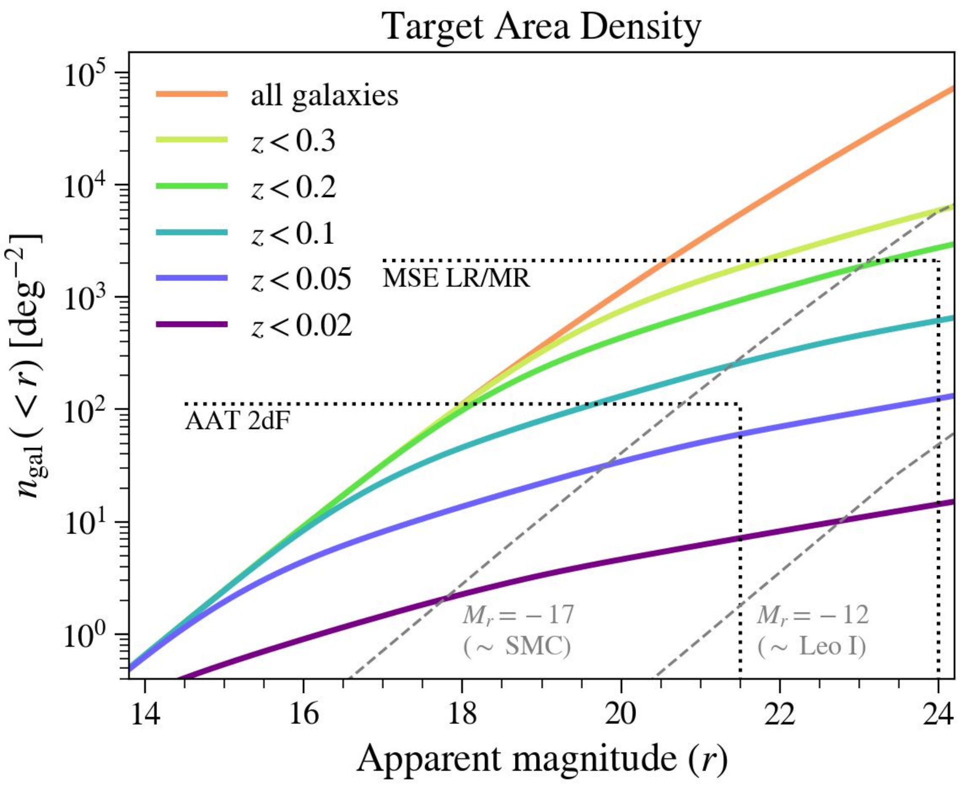
SAGA science and techniques

New dataset of very nearby dwarf galaxies
Puts MW in cosmological context
Rich astrophysics in satellite LF and demographics



[YYM, Geha, Weschler+, in prep.]

Photometric selection for very low-z galaxies
Training data for photo-z calibration

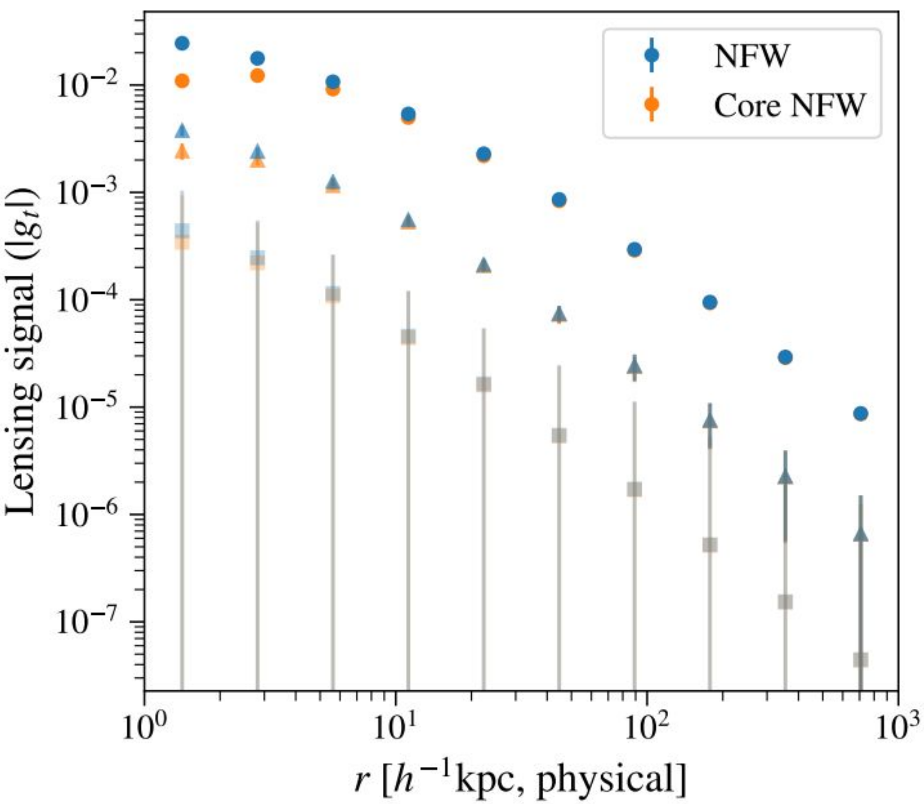


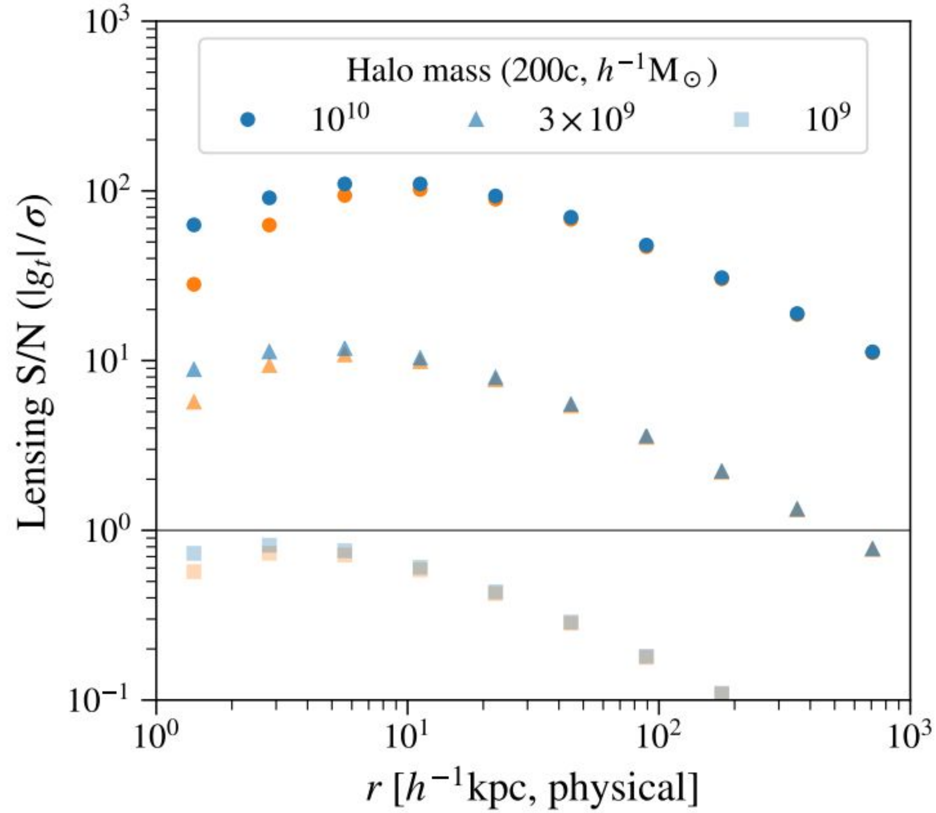
[The MSE Science Team+ YYM+ 1904.04907]

Beyond SAGA - What can we do with VRO/LSST?

VRO/LSST will identify enormous nearby dwarf galaxies, and they can potentially
constraints on the dark matter profiles with weak lensing analysis

Challenges include (1) distance measurement (2) shape noise

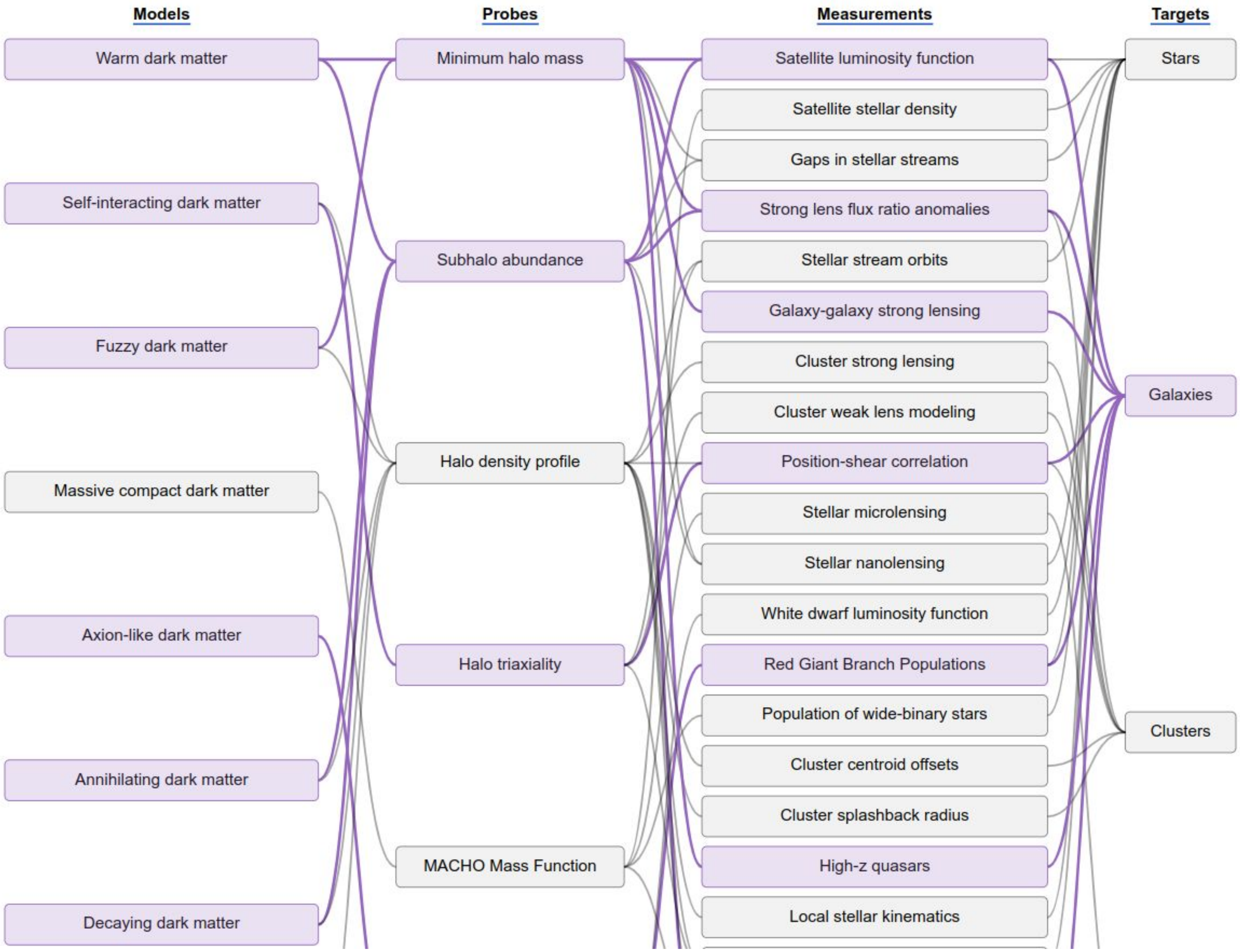




Drlica-Wagner, YYM+ 2019
arXiv:1902.01055

Probing the Nature of Dark Matter with LSST

Co-lead with Alex Drlica-Wagner, Keith Bechtol



lsstdarkmatter.github.io/dark-matter-graph/

White paper: https://arxiv.org/abs/1902.01055

Dark Matter Working Group in LSST DESC

Co-lead with Alex Drlica-Wagner, Keith Bechtol

LSST DESC Dark Energy Science Collaboration

5 main "astrophysical probes" of dark matter

1. Measuring the **minimum halo mass** to test light thermal relics and other dark matter models that suppress halo formation
2. Measuring **halo profiles and shapes** to test if they have been altered by dark matter microphysics
3. Identifying **compact objects** (e.g., primordial black holes) which might make up some fraction of the dark matter
4. Using **large-scale structure** to explore dark matter and dark sector physics
5. Probing **anomalous energy losses in stars**: dark matter that couples to the standard model may change the thermodynamics of stars, altering their internal structure, evolution, and lifetime

Astrophysical constraints on dark matter are not just complementary to particle experiments. They are essential to each other as they must connect to tell the full story.

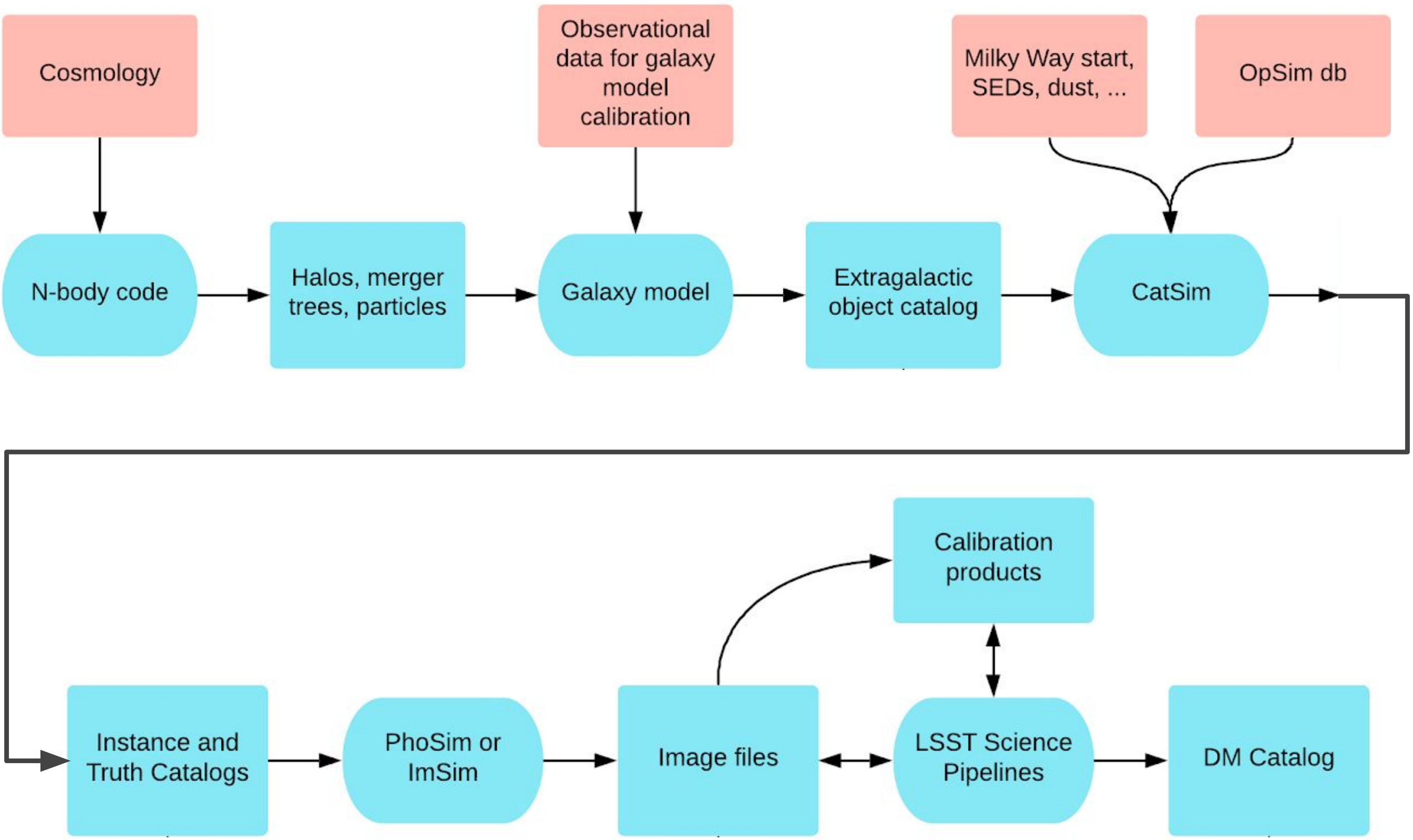
VRO/LSST will come online sooner than you think!

Rubin Observatory

LSST

2021 commissioning & science verification. 2023 full science operation

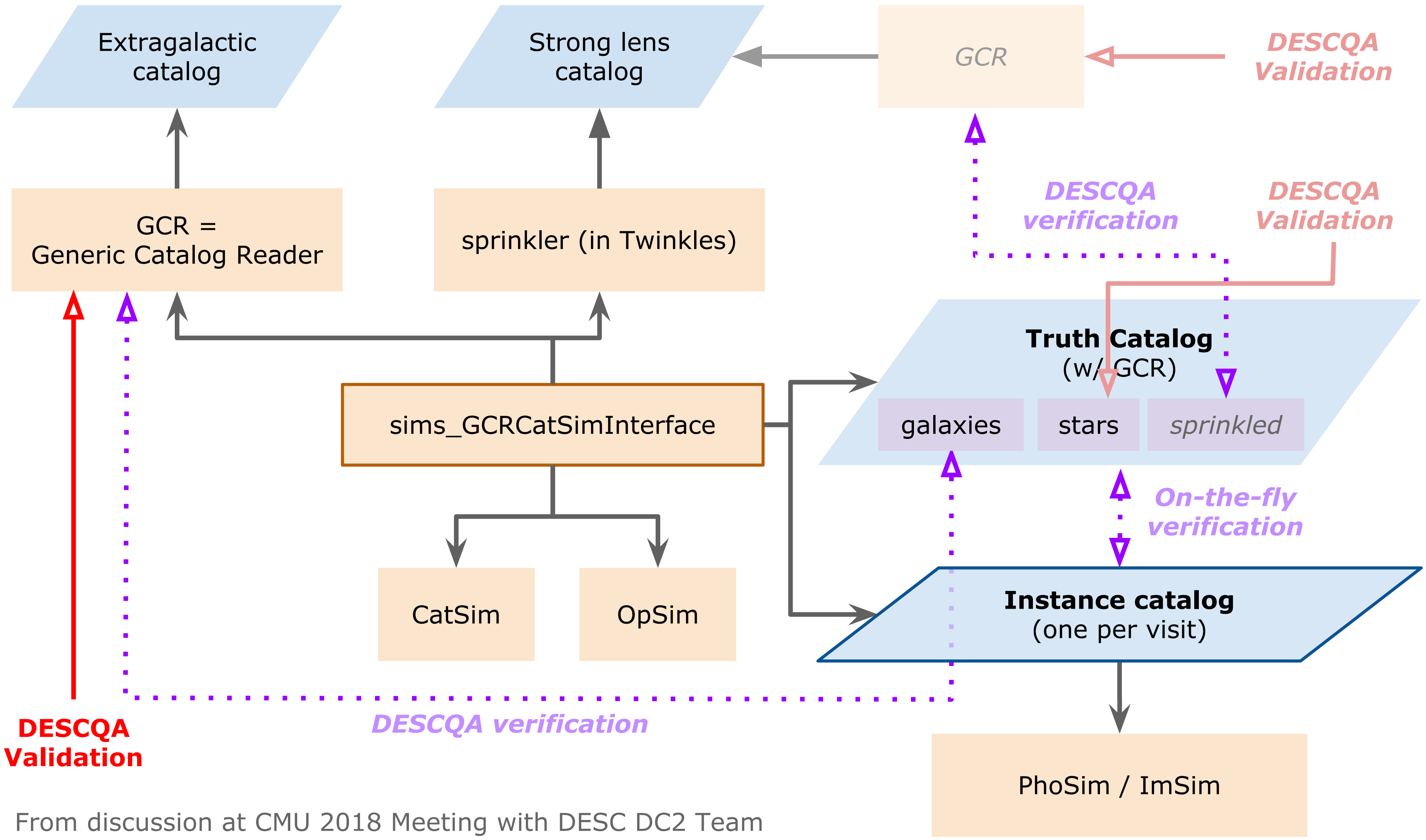
DESC Data Challenge 2 end-to-end simulation



LSST Dark Energy Science Collaboration + YYM (in prep). Figure credit: Katrin Heitmann & DESC DC2 team

Input catalog verification & validation

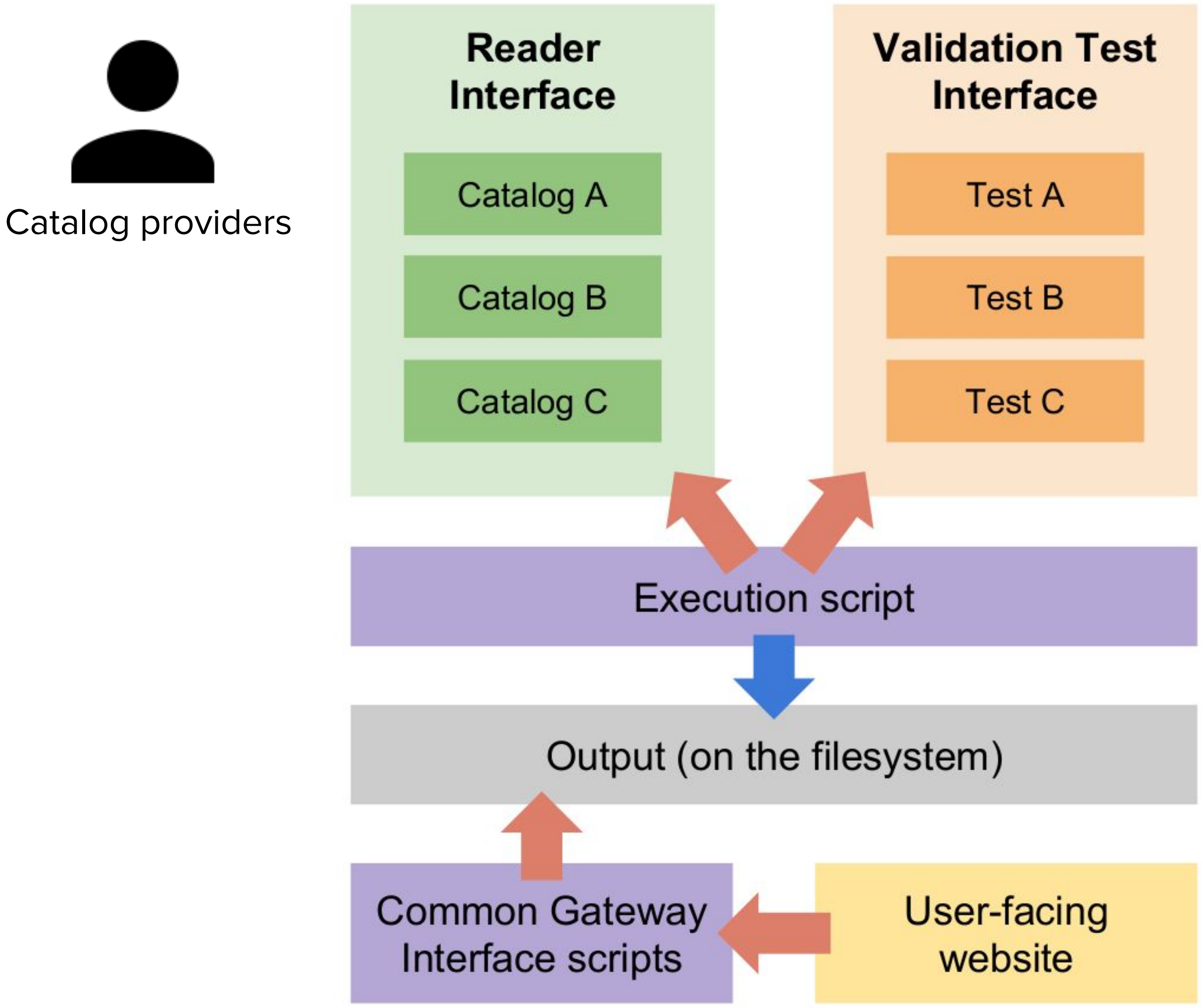
TC; DR: - Use truth catalog to verify/validate instance catalog.
- Need to implement the components that are greyed out in this diagram.



From discussion at CMU 2018 Meeting with DESC DC2 Team
Diagram by YYM

DESCQA: DESC Quality Assurance

A framework for validating and testing mock galaxy catalogs



YYM+ (LSST DESC) 2018 ApJS

DESCQA: DESC Quality Assurance

Web interface for easy access / evaluation

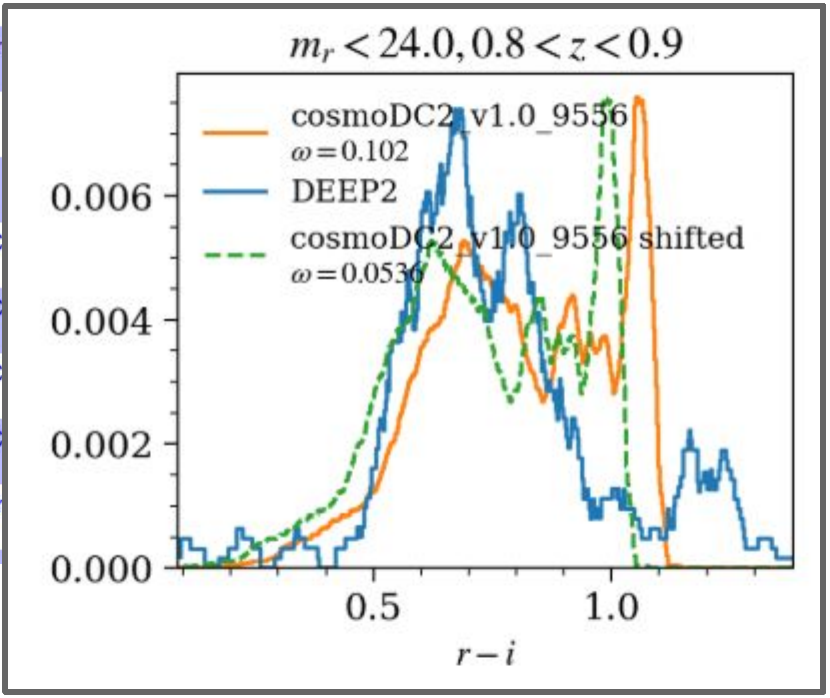
DESCQA (v2): LSST DESC Quality Assurance for Galaxy Catalogs

<< | >> 1 2 3 4 5

Users: kovacs *Tests:* *Catalogs:* cosmoDC2_v1.0 Search

Legend: *Run did not successfully complete* *Run completed but some tests have execution errors* *All tests successfully completed (but may be skipped or may not pass the test)*

2018-11-21_2 (kovacs)	green	TESTS: CheckColors CATALOGS: cosmoDC2_v1.0_9813_10193
2018-11-21_1 (kovacs)	green	TESTS: Color_Dist_SDSS CATALOGS: cosmoDC2_v1.0_9813_10193
2018-11-21 (kovacs)	green	TESTS: Color_Dist_DEEP2 CATALOGS: cosmoDC2_v1.0_9813_10193
2018-11-16_3 (kovacs)	green	TESTS: SkyArea CATALOGS: cosmoDC2_v1.0_9556
2018-10-11_1 (kovacs)	green	TESTS: ApparentMagFuncTest_HSCi | ApparentMagFuncTest_HSCr CATALOGS: catsim_9556_addon_soln1 | cosmoDC2_v1.0_9556
2018-10-10_5 (kovacs)	green	TESTS: Color_Dist_DEEP2_with_LSST CATALOGS: catsim_9556_addon_soln1 | cosmoDC2_v1.0_9556
2018-10-10_4 (kovacs)	yellow	TESTS: Color_Dist_DEEP2_with_LSST CATALOGS: catsim_9556_addon_soln1 | cosmoDC2_v1.0_9556
2018-10-10_3 (kovacs)	yellow	TESTS: ApparentMagFuncTest_HSCg | ApparentMagFuncTest_HSC CATALOGS: catsim_9556_addon_soln1 | cosmoDC2_v1.0_9556
2018-10-10_2 (kovacs)	yellow	TESTS: ApparentMagFuncTest_HSCg | ApparentMagFuncTest_HSC CATALOGS: catsim_9556_addon_soln1 | cosmoDC2_v1.0_9556
2018-10-10_1 (kovacs)	yellow	TESTS: ApparentMagFuncTest_HSCg | ApparentMagFuncTest_HSC CATALOGS: catsim_9556_addon_soln1 | cosmoDC2_v1.0_9556
2018-10-10 (kovacs)	green	TESTS: ApparentMagFuncTest_HSCg | ApparentMagFuncTest_HSC CATALOGS: catsim_9556_addon_soln1 | cosmoDC2_v1.0_9556
2018-09-25_5 (kovacs)	green	TESTS: ApparentMagFuncTest_HSCi | ApparentMagFuncTest_HSCr CATALOGS: cosmoDC2_v1.0_564 | proto-dc2_v3.0



YYM+ (LSST DESC) 2018 ApJS

LSSTDESC / **descqa** ✓

Unwatch 26 | Unstar 4 | Fork 26

Code | Issues 23 | Pull requests 11 | Releases 8 | More | Settings

Filters | is:pr label:"validation: extragalactic" sort:upda | Labels | Milestones | **New pull request**

Clear current search query, filters, and sorts

9 Open ✓ 25 Closed | Open All | Author | Labels | Projects | Milestones | Reviews | Assignee | Sort

velocity dispersion relationship of galaxy clusters ✕ — 2
#132 opened on Aug 3, 2018 by jbbutler • Review required • updated 23 days ago
validation: extragalactic

issue109 - Adding validation test for stellar mass distribution of galaxies and their number densities ✕ — 1
#146 opened on Aug 22, 2018 by Andromedanita • Review required • updated on Dec 10, 2018
developing | validation: extragalactic

redmapper conditional luminosity function test ✕ — 18
#102 opened on Apr 10, 2018 by chto • Changes requested • updated on Dec 9, 2018
validation: extragalactic

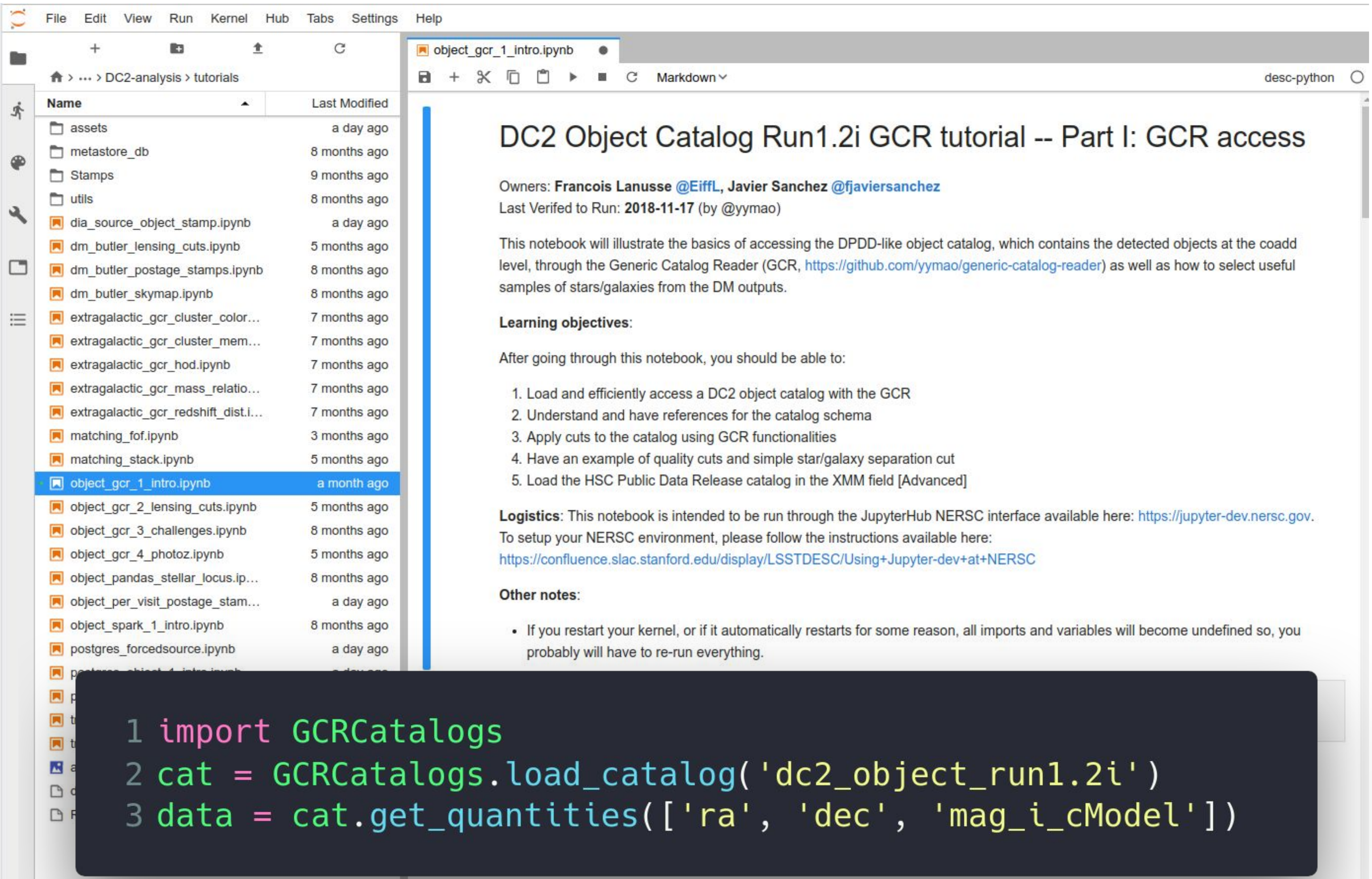
Size luminosity test • — 37
#95 opened on Mar 26, 2018 by vvinuv • Review required • updated on Dec 9, 2018
validation: extragalactic

red sequence validation test ✕ — 15
#101 opened on Apr 9, 2018 by j-dr • Changes requested • updated on Dec 5, 2018
validation: extragalactic

add new validation datasets to galaxy-shear correlation test (#128) ✕ — 24
#131 opened on Aug 3, 2018 by chihway • Review required • updated on Dec 5, 2018
validation data | validation: extragalactic

LSST DESC Dark Energy Science Collaboration

Enabling the community: “Stack Club” in DESC



DC2 Tutorials

LSST DESC Dark Energy Science Collaboration

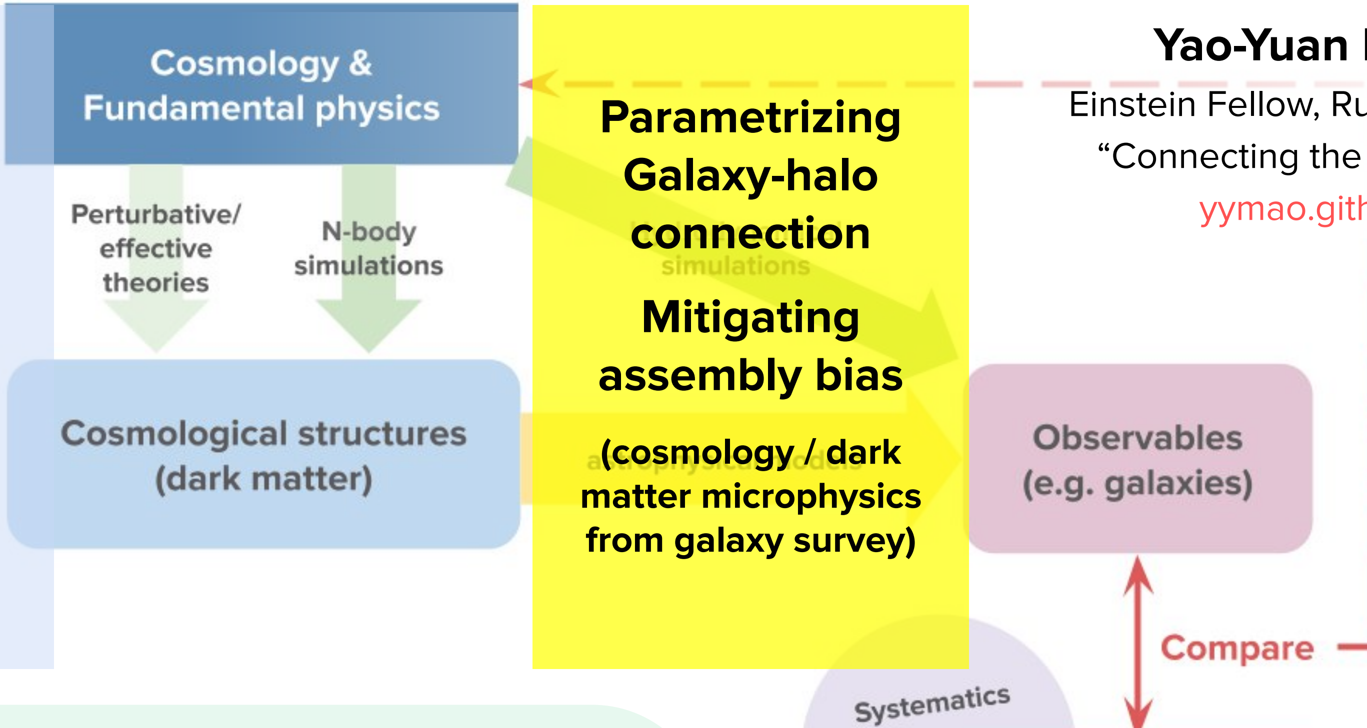
This directory contains tutorial and demonstration notebooks convering how to access and use the DC2 datasets. See the index table below for links to the notebook code, and an auto-rendered view of the notebook with outputs.

Notebook	Short description	Links	Owner
Object catalog GCR Tutorial Part I: GCR access	Use the GCR for simple access to the object catalogs	ipynb, rendered build passing	Francois Lanusse, Javier Sanchez
Object catalog GCR Tutorial Part II: Lensing Cuts	Use the GCR to access the object catalog and build a lensing sample similar to the HSC Y1 shape catalog	ipynb, rendered build passing	Francois Lanusse, Javier Sanchez
Object catalog GCR Tutorial Part III: Guided Challenges	Use the GCR to access the object catalog and solve some typical data analysis problems	ipynb, rendered build passing	Francois Lanusse, Javier Sanchez
Object catalog GCR Tutorial Part IV: Photo-z information	Use the GCR to access the Photo-z information that are provided as an "add-on" to the object catalog	ipynb, rendered build passing	Yao-Yuan Mao, Sam Schmidt
Object catalog with Spark	Introduction of using Spark to access the object catalogs	ipynb, rendered build passing	Julien Peloton

N-body simulations

Velocity distribution
(direct detection)

Substructure & halo profile
(strong lensing, indirect detection)



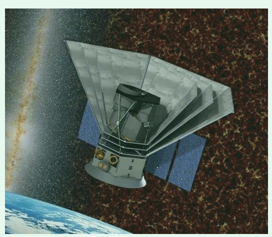
Parametrizing Galaxy-halo connection

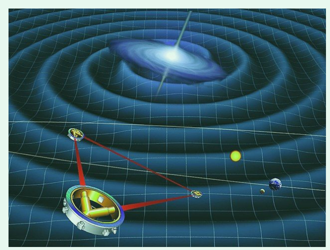
Mitigating assembly bias

(cosmology / dark matter microphysics from galaxy survey)

Yao-Yuan Mao
Einstein Fellow, Rutgers
“Connecting the dots”
yymao.github.io

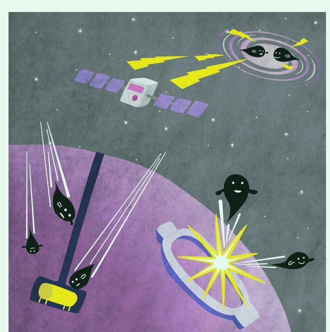
Rubin Observatory LSST





euclid

SIMONS OBSERVATORY



WIDE-FIELD INFRARED SURVEY TELESCOPE WFIRST ASTROPHYSICS • DARK ENERGY • EXOPLANETS

CMB-S4 Next Generation CMB Experiment

SAGA Survey

LSST Dark matter

DC2 Challenge in LSST DESC

Building a community to connect thoery and observations