Breaking the degeneracy between adiabatic and impulsive cusp-core transformation mechanisms

Jan David Burger

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2021

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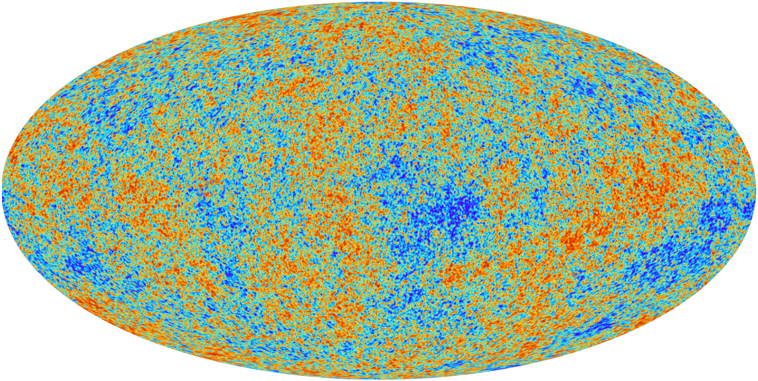
Structure formation in ΛCDM

- CMB: $\frac{T-\bar{T}}{\bar{T}} \sim 10^{-5}$



ESA/Planck

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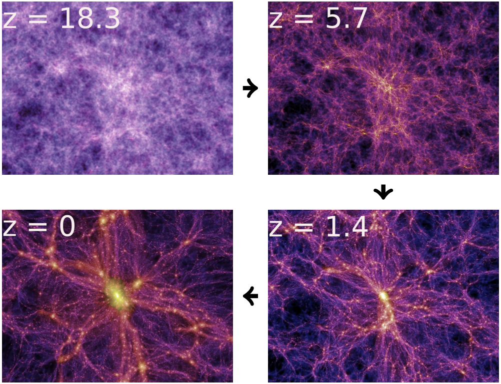

Springel et. al. 2005

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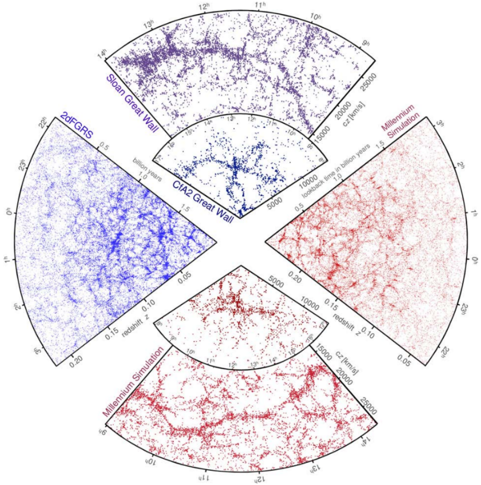
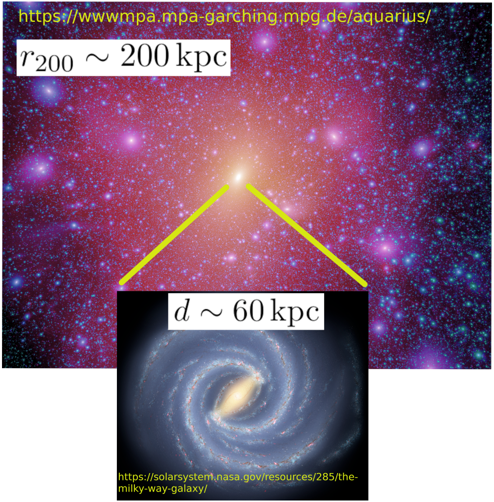
- Simulated structure matches observations on large scales

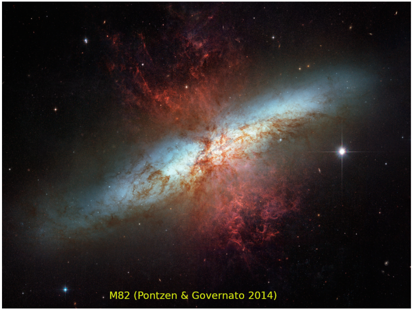


Springel et. al. 2006

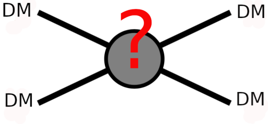
Challenges on small scales



Baryonic physics



DM particle physics



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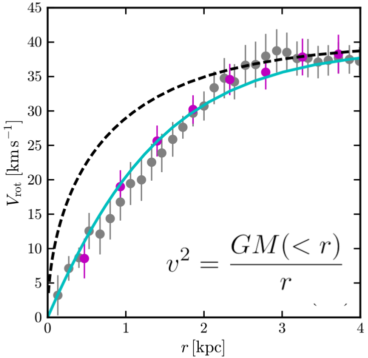

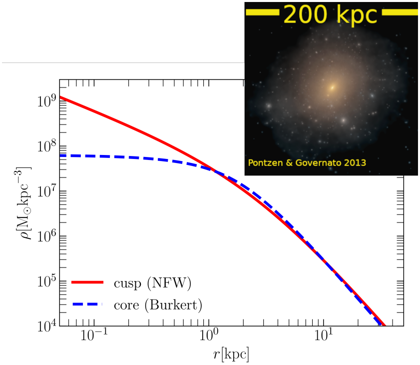

Bullock & Boylan-Kolchin 2017

- Rotation curves of some dwarf galaxies rise slower than expected
- Their host DM haloes appear to be cored instead of cuspy

Scope of this presentation

- Inner density profile of simulated CDM haloes has a universal, cuspy shape
- Measured rotation curves of dwarf galaxies suggest DM haloes with constant density cores
- Theory and observation need to be reconciled by core formation mechanisms
- Different core formation mechanisms must lead to (nearly) identical, i.e. degenerate final halo density profiles
- The timescale of the cusp-core transformation is different for different feasible mechanisms
- Key motivation: Can we use this difference to break the degeneracy between core formation mechanisms?

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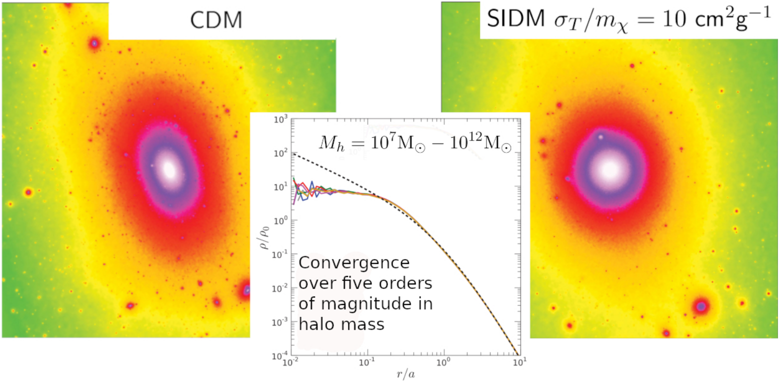
Core formation mechanisms - Self-interacting DM



Vogelsberger et al. 2012

- Elastic scattering between DM particles →heat exchange
- Scattering rate regulated by momentum transfer cross section:

$$P_{ij} \propto \rho_i \frac{\sigma_T}{m_\chi} v_{ij} \Delta t_i,$$

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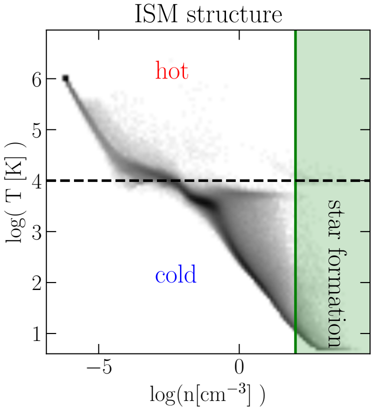
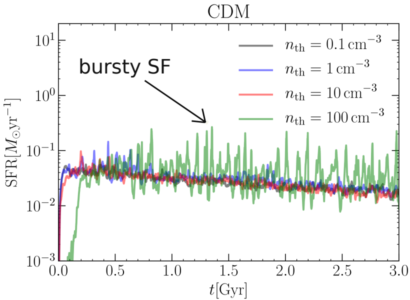
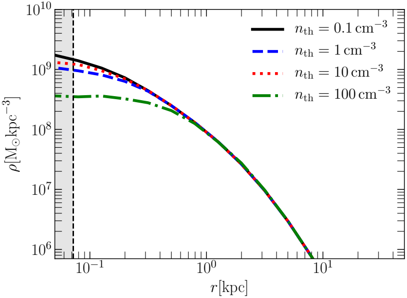
Core formation mechanisms - SN Feedback

- Bursty star formation causes impulsive SNF
- Core formation if central potential is dominated by baryons







Analytic models for SNF

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  - External potential mimicking a galaxy
  - Scheme to model the formation of "superbubbles"
  - Distribution of "superbubbles" determined by external potential

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  - Distribution of "superbubbles" determined by external potential
- Free parameters of two-component model:
  - Galaxy type and galaxy size
  - Energy injection time
  - Total amount of injected energy

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Adiabatic and impulsive evolution

- In static potentials with spherical symmetry

$$H(\mathbf{x}, \mathbf{p}) \to H(J_r, L, L_z),$$

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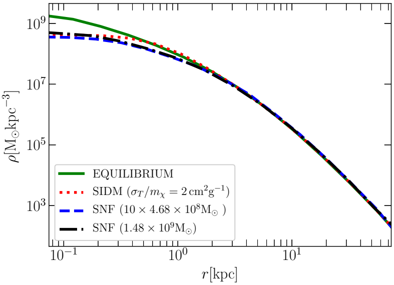
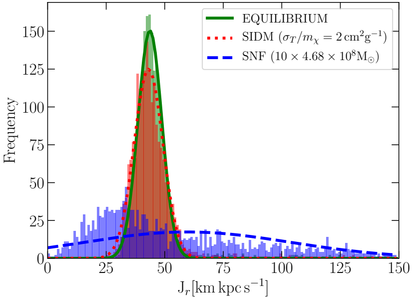
Key idea

Adiabatic /impulsive core formation mechanisms may affect the kinematic properties of stars in distinct ways.

Core formation through SIDM and SNF





Burger & Zavala 2019

- 10^7 DM particles, $M_{200} \sim 1.5 \times 10^{10} M_\odot$, $c_{200} = 15$
- One-component model for SNF, Probabilistic model for SIDM

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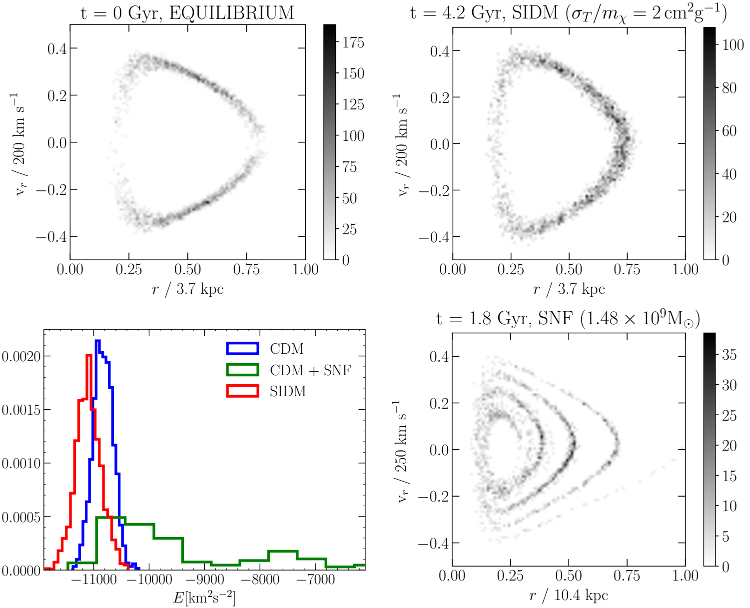
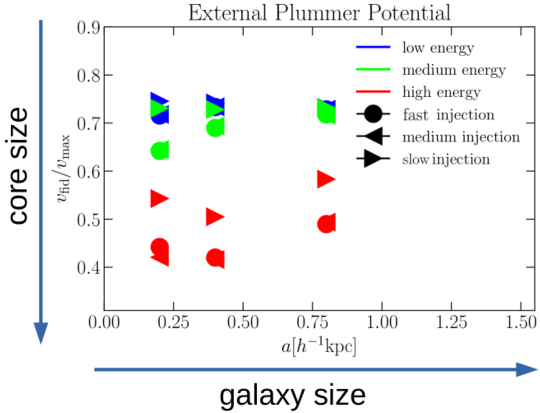
Orbital families and phase mixing



Burger & Zavala 2019

Evolution of circular velocity curves



Burger & Zavala 2021

- Two-component model, initially $M_h = 10^{10} h^{-1}\mathrm{M}_\odot$ $c_{200} = 13$
- Galaxy size, injected energy and injection time affect core size
- Similar picture for Plummer sphere and disk

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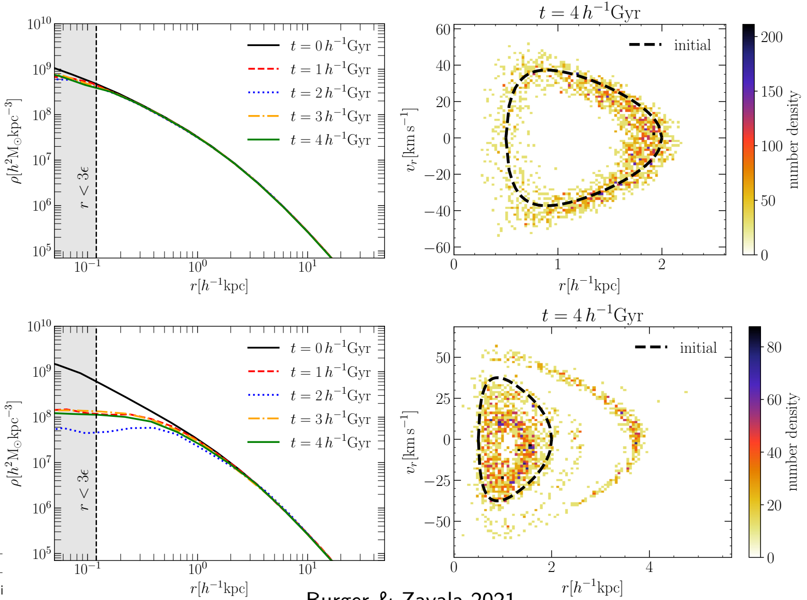
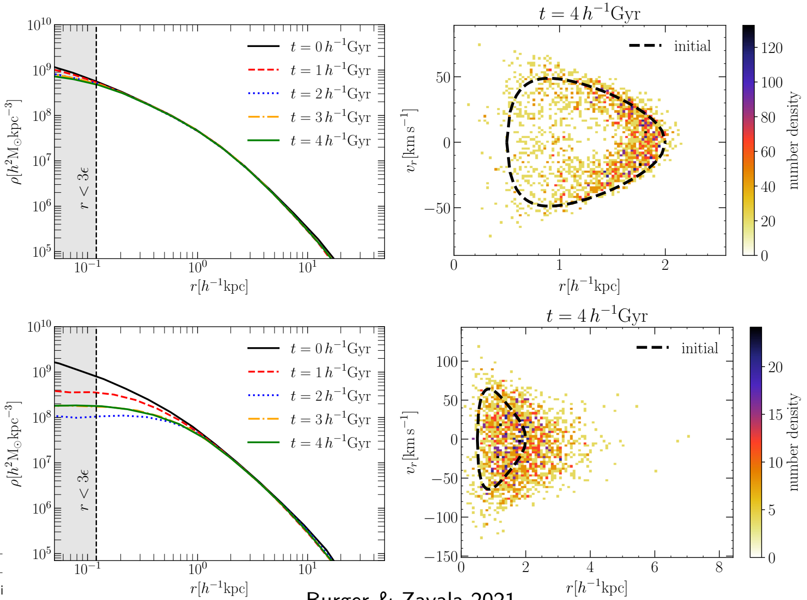
Orbital families and symmetry: Plummer sphere



Burger & Zavala 2021

Orbital families and symmetry: Flat disk



Burger & Zavala 2021

Hydrodynamic simulations of an isolated dwarf

- Set up ICs of an isolated SMC-analog in a live DM halo
  - $M_h \sim 1.6 \times 10^{10} \mathrm{M}_\odot \qquad c_{200} \sim 17$
  - Gas disk, stellar disk & stellar bulge $\sim 5\%$ of halo mass
  - $R_\star = 0.7\,\mathrm{kpc} \qquad R_\mathrm{gas} = 2.1\,\mathrm{kpc}$
  - Gas with $Z = Z_\odot$, $T = 10^4\,\mathrm{K}$, and in hydrostatic equilibrium
  - Particle / gas cell mass $\sim 10^3\,\mathrm{M}_\odot$

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- Systematically vary $n_{\rm th}$ and σ_T/m_χ in suite of 16 simulations
- Goal: break degeneracy between adiabatically and impulsively formed cores with kinematic properties of stars / gas

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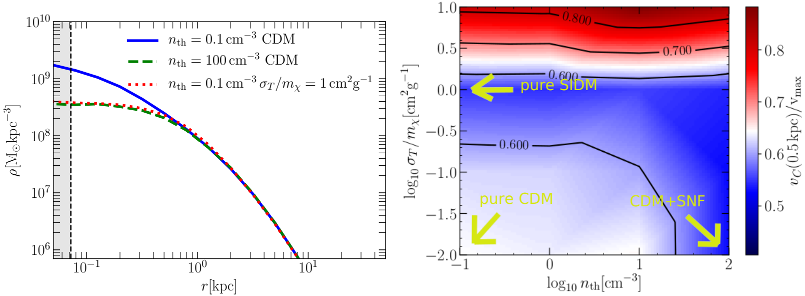
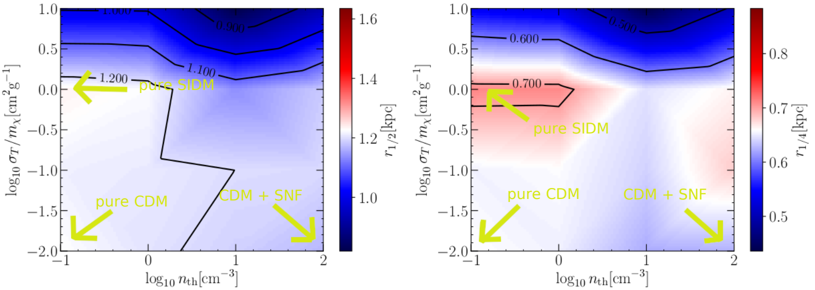
Degeneracy of DM density profiles



Burger et al. 2021

Different combinations of $n_{\rm th}$ and σ_T/m_χ can produce cores of a similar size!

Breaking the degeneracy



Burger et al. 2021

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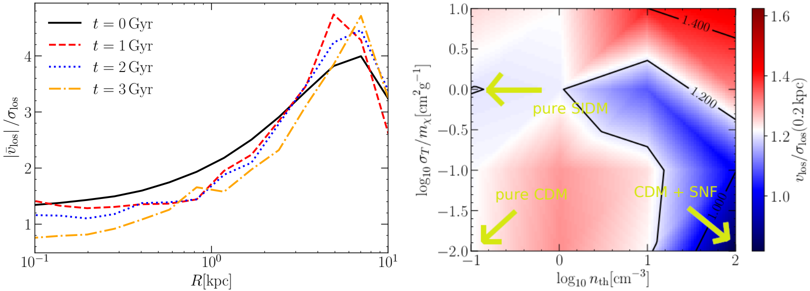

Burger et al. 2021

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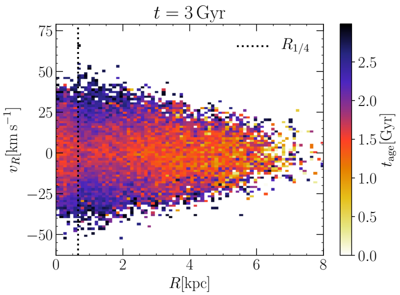

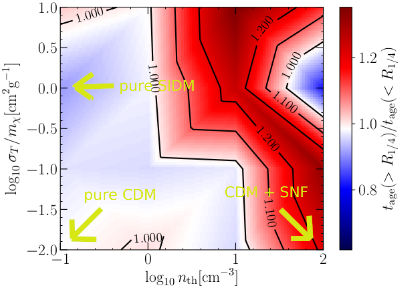

Burger et al. 2021

- Adiabatic core formation causes migration of stellar orbits
- Impulsive SNF can lead to an increase in random gas motion
- Impulsive SNF can cause large stellar age gradients

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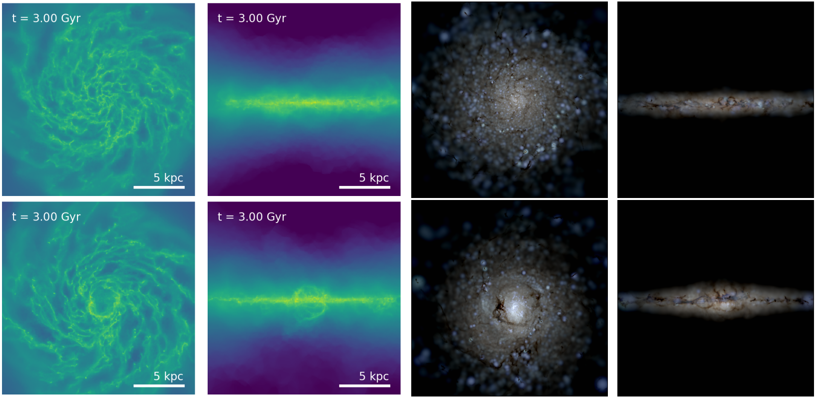
CDM runs – low vs high star formation threshold



Burger et al., in prep.

- Compare CDM runs with $n_{\rm th} = 0.1\,{\rm cm}^{-3}$ and $n_{\rm th} = 100\,{\rm cm}^{-3}$
- Supperbubble created by impulsive SNF is apparent in the edge-on projection of the gas

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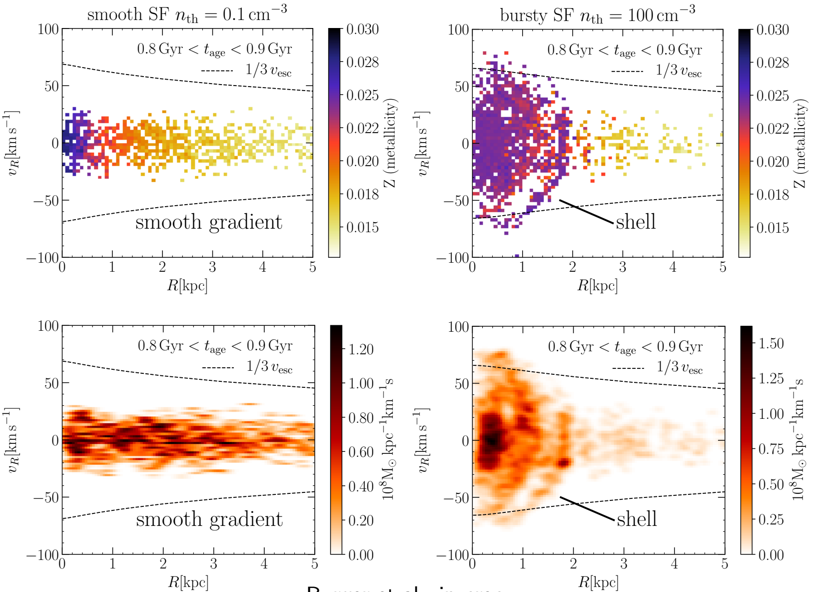
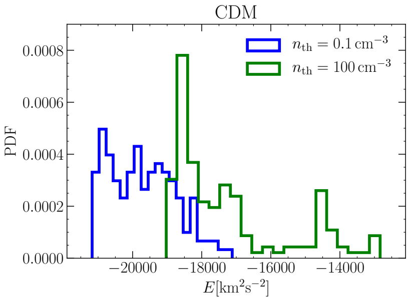
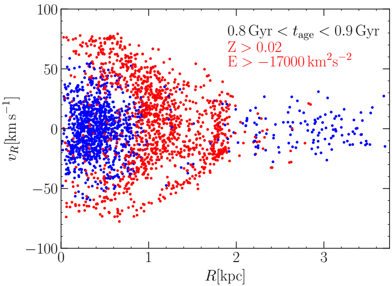
Phase space distribution of mono-age stars



Burger et al., in prep.

Explaining the shell feature





Burger et al., in prep.

- Stars of similar age and metallicity form orbital families
- Look at 150 most metal-rich stars
- Impulsive SNF causes discontinuous energy increase
- High-energy particles make up the shell →phase mixing

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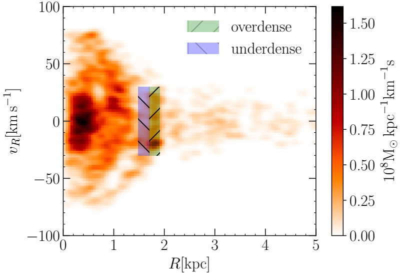
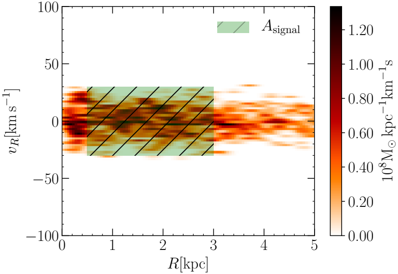
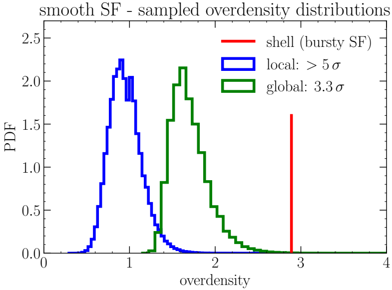
Significance of the shell feature







Burger et al., in prep.

- Use smooth distribution as target distribution for random sampling
- Determine likelihood of overdensity being a chance occurrence
- Feature has local (global) significance of $> 5\sigma$ (3.3σ)

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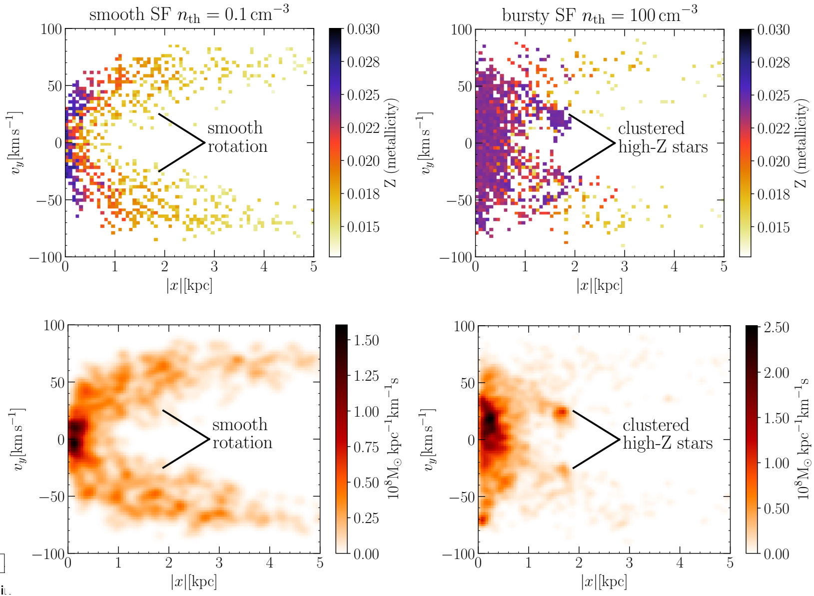
LOS projection of phase space shell



Burger et al., in prep.

Conclusion and outlook

- Both SIDM and SNF are viable cusp-core transformation mechanisms at the scale of dwarf galaxies

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- We need cosmological simulations to further quantify the signal(s) and take environmental effects into account
- Required observational data is likely available 5-10 years down the road (e.g. Roman Space Telescope)

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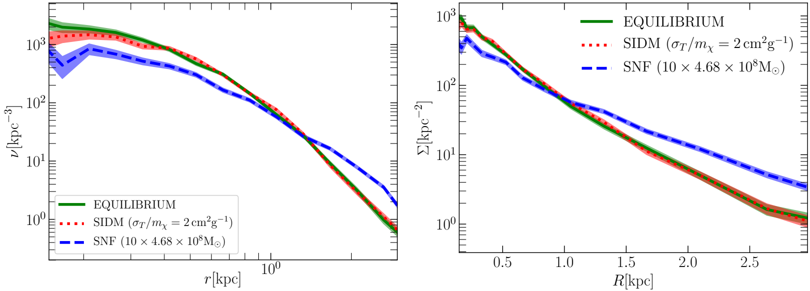
References

This presentation contains results from four research articles:

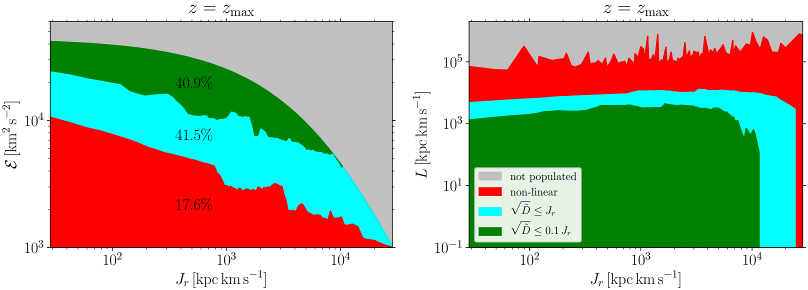
- *The nature of core formation in dark matter haloes: adiabatic or impulsive?* by Jan D. Burger and Jesús Zavala, 1810.10024
- *SN-driven mechanism of cusp-core transformation: an appraisal* by Jan D. Burger and Jesús Zavala, 2103.01231
- *Degeneracies Between Self-interacting Dark Matter and Supernova Feedback as cusp-core transformation mechanisms* by Jan D. Burger, Jesús Zavala, Laura V. Sales, Mark Vogelsberger, Federico Marinacci, and Paul Torrey, 2108.07358
- *Kinematic signatures of impulsive supernova feedback in dwarf galaxies* by Jan D. Burger, Jesús Zavala, Laura V. Sales, Mark Vogelsberger, Federico Marinacci, and Paul Torrey, in prep.

Thank you for your attention !

Plummer profiles



Action condition in J_r-L space



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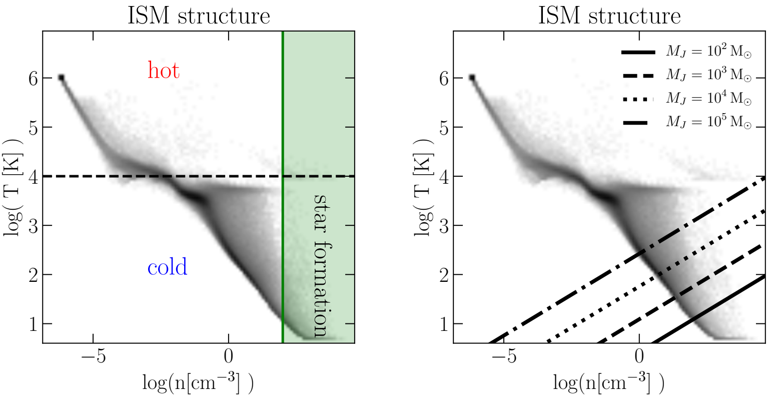
$n - T$ diagram and Jeans mass



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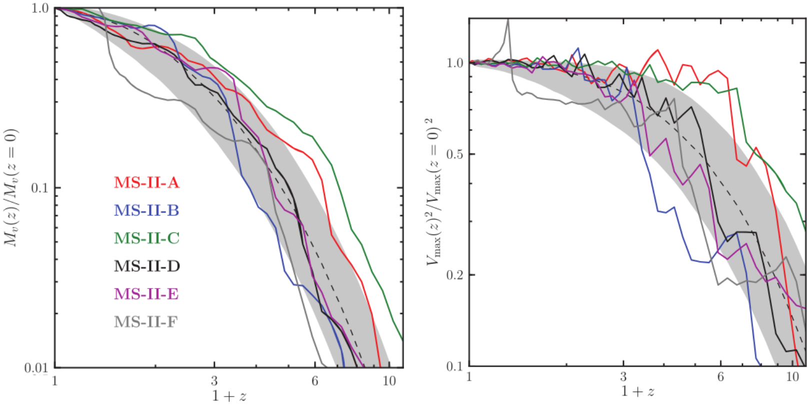
BK mass accretion history



Boylan-Kolchin et al., 2010

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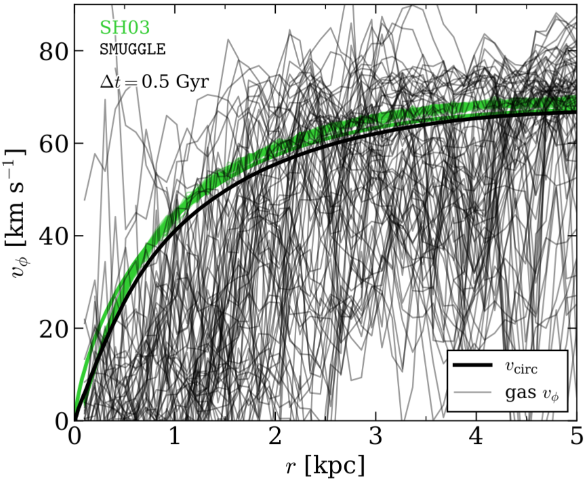
SMUGGLE rotation curves



Jahn et al., in prep.

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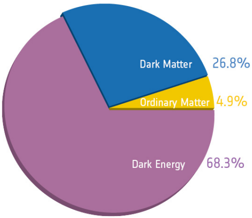
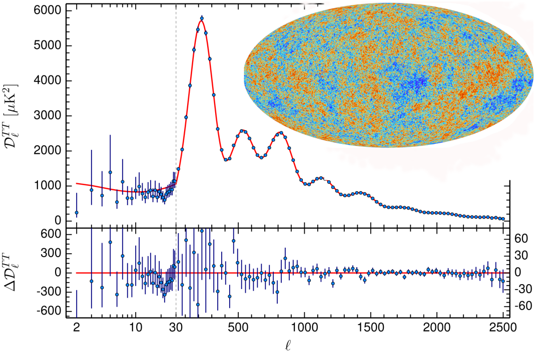
Evidence for dark matter





ESA/Planck

- Angular power spectrum of the CMB temperature fluctuations

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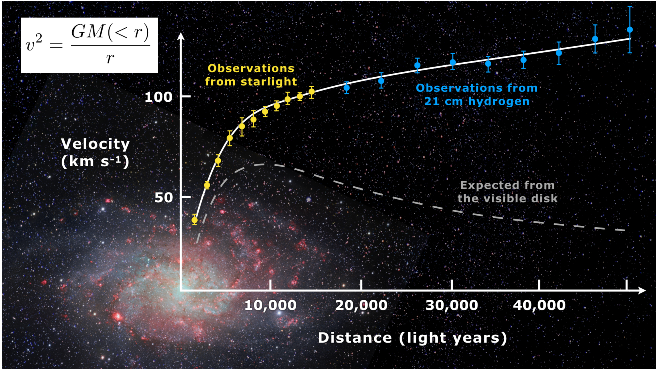
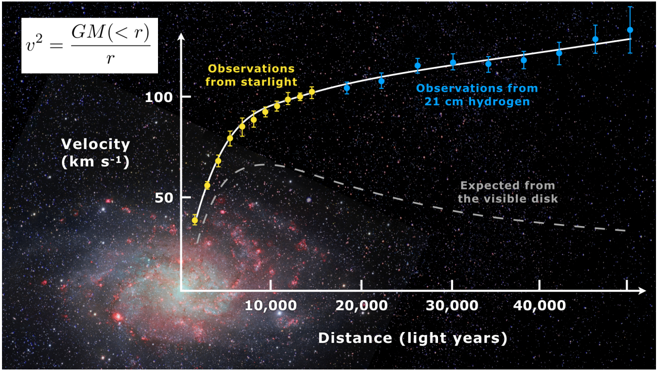
Evidence for dark matter



- Angular power spectrum of the CMB temperature fluctuations
- The inner kinematics of observed galaxies and galaxy clusters

Evidence for dark matter



- Angular power spectrum of the CMB temperature fluctuations
- The inner kinematics of observed galaxies and galaxy clusters
- There is also strong evidence for DM from cosmic structure formation

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Radial actions in evolving spherical potentials

- In static potentials with spherical symmetry

$$H(\mathbf{x}, \mathbf{p}) \to H(J_r, L, L_z),$$

where the actions are conserved quantities

- In mildly time-dependent potentials, the actions of kinematic tracers (nearly massless particles) evolve as

$$J_r = J_{r'} + (\mathbf{r} \cdot \dot{\mathbf{r}}) \frac{\dot{R}}{R} \frac{P(E, L, t)}{2\pi} \equiv J_{r'} + \Delta_{J_r}$$

- $\dot{R}/R$ depends on the rate of change in both amplitude and shape of the potential
- $P(E, L, t)/2\pi$ is the reduced radial period

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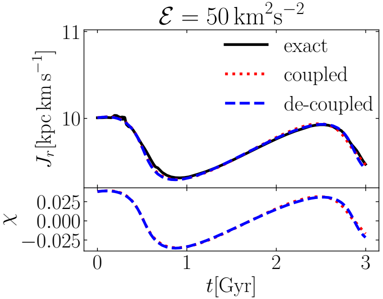
Radial actions of tracer particles

$$\Phi(r,t) = -\frac{GM_0(1+\epsilon t)}{r}$$
$$\log_{10}(M_0/M_\odot) = 8$$
$$\epsilon^{-1} = 30\,\mathrm{Gyr}$$



Burger et al. 2020

- The first-order approximation is accurate if the potentials evolves slowly relative to the tracer's orbital time

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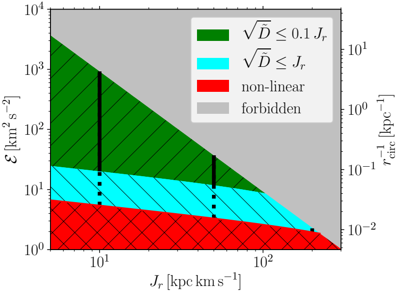
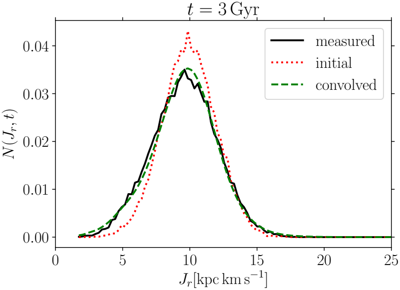
Radial actions of tracer particles





Burger et al. 2020

- The first-order approximation is accurate if the potentials evolves slowly relative to the tracer's orbital time
- A diffusion theory with drift $\tilde{C} \sim \langle \Delta_{J_r} \rangle$ and diffusion $\tilde{D} \sim \langle \Delta^2_{J_r} \rangle$ accurately predicts the evolution of radial action distributions for $\tilde{D} \ll J_r^2$

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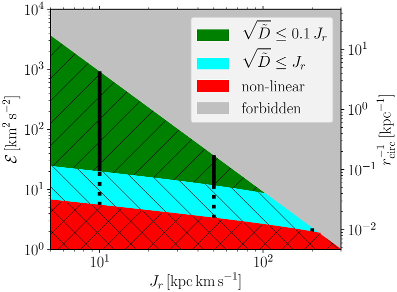
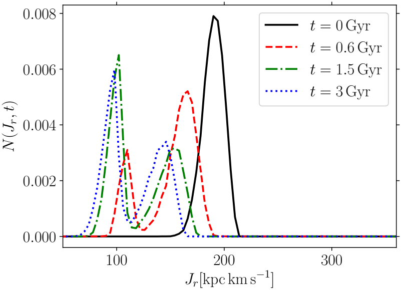
Radial actions of tracer particles





Burger et al. 2020

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- A diffusion theory with drift $\tilde{C} \sim \langle \Delta_{J_r} \rangle$ and diffusion $\tilde{D} \sim \langle \Delta^2_{J_r} \rangle$ accurately predicts the evolution of radial action distributions for $\tilde{D} \ll J_r^2$, but fails for $\tilde{D} \gtrsim J_r^2$