Constraining the mass of warm dark matter particle with dwarf galaxies using cosmological simulations

Study based on the DREAMS project

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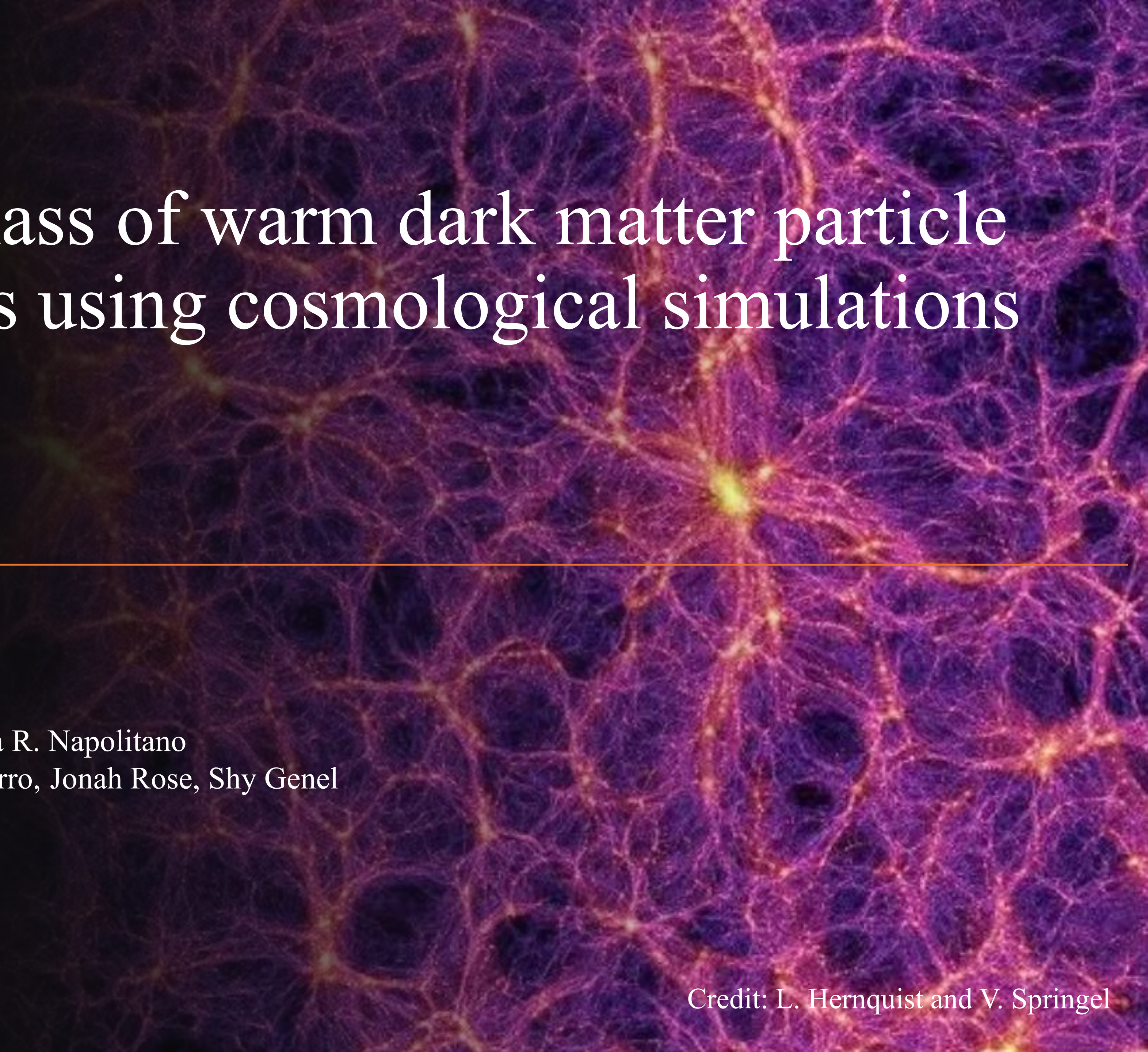
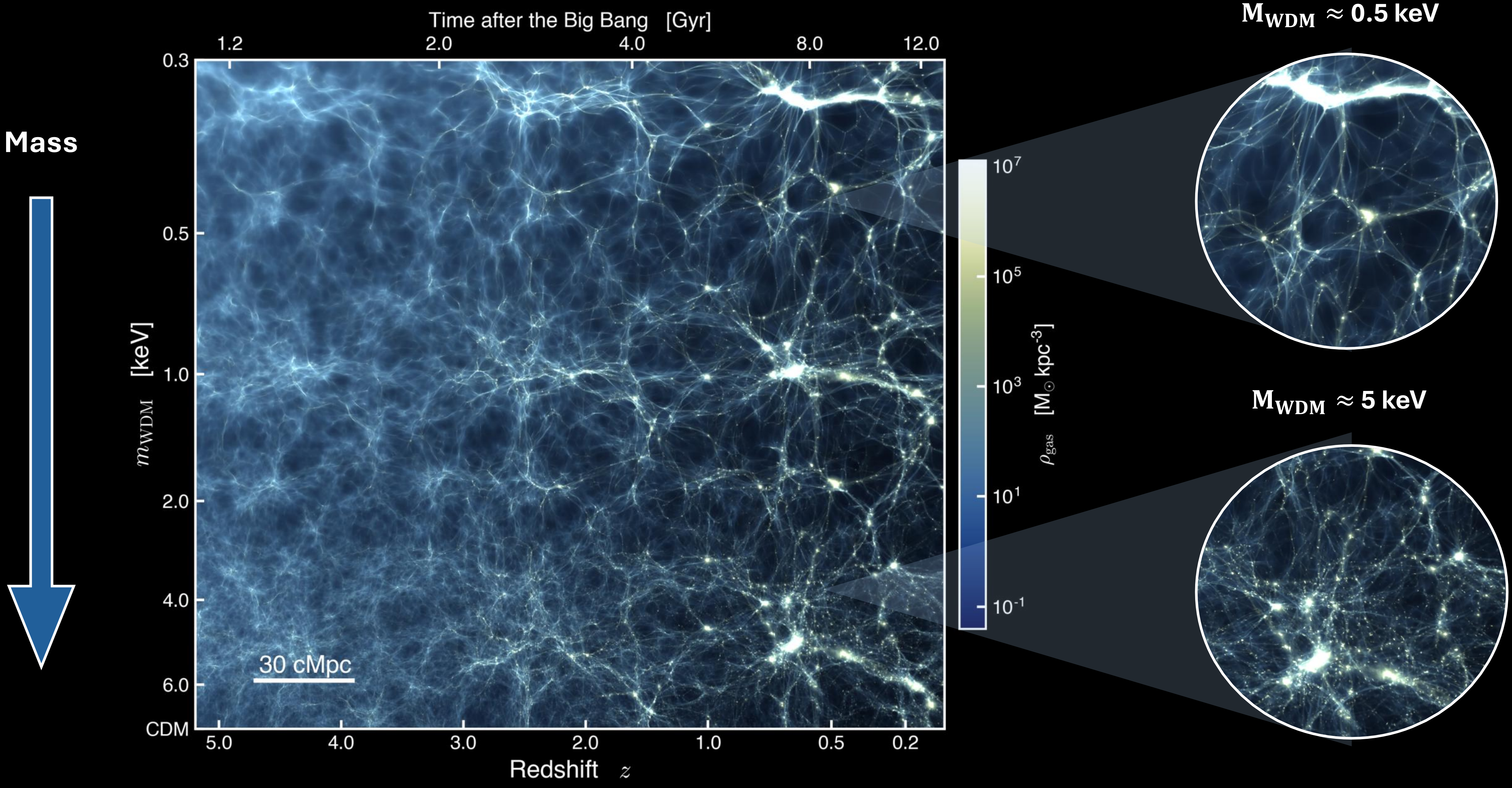
DREAMS project: Francisco Villaescusa-Navarro, Jonah Rose, Shy Genel

Dark Matter 2025, Santander
2-6 June, 2025

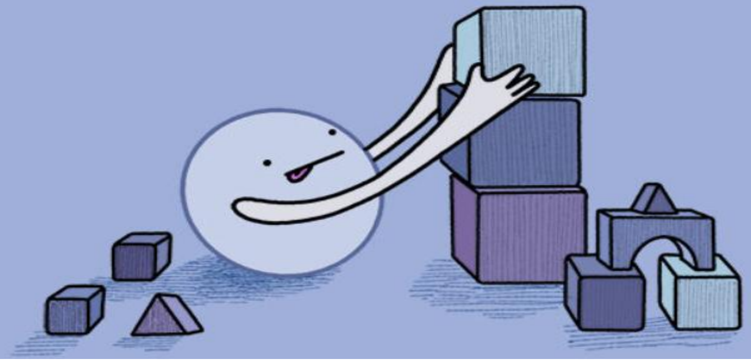


Credit: L. Hernquist and V. Springel



Credit: Department of Astronomy & Astrophysics, 1156 High Street, Santa Cruz

CDM vs WDM



ΛCDM's small-scale issues:

Too-big-to-fail, and missing satellites highlight tensions with observations.

The WDM is a simple alternative!

- Adds one parameter (particle mass in keV).
- Dampens small scales, addressing ΛCDM issues like missing satellites.

Illustration by Sandbox Studio, Chicago with Corinne Mucha

DREAMS project

DaRk mattEr and Astrophysics with Machine learning and Simulations.

Two types of simulations: **Uniform Box** and **MW zoom-in**

Dark Matter Prescription	# of Sims	Simulation Type	Baryon Prescription	Cosmology	Mass Resolution $[h^{-1}\Omega_m M_\odot]$	Spatial Resolution $[h^{-1}$ pc$]$
Cold Dark Matter	1024	Milky Way	N-body	Varied	4.0×10^6	305
	1024	Milky Way	TNG	Varied	4.0×10^6	305
Warm Dark Matter	200	Uniform Box	N-body	Fixed	3.3×10^7	1000
	1000	Uniform Box	N-body	Varied	2.6×10^8	1000
	1024	Uniform Box	TNG	Varied	2.6×10^8	1000
	1024	Milky Way	TNG	Fixed	4.0×10^6	305

Scale lengths:

Uniform box	25000 h^{-1} kpc
MW zoom-in	200 h^{-1} kpc

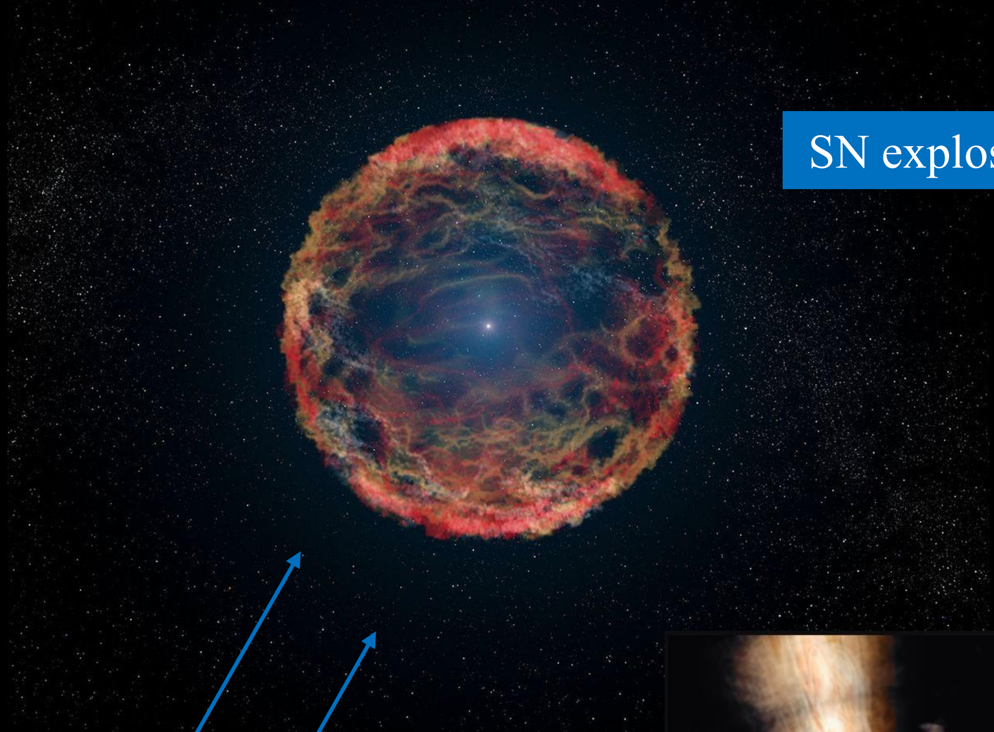
Parameters in WDM DREAMS simulations

COSMOLOGY

Ω_m → Matter density

σ_8 → Amplitude of fluctuations

M_{WDM} → Warm dark matter mass

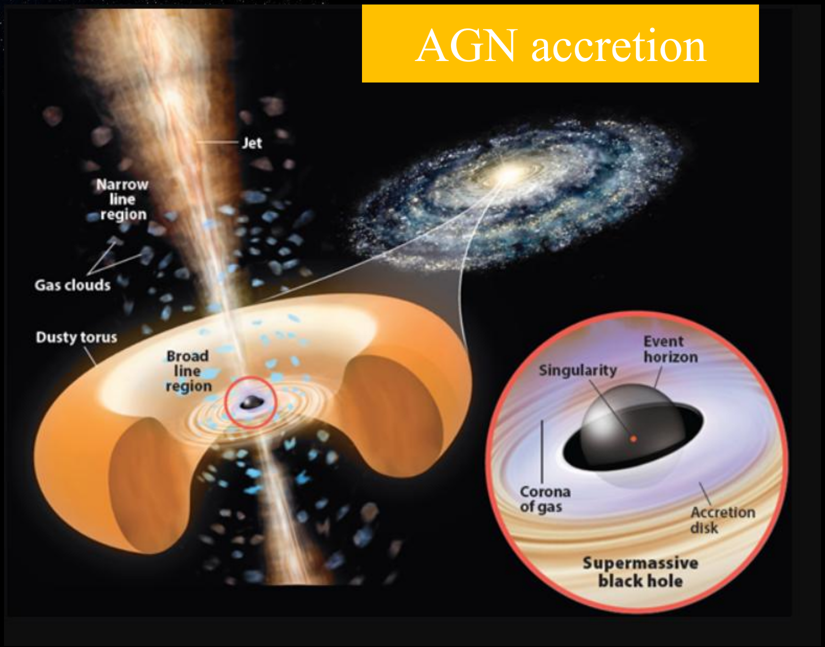


ASTROPHYSICS

A_{SN1} → Wind-driving energy in SN feedback

A_{SN2} → Efficiency of gas ejection in SN feedback

BH_{FF} → High-accretion efficiency in AGN feedback



SN NASA's Goddard Space Flight Center, AGN Roen Kelly

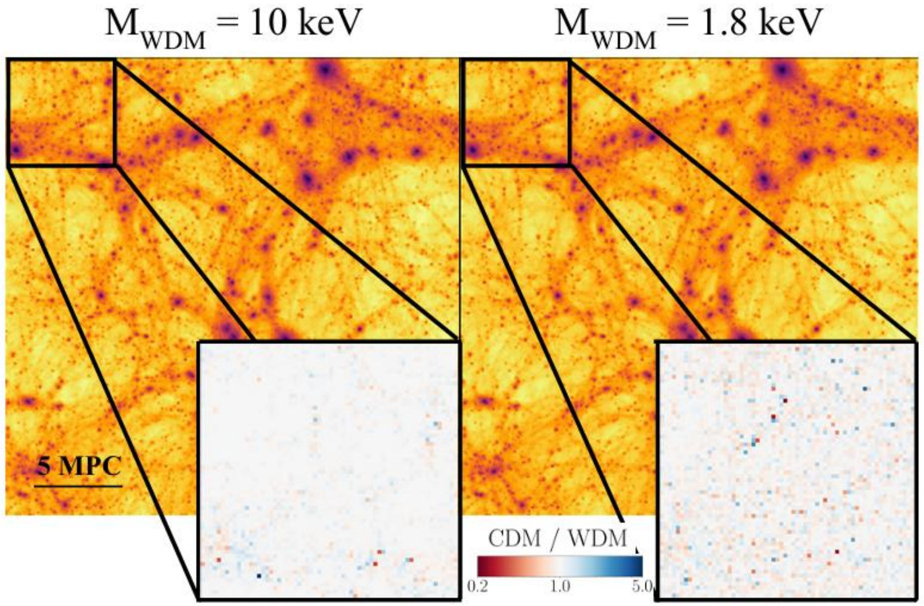
WDM implementation

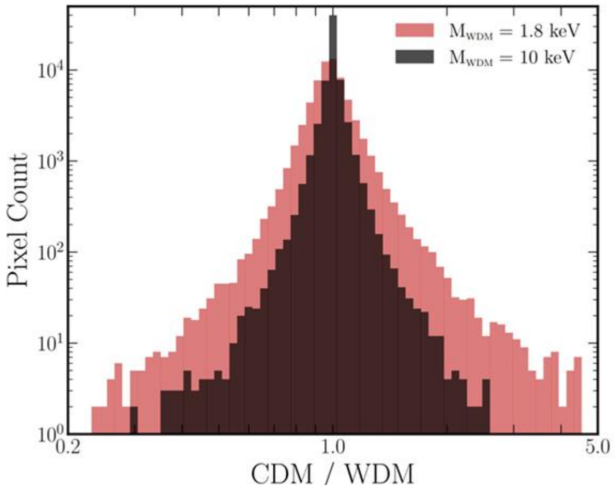
Suppression of the initial matter power spectrum simulates thermal-relic WDM vs. CDM.

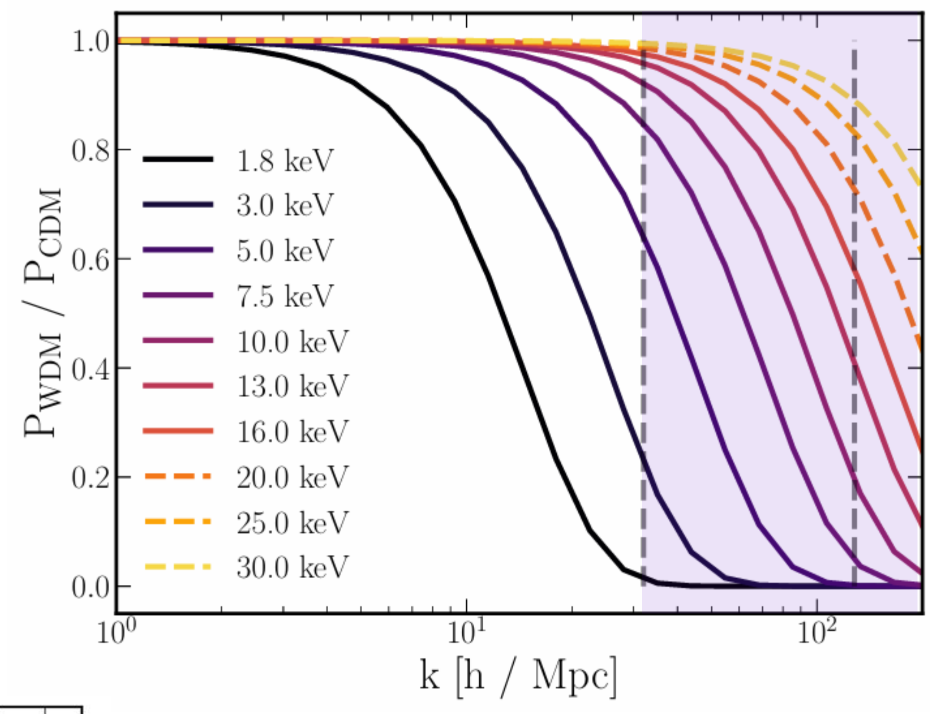
$$P_{\mathrm{WDM}}(k) = \beta(k) P_{\mathrm{CDM}}(k)$$

$$\beta(k) = \left(\left(1 + (\alpha k)^{2.4}\right)^{-5.0/1.2} \right)^2$$

$$\alpha = 0.048\ h^{-1}\ \mathrm{Mpc} \left(\frac{\mathrm{M_{WDM}}}{\mathrm{keV}}\right)^{-1.15} \left(\frac{\Omega_\mathrm{m} - \Omega_\mathrm{b}}{0.4}\right)^{0.15} \left(\frac{\mathrm{h}}{0.65}\right)^{1.3}$$







Low-mass galaxies should be more sensitive to the free-streaming effects of WDM.

Rose et al 2024

Workflow Overview

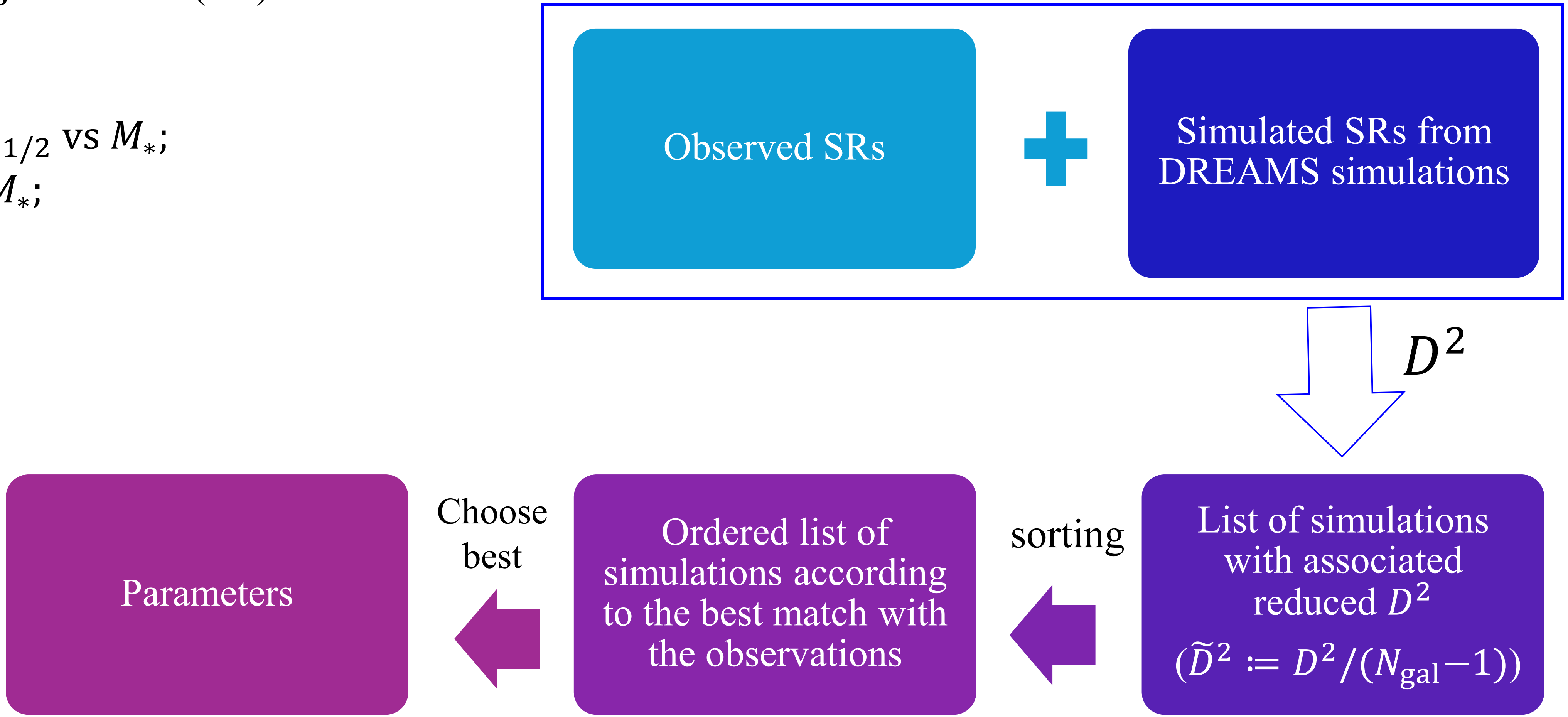
Galactic scaling relations as DM tests	Focus on central quantities
Assess impact of parameters on scaling laws	Compare simulations at different resolutions
Compare simulations with observational data	Introduce custom distance estimator; compare with LVD and the SPARC dataset
Evaluate WDM impact on galaxy abundance	Compare with observation (future Euclid results)

LVDB: Pace, A. B. 2024;
SPARC: Lelli, F., McGaugh, S. S., & Schombert, J. M. 2016, AJ, 152, 157

Scaling Relations and Fitting procedure

Galaxy Scaling Relations (SR) considered:

- $R_{*,1/2}$ vs M_*;
- $M_{\mathrm{tot},1/2}$ $/M_{*,1/2}$ vs M_*;
- $M_{\mathrm{DM},1/2}$ vs M_*;
- M_{tot} vs M_*;



Uncertainties obtained via boostrap on both observed and simulated datasets.

[1]Lelli+16, Tortora+19

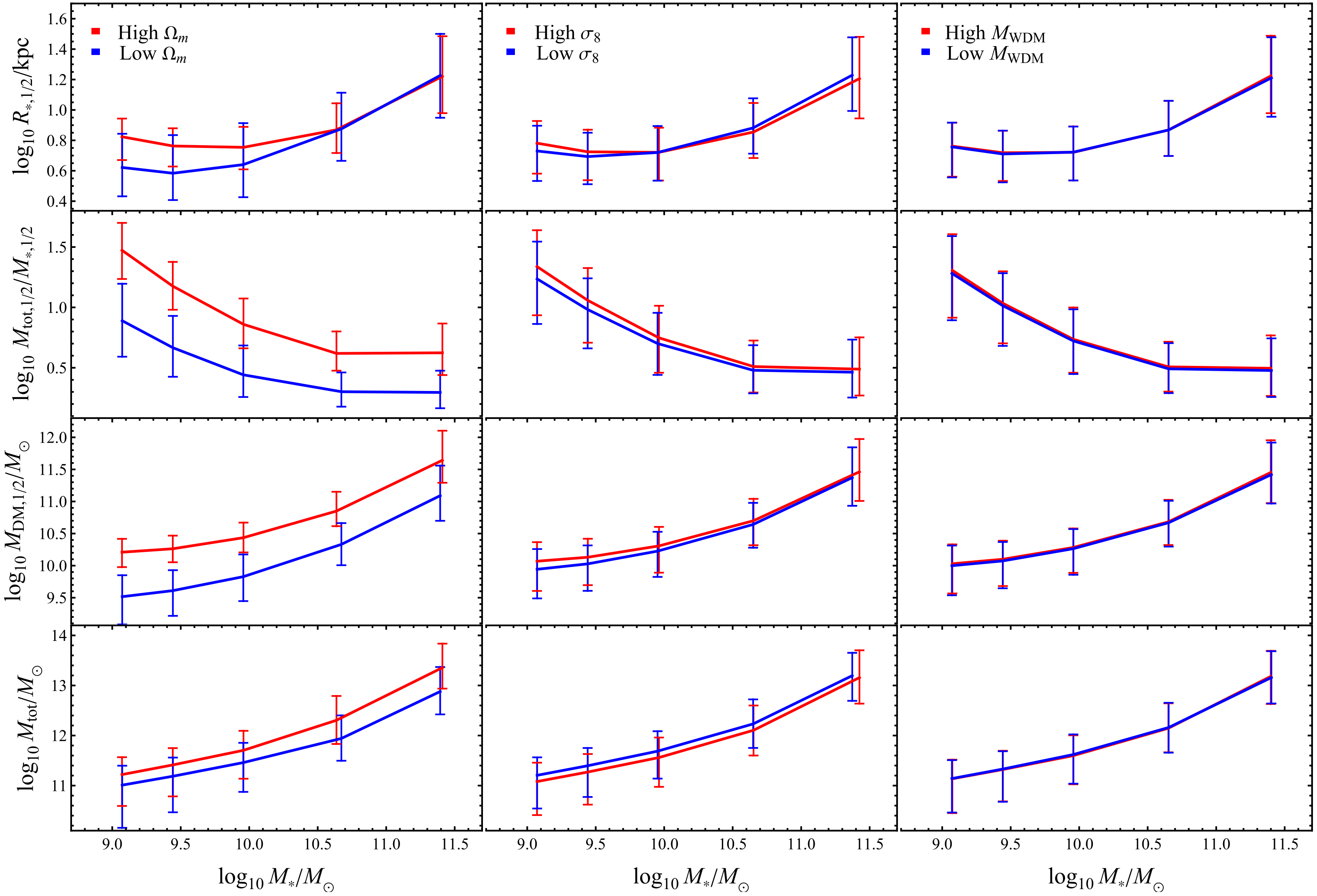
Uniform-box: cosmology and galaxy scaling

Ω_m → Shifts scaling relations upward; Great impact on scaling relations.

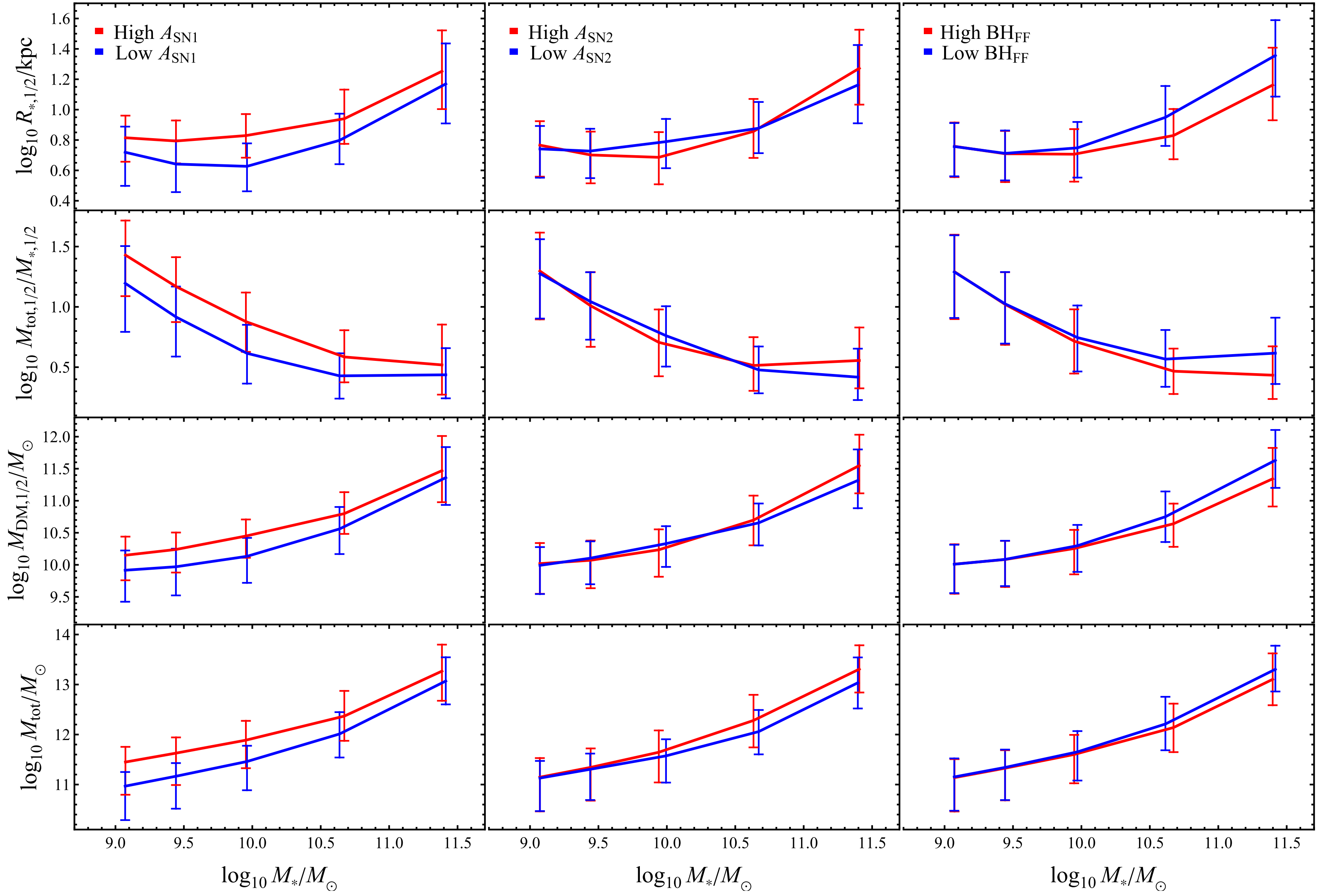
σ_8 → More DM and total-to-stellar mass ratio within $R_{1/2}$, lower total mass; Size-mass trend inverts.

M_{WDM} → No significant impact on scaling relations.

Parameter	Low Range	Low Median	High Range	High Median
Ω_m	< 0.25	0.19	≥ 0.35	0.43
σ_8	< 0.75	0.68	≥ 0.85	0.93
A_{SN1}	< 1	0.6 (0.5)	≥ 2	2.8 (2.8)
A_{SN2}	< 1	0.7 (0.7)	≥ 1	1.4 (1.4)
BH_{FF}	< 1	0.6 (0.5)	≥ 2	3.0 (2.9)
M_{WDM} [keV]	< 2	1.9 (1.9)	≥ 10	12.3 (15.4)



Uniform-box: astrophysics and galaxy scaling



$\mathbf{A_{SN1}}$ → Shifts all scaling relations upward; Effect is almost independent of stellar mass.

$\mathbf{A_{SN2}}$ → Lower total galaxy mass; Other trends vary depending on the galaxy's stellar mass.

$\mathbf{BH_{FF}}$ → Suppresses all four scaling relations at high stellar mass.

Parameter	Low		High	
	Range	Median	Range	Median
Ω_m	< 0.25	0.19	≥ 0.35	0.43
σ_8	< 0.75	0.68	≥ 0.85	0.93
A_{SN1}	< 1	0.6 (0.5)	≥ 2	2.8 (2.8)
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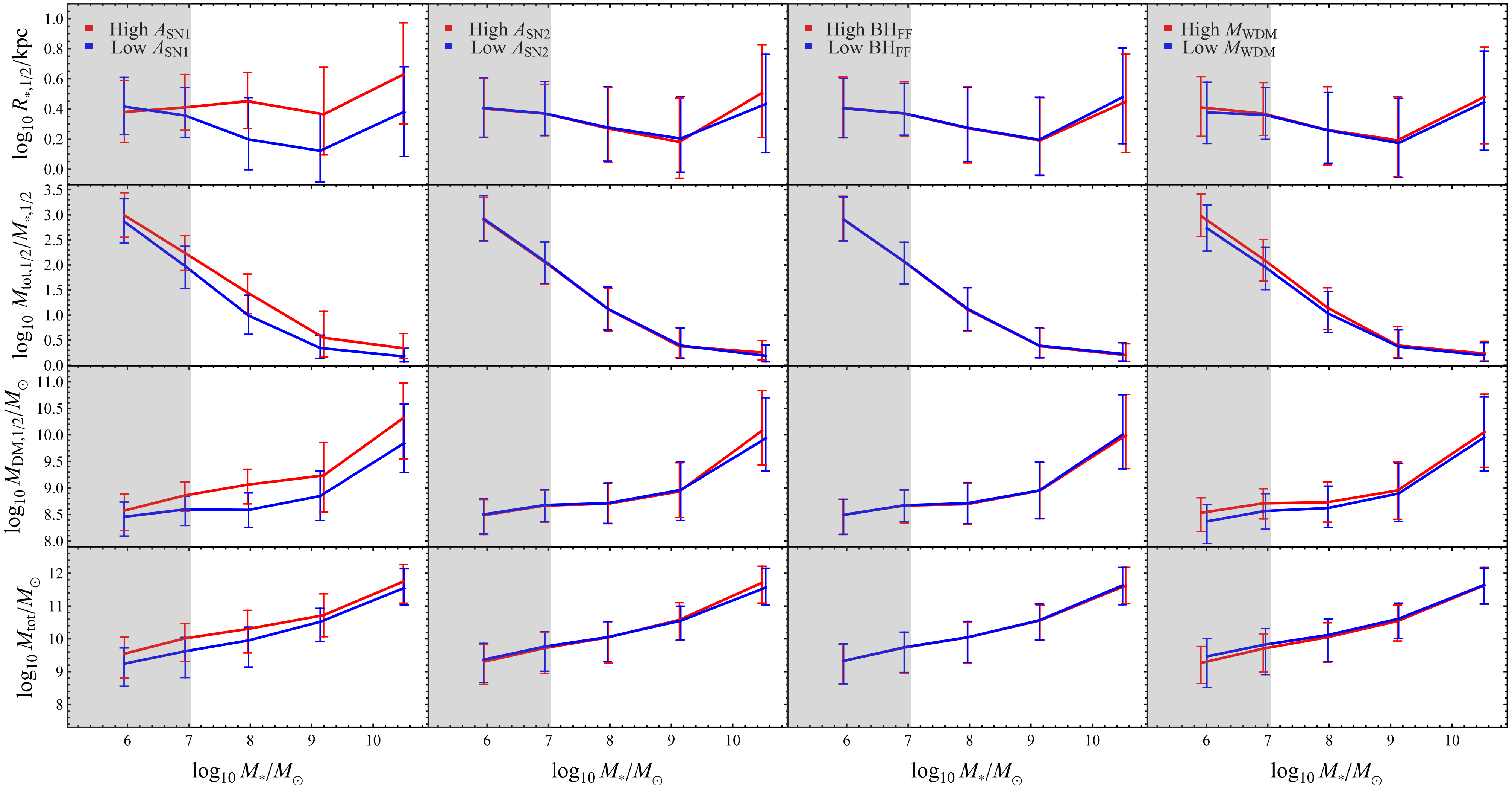
M_{WDM} [keV]	< 2	1.9 (1.9)	≥ 10	12.3 (15.4)

MW zoom-in: astrophysics, WDM mass and galaxy scaling

A_{SN1} → Shifts scaling relations upward; Dominant regulator of star formation in this mass regime.

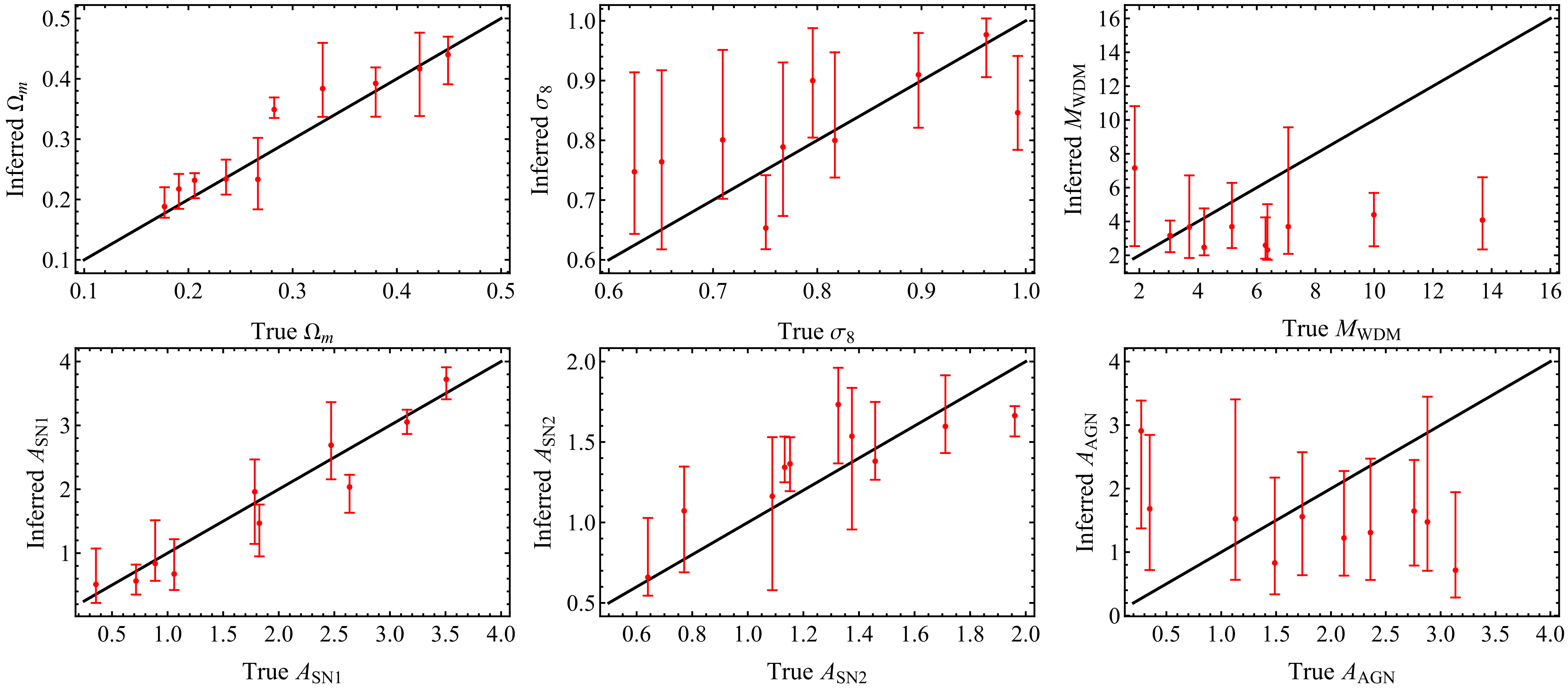
A_{SN2} and **BH_{FF}** → Negligible impact on scaling relations.

M_{WDM} → Higher DM content and fraction within $R_{1/2}$; Effects, mostly in lowest-mass bins.



Evaluation of the fitting procedure

Uniform Box



Good agreement

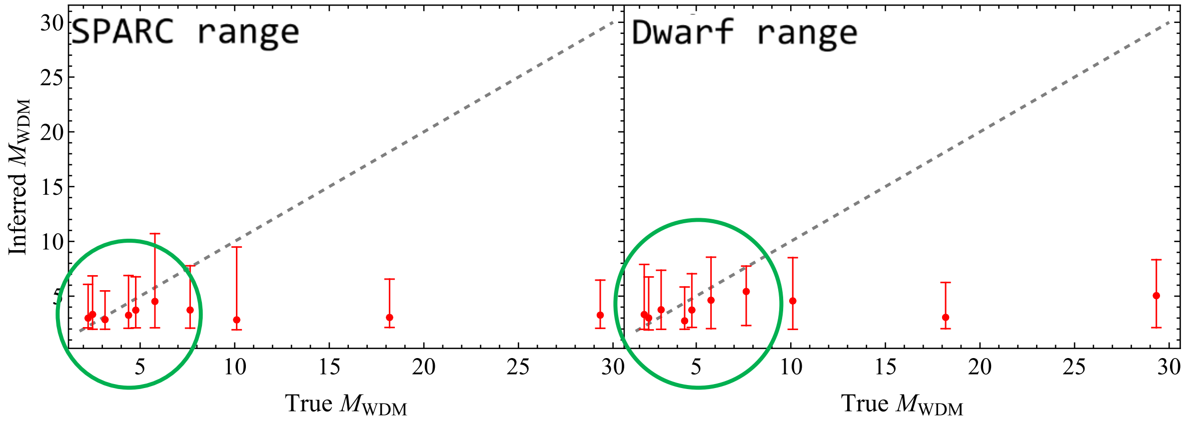
Higher uncertainty in estimates

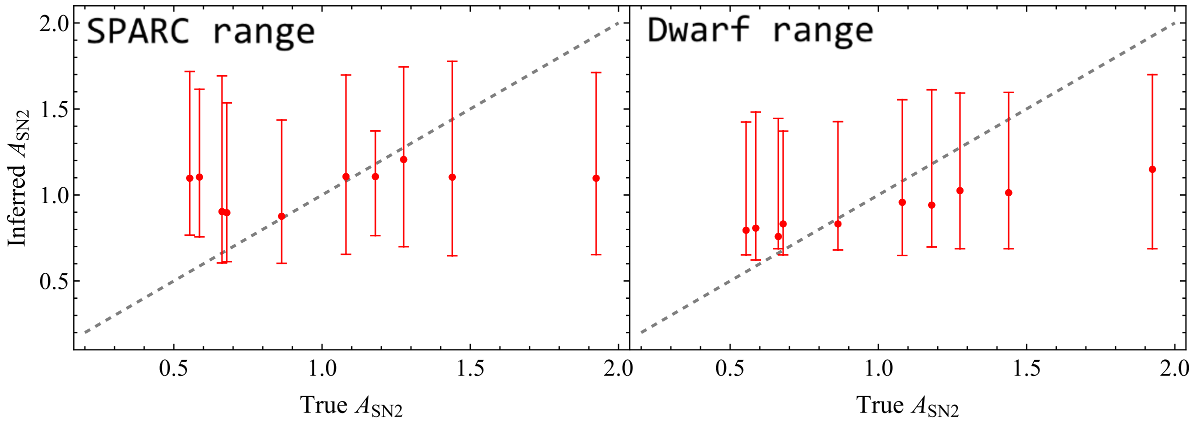
Parameters not recovered

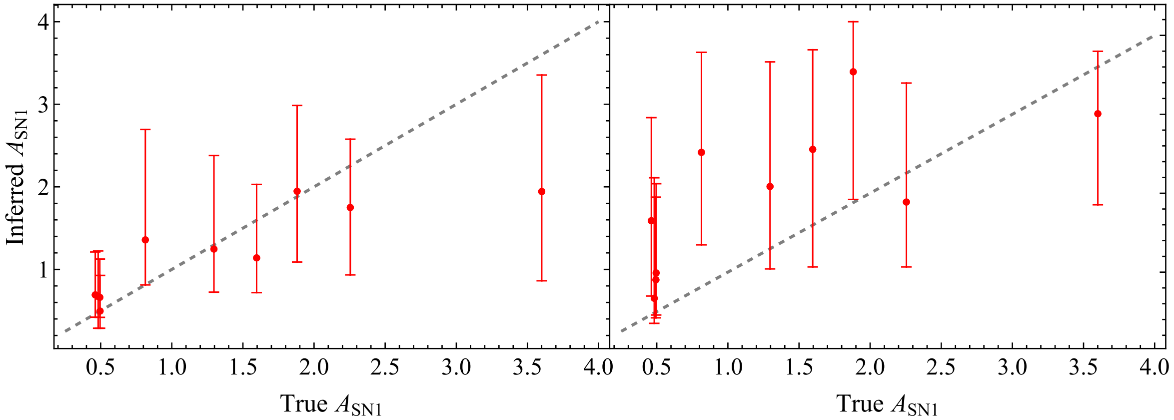
Evaluation of the fitting procedure

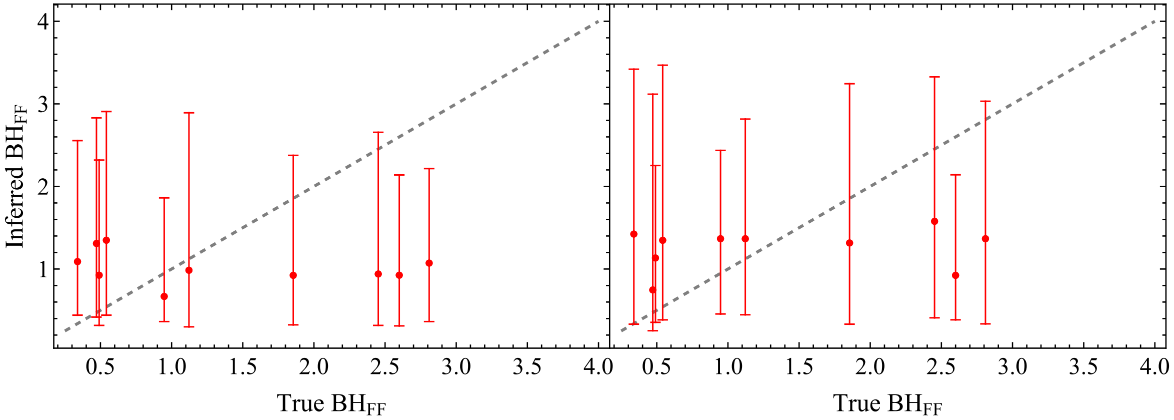
MW Zoom-in

WDM mass recovered up to 7–8 keV





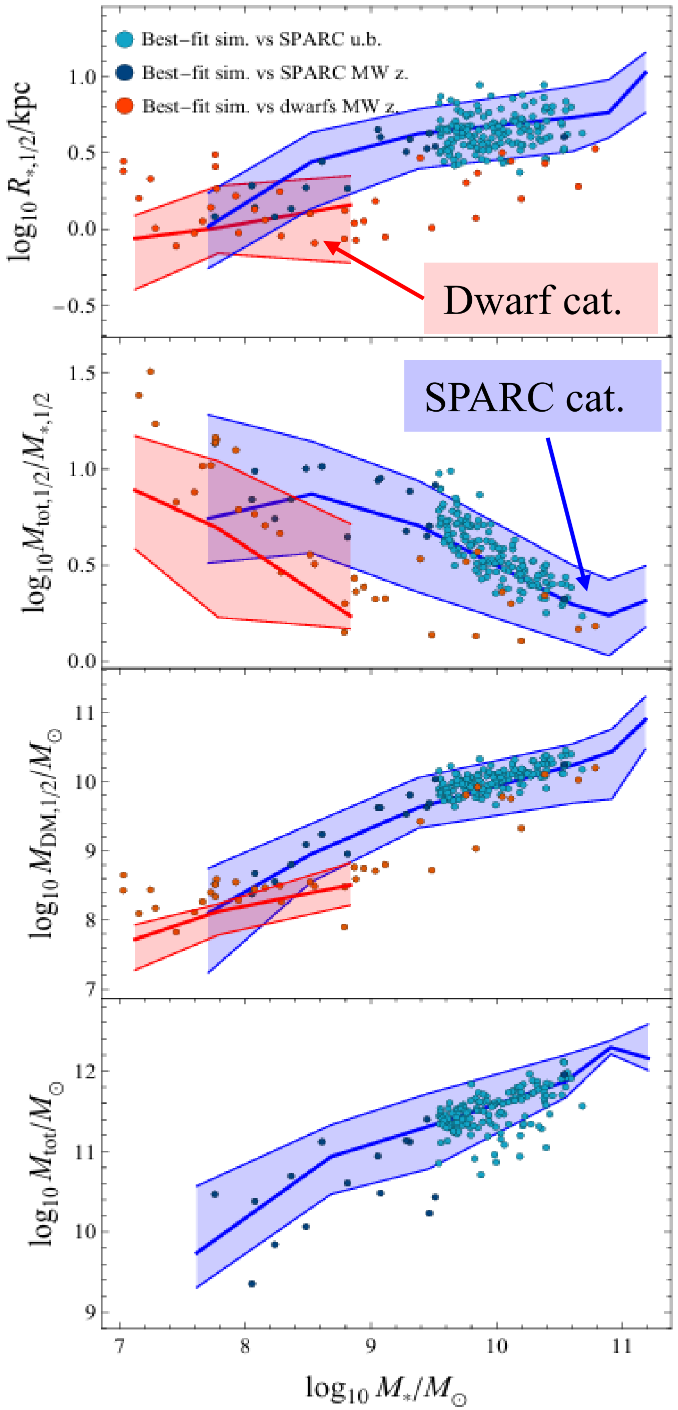


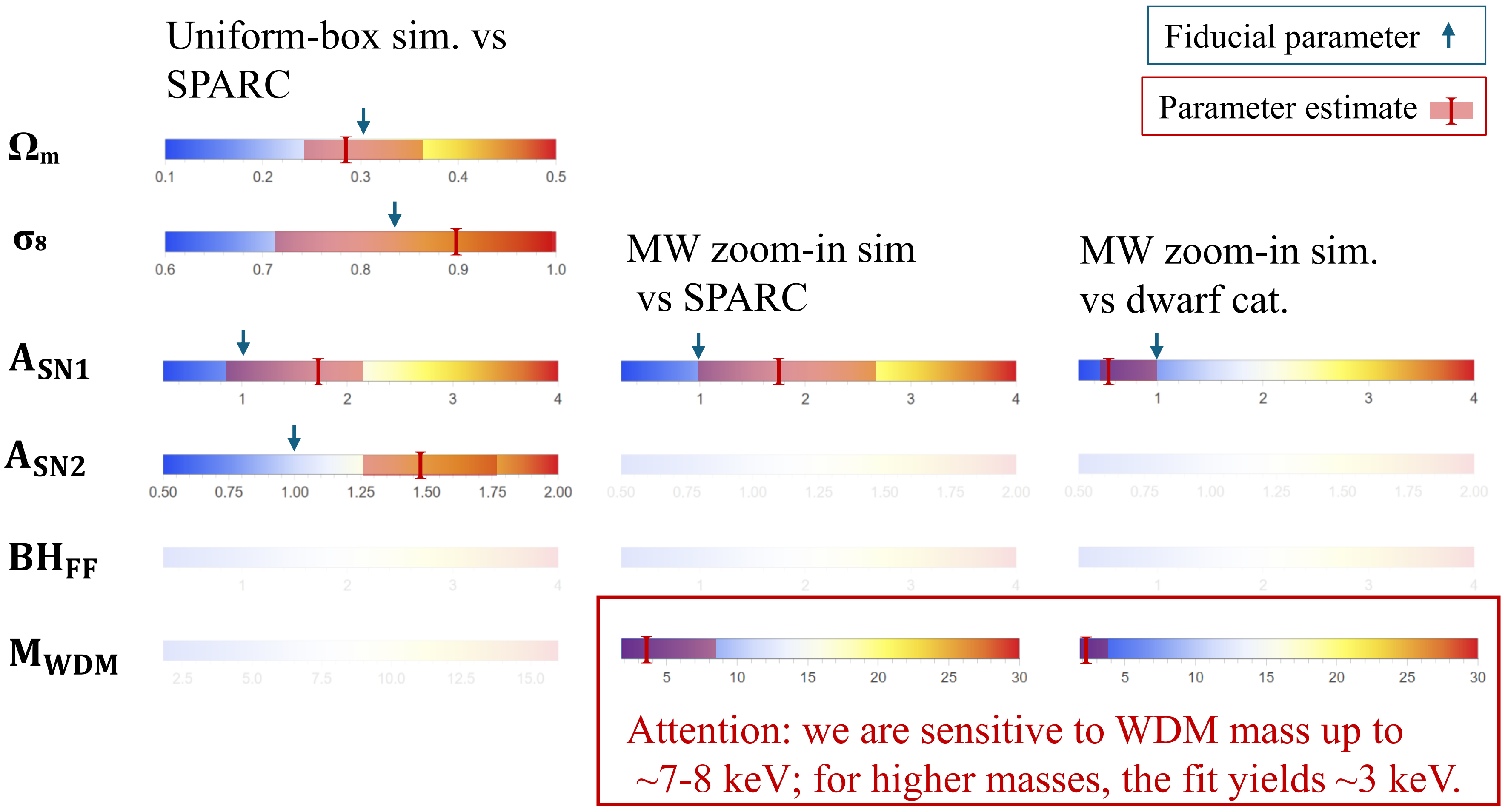


$\mathbf{A_{SN1}}$: uncertain parameter estimate

Parameters not recovered

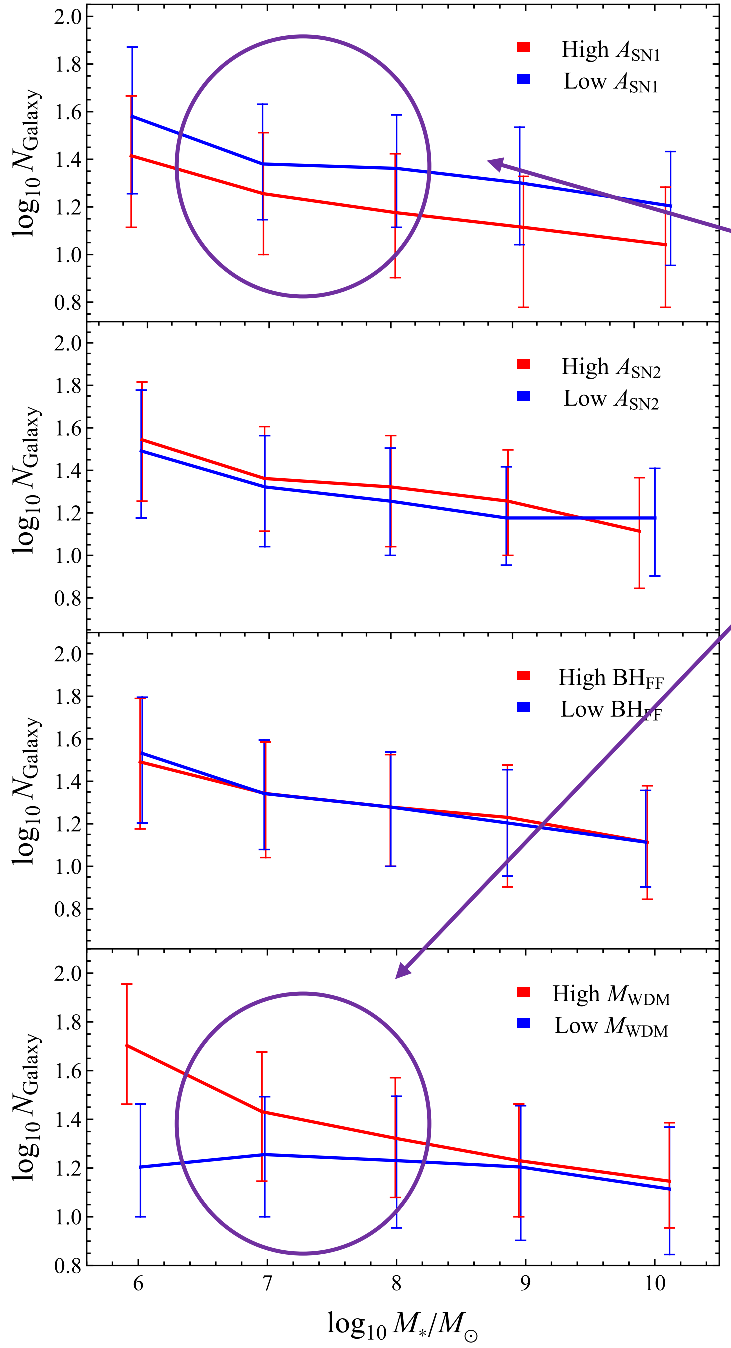
Simulations vs. observations: parameter estimates





- Fits to the SPARC catalog suggest that the SN feedback should be stronger than in the fiducial model.
- High-resolution simulations tend to overestimate the trends observed in dwarf galaxies.

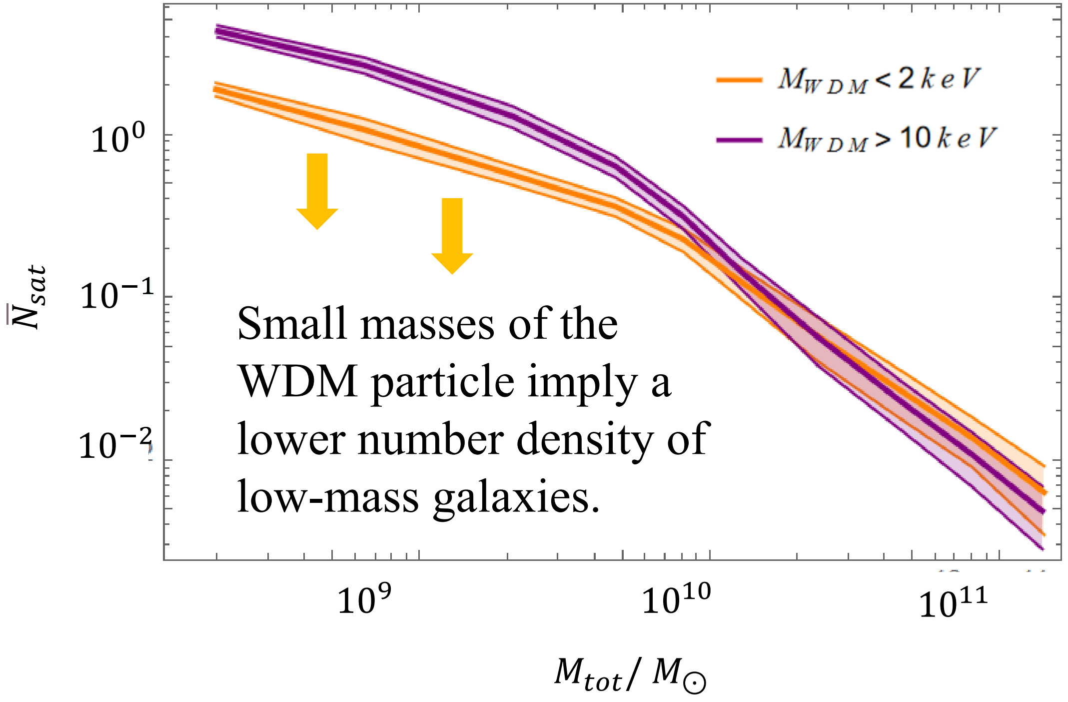
Number of galaxies



SN1 produces a vertical shift in the number of galaxies.

The mass of WDM changes the number of galaxies depending on their total stellar mass.

Number density of satellites



Conclusions

- The WDM mass impacts scaling relations for low-mass galaxies.
- Degeneracy with astrophysical feedback complicates mass determination.
- High-resolution simulations struggle to match dwarf galaxy sizes.
- Our analysis provides insight into which cosmological and astrophysical processes are most consistent with observations in a WDM scenarios.

Next step:

- Using literature data and Euclid's new dwarf galaxies to compare observed and predicted galaxy densities, refining WDM mass constraints.

Marleau et al 2024, 2025