Cosmological hydrodynamic simulations are the most powerful theoretical tools to study stellar halos...

...you just have to solve galaxy formation first.
comparison of cosmological hydrodynamic simulations with other theoretical tools

key advantages

• self-consistently include and resolve (as best can) additional physics (hydrodynamics, star formation, stellar evolution & feedback, black holes)

• model non-linearities and non-equilibrium processes (cosmological and stellar) that simpler models cannot

• more readily create high-fidelity synthetic observations to robustly compare with and test against observations
comparison of cosmological hydrodynamic simulations with other theoretical tools

**key downsides**

- much more computationally expensive
  - 20-100 x more expensive than gravity-only (same resolution)
  - limited to lower resolution than DM-only / idealized
- difficult to survey parameter space / uncertainties
- results may depend on uncertain and/or unresolved (astro)physics (star formation, evolution, feedback, etc)
- results depend on fidelity of entire model space
  - difficult to isolate physical processes for detailed understanding
comparison of cosmological hydrodynamic simulations with other theoretical tools

**key idea**

self-consistency and inter-dependence of physics in cosmological hydrodynamic simulations is both a strength and (for now) a limitation
cosmological hydrodynamic simulations
state of the art (to $z = 0$)

Big Box ($\sim 100$ Mpc)
Illustris, EAGLE, Horizon-AGN,
Mufasa, BAHAMAS, etc

Zoom-in ($\sim 1$ Mpc)
MW: Eris, FIRE, Auriga, APOSTLE,
Gasoline, NIHAO, etc
Clusters: RomulusC, Omega500, etc
Big Box versus Zoom-in

**Big Box**
- model large-scale structure
- large statistical samples
- multiple environments at once
- lower resolution
  - particle mass $\sim 10^6 \, M_\text{sun}$
  - spatial $\sim 1 \, \text{kpc}$
  - rely on more phenomenological ‘sub-grid’ models

**Zoom-in**
- cannot model LSS
- one—few halos at a time
- single environment at once
  (but can zoom-in on different ones)
- higher resolution
  - particle mass $\sim 30-10,000 \, M_\text{sun}$
  - spatial $\sim 1 \, \text{pc}$
  - start to resolve ‘sub-grid’ scales: GMCs, star clusters, supernovae blast waves
state of the art

Big Box & cluster zoom-in to $z = 0$

- similar resolution for galaxy cluster zoom-in and Big Box simulations
- baryonic mass resolution $\approx 10^5$-$10^6 \, M_{\odot}$
- spatial resolution $\approx 1 \, \text{kpc}$
- number of galaxy clusters 10’s - 100’s
- number of MW-mass systems lots!

<table>
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<tr>
<th>Name</th>
<th>Spatial Res.</th>
<th>$M_{DM}$</th>
<th>$M_{gas}$</th>
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state of the art
Milky Way-mass galaxy to $z = 0$
hydromechanics

Euler equation: \[ \frac{dv}{dt} = \frac{-\nabla P}{\rho} - \nabla \Phi \]

Continuity equation: \[ \frac{d\rho}{dt} + \rho \nabla \cdot \mathbf{v} = 0 \]

First law of thermodynamics: \[ \frac{du}{dt} = -\frac{P}{\rho} \nabla \cdot \mathbf{v} - \frac{\Lambda(u, \rho)}{\rho} \]

Equation of state of ideal monoatomic gas: \[ P = (\gamma - 1) \rho u, \quad \gamma = \frac{5}{3} \]
hydrodynamics

- **smooth particle hydrodynamics (SPH)**
  - Lagrangian, adaptive, conserves (angular) momentum well
  - difficulty in capturing fluid instabilities/mixing/shocks
  - fast!

- **adaptive mesh refinement (AMR)**
  - Eulerian, models fluid mixing, shocks, and instabilities well
  - can have difficulty with (angular) momentum conservation, grid alignment effects
  - often slower (supersonic fluid advection across cell)
new hybrid hydrodynamic methods

- Lagrangian: moves with flow
- conserves mass, momentum, energy, (angular) momentum
- no imposed geometry
- captures shocks & instabilities
- now with magneto-hydrodynamics!
- but seems not to matter much for galaxy formation

AREPO moving mesh
Springel 2010

Gizmo mesh-free
Hopkins 2015
importance of hydrodynamics methods

- unimportant for dwarf galaxies
- important for massive (>~MW mass) halos with hot gas
- but details of stellar (feedback) physics more important! (e.g. Scannapieco et al 2012)

MW-mass halo: Hopkins, Wetzel et al 2018
also Springel, Sijaki, Keres, Vogelsbserger et al papers in 2012
star formation

common model requirements

- dense gas
  - \( n_{\text{SF}} > 0.1 - 1000 \text{ atoms/cm}^3 \)
  - note: MW ISM \( n_{\text{ave}} \approx 1 \text{ atom/cm}^3 \)
- molecular gas
- self-gravitating / jeans unstable

star-formation model can affect

- smoothness of SFH (burstiness)
- DM core formation
- in-situ stellar halo formation
stellar feedback (+AGN)

supernovae
- core-collapse (prompt)
  - most important (10x as many as type Ia)
- type Ia (delayed)

stellar radiation
- radiation pressure
- photoionization heating (HII regions)
- photoelectric heating (via dust)
- self-consistent radiation hydrodynamics (development)

stellar winds
- massive O & B stars (prompt)
- AGB stars (delayed)

cosmic rays (development)
- supernovae shocks, mergers
at sufficiently high resolution, feedback methods converge, because hydrodynamics resolves them (no longer ‘sub-grid’)
star formation and stellar (+AGN) feedback

key idea about ‘sub-grid’

models for star formation and stellar (+AGN) feedback in a cosmological setting always (within our lifetime) will need to rely on ‘sub-grid’ components
considerations for modeling stellar halos

- cosmological hydrodynamic simulations can model formation of both ex-situ (accreted) and in-situ (mergers, feedback) stellar halo

- ex-situ
  - cosmological = correct orbits
  - need to correctly model satellite masses and sizes

- in-situ
  - powerful capability of cosmo hydro
  - need to model correct mergers and impact of feedback
cosmo hydro simulations now form realistic populations of satellites (MW-mass and cluster-mass halos)

FIRE
Garrison-Kimmel et al 2018

APOSTLE
Sawala et al 2016

Auriga
Simpson et al 2018

NIHAO
Buck et al 2018

Andrew Wetzel
cosmological hydrodynamic simulations are critical for modeling contribution from in-situ stars
cosmological hydrodynamic simulations —> synthetic observations

- cosmological hydrodynamic simulations can be translated into **high-fidelity** synthetic observations
- robust comparison of model/simulation predictions against observations **requires** these mock catalogs!
- this is difficult to do well - foster/fund/reward those working to develop these methods!

example: synthetic Gaia surveys

**Ananke** from Latte FIRE simulations (Sanderson, Wetzel et al 2018)

**Aurigaia** from Auriga simulations (Grand et al 2018)
cosmological hydrodynamic simulations
status, limitations, and future directions

- need both Big Box (large-scale structure, statistics) and Zoom-in (resolve sub-grid scales, low-mass systems)

- **key limitations**
  - finite resolution
  - include more physical processes (e.g. cosmic rays)
  - model physical processes better (e.g. radiation hydrodynamics)
  - uncertainties in stellar evolution!

- next steps: resolve star (globular) clusters (and streams!)

- galaxy-wide properties are less discriminating in testing models - move to smaller scales and/or beyond galaxies (stellar halos!)