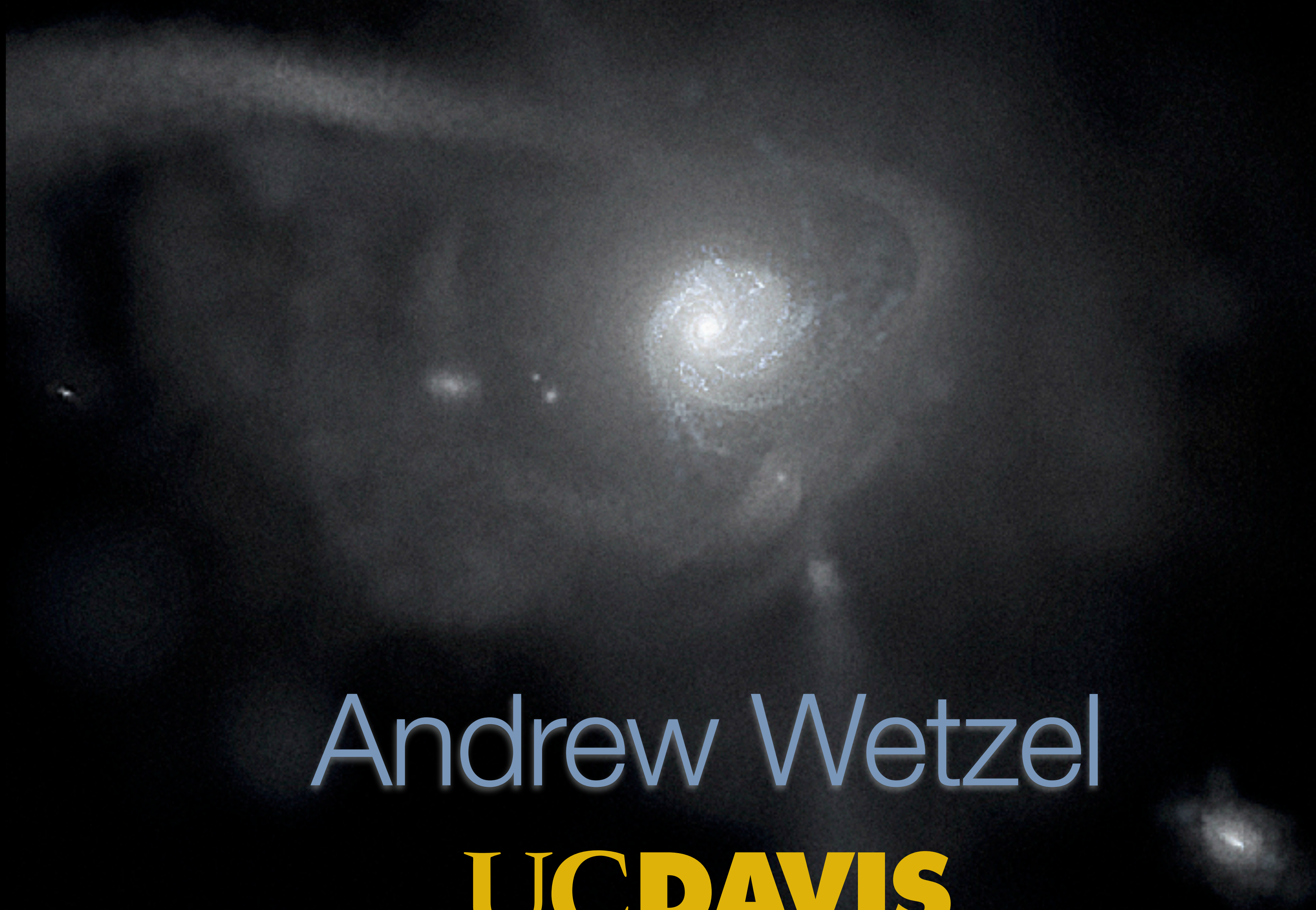
Cosmological Hydrodynamic Simulations



10 kpc

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SUMMARY OF THIS TALK

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

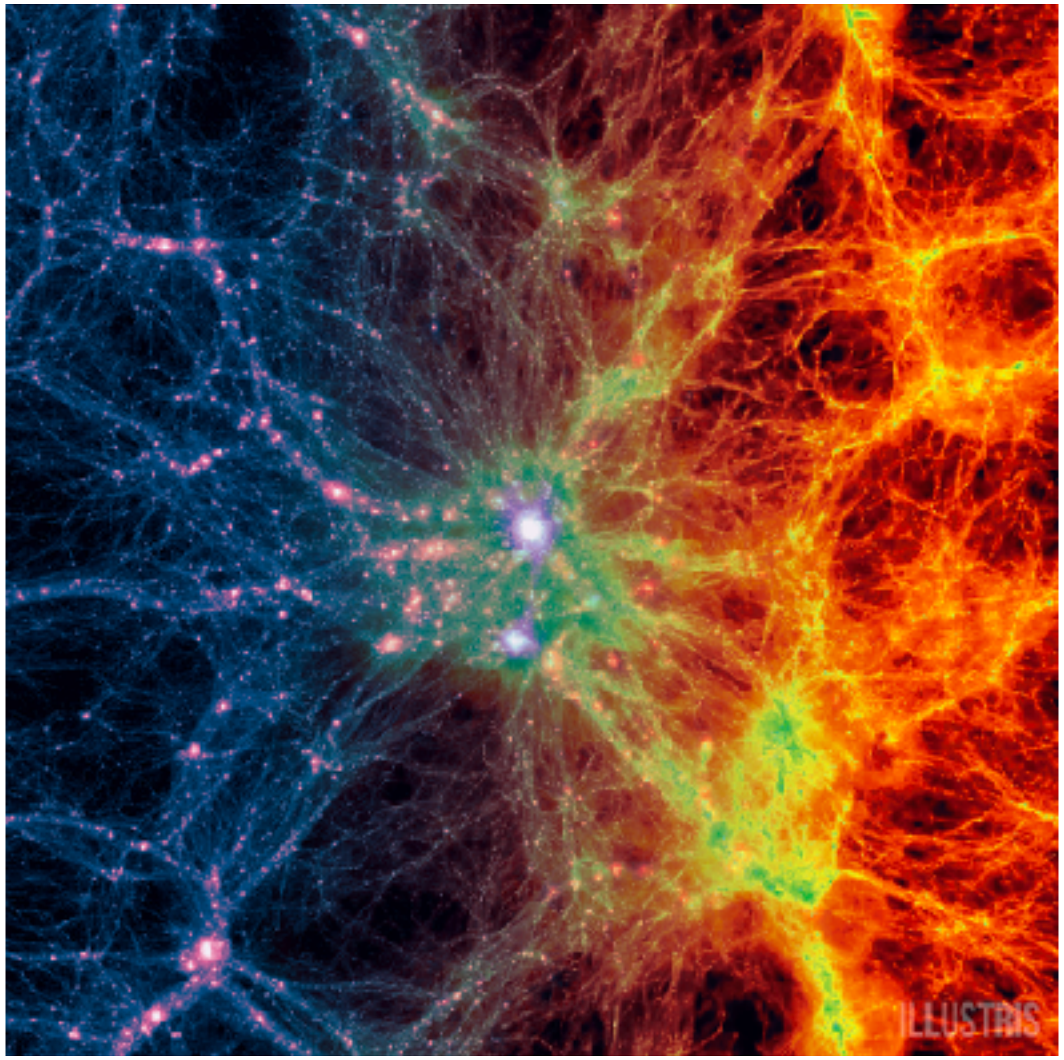
key idea

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)

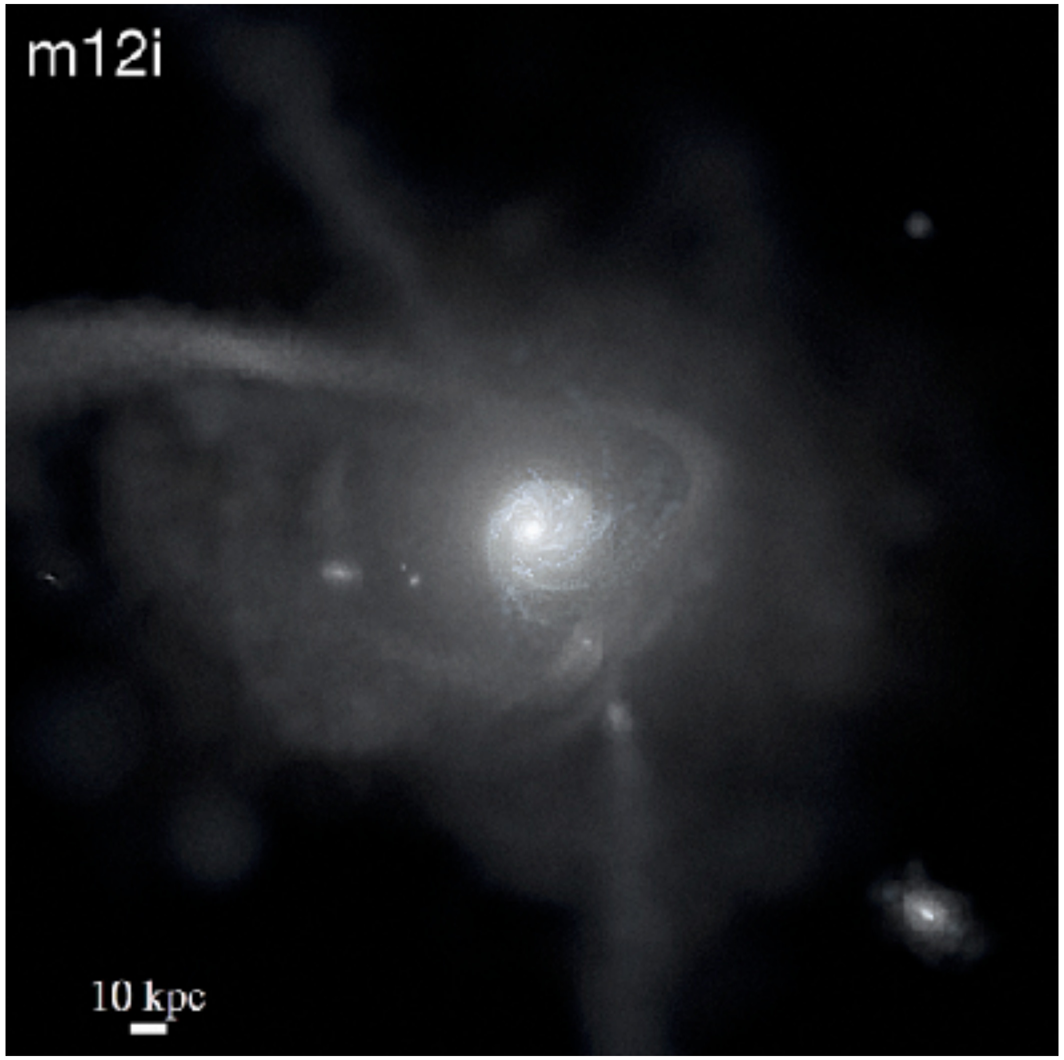
Big Box (~100 Mpc)

Illustris, EAGLE, Horizon-AGN, Mufasa, BAHAMAS, etc



Zoom-in (~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 >~ 10^6 M_{sun}
  - spatial >~ 1 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 >~ 30-10,000 M_{sun}
  - spatial >~1 pc
- start to resolve 'sub-grid' scales: GMCs, star clusters, supernovae blast waves

state of the art

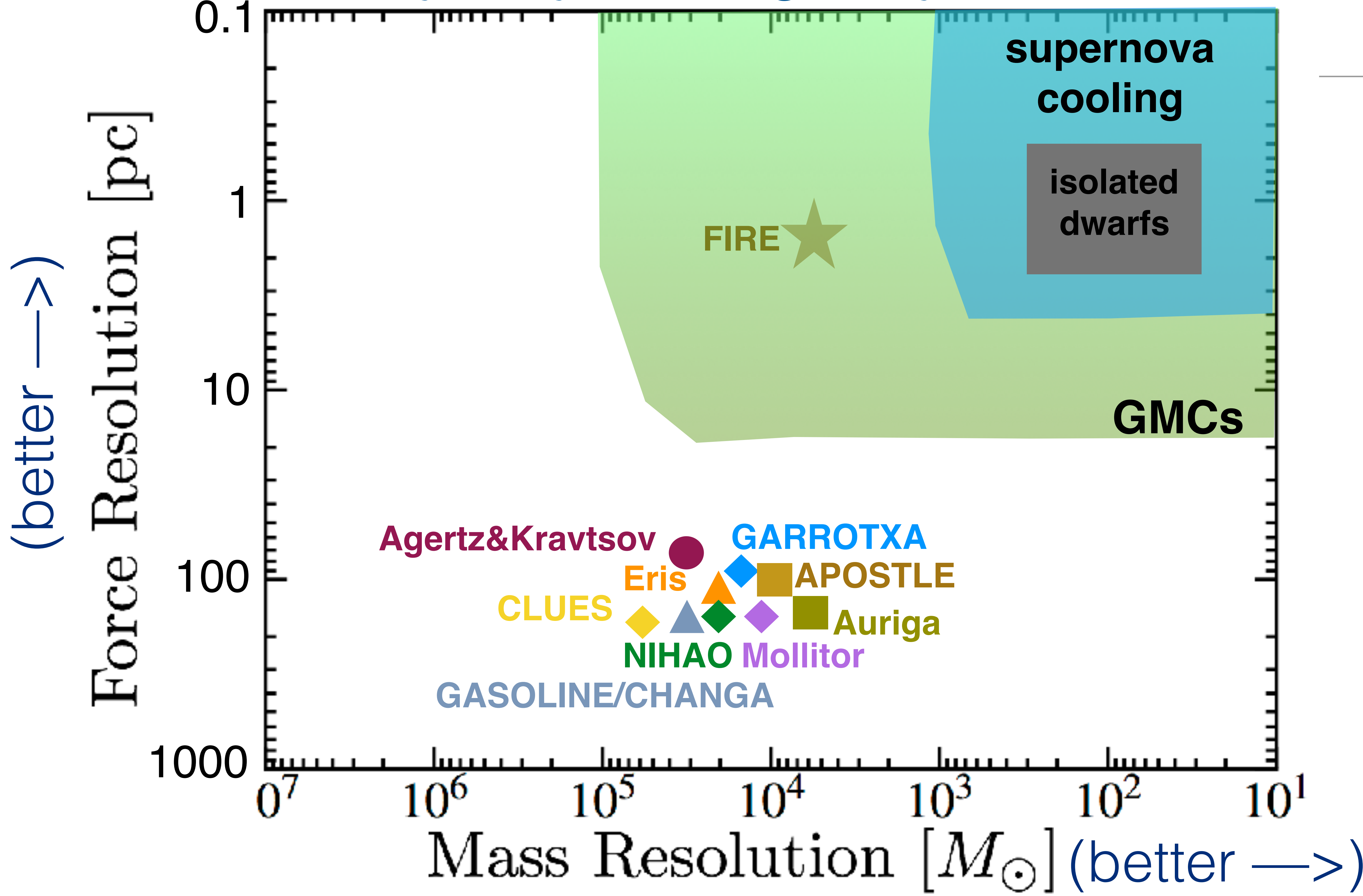
Big Box & cluster zoom-in to z = 0

- similar resolution for galaxy cluster zoom-in and Big Box simulations
- baryonic mass resolution **>~ 10^5-10^6 M_{sun}**
- spatial resolution **>~1 kpc**
- number of galaxy clusters **10's - 100's**
- number of MW-mass systems **lots!**

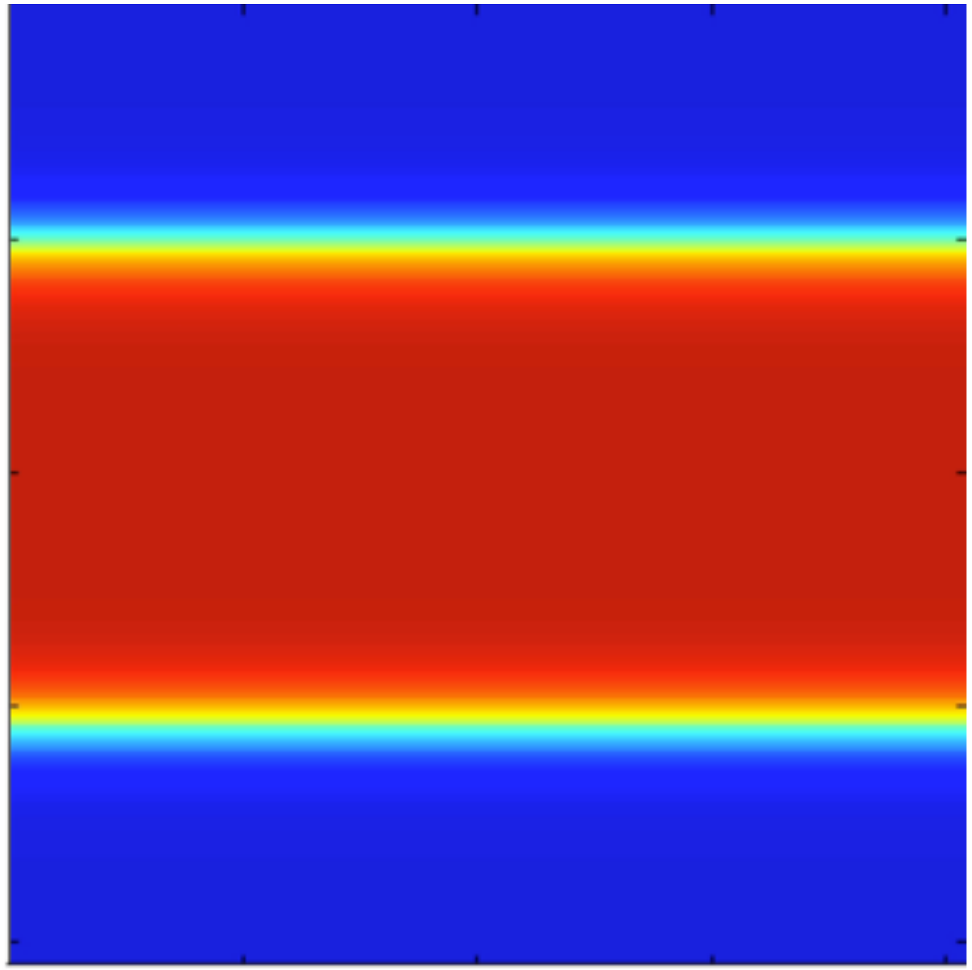
Tremmel et al 2018

	Name	Spatial Res.[a] kpc	M_{DM} $M_\odot$	M_{gas} $M_\odot$
cluster zoom	**RomulusC**	0.25	3.4×10^5	2.1×10^5
big box	TNG300[b]	1.5	7.9×10^7	7.4×10^6
big box	TNG100[b]	0.75	5.1×10^6	9.4×10^5
big box	TNG50 (in progress[c])	0.3	4.4×10^5	8.5×10^4
big box	Horizon-AGN[d]	1	8.0×10^7	1.0×10^7
big box	Magneticum[e]	10	1.3×10^{10}	2.9×10^9
	Magneticum[e] high res	3.75	6.9×10^8	1.4×10^8
	Magneticum[e] ultra high res	1.4	3.6×10^7	7.3×10^6
cluster zoom	C-EAGLE[f,g]	0.7	9.6×10^6	1.8×10^6
big box	EAGLE[g] (50, 100 Mpc)	0.7	9.6×10^6	1.8×10^6
cluster zoom	Omega500[h]	5.4	1.6×10^9	2.7×10^8
	MACSIS[i]	5.9	5.7×10^9	1.0×10^9
big box	BAHAMAS[j]	5.9	5.7×10^9	1.0×10^9
cluster zoom	Rhapsody-G[k]	5.0	1.0×10^9	1.9×10^8

state of the art
Milky Way-mass galaxy to z = 0



hydrodynamics



Euler equation: $$\frac{\mathrm{d}\mathbf{v}}{\mathrm{d}t} = -\frac{\nabla P}{\rho} - \nabla\Phi$$

Continuity equation: $$\frac{\mathrm{d}\rho}{\mathrm{d}t} + \rho\nabla\cdot\mathbf{v} = 0$$

First law of thermodynamics: $$\frac{\mathrm{d}u}{\mathrm{d}t} = -\frac{P}{\rho}\nabla\cdot\mathbf{v} - \frac{\Lambda(u,\rho)}{\rho}$$

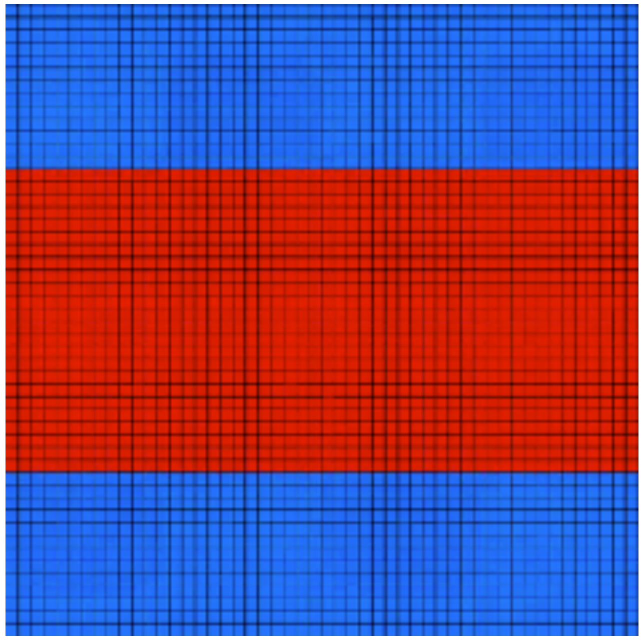
Equation of state of ideal monoatomic gas: $$P = (\gamma - 1)\rho u\ , \qquad \gamma = 5/3$$

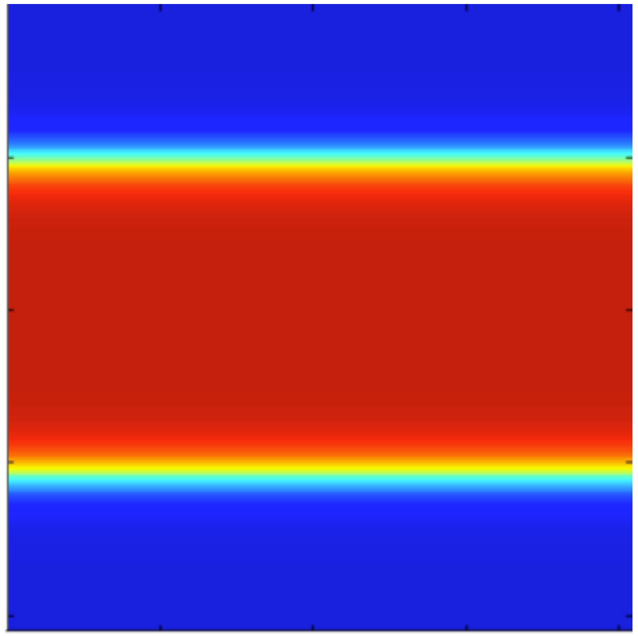
hydrodynamics

- **smooth particle hydrodynamics (SPH)**
  - Lagrangian, adaptive, conserves (angular) momentum well
  - difficultly 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

AREPO
moving mesh
Springel 2010



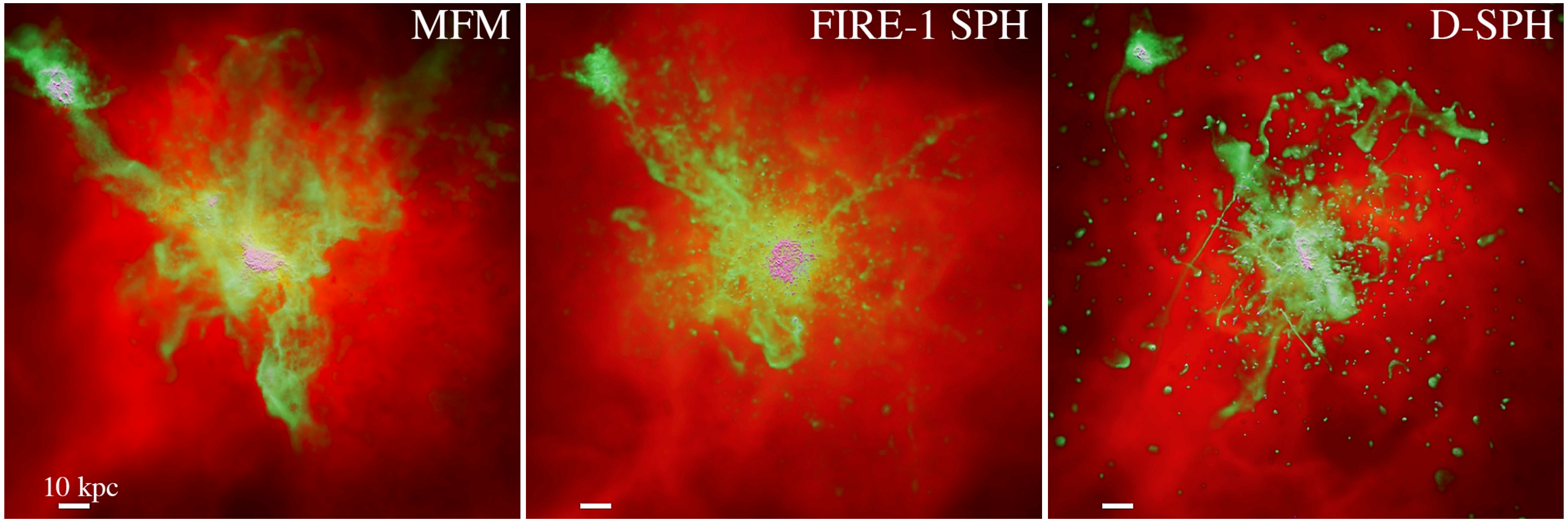


Gizmo
mesh-free
Hopkins 2015

- 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

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)

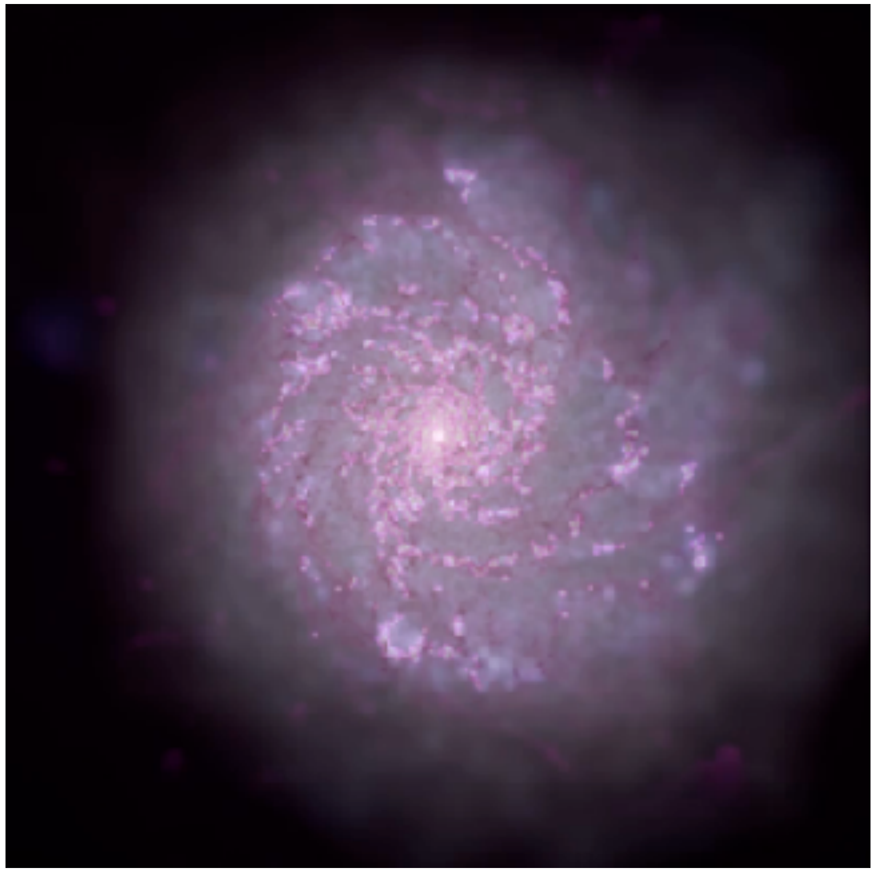


MW-mass halo: Hopkins, Wetzel et al 2018
also Springel, Sijaki, Keres, Vogelsbserger et al papers in 2012

star formation

common model requirements

- dense gas
  - $n_{SF} > 0.1$ - 1000 atoms/cm^3
  - note: MW ISM n_{ave} ~1 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-collape (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*)

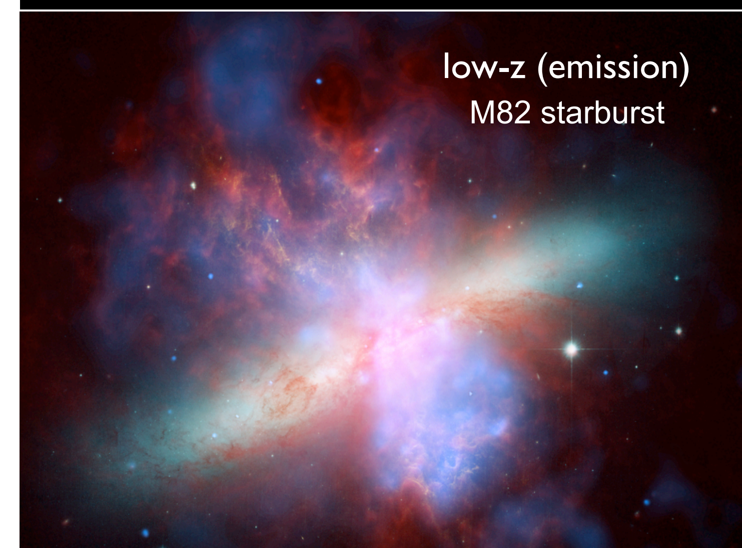
stellar winds

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

cosmic rays (*development*)

- supernovae shocks, mergers

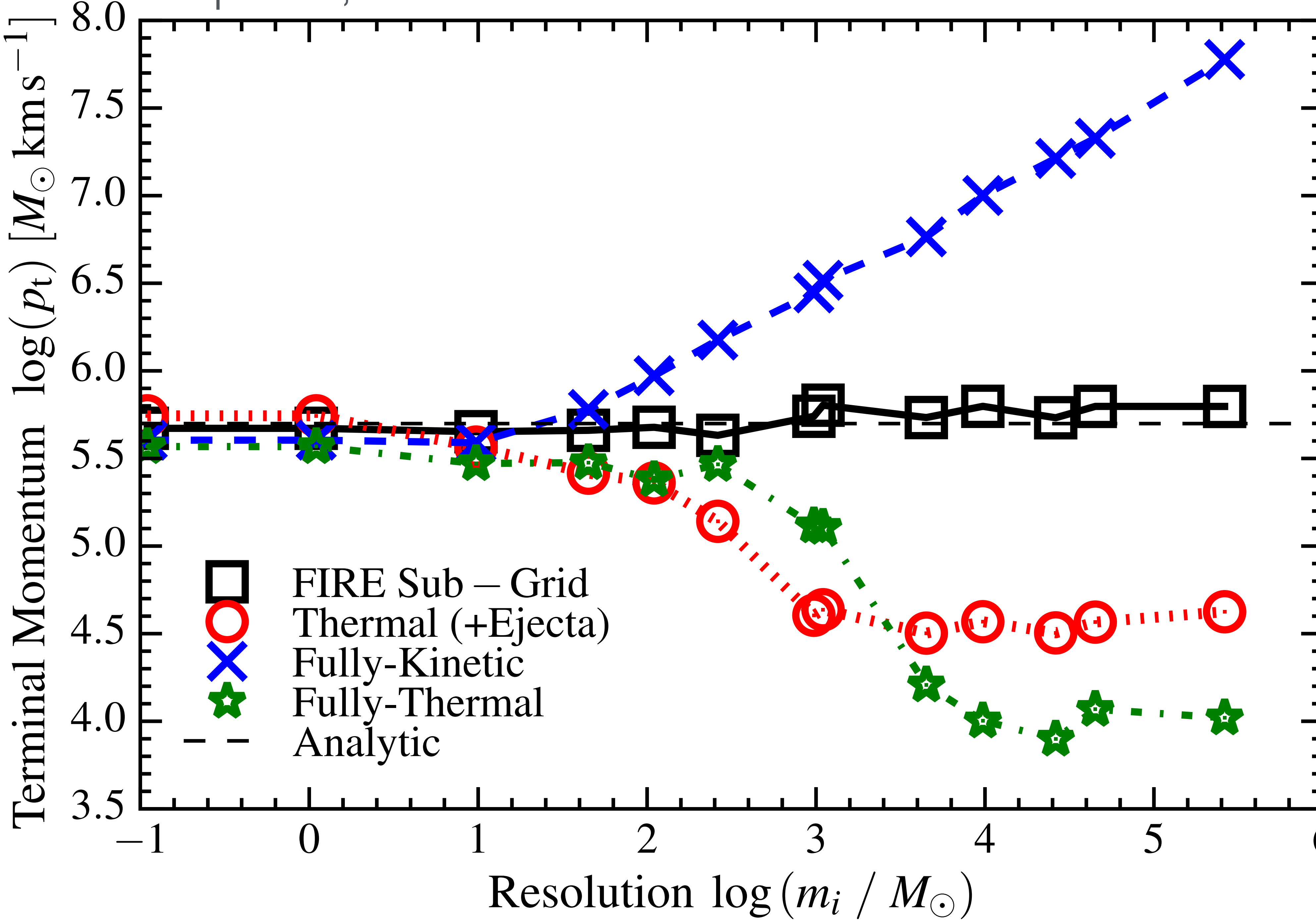
stellar scale



galaxy scale

stellar feedback

Hopkins, Wetzel et al 2018



at sufficiently high resolution, feedback methods converge, because hydrodynamics resolves them (no longer 'sub-grid')

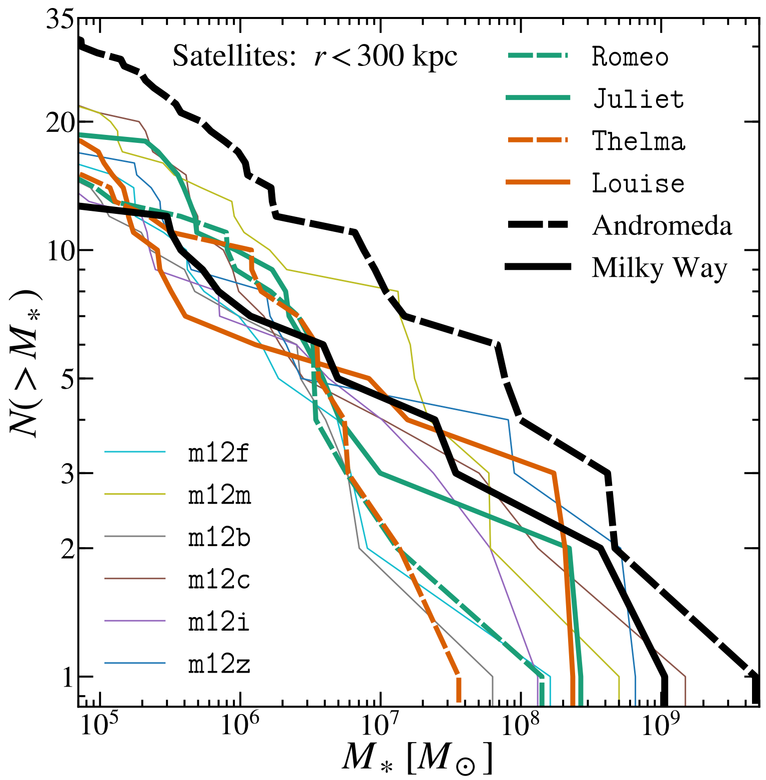
key idea about ‘sub-grid’

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

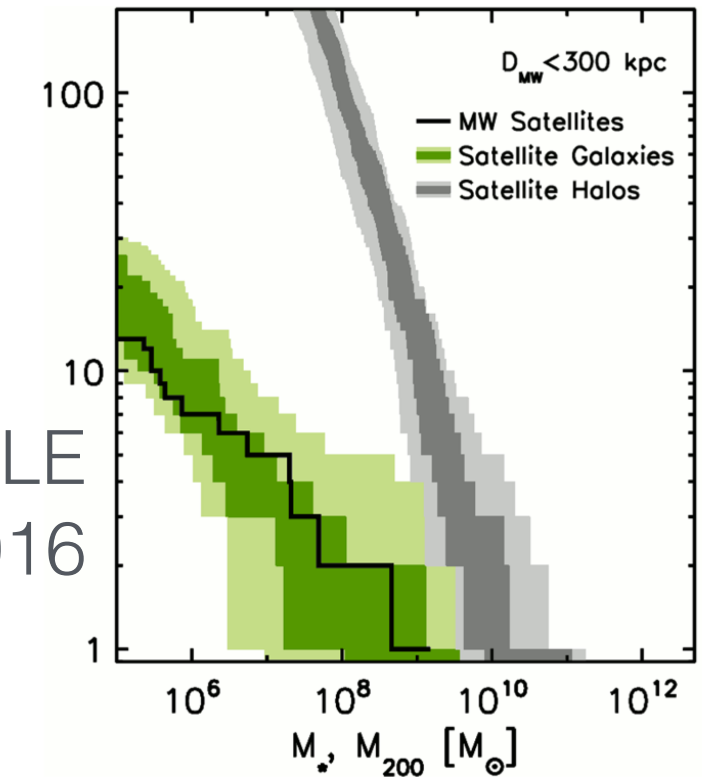
considerations for modeling stellar halos

- 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)

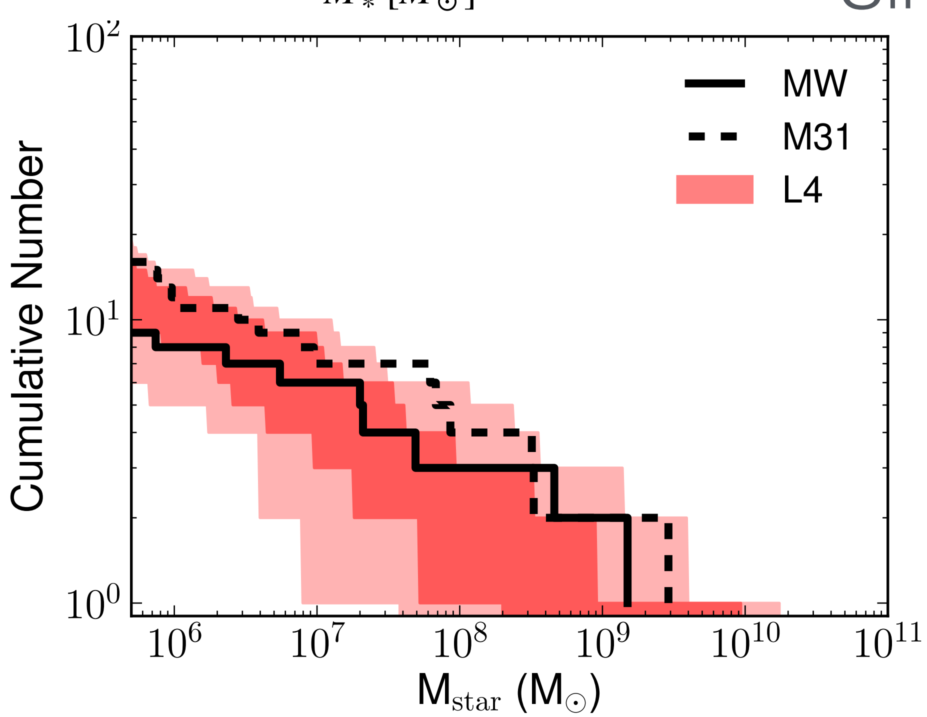


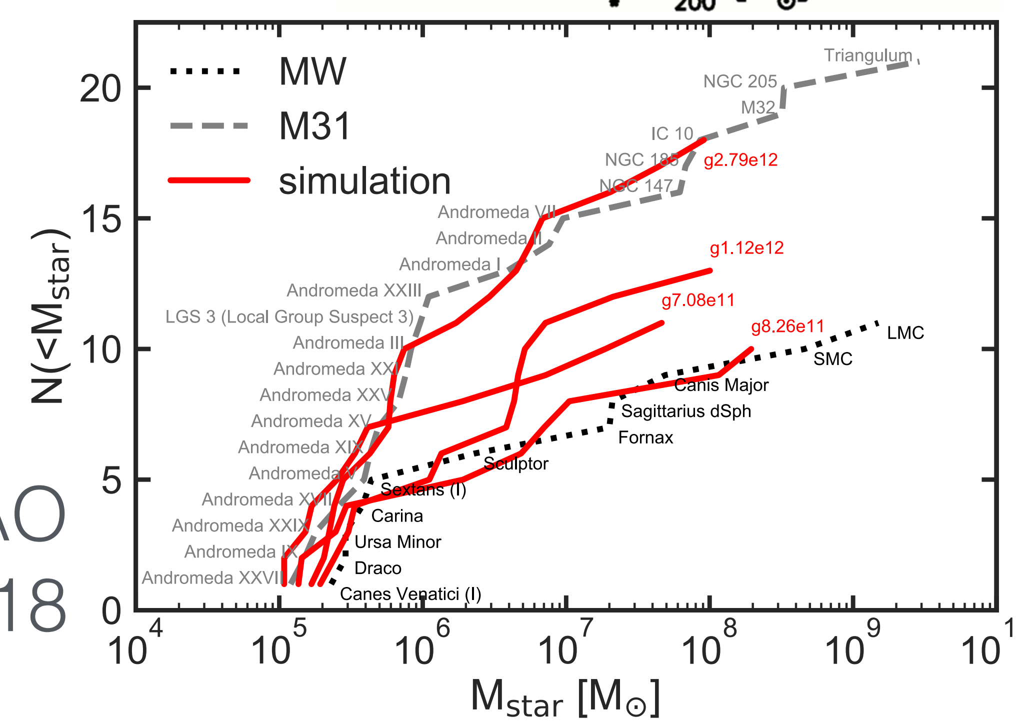
FIRE
Garrison-Kimmel et al 2018



APOSTLE
Sawala et al 2016

Auriga
Simpson et al 2018

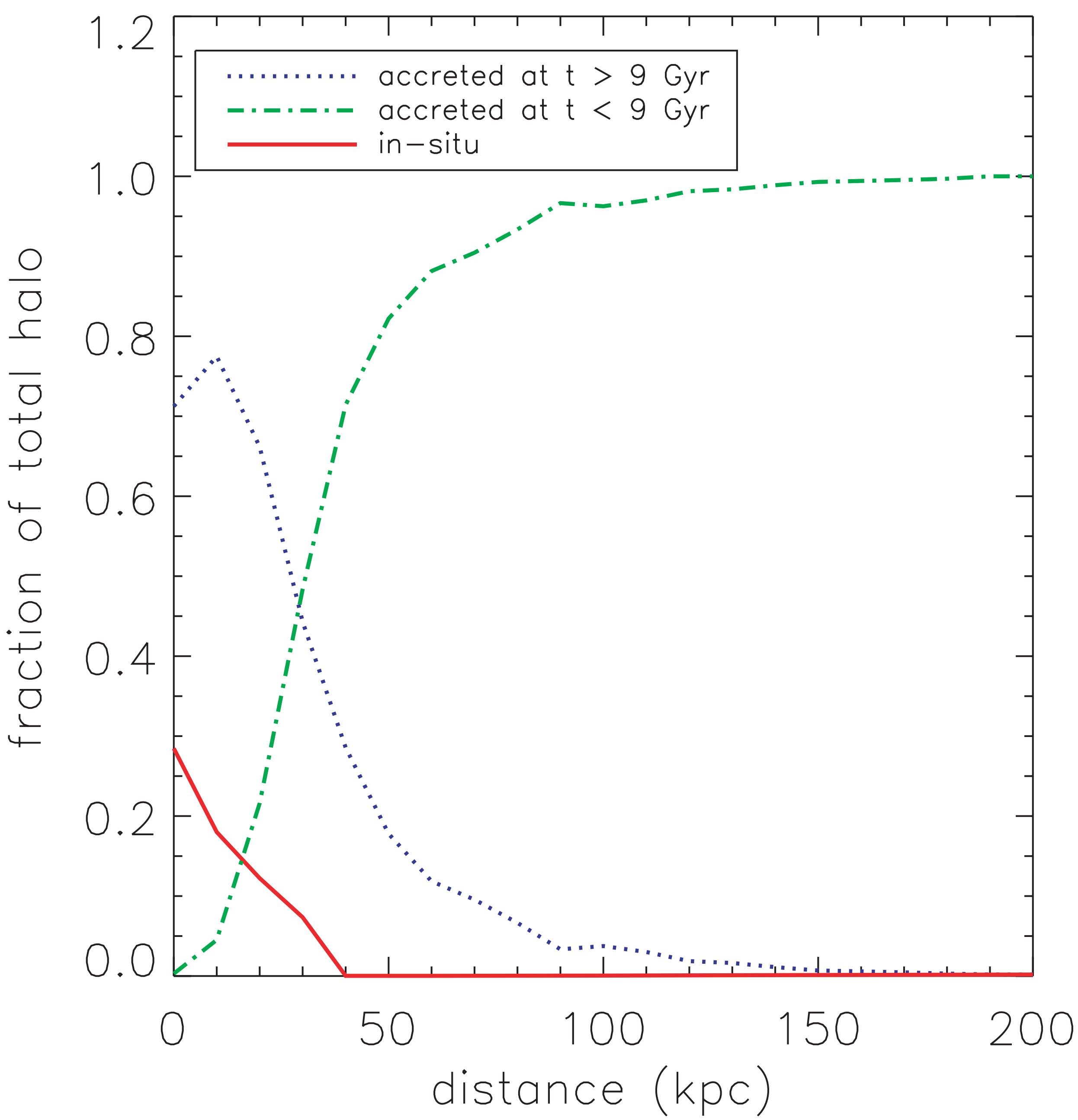




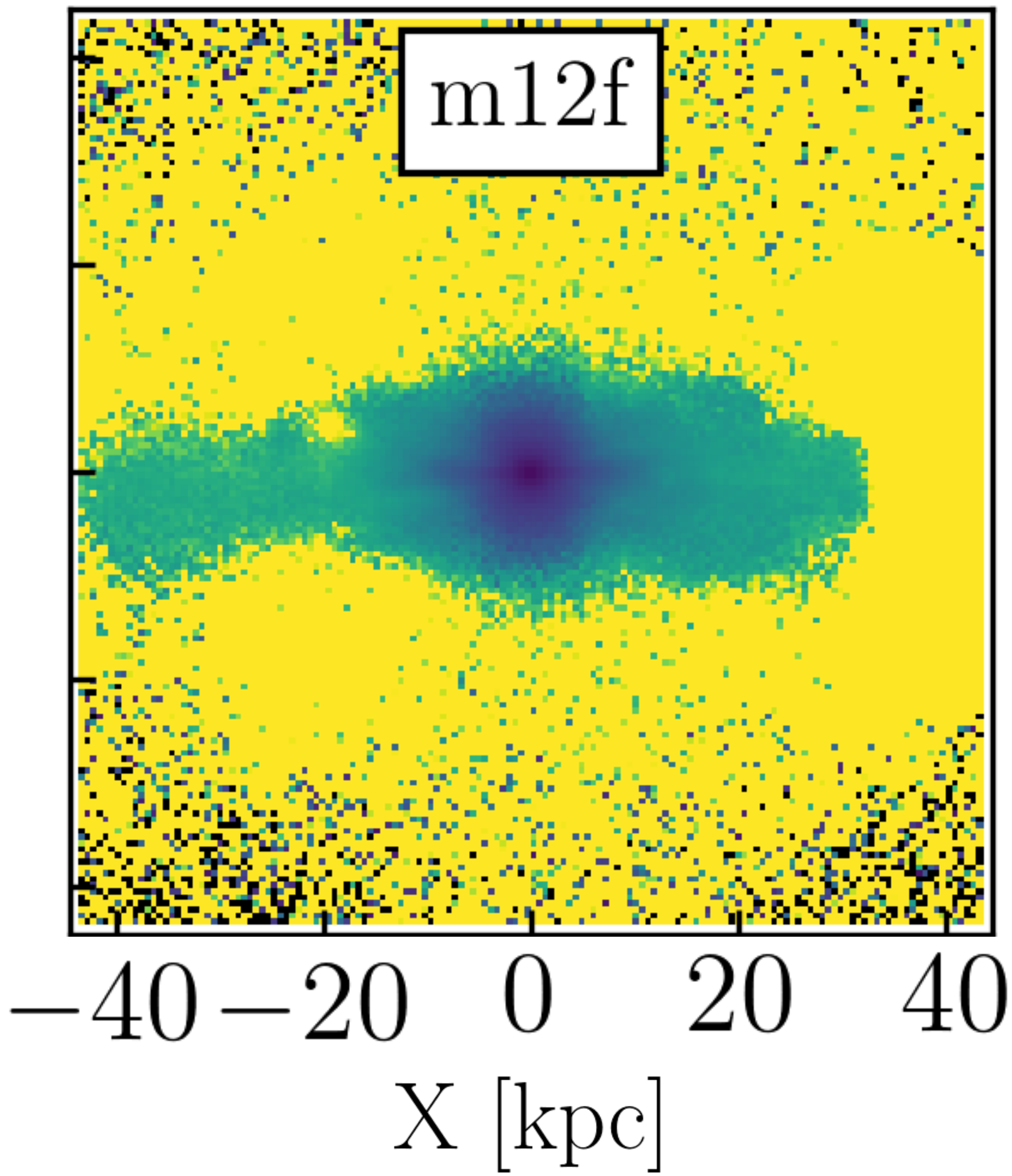
NIHAO
Buck et al 2018

cosmological hydrodynamic simulations are critical for modeling contribution from **in-situ** stars

Zolotov et al 2009

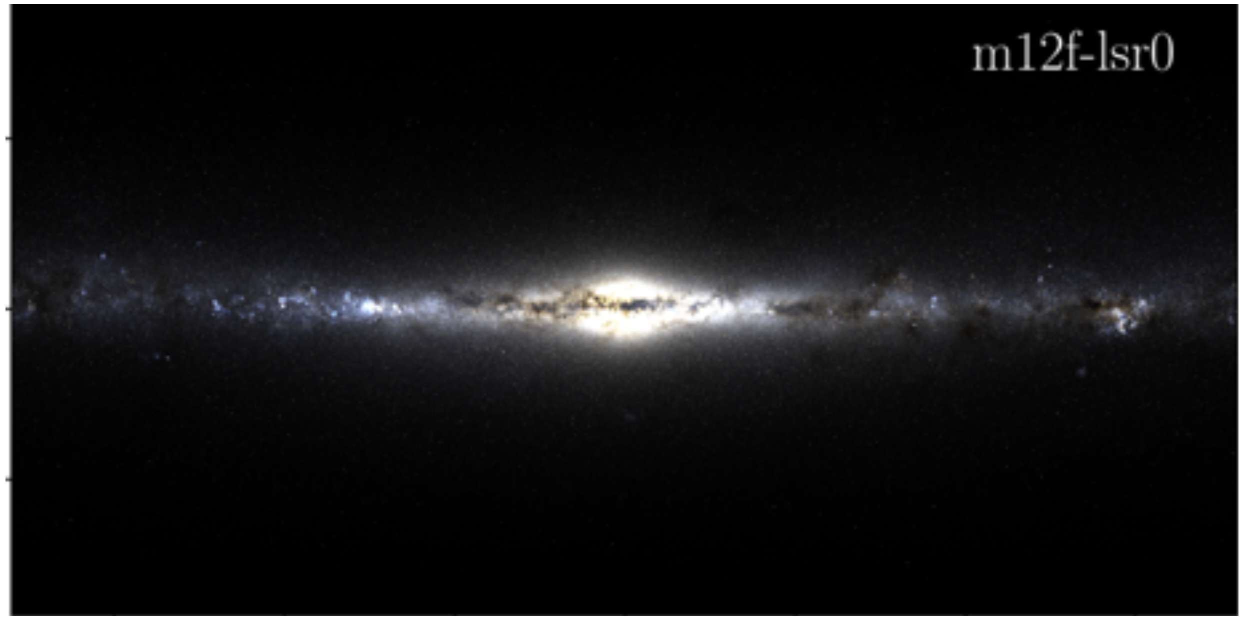


Sanderson et al 2018



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!)