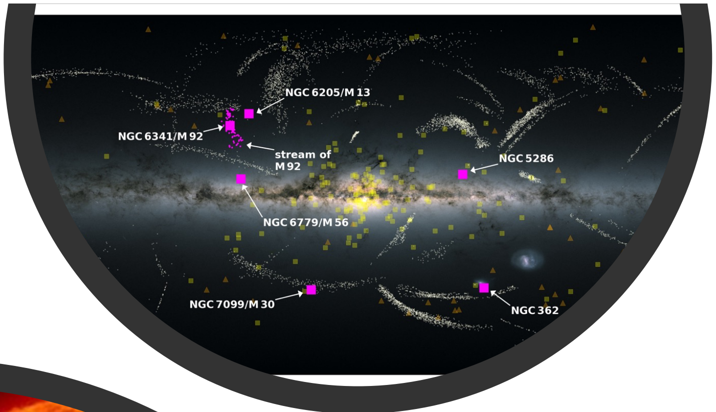
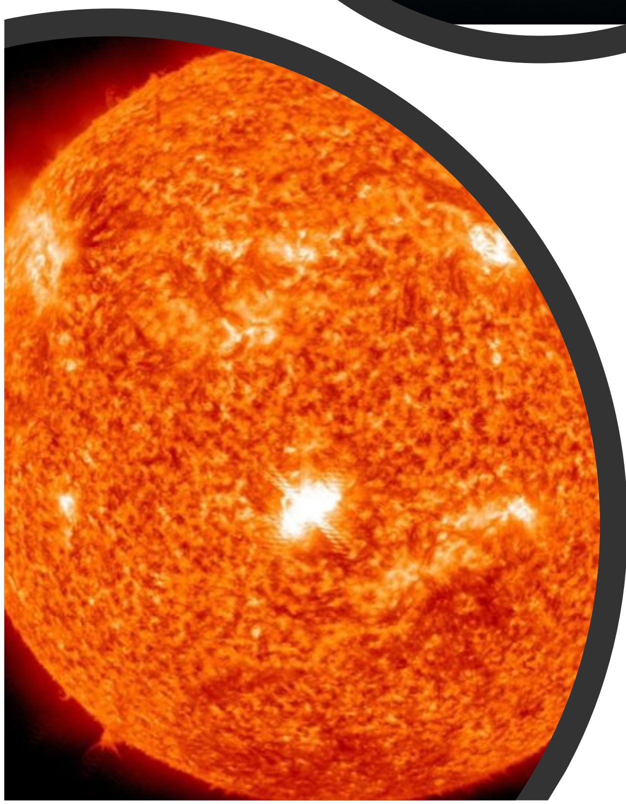
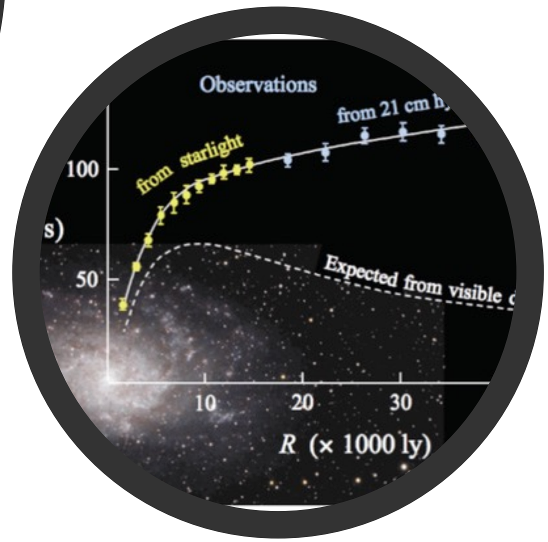
Preparing simulations for the precision era of dark matter cosmology

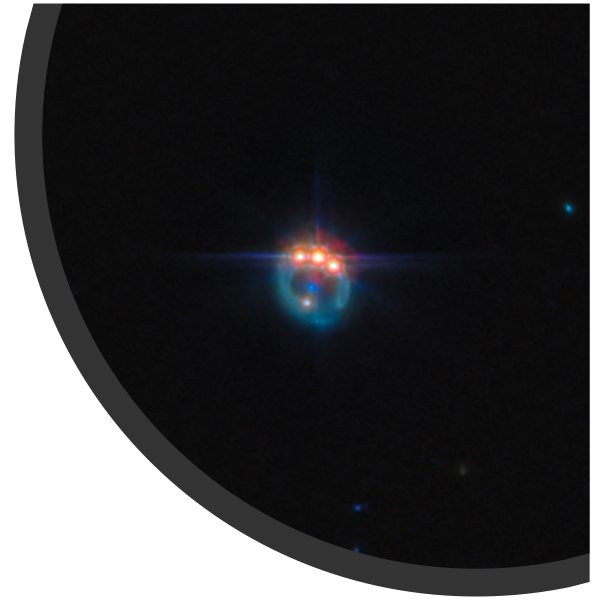
Annika Peter
The Ohio State University

N-Body Shop https://astro.washington.edu/n-body-shop

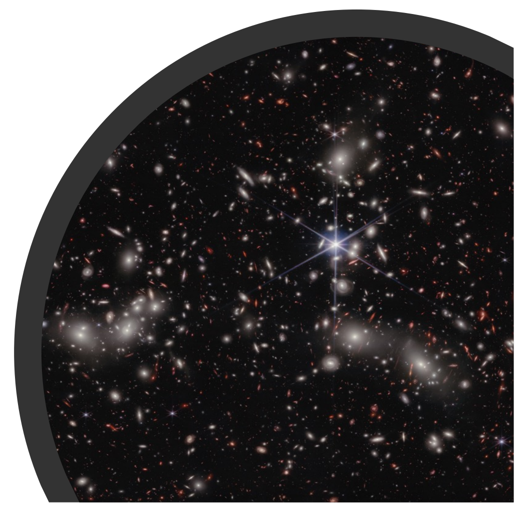




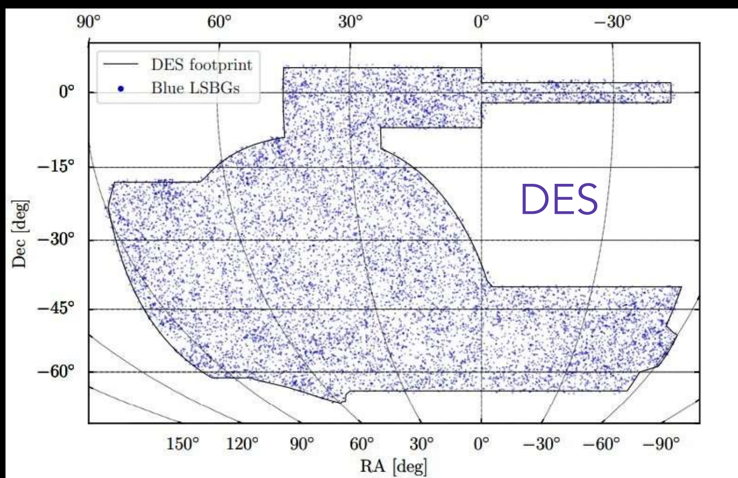


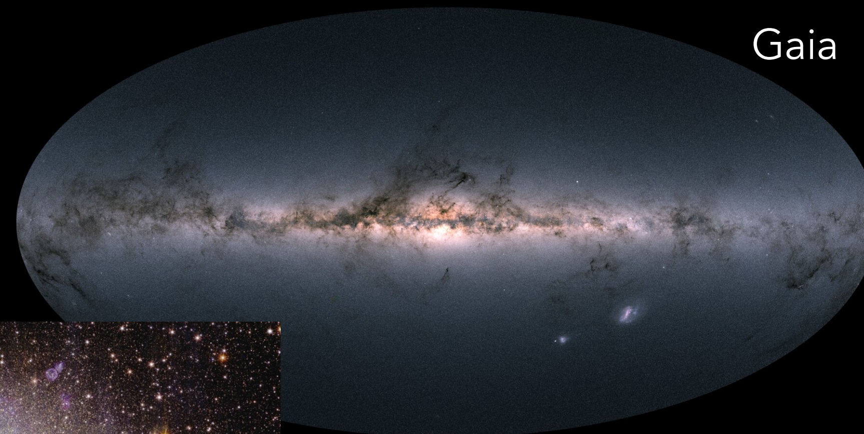


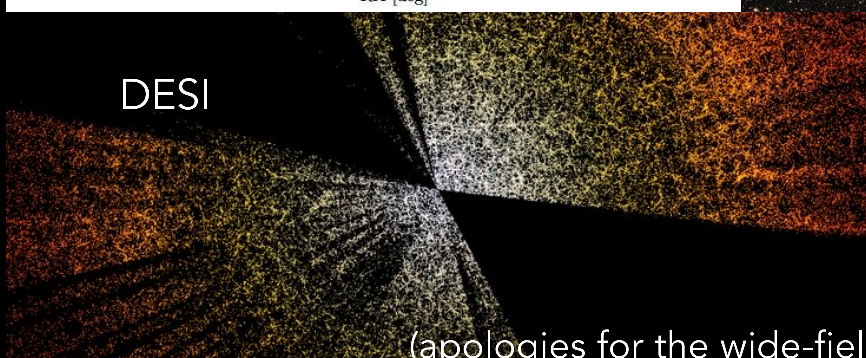
Many probes of dark matter in the cosmos

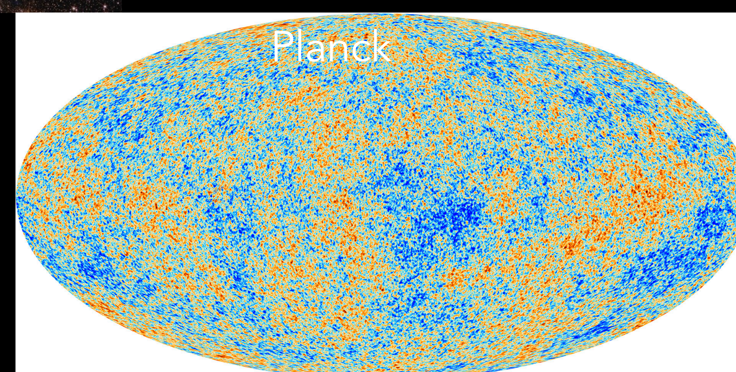


Much data



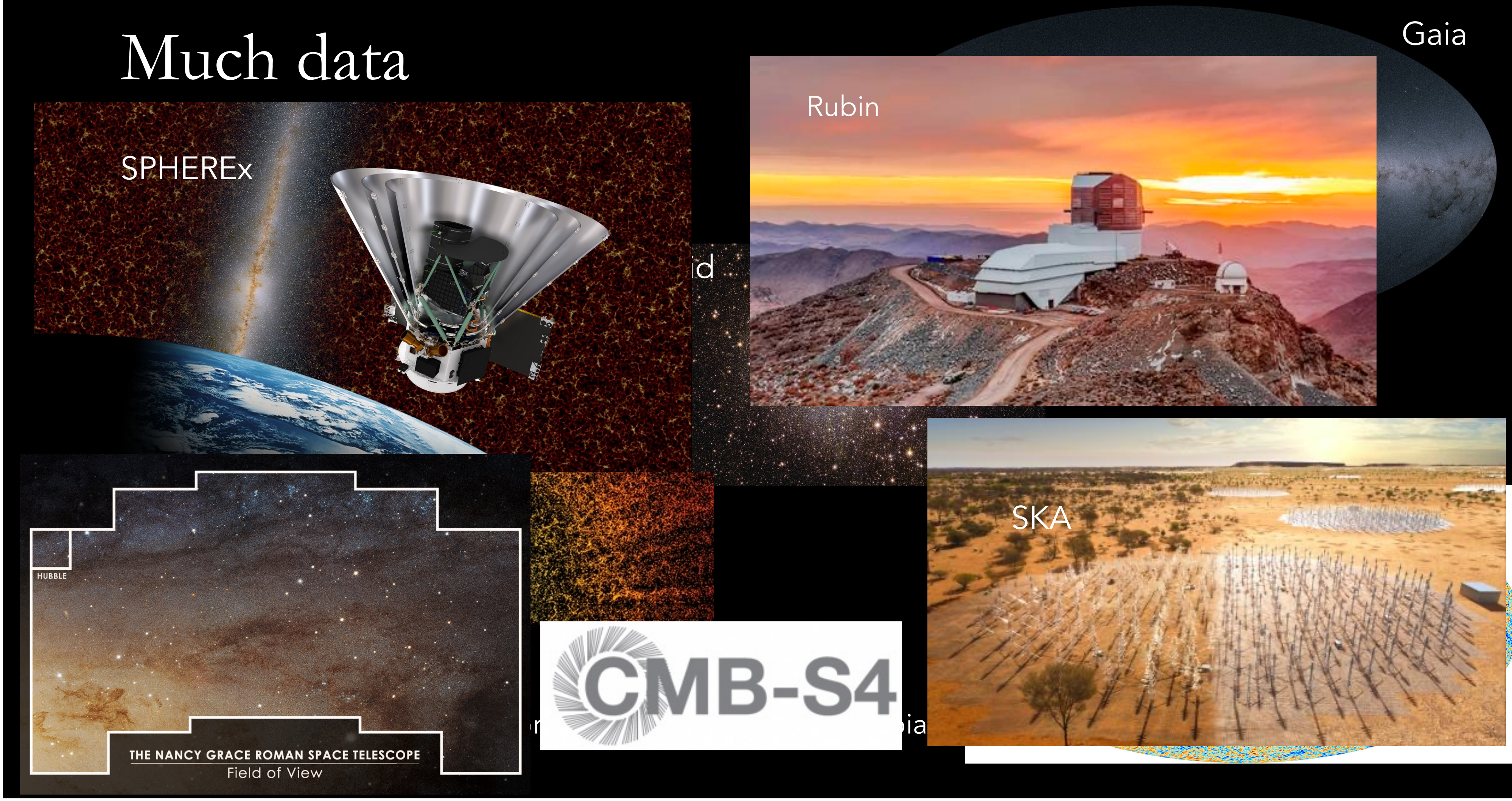


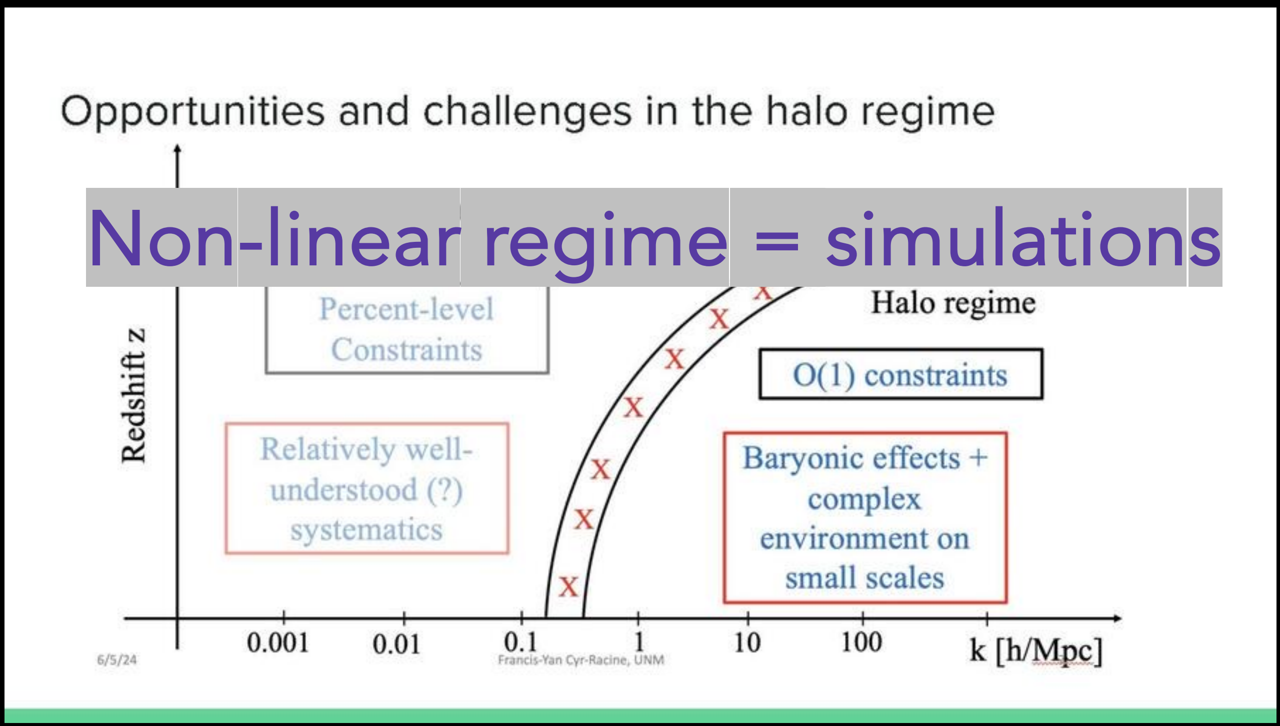




(apologies for the wide-field and optical bias)

Much data


Gaia
Rubin
SPHEREx
SKA
CMB-S4
HUBBLE
THE NANCY GRACE ROMAN SPACE TELESCOPE
Field of View

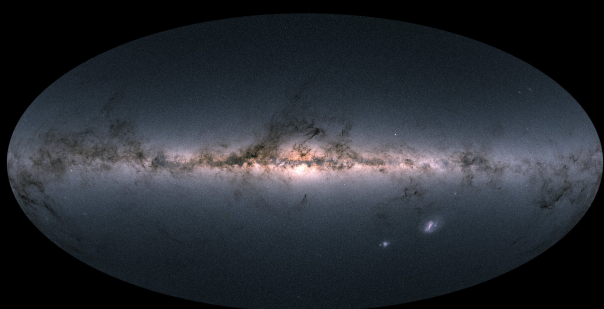


A (the?) challenge

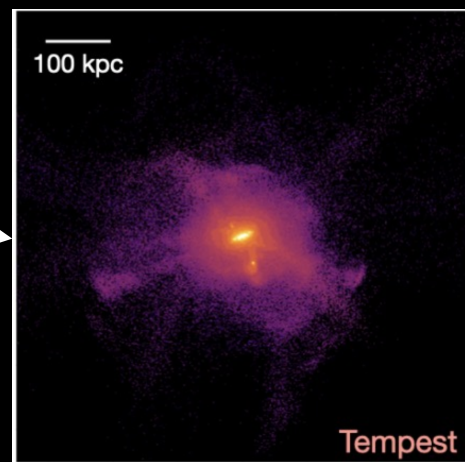
Francis-Yan Cyr-Racine @ KITP, via Elisabeth Krause

From Lagrangian to Likelihood & back again

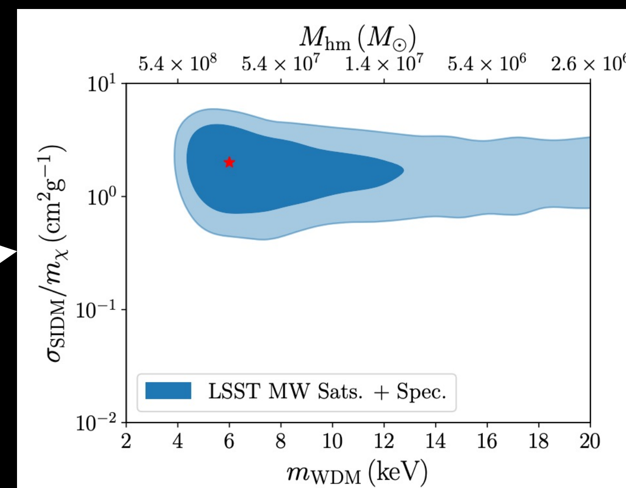
Observation



Simulation



Parameter Constraints



Wright+ 2024

Drlica-Wagner+ 2019

Strategy

A process in six parts, following this white Snowmass white paper:

Snowmass2021 Cosmic Frontier White Paper: Cosmological Simulations for Dark Matter Physics

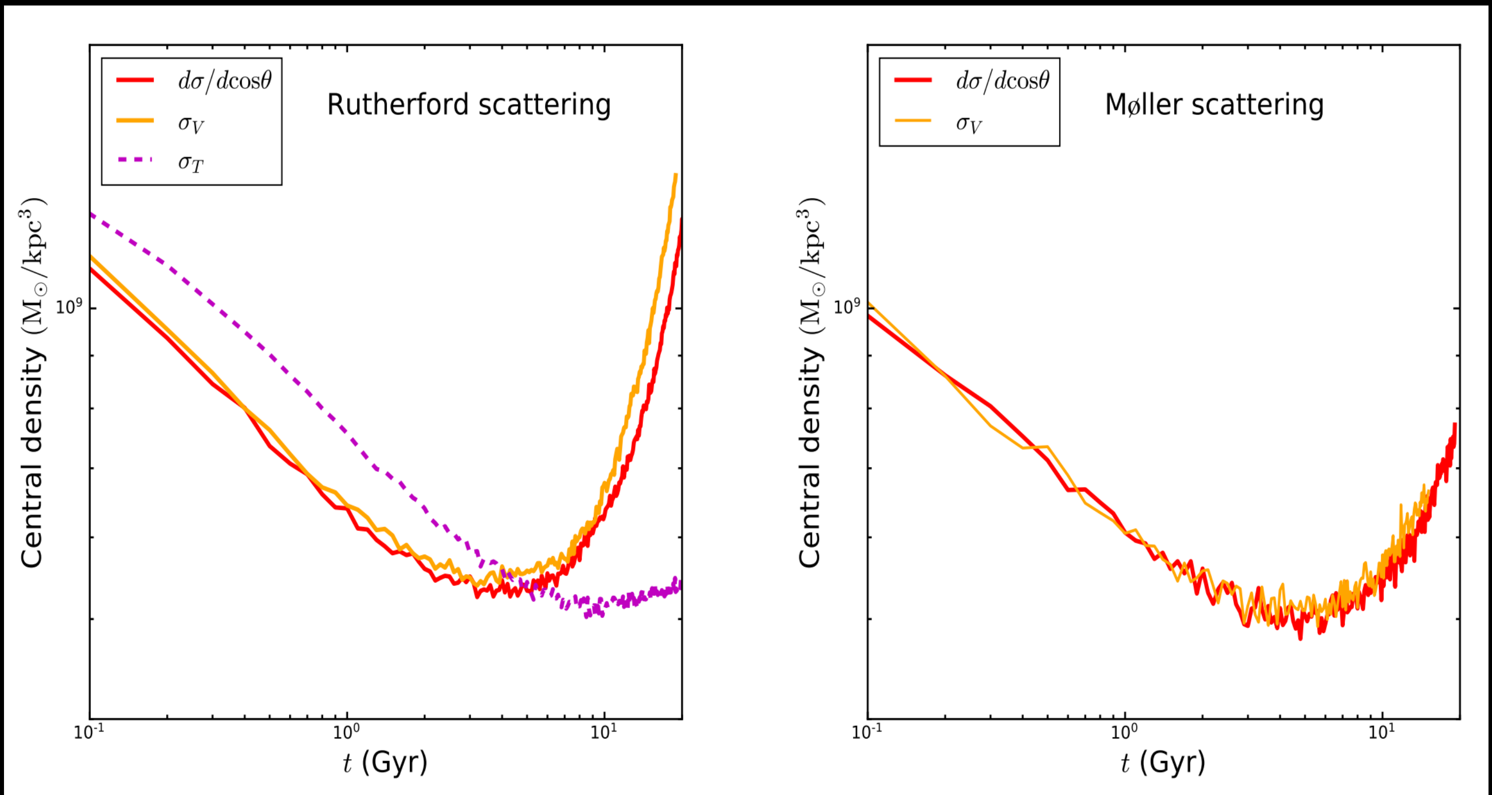
Arka Banerjee[1,2,†], Kimberly K. Boddy[3], Francis-Yan Cyr-Racine[4], Adrienne L. Erickcek[5], Daniel Gilman[6], Vera Gluscevic[7], Stacy Kim[8], Benjamin V. Lehmann[9,10], Yao-Yuan Mao[11], Philip Mocz[12], Ferah Munshi[13,†], Ethan O. Nadler[14,7], Lina Necib[15], Aditya Parikh[16], Annika H. G. Peter[17,†], Laura Sales[18], Mark Vogelsberger[15], and Anna C. Wright[19]

Most examples focus on Self-Interacting Dark Matter

1. Close collaboration between simulators and particle theorists

- What particle dark matter models should we focus on?
- How to connect to measurements from laboratory experiments, for self-consistent constraints on model parameters?
- How do we translate the microphysics of particle models to the macroscopic scales that matter for cosmology?

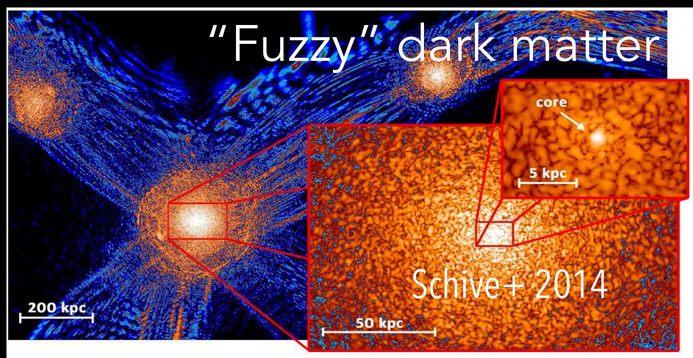
1. Example: which SIDM cross section matters in simulation?

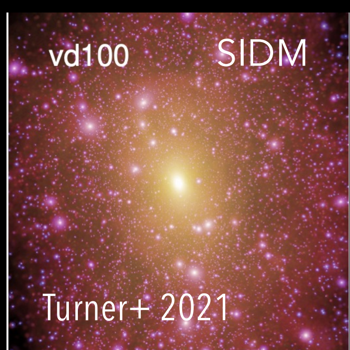


Yang & Yu 2022

2. Algorithm development and code comparison tests

So, you have a new dark matter model to test…





Is for code optimized for your problem?

Is your simulation giving accurate results?

…at the resolution you need for your problem?

…and how do you know?

Are the results robust to baryons?

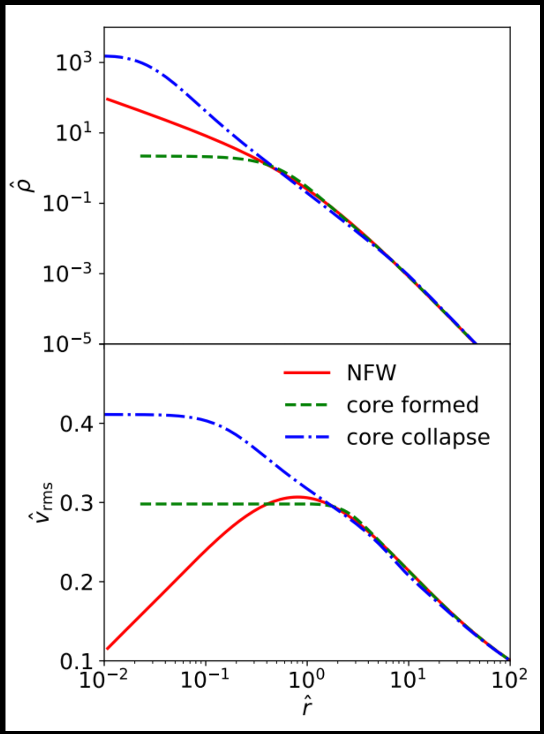
Are your analysis tools picking up everything they should?

NOTE: we still worry about ALL of these things for the "vanilla" case of CDM.

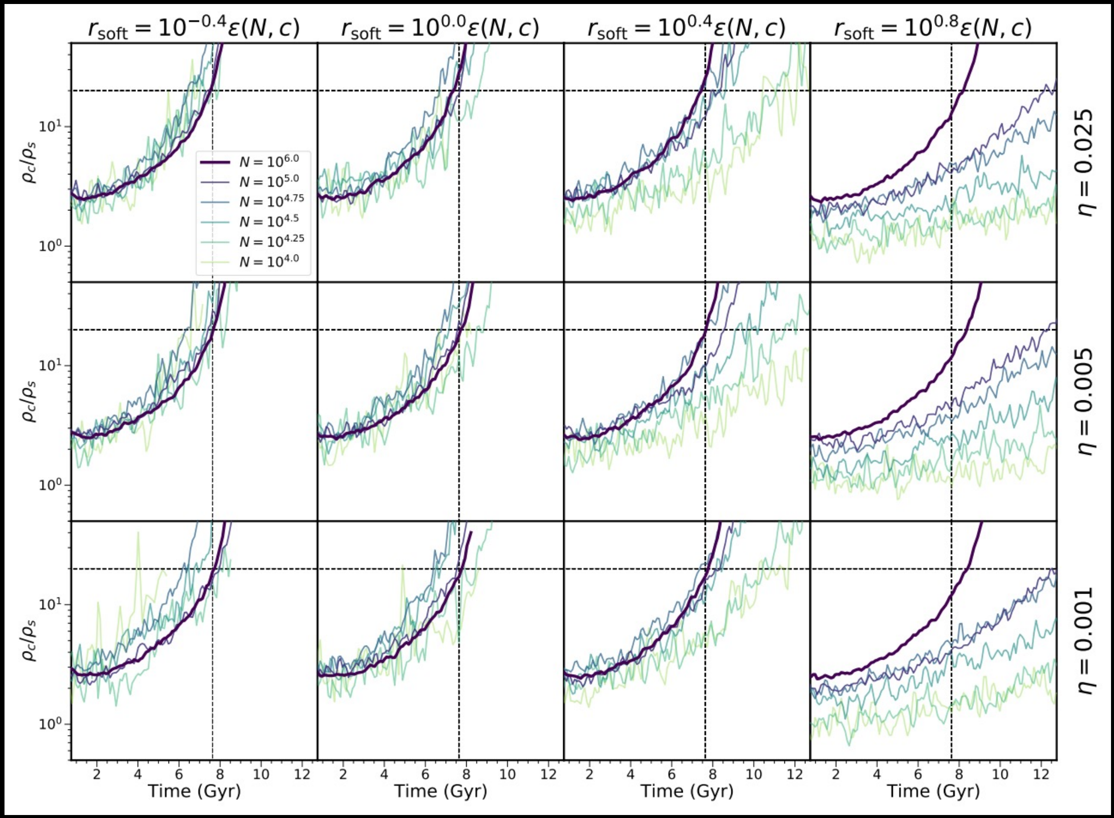
2. Example: core collapse in SIDM

See also Palubski+ 2024, Fischer+ 2024

From low to high density

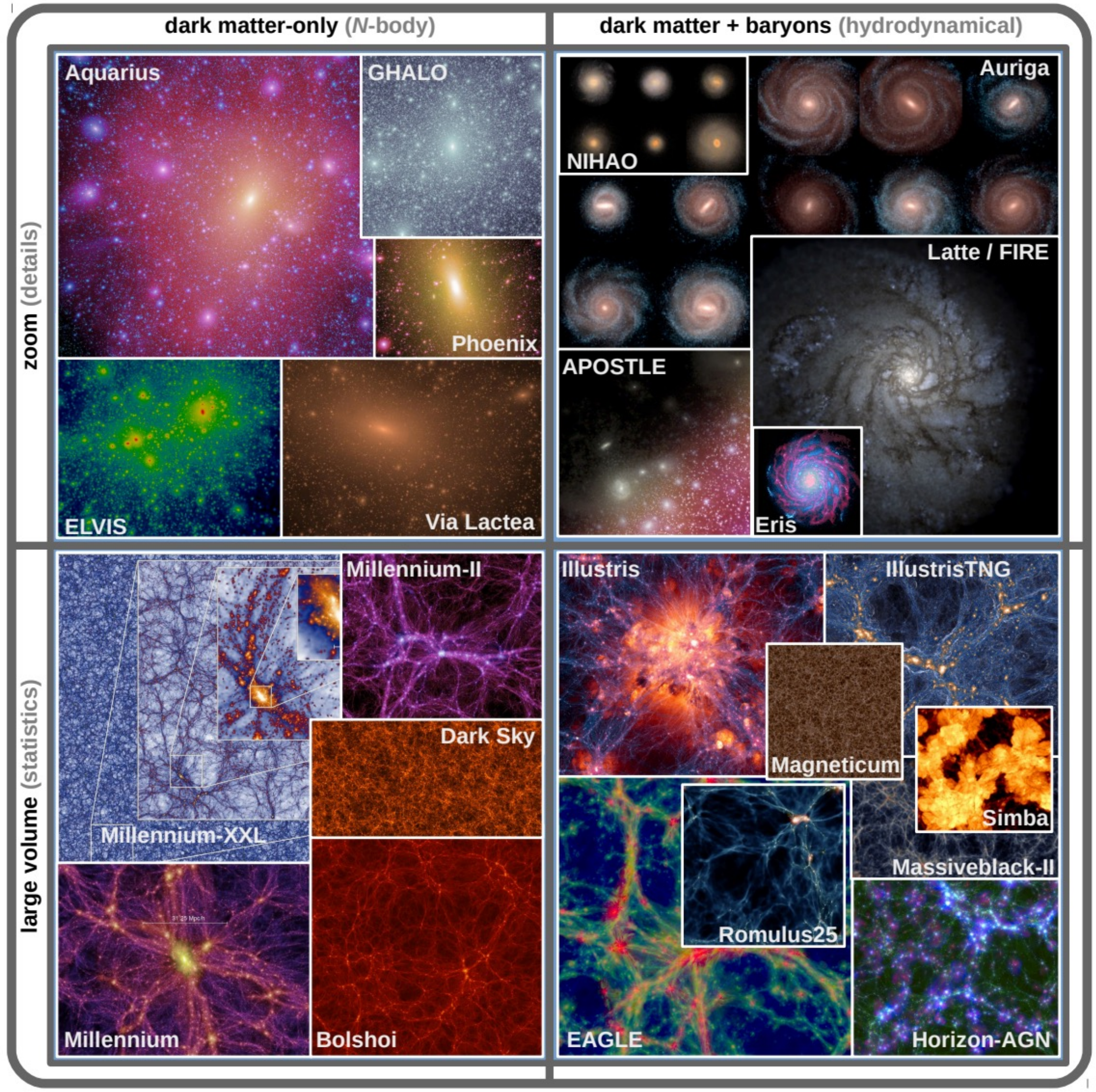


Yang+ 2022



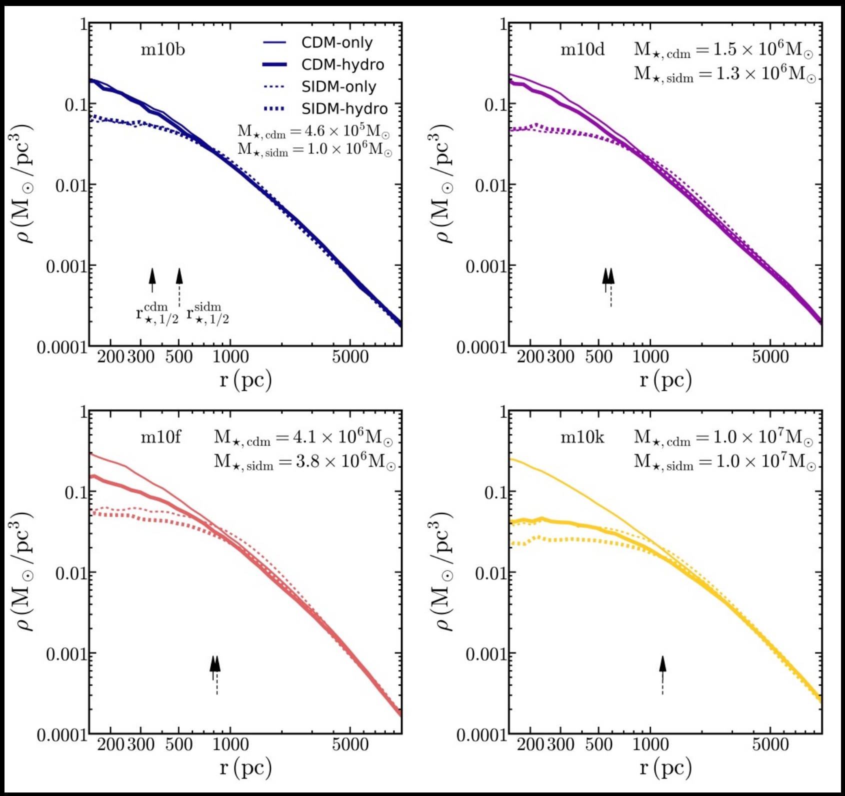
Mace+ 2024

3. Performing simulations with full hydrodynamics with validated subgrid models and numerical resolution

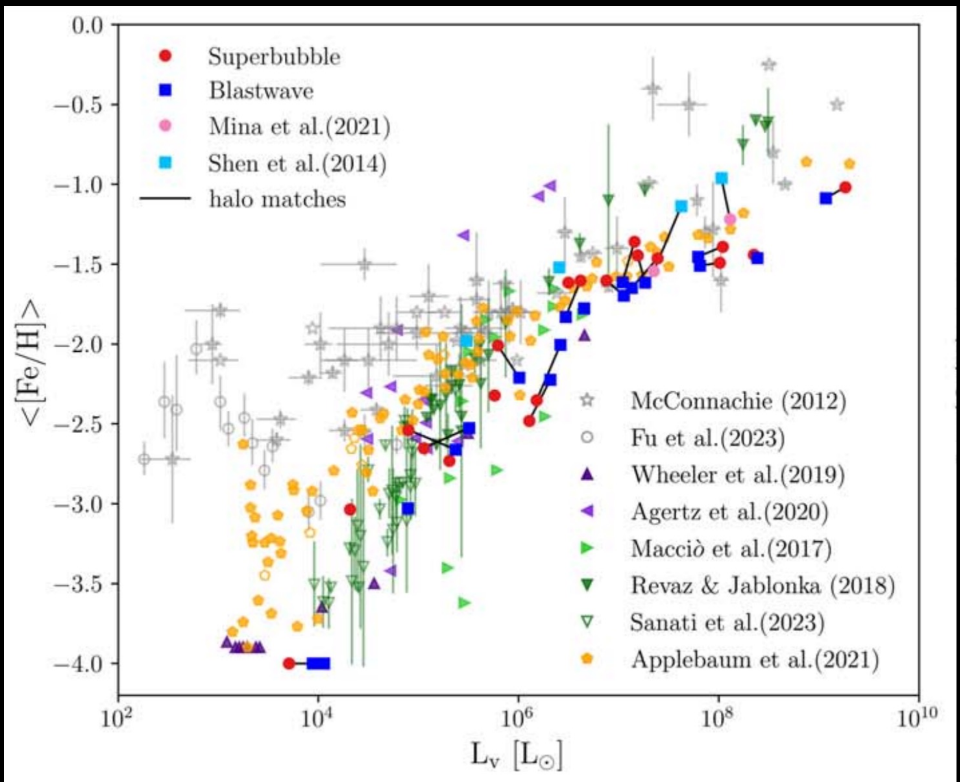


Vogelsberger+ 2020

3. Performing simulations with full hydrodynamics with validated subgrid models and numerical resolution

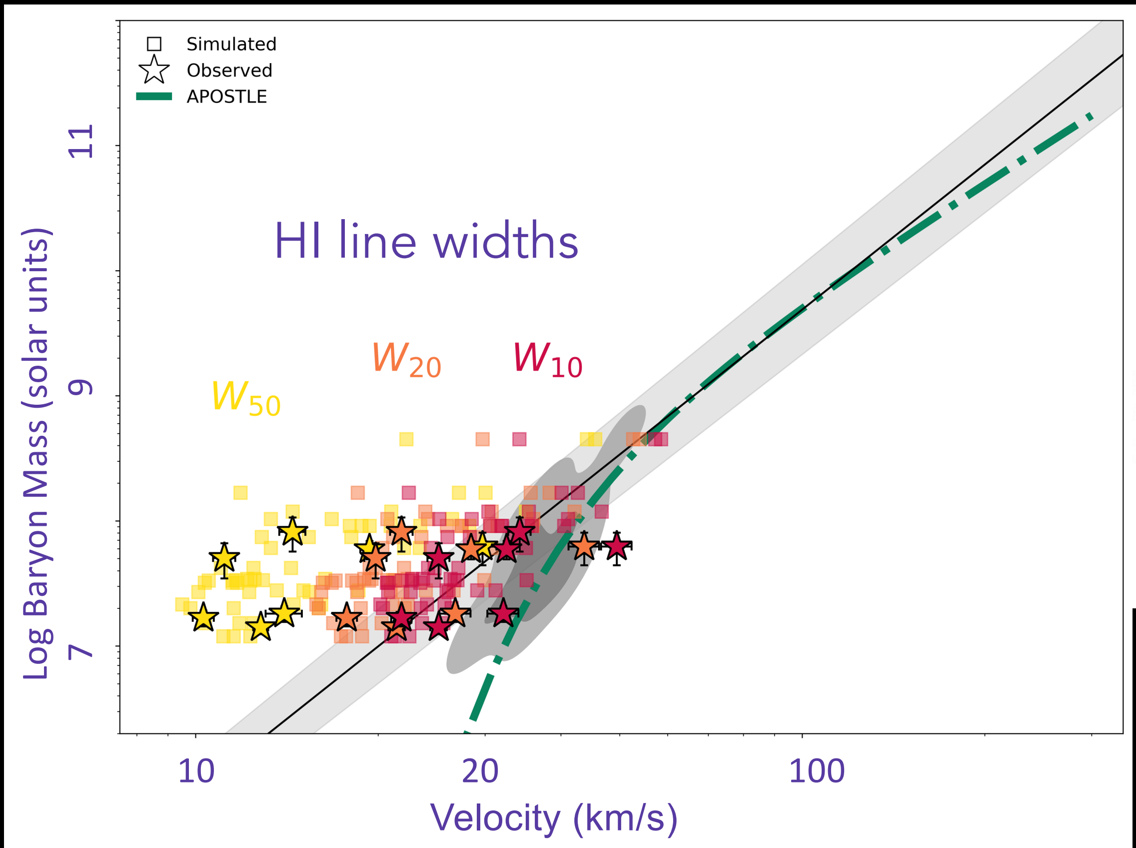


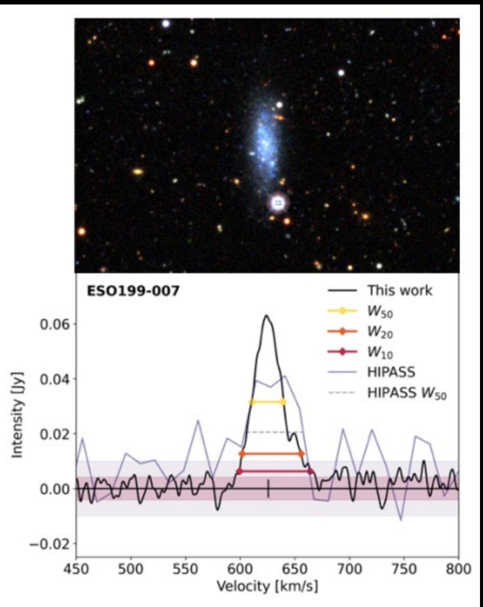
Robles+ 2017



Azartash-Namin+ 2024

4. Analysis of outputs in the realm of observations





Sardone+ 2024

5. Fast realizations of observables for inference of DM properties

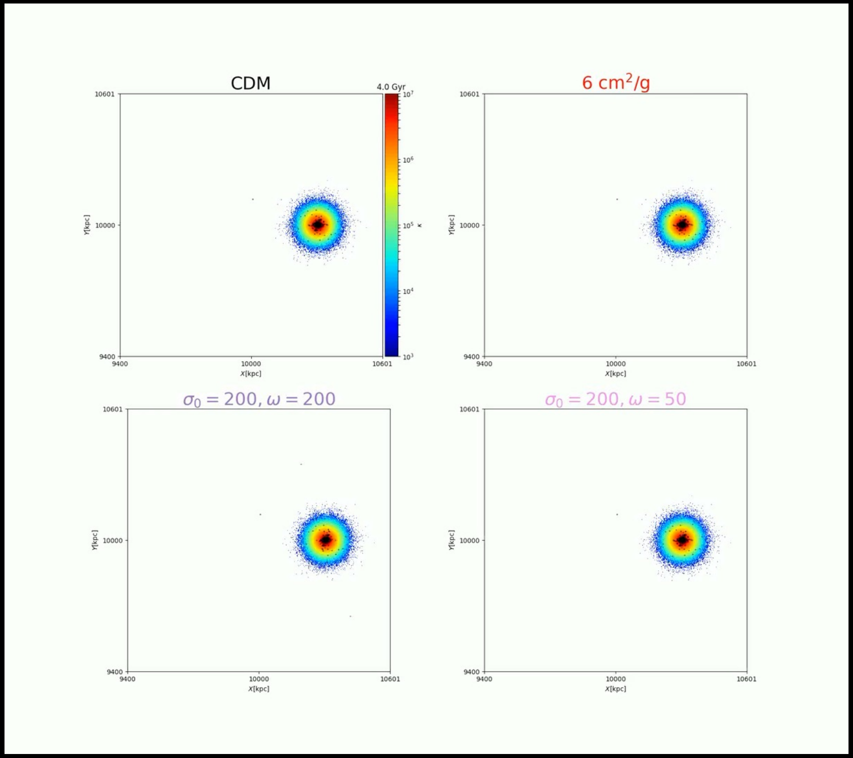
The model space is huge, and the target space is diverse.

How do we sample enough of the former, and have adequate representations (for some very different applications) for the latter?

A. Reduce cost of individual simulations (or individual realizations)

B. Reduce the number of simulations used in each analysis

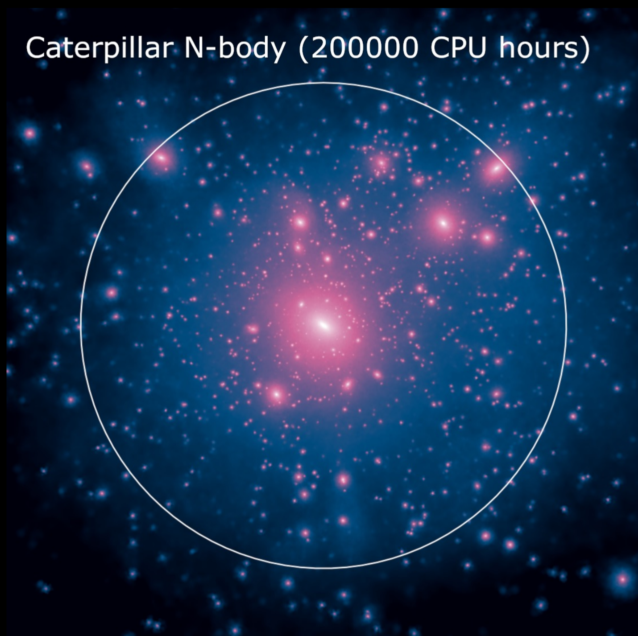
A. Reduce cost of individual simulations (or realizations)

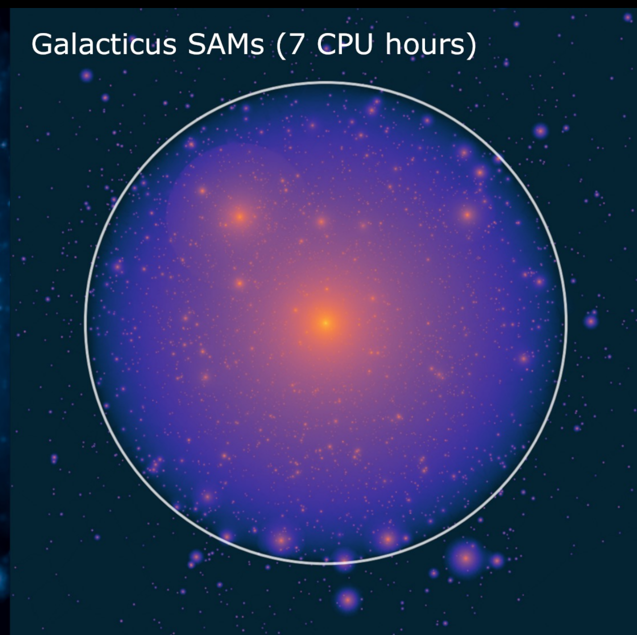


Controlled simulations

Zeng+ in prep., see also Zeng+ 2023

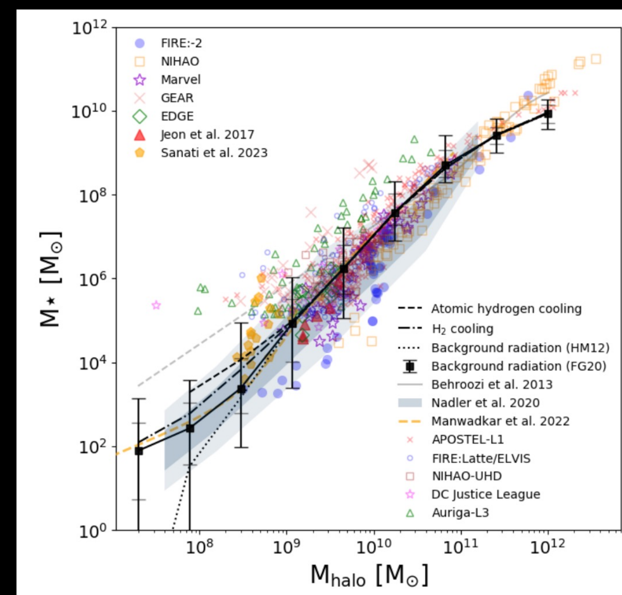
A. Reduce cost of individual simulations (or realizations)





Du+ in prep.

Semi-analytic models



Ahvazi+ 2024

B. Reduce the number of simulations used in each analysis

Emulators, ML?

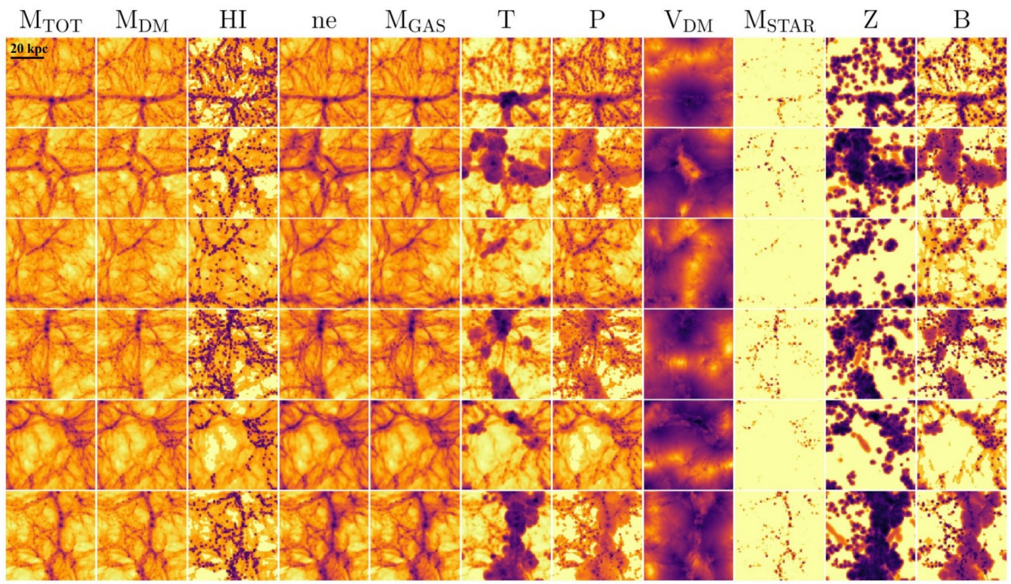


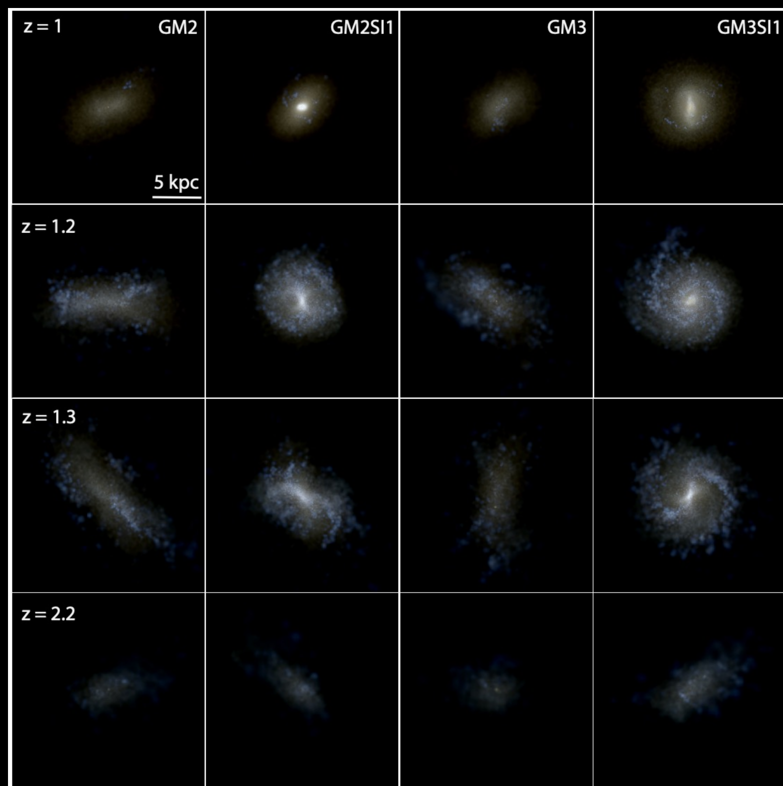
Figure 4. Image slices from the WDM uniform-box suite with varied cosmology and TNG physics. Each column represents a three-dimensional reconstruction of the given property that is then projected onto two dimensions: total matter density, M_{TOT}; dark matter density, M_{DM}; neutral hydrogen gas density, HI; electron number density, ne; baryonic gas density, M_{GAS}; gas temperature, T; gas pressure, P; dark matter velocity modulus (speed), V_{DM}; stellar mass density, M_{STAR}; gas metallicity, Z; and magnetic field strength, B. Each row represents a projection from a different simulation taken randomly from the suite. Each image covers a $25 \times 25 \times 5\ h^{-1}$ Mpc volume projected along the short axis.

DREAMS; Rose+ 2024

6. Identifying novel signatures from simulations and guidance to observers

Milky Way analogs

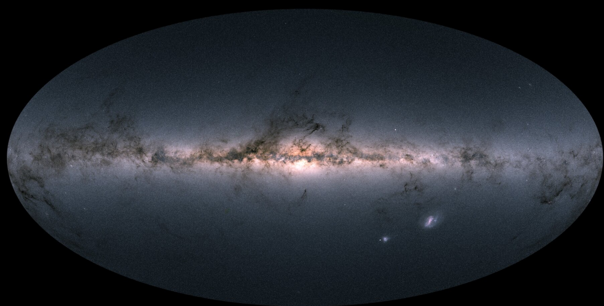
CDM SIDM CDM SIDM



Initial condition 2 Initial condition 3

Cruz+ 2021

Simulations as mediators



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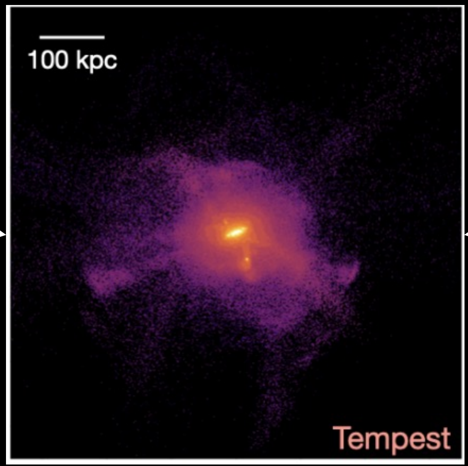

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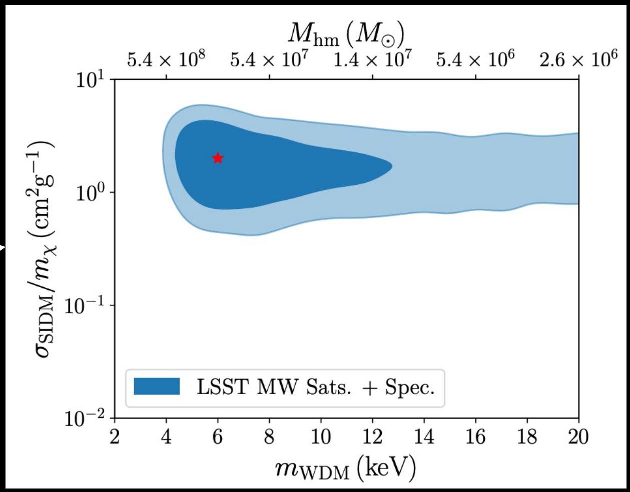

Wright+ 2024

Drlica-Wagner+ 2019